Neutron Spin Echo spectroscopy and Magnetism

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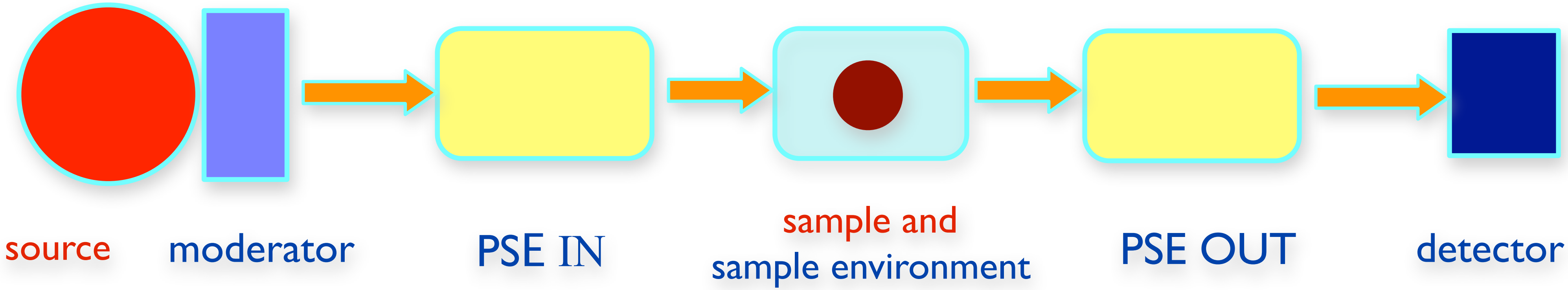
TU Delft

- Magnetic scattering
- Paramagnetic NSE
- Ferromagnetic NSE: magnetic fields
- Intensity modulated NSE: for samples depolarising the neutron beam: ferromagnets, superconductors
- Polarimetric NSE: chirality

from the source to the detector



Neutron flux

$$\varphi = \Phi \; \eta \; \boxed{dE \; d\Omega} \; / \; 4\pi$$

source flux distribution

intensity losses

field of neutron instrumentation

definition of the beam : Q, E and polarisation

Neutron Spin Echo

why ?

very high resolution

how ?

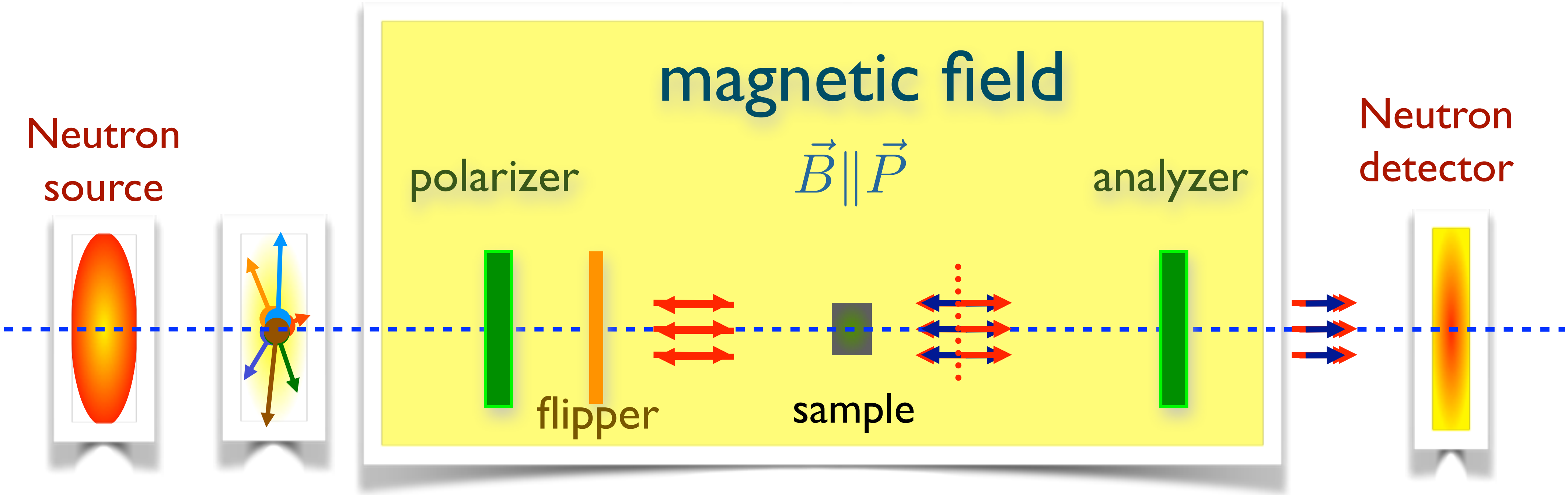
using the transverse components of beam polarization

Larmor precession

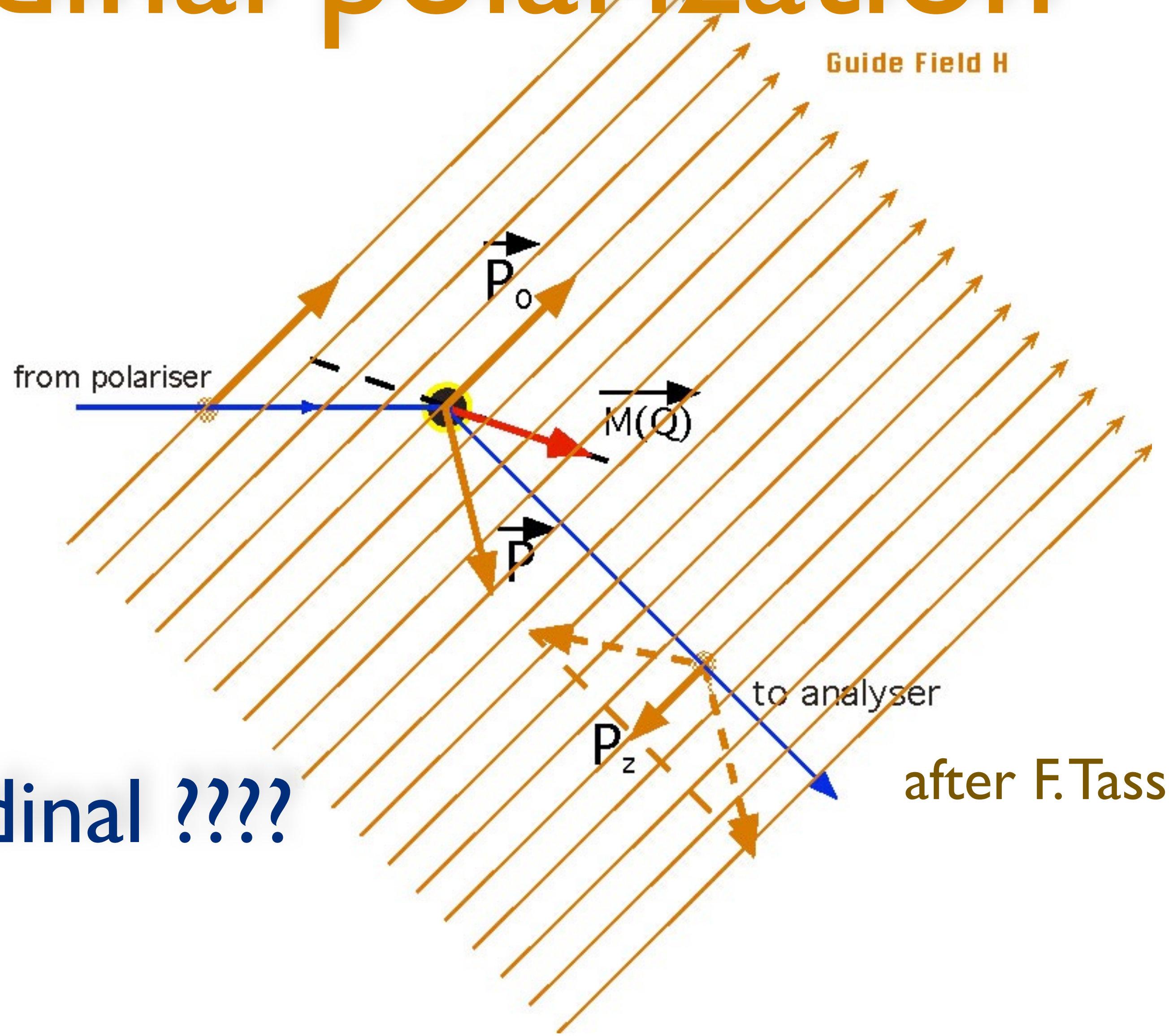
Polarized Neutrons

- polarizer
- analyzer

magnetic field (guide - precession)



Longitudinal polarization analysis



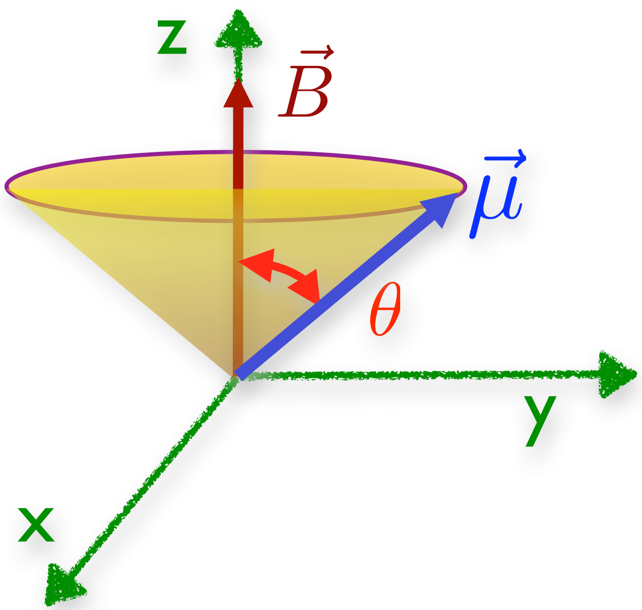
after F. Tasset

Why longitudinal ????

Larmor Precession

Motion of the polarization of a neutron beam in a magnetic field

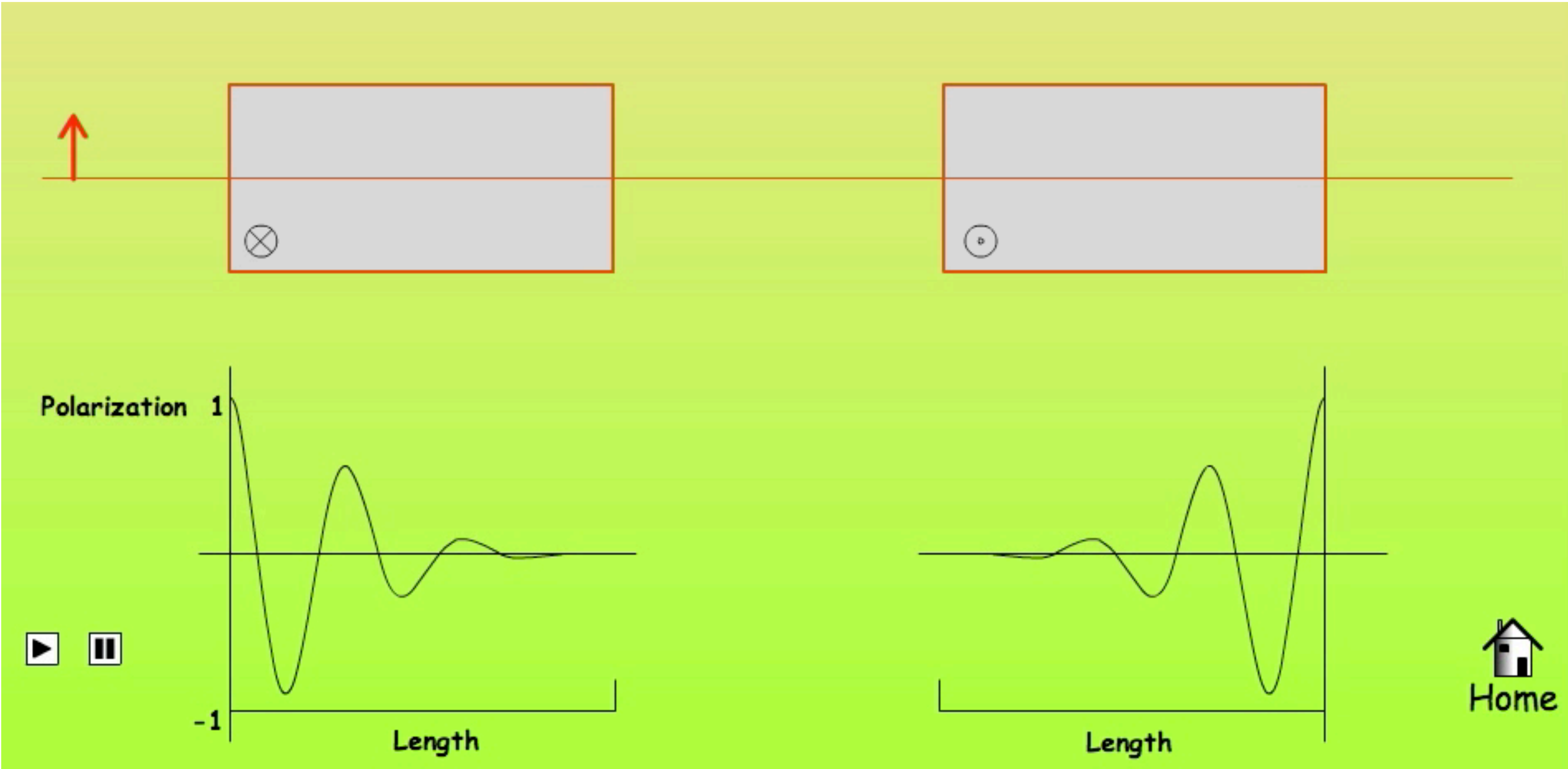
$$\frac{d\vec{\mu}}{dt} = \gamma \cdot (\vec{\mu} \times \vec{B}) = \vec{\mu} \times \vec{\omega}_L$$



Gyromagnetic ratio of neutrons

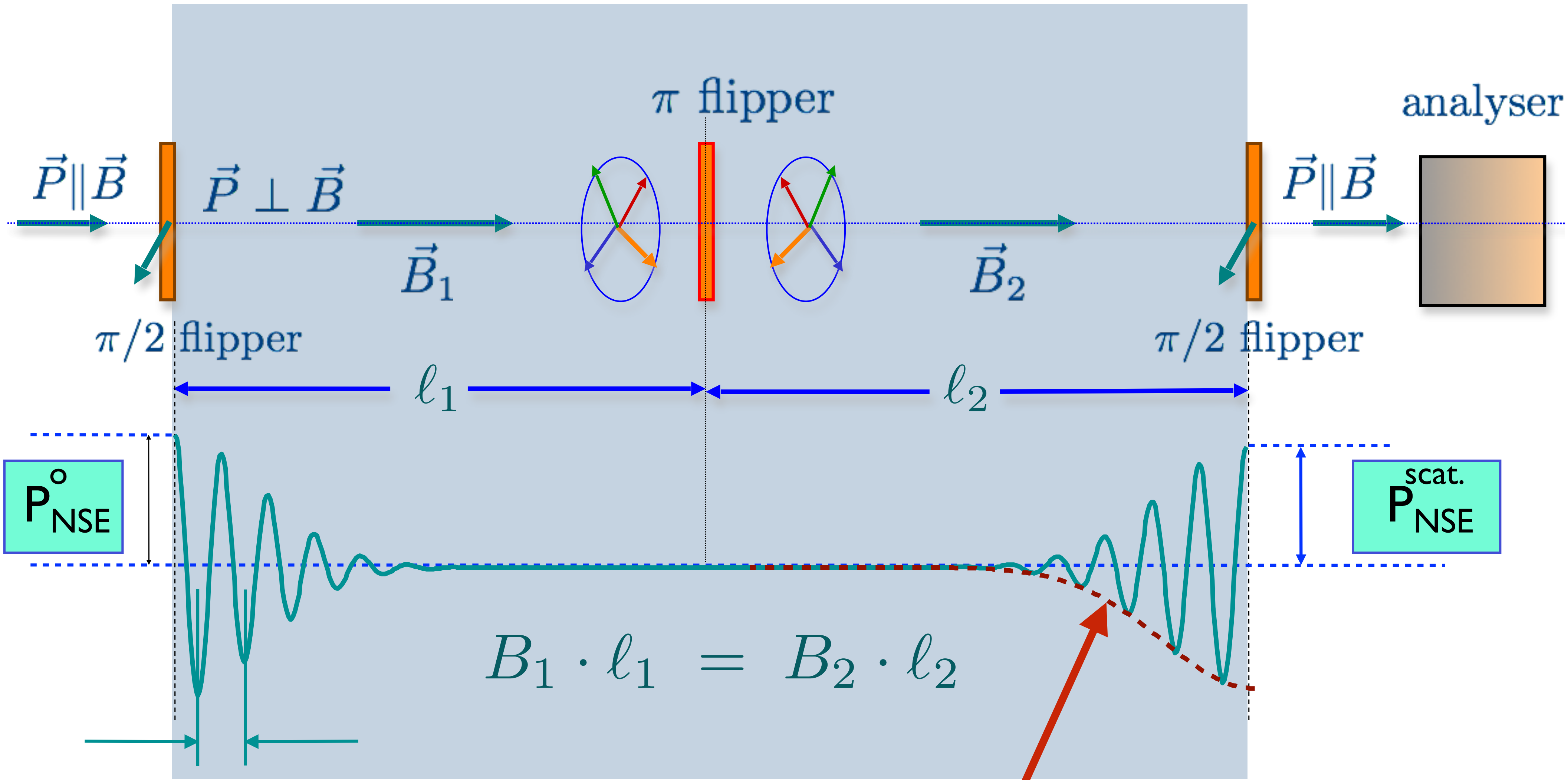
$$\gamma = 183.2 \text{ rad MHz T}^{-1}$$

$$\phi = \gamma\, B\, t_{tof} = \gamma\, B\, \ell / \mathrm{v}$$



after R. Gähler

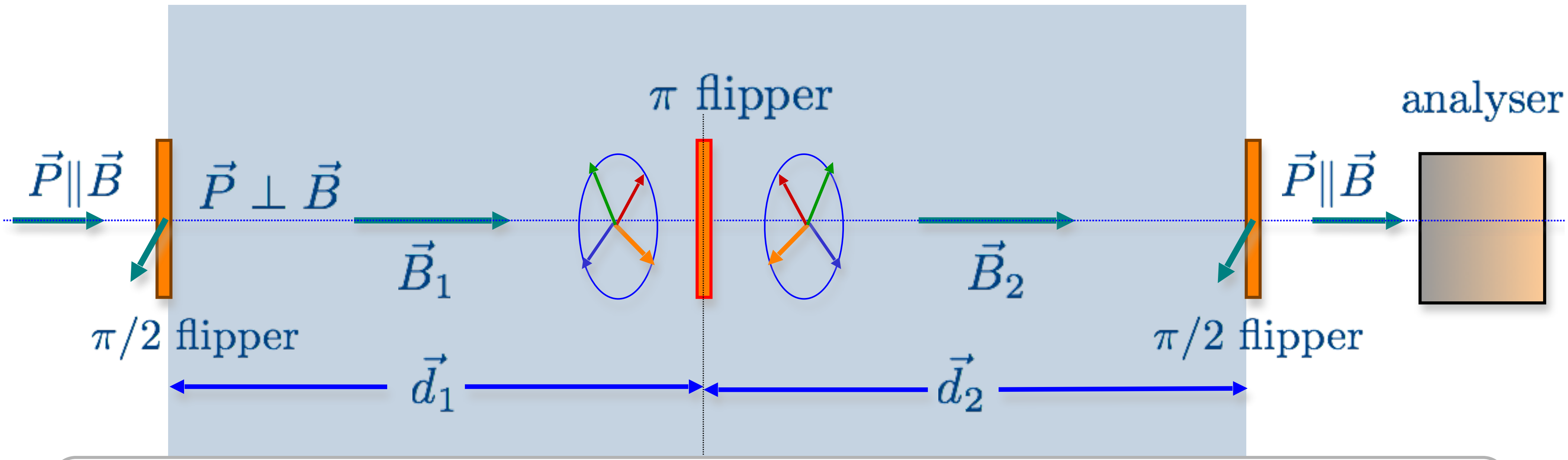
neutron spin echo spectroscopy



$1.357\,10^{-5}\,T \cdot m/\lambda[nm]$

$$P_{NSE,\|\vec{B}} = \langle cos\,((\phi)\rangle = \int f\,(\mathrm{v})\,cos\,(\phi)\,d\mathrm{v}$$

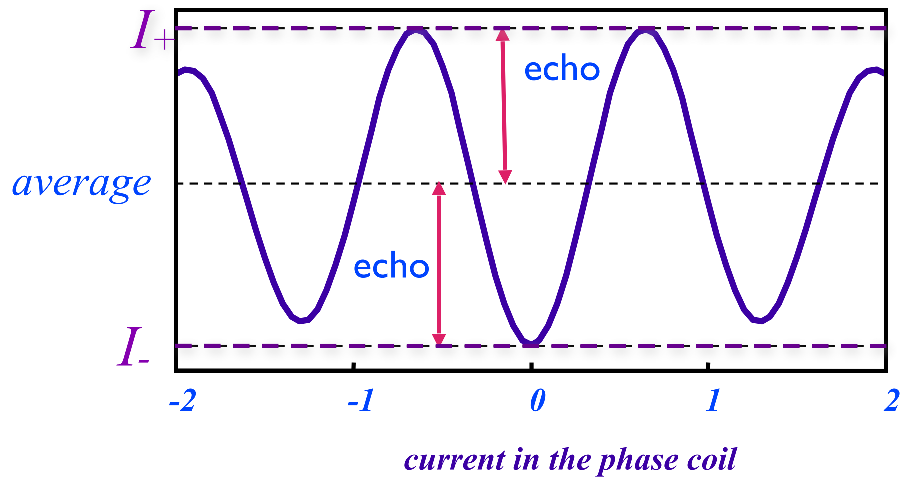
neutron spin echo spectroscopy



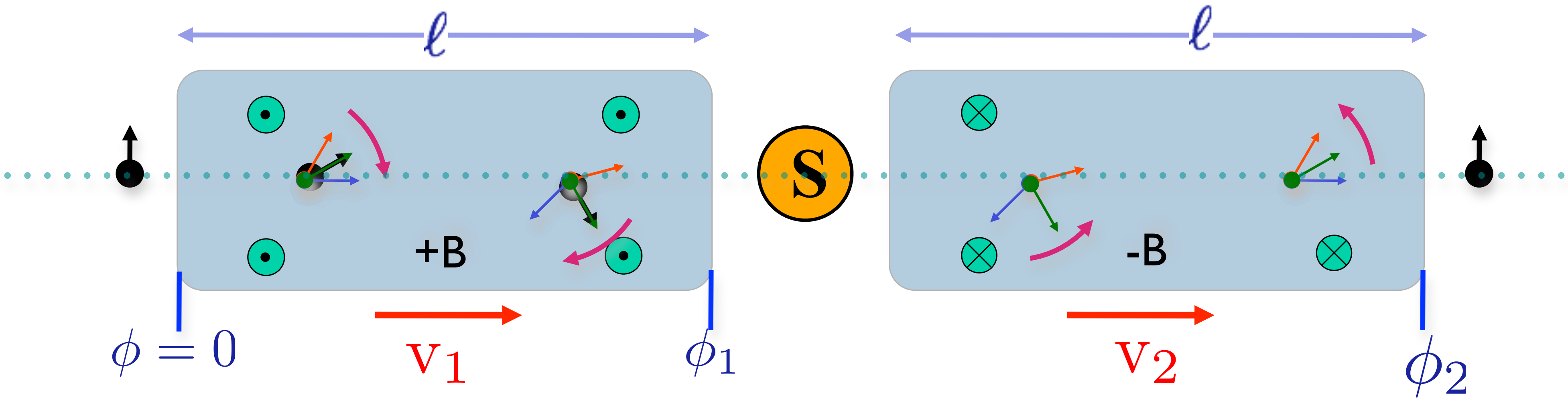
ideally

echo modulation = $(I_+ - I_-) / 2$

for $|\vec{P}| = 1$



basic equations

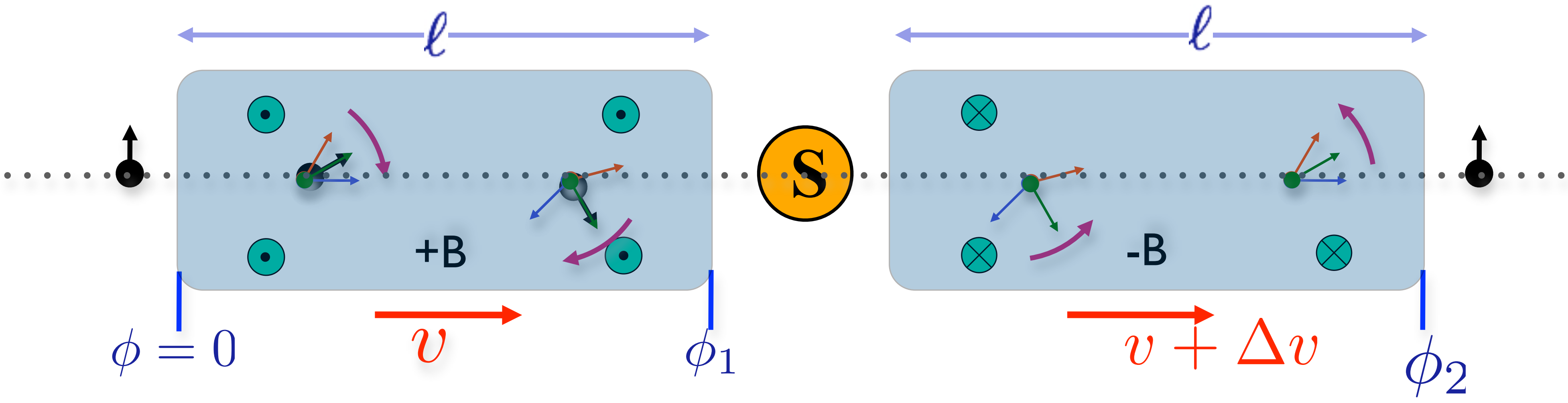


$$\phi_1 = \omega_L \cdot \ell/\mathrm{v}_1 \qquad \phi_2 = \omega_L \cdot \ell\,(1/\mathrm{v}_1 - 1/\mathrm{v}_2)$$

for $\mathrm{v}_1 = \mathrm{v}$ and $\mathrm{v}_2 = \mathrm{v} + \Delta\mathrm{v} \;\Rightarrow$

