Overview on Superconductivity Research in Quantum Phenomena Group

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Das PUMA, MLZ (FRM-II) / Technical Universität München

Quantum Phenomena in condensed matters

- Highly frustrated magnets
- Emergent topological states
- Spin-orbit entanglement
- Unconventional superconductivity
- Magnetic order/spin dynamics/FFL
- Quantum critical point
- Magnetic nanoparticles
- Heterostructures
- Multiferroics oxides

Quantum Phenomena in condensed matters

- Highly frustrated magnets
- Emergent topological states
- Spin-orbit entanglement
- **Unconventional superconductivity *with INS***
- Magnetic order/spin dynamics/FFL
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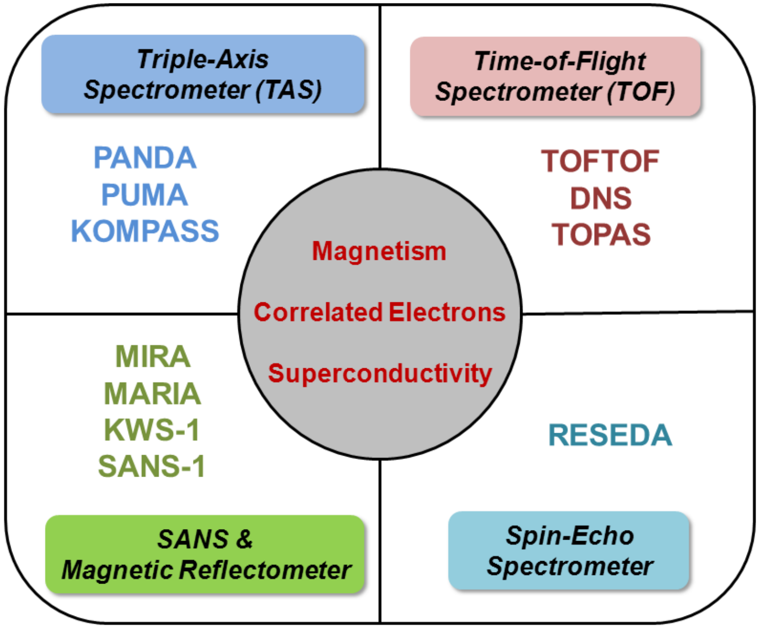
- Magnetic nanoparticles
- Heterostructures
- Multiferroics oxides



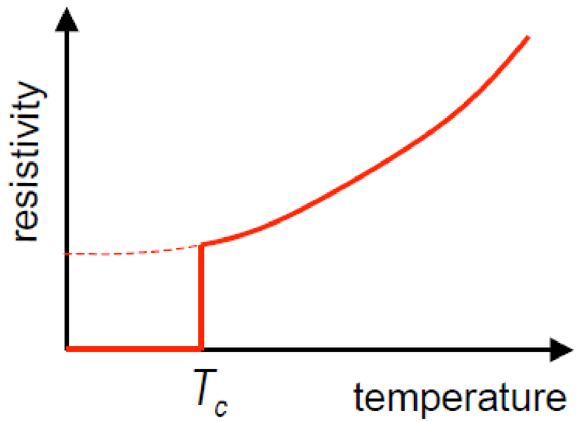
Y. Su

Outline

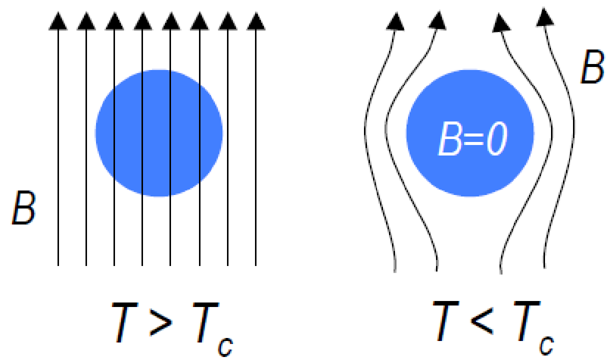
- Conventional & unconventional superconductors
  - → long standing question…
- Inelastic neutron scattering (TAS – PUMA)
- INS on conventional superconductors
- INS on unconventional superconductors
- What QP group can do more on SC research?

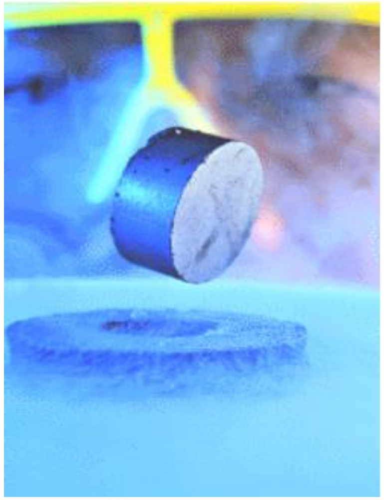
Superconductor – no electrical resistance

electrical resistance (1911)



field expulsion (1933)
Meissner-Ochsenfeld effect





Industrial application – SCMagLev train, SC cable, etc.

Max. speed: 581 km/h
JR-MagLev, Japan

RWE AG, Essen

Scholarly pursuits – General theory

Field expulsion – London equation

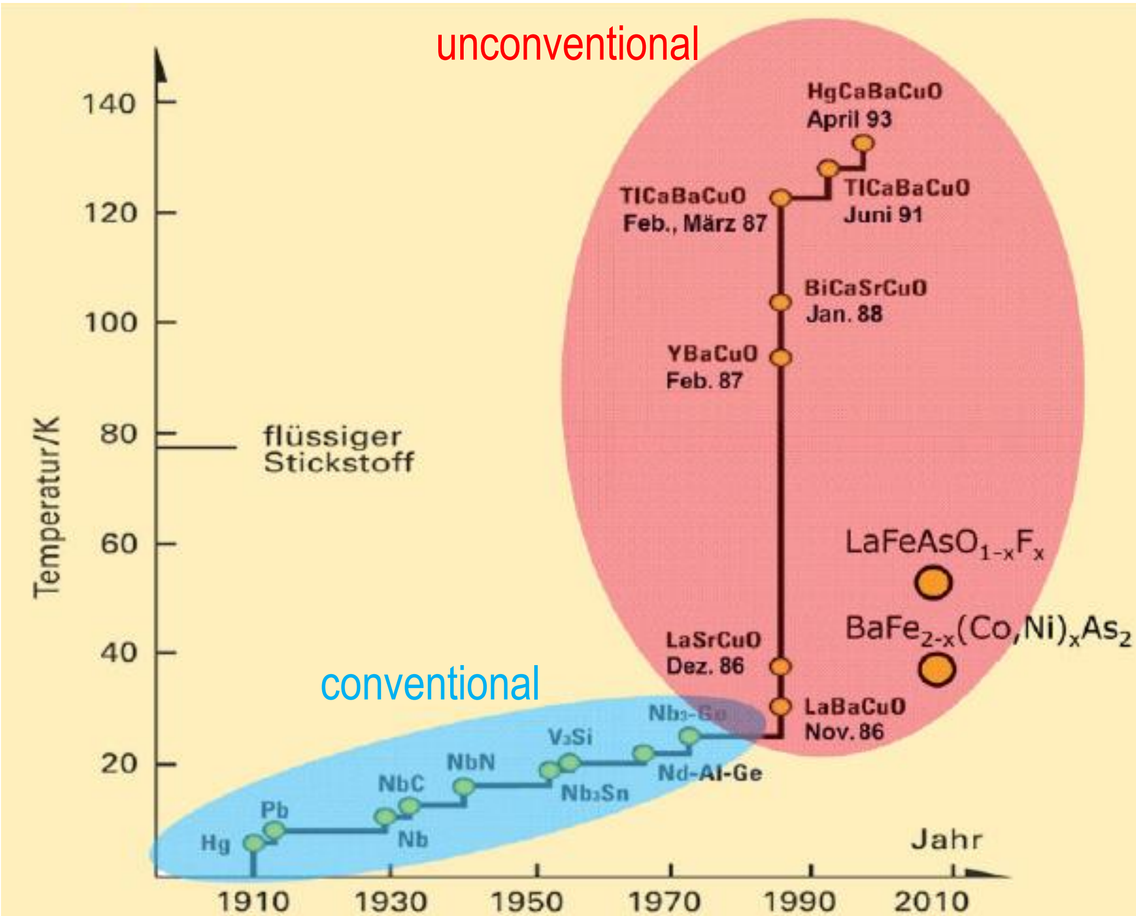
$$\vec{\nabla}^2 \vec{B} = \frac{8\pi e^2}{mc^2} |\psi_0|^2 \vec{B} = \lambda^{-2} \vec{B}$$

$$\vec{\nabla}^2 \vec{A} = \lambda^{-2} \vec{A}$$

massive photons

Anderson-Higgs mechanism

Chasing the highest transition temperature ever…



New superconductor has been found in a iron-based materials (2008)

