Opportunities for Studying Superconductivity with X-ray Echo Spectroscopy

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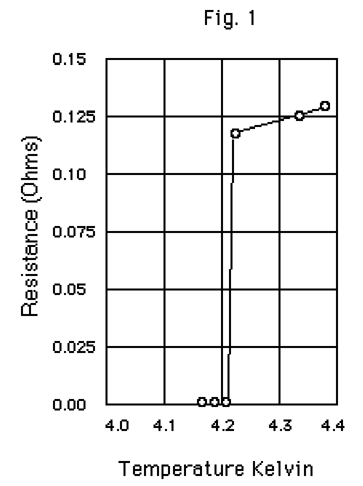
Sept. 9, 2016

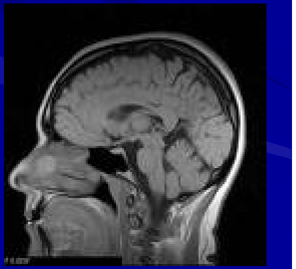
Superconductivity

- Properties
  - Resistance goes to zero at the transition temperature T_c.
  - SC expels magnetic field (Meissner)
    - Perfect diamagnet



Onnes, Mercury, 1911

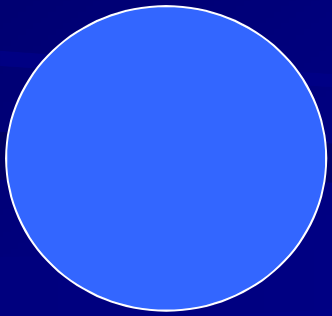
http://www.tgerding.com/projects/healthcare



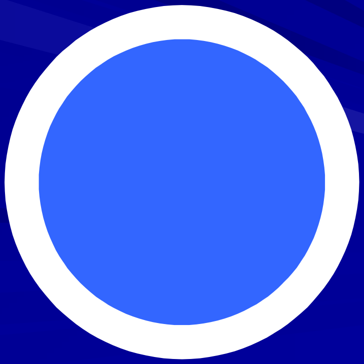
www.melissamemorial.org /CMS/Show?id=18

WHY?
Standard Superconductors

- Standard SC follow BCS theory
  - Electrons are paired
  - Phonons provide pairing (e-p coupling)
  - *s*-wave superconductivity
    - Fermi surface is gapped uniformly
      - Gap is region of forbidden states
        - Gap is ~ $2\Delta \sim 3.5\,T_c$



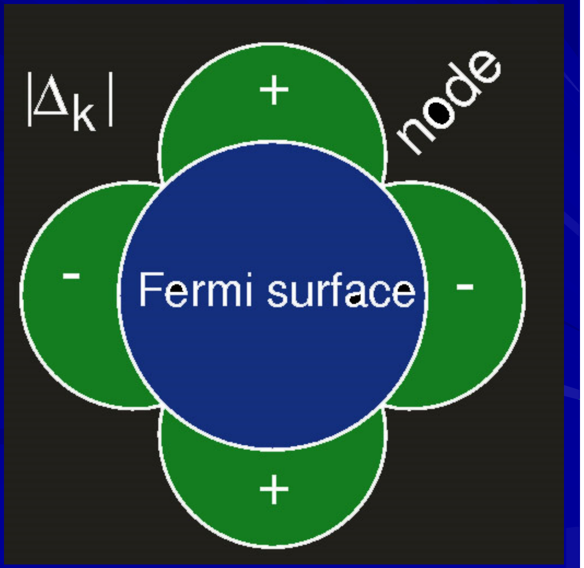
Fermi Surface



Fermi Surface with gap

Exotic Superconductors

- Properties
  - – Electrons are paired but how?
  - – Pairing mechanism non – phonon
    - Magnetic excitations, plasmons, ??
  - – Gap anisotropic
    - Nodes on the gap
    - Sign change of order parameter
- Examples
  - – Copper oxides systems
  - – Iron arsenic systems
  - – Heavy fermion
  - – Organic superconductors



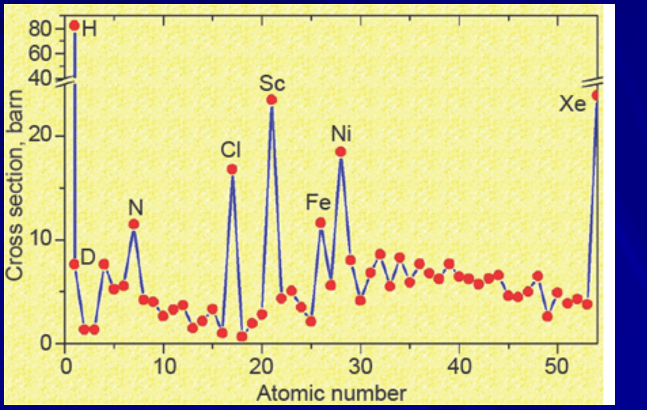
http://www.phys.ufl.edu/~pjh/research/dwave1.jpg

Fundamental Questions For SC

- Phonon mediated superconductors
  - Which phonons, softening, dispersion
  - e-p coupling constant
  - Band gap
- Exotic SC
  - Source of electron binding when not phonons
  - Structure of energy gap

- Basic understanding of material

Other Phonon Techniques

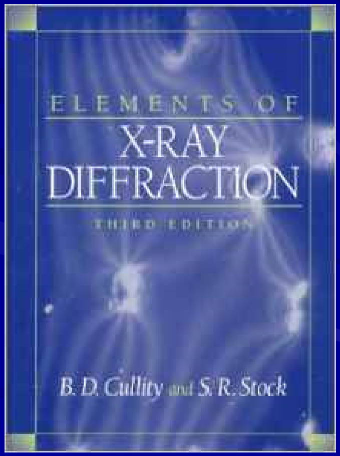


Johnson Matthey Technol. Rev., 2016, 60, (2), 132

- Neutron
  - Higher resolution
  - More developed technique
  - Different coupling to atoms
  - Can study magnetic excitations
- Raman
  - Sees only small part of Brillouin zone (~1%)
  - Very high flux
  - Selection rules limit excitations it can see
  - Can focus to small samples
- EELS and He atom scattering
  - Surface probes for phonons
  - High vacuum

Inelastic X-ray Scattering

- X-rays
  - Complete Brillouin zone
  - Penetrates
    - Not a surface probe
    - High P or other environments
  - Lacks kinematic/isotopic restrictions for neutrons
  - Can access small samples
    - Spallation Neutron Source 1 mm^3
    - IXS (10 micron)^3 – 10^6 times smaller

