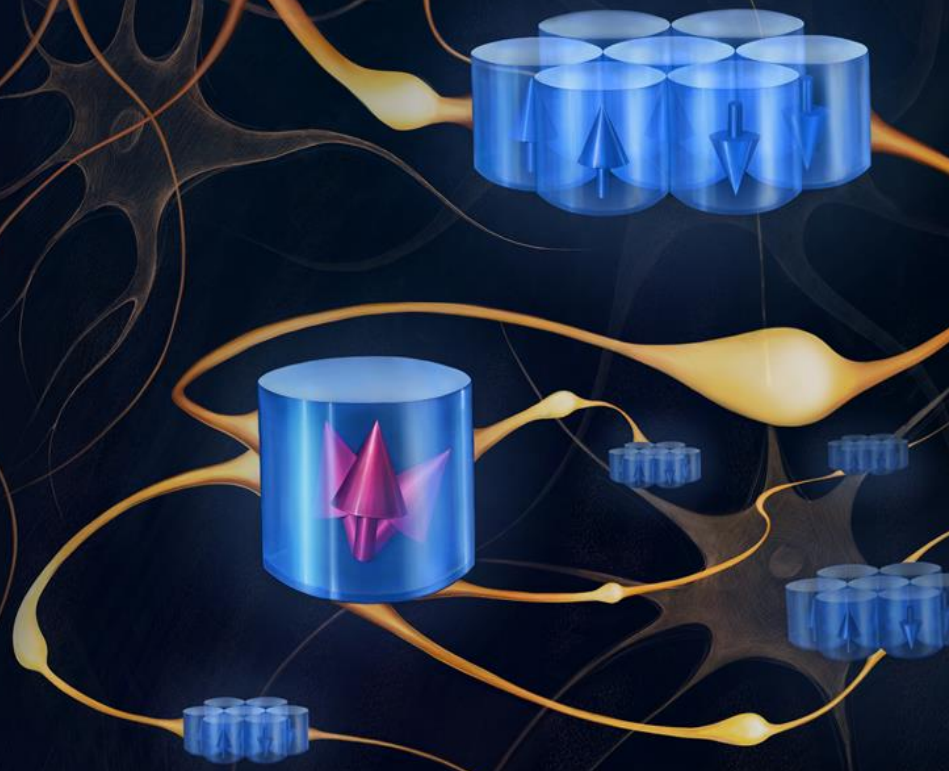
SPICE workshop, Mainz 2019

Antiferromagnet/ferromagnet heterostructures as synapses and neurons

A. Kurenkov[1-3], S. DuttaGupta[1-3], C. Zhang[1,4,5]
S. Fukami[1-3,5,6], Y. Horio[1] and H. Ohno[1-3,5,6]

[1] Laboratory for Nanoelectronics and Spintronics, RIEC,
[2] CSIS, [3] CSRN, [4] FRIS, [5] CIES, [6] WPI-AIMR (Tohoku University)

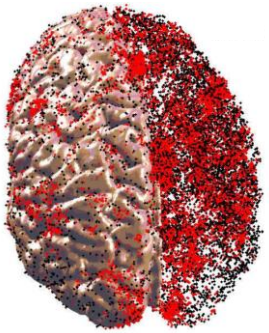


TOHOKU UNIVERSITY

RIEC

CSRN

Spiking neural networks with CMOS



1 million neurons

PNAS 105, 3593 (**2008**)

0.001% of the human brain
1/60th of its speed
3 GHz CPU **x60**

100 billion neurons at full speed

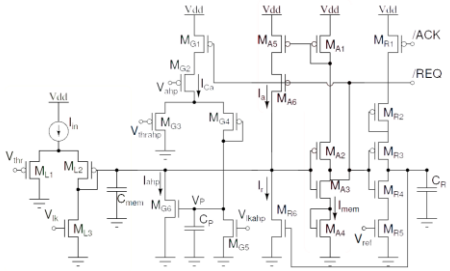
=

$60 \times 10^5 \times 60$

=

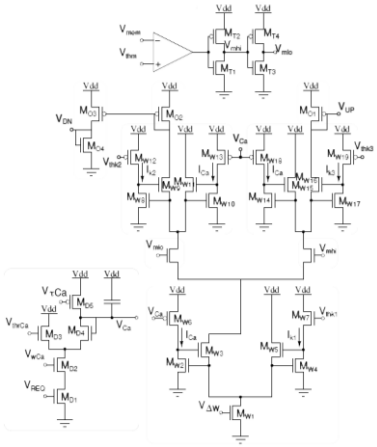
36 million CPUs /

CMOS-based neuron



E. Chicca *et al.*, *Proc. IEEE* 102, 9 (2014)

CMOS-based synapse



10^{11} neurons and 10^{15} synapses

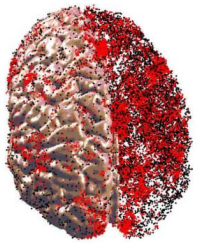
≈

10^{16} transistors

≈

2 million CPUs /

Spiking neural networks with CMOS



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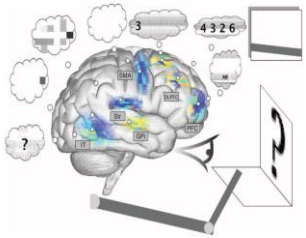
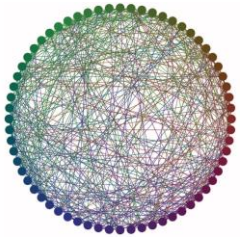
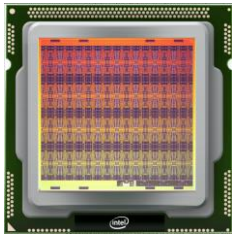


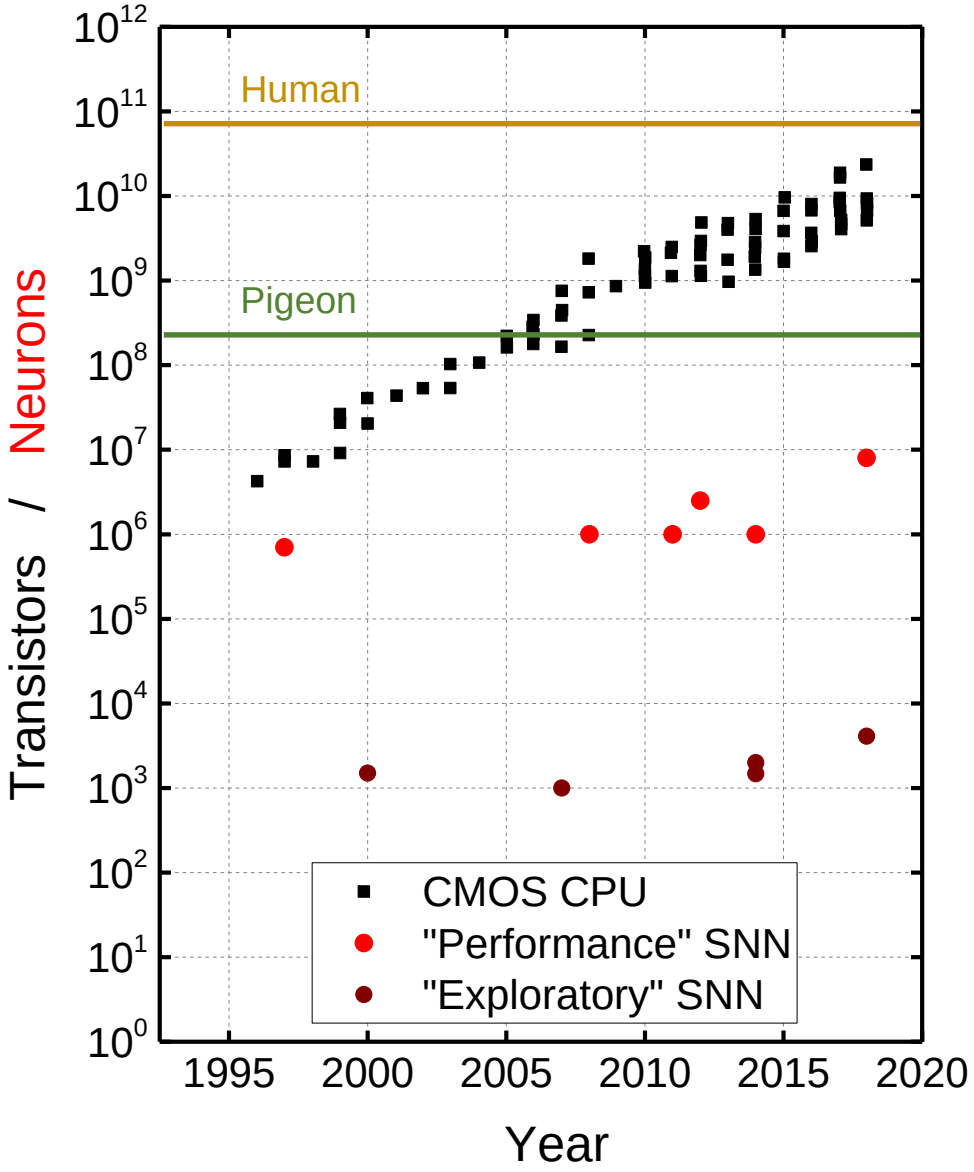
2.5 million neurons
Science 338, 1202 (**2012**)



1 million neurons
Science 345, 6197 (**2014**)
"True North" by IBM



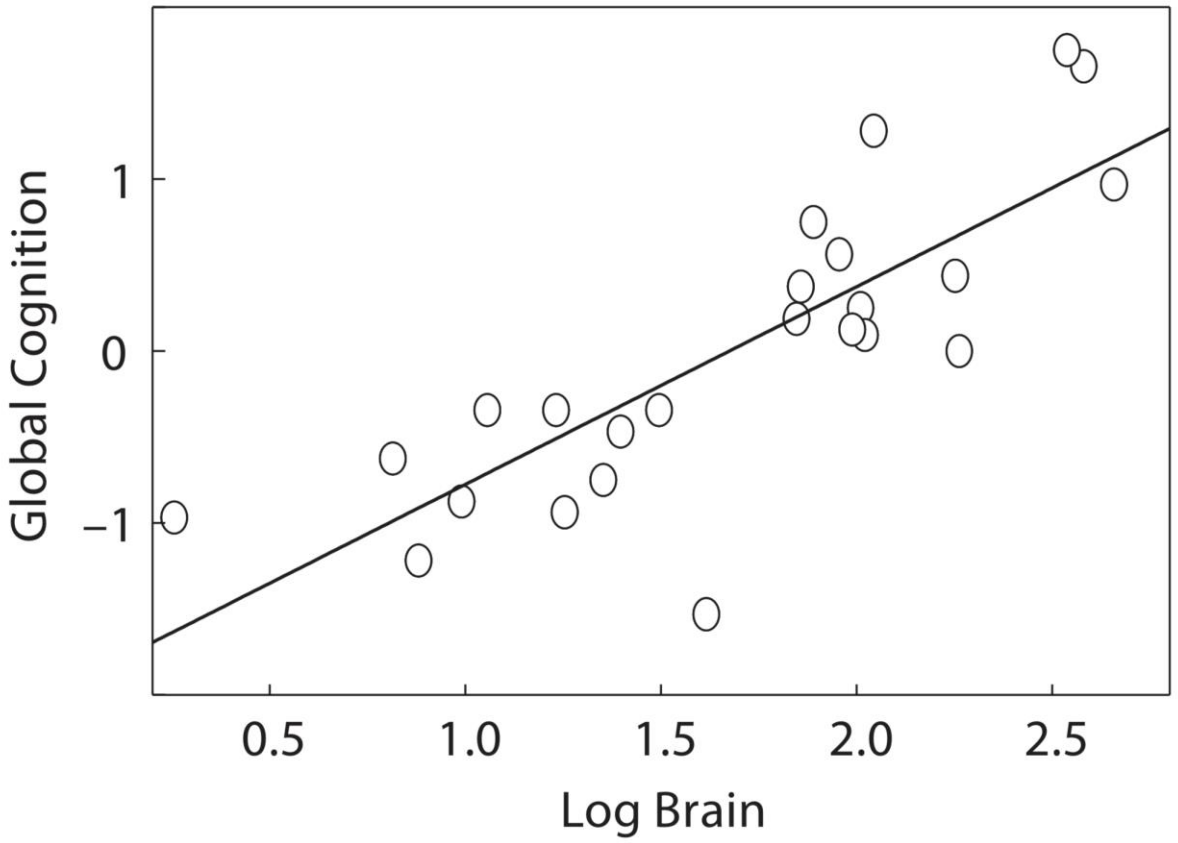
8 million neurons
IEEE Micro, 38, 1 (**2018**)
"Loihi" by Intel



