A Comparative Framework for Preconditioned Lasso Algorithms — Supplementary Material —

1 Preconditioning Algorithms

In this section we briefly show how to express PBHT and HJ in a framework that runs Lasso on modified variables $P_X X$ and $P_y y$.

1.1 Huang and Jojic [1] (HJ)

Consider the SVD $X = UDV^\top$, where U is $n \times n$, V is $p \times p$ and D is an $n \times p$ "diagonal" matrix with entries $d_1 < \ldots < d_n$[1]. Define two groups of left and right singular vectors associated with the q smallest and $n - q$ largest singular values. Let the groups be defined by U_q, U_{n-q} and V_q, V_{n-q}. Suppose HJ chooses as its row-basis the $n-q$ largest right singular vectors, V_{n-q}. Then, from Table 1 of Huang and Jojic [1] we find that

$$
\begin{aligned}
Z &= XV_{n-q} = U_{n-q}\text{diag}(\{d_j\}_{j>q}) && (1)\\
\bar{X} &= R = X - ZV_{n-q}^\top && (2)\\
&= X - U_{n-q}\text{diag}(\{d_j\}_{j>q})V_{n-q}^\top && (3)\\
&= U_q\text{diag}(\{d_i\}_{i\leq q})V_q^\top && (4)\\
&= U_q U_q^\top X && (5)\\
\bar{y} &= y - Z(Z^\top Z)^{-1}Z^\top y && (6)\\
&= y - U_{n-q}U_{n-q}^\top y && (7)\\
&= U_q U_q^\top y && (8)
\end{aligned}
$$

So HJ sets $P_X = P_y = U_{\mathcal{A}} U_{\mathcal{A}}^\top$ for a suitably estimated subspace $U_{\mathcal{A}}$

1.2 Paul et al. [2] (PBHT)

Suppose PBHT identifies as X_q the q columns of X that are most correlated with y (i.e., where $|X_j^\top y|/\|X_j\|_2$ is largest). Consider the SVD $X_q = UDV^\top$, where U is $n \times n$, V is $q \times q$ and D is $n \times q$. Paul et al. [2] use V to find the projection matrix P_q. Let the columns of V be denoted by $v_{q'}$ and those of U by $u_{q'}$. From Section 4.5 and Eq. (13) in Paul el al. [2][2].

$$
\begin{aligned}
P_q &= \sum_{q'=1}^{q} \frac{1}{\|X_q v_{q'}\|_2^2} X_q v_{q'} v_{q'}^\top X_q^\top && (9)\\
&= \sum_{q'=1}^{q} \frac{1}{d_{q'}^2} u_{q'} d_{q'}^2 u_{q'}^\top = U_q U_q^\top && (10)\\
\bar{X} &= X && (11)\\
\bar{y} &= P_q y = U_q U_q^\top y, && (12)
\end{aligned}
$$

where U_q consists of the first q columns of U. Thus, PBHT sets $P_X = I_{n\times n}$ and $P_y = U_{\mathcal{A}} U_{\mathcal{A}}^\top$ for a suitably estimated subspace $U_{\mathcal{A}}$

[1] For ease of presentation, we let the d_i be distinct.

[2] Note that they switch V with U relative to our notation.

2 Proof of Lemma 1

Lemma 1. *Suppose that $X_S^\top X_S$ is invertible, $|\mu_j| < 1\ \forall j \in S^c$ and sgn$(\beta_i^*)\gamma_i > 0\ \forall i \in S$. Then the Lasso has a unique solution $\hat{\beta}$ which recovers the signed support (i.e., $S_\pm(\hat{\beta}) = S_\pm(\beta^*)$) if and only if $\lambda_l < \lambda < \lambda_u$, where*

$$\lambda_l = \max_{j \in S^c} \frac{\eta_j}{(2[\![\eta_j > 0]\!] - 1) - \mu_j} \qquad\qquad \lambda_u = \min_{i \in S} \left| \frac{\beta_i^* + \epsilon_i}{\gamma_i} \right|_+, \tag{13}$$

$[\![\cdot]\!]$ denotes the indicator function and $|\cdot|_+ = \max(0, \cdot)$ denotes the hinge function. On the other hand, if $X_S^\top X_S$ is not invertible, then the signed support cannot in general be recovered.

Proof. For a particular choice of λ, and instances X, β^*, w, Lemmas 2 and 3 of Wainwright give conditions under which Lasso produces a unique $\hat{\beta}$ which recovers the signed support. If $X_S^\top X_S$ is invertible, then by Lemmas 2 and 3

$$S_\pm(\hat{\beta}) = S_\pm(\beta^*) \iff \forall j \in S^c\ \ |Z_j| < 1 \text{ and } \forall i \in S\ \ \text{sgn}(\beta_i^* + \Delta_i) = \text{sgn}(\beta_i^*), \tag{14}$$

where

$$Z_j \triangleq \mu_j + \frac{1}{\lambda}\eta_j \tag{15}$$
$$\mu_j = X_j^\top X_S (X_S^\top X_S)^{-1} \text{sgn}(\beta_S^*) \tag{16}$$
$$\eta_j = X_j^\top \left(I_{n \times n} - X_S (X_S^\top X_S)^{-1} X_S^\top \right) \frac{w}{n} \tag{17}$$
$$\Delta_i \triangleq \epsilon_i - \lambda\gamma_i \tag{18}$$
$$\epsilon_i = e_i^\top \left(\frac{1}{n} X_S^\top X_S \right)^{-1} \frac{1}{n} X_S^\top w \tag{19}$$
$$\gamma_i = e_i^\top \left(\frac{1}{n} X_S^\top X_S \right)^{-1} \text{sgn}(\beta_S^*) \tag{20}$$

We can invert Lemmas 2 and 3 and derive from them conditions on λ so that signed support recovery can be guaranteed.

Ensure $\forall j \in S^c, |Z_j| < 1$

For this to hold, we need $\forall j \in S^c$,

$$|Z_j| = \left| \mu_j + \frac{1}{\lambda}\eta_j \right| < 1. \tag{21}$$

Since we assumed that $|\mu_j| < 1\ \ \forall j \in S^c$, we have:

Case 1a: $\eta_j \geq 0$

We need for every $j \in S^c$

$$\mu_j + \frac{1}{\lambda}\eta_j < 1 \tag{22}$$
$$\frac{1}{\lambda}\eta_j < 1 - \mu_j \tag{23}$$
$$\lambda > \frac{\eta_j}{1 - \mu_j} \tag{24}$$

Case 1b: $\eta_j \leq 0$

We need for every $j \in S^c$

$$\mu_j + \frac{1}{\lambda}\eta_j > -1 \tag{25}$$
$$\frac{1}{\lambda}\eta_j > -1 - \mu_j \tag{26}$$
$$\lambda > -\frac{\eta_j}{1+\mu_j} = \frac{\eta_j}{-1-\mu_j}. \tag{27}$$

Combining, we need

$$\lambda > \lambda_l = \max_{j \in S^c} \frac{\eta_j}{(2[\![\eta_j > 0]\!] - 1) - \mu_j} \geq 0. \tag{28}$$

Ensure $\forall i \in S, \mathbf{sgn}(\beta_i^* + \Delta_i) = \mathbf{sgn}(\beta_i^*)$

Since we assumed $\text{sgn}(\beta_i^*)\gamma_i > 0 \ \ \forall i \in S$, we have in particular that $\gamma_i \neq 0$. Then

