Appendix for "Random Feature Stein Discrepancies"

A Proof of Proposition 3.1: KSD-ΦSD inequality

We apply the generalized Hölder's inequality and the Babenko-Beckner inequality in turn to find

$$\begin{aligned}\mathrm{KSD}_k^2(Q_N, P) &= \textstyle\sum_{d=1}^D \int |\mathscr{F}(Q_N(\mathcal{T}_d\Phi))(\omega)|^2\rho(\omega)\,\mathrm{d}\omega \le \|\rho\|_{L^t} \sum_{d=1}^D \|\mathscr{F}(Q_N(\mathcal{T}_d\Phi))\|_{L^s}^2 \\ &\le c_{r,d}^2 \|\rho\|_{L^t} \textstyle\sum_{d=1}^D \|Q_N(\mathcal{T}_d\Phi)\|_{L^r}^2 = c_{r,d}^2\|\rho\|_{L^t}\, \Phi\mathrm{SD}_{\Phi,r}^2(Q_N, P),\end{aligned}$$

where $t = \frac{r}{2-r}$ and $c_{r,d} := (r^{1/r}/s^{1/s})^{d/2} \le 1$ for $s = r/(r-1)$.

B Proof of Theorem 3.2: Tilted KSDs detect non-convergence

For any vector-valued function f, let $M_1(f) = \sup_{x,y:\|x-y\|_2=1}\|f(x)-f(y)\|_2$. The result will follow from the following theorem which provides an upper bound on the bounded Lipschitz metric $d_{BL_{\|\cdot\|_2}}(\mu, P)$ in terms of the KSD and properties of A and Ψ. Let $b := \nabla \log p$.

Theorem B.1 (Tilted KSD lower bound)**.** *Suppose $P \in \mathcal{P}$ and $k(x,y) = A(x)\Psi(x-y)A(y)$ for $\Psi \in C^2$ and $A \in C^1$ with $A > 0$ and $\nabla \log A$ bounded and Lipschitz. Then there exists a constant $\mathcal{M}_P$ such that, for all $\epsilon > 0$ and all probability measures μ,*

$$d_{BL_{\|\cdot\|_2}}(\mu, P) \le \epsilon + C\,\mathrm{KSD}_k(\mu, P),$$

where

$$C := (2\pi)^{-d/4}\|1/A\|_{L^2}\mathcal{M}_P H\big(\mathbb{E}[\|G\|_2 B(G)](1 + M_1(\log A) + \mathcal{M}_P M_1(b + \nabla\log A))\epsilon^{-1}\big)^{1/2},$$

$H(t) := \sup_{\omega\in\mathbb{R}^d} e^{-\|\omega\|_2^2/(2t^2)}/\hat{\Psi}(\omega)$, G is a standard Gaussian vector, and $B(y) := \sup_{x\in\mathbb{R}^d, u\in[0,1]} A(x)/A(x+uy)$.

Remarks By bounding H and optimizing over ϵ, one can derive rates of convergence in $d_{BL_{\|\cdot\|_2}}$. Thm. 5 and Sec. 4.2 of Gorham et al. [12] provide an explicit value for the *Stein factor* $\mathcal{M}_P$.

Let $A_\mu(x) = A(x - \mathbb{E}_{X\sim\mu}[X])$. Since $\|1/A\|_{L^2} = \|1/A_\mu\|_{L^2}$, $M_1(\log A_\mu) \le M_1(\log A)$, $M_1(\nabla \log A_\mu) \le M_1(\nabla\log A)$, and $\sup_{x\in\mathbb{R}^d,u\in[0,1]} A_\mu(x)/A_\mu(x+uy) = B(y)$, the exact conclusion of Theorem B.1 also holds when $k(x,y) = A_\mu(x)\Psi(x-y)A_\mu(y)$. Moreover, since $\log A$ is Lipschitz, $B(y) \le e^{\|y\|_2}$ so $\mathbb{E}[\|G\|_2 B(G)]$ is finite. Now suppose $\mathrm{KSD}_k(\mu_N, P) \to 0$ for a sequence of probability measures $(\mu_N)_{N\ge1}$. For any $\epsilon > 0$, $\limsup_n d_{BL_{\|\cdot\|_2}}(\mu_N, P) \le \epsilon$, since $H(t)$ is finite for all $t > 0$. Hence, $d_{BL_{\|\cdot\|_2}}(\mu_N, P) \to 0$, and, as $d_{BL_{\|\cdot\|_2}}$ metrizes weak convergence, $\mu_N \Rightarrow P$.

B.1 Proof of Theorem B.1: Tilted KSD lower bound

Our proof parallels that of [11, Thm. 13]. Fix any $h \in BL_{\|\cdot\|_2}$. Since $A \in C^1$ is positive, Thm. 5 and Sec. 4.2 of Gorham et al. [12] imply that there exists a $g \in C^1$ which solves the Stein equation $\mathcal{T}_P(Ag) = h - \mathbb{E}_P[h(Z)]$ and satisfies $M_0(Ag) \le \mathcal{M}_P$ for $\mathcal{M}_P$ a constant independent of A, h, and g. Since $1/A \in L^2$, we have $\|g\|_{L^2} \le \mathcal{M}_P\|1/A\|_{L^2}$.

Since $\nabla \log A$ is bounded, $A(x) \le \exp(\gamma\|x\|)$ for some γ. Moreover, any measure in $\mathcal{P}$ is sub-Gaussian, so P has finite exponential moments. Hence, since A is also positive, we may define the tilted probability measure P_A with density proportional to Ap. The identity $\mathcal{T}_P(Ag) = A\mathcal{T}_{P_A} g$ implies that

$$M_0(A\nabla\mathcal{T}_{P_A} g) = M_0(\nabla\mathcal{T}_P(Ag) - \mathcal{T}_P(Ag)\nabla\log A) \le 1 + M_1(\log A).$$

Since b and $\nabla \log A$ are Lipschitz, we may apply the following lemma, proved in Appendix B.2 to deduce that there is a function $g_\epsilon \in \mathcal{K}_{k_1}^d$ for $k_1(x,y) := \Psi(x-y)$ such that $|(\mathcal{T}_P(Ag_\epsilon))(x) - (\mathcal{T}_P(Ag))(x)| = A(x)|(\mathcal{T}_{P_A}g_\epsilon)(x) - (\mathcal{T}_{P_A}g)(x)| \le \epsilon$ for all x with norm

$$\begin{aligned}&\|g_\epsilon\|_{\mathcal{K}_{k_1}^d} \\ &\le (2\pi)^{-d/4} H\big(\mathbb{E}[\|G\|_2 B(G)](1 + M_1(\log A) + \mathcal{M}_P M_1(b + \nabla\log A))\epsilon^{-1}\big)^{1/2}\|1/A\|_{L^2}\mathcal{M}_P.\end{aligned} \tag{4}$$

