ULTRA-HIGH FREQUENCY SPECTRUM OF NEURONAL ACTIVITY

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What does „Ultra-high frequency spectrum of neuronal activity“ mean?

- activity of spiking network models exhibits fast oscillations (>200 Hz)
- caused by inhibition-dominated excitatory-inhibitory loops [1, 2]

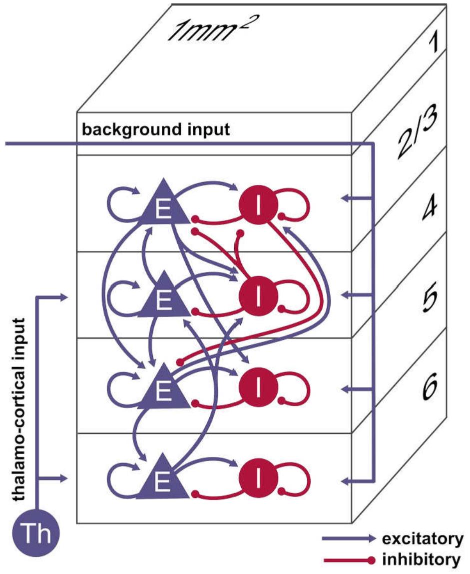


Figure taken from [3]

- 5 stripes within 50 ms → ~100 Hz
- 17 stripes within 50 ms → ~340 Hz

How can we understand these fast oscillations?