$$\phi_2 = \omega_L\,\ell\left[1/\mathrm{v} - 1/\left(\mathrm{v} + \Delta\mathrm{v}\right)\right] \approx \omega_L \ell \Delta\mathrm{v}/\mathrm{v}^2 = \omega_L\, t\, \Delta\mathrm{v}/\mathrm{v}$$

basic equations



scattering theory : $\Delta \mathrm{v} \;\rightarrow\; \omega$

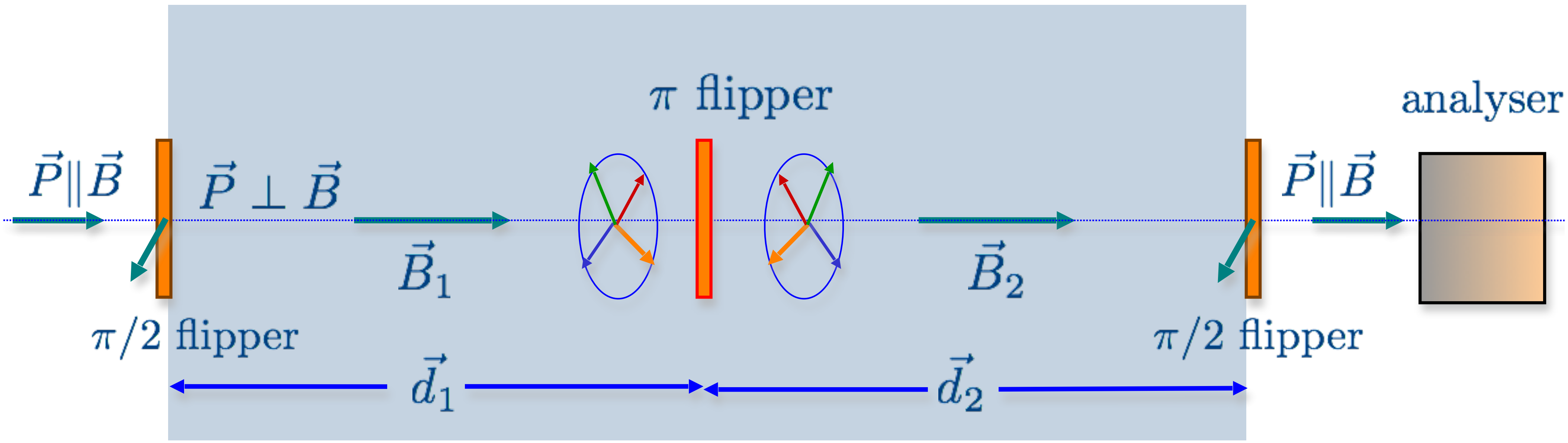
$$\hbar\omega = m/2 \cdot \left(\mathrm{v}_1^2 - \mathrm{v}_2^2\right) = m/2 \cdot \left(\mathrm{v}_1 - \mathrm{v}_2\right)\left(\mathrm{v}_1^2 + \mathrm{v}_2^2\right) \approx m \cdot \mathrm{v} \cdot \Delta\mathrm{v}$$

$$\phi_2 = \omega_L\, \ell \left[1/\mathrm{v} - 1/\left(\mathrm{v} + \Delta\mathrm{v}\right)\right] \approx \omega_L \ell \Delta\mathrm{v}/\mathrm{v}^2 = \omega_L\, t\, \Delta\mathrm{v}/\mathrm{v}$$

$$\Rightarrow \phi_2 = \phi = t_{NSE} \cdot \omega$$

and $\quad t_{NSE} = \omega_L \cdot \ell \cdot \hbar / \left(m\mathrm{v}^3\right)$

neutron spin echo spectroscopy



$$P_{NSE} = P_s \langle cos(\phi - \langle\phi\rangle)\rangle = P_s \frac{\int S(Q,\omega)\, cos[t\,(\omega-\omega_o)]\, d\omega}{\int S(Q,\omega)\, d\omega}$$

for quasi-elastic scattering $\omega_o = 0$

$$P^{scat}_{NSE}/P_s = \Re\,[S(Q,t)]/S(Q) = I(Q,t)$$

most generaly $\phi - \langle\phi\rangle = f(\vec{q},\omega) \propto S(\vec{(Q)},t)$

locally

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- Magnetic scattering
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- Polarimetric NSE: chirality

The vector interaction of a polarised neutron beam with magnetic moments

$$S_m(\vec{Q},\omega) = (\gamma\rho_o)^2 \, \frac{k_f}{k_i} \left[\sum_{q_i,q_f} p_{q_i} \boxed{\left[\langle q_i | m_\perp^* | q_f \rangle \cdot \langle q_f | m_\perp | q_i \rangle \right.} \right] \delta(E_f - E_i + h\omega)$$

for an unpolarised beam

$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega)$$

Blume-Maleev equations: magnetic part

The vector interaction of a polarised neutron beam with magnetic moments

$$S_m(\vec{Q},\omega) = (\gamma\rho_o)^2 \frac{k_f}{k_i}\left[\sum_{q_i,q_f} \cdot i\,\vec{P}_i \cdot \left(\langle q_i|m_\perp^*|q_f\rangle \times \langle q_f|m_\perp|q_i\rangle\right)\right]\right]\delta(E_f - E_i + h\omega)$$

the polarisation dependent term:

$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega) \quad - \eta\,\zeta\,\vec{P}_i \cdot \hat{Q}$$

$\eta =$ 1 totally chiral
0 non-chiral

$\zeta =$ $+1$ right handed
-1 left handed

The vector interaction of a polarised neutron beam with magnetic moments

$$S_m(\vec{Q},\omega) = (\gamma\rho_o)^2 \frac{k_f}{k_i} \Bigg[\sum_{q_i,q_f} p_{q_i} \left[\langle q_i | m_\perp^* | q_f \rangle \cdot \langle q_f | m_\perp | q_i \rangle + \right.$$

$$\left. + i\, \vec{P}_i \cdot \left(\langle q_i | m_\perp^* | q_f \rangle \times \langle q_f | m_\perp | q_i \rangle \right) \right] \Bigg] \delta(E_f - E_i + h\omega)$$

$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega)(1 - \eta\, \zeta\, \vec{P}_i \cdot \hat{Q})$$

$$\eta = \begin{array}{ll} 1 & \text{totally chiral} \\ 0 & \text{non-chiral} \end{array}$$

$$\zeta = \begin{array}{ll} +1 & \text{right handed} \\ -1 & \text{left handed} \end{array}$$

The vector interaction of a polarised neutron beam with magnetic moments

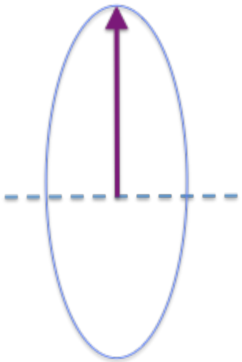
$$S_m(\vec{Q},\omega) = (\gamma\rho_o)^2 \frac{k_f}{k_i} \left[\sum_{q_i,q_f} p_{q_i} \left[\langle q_i|m_\perp^*|q_f\rangle \cdot \langle q_f|m_\perp|q_i\rangle + \right.\right.$$

$$\left.\left. + i\,\vec{P}_i \cdot (\langle q_i|m_\perp^*|q_f\rangle \times \langle q_f|m_\perp|q_i\rangle)\right]\right] \delta(E_f - E_i + h\omega)$$

$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega)(1 - \eta\ \zeta\ \vec{P}_i \cdot \hat{Q})$$

$$\vec{P}_f = -\hat{Q}\left[\hat{Q} \cdot \vec{P}_i + \zeta\,\eta\right]$$

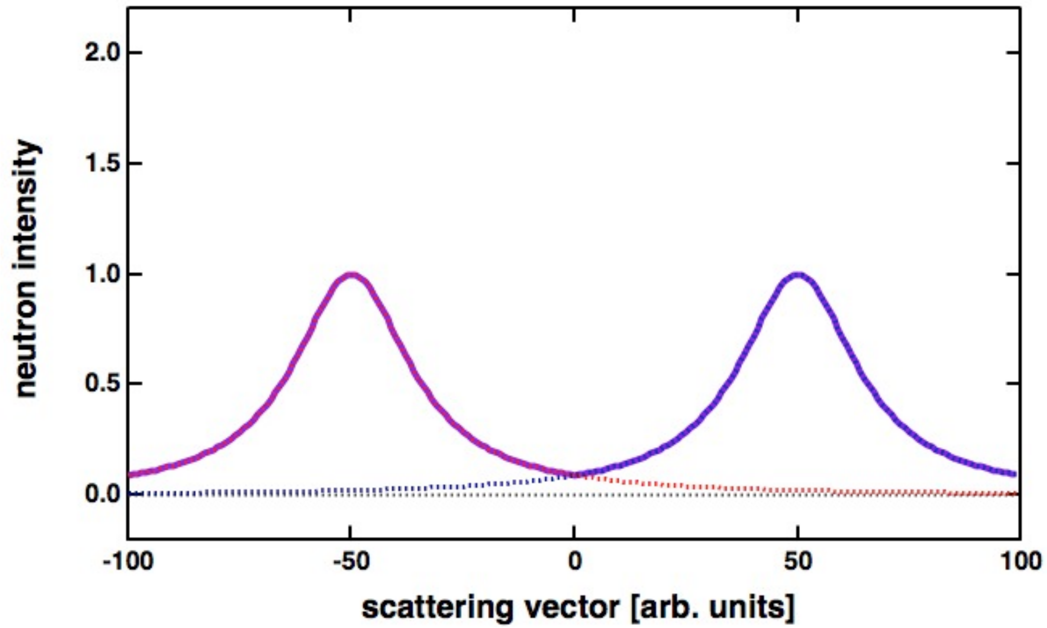
The interaction of a neutron beam with magnetic moments

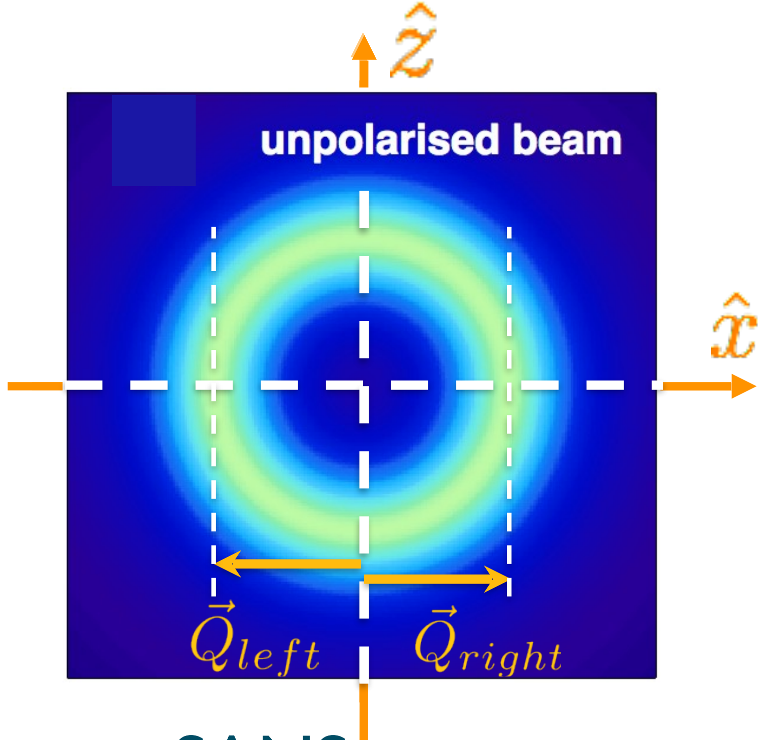


$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega)(1 - \eta\ \zeta\ \vec{P}_i \cdot \hat{Q})$$

$$\phi = 90^\circ \quad \eta = 1$$

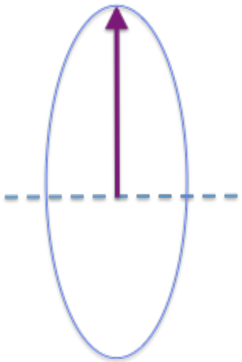
unpolarised neutron beam





SANS pattern

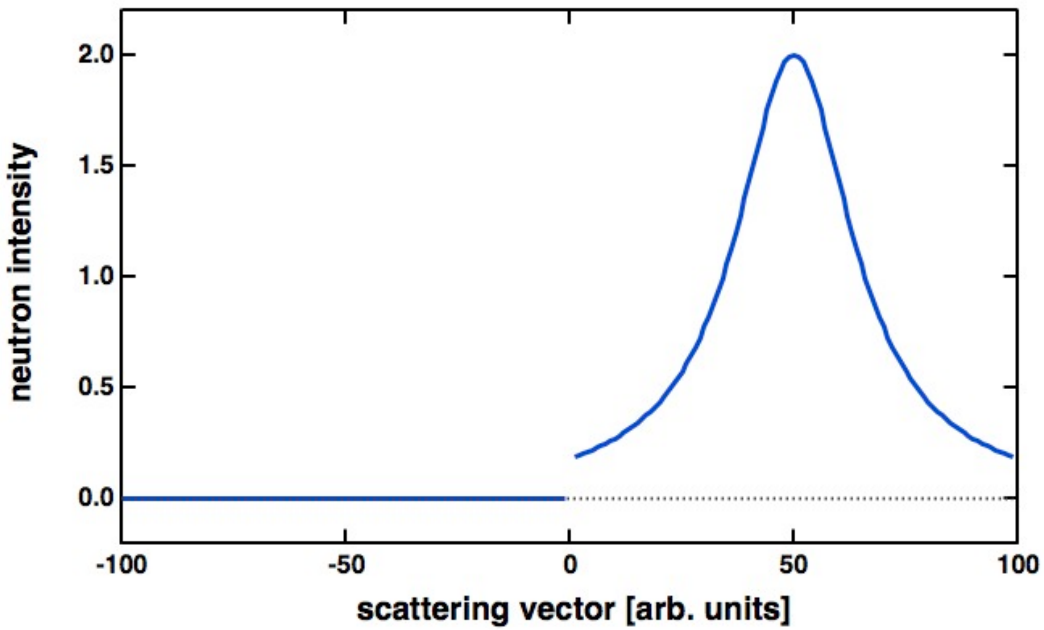
The interaction of a neutron beam with magnetic moments

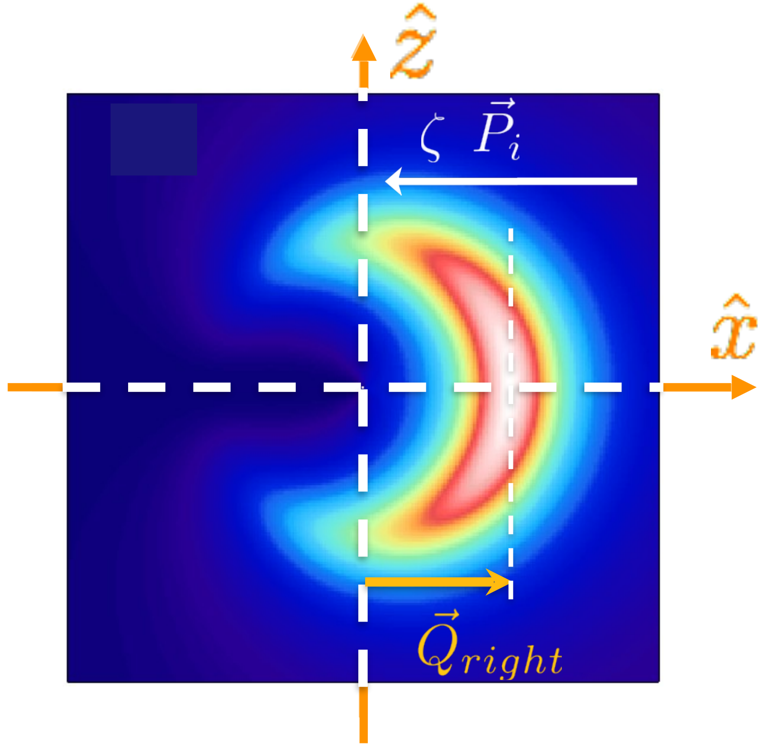


$$S_m(\vec{Q},\omega) = S_m^o(\vec{Q},\omega)(1 - \eta\ \zeta\ \vec{P}_i \cdot \hat{Q})$$

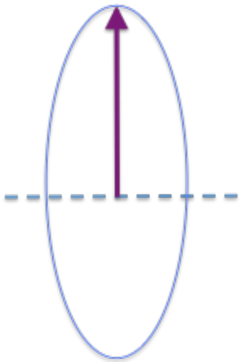
$$\phi = 90^\circ \quad \eta = 1$$

polarised neutrons





The interaction of a neutron beam with magnetic moments

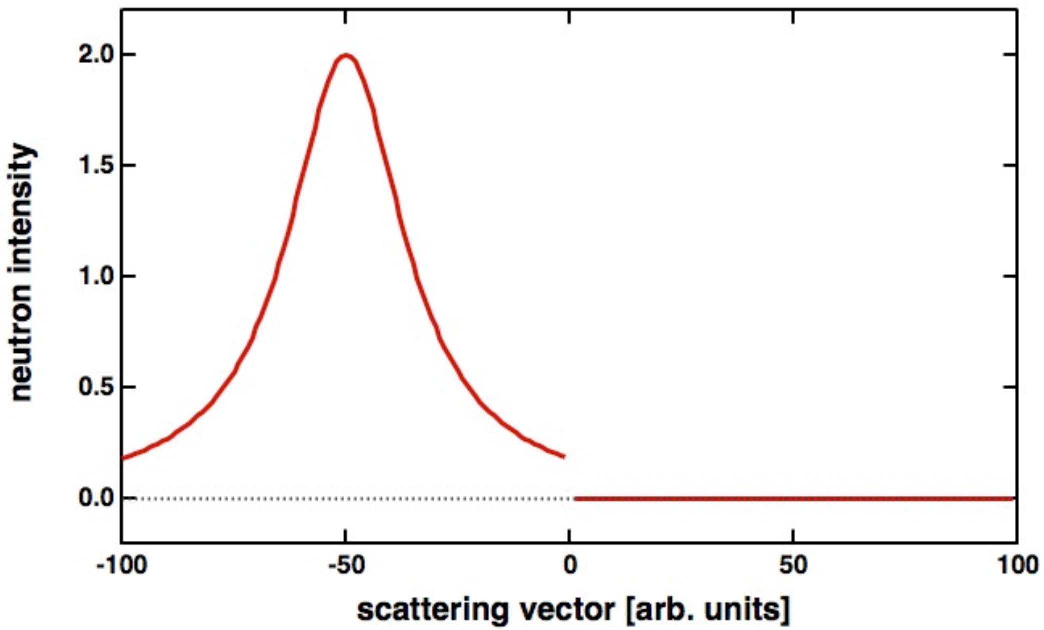


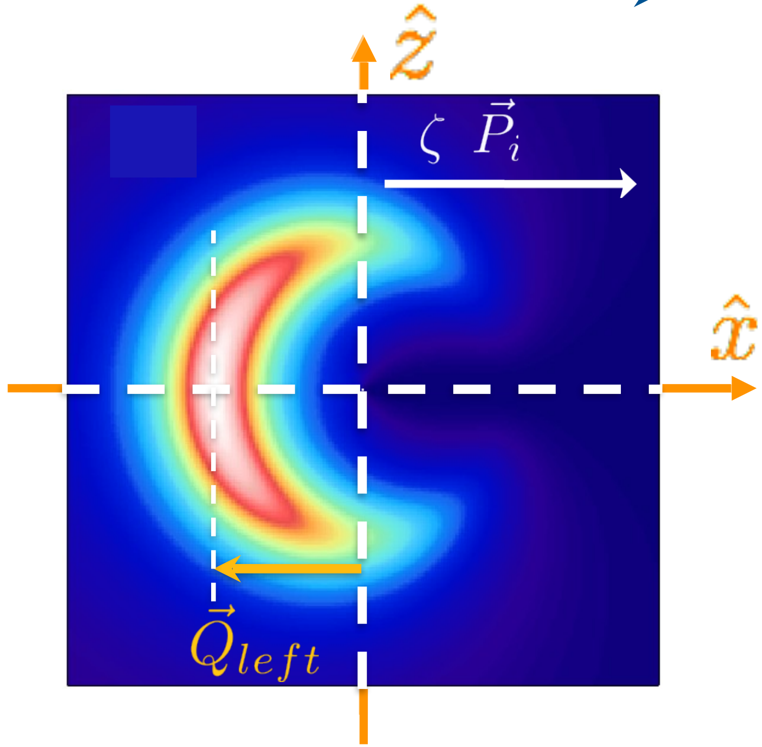
$$S_m(\vec{Q},\omega) = S^o_m(\vec{Q},\omega)(1 - \eta\ \zeta\ \vec{P}_i \cdot \hat{Q})$$

$$\phi = 90^\circ \quad \eta = 1$$

$$\zeta\ \vec{P}_i$$

polarised neutrons





the vector interaction of a polarised neutron beam with magnetic moments provides direct information on the topology of the magnetic moments

if the topology of the magnetic moments is known

the vector interaction of a polarised neutron beam with magnetic moments provides direct information on the topology of the neutron magnetic moments

- Magnetic scattering
- Paramagnetic NSE
- Ferromagnetic NSE: magnetic fields
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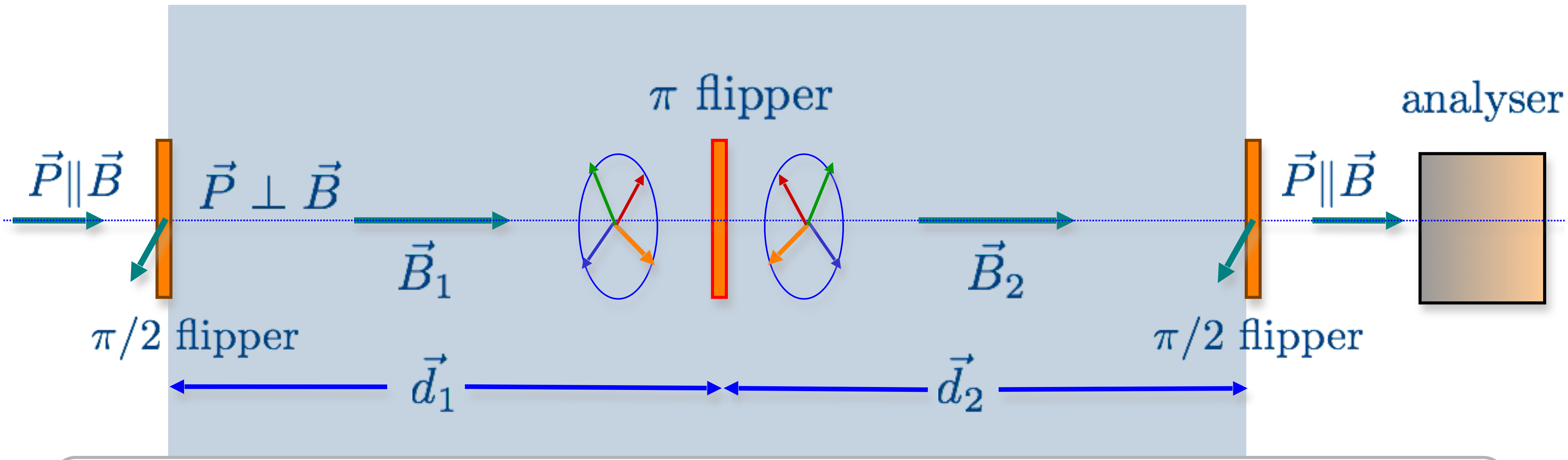
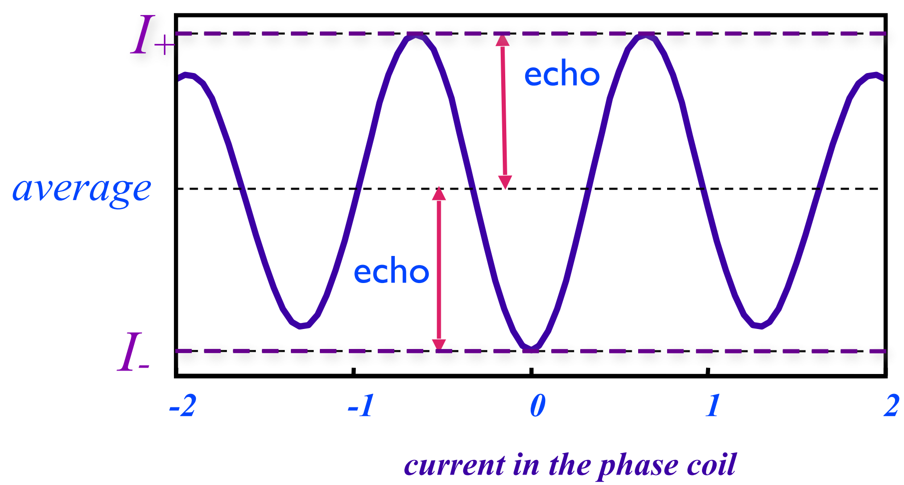
neutron spin echo spectroscopy



