Probing Magnetization Dynamics with Soft X-Rays

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Berkeley - ALS:

A. Scholl

magnetization dynamics

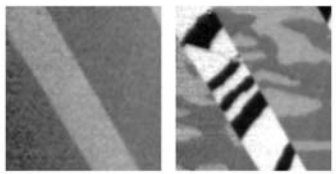
Space

The Microworld

10^{-3} m – 1 mm

100 μm

AFM & FM domains

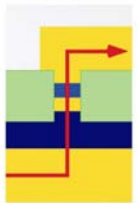


10 μm

10^{-6} m – 1 μm

Recorded "bits"

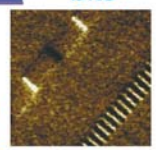
Spin injection



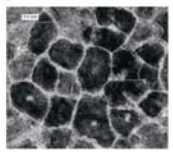
The Nanoworld

100 nm

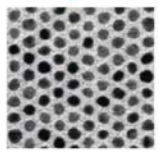
Media grains



10 nm



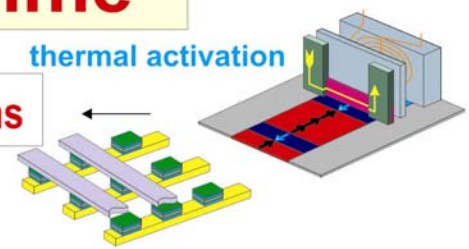
Nano-particles



10^{-9} m – 1 nm

Time

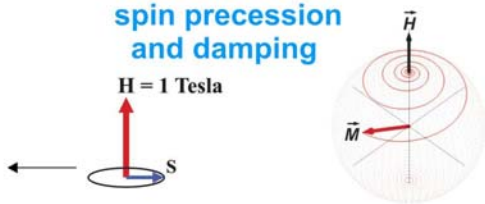
thermal activation



10^{-9} s – 1 ns

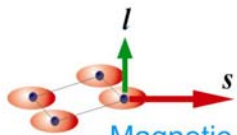
100 ps

spin precession and damping



10 ps

10^{-12} s – 1 ps



Spin-orbit coupling

Magnetic anisotropy

100 fs

10 fs

Exchange interaction

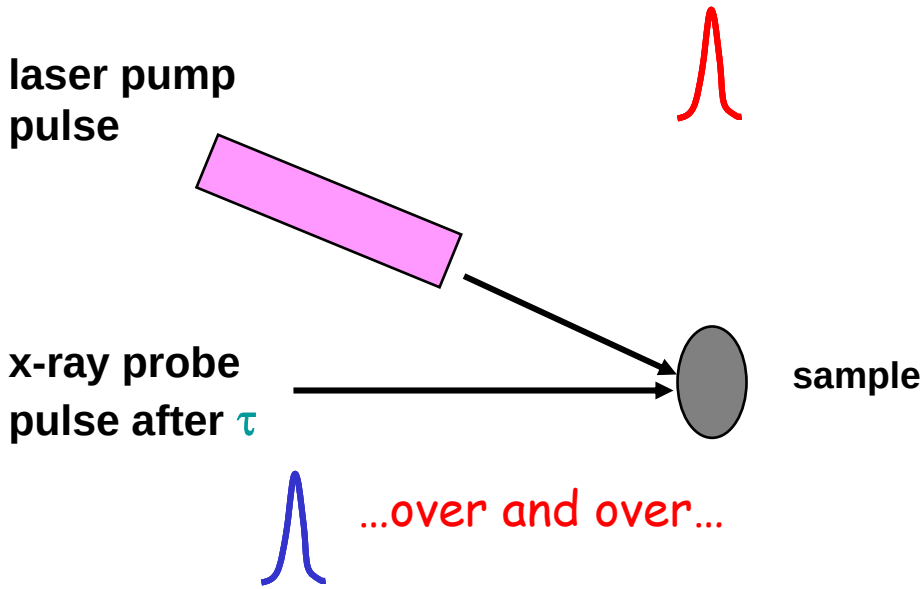
10^{-15} s – 1 fs

Today
Lasers
X-rays

Ultrafast

Note: Δt (fs) = 4 / ΔE (eV)

Present: Pump/Probe Experiments



Can produce various pump pulses:

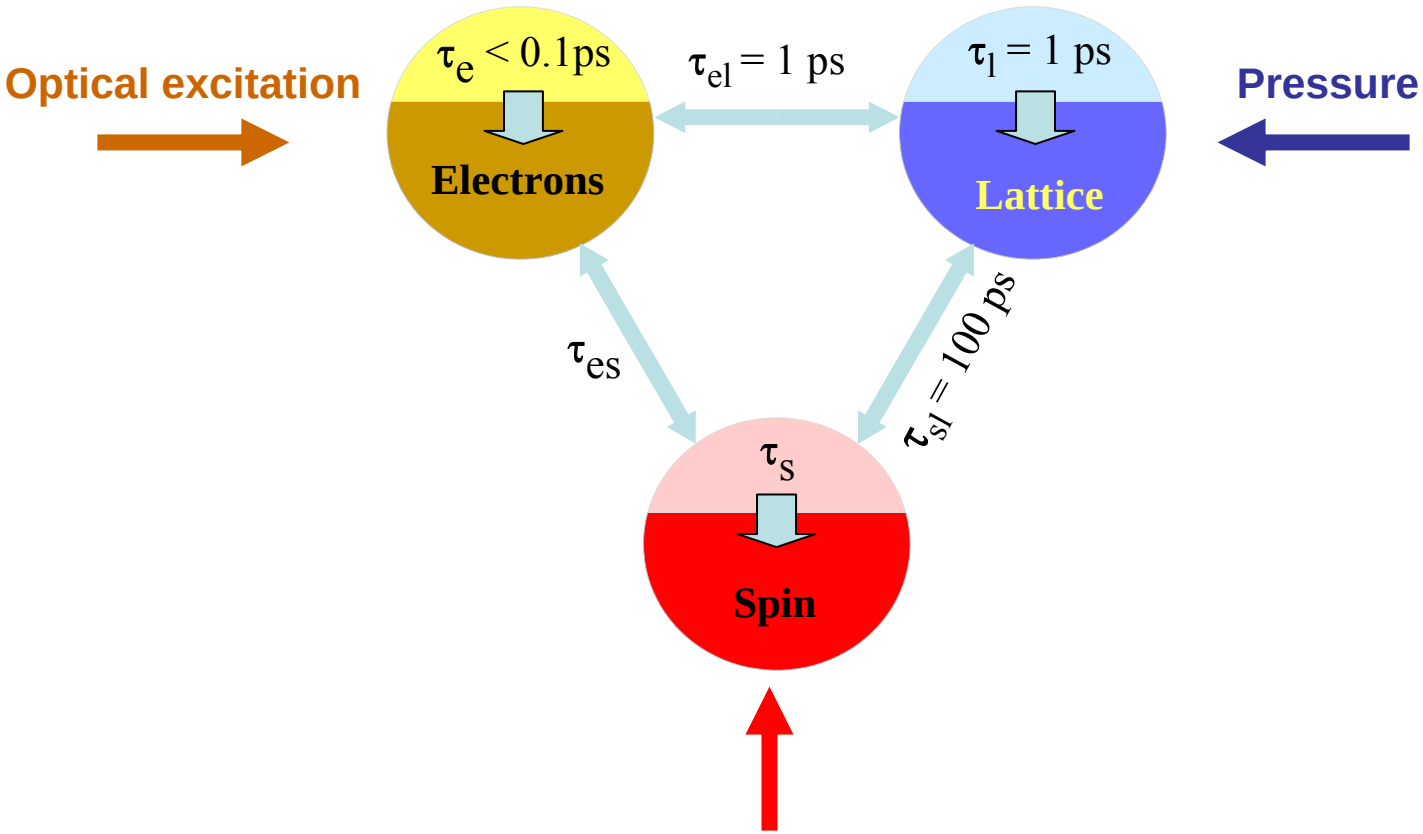
- **heat electrons (photon pulse)**
- **kick magnetization (field pulse)**
- **heat lattice (pressure pulse)**

Process has to be reversible:

Not enough intensity for single shot experiments

Non-Equilibrium Magnetization Dynamics

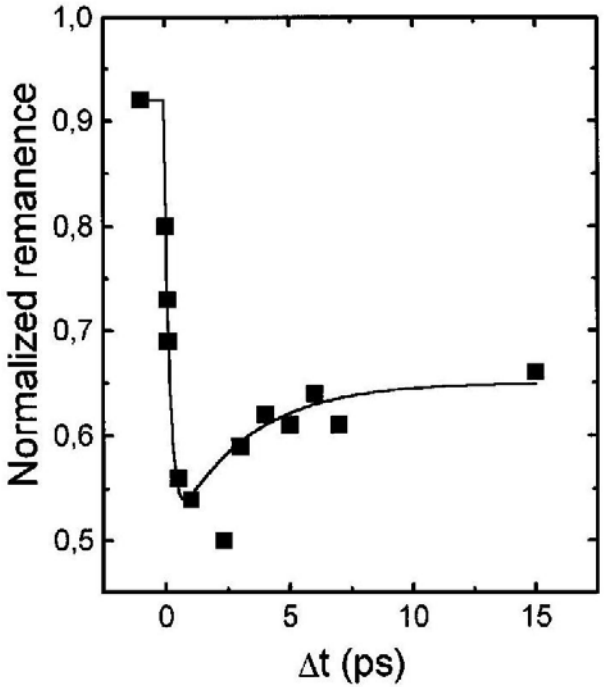
transfer of **energy** and **angular momentum**



Science: Mechanisms of energy and angular momentum transfer
Technology: How fast can we switch reliably?

