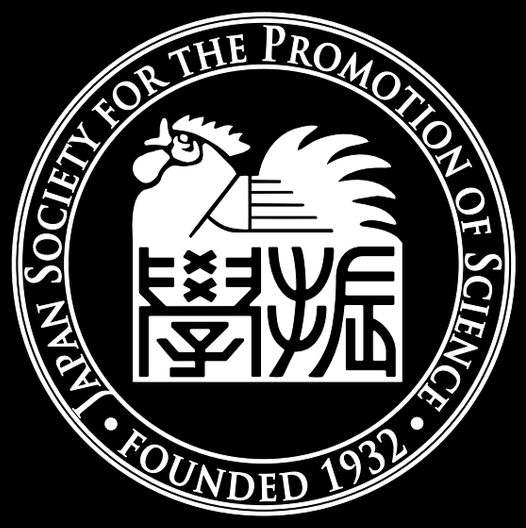
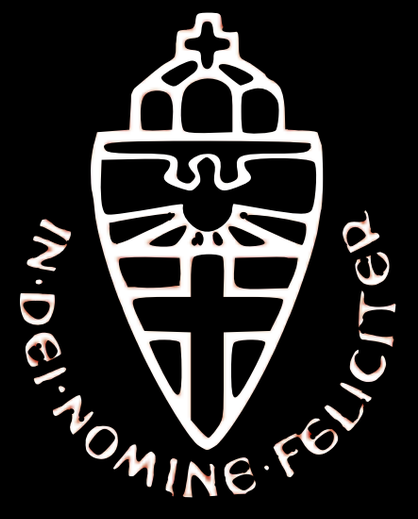
Ultrafast optical manipulation of magnetic materials

D. Bossini

Technical University Dortmund, Germany





Ultrafast

- ultrafast demagnetisation
- all-optical switching
- inverse-Faraday effect
- magnetic phase-transitions

Optics

Spintronics

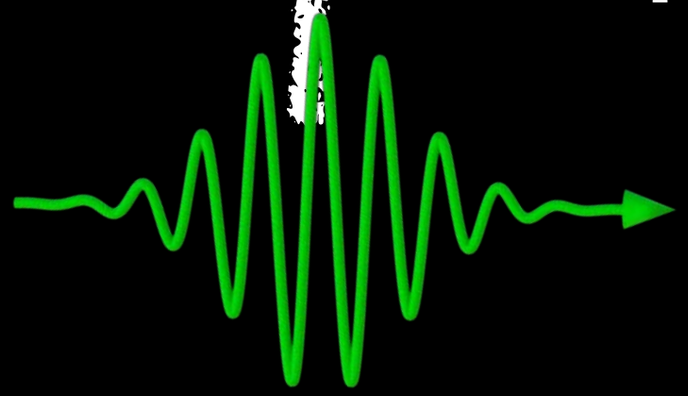
- spin pumping
- spin-Hall effect
- spin Seebeck effect
- magneto-resistance

Transport

Antiferromagnets

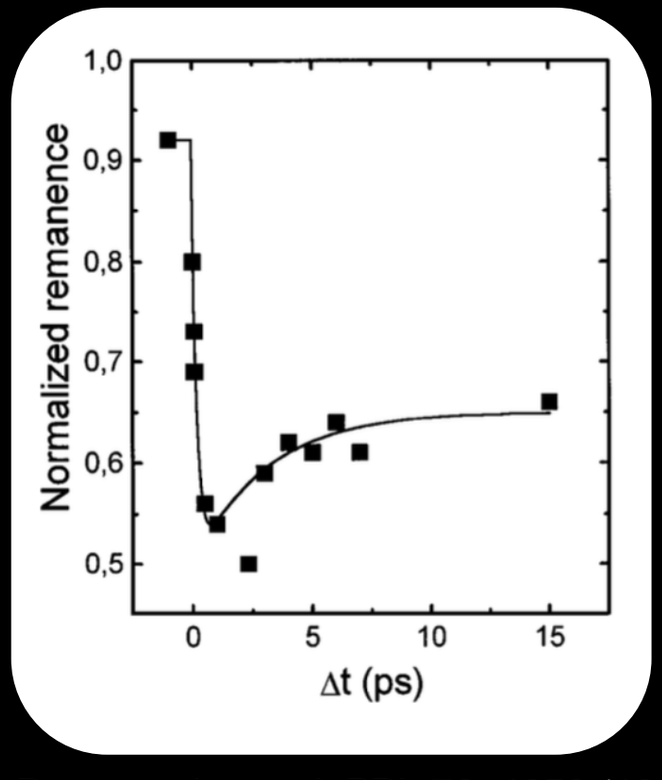
Ultrafast Spintronics

Femtosecond time-scale
Limited dissipations



Antiferromagnets

Metallic magnets

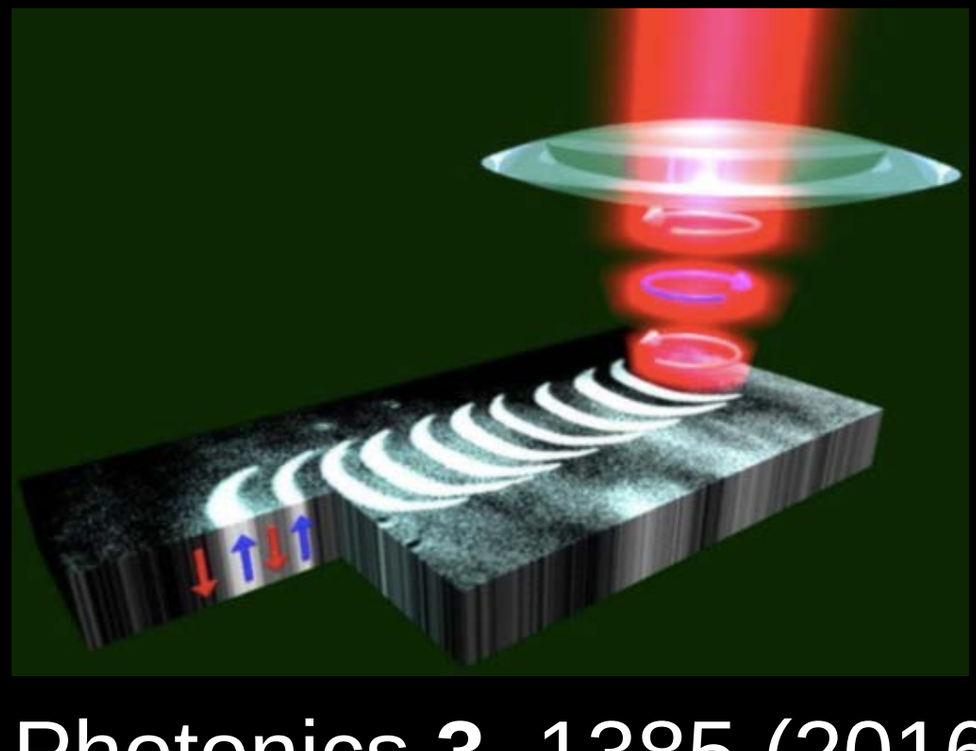


E. Beaurepaire et al. PRL **76**, 4250 (1996)

E. Beaurepaire
1959-2018

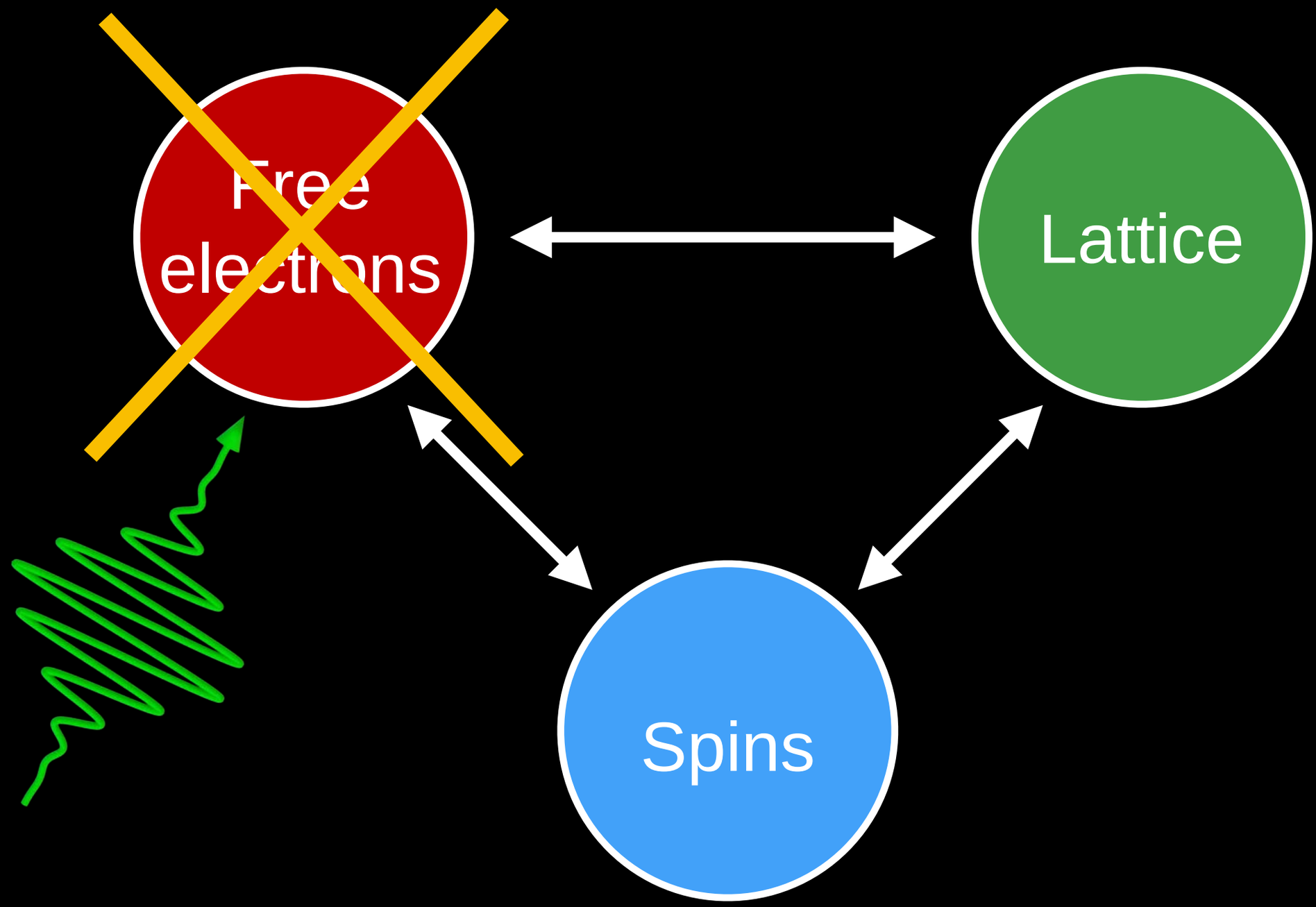
J. Y. Bigot
1956-2018

C. Stanciu et al. Phys. Rev. Lett. **99**, 047601 (2007)
M. Savoini et al. PRB **86**, 140404 (2012)
T. Liu et al. Nano Letters **15**, 6862 (2015)

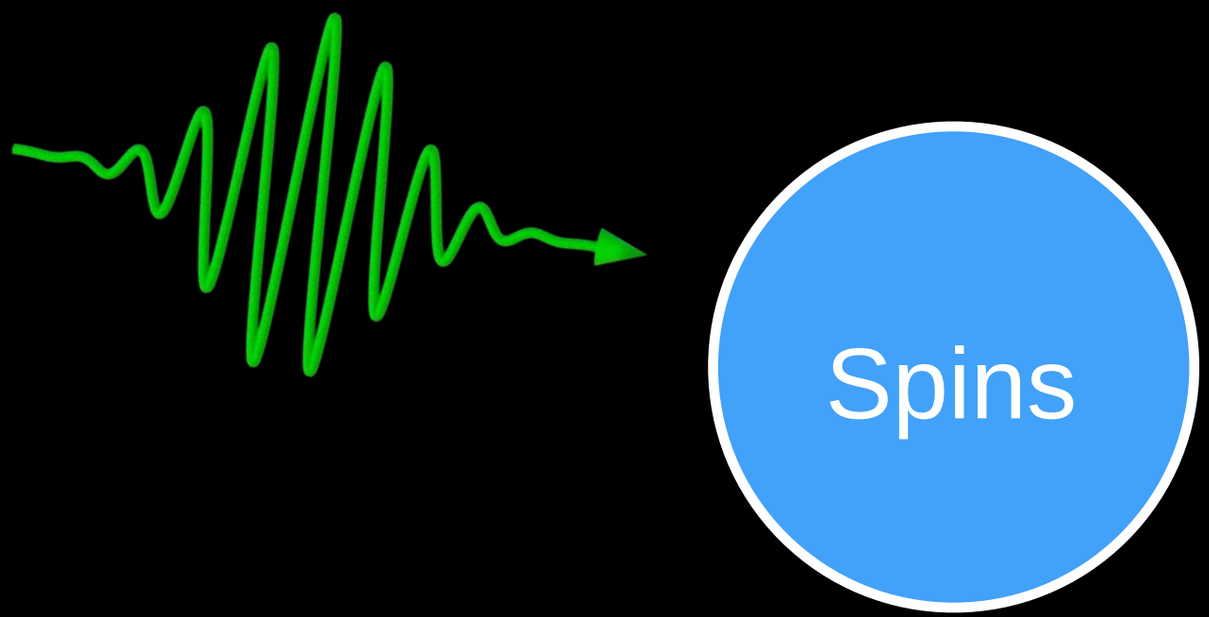


D. Bossini et al. ACS Photonics **3**, 1385 (2016)

Metallic magnets



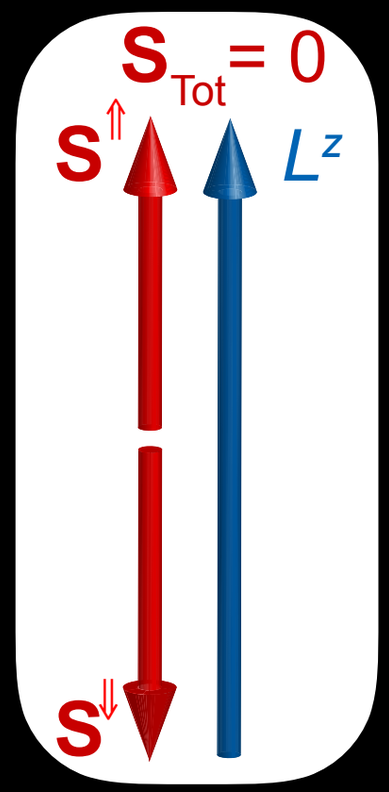
Dielectric magnets



Spin dynamics ?

Dielectric antiferromagnet

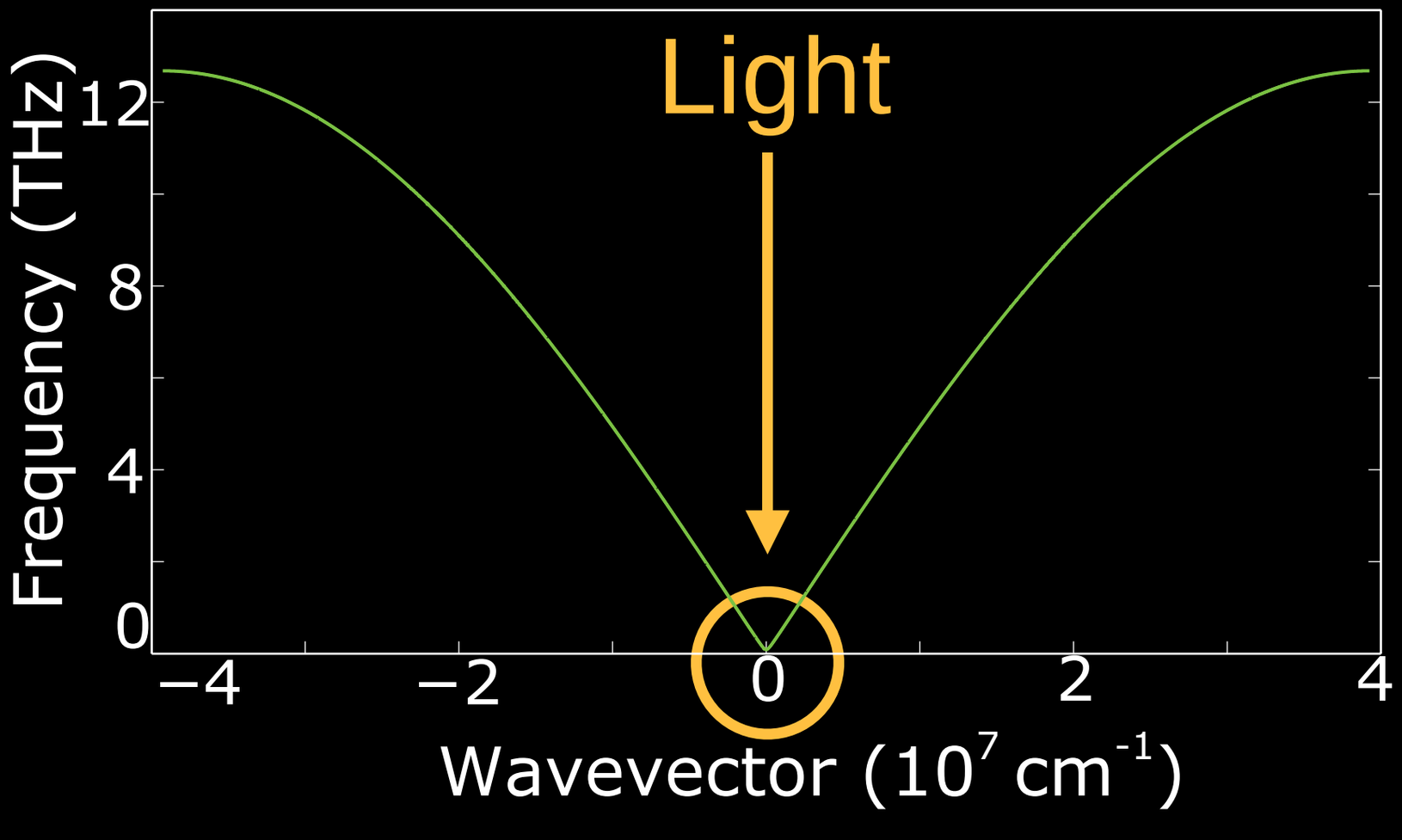
- No free electrons
- Majority of ordered materials
- No stray field
- Intrinsically faster spin dynamics



$$\boldsymbol{L} \equiv \boldsymbol{S}^{\Uparrow} - \boldsymbol{S}^{\Downarrow}$$

$$\hat{H} = J \sum_{\langle i,j \rangle} \hat{\boldsymbol{S}}_i^{\Uparrow} \cdot \hat{\boldsymbol{S}}_j^{\Downarrow} + g\mu_B H_A \left(\sum_i \hat{S}_i^{z\Uparrow} - \sum_j \hat{S}_j^{z\Downarrow} \right)$$

