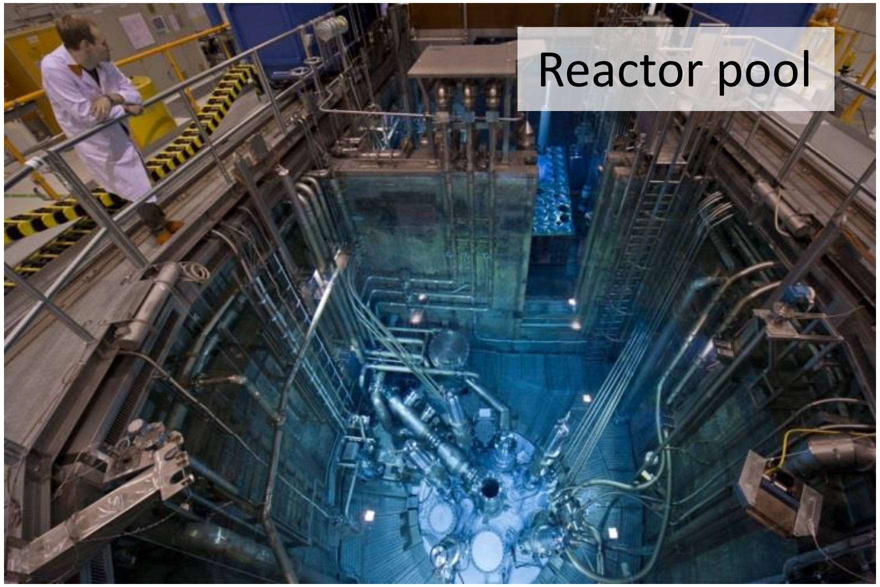
Czech-Bavarian

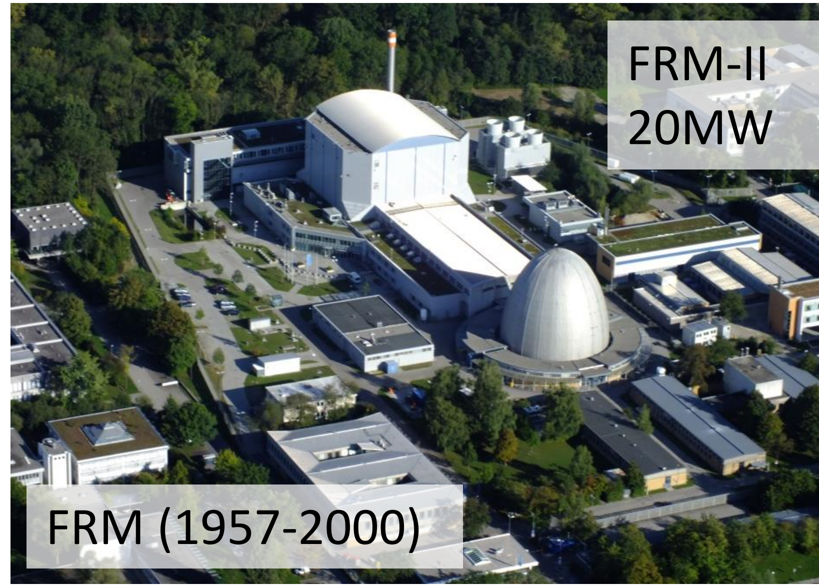
MINI-SCHOOL 2020

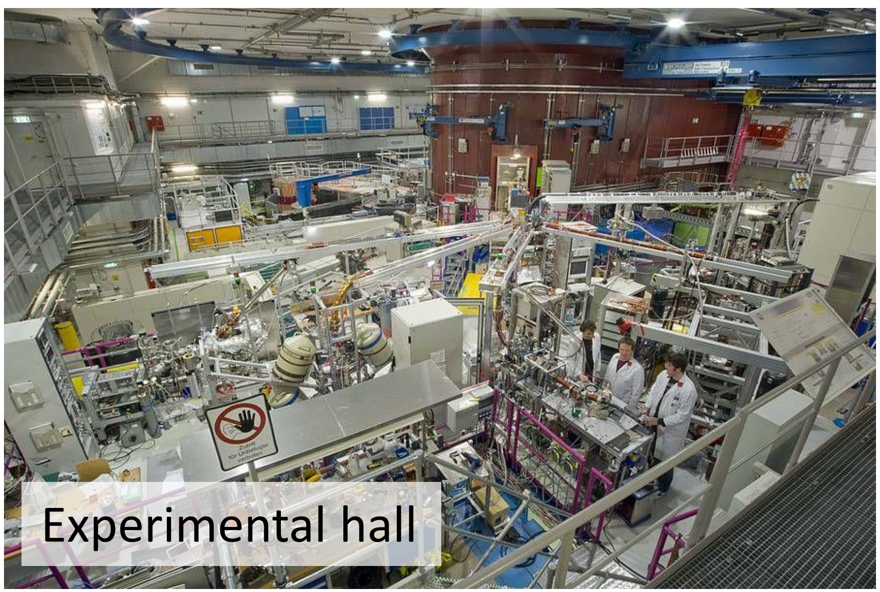
on large scale facilities and open data

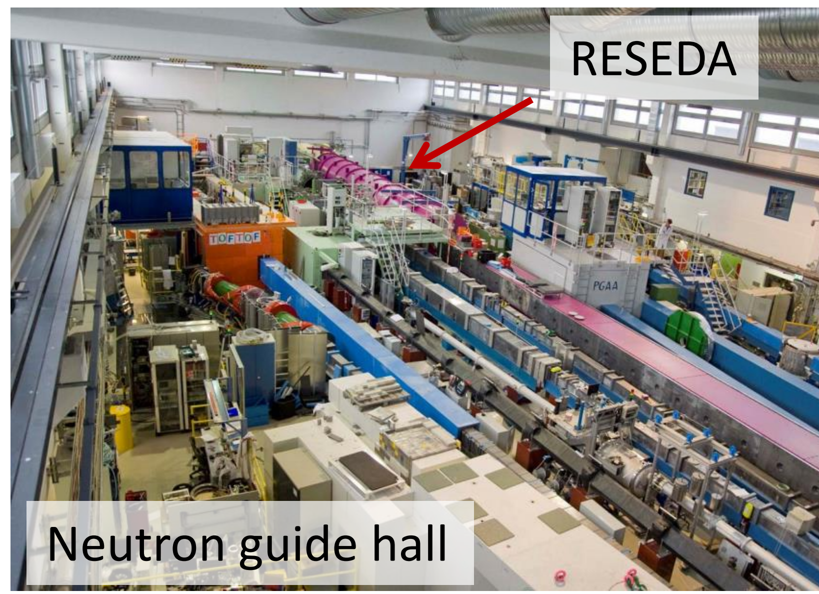
Neutron Spin Echo Techniques

Dr. Johanna K. Jochum


Reactor pool


FRM-II
20MW
FRM (1957-2000)


Experimental hall


RESEDA
Neutron guide hall

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Introduction:

- Lamor Precession and Spin Flippers
- Neutron Spin Echo (NSE)
- Neutron Resonant Spin Echo (NRSE)
- Modulation of IntEnsity with Zero Effort (MIEZE)

MIEZE Science cases

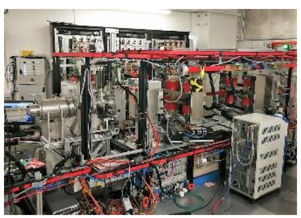
- Example 1) Fluctuations below T_c in ferromagnetic Iron
- Example 2) Weak crystallization of fluctuating skyrmion textures in MnSi

Neutron Spin Echo
Mezei (1972)

Neutron Resonant Spin Echo
Goloub & Gähler (1987)

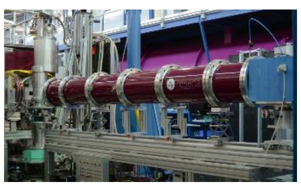
MIEZE
Gähler, Goloub & Keller
(1992)

Larmor*@ISIS
VinRose*@J-PARC



L-MIEZE
Häußler (2011)

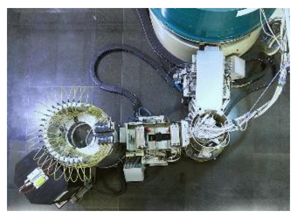
RESEDA*@FRMII



LNRSE
Häußler (2004)

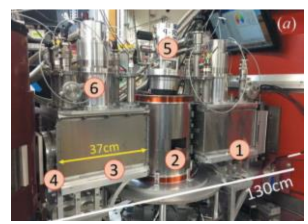
NRSE-TAS
Keller (2002)

TRISP@FRMII
FLEXX@BERII
ZETA@ILL



NSE-TAS
Mezei (1977)

NSE-TAS with
SC Wollaston
prisms
(Pynn 2014)



IN11A @ILL
IN15 @ILL

IN15 upgrade @ILL
J-NSE @FRMII
SNS-NSE @SNS

Wide Angle Spin Echo
Mezei (1980)

IN11C @ILL
SPAN @HZB
WASP @ILL

*The three MIEZE Instruments Larmor, VinRose and RESEDA all offer an NRSE option as well

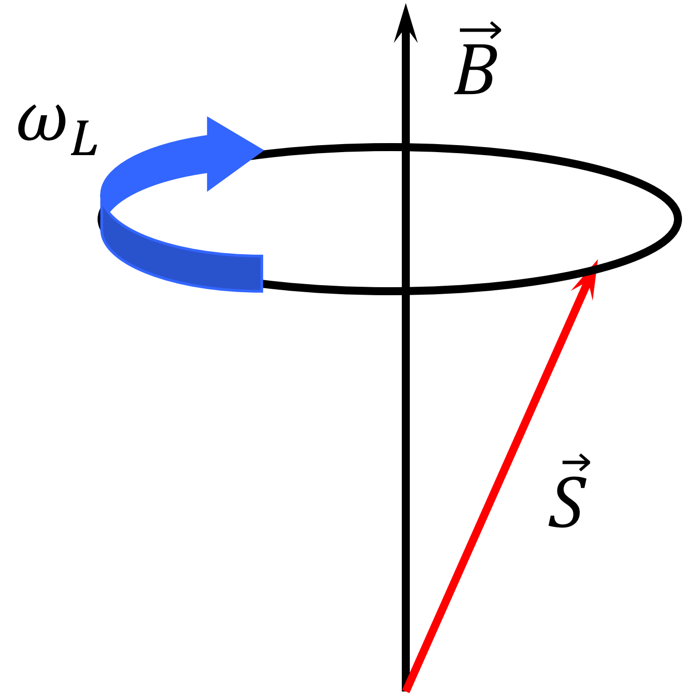
Not shown here: Larmor precession methods: SESANS, SEMSANS, etc.

Lamor Precession of a Neutron Spin in a magnetic Field

- A neutron will experience a torque from a magnetic field $\vec{B}$ perpendicular to $\vec{S}$

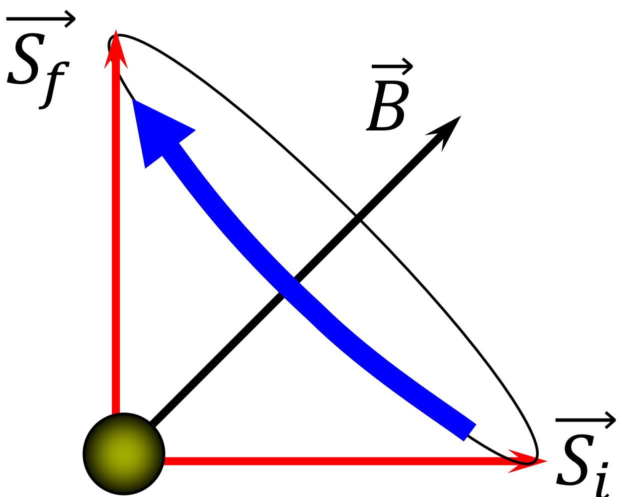
- The spin begins to precess with the Lamorfrequency field $\omega_L = \gamma B$, where γ is the Gyromagnetic ratio:

$$\gamma = 1.832 \times 10^8 \frac{1}{sT} = 29.164 \frac{MHz}{T}$$



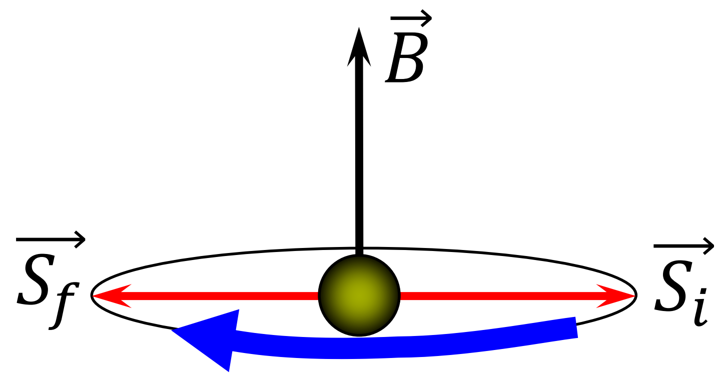
Spin Flippers

- The Lamorprecession can be used to flip the neutron spin by a specified amount:
- In General: $\phi = \frac{\gamma \vec{B} m_n d}{h} \lambda \rightarrow B = \frac{h\phi}{\gamma m_n \lambda d}$



$\frac{\pi}{2}$ – flipper

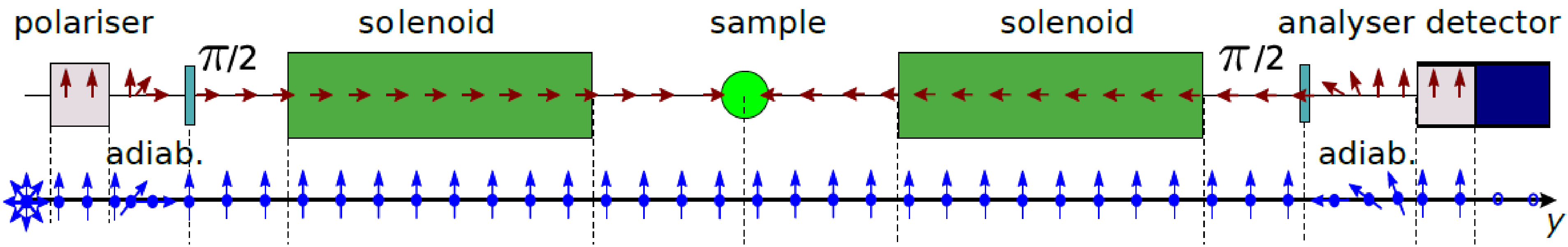
$$B = \frac{h\pi}{2\gamma m_n \lambda d}$$



π – flipper

$$B = \frac{h\pi}{\gamma m_n \lambda d}$$

Neutron Spin Echo



Total phase:

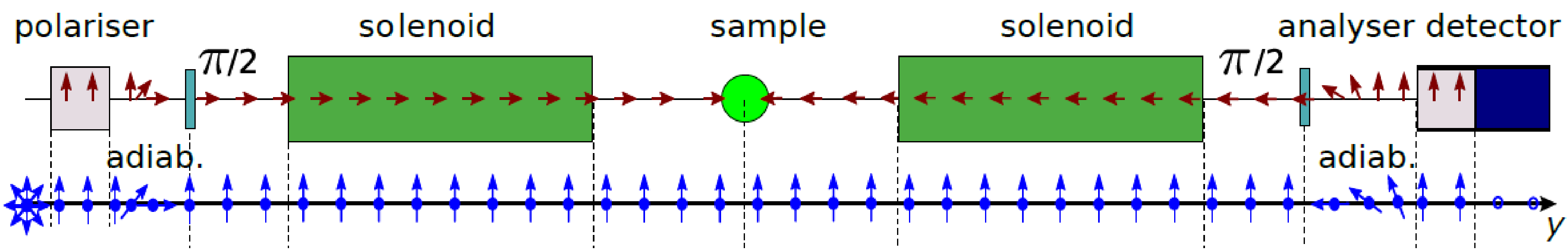
$$\varphi_{NSE} = \gamma_n B (t_i - t_f) = \gamma_n B L \left(\frac{1}{v_i} - \frac{1}{v_f} \right)$$

$$v_i = v_f + \delta v \quad \Longrightarrow \quad \hbar\omega = \frac{m_n}{2} \cdot (v_i^2 - v_f^2) \sim m_n v_i \delta v$$

$$\Longrightarrow \quad \varphi_{NSE} = \omega \underbrace{\boxed{\left(\frac{\hbar \gamma_n B L}{m_n v_i^3} \right)}}_{\text{"Spin Echo" time } \tau}$$

F. Mezei, Z. Physik **255** (1972) 146; F. Mezei, C. Pappas and Th. Gutberlet (Eds.), Neutron Spin Echo Spectroscopy: Basics, Trends and Applications, Lecture Notes in Physics **601** (2003)

Neutron Spin Echo



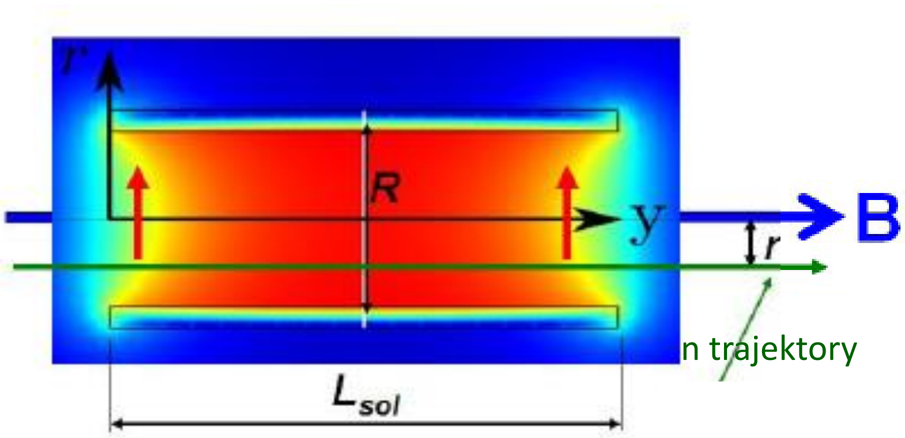
Measured polarization:

$$P_{NSE} = \langle \cos \varphi_{NSE} \rangle = \left. \frac{\int S(Q,\omega)\cos(\omega\tau)d\omega}{\int S(Q,\omega)d\omega} \right|_{Q=Q_0} \propto S(Q_0,\tau)$$

F. Mezei, Z. Physik **255** (1972) 146; F. Mezei, C. Pappas and Th. Gutberlet (Eds.), Neutron Spin Echo Spectroscopy: Basics, Trends and Applications, Lecture Notes in Physics **601** (2003)

Limitations of conventional NSE

- Limitations in field homogienities:



Parallel beam:

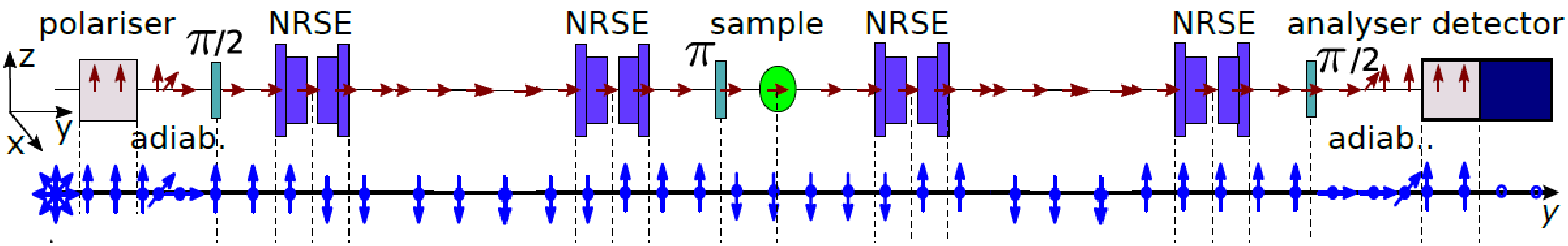
$$J(r) \simeq B_0 L_{sol}\left(1 + \frac{r^2}{2RL_{sol}}\right)$$

Divergent beam:

field optimization

- Low SE times
  The SE times are limited on the lower end due to the necessity of a finite field integral. Otherwise beam polarization is lost

Longitudinal NRSE



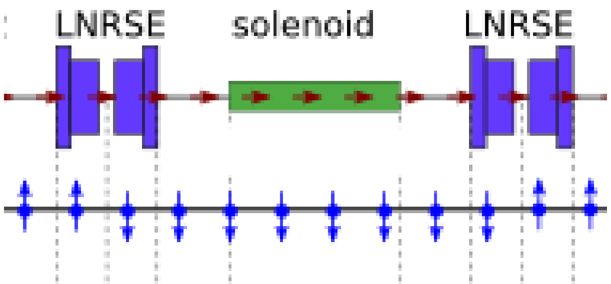
Solenoids replaced by Resoant Spin Flippers
→ better field homogeneity

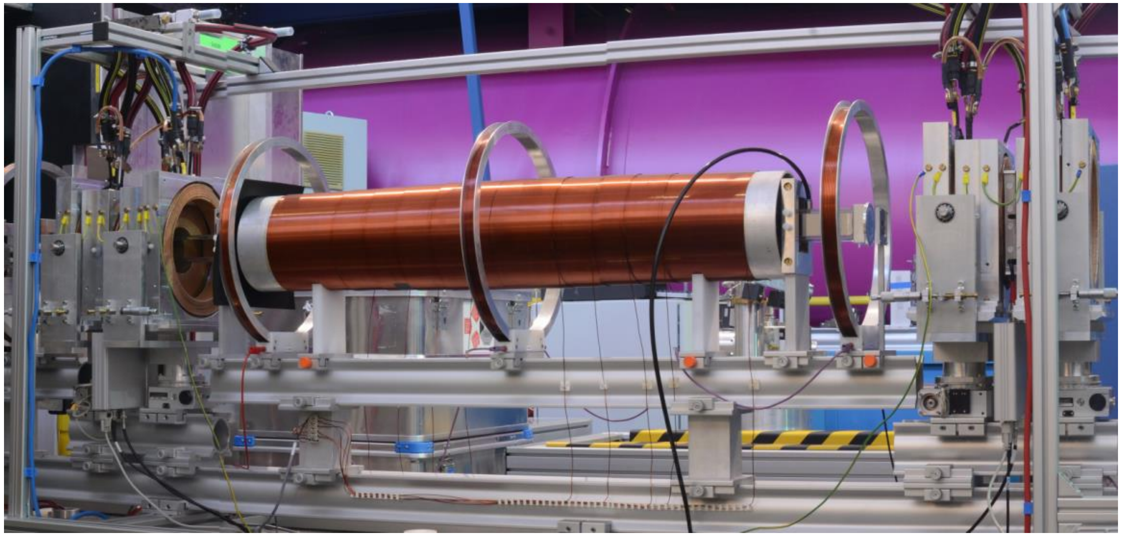
Total phase:

$$\varphi_{NRSE} = 2 \times \omega_{rf} L / v = 2 \times \varphi_{NSE}$$

Towards Low Spin Echo Times

- One big Limitation of NRSE: Bloch-Siegert Shift: $B_{rf} \ll B_0$, $\omega_{min} = 35$ kHz
  → limits the minimum τ
- Solution: Field subtraction coil





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

Towards Low Spin Echo Times

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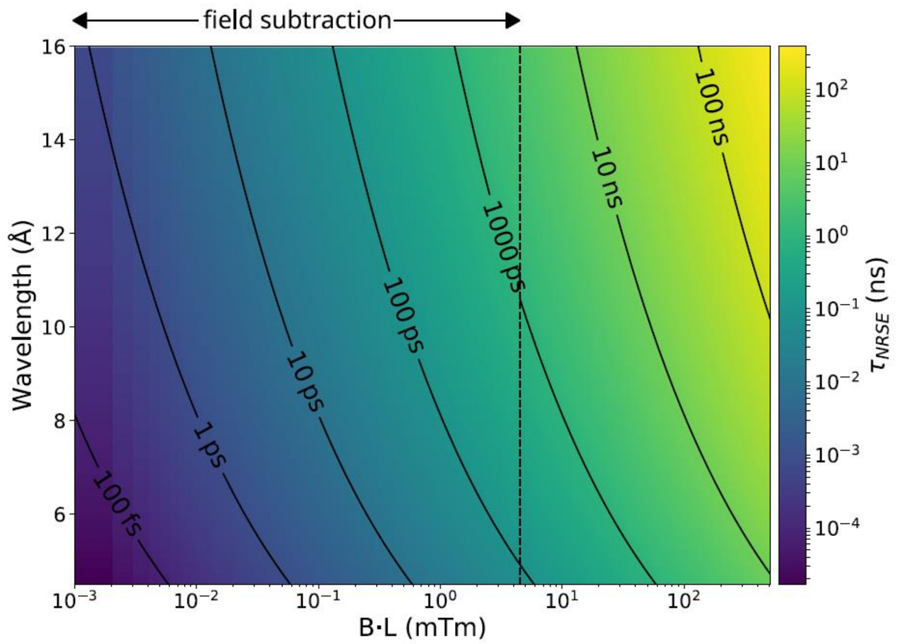
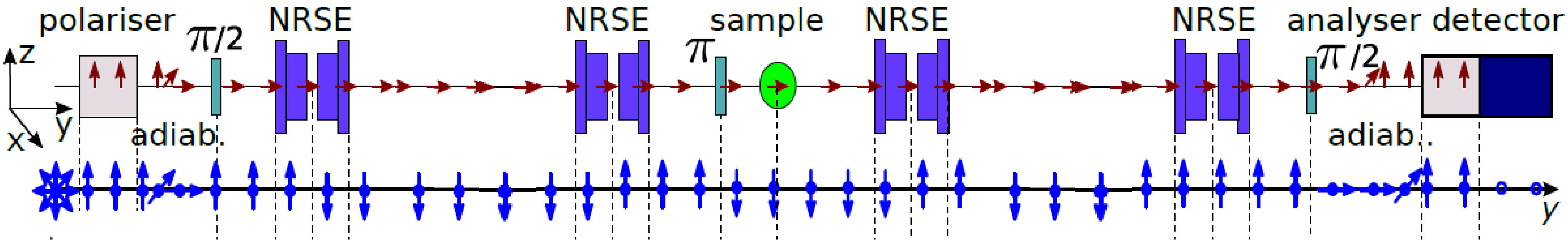


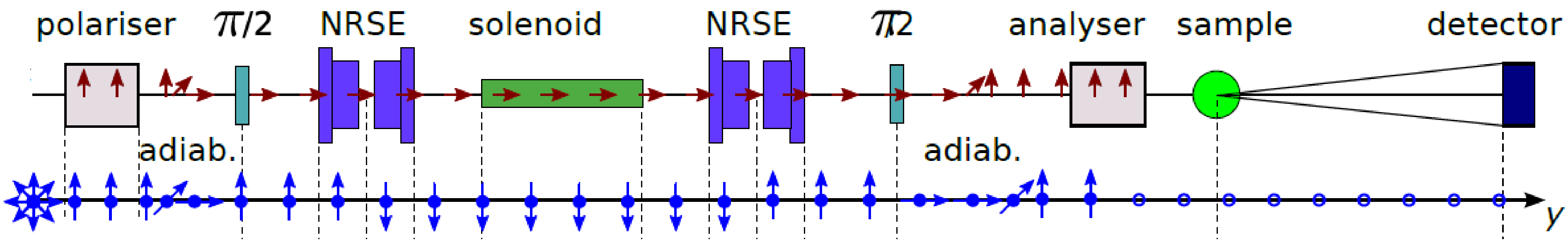
extremely large dynamic range!