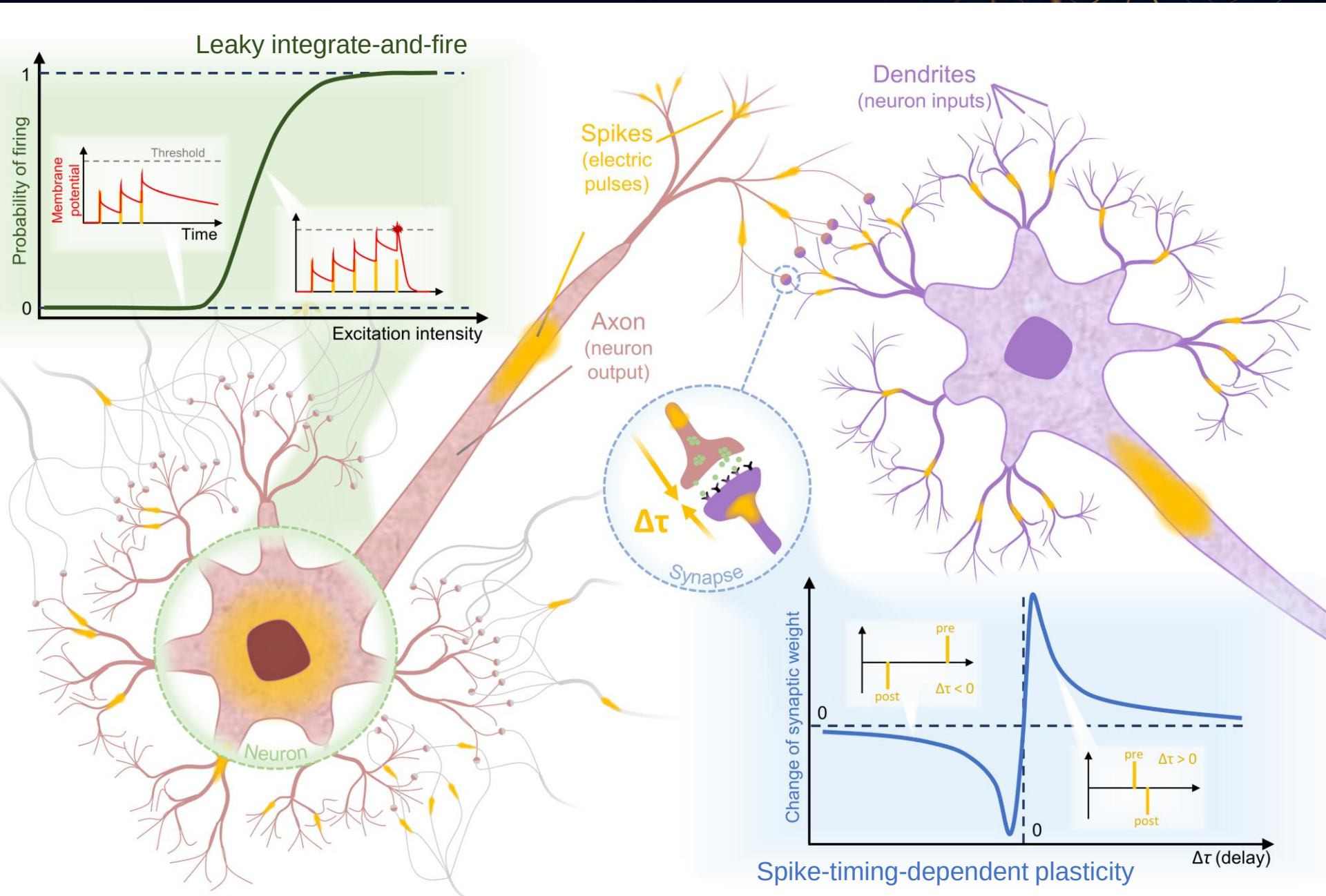
Why bother with number of neurons?

"Overall brain size … best predicts cognitive ability across non-human primates"

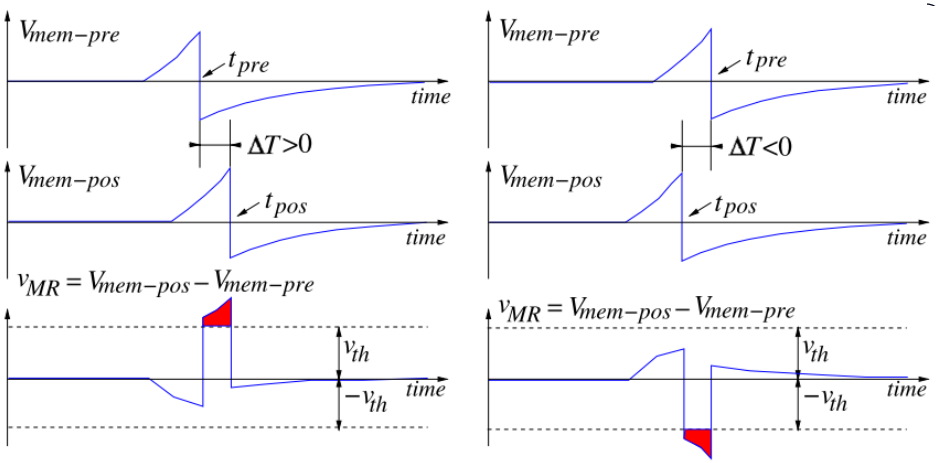
R. O. Deaner *et al., Brain Behav. Evol.* 70, 115 (2007)



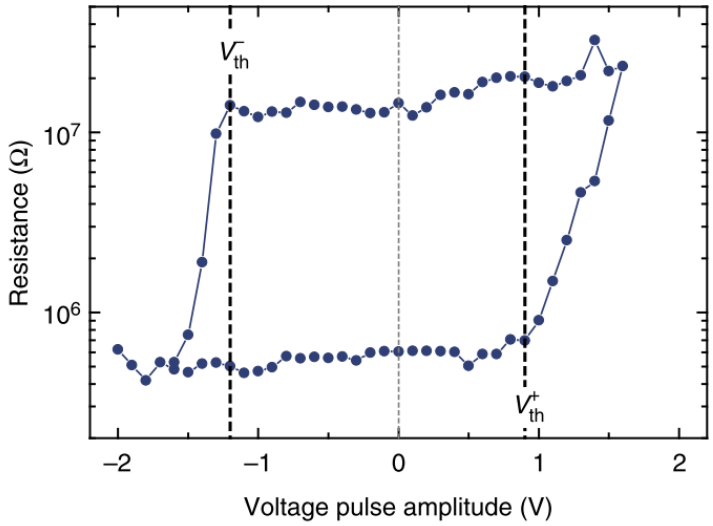
What properties are we seeking?



New material approaches

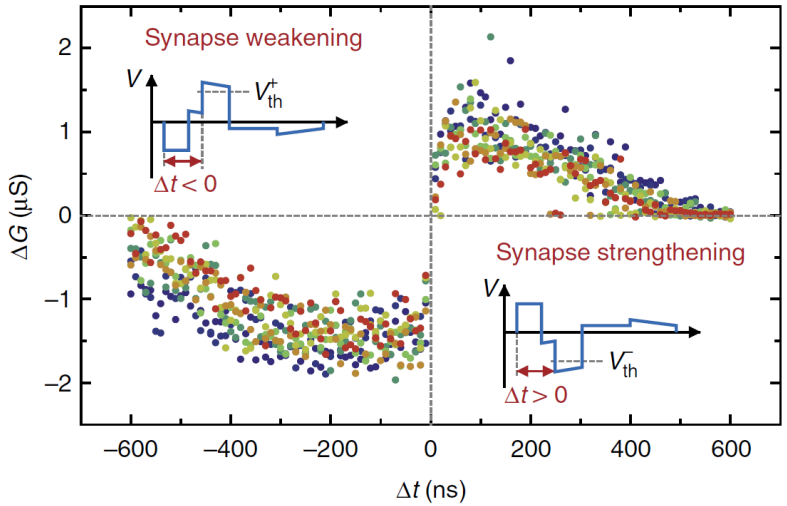


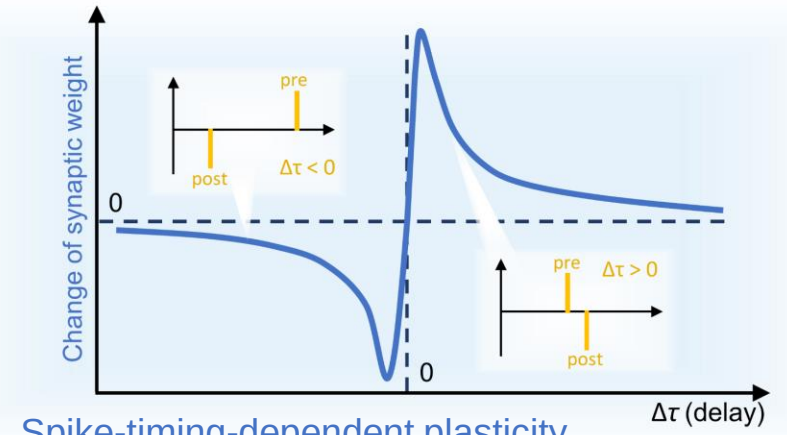
C. Zamarreno-Rames *et al., Front. Neurosci.* 5, 26 (2011)



Ferroelectric cell

S. Boyn *et al., Nat. Commun.* 8, 14736 (2017)

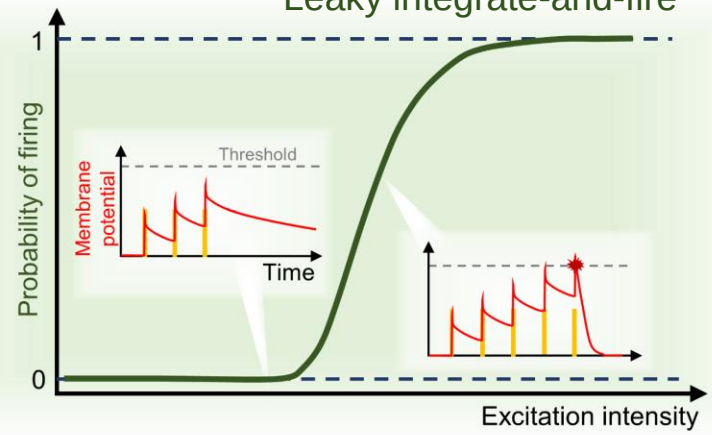




Spike-timing-dependent plasticity

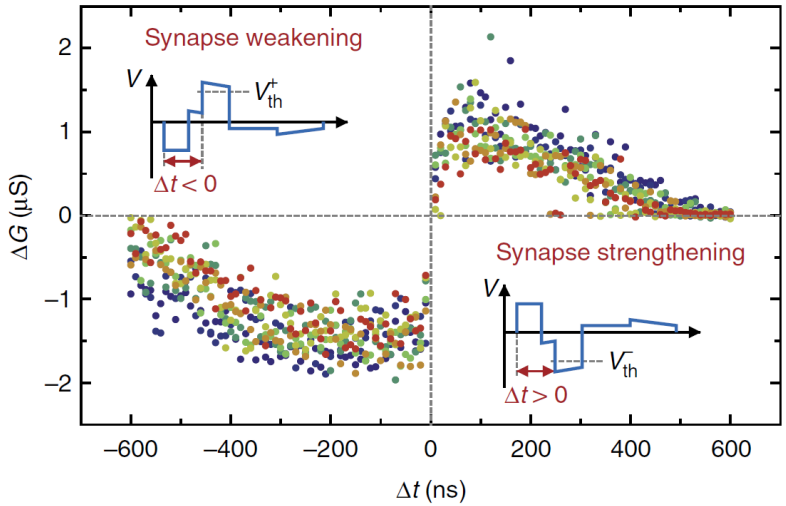
New material approaches

Leaky integrate-and-fire



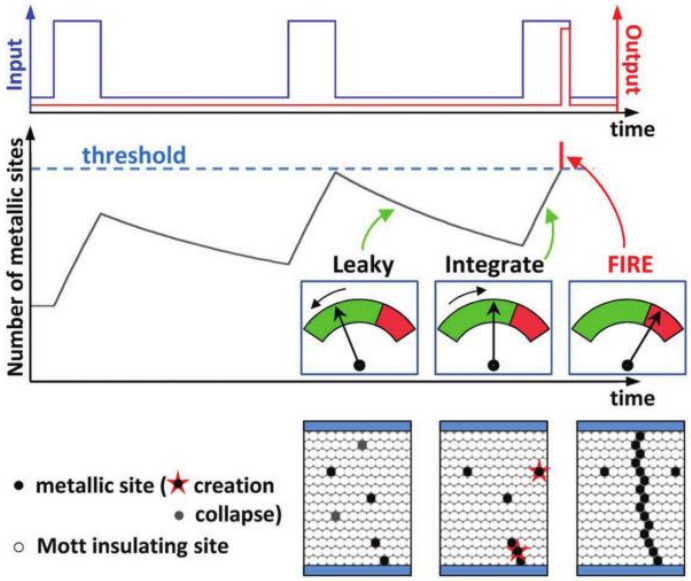
Ferroelectric cell

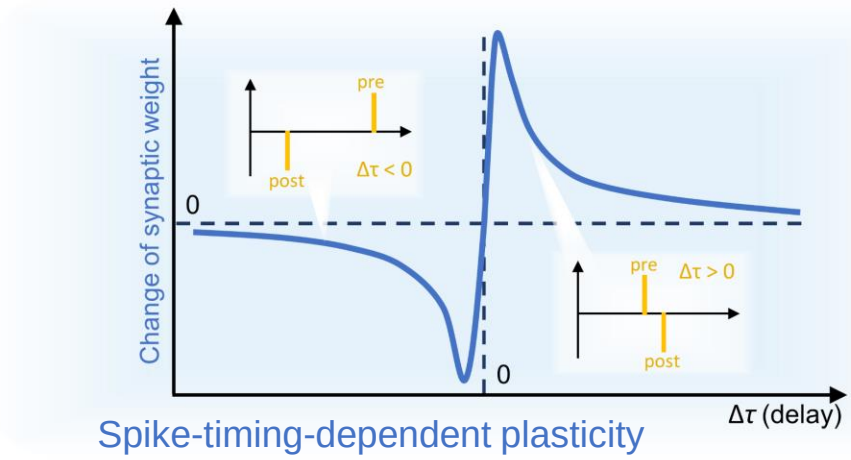
S. Boyn *et al., Nat. Commun.* 8, 14736 (2017)



