

ESTIMATION OF HIGH-DIMENSIONAL LOW-RANK MATRICES¹

BY ANGELIKA ROHDE AND ALEXANDRE B. TSYBAKOV

Universität Hamburg and CREST

Suppose that we observe entries or, more generally, linear combinations of entries of an unknown $m \times T$ -matrix A corrupted by noise. We are particularly interested in the high-dimensional setting where the number mT of unknown entries can be much larger than the sample size N . Motivated by several applications, we consider estimation of matrix A under the assumption that it has small rank. This can be viewed as dimension reduction or sparsity assumption. In order to shrink toward a low-rank representation, we investigate penalized least squares estimators with a Schatten- p quasi-norm penalty term, $p \leq 1$. We study these estimators under two possible assumptions—a modified version of the restricted isometry condition and a uniform bound on the ratio “empirical norm induced by the sampling operator/Frobenius norm.” The main results are stated as nonasymptotic upper bounds on the prediction risk and on the Schatten- q risk of the estimators, where $q \in [p, 2]$. The rates that we obtain for the prediction risk are of the form rm/N (for $m = T$), up to logarithmic factors, where r is the rank of A . The particular examples of multi-task learning and matrix completion are worked out in detail. The proofs are based on tools from the theory of empirical processes. As a by-product, we derive bounds for the k th entropy numbers of the quasi-convex Schatten class embeddings $S_p^M \hookrightarrow S_2^M$, $p < 1$, which are of independent interest.

1. Introduction. Consider the observations (X_i, Y_i) satisfying the model

$$(1.1) \quad Y_i = \text{tr}(X_i' A^*) + \xi_i, \quad i = 1, \dots, N,$$

where $X_i \in \mathbb{R}^{m \times T}$ are given matrices (m rows, T columns), $A^* \in \mathbb{R}^{m \times T}$ is an unknown matrix, ξ_i are i.i.d. random errors, $\text{tr}(B)$ denotes the trace of

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square matrix B and X' stands for the transposed of X . Our aim is to estimate the matrix A^* and to predict the future Y -values based on the sample (X_i, Y_i) , $i = 1, \dots, N$.

We will call model (1.1) the *trace regression model*. Clearly, for $T = 1$ it reduces to the standard regression model. The “design” matrices X_i will be called *masks*. This name is motivated by the fact that we focus on the applications of trace regression where X_i are very sparse, that is, contain only a small percentage of nonzero entries. Therefore, multiplication of A^* by X_i masks most of the entries of A^* . The following two examples are of particular interest.

(i) *Point masks*. For some, typically small, integer d the point masks X_i are defined as elements of the set

$$\mathcal{X}_d = \left\{ \sum_{i=1}^d e_{k_i}(m) e'_{l_i}(T) : 1 \leq k_i \leq m, 1 \leq l_i \leq T, \right. \\ \left. \text{with } (k_i, l_i) \neq (k_{i'}, l_{i'}) \text{ for } i \neq i' \right\},$$

where $e_k(m)$ are the canonical basis vectors of \mathbb{R}^m . In particular, for $d = 1$ the point masks X_i are matrices that have only one nonzero entry, which equals to 1. The problem of estimation of A^* in this case becomes the problem of *matrix completion*; the observations Y_i are just some selected entries of A^* corrupted by noise, and the aim is to reconstruct all the entries of A . The problem of matrix completion dates back at least to Srebro, Rennie and Jaakkola (2005), Srebro and Shraibman (2005) and is mainly motivated by applications in recommendation systems. We will analyze the following two special cases of matrix completion:

- *USR (Uniform Sampling at Random) matrix completion*. The masks X_i are independent, uniformly distributed on

$$\mathcal{X}_1 = \{e_k(m) e'_l(T) : 1 \leq k \leq m, 1 \leq l \leq T\},$$

and independent from ξ_1, \dots, ξ_N .

- *Collaborative sampling (CS) matrix completion*. The masks X_i (random or deterministic) belong to \mathcal{X}_1 , are all distinct and independent from ξ_1, \dots, ξ_N .

The CS matrix completion model is natural to describe recommendation systems where every user rates every product only once. The USR matrix completion can be used for transmission of a large-dimensional matrix through a noisy communication channel; only a chosen small number of entries is transmitted, and nevertheless the original matrix A^* can be reconstructed by the receiver. An important feature of the real-world matrix completion

problems is that the number of observed entries is much smaller than the size of the matrix: $N \ll mT$, whereas mT can be very large. For example, mT is of the order of hundreds of millions for the Netflix problem.

(ii) *Column or row masks.* If X_i has only a small number d of nonzero columns or rows, it is called column or row mask, respectively. We suppose here that d is much smaller than m and T . A remarkable case $d = 1$ is covering the problem known in Statistics and Econometrics as longitudinal (or panel, or cross-section) data analysis and in Machine Learning as multi-task learning. In what follows, we will designate this problem as multi-task learning, to avoid ambiguity. In the simplest version of multi-task learning, we have $N = nT$ where T is the number of tasks (for instance, in image detection each task t is associated with a particular type of visual object, e.g., face, car, chair, etc.), and n is the number of observations per task. The tasks are characterized by vectors of parameters $a_t^* \in \mathbb{R}^m$, $t = 1, \dots, T$, which constitute the columns of matrix A^* :

$$A^* = (a_1^* \cdots a_T^*).$$

The X_i are column masks, each containing only one nonzero column $\mathbf{x}^{(t,s)} \in \mathbb{R}^m$ (with the convention that $\mathbf{x}^{(t,s)}$ is the t th column):

$$X_i \in \{(0 \cdots 0 \underbrace{\mathbf{x}^{(t,s)}}_t 0 \cdots 0), t = 1, \dots, T, s = 1, \dots, n\}.$$

The column $\mathbf{x}^{(t,s)}$ is interpreted as the vector of predictor variables corresponding to s th observation for the t th task. Thus, for each $i = 1, \dots, N$ there exists a pair (t, s) with $t = 1, \dots, T, s = 1, \dots, n$, such that

$$(1.2) \quad \text{tr}(X_i' A^*) = (a_t^*)' \mathbf{x}^{(t,s)}.$$

If we denote by $Y^{(t,s)}$ and $\xi^{(t,s)}$ the corresponding values Y_i and ξ_i , then the trace regression model (1.1) can be written as a collection of T standard regression models:

$$Y^{(t,s)} = (a_t^*)' \mathbf{x}^{(t,s)} + \xi^{(t,s)}, \quad t = 1, \dots, T, s = 1, \dots, n.$$

This is the usual formulation of the multi-task learning model in the literature.

For both examples given above, the matrices X_i are sparse in the sense that they have only a small portion of nonzero entries. On the other hand, such a sparsity property is not necessarily granted for the target matrix A^* . Nevertheless, we can always characterize A^* by its rank $r = \text{rank}(A^*)$, and say that a matrix is sparse if it has small rank; cf. Recht, Fazel and Parrilo (2010). For example, the problem of estimation of a square matrix $A^* \in \mathbb{R}^{m \times m}$ is a parametric problem which is formally of dimension m^2 but it has only $(2m - r)r$ free parameters. If r is small as compared to m , then

the intrinsic dimension of the problem is of the order rm . In other words, the rank sparsity assumption $r \ll m$ is a dimension reduction assumption. This assumption will be crucial for the interpretation of our results. Another sparsity assumption that we will consider is that Schatten- p norm of A^* (see the definition in Section 2 below) is small for some $0 < p \leq 1$. This is an analog of sparsity expressed in terms of the ℓ_p norm, $0 < p \leq 1$, in vector estimation problems.

Estimation of high-dimensional matrices has been recently studied by several authors in settings different from the ours [cf., e.g., Meinshausen and Bühlmann (2006), Bickel and Levina (2008), Ravikumar et al. (2008), Amini and Wainwright (2009), Cai, Zhang and Zhou (2010) and the references cited therein]. Most of attention was devoted to estimation of a large covariance matrix or its inverse. In these papers, sparsity is characterized by the number of nonzero entries of a matrix.

Candès and Recht (2009), Candès and Tao (2009), Gross (2009), Recht (2009) considered the nonnoisy setting ($\xi_i \equiv 0$) of the matrix completion problem under conditions that the singular vectors of A^* are sufficiently spread out on the unit sphere or “incoherent.” They focused on exact recovery of A^* . Until now, the sharpest results are those of Gross (2009) and Recht (2009) who showed that under “incoherence condition” the exact recovery is possible with high probability if $N > Cr(m+T)\log^2 m$ with some constant $C > 0$ when we observe N entries of a matrix $A^* \in \mathbb{R}^{m \times T}$ with locations uniformly sampled at random. Candès and Plan (2010a), Keshavan, Montanari and Oh (2009) explored the same setting in the presence of noise, proposed estimators \hat{A} of A^* and evaluated their Frobenius norm $\|\hat{A} - A^*\|_F$. The better bounds are in Keshavan, Montanari and Oh (2009) who suggest \hat{A} such that for $A^* \in \mathbb{R}^{m \times T}$ and $T = \alpha m$ with $\alpha > 1$ the squared error $\|\hat{A} - A^*\|_F^2$ is of the order $\alpha^{5/2}rm^3(\log N)/N$ with probability close to 1 when the noise is i.i.d. Gaussian.

In this paper, we consider the general noisy setting of the trace regression problem. We study a class of Schatten- p estimators \hat{A} , that is, the penalized least squares estimators with a penalty proportional to Schatten- p norm; cf. (2.5). The special case $p = 1$ corresponds to the “matrix Lasso.” We study the convergence properties of their prediction error

$$\hat{d}_{2,N}(\hat{A}, A^*)^2 = N^{-1} \sum_{i=1}^N \text{tr}^2(X_i'(\hat{A} - A^*))$$

and of their Schatten- q error. The main contributions of this paper are the following.

- (a) For all $0 < p \leq 1$, under various assumptions on the masks X_i (no assumption, USR matrix completion, CS matrix completionmatrix compl) we obtain different bounds on the prediction error of Schatten- p estimators involving the Schatten- p norm of A^* .

- (b) For p sufficiently close to 0, under a mild assumption on X_i , we show that Schatten- p estimators achieve the prediction error rate of convergence $\frac{r \max(m, T)}{N}$, up to a logarithmic factor. This result is valid for matrices A^* whose eigenvalues are not exponentially large in N . It covers the matrix completion and high-dimensional multi-task learning problems.
- (c) For all $0 < p \leq 1$, we obtain upper bounds for the prediction error under the matrix Restricted Isometry (RI) condition on the masks X_i , which is a rather strong condition, and under the assumption that $\text{rank}(A^*) \leq r$. We also derive the bounds for the Schatten- q error of \hat{A} . The rate in the bounds for the prediction error is $r \max(m, T)/N$ when the RI condition is satisfied with scaling factor 1 (i.e., for the case not related to matrix completion and high-dimensional multi-task learning).
- (d) We prove the lower bounds showing that the rate $r \max(m, T)/N$ is minimax optimal for the prediction error and Schatten-2 (i.e., Frobenius) norm estimation error under the RI condition on the class of matrices A^* of rank smaller than r . Our result is even more general because we prove our lower bound on the intersection of the Schatten-0 ball with the Schatten- p ball for any $0 < p \leq 1$, which allows us to show minimax optimality of the upper bounds of (a) as well. Furthermore, we prove minimax lower bounds for collaborative sampling and USR matrix completion problems.

The main point of this paper is to show that the suitably tuned Schatten estimators attain the optimal rate of prediction error up to logarithmic factors. The striking fact is that we can achieve this not only under the very restrictive assumption, such as the RI condition, but also under very mild assumptions on the masks X_i .

Finally, it is useful to compare the results for matrix estimation when the sparsity is expressed by the rank with those for the high-dimensional vector estimation when the sparsity is expressed by the number of nonzero components of the vector. For the vector estimation, we have the linear model

$$Y_i = X_i' \beta + \xi_i, \quad i = 1, \dots, N,$$

where $X_i \in \mathbb{R}^p$, $\beta \in \mathbb{R}^p$ and, for example, ξ_i are i.i.d. $\mathcal{N}(0, 1)$ random variables. Consider the high-dimensional case $p \gg N$. (This is analogous to the assumption $m^2 \gg N$ in the matrix problem and means that the nominal dimension is much larger than the sample size.) The sparsity assumption for the vector case has the form $s \ll N$, where s is the number of nonzero components, or the *intrinsic dimension* of β . Let $\hat{\beta}$ be an estimator of β . Then the optimal rate of convergence of the prediction risk $N^{-1} \sum_{i=1}^N (X_i'(\hat{\beta} - \beta))^2$ on the class of vectors β with given s is of the order s/N , up to logarithmic factors. This rate is shown to be attained, up to logarithmic factors, for many

estimators, such as the BIC, the Lasso, the Dantzig selector, Sparse Exponential Weighting, etc.; cf., for example, Bunea, Tsybakov and Wegkamp (2007), Koltchinskii (2008), Bickel, Ritov and Tsybakov (2009), Dalalyan and Tsybakov (2008). Note that this rate is of the form $\frac{\text{intrinsic dimension}}{\text{sample size}} = \frac{s}{N}$, up to a logarithmic factor. The general interpretation is therefore completely analogous to that of the matrix case: Assume for simplicity that A^* is a square $m \times m$ matrix with $\text{rank}(A^*) = r$. As mentioned above, the *intrinsic dimension* (the number of parameters to be estimated to recover A^*) is then $(2m - r)r$, which is of the order $\sim rm$ if $r \ll m$. An interesting difference is that the logarithmic risk inflation factor is inevitable in the vector case [cf. Donoho et al. (1992), Foster and George (1994)], but not in the matrix problem, as our results reveal.

This paper is organized as follows. In Section 2, we introduce notation, some definitions, basic facts about the Schatten quasi-norms and define the Schatten- p estimators. Section 3 describes elementary steps in their convergence analysis and presents two general approaches to upper bounds on the estimation and prediction error (cf. Theorems 1 and 2) depending on the efficient noise level τ . Our main results are stated in Sections 4, 5 (matrix completion), 6 (multi-task learning). They are obtained from Theorems 1 and 2 by specifying the effective noise level τ under particular assumptions on the masks X_i . Concentration bounds for certain random matrices leading to the expressions for the effective noise level are collected in Section 8. Section 7 is devoted to minimax lower bounds. Sections 9 and 10 contain the main proofs. Finally, in Section 11 we establish bounds for the k th entropy numbers of the quasi-convex Schatten class embeddings $S_p^M \hookrightarrow S_2^M$, $p < 1$, which are needed for our proofs and are of independent interest.

2. Preliminaries.

2.1. *Notation, definitions and basic facts.* We will write $|\cdot|_2$ for the Euclidean norm in \mathbb{R}^d for any integer d . For any matrix $A \in \mathbb{R}^{m \times T}$, we denote by $A_{(j,\cdot)}$ for $1 \leq j \leq m$ its j th row and write $A_{(\cdot,k)}$ for its k th column, $1 \leq k \leq T$. We denote by $\sigma_1(A) \geq \sigma_2(A) \geq \dots \geq 0$ the singular values of A . The (quasi-)norm of some (quasi-) Banach space \mathcal{B} is canonically denoted by $\|\cdot\|_{\mathcal{B}}$. In particular, for any matrix $A \in \mathbb{R}^{m \times T}$ and $0 < p < \infty$ we consider the Schatten (quasi-)norms

$$\|A\|_{S_p} = \left(\sum_{j=1}^{\min(m,T)} \sigma_j(A)^p \right)^{1/p} \quad \text{and} \quad \|A\|_{S_\infty} = \sigma_1(A).$$

The Schatten spaces S_p are defined as spaces of all matrices $A \in \mathbb{R}^{m \times T}$ equipped with quasi-norm $\|A\|_{S_p}$. In particular, the Schatten-2 norm coin-

cides with the Frobenius norm

$$\|A\|_{S_2} = \sqrt{\text{tr}(A'A)} = \left(\sum_{i,j} a_{ij}^2 \right)^{1/2},$$

where a_{ij} denote the elements of matrix $A \in \mathbb{R}^{m \times T}$. Recall that for $0 < p < 1$ the Schatten spaces S_p are not normed but only quasi-normed, and $\|\cdot\|_{S_p}^p$ satisfies the inequality

$$(2.1) \quad \|A + B\|_{S_p}^p \leq \|A\|_{S_p}^p + \|B\|_{S_p}^p$$

for any $0 < p \leq 1$ and any two matrices $A, B \in \mathbb{R}^{m \times T}$; cf. McCarthy (1967) and Rotfeld (1969). We will use the following well-known *trace duality* property:

$$|\text{tr}(A'B)| \leq \|A\|_{S_1} \|B\|_{S_\infty} \quad \forall A, B \in \mathbb{R}^{m \times T}.$$

2.2. Characteristics of the sampling operator. Let $\mathcal{L}: \mathbb{R}^{m \times T} \rightarrow \mathbb{R}^N$ be the *sampling operator*, that is, the linear mapping defined by

$$A \mapsto (\text{tr}(X_1' A), \dots, \text{tr}(X_N' A)) / \sqrt{N}.$$

We have

$$|\mathcal{L}(A)|_2^2 = N^{-1} \sum_{i=1}^N \text{tr}^2(X_i' A).$$

Depending on the context, we also write $\hat{d}_{2,N}(A, B)$ for $|\mathcal{L}(A - B)|_2$, where A and B are any matrices in $\mathbb{R}^{m \times T}$. Unless the reverse is explicitly stated, we will tacitly assume that the matrices X_i are nonrandom.

