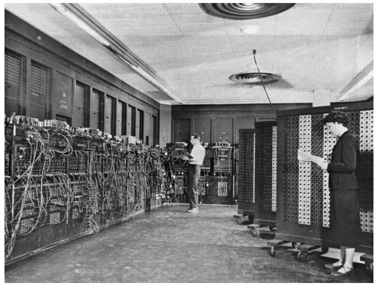
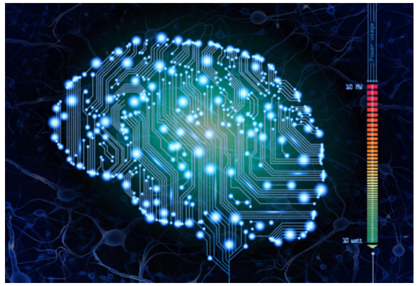
# All-optical Control of Magnetism

## *from fundamentals to brain inspired computing*





**Theo Rasing**

**Radboud University Nijmegen**

**Institute for Molecules and Materials**

# New Commodity- Data is the New Oil

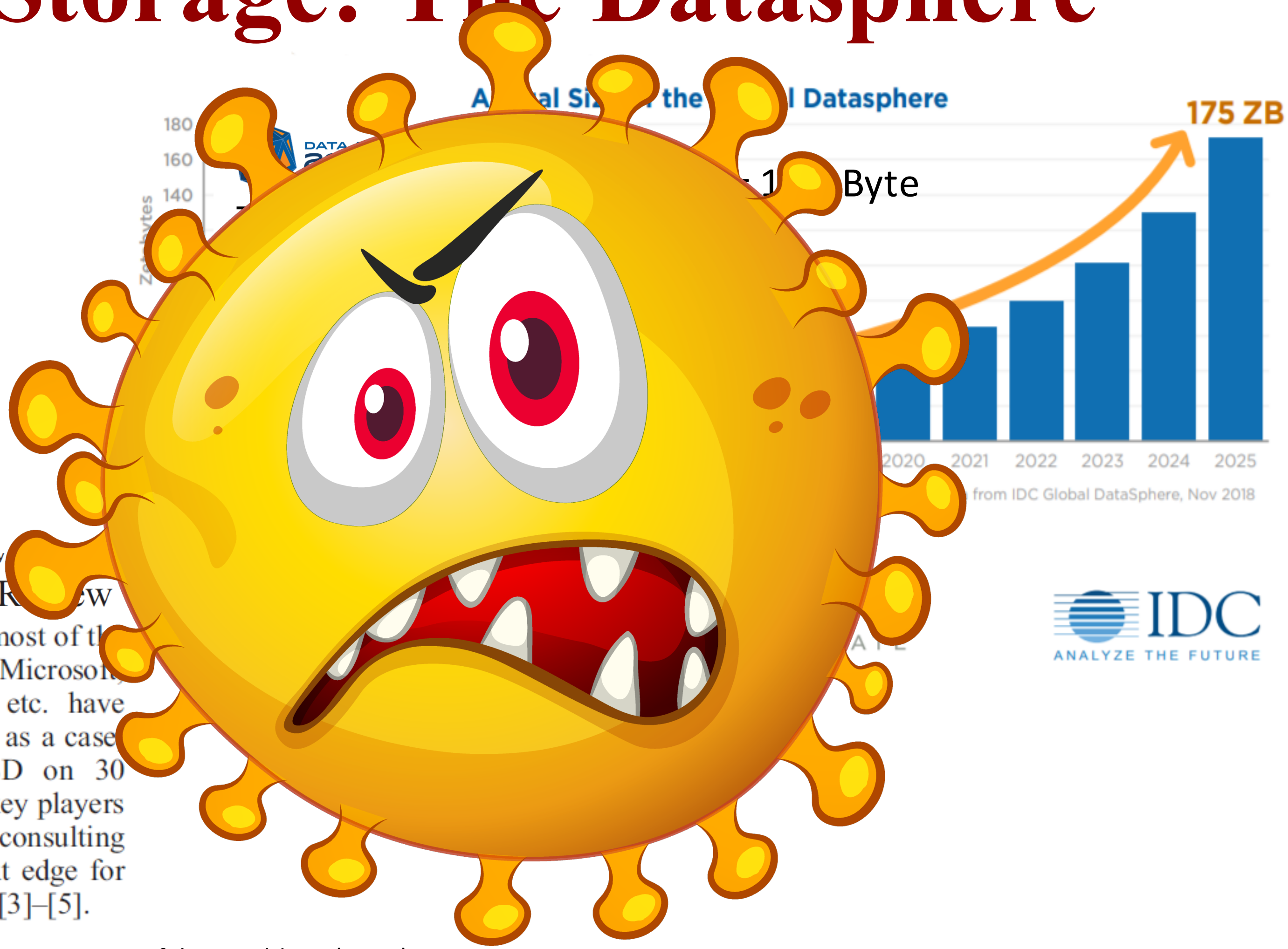
**"Just as the politics of oil shaped the 20th century industrial economy, so the politics of data will shape the 21st century digital economy… data is the new oil, the vital fuel of our digital economy,"**

**Andrew Keen, CNN newspaper, Jan 27, 2012**

## Driven by 2 major trends

- **Big Data:** social networks, online commerce, consumer buying trends, marketing strategies, medical trends, financial services, social studies, …
- **Cloud Computing:** permanent accessibility from vast number of smart mobile devices

# Big Data Storage: The Datasphere*


IDC
ANALYZE THE FUTURE

2019 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology

Big Data Impacts and Challenges: A R… ew

of the information " [3]. Over the past few years, most of th… primary technology player, including IBM, EMC, Microsoft, Oracle, Google, Facebook, SAS, and Amazon etc. have begun their Big Data plans. By highlighting IBM as a case since 2005, IBM has invested 16 billion USD on 30 properties related to Big Data. Many of Big Data key players like SAS Institute, Gartner, IBM, McKinsey consulting corporations indicated to the Big Data as the next edge for innovation, productivity, competition, and quality [3]–[5].

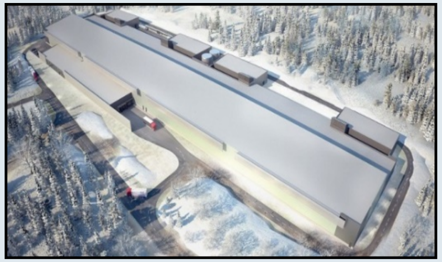
*Reinsel, D., Gantz, J. & Rydning, J. DataAge 2025 - The Digitization of the World. 28 (2018).

# Lots of Data = Lots of Energy

Casa Sinova, Mainz, Germany

**7% of electricity produced in the world**

Google
(The Netherlands)



Facebook
(Sweden)

**30 Google searches = boil 1 litre of water**

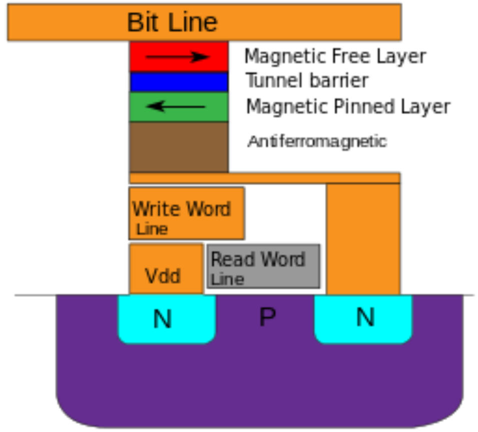
**6 billion searches per day!**

# Magnetic storage is the way!


Figure 1: A 5MB IBM hard disk drive is loaded onto an aeroplane in 1956

1956: 1st IBM 5 MB hard disk drive, US $50,000

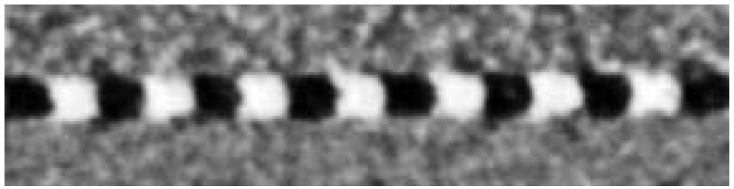
Conventional Hard Disk drives

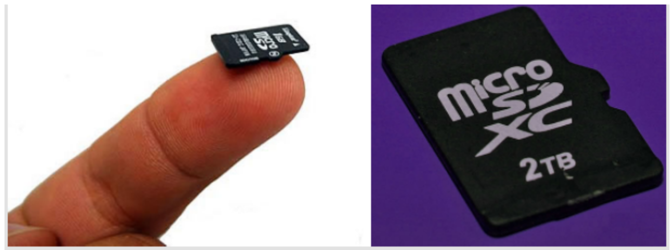



Magnetoresistive Random-Access Memory (MRAM)

**Today: 3 TB hard disk drive US$ 100 = 0.03$/Gb**

Bits 0 or 1 are associated to magnetic states "up" or "down"



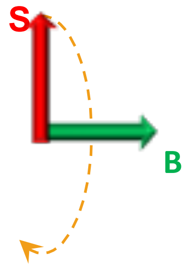



Toshiba 2 TB micro SD card

# Direct All-Optical Switching by femto-second laser pulses: *counterintuitive?*

***Simple single spin problem***

$$\frac{\partial \boldsymbol{S}_i}{dt} = -\gamma \boldsymbol{S}_i \times \mathbf{B}_{\mathbf{eff}}$$

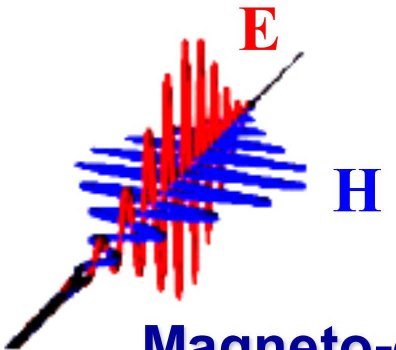



***Intuitive estimate:***
*If 100 fs pulse reverses the magnetization, it should act as an **effective magnetic field of about 90 Tesla** ( γ=28 GHz/T)!*

*Light acts as a magnetic field, which is **either strong** (>>1 Tesla) **or stays long** (>>100 fs).*

**Why?**

# Magneto-optics and Opto-magnetism



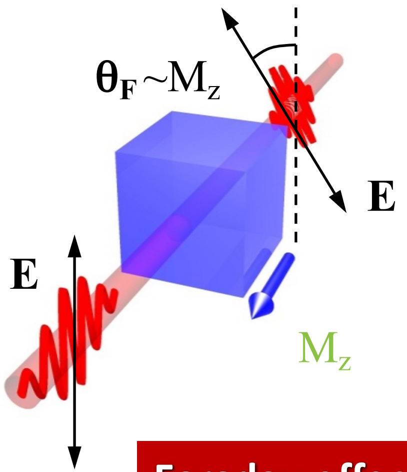

$$\varepsilon(\vec{M}) = \begin{pmatrix} \varepsilon_{xx} & i\varepsilon_{xy} & 0 \\ -i\varepsilon_{xy} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

## Magneto-optics

## Opto-magnetism

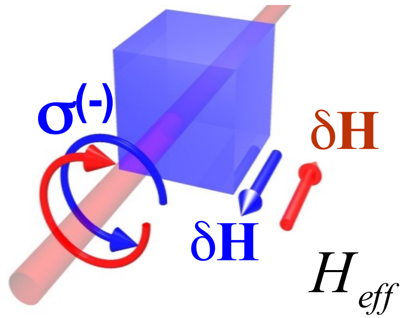
L. P . Pitaevskii, Sov. Phys. JETP **12**, 1008 (1961).
J. P. van der Ziel et al, Phys. Rev. Lett. **15**,190 (1965).

