

Abstract

Neurons communicate through patterns of spike timing. Current technologies now allow simultaneous recordings. We develop a method to infer the collective organization of the neurons from spike data. Our method utilises the pairwise van Rossum distance, to construct a network of neurons where edge weights relate to their similarity. We hypothesise that synchronised neuronal assemblies will appear as clustered communities in the network. We employ Louvain algorithm to detect such assemblies. We validate our approach using synthetic spike train data and simulated data from a LIF network, where the ground truth is known. We then apply our method to electrophysiology recordings from Allen Institute.

Workflow

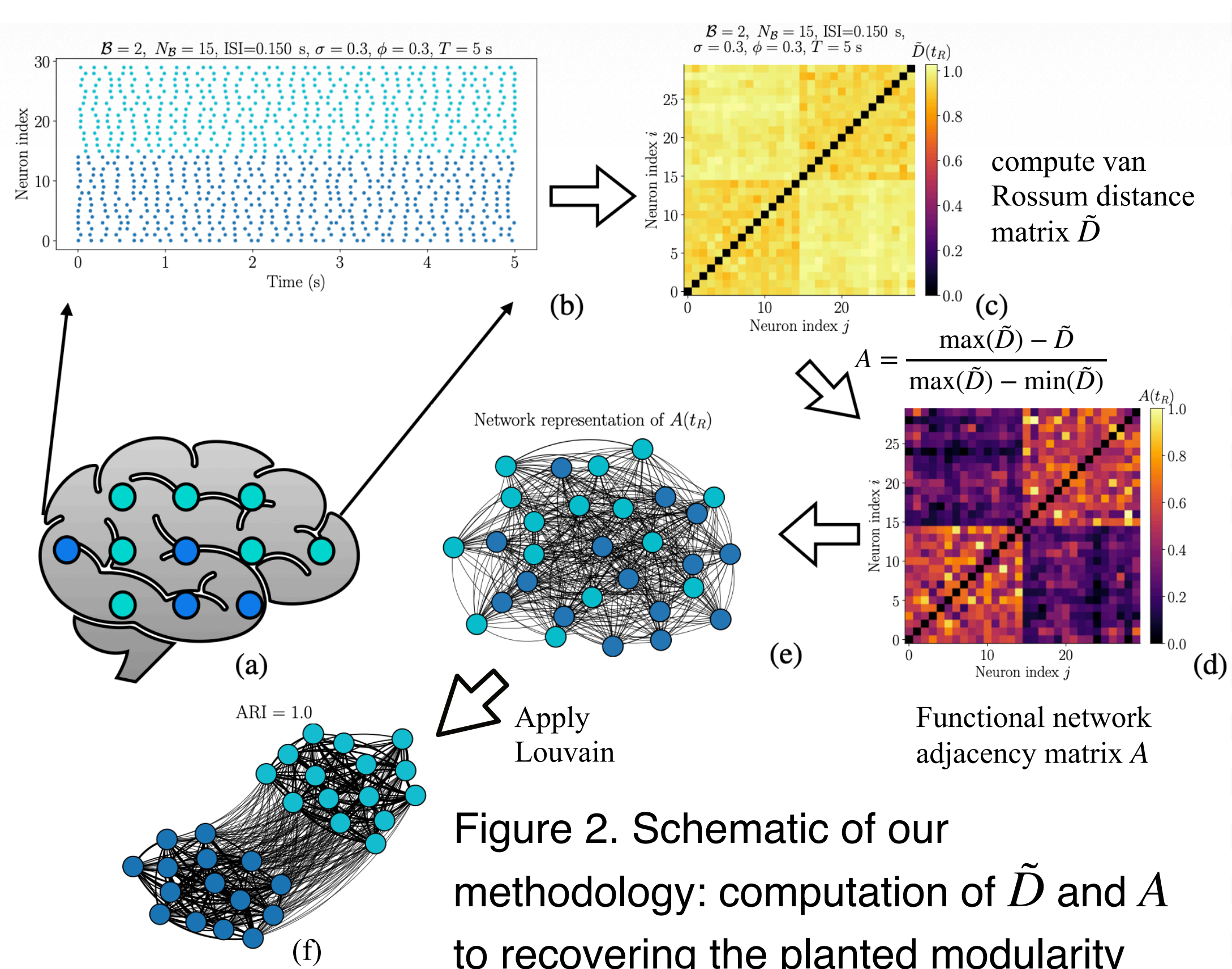


Figure 2. Schematic of our methodology: computation of \tilde{D} and A to recovering the planted modularity using Louvain algorithm.