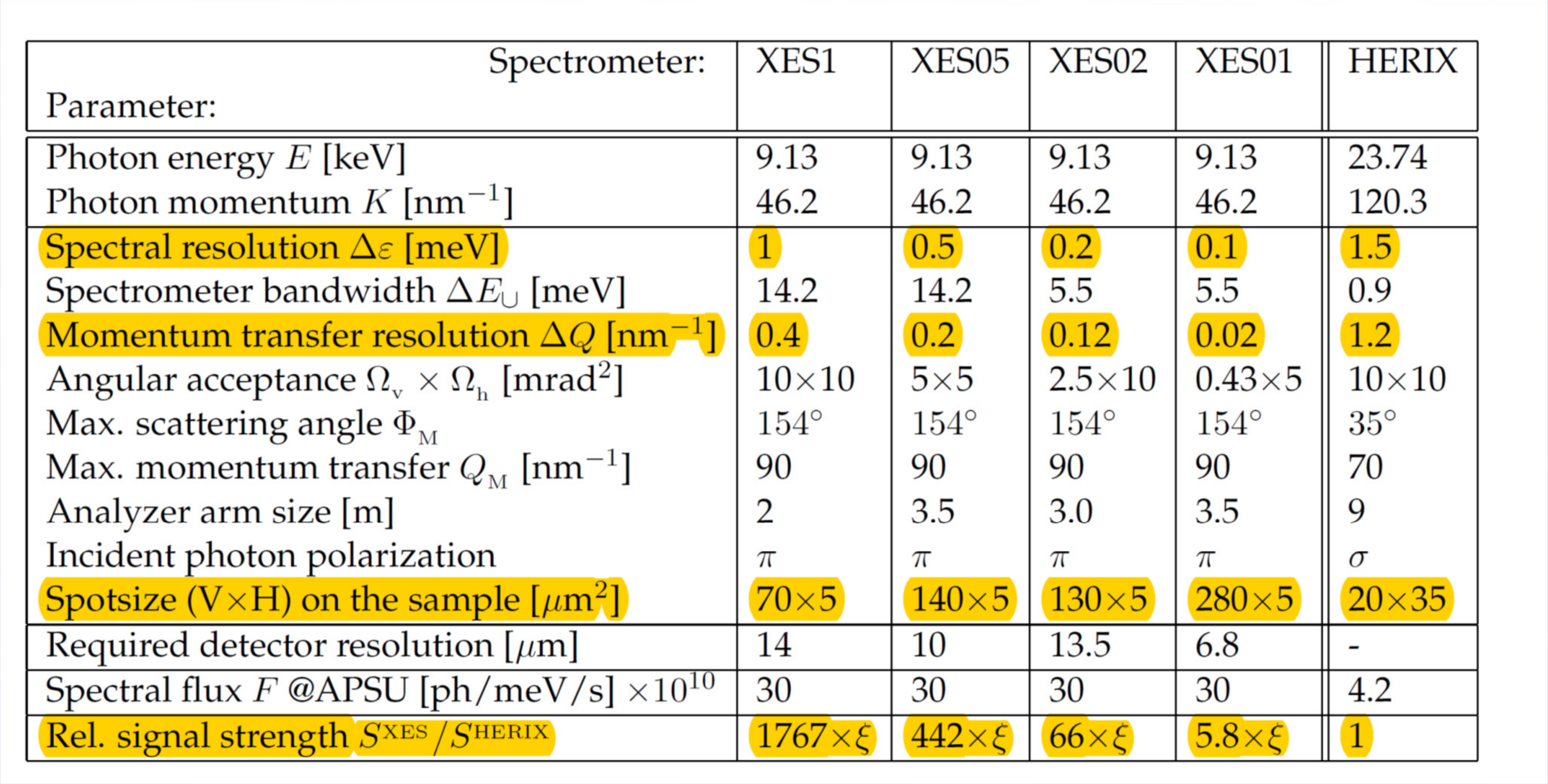


ELEMENTS OF
X-RAY
DIFFRACTION
THIRD EDITION
B. D. Cullity and S. R. Stock

Small samples – almost POWDERS

- **Grind to pass 325 mesh Screen - Cullity**
  - **325 mesh = 44 microns**
- **Ideal probe for new materials**

X-ray Echo Spectroscopy

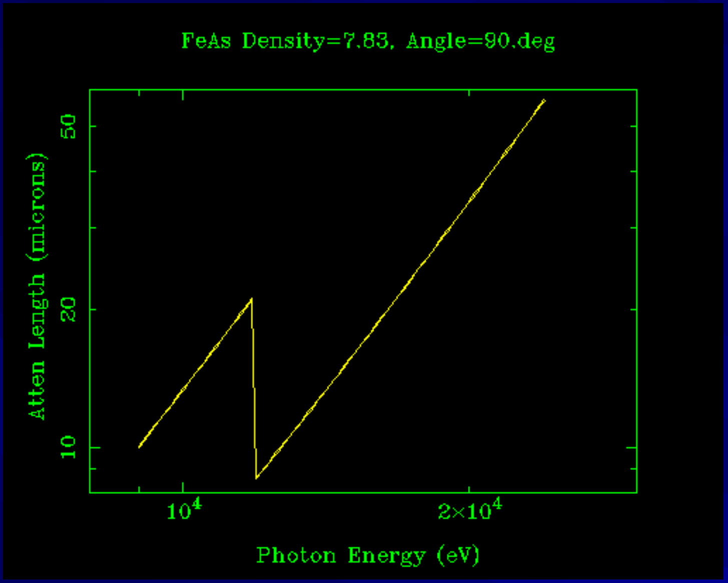


Spectrometer: Parameter:	XES1	XES05	XES02	XES01	HERIX
Photon energy E [keV]	9.13	9.13	9.13	9.13	23.74
Photon momentum K [nm^{-1}]	46.2	46.2	46.2	46.2	120.3
Spectral resolution $\Delta\varepsilon$ [meV]	1	0.5	0.2	0.1	1.5
Spectrometer bandwidth $\Delta E_{\cup}$ [meV]	14.2	14.2	5.5	5.5	0.9
Momentum transfer resolution ΔQ [nm^{-1}]	0.4	0.2	0.12	0.02	1.2
Angular acceptance $\Omega_{\mathrm{v}} \times \Omega_{\mathrm{h}}$ [mrad^2]	10×10	5×5	2.5×10	0.43×5	10×10
Max. scattering angle Φ_{M}	154°	154°	154°	154°	35°
Max. momentum transfer Q_{M} [nm^{-1}]	90	90	90	90	70
Analyzer arm size [m]	2	3.5	3.0	3.5	9
Incident photon polarization	π	π	π	π	σ
Spotsize (V×H) on the sample [μm^2]	70×5	140×5	130×5	280×5	20×35
Required detector resolution [μm]	14	10	13.5	6.8	-
Spectral flux F @APSU [ph/meV/s] $\times 10^{10}$	30	30	30	30	4.2
Rel. signal strength $S^{\mathrm{XES}}/S^{\mathrm{HERIX}}$	$1767\times\xi$	$442\times\xi$	$66\times\xi$	$5.8\times\xi$	1

