

Complete Dictionary Recovery over the Sphere I: Overview and the Geometric Picture

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Abstract

We consider the problem of recovering a complete (i.e., square and invertible) matrix \mathbf{A}_0 , from $\mathbf{Y} \in \mathbb{R}^{n \times p}$ with $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$, provided \mathbf{X}_0 is sufficiently sparse. This recovery problem is central to the theoretical understanding of dictionary learning, which seeks a sparse representation for a collection of input signals, and finds numerous applications in modern signal processing and machine learning. We give the first efficient algorithm that provably recovers \mathbf{A}_0 when \mathbf{X}_0 has $O(n)$ nonzeros per column, under suitable probability model for \mathbf{X}_0 . In contrast, prior results based on efficient algorithms provide recovery guarantees when \mathbf{X}_0 has only $O(n^{1-\delta})$ nonzeros per column for any constant $\delta \in (0, 1)$.

Our algorithmic pipeline centers around solving a certain nonconvex optimization problem with a spherical constraint. In this paper, we provide a geometric characterization of the high-dimensional objective landscape. In particular, we show that the problem is highly structured: with high probability there are no “spurious” local minimizers and all saddle points are second-order. This distinctive structure makes the problem amenable to efficient algorithms. In a companion paper [3], we design a second-order trust-region algorithm over the sphere that provably converges to a local minimizer with an arbitrary initialization, despite the presence of saddle points.

Index Terms

Dictionary learning, Nonconvex optimization, Spherical constraint, Escaping saddle points, Trust-region method, Manifold optimization, Function landscape, Second-order geometry, Inverse problem, Structured signal, Nonlinear approximation

I. INTRODUCTION

Given p signal samples from \mathbb{R}^n , i.e., $\mathbf{Y} \doteq [\mathbf{y}_1, \dots, \mathbf{y}_p]$, is it possible to construct a dictionary $\mathbf{A} \doteq [\mathbf{a}_1, \dots, \mathbf{a}_m]$ with m much smaller than p , such that $\mathbf{Y} \approx \mathbf{A}\mathbf{X}$ and the coefficient matrix \mathbf{X} has as few nonzeros as possible? In other words, this model *dictionary learning* (DL) problem seeks a concise representation for a collection of input signals. Concise signal representations play a central role in compression, and also prove useful for many other important tasks, such as signal acquisition, denoising, and classification.

Traditionally, concise signal representations have relied heavily on explicit analytic bases constructed in nonlinear approximation and harmonic analysis. This constructive approach has proved highly successfully; the numerous theoretical advances in these fields (see, e.g., [4]–[8] for summary of relevant results) provide ever more powerful representations, ranging from the classic Fourier to modern multidimensional, multidirectional, multiresolution bases, including wavelets, curvelets, ridgelets, and so on. However, two challenges confront practitioners in adapting these results to new domains: which function class best describes signals at hand, and consequently which representation is most appropriate. These challenges are coupled, as function classes with known “good” analytic bases are rare.¹

Around 1996, neuroscientists Olshausen and Field discovered that sparse coding, the principle of encoding a signal with few atoms from a learned dictionary, reproduces important properties of the receptive fields of the simple cells that perform early visual processing [10], [11]. The discovery has spurred a flurry of algorithmic developments and successful applications for DL in the past two decades, spanning classical image processing, visual recognition, compressive signal acquisition, and also recent deep architectures for signal classification (see, e.g., [12], [13] for review of this development).

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¹As Donoho et al [9] put it, “...in effect, uncovering the optimal codebook structure of naturally occurring data involves more challenging empirical questions than any that have ever been solved in empirical work in the mathematical sciences.”

The learning approach is particularly relevant to modern signal processing and machine learning, which deal with data of huge volume and great variety (e.g., images, audios, graphs, texts, genome sequences, time series, etc). The proliferation of problems and data seems to preclude analytically deriving optimal representations for each new class of data in a timely manner. On the other hand, as datasets grow, learning dictionaries directly from data looks increasingly attractive and promising. When armed with sufficiently many data samples of one signal class, by solving the model DL problem, one would expect to obtain a dictionary that allows sparse representation for the whole class. This hope has been borne out in a number of successful examples [12], [13] and theories [14]–[17].

A. Theoretical and Algorithmic Challenges

In contrast to the above empirical successes, the theoretical study of dictionary learning is still developing. For applications in which dictionary learning is to be applied in a “hands-free” manner, it is desirable to have efficient algorithms which are guaranteed to perform correctly, when the input data admit a sparse model. There have been several important recent results in this direction, which we will review in Section I-E, after our sketching main results. Nevertheless, obtaining algorithms that provably succeed under broad and realistic conditions remains an important research challenge.

To understand where the difficulties arise, we can consider a model formulation, in which we attempt to obtain the dictionary \mathbf{A} and coefficients \mathbf{X} which best trade-off sparsity and fidelity to the observed data:

$$\text{minimize}_{\mathbf{A} \in \mathbb{R}^{n \times m}, \mathbf{X} \in \mathbb{R}^{m \times p}} \lambda \|\mathbf{X}\|_1 + \frac{1}{2} \|\mathbf{A}\mathbf{X} - \mathbf{Y}\|_F^2, \text{ subject to } \mathbf{A} \in \mathcal{A}. \quad (\text{I.1})$$

Here, $\|\mathbf{X}\|_1 \doteq \sum_{i,j} |X_{ij}|$ promotes sparsity of the coefficients, $\lambda \geq 0$ trades off the level of coefficient sparsity and quality of approximation, and \mathcal{A} imposes desired structures on the dictionary.

This formulation is nonconvex: the admissible set \mathcal{A} is typically nonconvex (e.g., orthogonal group, matrices with normalized columns)², while the most daunting nonconvexity comes from the bilinear mapping: $(\mathbf{A}, \mathbf{X}) \mapsto \mathbf{A}\mathbf{X}$. Because (\mathbf{A}, \mathbf{X}) and $(\mathbf{A}\mathbf{\Pi}\mathbf{\Sigma}, \mathbf{\Sigma}^{-1}\mathbf{\Pi}^*\mathbf{X})$ result in the same objective value for the conceptual formulation (I.1), where $\mathbf{\Pi}$ is any permutation matrix, and $\mathbf{\Sigma}$ any diagonal matrix with diagonal entries in $\{\pm 1\}$, and $(\cdot)^*$ denotes matrix transpose. Thus, we should expect the problem to have combinatorially many global minimizers. Because there are multiple isolated global minimizers, the problem does not appear to be amenable to convex relaxation (see similar discussions in, e.g., [20] and [21]).³ This contrasts sharply with problems in sparse recovery and compressed sensing, in which simple convex relaxations are often provably effective [24]–[33]. Is there any hope to obtain global solutions to the DL problem?

B. An Intriguing Numerical Experiment with Real Images

We provide empirical evidence in support of a positive answer to the above question. Specifically, we learn orthogonal bases (orthobases) for real images patches. Orthobases are of interest because typical hand-designed dictionaries such as discrete cosine (DCT) and wavelet bases are orthogonal, and orthobases seem competitive in performance for applications such as image denoising, as compared to overcomplete dictionaries [34]⁴.

We divide a given greyscale image into 8×8 non-overlapping patches, which are converted into 64-dimensional vectors and stacked column-wise into a data matrix \mathbf{Y} . Specializing (I.1) to this setting, we obtain the optimization problem:

$$\text{minimize}_{\mathbf{A} \in \mathbb{R}^{n \times n}, \mathbf{X} \in \mathbb{R}^{n \times p}} \lambda \|\mathbf{X}\|_1 + \frac{1}{2} \|\mathbf{A}\mathbf{X} - \mathbf{Y}\|_F^2, \text{ subject to } \mathbf{A} \in O_n. \quad (\text{I.2})$$

²For example, in nonlinear approximation and harmonic analysis, orthonormal basis or (tight-)frames are preferred; to fix the scale ambiguity discussed in the text, a common practice is to require that \mathbf{A} to be column-normalized. There is no obvious reason to believe that convexifying these constraint sets would leave the optima unchanged. For example, the convex hull of the orthogonal group O_n is the operator norm ball $\{\mathbf{X} \in \mathbb{R}^{n \times n} : \|\mathbf{X}\| \leq 1\}$. If there are no effective symmetry breaking constraints, any convex objective function tends to have minimizers inside the ball, which obviously will not be orthogonal matrices. Other ideas such as lifting may not play together with the objective function, nor yield tight relaxations (see, e.g., [18], [19]).

³Semidefinite programming (SDP) lifting may be one useful general strategy to convexify bilinear inverse problems, see, e.g., [22], [23]. However, for problems with general nonlinear constraints, it is unclear whether the lifting always yield tight relaxation, consider, e.g., [18], [19] again.

⁴See Section I-C for more detailed discussions of this point. [35] also gave motivations and algorithms for learning (union of) orthobases as dictionaries.

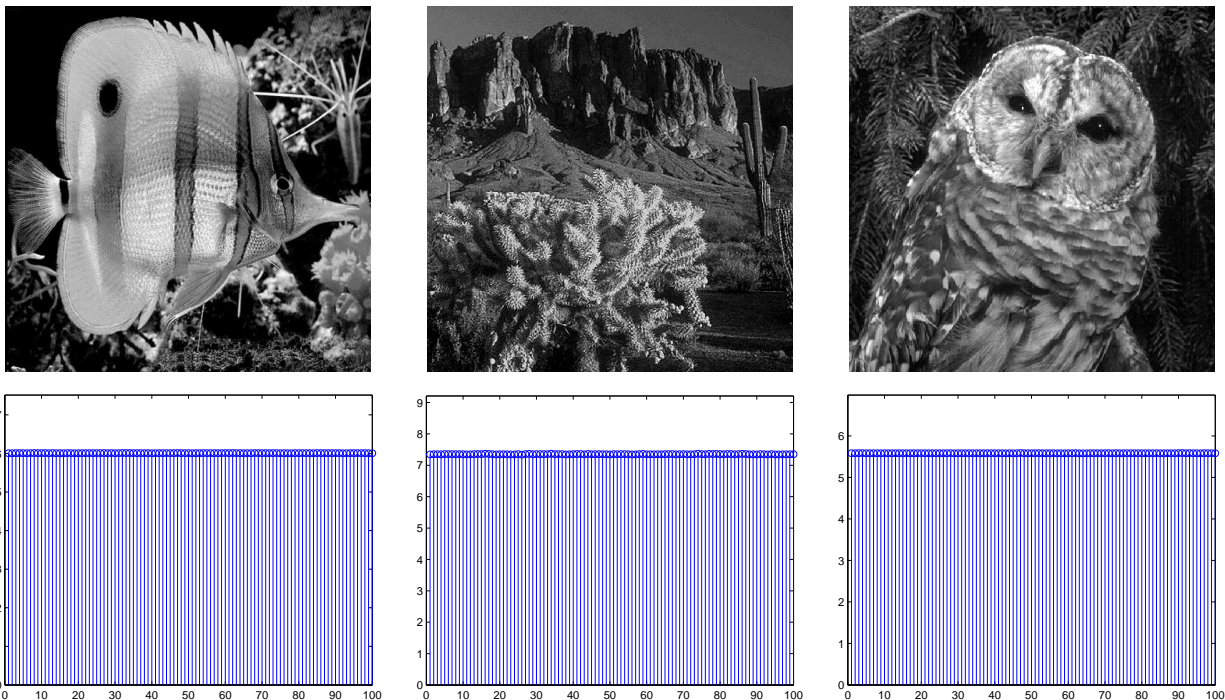


Fig. 1: **Alternating direction method for (I.2) on uncompressed real images seems to always produce the same solution!** **Top:** Each image is 512×512 in resolution and encoded in the uncompressed `pgm` format (uncompressed images to prevent possible bias towards standard bases used for compression, such as DCT or wavelet bases). Each image is evenly divided into 8×8 non-overlapping image patches (4096 in total), and these patches are all vectorized and then stacked as columns of the data matrix \mathbf{Y} . **Bottom:** Given each \mathbf{Y} , we solve (I.2) 100 times with independent and randomized (uniform over the orthogonal group) initialization \mathbf{A}_0 . The plots show the values of $\|\mathbf{A}_\infty^* \mathbf{Y}\|_1$ across the independent repetitions. They are virtually the same and the relative differences are less than 10^{-3} !

To derive a concrete algorithm for (I.2), one can deploy the alternating direction method (ADM)⁵, i.e., alternately minimizing the objective function with respect to (w.r.t.) one variable while fixing the other. The iteration sequence actually takes very simple form: for $k = 1, 2, 3, \dots$,

$$\mathbf{X}_k = \mathcal{S}_\lambda [\mathbf{A}_{k-1}^* \mathbf{Y}], \quad \mathbf{A}_k = \mathbf{U}\mathbf{V}^* \text{ for } \mathbf{U}\mathbf{D}\mathbf{V}^* = \text{SVD}(\mathbf{Y}\mathbf{X}_k^*)$$

where $\mathcal{S}_\lambda[\cdot]$ denotes the well-known soft-thresholding operator acting elementwise on matrices, i.e., $\mathcal{S}_\lambda[x] \doteq \text{sign}(x) \max(|x| - \lambda, 0)$ for any scalar x .

Fig. 1 shows what we obtained using the simple ADM algorithm, with *independent and randomized initializations*:

The algorithm seems to always produce the same optimal value, regardless of the initialization.

This observation implies the heuristic ADM algorithm may *always converge to one global minimizer!*⁶ Equally surprising is that the phenomenon has been observed on real images⁷. One may imagine only random data typically have “favorable” structures; in fact, almost all existing theories for DL pertain only to random data [40]–[45].

C. Dictionary Recovery and Our Results

In this paper, we take a step towards explaining the surprising effectiveness of nonconvex optimization heuristics for DL. We focus on the *dictionary recovery* (DR) setting: given a data matrix \mathbf{Y} generated as $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$, where

⁵This method is also called alternating minimization or (block) coordinate descent method. see, e.g., [36], [37] for classic results and [38], [39] for several interesting recent developments.

⁶Technically, the converge to global solutions is surprising because even convergence of ADM to critical points is atypical, see, e.g., [38], [39] and references therein. Section III includes more detailed discussions on this point.

⁷Actually the same phenomenon is also observed for simulated data when the coefficient matrix obeys the Bernoulli-Gaussian model, which is defined later. The result on real images supports that previously claimed empirical successes over two decades may be non-incidental.

$\mathbf{A}_0 \in \mathcal{A} \subseteq \mathbb{R}^{n \times m}$ and $\mathbf{X}_0 \in \mathbb{R}^{m \times p}$ is “reasonably sparse”, try to recover \mathbf{A}_0 and \mathbf{X}_0 . Here recovery means to return any pair $(\mathbf{A}_0 \mathbf{\Pi} \mathbf{\Sigma}, \mathbf{\Sigma}^{-1} \mathbf{\Pi}^* \mathbf{X}_0)$, where $\mathbf{\Pi}$ is a permutation matrix and $\mathbf{\Sigma}$ is a nonsingular diagonal matrix, i.e., recovering up to sign, scale, and permutation.

To define a reasonably simple and structured problem, we make the following assumptions:

- The target dictionary \mathbf{A}_0 is complete, i.e., square and invertible ($m = n$). In particular, this class includes orthogonal dictionaries. Admittedly overcomplete dictionaries tend to be more powerful for modeling and to allow sparser representations. Nevertheless, most classic hand-designed dictionaries in common use are orthogonal. Orthobases are competitive in performance for certain tasks such as image denoising [34], and admit faster algorithms for learning and encoding.⁸
- The coefficient matrix \mathbf{X}_0 follows the Bernoulli-Gaussian (BG) model with rate θ : $[\mathbf{X}_0]_{ij} = \Omega_{ij} V_{ij}$, with $\Omega_{ij} \sim \text{Ber}(\theta)$ and $V_{ij} \sim \mathcal{N}(0, 1)$, where all the different random variables are jointly independent. We write compactly $\mathbf{X}_0 \sim_{i.i.d.} \text{BG}(\theta)$.

In this paper, we provide a nonconvex formulation for the DR problem, and characterize the geometric structure of the formulation that allows development of efficient algorithms for optimization. In the companion paper [3], we derive an efficient algorithm taking advantage of the structure, and describe a complete algorithmic pipeline for efficient recovery. Together, we prove the following result:

Theorem I.1 (Informal statement of our results, a detailed version included in the companion paper [3]). *For any $\theta \in (0, 1/3)$, given $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$ with \mathbf{A}_0 a complete dictionary and $\mathbf{X}_0 \sim_{i.i.d.} \text{BG}(\theta)$, there is a polynomial time algorithm that recovers (up to sign, scale, and permutation) \mathbf{A}_0 and \mathbf{X}_0 with high probability (at least $1 - O(p^{-6})$) whenever $p \geq p_*(n, 1/\theta, \kappa(\mathbf{A}_0), 1/\mu)$ for a fixed polynomial $p_*(\cdot)$, where $\kappa(\mathbf{A}_0)$ is the condition number of \mathbf{A}_0 and μ is a parameter that can be set as $cn^{-5/4}$ for a fixed positive numerical constant c .*

Obviously, even if \mathbf{X}_0 is known, one needs $p \geq n$ to make the identification problem well posed. Under our particular probabilistic model, a simple coupon collection argument implies that one needs $p \geq \Omega(\frac{1}{\theta} \log n)$ to ensure all atoms in \mathbf{A}_0 are observed with high probability (w.h.p.). To ensure that an efficient algorithm exists may demand more. Our result implies when p is polynomial in n , $1/\theta$ and $\kappa(\mathbf{A}_0)$, recovery with efficient algorithm is possible.

The parameter θ controls the sparsity level of \mathbf{X}_0 . Intuitively, the recovery problem is easy for small θ and becomes harder for large θ .⁹ It is perhaps surprising that an efficient algorithm can succeed up to constant θ , i.e., linear sparsity in \mathbf{X}_0 . Compared to the case when \mathbf{A}_0 is known, there is only at most a constant gap in the sparsity level one can deal with.

For DL, our result gives the first efficient algorithm that provably recovers complete \mathbf{A}_0 and \mathbf{X}_0 when \mathbf{X}_0 has $O(n)$ nonzeros per column under appropriate probability model. Section I-E provides detailed comparison of our result with other recent recovery results for complete and overcomplete dictionaries.

D. Main Ingredients and Innovations

In this section we describe three main ingredients that we use to obtain the stated result.

1) **A Nonconvex Formulation:** Since $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$ and \mathbf{A}_0 is complete, $\text{row}(\mathbf{Y}) = \text{row}(\mathbf{X}_0)$ ($\text{row}(\cdot)$ denotes the row space of a matrix) and hence rows of \mathbf{X}_0 are sparse vectors in the known (linear) subspace $\text{row}(\mathbf{Y})$. We can use this fact to first recover the rows of \mathbf{X}_0 , and subsequently recover \mathbf{A}_0 by solving a system of linear equations. In fact, for $\mathbf{X}_0 \sim_{i.i.d.} \text{BG}(\theta)$, rows of \mathbf{X}_0 are the n sparsest vectors (directions) in $\text{row}(\mathbf{Y})$ w.h.p. whenever $p \geq \Omega(n \log n)$ [40]. Thus one might try to recover rows of \mathbf{X}_0 by solving

$$\text{minimize } \|\mathbf{q}^* \mathbf{Y}\|_0 \quad \text{subject to } \mathbf{q} \neq \mathbf{0}. \quad (\text{I.3})$$

The objective is discontinuous, and the domain is an open set. In particular, the homogeneous constraint is nonconventional and tricky to deal with. Since the recovery is up to scale, one can remove the homogeneity by fixing

⁸Empirically, there is no systematic evidence supporting that overcomplete dictionaries are strictly necessary for good performance in all published applications (though [11] argues for the necessity from neuroscience perspective). Some of the ideas and tools developed here for complete dictionaries may also apply to certain classes of structured overcomplete dictionaries, such as tight frames. See Section III for relevant discussion.

⁹Indeed, when θ is small enough such that columns of \mathbf{X}_0 are predominately 1-sparse, one directly observes scaled versions of the atoms (i.e., columns of \mathbf{X}_0); when \mathbf{X}_0 is fully dense corresponding to $\theta = 1$, recovery is never possible as one can easily find another complete \mathbf{A}'_0 and fully dense \mathbf{X}'_0 such that $\mathbf{Y} = \mathbf{A}'_0 \mathbf{X}'_0$ with \mathbf{A}'_0 not equivalent to \mathbf{A}_0 .

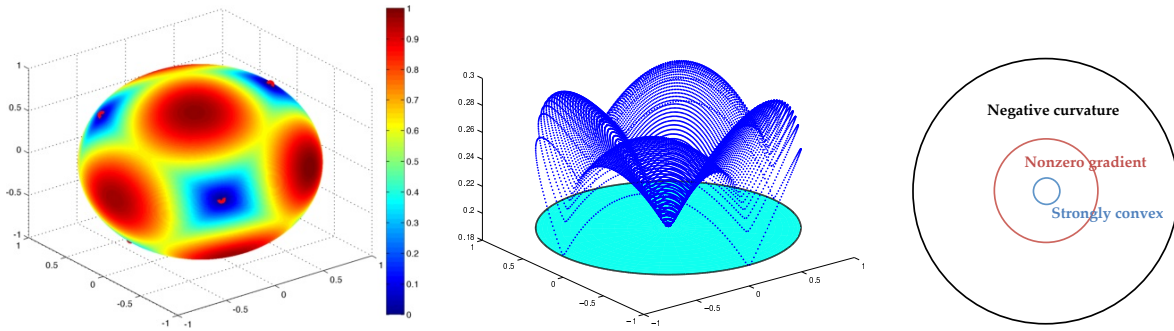


Fig. 2: **Why is dictionary learning over \mathbb{S}^{n-1} tractable?** Assume the target dictionary \mathbf{A}_0 is orthogonal. **Left:** Large sample objective function $\mathbb{E}_{\mathbf{X}_0} [f(\mathbf{q})]$. The only local minimizers are the columns of \mathbf{A}_0 and their negatives. **Center:** The same function, visualized as a height above the plane \mathbf{a}_1^\perp (\mathbf{a}_1 is the first column of \mathbf{A}_0 , and is also a global minimizer). **Right:** Around \mathbf{a}_1 , the function exhibits a small region of positive curvature, a region of large gradient, and finally a region in which the direction away from \mathbf{a}_1 is a direction of negative curvature.

the scale of \mathbf{q} . Known relaxations [40], [46] fix the scale by setting $\|\mathbf{q}^* \mathbf{Y}\|_\infty = 1$, where $\|\cdot\|_\infty$ is the elementwise ℓ^∞ norm. The optimization problem reduces to a sequence of convex programs, which recover $(\mathbf{A}_0, \mathbf{X}_0)$ for very sparse \mathbf{X}_0 , but provably break down when columns of \mathbf{X}_0 has more than $O(\sqrt{n})$ nonzeros, or $\theta \geq \Omega(1/\sqrt{n})$. Inspired by our previous image experiment, we work with a *nonconvex* alternative¹⁰:

$$\text{minimize } f(\mathbf{q}; \hat{\mathbf{Y}}) \doteq \frac{1}{p} \sum_{k=1}^p h_\mu(\mathbf{q}^* \hat{\mathbf{y}}_k), \text{ subject to } \|\mathbf{q}\| = 1, \quad (\text{I.4})$$

where $\hat{\mathbf{Y}} \in \mathbb{R}^{n \times p}$ is a proxy for \mathbf{Y} (i.e., after appropriate processing), k indexes columns of $\hat{\mathbf{Y}}$, and $\|\cdot\|$ is the usual ℓ^2 norm for vectors. Here $h_\mu(\cdot)$ is chosen to be a convex smooth approximation to $|\cdot|$, namely,

$$h_\mu(z) = \mu \log \left(\frac{\exp(z/\mu) + \exp(-z/\mu)}{2} \right) = \mu \log \cosh(z/\mu), \quad (\text{I.5})$$

which is infinitely differentiable and μ controls the smoothing level.¹¹ The spherical constraint is nonconvex. Hence, a-priori, it is unclear whether (I.4) admits efficient algorithms that attain global optima. Surprisingly, simple descent algorithms for (I.4) exhibit very striking behavior: on many practical numerical examples¹², they appear to produce global solutions. Our next section will uncover interesting geometrical structures underlying the phenomenon.

2) **A Glimpse into High-dimensional Function Landscape:** For the moment, suppose \mathbf{A}_0 is orthogonal, and take $\hat{\mathbf{Y}} = \mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$ in (I.4). Fig. 2 (left) plots $\mathbb{E}_{\mathbf{X}_0} [f(\mathbf{q}; \mathbf{Y})]$ over $\mathbf{q} \in \mathbb{S}^2$ ($n = 3$). Remarkably, $\mathbb{E}_{\mathbf{X}_0} [f(\mathbf{q}; \mathbf{Y})]$ has no spurious local minimizers. In fact, every local minimizer $\hat{\mathbf{q}}$ produces a row of \mathbf{X}_0 : $\hat{\mathbf{q}}^* \mathbf{Y} = \mathbf{e}_i^* \mathbf{X}_0$ for a certain $i \in \{1, \dots, n\}$.

To better illustrate the point, we take the particular case $\mathbf{A}_0 = \mathbf{I}$ and project the upper hemisphere above the equatorial plane \mathbf{e}_3^\perp onto \mathbf{e}_3^\perp . The projection is bijective and we equivalently define a reparameterization $g: \mathbf{e}_3^\perp \mapsto \mathbb{R}^2$ of f . Fig. 2 (center) plots the graph of g . Obviously the only local minimizers are $\mathbf{0}, \pm \mathbf{e}_1, \pm \mathbf{e}_2$, and they are also global minimizers. Moreover, the apparent nonconvex landscape has interesting structures around $\mathbf{0}$: when moving away from $\mathbf{0}$, one sees successively a strongly convex region, a nonzero gradient region, and a region where at each point one can always find a direction of negative curvature, as shown schematically in Fig. 2 (right). This geometry implies that at any nonoptimal point, there is always at least one direction of descent. Thus, any algorithm that can take advantage of the descent directions will likely converge to one global minimizer, irrespective of initialization.

Two challenges stand out when implementing this idea. For geometry, one has to show similar structure exists for general complete \mathbf{A}_0 , in high dimensions ($n \geq 3$), when the number of observations p is finite (vs. the expectation

¹⁰A similar formulation has been proposed in [47] in the context of blind source separation; see also [48].

¹¹In fact, there is nothing special about this choice and we believe that any valid smooth (twice continuously differentiable) approximation to $|\cdot|$ would work and yield qualitatively similar results. We also have some preliminary results showing the latter geometric picture remains the same for certain nonsmooth functions, such as a modified version of the Huber function, though the analysis involves handling a different set of technical subtleties. The algorithm also needs additional modifications.

¹²... not restricted to the model we assume here for \mathbf{A}_0 and \mathbf{X}_0 .

in the experiment). For algorithms, we need to be able to take advantage of this structure without knowing \mathbf{A}_0 ahead of time. In Section I-D3, we describe a Riemannian trust region method which addresses the latter challenge.

a) Geometry for orthogonal \mathbf{A}_0 .: In this case, we take $\hat{\mathbf{Y}} = \mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$. Since $f(\mathbf{q}; \mathbf{A}_0 \mathbf{X}_0) = f(\mathbf{A}_0^* \mathbf{q}; \mathbf{X}_0)$, the landscape of $f(\mathbf{q}; \mathbf{A}_0 \mathbf{X}_0)$ is simply a rotated version of that of $f(\mathbf{q}; \mathbf{X}_0)$, i.e., when $\mathbf{A}_0 = \mathbf{I}$. Hence we will focus on the case when $\mathbf{A}_0 = \mathbf{I}$. Among the $2n$ symmetric sections of \mathbb{S}^{n-1} centered around the signed basis vectors $\pm e_1, \dots, \pm e_n$, we work with the symmetric section around e_n as an example. The result will carry over to all sections with the same argument; together this provides a complete characterization of the function $f(\mathbf{q}; \mathbf{X}_0)$ over \mathbb{S}^{n-1} .

