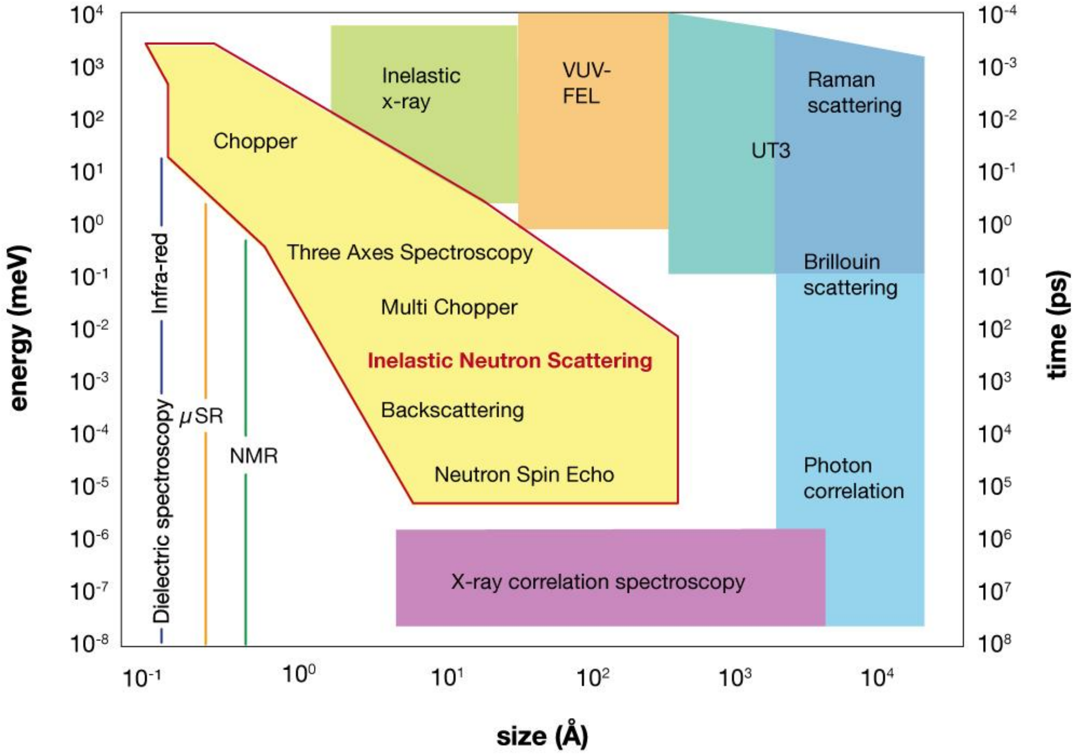
Longitudinal Neutron Resonance Spin Echo (and MIEZE)

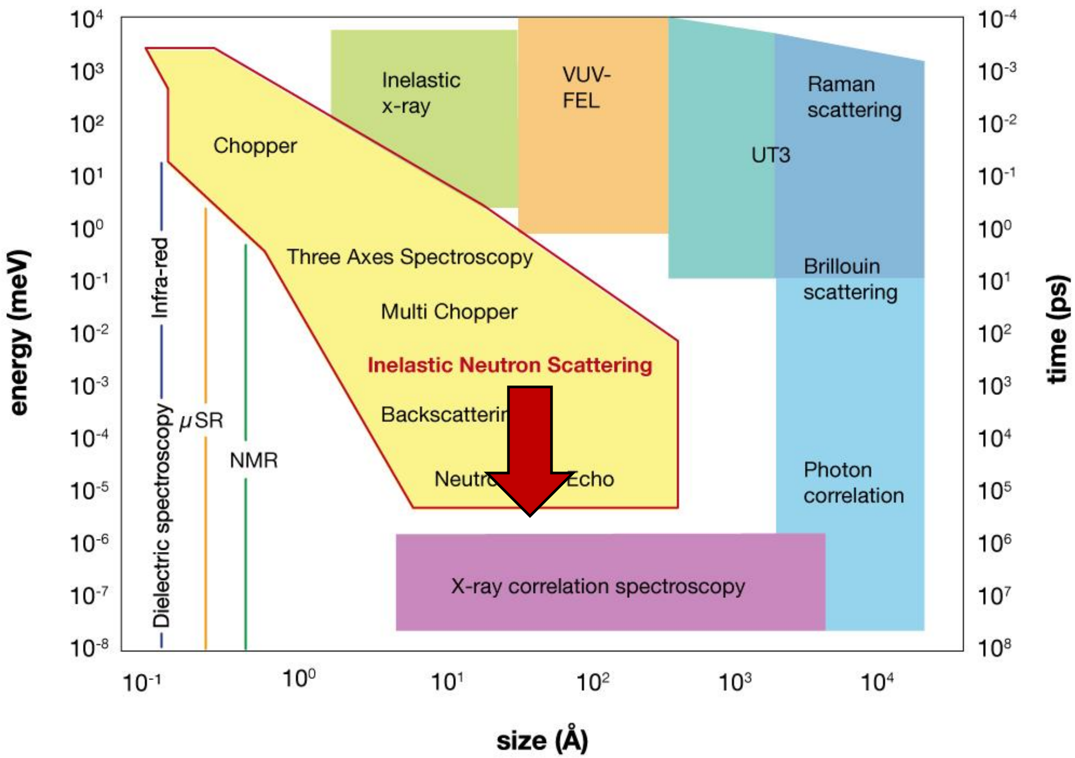
Christian Franz
Technische Universität München


Main themes
• Longitudinal Resonance Spin echo the future ?

Adding a magnetic field axis to high resolution spectroscopy

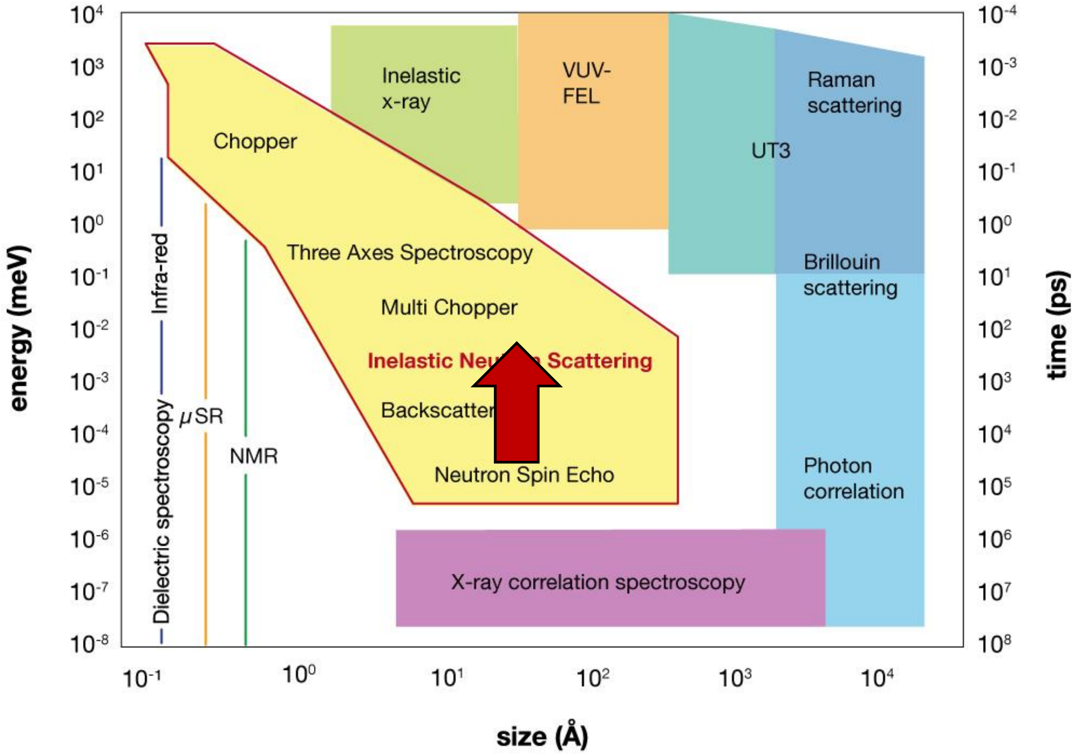


Adding a magnetic field axis to high resolution spectroscopy



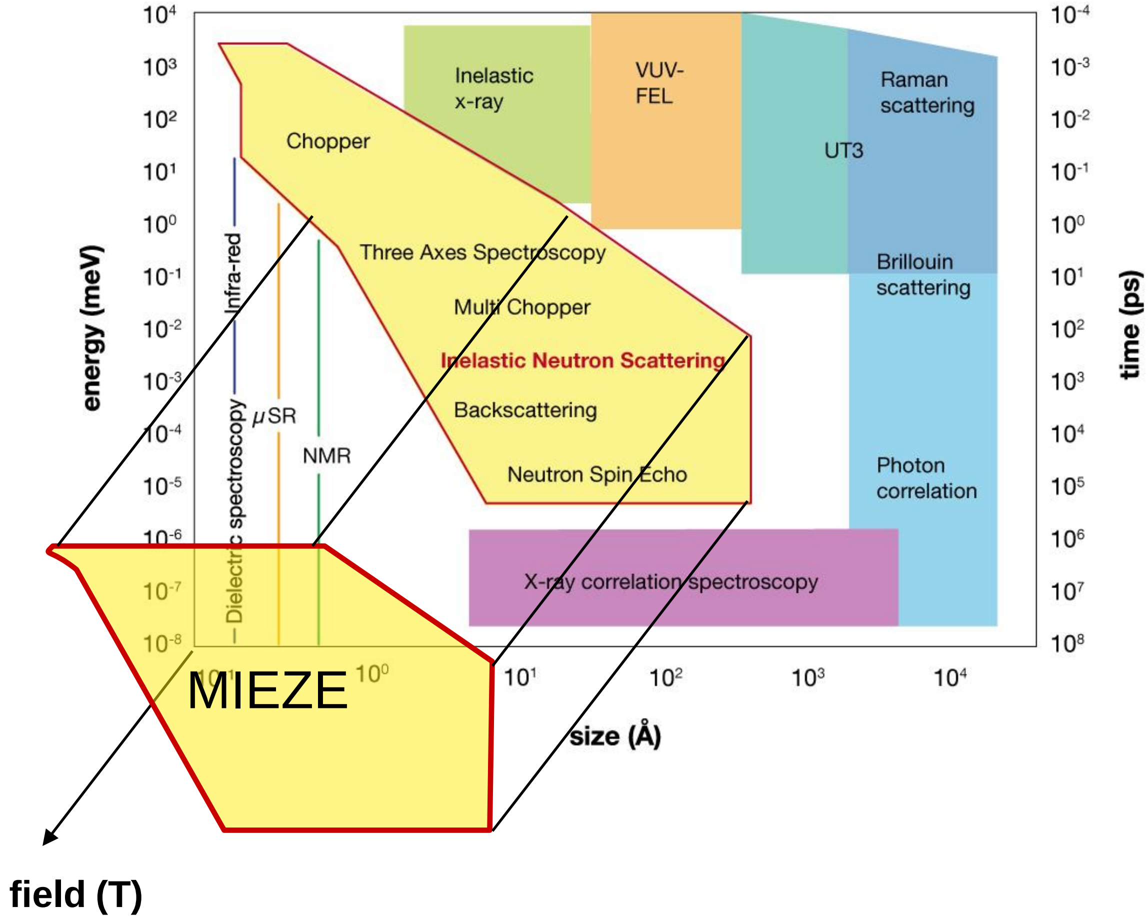
See Talks
S. Pasini
O.Holderer
P. Falus

Adding a magnetic field axis to high resolution spectroscopy



See Talk
G. Ehlers

Adding a magnetic field axis to high resolution spectroscopy

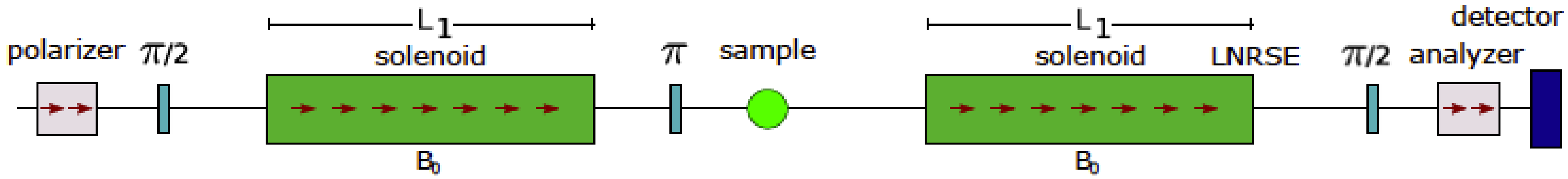


Part I: Instrumentation

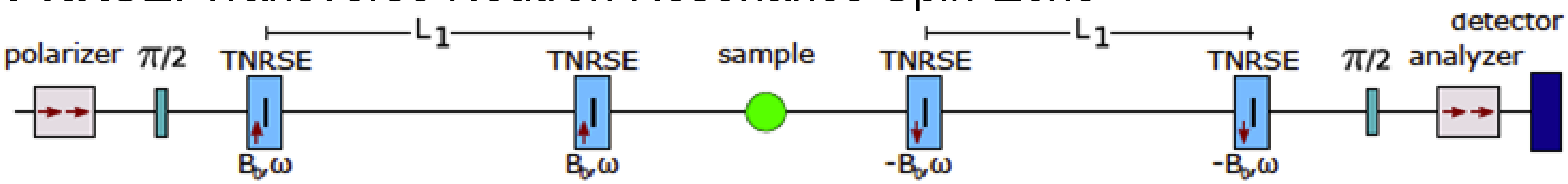
Neutron Spin-Echo Techniques

classical methods

NSE: Neutron Spin-Echo

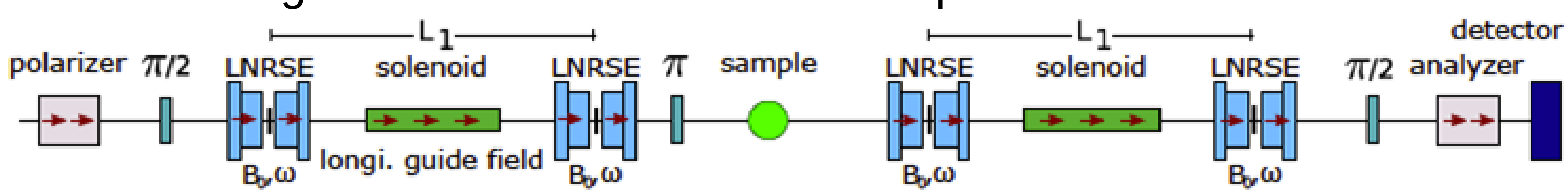


T-NRSE: Transverse Neutron Resonance Spin-Echo

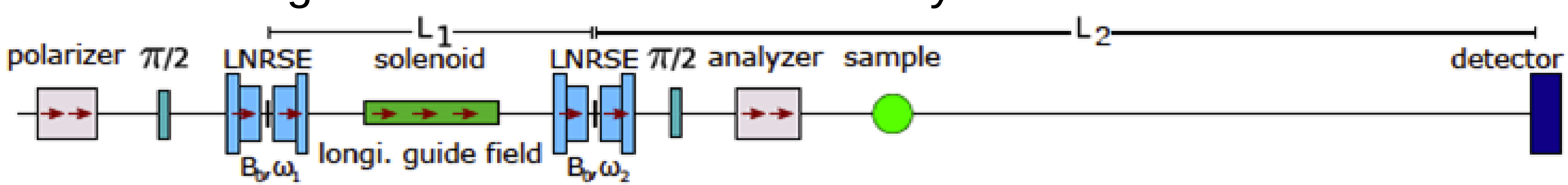


recent development

L-NRSE: Longitudinal Neutron Resonance Spin-Echo

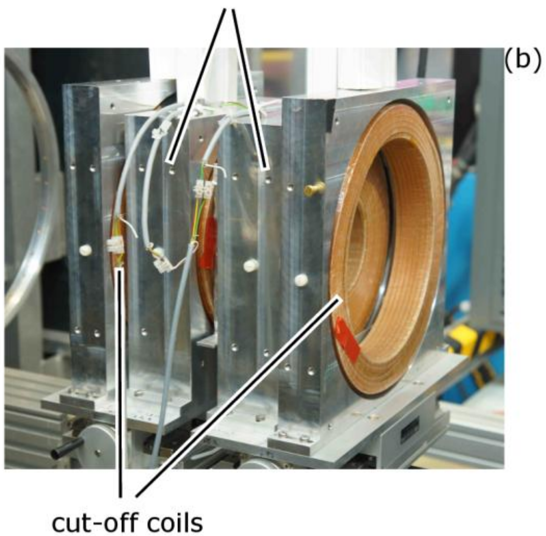


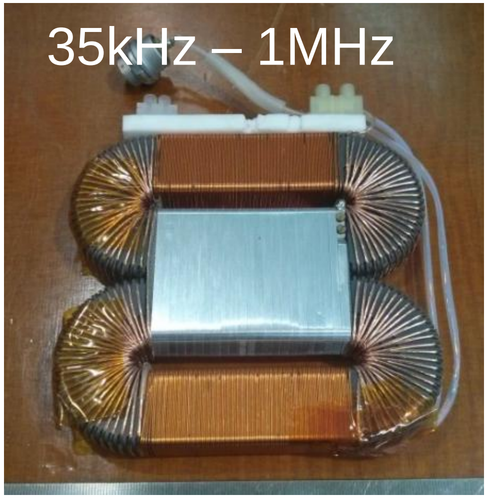
L-MIEZE: Longitudinal Modulation of Intensity with Zero Effort

