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Abstract

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1. GLRT

Suppose $\{X_{i1}, \ldots, X_{in_i}\}$ are i.i.d. distributed as $N(\mu_i, \Sigma)$ for $1 \le i \le K$. Let $\mathbf{X}_i = (X_{i1}, \ldots, X_{in_i})$ for $i = 1, \ldots, k$. The k samples are independent. μ_i, $i = 1 \ldots, k$ and $\Sigma > 0$ are unknown. An interesting problem in multivariate analysis is to test the hypotheses

$$H : \mu_1 = \mu_2 = \cdots = \mu_k \quad v.s. \quad K : \mu_i \neq \mu_j \text{ for some } i \neq j. \tag{1}$$

Let $\mathbf{Z} = (X_1, \ldots, X_k)$.

$$f(Z; \mu_1, \ldots, \mu_k, \Sigma) = \prod_{i=1}^{k} \Big[(2\pi)^{-n_i p/2} |\Sigma|^{-n_i/2} \exp(-\frac{1}{2} \mathrm{tr} \Sigma^{-1} \sum_{j=1}^{n_i} (x_{ij} - \mu_i)(x_{ij} - \mu_i)^T)\Big].$$

Assume $n = \sum_{i=1}^{p} n_i < p$. Let $a \in \mathbb{R}^p$ be a vector satisfying $a^T a = 1$. Then

$$f_a(a^T Z; \mu_1, \ldots, \mu_k, \Sigma) = (2\pi)^{-n/2} |a^T \Sigma a|^{-n/2} \exp\Big(-\frac{1}{2a^T \Sigma a} \sum_{i=1}^{k} \sum_{j=1}^{n_i} (a^T x_{ij} - a^T \mu_i)^2\Big)$$

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$$\max_{\mu_1,\ldots,\mu_k,\Sigma} f_a(a^T Z, \mu_1, \ldots, \mu_k, \Sigma) = (2\pi)^{-n/2}\Big(\sum_{i=1}^{k}\sum_{j=1}^{n_i}(a^T x_{ij} - a^T \bar{\mathbf{X}}_i)^2\Big)^{-n/2} e^{-n/2} \tag{2}$$

Let $S_i = \sum_{j=1}^{n_i}(x_{ij} - \bar{\mathbf{X}}_i)(x_{ij} - \bar{\mathbf{X}}_i)^T$ and $S = \sum_{i=1}^{k} S_i$.

Under H, we have

$$\max_{\mu,\Sigma} f_a(a^T Z, \mu, \ldots, \mu, \Sigma) = (2\pi)^{-n/2}\Big(\sum_{i=1}^{k}\sum_{j=1}^{n_i}(a^T x_{ij} - a^T \bar{\mathbf{X}})^2\Big)^{-n/2} e^{-n/2} \tag{3}$$

The generalized likelihood ratio test statistic is defined as

$$T(Z) = \max_{a^T a=1, a^T S a=0} a^T \sum_{i=1}^{k} n_i(\bar{\mathbf{X}}_i - \bar{\mathbf{X}})(\bar{\mathbf{X}}_i - \bar{\mathbf{X}})^T a \tag{4}$$

Let $J = \mathrm{diag}(n_1^{-1/2}\mathbf{1}_{n_1}, \ldots, n_k^{-1/2}\mathbf{1}_{n_k})$. Then $S = Z(I_n - JJ^T)Z^T$ and

$$\sum_{i=1}^{k} n_i(\bar{\mathbf{X}}_i - \bar{\mathbf{X}})(\bar{\mathbf{X}}_i - \bar{\mathbf{X}})^T = Z(JJ^T - \frac{1}{n}\mathbf{1}_n\mathbf{1}_n^T)Z^T. \tag{5}$$

The matrix $I_n - JJ^T$, $JJ^T - \frac{1}{n}\mathbf{1}_n\mathbf{1}_n^T$ and $\frac{1}{n}\mathbf{1}_n\mathbf{1}_n^T$ are all projection matrix and pairwise orthogonal with rank $n-k$, $k-1$ and 1.

