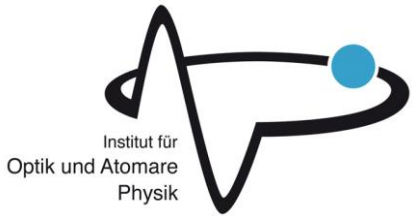
Exchange scaling of ultrafast angular momentum transfer in *4f* antiferromagnets

Will Windsor

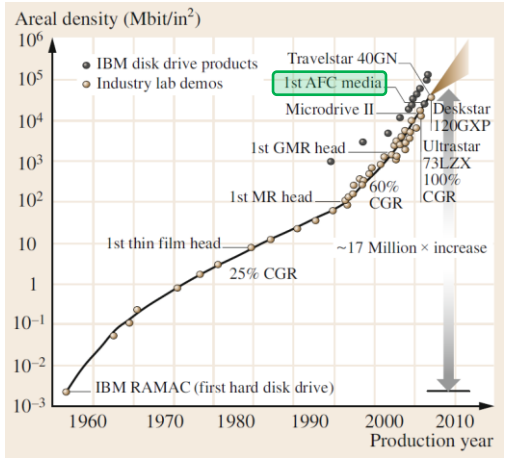
SPICE workshop: ultrafast antiferromagnetic writing

Mainz 9.5.2022



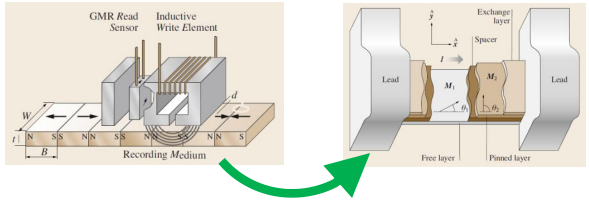
What I'd start with elsewhere….

Digital recording



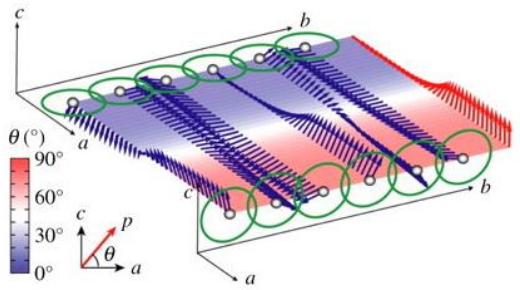
hard disk read/write head

spin-valve read element

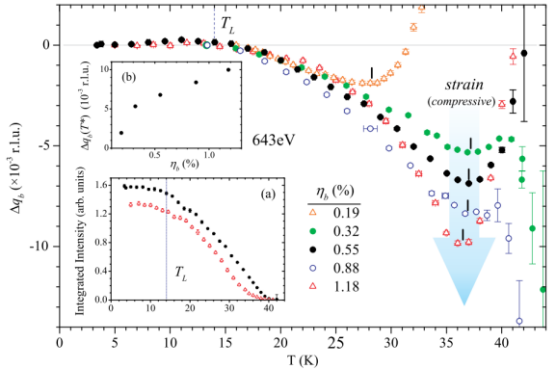


Tannous C., Comstock R.L. (2017)
doi.org/10.1007/978-3-319-48933-9_49

New properties available with AF

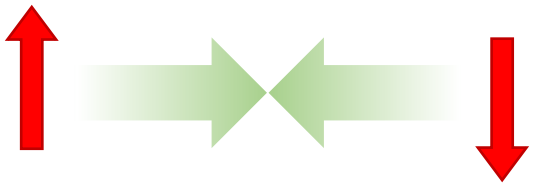


Kagawa PRL 102, 057604 (2009)

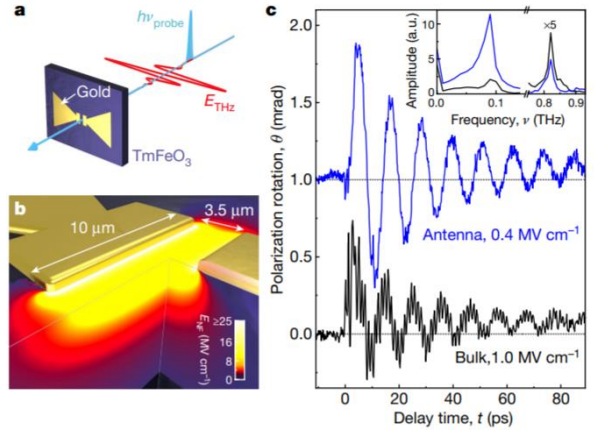


Windsor, PRL 113, 167202 (2014)

Particular ultrafast prospects

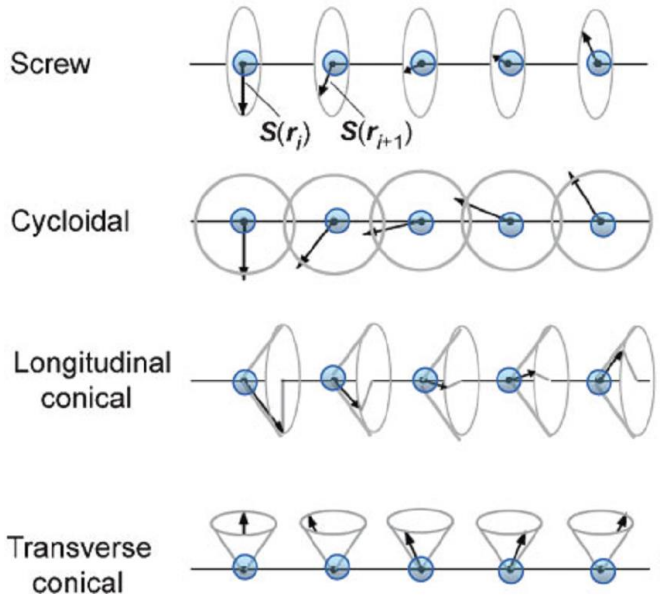


Dissipation-free AF demagnetization

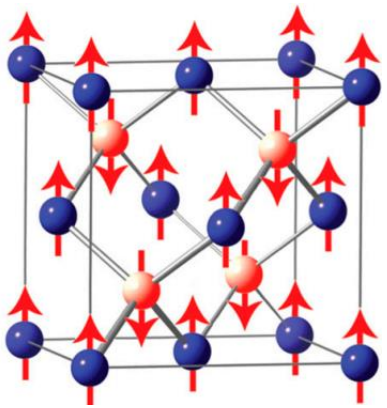


Schlauderer, Nature 569, 383–387 (2019)

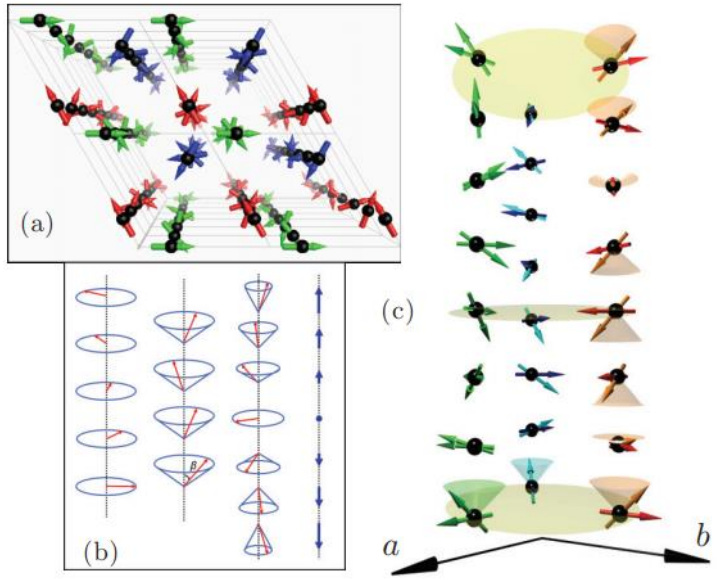
Antiferromagnets are cool.



Tokura, Phil. Trans. RSA 369 (2011)



MacDougall, PNAS 108, 38, 15693 (2011)



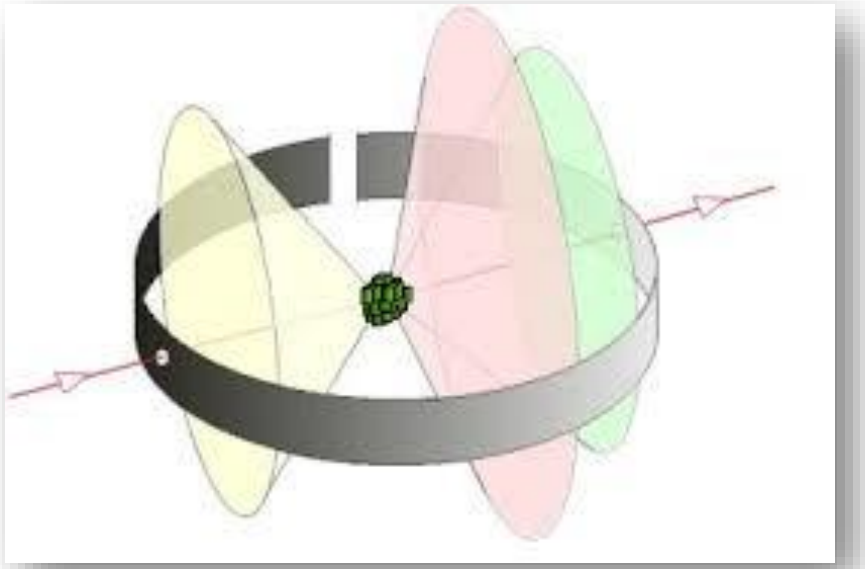
Scagnoli et al, PRB 88 104417 (2013)

How do we resolve such spin structures?

Magnetic diffraction.

Detection of Antiferromagnetism by Neutron Diffraction*

C. G. SHULL
Oak Ridge National Laboratory, Oak Ridge, Tennessee
AND
J. SAMUEL SMART
Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland
August 29, 1949



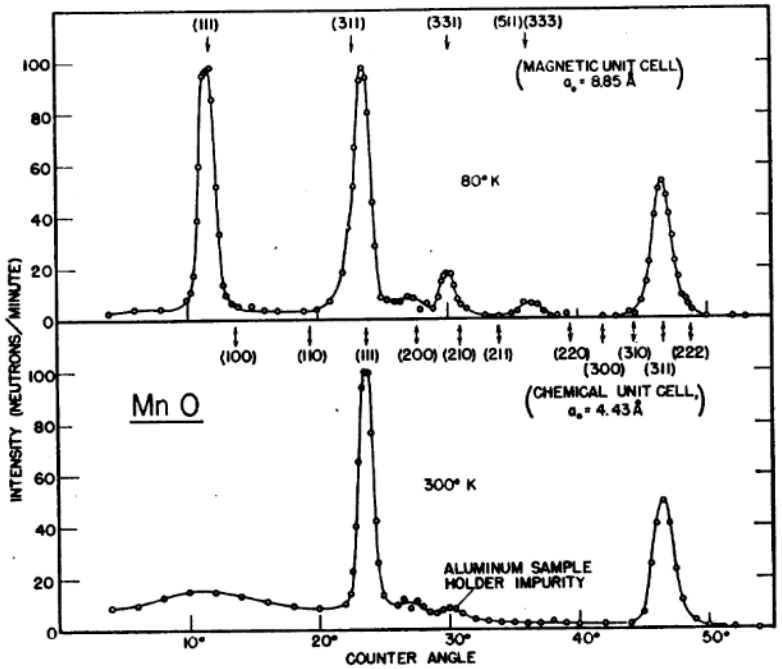
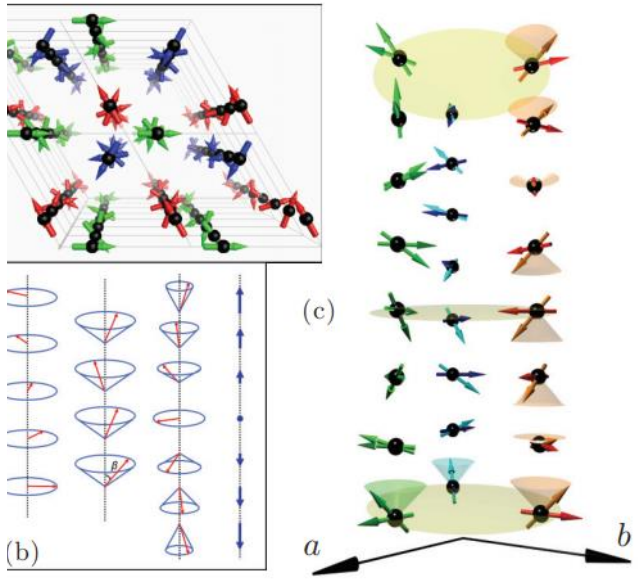
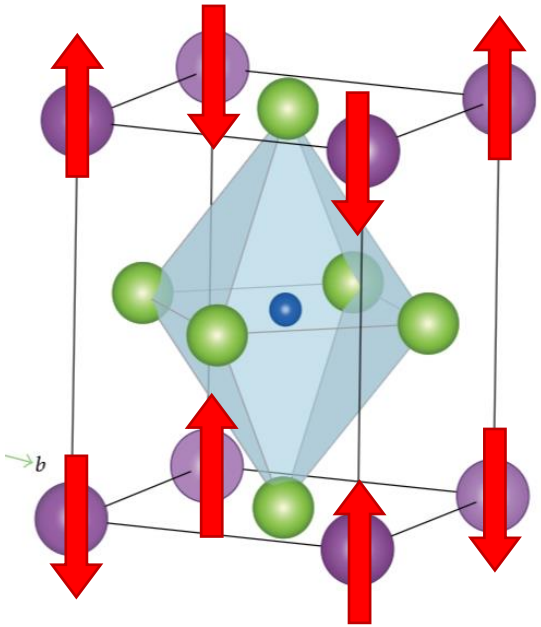
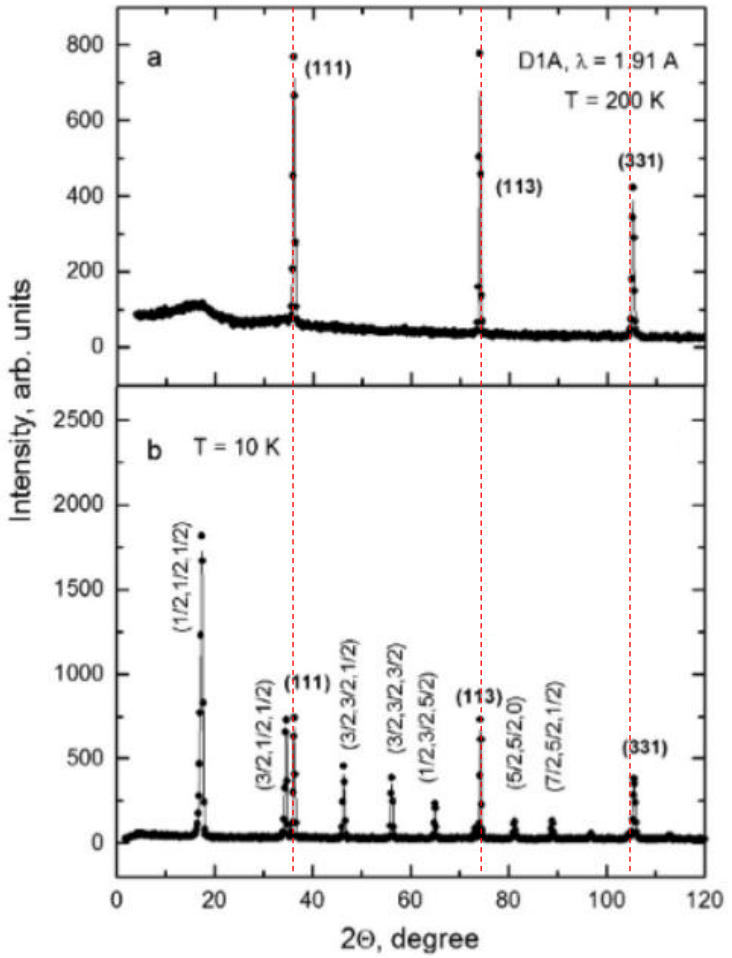


