Spectrally-resolved femtosecond reflectivity relaxation dynamics in undoped SDW 122-structure iron based pnictides

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A description of this work can be found in:
PRB **81**, 224504 (2010); PRB **82**, 012505 (2010); PRB **86**, 024519 (2012); PRB **89**, 165131 (2014)

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)

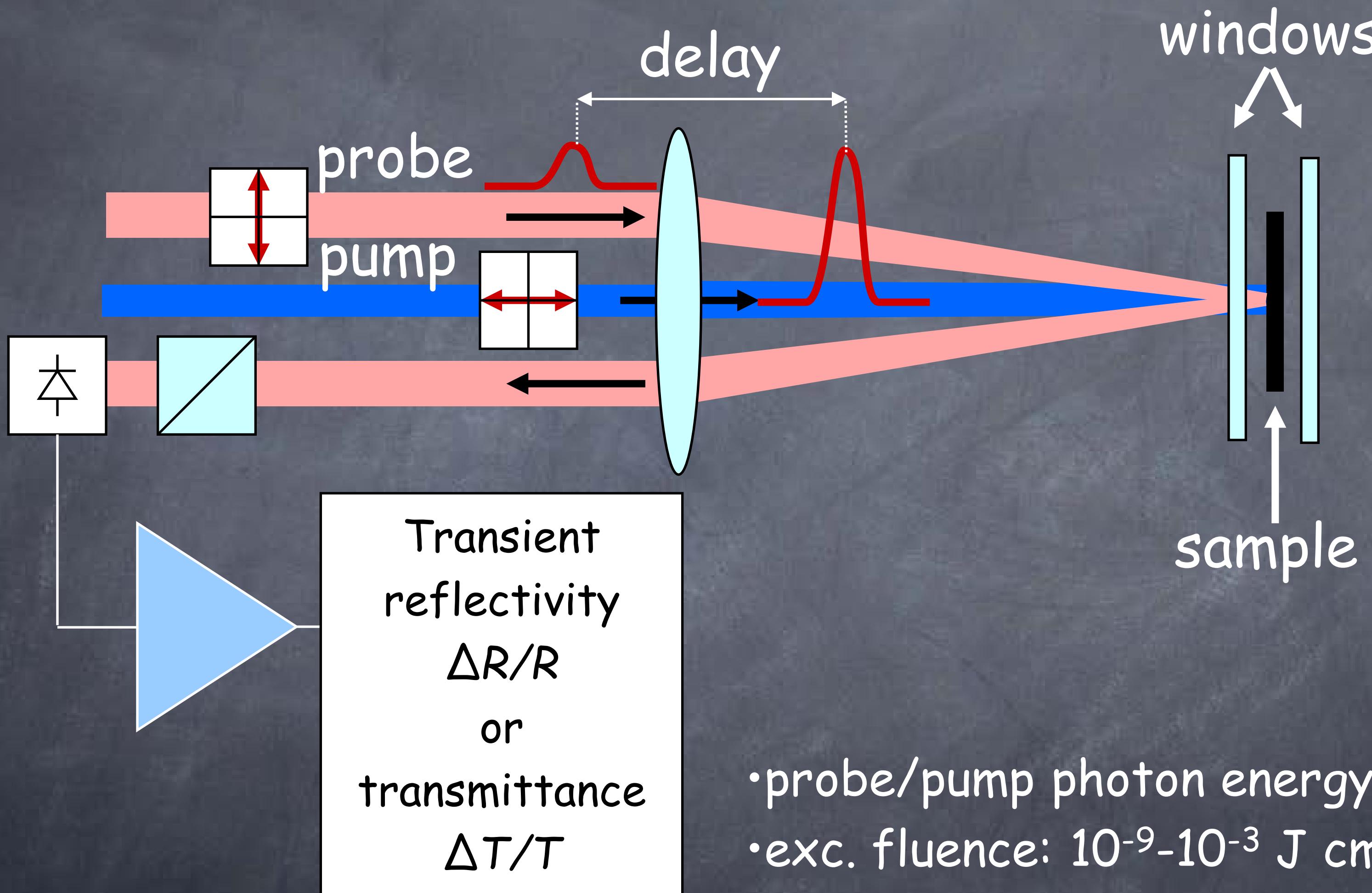
1111:

J. Karpinski, N.D. Zhigadlo,
Z. Bukowski, S. Katrych, Laboratory for Solid State Physics, ETH Zürich, Switzerland and LPMC, EPFL, Lausanne, Switzerland

Outline

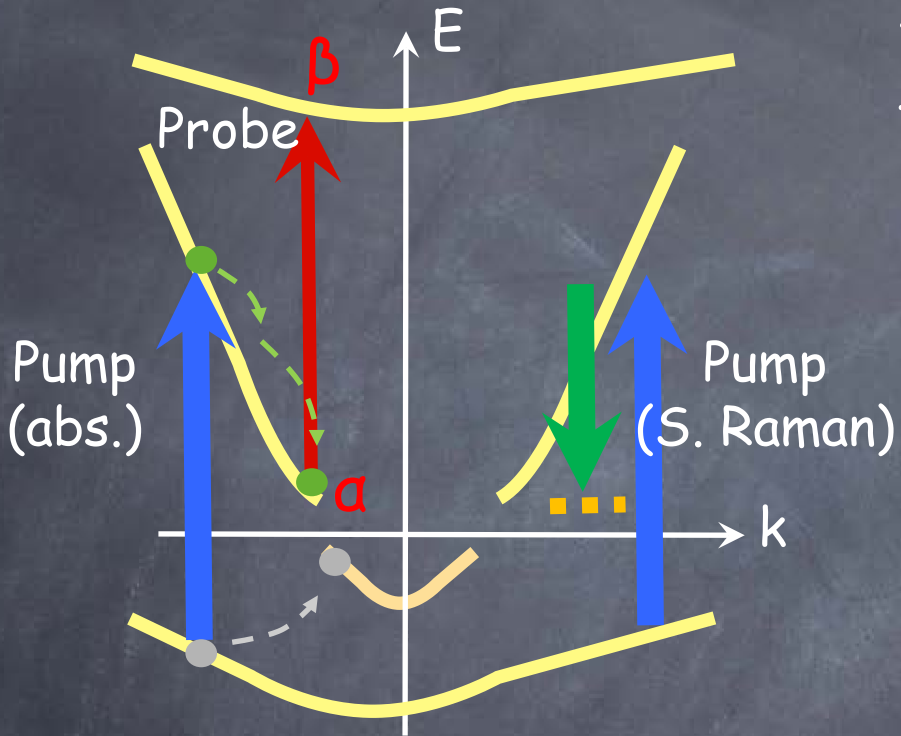
- Introduction to all-optical transient spectroscopy
- Quasiparticle relaxation bottleneck in systems with small gap: the Rothwarf-Taylor bottleneck
- Dynamics of the CDW state. Is there a Rothwarf-Taylor bottleneck at all?
- Dynamics of the SDW state in iron based pnictides
- Ultrafast SDW state destruction and recovery
- Conclusions

Time resolved optical spectroscopy setup

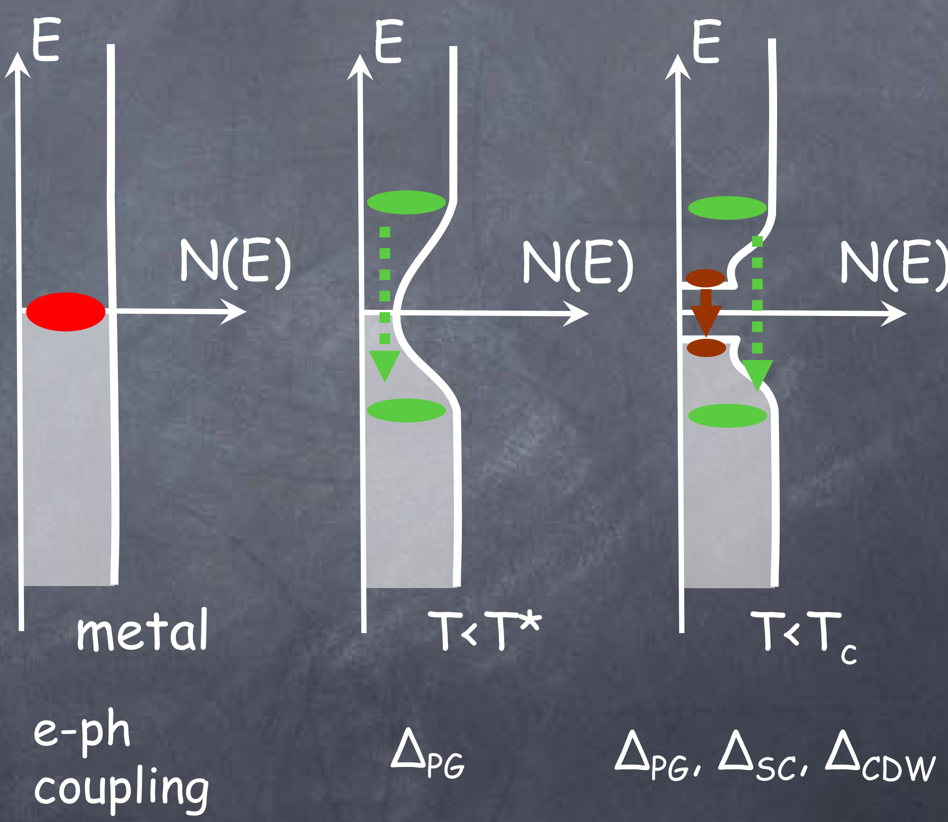


- probe/pump photon energy: IR - UV
- exc. fluence: 10^{-9}-10^{-3} J cm^2/pulse
- pulselengths ~50 fs

Transient reflectivity (transmittance)



The transient reflectivity probes the photoexcited QP density.