Franz et al., NIMA 939 (2019), 22-29

Longitudinal NRSE



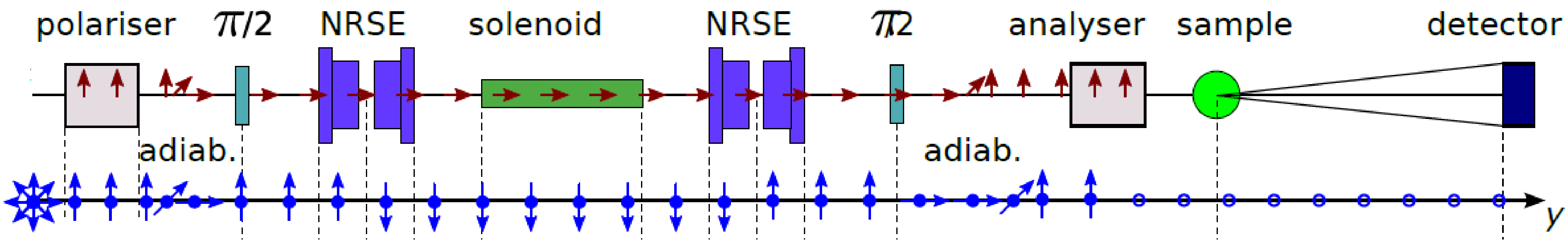
Longitudinal MIEZE

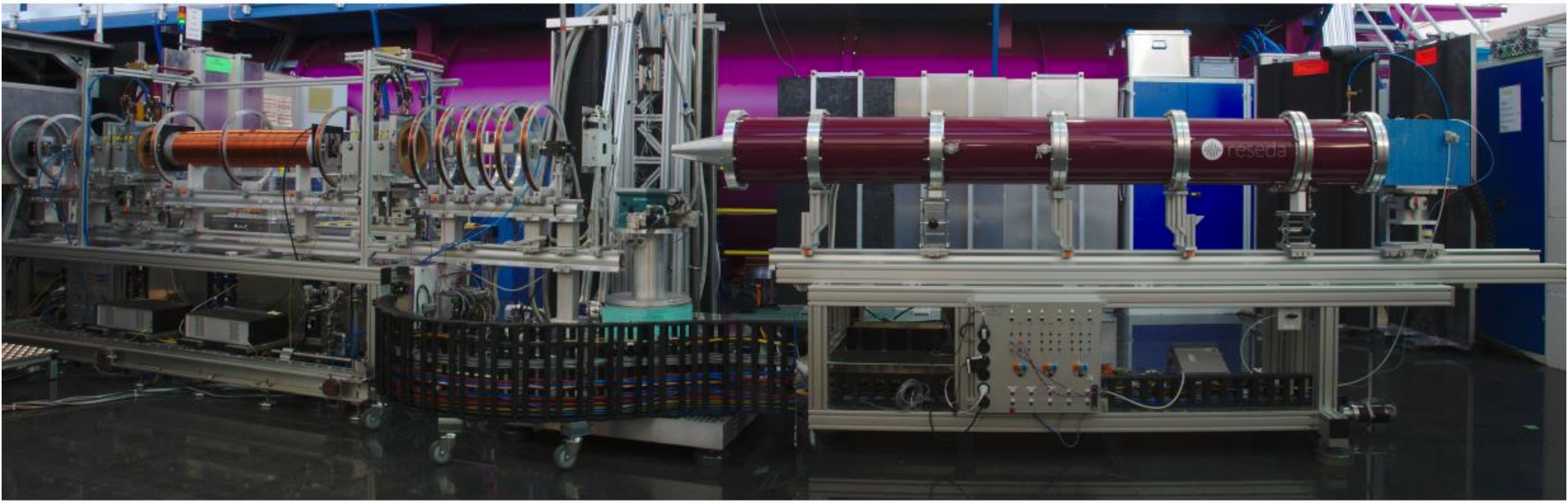


- No more spin manipulation after the sample
- Phase is translated into a sinusoidal intensity modulation by analyzer

→ allows depolarizing environments (magnetic fields), depolarizing samples (ferromagnets, superconductors…), and strong incoherent scatterers (H – containing samples)

Longitudinal MIEZE





NRSE vs MIEZE

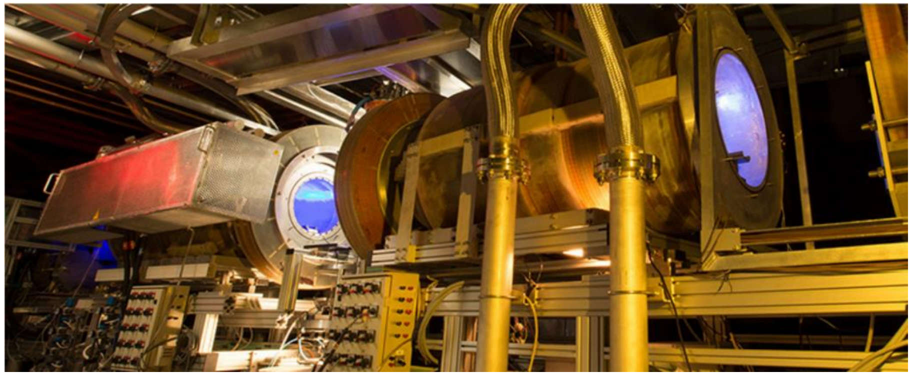
Neutron Resonance Spin Echo

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

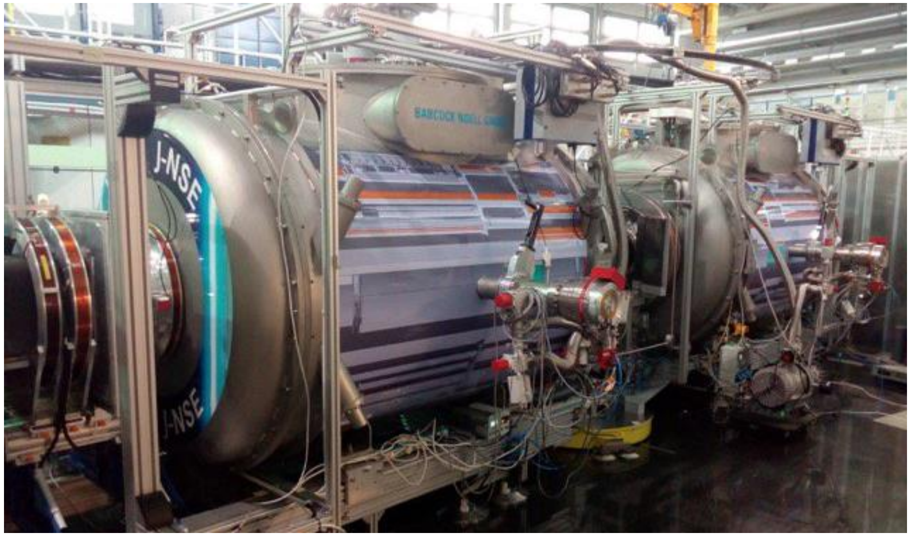
Modulation of Intensity with zero effort

- Similar to high-resolution TOF (or SANS with energy resolution)
- Magnetic field possible (17T unshielded proven)
- Ferromagnetic samples possible (see data on UGe_2)
- Ideal for incoherent scattering (see data on pure water!)
- ✘ Reduced resolution (depends on detector position)
- ✘ Momentum transfer limited by sample geometry (and size)

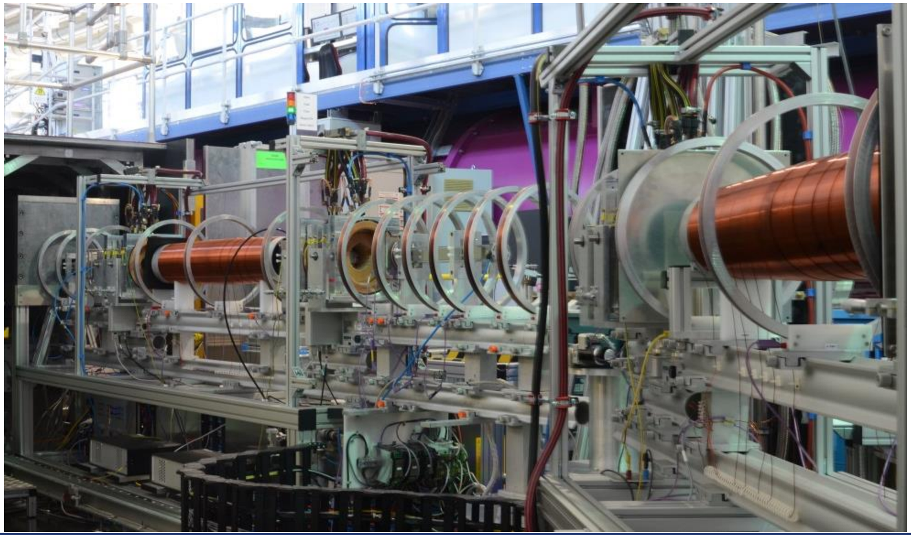
Classical NSE: IN15



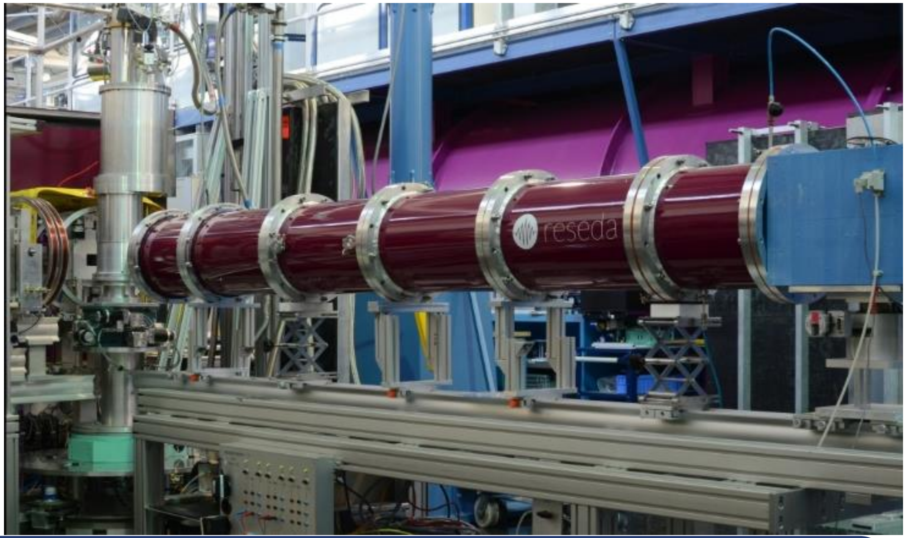
Classical NSE with SC coils: J-NSE



L-NRSE: RESEDA, arm 1

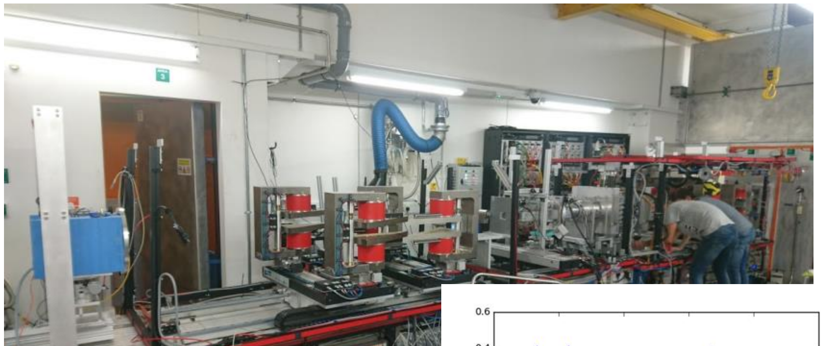


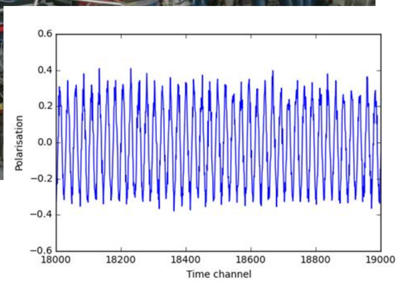
L-MIEZE: RESEDA, arm 2



MIEZE worldwide

MIEZE TOF @ Larmor (ISIS)

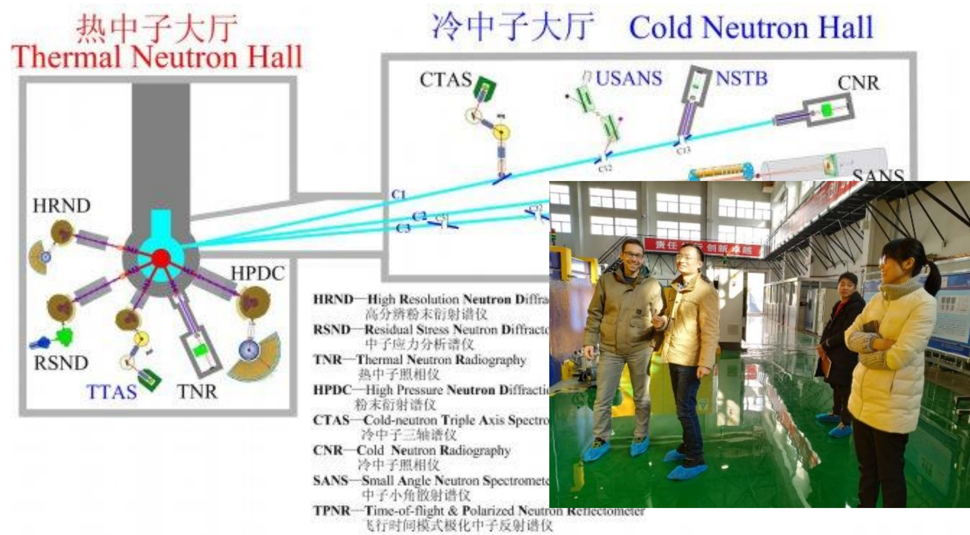




Geerits *et al.* Rev. Sci. Instrum. **90**, 125101 (2019)

VIN ROSE @ J-PARC

MIEZE @ CMRR (Mianyang, China)



MIEZE @ PIK (Russia)

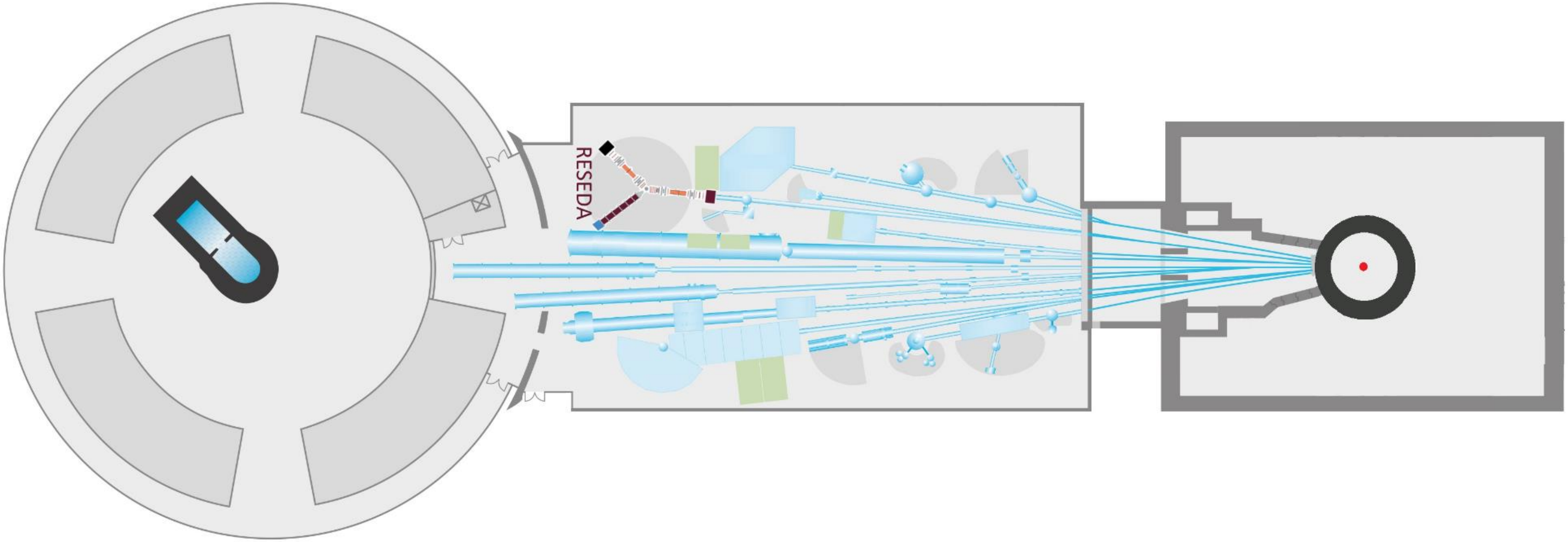
- copy of LMIEZE
- advice on cost/equipment