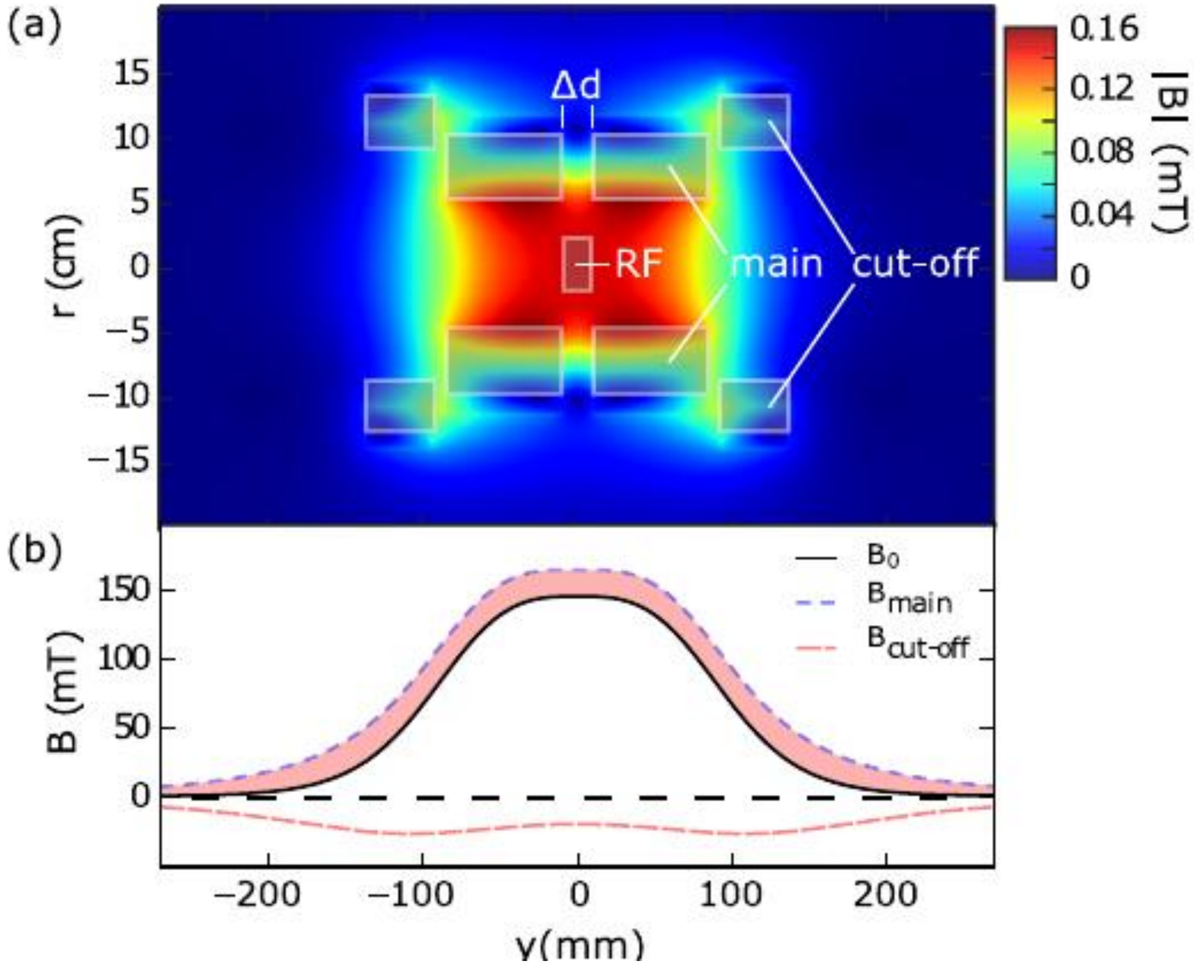


Häußler et al. PCCP **7** 1245 (2005)

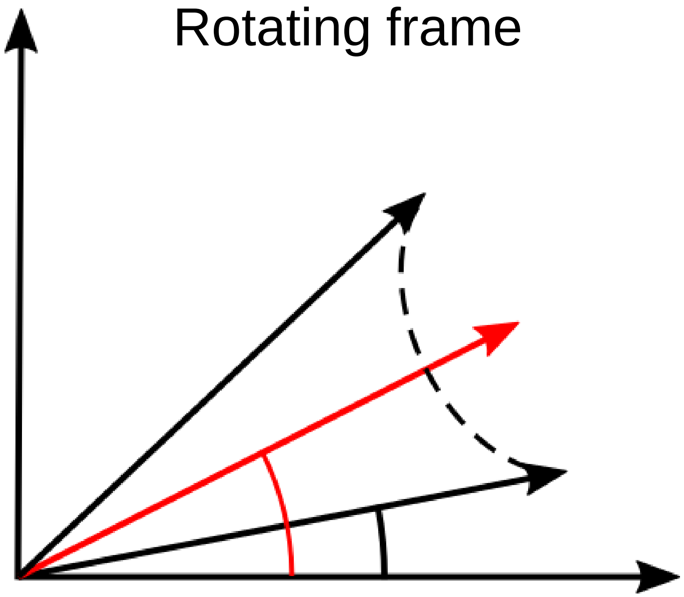
(longitudinal) Resonant Flipper

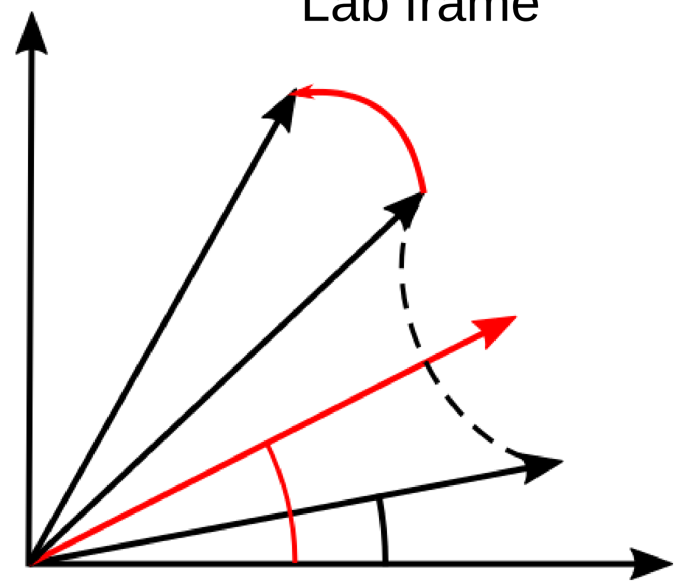






Resonant Flip: One Coil



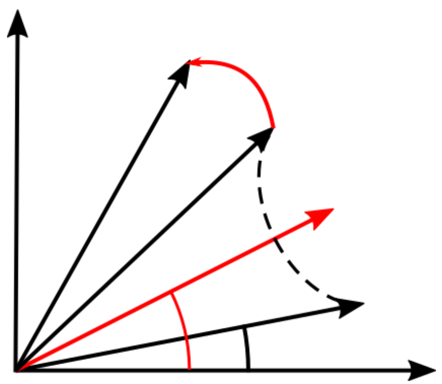


$$\pi - Flip \quad : 2(\varphi_{HF1} - \varphi_0)$$

$$\varphi = \varphi_0 + 2(\varphi_{HF1} - \varphi_0) + \omega t$$
$$= 2\varphi_{HF1} - \varphi_0 + \omega t$$

Resonant Flip: Two Coils

1st coil



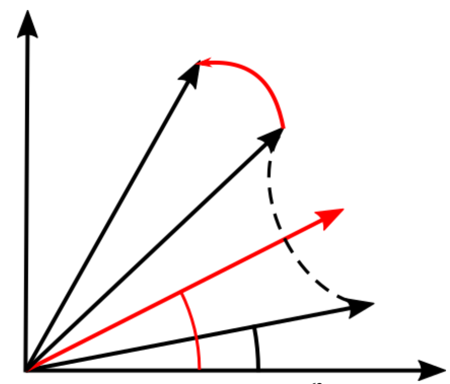
$$\varphi = 2\varphi_{HF\,1} - \varphi_0 + \omega t$$

Flight path

L, v

$$\varphi_{HF\,2} = \omega \frac{L}{v} + \varphi_{HF\,1}$$

2nd coil



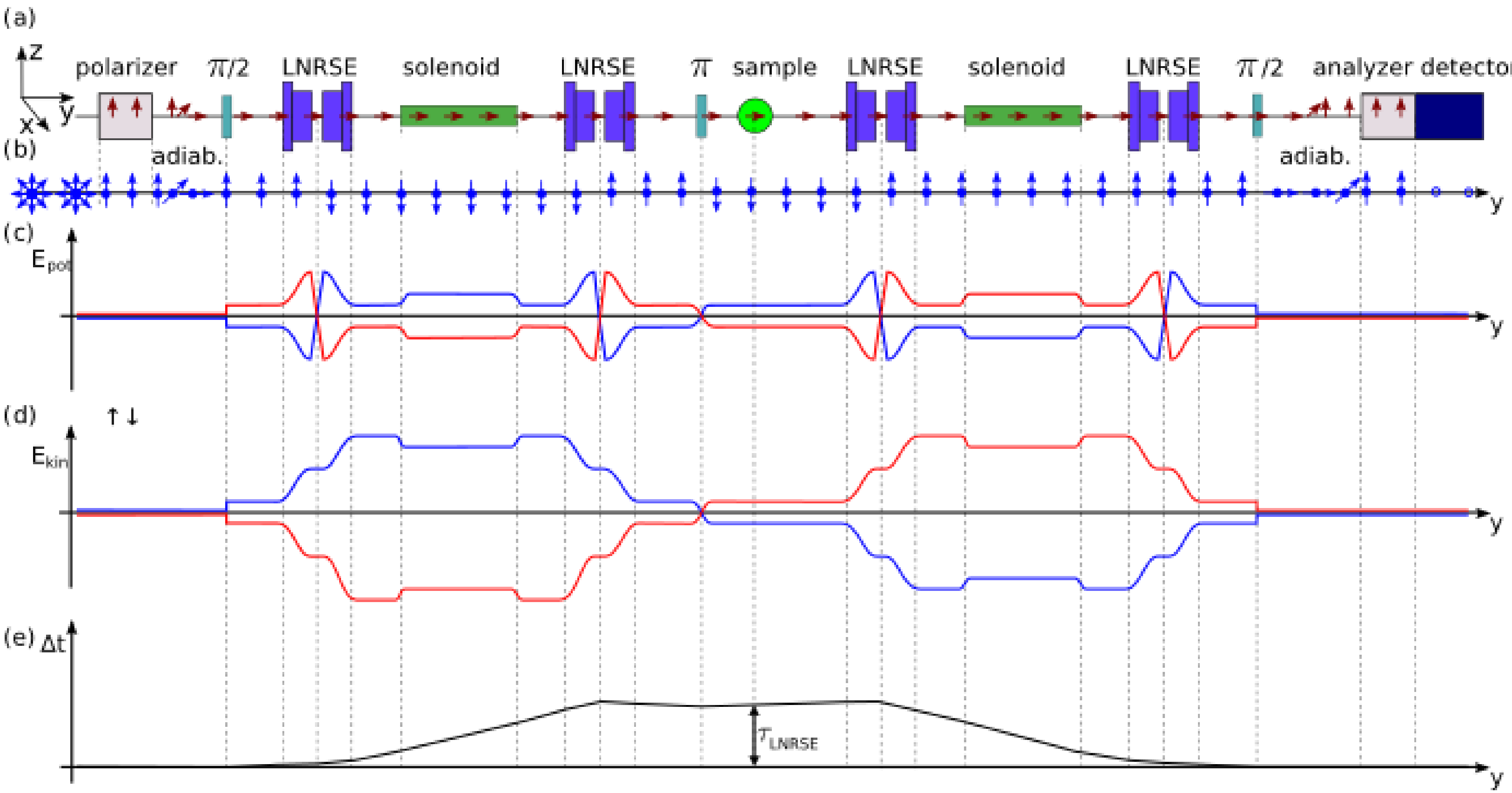
$$\varphi_{res} = 2\varphi_{HF\,2} + \omega t - \overbrace{(2\varphi_{HF\,1} + \omega t - \varphi_0)}^{\varphi_2}$$

$$= \underbrace{2(\varphi_{HF\,2} - \varphi_{HF\,1})}_{\Delta\varphi} - \varphi_0$$

$$\Delta\varphi = 2(\overbrace{\omega \cdot \frac{L}{v} + \varphi_{HF\,1}}^{\varphi_{HF\,2}} - \varphi_{HF\,1}) = 2\omega \cdot \frac{L}{v} = \boxed{2\frac{\gamma B_0 L}{v}}$$

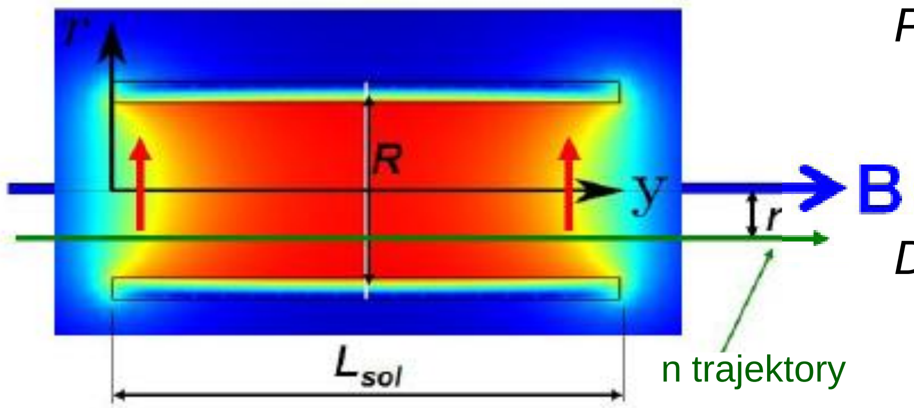
= 2x NSE

Semi-classical description



$$\left|+\right\rangle_x = \frac{1}{\sqrt{2}}\left(\left|+\right\rangle_z + \left|-\right\rangle_z\right)$$