Van Rossum distance

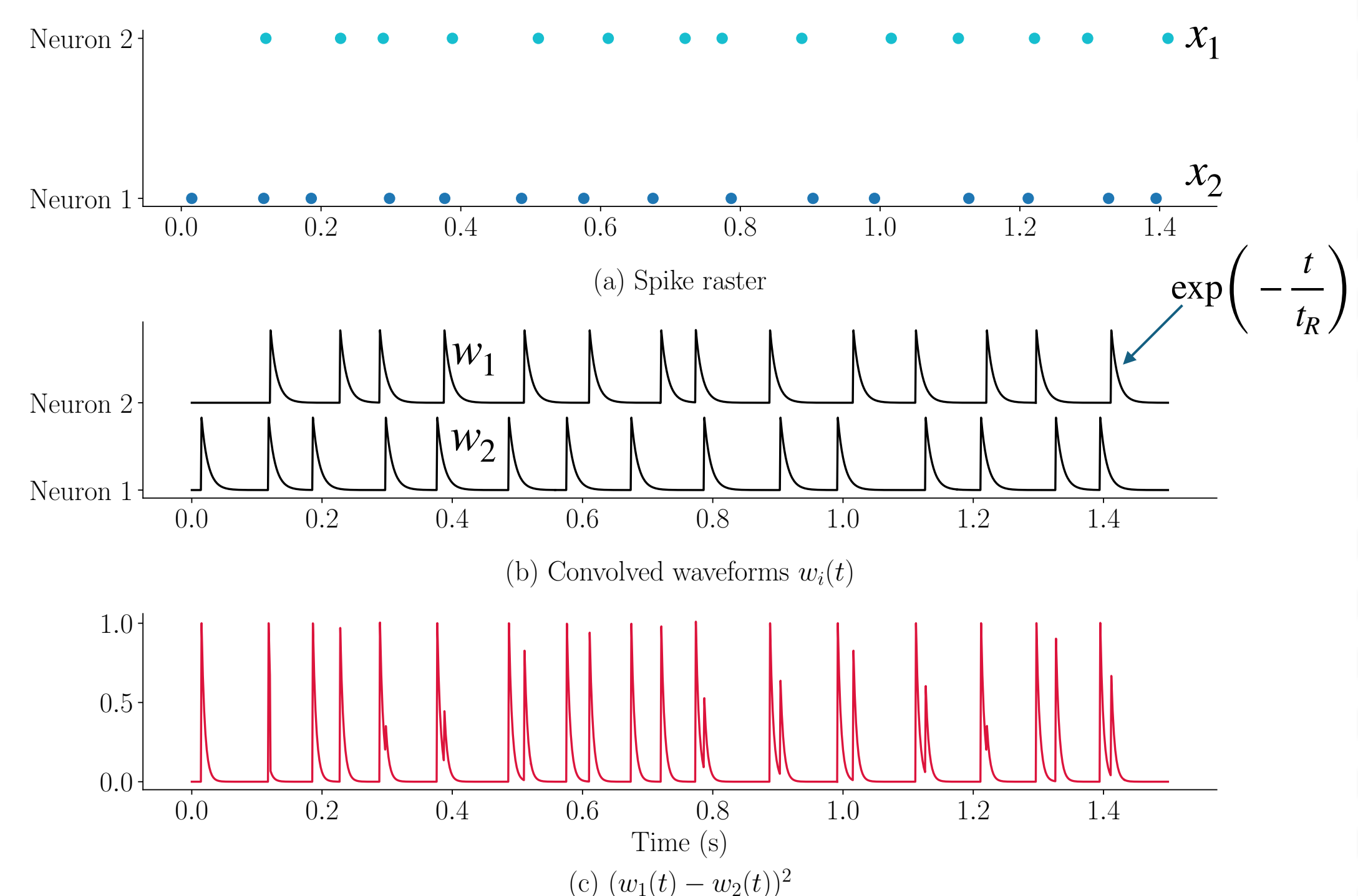


Figure 1. Steps to compute van Rossum distance.

$$\tilde{D}_{ij}(t_R) = \frac{1}{\sqrt{N_{ij}}} \sqrt{\frac{1}{t_R} \lim_{T \rightarrow \infty} \int_0^T (w_i(t) - w_j(t))^2 dt}$$

Louvain algorithm

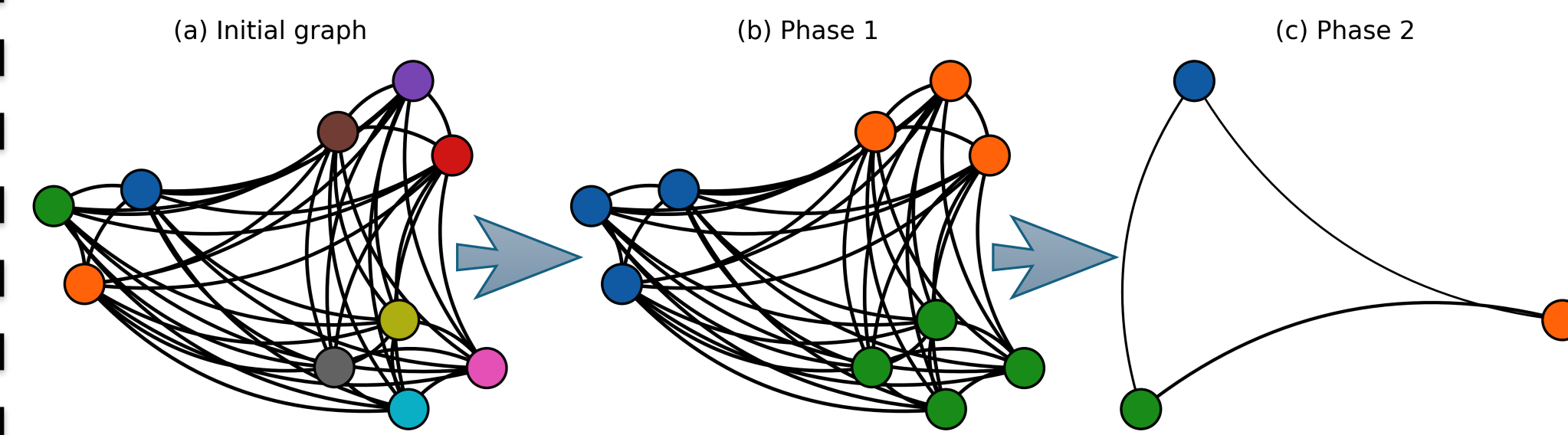


Figure 3. Louvain algorithm: used for community detection.

