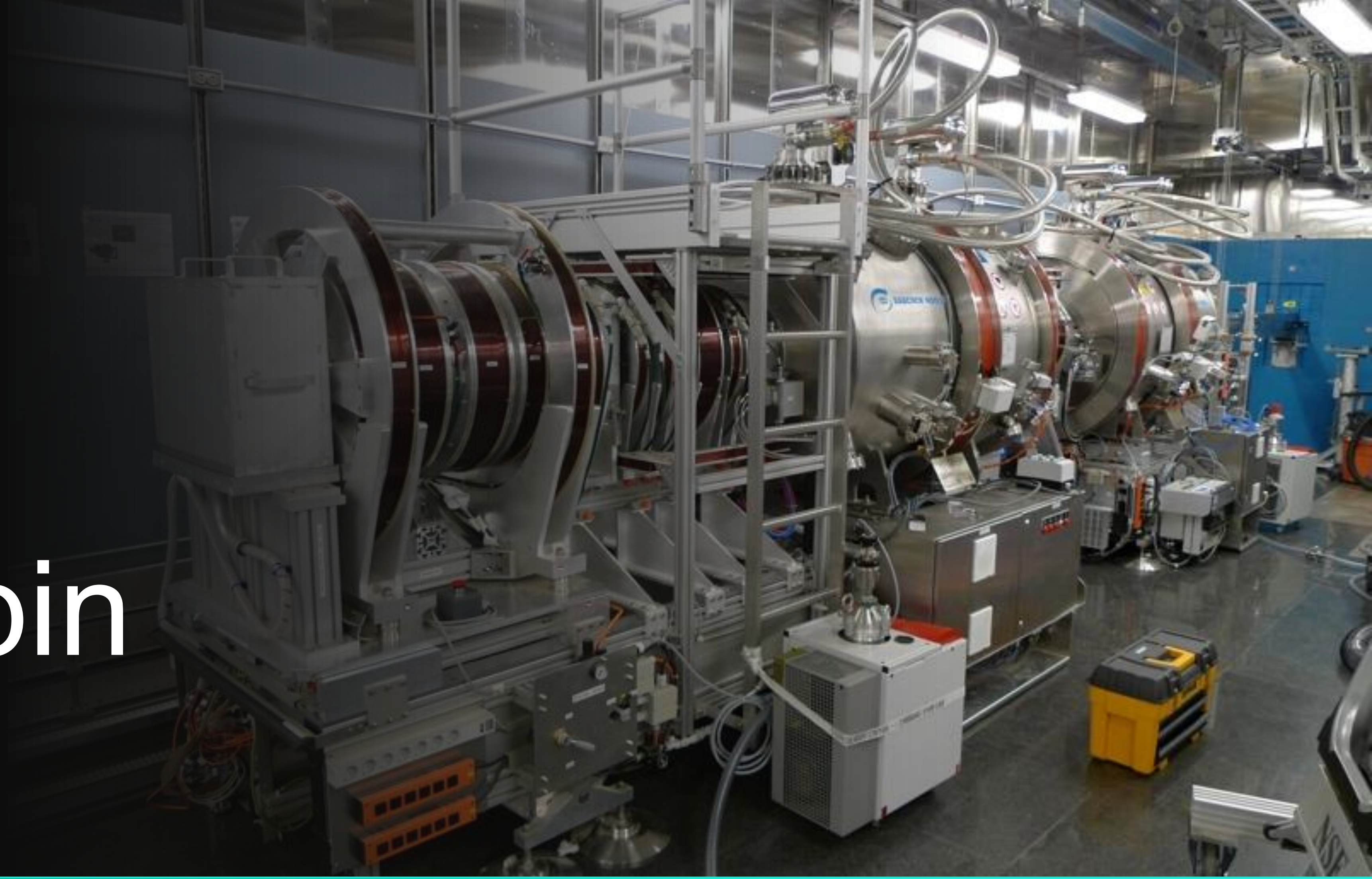
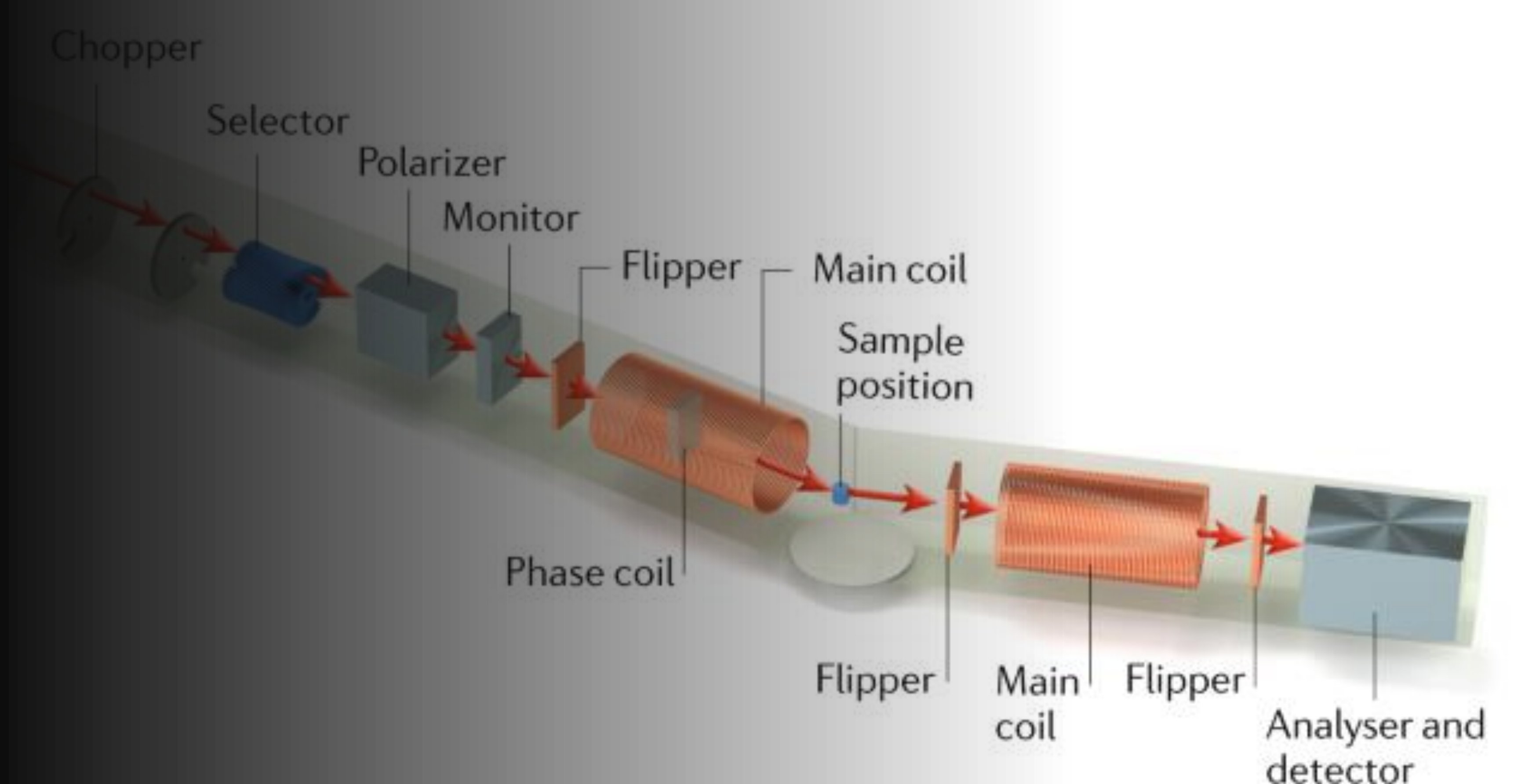
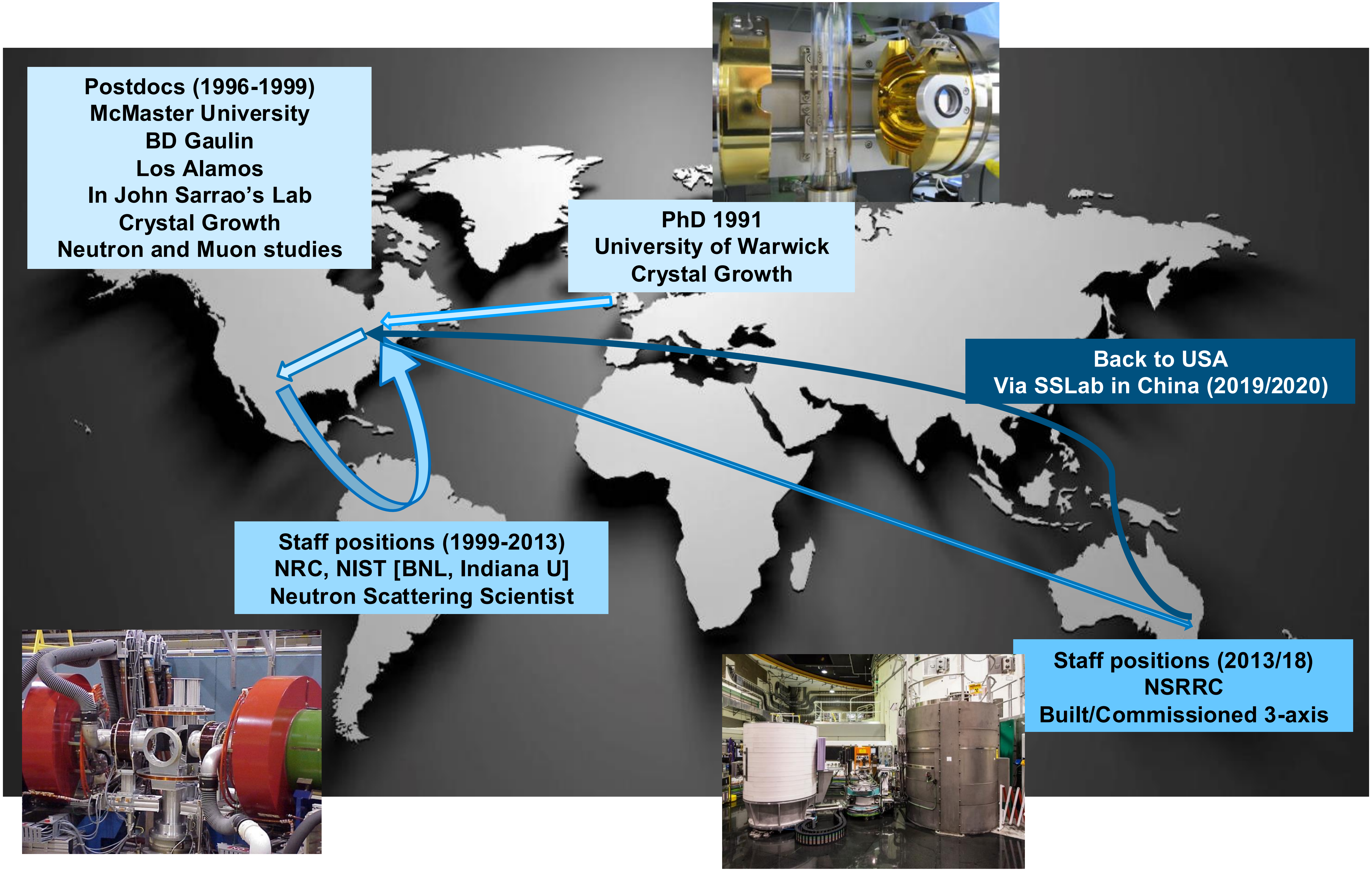
A, b, c's of Neutron Spin Echo