We will denote by $\phi_{\max}(1)$ the maximal rank-1 restricted eigenvalue of \mathcal{L} :

$$(2.2) \quad \phi_{\max}(1) = \sup_{A \in \mathbb{R}^{m \times T} : \text{rank}(A)=1} \frac{|\mathcal{L}(A)|_2}{\|A\|_{S_2}}.$$

We now introduce two basic assumptions on the sampling operator that will be used in the sequel. The sampling operator \mathcal{L} will be called *uniformly bounded* if there exists a constant $c_0 < \infty$ such that

$$(2.3) \quad \sup_{A \in \mathbb{R}^{m \times T} \setminus \{0\}} \frac{|\mathcal{L}(A)|_2^2}{\|A\|_{S_2}^2} \leq c_0 \quad \text{uniformly in } m, T \text{ and } N.$$

Clearly, if \mathcal{L} is uniformly bounded, then $\phi_{\max}^2(1) \leq c_0$. Condition (2.3) is trivially satisfied with $c_0 = 1$ for USR matrix completion and with $c_0 = 1/N$ for CS matrix completion.

The sampling operator \mathcal{L} is said to satisfy the *Restricted Isometry condition* RI (r, ν) for some integer $1 \leq r \leq \min(m, T)$ and some $0 < \nu < \infty$ if there exists a constant $\delta_r \in (0, 1)$ such that

$$(2.4) \quad (1 - \delta_r) \|A\|_{S_2} \leq \nu |\mathcal{L}(A)|_2 \leq (1 + \delta_r) \|A\|_{S_2}$$

for all matrices $A \in \mathbb{R}^{m \times T}$ of rank at most r .

A difference of this condition from the Restricted Isometry condition, introduced by Candès and Tao (2005) in the vector case or from its analog for the matrix case suggested by Recht, Fazel and Parrilo (2010), is that we state it with a *scaling factor* ν . This factor is introduced to account for the fact that the masks X_i are typically very sparse, so that they do not induce isometries with coefficient close to one. Indeed, ν will be large in the examples that we consider below.

2.3. Least squares estimators with Schatten penalty. In this paper, we study the estimators \hat{A} defined as a solution of the minimization problem

$$(2.5) \quad \min_{A \in \mathbb{R}^{m \times T}} \left(\frac{1}{N} \sum_{i=1}^N (Y_i - \text{tr}(X_i' A))^2 + \lambda \|A\|_{S_p}^p \right)$$

with some fixed $0 < p \leq 1$ and $\lambda > 0$. The case $p = 1$ (matrix Lasso) is of outstanding interest since the minimization problem is then convex and thus can be efficiently solved in polynomial time. We call \hat{A} the *Schatten- p estimator*. Such estimators have been recently considered by many authors motivated by applications to multi-task learning and recommendation systems. Probably, the first study is due to Srebro, Rennie and Jaakkola (2005) who dealt with binary classification and considered the Schatten-1 estimator with the hinge loss rather than squared loss. Argyriou et al. (2008), Argyriou, Evgeniou and Pontil (2008), Argyriou, Michelli and Pontil (2010), Bach (2008), Abernethy et al. (2009) discussed connections of (2.5) to other related minimization problems, along with characterizations of the solutions and computational issues, mainly focusing on the convex case $p = 1$. Also for the nonconvex case ($0 < p < 1$), Argyriou et al. (2008), Argyriou, Evgeniou and Pontil (2008) suggested an algorithm of approximate computation of Schatten- p estimator or its analogs. However, for $0 < p < 1$ the methods can find only a local minimum in (2.5), so that Schatten estimators with such p remain for the moment mainly of theoretical value. In particular, analyzing these estimators reveals, which rates of convergence can, in principle, be attained.

The statistical properties of Schatten estimators are not yet well understood. To our knowledge, the only previous study is that of Bach (2008) showing that for $p = 1$, under some condition on X_i 's [analogous to strong irreducibility condition in the vector case; cf. Meinshausen and Bühlmann

(2006), Zhao and Yu (2006)], $\text{rank}(A^*)$ is consistently recovered by $\text{rank}(\hat{A})$ when m, T are fixed and $N \rightarrow \infty$. Our results are of a different kind. They are nonasymptotic and meaningful in the case $mT \gg N > \max(m, T)$. Furthermore, we do not consider the recovery of the rank, but rather the estimation and prediction properties of Schatten- p estimators.

After this paper has been submitted, we became aware of interesting contemporaneous and independent works by Candès and Plan (2010b), Negahban et al. (2009) and Negahban and Wainwright (2011). Those papers focus on the bounds for the Schatten-2 (i.e., Frobenius) norm error of the matrix Lasso estimator under the matrix RI condition. This is related to the particular instance of our results in item (c) above with $p = 1$ and $q = 2$. Their analysis of this case is complementary to ours in several aspects. Negahban and Wainwright (2011) derive their bound under the assumption that X_i are matrices with i.i.d. standard Gaussian elements and A^* belongs to a Schatten- p' ball with $0 \leq p' \leq 1$, which leads to rates different from ours if $p' \neq 0$. An assumption used in this context in Negahban and Wainwright (2011) is that $N > mT$ (in our notation), which excludes the high-dimensional case $mT \gg N$ that we are mainly interested in. Candès and Plan (2010b) consider approximately low-rank matrices, explore the closely related matrix Dantzig selector and provide lower bounds corresponding to a special case of item (d) above. The results of these papers do not cover the matrix completion and multi-task learning problems, which are in the main focus of our study. We also mention a more recent work by Bunea, She and Wegkamp (2010) dealing with a special case of our model and analyzing matrix estimators penalized by the rank.

3. Two schemes of analyzing Schatten estimators. In this section, we discuss two schemes of proving upper bounds on the prediction error of \hat{A} . The first bound involves only the Schatten- p norm of matrix A^* . The second involves only the rank of A^* but needs the RI condition on the sampling operator.

We start by sketching elementary steps in the convergence analysis of Schatten- p estimators. By the definition of \hat{A} ,

$$\frac{1}{N} \sum_{i=1}^N (Y_i - \text{tr}(X_i' \hat{A}))^2 + \lambda \|\hat{A}\|_{S_p}^p \leq \frac{1}{N} \sum_{i=1}^N (Y_i - \text{tr}(X_i' A^*))^2 + \lambda \|A^*\|_{S_p}^p.$$

Recalling that $Y_i = \text{tr}(X_i' A^*) + \xi_i$, we can transform this by a simple algebra to

$$(3.1) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq \frac{2}{N} \sum_{i=1}^N \xi_i \text{tr}((\hat{A} - A^*)' X_i) + \lambda (\|A^*\|_{S_p}^p - \|\hat{A}\|_{S_p}^p).$$

TABLE 1

Effective noise level for uniformly bounded \mathcal{L} , USR and collaborative sampling matrix completion. Here $M = \max(m, T)$, and the constants $c > 0, c(p) > 0$ depend only on σ

Assumptions on X_i	Assumptions on N, m, T, p	Value of τ
Uniformly bounded \mathcal{L}	$0 < p \leq 1$	$c(p)(M/N)^{1-p/2}$
USR matrix completion	$p = 1, (m + T)mT > N$	$c \min(M/N, (\log M)/\sqrt{N})$
CS matrix completion	$p = 1$	$cM^{1/2}/N$

In the sequel, inequality (3.1) will be referred to as basic inequality and the random variable $N^{-1} \sum_{i=1}^N \xi_i \operatorname{tr}((\hat{A} - A^*)' X_i)$ will be called the *stochastic term*. The core in the analysis of Schatten- p estimators consists in proving tight bounds for the right-hand side of the basic inequality (3.1). For this purpose, we first need a control of the stochastic term. Section 8 below demonstrates that such a control strongly depends on the properties of \mathcal{L} , that is, of the problem at hand. In summary, Section 8 establishes that, under suitable conditions, for any $0 < p \leq 1$ the stochastic term can be bounded for all $\delta > 0$ with probability close to 1 as follows:

$$(3.2) \quad \left| \frac{1}{N} \sum_{i=1}^N \xi_i \operatorname{tr}(X_i'(\hat{A} - A^*)) \right| \leq \begin{cases} \tau \|\hat{A} - A^*\|_{S_1}, & \text{for } p = 1, \\ \frac{\delta}{2} \hat{d}_{2,N}(\hat{A}, A^*)^2 + \tau \delta^{p-1} \|\hat{A} - A^*\|_{S_p}^p, & \text{for } 0 < p < 1, \end{cases}$$

where $0 < \tau < \infty$ depends on m, T and N . The quantity τ plays a crucial role in this bound. We will call τ the *effective noise level*. Exact expressions for τ under various assumptions on the sampling operator \mathcal{L} and on the noise ξ_i are derived in Section 8. In Table 1, we present the values of τ for three important examples under the assumption that ξ_i are i.i.d. Gaussian $\mathcal{N}(0, \sigma^2)$ random variables. In the cases listed in Table 1, inequality (3.2) holds with probability $1 - \varepsilon$, where $\varepsilon = (1/C) \exp(-C(m + T))$ (first and third example) and $\varepsilon = (1/C')(\max(m, T) + 1)^{-C'}$ (second example) with constants $C, C' > 0$ independent of N, m, T .

The following two points will be important to understand the subsequent results:

- In this paper, we will always choose the regularization parameter λ in the form $\lambda = 4\tau$.
- With this choice of λ , the *effective noise level* τ characterizes the rate of convergence of the Schatten estimator. The smaller is τ , the faster is the rate.

In particular, the first line in Table 1 reveals that when $M = \max(m, T) < N$ the largest τ corresponds to $p = 1$ and it becomes smaller when p decreases to 0. This suggests that choosing Schatten- p estimators with $p < 1$ and especially p close to 0 might be advantageous. Note that the assumption of uniform boundedness of \mathcal{L} is very mild. For example, it is trivially satisfied with $c_0 = 1$ for USR matrix completion and with $c_0 = 1/N$ for CS matrix completion. However, in these two cases a specific analysis leads to sharper bounds on the effective noise level (i.e., on the rate of convergence of the estimators); cf. the second and third lines of Table 1.

In this section, we provide two bounds on the prediction error of \hat{A} with a general effective noise level τ . We then detail them in Sections 4–6 for particular values of τ depending on the assumptions on the X_i . The first bound involves the Schatten- p norm of matrix A^* .

THEOREM 1. *Let $A^* \in \mathbb{R}^{m \times T}$, and let $0 < p \leq 1$. Assume that (3.2) holds with probability at least $1 - \varepsilon$ for some $\varepsilon > 0$ and $0 < \tau < \infty$. Let \hat{A} be the Schatten- p estimator defined as a minimizer of (2.5) with $\lambda = 4\tau$. Then*

$$(3.3) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 16\tau \|A^*\|_{S_p}^p$$

holds with probability at least $1 - \varepsilon$.

PROOF. From (3.1) and (3.2) with $\delta = 1/2$ and $\lambda = 4\tau$, we get

$$\hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 8\tau (\|\hat{A} - A^*\|_{S_p}^p + \|A^*\|_{S_p}^p - \|\hat{A}\|_{S_p}^p).$$

This and the p -norm inequality (2.1) yield (3.3). \square

The bound (3.3) depends on the magnitude of the elements of A^* via $\|A^*\|_{S_p}$. The next theorem shows that under the RI condition this dependence can be avoided, and only the rank of A^* affects the rate of convergence.

THEOREM 2. *Let $A^* \in \mathbb{R}^{m \times T}$ with $\text{rank}(A^*) \leq r$, and let $0 < p \leq 1$. Assume that (3.2) holds with probability at least $1 - \varepsilon$ for some $\varepsilon > 0$ and $0 < \tau < \infty$. Assume also that the Restricted Isometry condition RI $((2+a)r, \nu)$ holds with some $0 < \nu < \infty$, with a sufficiently large $a = a(p)$ depending only on p and with $0 < \delta_{(2+a)r} \leq \delta_0$ for a sufficiently small $\delta_0 = \delta_0(p)$ depending only on p .*

Let \hat{A} be the Schatten- p estimator defined as a minimizer of (2.5) with $\lambda = 4\tau$. Then with probability at least $1 - \varepsilon$ we have

$$(3.4) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C_1 r \tau^{2/(2-p)} \nu^{2p/(2-p)},$$

$$(3.5) \quad \|\hat{A} - A^*\|_{S_q}^q \leq C_2 r \tau^{q/(2-p)} \nu^{2q/(2-p)} \quad \forall q \in [p, 2],$$

where C_1 and C_2 are constants, C_1 depends only on p and C_2 depends on p and q .

Proof of Theorem 2 is given in Section 9. The values $a = a(p)$ and $\delta_0(p)$ can be deduced from the proof. In particular, for $p = 1$ it is sufficient to take $a = 19$.

REMARK 1. Note that if $\nu = 1$ the rates in (3.4) and (3.5) do not depend on p if we assume in addition the uniform boundedness of \mathcal{L} , which is a very mild condition. Indeed, taking the value of τ from the first line of Table 1 we see that $r\tau^{2/(2-p)}\nu^{2p/(2-p)} \sim rM/N$ for all $0 < p \leq 1$. Thus, under the RI condition, using Schatten- p estimators with $p < 1$ does not improve the rate of convergence on the class of matrices A^* of rank at most r .

Discussion about the scaling factor ν . Remark 1 deals with the case $\nu = 1$, which seems to be not always appropriate for trace regression models. To our knowledge, the only available examples of matrices X such that the sampling operator \mathcal{L} satisfies the RI condition with $\nu = 1$ are *complete matrices*, that is, matrices with all nonzero entries, which are random and have specific distributions [typically, i.i.d. Rademacher or Gaussian entries; cf. Recht, Fazel and Parrilo (2010)]. Except for degenerate cases [such as $N = mT$, the X_i distinct and of the form $\sqrt{N}e_k(m)e_l(T)'$ for $1 \leq k \leq m, 1 \leq l \leq T$] the sampling operator \mathcal{L} defines typically a restricted isometry with $\nu = 1$ only if the matrices X_i contain a considerable number of (uniformly bounded) nonzero entries.

Let us now specify the form of the RI condition in the context of multi-task learning discussed in the Introduction. Using (1.2) for a matrix $A = (a_1 \cdots a_T)$, we obtain

$$\begin{aligned} |\mathcal{L}(A)|_2^2 &= N^{-1} \sum_{i=1}^N \text{tr}^2(X_i' A) \\ &= N^{-1} \sum_{t=1}^T \sum_{s=1}^n a_t' \mathbf{x}^{(t,s)} (\mathbf{x}^{(t,s)})' a_t = T^{-1} \sum_{t=1}^T a_t' \Psi_t a_t, \end{aligned}$$

where $\Psi_t = n^{-1} \sum_{s=1}^n \mathbf{x}^{(t,s)} (\mathbf{x}^{(t,s)})'$ is the Gram matrix of predictors for the t th task. These matrices correspond to T separate regression models. The standard assumption is that they are normalized so that all the diagonal elements of each Ψ_t are equal to 1. This suggests that the natural RI scaling factor ν for such model is of the order $\nu \sim \sqrt{T}$. For example, in the simplest case when all the matrices Ψ_t are just equal to the $m \times m$ identity matrix, we find $|\mathcal{L}(A)|_2^2 = T^{-1} \sum_{t=1}^T a_t' \Psi_t a_t = T^{-1} \|A\|_{S_2}^2$. Similarly, we get the RI condition with scaling factor $\nu \sim \sqrt{T}$ when the spectra of all the Gram matrices $\Psi_t, t = 1, \dots, T$, are included in a fixed interval $[a, b]$ with $0 < a < b < \infty$. However, this excludes the high-dimensional task regressions, such

that the number of parameters m is larger than the sample size, $m > n$. In conclusion, application of the matrix RI techniques in multi-task learning is restricted to low-dimensional regression and the scaling factor is $\nu \sim \sqrt{T}$.

