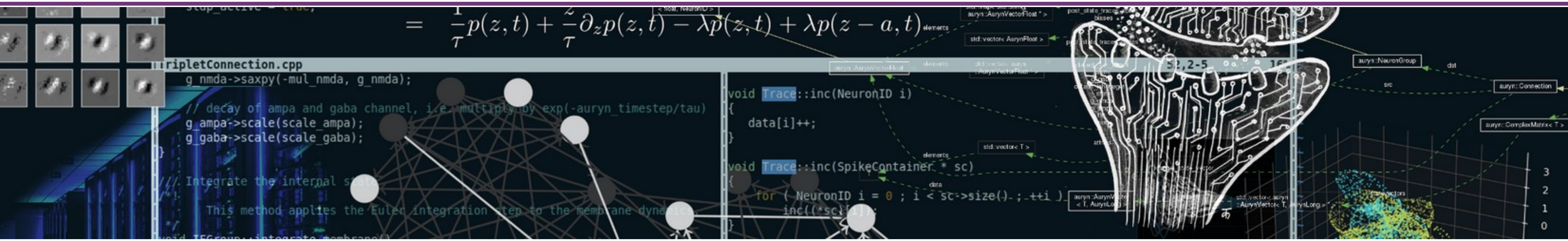
FMI
Friedrich Miescher Institute
for Biomedical Research

University
of Basel



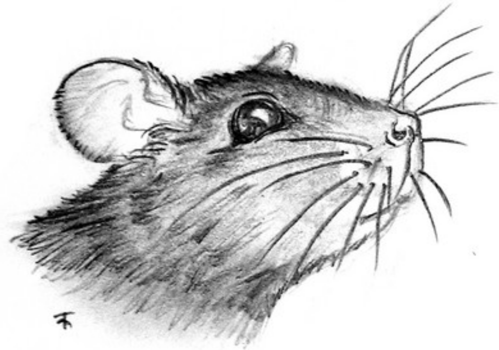
The temporal paradox of Hebbian learning and homeostatic plasticity

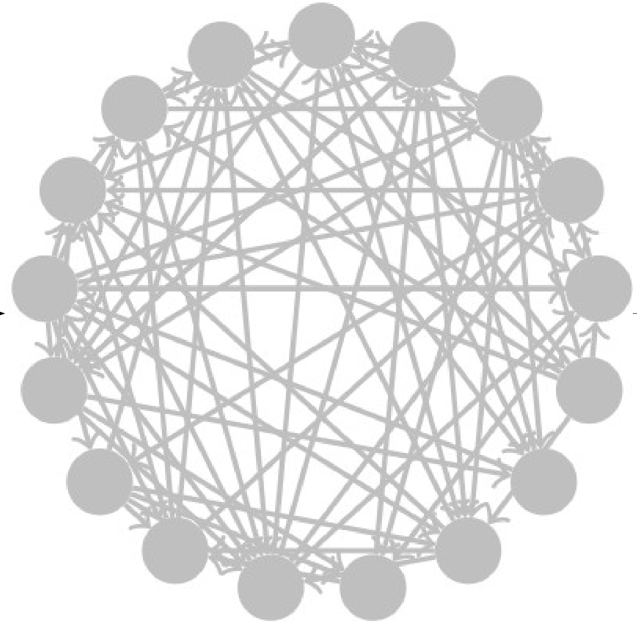
Doctoral Class in Neurophysics, 12-16 June 2023

Friedemann Zenke
Computational Neuroscience @ FMI
www.zenkelab.org

The space of all possible networks is ginormous

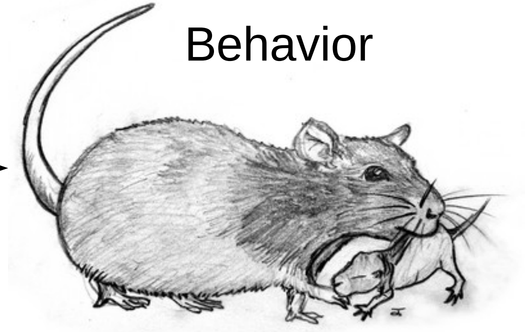
Sensory inputs





$n = 17$

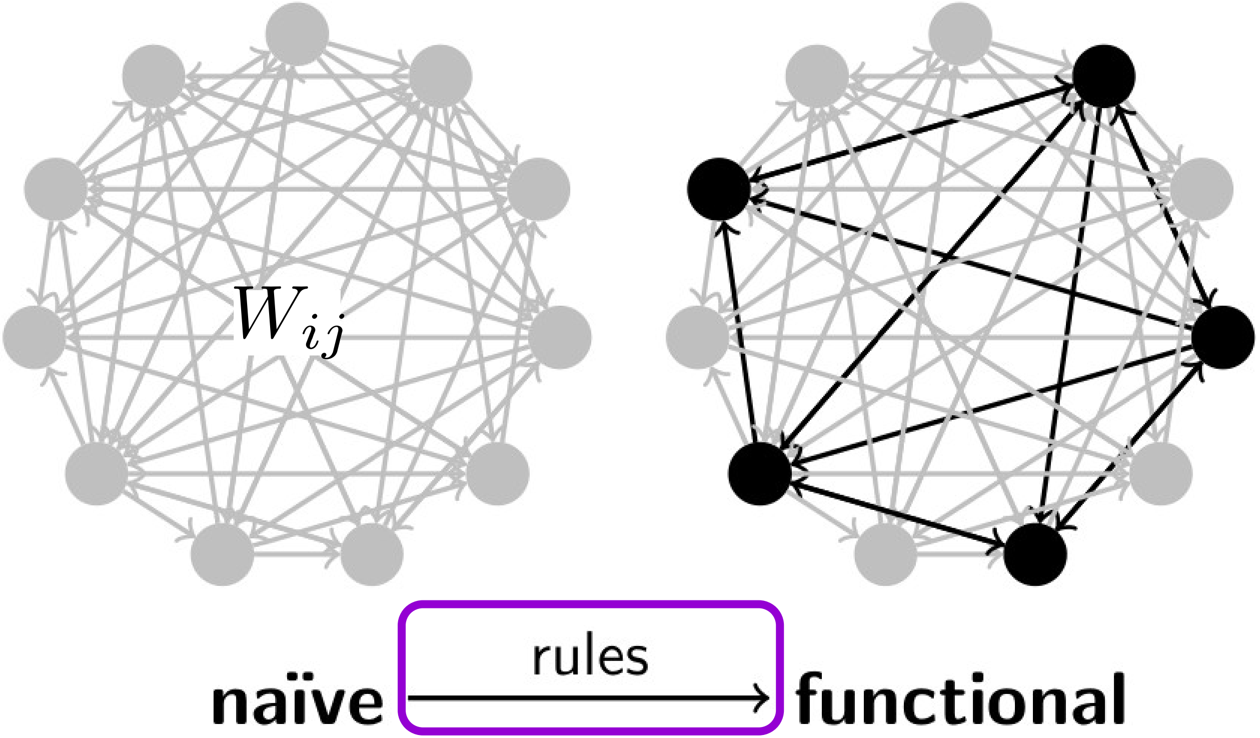
Behavior



Possible configurations

$$2^{(17^2)} \approx 9.9 \times 10^{86}$$

Learning rules navigate this search space



"learning rules" $\Delta W_{ij}(t)$ or $\frac{W_{ij}(t)}{dt}$

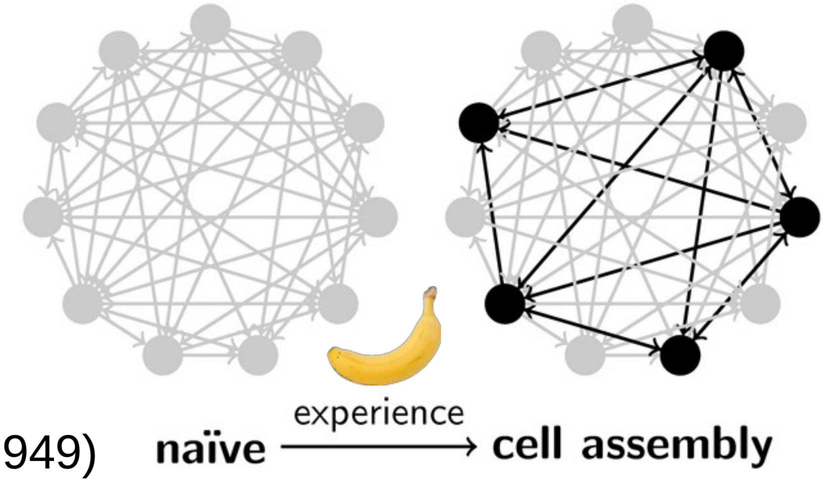
Overview

- Hebbian plasticity, cell assemblies, and instability
- Phenomenological (Hebbian) plasticity models
- Homeostatic plasticity
- The temporal paradox of Hebbian learning and homeostatic plasticity
- Ways out of the paradox:
  A model of stable learning in plastic network models

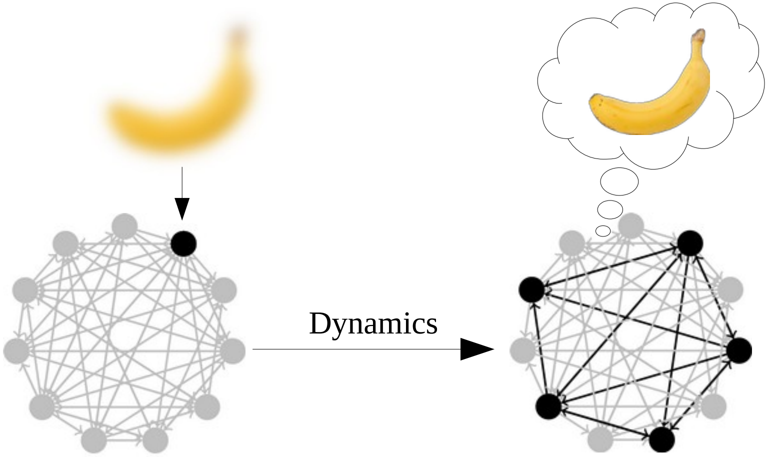
Hebbian plasticity – A putative mechanism for associative learning of structure

The "prophecy": Who fires together wires together

$$\Delta W_{ij}(t) \propto (\text{pre})(\text{post})$$



Hebb (1949)



Energy landscape

"memory"

"attractor dynamics"

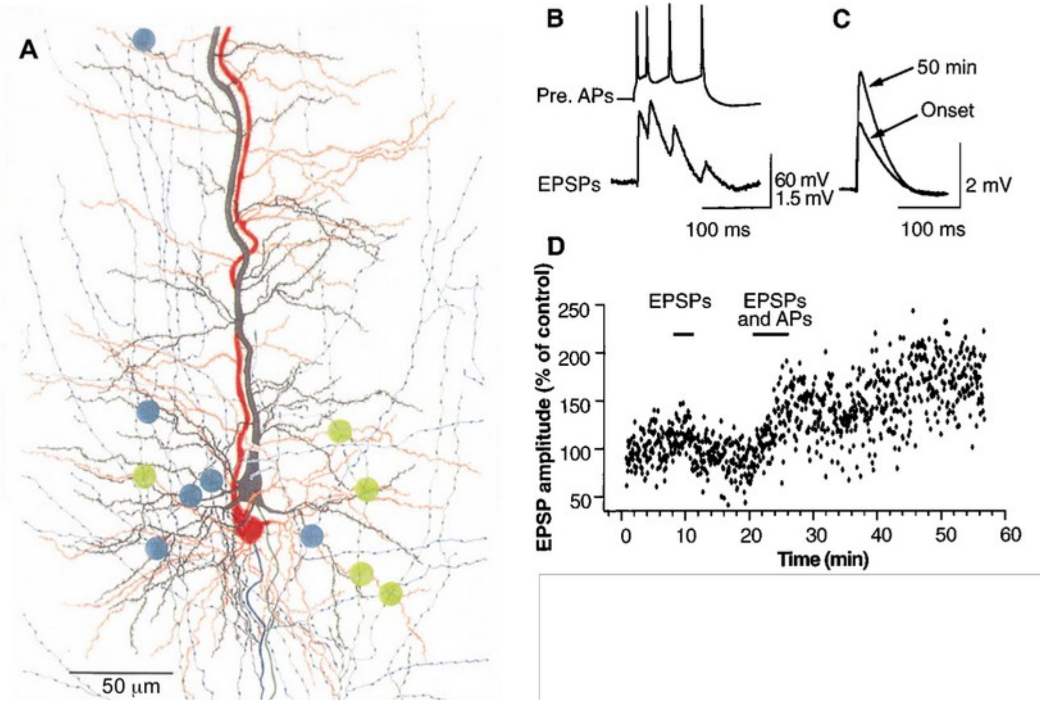
Experimental confirmation
Co-activity increases synaptic strength

J. Physiol. (1973), **232**, *pp.* 331–356 **331**
With 12 text-figures
Printed in Great Britain

LONG-LASTING POTENTIATION OF SYNAPTIC TRANSMISSION IN THE DENTATE AREA OF THE ANAESTHETIZED RABBIT FOLLOWING STIMULATION OF THE PERFORANT PATH

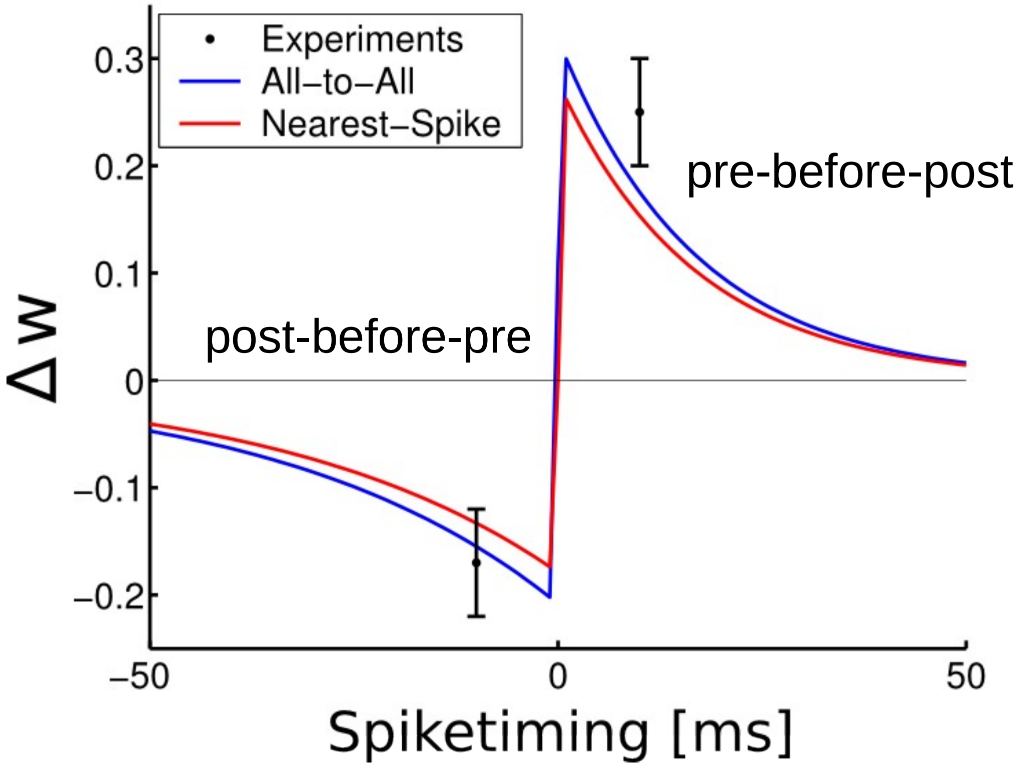
By T. V. P. BLISS and T. LØMO

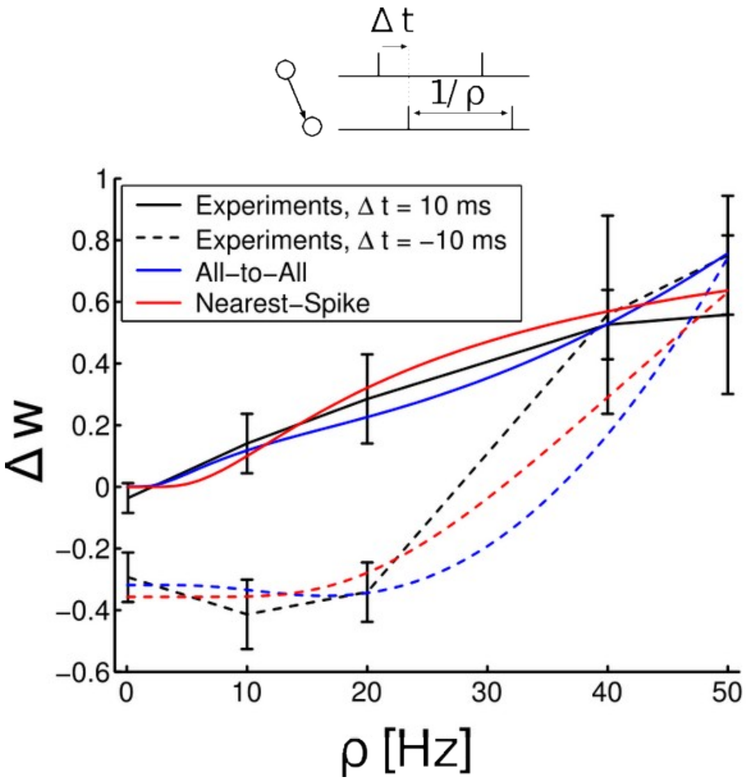
Bliss, T.V.P., and Lømo, T. (1973)