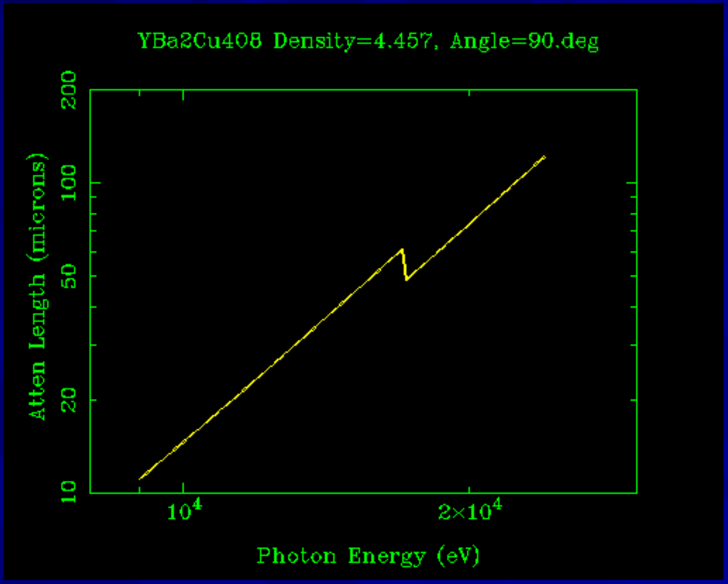
$$\xi = L_{\mathrm{s}}^{\mathrm{XES}} / L_{\mathrm{s}}^{\mathrm{HERIX}}$$

Length Reduction Effects

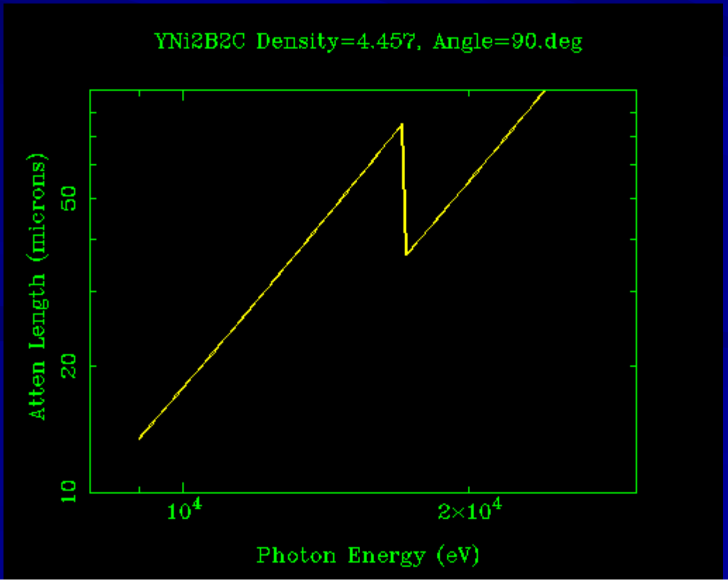
FeAs (~5)



YBCO (~25)



YNiBC (~6)