Optical excitation: Ni metal

MOKE: pump-probe



E. Baurepaire, J. C. Merle,
A. Daunois, and J. Y. Bigot
PRL **76**,4250 (1996)

VOLUME 85, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 2000

Ultrafast Magneto-Optics in Nickel: Magnetism or Optics?

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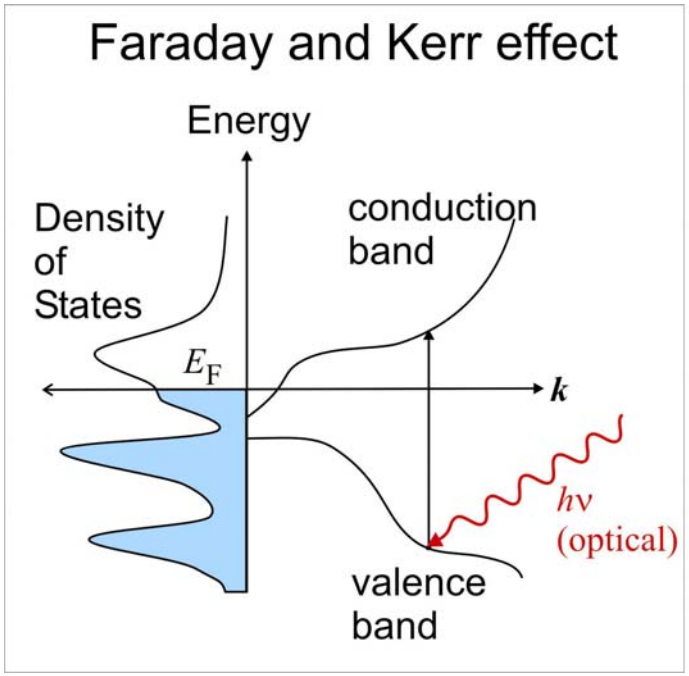
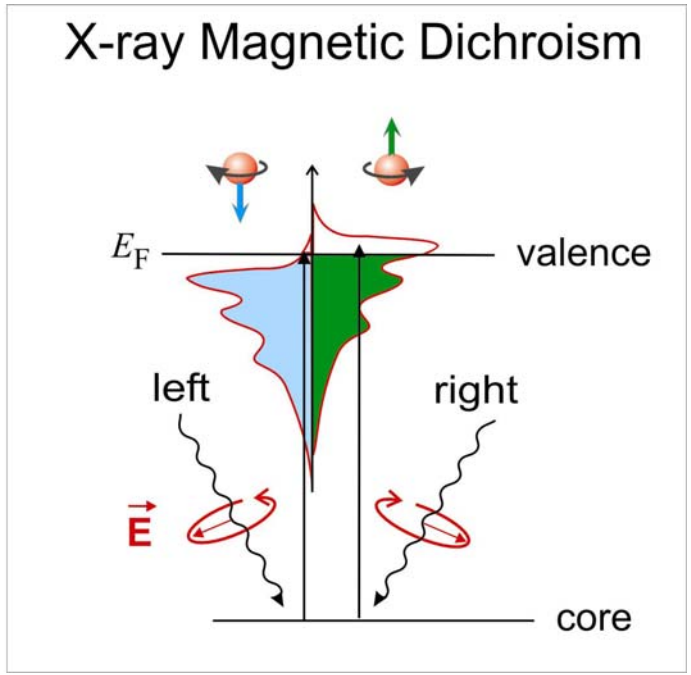
Eindhoven University of Technology, Department of Applied Physics, COBRA Research Institute, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands
(Received 22 February 2000)

Optical excitation studies benefit from x-ray probe

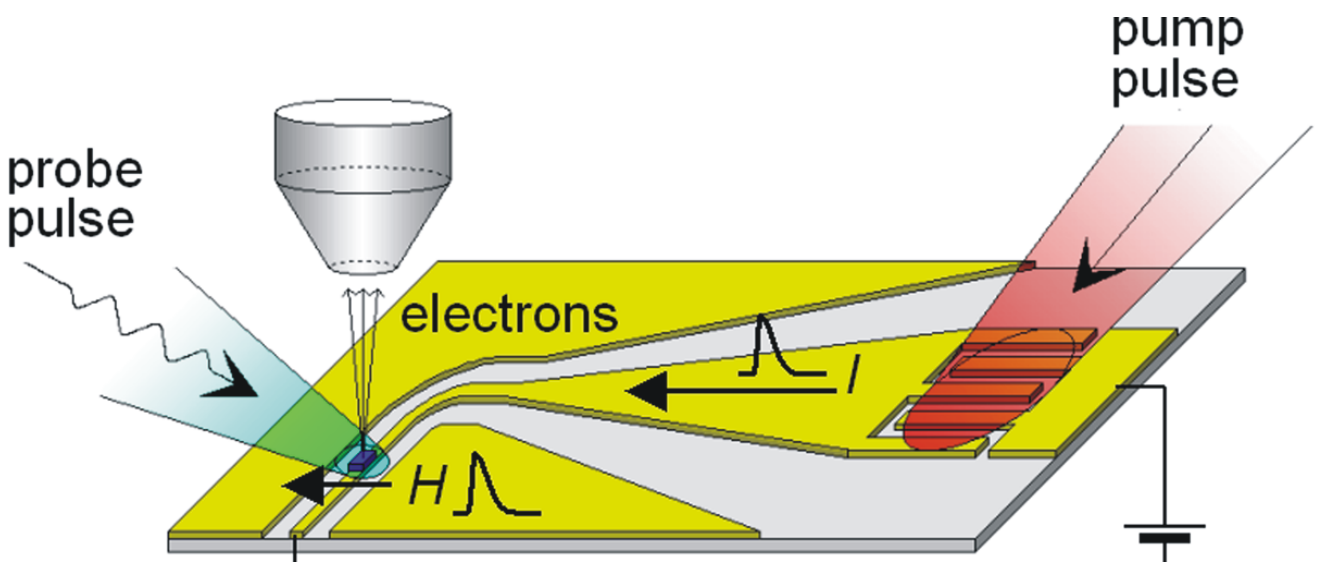




- **spin moments,**
- **orbital moments**
- **nanoscale resolution**

But – need sub- 50-ps time resolution:
streak camera, slicing, XFELs

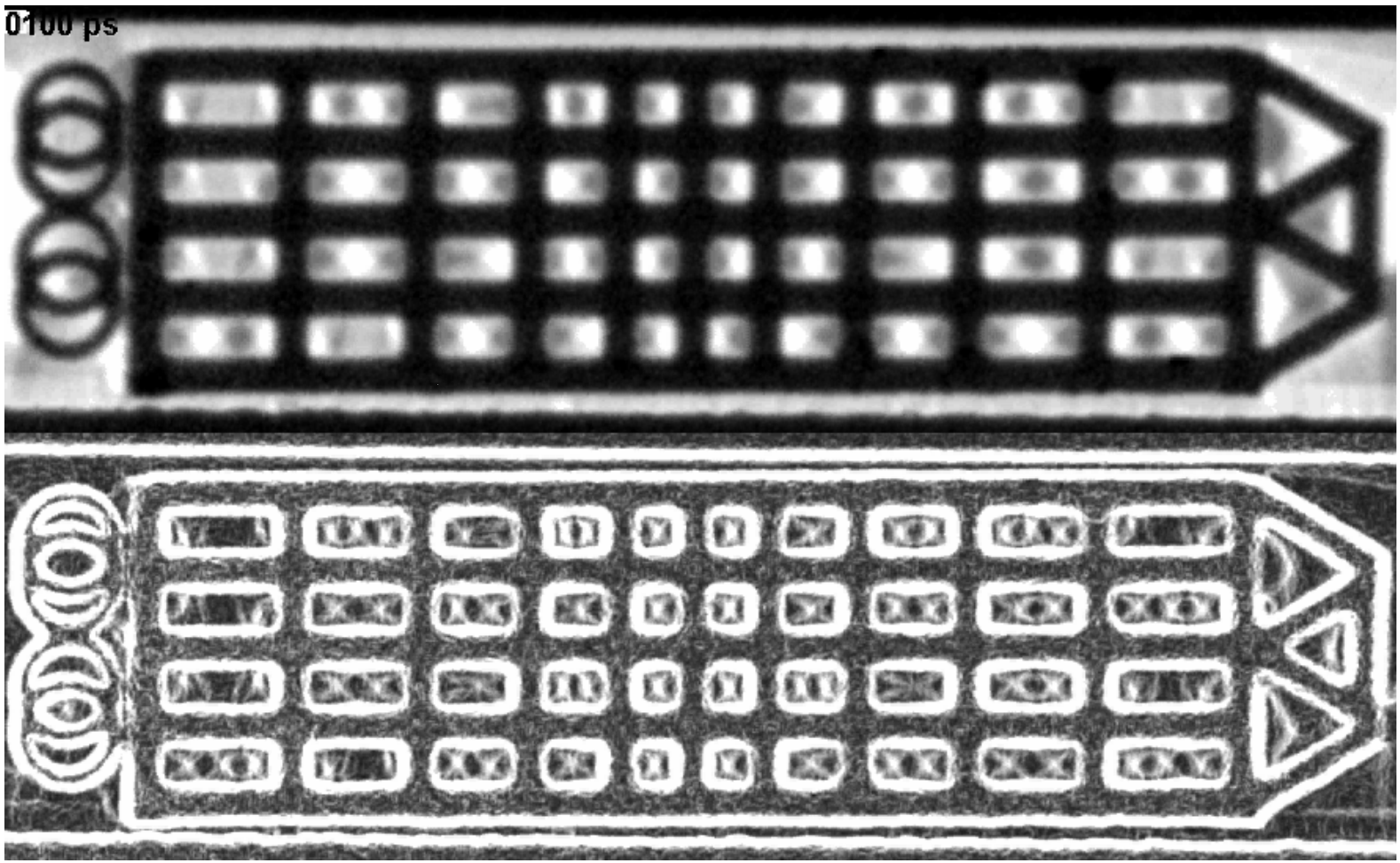
Magnetic Excitation - Today:
Imaging of Nanoscale Magnetization Dynamics