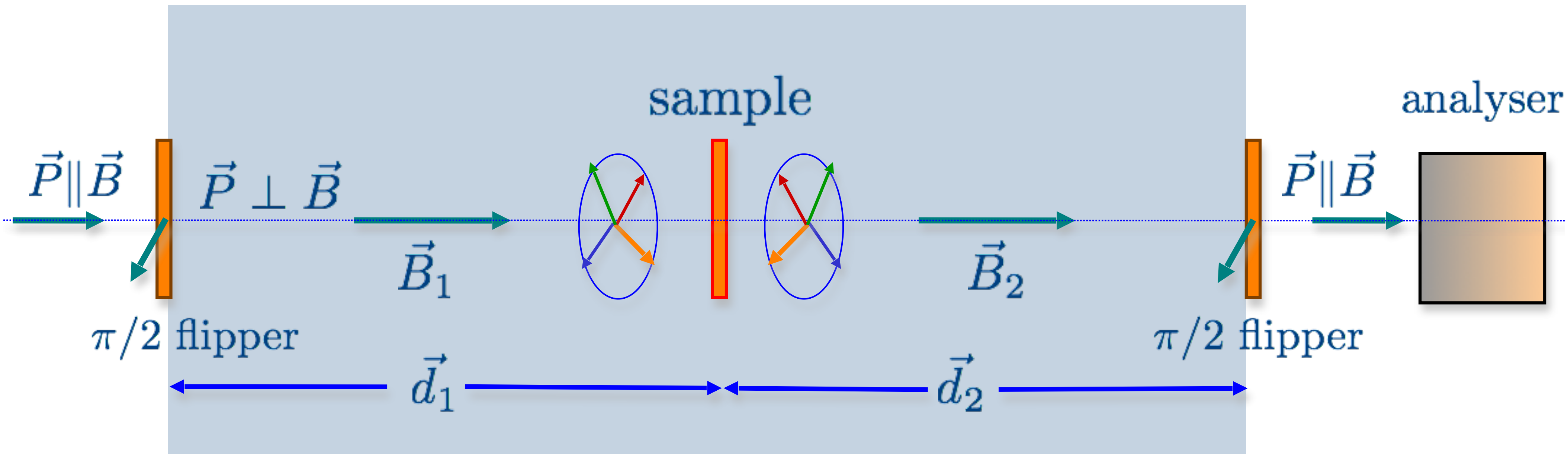
ideally

echo modulation = $(I_+ - I_-) / 2$

for $|\vec{P}| = 1$



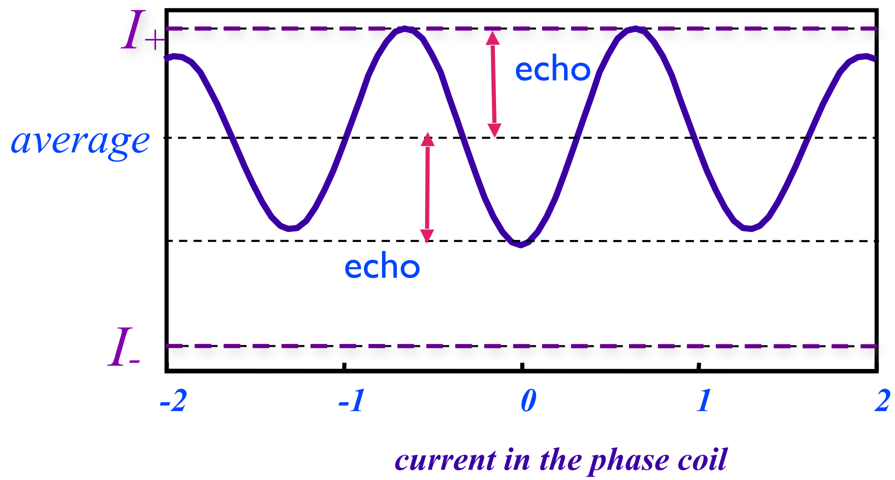
paramagnetic neutron spin echo spectroscopy



ideally

echo modulation = $(I_+ - I_-) / 3$

for $|\vec{P}| = 1$



magnetic scattering : $\vec{P}_f = -\hat{Q}\left[\hat{Q}\cdot\vec{P}_i + \zeta\,\eta\right]$

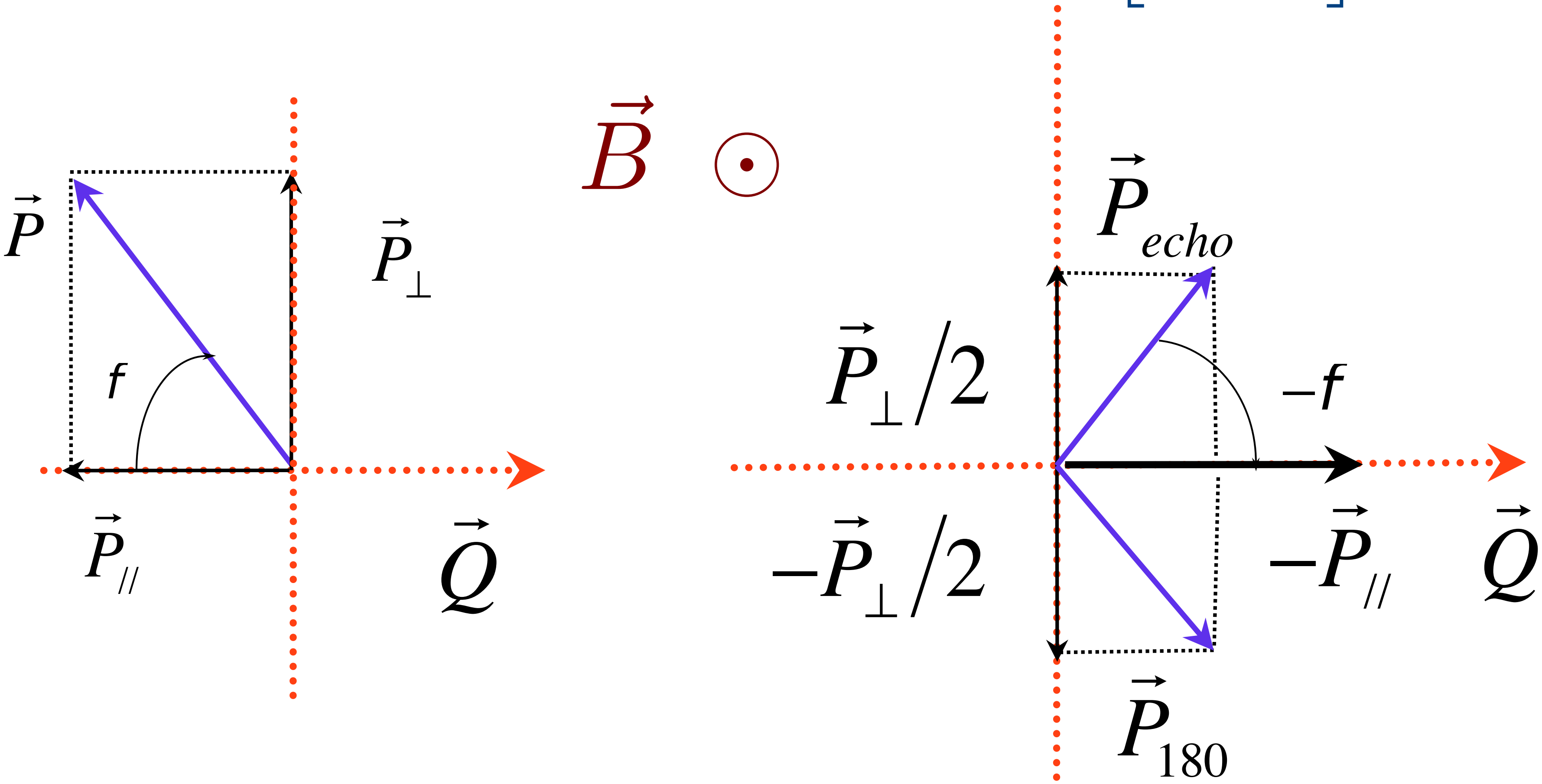
paramagnetic scattering : $\vec{P}_f = -\hat{Q}\left[\hat{Q}\cdot\vec{P}_i\right]$

$\Rightarrow \hat{Q}$ is of crucial importance

	paramagnetic scattering	chiral magnetic scattering
$\vec{P}_i \parallel \hat{Q}$		
$\vec{P}_i \perp \hat{Q}$		

magnetic scattering : $\vec{P}_f = -\hat{Q}\left[\hat{Q}\cdot\vec{P}_i + \zeta\,\eta\right]$

paramagnetic scattering : $\vec{P}_f = -\hat{Q}\left[\hat{Q}\cdot\vec{P}_i\right]$

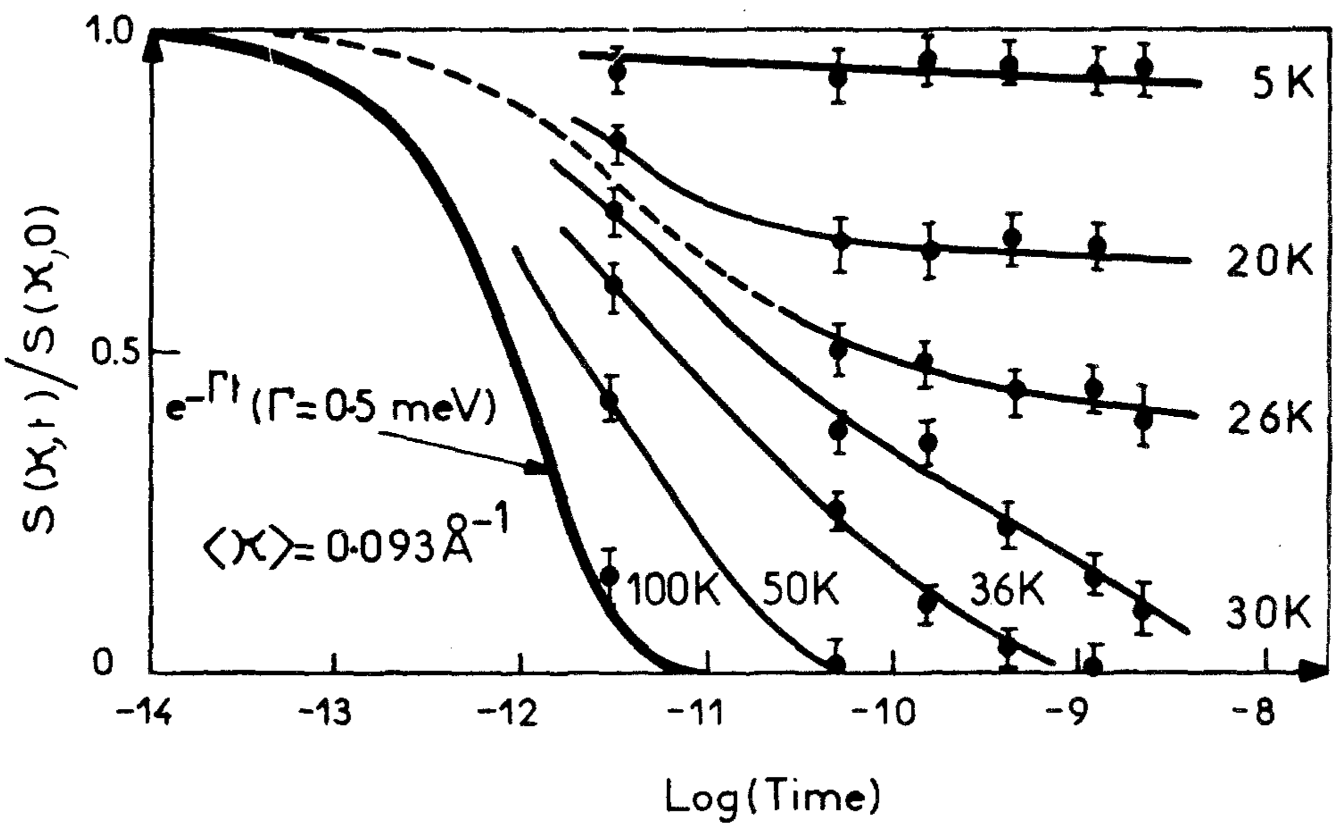


the π flipper is the sample

Murani, Mezei, 1980

first direct observation of stretched exponential relaxation in glassy systems

CuMn 5%



Murani, Mezei, 1980

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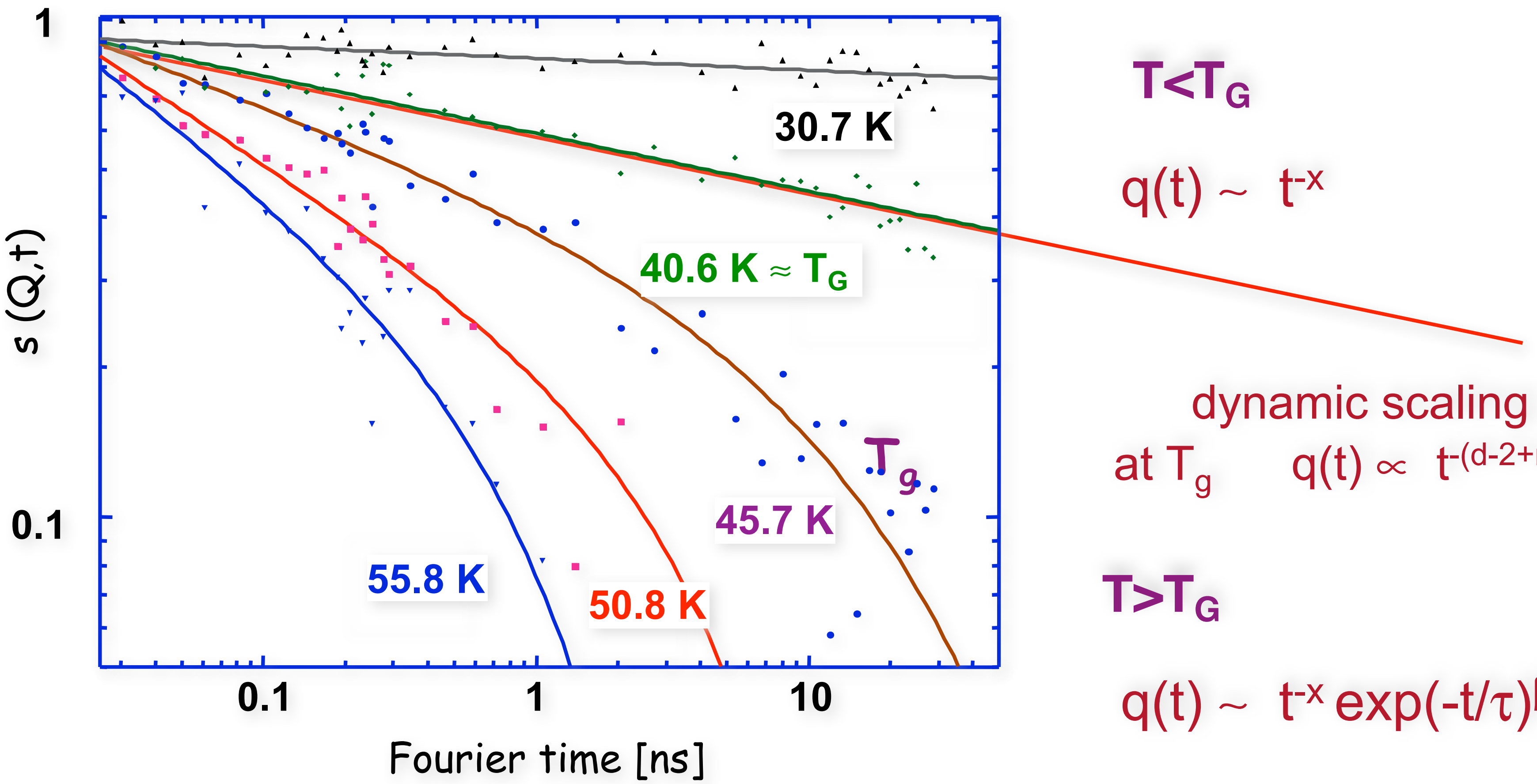
more accurate measurements on AuFe 14% show deviations from the stretched exponential



$T<T_G$

$q(t) \sim t^{-x}$

dynamic scaling

at T_g $\quad q(t) \propto t^{-(d-2+\eta)/2z}$

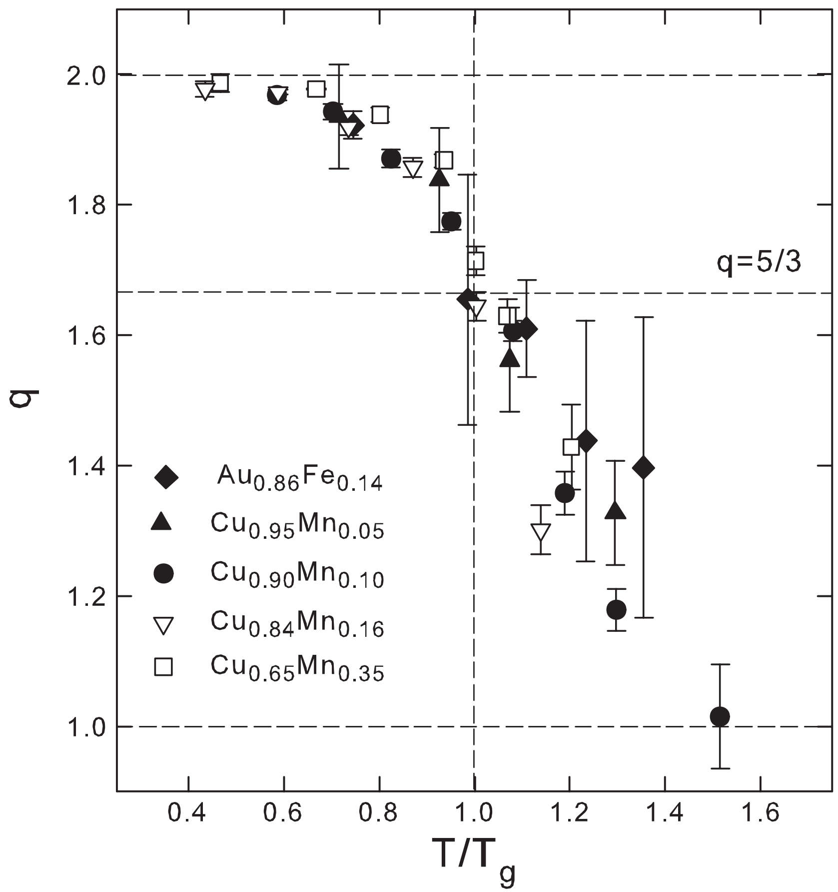
$T>T_G$

$q(t) \sim t^{-x} \exp(-t/\tau)^{\beta}$

CP et al. PRB 2003, R. Pickup et al. PRL 2009

all relaxation functions of spin glasses follow the same universal function

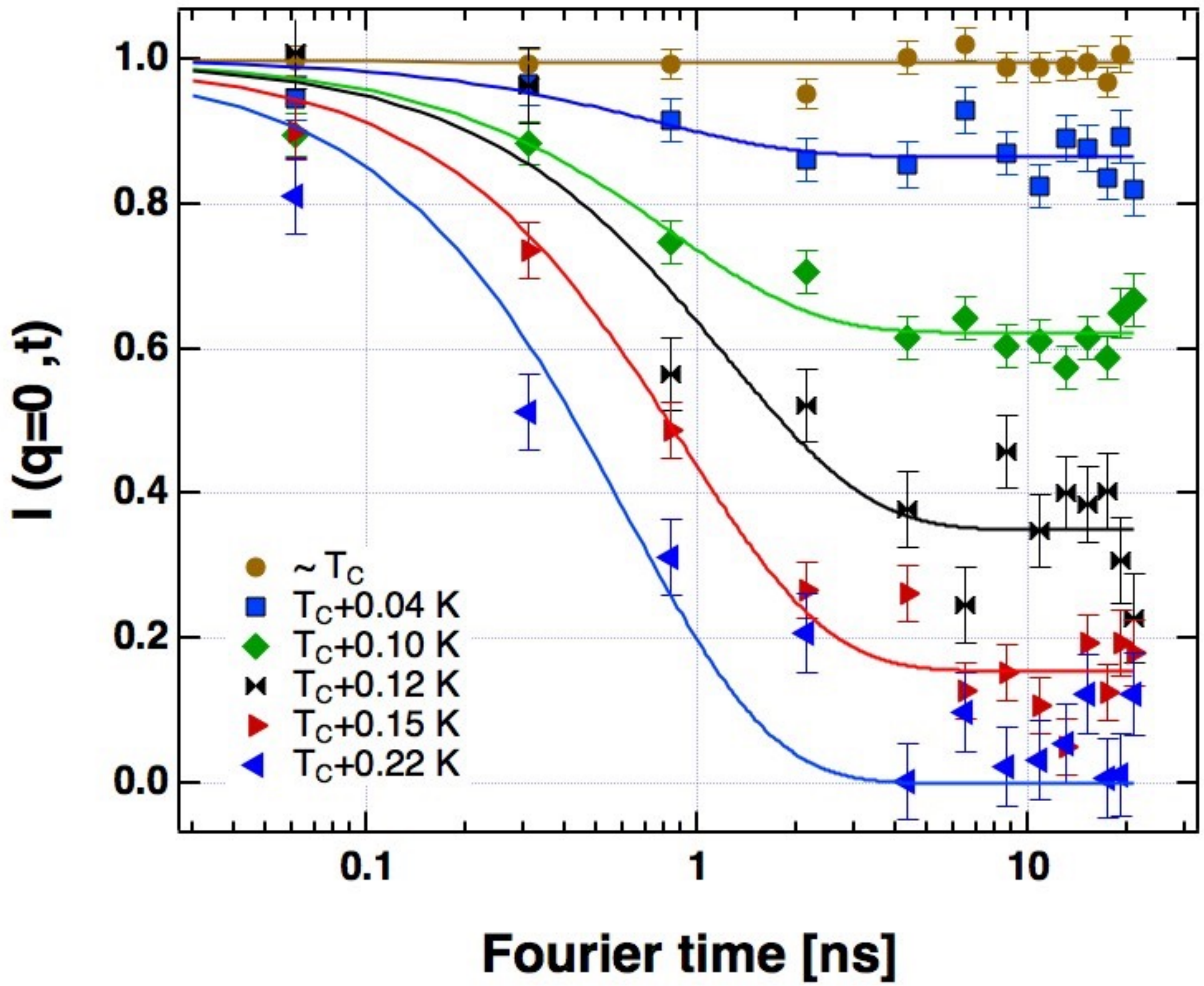
$$I(Q,t) = \left[1 + \left(\frac{q-1}{2-q}\right)\left(\frac{t}{\tau}\right)\right]^{(2-q)/(q-1)}$$

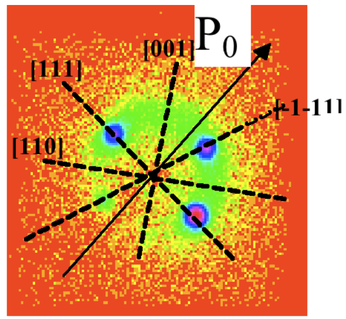


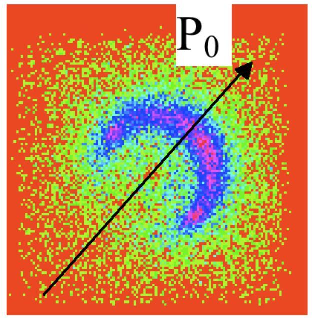
non extensive entropy breakdown of Boltzmann statistics at T_G

=> power low relaxation below T_G

Paramagnetic NSE also works for chiral scattering
the case of MnSi







after Grigoriev et al
PRB 2004

CP et al. PRL 2009, PRB 2011

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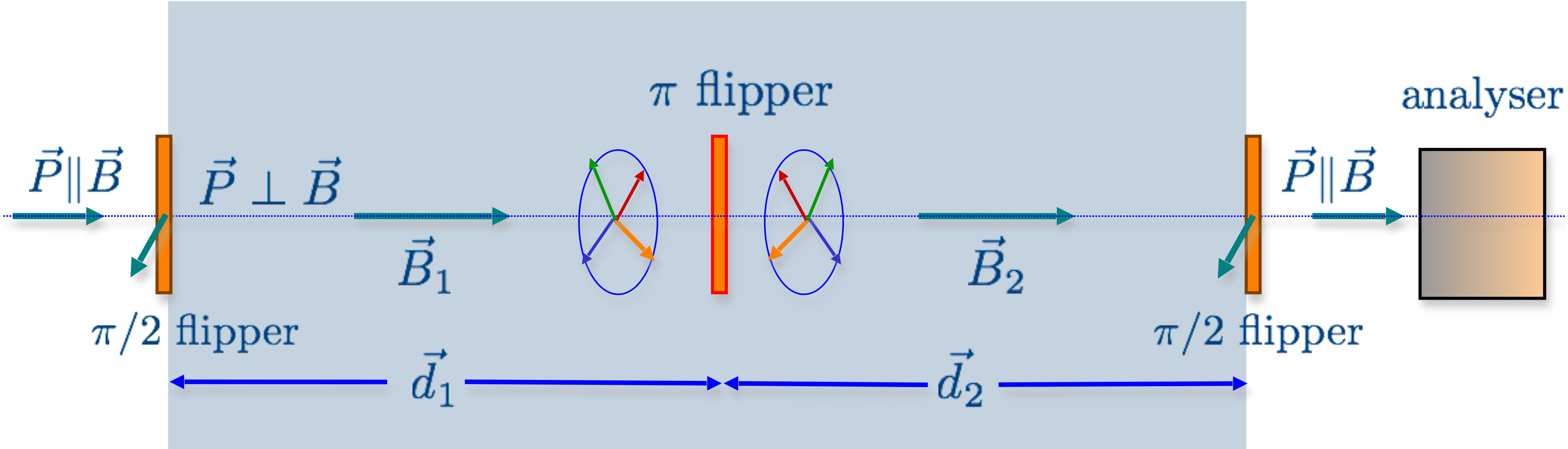
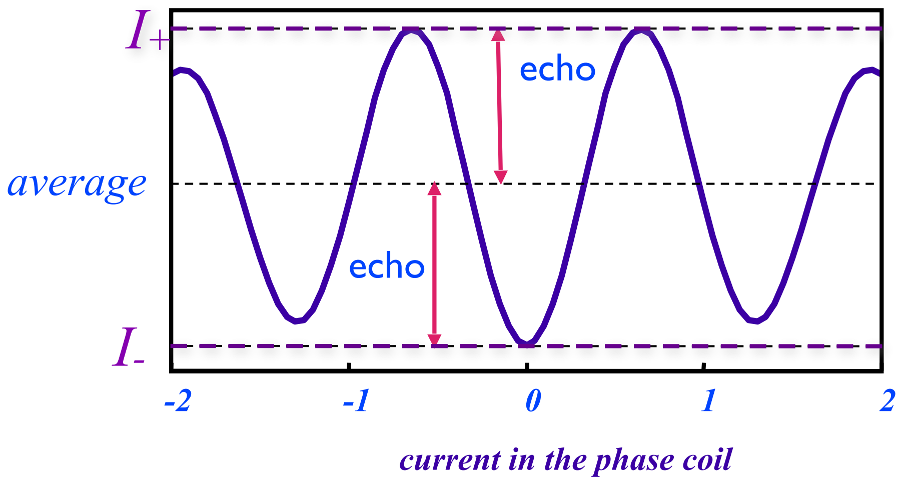
neutron spin echo spectroscopy