FIG. 1. Neutron diffraction patterns for MnO at room temperature and at 80°K.



Scagnoli et al, PRB 88 104417 (2013)

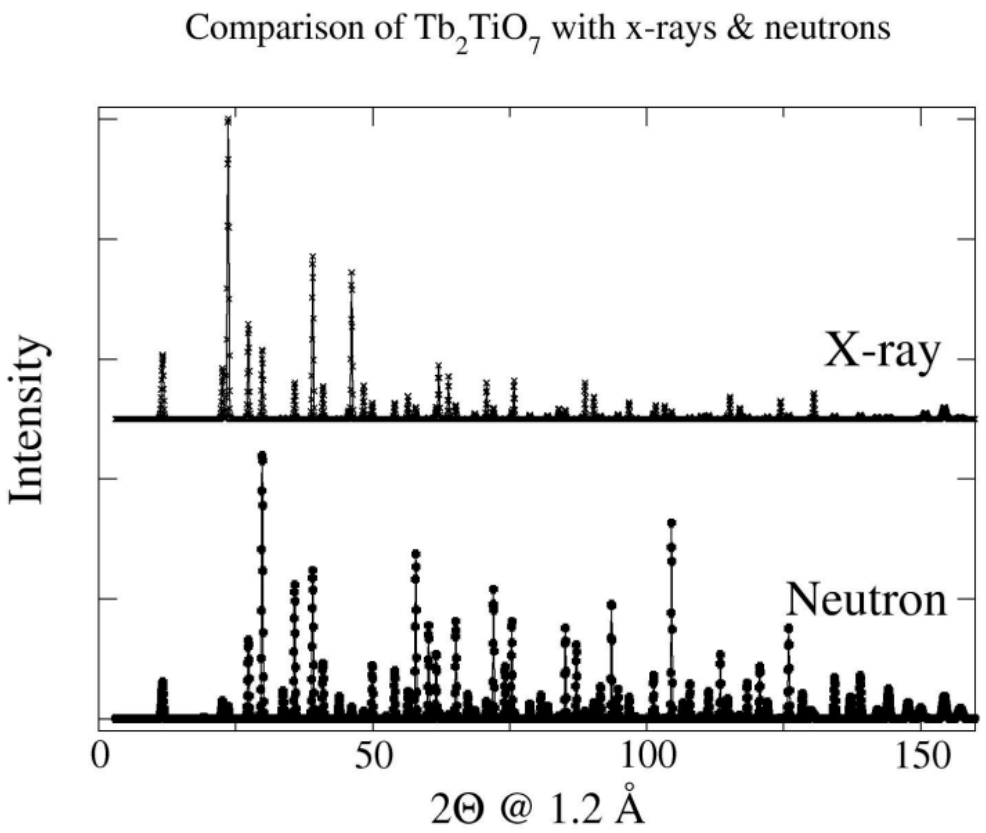




Abramova, J. Alloys and Compounds 632 (2015) 563–567

But neutrons don’t come in ultrafast pulses… x-rays do….

X-rays are sometimes a compromise….

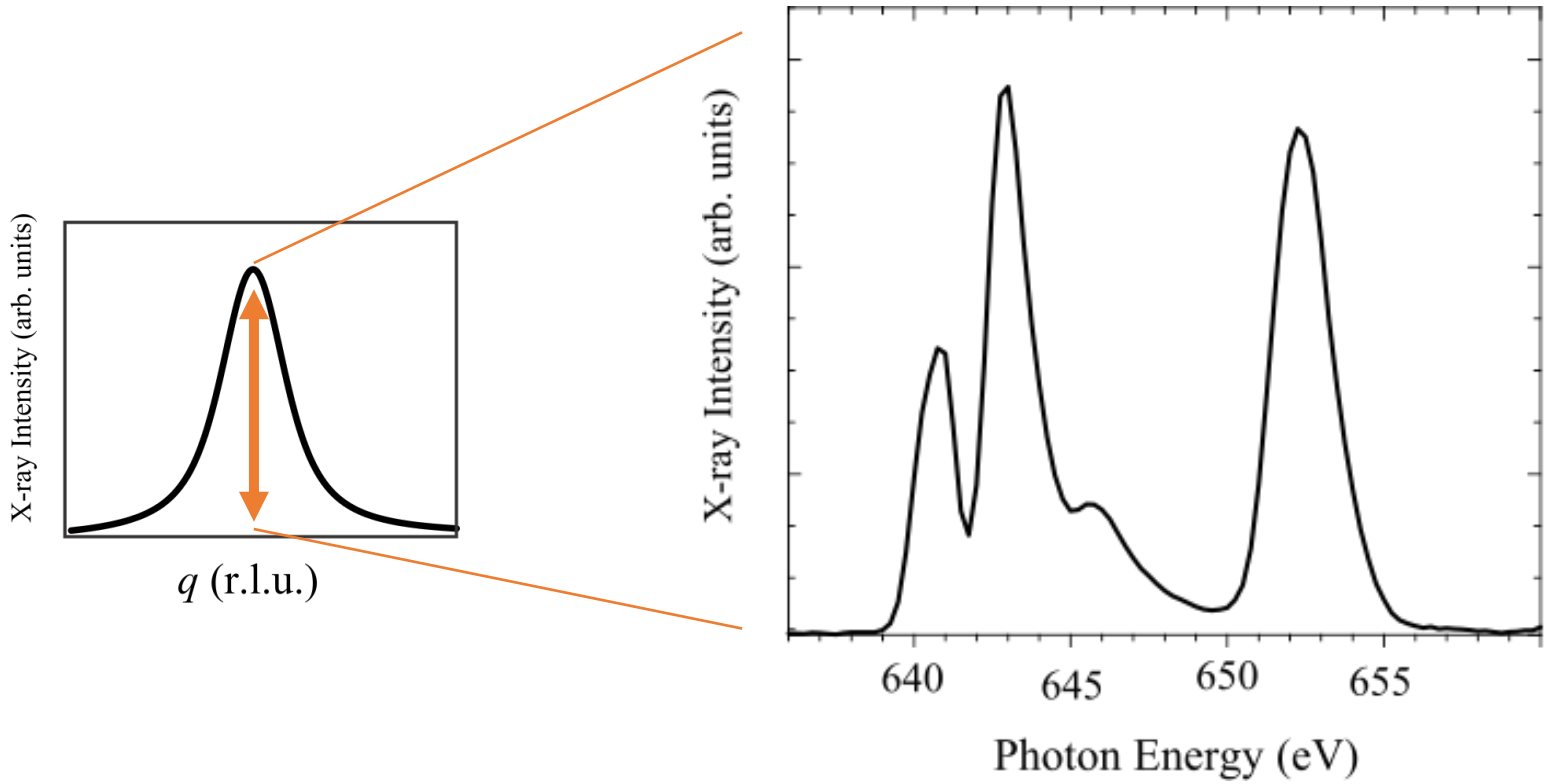


https://neutrons.ornl.gov/sites/default/files/Toby%202018_NXintro2powder_2up.pdf

….especially for magnetism

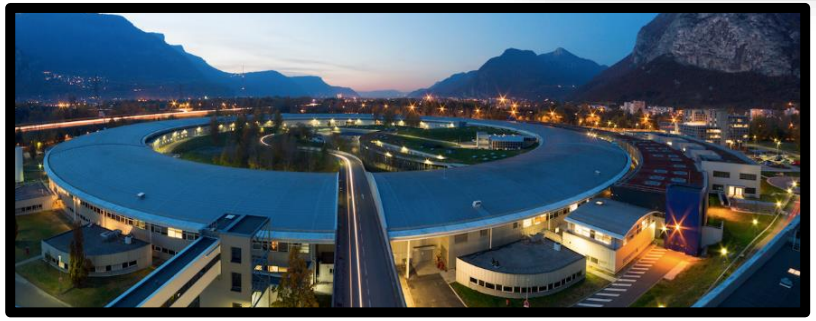
- X-ray magnetic diffraction has a prefactor $\left(\frac{\hbar\omega}{m_e c^2}\right)^2$ compared to Thompson scattering
- At 1 KeV this is ~3.8e-6
- So we use resonances…

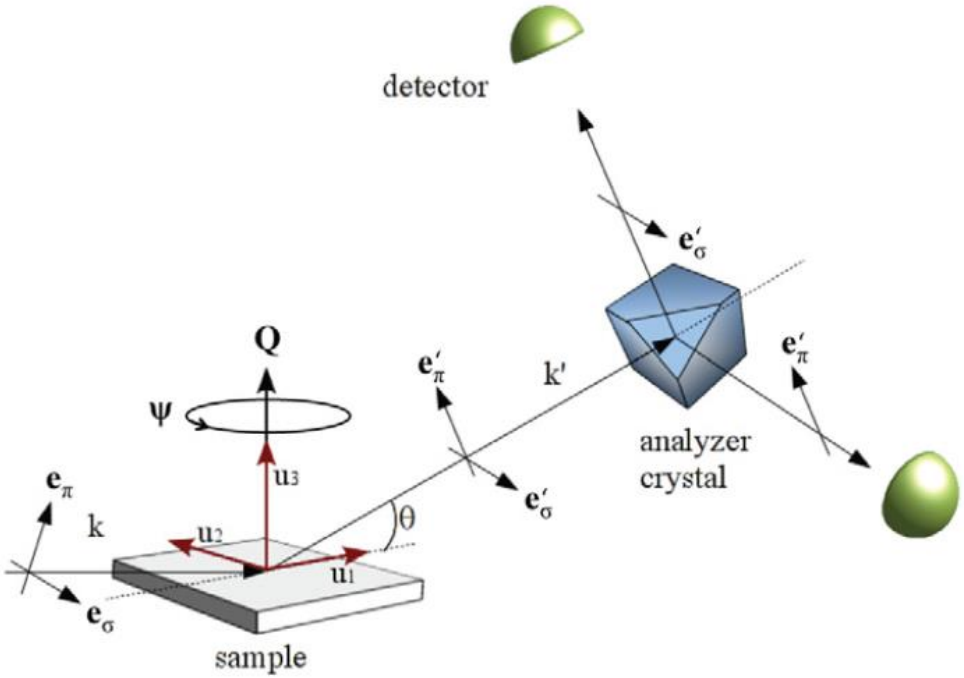
Resonance enables *practical* magnetic X-ray diffraction



Resonant X-ray diffraction

HZB Helmholtz Zentrum Berlin

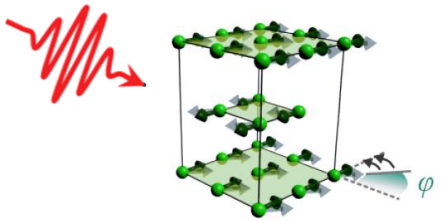




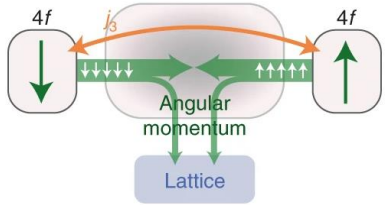
Fink, Rep. Prog. Phys. **76** (2013) 056502