MIEZE @ HFIR & SNS

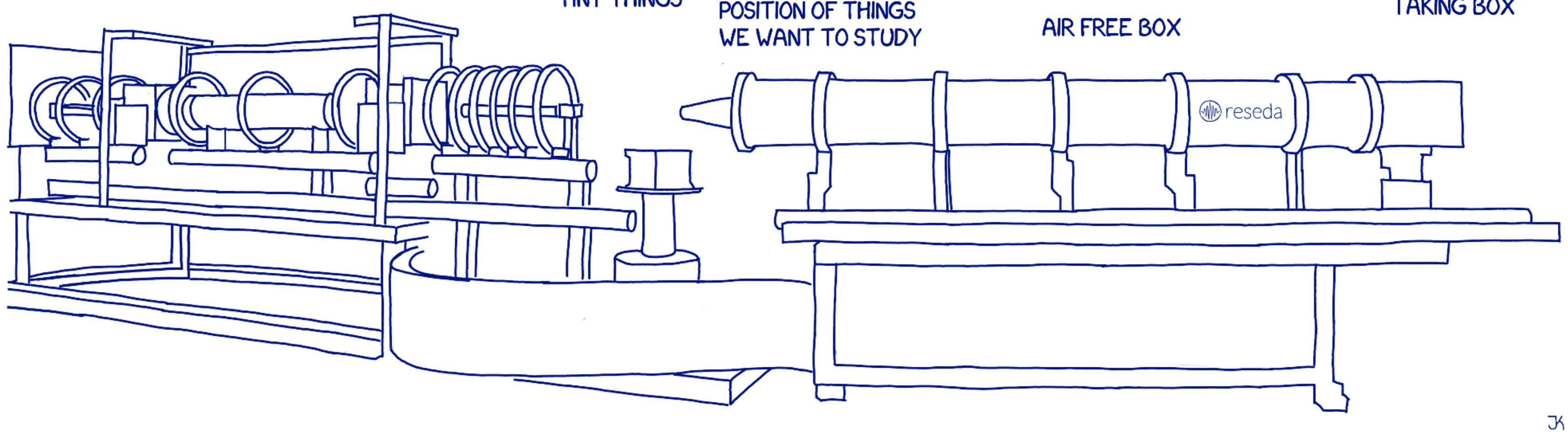
- commissioning of MIEZE
- exchange on SESANS

Experimental Setup

Beamport NL5-S: cold neutrons (3.5 - 15Å)
curved guide 40m long, r = 1640m, m= 2
beam size 3.6 x 3.6 cm^2

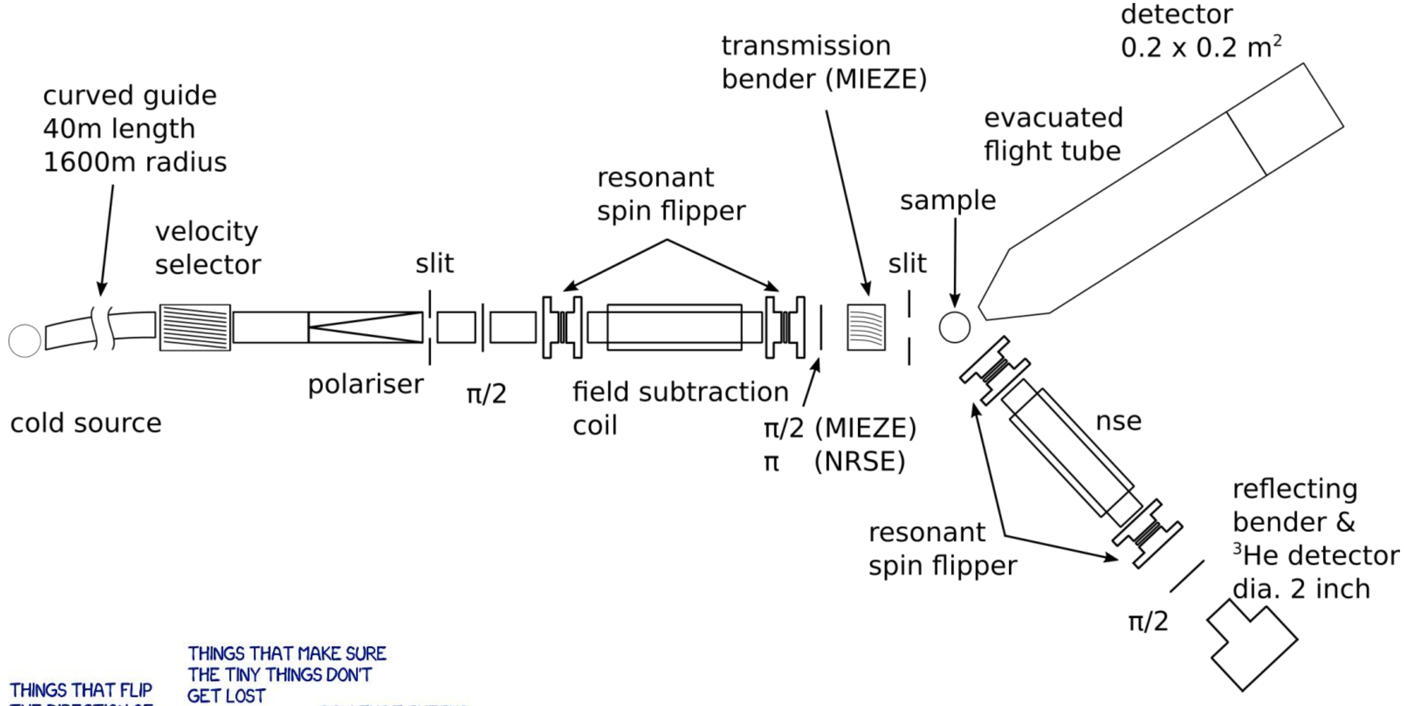


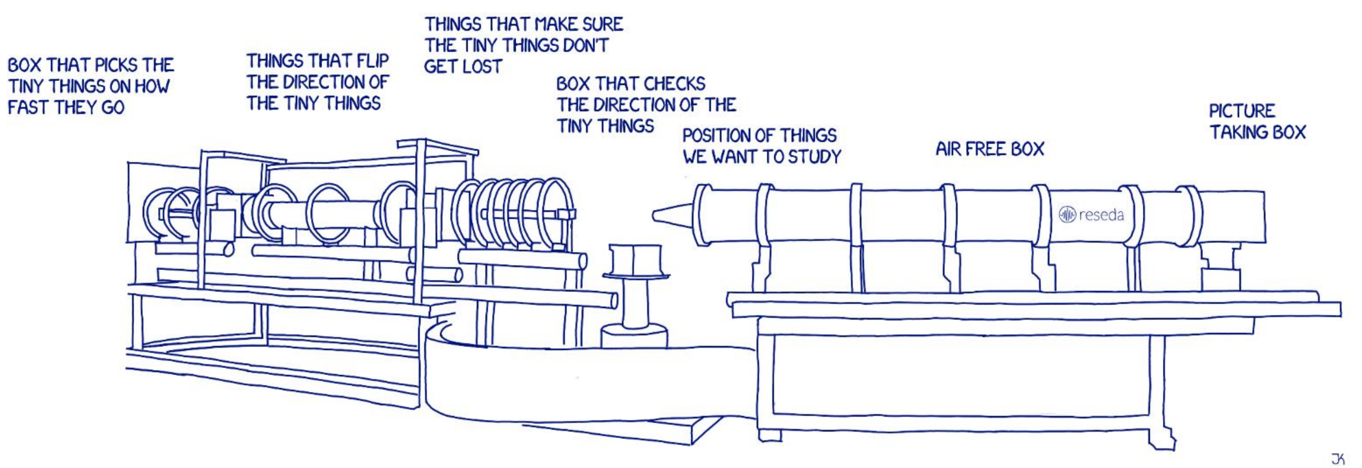
RESEDA EXPLAINED USING THE TEN HUNDRED MOST USED WORDS



reseda

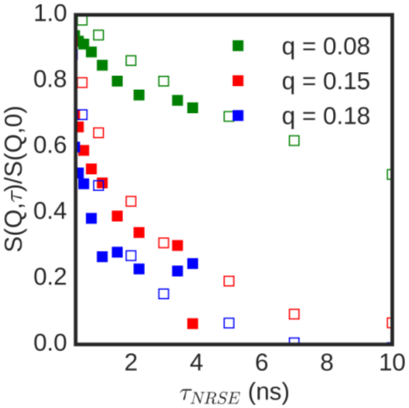
Experimental Setup



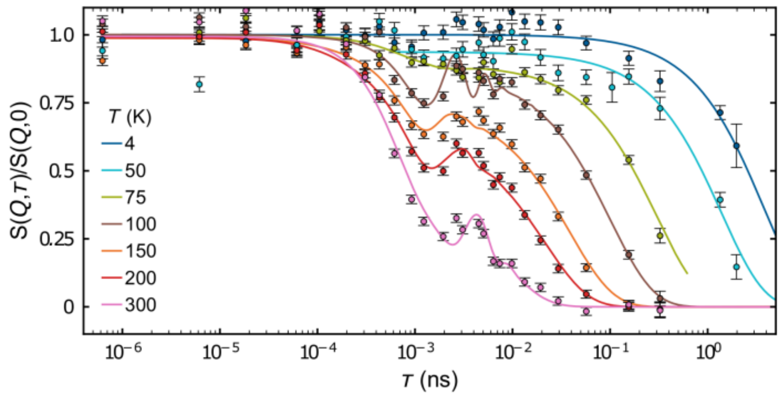


What can you measure @RESEDA?

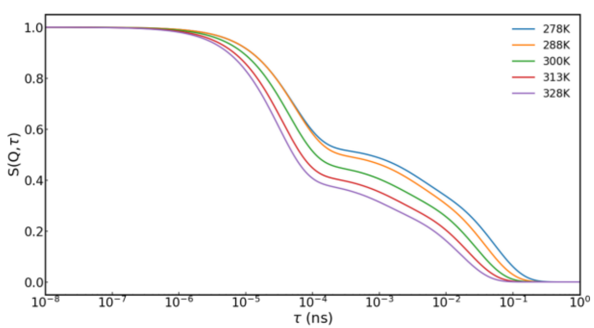
NRSE: Anything you can measure with NSE



MIEZE: inelastic measurements

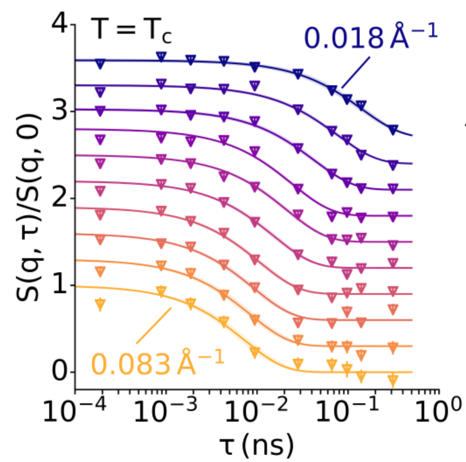


MIEZE: strong incoherent scattering

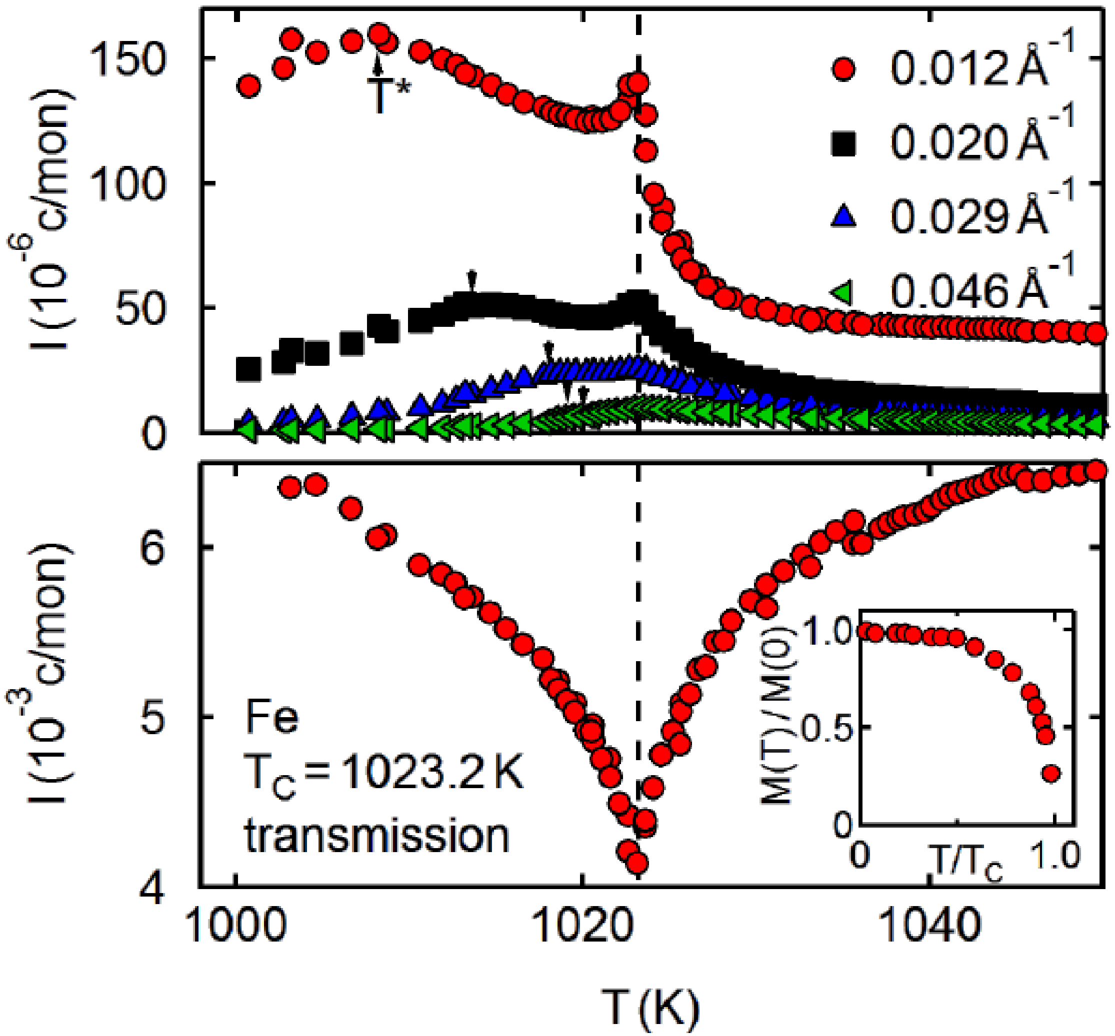


MIEZE-SANS:

- Ferromagnets
- Skyrmions
- Superconductors
- Magnetic NPs



Fluctuations at the Curie Point in Iron



Steffen Säubert

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)
Säubert et al. PRB 99, 184423

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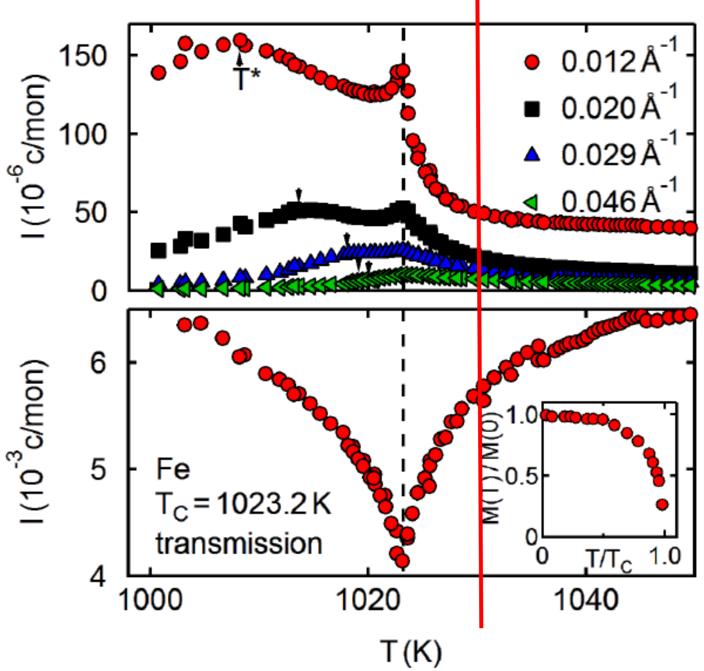

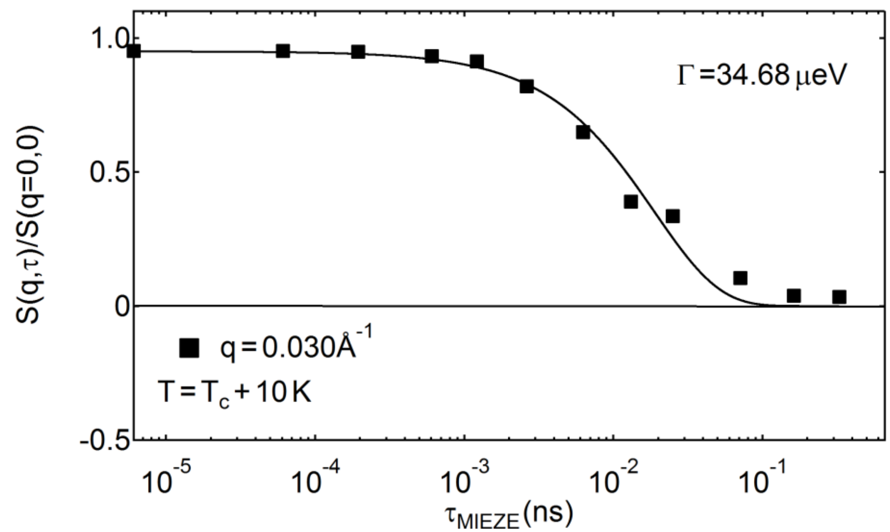

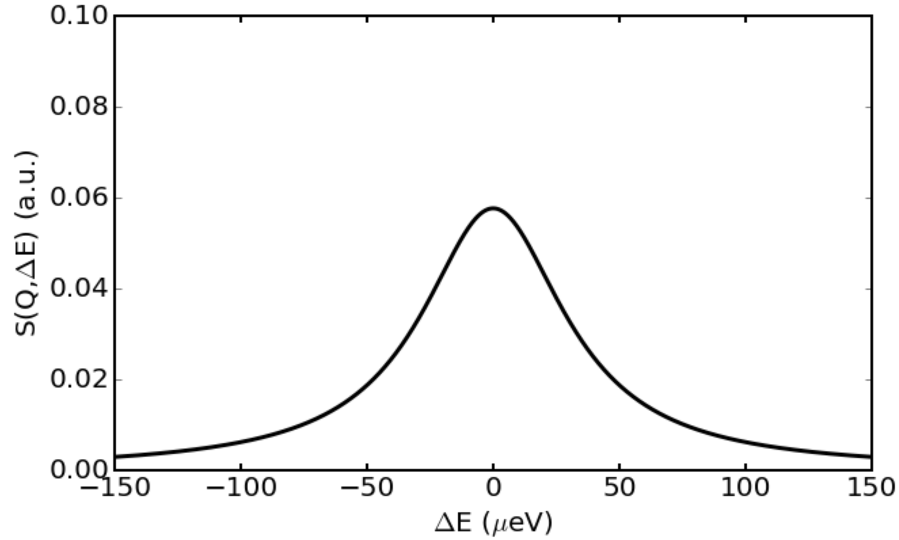

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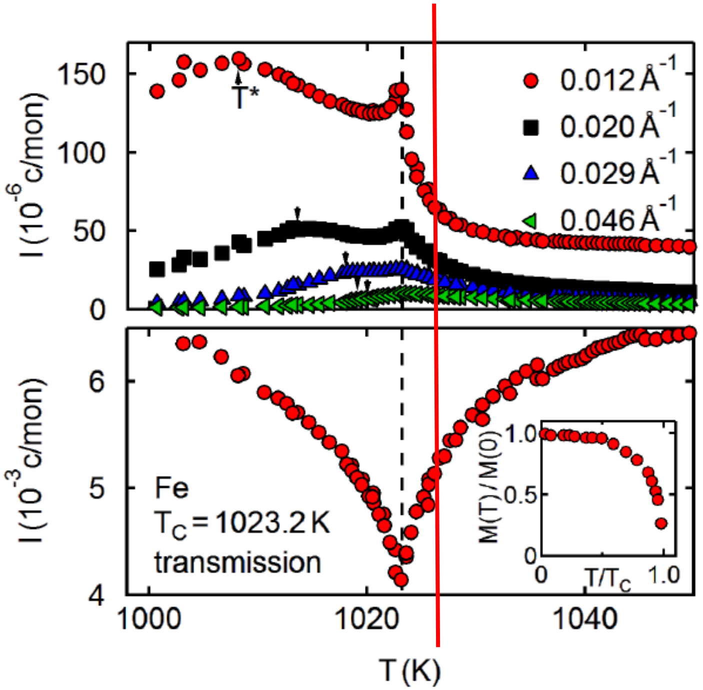

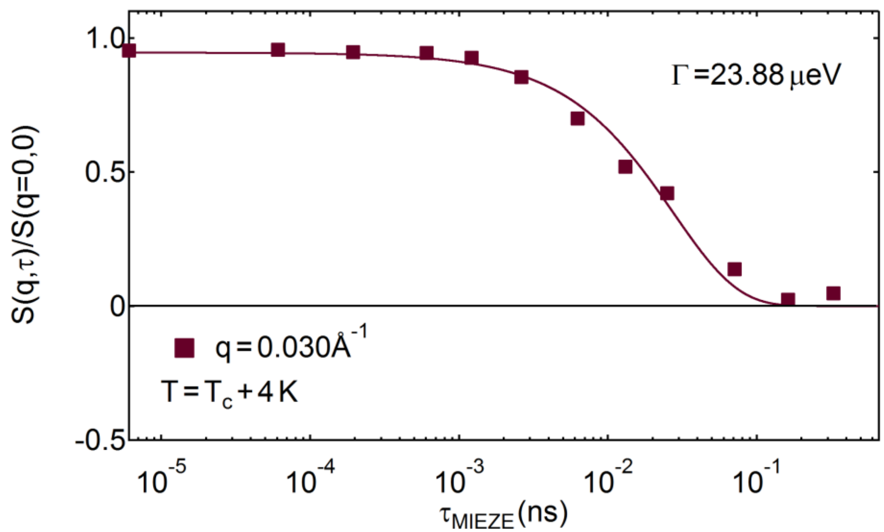

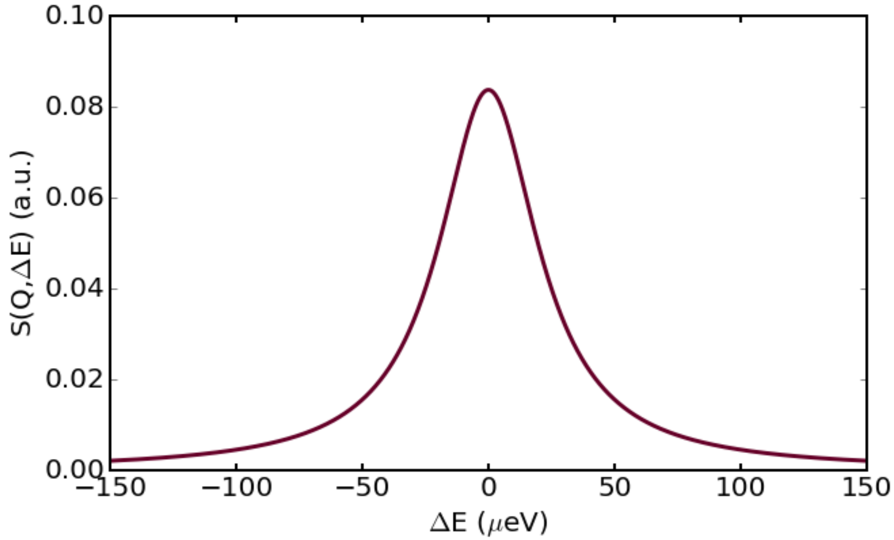

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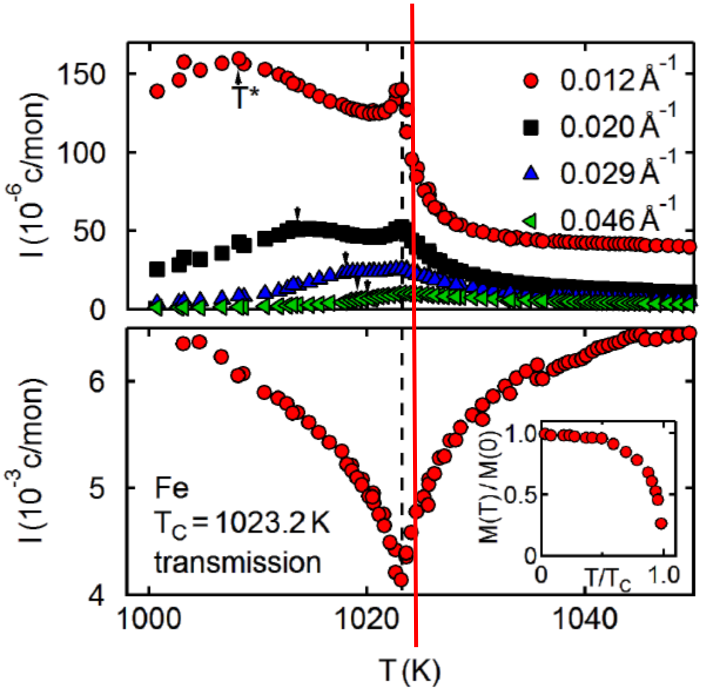

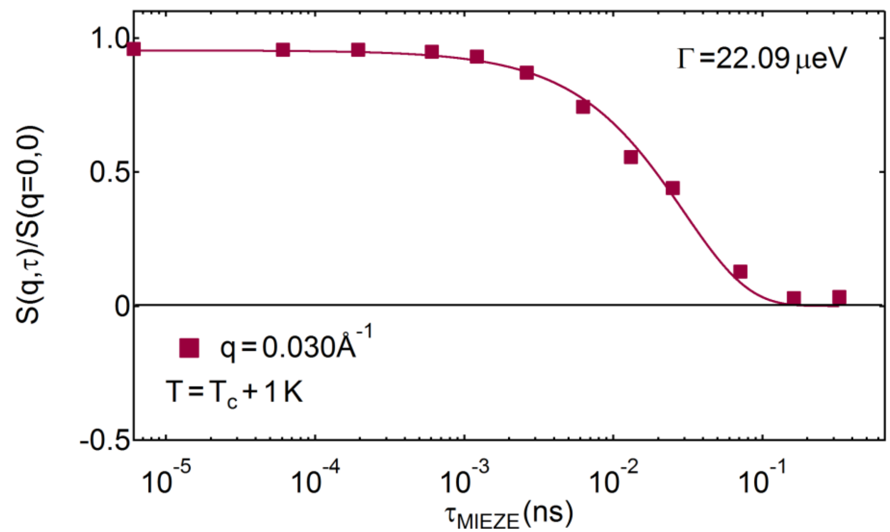

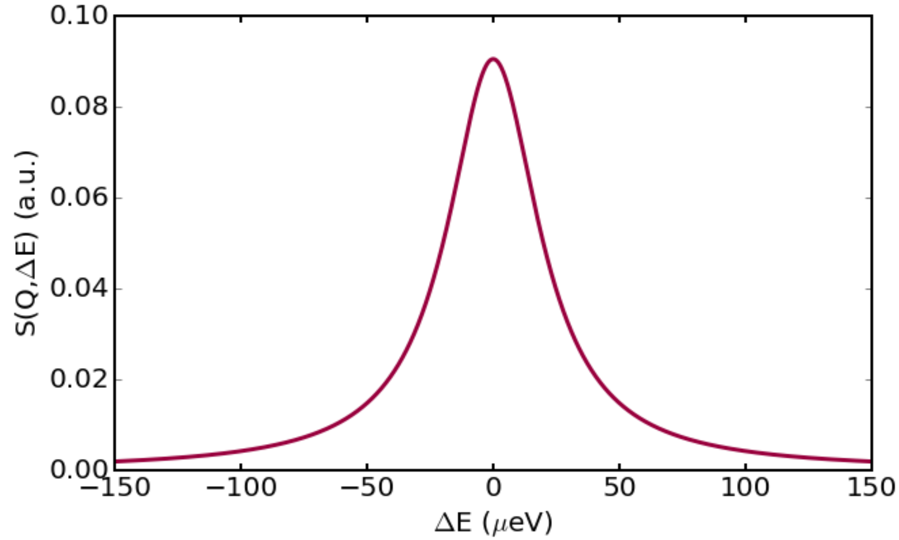

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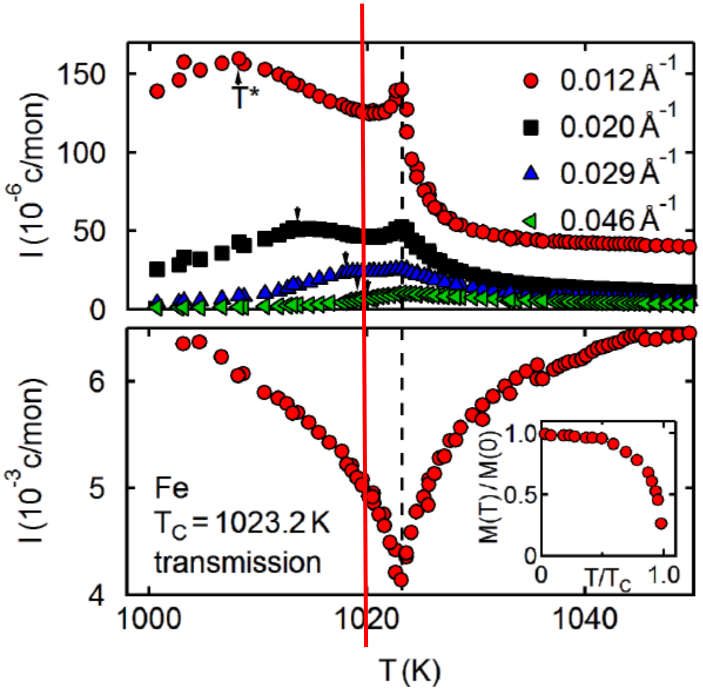

