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Connectivity-informed spatio-temporal MEG source reconstruction: Simulation results using a MAR model

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Abstract: Recovering brain activity from M/EEG measurements is an ill-posed problem and prior constraints need to be introduced in order to obtain unique solution [1]. The majority of the methods use spatial and/or temporal constraints, without taking account of long-range connectivity. In this work, we propose a new connectivity-informed spatio-temporal approach to constrain the inverse problem using supplementary information coming from diffusion MRI. We present results based on simulated brain activity using a Multivariate Autoregressive Model, with realistic subject anatomy obtained from Human Connectome Project [4] dataset.

1. The forward problem

The relationship between source amplitudes and M/EEG measurements is expressed by the following linear model:

$$M = GJ + \epsilon \quad \text{where}$$

- $M \in \mathbb{R}^{N \times T}$ matrix of M/EEG signals measured at N sensors at T time instants
- $G \in \mathbb{R}^{N \times S}$ forward operator (leadfield matrix), where each column corresponds to forward field of one of S sources
- $J \in \mathbb{R}^{S \times T}$ unknown matrix of S source amplitudes (current distribution) along time
- ϵ additive white Gaussian noise
 - The source space of size S is parcellated into R cortical regions according to Desikan-Killiany atlas [5], where $R=68$ ($S \gg R$).
 - Brain is modelled as a simple undirected graph with R nodes.

2. The inverse problem

Consider the minimization problem: $\hat{J} = \arg \min_J \{ \|M - GJ\|_2^2 + \lambda \|LJ\|_2^2 \}$

LORETA

Our approach

- Low resolution brain electromagnetic tomography (**LORETA**) [2] assumes simultaneous and synchronous activations of neighbouring brain areas.
- Maximally smooth solution – minimal norm of discrete Laplacian of the current distribution.

- Include supplementary information from diffusion MRI in the regularization:
 - **anatomical** (long-range) **connections**
 - **transmission delays** Δ_f between cortical regions

- Recovered source amplitudes are obtained by:

$$\hat{J}_L = (G^T G + \lambda L^T L)^{-1} G^T M$$

$$\hat{J}_C = (\tilde{G}^T \tilde{G} + \lambda \tilde{L}^T \tilde{L})^{-1} \tilde{G}^T M$$

λ^* – optimal regularization parameter – chosen using Generalized Cross-Validation

- L – symmetric normalized **Laplacian matrix** computed on the cortical regions:

$$L^{symm} = I - D^{-1/2} A D^{-1/2}$$

- D – degree matrix

- A – symmetric ($R \times R$) **adjacency matrix** (connectivity) **matrix** on the cortical mesh with elements:

$$a_{ij} = \begin{cases} 1, & \text{if vertices } i \text{ \& } j \text{ are connected by an edge} \\ 0, & \text{otherwise} \end{cases}$$