Overview

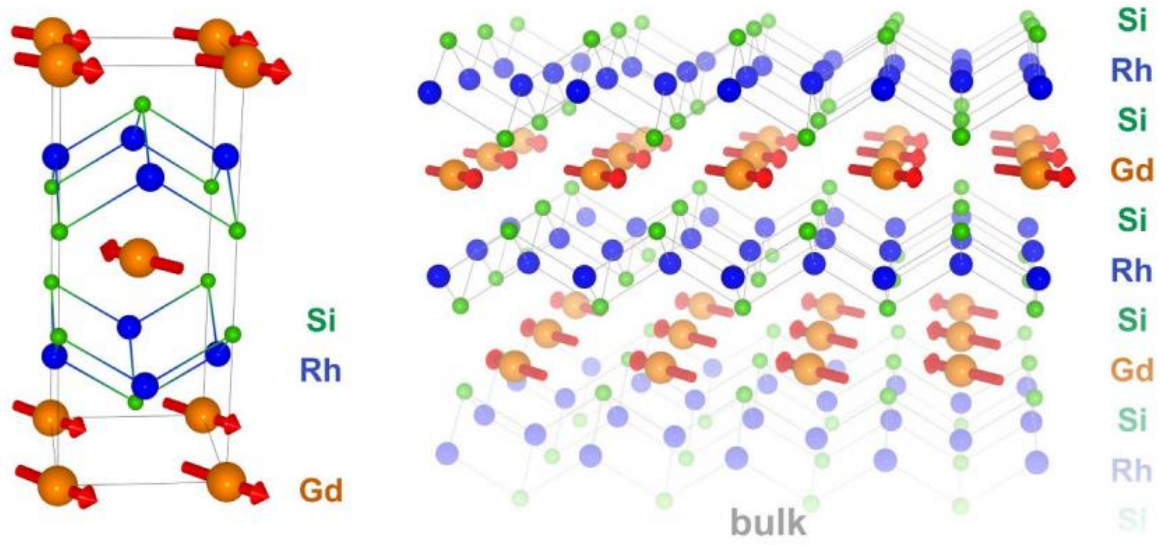
Deterministic control of an AF spin arrangement