Markram, H., Lübke, J., Frotscher, M., and Sakmann, B. (1997)

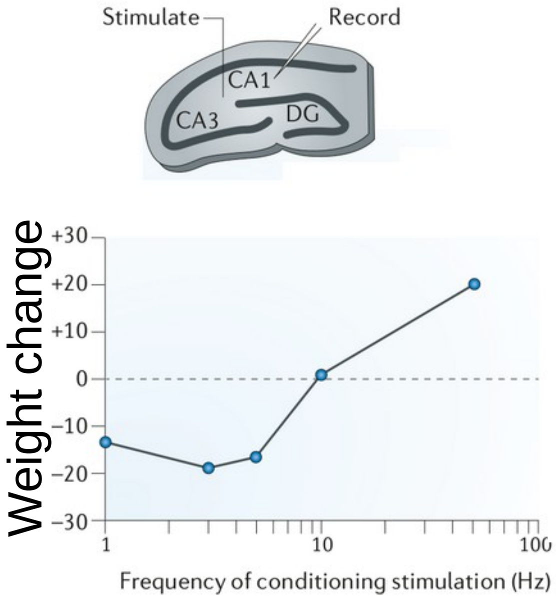
Triplet STDP – A data-driven plasticity model

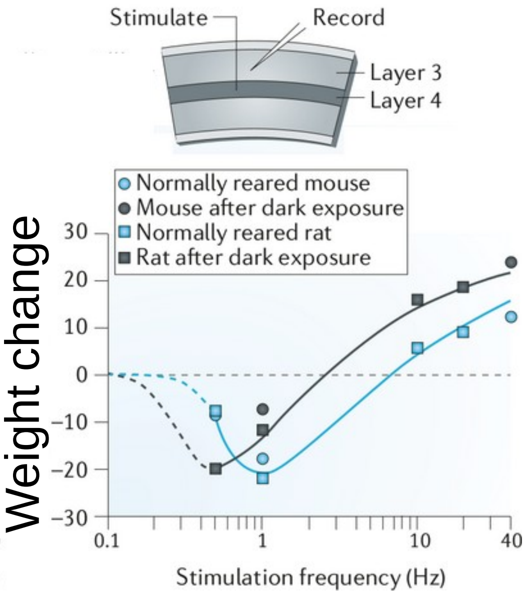




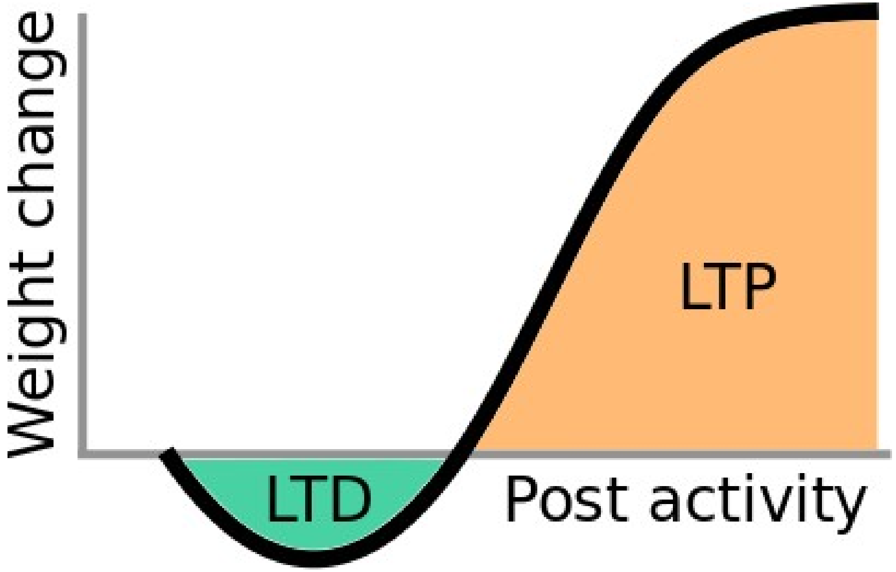
Pfister & Gerstner (2006)
Experiments: Sjöström et al. (2001)

Hebbian plasticity in the brain
The sign of plasticity depends on postsynaptic quantities

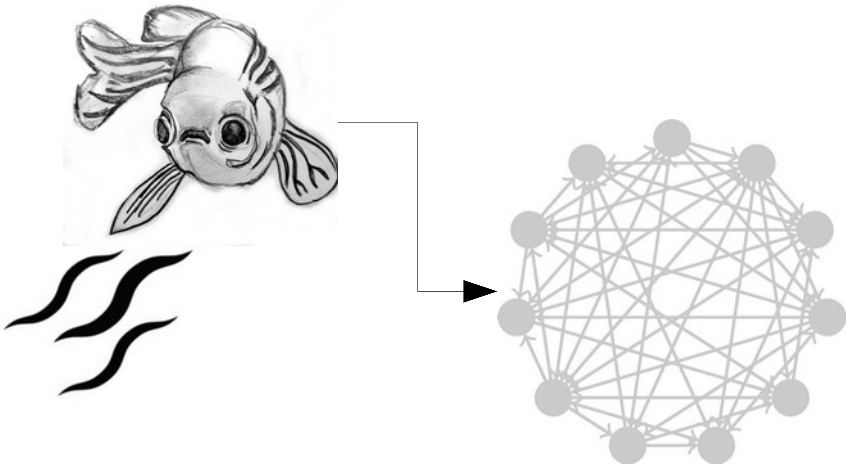


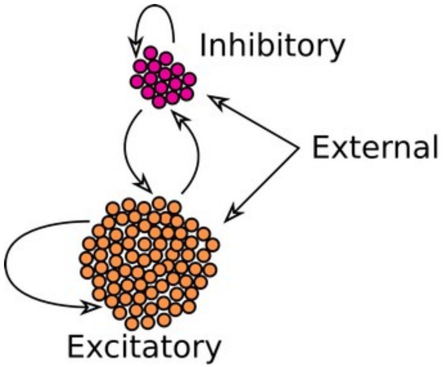


Remember:

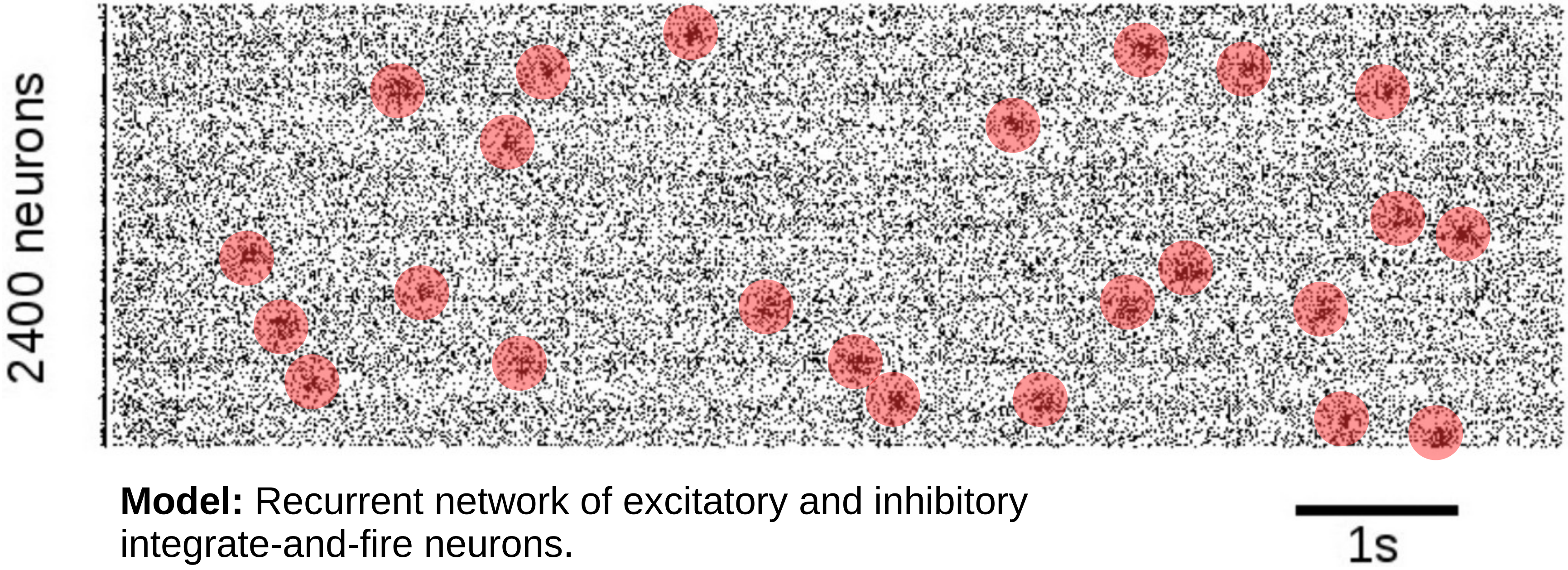


Cooper and Bear (2012). *Nat Rev Neurosci* 13, 798–810.

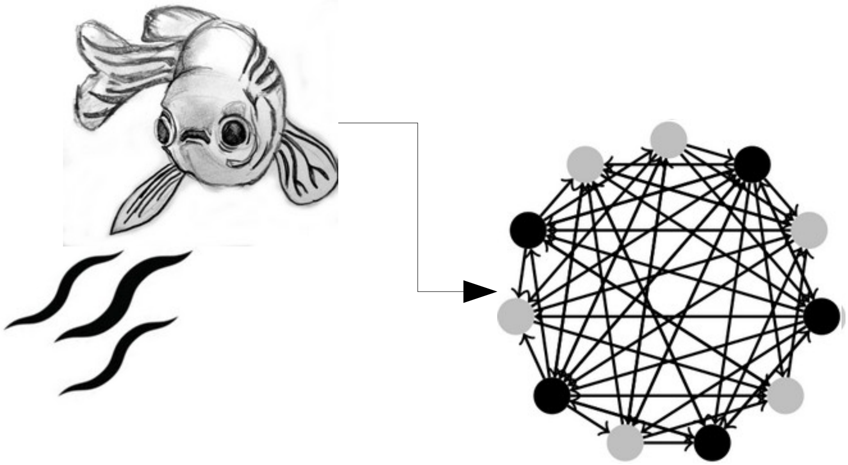




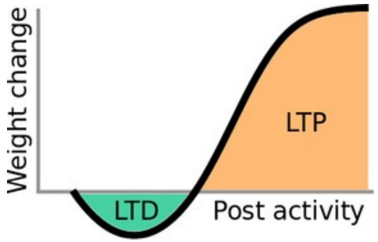
No plasticity

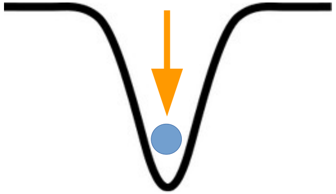


Model: Recurrent network of excitatory and inhibitory integrate-and-fire neurons.

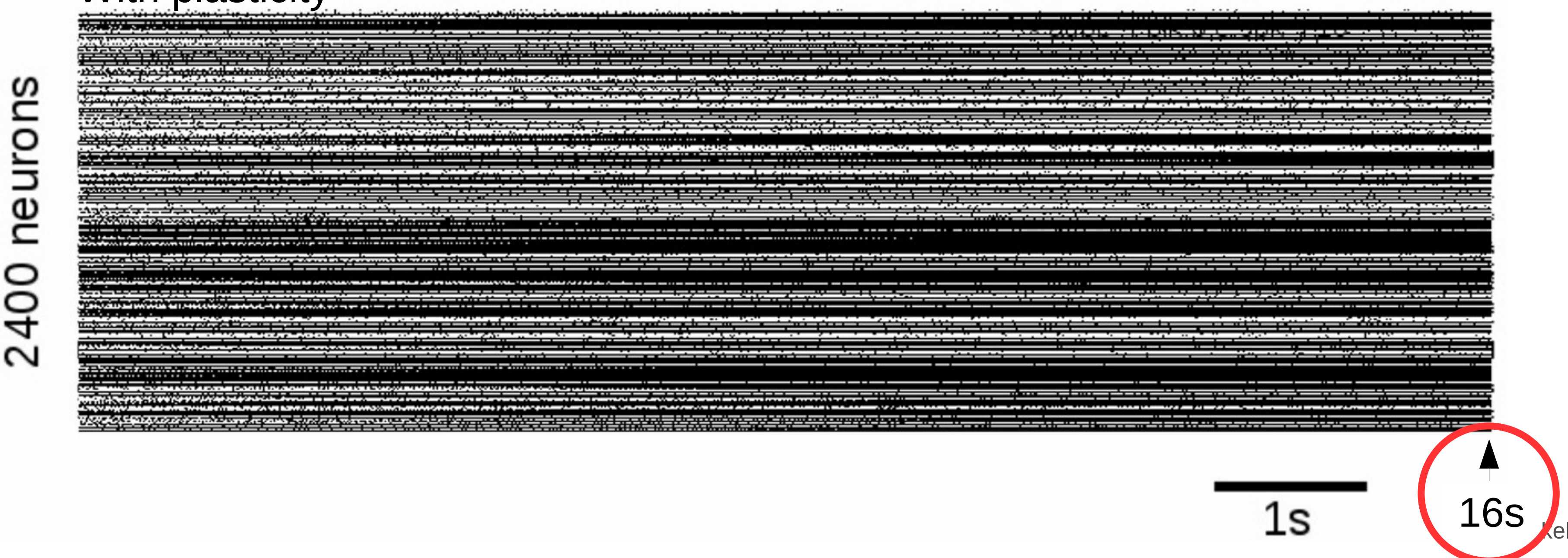


Run-away dynamics





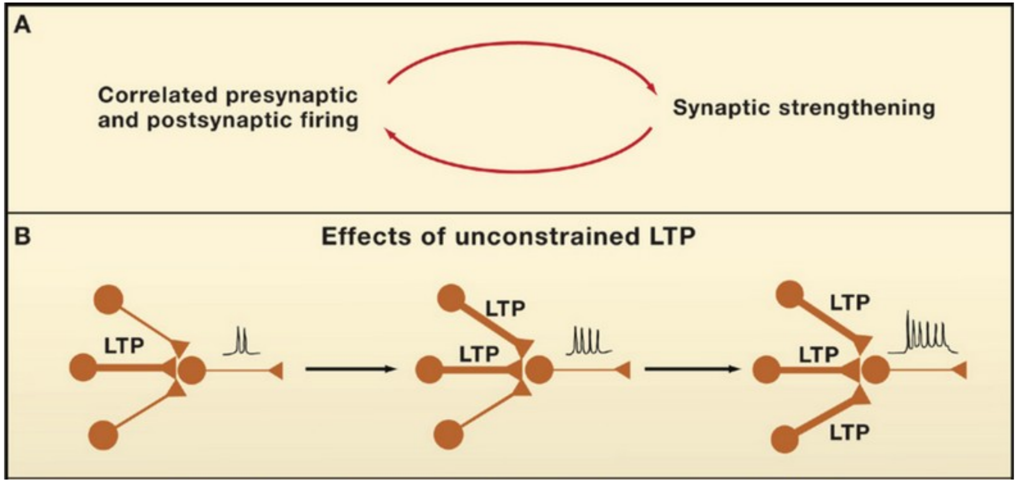
With plasticity



Important insights

- Hebbian plasticity is unstable → need “homeostasis”
- Run-away potentiation destroys memories
- Time course of run-away on the order of seconds