Let $\tilde{J}$ be a $n \times (n-k)$ matrix satisfied $\tilde{J}\tilde{J}^T = I - JJ^T$. Then $S = Z\tilde{J}\tilde{J}^T Z^T$ and Note that

$$Z(JJ^T - \frac{1}{n}\mathbf{1}_n\mathbf{1}_n^T)Z^T = ZJ(I_k - \frac{1}{n}J^T\mathbf{1}_n\mathbf{1}_n^T J)J^T Z^T.$$

Note that $I_k - \frac{1}{n}J^T\mathbf{1}_n\mathbf{1}_n^T J$ is a projection matrix with rank $k-1$. Let C be a $k \times (k-1)$ matrix satisfied $CC^T = I_k - \frac{1}{n}J^T\mathbf{1}_n\mathbf{1}_n^T J$.

In Proposition 1, letting $A = Z\tilde{J}$ and $B = ZJCC^T J^T Z^T$ yields

$$\begin{aligned} T(Z) &= \lambda_{max}\big((I_p - Z\tilde{J}(\tilde{J}^T Z^T Z\tilde{J})^{-1}\tilde{J}^T Z^T)ZJCC^T J^T Z^T(I_p - Z\tilde{J}(\tilde{J}^T Z^T Z\tilde{J})^{-1}\tilde{J}^T Z^T)\big) \\ &= \lambda_{max}\big(C^T J^T Z^T(I_p - Z\tilde{J}(\tilde{J}^T Z^T Z\tilde{J})^{-1}\tilde{J}^T Z^T)ZJC\big). \end{aligned}$$

Note that

$$\begin{aligned} &\Big(\begin{pmatrix} J^T \\ \tilde{J}^T \end{pmatrix} Z^T Z \begin{pmatrix} J & \tilde{J} \end{pmatrix}\Big)^{-1} \\ &= \begin{pmatrix} J^T Z^T Z J & J^T Z^T Z\tilde{J} \\ \tilde{J}^T Z^T Z J & \tilde{J}^T Z^T Z\tilde{J} \end{pmatrix}^{-1} = \begin{pmatrix} J^T(Z^T Z)^{-1}J & J^T(Z^T Z)^{-1}\tilde{J} \\ \tilde{J}^T(Z^T Z)^{-1}J & \tilde{J}^T(Z^T Z)^{-1}\tilde{J} \end{pmatrix}. \end{aligned} \tag{6}$$

It follows that

$$
\begin{aligned}
&\left(J^T(Z^TZ)^{-1}J\right)^{-1}\\
=&J^TZ^TZJ - J^TZ^TZ\tilde{J}(\tilde{J}^TZ^TZ\tilde{J})^{-1}\tilde{J}^TZ^TZJ \\
=&J^TZ^T(I_p - Z\tilde{J}(\tilde{J}^TZ^TZ\tilde{J})^{-1}\tilde{J}^TZ^T)ZJ
\end{aligned} \tag{7}
$$

It follows that

$$
T(Z) = \lambda_{\max}\Big(C^T\left(J^T(Z^TZ)^{-1}J\right)^{-1}C\Big) \tag{8}
$$

Proposition 1. *Suppose A is a $p \times r$ matrix with rank r and B is a $p \times p$ non-zero semi-definite matrix. Let $H_A = A(A^TA)^{-1}A^T$. Then*

$$
\max_{a^Ta=1, a^TAA^Ta=0} a^TBa = \lambda_{\max}\big((I_p - H_A)B(I_p - H_A)\big). \tag{9}
$$

Proof. Note that $a^TAA^Ta = 0$ is equivalent to $A^Ta = 0$ and is in turn equivalent to $H_Aa = 0$. In this circumstance, $a = (I_p - H_A)a$. Then

$$
\begin{aligned}
\max_{a^Ta=1, a^TAA^Ta=0} a^TBa &= \max_{a^Ta=1, H_Aa=0} a^TBa \\
&= \max_{a^Ta=1, H_Aa=0} a^T(I_p - H_A)B(I_p - H_A)a.
\end{aligned} \tag{10}
$$

It's obvious that (10) $\leq \lambda_{\max}\big((I-H_A)B(I-H_A)\big)$. On the other hand, let α_1 be one eigenvector corresponding to the largest eigenvalue of $(I - H_A)B(I - H_A)$. Note that the row of H_A are all eigenvetors of $(I-H_A)B(I-H_A)$ corresponding to eigenvalue 0. It follows that $H_A\alpha_1 = 0$. Now that α_1 satisfies the constraint of (10), (10) is maximized when $a = \alpha_1$.

