Three axis spin echo - examples from TRISP

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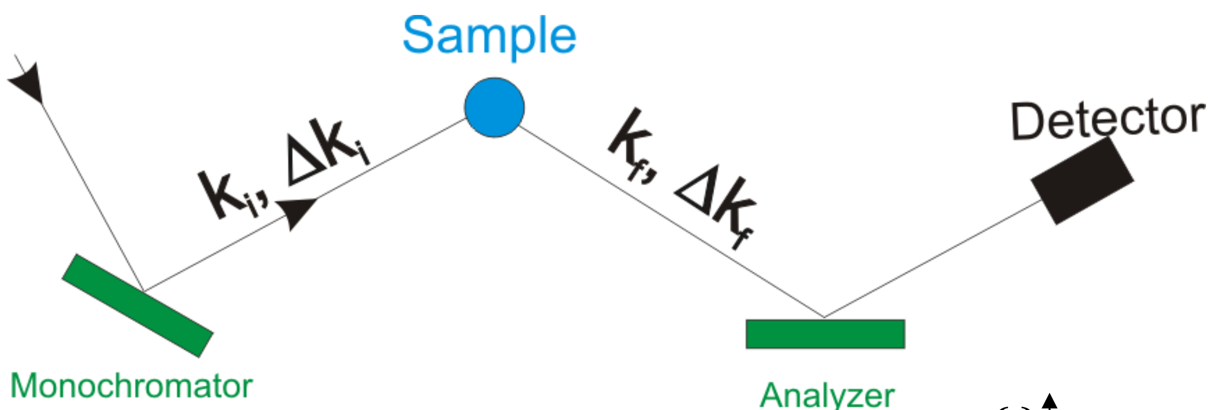
outline

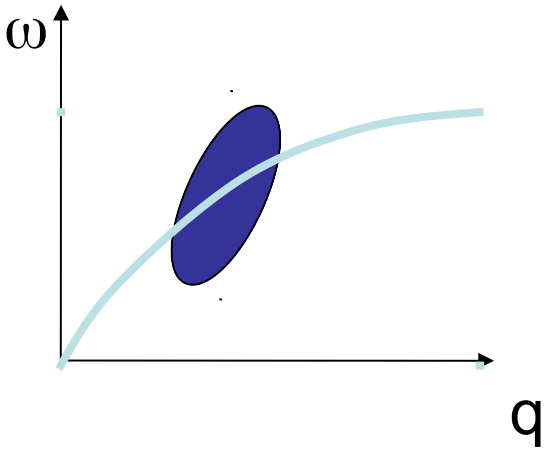
- basic principles of spin-echo TAS
- phonon lifetimes in elemental superconductors
- magnon lifetimes, critical scattering
- high resolution diffraction (Larmor diffraction)

conventional triple axis spectrometer



$$\hbar\omega = \frac{\hbar^2}{2m}(\mathbf{k}_i^2 - \mathbf{k}_f^2)$$

$$\mathbf{q} = \mathbf{k}_i - \mathbf{k}_f$$

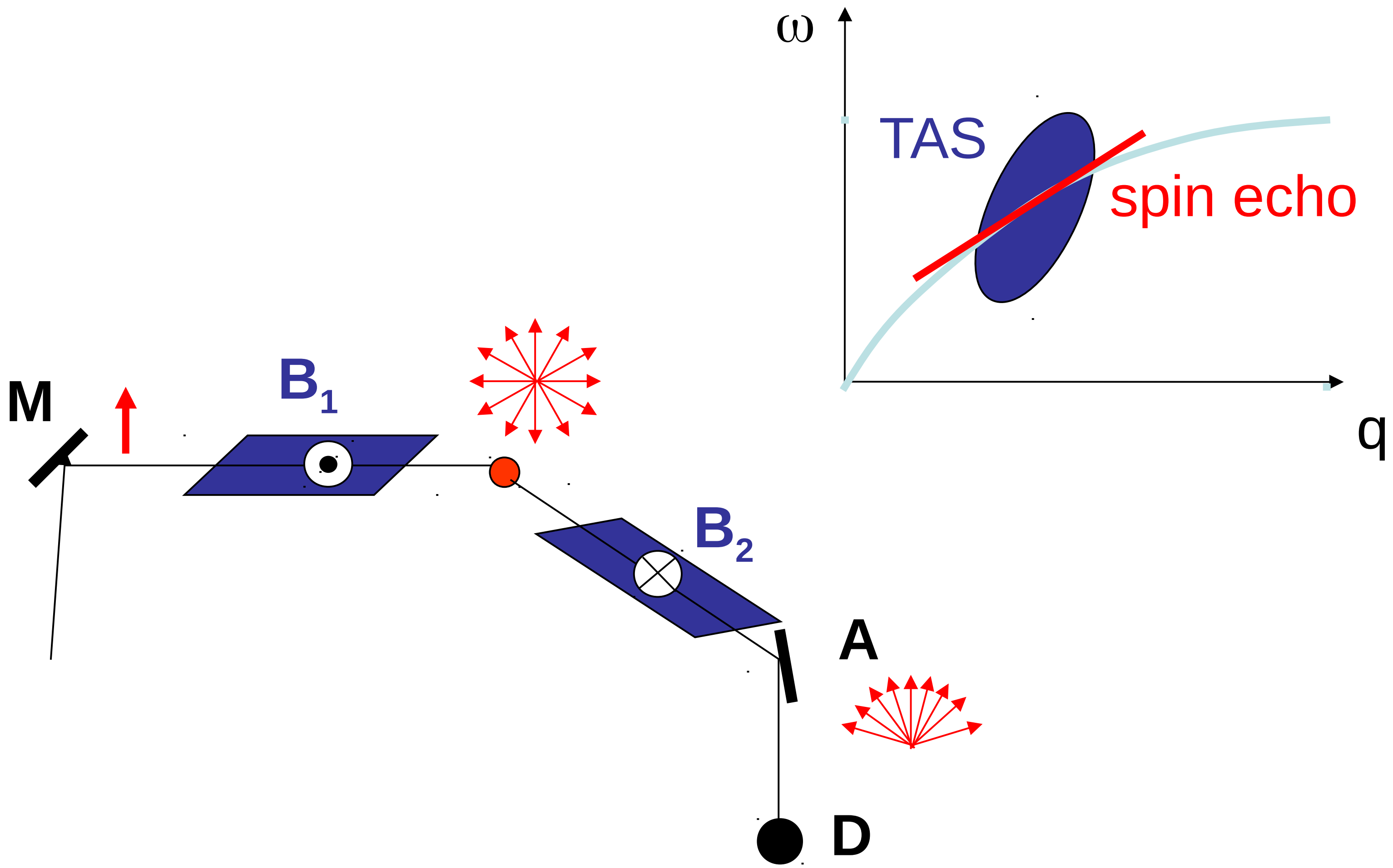


excitation energy: <100meV
energy resolution: typ. 10%

resolution ~ 1/intensity

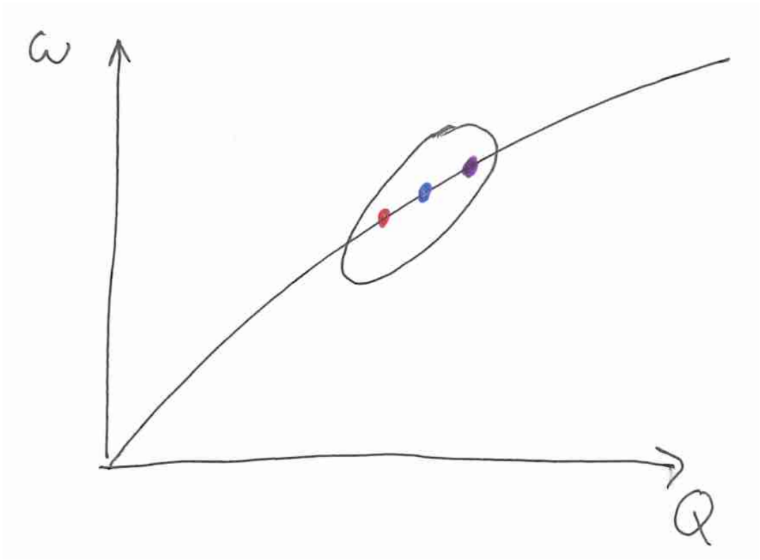
-> not sufficient to resolve linewidths

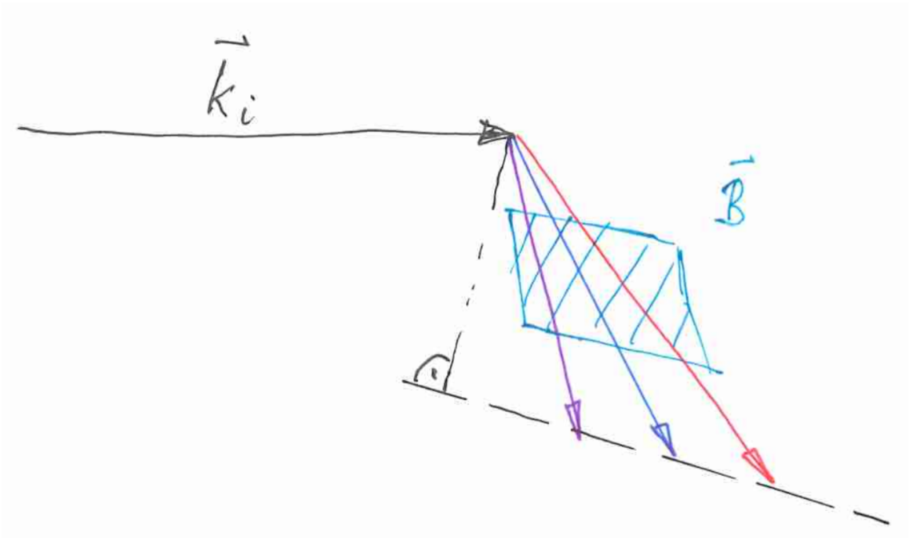
solution Mezei 1977: spin echo + TAS
tilted coil technique



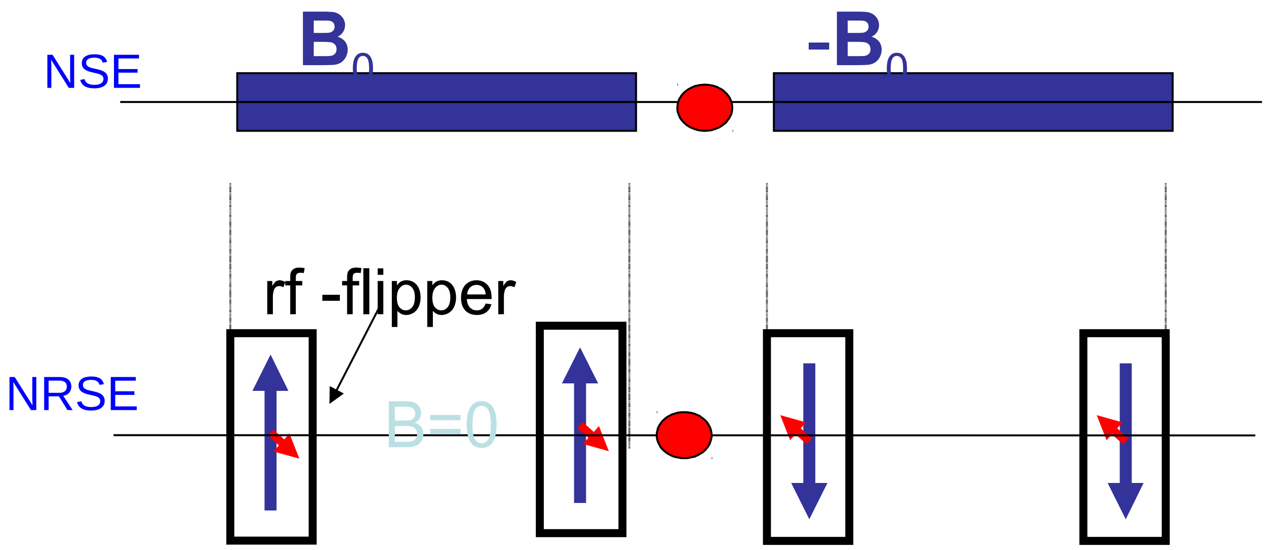
Mezei, Pynn, Spin Echo Bible (1980)

focusing I - Pynn picture





NRSE (neutron resonance SE)



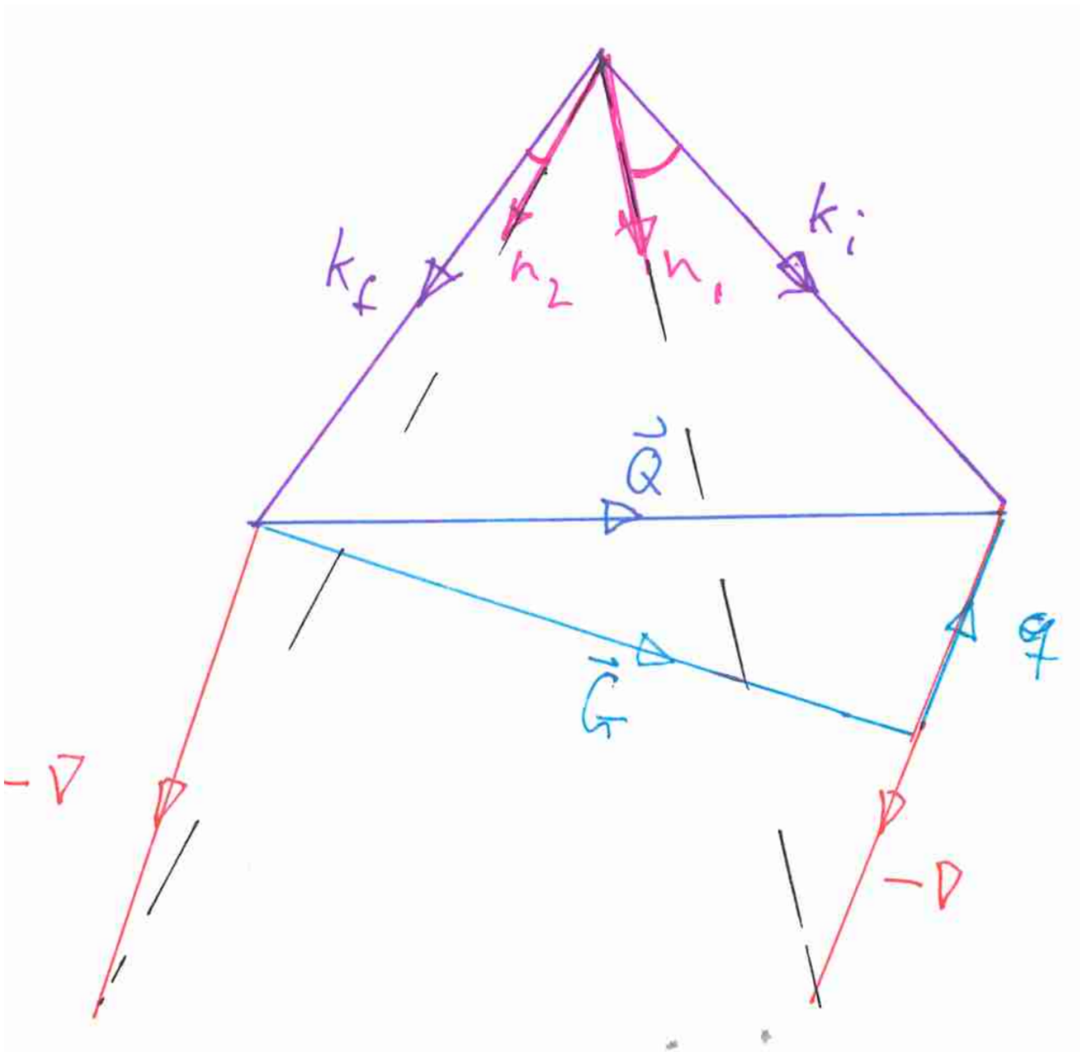
+ NRSE:

- precise field boundaries (windings of rf –flipper)
- high stability (RF oszill. vs. large DC coil)
- no stray fields (*bootstrap* coils)
- mu-metal shield possible
- dispersive excitations (phonons, magnons)
-

+ NSE:

- better resolution for quasielastic small *Q*
- multidetector setups

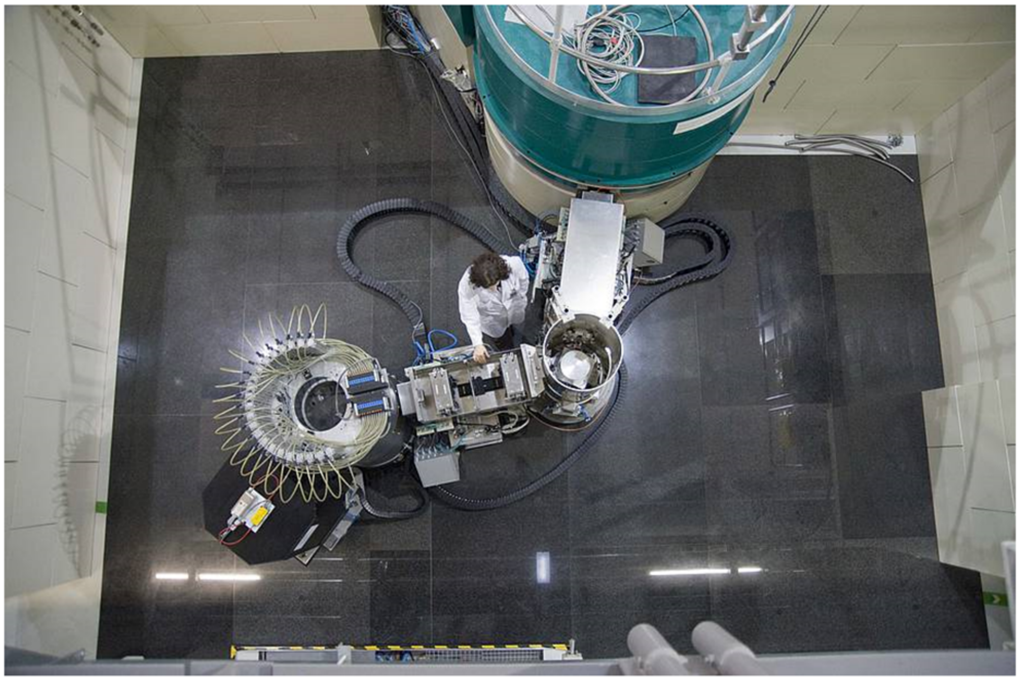
focusing II - scattering triangle

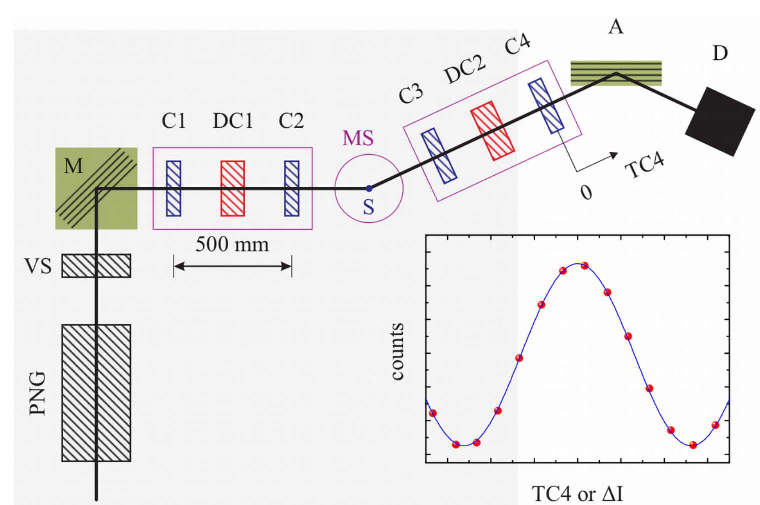


$$n_i \parallel k_i - \frac{d\omega}{dq}$$

$$n_f \parallel k_f - \frac{d\omega}{dq}$$

TAS spin-echo and Larmor diffraction



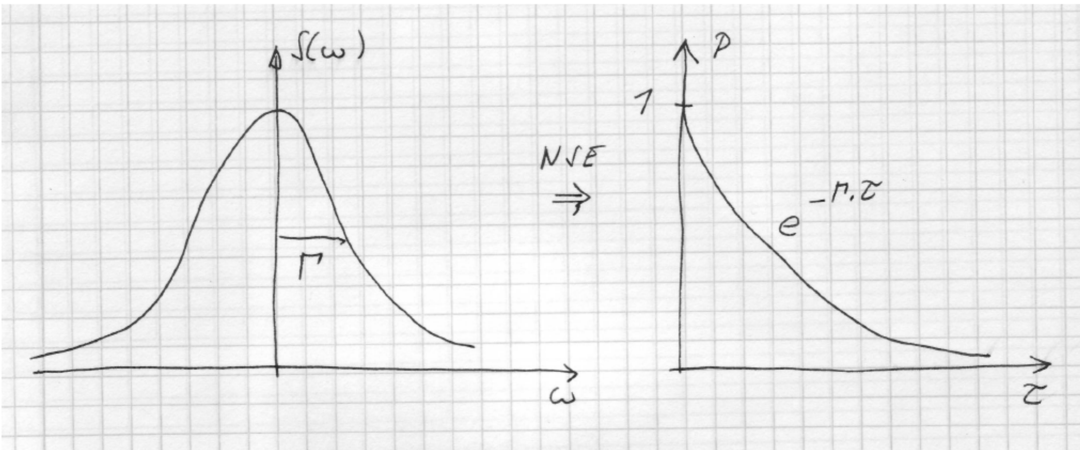


thermal E = 0.4 – 60 meV
resolution 1-10 µeV
LD mode: $\Delta d/d \sim 10^{-6}$

spin echo polarization

$$P(\tau) = P_{\mathrm{res}} \times \cos(\omega_0 \tau) \times \int S(\omega)\cos(\omega\tau)d\omega$$