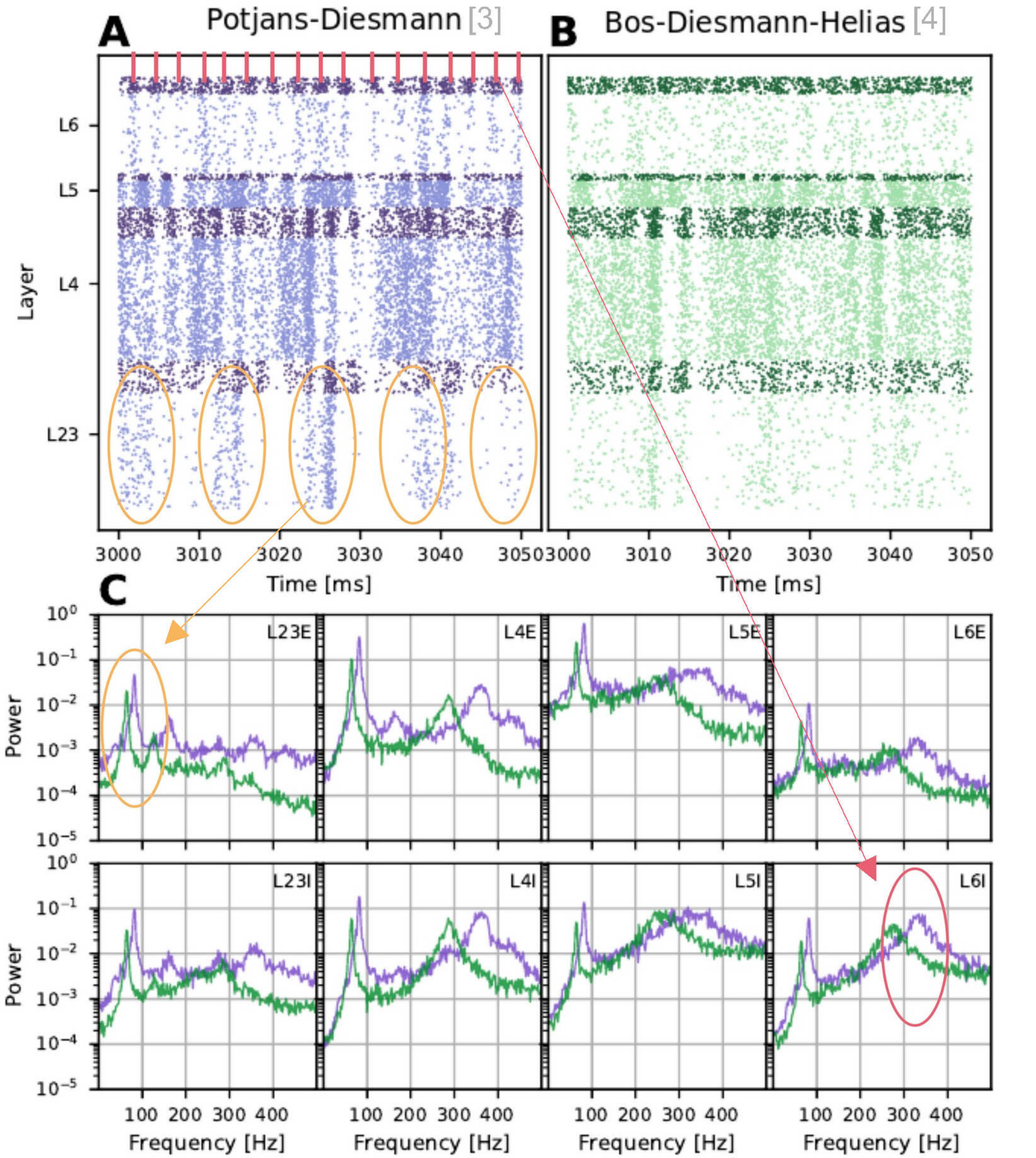
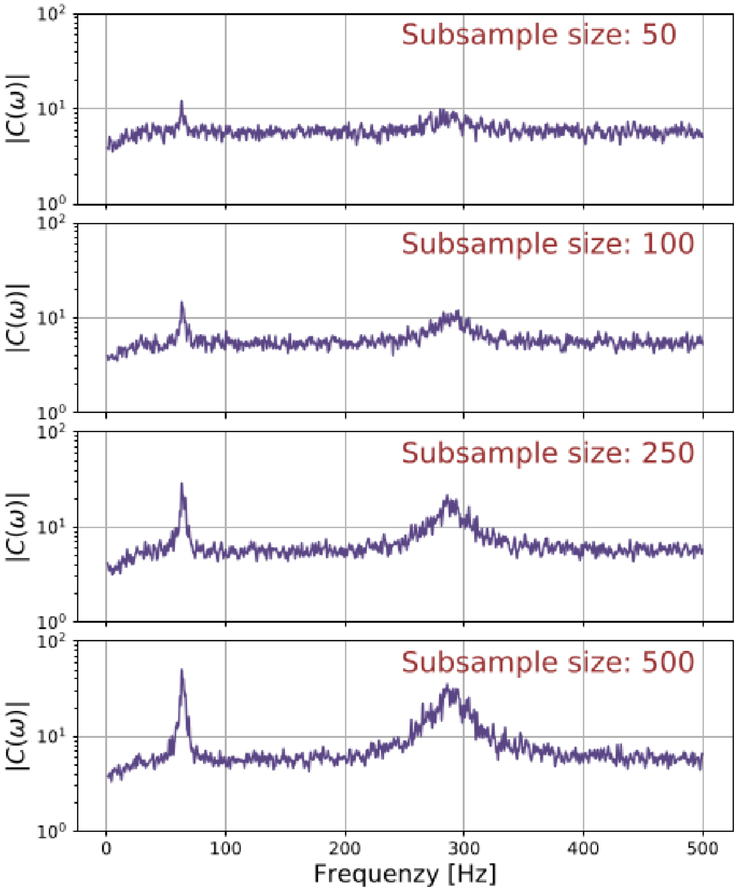


Figure adapted from Fig. 4.3 in [5]

[1] Brunel, J Comput Neurosci (2000).
[2] Brunel, & Wang, J Neurophysiol (2003).
[3] Potjans & Diesmann, Cereb Cortex (2014).
[4] Bos, H. et al., PLOS CB (2016).
[5] Helin, R., Master thesis (2019).

Can fast oscillations be observed in experimental data?



Power spectral density for different number of spike trains. PSD of spike trains of 50 (top), 100, 250 and 500 (bottom) L4I neurons, normalized to equal background power for all neuron counts. PSD is calculated over 9s of spike data, averaged over ten trials and smoothed with a Gaussian kernel of width 3 ms.