□

2. Schott's method

$$
E = ZZ^T - \sum_{i=1}^{k} n_i\bar{X}_i\bar{X}_i^T.
$$

$$
H = \sum_{i=1}^{k} n_i\bar{X}_i\bar{X}_i^T - n\bar{X}\bar{X}^T.
$$

$$\operatorname{tr} E = \operatorname{tr} Z^T Z - \operatorname{tr} J^T Z^T Z J.$$

$$\operatorname{tr} H = \operatorname{tr} J^T Z^T Z J - \frac{1}{n} 1_n^T Z^T Z 1_n$$

$$T_{SC} = \frac{1}{\sqrt{n-1}} \left(\frac{1}{k-1} \operatorname{tr} H - \frac{1}{n-k} \operatorname{tr} E \right)$$

3. Theory

Let $Z\tilde{J} = U_{Z\tilde{J}} D_{Z\tilde{J}} V_{Z\tilde{J}}^T$ be the singular value decomposition of $Z\tilde{J}$. Let $H_{Z\tilde{J}} = U_{Z\tilde{J}} U_{Z\tilde{J}}^T$. $T(Z) = \lambda_{\max}(C^T J^T Z^T (I_p - H_{Z\tilde{J}}) Z J C)$.

ZJC is independent of $H_{Z\tilde{J}}$

$$\mathrm{E}(Z\tilde{J}) = O_{p \times (n-k)}$$

Let $\Sigma = U \Lambda U^T$. Then

$$Z\tilde{J} = U \Lambda^{1/2} G_1,$$

where G_1 is a $p \times (n-k)$ matrix with i.i.d. $N(0,1)$ entries.

$$\mathrm{E}(ZJ) = (\sqrt{n_1}\mu_1, \ldots, \sqrt{n_k}\mu_k) \stackrel{def}{=} \mu_f$$

And

$$ZJC = \mu_f C + U \Lambda_{1/2} G_2$$

where G_2 is a $p \times (k-1)$ matrix with i.i.d. $N(0,1)$ entries.

Then

$$\begin{aligned} T(Z) \sim \lambda_{\max}(G_2^T \Lambda^{1/2} U^T (I_P - H_{Z\tilde{J}}) U \Lambda_{1/2} G_2 + \mu_f^T (I_p - H_{Z\tilde{J}}) \mu_f + \\ \mu_f^T (I_p - H_{Z\tilde{J}}) U \Lambda^{1/2} G_2 + G_2^T \Lambda^{1/2} U^T (I_P - H_{Z\tilde{J}}) \mu_f) \end{aligned}$$

We have

$$G_2^T \Lambda^{1/2} U^T (I_p - H_{Z\tilde{J}}) U \Lambda_{1/2} G_2 \sim \sum_{i=1}^{p} \lambda_i (\Lambda^{1/2} U^T (I_p - H_{Z\tilde{J}}) U \Lambda^{1/2}) \xi_i \xi_i^T$$

where $\xi_i \overset{i.i.d.}{\sim} N(0, I_{k-1})$.

The eigenvalues of $\Lambda^{1/2}U^T(I_p - H_{Z\tilde{J}})U\Lambda^{1/2}$ equal to those of $(I_p - H_{Z\tilde{J}})U\Lambda U^T(I_p - H_{Z\tilde{J}})$.

Let $U = (U_1, U_2)$ and $\Sigma = \text{diag}(\Lambda_1, \Lambda_2)$, where U_1 is $p \times r$ and Λ_1 is $r \times r$. Assume $cI_{p-r} \leq \Lambda_2 \leq CI_{p-r}$.