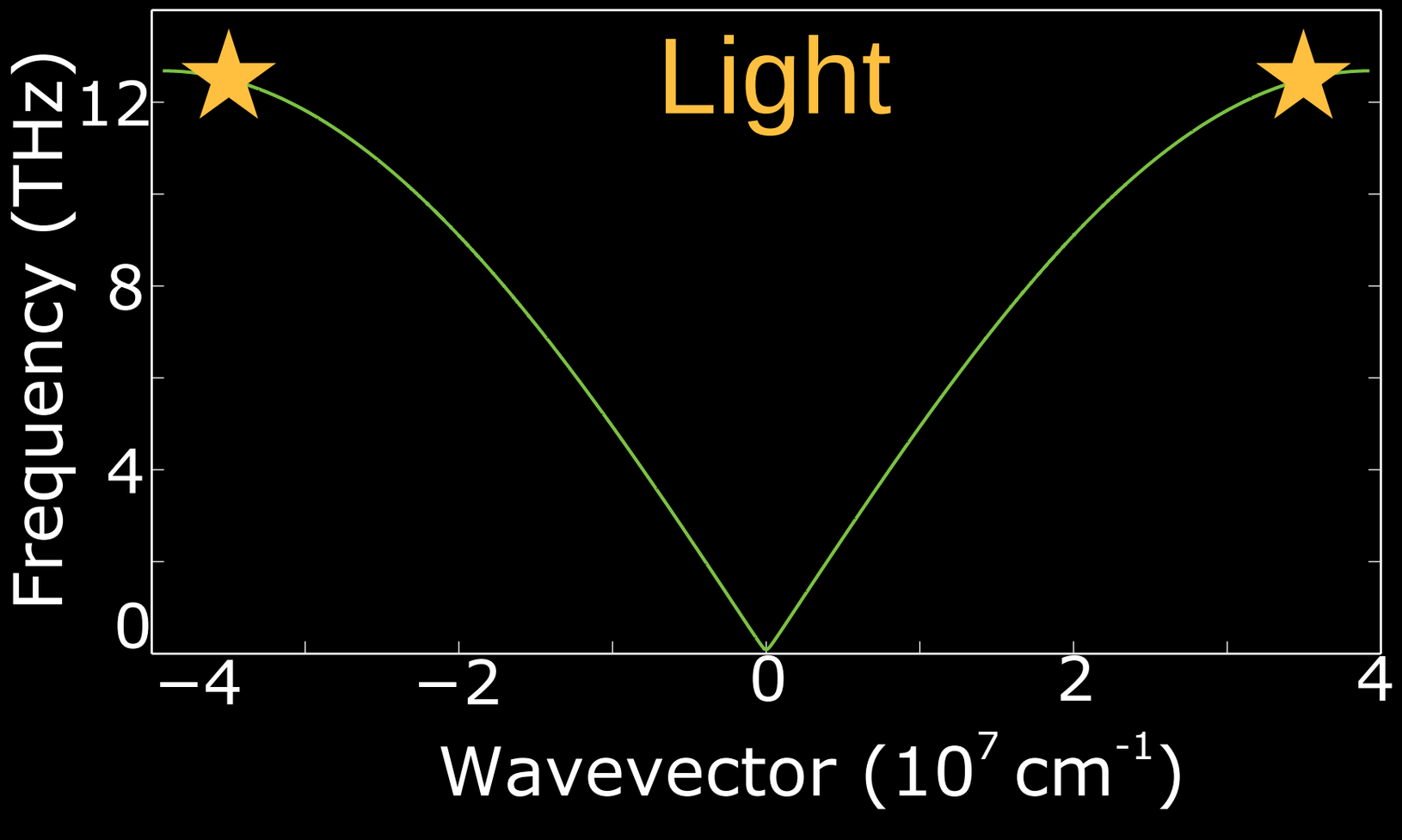
Collective spin dynamics



Ferromagnet $\omega \propto H_A$ 1-10 GHz

Antiferromagnet $\omega \propto \sqrt{H_A H_{ex}}$ 0.1-1 THz

Faster dynamics in AFs

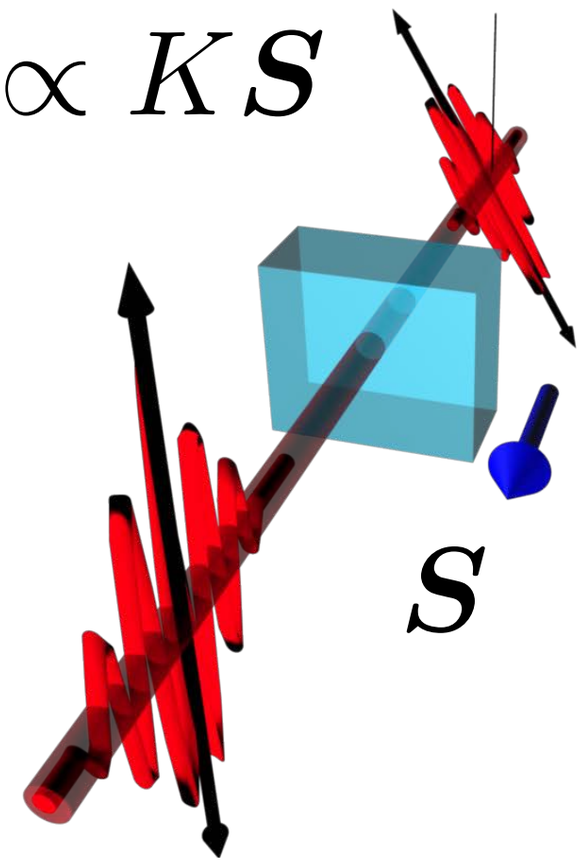


Antiferromagnet 10-100 THz

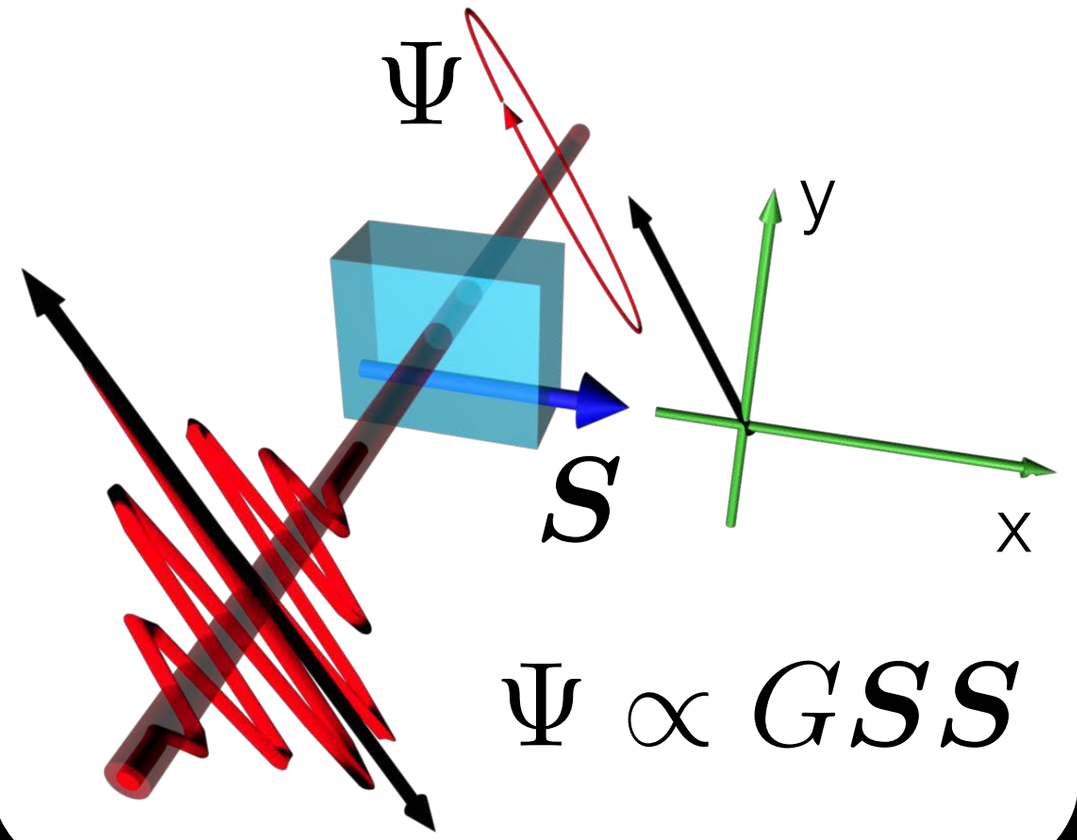
Ferromagnet 1-10 GHz

Magneto-optical effects

$\theta \propto KS$



Faraday rotation

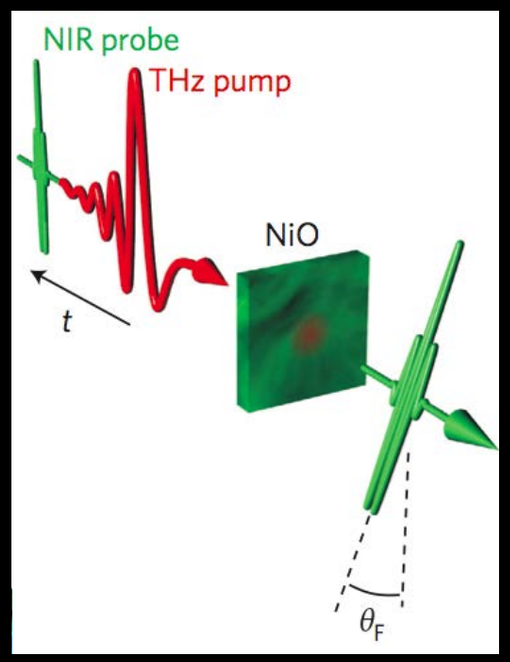


Magnetic linear birefringence

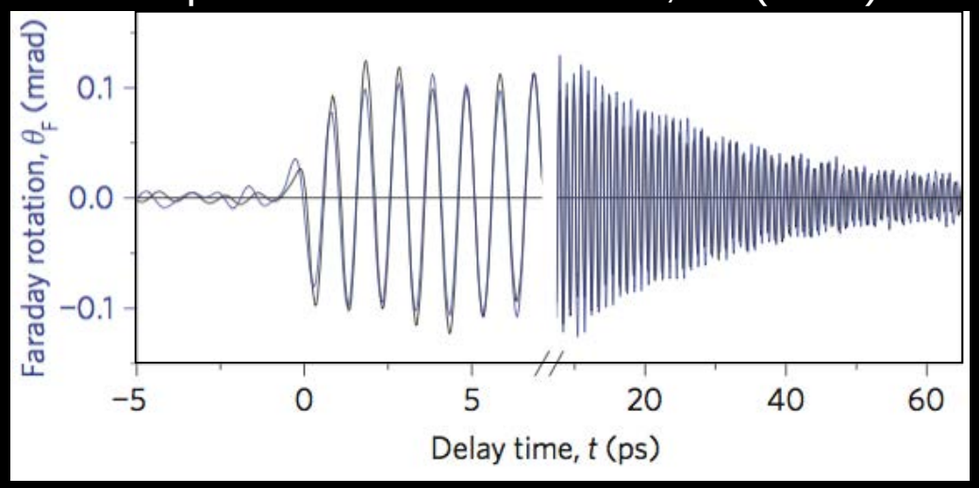
Ultrafast spin excitation

- ✓ Field-driven spin dynamics
- ✓ Spin flip process involved: $\Delta S = 1$
- ✓ Steady field? $\Delta S = 1$?

Femtosecond pulsed magnetic field in resonance condition (magnetic dipole transitions)

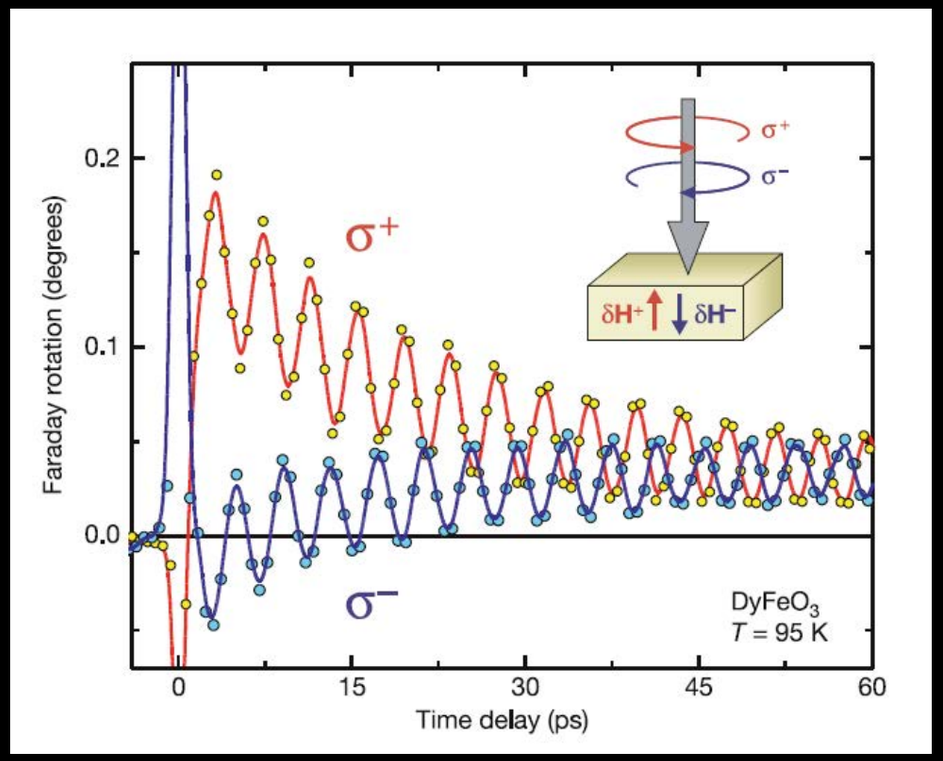


T. Kampfrath *et al.* Nat. Phot. **5**, 31 (2011)



Opto-magnetism

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



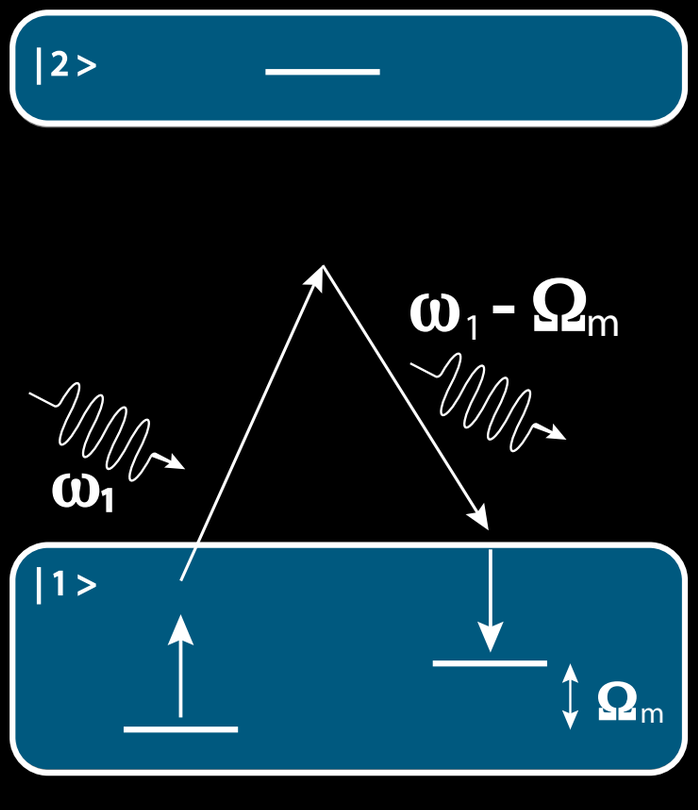
- ✓ Excitation of coherent spin waves
- ✓ Magneto-optical probe: Faraday rotation
- ✓ Pump wavelength: 800 nm

Pump beam $\approx 10^{14}$ Hz

Spin wave $\approx 10^{11}$ Hz

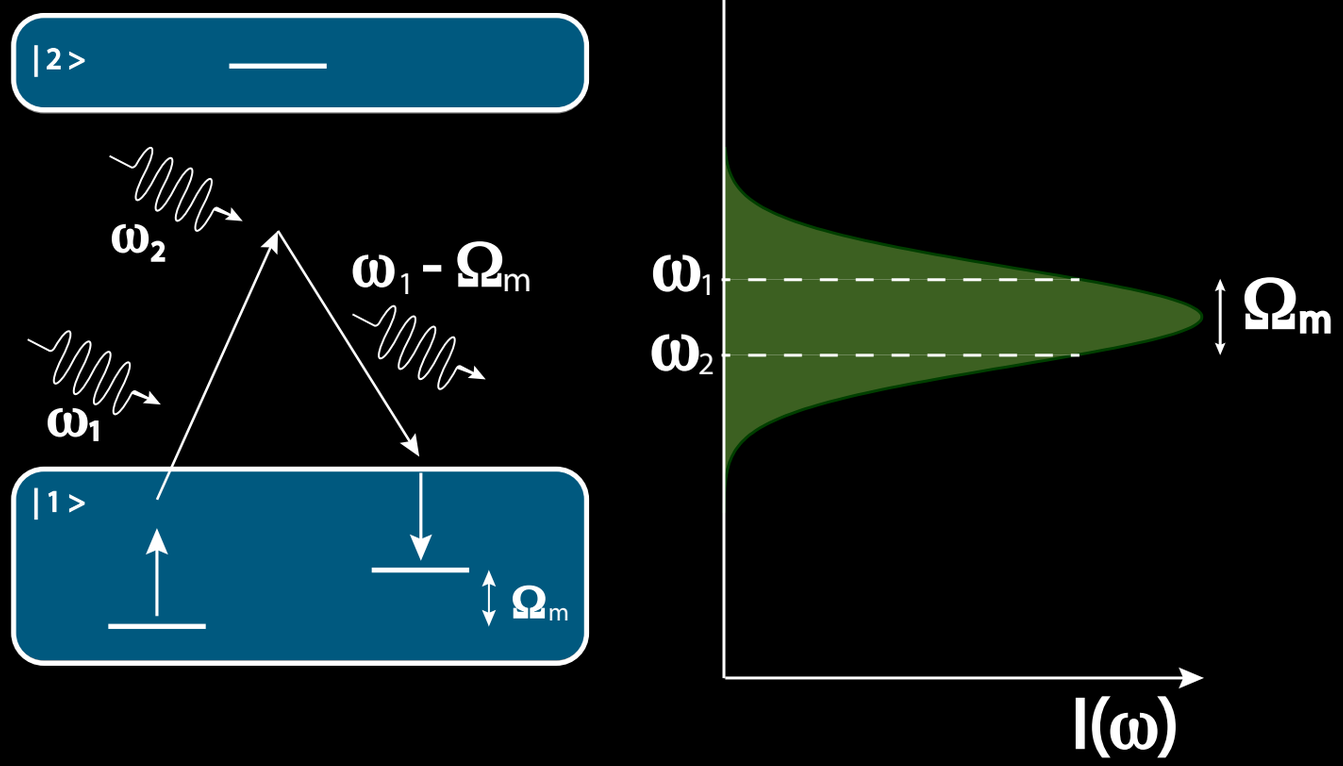
~~Resonant magnetic dipole coupling ?~~

Raman Scattering

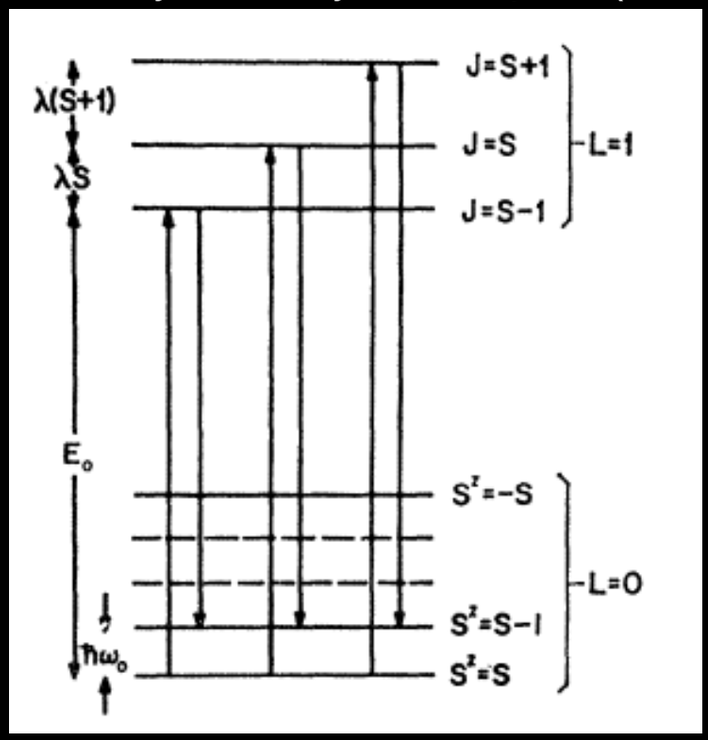


- ✓ Inelastic light scattering
- ✓ Spontaneous process
  low efficiency (10^{-7}-10^{-9})