Scaling of angular momentum transfer in 4f antiferromagnets

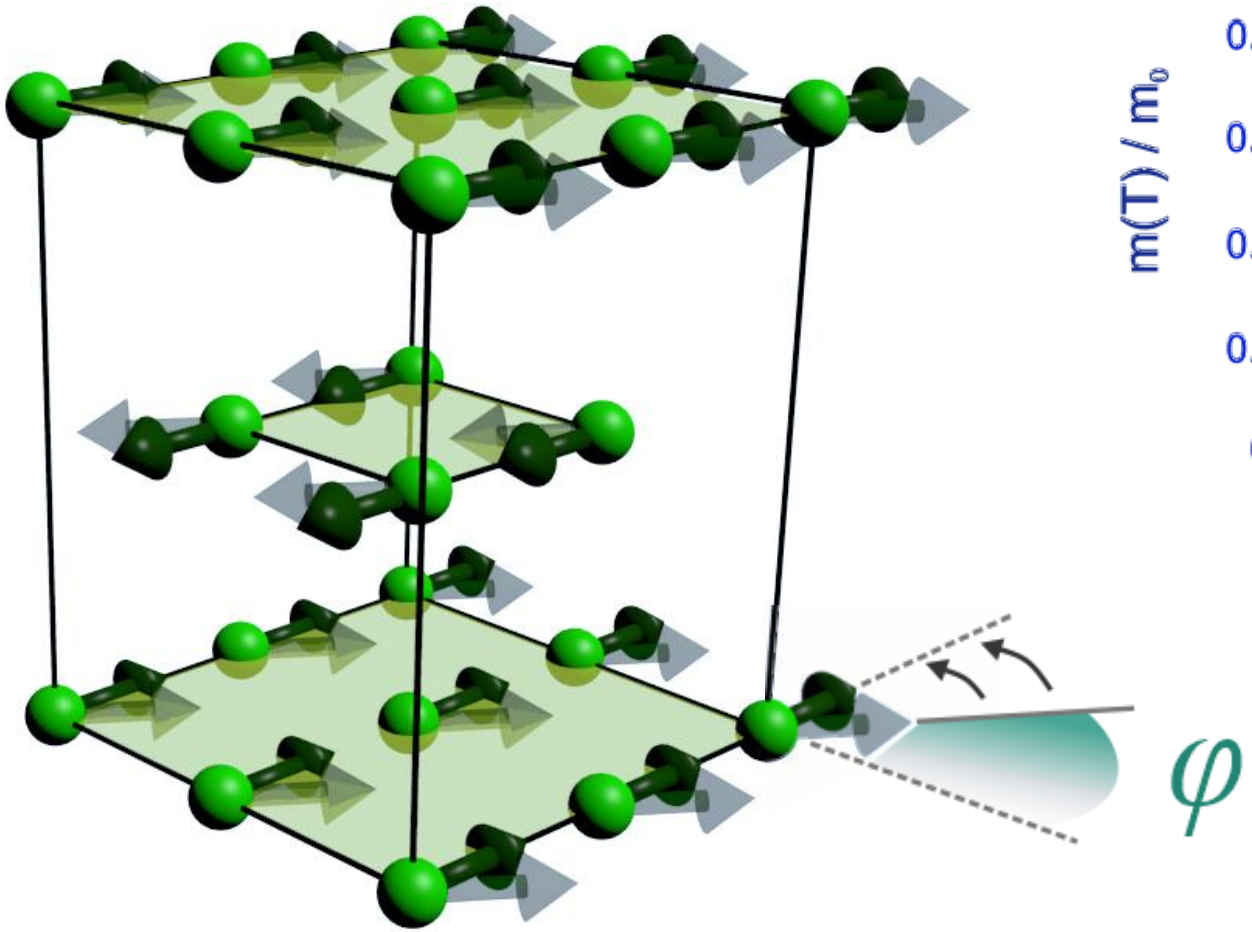


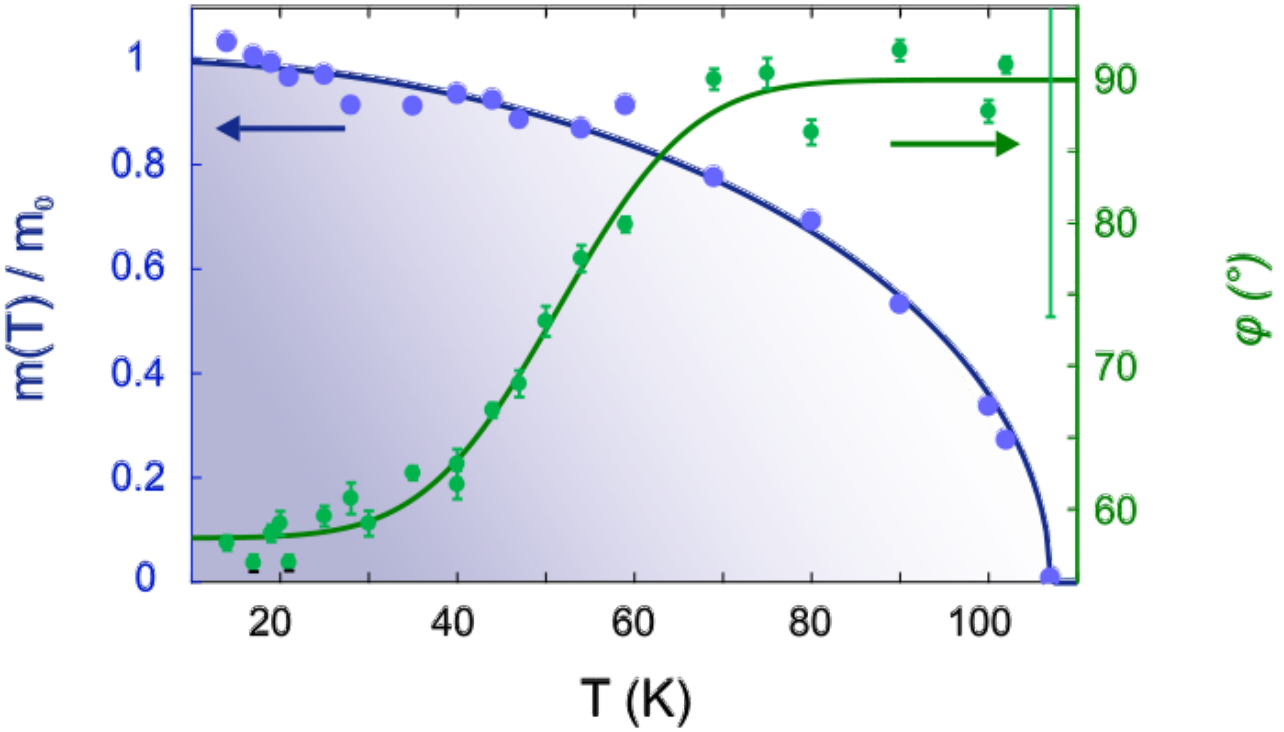
Model system – $GdRh_2Si_2$

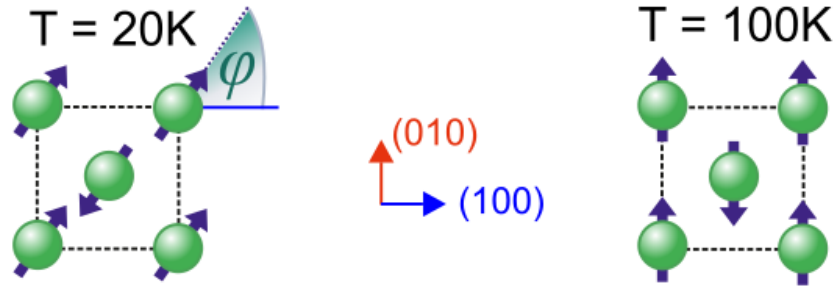


Equilibrium behavior

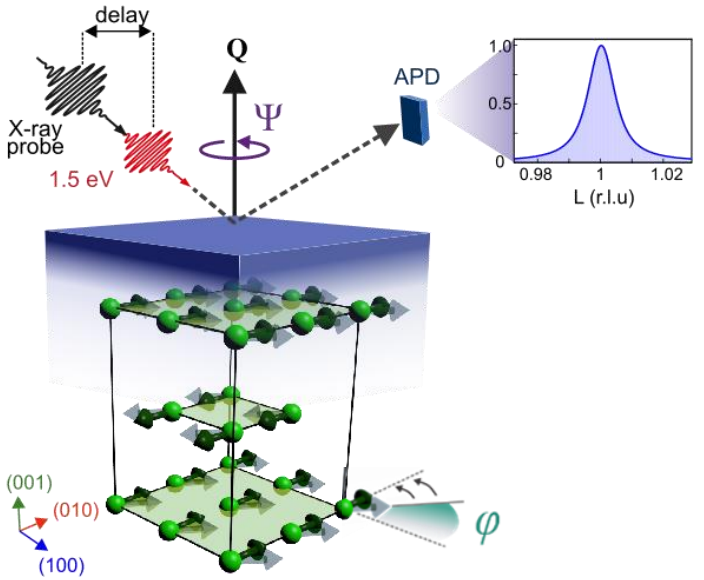
$GdRh_2Si_2$

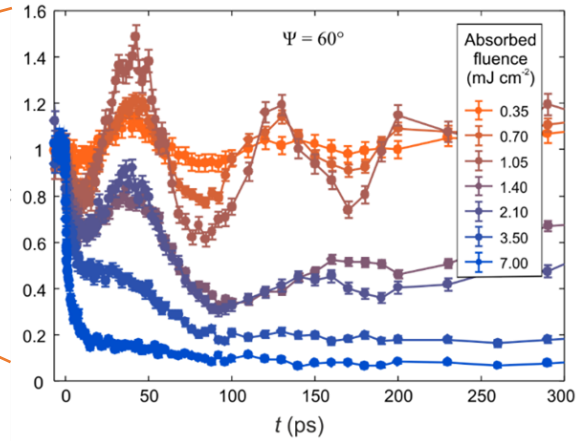


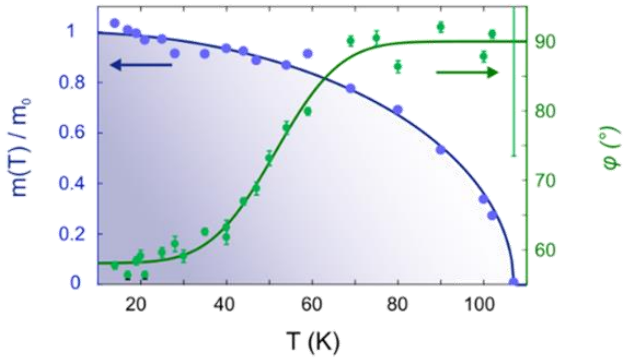




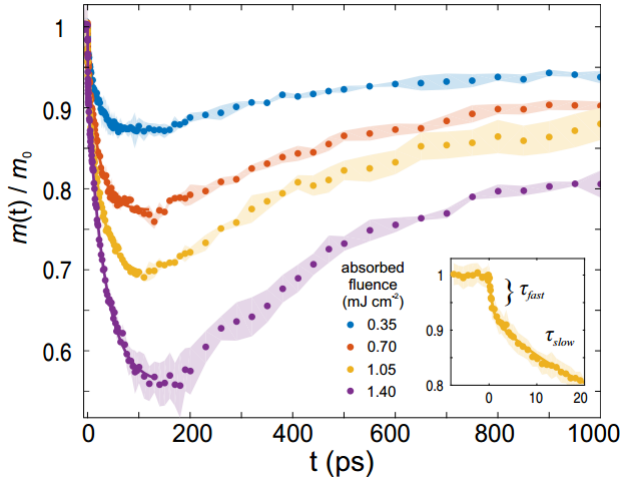
$GdRh_2Si_2$ – Dynamic Behavior



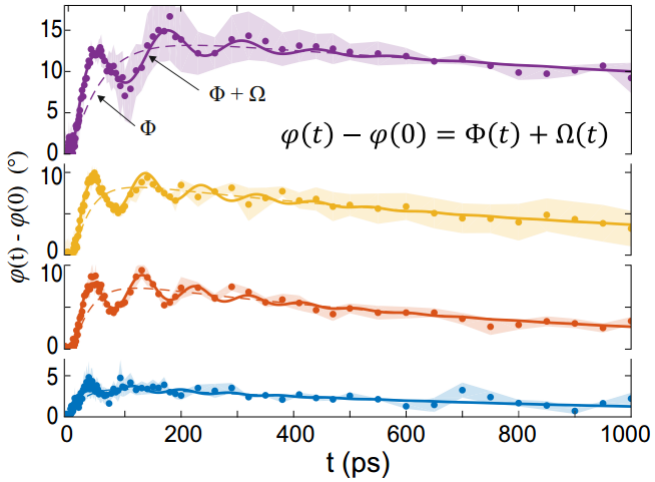




$m(t)$ - demagnetization

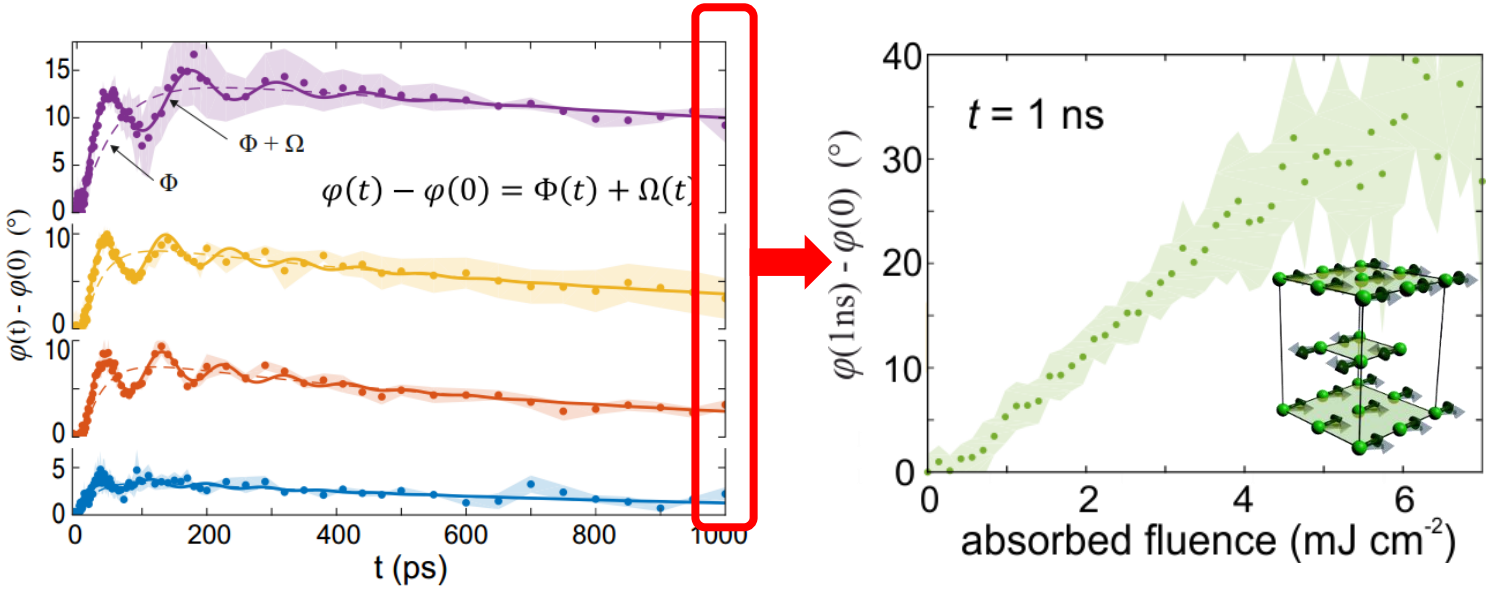


$\varphi(t)$ - reorientation

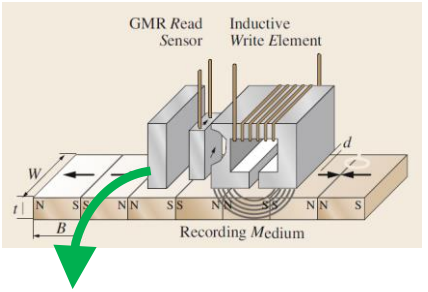


Deterministic control

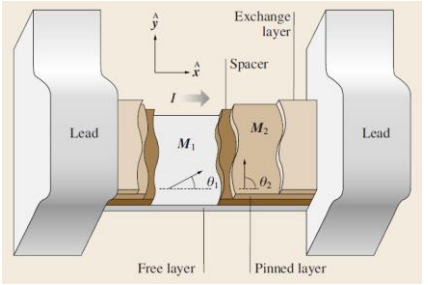
Easy axis of Gd in $GdRh_2Si_2$



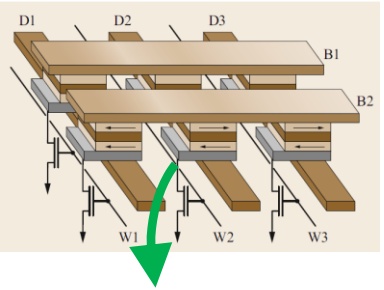
hard disk read/write head



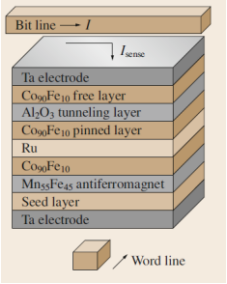
spin-valve read element



MRAM

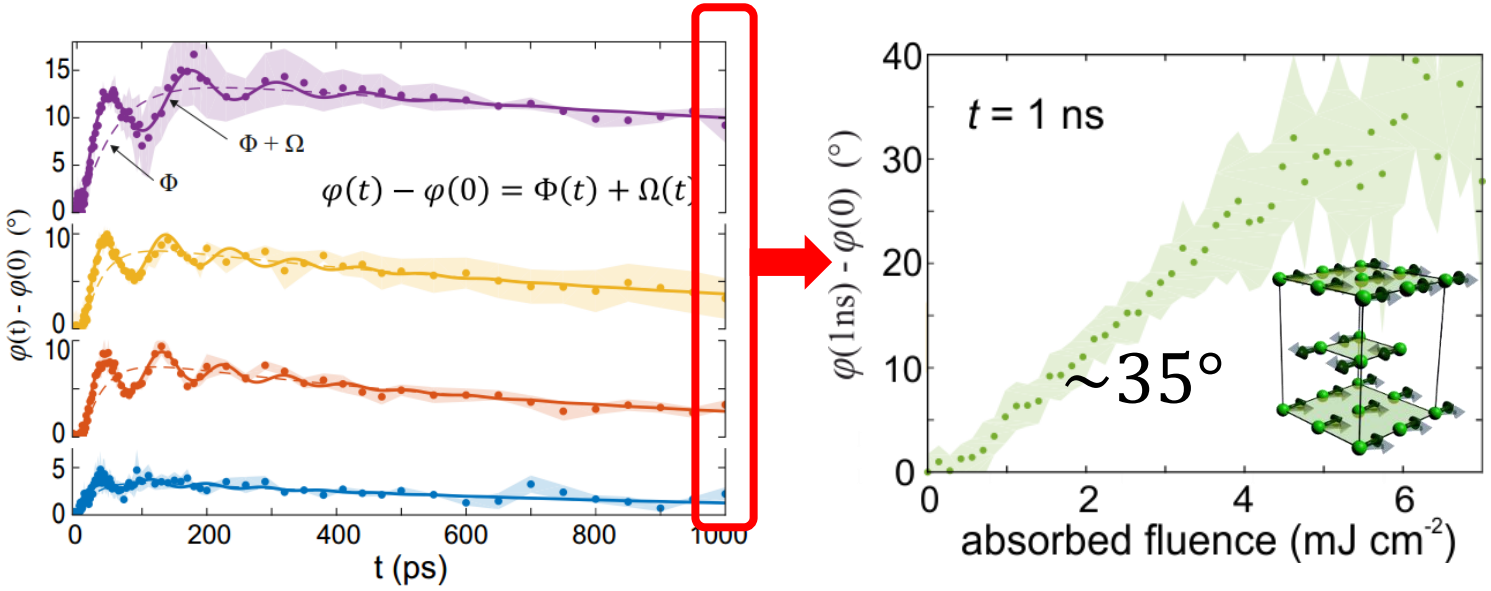


Magnetic tunnel junction

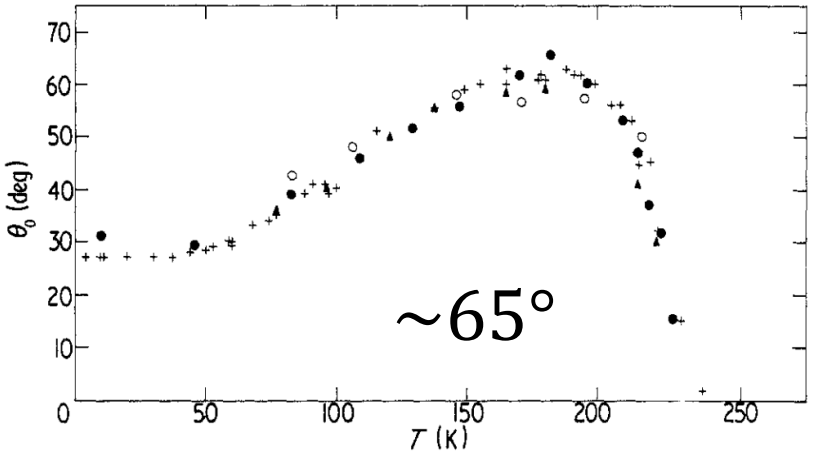


Outlook: Gd-based spintronics

Easy axis of Gd in $GdRh_2Si_2$



Easy axis of Gd Metal

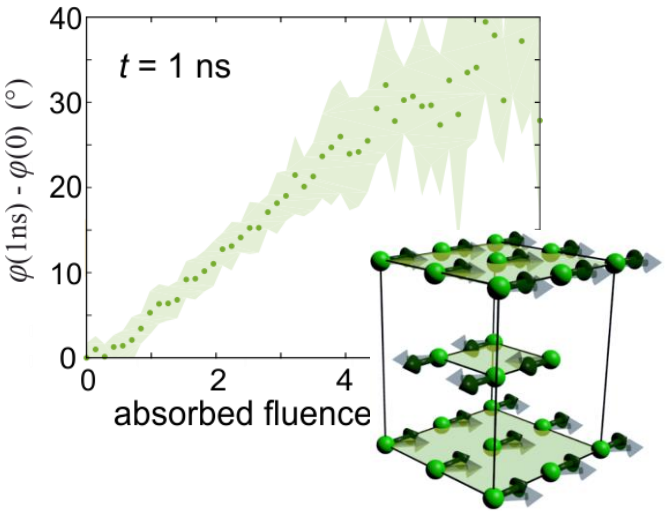


Corner & Tanner, J. Phys. C 9, 627–633 (1975)

Summary

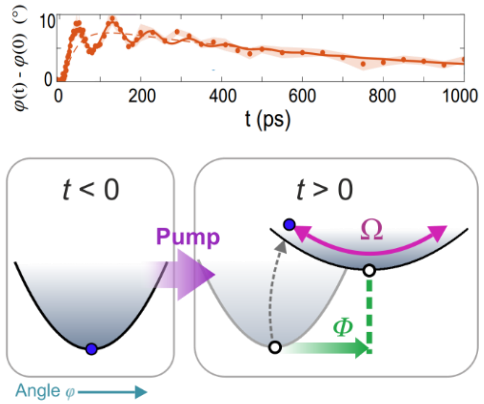
We can solve spin structures in the time domain!

Deterministic control
of the long-range AF order



Transient anisotropy potential
(quantitatively determined)

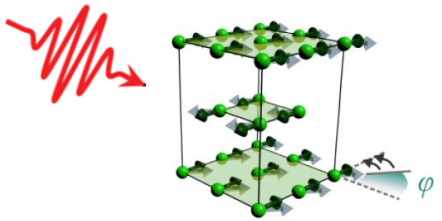
$$U(\varphi) = \frac{1}{2} K \sin^2(\varphi - \Phi)$$



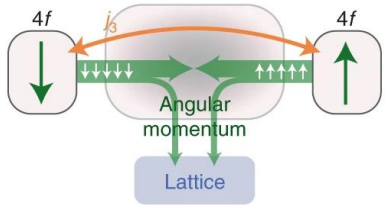
Windsor et al., Commun. Physics 3, 139 (2020)

Overview

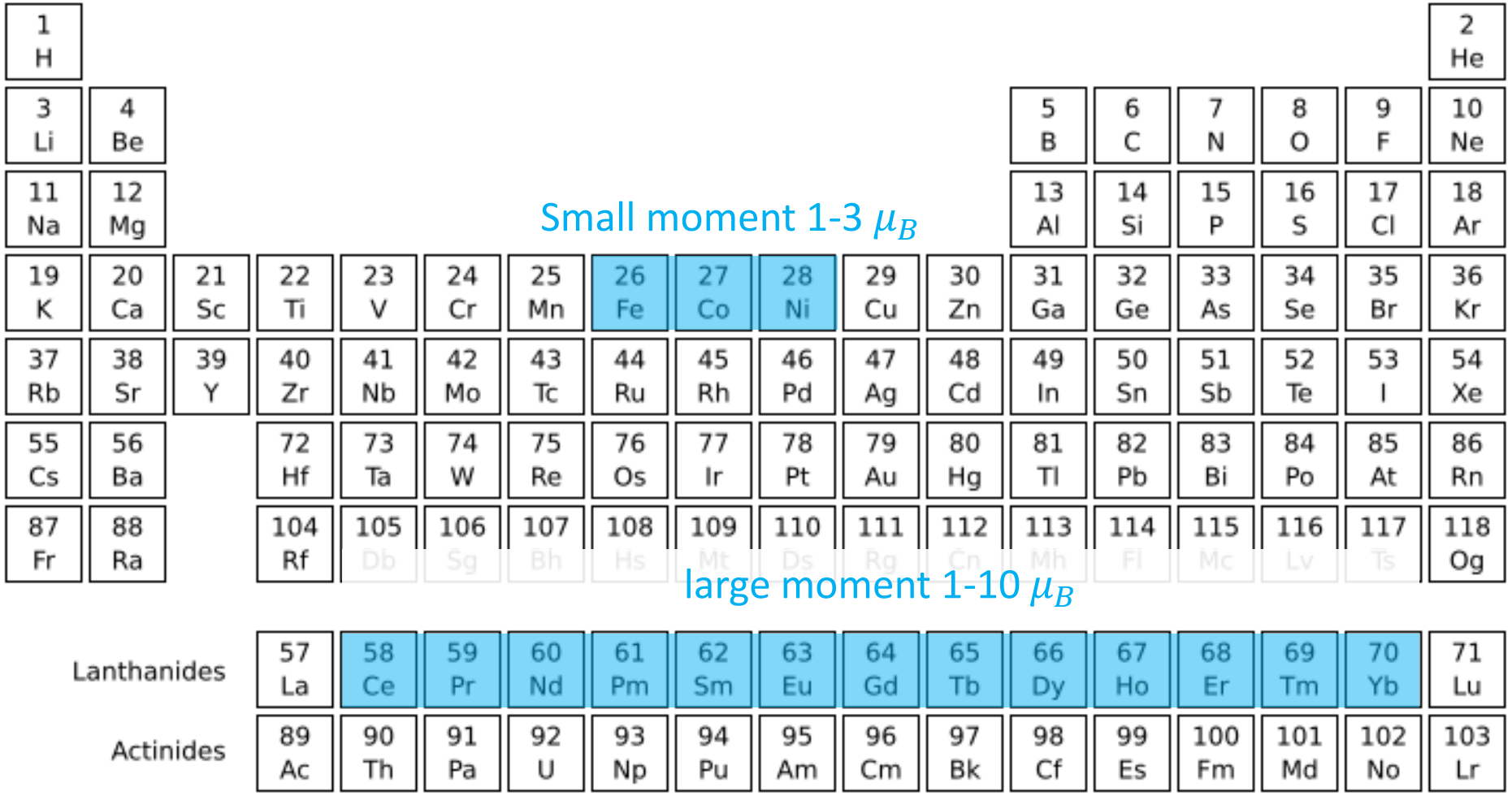
Deterministic control of an AF spin arrangement