$$
\begin{aligned}
&(I_p - H_{Z\tilde{J}})U\Lambda U^T(I_p - H_{Z\tilde{J}}) \\
=&(I_p - H_{Z\tilde{J}})U_1\Lambda_1 U_1^T(I_p - H_{Z\tilde{J}}) + (I_p - H_{Z\tilde{J}})U_2\Lambda_2 U_2^T(I_p - H_{Z\tilde{J}}) = R_1 + R_2
\end{aligned}
$$

$$
\begin{aligned}
&\lambda_{\max}\big((I_p - H_{Z\tilde{J}})U_1\Lambda_1 U_1^T(I_p - H_{Z\tilde{J}})\big) = \lambda_{\max}\big(\Lambda_1^{1/2}U_1^T(I_p - H_{Z\tilde{J}})U_1\Lambda_1^{1/2}\big) \\
&\leq \lambda_{\max}\big(\Lambda_1^{1/2}U_1^T(I_p - U_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^T)U_1\Lambda_1^{1/2}\big) \leq \lambda_1\lambda_{\max}\big(U_1^T(I_p - U_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^T)U_1\big) \\
&= \lambda_1\lambda_{\max}\big(I_r - U_1^T U_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^T U_1\big)
\end{aligned}
$$

We need to investigate the behavior of $U_{Z\tilde{J}}$.

$$
G_1^T\Lambda G_1 = \tilde{J}^T Z^T Z\tilde{J} = V_{Z\tilde{J}}D_{Z\tilde{J}}^2 V_{Z\tilde{J}}^T
$$

Note that

$$
G_1^T\Lambda G_1 = G_{1[1:r,]}^T\Lambda_1 G_{1[1:r,]} + G_{1[(r+1):p,]}^T\Lambda_2 G_{1[(r+1):p,]}
$$

For $i = 1, \ldots, r$,

$$
\begin{aligned}
&\lambda_i(G_{1[1:r,]}^T\Lambda_1 G_{1[1:r,]}) \geq \lambda_i(G_{1[1:r,]}^T \,\text{diag}(\lambda_i I_i, O_{(r-i)\times(r-i)})G_{1[1:r,]}) \\
=&\lambda_i\lambda_i(G_{1[1:i,]}G_{1[1:i,]}^T) = \lambda_i n(1 + o_P(1))
\end{aligned}
$$

The last equality holds since $n^{-1}G_{1[1:i,]}G_{1[1:i,]}^T \xrightarrow{P} I_i$ by law of large numbers. On the other hand, for $i = 1, \ldots, r$,

$$
\begin{aligned}
&\lambda_i(G_{1[1:r,]}^T\Lambda_1 G_{1[1:r,]}) \\
=&\lambda_i\Big(G_{1[1:r,]}^T\big(\text{diag}(\lambda_1, \ldots, \lambda_{i-1}, O_{(r-i+1)\times(r-i+1)}) + \text{diag}(O_{(i-1)\times(i-1)}, \lambda_i, \ldots, \lambda_r)\big)G_{1[1:r,]}\Big) \\
\leq&\lambda_1(G_{1[1:r,]}^T \,\text{diag}(O_{(i-1)\times(i-1)}, \lambda_i, \ldots, \lambda_r)G_{1[1:r,]}) \leq \lambda_1(G_{1[1:r,]}^T \,\text{diag}(O_{(i-1)\times(i-1)}, \lambda_i I_{r-i+1})G_{1[1:r,]}) \\
=&\lambda_i\lambda_1(G_{1[i:r,]}G_{1[i:r,]}^T) = \lambda_i n(1 + o_P(1))
\end{aligned}
$$

where the first inequality holds by Weyl's inequality. It follows that $\lambda_i(G_{1[1:r,]}^T\Lambda_1 G_{1[1:r,]}) = \lambda_i n(1+o_P(1))$ for $i=1,\dots,r$.

Note that $\lambda_{\max}(G_{1[(r+1):p,]}^T\Lambda_2 G_{1[(r+1):p,]}) \le C\lambda_{\max}(G_{1[(r+1):p,]}^T G_{1[(r+1):p,]}) = O_P(p)$ by Bai-Yin's law, here we have assumed $n/p=O(1)$. Assume $p/(\lambda_r n)\to 0$, we can deduce that $D_{Z\tilde{J}[i,i]}^2 = \lambda_i(G_1^T\Lambda G_1) = \lambda_i n(1+o_P(1))$, $i=1,\dots,r$.