Lemma B.2 (Stein approximations with finite RKHS norm)**.** *Consider a function $A : \mathbb{R}^d \to \mathbb{R}$ satisfying $B(y) := \sup_{x \in \mathbb{R}^d, u \in [0,1]} A(x)/A(x+uy)$. Suppose $g : \mathbb{R}^d \to \mathbb{R}^d$ is in $L^2 \cap C^1$. If P has Lipschitz log density, and $k(x,y) = \Psi(x-y)$ for $\Psi \in C^2$ with generalized Fourier transform $\hat{\Psi}$, then for every $\epsilon \in (0,1]$, there is a function $g_\epsilon : \mathbb{R}^d \to \mathbb{R}^d$ such that $|(\mathcal{T}_P g_\epsilon)(x) - (\mathcal{T}_P g)(x)| \leq \epsilon/A(x)$ for all $x \in \mathbb{R}^d$ and*

$$\|g_\epsilon\|_{\mathcal{K}_k^d} \leq (2\pi)^{-d/4} H\big(\mathbb{E}[\|G\|_2 B(G)](M_0(A\nabla\mathcal{T}_P g) + M_0(Ag)M_1(b))\epsilon^{-1}\big)^{1/2}\|g\|_{L^2},$$

where $H(t) := \sup_{\omega \in \mathbb{R}^d} e^{-\|\omega\|_2^2/(2t^2)}/\hat{\Psi}(\omega)$ and G is a standard Gaussian vector.

Since $\|Ag_\epsilon\|_{\mathcal{K}_k^d} = \|g_\epsilon\|_{\mathcal{K}_{k_1}^d}$, the triangle inequality and the definition of the KSD now yield

$$\begin{aligned}|\mathbb{E}_\mu[h(X)] - \mathbb{E}_P[h(Z)]| &= |\mathbb{E}_\mu[(\mathcal{T}_P(Ag))(X)]| \\ &\leq |\mathbb{E}[(\mathcal{T}_P(Ag))(X) - (\mathcal{T}_P(Ag_\epsilon))(X)]| + |\mathbb{E}_\mu[(\mathcal{T}_P(Ag_\epsilon))(X)]| \\ &\leq \epsilon + \|g_\epsilon\|_{\mathcal{K}_{k_1}^d}\ \mathrm{KSD}_k(\mu, P).\end{aligned}$$

The advertised conclusion follows by applying the bound (4) and taking the supremum over all $h \in BL_{\|\cdot\|}$.

B.2 Proof of Lemma B.2: Stein approximations with finite RKHS norm

Assume $M_0(A\nabla\mathcal{T}_P g) + M_0(Ag) < \infty$, as otherwise the claim is vacuous. Our proof parallels that of Gorham and Mackey [11, Lem. 12]. Let Y denote a standard Gaussian vector with density ρ. For each $\delta \in (0,1]$, we define $\rho_\delta(x) = \delta^{-d}\rho(x/\delta)$, and for any function f we write $f_\delta(x) \triangleq \mathbb{E}[f(x+\delta Y)]$. Under our assumptions on $h = \mathcal{T}_P g$ and B, the mean value theorem and Cauchy-Schwarz imply that for each $x \in \mathbb{R}^d$ there exists $u \in [0,1]$ such that

$$\begin{aligned}|h_\delta(x) - h(x)| &= |\mathbb{E}_\rho[h(x+\delta Y) - h(x)]| = |\mathbb{E}_\rho[\langle \delta Y, \nabla h(x+\delta Y u)\rangle]| \\ &\leq \delta M_0(A\nabla\mathcal{T}_P g)\,\mathbb{E}_\rho[\|Y\|_2/A(x+\delta Y u)] \leq \delta M_0(A\nabla\mathcal{T}_P g)\,\mathbb{E}_\rho[\|Y\|_2 B(Y)]/A(x).\end{aligned}$$

Now, for each $x \in \mathbb{R}^d$ and $\delta > 0$,

$$\begin{aligned}h_\delta(x) &= \mathbb{E}_\rho[\langle b(x+\delta Y), g(x+\delta Y)\rangle] + \mathbb{E}[\langle \nabla, g(x+\delta Y)\rangle] \quad \text{and} \\ (\mathcal{T}_P g_\delta)(x) &= \mathbb{E}_\rho[\langle b(x), g(x+\delta Y)\rangle] + \mathbb{E}[\langle \nabla, g(x+\delta Y)\rangle],\end{aligned}$$

so, by Cauchy-Schwarz, the Lipschitzness of b, and our assumptions on g and B,

$$\begin{aligned}|(\mathcal{T}_P g_\delta)(x) - h_\delta(x)| &= |\mathbb{E}_\rho[\langle b(x) - b(x+\delta Y), g(x+\delta Y)\rangle]| \\ &\leq \mathbb{E}_\rho[\|b(x) - b(x+\delta Y)\|_2 \|g(x+\delta Y)\|_2] \\ &\leq M_0(Ag)M_1(b)\,\delta\,\mathbb{E}_\rho[\|Y\|_2/A(x+\delta Y)] \leq M_0(Ag)M_1(b)\,\delta\,\mathbb{E}_\rho[\|Y\|_2 B(Y)]/A(x).\end{aligned}$$

Thus, if we fix $\epsilon > 0$ and define $\tilde{\epsilon} = \epsilon/(\mathbb{E}_\rho[\|Y\|_2 B(Y)](M_0(A\nabla\mathcal{T}_P g) + M_0(Ag)M_1(b)))$, the triangle inequality implies

$$|(\mathcal{T}_P g_{\tilde{\epsilon}})(x) - (\mathcal{T}_P g)(x)| \leq |(\mathcal{T}_P g_{\tilde{\epsilon}})(x) - h_{\tilde{\epsilon}}(x)| + |h_{\tilde{\epsilon}}(x) - h(x)| \leq \epsilon/A(x).$$

To conclude, we will bound $\|g_\delta\|_{\mathcal{K}_k^d}$. By Wendland [29, Thm. 10.21],

$$\begin{aligned}\|g_\delta\|_{\mathcal{K}_k^d}^2 &= (2\pi)^{-d/2}\int_{\mathbb{R}^d} \frac{|\hat{g_\delta}(\omega)|^2}{\hat{\Phi}(\omega)}\,d\omega = (2\pi)^{d/2}\int_{\mathbb{R}^d} \frac{|\hat{g}(\omega)|^2 \hat{\rho}_\delta(\omega)^2}{\hat{\Phi}(\omega)}\,d\omega \\ &\leq (2\pi)^{-d/2}\left\{\sup_{\omega \in \mathbb{R}^d} \frac{e^{-\|\omega\|_2^2\delta^2/2}}{\hat{\Phi}(\omega)}\right\}\int_{\mathbb{R}^d} |\hat{g}(\omega)|^2\,d\omega,\end{aligned}$$

where we have used the Convolution Theorem [29, Thm. 5.16] and the identity $\hat{\rho_\delta}(\omega) = \hat{\rho}(\delta\omega)$. Finally, an application of Plancherel's theorem [14, Thm. 1.1] gives $\|g_\delta\|_{\mathcal{K}_k^d} \leq (2\pi)^{-d/4}F(\delta^{-1})^{1/2}\|g\|_{L^2}$.

C Proof of Proposition 3.3

We begin by establishing the ΦSD convergence claim. Define the target mean $m_P := \mathbb{E}_{Z\sim P}[Z]$. Since $\log A$ is Lipschitz and $A > 0$, $A_N \le Ae^{m_N}$ and hence $P(A_N) < \infty$ and $\mathbb{E}_P\left[A_N(Z)\|Z\|_2^2\right] < \infty$ for all N by our integrability assumptions on P.