Case 2a: $\beta_i^* > 0$

Since $\text{sgn}(\beta_i^*)\gamma_i > 0$, we have $\gamma_i > 0$. Then we need

$$\beta_i^* + \Delta_i = \beta_i^* + \epsilon_i - \lambda\gamma_i > 0 \tag{29}$$
$$\lambda\gamma_i < \beta_i^* + \epsilon_i \tag{30}$$
$$\lambda < \frac{\beta_i^* + \epsilon_i}{\gamma_i} \tag{31}$$

Case 2b: $\beta_i^* < 0$

Since $\text{sgn}(\beta_i^*)\gamma_i > 0$, we have $\gamma_i < 0$. We need

$$\beta_i^* + \Delta_i = \beta_i^* + \epsilon_i - \lambda\gamma_i < 0 \tag{32}$$
$$\lambda\gamma_i > \beta_i^* + \epsilon_i \tag{33}$$
$$\lambda < \frac{\beta_i^* + \epsilon_i}{\gamma_i} \tag{34}$$

Hence, overall we need

$$\lambda < \min_{i \in S} \frac{\beta_i^* + \epsilon_i}{\gamma_i}. \tag{35}$$

Although the previous equation could be used to make a definition for λ_u, it will be beneficial later if $\lambda_u \geq 0$. Because $\lambda_l \geq 0$, signed support recovery will not be possible whenever $\min_{i\in S}(\beta_i^* + \epsilon_i)/\gamma_i \leq 0$. Thus, we will define

$$\lambda_u = \min_{i \in S} \left| \frac{\beta_i^* + \epsilon_i}{\gamma_i} \right|_+, \tag{36}$$

where $|\cdot|_+ = \max(0, \cdot)$ is the hinge function. Signed support recovery occurs iff $\lambda_l < \lambda < \lambda_u$. On the other hand, if $X_S^\top X_S$ is not invertible, the columns of X_S are linearly dependent and so the signed support cannot be recovered in general. $\square$

3 Proofs of Section 4

To simplify the proofs of Section 4, we will make repeated use of the following lemma.

Lemma 2. *Suppose U, V are orthonormal bases for subspaces lying in $\mathbb{R}^n$. That is, U is $n \times q$, with $q \leq n$ and $U^\top U = I_{q\times q}$, and V is $n \times r$, with $r \leq n$ and $V^\top V = I_{r\times r}$. Suppose the matrix B has a column space spanned by U. If span$(U) \subseteq$ span(V))*

$$VV^\top B = B \tag{37}$$

Proof. Because B has a column space spanned by U, we can write $B = UR$ for some matrix R. Furthermore, because span$(U) \subseteq$ span(V)), we may write $U = VT$, for some $r \times q$ matrix T, with $q \leq r$. Indeed we know that T has orthonormal columns, since $U^\top U = T^\top V^\top VT = T^\top T = I_{q\times q}$. Hence, we can write $B = VTR$, where T is some orthonormal matrix. Now

$$VV^\top B = VV^\top VTR = VTR = B. \tag{38}$$

□

3.1 Proof of Theorem 1

Theorem 1. *Suppose that the conditions of Lemma 1 are met for a fixed instance of X, β^*. If span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$, then after preconditioning using HJ the conditions continue to hold, and*

$$\frac{\lambda_u}{\lambda_l} \preceq \frac{\bar{\lambda}_u}{\bar{\lambda}_l}, \tag{39}$$

where the stochasticity on both sides is due to independent noise vectors w. On the other hand, if $X_S^\top P_X^\top P_X X_S$ is not invertible then HJ cannot in general recover the signed support.

Proof. We have $P_X = P_y = U_{\mathcal{A}} U_{\mathcal{A}}^\top$. With this, $\bar{w} = U_{\mathcal{A}} U_{\mathcal{A}}^\top w$. First, consider the case that span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$. Using Lemmas 1 and 2 we have

$$\begin{aligned}
\bar{\mu}_j &= X_j^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S (X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S)^{-1} \text{sgn}(\beta_S^*) &(40)\\
&= X_j^\top X_S (X_S^\top X_S)^{-1} \text{sgn}(\beta_S^*) = \mu_j &(41)\\
\bar{\gamma}_i &= e_i^\top \left(\frac{1}{n} X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S \right)^{-1} \text{sgn}(\beta_S^*) &(42)\\
&= e_i^\top \left(\frac{1}{n} X_S^\top X_S \right)^{-1} \text{sgn}(\beta_S^*) = \gamma_i &(43)\\
\bar{\eta}_j &= X_j^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \left(I_{n\times n} - U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S (X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S)^{-1} X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \right) U_{\mathcal{A}} U_{\mathcal{A}}^\top \frac{w}{n} &(44)\\
&= X_j^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \left(I_{n\times n} - X_S \left(X_S^\top X_S \right)^{-1} X_S^\top \right) U_{\mathcal{A}} U_{\mathcal{A}}^\top \frac{w}{n} &(45)\\
&= X_j^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \left(I_{n\times n} - U_S U_S^\top \right) U_{\mathcal{A}} U_{\mathcal{A}}^\top \frac{w}{n} &(46)\\
&= X_j^\top \left(U_{\mathcal{A}} U_{\mathcal{A}}^\top - U_S U_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \right) \frac{w}{n} &(47)\\
&= X_j^\top \left(I_{n\times n} - U_S U_S^\top \right) U_{\mathcal{A}} U_{\mathcal{A}}^\top \frac{w}{n} &(48)\\
\bar{\epsilon}_i &= e_i^\top \left(\frac{1}{n} X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top X_S \right)^{-1} X_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top \frac{w}{n} &(49)\\
&= e_i^\top \left(\frac{1}{n} X_S^\top X_S \right)^{-1} X_S^\top \frac{w}{n} = \epsilon_i. &(50)
\end{aligned}$$

We immediately see that if the conditions of Lemma 1 hold for the original problem (i.e., $X_S^\top X_S$ is invertible, $|\mu_j| < 1 \;\; \forall j \in S^c$ and $\text{sgn}(\beta_i^*)\gamma_i > 0 \;\; \forall i \in S$), they continue to hold after preconditioning using HJ (i.e., $\bar{X}_S^\top \bar{X}_S$ is invertible, $|\bar{\mu}_j| < 1 \;\; \forall j \in S^c$ and $\text{sgn}(\beta_i^*)\bar{\gamma}_i > 0 \;\; \forall i \in S$). Furthermore, we have $\bar{\lambda}_u = \lambda_u$. Next, we must show that $\bar{\lambda}_l \preceq \lambda_l$. We will simplify this task as follows. Note that

$$\begin{aligned}
\bar{\lambda}_l &= \max_{j\in S^c} \frac{\bar{\eta}_j}{(2[\![\bar{\eta}_j > 0]\!] - 1) - \bar{\mu}_j} = \max\left(\max_{j\in S^c} \frac{\bar{\eta}_j}{-1 - \bar{\mu}_j}, \max_{j\in S^c} \frac{\bar{\eta}_j}{1 - \bar{\mu}_j} \right) &(51)\\
&= \max\left(\left\{ \frac{\bar{\eta}_j}{-1 - \bar{\mu}_j}, \frac{\bar{\eta}_j}{1 - \bar{\mu}_j} \right\}_{j\in S^c} \right) &(52)\\
\lambda_l &= \max_{j\in S^c} \frac{\eta_j}{(2[\![\eta_j > 0]\!] - 1) - \mu_j} = \max\left(\max_{j\in S^c} \frac{\eta_j}{-1 - \mu_j}, \max_{j\in S^c} \frac{\eta_j}{1 - \mu_j} \right) &(53)\\
&= \max\left(\left\{ \frac{\eta_j}{-1 - \mu_j}, \frac{\eta_j}{1 - \mu_j} \right\}_{j\in S^c} \right) &(54)
\end{aligned}$$