Limitations of conventional NSE



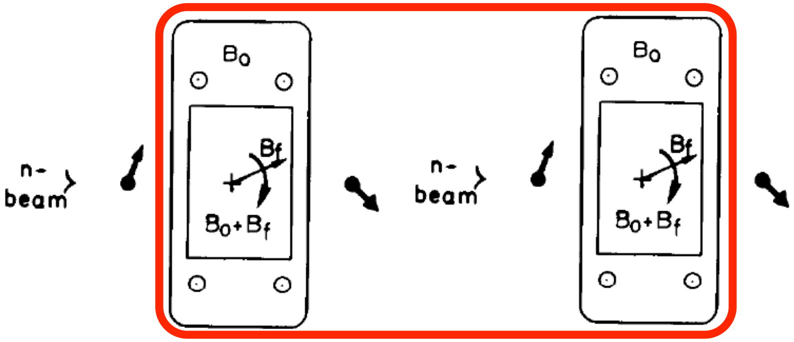
Parallel beam:

$$J(r) \simeq B_0 L_{sol} \left(1 + \frac{r^2}{2RL_{sol}}\right)$$

Divergent beam:

field optimization

Limitations of transversal NRSE

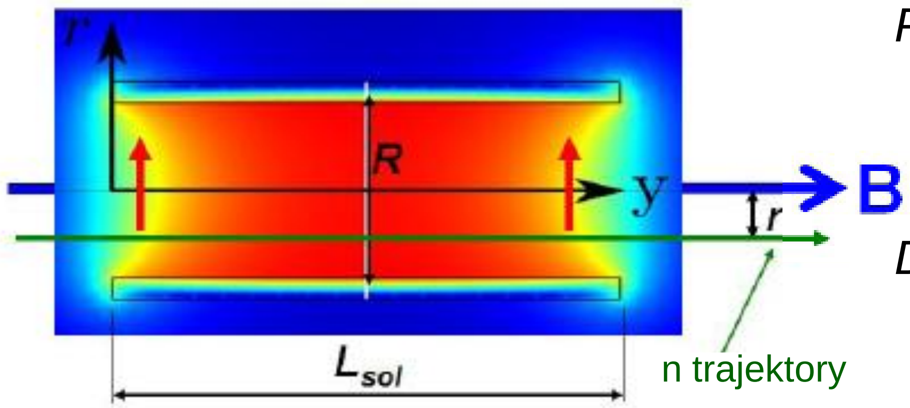


B_0 field not symmetric to n beam
sensitive to surface of B_0 coil

(Maximum Spin Echo Time few ns)

Golub & Gähler., Phys. Lett. A **123**, 43 (1987)

Limitations of conventional NSE



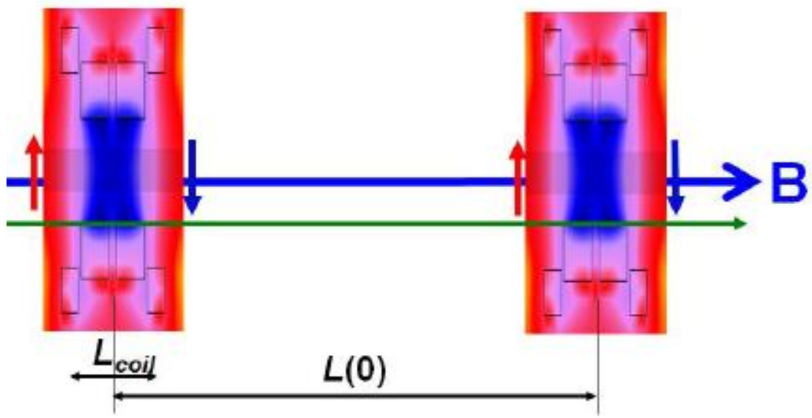
Parallel beam:

$$J(r) \simeq B_0 L_{sol}\left(1 + \frac{r^2}{2RL_{sol}}\right)$$

Divergent beam:

field optimization

Advantages of longitudinal NRSE



Parallel beam:

$$J(r) = B_0 L(0)$$

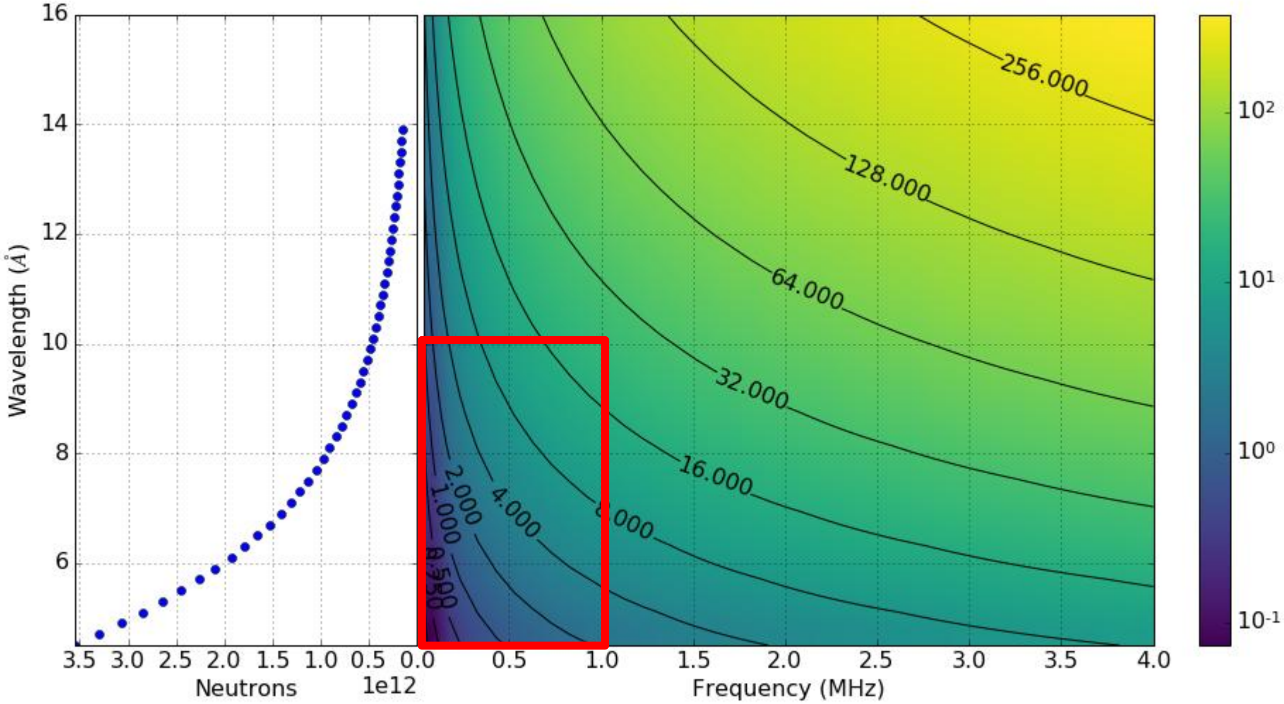
No corrections necessary!

Divergent beam:

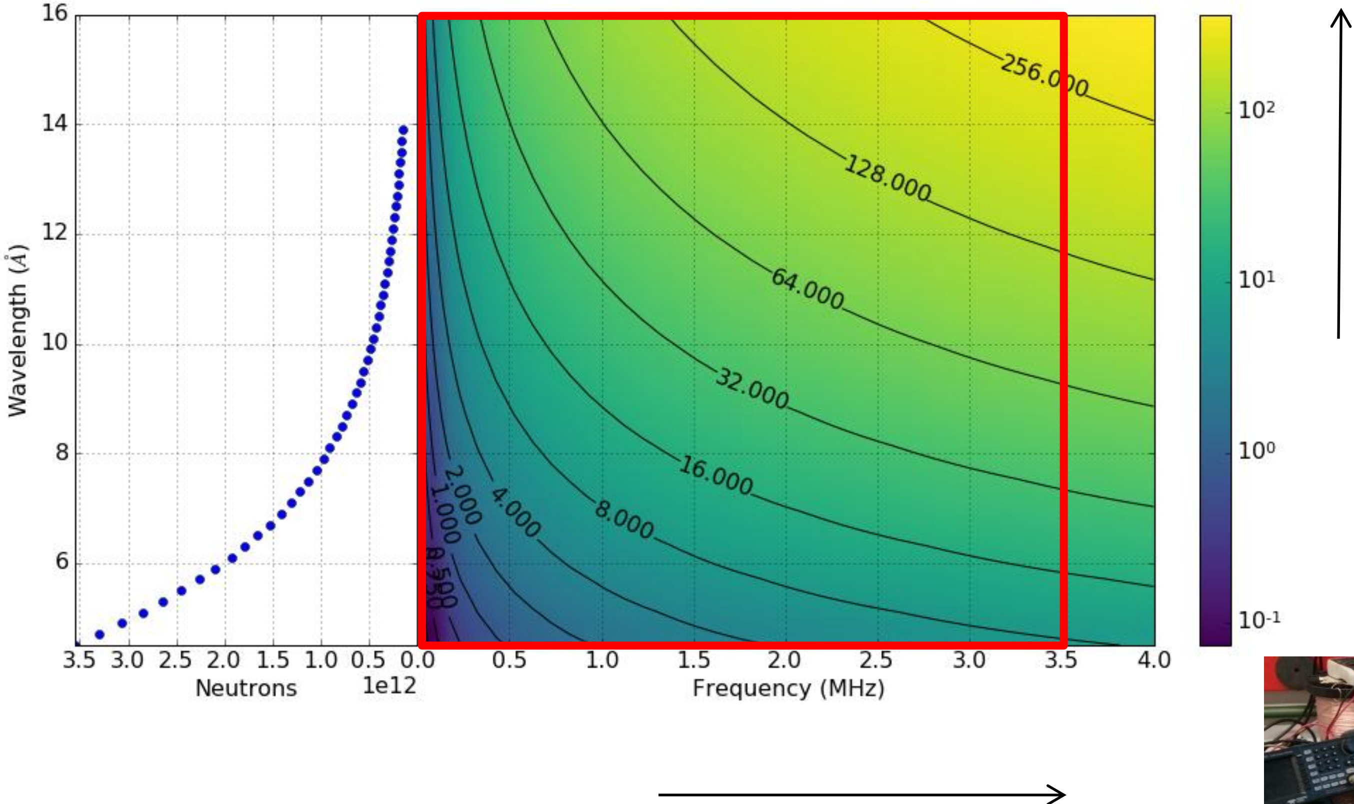
Fresnel correction reduced by $\frac{L_{coil}}{L(0)}$

Häußler et al., Chem. Phys. **292**, 501 (2003)

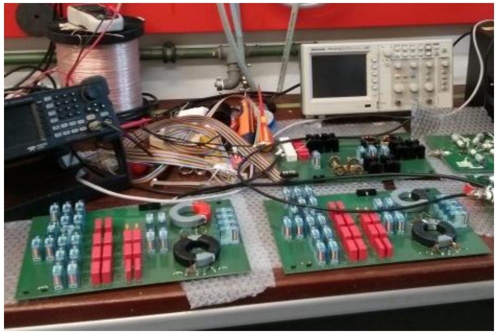
Towards High Spin-Echo Times



Towards High Spin-Echo Times



new polariser
Now delivered!

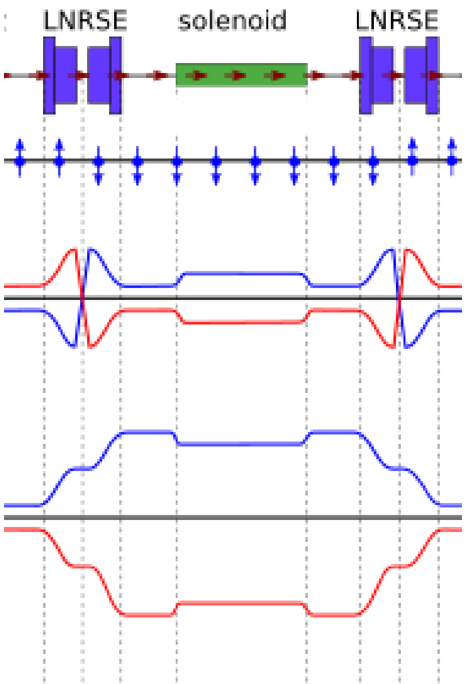


Main constraint:
Software!

3.8 MHz in tests achieved
(new LNRSE flipper)

Towards Low Spin Echo Times

Remember the minus in front of the initial phase in the classical picture?



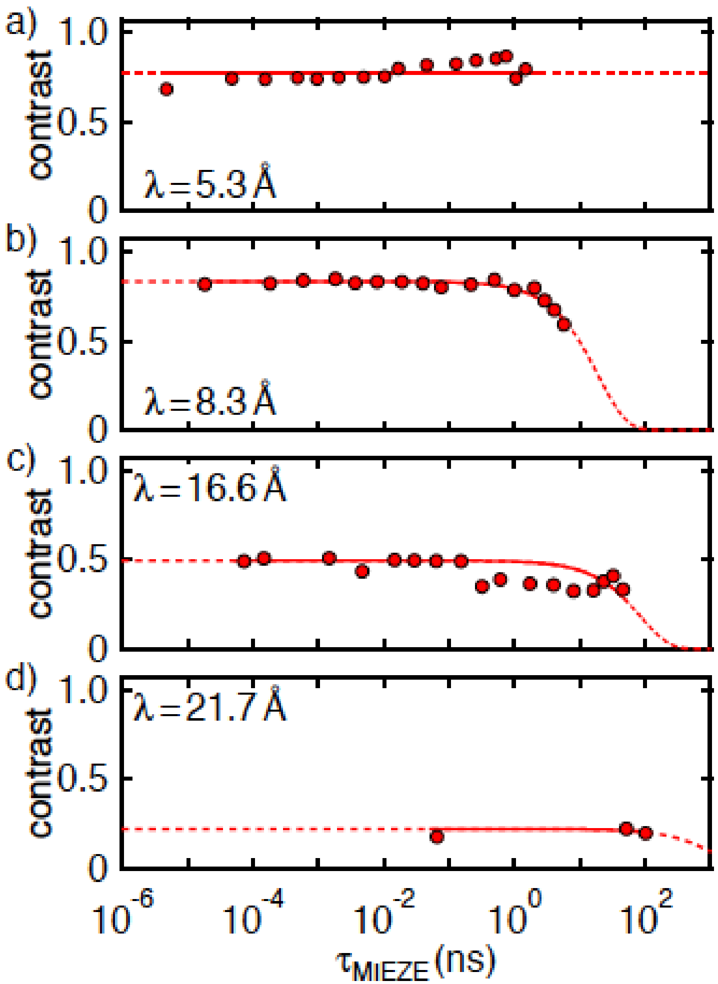
ω = 35 kHz

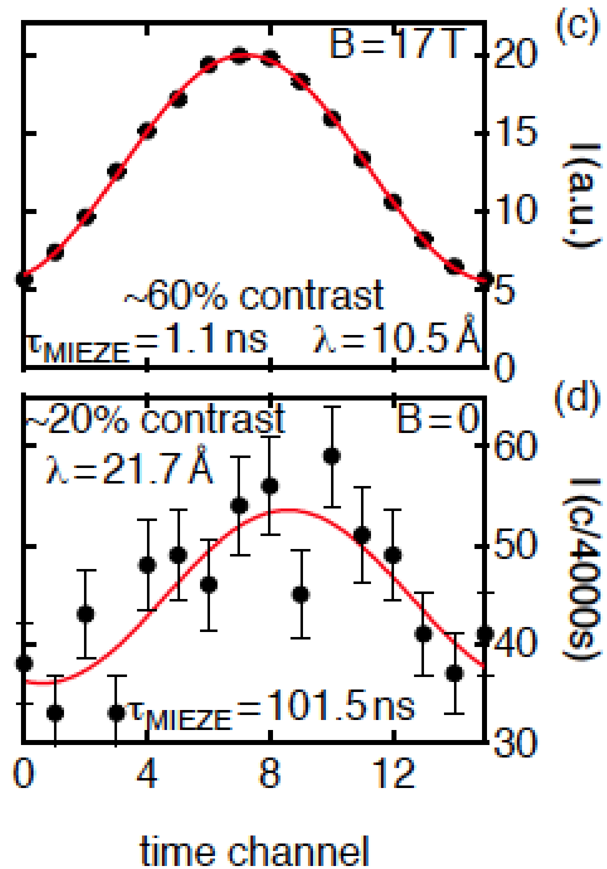
Substract field integral by NSE coil (OFS)

$$\varphi_{res} = \underbrace{2(\varphi_{HF2} - \varphi_{HF1})}_{\Delta\varphi} - \varphi_0$$

