All-optical femtosecond relaxation dynamics in iron based pnictides

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Acknowledgements

optical:

A. Pogrebna, L. Stojchevska, N. Vujičić,

V. Kabanov, D. Mihailovic, JSI, Ljubljana

samples:

122:

I. R. Fisher, J.-H. Chu, Stanford University, Stanford, USA, (Ba-122)

Z. A. Xu, X. Lin, G. H. Cao, Zhejiang University, Hangzhou, People's Republic of China, (Sr-122, Eu-122)

D. Feng, Z. R. Ye, Fudan University, Shanghai, People's Republic of China

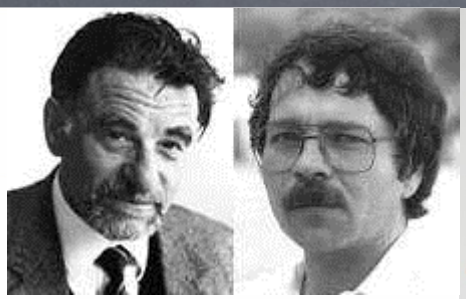
1111:

J. Karpinski, N.D. Zhigadlo,

Z. Bukowski, S. Katrych, Laboratory for Solid State Physics, ETH Zürich, Switzerland and LPMC, EPFL, Lausanne, Switzerland

Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Possible High T_c Superconductivity in the Ba – La – Cu – O System



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Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs (x = 0.05–0.12) with T_c = 26 K

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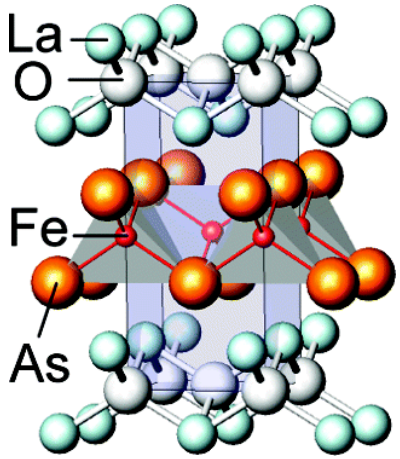
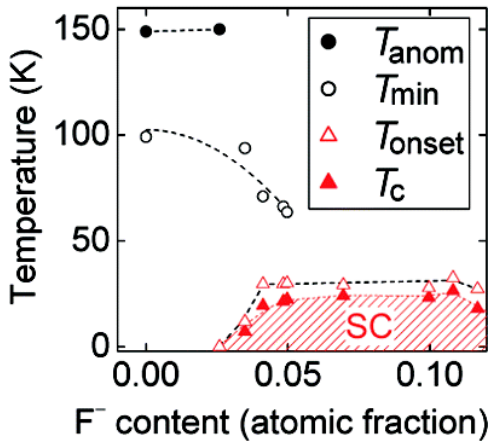
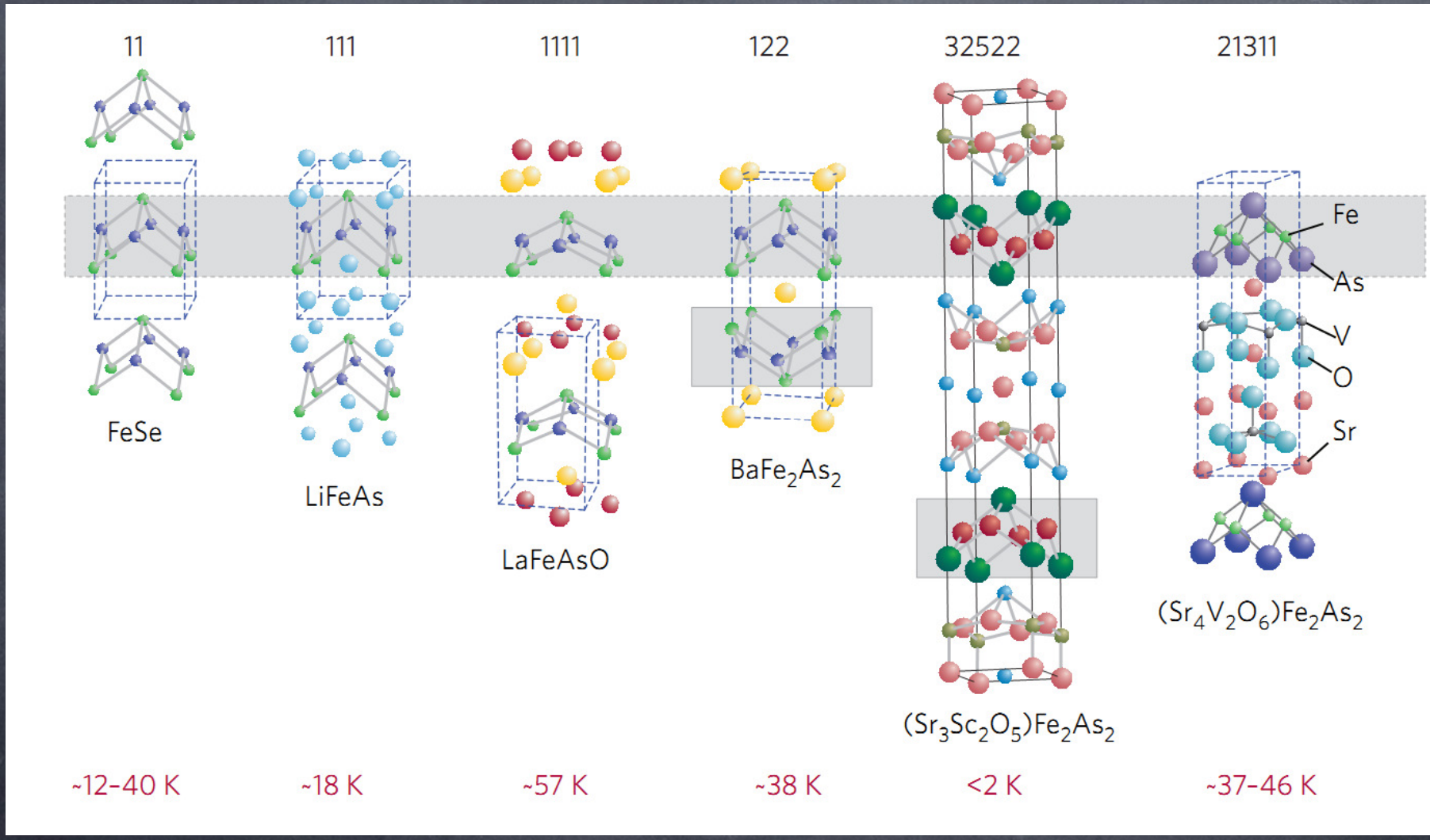




Outline

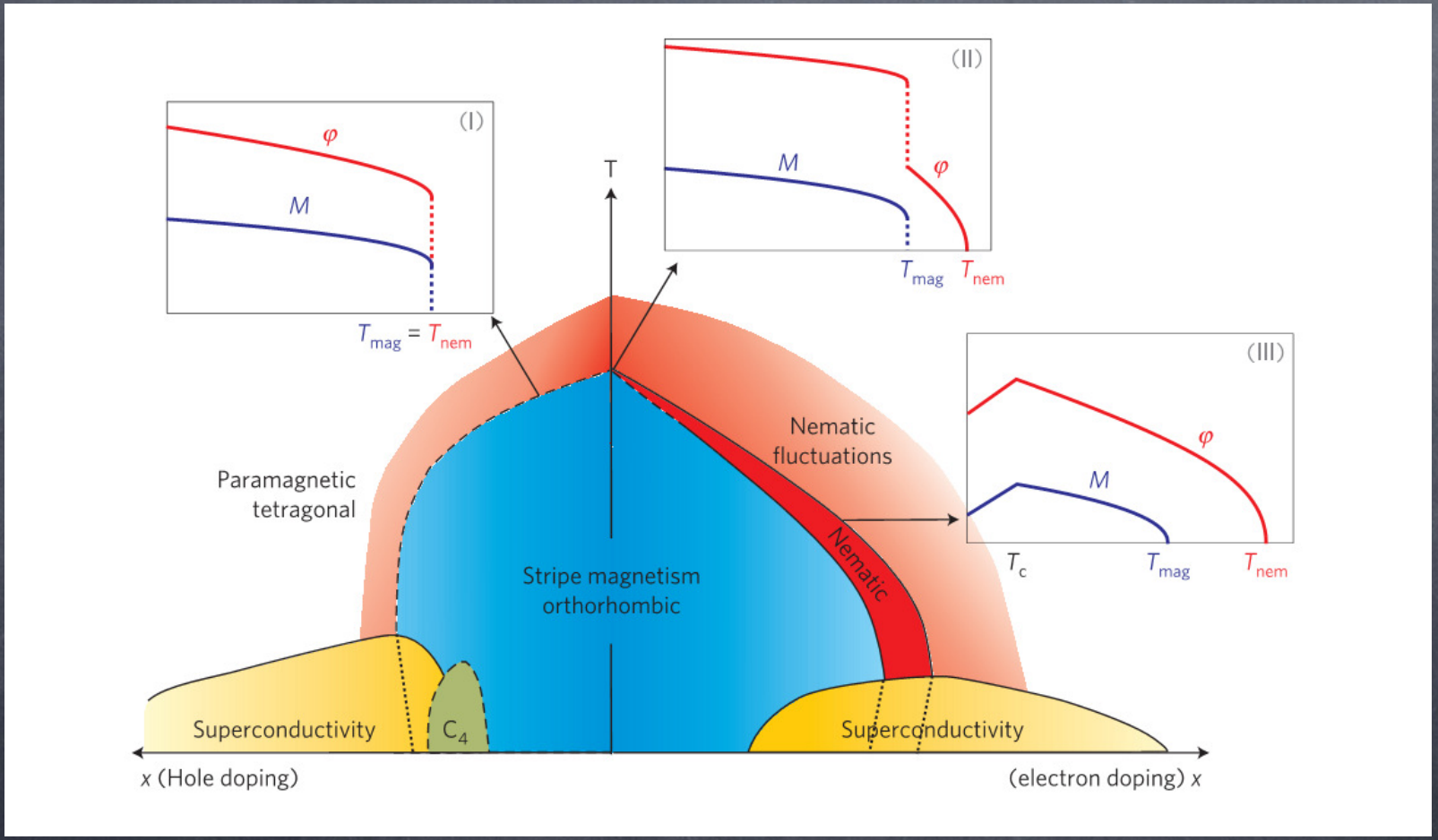
- Background
- SC gap and related dynamics from all-optical transient response
- Nematic fluctuations in normal state
- Coexistence of ferromagnetism with superconductivity in Eu-122

Fe based superconductors



C. W. Chu, *Nature Physics* **5**, 787 - 789 (2009)

Schematic phase diagram of iron based superconductors

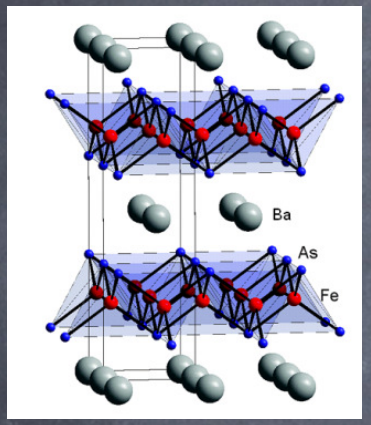


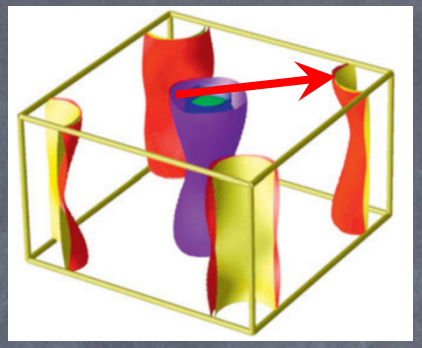
Fernandes *et al.*, Nature Physics 10, 97 (2014).

The 122 structure

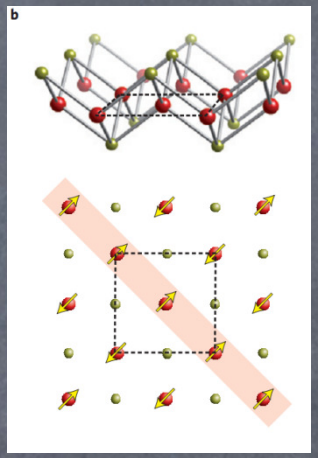
Ba-122:

- $(Ba,K)Fe_2As_2$, $T_{c,max} \approx 40K$ (hole dop.)
- $Ba(Fe,Co)_2As_2$, $T_{c,max} \approx 24K$ (electron dop.)
- $BaFe_2(As,P)_2$, $T_{c,max} \approx 30K$ (isovalent dop.)