Mott insulator

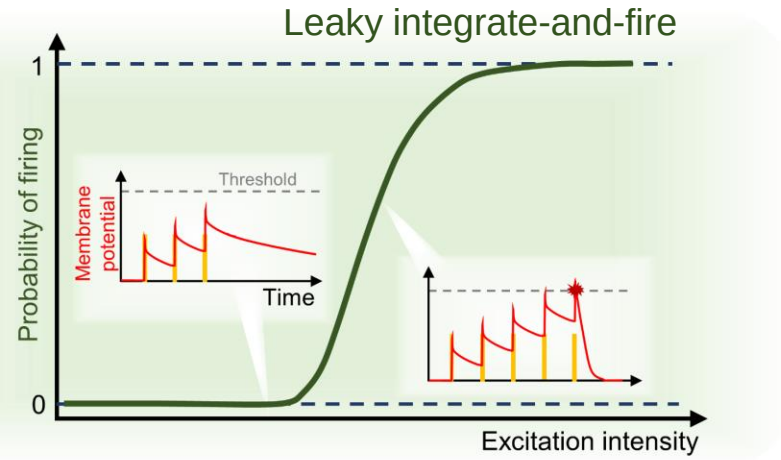
P. Stoliar *et al., Adv. Funct. Mater.* 27, 11 (2017)





Spike-timing-dependent plasticity

New material approaches



S. Boyn *et al., Nat. Commun.* 8, 14736 (2017)

[Ferroelectric tunnel junction]

P. Krzysteczko *et al.*, *Adv. Mater*. 24, 762 (2012)

[Magnetic tunnel junction]

Y.-F. Wang *et al., Sci. Rep.* 5, 10150 (2015)

[Resistive]

D. Kuzum *et al., Nano Lett.* 12, 2179 (2012)

Y. Li *et al.*, *Sci. Rep.*3, 1619 (2013)

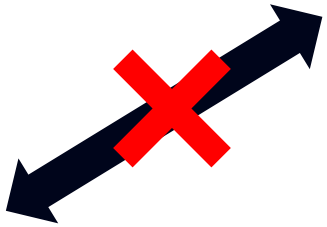
[Phase-change]

F. Alibart *et al.*, *Adv. Funct. Mater.* 22, 609 (2012)

[Hybrid organic-nanoparticle]

M. T. Sharbati *et al., Adv. Mater.* 30, 1802353 (2018)

[Graphene]



P. Stoliar *et al., Adv. Funct. Mater.* 27, 11 (2017)

Pickett *et al., Nat. Mater.* 12, 114 (2013)

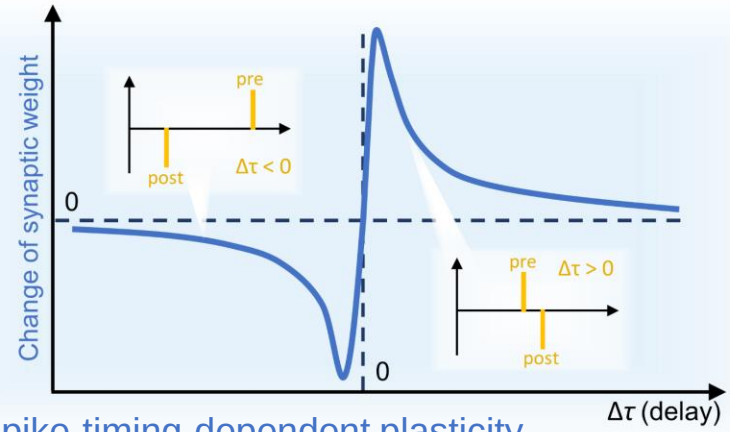
H. Lim *et al. Sci. Rep.* 5, 9776 (2015)

[Mott insulators]

S. Dutta *et al.*, *Sci. Rep.* 7, 8257 (2017)

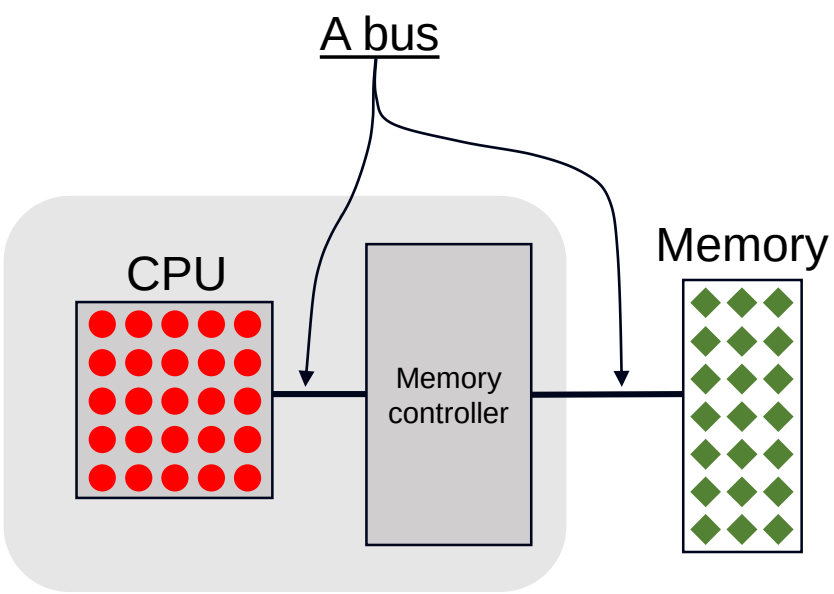
Z. Wang *et al., Proc. Int. Electron Devices Meeting (IEDM)* p. 13.3.1 (2018)

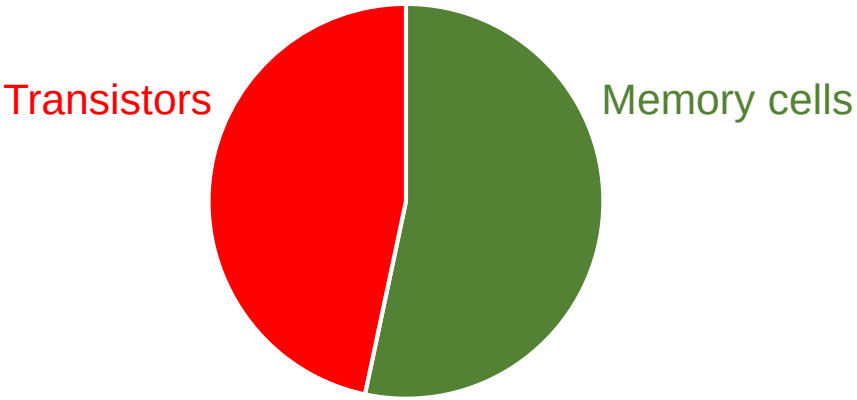
[MOSFET / CMOS]