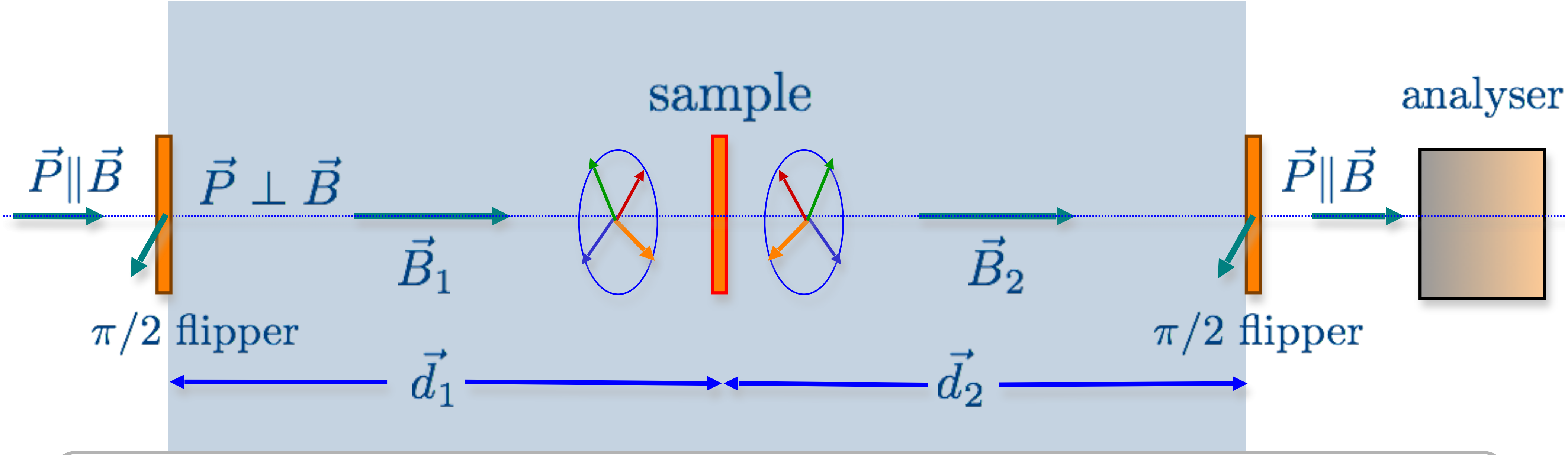
ideally

echo modulation = $(I_+ - I_-)/2$

for $|\vec{P}| = 1$



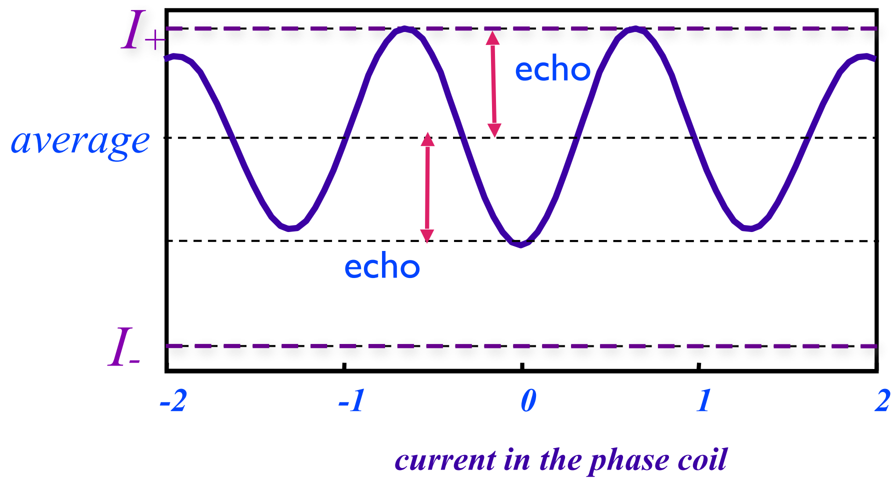
paramagnetic neutron spin echo spectroscopy



ideally

echo modulation = $(I_+ - I_-) / 3$

for $|\vec{P}| = 1$



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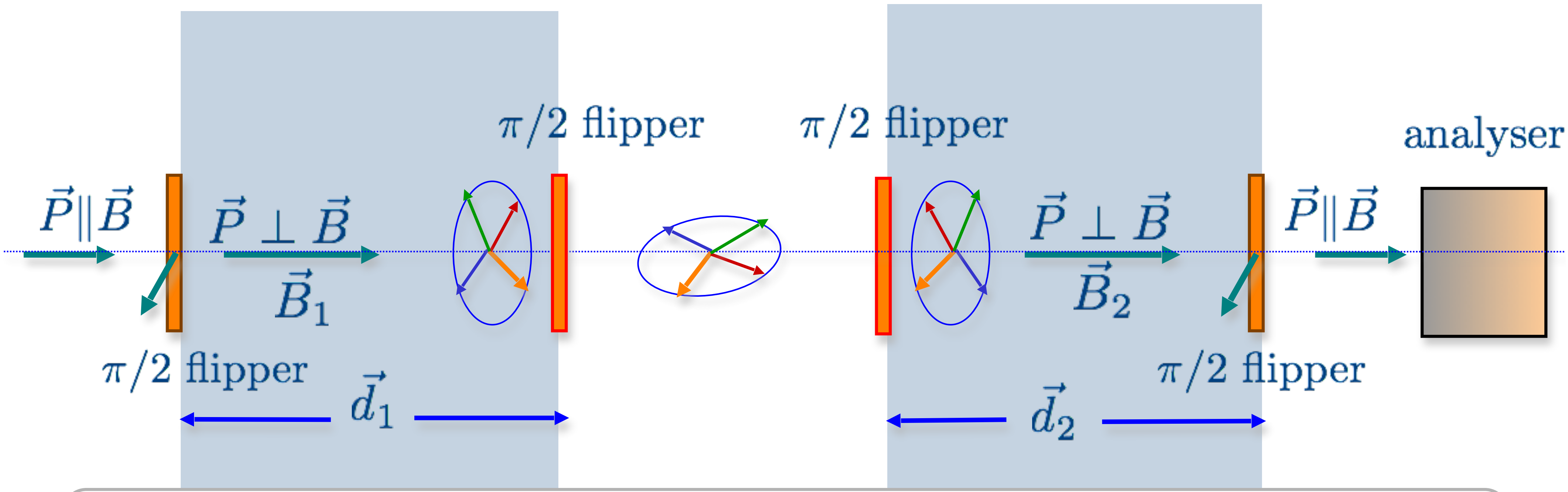
ferromagnetic neutron spin echo



ideally

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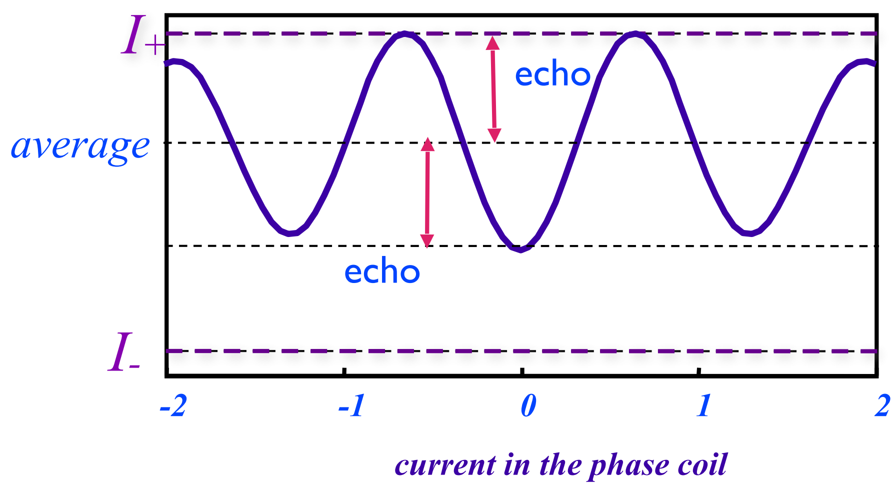
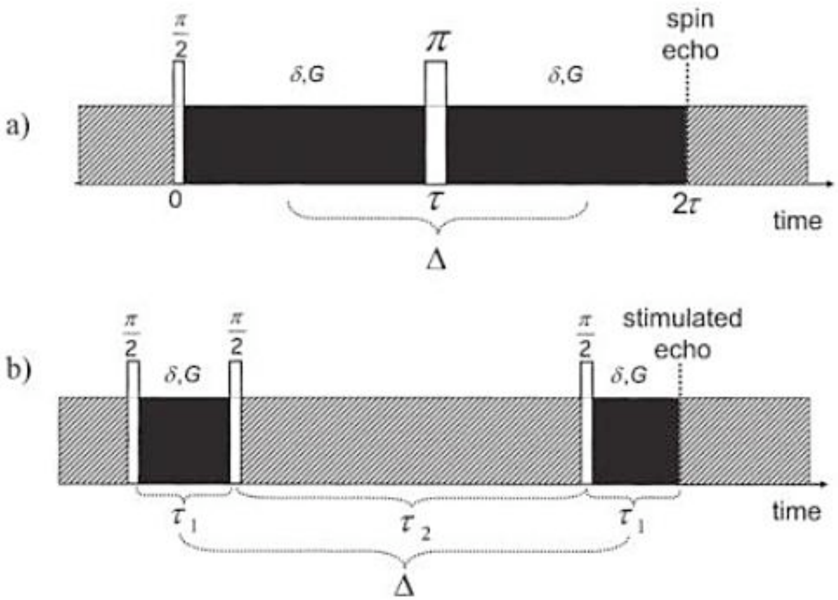
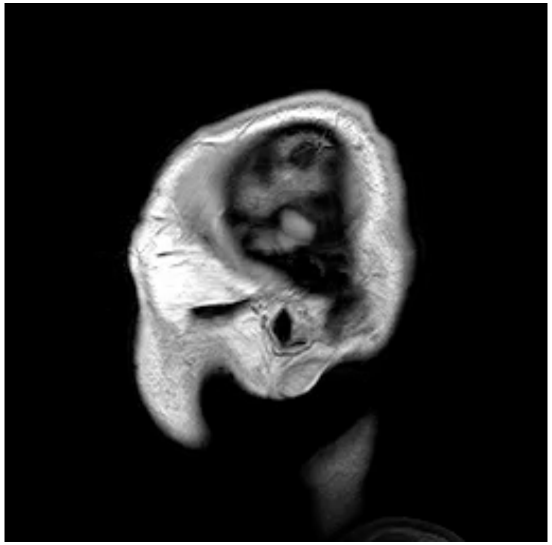


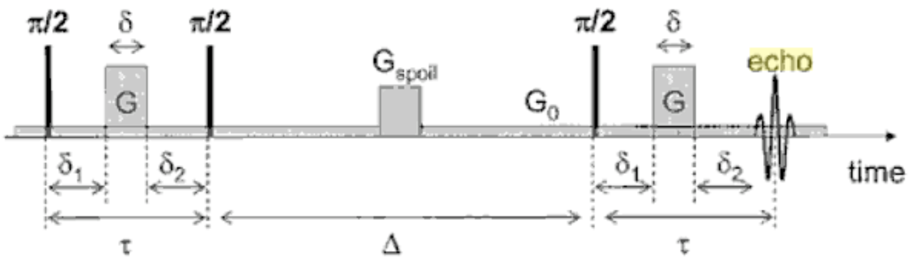
NMR spin echos

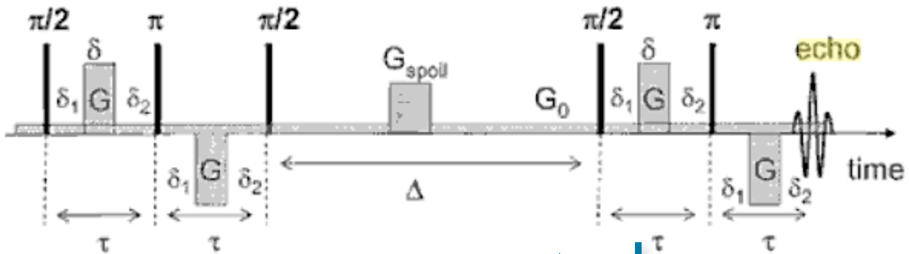


after Ardelean and Kimmich



pulsed field stimulated spin echo





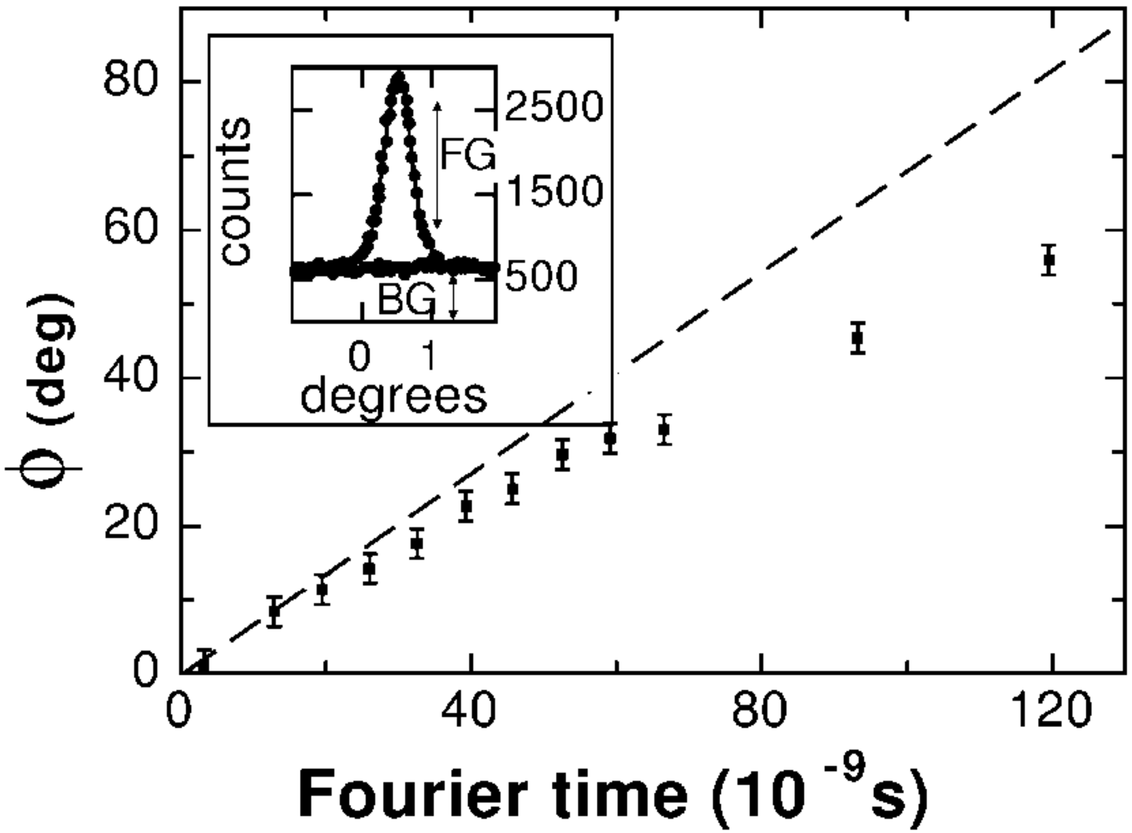
compensated
pulsed field stimulated spin echo

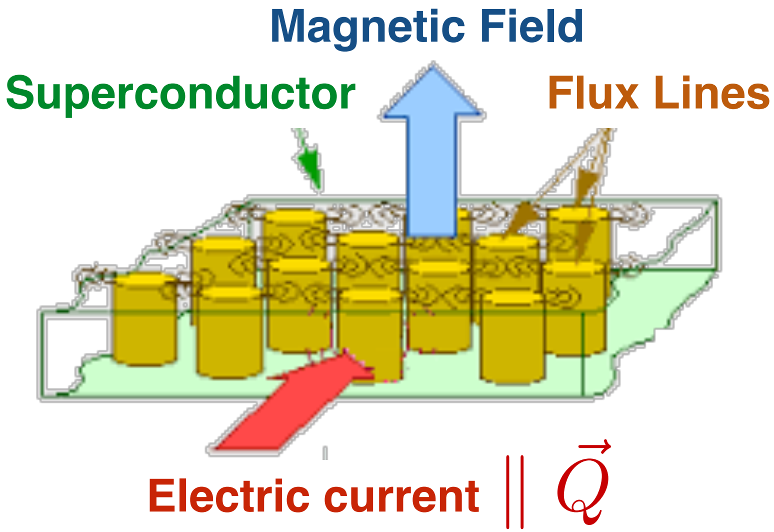
Measurement of Vortex Motion in the Type-II Nb-Ta Superconductor

energy change of neutrons after diffraction by a moving Flux Line Lattice :

$$\omega = \hbar \ \vec{Q} \cdot \vec{v}_L \qquad , \phi = \omega \ t/\hbar \quad \Rightarrow \quad \phi = \vec{Q} \cdot \vec{v}_L t$$

Phase of the NSE group measured at 2.2 K, 0.3 T and 20 Å





E.M. Forgan et al. PRL 2000

TU Delft

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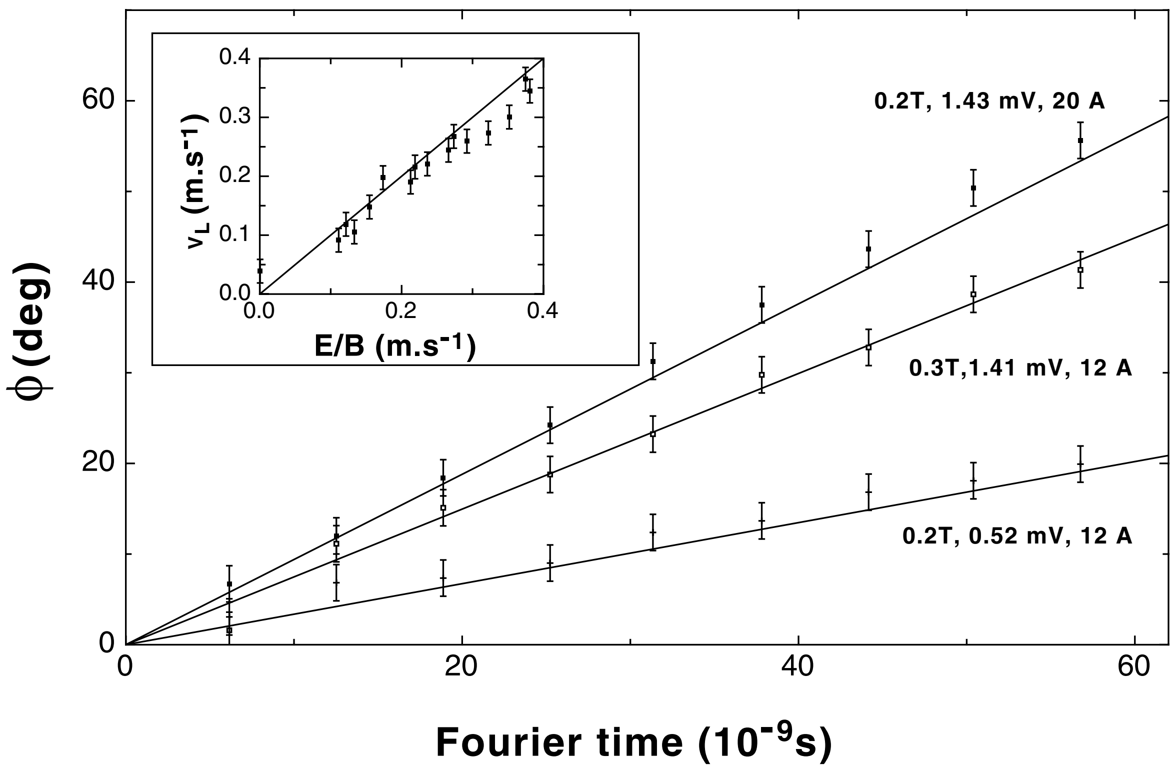
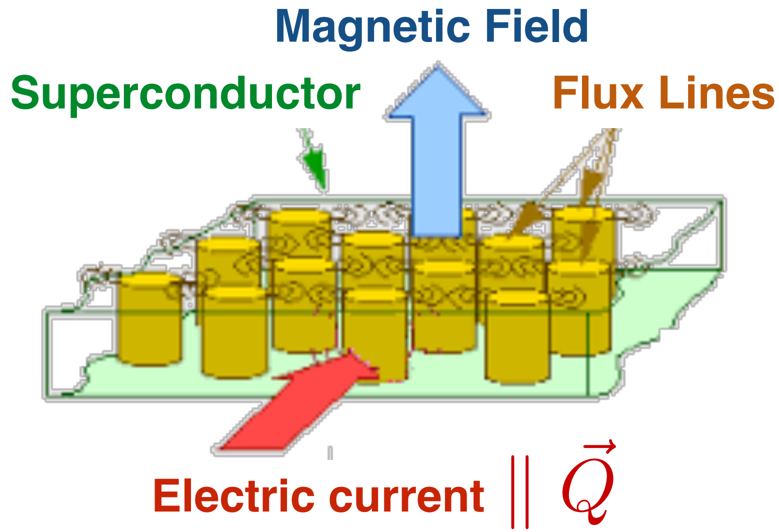
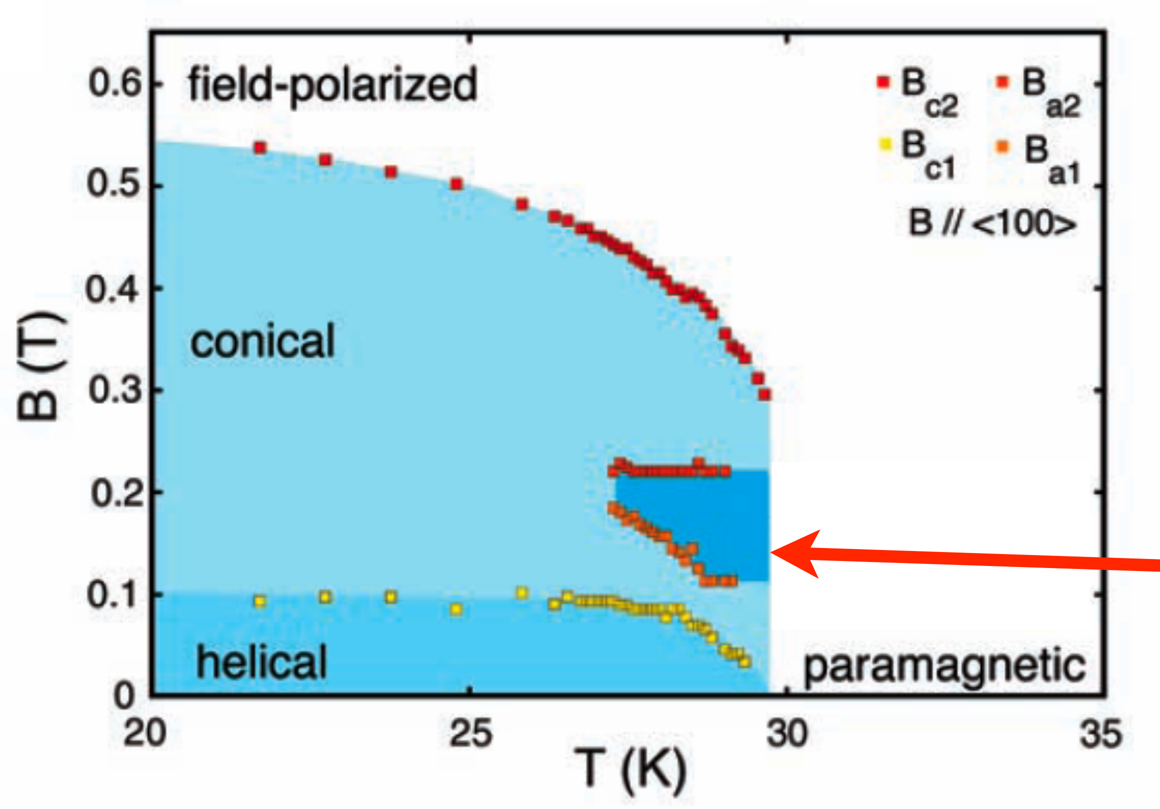
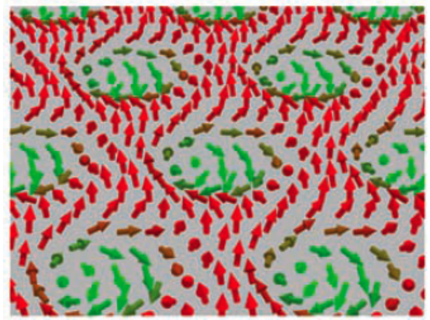