The reason for the failure of the RI approach is that the masks X_i are sparse. The sparser are X_i , the larger is ν . The extreme situation corresponds to matrix completion problems. Indeed, if $N < mT$, then there exists a matrix of rank 1 in the null-space of the sampling operator \mathcal{L} and hence the RI condition cannot be satisfied. For $N \geq mT$ we can have the RI condition with scaling factor $\nu \sim \sqrt{mT}$, but $N \geq mT$ means that essentially all the entries are observed, so that the very problem of completion does not arise.

4. Upper bounds under mild conditions on the sampling operator. The above discussion suggests that Theorem 2 and, in general, the argument based on the restricted isometry or related conditions are not well adapted for several interesting settings. Motivated by this, we propose another approach described in the next theorem, which requires only the comparably mild uniform boundedness condition (2.3). For simplicity, we focus on Gaussian errors ξ_i . Set $M = \max(m, T)$.

THEOREM 3. *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Assume that $M > 1$, $N > eM$ and that the uniform boundedness condition (2.3) is satisfied. Let $A^* \in \mathbb{R}^{m \times T}$ with $\text{rank}(A^*) \leq r$ and the maximal singular value $\sigma_1(A^*) \leq (N/M)^{C^*}$ for some $0 < C^* < \infty$. Set $p = (\log(N/M))^{-1}$, $c_\kappa = (2\kappa - 1)(2\kappa)^{\kappa^{-1}/(2\kappa-1)}$ where $\kappa = (2-p)/(2-2p)$ and*

$$(4.1) \quad \lambda = 4c_\kappa(\vartheta/p)^{1-p/2} \left(\frac{M}{N}\right)^{1-p/2}$$

for some $\vartheta \geq C^2$ and C a universal positive constant independent of r , M and N . Then the Schatten- p estimator \hat{A} defined as a minimizer of (2.5) with λ as in (4.1) satisfies

$$(4.2) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C_3 \vartheta \frac{rM}{N} \log\left(\frac{N}{M}\right)$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$ where the positive constant C_3 is independent of r , M and N .

PROOF. Inequality (3.2) holds with probability at least $1 - C \exp(-\vartheta M/C^2)$ by Lemma 5. We then use (3.3) and note that, under our choice of p , $\tau \leq c\vartheta M/(Np)$ for some constant $c < \infty$, which does not depend on M and N , and

$$\|A^*\|_{S_p}^p \leq r[\sigma_1(A^*)]^p \leq r \left(\frac{N}{M}\right)^{C^*p} = \exp(C^*)r.$$

□

Finally, we give the following theorem quantifying the rates of convergence of the prediction risk in terms of the Schatten norms of A^* . Its proof is straightforward in view of Theorem 1 and Lemmas 2 and 5.

THEOREM 4. *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables and $A^* \in \mathbb{R}^{m \times T}$. Then the Schatten- p estimator \hat{A} has the following properties:*

(i) *Let $p = 1$, and $\lambda = 32\sigma\phi_{\max}(1)\sqrt{(m+T)/N}$. Then*

$$(4.3) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C\sigma\phi_{\max}(1)\|A^*\|_{S_1} \sqrt{\frac{m+T}{N}}$$

with probability at least $1 - 2\exp\{-(2 - \log 5)(m+T)\}$ where $C > 0$ is an absolute constant.

(ii) *Let $0 < p < 1$ and let the uniform boundedness condition (2.3) hold. Set λ as in (4.1). Then*

$$(4.4) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C\|A^*\|_{S_p}^p \left(\frac{M}{N}\right)^{1-p/2}$$

with probability at least $1 - C\exp(-\vartheta M/C^2)$ where $M = \max(m, T)$ and the constant $C > 0$ is independent of r , M and N .

In Theorem 5 below we show that these rates are optimal in a minimax sense on the corresponding Schatten- p balls for the sampling operators satisfying the RI condition.

5. Upper bounds for noisy matrix completion. As discussed in Section 3, for matrix completion problems the restricted isometry argument as in Theorem 2 is not applicable. We will therefore use Theorems 1 and 3. First, combining Theorem 1 with Lemma 3 of Section 8 we get the following corollary.

COROLLARY 1 (USR matrix completion). (i) *Let the i.i.d. zero-mean random variables ξ_i satisfy the Bernstein condition (8.2). Assume that $mT(m+T) > N$ and consider the USR matrix completion model. Let τ_2 be given by (8.10) with some $D \geq 2$. Then the Schatten-1 estimator \hat{A} defined with $\lambda = 4\tau_2$ satisfies*

$$(5.1) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 16\bar{C}\|A^*\|_{S_1} \frac{m+T}{N}$$

with probability at least $1 - 4\exp\{-(2 - \log 5)(m+T)\}$, where $\bar{C} = 4\sigma\sqrt{10D} + 8HD$.

(ii) Let the i.i.d. zero-mean random variables ξ_i satisfy the light tail condition (8.3), and let τ_3 be given by (8.11) for some $B > 0$. Then the Schatten-1 estimator \hat{A} defined with $\lambda = 4\tau_3$ satisfies

$$(5.2) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 16 \|A^*\|_{S_1} \sqrt{B} \frac{\sigma \log(\max(m+1, T+1))}{\sqrt{N}}$$

with probability at least $1 - (1/C)\max(m+1, T+1)^{-CB}$ for some constant $C > 0$ which does not depend on m, T and N .

Next, combining Theorem 3 with Lemma 5 of Section 8 we get the following corollary.

COROLLARY 2 (USR matrix completion, nonconvex penalty). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Assume that $M = \max(m, T) > 1$, $N > eM$ and consider the USR matrix completion model. Let $A^* \in \mathbb{R}^{m \times T}$ with $\text{rank}(A^*) \leq r$ and the maximal singular value $\sigma_1(A^*) \leq (N/M)^{C^*}$ for some $0 < C^* < \infty$. Set $p = (\log(N/M))^{-1}$, $c_\kappa = (2\kappa - 1)(2\kappa)^{-1/(2\kappa - 1)}$ where $\kappa = (2 - p)/(2 - 2p)$ and*

$$\lambda = 4c_\kappa(\vartheta/p)^{1-p/2} \left(\frac{M}{N}\right)^{1-p/2}$$

for some $\vartheta \geq C^2$ with a universal constant $C > 0$, independent of r, M and N . Then the Schatten- p estimator \hat{A} defined as a minimizer of (2.5) satisfies

$$(5.3) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C_3 \vartheta \frac{rM}{N} \log\left(\frac{N}{M}\right)$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$, where the positive constant C_3 is also independent of r, M and N .

Note that the bounds of Corollaries 1(i) and 2 achieve the rate $r \max(m, T)/N$, up to logarithmic factors under different conditions on the maximal singular value of A^* . If $\max(m, T) < N < mT$ then the condition in Corollary 2 does not imply more than a polynomial in $\max(m, T)$ growth on $\sigma_1(A^*)$, which is a mild assumption. On the other hand, (5.1) requires uniform boundedness of $\sigma_1(A^*)$ by some constant to achieve the same rate. However, the estimators of Corollary 2 correspond to nonconvex penalty and are computationally hard.

We now turn to the collaborative sampling matrix completion. The next corollary follows from combination of Theorem 1 with Lemmas 3 and 4 of Section 8.

COROLLARY 3 (Collaborative sampling). *Consider the problem of matrix completion with collaborative sampling.*

(i) *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Let τ_4 be given by (8.12) with some $D \geq 2$. Then the Schatten-1 estimator \hat{A} defined with $\lambda = 4\tau_4$ satisfies*

$$(5.4) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 16\bar{C} \|A^*\|_{S_1} \frac{\sqrt{m+T}}{N}$$

with probability at least $1 - 2 \exp\{-(D - \log 5)(m + T)\}$, where $\bar{C} = 8\sigma\sqrt{D}$.

(ii) *Let ξ_1, \dots, ξ_N be i.i.d. zero-mean random variables satisfying the Bernstein condition (8.2). Let τ_5 be given by (8.13) with some $D \geq 2$. Then the Schatten-1 estimator \hat{A} defined with $\lambda = 4\tau_5$ satisfies*

$$(5.5) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 64 \|A^*\|_{S_1} \frac{\sigma \sqrt{2D(m+T)} + 2HD(m+T)}{N}$$

with probability at least $1 - 2 \exp\{-(D - \log 5)(m + T)\}$.

REMARK 2. Using the inequality $\|A\|_{S_1} \leq \sqrt{r} \|A\|_{S_2}$ for matrices A of rank at most r , we find that the bound (5.4) is minimax optimal on the class of matrices

$$\{A \in \mathbb{R}^{m \times T} : \text{rank}(A) \leq r, \|A\|_{S_2}^2 \leq C\sigma^2 r \max(m, T)\}$$

for some constant $C > 0$, if the masks X_1, \dots, X_N fulfill the dispersion condition of Theorem 7 below. It is further interesting to note that the construction in the proof of the lower bound in Theorem 7 fails if the restriction is $\|A\|_{S_2}^2 \leq \delta^2$ where δ^2 of smaller order than $r \max(m, T)$.

6. Upper bounds for multi-task learning. For multi-task learning, we can apply both Theorems 2 and 3. Theorem 2 imposes a strong assumption on the masks X_i , namely the RI condition. Nevertheless, the advantage is that Theorem 2 covers the computationally easy case $p = 1$.

COROLLARY 4 (Multi-task learning; RI condition). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Consider the multi-task learning problem with $\text{rank}(A^*) \leq r$. Assume that the spectra of the Gram matrices Ψ_t are uniformly in t bounded from above by a constant $c_1 < \infty$. Assume also that the Restricted Isometry condition RI ($21r, \nu$) holds with some $0 < \nu < \infty$ and with $0 < \delta_{21r} \leq \delta_0$ for a sufficiently small δ_0 . Set*

$$\lambda = 32\sigma \sqrt{\frac{c_1(m+T)}{nT^2}}.$$

Let \hat{A} be the Schatten-1 estimator with this parameter λ . Then with probability at least $1 - 2 \exp\{-(2 - \log 5)(m + T)\}$ we have

$$\begin{aligned} \hat{d}_{2,N}(\hat{A}, A^*)^2 &\leq \bar{C}_1 c_1 \sigma^2 r \nu^2 \left(\frac{m+T}{nT^2} \right), \\ \|\hat{A} - A^*\|_{S_q}^q &\leq \bar{C}_2 c_1^{q/2} \sigma^q r \nu^{2q} \left(\frac{m+T}{nT^2} \right)^{q/2} \quad \forall q \in [1, 2], \end{aligned}$$

where \bar{C}_1 is an absolute constant and \bar{C}_2 depends only on q .

The proof of Corollary 4 is straightforward in view of Theorem 2, Lemma 2 and the fact that, under the premise of Corollary 4, we have $|\mathcal{L}(A)|_2^2 = T^{-1} \sum_{t=1}^T a_t' \Psi_t a_t \leq (c_1/T) \|A\|_{S_2}^2$ for all matrices $A \in \mathbb{R}^{m \times T}$, so that the sampling operator is uniformly bounded [(2.3) holds with $c_0 = c_1/T$], and thus $\phi_{\max}(1) \leq \sqrt{c_0} \leq \sqrt{c_1/T}$.

Taking in the bounds of Corollary 4 the natural scaling factor $\nu \sim \sqrt{T}$, we obtain the following inequalities:

$$(6.1) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq \tilde{C}_1 \frac{r(m+T)}{nT},$$

$$(6.2) \quad \frac{1}{T} \|\hat{A} - A^*\|_{S_2}^2 \leq \tilde{C}_2 \frac{r(m+T)}{nT},$$

where the constants \tilde{C}_1 and \tilde{C}_2 do not depend on m, T and n .

A remarkable fact is that the rates in Corollary 4 are free of logarithmic inflation factor. This is one of the differences between the matrix estimation problems and vector estimation ones, where the logarithmic risk inflation is inevitable, as first noticed by Donoho et al. (1992), Foster and George (1994). For more details about optimal rates of sparse estimation in the vector case, see Rigollet and Tsybakov (2010).

Since the Group Lasso is a special case of the nuclear norm penalized minimization on block-diagonal matrices [cf., e.g., Bach (2008)] Corollary 4 and the bounds (6.1), (6.2) imply the corresponding bounds for the Group Lasso under the low-rank assumption. To note the difference with from the previous results for the Group Lasso, we consider, for example, those obtained in multi-task setting by Lounici et al. (2009, 2010). The main difference is that the sparsity index s appearing in Lounici et al. (2009, 2010) is now replaced by r . In Lounici et al. (2009, 2010), the columns a_t^* of A^* are supposed to be sparse, with the sets of nonzero elements of cardinality not more than s , whereas here the sparsity is characterized by the rank r of A^* .

Finally, we give the following result based on application of Theorem 3.

COROLLARY 5 (Multi-task learning; uniformly bounded \mathcal{L}). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables, and assume that $n > e$. Consider*

the multi-task learning problem with $A^* \in \mathbb{R}^{m \times T}$, $\text{rank}(A^*) \leq r$, such that the maximal singular value $\sigma_1(A^*) \leq n^{C^*}$ for some $0 < C^* < \infty$. Assume that the spectra of the Gram matrices Ψ_t are uniformly in t bounded from above by $c_0 T$ where $c_0 < \infty$ is a constant. Set $p = (\log n)^{-1}$, $c_\kappa = (2\kappa - 1)(2\kappa)^{-1/(2\kappa-1)}$ where $\kappa = (2 - p)/(2 - 2p)$ and

$$\lambda = 4c_\kappa(\vartheta/p)^{1-p/2} \left(\frac{1}{n}\right)^{1-p/2}$$

for some $\vartheta \geq C^2$ and a universal constant $C > 0$, independent of r , m and n . Then the Schatten- p estimator \hat{A} with this parameter λ satisfies

$$(6.3) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C_3 \vartheta \frac{rM}{nT} \log n$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$ where $M = \max(m, T)$, and the positive constant C_3 is independent of r , m and n .

Corollary 5 follows from Theorem 3. Indeed, it suffices to remark that, under the premises of Corollary 5, we have $|\mathcal{L}(A)|_2^2 = T^{-1} \sum_{t=1}^T a_t' \Psi_t a_t \leq c_0 \|A\|_{S_2}^2$ for all matrices $A \in \mathbb{R}^{m \times T}$, so that the sampling operator is uniformly bounded; cf. (2.3).

For $m = T$, we can write (6.3) in the form

$$(6.4) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq C_3' \frac{rm}{nT} \log n.$$

Clearly, this bound achieves the optimal rate “intrinsic dimension/sample size” $\sim rm/N$, up to logarithms (recall that $N = nT$ in the multi-task learning). The bounds (6.1) and (6.2) achieve this rate in a more precise sense because they are free of extra logarithmic factors.

Another remark concerns the possible range of m . It follows from the discussion in Section 3 that the “dimension larger than the sample size” framework is not covered by Corollary 4 since this corollary relies on the RI condition. In contrast, the bounds of Corollary 5 make sense when the dimension m is larger than the sample size n of each task; we only need to have $m \ll \exp(n)$ for Corollary 5 to be meaningful. Corollary 5 holds when the RI assumption is violated and under a mild condition on the masks X_i . The price to pay is to assume that the singular values of A^* do not grow exponentially fast. Also, the estimator of Corollary 5 corresponds to $p < 1$, so it is computationally hard.

7. Minimax lower bounds. In this section, we derive lower bounds for the prediction error, which show that the upper bounds that we have proved are optimal in a minimax sense for two scenarios: (i) under the RI condition and (ii) for matrix completion with collaborative sampling. We also

provide a lower bound for USR matrix completion. Under the RI condition with $\nu = 1$, minimax lower bounds for the Frobenius norm $\|\hat{A} - A^*\|_{S_2}$ on ‘‘Schatten-0’’ balls $\{A^* \in \mathbb{R}^{m \times T} : \text{rank}(A^*) \leq r\}$ are derived in Candès and Plan (2010b) with a technique different from ours, which does not allow one to include further boundedness constraints on A^* in addition to that it has rank at most r . Specifically, they prove their lower bound by passage to Bayes risk with an unbounded support prior (Gaussian prior). Our lower bounds are more general in the sense that they are obtained on smaller sets, namely, the intersections of Schatten-0 and Schatten- p balls. This is similar in spirit to Rigollet and Tsybakov (2010) establishing minimax lower bounds on the intersection of ℓ_0 and ℓ_1 balls for the vector sparsity scenario. In what follows, we denote by $\inf_{\hat{A}}$ the infimum over all estimators based on $(X_1, Y_1), \dots, (X_N, Y_N)$, and for any $A \in \mathbb{R}^{m \times T}$ we denote by \mathbb{P}_A the probability distribution of (Y_1, \dots, Y_N) satisfying (1.1) with $A^* = A$.