where the $\bar{\mu}_j = \mu_j$ are fixed because X, β^* are fixed. By our derivation in Eq. (48), the effect of preconditioning on η_j can be viewed as further restricting the subspace in which the noise w lies, while keeping X_j and μ_j fixed. Specifically, in η_j, w is pre-multiplied by $\left(I_{n\times n} - U_S U_S^\top \right)$, while in $\bar{\eta}_j$ it is pre-multiplied by $\left(I_{n\times n} - U_S U_S^\top \right) U_{\mathcal{A}} U_{\mathcal{A}}^\top$. Whatever $U_{\mathcal{A}}$, the latter projection eliminates at least as large a subspace as the former. Because the X_j and $\bar{\mu}_j = \mu_j$ are fixed, it follows by symmetry of the Gaussian that

$$\bar{\lambda}_l = \max\left(\left\{\frac{\bar{\eta}_j}{-1-\bar{\mu}_j}, \frac{\bar{\eta}_j}{1-\bar{\mu}_j}\right\}_{j\in S^c}\right) \preceq \max\left(\left\{\frac{\eta_j}{-1-\mu_j}, \frac{\eta_j}{1-\mu_j}\right\}_{j\in S^c}\right) = \lambda_l, \tag{55}$$

where the stochasticity is due to the noise w. Rewriting some of the variables, we observe that $\bar{\lambda}_l$ and λ_l are both independent of $\bar{\lambda}_u = \lambda_u$. Specifically, if span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$ then using Lemma 2

$$\eta_j = \frac{1}{n} X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) w \tag{56}$$

$$\bar{\eta}_j = \frac{1}{n} X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}} U_{\mathcal{A}}^\top w \tag{57}$$

$$\epsilon_i = \frac{1}{n} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^\top U_S U_S^\top w \tag{58}$$

$$= \bar{\epsilon}_i = \frac{1}{n} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^\top U_S U_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top w \tag{59}$$

Since the variables $\left(I_{n\times n} - U_S U_S^\top\right) w$ and $U_S U_S^\top w$ are jointly Gaussian distributed with zero covariance, they are independent. Thus, η_j and $\epsilon_i = \bar{\epsilon}_i$ are independent, and because randomness is only due to the noise w, therefore also λ_l and $\lambda_u = \bar{\lambda}_u$. By the same reasoning, $\left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}} U_{\mathcal{A}}^\top w$ and $U_S U_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top w$ are independent. This in turn implies that $\bar{\lambda}_l$ and $\bar{\lambda}_u = \lambda_u$ are independent. We now combine these results: Recall that we defined $1/\bar{\lambda}_l = \infty$ and $1/\lambda_l = \infty$ if $\bar{\lambda}_l = 0$ or $\lambda_l = 0$. Because $\bar{\lambda}_l \preceq \lambda_l$ and $\bar{\lambda}_l \geq 0$, $\lambda_l \geq 0$, we have that $1/\lambda_l \preceq 1/\bar{\lambda}_l$. Next, because both $1/\bar{\lambda}_l, 1/\lambda_l$ are independent of $\bar{\lambda}_u = \lambda_u \geq 0$, we have

$$\frac{\lambda_u}{\lambda_l} \preceq \frac{\bar{\lambda}_u}{\bar{\lambda}_l}. \tag{60}$$

On the other hand, if $X_S^\top P_X^\top P_X X_S$ is not invertible, the conditions of Lemma 1 are not met, and so signed support recovery is in general not possible. $\square$

3.2 Proof of Theorem 2

Theorem 2. *Suppose that the conditions of Lemma 1 are met for a fixed instance of X, β^*. If span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$, then after preconditioning using PBHT the conditions continue to hold, and*

$$\frac{\lambda_u}{\lambda_l} \preceq \frac{\bar{\lambda}_u}{\bar{\lambda}_l}, \tag{61}$$

where the stochasticity on both sides is due to independent noise vectors w. On the other hand, if span$(U_{S^c}) =$ span$(U_{\mathcal{A}})$, then PBHT cannot recover the signed support.

Proof. We have $P_X = I_{n\times n}, P_y = U_{\mathcal{A}}U_{\mathcal{A}}^\top$. With this, $\bar{w} = (U_{\mathcal{A}}U_{\mathcal{A}}^\top - I_{n\times n})X\beta^* + U_{\mathcal{A}}U_{\mathcal{A}}^\top w$. Now let us consider the case that span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$. Using Lemma 2 we have

$$\bar{\mu}_j = X_j^\top X_S(X_S^\top X_S)^{-1}\text{sgn}(\beta_S^*) = \mu_j \tag{62}$$

$$\bar{\gamma}_i = e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} \text{sgn}(\beta_S^*) = \gamma_i \tag{63}$$

$$\bar{\eta}_j = \frac{1}{n}X_j^\top \left(I_{n\times n} - U_S U_S^\top\right)\left((U_{\mathcal{A}}U_{\mathcal{A}}^\top - I_{n\times n})X\beta^* + U_{\mathcal{A}}U_{\mathcal{A}}^\top w\right) \tag{64}$$

$$= X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}}U_{\mathcal{A}}^\top \frac{w}{n} \tag{65}$$

$$\bar{\epsilon}_i = \frac{1}{n}e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} X_S^\top \left((U_{\mathcal{A}}U_{\mathcal{A}}^\top - I_{n\times n})X\beta^* + U_{\mathcal{A}}U_{\mathcal{A}}^\top w\right) \tag{66}$$

$$= \frac{1}{n}e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} X_S^\top U_{\mathcal{A}}U_{\mathcal{A}}^\top w = \epsilon_i. \tag{67}$$

Since $P_X = I_{n\times n}$, we immediately see that if the conditions of Lemma 1 hold for the original problem, they continue to hold after preconditioning using PBHT. Furthermore, we see that $\bar{\lambda}_u = \lambda_u$. Next, we must show that $\bar{\lambda}_l \preceq \lambda_l$. We will approach this task in a similar manner as in Theorem 1. For completeness we repeat the main steps here. Note that

$$\bar{\lambda}_l = \max\left(\left\{\frac{\bar{\eta}_j}{-1-\bar{\mu}_j}, \frac{\bar{\eta}_j}{1-\bar{\mu}_j}\right\}_{j\in S^c}\right) \qquad \lambda_l \quad = \max\left(\left\{\frac{\eta_j}{-1-\mu_j}, \frac{\eta_j}{1-\mu_j}\right\}_{j\in S^c}\right). \tag{68}$$