Krautloher, *Rev.Sci.Inst*. **87**, 125110 (2016)

Extreme Dynamic Range – Long SE times – Large Fields





Kindervater et al., EPJ-WC **83**, 03008 (2015)
Kindervater et al., to be published

Longitudinal vs. transversal

Transverse field geometry

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- Larmor diffraction
- Phonon focussing
  see T. Keller

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- Field inhomogenities
- Beam divergence

Longitudinal field geometry

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- Self-correction for non-divergent beams
- Fresnel, Pythagoras coils
- Large dynamic range

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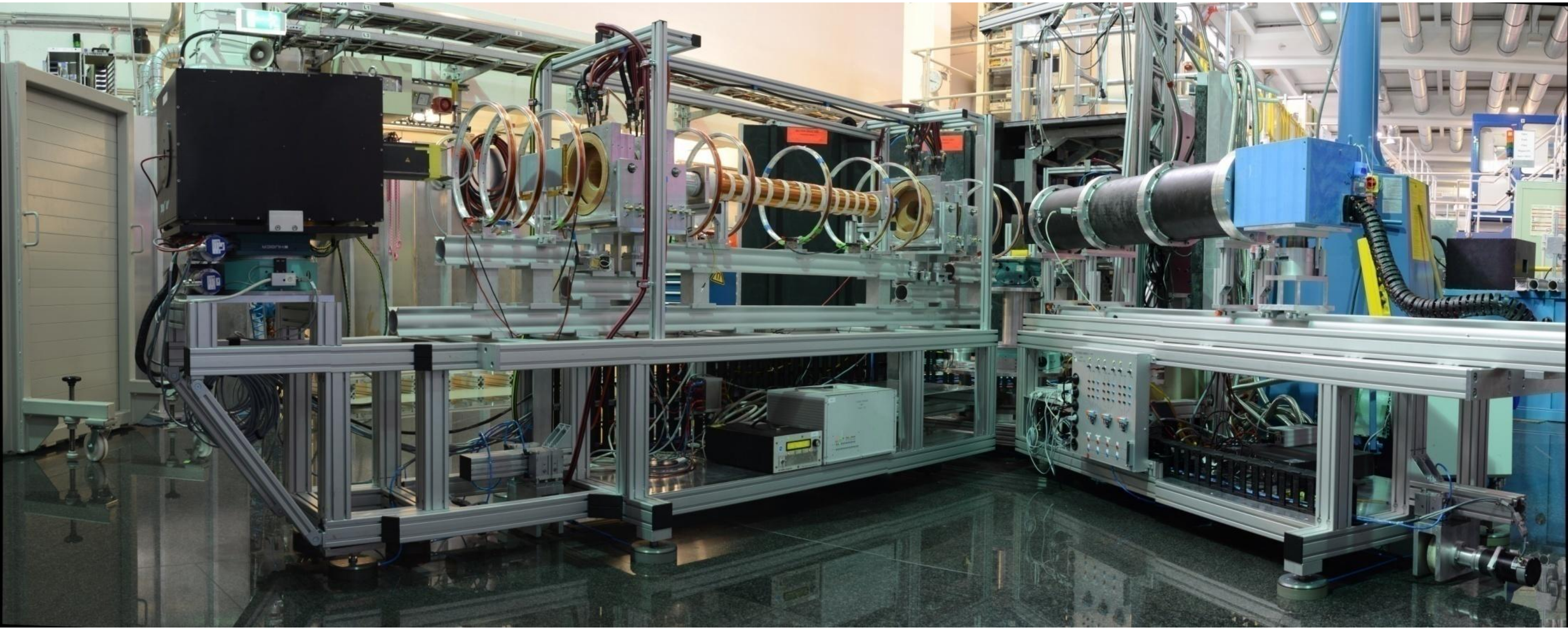
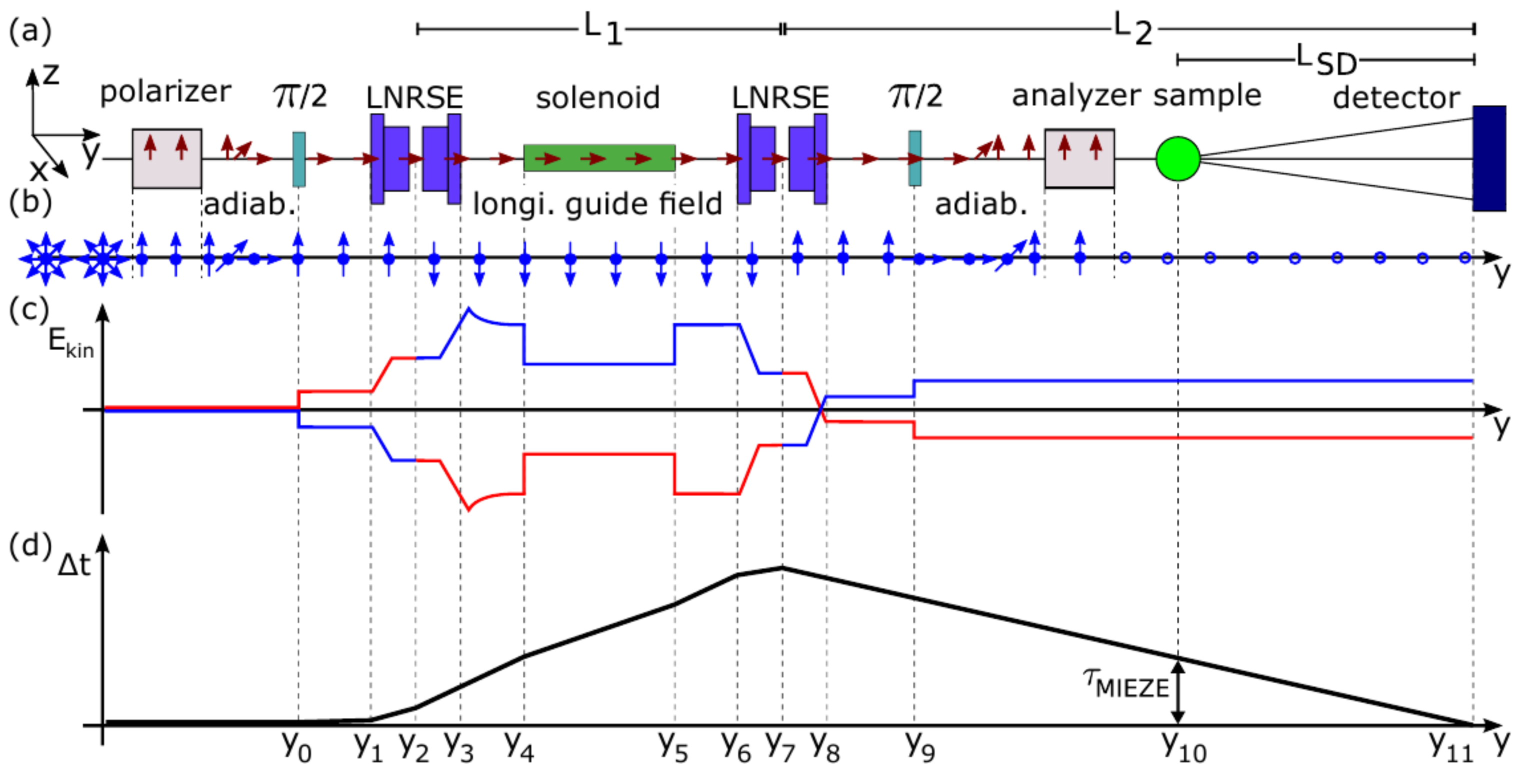
- no Larmor diffraction
- no inelastic focussing

Häußler, Schmidt, Chem. Phys., 2005, 7, 1245-1249

reseda



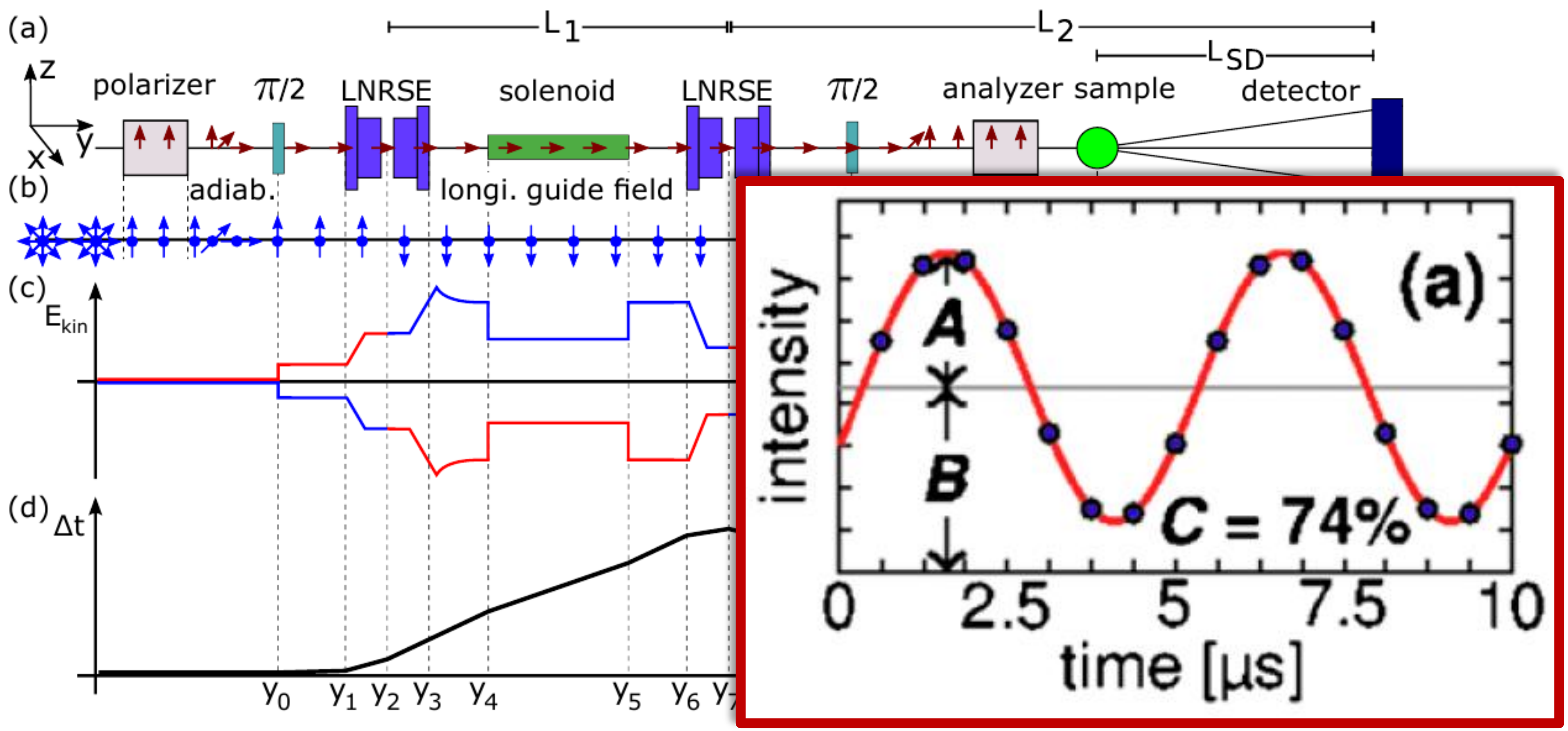
Longitudinal Modulation of Intensity with Zero Effort



$$\frac{(\omega_2 - \omega_1)}{\omega_1} = \frac{L_2}{L_1} \qquad \tau_{MIEZE} = \frac{2h \cdot L_{SD} \cdot \Delta\omega}{m \cdot v^3}$$

F. Haselbeck, Master Thesis (2015)

Longitudinal Modulation of Intensity with Zero Effort



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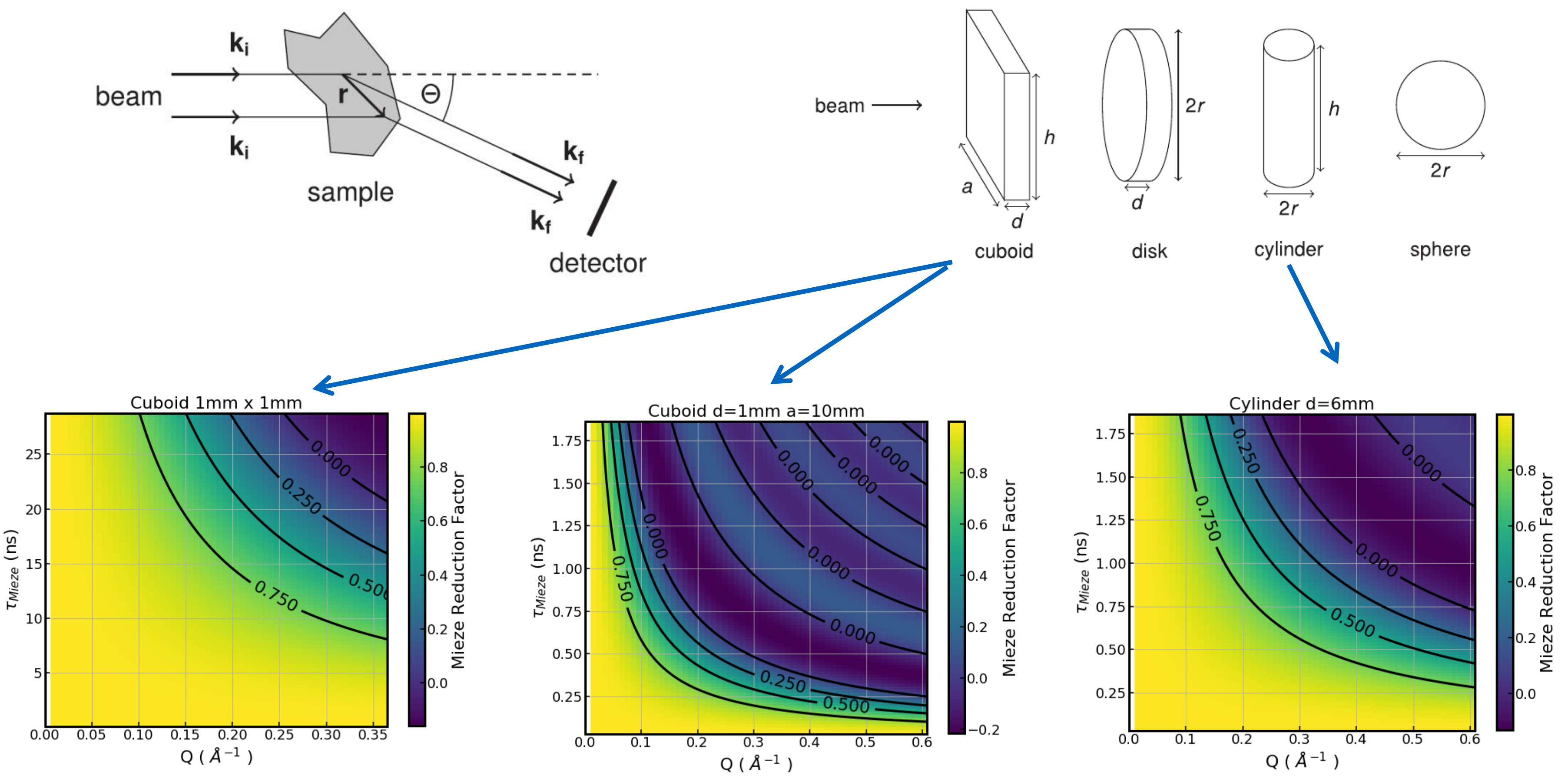
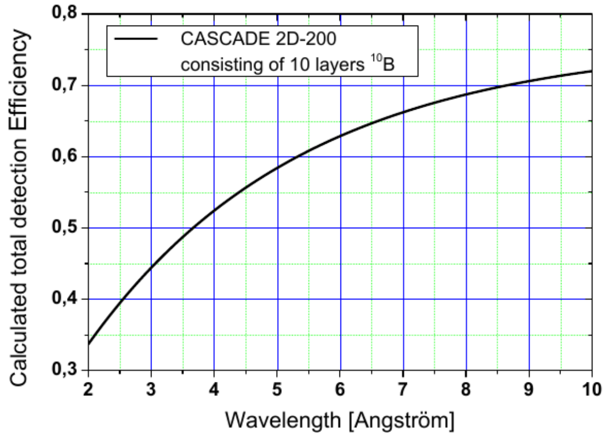
F. Haselbeck, Master Thesis (2015)