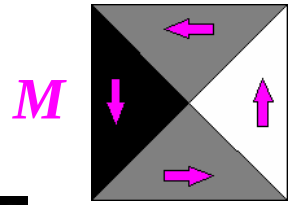


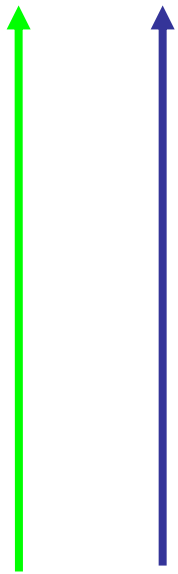
Pump / probe requires reversibility of excitation process
- not enough intensity to obtain single shot images

Cannot presently study irreversible processes:
this would require single shot pictures

Magnetic Patterns in 20 nm $Co_{90}Fe_{10}$ films on waveguide







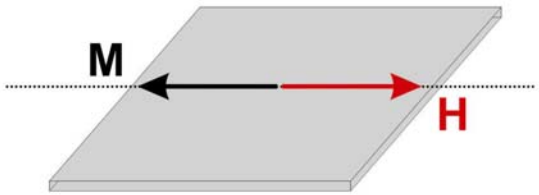
x-ray "spin" **Field pulse**

S.-B. Choe, Y. Acremann, A. Scholl, A. Bauer, A. Doran, J. Stöhr, H.A. Padmore, Science **304**, 430 (2004)

Nanaoscale Magnetization Dynamics - Smaller and Faster

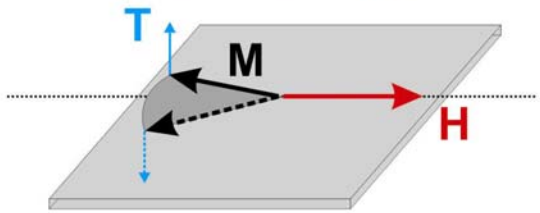
Today's Switching Process - about 1 ns

No torque on **M**
no switching



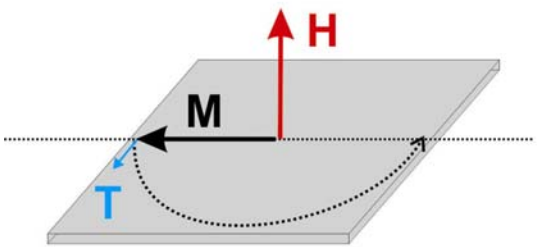
easy axis

Thermal excitation → torque **T**=**H** x **M**
starts switching process



Explore faster and more efficient switching

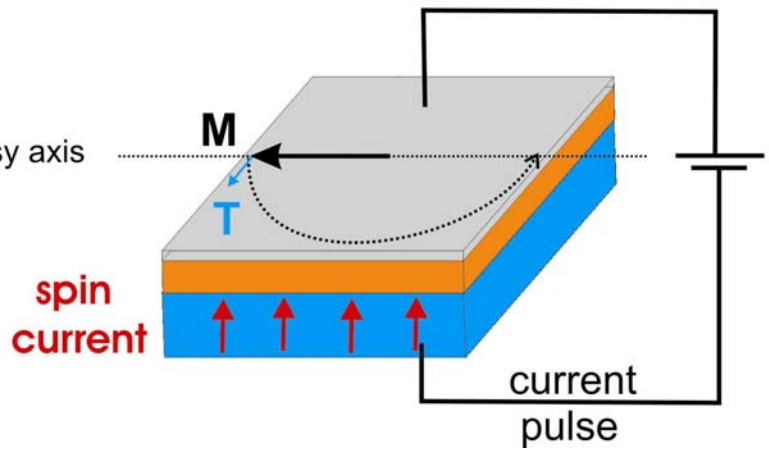
Maximum torque on **M**
"precessional switching"



H = 1 Tesla ⟶ 10 ps

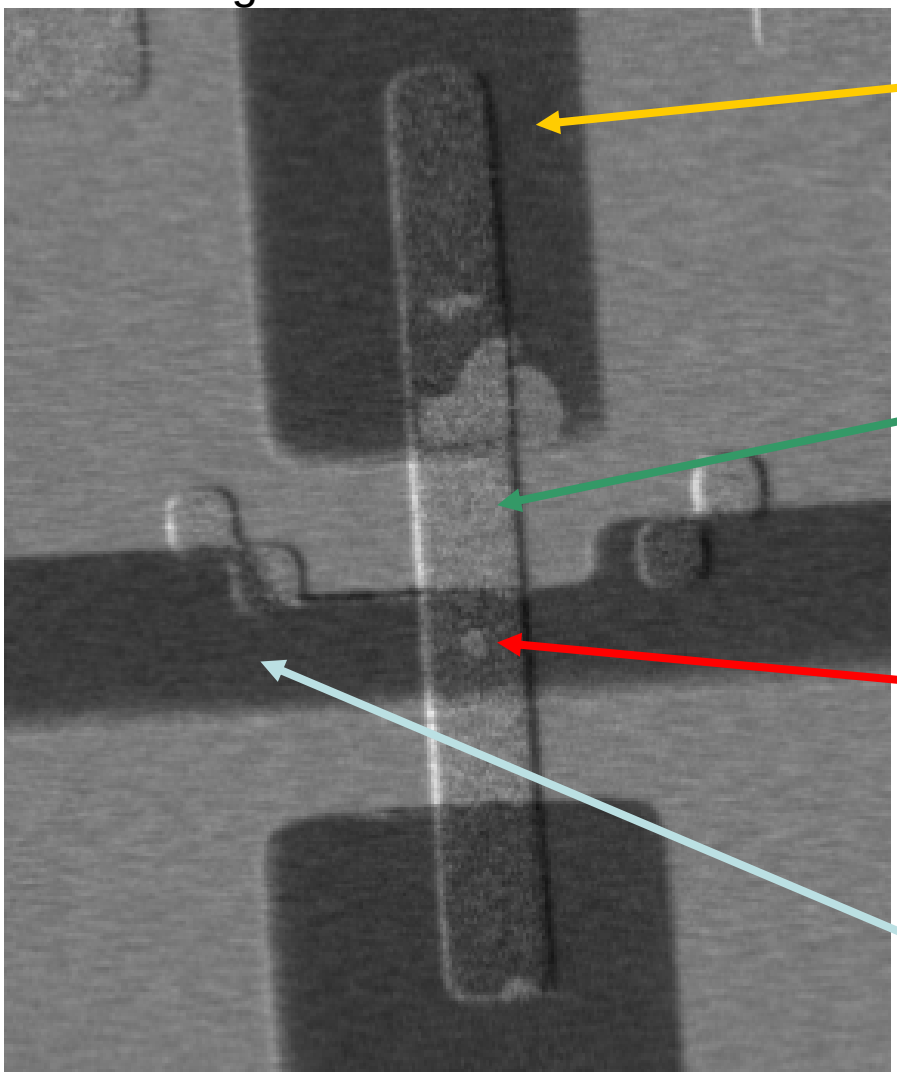
easy axis

Switching by spin currents
"exchange switching"



STXM image of spin injection structure

STXM image of device



1. Cu lead delivers current to device
2. Pt lead guides current to bottom of spin injection pillar
3. Current flows through pillar, switching second ferromagnet
4. Current extracted through second Cu lead

Challenge is nanoscale sample production – pillar diameter is < 100 nm

Why are irreversible or random processes important?

Two examples:

1. **Technology:**

   • **Reversible** processes are required for technology
   but
   • **Irreversible** processes determine technological limit !