THEOREM 5 (Lower bound—Restricted Isometry). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables for some $\sigma^2 > 0$. Let $M = \max(m, T) \geq 8$, $r \geq 1$, $\min(T, m) \geq r$ and for $0 < \alpha < 1/8$ define*

$$\psi_{M,N,r,\Delta} = \min\left(\frac{rM}{N}, \Delta^p \left(\frac{M}{N}\right)^{1-p/2}, \Delta^2\right),$$

$$C(\alpha) = \frac{\alpha(1 - \delta_r)^2}{2^{2/p}(1 + \delta_r)^2} \frac{\log 2}{128} \quad \text{and} \quad C(\alpha, \nu) = \frac{\alpha}{2^{2/p}(1 + \delta_r)^2} \frac{\log 2}{128} \nu^2.$$

(i) *Assume that the sampling operator \mathcal{L} satisfies the right-hand side inequality in the RI (r, ν) -condition (2.4) for some $\delta_r \in (0, 1)$. Then for any $p \in (0, 2]$, $\Delta > 0$, $0 < \alpha < 1/8$,*

$$(7.1) \quad \inf_{\hat{A}} \sup_{\substack{A^* \in \mathbb{R}^{m \times T}: \\ \text{rank}(A^*) \leq r, \|A^*\|_{S_p} \leq \Delta \nu \sigma}} \mathbb{P}_{A^*}(\|\hat{A} - A^*\|_{S_2}^2 > C(\alpha, \nu) \sigma^2 \psi_{M,N,r,\Delta}) \geq \beta,$$

where $\beta = \beta(M, \alpha) > 0$ is such that $\beta(M, \alpha) \rightarrow 1$ as $M \rightarrow \infty, \alpha \rightarrow 0$.

(ii) *Assume that the sampling operator \mathcal{L} satisfies the RI (r, ν) -condition (2.4) for some $\delta_r \in (0, 1)$. Then for any $p \in (0, 2]$, $\Delta > 0$, $0 < \alpha < 1/8$, with β as in (7.1),*

$$(7.2) \quad \inf_{\hat{A}} \sup_{\substack{A^* \in \mathbb{R}^{m \times T}: \\ \text{rank}(A^*) \leq r, \|A^*\|_{S_p} \leq \Delta \nu \sigma}} \mathbb{P}_{A^*}(\hat{d}_{2,N}(\hat{A}, A^*)^2 > C(\alpha) \sigma^2 \psi_{M,N,r,\Delta}) \geq \beta.$$

REMARK 3. It is worth to note that $C(\alpha)$ and $\beta(M, \alpha)$ do not depend on the constant ν of the RI condition.

PROOF OF THEOREM 5. Without loss of generality, we assume that $M = m \geq T$. For a constant $\gamma > 0$ and an integer $s \in \{1, 2, \dots, r\}$, both to be specified later, define

$$\mathcal{A}_{s,\gamma} = \{A = (a_{ij}) \in \mathbb{R}^{m \times T} : a_{ij} \in \{0, \gamma\nu/\sqrt{N}\} \text{ if } 1 \leq j \leq s; a_{ij} = 0 \text{ otherwise}\}.$$

By construction, any element of $\mathcal{A}_{s,\gamma}$ as well as the difference of any two elements of $\mathcal{A}_{s,\gamma}$ has rank at most s . Due to the Varshamov–Gilbert bound [cf. Lemma 2.9 in Tsybakov (2009)], there exists a subset $\mathcal{A}_{s,\gamma}^0 \subset \mathcal{A}_{s,\gamma}$ of cardinality $\text{Card}(\mathcal{A}_{s,\gamma}^0) \geq 2^{sm/8}$ containing $A_0 = 0$ such that for any two distinct elements A_1 and A_2 of $\mathcal{A}_{s,\gamma}^0$,

$$(7.3) \quad \hat{d}_{2,N}(A_1, A_2)^2 \geq \nu^{-2}(1 - \delta_r)^2 \|A_1 - A_2\|_{S_2}^2 \geq (1 - \delta_r)^2 \frac{\gamma^2 sM}{8},$$

where the first inequality follows from the left-hand side inequality in the RI condition (2.4) and is only used to prove (7.2). We will prove (7.2); the proof of (7.1) is analogous in view of the second inequality in (7.3).

Then, for any $A_1 \in \mathcal{A}_{s,\gamma}^0$, the Kullback–Leibler divergence $K(\mathbb{P}_{A_0}, \mathbb{P}_{A_1})$ between \mathbb{P}_{A_0} and \mathbb{P}_{A_1} satisfies

$$(7.4) \quad K(\mathbb{P}_{A_0}, \mathbb{P}_{A_1}) = \frac{N}{2\sigma^2} \hat{d}_{2,N}(A_0, A_1)^2 \leq \frac{\gamma^2}{2\sigma^2} (1 + \delta_r)^2 sM,$$

where we used again the RI condition. We now apply Theorem 2.5 in Tsybakov (2009). Fix some $\alpha \in (0, 1/8)$. Note that the condition

$$(7.5) \quad \frac{1}{\text{Card}(\mathcal{A}_{s,\gamma}^0) - 1} \sum_{A \in \mathcal{A}_{s,\gamma}^0} K(\mathbb{P}_A, \mathbb{P}_{A_0}) \leq \alpha \log(\text{Card}(\mathcal{A}_{s,\gamma}^0) - 1)$$

is satisfied for $\gamma^2 \leq \alpha\sigma^2(\log 2)/(4(1 + \delta_r)^2)$. Define

$$r_\Delta = \arg \min \left\{ l \in \mathbb{N} : \Delta^p \leq l \left(\frac{M}{N} \right)^{p/2} \right\},$$

and consider separately the following three cases.

The case $r_\Delta = 1$. In this case, $\psi_{M,N,r,\Delta} = \Delta^2$ for any $r \geq 1$, and $\Delta^2 N/M \leq 1$. Set

$$s_1 = 1 \quad \text{and} \quad \gamma_1 = \left(\frac{\alpha}{(1 + \delta_r)^2} \frac{\log 2}{4} \sigma^2 \Delta^2 \frac{N}{M} \right)^{1/2}.$$

Then $\|A\|_{S_p} \leq \|A\|_{S_2} \leq \sqrt{M/N} \nu \gamma \leq \Delta \nu \sigma$ for all $A \in \mathcal{A}_{1,\gamma_1}$, i.e., \mathcal{A}_{1,γ_1} is contained in the set

$$\{A \in \mathbb{R}^{m \times T} : \text{rank}(A) \leq r, \|A\|_{S_p} \leq \Delta \nu \sigma\}.$$

Now, inequality (7.3) shows that $\hat{d}_{2,N}(A_1, A_2)^2 \geq 4C(\alpha)\sigma^2\Delta^2$ for any two distinct elements $A_1, A_2 \in \mathcal{A}_{1,\gamma_1}^0$, while $\Delta^2 N/M \leq 1$ implies that $\gamma_1^2 \leq \alpha\sigma^2(\log 2)/(4(1 + \delta_r)^2)$. Hence, condition (7.5) is satisfied.

The case $2 \leq r_\Delta \leq r$. In this case, the rate $\psi_{M,N,r,\Delta}$ is equal to $\Delta^p(M/N)^{1-p/2}$. We consider the set $\mathcal{A}_{r_\Delta,\gamma_2}^0$ with some γ_2 to be specified below. For $A \in \mathcal{A}_{r_\Delta,\gamma_2}^0$, we have $\|A\|_{S_p}^2 \leq r_\Delta^{(2-p)/p} \|A\|_{S_2}^2 \leq r_\Delta^{2/p} \gamma_2^2 \nu^2 M/N$. Since also $r_\Delta \leq 2\Delta^p(N/M)^{p/2}$ when $r_\Delta \geq 2$, it follows that $\|A\|_{S_p} \leq \Delta\nu\sigma$ whenever

$$(7.6) \quad \gamma_2 \leq 2^{-1/p}\sigma.$$

Now define

$$s_2 = r_\Delta \quad \text{and} \quad \gamma_2 = 2^{-1/p} \left(\frac{\alpha}{(1 + \delta_r)^2} \frac{\log 2}{4} \sigma^2 \right)^{1/2}.$$

Then (7.5) is satisfied and γ_2 fulfills also the constraint (7.6), since $\alpha < 1/8$, $(\log 2)/4 < 1$. Thus, $\mathcal{A}_{r_\Delta,\gamma_2}^0$ is a subset of matrices $A \in \mathbb{R}^{m \times T}$ with $\text{rank}(A) \leq r$ and $\|A\|_{S_p} \leq \Delta\nu\sigma$. Finally, (7.3) implies that

$$\begin{aligned} \hat{d}_{2,N}(A_1, A_2)^2 &\geq (1 - \delta_r)^2 \frac{\gamma_2^2 r_\Delta M}{8N} \geq (1 - \delta_r)^2 \frac{\gamma_2^2}{8} \Delta^p \left(\frac{M}{N} \right)^{1-p/2} \\ &= 4C(\alpha)\sigma^2 \Delta^p \left(\frac{M}{N} \right)^{1-p/2} \end{aligned}$$

for any two distinct elements A_1, A_2 of $\mathcal{A}_{r_\Delta,\gamma_2}$.

The case $r_\Delta > r$. In this case, $\psi_{M,N,\Delta,r} = rM/N$. The conditions required in Theorem 2.5 of Tsybakov (2009) follow immediately as above, this time with the set of matrices $\mathcal{A}_{r,\gamma_3}^0$, where $\gamma_3^2 = \alpha\sigma^2(\log 2)/(4(1 + \delta_r)^2)$. \square

REMARK 4. Theorem 5 implies that the rates of convergence in Theorem 4 are optimal in a minimax sense on Schatten- p balls $\{A^* \in \mathbb{R}^{m \times T} : \|A^*\|_{S_p} \leq \Delta\}$ under the RI condition and natural assumptions on m, T and N . Indeed, using Theorem 5 with no restriction on the rank [i.e., when $r = \min(m, T)$], and putting for simplicity $\Delta = 1$, we find that the rate in the lower bound is of the order $\min(\min(m, T)M/N, (M/N)^{1-p/2}, 1)$. For $m = T (= M)$ and $m^3 > N > m$ this minimum equals $(M/N)^{1-p/2}$, which coincides with the upper bound of Theorem 4.

The lower bound for the prediction error (7.2) in the above theorem does not apply to matrix completion with $N < mT$ since then the Restricted Isometry condition cannot be satisfied, as discussed in Section 3. However, for the bound (7.1) we only need the right-hand side inequality in the RI condition. For example, the latter is trivially satisfied for CS matrix completion with $\nu = \sqrt{N}$ and $\delta_r = 0$. This yields the following corollary.

COROLLARY 6 (Lower bound—CS matrix completion). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables for some $\sigma^2 > 0$. Let $M = \max(m, T) \geq 8$, $r \geq 1$, $\min(T, m) \geq r$, and consider the problem of CS matrix completion. Then for any $p \in (0, 2]$, $\Delta > 0$, $0 < \alpha < 1/8$,*

$$\inf_{\hat{A}} \sup_{\substack{A^* \in \mathbb{R}^{m \times T}: \\ \text{rank}(A^*) \leq r, \|A^*\|_{S_p} \leq \Delta \sqrt{N} \sigma}} \mathbb{P}_{A^*} \left(\frac{1}{N} \|\hat{A} - A^*\|_{S_2}^2 > C'(\alpha) \sigma^2 \psi_{M, N, r, \Delta} \right) \geq \beta,$$

where $C'(\alpha) = \alpha(\log 2)2^{-2/p}/128$ and $\beta = \beta(M, \alpha)$, $\psi_{M, N, r, \Delta}$ are as in Theorem 5.

The model of uniform sampling without replacement considered in Candès and Recht (2009) is a particular case of CS matrix completion. In the noisy case, Keshavan, Montanari and Oh (2009) obtain upper bounds under such a sampling scheme with the rate rM/N , up to logarithmic factors. The lower bound of Corollary 6 is of the same order when $\Delta = \infty$, that is, for the class of matrices of rank smaller than r . However, Keshavan, Montanari and Oh (2009) obtained their bounds on some subclasses of this class characterized by additional strong restrictions.

It is useful to note that for bounds of the type (7.1) it is enough to have a condition on \mathcal{L} in expectation, as specified in the next theorem.

THEOREM 6. *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables for some $\sigma^2 > 0$. Let $M = \max(m, T) \geq 8$, $r \geq 1$, $\min(T, m) \geq r$, and assume that X_1, \dots, X_N are random matrices independent of ξ_1, \dots, ξ_N , and the sampling operator satisfies $\nu^2 \mathbb{E}|\mathcal{L}(A)|_2^2 \leq \|A\|_{S_2}^2$ for some $\nu > 0$ and all $A \in \mathbb{R}^{m \times T}$ such that $\text{rank}(A) \leq r$. Then for any $p \in (0, 2]$, $\Delta > 0$, $0 < \alpha < 1/8$,*

$$\inf_{\hat{A}} \sup_{\substack{A^* \in \mathbb{R}^{m \times T}: \\ \text{rank}(A^*) \leq r, \|A^*\|_{S_p} \leq \Delta \nu \sigma}} \mathbb{P}_{A^*} \left(\frac{1}{\nu^2} \|\hat{A} - A^*\|_{S_2}^2 > C'(\alpha) \sigma^2 \psi_{M, N, r, \Delta} \right) \geq \beta,$$

where $C'(\alpha) = \alpha(\log 2)2^{-2/p}/128$ and $\beta = \beta(M, \alpha)$, $\psi_{M, N, r, \Delta}$ are as in Theorem 5.

PROOF. We proceed as in Theorem 5, with the only difference in the bound on the Kullback–Leibler divergence. Indeed, under our assumptions, instead of (7.4) we have

$$(7.7) \quad K(\mathbb{P}_{A_0}, \mathbb{P}_{A_1}) = \frac{N}{2\sigma^2} \mathbb{E}(\hat{d}_{2, N}(A_0, A_1)^2) \leq \frac{N}{2\nu^2} \|A_0 - A_1\|_{S_2}^2 \leq \frac{\gamma^2 s M}{2\sigma^2}. \quad \square$$

Theorem 6 applies to USR matrix completion with $\nu = \sqrt{mT}$. Indeed, in that case $mT \mathbb{E}|\mathcal{L}(A)|_2^2 = \|A\|_{S_2}^2$. In particular, Theorem 6 with $\Delta = \infty$

shows that on the class of matrices of rank smaller than r the lower bound of estimation in the squared Frobenius norm for USR matrix completion is of the order rM/N .

The next theorem gives a lower bound for the prediction error under collaborative sampling without the RI condition. Instead, we only impose a rather natural condition that the observed noisy entries are sufficiently well dispersed, that is, there exist r rows or r columns with more than κMr observations for some fixed $\kappa \in (0, 1]$. We state the result with an additional constraint on the Frobenius norm of A^* , in order to fit the corresponding upper bound (cf. Remark 2 in Section 5).

THEOREM 7 (Lower bound—CS matrix completion). *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables for some $\sigma^2 > 0$ and assume that the masks $X_1 = e_{i_1}(m)e'_{j_1}(T), \dots, X_N = e_{i_N}(m)e'_{j_N}(T)$ are pairwise different. Let $\min(T, m) \geq r$ and $\kappa Mr \geq 8$ for some fixed $\kappa \in (0, 1]$, where $M = \max(m, T)$. Assume furthermore that the following dispersion condition holds: there exist numbers $1 \leq k_1 < \dots < k_r \leq T$ or $1 \leq k'_1 < \dots < k'_r \leq m$ such that either the set $\{(i_1, j_1), \dots, (i_N, j_N)\} \cap \{(i, k_1), \dots, (i, k_r) : i = 1, \dots, m\}$ or the set $\{(i_1, j_1), \dots, (i_N, j_N)\} \cap \{(k'_1, j), \dots, (k'_r, j) : j = 1, \dots, T\}$ has cardinality at least $\kappa Mr + 1$. Define $\mathcal{C}_{\delta, r} = \{A \in \mathbb{R}^{m \times T} : \text{rank}(A) \leq r \text{ and } \|A\|_{S_2} \leq \delta\}$. Then for any $0 < \alpha < 1/8$ and $\delta^2 \geq \alpha \sigma^2 (\log 2)(\kappa Mr + 1)/4$,*

$$\inf_{\hat{A}} \sup_{A^* \in \mathcal{C}_{\delta, r}} \mathbb{P}_{A^*} \left(\hat{d}_{2, N}(\hat{A}, A^*)^2 > C'(\alpha) \frac{\sigma^2 \kappa r M}{N} \right) \geq \beta(\kappa M, \alpha) > 0,$$

with a function $\beta \rightarrow 1$ as $\kappa M \rightarrow \infty, \alpha \rightarrow 0$ and $C'(\alpha) = \alpha(\log 2)/128$.

