

A Proof of Theorem 6

We establish Theorem 6 in this section. First, we introduce the notion of contiguity of measures

Definition 2. Let $\{P_n\}$ and $\{Q_n\}$ be two sequences of probability measures on the measurable space $(\Omega_n, \mathcal{F}_n)$. We say that P_n is contiguous to Q_n if for any sequence of events A_n with $Q_n(A_n) \rightarrow 0$, $P_n(A_n) \rightarrow 0$.

It is standard that for two sequences of probability measures P_n and Q_n with P_n contiguous to Q_n , $\limsup_{n \rightarrow \infty} d_{TV}(P_n, Q_n) < 1$. The following lemma provides sufficient conditions for establishing contiguity of two sequence of probability measures.

Lemma 10 (see e.g. [MRZ15]). Let P_n and Q_n be two sequences of probability measures on $(\Omega_n, \mathcal{F}_n)$. Then P_n is contiguous to Q_n if

$$\mathbb{E}_{Q_n} \left[\left(\frac{dP_n}{dQ_n} \right)^2 \right]$$

exists and remains bounded as $n \rightarrow \infty$.

Our next result establishes that asymptotically error-free detection is impossible below the conjectured detection boundary.

Lemma 11. Let $\lambda, \mu > 0$ with $\lambda^2 + \frac{\mu^2}{\gamma} < 1$. Then $\mathbb{P}_{\lambda, \mu}$ is contiguous to $\mathbb{P}_{0,0}$.

To establish that consistent detection is possible above this boundary, we need the following lemma. Recall the matrices A, B from the Gaussian model (8), (9).

Lemma 12. Let $b_* = \frac{2\mu}{\lambda\gamma}$. Define

$$T = \sup_{\|x\|=\|y\|=1} [\langle x, Ax \rangle + b_* \langle x, By \rangle].$$

(i) Under $\mathbb{P}_{0,0}$, as $n, p \rightarrow \infty$, $T \rightarrow 2\sqrt{1 + \frac{b_*^2\gamma}{4}} + b_*$ almost surely.

(ii) Let $\lambda, \mu > 0$, $\varepsilon > 0$, with $\lambda^2 + \frac{\mu^2}{\gamma} > 1 + \varepsilon$. Then as $n, p \rightarrow \infty$,

$$\mathbb{P}_{\lambda, \mu} \left(T > 2\sqrt{1 + \frac{b_*^2\gamma}{4}} + b_* + \delta \right) \rightarrow 1,$$

where $\delta := \delta(\varepsilon) > 0$.

(iii) Further, define

$$\tilde{T}(\tilde{\delta}) = \sup_{\|x\|=\|y\|=1, 0 < \langle x, v \rangle < \tilde{\delta}\sqrt{n}} [\langle x, Ax \rangle + b_* \langle x, By \rangle].$$

Then for each $\delta > 0$, there exists $\tilde{\delta} > 0$ sufficiently small, such that as $n, p \rightarrow \infty$,

$$\mathbb{P}_{\lambda, \mu} \left(\tilde{T}(\tilde{\delta}) < 2\sqrt{1 + \frac{b_*^2\gamma}{4}} + b_* + \frac{\delta}{2} \right) \rightarrow 1.$$

We defer the proofs of Lemma 11 and Lemma 12 to Sections A.1 and Section A.5 respectively, and complete the proof of Theorem 6, armed with these results.

Proof of Theorem 6. The proof is comparatively straightforward, once we have Lemma 11 and 12. Note that Lemma 11 immediately implies that $\mathbb{P}_{\lambda, \mu}$ is contiguous to $\mathbb{P}_{0,0}$ for $\lambda^2 + \frac{\mu^2}{\gamma} < 1$.

Next, let $\lambda, \mu > 0$ such that $\lambda^2 + \frac{\mu^2}{\gamma} > 1 + \varepsilon$ for some $\varepsilon > 0$. In this case, consider the test which rejects the null hypothesis H_0 if $T > 2\sqrt{1 + \frac{b_*^2\gamma}{4}} + b_* + \delta$. Lemma 12 immediately implies that the Type I and II errors of this test vanish in this setting.

Finally, we prove that weak recovery is possible whenever $\lambda^2 + \frac{\mu^2}{\gamma} > 1$. To this end, let (\hat{x}, \hat{y}) be the maximizer of $\langle x, Ax \rangle + b_* \langle y, Bx \rangle$, with $\|x\| = \|y\| = 1$. Combining parts (ii) and (iii) of Lemma 12, we conclude that \hat{x} achieves weak recovery of the community assignment vector. \square

A.1 Proof of Lemma 11

Fix $\lambda, \mu > 0$ satisfying $\lambda^2 + \frac{\mu^2}{\gamma} < 1$. We start with the likelihood,

$$L(u, v) = \frac{d\mathbb{P}_{\lambda, \mu}}{d\mathbb{P}_{0,0}} = L_1(u, v)L_2(u, v),$$

$$L_1(u, v) = \exp \left[\frac{\lambda}{2} \langle A, vv^T \rangle - \frac{\lambda^2 n}{4} \right]. \quad (40)$$

$$L_2(u, v) = \exp \left[p \sqrt{\frac{\mu}{n}} \langle B, uv^T \rangle - \frac{\mu p}{2} \|u\|^2 \right]. \quad (41)$$

We denote the prior joint distribution of (u, v) as π , and set

$$L_\pi = \mathbb{E}_{(u, v) \sim \pi} [L(u, v)].$$

To establish contiguity, we bound the second moment of L_π under the null hypothesis, and appeal to Lemma 10. In particular, we denote $\mathbb{E}_0[\cdot]$ to be the expectation operator under the distribution $P_{(0,0)}$ and compute

$$\mathbb{E}_0[L_\pi^2] = \mathbb{E}_0[\mathbb{E}_{(u_1, v_1), (u_2, v_2)} [L(u_1, v_1)L(u_2, v_2)]] = \mathbb{E}_{(u_1, v_1), (u_2, v_2)} [\mathbb{E}_0 [L(u_1, v_1)L(u_2, v_2)]] ,$$

where $(u_1, v_1), (u_2, v_2)$ are i.i.d. draws from the prior π , and the last equality follows by Fubini's theorem. We have, using (40) and (41),

$$\begin{aligned} & L(u_1, v_1)L(u_2, v_2) \\ &= \exp \left[-\frac{\lambda^2 n}{2} - \frac{\mu p}{2n} (\|u_1\|^2 + \|u_2\|^2) + \frac{\lambda}{2} \langle A, v_1 v_1^T + v_2 v_2^T \rangle + p \sqrt{\frac{\mu}{n}} \langle B, u_1 v_1^T + u_2 v_2^T \rangle \right]. \end{aligned}$$

Taking expectation under $\mathbb{E}_0[\cdot]$, upon simplification, we obtain,

$$\mathbb{E}_0[L_\pi^2] = \mathbb{E}_{(u_1, v_1), (u_2, v_2)} \left[\exp \left[\frac{\lambda^2}{2n} \langle v_1, v_2 \rangle^2 + \frac{\mu p}{n} \langle u_1, u_2 \rangle \langle v_1, v_2 \rangle \right] \right] \quad (42)$$

$$= \mathbb{E}_{(u_1, v_1), (u_2, v_2)} \left[\exp \left[n \left(\frac{\lambda^2}{2} \left(\frac{\langle v_1, v_2 \rangle}{n} \right)^2 + \frac{\mu}{\gamma} \langle u_1, u_2 \rangle \frac{\langle v_1, v_2 \rangle}{n} \right) \right] \right] \quad (43)$$

$$= \mathbb{E} \left[\exp \left[n \left(\frac{\lambda^2}{2} X^2 + \frac{\mu}{\gamma} XY \right) \right] \right] \quad (44)$$