We again invoke the projection trick described above, this time onto the equatorial plane e_n^\perp . This can be formally captured by the reparameterization mapping:

$$\mathbf{q}(\mathbf{w}) = \left(\mathbf{w}, \sqrt{1 - \|\mathbf{w}\|^2} \right), \quad \mathbf{w} \in \mathbb{B}^{n-1}, \quad (\text{I.6})$$

where \mathbf{w} is the new variable in $e_n^\perp \cap \mathbb{B}^{n-1}$ and \mathbb{B}^{n-1} is the unit ball in \mathbb{R}^{n-1} . We first study the composition $g(\mathbf{w}; \mathbf{X}_0) \doteq f(\mathbf{q}(\mathbf{w}); \mathbf{X}_0)$ over the set

$$\Gamma \doteq \left\{ \mathbf{w} : \|\mathbf{w}\| < \sqrt{\frac{4n-1}{4n}} \right\}. \quad (\text{I.7})$$

It can be verified the section we chose to work with is contained in this set¹³.

Our analysis characterizes the properties of $g(\mathbf{w}; \mathbf{X}_0)$ by studying three quantities

$$\nabla^2 g(\mathbf{w}; \mathbf{X}_0), \quad \frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0)}{\|\mathbf{w}\|}, \quad \frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2}$$

respectively over three consecutive regions moving away from the origin, corresponding to the three regions in Fig. 2 (right). In particular, through typical expectation-concentration style argument, we show that there exists a positive constant c such that

$$\nabla^2 g(\mathbf{w}; \mathbf{X}_0) \succeq \frac{1}{\mu} c \theta \mathbf{I}, \quad \frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0)}{\|\mathbf{w}\|} \geq c \theta, \quad \frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} \leq -c \theta \quad (\text{I.8})$$

over the respective regions w.h.p., confirming our low-dimensional observations described above. In particular, the favorable structure we observed for $n = 3$ persists in high dimensions, w.h.p., even when p is large *yet finite*, for the case \mathbf{A}_0 is orthogonal. Moreover, the local minimizer of $g(\mathbf{w}; \mathbf{X}_0)$ over Γ is very close to $\mathbf{0}$, within a distance of $O(\mu)$.

b) Geometry for complete \mathbf{A}_0 .: For general complete dictionaries \mathbf{A}_0 , we hope that the function f retains the nice geometric structure discussed above. We can ensure this by ‘‘preconditioning’’ \mathbf{Y} such that the output looks as if being generated from a certain orthogonal matrix, possibly plus a small perturbation. We can then argue that the perturbation does not significantly affect qualitative properties of the landscape of the objective function. Write

$$\bar{\mathbf{Y}} = \left(\frac{1}{p\theta} \mathbf{Y} \mathbf{Y}^* \right)^{-1/2} \mathbf{Y}. \quad (\text{I.9})$$

Note that for $\mathbf{X}_0 \sim_{i.i.d.} \text{BG}(\theta)$, $\mathbb{E}[\mathbf{X}_0 \mathbf{X}_0^*] / (p\theta) = \mathbf{I}$. Thus, one expects $\frac{1}{p\theta} \mathbf{Y} \mathbf{Y}^* = \frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^*$ to behave roughly like $\mathbf{A}_0 \mathbf{A}_0^*$ and hence $\bar{\mathbf{Y}}$ to behave like

$$(\mathbf{A}_0 \mathbf{A}_0^*)^{-1/2} \mathbf{A}_0 \mathbf{X}_0 = \mathbf{U} \mathbf{V}^* \mathbf{X}_0 \quad (\text{I.10})$$

where we write the SVD of \mathbf{A}_0 as $\mathbf{A}_0 = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^*$. It is easy to see $\mathbf{U} \mathbf{V}^*$ is an orthogonal matrix. Hence the preconditioning scheme we have introduced is technically sound.

Our analysis shows that $\bar{\mathbf{Y}}$ can be written as

$$\bar{\mathbf{Y}} = \mathbf{U} \mathbf{V}^* \mathbf{X}_0 + \mathbf{\Xi} \mathbf{X}_0, \quad (\text{I.11})$$

where $\mathbf{\Xi}$ is a matrix with small magnitude. Simple perturbation argument shows that the constant c in (I.8) is at most shrunk to $c/2$ for all \mathbf{w} when p is sufficiently large. Thus, the qualitative aspects of the geometry have not been changed by the perturbation.

¹³Indeed, if $\langle \mathbf{q}, \mathbf{e}_n \rangle \geq |\langle \mathbf{q}, \mathbf{e}_i \rangle|$ for any $i \neq n$, $1 - \|\mathbf{w}\|^2 = q_n^2 \geq 1/n$, implying $\|\mathbf{w}\|^2 \leq \frac{n-1}{n} < \frac{4n-1}{4n}$. The reason we have defined an open set instead of a closed (compact) one is to avoid potential trivial local minimizers located on the boundary.

3) **A Second-order Algorithm on Manifold: Riemannian Trust-Region Method:** We do not know \mathbf{A}_0 ahead of time, so our algorithm needs to take advantage of the structure described above without knowledge of \mathbf{A}_0 . Intuitively, this seems possible as the descent direction in the \mathbf{w} space appears to also be a local descent direction for f over the sphere. Another issue is that although the optimization problem has no spurious local minimizers, it does have many saddle points with indefinite Hessian, which we call *second-order saddle points* or *ridable saddles*¹⁴ (Fig. 2). We can use second-order information to guarantee to escape such saddle points. In the companion paper [3], we derive an algorithm based on the Riemannian trust region method (TRM) [51], [52] over the sphere for this purpose. There are other algorithmic possibilities; see, e.g., [50].

We provide here only the basic intuition why a local minimizer can be retrieved by the second-order trust-region method. For a function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ and an unconstrained optimization problem

$$\min_{\mathbf{x} \in \mathbb{R}^n} f(\mathbf{x}),$$

typical (second-order) TRM proceeds by successively forming a second-order approximation to f at the current iterate,

$$\widehat{f}(\boldsymbol{\delta}; \mathbf{x}^{(k-1)}) \doteq f(\mathbf{x}^{(k-1)}) + \nabla^* f(\mathbf{x}^{(k-1)})\boldsymbol{\delta} + \frac{1}{2}\boldsymbol{\delta}^* \mathbf{Q}(\mathbf{x}^{(k-1)})\boldsymbol{\delta}, \quad (\text{I.12})$$

where $\mathbf{Q}(\mathbf{x}^{(k-1)})$ is a proxy for the Hessian matrix $\nabla^2 f(\mathbf{x}^{(k-1)})$, which encodes the second-order geometry. The next movement direction is determined by seeking a minimum of $\widehat{f}(\boldsymbol{\delta}; \mathbf{x}^{(k-1)})$ over a small region, normally a norm ball $\|\boldsymbol{\delta}\|_p \leq \Delta$, called the trust region, inducing the well studied trust-region subproblem that can efficiently be solved:

$$\boldsymbol{\delta}^{(k)} \doteq \arg \min_{\boldsymbol{\delta} \in \mathbb{R}^n, \|\boldsymbol{\delta}\|_p \leq \Delta} \widehat{f}(\boldsymbol{\delta}; \mathbf{x}^{(k-1)}), \quad (\text{I.13})$$

where Δ is called the trust-region radius that controls how far the movement can be made. If we take $\mathbf{Q}(\mathbf{x}^{(k-1)}) = \nabla^2 f(\mathbf{x}^{(k-1)})$ for all k , then whenever the gradient is nonvanishing or the Hessian is indefinite, we expect to decrease the objective function by a concrete amount provided $\|\boldsymbol{\delta}\|$ is sufficiently small. Since the domain is compact, the iterate sequence ultimately moves into the strongly convex region, where the trust-region algorithm behaves like a typical Newton algorithm. All these are generalized to our objective over the sphere and made rigorous in the companion paper [3].

E. Prior Arts and Connections

It is far too ambitious to include here a comprehensive review of the exciting developments of DL algorithms and applications after the pioneer work [10]. We refer the reader to Chapter 12 - 15 of the book [12] and the survey paper [13] for summaries of relevant developments in image analysis and visual recognition. In the following, we focus on reviewing recent developments on the theoretical side of dictionary learning, and draw connections to problems and techniques that are relevant to the current work.

a) *Theoretical Dictionary Learning:* The theoretical study of DL in the recovery setting started only very recently. [53] was the first to provide an algorithmic procedure to correctly extract the generating dictionary. The algorithm requires exponentially many samples and has exponential running time; see also [54]. Subsequent work [20], [21], [55]–[57] studied when the target dictionary is a local optimizer of natural recovery criteria. These meticulous analyses show that polynomially many samples are sufficient to ensure local correctness under natural assumptions. However, these results do not imply that one can design efficient algorithms to obtain the desired local optimizer and hence the dictionary.

[40] initiated the on-going research effort to provide efficient algorithms that globally solve DR. They showed that one can recover a complete dictionary \mathbf{A}_0 from $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0$ by solving a certain sequence of linear programs, when \mathbf{X}_0 is a sparse random matrix with $O(\sqrt{n})$ nonzeros per column. [41], [43] and [42], [45] gave efficient algorithms that provably recover overcomplete ($m \geq n$) and incoherent dictionaries, based on a combination of {clustering or spectral initialization} and local refinement. These algorithms again succeed when \mathbf{X}_0 has $\tilde{O}(\sqrt{n})$ ¹⁵ nonzeros per column. Recent work [58] provided the first polynomial-time algorithm that provably recovers

¹⁴See [49] and [50].

¹⁵The \tilde{O} suppresses some logarithm factors.

most “nice” overcomplete dictionaries when \mathbf{X}_0 has $O(n^{1-\delta})$ nonzeros per column for any constant $\delta \in (0, 1)$. However, the proposed algorithm runs in super-polynomial (quasipolynomial) time when the sparsity level goes up to $O(n)$. Similarly, [44] also proposed a super-polynomial time algorithm that guarantees recovery with (almost) $O(n)$ nonzeros per column. By comparison, we give the first *polynomial-time* algorithm that provably recovers complete dictionary \mathbf{A}_0 when \mathbf{X}_0 has $O(n)$ nonzeros per column.

Aside from efficient recovery, other theoretical work on DL includes results on identifiability [53], [54], [59], generalization bounds [14]–[17], and noise stability [60].

b) Finding Sparse Vectors in a Linear Subspace: We have followed [40] and cast the core problem as finding the sparsest vectors in a given linear subspace, which is also of independent interest. Under a planted sparse model¹⁶, [46] showed that solving a sequence of linear programs similar to [40] can recover sparse vectors with sparsity up to $O(p/\sqrt{n})$, sublinear in the vector dimension. [48] improved the recovery limit to $O(p)$ by solving a nonconvex sphere-constrained problem similar to (I.4)¹⁷ via an ADM algorithm. The idea of seeking rows of \mathbf{X}_0 sequentially by solving the above core problem sees precursors in [47] for blind source separation, and [61] for matrix sparsification. [47] also proposed a nonconvex optimization similar to (I.4) here and that employed in [48].

c) Nonconvex Optimization Problems: For other nonconvex optimization problems of recovery of structured signals¹⁸, including low-rank matrix completion/recovery [70]–[79], phase retrieval [80]–[83], tensor recovery [84]–[87], mixed regression [88], [89], structured element pursuit [48], and recovery of simultaneously structured signals [89], numerical linear algebra and optimization [90], [91], the initialization plus local refinement strategy adopted in theoretical DL [41]–[45] is also crucial: nearness to the target solution enables exploiting the local property of the optimizing objective to ensure that the local refinement succeeds.¹⁹ By comparison, we provide a complete characterization of the global geometry, which admits efficient algorithms without any special initialization.

d) Independent Component Analysis (ICA) and Other Matrix Factorization Problems: DL can also be considered in the general framework of matrix factorization problems, which encompass the classic principal component analysis (PCA), ICA, and clustering, and more recent problems such as nonnegative matrix factorization (NMF), multi-layer neural nets (deep learning architectures). Most of these problems are NP-hard. Identifying tractable cases of practical interest and providing provable efficient algorithms are subject of on-going research endeavors; see, e.g., recent progresses on NMF [95], and learning deep neural nets [96]–[99].

ICA factors a data matrix \mathbf{Y} as $\mathbf{Y} = \mathbf{A}\mathbf{X}$ such that \mathbf{A} is square and rows of \mathbf{X} achieve maximal statistical independence [100], [101]. In theoretical study of the recovery problem, it is often assumed that rows of \mathbf{X}_0 are (weakly) independent (see, e.g., [102]–[104]). Our i.i.d. probability model on \mathbf{X}_0 implies rows of \mathbf{X}_0 are independent, aligning our problem perfectly with the ICA problem. More interestingly, the log cosh objective we analyze here was proposed as a general-purpose *contrast function* in ICA that has not been thoroughly analyzed [105], and algorithm and analysis with another popular contrast function, the fourth-order cumulants, indeed overlap with ours considerably [103], [104]²⁰. While this interesting connection potentially helps port our analysis to ICA, it is a fundamental question to ask what is playing the vital role for DR, sparsity or independence.

Fig. 3 helps shed some light in this direction, where we again plot the asymptotic objective landscape with the natural reparameterization as in Section I-D2. From the left and central panels, it is evident that even without independence, \mathbf{X}_0 with sparse columns induces the familiar geometric structures we saw in Fig. 2; such structures are broken when the sparsity level becomes large. We believe all our later analyses can be generalized to the correlated cases we experimented with. On the other hand, from the right panel²¹, it seems that with independence, the function landscape undergoes a transition as sparsity level grows - target solution goes from minimizers of the objective to the maximizers of the objective. Without adequate knowledge of the true sparsity, it is unclear whether

¹⁶... where one sparse vector embedded in an otherwise random subspace.

¹⁷The only difference is that they chose to work with the Huber function as a proxy of the $\|\cdot\|_1$ function.

¹⁸This is a body of recent work studying nonconvex recovery up to statistical precision, including, e.g., [62]–[69].

¹⁹The powerful framework [38], [39] to establish local convergence of ADM algorithms to critical points applies to DL/DR also, see, e.g., [92]–[94]. However, these results do not guarantee to produce global optima.

²⁰Nevertheless, the objective functions are apparently different. Moreover, we have provided a complete geometric characterization of the objective, in contrast to [103], [104]. We believe the geometric characterization could not only provide insight to the algorithm, but also help improve the algorithm in terms of stability and also finding all components.

²¹We have not showed the results on the BG model here, as it seems the structure persists even when θ approaches 1. We suspect the “phase transition” of the landscape occurs at different points for different distributions and Gaussian is the outlying case where the transition occurs at 1.

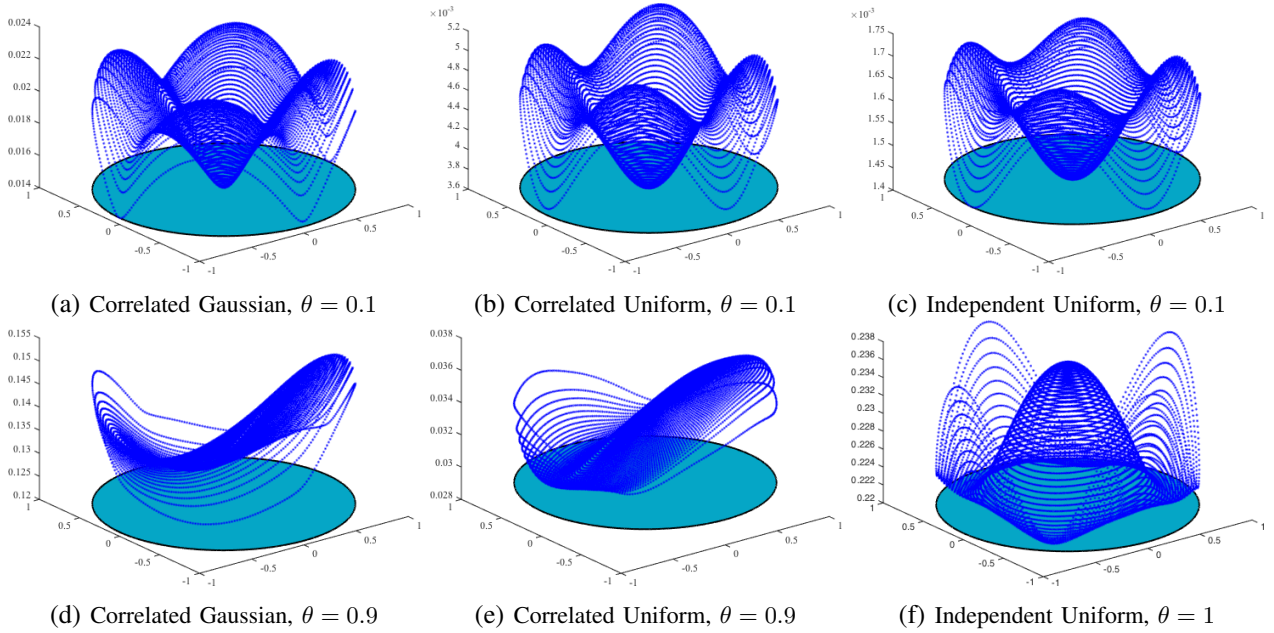


Fig. 3: Asymptotic function landscapes when rows of \mathbf{X}_0 are not independent. W.l.o.g., we again assume $\mathbf{A}_0 = \mathbf{I}$. In (a) and (d), $\mathbf{X}_0 = \mathbf{\Omega} \odot \mathbf{V}$, with $\mathbf{\Omega} \sim_{i.i.d.} \text{Ber}(\theta)$ and columns of \mathbf{X}_0 i.i.d. Gaussian vectors obeying $\mathbf{v}_i \sim \mathcal{N}(\mathbf{0}, \mathbf{\Sigma}^2)$ for symmetric $\mathbf{\Sigma}$ with 1's on the diagonal and i.i.d. off-diagonal entries distributed as $\mathcal{N}(0, \sqrt{2}/20)$. Similarly, in (b) and (e), $\mathbf{X}_0 = \mathbf{\Omega} \odot \mathbf{W}$, with $\mathbf{\Omega} \sim_{i.i.d.} \text{Ber}(\theta)$ and columns of \mathbf{X}_0 i.i.d. vectors generated as $\mathbf{w}_i = \mathbf{\Sigma} \mathbf{u}^i$ with $\mathbf{u}_i \sim_{i.i.d.} \text{Uniform}[-0.5, 0.5]$. For comparison, in (c) and (f), $\mathbf{X}_0 = \mathbf{\Omega} \odot \mathbf{W}$ with $\mathbf{\Omega} \sim_{i.i.d.} \text{Ber}(\theta)$ and $\mathbf{W} \sim_{i.i.d.} \text{Uniform}[-0.5, 0.5]$. Here \odot denote the elementwise product, and the objective function is still based on the log cosh function as in (I.4).

one would like to minimize or maximize the objective.²² This suggests that sparsity, instead of independence, makes our current algorithm for DR work.

e) Nonconvex Problems with Similar Geometric Structure: Besides ICA discussed above, it turns out that a handful of other practical problems arising in signal processing and machine learning induce the “no spurious minimizers, all saddles are second-order” structure under natural setting, including the eigenvalue problem, generalized phase retrieval [106], tensor decomposition [50], linear neural nets learning [107]. [49] gave a review of these problems, and discussed how the methodology developed in this and the companion paper [3] can be generalized to solve those problems.

F. Notations, and Reproducible Research

We use bold capital and small letters such as \mathbf{X} and \mathbf{x} to denote matrices and vectors, respectively. Small letters are reserved for scalars. Several specific mathematical objects we will frequently work with: O_k for the orthogonal group of order k , \mathbb{S}^{n-1} for the unit sphere in \mathbb{R}^n , \mathbb{B}^n for the unit ball in \mathbb{R}^n , and $[m] \doteq \{1, \dots, m\}$ for positive integers m . We use $(\cdot)^*$ for matrix transposition, causing no confusion as we will work entirely on the real field. We use superscript to index rows of a matrix, such as \mathbf{x}^i for the i -th row of the matrix \mathbf{X} , and subscript to index columns, such as \mathbf{x}_j . All vectors are defaulted to column vectors. So the i -th row of \mathbf{X} as a row vector will be written as $(\mathbf{x}^i)^*$. For norms, $\|\cdot\|$ is the usual ℓ^2 norm for a vector and the operator norm (i.e., $\ell^2 \rightarrow \ell^2$) for a matrix; all other norms will be indexed by subscript, for example the Frobenius norm $\|\cdot\|_F$ for matrices and the element-wise max-norm $\|\cdot\|_\infty$. We use $\mathbf{x} \sim \mathcal{L}$ to mean that the random variable \mathbf{x} is distributed according to the law \mathcal{L} . Let \mathcal{N} denote the Gaussian law. Then $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ means that \mathbf{x} is a standard Gaussian vector. Similarly, we use $\mathbf{x} \sim_{i.i.d.} \mathcal{L}$ to mean elements of \mathbf{x} are independently and identically distributed according to the law \mathcal{L} . So

²²For solving the ICA problem, this suggests the log cosh contrast function, that works well empirically [105], may not work for all distributions (rotation-invariant Gaussian excluded of course), at least when one does not process the data (say perform certain whitening or scaling).

the fact $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$ is equivalent to that $\mathbf{x} \sim_{i.i.d.} \mathcal{N}(0, 1)$. One particular distribution of interest for this paper is the Bernoulli-Gaussian with rate θ : $Z \sim B \cdot G$, with $G \sim \mathcal{N}(0, 1)$ and $B \sim \text{Ber}(\theta)$. We also write this compactly as $Z \sim \text{BG}(\theta)$. We frequently use indexed C and c for numerical constants when stating and proving technical results. The scopes of such constants are local unless otherwise noted. We use standard notations for most other cases, with exceptions clarified locally.

The codes to reproduce all the figures and experimental results are available online:

https://github.com/sunju/dl_focm.

II. THE HIGH-DIMENSIONAL FUNCTION LANDSCAPE

To characterize the function landscape of $f(\mathbf{q}; \mathbf{X}_0)$ over \mathbb{S}^{n-1} , we mostly work with the function

$$g(\mathbf{w}) \doteq f(\mathbf{q}(\mathbf{w}); \mathbf{X}_0) = \frac{1}{p} \sum_{k=1}^p h_\mu(\mathbf{q}(\mathbf{w})^* (\mathbf{x}_0)_k), \quad (\text{II.1})$$

induced by the reparametrization

$$\mathbf{q}(\mathbf{w}) = (\mathbf{w}, \sqrt{1 - \|\mathbf{w}\|^2}), \quad \mathbf{w} \in \mathbb{B}^{n-1}. \quad (\text{II.2})$$

In particular, we focus our attention to the smaller set

$$\Gamma = \left\{ \mathbf{w} : \|\mathbf{w}\| < \sqrt{\frac{4n-1}{4n}} \right\}, \quad (\text{II.3})$$

because $\mathbf{q}(\Gamma)$ contains all points $\mathbf{q} \in \mathbb{S}^{n-1}$ with $n \in \arg \max_{i \in \pm[n]} \mathbf{q}^* \mathbf{e}_i$ and we can similarly characterize other parts of f on \mathbb{S}^{n-1} using projection onto other equatorial planes. Note that over Γ , $q_n = (1 - \|\mathbf{w}\|^2)^{1/2} \geq 1/(2\sqrt{n})$.

A. Main Geometric Theorems

Theorem II.1 (High-dimensional landscape - orthogonal dictionary). *Suppose $\mathbf{A}_0 = \mathbf{I}$ and hence $\mathbf{Y} = \mathbf{A}_0 \mathbf{X}_0 = \mathbf{X}_0$. There exist positive constants c_* and C , such that for any $\theta \in (0, 1/2)$ and $\mu < \min\{c_a \theta n^{-1}, c_b n^{-5/4}\}$, whenever $p \geq \frac{C}{\mu^2 \theta^2} n^3 \log \frac{n}{\mu \theta}$, the following hold simultaneously with high probability:*

$$\nabla^2 g(\mathbf{w}; \mathbf{X}_0) \succeq \frac{c_* \theta}{\mu} \mathbf{I} \quad \forall \mathbf{w} \quad \text{s.t.} \quad \|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}, \quad (\text{II.4})$$

$$\frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0)}{\|\mathbf{w}\|} \geq c_* \theta \quad \forall \mathbf{w} \quad \text{s.t.} \quad \frac{\mu}{4\sqrt{2}} \leq \|\mathbf{w}\| \leq \frac{1}{20\sqrt{5}} \quad (\text{II.5})$$

$$\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} \leq -c_* \theta \quad \forall \mathbf{w} \quad \text{s.t.} \quad \frac{1}{20\sqrt{5}} \leq \|\mathbf{w}\| \leq \sqrt{\frac{4n-1}{4n}}, \quad (\text{II.6})$$

and the function $g(\mathbf{w}; \mathbf{X}_0)$ has exactly one local minimizer \mathbf{w}_* over the open set $\Gamma \doteq \left\{ \mathbf{w} : \|\mathbf{w}\| < \sqrt{\frac{4n-1}{4n}} \right\}$, which satisfies

$$\|\mathbf{w}_* - \mathbf{0}\| \leq \min \left\{ \frac{c_c \mu}{\theta} \sqrt{\frac{n \log p}{p}}, \frac{\mu}{16} \right\}. \quad (\text{II.7})$$

In particular, with this choice of p , the probability the claim fails to hold is at most $4np^{-10} + \theta(np)^{-7} + \exp(-0.3\theta np) + c_d \exp(-c_e p \mu^2 \theta^2 / n^2)$. Here c_a through c_e are all positive numerical constants.

Here $\mathbf{q}(\mathbf{0}) = \mathbf{e}_n$, which exactly recovers the last row of \mathbf{X}_0 , \mathbf{x}_0^n . Though the unique local minimizer \mathbf{w}_* may not be $\mathbf{0}$, it is very near to $\mathbf{0}$. Hence the resulting $\mathbf{q}(\mathbf{w}_*)$ produces a close approximation to \mathbf{x}_0^n . Note that $\mathbf{q}(\Gamma)$ (strictly) contains all points $\mathbf{q} \in \mathbb{S}^{n-1}$ such that $n = \arg \max_{i \in \pm[n]} \mathbf{q}^* \mathbf{e}_i$. We can characterize the graph of the function $f(\mathbf{q}; \mathbf{X}_0)$ in the vicinity of other signed basis vector $\pm \mathbf{e}_i$ simply by changing the plane \mathbf{e}_n^\perp to \mathbf{e}_i^\perp . Doing this $2n$ times (and multiplying the failure probability in Theorem II.1 by $2n$), we obtain a characterization of $f(\mathbf{q}; \mathbf{X}_0)$ over the entirety of \mathbb{S}^{n-1} .²³ The result is captured by the next corollary.

²³In fact, it is possible to pull the very detailed geometry captured in (II.4) through (II.6) back to the sphere (i.e., the \mathbf{q} space) also; analysis of the Riemannian trust-region algorithm later does part of these. We will stick to this simple global version here.