$$\frac{\partial \varepsilon}{\partial M} = \alpha$$




$$\theta_F = \pi \frac{L}{\lambda} \frac{\alpha M}{\sqrt{\varepsilon}}$$

**Faraday effect**

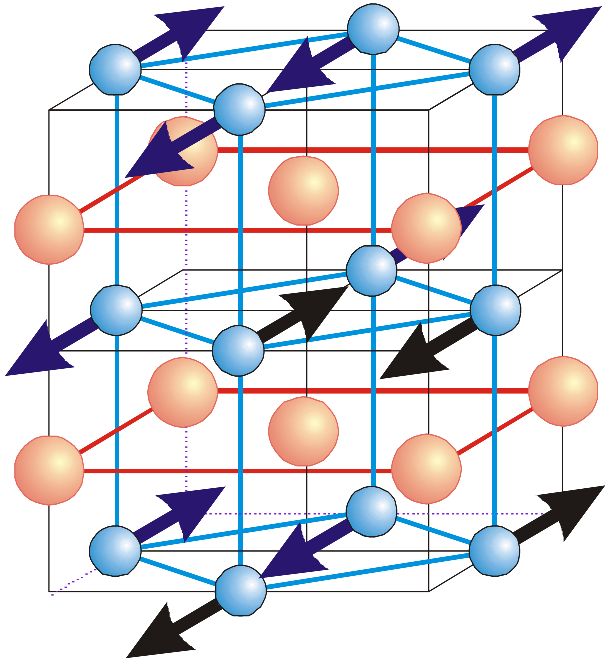


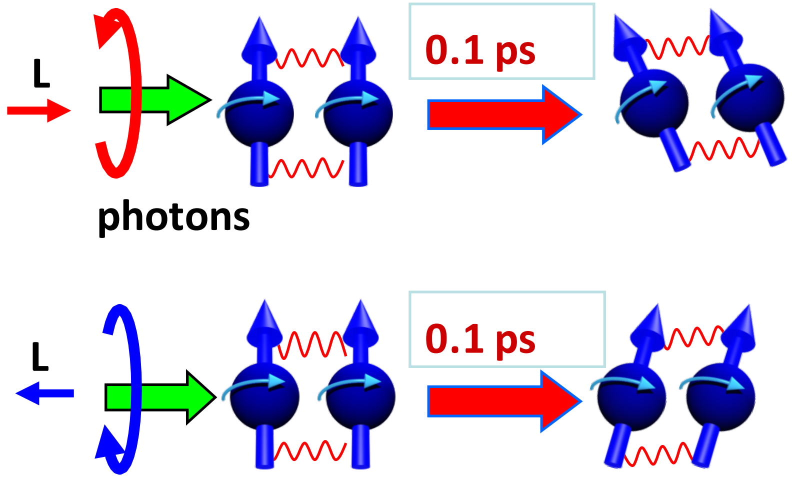

$$H_{eff}(0) = \alpha \frac{\varepsilon_0}{\mu_0} E(\omega) E^*(\omega)$$

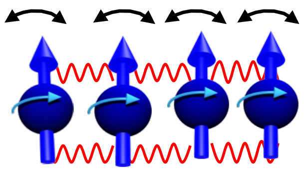
**Inverse Faraday effect**

# Ultrafast excitation of spins via IFE in $DyFeO_3$

## (all-optical spin resonance)





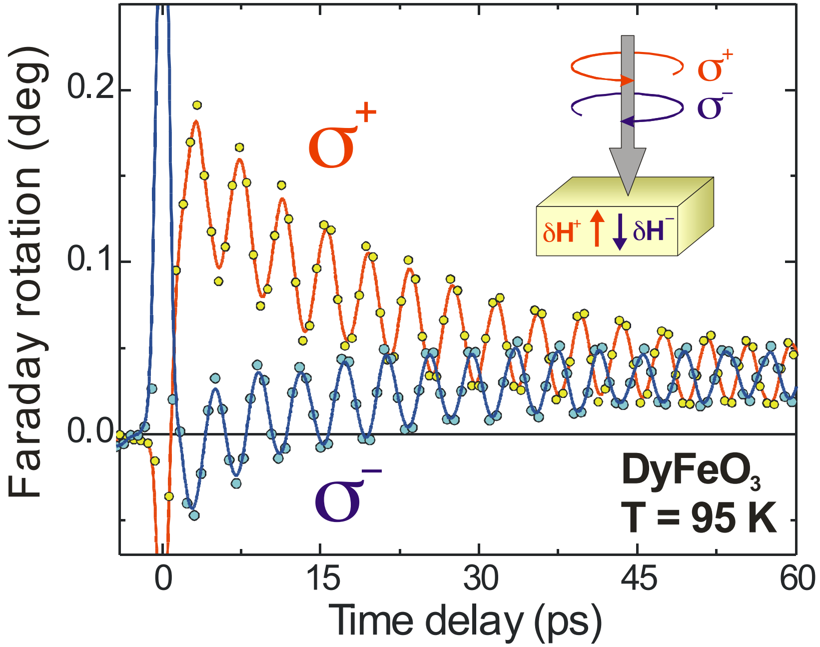



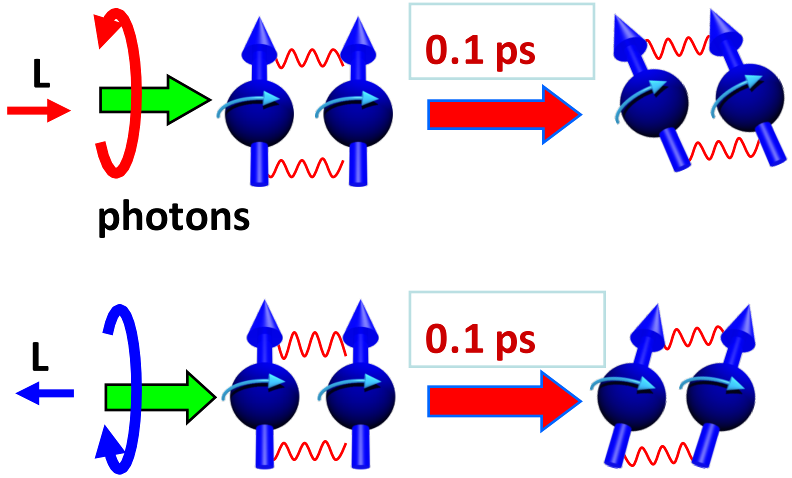
A. Kimel et al, Nature 435 655 (2005)

# Ultrafast excitation of spins via IFE in $DyFeO_3$

## (all-optical spin resonance)

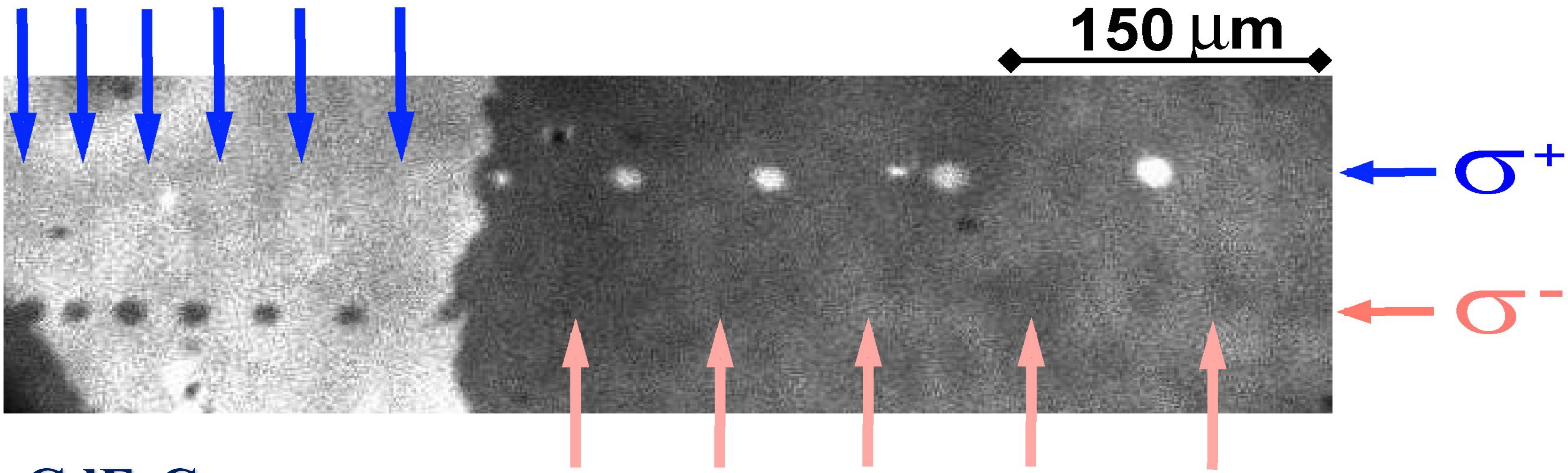
**100 fs laser pulse of 50 mJ/cm²**
**is equivalent to 100 fs pulse of 1 T**
***(but yielding only few degrees tilt)***




# How to switch ?

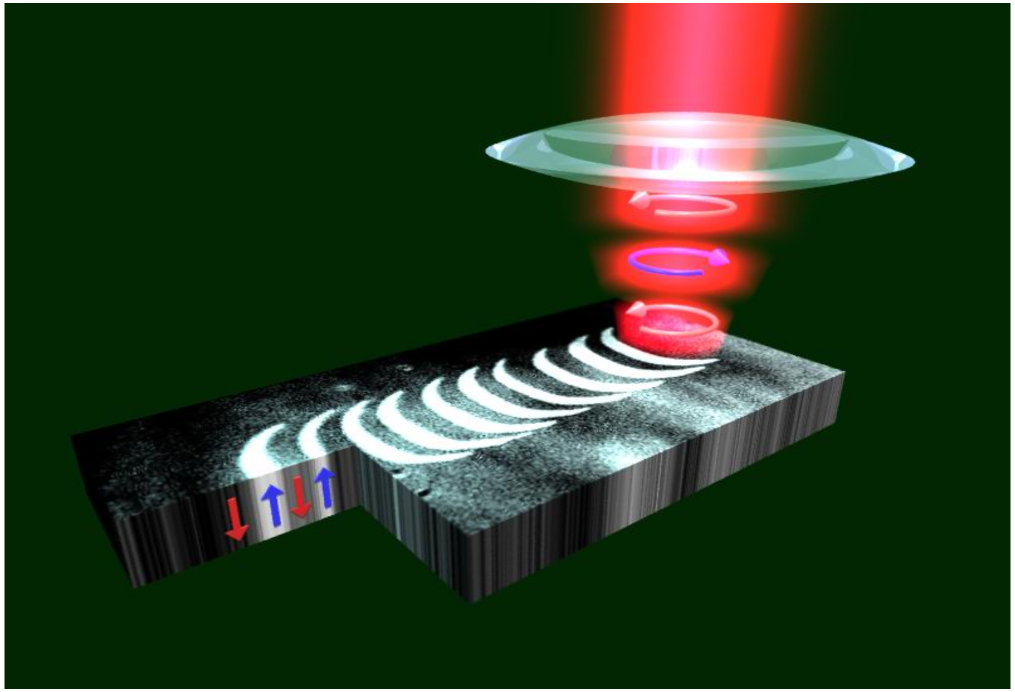
# switching by single 100 fs laser pulse!

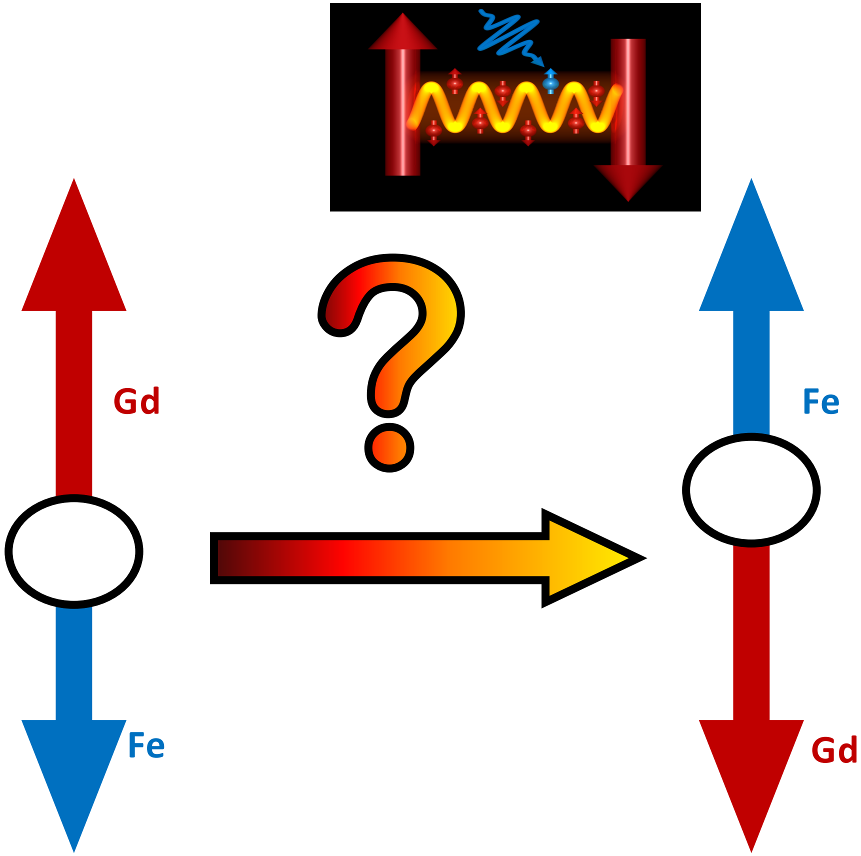



**GdFeCo**

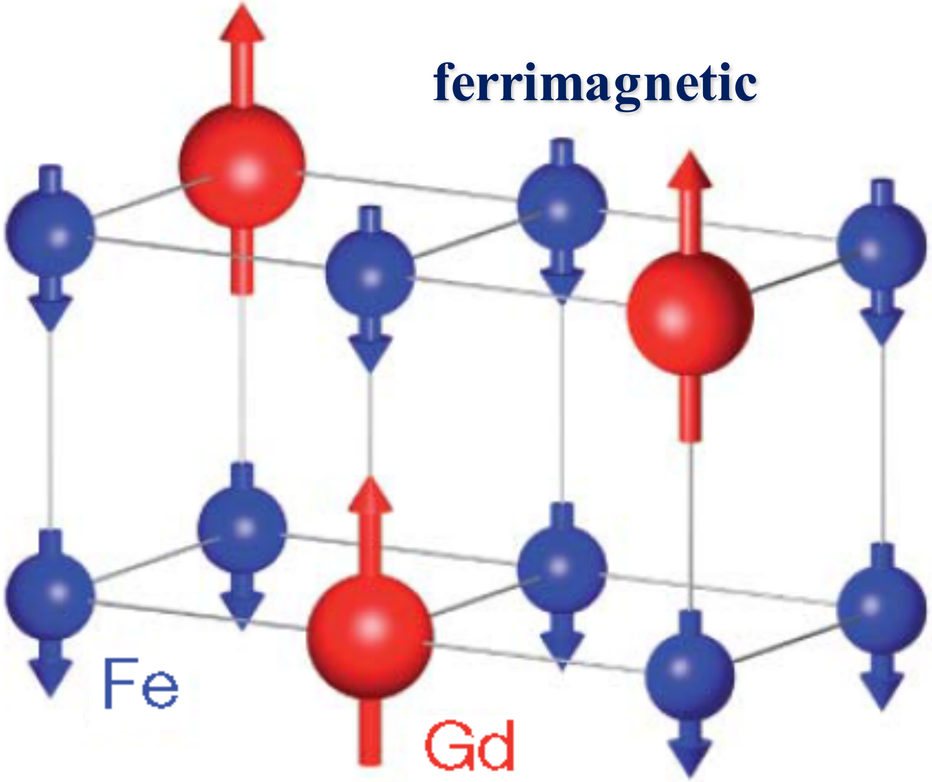
**C.D. Stanciu et al., PRL 99,047601 (2007)**