MIEZE Geometry Reduction Factor



Brandl et al. *NIMA* **654** 394 (2011)

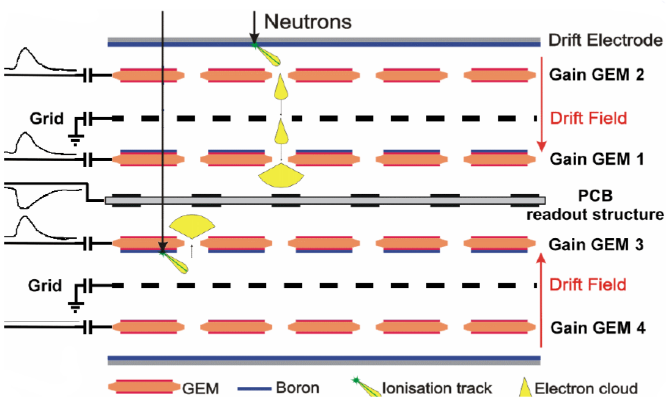
Technical Requirements: „Flat“ Detector

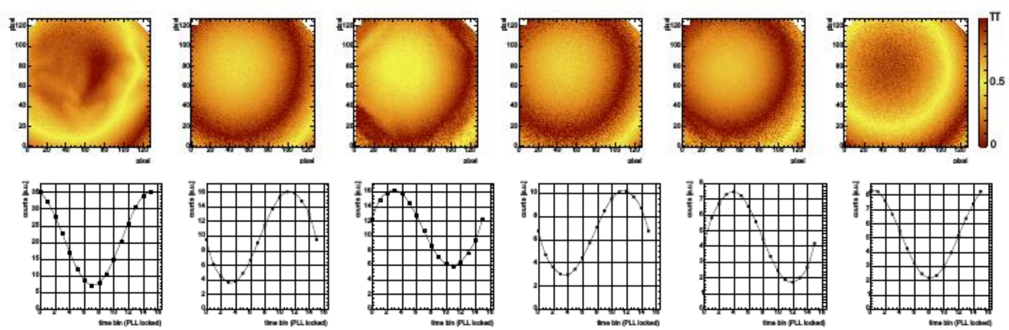


$^{10}B + n \rightarrow {}^{7}Li + \alpha$

20x20cm, 128x128px

CDT Cascade Detector Technologies, Heidelberg, Germany





Haussler, Rev. Sci. Instr. **82** (2011)
Köhli et al. NIMA **828** 242–249 (2016)

NRSE vs MIEZE

Neutron Resonance Spin Echo

- ● Similar to conventional NSE (smaller detector area)
- ● Very high resolution possible
- ● High momentum transfers possible
- ✘ No external magnetic field
- ✘ Magnetic samples difficult (see K.Pappas)
- ✘ Strong incoherent scatterer reduce polarisation (deuteration)

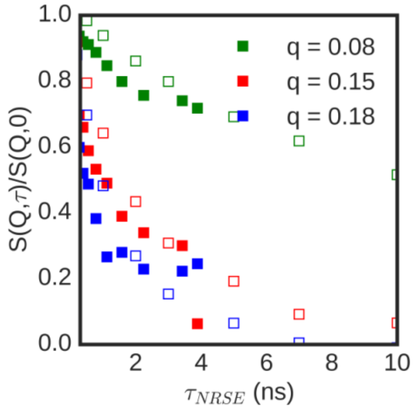
Modulation of Intensity by zero effort

- ● Similar to high-resolution TOF (or SANS with energy resolution)
- ● Magnetic field possible (17T unshielded proven)
- ● Ferromagnetic samples possible (see data on Iron)
- ● Ideal for incoherent scattering (~~see data on Clays~~)
- ✘ Reduced resolution (0.5 at Reseda)
- ✘ Momentum transfer limited by sample geometry (and size)

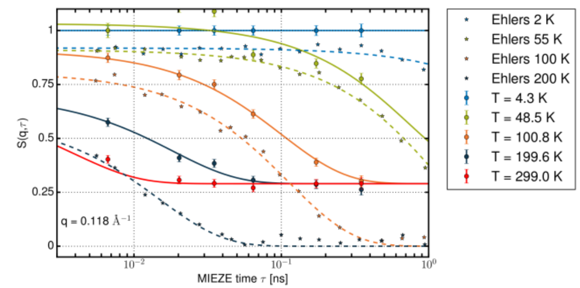
Part II: Recent Science

What can you do with it?

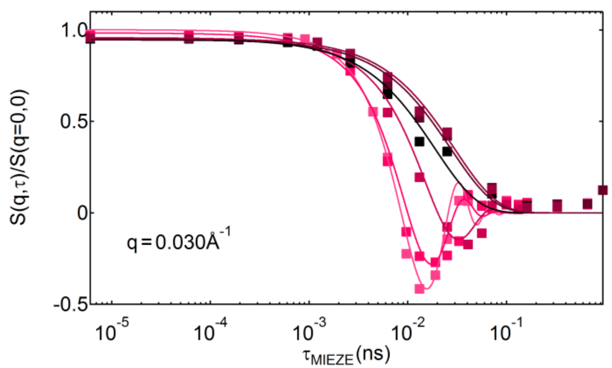
NRSE: PEP in d-decane



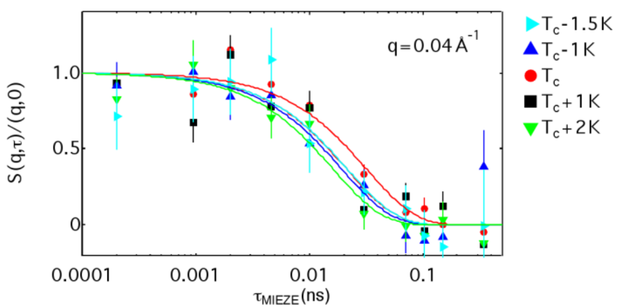
MIEZE: $Ho_2Ti_2O_7$, potential standard sample



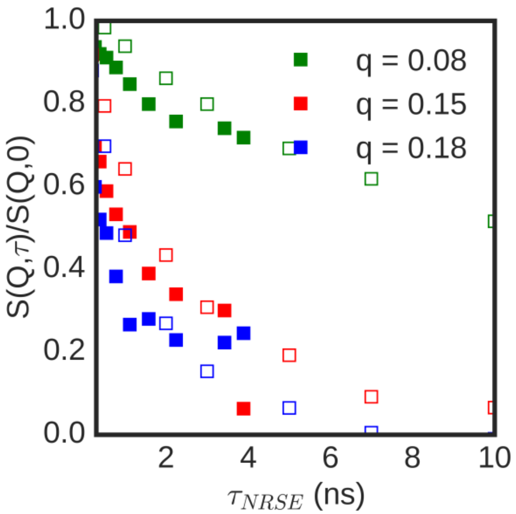
MIEZE: Inelastic measurements on FM Iron

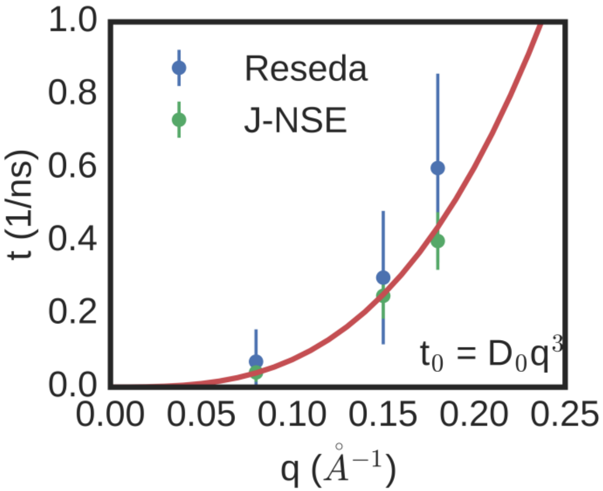


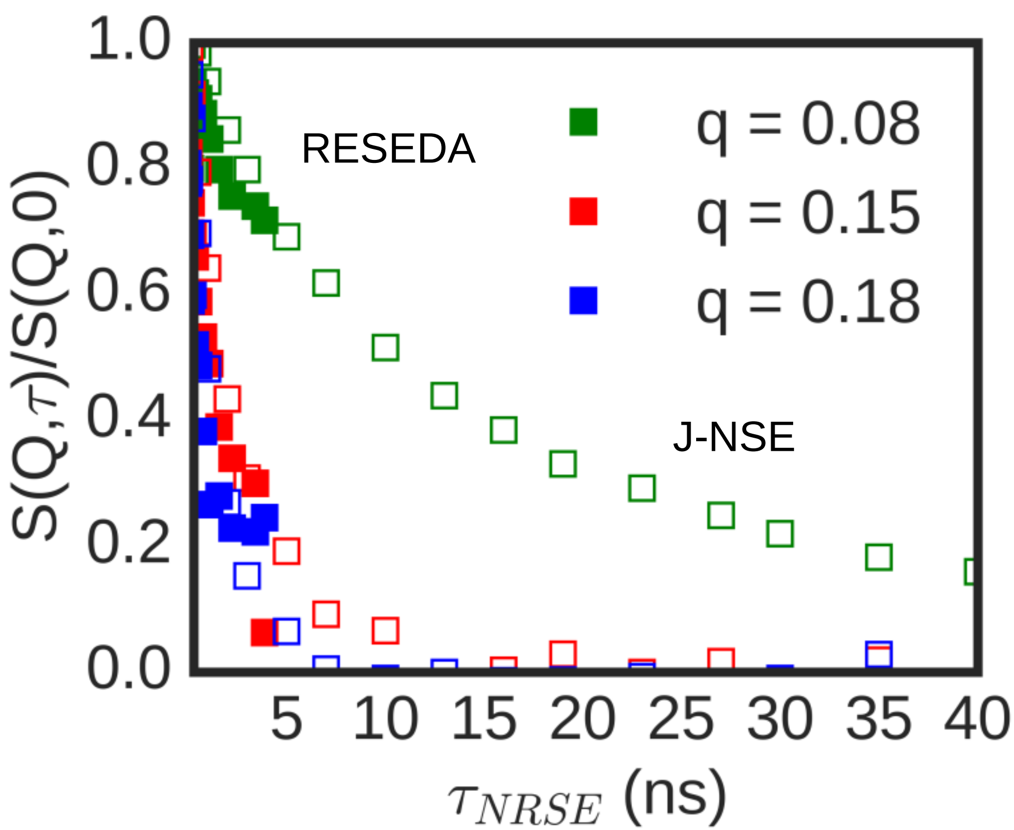
MIEZE: Quantum phase transition in the ferromagnetic superconductor UGe_2



L-NRSE: PEP in d-decane

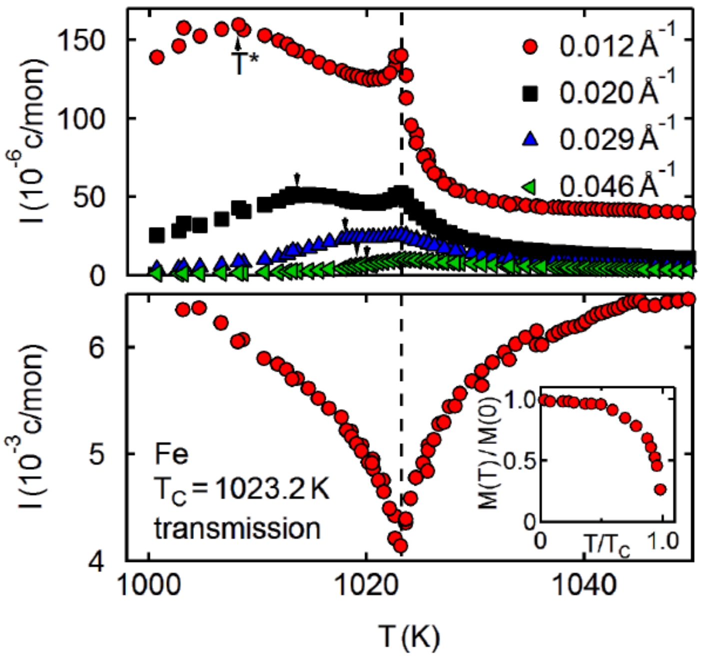






Sample: O. Holderer, J-NSE

Fluctuations at the Curie Point in Iron



See talk C. Pappas
Ferromagnetic Spin Echo

P. Rêsibois and C. Piette, Phys. Rev. Lett. 24, 514 (1970)
E. Frey and F. Schwabl, Physics Letters A, 49 (1987)
Kindervater et al. PRB, 95, 014429 (2017)

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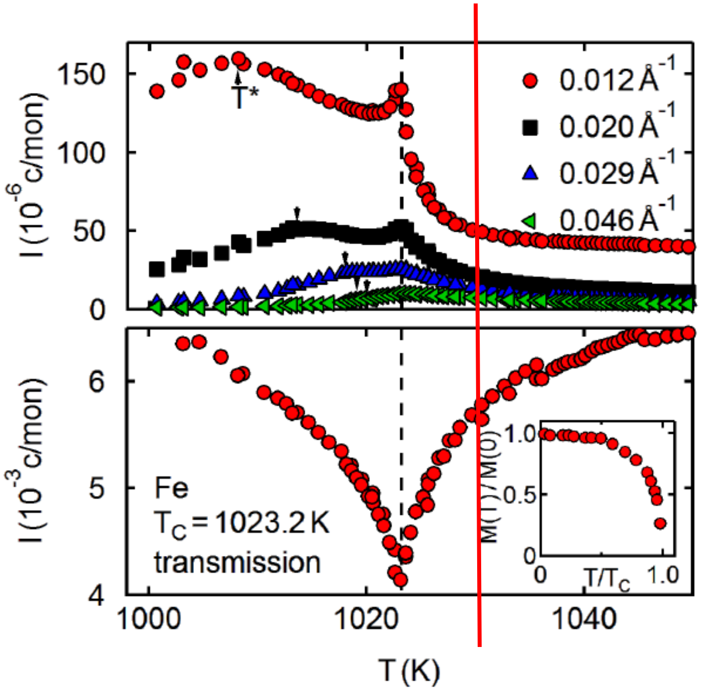