Impulsive Stimulated Raman Scattering (ISRS)



P. Fleury *et al.* Phys. Rev. **2,** 514 (1968)



Raman on

Spin-flip driven by L-S coupling in the excited state

Light-spin interaction

- Light scattering: non-dissipative approximation
- Electric dipole approximation

$$\hat{\mathcal{H}} = \sum_{\lambda,\nu} \epsilon^{\lambda\nu}(\hat{\boldsymbol{S}}) E^{\lambda} E^{\nu}$$

Expansion dielectric tensor

$$\epsilon^{\lambda\nu} = \sum_{i} \sum_{\gamma} K^{\lambda\nu\gamma} \langle \hat{S}_i^{\gamma} \rangle + \sum_{i} \sum_{\gamma\delta} G^{\lambda\nu\gamma\delta} \langle \hat{S}_i^{\gamma} \rangle \langle \hat{S}_i^{\delta} \rangle + \sum_{i,j} \sum_{\gamma\delta} \rho^{\lambda\nu\gamma\delta} \langle \hat{S}_i^{\gamma\Uparrow} \hat{S}_j^{\delta\Downarrow} \rangle$$

M. Cottam and D. Lockwood, *Light Scattering in Magnetic Solids* (Wiley-Interscience, 1986)

$$\epsilon^{\lambda\nu} = \sum_i \sum_\gamma K^{\lambda\nu\gamma} \langle \hat{S}_i^\gamma \rangle + \sum_i \sum_{\gamma\delta} G^{\lambda\nu\gamma\delta} \langle \hat{S}_i^\gamma \rangle \langle \hat{S}_i^\delta \rangle + \sum_{i,j} \sum_{\gamma\delta} \rho^{\lambda\nu\gamma\delta} \langle \hat{S}_i^{\gamma\Uparrow} \hat{S}_j^{\delta\Downarrow} \rangle$$

Raman scattering on magnons

Opto-magnetism

Magneto-optics

Non-dissipative light-matter interaction

General concept

Weak ferromagnet

$DyFeO_3$

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

Anti-ferromagnet

NiO

T. Satoh *et al.* Phys. Rev. Lett. **105,** 077402 (2010)

Ferrimagnet

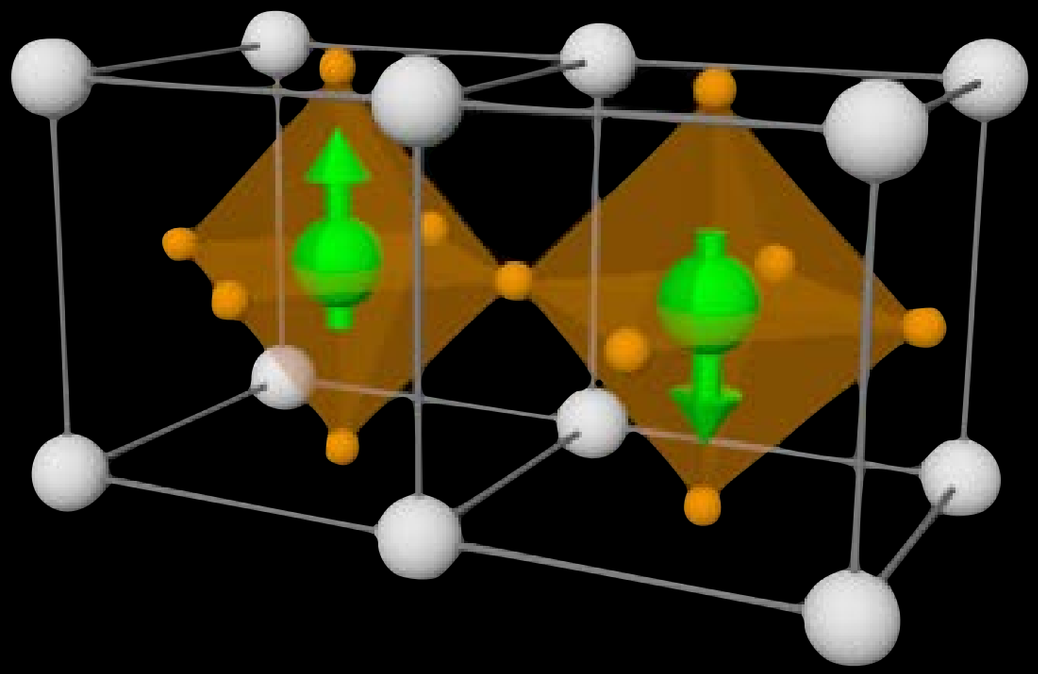
$Lu_{3-x-y}Y_xBi_yFe_{5-z}Ga_zO_{12}$

F. Hansteen *et al.* Phys. Rev. Lett. **95,** 047402 (2005)

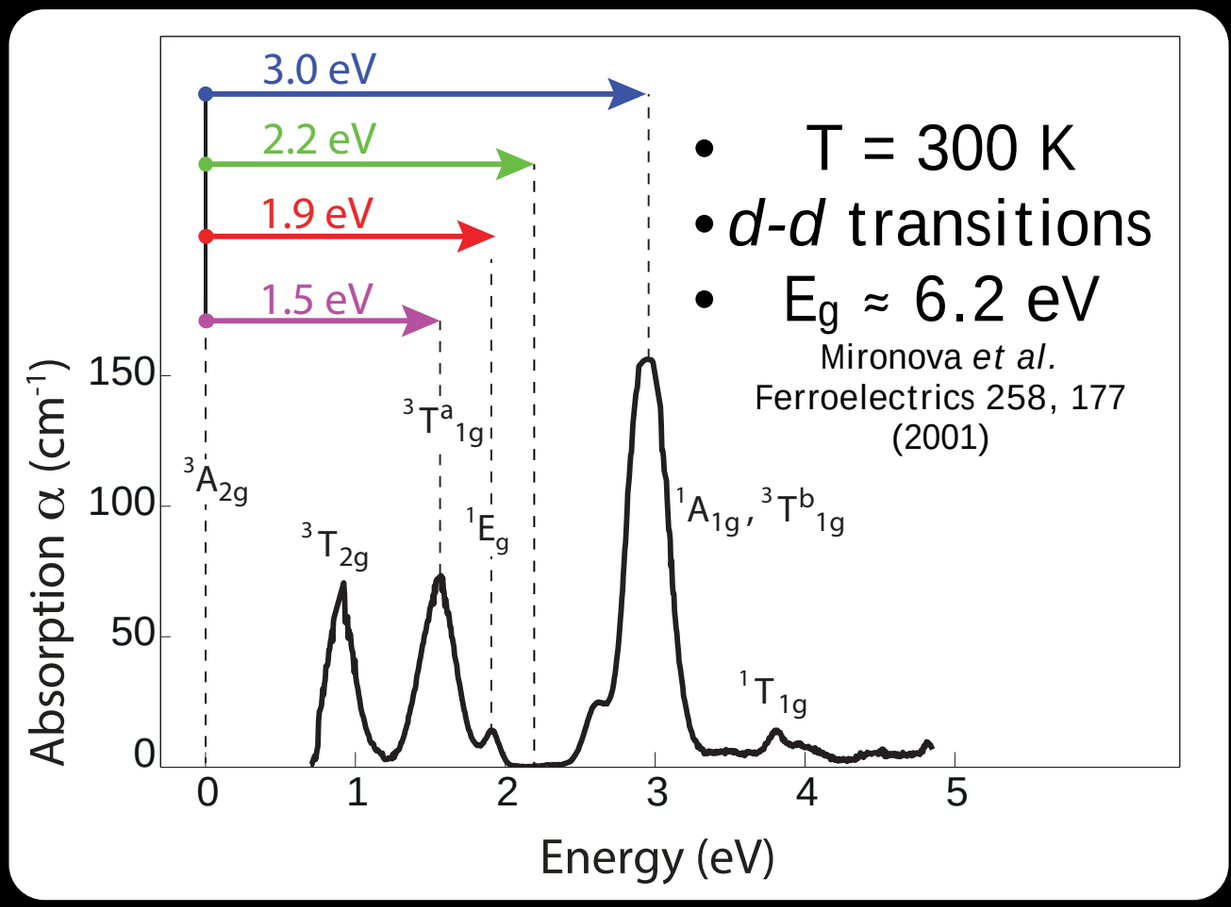
- ~~Is magnetization necessary ?~~
- ✓ Unavoidable direct laser-induced thermal load
- ✓ Giant spin-orbit coupling in the ground state required
- ✓ Limited to low-frequencies

Opto-magnetism without absorption

Sample: $KNiF_3$



Cubic Heisenberg AF
(T_N = 246 K)



Magnetic linear birefringence

Dynamics: $\Delta \boldsymbol{M} \propto \gamma \boldsymbol{L} \times \dfrac{\partial \boldsymbol{L}}{\partial t}$

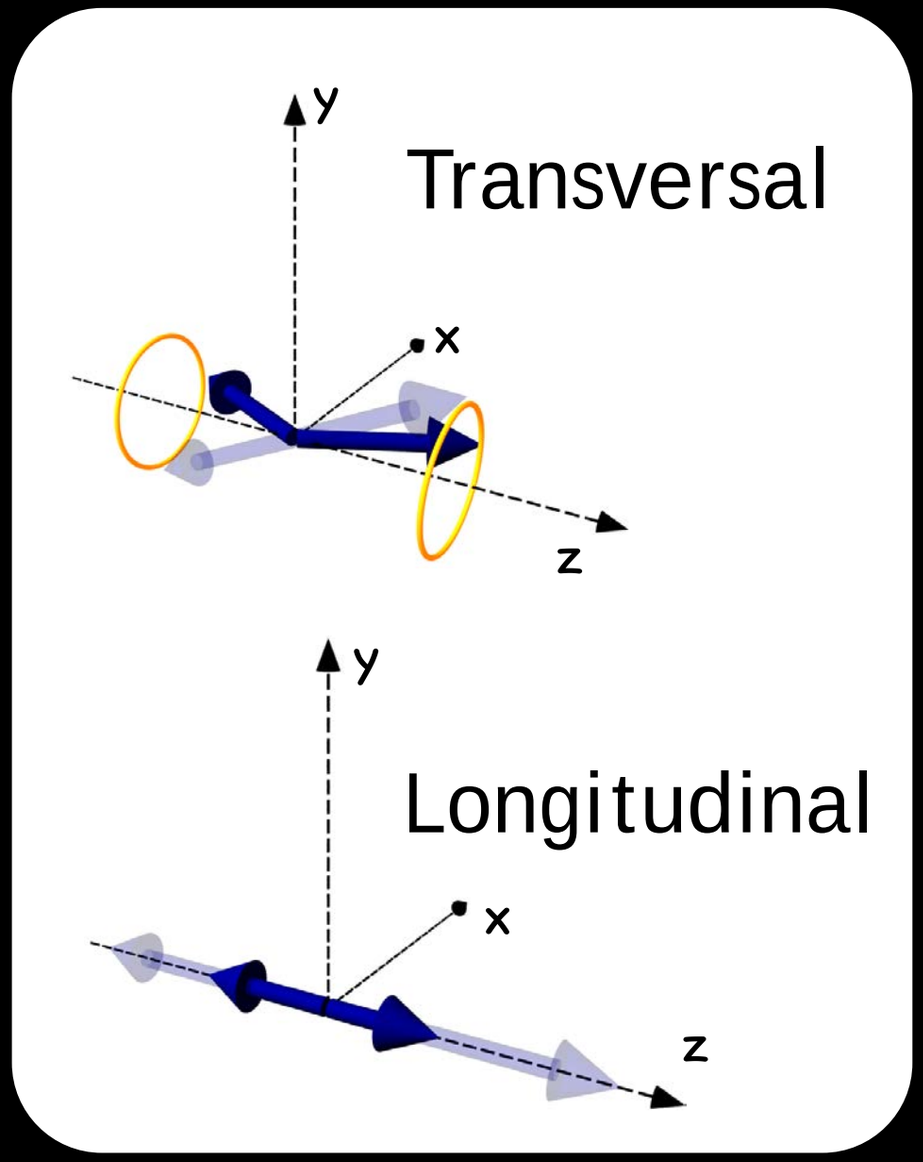
A.F Andreev et al Sov. Phys. Usp. **23,** 21 (1980)

Quadratic MO effect: $\propto L_z L_y + L_z^2$

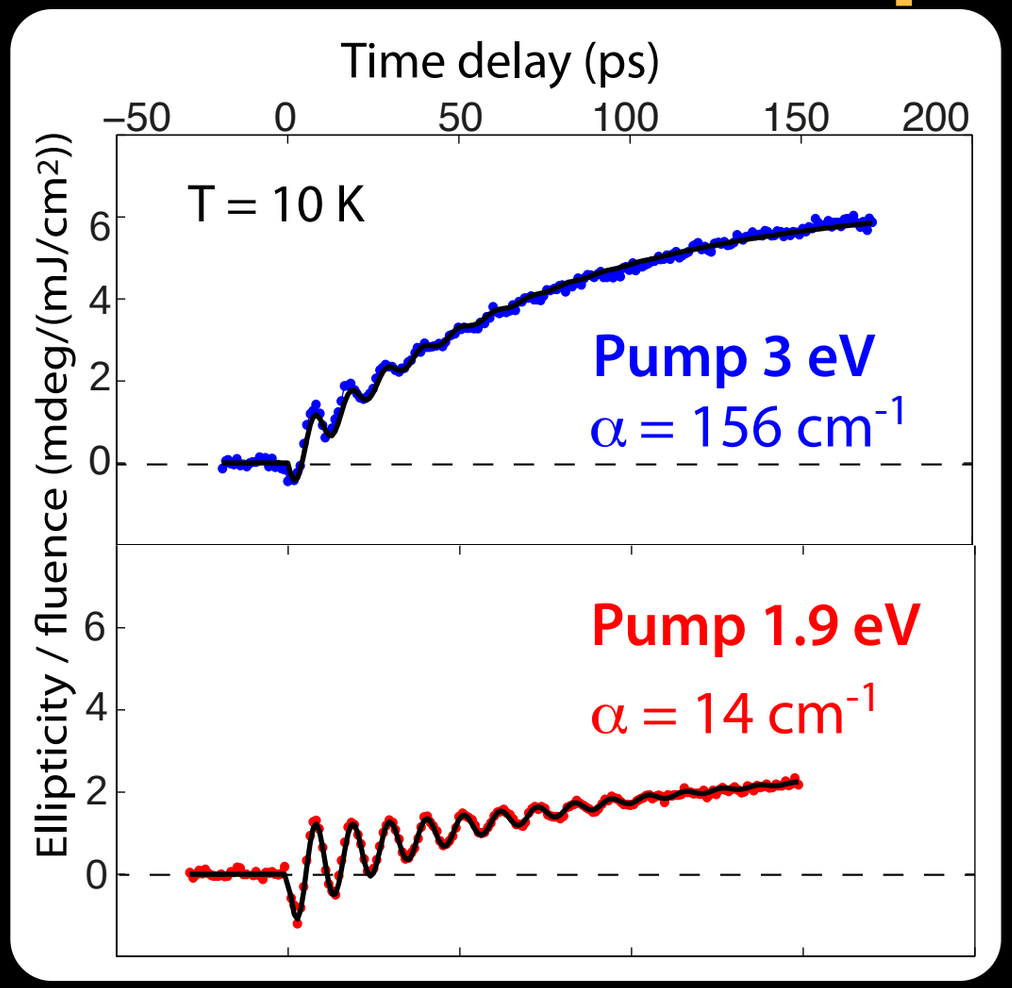
J. Ferre and G. Gehring, *Rep. Prog. Phys.* **47,** 513 (1984)