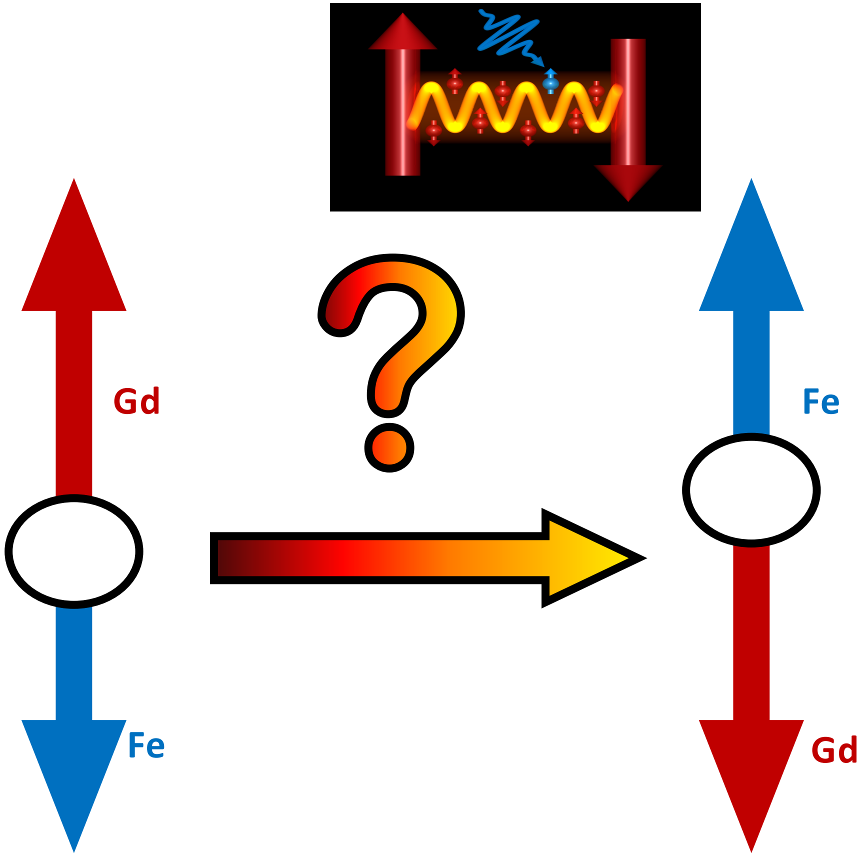
# Femtosecond laser reversal: role of exchange?





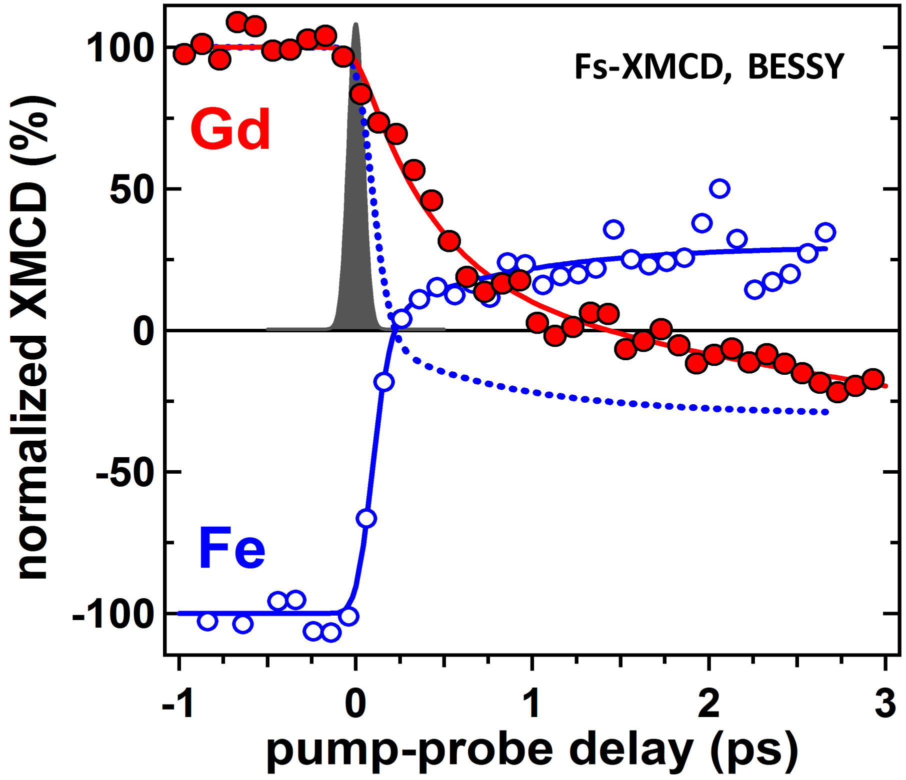
# Femtosecond laser reversal: role of exchange?