Suppose $\mathcal{W}_{A_N}(Q_N, P) \to 0$, and, for any probability measure μ with $\mu(A_N) < \infty$, define the tilted probability measure μ_{A_N} via $d\mu_{A_N}(x) = d\mu(x)A_N(x)$. By the definition of $\mathcal{W}_{A_N}$, we have $|Q_N(A_N h) - P(A_N h)| \to 0$ for all $h \in \mathcal{H}$. In particular, since the constant function $h(x) = 1$ is in $\mathcal{H}$, we have $|Q_N(A_N) - P(A_N)| \to 0$. In addition, since the functions $f_N(x) = (x - m_N)/A_N(x)$ are uniformly Lipschitz in N, we have $m_N - m_P = Q_N(f_N) - P(f_N) \to 0$ and thus $A_N \to A_P$ for $A_P(x) := A(x - m_P) > 0$. Therefore, $P(A_N) \to P(A_P) > 0$, and, as x/y is a continuous function of (x, y) when $y > 0$, we have

$$Q_{N,A_N}(h) - P_{A_N}(h) = Q_N(A_N h)/Q_N(A_N) - P(A_N h)/P(A_N) \to 0$$

and hence the 1-Wasserstein distance $d_{\mathcal{H}}(Q_{N,A_N}, P_{A_N}) \to 0$.

Now note that, for any $g \in \mathcal{G}_{\Phi/A_N,r}$,

$$\begin{aligned}
Q_N(\mathcal{T}A_N g) &= Q_N(A_N \mathcal{T}_{P_{A_N}} g) = Q_N(A_N)Q_{N,A_N}(\mathcal{T}_{P_{A_N}} g) \\
&= ((Q_N(A_N) - P(A_N)) + P(A_N))Q_{N,A_N}(\mathcal{T}_{P_{A_N}} g) \\
&\le (\mathcal{W}_{A_N}(Q_N, P) + P(A_N))Q_{N,A_N}(\mathcal{T}_{P_{A_N}} g)
\end{aligned}$$

where $\mathcal{T}_{P_{A_N}}$ is the Langevin operator for the tilted measure P_{A_N}, defined by

$$(\mathcal{T}_{P_{A_N}} g)(x) = \sum_{d=1}^{D} (p(x)A_N(x))^{-1}\partial_{x_d}(p(x)A_N(x)g_d(x)).$$

Taking a supremum over $g \in \mathcal{G}_{\Phi/A_N,r}$, we find

$$\Phi\mathrm{SD}_{\Phi,r}(Q_N, P) \le (\mathcal{W}_{A_N}(Q_N, P) + P(A_N))\, \Phi\mathrm{SD}_{\Phi/A_N,r}(Q_{N,A_N}, P_{A_N}).$$

Furthermore, since $\Phi(x, z)/A_N(x) = F(x - z)$, Hölder's inequality implies

$$\begin{aligned}
\sup_{x\in\mathbb{R}^D} \|g(x)\|_\infty &\le \|F\|_{L^r}, \\
\sup_{x\in\mathbb{R}^D, d\in[D]} \|\partial_{x_d} g(x)\|_\infty &\le \|\partial_{x_d} F\|_{L^r}, \quad \text{and} \\
\sup_{x\in\mathbb{R}^D, d,d'\in[D]} \left\|\partial_{x_d}\partial_{x_{d'}} g(x)\right\|_\infty &\le \left\|\partial_{x_d}\partial_{x_{d'}} F\right\|_{L^r}
\end{aligned}$$

for each $g \in \mathcal{G}_{\Phi/A_N,r}$. Since $\nabla \log p$ and $\nabla \log A_N$ are Lipschitz and $\mathbb{E}_P\left[A_N(Z)\|Z\|_2^2\right] < \infty$, we may therefore apply [11, Lem. 18] to discover that $\Phi\mathrm{SD}_{\Phi/A_N,r}(Q_{N,A_N}, P_{A_N}) \to 0$ and hence $\Phi\mathrm{SD}_{\Phi,r}(Q_N, P) \to 0$ whenever the 1-Wasserstein distance $d_{\mathcal{H}}(Q_{N,A_N}, P_{A_N}) \to 0$.

To see that $\mathrm{R}\Phi\mathrm{SD}^2_{\Phi,r,\nu_N,M_N}(Q_N, P) \xrightarrow{P} 0$ whenever $\Phi\mathrm{SD}^2_{\Phi,r}(Q_N, P) \to 0$, first note that since $r \in [1, 2]$, we may apply Jensen's inequality to obtain

$$\begin{aligned}
\mathbb{E}[\mathrm{R}\Phi\mathrm{SD}^2_{\Phi,r,\nu_N,M_N}(Q_N, P)] &= \mathbb{E}[\textstyle\sum_{d=1}^{D}(\frac{1}{M}\sum_{m=1}^{M} \nu_N(Z_m)^{-1}|Q_N(\mathcal{T}_d\Phi)(Z_m)|^r)^{2/r}] \\
&\le \textstyle\sum_{d=1}^{D}(\mathbb{E}[\frac{1}{M}\sum_{m=1}^{M} \nu_N(Z_m)^{-1}|Q_N(\mathcal{T}_d\Phi)(Z_m)|^r])^{2/r} \\
&= \Phi\mathrm{SD}^2_{\Phi,r}(Q_N, P).
\end{aligned}$$

Hence, by Markov's inequality, for any $\epsilon > 0$,

$$\mathbb{P}[\mathrm{R}\Phi\mathrm{SD}^2_{\Phi,r,\nu_N,M_N}(Q_N, P) > \epsilon] \le \mathbb{E}[\mathrm{R}\Phi\mathrm{SD}^2_{\Phi,r,\nu_N,M_N}(Q_N, P)]/\epsilon \le \Phi\mathrm{SD}^2_{\Phi,r}(Q_N, P)/\epsilon \to 0,$$

yielding the result.

D Proof of Proposition 3.6

To achieve the first conclusion, for each $d \in [D]$, apply Corollary M.2 with δ/D in place of δ to the random variable

$$\tfrac{1}{M}\sum_{m=1}^{M} w_d(Z_m, Q_N).$$

The first claim follows by plugging in the high probability lower bounds from Corollary M.2 into $\mathrm{R\Phi SD}^2_{\Phi,r,\nu,M}(Q_N, P)$ and using the union bound.

The equality $\mathbb{E}[Y_d] = \Phi\mathrm{SD}^r_{\Phi,r}(Q_N, P)$, the KSD-ΦSD inequality of Proposition 3.1 ($\Phi\mathrm{SD}^r_{\Phi,r}(Q_N, P) \geq \mathrm{KSD}^r_k(Q_N, P)\|\rho\|^{-r/2}_{L^t}$), and the assumption $\mathrm{KSD}_k(Q_N, P) \gtrsim N^{-1/2}$ imply that $\mathbb{E}[Y_d] \gtrsim N^{-r/2}\|\rho\|^{-r/2}_{L^t}$. Plugging this estimate into the initial importance sample size requirement and applying the KSD-ΦSD inequality once more yield the second claim.