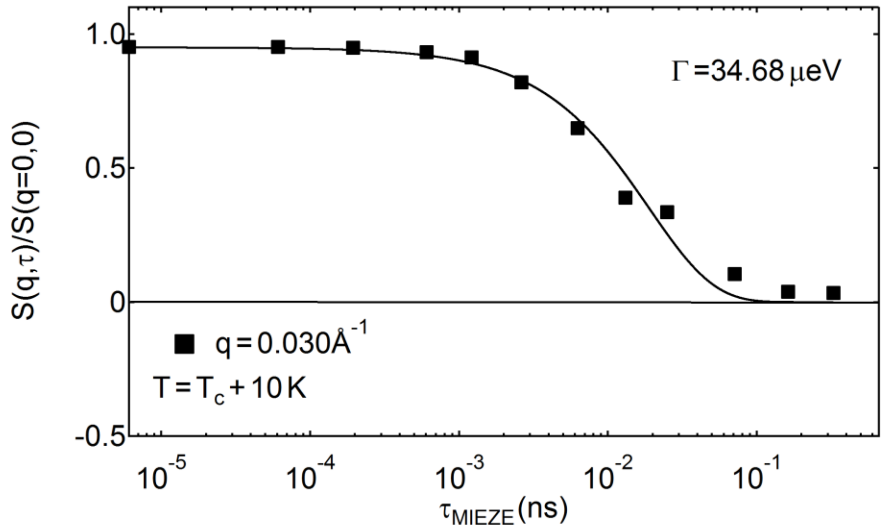

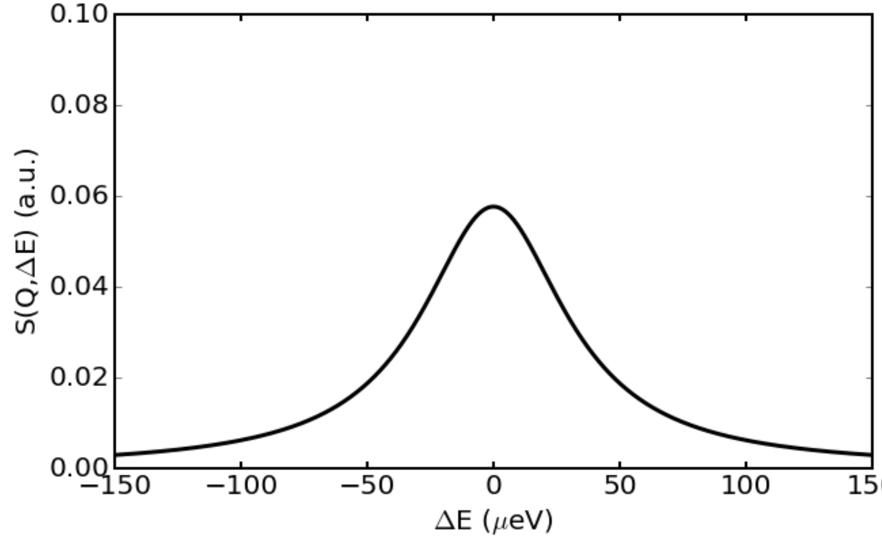

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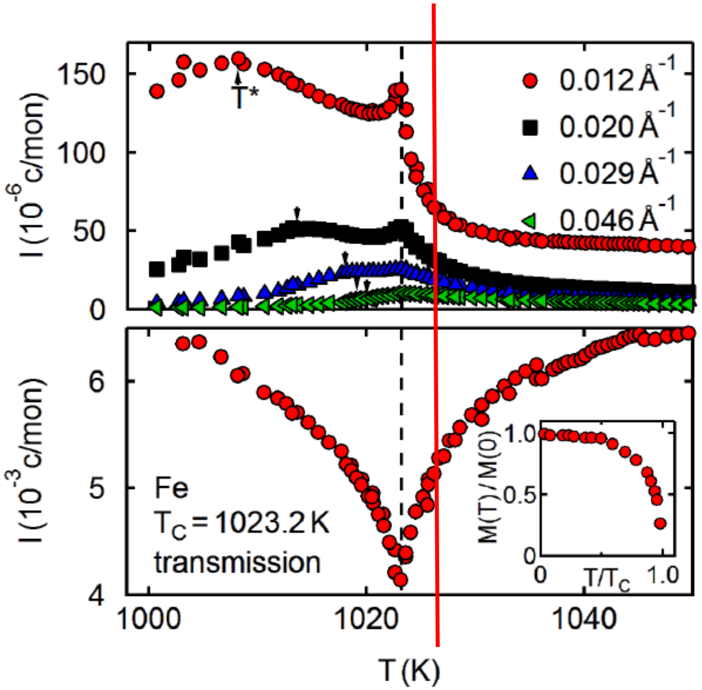

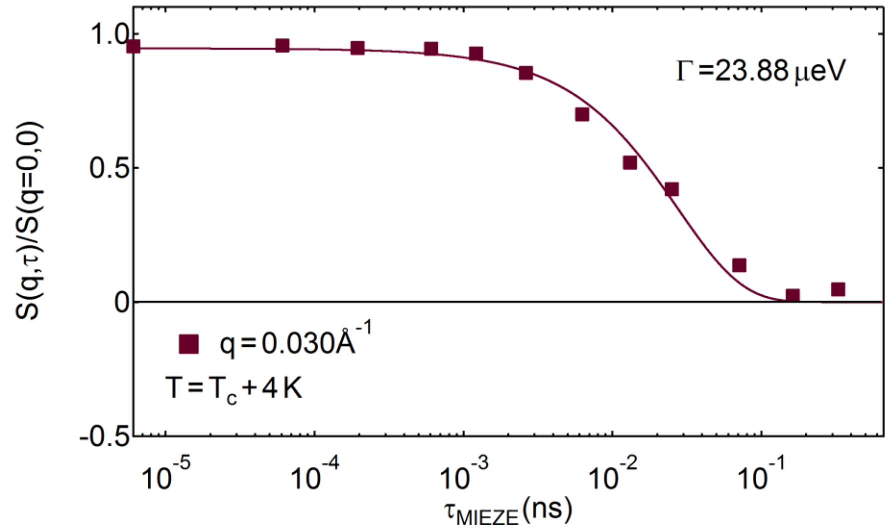

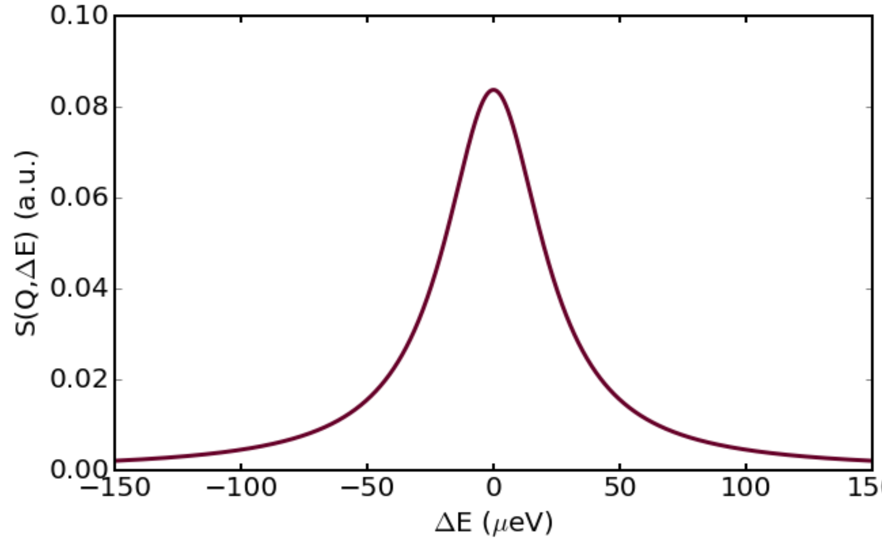

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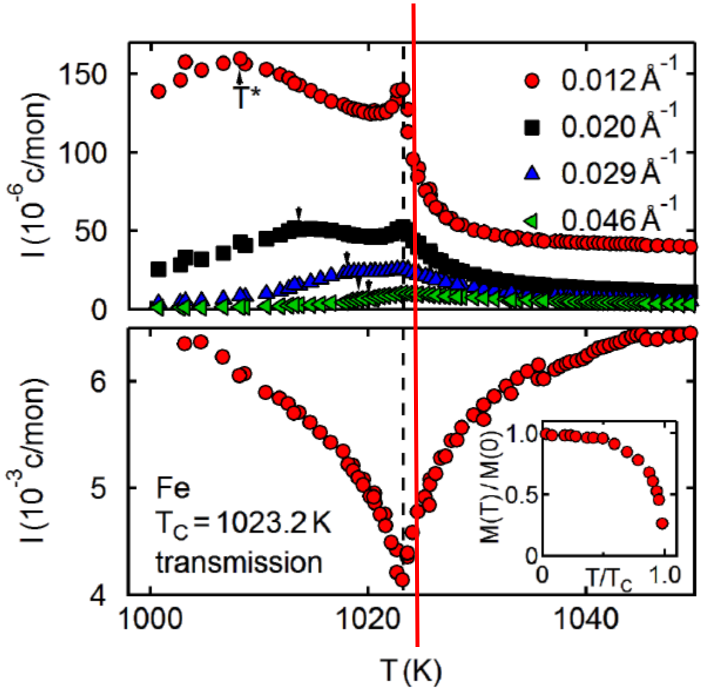

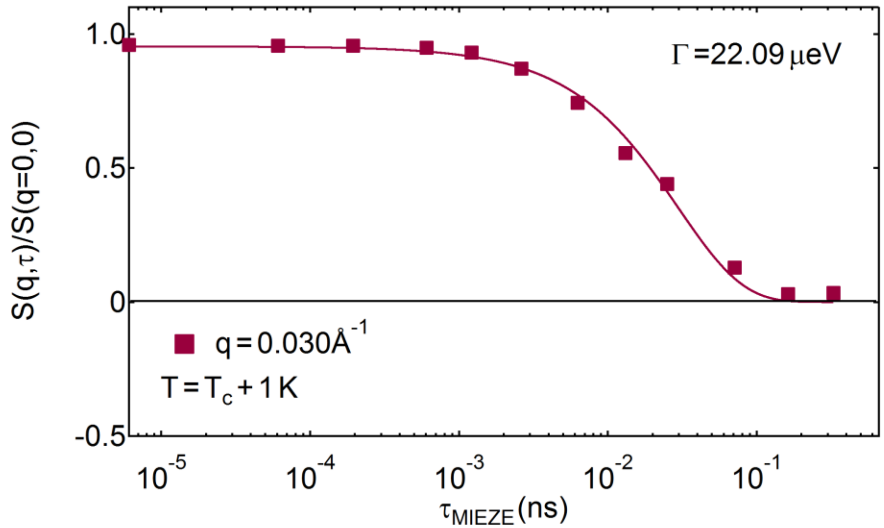

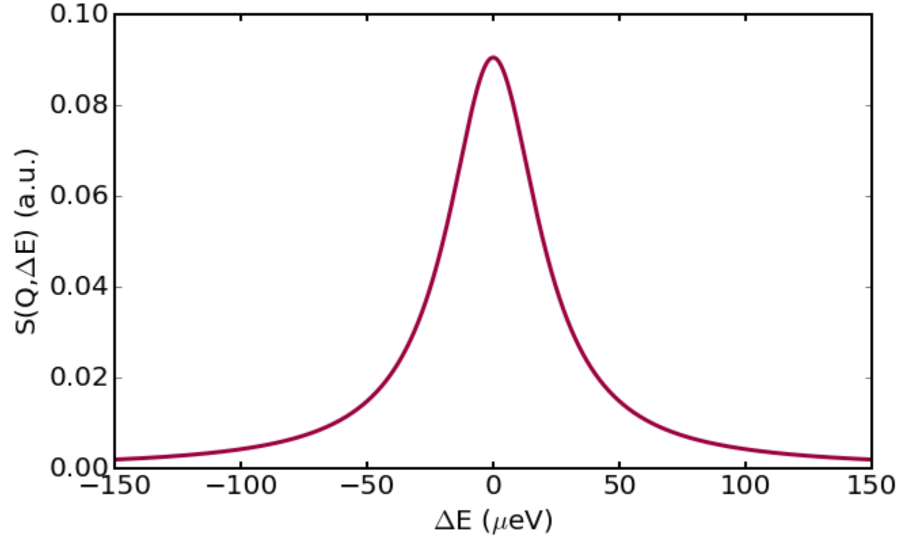

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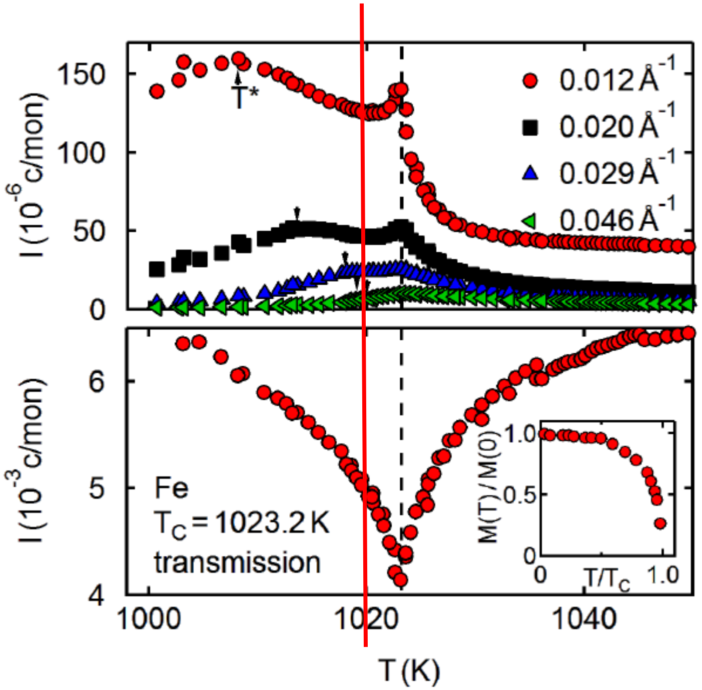

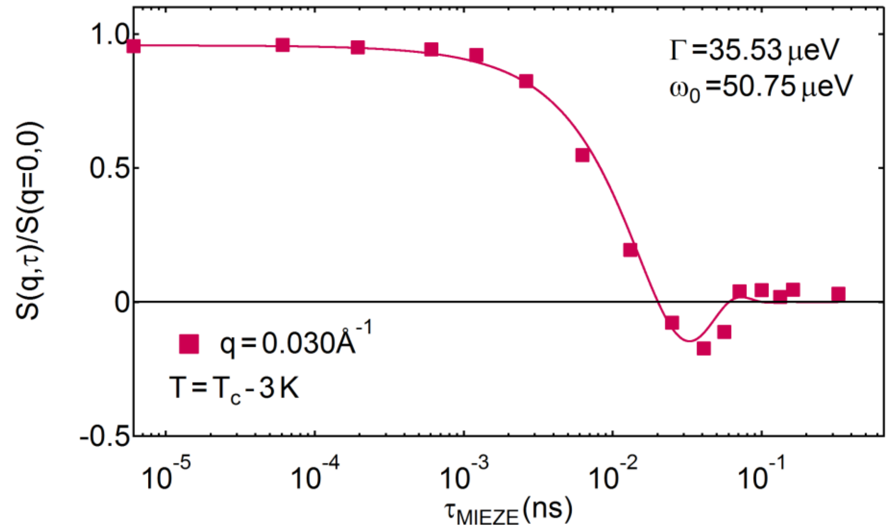

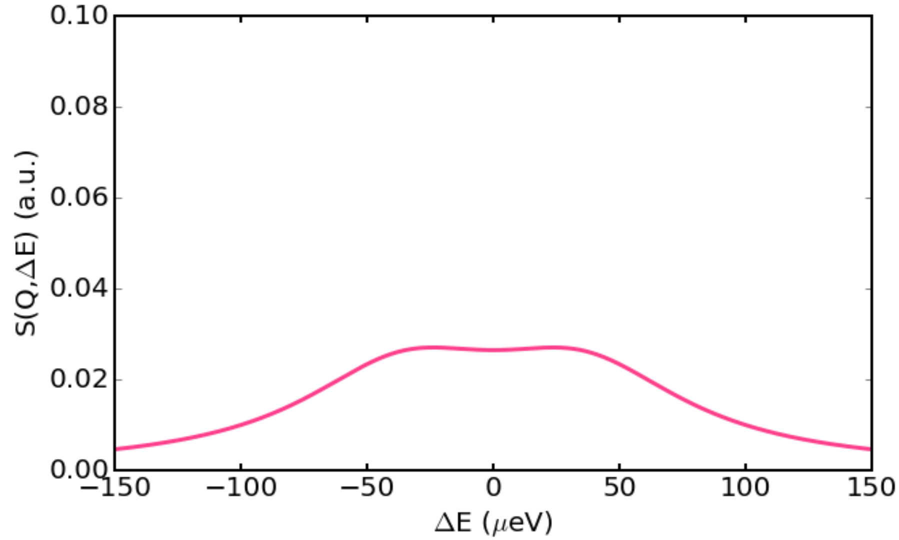

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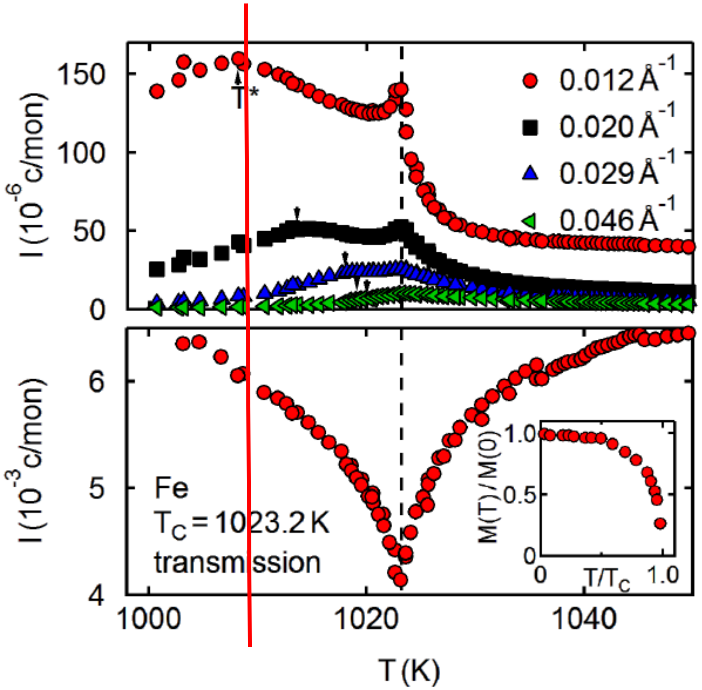