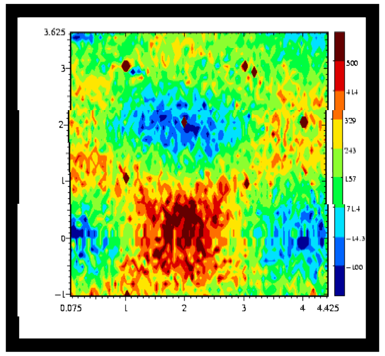




How did I get here



Professional Efforts

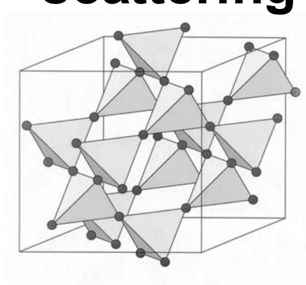


Crystal Growth Initiative

1996

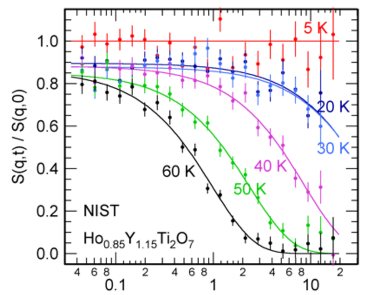
1999

Magnetic neutron scattering program



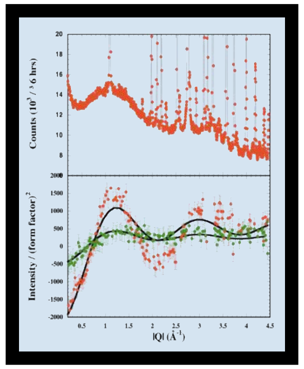
Lead the Brookhaven/NIST Alliance

2002



2006

NSE & develop Magnetic Echo in USA



Frustrated Magnetism@IIP Brazil

EiC

Journal of Physics

Condensed Matter

2013

Neutron Scattering Group Leader in Australia

HFM 2016

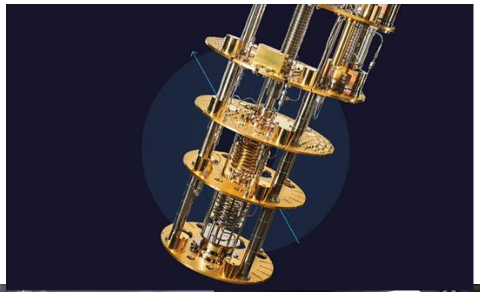
APS physics

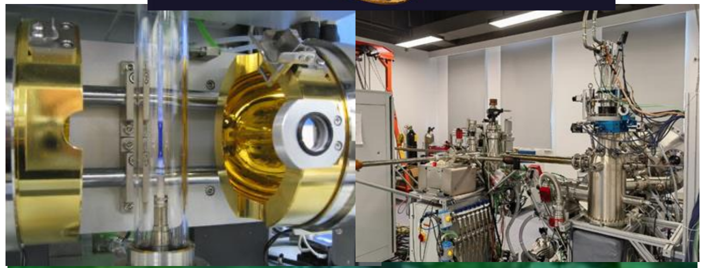
FECS

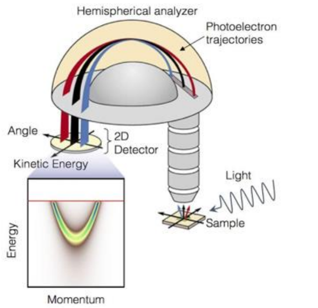
APS physics

IDEA

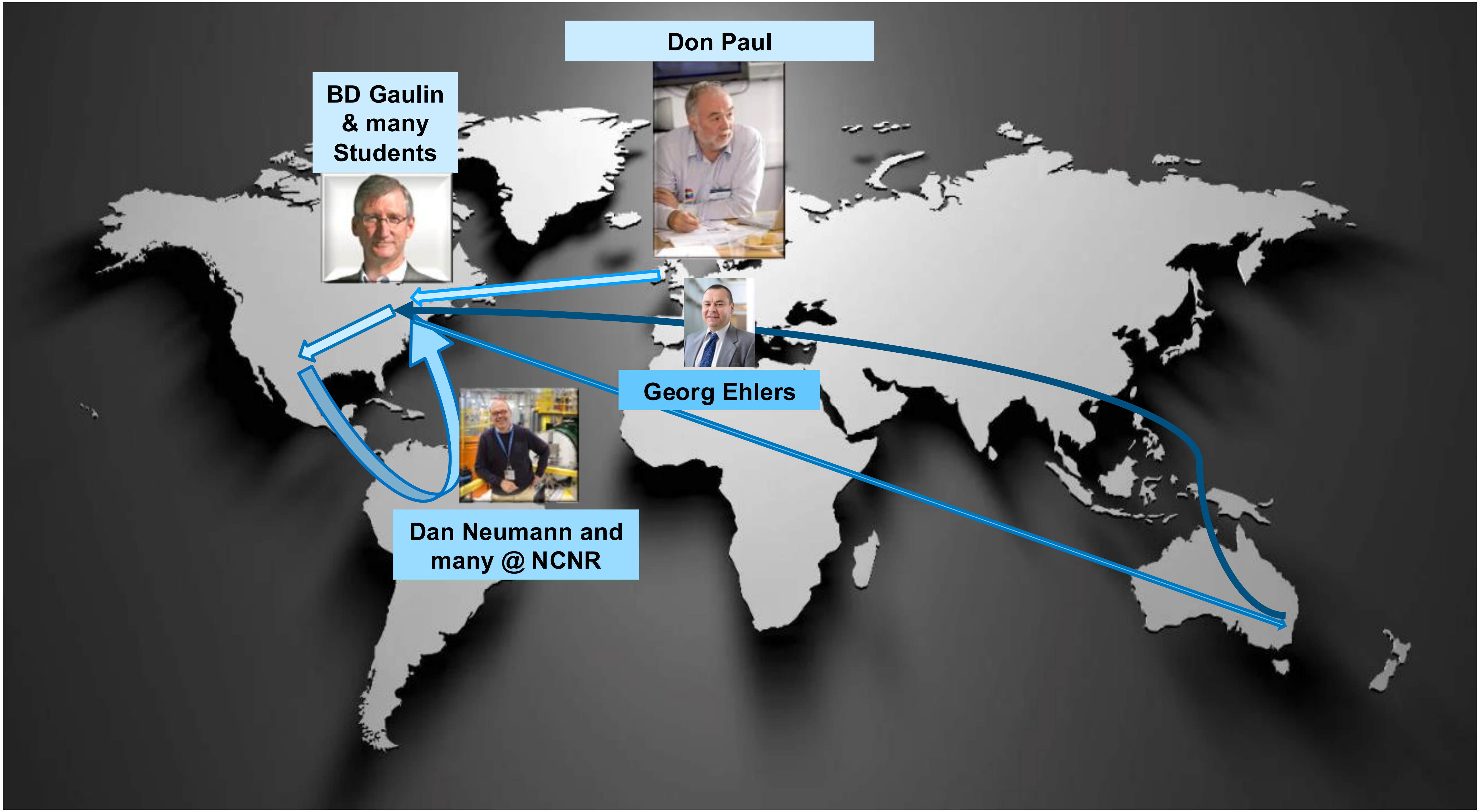
Build a Quantum material lab in China



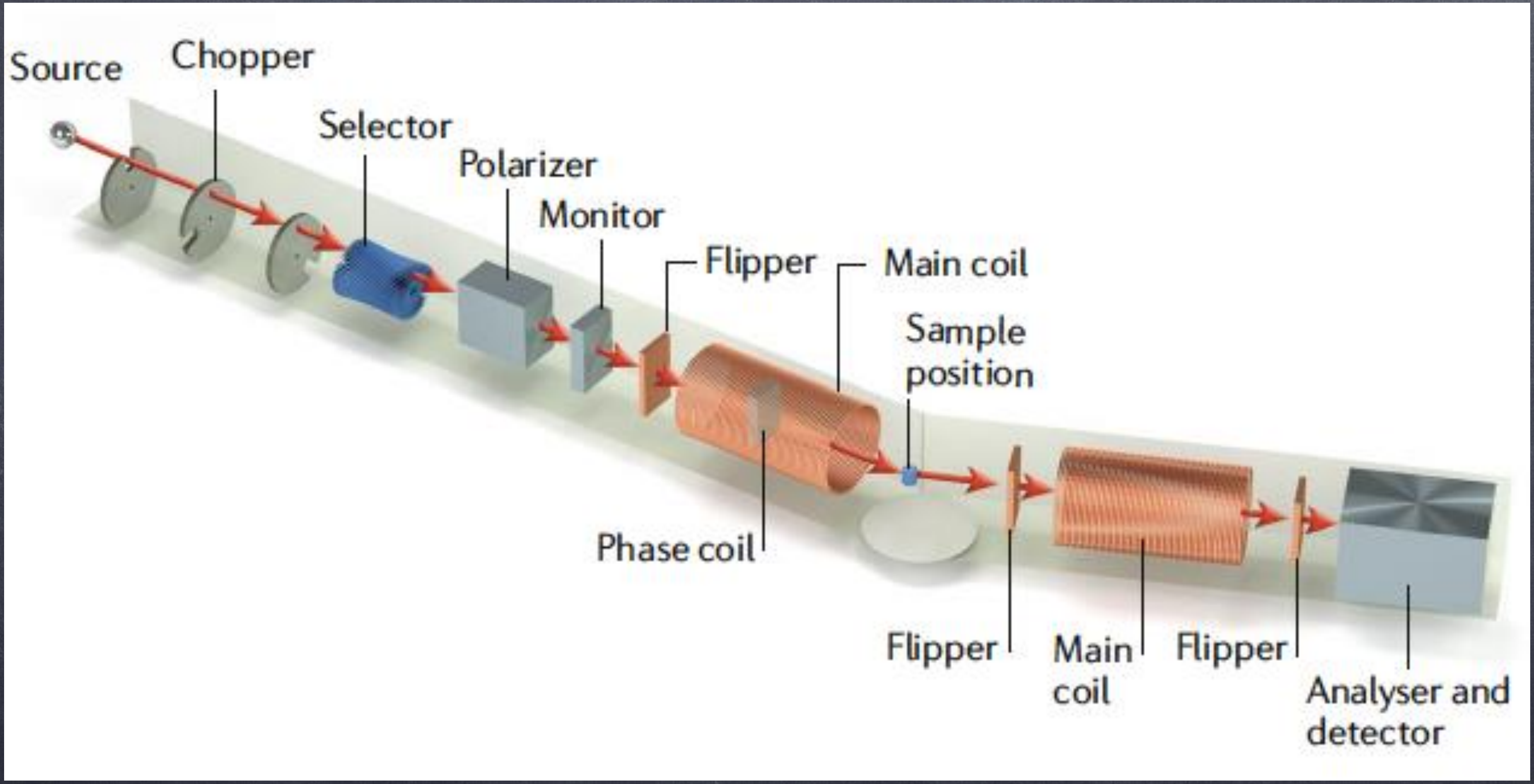




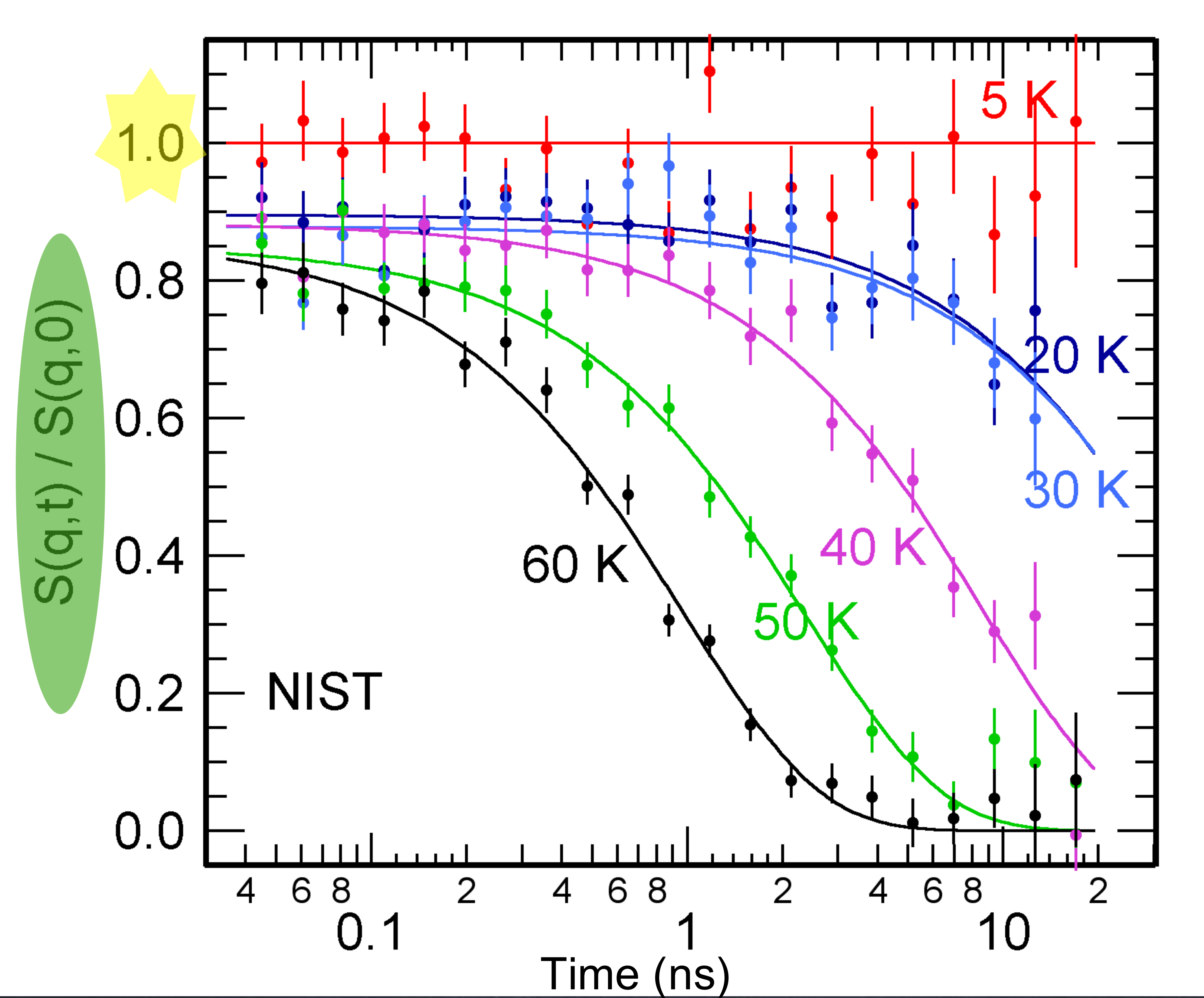
Network of Mentors



Enough about me



Simple Take Home



Some Reading

J.S. Gardner, G. Ehlers, A. Faraone, and V. Garcia-Sakai "*High-resolution neutron spectroscopy using backscattering and neutron spin-echo spectrometers in soft and hard condensed matter*" Nature Reviews Physics, 2, 103 (2020).

Stephen Lovesey: Theory of Neutron Scattering from Condensed Matter, Vol. 2, Clarendon Press, Oxford, 1986.

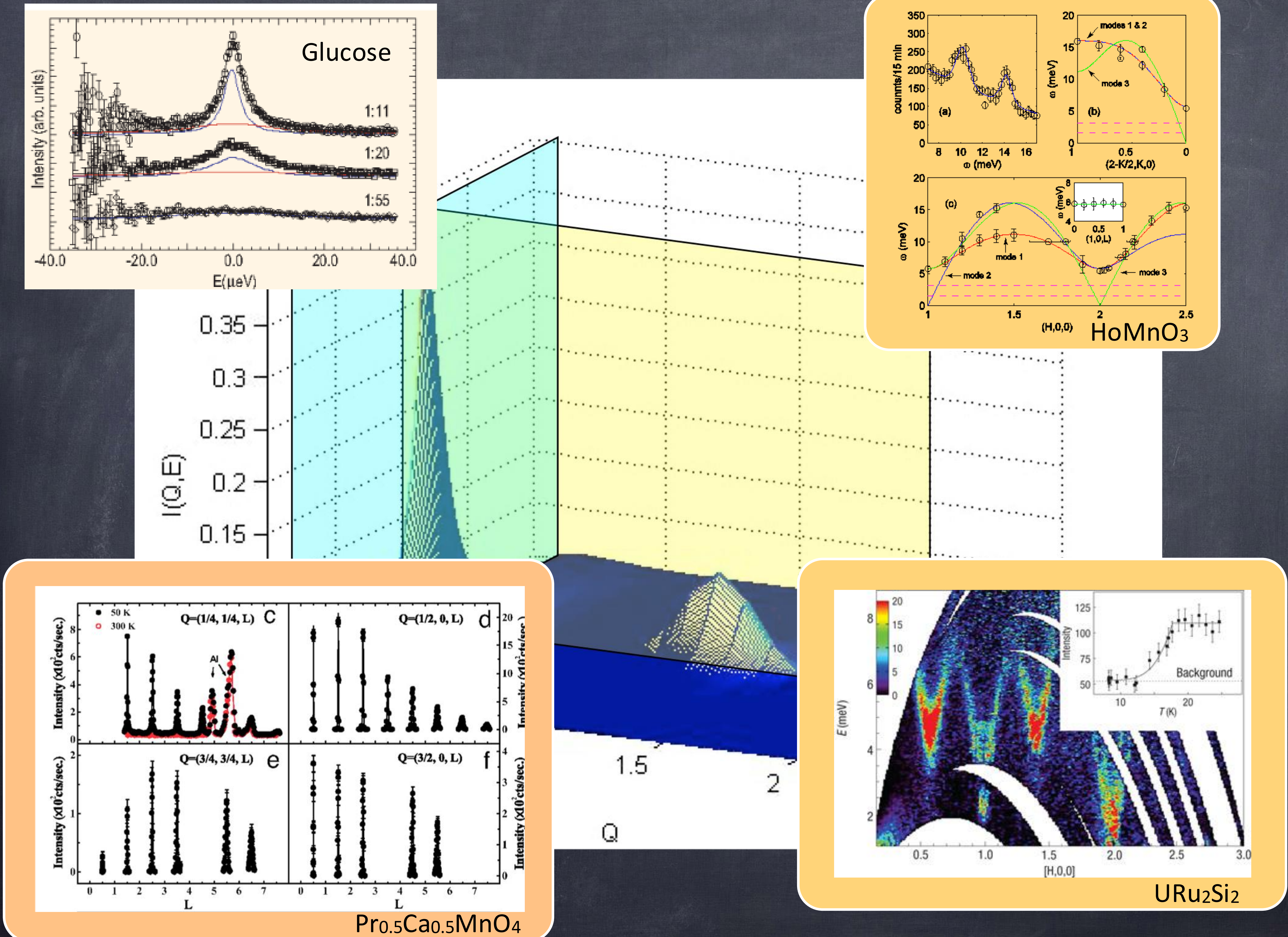
F. Mezei (Ed.): Neutron Spin-Echo, Lecture Notes in Physics 128, Springer, Heidelberg, 1980.

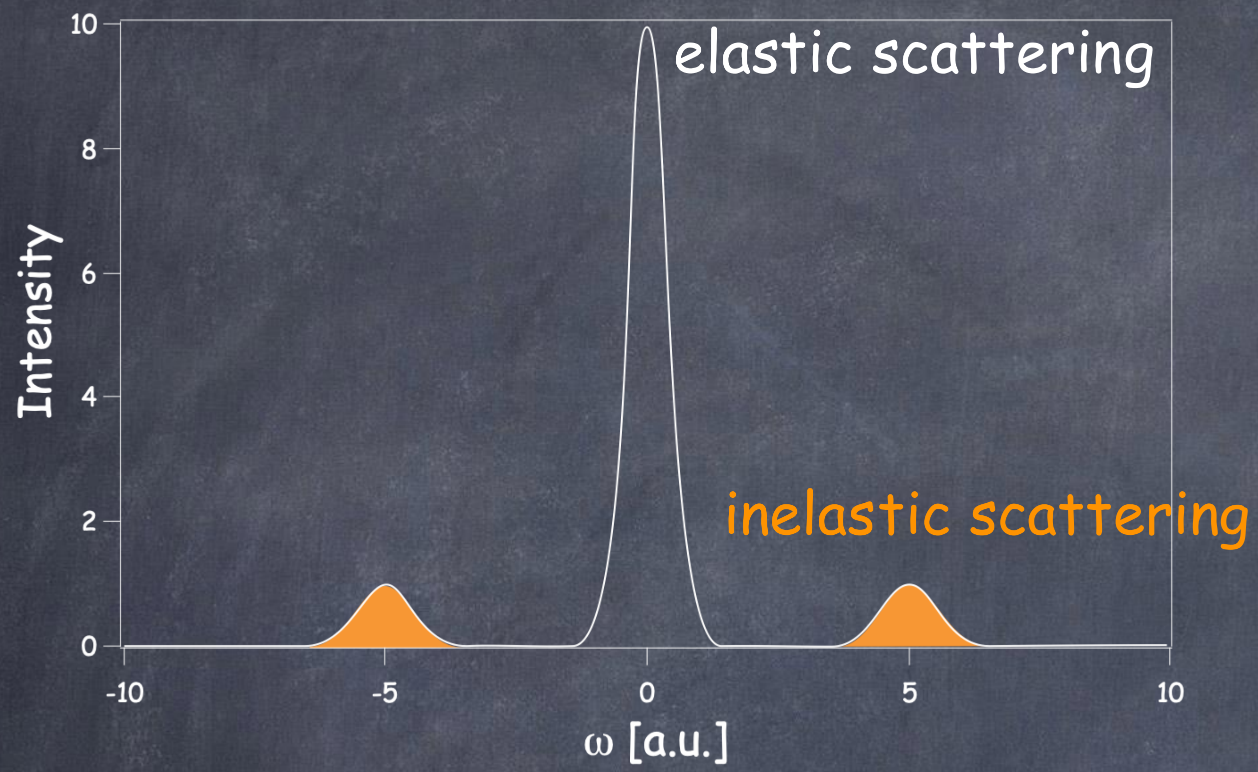
F. Mezei, C. Pappas, T. Gutberlet (Eds.): Neutron Spin-Echo Spectroscopy (2nd workshop), Lecture Notes in Physics 601, Springer, Heidelberg, 2003.