As before, the effect of preconditioning on η_j can be viewed as further restricting the subspace in which the noise w lies, while keeping X_j and μ_j fixed. Specifically, in η_j, w is pre-multiplied by $\left(I_{n\times n} - U_S U_S^\top\right)$, while in $\bar{\eta}_j$ it is pre-multiplied by $\left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}}U_{\mathcal{A}}^\top$. Whatever $U_{\mathcal{A}}$, the latter projection eliminates at least as large a subspace as the former and so because the X_j and $\bar{\mu}_j = \mu_j$ are fixed, it follows that

$$\bar{\lambda}_l = \max\left(\left\{\frac{\bar{\eta}_j}{-1-\bar{\mu}_j}, \frac{\bar{\eta}_j}{1-\bar{\mu}_j}\right\}_{j\in S^c}\right) \preceq \max\left(\left\{\frac{\eta_j}{-1-\mu_j}, \frac{\eta_j}{1-\mu_j}\right\}_{j\in S^c}\right) = \lambda_l, \tag{69}$$

where the stochasticity is due to the noise w. The remaining part of the theorem again mirrors that of Theorem 1, which we repeat here for completeness. Rewriting some of the variables we observe that $\bar{\lambda}_l$ and λ_l are both independent of $\bar{\lambda}_u = \lambda_u$. Specifically, if span$(U_S) \subseteq$ span$(U_{\mathcal{A}})$ then using Lemma 2

$$\eta_j = \frac{1}{n}X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) w \tag{70}$$

$$\bar{\eta}_j = \frac{1}{n}X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}}U_{\mathcal{A}}^\top w \tag{71}$$

$$\epsilon_i = \frac{1}{n}e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} X_S^\top U_S U_S^\top w \tag{72}$$

$$= \bar{\epsilon}_i = \frac{1}{n}e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} X_S^\top U_S U_S^\top U_{\mathcal{A}}U_{\mathcal{A}}^\top w \tag{73}$$

Since $\left(I_{n\times n} - U_S U_S^\top\right) w$ and $U_S U_S^\top w$ are jointly Gaussian with zero covariance, they are independent. Thus, η_j and $\epsilon_i = \bar{\epsilon}_i$ are independent and so are λ_l and $\lambda_u = \bar{\lambda}_u$. By similar reasoning, $\left(I_{n\times n} - U_S U_S^\top\right) U_{\mathcal{A}} U_{\mathcal{A}}^\top w$ and $U_S U_S^\top U_{\mathcal{A}} U_{\mathcal{A}}^\top w$ are independent, hence so are $\bar{\lambda}_l$ and $\bar{\lambda}_u = \lambda_u$. We now combine these results: Because $\bar{\lambda}_l \preceq \lambda_l$ and $\bar{\lambda}_l \geq 0$, $\lambda_l \geq 0$, we have that $1/\lambda_l \preceq 1/\bar{\lambda}_l$. Next, because both $1/\bar{\lambda}_l, 1/\lambda_l$ are independent of $\bar{\lambda}_u = \lambda_u \geq 0$, we have

$$\frac{\lambda_u}{\lambda_l} \preceq \frac{\bar{\lambda}_u}{\bar{\lambda}_l}, \tag{74}$$

On the other hand, if $\text{span}(U_{S^c}) = \text{span}(U_{\mathcal{A}})$

$$\bar{\mu}_j = X_j^\top X_S (X_S^\top X_S)^{-1} \text{sgn}(\beta_S^*) = \mu_j \tag{75}$$

$$\bar{\gamma}_i = e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} \text{sgn}(\beta_S^*) = \gamma_i \tag{76}$$

$$\bar{\eta}_j = \frac{1}{n} X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) \left((U_{\mathcal{A}} U_{\mathcal{A}}^\top - I_{n\times n}) X\beta^* + U_{\mathcal{A}} U_{\mathcal{A}}^\top w\right) \tag{77}$$

$$= \frac{1}{n} X_j^\top \left(I_{n\times n} - U_S U_S^\top\right) w = \eta_j \tag{78}$$

$$\bar{\epsilon}_i = \frac{1}{n} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^\top \left((U_{\mathcal{A}} U_{\mathcal{A}}^\top - I_{n\times n}) X\beta^* + U_{\mathcal{A}} U_{\mathcal{A}}^\top w\right) \tag{79}$$

$$= \frac{1}{n} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^\top \left(U_{\mathcal{A}} U_{\mathcal{A}}^\top w - X\beta^*\right) \tag{80}$$

$$= -e_i^\top \left(X_S^\top X_S\right)^{-1} X_S^\top X \beta^* \tag{81}$$

$$= -e_i^\top \left(X_S^\top X_S\right)^{-1} X_S^\top X_S \beta_S^* \tag{82}$$

$$= -\beta_i^* \tag{83}$$

Thus the conditions of Lemma 1 continue to hold and we have $\bar{\lambda}_l = \lambda_l$ and

$$\bar{\lambda}_u = \min_{i\in S} \left|\frac{\beta_i^* + \bar{\epsilon}_i}{\bar{\gamma}_i}\right|_+ = \min_{i\in S} \left|\frac{\beta_i^* - \beta_i^*}{\bar{\gamma}_i}\right|_+ = 0 \tag{84}$$

Recall that in Section 3.2 of the main paper we defined $\bar{\lambda}_u/\bar{\lambda}_l \triangleq 0$ if $\bar{\lambda}_u = \bar{\lambda}_l = 0$. Because $\bar{\lambda}_l$ is with probability 1 non-negative, this means that with probability 1, $\bar{\lambda}_u/\bar{\lambda}_l = 0$ and signed support recovery is not possible. $\square$

4 Proofs of Section 5

Lemma 3. *Assume that the spectra Σ_S, Σ_{S^c} are derived by normalizing unconstrained spectra $\hat{\Sigma}_S$ and $\hat{\Sigma}_{S^c}$ as*

$$\Sigma_S = \frac{\hat{\Sigma}_S}{\|\hat{\Sigma}_S\|_F}\sqrt{kn} \tag{85}$$

$$\Sigma_{S^c} = \frac{\hat{\Sigma}_{S^c}}{\|\hat{\Sigma}_{S^c}\|_F}\sqrt{(p-k)n}. \tag{86}$$

Then the squared column norms of X are on expectation n.

Proof. We have $\forall i \in S$,

$$E(X_i^\top X_i) = E(v_{S,i,\cdot}\Sigma_S^\top U^\top U \Sigma_S v_{S,i,\cdot}^\top) \tag{87}$$

$$= knE\left(v_{S,i,\cdot}\frac{\hat{\Sigma}_S^\top\hat{\Sigma}_S}{\|\hat{\Sigma}_S\|_F^2}v_{S,i,\cdot}^\top\right) \tag{88}$$

$$= kn\sum_{i'=1}^{k} E\left(v_{S,i,i'}^2\right)\frac{\hat{\sigma}_{S,i'}^2}{\|\hat{\Sigma}_S\|_F^2} = n, \tag{89}$$

and $\forall j \in S^c$,

$$E(X_j^\top X_j) = E(v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top U^\top U \Sigma_{S^c} v_{S^c,j-k,\cdot}^\top) \tag{90}$$

$$= (p-k)nE\left(v_{S^c,j-k,\cdot}\frac{\hat{\Sigma}_{S^c}^\top\hat{\Sigma}_{S^c}}{\|\hat{\Sigma}_{S^c}\|_F^2}v_{S^c,j-k,\cdot}^\top\right) \tag{91}$$

$$= (p-k)n\sum_{j'=1}^{p-k} E\left(v_{S^c,j-k,j'}^2\right)\frac{\hat{\sigma}_{S^c,j'}^2}{\|\hat{\Sigma}_{S^c}\|_F^2} = n. \tag{92}$$