Note that

$$U\Lambda^{1/2}G_1G_1^T\Lambda^{1/2}U^T = U_{Z\tilde{J}}D_{Z\tilde{J}}^2U_{Z\tilde{J}}^T$$

then

$$G_1G_1^T = \Lambda^{-1/2}U^TU_{Z\tilde{J}}D_{Z\tilde{J}}^2U_{Z\tilde{J}}^TU\Lambda^{-1/2}$$

and

$$\begin{aligned}
G_{1[(r+1):p,]}G_{1[(r+1):p,]}^T &= \Lambda_2^{-1/2}U_{[,(r+1):p]}^TU_{Z\tilde{J}}D_{Z\tilde{J}}^2U_{Z\tilde{J}}^TU_{[,(r+1):p]}\Lambda_2^{-1/2}\\
&\ge \Lambda_2^{-1/2}U_{[,(r+1):p]}^TU_{Z\tilde{J}[,1:r]}D_{Z\tilde{J}[1:r,1:r]}^2U_{Z\tilde{J}[,1:r]}^TU_{[,(r+1):p]}\Lambda_2^{-1/2}\\
&\ge D_{Z\tilde{J}[r,r]}^2\Lambda_2^{-1/2}U_{[,(r+1):p]}^TU_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^TU_{[,(r+1):p]}\Lambda_2^{-1/2}
\end{aligned}$$

Thus,

$$\lambda_{\max}(U_{[,(r+1):p]}^TU_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^TU_{[,(r+1):p]}) \le \frac{C}{D_{Z\tilde{J}[r,r]}^2}\lambda_1(G_{1[(r+1):p,]}G_{1[(r+1):p,]}^T) = O_P(\frac{p}{\lambda_r n})$$

Note that

$$\begin{aligned}
&\lambda_{\max}(U_{[,(r+1):p]}^TU_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^TU_{[,(r+1):p]}) = \lambda_{\max}(U_{Z\tilde{J}[,1:r]}^TU_{[,(r+1):p]}U_{[,(r+1):p]}^TU_{Z\tilde{J}[,1:r]})\\
=&\lambda_{\max}(U_{Z\tilde{J}[,1:r]}^T(I_p-U_1U_1^T)U_{Z\tilde{J}[,1:r]}) = \lambda_{\max}(I_r-U_{Z\tilde{J}[,1:r]}^TU_1U_1^TU_{Z\tilde{J}[,1:r]})\\
=&1-\lambda_{\min}(U_{Z\tilde{J}[,1:r]}^TU_1U_1^TU_{Z\tilde{J}[,1:r]}) = 1-\lambda_{\min}(U_1^TU_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^TU_1)\\
=&\lambda_{\max}(I_r-U_1^TU_{Z\tilde{J}[,1:r]}U_{Z\tilde{J}[,1:r]}^TU_1)
\end{aligned}$$

Therefore $\lambda_{\max}(R_1) = O_P(\frac{\lambda_1 p}{\lambda_r n})$

Having this, we can deal with R_1+R_2

For $i=1,\dots,r$,

$$\lambda_i(R_1+R_2) \le \lambda_1(R_1+R_2) \le \lambda_1(R_1)+\lambda_1(R_2) \le O_P(\frac{\lambda_1 p}{\lambda_r n})+C$$

For $i=r+1,\dots,p-r$,

$$\lambda_i(R_1+R_2) \le \lambda_{i-r}(R_2) = \lambda_{i-r}\big(\Lambda_2^{1/2}U_2^T(I_p-H_{Z\tilde{J}})U_2\Lambda_2^{1/2}\big) \le \lambda_{i-r}(\Lambda_2) = \lambda_i$$

On the other hand, for $i = 1, \ldots, p-r-n+k$,

$$\begin{aligned}\lambda_i(R_1+R_2) \geq \lambda_i(R_2) = \lambda_i\big(\Lambda_2^{1/2}U_2^T(I_p - H_{Z\tilde{J}})U_2\Lambda_2^{1/2}\big)\\ =&\lambda_i\big(\Lambda_2 - \Lambda_2^{1/2}U_2^T H_{Z\tilde{J}}U_2\Lambda_2^{1/2}\big) \geq \lambda_{i+n-k}\end{aligned}$$

The last equality holds since $U_2^T H_{Z\tilde{J}} U_2$ is at most of rank $n-k$.

