Master’s colloquium

Stabilization of the orientation map in a computational model of L4 in V1 of macaque monkey

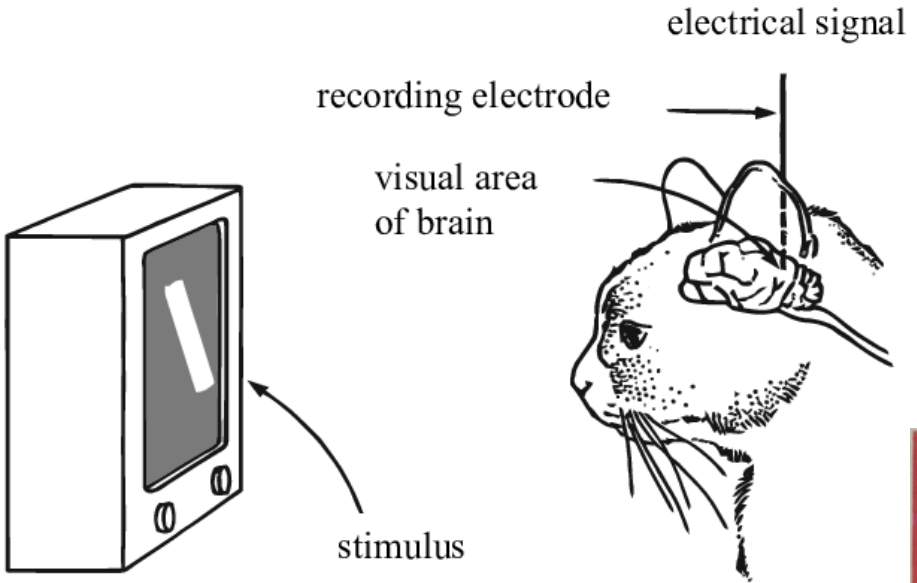
Silas Theinen

Institute for Advanced Simulation (IAS-6) Jülich Research Centre, Jülich, Germany

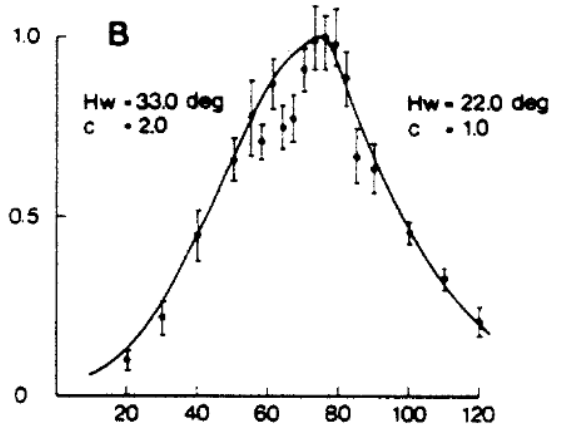
Supervisors:
Prof. Dr. Markus Diesmann
Prof. Dr. Andreas Offenhäusser

Advisor:
Anno Kurth

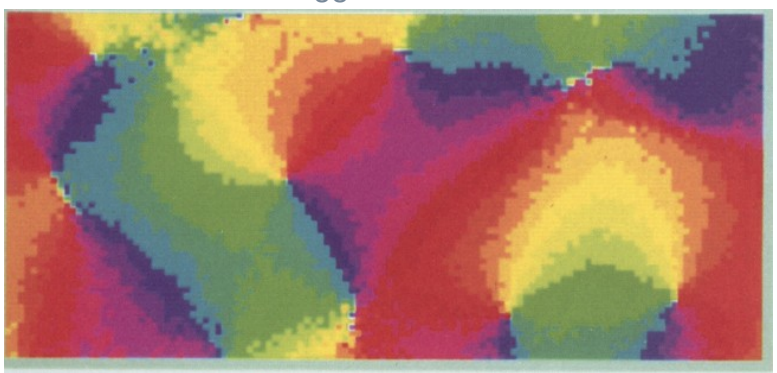
Orientation map and tuning curves



Hubel and Wiesel 1959 (Visualization by Anh Nguyen et. al. 2019)

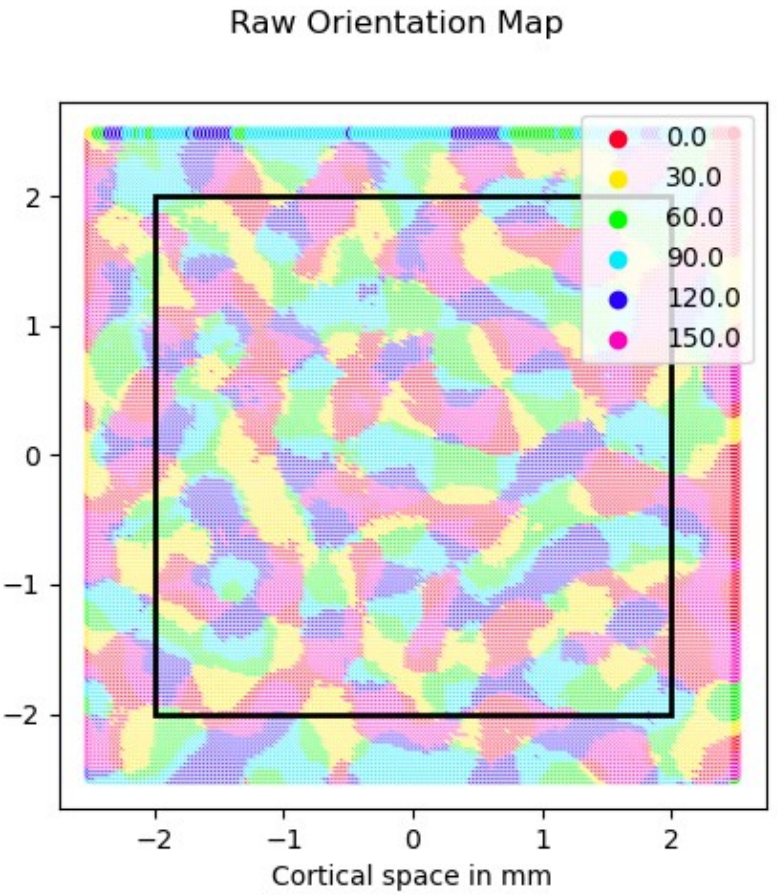


Heggelund and Albus 1977



Bonhoeffer and Grinvald 1993

Orientation Map



- Cortical map with color indicating preferred bar angle
- Orientation preference is spatially organized
- Orientation preference clusters in iso-orientation domains

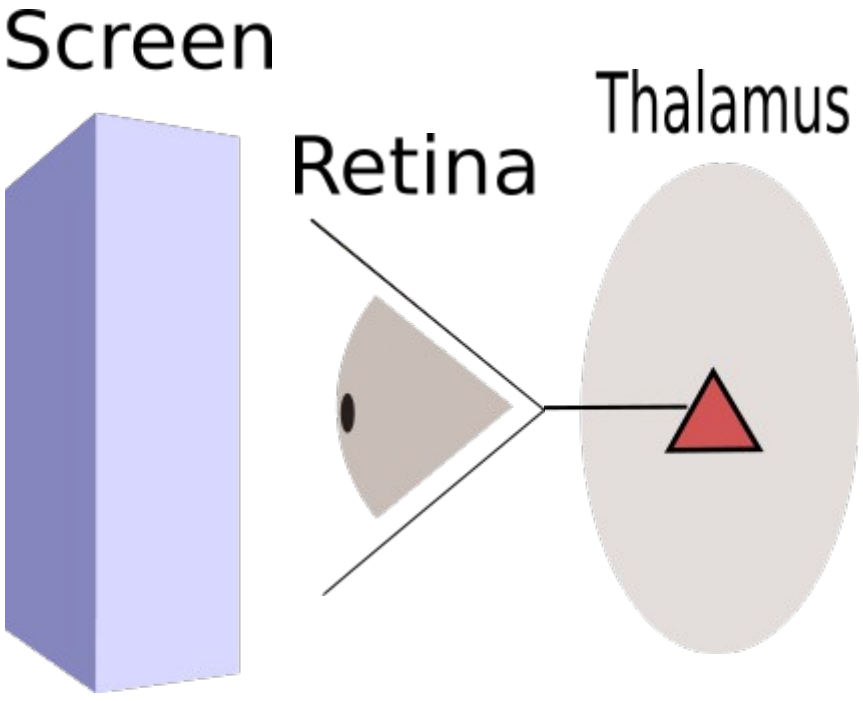
Spiking network simulation

- We model the experimental setup using spiking neural network simulations (NEST Simulator)
- Use conductance based leaky integrate and fire neurons

Research Questions

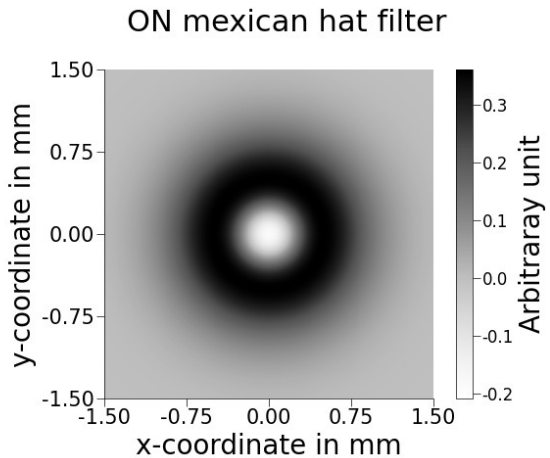
- **How does the spatial connectivity support the orientation preference?**
- **How robust is the network to input of various shape and strength?**

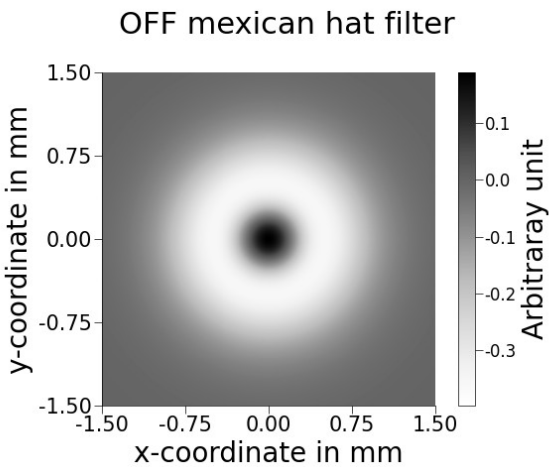
Retina and thalamus model



- Adapt lgn model from Kurth and Albers
- Improve lgn model by adding retina model to it
- Able to read in arbitrary sequences of gray-scale pictures