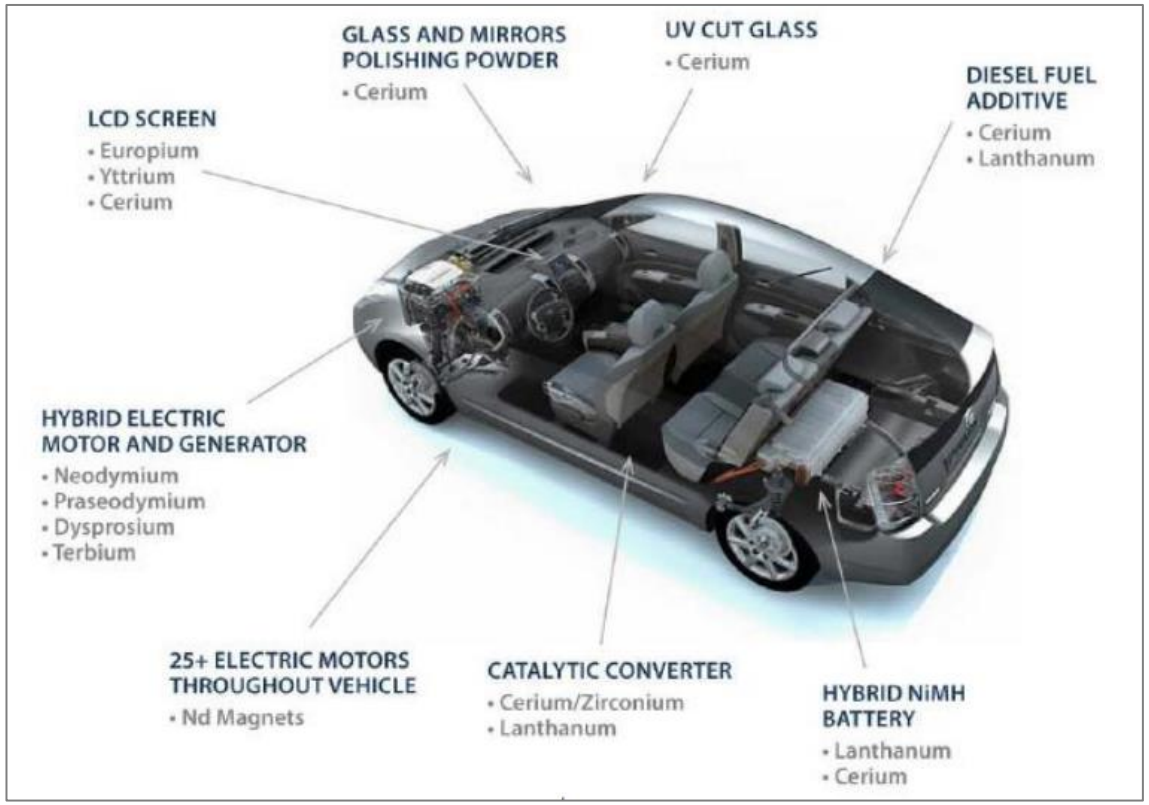
Scaling of angular momentum transfer in 4f antiferromagnets



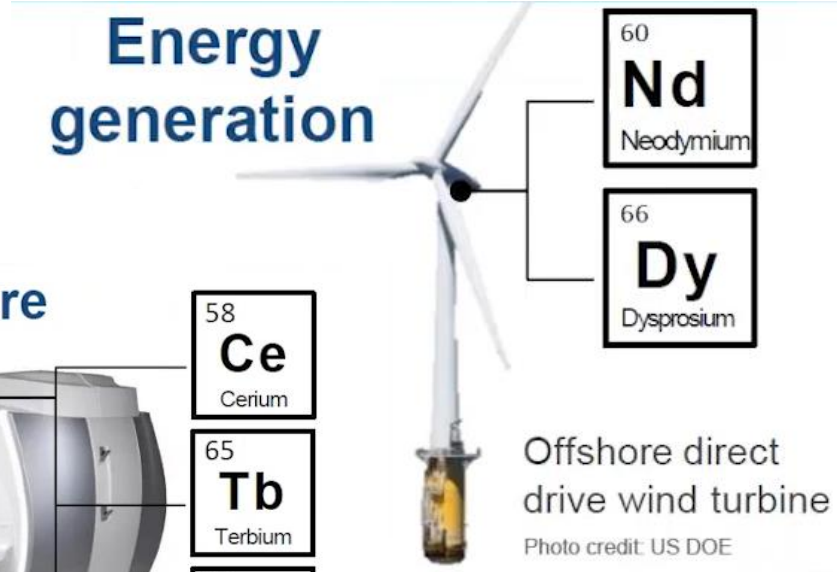
Intro to lanthanides



Lanthanides are important



Source: 'The Automotive Industry: A Major Rare Earths Consumer', 3 rd International Rare Earths Conference, Dudley J Kingsnorth, November 2007

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EXPLAINER: Why Rare Earths Are the Key to Just About... SHARE:

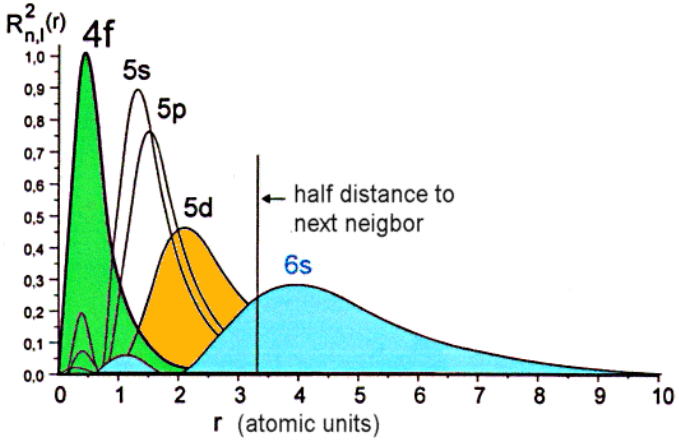
EXPLAINER

Why Rare Earths Are the Key to Just About Everything

They're not actually that rare, but their importance to almost all modern technologies cannot be overstated.

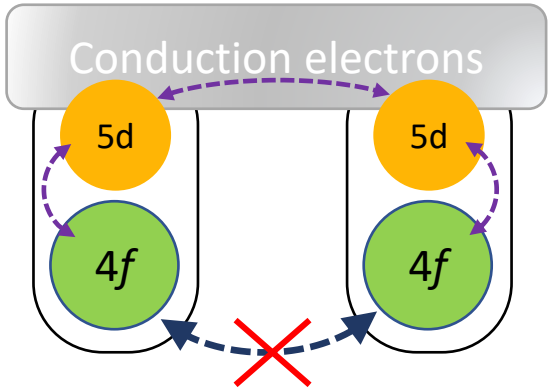
Magnetic coupling in lanthanides

4*f* states are very localized

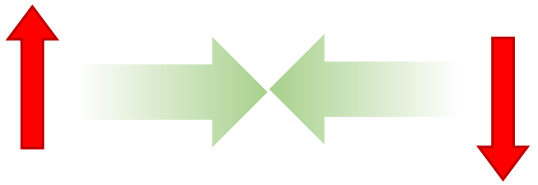


RKKY – indirect exchange

$$\mathcal{J}_S(\mathbf{q}) = \frac{V}{N\mu_B^2}|I(\mathbf{q})|^2\chi(\mathbf{q}).$$



Can AF demagnetization occur with RKKY?



Dissipation-free AF demagnetization

Yes.

PRL 119, 197202 (2017) PHYSICAL REVIEW LETTERS week ending 10 NOVEMBER 2017

Ultrafast and Energy-Efficient Quenching of Spin Order: Antiferromagnetism Beats Ferromagnetism

Nele Thielemann-Kühn,[1,2,*] Daniel Schick,[1] Niko Pontius,[1] Christoph Trabant,[1,2,3] Rolf Mitzner,[1] Karsten Holldack,[1] Hartmut Zabel,[4] Alexander Föhlisch,[1,2] and Christian Schüßler-Langeheine[1]

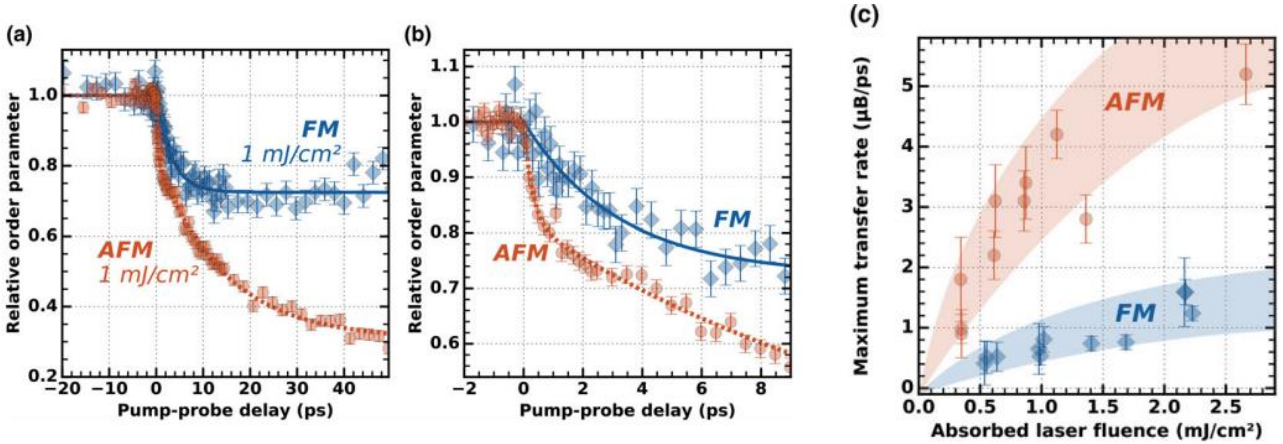
[1]*Institut für Methoden und Instrumentierung der Forschung mit Synchrotronstrahlung, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Albert-Einstein-Straße 15, 12489 Berlin, Germany*

[2]*Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Straße 24/25, 14476 Potsdam, Germany*

[3]*II. Physikalisches Institut, Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany*

[4]*Institut für Physik, Johannes-Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany*

(Received 15 March 2017; revised manuscript received 20 September 2017; published 6 November 2017)

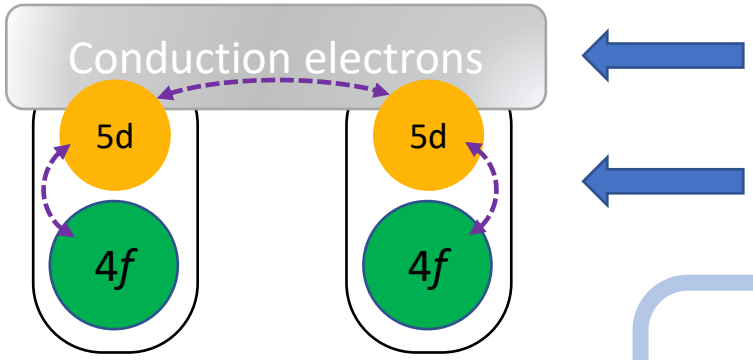


Lets use this!

Can we tune RKKY's strength to optimize ultrafast dynamics?

RKKY – indirect exchange

$$\mathcal{J}_S(\mathbf{q}) = \frac{V}{N\mu_B^2}|I(\mathbf{q})|^2\chi(\mathbf{q}).$$



Routes to alter $\mathcal{J}_S(\mathbf{q})$

$\chi(\boldsymbol{q})$ - e.g. tuning the occupation at the fermi level,

$I(\boldsymbol{q})$ - on-site overlap is not easily accessible

overlap is sensitive to filling of the 4f shell.

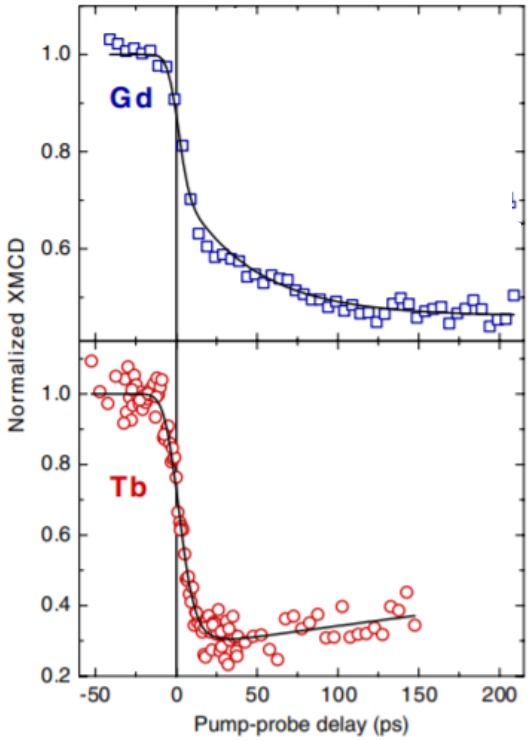
How does 4*f* filling affect spin dynamics?