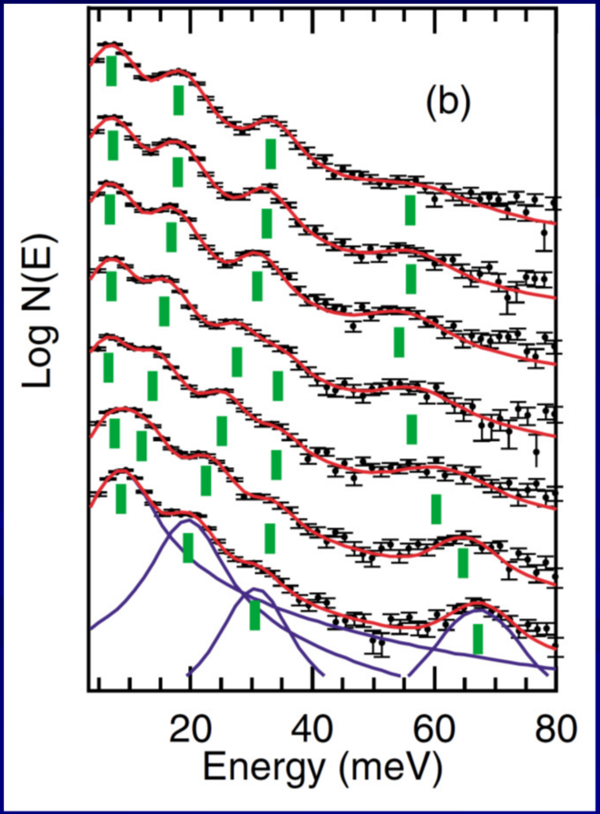


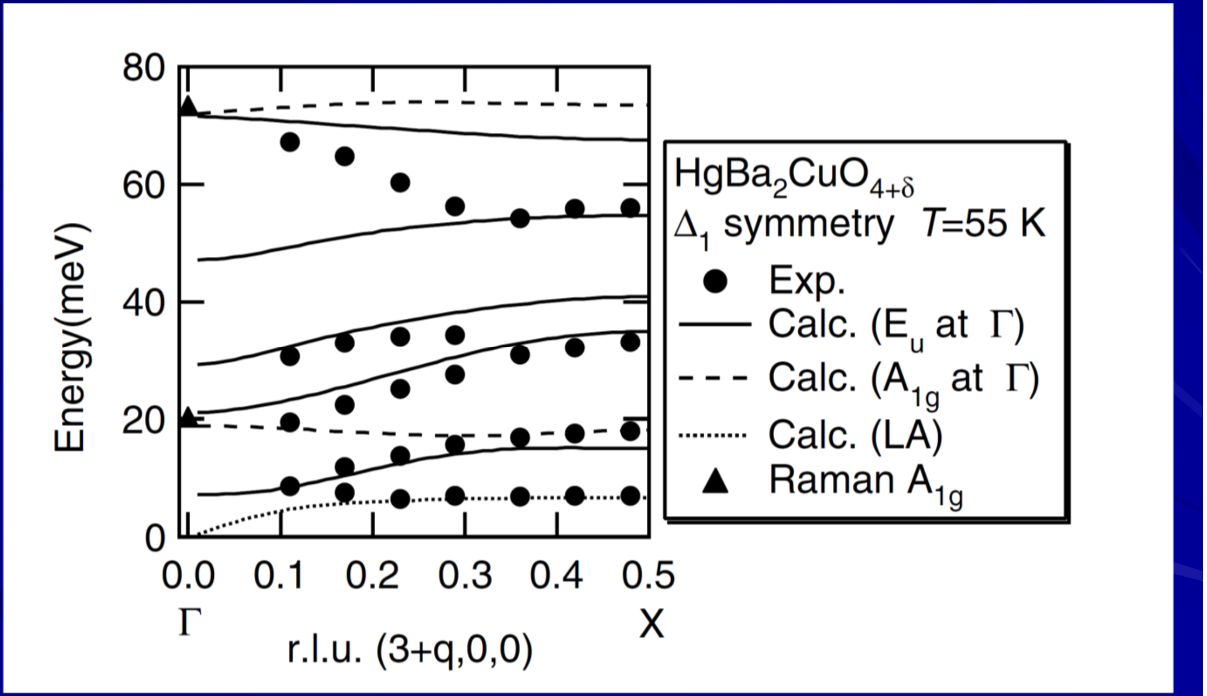
Calculations from CXRO online software

High T_c SCs

- Role of phonons??
  - – Weak Phonon signal
  - – Many modes

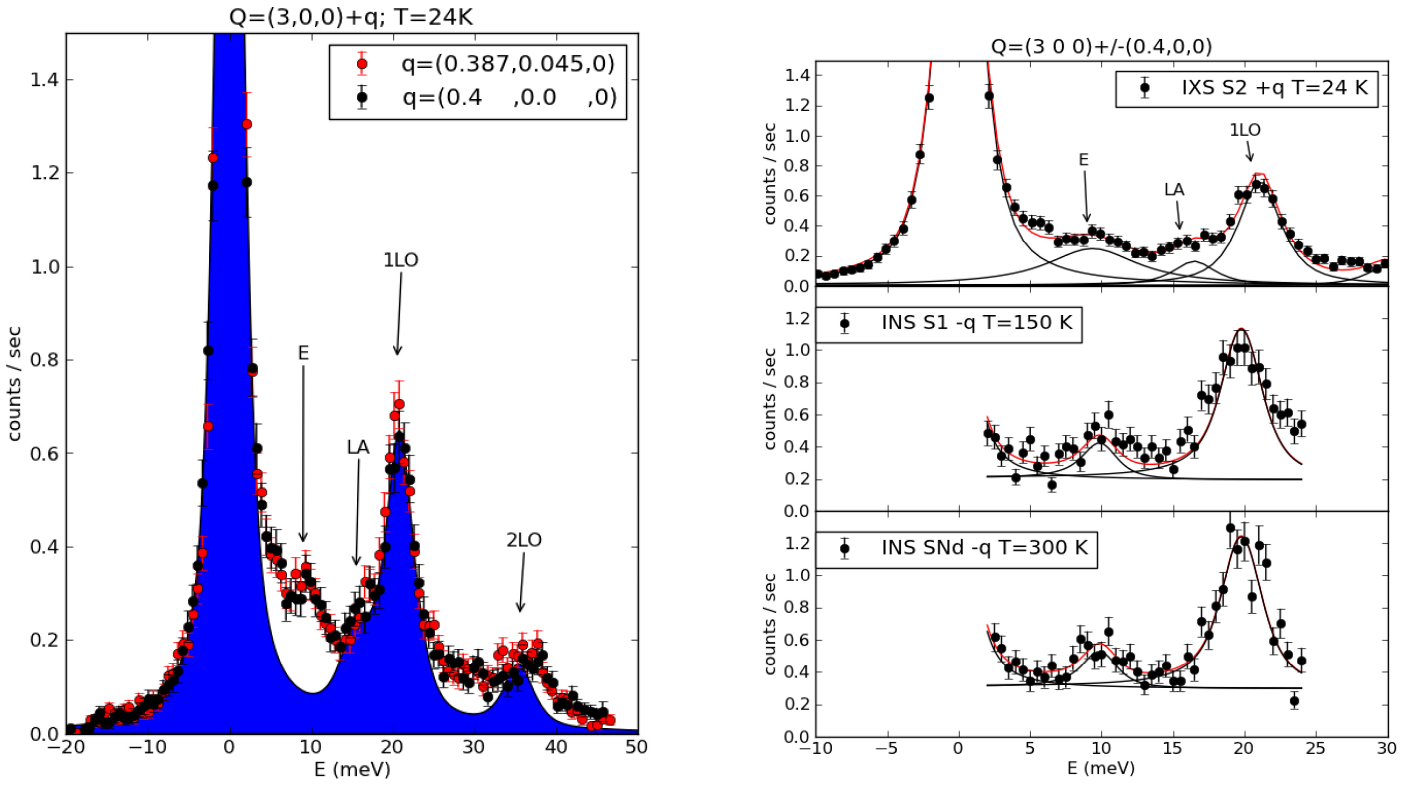
$HgBa_2CuO_{4+\delta}$





Baron et al., PRL 92 197005, 2004