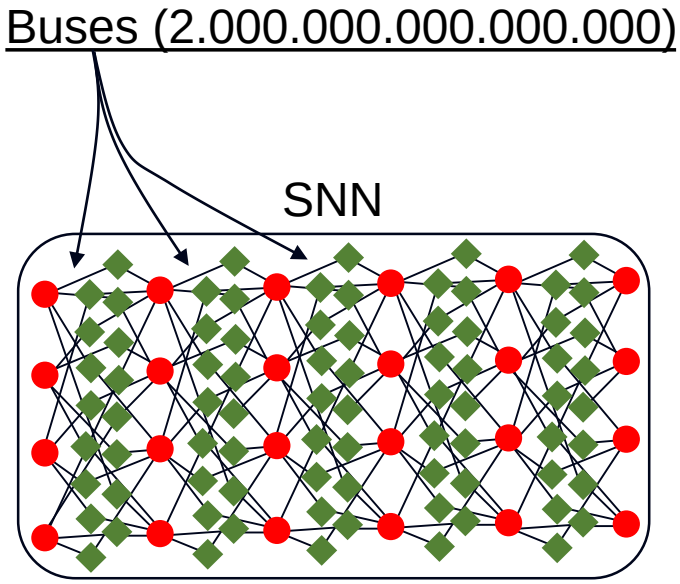


Spike-timing-dependent plasticity

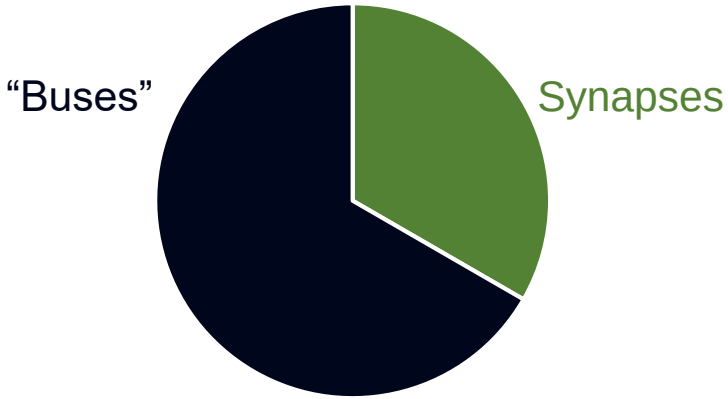
The problem of uniformity





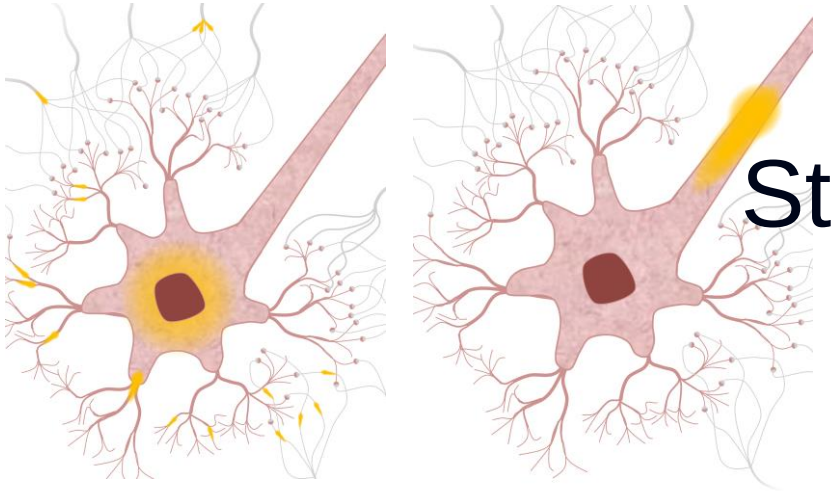


Equal to 285.000 Intel i9 CPUs assuming
single-transistor converters

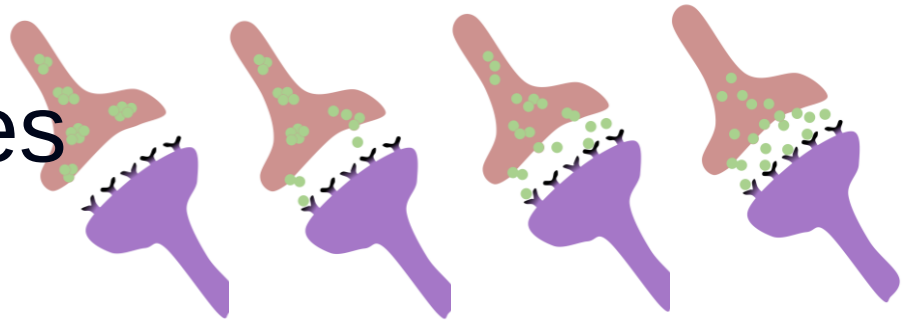


States and Rules

Binary

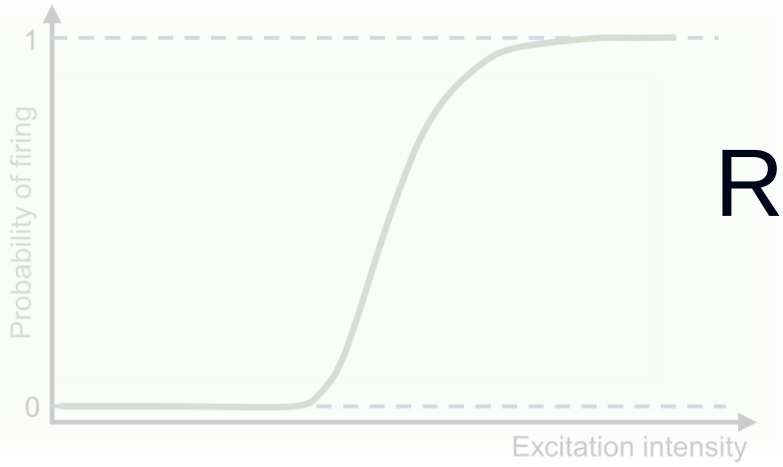


Memristive



States

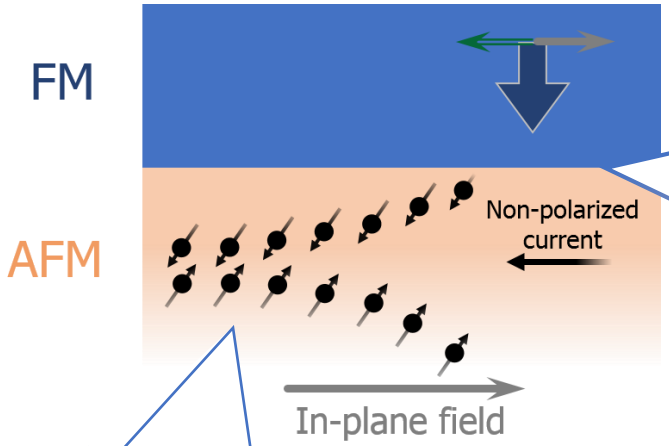
Leaky integrate-and-fire

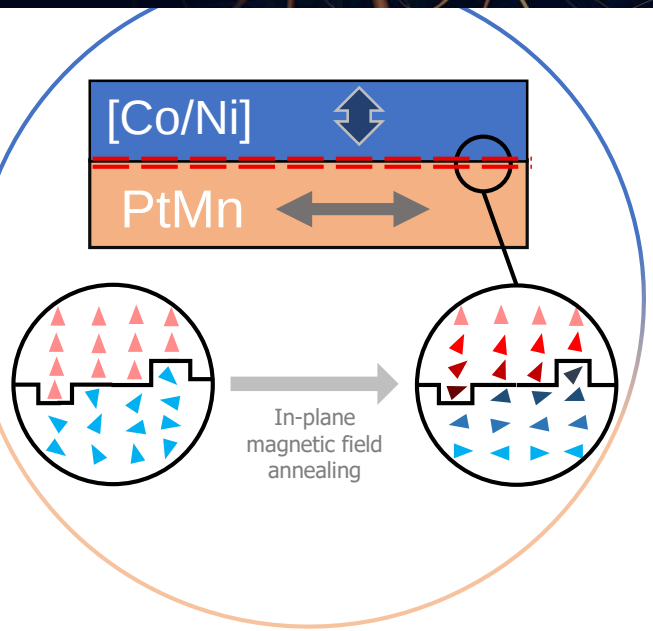


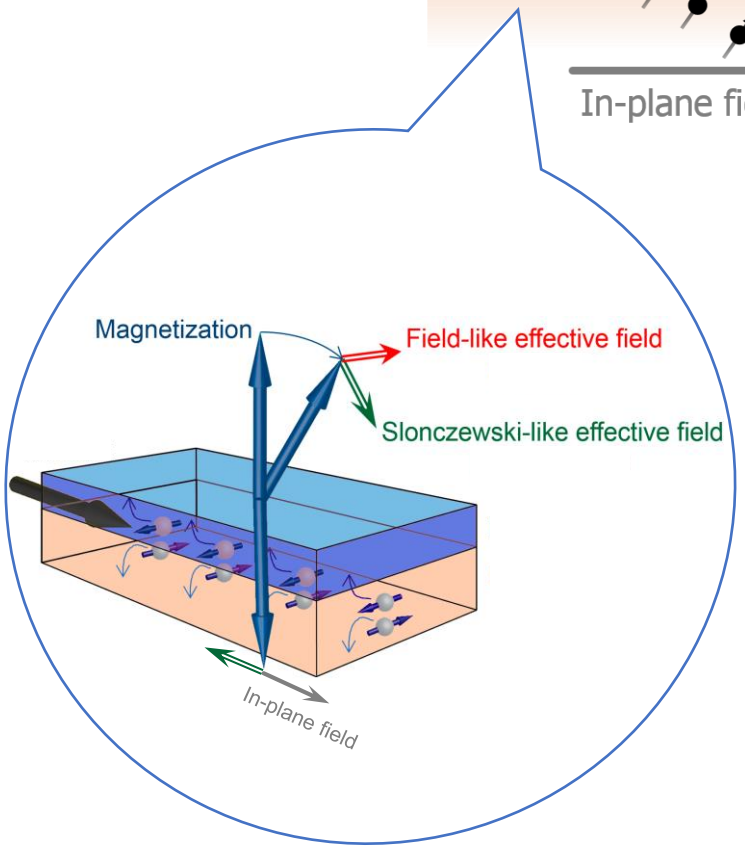
Spike-timing-dependent plasticity

Rules

Material system

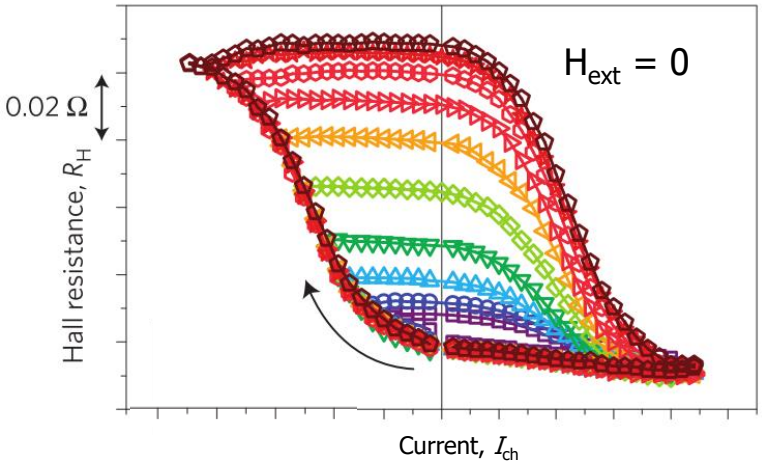




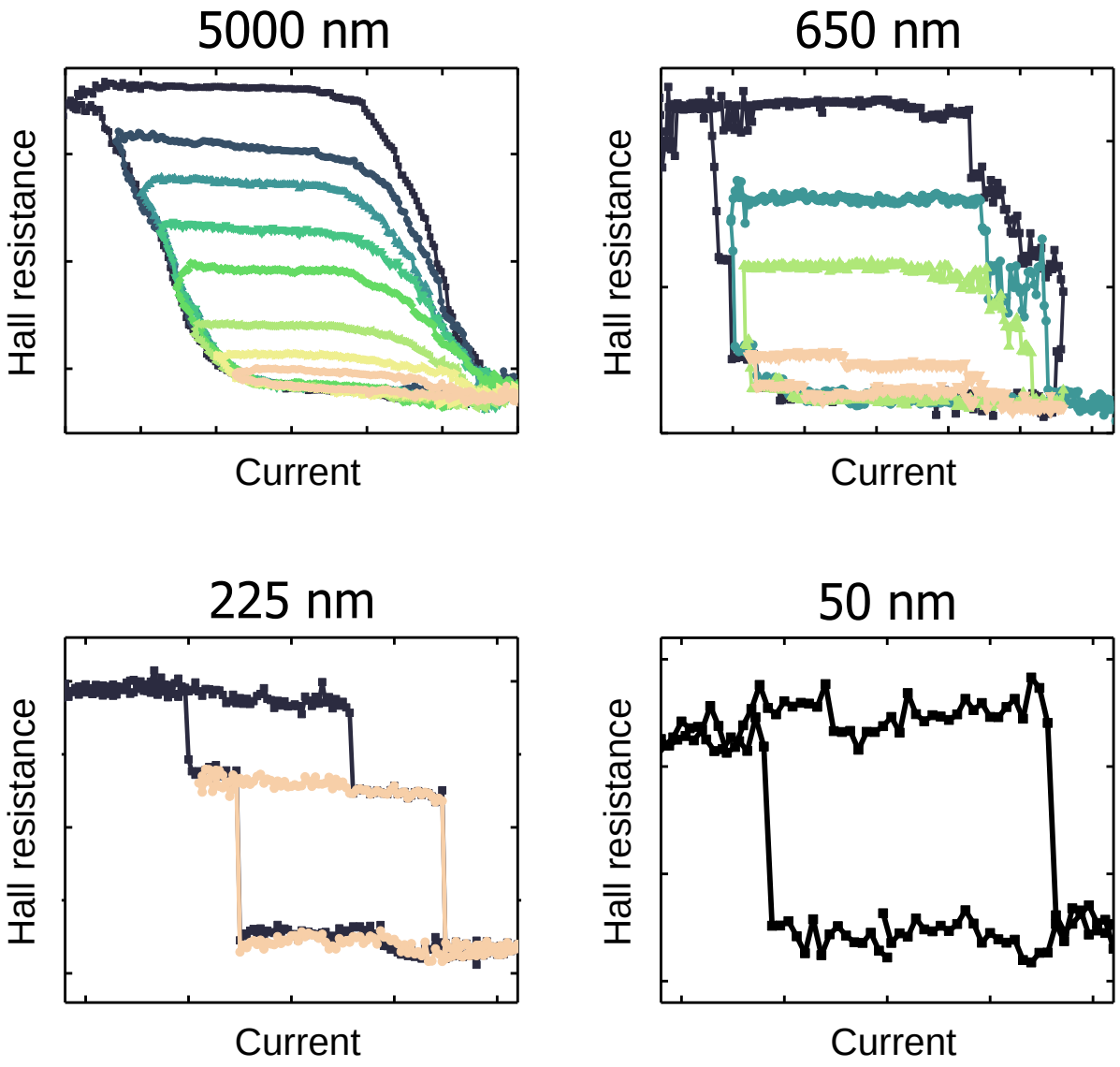


Field-free SOT switching

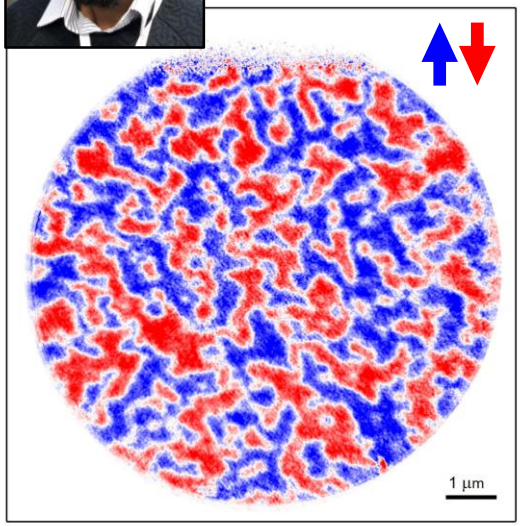
S. Fukami, A. K. *et al. Nat. Mater.* **15**, 535 (2016)



Size-dependent SOT switching



Poster by Gunasheel Krishnaswamy

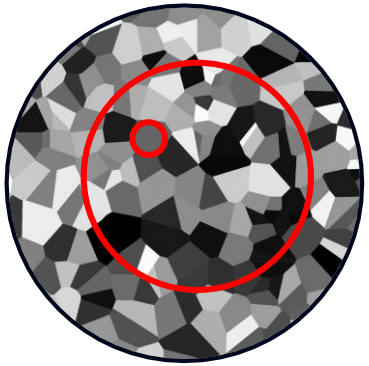


In collaboration with M. Baumgartner, G. Sala, G. Krishnaswamy, P. Gambardella [ETH Zurich, Switzerland] and F. Maccherozzi, S. S. Dhesi [Diamond Light Source, UK]

Measured at Diamond Light Sourcce (UK) end-station I06

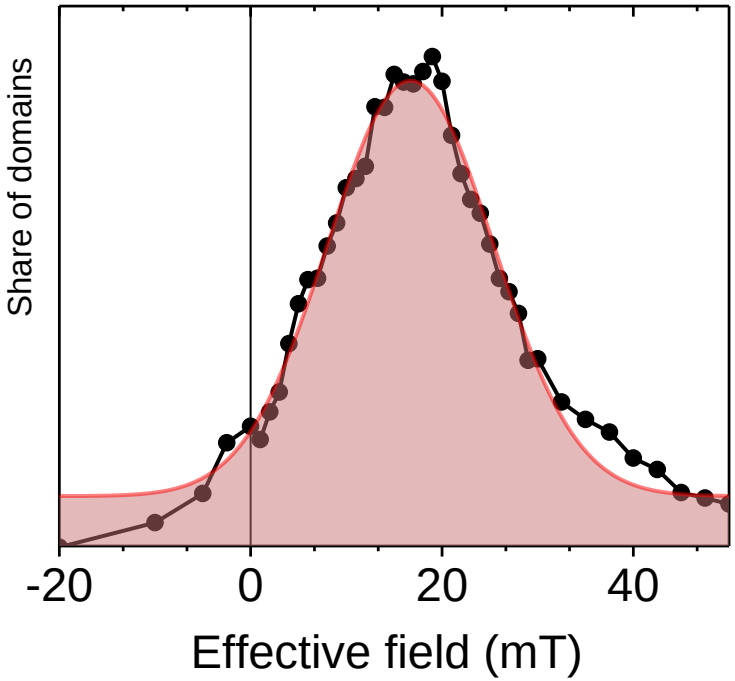
A. Kurenkov *et al., Appl. Phys. Lett.* 110, 092410 (2017)