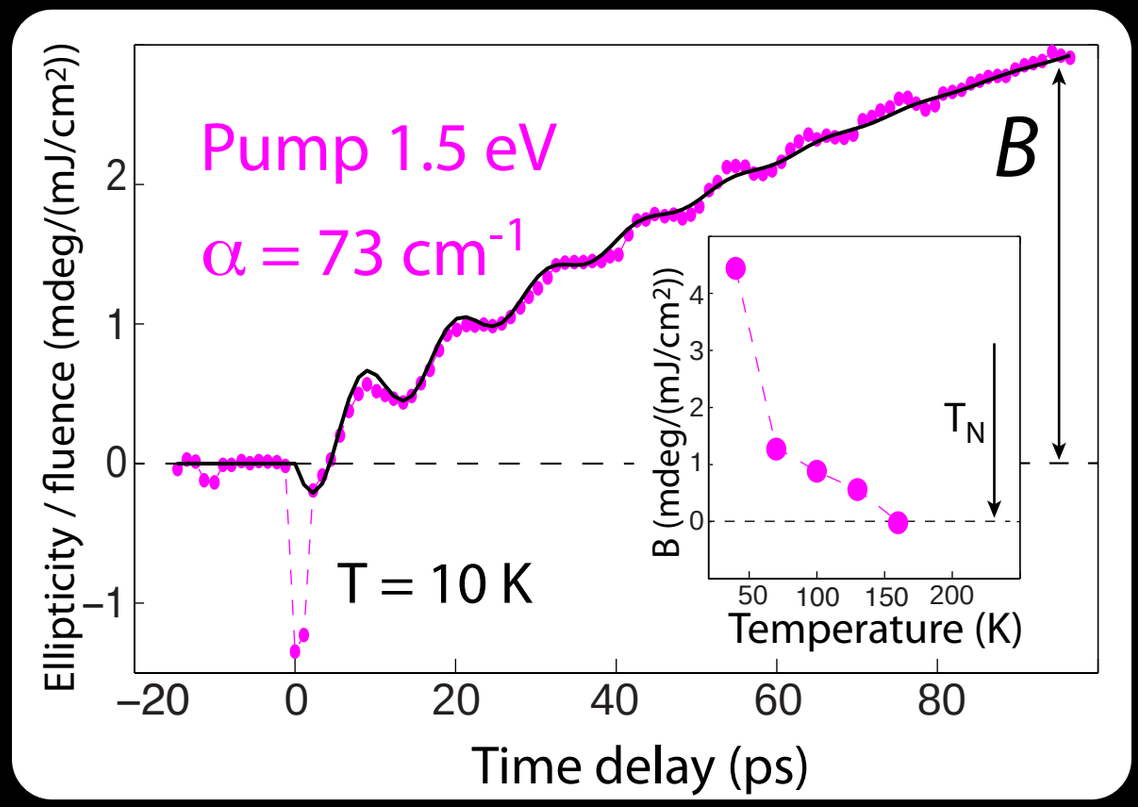
$$\Delta \mathrm{MLB} \propto L_z \Delta L_y + L_z \Delta L_z$$

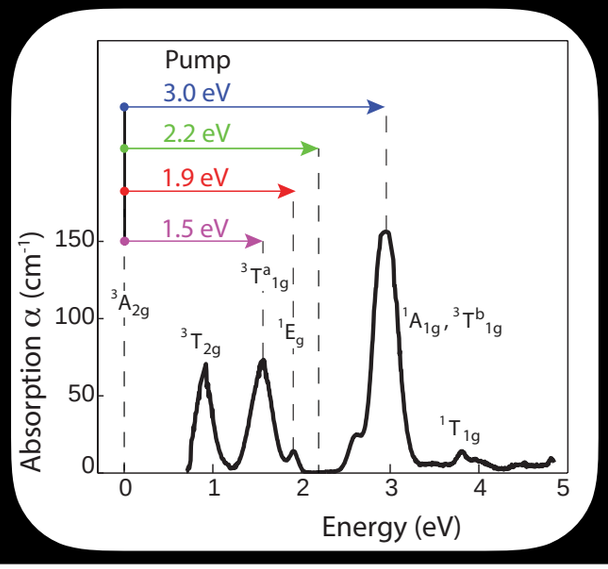
Simultaneous measurement of
transversal and
longitudinal spin dynamics



Dissipative regime





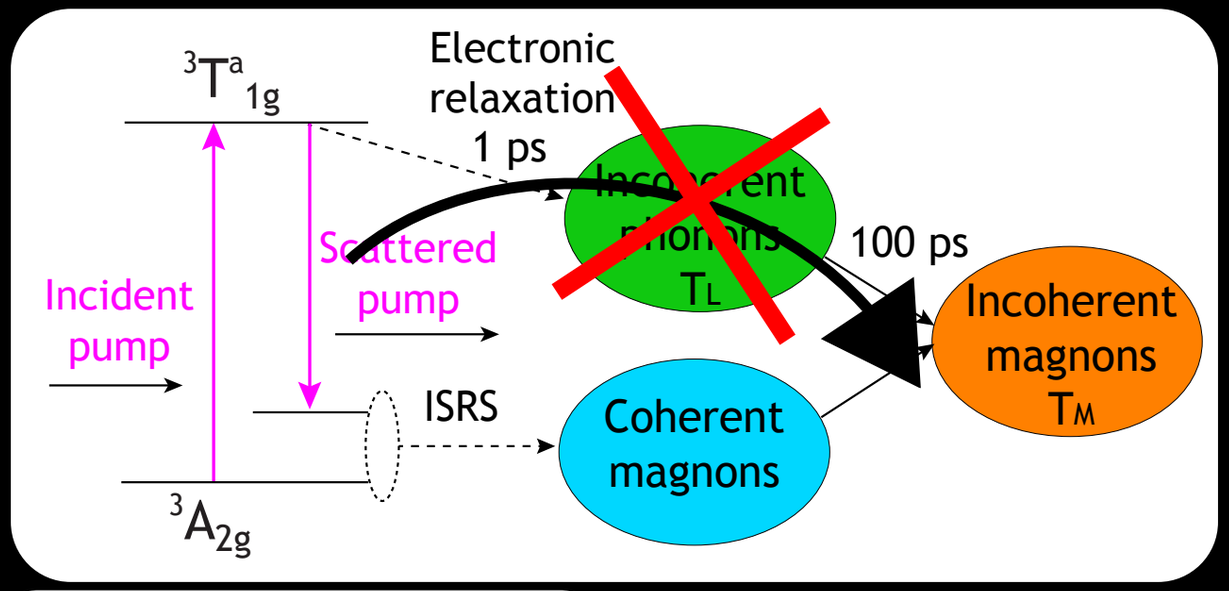


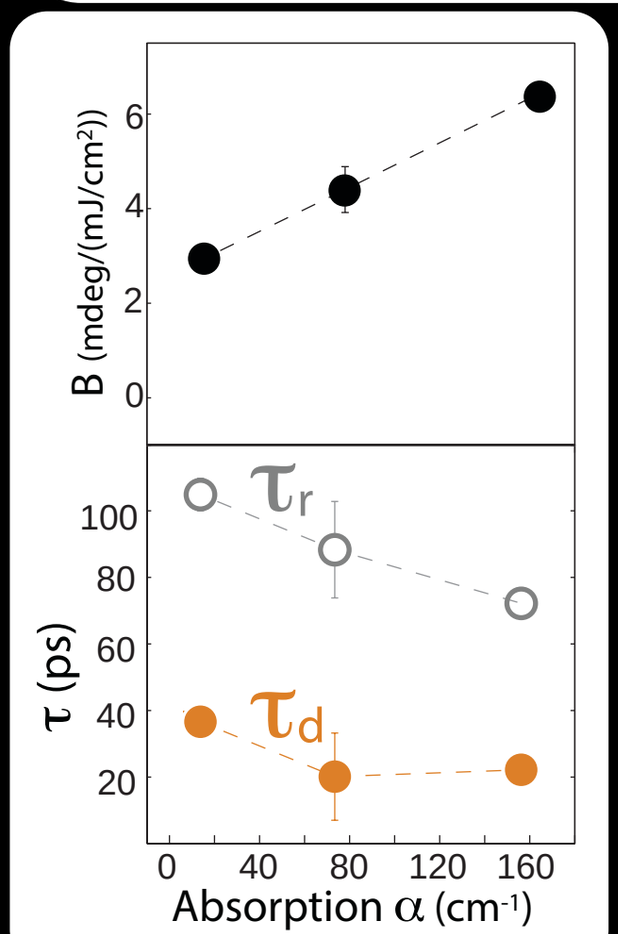
$$f(t) = \theta(t)[A\sin(2\pi\nu t)e^{(-t/\tau_d)} + B(1 - e^{(-t/\tau_r)})]$$

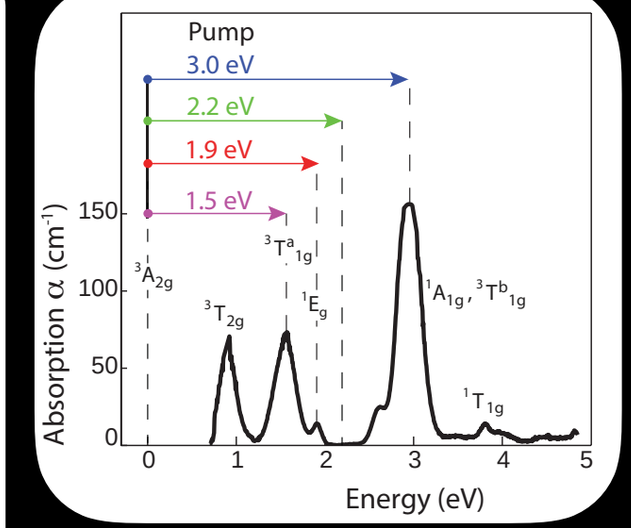
Transversal — Longitudinal

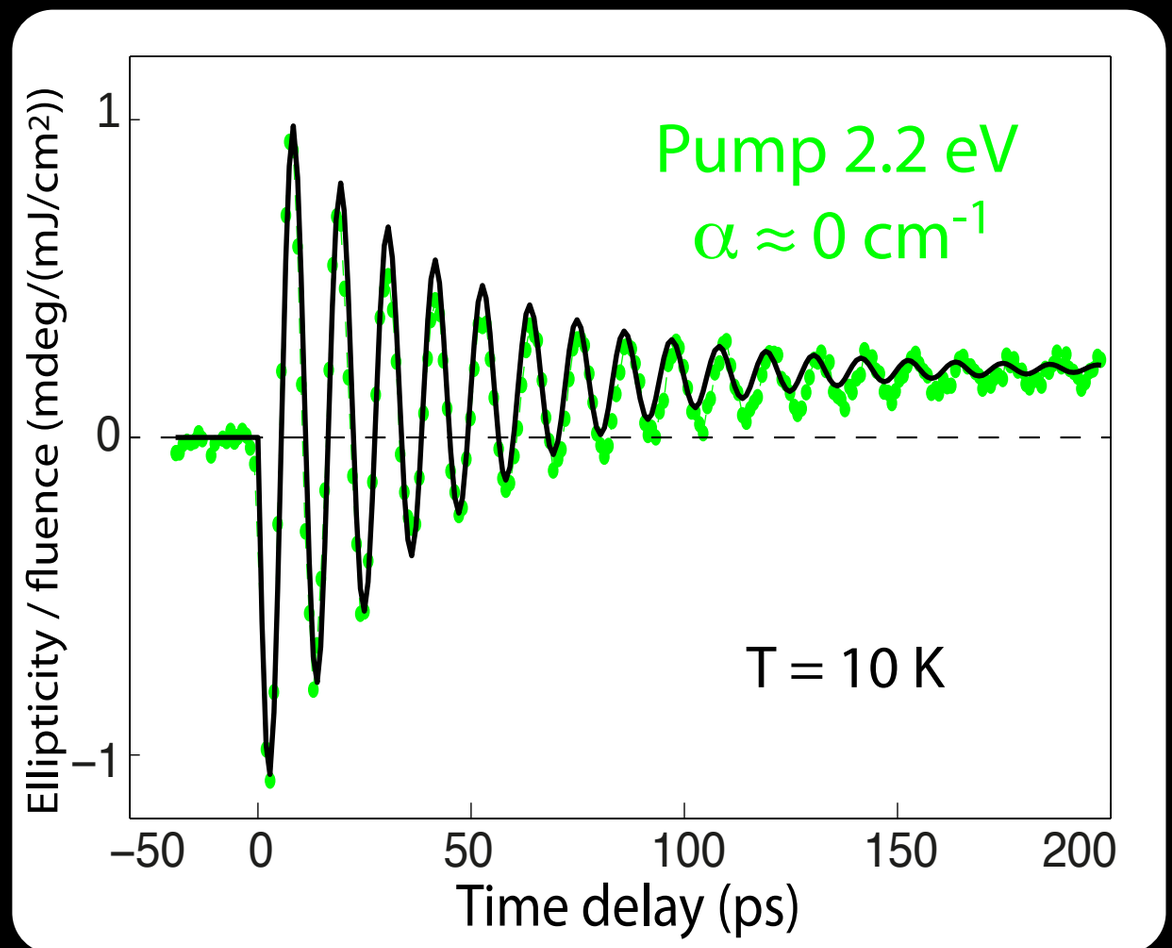
Two time-scales

Non-dissipative regime





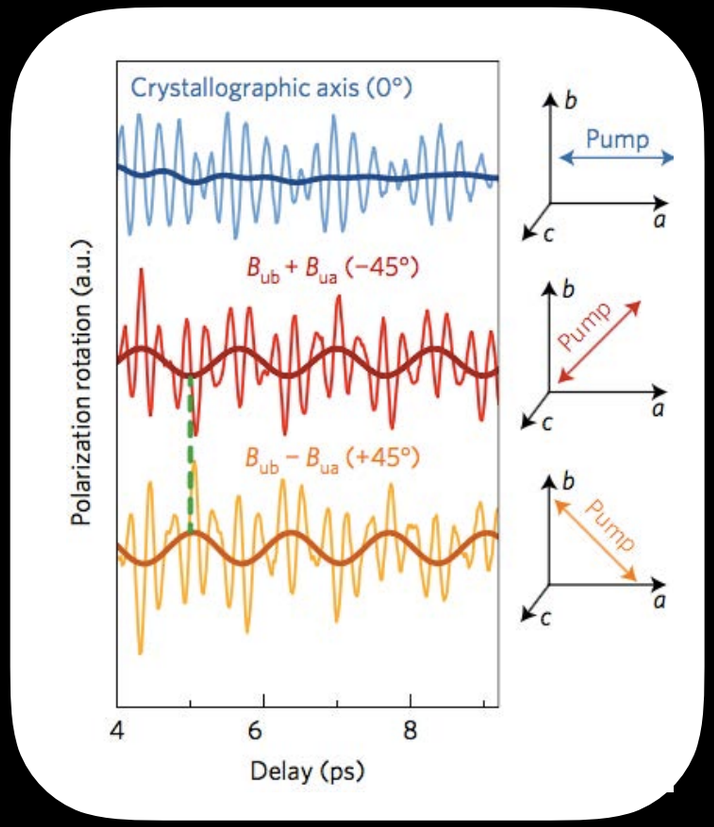




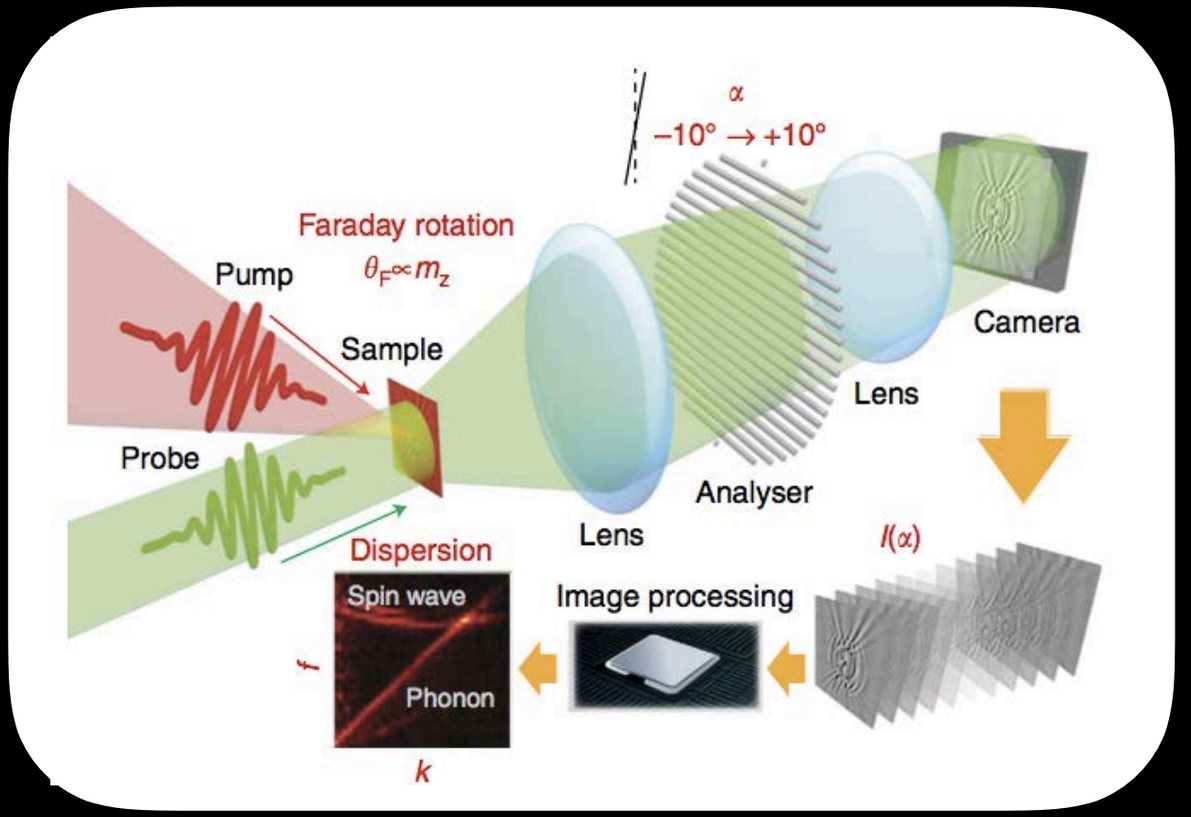
D.Bossini et al PRB. **89** (R), 060405 (2014)