- population rate spectrum can be decomposed [5,6]:

$$C(\omega) = \underbrace{\sum_{i=1}^{N} A_i(\omega)}_{\text{single neuron power spectra } \propto\, N} + \overbrace{\sum_{\substack{i=1\\ j\neq i}}^{N} C_{ij}(\omega)}^{\text{cross-spectra of pairs of neurons } \propto\, N^2}$$

- single-neuron spectra dominate for low numbers of neurons (~100)
- population measures obtained from large neuron ensembles (e.g., LFP) should show a pronounced peak

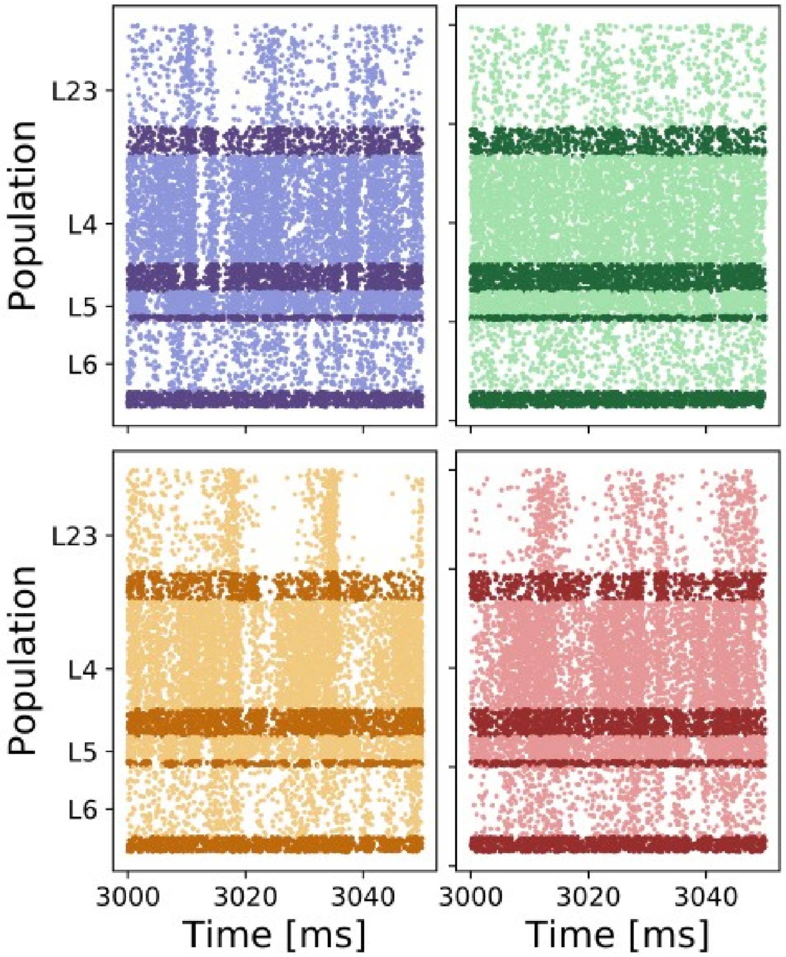
Coherent oscillations in the population activity may go unnoticed in experimental spike recordings.

Figure taken from [6]