The rigid band approximation:

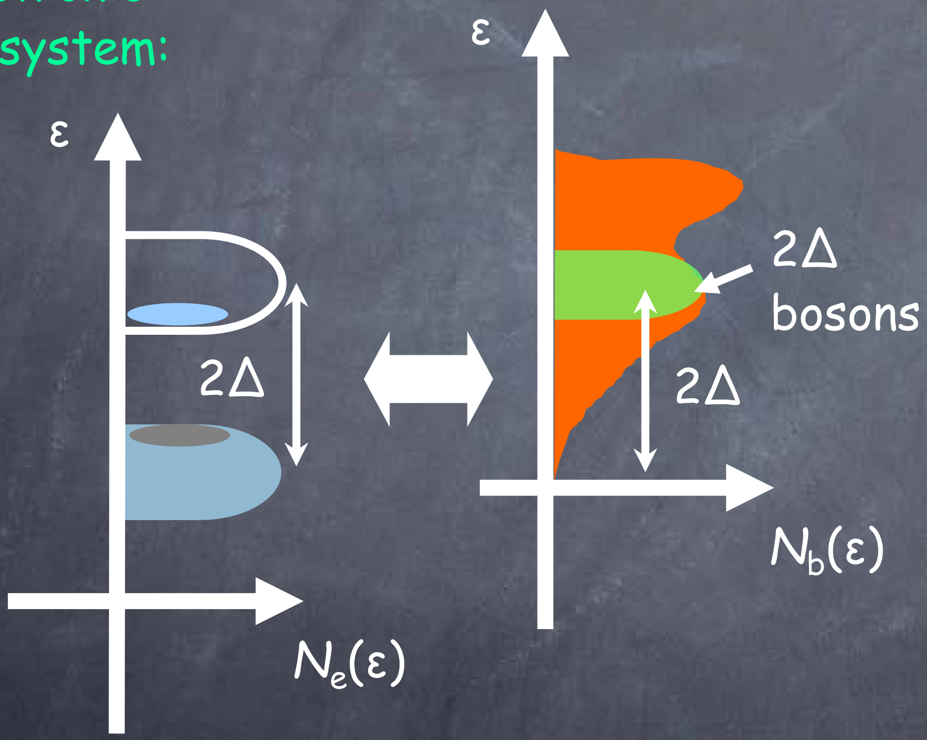
$$\Delta R_{\alpha,\beta} \propto \int \mathrm{d}^3k[|M_{\alpha,\beta}(\mathbf{k})|^2 \Delta f_{\alpha}(\mathbf{k}) \times g(\epsilon_{\beta}(\mathbf{k}) - \epsilon_{\alpha}(\mathbf{k}) - \hbar\omega_{\mathrm{probe}})].$$

Bottleneck in systems with small gap

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

electronic subsystem:

bosonic subsystem:



Energy conservation:

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

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

BCS T-dependent gap:

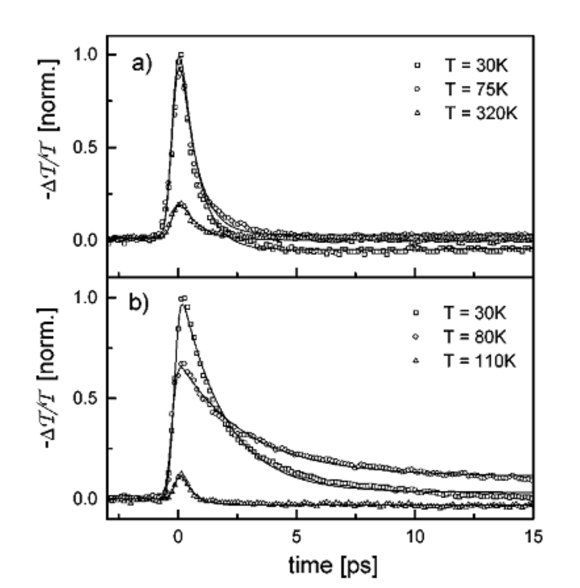
$$n_{pe} = \frac{\mathcal{E}_I/(\Delta(T) + k_B T/2)}{1 + \dfrac{2\nu}{N(0)\hbar\Omega_c}\sqrt{\dfrac{2k_BT}{\pi\Delta(T)}}\exp[-\Delta(T)/k_BT]}.$$

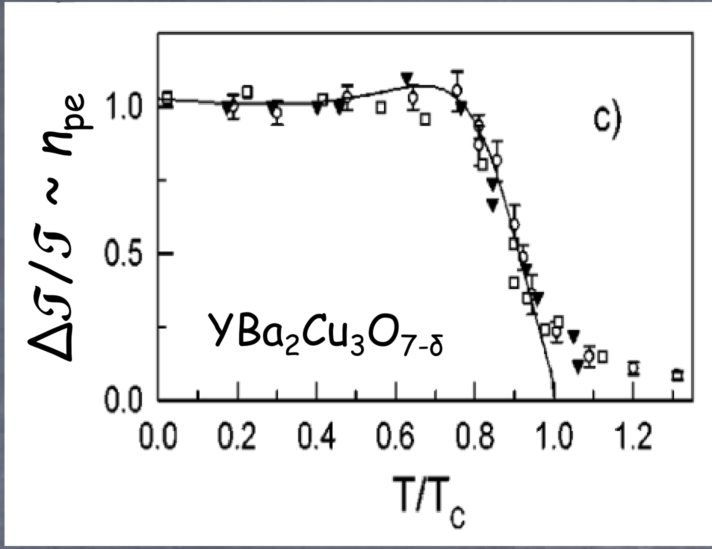
V.V. Kabanov et al., PRB 59, 1497 (1999)

$N(0)\hbar\Omega_c$ no. of involved electronic degrees of freedom

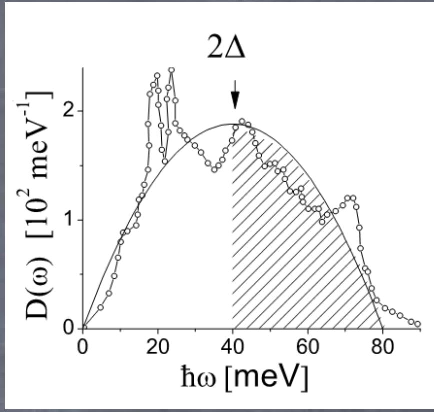
ν no. of involved boson degrees of freedom

Bottleneck in superconductors





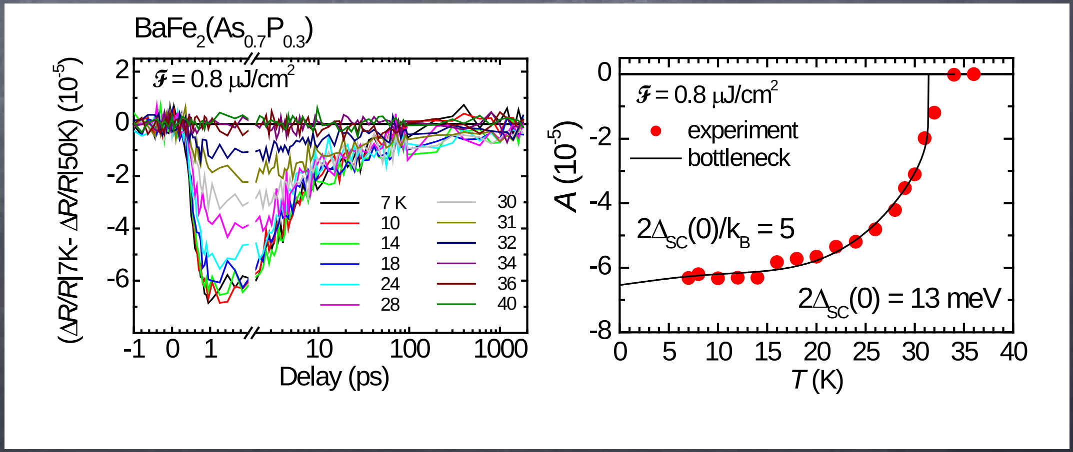
V.V. Kabanov et al., PRB 59, 1497 (1999)



B. Renker et al.,
Physica B **165-166**, 1237 (1990)

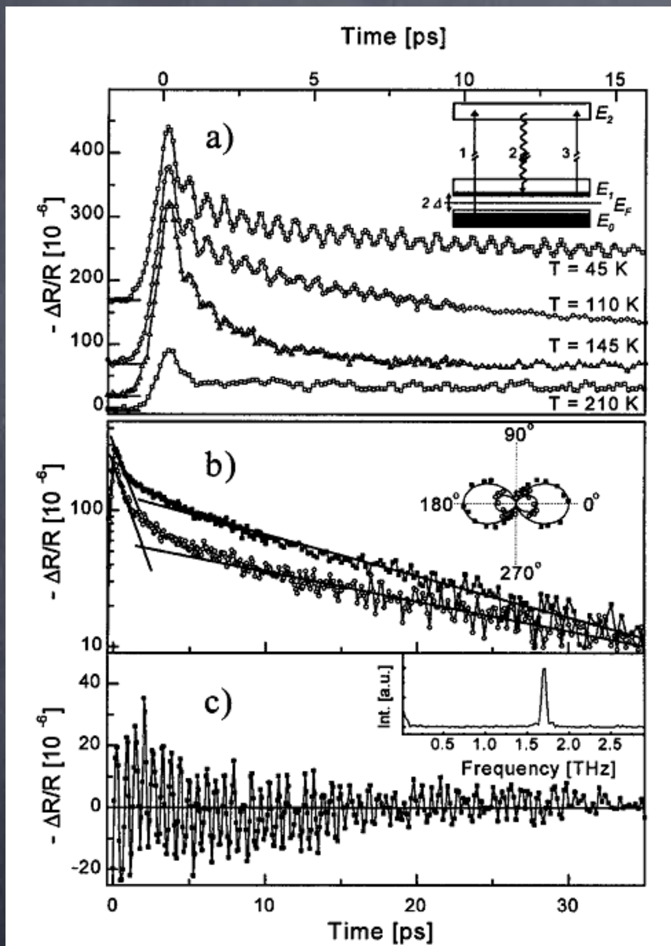
$$\Delta R_{\alpha,\beta} \propto \int d^3k[|M_{\alpha,\beta}(\mathbf{k})|^2 \Delta f_\alpha(\mathbf{k}) \times g(\epsilon_\beta(\mathbf{k}) - \epsilon_\alpha(\mathbf{k}) - \hbar\omega_{\mathrm{probe}})].$$

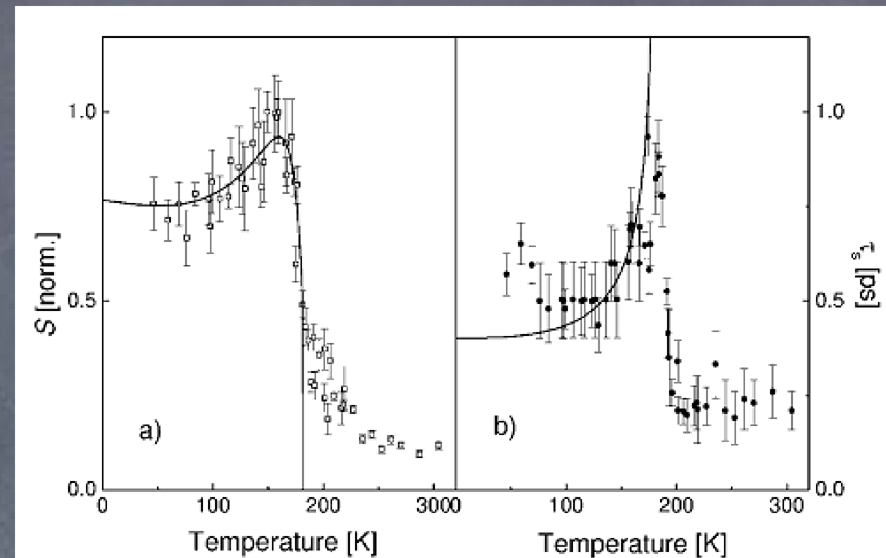
$$n_{pe} = \frac{\mathcal{E}_I/(\mathbf{\Delta}(T) + k_B T/2)}{1 + \frac{2\nu}{N(0)\hbar\Omega_c}\sqrt{\frac{2k_B T}{\pi\mathbf{\Delta}(T)}}\exp[-\mathbf{\Delta}(T)/k_B T]}.$$