Corollary II.2. *Suppose $\mathbf{A}_0 = \mathbf{I}$ and hence $\mathbf{Y} = \mathbf{A}_0\mathbf{X}_0 = \mathbf{X}_0$. There exist positive constant C , such that for any $\theta \in (0, 1/2)$ and $\mu < \min\{c_a\theta n^{-1}, c_b n^{-5/4}\}$, whenever $p \geq \frac{C}{\mu^2\theta^2} n^3 \log \frac{n}{\mu\theta}$, with probability at least $1 - 8n^2 p^{-10} - \theta(np)^{-7} - \exp(-0.3\theta np) - c_c \exp(-c_d p \mu^2 \theta^2 / n^2)$, the function $f(\mathbf{q}; \mathbf{X}_0)$ has exactly $2n$ local minimizers over the sphere \mathbb{S}^{n-1} . In particular, there is a bijective map between these minimizers and signed basis vectors $\{\pm \mathbf{e}_i\}_i$, such that the corresponding local minimizer \mathbf{q}_* and $\mathbf{b} \in \{\pm \mathbf{e}_i\}_i$ satisfy*

$$\|\mathbf{q}_* - \mathbf{b}\| \leq \sqrt{2} \min \left\{ \frac{c_c \mu}{\theta} \sqrt{\frac{n \log p}{p}}, \frac{\mu}{16} \right\}. \quad (\text{II.8})$$

Here c_a to c_d are numerical constants (possibly different from that in the above theorem).

Proof: By Theorem II.1, over $\mathbf{q}(\Gamma)$, $\mathbf{q}(\mathbf{w}_*)$ is the unique local minimizer. Suppose not. Then there exist $\mathbf{q}' \in \mathbf{q}(\Gamma)$ with $\mathbf{q}' \neq \mathbf{q}(\mathbf{w}_*)$ and $\varepsilon > 0$, such that $f(\mathbf{q}'; \mathbf{X}_0) \leq f(\mathbf{q}; \mathbf{X}_0)$ for all $\mathbf{q} \in \mathbf{q}(\Gamma)$ satisfying $\|\mathbf{q}' - \mathbf{q}\| < \varepsilon$. Since the mapping $\mathbf{w} \mapsto \mathbf{q}(\mathbf{w})$ is $2\sqrt{n}$ -Lipschitz (Lemma IV.7), $g(\mathbf{w}(\mathbf{q}'); \mathbf{X}_0) \leq g(\mathbf{w}(\mathbf{q}); \mathbf{X}_0)$ for all $\mathbf{w} \in \Gamma$ satisfying $\|\mathbf{w}(\mathbf{q}') - \mathbf{w}(\mathbf{q})\| < \varepsilon / (2\sqrt{n})$, implying $\mathbf{w}(\mathbf{q}')$ is a local minimizer different from \mathbf{w}_* , a contradiction. Let $\|\mathbf{w}_* - \mathbf{0}\| = \eta$. Straightforward calculation shows

$$\|\mathbf{q}(\mathbf{w}_*) - \mathbf{e}_n\|^2 = (1 - \sqrt{1 - \eta^2})^2 + \eta^2 = 2 - 2\sqrt{1 - \eta^2} \leq 2\eta^2.$$

Repeating the argument $2n$ times in the vicinity of other signed basis vectors $\pm \mathbf{e}_i$ gives $2n$ local minimizers of f . Indeed, the $2n$ symmetric sections cover the sphere with certain overlaps, and a simple calculation shows that no such local minimizer lies in the overlapped regions (due to nearness to a signed basis vector). There is no extra local minimizers, as any extra local minimizer must be contained in at least one of the $2n$ symmetric sections, making two different local minimizers in one section, contradicting the uniqueness result we obtained above. ■

Though the $2n$ isolated local minimizers may have different objective values, they are equally good in the sense any of them helps produce a close approximation to a certain row of \mathbf{X}_0 . As discussed in Section I-D2, for cases \mathbf{A}_0 is an orthobasis other than \mathbf{I} , the landscape of $f(\mathbf{q}; \mathbf{Y})$ is simply a rotated version of the one we characterized above.

Theorem II.3 (High-dimensional landscape - complete dictionary). *Suppose \mathbf{A}_0 is complete with its condition number $\kappa(\mathbf{A}_0)$. There exist positive constants c_* (particularly, the same constant as in Theorem II.1) and C , such that for any $\theta \in (0, 1/2)$ and $\mu < \min\{c_a\theta n^{-1}, c_b n^{-5/4}\}$, when $p \geq \frac{C}{c_*^2\theta} \max\left\{\frac{n^4}{\mu^4}, \frac{n^5}{\mu^2}\right\} \kappa^8(\mathbf{A}_0) \log^4\left(\frac{\kappa(\mathbf{A}_0)n}{\mu\theta}\right)$ and $\bar{\mathbf{Y}} \doteq \sqrt{p\theta}(\mathbf{Y}\mathbf{Y}^*)^{-1/2}\mathbf{Y}$, $\mathbf{U}\Sigma\mathbf{V}^* = \text{SVD}(\mathbf{A}_0)$, the following hold simultaneously with high probability:*

$$\nabla^2 g(\mathbf{w}; \mathbf{V}\mathbf{U}^*\bar{\mathbf{Y}}) \succeq \frac{c_*\theta}{2\mu} \mathbf{I} \quad \forall \mathbf{w} \quad \text{s.t.} \quad \|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}, \quad (\text{II.9})$$

$$\frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{V}\mathbf{U}^*\bar{\mathbf{Y}})}{\|\mathbf{w}\|} \geq \frac{1}{2} c_* \theta \quad \forall \mathbf{w} \quad \text{s.t.} \quad \frac{\mu}{4\sqrt{2}} \leq \|\mathbf{w}\| \leq \frac{1}{20\sqrt{5}} \quad (\text{II.10})$$

$$\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{V}\mathbf{U}^*\bar{\mathbf{Y}}) \mathbf{w}}{\|\mathbf{w}\|^2} \leq -\frac{1}{2} c_* \theta \quad \forall \mathbf{w} \quad \text{s.t.} \quad \frac{1}{20\sqrt{5}} \leq \|\mathbf{w}\| \leq \sqrt{\frac{4n-1}{4n}}, \quad (\text{II.11})$$

and the function $g(\mathbf{w}; \mathbf{V}\mathbf{U}^*\bar{\mathbf{Y}})$ has exactly one local minimizer \mathbf{w}_* over the open set $\Gamma \doteq \left\{ \mathbf{w} : \|\mathbf{w}\| < \sqrt{\frac{4n-1}{4n}} \right\}$, which satisfies

$$\|\mathbf{w}_* - \mathbf{0}\| \leq \mu/7. \quad (\text{II.12})$$

In particular, with this choice of p , the probability the claim fails to hold is at most $4np^{-10} + \theta(np)^{-7} + \exp(-0.3\theta np) + p^{-8} + c_d \exp(-c_e p \mu^2 \theta^2 / n^2)$. Here c_a through c_e are all positive numerical constants.

Corollary II.4. *Suppose \mathbf{A}_0 is complete with its condition number $\kappa(\mathbf{A}_0)$. There exist positive constants c_* (particularly, the same constant as in Theorem II.1) and C , such that for any $\theta \in (0, 1/2)$ and $\mu < \min\{c_a\theta n^{-1}, c_b n^{-5/4}\}$, when $p \geq \frac{C}{c_*^2\theta} \max\left\{\frac{n^4}{\mu^4}, \frac{n^5}{\mu^2}\right\} \kappa^8(\mathbf{A}_0) \log^4\left(\frac{\kappa(\mathbf{A}_0)n}{\mu\theta}\right)$ and $\bar{\mathbf{Y}} \doteq \sqrt{p\theta}(\mathbf{Y}\mathbf{Y}^*)^{-1/2}\mathbf{Y}$, $\mathbf{U}\Sigma\mathbf{V}^* = \text{SVD}(\mathbf{A}_0)$, with probability at least $1 - 8n^2 p^{-10} - \theta(np)^{-7} - \exp(-0.3\theta np) - p^{-8} - c_d \exp(-c_e p \mu^2 \theta^2 / n^2)$, the function $f(\mathbf{q}; \mathbf{V}\mathbf{U}^*\bar{\mathbf{Y}})$ has exactly $2n$ local minimizers over the sphere \mathbb{S}^{n-1} . In particular, there is a bijective map*

between these minimizers and signed basis vectors $\{\pm \mathbf{e}_i\}_i$, such that the corresponding local minimizer \mathbf{q}_* and $\mathbf{b} \in \{\pm \mathbf{e}_i\}_i$ satisfy

$$\|\mathbf{q}_* - \mathbf{b}\| \leq \sqrt{2}\mu/7. \quad (\text{II.13})$$

Here c_a through c_d are numerical constants (possibly different from that in the above theorem).

We omit the proof to Corollary II.4 as it is almost identical to that of corollary II.2.

From the above theorems, it is clear that for any saddle point in the \mathbf{w} space, the Hessian has at least one negative eigenvalue with an associated eigenvector $\mathbf{w}/\|\mathbf{w}\|$. Now the question is whether all saddle points of f on \mathbb{S}^{n-1} are “second-order”, since as alluded to in Section I-D3, we need to perform actual optimization in the \mathbf{q} space. This is indeed true, but we will only argue informally in the companion paper [3]. The arguments need to be put in the language of Riemannian geometry, and we can switch back and forth between \mathbf{q} and \mathbf{w} spaces in our algorithm analysis without stating this fact.

B. Useful Technical Lemmas and Proof Ideas for Orthogonal Dictionaries

The proof of Theorem II.1 is conceptually straightforward: one shows that $\mathbb{E}_{\mathbf{X}_0} [g(\mathbf{w}; \mathbf{X}_0)]$ has the claimed properties, and then proves that each of the quantities of interest concentrates uniformly about its expectation. The detailed calculations are nontrivial.

Note that

$$\mathbb{E}_{\mathbf{X}_0} [g(\mathbf{q}; \mathbf{X}_0)] = \mathbb{E}_{\mathbf{x} \sim i.i.d. \text{BG}(\theta)} [h_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x})].$$

The next three propositions show that in the expected function landscape, we see successively strongly convex region, nonzero gradient region, and directional negative curvature region when moving away from zero, as depicted in Fig. 2 and sketched in Section I-D2.

Proposition II.5. *There exists a positive constant c , such that for every $\theta \in (0, 1/2)$ and any $R_h \in (0, \sqrt{\frac{4n-1}{4n}})$, if $\mu \leq c \min\{\theta R_h^2 n^{-1}, R_h n^{-5/4}\}$, it holds for every \mathbf{w} satisfying $R_h \leq \|\mathbf{w}\| \leq \sqrt{\frac{4n-1}{4n}}$ that*

$$\frac{\mathbf{w}^* \nabla_{\mathbf{w}}^2 \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \mathbf{w}}{\|\mathbf{w}\|^2} \leq -\frac{\theta}{2\sqrt{2\pi}}.$$

Proof: See Page 15 under Section IV-A1. ■

Proposition II.6. *For every $\theta \in (0, 1/2)$ and every $\mu \leq 9/50$, it holds for every \mathbf{w} satisfying $r_g \leq \|\mathbf{w}\| \leq R_g$, where $r_g = \mu/(6\sqrt{2})$ and $R_g = (1-\theta)/(10\sqrt{5})$, that*

$$\frac{\mathbf{w}^* \nabla_{\mathbf{w}} \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})]}{\|\mathbf{w}\|} \geq \frac{\theta}{20\sqrt{2\pi}}.$$

Proof: See Page 19 under Section IV-A2. ■

Proposition II.7. *For every $\theta \in (0, 1/2)$, and every $\mu \leq 1/(20\sqrt{n})$, it holds for every \mathbf{w} satisfying $\|\mathbf{w}\| \leq \mu/(4\sqrt{2})$ that*

$$\nabla_{\mathbf{w}}^2 \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \succeq \frac{\theta}{25\sqrt{2\pi}\mu} \mathbf{I}.$$

Proof: See Page 21 under Section IV-A3. ■

To prove that the above hold qualitatively for finite p , i.e., the function $g(\mathbf{w}; \mathbf{X}_0)$, we will need first prove that for a fixed \mathbf{w} each of the quantity of interest concentrate about their expectation w.h.p., and the function is nice enough (Lipschitz) such that we can extend the results to all \mathbf{w} via a discretization argument. The next three propositions provide the desired pointwise concentration results.

Proposition II.8. *Suppose $0 < \mu \leq 1/\sqrt{n}$. For every $\mathbf{w} \in \Gamma$, it holds that for any $t > 0$,*

$$\mathbb{P} \left[\left| \frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} - \mathbb{E} \left[\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} \right] \right| \geq t \right] \leq 4 \exp \left(-\frac{p\mu^2 t^2}{512n^2 + 32n\mu t} \right).$$

Proof: See Page 24 under Section IV-A4. ■

Proposition II.9. For every $\mathbf{w} \in \Gamma$, it holds that for any $t > 0$,

$$\mathbb{P} \left[\left| \frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0)}{\|\mathbf{w}\|} - \mathbb{E} \left[\frac{\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0)}{\|\mathbf{w}\|} \right] \right| \geq t \right] \leq 2 \exp \left(-\frac{pt^2}{8n + 4\sqrt{nt}} \right).$$

Proof: See Page 25 under Section IV-A4. ■

Proposition II.10. Suppose $0 < \mu \leq 1/\sqrt{n}$. For every $\mathbf{w} \in \Gamma \cap \{\mathbf{w} : \|\mathbf{w}\| \leq 1/4\}$, it holds that for any $t > 0$,

$$\mathbb{P} \left[\|\nabla^2 g(\mathbf{w}; \mathbf{X}_0) - \mathbb{E} [\nabla^2 g(\mathbf{w}; \mathbf{X}_0)]\| \geq t \right] \leq 4n \exp \left(-\frac{p\mu^2 t^2}{512n^2 + 32\mu nt} \right).$$

Proof: See Page 25 under Section IV-A4. ■

The next three propositions provide the desired Lipschitz results.

Proposition II.11 (Hessian Lipschitz). Fix any $r_\wedge \in (0, 1)$. Over the set $\Gamma \cap \{\mathbf{w} : \|\mathbf{w}\| \geq r_\wedge\}$, $\mathbf{w}^* \nabla^2 g(\mathbf{w}; \mathbf{X}_0) \mathbf{w} / \|\mathbf{w}\|^2$ is L_\wedge -Lipschitz with

$$L_\wedge \leq \frac{16n^3}{\mu^2} \|\mathbf{X}_0\|_\infty^3 + \frac{8n^{3/2}}{\mu r_\wedge} \|\mathbf{X}_0\|_\infty^2 + \frac{48n^{5/2}}{\mu} \|\mathbf{X}_0\|_\infty^2 + 96n^{5/2} \|\mathbf{X}_0\|_\infty.$$

Proof: See Page 29 under Section IV-A5. ■

Proposition II.12 (Gradient Lipschitz). Fix any $r_g \in (0, 1)$. Over the set $\Gamma \cap \{\mathbf{w} : \|\mathbf{w}\| \geq r_g\}$, $\mathbf{w}^* \nabla g(\mathbf{w}; \mathbf{X}_0) / \|\mathbf{w}\|$ is L_g -Lipschitz with

$$L_g \leq \frac{2\sqrt{n} \|\mathbf{X}_0\|_\infty}{r_g} + 8n^{3/2} \|\mathbf{X}_0\|_\infty + \frac{4n^2}{\mu} \|\mathbf{X}_0\|_\infty^2.$$

Proof: See Page 30 under Section IV-A5. ■

Proposition II.13 (Lipschitz for Hessian around zero). Fix any $r_\cup \in (0, 1/2)$. Over the set $\Gamma \cap \{\mathbf{w} : \|\mathbf{w}\| \leq r_\cup\}$, $\nabla^2 g(\mathbf{w}; \mathbf{X}_0)$ is L_\cup -Lipschitz with

$$L_\cup \leq \frac{4n^2}{\mu^2} \|\mathbf{X}_0\|_\infty^3 + \frac{4n}{\mu} \|\mathbf{X}_0\|_\infty^2 + \frac{8\sqrt{2}\sqrt{n}}{\mu} \|\mathbf{X}_0\|_\infty^2 + 8 \|\mathbf{X}_0\|_\infty.$$

Proof: See Page 30 under Section IV-A5. ■

Integrating the above pieces, Section IV-B provides a complete proof of Theorem II.1.

C. Extending to Complete Dictionaries

As hinted in Section I-D2, instead of proving things from scratch, we build on the results we have obtained for orthogonal dictionaries. In particular, we will work with the preconditioned data matrix

$$\bar{\mathbf{Y}} \doteq \sqrt{p\theta} (\mathbf{Y}\mathbf{Y}^*)^{-1/2} \mathbf{Y} \tag{II.14}$$

and show that the function landscape $f(\mathbf{q}; \bar{\mathbf{Y}})$ looks qualitatively like that of orthogonal dictionaries (up to a global rotation), provided that p is large enough.

The next lemma shows $\bar{\mathbf{Y}}$ can be treated as being generated from an orthobasis with the same BG coefficients, plus small noise.

Lemma II.14. For any $\theta \in (0, 1/2)$, suppose \mathbf{A}_0 is complete with condition number $\kappa(\mathbf{A}_0)$ and $\mathbf{X}_0 \sim_{i.i.d.} \text{BG}(\theta)$. Provided $p \geq C\kappa^4(\mathbf{A}_0)\theta n^2 \log(n\theta\kappa(\mathbf{A}_0))$, one can write $\bar{\mathbf{Y}}$ as defined in (II.14) as

$$\bar{\mathbf{Y}} = \mathbf{U}\mathbf{V}^* \mathbf{X}_0 + \Xi \mathbf{X}_0,$$

for a certain Ξ obeying $\|\Xi\| \leq 20\kappa^4(\mathbf{A}) \sqrt{\frac{\theta n \log p}{p}}$, with probability at least $1 - p^{-8}$. Here $\mathbf{U}\Sigma\mathbf{V}^* = \text{SVD}(\mathbf{A}_0)$, and C is a positive numerical constant.

Proof: See Page 33 under Section IV-C. ■

Notice that UV^* above is orthogonal, and that landscape of $f(\mathbf{q}; \bar{\mathbf{Y}})$ is simply a rotated version of that of $f(\mathbf{q}; \mathbf{V}U^*\bar{\mathbf{Y}})$, or using the notation in the above lemma, that of $f(\mathbf{q}; \mathbf{X}_0 + \mathbf{V}U^*\tilde{\mathbf{\Xi}}\mathbf{X}_0) = f(\mathbf{q}; \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0)$ assuming $\tilde{\mathbf{\Xi}} \doteq \mathbf{V}U^*\tilde{\mathbf{\Xi}}$. So similar to the orthogonal case, it is enough to consider this ‘‘canonical’’ case, and its ‘‘canonical’’ reparametrization:

$$g(\mathbf{w}; \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0) = \frac{1}{p} \sum_{k=1}^p h_{\mu}(\mathbf{q}^*(\mathbf{w})(\mathbf{x}_0)_k + \mathbf{q}^*(\mathbf{w})\tilde{\mathbf{\Xi}}(\mathbf{x}_0)_k).$$

The following lemma provides quantitative comparison between the gradient and Hessian of $g(\mathbf{w}; \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0)$ and that of $g(\mathbf{w}; \mathbf{X}_0)$.

Lemma II.15. *There exist positive constants C_a and C_b , such that for all $\mathbf{w} \in \Gamma$,*

$$\begin{aligned} \left\| \nabla_{\mathbf{w}} g(\mathbf{w}; \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0) - \nabla_{\mathbf{w}} g(\mathbf{w}; \mathbf{X}_0) \right\| &\leq C_a \frac{n}{\mu} \log(np) \|\tilde{\mathbf{\Xi}}\|, \\ \left\| \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0) - \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}_0) \right\| &\leq C_b \max\left\{ \frac{n^{3/2}}{\mu^2}, \frac{n^2}{\mu} \right\} \log^{3/2}(np) \|\tilde{\mathbf{\Xi}}\| \end{aligned}$$

with probability at least $1 - \theta(np)^{-7} - \exp(-0.3\theta np)$.

Proof: See Page 34 under Section IV-C. ■

Combining the above two lemmas, it is easy to see when p is large enough, $\|\tilde{\mathbf{\Xi}}\| = \|\mathbf{\Xi}\|$ is then small enough (Lemma II.14), and hence the changes to the gradient and Hessian caused by the perturbation are small. This gives the results presented in Theorem II.3; see Section IV-C for the detailed proof. In particular, for the p chosen in Theorem II.3, it holds that

$$\|\tilde{\mathbf{\Xi}}\| \leq c c_{\star} \theta \left(\max\left\{ \frac{n^{3/2}}{\mu^2}, \frac{n^2}{\mu} \right\} \log^{3/2}(np) \right)^{-1} \quad (\text{II.15})$$

for a certain constant c which can be made arbitrarily small by making the constant C in p large.

III. DISCUSSION

The dependency of p on n and other paramters could be suboptimal due to several factors: (1) The ℓ^1 proxy. The derivative and Hessians of the log cosh function we adopted entail the tanh function, which is not amenable to effective approximation and affects the sample complexity; (2) Space of geometric characterization. It seems working directly on the sphere (i.e., in the \mathbf{q} space) could simplify and possibly improve certain parts of the analysis; (3) Dealing with the complete case. Treating the complete case directly, rather than using (pessimistic) bounds to treat it as a perturbation of the orthogonal case, is very likely to improve the sample complexity. Particularly, general linear transforms may change the space significantly, such that preconditioning and comparing to the orthogonal transforms may not be the most efficient way to proceed.

It is possible to extend the current analysis to other dictionary settings. Our geometric structures (and algorithms) allow plug-and-play noise analysis. Nevertheless, we believe a more stable way of dealing with noise is to directly extract the whole dictionary, i.e., to consider geometry and optimization (and perturbation) over the orthogonal group. This will require additional nontrivial technical work, but likely feasible thanks to the relatively complete knowledge of the orthogonal group [52], [108]. A substantial leap forward would be to extend the methodology to recovery of *structured* overcomplete dictionaries, such as tight frames. Though there is no natural elimination of one variable, one can consider the marginalization of the objective function wrt the coefficients and work with hidden functions.²⁴ For the coefficient model, as we alluded to in Section I-E, our analysis and results likely can be carried through to coefficients with statistical dependence and physical constraints.

The connection to ICA we discussed in Section I-E suggests our geometric characterization and algorithms can be modified for the ICA problem. This likely will provide new theoretical insights and computational schemes to ICA. In the surge of theoretical understanding of nonconvex heuristics [41]–[45], [48], [70]–[75], [80], [81], [84],

²⁴This recent work [45] on overcomplete DR has used a similar idea. The marginalization taken there is near to the global optimum of one variable, where the function is well-behaved. Studying the global properties of the marginalization may introduce additional challenges.

[85], [88], [89], [89], the initialization plus local refinement strategy mostly differs from practice, whereby random initializations seem to work well, and the analytic techniques developed in that line are mostly fragmented and highly specialized. The analytic and algorithmic framework we developed here holds promise to provide a coherent account of these problems, see [49]. In particular, we have intentionally separated the geometric characterization and algorithm development and analysis in hope of making both parts modular. It is interesting to see how far we can streamline the geometric characterization. Moreover, the separation allows development of more provable and practical algorithms, say in the direction of [50].

IV. PROOFS OF TECHNICAL RESULTS

In this section, we provide complete proofs for technical results stated in Section II. Before that, let us introduce some notations and common results that will be used later throughout this section. Since we deal with BG random variables and random vectors, it is often convenient to write such vector explicitly as $\mathbf{x} = [\Omega_1 v_1, \dots, \Omega_n v_n] = \mathbf{\Omega} \odot \mathbf{v}$, where $\Omega_1, \dots, \Omega_n$ are i.i.d. Bernoulli random variables and v_1, \dots, v_n are i.i.d. standard normal. For a particular realization of such random vector, we will denote the support as $\mathcal{I} \subset [n]$. Due to the particular coordinate map in use, we will often refer to subset $\mathcal{J} \doteq \mathcal{I} \setminus \{n\}$ and the random vectors $\bar{\mathbf{x}} \doteq [\Omega_1 v_1, \dots, \Omega_{n-1} v_{n-1}]$ and $\bar{\mathbf{v}} \doteq [v_1, \dots, v_{n-1}]$ in \mathbb{R}^{n-1} . By Lemma A.1, it is not hard to see that

$$\nabla_{\mathbf{w}} h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x}) = \tanh\left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu}\right) \left(\bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w}\right), \quad (\text{IV.1})$$

$$\begin{aligned} \nabla_{\mathbf{w}}^2 h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x}) &= \frac{1}{\mu} \left[1 - \tanh^2\left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu}\right)\right] \left(\bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w}\right) \left(\bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w}\right)^* \\ &\quad - x_n \tanh\left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu}\right) \left(\frac{1}{q_n(\mathbf{w})} \mathbf{I} + \frac{1}{q_n^3(\mathbf{w})} \mathbf{w} \mathbf{w}^*\right). \end{aligned} \quad (\text{IV.2})$$

A. Proofs for Section II-B

1) *Proof of Proposition II.5:* The proof involves some delicate analysis, particularly polynomial approximation of the function $f(t) = \frac{1}{(1+t)^2}$ over $t \in [0, 1]$. This is naturally induced by the $1 - \tanh^2(\cdot)$ function. The next lemma characterizes one polynomial approximation of $f(t)$.

Lemma IV.1. *Consider $f(t) = \frac{1}{(1+t)^2}$ for $t \in [0, 1]$. For every $T > 1$, there is a sequence b_0, b_1, \dots , with $\|\mathbf{b}\|_{\ell^1} = T < \infty$, such that the polynomial $p(t) = \sum_{k=0}^{\infty} b_k t^k$ satisfies*

$$\|f - p\|_{L^1[0,1]} \leq \frac{1}{2\sqrt{T}}, \quad \|f - p\|_{L^\infty[0,1]} \leq \frac{1}{\sqrt{T}},$$

In particular, one can choose $b_k = (-1)^k (k+1) \beta^k$ with $\beta = 1 - 1/\sqrt{T} < 1$ such that

$$p(t) = \frac{1}{(1+\beta t)^2} = \sum_{k=0}^{\infty} (-1)^k (k+1) \beta^k t^k.$$

Moreover, such sequence satisfies $0 < \sum_{k=0}^{\infty} \frac{b_k}{(1+k)^3} < \sum_{k=0}^{\infty} \frac{|b_k|}{(1+k)^3} < 2$.