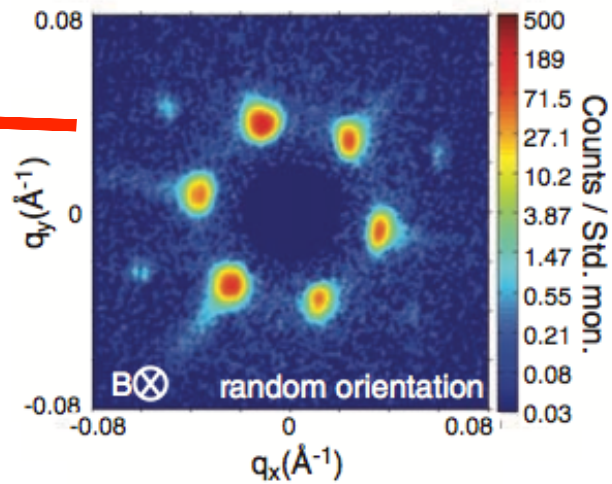


E.M. Forgan et al. PRL 2000

…. and again the case of MnSi







S. Mühlbauer et al., Science 2009

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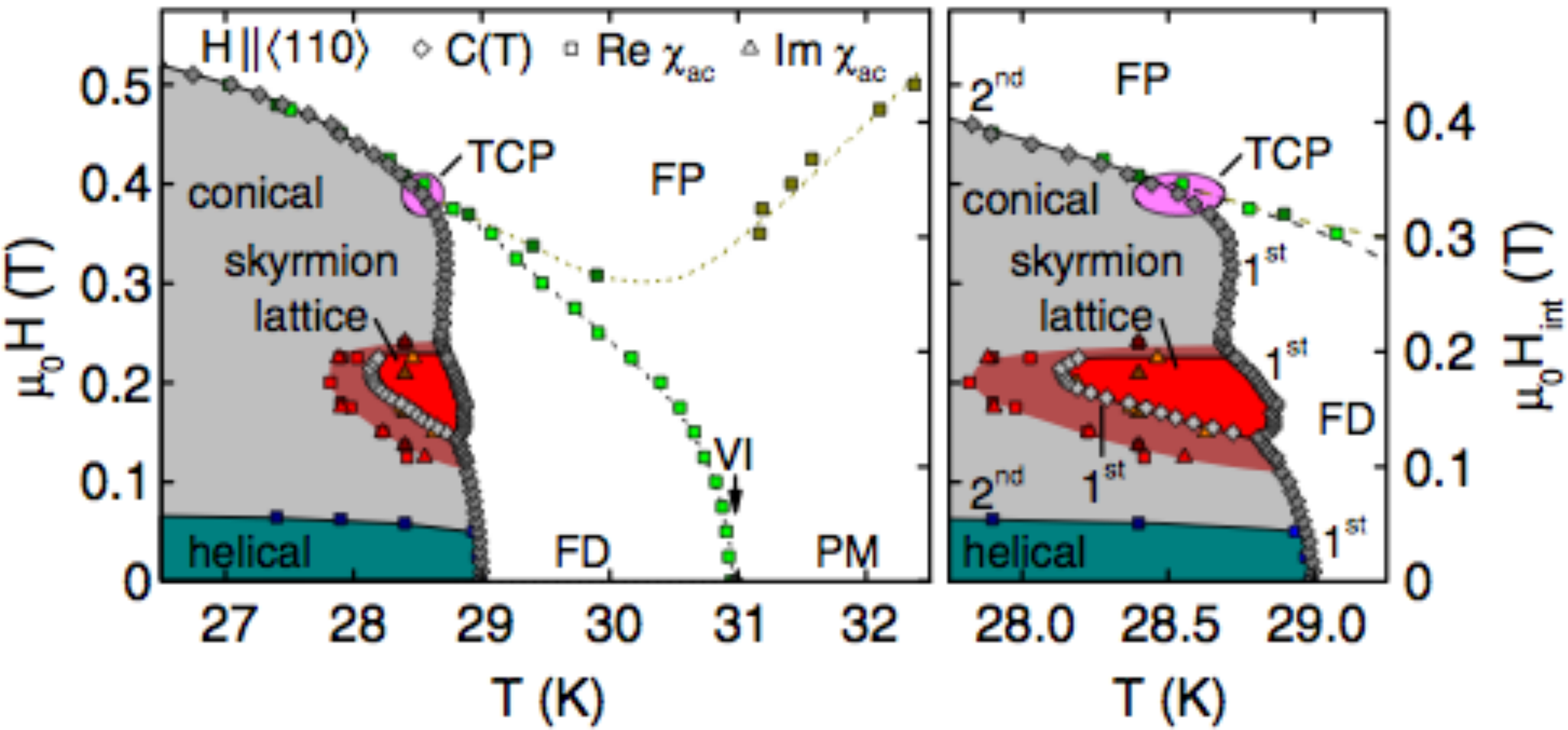
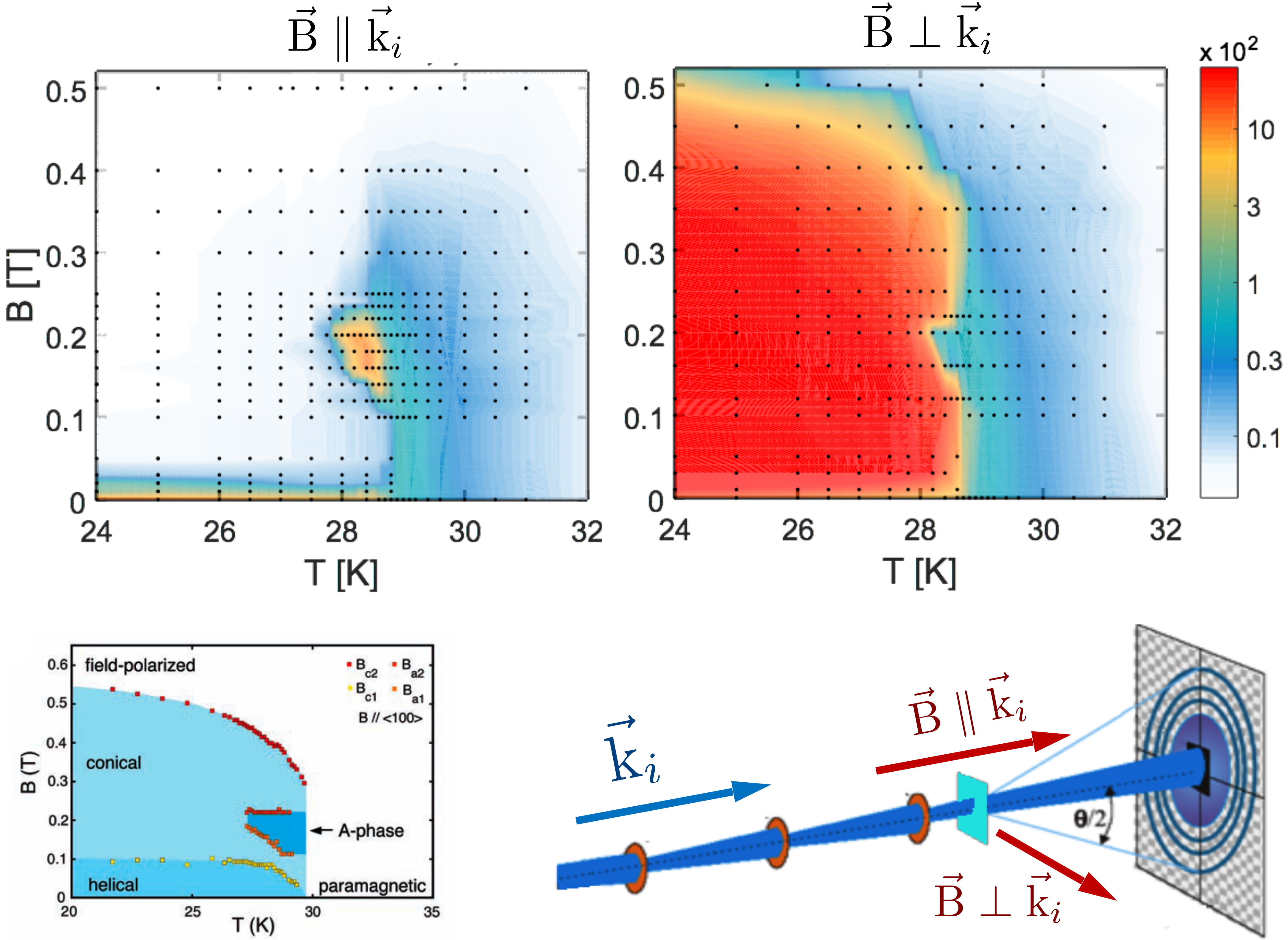
Phase diagram of MnSi
Hierarchy of energies – Bak and Jensen

existence of a TCP ? What are the implications ?



A. Bauer et al. PRL 110 (2013)

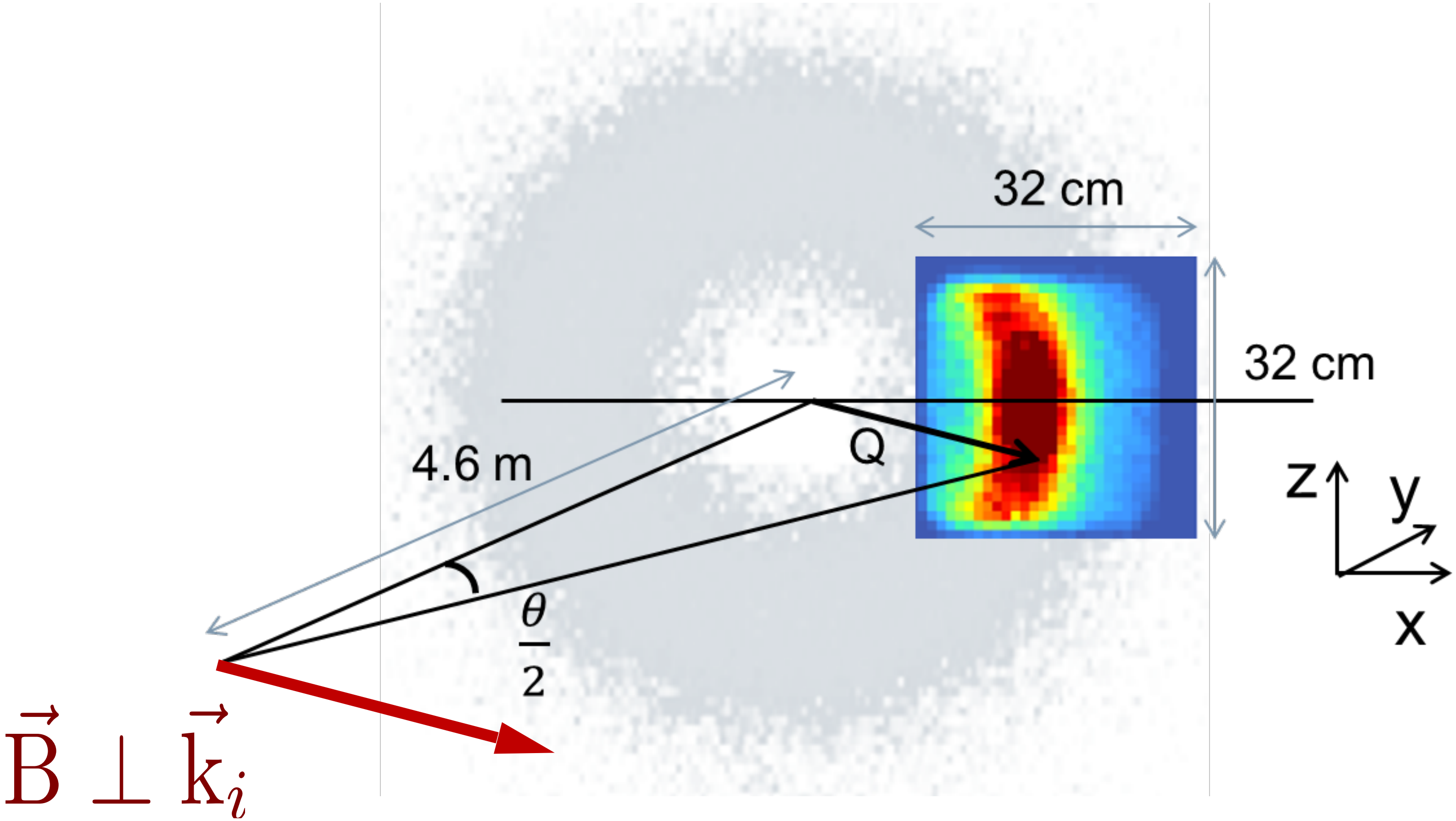


$\vec{B} \parallel \vec{k}_i$
$\vec{B} \perp \vec{k}_i$
B [T]
T [K]
x 10^2
10
3
1
0.3
0.1
field-polarized
conical
helical
A-phase
paramagnetic
B_{c2}
B_{a2}
B_{c1}
B_{a1}
B // <100>
B (T)
T (K)
$\vec{k}_i$
$\theta/2$

Evolution of fluctuations

Seen by with ferromagnetic NSE on IN15

$$I(Q,t) = \frac{C}{(Q - 2\pi/\ell)^2 + 1/\xi^2} \quad e^{[-t/\tau_0]} = S(Q) \;\; e^{[-t/\tau_0]}$$



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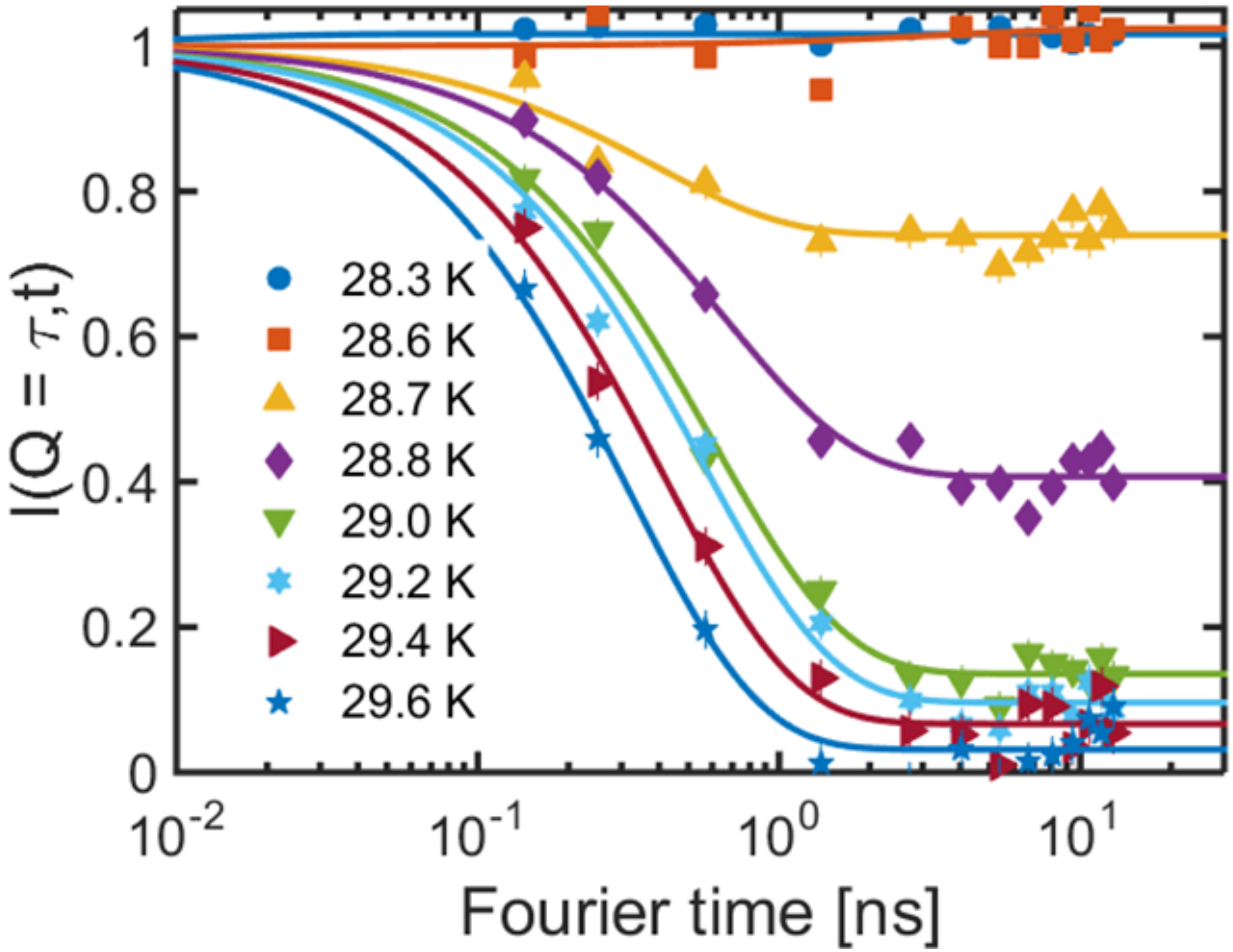
RELAXATION DOES NOT CHANGE WITH FIELD !

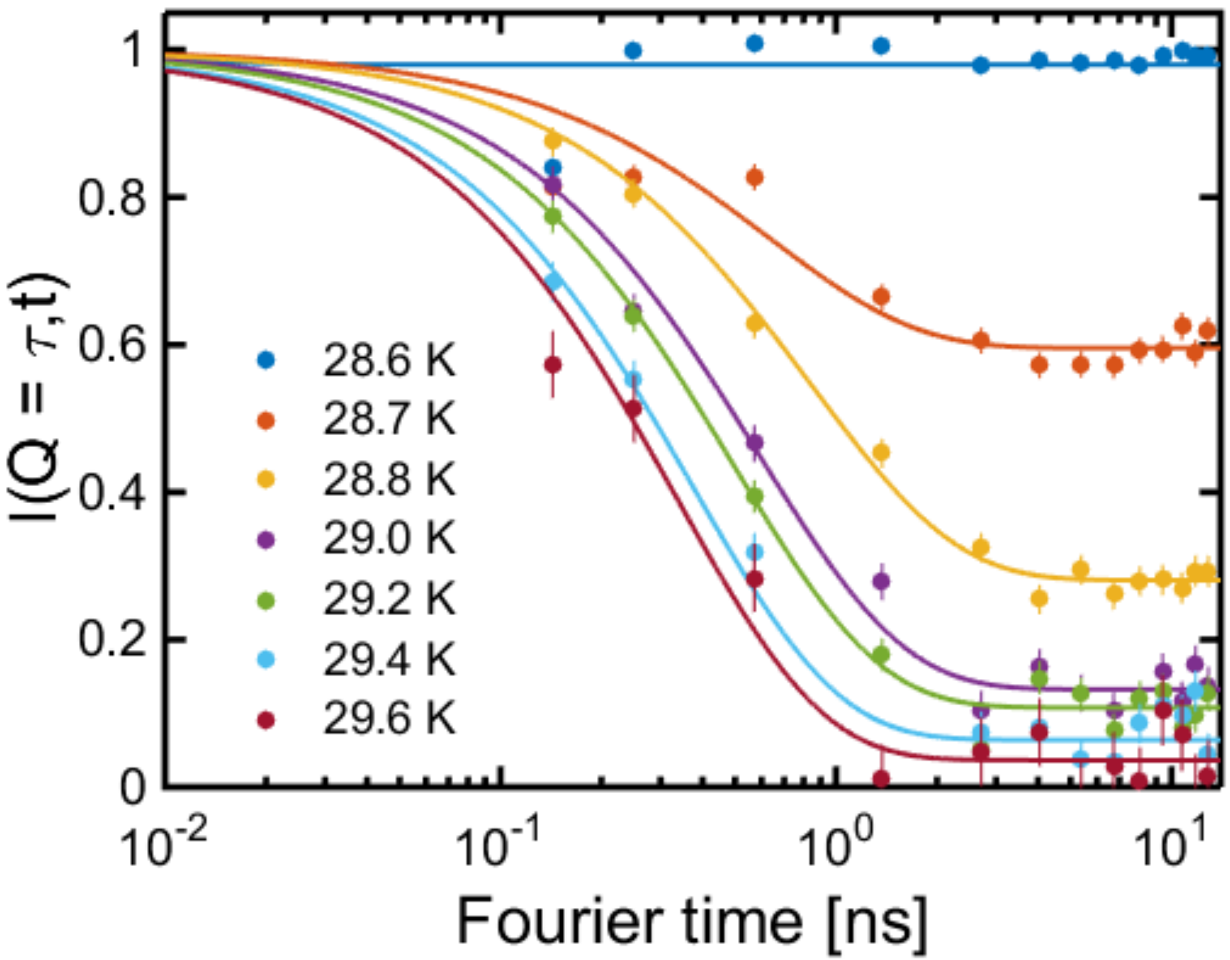


B = 0.16 T

CP et al, PRL in print

TU Delft

RELAXATION DOES NOT CHANGE WITH FIELD !

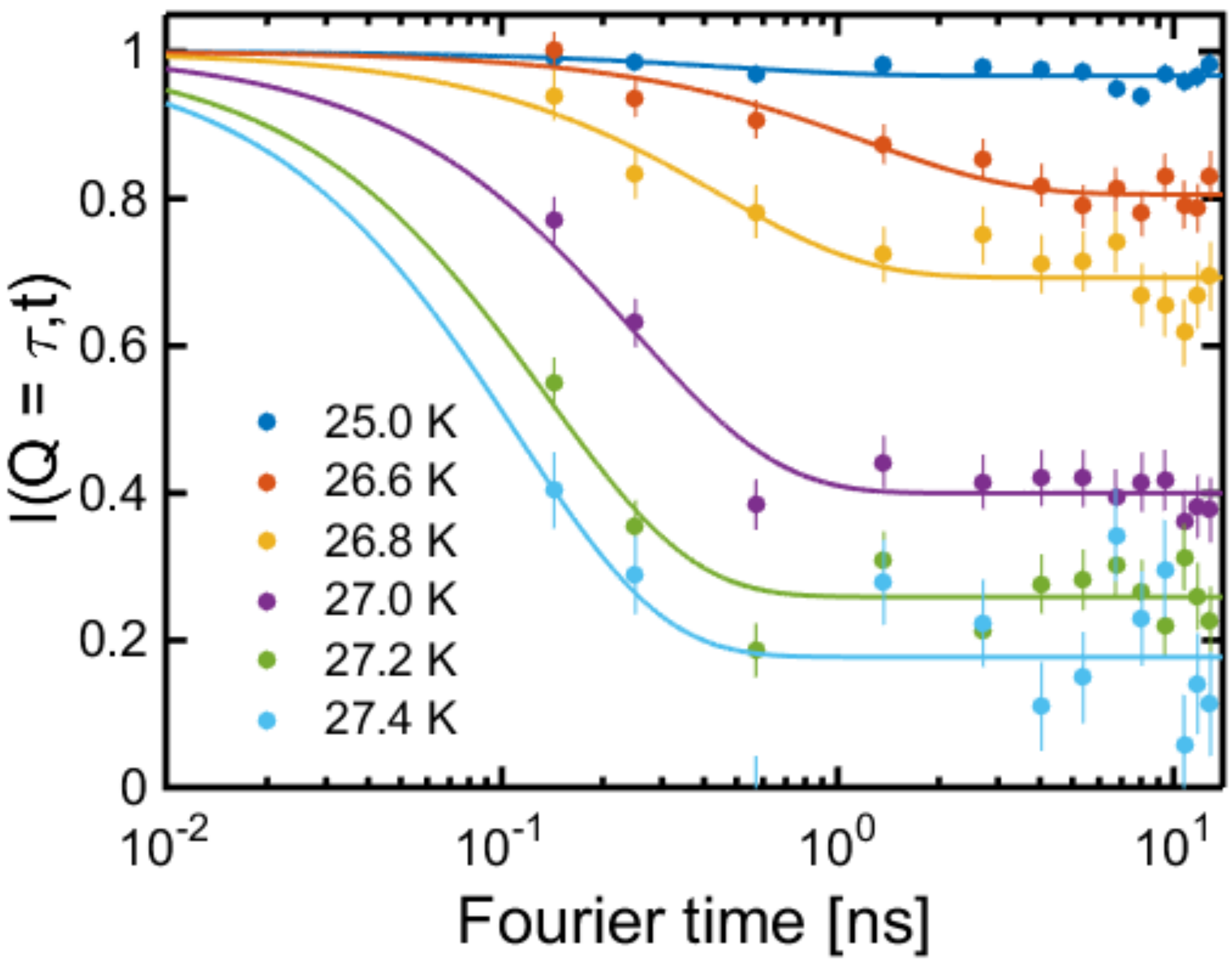


B = 0.24 T

CP et al, PRL in print

TU Delft

RELAXATION DOES NOT CHANGE WITH FIELD !

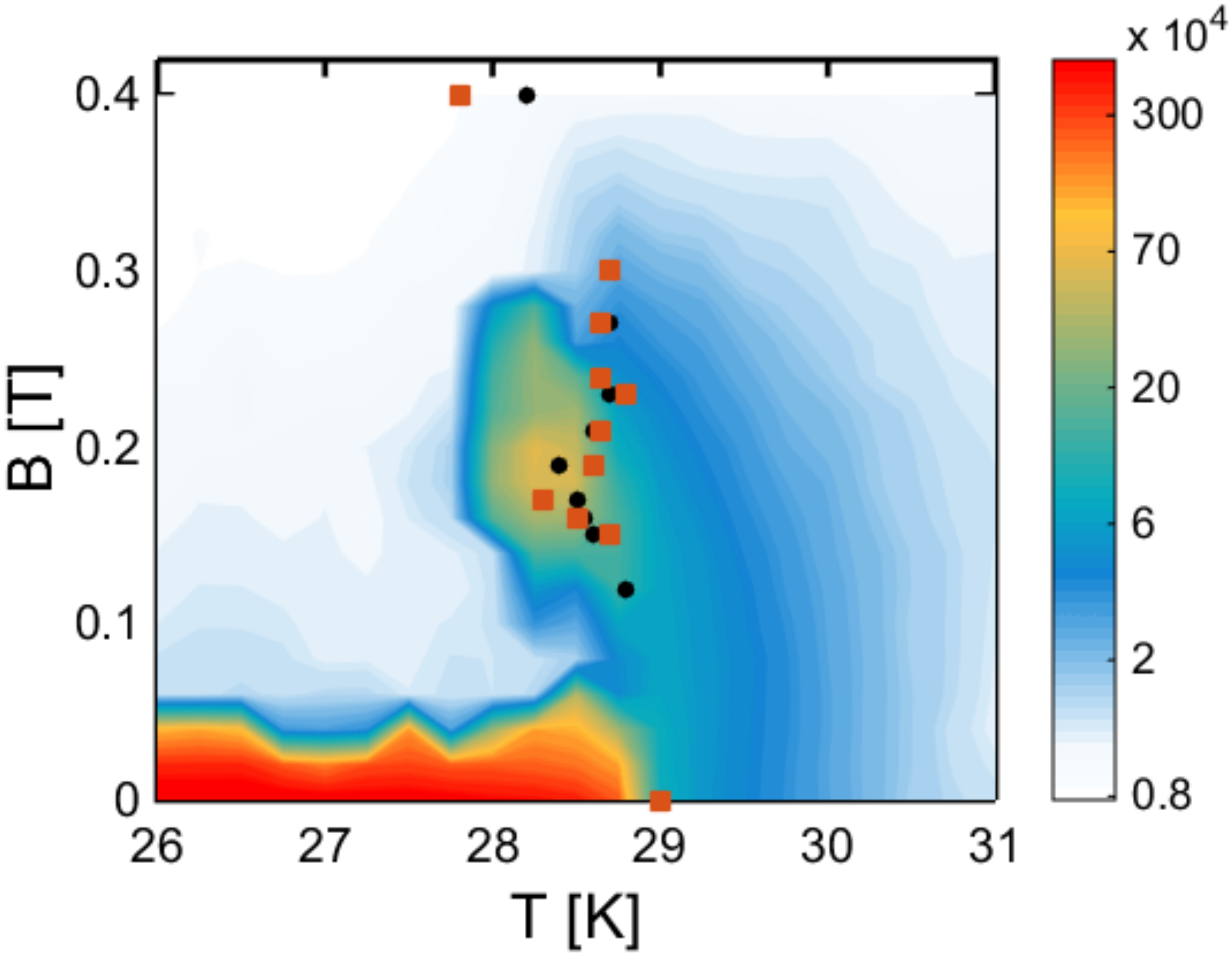


EXCEPT
for

$B = 0.5$ T

CP et al, PRL in print

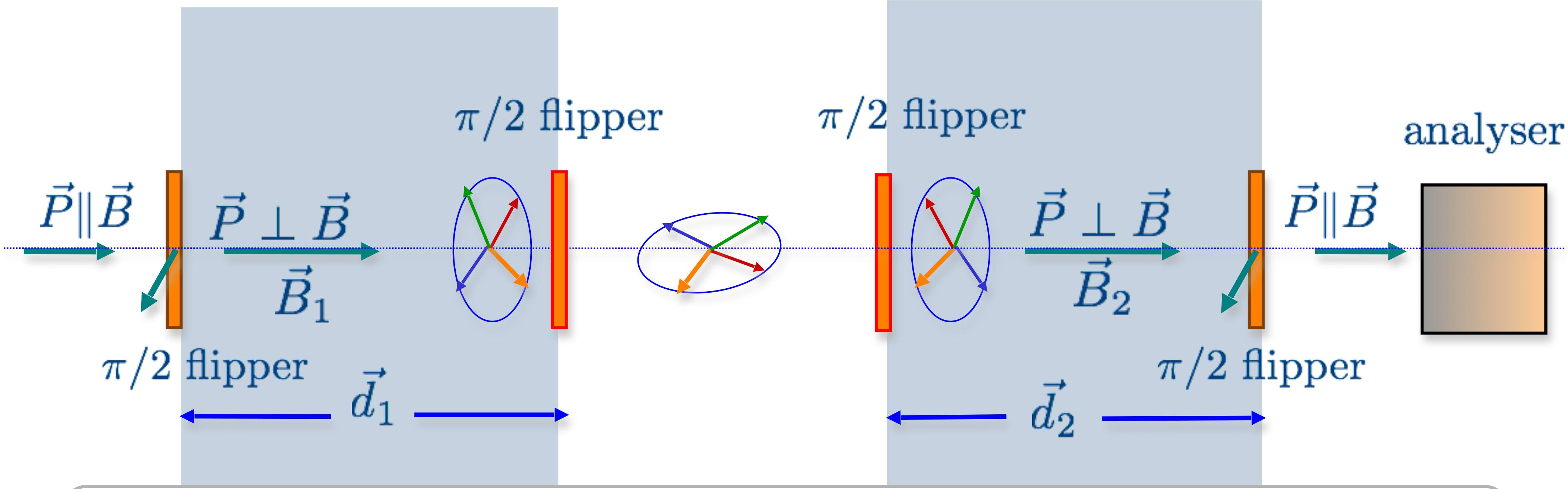
Fluctuations co-exist with the SKL phase