E Proof of Proposition 3.7

It turns out that we obtain $(C, 1)$ moments whenever the weight functions $w_d(z, Q_N)$ are bounded. Let $\mathcal{Q}(\Phi, \nu, C') := \{Q_N \mid \sup_{z,d} w_d(z, Q_N) < C'\}$.

Proposition E.1. *For any $C > 0$, (Φ, r, ν) yields $(C, 1)$ second moments for P and $\mathcal{Q}(\Phi, \nu, C')$.*

Proof It follows from the definition of $\mathcal{Q}(\Phi, \nu, C)$ that

$$\sup_{Q_N \in \mathcal{Q}(\Phi,\nu,C)} \sup_{d,z} |(Q_N \mathcal{T}_d \Phi)(z)|^r/\nu(z) \leq C.$$

Hence for any $Q_N \in \mathcal{Q}(\Phi, \nu, C)$ and $d \in [D]$, $Y_d \leq C$ a.s. and thus

$$\mathbb{E}[Y_d^2] \leq C'\mathbb{E}[Y_d].$$

□

Thus, to prove Proposition 3.7 it suffices to have uniform bound for $w_d(z, Q_N)$ for all $Q_N \in \mathcal{Q}(\mathcal{C}')$. Let $\sigma(x) := 1 + \|x\|$ and fix some $Q \in \mathcal{Q}(\mathcal{C}')$. Then $\nu(z) = Q_N(\sigma\Phi(\cdot, z))/C(Q_N)$, where $C(Q_N) := \|F\|_{L^1}\mathcal{Q}(\sigma A(\cdot - m_N)) \leq \|F\|_{L^1}\mathcal{C}'$. Moreover, for $c, c' > 0$ not depending on Q_N,

$$\begin{aligned}
|(Q_N \mathcal{T}_d \Phi)(z)|^r &\leq Q_N(|\partial_d \log p + \partial_d \log A(\cdot - m_N) + \partial_d \log F(\cdot - z)|\Phi(\cdot, z))^r \\
&\leq c Q_N(|1 + \|\cdot\| + \|\cdot - m_N\|^a|\Phi(\cdot, z))^r \\
&\leq c'(\mathcal{C}')^{r-1} Q_N(\sigma\Phi(\cdot, z)).
\end{aligned}$$

Thus,

$$w_d(z, Q_N) = \frac{|(Q_N \mathcal{T}_d \Phi)(z)|^r}{\nu(z)} \leq \frac{C(\mathcal{Q})c'(\mathcal{C}')^{r-1} Q_N(\sigma\Phi(\cdot, z))}{Q_N(\sigma\Phi(\cdot, z))} \leq c'(\mathcal{C}')^r \|F\|_{L^1}.$$

F Technical Lemmas

Lemma F.1. *If $P \in \mathcal{P}$, Assumptions A to D hold, and (3) holds, then for any $\lambda \in (1/2, \overline{\lambda})$,*

$$|(Q_N \mathcal{T}_d \Phi)(z)| \leq C_{\lambda,\mathcal{C}}\, \mathrm{KSD}^{2\lambda-1}_{k_d}.$$

Proof Let $\varsigma_d(\omega) := (1 + \omega_d)^{-1} Q_N(\mathcal{T}_d A(\cdot - m_N) e^{-i\omega \cdot \cdot})$. Applying Proposition H.1 with $\mathcal{D} = Q_N \mathcal{T}_d A(\cdot - m_N)$, $h = F$, $\varrho(\omega) = 1 + \omega_d$, and $t = 1/2$ yields

$$|(Q_N \mathcal{T}_d \Phi)(z)| \leq \|F\|_{\Psi^{(\lambda)}} \left(\|\varsigma_d\|_{L^\infty} \|(1 + \partial_d)\Psi^{(1/4)}\|_{L^2}\right)^{2-2\lambda} \|Q_N \mathcal{T}_d \Phi\|^{2\lambda-1}_{\Psi}$$

The finiteness of $\|F\|_{\Psi^{(\lambda)}}$ follows from Assumption C. Using $P \in \mathcal{P}$, Assumption A, and (3) we have

$$\begin{aligned}
\varsigma_d(\omega) &= (1 + \omega_d)^{-1} Q_N([\partial_d \log p + \partial_d \log A(\cdot - m_N) - i\omega_d] A(\cdot - m_N) e^{-i\omega \cdot \cdot}) \\
&\leq C Q_N([1 + \|\cdot\|] A(\cdot - m_N) \\
&\leq C\mathcal{C}',
\end{aligned}$$

so $\|\varsigma_d\|_{L^\infty}$ is finite. The finiteness of $\|(1+\partial_d)\Psi^{(1/4)}\|_{L^2}$ follows from the Plancherel theorem and Assumption D. The result now follows upon noting that $\|Q_N \mathcal{T}_d \Phi\|_{\Psi} = \mathrm{KSD}_{k_d}$. ☐

Lemma F.2. *If $P \in \mathcal{P}$, Assumptions A and B hold, and (3) holds, then for some $b \in [0,1), C_b > 0$,*

$$|Q_N \mathcal{T}_d \Phi(z)| \leq C_b F(z - m_N)^{1-b}.$$

Moreover, $b = 0$ if $s = 0$.

Proof We have (with C a constant changing line to line)

$$\begin{aligned}
|Q_N \mathcal{T}_d \Phi(z)| &\leq Q_N |\mathcal{T}_d \Phi(\cdot, z)| \\
&= Q_N(|\partial_d \log p + \partial_d \log A(\cdot - m_N) + \partial_d \log F(\cdot - z)| A(\cdot - m_N) F(\cdot - z)) \\
&\leq C Q_N(|1 + \|\cdot\| + \|\cdot - z\|^s | A(\cdot - m_N) F(\cdot - m_N)^{-1}) F(z - m_N) \\
&\leq C Q_N(|1 + \|\cdot\| + \|\cdot - m_N\|^s + \|z - m_N\|^s | A(\cdot - m_N) F(\cdot - m_N)^{-1}) F(z - m_N) \\
&\leq C \mathcal{C}(1 + \|z - m_N\|^s) F(z - m_N).
\end{aligned}$$

By assumption $(1 + \|z\|^s) F(z) \to 0$ as $\|z\| \to \infty$, so for some $C_b > 0$ and $b \in [0,1)$, $(1 + \|z - m_N\|^s) \leq C_b F(z)^{-b}$. ☐