Proof: See page 38 under Section B. ■

Lemma IV.2. *Let $X \sim \mathcal{N}(0, \sigma_X^2)$ and $Y \sim \mathcal{N}(0, \sigma_Y^2)$. We have*

$$\begin{aligned} \mathbb{E} \left[\left(1 - \tanh^2\left(\frac{X+Y}{\mu}\right)\right) X^2 \mathbb{1}_{X+Y>0} \right] &\leq \\ &\frac{1}{\sqrt{2\pi}} \frac{\mu \sigma_X^2 \sigma_Y^2}{(\sigma_X^2 + \sigma_Y^2)^{3/2}} + \frac{\mu^3 \sigma_X^2 \sigma_Y^2}{(\sigma_X^2 + \sigma_Y^2)^{3/2}} + \frac{3}{4\sqrt{2\pi}} \frac{\sigma_X^2 \mu^3}{(\sigma_X^2 + \sigma_Y^2)^{5/2}} (3\mu^2 + 4\sigma_X^2). \end{aligned}$$

Proof: For $x + y > 0$, let $z = \exp\left(-2\frac{x+y}{\mu}\right) \in [0, 1]$, then $1 - \tanh^2\left(\frac{x+y}{\mu}\right) = \frac{4z}{(1+z)^2}$. Fix any $T > 1$ to be determined later, by Lemma IV.1, we choose the polynomial $p_\beta(z) = \frac{1}{(1+\beta z)^2}$ with $\beta = 1 - 1/\sqrt{T}$ to upper bound $f(z) = \frac{1}{(1+z)^2}$. So we have

$$\begin{aligned} \mathbb{E}\left[\left(1 - \tanh^2\left(\frac{X+Y}{\mu}\right)\right) X^2 \mathbb{1}_{X+Y>0}\right] &= 4\mathbb{E}\left[Z f(Z) X^2 \mathbb{1}_{X+Y>0}\right] \\ &\leq 4\mathbb{E}\left[Z p_\beta(Z) X^2 \mathbb{1}_{X+Y>0}\right] \\ &= 4 \sum_{k=0}^{\infty} \left\{ b_k \mathbb{E}\left[Z^{k+1} X^2 \mathbb{1}_{X+Y>0}\right] \right\}, \end{aligned}$$

where $b_k = (-1)^k (k+1)\beta^k$, and the exchange of infinite summation and expectation above is justified in view that

$$\sum_{k=0}^{\infty} |b_k| \mathbb{E}\left[Z^{k+1} X^2 \mathbb{1}_{X+Y>0}\right] \leq \sum_{k=0}^{\infty} |b_k| \mathbb{E}\left[X^2 \mathbb{1}_{X+Y>0}\right] \leq \sigma_X^2 \sum_{k=0}^{\infty} |b_k| < \infty$$

and the dominated convergence theorem (see, e.g., theorem 2.24 and 2.25 of [109]). By Lemma B.1, we have

$$\begin{aligned} &\sum_{k=0}^{\infty} \left\{ b_k \mathbb{E}\left[Z^{k+1} X^2 \mathbb{1}_{X+Y>0}\right] \right\} \\ &= \sum_{k=0}^{\infty} (-\beta)^k (k+1) \left[\left(\sigma_X^2 + \frac{4(k+1)^2}{\mu^2} \sigma_X^4 \right) \exp\left(\frac{2(k+1)^2}{\mu^2} (\sigma_X^2 + \sigma_Y^2)\right) \Phi^c\left(\frac{2(k+1)}{\mu} \sqrt{\sigma_X^2 + \sigma_Y^2}\right) \right. \\ &\quad \left. - \frac{2(k+1)}{\mu} \frac{\sigma_X^4}{\sqrt{2\pi} \sqrt{\sigma_X^2 + \sigma_Y^2}} \right] \\ &\leq \frac{1}{\sqrt{2\pi}} \sum_{k=0}^{\infty} (-\beta)^k (k+1) \left[\frac{\sigma_X^2 \mu}{2(k+1) \sqrt{\sigma_X^2 + \sigma_Y^2}} - \frac{\sigma_X^2 \mu^3}{8(k+1)^3 (\sigma_X^2 + \sigma_Y^2)^{3/2}} - \frac{\mu \sigma_X^4}{2(k+1) (\sigma_X^2 + \sigma_Y^2)^{3/2}} \right] \\ &\quad + \frac{3}{\sqrt{2\pi}} \sum_{k=0}^{\infty} \beta^k (k+1) \left(\sigma_X^2 + \frac{4(k+1)^2}{\mu^2} \sigma_X^4 \right) \frac{\mu^5}{32(k+1)^5 (\sigma_X^2 + \sigma_Y^2)^{5/2}}, \end{aligned}$$

where we have applied Type I upper and lower bounds for $\Phi^c(\cdot)$ to even k and odd k respectively and rearrange the terms to obtain the last line. Using the following estimates (see Lemma IV.1)

$$\sum_{k=0}^{\infty} (-\beta)^k = \frac{1}{1+\beta}, \quad \sum_{k=0}^{\infty} \frac{b_k}{(k+1)^3} \geq 0, \quad \sum_{k=0}^{\infty} \frac{|b_k|}{(k+1)^5} \leq \sum_{k=0}^{\infty} \frac{|b_k|}{(k+1)^3} \leq 2,$$

we obtain

$$\begin{aligned} \sum_{k=0}^{\infty} \left\{ b_k \mathbb{E}\left[Z^{k+1} X^2 \mathbb{1}_{X+Y>0}\right] \right\} &\leq \\ &\frac{1}{2\sqrt{2\pi}} \frac{\mu \sigma_X^2 \sigma_Y^2}{(\sigma_X^2 + \sigma_Y^2)^{3/2}} \frac{1}{1+\beta} + \frac{3}{16\sqrt{2\pi}} \frac{\sigma_X^2 \mu^3}{(\sigma_X^2 + \sigma_Y^2)^{5/2}} (3\mu^2 + 4\sigma_X^2). \end{aligned}$$

Noticing $\frac{1}{1+\beta} < \frac{1}{2} + \frac{1}{2\sqrt{T}}$ and choosing $T = \mu^{-4}$, we obtain the desired result. \blacksquare

Lemma IV.3. Let $X \sim \mathcal{N}(0, \sigma_X^2)$ and $Y \sim \mathcal{N}(0, \sigma_Y^2)$. We have

$$\begin{aligned} \mathbb{E}\left[\tanh\left(\frac{X+Y}{\mu}\right) X\right] &\geq \\ &\frac{2\sigma_X^2}{\sqrt{2\pi} \sqrt{\sigma_X^2 + \sigma_Y^2}} - \frac{4\mu^2 \sigma_X^2}{\sqrt{2\pi} \sqrt{\sigma_X^2 + \sigma_Y^2}} - \frac{2\sigma_X^2 \mu^2}{\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{3/2}} - \frac{3\sigma_X^2 \mu^4}{2\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{5/2}}. \end{aligned}$$

Proof: By Lemma B.1, we know

$$\mathbb{E} \left[\tanh \left(\frac{X+Y}{\mu} \right) X \right] = \frac{\sigma_X^2}{\mu} \mathbb{E} \left[1 - \tanh^2 \left(\frac{X+Y}{\mu} \right) \right]$$

Similar to the proof of the above lemma, for $x+y > 0$, let $z = \exp\left(-\frac{2x+y}{\mu}\right)$ and $f(z) = \frac{1}{(1+z)^2}$. Fixing any $T > 1$, we will use $4zp_\beta(z) = \frac{4z}{(1+\beta z)^2}$ to approximate the $1 - \tanh^2\left(\frac{x+y}{\mu}\right) = 4zf(z)$ function from above, where again $\beta = 1 - 1/\sqrt{T}$. So we obtain

$$\begin{aligned} \mathbb{E} \left[1 - \tanh^2 \left(\frac{X+Y}{\mu} \right) \right] &= 8\mathbb{E} [f(Z) Z \mathbb{1}_{X+Y>0}] \\ &= 8\mathbb{E} [p_\beta(Z) Z \mathbb{1}_{X+Y>0}] - 8\mathbb{E} [(p_\beta(Z) - f(Z)) Z \mathbb{1}_{X+Y>0}]. \end{aligned}$$

Now for the first term, we have

$$\mathbb{E} [p_\beta(Z) Z \mathbb{1}_{X+Y>0}] = \sum_{k=0}^{\infty} b_k \mathbb{E} [Z^{k+1} \mathbb{1}_{X+Y>0}],$$

justified as $\sum_{k=0}^{\infty} |b_k| \mathbb{E} [Z^{k+1} \mathbb{1}_{X+Y>0}] \leq \sum_{k=0}^{\infty} |b_k| < \infty$ making the dominated convergence theorem (see, e.g., theorem 2.24 and 2.25 of [109]) applicable. To proceed, from Lemma B.1, we obtain

$$\begin{aligned} &\sum_{k=0}^{\infty} b_k \mathbb{E} [Z^{k+1} \mathbb{1}_{X+Y>0}] \\ &= \sum_{k=0}^{\infty} (-\beta)^k (k+1) \exp\left(\frac{2}{\mu^2} (k+1)^2 (\sigma_X^2 + \sigma_Y^2)\right) \Phi^c\left(\frac{2}{\mu} (k+1) \sqrt{\sigma_X^2 + \sigma_Y^2}\right) \\ &\geq \frac{1}{\sqrt{2\pi}} \sum_{k=0}^{\infty} (-\beta)^k (k+1) \left(\frac{\mu}{2(k+1) \sqrt{\sigma_X^2 + \sigma_Y^2}} - \frac{\mu^3}{8(k+1)^3 (\sigma_X^2 + \sigma_Y^2)^{3/2}} \right) \\ &\quad - \frac{3}{\sqrt{2\pi}} \sum_{k=0}^{\infty} \beta^k (k+1) \frac{\mu^5}{32(k+1)^5 (\sigma_X^2 + \sigma_Y^2)^{5/2}}, \end{aligned}$$

where we have applied Type I upper and lower bounds for $\Phi^c(\cdot)$ to odd k and even k respectively and rearrange the terms to obtain the last line. Using the following estimates (see Lemma IV.1)

$$\sum_{k=0}^{\infty} (-\beta)^k = \frac{1}{1+\beta}, \quad 0 \leq \sum_{k=0}^{\infty} \frac{b_k}{(k+1)^3} \leq \sum_{k=0}^{\infty} \frac{|b_k|}{(k+1)^5} \leq \sum_{k=0}^{\infty} \frac{|b_k|}{(k+1)^3} \leq 2,$$

we obtain

$$\begin{aligned} \sum_{k=0}^{\infty} b_k \mathbb{E} [Z^{k+1} \mathbb{1}_{X+Y>0}] &\geq \\ &\frac{\mu}{2\sqrt{2\pi} \sqrt{\sigma_X^2 + \sigma_Y^2}} \frac{1}{1+\beta} - \frac{\mu^3}{4\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{3/2}} - \frac{3\mu^5}{16\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{5/2}}. \end{aligned}$$

To proceed, by Lemma B.1 and Lemma IV.1, we have

$$\mathbb{E} [(p_\beta(Z) - f(Z)) Z \mathbb{1}_{X+Y>0}] \leq \|p - f\|_{L^\infty[0,1]} \mathbb{E} [Z \mathbb{1}_{X+Y>0}] \leq \frac{\mu}{2\sqrt{2\pi T} \sqrt{\sigma_X^2 + \sigma_Y^2}},$$

where we have also used Type I upper bound for $\Phi^c(\cdot)$. Combining the above estimates, we get

$$\begin{aligned} \mathbb{E} \left[\tanh \left(\frac{X+Y}{\mu} \right) X \right] &\geq \\ &\frac{4\sigma_X^2}{\sqrt{2\pi} \sqrt{\sigma_X^2 + \sigma_Y^2}} \left(\frac{1}{1+\beta} - \frac{1}{\sqrt{T}} \right) - \frac{2\sigma_X^2 \mu^2}{\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{3/2}} - \frac{3\sigma_X^2 \mu^4}{2\sqrt{2\pi} (\sigma_X^2 + \sigma_Y^2)^{5/2}}. \end{aligned}$$

Noticing $\frac{1}{1+\beta} > \frac{1}{2}$ and taking $T = \mu^{-4}$, we obtain the claimed result. ■

Proof: (of Proposition II.5) For any $i \in [n-1]$, we have

$$\int_0^1 \int_{\mathbf{x}} \left| \frac{\partial}{\partial w_i} h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x}) \right| \mu(d\mathbf{x}) dw_i \leq \int_0^1 \int_{\mathbf{x}} \left(|x_i| + |x_n| \frac{1}{q_n(\mathbf{w})} \right) \mu(d\mathbf{x}) dw_i < \infty.$$

Hence by Lemma A.3 we obtain $\frac{\partial}{\partial w_i} \mathbb{E}[h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] = \mathbb{E}\left[\frac{\partial}{\partial w_i} h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})\right]$. Moreover for any $j \in [n-1]$,

$$\begin{aligned} \int_0^1 \int_{\mathbf{x}} \left| \frac{\partial^2}{\partial w_j \partial w_i} h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x}) \right| \mu(d\mathbf{x}) dw_j \leq \\ \int_0^1 \int_{\mathbf{x}} \left[\frac{1}{\mu} \left(|x_i| + \frac{|x_n|}{q_n(\mathbf{w})} \right) \left(|x_j| + \frac{|x_n|}{q_n(\mathbf{w})} \right) + |x_n| \left(\frac{1}{q_n(\mathbf{w})} + \frac{1}{q_n^3(\mathbf{w})} \right) \right] \mu(d\mathbf{x}) dw_i < \infty. \end{aligned}$$

Invoking Lemma A.3 again we obtain

$$\frac{\partial^2}{\partial w_j \partial w_i} \mathbb{E}[h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] = \frac{\partial}{\partial w_j} \mathbb{E}\left[\frac{\partial}{\partial w_i} h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})\right] = \mathbb{E}\left[\frac{\partial^2}{\partial w_j \partial w_i} h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})\right].$$

The above holds for any pair of $i, j \in [n-1]$, so it follows that

$$\nabla_{\mathbf{w}}^2 \mathbb{E}[h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] = \mathbb{E}[\nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})].$$

Hence it is easy to see that

$$\begin{aligned} & \mathbf{w}^* \nabla_{\mathbf{w}}^2 \mathbb{E}[h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \mathbf{w} \\ &= \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \left(\mathbf{w}^* \bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \|\mathbf{w}\|^2 \right)^2 \right] - \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \frac{x_n}{q_n^3(\mathbf{w})} \|\mathbf{w}\|^2 \right]. \end{aligned}$$

Now the first term is

$$\begin{aligned} & \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \left(\mathbf{w}^* \bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \|\mathbf{w}\|^2 \right)^2 \right] \\ &= \frac{2(1-\theta)}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}}{\mu} \right) \right) (\mathbf{w}^* \bar{\mathbf{x}})^2 \mathbb{1}_{\mathbf{w}^* \bar{\mathbf{x}} > 0} \right] \\ & \quad - \frac{4\theta}{\mu} \frac{\|\mathbf{w}\|^2}{q_n^2(\mathbf{w})} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}^* \bar{\mathbf{x}} + q_n(\mathbf{w}) x_n}{\mu} \right) \right) (\mathbf{w}^* \bar{\mathbf{x}}) (q_n(\mathbf{w}) x_n) \mathbb{1}_{\mathbf{w}^* \bar{\mathbf{x}} + q_n(\mathbf{w}) x_n > 0} \right] \\ & \quad + \frac{2\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_v \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) \right) (\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}})^2 \mathbb{1}_{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n > 0} \right] \\ & \quad + \frac{2\theta}{\mu} \frac{\|\mathbf{w}\|^4}{q_n^4(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \mathbb{E}_v \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) \right) (q_n(\mathbf{w}) v_n)^2 \mathbb{1}_{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n > 0} \right] \\ & \leq \frac{8(1-\theta)}{\mu} \mathbb{E} \left[\exp \left(-2 \frac{\mathbf{w}^* \bar{\mathbf{x}}}{\mu} \right) (\mathbf{w}^* \bar{\mathbf{x}})^2 \mathbb{1}_{\mathbf{w}^* \bar{\mathbf{x}} > 0} \right] \\ & \quad + \frac{8\theta}{\mu} \frac{\|\mathbf{w}\|^2}{q_n^2(\mathbf{w})} \mathbb{E} \left[\exp \left(-\frac{2}{\mu} (\mathbf{w}^* \bar{\mathbf{x}} + q_n(\mathbf{w}) x_n) \right) (\mathbf{w}^* \bar{\mathbf{x}} + q_n(\mathbf{w}) x_n)^2 \mathbb{1}_{\mathbf{w}^* \bar{\mathbf{x}} + q_n(\mathbf{w}) x_n > 0} \right] \\ & \quad + \frac{2\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{X,Y} \left[\left(1 - \tanh^2 \left(\frac{X+Y}{\mu} \right) \right) Y^2 \mathbb{1}_{X+Y > 0} \right] \\ & \quad + \frac{2\theta}{\mu} \frac{\|\mathbf{w}\|^4}{q_n^4(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{X,Y} \left[\left(1 - \tanh^2 \left(\frac{X+Y}{\mu} \right) \right) X^2 \mathbb{1}_{X+Y > 0} \right], \end{aligned}$$

where conditioned on each support set \mathcal{J} , we let $X \doteq q_n(\mathbf{w}) v_n \sim \mathcal{N}(0, q_n^2(\mathbf{w}))$ and $Y \doteq \mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} \sim \mathcal{N}(0, \|\mathbf{w}_{\mathcal{J}}\|^2)$. Noticing the fact $t \mapsto \exp(-2t/\mu) t^2$ for $t > 0$ is maximized at $t = \mu$ with maximum value $\exp(-2) \mu^2$, and in

view of the estimate in Lemma IV.2, we obtain

$$\begin{aligned}
 & \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \left(\mathbf{w}^* \bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \|\mathbf{w}\|^2 \right)^2 \right] \\
 & \leq 8 \exp(-2) \left(1 - \theta + \frac{\|\mathbf{w}\|^2}{q_n^2(\mathbf{w})} \theta \right) \mu \\
 & \quad + \frac{2\theta}{\mu} \mathbb{E}_{\mathcal{J}} \left[\frac{1}{\sqrt{2\pi}} \frac{\mu \|\mathbf{w}_{\mathcal{J}}\|^2 q_n^2(\mathbf{w})}{\|\mathbf{q}_{\mathcal{I}}\|^3} + \frac{\mu^3 \|\mathbf{w}_{\mathcal{J}}\|^2 q_n^2(\mathbf{w})}{\|\mathbf{q}_{\mathcal{I}}\|^3} + \frac{3}{4\sqrt{2\pi}} \frac{\|\mathbf{w}_{\mathcal{J}}\|^2 \mu^3}{\|\mathbf{q}_{\mathcal{I}}\|^5} (3\mu^2 + 4\|\mathbf{w}_{\mathcal{J}}\|^2) \right] \\
 & \quad + \frac{2\theta}{\mu} \frac{\|\mathbf{w}\|^4}{q_n^4(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \left[\frac{1}{\sqrt{2\pi}} \frac{\mu \|\mathbf{w}_{\mathcal{J}}\|^2 q_n^2(\mathbf{w})}{\|\mathbf{q}_{\mathcal{I}}\|^3} + \frac{\mu^3 \|\mathbf{w}_{\mathcal{J}}\|^2 q_n^2(\mathbf{w})}{\|\mathbf{q}_{\mathcal{I}}\|^3} + \frac{3}{4\sqrt{2\pi}} \frac{q_n^2(\mathbf{w}) \mu^3}{\|\mathbf{q}_{\mathcal{I}}\|^5} (3\mu^2 + 4q_n^2(\mathbf{w})) \right] \\
 & \leq \frac{2\theta}{\sqrt{2\pi} q_n^2(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \left[\frac{\|\mathbf{w}_{\mathcal{J}}\|^2}{\|\mathbf{q}_{\mathcal{I}}\|^3} \right] + \frac{11}{20} \mu \left(2 + \frac{1}{q_n^2(\mathbf{w})} \right) + 2\theta \mu^2 \left(1 + \frac{3}{\sqrt{2\pi} q_n(\mathbf{w})} + \frac{1}{q_n^3(\mathbf{w})} + \frac{3}{\sqrt{2\pi} q_n^5(\mathbf{w})} \right),
 \end{aligned}$$

where we have used $\mu < q_n(\mathbf{w}) \leq \|\mathbf{q}_{\mathcal{I}}\|$ and $\|\mathbf{w}_{\mathcal{J}}\| \leq \|\mathbf{q}_{\mathcal{I}}\|$ and $\|\mathbf{w}\| \leq 1$ and $\theta \in (0, 1/2)$ to simplify the intermediate quantities to obtain the last line. Similarly for the second term, we obtain

$$\begin{aligned}
 & \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \frac{x_n}{q_n^3(\mathbf{w})} \|\mathbf{w}\|^2 \right] \\
 & = \frac{\|\mathbf{w}\|^2 \theta}{q_n^4(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\tanh \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) x_n q_n(\mathbf{w}) \right] \\
 & \geq \frac{\|\mathbf{w}\|^2 \theta}{q_n^4(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \left[\frac{2q_n^2(\mathbf{w})}{\sqrt{2\pi} \|\mathbf{q}_{\mathcal{I}}\|} - \frac{4\mu^2 q_n^2(\mathbf{w})}{\sqrt{2\pi} \|\mathbf{q}_{\mathcal{I}}\|} - \frac{2q_n^2(\mathbf{w}) \mu^2}{\sqrt{2\pi} \|\mathbf{q}_{\mathcal{I}}\|^3} - \frac{3q_n^2(\mathbf{w}) \mu^4}{2\sqrt{2\pi} \|\mathbf{q}_{\mathcal{I}}\|^5} \right] \\
 & \geq \sqrt{\frac{2}{\pi}} \frac{\theta}{q_n^2(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \left[\frac{\|\mathbf{w}\|^2}{\|\mathbf{q}_{\mathcal{I}}\|} \right] - \frac{4\theta \mu^2}{\sqrt{2\pi}} \left(\frac{1}{q_n^3(\mathbf{w})} + \frac{1}{q_n^5(\mathbf{w})} \right).
 \end{aligned}$$

Collecting the above estimates, we obtain

$$\begin{aligned}
 & \mathbf{w}^* \nabla_{\mathbf{w}}^2 \mathbb{E} [h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \mathbf{w} \\
 & \leq \sqrt{\frac{2}{\pi}} \frac{\theta}{q_n^2(\mathbf{w})} \mathbb{E}_{\mathcal{J}} \left[\frac{\|\mathbf{w}_{\mathcal{J}}\|^2}{\|\mathbf{q}_{\mathcal{I}}\|^3} - \frac{\|\mathbf{w}\|^2 (\|\mathbf{w}_{\mathcal{J}}\|^2 + q_n^2(\mathbf{w}))}{\|\mathbf{q}_{\mathcal{I}}\|^3} \right] \\
 & \quad + \frac{11}{20} \mu \left(2 + \frac{1}{q_n^2(\mathbf{w})} \right) + 2\theta \mu^2 \left(1 + \frac{3}{\sqrt{2\pi} q_n(\mathbf{w})} + \frac{2}{q_n^3(\mathbf{w})} + \frac{5}{\sqrt{2\pi} q_n^5(\mathbf{w})} \right) \\
 & \leq -\sqrt{\frac{2}{\pi}} \theta \mathbb{E} \left[\frac{\|\mathbf{w}_{\mathcal{J}^c}\|^2}{\|\mathbf{q}_{\mathcal{I}}\|^3} \right] + \frac{11}{10} \mu + \frac{11}{20} \frac{\mu}{q_n(\mathbf{w})} + 2\theta \mu^2 \left(1 + \frac{6}{q_n^5(\mathbf{w})} \right) \\
 & \leq -\sqrt{\frac{2}{\pi}} \theta (1 - \theta) \|\mathbf{w}\|^2 \mathbb{E} \left[\frac{1}{\|\mathbf{q}_{\mathcal{I}}\|^3} \right] + \frac{11}{10} \mu + \frac{11}{20} \frac{\mu}{q_n^2(\mathbf{w})} + 2\theta \mu^2 \left(1 + \frac{6}{q_n^5(\mathbf{w})} \right), \tag{IV.3}
 \end{aligned}$$

where to obtain the last line we have invoked the association inequality in Lemma A.2, as both $\|\mathbf{w}_{\mathcal{J}^c}\|^2$ and $1/\|\mathbf{q}_{\mathcal{I}}\|^3$ both coordinatewise nonincreasing w.r.t. the index set. Substituting the upper bound for μ into (IV.3) and noting $R_h \leq \|\mathbf{w}\|$ and also noting the fact $q_n(\mathbf{w}) \geq \frac{1}{\sqrt{4n}}$ (implied by the assumption $\|\mathbf{w}\| \leq \sqrt{\frac{4n-1}{4n}}$), we obtain the claimed result. \blacksquare

2) *Proof of Proposition II.6:* *Proof:* By similar consideration as proof of the above proposition, the following is justified:

$$\nabla_{\mathbf{w}} \mathbb{E} [h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] = \mathbb{E} [\nabla_{\mathbf{w}} h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x})].$$

Now consider

$$\begin{aligned} \mathbf{w}^* \nabla \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] &= \nabla \mathbb{E} [\mathbf{w}^* h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \\ &= \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) (\mathbf{w}^* \bar{\mathbf{x}}) \right] - \frac{\|\mathbf{w}\|^2}{q_n} \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) x_n \right]. \end{aligned} \quad (\text{IV.4})$$

For (IV.4), we next provide a lower bound for the first expectation and an upper bound for the second expectation. For the first, we have

$$\begin{aligned} &\mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) (\mathbf{w}^* \bar{\mathbf{x}}) \right] \\ &= \theta \mathbb{E}_{\mathcal{J}} \left[\mathbb{E}_v \left[\tanh \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) (\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}}) \right] \right] + (1 - \theta) \mathbb{E}_{\mathcal{J}} \left[\mathbb{E}_v \left[\tanh \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}}}{\mu} \right) (\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}}) \right] \right] \\ &= \theta \mathbb{E}_{\mathcal{J}} \left[\mathbb{E}_{X,Y} \left[\tanh \left(\frac{X+Y}{\mu} \right) Y \right] \right] + (1 - \theta) \mathbb{E}_{\mathcal{J}} \left[\mathbb{E}_Y \left[\tanh \left(\frac{Y}{\mu} \right) Y \right] \right], \end{aligned}$$

where $X \doteq q_n(\mathbf{w}) v_n \sim \mathcal{N}(0, q_n^2(\mathbf{w}))$ and $Y \doteq \mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} \sim \mathcal{N}(0, \|\mathbf{w}_{\mathcal{J}}\|^2)$. Now by Lemma A.2 we obtain

$$\mathbb{E} \left[\tanh \left(\frac{X+Y}{\mu} \right) Y \right] \geq \mathbb{E} \left[\tanh \left(\frac{X+Y}{\mu} \right) \right] \mathbb{E}[Y] = 0,$$

as $\tanh\left(\frac{X+Y}{\mu}\right)$ and X are both coordinatewise nondecreasing function of X and Y . Using the $\tanh(z) \geq (1 - \exp(-2z))/2$ lower bound for $z > 0$ and integral results in Lemma B.1, we obtain

$$\begin{aligned} \mathbb{E} \left[\tanh \left(\frac{Y}{\mu} \right) Y \right] &= 2 \mathbb{E} \left[\tanh \left(\frac{Y}{\mu} \right) Y \mathbb{1}_{Y>0} \right] \\ &\geq \mathbb{E} \left[\left(1 - \exp \left(-\frac{2Y}{\mu} \right) \right) Y \mathbb{1}_{Y>0} \right] \\ &= \frac{2\sigma_Y^2}{\mu} \exp \left(\frac{2\sigma_Y^2}{\mu^2} \right) \Phi^c \left(\frac{2\sigma_Y}{\mu} \right) \\ &\geq \frac{2\sigma_Y^2}{\mu\sqrt{2\pi}} \left(\sqrt{1 + \frac{\sigma_Y^2}{\mu^2}} - \frac{\sigma_Y}{\mu} \right) \\ &\geq \frac{2\sigma_Y^2}{\mu\sqrt{2\pi}} \left(\sqrt{1 + \frac{\|\mathbf{w}\|^2}{\mu^2}} - \frac{\|\mathbf{w}\|}{\mu} \right), \end{aligned}$$

where at the second last inequality we have used Type III lower bound for Gaussian upper tail $\Phi^c(\cdot)$ (Lemma A.4), and at the last we have used the fact that $t \mapsto \sqrt{1+t^2} - t$ is a monotonic decreasing function over $t > 0$ and that $\sigma_Y = \|\mathbf{w}_{\mathcal{J}}\| \leq \|\mathbf{w}\|$. Collecting the above estimates, we have

$$\begin{aligned} \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) (\mathbf{w}^* \bar{\mathbf{x}}) \right] &\geq (1 - \theta) \mathbb{E}_{\mathcal{J}} \left[\frac{2\|\mathbf{w}_{\mathcal{J}}\|^2}{\mu\sqrt{2\pi}} \left(\sqrt{1 + \frac{\|\mathbf{w}\|^2}{\mu^2}} - \frac{\|\mathbf{w}\|}{\mu} \right) \right] \\ &\geq (1 - \theta) \mathbb{E}_{\mathcal{J}} \left[\frac{2\|\mathbf{w}_{\mathcal{J}}\|^2}{\mu\sqrt{2\pi}} \frac{\mu}{10\|\mathbf{w}\|} \right] \\ &\geq \frac{\theta(1 - \theta)\|\mathbf{w}\|}{5\sqrt{2\pi}}, \end{aligned} \quad (\text{IV.5})$$

where at the second line we have used the assumption that $\|\mathbf{w}\| \geq \frac{\mu}{6\sqrt{2}}$ and also the fact that $\sqrt{1+x^2} \geq x + \frac{1}{10x}$ for $x \geq \frac{1}{6\sqrt{2}}$.