PROOF. We proceed as in the case $\Delta = \infty, p = 2, \nu = \sqrt{N}$ of Theorem 5 taking a different set \mathcal{A}^0 instead $\mathcal{A}_{s, \gamma}^0$. Let, for definiteness, the dispersion condition be satisfied with the set of indices $\mathcal{K} = \{(i_1, j_1), \dots, (i_N, j_N)\} \cap \{(i, k_1), \dots, (i, k_r) : i = 1, \dots, m\}$. Then there exists a subset \mathcal{K}' of \mathcal{K} with cardinality $\text{Card}(\mathcal{K}') = \lceil \kappa Mr \rceil$. We define

$$\mathcal{A} = \{A = (a_{ij}) \in \mathbb{R}^{m \times T} : a_{ij} \in \{0, \gamma\} \text{ if } (i, j) \in \mathcal{K}'; a_{ij} = 0 \text{ otherwise}\}.$$

Any element of \mathcal{A} as well as the difference of any two elements of \mathcal{A} has rank at most r , and $\|A\|_{S_2}^2 \leq \gamma^2 \lceil \kappa Mr \rceil, \forall A \in \mathcal{A}$. So, $\mathcal{A} \subset \mathcal{C}_{\delta, r}$ if $\gamma^2(\kappa Mr + 1) \leq \delta^2$. As in Theorem 5, the Varshamov–Gilbert bound implies that there exists a subset $\mathcal{A}^0 \subset \mathcal{A}$ of cardinality $\text{Card}(\mathcal{A}^0) \geq 2^{\lceil \kappa Mr \rceil / 8}$ containing $A_0 = 0$, that for any two distinct elements A_1 and A_2 of \mathcal{A}^0 ,

$$\hat{d}_{2, N}(A_1, A_2)^2 = N^{-1} \|A_1 - A_2\|_{S_2}^2 \geq \frac{\gamma^2 \lceil \kappa Mr \rceil}{8N}.$$

Instead of the bound (7.4), we have now the inequality $K(\mathbb{P}_{A_0}, \mathbb{P}_{A_1}) \leq \frac{\gamma^2}{2\sigma^2} \lceil \kappa Mr \rceil$ for any $A_1 \in \mathcal{A}^0$. Finally, we choose $\gamma^2 = \alpha \sigma^2 (\log 2)/4$. With these

modifications, the rest of the proof is the same as that of Theorem 5 in the case $r_\Delta > r$. \square

8. Control of the stochastic term. We consider two approaches for bounding the stochastic term $N^{-1} \sum_{i=1}^N \xi_i \text{tr}((\hat{A} - A^*)' X_i)$ on the right-hand side of the basic inequality (3.1). The first one used for $p = 1$ consists in application of the trace duality

$$(8.1) \quad \left| \frac{1}{N} \sum_{i=1}^N \xi_i \text{tr}((\hat{A} - A^*)' X_i) \right| \leq \|\hat{A} - A^*\|_{S_1} \|\mathbf{M}\|_{S_\infty}$$

with $\mathbf{M} = N^{-1} \sum_{i=1}^N \xi_i X_i$ and then of suitable exponential bounds for the spectral norm of \mathbf{M} under different conditions on X_i , $i = 1, \dots, N$. The second approach used to treat the case $0 < p < 1$ (nonconvex penalties) (cf. Section 8.2) is based on refined empirical process techniques. Proofs of the results of this section are deferred to Section 10.

8.1. *Tail bounds for the spectral norm of random matrices.* We say that the random variables ξ_i , $i = 1, \dots, N$, satisfy the *Bernstein condition* if

$$(8.2) \quad \max_{1 \leq i \leq N} \mathbb{E}|\xi_i|^l \leq \frac{1}{2} l! \sigma^2 H^{l-2}, \quad l = 2, 3, \dots,$$

with some finite constants σ and H , and we say that they satisfy the *light tail condition* if

$$(8.3) \quad \max_{1 \leq i \leq N} \mathbb{E}(\exp(\xi_i^2/\sigma^2)) \leq \exp(1)$$

for some positive constant σ^2 .

LEMMA 1. *Let the i.i.d. zero-mean random variables ξ_i satisfy the Bernstein condition (8.2). Let also either*

$$(8.4) \quad \max_{1 \leq j \leq m} \frac{1}{N} \sum_{i=1}^N |X_{i(j,\cdot)}|_2^2 \leq S_{\text{row}}^2$$

and

$$(8.5) \quad \max_{1 \leq j \leq m, 1 \leq i \leq N} |X_{i(j,\cdot)}|_2 \leq H_{\text{row}}$$

or the conditions

$$(8.6) \quad \max_{1 \leq k \leq T} \frac{1}{N} \sum_{i=1}^N |X_{i(\cdot,k)}|_2^2 \leq S_{\text{col}}^2$$

and

$$(8.7) \quad \max_{1 \leq k \leq T, 1 \leq i \leq N} |X_{i(\cdot, k)}|_2 \leq H_{\text{col}}$$

hold true with some constants $S_{\text{row}}, H_{\text{row}}, S_{\text{col}}, H_{\text{col}}$. Let $D > 1$. Then, respectively, with probability at least $1 - 2/m^{D-1}$ or at least $1 - 2/T^{D-1}$ we have

$$(8.8) \quad \|\mathbf{M}\|_{S_\infty} \leq \tau,$$

where $\tau = \tau_{\text{row}} = C_{\text{row}} \sqrt{m(\log m)/N}$ if (8.4) and (8.5) are satisfied or $\tau = \tau_{\text{col}} = C_{\text{col}} \sqrt{T(\log T)/N}$ if (8.6) and (8.7) hold. Here

$$C_{\text{row}} = \left(\sqrt{2D\sigma^2 S_{\text{row}}^2} + 2DH_{\text{row}}H \sqrt{\frac{\log m}{N}} \right),$$

$$C_{\text{col}} = \left(\sqrt{2D\sigma^2 S_{\text{col}}^2} + 2DH_{\text{col}}H \sqrt{\frac{\log T}{N}} \right).$$

LEMMA 2. Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Then, for any $D \geq 2$,

$$(8.9) \quad \|\mathbf{M}\|_{S_\infty} \leq 4\sqrt{2D}\sigma\phi_{\max}(1)\sqrt{\frac{m+T}{N}} =: \tau_1$$

with probability at least $1 - 2\exp\{-(D - \log 5)(m + T)\}$, where $\phi_{\max}(1)$ is the maximal rank 1 eigenvalue of the sampling operator \mathcal{L} .

If m and T have the same order of magnitude, the bound of Lemma 2 is better, since it does not contain extra logarithmic factors. On the other hand, if m and T differ dramatically, for example, $m \gg T$, then Lemma 1 can provide a significant improvement. Indeed, the ‘‘column’’ version of Lemma 1 guarantees the rate $\tau \sim \sqrt{T \log T} / \sqrt{N}$ which in this case is much smaller than $\sqrt{m/N}$. In all the cases, the concentration rate in Lemma 2 is exponential and thus faster than in Lemma 1.

The next lemma treats the stochastic term for USR matrix completion.

LEMMA 3 (USR matrix completion). (i) Let the i.i.d. zero-mean random variables ξ_i satisfy the Bernstein condition (8.2). Consider the USR matrix completion problem and assume that $mT(m+T) > N$. Then, for any $D \geq 2$,

$$(8.10) \quad \|\mathbf{M}\|_{S_\infty} \leq (4\sigma\sqrt{10D} + 8HD) \frac{m+T}{N} =: \tau_2$$

with probability at least $1 - 4\exp\{-(2 - \log 5)(m + T)\}$.

(ii) Assume that the i.i.d. zero-mean random variables ξ_i satisfy the light tail condition (8.3) for some $\sigma^2 > 0$. Then for any $B > 0$,

$$(8.11) \quad \|\mathbf{M}\|_{S_\infty} \leq \sqrt{B} \frac{\sigma \log(\max(m+1, T+1))}{\sqrt{N}} =: \tau_3$$

with probability at least $1 - (1/C)\max(m+1, T+1)^{-CB}$ for some constant $C > 0$ which does not depend on m, T and N .

The proof of part (i) is based on a refinement of a technique in Vershynin (2007), whereas that of part (ii) follows immediately from the large deviations inequality of Nemirovski (2004). For example, if $\xi_i \sim \mathcal{N}(0, \sigma^2)$, in which case both results apply, the bound (ii) is tighter than (i) for sample sizes $N \ll (m+T)^2$ which is the most interesting case for matrix completion.

Much tighter bounds are available when the X_i are constrained to be pairwise different. Besides it is noteworthy that the rates in (8.12) and (8.13) below are different for Gaussian and Bernstein errors.

LEMMA 4 (Collaborative sampling). *Consider the problem of CS matrix completion.*

(i) Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Then, for any $D \geq 2$,

$$(8.12) \quad \|\mathbf{M}\|_{S_\infty} \leq 8\sigma\sqrt{D} \frac{\sqrt{m+T}}{N} =: \tau_4$$

with probability at least $1 - 2\exp\{-(D - \log 5)(m+T)\}$.

(ii) Let ξ_1, \dots, ξ_N be i.i.d. zero-mean random variables satisfying the Bernstein condition (8.2). Then, for any $D \geq 2$ and

$$(8.13) \quad \|\mathbf{M}\|_{S_\infty} \leq \frac{4\sigma\sqrt{2D(m+T)} + 8HD(m+T)}{N} =: \tau_5$$

with probability at least $1 - 2\exp\{-(D - \log 5)(m+T)\}$.

(iii) Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables. Then for any $A > 1$,

$$\|\mathbf{M}\|_{S_\infty} \leq \frac{\sigma\sqrt{2A\log(m+T)}}{N} \max \left\{ \left\| \sum_{i=1}^N X_i' X_i \right\|_{S_\infty}^{1/2}, \left\| \sum_{i=1}^N X_i X_i' \right\|_{S_\infty}^{1/2} \right\} =: \tau_6$$

with probability at least $1 - 2(m+T)^{1-A}$.

Since the masks X_i are distinct, the maximum appearing in (iii) is bounded by $\sqrt{\max(m, T)}$; in case it is attained, the bound (8.12) is slightly stronger since it is free from the logarithmic factor. For $N \ll mT$ the tightness of the bound in (iii) depends strongly on the geometry of the X_i 's and the maximum can be significantly smaller than $\sqrt{\max(m, T)}$. Note also that the concentration in (8.12) is exponential, while it is only polynomial in (iii).

8.2. *Concentration bounds for the stochastic term under nonconvex penalties.* The last bound in this section applies in the case $0 < p < 1$. It is given in the following lemma.

LEMMA 5. *Let ξ_1, \dots, ξ_N be i.i.d. $\mathcal{N}(0, \sigma^2)$ random variables, $0 < p < 1$ and $M = \max(m, T)$. Assume that the sampling operator \mathcal{L} is uniformly bounded; cf. (2.3). Set $c_\kappa = (2\kappa - 1)(2\kappa)\kappa^{-1/(2\kappa-1)}$ where $\kappa = (2 - p)/(2 - 2p)$. Then for any fixed $\delta > 0$, $\vartheta \geq C^2$ and $\tau_7 = c_\kappa(\vartheta/p)^{1-p/2}(M/N)^{1-p/2}$ we have*

$$(8.14) \quad \left| \frac{1}{N} \sum_{i=1}^N \xi_i \operatorname{tr}(X'_i(\hat{A} - A^*)) \right| \leq \frac{\delta}{2} \hat{d}_{2,N}(\hat{A}, A^*)^2 + \tau_7 \delta^{p-1} \|\hat{A} - A^*\|_{S_p}^p$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$ for some constant $C = C(p, c_0, \sigma^2) > 0$ which is independent of M and N and satisfies $\sup_{0 < p \leq q} C(p, c_0, \sigma) < \infty$ for all $q < 1$.

Note at this point that we cannot rely the proof of Lemma 5 directly on the trace duality and norm interpolation (cf. Lemma 11), that is, on the inequalities

$$(8.15) \quad \left| \frac{1}{N} \sum_{i=1}^N \xi_i \operatorname{tr}(X'_i(\hat{A} - A^*)) \right| \leq \|\hat{A} - A^*\|_{S_1} \|\mathbf{M}\|_{S_\infty} \\ \leq \|\hat{A} - A^*\|_{S_2}^{1-p/(2-p)} \|\hat{A} - A^*\|_{S_p}^{p/(2-p)} \|\mathbf{M}\|_{S_\infty}.$$

Indeed, one may think that we could have bounded here the S_∞ -norm of \mathbf{M} in the same way as in Section 8.1, and then the proof would be complete after suitable decoupling if we were able to bound from above $\|\hat{A} - A^*\|_{S_2}^2$ by $\hat{d}_{2,N}(\hat{A}, A^*)^2$ times a constant factor. However, this is not possible. Even the Restricted Isometry condition cannot help here because $\hat{A} - A^*$ is not necessarily of small rank. Nevertheless, we will show that by other techniques it is possible to derive an inequality similar to (8.15) with $\hat{d}_{2,N}(\hat{A}, A^*)$ instead of $\|\hat{A} - A^*\|_{S_2}$. Further details are given in Sections 10 and 11.

9. Proof of Theorem 2.

Preliminaries. We first give two lemmas on matrix decomposition needed in our proof, which are essentially provided by Recht, Fazel and Parrilo (2010) [subsequently, RFP(10) for short].

LEMMA 6. *Let A and B be matrices of the same dimension. If $AB' = 0$, $A'B = 0$, then*

$$\|A + B\|_{S_p}^p = \|A\|_{S_p}^p + \|B\|_{S_p}^p \quad \forall p > 0.$$

PROOF. For $p = 1$ the result is Lemma 2.3 in RFP(10). The argument obviously extends to any $p > 0$ since RFP(10) show that the singular values of $A + B$ are equal to the union (with repetition) of the singular values of A and B . \square

LEMMA 7. *Let $A \in \mathbb{R}^{m \times T}$ with $\text{rank}(A) = r$ and singular value decomposition $A = U\Lambda V'$. Let $B \in \mathbb{R}^{m \times T}$ be arbitrary. Then there exists a decomposition $B = B_1 + B_2$ with the following properties:*

- (i) $\text{rank}(B_1) \leq 2\text{rank}(A) = 2r$,
- (ii) $AB_2' = 0$, $A'B_2 = 0$,
- (iii) $\text{tr}(B_1'B_2) = 0$,
- (iv) B_1 and B_2 are of the form

$$B_1 = U \begin{pmatrix} \tilde{B}_{11} & \tilde{B}_{12} \\ \tilde{B}_{21} & 0 \end{pmatrix} V' \quad \text{and} \quad B_2 = U \begin{pmatrix} 0 & 0 \\ 0 & \tilde{B}_{22} \end{pmatrix} V' \\ \text{with } \tilde{B}_{11} \in \mathbb{R}^{r \times r}.$$

The points (i)–(iii) are the statement of Lemma 3.4 in RFP(08), the representation (iv) is provided in its proof.

PROOF OF THEOREM 2. First note that there exists a decomposition $\hat{A} = \hat{A}^{(1)} + \hat{A}^{(2)}$ with the following properties:

- (i) $\text{rank}(\hat{A}^{(1)} - A^*) \leq 2\text{rank}(A^*) = 2r$,
- (ii) $A^*(\hat{A}^{(2)})' = 0$, $(A^*)'\hat{A}^{(2)} = 0$,
- (iii) $\text{tr}((\hat{A}^{(1)} - A^*)'\hat{A}^{(2)}) = 0$.

This follows from Lemma 7 with $A = A^*$ and $B = \hat{A} - A^*$. In the notation of Lemma 7, we have $B_1 = \hat{A}^{(1)} - A^*$ and $B_2 = \hat{A}^{(2)}$.

From the basic inequalities (3.1) and (3.2) with $\delta = 1/2$, we find

$$(9.1) \quad (1 - I_{\{0 < p < 1\}}/2) \hat{d}_{2,N}(\hat{A}, A^*)^2 \\ \leq 2^{2-p} \tau \|\hat{A} - A^*\|_{S_p}^p + 4\tau (\|A^*\|_{S_p}^p - \|\hat{A}\|_{S_p}^p).$$

In particular, for the case $p = 1$,

$$(9.2) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 2\tau \|\hat{A} - A^*\|_{S_p}^p + 4\tau (\|A^*\|_{S_p}^p - \|\hat{A}\|_{S_p}^p).$$

For brevity, we will conduct the proof with the numerical constants given in (9.2), that is, with those for $p = 1$. The proof for general p differs only in the values of the constants, but their expressions become cumbersome.