Size-dependent SOT switching

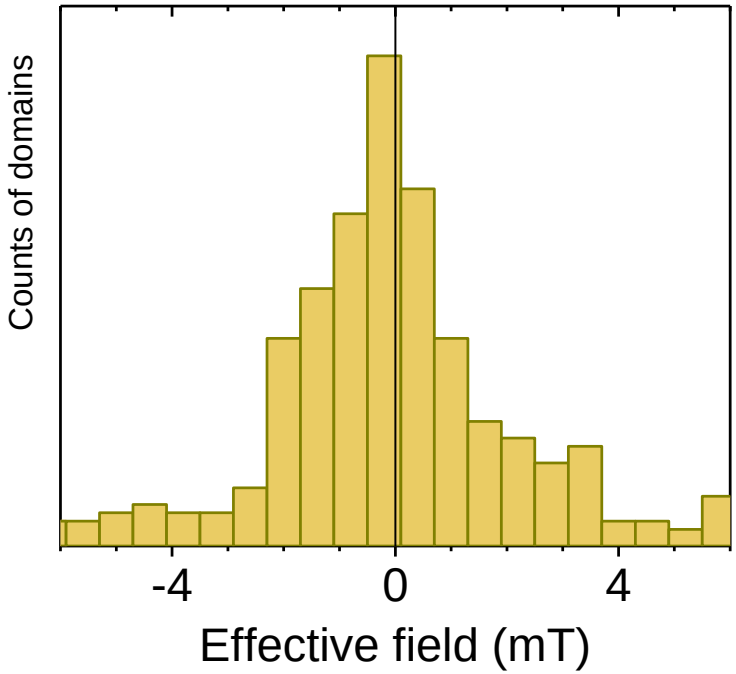


Variation of exchange bias

In-plane component



Out-of-plane component



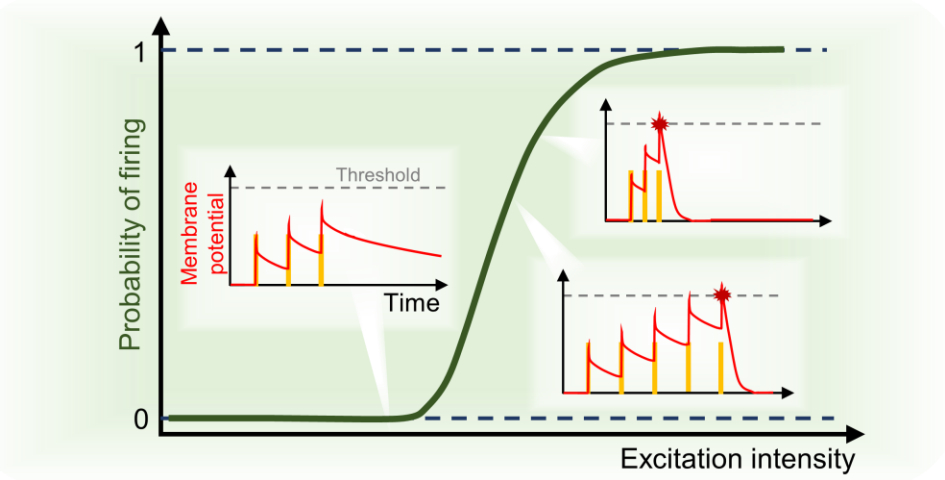
A. Kurenkov *et al., Appl. Phys. Lett.* 110, 092410 (2017)