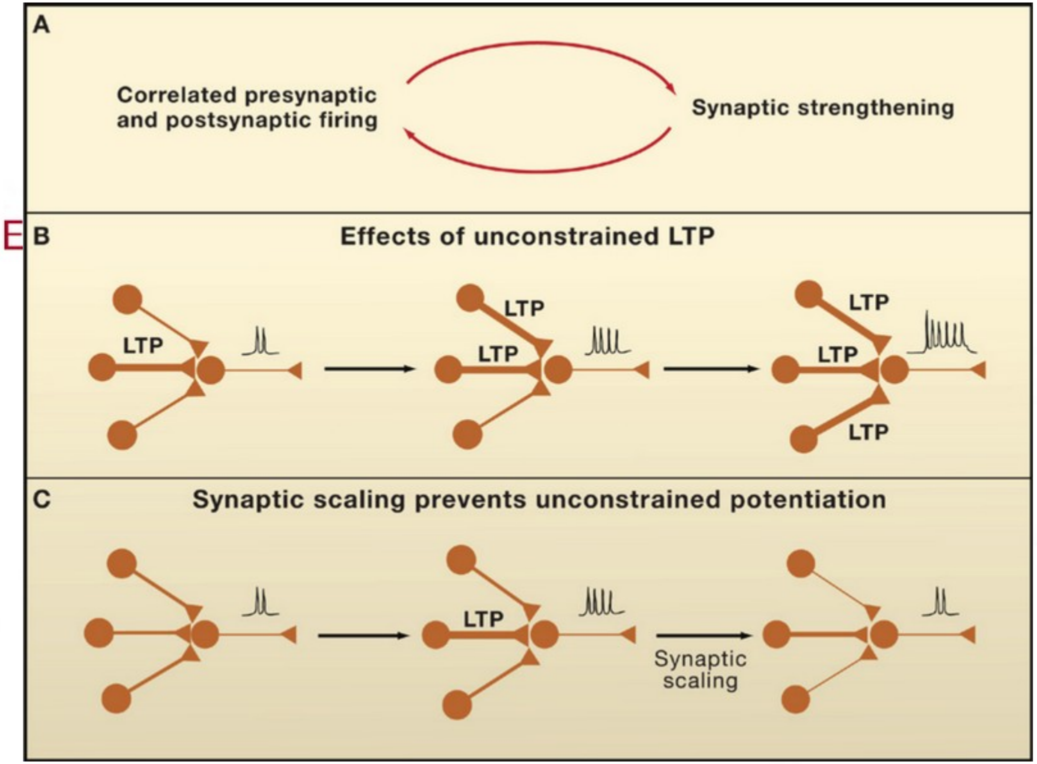
Homeostatic plasticity
Something to prevent all weights from going up



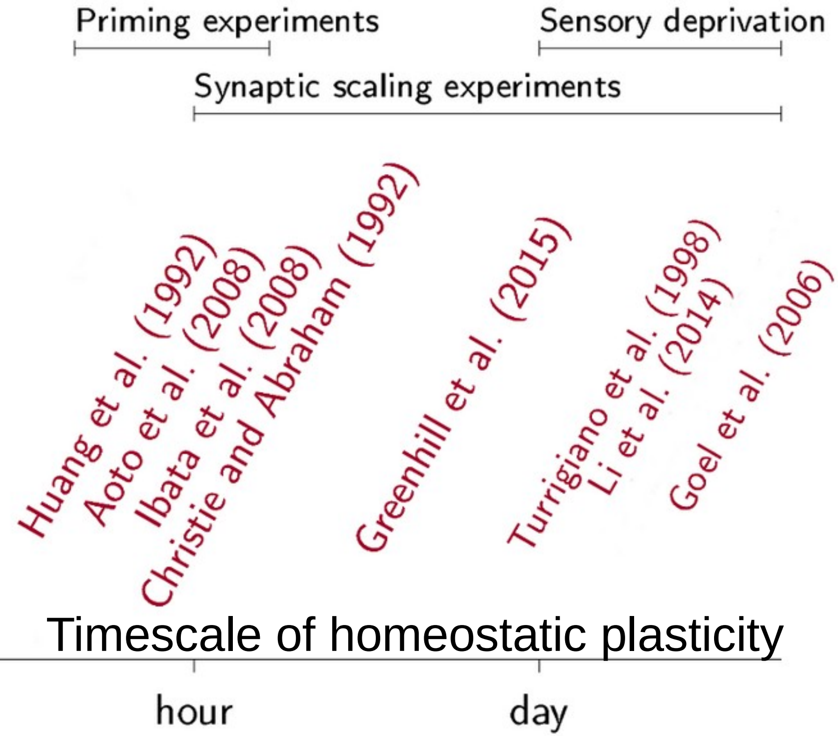
Need for weight normalization pointed out in theoretical work
von der Malsburg, C. (1973)

Turrigiano, G.G. (2008); Turrigiano et al (1998)

How fast is homeostatic plasticity?



meta-plasticity



Timescale of homeostatic plasticity

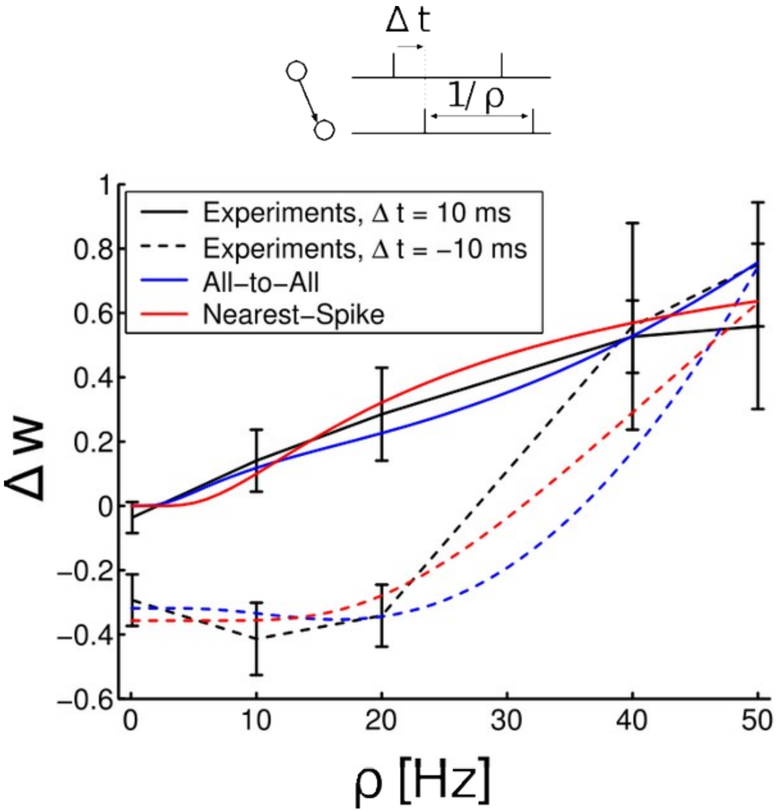
Turrigiano, G.G. (2008)

Zenke & Gerstner (2017)

Synaptic Homeostasis Hypothesis

”Sleep is the price the brain pays for plasticity”

Metaplasticity: Extending Hebbian with homeostatic plasticity



Pfister & Gerstner (2006)
Experiments: Sjöström et al. (2001)

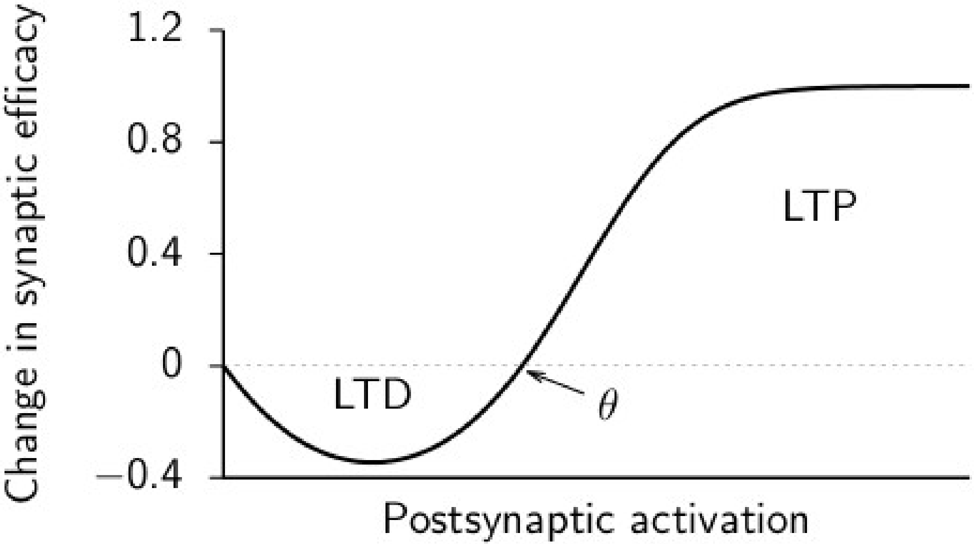
Extending Hebbian with homeostatic plasticity

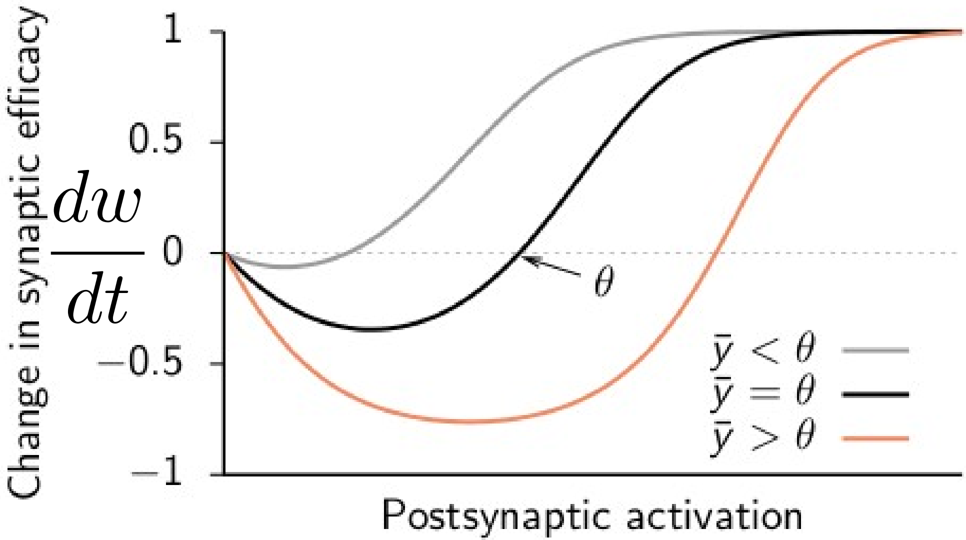
$$\frac{dw_i}{dt} = y\left(y - \theta_M\right)x_i$$

$$\theta_M \equiv \frac{y^2}{\kappa}$$

BCM theory

$$\tau\frac{dy}{dt} = -\bar{y} + y$$





$$\frac{dw}{dt}$$

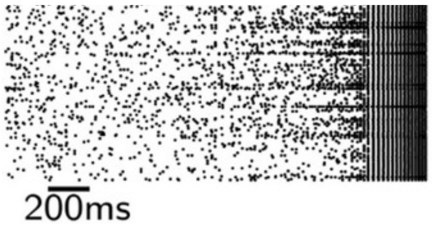
$$y = \sum_i w_i x_i$$

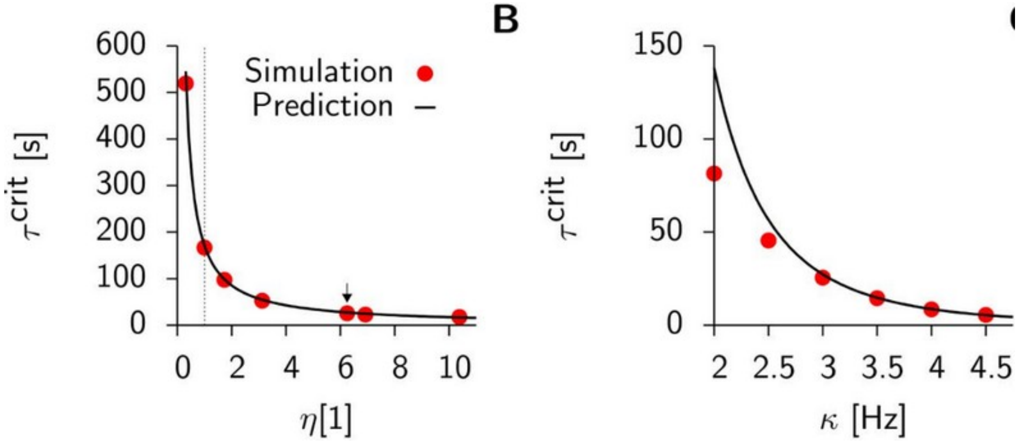
(Bienenstock et al., 1982)

Time constant of homeostasis determines stability

$$\tau < \tau^{\text{crit}} \equiv \frac{\Theta \tau_w}{\eta \gamma \kappa}$$

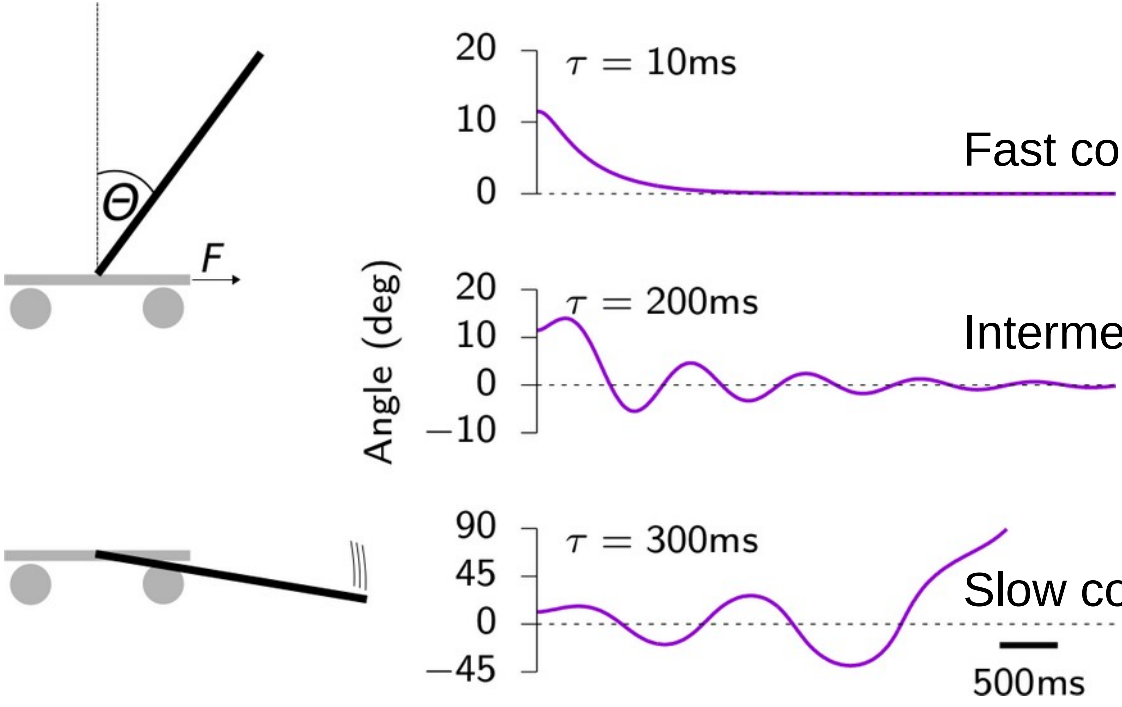
We will derive this in the exercise.