Edges between neighbouring nodes

- (adjacent brain areas) \rightarrow **short-range connections**

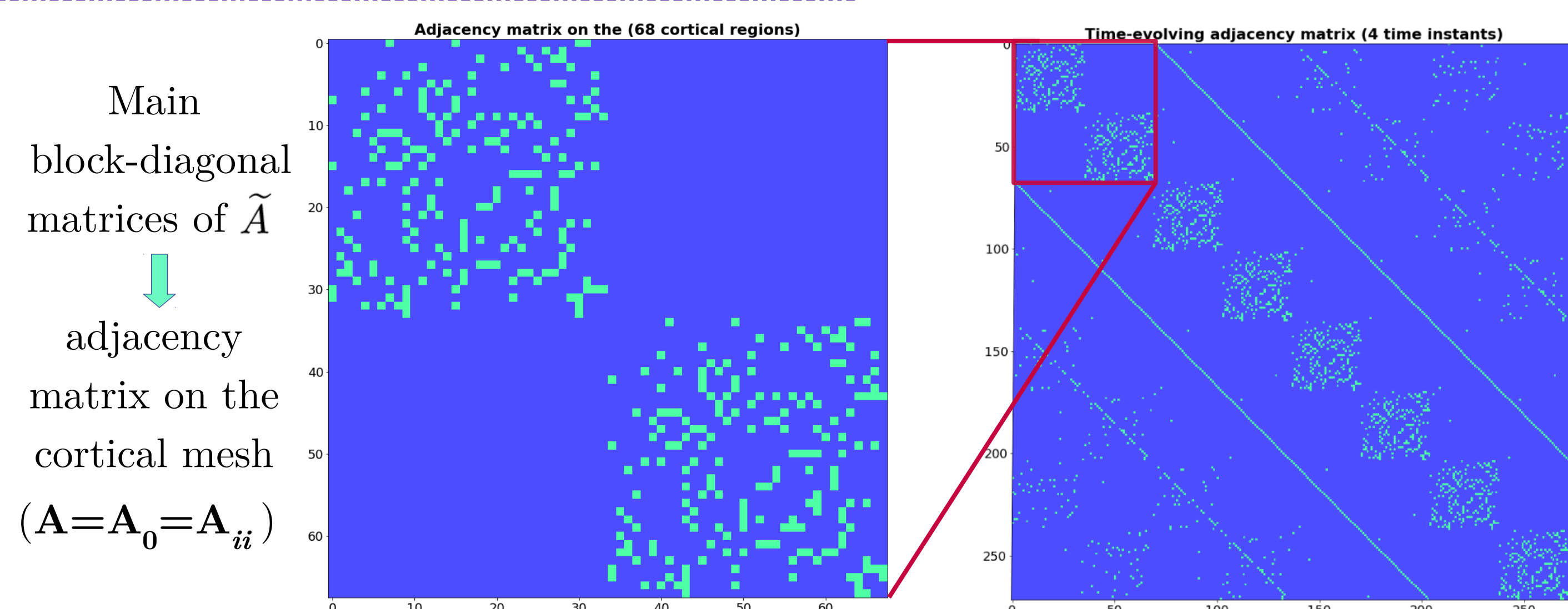
- \tilde{G} – block-diagonal leadfield matrix of size $(N \times T) \times (R \times T)$

- \tilde{L} – **time-evolving** block-diagonal normalized **Laplacian matrix**

- \tilde{A} – spatio-temporal adjacency matrix of size $(R \times T) \times (R \times T)$ that evolves with time according to long-range connectivity

- edges between neighboring nodes
- **short-range & long-range connections**

$$\tilde{A} = \begin{bmatrix} A_0 & A_1 & \dots & A_{T-2} & A_{T-1} \\ A_1 & A_0 & \dots & \dots & A_{T-2} \\ \vdots & \dots & \dots & \dots & \vdots \\ A_{T-2} & \dots & \dots & A_0 & A_1 \\ A_{T-1} & A_{T-2} & \dots & A_1 & A_0 \end{bmatrix}$$



Main block-diagonal matrices of \tilde{A}
 \downarrow
adjacency matrix on the cortical mesh ($A=A_0=A_{ii}$)

3. Simulation of cortical activity

- Simulations were performed using MNE-Python software [3] based on realistic subject anatomy from HCP dataset [4].
- Activity of all sources can be modeled as a Vector Autoregressive model [6] of order p (**VAR(p)**):