For the second expectation of (IV.4), we have

$$\mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) x_n \right] \leq \theta \mathbb{E} \left[\left| \tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right| |v_n| \right] \leq \theta \sqrt{\frac{2}{\pi}}, \quad (\text{IV.6})$$

as $\tanh(\cdot)$ is bounded by one in magnitude. Plugging the results of (IV.5) and (IV.6) into (IV.4) and noticing that $q_n(\mathbf{w})^2 + \|\mathbf{w}\|^2 = 1$ we obtain

$$\mathbf{w}^* \nabla \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \geq \frac{\theta \|\mathbf{w}\|}{\sqrt{2\pi}} \left[\frac{1-\theta}{5} - \frac{2\|\mathbf{w}\|}{\sqrt{1-\|\mathbf{w}\|^2}} \right] \geq \frac{\theta(1-\theta)\|\mathbf{w}\|}{10\sqrt{2\pi}},$$

where we have invoked the assumption that $\|\mathbf{w}\| \leq \frac{1}{10\sqrt{5}}(1-\theta)$ to provide the upper bound $\frac{2\|\mathbf{w}\|}{\sqrt{1-\|\mathbf{w}\|^2}} \leq \frac{1}{10}(1-\theta)$. We then choose the particular ranges as stated for μ and θ to ensure $r_g < R_g$, completing the proof. ■

3) *Proof of Proposition II.7:* *Proof:* By consideration similar to proof of Proposition II.5, we can exchange the hessian and expectation, i.e.,

$$\nabla_{\mathbf{w}}^2 \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] = \mathbb{E} [\nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})].$$

We are interested in the expected Hessian matrix

$$\begin{aligned} \nabla_{\mathbf{w}}^2 \mathbb{E} [h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] &= \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \left(\bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w} \right) \left(\bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w} \right)^* \right] \\ &\quad - \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \left(\frac{x_n}{q_n(\mathbf{w})} \mathbf{I} + \frac{x_n}{q_n^3(\mathbf{w})} \mathbf{w} \mathbf{w}^* \right) \right] \end{aligned}$$

in the region that $0 \leq \|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}$.

When $\mathbf{w} = \mathbf{0}$, by Lemma B.1, we have

$$\begin{aligned} &\mathbb{E} [\nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] |_{\mathbf{w}=\mathbf{0}} \\ &= \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{x_n}{\mu} \right) \right) \bar{\mathbf{x}} \bar{\mathbf{x}}^* \right] - \mathbb{E} \left[\tanh \left(\frac{x_n}{\mu} \right) x_n \right] \mathbf{I} \\ &= \frac{\theta(1-\theta)}{\mu} \mathbf{I} + \frac{\theta^2}{\mu} \mathbb{E}_{v_n} \left[1 - \tanh^2 \left(\frac{v_n}{\mu} \right) \right] \mathbf{I} - \frac{\theta}{\mu} \mathbb{E}_{v_n} \left[1 - \tanh^2 \left(\frac{v_n}{\mu} \right) \right] \mathbf{I} \\ &= \frac{\theta(1-\theta)}{\mu} \mathbb{E}_{v_n} \left[\tanh^2 \left(\frac{q_n(\mathbf{w}) v_n}{\mu} \right) \right] \mathbf{I}. \end{aligned}$$

Simple calculation based on Lemma B.1 shows

$$\mathbb{E}_{v_n} \left[\tanh^2 \left(\frac{v_n}{\mu} \right) \right] \geq 2 \left(1 - 4 \exp \left(-\frac{2}{\mu^2} \right) \Phi^c \left(\frac{2}{\mu} \right) \right) \geq 2 \left(1 - \frac{2}{\sqrt{2\pi}} \mu \right).$$

Invoking the assumptions $\mu \leq \frac{1}{20\sqrt{n}} \leq 1/20$ and $\theta < 1/2$, we obtain

$$\mathbb{E} [\nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] |_{\mathbf{w}=\mathbf{0}} \succeq \frac{\theta(1-\theta)}{\mu} \left(2 - \frac{4}{\sqrt{2\pi}} \mu \right) \mathbf{I} \succeq \frac{\theta}{\mu} \left(1 - \frac{1}{10\sqrt{2\pi}} \right) \mathbf{I}.$$

When $0 < \|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}$, we aim to derive a semidefinite lower bound for

$$\begin{aligned} &\mathbb{E} [\nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \\ &= \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \bar{\mathbf{x}} \bar{\mathbf{x}}^* \right] - \frac{1}{q_n^2(\mathbf{w})} \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) q_n(\mathbf{w}) x_n \right] \mathbf{I} \\ &\quad - \frac{1}{\mu q_n^2(\mathbf{w})} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) q_n(\mathbf{w}) x_n (\mathbf{w} \bar{\mathbf{x}}^* + \bar{\mathbf{x}} \mathbf{w}^*) \right] \\ &\quad + \frac{1}{q_n^4(\mathbf{w})} \left\{ \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) (q_n(\mathbf{w}) x_n)^2 \right] - \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) q_n(\mathbf{w}) x_n \right] \right\} \mathbf{w} \mathbf{w}^*. \quad (\text{IV.7}) \end{aligned}$$

We will first provide bounds for the last two lines and then tackle the first which is slightly more tricky. For the second line, we have

$$\begin{aligned}
 & \frac{1}{\mu q_n^2(\mathbf{w})} \left\| \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) q_n(\mathbf{w}) x_n (\mathbf{w} \bar{\mathbf{x}}^* + \bar{\mathbf{x}} \mathbf{w}^*) \right] \right\| \\
 & \leq \frac{2}{\mu q_n^2(\mathbf{w})} \left\| \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) q_n(\mathbf{w}) x_n \bar{\mathbf{x}} \right] \mathbf{w}^* \right\| \\
 & \leq \frac{2}{\mu q_n^2(\mathbf{w})} \left\| \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) q_n(\mathbf{w}) x_n \bar{\mathbf{x}} \right] \right\| \|\mathbf{w}\| \\
 & \leq \frac{2}{\mu q_n(\mathbf{w})} \theta^2 \mathbb{E}[|v_n|] \mathbb{E}[\|\bar{\mathbf{v}}\|] \|\mathbf{w}\| \\
 & \leq \frac{4\theta^2}{\pi \mu q_n(\mathbf{w})} \sqrt{n} \|\mathbf{w}\| \leq \frac{\theta}{\mu} \frac{4\theta \sqrt{n} \|\mathbf{w}\|}{\pi \sqrt{1 - \|\mathbf{w}\|^2}} \leq \frac{\theta}{\mu} \frac{1}{40\pi},
 \end{aligned}$$

where from the third to the fourth line we have used $\left\| 1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right\| \leq 1$, Jensen's inequality for the $\|\cdot\|$ function, and independence of x_n and $\bar{\mathbf{x}}$, and to obtain the last bound we have invoked the $\|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}$, $\mu \leq \frac{1}{20\sqrt{n}}$, and $\theta < \frac{1}{2}$ assumptions. For the third line in (IV.7), by Lemma A.1 and Lemma B.1,

$$\begin{aligned}
 & \left| \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) (q_n(\mathbf{w}) x_n)^2 \right] - \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) q_n x_n \right] \right| \\
 & = \left| \frac{\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) \right) (q_n(\mathbf{w}) v_n)^2 \right] \right. \\
 & \quad \left. - \theta \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\tanh \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) q_n(\mathbf{w}) v_n \right] \right| \\
 & = \frac{\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) \right) ((q_n(\mathbf{w}) v_n)^2 + q_n^2(\mathbf{w})) \right] \\
 & \leq \frac{8\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\exp \left(-\frac{2}{\mu} (\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n) \right) ((q_n(\mathbf{w}) v_n)^2 + q_n^2(\mathbf{w})) \mathbb{1}_{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n > 0} \right] \\
 & \leq \frac{8\theta}{\sqrt{2\pi}} \mathbb{E}_{\mathcal{J}} \left[\frac{q_n^2(\mathbf{w})}{\sqrt{q_n^2(\mathbf{w}) + \|\mathbf{w}_{\mathcal{J}}\|^2}} \right] \leq \frac{8\theta q_n(\mathbf{w})}{\sqrt{2\pi}}.
 \end{aligned}$$

Thus, we have

$$\begin{aligned}
 & \frac{1}{q_n^4(\mathbf{w})} \left\{ \frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^* \mathbf{x}}{\mu} \right) \right) (q_n x_n)^2 \right] - \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^* \mathbf{x}}{\mu} \right) q_n x_n \right] \right\} \mathbf{w} \mathbf{w}^* \\
 & \succeq -\frac{8\theta}{q_n^3(\mathbf{w}) \sqrt{2\pi}} \|\mathbf{w}\|^2 \mathbf{I} \succeq -\frac{\theta}{\mu} \left(\frac{64n^{3/2} \mu \|\mathbf{w}\|^2}{q_n^3(\mathbf{w}) \sqrt{2\pi}} \right) \mathbf{I} \succeq -\frac{\theta}{\mu} \frac{1}{4000\sqrt{2\pi}} \mathbf{I},
 \end{aligned}$$

where we have again used $\|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}$, $\mu \leq \frac{1}{20\sqrt{n}}$, and $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ assumptions to simplify the final bound.

To derive a lower bound for the first line of (IV.7), we lower bound the first term and upper bound the second. The latter is easy: using Lemma A.1 and Lemma B.1,

$$\begin{aligned}
 & \frac{1}{q_n^2(\mathbf{w})} \mathbb{E} \left[\tanh \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) q_n(\mathbf{w}) x_n \right] \\
 & = \frac{\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[1 - \tanh^2 \left[\frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right] \right] \\
 & \leq \frac{8\theta}{\mu} \mathbb{E}_{\mathcal{J}} \mathbb{E}_{\mathbf{v}} \left[\exp \left(-2 \frac{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n}{\mu} \right) \mathbb{1}_{\mathbf{w}_{\mathcal{J}}^* \bar{\mathbf{v}} + q_n(\mathbf{w}) v_n > 0} \right] \\
 & \leq \frac{4\theta}{\sqrt{2\pi} q_n(\mathbf{w})} \leq \frac{\theta}{\mu} \frac{8\sqrt{n}\mu}{\sqrt{2\pi}} \leq \frac{\theta}{\mu} \frac{2}{5\sqrt{2\pi}},
 \end{aligned}$$

where we have again used assumptions that $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ and $\mu \leq \frac{1}{20\sqrt{n}}$ to simplify the last bound. To lower bound the first term, first note that

$$\frac{1}{\mu} \mathbb{E} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{q}^*(\mathbf{w}) \mathbf{x}}{\mu} \right) \right) \bar{\mathbf{x}} \bar{\mathbf{x}}^* \right] \geq \frac{1-\theta}{\mu} \mathbb{E}_{\bar{\mathbf{x}}} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}}{\mu} \right) \right) \bar{\mathbf{x}} \bar{\mathbf{x}}^* \right].$$

We set out to lower bound the expectation as

$$\mathbb{E}_{\bar{\mathbf{x}}} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}}{\mu} \right) \right) \bar{\mathbf{x}} \bar{\mathbf{x}}^* \right] \geq \theta \beta \mathbf{I}$$

for some scalar $\beta > 0$. Suppose \mathbf{w} has $k \in [n-1]$ nonzeros, w.l.o.g., further assume the first k elements of \mathbf{w} are these nonzeros. It is easy to see the expectation above has a block diagonal structure $\text{diag}(\boldsymbol{\Sigma}; \alpha \theta \mathbf{I}_{n-1-k})$, where

$$\alpha \doteq \mathbb{E}_{\bar{\mathbf{x}}} \left[\left(1 - \tanh^2 \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}}{\mu} \right) \right) \right].$$

So in order to derive the $\theta \beta \mathbf{I}$ lower bound as desired, it is sufficient to show $\boldsymbol{\Sigma} \succeq \theta \beta \mathbf{I}$ and $\beta \leq \alpha$ for some $0 < \beta < 1$, i.e., letting $\tilde{\mathbf{w}} \in \mathbb{R}^k$ be the subvector of nonzero elements,

$$\mathbb{E}_{\tilde{\mathbf{x}} \sim i.i.d. \text{BG}(\theta)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}^* \tilde{\mathbf{x}}}{\mu} \right) \right) \tilde{\mathbf{x}} \tilde{\mathbf{x}}^* \right] \succeq \theta \beta \mathbf{I},$$

which is equivalent to that for all $\mathbf{z} \in \mathbb{R}^k$ such that $\|\mathbf{z}\| = 1$,

$$\mathbb{E}_{\tilde{\mathbf{x}} \sim i.i.d. \text{BG}(\theta)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}^* \tilde{\mathbf{x}}}{\mu} \right) \right) (\tilde{\mathbf{x}}^* \mathbf{z})^2 \right] \geq \theta \beta.$$

It is then sufficient to show that for any nontrivial support set $\mathcal{S} \subset [k]$ and any vector $\mathbf{z} \in \mathbb{R}^k$ such that $\text{supp}(\mathbf{z}) = \mathcal{S}$ with $\|\mathbf{z}\| = 1$,

$$\mathbb{E}_{\tilde{\mathbf{v}} \sim i.i.d. \mathcal{N}(0,1)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \mathbf{z})^2 \right] \geq \beta.$$

To see the implication, suppose the latter claimed holds, then for any \mathbf{z} with unit norm,

$$\begin{aligned} & \mathbb{E}_{\tilde{\mathbf{x}} \sim i.i.d. \text{BG}(\theta)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}^* \tilde{\mathbf{x}}}{\mu} \right) \right) (\tilde{\mathbf{x}}^* \mathbf{z})^2 \right] \\ &= \sum_{s=1}^k \theta^s (1-\theta)^{k-s} \sum_{\mathcal{S} \in \binom{[k]}{s}} \mathbb{E}_{\tilde{\mathbf{v}} \sim i.i.d. \mathcal{N}(0,1)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \mathbf{z}_{\mathcal{S}})^2 \right] \\ &\geq \sum_{s=1}^k \theta^s (1-\theta)^{k-s} \sum_{\mathcal{S} \in \binom{[k]}{s}} \beta \|\mathbf{z}_{\mathcal{S}}\|^2 = \beta \mathbb{E}_{\mathcal{S}} \left[\|\mathbf{z}_{\mathcal{S}}\|^2 \right] = \theta \beta. \end{aligned}$$

Now for any fixed support set $\mathcal{S} \subset [k]$, $\mathbf{z} = \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}} \mathbf{z} + (\mathbf{I} - \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}}) \mathbf{z}$. So we have

$$\begin{aligned} & \mathbb{E}_{\tilde{\mathbf{v}} \sim i.i.d. \mathcal{N}(0,1)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \mathbf{z})^2 \right] \\ &= \mathbb{E}_{\tilde{\mathbf{v}}} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}} \mathbf{z})^2 \right] + \mathbb{E}_{\tilde{\mathbf{v}}} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* (\mathbf{I} - \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}}) \mathbf{z})^2 \right] \\ &= \frac{(\tilde{\mathbf{w}}_{\mathcal{S}}^* \mathbf{z})^2}{\|\mathbf{w}_{\mathcal{S}}\|^4} \mathbb{E}_{\tilde{\mathbf{v}}} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \tilde{\mathbf{w}}_{\mathcal{S}})^2 \right] + \mathbb{E}_{\tilde{\mathbf{v}}} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \right) \right] \mathbb{E}_{\tilde{\mathbf{v}}} \left[(\tilde{\mathbf{v}}^* (\mathbf{I} - \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}}) \mathbf{z})^2 \right] \\ &\geq 2 \frac{(\tilde{\mathbf{w}}_{\mathcal{S}}^* \mathbf{z})^2}{\|\mathbf{w}_{\mathcal{S}}\|^4} \mathbb{E}_{\tilde{\mathbf{v}}} \left[\exp \left(-\frac{2\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) (\tilde{\mathbf{v}}^* \tilde{\mathbf{w}}_{\mathcal{S}})^2 \mathbb{1}_{\tilde{\mathbf{v}}^* \tilde{\mathbf{w}}_{\mathcal{S}} > 0} \right] + 2 \mathbb{E}_{\tilde{\mathbf{v}}} \left[\exp \left(-\frac{2\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}}}{\mu} \right) \mathbb{1}_{\tilde{\mathbf{w}}_{\mathcal{S}}^* \tilde{\mathbf{v}} > 0} \right] \|(\mathbf{I} - \mathcal{P}_{\tilde{\mathbf{w}}_{\mathcal{S}}}) \mathbf{z}\|^2. \end{aligned}$$

Using expectation result from Lemma B.1, and applying Type III lower bound for Gaussian tails, we obtain

$$\begin{aligned} & \mathbb{E}_{\tilde{\mathbf{v}} \sim i.i.d. \mathcal{N}(0,1)} \left[\left(1 - \tanh^2 \left(\frac{\tilde{\mathbf{w}}_S^* \tilde{\mathbf{v}}}{\mu} \right) \right) (\tilde{\mathbf{v}}^* \mathbf{z})^2 \right] \\ & \geq \frac{1}{\sqrt{2\pi}} \left(\sqrt{4 + \frac{4 \|\tilde{\mathbf{w}}_S\|^2}{\mu^2}} - \frac{2 \|\tilde{\mathbf{w}}_S\|}{\mu} \right) - \frac{4 (\tilde{\mathbf{w}}_S^* \mathbf{z})^2}{\mu \sqrt{2\pi} \|\tilde{\mathbf{w}}_S\|} \\ & \geq \frac{1}{\sqrt{2\pi}} \left(2 - \frac{3}{4} \sqrt{2} \right), \end{aligned}$$

where we have used Cauchy-Schwarz to obtain $(\tilde{\mathbf{v}}^* \mathbf{z})^2 \leq \|\tilde{\mathbf{v}}^*\|^2$ and invoked the assumption $\|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}}$ to simplify the last bound. On the other hand, we similarly obtain

$$\alpha = \mathbb{E}_{\mathcal{J}} \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{w}_{\mathcal{J}}\|^2)} [1 - \tanh^2(Z/\mu)] \geq \frac{2}{\sqrt{2\pi}} \frac{\sqrt{4\|\mathbf{w}\|^2/\mu^2 + 4} - 2\|\mathbf{w}\|/\mu}{2} \geq \frac{1}{\sqrt{2\pi}} \left(2 - \frac{1}{2} \sqrt{2} \right).$$

So we can take $\beta = \frac{1}{\sqrt{2\pi}} (2 - \frac{3}{4} \sqrt{2}) < 1$.

Putting together the above estimates for the case $\mathbf{w} \neq \mathbf{0}$, we obtain

$$\mathbb{E} [\nabla_{\mathbf{w}}^2 h_{\mu}(\mathbf{q}^*(\mathbf{w}) \mathbf{x})] \succeq \frac{\theta}{\mu \sqrt{2\pi}} \left(1 - \frac{3}{8} \sqrt{2} - \frac{\sqrt{2\pi}}{40\pi} - \frac{1}{4000} - \frac{2}{5} \right) \mathbf{I} \succeq \frac{1}{25\sqrt{2\pi}} \frac{\theta}{\mu} \mathbf{I}.$$

Hence for all \mathbf{w} , we can take the $\frac{1}{25\sqrt{2\pi}} \frac{\theta}{\mu}$ as the lower bound, completing the proof. \blacksquare

4) *Proof of Pointwise Concentration Results:* To avoid clutter of notations, in this subsection we write \mathbf{X} to mean \mathbf{X}_0 ; similarly \mathbf{x}_k for $(\mathbf{x}_0)_k$, the k -th column of \mathbf{X}_0 . The function $g(\mathbf{w})$ means $g(\mathbf{w}; \mathbf{X}_0)$. We first establish a useful comparison lemma between random i.i.d. Bernoulli random vectors random i.i.d. normal random vectors.

Lemma IV.4. *Suppose $\mathbf{z}, \mathbf{z}' \in \mathbb{R}^n$ are independent and obey $\mathbf{z} \sim i.i.d. \text{BG}(\theta)$ and $\mathbf{z}' \sim i.i.d. \mathcal{N}(0, 1)$. Then, for any fixed vector $\mathbf{v} \in \mathbb{R}^n$, it holds that*

$$\begin{aligned} \mathbb{E} [|\mathbf{v}^* \mathbf{z}|^m] & \leq \mathbb{E} [|\mathbf{v}^* \mathbf{z}'|^m] = \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{v}\|^2)} [|Z|^m], \\ \mathbb{E} [\|\mathbf{z}\|^m] & \leq \mathbb{E} [\|\mathbf{z}'\|^m], \end{aligned}$$

for all integers $m \geq 1$.

Proof: See page 38 under Section B. \blacksquare

Now, we are ready to prove Proposition II.8 to Proposition II.10 as follows.

Proof: (of Proposition II.8) Let

$$Y_k = \frac{1}{\|\mathbf{w}\|^2} \mathbf{w}^* \nabla^2 h_{\mu}(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) \mathbf{w},$$

then $\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} = \frac{1}{p} \sum_{k=1}^p Y_k$. For each Y_k ($k \in [p]$), from (IV.2), we know that

$$Y_k = \frac{1}{\mu} \left(1 - \tanh^2 \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \right) \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|} - \frac{x_k(n) \|\mathbf{w}\|}{q_n(\mathbf{w})} \right)^2 - \tanh \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \frac{x_k(n)}{q_n^3(\mathbf{w})}.$$

Writing $Y_k = W_k + V_k$, where

$$\begin{aligned} W_k &= \frac{1}{\mu} \left(1 - \tanh^2 \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \right) \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|} - \frac{x_k(n) \|\mathbf{w}\|}{q_n(\mathbf{w})} \right)^2, \\ V_k &= - \tanh \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \frac{x_k(n)}{q_n^3(\mathbf{w})}. \end{aligned}$$

Then by similar argument as in proof to Proposition II.9, we have for all integers $m \geq 2$ that

$$\begin{aligned} \mathbb{E}[|W_k|^m] &\leq \frac{1}{\mu^m} \mathbb{E} \left[\left| \frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|} - \frac{x_k(n) \|\mathbf{w}\|}{q_n(\mathbf{w})} \right|^{2m} \right] \leq \frac{1}{\mu^m} \mathbb{E}_{Z \sim \mathcal{N}(0, 1/q_n^2(\mathbf{w}))} [|Z|^{2m}] \\ &\leq \frac{1}{\mu^m} (2m-1)!! (4n)^m \leq \frac{m!}{2} \left(\frac{4n}{\mu} \right)^m, \\ \mathbb{E}[|V_k|^m] &\leq \frac{1}{q_n^{3m}(\mathbf{w})} \mathbb{E}[|v_k(n)|^m] \leq (2\sqrt{n})^{3m} (m-1)!! \leq \frac{m!}{2} (8n\sqrt{n})^m, \end{aligned}$$

where we have again used the assumption that $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to simplify the result. Taking $\sigma_W^2 = 16n^2/\mu^2 \geq \mathbb{E}[W_k^2]$, $R_W = 4n/\mu$ and $\sigma_V^2 = 64n^3 \geq \mathbb{E}[V_k^2]$, $R_V = 8n\sqrt{n}$, and considering $S_W = \frac{1}{p} \sum_{k=1}^p W_k$ and $S_V = \frac{1}{p} \sum_{k=1}^p V_k$, then by Lemma A.8, we obtain

$$\begin{aligned} \mathbb{P} \left[|S_W - \mathbb{E}[S_W]| \geq \frac{t}{2} \right] &\leq 2 \exp \left(-\frac{p\mu^2 t^2}{128n^2 + 16n\mu t} \right), \\ \mathbb{P} \left[|S_V - \mathbb{E}[S_V]| \geq \frac{t}{2} \right] &\leq 2 \exp \left(-\frac{pt^2}{512n^3 + 32n\sqrt{nt}} \right). \end{aligned}$$

Combining the above results, we obtain

$$\begin{aligned} \mathbb{P} \left[\left| \frac{1}{p} \sum_{k=1}^p X_k - \mathbb{E}[X_k] \right| \geq t \right] &= \mathbb{P}[|S_W - \mathbb{E}[S_W] + S_V - \mathbb{E}[S_V]| \geq t] \\ &\leq \mathbb{P} \left[|S_W - \mathbb{E}[S_W]| \geq \frac{t}{2} \right] + \mathbb{P} \left[|S_V - \mathbb{E}[S_V]| \geq \frac{t}{2} \right] \\ &\leq 2 \exp \left(-\frac{p\mu^2 t^2}{128n^2 + 16n\mu t} \right) + 2 \exp \left(-\frac{pt^2}{512n^3 + 32n\sqrt{nt}} \right) \\ &\leq 4 \exp \left(-\frac{p\mu^2 t^2}{512n^2 + 32n\mu t} \right), \end{aligned}$$

provided that $\mu \leq \frac{1}{\sqrt{n}}$, as desired. ■

Proof: (of Proposition II.9) Let

$$X_k = \frac{\mathbf{w}^*}{\|\mathbf{w}\|_2} \nabla h_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k),$$

then $\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|_2} = \frac{1}{p} \sum_{k=1}^p X_k$. For each $X_k, k \in [p]$, from (IV.1), we know that

$$|X_k| = \left| \tanh \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \left(\frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|} - \frac{\|\mathbf{w}\|_2 x_k(n)}{q_n(\mathbf{w})} \right) \right| \leq \left| \frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|} - \frac{\|\mathbf{w}\|_2 x_k(n)}{q_n(\mathbf{w})} \right|,$$

as the magnitude of $\tanh(\cdot)$ is bounded by one. Because $\frac{\mathbf{w}^* \bar{\mathbf{x}}_k}{\|\mathbf{w}\|_2} - \frac{\|\mathbf{w}\|_2 x_k(n)}{q_n(\mathbf{w})} = \left(\frac{\mathbf{w}}{\|\mathbf{w}\|}, -\frac{\|\mathbf{w}\|}{q_n(\mathbf{w})} \right)^* \mathbf{x}_k$ and $\mathbf{x}_k \sim i.i.d.$ BG(θ), invoking Lemma IV.4, we obtain for every integer $m \geq 2$ that

$$\mathbb{E}[|X_k|^m] \leq \mathbb{E}_{Z \sim \mathcal{N}(0, 1/q_n^2(\mathbf{w}))} [|Z|^m] \leq \frac{1}{q_n^m(\mathbf{w})} (m-1)!! \leq \frac{m!}{2} (4n) (2\sqrt{n})^{m-2},$$

where the Gaussian moment can be looked up in Lemma A.5 and we used the fact that $(m-1)!! \leq m!/2$ and the assumption that $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to get the result. Thus, by taking $\sigma^2 = 4n \geq \mathbb{E}[X_k^2]$ and $R = 2\sqrt{n}$, and we obtain the claimed result by invoking Lemma A.8. ■