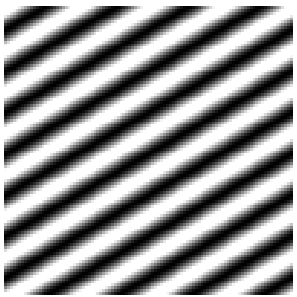
Retina and Thalamus model

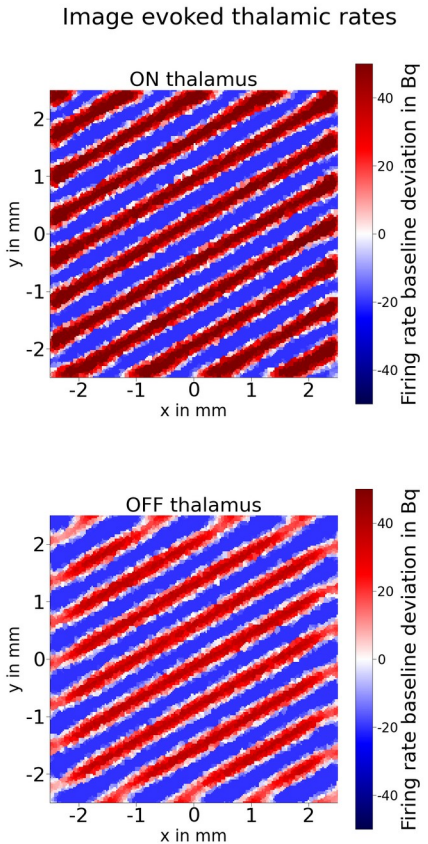


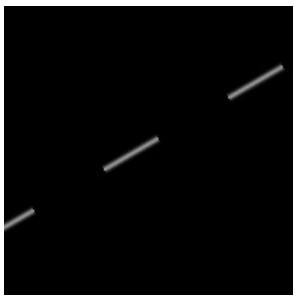


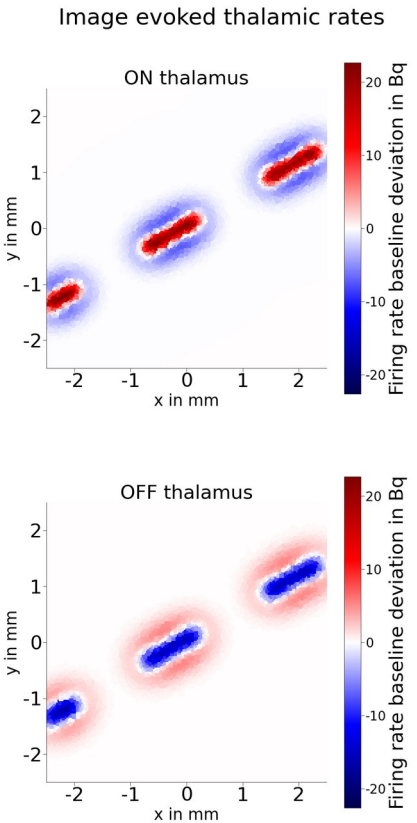
- Two kinds of Thalamic neurons exist
- ON neurons prefer stimuli with bright center and dark surrounding
- OFF neurons prefer stimuli with dark center and bright surrounding

Evoked thalamic rates



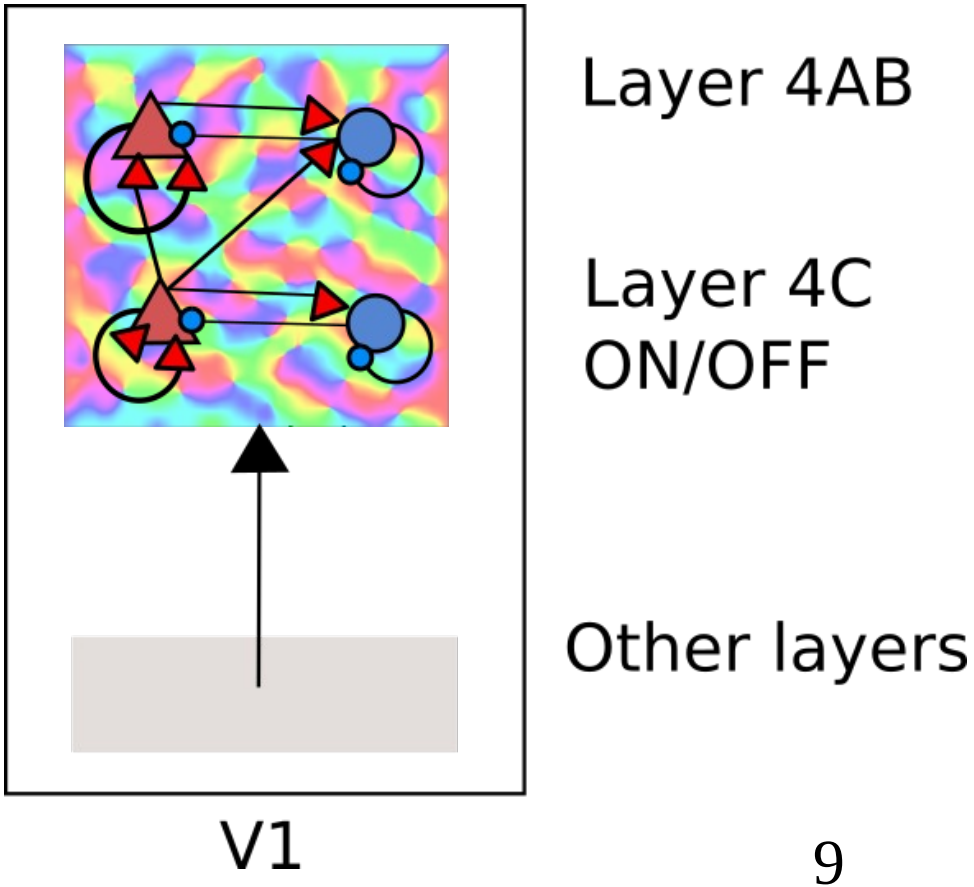




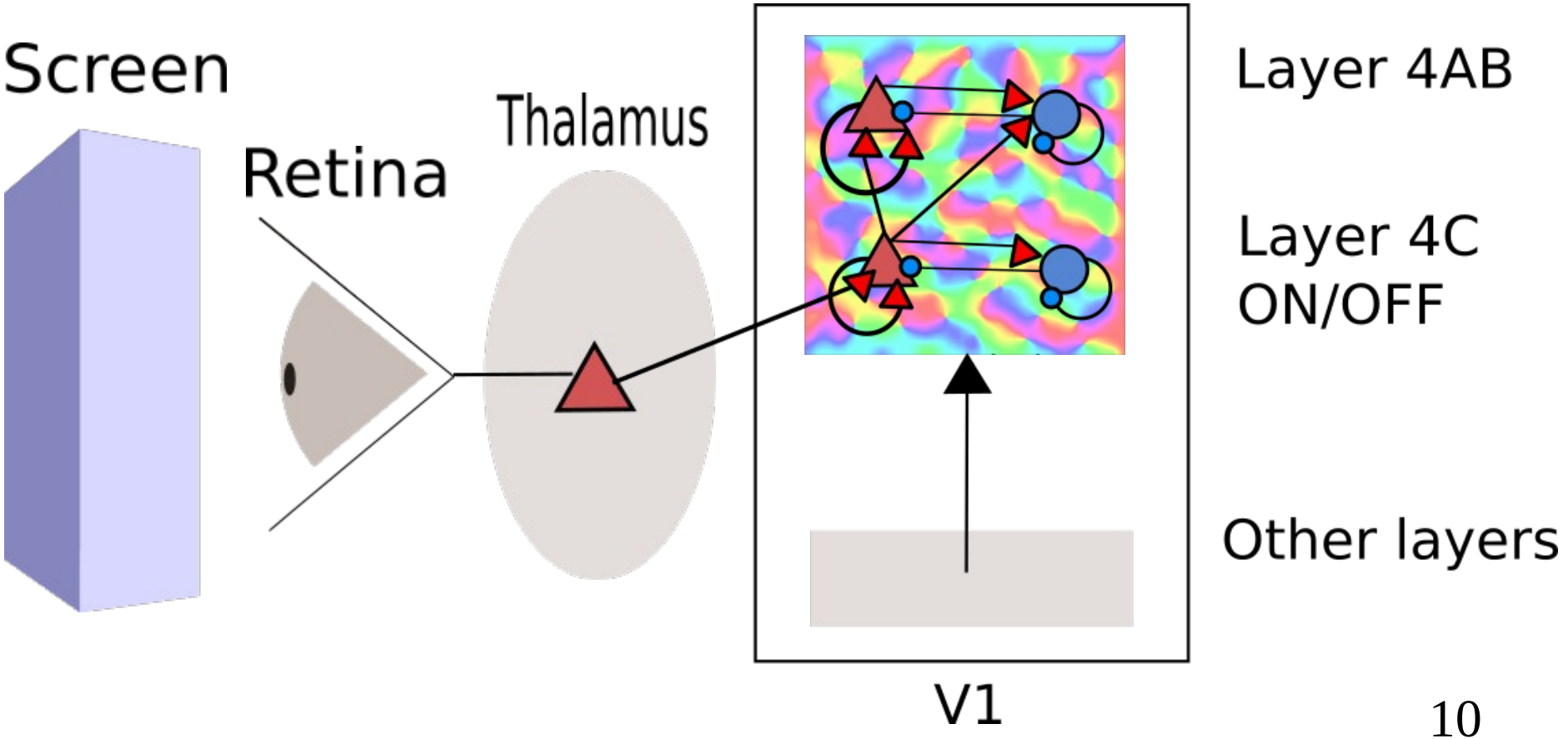


Layer 4 in V1

- Adapt layer 4 from the V1 model of Kurth and Albers
- Randomly distribute cortical neurons on a 25 mm² area.
- Layer 4 is split in L4C ON, L4C OFF and L4AB

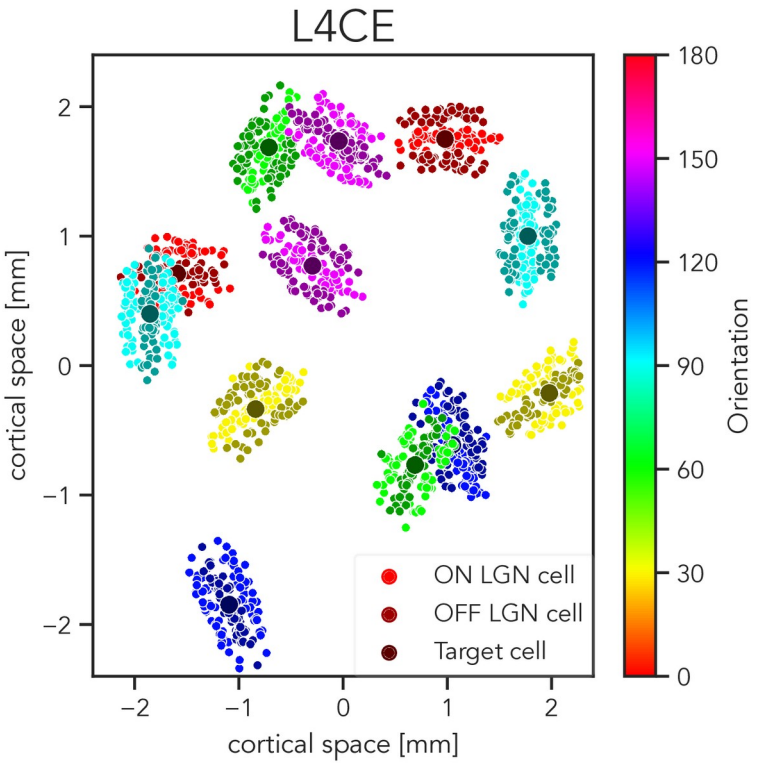


Full Network



Thalamo cortical connections

- L4C is the primary input layer
- Neurons in L4C have a receptive field in the form of a Gabor filter
- The preferred orientation of a neuron in L4C determines its Gabor angle