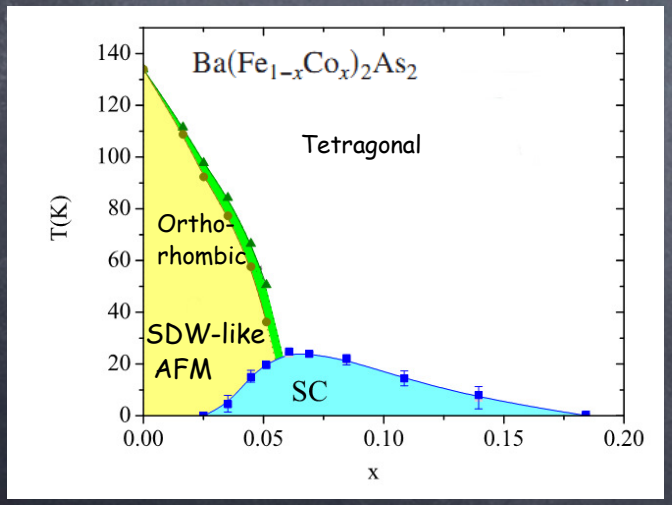




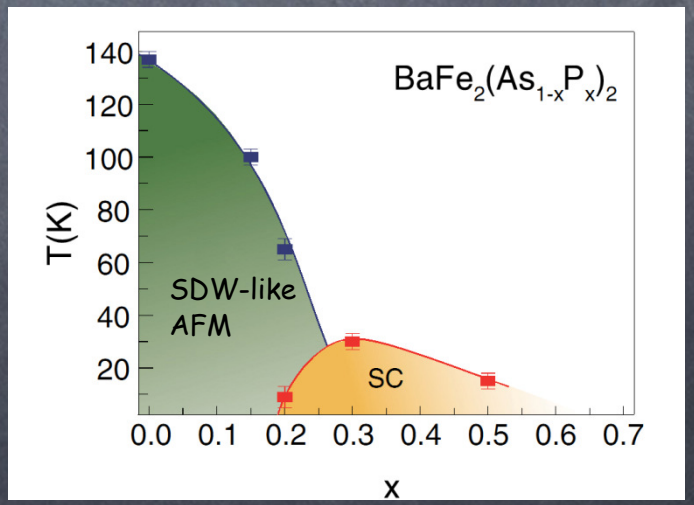
I.I. Mazin *et al.*
Physica C **469**, 614–627 (2009)



J. Paglione, R. L. Greene,
Nat. Phys. 6, 645–658 (2010)

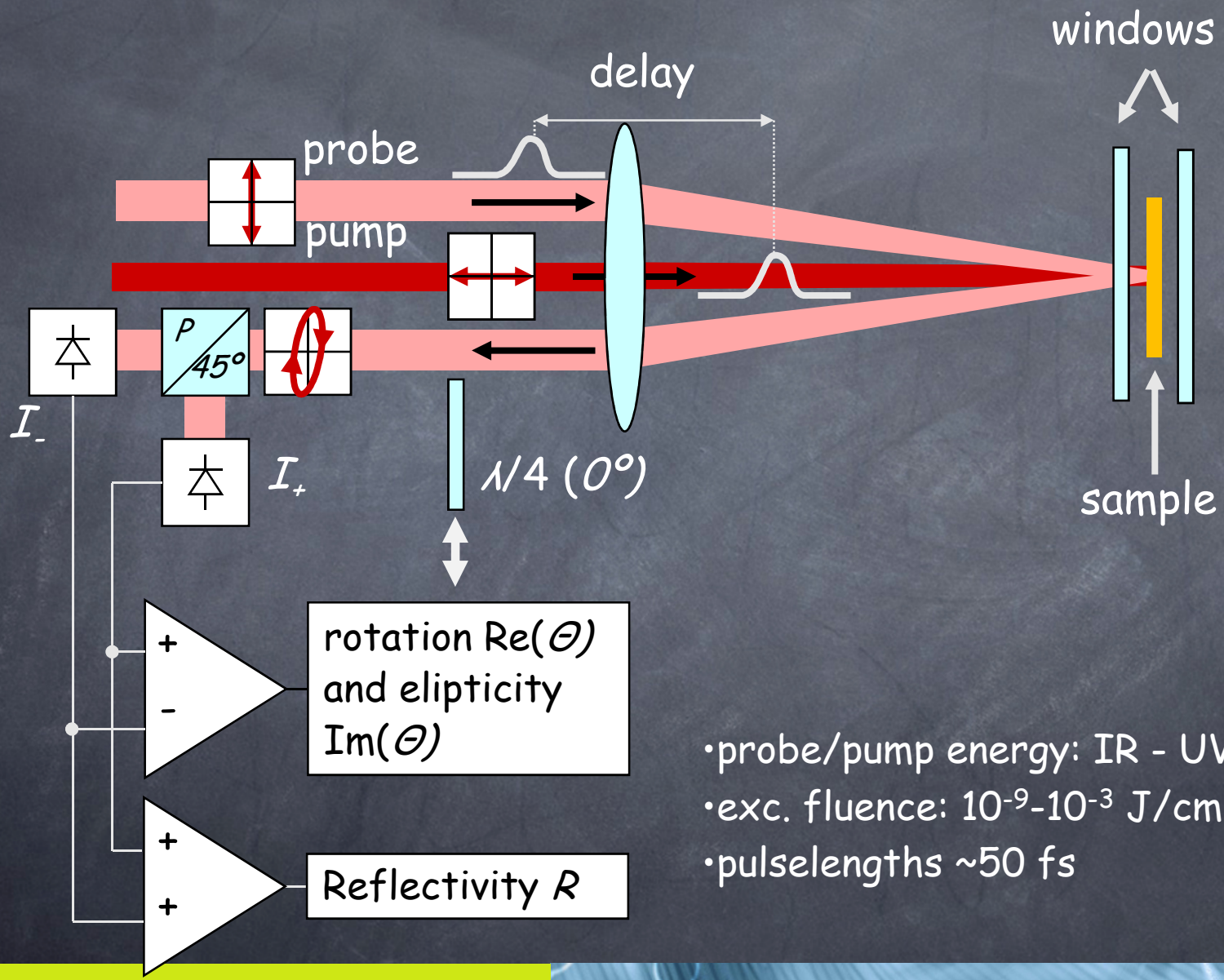


J.-H. Chu *et al.*, Phys. Rev. B 79, 014506 (2009)



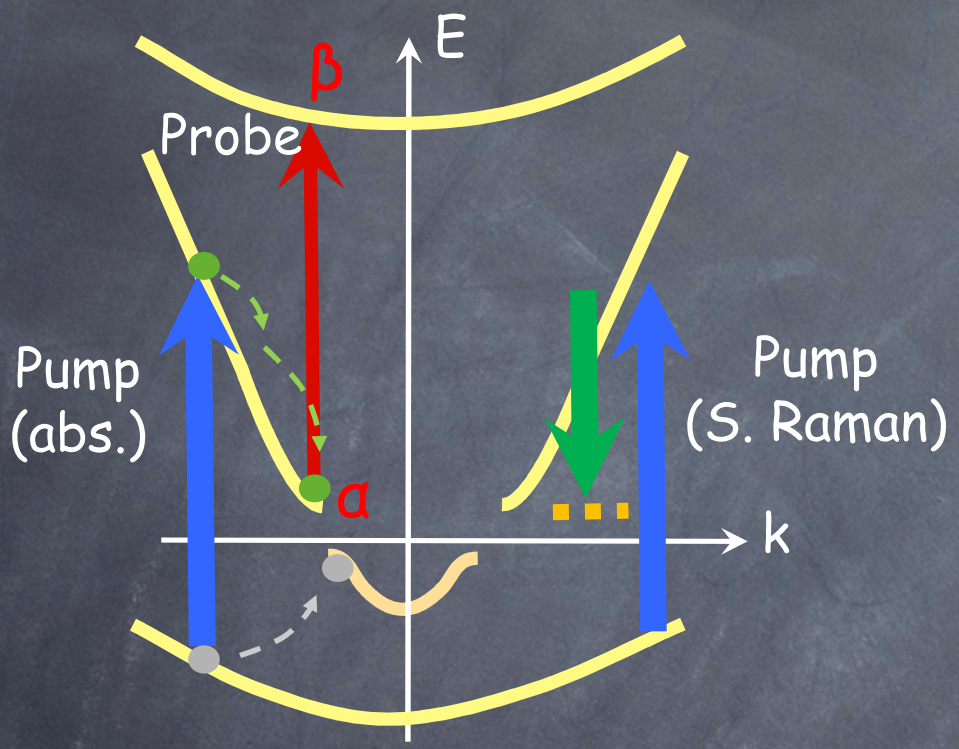
Z. R. Ye *et al.*, Phys. Rev. B 86, 035136 (2012)

Time resolved optical spectroscopy



- probe/pump energy: IR - UV
- exc. fluence: 10^{-9}-10^{-3} J/cm^2/pulse
- pulselengths ~50 fs

Transient reflectivity (transmittance)



Dielectric constant

$$\int \mathrm{d}^3k[|M_{\alpha,\beta}(\mathbf{k})|^2 \frac{f_\alpha(\mathbf{k})-f_\beta(\mathbf{k})}{\epsilon_\beta(\mathbf{k})-\epsilon_\alpha(\mathbf{k})-\hbar\omega_{\mathrm{probe}}}$$

Photoinduced absorption

$$\delta R_{\alpha,\beta} \propto \int \mathrm{d}^3k[|M_{\alpha,\beta}(\mathbf{k})|^2 \delta f_\alpha(\mathbf{k})\times \times g\left(\epsilon_\beta(\mathbf{k})-\epsilon_\alpha(\mathbf{k})-\hbar\omega_{\mathrm{probe}}\right)$$

$$\delta R = (\gamma_0 + \eta|\Psi(T)|^2)n_{\mathrm{pe}}$$

Collective degrees of freedom

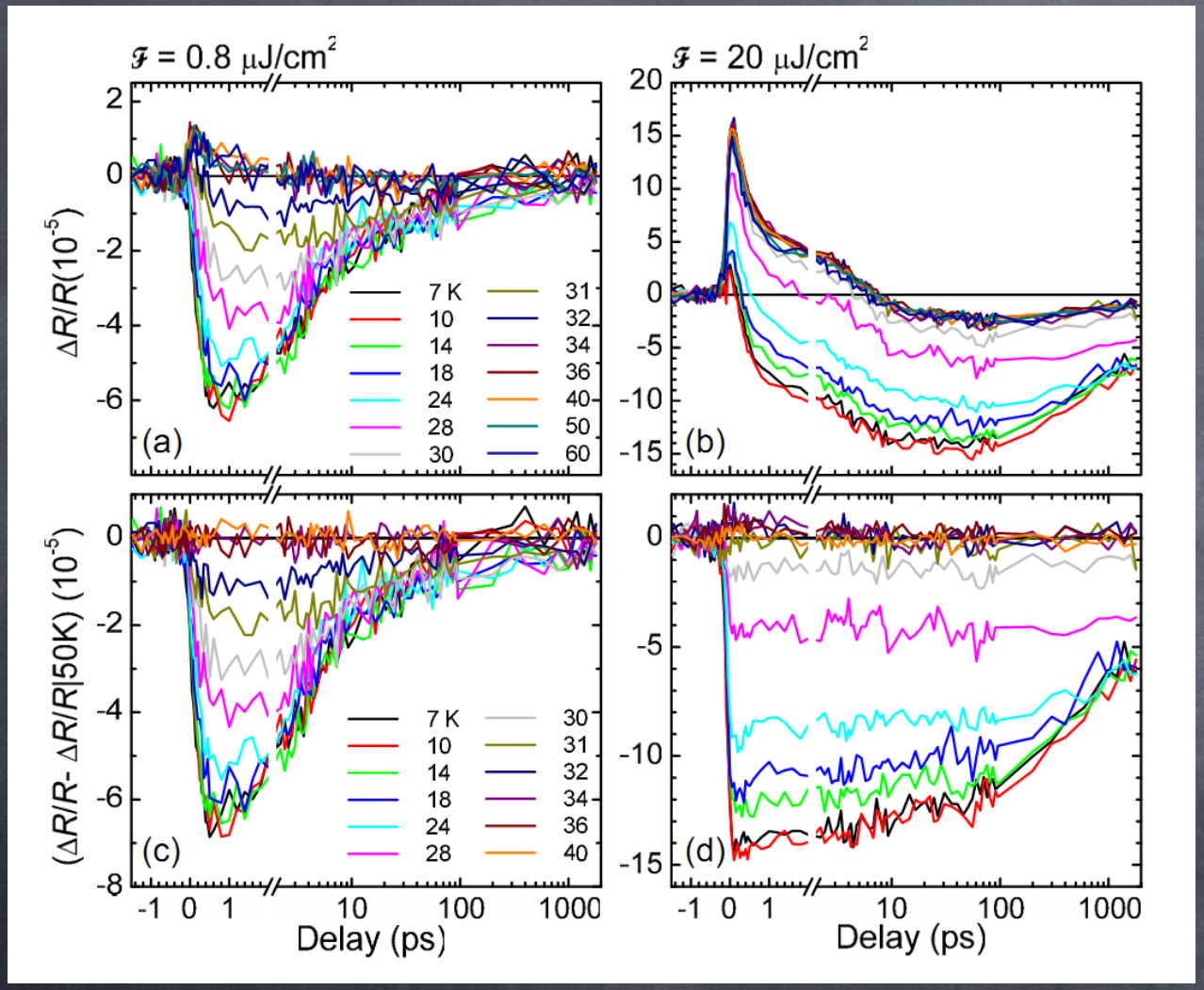
$$\delta R(t) = \frac{\partial R}{\partial \Psi}\delta\Psi(t)$$

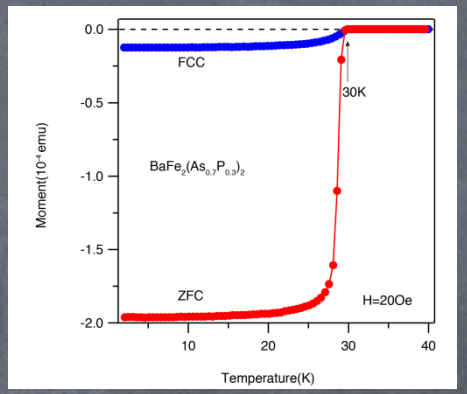
Bottleneck: BCS *T*-dependent gap

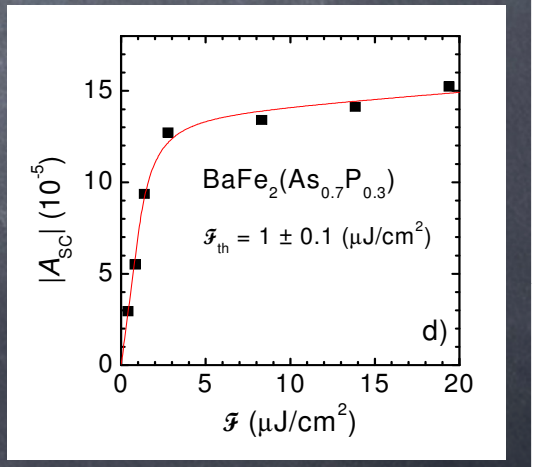
$$n_{pe} = \frac{\mathcal{E}_I/(\mathbf{\Delta}(T)+k_BT/2)}{1+\frac{2\nu}{N(0)\hbar\Omega_c}\sqrt{\frac{2k_BT}{\pi\mathbf{\Delta}(T)}}\exp[-\mathbf{\Delta}(T)/k_BT]}.$$

V.V. Kabanov et al., PRB 59, 1497 (1999).