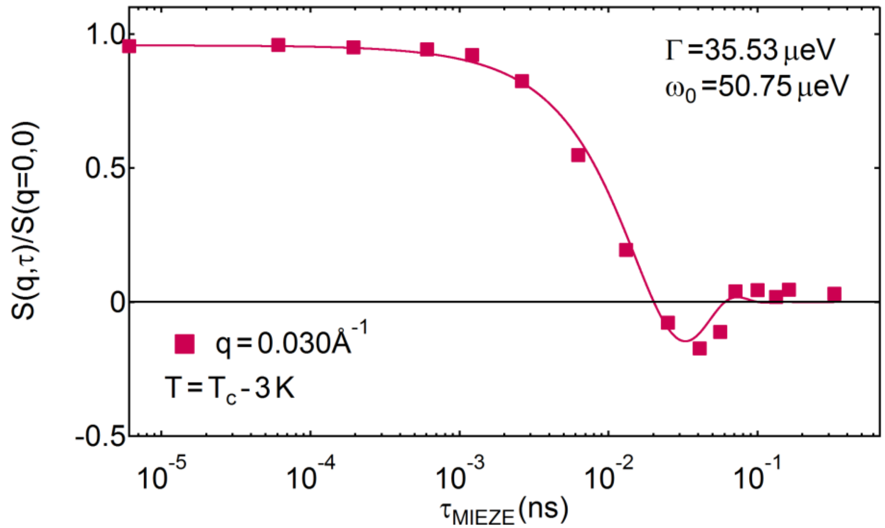

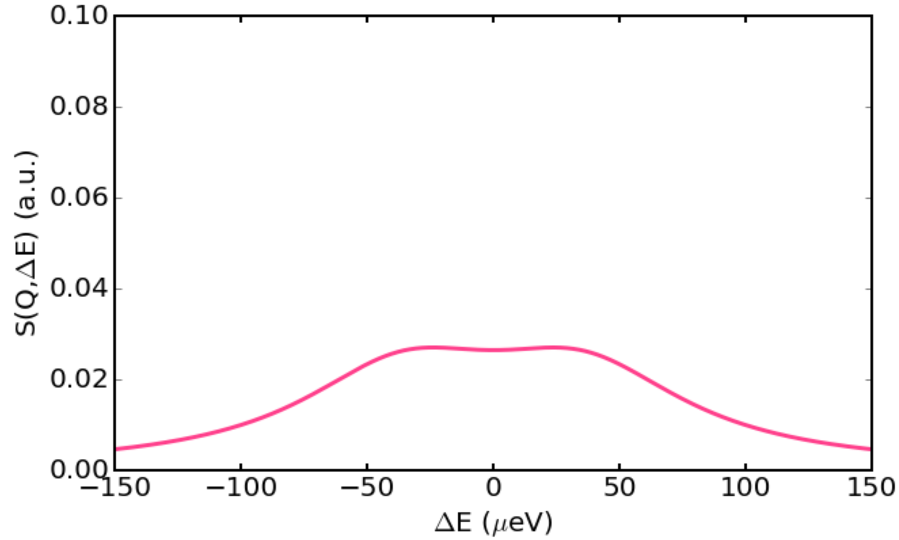

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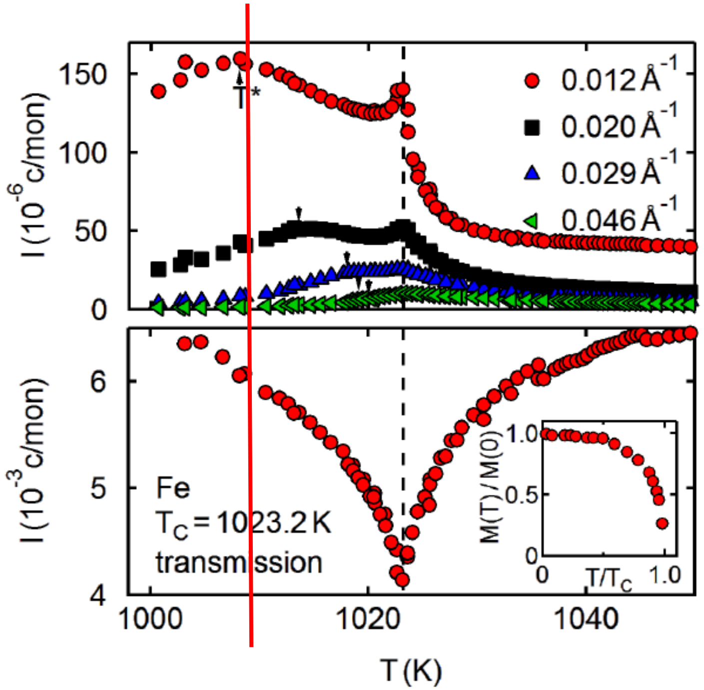

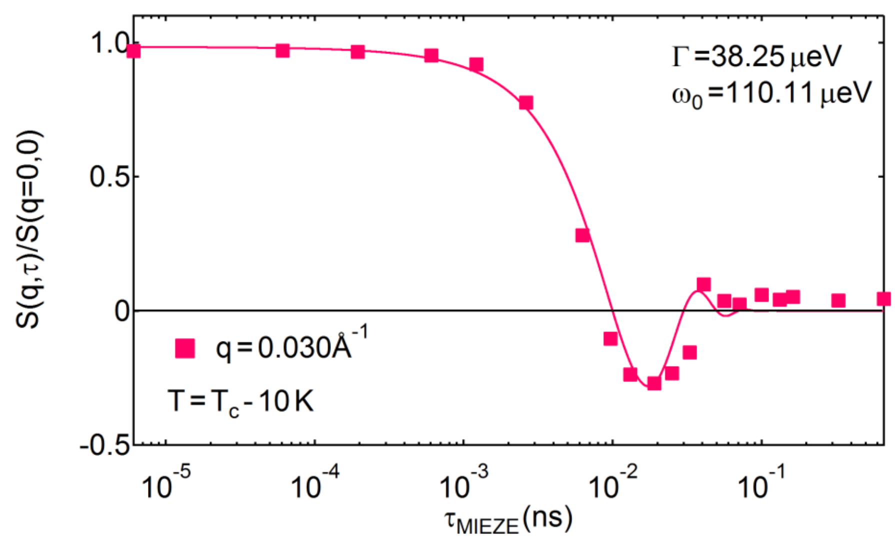

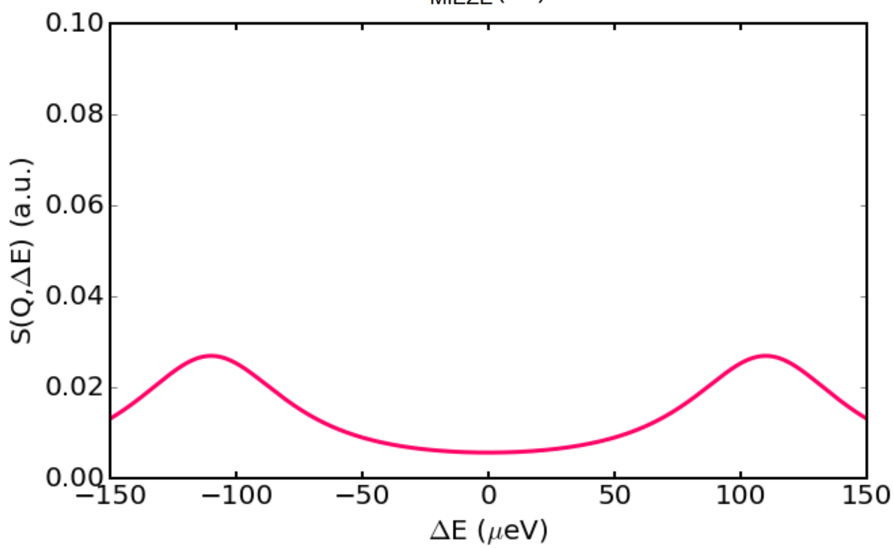

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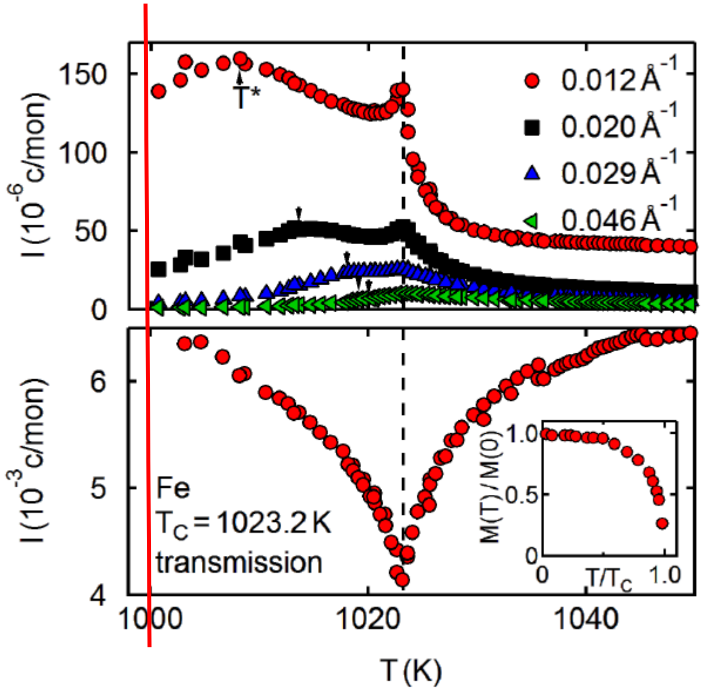
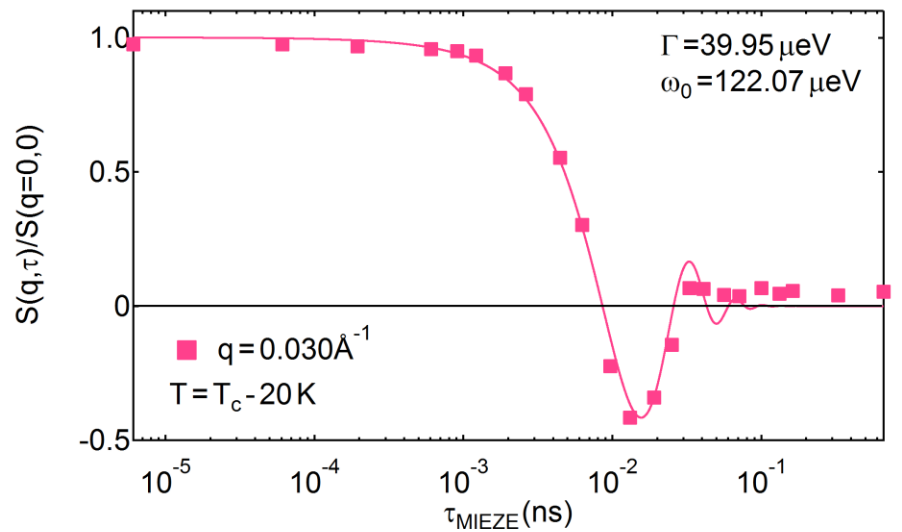
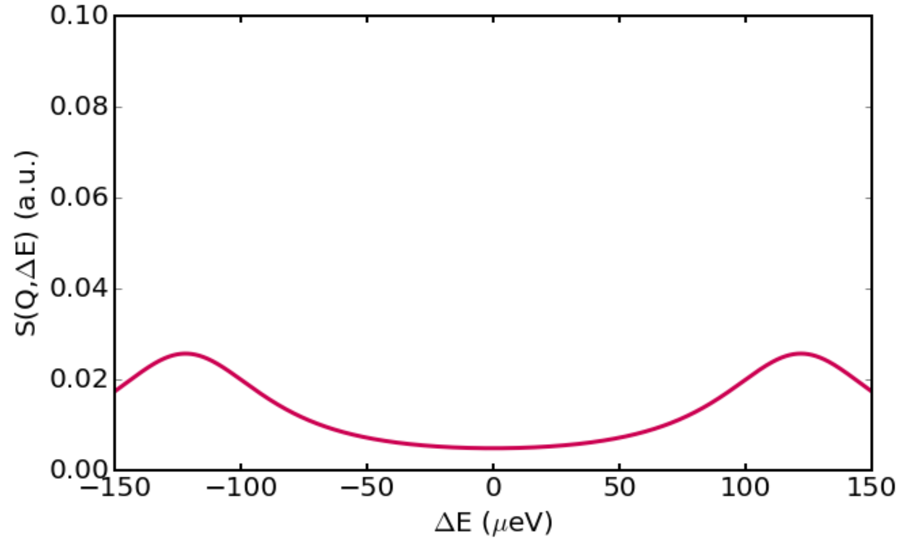
Säubert et al. PRB 99, 184423 (2019)