Lorentzian: $S(\omega) = \frac{1}{\pi} \cdot \frac{\Gamma}{\Gamma^2 + \omega^2}$ $\qquad P(\tau_{\mathrm{NSE}}) = \exp(-\Gamma \cdot \tau_{\mathrm{NSE}})$



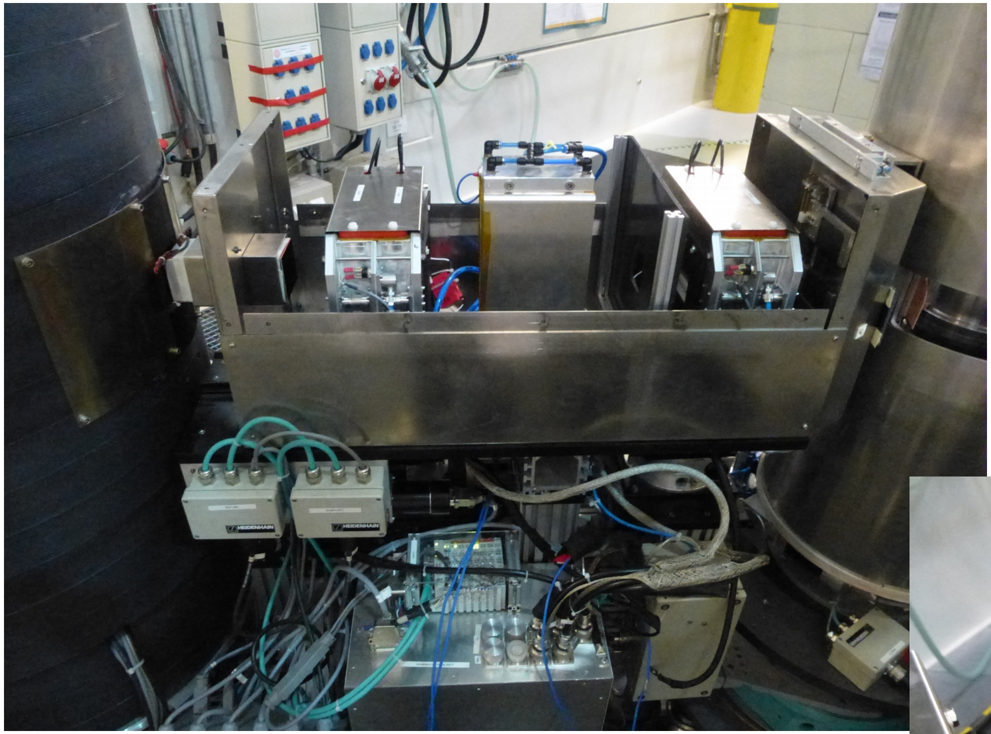
$$P = \frac{1}{N} \int \exp\left(-\tfrac{1}{2}\widetilde{\mathbf{J}}^T \widetilde{\mathbf{L}}_{\mathrm{I}} \widetilde{\mathbf{J}}\right) \mathrm{d}\widetilde{J}_n$$
$$\times \int S(\omega) \exp(-i\tau\Delta\omega)\, \mathrm{d}\Delta\omega + \mathrm{c.c.}$$

resolution matrix includes:
- TAS resolution (Popovici)
- sample mosaic, d-spacing spread
- curvature of dispersion sheet

missing:
detuning, mode splitting, several branches

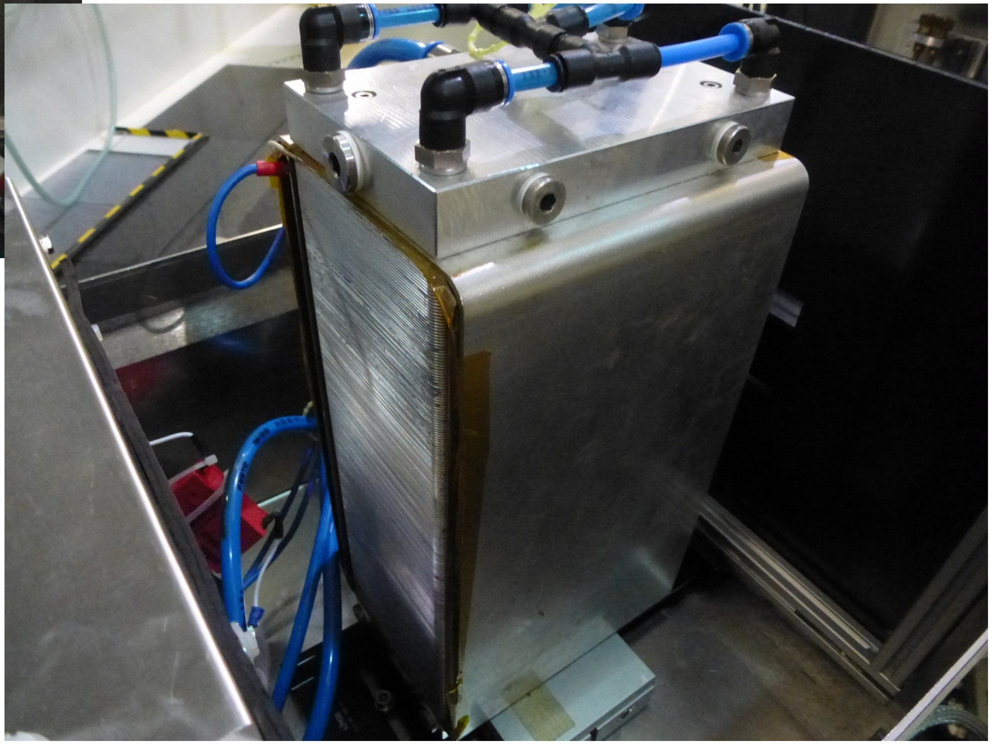
Habicht, J. Appl. Cryst. 36, 1307 (2003)

coils

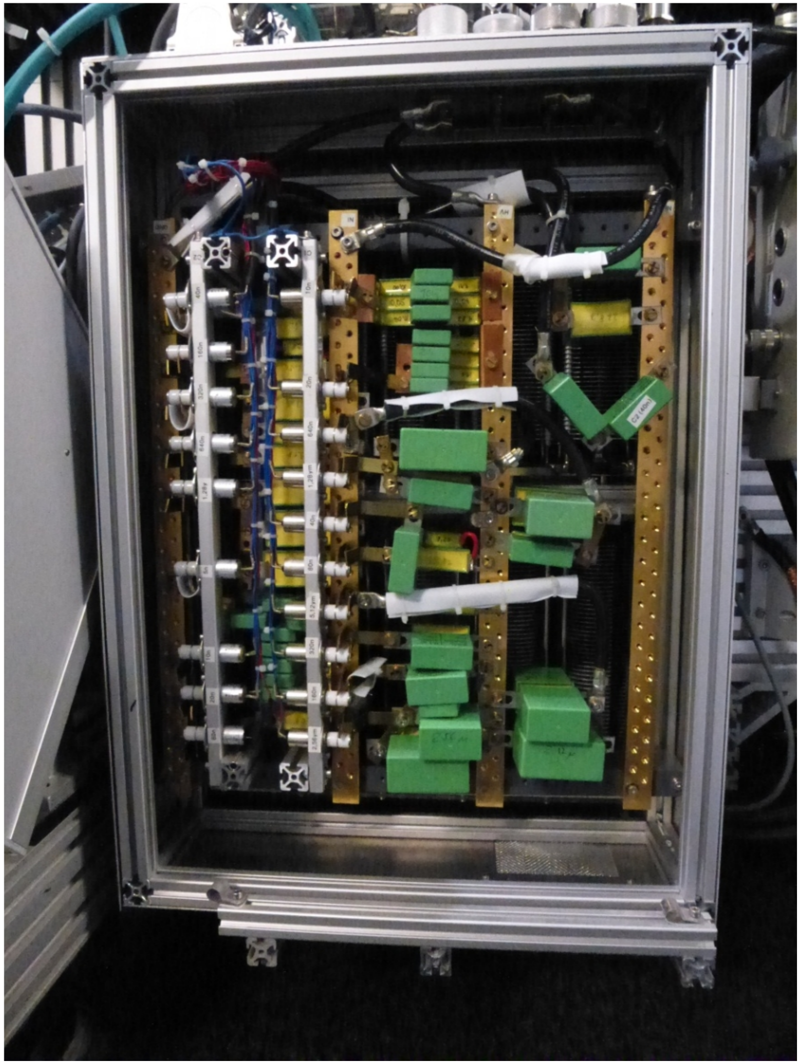


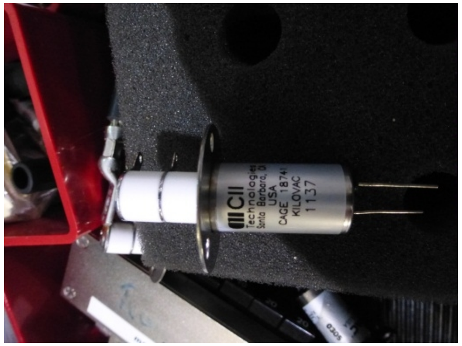
RF flippers

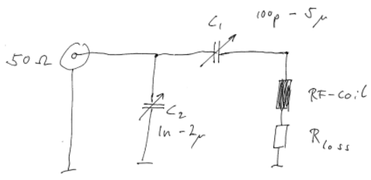
small τ DC coil

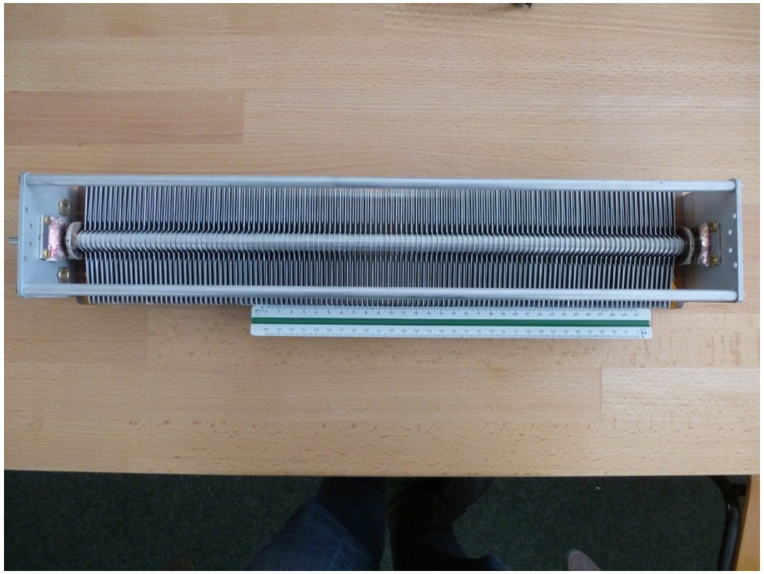


impedance matching

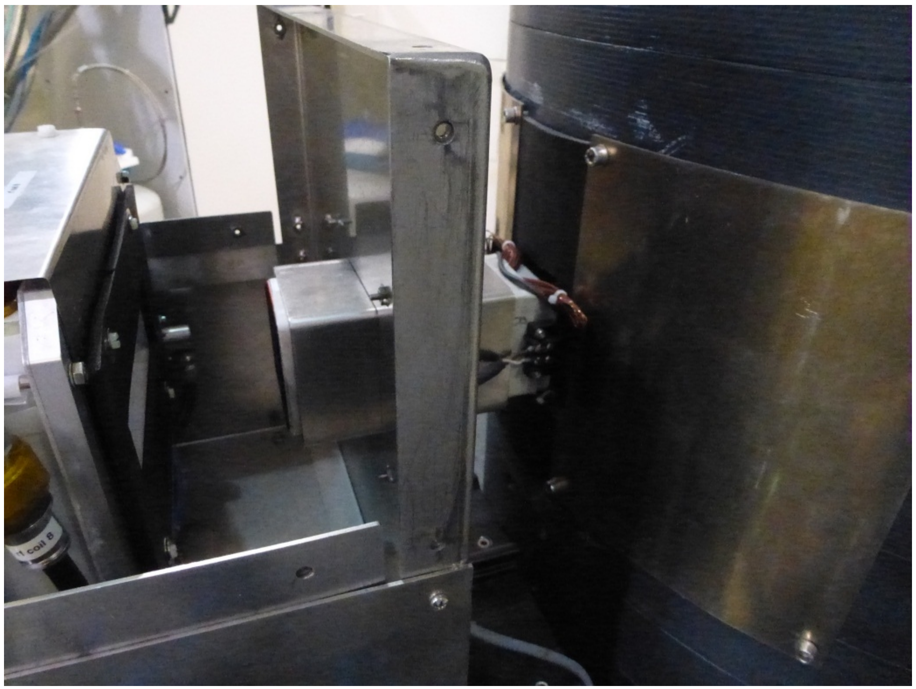




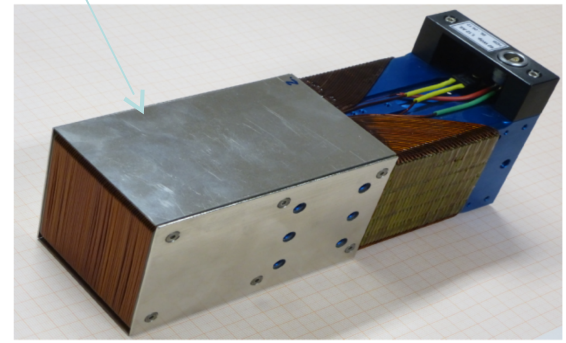


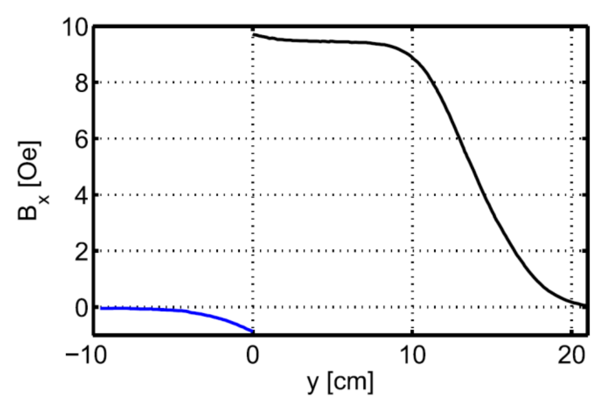


coupling coil



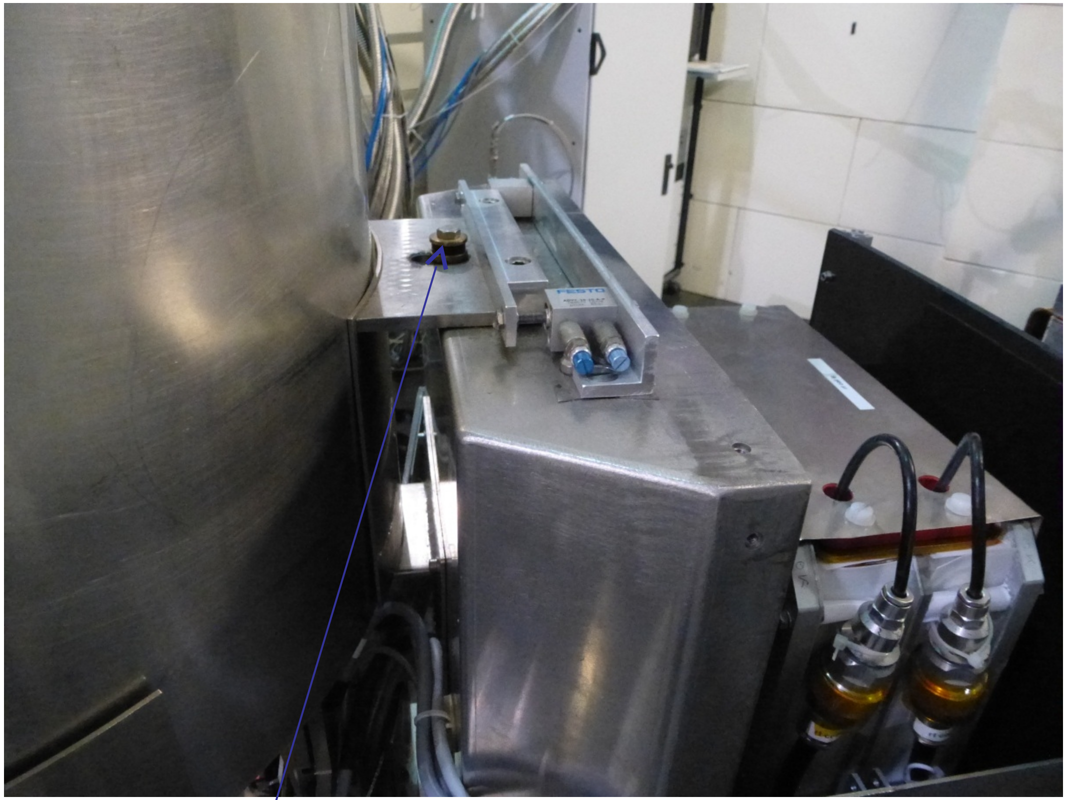
mu-metal yoke (design Felix Groitl)