Synthetic data

1. Synthetic raster: $t_b^k = (\phi_b + k) \times \text{ISI} + \zeta^k$.
2. Noise $\zeta^k \sim U[-\sigma_{\max}, \sigma_{\max}]$, where $\sigma_{\max} = \text{round}(\text{ISI} \times \sigma)$.

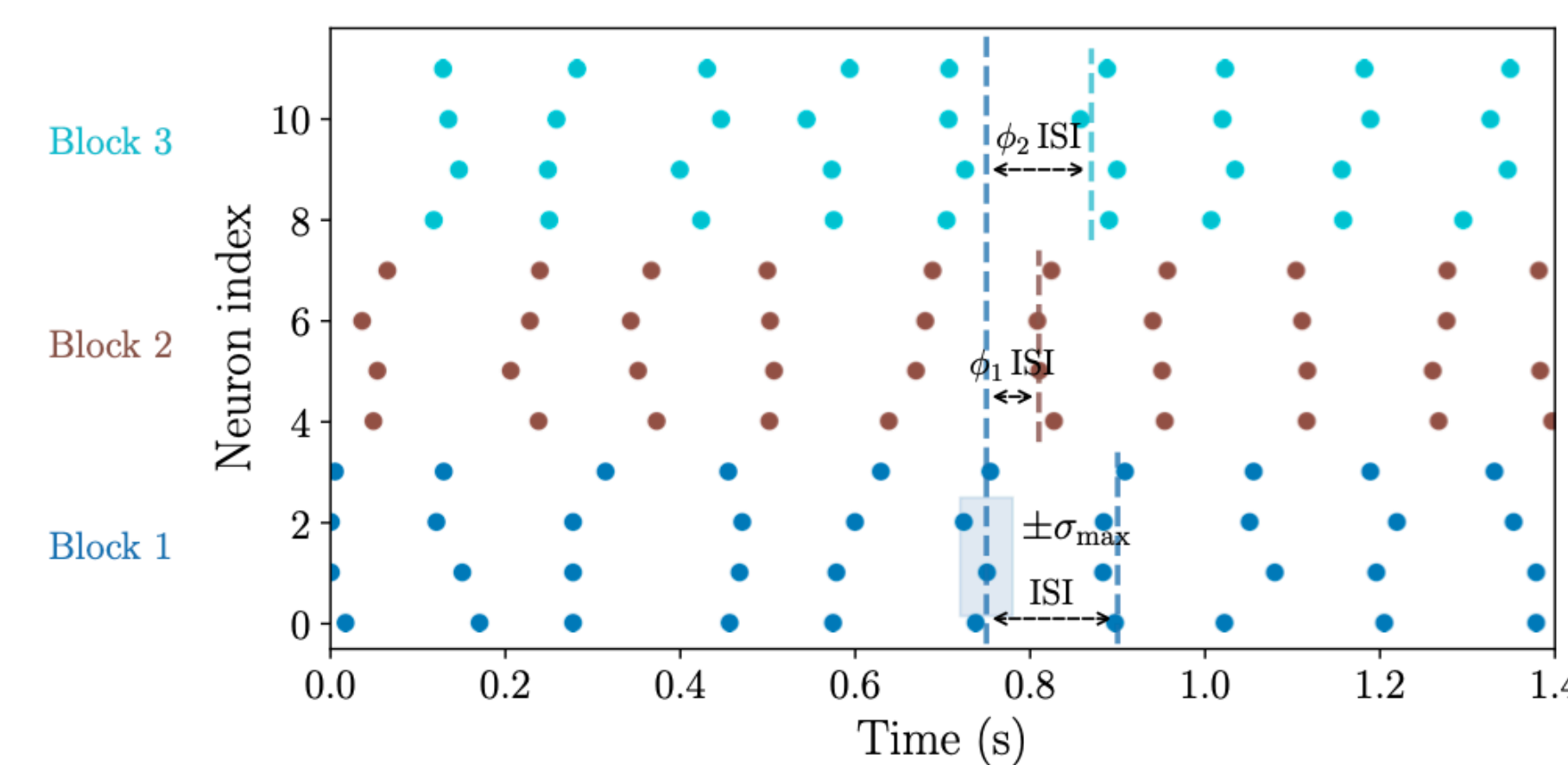


Figure 4. Schematic of a synthetic raster indicating the phase differences ϕ_b and noise levels σ .