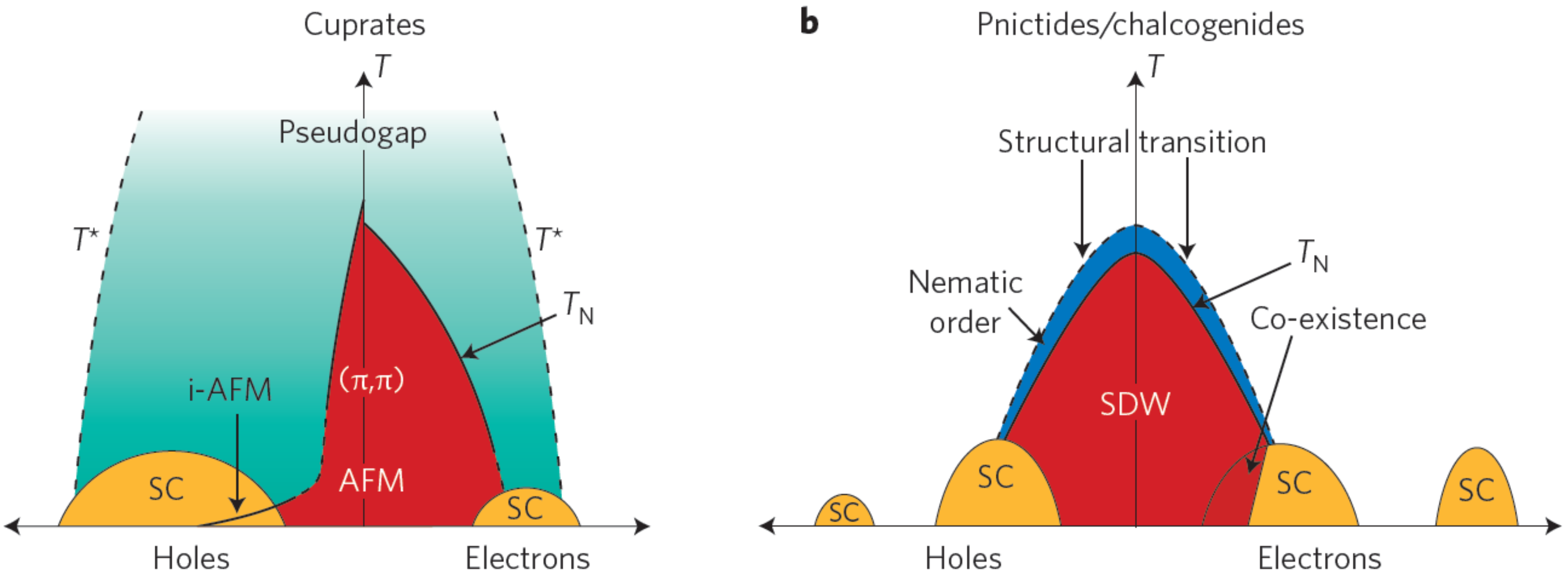
The highest T_c in FeSC → 109K (thin film)

Microscopic theory for conventional SC had been established by Bardeen-Copper-Schrieffer (BCS theory) in 1957.

B. Keimer *et al.*, **Phys. Unserer Zeit** (2012)

Microscopic understanding of mechanism for unconventional superconductors has not been reached yet.

Phase diagram of high-T_c superconductors



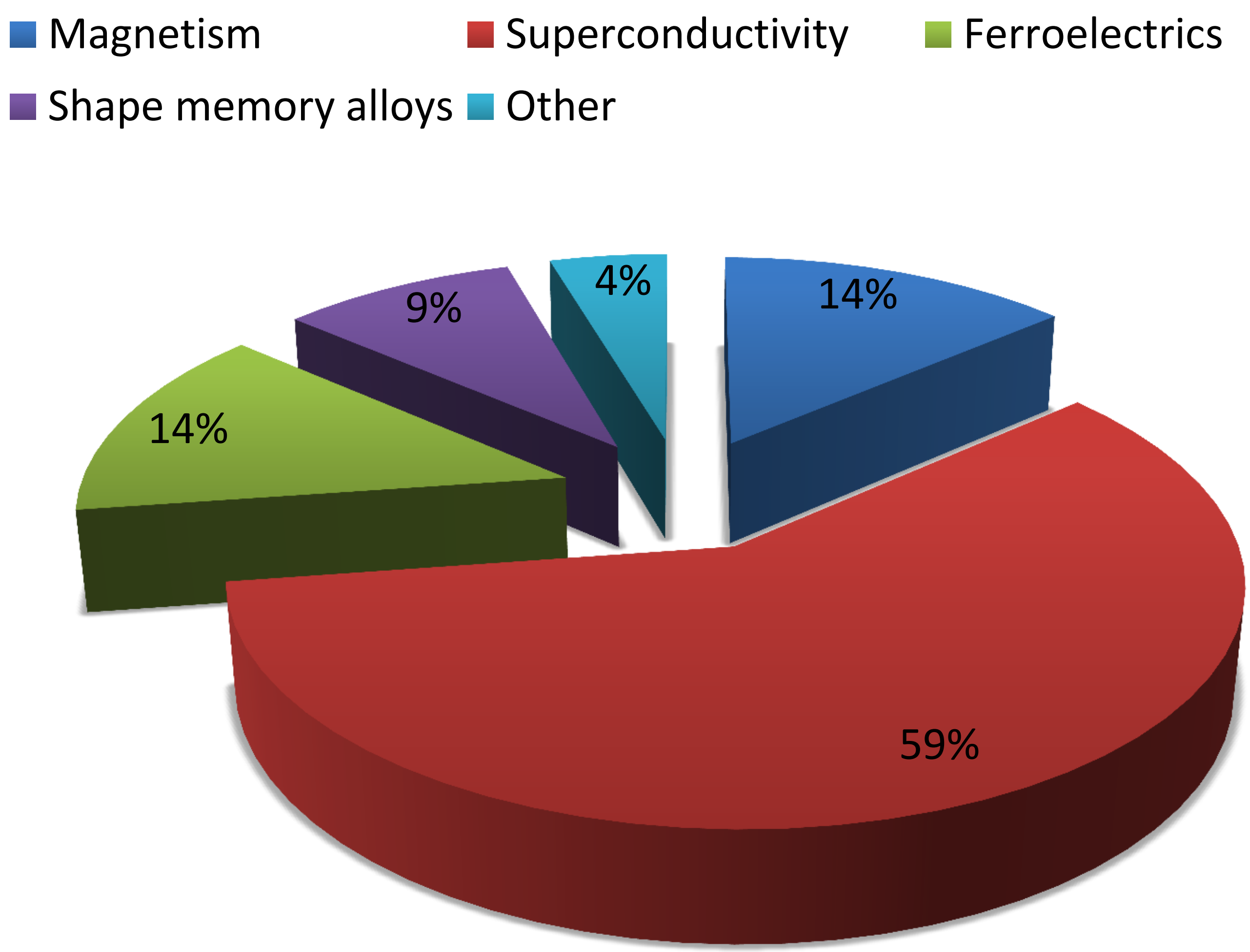
D. N. Basov and A. V. Chubukov, **Nature Physics** (2011)

What is the role of antiferromagnetism in superconductivity?