Zero Absorption Criterion

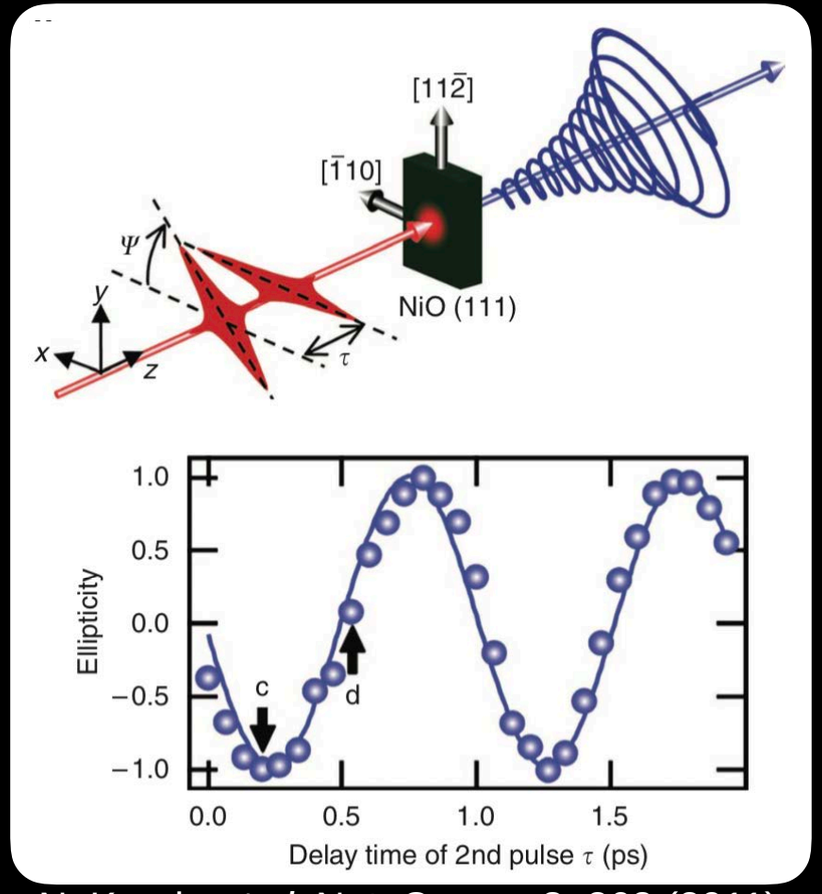
$$\tau_d = \tau_r$$



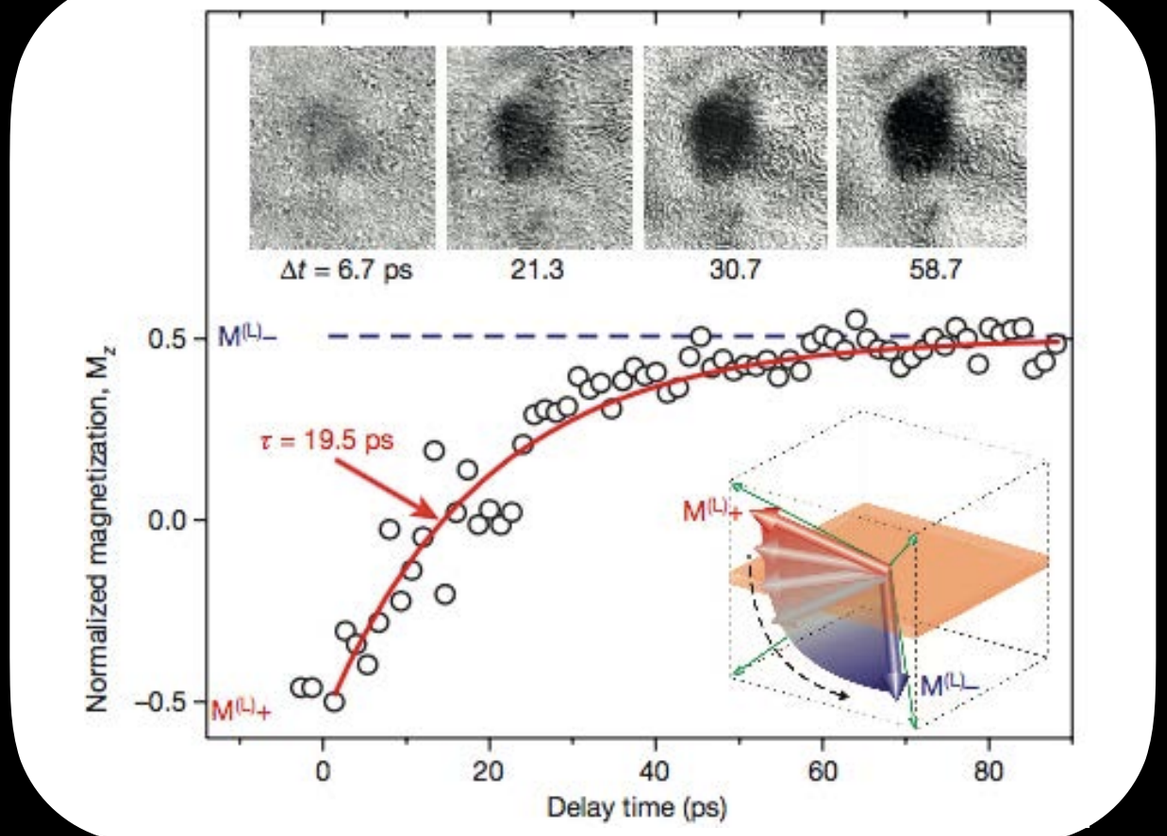
T. Nova, **DB** *et al.*
Nat. Phys. **13,** 132 (2016)



Y. Hashimoto, **DB** *et al.*
Nat. Comm. **8,** 15859
(2017)

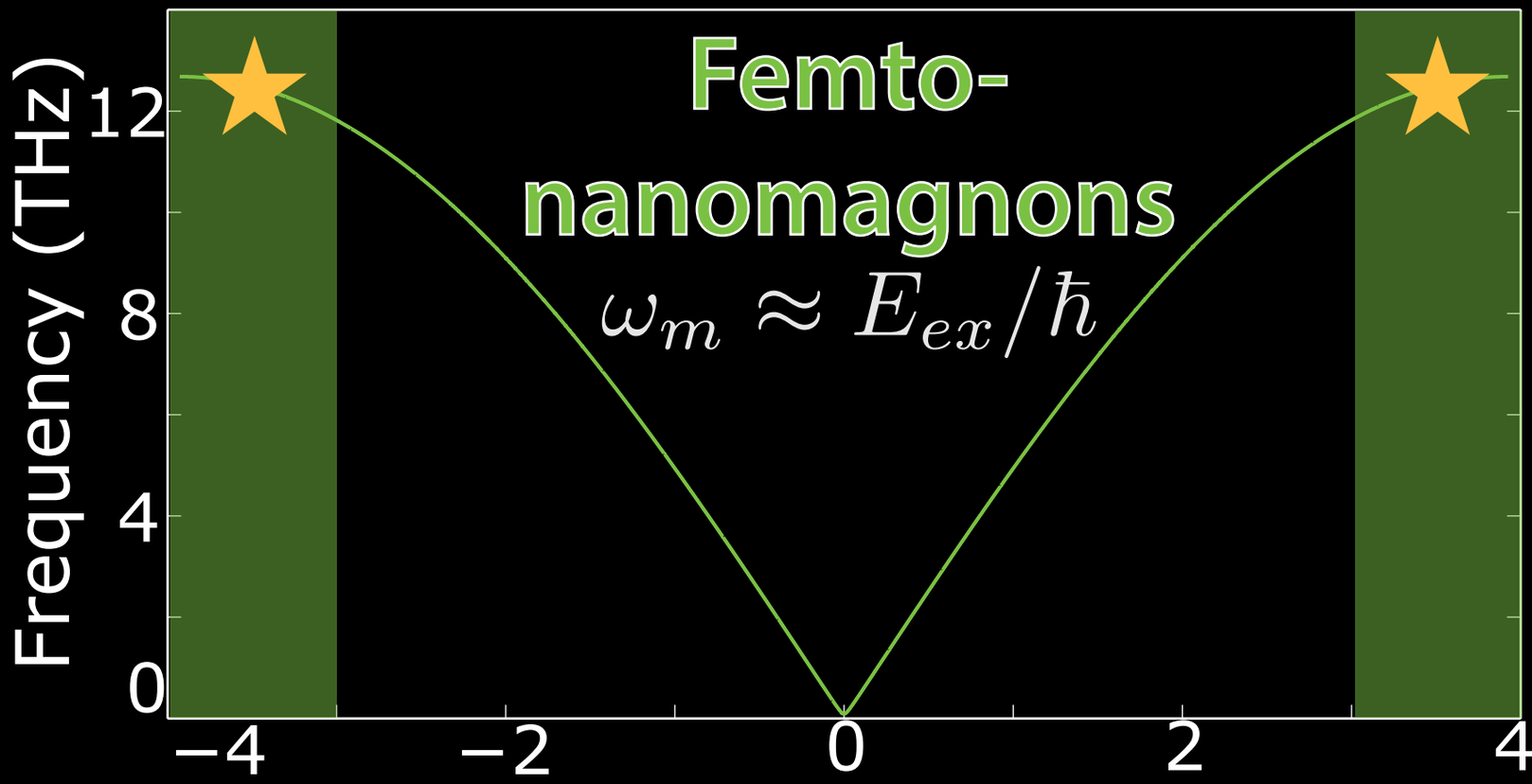


N. Kanda *et al.* Nat. Comm. **2,** 362 (2011)

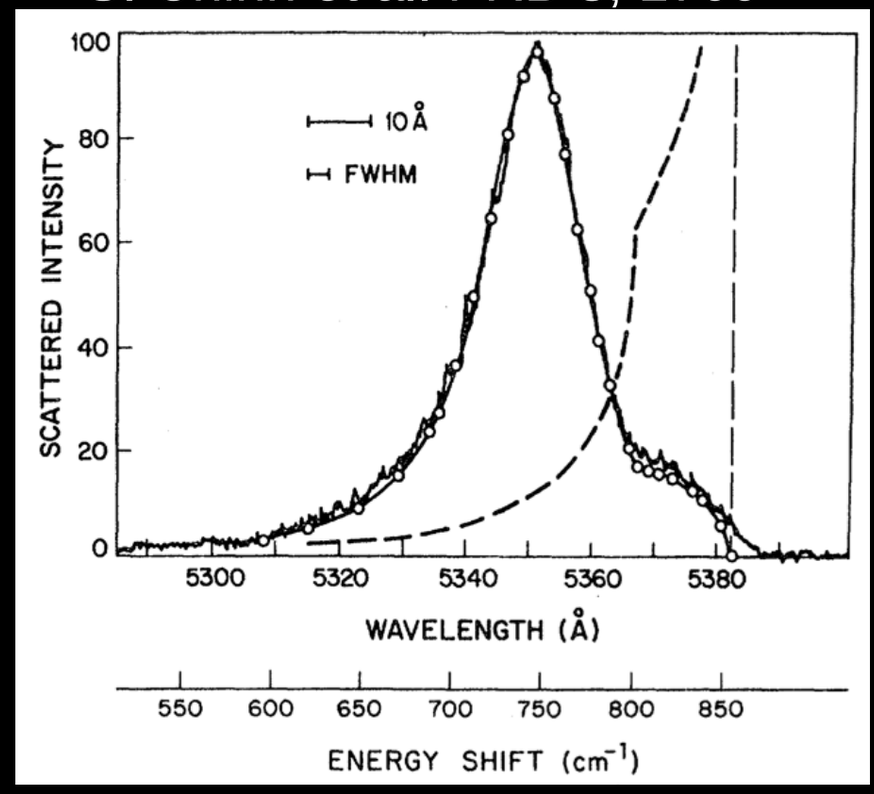


A. Stupakiewicz *et al.* Nature **542,** 71 (2017)

Shortest spin timescale



S. Chinn et al. PRB **3**, 1709



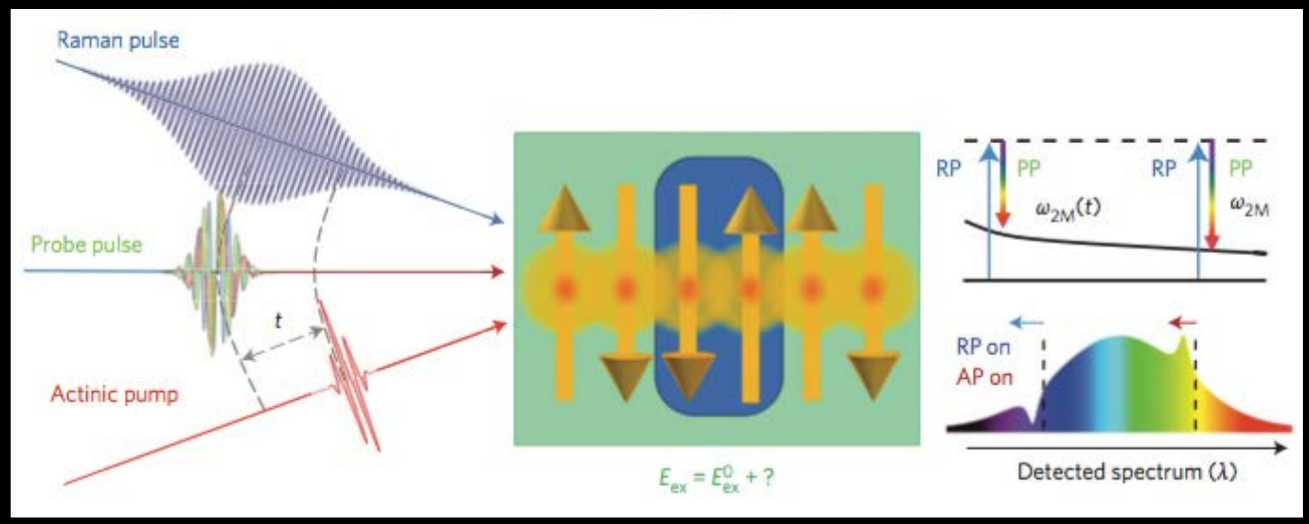
$KNiF_3$

- Light-induced magnon pairs: ***two-magnon mode***
- Spin and momentum conservation
- $\mathbf{k}_{\text{light}} = \mathbf{k}_1 + \mathbf{k}_2$ High-wavevector region: $\omega_{2M} \approx \omega_1 + \omega_2$

