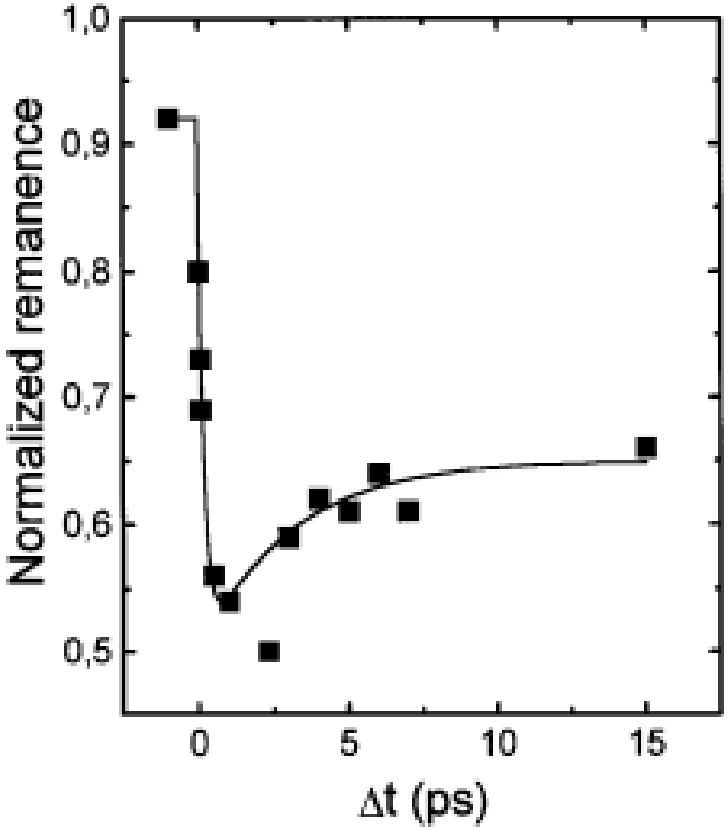
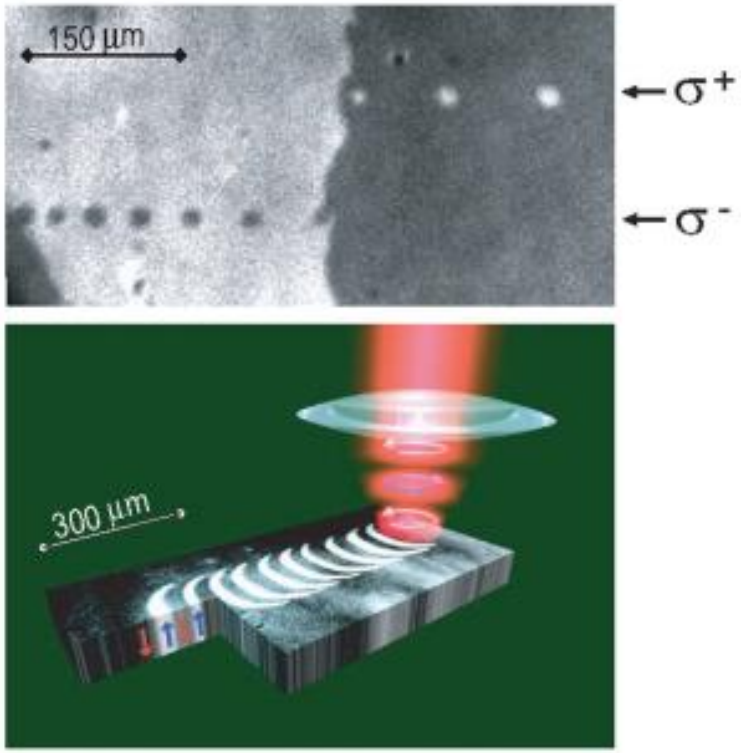
# Imaging ultrafast demagnetization dynamics after a spatially localized optical excitation

C. von Korff Schmising[1], B. Pfau[1], C. M. Günther[1], M. Schneider[1], M. Giovanella[1], B. Vodungbo[2], J. Perron[2], J. Lüning[2], L. Müller[3], F. Capotondi[4], E. Pedersoli[4], N. Mahne[4], S. Eisebitt[1]

[1]Technische Universität Berlin, Germany
[2]Sorbonne Universités, UPMC Université Paris/CNRS, UMR 7614, LCPMR, France
[3]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[4] Elettra-Sincrotrone Trieste, FERMI, Italy

# Ultrafast Demagnetization after Laser Excitation

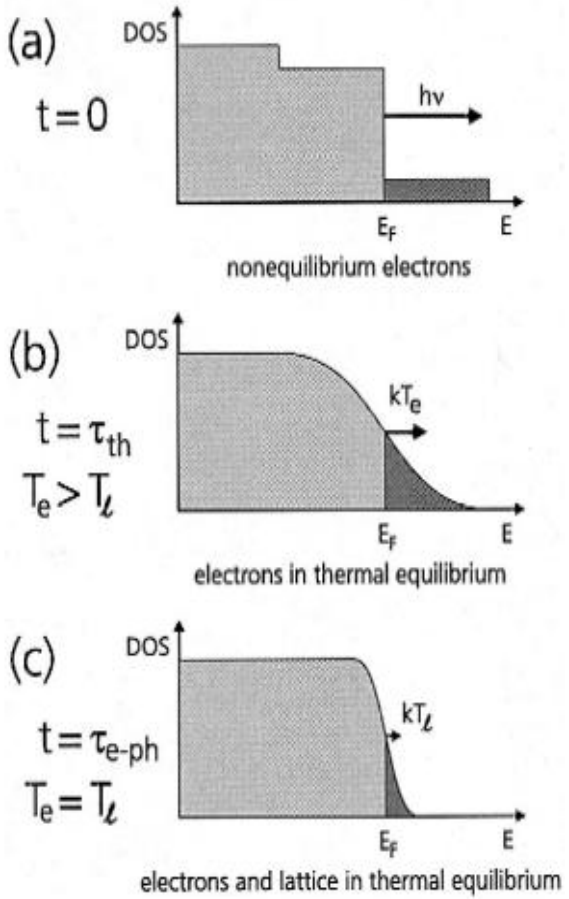



E. Beaurepaire, PRL, **76**, 4250 (1996)

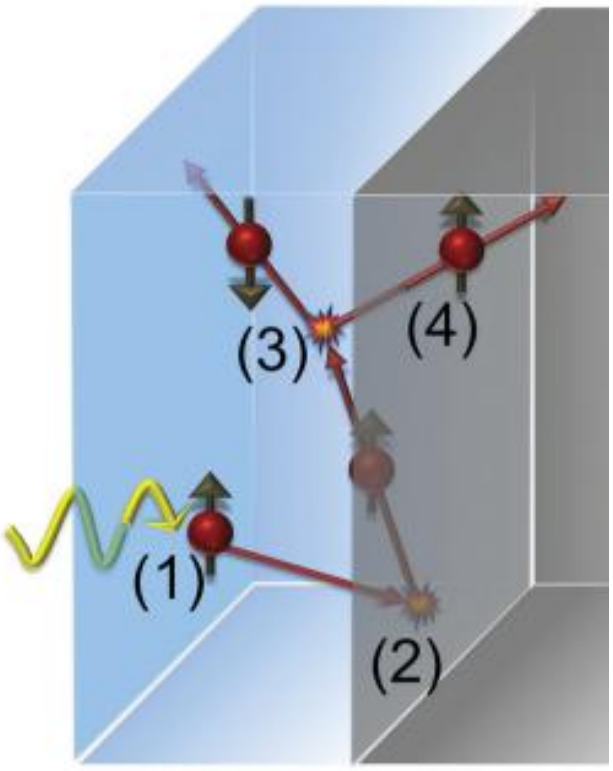
C. D. Stanciu, PRL, **99**, 047601 (2007)