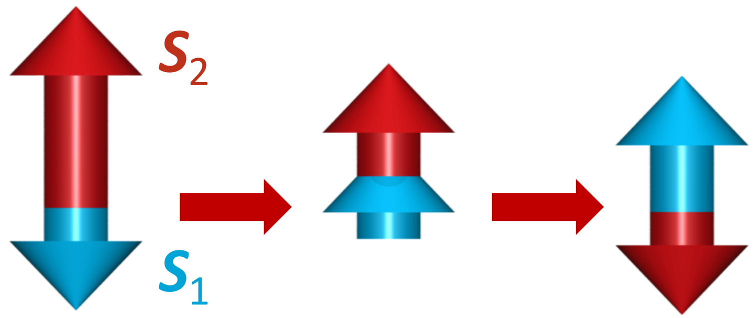




$J_{Fe\text{-}Gd} \sim$ 30-50T

# Laser heat induced magnetization reversal!




I. Radu et al, *BESSY, Nature* 472, 205-208 (2011)




$$dS_1/dt = -dS_2/dt$$

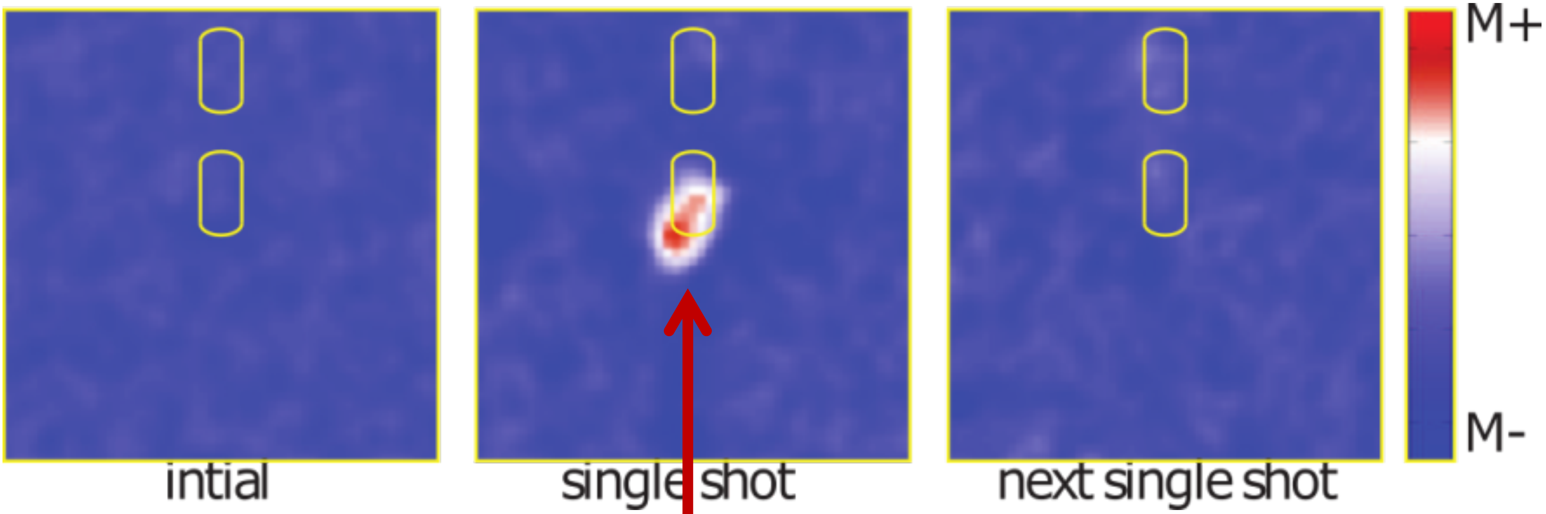
*J.H. Mentink et al., PRL 057202, 2012*

*T. Ostler et al, Nature Comm.3, 666, 2012*

# reversal of magnetization driven by exchange!!!

# Nanoscale switching with plasmonic antennas

## (with Bert Hecht, Wuerzburg)

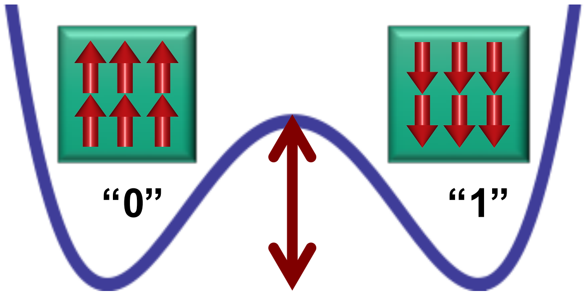



**40 nm Switching!!**

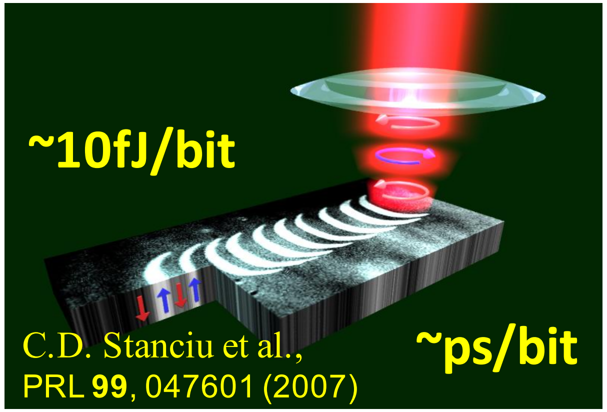
Tian-Min Liu et al, Nano Letters, 2015

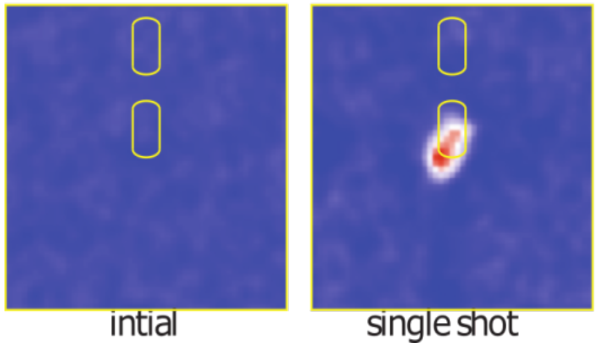
# opto-magnetic data storage


~1ns

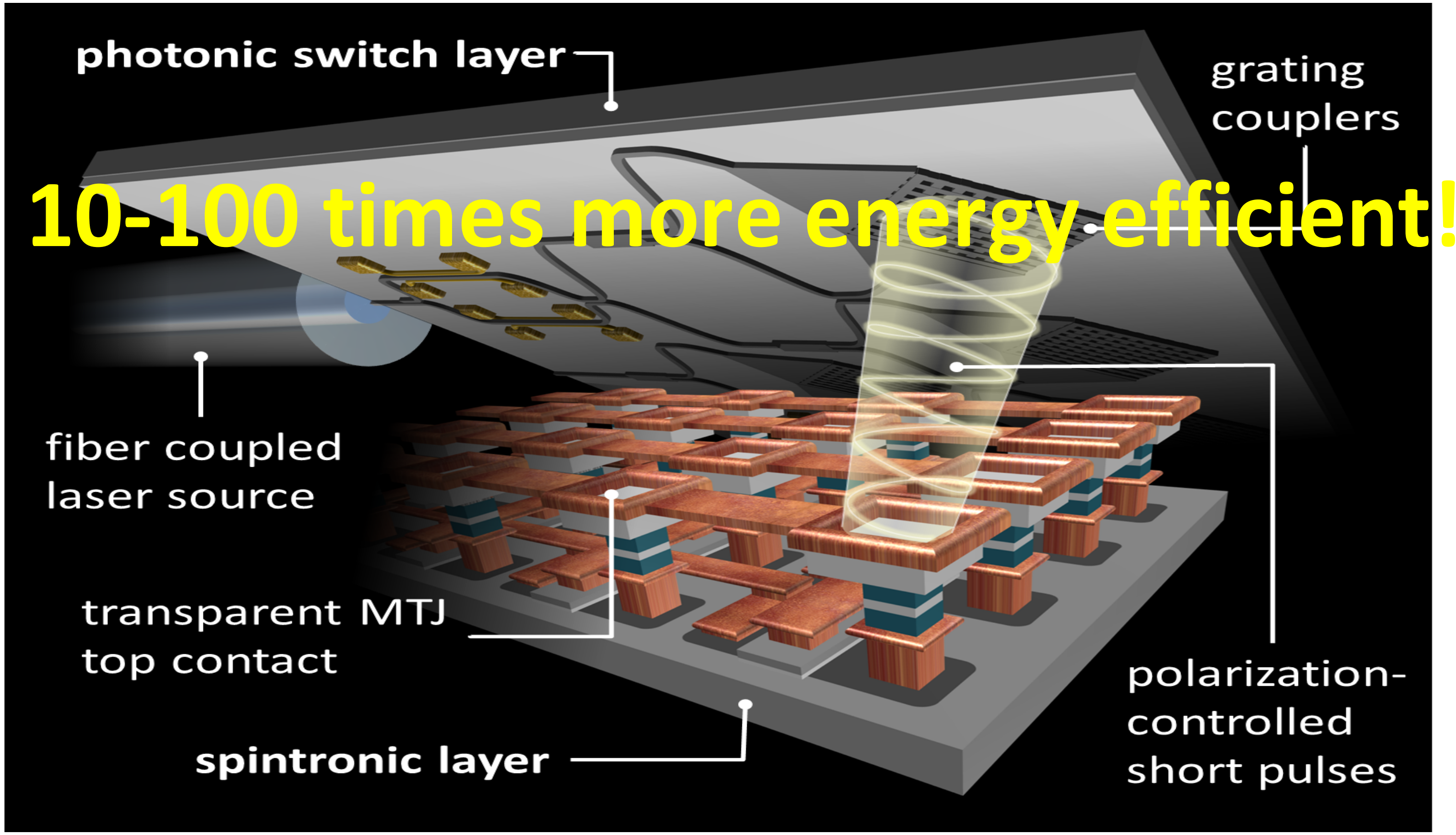



60 $k_B T \sim 10^{-19}$ J



# Spintronic-Photonic Integrated Circuit platform for novel Electronics *(SPICE)*



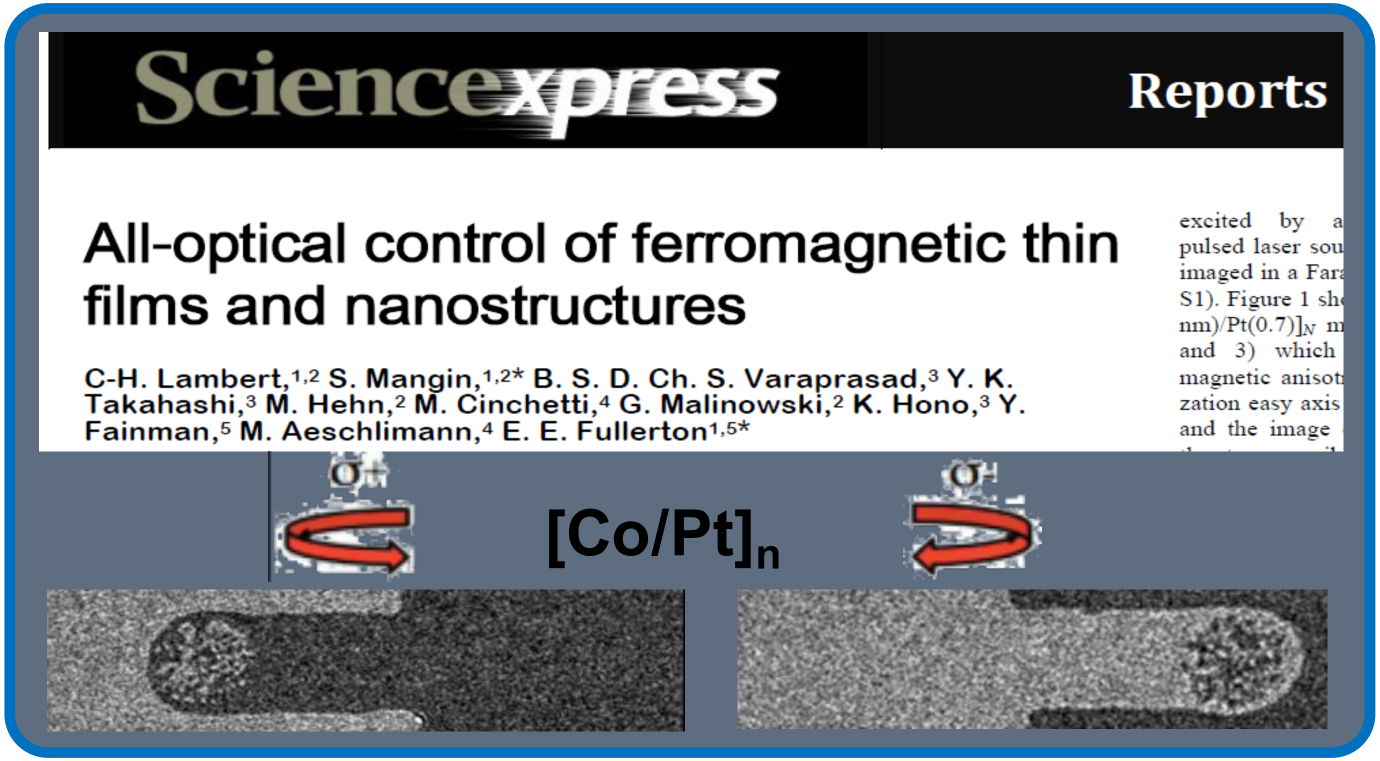

**With: Aarhus University, IMEC, CEA SpinTEC, QuantumWise**

# Spintronic-Photonic Integrated Circuit platform for novel Electronics *(SPICE)*

- L. Avilés-Félix, L. Álvaro-Gómez, G. Li, C.S. Davies, A. Olivier, M. Rubio-Roy, S. Auffret, A. Kirilyuk, A.V. Kimel, Th. Rasing, L.D. Buda-Prejbeanu, R.C. Sousa, B. Dieny, I.L. Prejbeanu, *Integration of Tb/Co multilayers within optically switchable perpendicular magnetic tunnel junctions*, **AIP Advances 9**, 125328 (2019)
- L. Avilés-Félix, A. Olivier, G. Li, C. S. Davies, L. Álvaro-Gómez, M. Rubio-Roy, S. Auffret, A. Kirilyuk, A. V. Kimel, Th. Rasing, L. D. Buda-Prejbeanu, R. C. Sousa, B. Dieny, I. L. Prejbeanu, *Single-shot all-optical switching of magnetization in Tb/Co multilayer-based electrodes*, **Scientific Reports 10**, 5211 (2020)
- L. Avilés-Félix, L. Farcis, Z. Jin, L. Álvaro-Gómez, G. Li, A. Kirilyuk, A. V. Kimel, Th. Rasing, B. Dieny, R. C. Sousa, I. L. Prejbeanu, L. D. Buda-Prejbeanu, *All-optical spin switching probability in Tb/Co multilayers, to appear in* **Scientific Reports (2021)**

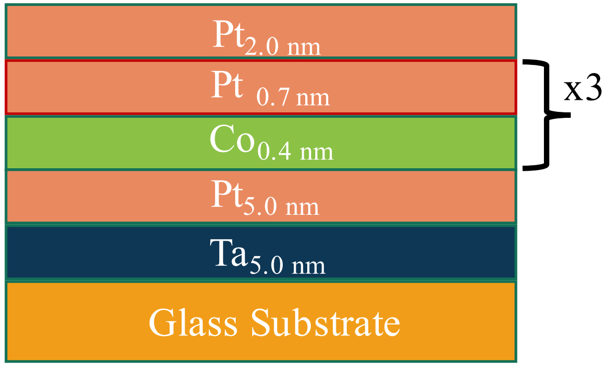
**With: Aarhus University, IMEC, CEA SpinTEC, QuantumWise**

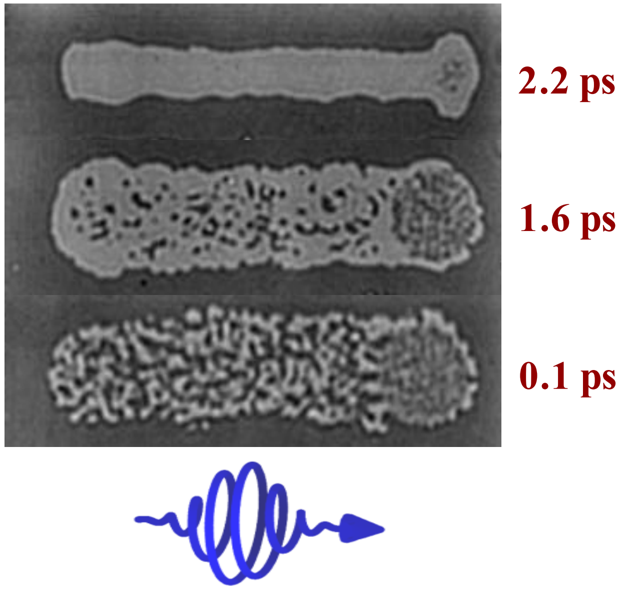
# AOS of CoPt (HDD material)?