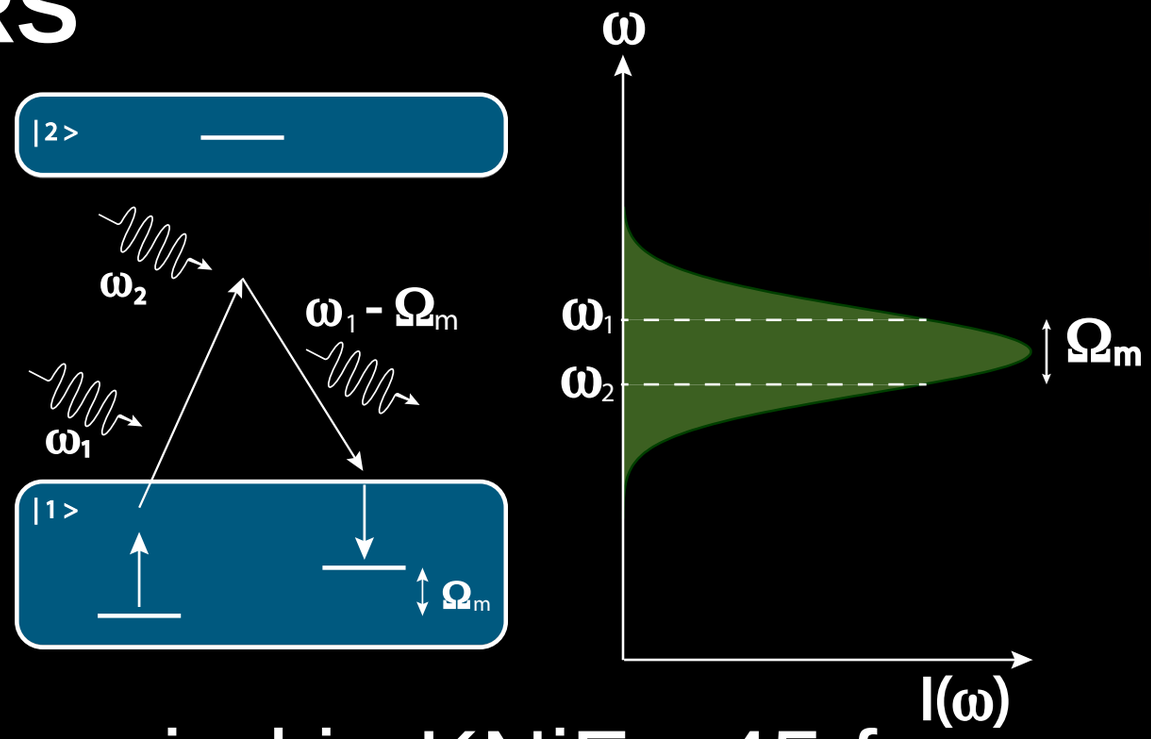
Experimental approaches

G. Batignagni, **DB**, et al Nat. Phot. **9,** 506 (2015)

Time-resolved stimulated Raman spectroscopy



ISRS



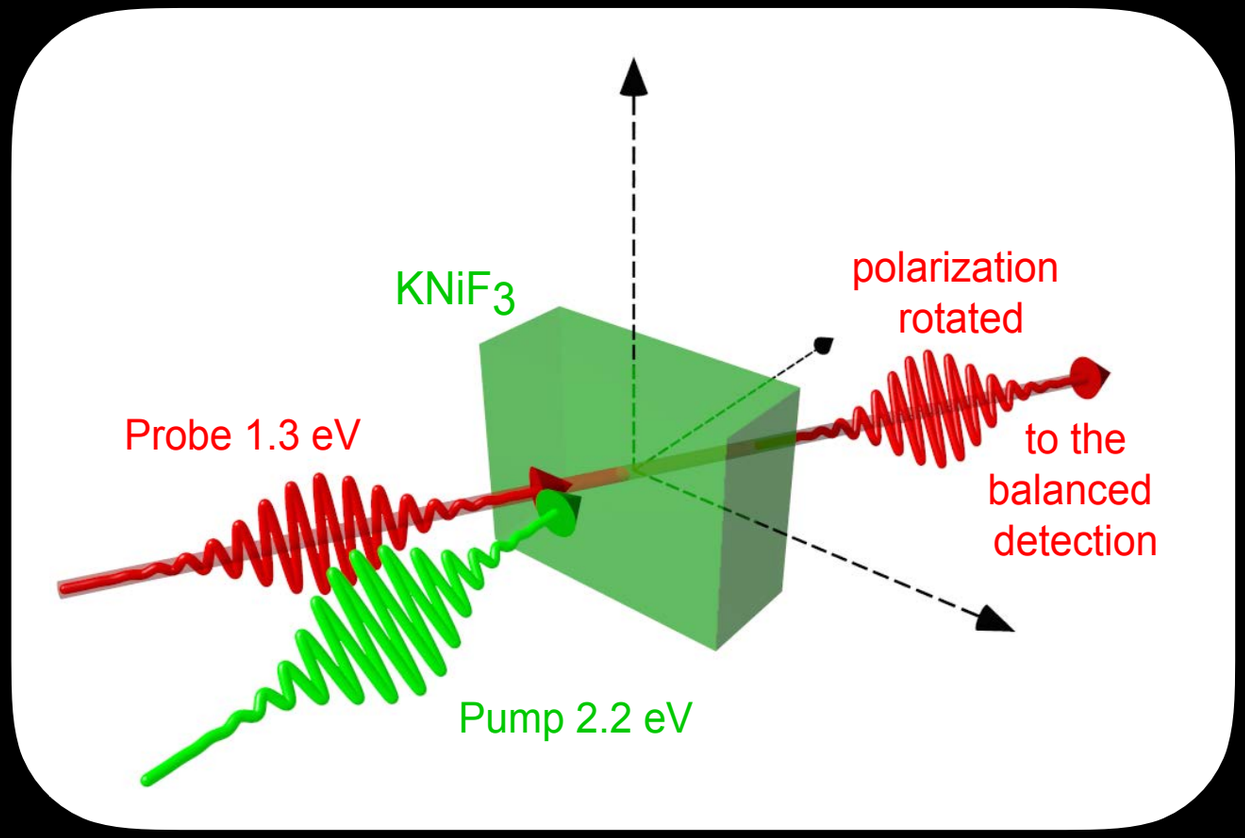
2M period in $KNiF_3$: 45 fs

Time domain

Pulses shorter than period

10 fs laser pulses

Experimental scheme



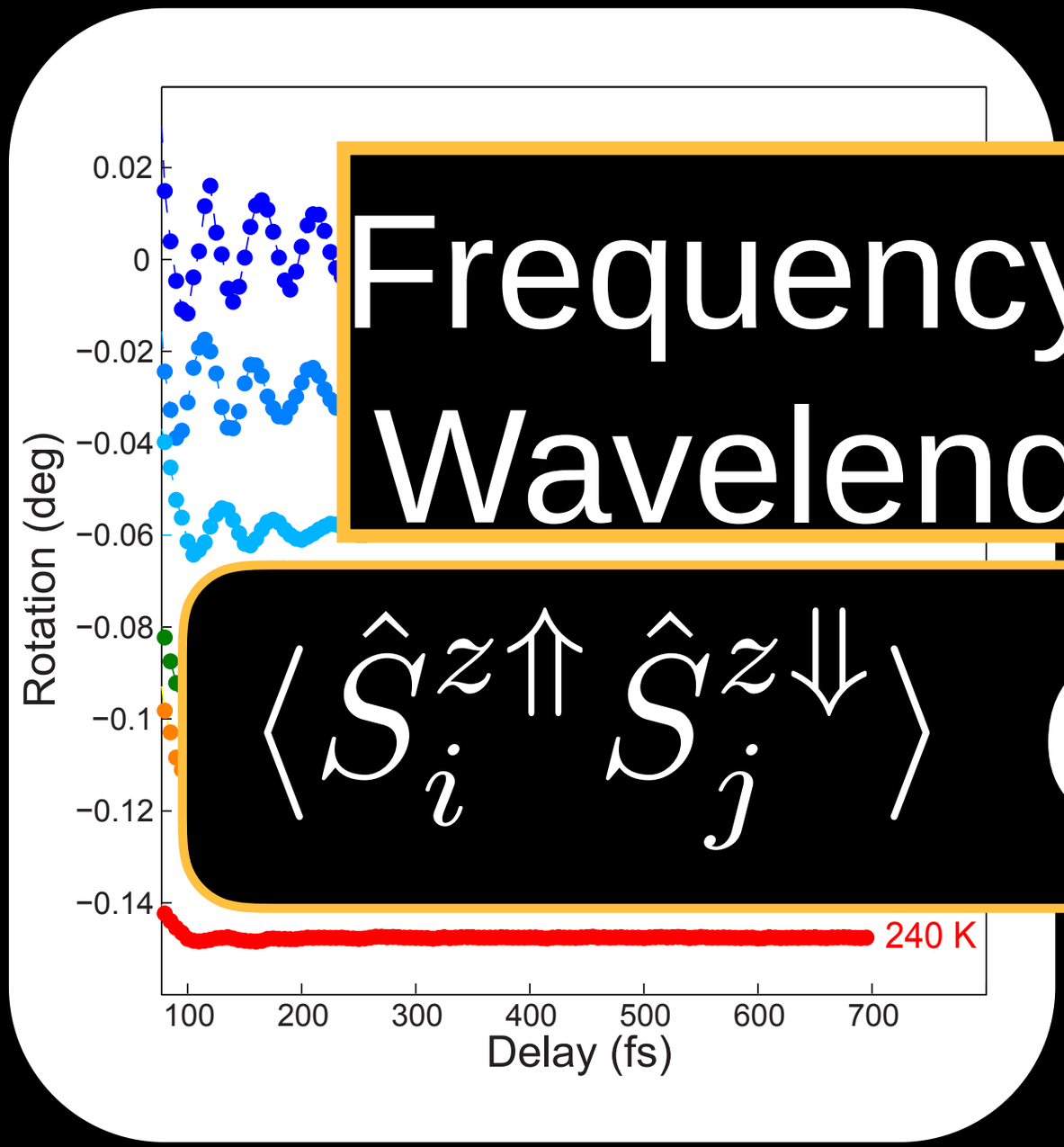
Low-dissipations:
Photon energies in transparency regions

All-optical detection via **second-order magneto-optics**

$$\epsilon_s^{\lambda\nu} = \sum_{ij}\sum_{\gamma\delta} \rho^{\lambda\nu\gamma\delta} \langle \hat{S}_i^{\gamma\Uparrow} \hat{S}_j^{\delta\Downarrow} \rangle$$

J. Ferrè *et al.* Rep. Prg. Phys **47**, 513 (1984)

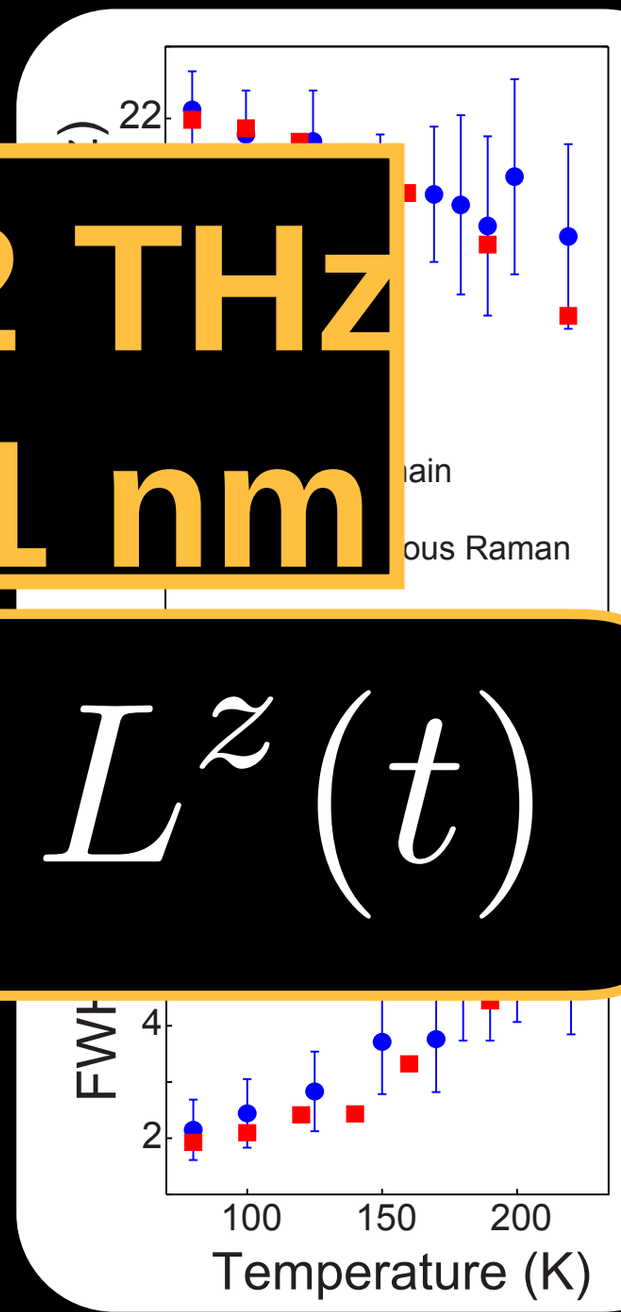
Results



Frequency: **22 THz**

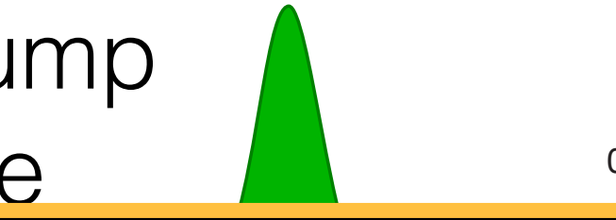
Wavelength: **1 nm**

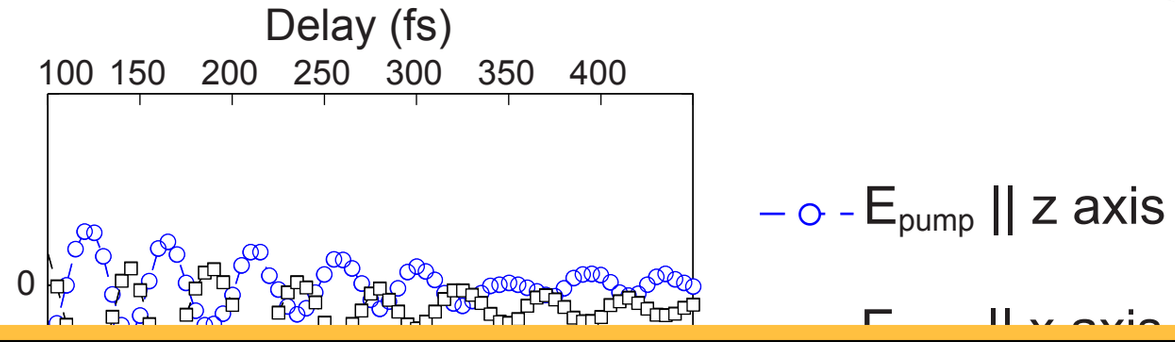
$$\langle \hat{S}_i^{z\Uparrow} \hat{S}_j^{z\Downarrow} \rangle \propto L^z(t)$$



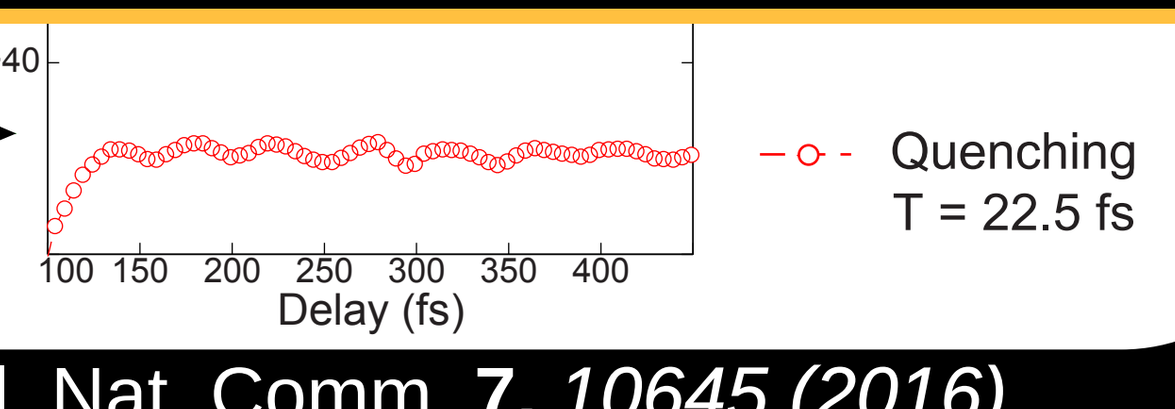
Manipulate the dynamics

One pump pulse



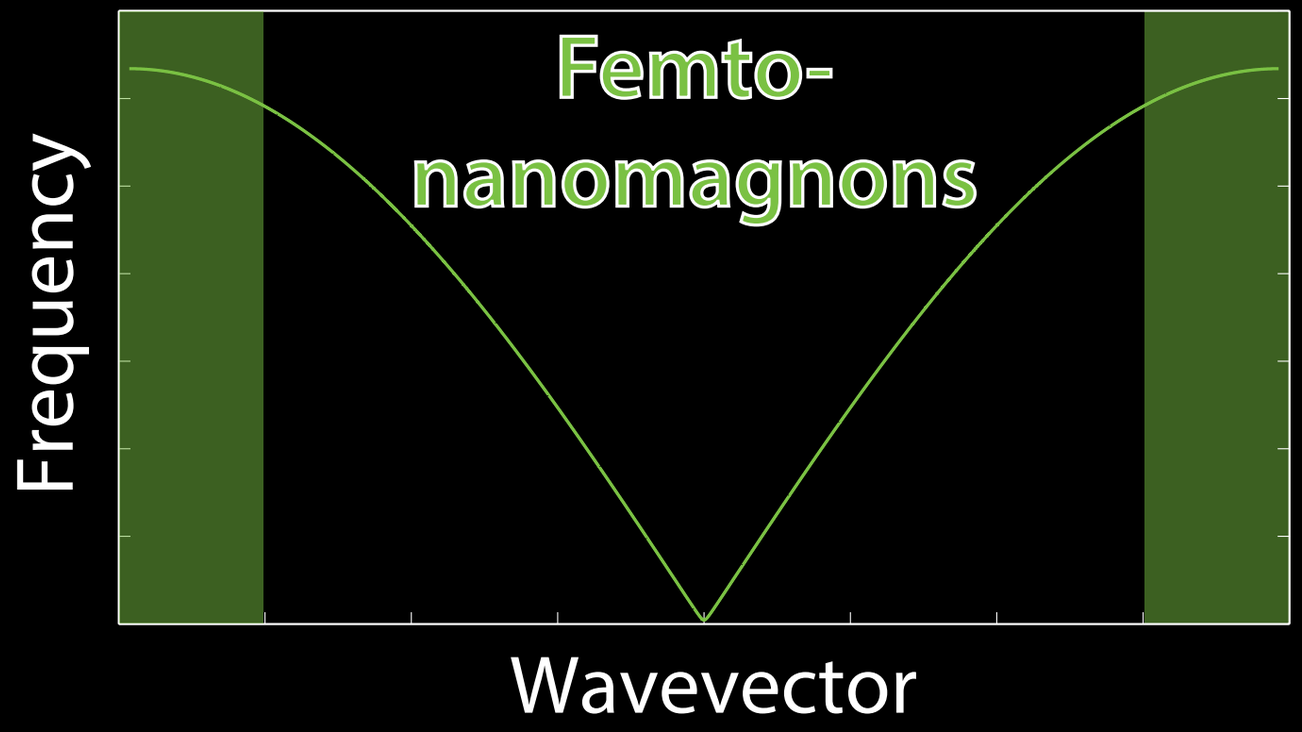


Coherent femtosecond manipulation of



D. Bossini et al. Nat. Comm. **7,** *10645 (2016)*

Magnon pumping



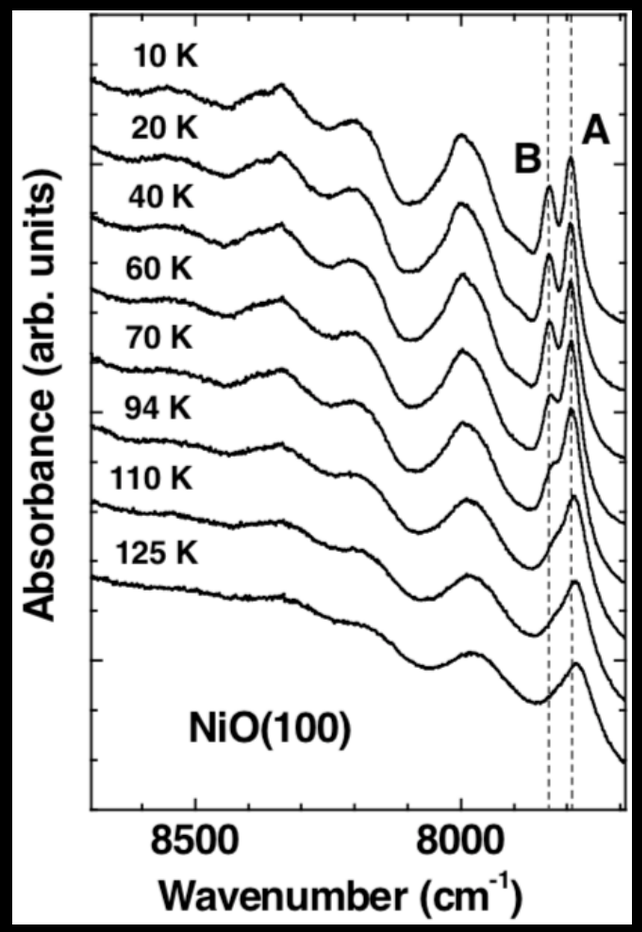
Exciton-Magnon

Tanabe et al. *Excitons in Magnetic Insulators* (1982)
Moriya et al. PRL **15**, 1023 (1965)

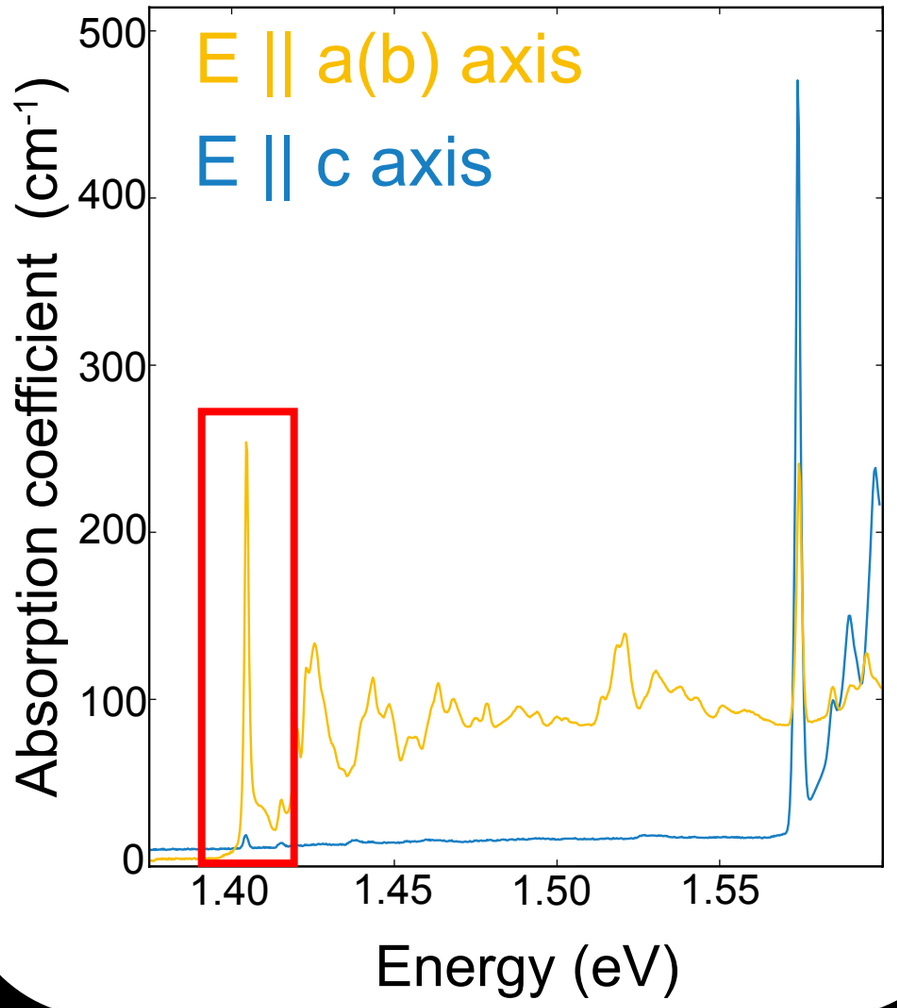
charges + magnons

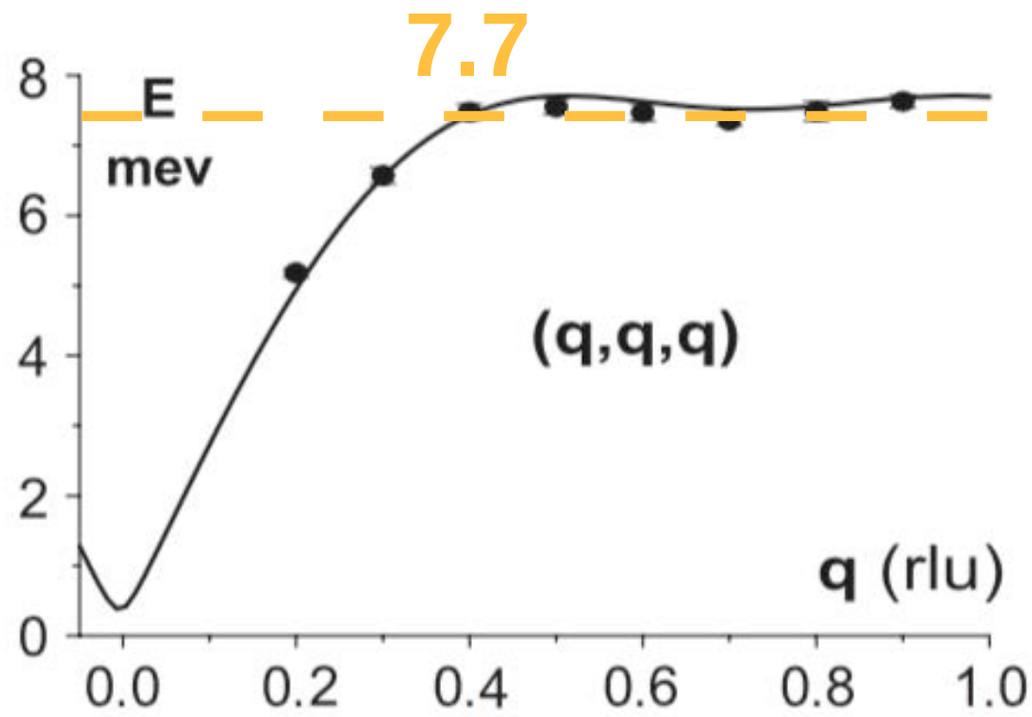
$\Delta S = 0$

Two-magnon mode: resonant pumping?