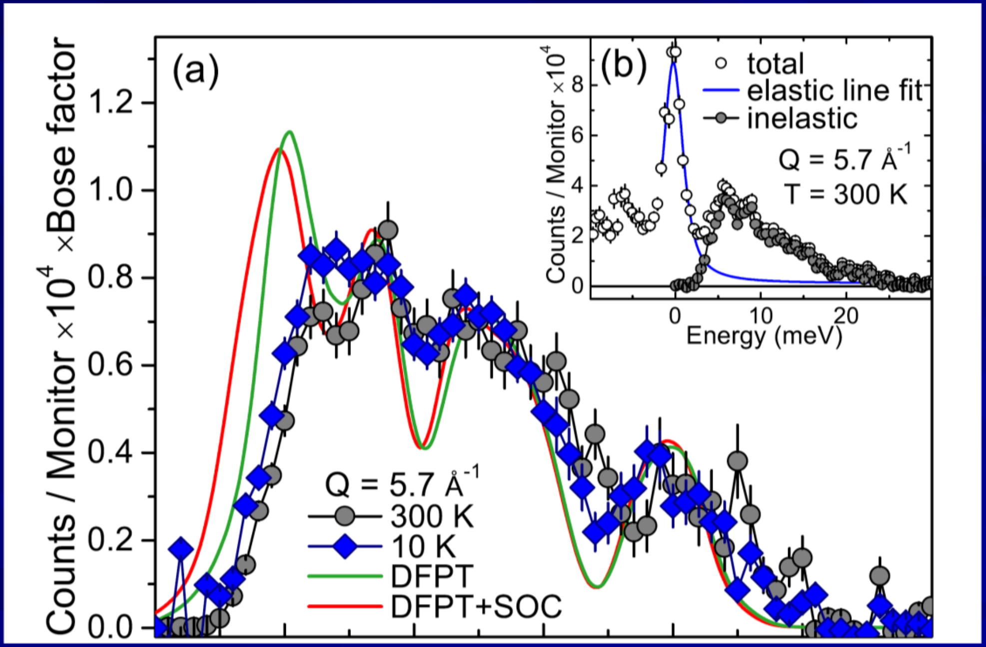
$(La,Nd)_{2-x}Sr_xCuO_4$



D’Astuto et al, arXiv:1502.04003v1

Classical SC - $SrPt_3P$

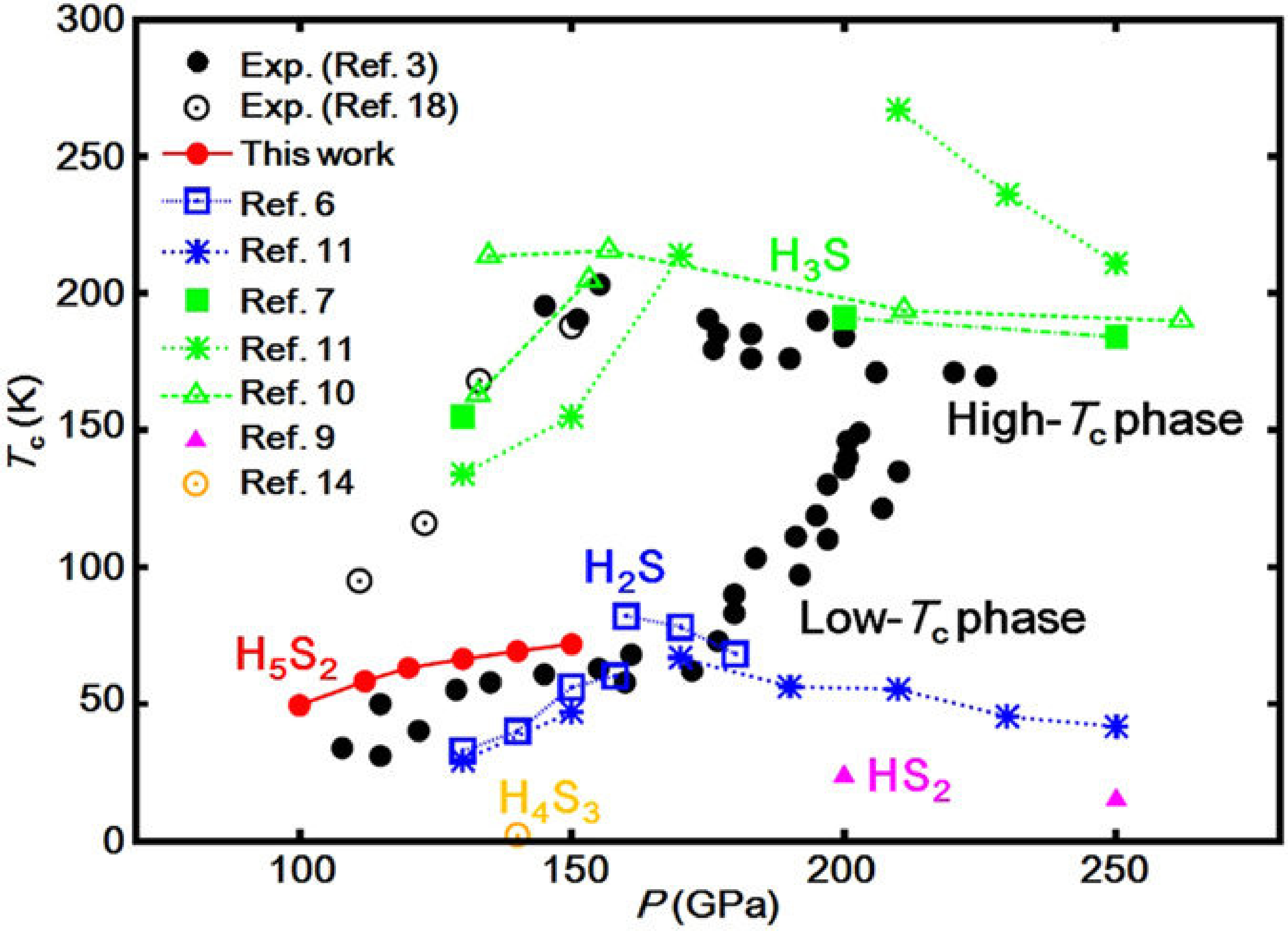
- Conventional SC with strong e-p coupling
- Test lattice models



Zocco et al., PHYSICAL REVIEW B **92**, 220504(R) (2015)