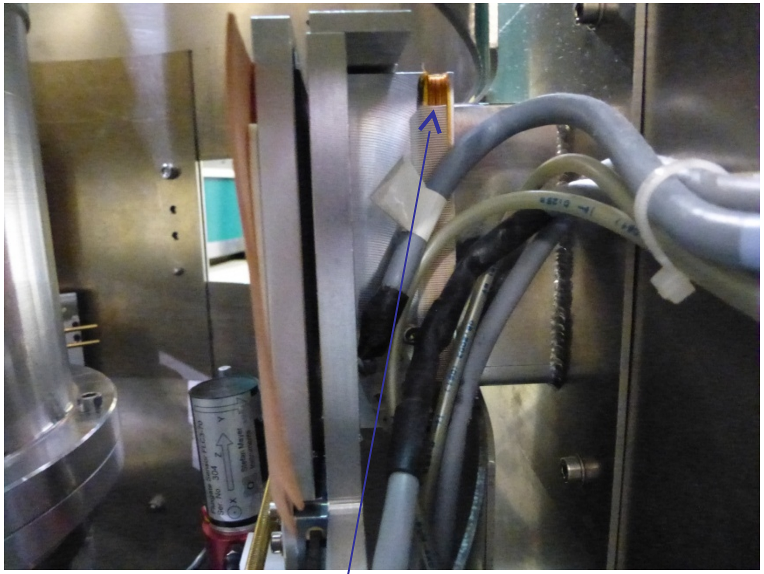
1mm wire, 0.7A

sample space



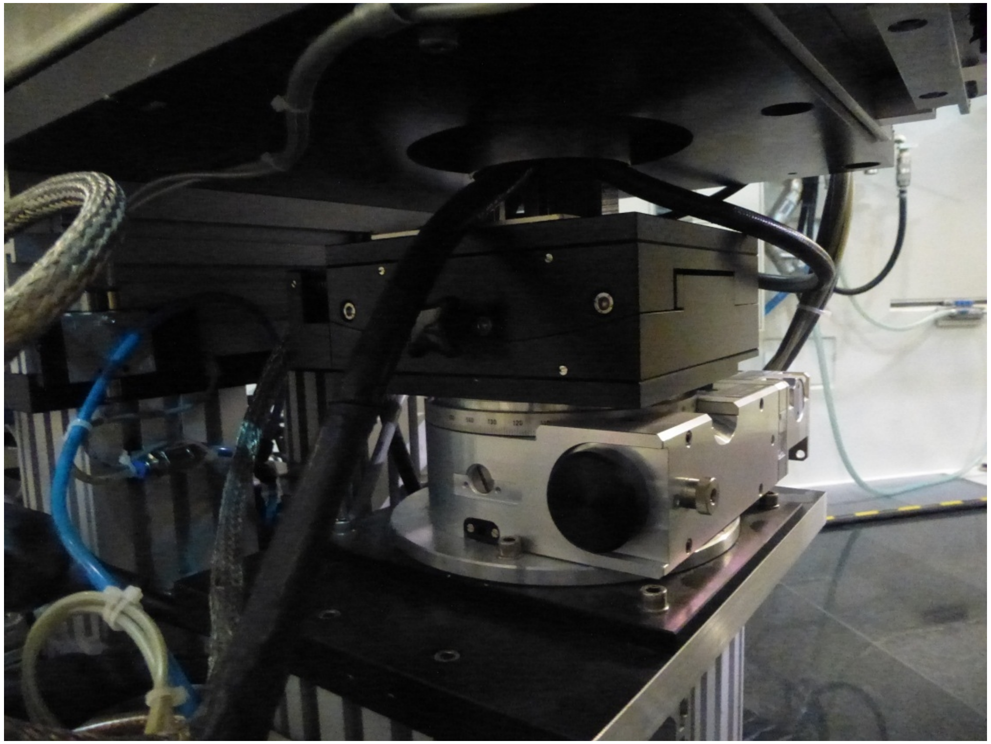
mu-metal connection (movable) from box
to sample cylinder

sample space

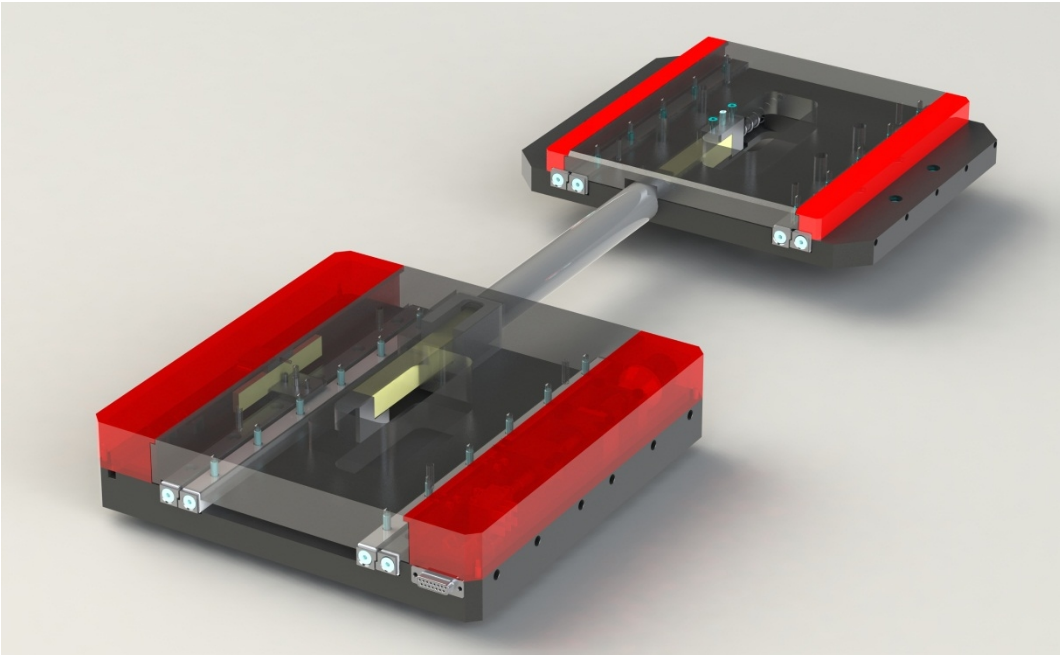


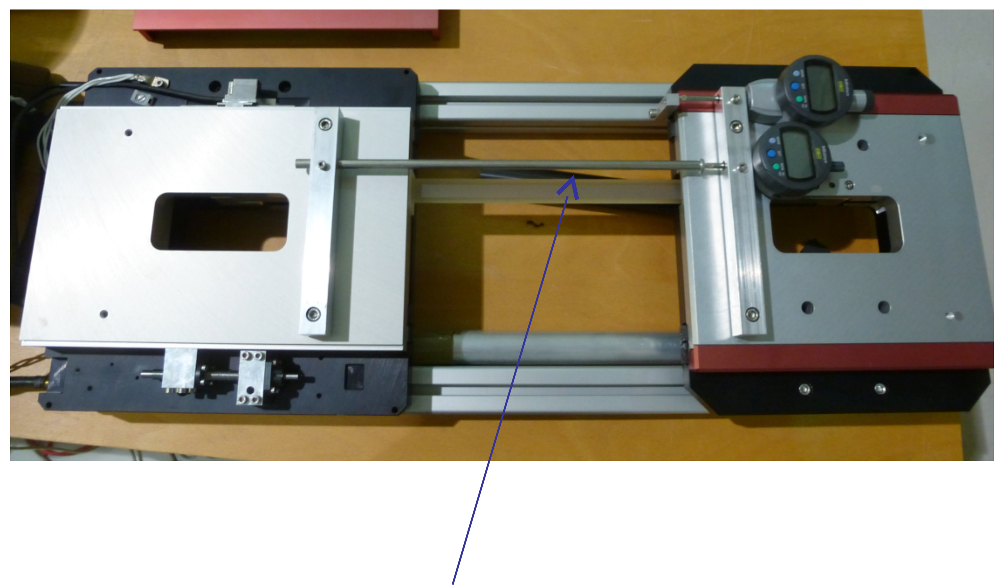
compensation coil for
longitudinal field on
mu-mutal chimney

3-D fluxgate (*Stefan Mayer*)
on telescope cylinder



rotation + simple goniometer





thermal drift compensation

Zerodur

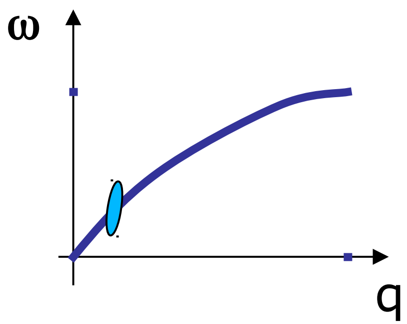
phonon spectroscopy in superconducting Nb and Pb

motivation

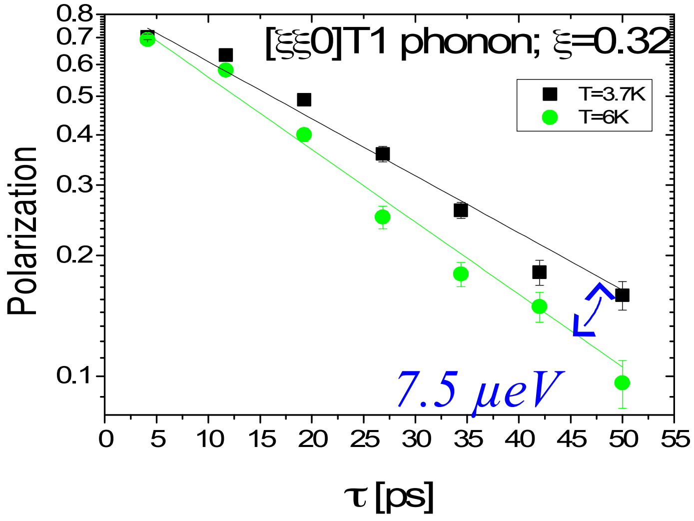
- e-p interaction -> cooper pairs in BCS theory
- pioneering TAS experiments by Shapiro et al. (Nb, Nb_3Sn)
- *ab-initio* calculations

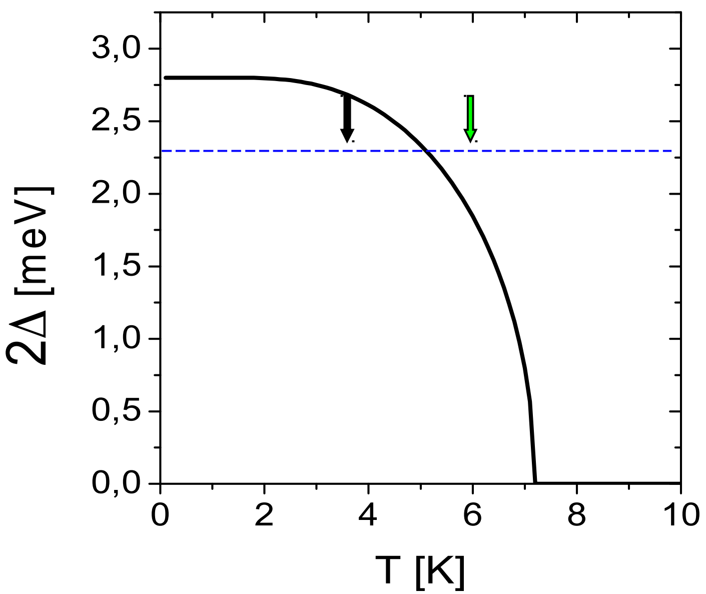
method (Shapiro): how to separate e-p interaction

Pb

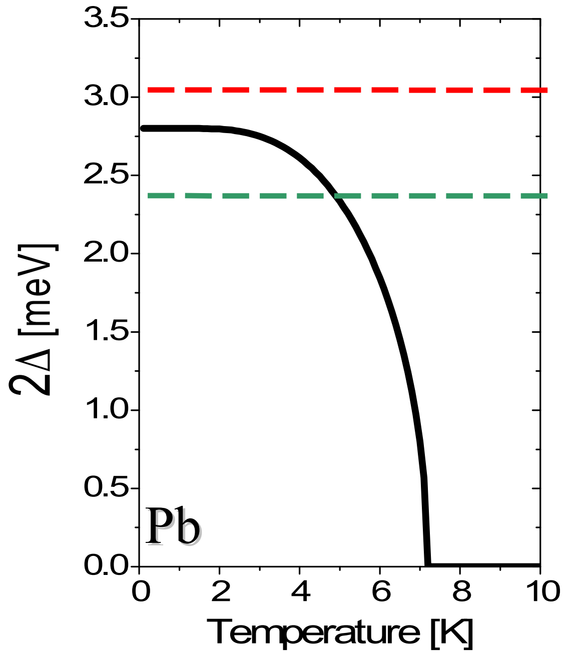


spin-echo

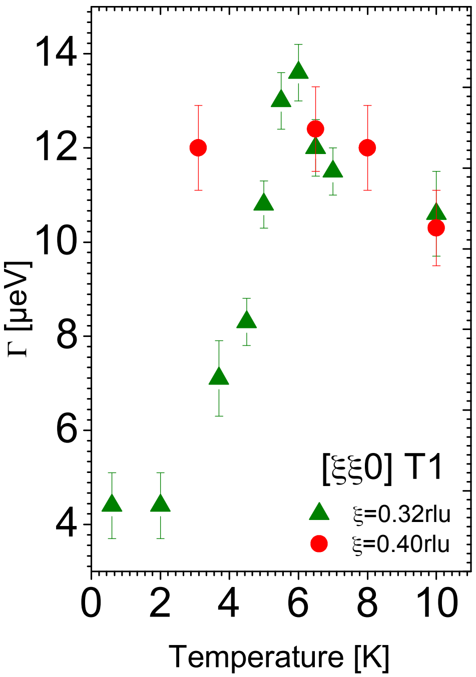




Pb



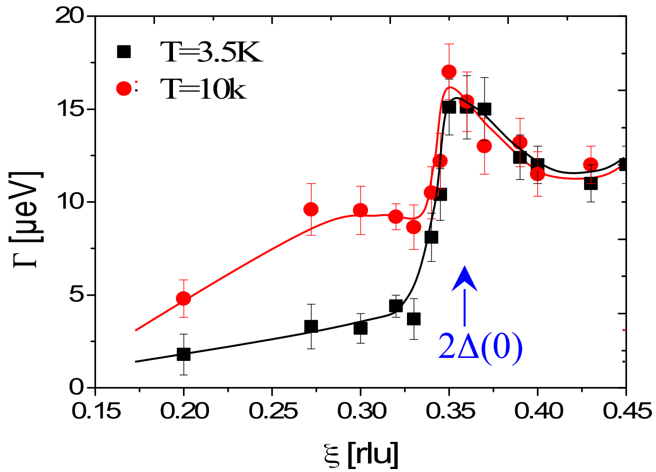
2Δ [meV]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Pb
0
2
4
6
8
10
Temperature [K]



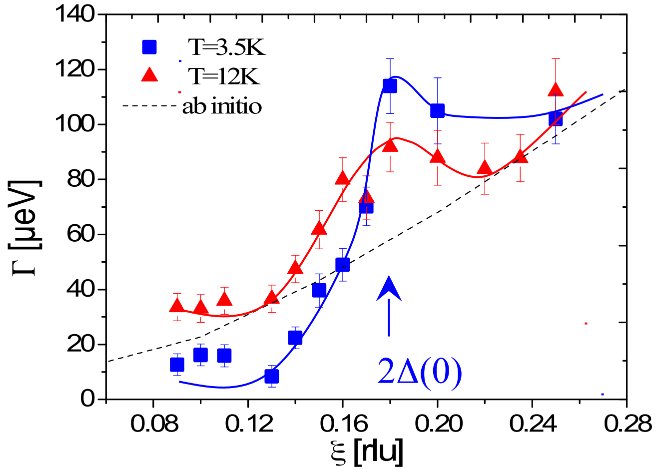
Γ [μeV]
14
12
10
8
6
4
[ξξ0] T1
ξ=0.32rlu
ξ=0.40rlu
0
2
4
6
8
10
Temperature [K]

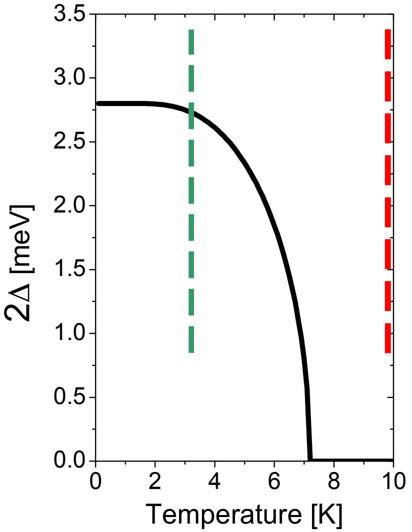
anomaly at 2Δ above Tc

Pb [110]T1



Nb [100]T

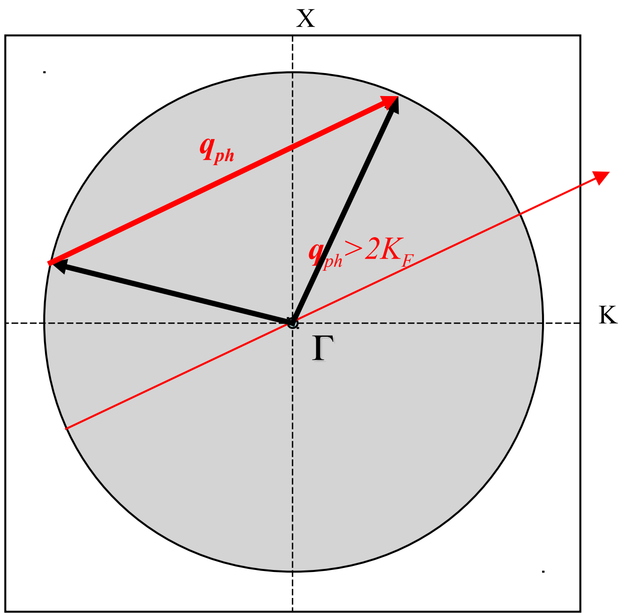




Pb

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

Kohn anomaly



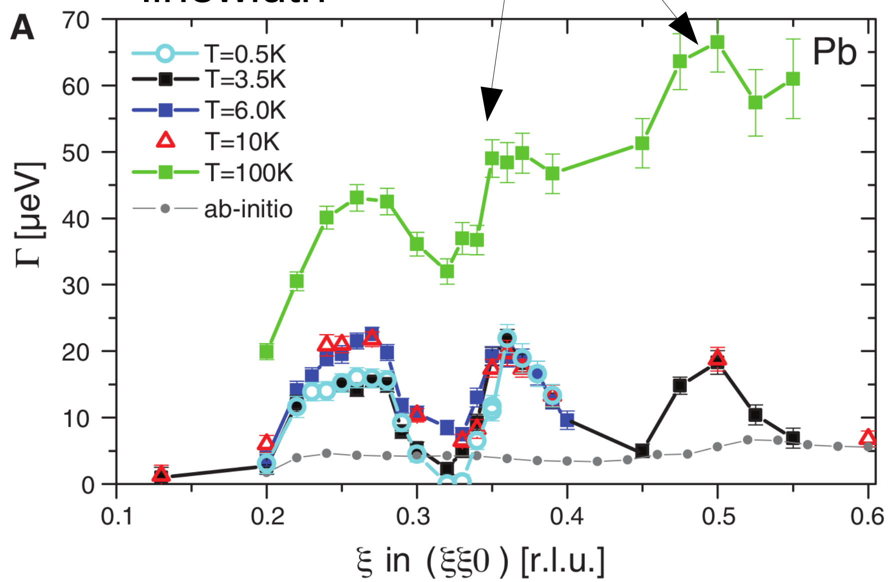
Kohn anomaly $\left|q_{ph}+K\right| = 2k_F$

Kohn anomaly limits 2Δ ?