Here that $X, Y \in [-1, +1]$ are independent, with X distributed as the normalized sum of n Radamacher random variables, and Y as the first coordinate of a uniform vector on the unit sphere. In particular, defining $h(s) = -((1+s)/2) \log((1+s)) - ((1-s)/2) \log((1-s))$, and denoting by f_Y the density of Y , we have, for $s \in (2/n)\mathbb{Z}$

$$\mathbb{P}(X = s) = \frac{1}{2^n} \binom{n}{n(1+s/2)} \quad (45)$$

$$\leq \frac{C}{n^{1/2}} e^{nh(s)} \quad (46)$$

$$f_Y(y) = \frac{\Gamma(p/2)}{\Gamma((p-1)/2)\Gamma(1/2)} (1-y^2)^{(p-3)/2} \quad (47)$$

$$\leq C\sqrt{n}(1-y^2)^{p/2}. \quad (48)$$

Approximating sums by integrals, and using $h(s) \leq -s^2/2$, we get

$$\mathbb{E}_0[L_\pi^2] \leq Cn \int_{[-1,1]^2} \exp \left\{ n \left[\frac{\lambda^2}{2} s^2 + \frac{\mu}{\gamma} sy + h(s) + \frac{1}{2\gamma} \log(1-y^2) \right] \right\} ds dy \quad (49)$$

$$\leq Cn \int_{\mathbb{R}^2} \exp \left\{ n \left[\frac{\lambda^2}{2} s^2 + \frac{\mu}{\gamma} sy - \frac{s^2}{2} - \frac{y^2}{2\gamma} \right] \right\} ds dy \leq C'. \quad (50)$$

The last step holds for $\lambda^2 + \mu^2/\gamma < 1$.

Next, we turn to the proof of Lemma 12. This is the main technical contribution of this paper, and uses a novel Gaussian process comparison argument based on Sudakov-Fernique comparison.

A.2 A Gaussian process comparison result

Let $Z \sim \mathbb{R}^{p \times n}$ and $W \sim \mathbb{R}^{n \times n}$ denote random matrices with independent entries as follows.

$$W_{ij} \sim \begin{cases} \mathcal{N}(0, \rho/n) & \text{if } i < j \\ \mathcal{N}(0, 2\rho/n) & \text{if } i = j \end{cases} \quad (51)$$

$$\begin{aligned} \text{where } W_{ij} &= W_{ji}, \\ Z_{ai} &\sim \mathcal{N}(0, \tau/p). \end{aligned} \quad (52)$$

For an integer $N > 0$, we let \mathbb{S}^N denote the sphere of radius \sqrt{N} in N dimensions, i.e. $\mathbb{S}^N = \{x \in \mathbb{R}^N : \|x\|_2^2 = N\}$. Furthermore let $u_0 \in \mathbb{S}^p$ and $v_0 \in \{\pm 1\}^n$ be fixed vectors. We denote the standard inner product between vectors $x, y \in \mathbb{R}^N$ as $\langle x, y \rangle = \sum_i x_i y_i$. The normalized version will be useful as well: we define $\langle x, y \rangle_N \equiv \sum_i x_i y_i / N$.

We are interested in characterizing the behavior of the following optimization problem in the limit high-dimensional limit $p, n \rightarrow \infty$ with constant aspect ratio $n/p = \gamma \in (0, \infty)$.

$$\text{OPT}(\lambda, \mu, b) \equiv \frac{1}{n} \mathbb{E} \max_{(x, y) \in \mathbb{S}^n \times \mathbb{S}^p} \left[\left(\frac{\lambda}{n} \langle x, v_0 \rangle^2 + \langle x, Wx \rangle \right) + b \left(\sqrt{\frac{\mu}{np}} \langle x, v_0 \rangle \langle y, u_0 \rangle + \langle y, Zx \rangle \right) \right].$$

We now introduce two different comparison processes which give upper and lower bounds to $\text{OPT}(\lambda, \mu, b)$. Their asymptotic values will coincide in the high dimensional limit $n, p \rightarrow \infty$ with $n/p = \gamma$. Let g_x, g_y, W_x and W_y be:

$$g_x \sim \mathcal{N}(0, (4\rho + b^2\tau)\mathbf{I}_n) \quad (53)$$

$$g_y \sim \mathcal{N}(0, b^2\tau n/p \mathbf{I}_p), \quad (54)$$

$$(W_x)_{ij} \sim \begin{cases} \mathcal{N}(0, (4\rho + b^2\tau)/n) & \text{if } i < j \\ \mathcal{N}(0, 2(4\rho + b^2\tau)/n) & \text{if } i = j \end{cases} \quad (55)$$

$$(W_y)_{ij} \sim \begin{cases} \mathcal{N}(0, b^2\tau n/p^2) & \text{if } i < j \\ \mathcal{N}(0, 2b^2\tau n/p^2) & \text{if } i = j \end{cases} \quad (56)$$

Proposition 13. *We have*

$$\begin{aligned} \text{OPT}(\lambda, \mu, b) &\leq \frac{1}{n} \mathbb{E} \max_{(x, y) \in \mathbb{S}^n \times \mathbb{S}^p} \left[\frac{\lambda}{n} \langle x, v_0 \rangle^2 + \langle x, g_x \rangle + b \sqrt{\frac{\mu}{np}} \langle x, v_0 \rangle \langle y, u_0 \rangle + \langle y, g_y \rangle \right] \\ \text{OPT}(\lambda, \mu, b) &\geq \frac{1}{n} \mathbb{E} \max_{(x, y) \in \mathbb{S}^n \times \mathbb{S}^p} \left[\frac{\lambda}{n} \langle x, v_0 \rangle^2 + \frac{1}{2} \langle x, W_x x \rangle + b \sqrt{\frac{\mu}{np}} \langle x, v_0 \rangle \langle y, u_0 \rangle + \frac{1}{2} \langle y, W_y y \rangle \right] \end{aligned} \quad (57)$$

Proof. The proof is via Sudakov-Fernique inequality. First we compute the distances induced by the three processes. For any pair $(x, y), (x', y')$:

$$\begin{aligned} \frac{1}{4n} (\mathbb{E} \{ (\langle x, Wx \rangle + b \langle y, Zx \rangle - \langle x', Wx' \rangle - b \langle y', Zx' \rangle)^2 \}) &= \rho(1 - \langle x, x' \rangle_n^2) + \frac{b^2\tau}{2}(1 - \langle x, x' \rangle_n \langle y, y' \rangle_p) \\ \frac{1}{n} (\mathbb{E} \{ (\langle x, g_x \rangle + \langle y, g_y \rangle - \langle x', g_x \rangle - \langle y', g_y \rangle)^2 \}) &= 2(4\rho + b^2\tau)(1 - \langle x, x' \rangle_n) + 2b^2\tau(1 - \langle y, y' \rangle_p) \\ \frac{1}{4n} (\mathbb{E} \{ (\langle x, W_x x \rangle + \langle y, W_y y \rangle - \langle x', W_x x' \rangle - \langle y', W_y y' \rangle)^2 \}) &= (\rho + \frac{b^2\tau}{4})(1 - \langle x, x' \rangle_n^2) + \frac{b^2\tau}{4}(1 - \langle y, y' \rangle_p^2). \end{aligned}$$

This immediately gives:

$$\begin{aligned}
& \frac{1}{n} (\mathbb{E} \{ (\langle x, Wx \rangle + b \langle y, Zx \rangle - \langle x', Wx' \rangle - b \langle y', Zx' \rangle)^2 \}) - \\
& \frac{1}{n} (\mathbb{E} \{ (\langle x, g_x \rangle + \langle y, g_y \rangle - \langle x', g_x \rangle - \langle y, g'_y \rangle)^2 \}) \\
& = -4\rho(1 - \langle x, x' \rangle_n)^2 - 2b^2\tau(1 - \langle x, x' \rangle_n)(1 - \langle y, y' \rangle_p) \leq 0, \\
& \frac{1}{4n} (\mathbb{E} \{ (\langle x, Wx \rangle + b \langle y, Zx \rangle - \langle x', Wx' \rangle - b \langle y', Zx' \rangle)^2 \}) - \\
& \frac{1}{4n} (\mathbb{E} \{ (\langle x, W_x x \rangle + \langle y, W_y y \rangle - \langle x', W_x x \rangle - \langle y', W_y y' \rangle)^2 \}) \\
& = \frac{b^2\tau}{4} (\langle x, x' \rangle_n - \langle y, y' \rangle_p)^2 \geq 0.
\end{aligned}$$

The claim follows. \square

An immediate corollary of this is the following tight characterization for the null value, i.e. the case when $\mu = \lambda = 0$:

Corollary 14. *For any ρ, τ as n, p diverge with $n/p \rightarrow \gamma$, we have*

$$\lim_{n \rightarrow \infty} \text{OPT}(0, 0) = \sqrt{4\rho + b^2\tau} + b\sqrt{\frac{\tau}{\gamma}} \quad (58)$$

Note that this upper bound generalizes the maximum eigenvalue and singular value bounds of W , Z respectively. In particular, the case $\tau = 0$ corresponds to the maximum eigenvalue of W , which yields $\text{OPT} = 2\sqrt{\rho}$ while the maximum singular value of Z can be recovered by setting ρ to 0 and b to 1, yielding $\text{OPT} = \sqrt{\tau}(1 + \gamma^{-1/2})$. Corollary 14 demonstrates the limit for the case when $\mu = \lambda = 0$. The following theorem gives the limiting value when λ, μ may be nonzero.