High Temperature Conventional SC

- Hydrogen Sulfide

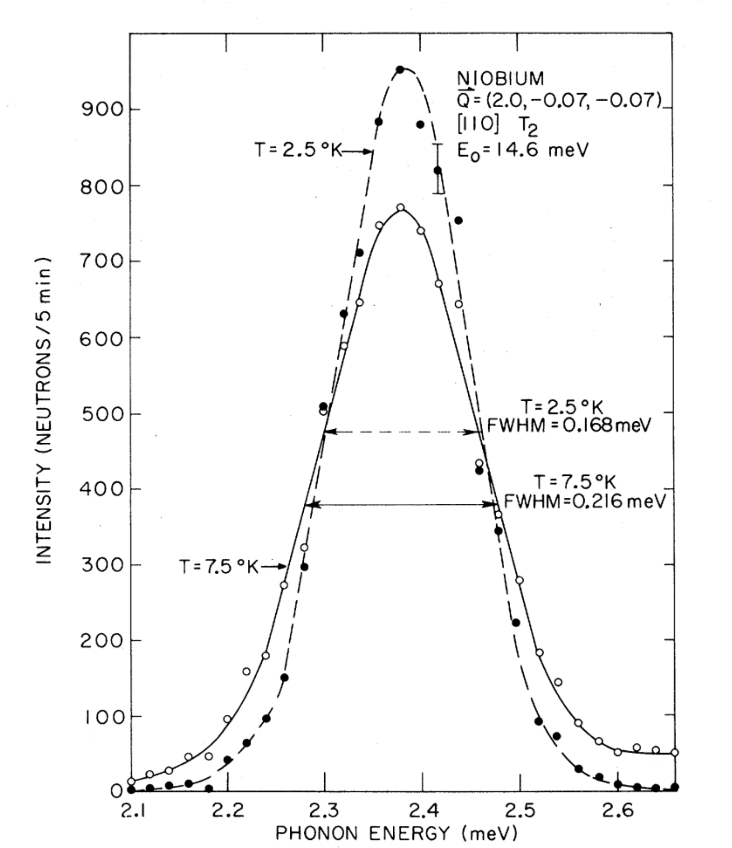


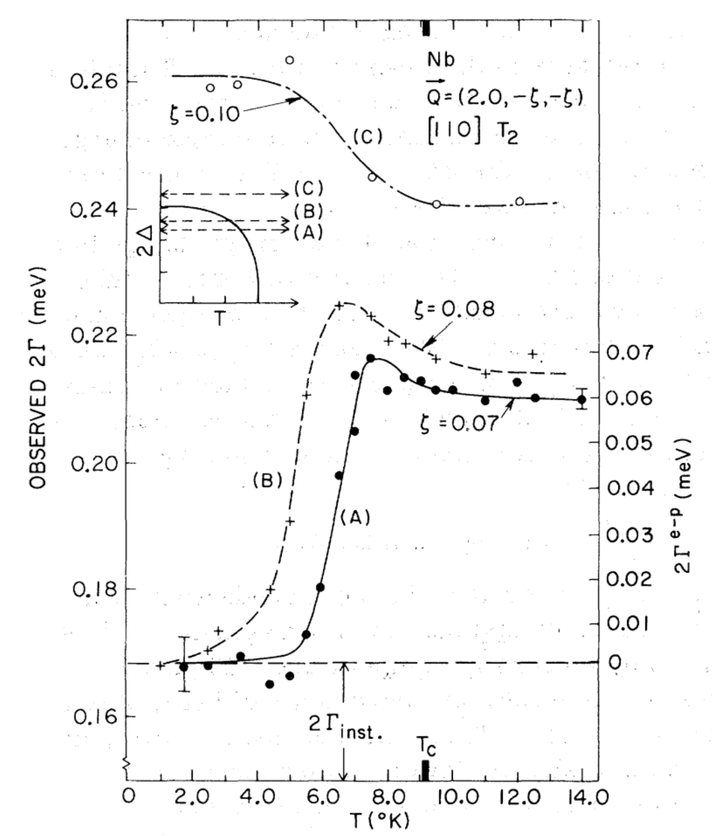
Ishikawa, Takahiro et al. *Scientific Reports* 6 (2016): 2016.

Phonon Shifts at SC transition

- First neutron measurements Nb (T_c ~ 9K)
  - – Shapiro, Shirane, Axe

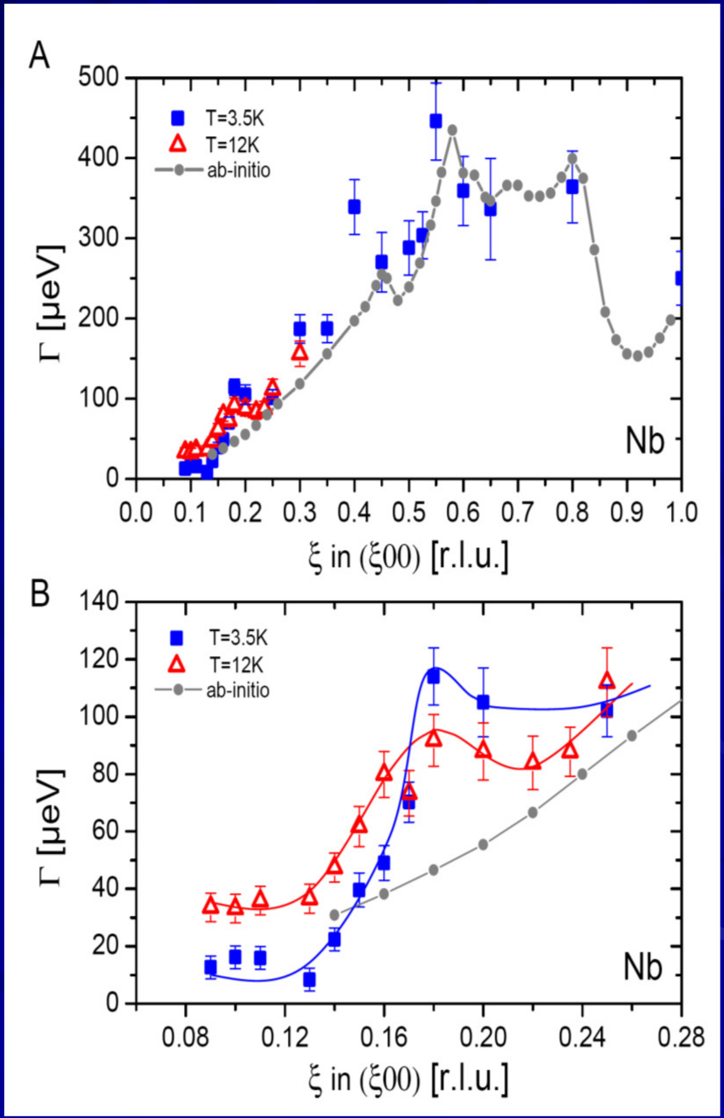
PRB 12, 4899 (1975)

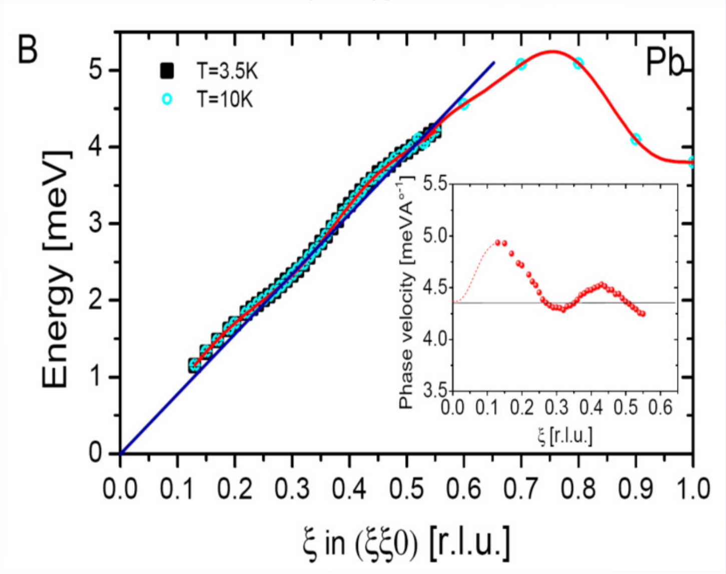




Phonon Line Width Spectroscopy

- Neutron Scattering on Nb
  - Superconductor $T_c = 9.3$ K
  - Phonon shifts below T_c
- Kohn anomalies corresponding to energy gap
- Correlation between superconductivity and Fermi nesting?