Application of the bottleneck model to a CDW

$K_{0.3}MoO_3$





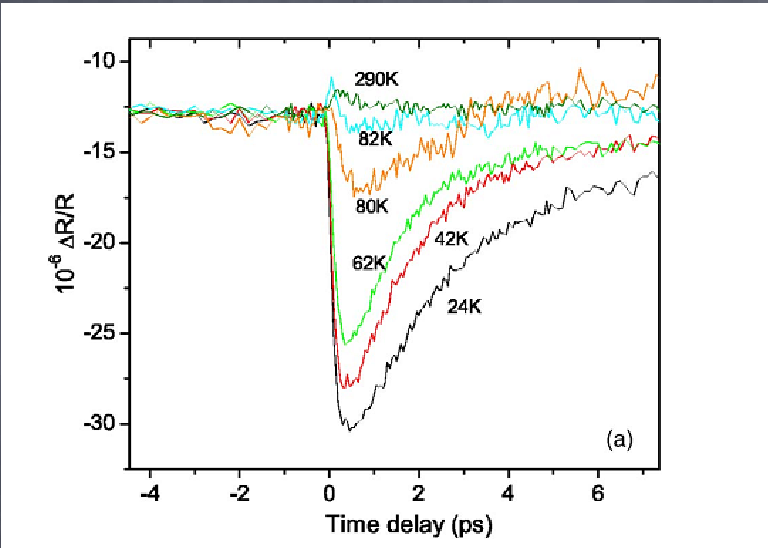
$$n_{pe} = \frac{\mathcal{E}_I / (\mathbf{\Delta}(T) + k_B T/2)}{1 + \dfrac{2\nu}{N(0)\hbar\Omega_c}\sqrt{\dfrac{2k_BT}{\pi\mathbf{\Delta}(T)}}\exp[-\mathbf{\Delta}(T)/k_BT]}.$$

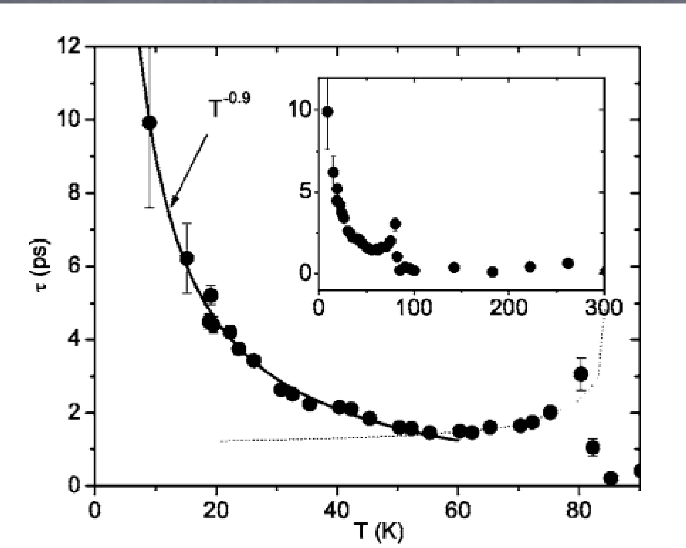
2Δ(0) ~ 150 meV > max. phonon energy

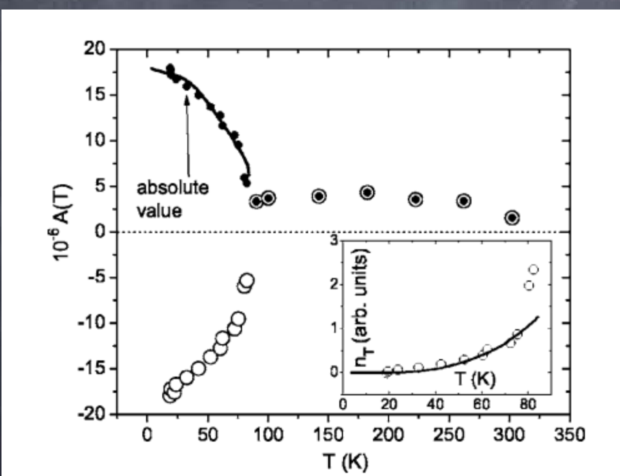
J. Demsar et al., PRL **83**, 800 (1999)

Application of the bottleneck model to a SDW

$UNiGa_5$ $T_N = 85$ K





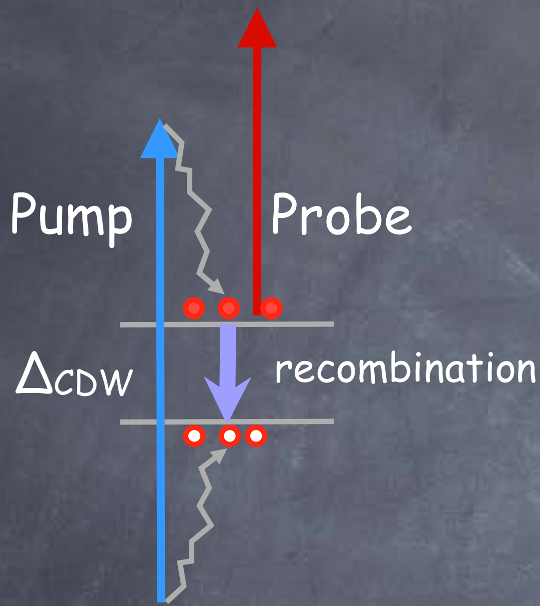


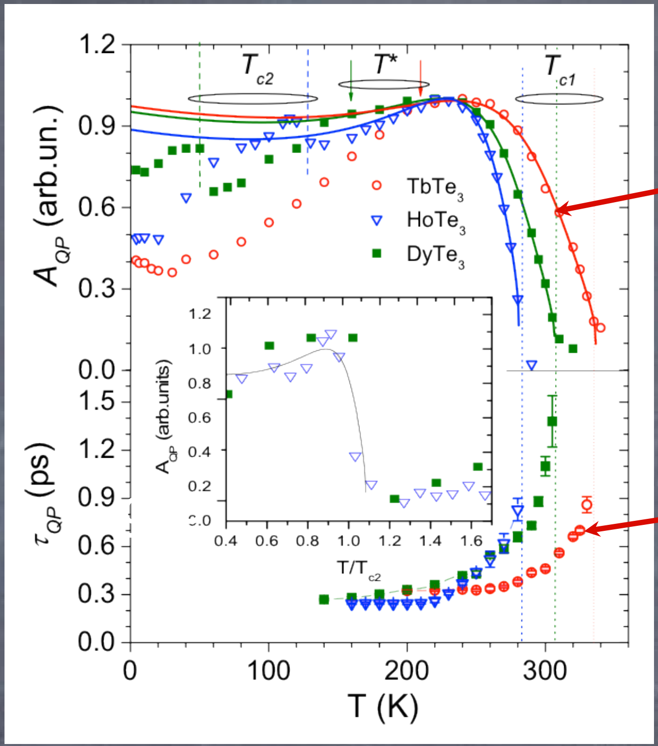
$$|A(T)| \propto \frac{\epsilon_I/[\Delta(T) + k_B T/2]}{1 + B\sqrt{\frac{2k_B T}{\pi\Delta(T)}}\exp\left(\frac{-\Delta(T)}{k_B T}\right)}$$

$$\Delta_0 = 1.7 k_B T_N$$

E. E. M. Chia et al., PRB **74**, 140409 (2006)

Bottleneck model in CDW state of tri-tellurides

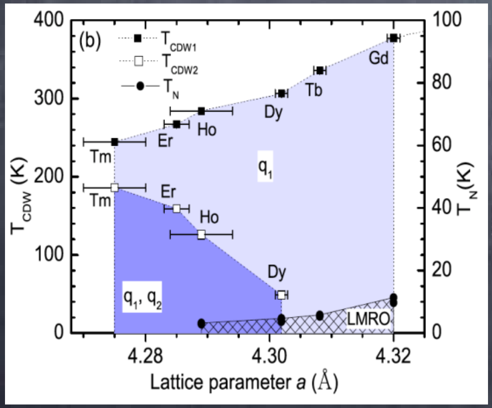




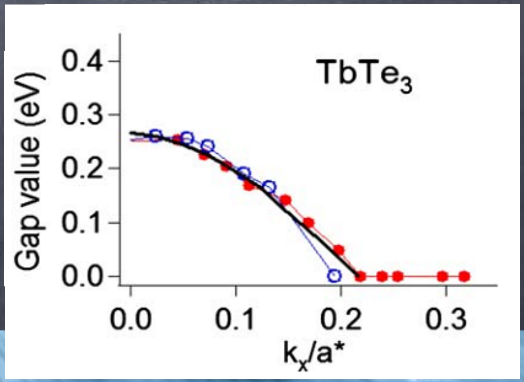
Yusupov et al., PRL 2008

The reflectivity amplitude (BCS-like T-dependence of the CDW gap)

The relaxation rate $1/\tau \propto \Delta(T)$

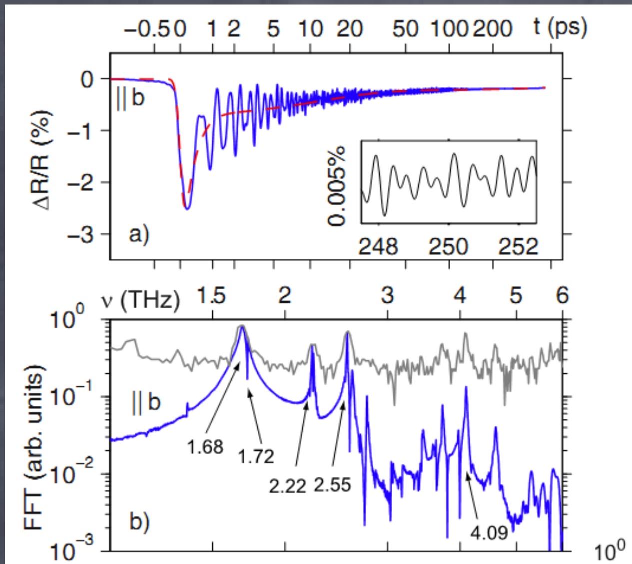


$TbTe_3$:
$\Delta(0) \sim 125$ meV



V. Brouet et al., Phys. Rev. B 77 , 235104 (2008)

Quasiparticle vs collective mode dynamics in CDW?