CP et al, PRL in print

- Magnetic scattering
- Paramagnetic NSE
- Ferromagnetic NSE: magnetic fields
- Intensity modulated NSE: for samples depolarising the neutron beam: ferromagnets, superconductors
- Polarimetric NSE: chirality

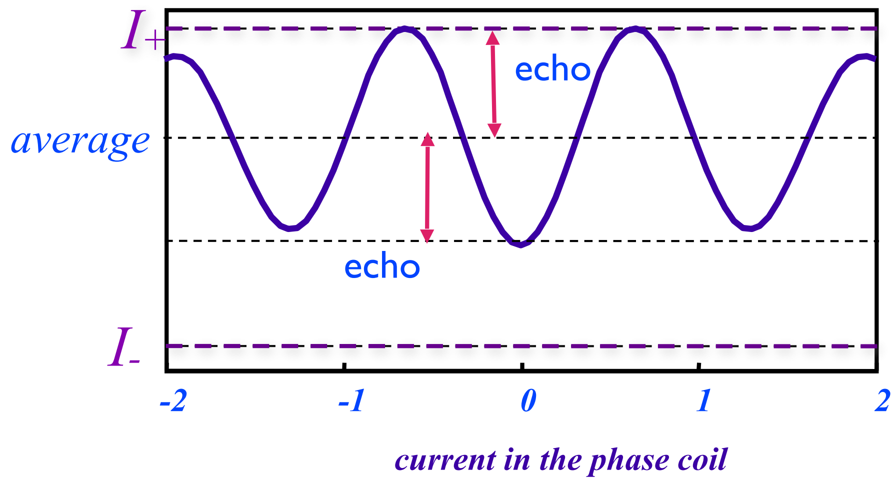
ferromagnetic neutron spin echo



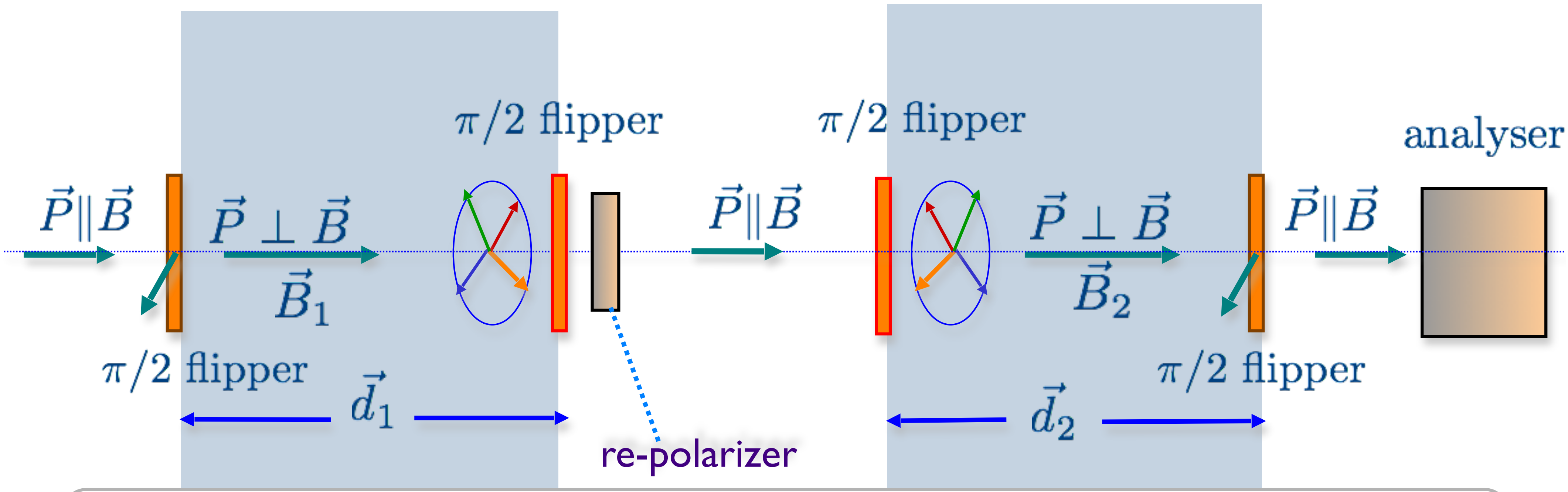
ideally

echo modulation = $(I_+ - I_-) / 3$

for $|\vec{P}| = 1$



intensity modulated neutron spin echo



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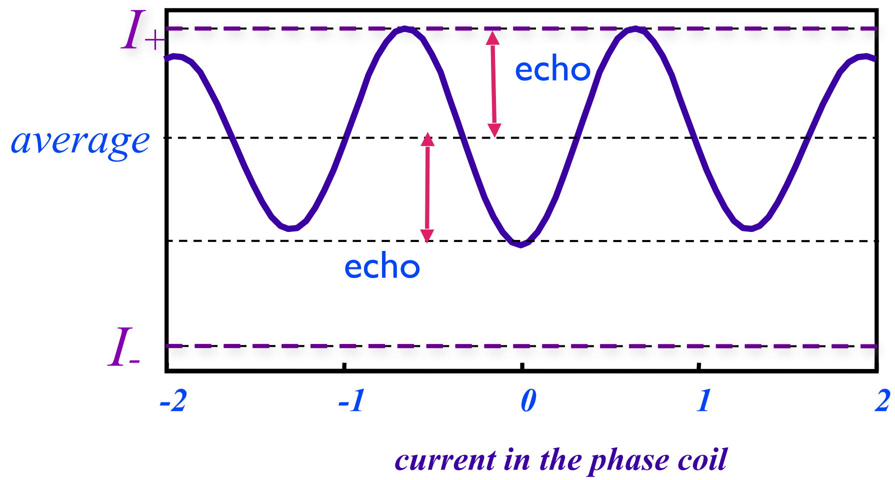
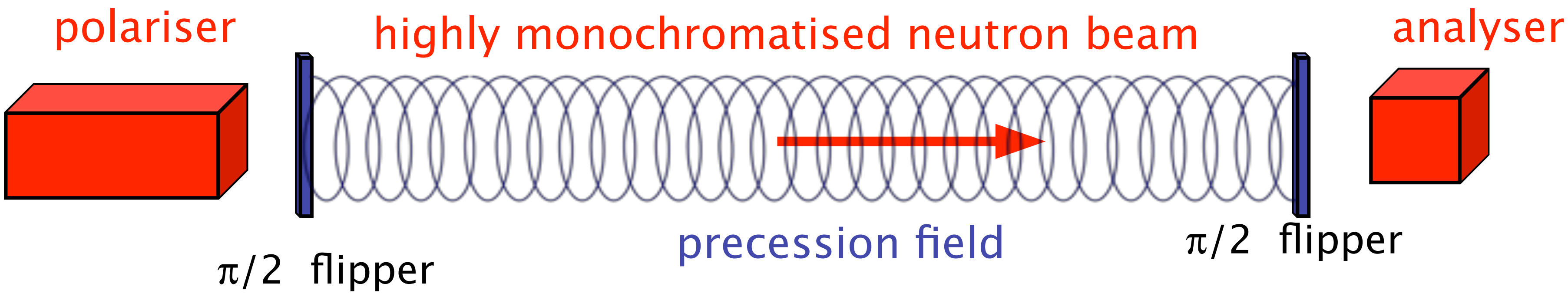
factor of 2 intensity loss



IMNSE - polarimetric NSE

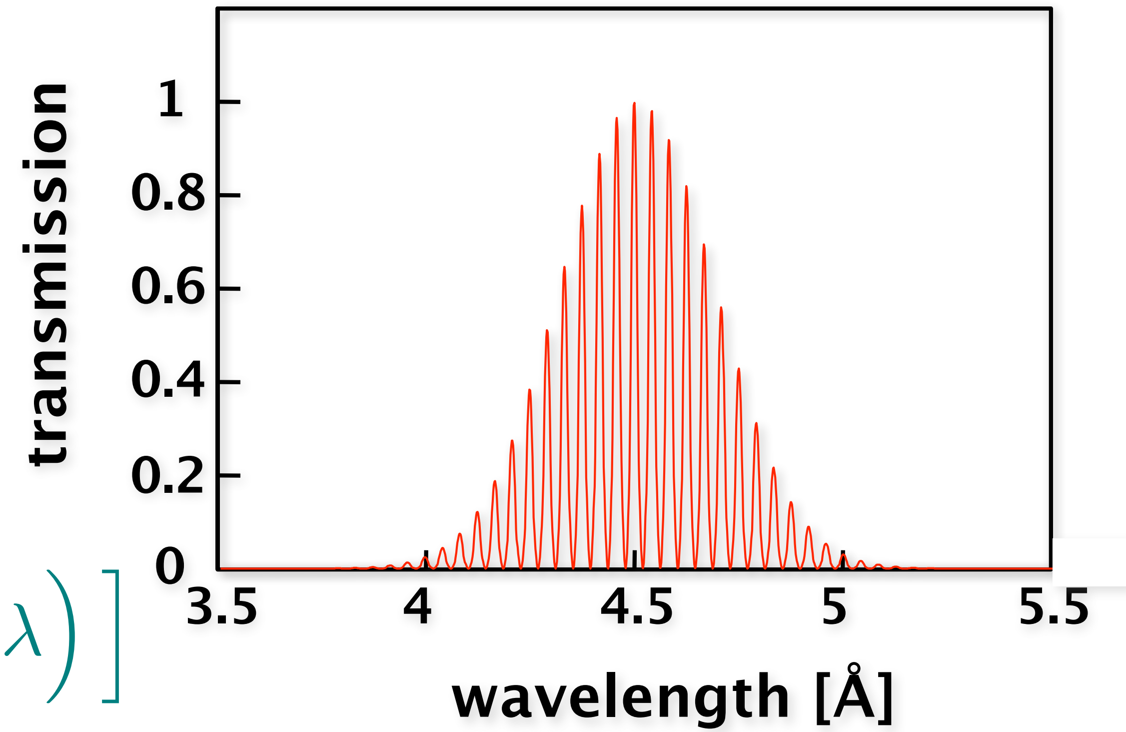
transmission of the sequence



$$\phi = \gamma\, B\, t_{tof} = \gamma\, B\, \ell / \mathrm{v}$$

$$= \frac{\gamma\, m}{h} B\, \ell\, \lambda$$

$$T(B, \lambda) = \left[1 + sin\left(\frac{\gamma\, m}{h} B\, \ell\, \lambda\right)\right]$$

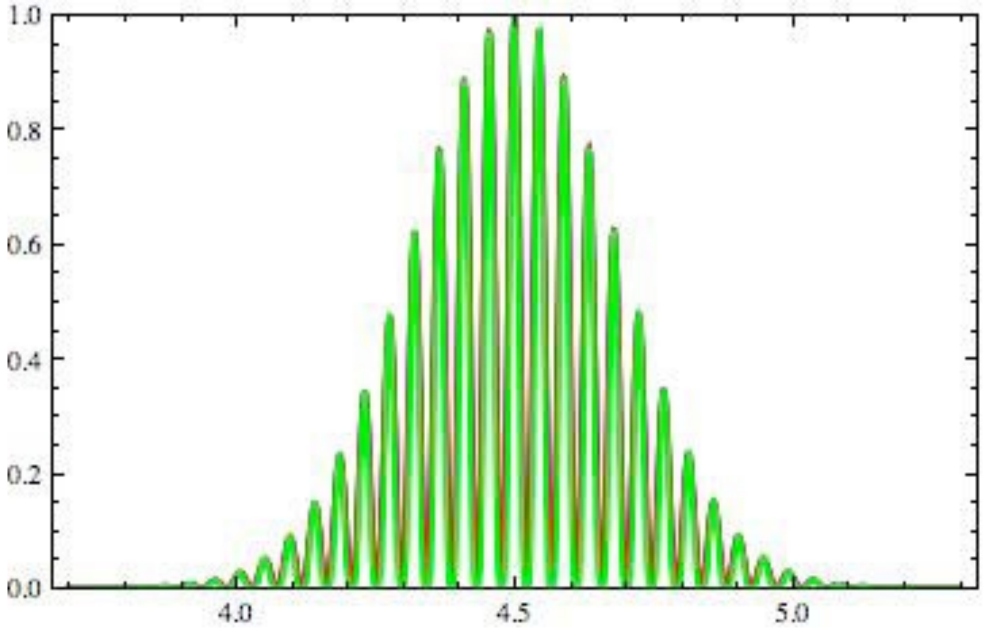


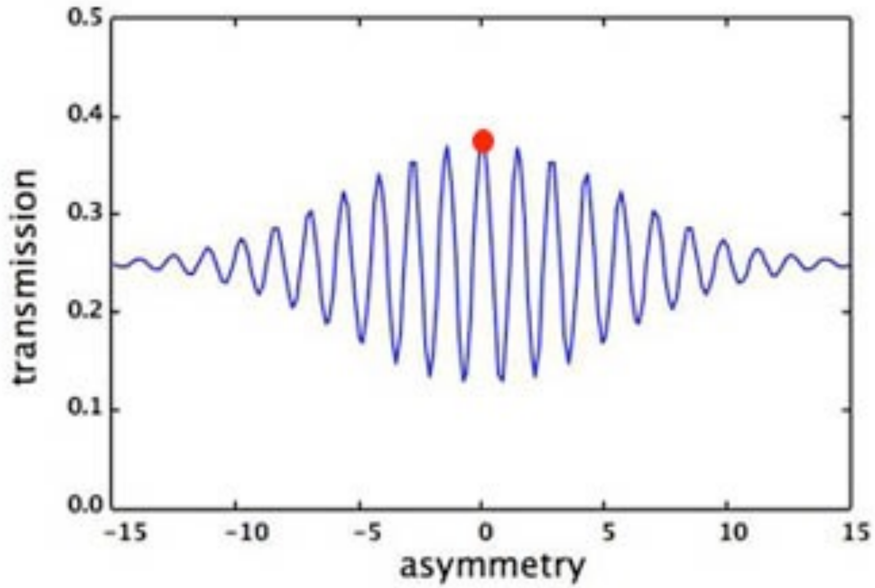
IMNSE - polarimetric NSE

transmission of the setup

$$\frac{I_{IMNSE}(\Delta I)}{I_0} = \int T_1(I+\Delta I,\lambda)\cdot T_2(I,\lambda)\cdot g(\lambda)\,d\lambda$$

$$g(\lambda) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right)$$





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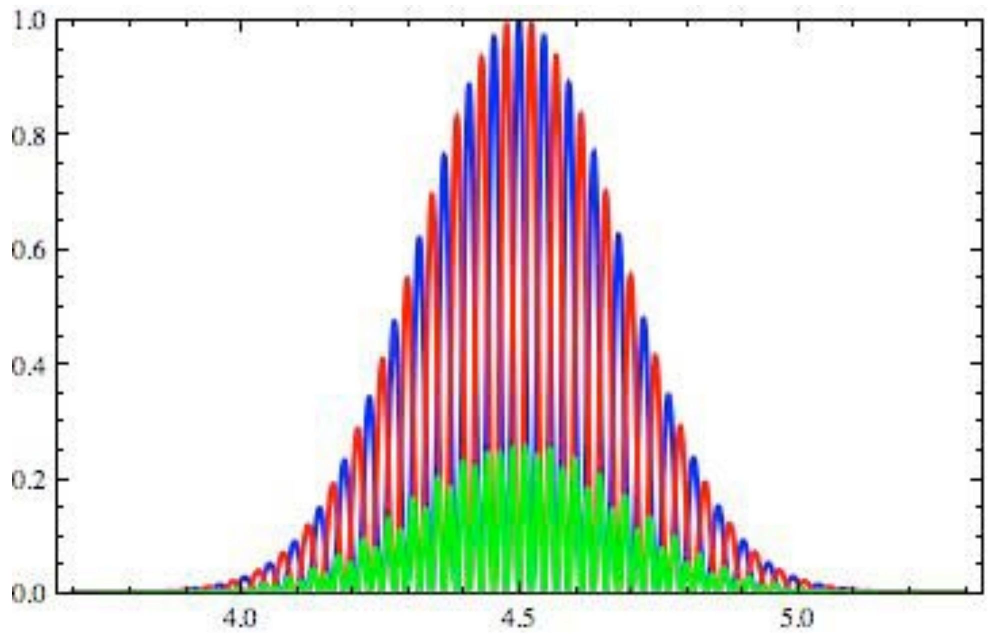

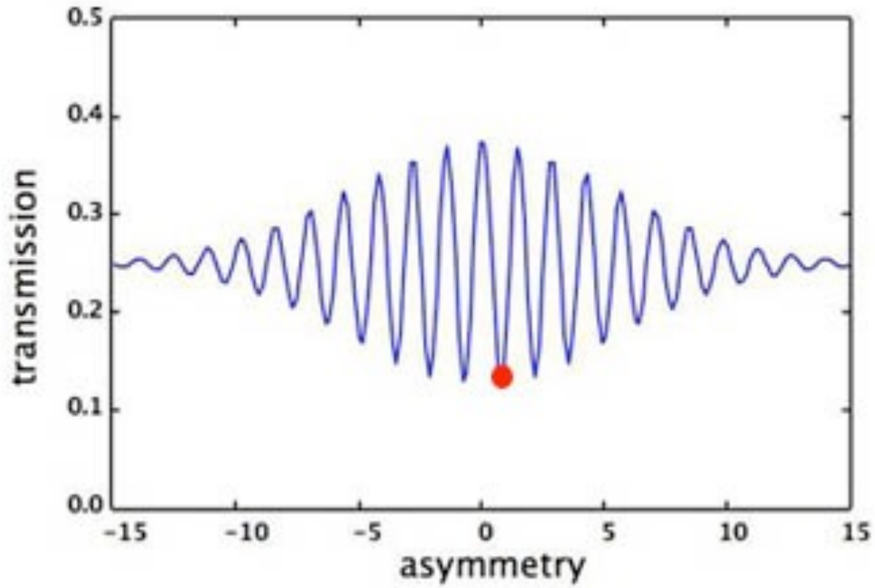

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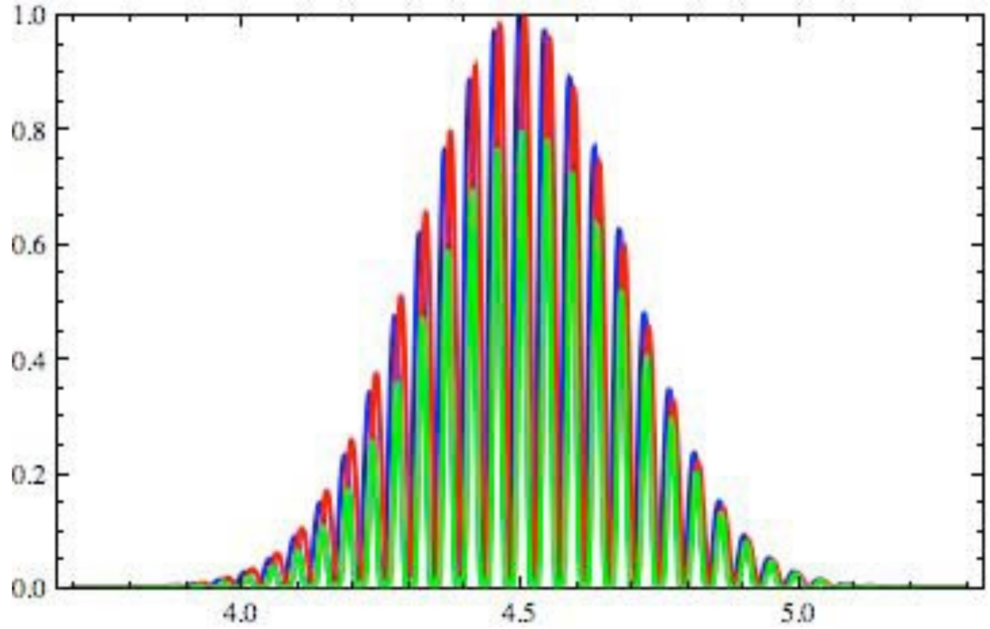

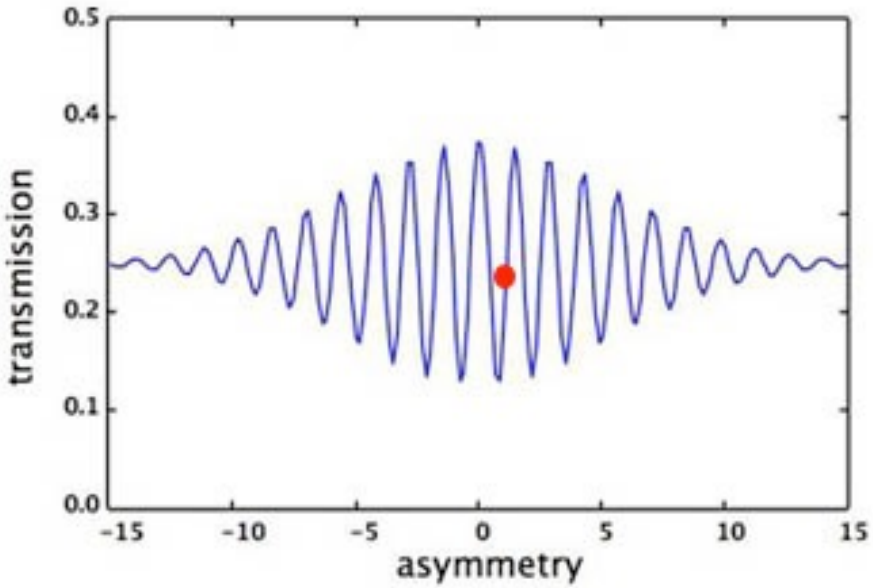

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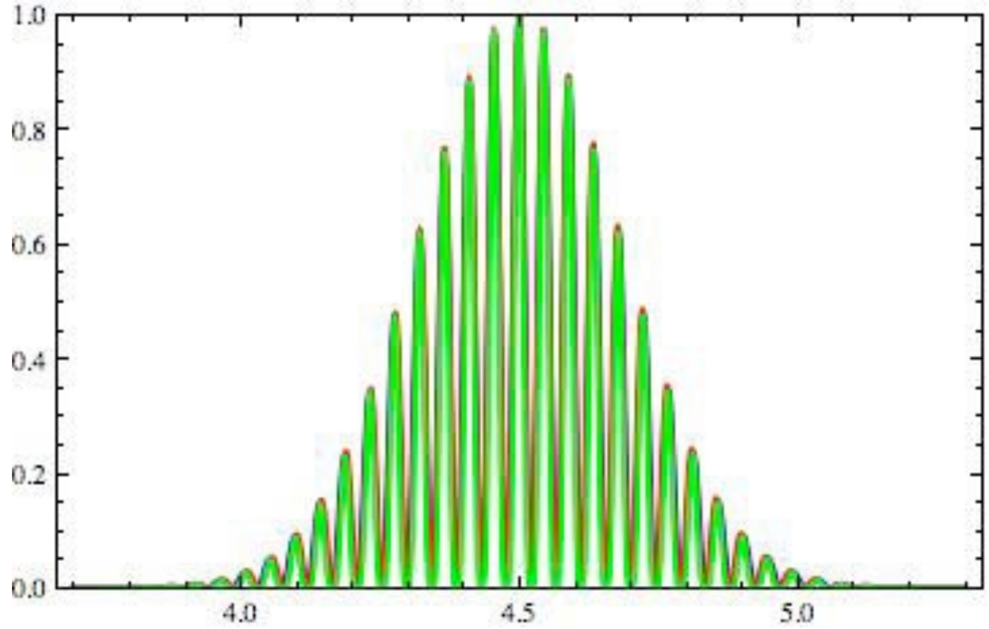

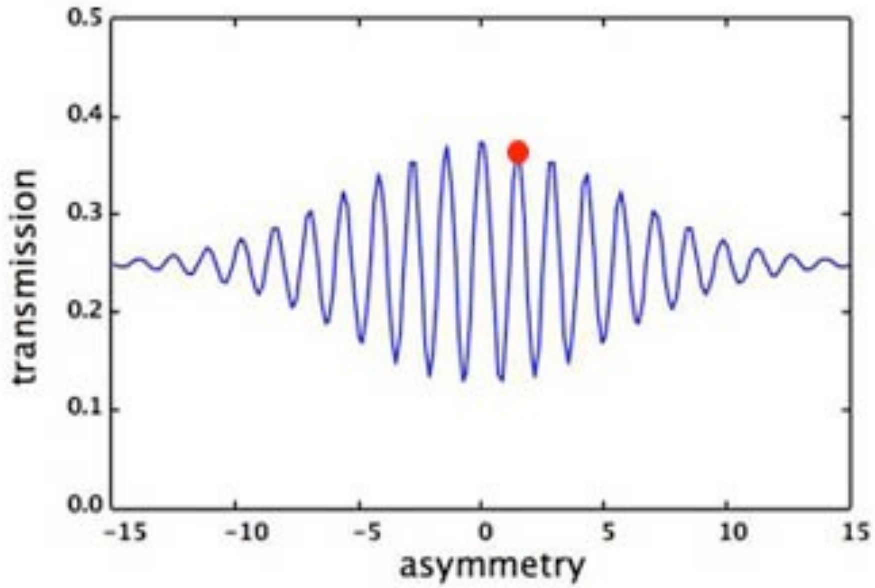

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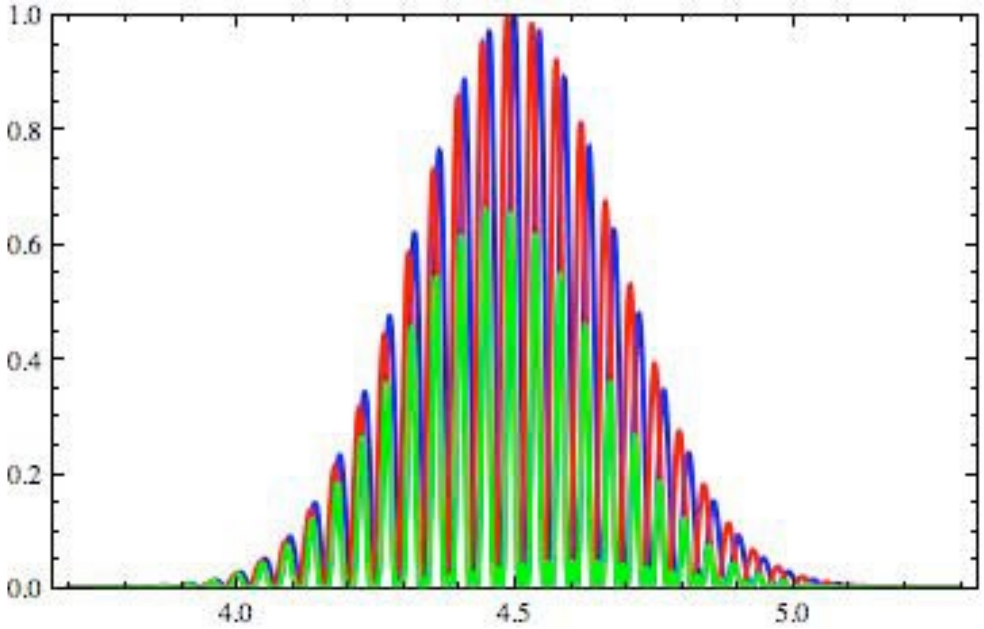