Theorem 15. *Suppose $G : \mathbb{R} \times \mathbb{R}_+ \rightarrow \mathbb{R}$ is as follows:*

$$G(\kappa, \sigma^2) = \begin{cases} \kappa/2 + \sigma^2/2\kappa & \text{if } \kappa^2 \geq \sigma^2, \\ \sigma & \text{otherwise.} \end{cases} \quad (59)$$

Then the optimal value $\text{OPT}(\lambda, \mu)$ is

$$\lim_{n \rightarrow \infty} \text{OPT}(\lambda, \mu) = \min_{t \geq 0} \{ G(2\lambda + b\mu t, 4\rho + b^2\tau) + \gamma^{-1} G(b/t, b^2\gamma\tau) \}. \quad (60)$$

If the minimum above occurs at $t = t_$ such that $G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) = \partial_\kappa G(\kappa, 4\rho + b^2\tau)|_{\kappa=2\lambda+b\mu t_*} > 0$, then $\lim_{n \rightarrow \infty} \text{OPT}(\lambda, \mu) > \sqrt{4\rho + b^2\tau} + \gamma^{-1} \sqrt{\frac{\tau}{\gamma}}$.*

A.3 Proof of Theorem 15: the upper bound

The following lemma removes the effect of the projection of g_x (g_y) along v_0 (resp. u_0). Let $F(x, y) = \frac{1}{n} [\lambda x_1^2 + \langle x, g_x \rangle + b\sqrt{\mu}x_1y_1 + \langle y, g_y \rangle]$. Further, let \tilde{g}_x (\tilde{g}_y) be the vectors obtained by setting the first coordinate of g_x (resp. g_y) to zero, and $\tilde{F}(x, y) = \frac{1}{n} [\lambda x_1^2 + \langle x, \tilde{g}_x \rangle + b\sqrt{\mu}x_1y_1 + \langle y, \tilde{g}_y \rangle]$.

Lemma 16. *The optima of F and \tilde{F} differ by at most $o(1)$. More precisely:*

$$\left| \mathbb{E} \max_{x, y} F(x, y) - \mathbb{E} \max_{x, y} \tilde{F}(x, y) \right| = O\left(\frac{1}{\sqrt{n}}\right).$$

Proof. For any x, y :

$$\begin{aligned}
F(x, y) &= \frac{1}{n} \left(\lambda x_1^2 + \langle x, g_x \rangle + \sqrt{\mu}x_1y_1 + \langle y, g_y \rangle \right) = \tilde{F}(x, y) + \frac{1}{n} (x_1(g_x)_1 + y_1(g_y)_1) \\
\left| F(x, y) - \tilde{F}(x, y) \right| &\leq \frac{1}{n} (\sqrt{n}|(g_x)_1| + \sqrt{p}|(g_y)_1|).
\end{aligned}$$

Maximizing each side over x, y and taking expectation yields the lemma. \square

With this in hand, we can concentrate on computing the maximum of $\tilde{F}(x, y)$.

Lemma 17. *Let \tilde{g}_x (\tilde{g}_y) be the projection of g_x (resp. g_y) orthogonal to the first basis vector. Then*

$$\limsup_{n \rightarrow \infty} \mathbb{E} \max_{(x, y) \in \mathbb{S}^n \times \mathbb{S}^p} \tilde{F}(x, y) \leq \min_{t \leq 0} G(2\lambda + b\mu t, 4\rho + b^2\tau) + \frac{1}{\gamma} G(b/t, b^2\gamma\tau) \quad (61)$$

Proof. Since $\tilde{F}(x, y)$ increases if we align the signs of x_1 and y_1 to +1, we can assume that they are positive. Furthermore, for fixed, positive x_1, y_1 , \tilde{F} is maximized if the other coordinates align with \tilde{g}_x and \tilde{g}_y respectively. Therefore:

$$\begin{aligned} \max_{x, y} \tilde{F}(x, y) &= \max_{x_1 \in [0, \sqrt{n}], y_1 \in [0, \sqrt{p}]} \frac{\lambda x_1^2}{n} + \sqrt{1 - \frac{x_1^2}{n}} \frac{\|\tilde{g}_x\|}{\sqrt{n}} + \frac{b\sqrt{\mu x_1 y_1}}{n} + \sqrt{1 - \frac{y_1^2}{p}} \frac{\sqrt{p} \|\tilde{g}_y\|}{n} \\ &= \max_{m_1, m_2 \in [0, 1]} \lambda m_1 + \sqrt{1 - m_1} \frac{\|\tilde{g}_x\|}{\sqrt{n}} + b\sqrt{\frac{\mu m_1 m_2 p}{n}} + \sqrt{1 - m_2} \frac{\sqrt{p} \|\tilde{g}_y\|}{n} \\ &\leq \max_{m_1, m_2 \in [0, 1]} \left(\lambda + \frac{b\mu t}{2} \right) m_1 + \sqrt{1 - m_1} \frac{\|\tilde{g}_x\|}{\sqrt{n}} + \frac{p}{n} \left(\frac{bm_2}{2t} + \sqrt{1 - m_2} \frac{\|\tilde{g}_y\|}{\sqrt{p}} \right) \\ &= G(2\lambda + b\mu t, \|\tilde{g}_x\|^2/n) + \frac{1}{\gamma} G\left(\frac{b}{t}, \|\tilde{g}_y\|^2/p\right), \end{aligned} \quad (62)$$

where the first equality is change of variables, the second inequality is the fact that $2\sqrt{ab} = \min_{t \geq 0} (at + b/t)$, and the final equality is by direct calculus.

Now let t_* be any minimizer of $G(2\lambda + b\mu t, 4\rho + b^2\tau) + \gamma^{-1}G(b/t, b^2\gamma\tau)$. We may assume that $t_* \notin \{0, \infty\}$, otherwise we can use $t_*(\varepsilon)$, an ε -approximate minimizer in $(0, \infty)$ in the argument below. Since the above holds for any t , we have:

$$\max_{x, y} \tilde{F}(x, y) \leq G(2\lambda + b\mu t_*, \|\tilde{g}_x\|^2/n) + \gamma^{-1}G(b/t_*, \|\tilde{g}_y\|^2/p). \quad (63)$$

By the strong law of large numbers, $\|\tilde{g}_x\|^2/n \rightarrow 4\rho + b^2\tau$ and $\|\tilde{g}_y\|^2/p \rightarrow b^2\gamma\tau$ almost surely. Further, as $G(\kappa, \sigma^2)$ is continuous in the second argument on $(0, \infty)$, when $\kappa \notin \{0, \infty\}$, almost surely:

$$\limsup_{n \rightarrow \infty} \max_{x, y} \tilde{F}(x, y) \leq G(2\lambda + b\mu t_*, 4\rho + b^2\tau) + \gamma^{-1}G(b/t_*, b^2\gamma\tau). \quad (64)$$

Taking expectations and using bounded convergence yields the lemma. \square

We can now prove the upper bound.