D. Richter, M. Monkenbusch, A. Arbe, and J. Colmenero, "*Neutron spin echo in polymer systems*" *Adv. in polym. Sci*, 174, 1 (2005).

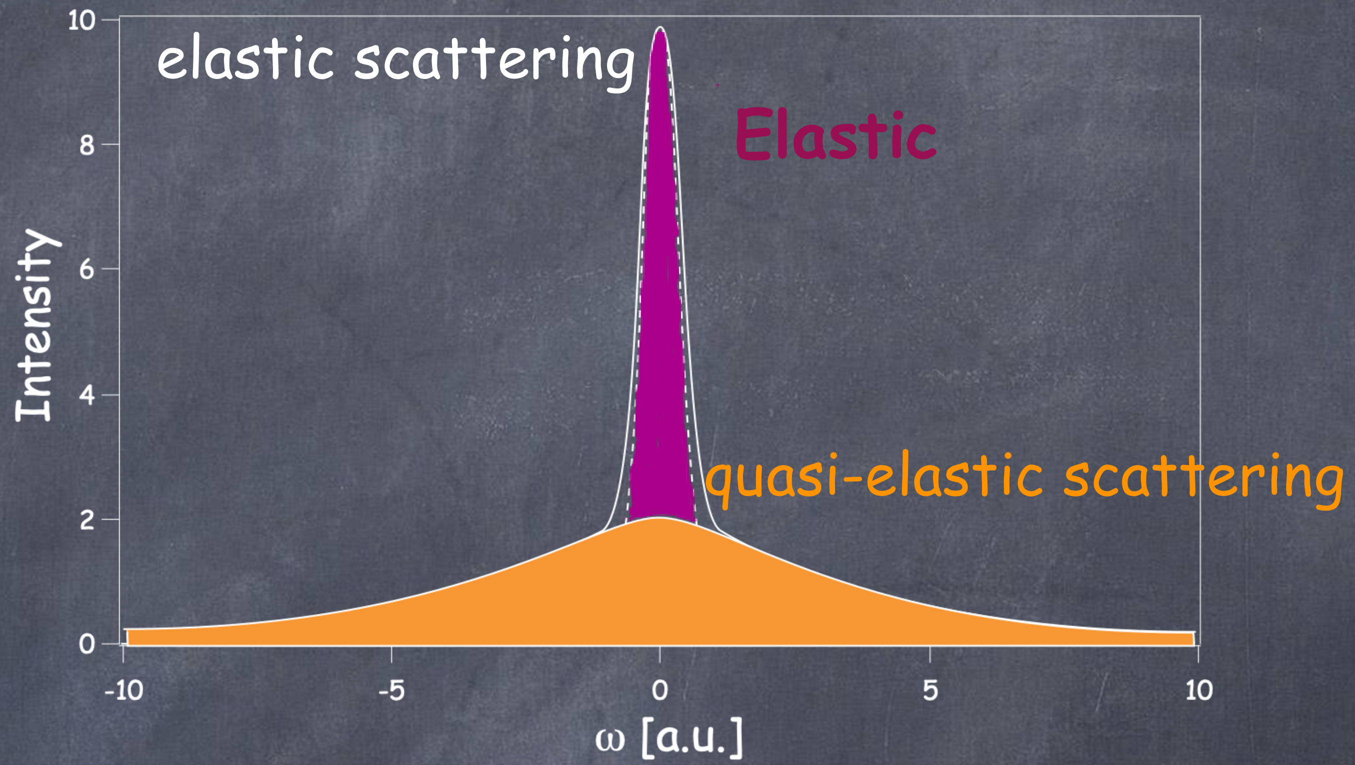
B. Farago, "*Recent developments and applications of NSE in soft matter*" *Curr. Opin. Colloid Interface Sci.*, 14, 391 (2009).

I. Hoffmann, "*Neutrons for the study of dynamics in soft matter systems*" *Colloid. Polym. Sci.*, 292, 2053 (2014).


Glucose
1:11
1:20
1:55
Intensity (arb. units)
E(μeV)
HoMnO3
modes 1 & 2
mode 3
mode 1
mode 2
counts/15 min
ω (meV)
(2-K/2,K,0)
(H,0,0)
(1,0,L)
I(Q,E)
Q
Pr0.5Ca0.5MnO4
Q=(1/4, 1/4, L)
Q=(1/2, 0, L)
Q=(3/4, 3/4, L)
Q=(3/2, 0, L)
50 K
300 K
Al
Intensity (x10²cts/sec.)
L
URu2Si2
E (meV)
[H,0,0]
Intensity
Background
T (K)



Excitation: the neutron interacts with an oscillation which has a finite energy transfer
c.f. Natural Modes, SHO



Relaxation: the neutron interacts with the system which finds a new equilibrium state.

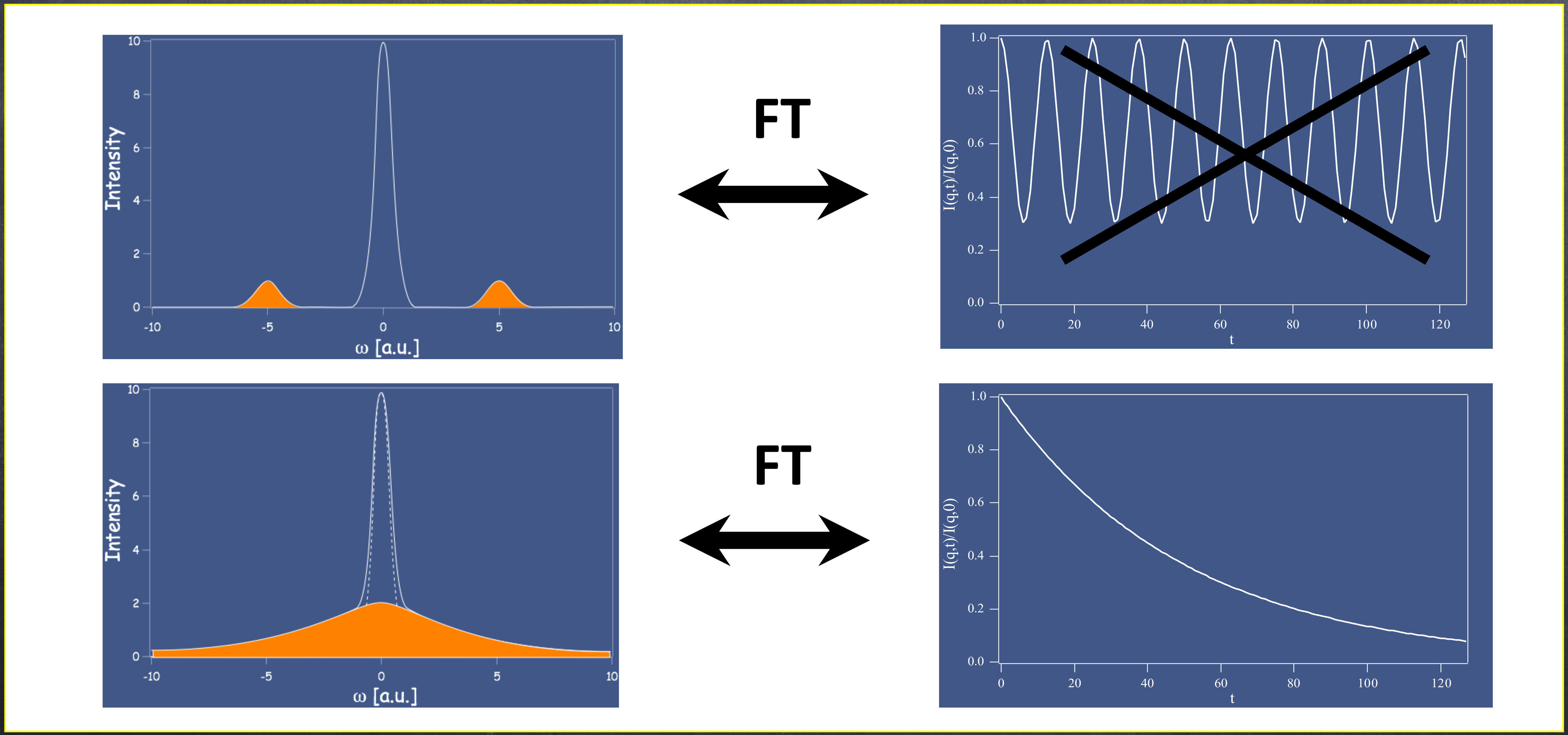
c.f. Diffusion, Brownian Motion

Time domain measurements

$$I(q,t) = \int S(q,\omega) \exp\left(-i\omega t\right) d\omega$$

Energy domain

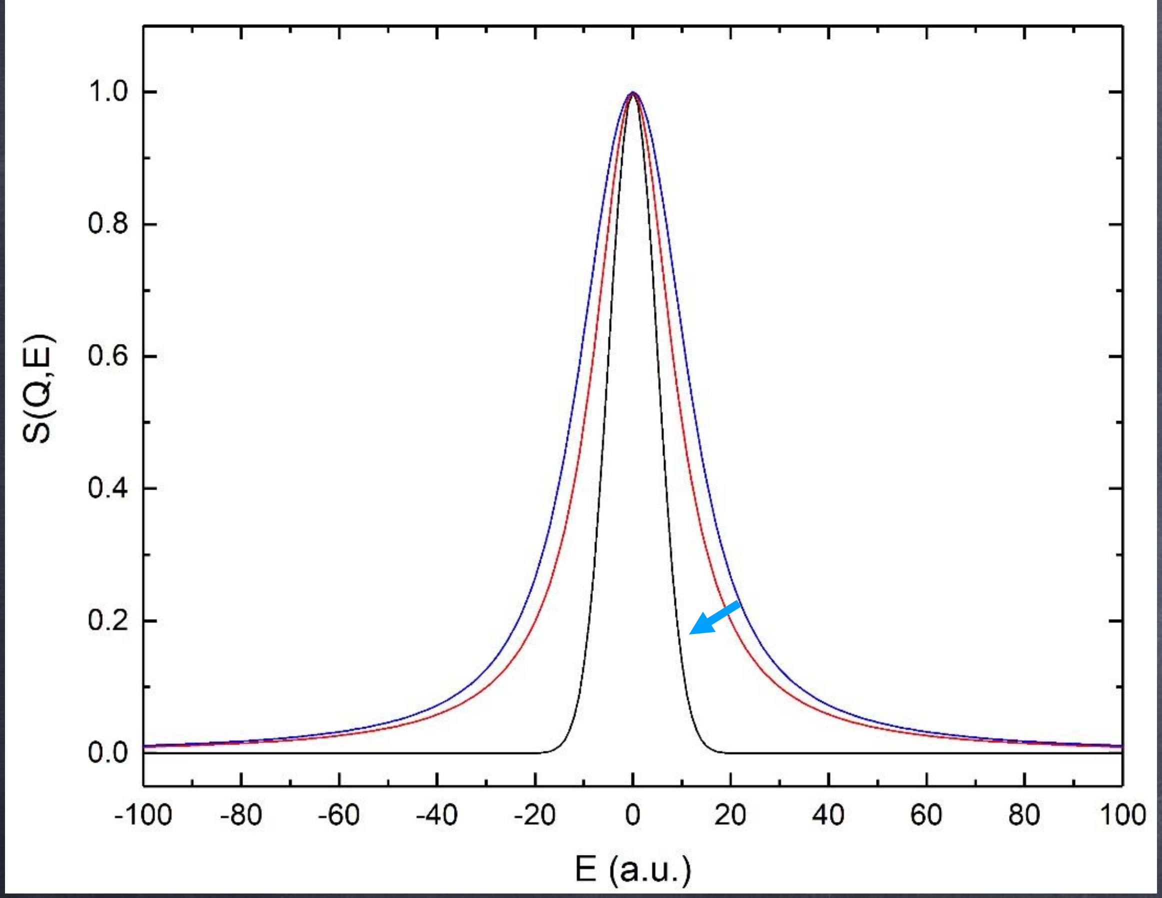
Time domain



Quasielastic scattering or relaxation processes are well studied in the time domain