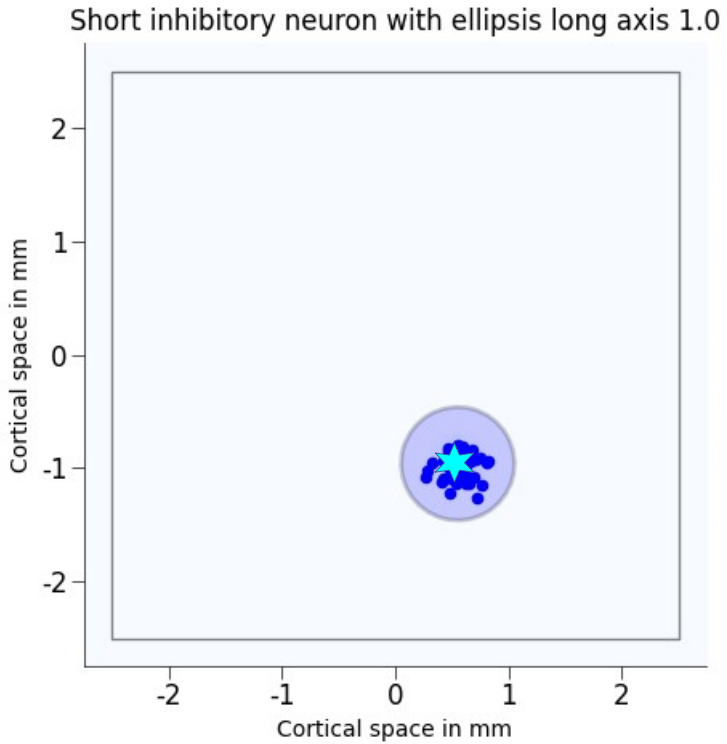
Adapted from Jasper Albers

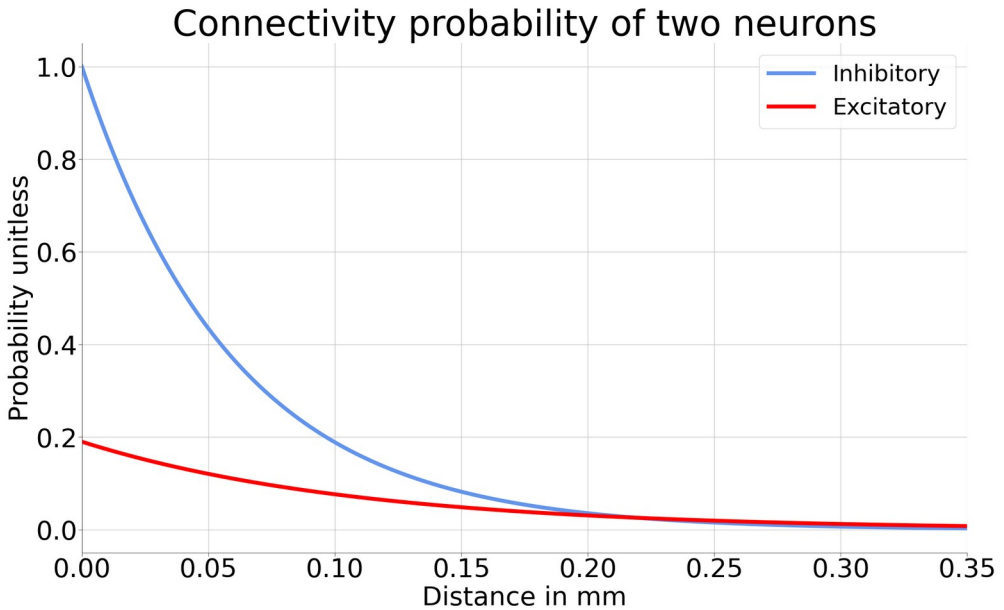
Intra-areal connections

Three intra-areal connections profiles from Kurth and Albers

- Medium range isotropic connectivity
- Short range push-pull connections (Only in L4C)
- Long range patchy connections (In every layer but L4C)

Isotropic connectivity

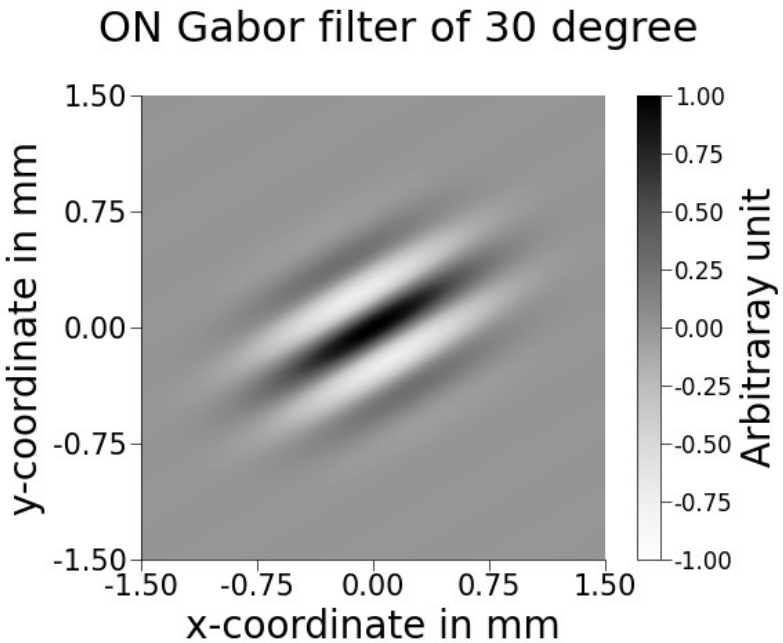




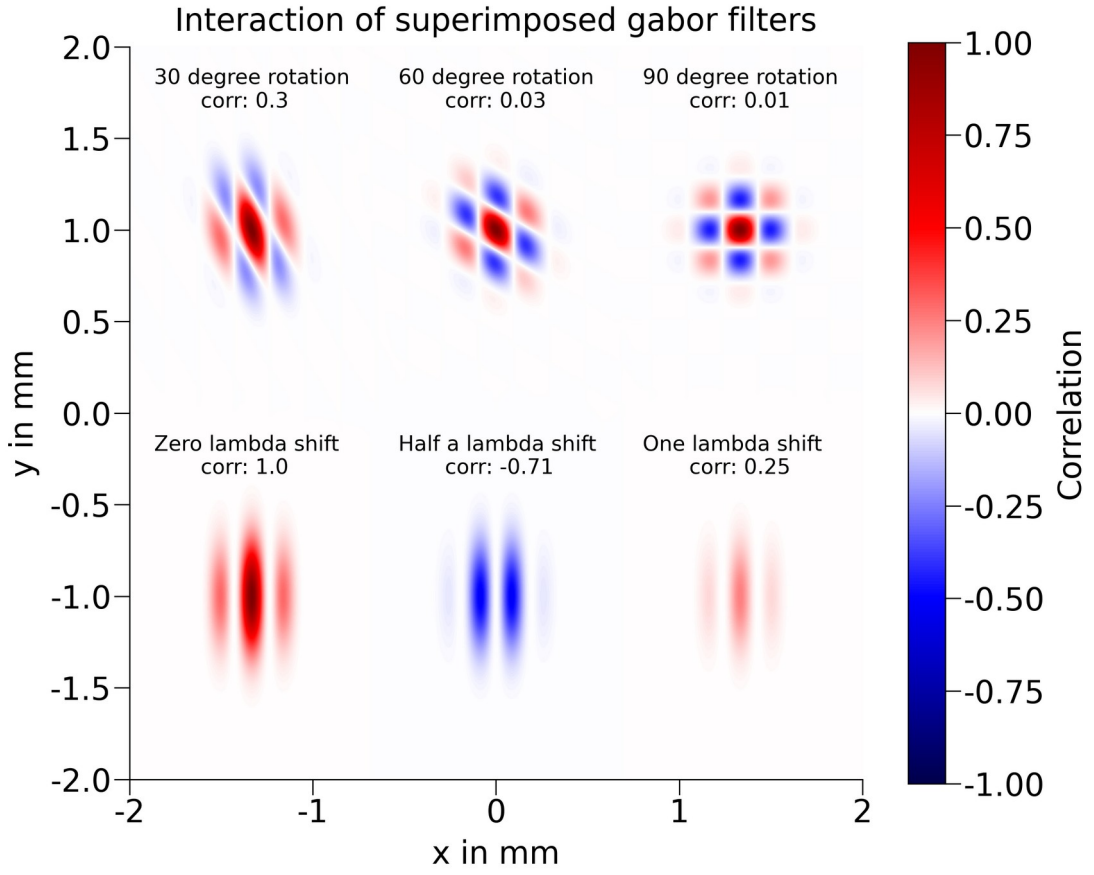
Exponentially with distance decaying connection probability

Push-pull connectivity

- Neurons that fire together wire together
- Nearby neurons correlate in their input
- Gabor like receptive fields overlap and create spatially complex correlations

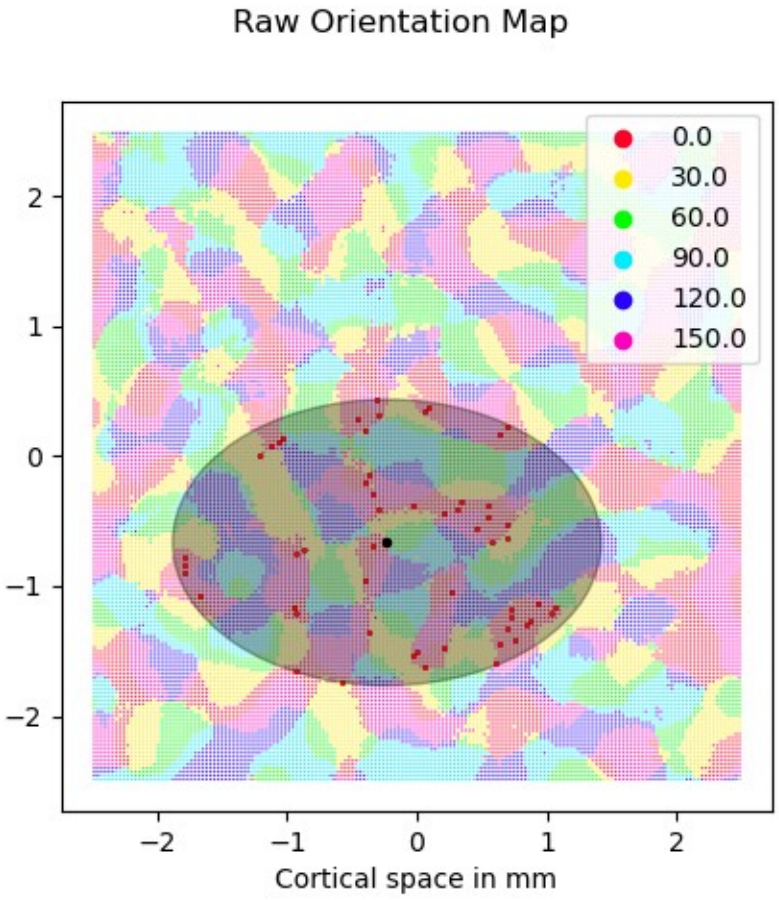


Push-pull connectivity



- Correlations of two neurons each
- Most push-pull connections between same orientation preferring neurons
- Unknown number of push-pull connections => free parameter

Patchy connections



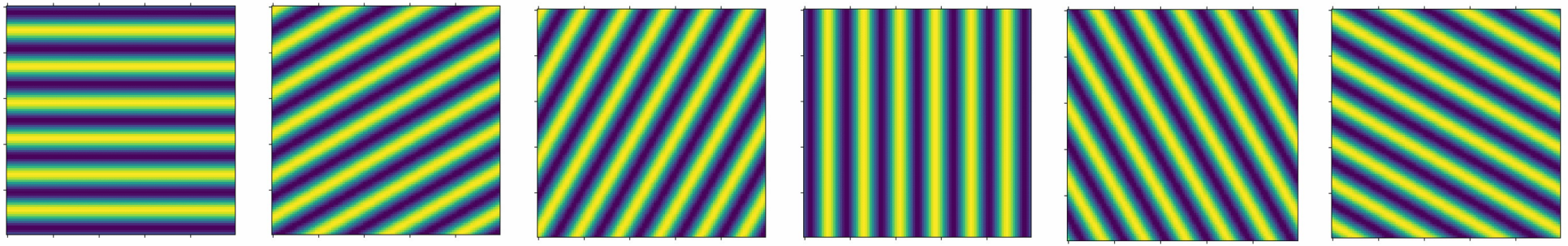
- Neurons assert long range patchy connections (not in L4C)
- Only same preferred orientation neurons connect via patchy connections
- Connections arise in an ellipse around the source neuron
- Unknown number of patchy connections => free parameter

Additional Intra-areal connections

Three additional intra-areal connections profiles

- Hebbian inspired weight modulation
- Super-localized inhibition
- Elliptical projecting inhibition