2. **Science:**

   Equilibrium magnetization dynamics at Curie temperature

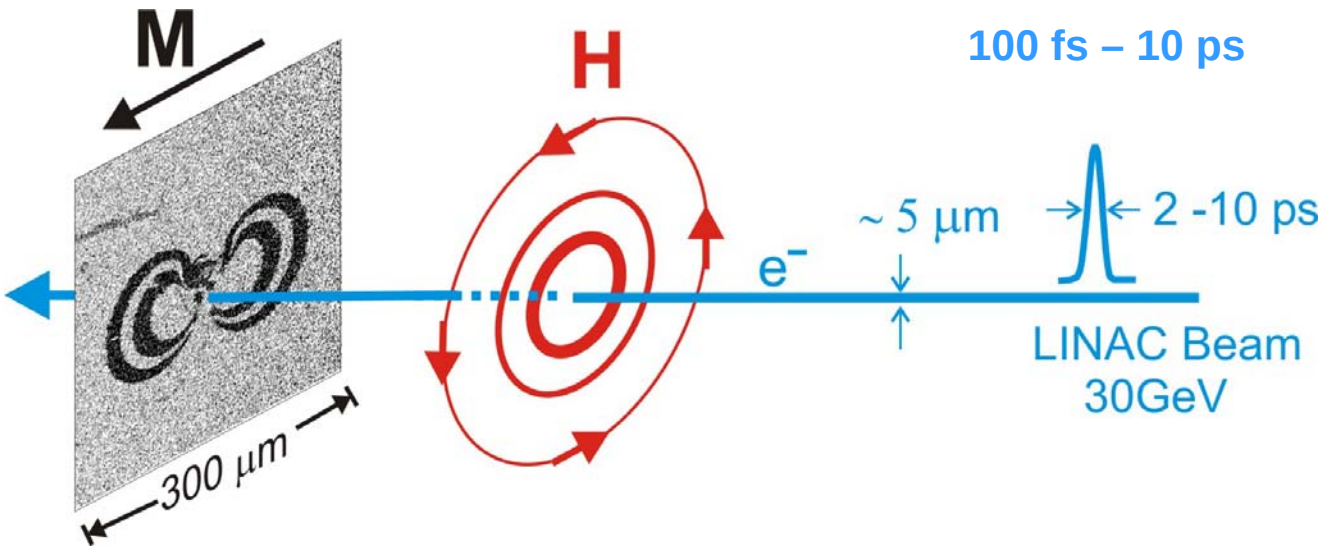
   Critical magnetizattion fluctuations are random

Such studies require single snapshot images !

Technology: Exploring the ultimate speed of magnetic recording

In R&D labs we can only produce 100 ps pulses – things still work fine

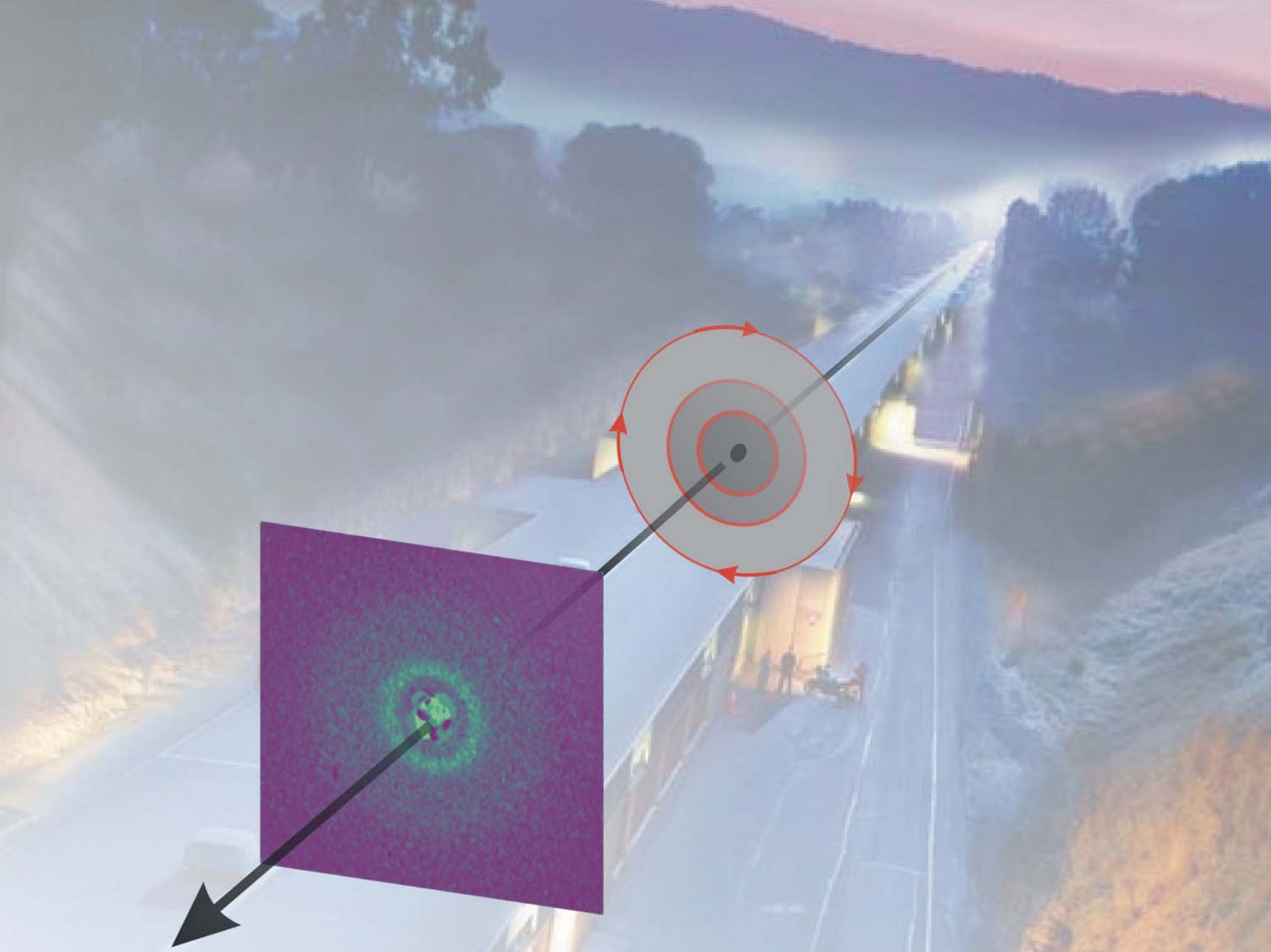
Unique method for faster switching



Relativity allows packing 10^{10} **electrons** into "bunch"

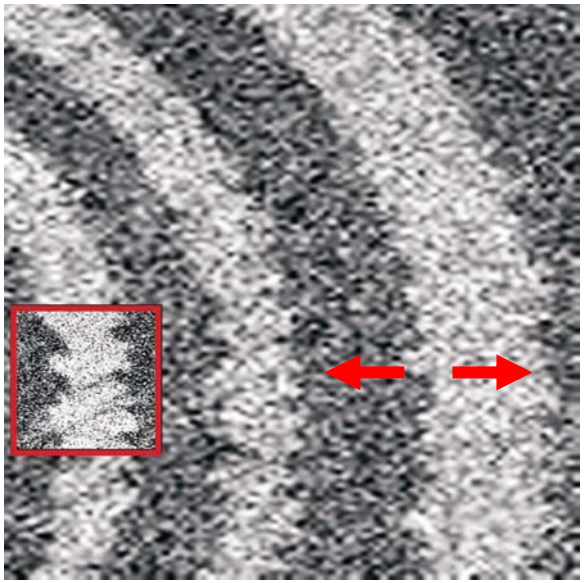
→ Ultra-short and high field pulses (up to 5 T)

Tudosa *et al.* Nature **428**, 831 (2004)