Using (2.1), we get

$$(9.3) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \\ \leq 2\tau \|\hat{A}^{(1)} - A^*\|_{S_p}^p + 4\tau \|A^*\|_{S_p}^p + 2\tau \|\hat{A}^{(2)}\|_{S_p}^p - 4\tau \|\hat{A}\|_{S_p}^p.$$

By (2.1) again and by Lemma 6,

$$\begin{aligned}\|\hat{A}\|_{S_p}^p &\geq \|A^* + \hat{A}^{(2)}\|_{S_p}^p - \|\hat{A}^{(1)} - A^*\|_{S_p}^p \\ &= \|A^*\|_{S_p}^p + \|\hat{A}^{(2)}\|_{S_p}^p - \|\hat{A}^{(1)} - A^*\|_{S_p}^p,\end{aligned}$$

since $(A^*)'\hat{A}^{(2)} = 0$ and $A^*(\hat{A}^{(2)})' = 0$ by construction. Together with (9.3) this yields

$$(9.4) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 2\tau\|\hat{A}^{(1)} - A^*\|_{S_p}^p - 2\tau\|\hat{A}^{(2)}\|_{S_p}^p + 4\tau\|\hat{A}^{(1)} - A^*\|_{S_p}^p,$$

from which one may deduce

$$(9.5) \quad \hat{d}_{2,N}(\hat{A}, A^*)^2 \leq 6\tau\|\hat{A}^{(1)} - A^*\|_{S_p}^p$$

and

$$(9.6) \quad \|\hat{A}^{(2)}\|_{S_p}^p \leq 3\|\hat{A}^{(1)} - A^*\|_{S_p}^p.$$

Consider now the following decomposition of the matrix $\hat{A}^{(2)}$. First, recall that $\hat{A}^{(2)}$ is of the form

$$\hat{A}^{(2)} = U \begin{pmatrix} 0 & 0 \\ 0 & \tilde{B}_{22} \end{pmatrix} V'.$$

Write $\tilde{B}_{22} = W_1 \Lambda(\tilde{B}_{22}) W_2'$ with diagonal matrix $\Lambda(\tilde{B}_{22})$ of dimension r' and $W_1' W_1 = W_2' W_2 = I_{r' \times r'}$ for some $r' \leq \min(m, T)$. In the next step, W_1 and W_2 are complemented to orthogonal matrices \bar{W}_1 and \bar{W}_2 of dimension $\min(m, T) \times \min(m, T)$. For instance, set

$$\bar{W}_2' = \begin{pmatrix} & 0 \\ * & W_2' \end{pmatrix} \in \mathbb{R}^{\min(m, T) \times \min(m, T)},$$

where $*$ complements the columns of the matrix $\begin{pmatrix} 0 \\ W_2' \end{pmatrix}$ to an orthonormal basis in $\mathbb{R}^{m \times T}$, and proceed analogously with W_1 . In particular, $\bar{W}_1' \bar{W}_1 = \bar{W}_2' \bar{W}_2 = I_{\min(m, T) \times \min(m, T)}$. Also

$$\hat{A}^{(2)} = U \begin{pmatrix} 0 & 0 \\ 0 & W_1 \Lambda(\tilde{B}_{22}) W_2' \end{pmatrix} V' = U \bar{W}_1 \begin{pmatrix} 0 & 0 \\ 0 & \Lambda(\tilde{B}_{22}) \end{pmatrix} \bar{W}_2' V' =: U \bar{W}_1 D \bar{W}_2' V'.$$

We now represent $\hat{A}^{(2)}$ as a finite sum of matrices $\hat{A}^{(2)} = \sum_{j=1}^{R'} \hat{A}_j^{(2)}$ with

$$\hat{A}_i^{(2)} = U \bar{W}_1 D_i \bar{W}_2' V'$$

and

$$D_i = \begin{pmatrix} 0 & 0 \\ 0 & \Lambda_i \end{pmatrix},$$

where the $r' \times r'$ diagonal matrix Λ_i has the form $\Lambda_i = \text{diag}(\lambda_j I_{\{j \in I_i\}})$, $i \geq 1$. We denote here by I_1 the set of ar indices from $\{1, \dots, \min(m, T)\}$ corresponding to the ar largest in absolute value diagonal entries of Λ , by I_2 the set of indices corresponding to the next ar largest in absolute value diagonal entries λ_j , etc. Clearly, the matrices $\hat{A}_k^{(2)}$ are mutually orthogonal: $\text{tr}((\hat{A}_j^{(2)})' \hat{A}_k^{(2)}) = 0$ for $j \neq k$ and $\text{rank}(\hat{A}_j^{(2)}) \leq ar$. Moreover, $\hat{A}_i^{(2)}$ is orthogonal to $\hat{A}^{(1)} - A^*$.

Let $\sigma_1 \geq \sigma_2 \geq \dots$ be the singular values of $\hat{A}^{(2)}$, then $\sigma_1 \geq \dots \geq \sigma_{ar}$ are the singular values of $\hat{A}_1^{(2)}$, $\sigma_{ar+1} \geq \dots \geq \sigma_{2ar}$ those of $\hat{A}_2^{(2)}$, etc. By construction, we have $\text{Card}(I_i) = ar$ for all i , and for all $k \in I_{i+1}$

$$\sigma_k \leq \min_{j \in I_i} \sigma_j \leq \left(\frac{1}{ar} \sum_{j \in I_i} \sigma_j^p \right)^{1/p}.$$

Thus,

$$\sum_{k \in I_{i+1}} \sigma_k^2 \leq ar \left(\frac{1}{ar} \sum_{j \in I_i} \sigma_j^p \right)^{2/p}$$

from which one can deduce for all $j \geq 2$:

$$\|\hat{A}_j^{(2)}\|_{S_2} = \left(\sum_{k \in I_j} \sigma_k^2 \right)^{1/2} \leq (ar)^{1/2-1/p} \left(\sum_{k \in I_{j-1}} \sigma_k^p \right)^{1/p} = (ar)^{1/2-1/p} \|\hat{A}_{j-1}^{(2)}\|_{S_p}$$

and consequently

$$\sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} \leq (ar)^{1/2-1/p} \sum_{j \geq 1} \|\hat{A}_j^{(2)}\|_{S_p}.$$

Because of the elementary inequality $x^{1/p} + y^{1/p} \leq (x + y)^{1/p}$ for any non-negative x, y and $0 < p \leq 1$,

$$\begin{aligned} \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_p} &= \sum_{j \geq 2} \left(\sum_{k \in I_j} \sigma_k^p \right)^{1/p} \leq \left(\sum_{j \geq 2} \sum_{k \in I_j} \sigma_k^p \right)^{1/p} \\ &\leq \left(\sum_k \sigma_k^p \right)^{1/p} = \|\hat{A}^{(2)}\|_{S_p}. \end{aligned}$$

Therefore,

$$\begin{aligned} \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} &\leq (ar)^{1/2-1/p} \|\hat{A}^{(2)}\|_{S_p} \\ &\leq 3^{1/p} (ar)^{1/2-1/p} \|\hat{A}^{(1)} - A^*\|_{S_p} \quad [\text{using inequality (9.6)}] \\ &\leq 3^{1/p} (ar)^{1/2-1/p} (2r)^{1/p-1/2} \|\hat{A}^{(1)} - A^*\|_{S_2}, \end{aligned}$$

where the last inequality results from $\text{rank}(\hat{A}^{(1)} - A^*) \leq 2r$ and

$$\left(\frac{1}{2r} \sum_{k \leq 2r} \sigma_k^p\right)^{1/p} \leq \left(\frac{1}{2r} \sum_{k \leq 2r} \sigma_k^2\right)^{1/2}.$$

Finally,

$$(9.7) \quad \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} \leq 3^{1/p} \left(\frac{a}{2}\right)^{1/2-1/p} \|\hat{A}^{(1)} - A^*\|_{S_2}.$$

We now proceed with the final argument. First, note that $\text{rank}((\hat{A}^{(1)} - A^*) + \hat{A}_1^{(2)}) \leq (2+a)r$. Next, by the triangular inequality, the restricted isometry condition and the orthogonality of $\hat{A}_j^{(2)}$ and $\hat{A}^{(1)} - A^*$ we obtain

$$(9.8) \quad \begin{aligned} \nu \hat{d}_{2,N}(\hat{A}, A^*) &= \nu |\mathcal{L}(\hat{A} - A^*)|_2 \\ &\geq \nu |\mathcal{L}(\hat{A}^{(1)} - A^* + \hat{A}_1^{(2)})|_2 - \nu \sum_{j \geq 2} |\mathcal{L}(\hat{A}_j^{(2)})|_2 \\ &\geq (1 - \delta_{(2+a)r}) \|\hat{A}^{(1)} - A^* + \hat{A}_1^{(2)}\|_{S_2} - (1 + \delta_{ar}) \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} \\ &\geq \|\hat{A}^{(1)} - A^*\|_{S_2} \left((1 - \delta_{(2+a)r}) - (1 + \delta_{ar}) 3^{1/p} \left(\frac{a}{2}\right)^{1/2-1/p} \right). \end{aligned}$$

Define

$$a = a(p) = \min\{k \in \mathbb{N} : k > (6^{1/p}/\sqrt{2})^{2p/(2-p)}\}.$$

Then $1 - 3^{1/p}(a/2)^{1/2-1/p} > 0$. Now, $\delta_{(2+a)r} \geq \delta_{ar}$, and thus

$$(1 - \delta_{(2+a)r}) - (1 + \delta_{ar}) 3^{1/p} \left(\frac{a}{2}\right)^{1/2-1/p} \geq \left(1 - 3^{1/p} \left(\frac{a}{2}\right)^{1/2-1/p}\right) - 2\delta_{(2+a)r} > 0$$

whenever

$$(9.9) \quad \delta_{(2+a)r} < \frac{1}{2} \left(1 - 3^{1/p} \left(\frac{a}{2}\right)^{1/2-1/p}\right).$$

In case of (9.9), there exists a universal constant $\kappa = \kappa(p)$ such that

$$(9.10) \quad \nu^2 \hat{d}_{2,N}(\hat{A}, A^*)^2 \geq \kappa \|\hat{A}^{(1)} - A^*\|_{S_2}^2.$$

Now, inequalities (9.5) and (9.10) yield

$$(9.11) \quad \kappa \|\hat{A}^{(1)} - A^*\|_{S_2}^2 \leq 6\tau\nu^2 \|\hat{A}^{(1)} - A^*\|_{S_p}^p \leq 6\tau\nu^2 (2r)^{1-p/2} \|\hat{A}^{(1)} - A^*\|_{S_2}^p,$$

where the second inequality results from the fact that $\text{rank}(\hat{A}^{(1)} - A^*) \leq 2r$, which implies

$$(9.12) \quad \|\hat{A}^{(1)} - A^*\|_{S_p} \leq (2r)^{1/p-1/2} \|\hat{A}^{(1)} - A^*\|_{S_2}.$$

From (9.11), we obtain

$$(9.13) \quad \kappa \|\hat{A}^{(1)} - A^*\|_{S_2}^{2-p} \leq 6\tau\nu^2(2r)^{1-p/2}.$$

Furthermore, from (9.5), (9.12) and (9.13) we find

$$(9.14) \quad \begin{aligned} \hat{d}_{2,N}(\hat{A}, A^*)^2 &\leq 6\tau(2r)^{1-p/2} \|\hat{A}^{(1)} - A^*\|_{S_2}^p \\ &\leq 2r(6\tau)^{2/(2-p)} \kappa^{-p/(2-p)} \nu^{2p/(2-p)}. \end{aligned}$$

This proves (3.4). It remains to prove (3.5). We first demonstrate (3.5) for $q = 2$, then for $q = p$, and finally obtain (3.5) for all $q \in [p, 2]$ by Schatten norm interpolation.

Using (9.7), (9.8), (9.14), we find

$$\begin{aligned} (1 - \delta_{(2+a)r}) \|\hat{A}^{(1)} - A^* + \hat{A}_1^{(2)}\|_{S_2} &\leq \nu \hat{d}_{2,N}(\hat{A}, A^*) + (1 + \delta_{ar}) \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} \\ &\leq C\sqrt{r}\tau^{1/(2-p)}\nu^{2/(2-p)} \end{aligned}$$

for some constant $C = C(p) > 0$. This and again (9.7) yield

$$\|\hat{A} - A^*\|_{S_2} \leq \|\hat{A}^{(1)} - A^* + \hat{A}_1^{(2)}\|_{S_2} + \sum_{j \geq 2} \|\hat{A}_j^{(2)}\|_{S_2} \leq C'\sqrt{r}\tau^{1/(2-p)}\nu^{2/(2-p)}$$

for some constant $C' = C'(p) > 0$. Thus, we have proved (3.5) for $q = 2$. Next, using inequalities (2.1) and (9.6) we obtain

$$\|\hat{A} - A^*\|_{S_p}^p \leq \|\hat{A}^{(1)} - A^*\|_{S_p}^p + \|\hat{A}^{(2)}\|_{S_p}^p \leq 4\|\hat{A}^{(1)} - A^*\|_{S_p}^p.$$

Combining this with (9.12) and (9.13) we get (3.5) for $q = p$. Finally, (3.5) for arbitrary $q \in [p, 2]$ follows from the norm interpolation formula

$$\|A\|_{S_q}^q \leq \|A\|_{S_p}^{p(2-q)/(2-p)} \|A\|_{S_2}^{2(q-p)/(2-p)};$$

cf. Lemma 11 of Section 11 with $\theta = \frac{p(2-p)}{q(2-q)}$. \square

10. Proofs of the lemmas.

PROOF OF LEMMA 1. First, observe that

$$\|\mathbf{M}\|_{S_\infty} = \sup_{\substack{u \in \mathbb{R}^T: \\ |u|_2=1}} |\mathbf{M}u|_2 \leq \sqrt{m} \max_{1 \leq j \leq m} \sup_{\substack{u \in \mathbb{R}^T: \\ |u|_2=1}} |u' \bar{\eta}_j|,$$

with vectors $\bar{\eta}_j = N^{-1} \sum_{i=1}^N \xi_i X_{i(j,\cdot)}$. Consequently, for any $t > 0$,

$$\begin{aligned} \mathbb{P}\left(\|\mathbf{M}\|_{S_\infty} \geq t\sqrt{\frac{m \log m}{N}}\right) &\leq \mathbb{P}\left(\sqrt{m} \max_{1 \leq j \leq m} |\bar{\eta}_j|_2 \geq t\sqrt{\frac{m \log m}{N}}\right) \\ &\leq m \max_{1 \leq j \leq m} \mathbb{P}\left(|\bar{\eta}_j|_2 \geq t\sqrt{\frac{\log m}{N}}\right). \end{aligned}$$

To proceed with the evaluation of the latter probability, we use the following concentration bound [Pinelis and Sakhanenko (1985)].

LEMMA 8. *Let ζ_1, \dots, ζ_N be independent zero mean random variables in a separable Hilbert space \mathcal{H} such that*

$$(10.1) \quad \sum_{i=1}^N \mathbb{E}\|\zeta_i\|_{\mathcal{H}}^l \leq \frac{1}{2} l! B^2 L^{l-2}, \quad l = 2, 3, \dots,$$

with some finite constants $B, L > 0$. Then

$$\mathbb{P}\left(\left\|\sum_{i=1}^N \zeta_i\right\|_{\mathcal{H}} \geq x\right) \leq 2 \exp\left(-\frac{x^2}{2B^2 + 2xL}\right) \quad \forall x > 0.$$

Setting $\zeta_i = \xi_i X_{i(j,\cdot)}$, $\mathcal{H} = \mathbb{R}^T$, note first that, by the Bernstein condition (8.2),

$$\begin{aligned} \sum_{i=1}^N \mathbb{E}\|\zeta_i\|_{\mathcal{H}}^l &= \mathbb{E}|\xi_i|^l \sum_{i=1}^N |X_{i(j,\cdot)}|_2^l \\ &\leq \frac{1}{2} l! \sigma^2 H^{l-2} \left(\max_j \sum_{i=1}^N |X_{i(j,\cdot)}|_2^2\right) \max_{i,j} |X_{i(j,\cdot)}|_2^{l-2} \\ &\leq \frac{1}{2} l! B^2 L^{l-2}, \end{aligned}$$

where $B^2 = \sigma^2 S_{\text{row}}^2 N$ and $L = H_{\text{row}} H$, that is, condition (10.1) is satisfied. Now an application of Lemma 8 yields for any $t > 0$

$$\begin{aligned} \mathbb{P}\left(|\bar{\eta}_j|_2 \geq t\sqrt{\frac{\log m}{N}}\right) &= \mathbb{P}\left(\left|\frac{1}{\sqrt{N}} \sum_{i=1}^N \xi_i\right|_2 > t\sqrt{\log m}\right) \\ &\leq 2 \exp\left(-\frac{N(\log m)t^2}{2B^2 + 2tL\sqrt{N \log m}}\right) \\ &= 2 \exp\left(-\frac{N(\log m)t^2}{2\sigma^2 S_{\text{row}}^2 N + 2tL\sqrt{N \log m}}\right). \end{aligned}$$

Define $t = \sqrt{2D\sigma^2 S_{\text{row}}^2} + 2DL\sqrt{\frac{\log m}{N}}$ for some $D > 1$. Then

$$\frac{t^2}{\bar{B} + \bar{L}t} \geq D, \quad \text{where } \bar{B} = 2\sigma^2 S_{\text{row}}^2, \bar{L} = 2L\sqrt{\frac{\log m}{N}}.$$

With this choice of t ,

$$\mathbb{P}\left(|\bar{\eta}_j|_2 \geq t\sqrt{\frac{\log m}{N}}\right) \leq 2\exp(-D\log m) = 2m^{-D}$$

and therefore $\mathbb{P}(\|\mathbf{M}\|_{S_\infty} \geq \tau_{\text{row}}) \leq 2m^{1-D}$, where

$$\tau_{\text{row}} = \left(\sqrt{2D\sigma^2 S_{\text{row}}^2} + 2DH_{\text{row}}H\sqrt{\frac{\log m}{N}}\right)\sqrt{\frac{m \log m}{N}}.$$

Similarly, using $\|\mathbf{M}\|_{S_\infty} = \sup_{|v|_2=1} |v'\mathbf{M}|_2$, and assuming (8.6) and (8.7), we get $\mathbb{P}(\|\mathbf{M}\|_{S_\infty} \geq \tau_{\text{col}}) \leq 2T^{1-D}$, where

$$\tau_{\text{col}} = \left(\sqrt{2D\sigma^2 S_{\text{col}}^2} + 2DH_{\text{col}}H\sqrt{\frac{\log T}{N}}\right)\sqrt{\frac{T \log T}{N}}. \quad \square$$

PROOF OF LEMMA 3. The matrix $\mathbf{M} = \frac{1}{N} \sum_{i=1}^N \xi_i X_i$ is a sum of i.i.d. random matrices. Therefore, part (ii) of the lemma follows by direct application of the large deviations inequality of Nemirovski (2004).