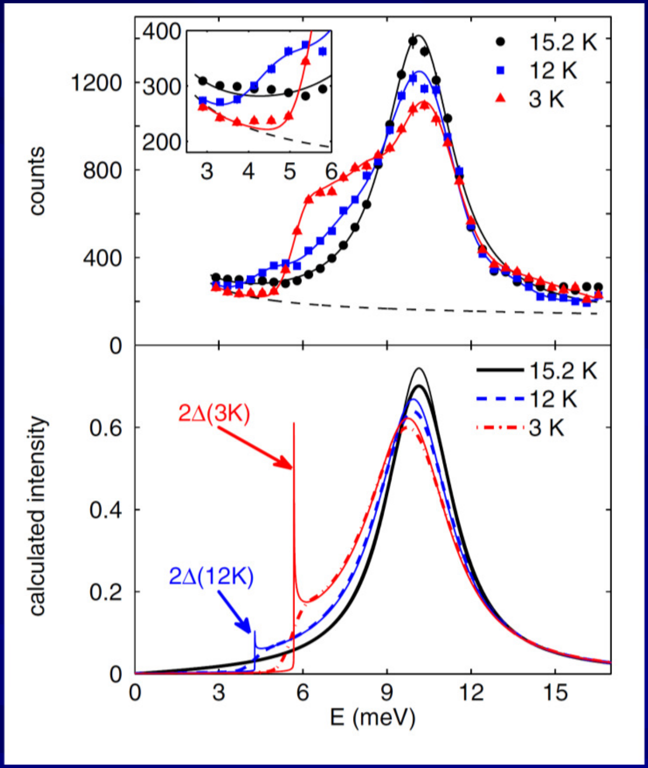




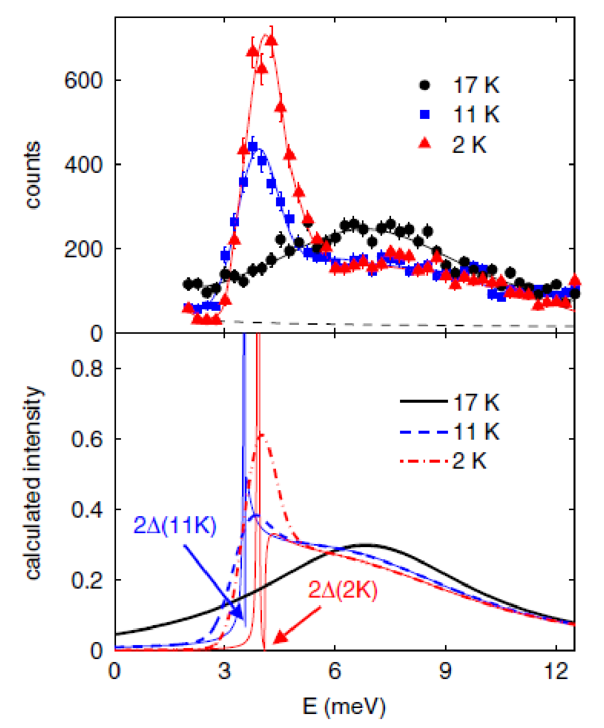
P. Aynajian et al., Science 319, 1509 (2008).

Neutron Work on YNi$_2$B$_2$C

- Conventional BCS Superconductor
  - Phonon shifts at SC transition

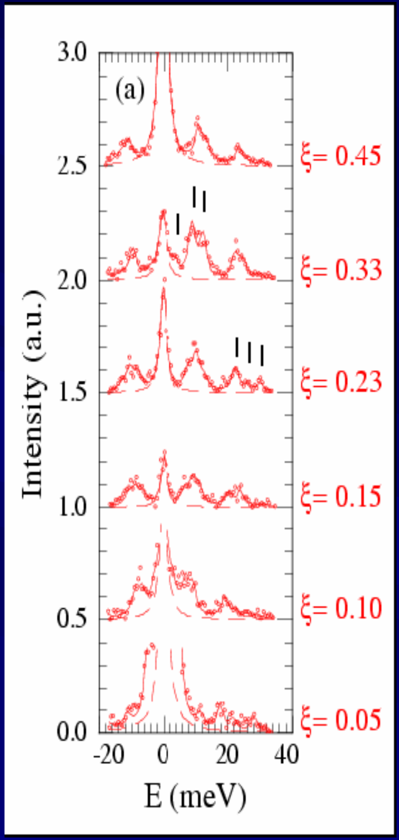


Weber et al.,
Phys. Rev. Lett.
101, 237002 (2008)

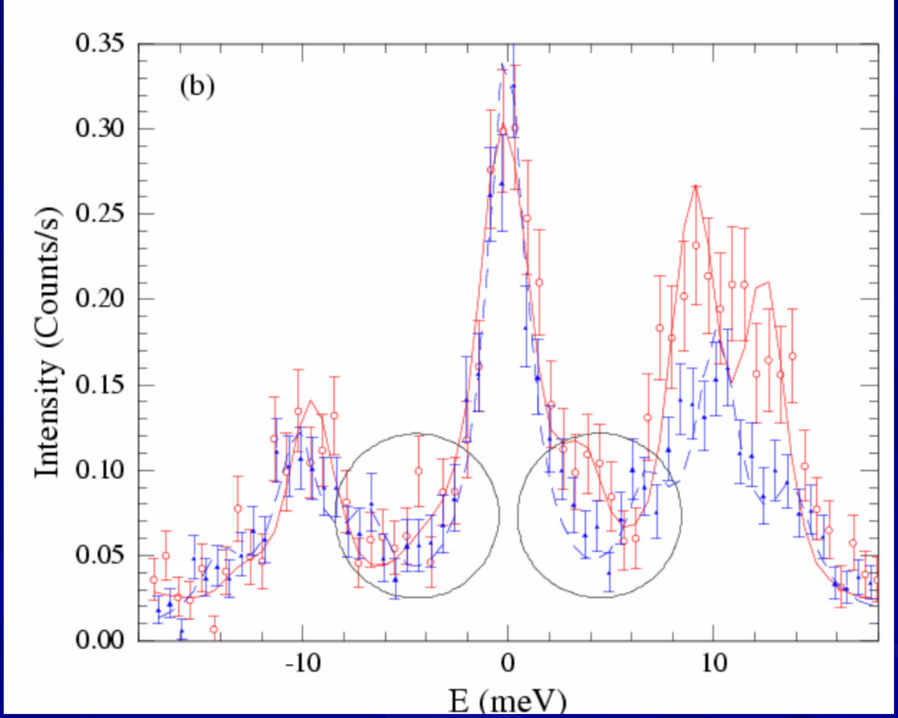


  - Spectral weight pushed out of gap region

Surface Phonon Scattering



$2H$-$NbSe_2$

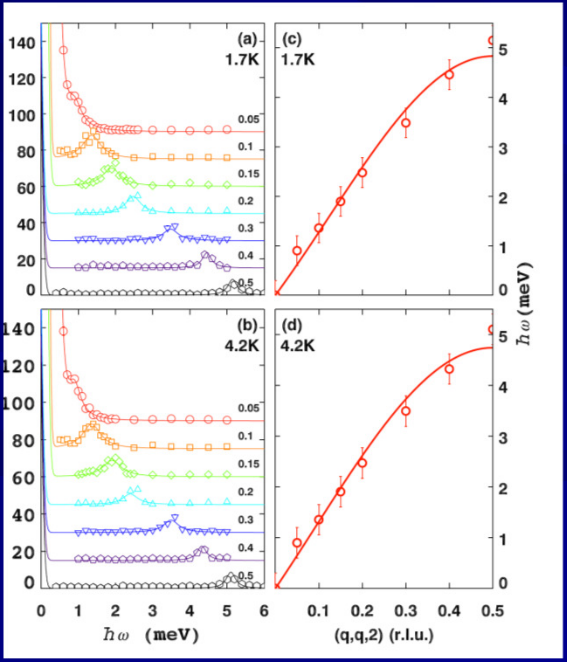


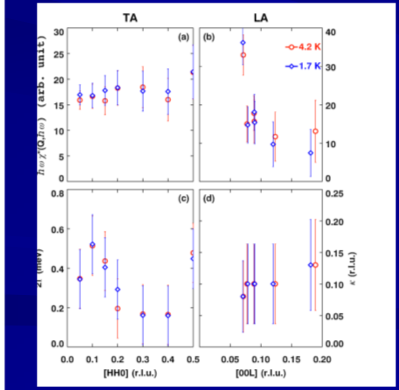
- Thin films (need to compare to e.g., He scattering)
- Buried interfaces?
- Study 2-d SC