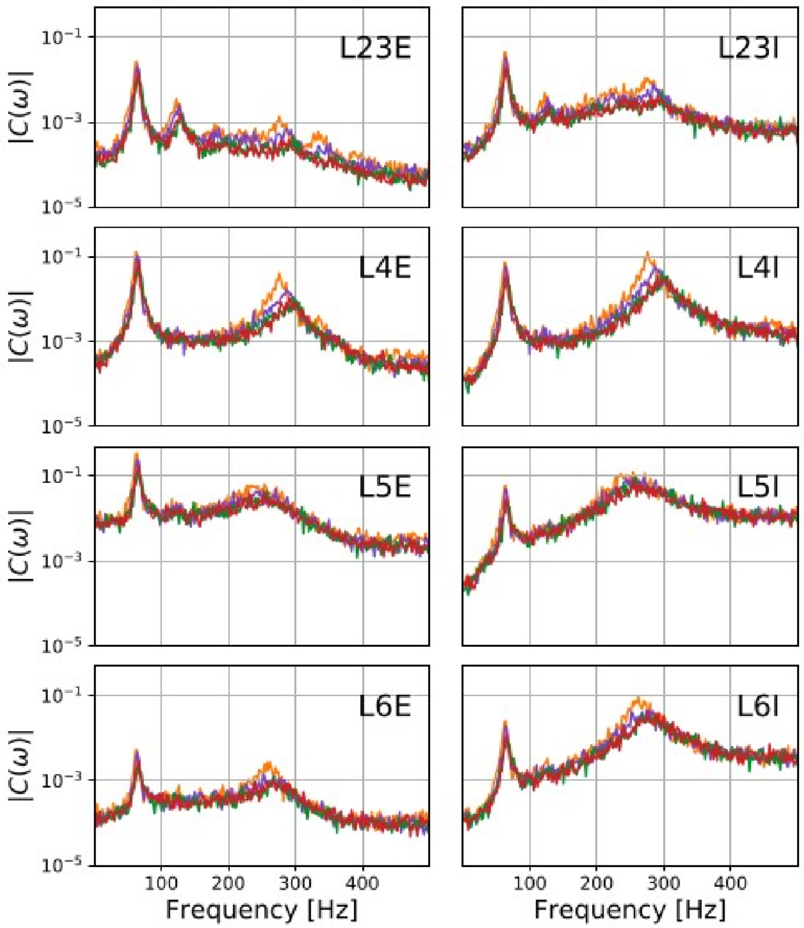
[6] Helin, R. et. al., Poster at SFN19

Figures taken from [6]
[6] Helin, R. et. al., Poster at SFN19

Do oscillations occur due to simulation artifacts?



Spike activity simulated with different simulation variants. All figures show 50ms of activity for the same model receiving the same input, but using different spike time and delay discretization. Color codes as in the text above; light colors mark excitatory neurons, dark colors inhibitory.



Power spectral density of spike activity for different simulation variants. Figures show PSD for excitatory layers (left) and inhibitory layers (right) in different cortical layers for the same model and color code as for the spike trains to the left. Trains binned with 1ms resolution and PSD averaged across 18 windows of 500ms.

Discrete spike times, discrete delays (default simulation)
Spike times bound to 0.1 ms time grid, delays rounded to nearest multiple of 0.1 ms.

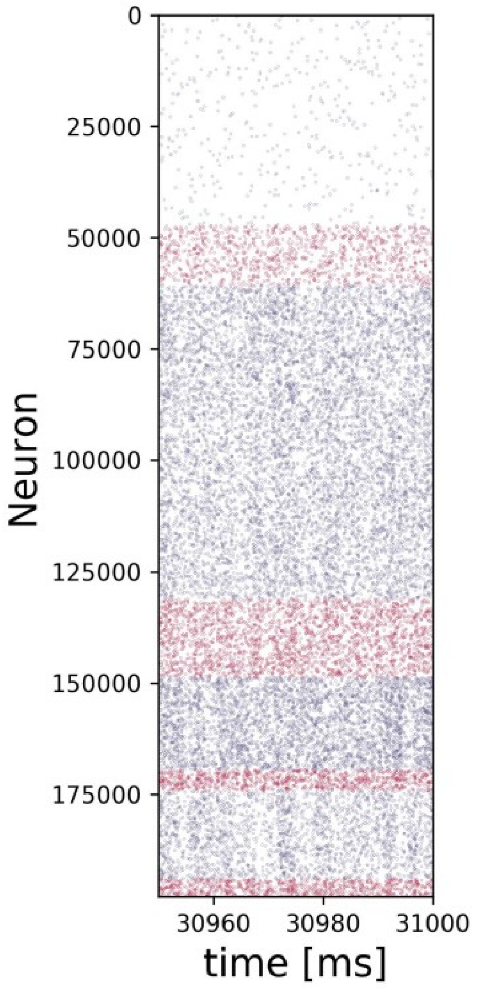
Continuous spike times, discrete delays
Spike times not bound to time grid, delays rounded to nearest multiple of 0.1 ms.