To prove part (i) of the lemma, we use bounds on maximal eigenvalues of subgaussian matrices due to Mendelson, Pajor and Tomczak-Jaegermann (2007); see also Vershynin (2007). However, direct application of these bounds (based on the overall subgaussianity) does not lead to rates that are accurate enough for our purposes. We therefore need to refine the argument using the specific structure of the matrices. Note first that

$$\|\mathbf{M}\|_{S_\infty} = \max_{v \in \mathcal{S}^{T-1}} |\mathbf{M}v|_2 = \max_{u \in \mathcal{S}^{m-1}, v \in \mathcal{S}^{T-1}} |u'\mathbf{M}v|,$$

where \mathcal{S}^{m-1} is the unit sphere in \mathbb{R}^m . Therefore, denoting by \mathcal{M}_m and \mathcal{M}_T the minimal $1/2$ -nets in Euclidean metric on \mathcal{S}^{m-1} and \mathcal{S}^{T-1} , respectively, we easily get

$$\|\mathbf{M}\|_{S_\infty} \leq 2 \max_{v \in \mathcal{M}_T} |\mathbf{M}v|_2 \leq 4 \max_{u \in \mathcal{M}_m, v \in \mathcal{M}_T} |u'\mathbf{M}v|.$$

Now, $\text{Card}(\mathcal{M}_m) \leq 5^m$ [cf. Kolmogorov and Tikhomirov (1959)] so that by the union bound, for any $\tau > 0$,

$$(10.2) \quad \mathbb{P}(\|\mathbf{M}\|_{S_\infty} \geq \tau) \leq 5^{m+T} \max_{u \in \mathcal{M}_m, v \in \mathcal{M}_T} \mathbb{P}(|u'\mathbf{M}v| \geq \tau/4).$$

It remains to bound the last probability in (10.2) for fixed u, v . Let us fix some $u \in \mathcal{S}^{m-1}, v \in \mathcal{S}^{T-1}$ and introduce the random event

$$\mathcal{A} = \left\{ \frac{1}{N} \sum_{i=1}^N (u' X_i v)^2 \leq \frac{5(m+T)}{N} \right\}.$$

Note that $\mathbb{E}(u' X_i v)^2 = \sum_{k=1}^m \sum_{l=1}^T u_k^2 v_l^2 \mathbb{P}(X_1 = e_k(m) e_l'(T)) = (mT)^{-1} |u|_2^2 \times |v|_2^2 = (mT)^{-1}$, and consider the zero-mean random variables $\eta_i = (u' X_i v)^2 - \mathbb{E}(u' X_i v)^2 = (u' X_i v)^2 - (mT)^{-1}$. We have $|\eta_i| \leq 2 \max_i (u' X_i v)^2 \leq 2|u|_2^2 |v|_2^2 = 2$. Furthermore,

$$\begin{aligned} \mathbb{E}(\eta_i^2) &\leq \mathbb{E}(u' X_i v)^4 \leq \sum_{k=1}^m \sum_{l=1}^T u_k^4 v_l^4 \mathbb{P}(X_1 = e_k(m) e_l'(T)) \\ &= (mT)^{-1} \sum_{k=1}^m u_k^4 \sum_{l=1}^T v_l^4 \leq (mT)^{-1}. \end{aligned}$$

Therefore, using Bernstein's inequality and the condition $(m+T)/N > (mT)^{-1}$ we get

$$\begin{aligned} \mathbb{P}(\mathcal{A}^c) &\leq 2 \exp\left(-\frac{N(4(m+T)/N)^2}{2(mT)^{-1} + (4/3)(4(m+T)/N)}\right) \\ (10.3) \quad &\leq 2 \exp(-2(m+T)), \end{aligned}$$

where \mathcal{A}^c is the complement of \mathcal{A} . We now bound the conditional probability

$$\mathbb{P}(|u' \mathbf{M} v| \geq \tau/4 | X_1, \dots, X_N) = \mathbb{P}\left(\left| \frac{1}{N} \sum_{i=1}^N \xi_i(u' X_i v) \right| \geq \tau/4 | X_1, \dots, X_N\right).$$

Note that conditionally on X_1, \dots, X_N , the $\xi_i(u' X_i v)$ are independent zero-mean random variables with

$$\sum_{i=1}^N \mathbb{E}(|\xi_i(u' X_i v)|^l | X_1, \dots, X_N) \leq \mathbb{E}|\xi_1|^l \sum_{i=1}^N |u' X_i v|^2 \quad \forall l \geq 2,$$

where we used the fact that $|u' X_i v|^{l-2} \leq (|u|_2 |v|_2)^{l-2} = 1$ for $l \geq 2$. This and the Bernstein condition (8.2) yield that, for $(X_1, \dots, X_N) \in \mathcal{A}$,

$$\sum_{i=1}^N \mathbb{E}(|\xi_i(u' X_i v)|^l | X_1, \dots, X_N) \leq \frac{l!}{2} B^2 H^{l-2}$$

with $B^2 = 5(m+T)\sigma^2$. Therefore, by Lemma 8, for $(X_1, \dots, X_N) \in \mathcal{A}$ we have

$$(10.4) \quad \mathbb{P}(|u' \mathbf{M} v| \geq \tau/4 | X_1, \dots, X_N) \leq 2 \exp\left(-\frac{N^2 \tau^2 / 16}{10\sigma^2(m+T) + N\tau H/2}\right).$$

For τ defined in (8.10) the last expression does not exceed $2\exp(-D(m+T))$. Together with (10.2) and (10.3), this proves the lemma. \square

PROOF OF LEMMA 2. We act as in the proof of Lemma 3 but since the matrices X_i are now deterministic, we do not need to introduce the event \mathcal{A} . By the definition of $\phi_{\max}(1)$,

$$\frac{1}{N} \sum_{i=1}^N (u' X_i v)^2 = |\mathcal{L}(uv')|_2^2 \leq \phi_{\max}^2(1) \|uv'\|_{S_2}^2 = \phi_{\max}^2(1)$$

for all $u \in \mathcal{S}^{m-1}, v \in \mathcal{S}^{T-1}$. Hence, $\frac{1}{N} \sum_{i=1}^N \xi_i(u' X_i v)$ is a zero-mean Gaussian random variable with variance not larger than $\phi_{\max}^2(1)\sigma^2/N$. Therefore,

$$\mathbb{P}(|u' \mathbf{M} v| \geq \tau/4) \leq 2 \exp\left(-\frac{N\tau^2}{32\phi_{\max}^2(1)\sigma^2}\right).$$

For τ as in (8.9) the last expression does not exceed $2\exp(-D(m+T))$. Combining this with (10.2), we get the lemma. \square

PROOF OF LEMMA 4. We proceed again as in the proof of Lemmas 3 and 2. Denote by Ω the set of pairs (k, l) such that $\{X_1, \dots, X_N\} = \{e_k(m)e_l'(T)\}$, $(k, l) \in \Omega$ (recall that all X_i are distinct by assumption). Then

$$(10.5) \quad \sum_{i=1}^N (u' X_i v)^2 = \sum_{(k,l) \in \Omega} u_k^2 v_l^2 \leq |u|_2^2 |v|_2^2 = 1$$

for any $u \in \mathcal{S}^{m-1}, v \in \mathcal{S}^{T-1}$. Hence, under the assumptions of part (i) of the lemma,

$$\mathbb{P}(|u' \mathbf{M} v| \geq \tau/4) \leq 2 \exp\left(-\frac{N^2\tau^2}{32\sigma^2}\right)$$

which does not exceed $2\exp(-D(m+T))$ for τ defined in (8.12). Combining this with (10.2) we get part (i) of the lemma. To prove part (ii) we note that, as in the proof of Lemma 3, $|u' X_i v|^{l-2} \leq 1$ for $l \geq 2$. This and (10.5) yield

$$\sum_{i=1}^N \mathbb{E}(|\xi_i(u' X_i v)|^l) \leq \frac{l!}{2} B^2 H^{l-2} \quad \forall l \geq 2,$$

with $B^2 = \sigma^2$. Therefore, by Lemma 8, we have

$$\mathbb{P}(|u' \mathbf{M} v| \geq \tau/4) \leq 2 \exp\left(-\frac{N^2\tau^2/16}{2\sigma^2 + N\tau H/2}\right),$$

and we complete the proof of (ii) in the same way as in Lemmas 3 and 2.

Part (iii) follows by an application of Theorem 2.1, Tropp (2010), after replacing every X_i by its self-adjoint dilation [see Paulsen (1986)]. \square

For the proof of Lemma 5 we will need some notation. The p th Schatten class of $M \times M$ -matrices is denoted by S_p^M , and we write

$$\mathcal{B}(S_p^M) = \{A \in \mathbb{R}^{M \times M} : \|A\|_{S_p} \leq 1\}$$

for the corresponding closed Schatten- p unit ball in $\mathbb{R}^{M \times M}$. For any pseudo-metric space (\mathcal{T}, d) and any $\varepsilon > 0$, we define the covering number

$$\mathcal{N}(\mathcal{T}, d, \varepsilon) = \min \left\{ \text{Card}(\mathcal{T}_0) : \mathcal{T}_0 \subset \mathcal{T} \text{ and } \inf_{s \in \mathcal{T}_0} d(t, s) \leq \varepsilon \text{ for all } t \in \mathcal{T} \right\}.$$

In other words, $\mathcal{N}(\mathcal{T}, d, \varepsilon)$ is the smallest number of closed balls of radius ε in the metric d needed to cover the set \mathcal{T} . We will sometimes write $\mathcal{N}(\mathcal{T}, \|\cdot\|, \varepsilon)$ instead of $\mathcal{N}(\mathcal{T}, d, \varepsilon)$ if the metric d is associated with the norm $\|\cdot\|$. The empirical norm $\|\cdot\|_{2,N}$ corresponds to $\hat{d}_{2,N}$, that is, for all $A \in \mathbb{R}^{M \times M}$,

$$\|A\|_{2,N}^2 = \frac{1}{N} \sum_{j=1}^N \text{tr}(A' X_j)^2.$$

PROOF OF LEMMA 5. Let us first assume that $m = T \equiv M$. Since

$$\sup_{B \in \mathbb{R}^{M \times M}} \left| \frac{(1/\sqrt{N}) \sum_{i=1}^N \xi_i \text{tr}(B' X_i)}{\|B\|_{2,N}^{1-p/(2-p)} \|B\|_{S_p}^{p/(2-p)}} \right| = \sup_{B \in \mathcal{B}(S_p^M)} \left| \frac{(1/\sqrt{N}) \sum_{i=1}^N \xi_i \text{tr}(B' X_i)}{\|B\|_{2,N}^{1-p/(2-p)}} \right|,$$

the expression on the LHS of (8.14) is not greater than

$$\begin{aligned} & \frac{\sqrt{M}}{\sqrt{p}\sqrt{N}} \hat{d}_{2,N}(\hat{A}, A^*)^{1-p/(2-p)} \|\hat{A} - A^*\|_{S_p}^{p/(2-p)} \\ & \times \sup_{B \in \mathcal{B}(S_p^M)} \left| \frac{(M/p)^{(p-2)/(2p)} N^{-1/2} \sum_{i=1}^N \xi_i \text{tr}(B' X_i)}{((M/p)^{(p-2)/(2p)} \|B\|_{2,N})^{1-p/(2-p)}} \right|. \end{aligned}$$

Due to the linear dependence in M of the ε -entropies of the quasi-convex Schatten class embeddings $S_p^M \hookrightarrow S_2^M$ (cf. Corollary 7) and the fact that the required bound should be uniform in M and in p for $p \searrow 0$, we introduced an additional weighting by $(M/p)^{(p-2)/2p}$. Now define

$$\mathcal{G}_{M,p} = \{A \in \mathbb{R}^{M \times M} : (M/p)^{(2-p)/(2p)} A \in \mathcal{B}(S_p^M)\}.$$

By the entropy bound of Corollary 7 and the uniform boundedness condition (2.3),

$$\log \mathcal{N}(\mathcal{G}_{M,p}, \hat{d}_{2,N}, \varepsilon) \leq \log \mathcal{N}(\mathcal{G}_{M,p}, \sqrt{c_0} \|\cdot\|_{S_2}, \varepsilon) \leq p\alpha_0(p) (\varepsilon/\sqrt{c_0})^{-2p/(2-p)}$$

whence

$$(10.6) \quad \int_0^\delta \sqrt{\log \mathcal{N}(\mathcal{G}_{M,p}, \hat{d}_{2,N}, \varepsilon)} d\varepsilon \leq c_0^{p/(2(2-p))} p\alpha_0(p) \frac{2-p}{2-2p} \delta^{1-p/(2-p)}.$$

We remark that due to the order specification of α_0 in Corollary 7, the expression

$$(10.7) \quad c_0^{p/(2(2-p))} p\alpha_0(p) \frac{2-p}{2-2p}$$

is uniformly bounded as long as p stays uniformly bounded away from 1. Note that for $p = 1$ the entropy integral on the LHS in (10.6) does not converge.

CLAIM 1. *For any $q \in (0, 1)$, there exist constants $c(q)$ and $c'(q)$, such that for all $0 < p \leq q$, all $0 < \delta \leq \sqrt{c_0}$ and uniformly in M and N ,*

$$(10.8) \quad \mathbb{P} \left(\sup_{\substack{B \in \mathcal{G}_{M,p}: \\ \|B\|_{2,N} \leq \delta}} \left| \frac{1}{\sqrt{N}} \sum_{j=1}^N \xi_j \operatorname{tr}(X_j' B) \right| \geq T \right) \leq c(q) \exp \left(-\frac{T^2}{c(q)^2 \delta^2} \right)$$

for all $T \geq c'(q) \delta^{1-p/(2-p)}$.

PROOF. The bound is essentially stated in van de Geer (2000) as Lemma 3.2 [further referred to as VG(00)]. The constant in VG(00) depends neither on the $\|\cdot\|_{2,N}$ -diameter of the function class nor on the function class itself and is valid, in particular, for $\varepsilon = 0$, in the notation of VG(00). The uniformity in $0 < p \leq q$ follows from the uniform boundedness of (10.7) over $p \in (0, q]$. The required case corresponds to $K = \infty$ in the notation of VG(00). Its proof follows by taking $\varepsilon = 0$ and applying the theorem of monotone convergence as $K \rightarrow \infty$, since the RHS of the inequality is independent of K . \square

CLAIM 2. *For any $q \in (0, 1)$, there exists a constant $C(q)$ such that for any $0 < p \leq q$*

$$(10.9) \quad \mathbb{P} \left(\sup_{B \in \mathcal{G}_{M,p}} \left| \frac{(1/\sqrt{N}) \sum_{j=1}^N \xi_j \operatorname{tr}(B' X_j)}{\|B\|_{2,N}^{1-p/(2-p)}} \right| \geq T \right) \leq C(q) \exp(-T^2 M / C(q)^2)$$

for all $T \geq C(q)$.