$$\hat{j}_t = \sum_{i=1}^p C_i \hat{j}_{t-i} + \omega_t \in \mathbb{R}^S$$

$$p = \max(\Delta_f) \quad \Delta_f = \frac{f_{length}}{speed} F_s$$

max delay found in all f streamlines

MAR coefficient matrices

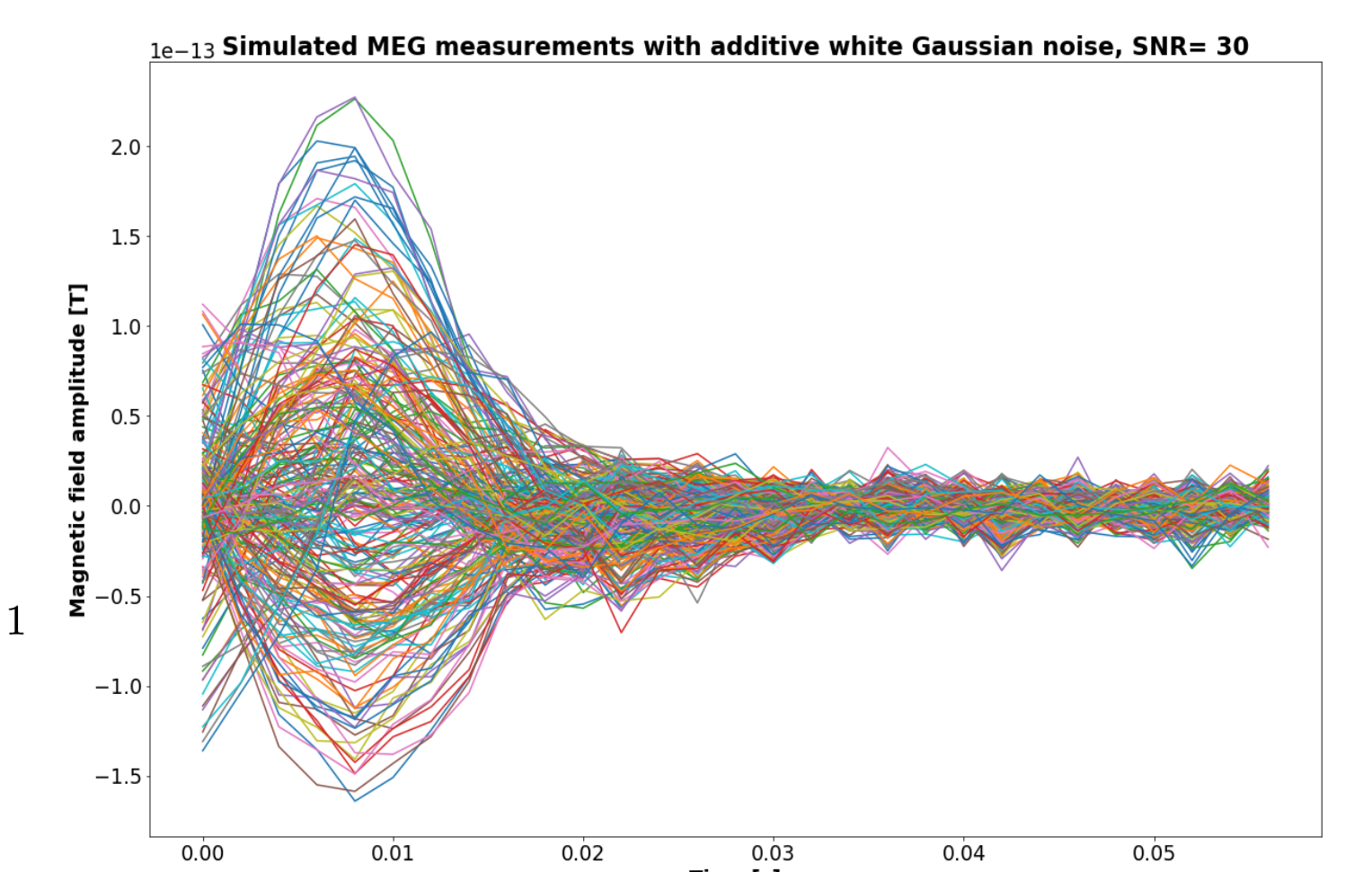
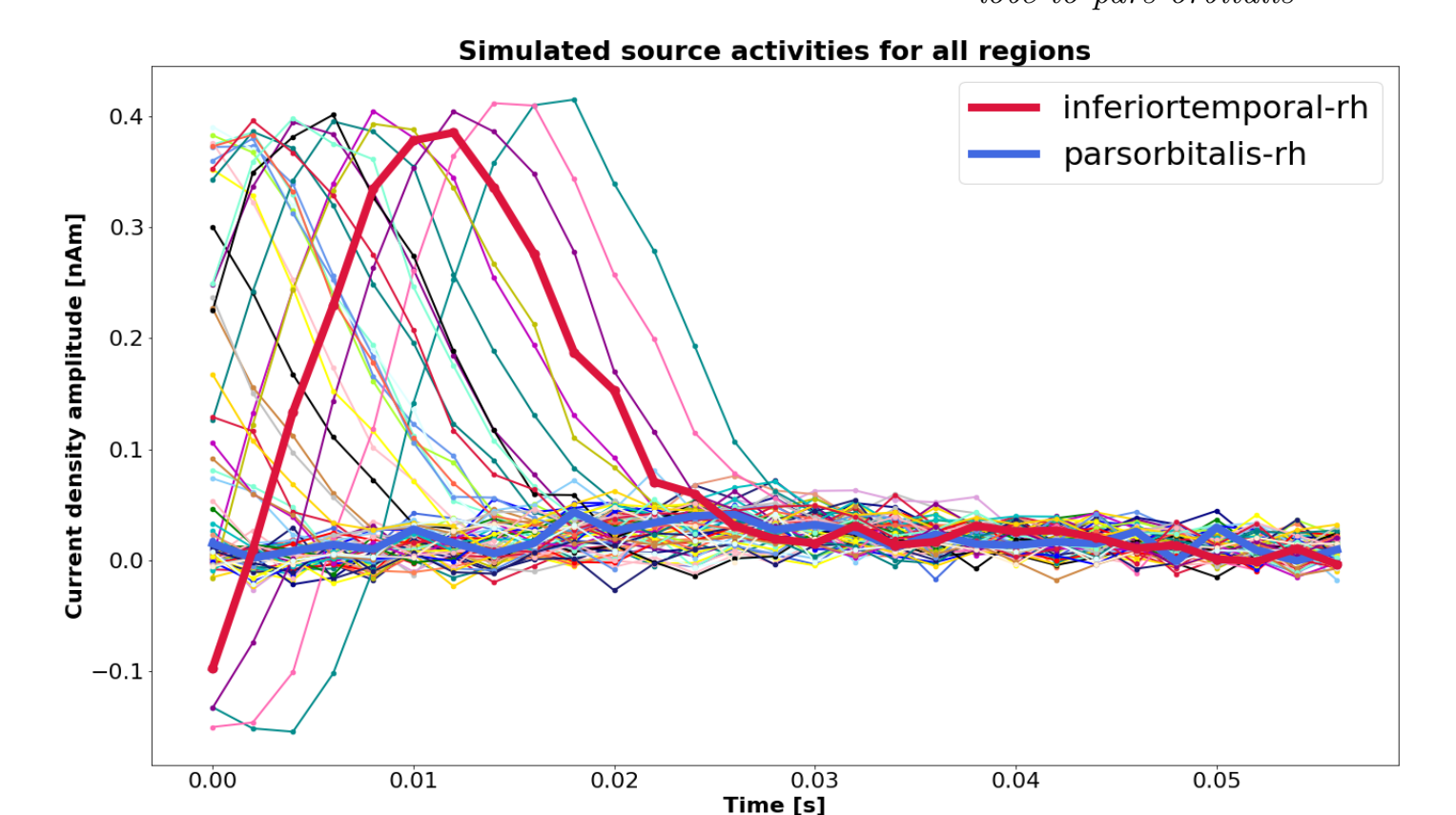
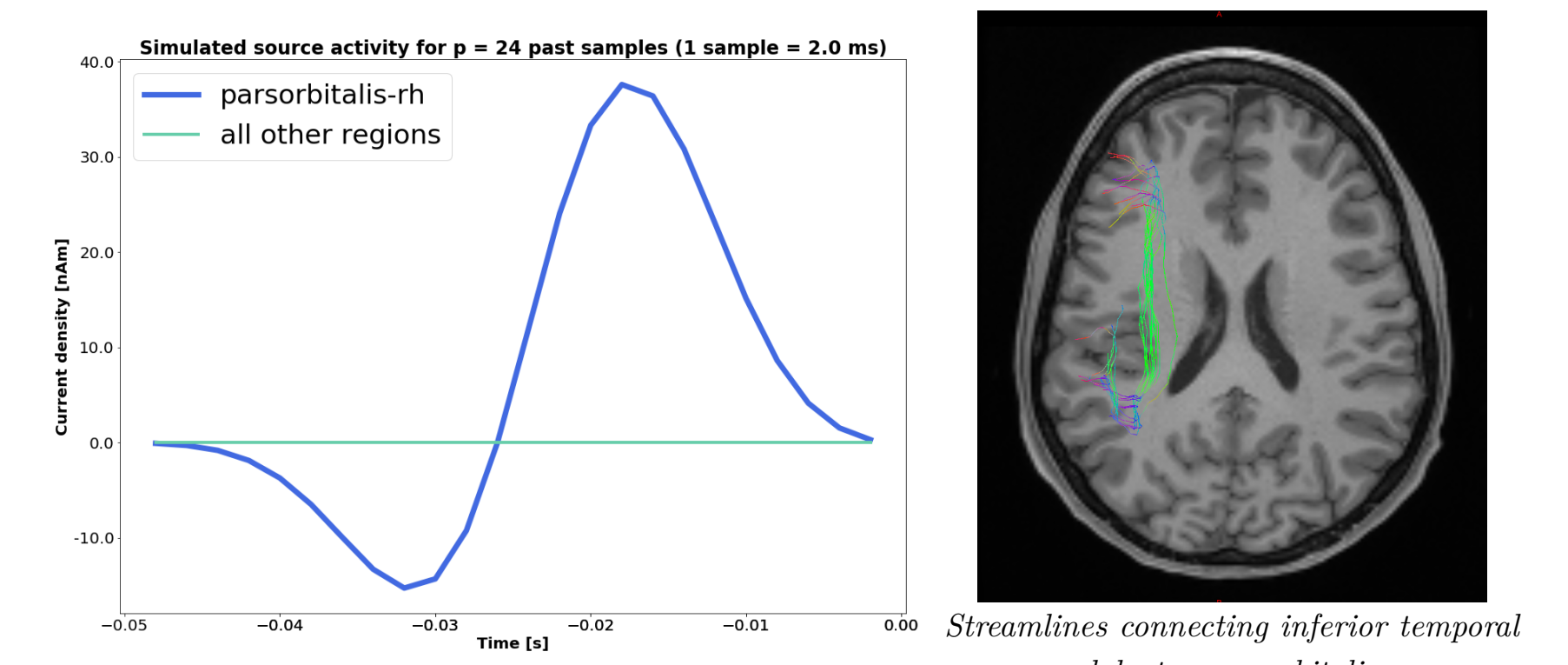
- $C_i \in \mathbb{R}^{S \times S}$ matrix defines the contribution of all sources at time $t-i$ to all sources at time t