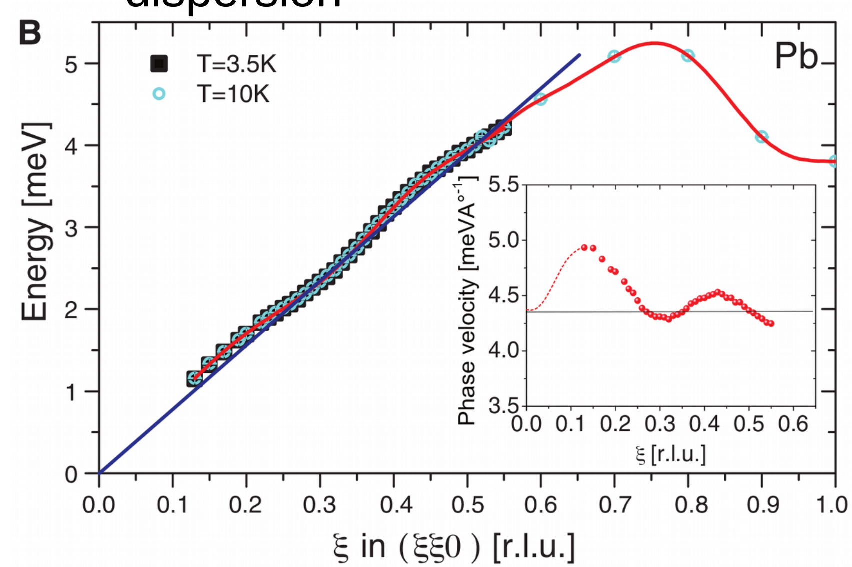
MAX-PLANCK-GESELLSCHAFT

Kohn anomalies

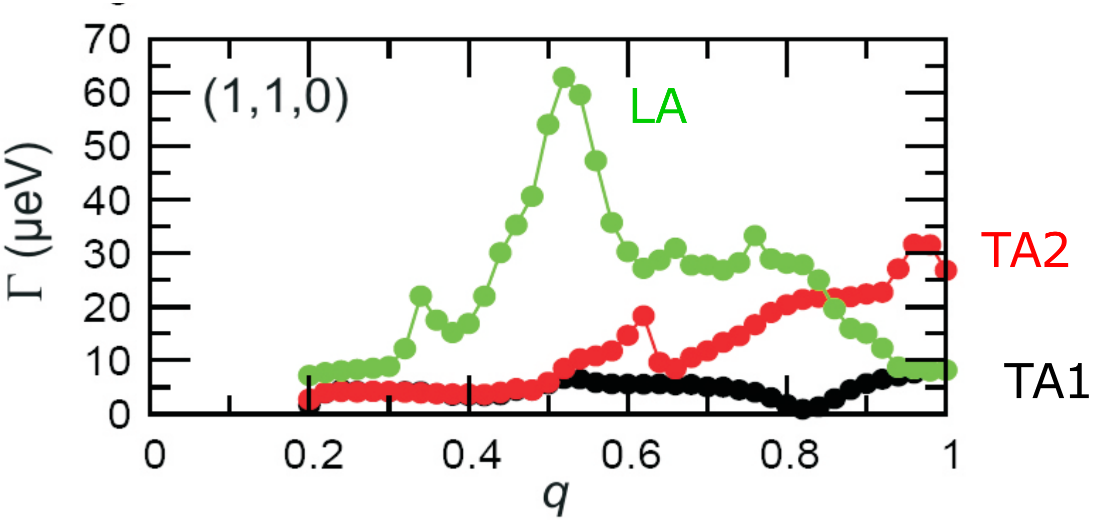
linewidth



dispersion

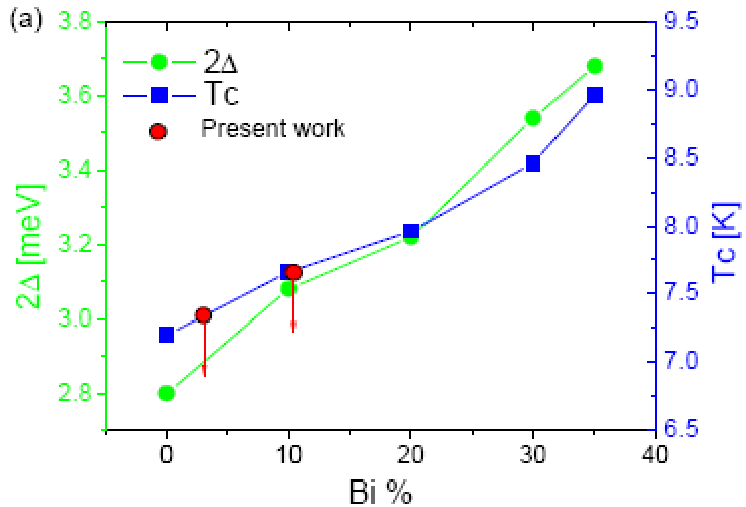


Aynajian et al., Science 319, 1509 (2008)

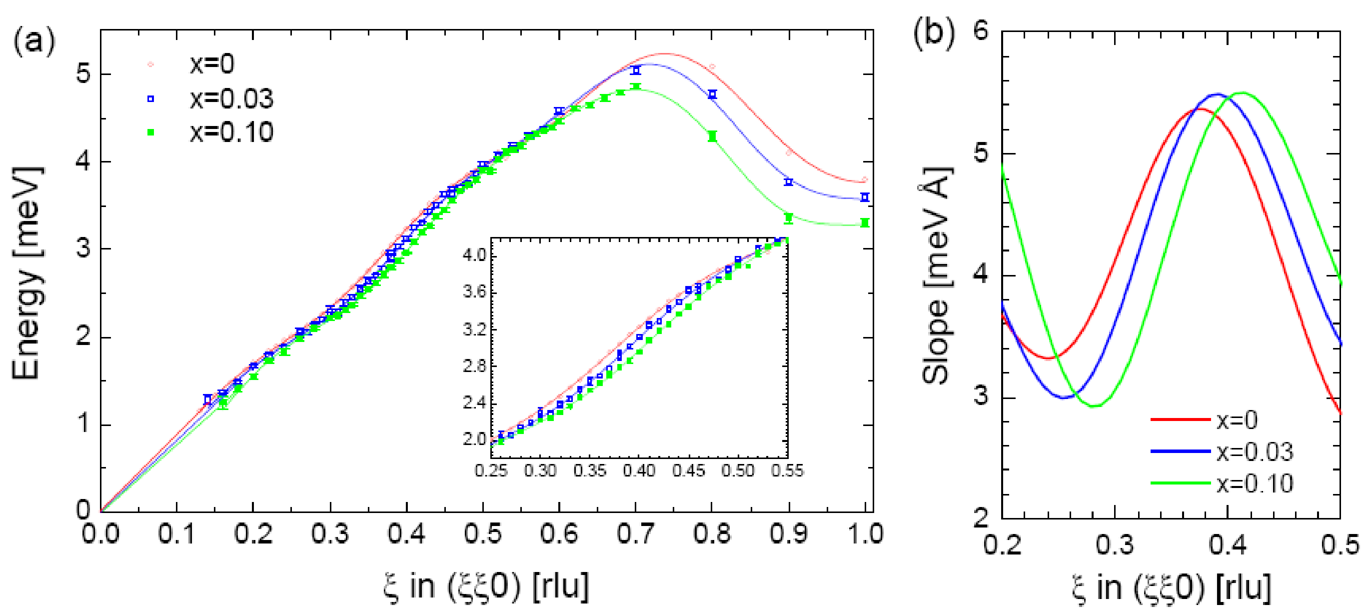


- LDA calculations predict Kohn anomalies for LA, but not TA modes

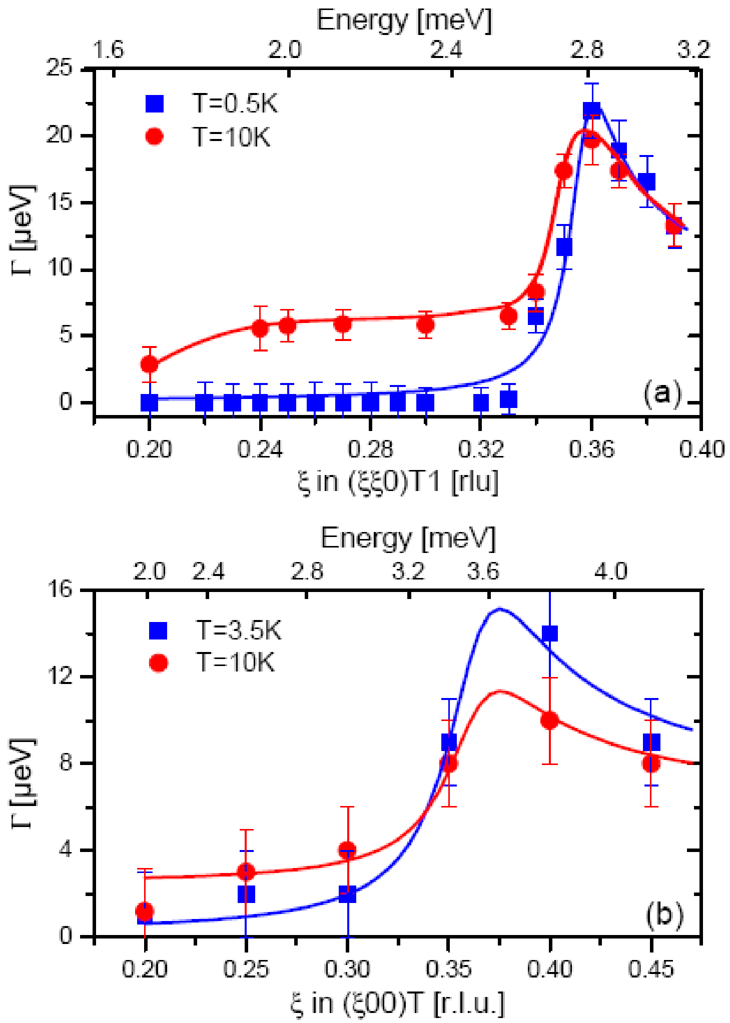
PbBi alloy

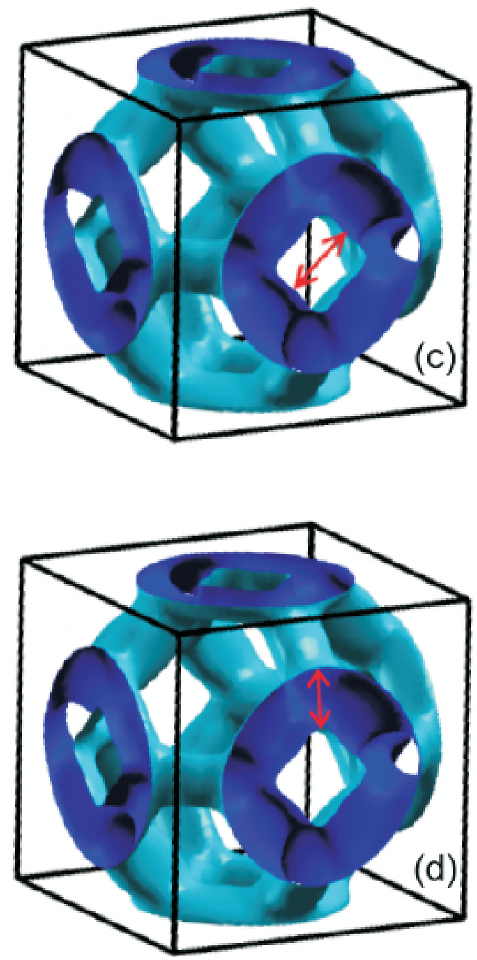


anomaly locked to 2Δ



Gap anisotropy (Pb)





along (110)

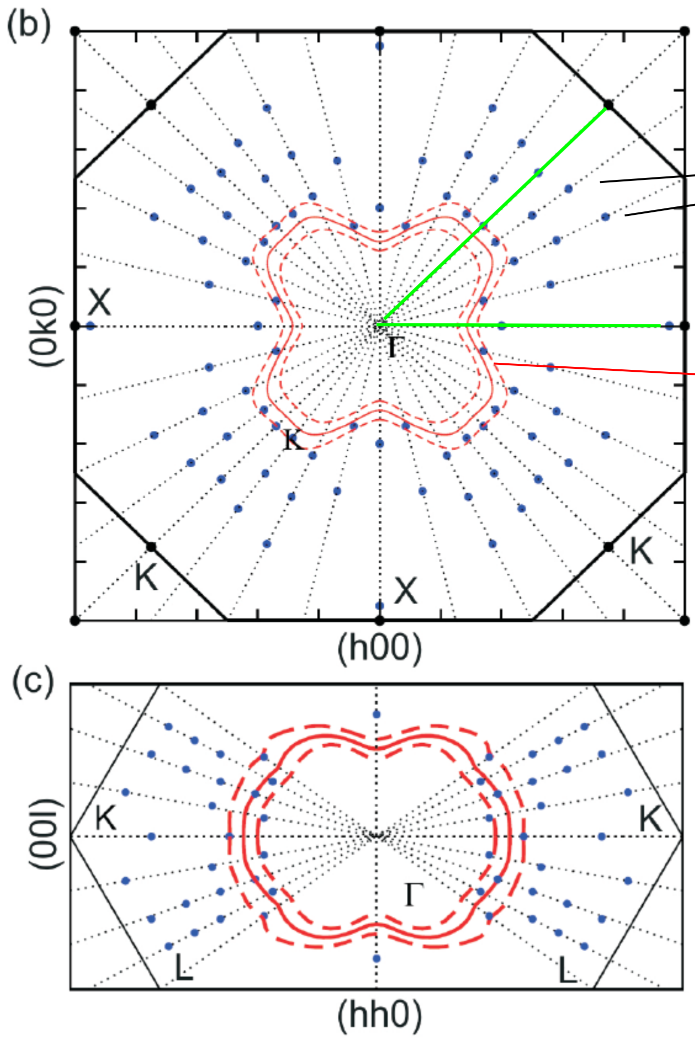
$2\Delta = 2.8$ meV

along (100)

$2\Delta = 3.6$ meV

lock-in to Kohn anomaly generates 20% gap anisotropy

Kohn anomaly surface (LDA)



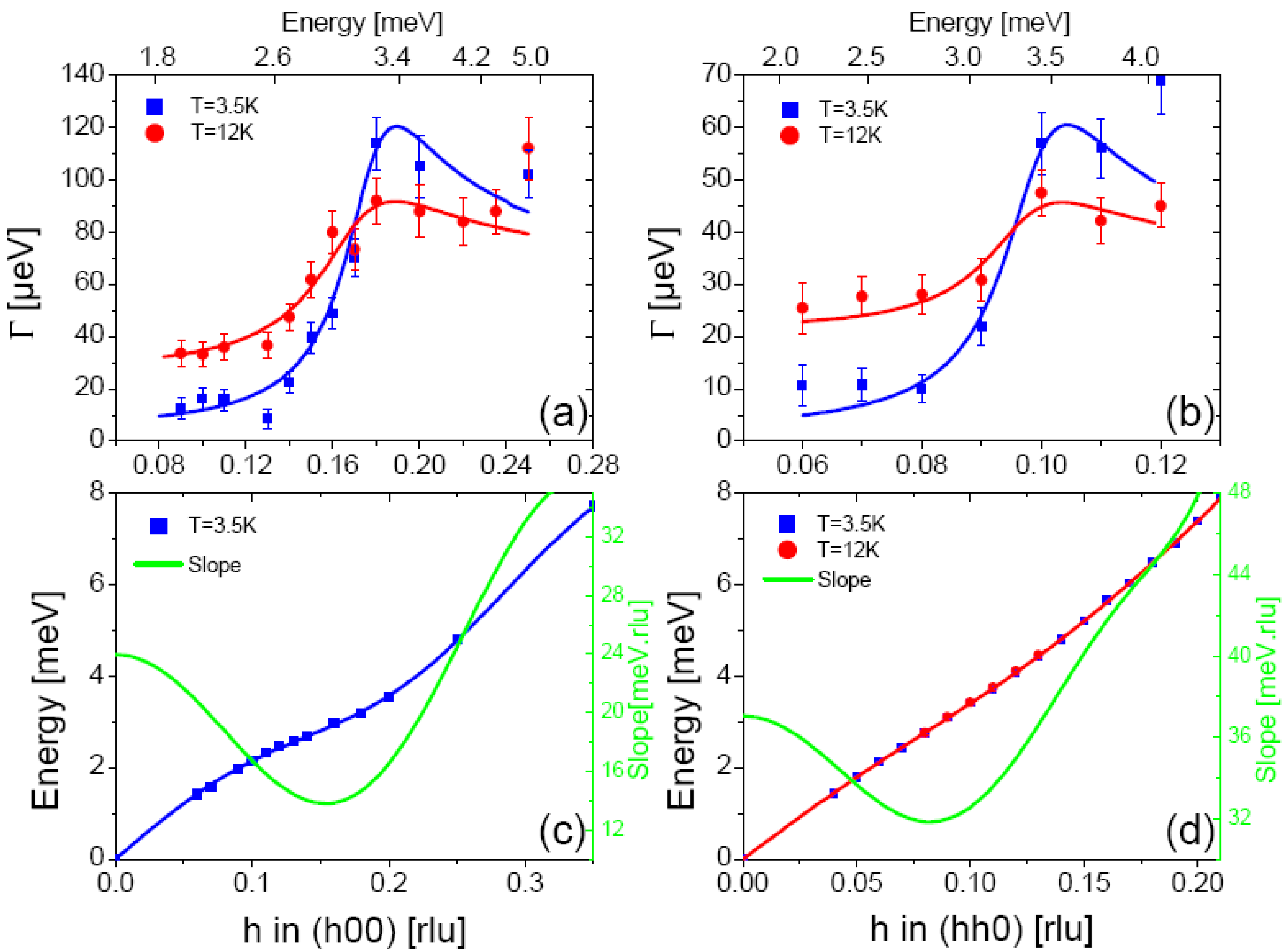
computed Kohn anomalies

tunneling gap (2.8 meV) ± 10 %

locking 2Δ(q) < - >
lowest-energy Kohn anomaly

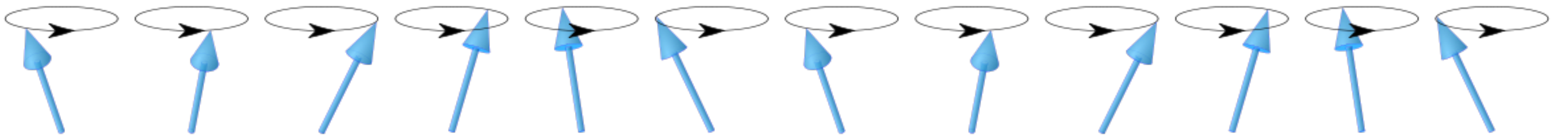
-> Δ(q) can be obtained by
geometrical construction

Niobium



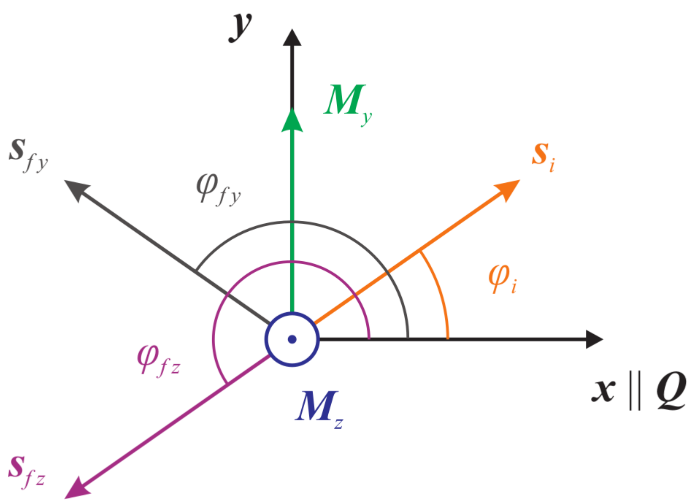
smaller gap anisotropy, same coincidence

spin excitations



selection rule:
- scattering only by spin fluctuations $\perp \mathbf{Q}$
- pi-flip around fluctuation