Theorem 15, upper bound. Using Proposition 13, Lemma 16 and Lemma 17 in order:

$$\text{OPT}(\lambda, \mu) \leq \mathbb{E}\{\max_{x, y} F(x, y)\} \quad (65)$$

$$\leq \mathbb{E}\{\max_{x, y} \tilde{F}(x, y)\} + o(n^{-1/3}) \quad (66)$$

$$\leq \min_t G(2\lambda + b\mu t, 4\rho + b^2\tau) + \frac{1}{\gamma} G(b/t, b^2\gamma\tau) + o(n^{-1/3}). \quad (67)$$

Taking limit $p \rightarrow \infty$ yields the result. \square

A.4 Proof of Theorem 15: the lower bound

Recall that t_* denotes the optimizer of the upper bound $G(2\lambda + b\mu t, 4\rho + b^2\tau) + \gamma^{-1}G(b/t, b^2\gamma\tau)$. By stationarity, we have:

$$b\mu G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) - \frac{b}{\gamma t_*^2} G'\left(\frac{b}{t_*}, b^2\gamma\tau\right) = 0. \quad (68)$$

Now we proceed in two cases. First, suppose $G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) = 0$. In this case $G'(b/t_*, b^2\gamma\tau)/t_*^2 = 0$, whence $G'(b/t_*, b^2\gamma\tau) = 0$. Indeed, the case when $t_* = \infty$ also satisfies this. However, this also implies that $2\lambda + b\mu t_* \leq \sqrt{4\rho + b^2\tau}$ and $t_* \geq (\gamma\tau)^{-1/2}$, whereby $G(2\lambda + b\mu t_*, 4\rho + b^2\tau) = \sqrt{4\rho + b^2\tau}$ and $G'(b/t_*, b^2\gamma\tau) = b\sqrt{\gamma\tau}$. In this case we consider \tilde{x}, \tilde{y} to be the principal eigenvectors of W_x, W_y rescaled to norms \sqrt{n}, \sqrt{p} respectively and, hence using (57),

$$\text{OPT}(\lambda, \mu, b) \geq \frac{1}{2n} \mathbb{E} \left[\langle \tilde{x}, W_x \tilde{x} \rangle + \langle \tilde{y}, W_y \tilde{y} \rangle \right] - o(1). \quad (69)$$

By standard results on GOE matrices the right hand side converges to $\sqrt{4\rho + b^2\tau} + b\sqrt{\frac{\tau}{\gamma}}$ implying the required lower bound.

Now consider the case that $G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) > 0$. Importantly, by stationarity we have

$$t_*^2 = \frac{G'(bt_*^{-1}, b^2\gamma\tau)}{\mu\gamma G'(2\lambda + b\mu t_*, 4\rho + b^2\tau)}, \quad (70)$$

and that t_* is finite since the numerator is decreasing in t_* . The key ingredient to prove the lower bound is the following result on the principal eigenvalue/eigenvector of a deformed GOE matrix.

Theorem 18 ([CDMF⁺09, KY13]). *Suppose $W \in \mathbb{R}^{n \times n}$ is a GOE matrix with variance σ^2 , i.e. $W_{ij} = W_{ji} \sim \mathcal{N}(0, (1 + \delta_{ij}\sigma^2/p))$ and $A = \kappa v_0 v_0^\top + W$ where v_0 is a unit vector. Then the following holds almost surely and in expectation:*

$$\lim_{n \rightarrow \infty} \lambda_1(A) = 2G(\kappa, \sigma^2) = \begin{cases} 2\sigma & \text{if } \kappa < \sigma \\ \kappa + \sigma^2/\kappa & \text{if } \kappa > \sigma. \end{cases} \quad (71)$$

$$\lim_{n \rightarrow \infty} \langle v_1(A), v_0 \rangle^2 = 2G'(\kappa, \sigma^2) = \begin{cases} 0 & \text{if } \kappa < \sigma, \\ 1 - \sigma^2/\kappa^2 & \text{if } \kappa > \sigma. \end{cases}, \quad (72)$$

where G' denotes the derivative with respect to the first argument.

For the prescribed t_* , define:

$$H(x, y) = \left(\lambda + \frac{b\mu t_*}{2} \right) \frac{\langle x, v_0 \rangle^2}{n^2} + \frac{\langle x, W_x x \rangle}{2n} + \frac{p}{n} \left(\frac{b\langle y, u_0 \rangle^2}{2t_* p^2} + \frac{\langle y, W_y y \rangle}{2p} \right) \quad (73)$$

Let \tilde{x}, \tilde{y} be the principal eigenvector of $(2\lambda + b\mu t_*)v_0 v_0^\top/n + W_x, bt_*^{-1}u_0 u_0^\top/p + W_y$, rescaled to norm \sqrt{n} and \sqrt{p} respectively. Further, we choose the sign of \tilde{x} so that $\langle \tilde{x}, v_0 \rangle \geq 0$, and analogously for \tilde{y} . Now, fixing an $\varepsilon > 0$, we have by Theorem 18, for every p large enough:

$$H(\tilde{x}, \tilde{y}) \geq G(2\lambda + b\mu t_*, 4\rho + b^2\tau) + \gamma^{-1}G(bt_*^{-1}, b^2\gamma\tau) - \varepsilon \quad (74)$$

$$\frac{\langle \tilde{x}, v_0 \rangle}{n} = \sqrt{2G'(2\lambda + b\mu t_*, 4\rho + b^2\tau)} + O(\varepsilon) \quad (75)$$

$$\frac{\langle \tilde{y}, u_0 \rangle}{p} = \sqrt{2G'(bt_*^{-1}, b^2\gamma\tau)} + O(\varepsilon) \quad (76)$$

We have, therefore:

$$\begin{aligned} \text{OPT}(\lambda, \mu, b) &\geq \mathbb{E} \left[H(\tilde{x}, \tilde{y}) + \left(\frac{b}{n} \sqrt{\frac{\mu}{np}} \langle \tilde{x}, v_0 \rangle \langle \tilde{y}, u_0 \rangle - \frac{b\mu t_* \langle \tilde{x}, v_0 \rangle^2}{2n^2} - \frac{b\langle y, u_0 \rangle^2}{2tnp} \right) \right] \\ &\geq G(2\lambda + b\mu t_*, 4\rho + b^2\tau) + \gamma^{-1}G(bt_*^{-1}, b^2\gamma\tau) + O(\varepsilon(t_* \vee t_*^{-1})) \\ &\quad + \left(2\sqrt{\frac{\mu}{\gamma}} G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) G'(bt_*^{-1}, b^2\gamma\tau) - b\mu t_* G'(2\lambda + b\mu t_*, 4\rho + b^2\tau) \right. \\ &\quad \left. - \frac{G'(bt_*^{-1}, b^2\gamma\tau)}{\gamma t_*} \right) \\ &\geq G(2\lambda + b\mu t_*, 4\rho + b^2\tau) + \gamma^{-1}G(bt_*^{-1}, b^2\gamma\tau) + O(\varepsilon(t_* \vee t_*^{-1})). \end{aligned} \quad (77)$$

Here the first inequality since we used a specific guess \tilde{x}, \tilde{y} , the second using Theorem 18 and the final inequality follows since the remainder term vanishes due to Eq. (70). Taking expectations and letting ε going to 0 yields the required lower bound.

Given Corollary 14 and Theorem 15, it is not too hard to establish Lemma 12, which we proceed to do next.