G Proof of Theorem 3.8: (C, γ) second moment bounds for $\mathrm{R\Phi SD}$

Take $Q_N \in \mathcal{Q}(\mathcal{C})$ fixed and let $w_d(z) := w_d(z, Q_N)$. For a set S let $\nu_S(S') := \int_{S \cap S'} \nu(\mathrm{d}z)$. Let $K := \{x \in \mathbb{R}^D \mid \|x - m_N\| \leq R\}$. Recall that $Z \sim \nu$ and $Y_d = w_d(Z)$. We have

$$\begin{aligned}
\mathbb{E}[Y_d^2] &= \mathbb{E}[w_d(Z)^2] = \mathbb{E}[w_d(Z)^2 \mathbb{1}(Z \in K)] + \mathbb{E}[w_d(Z)^2 \mathbb{1}(Z \notin K)] \\
&\leq \|w_d\|_{L^1(\nu)} \|w_d \mathbb{1}(\cdot \in K)\|_{L^\infty(\nu)} + \|\mathbb{1}(\cdot \notin K)\|_{L^1(\nu)} \|w_d^2 \mathbb{1}(\cdot \notin K)\|_{L^\infty(\nu)} \\
&= \|Q_N \mathcal{T}_d \Phi\|_{L^r}^r \sup_{z \in K} w_d(z) + \nu(K^\complement) \sup_{z \in K^\complement} w_d(z)^2 \\
&= \mathbb{E}[Y_d] \sup_{z \in K} w_d(z) + \nu(K^\complement) \sup_{z \in K^\complement} w_d(z)^2
\end{aligned}$$

Without loss of generality we can take $\nu(z) = \Psi(z - m_N)^{\xi r} / \|\Psi^{\xi r}\|_{L^1}$, since a different choice of ν only affects constant factors. Applying Lemma F.1, Assumption D, and (2), we have

$$\begin{aligned}
\sup_{z \in K} w_d(z) &\leq C_{\lambda,\mathcal{C}}^r \, \mathrm{KSD}_{k_d}^{r(2\lambda - 1)} \sup_{z \in K} \nu(z)^{-1} \\
&\leq C_{\lambda,\mathcal{C}}^r \|\Psi^{\xi r}\|_{L^1} \sup_{z \in K} F(z - m_N)^{-\xi r} \, \mathrm{KSD}_{k_d}^{r(2\lambda - 1)} \\
&\leq C_{\lambda,\mathcal{C}}^r \underline{c}^{-\xi r} \|\Psi^{\xi r}\|_{L^1} \|\hat{\Psi}/\hat{F}^2\|_{L^t} f(R)^{-\xi r} \|Q_N \mathcal{T}_d \Phi\|_{L^r}^{r(2\lambda - 1)} \\
&= C_{\lambda,\mathcal{C}}^r \|(\Psi/\underline{c})^{\xi r}\|_{L^1} \|\hat{\Psi}/\hat{F}^2\|_{L^t} f(R)^{-\xi r} \mathbb{E}[Y_d]^{2\lambda - 1}.
\end{aligned}$$

Applying Lemma F.2 we have

$$\begin{aligned}
\sup_{z \in K^\complement} w_d(z)^2 &\leq C_b^2 \sup_{z \in K^\complement} F(z - m_N)^{2(1-b)r} / \nu(z)^2 \\
&= C_b^2 \|\Psi^{\xi r}\|_{L^1}^2 \sup_{z \in K^\complement} F(z - m_N)^{2(1-b-\xi)r} \\
&= C_b^2 \|\Psi^{\xi r}\|_{L^1}^2 f(R)^{2(1-b-\xi)r}.
\end{aligned}$$

Thus, we have that

$$\mathbb{E}[Y_d^2] \leq C_{\lambda,\mathcal{C},r,\xi} \mathbb{E}[Y_d]^{2\lambda} f(R)^{-\xi r} + C_{b,\xi r} f(R)^{2(1-b-\xi)r}.$$

As long as $\mathbb{E}[Y_d]^{2\lambda} \leq C_{b,\xi r} f(0)^{2(1-b-\xi/2)r} / C_{\lambda,\mathcal{C},r,\xi}$, since f is continuous and non-increasing to zero we can choose R such that $f(R)^{2(1-b-\xi)r} = C_{\lambda,\mathcal{C},r,\xi} \mathbb{E}[Y_d]^{2\lambda} / C_{b,\xi r}$ and the result follows for

$$\mathbb{E}[Y_d]^{2\lambda} \leq C_{b,\xi r} f(0)^{2(1-b-\xi/2)r} / C_{\lambda,\mathcal{C},r,\xi}.$$

Otherwise, we can guarantee that $\mathbb{E}[Y_d^2] \leq C_\alpha \mathbb{E}[Y_d]^{2-\gamma_\alpha}$ be choosing C_α sufficiently large, since by assumption $\mathbb{E}[Y_d]$ is uniformly bounded over $Q_N \in \mathcal{Q}(\mathcal{C})$.

H A uniform MMD-type bound

Let $\mathcal{D}$ denote a tempered distribution and Ψ a stationary kernel. Also, define $\hat{\mathcal{D}}(\omega) := \mathcal{D}_x e^{-i\langle \omega, \hat{x}\rangle}$.

Proposition H.1. *Let h be a symmetric function such that for some $s \in (0,1]$, $h \in \mathcal{K}_{\Psi^{(s)}}$ and $\mathcal{D}_x h(\hat{x} - \cdot) \in \mathcal{K}_{\Psi^{(s)}}$. Then*

$$|\mathcal{D}_x h(\hat{x} - z)| \leq \|h\|_{\Psi^{(s)}} \left\|\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\right\|_{\Psi^{(s)}}$$

and for any $t \in (0,s)$ any function $\varrho(\omega)$,

$$\left\|\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\right\|_{\Psi^{(s)}}^{1-t} \leq \left(\left\|\varrho^{-1}\hat{\mathcal{D}}\right\|_{L^\infty} \left\|\varrho \hat{\Psi}^{t/2}\right\|_{L^2}\right)^{1-s} \|\mathcal{D}_x \Psi(\hat{x} - \cdot)\|_{\Psi}^{s-t}.$$

Furthermore, if for some $c > 0$ and $r \in (0, s/2)$, $\hat{h} \leq c\,\hat{\Psi}^r$, then

$$\|h\|_{\Psi^{(s)}} \leq \frac{c\left\|\Psi^{(r-s/2)}\right\|_{L^2}}{(2\pi)^{d/4}}.$$

Proof The first inequality follows from an application of Cauchy-Schwartz:

$$\begin{aligned}
|\mathcal{D}_x h(\hat{x} - z)| &= |\langle h(\cdot - z), \mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\rangle_{\Psi^{(s)}}| \\
&\leq \|h(\cdot - z)\|_{\Psi^{(s)}} \left\|\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\right\|_{\Psi^{(s)}} \\
&= \|h\|_{\Psi^{(s)}} \left\|\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\right\|_{\Psi^{(s)}}.
\end{aligned}$$

For the first norm, we have

$$\begin{aligned}
\|h\|_{\Phi^{(s)}}^2 &= (2\pi)^{-d/2} \int \frac{\hat{h}^2(\omega)}{\hat{\Phi}^s(\omega)}\, \mathrm{d}\omega \\
&\leq c^2 (2\pi)^{-d/2} \int \hat{\Phi}^{2r-s}(\omega)\, \mathrm{d}\omega \\
&= c^2 (2\pi)^{-d/2} \left\|\Psi^{(r-s/2)}\right\|_{L^2}^2.
\end{aligned}$$