→ Can collective antiferromagnetic fluctuations be a source of electron pairing?
(analogous to phonons in conventional superconductors)

→ Inelastic neutron scattering experiment can help…

Proposals at PUMA (2008 - 2014)



Experimental method: spectroscopy

Experimental determination of dynamics and excited states

	q-averaged	**q-resolved**
crystal lattice		neutrons (nuclei) x-rays (core el)
electron charge	optics tunneling	photoemission electrons x-rays
electron spin	muons EPR NMR	neutrons RIXS

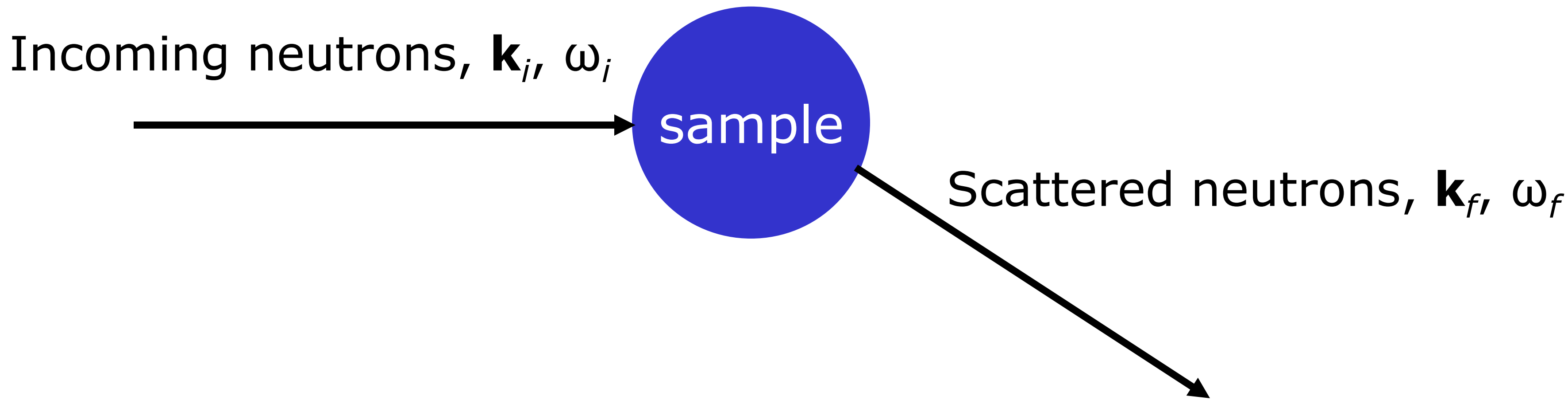
Neutron scattering

	neutron	electron
mass	$m_n = 1.675 \times 10^{-27} kg$	$m_e = 9.109 \times 10^{-31} kg$
charge	0	e
spin	$s = ½$	$s = ½$
magnetic dipole moment	$\mu_n = \frac{-e\hbar}{2m_n} g s_n$ with $g_n = 3.826$	$\mu_e = \frac{-e\hbar}{2m_e} g s_e$ with $g_e = 2.0$
energy	$E = \frac{\hbar^2 k^2}{2m_n}$ $\quad k = \frac{2\pi}{\lambda}$ $E[meV] = \frac{81.81}{\lambda^2 [\mathring{A}]}$	$E = \frac{\hbar^2 k^2}{2m_e}$ $E[eV] = \frac{150.26}{\lambda^2 [\mathring{A}]}$

Interaction of neutrons with matter

	elastic scattering	inelastic scattering
strong-force interaction (“nuclear scattering”)	position of nuclei in solid (lattice structure)	lattice vibrations (phonons)
magnetic interaction	position and orientation of electronic magnetic moments in solids (ferromagnetism, antiferromagnetism)	spin excitations (magnons, spin waves)

Inelastic neutron scattering



Momentum: $\mathbf{Q} = \mathbf{k}_f - \mathbf{k}_i$

Energy: $\omega = \omega_f - \omega_i = \hbar/2m_n(k_f^2 - k_i^2)$

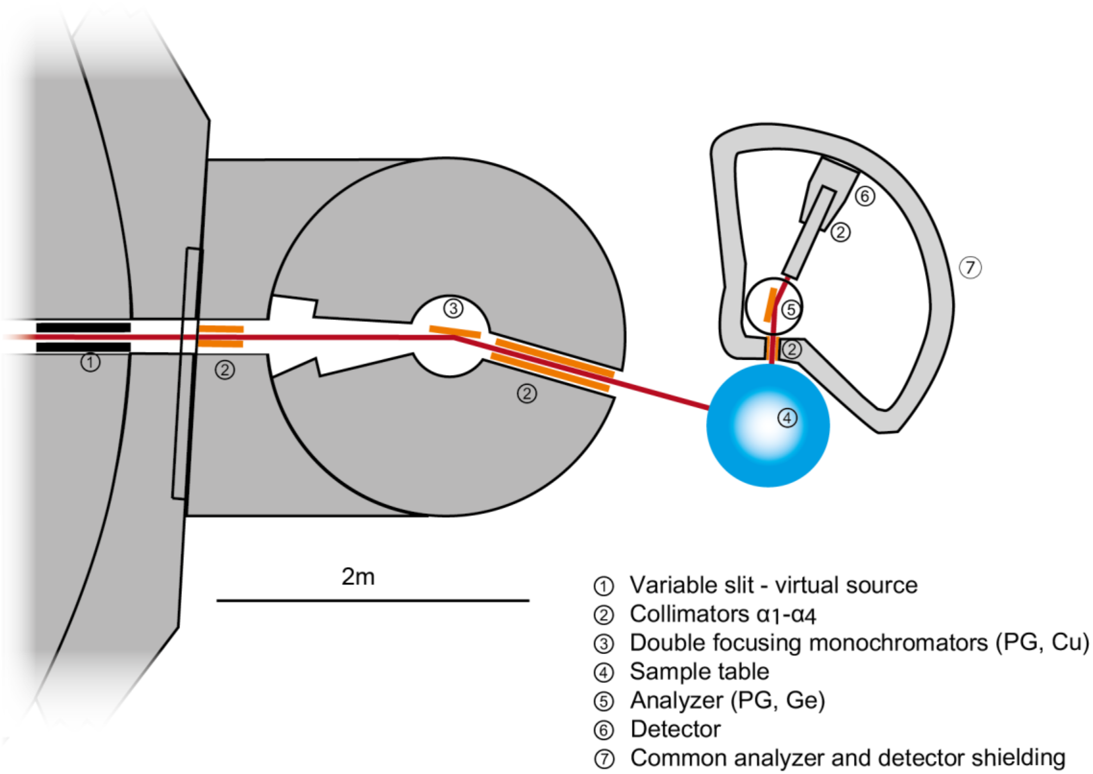
if $\omega \neq 0$, inelastic scattering.

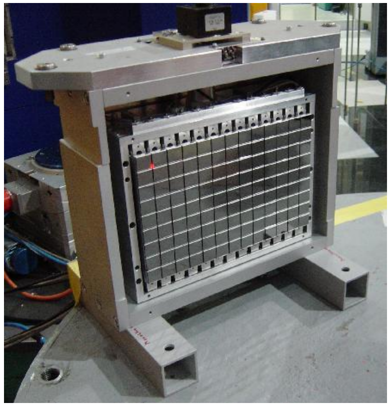
What we measure is a cross section as a function of **Q** and ω.

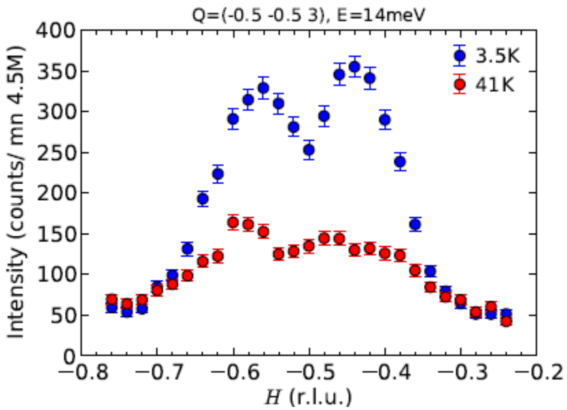
Magnetic scattering case...

$$\frac{d^2\sigma}{d\Omega dE_f} = N\frac{k_f}{k_i}(\gamma r_0)^2|F_M(\mathbf{Q})|^2\sum_{\alpha,\beta}(\delta_{\alpha\beta} - \hat{Q}_\alpha\hat{Q}_\beta)\mathbf{S}^{\alpha\beta}(\mathbf{Q},\omega)$$