A.5 Proof of Lemma 12

Recall $b_* = \frac{2\mu}{\lambda\gamma}$. Part (i) follows directly from Corollary 14, upon setting $\rho = \tau = 1$, and $b = b_*\sqrt{\gamma}$. To establish part (ii), we use Theorem 15. In particular, it suffices to establish that with this specific choice of $b = b_*\sqrt{\gamma}$, for any (λ, μ) with $\lambda^2 + \mu^2/\gamma > 1$, the minimizer t_* of $G(2\lambda + b\mu t, 4 + b^2) + \gamma^{-1}G(b/t, b^2\gamma)$ satisfies $G'(2\lambda + b\mu t_*, 4 + b^2) > 0$. Let us assume, if possible, that $G(2\lambda + b\mu t_*, 4 + b^2) = 0$. Using the stationary point condition (68), in this case $G'(b/t_*, b^2\gamma) = 0$. Next, using the definition of G (59), observe that this implies

$$t_* > \frac{1}{\sqrt{\gamma}}, \quad 2\lambda + \frac{2\mu^2}{\lambda\sqrt{\gamma}}t_* < \sqrt{4 + \frac{4\mu^2}{\lambda^2\gamma}}.$$

These imply:

$$\frac{2}{\lambda} \left(\lambda^2 + \frac{\mu^2}{\gamma} \right) < 2\lambda + 2 \frac{\mu^2 t_*}{\lambda\mu\sqrt{\gamma}} \quad (79)$$

$$< \sqrt{4 + \frac{4\mu^2}{\lambda^2\gamma}} \quad (80)$$

$$= \frac{2}{\lambda} \sqrt{\lambda^2 + \frac{\mu^2}{\gamma}}. \quad (81)$$

That this is impossible whenever $\lambda^2 + \frac{\mu^2}{\gamma} > 1$. This establishes part (ii). To establish part (iii), we again use the upper bound from Proposition 13, and note that for $0 < \langle x, v \rangle < \tilde{\delta}\sqrt{n}$,

$$\mathbb{E}[\tilde{T}(\tilde{\delta})] \leq \lambda\tilde{\delta}^2 + \sqrt{4 + b_*^2} + \max_{\|y\|=1} \{b_*\sqrt{\mu}\tilde{\delta}\langle u, y \rangle + \frac{1}{\gamma}\langle y, g \rangle\},$$

where $g \sim \mathcal{N}(0, b^2\gamma I_p/p)$. The proof follows using continuity in $\tilde{\delta}$. This completes the proof.

B Proof of Lemma 8

Recall the distributional recursion specified by density evolution (Definition 1).

$$\begin{aligned} \bar{m}'|_U &\stackrel{d}{=} \mu U \mathbb{E}[V\bar{\eta}] + \zeta_1 \sqrt{\mu \mathbb{E}[\bar{\eta}^2]}, \\ \bar{\eta}'|_{V'=+1} &\stackrel{d}{=} \frac{\lambda}{\sqrt{d}} \left[\sum_{k=1}^{k_+} \bar{\eta}_k|_+ + \sum_{k=1}^{k_-} \bar{\eta}_k|_- \right] - \lambda\sqrt{d}\mathbb{E}[\bar{\eta}] + \frac{\mu}{\gamma} \mathbb{E}[U\bar{m}] + \zeta_2 \sqrt{\frac{\mu}{\gamma} \mathbb{E}[\bar{m}^2]}, \end{aligned}$$

where $V \sim U(\{\pm 1\})$, $U \sim \mathcal{N}(0, 1)$, $k_+ \sim \text{Poisson}\left(\frac{d+\lambda\sqrt{d}}{2}\right)$, $k_- \sim \text{Poisson}\left(\frac{d-\lambda\sqrt{d}}{2}\right)$, $\zeta_1, \zeta_2 \sim \mathcal{N}(0, 1)$ are all mutually independent. Further, $\{\bar{\eta}_k|_+\}$ are iid random variables, distributed as $\bar{\eta}|_{V=+1}$. Similarly, $\{\bar{\eta}_k|_-\}$ are iid random variables, distributed as $\bar{\eta}|_{V=-1}$. Finally, we require the collections to be mutually independent, and independent of the other auxiliary variables defined above.

Given these distributional recursions, we compute the vector of moments

$$\begin{aligned} \mathbb{E}[V'\bar{\eta}'] &= \lambda^2 \mathbb{E}[V\bar{\eta}] + \frac{\mu}{\gamma} \mathbb{E}[U\bar{m}] \\ \mathbb{E}[U'\bar{m}'] &= \mu \mathbb{E}[V\bar{\eta}] \\ \mathbb{E}[\bar{\eta}'^2] &= \lambda^2 \mathbb{E}[\bar{\eta}^2] + \frac{\mu^2}{\gamma^2} \mathbb{E}^2[U\bar{m}] + \frac{\mu}{\gamma} \mathbb{E}[\bar{m}^2] + 2 \frac{\lambda^2}{\gamma} \mathbb{E}[U\bar{m}] \mathbb{E}[V\bar{\eta}] \\ \mathbb{E}[\bar{m}'^2] &= \mu^2 \mathbb{E}^2[V\bar{\eta}] + \mu \mathbb{E}[\bar{\eta}^2] \end{aligned}$$

Thus the induced mapping on moments $\phi^{\text{DE}} : \mathbb{R}^4 \rightarrow \mathbb{R}^4$, $\phi^{\text{DE}}(z_1, z_2, z_3, z_4) = (\phi_1, \phi_2, \phi_3, \phi_4)$, with

$$\begin{aligned}\phi_1 &= \lambda^2 z_1 + \frac{\mu}{\gamma} z_2 \\ \phi_2 &= \mu z_1 \\ \phi_3 &= \frac{\mu^2}{\gamma^2} z_2^2 + \frac{2\lambda^2}{\gamma} z_1 z_2 + \lambda^2 z_3 + \frac{\mu}{\gamma} z_4, \\ \phi_4 &= \mu^2 z_1^2 + \mu z_3.\end{aligned}$$

The Jacobian of ϕ^{DE} at 0 is, up to identical row/column permutation:

$$J = \begin{bmatrix} \lambda^2 I_2 & \frac{\mu}{\gamma} I_2 \\ \mu I_2 & 0 \end{bmatrix}.$$

By direct computation, we see that z is an eigenvalue of J if and only if $z^2 - \lambda^2 z - \frac{\mu^2}{\gamma} = 0$. Consider the quadratic function $f(z) = z^2 - \lambda^2 z - \frac{\mu^2}{\gamma}$ and note that $f(0) < 0$. Thus to check whether f has a root with magnitude greater than 1, it suffices to check its value at $z = 1, -1$. Note that if $\lambda^2 + \frac{\mu^2}{\gamma} > 1$, $f(1) < 0$ and thus J has an eigenvalue greater than 1. Conversely, if $\lambda^2 + \frac{\mu^2}{\gamma} < 1$, $f(1) > 0$ and $f(-1) = 1 + \lambda^2 - \frac{\mu^2}{\gamma} > 1 - \frac{\mu^2}{\gamma} > 0$. This completes the proof.

C Proof of Theorem 4

We prove Theorem 4 in this Section. Recall the matrix mean square errors

$$\begin{aligned}\text{MMSE}(v; A, B) &= \frac{1}{n(n-1)} \mathbb{E} \left[\|vv^T - \mathbb{E}[vv^T | A, B]\|_F^2 \right], \\ \text{MMSE}(v; A^G, B) &= \frac{1}{n(n-1)} \mathbb{E} \left[\|vv^T - \mathbb{E}[vv^T | A^G, B]\|_F^2 \right].\end{aligned}$$

The following lemma is immediate from Lemma 4.6 in [DAM16].

Lemma 19. *Let $\hat{v} = \hat{v}(A, B)$ be any estimator so that $\|\hat{v}\|_2 = \sqrt{n}$. Then*

$$\liminf_{n \rightarrow \infty} \frac{\langle \hat{v}, v \rangle}{n} > 0 \text{ in probability} \Rightarrow \limsup_{n \rightarrow \infty} \text{MMSE}(v; A, B) < 1. \quad (82)$$

Furthermore, if $\limsup_{n \rightarrow \infty} \text{MMSE}(v; A, B) < 1$, there exists an estimator $\hat{s}(A, B)$ with $\|\hat{s}(A, B)\|_2 = \sqrt{n}$ so that, in probability:

$$\liminf_{n \rightarrow \infty} \frac{\langle \hat{s}, v \rangle}{n} > 0. \quad (83)$$

Indeed, the same holds for the observation model A^G, B .