Resonant magnon pumping



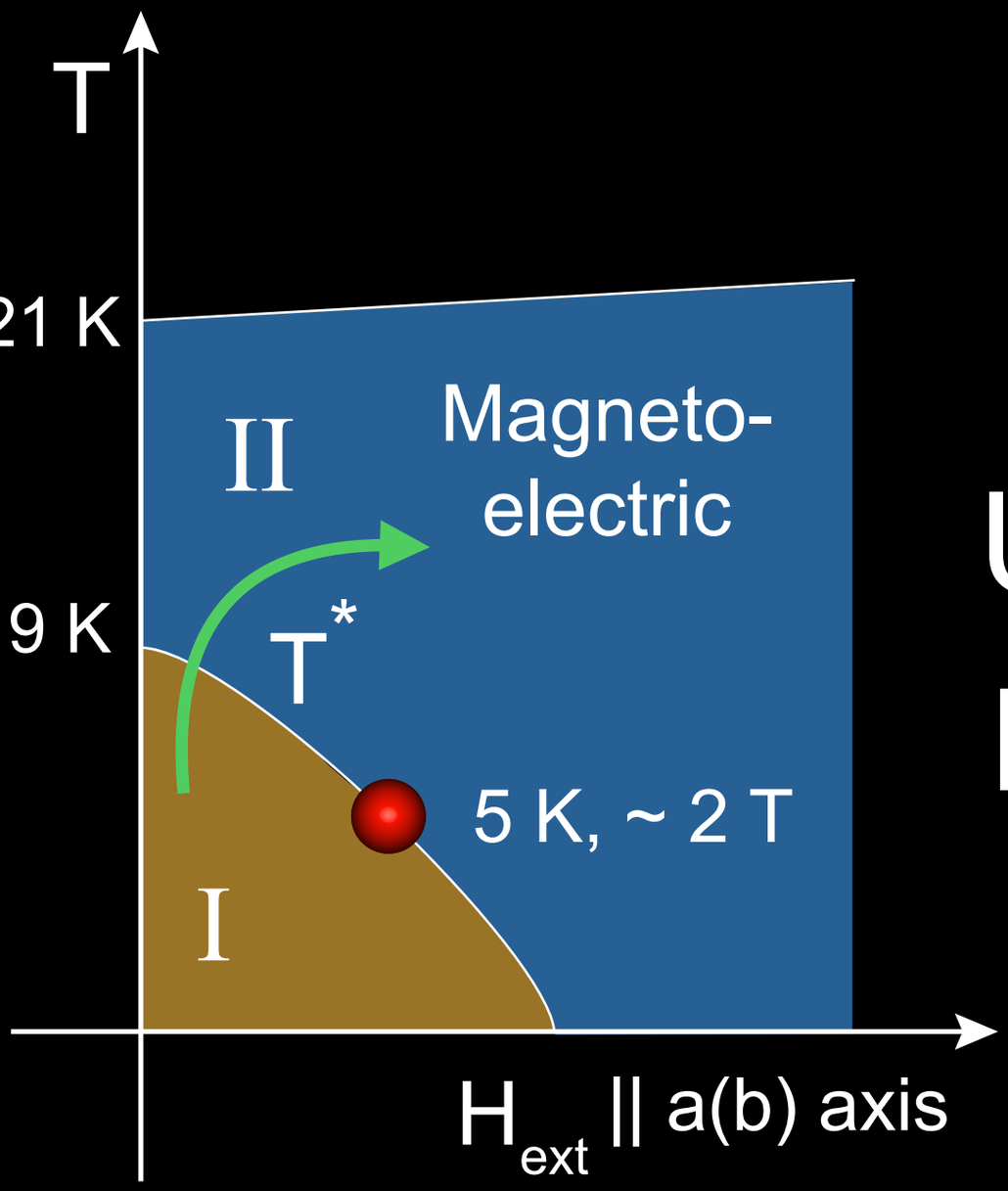


Martynov et al. J. MMM **299**, 75 (2006)

Band gap ~ 3.7 eV

Exciton-Magnon
Femto-nanomagnons

Ultrafast ME activation



CuB_2O_4

Fiebig et al. J. App. Phys. **93**, 6960 (2003)

Phase-transition

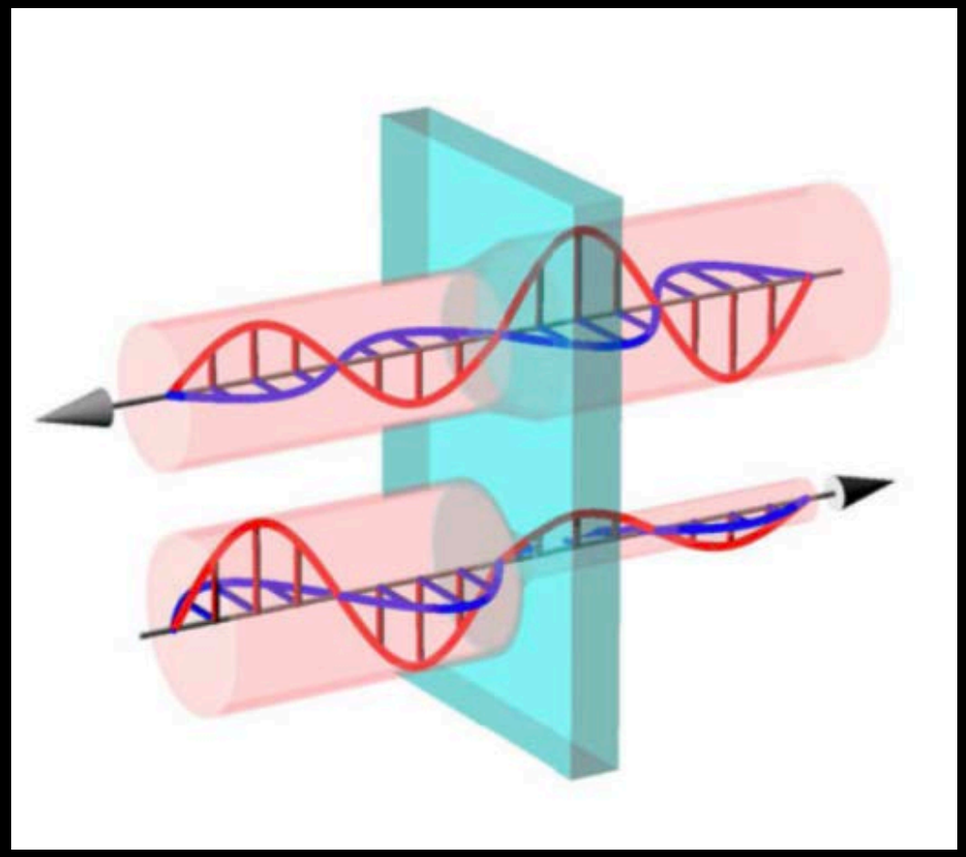
Ultrafast ME activation

E-field control of spins

Femtosecond

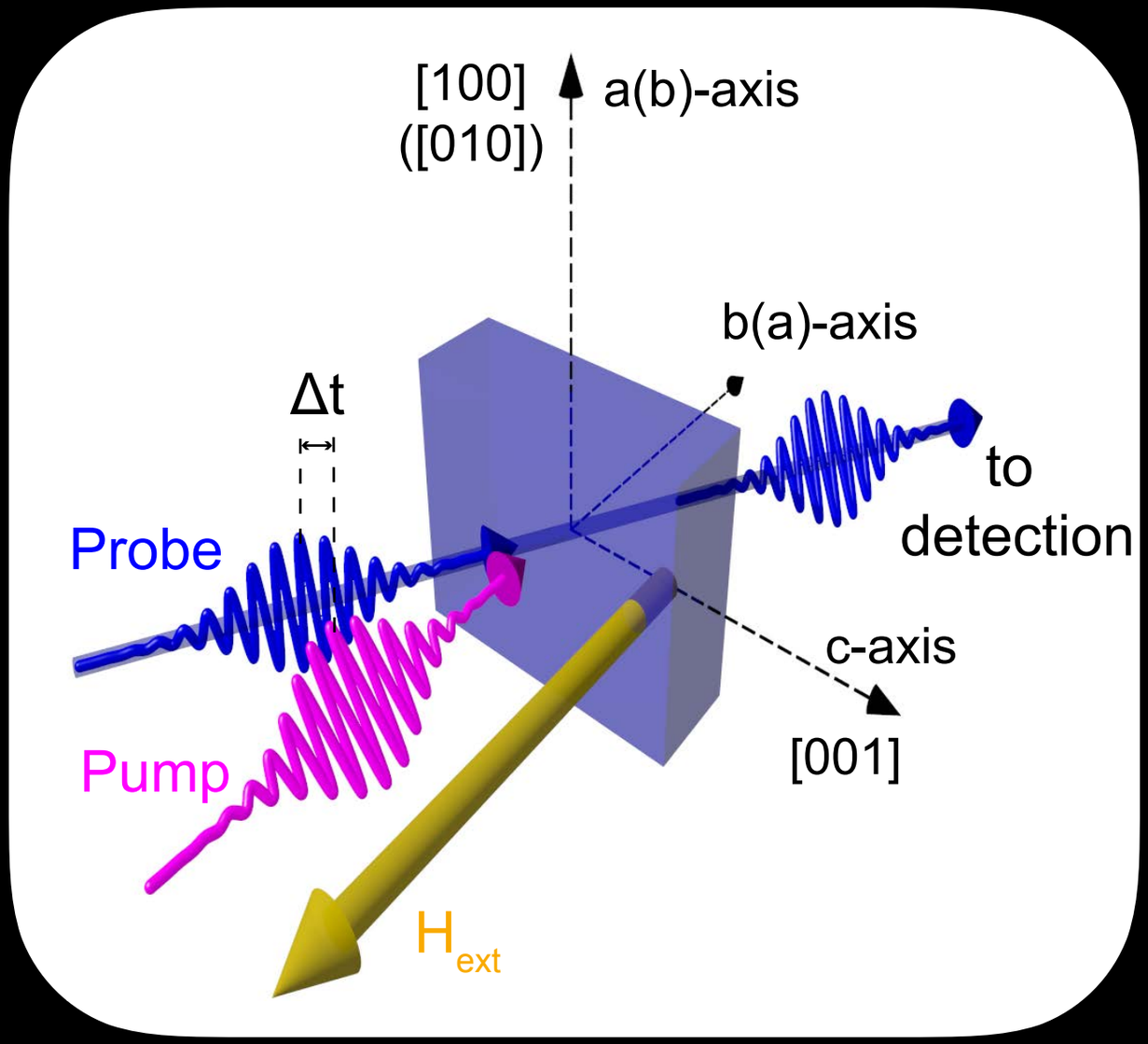
Low-dissipations

Experimental scheme



S. Toyoda et al., Phys. Rev. Lett 115, 267207

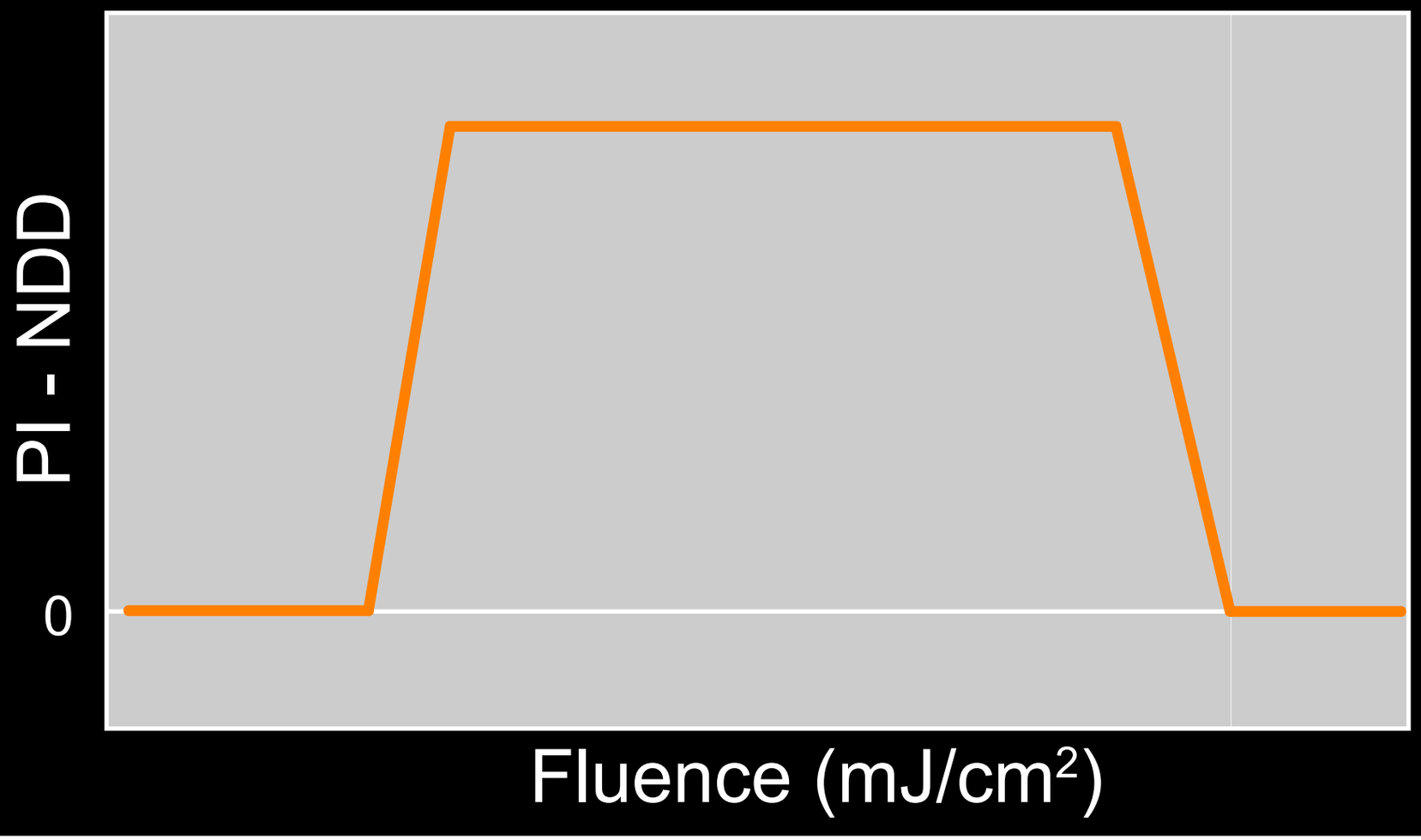
Non-reciprocal directional dichroism (NDD)