# Theory of Ultrafast Demagnetization
# Electron-Phonon Scattering with Spin Flip

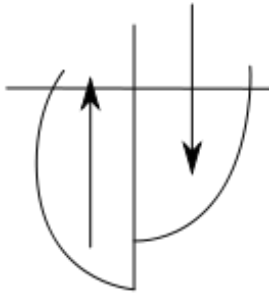



- Electron excitation with laser pulse d→ sp, spin conserving (ballistic transport of electrons 1nm/fs)
- thermalization electron-electron scattering, spin conserving
- Electron – phonon/impurity scattering with spin-flip probability $\propto \alpha_{EY}$ (Elliot-Yafet Scattering).
- predicts a critical slowing down of the magnetization for T→ $T_C$ (slower remagnetization)
- Controversy over the size of spin flip probability

# Theory of Ultrafast Demagnetization
# Superdiffusive Spin Transport



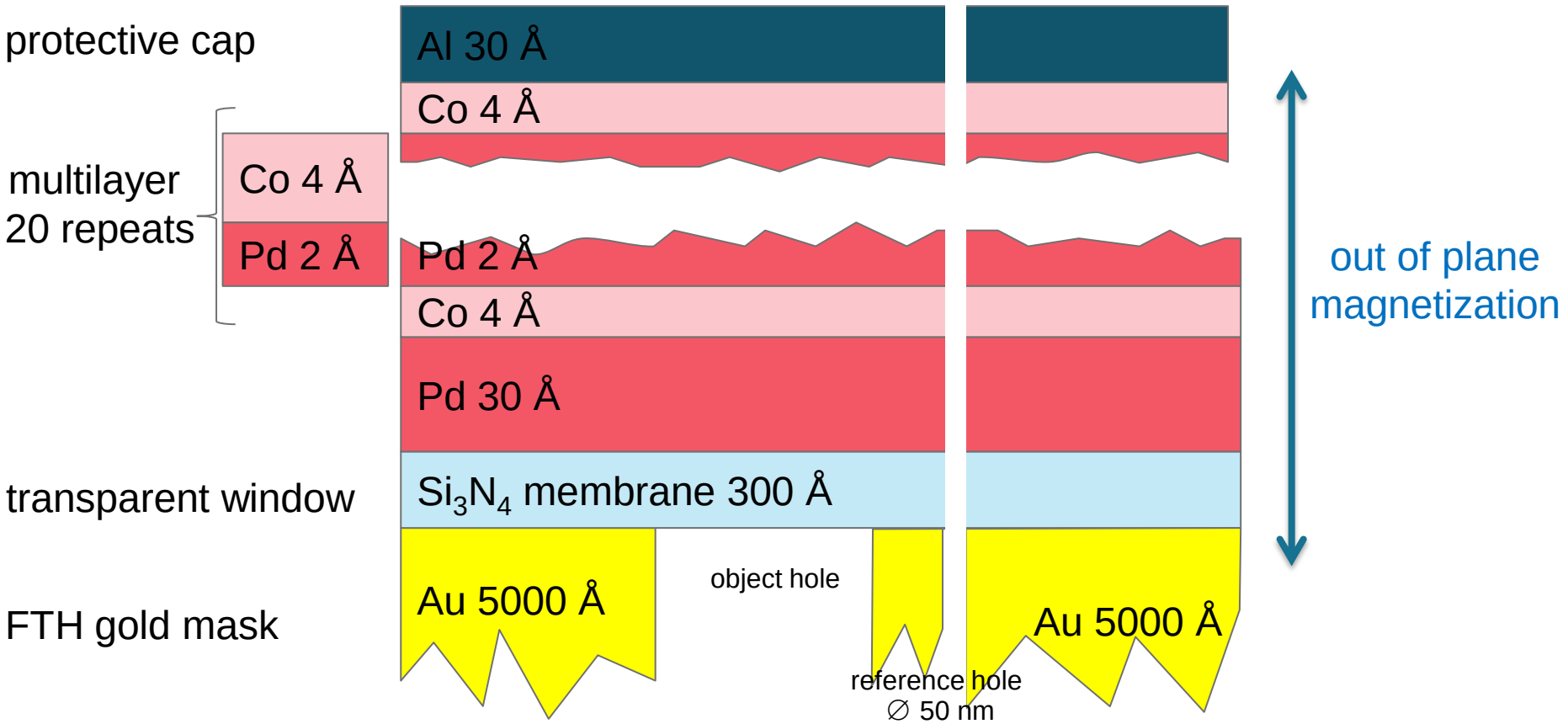

- Electron excitation with laser pulse d→ sp, spin conserving
- Cascading process by inelastic electron-electron scattering (3)
- Mobile sp-electrons differ in life time and velocities for majority and minority electrons.
  - lifetimes: $\tau \approx 30$ fs – 5 fs (depending on $E\text{-}E_F$), $\tau_{up}/\tau_{down} \approx$ 1.2-2 (depending on $E\text{-}E_F$)
  - Velocities: $v \approx 1$ nm/fs



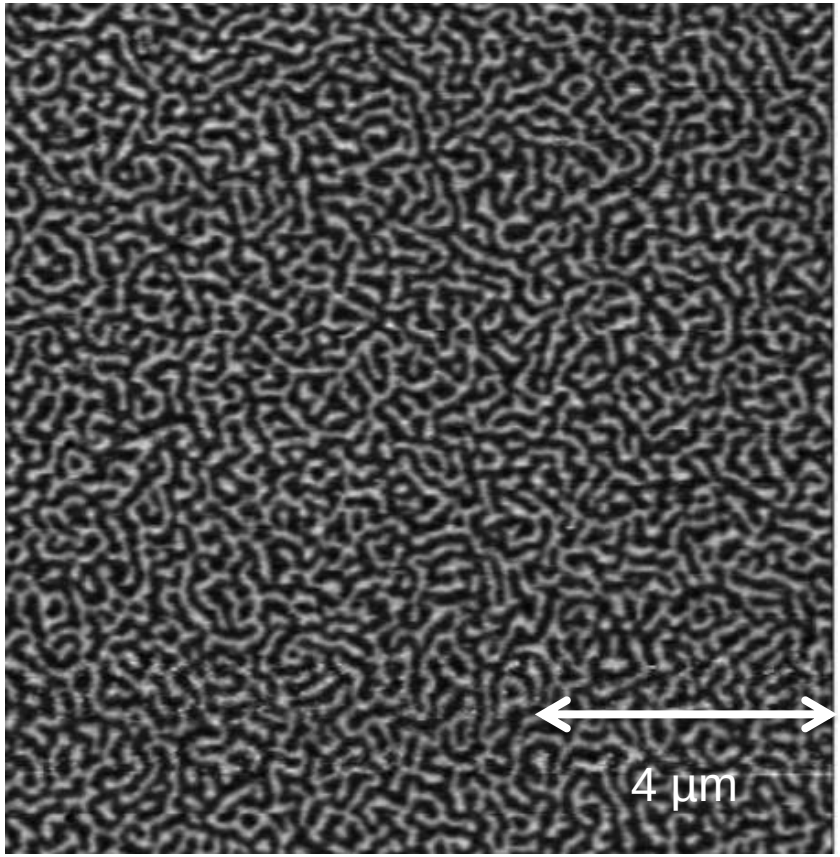
- We need sub 100 nm spatial resolution and sub 100 fs temporal resolution

M. Battiato, PRL, **105**, 027203 (2010)

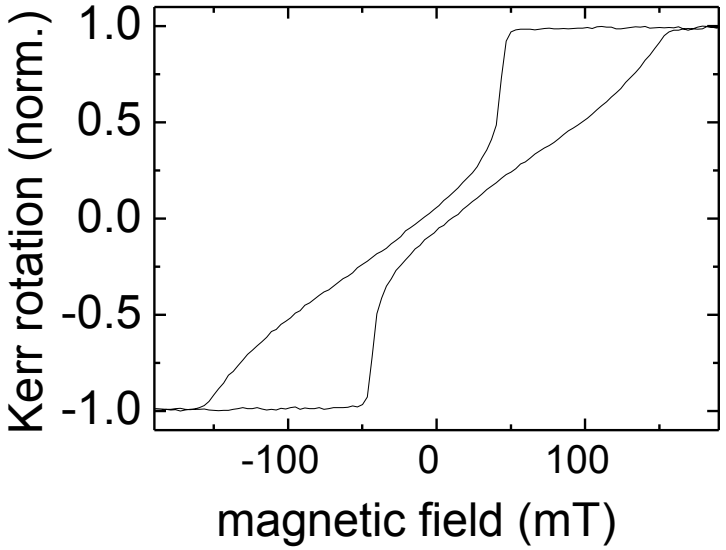
# Sample System Pd(20)/[Co(4)/Pd(2)]$_{20}$ Al(30) Å