Proof of Theorem 4. Consider first the case $\lambda^2 + \frac{\mu^2}{\gamma} < 1$. For any $\theta \in [0, \lambda]$, $\theta^2 + \mu^2/\gamma < 1$ as well. Suppose we have $A(\theta), B$ according to model (8), (9) where λ is replaced with θ . By Theorem 6 (applied at θ) and the second part of Lemma 19, $\liminf_{n \rightarrow \infty} \text{MMSE}(v; A(\theta), B) = 1$. Using the I-MMSE identity [GSV05], this implies

$$\lim_{n \rightarrow \infty} \frac{1}{n} (I(v; A(\theta), B) - I(v; A(0), B)) = \frac{\theta^2}{4}. \quad (84)$$

By Theorem 5, for all $\theta \in [0, \lambda]$

$$\lim_{d \rightarrow \infty} \lim_{n \rightarrow \infty} \frac{1}{n} (I(v; A^G(\theta), B) - I(v; A^G(0), B)) = \frac{\theta^2}{4}, \quad (85)$$

$$\text{and, therefore } \lim_{n \rightarrow \infty} \text{MMSE}(v; A^G, B) = 1 \quad (86)$$

This implies, via the first part of Lemma 19 that for any estimator $\hat{v}(A^G, B)$, we have $\limsup_{n \rightarrow \infty} |\langle \hat{v}, v \rangle|/n = 0$ in probability, as required.

Conversely, consider the case $\lambda^2 + \frac{\mu^2}{\gamma} > 1$. We may assume that $\mu^2/\gamma < 1$, as otherwise the result follows from Theorem 2. Let $\lambda_0 = (1 - \mu^2/\gamma)^{1/2}$.

Now, by the same argument for Eqs.(84), (85), we obtain for all $\theta_1, \theta_2 \in [\lambda_0, \lambda]$:

$$\limsup_{n \rightarrow \infty} \frac{1}{n} (I(v; A(\theta_1), B) - I(v; A(\theta_2), B)) < \frac{\theta_1^2 - \theta_2^2}{4}. \quad (87)$$

Applying Theorem 5, we have for all $\theta_1, \theta_2, \theta \in [\lambda_0, \lambda]$:

$$\lim_{d \rightarrow \infty} \limsup_{n \rightarrow \infty} \frac{1}{n} (I(v; A^G(\theta_1), B) - I(v; A^G(\theta_2), B)) < \frac{\theta_1^2 - \theta_2^2}{4} \quad (88)$$

$$\text{and therefore, } \limsup \text{MMSE}(v; A^G(\theta), B) < 1. \quad (89)$$

Applying then Lemma 19 implies that we have an estimator $\hat{s}(A^G, B)$ with non-trivial overlap i.e. in probability:

$$\lim_{d \rightarrow \infty} \liminf_{n \rightarrow \infty} \frac{\langle \hat{s}, v \rangle}{n} > 0. \quad (90)$$

This completes the proof. □

D Belief propagation: derivation

In this section we will derive the belief propagation algorithm. Recall the observation model for $(A^G, B) \in \mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$ in Eqs. (1), (2):

$$A_{ij}^G = \begin{cases} 1 & \text{with probability } \frac{d + \lambda \sqrt{d} v_i v_j}{n} \\ 0 & \text{otherwise.} \end{cases} \quad (91)$$

$$B_{qi} = \sqrt{\frac{\mu}{n}} u_q v_i + Z_{qi}, \quad (92)$$

where u_q and Z_{qi} are independent $N(0, 1/p)$ variables.

We will use the following conventions throughout this section to simplify some of the notation. We will index nodes in the graph, i.e. elements in $[n]$ with $i, j, k \dots$ and covariates, i.e. elements in $[p]$ with q, r, s, \dots . We will use ‘ \simeq ’ to denote equality of probability distributions (or densities) up to an omitted proportionality constant, that may change from line to line. We will omit the superscript G in A^G . In the graph G , we will denote neighbors of a node i with ∂i and non-neighbors with ∂i^c .

We start with the posterior distribution of u, v given the data A, B :

$$\text{d}\mathbb{P}\{u, v | A, B\} = \frac{\text{d}\mathbb{P}\{A, B | u, v\}}{\text{d}\mathbb{P}\{A, B\}} \text{d}\mathbb{P}\{u, v\} \quad (93)$$

$$\begin{aligned} &\simeq \prod_{i < j} \left(\frac{d + \lambda \sqrt{d} v_i v_j}{n} \right)^{A_{ij}} \left(1 - \frac{d + \lambda \sqrt{d} v_i v_j}{n} \right)^{1 - A_{ij}} \\ &\cdot \prod_{q, i} \exp \left(\sqrt{\frac{\mu p^2}{n}} B_{qi} u_q v_i \right) \prod_q \exp \left(- \frac{p(1 + \mu)}{2} u_q^2 \right). \end{aligned} \quad (94)$$

The belief propagation algorithm operates ‘messages’ $\nu_{i \rightarrow j}^t, \nu_{q \rightarrow i}^t, \nu_{i \rightarrow q}^t$ which are probability distributions. They represent the marginals of the variables v_i, u_q in the absence of variables v_j, u_q , in the posterior distribution $\text{d}\mathbb{P}\{u, v | A, B\}$. We denote by $\mathbb{E}_{i \rightarrow j}^t, \mathbb{E}_{q \rightarrow i}^t, \mathbb{E}_{i \rightarrow q}^t$ expectations with respect to

these distributions. The messages are computed using the following update equations:

$$\nu_{i \rightarrow j}^{t+1}(v_i) \simeq \prod_{q \in [p]} \mathbb{E}_{q \rightarrow i}^t \left\{ \exp \left(\sqrt{\frac{\mu p^2}{n}} B_{qi} v_i u_q \right) \right\} \prod_{k \in \partial i \setminus j} \mathbb{E}_{k \rightarrow i}^t \left(\frac{d + \lambda \sqrt{d} v_i v_k}{n} \right) \prod_{k \in \partial i^c \setminus j} \mathbb{E}_{k \rightarrow i}^t \left(1 - \frac{d + \lambda \sqrt{d} v_i v_k}{n} \right), \quad (95)$$

$$\nu_{i \rightarrow q}^{t+1}(v_i) \simeq \prod_{r \in [p] \setminus q} \mathbb{E}_{r \rightarrow i}^t \left\{ \exp \left(\sqrt{\frac{\mu p^2}{n}} B_{ri} v_i u_r \right) \right\} \prod_{k \in \partial i} \mathbb{E}_{k \rightarrow i}^t \left(\frac{d + \lambda \sqrt{d} v_i v_k}{n} \right) \prod_{k \in \partial i^c} \mathbb{E}_{k \rightarrow i}^t \left(1 - \frac{d + \lambda \sqrt{d} v_i v_k}{n} \right), \quad (96)$$

$$\nu_{q \rightarrow i}^{t+1}(u_q) \simeq \exp \left(-\frac{p(1+\mu)u_q^2}{2} \right) \prod_{j \neq i} \mathbb{E}_{j \rightarrow q}^t \left\{ \exp \left(\sqrt{\frac{\mu p^2}{n}} B_{qj} v_j u_q \right) \right\}. \quad (97)$$

As is standard, we define ν_i^t, ν_q^t in the same fashion as above, except without the removal of the incoming message.

D.1 Reduction using Gaussian ansatz

The update rules (95), (96), (97) are in terms of probability distributions, i.e. measures on the real line or $\{\pm 1\}$. We reduce them to update rules on real numbers using the following analytical ansatz. The measure $\nu_{i \rightarrow j}^t$ on $\{\pm 1\}$ can be summarized using the log-odds ratio:

$$\eta_{i \rightarrow j}^t \equiv \frac{1}{2} \log \frac{\nu_{i \rightarrow j}^t(+1)}{\nu_{i \rightarrow j}^t(-1)}, \quad (98)$$

and we similarly define $\eta_{i \rightarrow q}^t, \eta_i^t$. In order to reduce the densities $\nu_{q \rightarrow i}^t$, we use the Gaussian ansatz:

$$\nu_{q \rightarrow i}^t = \mathcal{N} \left(\frac{m_{q \rightarrow i}^t}{\sqrt{p}}, \frac{\tau_{q \rightarrow i}^t}{p} \right). \quad (99)$$

With Equations (98) and (99) we can now simplify Equations (95) to (97). The following lemma computes the inner marginalizations in Equations (95) to (97). We omit the proof.