□

4.1 Proof of Theorem 3

Theorem 3. *Assume the Lasso problem was generated according to the generative model of Section 5.1 in the main paper with* $\forall i \in \sigma(S), \hat{\sigma}_{S,i} = 1$, $\hat{\sigma}_{S^c,i} = \kappa$ *and* $\forall j \in \sigma(S^c)$, $\hat{\sigma}_{S^c,j} = 1$ *and that* $\kappa < \sqrt{n-k}/\sqrt{k(p-k-1)}$. *Then the conditions of Lemma 1 hold before and after preconditioning using JR. Moreover,*

$$\frac{\bar{\lambda}_u}{\bar{\lambda}_l} = \frac{(p-k)}{n + p\kappa^2 - k}\frac{\lambda_u}{\lambda_l}. \tag{93}$$

Proof. Normalizing $\hat{\Sigma}_S$ and $\hat{\Sigma}_{S^c}$ to yield Σ_S, Σ_{S^c}, as required by the model for X,

$$\sigma_{S,i} = \frac{\sqrt{kn}}{\sqrt{k}} = \sqrt{n} \qquad \forall i \in \sigma(S) \tag{94}$$

$$\sigma_{S^c,i} = \frac{\sqrt{n(p-k)}\kappa}{\sqrt{k\kappa^2 + n - k}} \quad \forall i \in \sigma(S) \qquad \sigma_{S^c,j} = \frac{\sqrt{n(p-k)}}{\sqrt{k\kappa^2 + n - k}} \quad \forall j \in \sigma(S^c). \tag{95}$$

Because Σ_S has constant spectrum, it is easy to see that $X_S^\top X_S = cI_{k\times k}$, for some $c > 0$. This means that $X_S^\top X_S$ is invertible and $\text{sgn}(\beta_i^*)\gamma_i > 0$. Let's look at the variables μ_j:

$$\begin{aligned}
|\mu_j| &= \left|X_j^\top X_S (X_S^\top X_S)^{-1} \text{sgn}(\beta_S^*)\right| && (96)\\
&= \left|v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top U^\top U \Sigma_S V_S^\top (V_S \Sigma_S^\top U^\top U \Sigma_S V_S^\top)^{-1} \text{sgn}(\beta_S^*)\right| && (97)\\
&= \left|v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top \Sigma_S V_S^\top V_S (\Sigma_S^\top \Sigma_S)^{-1} V_S^\top \text{sgn}(\beta_S^*)\right| && (98)\\
&= \left|v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top \Sigma_S (\Sigma_S^\top \Sigma_S)^{-1} V_S^\top \text{sgn}(\beta_S^*)\right| && (99)\\
&= \left|\left[v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top\right]_{(1:k)} \Sigma_{S,(1:k),(1:k)}^{-1} V_S^\top \text{sgn}(\beta_S^*)\right| && (100)\\
&= \left|\left[v_{S^c,j-k,\cdot}\frac{\sqrt{n(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}}\right]_{(1:k)} \frac{1}{\sqrt{n}} V_S^\top \text{sgn}(\beta_S^*)\right| && (101)\\
&= \frac{\sqrt{(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}} \left|\left[v_{S^c,j-k,\cdot}\right]_{(1:k)} V_S^\top \text{sgn}(\beta_S^*)\right| && (102)\\
&\overset{\text{Cauchy}}{\leq} \frac{\sqrt{(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}} \left\|V_S \left[v_{S^c,j-k,\cdot}\right]_{(1:k)}^\top\right\|_2 \|\text{sgn}(\beta_S^*)\|_2 && (103)\\
&= \frac{\sqrt{k(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}} \left\|V_S \left[v_{S^c,j-k,\cdot}\right]_{(1:k)}^\top\right\|_2 && (104)\\
&\leq \frac{\sqrt{k(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}} \|V_S\|_2 \left\|\left[v_{S^c,j-k,\cdot}\right]_{(1:k)}\right\|_2 && (105)\\
&\leq \frac{\sqrt{k(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}}. && (106)
\end{aligned}$$

Because $\kappa < \sqrt{(n-k)/(k(p-k-1))}$,

$$\begin{aligned}
\frac{\sqrt{k(p-k)}\kappa}{\sqrt{k\kappa^2+n-k}} &< \frac{\sqrt{k(p-k)}\sqrt{\frac{n-k}{k(p-k-1)}}}{\sqrt{k\frac{n-k}{k(p-k-1)} + n - k}} && (107)\\
&= \frac{\sqrt{\frac{(p-k)(n-k)}{p-k-1}}}{\sqrt{\frac{n-k+(n-k)(p-k-1)}{p-k-1}}} = \frac{\sqrt{\frac{(p-k)(n-k)}{p-k-1}}}{\sqrt{\frac{(n-k)(p-k)}{p-k-1}}} = 1, && (108)
\end{aligned}$$

and so the conditions of Lemma 1 are met. We can then apply Lemma 1 and simplify the resulting upper and lower bounds λ_u, λ_l on λ. Plugging in Σ_S and Σ_{S^c} we see that the data matrix X satisfies

$$
\begin{aligned}
XX^\top &= U\left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]\left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top U^\top && (109)\\
&= U\left[\Sigma_S \Sigma_S^\top + \Sigma_{S^c}\Sigma_{S^c}^\top\right] U^\top && (110)\\
&\triangleq UDD^\top U^\top. && (111)
\end{aligned}
$$

From this we see that $X = UDV^\top$ has left eigenvectors U and singular values

$$
\begin{aligned}
d_i &= \sqrt{\sigma_{S,i}^2 + \sigma_{S^c,i}^2} = \sqrt{n + \frac{n(p-k)\kappa^2}{k\kappa^2 + n - k}} \quad \forall i \in \sigma(S) && (112)\\
d_j &= \sqrt{\frac{n(p-k)}{k\kappa^2 + n - k}} \qquad \forall j \in \sigma(S^c). && (113)
\end{aligned}
$$

Recall that for JR, $P_X = P_y = U\left(DD^\top\right)^{-1/2} U^\top$. After projecting, we find that

$$
\begin{aligned}
\bar{\mu}_j &= X_j^\top P_X^\top P_X X_S (X_S^\top P_X^\top P_X X_S)^{-1} \text{sgn}(\beta_S^*) && (114)\\
&= \left| v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top U^\top P_X^\top P_X U \Sigma_S V_S^\top (V_S \Sigma_S^\top U^\top P_X^\top P_X U \Sigma_S V_S^\top)^{-1} \text{sgn}(\beta_S^*) \right| && (115)\\
&= \left| v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1} \Sigma_S V_S^\top \left(V_S \Sigma_S^\top \left(DD^\top\right)^{-1} \Sigma_S V_S^\top\right)^{-1} \text{sgn}(\beta_S^*) \right| && (116)\\
&= \left| v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1} \Sigma_S \left(\Sigma_S^\top \left(DD^\top\right)^{-1} \Sigma_S\right)^{-1} V_S^\top \text{sgn}(\beta_S^*) \right| && (117)\\
&= \left| v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top \Sigma_S \left(\Sigma_S^\top \Sigma_S\right)^{-1} V_S^\top \text{sgn}(\beta_S^*) \right| = \mu_j && (118)\\
\bar{\gamma}_i &= e_i^\top \left(\frac{1}{n} X_S^\top P_X^\top P_X X_S\right)^{-1} \text{sgn}(\beta_S^*) && (119)\\
&= \left(n + \frac{n(p-k)\kappa^2}{k\kappa^2 + n - k}\right) e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} \text{sgn}(\beta_S^*) && (120)\\
&= \left(n + \frac{n(p-k)\kappa^2}{k\kappa^2 + n - k}\right) \gamma_i && (121)
\end{aligned}
$$