The Ultimate Speed of Magnetic Switching

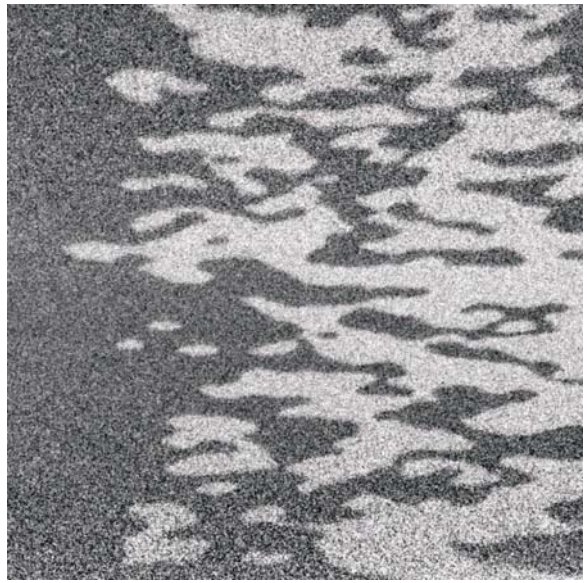
t_{pulse}= **3 ps**



90 μm

Deterministic switching

t_{pulse}= **100 fs**



90 μm

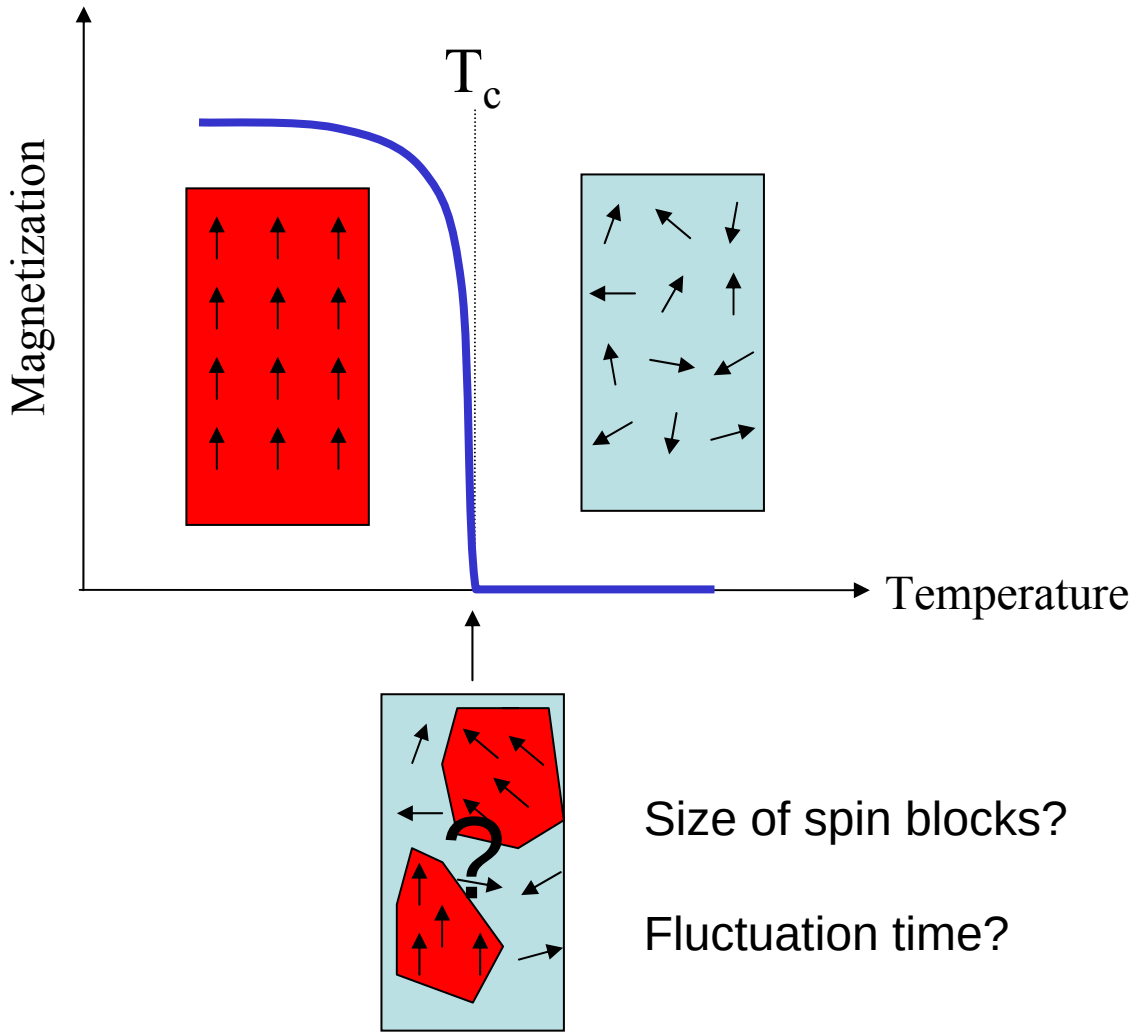
Chaotic switching

Under ultrafast excitation the magnetization fractures !

Tudosa *et al.* Nature **428**, 831 (2004) and unpublished

Science: Equilibrium Magnetization Dynamics

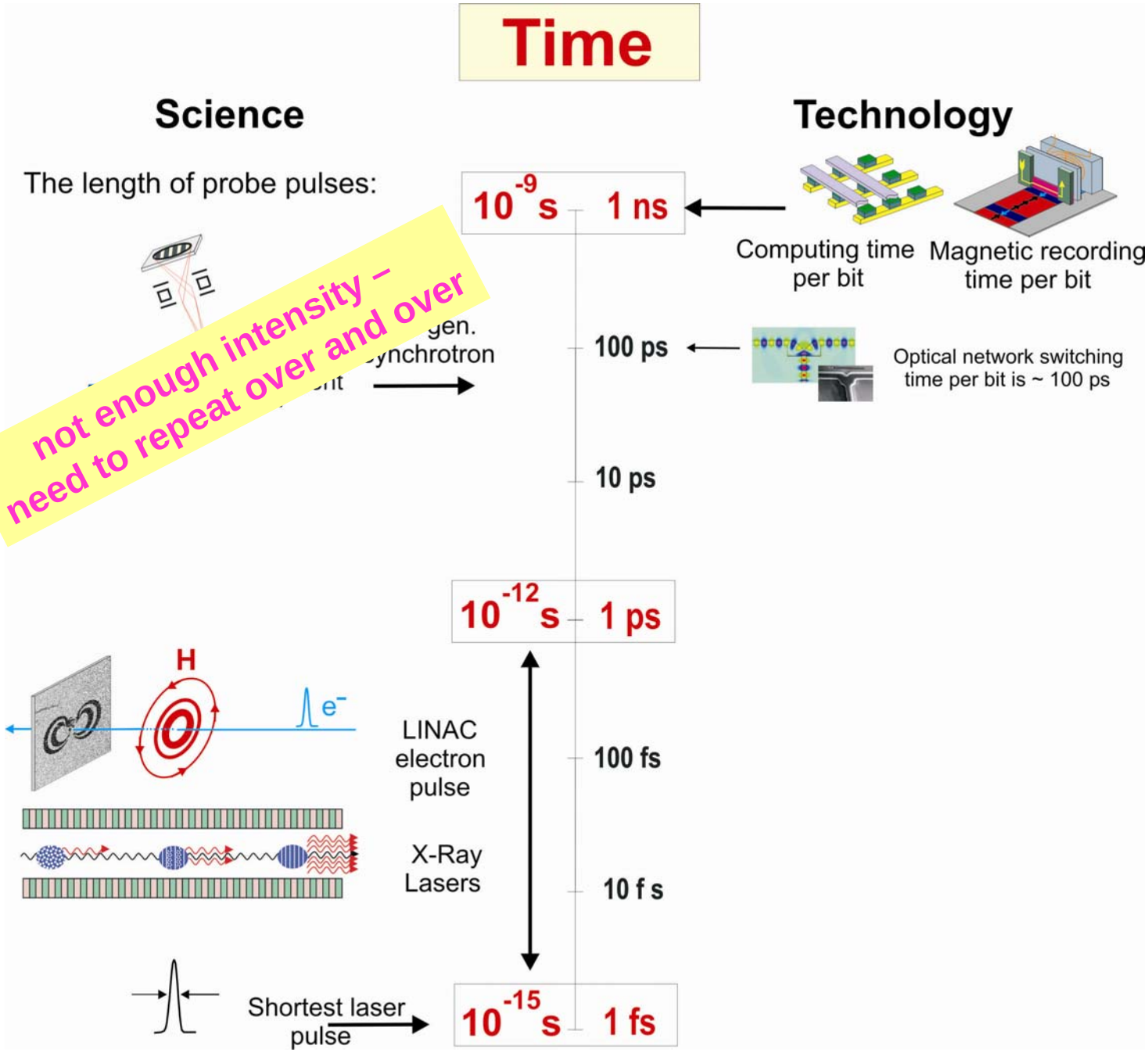
critical fluctuations



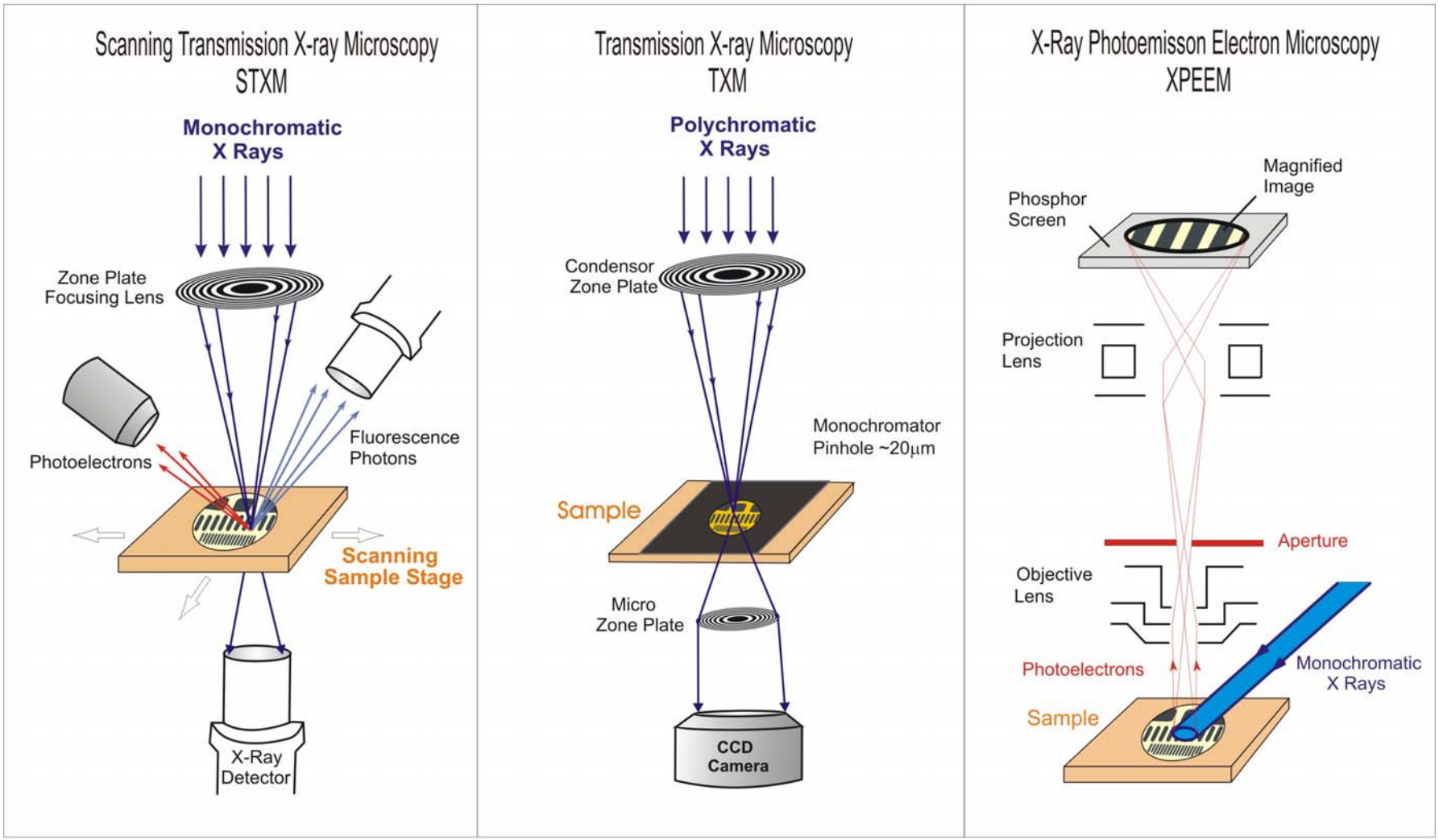
Size of spin blocks?