Fluctuations at the Curie Point in Iron

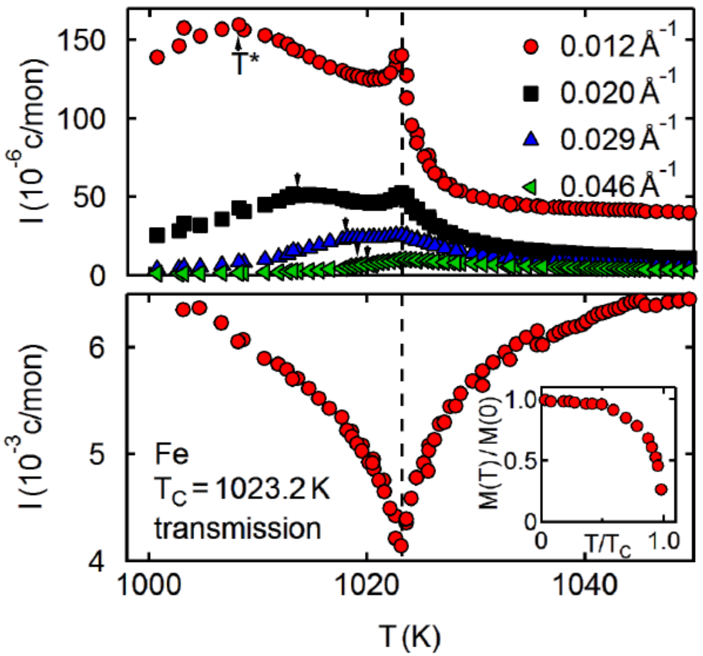


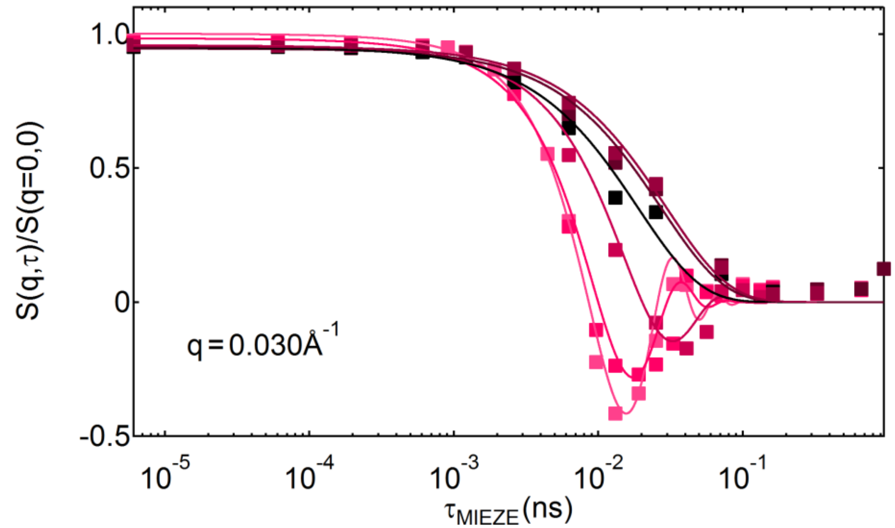


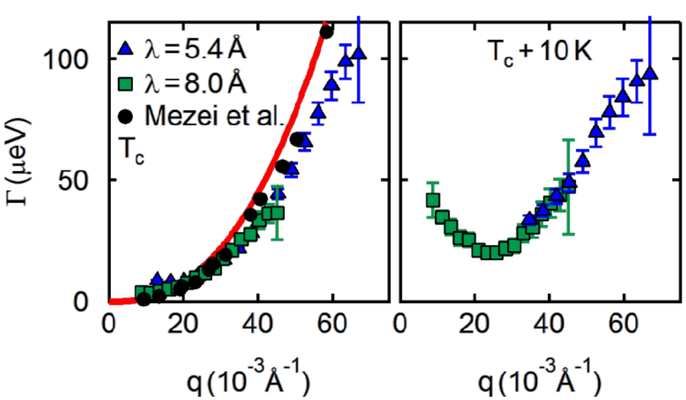


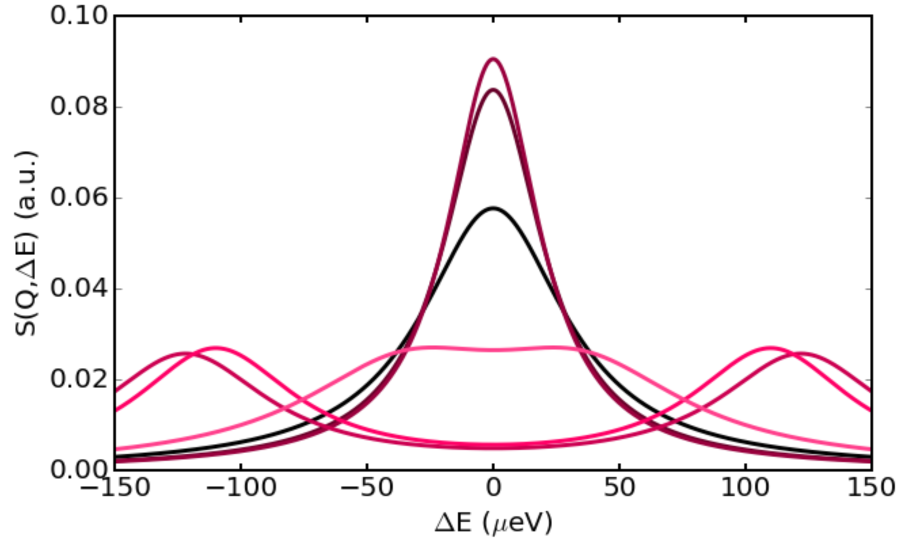
P. Rêsibois and C. Piette, Phys. Rev. Lett. 24, 514 (1970)
E. Frey and F. Schwabl, Physics Letters A, 49 (1987)
Kindervater et al. PRB, 95, 014429 (2017)
Säubert et al. PRB 99, 184423 (2019)

Fluctuations at the Curie Point in Iron

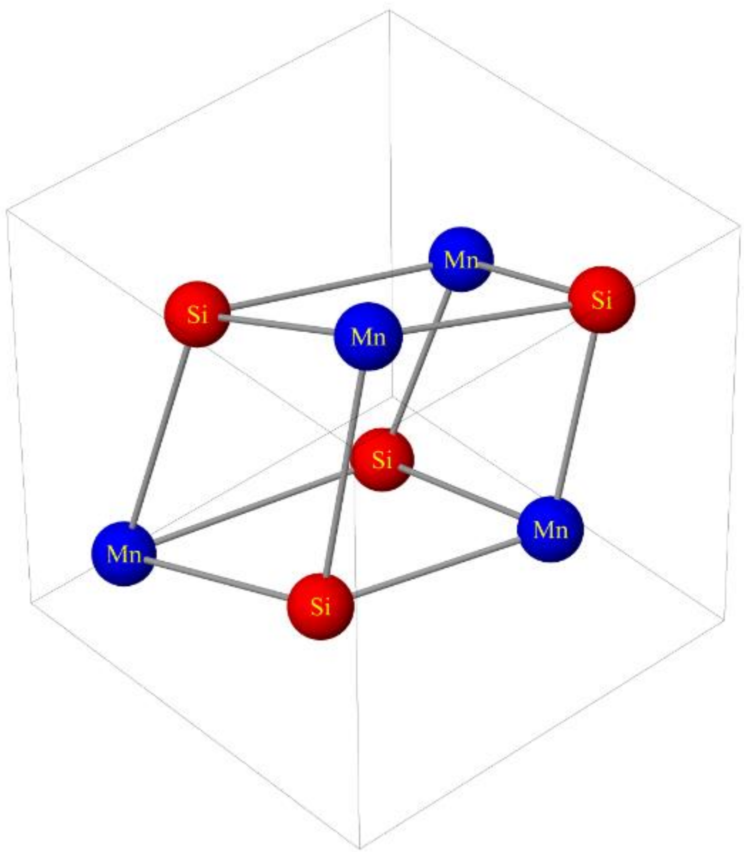




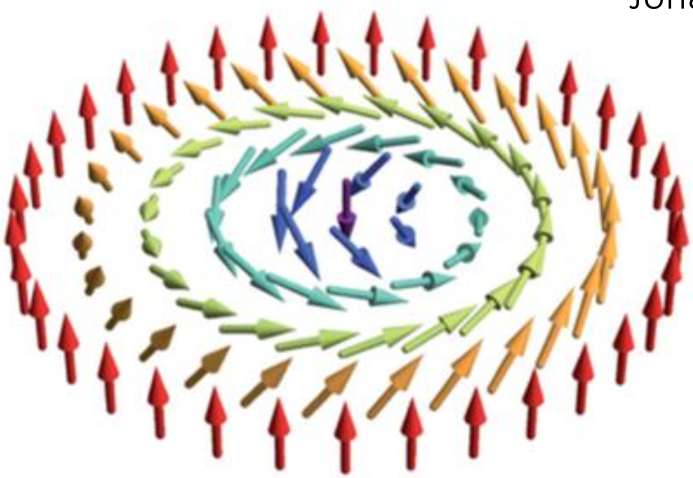




Example 2: Weak crystallization of fluctuating skyrmion textures in MnSi

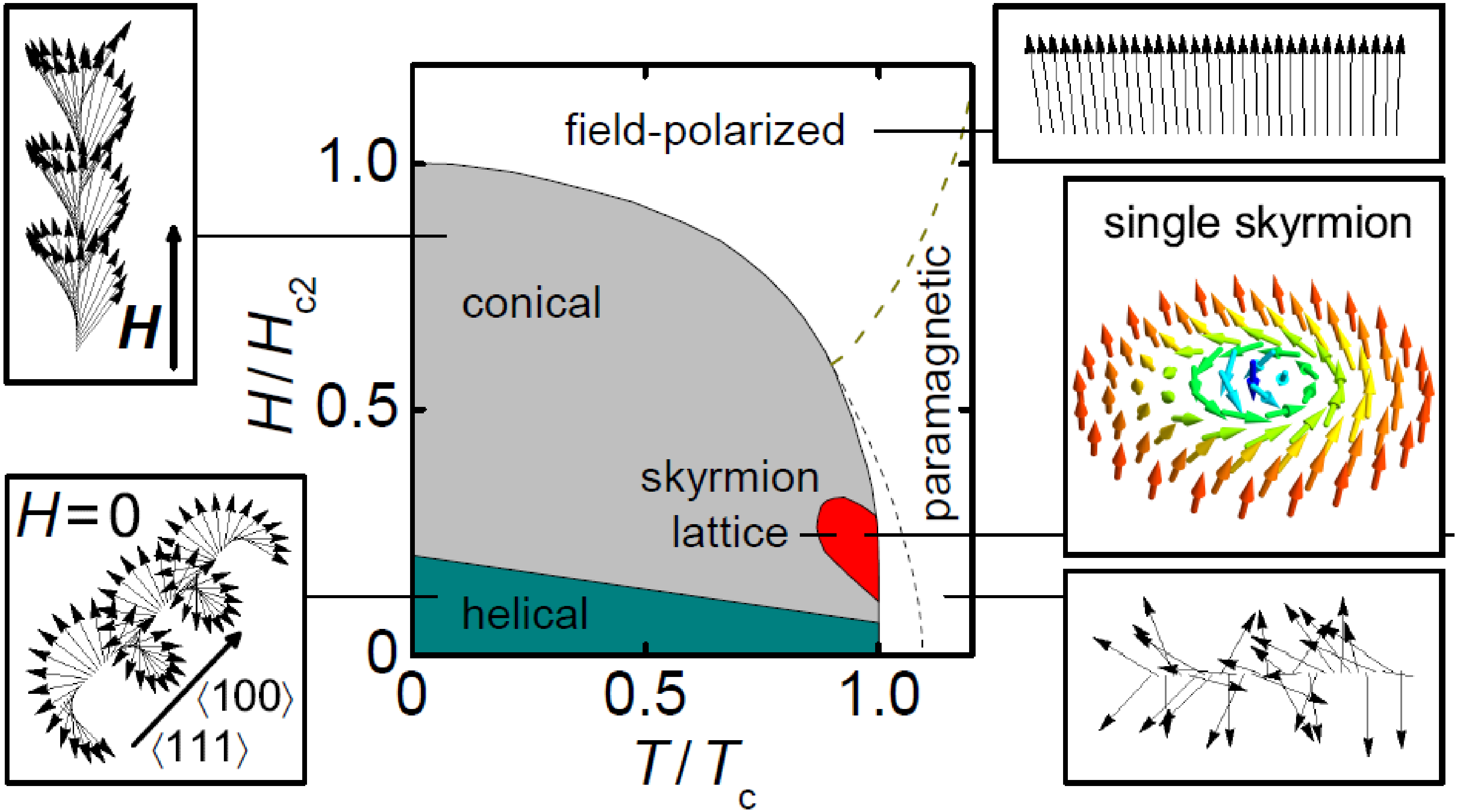


Jonas Kindervater



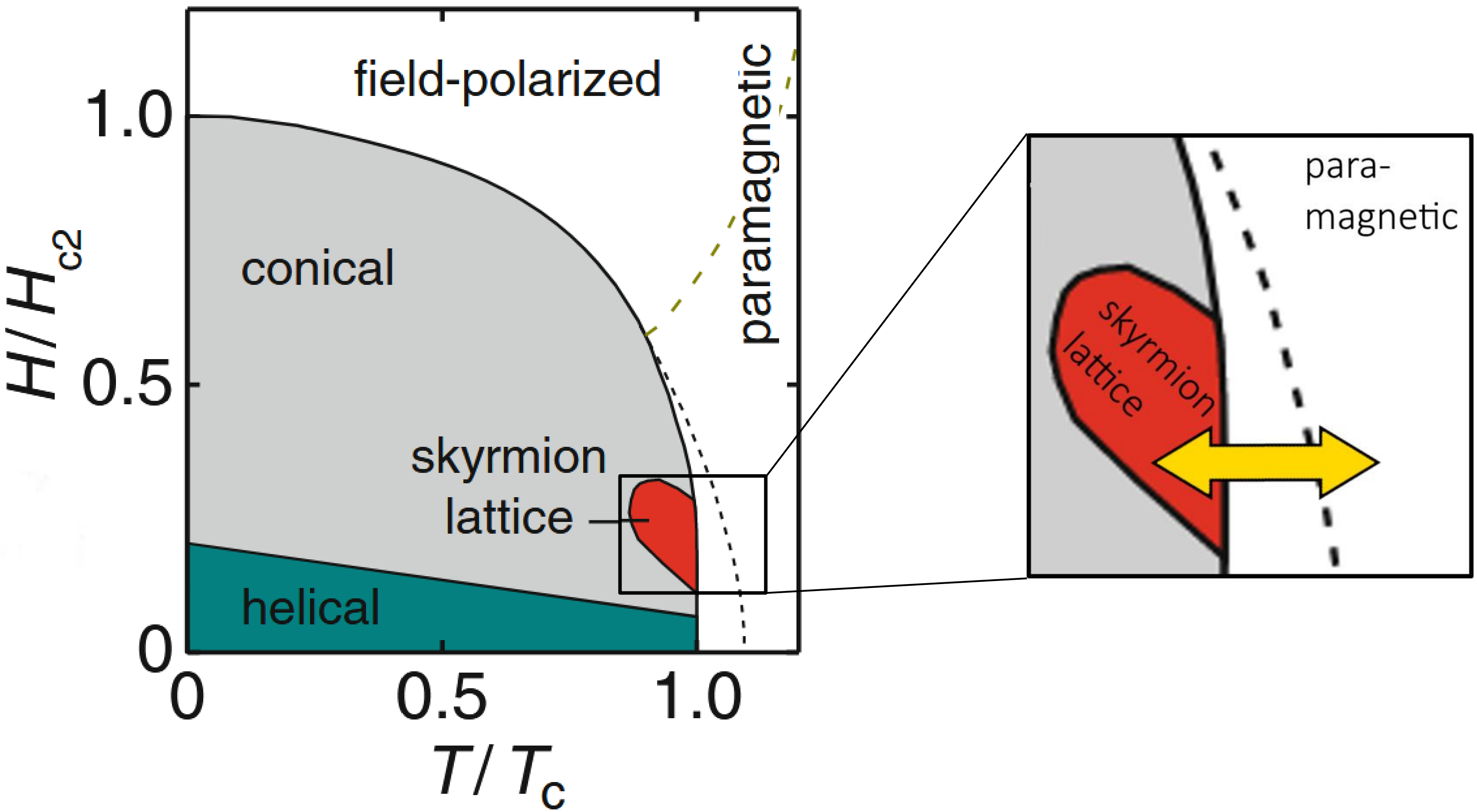
PhD Thesis, Marc Janoscheck

Weak crystallization of fluctuating skyrmion textures in MnSi



A. Bauer et C. Pfleiderer, Topological Structures in Ferroic Materials, Springer Series in Materials Science 228, DOI 10.1007/978-3-319-25301-5_1

Weak crystallization of fluctuating skyrmion textures in MnSi

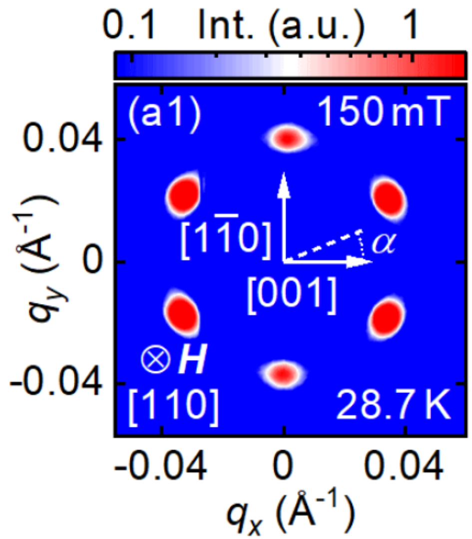


A. Bauer et C. Pfleiderer, Topological Structures in Ferroic Materials, Springer Series in Materials Science 228, DOI 10.1007/978-3-319-25301-5_1

Weak crystallization of fluctuating skyrmion textures in MnSi

SANS:

Skyrmion charakteristics outside of phase boundary!