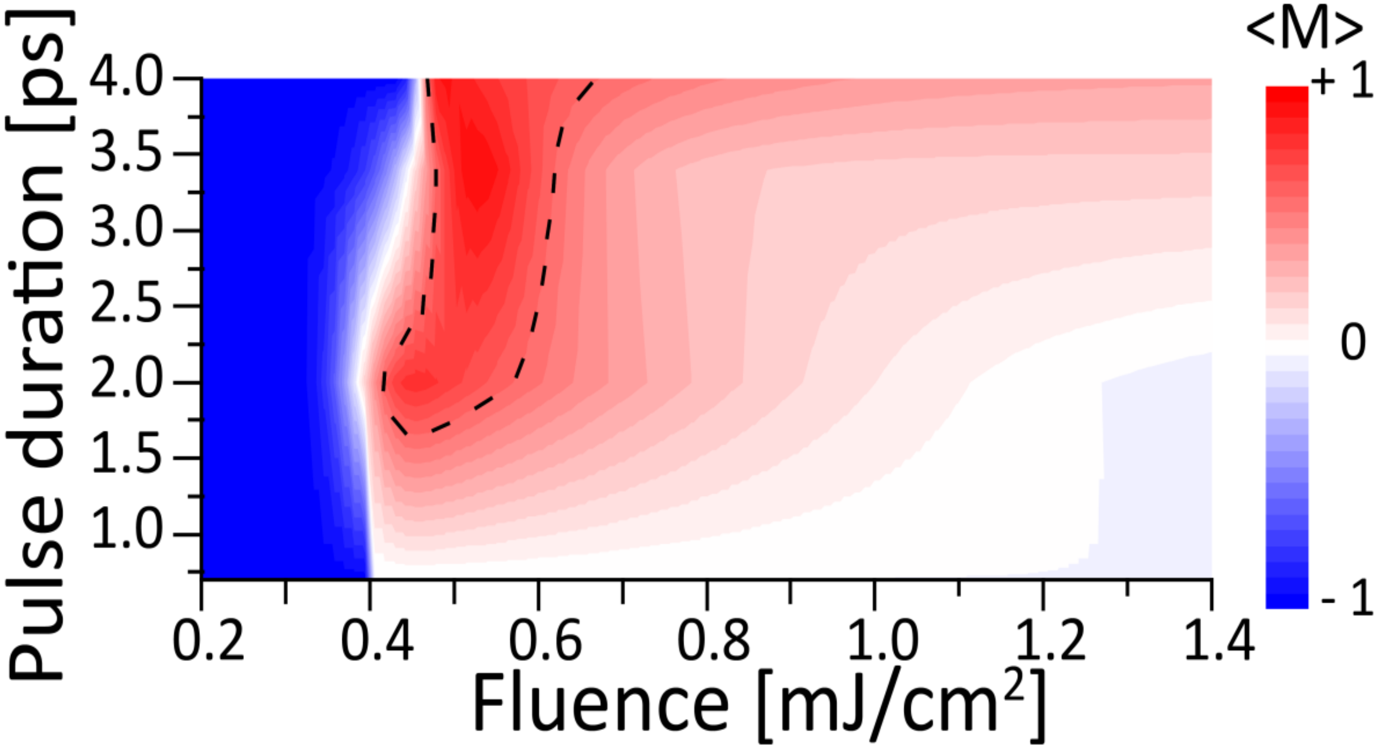



## what's the mechanism?

# HD-AOS in Co/Pt multilayer



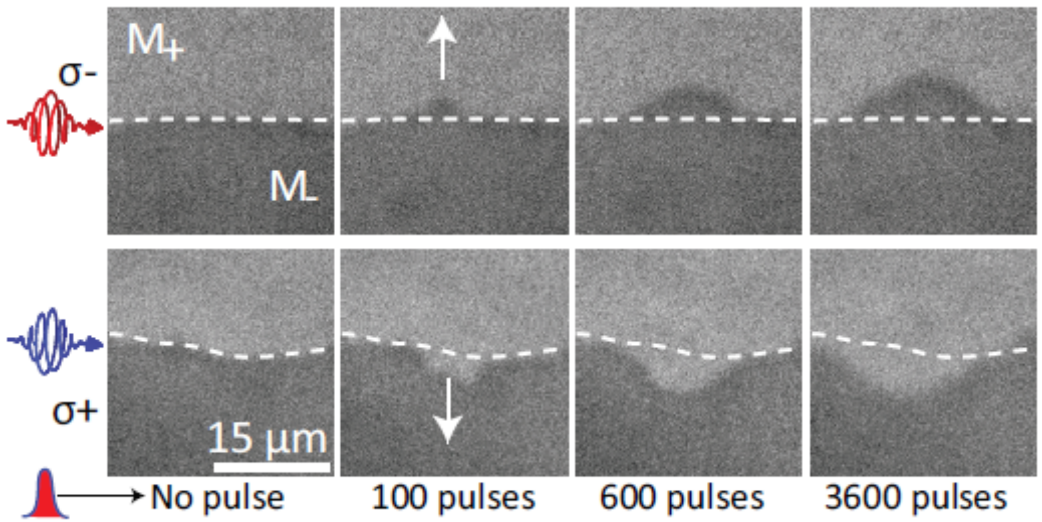





Y. Tsema et al, APL 2016,

R. Medapalli et. al., Phys. Rev. B 96, 224421 (2017)

# Deterministic displacement of domain walls



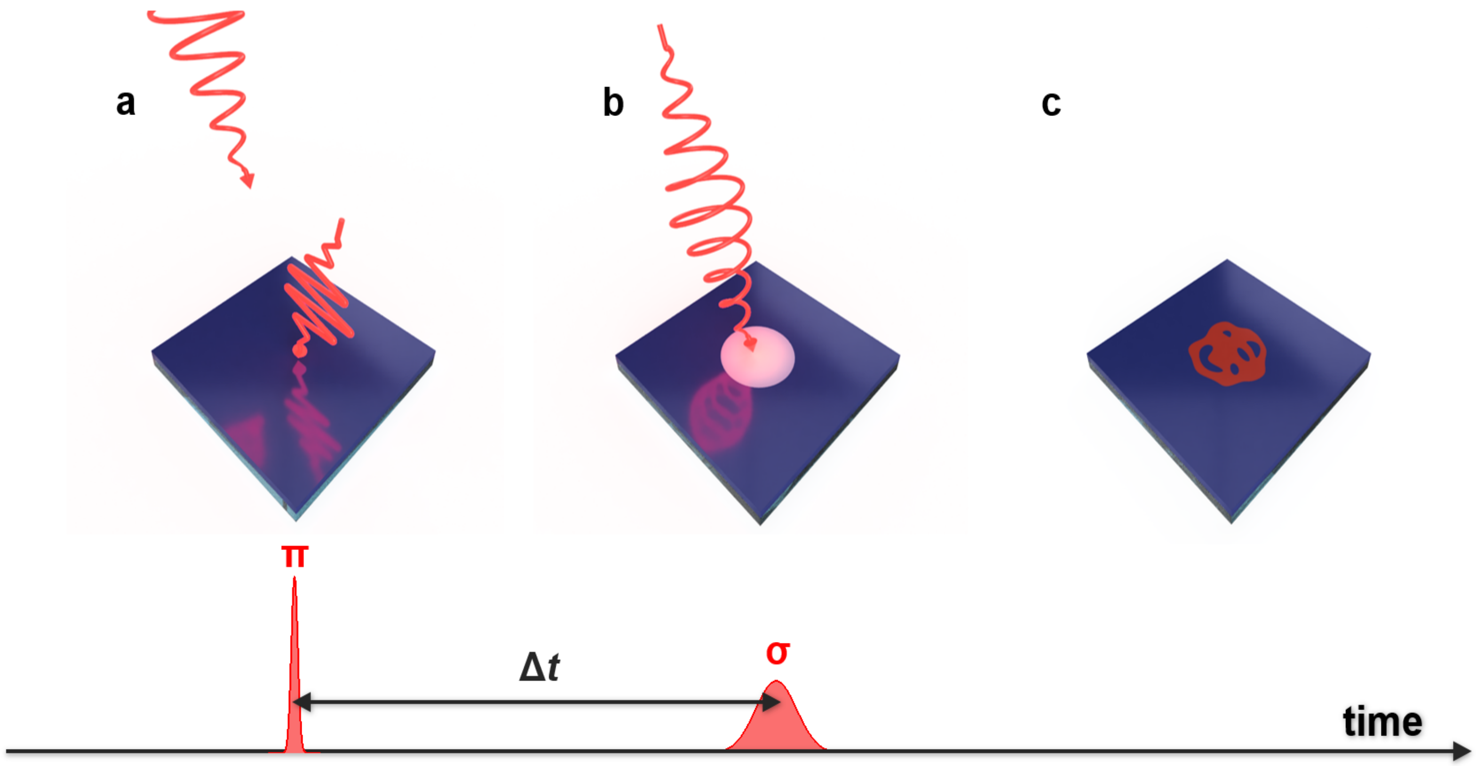

**Stochastic nucleation & growth!!!**

2 mJ/pulse @ 0.4 mJ/cm$^2$ takes many (~100) pulses!!

***(2 step process!)***

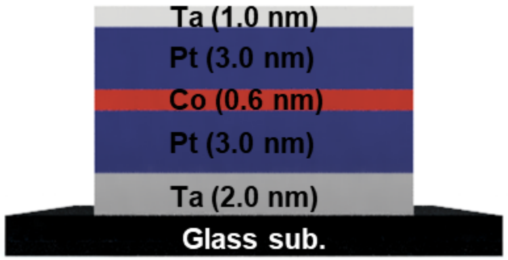
***Can´t we do better?***

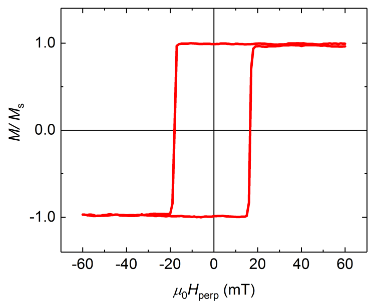
# Concept for dual pulse HD-AOS



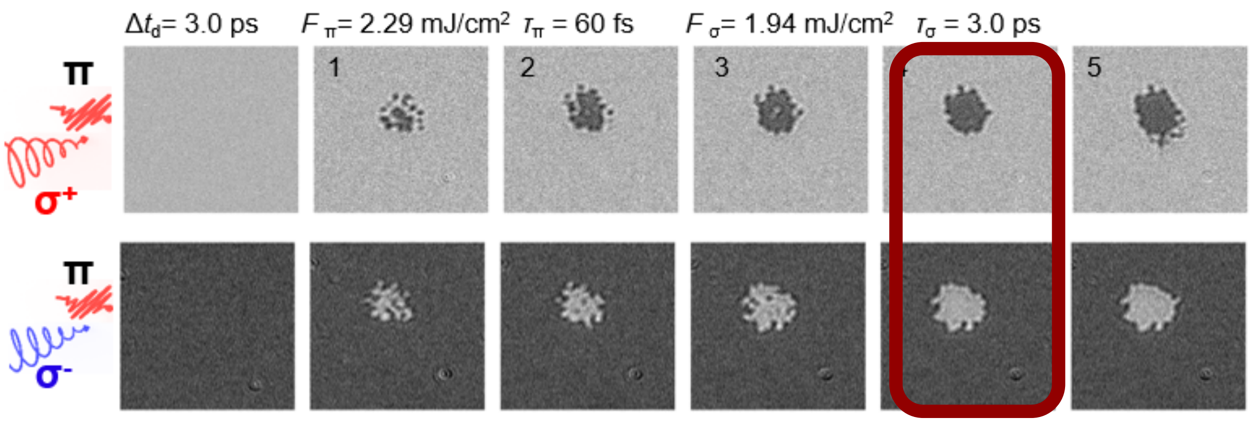
# Dual pulse HD-AOS in Co/Pt

**Co/Pt**



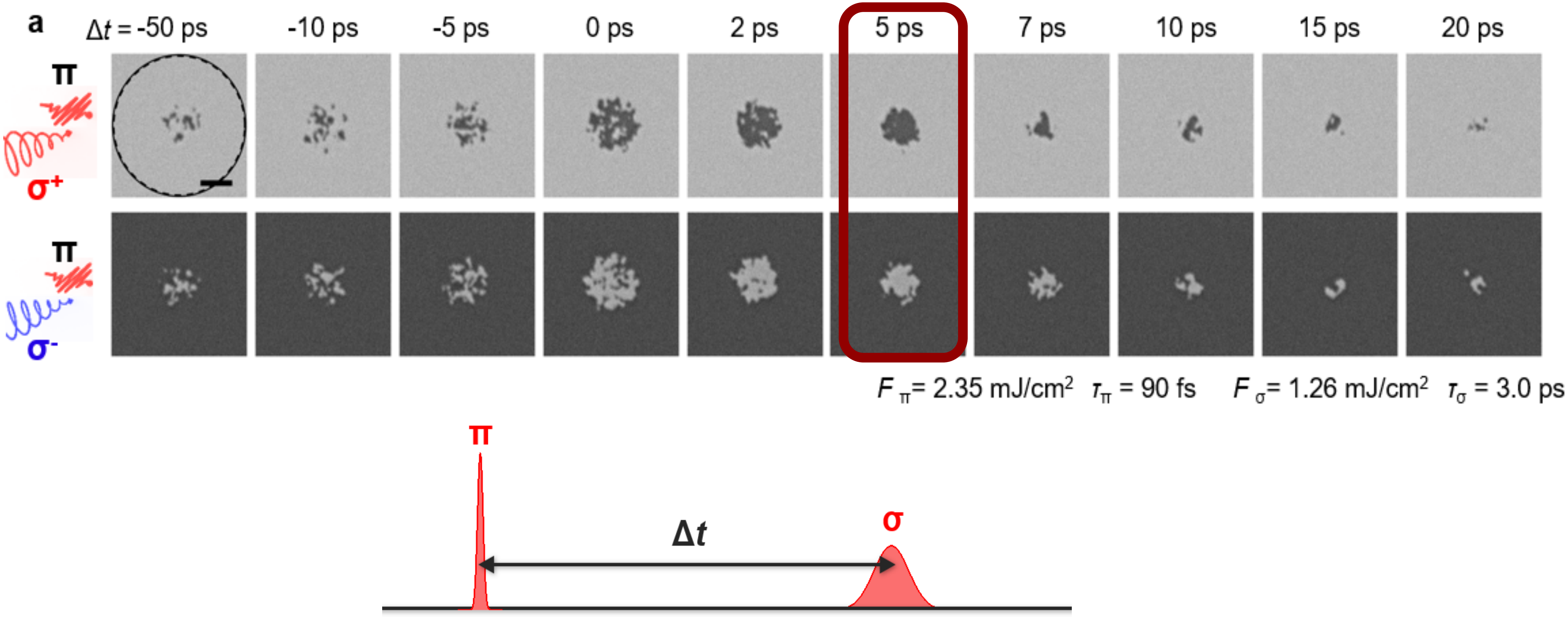

- Pulse separation = 2.0 ps,
- Pulse width = 60 fs (π) and 3.0 ps (σ)