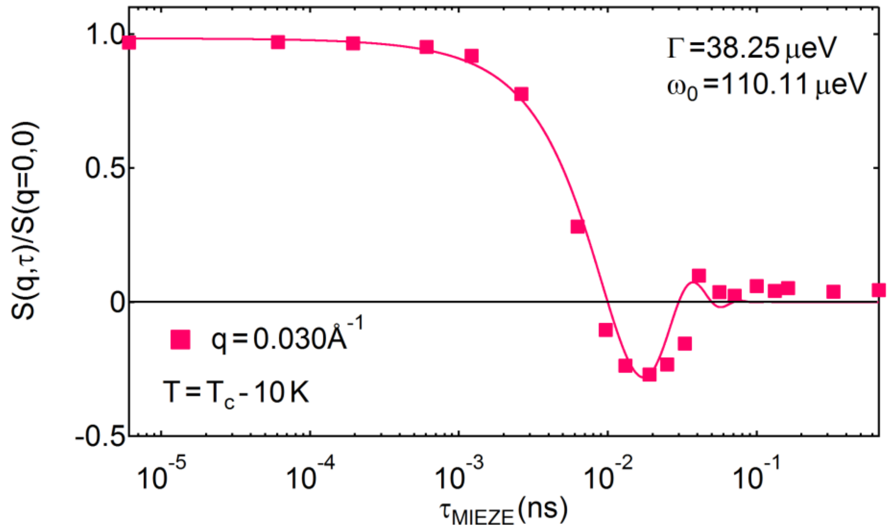

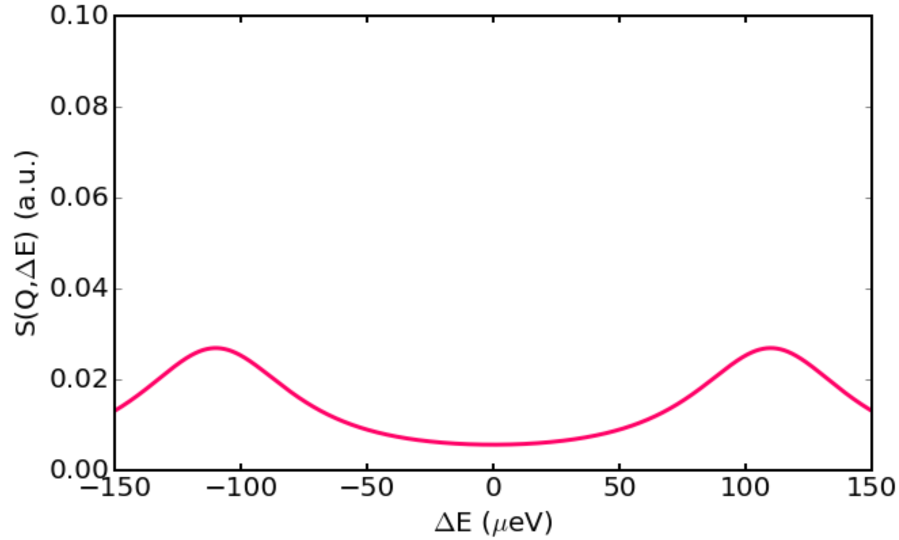

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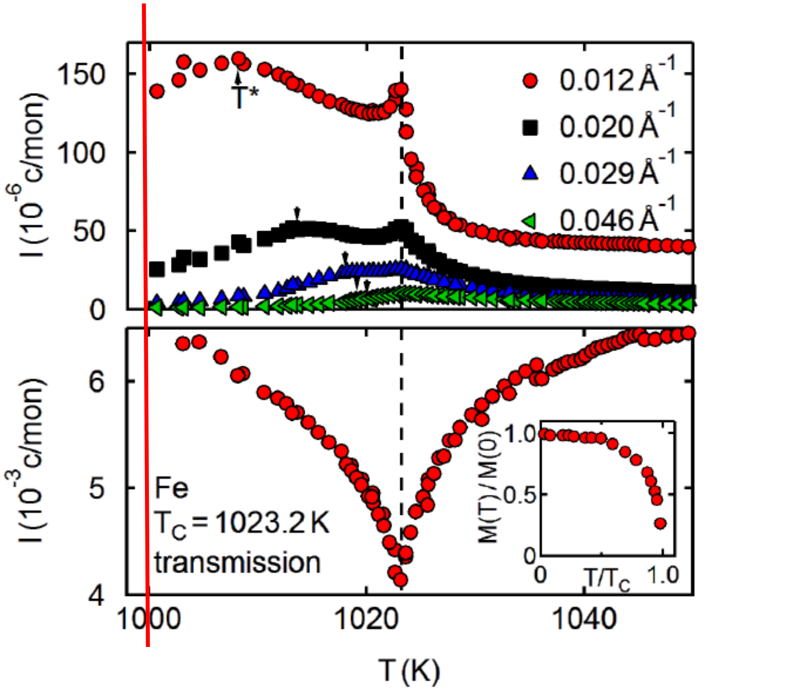
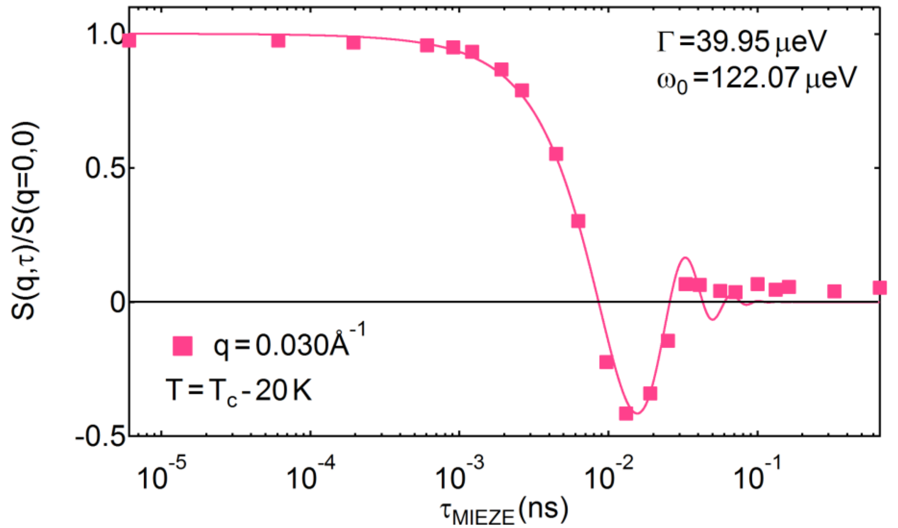
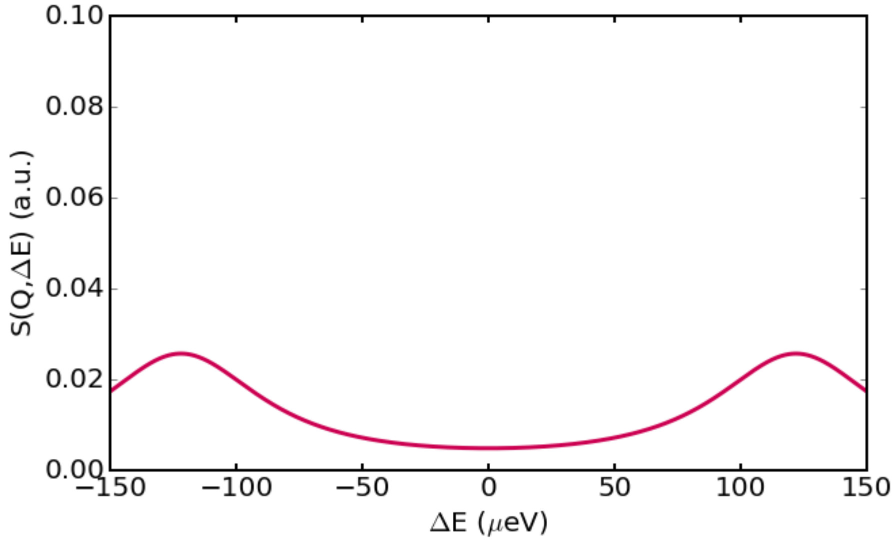
Kindervater et al. PRB, 95, 014429 (2017)

Fluctuations at the Curie Point in Iron







P. Rêsibois and C. Piette, Phys. Rev. Lett. 24, 514 (1970)
E. Frey and F. Schwabl, Physics Letters A, 49 (1987)
Kindervater et al. PRB, 95, 014429 (2017)

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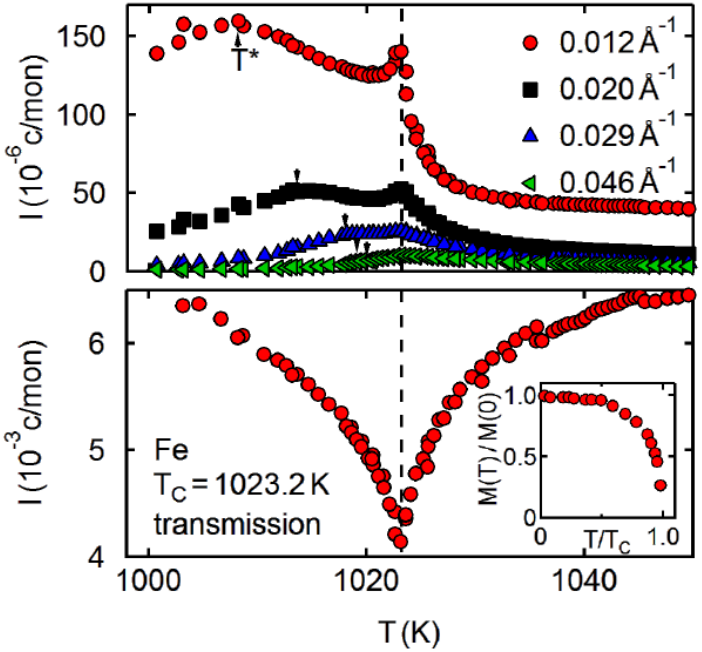
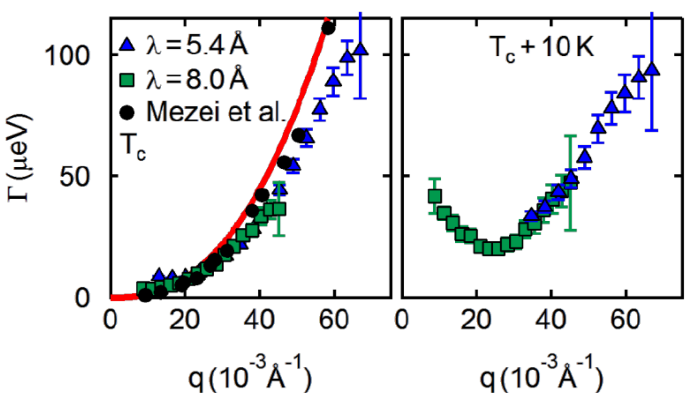
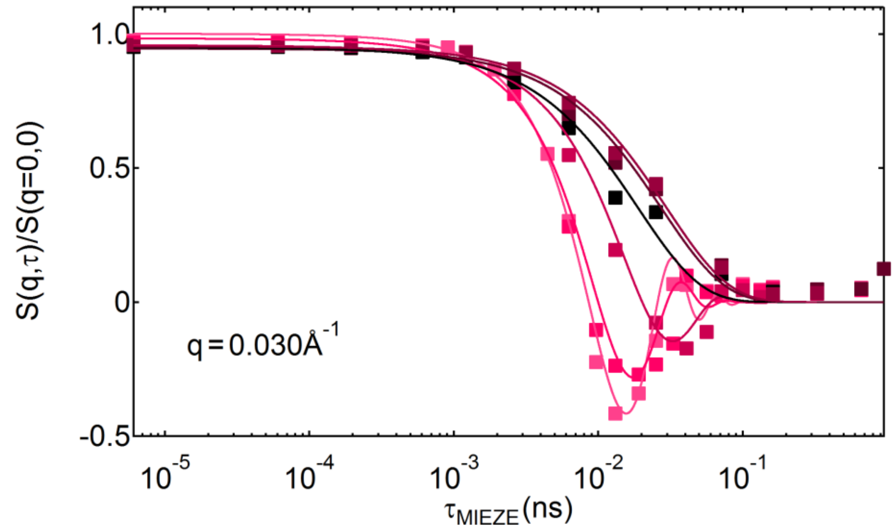
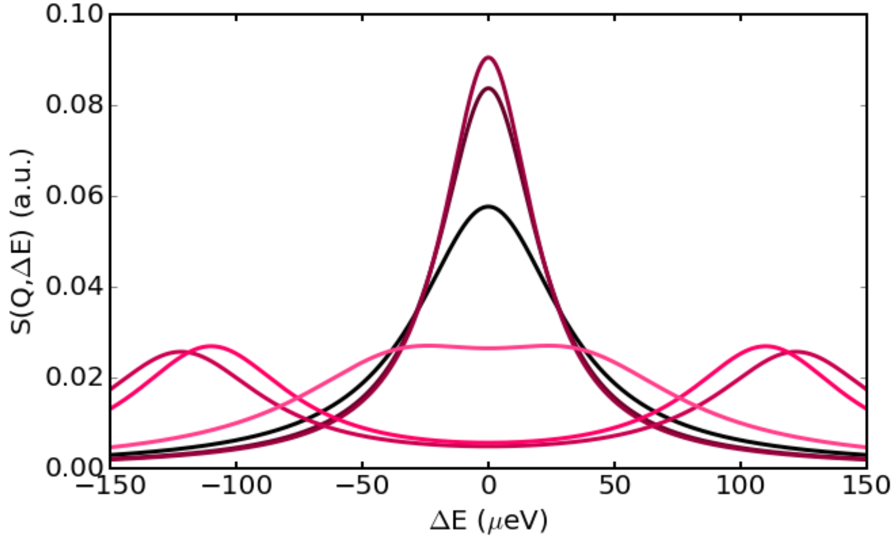