Skyrmion lattice

J. Kindervater et al., PRX 9, 041059 (2019)

Weak crystallization of fluctuating skyrmion textures in MnSi

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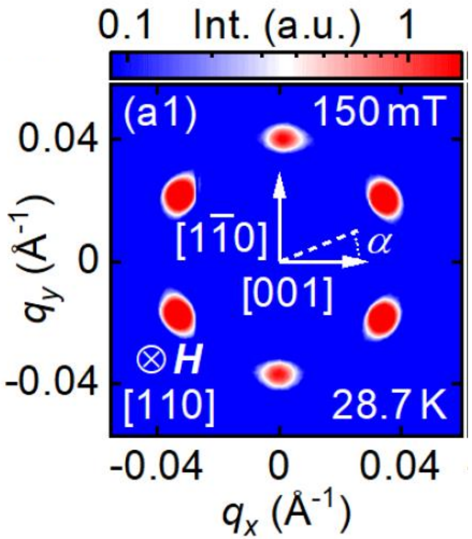
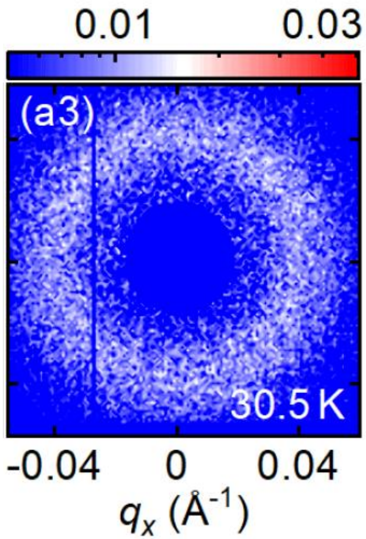


Skyrmion lattice



Paramagnetic

J. Kindervater et al., PRX 9, 041059 (2019)

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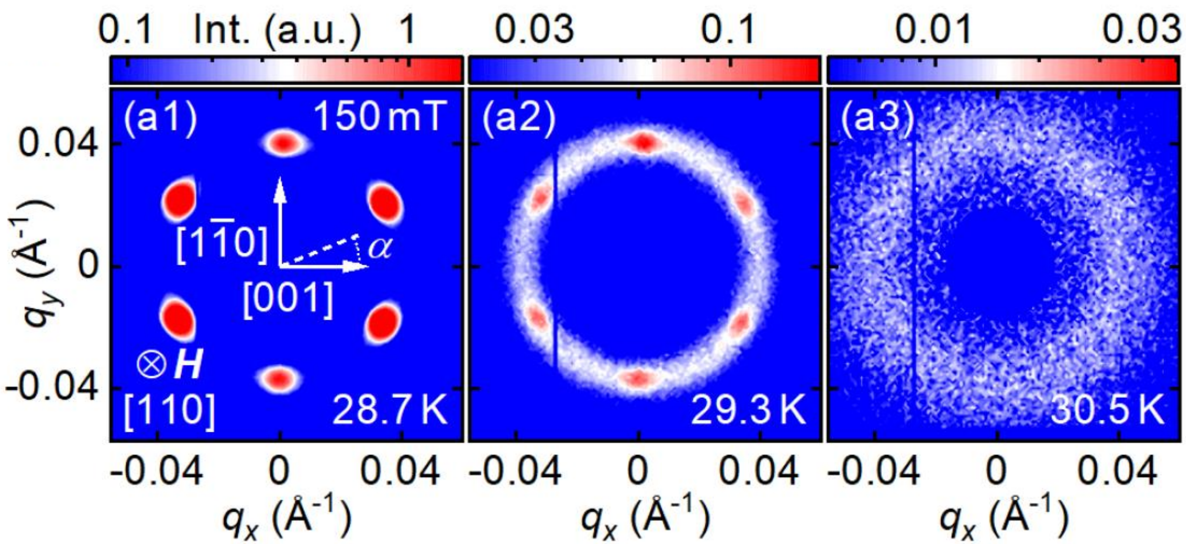

Skyrmion lattice

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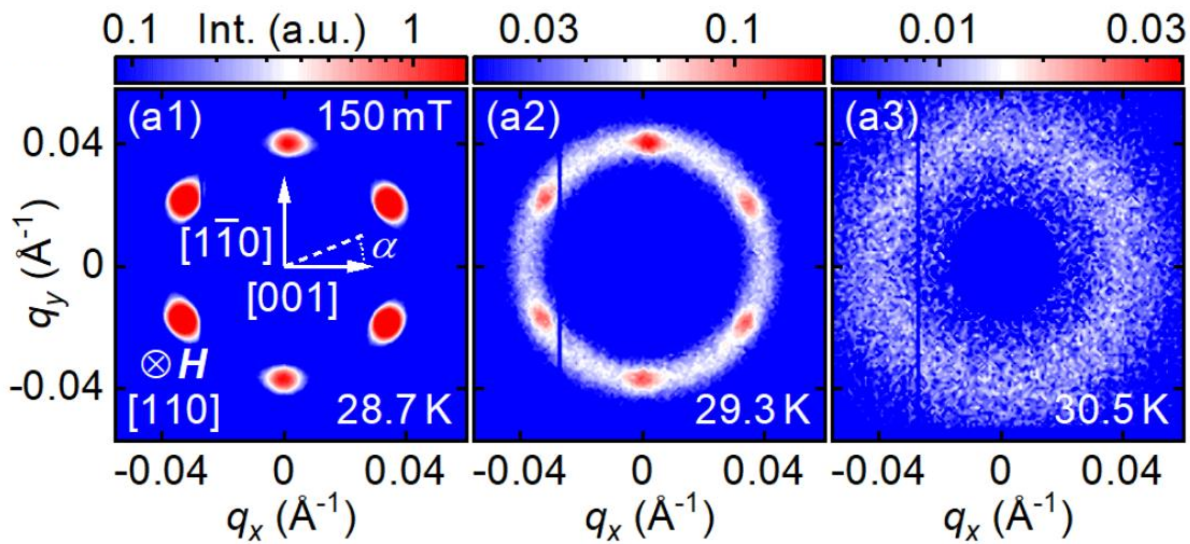


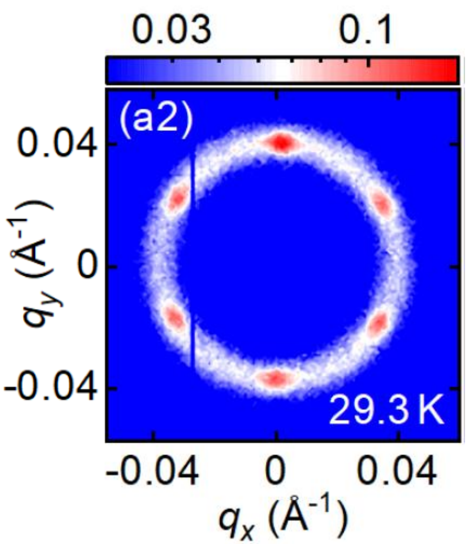
Skyrmion lattice

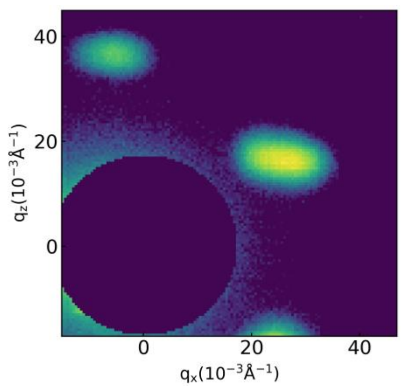
Paramagnetic

To confirm that these are not static remnants of the skyrmion lattice → RESEDA

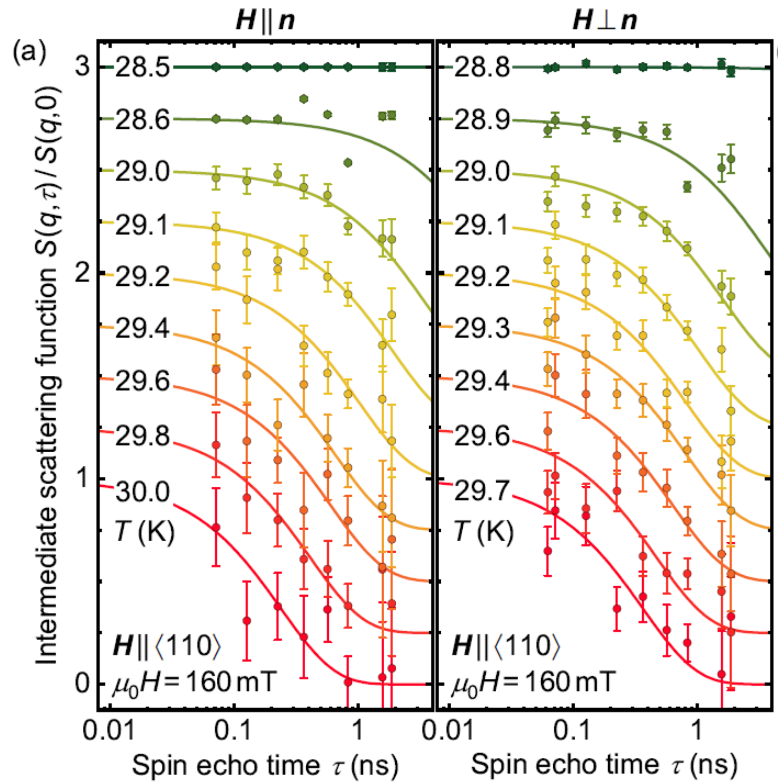
J. Kindervater et al., PRX 9, 041059 (2019)

Weak crystallization of fluctuating skyrmion textures in MnSi





RESEDA



J. Kindervater et al., PRX 9, 041059 (2019)

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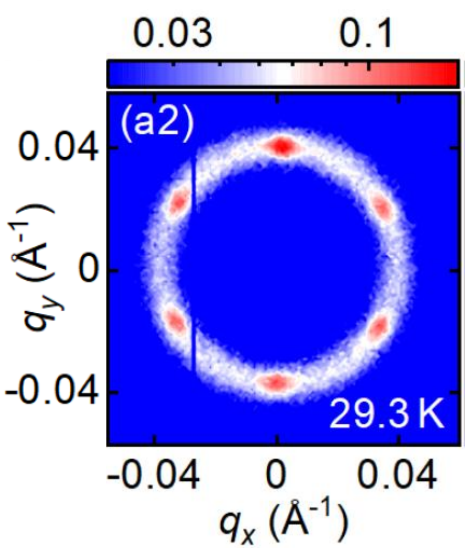
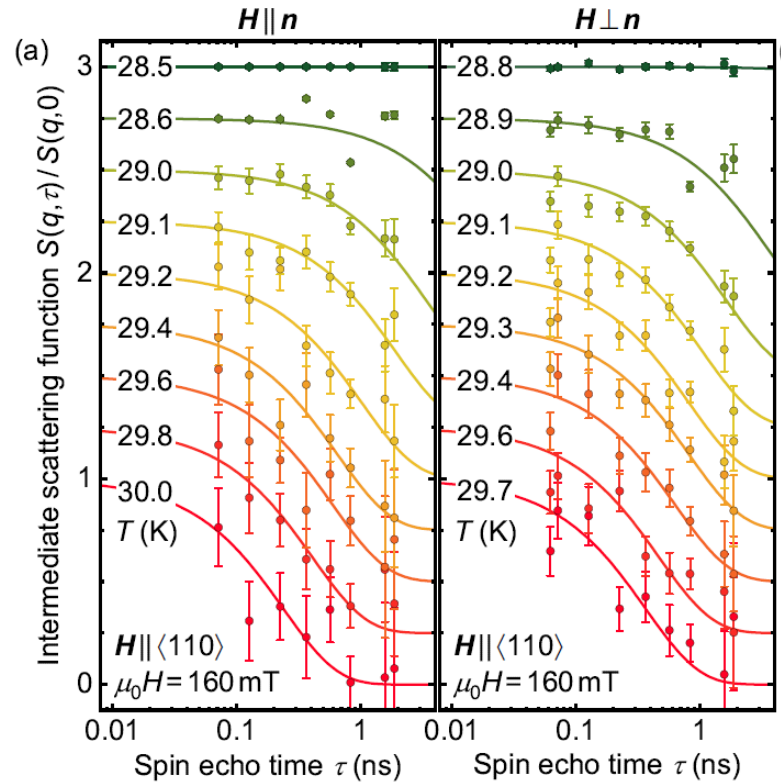


RESEDA



Skyrmion lattice phase: static magnetic order!
29.3K : fluctuations with lifetime around 1ns

J. Kindervater et al., PRX 9, 041059 (2019)

Team reseda

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Peter Böni

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Franz X. Haslbeck

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Peter Wild

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