Rules: local time

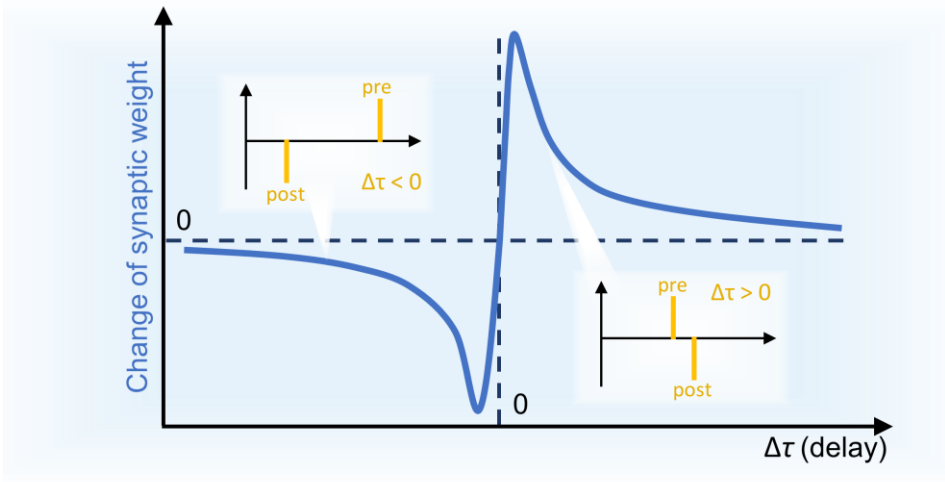
Binary

Memristive

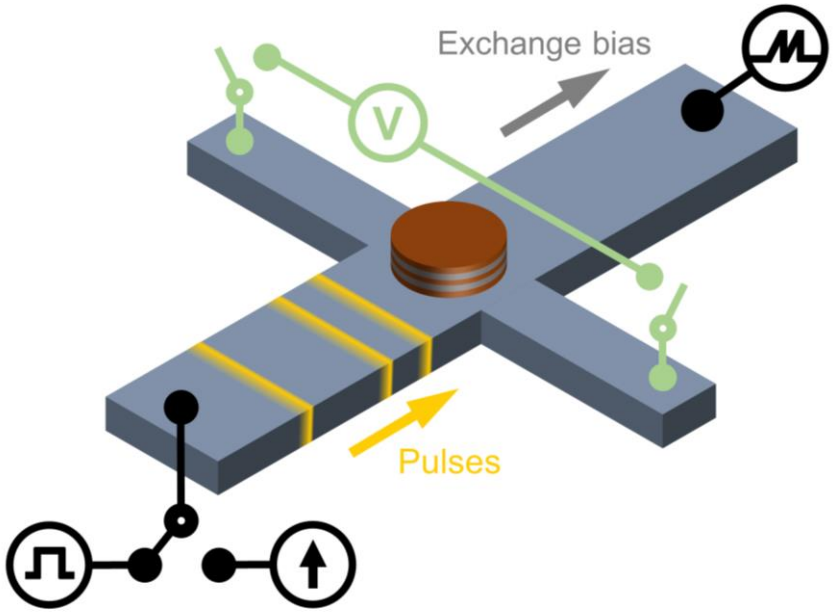
Leaky integrate-and-fire

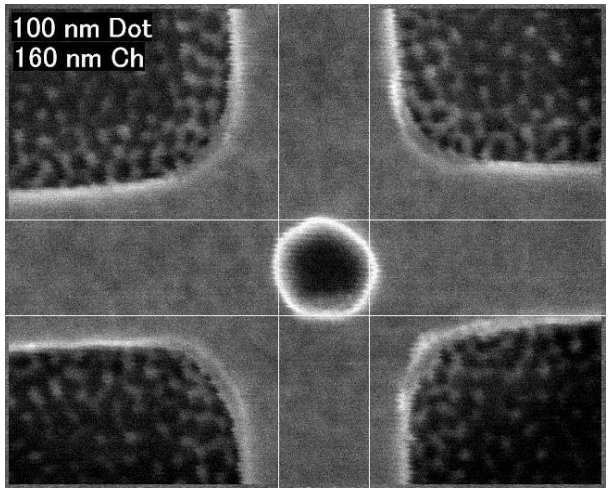


Spike-timing-dependent plasticity

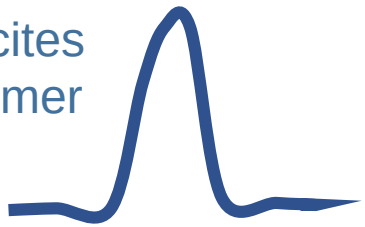


Local time

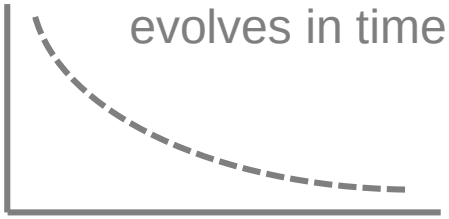


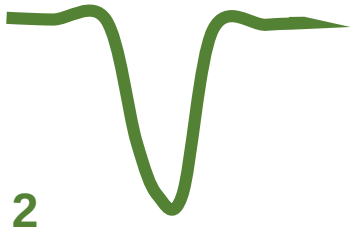


Pulse 1
excites
a timer



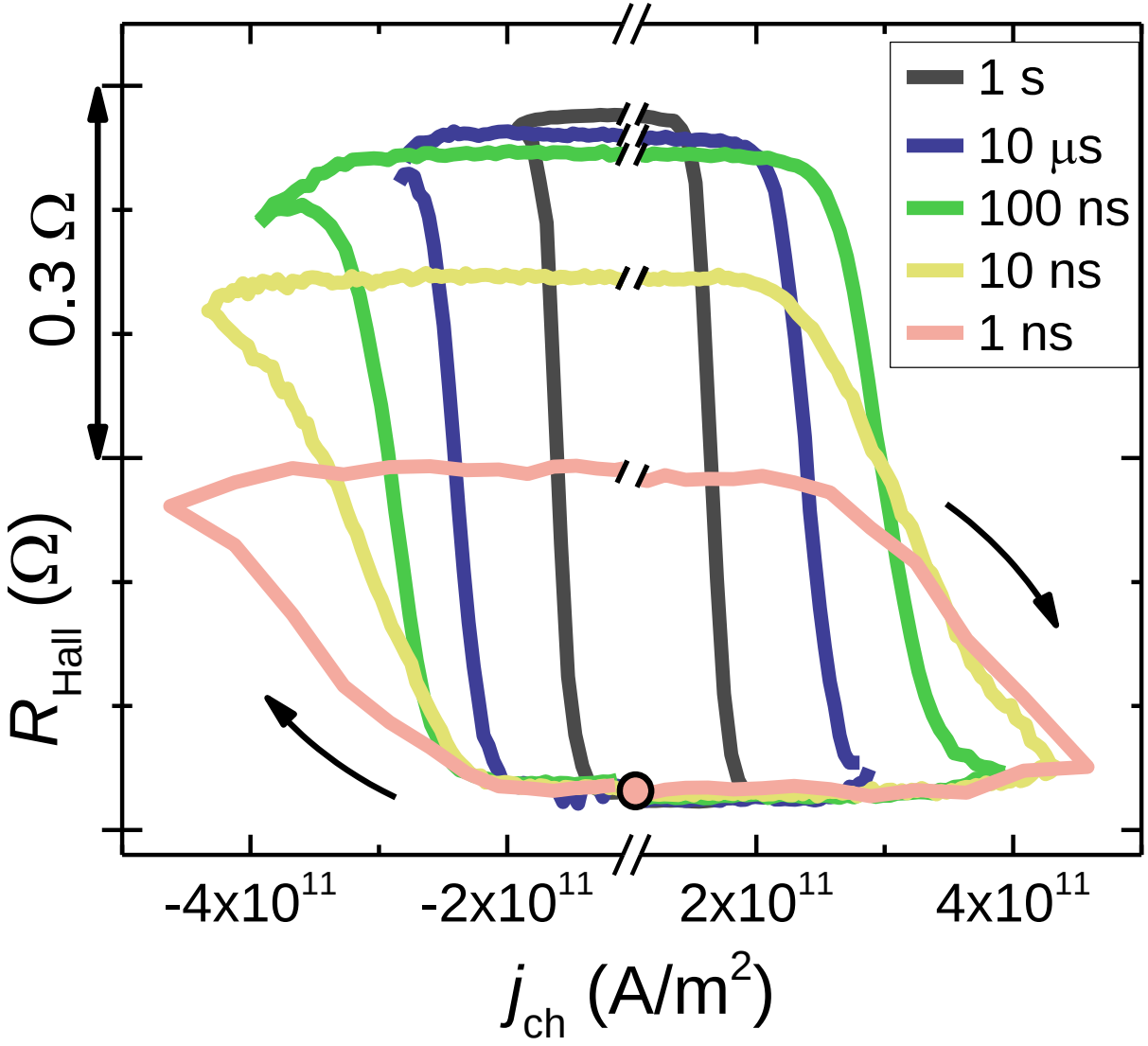
Timer
evolves in time



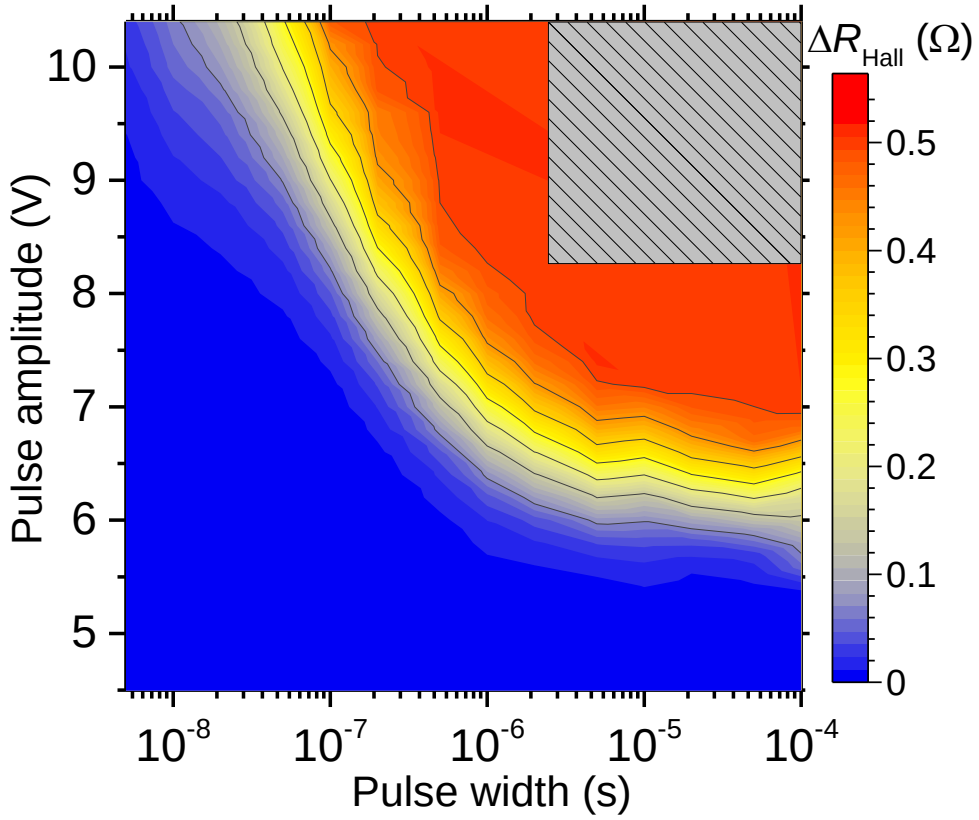


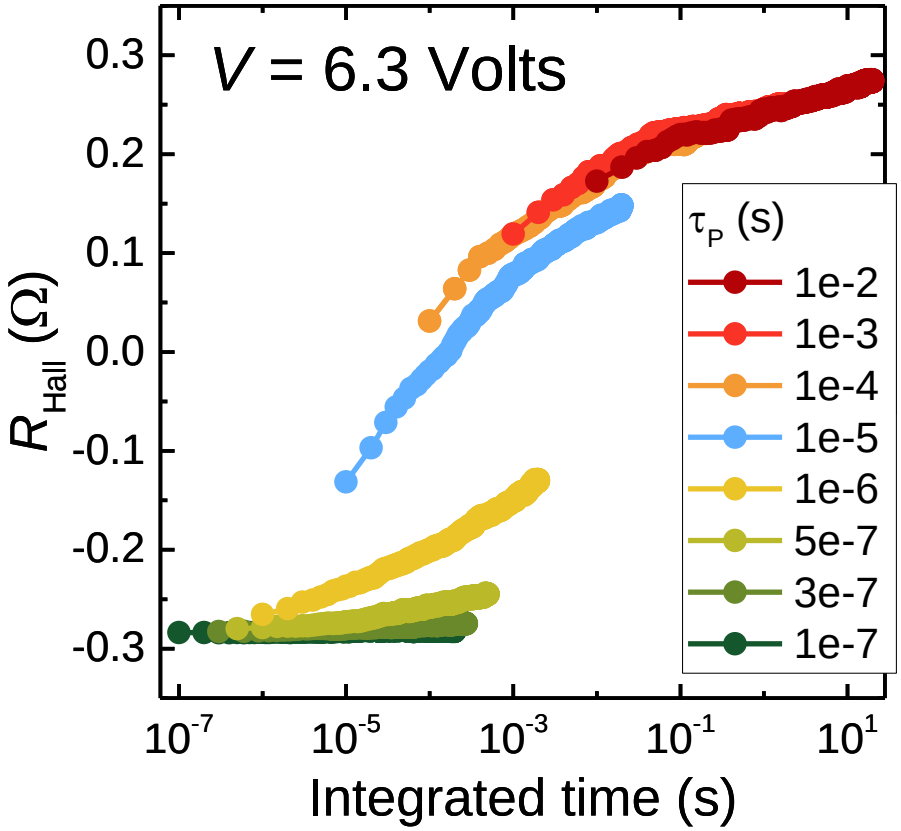
Pulse 2
“reads” the timer and
changes system
accordingly