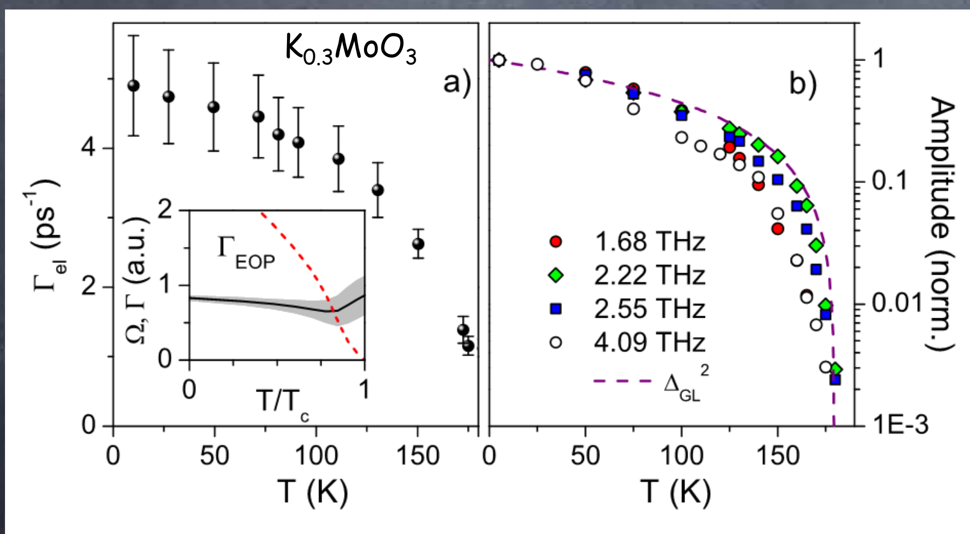


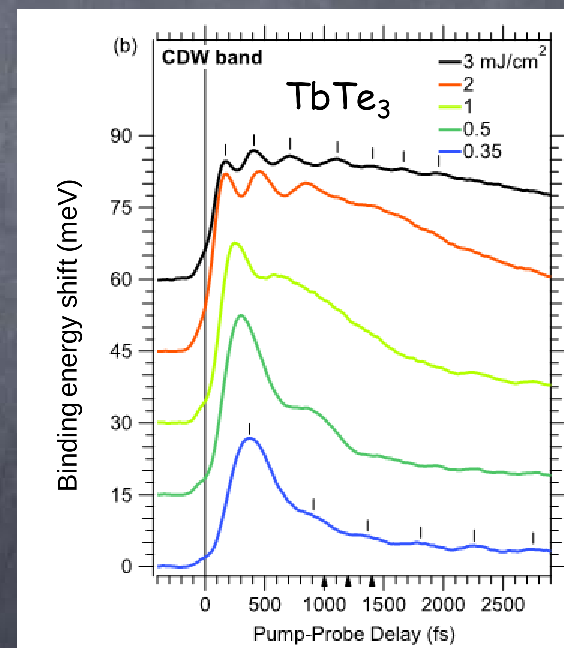
Overdamped electronic order parameter: $x = \psi(t) - \psi_{eq}$

$$\dot{x}_1 = -2\kappa\alpha\left(T_c - T + \frac{m^2}{2\alpha\Omega_0^2}\right)x_1 - \kappa m y_1$$

$$\ddot{y}_1 = -\Omega_0^2 y_1 - m x_1,$$

Phonon(s)





Schaefer et al., PRL **105**, 066402 (2010)

F. Schmitt et al., New Journal of Physics **13**, 063022 (2011)

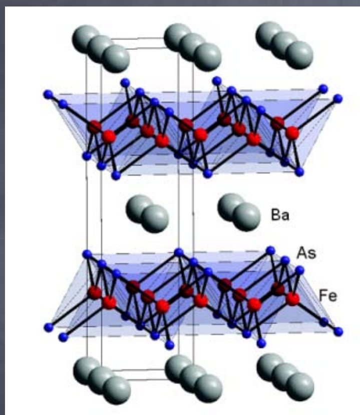
Fe based pnictides

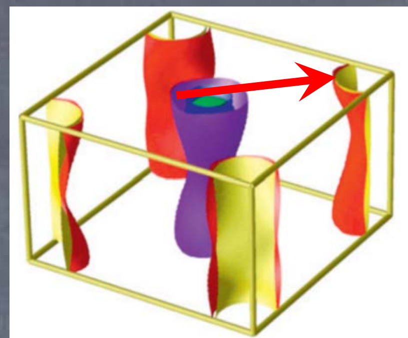
Ba-122:

- $Ba(Fe,Co)_2As_2$, $T_{c,max} \approx 24K$

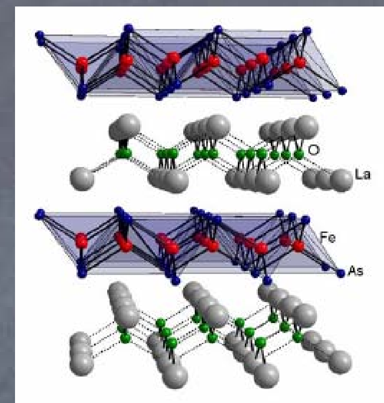
Sm-1111:

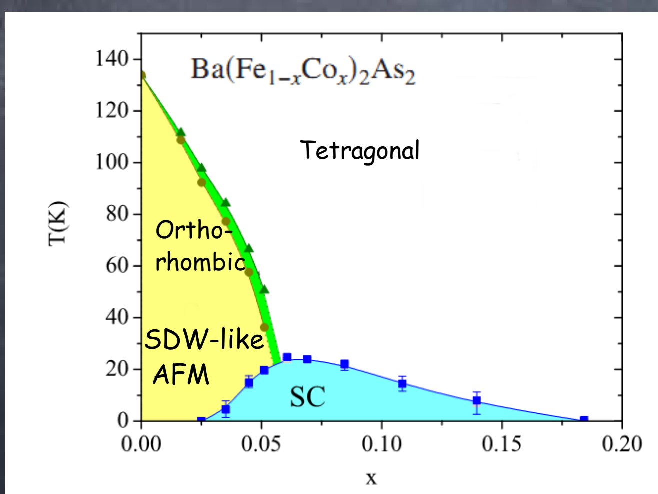
- $SmFeAs(O,F)$, $T_{c,max} \approx 55K$
- $Sm(Fe,Co)AsO$, $T_{c,max} \approx 17K$



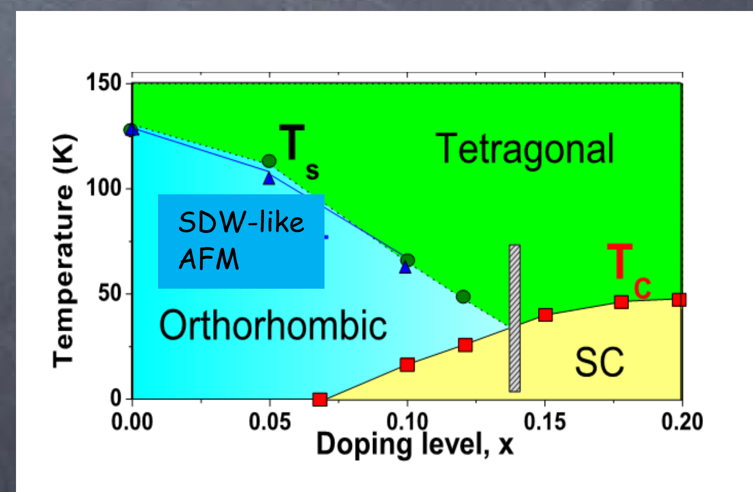


I.I. Mazin *et al.*
Physica C **469**, 614-627 (2009)





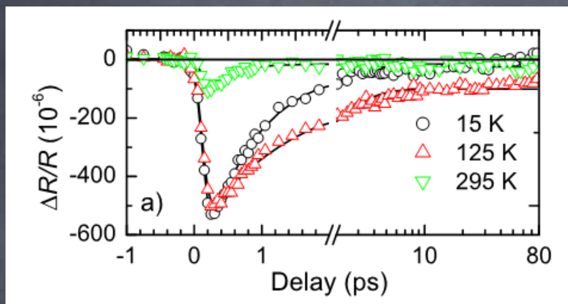
J.-H. Chu *et al.*, Phys. Rev. B 79, 014506 (2009)

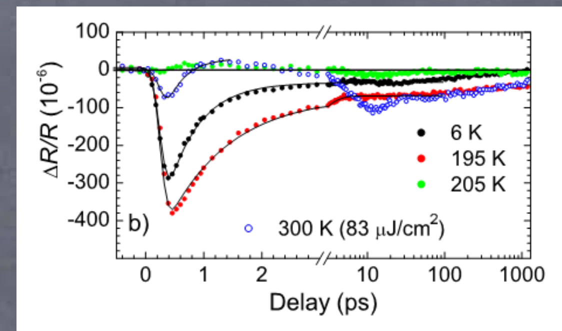


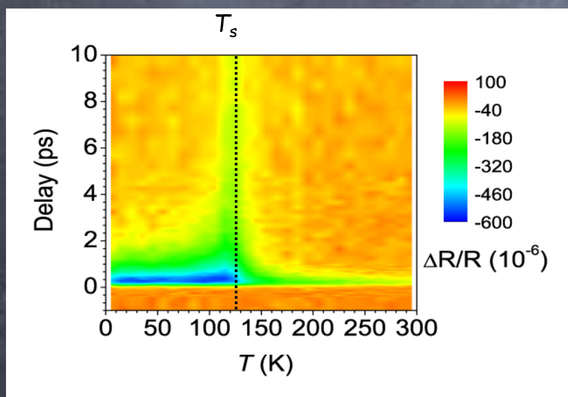
Mrgadonna *et al.*, Phys. Rev. B 79, 014503 (2009)

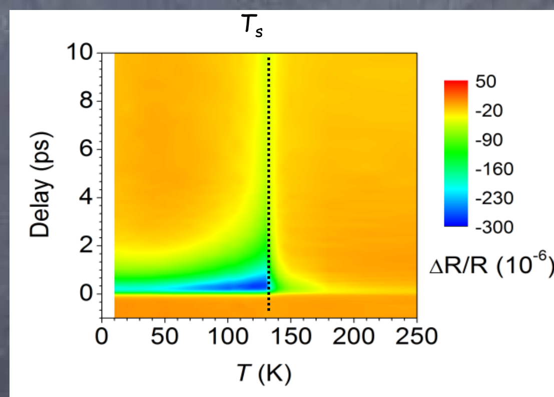
low-T SDW Fe ordered moment ~0.9 μ_B

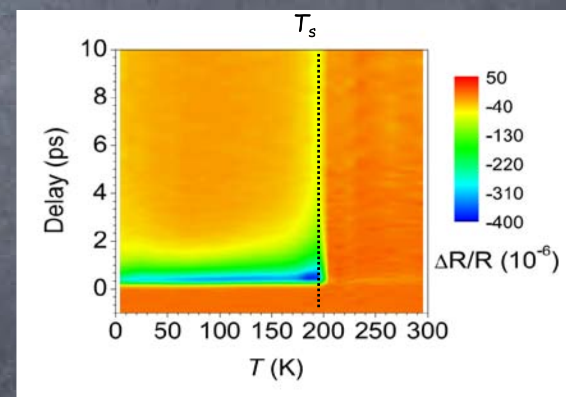
Comparison of ΔR/R transients in undoped (SDW) compounds (1.55 eV probe)