LIF neurons

We consider a stochastic block model (SBM) network of N leaky integrate-and-fire (LIF) neurons where each node follows:

$$C_m \frac{dV_i}{dt} = g_{L,i}(V_L - V_i) + s_{E,i}(t)(V_E - V_i) + s_{I,i}(t)(V_I - V_i),$$

$$\frac{ds_{E,j}}{dt} = -\frac{s_{E,j}}{\tau_E} + \sum_{i \in E} \frac{g_E}{\tau_E} A_{ij} \delta(t - t_i^{\text{spike}}) + \frac{f_{E(j)}}{\tau_E} \frac{dQ_j(t)}{dt},$$

$$\frac{ds_{I,j}}{dt} = -\frac{s_{I,j}}{\tau_I} + \sum_{i \in I} \frac{g_I}{\tau_I} A_{ij} \delta(t - t_i^{\text{spike}}).$$

Allen Neuropixels data

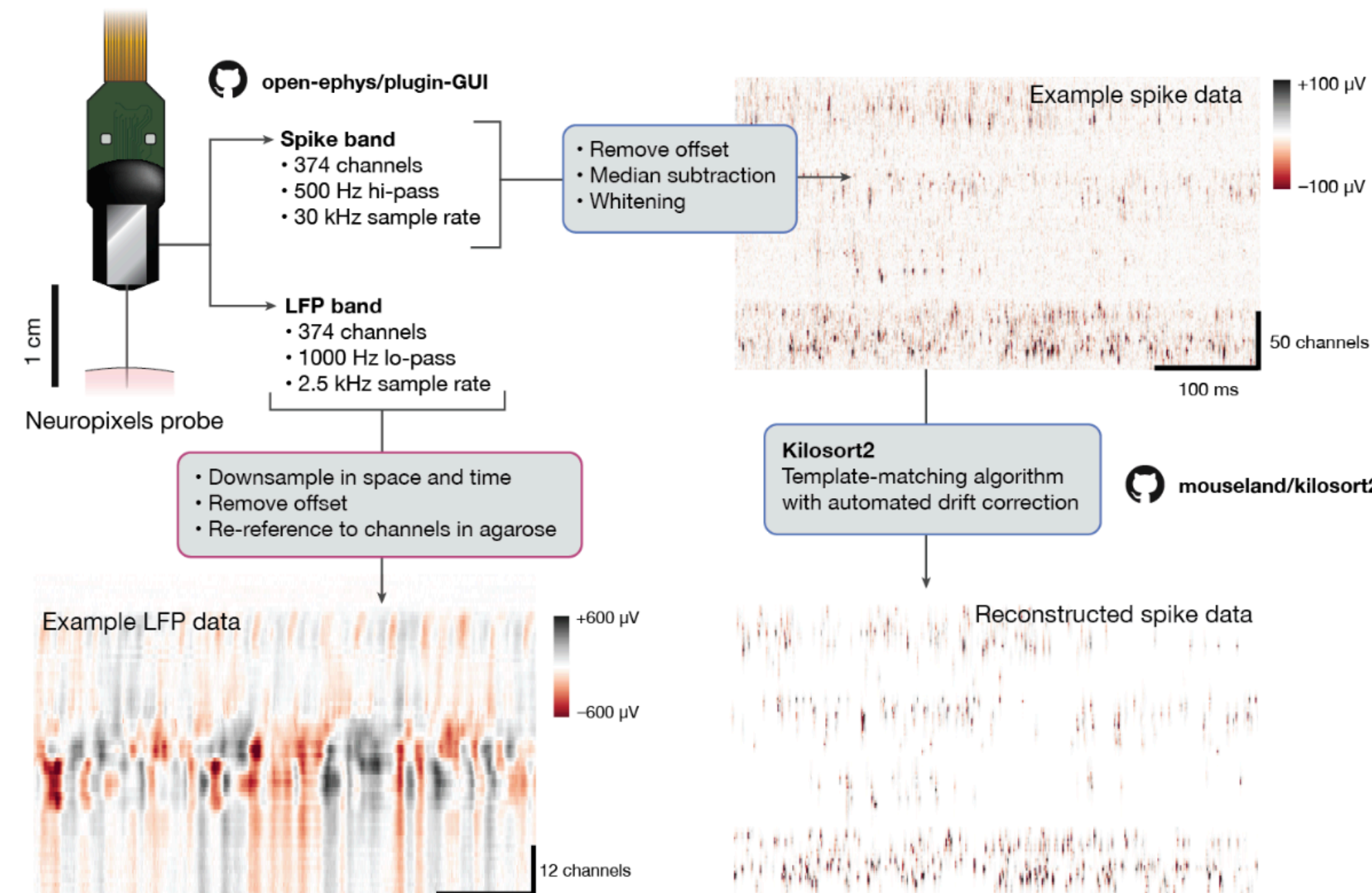


Figure 5: Data from Allen Institute for Brain Science. Image credit: [https://allensdk.readthedocs.io/en/latest/visual_coding_neuropixels.html]