Lemma 20. *With ν^t, \mathbb{E}^t as defined as per Equations (95) to (97) and η^t, m^t, τ^t as in Equations (98) and (99) we have*

$$\mathbb{E}_{q \rightarrow i}^t \exp \left(\sqrt{\frac{\mu p^2}{n}} B_{qi} v_i u_q \right) = \exp \left(\sqrt{\frac{\mu p}{n}} B_{qi} v_i m_{q \rightarrow i}^t + \frac{\mu p}{2n} B_{qi}^2 \tau_{q \rightarrow i}^t \right), \quad (100)$$

$$\mathbb{E}_{i \rightarrow j}^t \left(\frac{d + \lambda \sqrt{d} v_i v_j}{n} \right) = \frac{d}{n} \left(1 + \frac{\lambda v_j}{\sqrt{d}} \tanh(\eta_{i \rightarrow j}^t) \right), \quad (101)$$

$$\mathbb{E}_{i \rightarrow j}^t \left(1 - \frac{d + \lambda \sqrt{d} v_i v_j}{n} \right) = 1 - \frac{d}{n} \left(1 + \frac{\lambda v_j}{\sqrt{d}} \tanh(\eta_{i \rightarrow j}^t) \right), \quad (102)$$

$$\mathbb{E}_{i \rightarrow q}^t \exp \left(p \sqrt{\frac{\mu}{n}} B_{qi} v_i u_q \right) = \frac{\cosh(\eta_{i \rightarrow q}^t + p \sqrt{\mu/n} B_{qi} u_q)}{\cosh \eta_{i \rightarrow q}^t}. \quad (103)$$

The update equations take a simple form using the following definitions

$$f(z; \rho) \equiv \frac{1}{2} \log \left(\frac{\cosh(z + \rho)}{\cosh(z - \rho)} \right), \quad (104)$$

$$\rho \equiv \tanh^{-1}(\lambda/\sqrt{d}), \quad (105)$$

$$\rho_n \equiv \tanh^{-1} \left(\frac{\lambda \sqrt{d}}{n - d} \right). \quad (106)$$

With this, we first compute the update equation for the node messages η^{t+1} . Using Equations (95), (96) and (100) to (103):

$$\eta_{i \rightarrow j}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_{q \rightarrow i}^t + \sum_{k \in \partial i \setminus j} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in \partial i \setminus j} f(\eta_{k \rightarrow i}^t; \rho_n), \quad (107)$$

$$\eta_{i \rightarrow q}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p] \setminus q} B_{ri} m_{r \rightarrow i}^t + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in \partial i^c} f(\eta_{k \rightarrow i}^t; \rho_n), \quad (108)$$

$$\eta_i^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_{q \rightarrow i}^t + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in \partial i^c} f(\eta_{k \rightarrow i}^t; \rho_n). \quad (109)$$

Now we compute the updates for $m_{a \rightarrow i}^t, \tau_{a \rightarrow i}^t$. We start from Equations (97) and (100), and use Taylor approximation assuming u_q, B_{jq} are both $O(1/\sqrt{p})$, as the ansatz (99) suggests.

$$\log \nu_{q \rightarrow i}^{t+1}(u_q) = \text{const.} + \frac{-p(1+\mu)}{2} u_q^2 + \sum_{j \in [n] \setminus i} \log \cosh \left(\eta_{j \rightarrow q}^t + p \sqrt{\frac{\mu}{n}} B_{qj} u_q \right) \quad (110)$$

$$= \text{const.} + \frac{-p(1+\mu)}{2} u_q^2 + \left(p \sqrt{\frac{\mu}{n}} \sum_{j \in [n] \setminus i} B_{qj} \tanh(\eta_{j \rightarrow q}^t) \right) u_q + \left(\frac{p^2 \mu}{2n} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_{j \rightarrow q}^t) \right) u_q^2 + O\left(\frac{1}{\sqrt{n}}\right). \quad (111)$$

Note that here we compute $\log \nu^{t+1}$ only up to constant factors (with slight abuse of the notation ‘ \simeq ’). It follows from this quadratic approximation that:

$$\tau_{q \rightarrow i}^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n] \setminus i} B_{qj}^2 \text{sech}^2(\eta_{j \rightarrow q}^t) \right)^{-1}, \quad (112)$$

$$m_{q \rightarrow i}^{t+1} = \tau_{q \rightarrow i}^{t+1} \sqrt{\frac{\mu}{\gamma}} \sum_{j \in [n] \setminus i} B_{qj} \tanh(\eta_{j \rightarrow q}^t) \quad (113)$$

$$= \frac{\sqrt{\mu/\gamma} \sum_{j \in [n] \setminus i} B_{qj} \tanh(\eta_{j \rightarrow q}^t)}{1 + \mu - \mu \gamma^{-1} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_{j \rightarrow q}^t)}. \quad (114)$$

Updates computing m_q^{t+1}, τ_q^{t+1} are analogous.

D.2 From message passing to approximate message passing

The updates for η^t, m^t derived in the previous section require keeping track of $O(np)$ messages. In this section, we further reduce the number of messages to $O(dn + p)$, i.e. linear in the size of the input graph observation.

The first step is to observe that the dependence of $\eta_{i \rightarrow j}^t$ on j is negligible when j is not a neighbor of i in the graph G . This derivation is similar to the presentation in [DKMZ11]. As $\sup_{z \in \mathbb{R}} f(z; \rho) \leq \rho$. Therefore, if i, j are not neighbors in G :

$$\eta_{i \rightarrow j}^t = \eta_i^t - f(\eta_{j \rightarrow i}^{t-1}; \rho_n) \quad (115)$$

$$= \eta_i^t + O(\rho_n) = \eta_i^t + O\left(\frac{1}{n}\right). \quad (116)$$

Now, for a pair i, j not connected, by Taylor expansion and the fact that $\partial_z f(z; \rho) \leq \tanh(\rho)$,

$$f(\eta_{i \rightarrow j}^t; \rho_n) - f(\eta_i^t; \rho_n) = O\left(\frac{\tanh(\rho_n)}{n}\right) = O\left(\frac{1}{n^2}\right). \quad (117)$$

Therefore, the update equation for $\eta_{i \rightarrow j}^{t+1}$ satisfies:

$$\eta_{i \rightarrow j}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_{q \rightarrow i}^t + \sum_{k \in \partial i \setminus j} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in [n]} f(\eta_k^t; \rho_n) + O\left(\frac{1}{n}\right), \quad (118)$$

$$\eta_i^{t+1} = \eta_{i \rightarrow j}^{t+1} + f(\eta_{j \rightarrow i}^t; \rho). \quad (119)$$

Similarly for $\eta_{i \rightarrow q}^{t+1}$ we have:

$$\eta_{i \rightarrow q}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p] \setminus q} B_{ri} m_{r \rightarrow i}^t + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in [n]} f(\eta_k^t; \rho_n) + O\left(\frac{1}{n}\right). \quad (120)$$

Ignoring $O(1/n)$ correction term, the update equations reduce to variables $(\eta_{i \rightarrow j}^t, \eta_i^t)$ where i, j are neighbors.