Proof: (of Proposition II.10) Let $\mathbf{Z}_k = \nabla_{\mathbf{w}}^2 h_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k)$, then $\nabla_{\mathbf{w}}^2 g(\mathbf{w}) = \frac{1}{p} \sum_{k=1}^p \mathbf{Z}_k$. From (IV.2), we know that

$$\mathbf{Z}_k = \mathbf{W}_k + \mathbf{V}_k$$

where

$$\begin{aligned} \mathbf{W}_k &= \frac{1}{\mu} \left(1 - \tanh^2 \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \right) \left(\bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right) \left(\bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right)^* \\ \mathbf{V}_k &= -\tanh \left(\frac{\mathbf{q}(\mathbf{w})^* \mathbf{x}_k}{\mu} \right) \left(\frac{x_k(n)}{q_n(\mathbf{w})} \mathbf{I} + \frac{x_k(n) \mathbf{w} \mathbf{w}^*}{q_n^3(\mathbf{w})} \right). \end{aligned}$$

For \mathbf{W}_k , we have

$$\begin{aligned} \mathbf{0} \preceq \mathbb{E}[\mathbf{W}_k^m] &\preceq \frac{1}{\mu^m} \mathbb{E} \left[\left\| \bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right\|^{2m-2} \left(\bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right) \left(\bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right)^* \right] \\ &\preceq \frac{1}{\mu^m} \mathbb{E} \left[\left\| \bar{\mathbf{x}}_k - \frac{x_k(n) \mathbf{w}}{q_n(\mathbf{w})} \right\|^{2m} \right] \mathbf{I} \\ &\preceq \frac{2^m}{\mu^m} \mathbb{E} \left[\left(\|\bar{\mathbf{x}}_k\|^2 + \frac{x_k^2(n) \|\mathbf{w}\|^2}{q_n^2(\mathbf{w})} \right)^m \right] \mathbf{I} \\ &\preceq \frac{2^m}{\mu^m} \mathbb{E} \left[\|\mathbf{x}_k\|^{2m} \right] \mathbf{I} \preceq \frac{2^m}{\mu^m} \mathbb{E}_{Z \sim \chi^2(n)} [Z^m] \mathbf{I}, \end{aligned}$$

where we have used the fact that $\|\mathbf{w}\|^2 / q_n^2(\mathbf{w}) = \|\mathbf{w}\|^2 / (1 - \|\mathbf{w}\|^2) \leq 1$ for $\|\mathbf{w}\|_2 \leq \frac{1}{4}$ and Lemma IV.4 to obtain the last line. By Lemma A.6, we obtain

$$\mathbf{0} \preceq \mathbb{E}[\mathbf{W}_k^m] \preceq \left(\frac{2}{\mu} \right)^m \frac{m!}{2} (2n)^m \mathbf{I} = \frac{m!}{2} \left(\frac{4n}{\mu} \right)^m \mathbf{I}.$$

Taking $R_W = \frac{4n}{\mu}$ and $\sigma_W^2 = \frac{16n^2}{\mu^2} \geq \mathbb{E}[\mathbf{W}_k^2]$, and letting $\mathbf{S}_W \doteq \frac{1}{p} \sum_{k=1}^p \mathbf{W}_k$, by Lemma A.9, we obtain

$$\mathbb{P} \left[\|\mathbf{S}_W - \mathbb{E}[\mathbf{S}_W]\| \geq \frac{t}{2} \right] \leq 2n \exp \left(-\frac{p\mu^2 t^2}{128n^2 + 16\mu n t} \right).$$

Similarly, for \mathbf{V}_k , we have

$$\begin{aligned} \mathbb{E}[\mathbf{V}_k^m] &\preceq \left(\frac{1}{q_n(\mathbf{w})} + \frac{\|\mathbf{w}\|^2}{q_n^3(\mathbf{w})} \right)^m \mathbb{E}[|x_k(n)|^m] \mathbf{I} \\ &\preceq (8n\sqrt{n})^m (m-1)!! \mathbf{I} \\ &\preceq \frac{m!}{2} (8n\sqrt{n})^m \mathbf{I}, \end{aligned}$$

where we have used the fact $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to simplify the result. Similar argument also shows $-\mathbb{E}[\mathbf{V}_k^m] \preceq m! (8n\sqrt{n})^m \mathbf{I} / 2$. Taking $R_V = 8n\sqrt{n}$ and $\sigma_V^2 = 64n^3$, and letting $\mathbf{S}_V \doteq \frac{1}{p} \sum_{k=1}^p \mathbf{V}_k$, again by Lemma A.9, we obtain

$$\mathbb{P} \left[\|\mathbf{S}_V - \mathbb{E}[\mathbf{S}_V]\| \geq \frac{t}{2} \right] \leq 2n \exp \left(-\frac{pt^2}{512n^3 + 32n\sqrt{nt}} \right).$$

Combining the above results, we obtain

$$\begin{aligned} \mathbb{P} \left[\left\| \frac{1}{p} \sum_{k=1}^p \mathbf{Z}_k - \mathbb{E}[\mathbf{Z}_k] \right\| \geq t \right] &= \mathbb{P} \left[\|\mathbf{S}_W - \mathbb{E}[\mathbf{S}_W] + \mathbf{S}_V - \mathbb{E}[\mathbf{S}_V]\| \geq t \right] \\ &\leq \mathbb{P} \left[\|\mathbf{S}_W - \mathbb{E}[\mathbf{S}_W]\| \geq \frac{t}{2} \right] + \mathbb{P} \left[\|\mathbf{S}_V - \mathbb{E}[\mathbf{S}_V]\| \geq \frac{t}{2} \right] \\ &\leq 2n \exp \left(-\frac{p\mu^2 t^2}{128n^2 + 16\mu n t} \right) + 2n \exp \left(-\frac{pt^2}{512n^3 + 32n\sqrt{nt}} \right) \\ &\leq 4n \exp \left(-\frac{p\mu^2 t^2}{512n^2 + 32\mu n t} \right), \end{aligned}$$

where we have simplified the final result based on the fact that $\mu \leq \frac{1}{\sqrt{n}}$. ■

5) *Proof of Lipschitz Results:* To avoid clutter of notations, in this subsection we write \mathbf{X} to mean \mathbf{X}_0 ; similarly \mathbf{x}_k for $(\mathbf{x}_0)_k$, the k -th column of \mathbf{X}_0 . The function $g(\mathbf{w})$ means $g(\mathbf{w}; \mathbf{X}_0)$. We need the following lemmas to prove the Lipschitz results.

Lemma IV.5. *Suppose that $\varphi_1 : U \rightarrow V$ is an L -Lipschitz map from a normed space U to a normed space V , and that $\varphi_2 : V \rightarrow W$ is an L' -Lipschitz map from V to a normed space W . Then the composition $\varphi_2 \circ \varphi_1 : U \rightarrow W$ is LL' -Lipschitz.*

Lemma IV.6. *Fix any $\mathcal{D} \subseteq \mathbb{R}^{n-1}$. Let $g_1, g_2 : \mathcal{D} \rightarrow \mathbb{R}$, and assume that g_1 is L_1 -Lipschitz, and g_2 is L_2 -Lipschitz, and that g_1 and g_2 are bounded over \mathcal{D} , i.e., $|g_1(\mathbf{x})| \leq M_1$ and $|g_2(\mathbf{x})| \leq M_2$ for all $\mathbf{x} \in \mathcal{D}$ with some constants $M_1 > 0$ and $M_2 > 0$. Then the function $h(\mathbf{x}) = g_1(\mathbf{x})g_2(\mathbf{x})$ is L -Lipschitz, with*

$$L = M_1L_2 + M_2L_1.$$

Lemma IV.7. *For every $\mathbf{w}, \mathbf{w}' \in \Gamma$, and every fixed \mathbf{x} , we have*

$$\begin{aligned} \left| \dot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}) - \dot{h}_\mu(\mathbf{q}(\mathbf{w}')^* \mathbf{x}) \right| &\leq \frac{2\sqrt{n}}{\mu} \|\mathbf{x}\| \|\mathbf{w} - \mathbf{w}'\|, \\ \left| \ddot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}) - \ddot{h}_\mu(\mathbf{q}(\mathbf{w}')^* \mathbf{x}) \right| &\leq \frac{4\sqrt{n}}{\mu^2} \|\mathbf{x}\| \|\mathbf{w} - \mathbf{w}'\|. \end{aligned}$$

Proof: We have

$$\begin{aligned} |q_n(\mathbf{w}) - q_n(\mathbf{w}')| &= \left| \sqrt{1 - \|\mathbf{w}\|^2} - \sqrt{1 - \|\mathbf{w}'\|^2} \right| = \frac{\|\mathbf{w} + \mathbf{w}'\| \|\mathbf{w} - \mathbf{w}'\|}{\sqrt{1 - \|\mathbf{w}\|^2} + \sqrt{1 - \|\mathbf{w}'\|^2}} \\ &\leq \frac{\max(\|\mathbf{w}\|, \|\mathbf{w}'\|)}{\min(q_n(\mathbf{w}), q_n(\mathbf{w}'))} \|\mathbf{w} - \mathbf{w}'\|. \end{aligned}$$

Hence it holds that

$$\begin{aligned} \|\mathbf{q}(\mathbf{w}) - \mathbf{q}(\mathbf{w}')\|^2 &= \|\mathbf{w} - \mathbf{w}'\|^2 + |q_n(\mathbf{w}) - q_n(\mathbf{w}')|^2 \leq \left(1 + \frac{\max(\|\mathbf{w}\|^2, \|\mathbf{w}'\|^2)}{\min(q_n^2(\mathbf{w}), q_n^2(\mathbf{w}'))} \right) \|\mathbf{w} - \mathbf{w}'\|^2 \\ &= \frac{1}{\min(q_n^2(\mathbf{w}), q_n^2(\mathbf{w}'))} \|\mathbf{w} - \mathbf{w}'\|^2 \leq 4n \|\mathbf{w} - \mathbf{w}'\|^2, \end{aligned}$$

where we have used the fact $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to get the final result. Hence the mapping $\mathbf{w} \mapsto \mathbf{q}(\mathbf{w})$ is $2\sqrt{n}$ -Lipschitz over Γ . Moreover it is easy to see $\mathbf{q} \mapsto \mathbf{q}^* \mathbf{x}$ is $\|\mathbf{x}\|_2$ -Lipschitz. By Lemma A.1 and the composition rule in Lemma IV.5, we obtain the desired claims. \blacksquare

Lemma IV.8. *For any fixed \mathbf{x} , consider the function*

$$t_{\mathbf{x}}(\mathbf{w}) \doteq \frac{\mathbf{w}^* \bar{\mathbf{x}}}{\|\mathbf{w}\|} - \frac{x_n}{q_n(\mathbf{w})} \|\mathbf{w}\|$$

defined over $\mathbf{w} \in \Gamma$. Then, for all \mathbf{w}, \mathbf{w}' in Γ such that $\|\mathbf{w}\| \geq r$ and $\|\mathbf{w}'\| \geq r$ for some constant $r \in (0, 1)$, it holds that

$$\begin{aligned} |t_{\mathbf{x}}(\mathbf{w}) - t_{\mathbf{x}}(\mathbf{w}')| &\leq 2 \left(\frac{\|\mathbf{x}\|}{r} + 4n^{3/2} \|\mathbf{x}\|_\infty \right) \|\mathbf{w} - \mathbf{w}'\|, \\ |t_{\mathbf{x}}(\mathbf{w})| &\leq 2\sqrt{n} \|\mathbf{x}\|, \\ |t_{\mathbf{x}}^2(\mathbf{w}) - t_{\mathbf{x}}^2(\mathbf{w}')| &\leq 8\sqrt{n} \|\mathbf{x}\| \left(\frac{\|\mathbf{x}\|}{r} + 4n^{3/2} \|\mathbf{x}\|_\infty \right) \|\mathbf{w} - \mathbf{w}'\|, \\ |t_{\mathbf{x}}^2(\mathbf{w})| &\leq 4n \|\mathbf{x}\|^2. \end{aligned}$$

Proof: First of all, we have

$$|t_{\mathbf{x}}(\mathbf{w})| = \left[\frac{\mathbf{w}^*}{\|\mathbf{w}\|}, -\frac{\|\mathbf{w}\|}{q_n(\mathbf{w})} \right] \mathbf{x} \leq \|\mathbf{x}\| \left(1 + \frac{\|\mathbf{w}\|^2}{q_n^2(\mathbf{w})} \right)^{1/2} = \frac{\|\mathbf{x}\|}{|q_n(\mathbf{w})|} \leq 2\sqrt{n} \|\mathbf{x}\|,$$

where we have used the assumption that $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to simplify the final result. The claim about $|t_x^2(\mathbf{w})|$ follows immediately. Now

$$|t_x(\mathbf{w}) - t_x(\mathbf{w}')| \leq \left| \left(\frac{\mathbf{w}}{\|\mathbf{w}\|} - \frac{\mathbf{w}'}{\|\mathbf{w}'\|} \right)^* \bar{\mathbf{x}} \right| + |x_n| \left| \frac{\|\mathbf{w}\|}{q_n(\mathbf{w})} - \frac{\|\mathbf{w}'\|}{q_n(\mathbf{w}')} \right|.$$

Moreover we have

$$\begin{aligned} \left| \left(\frac{\mathbf{w}}{\|\mathbf{w}\|} - \frac{\mathbf{w}'}{\|\mathbf{w}'\|} \right)^* \bar{\mathbf{x}} \right| &\leq \|\bar{\mathbf{x}}\| \left\| \frac{\mathbf{w}}{\|\mathbf{w}\|} - \frac{\mathbf{w}'}{\|\mathbf{w}'\|} \right\| \leq \|\mathbf{x}\| \frac{\|\mathbf{w} - \mathbf{w}'\| \|\mathbf{w}'\| + \|\mathbf{w}'\| \|\|\mathbf{w}\| - \|\mathbf{w}'\|\|}{\|\mathbf{w}\| \|\mathbf{w}'\|} \\ &\leq \frac{2\|\mathbf{x}\|}{r} \|\mathbf{w} - \mathbf{w}'\|, \end{aligned}$$

where we have used the assumption that $\|\mathbf{w}\| \geq r$ to simplify the result. Noticing that $t \mapsto t/\sqrt{1-t^2}$ is continuous over $[a, b]$ and differentiable over (a, b) for any $0 < a < b < 1$, by mean value theorem,

$$\left| \frac{\|\mathbf{w}\|}{q_n(\mathbf{w})} - \frac{\|\mathbf{w}'\|}{q_n(\mathbf{w}')} \right| \leq \sup_{\mathbf{w} \in \Gamma} \frac{1}{(1 - \|\mathbf{w}\|^2)^{3/2}} \|\mathbf{w} - \mathbf{w}'\| \leq 8n^{3/2} \|\mathbf{w} - \mathbf{w}'\|,$$

where we have again used the assumption that $q_n(\mathbf{w}) \geq \frac{1}{2\sqrt{n}}$ to simplify the last result. Collecting the above estimates, we obtain

$$|t_x(\mathbf{w}) - t_x(\mathbf{w}')| \leq \left(2\frac{\|\mathbf{x}\|}{r} + 8n^{3/2} \|\mathbf{x}\|_\infty \right) \|\mathbf{w} - \mathbf{w}'\|,$$

as desired. For the last one, we have

$$\begin{aligned} |t_x^2(\mathbf{w}) - t_x^2(\mathbf{w}')| &= |t_x(\mathbf{w}) - t_x(\mathbf{w}')| |t_x(\mathbf{w}) + t_x(\mathbf{w}')| \\ &\leq 2 \sup_{\mathbf{s} \in \Gamma} |t_x(\mathbf{s})| |t_x(\mathbf{w}) - t_x(\mathbf{w}')|, \end{aligned}$$

leading to the claimed result once we substitute estimates of the involved quantities. ■

Lemma IV.9. *For any fixed \mathbf{x} , consider the function*

$$\Phi_{\mathbf{x}}(\mathbf{w}) = \frac{x_n}{q_n(\mathbf{w})} \mathbf{I} + \frac{x_n}{q_n^3(\mathbf{w})} \mathbf{w} \mathbf{w}^*$$

defined over $\mathbf{w} \in \Gamma$. Then, for all $\mathbf{w}, \mathbf{w}' \in \Gamma$ such that $\|\mathbf{w}\| < r$ and $\|\mathbf{w}'\| < r$ with some constant $r \in (0, \frac{1}{2})$, it holds that

$$\begin{aligned} \|\Phi_{\mathbf{x}}(\mathbf{w})\| &\leq 2\|\mathbf{x}\|_\infty, \\ \|\Phi_{\mathbf{x}}(\mathbf{w}) - \Phi_{\mathbf{x}}(\mathbf{w}')\| &\leq 4\|\mathbf{x}\|_\infty \|\mathbf{w} - \mathbf{w}'\|. \end{aligned}$$

Proof: Simple calculation shows

$$\|\Phi_{\mathbf{x}}(\mathbf{w})\| \leq \|\mathbf{x}\|_\infty \left(\frac{1}{q_n(\mathbf{w})} + \frac{\|\mathbf{w}\|^2}{q_n^3(\mathbf{w})} \right) = \frac{\|\mathbf{x}\|_\infty}{q_n^3(\mathbf{w})} \leq \frac{\|\mathbf{x}\|_\infty}{(1-r^2)^{3/2}} \leq 2\|\mathbf{x}\|_\infty.$$

For the second one, we have

$$\begin{aligned} \|\Phi_{\mathbf{x}}(\mathbf{w}) - \Phi_{\mathbf{x}}(\mathbf{w}')\| &\leq \|\mathbf{x}\|_\infty \left\| \frac{1}{q_n(\mathbf{w})} \mathbf{I} + \frac{1}{q_n^3(\mathbf{w})} \mathbf{w} \mathbf{w}^* - \frac{1}{q_n(\mathbf{w}')} \mathbf{I} - \frac{1}{q_n^3(\mathbf{w}')} \mathbf{w}' (\mathbf{w}')^* \right\| \\ &\leq \|\mathbf{x}\|_\infty \left(\left| \frac{1}{q_n(\mathbf{w})} - \frac{1}{q_n(\mathbf{w}')} \right| + \left| \frac{\|\mathbf{w}\|^2}{q_n^3(\mathbf{w})} - \frac{\|\mathbf{w}'\|^2}{q_n^3(\mathbf{w}')} \right| \right). \end{aligned}$$

Now

$$\left| \frac{1}{q_n(\mathbf{w})} - \frac{1}{q_n(\mathbf{w}')} \right| = \frac{|q_n(\mathbf{w}) - q_n(\mathbf{w}')|}{q_n(\mathbf{w}) q_n(\mathbf{w}')} \leq \frac{\max(\|\mathbf{w}\|, \|\mathbf{w}'\|)}{\min(q_n^3(\mathbf{w}), q_n^3(\mathbf{w}'))} \|\mathbf{w} - \mathbf{w}'\| \leq \frac{4}{3\sqrt{3}} \|\mathbf{w} - \mathbf{w}'\|,$$

where we have applied the estimate for $|q_n(\mathbf{w}) - q_n(\mathbf{w}')|$ as established in Lemma IV.7 and also used $\|\mathbf{w}\| \leq 1/2$ and $\|\mathbf{w}'\| \leq 1/2$ to simplify the above result. Further noticing $t \mapsto t^2/(1-t^2)^{3/2}$ is differentiable over $t \in (0, 1)$, we apply the mean value theorem and obtain

$$\left| \frac{\|\mathbf{w}\|^2}{q_n^3(\mathbf{w})} - \frac{\|\mathbf{w}'\|^2}{q_n^3(\mathbf{w}')} \right| \leq \sup_{\mathbf{s} \in \Gamma, \|\mathbf{s}\| \leq r < \frac{1}{2}} \frac{\|\mathbf{s}\|^3 + 2\|\mathbf{s}\|}{(1 - \|\mathbf{s}\|^2)^{5/2}} \|\mathbf{w} - \mathbf{w}'\| \leq \frac{4}{\sqrt{3}} \|\mathbf{w} - \mathbf{w}'\|.$$

Combining the above estimates gives the claimed result. ■

Lemma IV.10. *For any fixed \mathbf{x} , consider the function*

$$\zeta_{\mathbf{x}}(\mathbf{w}) = \bar{\mathbf{x}} - \frac{x_n}{q_n(\mathbf{w})} \mathbf{w}$$

defined over $\mathbf{w} \in \Gamma$. Then, for all $\mathbf{w}, \mathbf{w}' \in \Gamma$ such that $\|\mathbf{w}\| \leq r$ and $\|\mathbf{w}'\| \leq r$ for some constant $r \in (0, \frac{1}{2})$, it holds that

$$\begin{aligned} \|\zeta_{\mathbf{x}}(\mathbf{w}) \zeta_{\mathbf{x}}(\mathbf{w})^* - \zeta_{\mathbf{x}}(\mathbf{w}') \zeta_{\mathbf{x}}(\mathbf{w}')^*\| &\leq 2n \|\mathbf{x}\|_{\infty}^2, \\ \|\zeta_{\mathbf{x}}(\mathbf{w}) \zeta_{\mathbf{x}}(\mathbf{w})^* - \zeta_{\mathbf{x}}(\mathbf{w}') \zeta_{\mathbf{x}}(\mathbf{w}')^*\| &\leq 8\sqrt{2}\sqrt{n} \|\mathbf{x}\|_{\infty}^2 \|\mathbf{w} - \mathbf{w}'\|. \end{aligned}$$

Proof: We have $\|\mathbf{w}\|^2/q_n^2(\mathbf{w}) \leq 1/3$ when $\|\mathbf{w}\| \leq r < 1/2$, hence it holds that

$$\|\zeta_{\mathbf{x}}(\mathbf{w}) \zeta_{\mathbf{x}}(\mathbf{w})^*\| \leq \|\zeta_{\mathbf{x}}(\mathbf{w})\|^2 \leq 2\|\bar{\mathbf{x}}\|^2 + 2x_n^2 \frac{\|\mathbf{w}\|}{q_n^2(\mathbf{w})} \leq 2n \|\mathbf{x}\|_{\infty}^2.$$

For the second, we first estimate

$$\begin{aligned} \|\zeta(\mathbf{w}) - \zeta(\mathbf{w}')\| &= \left\| x_n \left(\frac{\mathbf{w}}{q_n(\mathbf{w})} - \frac{\mathbf{w}'}{q_n(\mathbf{w}')} \right) \right\| \leq \|\mathbf{x}\|_{\infty} \left\| \frac{\mathbf{w}}{q_n(\mathbf{w})} - \frac{\mathbf{w}'}{q_n(\mathbf{w}')} \right\| \\ &\leq \|\mathbf{x}\|_{\infty} \left(\frac{1}{q_n(\mathbf{w})} \|\mathbf{w} - \mathbf{w}'\| + \|\mathbf{w}'\| \left| \frac{1}{q_n(\mathbf{w})} - \frac{1}{q_n(\mathbf{w}')} \right| \right) \\ &\leq \|\mathbf{x}\|_{\infty} \left(\frac{1}{q_n(\mathbf{w})} + \frac{\|\mathbf{w}'\|}{\min\{q_n^3(\mathbf{w}), q_n^3(\mathbf{w}')\}} \right) \|\mathbf{w} - \mathbf{w}'\| \\ &\leq \|\mathbf{x}\|_{\infty} \left(\frac{2}{\sqrt{3}} + \frac{4}{3\sqrt{3}} \right) \|\mathbf{w} - \mathbf{w}'\| \leq 4\|\mathbf{x}\|_{\infty} \|\mathbf{w} - \mathbf{w}'\|. \end{aligned}$$

Thus, we have

$$\begin{aligned} \|\zeta_{\mathbf{x}}(\mathbf{w}) \zeta_{\mathbf{x}}(\mathbf{w})^* - \zeta_{\mathbf{x}}(\mathbf{w}') \zeta_{\mathbf{x}}(\mathbf{w}')^*\| &\leq \|\zeta(\mathbf{w})\| \|\zeta(\mathbf{w}) - \zeta(\mathbf{w}')\| + \|\zeta(\mathbf{w}) - \zeta(\mathbf{w}')\| \|\zeta(\mathbf{w}')\| \\ &\leq 8\sqrt{2}\sqrt{n} \|\mathbf{x}\|_{\infty}^2 \|\mathbf{w} - \mathbf{w}'\|, \end{aligned}$$

as desired. ■

Now, we are ready to prove all the Lipschitz propositions.