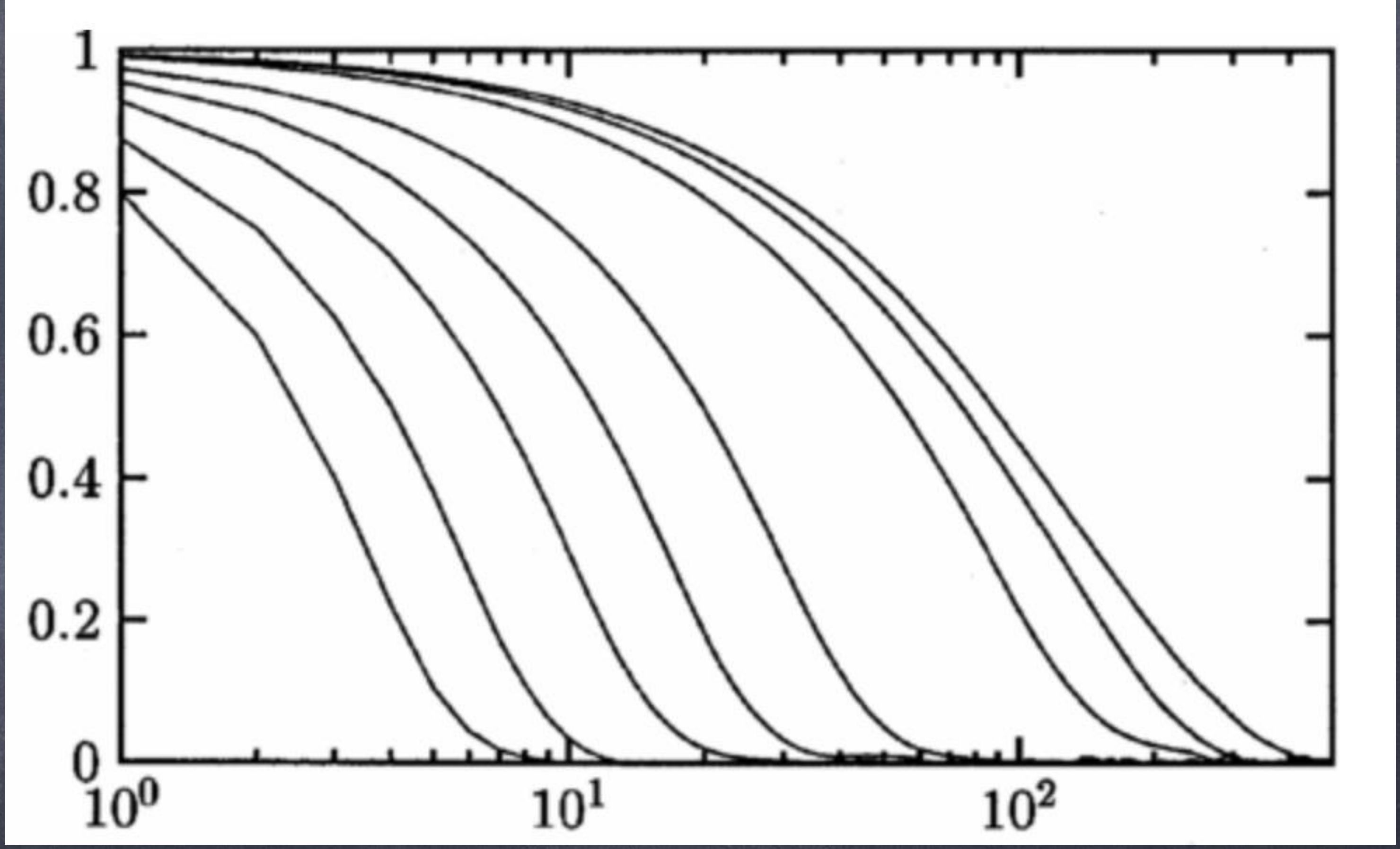
Why? Well one reason why

Higher flux,
Quicker experiment



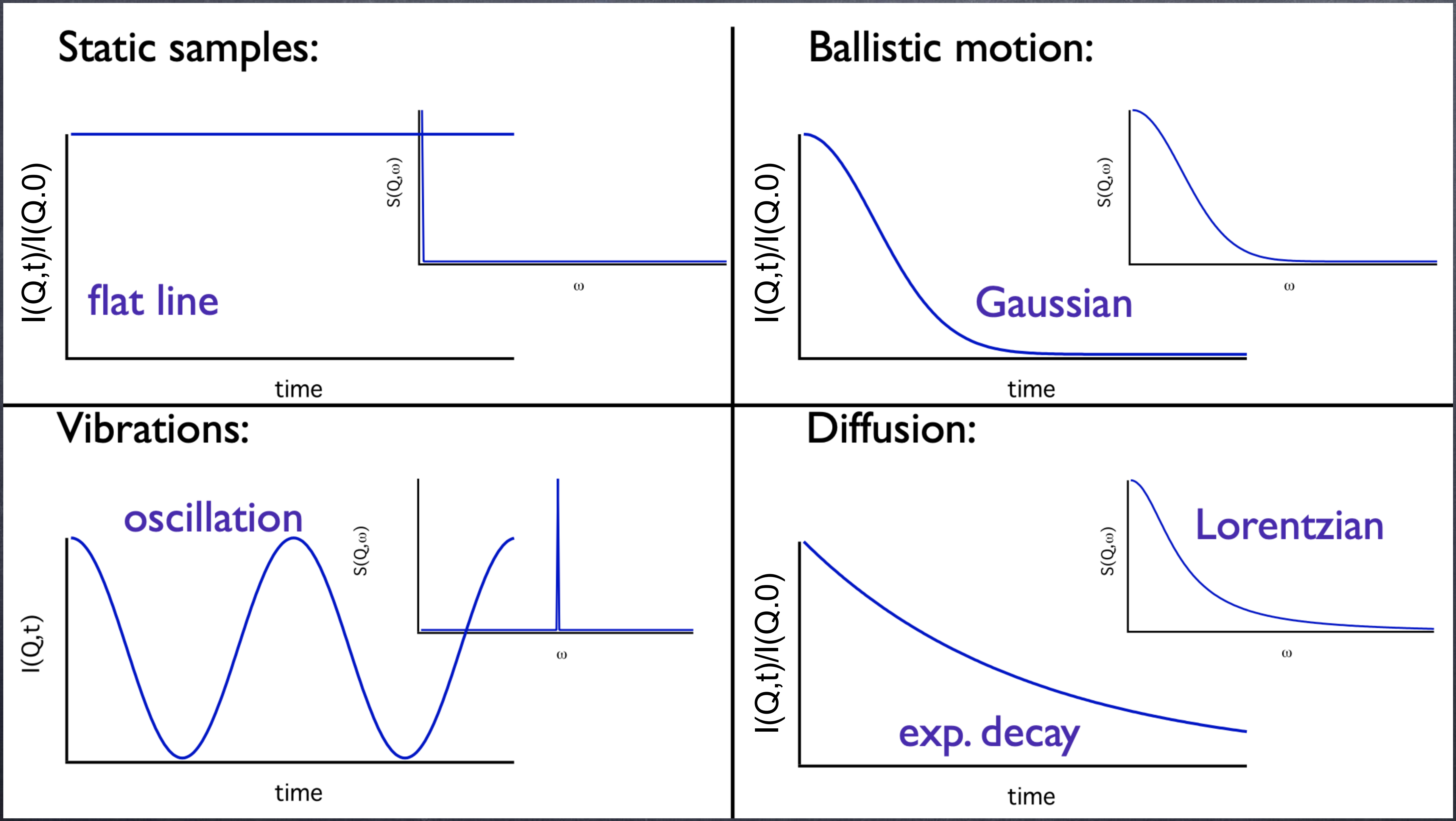
BUT, is you approach the Instrument resolution (Slower) interpretation gets difficult

Low flux,
Slow experiment



BUT, better E- resolution allows us to measure (Slower) things

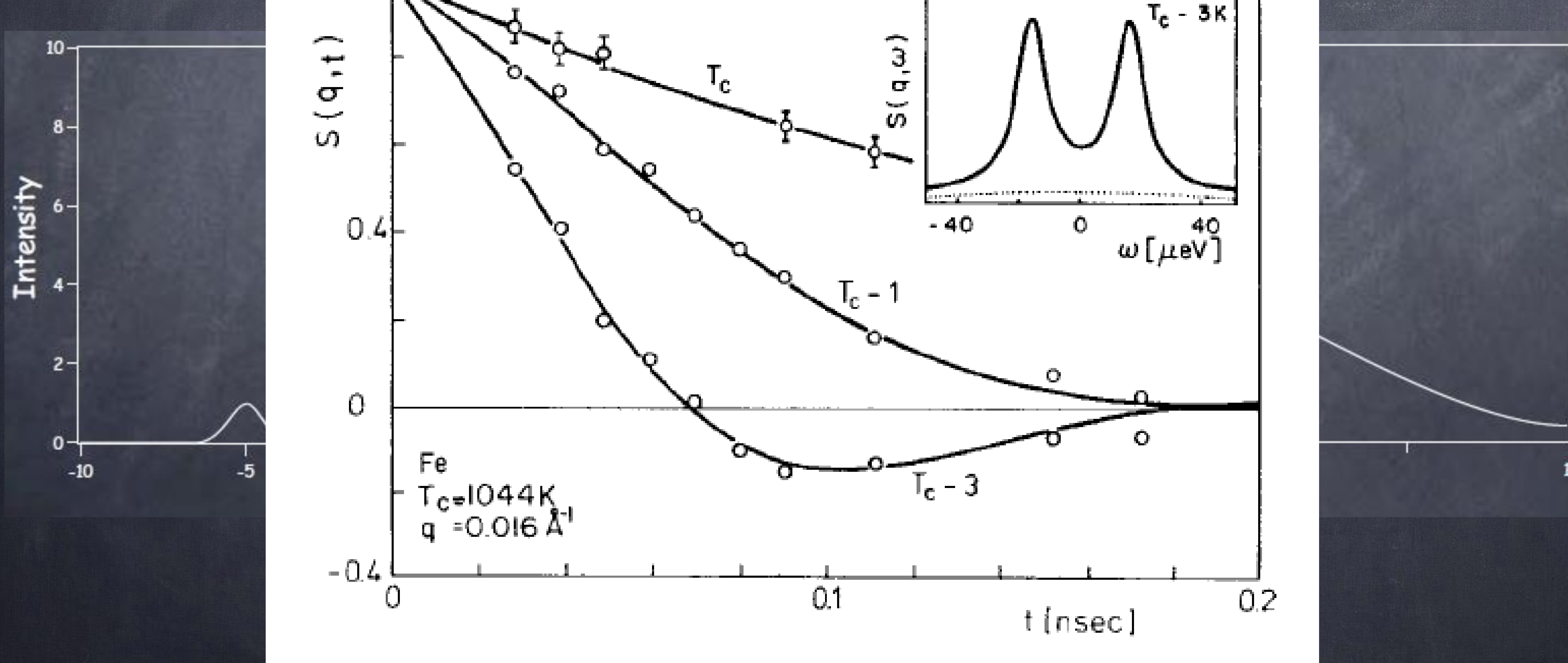
Mathematically more basics



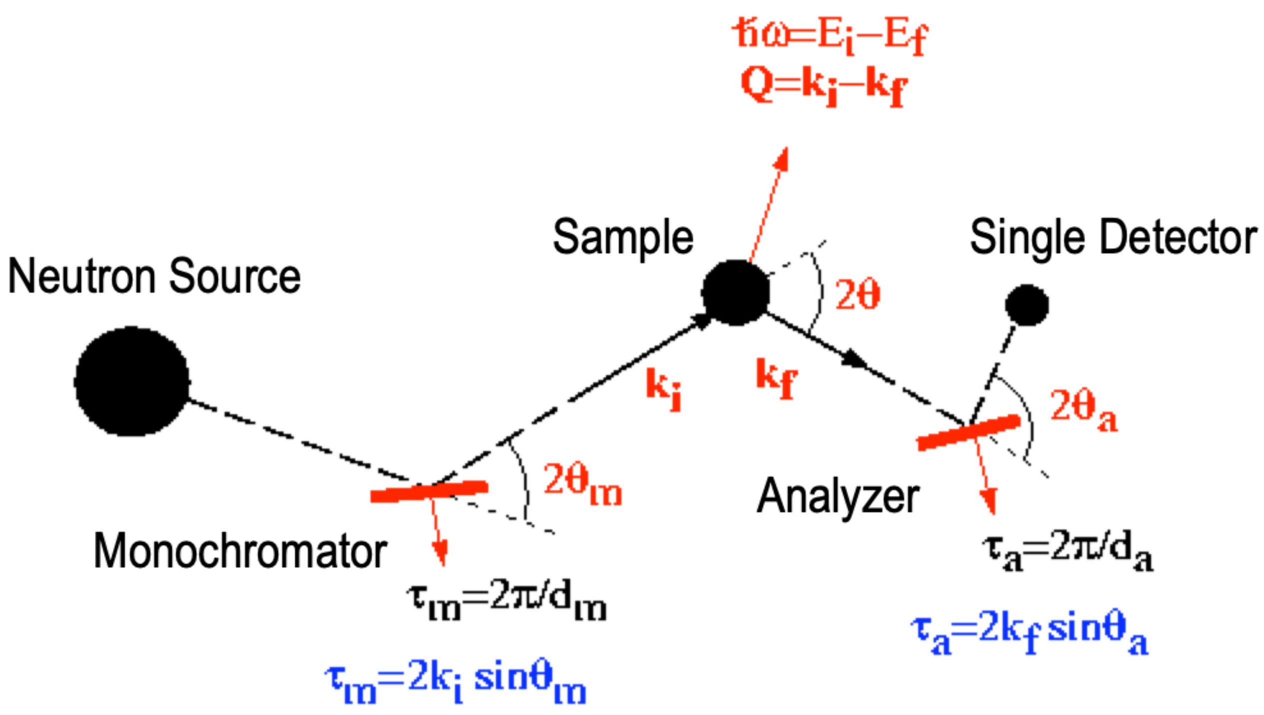
Time domain measurements

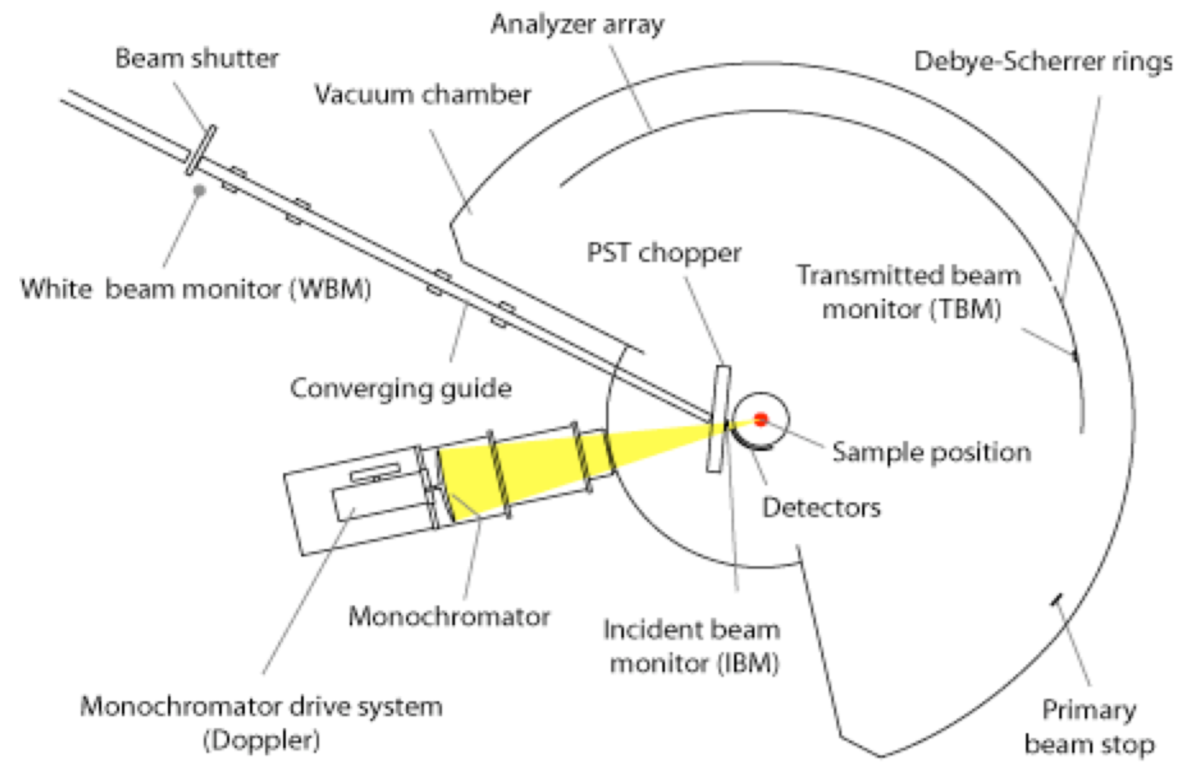
$$I(q,t) = \int S(q,\omega) \exp(-i\omega t) d\omega$$

En … in



So Far, you have learnt





10^2 μeV

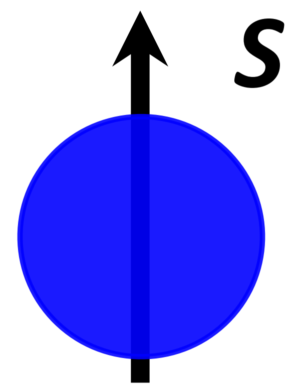
10^0 μeV

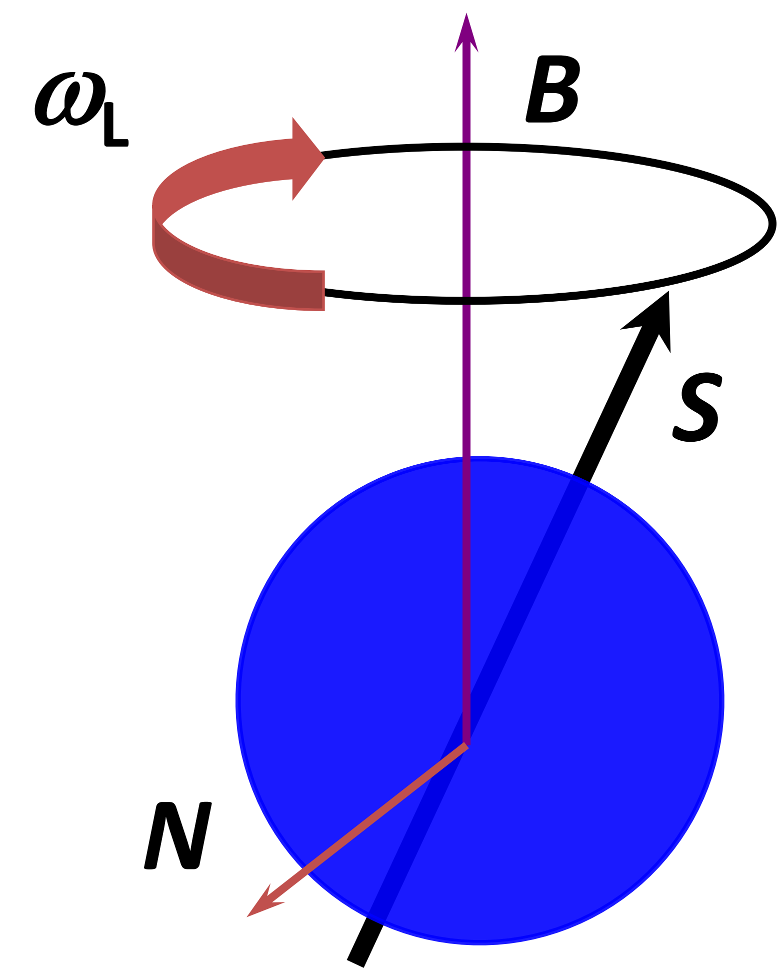
The Idea of Neutron Spin Echo

NSE Breaks the Relationship between Intensity & Resolution

- Traditional Instruments – use collimators, monochromators, choppers etc to define both $\underline{k}_i$ and $\underline{k}_f$ in order to define E and $\underline{Q}$ accurately
- NSE – measure the *difference* between appropriate components of $\underline{k}_i$ and $\underline{k}_f$ (original use: measure $\underline{k}_i - \underline{k}_f$ i.e. energy change)
- NSE – use the neutron's spin polarization to encode the difference between components of $\underline{k}_i$ and $\underline{k}_f$
- NSE – can use large beam divergence &/or poor monochromatization to increase signal intensity, while maintaining great resolution