Synthetic data results

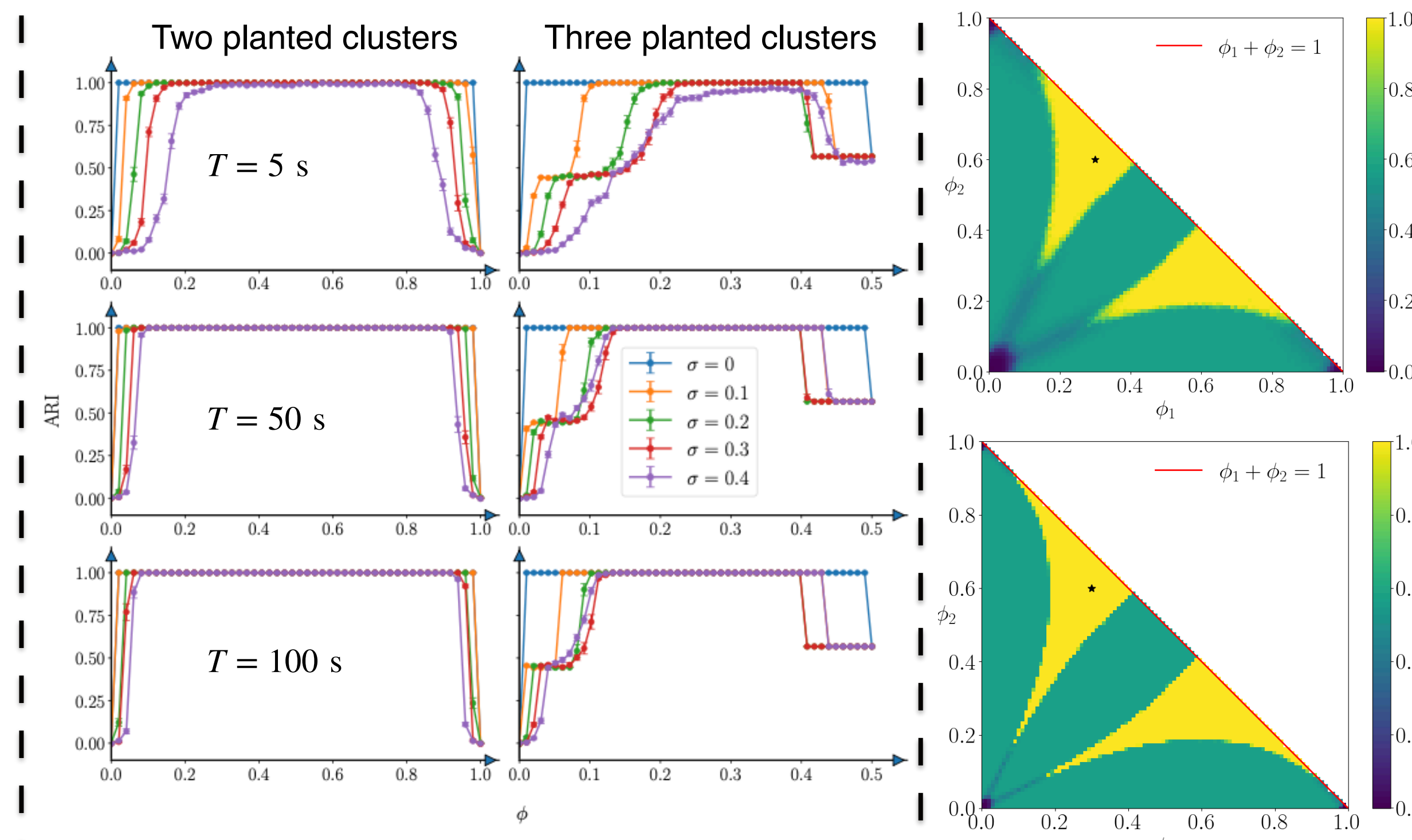


Figure 6. ARI as a function of ϕ for different σ and T . Simulation is for $N = 120$ neurons and $\text{ISI} = 0.1$ s. For a small ϕ , ARI is low due to overlap. As ϕ increases, $\text{ARI} \approx 1$. Circular nature of ϕ leads to low ARI for large value. There are partial merging of blocks for three blocks: intermediate ARI. The area under the curve for a higher σ is lower while large T : more robust recovery.

Figure 7. $\text{ARI}(\phi_1, \phi_2)$ for three blocks. High ARI (yellow colour) occurs when all the pairwise circular phase separations are large. Also, an increase in T sharpens the boundaries, whereas high σ reduces the recovery regime.