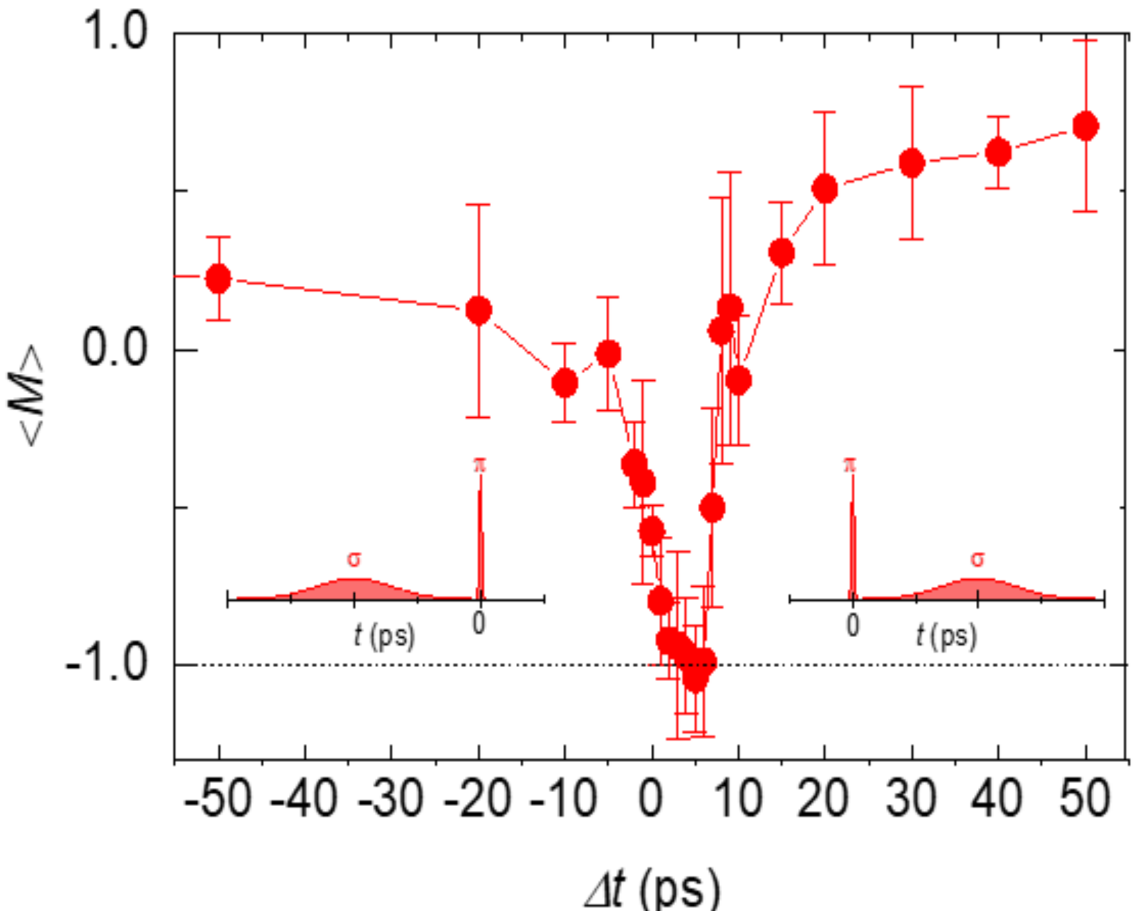

**4 pairs of pulses can fully switch the magnetization!!!**

**100 → 8 pulses!**

# Pulse separation dependence



# Pulse separation dependence




short pulse interval:
domains paramagnetic
(cumulative heating)

long pulse interval:
low T slows down
DW motion.

**spin temperature close to but below $T_C$!**

K. Yamada, et al,submitted (2021)

**latest results: 1 pair, 2 pulses!**

# End of Moore's law?

ars TECHNICA SIGN IN

*TECHNOLOGY LAB —*

## Moore's law really is dead this time

The chip industry is no longer going to treat Gordon Moore's law as the target to aim for.

PETER BRIGHT - 2/11/2016, 2:22 AM

The Telegraph ALL SECTIONS

Technology More

Technology

## End of Moore's Law? What's next could be more exciting

MADHUMITA MURGIA
HEAD OF TECHNOLOGY

25 FEBRUARY 2016 • 7:30PM

**Computing**

## Moore's Law Is Dead. Now What?

Shrinking transistors have powered 50 years of advances in computing—but now other ways must be found to make computers more capable.

by Tom Simonite May 13, 2016

**Mobile apps, video games, spreadsheets, and accurate weather forecasts:** that's just a sampling of the life-changing things made possible by the reliable, exponential growth in the power of computer chips over the past five decades.

But in a few years technology companies may have to work harder to bring us advanced new use cases for computers. The continual cramming of more silicon transistors onto chips, known as Moore's Law, has been the feedstock of exuberant innovation in computing. Now it looks to be slowing to a halt.

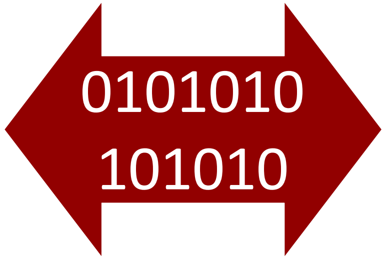
## Microsoft Ends Moore's Law, Builds a Supercomputer in the Cloud

WebProNews (http://www.webpronews.com/author/admin/) / 10.17.2016 /

# End of smaller and faster?

I. End of "Moore": too much heat

II. Higher density = too much energy




III. von Neumann bottleneck: transfer information back and forth

# Create a new paradigm, beyond von Neumann

# Supercomputer versus Brain:

**10 MW**

Processing and storage

**Separated and serial**

**10 W**

Processing and storage

**Integrated and parallel!**

Dec 2016

The New York Times Magazine

# The Great A.I. Awakening


**Rule base + brute force**

1997, IBM Deep Blue


**Learning + pattern recognition**

2016, Google AlphaGo

Dec 2016

The New York Times Magazine

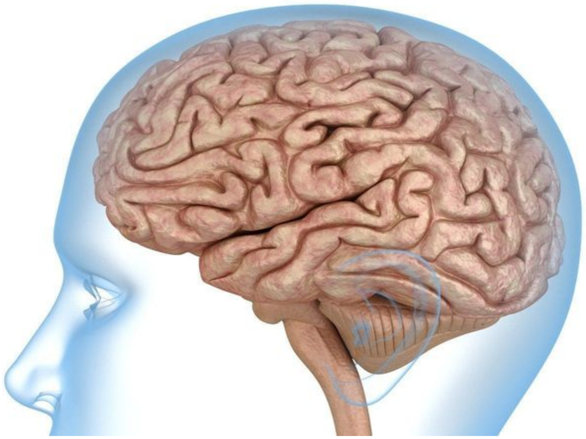
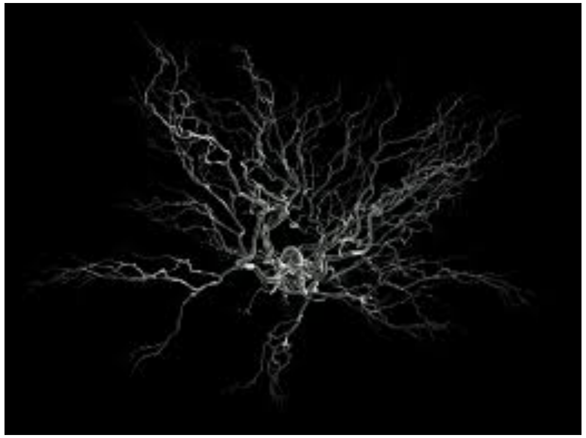
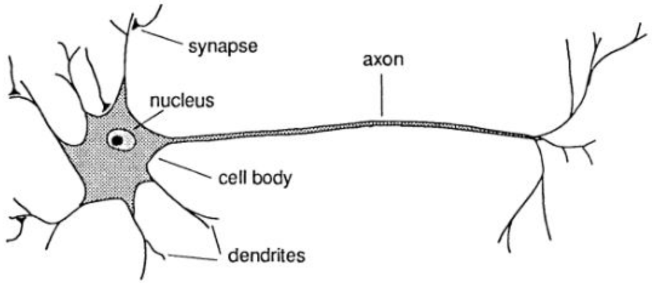
# The Great A.I. Awakening

**Program that learns!**

**Requires energy consuming supercomputer**


# Paradigm shift: *to develop materials that "learn"*

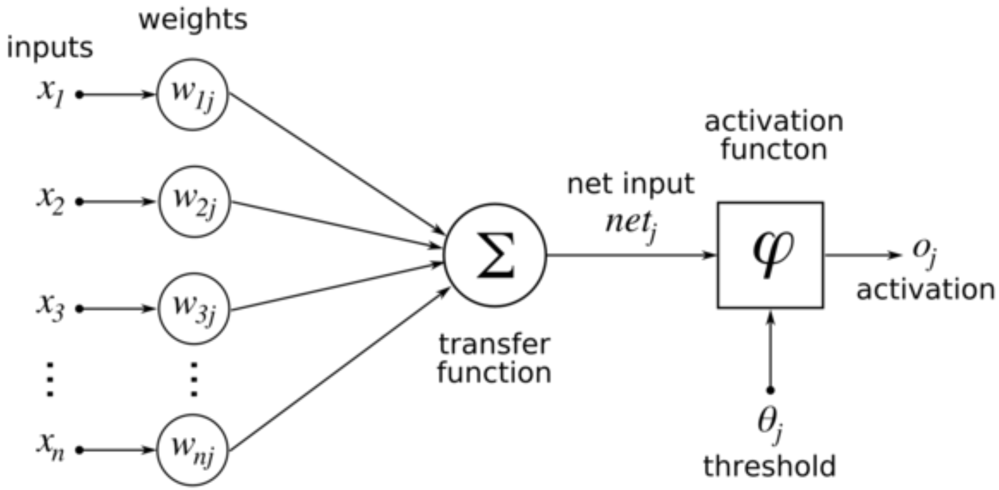
# What happens at a single neuron?


**Single neurons are connected by synapses**

***a scheme with adaptation ....***

# Synaptic Neuron Memory



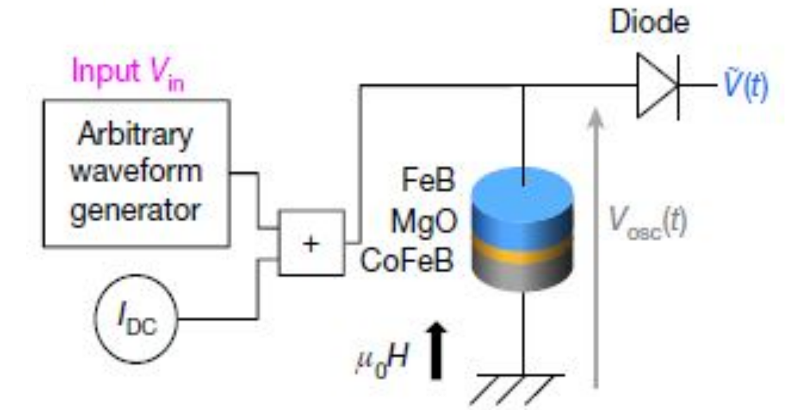

**Artificial neuron: <u>many inputs</u> and <u>one output</u>**

**Decision making: Summation of weights of individual <u>inputs</u>**

**The neuron fires :** $X_1W_1 + X_2W_2 + X_3W_3 + \ldots > T$

- **Stable intermediate memory states required for synaptic memory**
- **Reconfigurable in terms of current flow**
- **Materials that can learn**

# Research on adaptable materials

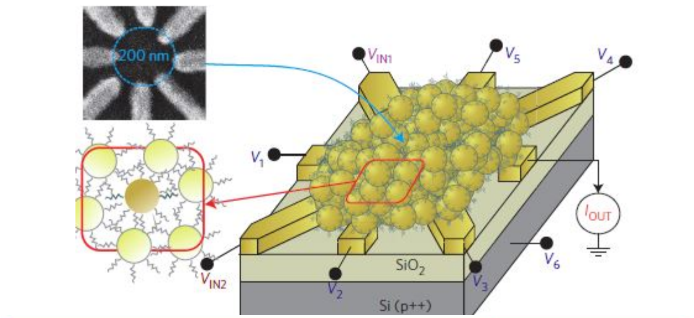



LETTER

doi:10.1038/nature23011

**Neuromorphic computing with nanoscale spintronic oscillators**

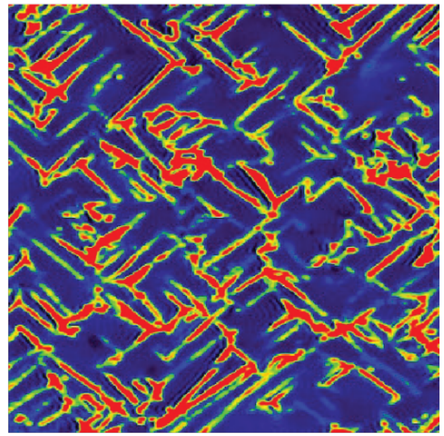
Jacob Torrejon[1], Mathieu Riou[1], Flavio Abreu Araujo[1], Sumito Tsunegi[2], Guru Khalsa[3]†, Damien Querlioz[4], Paolo Bortolotti[1], Vincent Cros[1], Kay Yakushiji[2], Akio Fukushima[2], Hitoshi Kubota[2], Shinji Yuasa[2], Mark D. Stiles[3] & Julie Grollier[1]