Neutron Precession





Neutron Properties

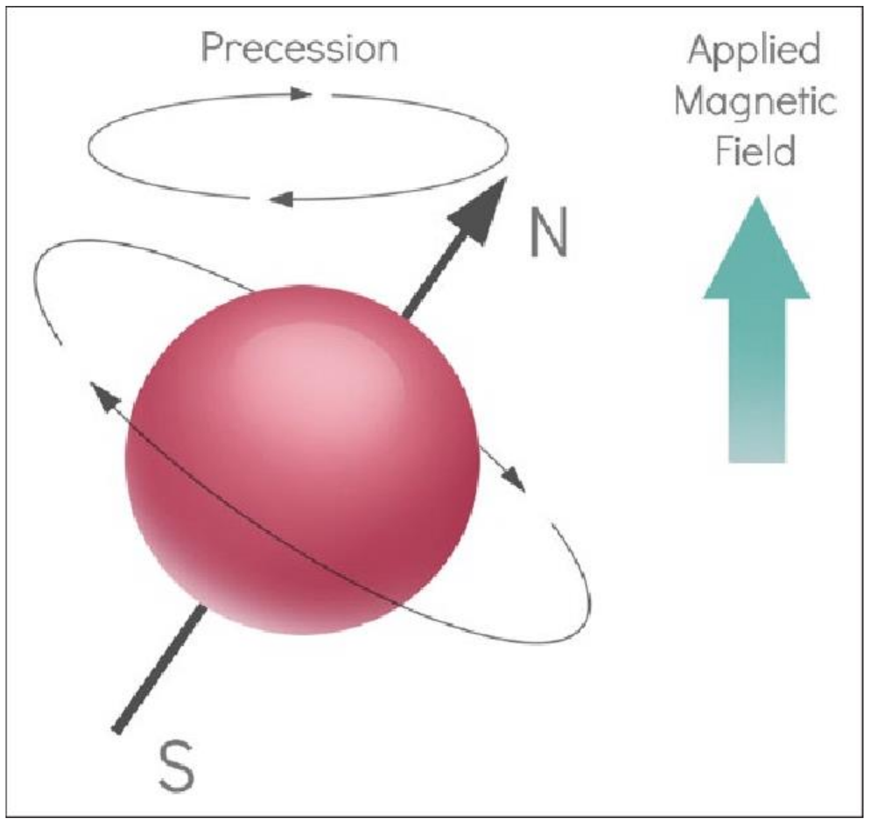
- Mass, $m_n = 1.675\times10^{-27}$ kg
- Spin, $S = 1/2$ [in units of $h/(2\pi)$]
- Gyromagnetic ratio $\gamma = g_n\mu_n/[h/(2\pi)] = 1.832\times10^{8}\ s^{-1}T^{-1}$ (29.164 MHz T^{-1})

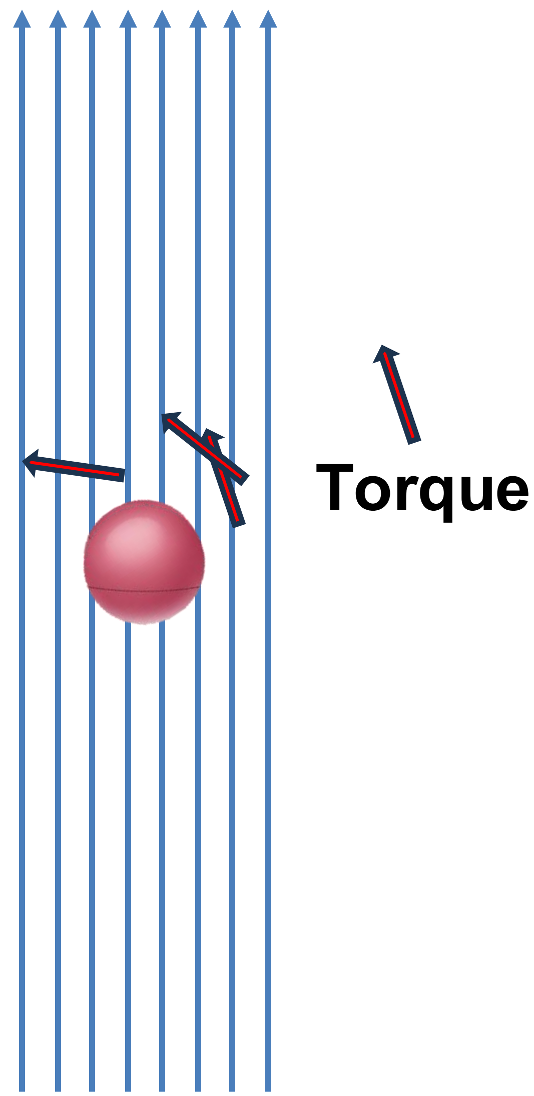
In a Magnetic Field

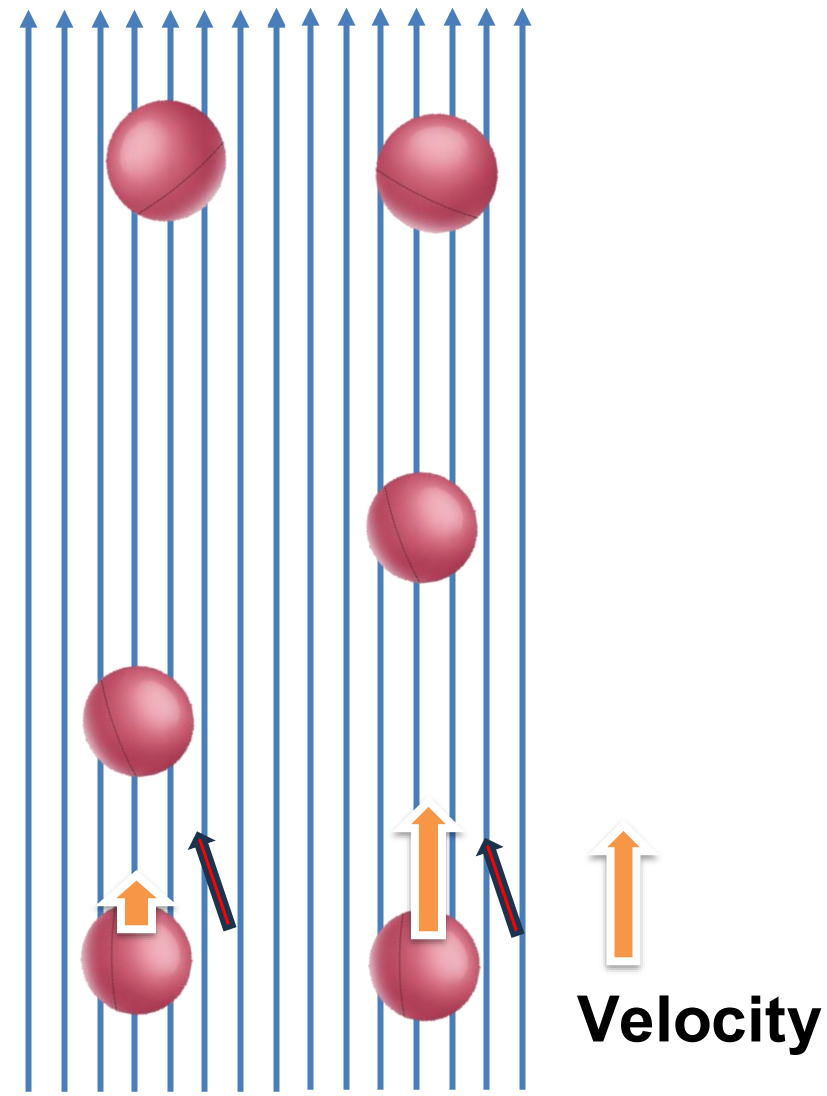
- The neutron experiences a torque from a magnetic field B perpendicular to its spin direction. ⟹ $N = S \times B$