LIF results

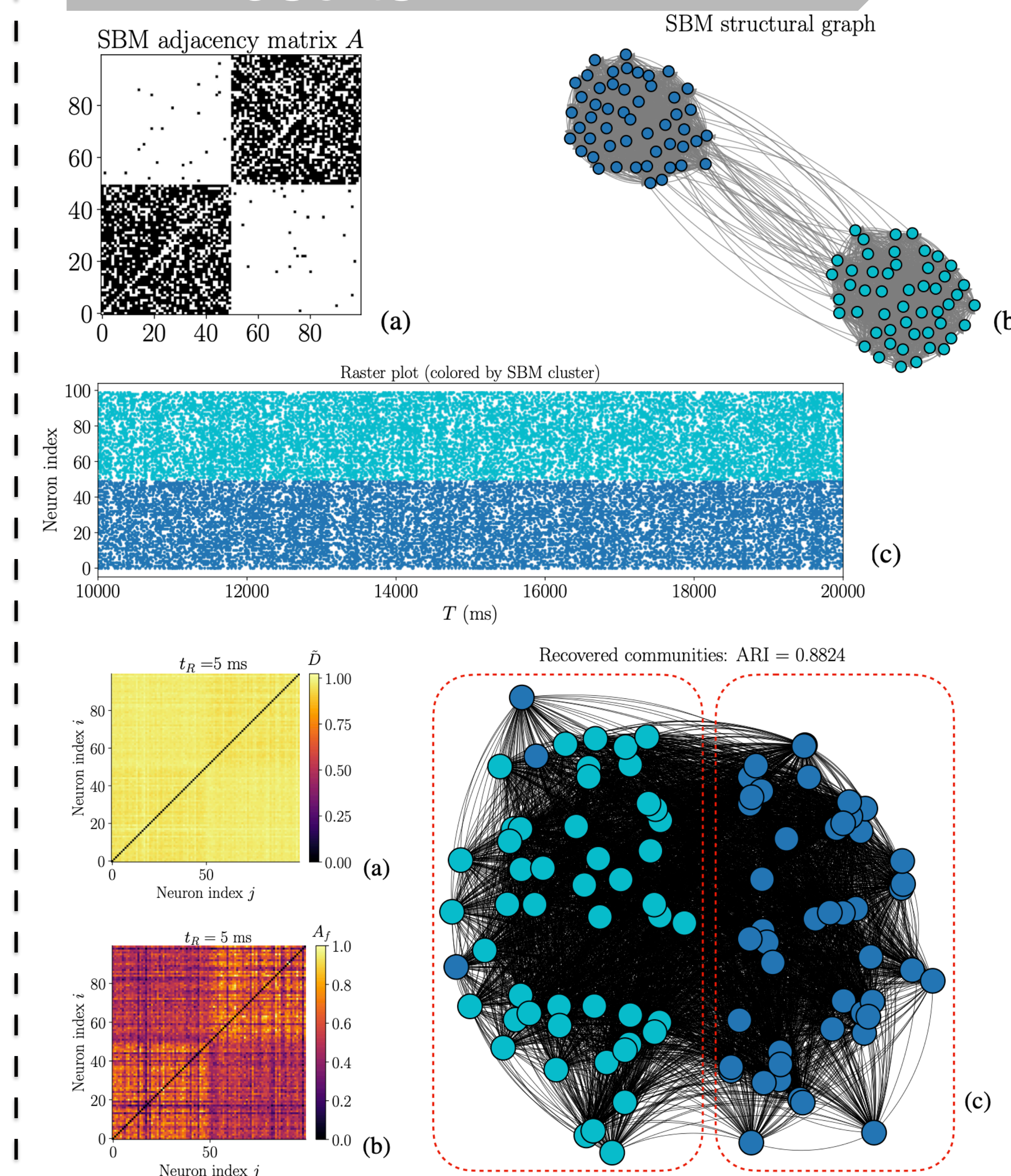


Figure 8. Application on the SBM network of LIF neurons. Showing a good recovery of the planted modularity with $\text{ARI} \approx 0.8824$