4*f* demagnetization in literature

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

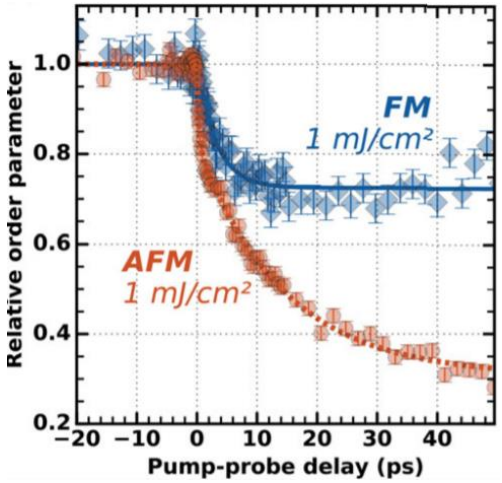
Gd & Tb

Wietstruk PRL 106, 127401 (2011)



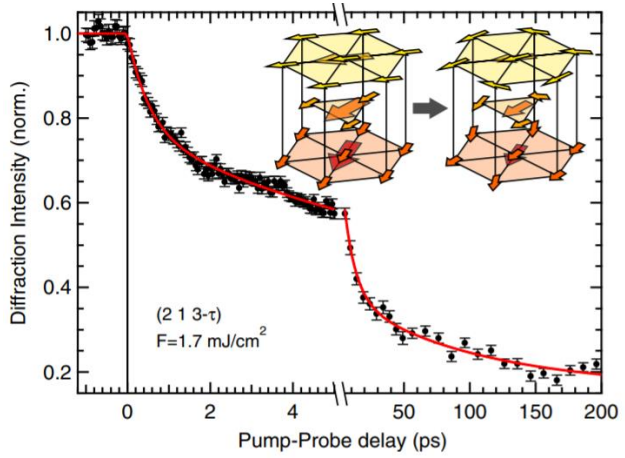
Dy

Thielemann-Kühn PRL 119, 197202 (2017)



Ho

Rettig PRL 116, 257202 (2016)

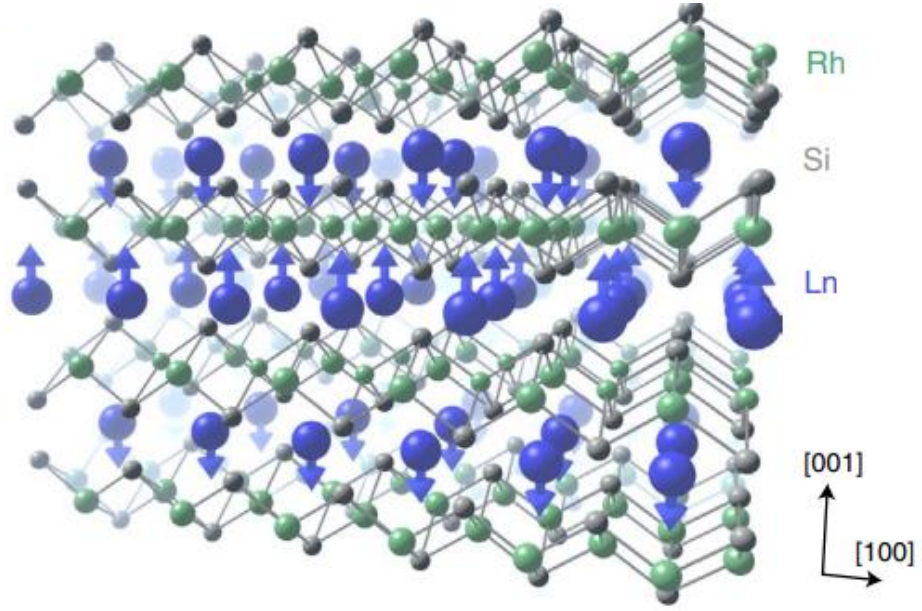


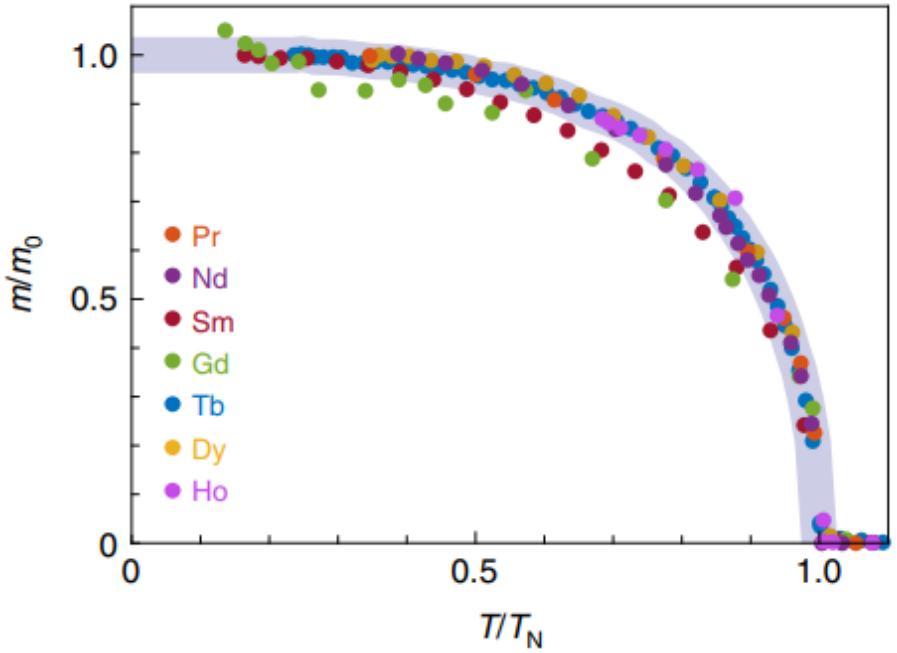
Inconclusive!

LnRh_2Si_2 – a series of boring antiferromagnets

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

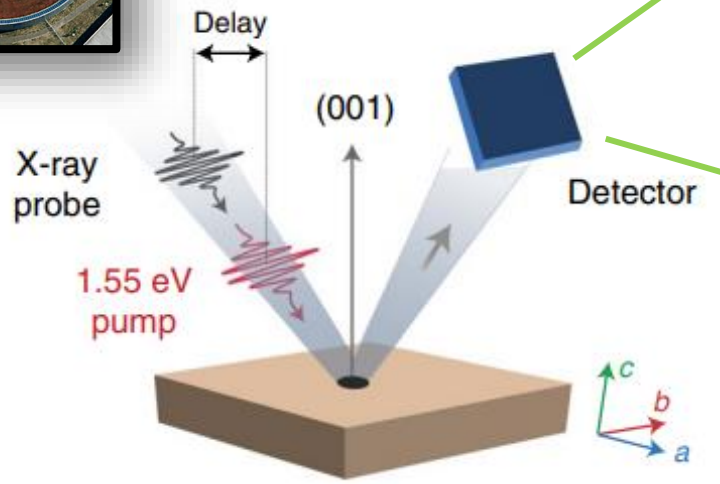
when changing the Ln ion, practically nothing changes