- **Dynamic source model** is defined by multivariate autoregressive (**MAR**) model:

$$\tilde{J}_t = \tilde{C} \tilde{J}_{t-1} + \tilde{\omega}_t = (j_t, j_{t-1}, \dots, j_{t-p+1})^T \in \mathbb{R}^{Sp \times 1}$$

- $\tilde{C} \in \mathbb{R}^{Sp \times Sp}$ augmented coefficient matrix

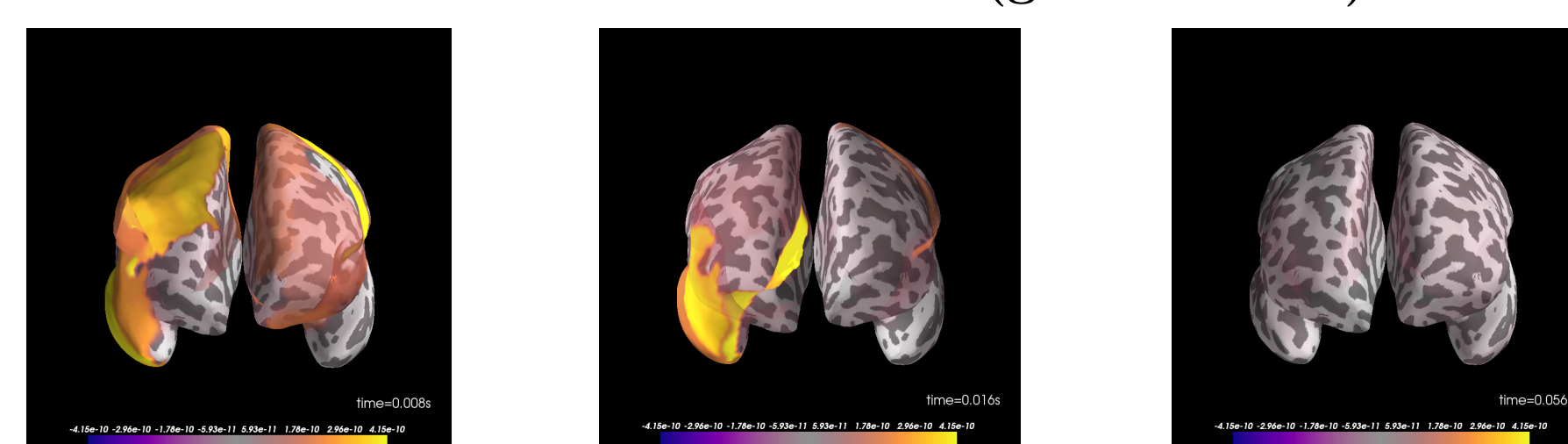
- Example: input signal (for p past samples) in right inferior frontal gyrus (**pars orbitalis**).