Superconducting response in $BaFe_2(As_{1-x}P_x)_2$

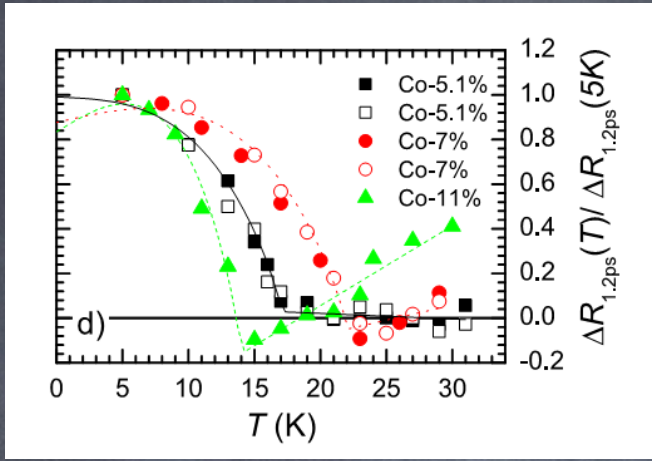


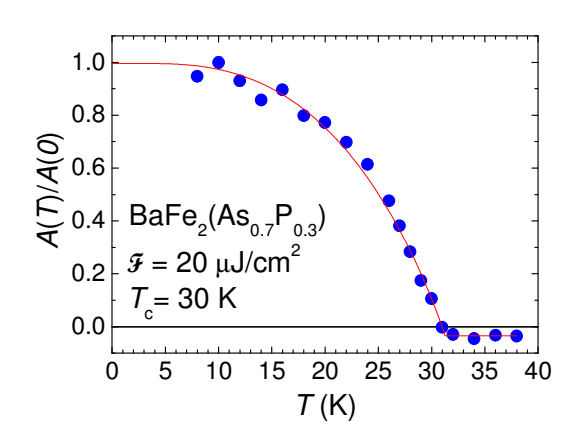




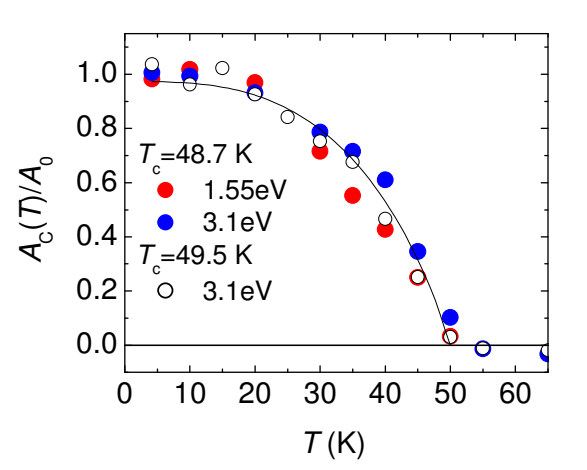
T dependence of the saturated response

$Ba(Fe_{1-x}Co_x)_2As_2$





$SmFeAs(O_{0.8}F_{0.2})$



$$\left|\frac{\Delta R}{R}\right|_{\mathcal{F}>\mathcal{F}_T} \propto \frac{\sigma_1^n - \sigma_1^s}{\sigma_1^n}$$

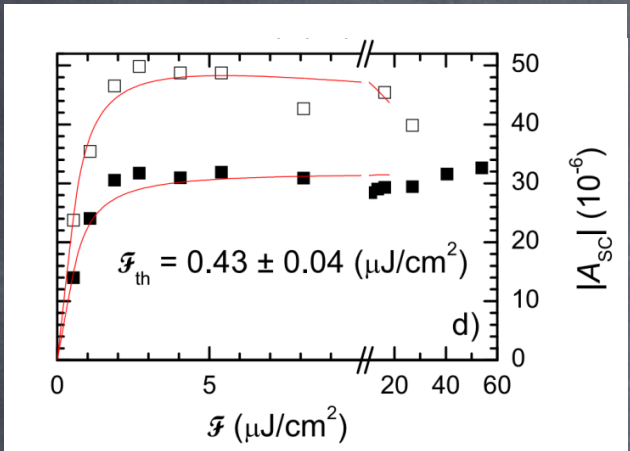
High frequency limit of the Mattis-Bardeen formula:

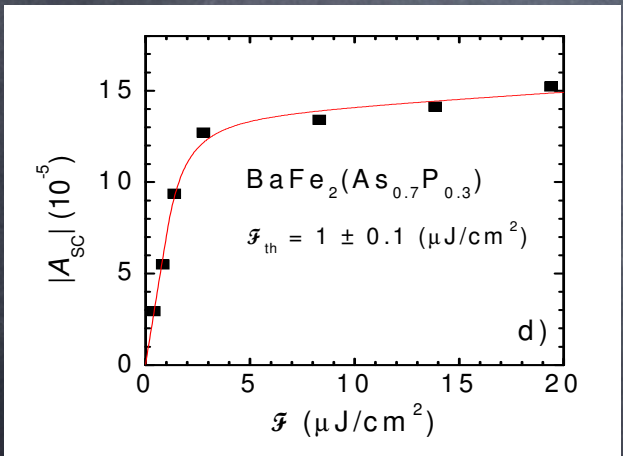
$$\frac{\Delta R}{R} \propto \left(\frac{\Delta(T)}{\hbar\omega}\right)^2 \log\left(\frac{3.3\hbar\omega}{\Delta(T)}\right)$$

The amplitude is consistent with the BCS T-dependence of the gap(s).

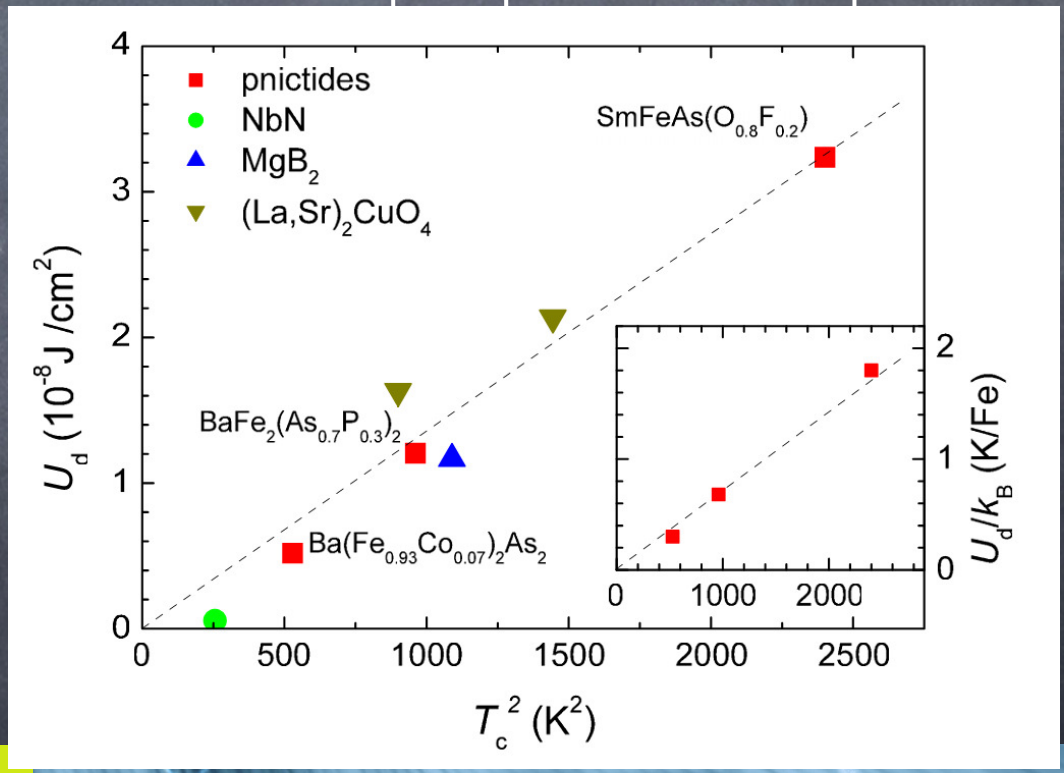
Destruction of SC condensate by optical impact

$Ba(Fe_{0.93}Co_{0.07})_2As_2$



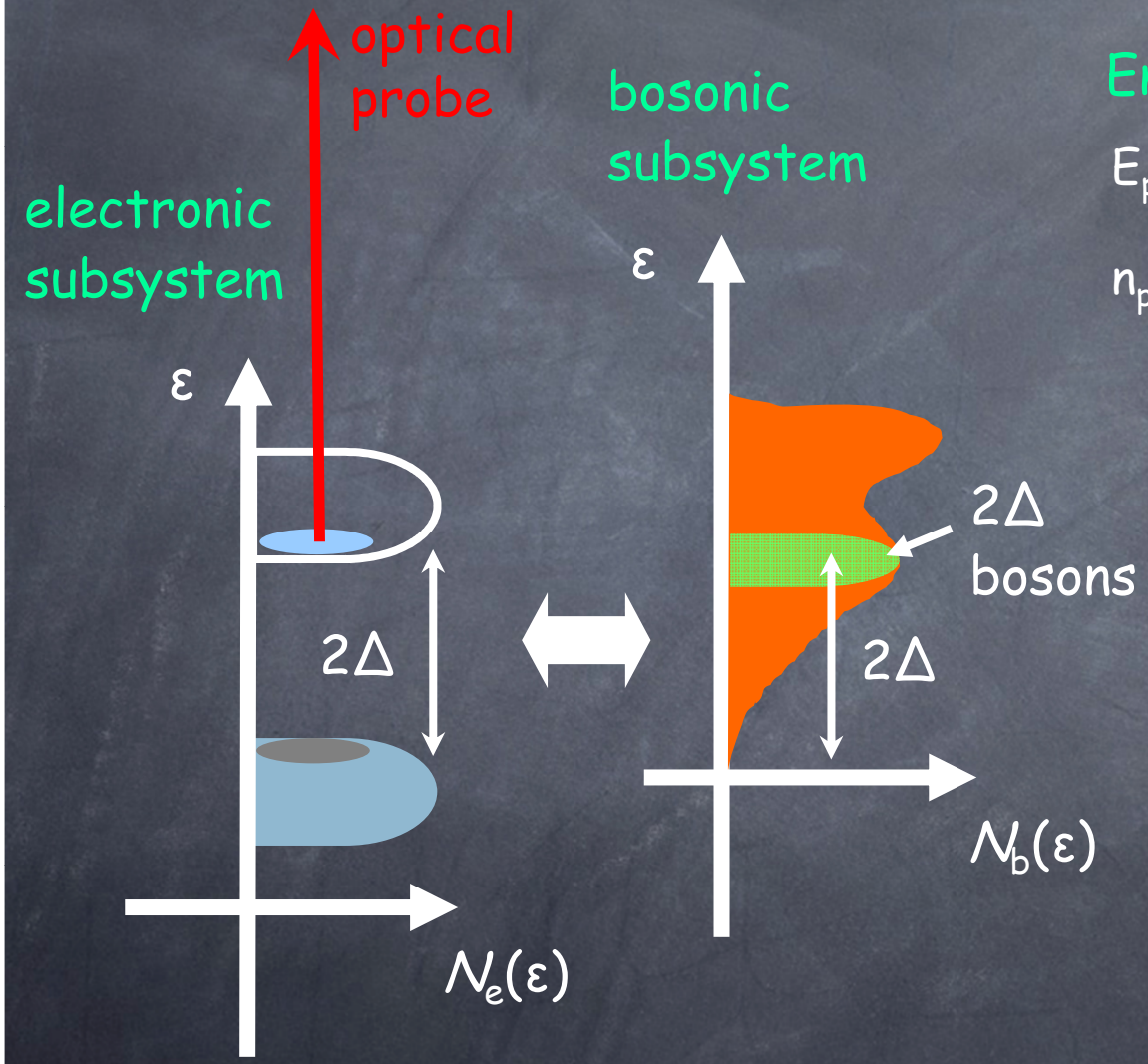


compound	T_c	U_p/k_B	U_p/U_c
$SmFeAs(O_{0.8}F_{0.2})$	49K	1.8 K/Fe (15 J/mol)	-
$BaFe_2(As_{0.7}P_{0.3})_2$	30K	0.66K/Fe (11 J/mol)	-
$Ba(Fe_{0.93}Co_{0.07})_2As_2$	23K	0.3 K/Fe (4.9 J/mol)	2
$La_{0.85}Sr_{0.15}CuO_4$	38K	2.6 K/Cu	8



SC state: bottleneck model

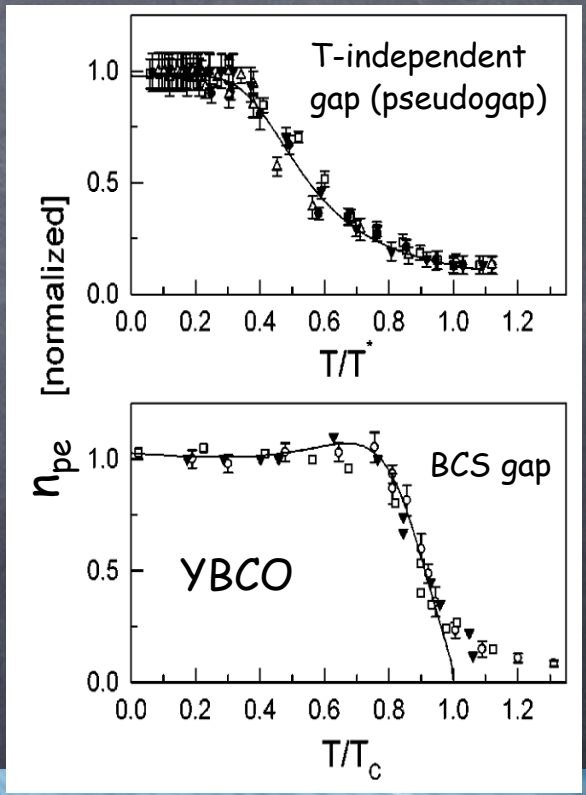
(weak perturbation) [Rothwarf-Taylor 1967, Kabanov 1999]



Energy conservation:

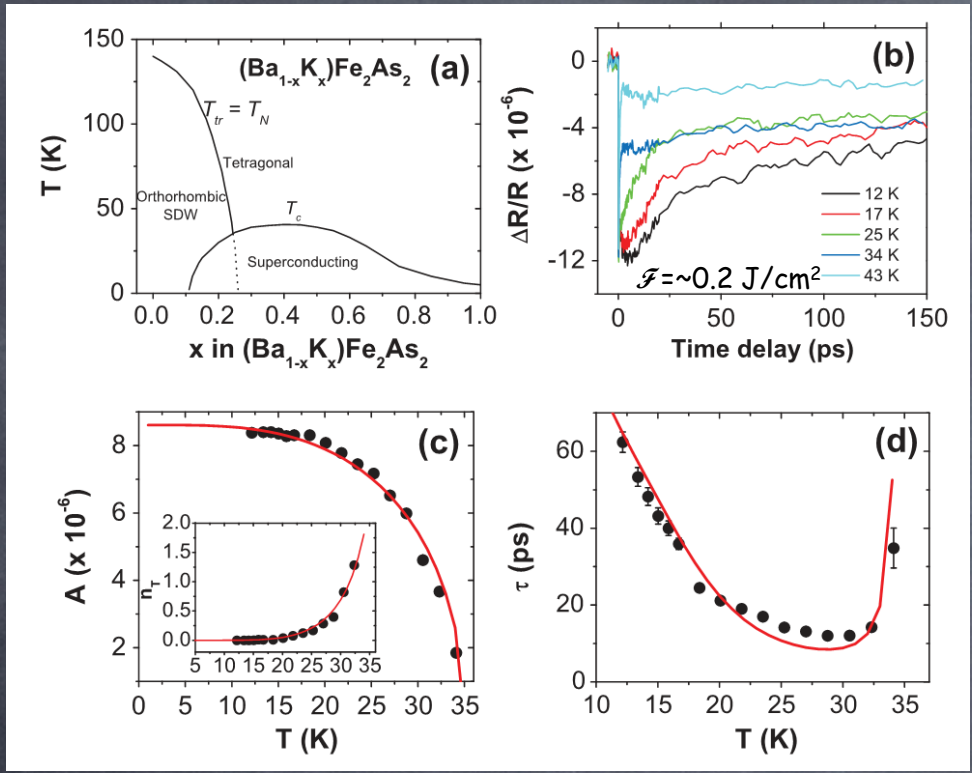
$E_{pump} = [c_e(T_{bath}) + c_{2\Delta b}(T_{bath})]\ \delta T_{el}$

$n_{pe}(T) = dn/dT\ \delta T_{el}$

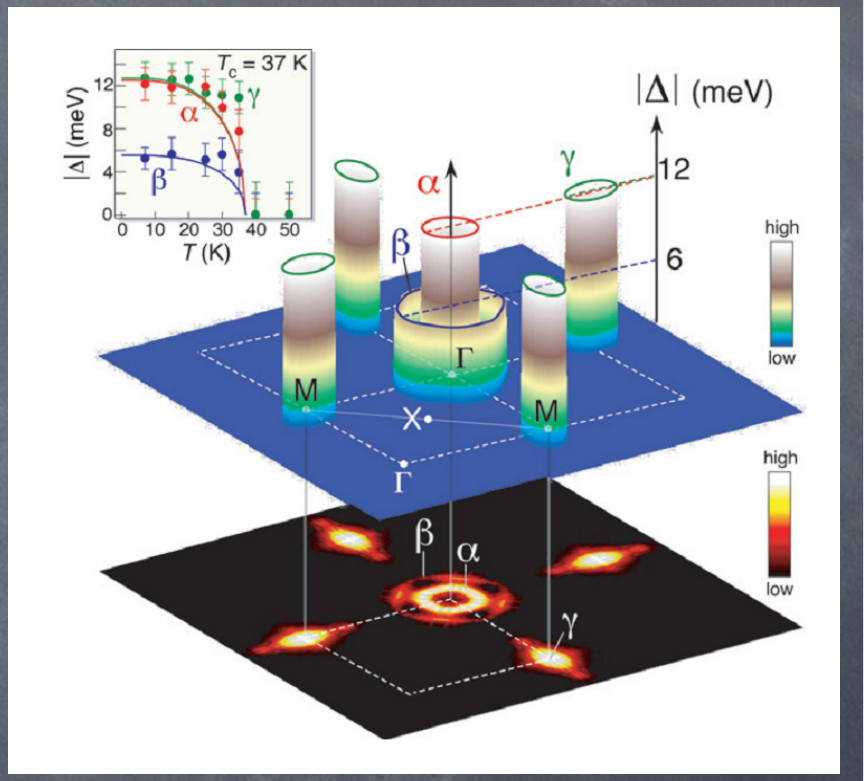


V.V. Kabanov et al., PRB 59, 1497 (1999)

Early result in hole doped $Ba_{0.6}K_{0.4}Fe_2As_2$



E.E. M. Chia *et al.*, PRL 104, 027003 (2010).

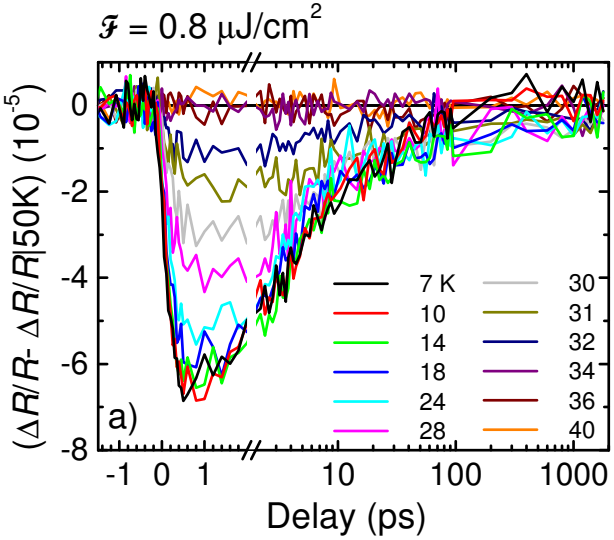


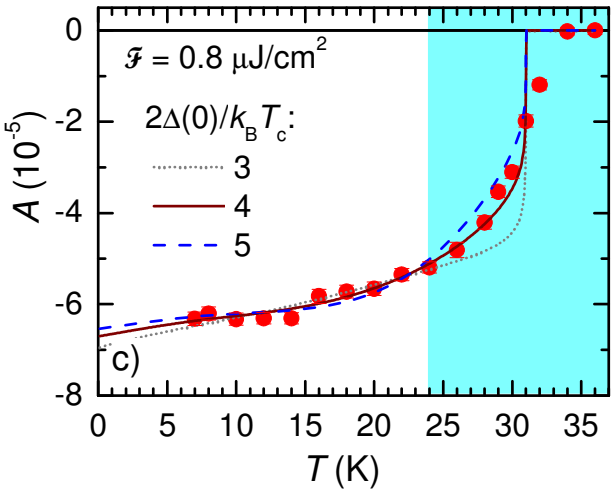
Ding *et al.*, EPL, 83, 47001 (2008).

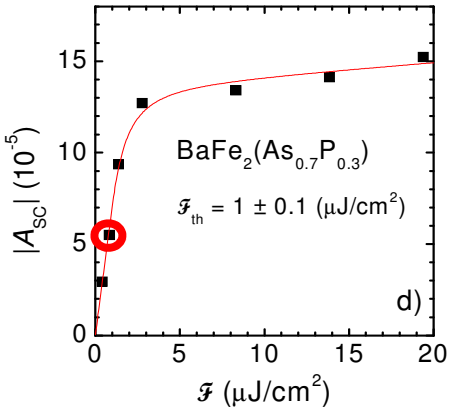
R-T fit:

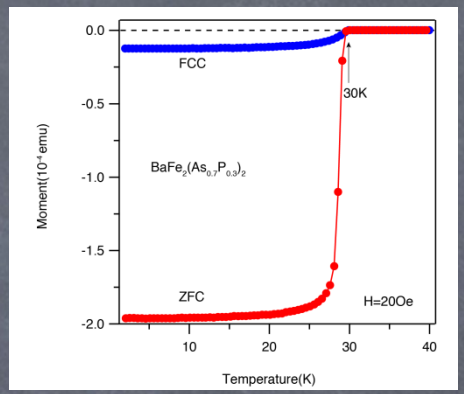
$2\Delta/k_B T_c = 3$, $\Delta = 4.6$ meV

Superconducting response in $BaFe_2(As_{1-x}P_x)_2$ @1.55-eV probe







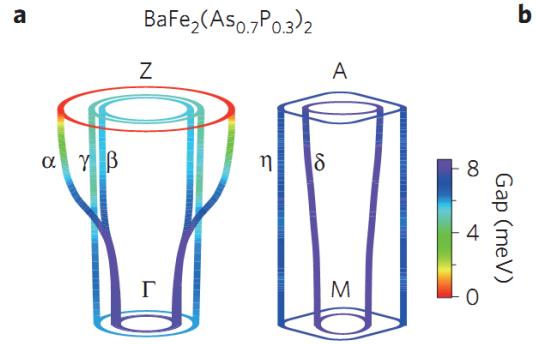


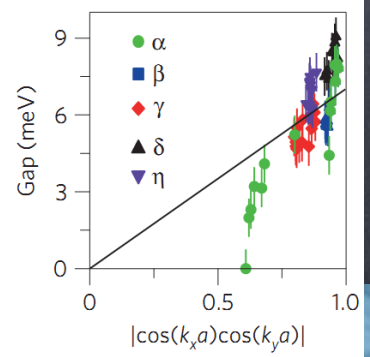
bottleneck: a *T*-dependent BCS gap:

$$n_{pe} = \frac{\mathcal{E}_I/(\Delta(T)+k_BT/2)}{1+\frac{2\nu}{N(0)\hbar\Omega_c}\sqrt{\frac{2k_BT}{\pi\Delta(T)}}\exp[-\Delta(T)/k_BT]}$$

V. V. Kabanov, J. Demsar, B. Podobnik, and D. Mihailovic, Phys. Rev. B **59**, 1497 (1999).

Δ_{SC} ~ 5 meV

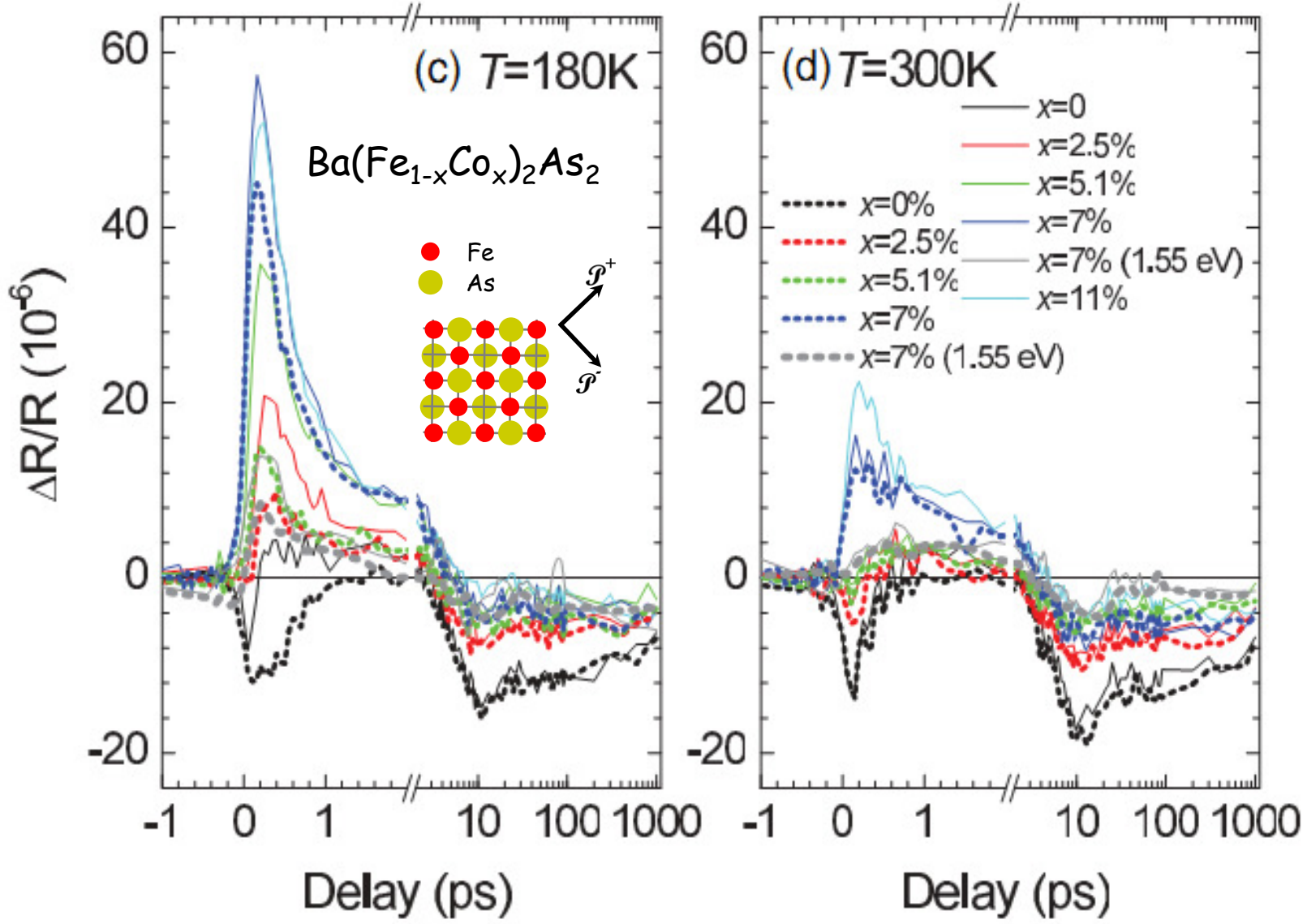




Y. Zhang et al., Nat. Phys. **8**, 371 (2012)

Pogrebna et al., PRB **92**, 144503 (2015)

Normal state nematic fluctuations

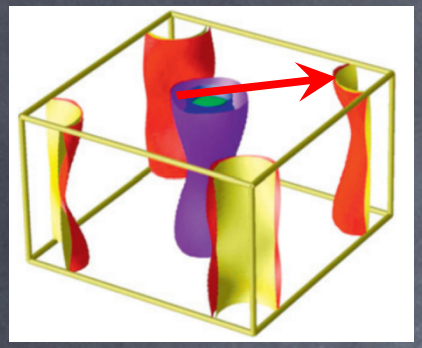


Transient response in the SC iron based pnictides

- BCS T-dependence of the SC gap(s).
- SC condensate destruction energy proportional to T_c^2.
- The superconducting gap magnitude of $2\Delta(0)/k_B T_c = 4 \pm 1$ in P doped Ba-122 is consistent with the gap on the γ- and β-hole Fermi surfaces.
- The relaxation dynamics detected by means of 1.55-eV probe photons in Ba-122 can therefore be attributed to the hole Fermi surfaces as suggested previously by Torchinsky *et al.*.
- Pseudogap due to the nematic fluctuations in the normal state.