Fluctuation time?

Toward femtosecond magnetic motion pictures …..

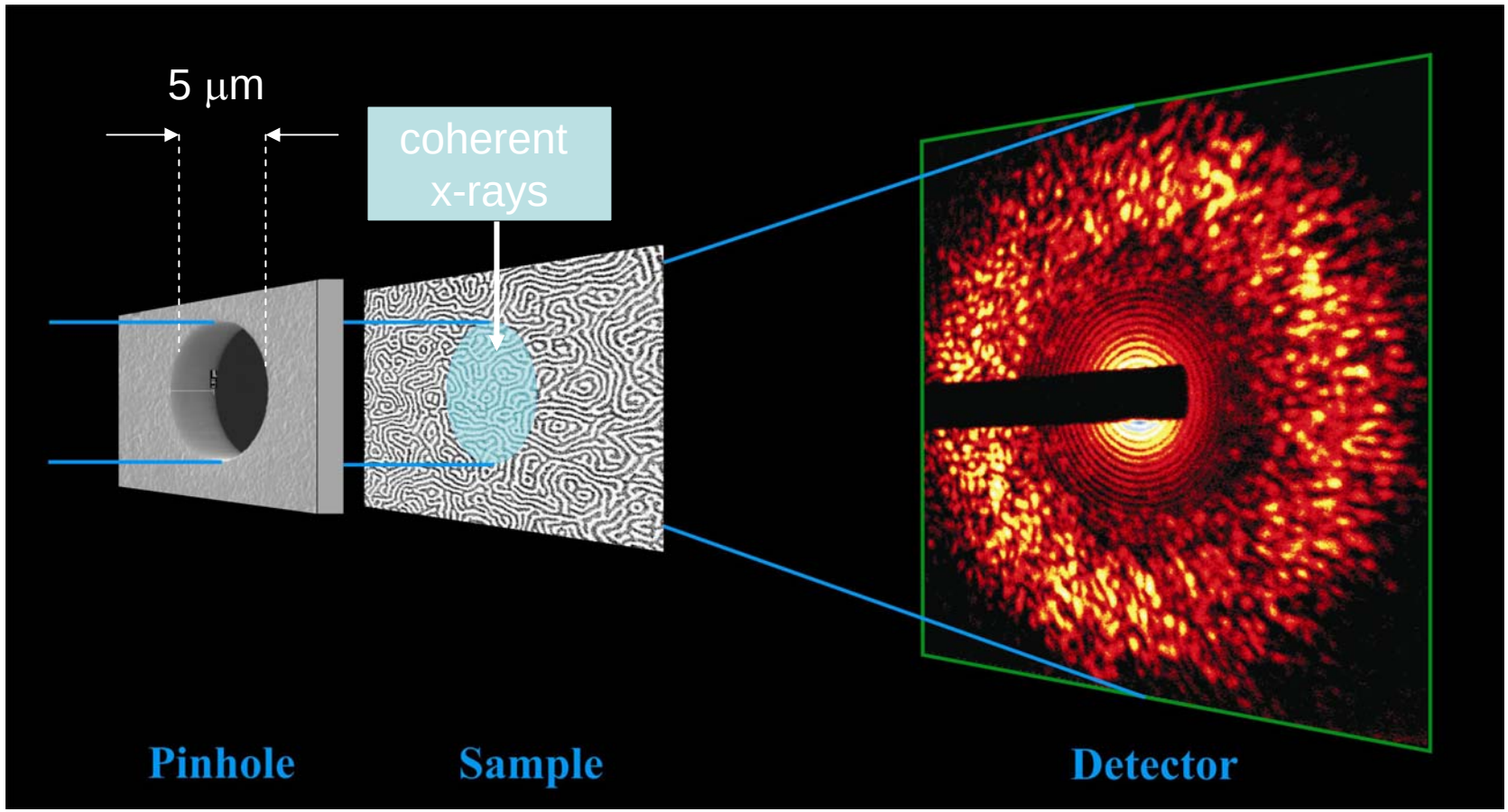

Time
Science
Technology
The length of probe pulses:
10^{-9} s
1 ns
Computing time per bit
Magnetic recording time per bit
gen.
ynchrotron
100 ps
Optical network switching time per bit is ~ 100 ps
not enough intensity – need to repeat over and over
10 ps
10^{-12} s
1 ps
H
e⁻
LINAC electron pulse
100 fs
X-Ray Lasers
10 f s
Shortest laser pulse
10^{-15} s
1 fs

X-Ray Microscopy Methods - toward Nanometer Resolution



Present resolution in the 20 - 40 nm range

Lensless Imaging by Coherent X-Ray Scattering *or* "Speckle"

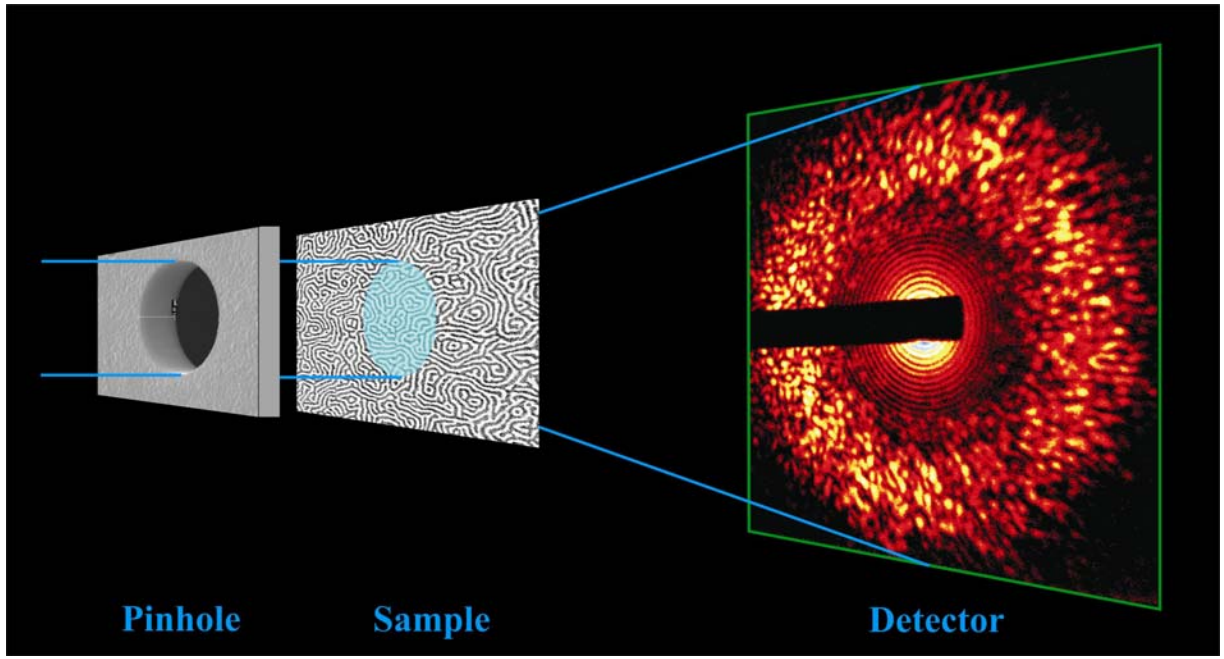


Eisebitt et al. (BESSY)

With present sources it takes minutes to take an image

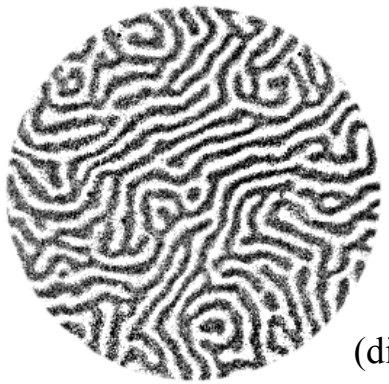
Challenge: Inversion from reciprocal to real space image