$SmFeAsO_{1-\delta}$

$T_N < T_s \approx 125K$

$BaFe_2As_2$

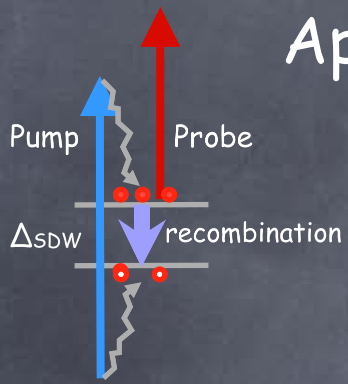
$T_N = T_s \approx 135K$

$SrFe_2As_2$

$T_N = T_s \approx 200K$

Stojchevska et al., PRB **82**, 012505 (2010)

Application of the bottleneck model to SDW

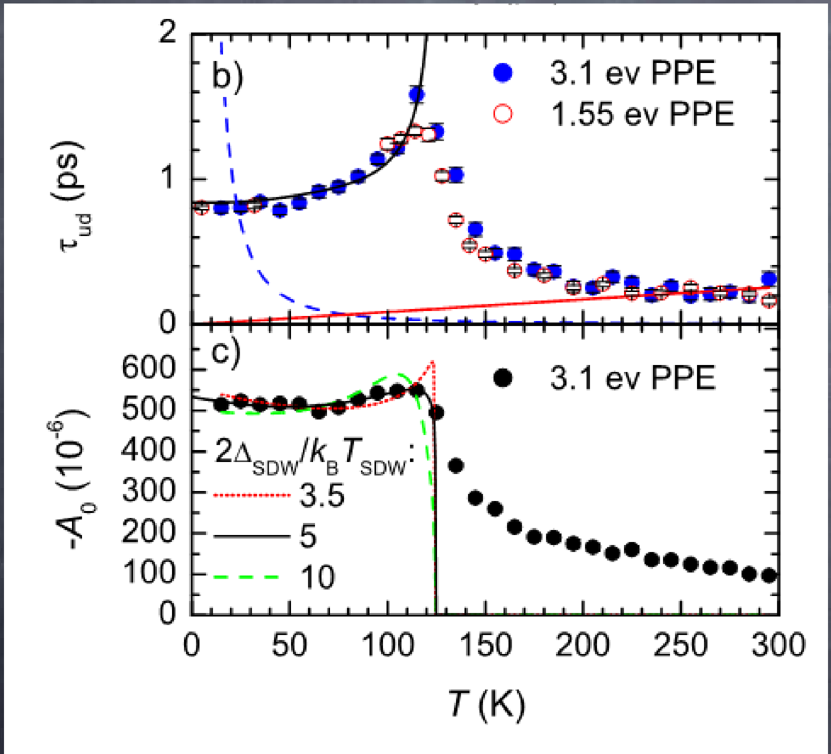


BCS T-dependent gap:

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

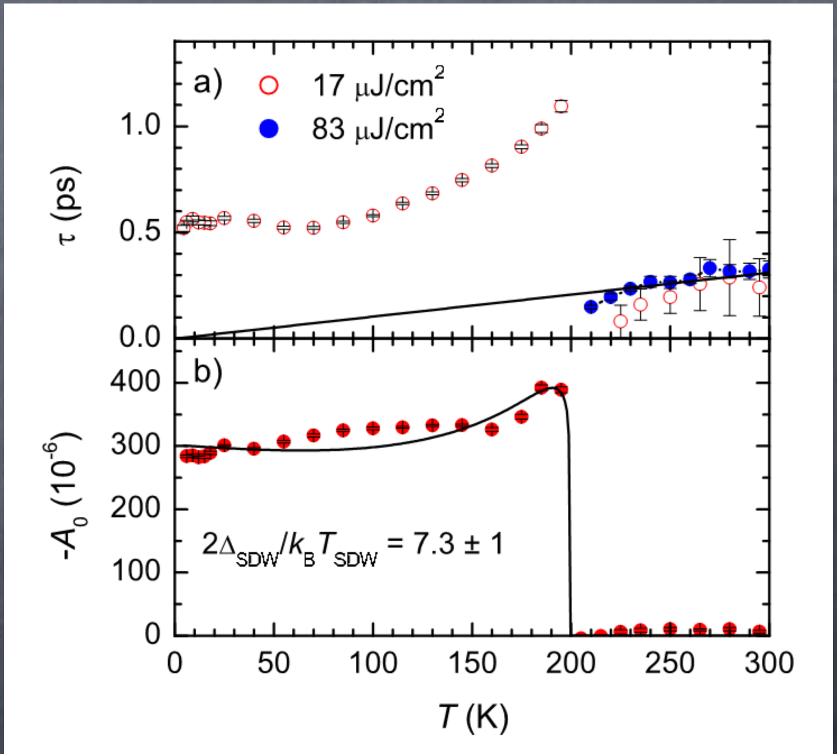
V.V. Kabanov et al., PRB 59, 1497 (1999)

$SmFeAsO_{1-\delta}$



Mertelj et al., PRB **81**, 224504 (2010)

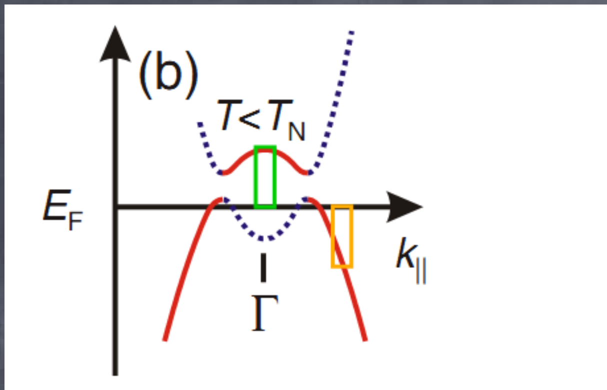
$SrFe_2As_2$

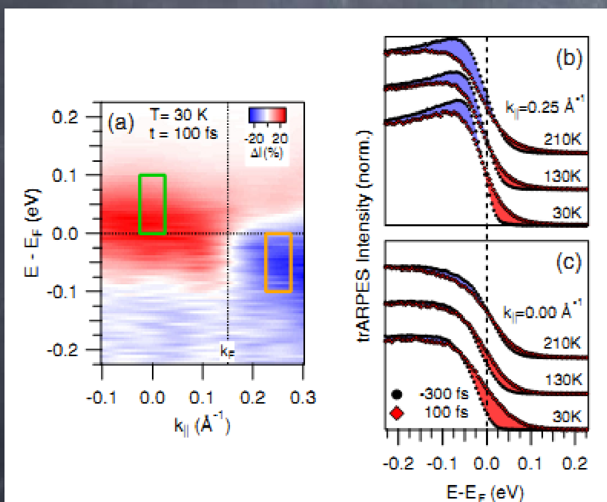


Stojchevska et al., PRB 82, 012505 (2010)

TR-ARPES in the SDW state

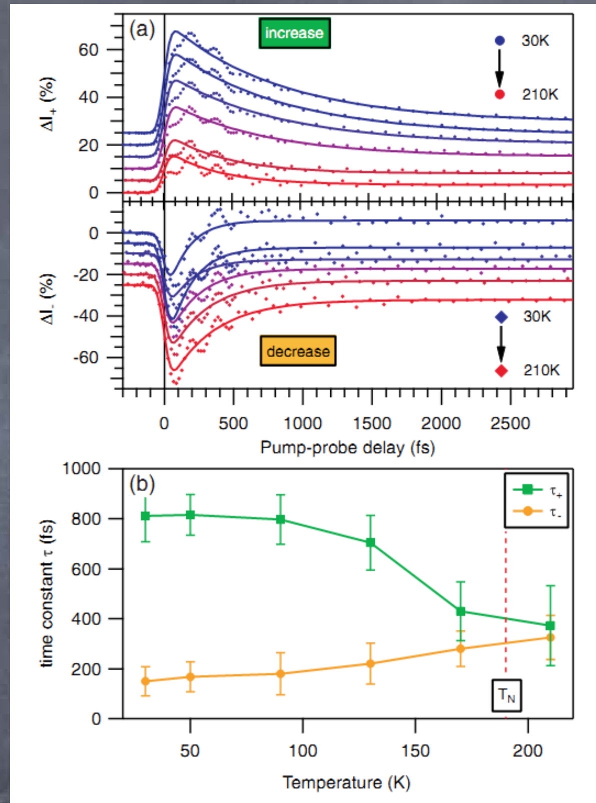
$EuFe_2As_2$



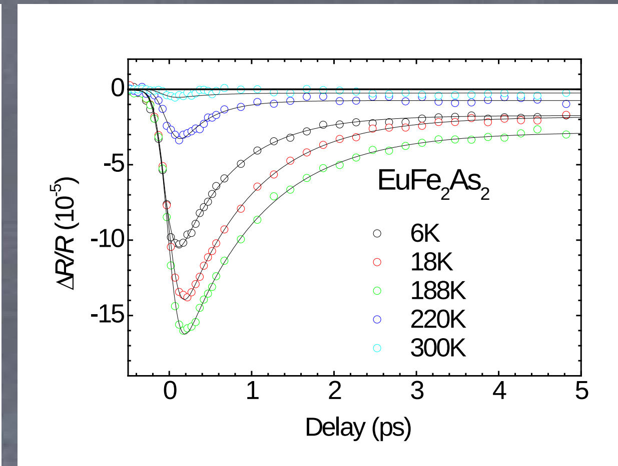


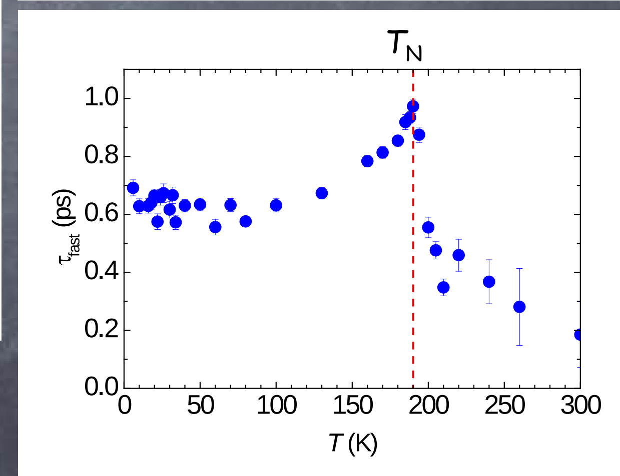
Rettig et. al., PRL **108**, 097002 (2012)