$$
\begin{aligned}
\bar{\eta}_j &= X_j^\top P_X^\top \left(I_{n\times n} - P_X X_S (X_S^\top P_X^\top P_X X_S)^{-1} X_S^\top P_X^\top\right) \frac{\bar{w}}{n} && (122)\\
&= v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top U^\top P_X^\top \\
&\quad \left(I_{n\times n} - P_X U \Sigma_S V_S^\top (V_S \Sigma_S^\top U^\top P_X^\top P_X U \Sigma_S V_S^\top)^{-1} V_S \Sigma_S^\top U^\top P_X^\top\right) \frac{P_X w}{n} && (123)\\
&= v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2} U^\top \\
&\quad \left(I_{n\times n} - U \left(DD^\top\right)^{-1/2} \Sigma_S \left(\Sigma_S^\top \left(DD^\top\right)^{-1} \Sigma_S\right)^{-1} \Sigma_S^\top \left(DD^\top\right)^{-1/2} U^\top\right) \frac{P_X w}{n} && (124)\\
&= v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2} U^\top \left(I_{n\times n} - U_S U_S^\top\right) \frac{P_X w}{n} && (125)\\
&= v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2} \left(U^\top - \begin{bmatrix} I_{k\times k} \\ 0 \end{bmatrix} U_S^\top\right) \frac{P_X w}{n} && (126)\\
&= v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2} \begin{bmatrix} 0 \\ U_{S^c}^\top \end{bmatrix} \frac{P_X w}{n} && (127)\\
&= \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2}\right]_{(k+1:n)} U_{S^c}^\top \frac{P_X w}{n} && (128)\\
&= \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2}\right]_{(k+1:n)} \begin{bmatrix} 0 & I_{n-k\times n-k} \end{bmatrix} \left(DD^\top\right)^{-1/2} U^\top \frac{w}{n} && (129)\\
&= \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2}\right]_{(k+1:n)} \begin{bmatrix} 0 & D^{-1}_{(k+1:n),(k+1:n)} \end{bmatrix} U^\top \frac{w}{n} && (130)\\
&= \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top \left(DD^\top\right)^{-1/2}\right]_{(k+1:n)} D^{-1}_{(k+1:n),(k+1:n)} U_{S^c}^\top \frac{w}{n} && (131)\\
&= \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top\right]_{(k+1:n)} D^{-2}_{(k+1:n),(k+1:n)} U_{S^c}^\top \frac{w}{n} && (132)\\
&= \frac{1}{n(p-k)/(k\kappa^2 + n - k)} \left[v_{S^c, j-k, \cdot} \Sigma_{S^c}^\top\right]_{(k+1:n)} U_{S^c}^\top \frac{w}{n} && (133)\\
&= \frac{1}{n(p-k)/(k\kappa^2 + n - k)} \eta_j && (134)\\
\bar{\epsilon}_i &= e_i^\top \left(\frac{1}{n} X_S^\top P_X^\top P_X X_S\right)^{-1} X_S^\top P_X^\top P_X \frac{w}{n} && (135)\\
&= e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^\top \frac{w}{n} = \epsilon_i && (136)\\
& && (137)
\end{aligned}
$$

Immediately we see that the conditions of Lemma 1 continue to hold after preconditioning using JR. Note that by the above derivation $(2[\![\bar{\eta}_j > 0]\!] - 1) - \bar{\mu}_j = (2[\![\eta_j > 0]\!] - 1) - \mu_j$, and so

$$
\begin{aligned}
\bar{\lambda}_l &= \max_{j\in S^c} \frac{\bar{\eta}_j}{(2[\![\bar{\eta}_j > 0]\!] - 1) - \bar{\mu}_j} = \frac{1}{n(p-k)/(k\kappa^2 + n - k)} \max_{j\in S^c} \frac{\eta_j}{(2[\![\eta_j > 0]\!] - 1) - \mu_j} && (138)\\
&= \frac{1}{n(p-k)/(k\kappa^2 + n - k)} \lambda_l && (139)\\
\bar{\lambda}_u &= \min_{i\in S} \left|\frac{\beta_i^* + \bar{\epsilon}_i}{\bar{\gamma}_i}\right|_+ = \frac{1}{n + (n(p-k)\kappa^2/(k\kappa^2 + n - k))} \min_{i\in S} \left|\frac{\beta_i^* + \epsilon_i}{\gamma_i}\right|_+ && (140)\\
&= \frac{1}{n + (n(p-k)\kappa^2/(k\kappa^2 + n - k))} \lambda_u. && (141)
\end{aligned}
$$

The new ratio $\bar{\lambda}_u/\bar{\lambda}_l$ of upper and lower bounds then becomes

$$\frac{\bar{\lambda}_u}{\bar{\lambda}_l} = \frac{n(p-k)/(k\kappa^2+n-k)}{n+(n(p-k)\kappa^2/(k\kappa^2+n-k))}\frac{\lambda_u}{\lambda_l} \tag{142}$$

$$= \frac{n(p-k)}{n(k\kappa^2+n-k)+n(p-k)\kappa^2}\frac{\lambda_u}{\lambda_l} \tag{143}$$

$$= \frac{p-k}{(k\kappa^2+n-k)+(p-k)\kappa^2}\frac{\lambda}{\lambda_l} \tag{144}$$

$$= \frac{p-k}{n+p\kappa^2-k}\frac{\lambda_u}{\lambda_l}. \tag{145}$$

□

4.2 Gaussian Designs with Piecewise Constant Spectra

The generative model presented in Section 5.1 of the paper uses an *orthonormal* column basis U to generate X. The question arises whether a more natural Gaussian design X exists that is in a sense equivalent to the orthonormal construction of Section 5.1. In this section we present a generative model that uses a Gaussian column "basis" that achieves this. As before, let V_S and V_{S^c} be random orthonormal bases of sizes $k \times k$ and $p-k \times p-k$ respectively and let Σ_S and Σ_{S^c} be rectangular matrices that are derived from matrices $\hat{\Sigma}_S, \hat{\Sigma}_{S^c}$ as in Section 5.1 of the paper. Let W^m be an $m \times n$ matrix of independent Gaussians with marginal distribution $\mathcal{N}(0,1)$. Then we let

$$X^m = \frac{1}{\sqrt{n}} W^m \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]. \tag{146}$$

We note that all columns of X are mean zero, and their squared norms are on expectation m:

$$\begin{aligned}
E(X_i^m) = E(Xe_i) &= \frac{1}{\sqrt{n}} E(W^m \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] e_i) && (147)\\
&= \frac{1}{\sqrt{n}} E(W^m) E(\left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] e_i) = 0 && (148)\\
E(X_i^{m\top} X_i^m) &= E(e_i^\top X^\top X e_i) && (149)\\
&= \frac{1}{n} E(e_i^\top \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top W^{m\top} W^m \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] e_i) && (150)\\
&= \frac{m}{n} E(e_i^\top \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] e_i) && (151)\\
&= \begin{cases} \frac{m}{n} \sum_{i'=1}^k E(v_{S,i,i'}^2) \sigma_{S,i'}^2 = m & \text{if } i \in S \\ \frac{m}{n} \sum_{i'=1}^n E(v_{S^c,i-k,i'}^2) \sigma_{S^c,i'}^2 = m & \text{if } i \in S^c \end{cases}. && (152)
\end{aligned}$$