Zenke et al. (2013)

Time constant of homeostasis determines stability



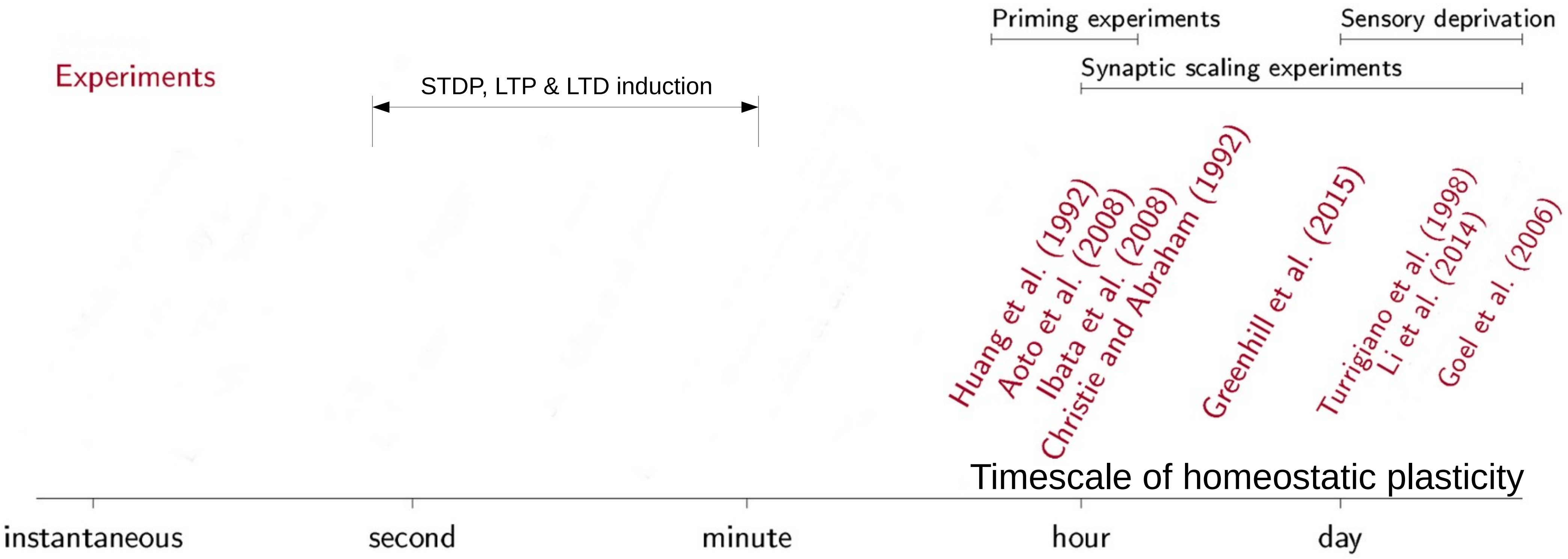
Fast controller

Intermediate

Slow controller → unstable

Zenke, Gerstner, and Ganguli (2017)

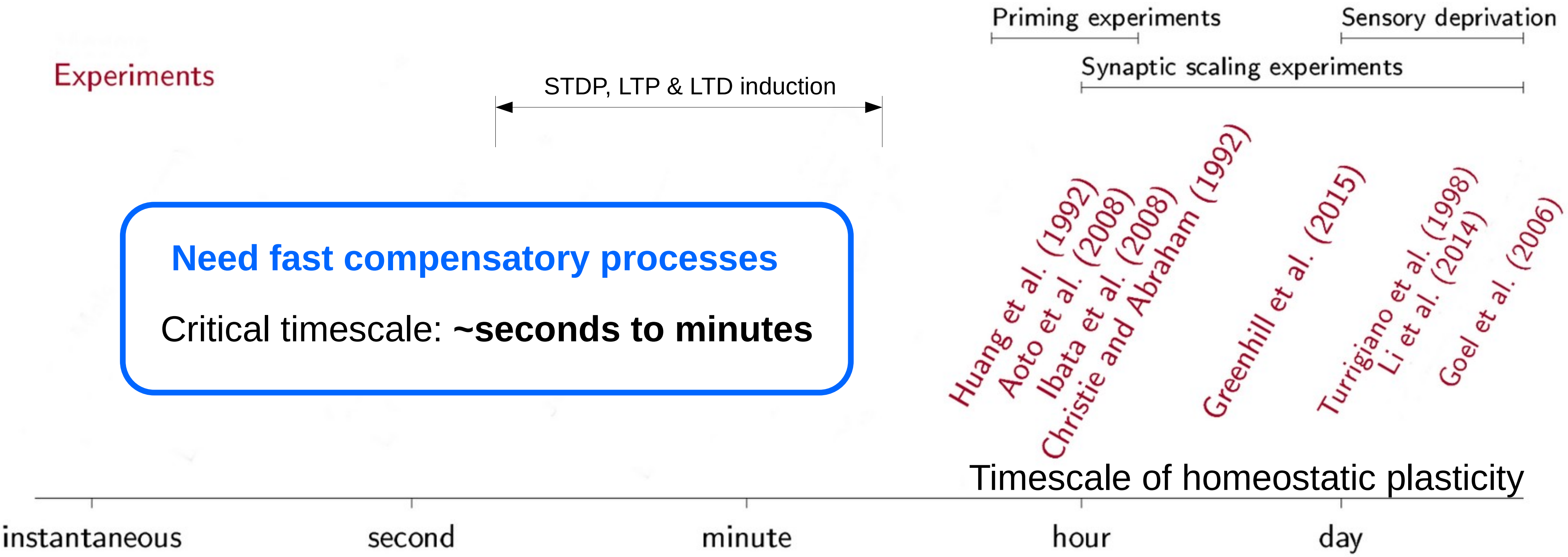
Problem: Homeostatic plasticity is too slow to stabilize plasticity in computer models



FMI.ch

Zenke and Gerstner (2017)

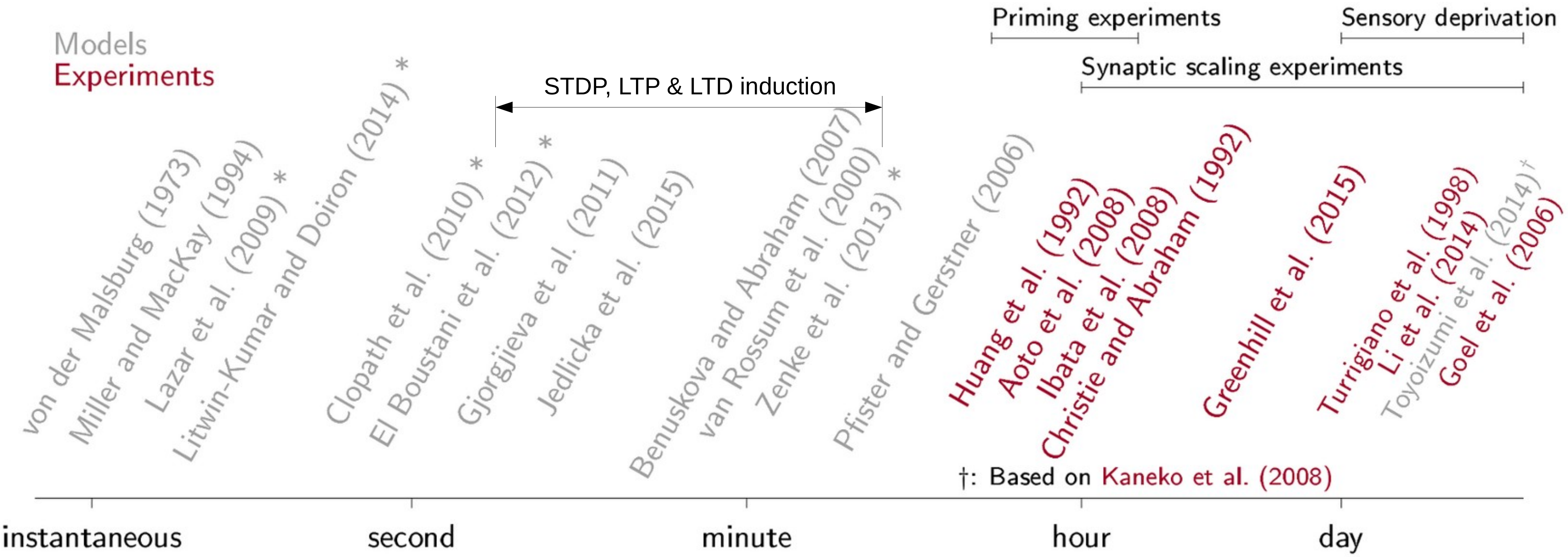
Problem: Homeostatic plasticity is too slow to stabilize plasticity in computer models



Need fast compensatory processes

Critical timescale: **~seconds to minutes**

Problem: Homeostatic plasticity is too slow to stabilize plasticity in computer models



The temporal paradox of Hebbian learning and homeostatic plasticity

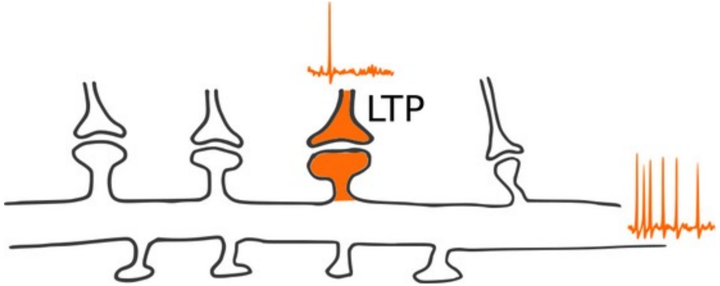
- Hebbian learning without/with slow homeostasis is unstable
- Experimentally observed homeostasis is slow
- Slow homeostasis in simulations leads to run-away activity
- Actual networks in neurobiology are stable

Need a theoretical understanding of *fast enough*

Possible ways out of the paradox

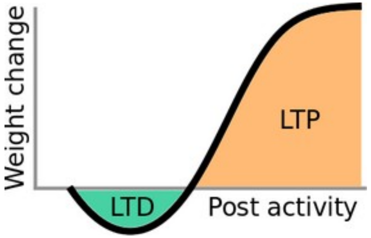
- Something is missing in our plasticity/homeostasis models
- **Idea:** Unobserved rapid stabilizing mechanisms are at work

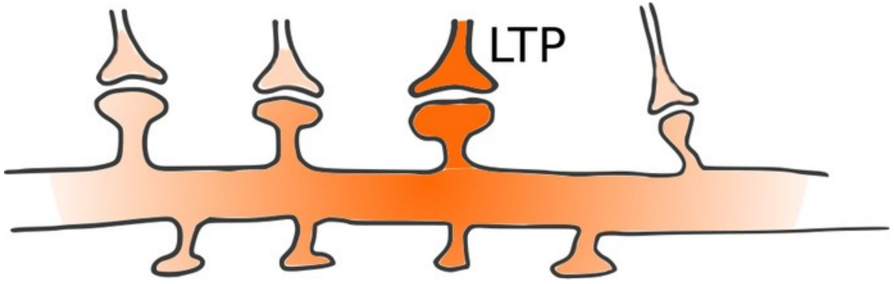
Problem: Slow homeostatic plasticity is unable to stabilize fast Hebbian plasticity



Weight dynamics

$$\frac{d}{dt}w = \quad - \text{LTD} + \text{LTP}$$





Need to

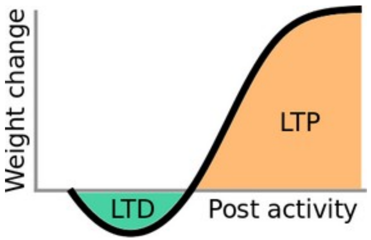
- Avoid runaway LTP at the homosynaptic pathway
- Prevent LTP at many “bystander” synapses

Idea: Hebbian and rapid compensatory plasticity cooperate on same timescale

- Learning takes place when something “interesting” happens

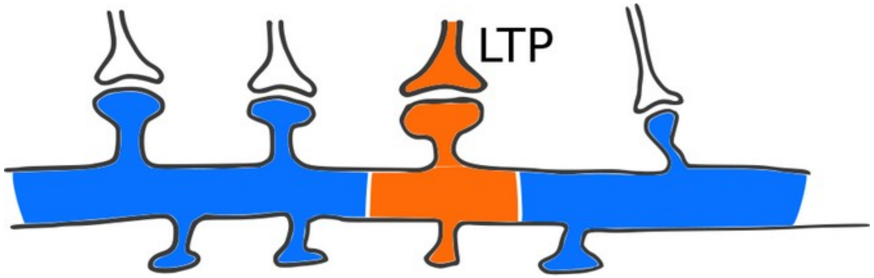
Weight dynamics

$$\frac{d}{dt}w = \underbrace{\text{Non-Hebb} - \text{LTD}}_{\approx 0} + \underbrace{\text{LTP} - \text{Non-Hebb}}_{\approx 0}$$



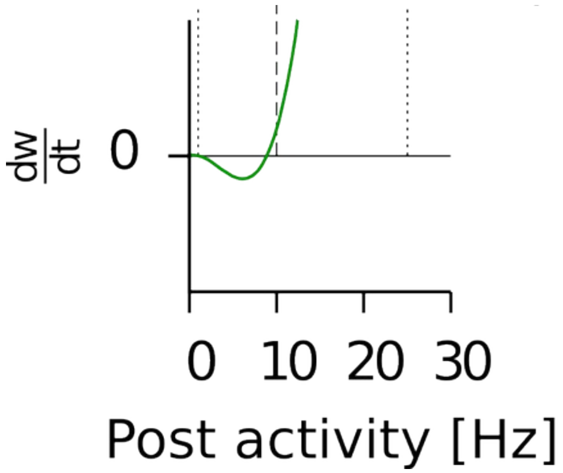
Constraints

- Stability (~ sec–min)
- Nonlinear onset
- Need to fit the data
- Should be “local”



→ Should be observable as a heterosynaptic effect.