Murphy et. al, PRL 95, 256104 (2005)

Topological Superconductors

- Topologically protected states
- Exotic Superconductivity
  - E.g. **Low-energy phonons and superconductivity in $Sn_{0.8}In_{0.2}Te$**

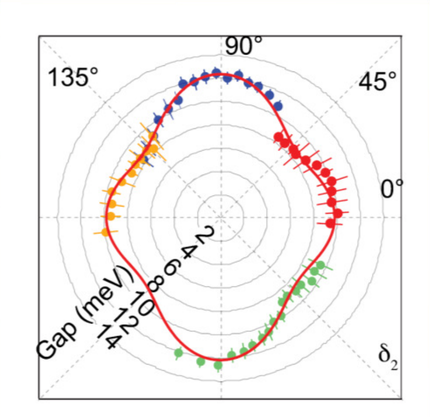




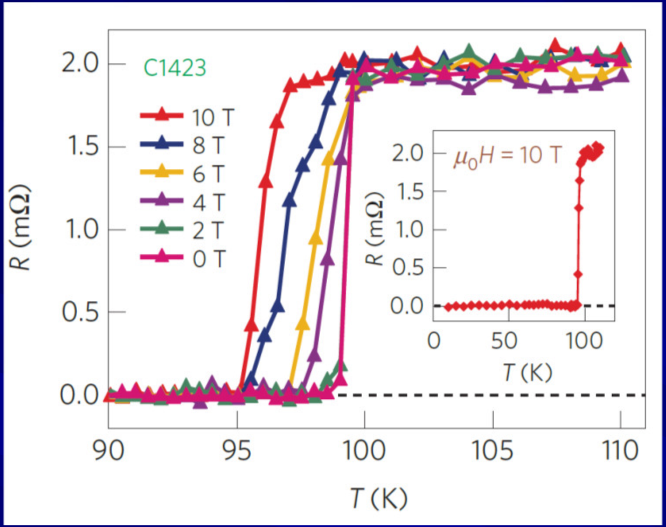
PHYSICAL REVIEW B **91**, 054522 (2015)

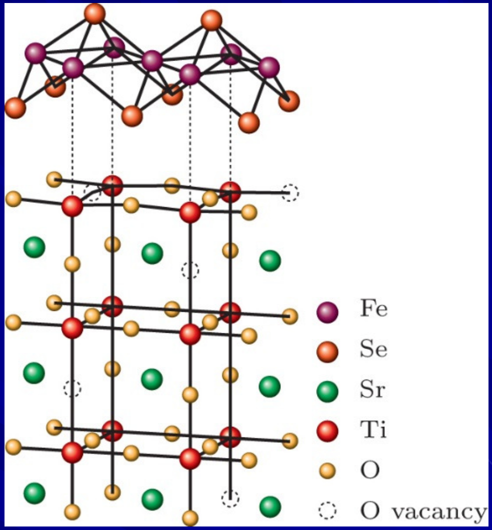
2-d Superconductivity

- FeSe layers on doped $SrTiO_3$
  - T_c ~100K
  - Bulk T_c ~9K



PRL **117,** 117001 (2016)



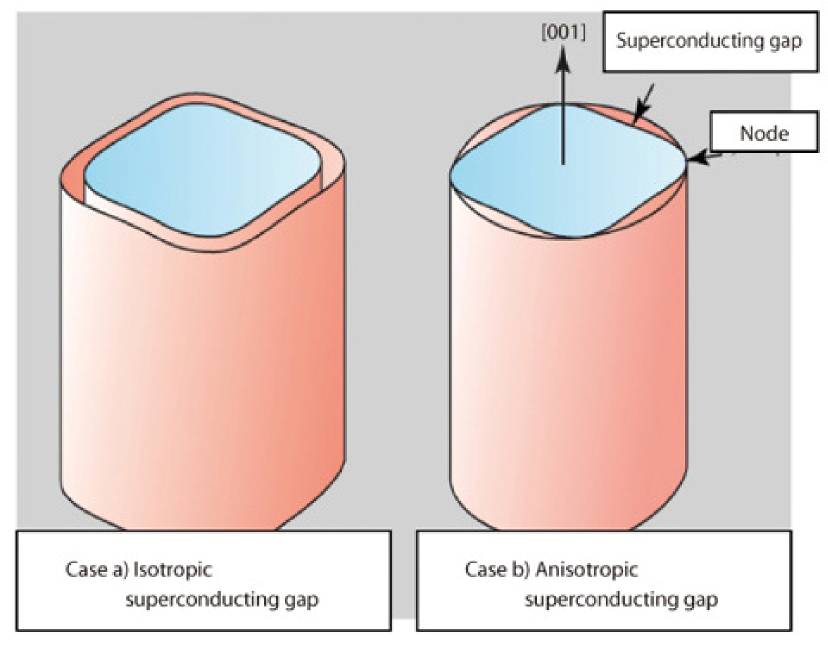


Ge et al., Nature Materials, 14, 285 (2014)

- Interface superconductivity
  - $CaCuO_2/BaCuO_2$ (80K)
  - LaCuO /$La_{1.55}Sr_{0.45}CuO_4$ (30K – 50K w/O_3)
  - $CaCuO_2/SrTiO_3$ (40K)

Direct Measurement of SC Gap?

- Scattering channel for excitation across gap
  - Directly measure
    - Johanson, PRB 53, 8726
    - 10 meV gap ~30K T_c
    - Phonon background?



http://jolisfukyu.tokai-sc.jaea.go.jp/fukyu/mirai-en/2006/img/honbun/6-9.jpg

Summary

- IXS phonon experiments flux limited
- X-ray echo provides as much as 10^3 gain in flux, allows for higher resolution (0.1 meV, 0.02 nm^{-1})
- Flux increases would allow
  - Large improvements in current techniques
    - Much faster data acquisition
    - Better surface scattering
  - New capabilities
    - Phonon studies of SC under pressure
    - Direct measurement excitation across SC gap?
    - Higher resolution studies
- Tremendous opportunity for SC research