Moreover, if V_S, V_{S^c} are fixed, then the rows of X are jointly Gaussian and

$$\begin{aligned}
E\left(X^{m\top} X^m\right) &= \frac{1}{n} \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top E\left(W^{m\top} W^m\right) \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] && (153)\\
&= \frac{m}{n} \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]. && (154)
\end{aligned}$$

So if $m = n$, the covariance matches empirical covariance of X constructed in Section 5.1 with V_S, V_{S^c} fixed. The standard Lasso application considers problems in which the noise vector has fixed variance: $w \sim \mathcal{N}(0, \sigma^2 I_{n\times n})$. In the next section we let the variance grow as $\sigma^2 m/n$ (i.e., we use noise vectors $w^m \sim \mathcal{N}(0, (\sigma^2 m/n) I_{m\times m})$) and see how the induced ratio of penalty parameter bounds behaves as $m \to \infty$. Growing the number of observations and noise variance simultaneously ensures that the problem doesn't become too easy.

4.3 Convergence of bounds ratios

For some fixed V_S, V_{S^c}, Σ_S, Σ_{S^c}, and β^* generate the following two independent Lasso problems.

$$y = X\beta^* + w \qquad X = U\left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] \qquad w \sim \mathcal{N}(0, \sigma^2 I_{n\times n}) \tag{155}$$

$$y^m = X^m\beta^* + w^m \qquad X^m = \frac{1}{\sqrt{n}} W^m \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] \quad w^m \sim \mathcal{N}\left(0, \frac{\sigma^2 m}{n} I_{m\times m}\right), \tag{156}$$

where U is a randomly chosen $n \times n$ orthonormal basis, W^m is a random $m \times n$ Gaussian ensemble, and the noise vectors w and w^m are independent. Now, let λ_u/λ_l be the ratio of penalty parameter bounds induced by Lemma 1 for the orthonormal construction in Eq. (155) and λ_u^m/λ_l^m the ratio of penalty parameter bounds for the Gaussian construction in Eq. (156). We will show the following.

Theorem 4. *Let V_S, V_{S^c}, Σ_S, Σ_{S^c} and β^* be fixed. If the conditions of Lemma 1 hold for X, β^*, then for m large enough they will hold for X^m, β^*. Furthermore, as $m \to \infty$*

$$\frac{\lambda_u^m}{\lambda_l^m} \xrightarrow{d} \frac{\lambda_u}{\lambda_l}, \tag{157}$$

where the stochasticity on the left is due to W^m, w^m and on the right is due to w.

Proof. Let the variables introduced by Lemma 1 for the orthogonal model in Eq. (155) be λ, $\lambda_l, \lambda_u, \epsilon_i, \gamma_i, \mu_j$ and η_j. Let the corresponding variables for the Gaussian model of Eq. (156) be $\lambda^m, \lambda_l^m, \lambda_u^m, \epsilon_i^m, \gamma_i^m, \mu_j^m$ and η_j^m. Similarly, let the counterparts to X_S and X_j be X_S^m and X_j^m.

Since we assumed that $V_S, V_{S^c}, \Sigma_S, \Sigma_{S^c}, \beta^*$ are fixed, we first show that γ_i^m and μ_j^m converge to the constants γ_i, μ_j. Using the Strong Law of Large Numbers and the Continuous Mapping Theorem,

$$\lim_{m\to\infty} \frac{1}{m} X^{m\top} X^m = \lim_{m\to\infty} \frac{1}{mn} \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right]^\top W^{m\top} W^m \left[\Sigma_S V_S^\top, \Sigma_{S^c} V_{S^c}^\top\right] \tag{158}$$

$$\overset{a.s.}{=} \frac{1}{n} X^\top X \tag{159}$$

This means that all inner products of columns of $X^m/\sqrt{m}$ converge. Then, assuming the conditions of Lemma 1 hold,

$$\lim_{m\to\infty} \gamma_i^m = \lim_{m\to\infty} e_i^\top \left(\frac{1}{m} X_S^{m\top} X_S^m\right)^{-1} \operatorname{sgn}(\beta_S^*) \tag{160}$$

$$\overset{a.s.}{=} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} \operatorname{sgn}(\beta_S^*) = \gamma_i \tag{161}$$

$$\lim_{m\to\infty} \mu_j^m = \lim_{m\to\infty} X_j^{m\top} X_S^m (X_S^{m\top} X_S^m)^{-1} \operatorname{sgn}(\beta_S^*) \tag{162}$$

$$= \lim_{m\to\infty} \frac{X_j^{m\top} X_S^m}{m} \left(\frac{1}{m} X_S^{m\top} X_S^m\right)^{-1} \operatorname{sgn}(\beta_S^*) \tag{163}$$

$$\overset{a.s.}{=} \frac{X_j^\top X_S}{n} \left(\frac{1}{n} X_S^\top X_S\right)^{-1} \operatorname{sgn}(\beta_S^*) = \mu_j \tag{164}$$

Thus, if the conditions of Lemma 1 hold for X, β^*, there is an m_0 so that if $m > m_0$ the conditions are also met by X^m, β^*. Assume from now on the conditions are met. By Lemma 1, signed support recovery requires that

$$\lambda^m < \lambda_u^m = \min_{i\in S} \left|\frac{\beta_i^* + \epsilon_i^m}{\gamma_i^m}\right|_+ \tag{165}$$

$$\lambda^m > \lambda_l^m = \max_{j\in S^c} \frac{\eta_j^m}{\left(2[\![\eta_j^m > 0]\!] - 1\right) - \mu_j^m}. \tag{166}$$

We will show that $\lambda_u^m/\lambda_l^m \xrightarrow{d} \lambda_u/\lambda_l$, where the randomness on the left hand side is due to W^m, w^m and the randomness in the right limit is due to the noise w in the ϵ_i and η_j. To show this convergence, observe that we can (with probability 1) write λ_u/λ_l as a continuous function of $\beta_i^*, \epsilon_i, \gamma_i, i \in S, \eta_j, \mu_j, j \in S^c$, since we have that $\gamma_i > 0, \mu_j \in (-1, +1)$, and $\mathbb{P}(\max_j \eta_j = 0) = 0$ if $\sigma^2 > 0$[3]. By the Continuous Mapping Theorem, convergence in distribution of λ_u^m/λ_l^m could then be guaranteed if we had the following joint convergence in distribution

$$\begin{bmatrix} \{\epsilon_i^m\}_{i\in S} \\ \{\gamma_i^m\}_{i\in S} \\ \{\eta_j^m\}_{j\in S^c} \\ \{\mu_j^m\}_{j\in S^c} \end{bmatrix} \xrightarrow{d} \begin{bmatrix} \{\epsilon_i\}_{i\in S} \\ \{\gamma_i\}_{i\in S} \\ \{\eta_j\}_{j\in S^c} \\ \{\mu_j\}_{j\in S^c} \end{bmatrix}. \tag{167}$$