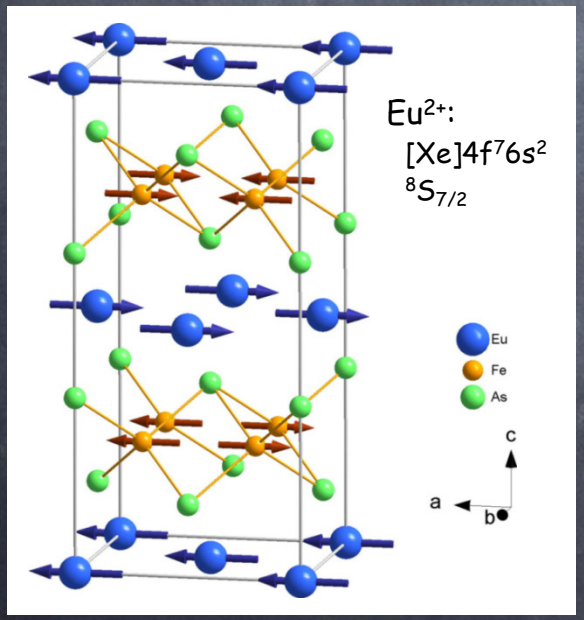
Eu^{2+}-spin related dynamics

Eu^{2+} spin ordering in $EuFe_2(As_{1-x}P_x)_2$ (Eu-122)

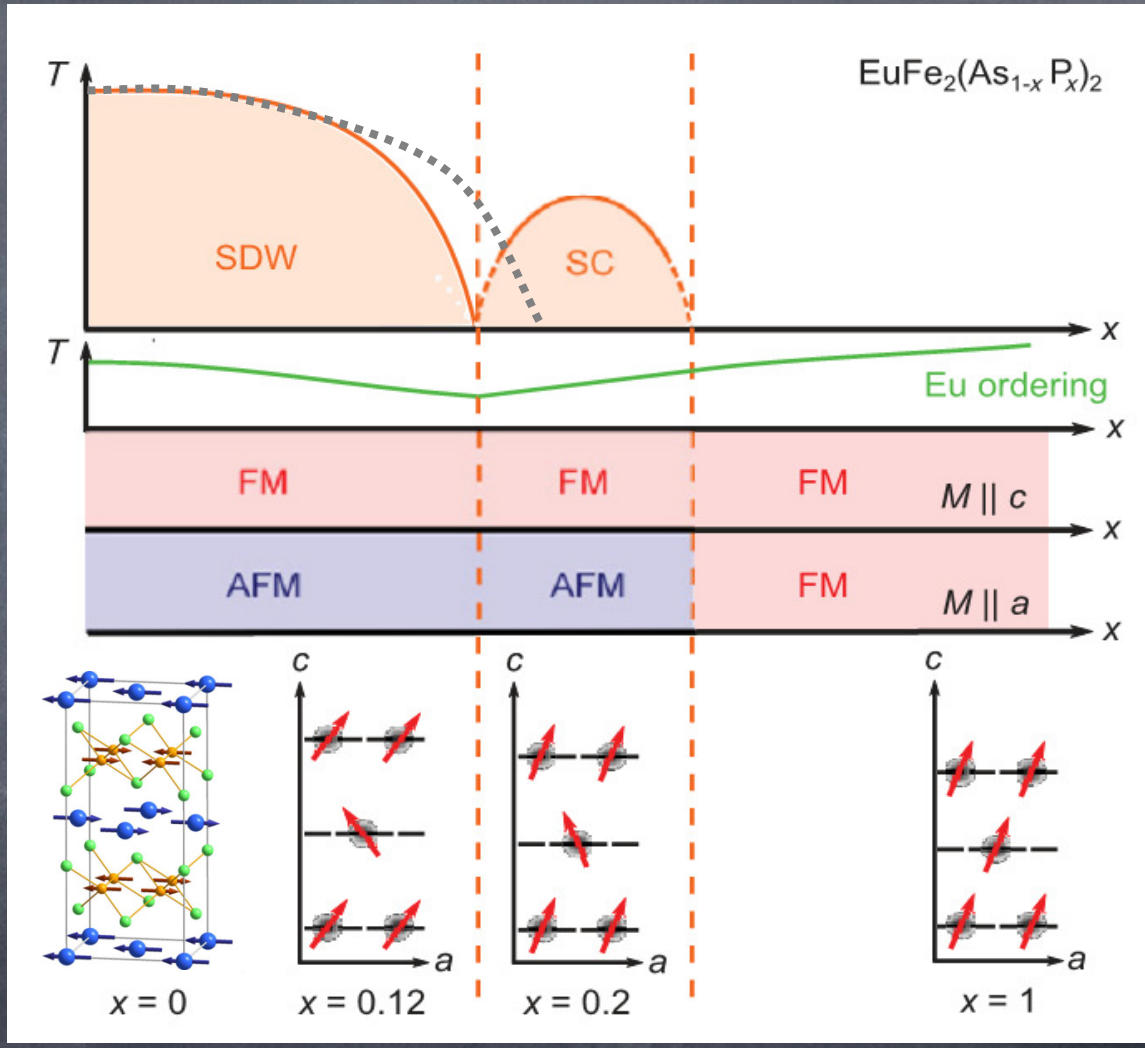


I.I. Mazin *et al.*
Physica C **469**, 614–627 (2009)

$EuFe_2(As_{1-x}P_x)_2$

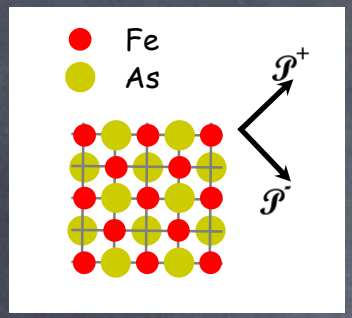


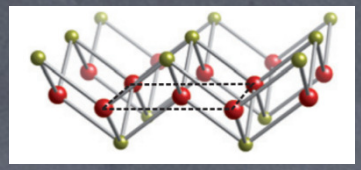
Y. Xiao et al.,
Phys. Rev. **B80**, 174424 (2009)



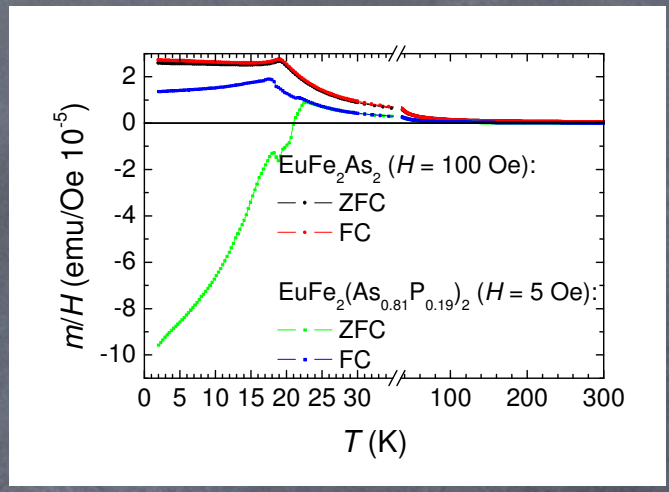
S. Zapf et al., Phys. Rev. **B84**, 140503(R) (2011)

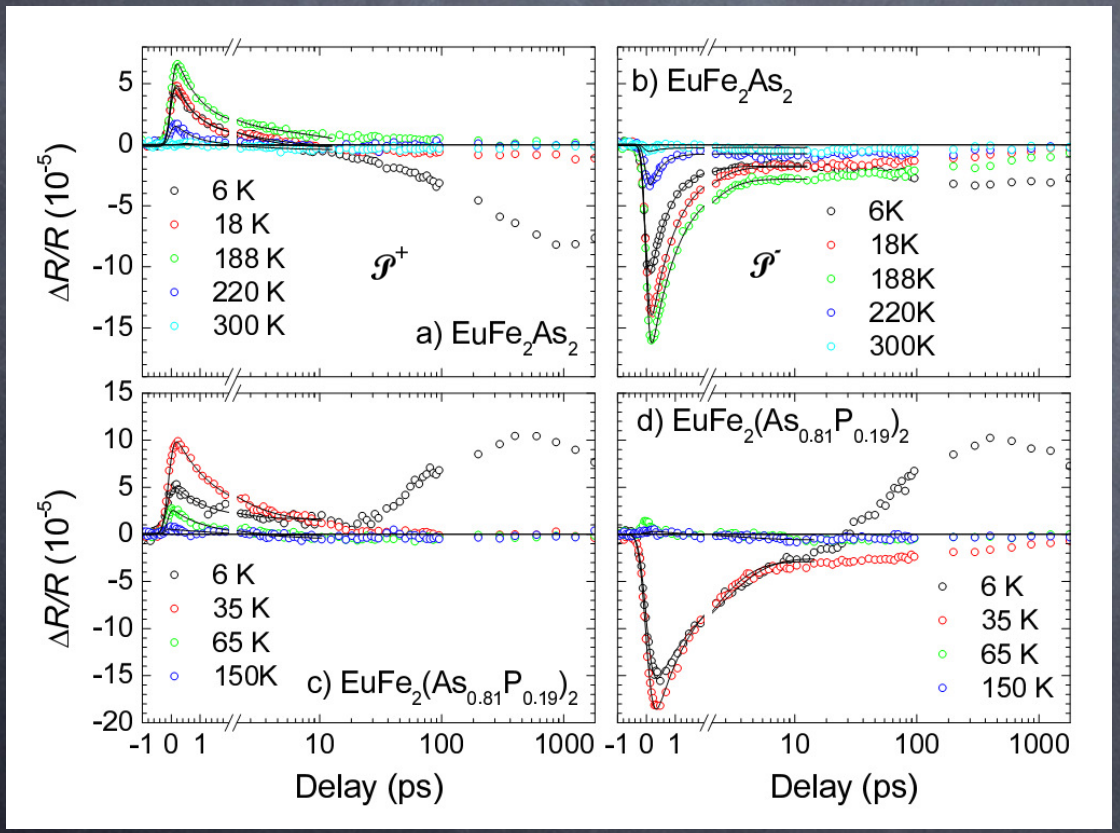
Transient reflectivity in Eu-122

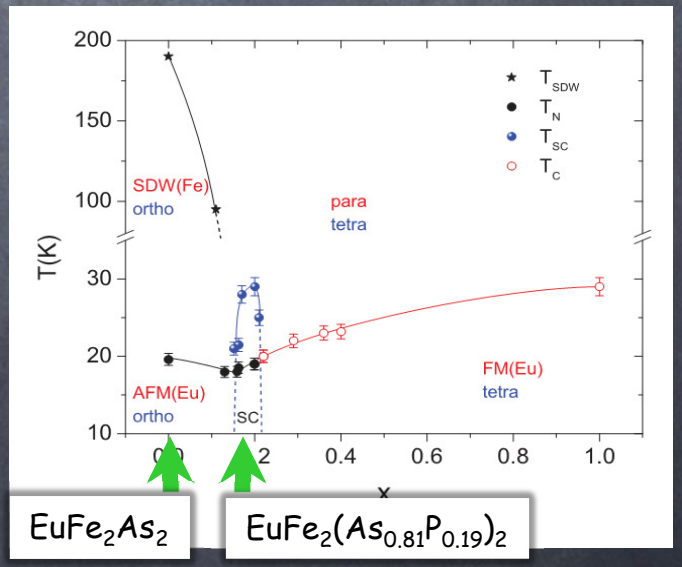




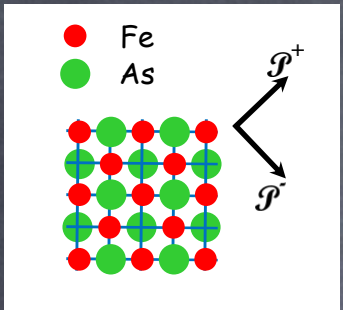
$\hbar\omega_{pump}$ = 1.55 eV
$\hbar\omega_{probe}$ = 1.55 eV