Hebbian plasticity without (with slow) homeostasis is unstable

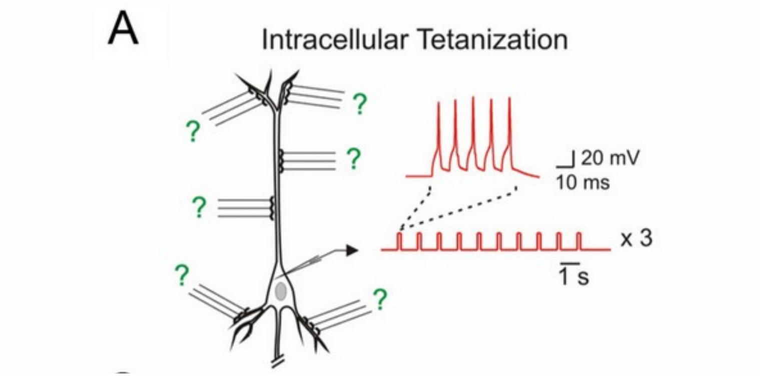


$$\frac{dw}{dt} \propto (\text{pre})\,(\text{post})\,((\text{post}) - \kappa)$$

Hebbian

Postsynaptic activation determines LTP/LTD

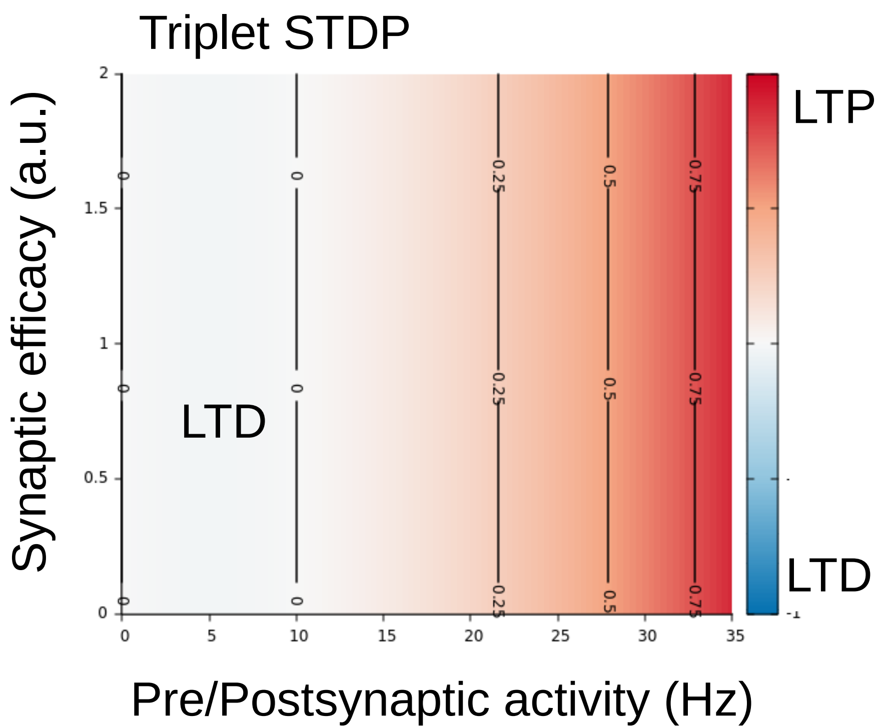
Non-Hebbian forms of plasticity: Heterosynaptic plasticity

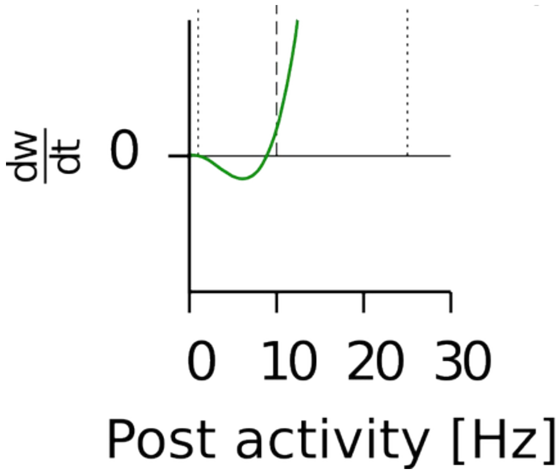


$$\frac{dw}{dt} \propto -\beta\,(\mathrm{post})^k\,(w - \tilde{w})$$

Chen et al. (2013)

Hebbian plasticity without heterosynaptic plasticity

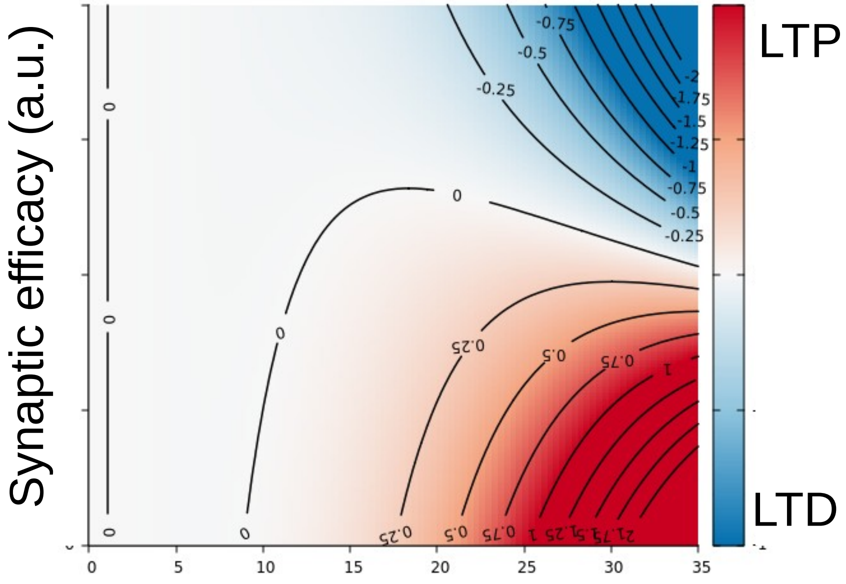




$$\frac{dw}{dt} \propto (\text{pre})\,(\text{post})\,((\text{post}) - \kappa)$$

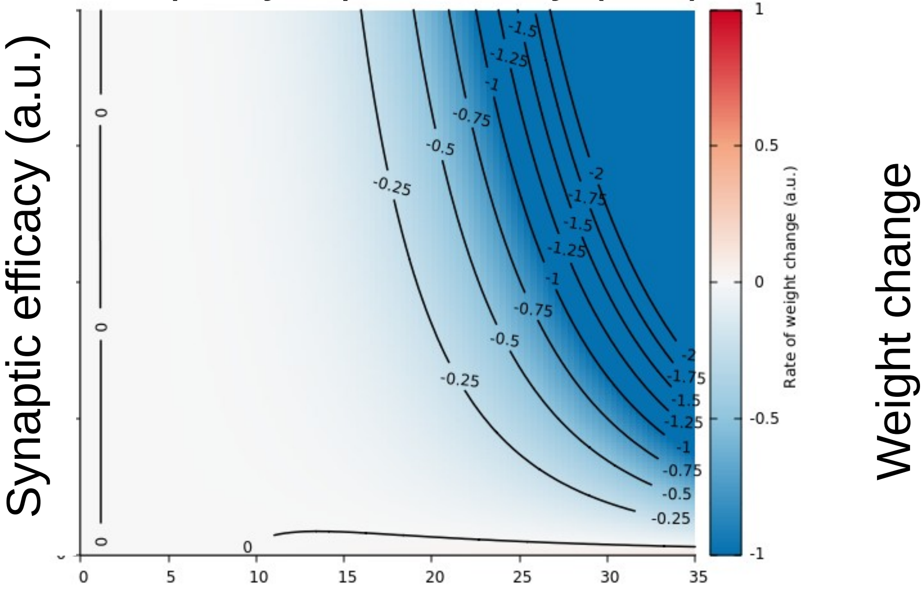
Hebbian learning with heterosynaptic plasticity is stable

Triplet STDP + heterosynaptic plasticity



Pre/Postsynaptic activity (Hz)

Low presynaptic activity (1Hz)



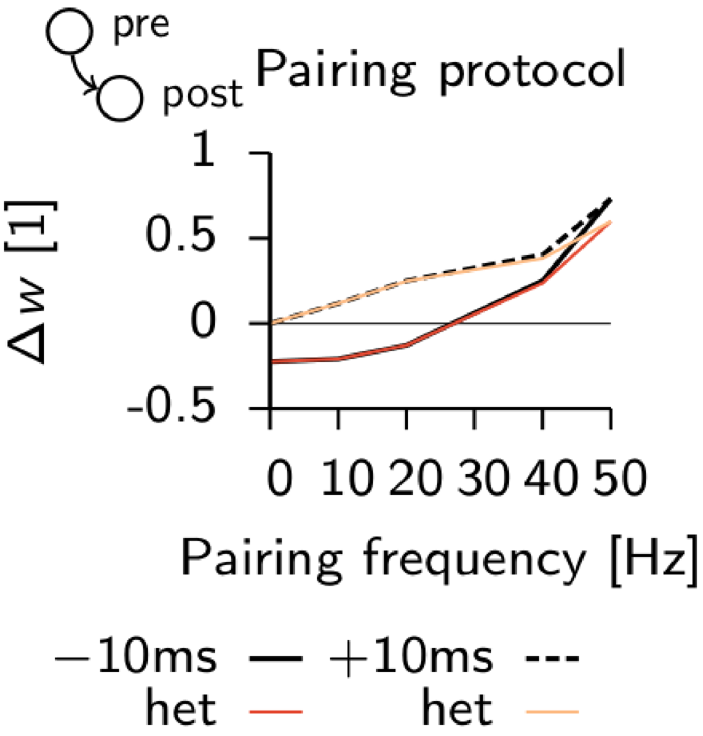
Postsynaptic activity (Hz)

$$\frac{dw}{dt} \propto (\mathrm{pre})\,(\mathrm{post})\,((\mathrm{post}) - \kappa) - \beta\,(\mathrm{post})^{k}\,(w - \tilde{w})$$

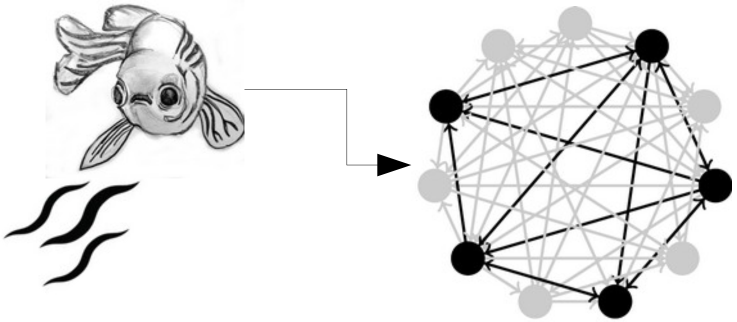
Heterosynaptic plasticity

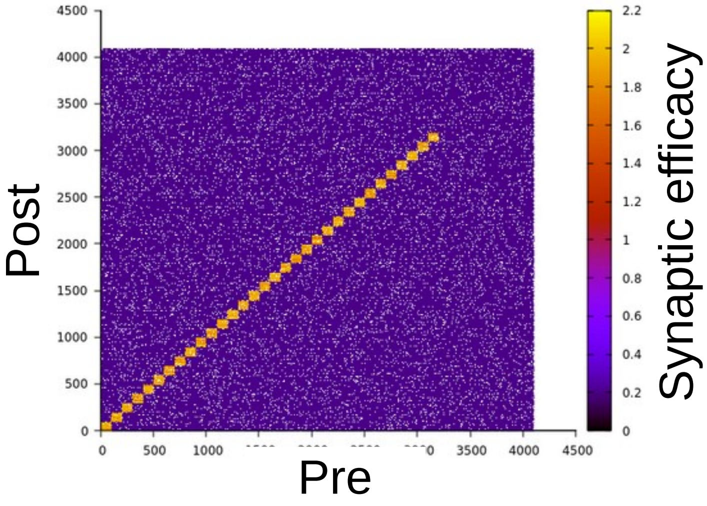
- Local
- Stabilizing

Heterosynaptic plasticity is consistent with experiments



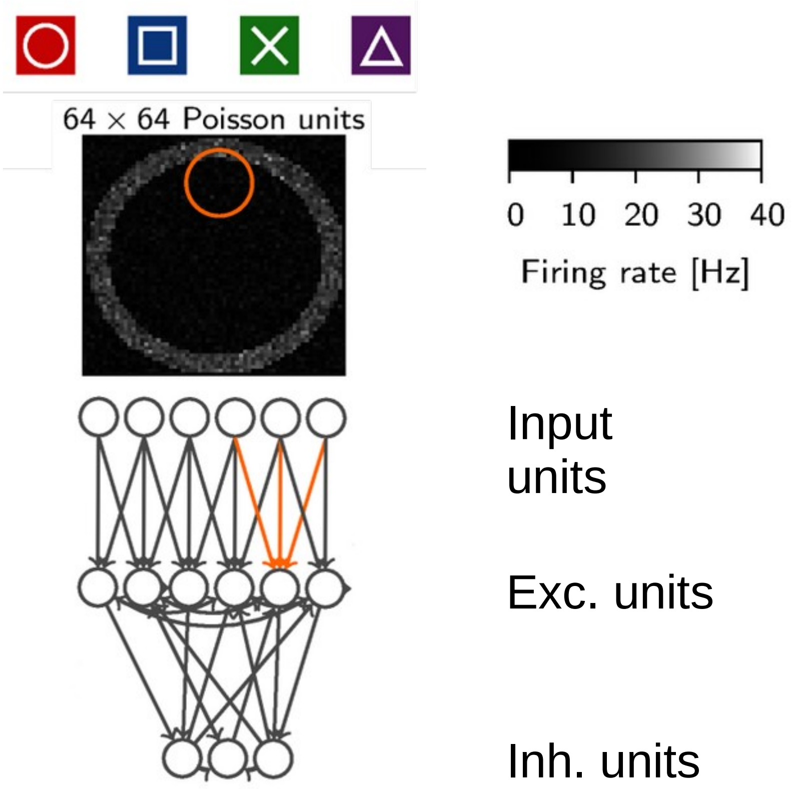
Rapid compensatory plasticity stabilizes network simulations

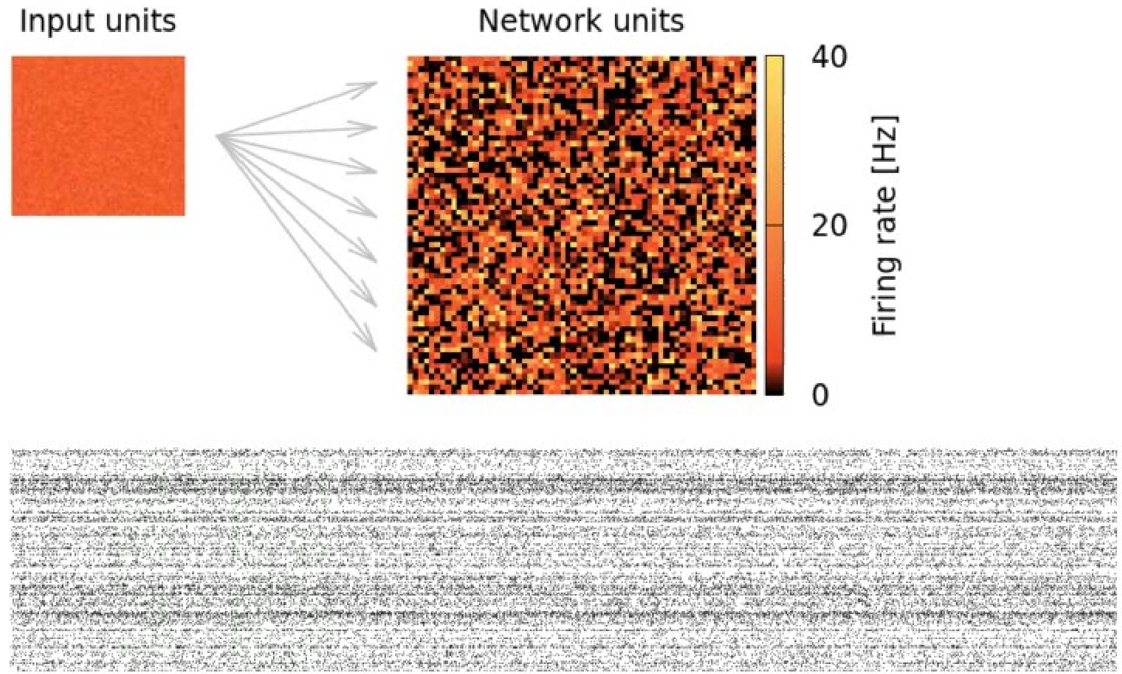




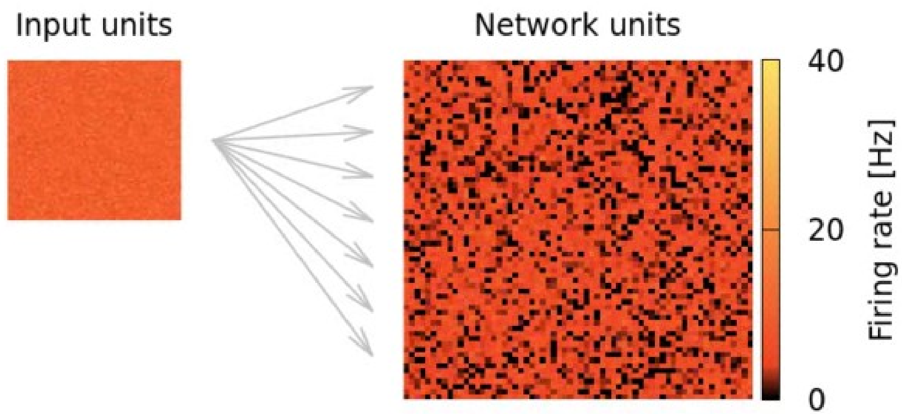
Memory storage an recall in a recurrent network model