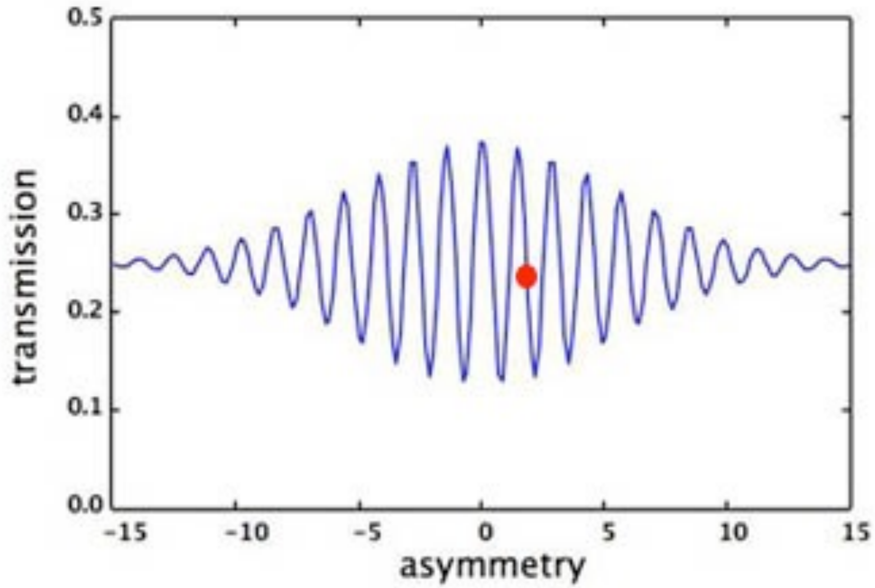

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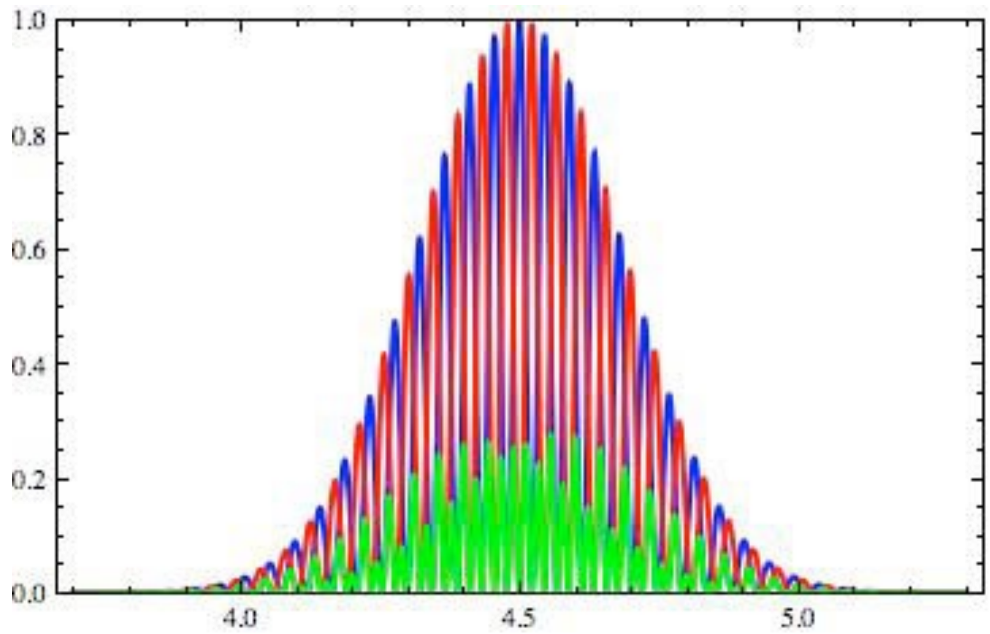

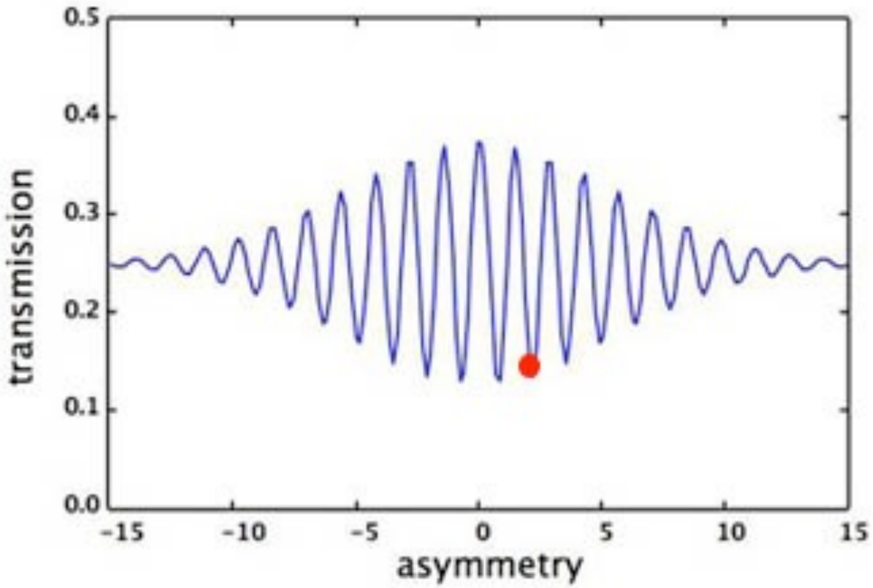

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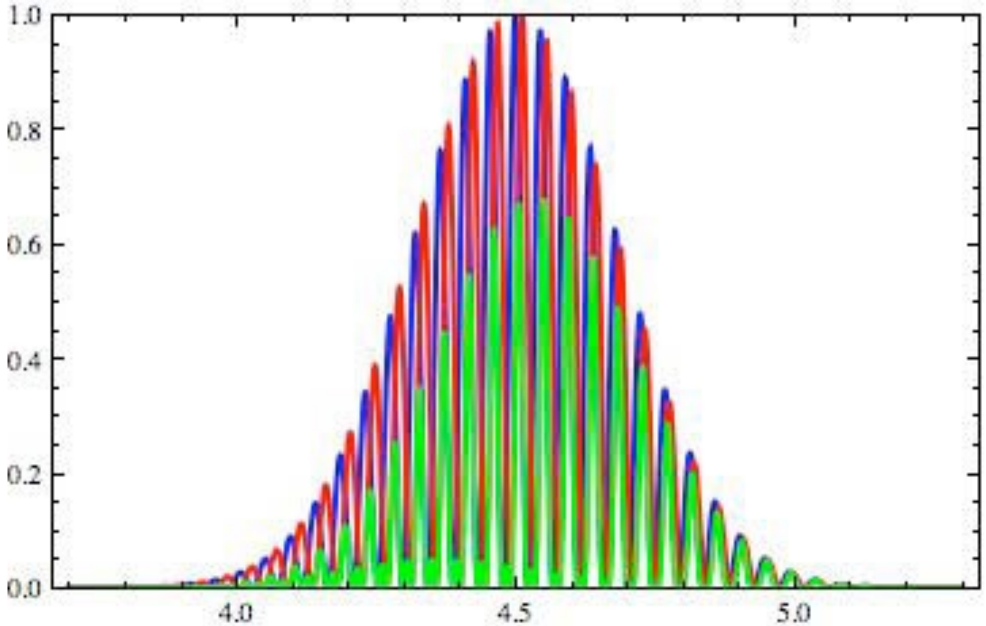

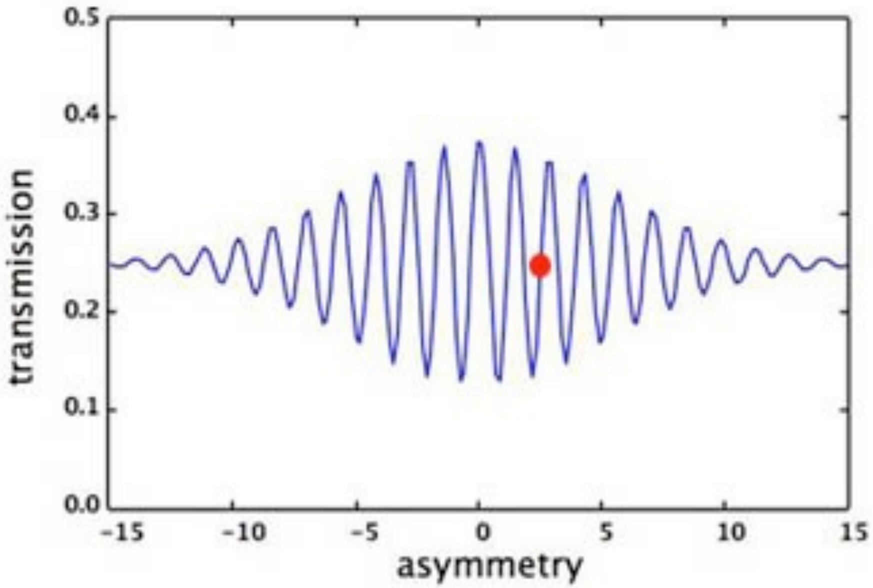

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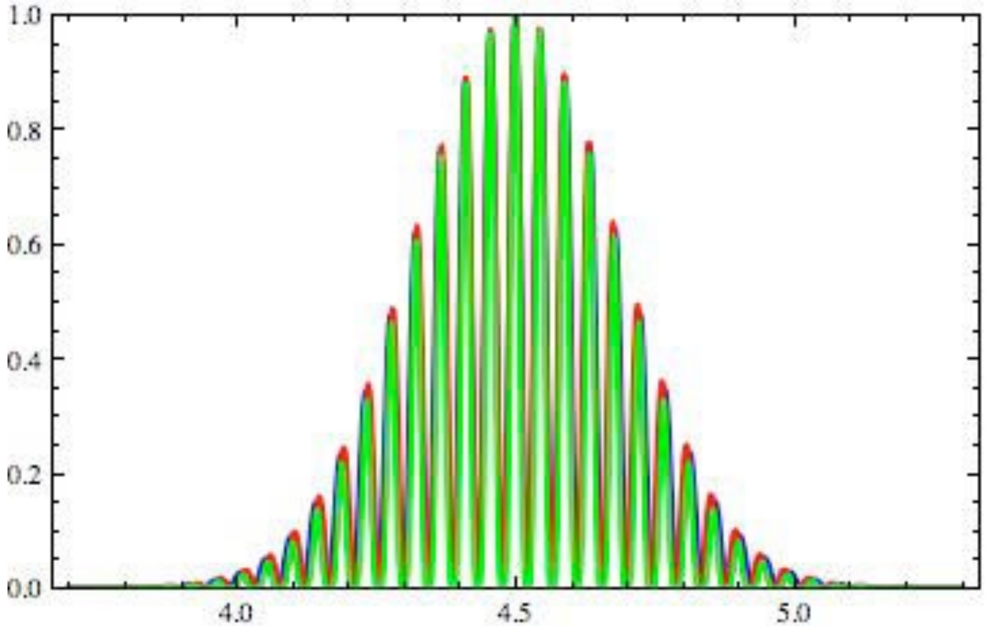

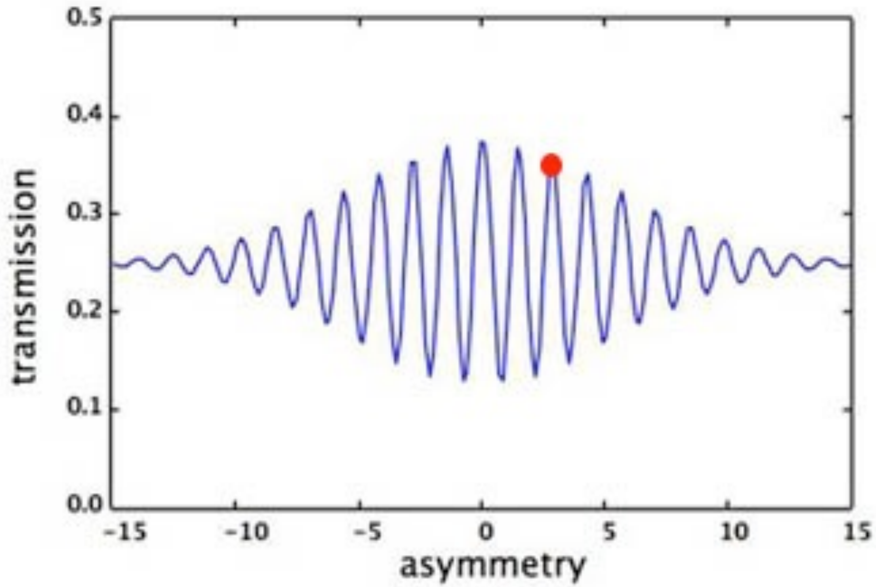

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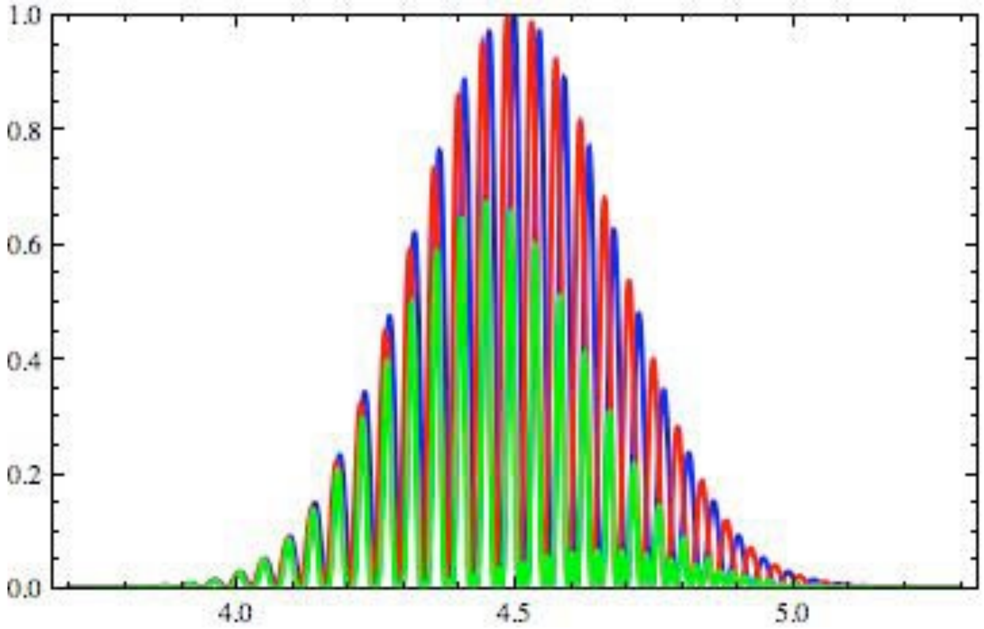

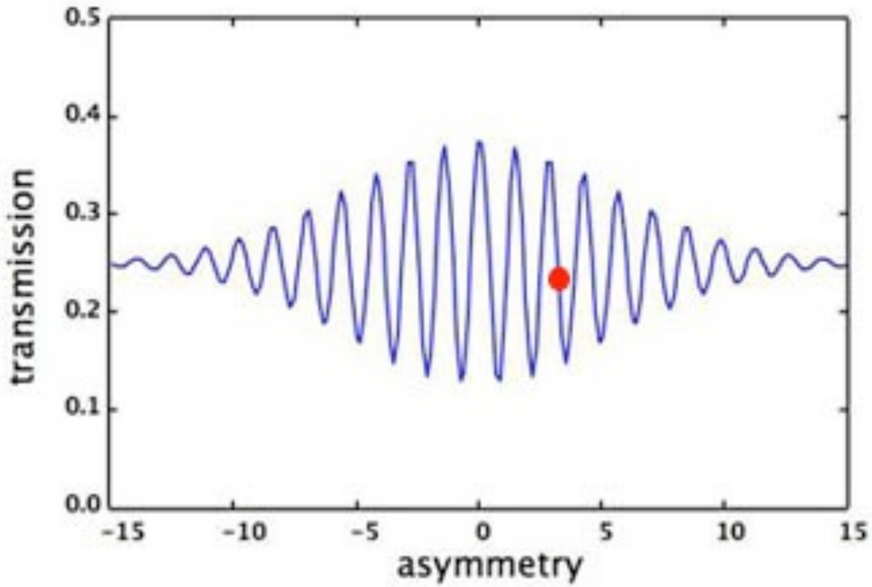

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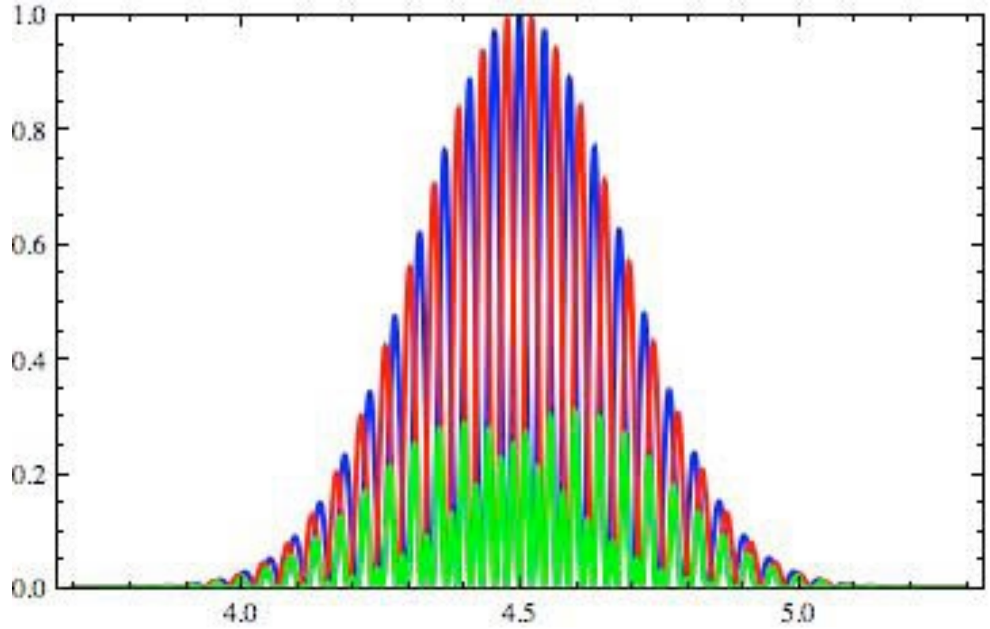

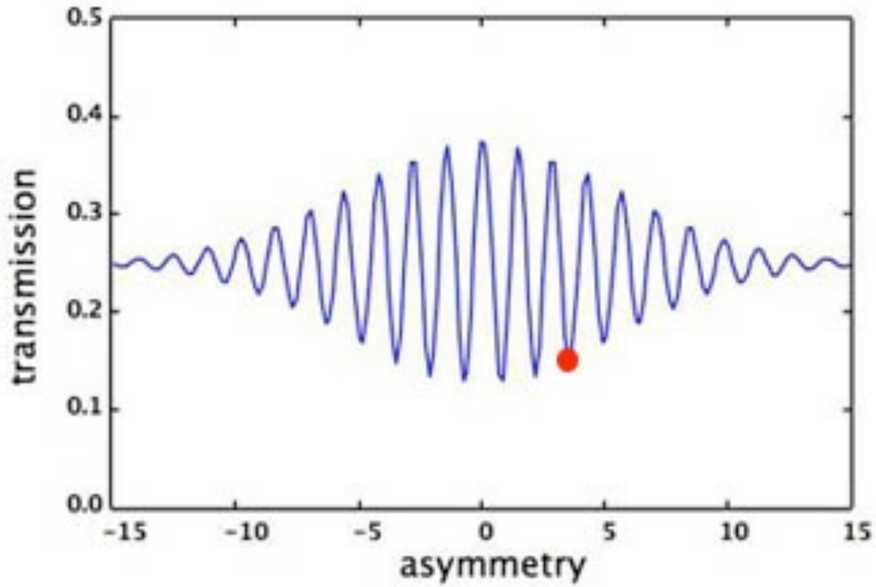

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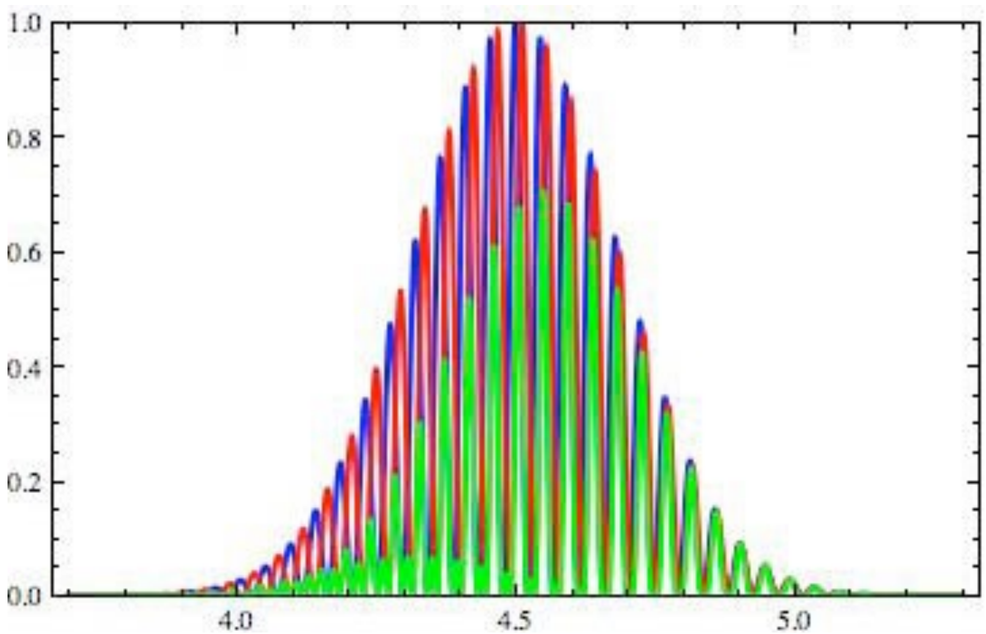

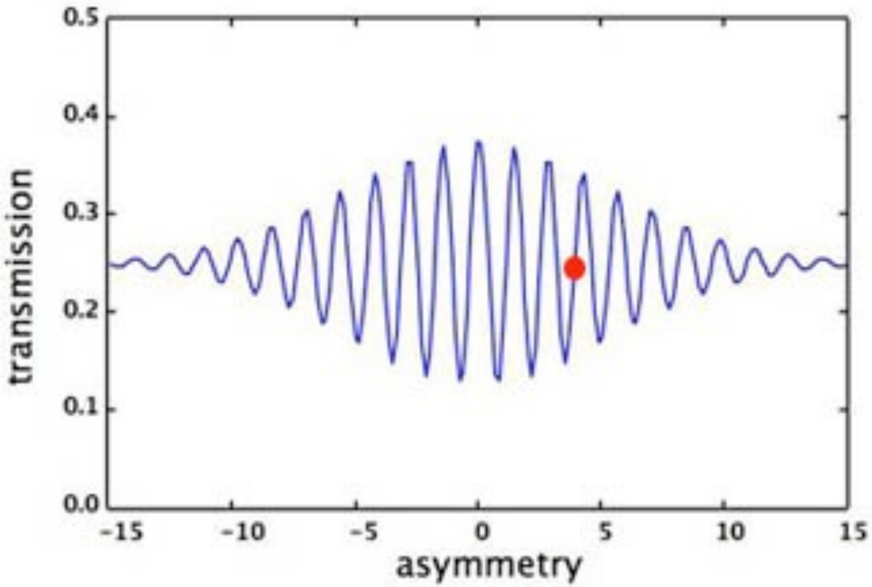

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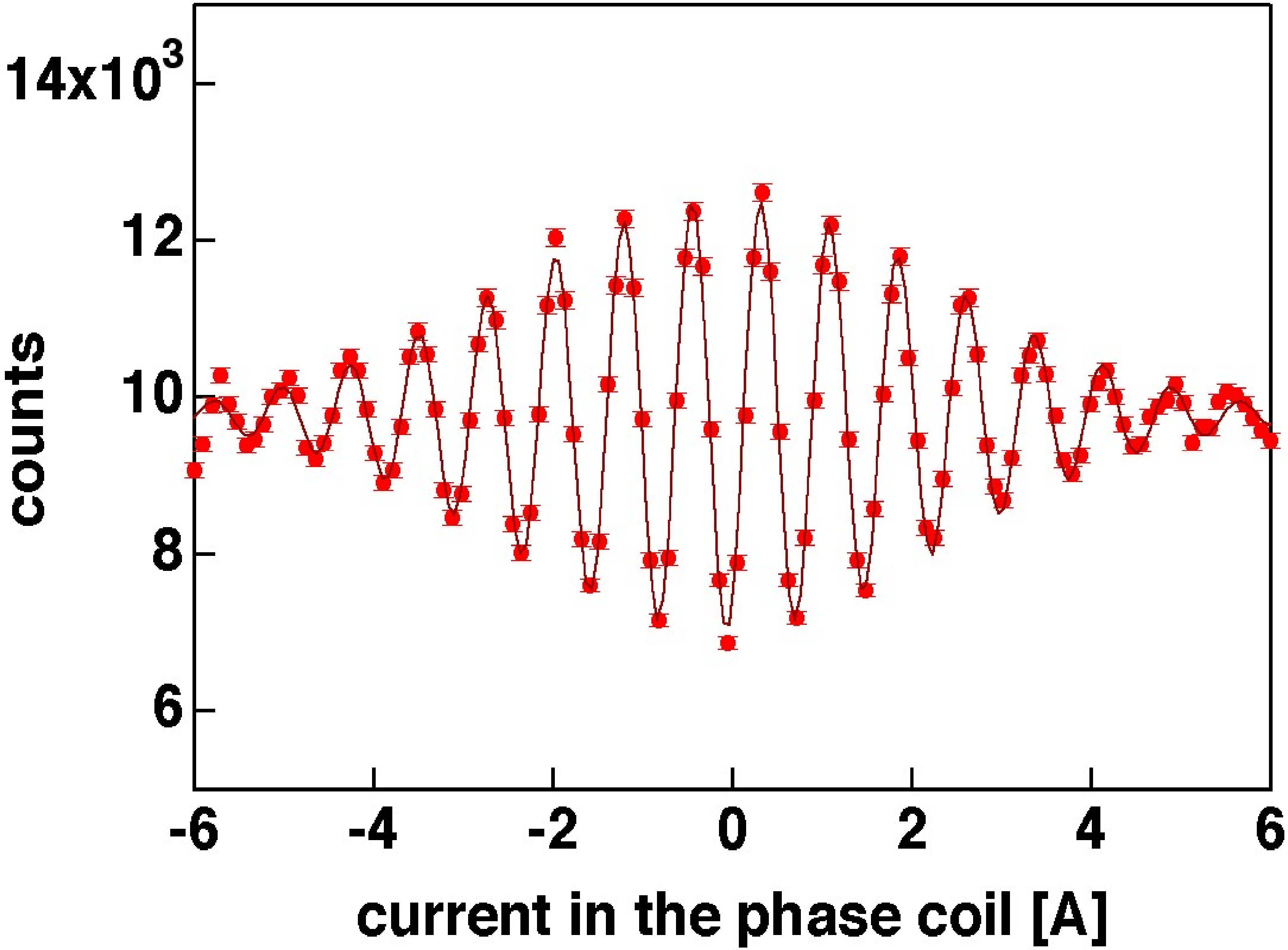
spin-flip scattering on the helical Bragg peak of MnSi below T_c