Thermal neutron 3-axis spectrometer PUMA





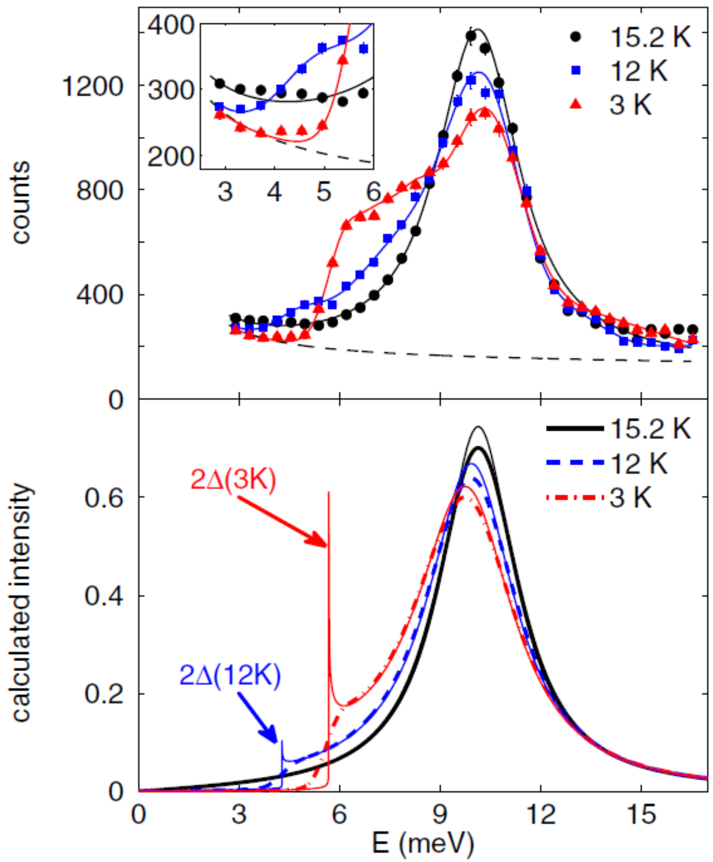


- Using Bragg reflection, monochromator selects a narrow band of neutron wavelength ($\boldsymbol{k}_i$, ω_i)
- Bragg scattering from analyzer selects scattered neutrons with unique energy and momentum ($\boldsymbol{k}_f$, ω_f)
- Flexible **Q**- and ω-positions
- Point by point scan (scan take a few hours)
- Max. energy ~ 100 meV (at thermal energy reactor)
- Polarization analysis
- Typical sample mass ~ 1g

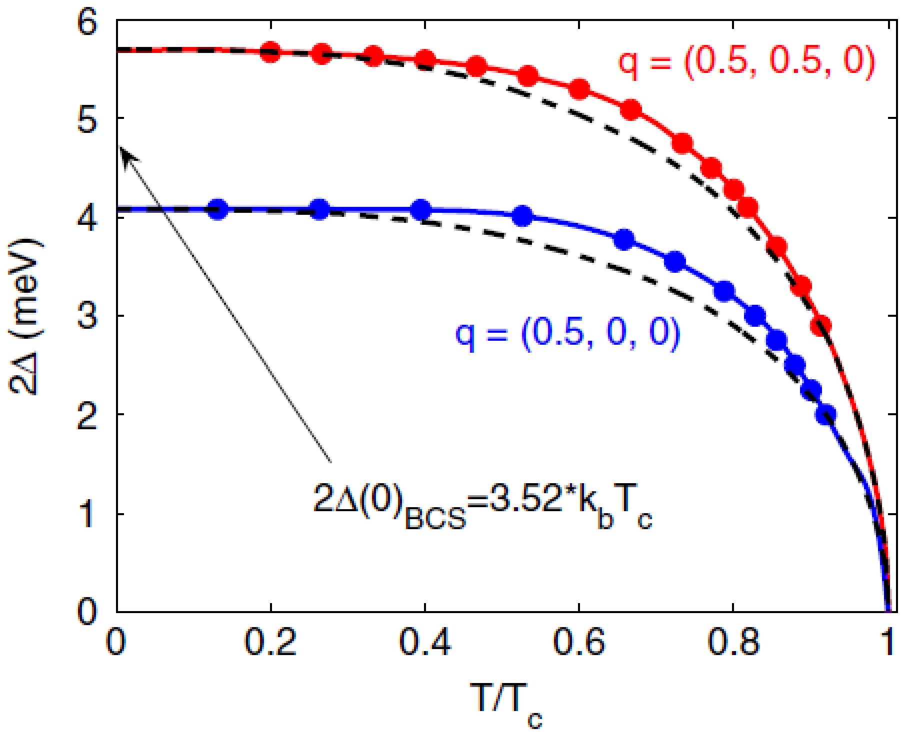
Inelastic neutron scattering on conventional superconductor

Superconducting gap in phonon spectra

Phonon spectra across T_c



T-dependence of 2Δ



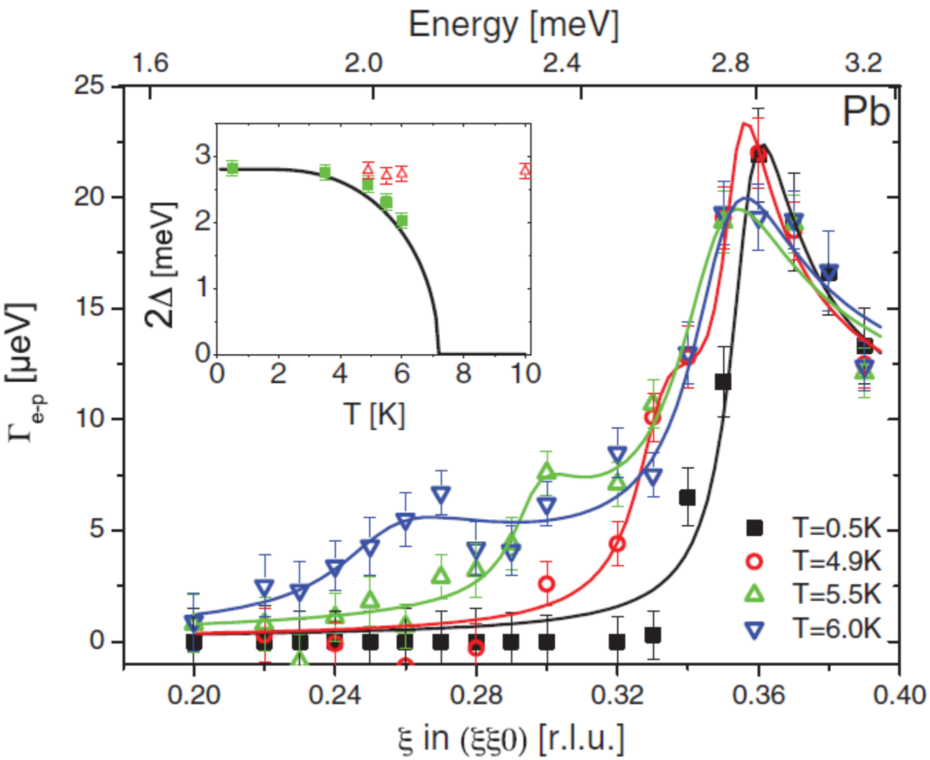
PUMA / F. Weber *et al.*, **PRB** (2012)
F. Weber *et al.*, **PRL** (2008)

Conventional superconductor YNi_2B_2C

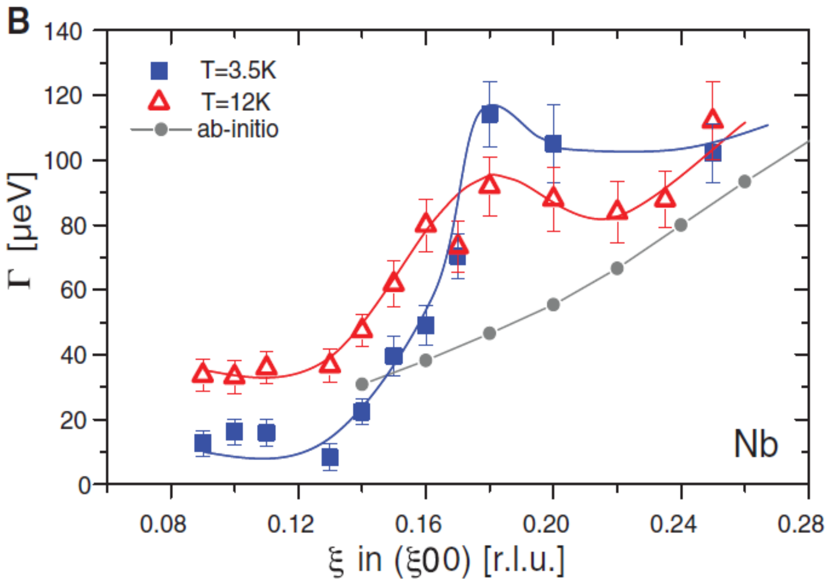
→ Phonon line shape changes due to opening 2Δ.