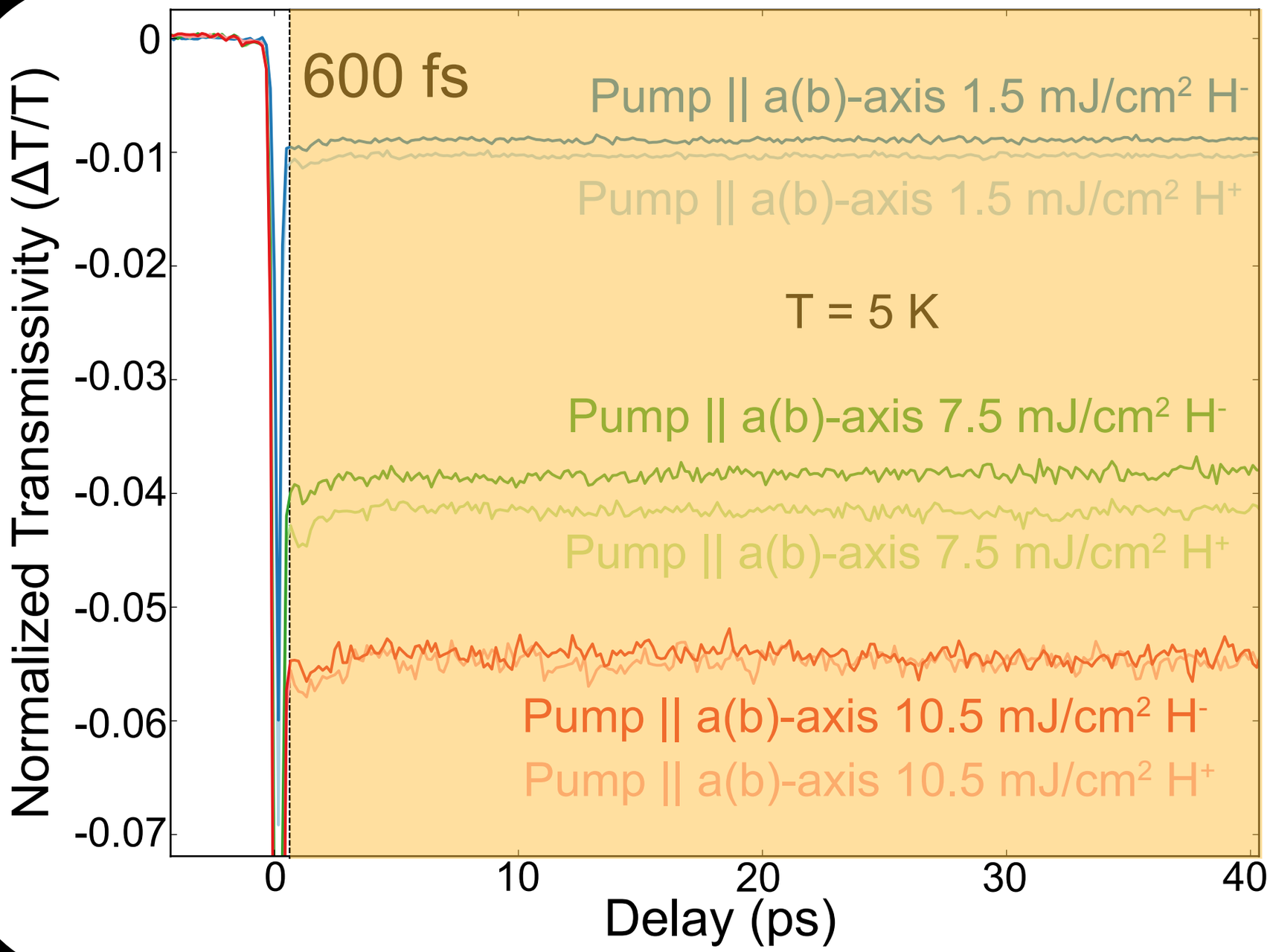
Detection: ΔT/T

Expectation

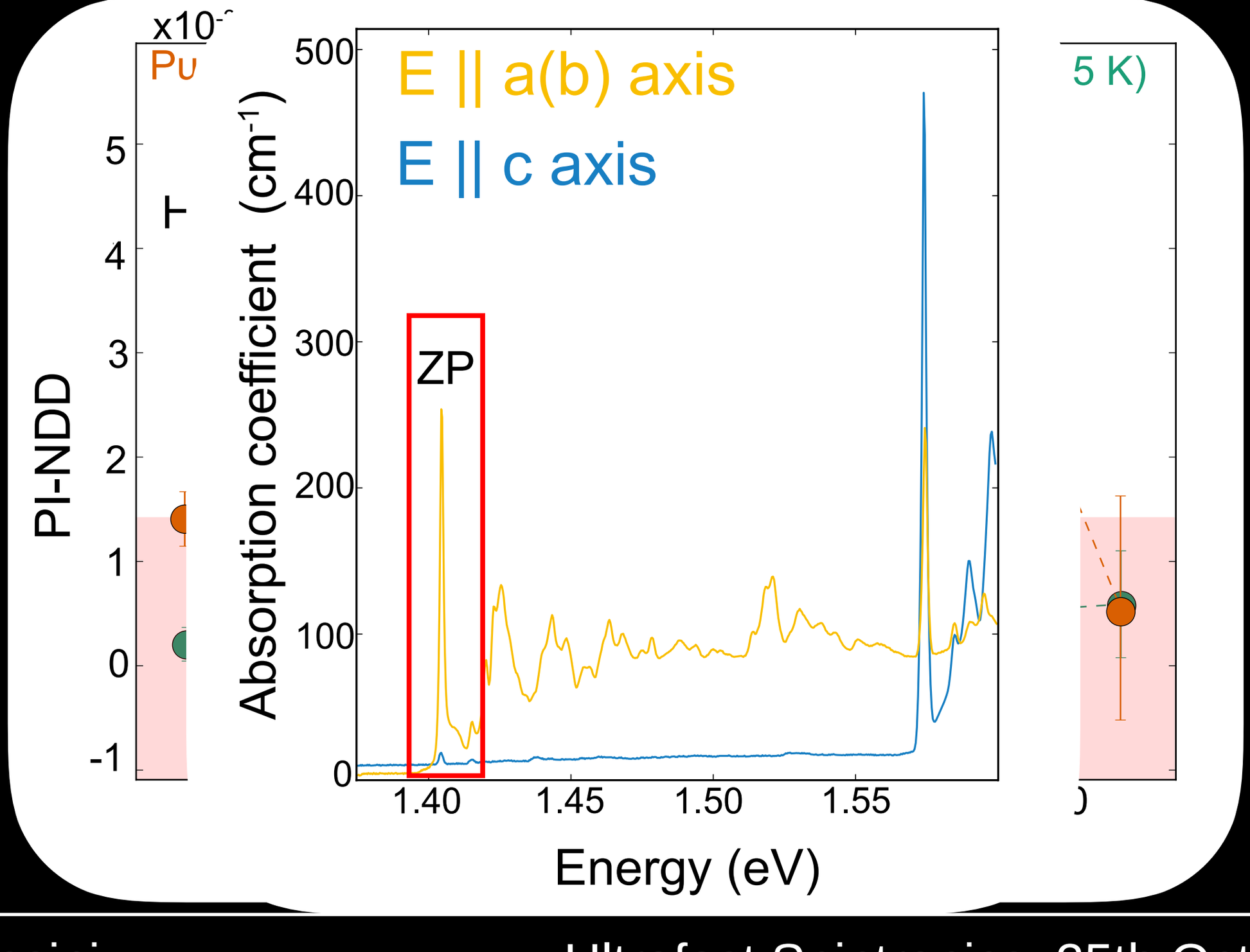
$$\text{PI-NDD} = \frac{\Lambda}{T}(H^{+}) - \frac{\Lambda}{T}(H^{-})$$



Pumping magnons

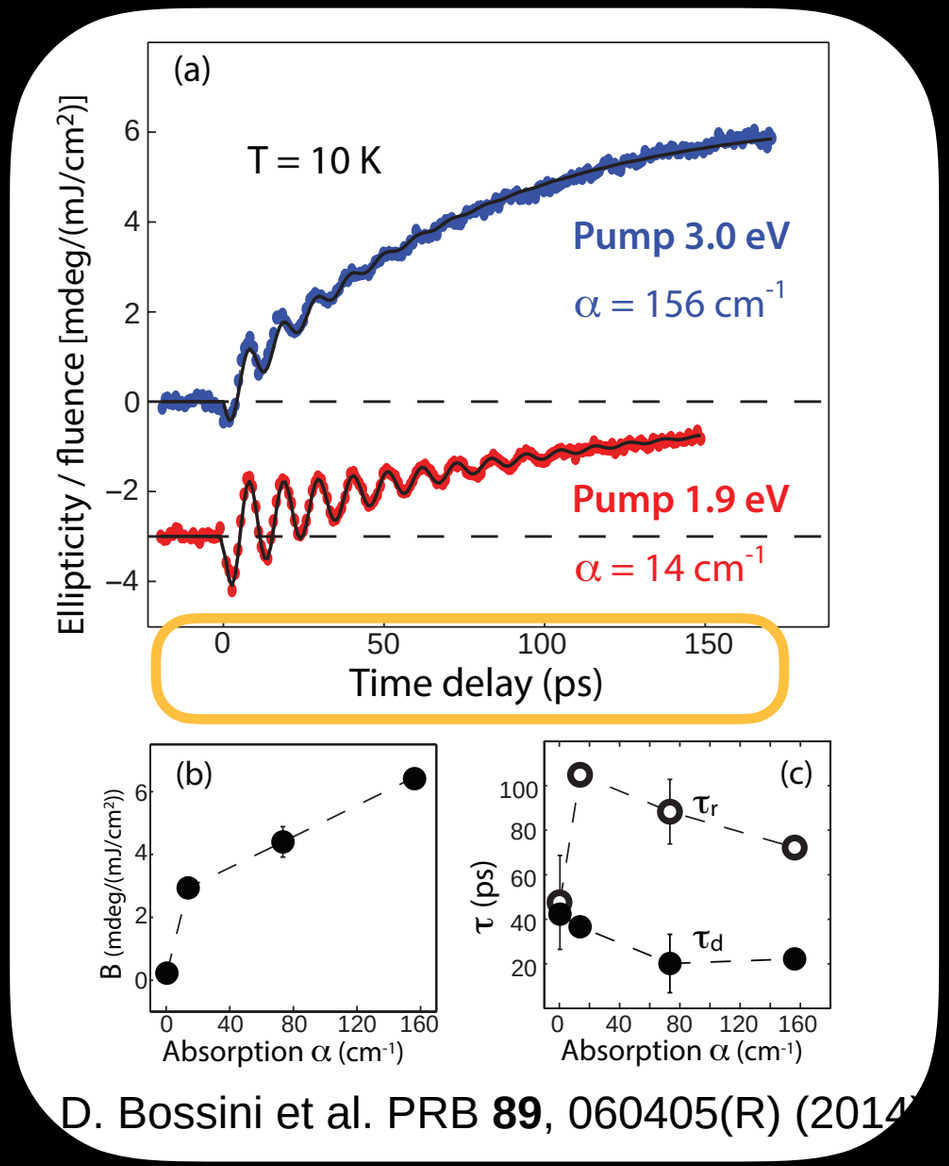


PhotoInduced-NDD



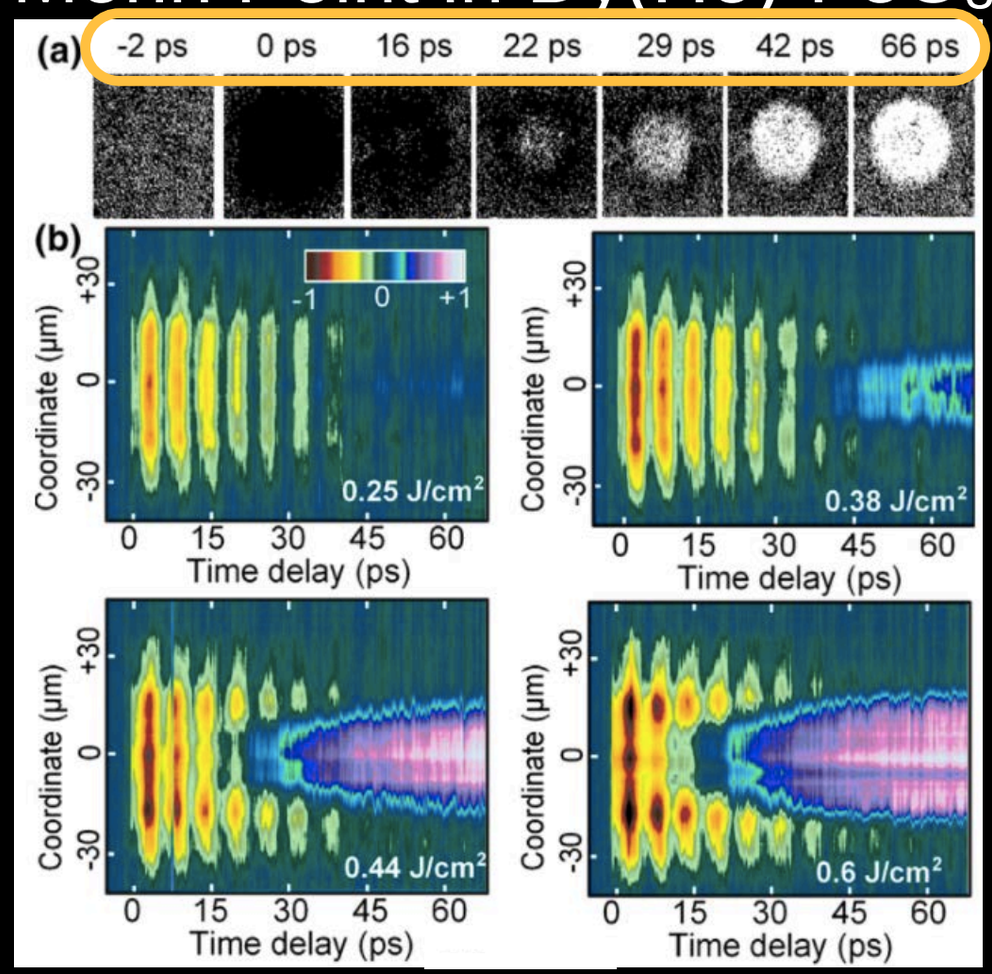
Magnetoelectricity photoinduced in 600 fs

D. Bossini et al. Nature Phys. (2018)



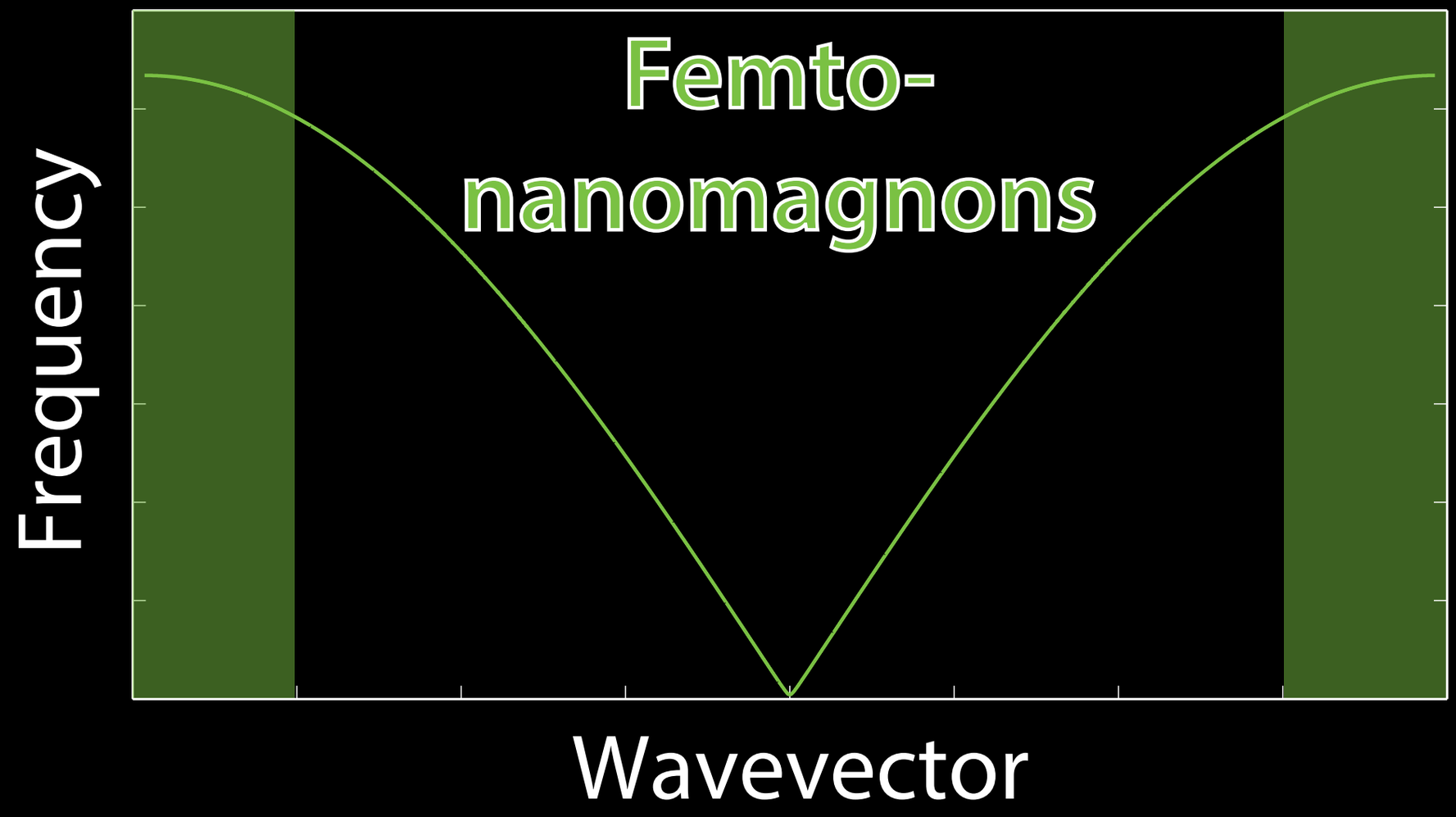
D. Bossini et al. PRB **89**, 060405(R) (2014)

Morin Point in Dy(Ho)-FeO_3



D. Afanasiev et al. PRL **116**, 097401 (2016)
D. Afanasiev et al. J.Phys.Cond.Matt. **29**, 224003 (2017)

Magnetic phase transition in **600 fs**?



Magnon-magnon interaction: **670 fs**

V.G. Ivanov et al. PRB. **88**, 094301 (2013)

Conclusions

- Excitation, control and detection of femtosecond coherent dynamics of order parameter
- Opto-magnetism without absorption throughout the Brillouin zone
- Femtosecond activation of the magneto-electricity

Outlook

- Femtosecond impulsive reversal of **L**
- Ultrafast manipulation of the exchange
- Manipulation of the magneto-electricity

Femtosecond Non-dissipative

COST Action MAGNETOFON

Work Group 3: dielectrics and magneto-electrics

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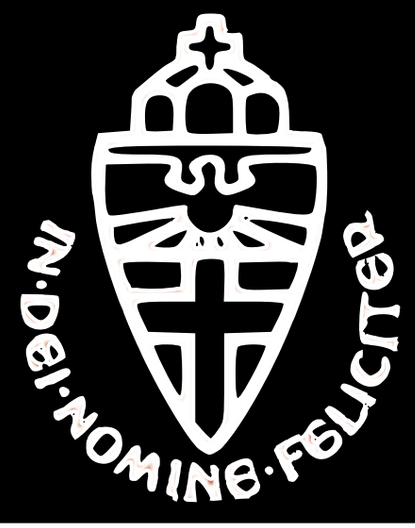

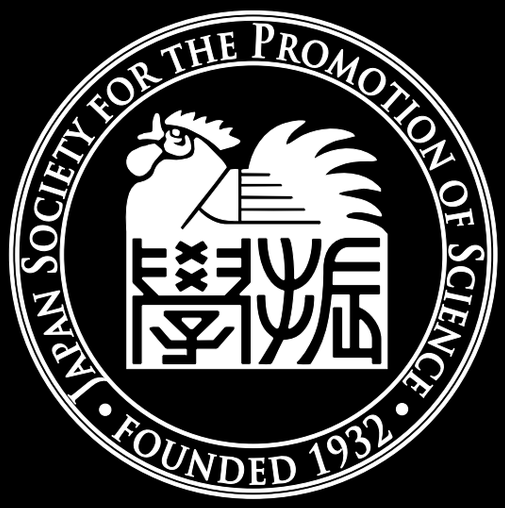

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