ARPES

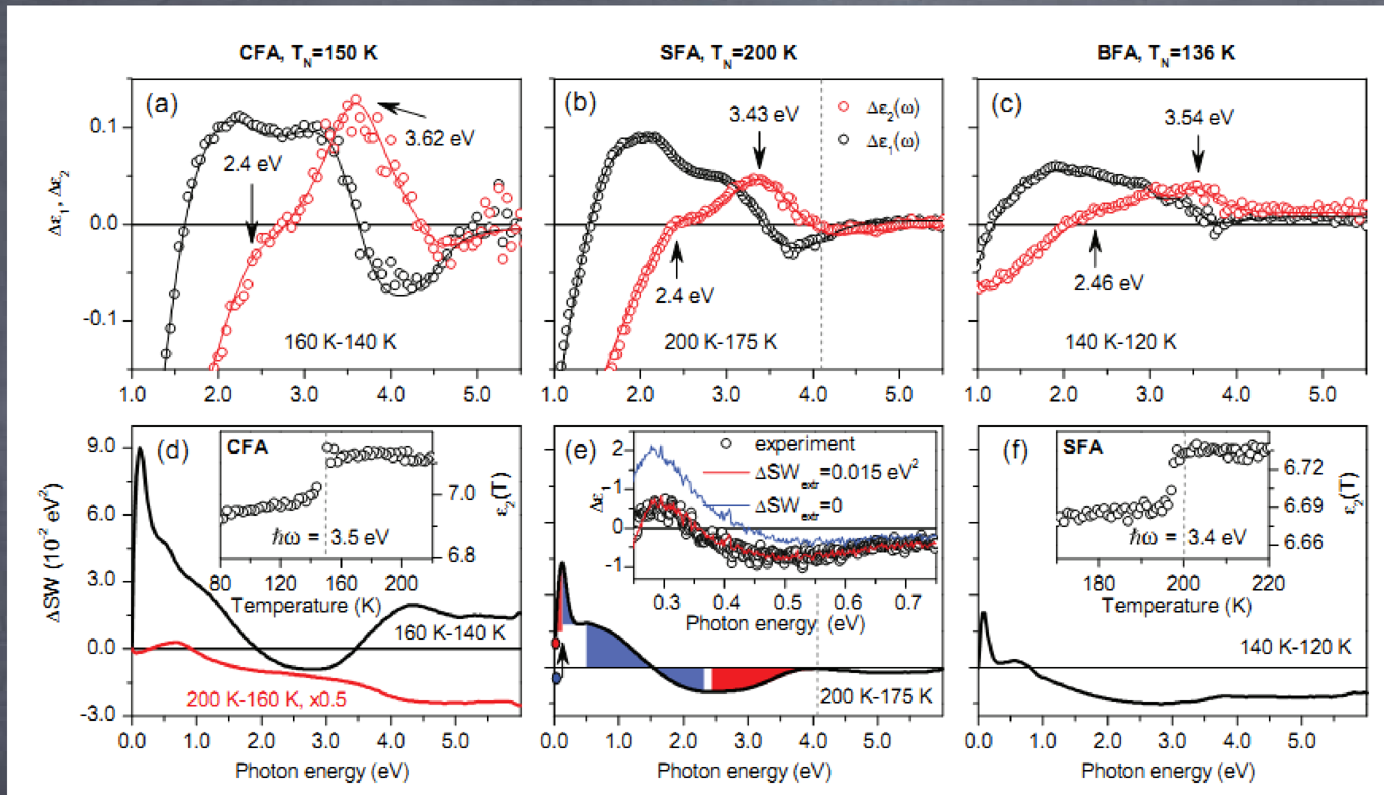


ALL-optical





Static optical response to the magneto-structural transition in $AeFe_2As_2$ (Ae=Ba, Cs, Sr)

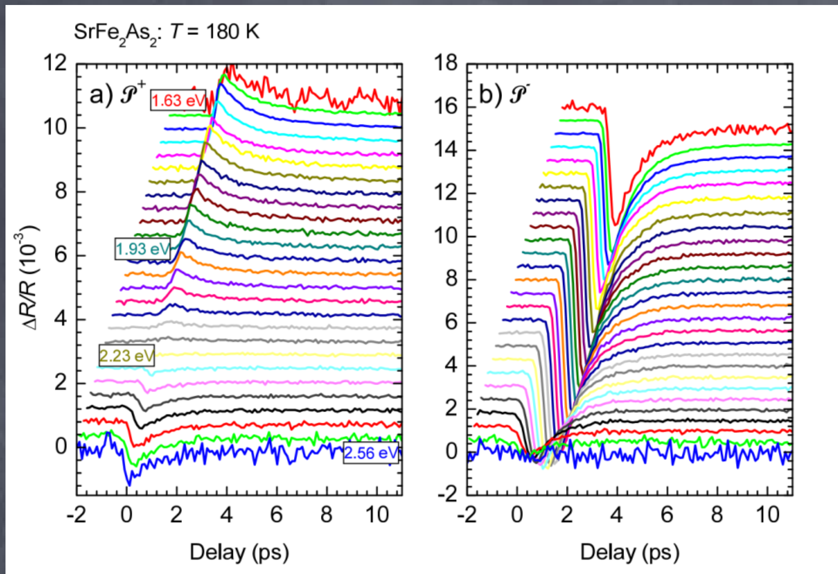


Charnukha et al., PRB **88**, 184511 (2013)

$$\varepsilon(\omega, T) = \varepsilon_0(\omega, T) + \frac{d\varepsilon(\omega)}{d\Delta}\Delta(T)$$

$$\delta R(\omega, t) \approx g_{QP}(\omega) n_{pe}(\omega, t) + \frac{dR(\omega)}{d\Delta}\delta\Delta(t) + \ldots$$

SDW state: spectral dependence

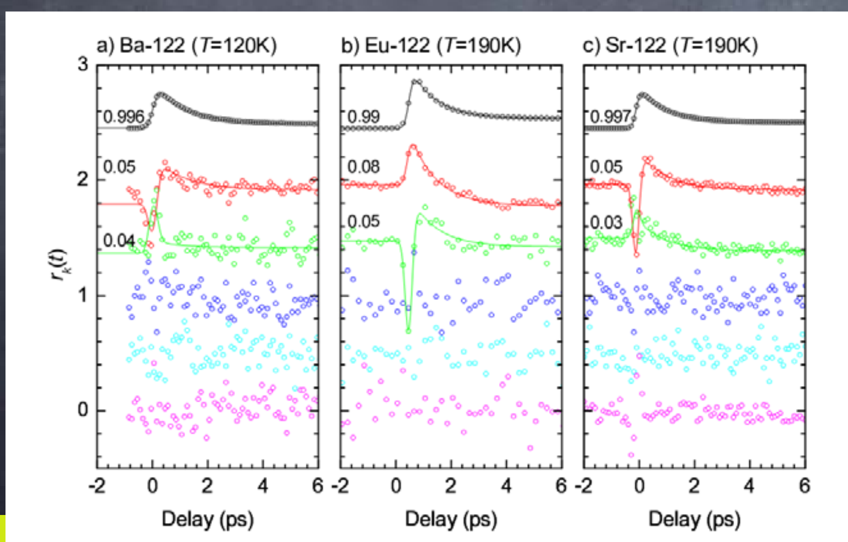


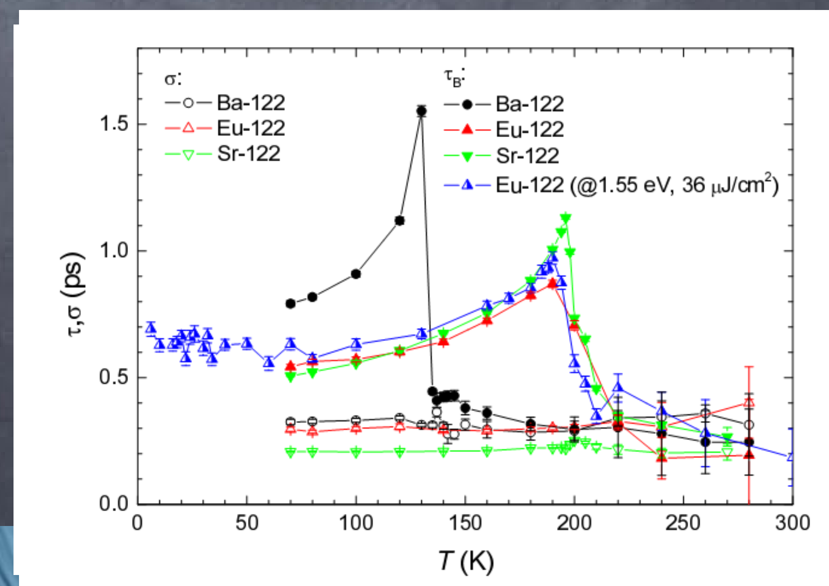
Pogrebna et al., PRB **89**, 165131 (2014)

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

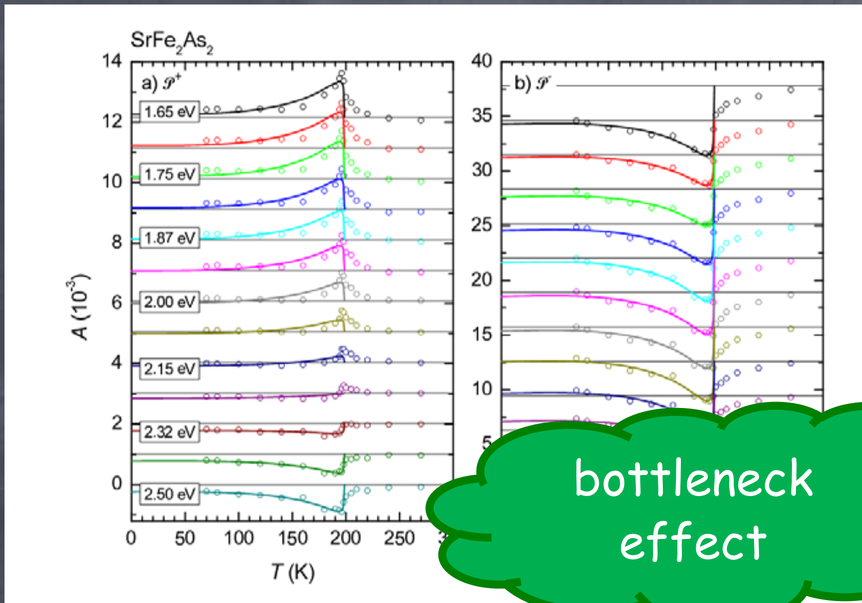
Singular value decomposition:

$$\left(\frac{\Delta R(t_j)}{R}\right)(\omega_{\mathrm{pr},i}) = \sum w_k u_{ik} v_{jk} = \sum A_k(\hbar\omega_{\mathrm{pr},i}) r_k(t_j).$$