Kohn anomaly in elemental superconductors

Phonon linewidth change in Pd across T_c



Kohn-anomaly in Nb



TRISP / P. Aynajian, T. Keller, B. Keimer *et al.*, **Science** (2008)

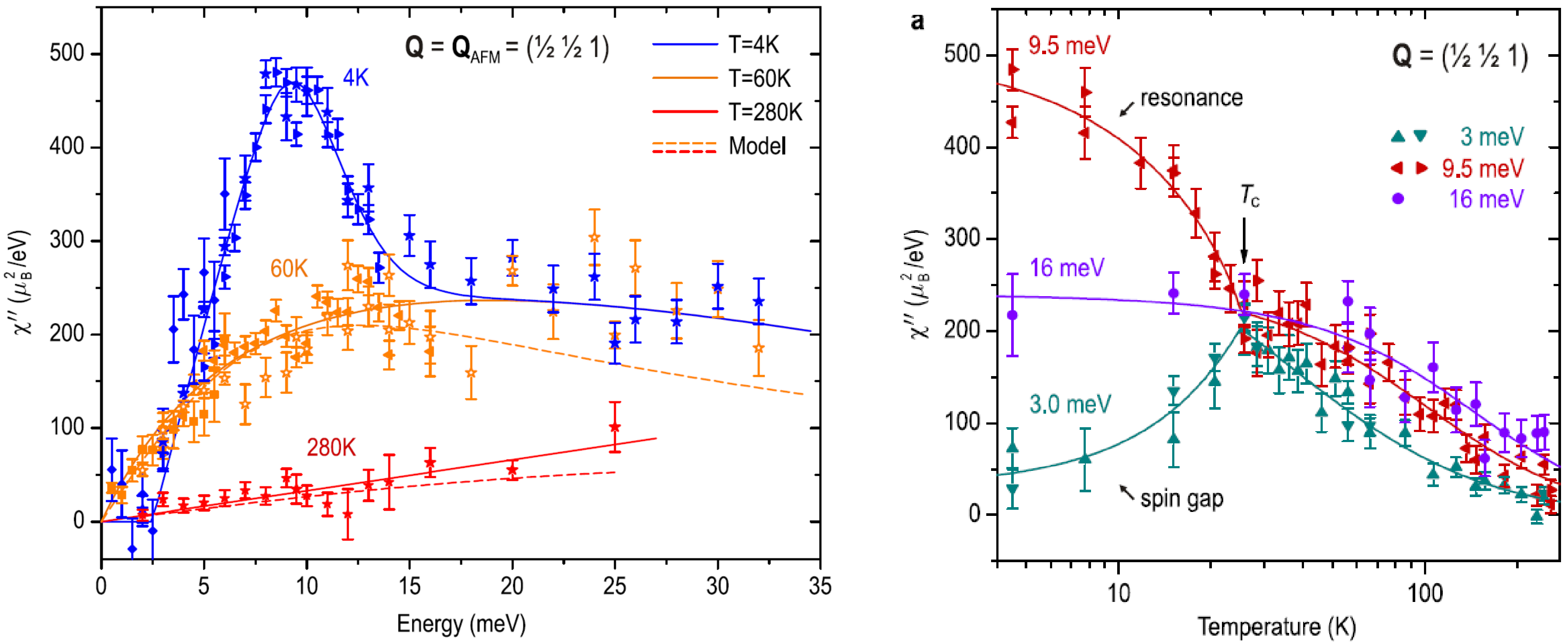
Kohn anomalies in superconductor Pd and Nb

→ many-body correlations beyond the standard theoretical framework

Inelastic neutron scattering on unconventional superconductor

Spin excitations in the superconducting state

Iron-based superconductors e.g., $Ba(Fe_{1-x}Co_x)_2As_2$

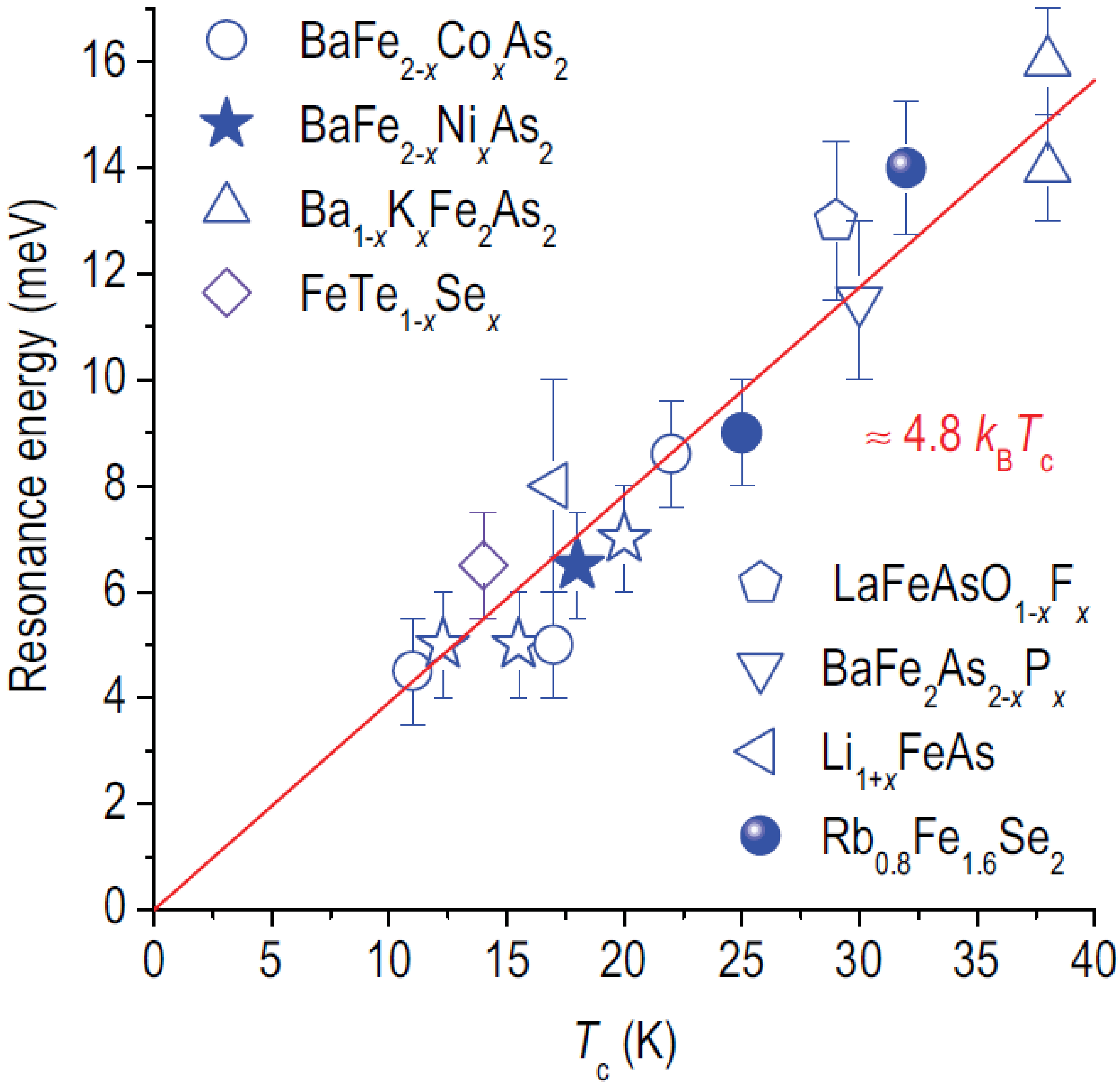


IN8, 2T, PANDA & PUMA / D. Inosov, J.T. Park, B. Keimer *et al.*, **Nat. Phys.** (2010)