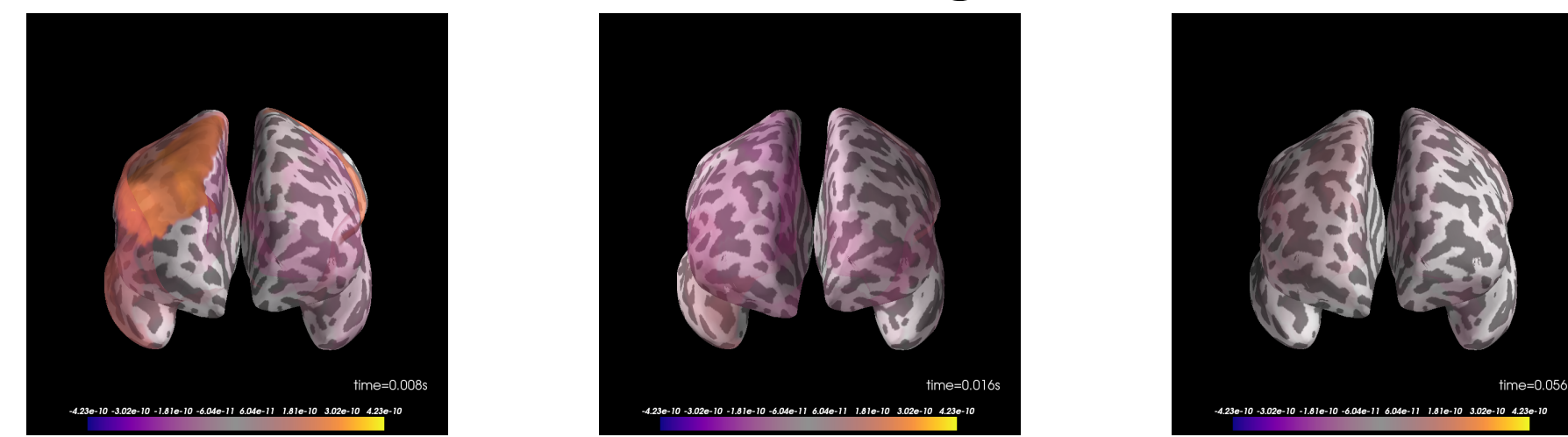
4. Results

- Results of reconstruction of cortical activity from simulated MEG measurements are presented and compared to original LORETA method.

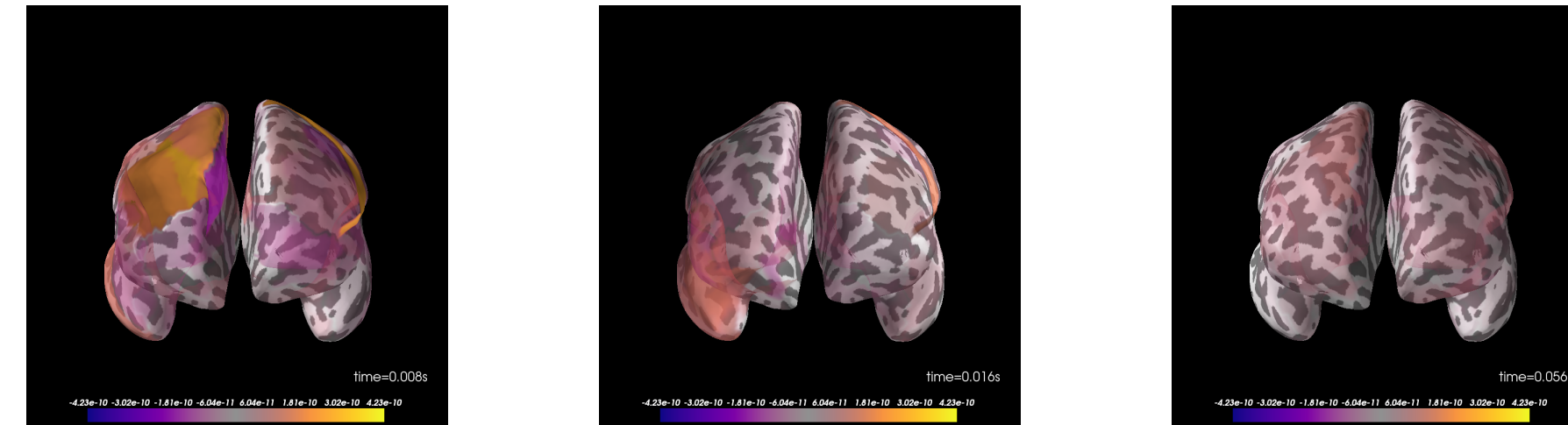
$t = 0.008$ s $t = 0.016$ s $t = 0.056$ s
Simulated cortical activities (ground truth)



Reconstructed sources – original LORETA



Reconstructed sources – connectivity-informed LORETA



5. Conclusion

- The preliminary results of MEG source reconstruction obtained using **simulated source activity** according to a **MAR model** and **spatio-temporal approach** for **inverse solution** were presented.

- We tackled the ill-posed problem in both space and time and obtained promising results in terms of amplitude and focality.

- Nevertheless, further simulations need to be performed with multiple subject in order to validate the preliminary results.

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