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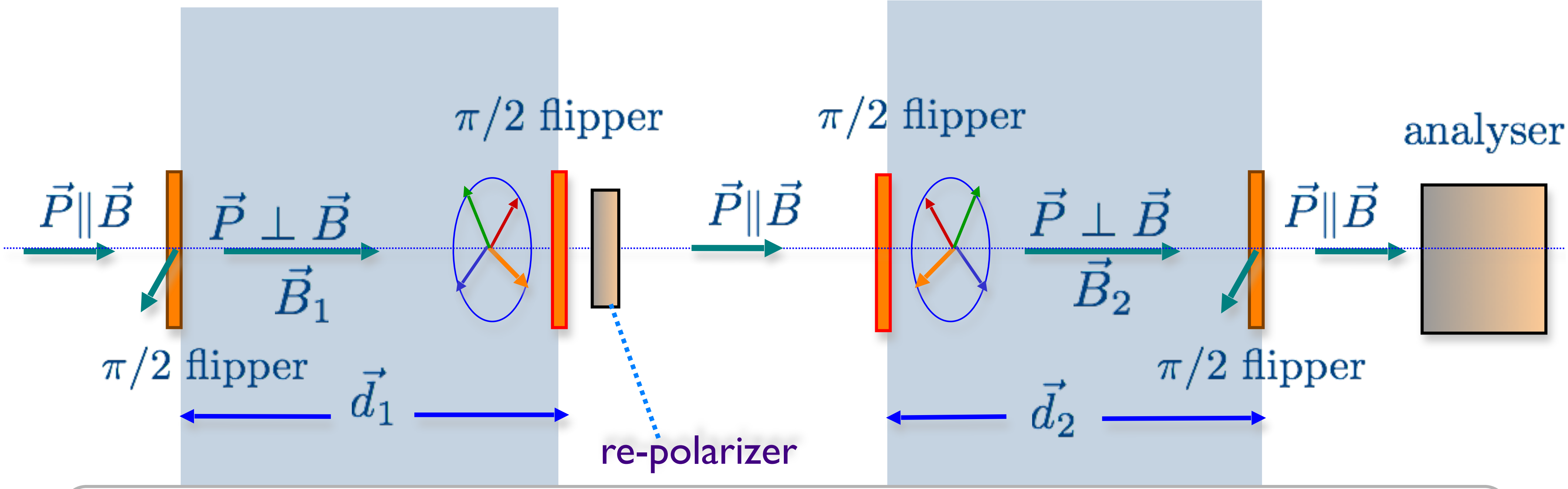
intensity modulated neutron spin echo

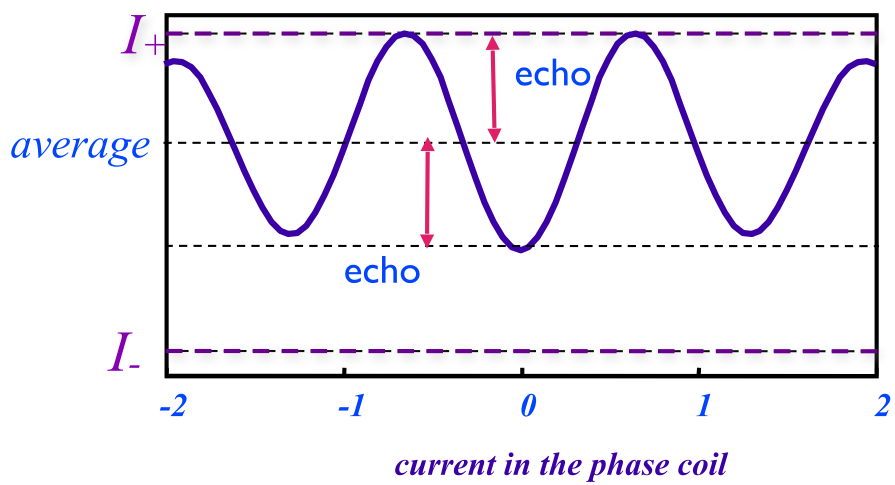


ideally

echo modulation = $(I_+ - I_-) / 3$

for $|\vec{P}| = 1$

factor of 2 intensity loss



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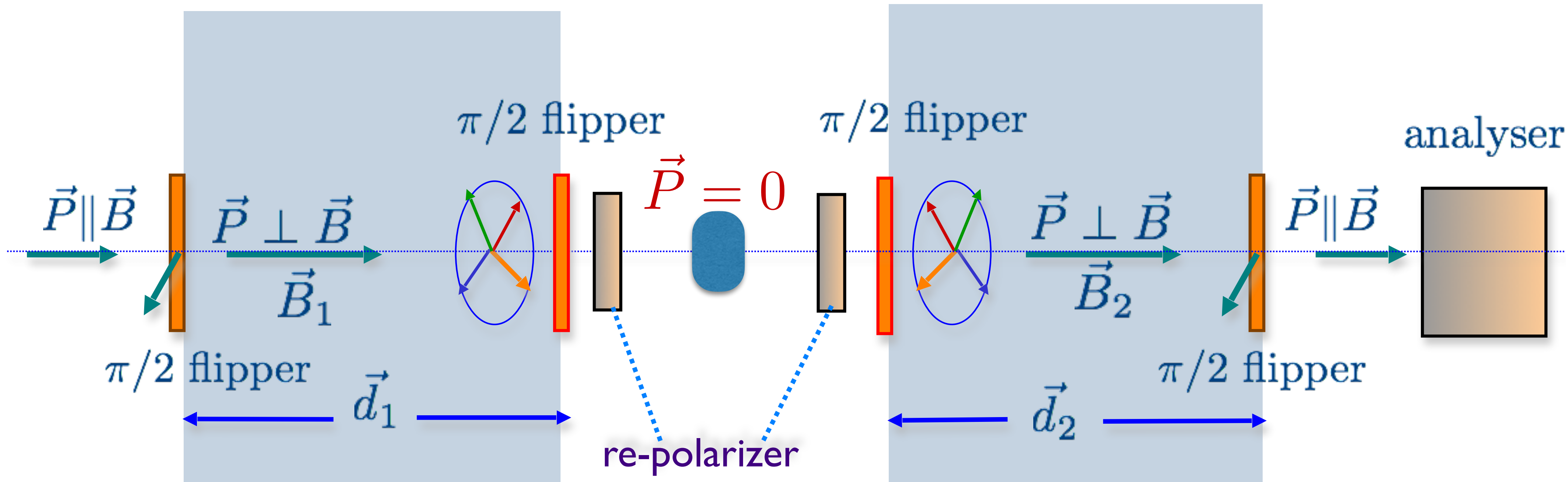

ideally

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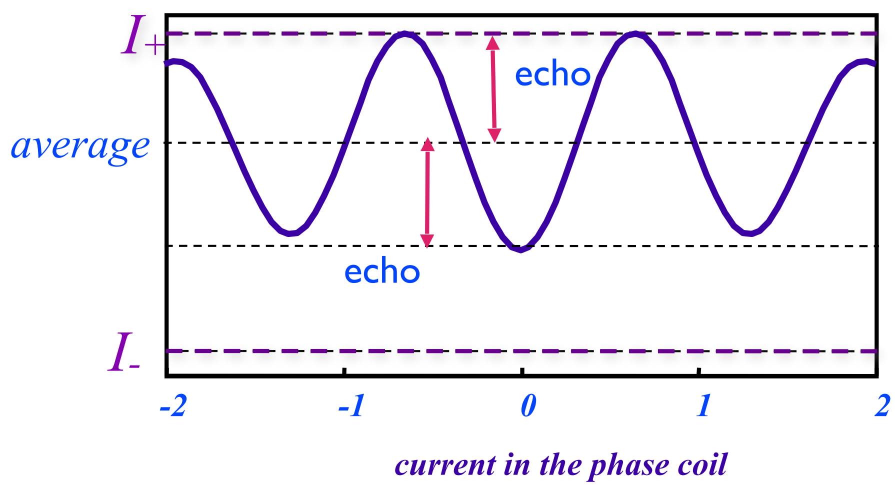
for $|\vec{P}| = 1$

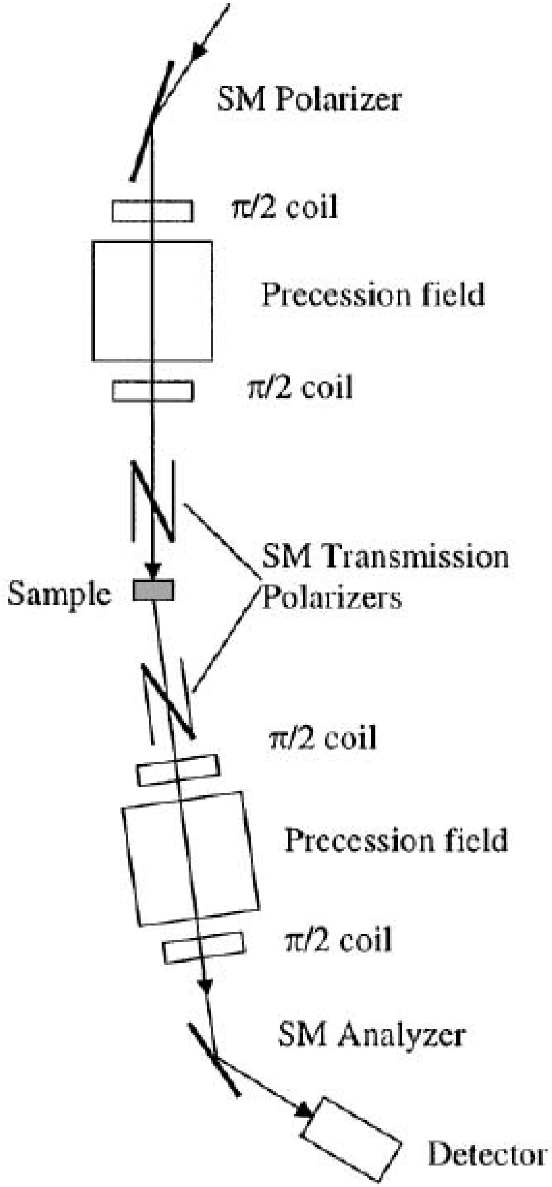
factor of 4 intensity loss

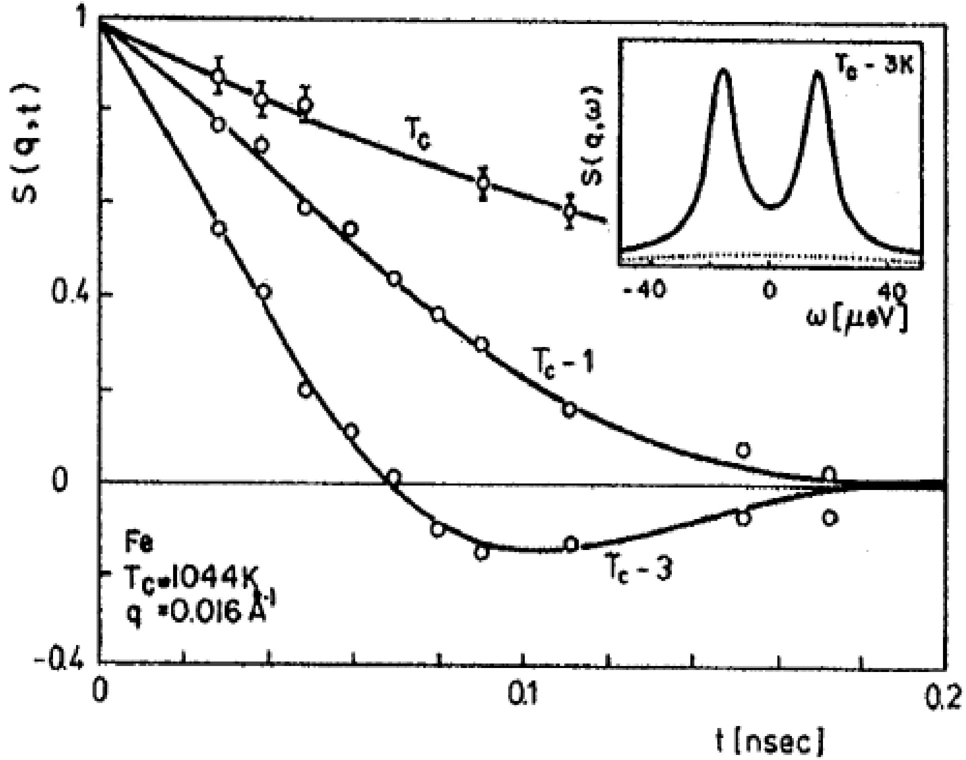


first IMNSE measurements

emergence of magnons in Fe

B. Farago, F. Mezei, Physica B (1986)





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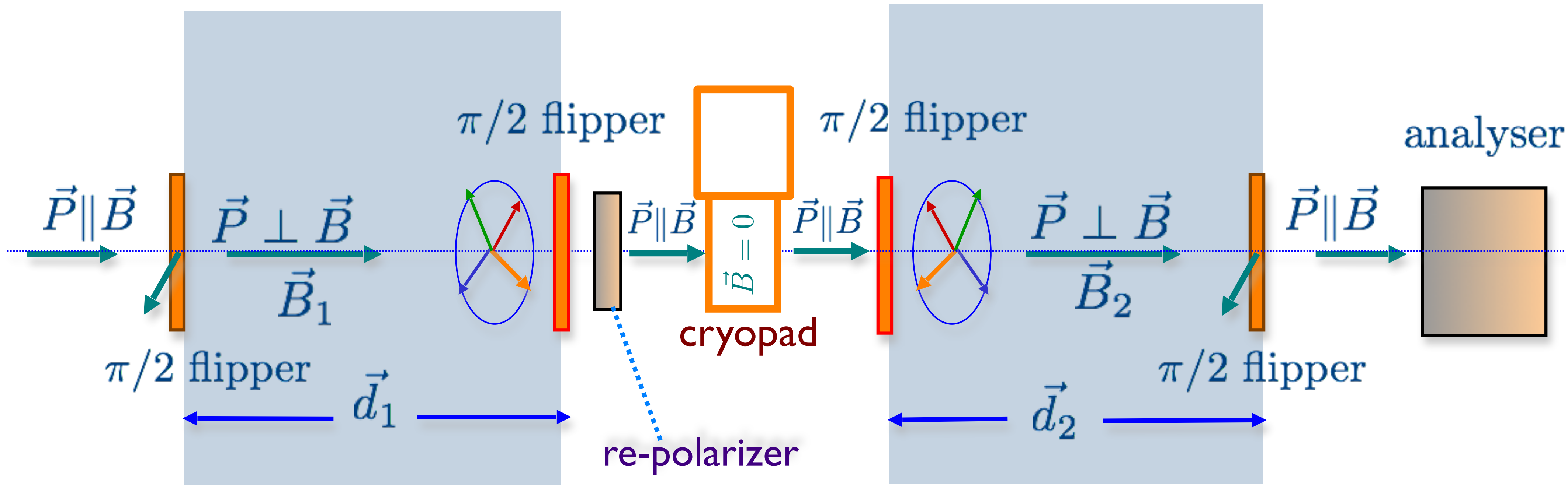

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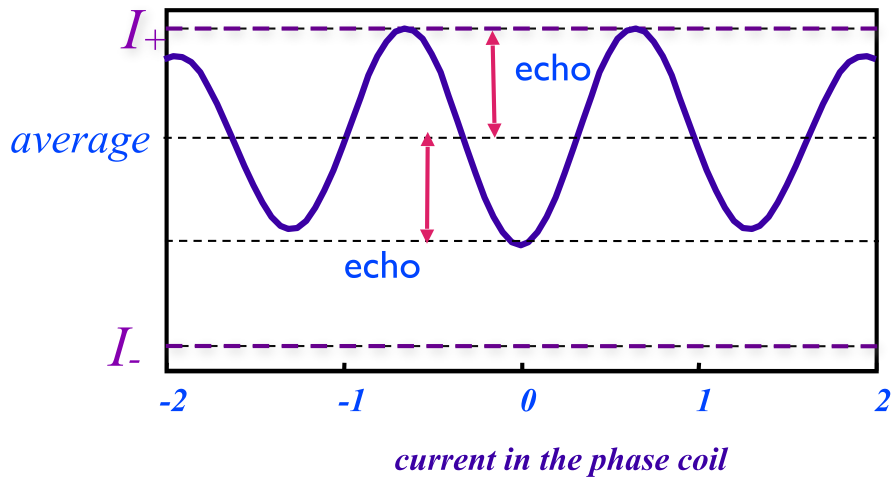
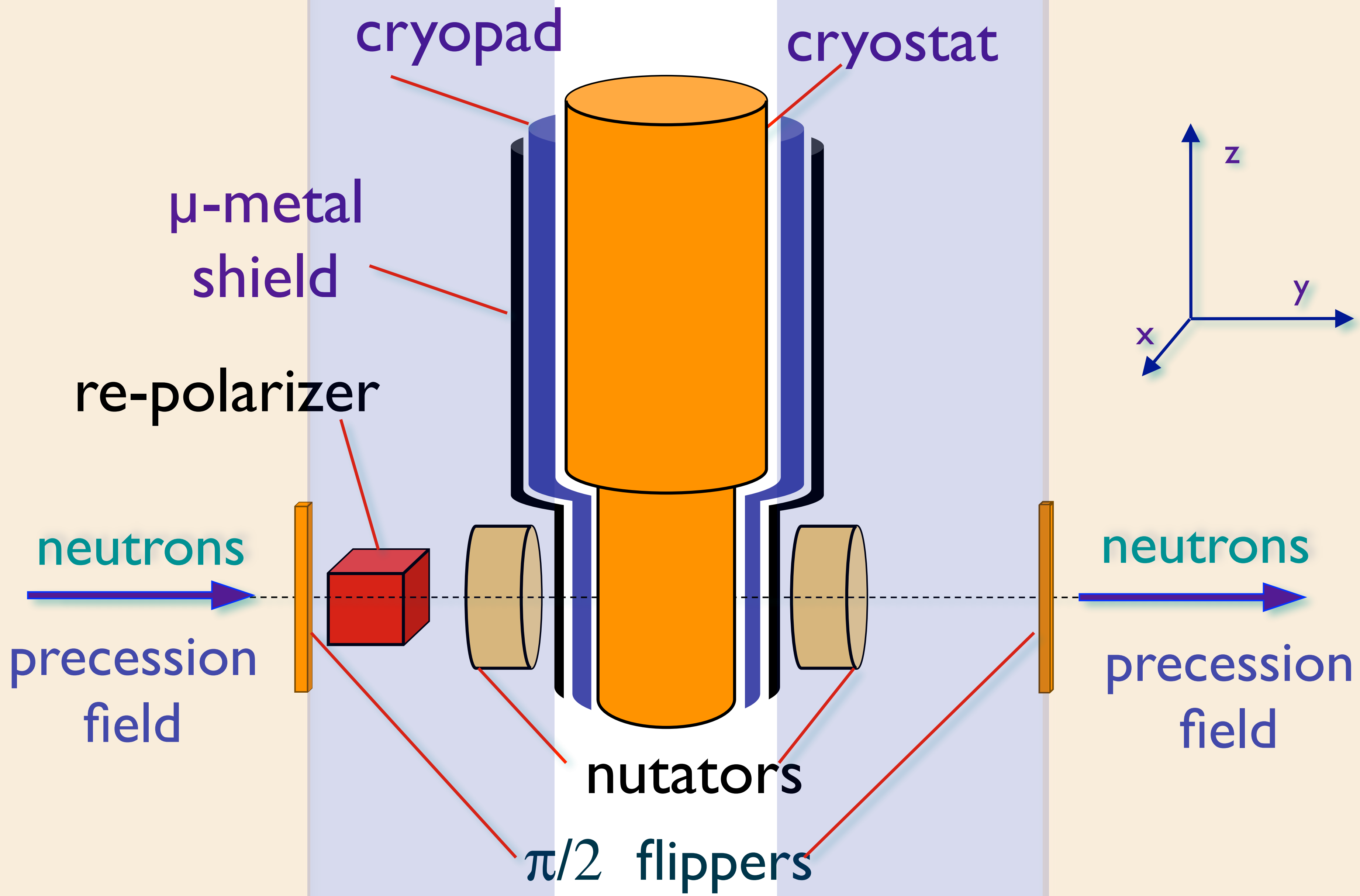
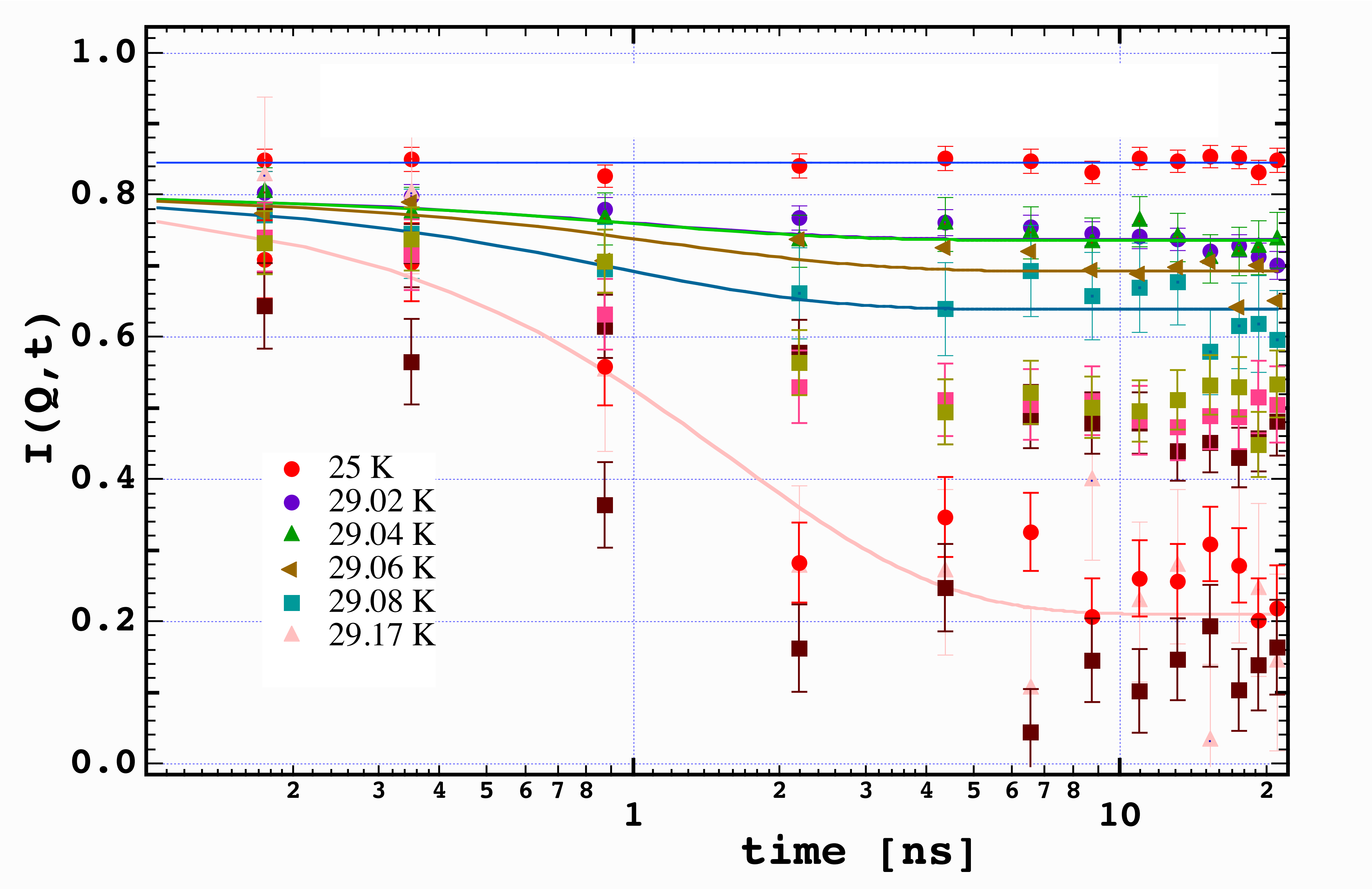


polarimetric neutron spin echo



CP et al NIMA 2008

chiral fluctuations in MnSi above T_c



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Ruth Pickup
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Lars Bannenberg
Rob Dalgliesh
Fengjiao Qian
Charles Dewhurst

and you for your attention !

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