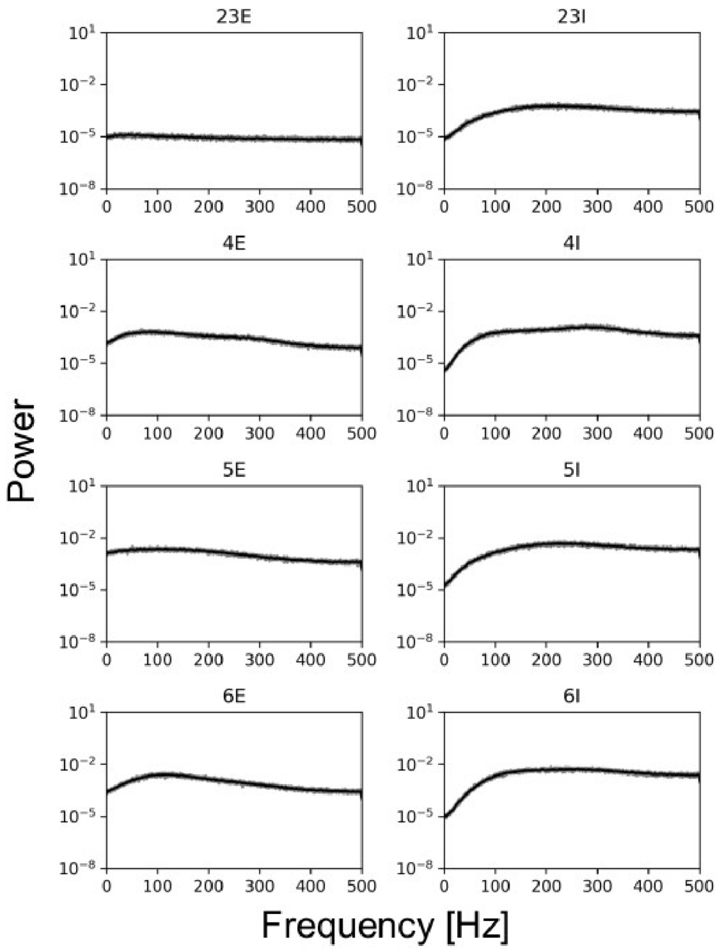
Discrete spike times, continuous delays
Spike times implicitly bound to 0.1 ms time grid, continuous range of delays.

Continuous spike times, continuous delays
Spike times not bound to time grid and continuous range of delays.

Simulation artifacts as origin of oscillations can be ruled out.

Are there models of same architecture, but without fast oscillations?





The V1 circuit within the multi-area model [7] does not show peaks in the power spectrum.

What is the key difference between the two models?

- synaptic density kept constant,
- number of neurons per population more then twice as large

Number of synapses per neuron (indegrees) reduced by a factor of ½!

$\tilde{M}_{\boldsymbol{d}}(\omega) = \tau_m \boldsymbol{J}\boldsymbol{K}\boldsymbol{H}(\omega)\boldsymbol{d}(\omega)$ is the effective connectivity matrix with

- membrane time constant τ_m
- weights $\boldsymbol{J}$
- indegrees $\boldsymbol{K}$
- transfer functions $\boldsymbol{H}$
- delay distribution matrix $\boldsymbol{d}$

[7] Schmidt, M. et al., PLOS CB (2018).

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[3] Potjans & Diesmann, Cereb Cortex (2014).
[4] Bos, H. Et al. PLOS CB (2016).
[7] Schmidt, M. et al., PLOS CB (2018).