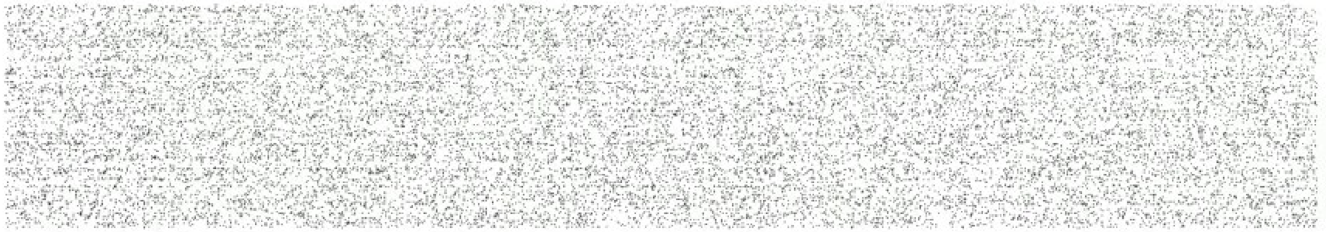
- Plasticity
  - Triplet STDP
  - Heterosynaptic plasticity
  - Transmitter triggered plasticity
  - Inhibitory plasticity
  - Short-term plasticity
  - Consolidation: $\tilde{w}(t)$
- Spiking network
  - 4096 excitatory IF, 1024 inhibitory IF
  - Conductance based synapses
  - Spike-triggered adaptation
  - Random sparse connectivity