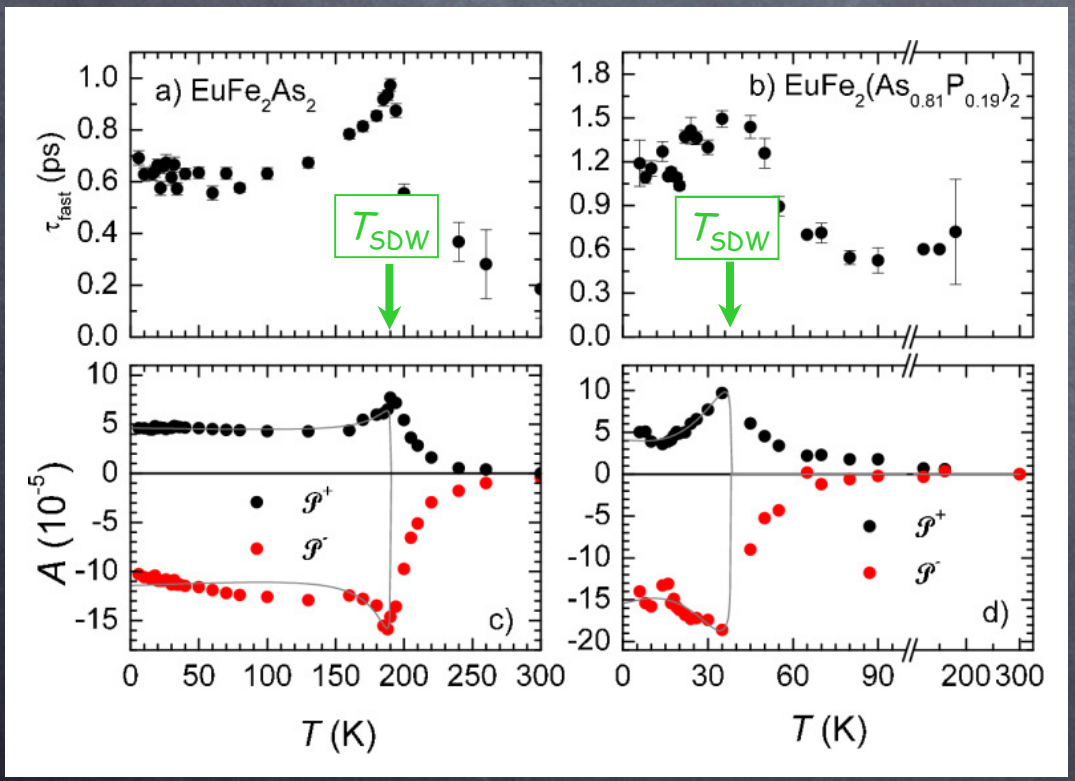


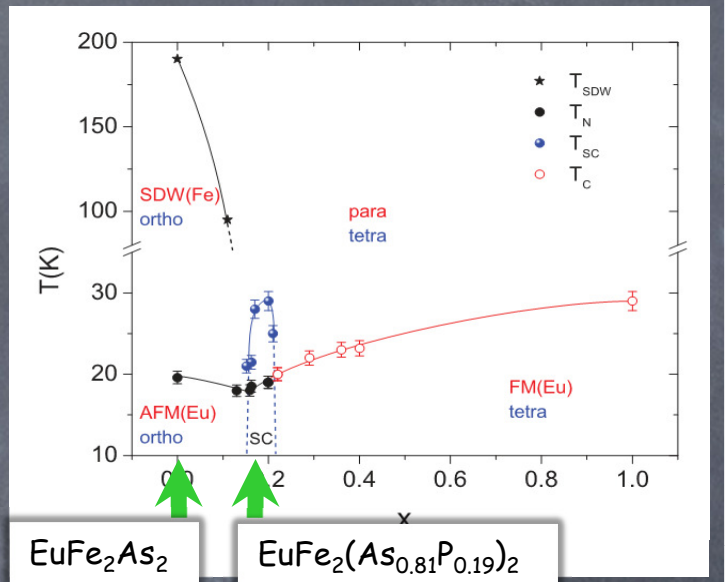


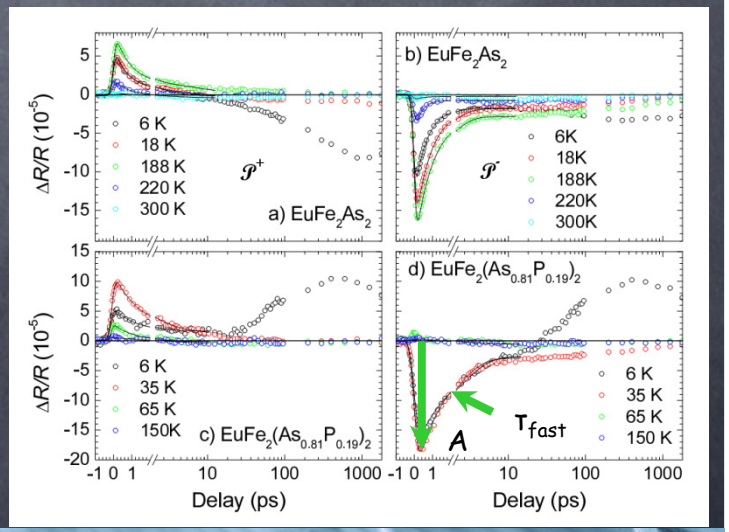
SDW related dynamic on sub-ps timescale



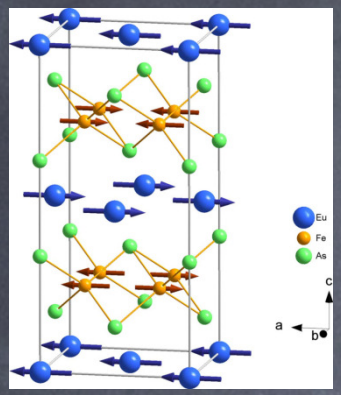
$\hbar\omega_{pump}$ = 1.55 eV
$\hbar\omega_{probe}$ = 1.55 eV

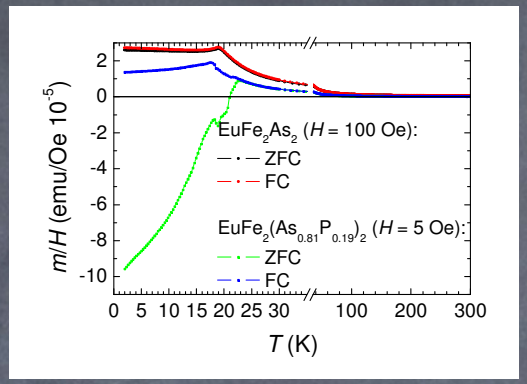


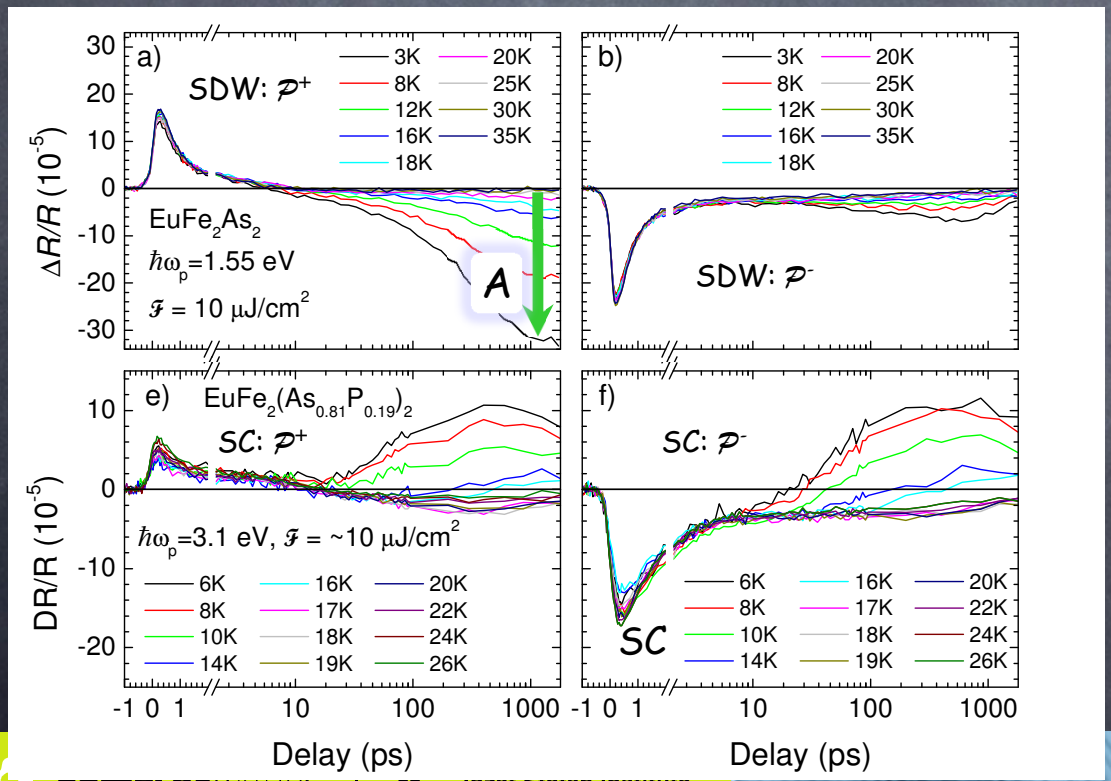


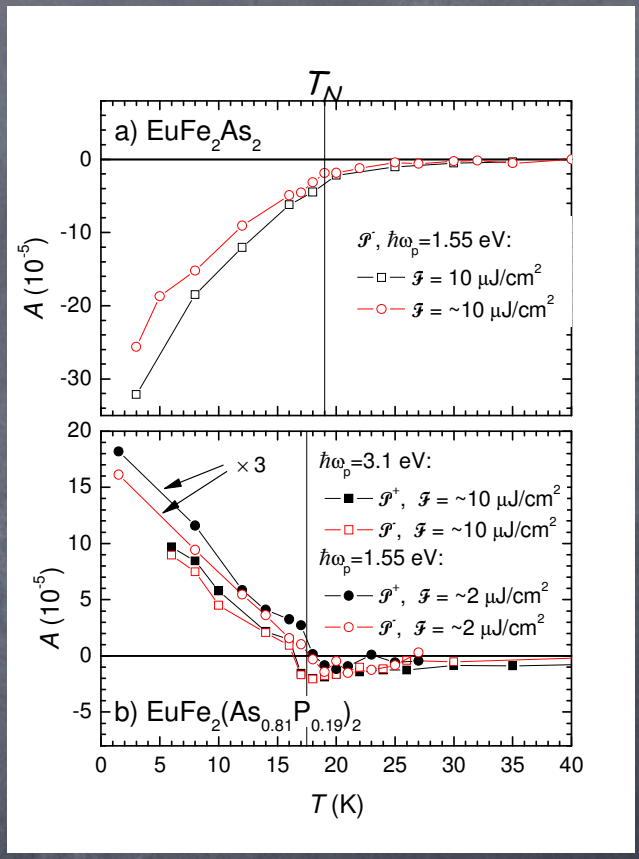


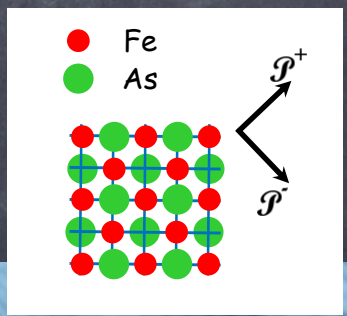
Slow dynamics due to Eu^{2+} spin ordering



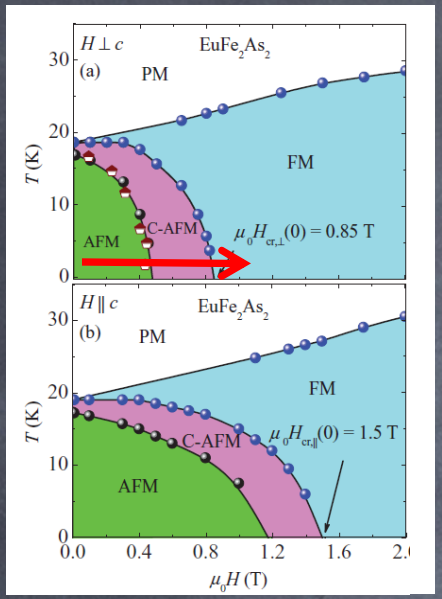




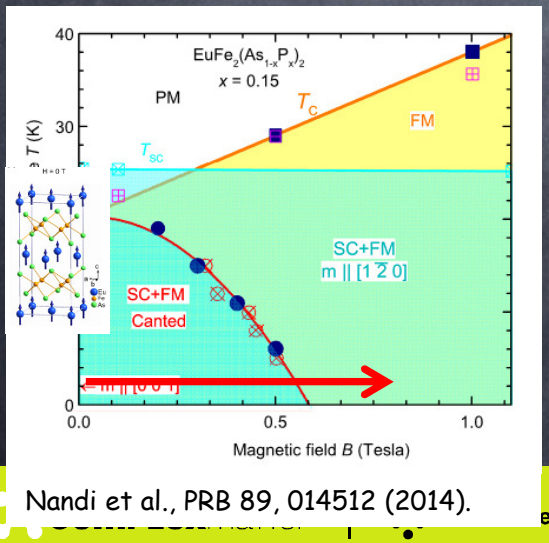




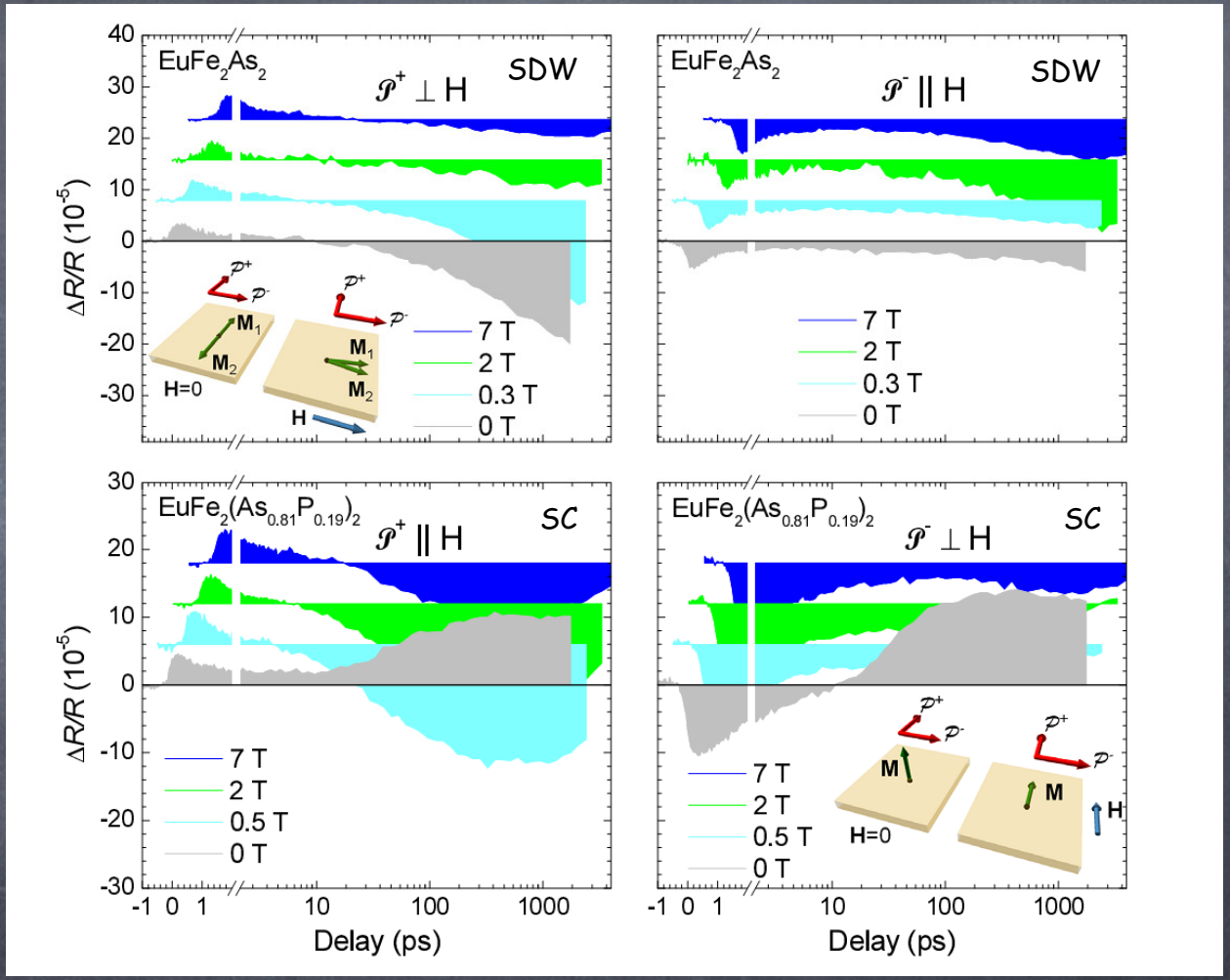
Eu^{2+} metamagnetic transitions in Eu-122



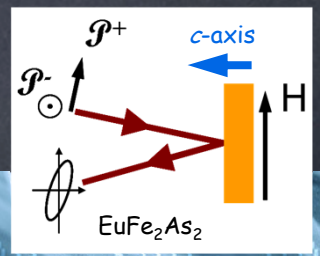
Z. Guguchia et al.,
Phys. Rev. B 84, 144506 (2011)



Nandi et al., PRB 89, 014512 (2014).