Magnetic resonant mode

→ Compelling evidence for magnetically mediated Cooper pairing

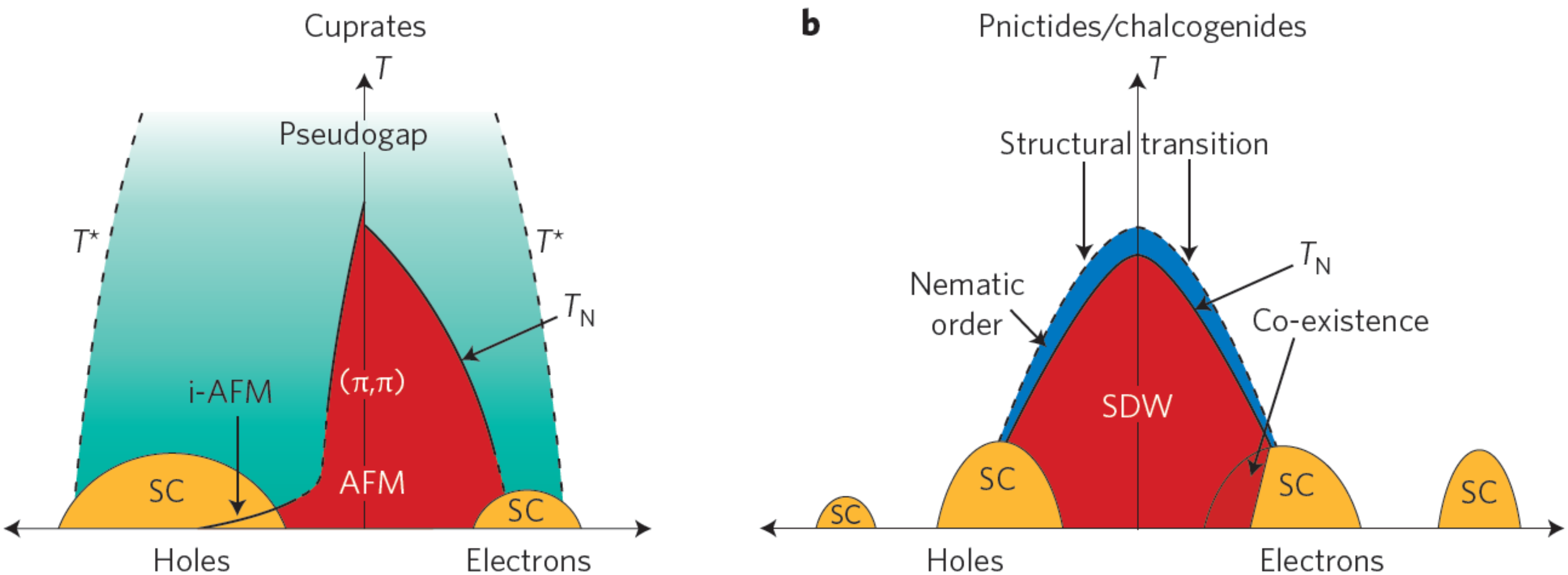
Correlation between E_r and T_c



Christianson *et al*., **Nature** (2008)
Lumsden *et al*., **PRL** (2009)
Chi *et al*., **PRL** (2009)
Inosov *et al*., **Nat. Phys.** (2010)
Pratt *et al*., **PRB** (2010)
J.T. Park *et al*., **PRB** (2010)
Qui *et al*., **PRL** (2010)
Lester *et al*., **PRB** (2010)
Li *et al*., **PRB** (2010)
Argyriou *et al*., **PRB** (2010)
Wang *et al*., **PRB** (2010)
Wen *et al*., **PRB** (2010)
Mook *et al*., **PRL** (2010)
Shamoto *et al*., **PRB** (2010)
Ishikada *et al*., **Phys. C** (2011)
Taylor *et al*., **PRB** (2011)
Zhang *et al*., **Sci. Rep.** (2011)

J.T. Park *et al*., **PRL** (2011)

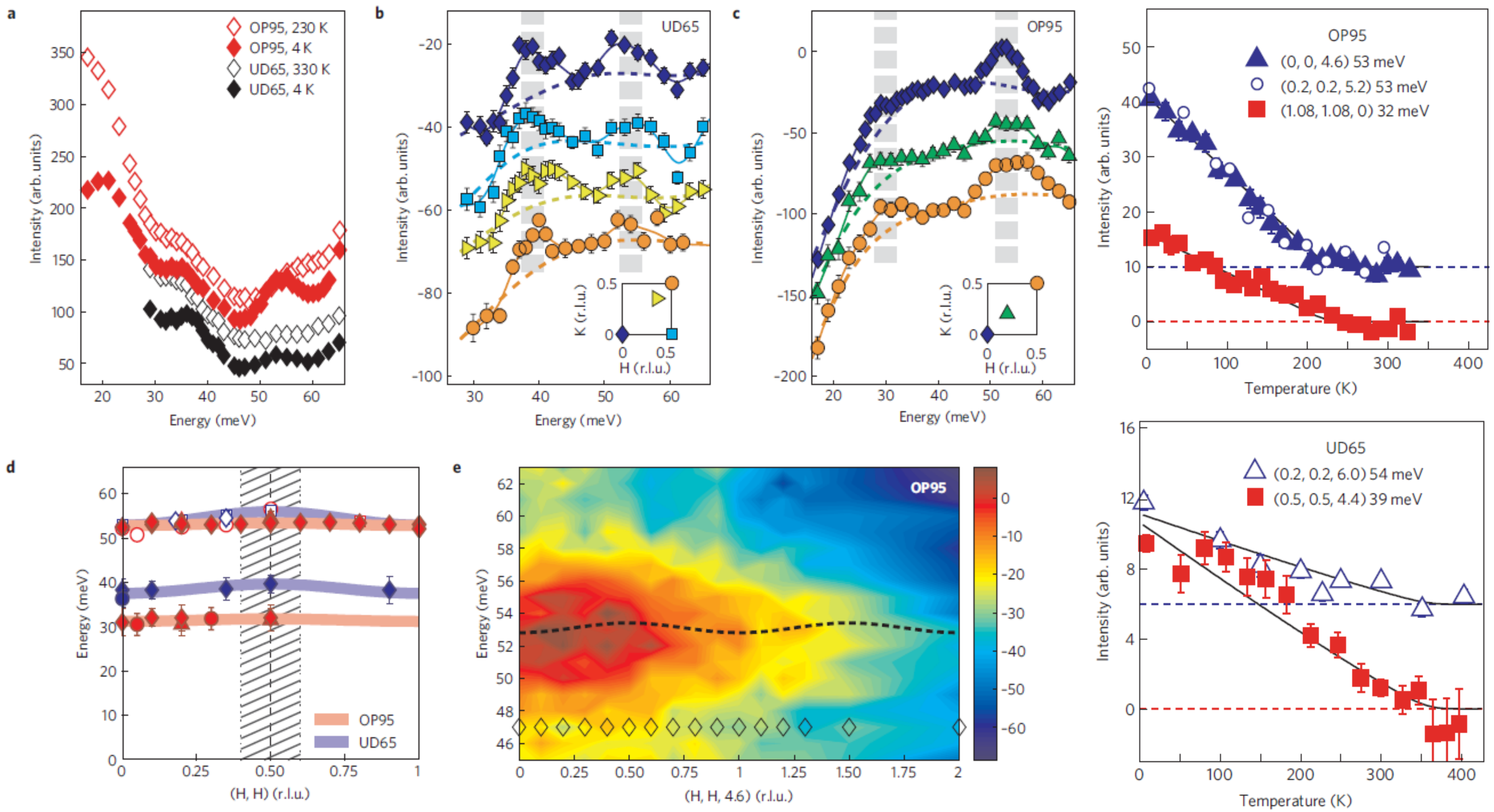
Phase diagram of high-T_c superconductors