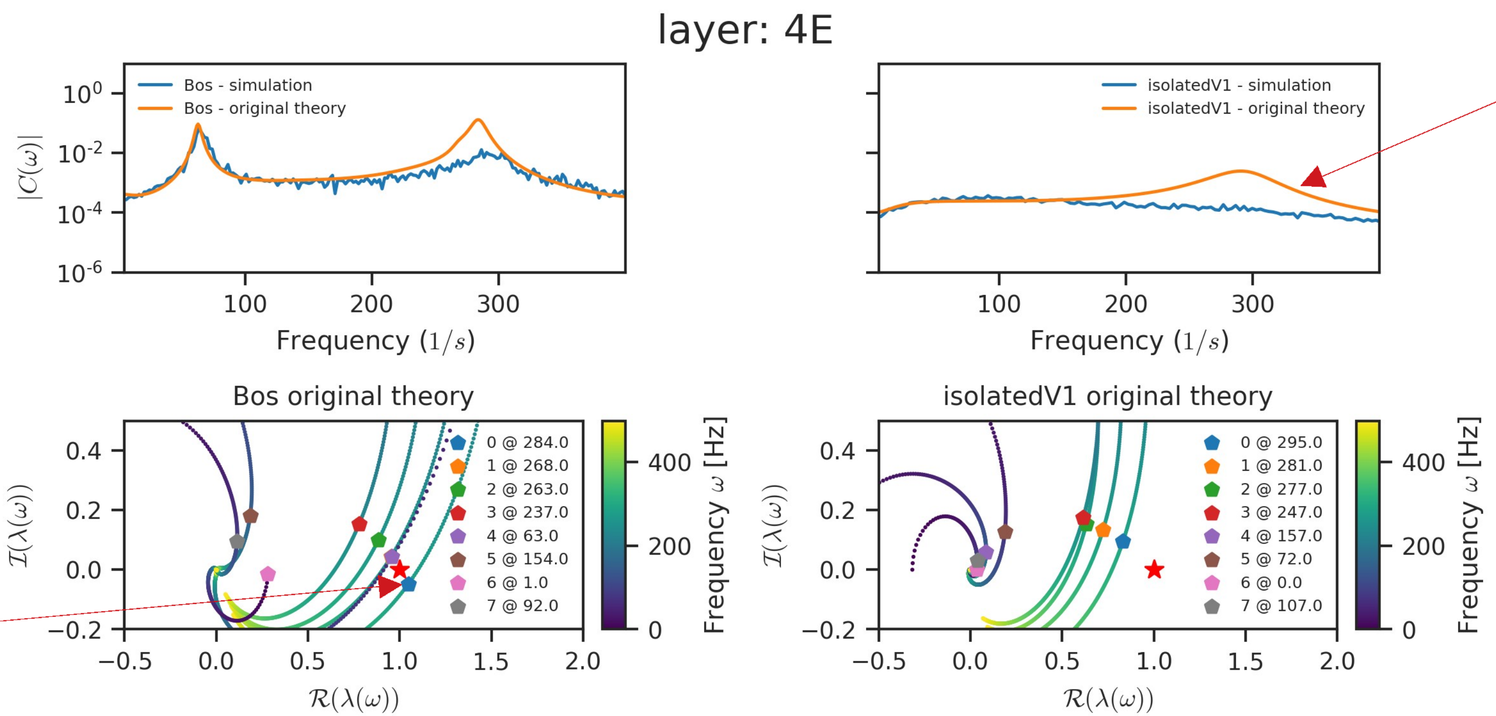
Can a combination of meanfield theory and linear response theory help us to understand the occurence of fast oscillations?

Potjans & Diesmann microcircuit modified by Bos [3,4]

- theory close to simulation
- fast oscillations in simulation and theory
  - peak magnitude overestimated

isolated V1 microcircuit from multi-area model [7]

- theory deviates from simulation over larger frequency range
- no fast oscillations in simulation, but theory predicts them



Problem 2: Wrong prediction of fast oscillations!

Problem 1: Eigenvalue beyond instability!

$$\mathbf{C}(\omega) \propto 1/(1-\lambda_k(\omega))$$

with λ_k being the eigenvalues of the effective connectivity matrix

Peak frequency and magnitude are determined by eigenvalues of the effective connectivty matrix approaching instability [4].