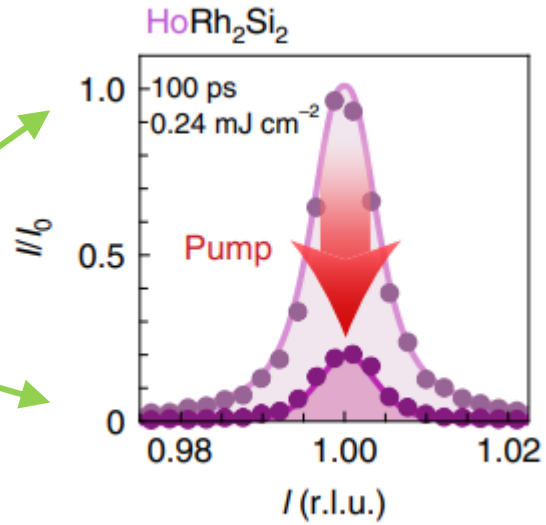


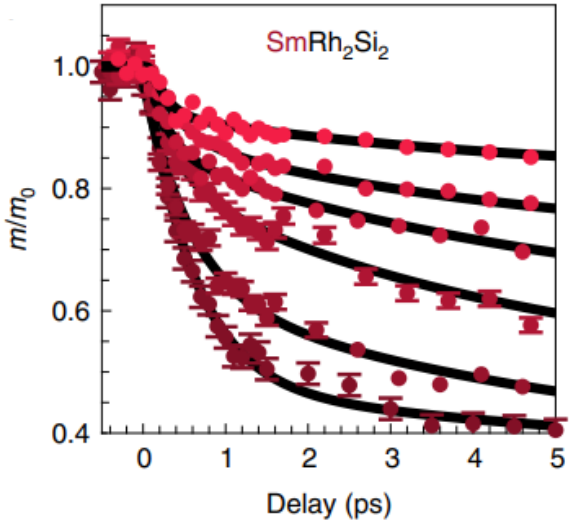


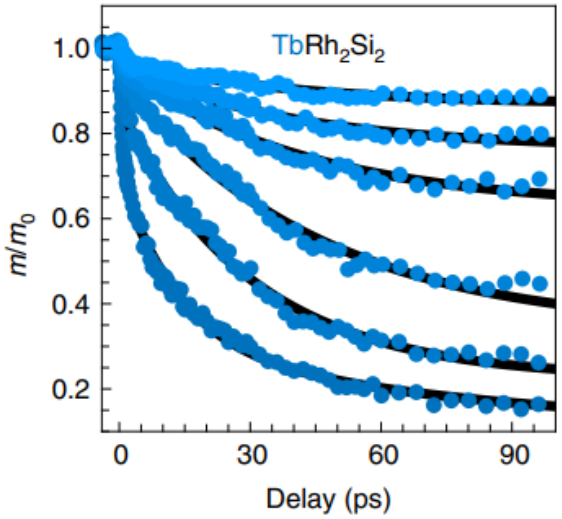
Experiment

HZB Helmholtz Zentrum Berlin

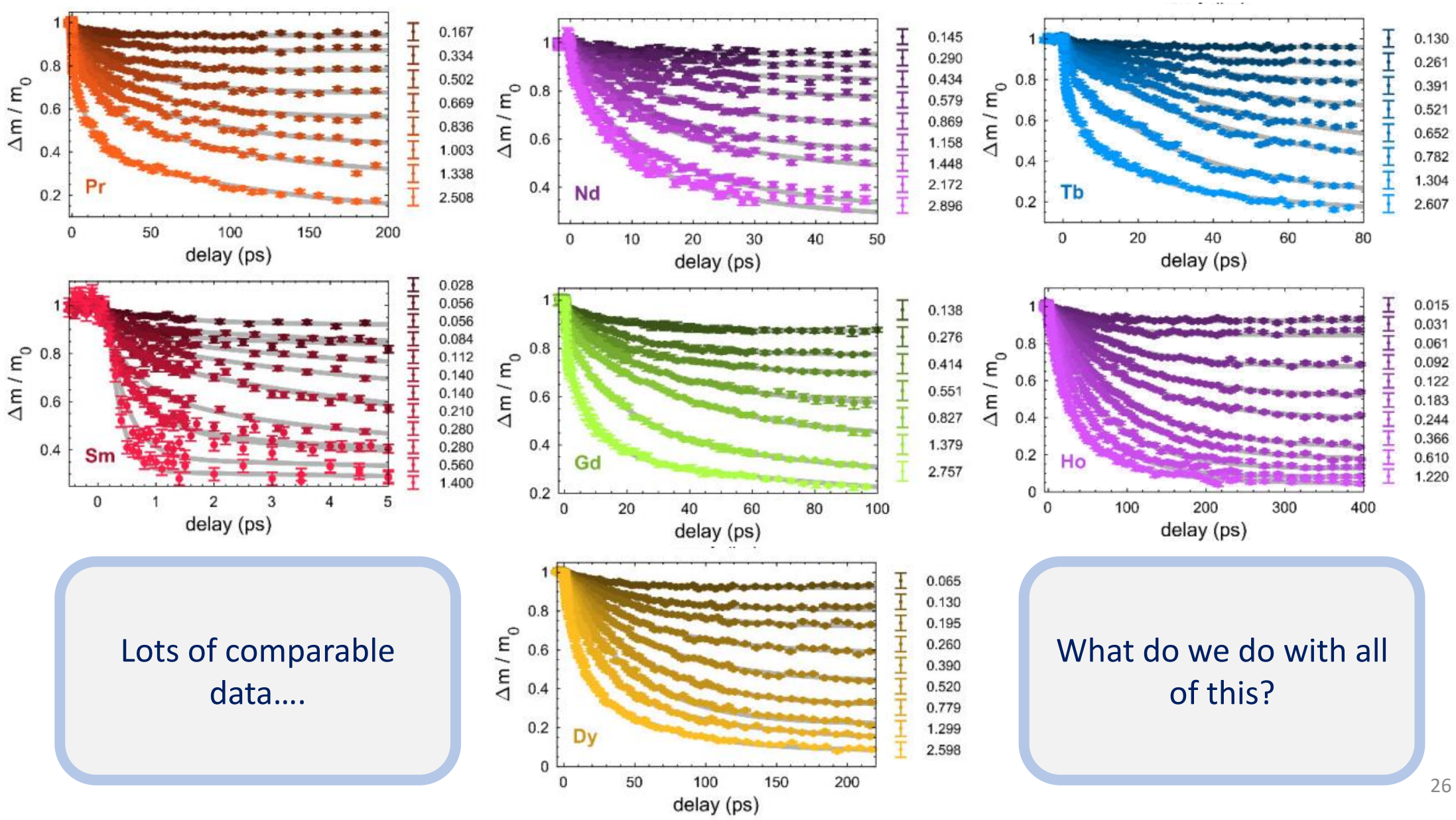








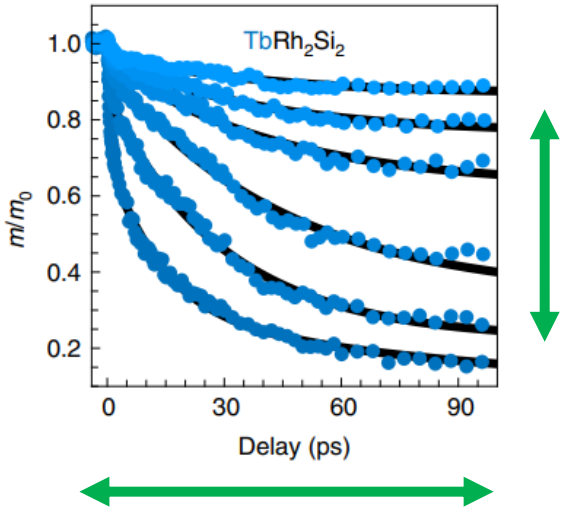
Lots of data that look almost the same…

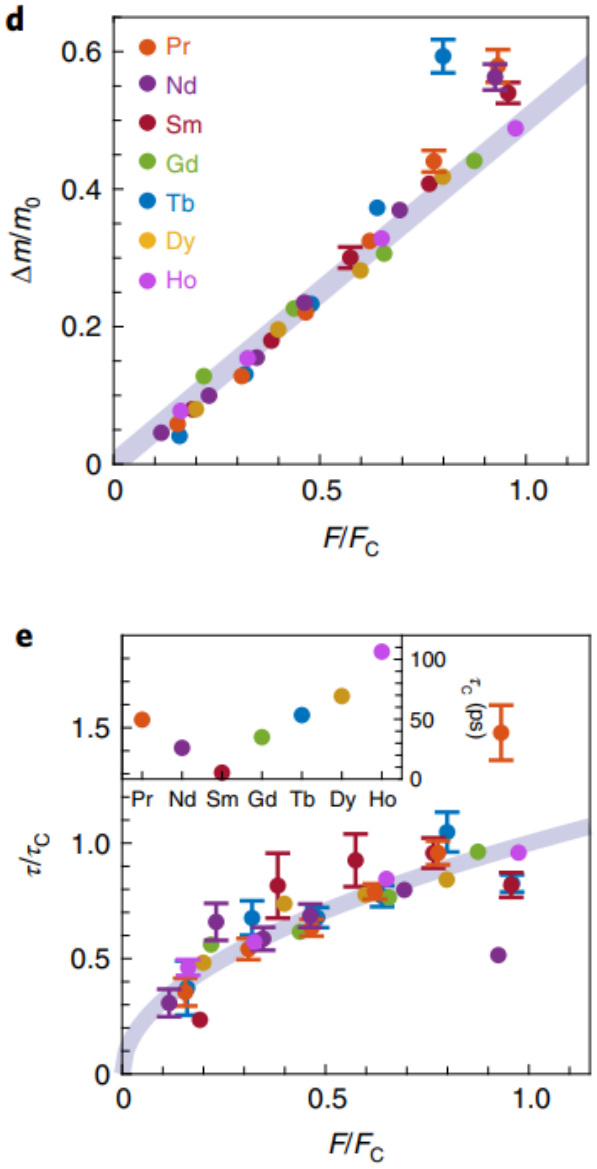


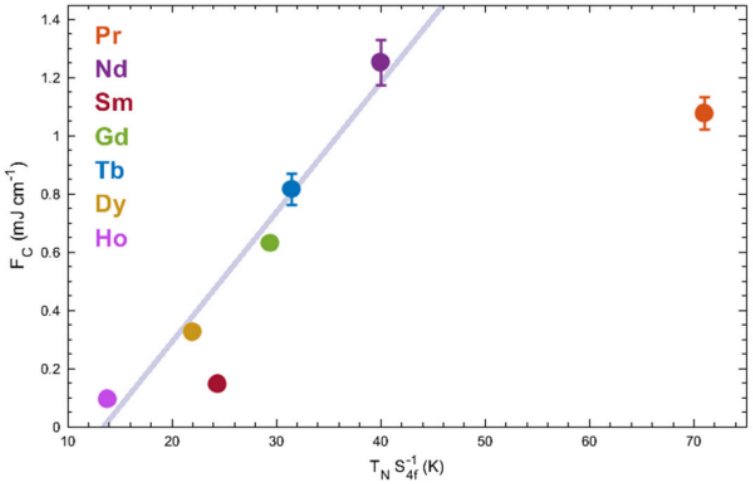
Lots of comparable data….

What do we do with all of this?

Scaling?

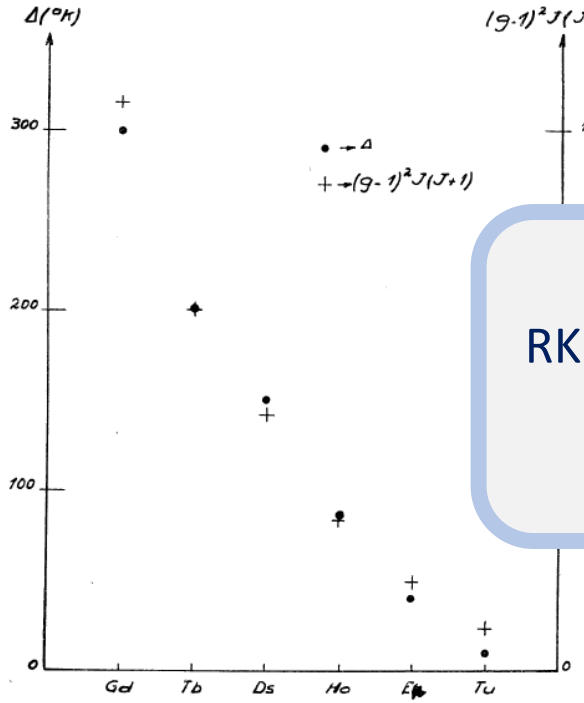

TbRh2Si2
m/m0
Delay (ps)


d
Pr
Nd
Sm
Gd
Tb
Dy
Ho
Δm/m0
F/FC
e
τ/τC
τC (ps)


Pr
Nd
Sm
Gd
Tb
Dy
Ho
FC (mJ cm-1)
TN S4f-1 (K)

de Gennes scaling $(g-1)^2 J(J+1)$

MAGNÉTISME. — *Sur les propriétés des métaux des terres rares.* Note (*) de M. **Pierre-Gilles de Gennes**, transmise par M. Francis Perrin.



2. Le couplage (2) produit également, dans le domaine paramagnétique, une résistivité par désordre de spin ρ_0 ([8]), ([9]), ([10]) qui est effectivement observée ([4]). Dans l'approximation de Born, on trouve

RKKY should/could also scale in this way!

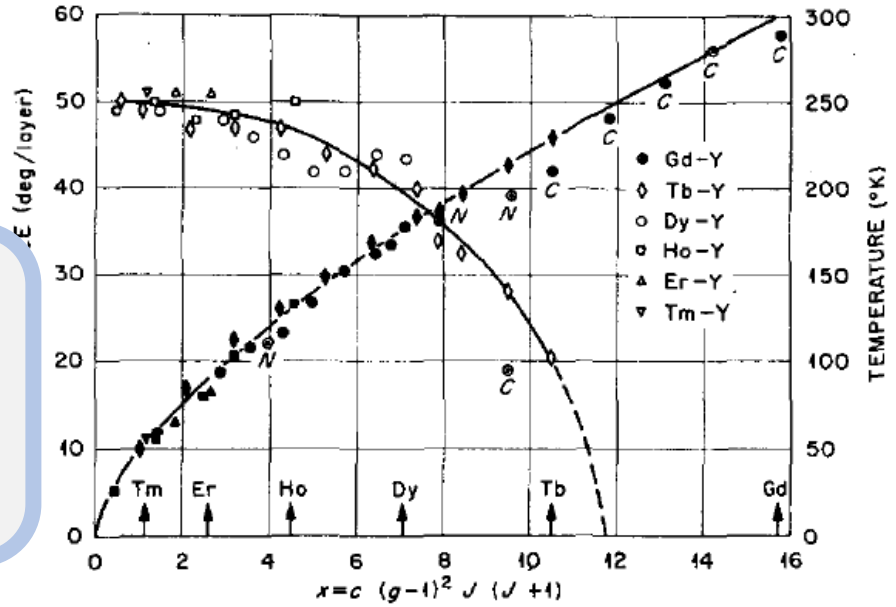


FIG. 6. Magnetic structure properties of R–Y alloys. The interlayer angles at the ordering temperature, on the left, and the ordering temperature, on the right, are universal functions of the average squared projection of S on J. The interlayer angle curve extrapolates to zero for $x=11.5$, approximately.

de Gennes, C. R. Acad. Sci. 247, 1836 (1958)

Koehler, JAP, 36, 1078 (1965)

Scaling (2)

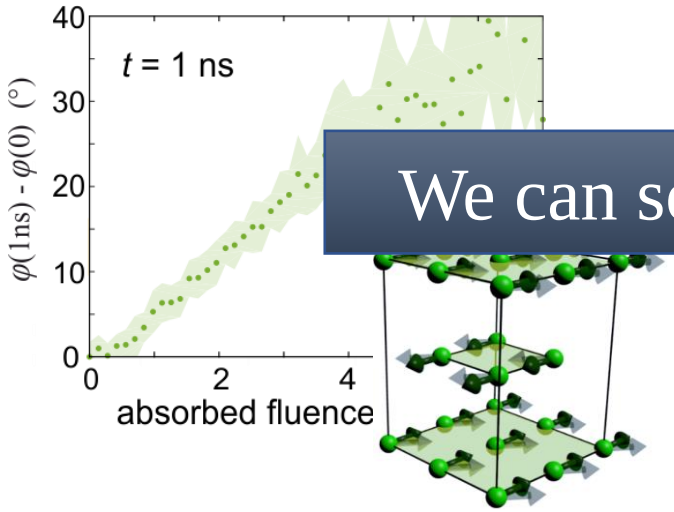
Define:
Angular momentum transfer rate
Units: μ_B/ps

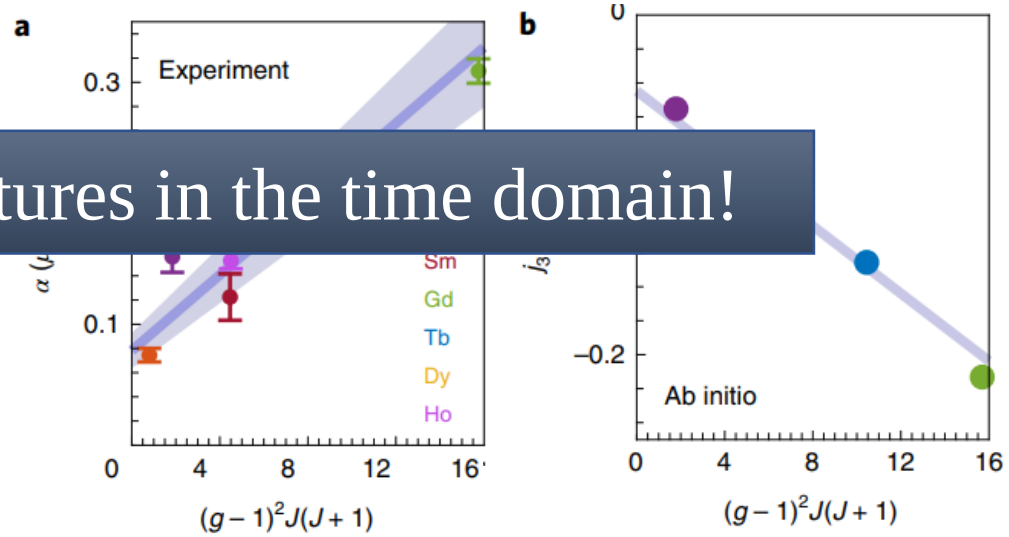
Spin dynamics are governed by RKKY, which can be controlled by 4f filling,

Summary

Deterministic control
of the long-range AF order

Scaling of angular momentum transfer rates
4f filling controls spin dynamics





We can solve spin structures in the time domain!

Windsor et al., Commun. Physics 3, 139 (2020)

Windsor et al., Nat. Mater. (2022).

Shameless advertising: lattice dynamics in NiO Windsor et al. PRL 126, 147202 (2021)

Thanks

Thank you for your attention!