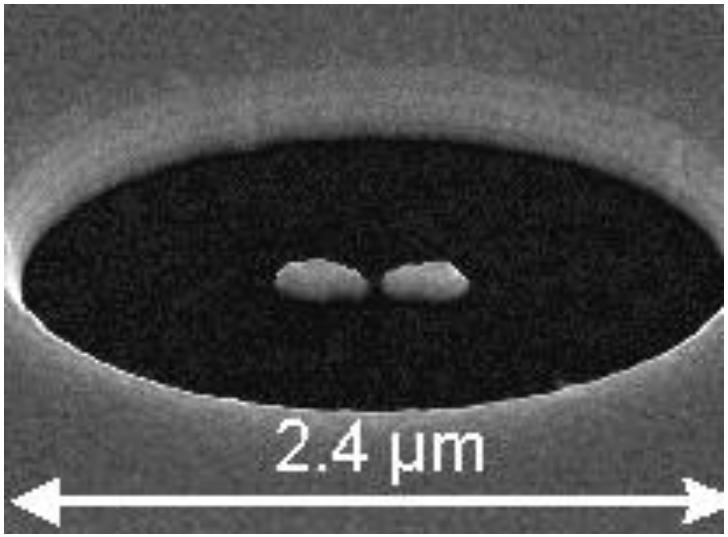
# Sample System Pd(20)/[Co(4)/Pd(2)]$_{20}$ Al(30) Å

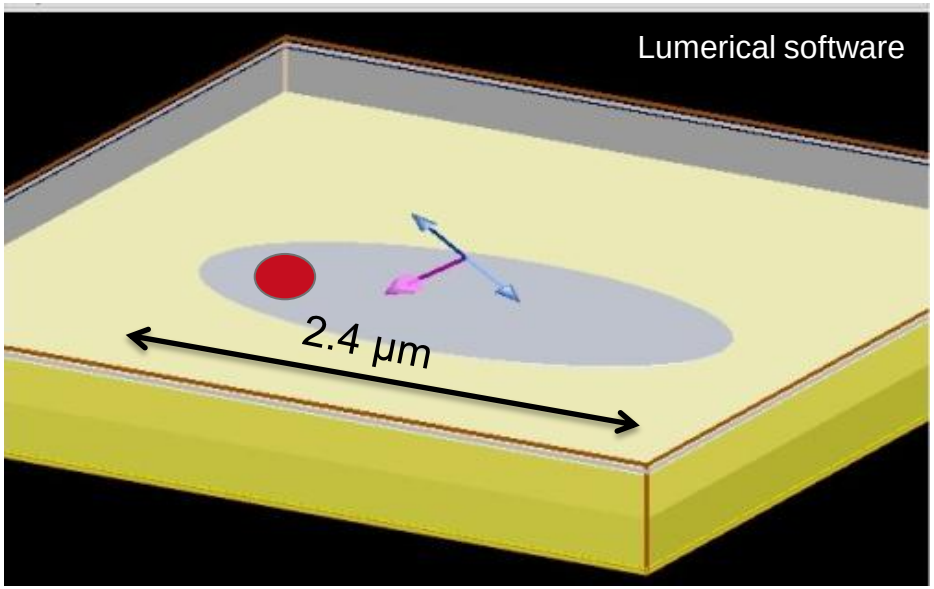



worm domain pattern
domain size ~70 nm

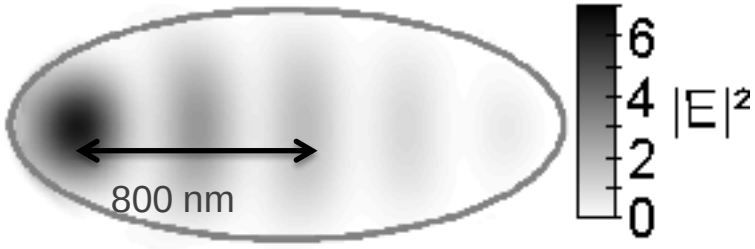


# Local enhancement by a standing wave




Elliptical object hole (a = 1.2 µm, b = 0.6 µm)
45 degree angle of incidence
P-polarized