Note that by the convolution theorem $\mathscr{F}(\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot))(\omega) = \hat{\mathcal{D}}(\omega)\hat{\Psi}^s(\omega)$. For the second norm, applying Jensen's inequality and Hölder's inequality yields

$$\begin{aligned}
\left\|\mathcal{D}_x \Psi^{(s)}(\hat{x} - \cdot)\right\|_{\Psi^{(s)}}^2 &= (2\pi)^{-d/2} \int \frac{\hat{\Psi}(\omega)^{2s}|\hat{\mathcal{D}}(\omega)|^2}{\hat{\Psi}^s(\omega)}\, \mathrm{d}\omega \\
&= (2\pi)^{-d/2} \left(\int \hat{\Psi}^t |\hat{\mathcal{D}}|^2\right) \int \frac{\hat{\Psi}(\omega)^t |\hat{\mathcal{D}}(\omega)|^2}{\int \hat{\Psi}^t |\hat{\mathcal{D}}|^2} \hat{\Psi}(\omega)^{s-t}\, \mathrm{d}\omega \\
&\leq (2\pi)^{-d/2} \left(\int \hat{\Psi}^t |\hat{\mathcal{D}}|^2\right) \left(\int \frac{\hat{\Psi}(\omega)^t |\hat{\mathcal{D}}(\omega)|^2}{\int \hat{\Psi}^t |\hat{\mathcal{D}}|^2} \Psi(\omega)^{1-t}\, \mathrm{d}\omega\right)^{\frac{s-t}{1-t}} \\
&= \left(\int \hat{\Psi}^t |\hat{\mathcal{D}}|^2\right)^{\frac{1-s}{1-t}} \|\mathcal{D}_x \Psi(\hat{x} - \cdot)\|_{\Psi}^{2\frac{s-t}{1-t}} \\
&\leq \left(\left\||\varrho^{-1}\hat{\mathcal{D}}|^2\right\|_{L^\infty} \int \varrho^2 \hat{\Psi}^t\right)^{\frac{1-s}{1-t}} \|\mathcal{D}_x \Psi(\hat{x} - \cdot)\|_{\Psi}^{2\frac{s-t}{1-t}} \\
&= \left(\left\|\varrho^{-1}\hat{\mathcal{D}}\right\|_{L^\infty}^2 \left\|\varrho \hat{\Psi}^{t/2}\right\|_{L^2}^2\right)^{\frac{1-s}{1-t}} \|\mathcal{D}_x \Psi(\hat{x} - \cdot)\|_{\Psi}^{2\frac{s-t}{1-t}}.
\end{aligned}$$

□

I Verifying Example 3.3: Tilted hyperbolic secant $\mathrm{R\Phi SD}$ properties

We verify each of the assumptions in turn. By construction or assumption each condition in Assumption A holds. Note in particular that $\Psi_{2a}^{\mathrm{sech}} \in C^\infty$. Since $e^{-a|x_d|} \le \mathrm{sech}(ax_d) \le 2e^{-a|x_d|}$, Assumption B holds with $\|\cdot\| = \|\cdot\|_1$, $f(R) = 2^d e^{-\sqrt{\frac{\pi}{2}}aR}$, and $\underline{c} = 2^{-d}$, and $s = 1$. In particular,

$$\begin{aligned}\partial_{x_d} \log \Psi_{2a}^{\mathrm{sech}}(x) &= \sqrt{2\pi}\, a \tanh(\sqrt{2\pi}\, a x_d) + \textstyle\sum_{d' \ne d}^{D} \log \mathrm{sech}(\sqrt{2\pi}\, a x_{d'}) \\ &\le (\sqrt{2\pi}\, a)(1 + \textstyle\sum_{d' \ne d}^{D} |x_{d'}|) \\ &\le (\sqrt{2\pi}\, a)(1 + \|x\|_1)\end{aligned}$$

and using Proposition L.3 we have that

$$\Psi_a^{\mathrm{sech}}(x - z) \le e^{\sqrt{\frac{\pi}{2}}a\|x\|_1} \Psi_a^{\mathrm{sech}}(z) \le 2^d \Psi_a^{\mathrm{sech}}(z)/\Psi_a^{\mathrm{sech}}(x).$$

Assumption C holds with $\overline{\lambda} = 1$ since for any $\lambda \in (0, 1)$, it follow from Proposition L.2 that

$$\widehat{f}_j/\hat{\Phi}_j^{\lambda/2} = \hat{\Psi}_{2a}^{\mathrm{sech}}/(\hat{\Psi}_a^{\mathrm{sech}})^{\lambda/2} \le 2^{d/2}(\hat{\Psi}_{2a}^{\mathrm{sech}})^{1-\lambda} \in L^2.$$

The first part of Assumption D holds as well since by (6), $\omega_d^2 \hat{\Psi}_a^{\mathrm{sech}}(\omega) = a^{-D}\omega_d^2 \Psi_{1/a}^{\mathrm{sech}}(\omega) \in L^1$.

Finally, to verify the second part of Assumption D, we first note that since $r = 2$, $t = \infty$. The assumption holds since by Proposition L.2, $\hat{\Psi}_a^{\mathrm{sech}}(\omega)/\hat{\Psi}_{2a}^{\mathrm{sech}}(\omega)^2 \le 1$.

J Verifying Example 3.4: IMQ $\mathrm{R\Phi SD}$ properties

We verify each of the assumptions in turn. By construction or assumption each condition in Assumption A holds. Note in particular that $\Psi_{c',\beta'}^{\mathrm{IMQ}} \in C^\infty$. Assumption B holds with $\|\cdot\| = \|\cdot\|_2$, $f(R) = ((c')^2 + R^2)^{\beta'}$, $\underline{c} = 1$, and $s = 0$. In particular,

$$|\partial_{x_d} \log \Psi_{c',\beta'}^{\mathrm{IMQ}}(x)| \le -\frac{2\beta'|x_d|}{(c')^2 + \|x\|_2^2} \le -2\beta'$$

and

$$\begin{aligned}\frac{\Psi_{c',\beta'}^{\mathrm{IMQ}}(x - z)}{\Psi_{c',\beta'}^{\mathrm{IMQ}}(z)} &= \left(\frac{(c')^2 + \|x - z\|_2^2}{(c')^2 + \|z\|_2^2}\right)^{-\beta'} \\ &\le \left(\frac{(c')^2 + 2\|z\|_2^2 + 2\|x\|_2^2}{(c')^2 + \|z\|_2^2}\right)^{-\beta'} \\ &\le \left(2 + 2\|x\|_2^2/(c')^2\right)^{-\beta'} \\ &= 2^{-\beta}\Psi_{c',\beta'}^{\mathrm{IMQ}}(x)^{-1}.\end{aligned}$$

By Wendland [29, Theorem 8.15], $\Psi_{c,\beta}^{\mathrm{IMQ}}$ has generalized Fourier transform

$$\widehat{\Psi_{c,\beta}^{\mathrm{IMQ}}}(\omega) = \frac{2^{1+\beta}}{\Gamma(-\beta)}\left(\frac{\|\omega\|_2}{c}\right)^{-\beta-D/2} K_{\beta+D/2}(c\|\omega\|_2),$$

where $K_v(z)$ is the modified Bessel function of the third kind. We write $a(\ell) \dot\sim b(\ell)$ to denote asymptotic equivalence up to a constant: $\lim_\ell a(\ell)/b(\ell) = c$ for some $c \in (0, \infty)$. Asymptotically [1, eq. 10.25.3],

$$\begin{aligned}&\hat{\Psi}_{c,\beta}^{\mathrm{IMQ}}(\omega) \dot\sim \|\omega\|_2^{-\beta-D/2-1/2} e^{-c\|\omega\|_2}, && \|\omega\|_2 \to \infty \quad \text{and} \\ &\hat{\Psi}_{c,\beta}^{\mathrm{IMQ}}(\omega) \dot\sim \|\omega\|_2^{-(\beta+D/2)-|\beta+D/2|} = \|\omega\|_2^{-(2\beta+D)_+} && \|\omega\|_2 \to 0.\end{aligned}$$