- Precession with the Larmor frequency: ⟹ $\omega_L = \gamma B$

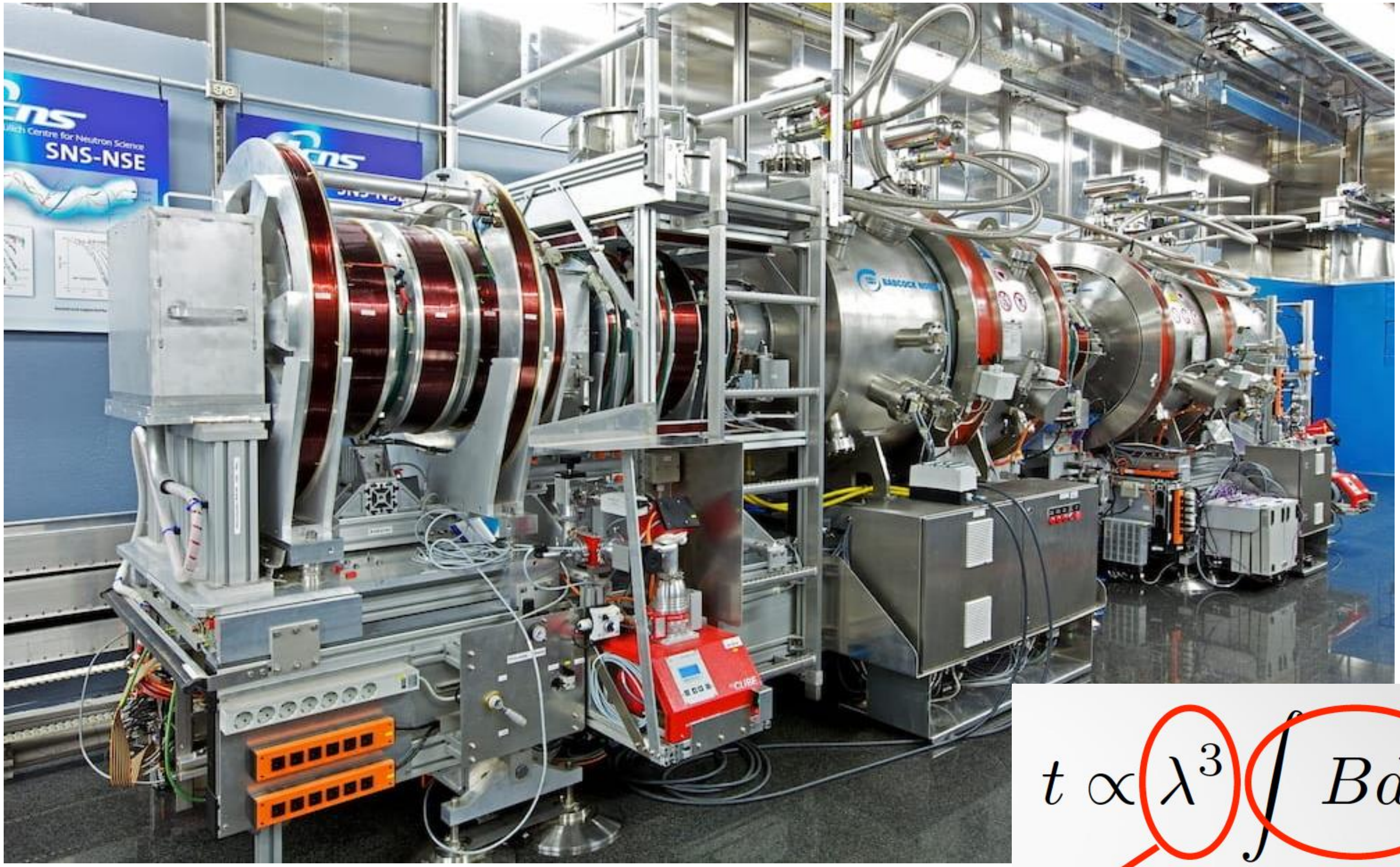
Spin in a Field







Spin Echo Principle

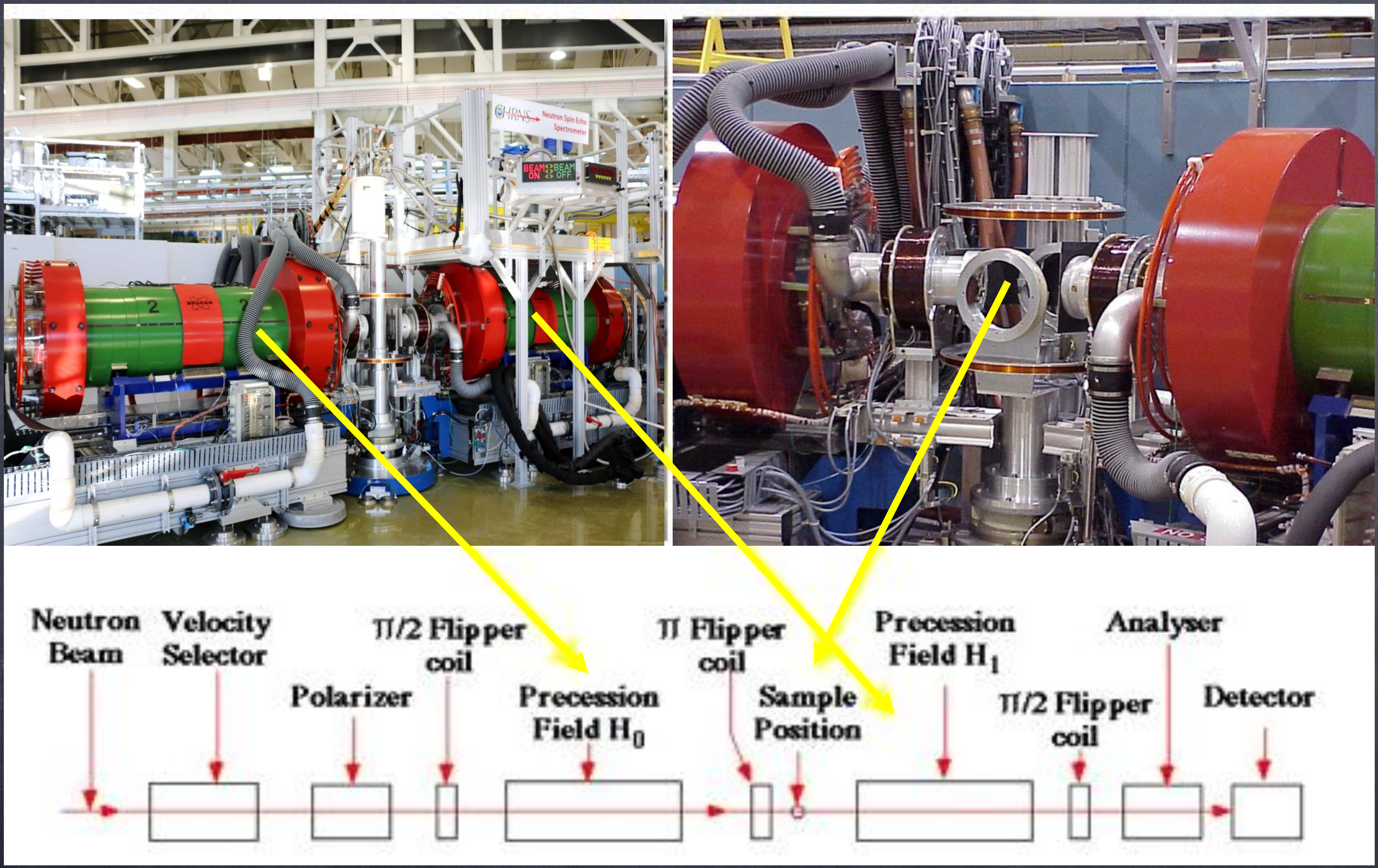


$$t \propto \lambda^3 \int B dl$$

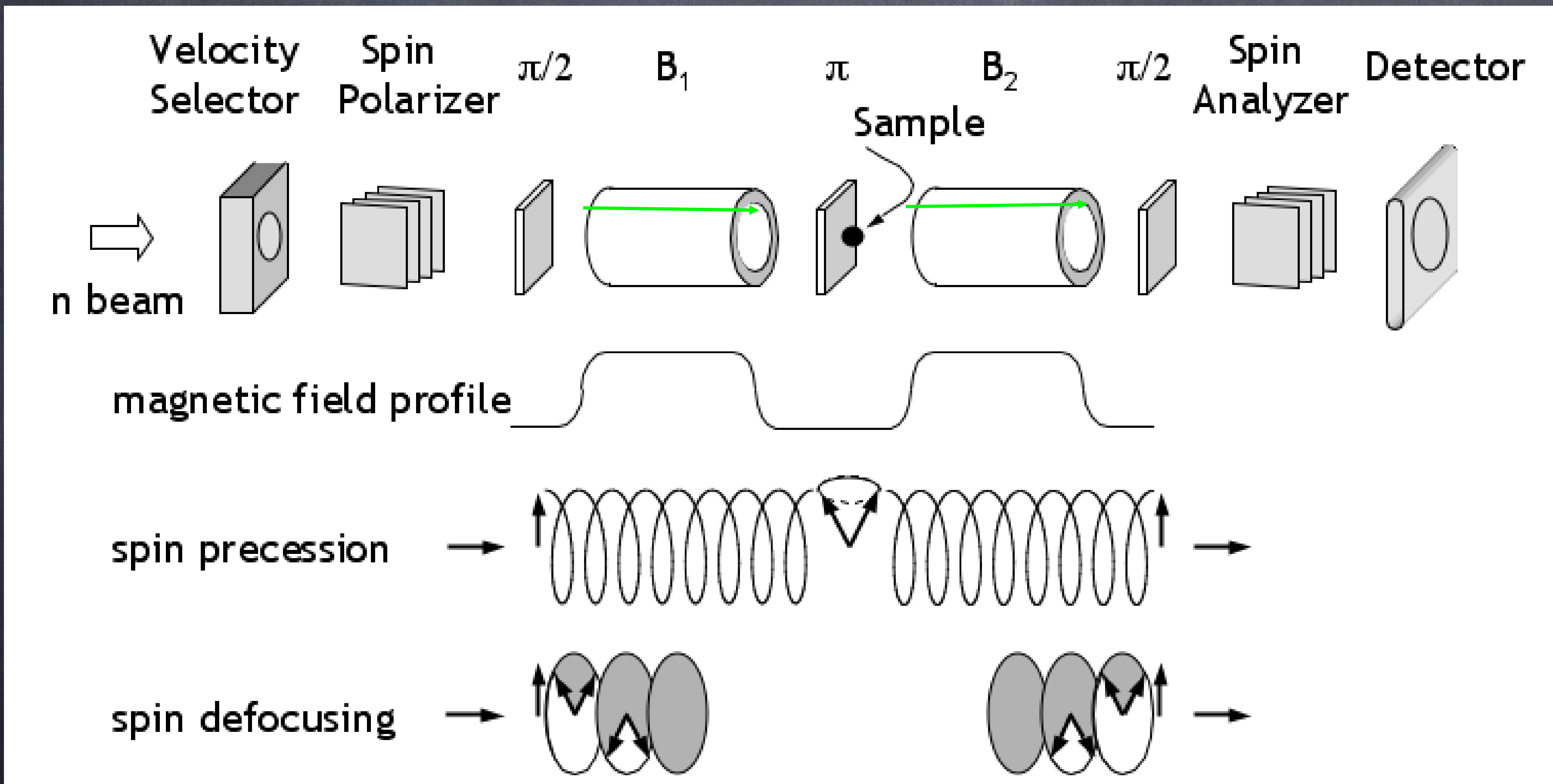
v. strong wavelength dependence

Field Integral from Solenoids

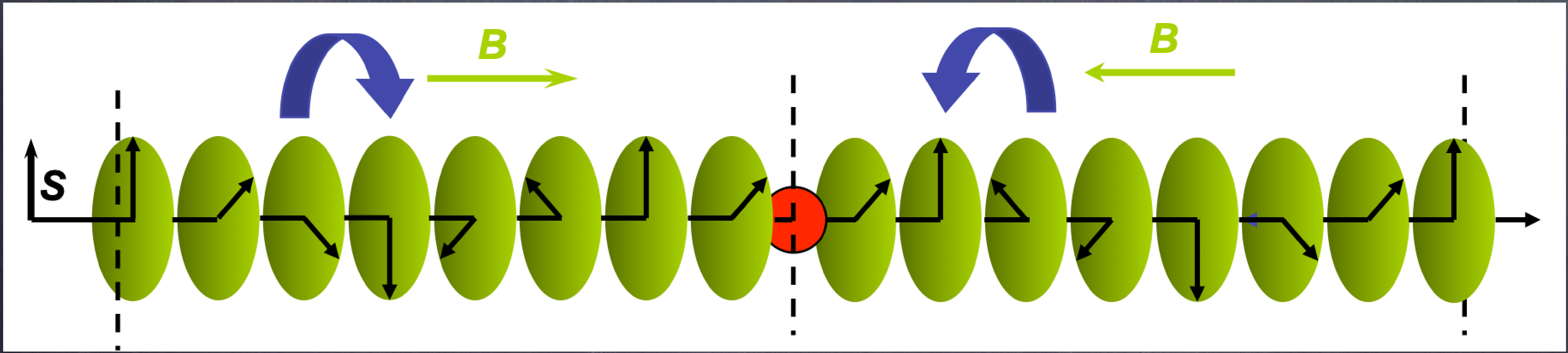
J.S. Gardner, G. Ehlers, A. Faraone, and V. Garcia-Sakai "High-resolution neutron spectroscopy using backscattering and neutron spin-echo spectrometers in soft and hard condensed matter" Nature Reviews Physics, 2, 103 (2020).



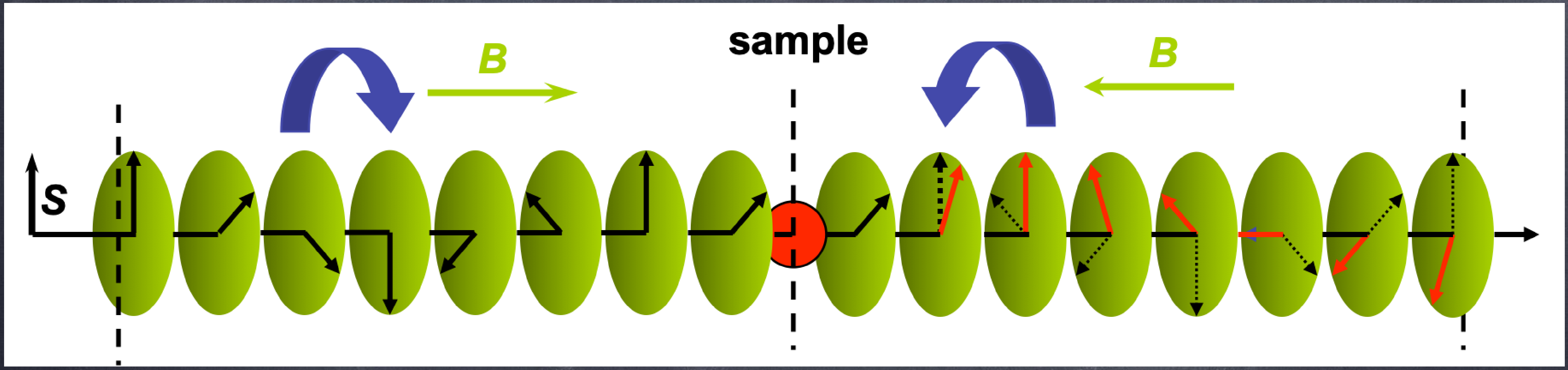
Main Components

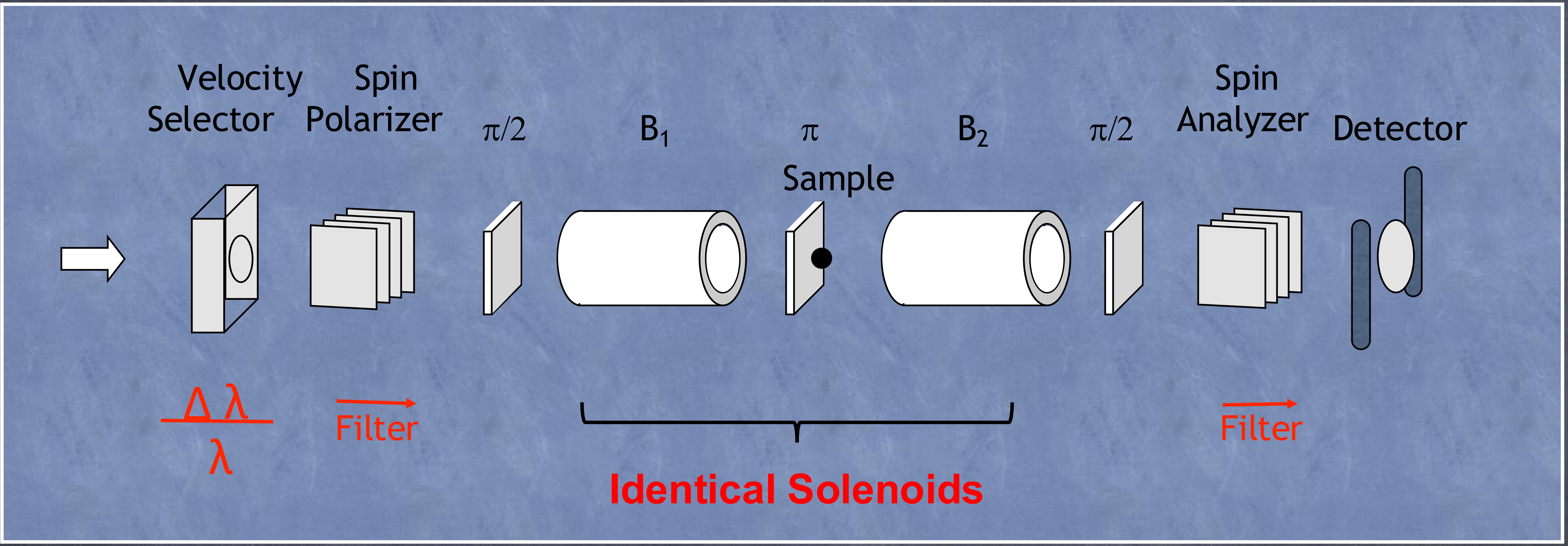

Velocity Selector
Spin Polarizer
π/2
B1
π
B2
π/2
Spin Analyzer
Detector
Sample
n beam
magnetic field profile
spin precession
spin defocusing