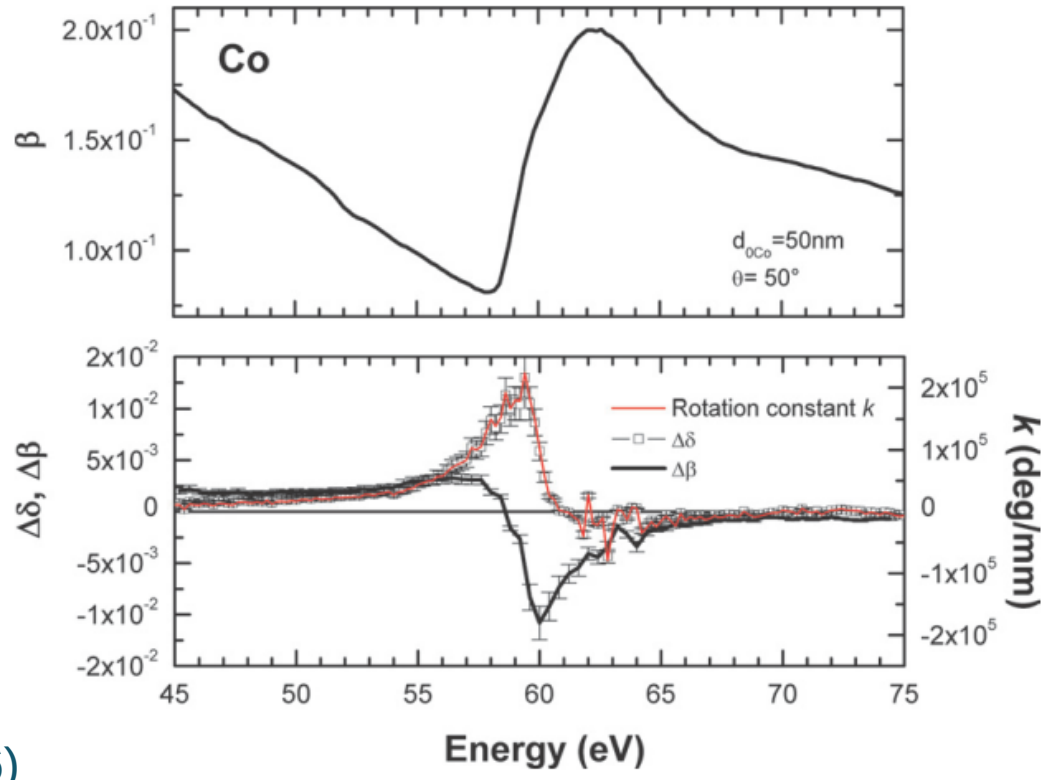
# Magnetic Contrast via XMCD Effect

$$n_{\pm} = 1 - (\delta \pm \Delta\delta) + \mathrm{i}(\beta \pm \Delta\beta)$$

$$n_{+} - n_{-} = 2(\Delta\delta + i\Delta\beta)$$

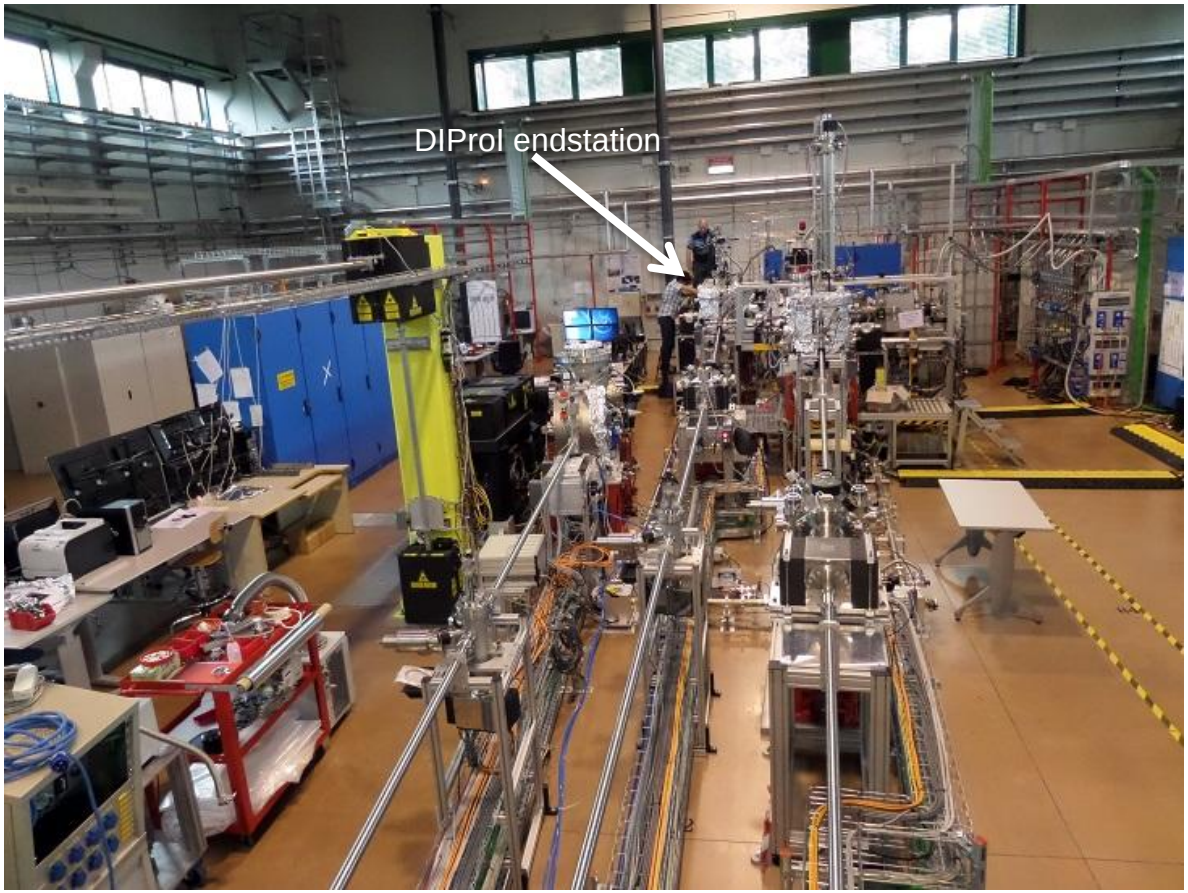
$$n_{+} - n_{-} \propto M$$

± left/right circular polarization

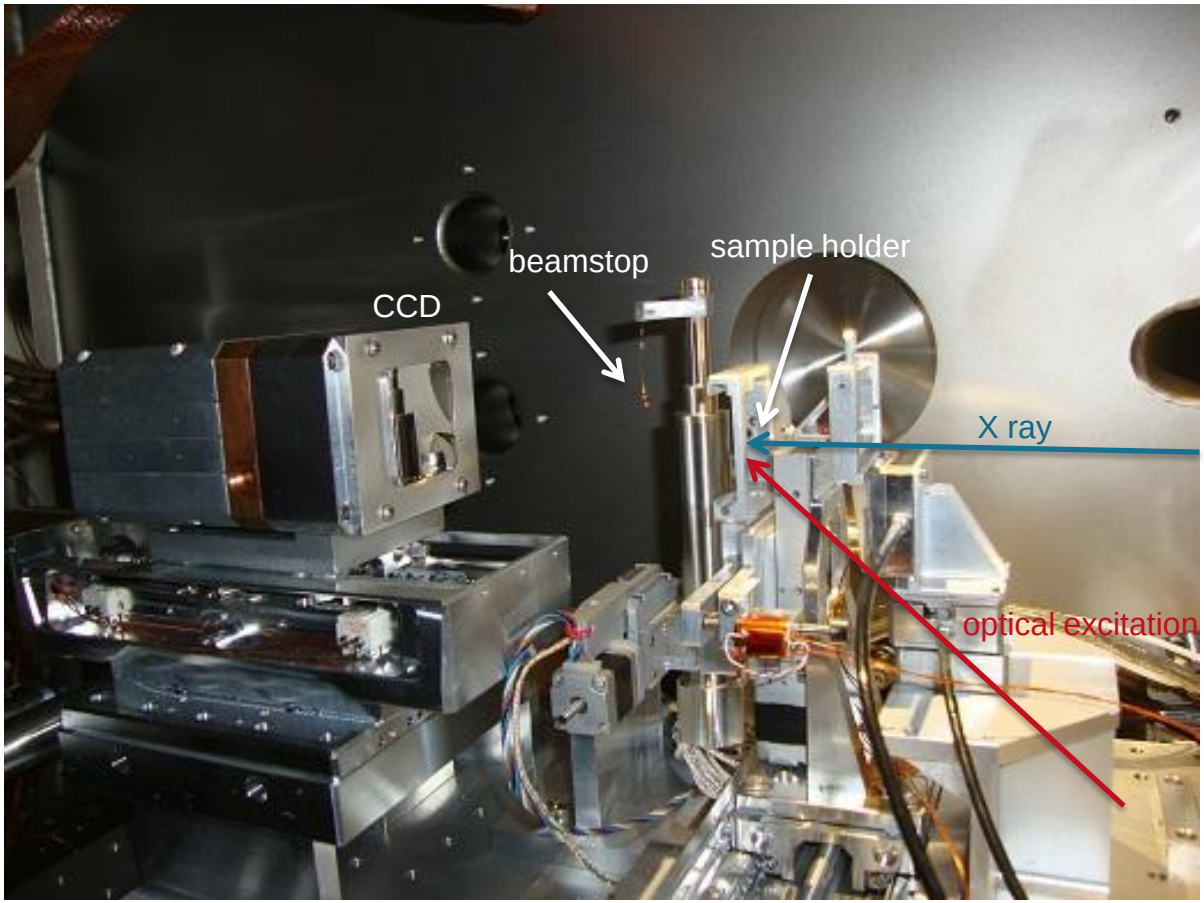



S. Valencia, NJP, **8**, 254 (2006)

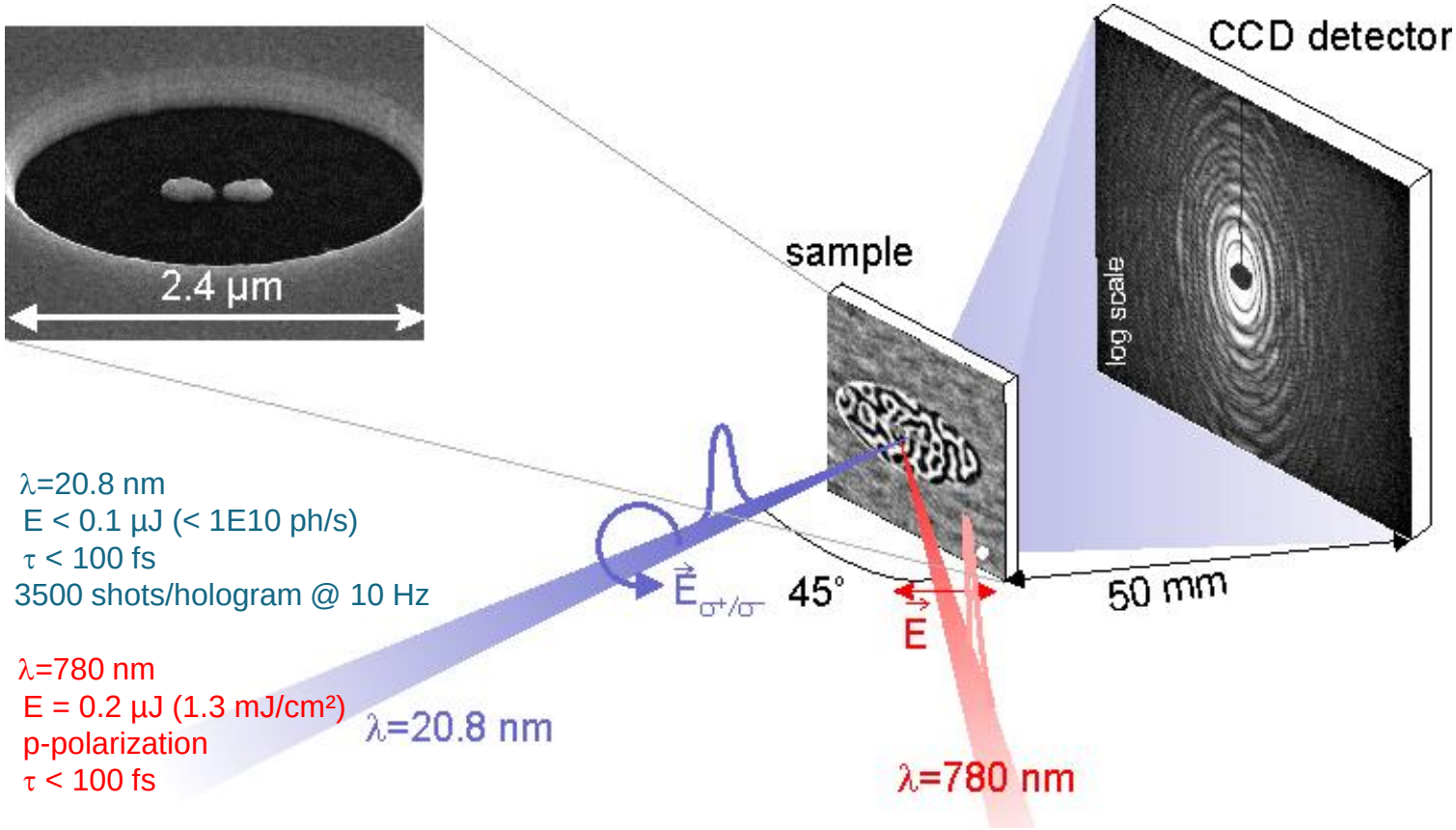