LETTERS
PUBLISHED ONLINE: 21 SEPTEMBER 2015 | DOI: 10.1038/NNANO.2015.207
nature nanotechnology

**Evolution of a designless nanoparticle network into reconfigurable Boolean logic**

S. K. Bose[1†‡], C. P. Lawrence[1,2‡], Z. Liu[1], K. S. Makarenko[1], R. M. J. van Damme[3], H. J. Broersma[2] and W. G. van der Wiel[1*]

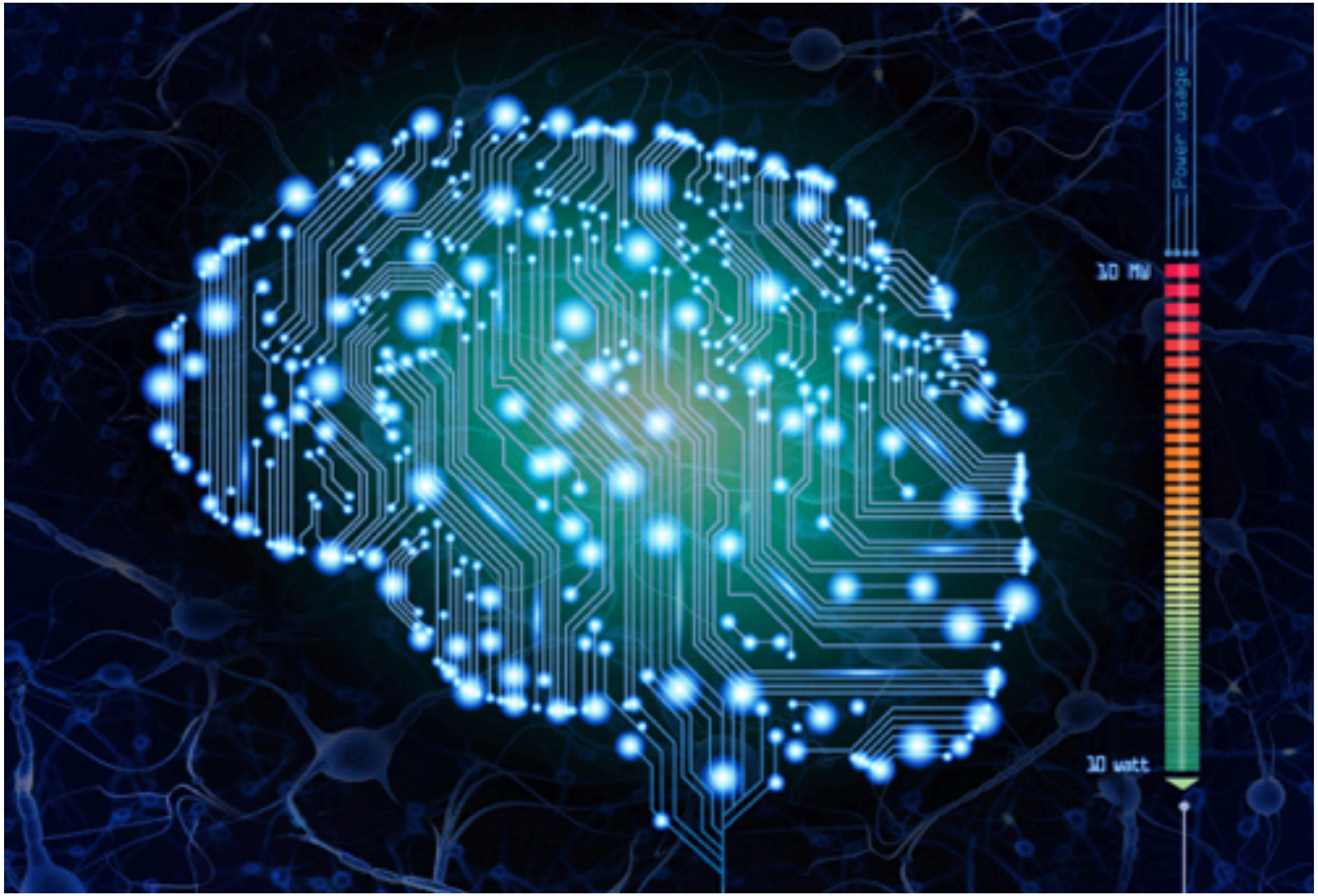


Noheda et al, Nature 2014

***Learning is done via external computer....***

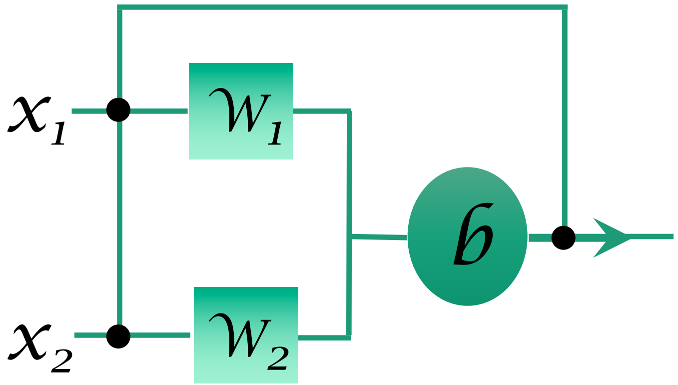
***Can we develop materials that learn?***

# *Computing with Magneto-Optics?*



# Perceptron learning: 'global' feedback

***Weights are computed after each pattern*** $(\mu)$




This image cannot

$$\Delta w_i = \eta \times sign(O_d^1 - O^1)x_i^1$$

$$w_i = w_i + \Delta w_i$$

$$O^2 = sign(x_i^2 w_i - b);$$

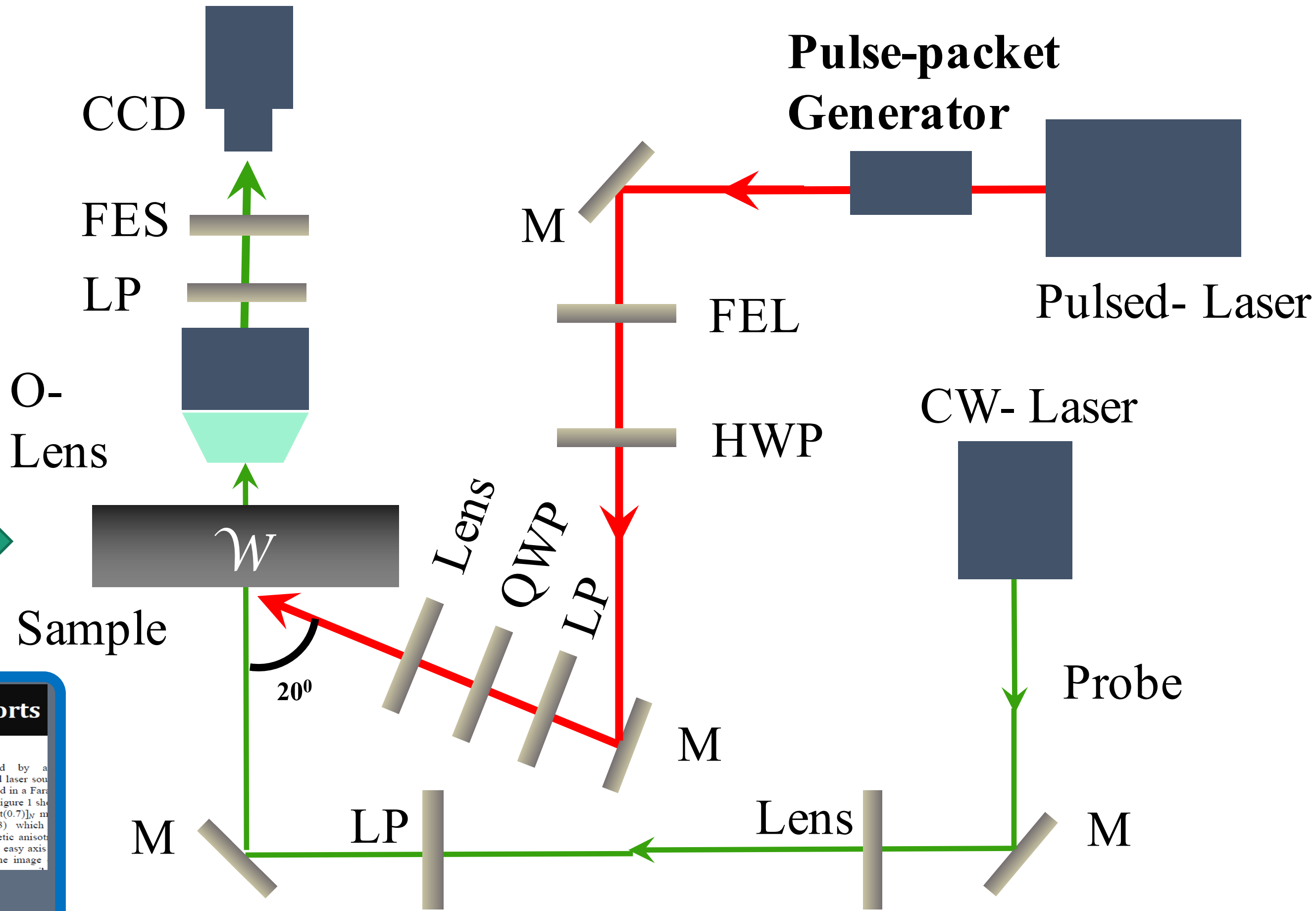
$$\Delta w_i = \eta \times sign(O_d^2 - O^2)x_i^2$$

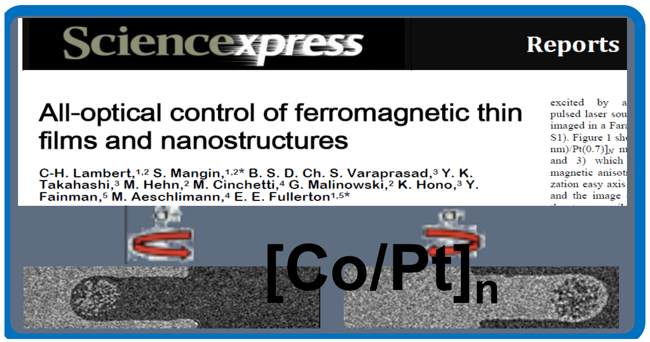
$$w_i = w_i + \Delta w_i$$

$O^3$ ....... $O^4$ .......

***No external storage required!*** ***$W_i$ in material!***

# Magneto-optical Implementation

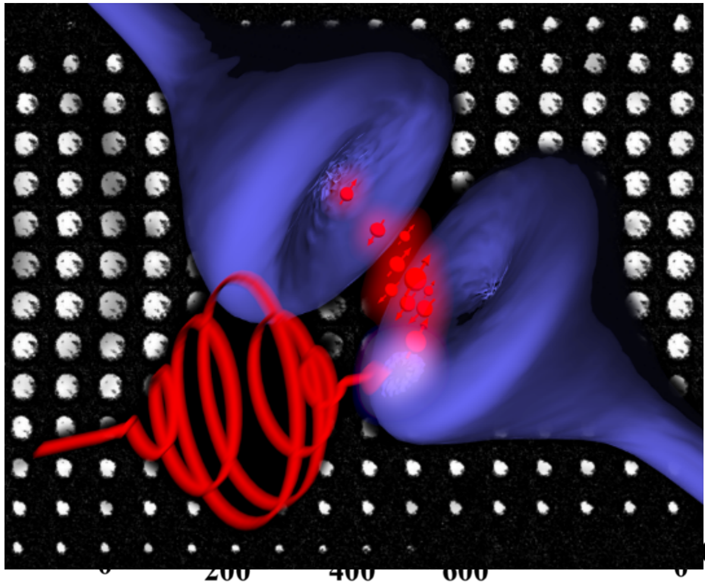




Sciencexpress Reports

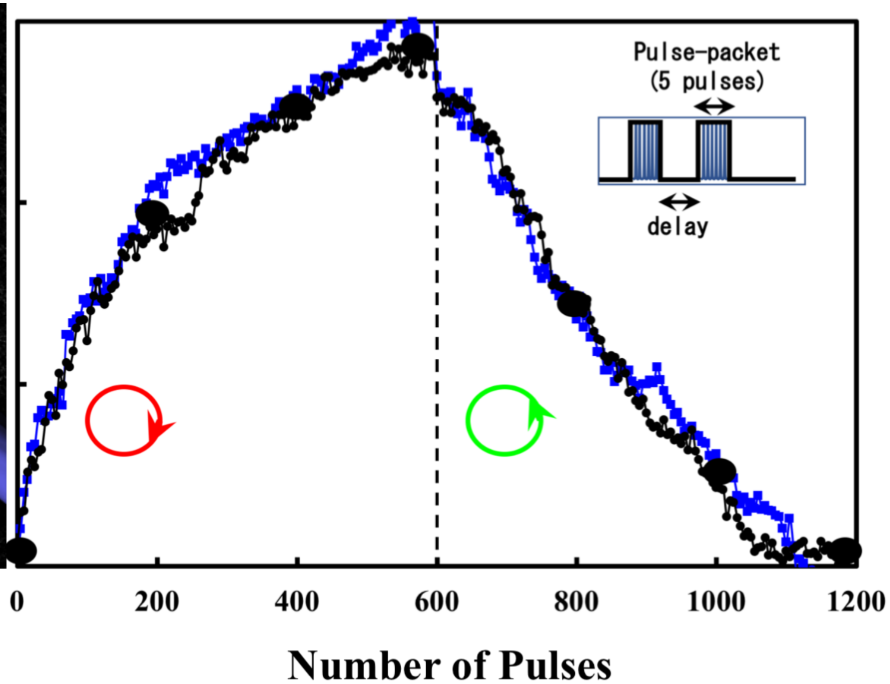
All-optical control of ferromagnetic thin films and nanostructures