Orientation map retrieve



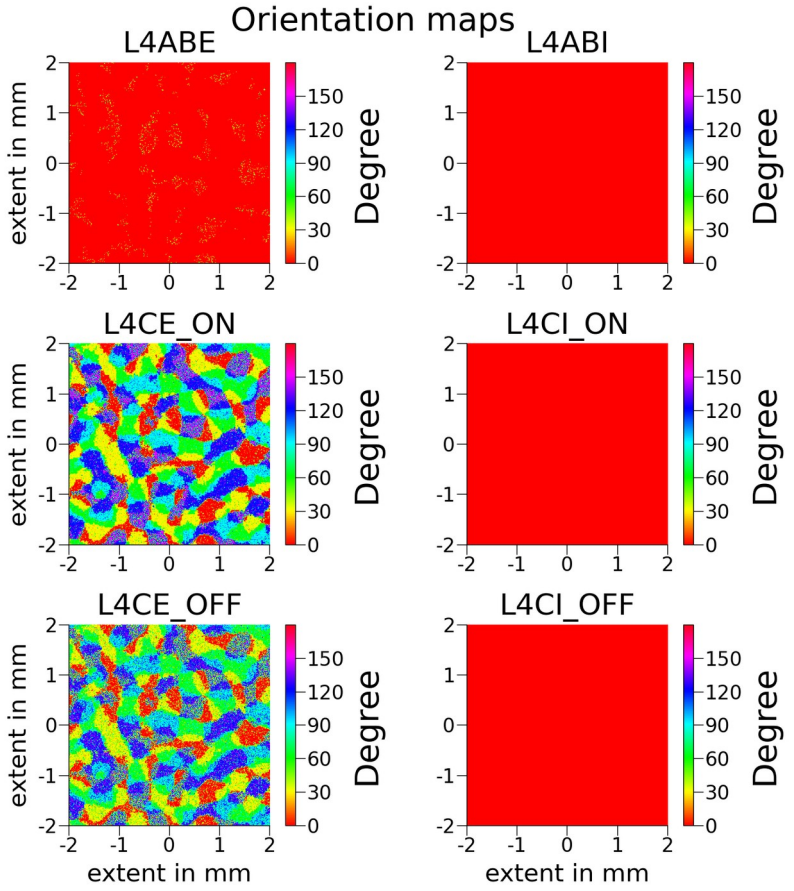
- Use leaky integrate and fire neurons
- Instantiate the network with thalamo-cortical connections only
- Measure the neurons response depending on a drifting gratings angle

Building up the network

Subsequently add connection patterns

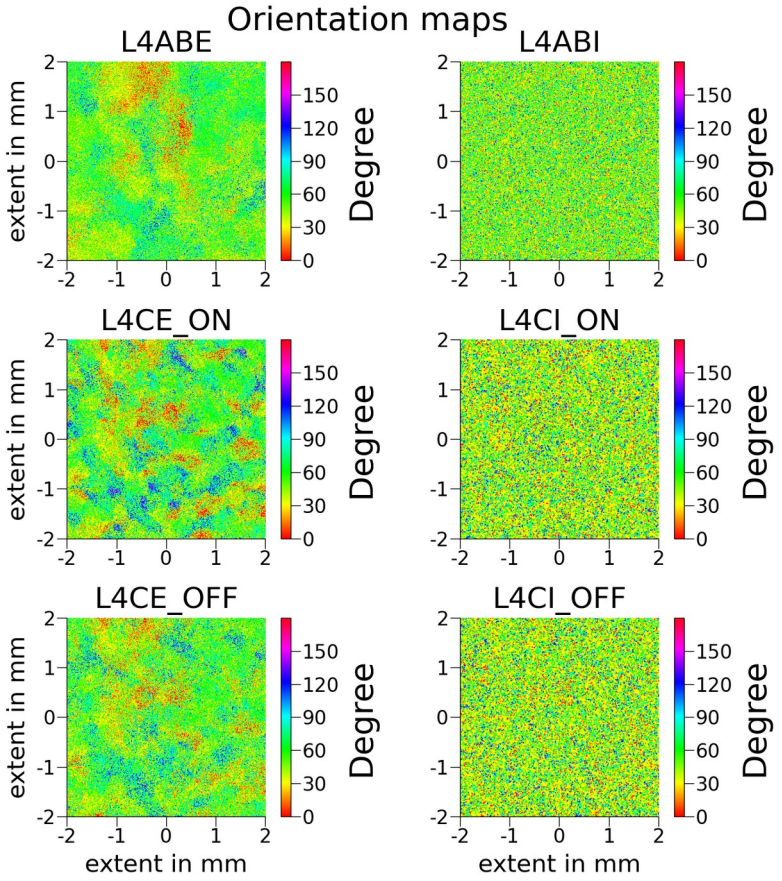
1. Add single connection pattern
2. Retrieve the orientation map
3. Measure effect of connection pattern
4. Repeat

Thalamo-cortical connections work



- Start with nework omitting intra-areal connections.
- Only thalamo-cortical connections exist
- The orientation map is visible => the input model is working

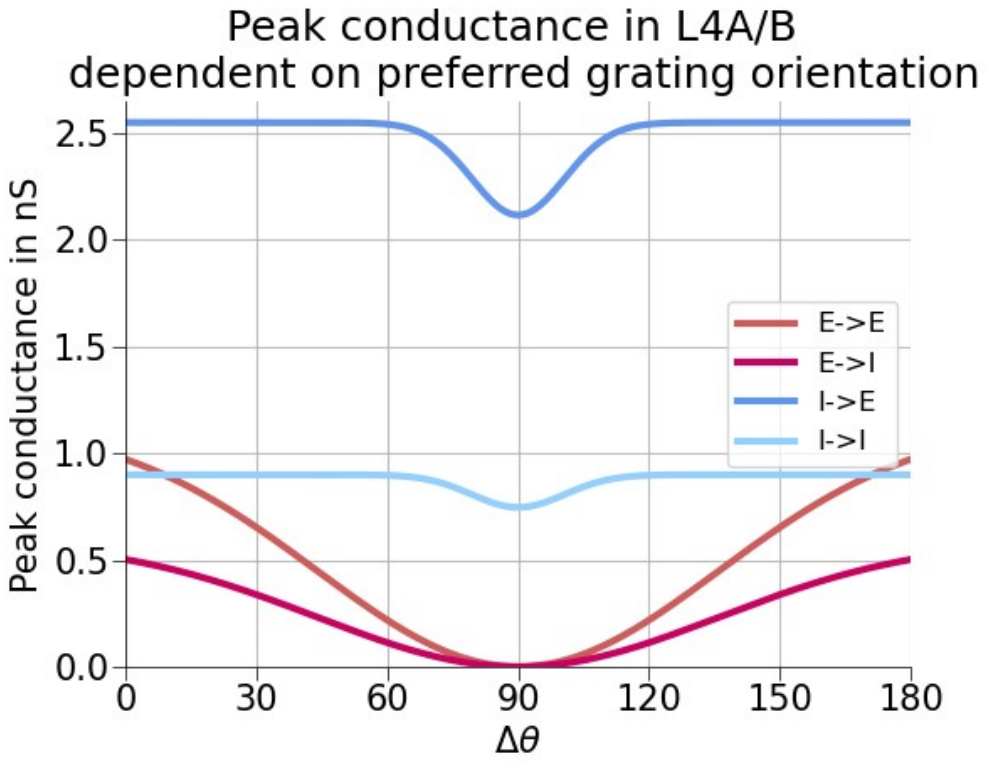
Isotropic connection network fails



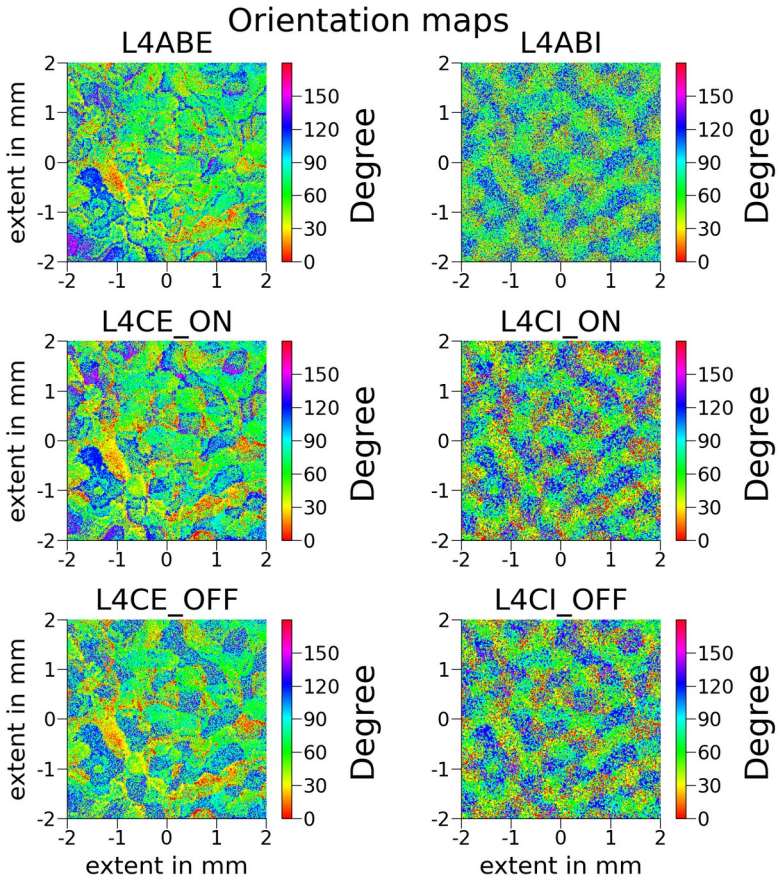
- Add isotropic connections to the network
- The orientation map retrieve does not work anymore
- The isotropic connectivity creates “Spill over excitation”

Hebbian inspired weight modulation

- Modulate the weights of neurons dependent on the preferred orientation
- Hebb proposed that neurons that fire together wire together
- Neurons of same preferred orientation receive similar input

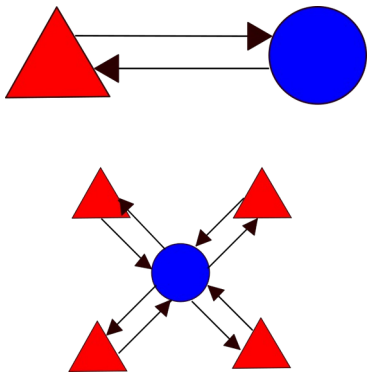


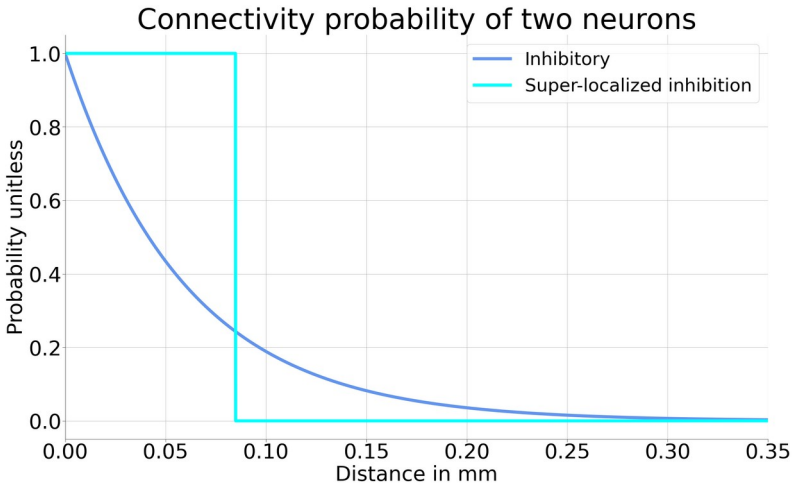
Weight modulation retrieves ormap



- The orientation map is partly retrievable in all layers
- L4C performs better than L4ABE