# Experimental Hall



# Experimental setup



# Fourier Transform Holography @FERMI Trieste, Italy with *seeded* and *circular polarized* soft X-ray pulses

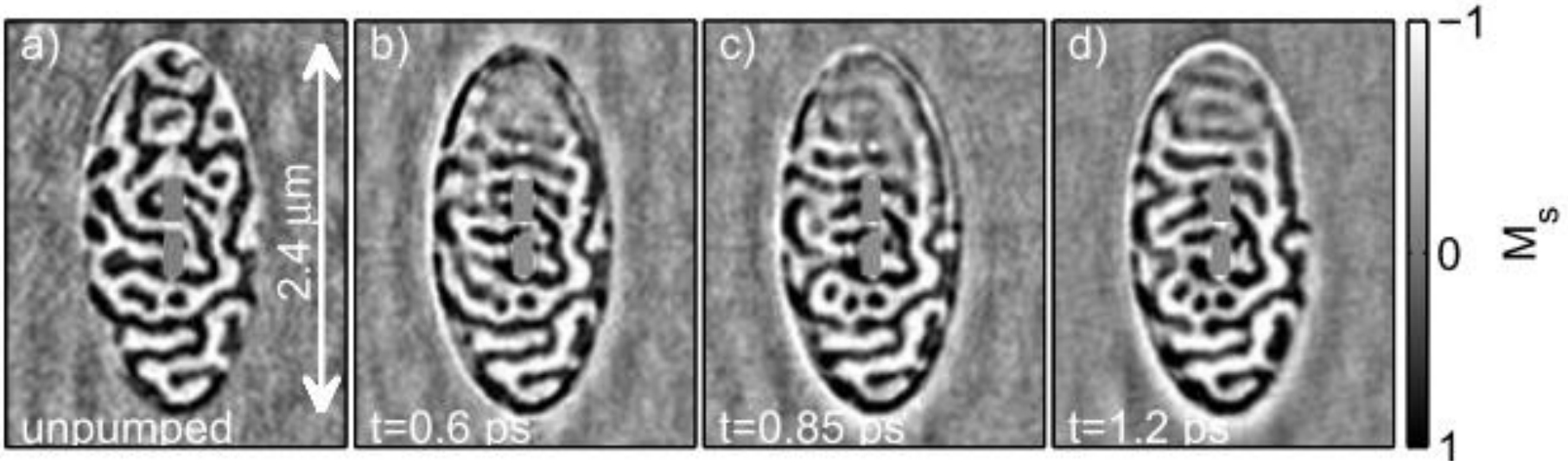



probe beam: λ=20.8 nm
E < 0.1 µJ (< 1E10 ph/s)
τ < 100 fs
3500 shots/hologram @ 10 Hz

pump beam: λ=780 nm
E = 0.2 µJ (1.3 mJ/cm²)
p-polarization
τ < 100 fs

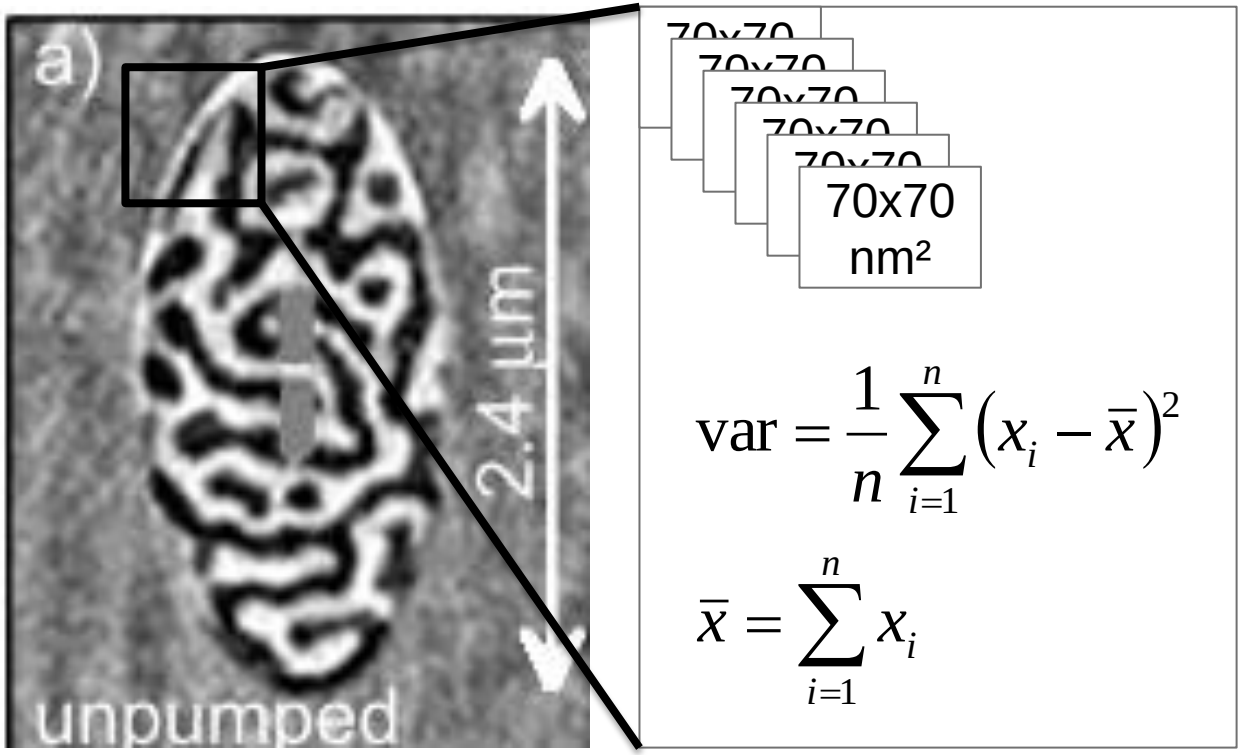
# Reconstruction by Fourier Transform of difference holograms : magnetic domain patterns