Proof: (of Proposition II.11) Let

$$F_k(\mathbf{w}) = \ddot{h}_{\mu}(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) t_{\mathbf{x}_k}^2(\mathbf{w}) + \dot{h}_{\mu}(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) \frac{x_k(n)}{q_n^3(\mathbf{w})}.$$

Then, $\frac{1}{\|\mathbf{w}\|^2} \mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w} = \frac{1}{p} \sum_{k=1}^p F_k(\mathbf{w})$. Noticing that $\ddot{h}_{\mu}(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k)$ is bounded by $1/\mu$ and $\dot{h}_{\mu}(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k)$ is bounded by 1, both in magnitude. Applying Lemma IV.6, Lemma IV.7 and Lemma IV.8, we can see $F_k(\mathbf{w})$ is $L_{\hat{\cdot}}^k$ -Lipschitz with

$$\begin{aligned} L_{\hat{\cdot}}^k &= 4n \|\mathbf{x}_k\|^2 \frac{4\sqrt{n}}{\mu^2} \|\mathbf{x}_k\| + \frac{1}{\mu} 8\sqrt{n} \|\mathbf{x}_k\| \left(\frac{\|\mathbf{x}_k\|}{r_{\hat{\cdot}}} + 4n^{3/2} \|\mathbf{x}_k\|_{\infty} \right) \\ &\quad + (2\sqrt{n})^3 \|\mathbf{x}_k\|_{\infty} \frac{2\sqrt{n}}{\mu} \|\mathbf{x}_k\| + \sup_{r_{\hat{\cdot}} < a < \sqrt{\frac{2n-1}{2n}}} \frac{3}{(1-a^2)^{5/2}} \|\mathbf{x}_k\|_{\infty} \\ &= \frac{16n^{3/2}}{\mu^2} \|\mathbf{x}_k\|^3 + \frac{8\sqrt{n}}{\mu r_{\hat{\cdot}}} \|\mathbf{x}_k\|^2 + \frac{48n^2}{\mu} \|\mathbf{x}_k\| \|\mathbf{x}_k\|_{\infty} + 96n^{5/2} \|\mathbf{x}_k\|_{\infty}. \end{aligned}$$

Thus, $\frac{1}{\|\mathbf{w}\|_2} \mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}$ is L_\cap -Lipschitz with

$$L_\cap \leq \frac{1}{p} \sum_{k=1}^p L_\cap^k \leq \frac{16n^3}{\mu^2} \|\mathbf{X}\|_\infty^3 + \frac{8n^{3/2}}{\mu r_\cap} \|\mathbf{X}\|_\infty^2 + \frac{48n^{5/2}}{\mu} \|\mathbf{X}\|_\infty^2 + 96n^{5/2} \|\mathbf{X}\|_\infty,$$

as desired. ■

Proof: (of Proposition II.12) We have

$$\left\| \frac{\mathbf{w}^*}{\|\mathbf{w}\|} \nabla g(\mathbf{w}) - \frac{\mathbf{w}'^*}{\|\mathbf{w}'\|} \nabla g(\mathbf{w}') \right\| \leq \frac{1}{p} \sum_{k=1}^p \left\| \dot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) t_{\mathbf{x}_k}(\mathbf{w}) - \dot{h}_\mu(\mathbf{q}(\mathbf{w}')^* \mathbf{x}_k) t_{\mathbf{x}_k}(\mathbf{w}') \right\|$$

where $\dot{h}_\mu(t) = \tanh(t/\mu)$ is bounded by one in magnitude, and $t_{\mathbf{x}_k}(\mathbf{w})$ and $t_{\mathbf{x}_k'}(\mathbf{w})$ is defined as in Lemma IV.8. By Lemma IV.6, Lemma IV.7 and Lemma IV.8, we know that $\dot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) t_{\mathbf{x}_k}(\mathbf{w})$ is L_k -Lipschitz with constant

$$L_k = \frac{2\|\mathbf{x}_k\|}{r_g} + 8n^{3/2} \|\mathbf{x}_k\|_\infty + \frac{4n}{\mu} \|\mathbf{x}_k\|^2.$$

Therefore, we have

$$\begin{aligned} \left\| \frac{\mathbf{w}^*}{\|\mathbf{w}\|} \nabla g(\mathbf{w}) - \frac{\mathbf{w}'^*}{\|\mathbf{w}'\|} \nabla g(\mathbf{w}') \right\| &\leq \frac{1}{p} \sum_{k=1}^p \left(\frac{2\|\mathbf{x}_k\|}{r_g} + 8n^{3/2} \|\mathbf{x}_k\|_\infty + \frac{4n}{\mu} \|\mathbf{x}_k\|^2 \right) \|\mathbf{w} - \mathbf{w}'\| \\ &\leq \left(\frac{2\sqrt{n}}{r_g} \|\mathbf{X}\|_\infty + 8n^{3/2} \|\mathbf{X}\|_\infty + \frac{4n^2}{\mu} \|\mathbf{X}\|_\infty^2 \right) \|\mathbf{w} - \mathbf{w}'\|, \end{aligned}$$

as desired. ■

Proof: (of Proposition II.13) Let

$$\mathbf{F}_k(\mathbf{w}) = \ddot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) \zeta_k(\mathbf{w}) \zeta_k(\mathbf{w})^* - \dot{h}_\mu(\mathbf{q}(\mathbf{w})^* \mathbf{x}_k) \Phi_k(\mathbf{w})$$

with $\zeta_k(\mathbf{w}) = \bar{\mathbf{x}}_k - \frac{\mathbf{x}_k(n)}{q_n(\mathbf{w})} \mathbf{w}$ and $\Phi_k(\mathbf{w}) = \frac{\mathbf{x}_k(n)}{q_n(\mathbf{w})} \mathbf{I} + \frac{\mathbf{x}_{n,k}}{q_n(\mathbf{w})} \mathbf{w} \mathbf{w}^*$. Then, $\nabla^2 g(\mathbf{w}) = \frac{1}{p} \sum_{k=1}^p \mathbf{F}_k(\mathbf{w})$. Using Lemma IV.6, Lemma IV.7, Lemma IV.9 and Lemma IV.10, and the facts that $\ddot{h}_\mu(t)$ is bounded by $1/\mu$ and that $\dot{h}_\mu(t)$ is bounded by 1 in magnitude, we can see $\mathbf{F}_k(\mathbf{w})$ is L_\cup^k -Lipschitz continuous with

$$\begin{aligned} L_\cup^k &= \frac{1}{\mu} \times 8\sqrt{2}\sqrt{n} \|\mathbf{x}_k\|_\infty^2 + \frac{2\sqrt{n}}{\mu^2} \|\mathbf{x}_k\| \times 2n \|\mathbf{x}_k\|_\infty^2 + 4 \|\mathbf{x}_k\|_\infty + \frac{2\sqrt{n}}{\mu} \|\mathbf{x}_k\| \times 2 \|\mathbf{x}_k\|_\infty \\ &\leq \frac{4n^{3/2}}{\mu^2} \|\mathbf{x}_k\| \|\mathbf{x}_k\|_\infty^2 + \frac{4\sqrt{n}}{\mu} \|\mathbf{x}_k\| \|\mathbf{x}_k\|_\infty + \frac{8\sqrt{2}\sqrt{n}}{\mu} \|\mathbf{x}_k\|_\infty^2 + 4 \|\mathbf{x}_k\|_\infty. \end{aligned}$$

Thus, we have

$$L_\cup \leq \frac{1}{p} \sum_{k=1}^p L_\cup^k \leq \frac{4n^2}{\mu^2} \|\mathbf{X}\|_\infty^3 + \frac{4n}{\mu} \|\mathbf{X}\|_\infty^2 + \frac{8\sqrt{2}\sqrt{n}}{\mu} \|\mathbf{X}\|_\infty^2 + 8 \|\mathbf{X}\|_\infty,$$

as desired. ■

B. Proofs of Theorem II.1

To avoid clutter of notations, in this subsection we write \mathbf{X} to mean \mathbf{X}_0 ; similarly \mathbf{x}_k for $(\mathbf{x}_0)_k$, the k -th column of \mathbf{X}_0 . The function $g(\mathbf{w})$ means $g(\mathbf{w}; \mathbf{X}_0)$. Before proving Theorem II.1, we record one useful lemma.

Lemma IV.11. *For any $\theta \in (0, 1)$, consider the random matrix $\mathbf{X} \in \mathbb{R}^{n_1 \times n_2}$ with $\mathbf{X} \sim_{i.i.d.} \text{BG}(\theta)$. Define the event $\mathcal{E}_\infty \doteq \left\{ 1 \leq \|\mathbf{X}\|_\infty \leq 4\sqrt{\log(np)} \right\}$. It holds that*

$$\mathbb{P}[\mathcal{E}_\infty^c] \leq \theta (np)^{-7} + \exp(-0.3\theta np).$$

Proof: See page 39 under Section B. ■

For convenience, we define three regions for the range of \mathbf{w} :

$$R_1 \doteq \left\{ \mathbf{w} \mid \|\mathbf{w}\| \leq \frac{\mu}{4\sqrt{2}} \right\}, \quad R_2 \doteq \left\{ \mathbf{w} \mid \frac{\mu}{4\sqrt{2}} \leq \|\mathbf{w}\| \leq \frac{1}{20\sqrt{5}} \right\},$$

$$R_3 \doteq \left\{ \mathbf{w} \mid \frac{1}{20\sqrt{5}} \leq \|\mathbf{w}\| \leq \sqrt{\frac{4n-1}{4n}} \right\}.$$

Proof: (of Theorem II.1) We will focus on deriving the qualitative result and hence be sloppy about constants. All indexed capital C or small c are numerical constants.

a) *Strong convexity in region R_1 .*: Proposition II.7 shows that for any $\mathbf{w} \in R_1$, $\mathbb{E}[\nabla^2 g(\mathbf{w})] \succeq \frac{c_1\theta}{\mu} \mathbf{I}$. For any $\varepsilon \in (0, \mu/(4\sqrt{2}))$, R_1 has an ε -net N_1 of size at most $(3\mu/(4\sqrt{2}\varepsilon))^n$. On \mathcal{E}_∞ , $\nabla^2 g$ is

$$L_1 \doteq \frac{C_2 n^2}{\mu^2} \log^{3/2}(np)$$

Lipschitz by Proposition II.13. Set $\varepsilon = \frac{c_1\theta}{3\mu L_1}$, so

$$\#N_1 \leq \exp\left(2n \log\left(\frac{C_3 n \log(np)}{\theta}\right)\right).$$

Let \mathcal{E}_1 denote the event

$$\mathcal{E}_1 = \left\{ \max_{\mathbf{w} \in N_1} \|\nabla^2 g(\mathbf{w}) - \mathbb{E}[\nabla^2 g(\mathbf{w})]\| \leq \frac{c_1\theta}{3\mu} \right\}.$$

On $\mathcal{E}_1 \cap \mathcal{E}_\infty$,

$$\sup_{\|\mathbf{w}\| \leq \mu/(4\sqrt{2})} \|\nabla^2 g(\mathbf{w}) - \mathbb{E}[\nabla^2 g(\mathbf{w})]\| \leq \frac{2c_1\theta}{3\mu},$$

and so on $\mathcal{E}_1 \cap \mathcal{E}_\infty$, (II.4) holds for any constant $c_* \leq c_1/3$. Setting $t = c_1\theta/3\mu$ in Proposition II.10, we obtain that for any fixed \mathbf{w} ,

$$\mathbb{P}\left[\|\nabla^2 g(\mathbf{w}) - \mathbb{E}[\nabla^2 g(\mathbf{w})]\| \geq \frac{c_1\theta}{3\mu}\right] \leq 4n \exp\left(-\frac{c_4 p \theta^2}{n^2}\right).$$

Taking a union bound, we obtain that

$$\mathbb{P}[\mathcal{E}_1^c] \leq 4n \exp\left(-\frac{c_4 p \theta^2}{n^2} + C_5 n \log(n) + C_5 n \log \log(p)\right).$$

b) *Large gradient in region R_2 .*: Similarly, for the gradient quantity, for $\mathbf{w} \in R_2$, Proposition II.6 shows that

$$\mathbb{E}\left[\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|}\right] \geq c_6 \theta.$$

Moreover, on \mathcal{E}_∞ , $\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|}$ is

$$L_2 \doteq \frac{C_7 n^2}{\mu} \log(np)$$

Lipschitz by Proposition II.12. For any $\varepsilon < \frac{1}{20\sqrt{5}}$, the set R_2 has an ε -net N_2 of size at most $\left(\frac{3}{20\varepsilon\sqrt{5}}\right)^n$. Set $\varepsilon = \frac{c_6\theta}{3L_2}$, so

$$\#N_2 \leq \exp\left(n \log\left(\frac{C_8 n^2 \log(np)}{\theta\mu}\right)\right).$$

Let \mathcal{E}_2 denote the event

$$\mathcal{E}_2 = \left\{ \max_{\mathbf{w} \in N_2} \left| \frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|} - \mathbb{E}\left[\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|}\right] \right| \leq \frac{c_6\theta}{3} \right\}.$$

On $\mathcal{E}_2 \cap \mathcal{E}_\infty$,

$$\sup_{\mathbf{w} \in R_2} \left| \frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|} - \mathbb{E}\left[\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|}\right] \right| \leq \frac{2c_6\theta}{3}, \quad (\text{IV.8})$$

and so on $\mathcal{E}_2 \cap \mathcal{E}_\infty$, (II.5) holds for any constant $c_* \leq c_6/3$. Setting $t = c_6\theta/3$ in Proposition II.9, we obtain that for any fixed $\mathbf{w} \in R_2$,

$$\mathbb{P} \left[\left| \frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|} - \mathbb{E} \left[\frac{\mathbf{w}^* \nabla g(\mathbf{w})}{\|\mathbf{w}\|} \right] \right| \right] \leq 2 \exp \left(-\frac{c_9 p \theta^2}{n} \right),$$

and so

$$\mathbb{P} [\mathcal{E}_2^c] \leq 2 \exp \left(-\frac{c_9 p \theta^2}{n} + n \log \left(\frac{C_8 n^2 \log(np)}{\theta \mu} \right) \right). \quad (\text{IV.9})$$

c) *Existence of negative curvature direction in R_3 .*: Finally, for any $\mathbf{w} \in R_3$, Proposition II.5 shows that

$$\mathbb{E} \left[\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} \right] \leq -c_9 \theta.$$

On \mathcal{E}_∞ , $\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2}$ is

$$L_3 = \frac{C_{10} n^3}{\mu^2} \log^{3/2}(np)$$

Lipschitz by Proposition II.11. As above, for any $\varepsilon \leq \sqrt{\frac{4n-1}{4n}}$, R_3 has an ε -net N_3 of size at most $(3/\varepsilon)^n$. Set $\varepsilon = c_9 \theta / 3 L_3$. Then

$$\#N_3 \leq \exp \left(n \log \left(\frac{C_{11} n^3 \log^{3/2}(np)}{\theta \mu^2} \right) \right).$$

Let \mathcal{E}_3 denote the event

$$\mathcal{E}_3 = \left\{ \max_{\mathbf{w} \in N_3} \left| \frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} - \mathbb{E} \left[\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} \right] \right| \leq \frac{c_9 \theta}{3} \right\}$$

On $\mathcal{E}_3 \cap \mathcal{E}_\infty$,

$$\sup_{\mathbf{w} \in R_3} \left| \frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} - \mathbb{E} \left[\frac{\mathbf{w}^* \nabla^2 g(\mathbf{w}) \mathbf{w}}{\|\mathbf{w}\|^2} \right] \right| \leq \frac{2c_9 \theta}{3},$$

and (II.6) holds with any constant $c_* < c_9/3$. Setting $t = c_9 \theta / 3$ in Proposition II.8 and taking a union bound, we obtain

$$\mathbb{P} [\mathcal{E}_3^c] \leq 4 \exp \left(-\frac{c_{12} p \mu^2 \theta^2}{n^2} + n \log \left(\frac{C_{11} n^3 \log^{3/2}(np)}{\theta \mu^2} \right) \right).$$

d) *The unique local minimizer located near $\mathbf{0}$.*: Let \mathcal{E}_g be the event that the bounds (II.4)-(II.6) hold. On \mathcal{E}_g , the function g is $\frac{c_* \theta}{\mu}$ -strongly convex over $R_1 = \{\mathbf{w} \mid \|\mathbf{w}\| \leq \mu / (4\sqrt{2})\}$. This implies that f has at most one local minimum on R_1 . It also implies that for any $\mathbf{w} \in R_1$,

$$g(\mathbf{w}) \geq g(\mathbf{0}) + \langle \nabla g(\mathbf{0}), \mathbf{w} \rangle + \frac{c\theta}{2\mu} \|\mathbf{w}\|^2 \geq g(\mathbf{0}) - \|\mathbf{w}\| \|\nabla g(\mathbf{0})\| + \frac{c_* \theta}{2\mu} \|\mathbf{w}\|^2.$$

So, if $g(\mathbf{w}) \leq g(\mathbf{0})$, we necessarily have

$$\|\mathbf{w}\| \leq \frac{2\mu}{c_* \theta} \|\nabla g(\mathbf{0})\|.$$

Suppose that

$$\|\nabla g(\mathbf{0})\| \leq \frac{c_* \theta}{32}. \quad (\text{IV.10})$$

Then $g(\mathbf{w}) \leq g(\mathbf{0})$ implies that $\|\mathbf{w}\| \leq \mu/16$. By Wierstrass's theorem, $g(\mathbf{w})$ has at least one minimizer \mathbf{w}_* over the compact set $S = \{\mathbf{w} \mid \|\mathbf{w}\| \leq \mu/10\}$. By the above reasoning, $\|\mathbf{w}_*\| \leq \mu/16$, and hence \mathbf{w}_* does not lie on the boundary of S . This implies that \mathbf{w}_* is a local minimizer of g . Moreover, as above,

$$\|\mathbf{w}_*\| \leq \frac{2\mu}{c_* \theta} \|\nabla g(\mathbf{0})\|.$$

We now use the vector Bernstein inequality to show that with our choice of p , (IV.10) is satisfied with high probability. Notice that

$$\nabla g(\mathbf{0}) = \frac{1}{p} \sum_{i=1}^p \dot{h}_\mu(x_i(n)) \bar{\mathbf{x}}_i,$$

and \dot{h}_μ is bounded by one in magnitude, so for any integer $m \geq 2$,

$$\mathbb{E} \left[\left\| \dot{h}_\mu(x_i(n)) \bar{\mathbf{x}}_i \right\|^m \right] \leq \mathbb{E} [\|\mathbf{x}_i\|^m] \leq \mathbb{E}_{Z \sim \chi(n)} [Z^m] \leq m! n^{m/2},$$

where we have applied the moment estimate for the $\chi(n)$ distribution shown in Lemma A.7. Applying the vector Bernstein inequality in Corollary A.10 with $R = \sqrt{n}$ and $\sigma^2 = 2n$, we obtain

$$\mathbb{P} [\|\nabla g(\mathbf{0})\| \geq t] \leq 2(n+1) \exp \left(-\frac{pt^2}{4n + 2\sqrt{nt}} \right)$$

for all $t > 0$. Using this inequality, it is not difficult to show that there exist constants $C_{13}, C_{14} > 0$ such that when $p \geq C_{13} n \log n$, with probability at least $1 - 4np^{-10}$,

$$\|\nabla g(\mathbf{0})\| \leq C_3 \sqrt{\frac{n \log p}{p}}. \quad (\text{IV.11})$$

When $\frac{p}{\log p} \geq \frac{C_{14} n}{\theta^2}$, for appropriately large C_{14} , (IV.11) implies (IV.10). Summing up failure probabilities completes the proof. \blacksquare

C. Proofs for Section II-C and Theorem II.3

Proof: (of Lemma II.14) By the generative model,

$$\bar{\mathbf{Y}} = \left(\frac{1}{p\theta} \mathbf{Y} \mathbf{Y}^* \right)^{-1/2} \mathbf{Y} = \left(\frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^* \right)^{-1/2} \mathbf{A}_0 \mathbf{X}_0.$$

Since $\mathbb{E} [\mathbf{X}_0 \mathbf{X}_0^* / (p\theta)] = \mathbf{I}$, we will compare $\left(\frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^* \right)^{-1/2} \mathbf{A}_0$ with $(\mathbf{A}_0 \mathbf{A}_0^*)^{-1/2} \mathbf{A}_0 = \mathbf{U} \mathbf{V}^*$. By Lemma B.2, we have

$$\begin{aligned} & \left\| \left(\frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^* \right)^{-1/2} \mathbf{A}_0 - (\mathbf{A}_0 \mathbf{A}_0^*)^{-1/2} \mathbf{A}_0 \right\| \\ & \leq \|\mathbf{A}_0\| \left\| \left(\frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^* \right)^{-1/2} - (\mathbf{A}_0 \mathbf{A}_0^*)^{-1/2} \right\| \\ & \leq \|\mathbf{A}_0\| \frac{2 \|\mathbf{A}_0\|^3}{\sigma_{\min}^4(\mathbf{A}_0)} \left\| \frac{1}{p\theta} \mathbf{X}_0 \mathbf{X}_0^* - \mathbf{I} \right\| = 2\kappa^4(\mathbf{A}_0) \left\| \frac{1}{p\theta} \mathbf{X}_0 \mathbf{X}_0^* - \mathbf{I} \right\| \end{aligned}$$

provided

$$\|\mathbf{A}_0\|^2 \left\| \frac{1}{p\theta} \mathbf{X}_0 \mathbf{X}_0^* - \mathbf{I} \right\| \leq \frac{\sigma_{\min}^2(\mathbf{A}_0)}{2} \iff \left\| \frac{1}{p\theta} \mathbf{X}_0 \mathbf{X}_0^* - \mathbf{I} \right\| \leq \frac{1}{2\kappa^2(\mathbf{A}_0)}.$$

On the other hand, by Lemma B.3, when $p \geq C_1 n^2 \log n$ for some large constant C_1 , $\left\| \frac{1}{p\theta} \mathbf{X}_0 \mathbf{X}_0^* - \mathbf{I} \right\| \leq 10 \sqrt{\frac{\theta n \log p}{p}}$ with probability at least $1 - p^{-8}$. Thus, when $p \geq C_2 \kappa^4(\mathbf{A}_0) \theta n^2 \log(n\theta\kappa(\mathbf{A}_0))$,

$$\left\| \left(\frac{1}{p\theta} \mathbf{A}_0 \mathbf{X}_0 \mathbf{X}_0^* \mathbf{A}_0^* \right)^{-1/2} \mathbf{A}_0 - (\mathbf{A}_0 \mathbf{A}_0^*)^{-1/2} \mathbf{A}_0 \right\| \leq 20\kappa^4(\mathbf{A}_0) \sqrt{\frac{\theta n \log p}{p}},$$

as desired. \blacksquare

Proof: (of Lemma II.15) To avoid clutter in notation, we write \mathbf{X} to mean \mathbf{X}_0 , and \mathbf{x}_k to mean $(\mathbf{x}_0)_k$ in this proof. We also let $\tilde{\mathbf{Y}} \doteq \mathbf{X}_0 + \tilde{\mathbf{\Xi}}\mathbf{X}_0$. Note the Jacobian matrix for the mapping $\mathbf{q}(\mathbf{w})$ is $\nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w}) = \begin{bmatrix} \mathbf{I}, -\mathbf{w}/\sqrt{1-\|\mathbf{w}\|^2} \end{bmatrix}$. Hence for any vector $\mathbf{z} \in \mathbb{R}^n$ and all $\mathbf{w} \in \Gamma$,

$$\|\nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})\mathbf{z}\| \leq \sqrt{n-1}\|\mathbf{z}\|_{\infty} + \frac{\|\mathbf{w}\|}{\sqrt{1-\|\mathbf{w}\|^2}}\|\mathbf{z}\|_{\infty} \leq 3\sqrt{n}\|\mathbf{z}\|_{\infty}.$$

Now we have

$$\begin{aligned} & \left\| \nabla_{\mathbf{w}}g(\mathbf{w}; \tilde{\mathbf{Y}}) - \nabla_{\mathbf{w}}g(\mathbf{w}; \mathbf{X}) \right\| \\ &= \left\| \frac{1}{p} \sum_{k=1}^p \dot{h}_{\mu}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k + \mathbf{q}^*(\mathbf{w})\tilde{\mathbf{\Xi}}\mathbf{x}_k) \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})(\mathbf{x}_k + \tilde{\mathbf{\Xi}}\mathbf{x}_k) - \frac{1}{p} \sum_{k=1}^p \dot{h}_{\mu}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k) \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})\mathbf{x}_k \right\| \\ &\leq \left\| \frac{1}{p} \sum_{k=1}^p \dot{h}_{\mu}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k + \mathbf{q}^*(\mathbf{w})\tilde{\mathbf{\Xi}}\mathbf{x}_k) \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})(\mathbf{x}_k + \tilde{\mathbf{\Xi}}\mathbf{x}_k - \mathbf{x}_k) \right\| \\ &\quad + \left\| \frac{1}{p} \sum_{k=1}^p [\dot{h}_{\mu}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k + \mathbf{q}^*(\mathbf{w})\tilde{\mathbf{\Xi}}\mathbf{x}_k) - \dot{h}_{\mu}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k)] \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})\mathbf{x}_k \right\| \\ &\leq \|\tilde{\mathbf{\Xi}}\| \left(\max_t \dot{h}_{\mu}(t) 3n \|\mathbf{X}\|_{\infty} + L_{\dot{h}_{\mu}} 3n \|\mathbf{X}\|_{\infty}^2 \right), \end{aligned}$$

where $L_{\dot{h}_{\mu}}$ denotes the Lipschitz constant for $\dot{h}_{\mu}(\cdot)$. Similarly, suppose $\|\tilde{\mathbf{\Xi}}\| \leq \frac{1}{2n}$, and also notice that

$$\left\| \frac{\mathbf{I}}{q_n(\mathbf{w})} + \frac{\mathbf{w}\mathbf{w}^*}{q_n^3(\mathbf{w})} \right\| \leq \frac{1}{q_n(\mathbf{w})} + \frac{\|\mathbf{w}\|^2}{q_n^3(\mathbf{w})} = \frac{1}{q_n^3(\mathbf{w})} \leq 2\sqrt{2}n^{3/2},$$

we obtain that

$$\begin{aligned} & \left\| \nabla_{\mathbf{w}}^2g(\mathbf{w}; \tilde{\mathbf{Y}}) - \nabla_{\mathbf{w}}^2g(\mathbf{w}; \mathbf{X}) \right\| \\ &\leq \left\| \frac{1}{p} \sum_{k=1}^p \left[\ddot{h}(\mathbf{q}^*(\mathbf{w})\tilde{\mathbf{y}}_k) \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})\tilde{\mathbf{y}}_k\tilde{\mathbf{y}}_k^* (\nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w}))^* - \ddot{h}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k) \nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w})\mathbf{x}_k\mathbf{x}_k^* (\nabla_{\mathbf{w}}\mathbf{q}(\mathbf{w}))^* \right] \right\| \\ &\quad + \left\| \frac{1}{p} \sum_{k=1}^p \left[\dot{h}(\mathbf{q}^*(\mathbf{w})\tilde{\mathbf{y}}_k) \left(\frac{\mathbf{I}}{q_n(\mathbf{w})} + \frac{\mathbf{w}\mathbf{w}^*}{q_n^3(\mathbf{w})} \right) \tilde{\mathbf{y}}_k(n) - \dot{h}(\mathbf{q}^*(\mathbf{w})\mathbf{x}_k) \left(\frac{\mathbf{I}}{q_n(\mathbf{w})} + \frac{\mathbf{w}\mathbf{w}^*}{q_n^3(\mathbf{w})} \right) \mathbf{x}_k(n) \right] \right\| \\ &\leq \frac{45}{2}L_{\ddot{h}_{\mu}}n^{3/2}\|\mathbf{X}\|_{\infty}^3\|\tilde{\mathbf{\Xi}}\| + \max_t \ddot{h}_{\mu}(t) \left(18n^{3/2}\|\mathbf{X}\|_{\infty}^2\|\tilde{\mathbf{\Xi}}\| + 10n^2\|\mathbf{X}\|_{\infty}^2\|\tilde{\mathbf{\Xi}}\|^2 \right) \\ &\quad + 3\sqrt{2}L_{\dot{h}_{\mu}}n^2\|\tilde{\mathbf{\Xi}}\|\|\mathbf{X}\|_{\infty}^2 + \max_t \dot{h}_{\mu}(t) 2\sqrt{2}n^2\|\tilde{\mathbf{\Xi}}\|\|\mathbf{X}\|_{\infty}, \end{aligned}$$

where $L_{\ddot{h}_{\mu}}$ denotes the Lipschitz constant for $\ddot{h}_{\mu}(\cdot)$. Since

$$\max_t \dot{h}_{\mu}(t) \leq 1, \quad \max_t \ddot{h}_{\mu}(t) \leq \frac{1}{\mu}, \quad L_{h_{\mu}} \leq 1, \quad L_{\dot{h}_{\mu}} \leq \frac{1}{\mu}, \quad L_{\ddot{h}_{\mu}} \leq \frac{2}{\mu^2},$$

and by Lemma IV.11, $\|\mathbf{X}\|_{\infty} \leq 4\sqrt{\log(np)}$ with probability at least $1 - \theta(np)^{-7} - \exp(-0.3\theta np)$, we obtain

$$\begin{aligned} \left\| \nabla_{\mathbf{w}}g(\mathbf{w}; \tilde{\mathbf{Y}}) - \nabla_{\mathbf{w}}g(\mathbf{w}; \mathbf{X}) \right\| &\leq C_1 \frac{n}{\mu} \log(np) \|\tilde{\mathbf{\Xi}}\|, \\ \left\| \nabla_{\mathbf{w}}^2g(\mathbf{w}; \tilde{\mathbf{Y}}) - \nabla_{\mathbf{w}}^2g(\mathbf{w}; \mathbf{X}) \right\| &\leq C_2 \max \left\{ \frac{n^{3/2}}{\mu^2}, \frac{n^2}{\mu} \right\} \log^{3/2}(np) \|\tilde{\mathbf{\Xi}}\| \end{aligned}$$

for numerical constants $C_1, C_2 > 0$. ■

Proof: (of Theorem II.3) Assume the constant c_* as defined in Theorem II.1. By Lemma II.14, when

$$p \geq \frac{C_1}{c_*^2 \theta} \max \left\{ \frac{n^4}{\mu^4}, \frac{n^5}{\mu^2} \right\} \kappa^8(\mathbf{A}_0) \log^4 \left(\frac{\kappa(\mathbf{A}_0) n}{\mu \theta} \right),$$

the magnitude of the perturbation is bounded as

$$\|\tilde{\Xi}\| \leq C_2 c_* \theta \left(\max \left\{ \frac{n^{3/2}}{\mu^2}, \frac{n^2}{\mu} \right\} \log^{3/2}(np) \right)^{-1},$$

where C_2 can be made arbitrarily small by making C_1 large. Combining this result with Lemma II.15, we obtain that for all $\mathbf{w} \in \Gamma$,

$$\begin{aligned} \left\| \nabla_{\mathbf{w}} g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) - \nabla_{\mathbf{w}} g(\mathbf{w}; \mathbf{X}) \right\| &\leq \frac{c_* \theta}{2} \\ \left\| \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) - \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}) \right\| &\leq \frac{c_* \theta}{2}, \end{aligned}$$

with probability at least $1 - p^{-8} - \theta (np)^{-7} - \exp(-0.3\theta np)$. In view of (II.11) in Theorem II.1, we have

$$\begin{aligned} \frac{\mathbf{w}^* g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} &= \frac{\mathbf{w}^* g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} + \frac{\mathbf{w}^* g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} - \frac{\mathbf{w}^* g(\mathbf{w}; \mathbf{X}_0) \mathbf{w}}{\|\mathbf{w}\|^2} \\ &\leq -c_* \theta + \left\| \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) - \nabla_{\mathbf{w}}^2 g(\mathbf{w}; \mathbf{X}) \right\| \leq -\frac{1}{2} c_* \theta. \end{aligned}$$

By similar arguments, we obtain (II.9) through (II.11) in Theorem II.3.