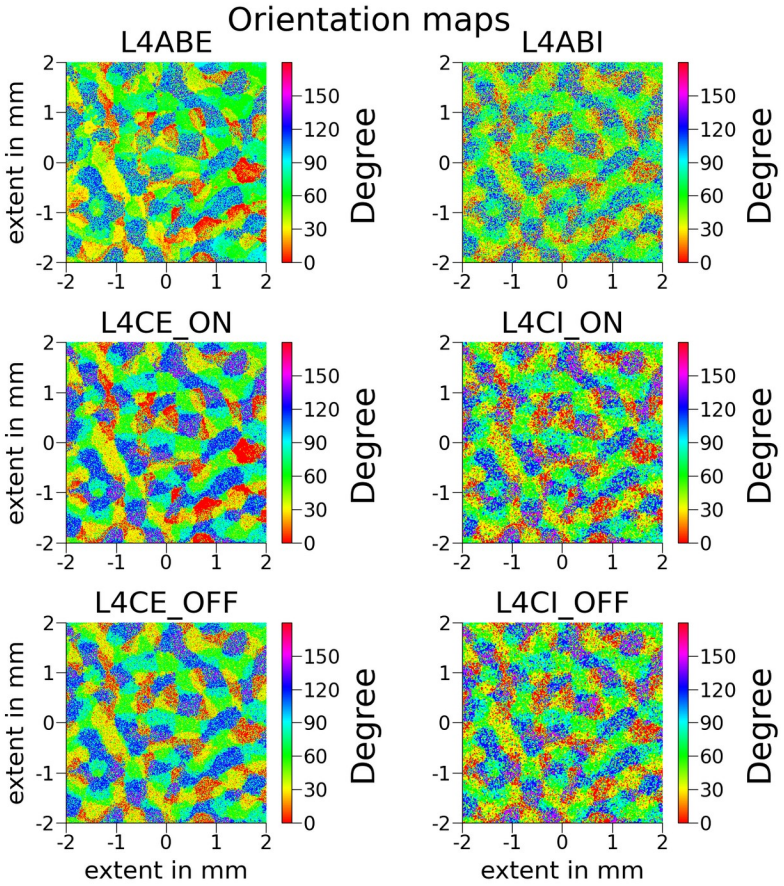
Super-localized inhibition

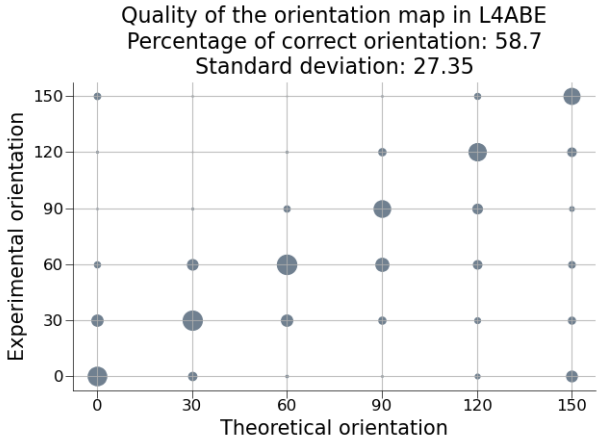




- Peng et. al. 2021 find an enhanced number of reciprocal connections
- They propose that this balances the firing rates
- Super-localizing inhibitory neurons enhances reciprocal connections (50% in L4C, 20% in L4AB)

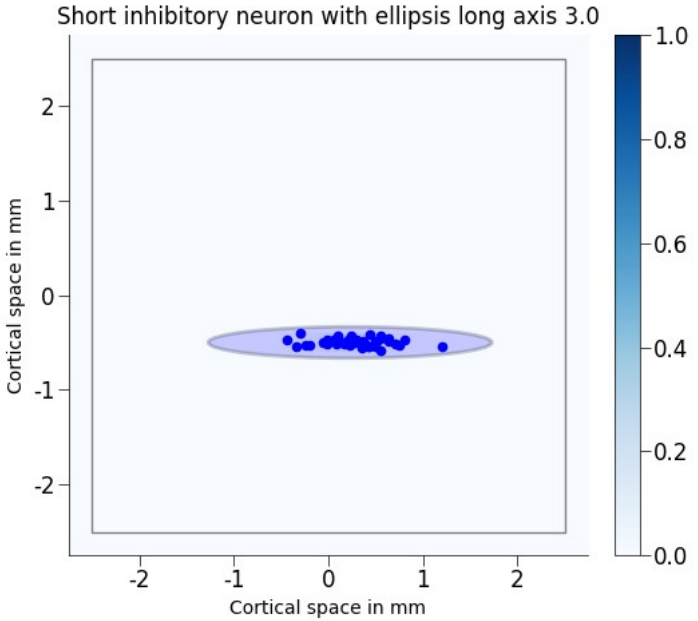
Sup-loc inhibition enhances ormap





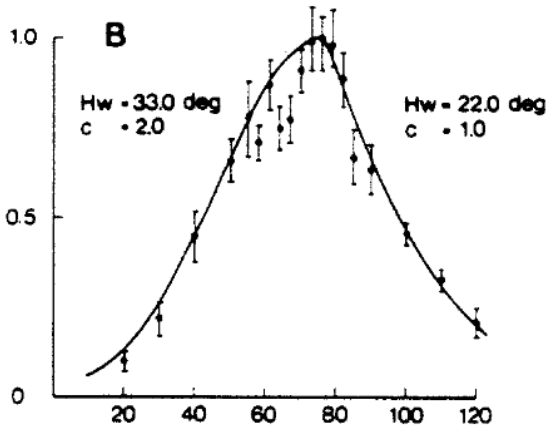
- More preferred angles are retrieved correct
- L4C performs better than L4AB
- Average firing rates are not influenced

Elliptical projecting inhibition

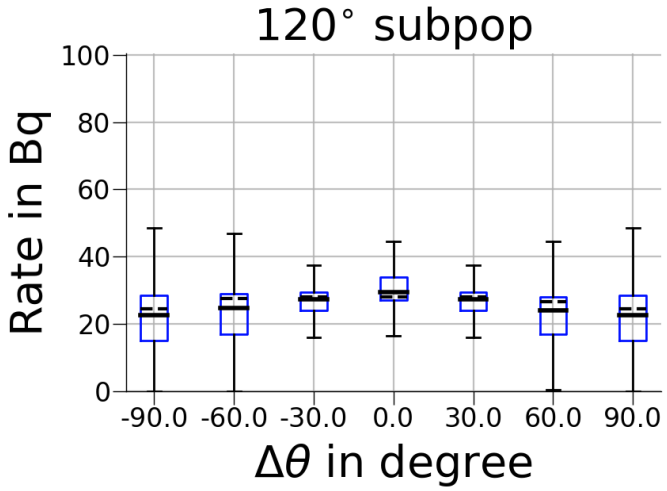


- Non super-localized inhibitory neurons project with an elliptic profile
- The average connection distance rises with increasing ellipses long axis

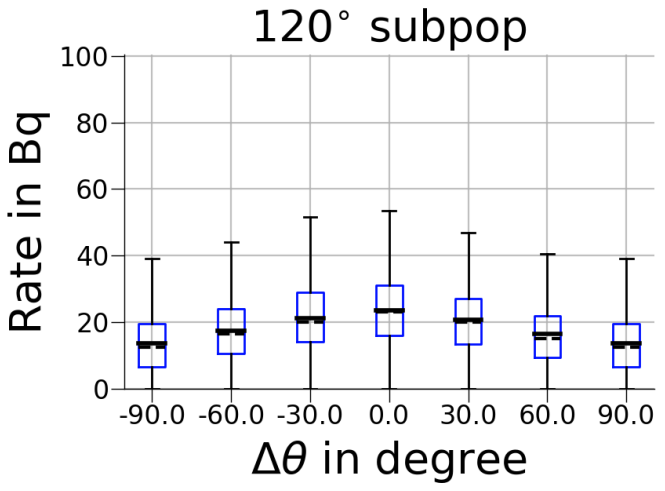
Elliptical inhibition increases tuning



Super-localized tuning curves



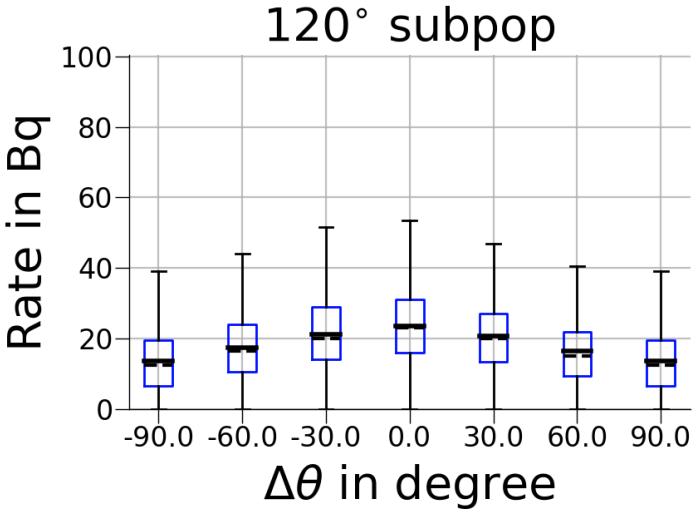
Elliptical projecting tuning curves



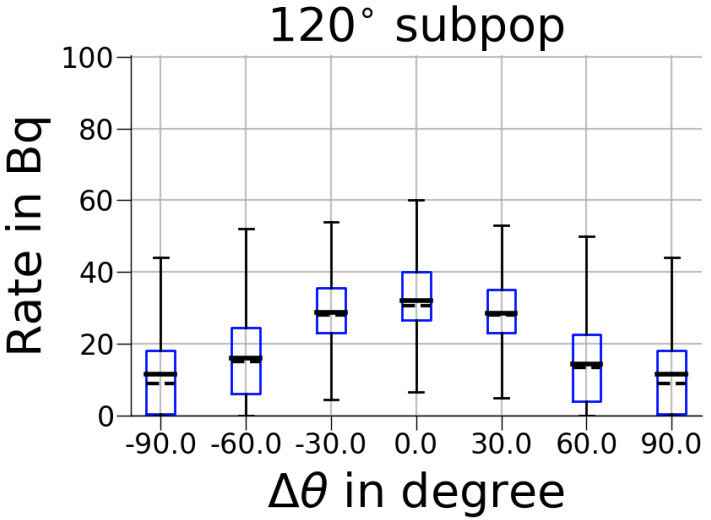
- Number of retrieved orientations remain constant
- The steepness of tuning curves increases

Push-pull conn increases tuning

Elliptical projecting tuning curves

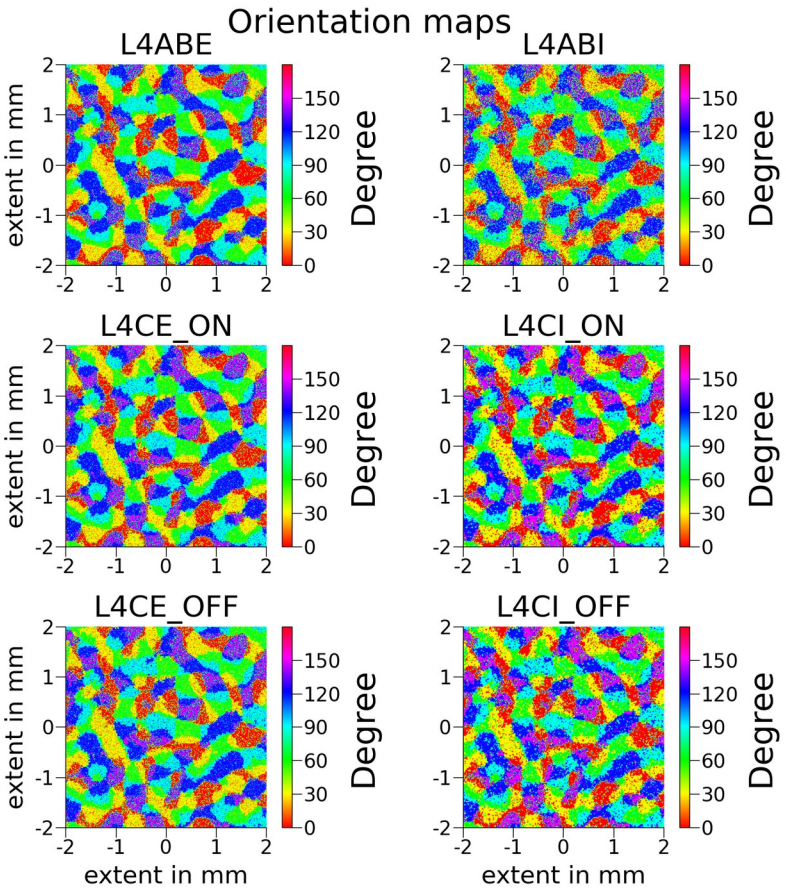


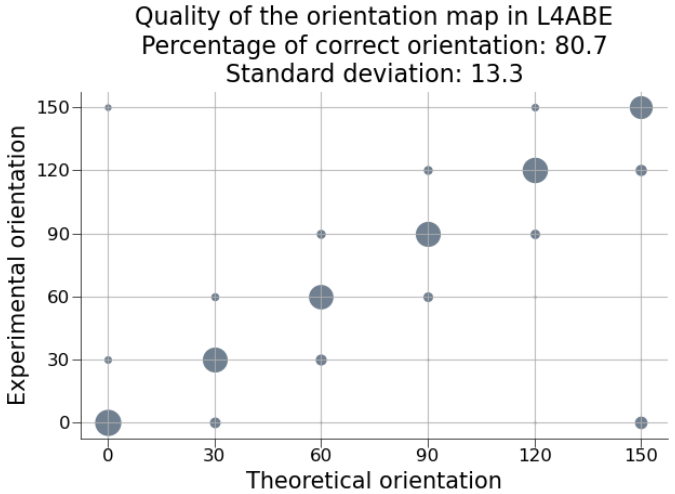
Push-pull tuning curves



- 35% push-pull connections keep the retrieved orientations constant
- Tuning curves are furthermore steepened