-> spin flips at the sample



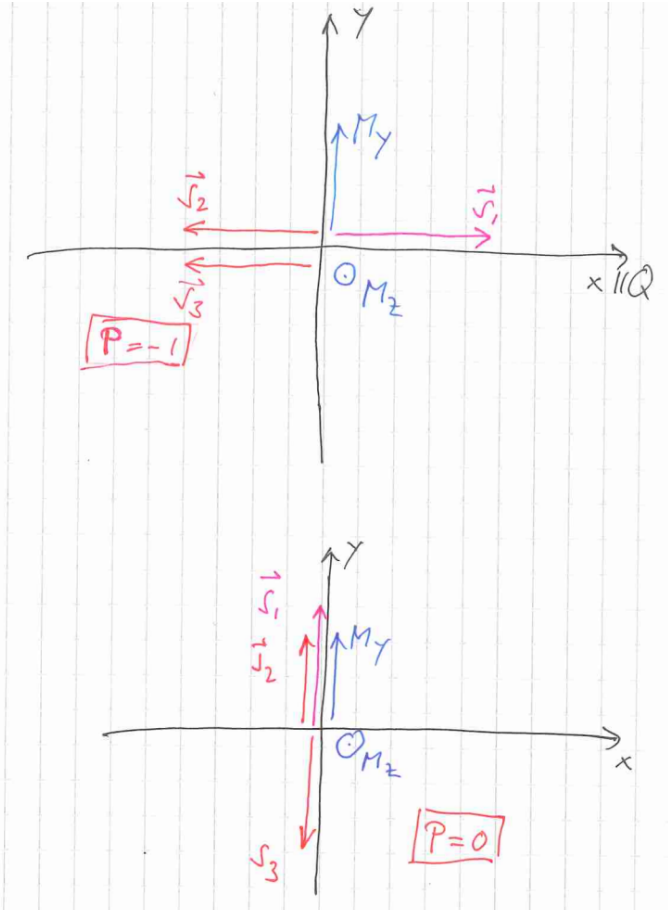
$$\phi_2 = \pi - \phi_1$$

minus sign acts like pi-flipper -> parallel fields

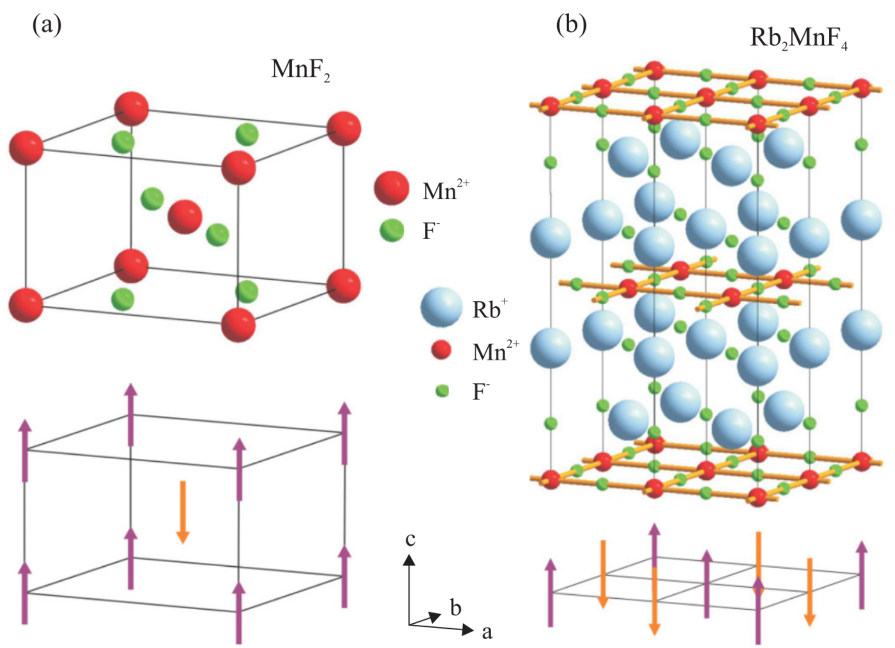
$$\phi_3 = \pi + \phi_1$$

-> conventional case, antiparallel fields
additional pi phase shifts echo group

mixing M_y and M_z



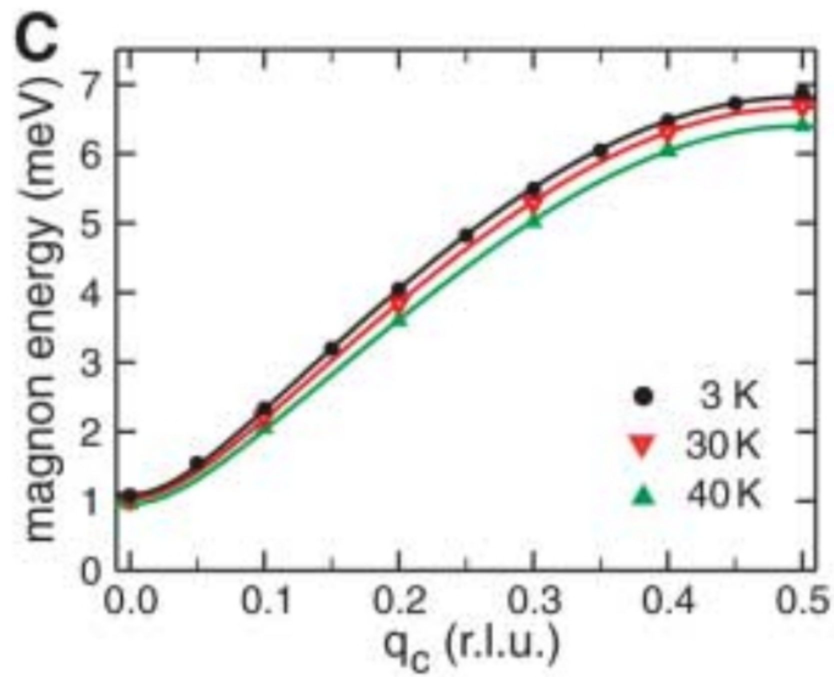
magnon linewidths and critical dynamics in s=5/2 AFs



3D: MnF_2

2D: Rb_2MnF_4

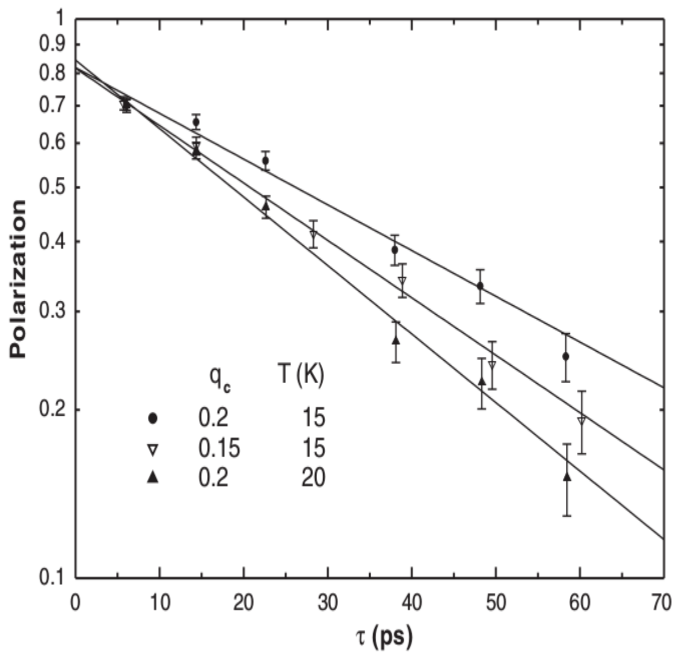
MnF_2



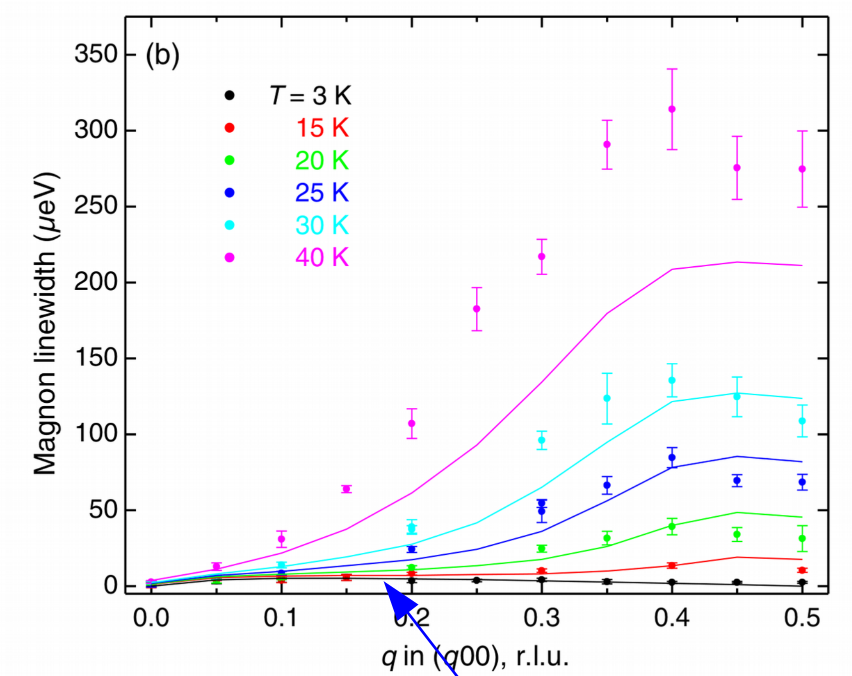
Heisenberg AFs + small uniaxial anisotropy (dipolar)

Tseng, PRB 94, 014424 (2016)

only M_y visible -> conventional signals



$$P \sim \exp(-\Gamma \times \tau)$$



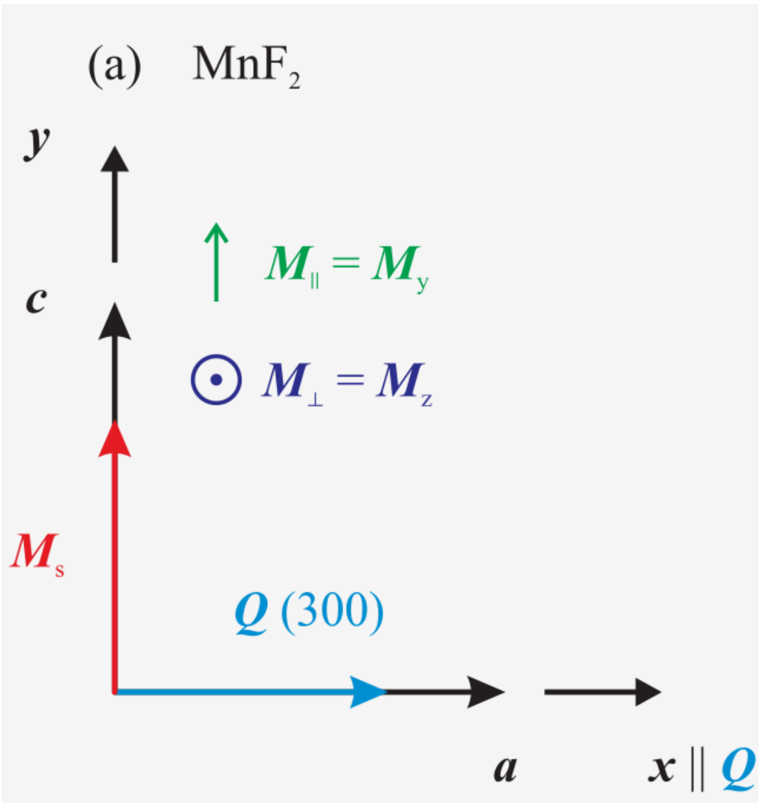
domain boundary scattering

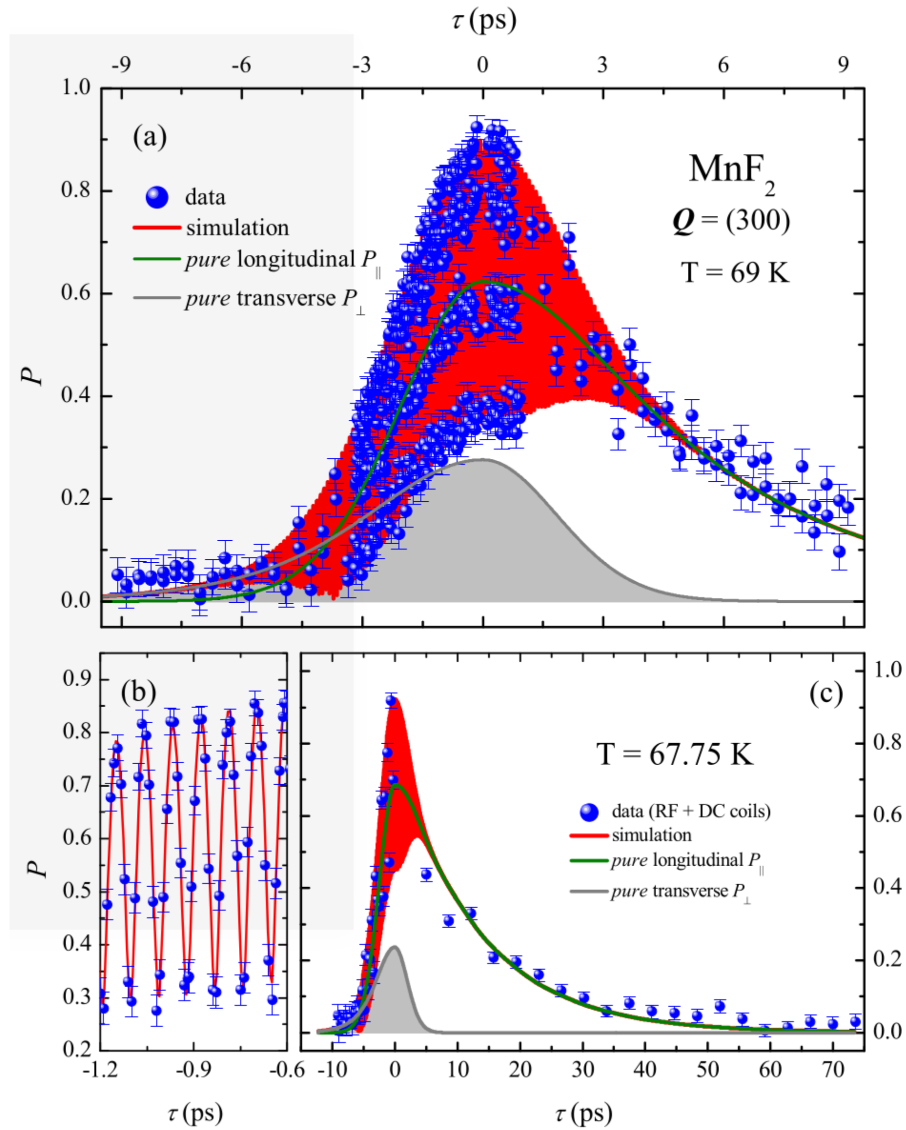
LW calculated 4-magnon process
-> magnon thermal conductivity

Bayrakci, Science 312, 1927 (2006)

Bayrakci, Tennant, et al., PRL 111, 017204 (2013)

critical scattering

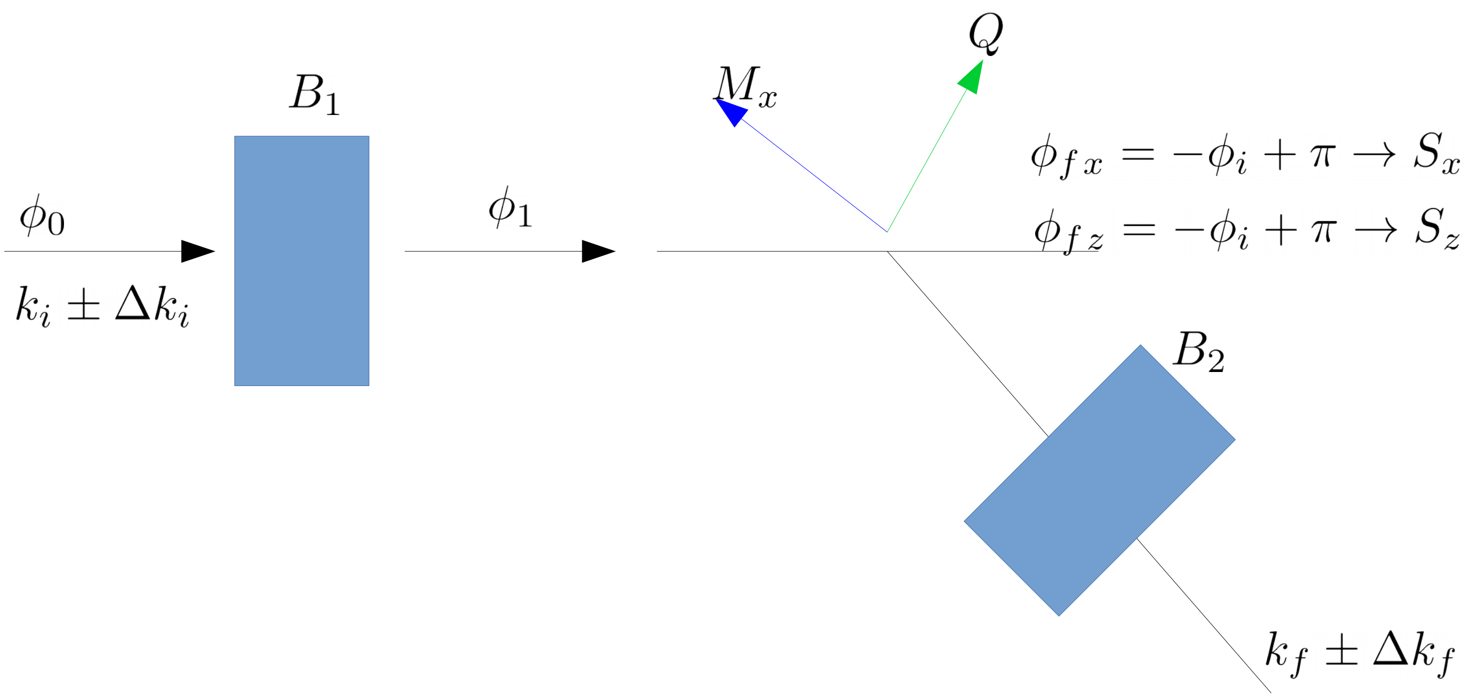




global fit, simulation of the spectrometer

Tseng, PRB 94, 014424 (2016)