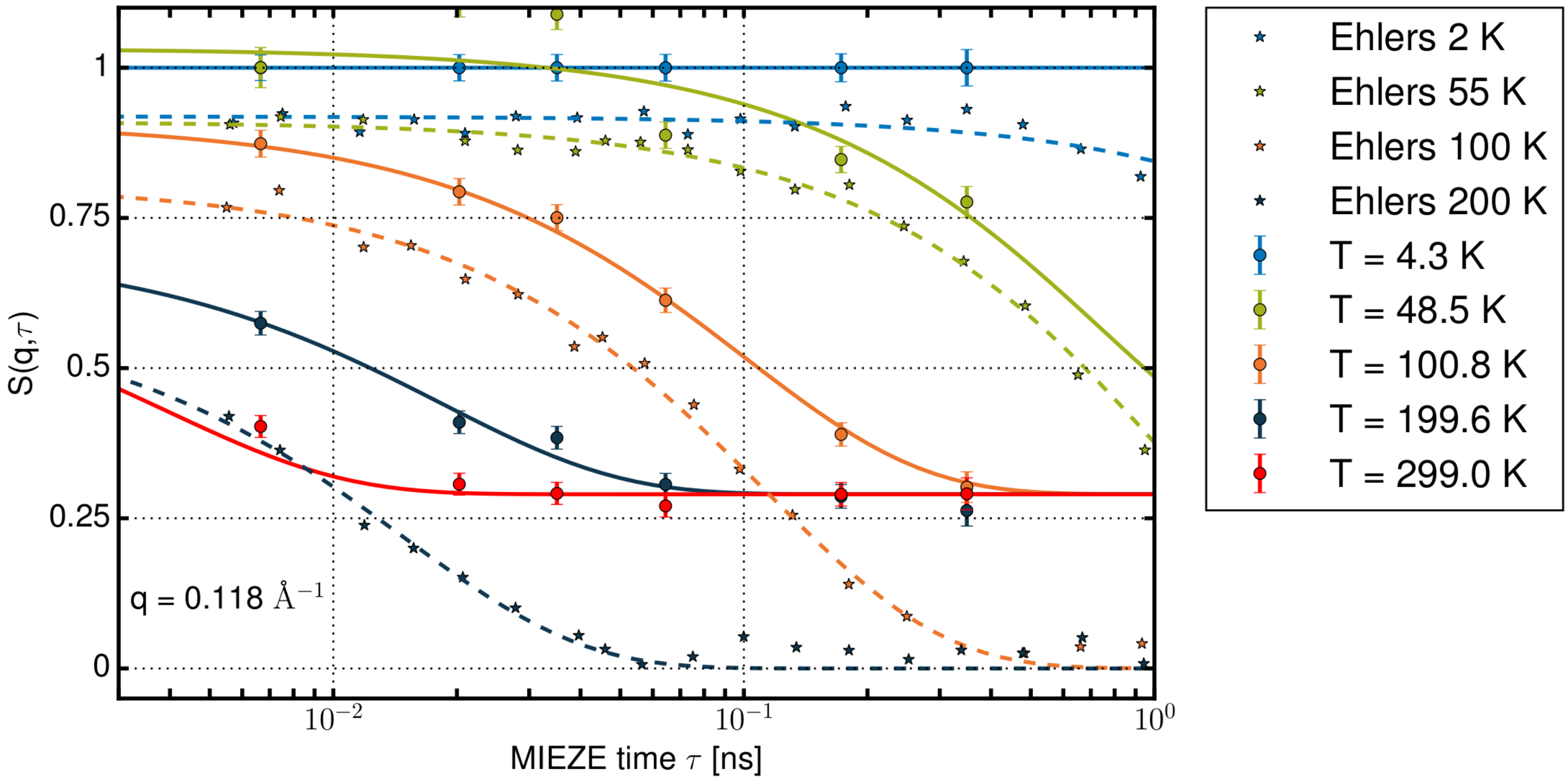






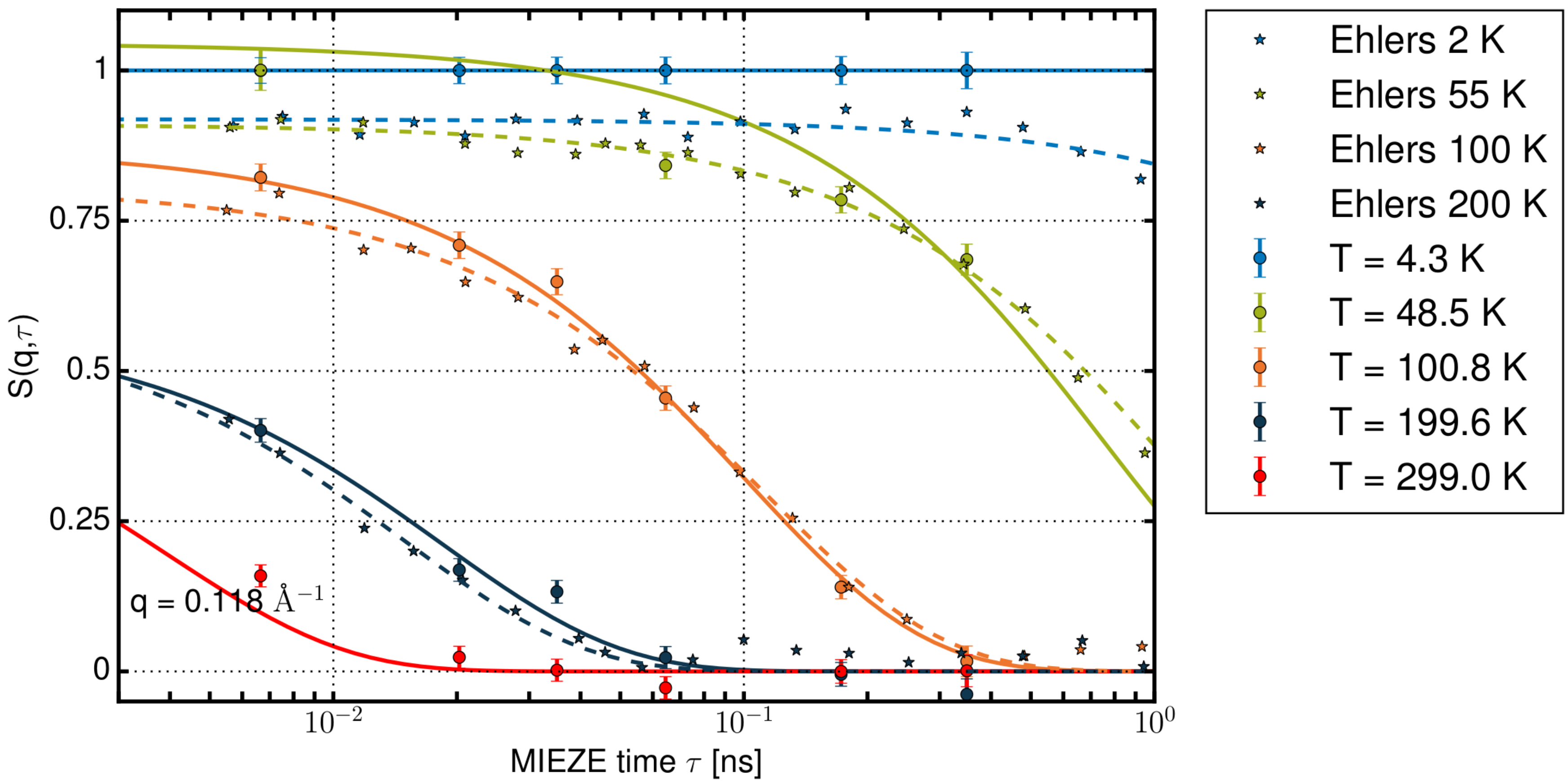
$Ho_2Ti_2O_7$

Elastic background to to reflections on Cadmium…



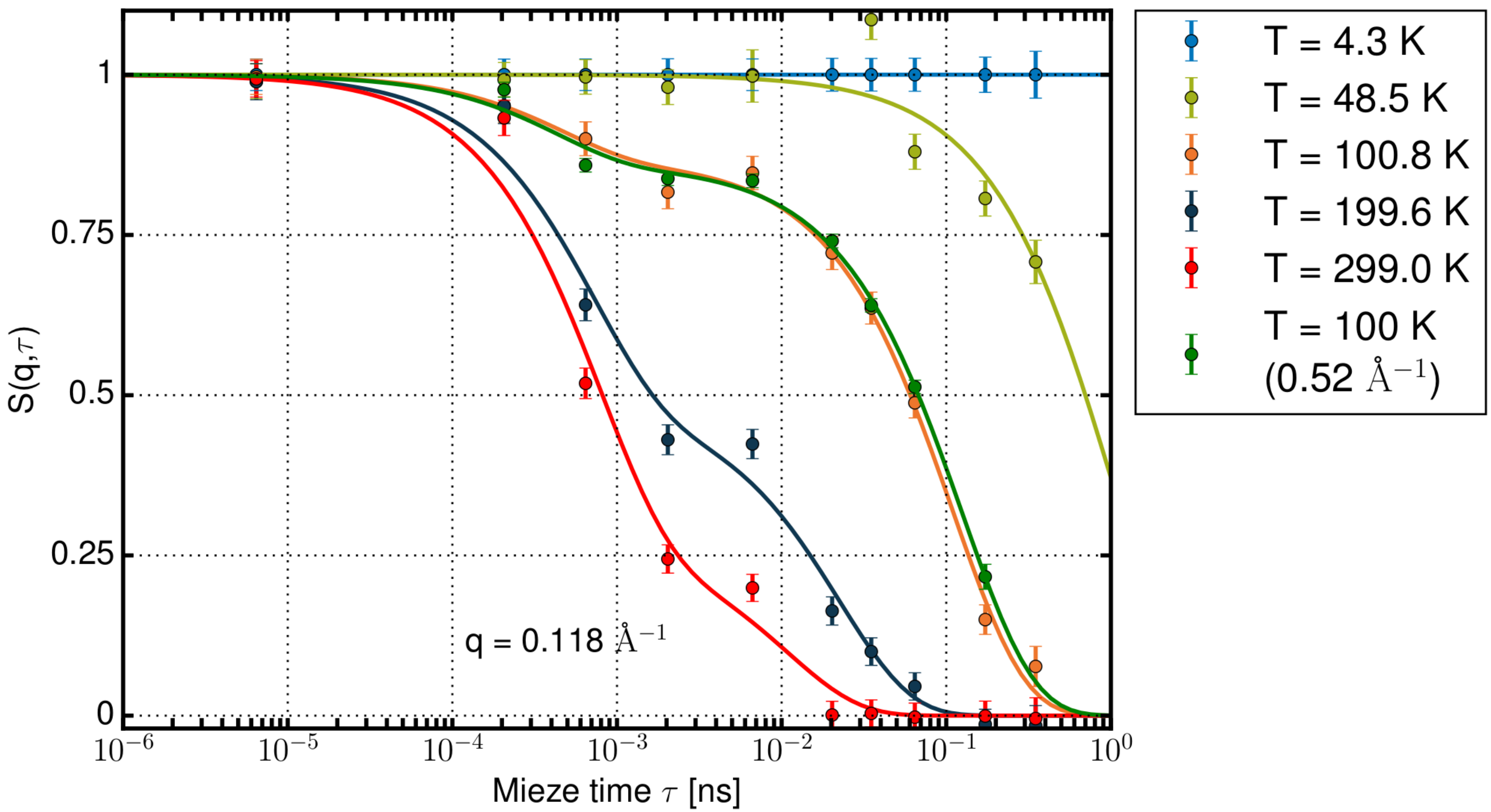
$Ho_2Ti_2O_7$

Background removed!

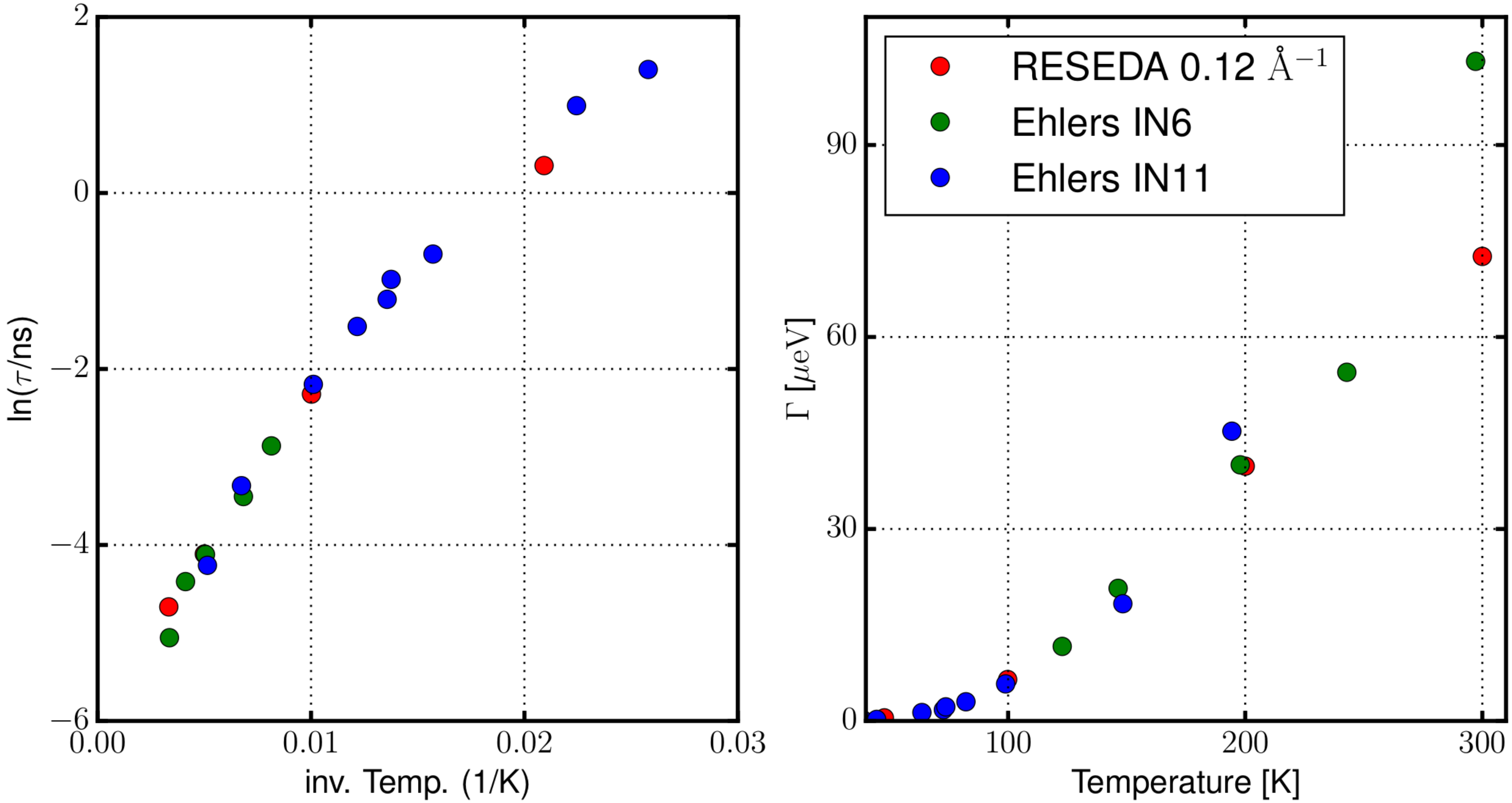


$Ho_2Ti_2O_7$

Lower Spin-Echo times in L-MIEZE possible – additional shoulder!



$Ho_2Ti_2O_7$


ln(τ/ns)
2
0
−2
−4
−6
0.00
0.01
0.02
0.03
inv. Temp. (1/K)
Γ [μeV]
90
60
30
0
100
200
300
Temperature [K]
RESEDA 0.12 Å^{-1}
Ehlers IN6
Ehlers IN11

Conclusion

Compared to conventional Neutron Spin Echo, L-NRSE has …

- (potentially) a higher resolution
- Shifted the technical challenge from magnetic fields to high frequency
- higher dynamic range (nominally 6 orders of magnitude!)
- a smaller detector area, can possibly be overcome by MIEZE-II with reduced resolution
- the MIEZE option for free