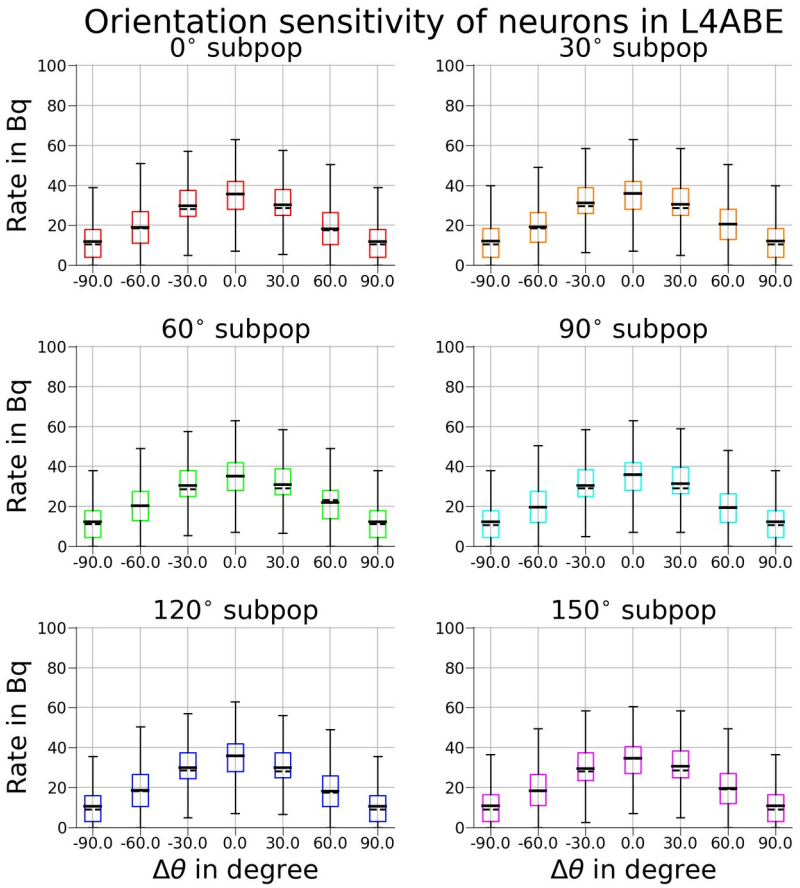
Patchy conn enhances ormap





- Finally 40% of the connections in L4ABE are now patchy connections
- The number of correctly retrieved orientations is strongly enhanced

Patchy conn increases tuning

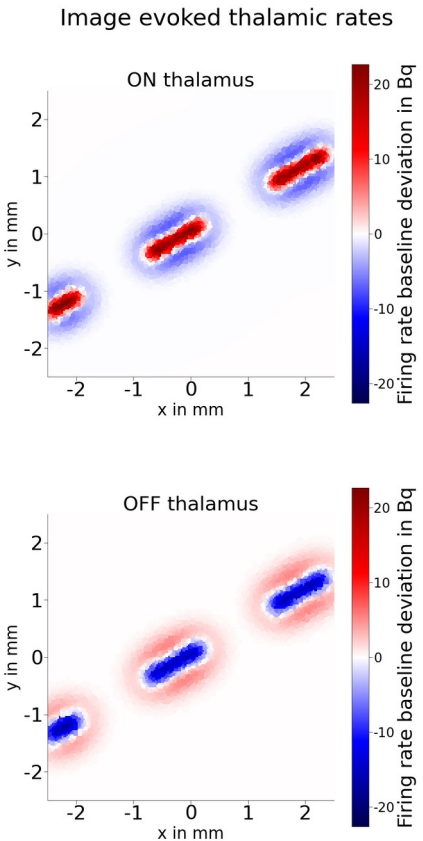


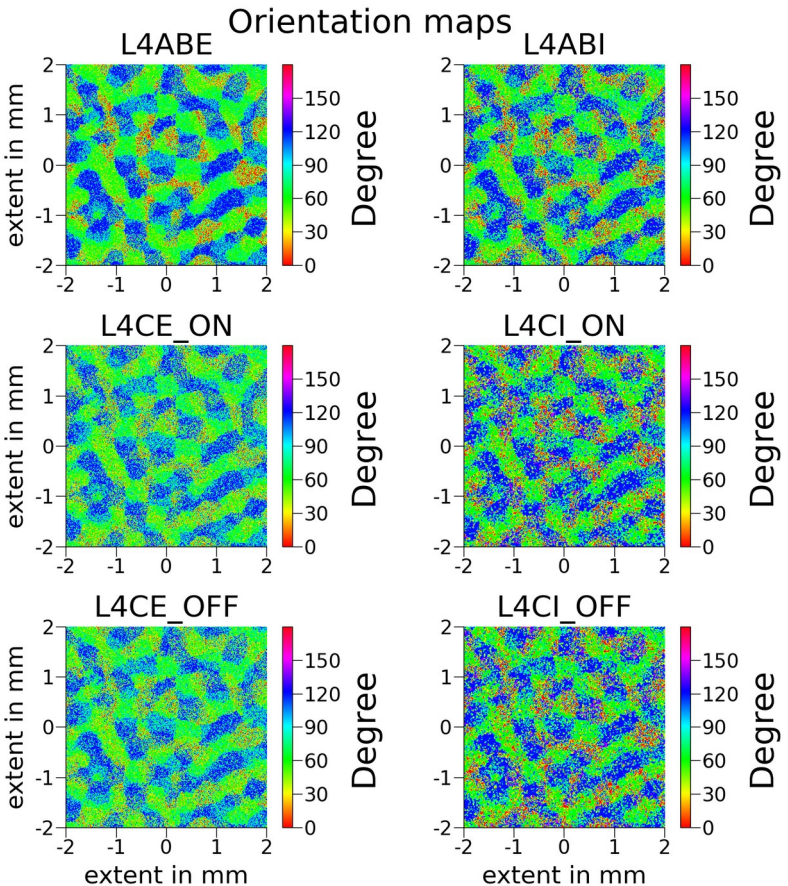
Neurons of preferred orientations fire with 3 times higher rate than non preferred ones

Additional network measures

- In the following we try different inputs
- Furthermore we analyze the spiking activity

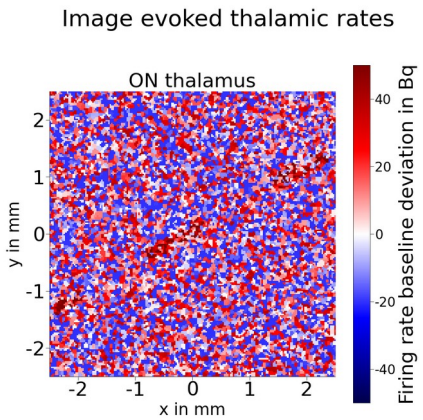
Dashed line retrieves ormap

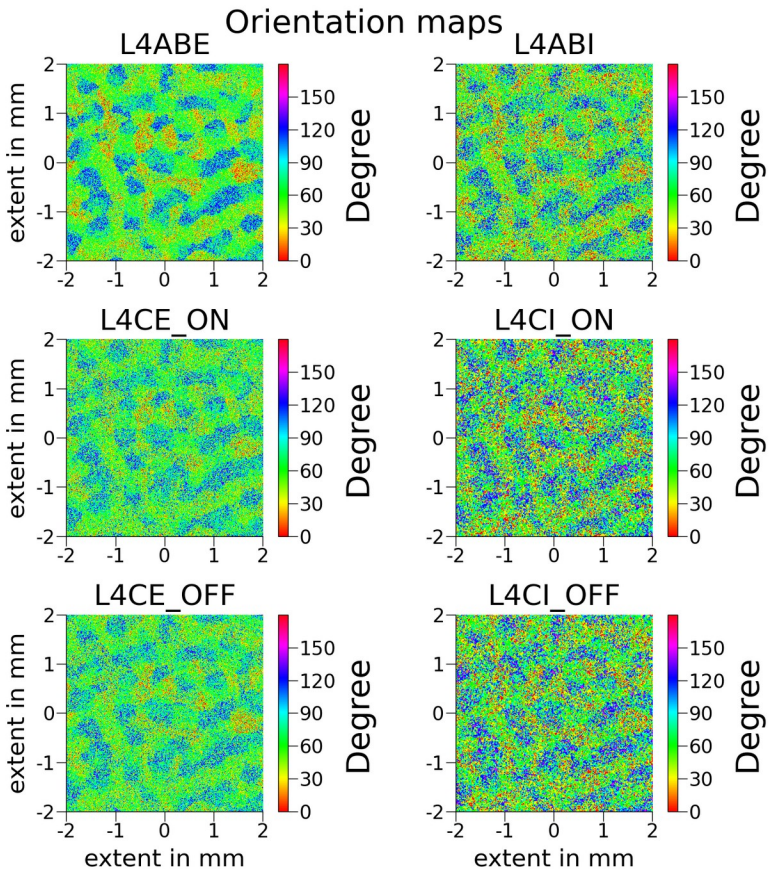




- Dashed lines retrieve the orientation map
- Also neurons not superimposed by the input are retrieved correctly

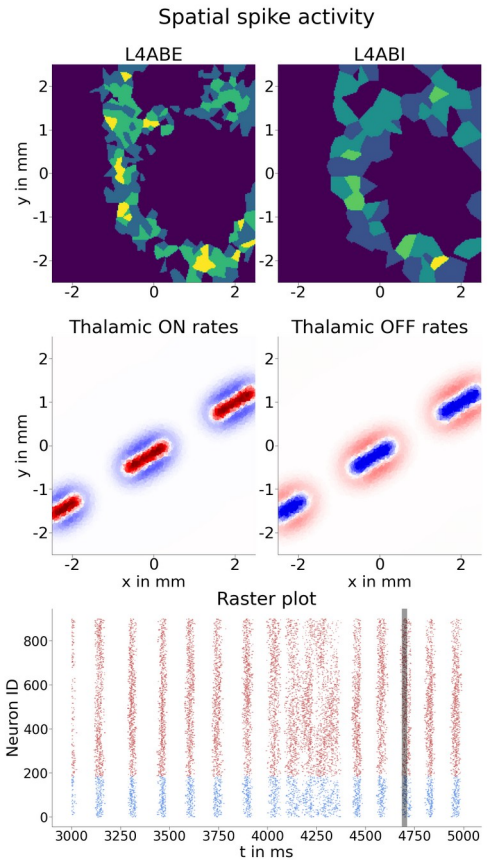
Noisy dashed line retrieves ormap





Adding noise to the dashed lines still retrieves the orientation map

Spatial waves



- Integrate 10ms of spiking activity each
- Interpolate spiking activity onto a grid resembling the neuron positions
- Meanwhile show the current thalamic ON and OFF input
- The black bar indicates the currently integrated time range