$$\sum_{i=1}^{p-r-n+k} \lambda_{i+n-k}^2 \leq \operatorname{tr}[(R_1+R_2)^2] \leq r(O_P(\frac{\lambda_1 p}{\lambda_r n}) + C)^2 + \sum_{i=r+1}^{p-r} \lambda_i^2$$

Or

$$|\operatorname{tr}[(R_1+R_2)^2] - \sum_{i=r+1}^{p} \lambda_i^2| \leq \sum_{i=r+1}^{n-k} \lambda_i^2 + \sum_{i=p-r+1}^{p} \lambda_i^2 + r(O_P(\frac{\lambda_1 p}{\lambda_r n}) + C)^2$$

Similarly,

$$|\operatorname{tr}[(R_1+R_2)] - \sum_{i=r+1}^{p} \lambda_i| \leq \sum_{i=r+1}^{n-k} \lambda_i + \sum_{i=p-r+1}^{p} \lambda_i + r(O_P(\frac{\lambda_1 p}{\lambda_r n}) + C)$$

Therefore, assume $\lim p/n \to \infty$ and $\frac{\lambda_1^2 p}{\lambda_r^2 n^2} \to 0$, we have

$$\operatorname{tr}[(R_1+R_2)^2] = (1 + o_P(1)) \sum_{i=r+1}^{p} \lambda_i^2$$

and

$$\operatorname{tr}[(R_1+R_2)] = \sum_{i=r+1}^{p} \lambda_i + O(n) + O_P(\frac{\lambda_1 p}{\lambda_r n}).$$

Note that

$$\frac{\lambda_1[(R_1+R_2)^2]}{\operatorname{tr}[(R_1+R_2)^2]} = \frac{\big(O_P(\frac{\lambda_1 p}{\lambda_r n}) + C\big)^2}{(1+o_P(1))\sum_{i=r+1}^{p}\lambda_i^2} \xrightarrow{P} 0.$$

Apply Lyapunov central limit theorem conditioning on $H_{Z\tilde{J}}$, we have

$$\big(\operatorname{tr}[(R_1+R_2)^2]\big)^{-1/2}\big(G_2^T\Lambda^{1/2}U^T(I_p - H_{Z\tilde{J}})U\Lambda_{1/2}G_2 - \operatorname{tr}(R_1+R_2)I_{k-1}\big) \xrightarrow{\mathcal{L}} W_{k-1}$$

where W_{k-1} is a $(k-1)\times(k-1)$ symmetric random matrix whose entries above the main diagonal are i.i.d. $N(0,1)$ and the entries on the diagonal are i.i.d. $N(0,2)$. By Slutsky's theorem, we have

$$\big(\sum_{i=r+1}^{p} \lambda_i^2\big)^{-1/2}\big(G_2^T\Lambda^{1/2}U^T(I_p - H_{Z\tilde{J}})U\Lambda_{1/2}G_2 - \sum_{i=r+1}^{p}\lambda_i^2\big) \xrightarrow{\mathcal{L}} W_{k-1}$$

And

$$
\begin{aligned}
&\mathrm{E}[\|\mu_f^T(I_p - H_{Z\tilde{J}})U\Lambda^{1/2}G_2\|_F^2|Z\tilde{J}] \\
=&(k-1)\operatorname{tr}(\mu_f^T(I_p - H_{Z\tilde{J}})U\Lambda U^T(I_p - H_{Z\tilde{J}})\mu_f) \\
\leq&(k-1)\lambda_1\big((I_p - H_{Z\tilde{J}})U\Lambda U^T(I_p - H_{Z\tilde{J}})\big)\|\mu_f\|_F^2 \\
=&(k-1)O_P(\frac{\lambda_1 p}{\lambda_r n})\|\mu_f\|_F^2 \\
=&(k-1)O_P(\frac{\lambda_1\sqrt{p}}{\lambda_r n})\sqrt{p}\|\mu_f\|_F^2 = o_P(p)
\end{aligned}
$$

The last equality holds when we assume $\frac{1}{\sqrt{p}}\|\mu_f\|_F^2 = O(1)$. Hence $\|\mu_f^T(I_p - H_{Z\tilde{J}})U\Lambda^{1/2}G_2\|_F^2 = o_P(p)$.

References