D. N. Basov and A. V. Chubukov, **Nature Physics** (2011)

Spin excitations in the normal state

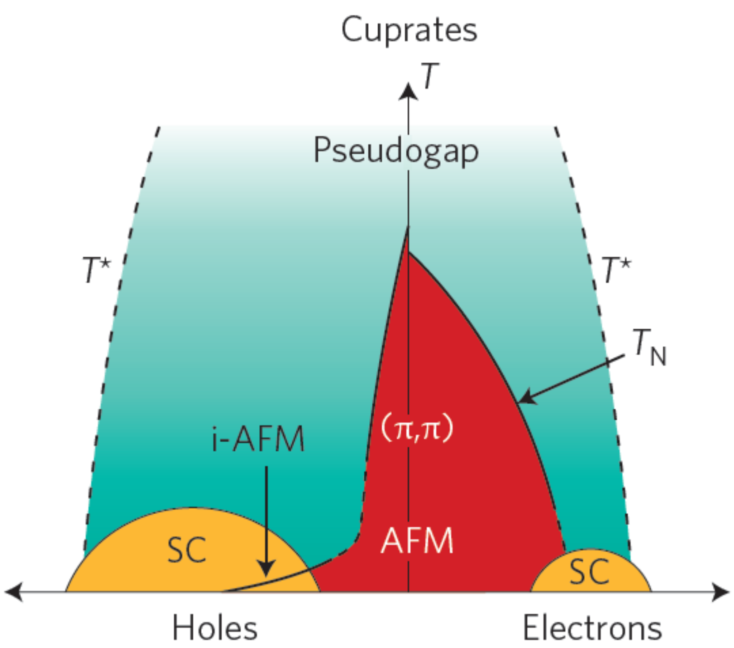
Hg-based Copper oxide superconductor

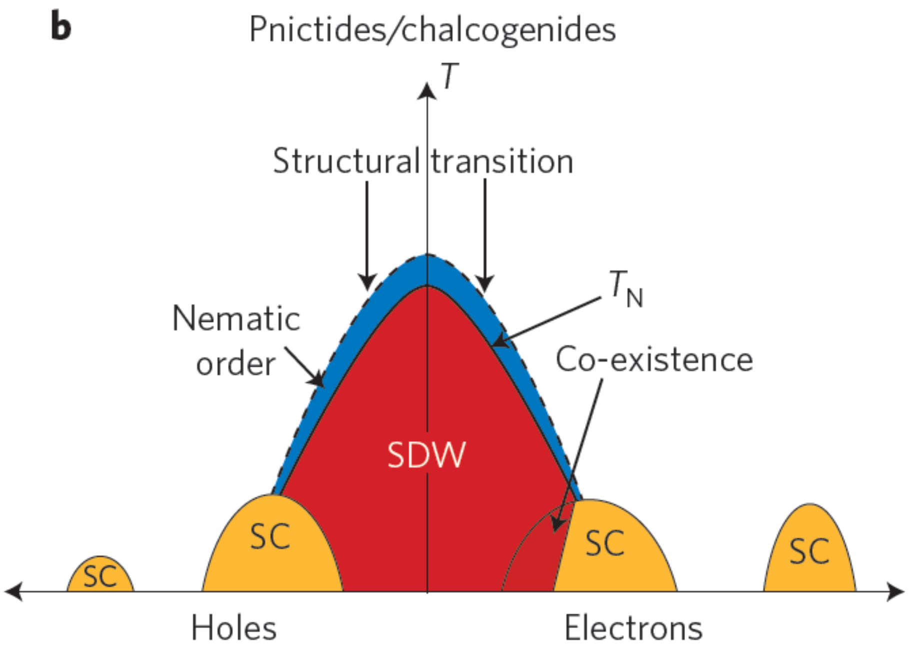


IN8, 2T, & PUMA / Yuan Li *et al.*, **Nat. Phys.** (2012)

Ising-like magnetic excitation → Pseudogap realted fluctuation

Phase diagram of high-T_c superconductors

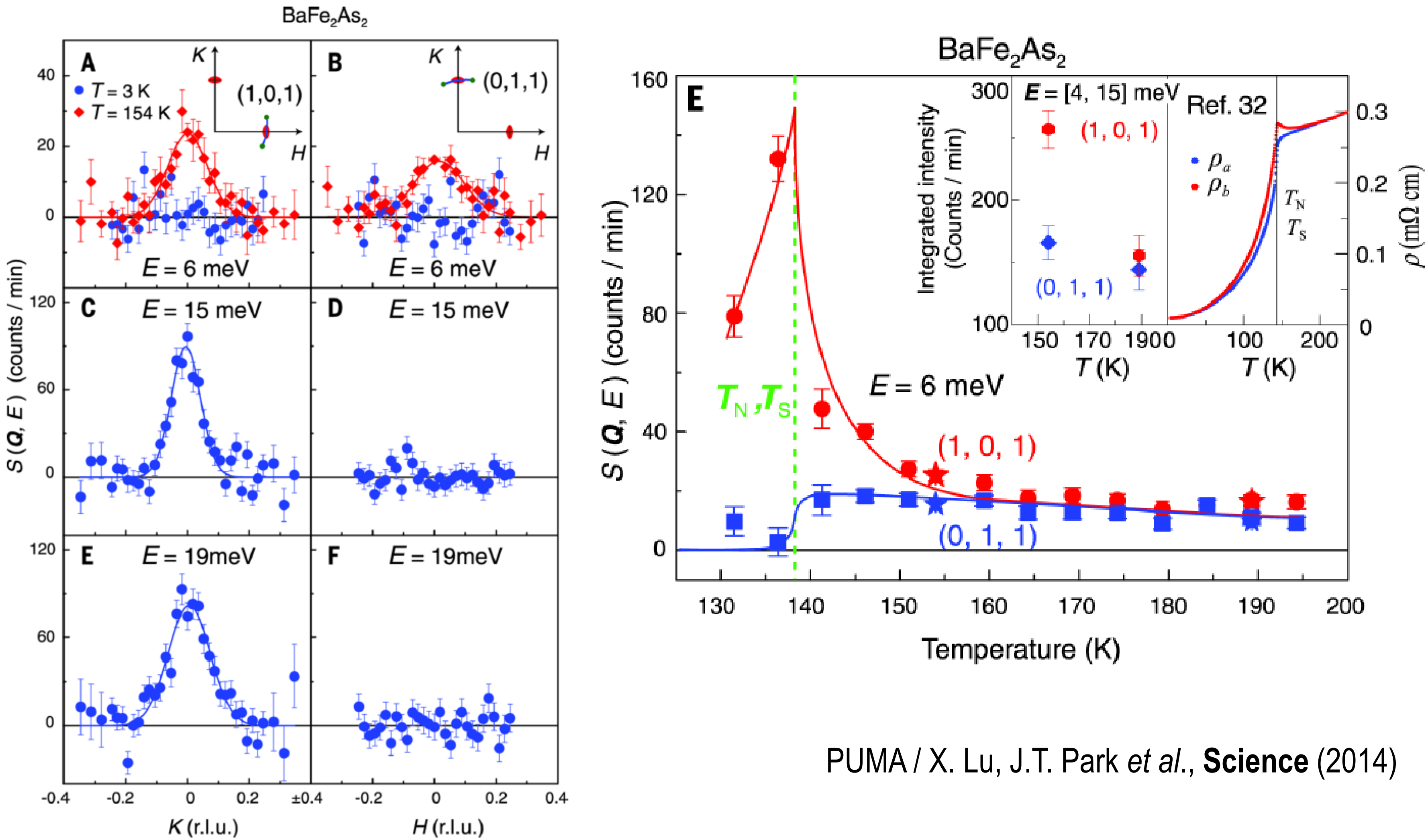




D. N. Basov and A. V. Chubukov, **Nature Physics** (2011)

Nematic spin correlations in Fe-based SC

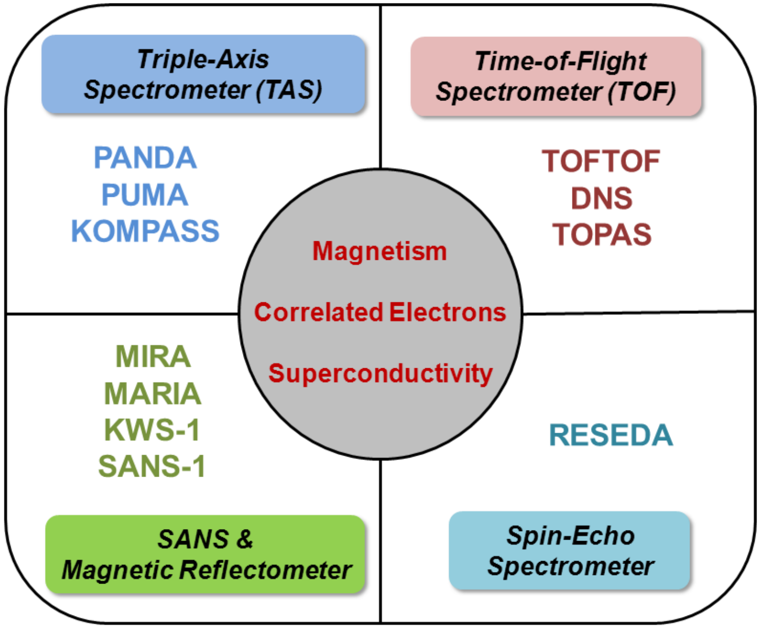
Detwinned single crystal of 122 ferropnictide



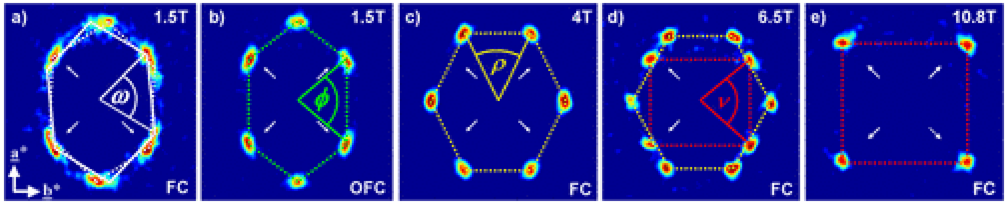
PUMA / X. Lu, J.T. Park *et al.*, **Science** (2014)