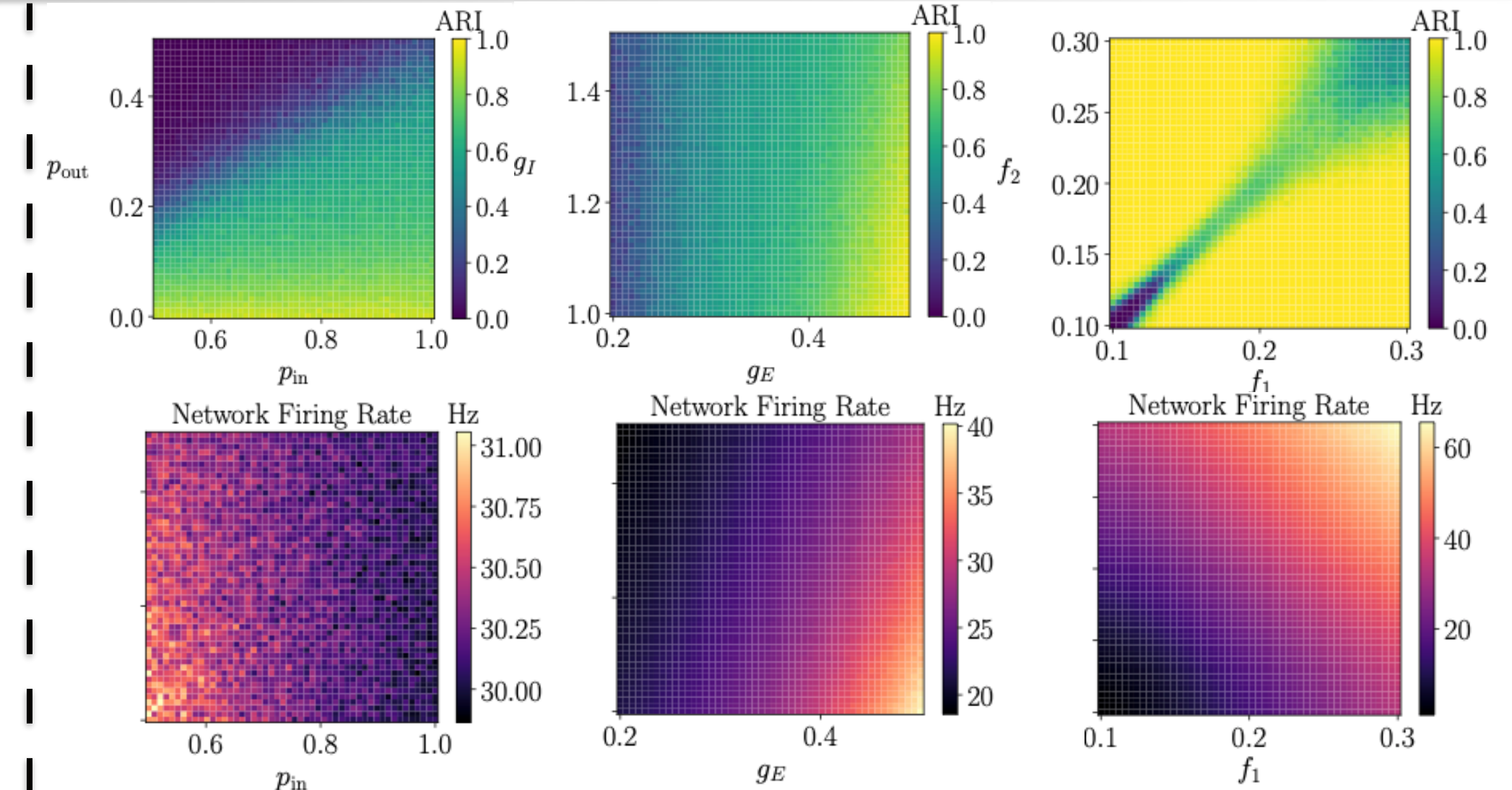


Figure 9. Parameter sweeps: ARI and firing rate with two clusters and $N = 100$. We see that community recovery is the strongest when structural modularity is high, excitation is sufficiently high, and the input drives differentiate between the clusters.