Spatial waves

- Spatial waves start at a certain position radially spreading out to the whole layer
- The starting point is random
- No trivial link between orientation map and spatial activity

Summary

- Adapt model of Layer 4 in V1 of macaque monkey
- Enhance it with retina model and dynamic input
- Investigate the orientation map under different configurations
- Calibrate three existing connectivity patterns
- Include and configure three new connectivity patterns

=> Various inputs retrieve the orientation map

=> The activity displays cortical waves radially spreading out

Outlook

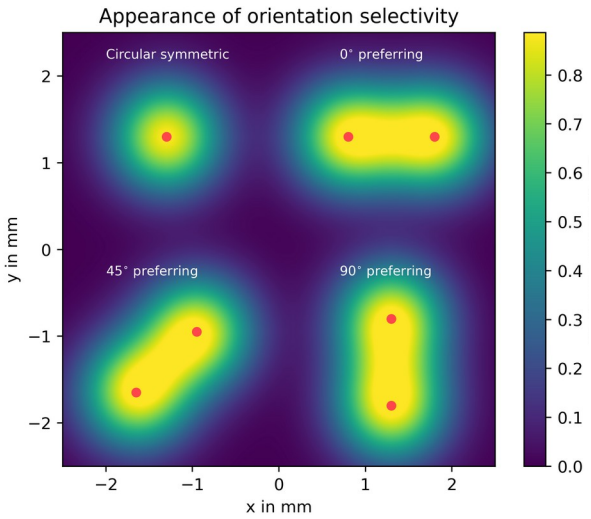
- Include plasticity
- Add other V1 layers
- Expand the 25 mm^2 area

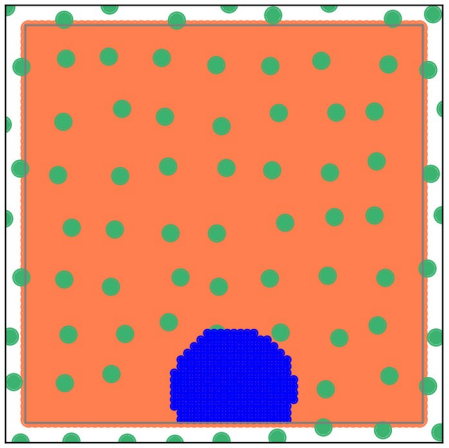
Appendix

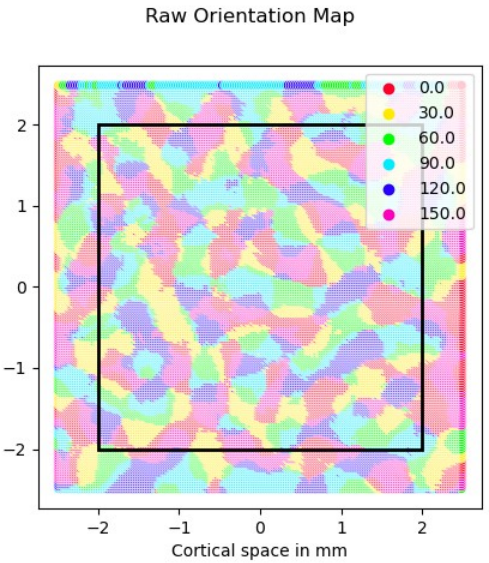
Retinotropic mapping

- More retinal centralized points are mapped onto a larger part of the cortex
- $f(\theta) = 180\ M \sin(\theta)$ mm (M is the magnification factor)
- Using a small slice of the central area of the cortex and setting M to 1, the retinotropic mapping becomes linear
- Therefore retinal and cortical layer may be just superimposed

Artificial orientation map creation

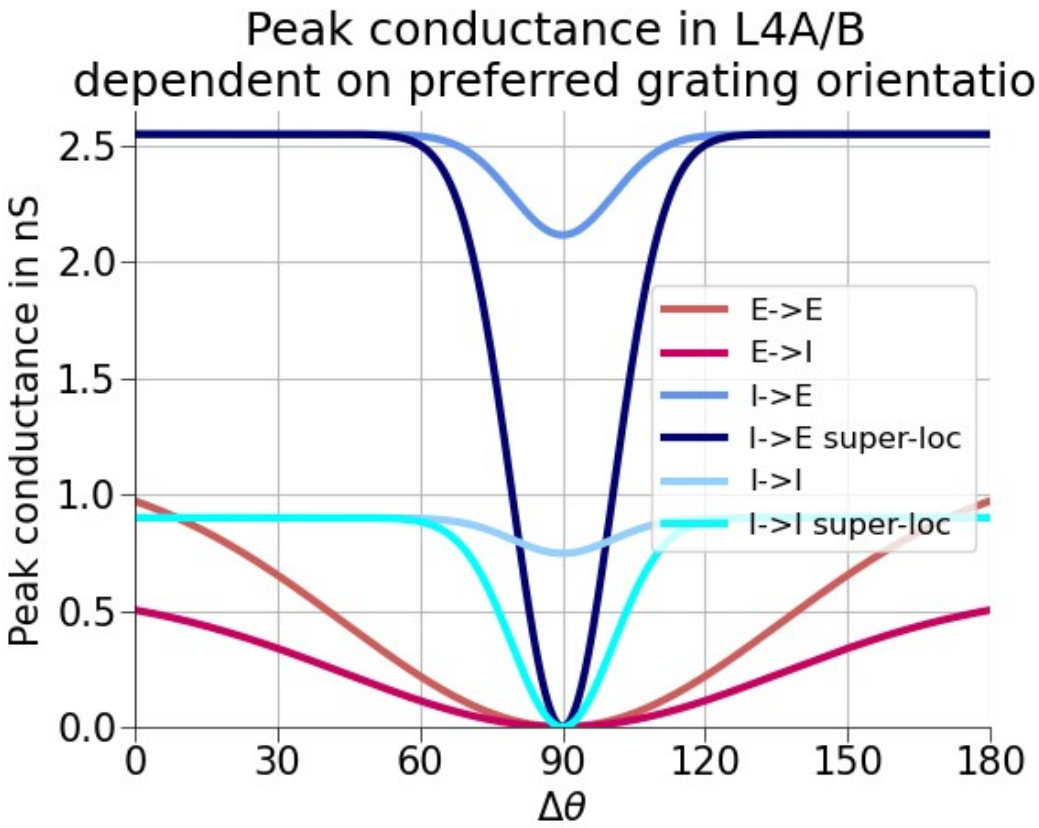






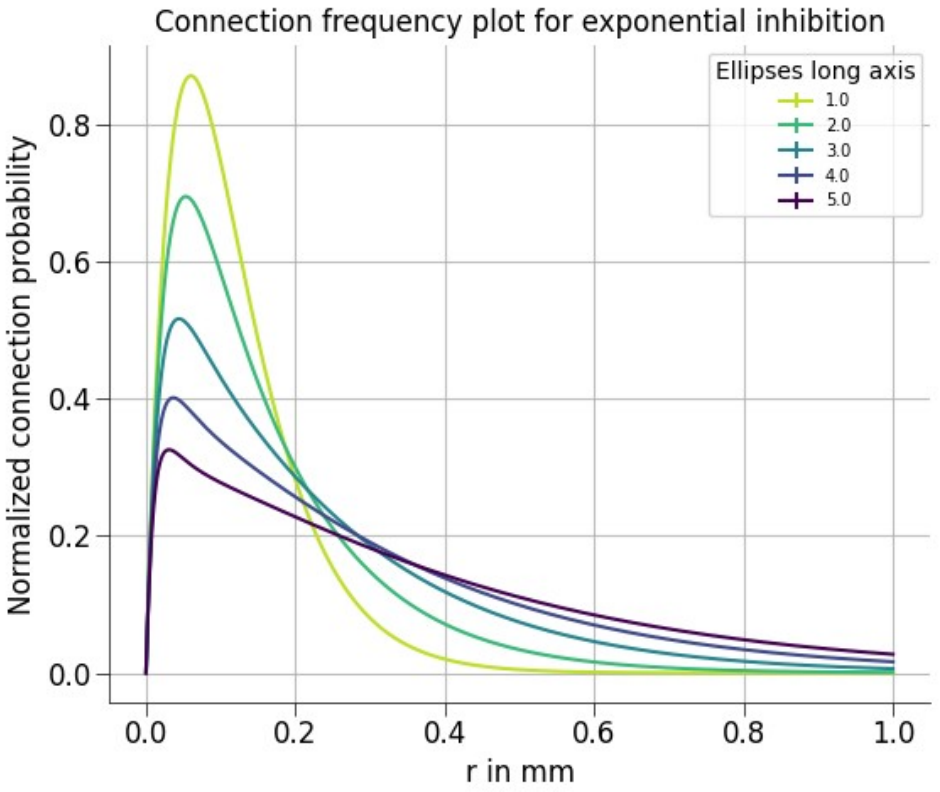
- First create a dummy thalamo cortical network with jittered thalamic neurons on a grid and randomly drawn positions for cortical neurons
- Each thalamic neuron projects with a 2D Gaussian to the cortical layer
- The asymmetrical overlaps of the thalamic projections create orientation preferences in the cortical layer

Full weight modulation

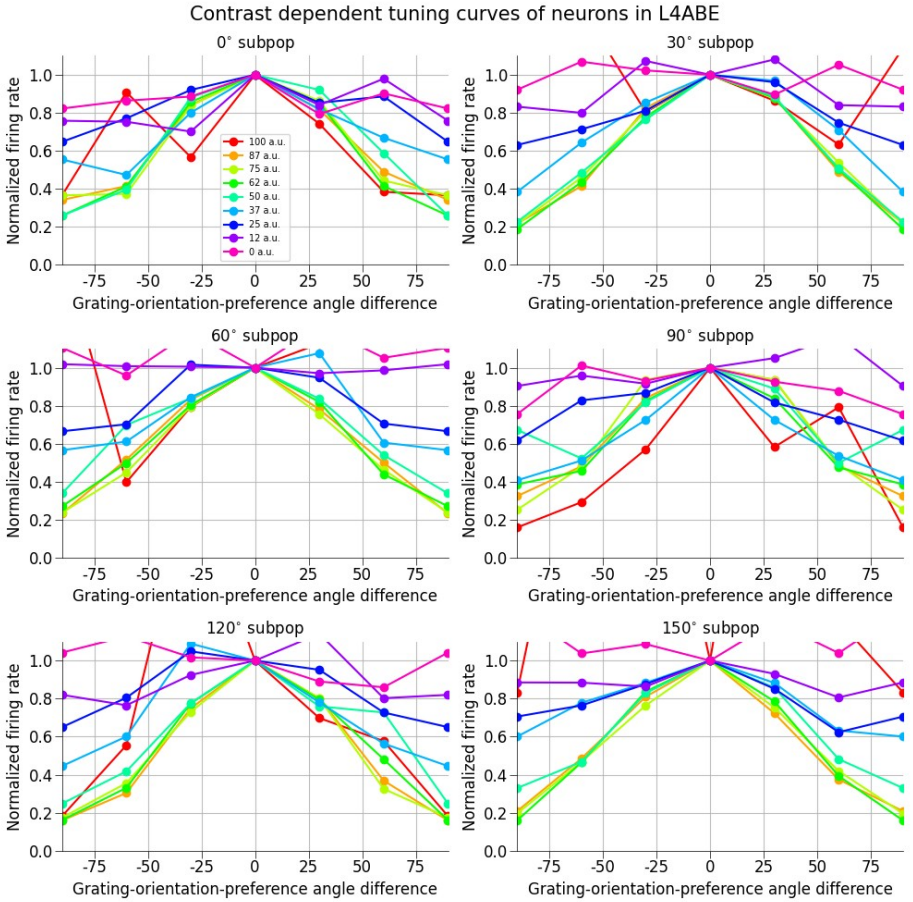


- Super-localized inhibitory neurons are strongly modulated
- Nevertheless, they rarely target neurons of different orientation preference making this modulation only minor in it effect