simplified ray tracing

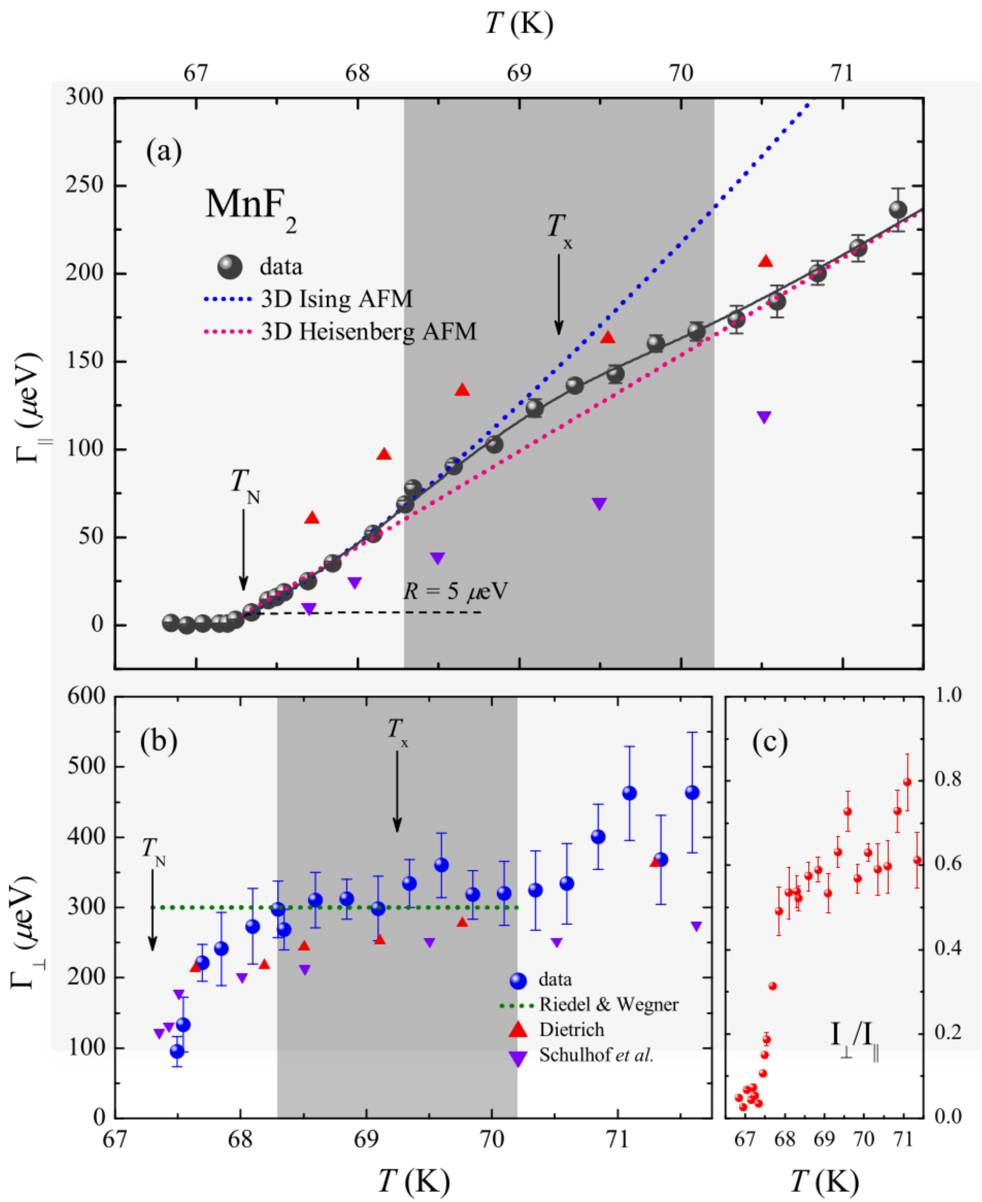


$$\phi_{f\,x} = -\phi_i + \pi \rightarrow S_x(\omega, \Gamma_x)$$

$$\phi_{f\,z} = -\phi_i + \pi \rightarrow S_z(\omega, \Gamma_z)$$

$$P(k_i, \Delta k_i, \Delta k_f, \omega, \Gamma_x, Gamma_z) = \langle \cos(\phi_f) \rangle$$

MnF2 critical scattering

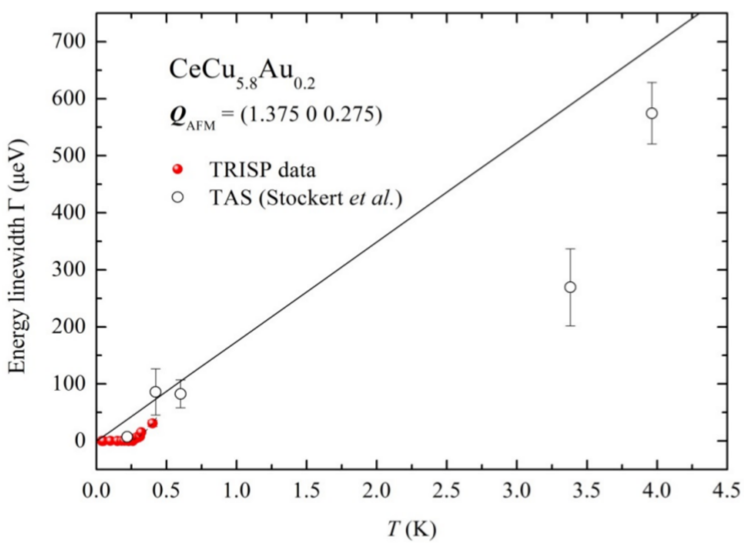


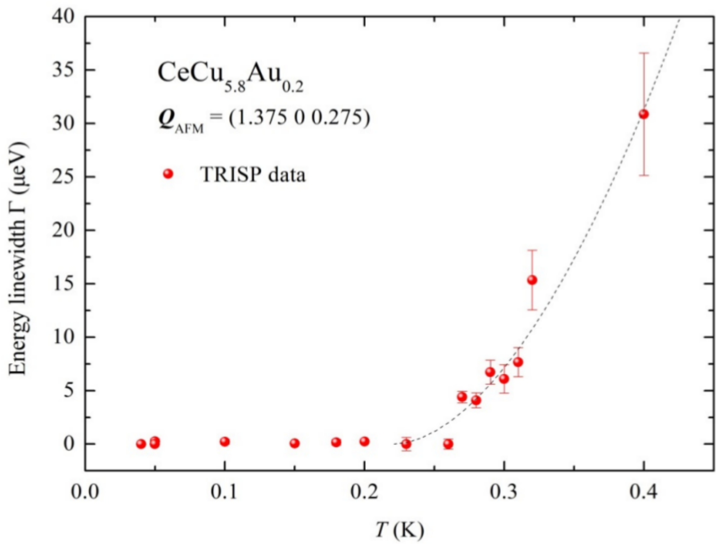
$$\Gamma \sim \xi^{-z}$$

Tseng, PRB 94, 014424 (2016)

$CeCu_{6-x}Au_x$ critical fluctuations

x= 0.2
T_N = 220mK
QC for x=0.1 or p~3kbar

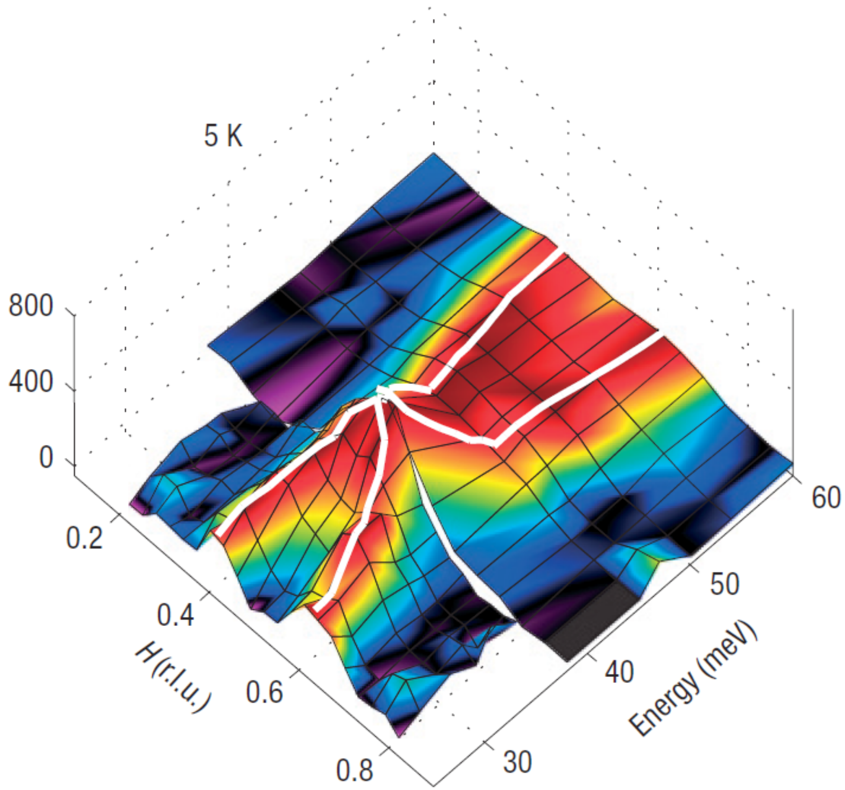


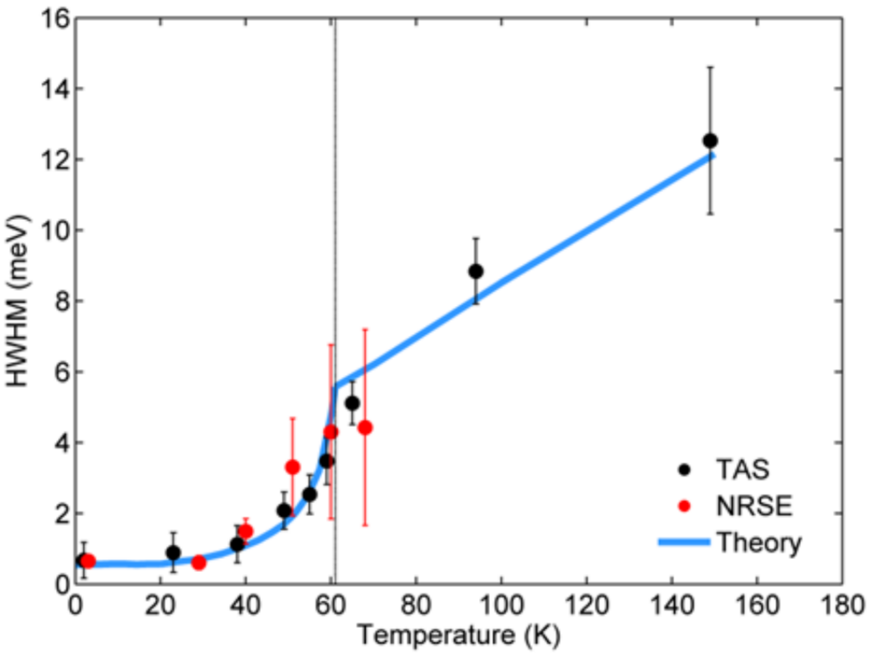


TAS: $\Gamma \sim T$

SE: crit. exponent z=1.75 (2DIA)

‘resonance mode’ $YBa_2Cu_3O_{6.5}$

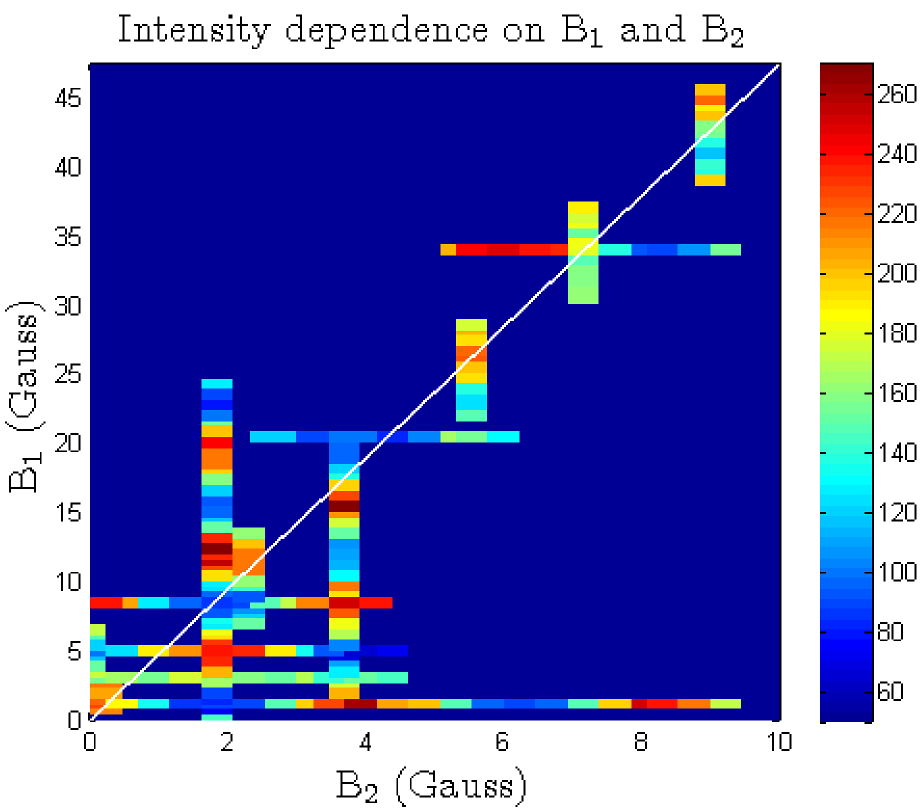


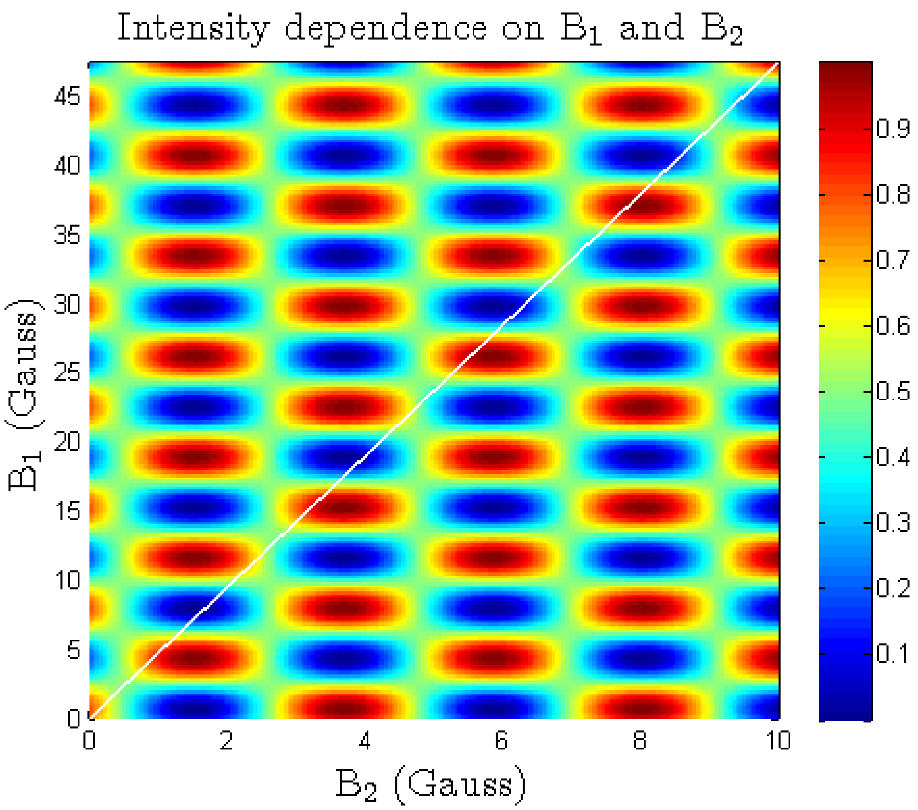


signature of d-wave symmetry
persists up to T* = 230K
low T:

A. Walters, T. Loew, J. Schmalian, B. Keimer (unpublished)

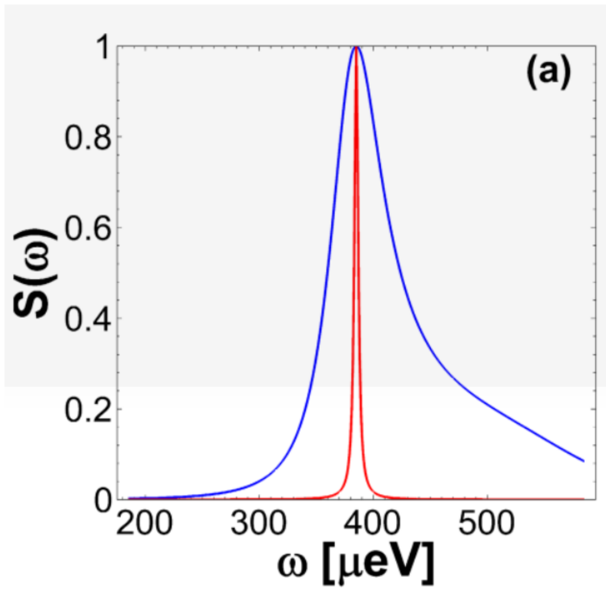
YBCO6.5 polarization signal

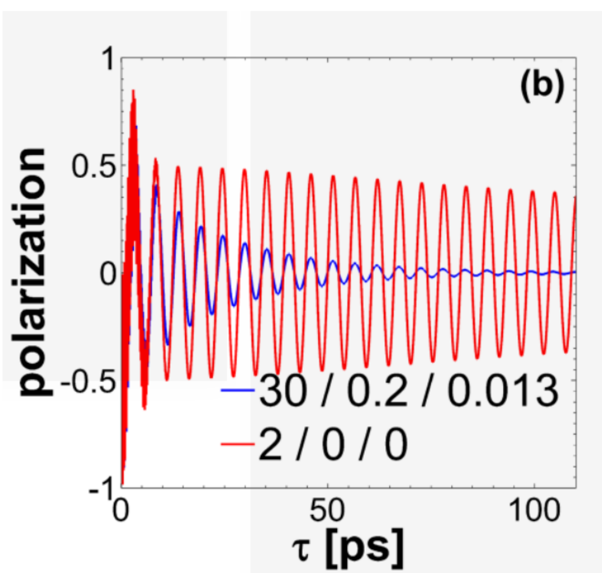


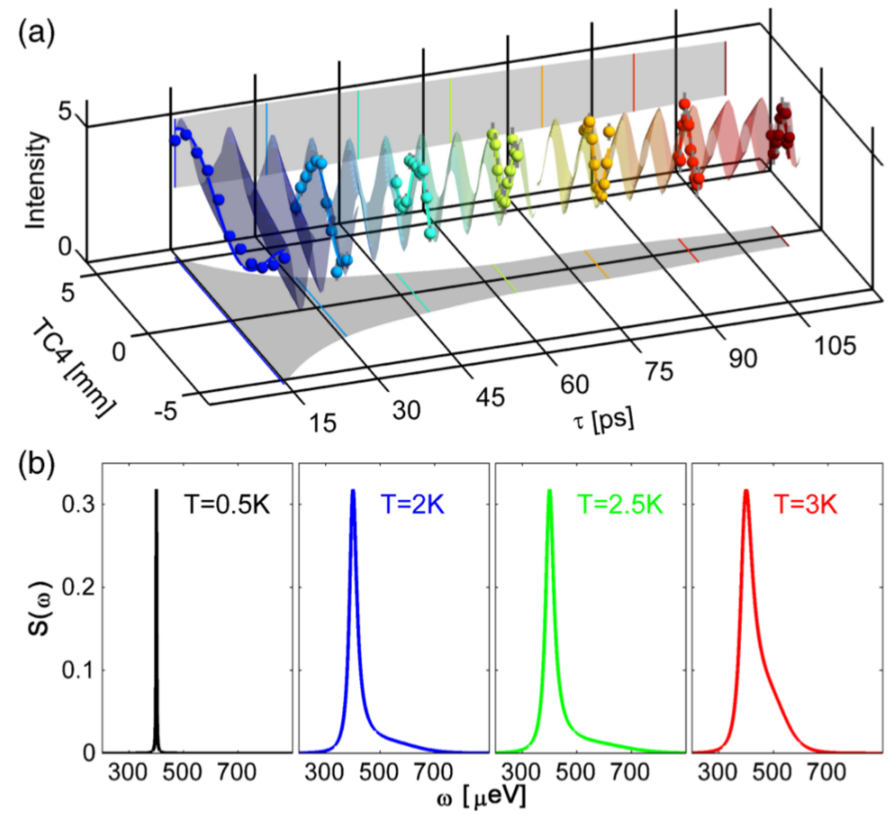


non-Lorentzian S(ω)