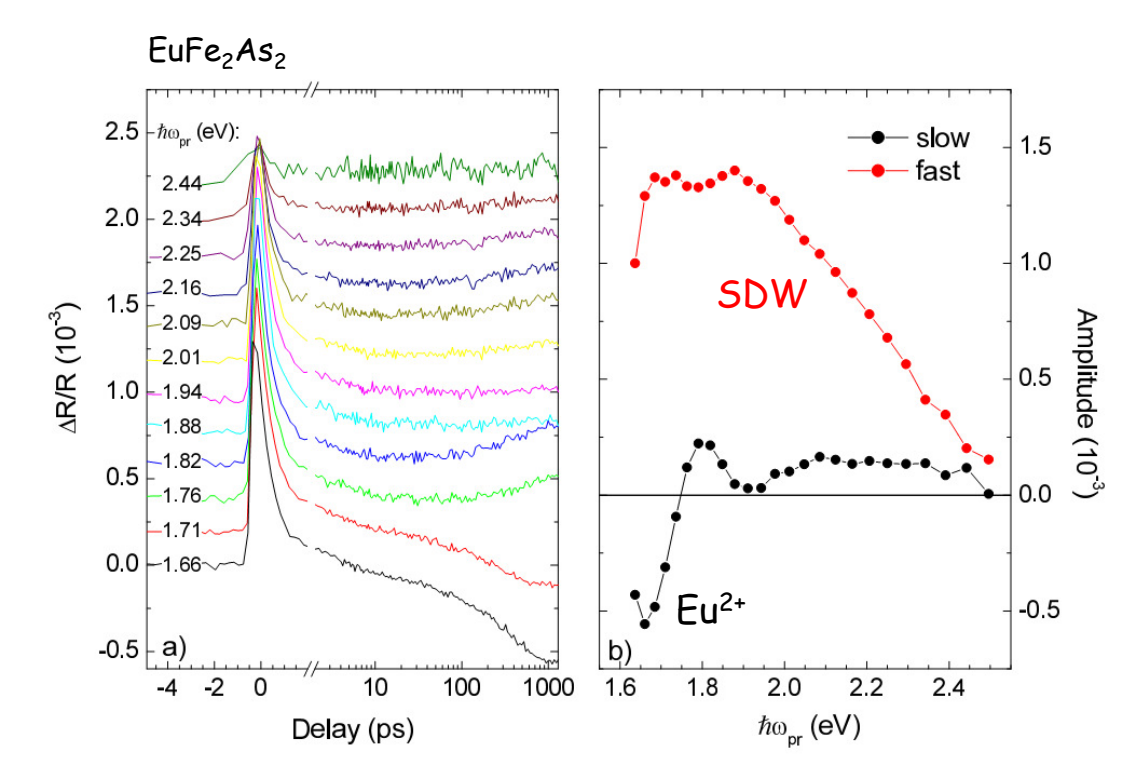


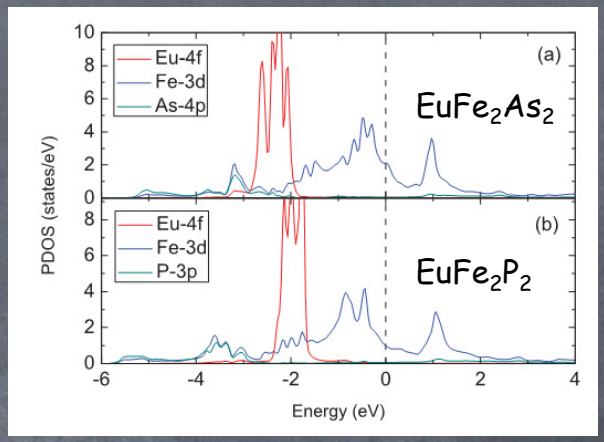
Pogrebna *et al.*, Sci. Rep. **5**, 7754 (2015)



Mechanism of the Eu^{2+} magnetooptical coupling

Eu^{2+}: $[Xe]4f^7 6s^2$ ($^8S_{7/2}$)

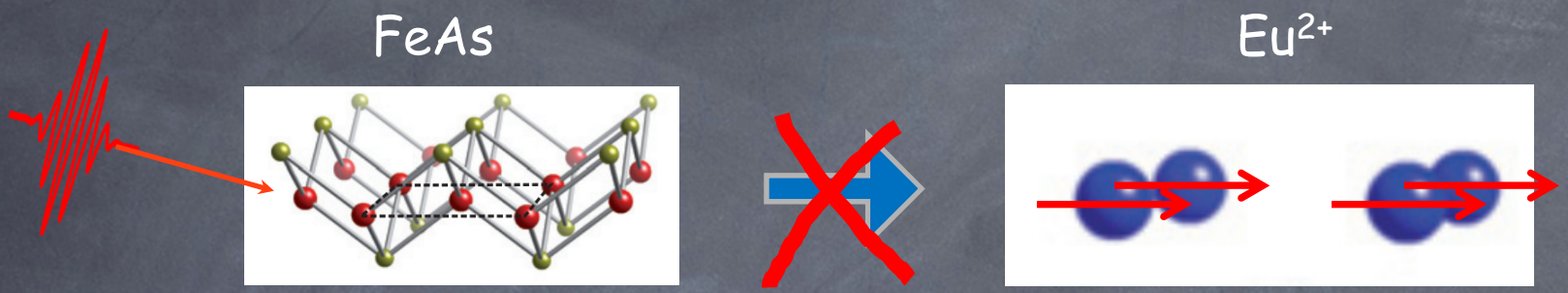


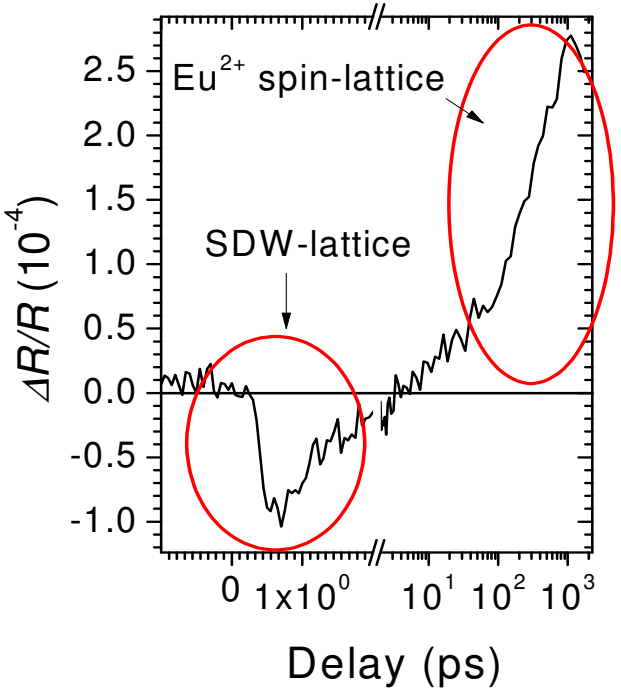


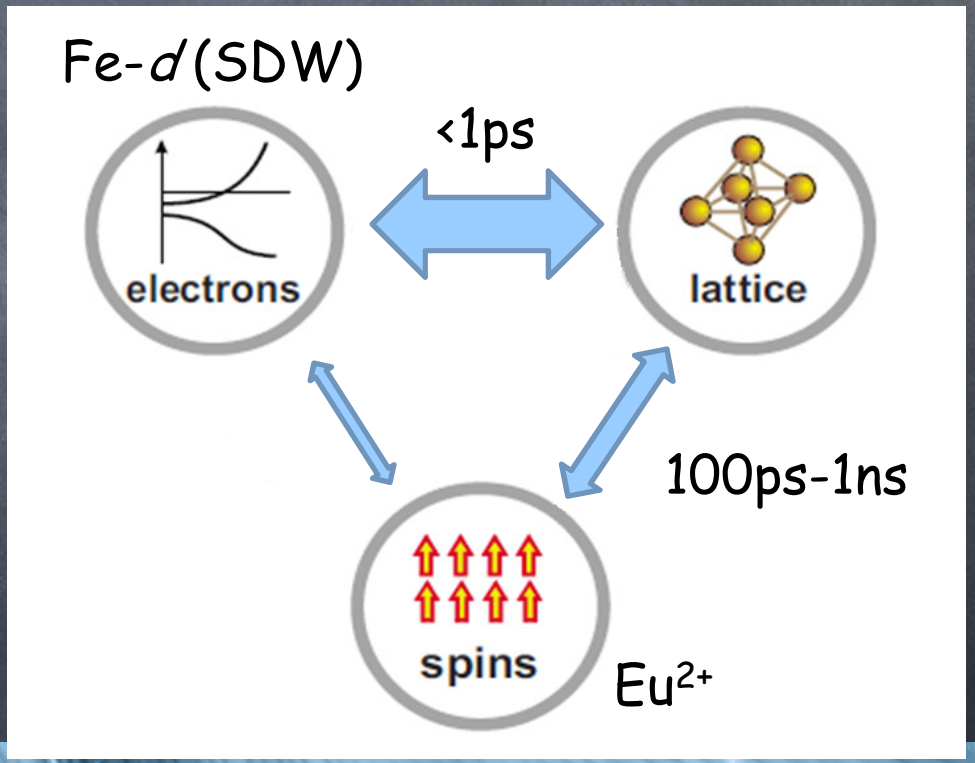
Li et al., PRB **86**, 155119 (2012).

Resonant Cotton-Mouton effect at $\hbar\omega_{probe}$ = 1.55 eV.

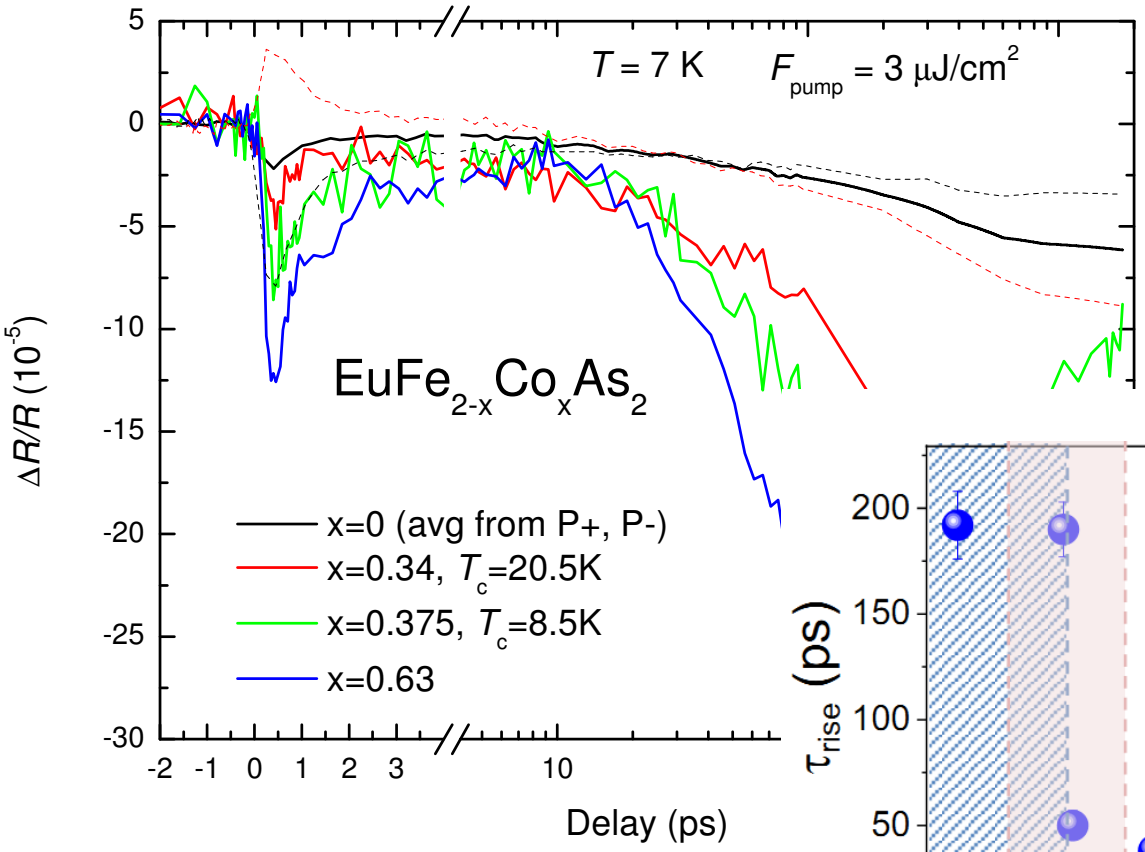
Slow photoexcited energy transfer to Eu^{2+} spins