To show the unique local minimizer over Γ is near $\mathbf{0}$, we note that (recall the last part of proof of Theorem II.1 in Section IV-B) $g(\mathbf{w}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0)$ being $\frac{c_* \theta}{2\mu}$ strongly convex near $\mathbf{0}$ implies that

$$\|\mathbf{w}_*\| \leq \frac{4\mu}{c_* \theta} \left\| \nabla g(\mathbf{0}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) \right\|.$$

The above perturbation analysis implies there exists $C_3 > 0$ such that when

$$p \geq \frac{C_3}{c_*^2 \theta} \max \left\{ \frac{n^4}{\mu^4}, \frac{n^5}{\mu^2} \right\} \kappa^8(\mathbf{A}_0) \log^4 \left(\frac{\kappa(\mathbf{A}_0) n}{\mu \theta} \right),$$

it holds that

$$\left\| \nabla_{\mathbf{w}} g(\mathbf{0}; \mathbf{X}_0 + \tilde{\Xi} \mathbf{X}_0) - \nabla_{\mathbf{w}} g(\mathbf{0}; \mathbf{X}) \right\| \leq \frac{c_* \theta}{400},$$

which in turn implies

$$\|\mathbf{w}_*\| \leq \frac{4\mu}{c_* \theta} \left\| \nabla g(\mathbf{0}; \mathbf{X}_0) \right\| + \frac{4\mu}{c_* \theta} \frac{c_* \theta}{400} \leq \frac{\mu}{8} + \frac{\mu}{100} < \frac{\mu}{7},$$

where we have recall the result that $\frac{2\mu}{c_* \theta} \left\| \nabla g(\mathbf{0}; \mathbf{X}_0) \right\| \leq \mu/16$ from proof of Theorem II.1. A simple union bound with careful bookkeeping gives the success probability. \blacksquare

APPENDIX A

TECHNICAL TOOLS AND BASIC FACTS USED IN PROOFS

In this section, we summarize some basic calculations that are useful throughout, and also record major technical tools we use in proofs.

Lemma A.1 (Derivates and Lipschitz Properties of $h_\mu(z)$). *For the sparsity surrogate*

$$h_\mu(z) = \mu \log \cosh(z/\mu),$$

the first two derivatives are

$$\dot{h}_\mu(z) = \tanh(z/\mu), \quad \ddot{h}_\mu(z) = [1 - \tanh^2(z/\mu)] / \mu.$$

Also, for any $z > 0$, we have

$$\begin{aligned} (1 - \exp(-2z/\mu))/2 &\leq \tanh(z/\mu) \leq 1 - \exp(-2z/\mu), \\ \exp(-2z/\mu) &\leq 1 - \tanh^2(z/\mu) \leq 4 \exp(-2z/\mu). \end{aligned}$$

Moreover, for any $z, z' \in \mathbb{R}$, we have

$$|\dot{h}_\mu(z) - \dot{h}_\mu(z')| \leq |z - z'|/\mu, \quad |\ddot{h}_\mu(z) - \ddot{h}_\mu(z')| \leq 2|z - z'|/\mu^2.$$

Lemma A.2 (Harris' Inequality, [110], see also Theorem 2.15 of [111]). *Let X_1, \dots, X_n be independent, real-valued random variables and $f, g : \mathbb{R}^n \mapsto \mathbb{R}$ be nonincreasing (nondecreasing) w.r.t. any one variable while fixing the others. Define a random vector $\mathbf{X} = (X_1, \dots, X_n) \in \mathbb{R}^n$, then we have*

$$\mathbb{E}[f(\mathbf{X})g(\mathbf{X})] \geq \mathbb{E}[f(\mathbf{X})]\mathbb{E}[g(\mathbf{X})].$$

Similarly, if f is nondecreasing (nonincreasing) and g is nonincreasing (nondecreasing) coordinatewise in the above sense, we have

$$\mathbb{E}[f(\mathbf{X})g(\mathbf{X})] \leq \mathbb{E}[f(\mathbf{X})]\mathbb{E}[g(\mathbf{X})].$$

Lemma A.3 (Differentiation under the Integral Sign). *Consider a function $F : \mathbb{R}^n \times \mathbb{R} \mapsto \mathbb{R}$ such that $\frac{\partial F(\mathbf{x}, s)}{\partial s}$ is well defined and measurable over $\mathcal{U} \times (0, t_0)$ for some open subset $\mathcal{U} \subset \mathbb{R}^n$ and some $t_0 > 0$. For any probability measure μ on \mathbb{R}^n and any $t \in (0, t_0)$ such that $\int_0^t \int_{\mathcal{U}} \left| \frac{\partial F(\mathbf{x}, s)}{\partial s} \right| \mu(d\mathbf{x}) ds < \infty$, it holds that*

$$\frac{d}{dt} \int_{\mathcal{U}} F(\mathbf{x}, t) \mu(d\mathbf{x}) = \int_{\mathcal{U}} \frac{\partial F(\mathbf{x}, t)}{\partial t} \mu(d\mathbf{x}), \quad \text{or} \quad \frac{d}{dt} \mathbb{E}_{\mathbf{x}}[F(\mathbf{x}, t) \mathbb{1}_{\mathcal{U}}] = \mathbb{E}_{\mathbf{x}} \left[\frac{\partial F(\mathbf{x}, t)}{\partial t} \mathbb{1}_{\mathcal{U}} \right].$$

Proof: See proof of Lemma A.4 in the technical report [2]. ■

Lemma A.4 (Gaussian Tail Estimates). *Let $X \sim \mathcal{N}(0, 1)$ and $\Phi(x)$ be CDF of X . For any $x \geq 0$, we have the following estimates for $\Phi^c(x) \doteq 1 - \Phi(x)$:*

$$\begin{aligned} \left(\frac{1}{x} - \frac{1}{x^3} \right) \frac{\exp(-x^2/2)}{\sqrt{2\pi}} &\leq \Phi^c(x) \leq \left(\frac{1}{x} - \frac{1}{x^3} + \frac{3}{x^5} \right) \frac{\exp(-x^2/2)}{\sqrt{2\pi}}, \quad (\text{Type I}) \\ \frac{x}{x^2 + 1} \frac{\exp(-x^2/2)}{\sqrt{2\pi}} &\leq \Phi^c(x) \leq \frac{1}{x} \frac{\exp(-x^2/2)}{\sqrt{2\pi}}, \quad (\text{Type II}) \\ \frac{\sqrt{x^2 + 4} - x}{2} \frac{\exp(-x^2/2)}{\sqrt{2\pi}} &\leq \Phi^c(x) \leq \left(\sqrt{2 + x^2} - x \right) \frac{\exp(-x^2/2)}{\sqrt{2\pi}} \quad (\text{Type III}). \end{aligned}$$

Proof: See proof of Lemma A.5 in the technical report [2]. ■

Lemma A.5 (Moments of the Gaussian RV). *If $X \sim \mathcal{N}(0, \sigma^2)$, then it holds for all integer $p \geq 1$ that*

$$\mathbb{E}[|X|^p] \leq \sigma^p (p-1)!!.$$

Lemma A.6 (Moments of the χ^2 RV). *If $X \sim \chi^2(n)$, then it holds for all integer $p \geq 1$ that*

$$\mathbb{E}[X^p] = 2^p \frac{\Gamma(p + n/2)}{\Gamma(n/2)} = \prod_{k=1}^p (n + 2k - 2) \leq p! (2n)^p / 2.$$

Lemma A.7 (Moments of the χ RV). *If $X \sim \chi(n)$, then it holds for all integer $p \geq 1$ that*

$$\mathbb{E}[X^p] = 2^{p/2} \frac{\Gamma(p/2 + n/2)}{\Gamma(n/2)} \leq p! n^{p/2}.$$

Lemma A.8 (Moment-Control Bernstein's Inequality for Scalar RVs, Theorem 2.10 of [112]). *Let X_1, \dots, X_p be i.i.d. real-valued random variables. Suppose that there exist some positive numbers R and σ^2 such that*

$$\mathbb{E}[|X_k|^m] \leq m! \sigma^2 R^{m-2} / 2, \quad \text{for all integers } m \geq 2.$$

Let $S \doteq \frac{1}{p} \sum_{k=1}^p X_k$, then for all $t > 0$, it holds that

$$\mathbb{P} [|S - \mathbb{E}[S]| \geq t] \leq 2 \exp\left(-\frac{pt^2}{2\sigma^2 + 2Rt}\right).$$

Lemma A.9 (Moment-Control Bernstein's Inequality for Matrix RVs, Theorem 6.2 of [113]). *Let $\mathbf{X}_1, \dots, \mathbf{X}_p \in \mathbb{R}^{d \times d}$ be i.i.d. random, symmetric matrices. Suppose there exist some positive number R and σ^2 such that*

$$\mathbb{E}[\mathbf{X}_k^m] \preceq m! \sigma^2 R^{m-2} / 2 \cdot \mathbf{I} \text{ and } -\mathbb{E}[\mathbf{X}_k^m] \preceq m! \sigma^2 R^{m-2} / 2 \cdot \mathbf{I}, \text{ for all integers } m \geq 2.$$

Let $\mathbf{S} \doteq \frac{1}{p} \sum_{k=1}^p \mathbf{X}_k$, then for all $t > 0$, it holds that

$$\mathbb{P} [\|\mathbf{S} - \mathbb{E}[\mathbf{S}]\| \geq t] \leq 2d \exp\left(-\frac{pt^2}{2\sigma^2 + 2Rt}\right).$$

Proof: See proof of Lemma A.10 in the technical report [2]. ■

Corollary A.10 (Moment-Control Bernstein's Inequality for Vector RVs). *Let $\mathbf{x}_1, \dots, \mathbf{x}_p \in \mathbb{R}^d$ be i.i.d. random vectors. Suppose there exist some positive number R and σ^2 such that*

$$\mathbb{E}[\|\mathbf{x}_k\|^m] \leq m! \sigma^2 R^{m-2} / 2, \text{ for all integers } m \geq 2.$$

Let $\mathbf{s} = \frac{1}{p} \sum_{k=1}^p \mathbf{x}_k$, then for any $t > 0$, it holds that

$$\mathbb{P} [\|\mathbf{s} - \mathbb{E}[\mathbf{s}]\| \geq t] \leq 2(d+1) \exp\left(-\frac{pt^2}{2\sigma^2 + 2Rt}\right).$$

Proof: See proof of Lemma A.11 in the technical report [2]. ■

Lemma A.11 (Integral Form of Taylor's Theorem). *Let $f(\mathbf{x}) : \mathbb{R}^n \mapsto \mathbb{R}$ be a twice continuously differentiable function, then for any direction $\mathbf{y} \in \mathbb{R}^n$, we have*

$$\begin{aligned} f(\mathbf{x} + t\mathbf{y}) &= f(\mathbf{x}) + t \int_0^1 \langle \nabla f(\mathbf{x} + s t\mathbf{y}), \mathbf{y} \rangle ds, \\ f(\mathbf{x} + t\mathbf{y}) &= f(\mathbf{x}) + t \langle \nabla f(\mathbf{x}), \mathbf{y} \rangle + t^2 \int_0^1 (1-s) \langle \nabla^2 f(\mathbf{x} + s t\mathbf{y}) \mathbf{y}, \mathbf{y} \rangle ds. \end{aligned}$$

APPENDIX B AUXILLARY RESULTS FOR PROOFS

Lemma B.1. *Let $X \sim \mathcal{N}(0, \sigma_X^2)$ and $Y \sim \mathcal{N}(0, \sigma_Y^2)$ be independent random variables and $\Phi^c(t) = \frac{1}{\sqrt{2\pi}} \int_t^\infty \exp(-x^2/2) dx$ be the complementary cumulative distribution function of the standard normal. For any $a > 0$, we have*

$$\mathbb{E}[X \mathbb{1}_{X>0}] = \frac{\sigma_X}{\sqrt{2\pi}}, \tag{B.1}$$

$$\mathbb{E}[\exp(-aX) X \mathbb{1}_{X>0}] = \frac{\sigma_X}{\sqrt{2\pi}} - a\sigma_X^2 \exp\left(\frac{a^2\sigma_X^2}{2}\right) \Phi^c(a\sigma_X), \tag{B.2}$$

$$\mathbb{E}[\exp(-aX) \mathbb{1}_{X>0}] = \exp\left(\frac{a^2\sigma_X^2}{2}\right) \Phi^c(a\sigma_X), \tag{B.3}$$

$$\begin{aligned} \mathbb{E}[\exp(-a(X+Y)) X^2 \mathbb{1}_{X+Y>0}] &= \sigma_X^2 (1 + a^2\sigma_X^2) \exp\left(\frac{a^2\sigma_X^2 + a^2\sigma_Y^2}{2}\right) \Phi^c\left(a\sqrt{\sigma_X^2 + \sigma_Y^2}\right) \\ &\quad - \frac{a\sigma_X^4}{\sqrt{2\pi}\sqrt{\sigma_X^2 + \sigma_Y^2}}, \end{aligned} \tag{B.4}$$

$$\mathbb{E}[\exp(-a(X+Y)) XY \mathbb{1}_{X+Y>0}] = a^2\sigma_X^2\sigma_Y^2 \exp\left(\frac{a^2\sigma_X^2 + a^2\sigma_Y^2}{2}\right) \Phi^c\left(a\sqrt{\sigma_X^2 + \sigma_Y^2}\right)$$

$$-\frac{a\sigma_X^2\sigma_Y^2}{\sqrt{2\pi}\sqrt{\sigma_X^2+\sigma_Y^2}}, \quad (\text{B.5})$$

$$\mathbb{E}[\tanh(aX)X] = a\sigma_X^2\mathbb{E}[1 - \tanh^2(aX)], \quad (\text{B.6})$$

$$\mathbb{E}[\tanh(a(X+Y))X] = a\sigma_X^2\mathbb{E}[1 - \tanh^2(a(X+Y))]. \quad (\text{B.7})$$

Proof: Equalities (B.1), (B.2), (B.3), (B.4) and (B.5) can be obtained by direct integrations. Equalities (B.6) and (B.7) can be derived using integration by part. ■

Proof: (of Lemma IV.1) Indeed $\frac{1}{(1+\beta t)^2} = \sum_{k=0}^{\infty} (-1)^k (k+1)\beta^k t^k$, as

$$\sum_{k=0}^{\infty} (-1)^k (k+1)\beta^k t^k = \sum_{k=0}^{\infty} (-\beta t)^k + \sum_{k=0}^{\infty} k(-\beta t)^k = \frac{1}{1+\beta t} + \frac{-\beta t}{(1+\beta t)^2} = \frac{1}{(1+\beta t)^2}.$$

The magnitude of the coefficient vector is

$$\|\mathbf{b}\|_{\ell^1} = \sum_{k=0}^{\infty} \beta^k (1+k) = \sum_{k=0}^{\infty} \beta^k + \sum_{k=0}^{\infty} k\beta^k = \frac{1}{1-\beta} + \frac{\beta}{(1-\beta)^2} = \frac{1}{(1-\beta)^2} = T.$$

Observing that $\frac{1}{(1+\beta t)^2} > \frac{1}{(1+t)^2}$ for $t \in [0, 1]$ when $0 < \beta < 1$, we obtain

$$\|p - f\|_{L^1[0,1]} = \int_0^1 |p(t) - f(t)| dt = \int_0^1 \left[\frac{1}{(1+\beta t)^2} - \frac{1}{(1+t)^2} \right] dt = \frac{1-\beta}{2(1+\beta)} \leq \frac{1}{2\sqrt{T}}.$$

Moreover, we have

$$\|f - p\|_{L^\infty[0,1]} = \max_{t \in [0,1]} p(t) - f(t) = \max_{t \in [0,1]} \frac{t(1-\beta)(2+t(1+\beta))}{(1+t)^2(1+\beta t)^2} \leq 1-\beta = \frac{1}{\sqrt{T}}.$$

Finally, notice that

$$\begin{aligned} \sum_{k=0}^{\infty} \frac{b_k}{(1+k)^3} &= \sum_{k=0}^{\infty} \frac{(-\beta)^k}{(1+k)^2} = \sum_{i=0}^{\infty} \left[\frac{\beta^{2i}}{(1+2i)^2} - \frac{\beta^{2i+1}}{(2i+2)^2} \right] \\ &= \sum_{i=0}^{\infty} \beta^{2i} \frac{(2i+2)^2 - \beta(2i+1)^2}{(2i+2)^2(2i+1)^2} > 0, \end{aligned}$$

where at the second equality we have grouped consecutive even-odd pair of summands. In addition, we have

$$\sum_{k=0}^n \frac{b_k}{(1+k)^3} \leq \sum_{k=0}^n \frac{|b_k|}{(1+k)^3} = \sum_{k=0}^n \frac{\beta^k}{(1+k)^2} \leq 1 + \sum_{k=1}^n \frac{1}{(1+k)k} = 2 - \frac{1}{n+1},$$

which converges to 2 when $n \rightarrow \infty$, completing the proof. ■

Proof: (of Lemma IV.4) The first inequality is obviously true for $\mathbf{v} = \mathbf{0}$. When $\mathbf{v} \neq \mathbf{0}$, we have

$$\begin{aligned} \mathbb{E}[|\mathbf{v}^* \mathbf{z}|^m] &= \sum_{\ell=0}^n \theta^\ell (1-\theta)^{n-\ell} \sum_{\mathcal{J} \in \binom{[n]}{\ell}} \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{v}_{\mathcal{J}}\|^2)} [|Z|^m] \\ &\leq \sum_{\ell=0}^n \theta^\ell (1-\theta)^{n-\ell} \sum_{\mathcal{J} \in \binom{[n]}{\ell}} \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{v}\|^2)} [|Z|^m] \\ &= \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{v}\|^2)} [|Z|^m] \sum_{\ell=0}^n \theta^\ell (1-\theta)^{n-\ell} \binom{n}{\ell} \\ &= \mathbb{E}_{Z \sim \mathcal{N}(0, \|\mathbf{v}\|^2)} [|Z|^m], \end{aligned}$$

where the second line relies on the fact $\|\mathbf{v}_{\mathcal{J}}\| \leq \|\mathbf{v}\|$ and that for a fixed order, central moment of Gaussian is monotonically increasing w.r.t. its variance. Similarly, to see the second inequality,

$$\begin{aligned} \mathbb{E} [\|\mathbf{z}\|^m] &= \sum_{\ell=0}^n \theta^\ell (1-\theta)^{n-\ell} \sum_{\mathcal{J} \in \binom{[n]}{\ell}} \mathbb{E} [\|\mathbf{z}'_{\mathcal{J}}\|^m] \\ &\leq \mathbb{E} [\|\mathbf{z}'\|^m] \sum_{\ell=0}^n \theta^\ell (1-\theta)^{n-\ell} \binom{n}{\ell} = \mathbb{E} [\|\mathbf{z}'\|^m], \end{aligned}$$

as desired. \blacksquare

Proof: (of Lemma IV.11) Consider one component of \mathbf{X} , i.e., $X_{ij} = B_{ij}V_{ij}$ for $i \in [n]$ and $j \in [p]$, where $B_{ij} \sim \text{Ber}(\theta)$ and $V_{ij} \sim \mathcal{N}(0, 1)$. We have

$$\mathbb{P} \left[|X_{ij}| > 4\sqrt{\log(np)} \right] \leq \theta \mathbb{P} \left[|V_{ij}| > 4\sqrt{\log(np)} \right] \leq \theta \exp(-8 \log(np)) = \theta (np)^{-8}.$$

And also

$$\mathbb{P} [|X_{ij}| < 1] = 1 - \theta + \theta \mathbb{P} [|V_{ij}| < 1] \leq 1 - 0.3\theta.$$

Applying a union bound as

$$\mathbb{P} \left[\|\mathbf{X}\|_{\infty} \leq 1 \text{ or } \|\mathbf{X}\|_{\infty} \geq 4\sqrt{\log(np)} \right] \leq (1 - 0.3\theta)^{np} + np\theta (np)^{-8} \leq \exp(-0.3\theta np) + \theta (np)^{-7},$$

we complete the proof. \blacksquare

Lemma B.2. Suppose $\mathbf{A} \succ \mathbf{0}$. Then for any symmetric perturbation matrix Δ with $\|\Delta\| \leq \frac{\sigma_{\min}(\mathbf{A})}{2}$, it holds that

$$\left\| (\mathbf{A} + \Delta)^{-1/2} - \mathbf{A}^{-1/2} \right\| \leq \frac{2 \|\mathbf{A}\|^{1/2} \|\Delta\|}{\sigma_{\min}^2(\mathbf{A})}. \quad (\text{B.8})$$

Proof: See proof of Lemma B.2 in the technical report [2]. \blacksquare

Lemma B.3. There exists a positive constant C such that for any $\theta \in (0, 1/2)$ and $n_2 > Cn_1^2 \log n_1$, the random matrix $\mathbf{X} \in \mathbb{R}^{n_1 \times n_2}$ with $\mathbf{X} \sim_{i.i.d.} \text{BG}(\theta)$ obeys

$$\left\| \frac{1}{n_2\theta} \mathbf{X} \mathbf{X}^* - \mathbf{I} \right\| \leq 10 \sqrt{\frac{\theta n_1 \log n_2}{n_2}} \quad (\text{B.9})$$

with probability at least $1 - n_2^{-8}$.

Proof: Observe that $\mathbb{E} \left[\frac{1}{\theta} \mathbf{x}_k \mathbf{x}_k^* \right] = \mathbf{I}$ for any column \mathbf{x}_k of \mathbf{X} and so $\frac{1}{n_2\theta} \mathbf{X} \mathbf{X}^*$ can be considered as a normalized sum of independent random matrices. Moreover, for any integer $m \geq 2$,

$$\mathbb{E} \left[\left(\frac{1}{\theta} \mathbf{x}_k \mathbf{x}_k^* \right)^m \right] = \frac{1}{\theta^m} \mathbb{E} \left[\|\mathbf{x}_k\|^{2m-2} \mathbf{x}_k \mathbf{x}_k^* \right].$$

Now $\mathbb{E} \left[\|\mathbf{x}_k\|^{2m-2} \mathbf{x}_k \mathbf{x}_k^* \right]$ is a diagonal matrix (as $\mathbb{E} \left[\|\mathbf{x}_k\|^2 x_k(i) x_k(j) \right] = -\mathbb{E} \left[\|\mathbf{x}_k\|^2 x_k(i) x_k(j) \right]$ for any $i \neq j$ by symmetry of the distribution) in the form $\mathbb{E} \left[\|\mathbf{x}_k\|^{2m-2} \mathbf{x}_k \mathbf{x}_k^* \right] = \mathbb{E} \left[\|\mathbf{x}\|^{2m-2} x(1)^2 \right] \mathbf{I}$ for $\mathbf{x} \sim_{i.i.d.} \text{BG}(\theta)$ with $\mathbf{x} \in \mathbb{R}^{n_1}$. Let $t^2(\mathbf{x}) = \|\mathbf{x}\|^2 - x(1)^2$. Then if $m = 2$,

$$\begin{aligned} \mathbb{E} \left[\|\mathbf{x}\|^2 x(1)^2 \right] &= \mathbb{E} [x(1)^4] + \mathbb{E} [t^2(\mathbf{x})] \mathbb{E} [x(1)^2] \\ &= \mathbb{E} [x(1)^4] + (n_1 - 1) (\mathbb{E} [x(1)^2])^2 = 3\theta + (n_1 - 1) \theta^2 \leq 3n_1\theta, \end{aligned}$$

where for the last simplification we use the assumption $\theta \leq 1/2$. For $m \geq 3$,

$$\begin{aligned}
 \mathbb{E} \left[\|\mathbf{x}\|^{2m-2} x(1)^2 \right] &= \sum_{k=0}^{m-1} \binom{m-1}{k} \mathbb{E} \left[t^{2k}(\mathbf{x}) x(1)^{2m-2k} \right] = \sum_{k=0}^{m-1} \binom{m-1}{k} \mathbb{E} \left[t^{2k}(\mathbf{x}) \right] \mathbb{E} \left[x(1)^{2m-2k} \right] \\
 &\leq \sum_{k=0}^{m-1} \binom{m-1}{k} \mathbb{E}_{Z \sim \chi^2(n_1-1)} \left[Z^k \right] \theta \mathbb{E}_{W \sim \mathcal{N}(0,1)} \left[W^{2m-2k} \right] \\
 &\leq \theta \sum_{k=0}^{m-1} \binom{m-1}{k} \frac{k!}{2} (2n_1 - 2)^k (2m - 2k)!! \\
 &\leq \theta 2^m \frac{m!}{2} \sum_{k=0}^{m-1} \binom{m-1}{k} (n_1 - 1)^k \\
 &\leq \frac{m!}{2} n_1^{m-1} 2^{m-1},
 \end{aligned}$$

where we have used the moment estimates for Gaussian and χ^2 random variables from Lemma A.5 and Lemma A.6, and also $\theta \leq 1/2$. Taking $\sigma^2 = 3n_1\theta$ and $R = 2n_1$, and invoking the matrix Bernstein in Lemma A.9, we obtain

$$\mathbb{E} \left[\left\| \frac{1}{p\theta} \sum_{k=1}^p \mathbf{x}_k \mathbf{x}_k^* - \mathbf{I} \right\| > t \right] \leq \exp \left(-\frac{n_2 t^2}{6n_1\theta + 4n_1 t} + 2 \log n_1 \right) \quad (\text{B.10})$$

for any $t \geq 0$. Taking $t = 10\sqrt{\theta n_1 \log(n_2)/n_2}$ gives the claimed result. \blacksquare

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