Loss of x-ray phase complicates image reconstruction

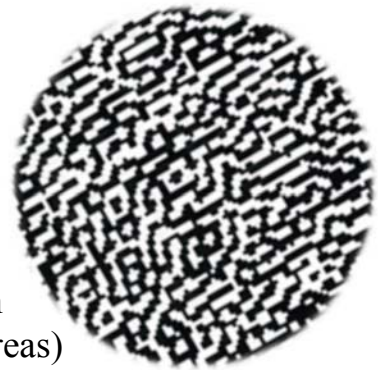


In principle: phase problem can be solved by “oversampling” speckle image

Transmission X-ray Microscopy

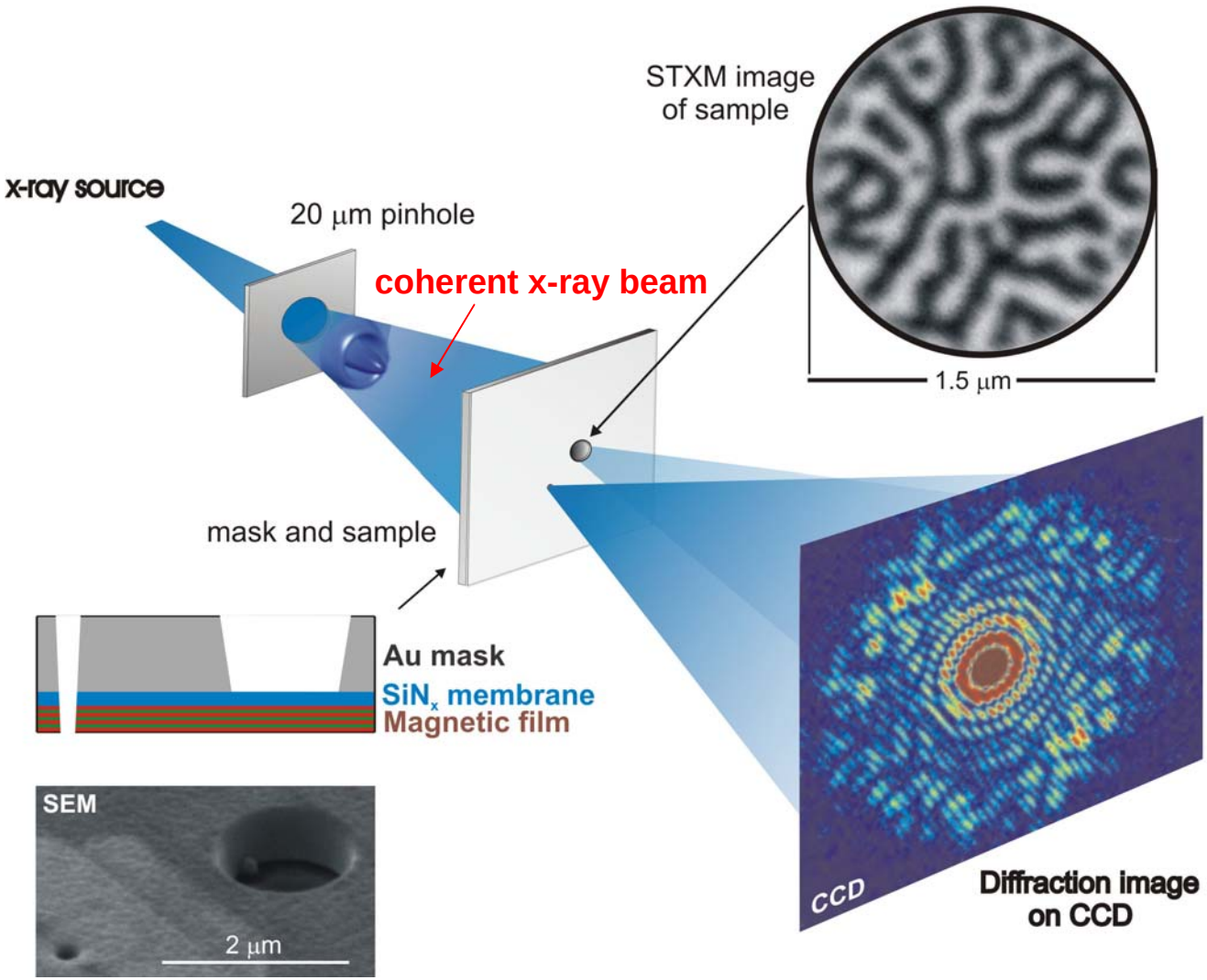


∅ 5 μm
(different areas)



Reconstruction from Speckle Intensities

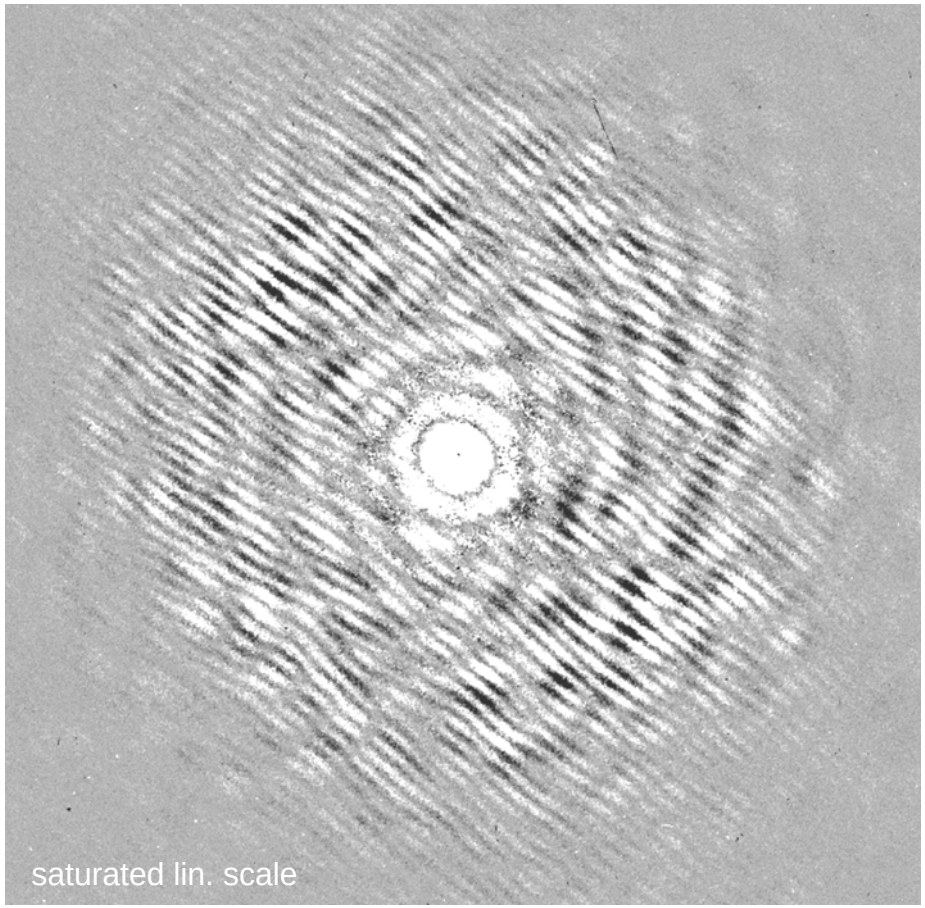
Toward single-shot imaging: soft x-ray spectro-holography



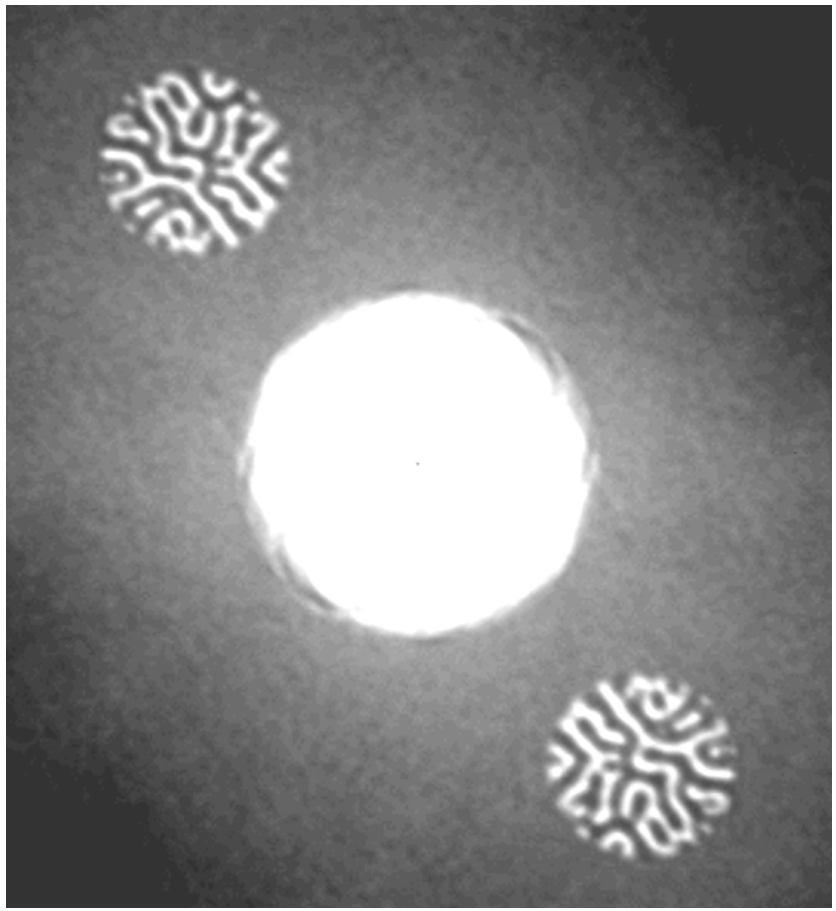
S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, J. Stöhr, *Nature* (in press)