Allen Neuropixels results

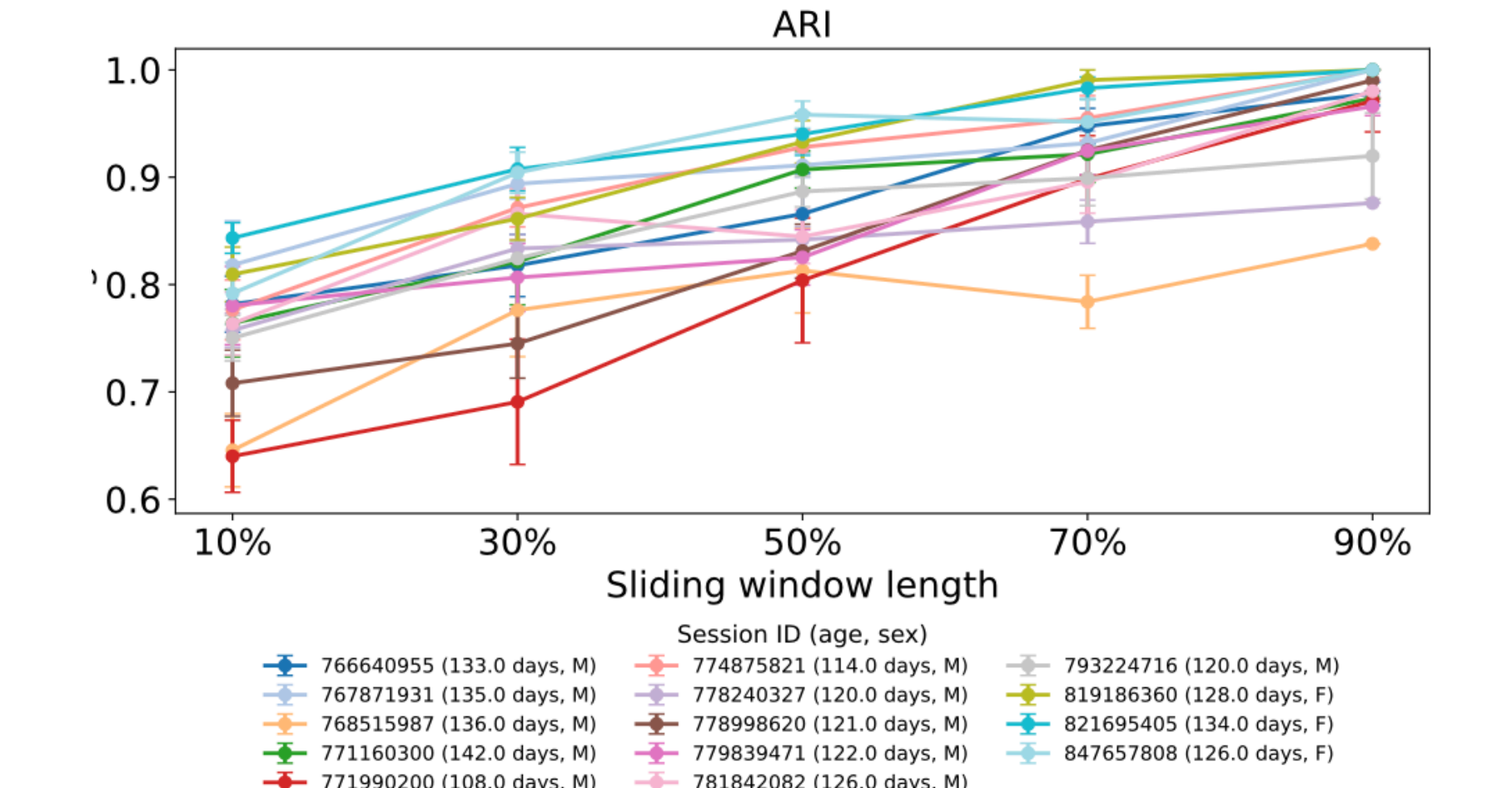


Figure 10. Robustness study: subsampled windows taken from longest stimulus. ARI increases with window length, reaching near-perfect agreement at larger windows.

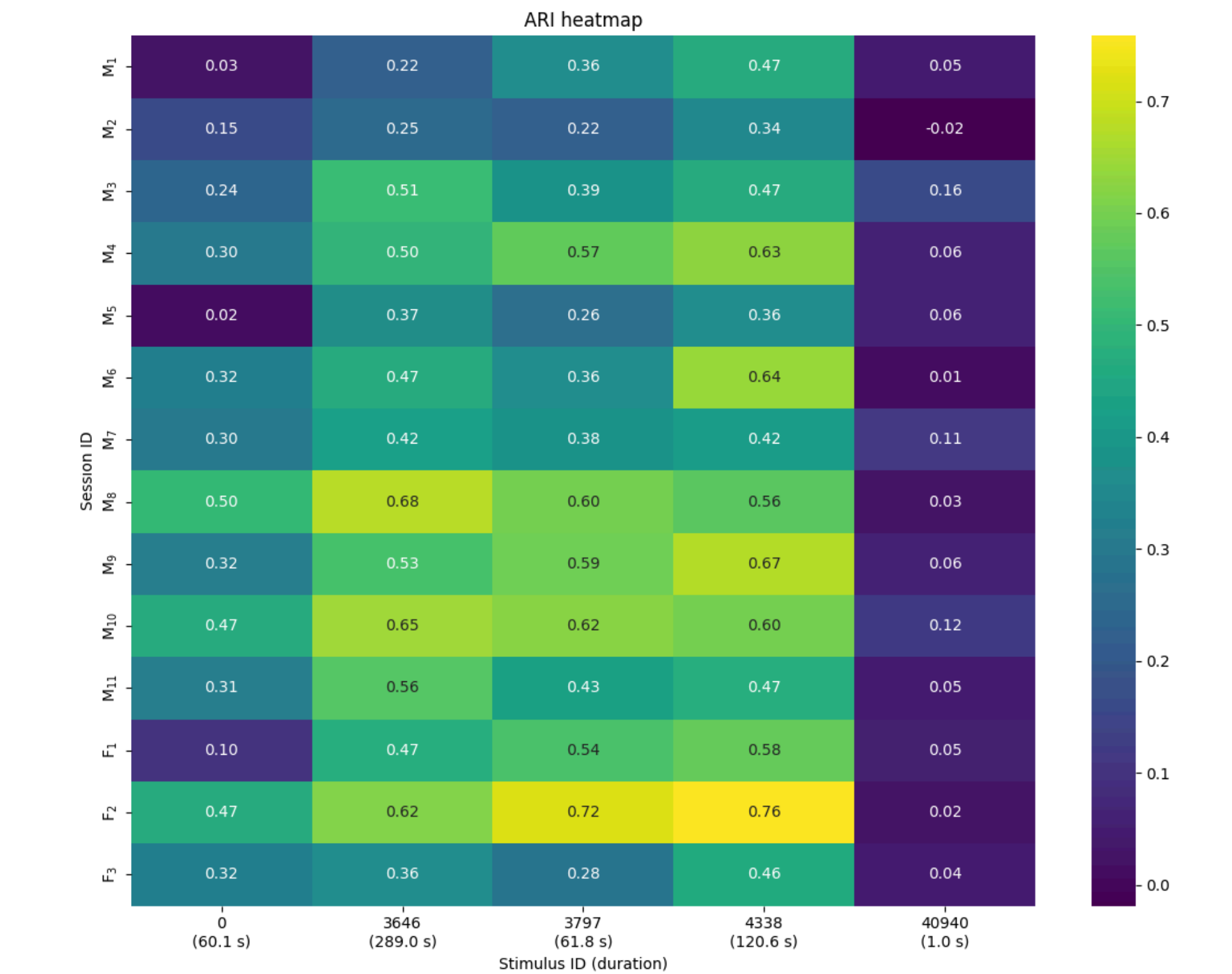


Figure 11. Cross presentation reproducibility test. Longer presentations show moderate to high agreement.

Conclusions

We have been able to combine a biologically meaningful spike-train similarity measure with network science tools to extract latent structures from complex neural recordings. We are able to show stable functional neural assemblies during spontaneous brain activity.

Acknowledgements

This work was supported by grant #22/FFP-P/11547 managed by Research Ireland.