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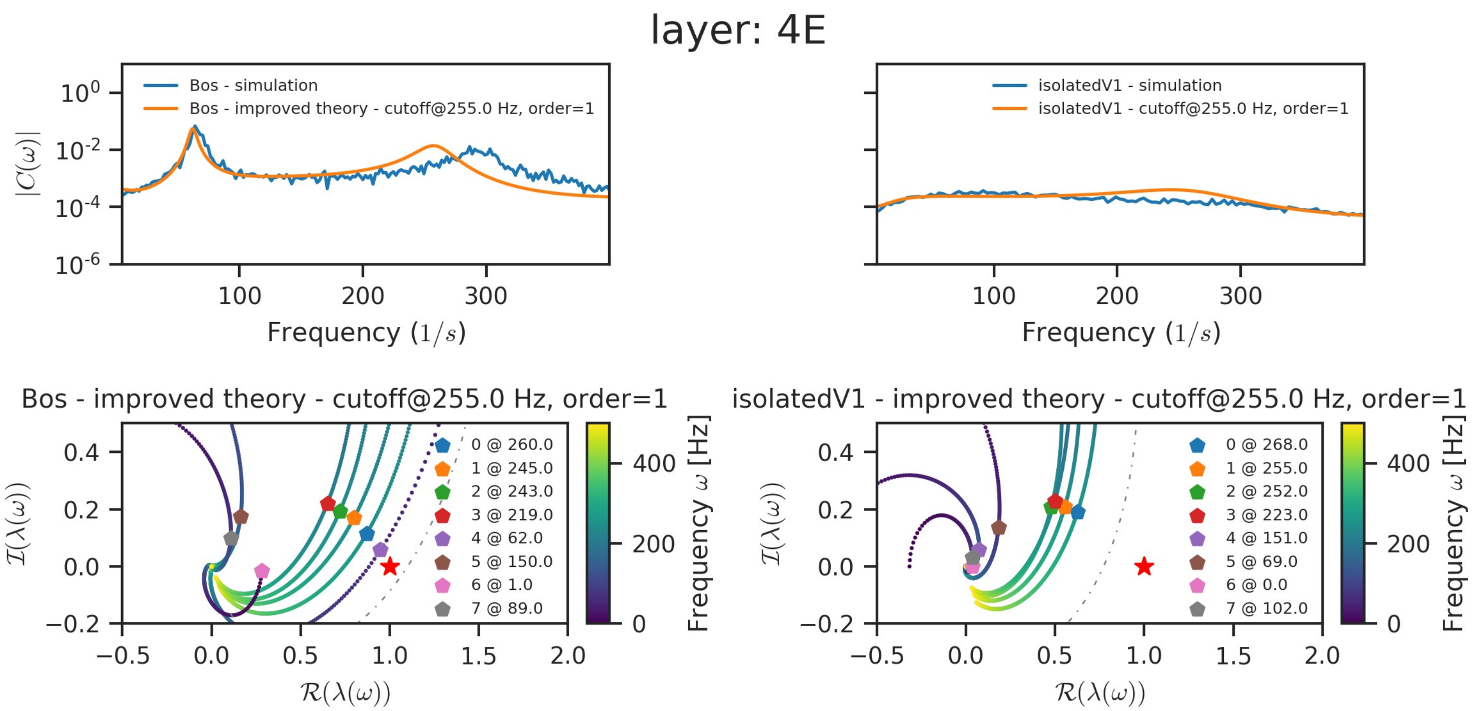
Can we adapt the theory such that the prediction for both microciruits improves?



The overestimation of the transfer function can be compensated by a semi-analytical correction!

- for high frequencies, the assumption made during linear response theoretical derivation of the transfer function [8], are not valid
- the transfer function is likely to be overestimated
- the ad-hoc addition of a low-pass filter improves the mean-field prediction

$$\tilde{\boldsymbol{M}}_{\boldsymbol{d}}(\omega) = \tau_m \boldsymbol{J}\boldsymbol{K}\boldsymbol{H'}(\omega)\boldsymbol{d}(\omega)$$

  - modified transfer functions $\boldsymbol{H'}$ contain an additional low-pass filter with cutoff-frequency ω_c

- eigenvalues are shifted leftwards → increased distance to instability

[8] Schuecker, J. et al., Phys Rev E (2015).

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ACKNOWLEDGEMENTS

THANKS A LOT FOR YOUR INTEREST!

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