$Cu(NO_3)_2 \cdot 2.5D_2O$, 1D bond alternating Heisenberg chain

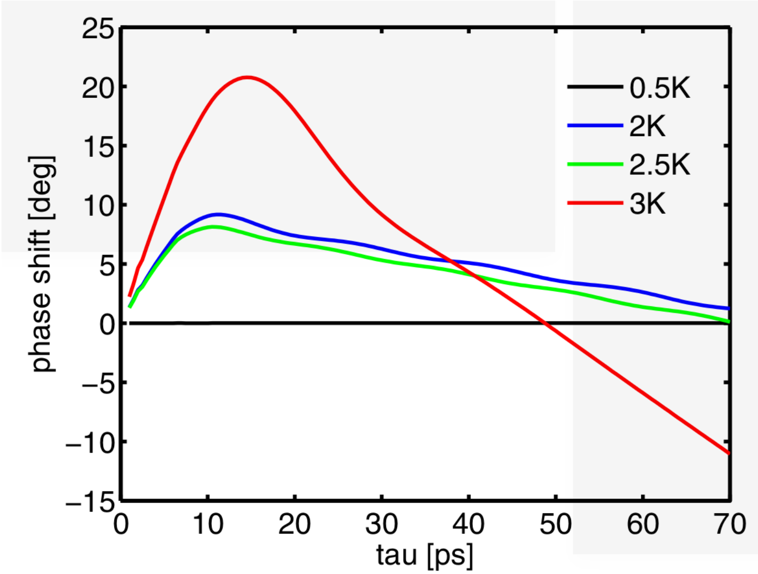


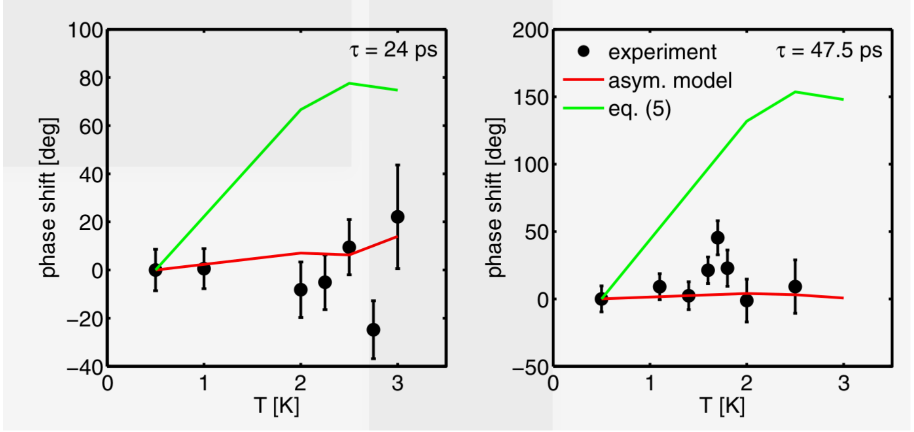




Groitl, PRB 93, 134404 (2016)

phase, non-Lorentzian





$$\Delta\phi = \Delta\omega \times \tau$$

only for symmetric S(ω)

Groitl, PRB 93, 134404 (2016)

MAX-PLANCK-GESELLSCHAFT

Larmor diffraction

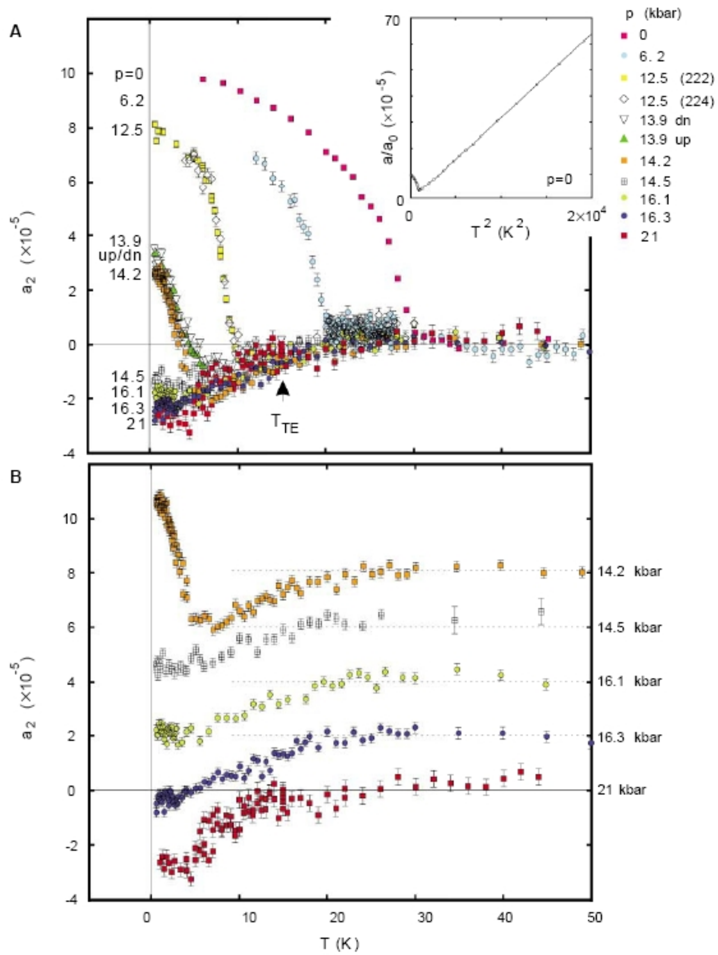
Larmor diffraction

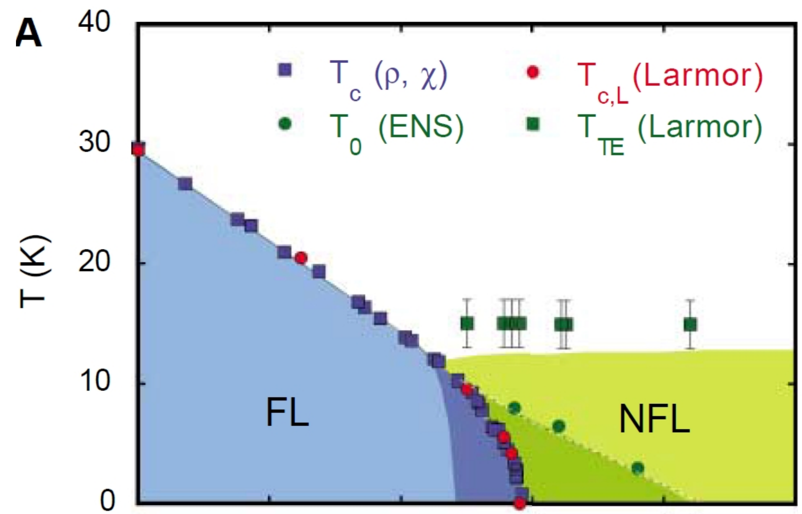
LD technique: Rekveldt , 1999
first experiments at FLEX
resolution $\Delta d/d = 10^{-6}$

current interest:
- thermal expansion p, low T
- distribution of d-values, peak splitting
- absolute d-values (calibration)

dilatometry <-> pressure
high resolution x-ray diffraction (10^{-5}) <-> temperature
neutron diffraction <-> resolution (10^{-4})

motivation: thermal expansion, pressure

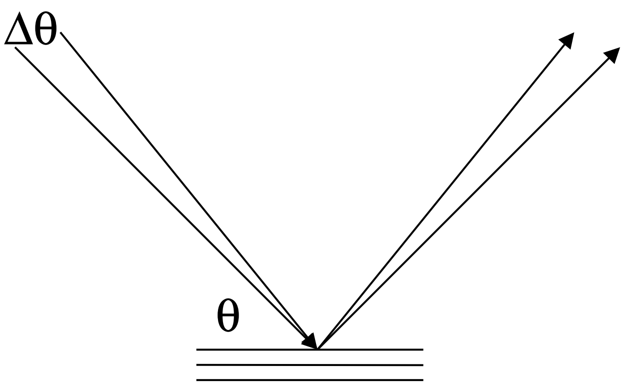




MnSi

Pfleiderer et al., Science 316, 1871, (2007)

diffraction



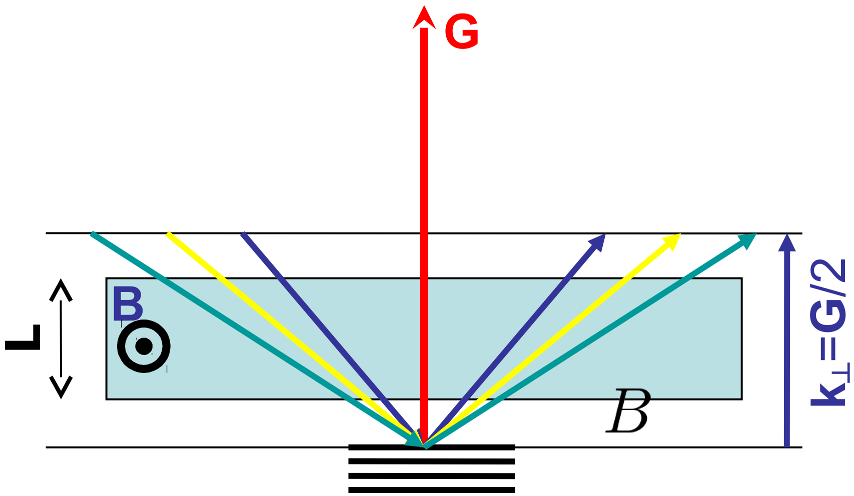
$$\frac{\Delta d}{d} = \frac{\Delta k}{k} + \Delta\theta \cdot \cot\theta$$

resolution=1/intensity

neutron: $\Delta d/d = 10^{-4}$
x-ray: 10^{-5}

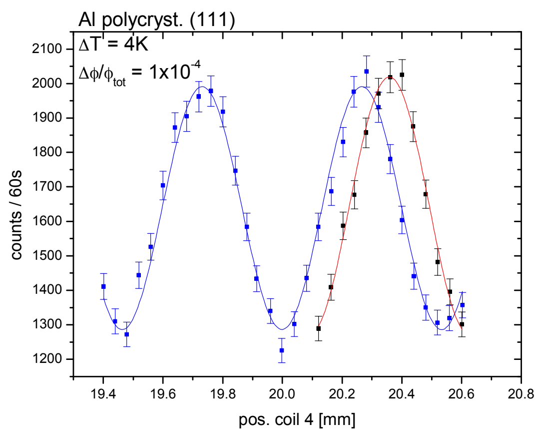
aim: try to measure *d* by a spin echo technique

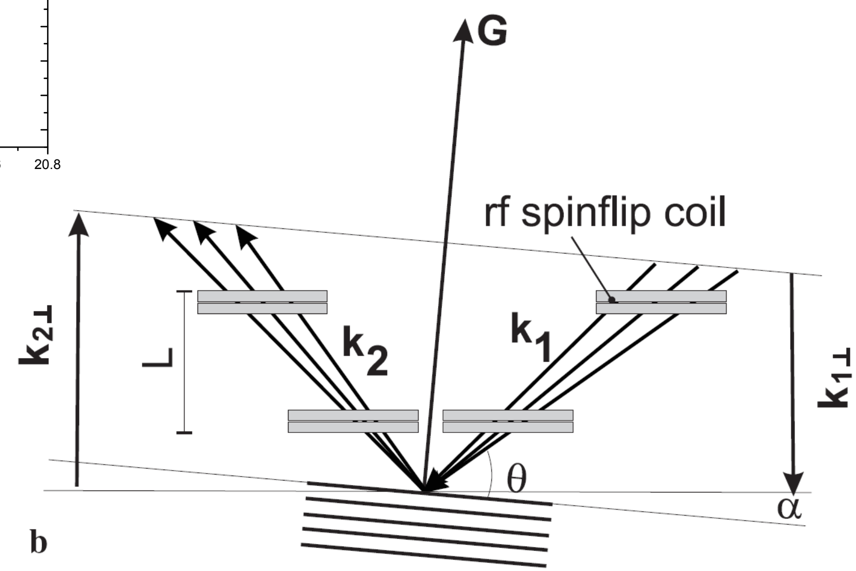
Rekveldt's solution



$$\phi_{Larmor} = \omega_L \cdot T = \omega_L \cdot \frac{2L}{\mathbf{v}_\perp} = \frac{2\pi\hbar}{m} \cdot \omega_L \cdot L \cdot d$$

LD using NRSE

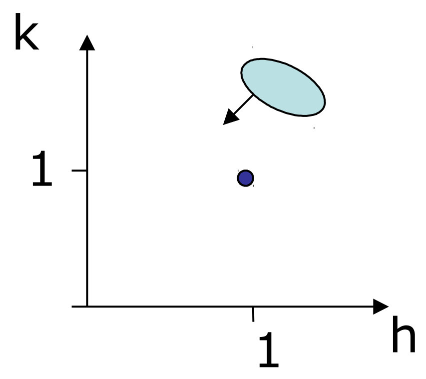


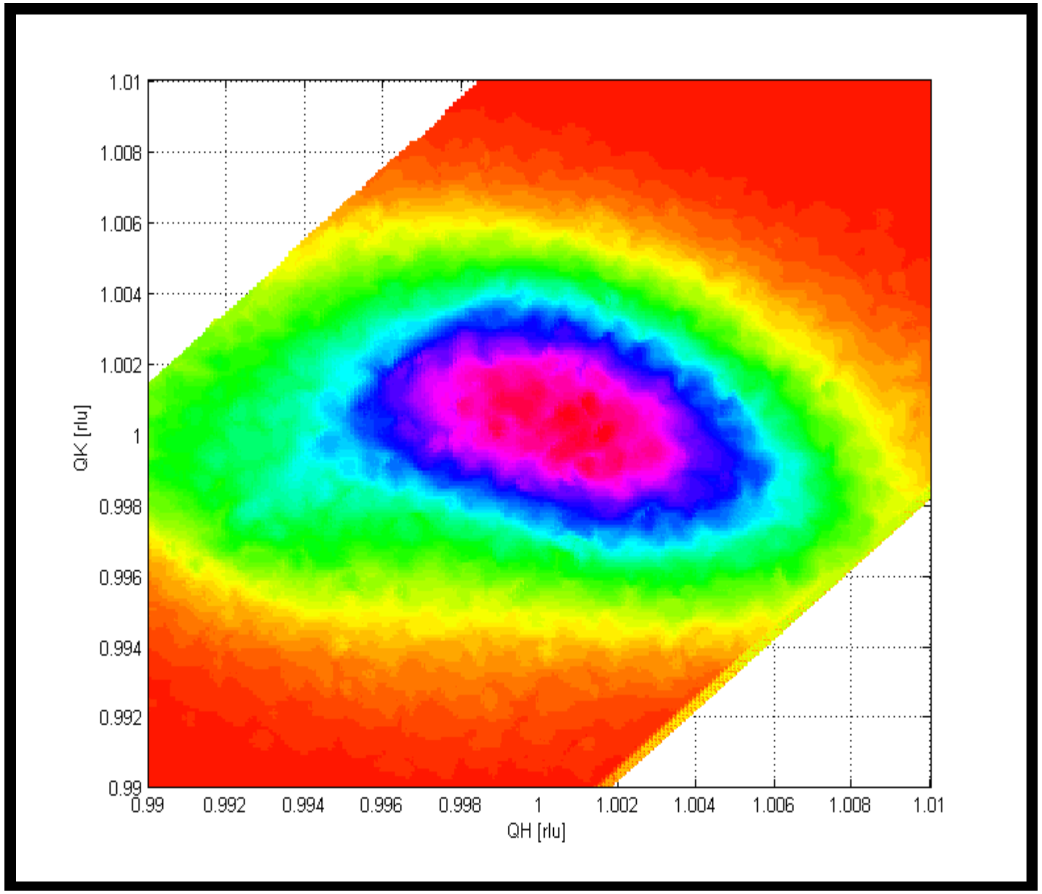


Δd/d resolution at TRISP: 1.6×10^{-6}

(110) Bragg reflection
Larmor diffraction (MnF_2)