spatial resolution < 70 nm



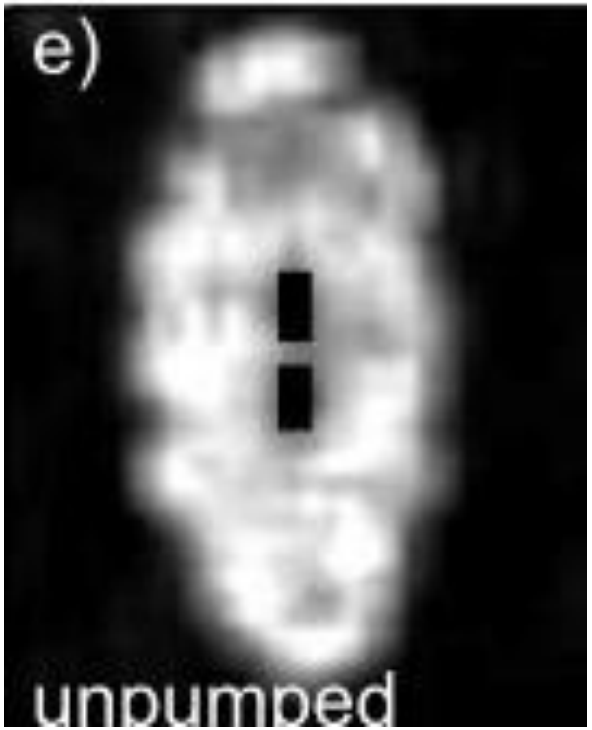

C. von Korff Schmising et al., Phys. Rev. Lett.,**112**, 217203 (2014)

# Variance matrices

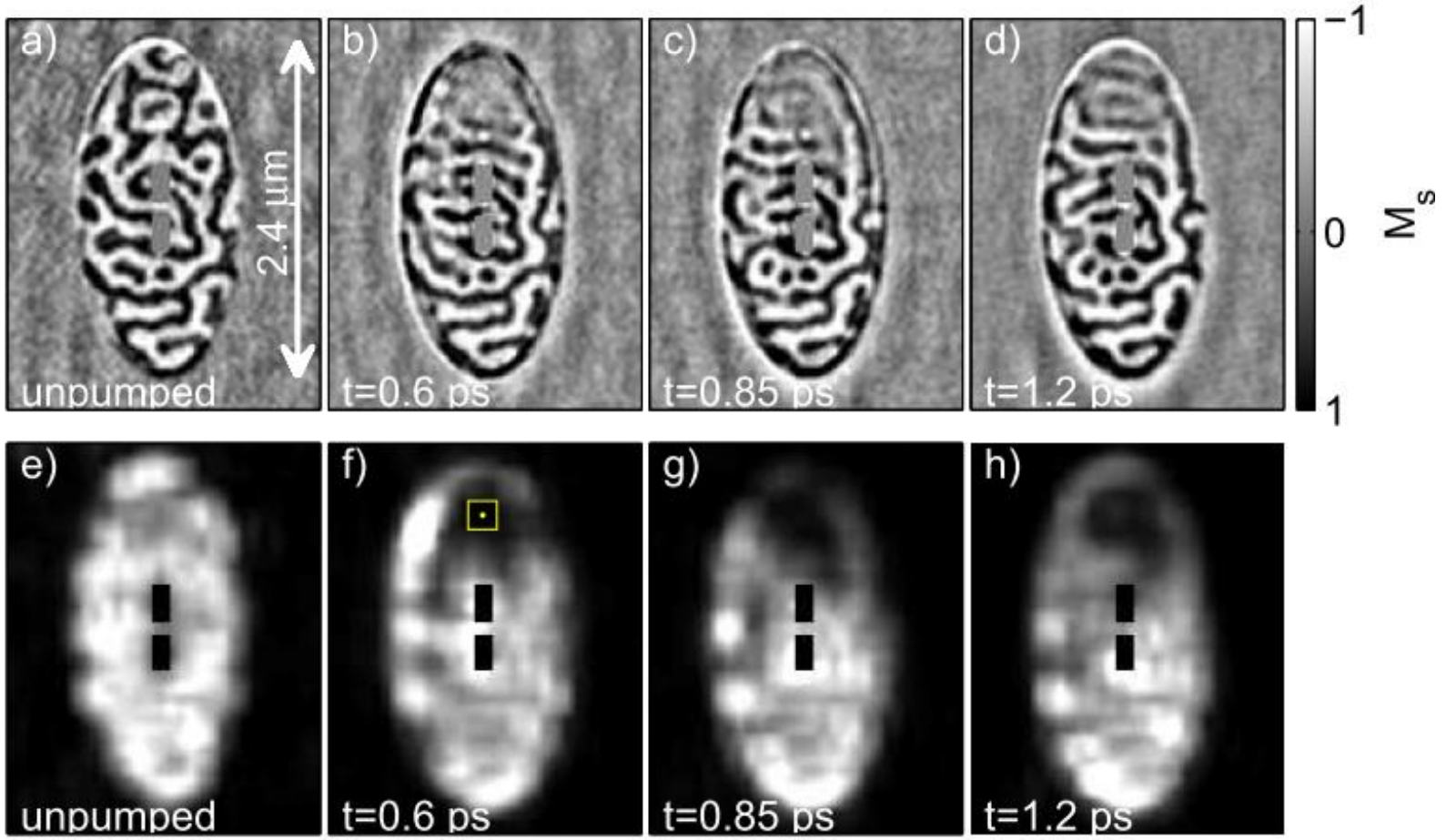



$$\mathrm{var} = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$$