Digital Image Reconstruction

Difference (RCP – LCP)



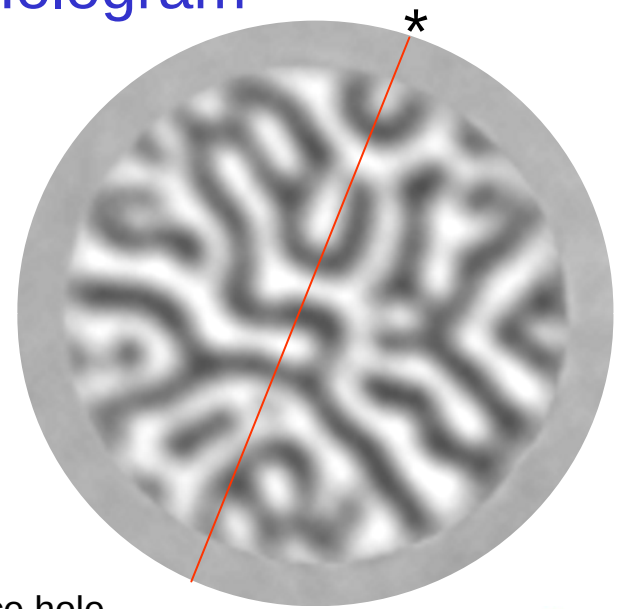
FFT (Difference)



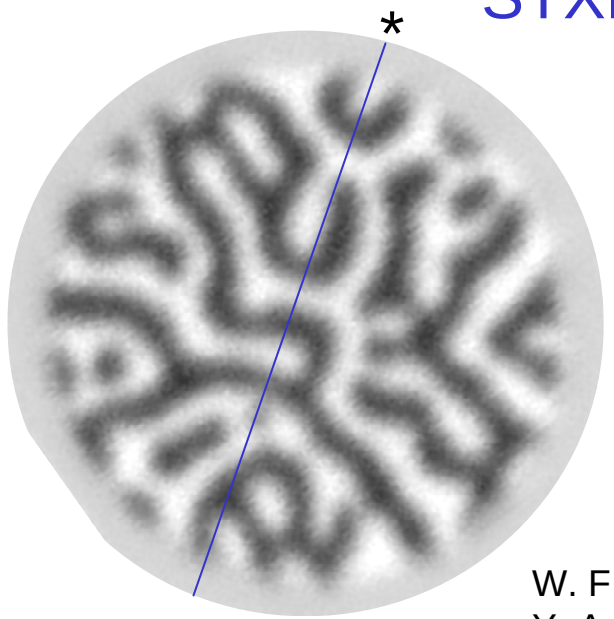
Convolution theorem applied to diffraction: FT(diffraction) = Autocorrelation (Object)

Is it real?

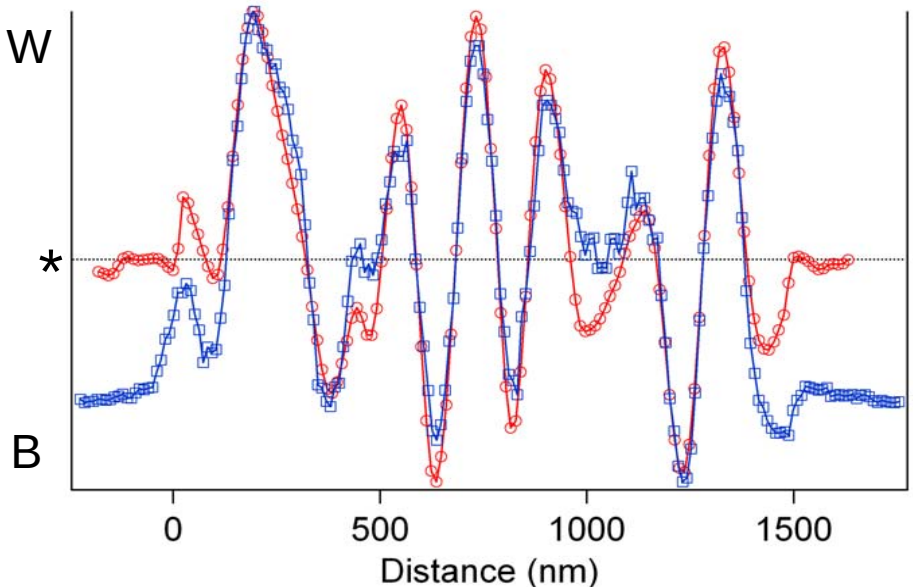
FT Hologram



STXM



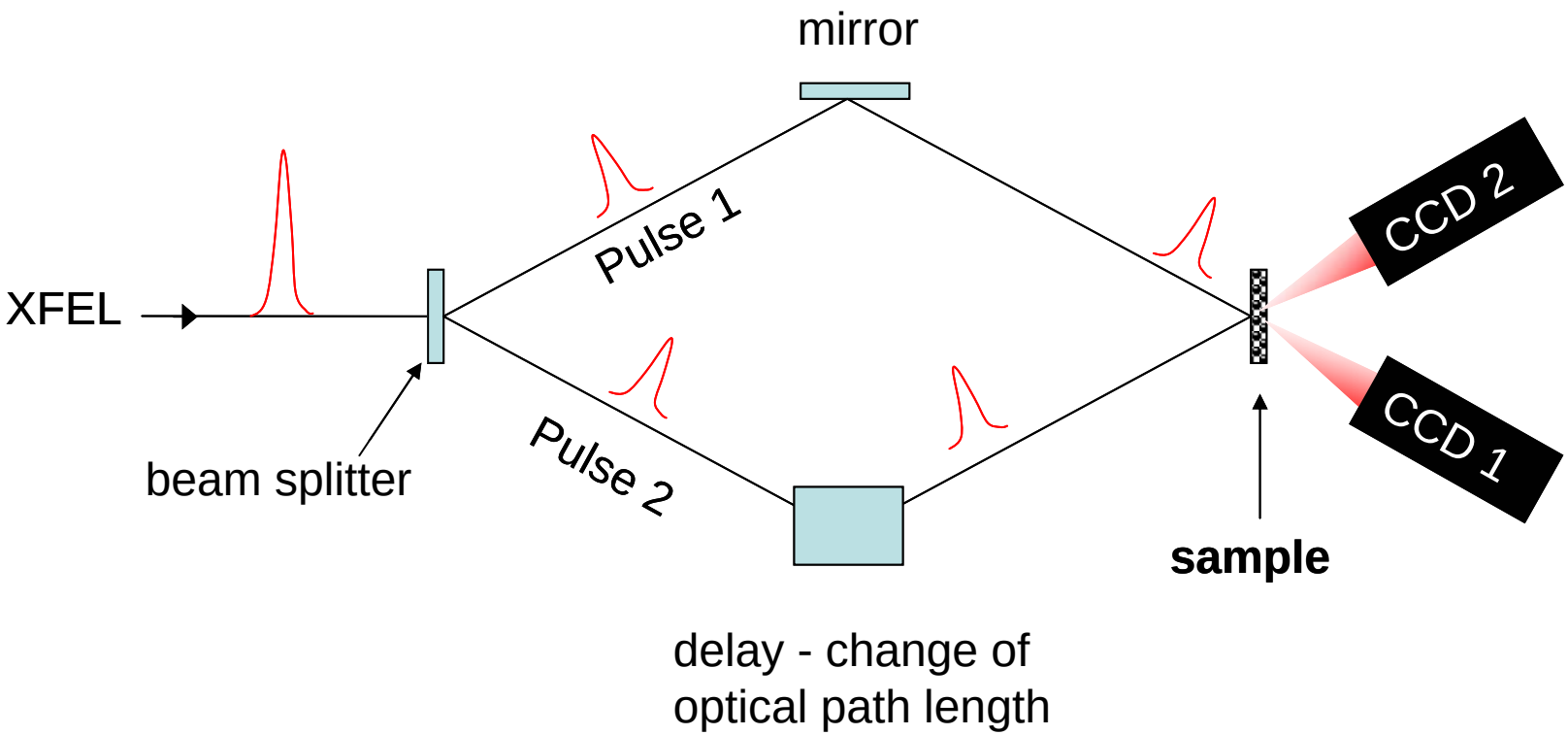
Reference hole
∅ 100 nm



W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm

Motion pictures with multiple pulses



Present detectors not fast enough for multiple images

For more, see: http://www-ssrl.slac.stanford.edu/stohr/index.htm

and

J. Stöhr and H. C. Siegmann
Magnetism: From Fundamentals to Nanoscale Dynamics
Springer 2005 (to be published)

Lake Tahoe, April 2004

The end