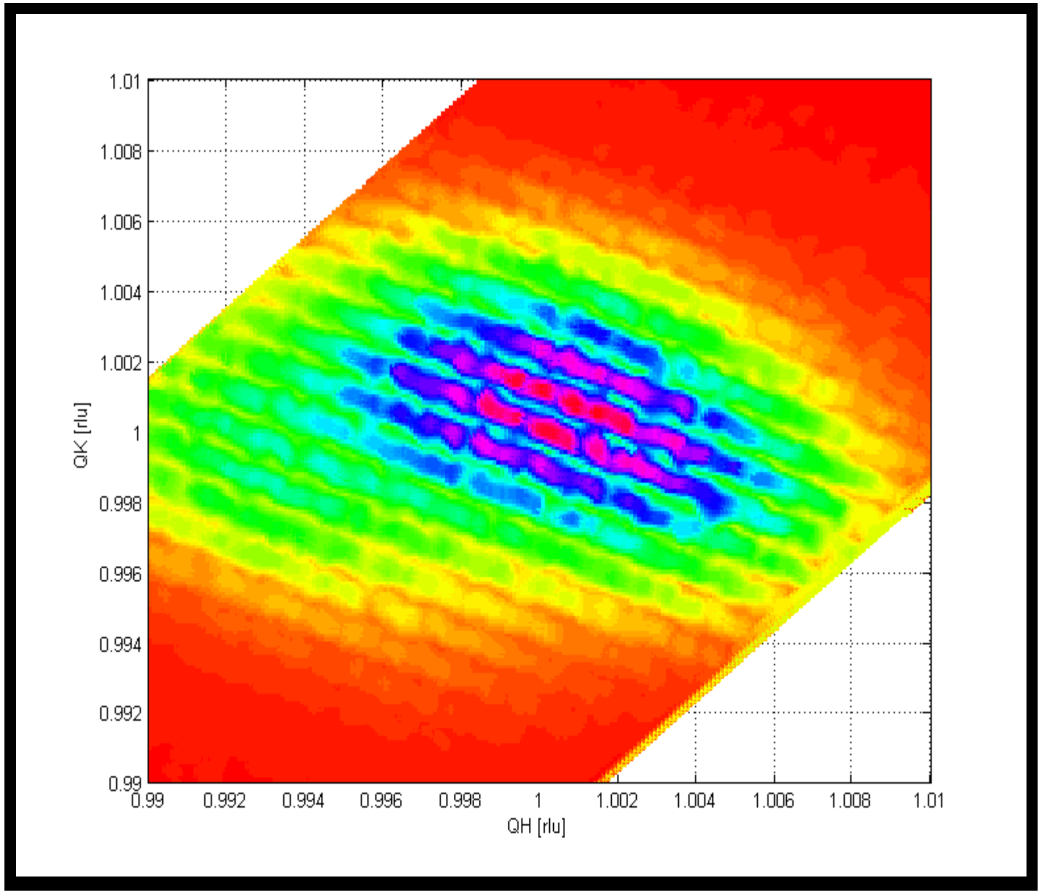
TAS only
NRSE off





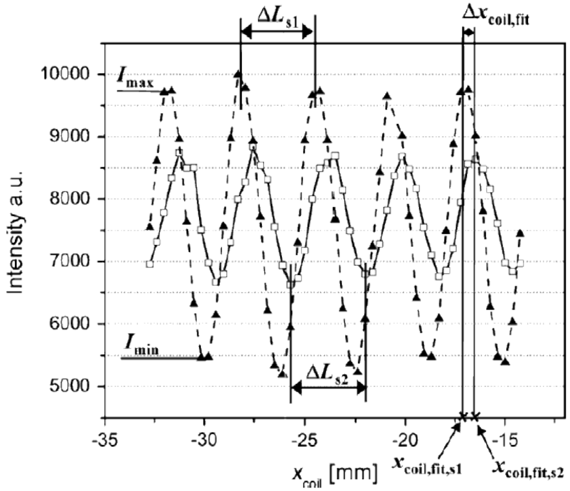
K. Habicht, FLEX

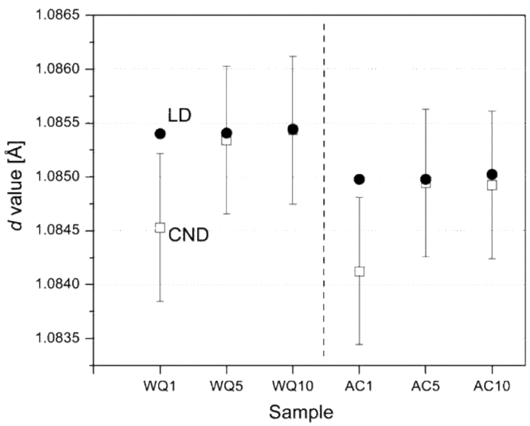
TAS +
NRSE on



K. Habicht, FLEX

materials science: Inconel 718 strain



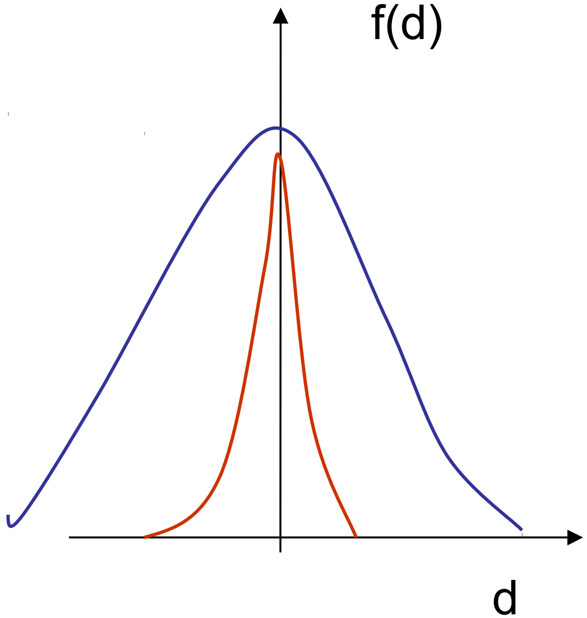


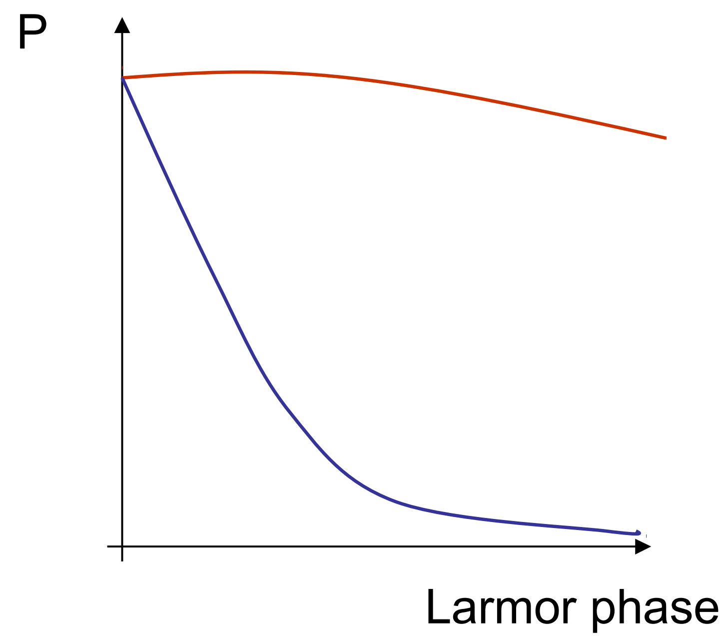
absolute d

distributions of d

J. Repper, Acta Materialia 58, 3459 (2010)

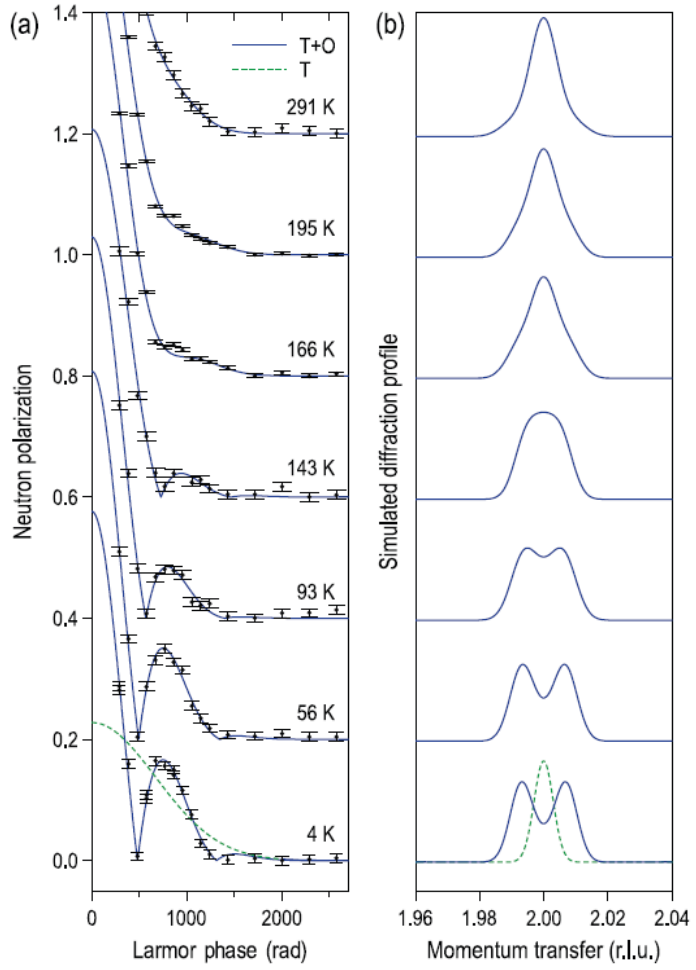
spread of d





$$P(\Phi) = \int f(d) \cos(d\ \Phi) dd$$

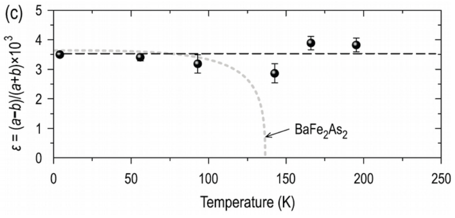
peak splitting



$Ba(Fe_{1-x}Mn_x)As_2$ (12%)

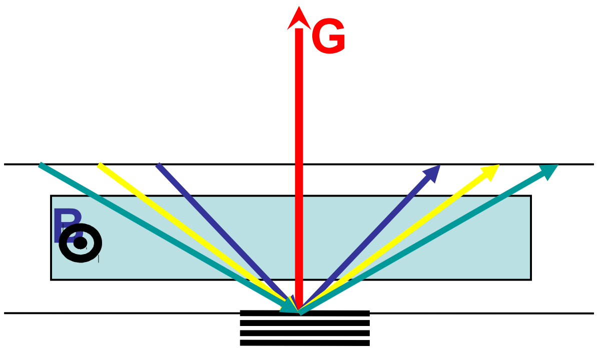
tetragonal -> orthorombic

(coexistance)

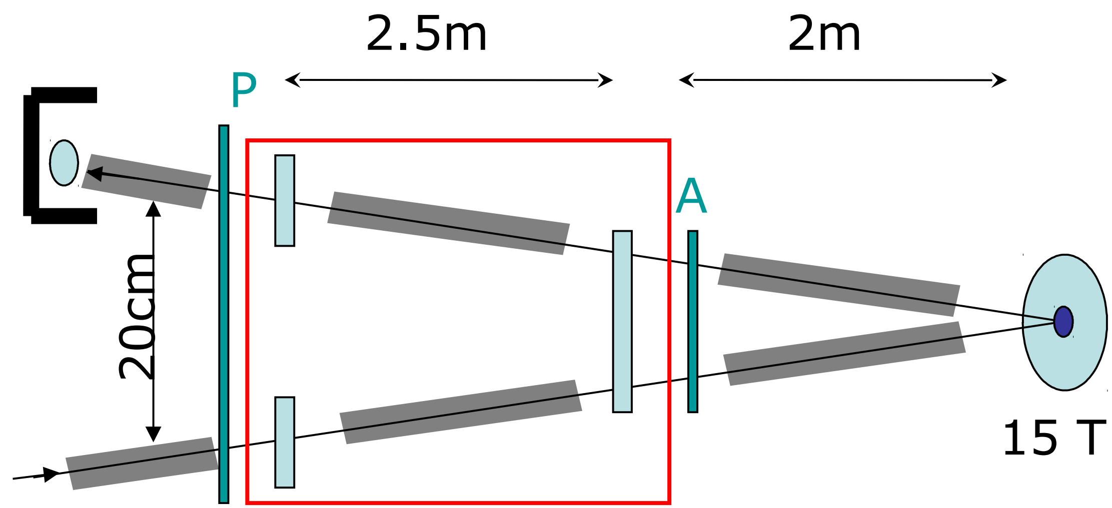


Inosov, Walters, Park et al., PRB **87**, 224425 (2013)

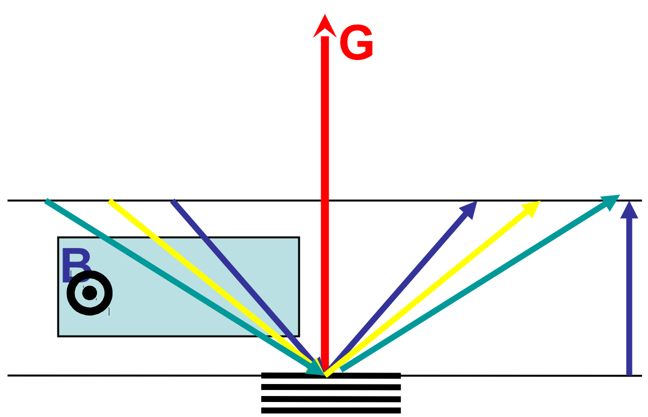
apendix 1: Larmor alternatives



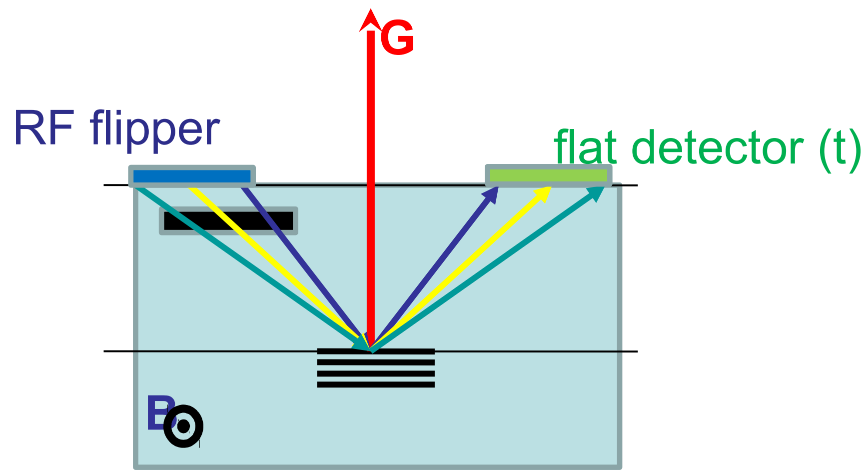
LD



LD + Mezei FM spin-echo



Rekveldt 1-arm

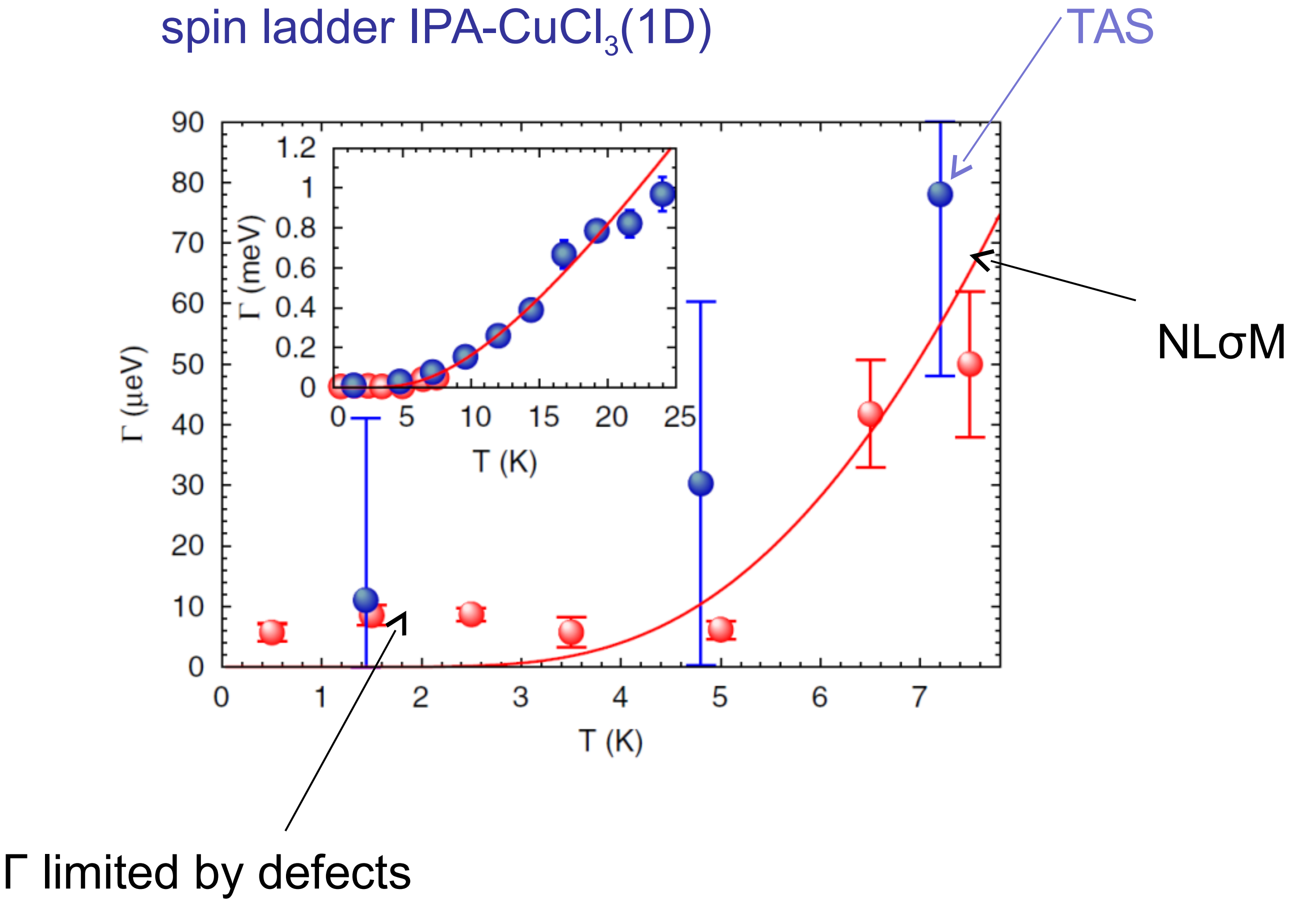


rf modulation

appendix

spin ladder IPA_CuCl$_3$

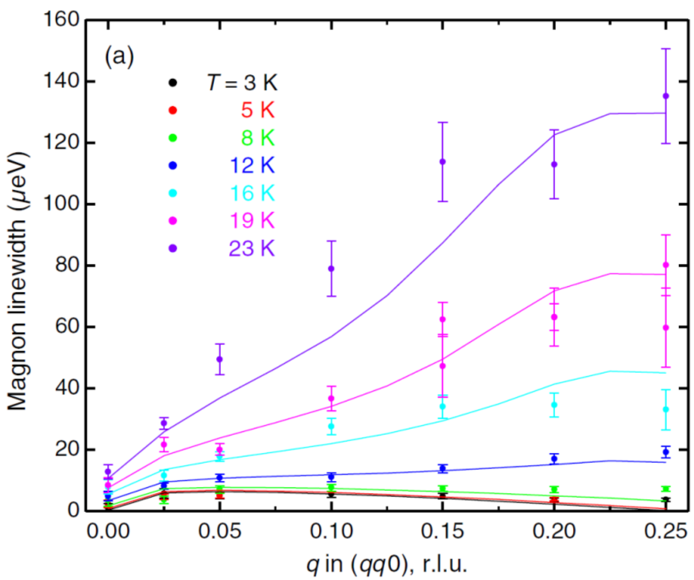
spin ladder IPA-CuCl$_3$(1D)



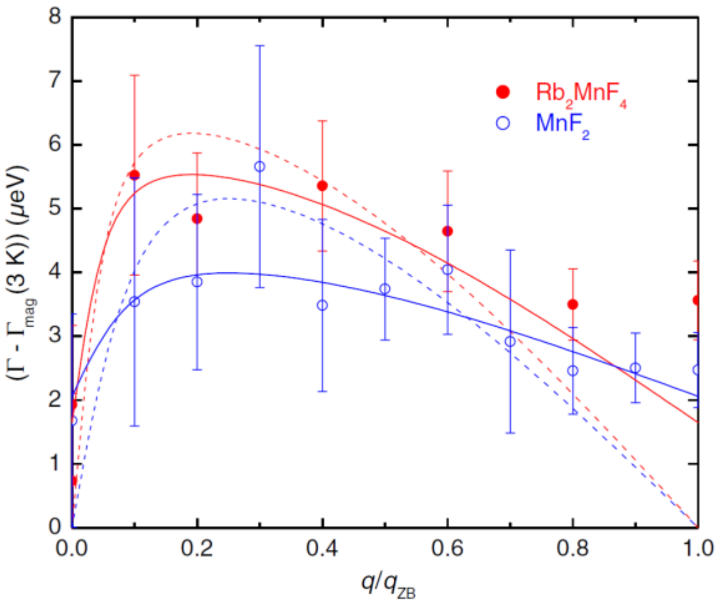
Nafradi, PRL **106**, 177202 (2011)

magnons in Rb_2MnF_4(2D) MnF_2 (3D)

Rb_2MnF_4



T=3K



-> Γ limited by antiferromagnetic domains
thermal transport

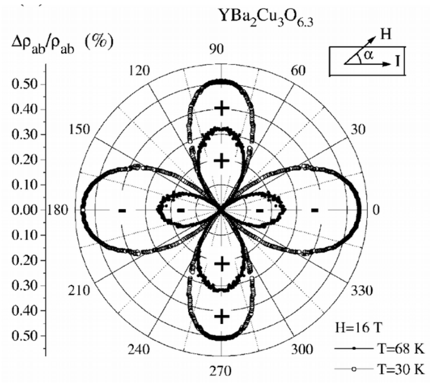
LD: domains ~500nm

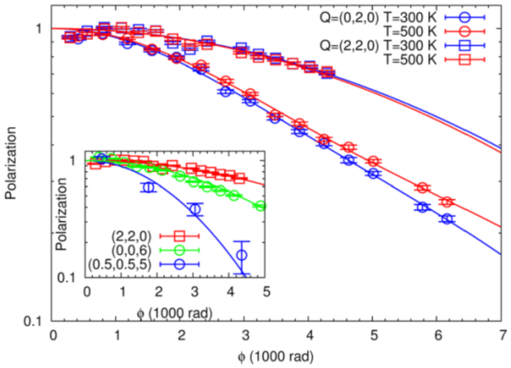
Bayrakci, Tennant, PRL **111**, 017204 (2013)

heterogeneity -> transport

magneto-resistance YBa2Cu3O6
-> reorientation of antiferromagnetic domains

domain size 300nm





Ando, PRL **83**, 2813 (1999)

Náfrádi, PRL **116**, 047001 (2016)

empty