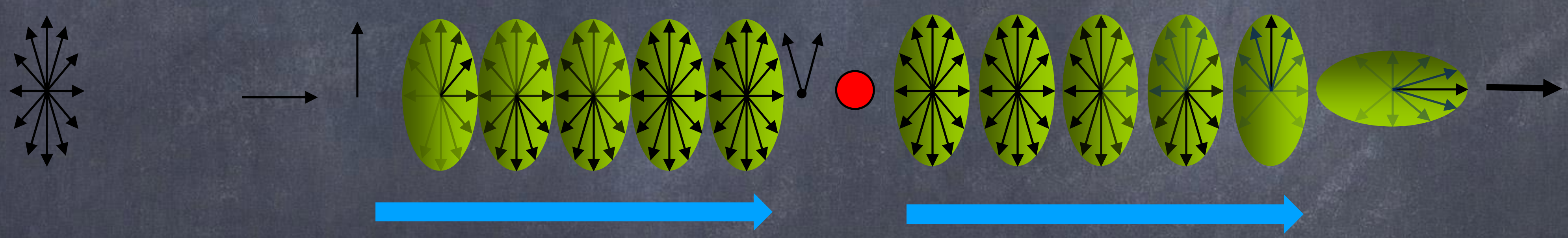
SINGLE Wavelength ELASTIC Scatter

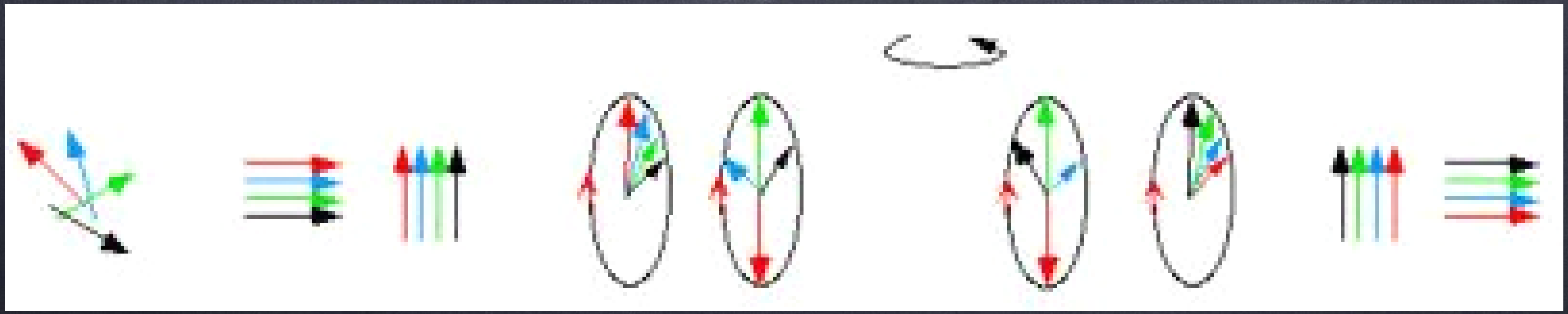


SINGLE Wavelength <u>INELASTIC</u> Scatter



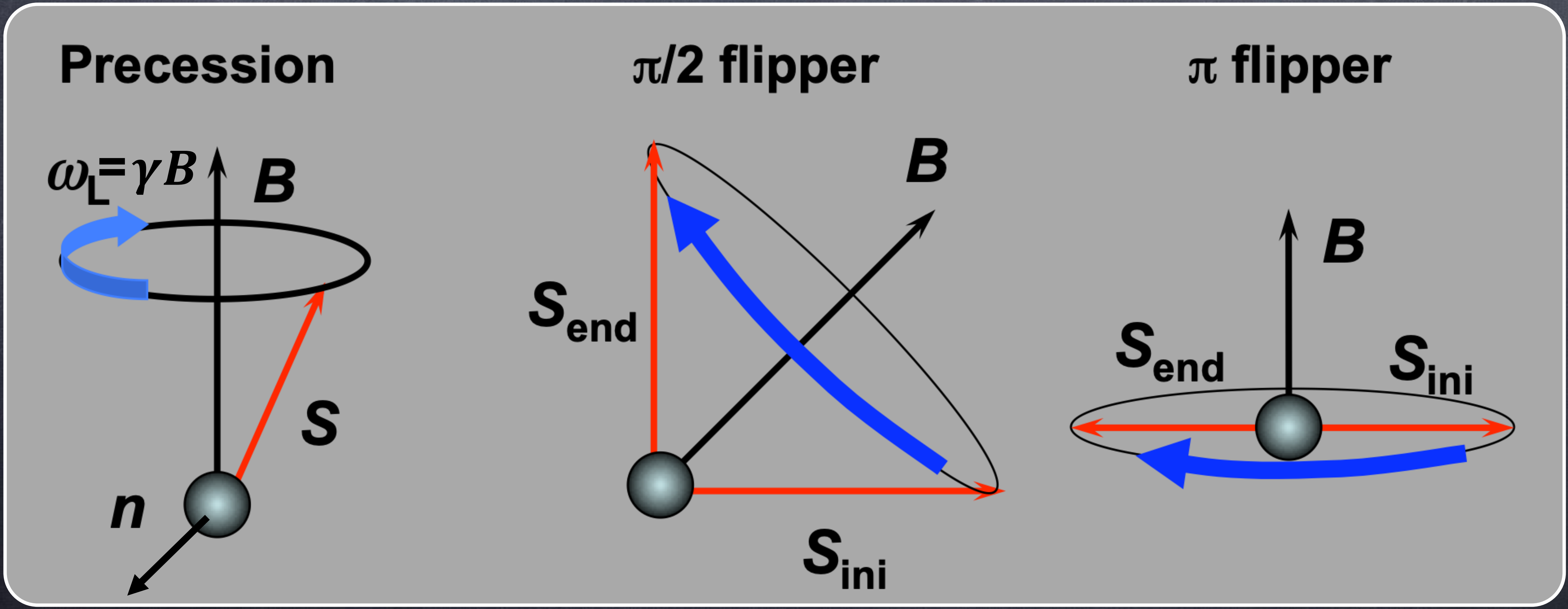






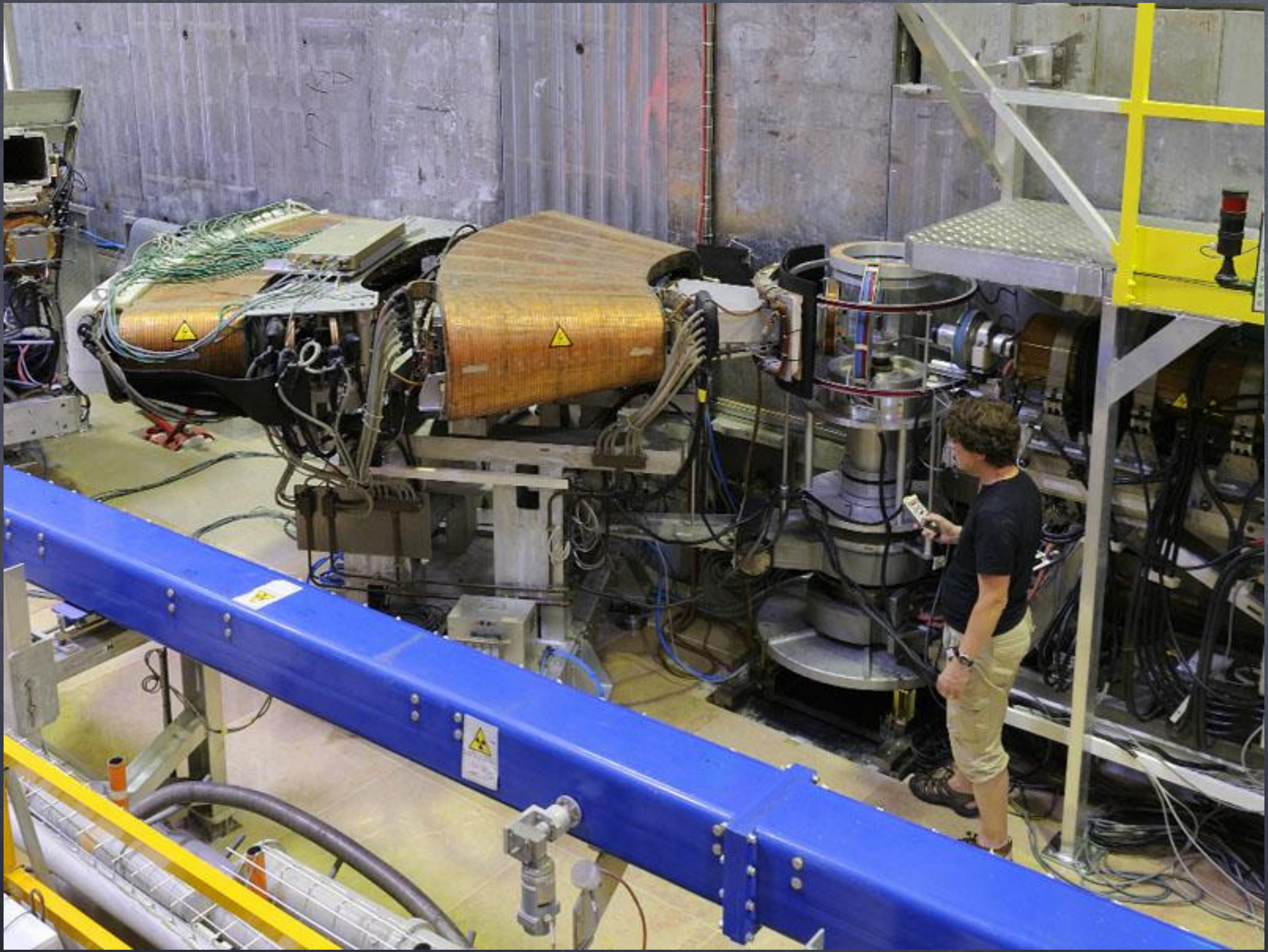
Polarized Beam

Re-Polarize The Beam

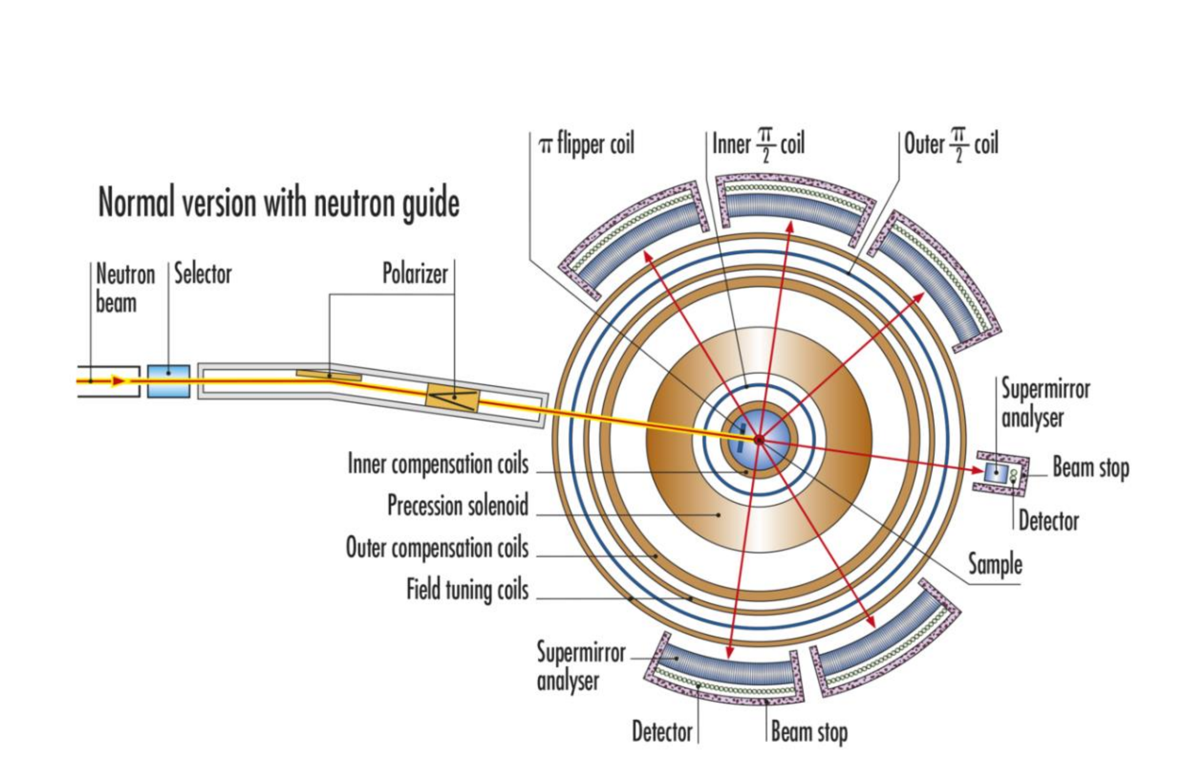


flipper (π or π/2)

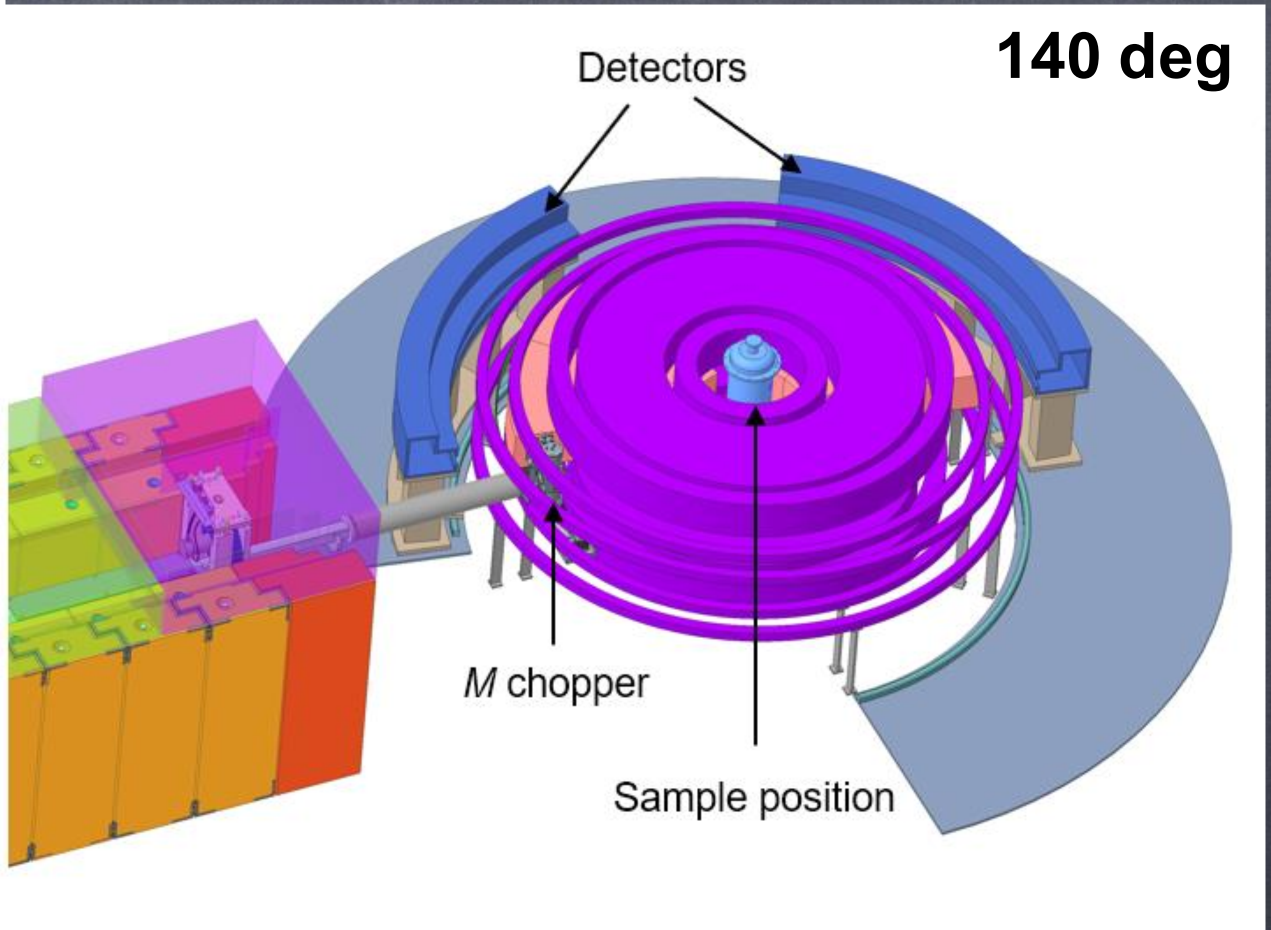
Standard Detector, BUT you can imagine bigger



Wide Angle (30 deg)



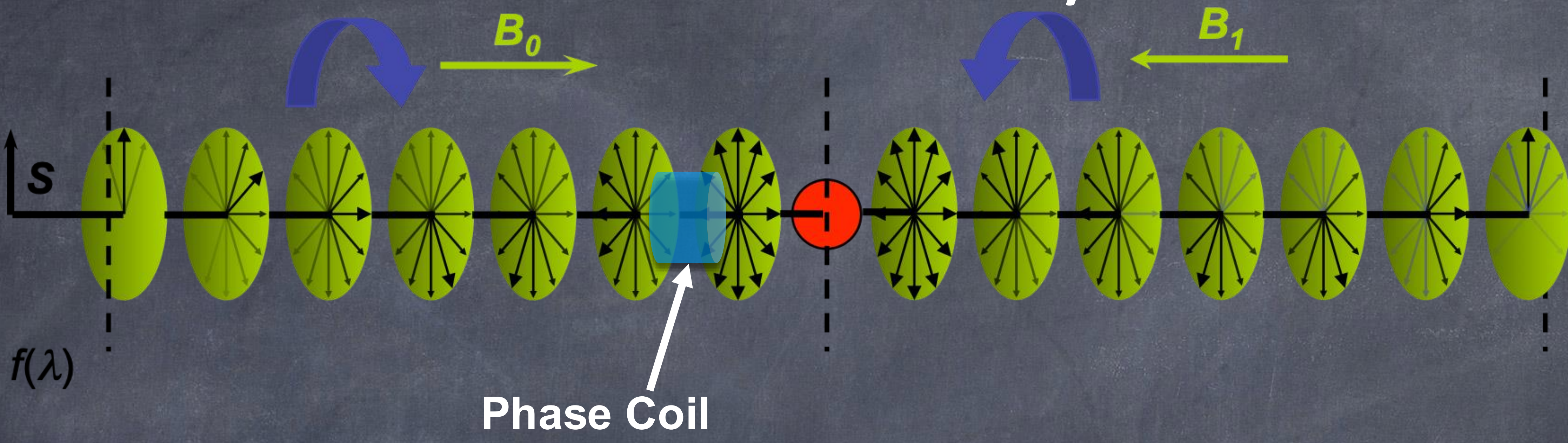
120 deg

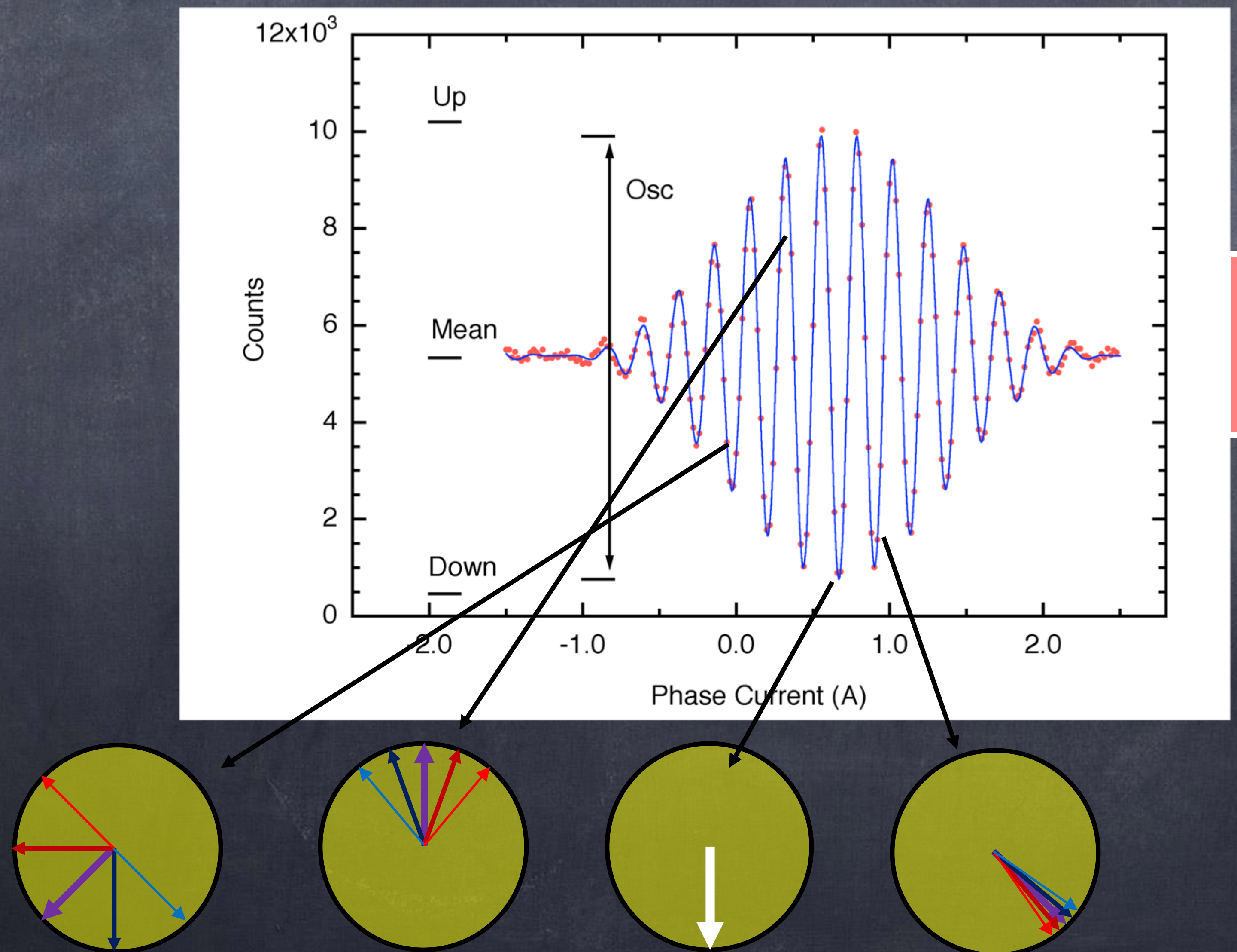


USA Dream

WASP / Expasne

What do we actually do?