Assumption C holds since for any $\lambda \in (0, \overline{\lambda})$,

$$\begin{aligned}\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'}/(\hat{\Psi}^{\mathrm{IMQ}}_{c,\beta})^{\lambda/2} &\sim \|\omega\|_2^{-(\beta'+D/2-1/2)+(\beta+D/2-1/2)\lambda/2} e^{(-c'+c\lambda/2)\|\omega\|_2}, \quad \|\omega\|_2 \to \infty \quad \text{and} \\ &\sim \|\omega\|_2^{\lambda(2\beta+D)_+/2-(2\beta'+D)_+} = \|\omega\|_2^{\lambda(2\beta+D)/2} \qquad \|\omega\|_2 \to 0,\end{aligned}$$

so $\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'}/(\hat{\Psi}^{\mathrm{IMQ}}_{c,\beta})^{\lambda/2} \in L^2$ as long as $c' = c\overline{\lambda}/2 > c\lambda/2$ and $\lambda(2\beta + D) > -D$. The first condition holds by construction and second condition is always satisfied, since $2\beta + D \geq 0 > -D$.

The first part of Assumption D holds as well since $\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'}(\omega)$ decreases exponentially as $\|\omega\|_2 \to \infty$ and $\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'}(\omega) \sim 1$ as $\|\omega\|_2 \to 0$, so $\omega_d^2 \hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'}(\omega)$ is integrable.

Finally, to verify the second part of Assumption D we first note that $t = r/(2-r) = -D/(D+4\beta'\underline{\xi})$. Thus,

$$\begin{aligned}\hat{\Psi}^{\mathrm{IMQ}}_{c,\beta}/(\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'})^2 &\dot{\sim} \|\omega\|_2^{-2(\beta+D/2-1/2)/2+2(\beta'+D/2-1/2))} e^{2(-c/2+c')\|\omega\|_2}, \quad \|\omega\|_2 \to \infty \quad \text{and} \\ &\dot{\sim} \|\omega\|_2^{2(2\beta'+D)_+-(2\beta+D)_+} = \|\omega\|_2^{-(2\beta+D)} \qquad \|\omega\|_2 \to 0,\end{aligned}$$

so $\hat{\Psi}^{\mathrm{IMQ}}_{c,\beta}/(\hat{\Psi}^{\mathrm{IMQ}}_{c',\beta'})^2 \in L^t$ whenever $c/2 > c'$ and

$$\frac{D}{(D+4\beta'\underline{\xi})}(2\beta + D) > -D \Leftrightarrow -\beta/(2\underline{\xi}) - D/(2\underline{\xi}) > \beta'.$$

Both these conditions hold by construction.

K Proofs of Proposition 4.1 and Theorem 4.3: Asymptotics of $\mathrm{R\Phi SD}$

The proofs of Proposition 4.1 and Theorem 4.3 rely on the following asymptotic result.

Theorem K.1. *Let $\xi_i : \mathbb{R}^D \times \mathcal{Z} \to \mathbb{R}$, $i = 1, \dots, I$, be a collection of functions; let $Z_{N,m} \overset{indep}{\sim} \nu_N$, where ν_N is a distribution on $\mathcal{Z}$; and let $X_n \overset{i.i.d.}{\sim} \mu$, where μ is absolutely continuous with respect to Lebesgue measure. Define the random variables $\xi_{N,nim} := \xi_i(X_n, Z_{N,m})$ and, for $r, s \geq 1$, the random variable*

$$F_{r,s,N} := \left(\sum_{i=1}^I \left(\sum_{m=1}^M \left|N^{-1}\sum_{n=1}^N \xi_{N,nim}\right|^r\right)^{s/r}\right)^{2/s}.$$

Assume that for all $N \geq 1$, $i \in [I]$, and $m \in [M]$, $\xi_{N,1im}$ has a finite second moment that that $\Sigma_{im,i'm'} := \lim_{N\to\infty} \mathrm{Cov}(\xi_{N,im}, \xi_{N,i'm'}) < \infty$ exists for all $i, i \in [I]$ and $m, m' \in [M]$. Then the following statements hold.

1. *If $\varrho_{N,im} := (\mu \times \nu_N)(\xi_i) = 0$ for all $i \in [N]$ then*

$$NF_{r,s,N} \overset{\mathcal{D}}{\Longrightarrow} \left(\sum_{i=1}^I \left(\sum_{m=1}^M |\zeta_{im}|^r\right)^{s/r}\right)^{2/s} \text{ as } N \to \infty, \tag{5}$$

   where $\zeta \sim \mathcal{N}(0, \Sigma)$.

2. *If $\varrho_{N,im} \neq 0$ for some i and m, then*

$$NF_{r,s,N} \overset{a.s.}{\to} \infty \text{ as } N \to \infty.$$

Proof Let $V_{N,im} = N^{-1/2}\sum_{n=1}^N \xi_{N,nim}$. By assumption $\|\Sigma\| < \infty$. Hence, by the multivariate CLT,

$$V_N - N^{1/2}\varrho_N \overset{\mathcal{D}}{\Longrightarrow} \mathcal{N}(0, \Sigma).$$

Observe that $NF_{r,s,N} = (\sum_{i=1}^I(\sum_{m=1}^M |V_{N,im}|^r)^{s/r})^{2/s}$. Hence if $\varrho = 0$, (5) follows from the continuous mapping theorem.

Assume $\varrho_{N,ij} \neq 0$ for some i and j and all $N \geq 0$. By the strong law of large numbers, $N^{-1/2}V_N \overset{a.s.}{\to} \varrho_\infty$. Together with the continuous mapping theorem conclude that $F_{r,s,N} \overset{a.s.}{\to} c$ for some $c > 0$. Hence $NF_{r,s,N} \overset{a.s.}{\to} \infty$. $\square$

When $r = s = 2$, the RΦSD is a degenerate V-statistic, and we recover its well-known distribution [24, Sec. 6.4, Thm. B] as a corollary. A similar result was used in Jitkrittum et al. [16] to construct the asymptotic null for the FSSD, which is degenerate U-statistic.

Corollary K.2. *Under the hypotheses of Theorem K.1(1),*

$$NF_{2,2,N} \overset{\mathcal{D}}{\Longrightarrow} \textstyle\sum_{i=1}^{I}\sum_{m=1}^{M}\lambda_{im}\omega_{im}^2 \text{ as } N \to \infty,$$

where $\lambda = \operatorname{eigs}(\Sigma)$ *and* $\omega_{ij} \overset{i.i.d.}{\sim} \mathscr{N}(0,1)$.