PROOF. First, observe that

$$\begin{aligned} \sup_{A \in \mathcal{G}_{M,p}} \|A\|_{2,N} &\leq \sqrt{c_0} \sup_{A \in \mathcal{G}_{M,p}} \|A\|_{S_2} \\ &\leq \sqrt{c_0} (M/p)^{(p-2)/(2p)} \sup_{A \in \mathcal{B}(S_2^M)} \|A\|_{S_2} = \sqrt{c_0} (M/p)^{(p-2)/(2p)}, \end{aligned}$$

where the last inequality follows from $\mathcal{B}(S_p^M) \subset \mathcal{B}(S_2^M)$. Define the decomposition of $\mathcal{G}_{M,p}$

$$\begin{aligned} \mathcal{G}_{M,p}^{(k)} &= \{A \in \mathcal{G}_{M,p} : (1/2)^k \sqrt{c_0}(M/p)^{(p-2)/(2p)} \\ &\leq \|A\|_{2,N} \leq (1/2)^{k-1} \sqrt{c_0}(M/p)^{(p-2)/(2p)}\}, \\ &k \in \mathbb{N}. \end{aligned}$$

Then by peeling-off the class $\mathcal{G}_{M,p}$, we obtain together with claim I for all $T \geq c'(q)$

$$\begin{aligned} &\mathbb{P}\left(\sup_{B \in \mathcal{G}_{M,p}} \left| \frac{(1/\sqrt{N}) \sum_{j=1}^N \xi_j \operatorname{tr}(B' X_j)}{\|B\|_{2,N}^{1-p/(2-p)}} \right| \geq T\right) \\ &\leq \sum_{k=1}^{\infty} \mathbb{P}\left(\sup_{B \in \mathcal{G}_{M,p}^{(k)}} \left| \frac{1}{\sqrt{N}} \sum_{j=1}^N \xi_j \operatorname{tr}(B' X_j) \right| \right. \\ &\quad \left. \geq T((1/2)^k \sqrt{c_0}(M/p)^{(p-2)/(2p)})^{1-p/(2-p)}\right) \\ &\leq \sum_{k=1}^{\infty} c(q) \exp\left(-\frac{T^2(1/2)^2((1/2)^k \sqrt{c_0}(M/p)^{(p-2)/(2p)})^{-2p/(2-p)}}{c(q)^2}\right) \\ (10.10) \quad &\leq \sum_{k=1}^{\infty} c(q) \exp\left(-\frac{T^2 M 2^{k(2p)/(2-p)} C_0(q)}{4pc(q)^2}\right) \end{aligned}$$

with the definition

$$C_0(q) = \inf_{0 < p \leq q} c_0^{-p/(2-p)}.$$

It remains to note that the last sum in (10.10) is bounded by $C(q) \exp(-T^2 M / C(q)^2)$ uniformly in $0 < p \leq q$ whenever $T \geq C(q)$ for some suitable constant $C(q)$. This follows from the fact that

$$\sum_{k=1}^{\infty} \exp(-p^{-1} 2^{k(2p)/(2-p)}) \leq \sum_{k=1}^{\infty} \frac{1}{p^{-1} 2^{k(2p)/(2-p)} + 1} \leq \frac{p}{1 - (1/2)^{(2p)/(2-p)}},$$

and the latter expression is bounded uniformly in $0 < p \leq q$. \square

In particular, the result reveals that the LHS of (8.14) is bounded by

$$(10.11) \quad \hat{d}_{2,N}(\hat{A}, A^*)^{1-p/(2-p)} \|\hat{A} - A^*\|_{S_p}^{p/(2-p)} \sqrt{\vartheta/p} \left(\frac{M}{N}\right)^{1/2}$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$ for any $\sqrt{\vartheta} \geq C(q)$.

We now use the following simple consequence of the concavity of the logarithm which is stated, for instance, in Tsybakov and van de Geer (2005) (Lemma 5).

LEMMA 9. *For any positive v , t and any $\kappa \geq 1$, $\delta > 0$ we have*

$$vt^{1/(2\kappa)} \leq (\delta/2)t + c_\kappa \delta^{-1/(2\kappa-1)} v^{2\kappa/(2\kappa-1)},$$

where $c_\kappa = (2\kappa - 1)(2\kappa)\kappa^{-1/(2\kappa-1)}$.

Taking in Lemma 9

$$t = \hat{d}_{2,N}(\hat{A}, A^*)^2, \quad v = \|\hat{A} - A^*\|_{S_p}^{p/(2-p)} \sqrt{\vartheta/p} \left(\frac{M}{N}\right)^{1/2},$$

and $\kappa = (2-p)/(2-2p)$ shows that for any $\delta > 0$

$$(10.11) \leq (\delta/2)\hat{d}_{2,N}(\hat{A}, A^*)^2 + \tau_7 \delta^{p-1} \|\hat{A} - A^*\|_{S_p}^p$$

with probability at least $1 - C \exp(-\vartheta M/C^2)$.

The case $m \neq T$ can be deduced from the above result by the following observation. For any matrix $B = (b_{ij}) \in \mathbb{R}^{m \times T}$, define the extension $\tilde{B} = (\tilde{b}_{ij}) \in \mathbb{R}^{M \times M}$ with $M = \max(m, T)$ as follows: $\tilde{b}_{ij} = b_{ij}$ for $1 \leq i \leq m$, $1 \leq j \leq T$ and $\tilde{b}_{ij} = 0$ otherwise. Then one easily checks that $\|\tilde{B}\|_{S_p} = \|B\|_{S_p}$ for all $p \in [0, \infty]$. Furthermore, $\text{tr}(B' X_i) = \text{tr}(\tilde{B}' \tilde{X}_i)$ and

$$\sup_{A \in \mathbb{R}^{M \times M} \setminus \{0\}} \frac{N^{-1} \sum_{k=1}^N \text{tr}(\tilde{X}_k' A)^2}{\|A\|_{S_2}^2} = \sup_{A \in \mathbb{R}^{m \times T} \setminus \{0\}} \frac{\|A\|_{2,N}^2}{\|A\|_{S_2}^2} \leq c_0.$$

Consequently, the result follows now from the already established proof for the case $m = T$. \square

11. Entropy numbers for quasi-convex Schatten class embeddings. Here we derive bounds for the k th entropy numbers of the embeddings $S_p^M \hookrightarrow S_2^M$ for $0 < p < 1$, where S_p^M denotes the p th Schatten class of real $M \times M$ -matrices. Corresponding results for the $l_p^M \hookrightarrow l_2^M$ -embeddings are given first by Edmunds and Triebel (1989) but their proof does not carry over to the Schatten spaces. Pajor (1998) provides bounds for the $S_p^M \hookrightarrow S_2^M$ -embeddings in the convex case, $p \geq 1$. His approach is based on the trace duality (Hölder's inequality for $p^{-1} + q^{-1} = 1$) and the geometric formulation of Sudakov's minoration

$$\varepsilon \sqrt{\log \mathcal{N}(A, |\cdot|_2, \varepsilon)} \leq c \mathbb{E} \sup_{t \in A} \langle G, t \rangle$$

for some positive constant c , with a d -dimensional standard Gaussian vector G and an arbitrary subset A of \mathbb{R}^d . Here $\|\cdot\|_2$ is the Euclidean norm in \mathbb{R}^d and $\langle \cdot, \cdot \rangle$ is the corresponding scalar product. Guédon and Litvak (2000) derive a slightly sharper bound for the $l_p \hookrightarrow l_q$ -embeddings than Edmunds and Triebel (1989) with a different technique. In addition, they prove lower bounds. We adjust their ideas concerning finite ℓ_p spaces to the nonconvex Schatten spaces.

We denote by $e_k(id_{p,r}^M)$ the k th entropy number of the embedding $S_p^M \hookrightarrow S_r^M$ for $0 < p < r \leq \infty$, that is, the infimum of all $\varepsilon > 0$ such that there exist 2^{k-1} balls in S_r^M of radius ε that cover $\mathcal{B}(S_p^M)$. For the general definition of k th entropy numbers $e_k(T: F \rightarrow E)$ of bounded linear operators T between quasi-Banach spaces F and E , we refer to Edmunds and Triebel (1996).

Recall that a homogeneous nonnegative functional $\|\cdot\|$ is called C -quasi-norm, if it satisfies for all x, y the inequality $\|x + y\| \leq C \max(\|x\|, \|y\|)$. Finally, any p -norm is a C -quasi-norm with $C = 2^{1/p}$ [cf., e.g., Edmunds and Triebel (1996), page 2]. We will use the following lemma.

LEMMA 10 [Guédon and Litvak (2000)]. *Assume that $\|\cdot\|_i$ are symmetric C_i -quasi-norms on \mathbb{R}^n for $i = 0, 1$, and for some $\theta \in (0, 1)$, $\|\cdot\|_\theta$ is a quasi-norm on \mathbb{R}^n such that $\|x\|_\theta \leq \|x\|_0^\theta \|x\|_1^{1-\theta}$ for all $x \in \mathbb{R}^n$. Then for any quasi-normed space F , any linear operator $T: F \rightarrow \mathbb{R}^n$, and all integers k and m , we have*

$$e_{m+k-1}(T: F \rightarrow E_\theta) \leq (C_0 e_m(T: F \rightarrow E_0))^\theta (C_1 e_k(T: F \rightarrow E_1))^{1-\theta},$$

where E_t stands for \mathbb{R}^n equipped with quasi-norm $\|\cdot\|_t$, $t \in \{0, \theta, 1\}$.

Guédon and Litvak (2000) did not specify the notion of symmetry they used. So we have to clarify that here a (quasi-)norm $\|\cdot\|$ is called symmetric if $(\mathbb{R}^n, \|\cdot\|)$ is isometrically isomorphic to a symmetrically (quasi-)normed operator ideal. This includes the diagonal operator spaces (finite ℓ_p) as well as the Schatten spaces. The proof of Lemma 10 follows the lines of Pietsch (1980), Proposition 12.1.12, replacing the triangle inequality by the quasi-triangle inequality. Recall that the Schatten classes S_p form interpolation couples like their commutative analogs ℓ_p .

LEMMA 11 (Interpolation inequality). *For $0 < p < q < r < \infty$, let $\theta \in [0, 1]$ be such that*

$$\frac{\theta}{p} + \frac{1-\theta}{r} = \frac{1}{q}.$$

Then, for all $A \in \mathbb{R}^{m \times T}$,

$$\|A\|_{S_q} \leq \|A\|_{S_p}^\theta \|A\|_{S_r}^{1-\theta}.$$

Proof is immediate in view of the inequalities

$$\sum_j a_j^q = \sum_j a_j^{\theta q} a_j^{(1-\theta)q} \leq \left(\sum_j a_j^p \right)^{\theta q/p} \left(\sum_j a_j^r \right)^{(1-\theta)q/r}$$

valid for any nonnegative a_j 's.

PROPOSITION 1 (Entropy numbers). *Let $0 < p < 1$, $p < r \leq \infty$. Then there exists an absolute constant β independent of p and r , such that for all integers k and M we have*

$$e_k(id_{p,r}^M) \leq \min \left\{ 1, \alpha(\beta, p, r) \left(\frac{M}{k} \right)^{1/p-1/r} \right\}$$

with

$$\alpha(\beta, p, r) \leq 2^{1+1/r} \left(\frac{\beta}{p} \right)^{1/p-1/r} \left(\frac{1}{1-p} \right)^{(1/p-1)(1/p-1/r)}.$$

PROOF. The fact that $e_k(id_{p,r}^M)$ is bounded by 1 is obvious, since $\mathcal{B}(S_p^M) \subset \mathcal{B}(S_r^M)$. Consider the other case. We start with $r = \infty$ and then extend the result to $r < \infty$ by interpolation. Fix some number $L > M$ and let $D = D(M, L, p)$ be the smallest constant which satisfies, for all $1 \leq k \leq L$,

$$(11.1) \quad e_k(id_{p,\infty}^M) \leq D \left(\frac{M}{k} \right)^{1/p}.$$

Let us show that $\alpha = \sup_{M,L} D(M, L, p)$ is finite. Since $\|\cdot\|_{S_p}$, $p < 1$, can be viewed as a quasi-norm on \mathbb{R}^{M^2} (isomorphic to $\mathbb{R}^{M \times M}$), Lemma 10 applies with $F = E_0 = S_p^M$, $E_1 = S_\infty^M$, $\theta = p$, $E_\theta = S_1^M$ and $m = 1$. This gives

$$(11.2) \quad e_k(id_{p,1}^M) \leq 4(e_k(id_{p,\infty}^M))^{1-p}.$$

Here the factor 4 follows from the relations $C_1 = 2$ and $C_0^p \leq 2$. Now, (11.2) and the factorization theorem for entropy numbers of bounded linear operators between quasi-Banach spaces [see, e.g., Edmunds and Triebel (1996), page 8], with factorization via S_1^M , leads to the bound

$$(11.3) \quad \begin{aligned} e_k(id_{p,\infty}^M) &\leq e_{[(1-p)k]}(id_{p,1}^M) e_{[pk]}(id_{1,\infty}^M) \\ &\leq 4(e_{[(1-p)k]}(id_{p,\infty}^M))^{1-p} e_{[pk]}(id_{1,\infty}^M), \end{aligned}$$

where for any $x \in (0, \infty)$, $[x]$ denotes the smallest integer which is larger or equal to x . Proposition 5 of Pajor (1998) entails $\log \mathcal{N}(\mathcal{B}(S_1^M), \|\cdot\|_{S_\infty}, \varepsilon) \leq cM/\varepsilon$, $\forall \varepsilon > 0$, and hence

$$(11.4) \quad e_k(id_{1,\infty}^M) \leq c'M/k$$

with constants c and c' independent of M , ε and k . Note that, in contrast to the $l_1^M \hookrightarrow l_\infty^M$ -embedding, for which the k th entropy numbers are bounded by $c''k^{-1} \log(1 + M/k)$ with some $c'' > 0$ and $\log_2 M \leq k \leq M$ [see, e.g., Edmunds and Triebel (1996), page 98], we have in (11.4) not a logarithmic but linear dependence of M in the upper bound. Plugging (11.1) and (11.4) into (11.3) yields

$$\begin{aligned} e_k(id_{p,\infty}^M) &\leq 4 \left(D \left(\frac{M}{(1-p)k} \right)^{1/p} \right)^{1-p} \frac{c'M}{pk} \\ &= \frac{4c'}{p} \left(\frac{1}{1-p} \right)^{(1-p)/p} D^{1-p} \left(\frac{M}{k} \right)^{1/p}. \end{aligned}$$

Thus, by definition of D ,

$$D^p \leq \frac{4c'}{p} \left(\frac{1}{1-p} \right)^{(1-p)/p},$$

which shows that D is uniformly bounded in M and L . This proves the proposition for $r = \infty$.

Consider now the case $r < \infty$. In view of Lemma 11 with $\theta = p/r$, we can apply Lemma 10 with $F = E_0 = S_p^M$, $E_1 = S_\infty^M$, $\theta = p/r$, $E_\theta = S_r^M$ and $m = 1$. This yields

$$\begin{aligned} e_k(id_{p,r}^M) &\leq 2^{1+1/r} (e_k(id_{p,\infty}^M))^{1-p/r} \\ &\leq 2^{1+1/r} D^{1-p/r} \left(\frac{M}{k} \right)^{1/p-1/r}. \end{aligned} \quad \square$$

COROLLARY 7. *For any $p \in (0, 1)$, there exists a positive constant $\alpha_0(p)$ such that for all integers $M \geq 1$ and any $\varepsilon \in (0, 1]$,*

$$\log \mathcal{N}(\mathcal{B}(S_p^M), \|\cdot\|_{S_2}, \varepsilon) \leq \alpha_0(p) M \varepsilon^{-2p/(2-p)}.$$

Moreover, $\alpha_0(p) = O(1/p)$ for $p \searrow 0$.

PROOF. The result follows by transforming the entropy number bound of Proposition 1 into an entropy bound. Specification of the constant in Proposition 1 yields

$$\alpha_0(p) = O\left(\frac{\beta}{p} \left(1 + \frac{p}{1-p} \right)^{(1-p)/p} \right) = O(1/p)$$

as $p \searrow 0$. \square

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FACHBEREICH MATHEMATIK
UNIVERSITÄT HAMBURG
BUNDESSTRASSE 55
D-20146 HAMBURG
GERMANY
E-MAIL: angelika.rohde@math.uni-hamburg.de

LABORATOIRE DE STATISTIQUE
CREST
3, AVENUE PIERRE LAROUSSE
F-92240 MALAKOFF CEDEX
FRANCE
E-MAIL: alexandre.tsybakov@upmc.fr