Switching by short pulses

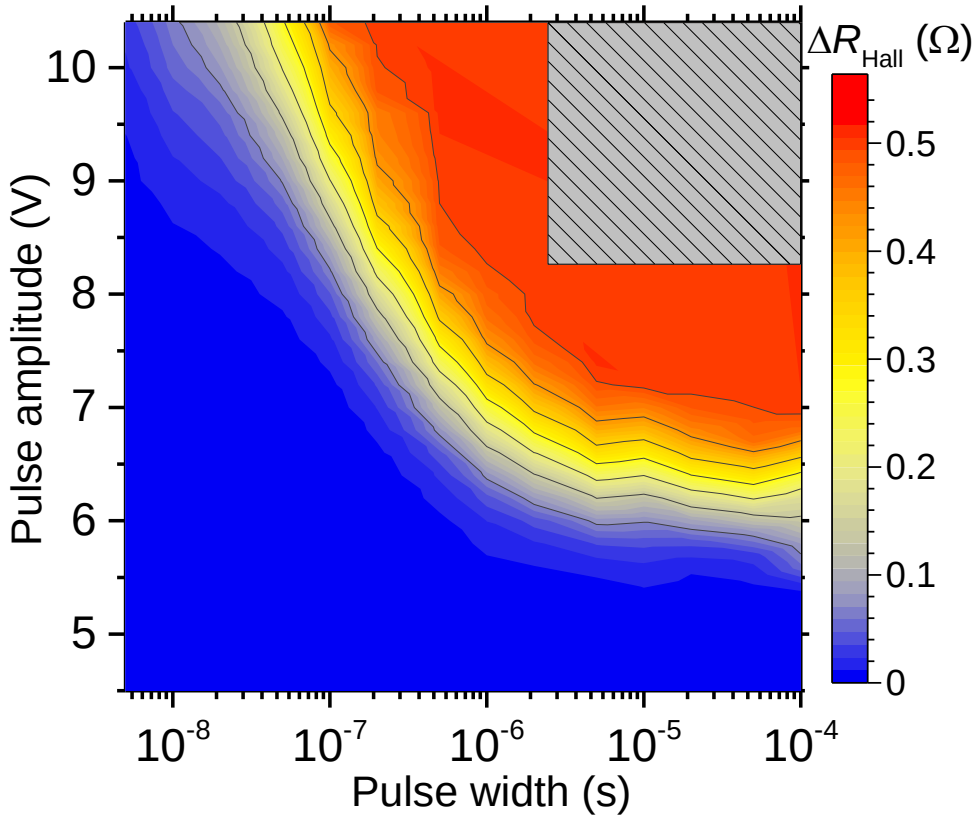


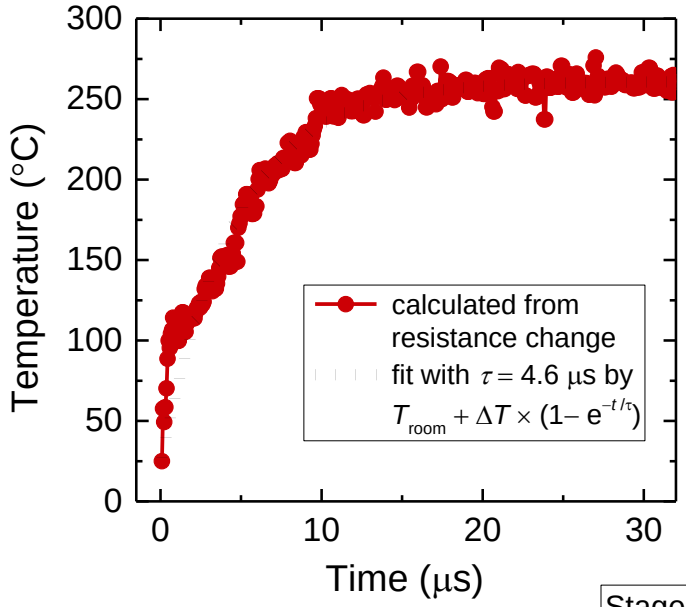
Effect of temperature dynamics

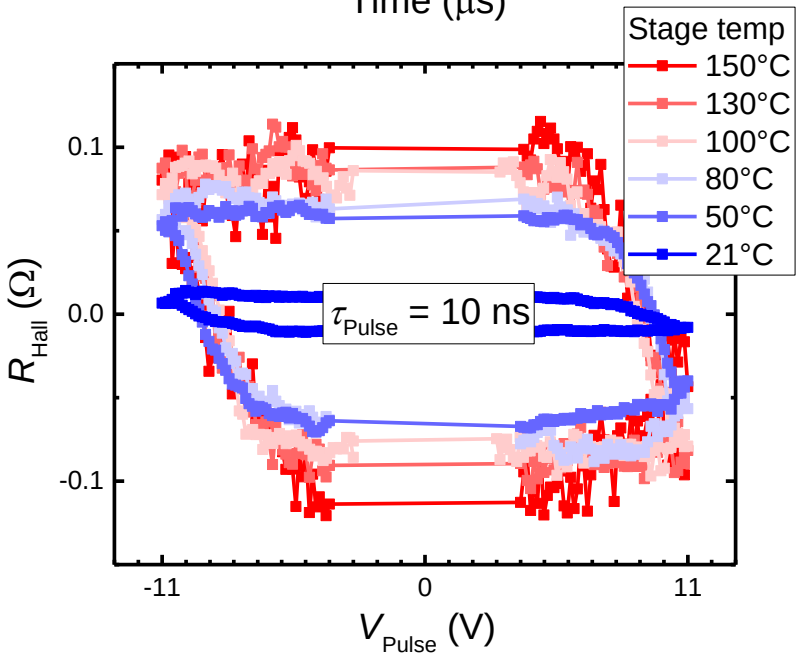




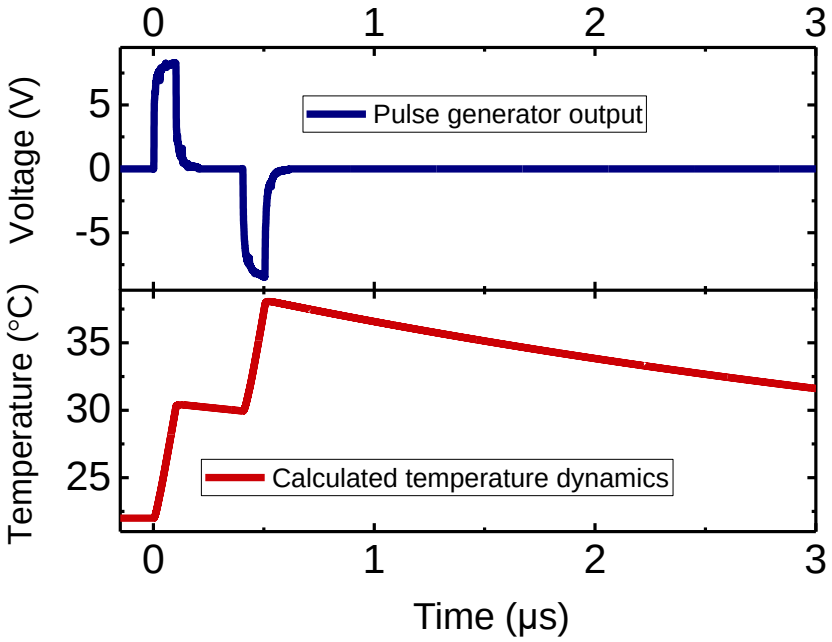
Effect of temperature dynamics

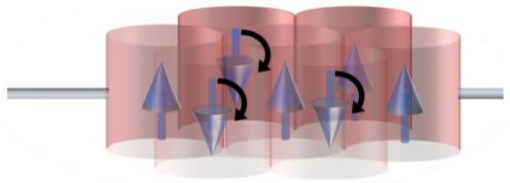


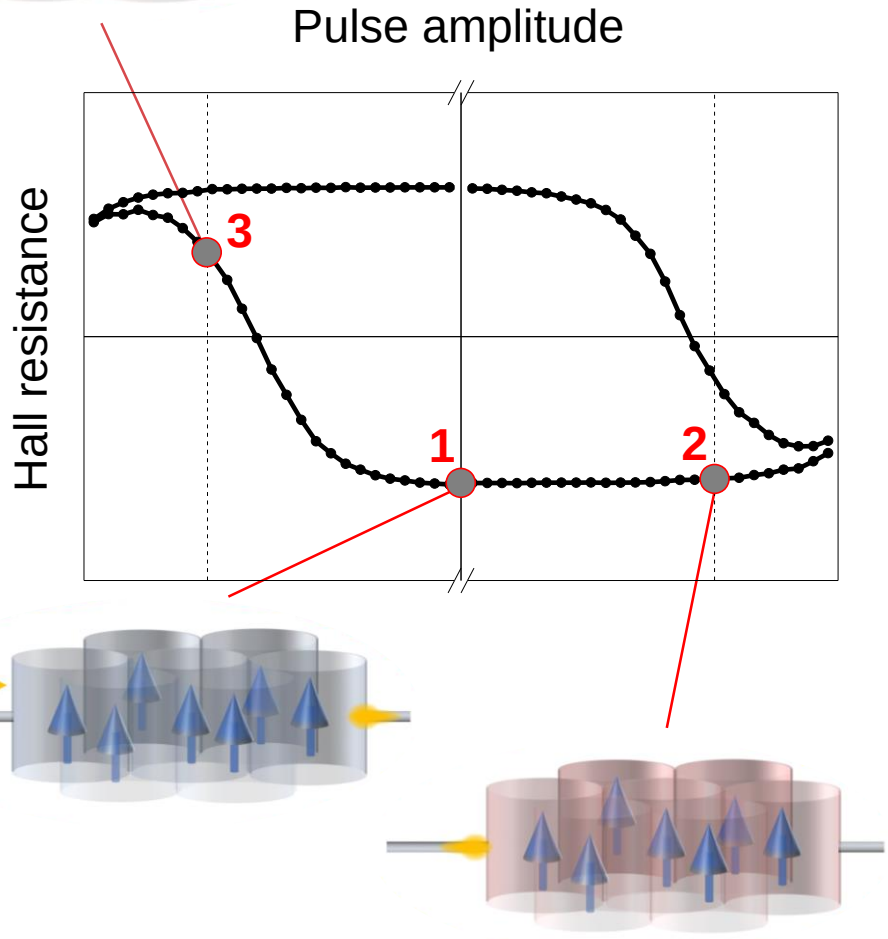




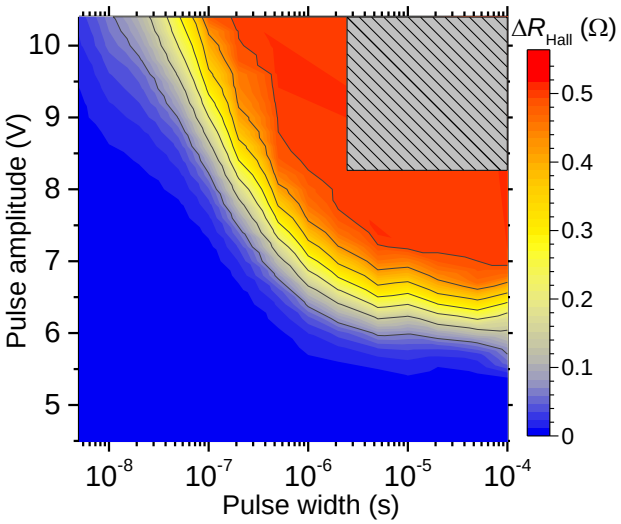
Temperature-based clock

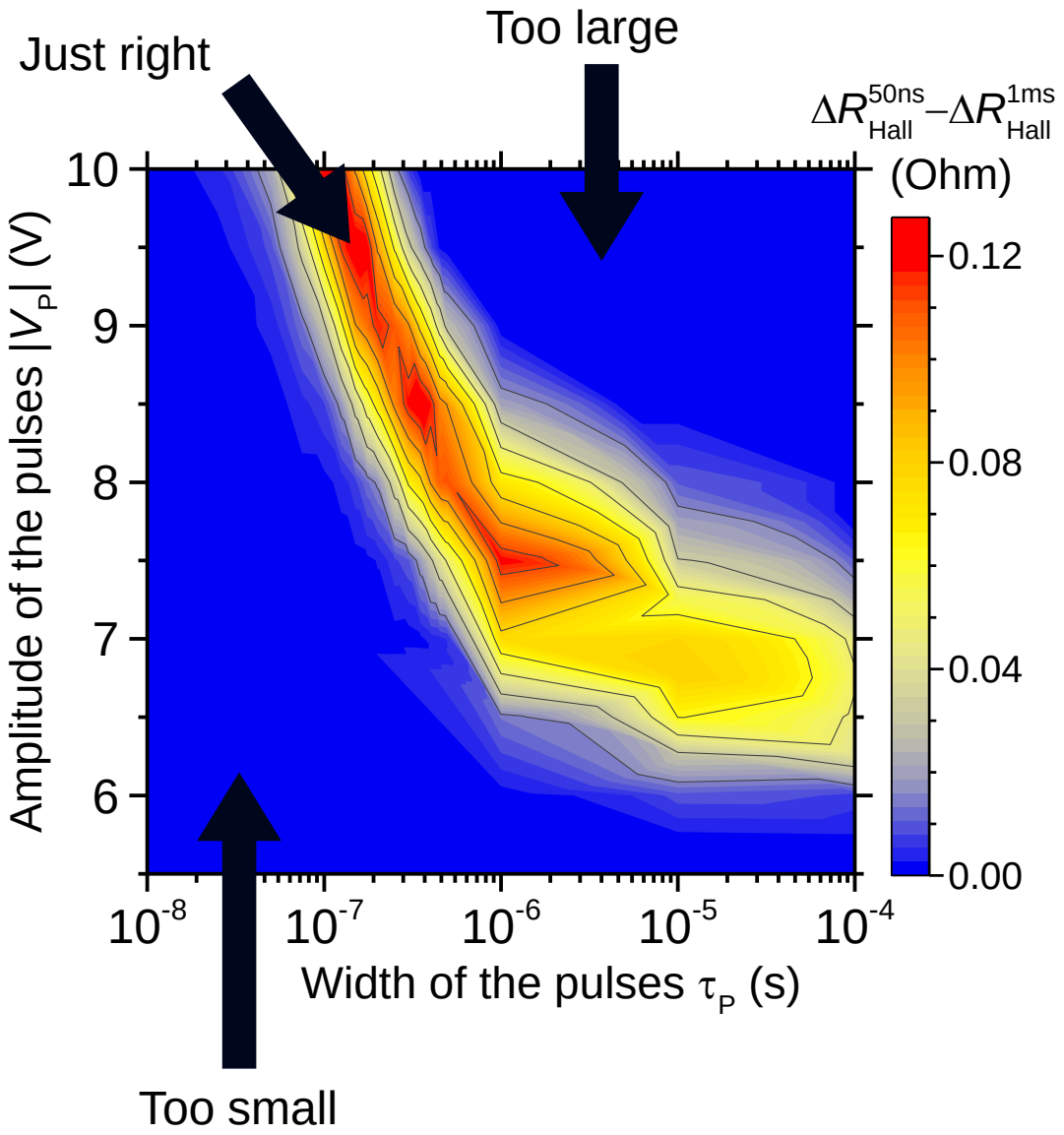




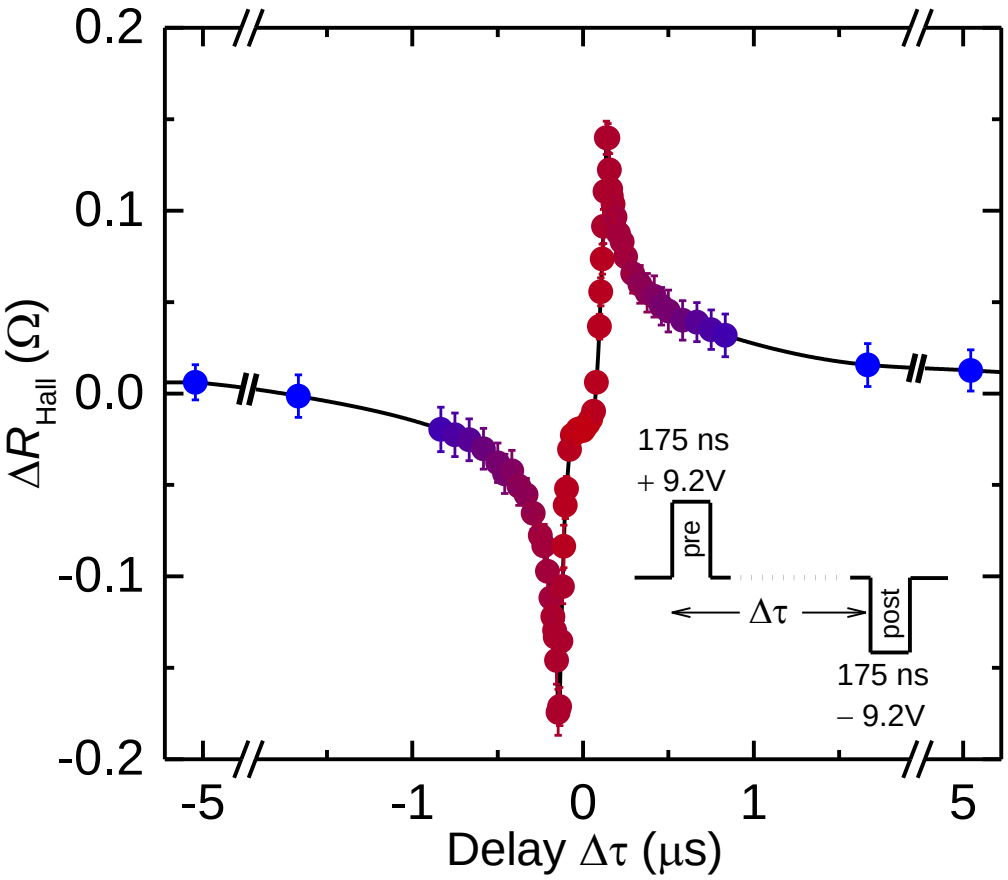


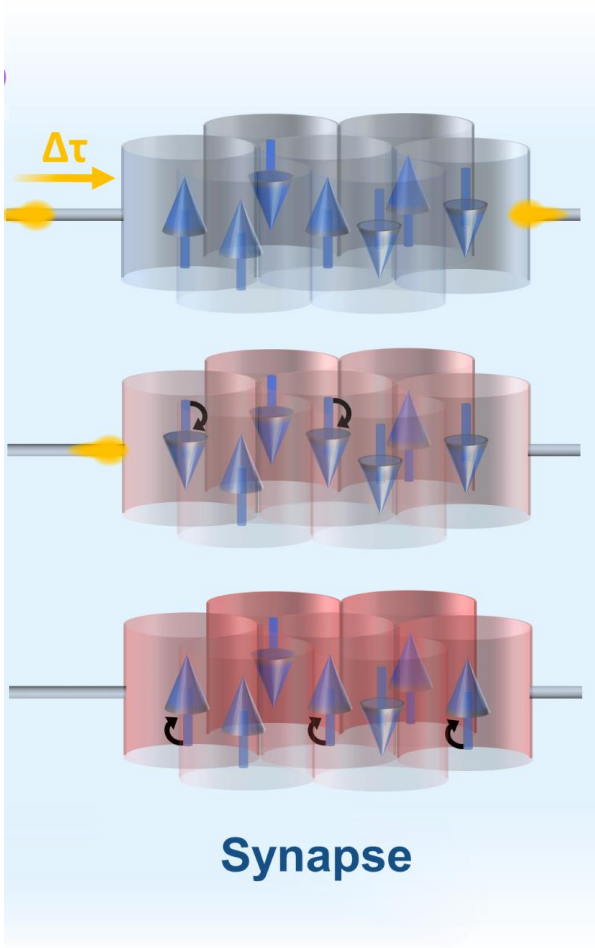
Temperature-based clock





Synaptic functionality





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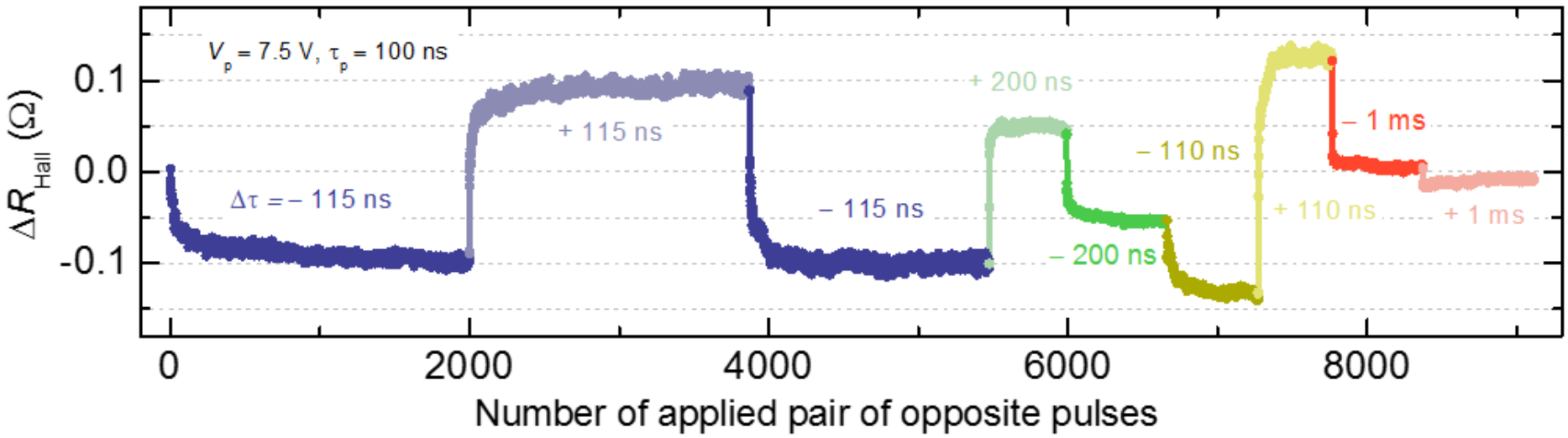
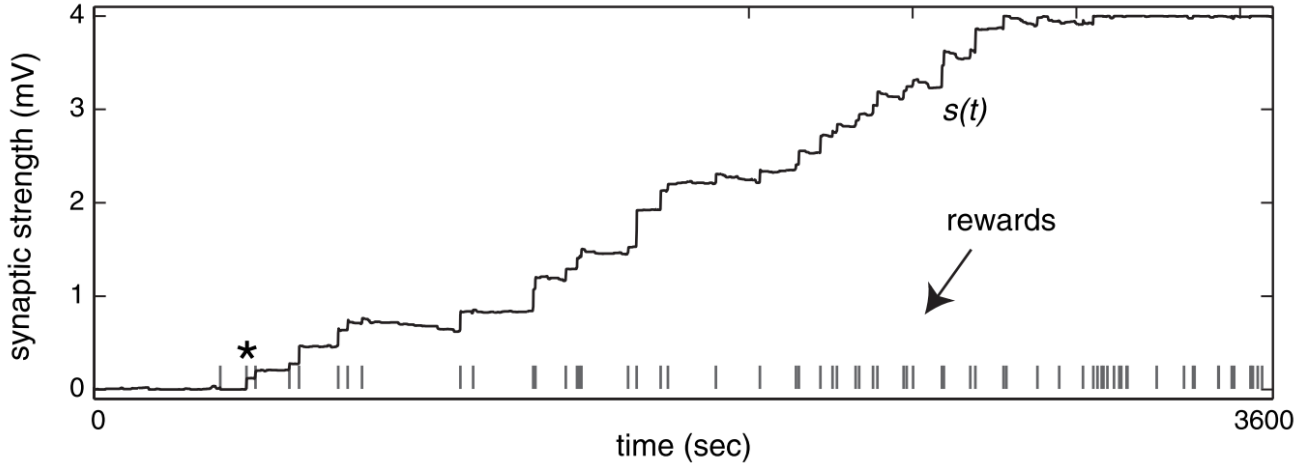
Synaptic learning



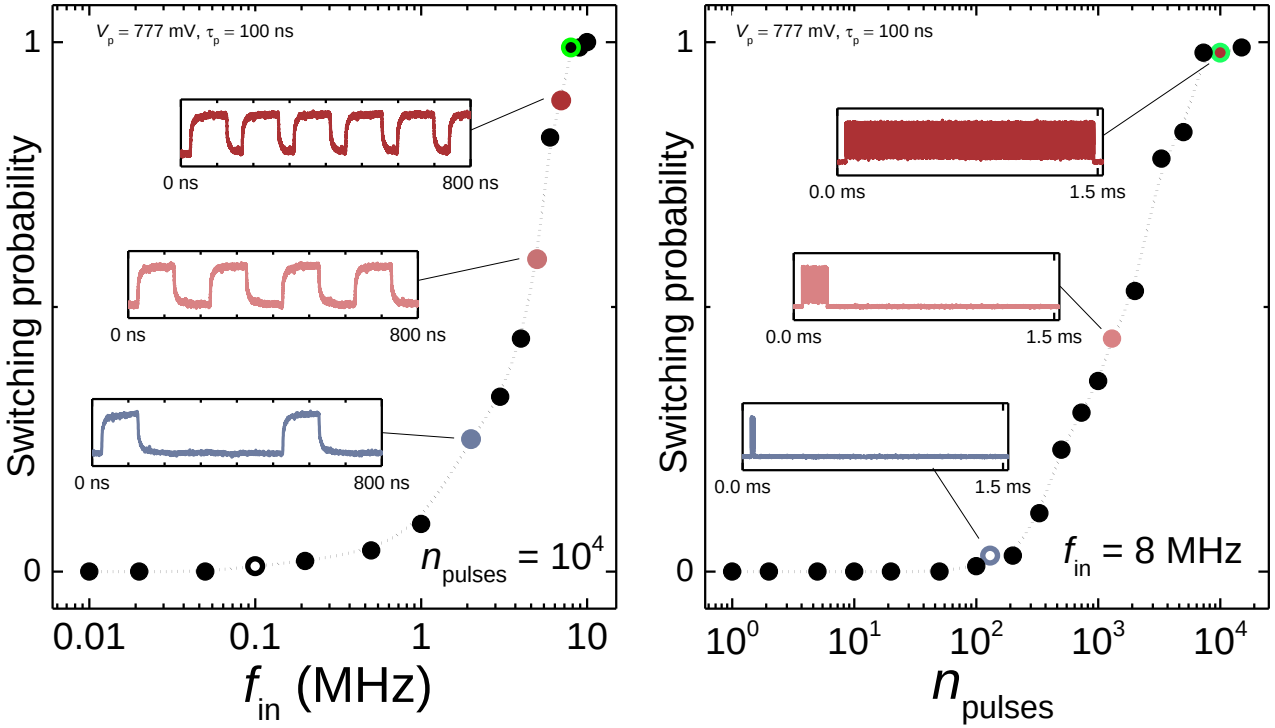


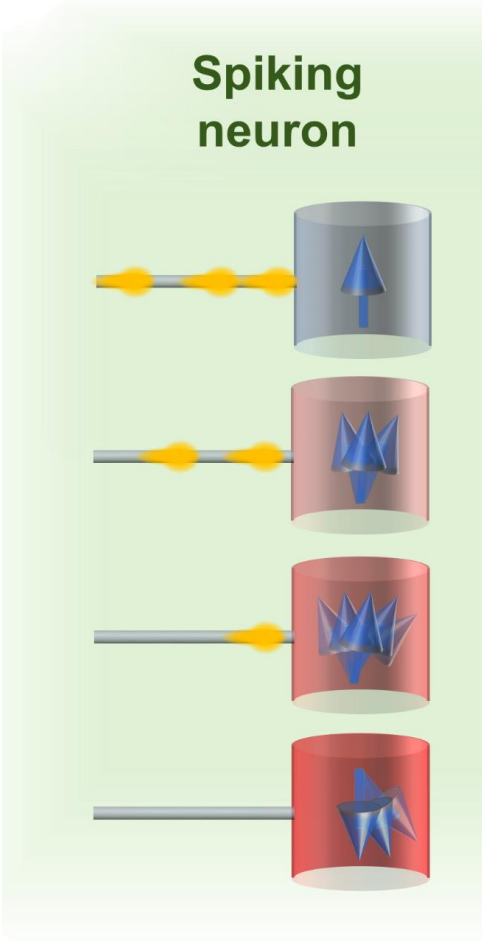
«Increase of synaptic strength by consistent coincidental firing of the pre- and post-neurons»

E. Izhikevich, *Cerebral Cortex* 17, 10 (2007)

Neuronal functionality

Simulation-intensity-dependent firing probability in the artificial neurons