Laurenz Rettig
Daniela Zahn
Sang-Eun Lee
Ralph Ernstorfer
Martin Wolf

Arthur Ernst

Urs Staub

Christian Schüßler-Langeheine
Niko Pontius
Torsten Kachel

Denis Vyalikh
Evgueni Chulkov

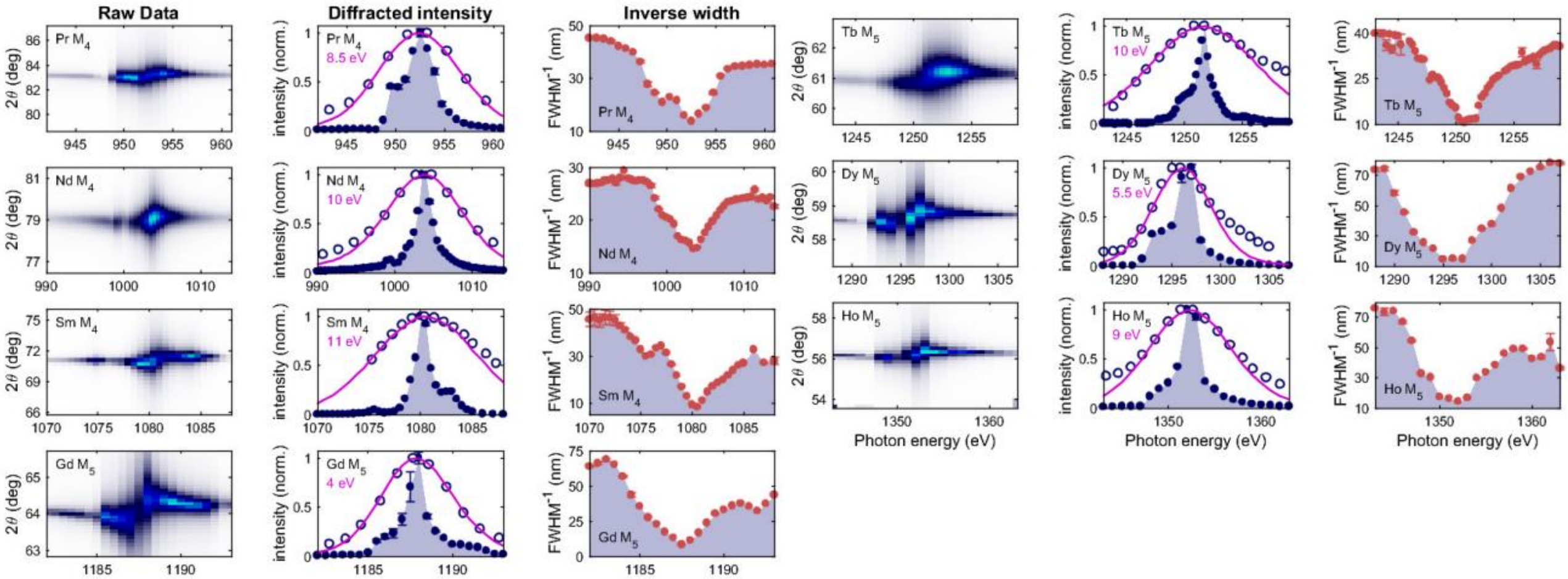
Cornelius Krellner
Kristin Kleimt

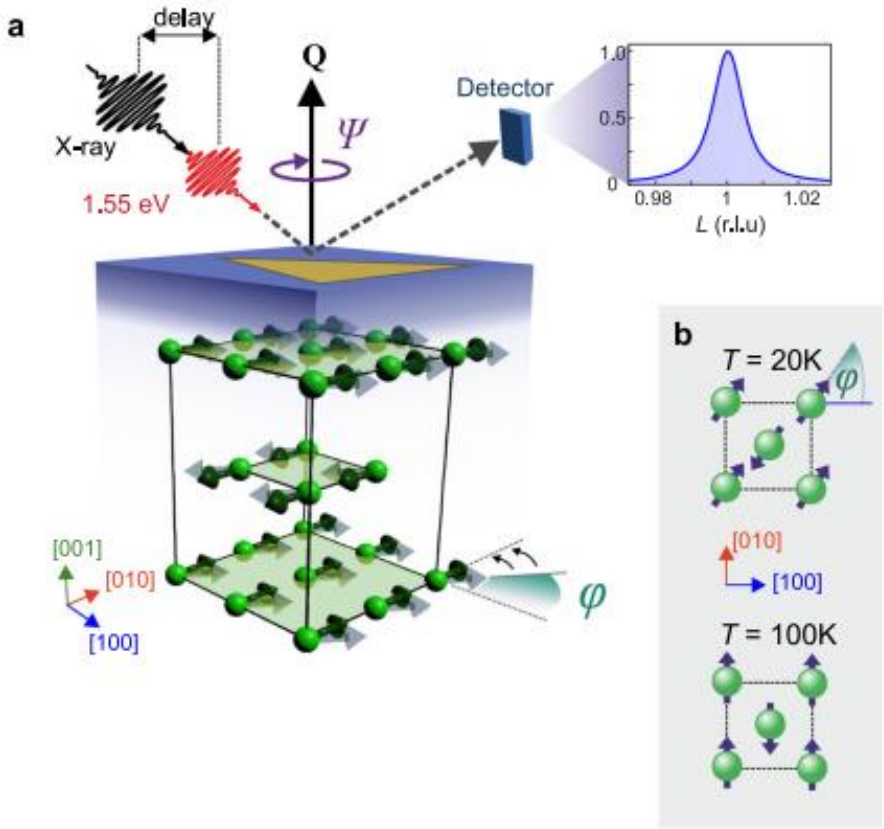
Danny Thonig

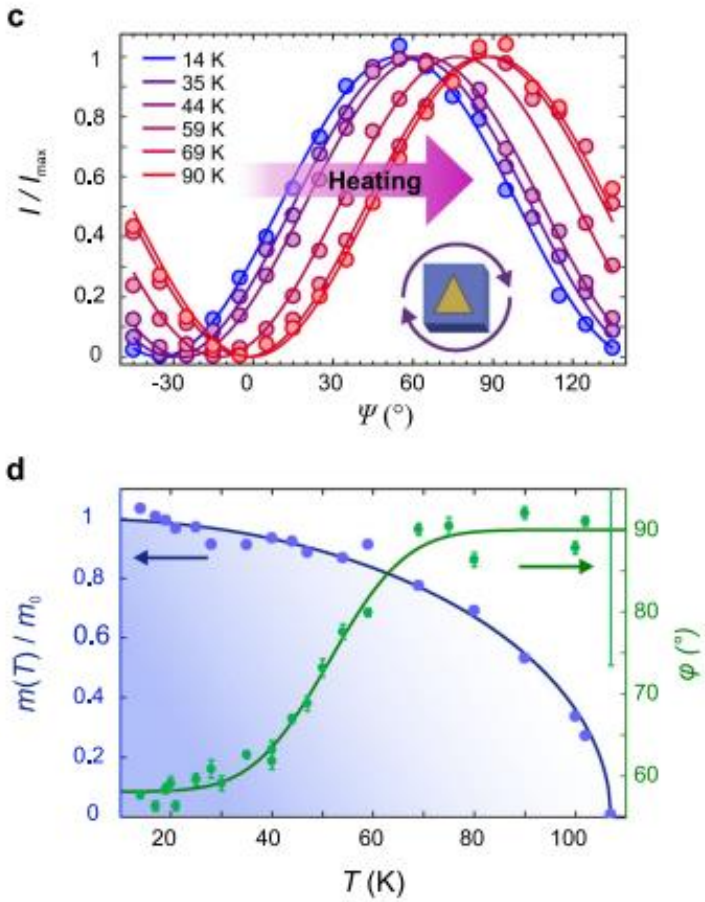
Kurt Kummer

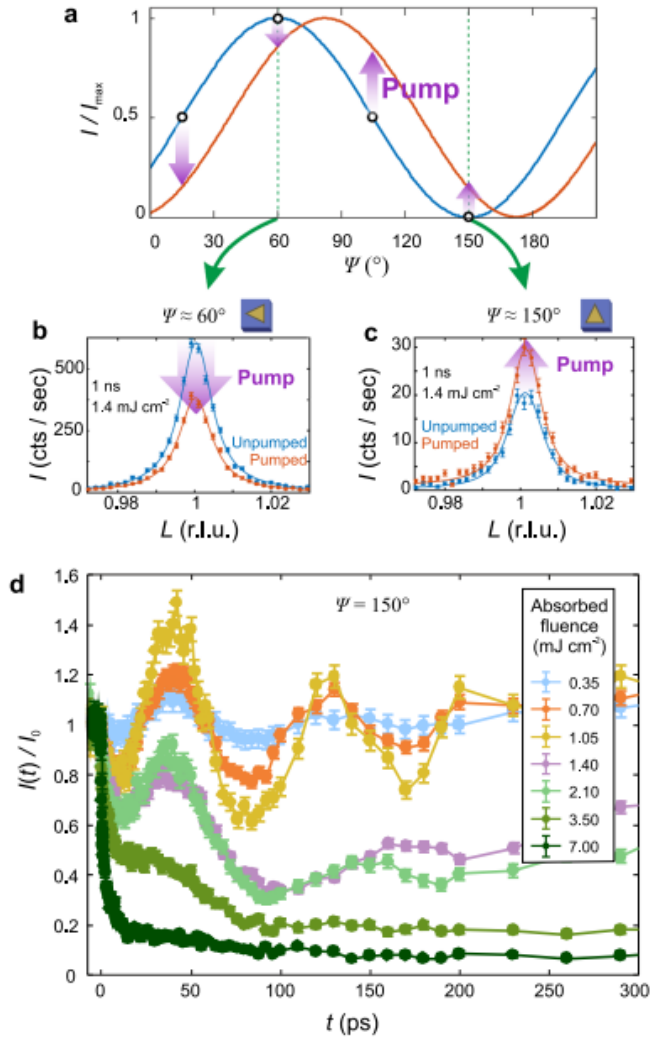
Olle Eriksson
Vladislav Borisov

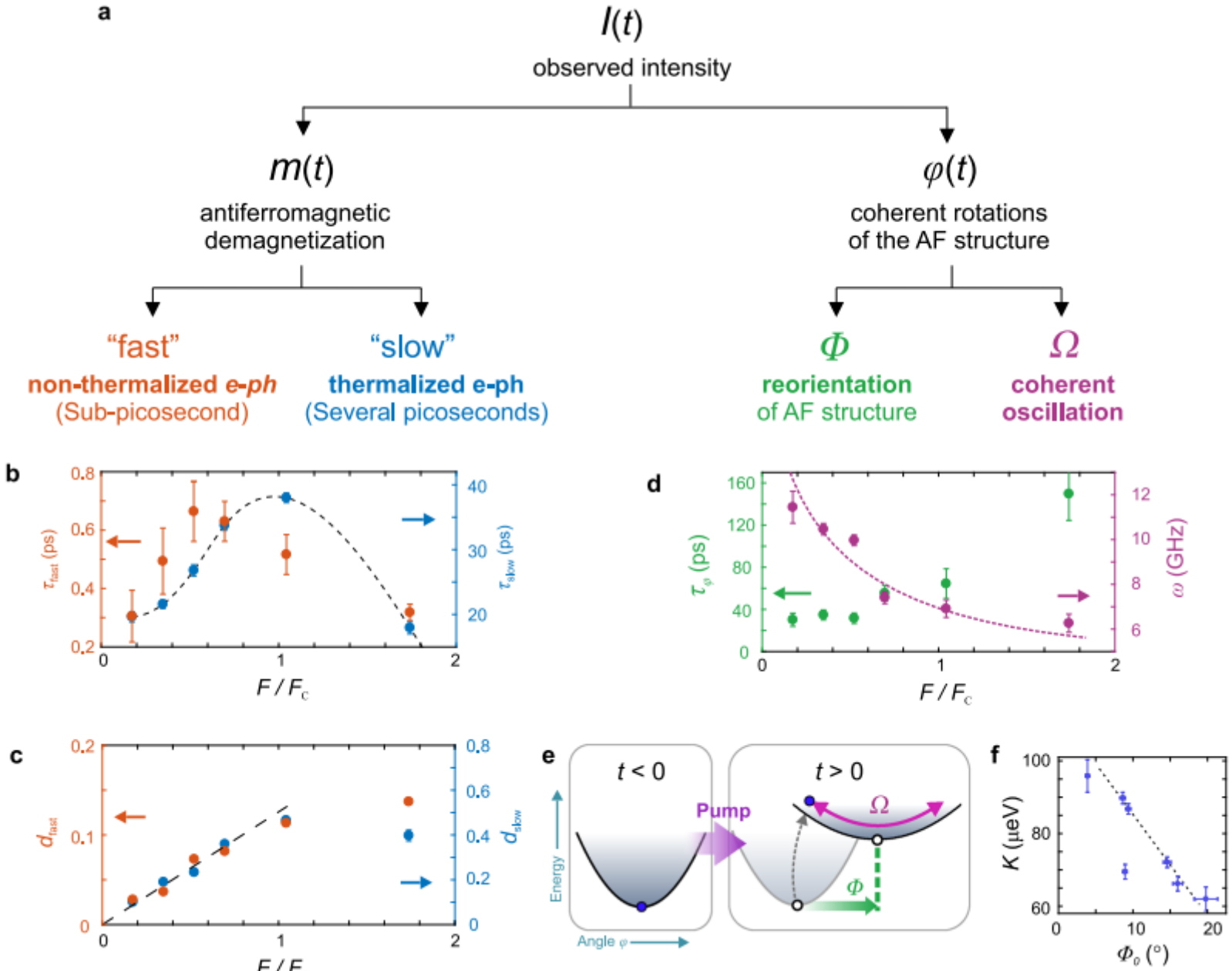
Do I have time to make backups?


Raw Data
Diffracted intensity
Inverse width
Pr M4
8.5 eV
Nd M4
10 eV
Sm M4
11 eV
Gd M5
4 eV
Tb M5
10 eV
Dy M5
5.5 eV
Ho M5
9 eV
2θ (deg)
intensity (norm.)
FWHM-1 (nm)
Photon energy (eV)


a
delay
Q
Ψ
X-ray
1.55 eV
Detector
1.0
0.5
0
0.98
1
1.02
L (r.l.u)
[001]
[010]
[100]
φ
b
T = 20K
φ
[010]
[100]
T = 100K


c
14 K
35 K
44 K
59 K
69 K
90 K
Heating
I / I_max
Ψ (°)
d
m(T) / m_0
φ (°)
T (K)


a
Pump
I / I_max
Ψ (°)
b
Ψ ≈ 60°
1 ns
1.4 mJ cm⁻²
Pump
Unpumped
Pumped
I (cts / sec)
L (r.l.u.)
c
Ψ ≈ 150°
d
Ψ = 150°
Absorbed fluence (mJ cm⁻²)
0.35
0.70
1.05
1.40
2.10
3.50
7.00
I(t) / I_0
t (ps)


a
I(t)
observed intensity
m(t)
antiferromagnetic demagnetization
φ(t)
coherent rotations of the AF structure
"fast"
non-thermalized e-ph
(Sub-picosecond)
"slow"
thermalized e-ph
(Several picoseconds)
Φ
reorientation of AF structure
Ω
coherent oscillation
b
τfast (ps)
τslow (ps)
F / Fc
c
dfast
dslow
F / Fc
d
τφ (ps)
ω (GHz)
F / Fc
e
t < 0
t > 0
Pump
Ω
Φ
Energy
Angle φ
f
K (μeV)
Φ0 (°)