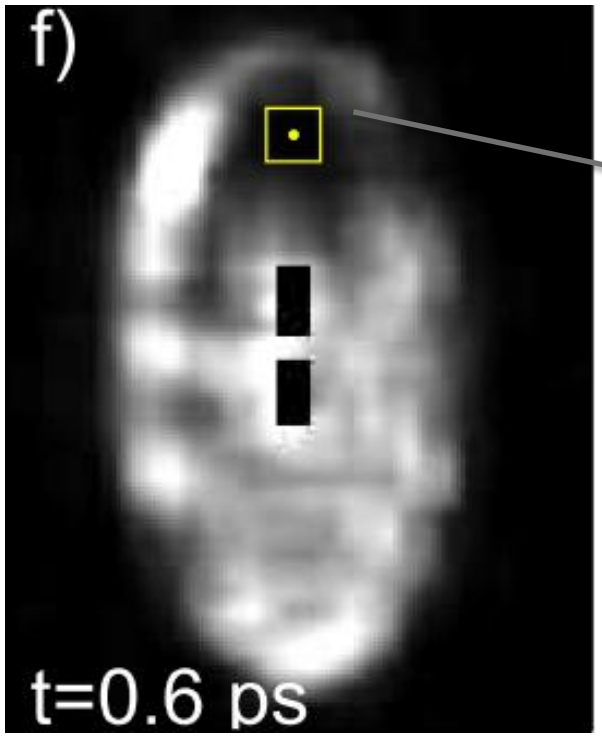
$$\bar{x} = \sum_{i=1}^{n} x_i$$



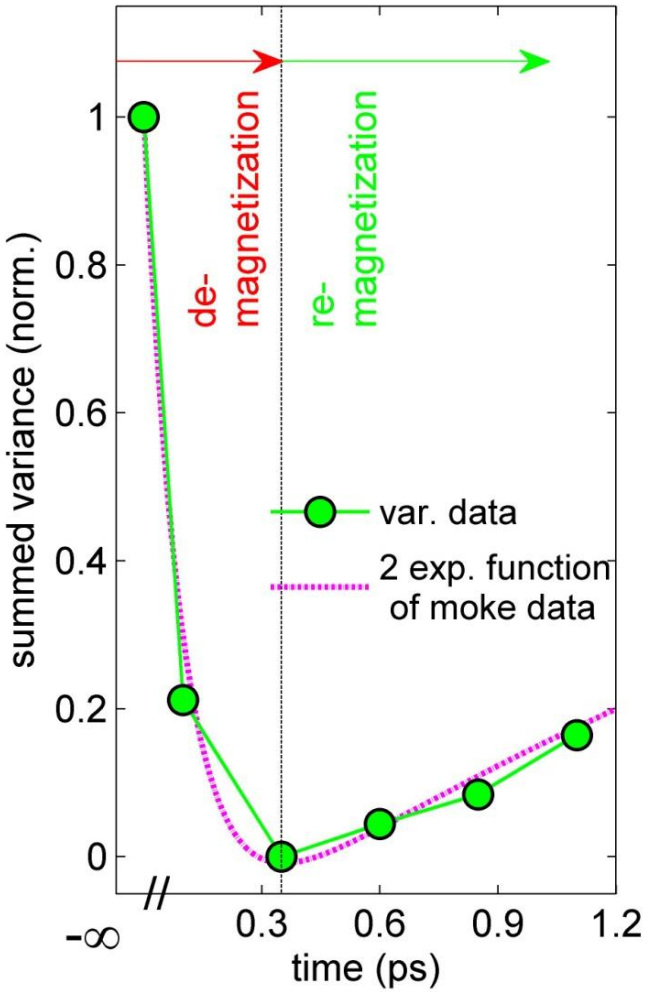
# Variance images



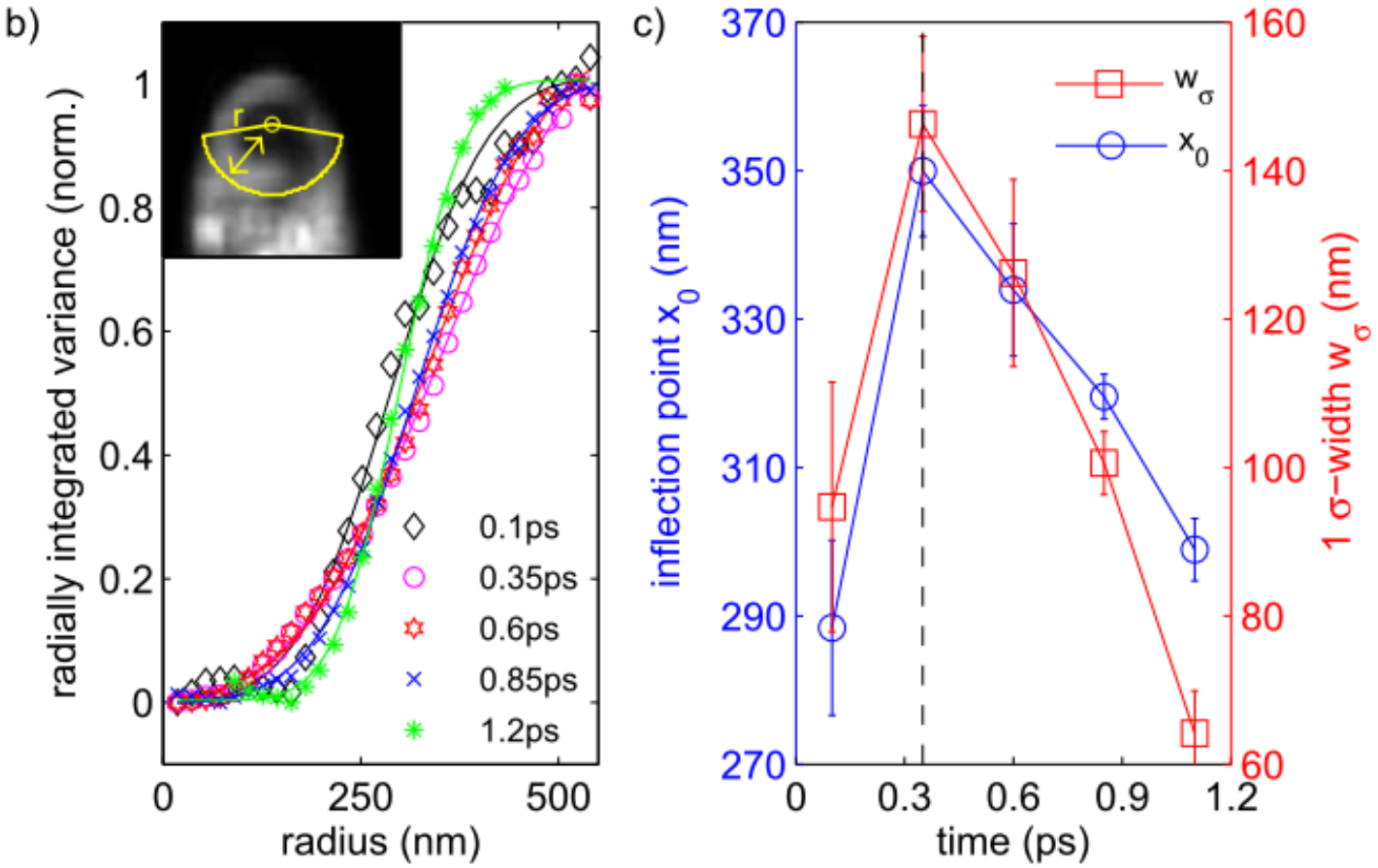
# Ultrafast demagnetization:
# time range: de-magnetization
# re-magnetization