Bottleneck model fits



bottleneck effect

sample	$2\Delta(0)/k_B T_{SDW}$	g_{ph}
Ba-122	8 ± 6	3.2 ± 1.1
Eu-122	13 ± 8	2.8 ± 1.4
Sr-122	8 ± 3	2.7 ± 0.8
$YBa_2Cu_3O_{7-\delta}$[1]	10	~ 60
*Ba-122	7.7^{30}, $\sim 9^{38}$	-
*Sr-122	8.7^{30}, $\sim 9^{38}$	-
*Eu-122	5.6^{39}	-

*optical conductivity

*Charnukha et al., PRB **88**, 184511 (2013); Hu et al., PRL **101**, 257005 (2008); Wu et al., PRB **79**, 155103 (2009)

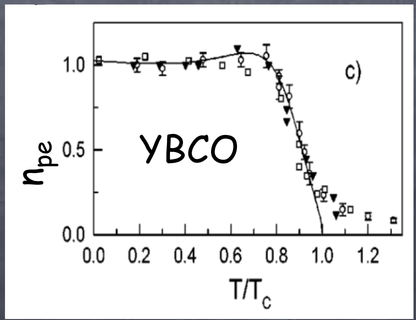
$$\Delta R = \left[\gamma_0 + \eta \frac{\Delta^2(T)}{\Delta^2(0)}\right] n_{pe}$$

$$n_{pe} \propto 1/\left[\left(\frac{2\Delta(T)}{k_B T_{SDW}} \ldots \frac{T}{T_{SDW}}\right)\left(1+g_{ph}\sqrt{\frac{k_B T}{\Delta(T)}}\exp\left(-\frac{\Delta(T)}{k_B T}\right)\right)\right]$$

matrix element effect

Δ(…

g_{ph} – ef… …lved bosons



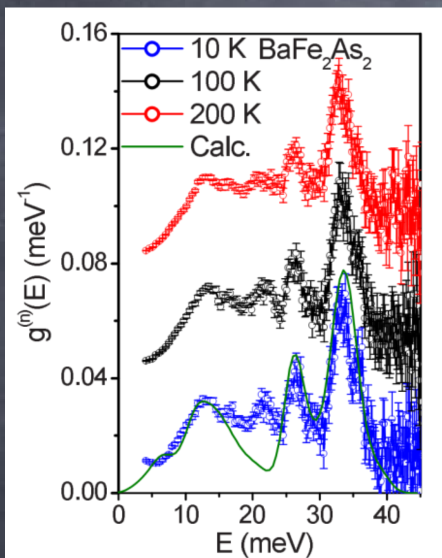
V.V. Kabanov et al., PRB 59, 1497 (1999)

Pogrebna et al., PRB B 89, 165131 (2014)

Bottleneck boson?

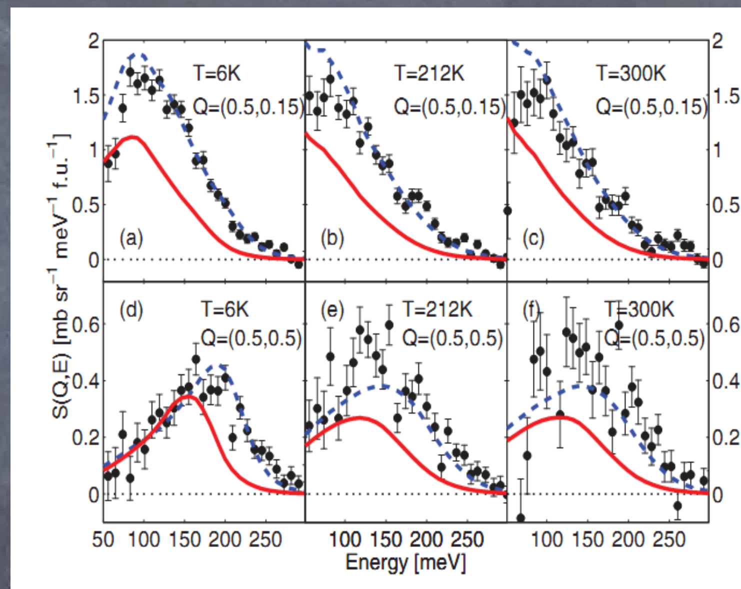
$2\Delta_{SDW}(0) = \sim 100\text{-}200$ meV

phonons:

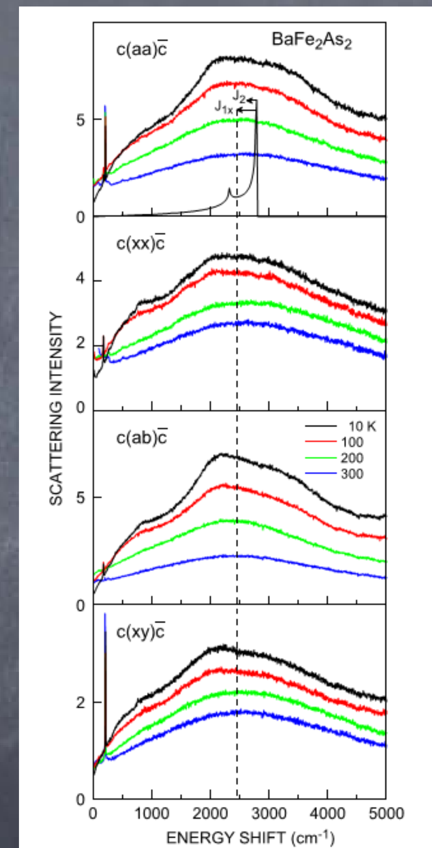


Mittal et al.,
PRB **78**, 104514 (2008)

magnons:



Ewings et al., PRB **83**, 214519 (2011)



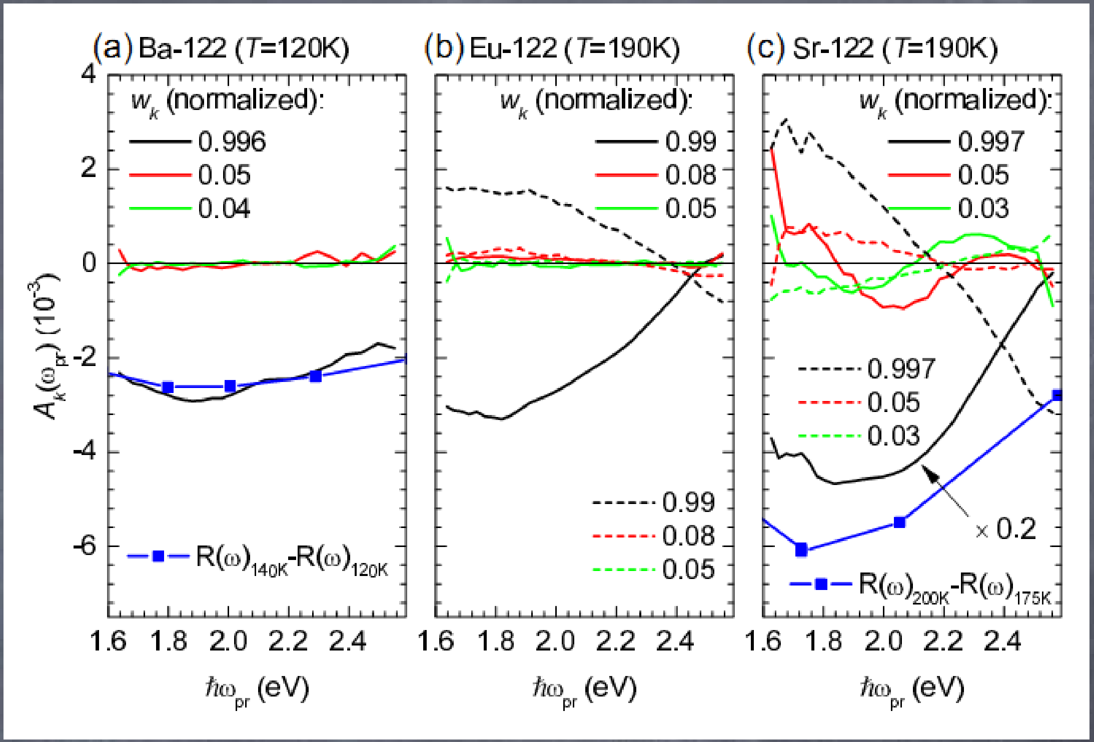
S. Sugai et al.,
J. Phys. Soc. Jpn. 81,
024718 (2012)

Magnons have a proper energy scale to play the role of the bottleneck boson.

Spectral dependence, comparison to equilibrium response

Equilibrium:

$$R|_{T>T_N} - R|_{T<T_N} \sim \frac{dR}{d\Delta}\Delta(T)$$



Transient:

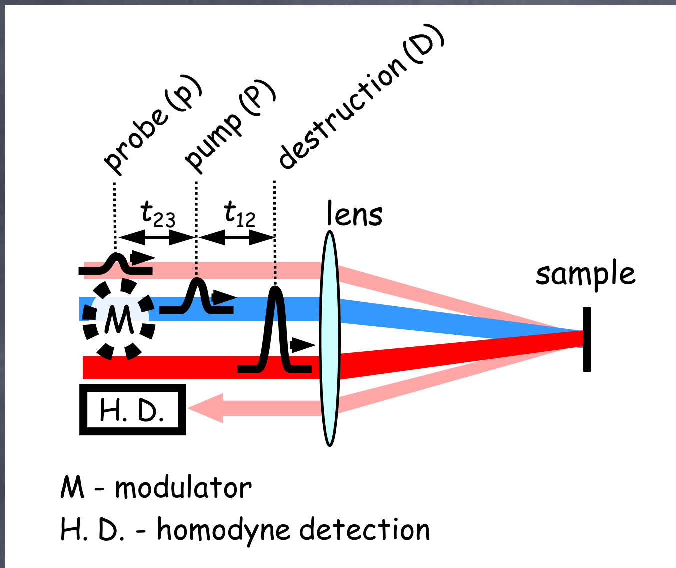
quasiparticle: $\delta R(t) \propto \int d^3k |M(\mathbf{k})|^2 g(\varepsilon_\beta - \varepsilon_\alpha - \hbar\omega)\, \delta f(\mathbf{k},t) \sim c_0(T,\Delta) n_{pe}(t)$