We now move to reduce updates for $\eta_{i \rightarrow q}^t$ and $m_{q \rightarrow i}^t$ to involving $O(n)$ variables. This reduction is more subtle than that of $\eta_{i \rightarrow j}^t$, where we are able to simply ignore the dependence of $\eta_{i \rightarrow j}^t$ on j if $j \notin \partial i$. We follow a derivation similar to that in [Mon12]. We use the ansatz:

$$\eta_{i \rightarrow q}^t = \eta_i^t + \delta \eta_{i \rightarrow q}^t \quad (121)$$

$$m_{q \rightarrow i}^t = m_q^t + \delta m_{q \rightarrow i}^t \quad (122)$$

$$\tau_{q \rightarrow i}^t = \tau_q^t + \delta \tau_{q \rightarrow i}^t, \quad (123)$$

where the corrections $\delta \eta_{i \rightarrow q}^t, \delta m_{q \rightarrow i}^t, \delta \tau_{q \rightarrow i}^t$ are $O(1/\sqrt{n})$. From Equations (97) and (120) at iteration t :

$$\begin{aligned} \eta_i^t + \delta \eta_{i \rightarrow q}^t &= \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p] \setminus q} B_{ri} (m_r^{t-1} + \delta m_{r \rightarrow i}^{t-1}) + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^{t-1}; \rho) - \sum_k f(\eta_k^{t-1}; \rho_n) \\ &= \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p]} B_{ri} (m_r^{t-1} + \delta m_{r \rightarrow i}^{t-1}) + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^{t-1}; \rho) - \sum_k f(\eta_k^{t-1}; \rho_n) - \sqrt{\frac{\mu}{\gamma}} (B_{qi} m_q^{t-1} + B_{qi} \delta m_{q \rightarrow i}^{t-1}). \end{aligned} \quad (124)$$

$$(125)$$

Notice that the last term is the only term that depends on q . Further, since $B_{qi} \delta m_{q \rightarrow i}^{t-1} = O(1/n)$ by our ansatz, we may safely ignore it to obtain

$$\eta_i^t = \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p]} B_{ri} (m_r^{t-1} + \delta m_{r \rightarrow i}^{t-1}) + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^{t-1}; \rho) - \sum_k f(\eta_k^{t-1}; \rho_n) \quad (126)$$

$$\delta \eta_{i \rightarrow q}^t = -\sqrt{\frac{\mu}{\gamma}} B_{qi} m_q^{t-1}. \quad (127)$$

We now use the update equation for $\tau_{q \rightarrow i}^{t+1}$:

$$\tau_q^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t + \delta \eta_{j \rightarrow q}^t) \right)^{-1} + O(1/n) \quad (128)$$

$$= \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 ((\text{sech}^2(\eta_j^t) - 2 \text{sech}^2(\eta_j^t) \tanh(\eta_j^t) \delta \eta_{j \rightarrow q}^t) \right)^{-1} + O(1/n), \quad (129)$$

where we expanded the equation to linear order in $\delta \eta_{i \rightarrow q}^t$ and ignored higher order terms. By the identification Equation (127):

$$\tau_q^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) + 2 \left(\frac{\mu}{\gamma} \right)^{3/2} \sum_{j \in [n]} B_{qj}^3 \text{sech}^2(\eta_j^t) \tanh(\eta_j^t) m_q^{t-1} \right)^{-1} + O(1/n). \quad (130)$$

Notice here, that there is no term that explicitly depends on i and the final term is $O(1/\sqrt{n})$ since $B_{qj} = O(1/\sqrt{n})$. Therefore, ignoring lower order terms, we have the identification:

$$\tau_q^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) \right)^{-1}, \quad (131)$$

$$\delta \tau_{q \rightarrow i}^{t+1} = 0. \quad (132)$$

Now we simplify the update for $m_{q \rightarrow i}^{t+1}$ using Taylor expansion to first order:

$$m_q^{t+1} + \delta m_{q \rightarrow i}^{t+1} = \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n] \setminus i} B_{qj} \tanh(\eta_j^t + \delta \eta_{j \rightarrow q}^t) \quad (133)$$

$$= \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n] \setminus i} (B_{qj} \tanh(\eta_j^t) + B_{qj} \text{sech}^2(\eta_j^t) \delta \eta_{j \rightarrow q}^t) \quad (134)$$

$$= \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n] \setminus i} \left(B_{qj} \tanh(\eta_j^t) - \sqrt{\frac{\mu}{\gamma}} B_{qj}^2 \text{sech}^2(\eta_j^t) m_q^{t-1} \right) \quad (135)$$

$$= \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n]} B_{qj} \tanh(\eta_j^t) - \frac{\mu}{\gamma \tau_q^{t+1}} \left(\sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) \right) m_q^{t-1} \\ - \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} (B_{qi} \tanh(\eta_i^t) - \sqrt{\mu/\gamma} B_{qi}^2 \text{sech}^2(\eta_i^t) m_q^{t-1}). \quad (136)$$

Only the final term is dependent on i , therefore we can identify:

$$m_q^{t+1} = \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n]} B_{qj} \tanh(\eta_j^t) - \frac{\mu}{\gamma \tau_q^{t+1}} \left(\sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) \right) m_q^{t-1}, \quad (137)$$

$$\delta m_{q \rightarrow i}^{t+1} = - \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} B_{qi} \tanh(\eta_i^t). \quad (138)$$

Here, as before, we ignore the lower order term in $\delta m_{q \rightarrow i}^{t+1}$. Now we can substitute the identification Equation (138) back in Equation (126) at iteration $t + 1$:

$$\eta_i^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{r \in [p]} B_{ri} m_r^t - \frac{\mu}{\gamma} \sum_{r \in [p]} \frac{B_{ri}^2}{\tau_r^t} \tanh(\eta_i^{t-1}) + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^t; \rho) - \sum_k f(\eta_k^t; \rho_n). \quad (139)$$

Collecting the updates for $\eta_i^t, \eta_{i \rightarrow j}^t, m_q^t$ we obtain the approximate message passing algorithm:

$$\eta_i^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_q^t - \frac{\mu}{\gamma} \left(\sum_{q \in [p]} \frac{B_{qi}^2}{\tau_q^t} \right) \tanh(\eta_i^{t-1}) + \sum_{k \in \partial i} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in [n]} f(\eta_k^t; \rho_n), \quad (140)$$

$$\eta_{i \rightarrow j}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_q^t - \frac{\mu}{\gamma} \left(\sum_{q \in [p]} \frac{B_{qi}^2}{\tau_q^t} \right) \tanh(\eta_i^{t-1}) + \sum_{k \in \partial i \setminus j} f(\eta_{k \rightarrow i}^t; \rho) - \sum_{k \in [n]} f(\eta_k^t; \rho_n), \quad (141)$$

$$m_q^{t+1} = \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n]} B_{qj} \tanh(\eta_j^t) - \frac{\mu}{\gamma \tau_q^{t+1}} \left(\sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) \right) m_q^{t-1} \quad (142)$$

$$\tau_q^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 \text{sech}^2(\eta_j^t) \right)^{-1}. \quad (143)$$

D.3 Linearized approximate message passing

This algorithm results from expanding the updates Equations (140) to (143) to linear order in the messages $\eta_i^t, \eta_{i \rightarrow j}^t$:

$$\eta_i^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_q^t - \frac{\mu}{\gamma} \left(\sum_{q \in [p]} \frac{B_{qi}^2}{\tau_q^t} \right) \eta_i^{t-1} + \frac{\lambda}{\sqrt{d}} \sum_{k \in \partial i} \eta_{k \rightarrow i}^t - \frac{\lambda \sqrt{d}}{n} \sum_{k \in [n]} \eta_k^t \quad (144)$$

$$\eta_{i \rightarrow j}^{t+1} = \sqrt{\frac{\mu}{\gamma}} \sum_{q \in [p]} B_{qi} m_q^t - \frac{\mu}{\gamma} \left(\sum_{q \in [p]} \frac{B_{qi}^2}{\tau_q^t} \right) \eta_i^{t-1} + \frac{\lambda}{\sqrt{d}} \sum_{k \in \partial i \setminus j} \eta_{k \rightarrow i}^t - \frac{\lambda \sqrt{d}}{n} \sum_{k \in [n]} \eta_k^t \quad (145)$$

$$m_q^{t+1} = \frac{\sqrt{\mu/\gamma}}{\tau_q^{t+1}} \sum_{j \in [n]} B_{qj} \eta_j^t - \frac{\mu}{\gamma \tau_q^{t+1}} \left(\sum_{j \in [n]} B_{qj}^2 \right) m_q^{t-1} \quad (146)$$

$$\tau_q^{t+1} = \left(1 + \mu - \frac{\mu}{\gamma} \sum_{j \in [n]} B_{qj}^2 \right)^{-1}. \quad (147)$$

This follows from the linear approximation $f(z; \rho) = \tanh(\rho)z$ for small z . The algorithm given in the main text follows by using the law of large numbers to approximate $\sum_{j \in [n]} B_{qj}^2 \approx 1/\gamma$, $\sum_{q \in [p]} B_{qj}^2 \approx 1$, and hence $\tau_q \approx 1$.