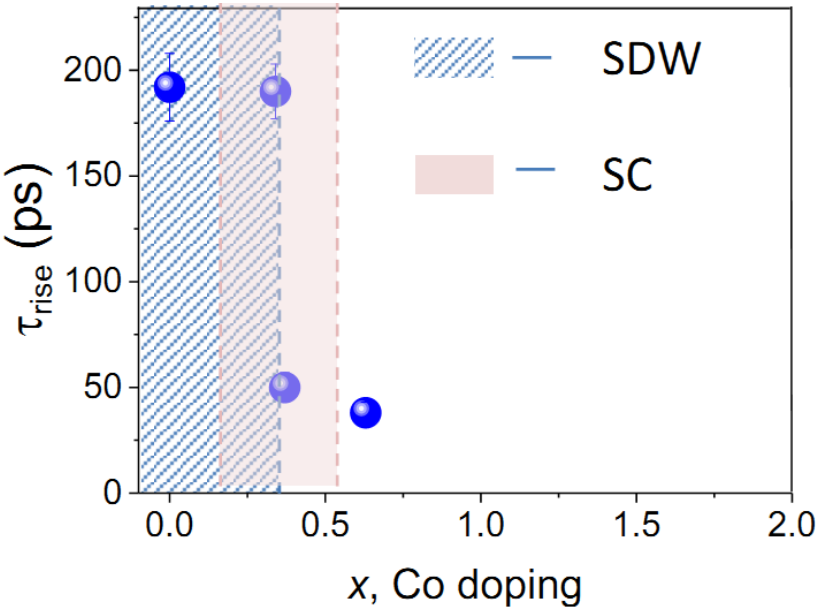




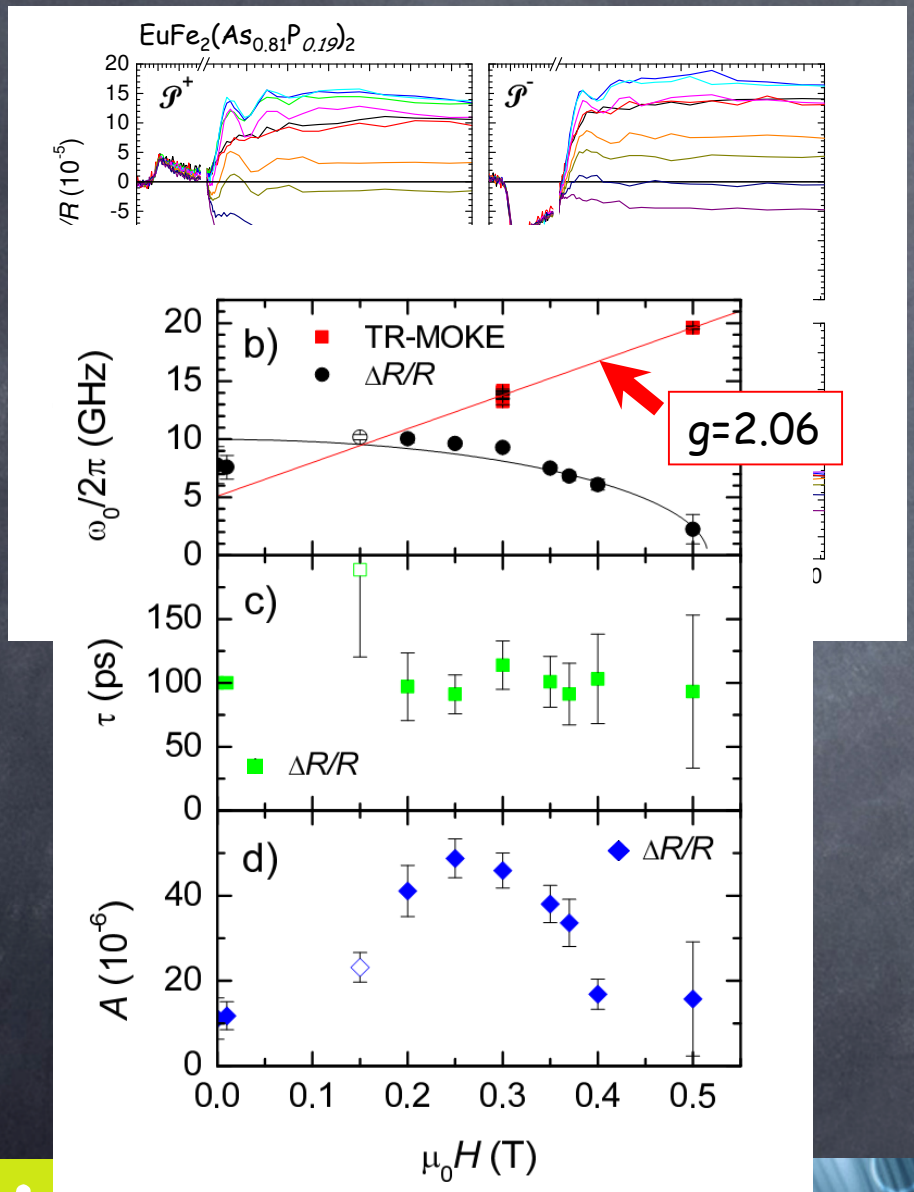


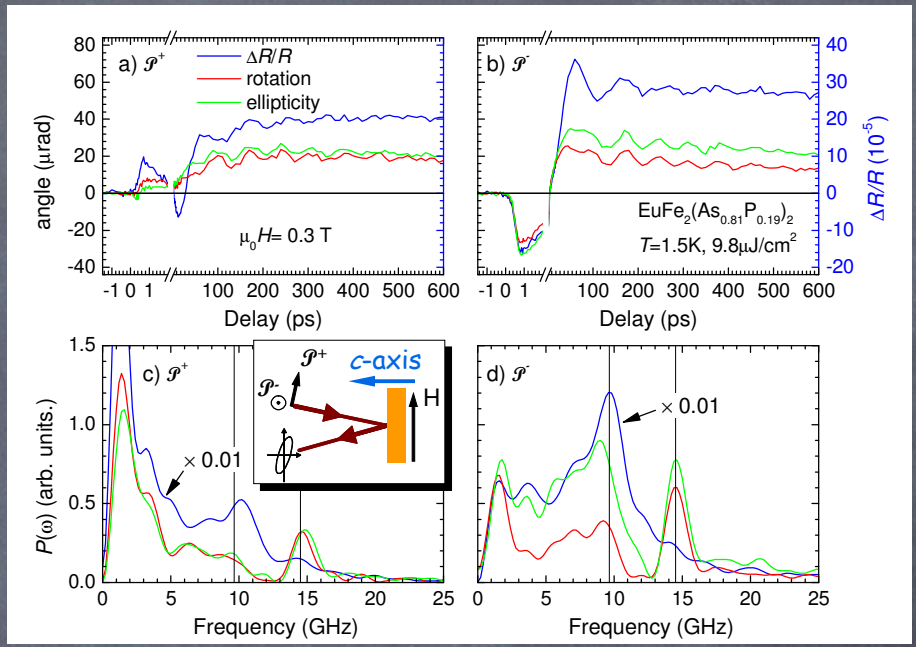
Co doped Eu-122





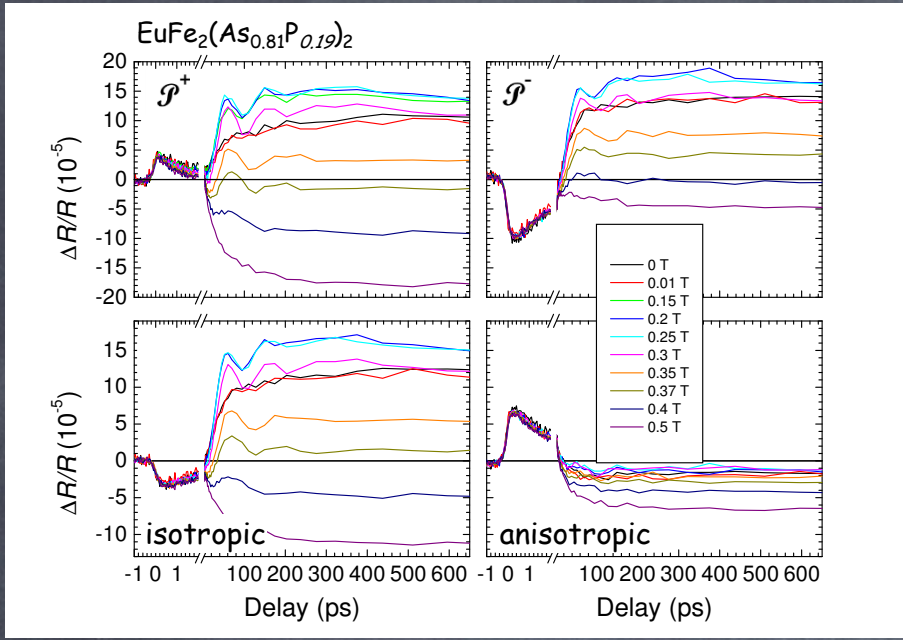
Coherent Eu^{2+} spin waves in superconducting Eu-122

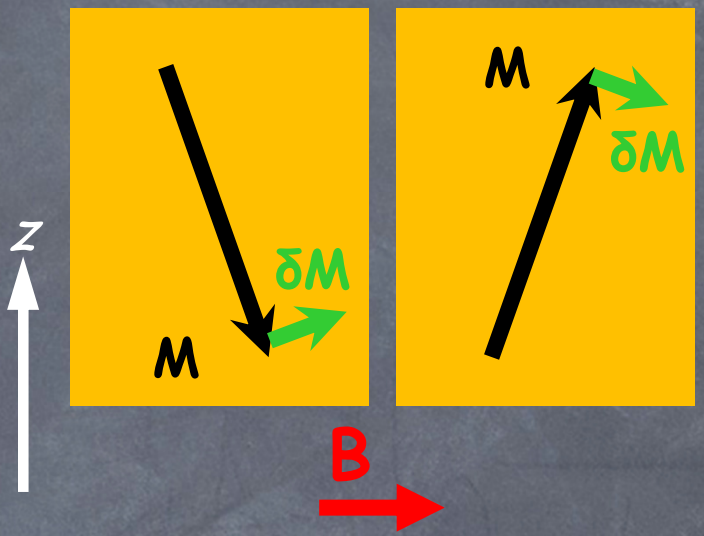




- Two spin-wave modes observed.
- Low freq. mode in-plane ~isotropic.
- High freq. mode out of plane.

Transient reflectivity response due to δM_z





$\delta M_{z,down} = -\delta M_{z,up}$

$M_{z,down}\delta M_{z,down} = M_{z,up}\delta M_{z,up}$

$$\delta\epsilon_{ii} = 2a_{iizz}M_z\delta M_z + 2a_{iixx}M_x\delta M_x + 2a_{iiyy}M_y\delta M_y$$

in-plane isotropic

$a_{xxzz} \sim a_{yyzz}$

(pseudotetragonal)

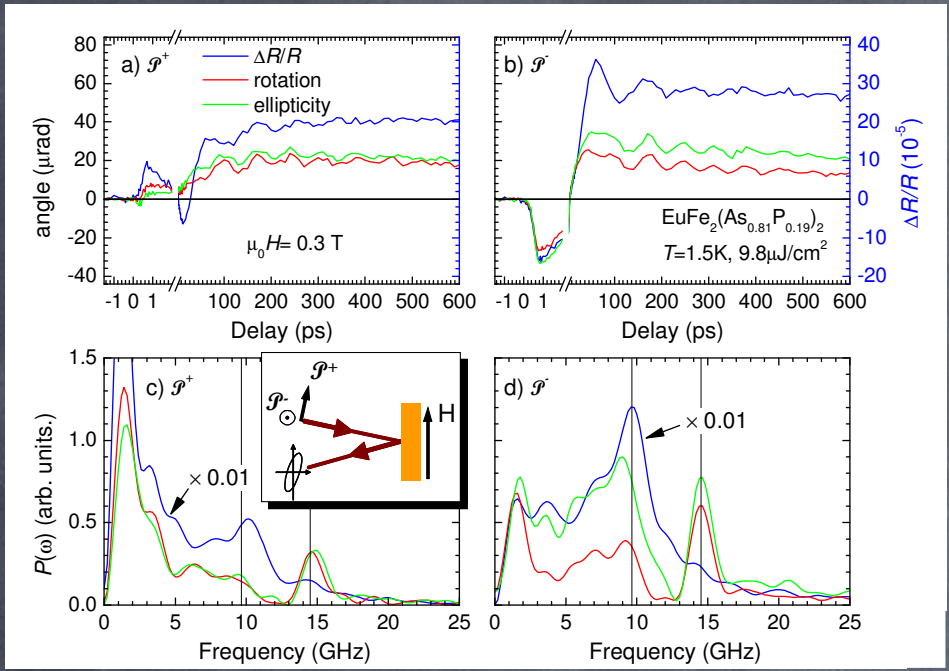
in-plane anisotropic

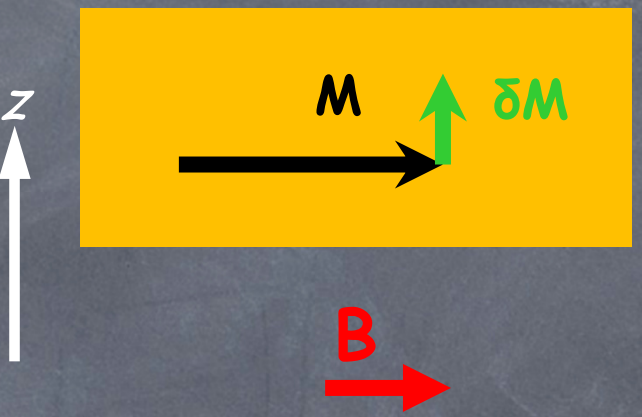
$M_x > M_y \sim 0$

$\Delta R/R \propto M_{z,down}\delta M_{z,down} + M_{z,up}\delta M_{z,up} > 0$

$\Delta\Phi_{Kerr} \propto \delta M_{z,down} + \delta M_{z,up} \approx 0$

TR-MOKE response also due to δM_z





$\Delta R/R \propto M_z \delta M_z \approx 0$

$\Phi_{Kerr} \propto \delta M_z > 0$

$$\delta\epsilon_{ii} = 2a_{iizz} M_z \delta M_z + 2a_{iixx} M_x \delta M_x + 2a_{iiyy} M_y \delta M_y$$

in-plane isotropic

$a_{xxzz} \sim a_{yyzz}$

(pseudotetragonal)

in-plane anisotropic

$M_x > M_y \sim 0$

Optical polarization analysis suggests the presence of two types of FM domains:

- c-axis (up,down)
- in-plane.

CAFM or helimagnetic orderings not supported.

Eu^{2+}-spin related dynamics

- Slow transients due to Eu^{2+} (sublattices) demagnetization.
- Eu^{2+} 4*f* levels ~1.7 eV from the Fermi level.
- Weak coupling of Eu^{2+} spins to Fe-*d* itinerant carriers.
- Coupling increases with P and Co doping, but remains rather weak.
- Two types of domains in superconducting $EuFe_2(As_{1-x}P_x)_2$.