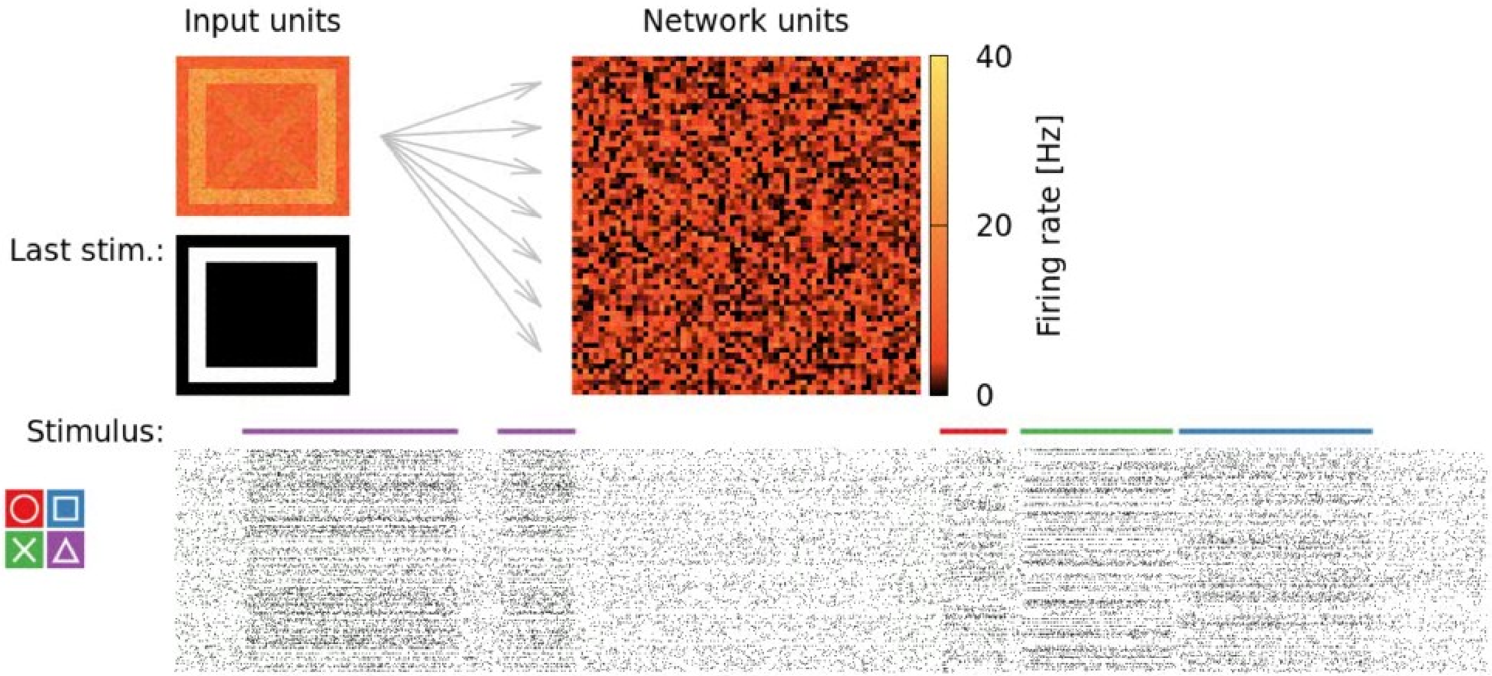


Plasticity inactive

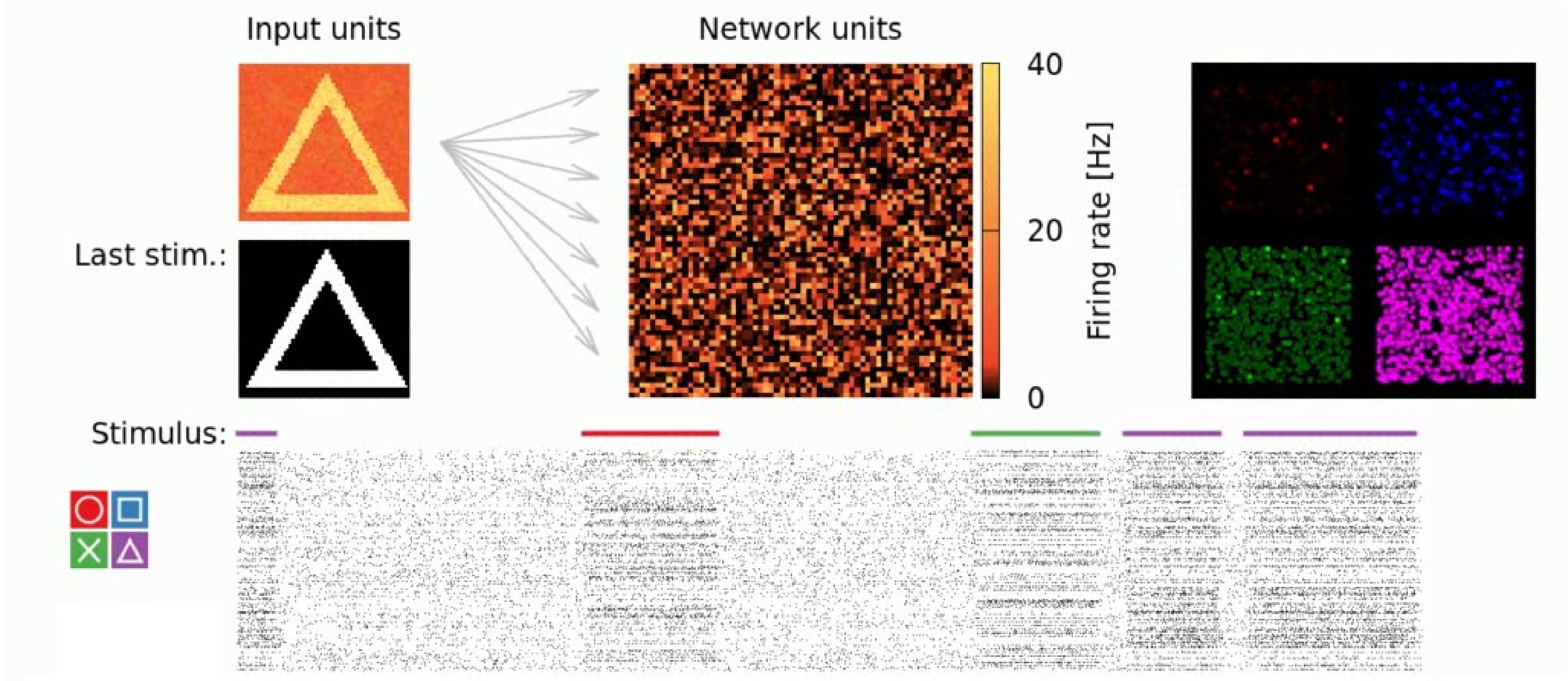




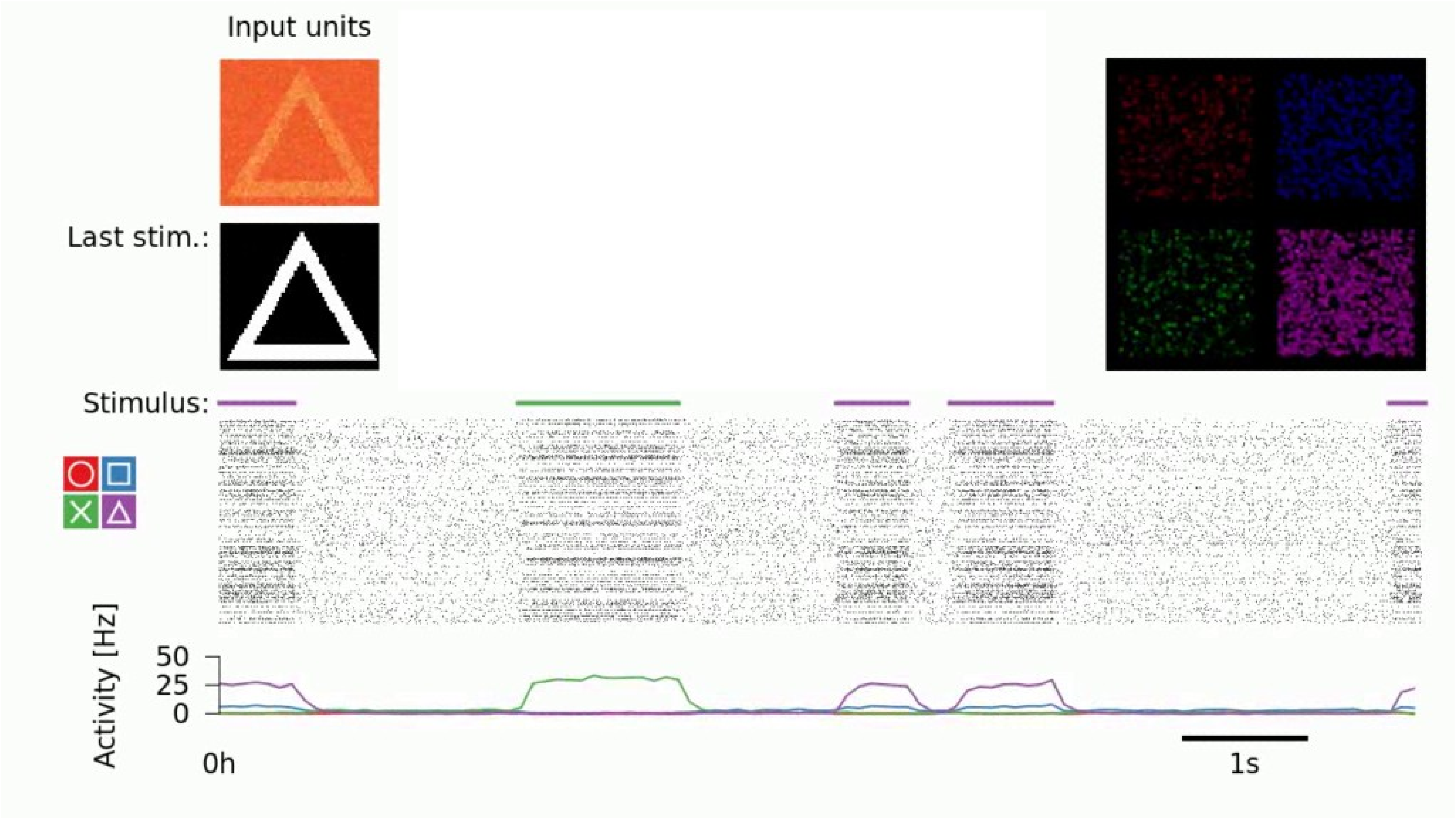
Hebbian & non-Hebbian plasticity active



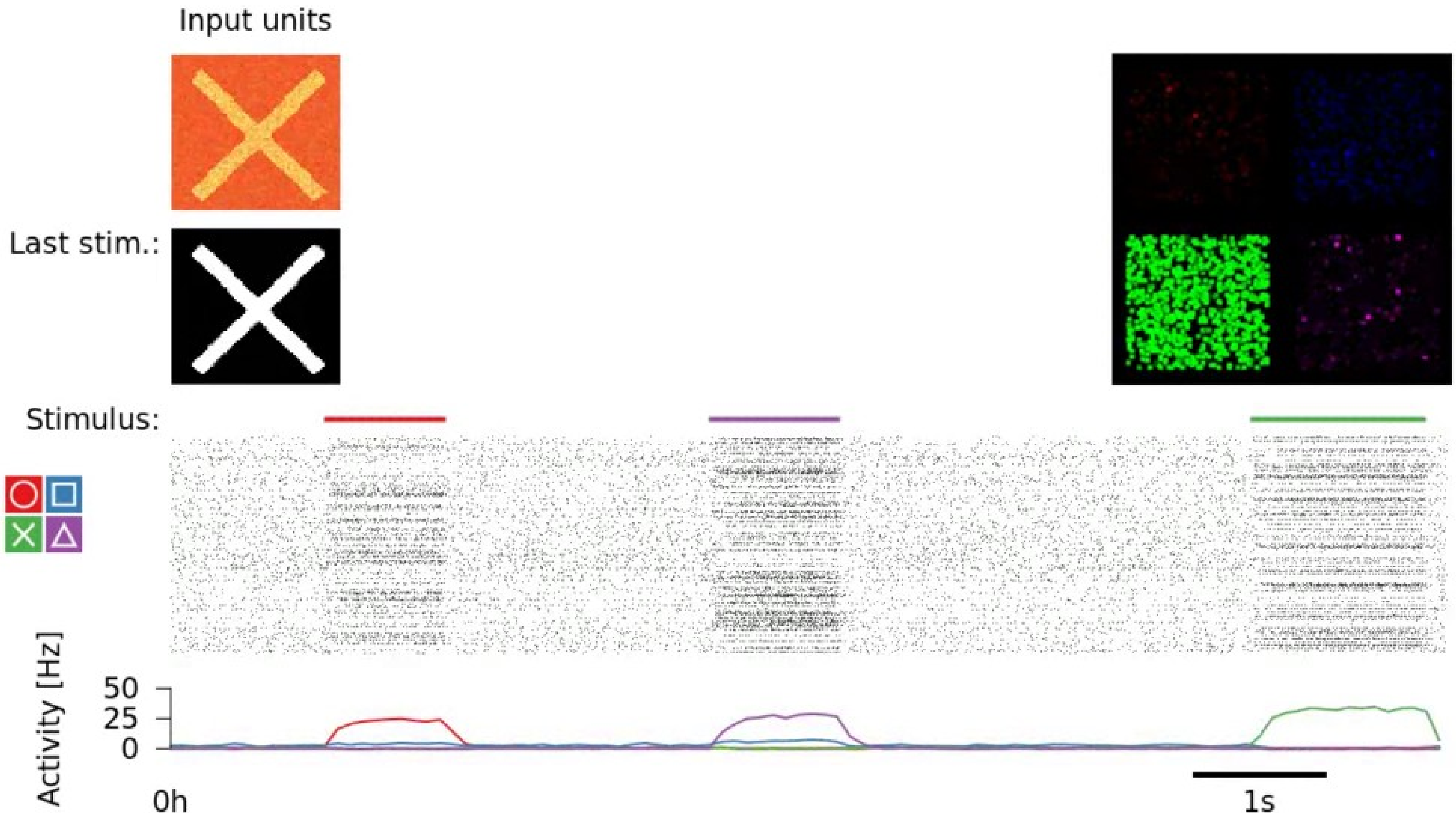
External stimuli



External stimuli



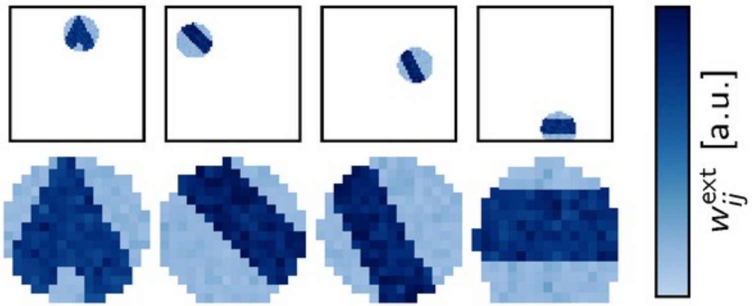
External stimuli



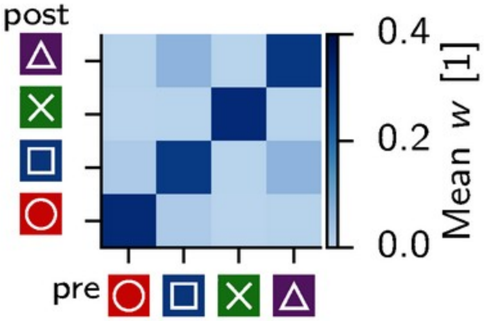
External stimuli

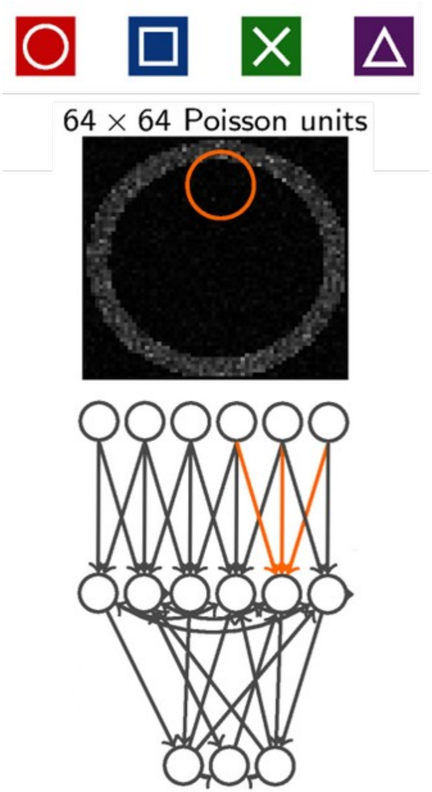
Receptive fields are refined and cell assemblies are formed

Input connections

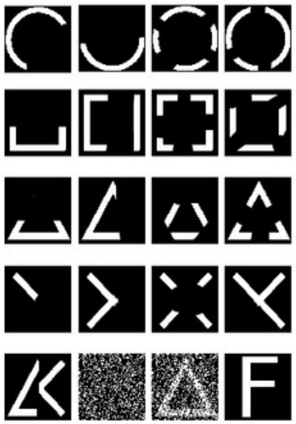


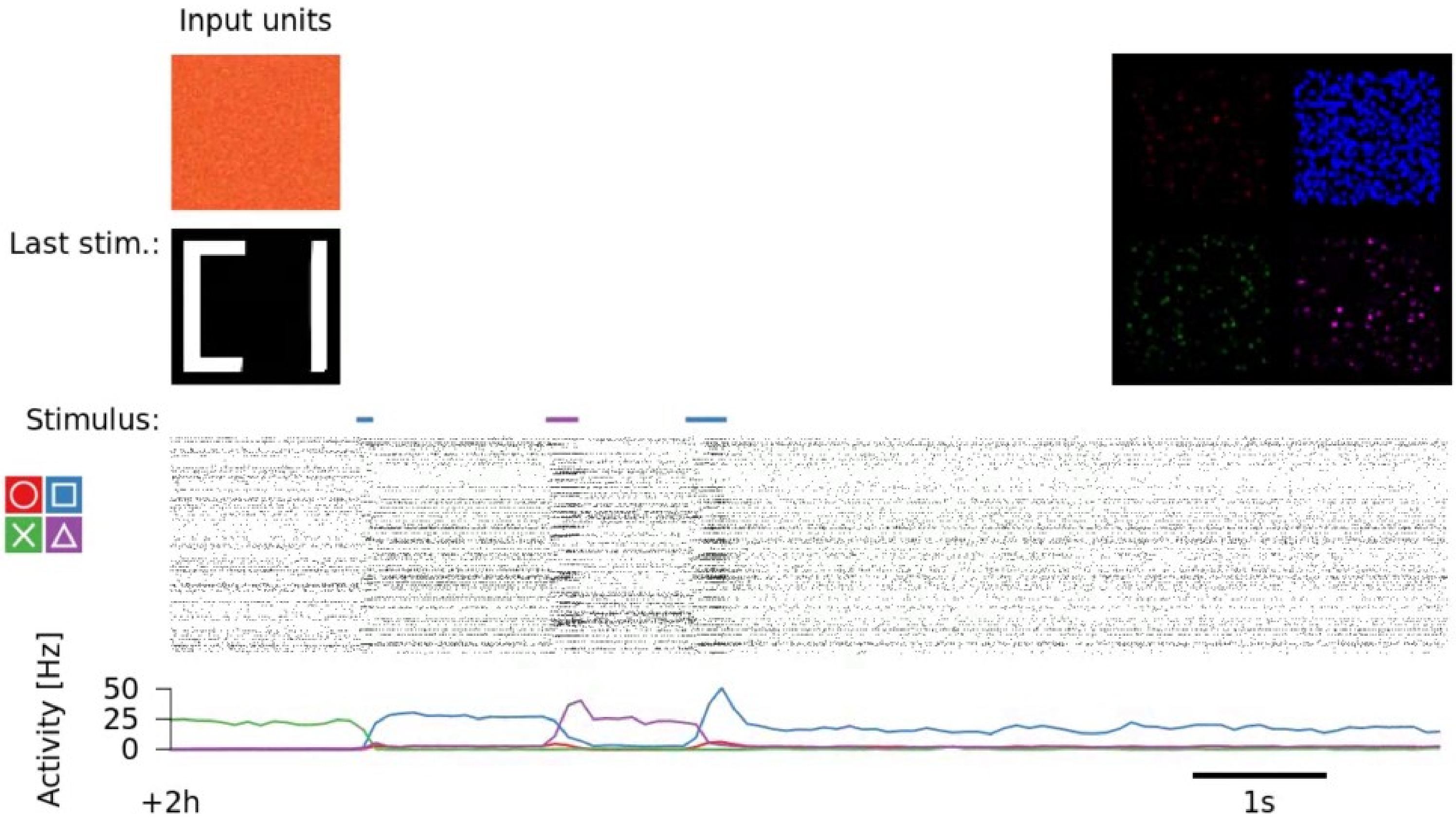
Recurrent connections



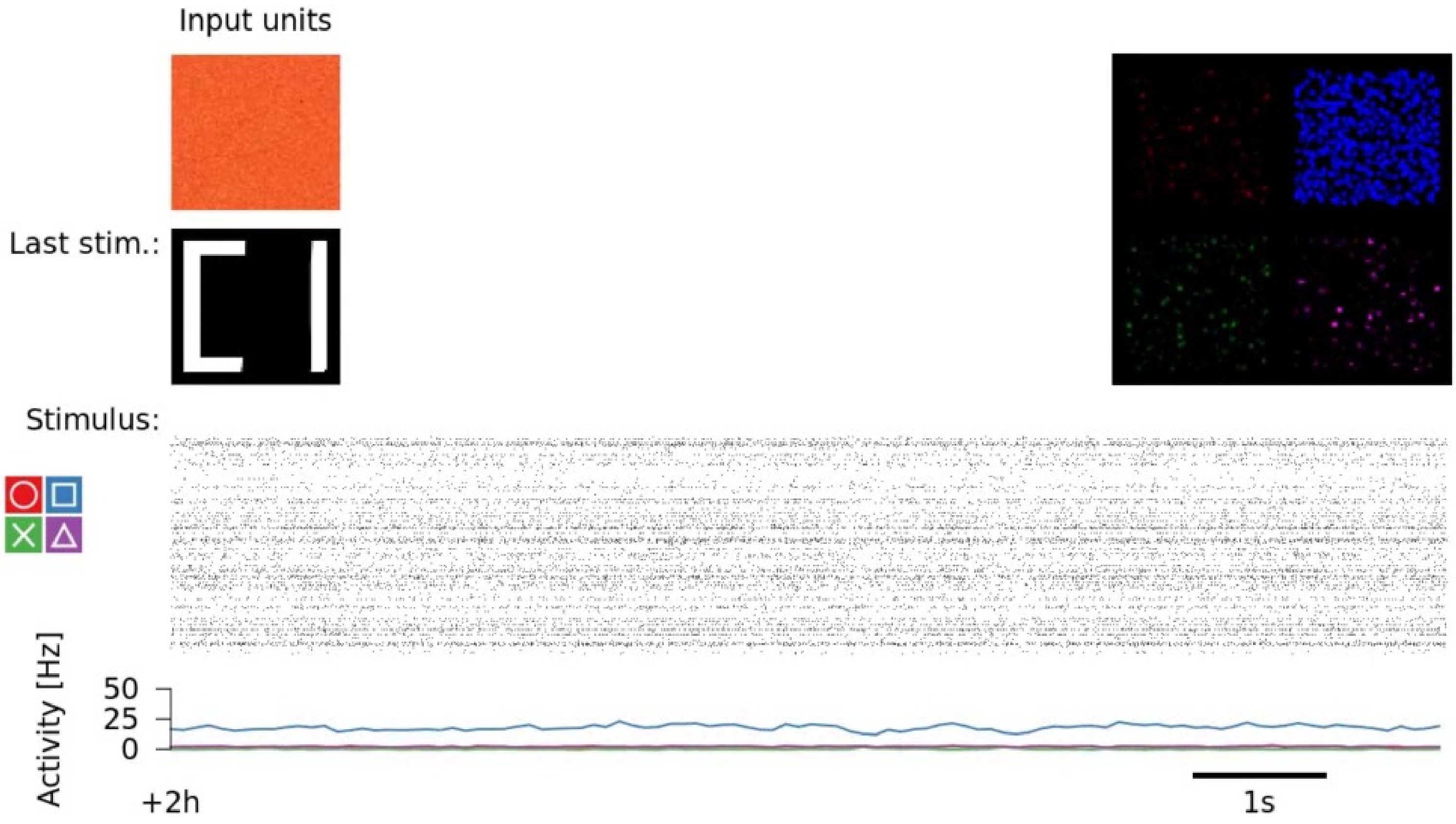


Distorted cues

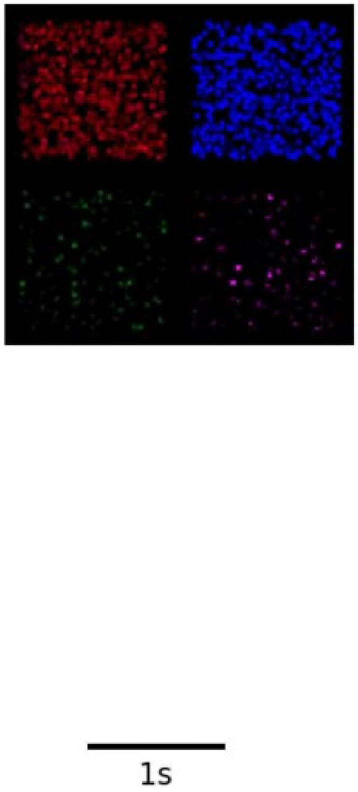




Distorted stimuli & recall (plasticity still active)

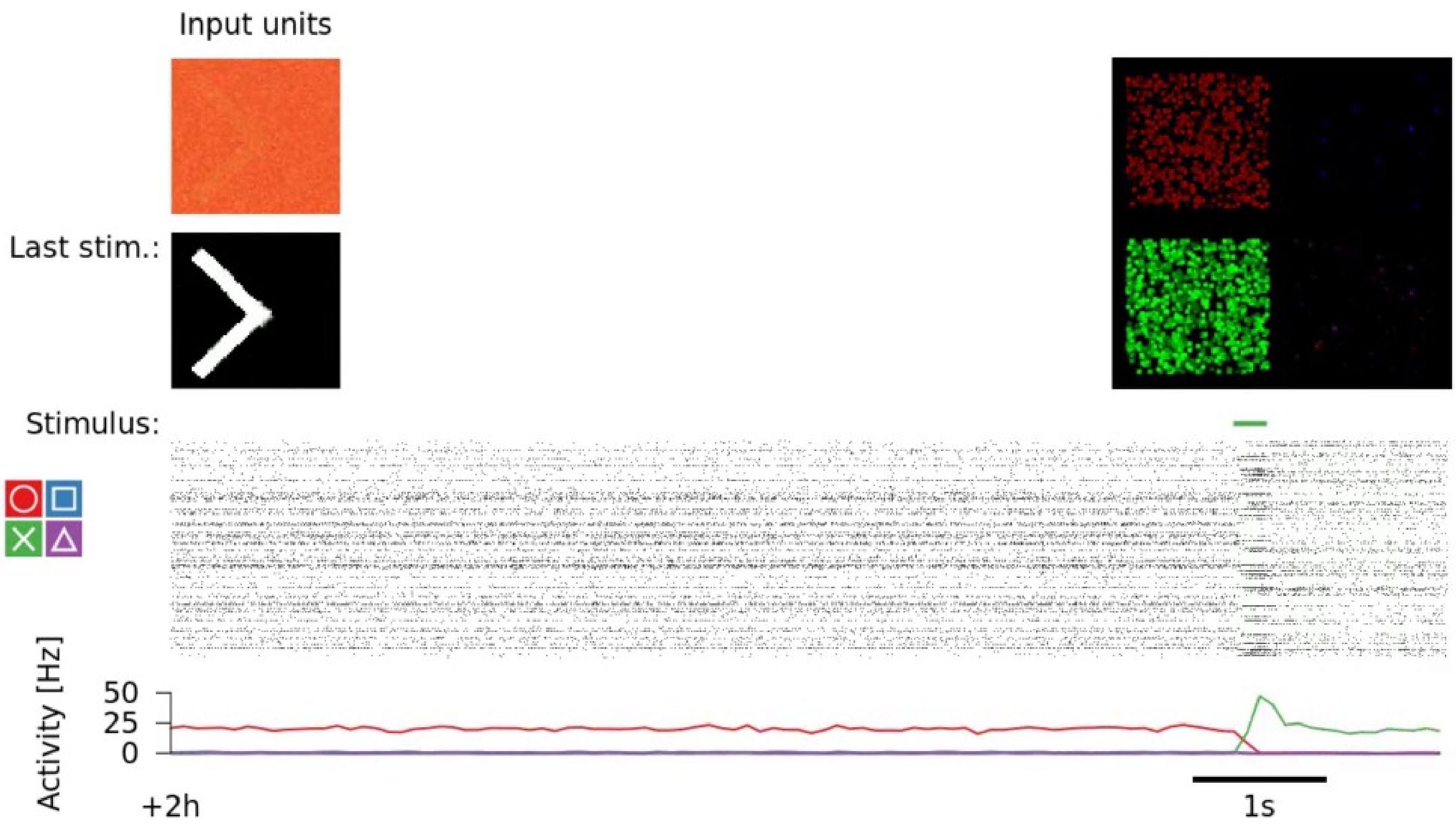


Distorted stimuli & recall (plasticity still active)