Because μ_j^m and γ_i^m converge to constants μ_j, γ_i, it remains to be shown that

$$\begin{bmatrix} \{\epsilon_i^m\}_{i\in S} \\ \{\eta_j^m\}_{j\in S^c} \end{bmatrix} \xrightarrow{d} \begin{bmatrix} \{\epsilon_i\}_{i\in S} \\ \{\eta_j\}_{j\in S^c} \end{bmatrix}. \tag{168}$$

To simplify notation, we will show only the marginal convergence, letting it be understood that the argument holds jointly. Using the Strong Law of Large Numbers and Slutsky's Lemma,

$$\lim_{m\to\infty} \epsilon_i^m = \lim_{m\to\infty} e_i^\top \left(\frac{1}{m} X_S^{m\top} X_S^m\right)^{-1} X_S^{m\top} \frac{w^m}{m} \tag{169}$$

$$\stackrel{d}{=} \lim_{m\to\infty} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} X_S^{m\top} \frac{w^m}{m} \tag{170}$$

$$\stackrel{d}{=} \lim_{m\to\infty} \frac{1}{\sqrt{n}} e_i^\top \left(\frac{1}{n} X_S^\top X_S\right)^{-1} V_S \Sigma_S^\top W^{m\top} \frac{w^m}{m} \tag{171}$$

$$\lim_{m\to\infty} \eta_j^m = \lim_{m\to\infty} X_j^{m\top} \left(I_{m\times m} - X_S^m (X_S^{m\top} X_S^m)^{-1} X_S^{m\top}\right) \frac{w^m}{m} \tag{172}$$

$$\stackrel{d}{=} \lim_{m\to\infty} X_j^{m\top} \left(I_{m\times m} - \frac{1}{m} X_S^m \left(\frac{1}{m} X_S^{m\top} X_S^m\right)^{-1} X_S^{m\top}\right) \frac{w^m}{m} \tag{173}$$

$$\stackrel{d}{=} \lim_{m\to\infty} X_j^{m\top} \left(I_{m\times m} - \frac{1}{m} X_S^m \left(\frac{1}{n} X_S{}^\top X_S\right)^{-1} X_S^{m\top}\right) \frac{w^m}{m} \tag{174}$$

$$\stackrel{d}{=} \lim_{m\to\infty} X_j^{m\top} \left(I_{m\times m} - \frac{1}{mn} W^m \Sigma_S V_S^\top \left(\frac{1}{n} V_S \Sigma_S^\top \Sigma_S V_S^\top\right)^{-1} V_S \Sigma_S^\top W^{m\top}\right) \frac{w^m}{m} \tag{175}$$

$$\stackrel{d}{=} \lim_{m\to\infty} X_j^{m\top} \left(I_{m\times m} - \frac{1}{m} W^m \Sigma_S \left(\Sigma_S^\top \Sigma_S\right)^{-1} \Sigma_S^\top W^{m\top}\right) \frac{w^m}{m} \tag{176}$$

$$\stackrel{d}{=} \lim_{m\to\infty} \frac{1}{\sqrt{n}} v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top W^{m\top} \left(I_{m\times m} - \frac{1}{m} W_S^m W_S^{m\top}\right) \frac{w^m}{m} \tag{177}$$

$$\stackrel{d}{=} \lim_{m\to\infty} \frac{1}{\sqrt{n}} v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top \left(W^{m\top} - \frac{1}{m} W^{m\top} W_S^m W_S^{m\top}\right) \frac{w^m}{m} \tag{178}$$

$$\stackrel{d}{=} \lim_{m\to\infty} \frac{1}{\sqrt{n}} v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top \left(W^{m\top} - \begin{bmatrix} I_{k\times k} \\ 0 \end{bmatrix} W_S^{m\top}\right) \frac{w^m}{m} \tag{179}$$

$$\stackrel{d}{=} \lim_{m\to\infty} \frac{1}{\sqrt{n}} \left[v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top\right]_{(k+1:n)} W_{S^c}^{m\top} \frac{w^m}{m} \tag{180}$$

Observe that since $V_S, V_{S^c}, \Sigma_S, \Sigma_{S^c}$ are fixed, the joint limit distribution of $\left[\{\epsilon_i^m\}_{i\in S}, \{\eta_j^m\}_{j\in S^c}\right]$ is determined by the limit distribution of the *shared* random variable $W^{m\top} w^m/m$. The following lemma allows us to exploit this

Lemma 4. *Let U be a (possibly random) $n \times n$ orthonormal matrix and $w \sim \mathcal{N}(0, \sigma^2 I_{n\times n})$. Then*

$$W^{m\top} \frac{w^m}{m} \xrightarrow{d} U^\top \frac{w}{\sqrt{n}}, \tag{181}$$

[3]To see this, note that $\left[v_{S^c,j-k,\cdot} \Sigma_{S^c}^\top\right]_{(k+1:n)}$ cannot be zero for all $j \in S^c$.

Proof. We show that for an independent $z \sim \mathcal{N}(0, \sigma^2 I_{m\times m})$

$$W^{m\top}\frac{w^m}{m} \xrightarrow{d} \lim_{m\to\infty} W^{m\top}\frac{w^m}{m} \overset{d}{=} \lim_{m\to\infty} W^{m\top}\frac{z}{\sqrt{mn}} \overset{d}{=} \lim_{m\to\infty} W^{m\top}\frac{\sigma z}{\|z\|_2\sqrt{n}} \overset{d}{=} U^\top \frac{w}{\sqrt{n}} \quad (182)$$

By simple application of the Central Limit Theorem to $W^{m\top}z/\sqrt{m}$ we see that the marginals of the third random variable are Gaussian. To clarify the dependency structure between the variables, we have further modified the statement by explicitly normalizing z on the right. We can do this using Slutsky's Lemma, because by the Strong Law of Large Numbers $\|z\|_2/\sqrt{m} \xrightarrow{a.s.} \sigma$. Now, since the elements of W^m are independent standard Gaussians, and z has been normalized to unit length, the limit distribution on the right consists of independent zero-mean Gaussians with variance σ^2/n. $\square$

Because V_S, V_{S^c}, Σ_S, Σ_{S^c} are fixed, we can use Lemma 4 to conclude that jointly

$$\begin{bmatrix} \{\epsilon_i^m\}_{i\in S} \\ \{\eta_j^m\}_{j\in S^c} \end{bmatrix} \xrightarrow{d} \begin{bmatrix} \left\{e_i^\top \left(\frac{1}{n}X_S^\top X_S\right)^{-1} V_S \Sigma_S^\top U^\top \frac{w}{n}\right\}_{i\in S} \\ \left\{\left[v_{S^c,j-k,\cdot}\Sigma_{S^c}^\top\right]_{(k+1:n)} U_{S^c}^\top \frac{w}{n}\right\}_{j\in S^c} \end{bmatrix} \overset{d}{=} \begin{bmatrix} \{\epsilon_i\}_{i\in S} \\ \{\eta_j\}_{j\in S^c} \end{bmatrix}. \quad (183)$$

Finally, an application of the Continuous Mapping Theorem to $\epsilon_i^m, \gamma_i^m, \eta_j^m, \mu_j^m$ then establishes that

$$\frac{\lambda_u^m}{\lambda_l^m} \xrightarrow{d} \frac{\lambda_u}{\lambda_l}. \quad (184)$$

$\square$

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