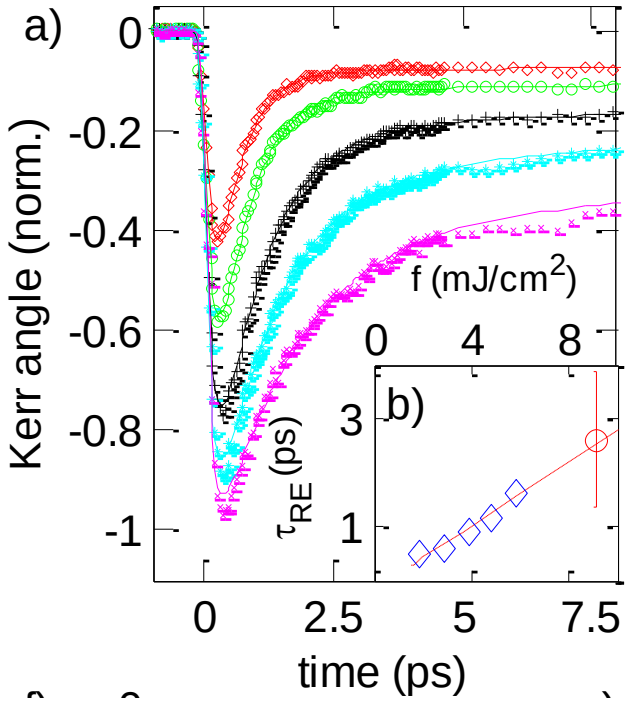

200x200 nm²

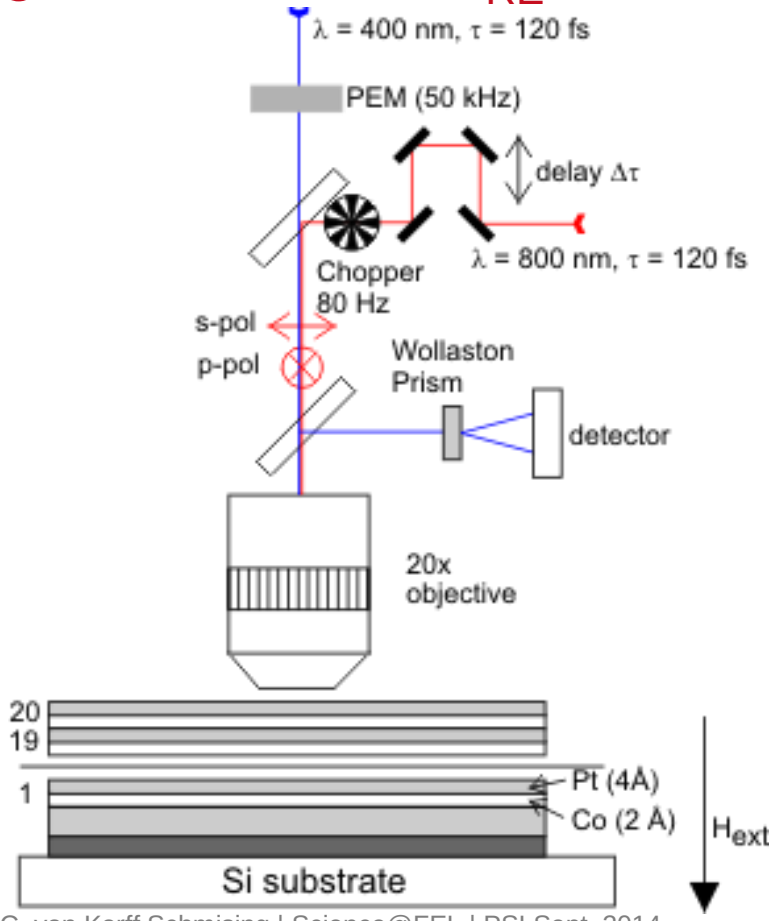


# Transient Change of the lateral magnetic profile

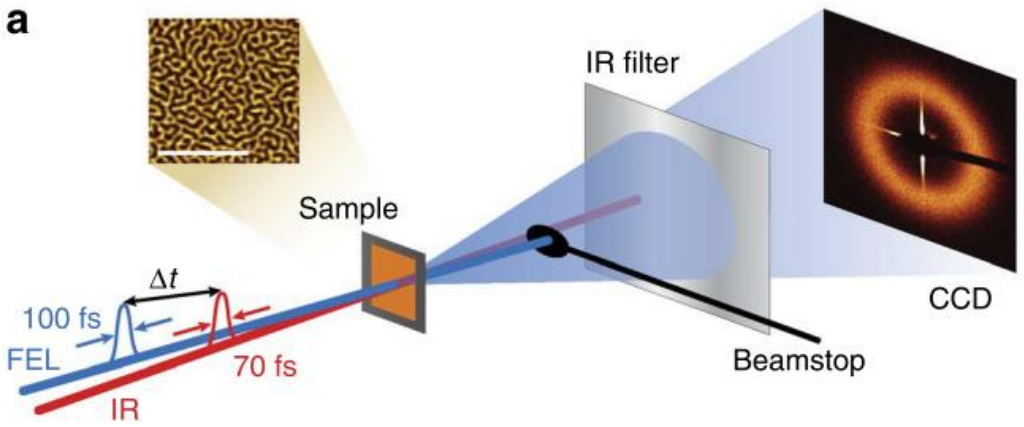


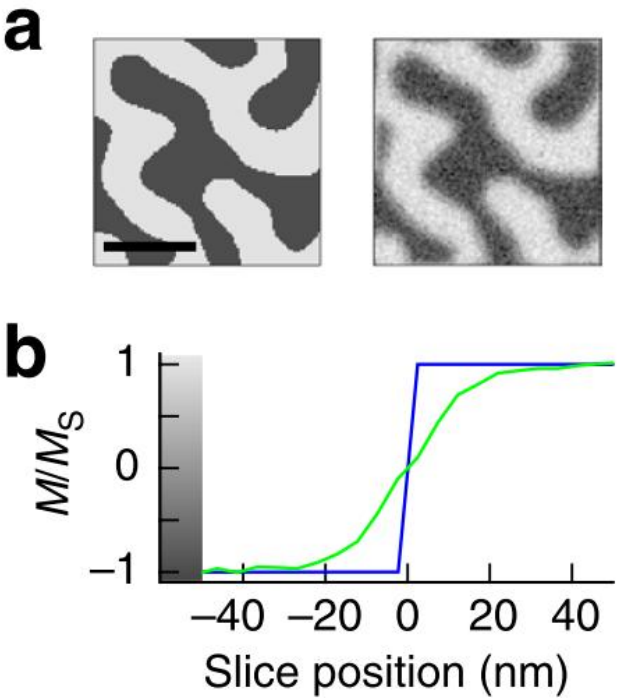
# Remagnetization:
# intensity dependent remagnetization rate $\tau_{RE}$



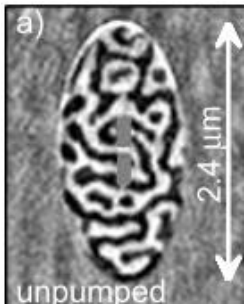
# Demagnetization
## Nanoscale spin structure after optical excitation



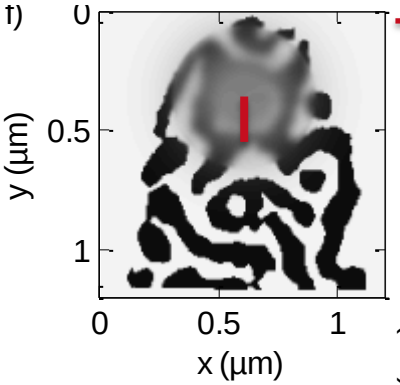




B. Pfau et al., Nat. Comun., **3**,1100 (2012)

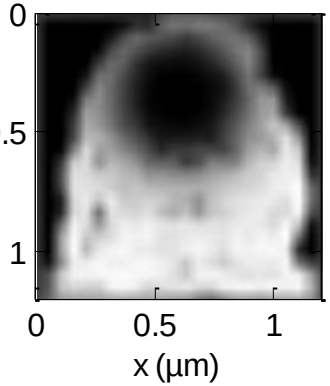
# Demagnetization:
# intensity dependent demagnetization rate $\tau_{DE}$



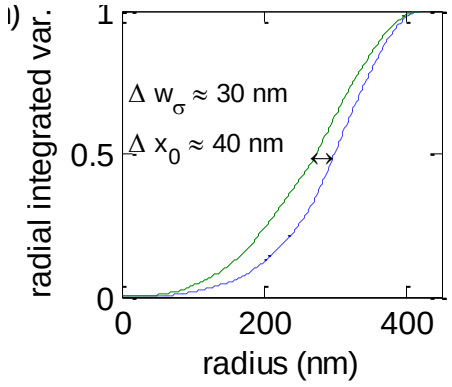

- digitize domain patter (Ms = ±1)
- simulate local reduction of magnetic contrast according to enhanced excitation pattern.
- simulate broadening of domain walls by 30 nm



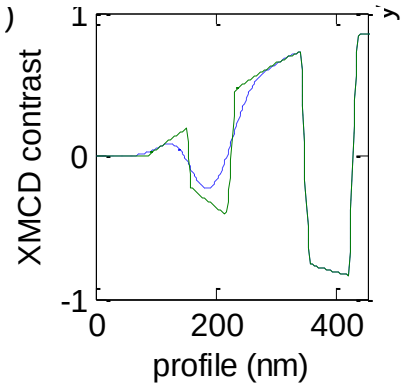

- calculate corresponding variance matrix




- calculate radial integration




- show lineout



## Conclusion

- Coherent imaging ultrafast demagnetization with sub-100nm spatial and 100fs temporal resolution.
- Changes of the lateral magnetic profile during re-magnetization due to intensity dependent re-magnetization rates.
- Evidence for ultrafast lateral spin transport in agreement with superdiffusive spin transport.

## Perspectives

- Optimization of the electric field enhancement of the excitation (e.g. by plasmonic antennas etc.)
- Element specific study of all optical switching in complex magnetic materials.
- Exploration of the fundamental spatial limits of light induced magnetization dynamics.