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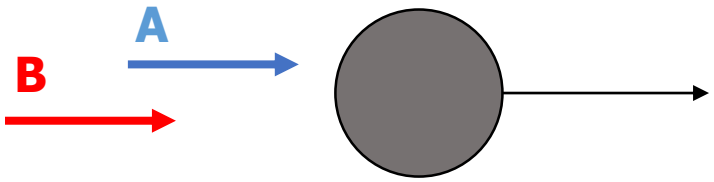
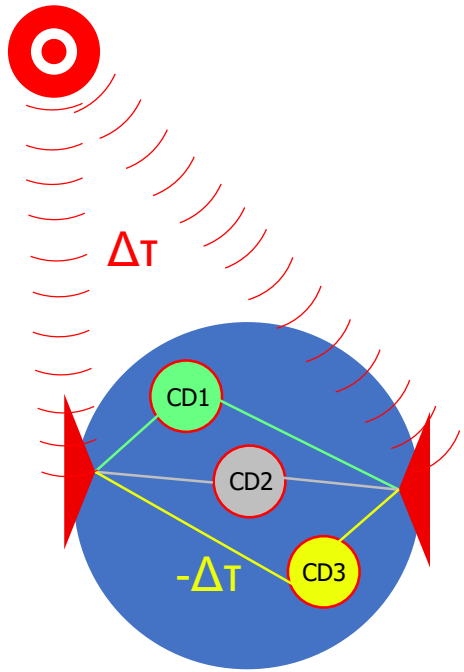
Coincidence detection

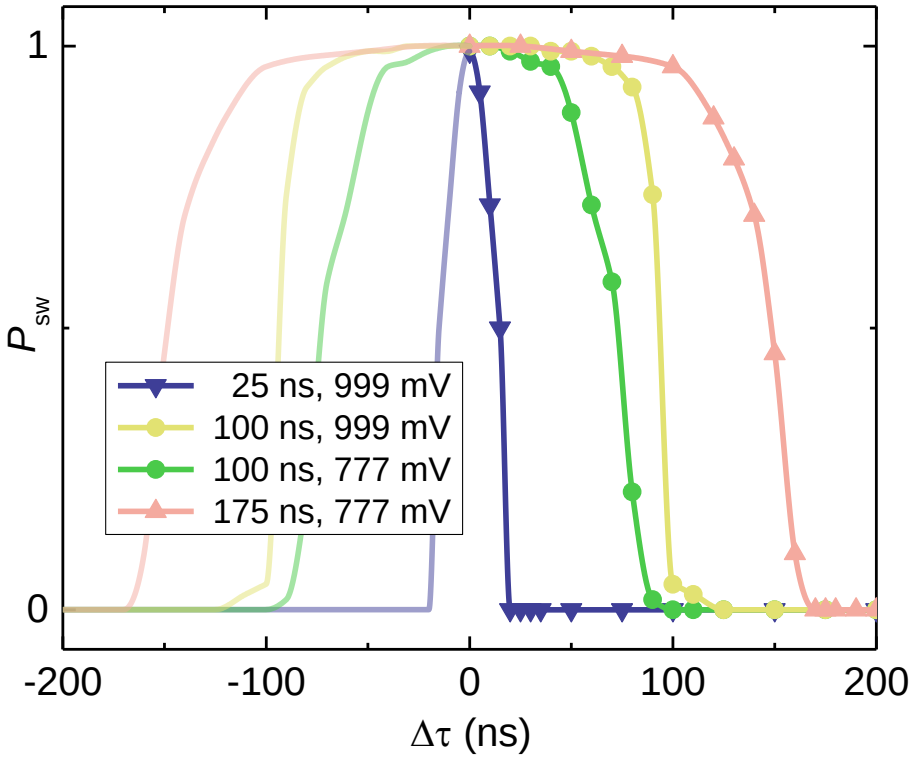


Outcome 1 if A and B happen within a time window
Outcome 2 if A and B are more separated

Sound localization

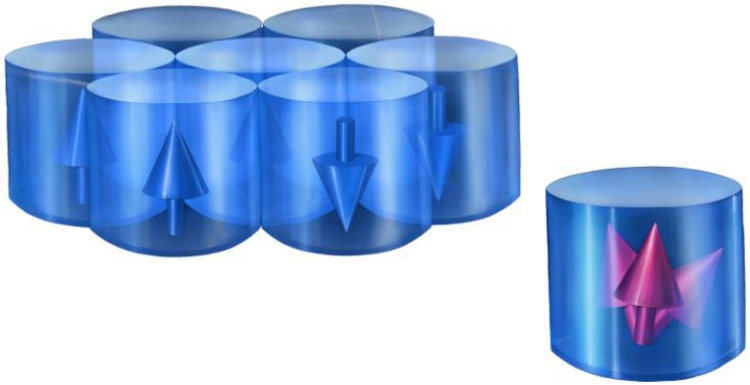
T. Franken *et al.*, *Nat. Neurosci.* 18, 444 (2015)





Conclusions

- Large-scale and efficient spiking neural networks can’t rely on CMOS
- Uniformity of new-materials synapses and neurons is crucial (because of the dense and highly interconnected nature of spiking networks)



- AFM/FM devices provide a uniform and scalable solution with all the benefits of spintronics (speed, endurance, scalability, 3D stacking)

Material requirements for a hardware SNN basis:

- Tunable switching behavior: binary and memristive
- Presence of dynamics that can be excited and read out

More details in
A. Kurenkov *et al.* Advanced Materials **31**, 1900636 (2019)

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