Anisotropic spectral weight between (pi,0) and (0,pi) above T_s

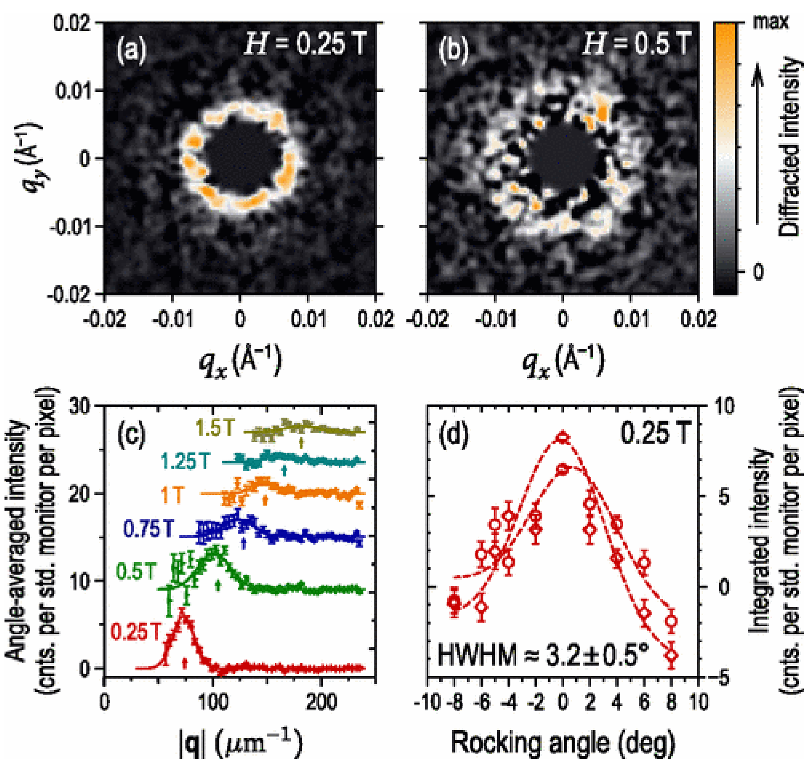
What QP group can do more on superconductivity research?

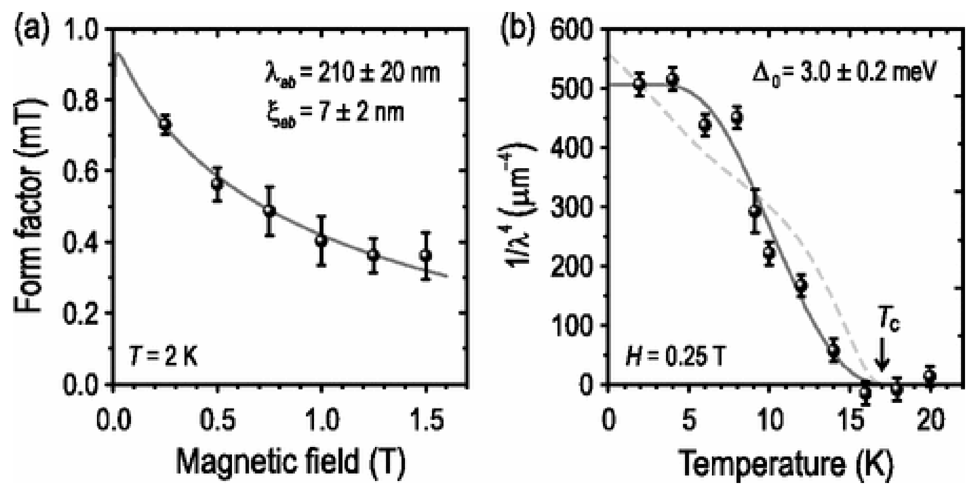


Vortex lattice studies in SANS



PSI / $YBa_2Cu_3O_7$ / J. White *et al.*, **PRL** (2009)





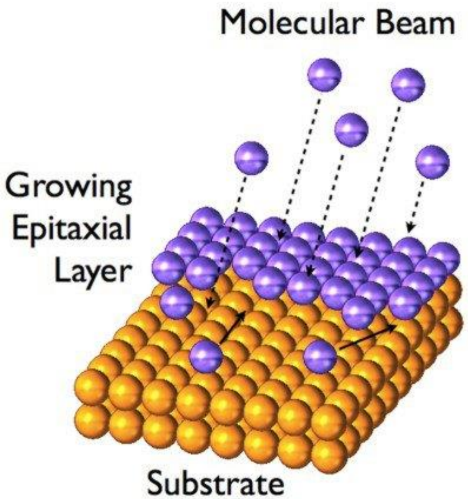
PSI / LiFeAs / D. S. Inosov, JTP *et al.*, **PRL** (2011)

Investigating superconducting energy gap structures and values

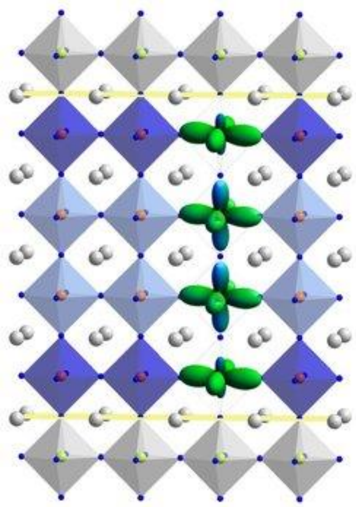
Multi-layer thin film fabraction & measurement

MBE team in QP group

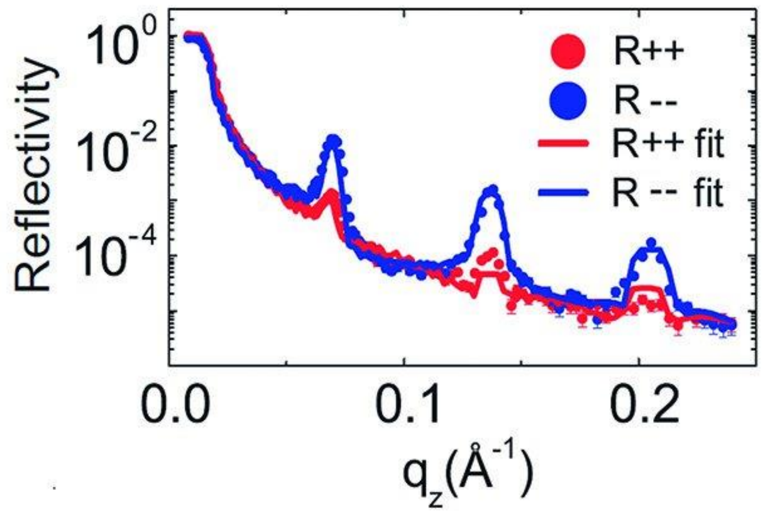
Neutron reflectometry



Epitaxial growth (schematic)



Nickelate / Abt. Keimer



N-REX / $La_{0.7}Sr_{0.3}MnO_3$-$SrRuO_3$
J.-H. Kim *et al*., **PRB** (2014)

By fabricating electronic structures on interfaces, one can construct high-T_c friendly system
→ study static response of magnetism
→ study dynamical properties with INS

This is not the end...

The highest T_c ever…

The room temperature superconductor in polymeric materials…

Design for a Room Temperature Superconductor

W. E. Pickett
Department of Physics, University of California, Davis, California, 95616
(Dated: February 3, 2008)

The vision of "room temperature superconductivity" has appeared intermittently but prominently in the literature since 1964, when W. A. Little and V. L. Ginzburg began working on the *problem of high temperature superconductivity* around the same time. Since that time the prospects for room temperature superconductivity have varied from gloom (around 1980) to glee (the years immediately after the discovery of HTS), to wait-and-see (the current feeling). Recent discoveries have clarified old issues, making it possible to construct the blueprint for a viable room temperature superconductor.

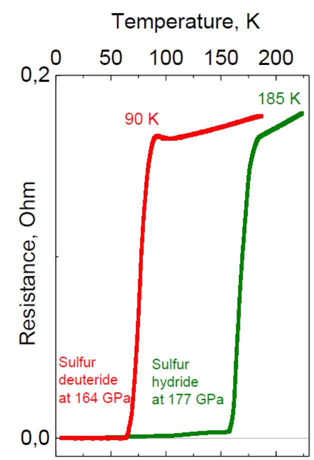
T_c of 190K has been recorded in hydrogen material under extreme pressure

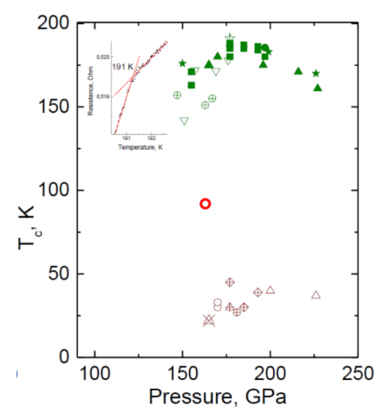
Conventional superconductivity at 190 K at high pressures

A.P. Drozdov, M. I. Eremets*, I. A. Troyan

Max-Planck Institut fur Chemie, Chemistry and Physics at High Pressures Group

Postfach 3060, 55020 Mainz, Germany





Interdisciplinary collaborations at MLZ