To apply these results to RΦSDs, take $s = 2$ and apply Theorem K.1 with $I = D$, $\xi_{N,dm} = \xi_{r,N,dm}$. Under $H_0 : \mu = P$, $P(\xi_{r,N,dm}) = 0$ for all $d \in [D]$ and $m \in [M]$, so part 1 of Theorem K.1 holds. On the other hand, when $\mu \neq P$, there exists some m and d for which $\mu(\xi_{r,dm}) \neq 0$. Thus, under $H_1 : \mu \neq P$ part 2 of Theorem K.1 holds.

The proof of Theorem 4.3 is essentially identical to that of Jitkrittum et al. [16, Theorem 3].

L Hyperbolic secant properties

Recall that the hyperbolic secant function is given by $\operatorname{sech}(a) = \frac{2}{e^a + e^{-a}}$. For $x \in \mathbb{R}^d$, define the hyperbolic secant kernel

$$\Psi_a^{\text{sech}}(x) := \operatorname{sech}\left(\sqrt{\frac{\pi}{2}}ax\right) := \prod_{i=1}^{d}\operatorname{sech}\left(\sqrt{\frac{\pi}{2}}ax_i\right).$$

It is a standard result that

$$\hat{\Psi}_a^{\text{sech}}(\omega) = a^{-D}\Psi_{1/a}^{\text{sech}}(\omega). \tag{6}$$

We can relate $\Psi_a^{\text{sech}}(x)^\xi$ to $\Psi_{a\xi}^{\text{sech}}(x)$, but to do so we will need the following standard result:

Lemma L.1. *For $a, b \geq 0$ and $\xi \in (0, 1]$,*

$$\frac{a^\xi + b^\xi}{2^{1-\xi}} \leq (a+b)^\xi \leq a^\xi + b^\xi.$$

Proof The lower bound follows from an application of Jensen's inequality and the upper bound follows from the concavity of $a \mapsto a^\xi$. $\square$

Proposition L.2. *For $\xi \in (0, 1]$,*

$$\Psi_a^{\text{sech}}(x)^\xi \leq \Psi_a^{\text{sech}}(\xi x) = \Psi_{a\xi}^{\text{sech}}(x) \leq 2^{d(1-\xi)}\Psi_a^{\text{sech}}(x)^\xi$$
$$2^{-d(1-\xi)}\hat{\Psi}_{a/\xi}^{\text{sech}}(x) \leq \hat{\Psi}_a^{\text{sech}}(x)^\xi \leq \hat{\Psi}_{a/\xi}^{\text{sech}}(x).$$

Thus, $\Psi_{a/\xi}^{\text{sech}}$ is equivalent to $(\Psi_a^{\text{sech}})^{(\xi)}$.

Proof Apply Lemma L.1 and (6). $\square$

Proposition L.3. *For all $x, y \in \mathbb{R}^d$ and $a > 0$,*

$$\Psi_a^{\text{sech}}(x - z) \leq e^{\sqrt{\frac{\pi}{2}}a\|x\|_1}\Psi_a^{\text{sech}}(z).$$

Proof Take $d = 1$ since the general case follows immediately. Without loss of generality assume that $x \geq 0$ and let $a' = \sqrt{\frac{\pi}{2}}a$. Then

$$\frac{\Psi_a^{\text{sech}}(x-z)}{\Psi_a^{\text{sech}}(z)} = \frac{e^{a'z} + e^{-a'z}}{e^{a'(x-z)} + e^{-a'(x-z)}} = \frac{e^{a'z} + e^{-a'z}}{e^{-a'z} + e^{2a'x}e^{a'z}}e^{a'x} \leq e^{a'x}.$$

$\square$

M Concentration inequalities

Theorem M.1 (Chung and Lu [5, Theorem 2.9])**.** *Let $X_1, \dots, X_m$ be independent random variables satisfying $X_i > -A$ for all $i = 1, \dots, m$. Let $X := \sum_{i=1}^m X_i$ and $\overline{X^2} := \sum_{i=1}^m \mathbb{E}[X_i^2]$. Then for all $t > 0$,*

$$\mathbb{P}(X \leq \mathbb{E}[X] - t) \leq e^{-\frac{1}{2}t^2/(\overline{X^2}+At/3)}.$$

Let $\hat{X} := \frac{1}{m}\sum_{i=1}^m X_i$.

Corollary M.2. *Let $X_1, \dots, X_m$ be i.i.d. nonnegative random variables with mean $\bar{X} := \mathbb{E}[X_1]$. Assume there exist $c > 0$ and $\gamma \in [0, 2]$ such that $\mathbb{E}[X_1^2] \leq c\bar{X}^{2-\gamma}$. If, for $\delta \in (0, 1)$ and $\varepsilon \in (0, 1)$,*

$$m \geq \frac{2c\log(1/\delta)}{\varepsilon^2}\bar{X}^{-\gamma},$$

then with probability at least $1-\delta$, $\hat{X} \geq (1-\varepsilon)\bar{X}$.

Proof Applying Theorem M.1 with $t = m\varepsilon\bar{X}$ and $A = 0$ yields

$$\mathbb{P}(\hat{X} \leq (1-\varepsilon)\bar{X}) \leq e^{-\frac{1}{2}\varepsilon^2 m\bar{X}^2/(c\mathbb{E}[X_1^2])} \leq e^{-\frac{1}{2c}\varepsilon^2 m\bar{X}^\gamma}.$$

Upper bounding the right hand side by δ and solving for m yields the result. □

Corollary M.3. *Let $X_1, \dots, X_m$ be i.i.d. nonnegative random variables with mean $\bar{X} := \mathbb{E}[X_1]$. Assume there exists $c > 0$ and $\gamma \in [0, 2]$ such that $\mathbb{E}[X_1^2] \leq c\bar{X}^{2-\gamma}$. Let $\epsilon' = |X^* - \bar{X}|$ and assume $\epsilon' \leq \eta X^*$ for some $\eta \in (0, 1)$. If, for $\delta \in (0, 1)$,*

$$m \geq \frac{2c\log(1/\delta)}{\varepsilon^2}\bar{X}^{-\gamma},$$

then with probability at least $1-\delta$, $\hat{X} \geq (1-\varepsilon)X^*$. In particular, if $\epsilon' \leq \frac{\sigma X^*}{\sqrt{n}}$ and $X^* \geq \frac{\sigma^2}{\eta^2 n}$, then with probability at least $1-\delta$, $\hat{X} \geq (1-\varepsilon)X^*$ as long as

$$m \geq \frac{2c(1-\eta)^2\eta^{2\gamma}}{\varepsilon^2\sigma^{2\gamma}\log(1/\delta)}n^\gamma.$$

Proof Apply Corollary M.2 with $\frac{\varepsilon X^*}{\bar{X}}$ in place of ε. □

Example M.1. If we take $\gamma = 1/4$ and $\eta = \varepsilon = 1/2$, then $X^* \geq \frac{4\sigma^2}{n}$ and $m \geq \frac{\sqrt{2}c\log(1/\delta)}{\sigma^{1/2}}n^{1/4}$ guarantees that $\hat{X} \geq \frac{1}{2}X^*$ with probability at least $1-\delta$.