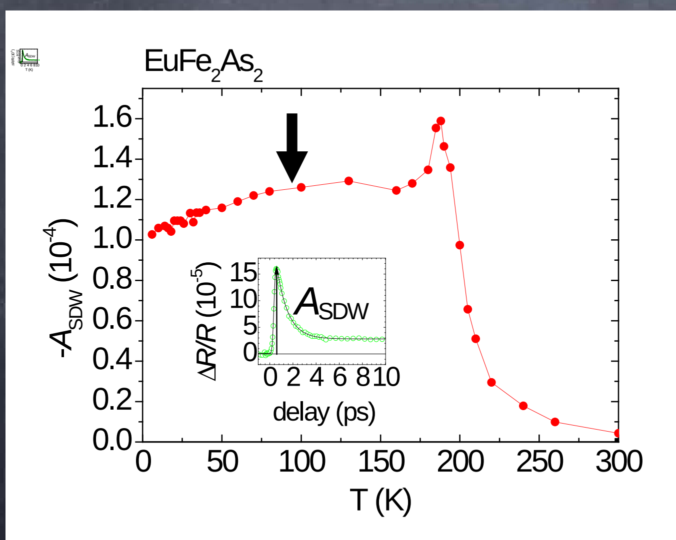
collective: $\delta R(t) \propto \frac{dR}{d\Delta}\delta\Delta(t) \sim c_1(T,\Delta) n_{pe}(t)$

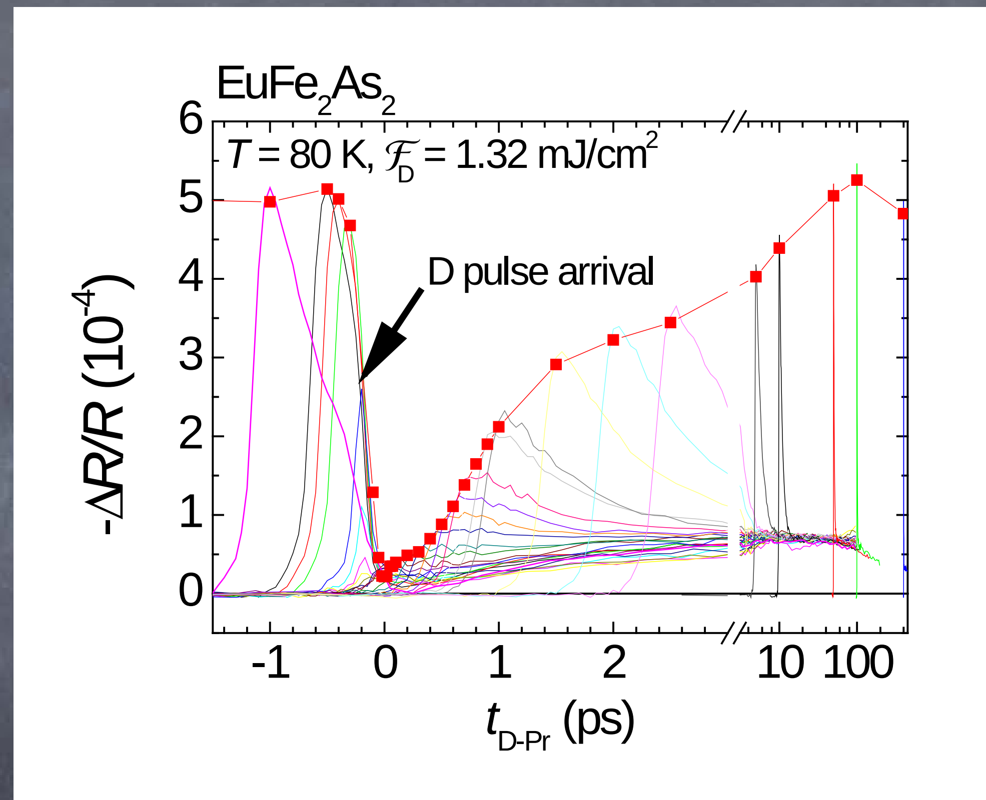
gap eq.: $\Delta = \sum V \frac{\Delta}{\sqrt{\Delta^2+\varepsilon_{\mathbf{k}'}^2}}[1-2f(\mathbf{k}')] \Rightarrow$ linear response: $\delta\Delta(t) \propto n_{pe}(t)$

amplitude mode: $\hbar\omega_A = \sqrt{(2\Delta)^2+(v_F q)^2}$, $\frac{1}{\omega_A} = \frac{\hbar}{2\Delta} \sim 3$ fs

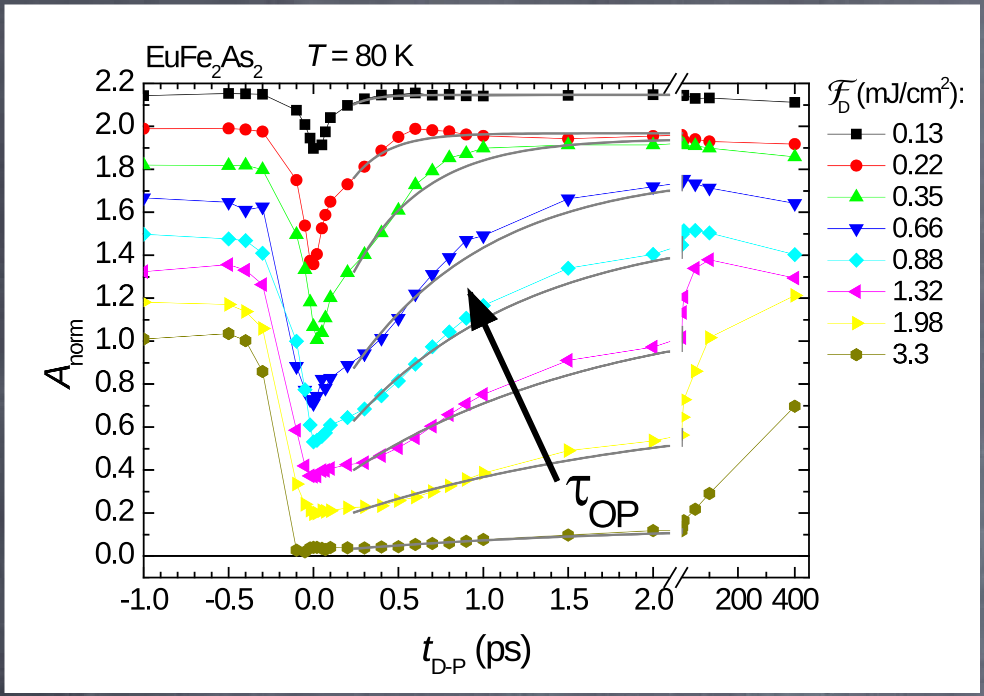
Multiple pump pulse technique

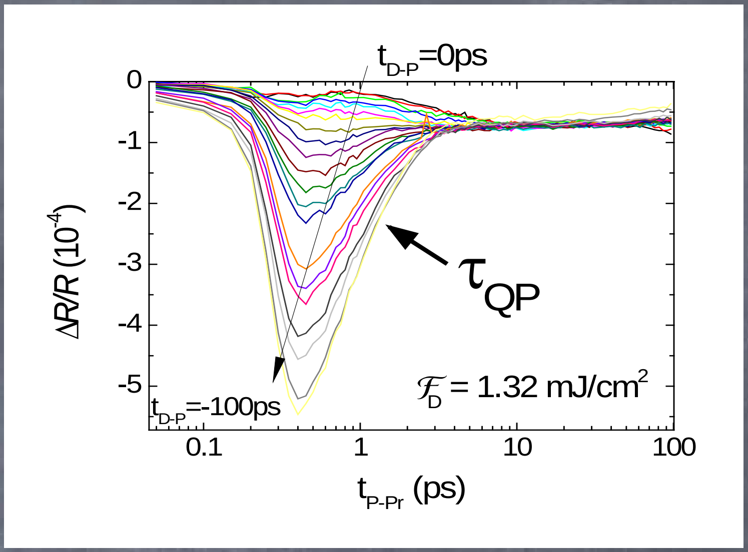


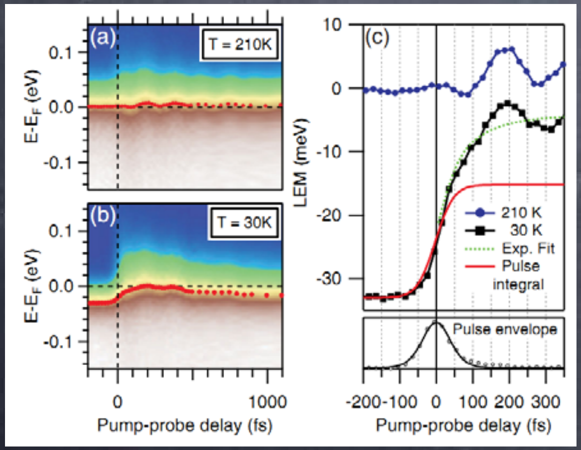




Order parameter dynamics upon quench







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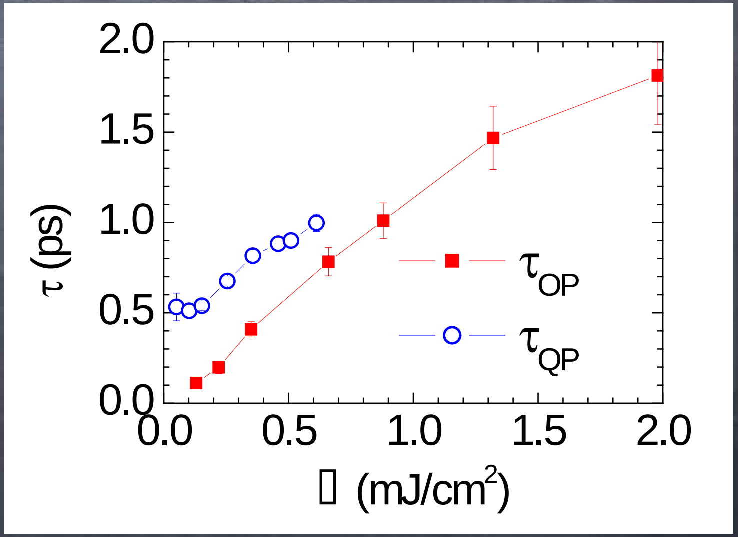

Conclusions

- CDWs: Rothwarf-Taylor bottleneck is possible just near the transition when the gap is still small. The all-optical transient response is not yet fully understood. The role of an overdamped collective electronic mode?
- SDW state of iron based pnictides: bottleneck governed relaxation dynamics at weak excitation.
- High energy magnons as the bottleneck bosons.
- Faster order parameter dynamics observed at higher excitation possibly driven by coherent SRS excitation of the order parameter.