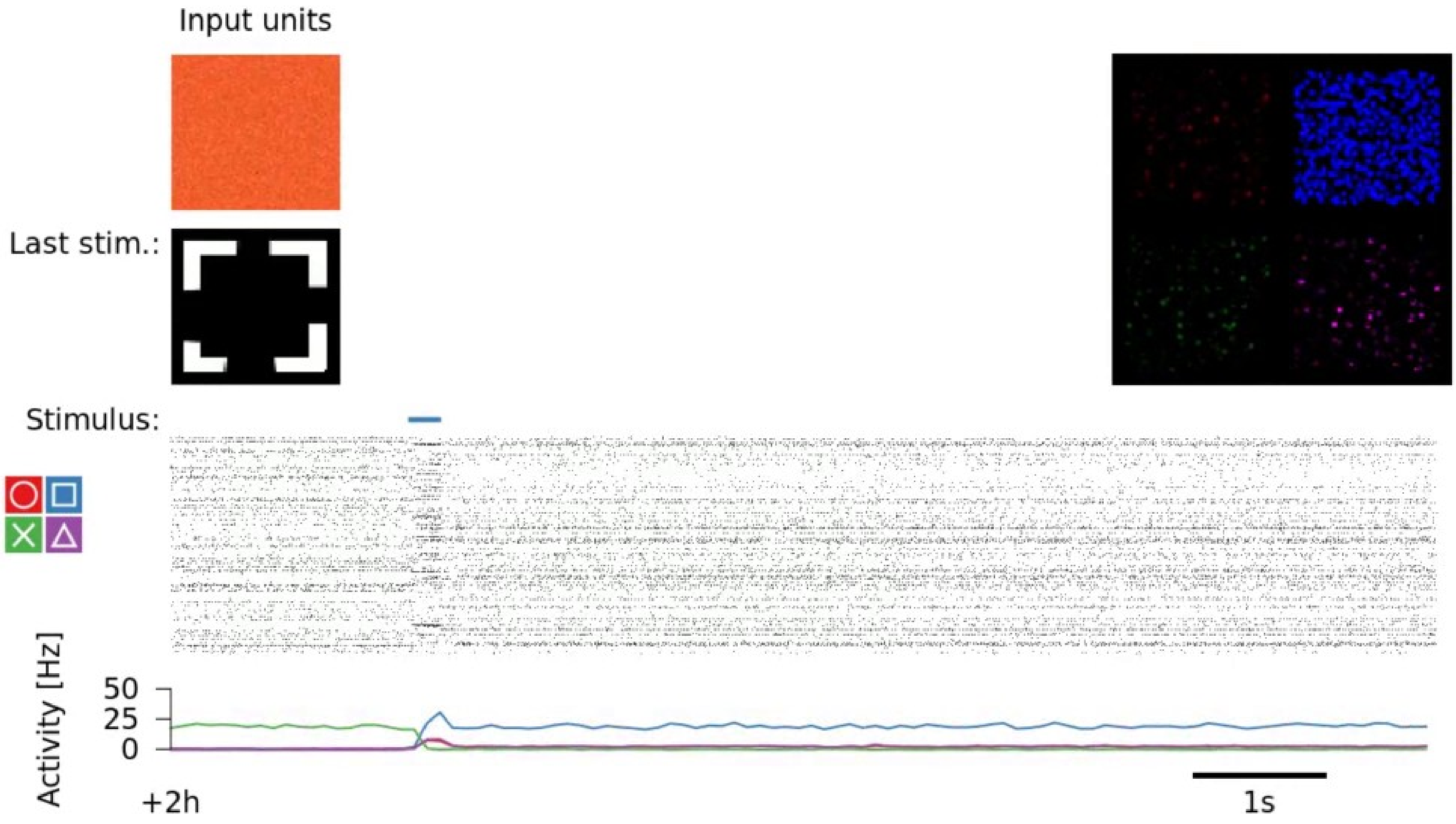


Distorted stimuli & recall (plasticity still active)

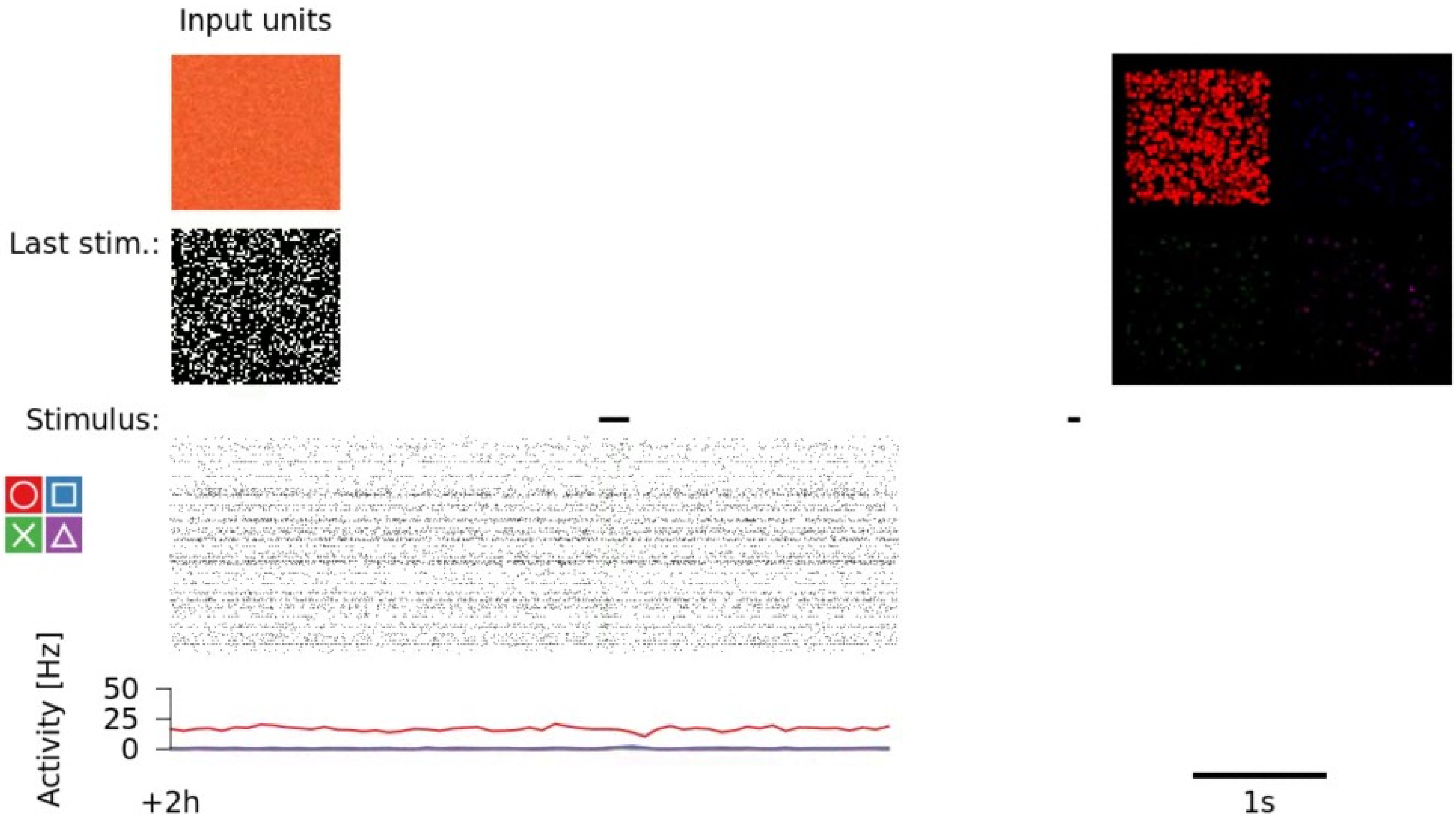
Distorted stimuli & recall (plasticity still active)



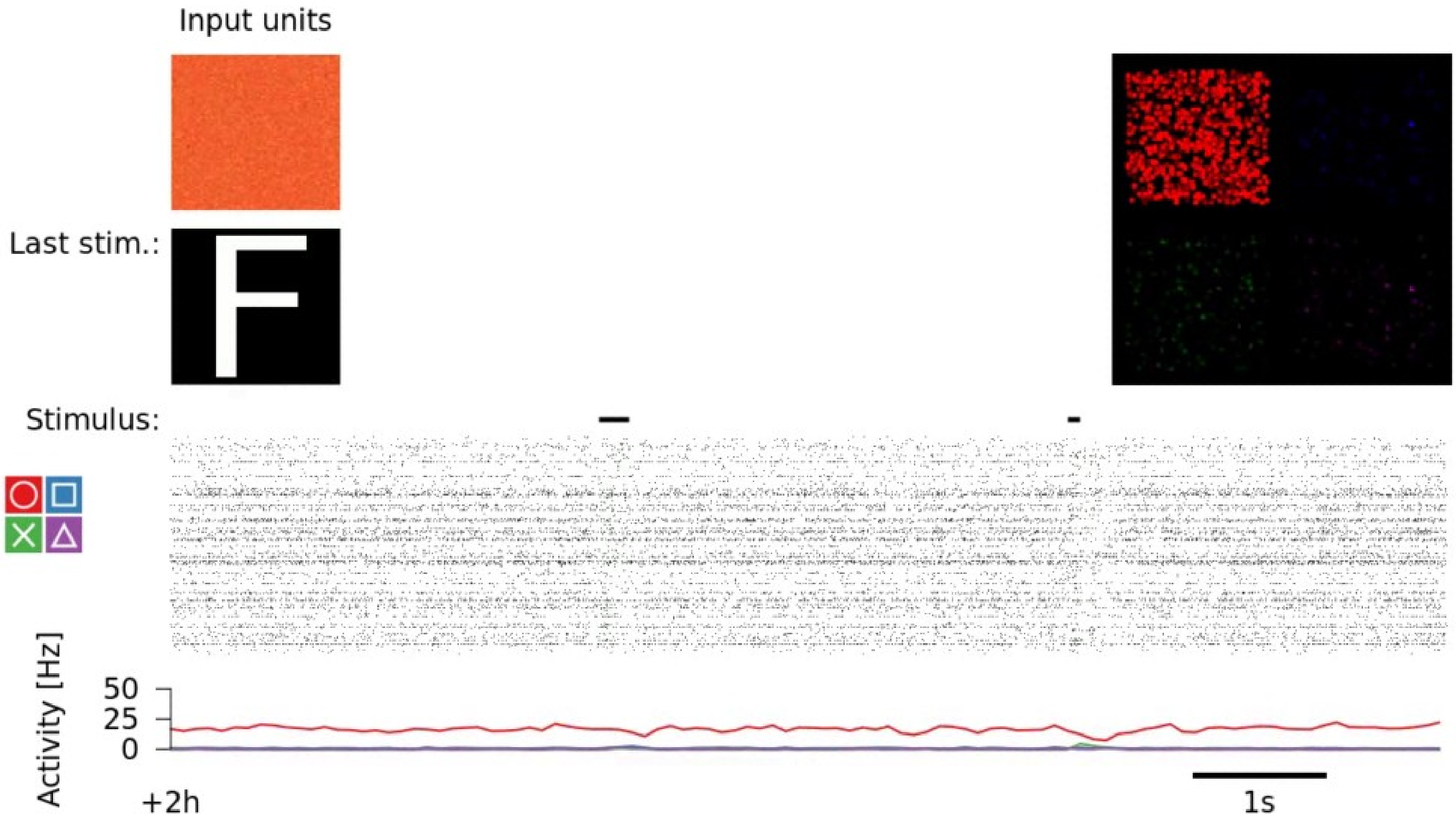
Distorted stimuli & recall (plasticity still active)



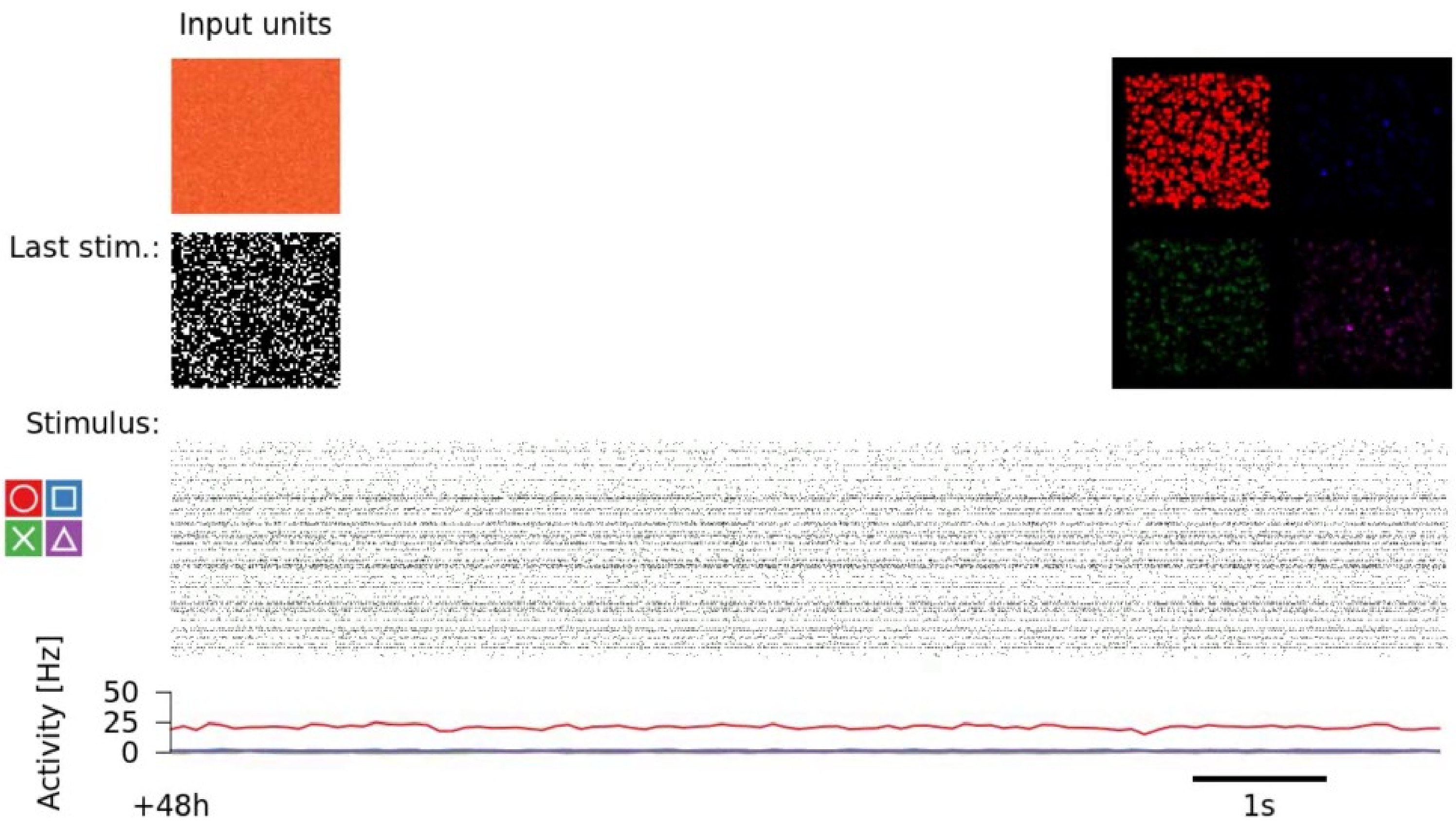
Distorted stimuli & recall (plasticity still active)



Unknown distractors



Unknown distractors



Learned representations stable for days

Summary

- The temporal paradox can be resolved if there are rapid compensatory plasticity mechanisms
- I have shown one example: heterosynaptic plasticity
- Other mechanisms are possible:
  - Inhibitory microcircuits
  - Other forms of metaplasticity
  - …

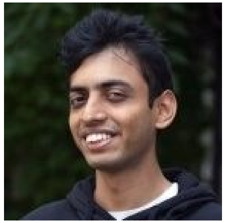
Thanks

INTERNATIONAL FMI PhD PROGRAM


Wulfram

The team https://zenkelab.org/team/


Axel Laborieux


Manu Srinath Halvagal


Julian Rossbroich


Julia Gygax


Peter Buttaroni


Jeremias Seitz


Atena Mohammadi

Zenke Lab est.2019

Funding

Swiss National Science Foundation

Artwork: kyadava.net