C-H. Lambert,1,2 S. Mangin,1,2* B. S. D. Ch. S. Varaprasad,3 Y. K. Takahashi,3 M. Hehn,2 M. Cinchetti,4 G. Malinowski,2 K. Hono,3 Y. Fainman,5 M. Aeschlimann,4 E. E. Fullerton1,5*

# Continously variable weights

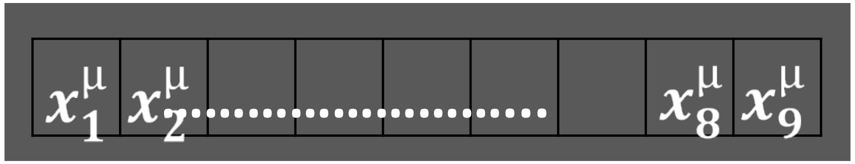


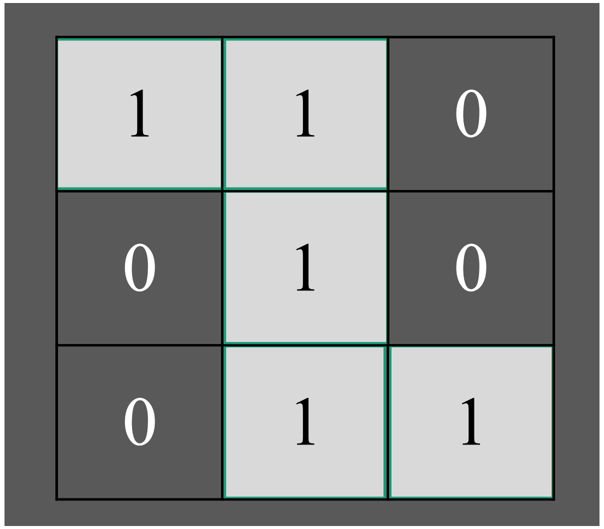
Number of Pulses



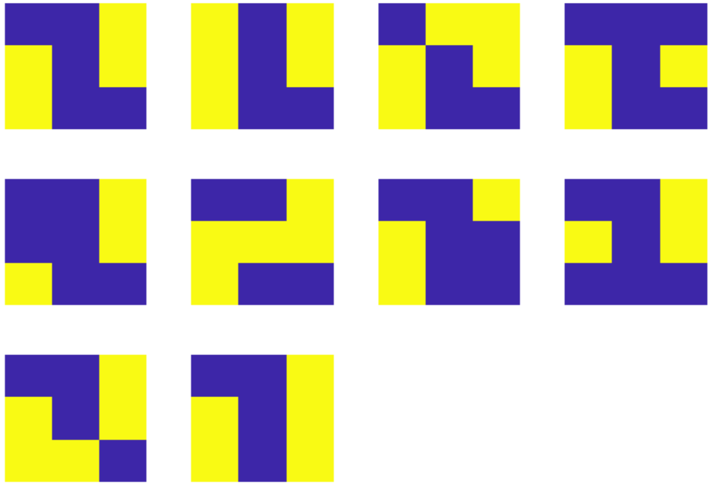

Reproducible adaptation of weights with
circularly polarized laser pulses
pulse width 4 ps, 5 pulses/packet fluence 1.3mJ/cm$^2$
***(A. Chachravarty et al, APL 2019)***

# Pattern recognition



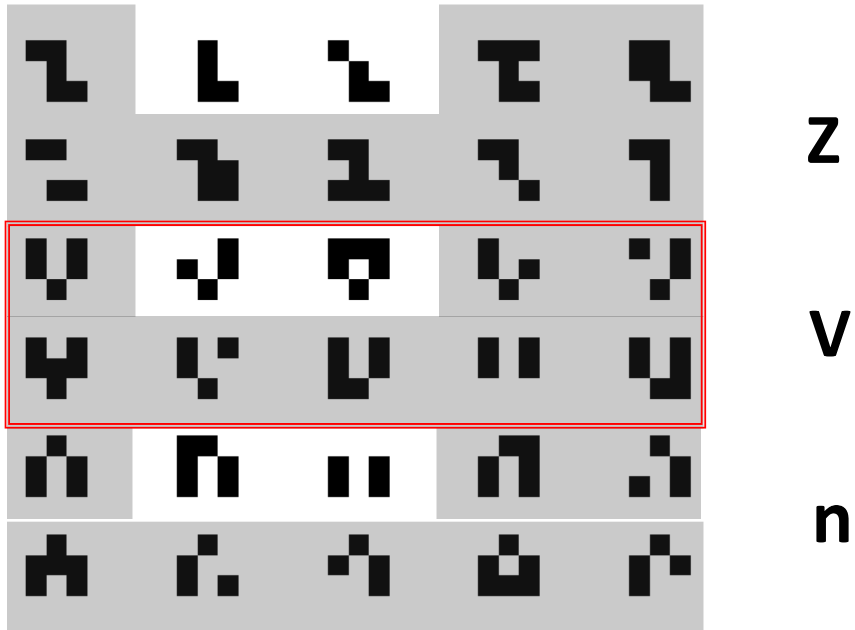




A weight is associated with each pixel



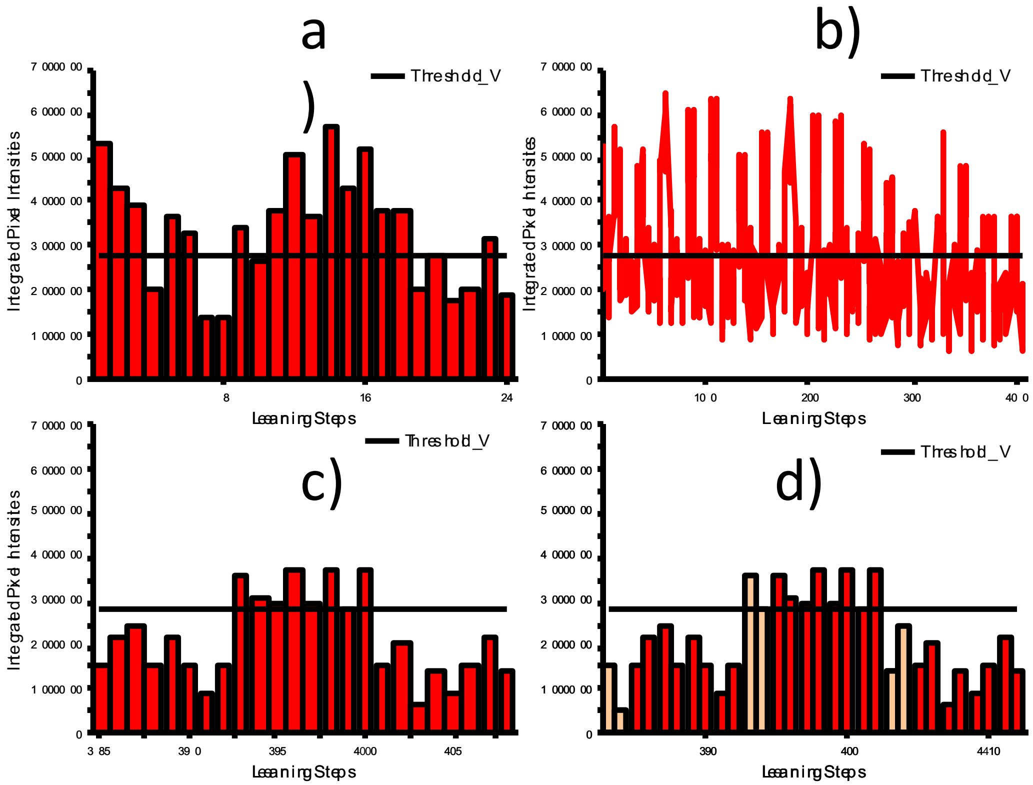
Perturbed pattern: flipping one pixel at a time

# Training/Operating the Network




**goal:** classify “v” from “z” and “n”

# Training/Operating the network



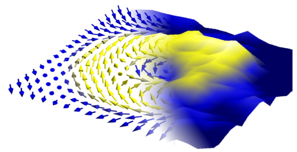

- ~400 steps: learning completed
- all unknown patterns classified

*(A. Chachravarty et al, in preparation)*

# Opto-magnetic neural network

- ✓ Realization of opto-magnetic synapses using ultrashort laser pulses on Co/Pt films
- ✓ Supervised learning with opto-magnetic synapses and global feedback
- ✓ No external storage needed: material that learns!
- ✓ pattern recognition achieved!
- ✓ Energy absorbed: 65 pJ/synapse/step (1.125 μm): Extrapolates to 20 fJ/synapse/step (20 nm)

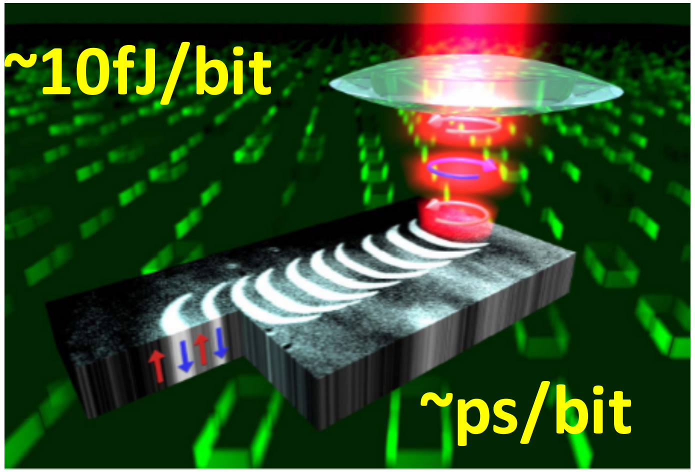
**Next steps: more inputs (+ photonic network, NIST data base) + 3D**

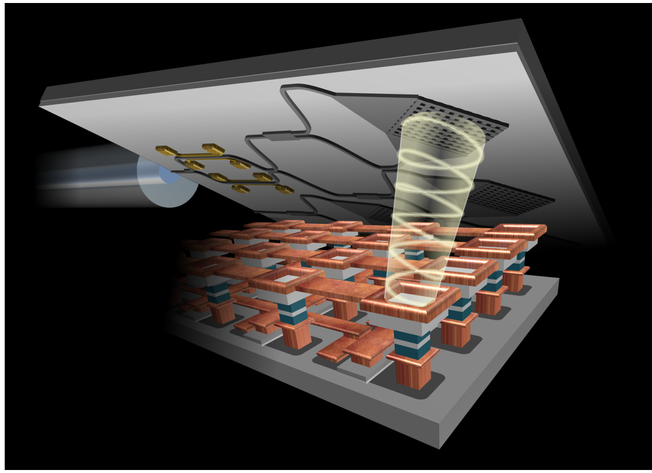


3D MAGiC

ERC Synergy Grant (with R. Dunin-Bukowski, S. Blugel, M. Klaui)

# *in summary*

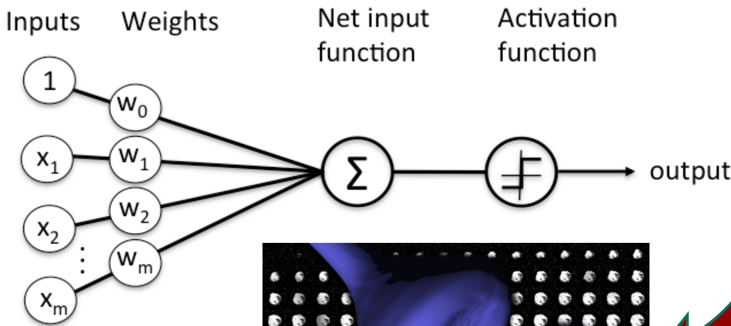


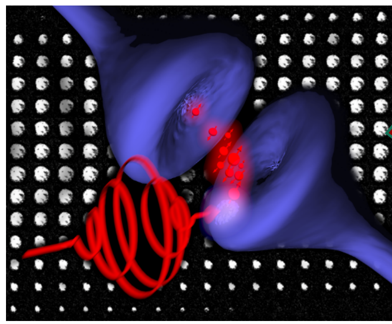



**Photon-spintronics**

**energy efficient**

**Brain-inspired computing!**



**outlook: learning on chip**

***(with the speed of light)***

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erc

***(PhD and PD positions available)***