Connections dependent on distance

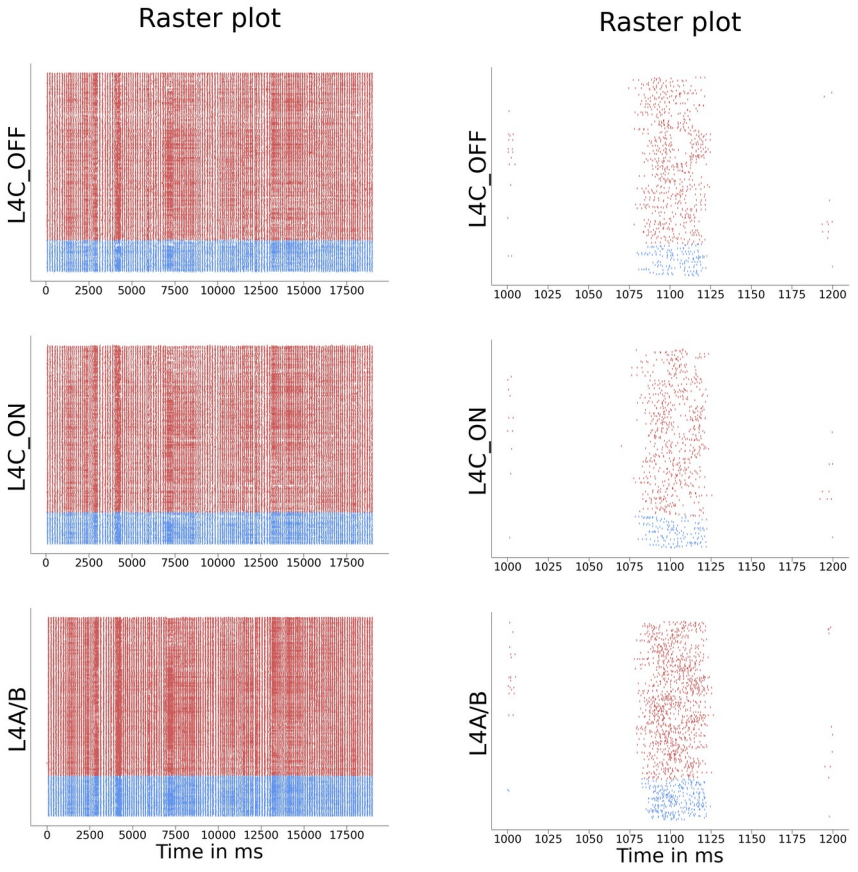


Contrast in-variance



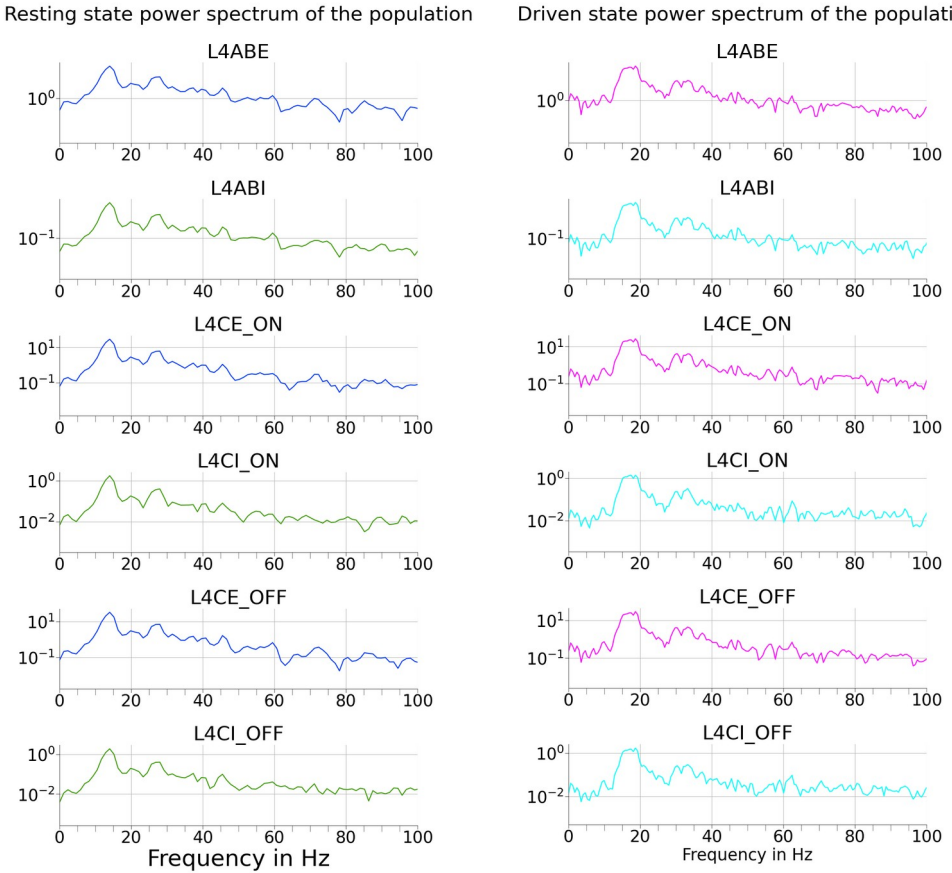
- Vary the contrast of the grating
- Plot normalized tuning curve
- The network shows similar tuning curves at many contrasts
- Below a certain contrast the shape changes

Raster plots



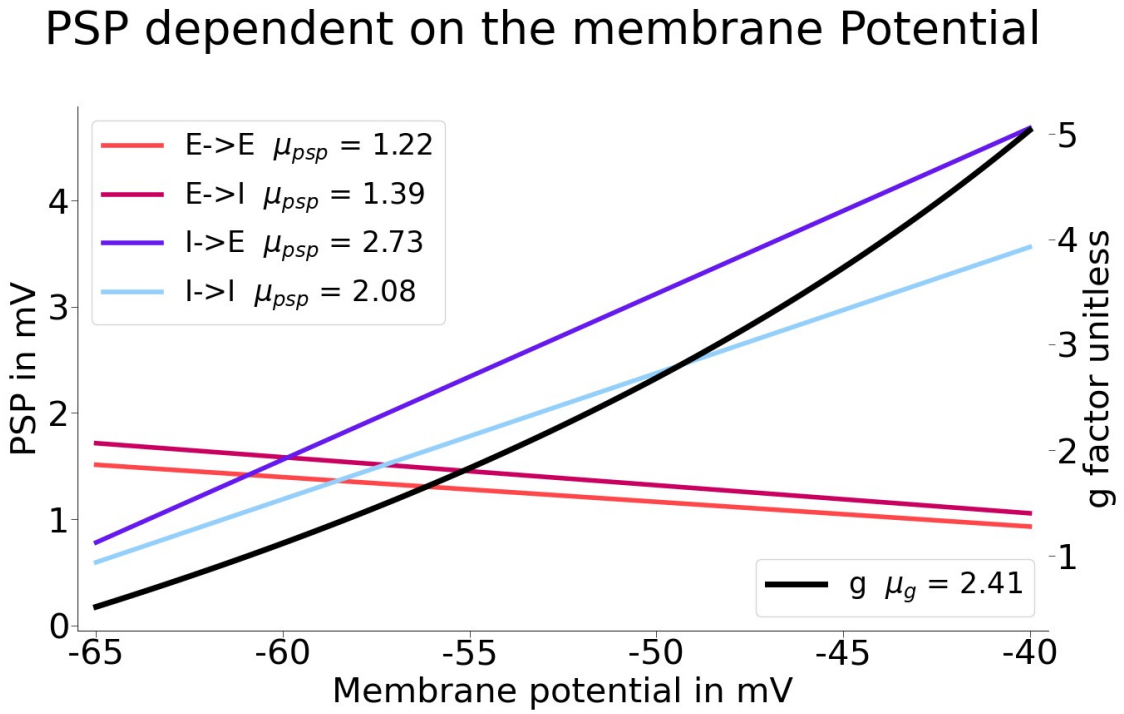
- The full data consists of 19 seconds spiking activity of 1.4 million neurons
- Cut out every 800th neuron
- Separately show a time sliced raster plot
- The spike times synchronize

Power spectra



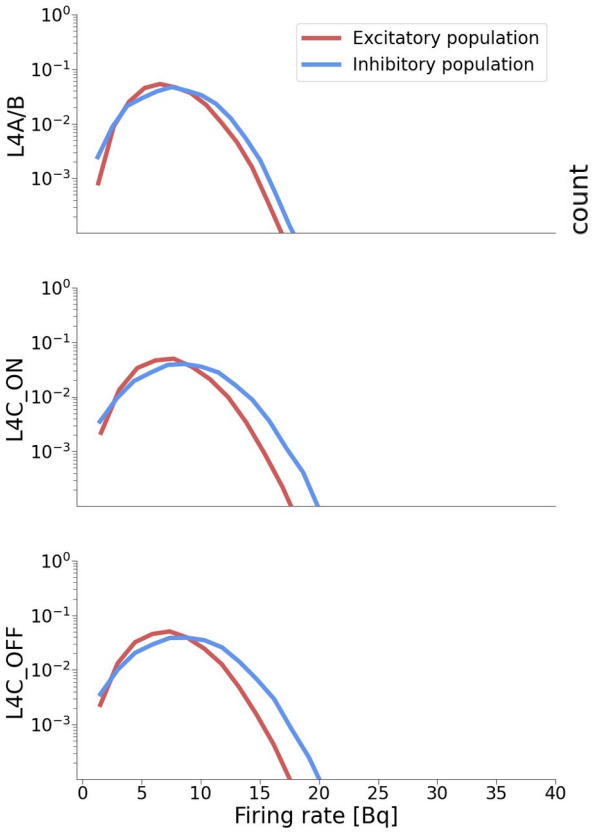
- Split power spectrum in resting and driven state
- Resting power spectrum has 14Hz peak and driven power spectrum has 19Hz peak
- Both peaks resemble the slow oscillations in the raster plots

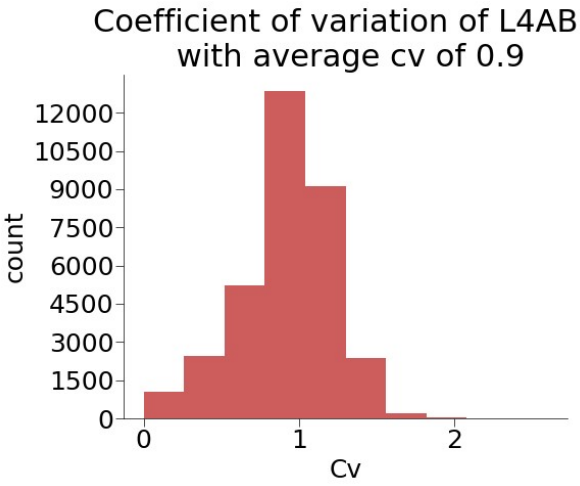
Network balancing

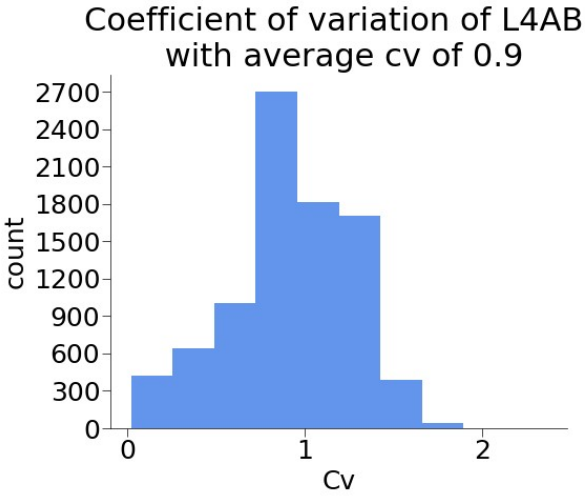


- The network utilizes conductance based neurons
- Post synaptic potentials are dependent on the membrane potential
- E I balancing changes with membrane potential

Firing rate distribution and Cv







- Inhibitory neurons have a higher average firing rate
- The coefficient of variation is below 1 (which a Poisson process would have) and is consistent with the literature (Softky et. al. 1993)