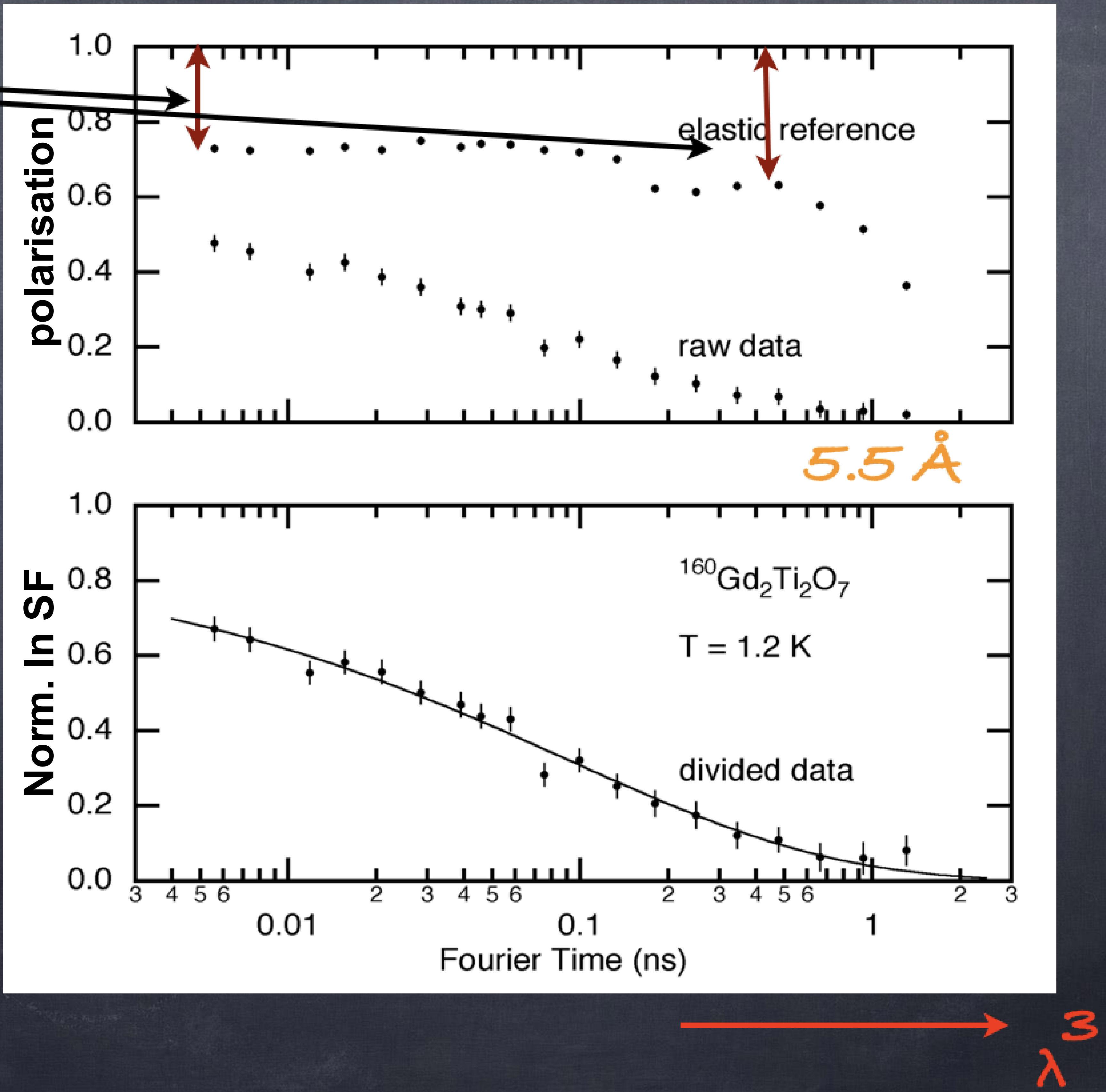


$$\frac{I(Q,t)}{I(Q)} \propto \frac{2A}{Up - Dwn}$$

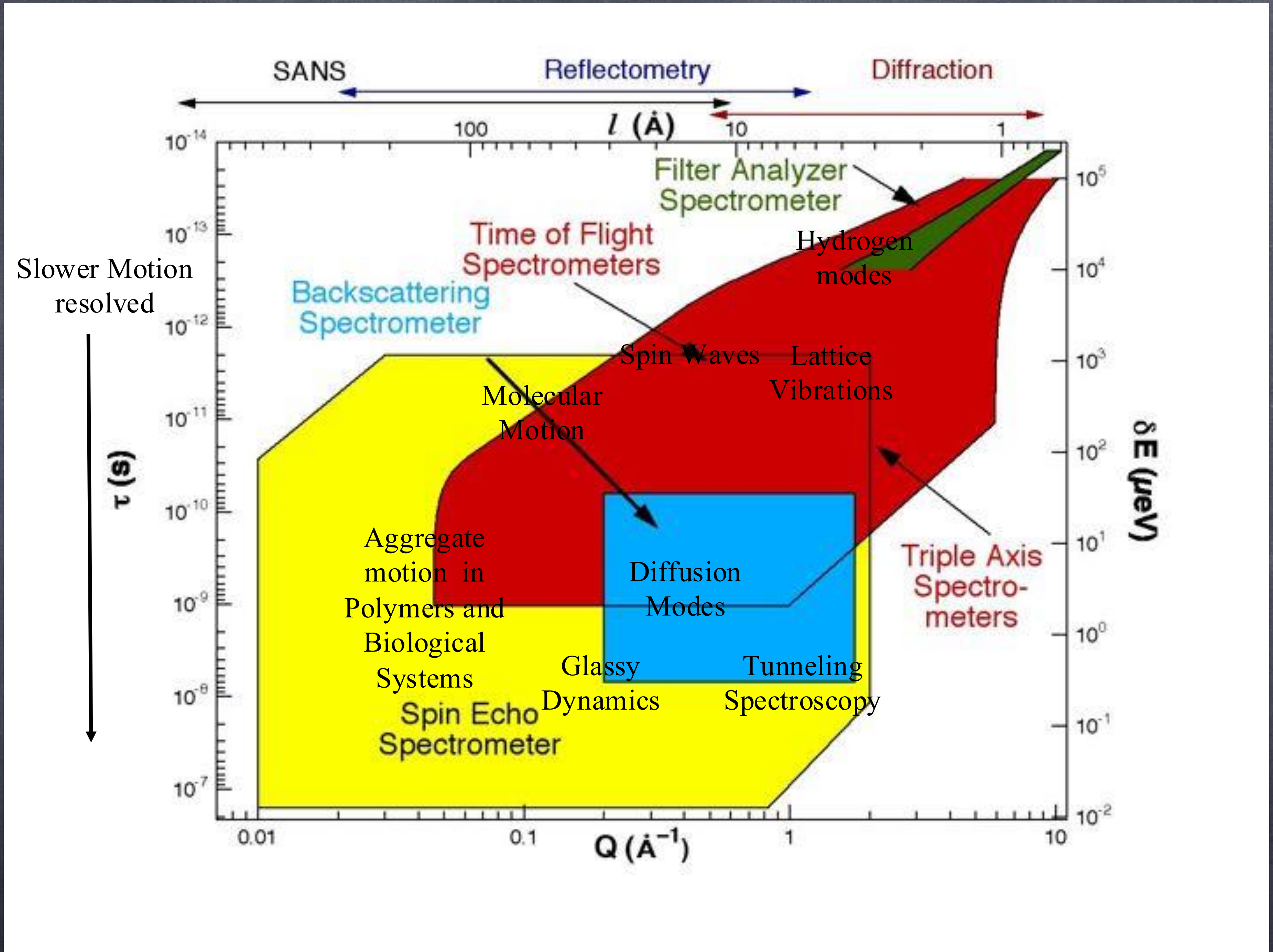
Data Analysis Procedure

Imperfections in the instrument

$$\frac{I(Q,t)}{I(Q,0)} = \frac{2A/(Up - Dwn)}{2A^R/(Up^R - Dwn^R)}$$



Now some Science

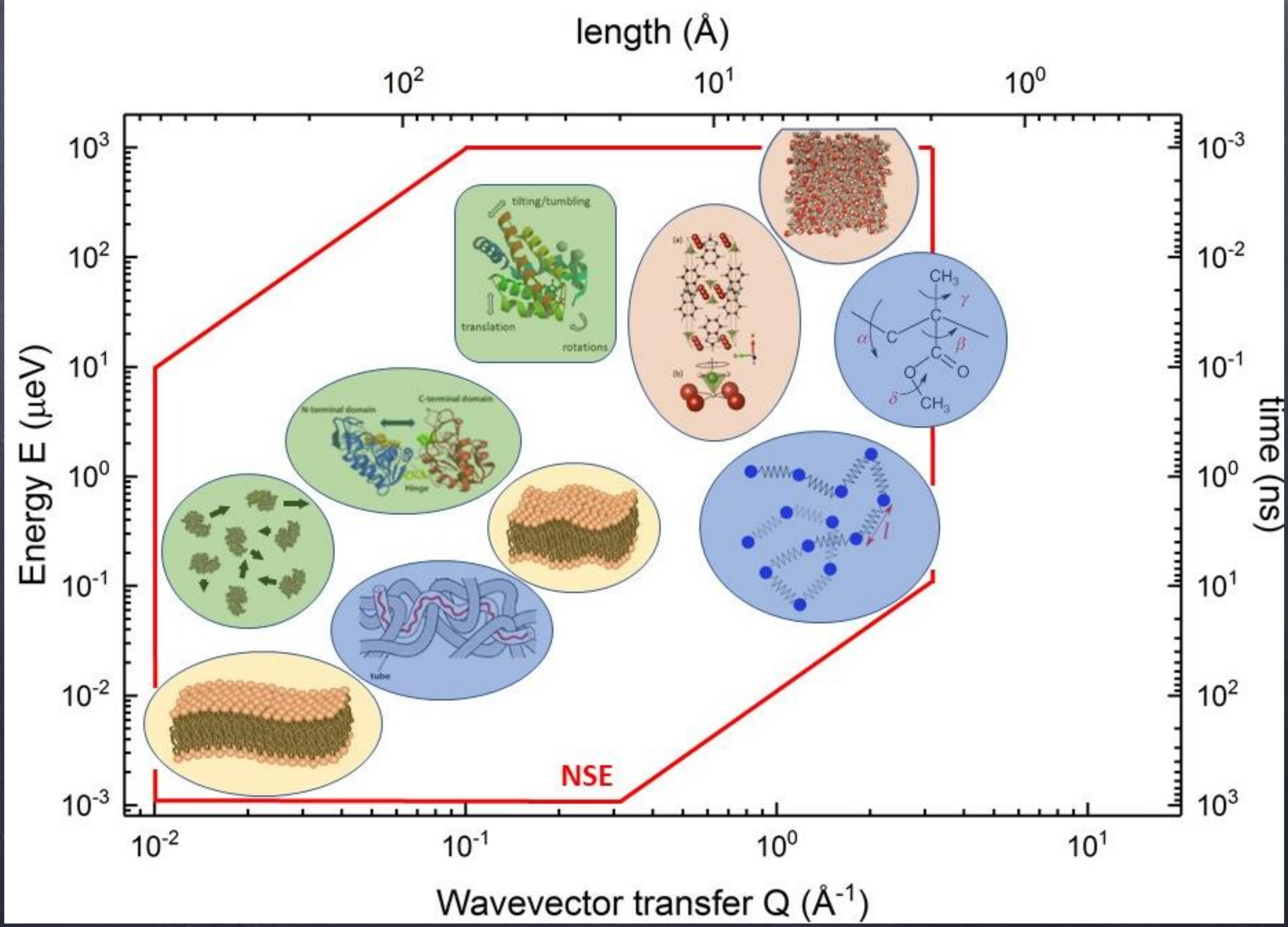


NSE Science

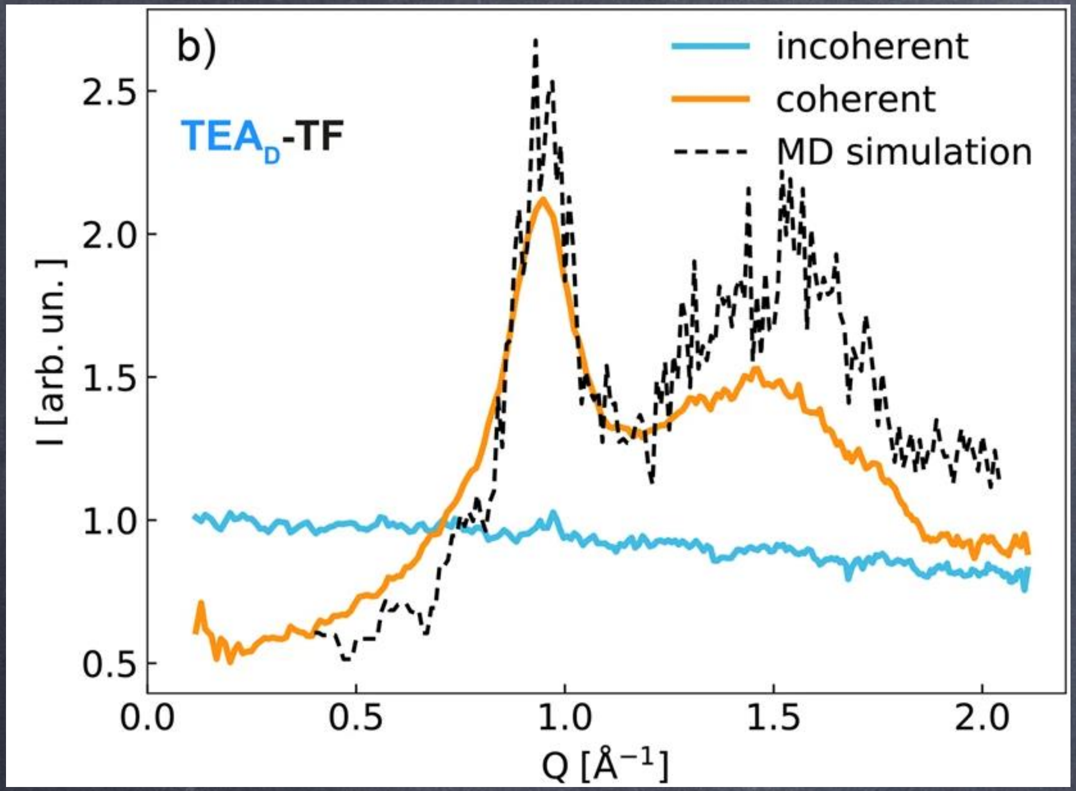
- Coherent Dynamics
  Density Fluctuations corresponding to some SANS pattern
  - Diffusion
  - Shape Fluctuations (Internal Dynamics)
  - Liquid and Glassy Systems
  - Polymer Dynamics

- Incoherent Dynamics
  Single particle
  motion of H atoms

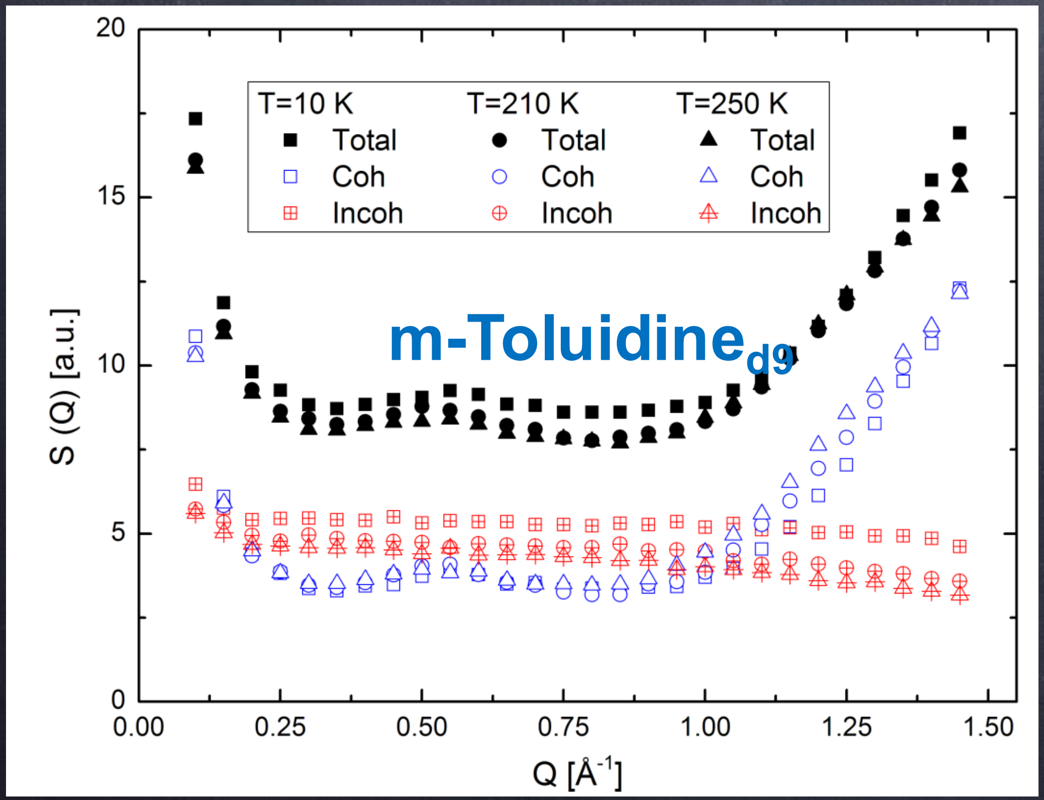
- Paramagnetic Dynamics
  Spin Glasses

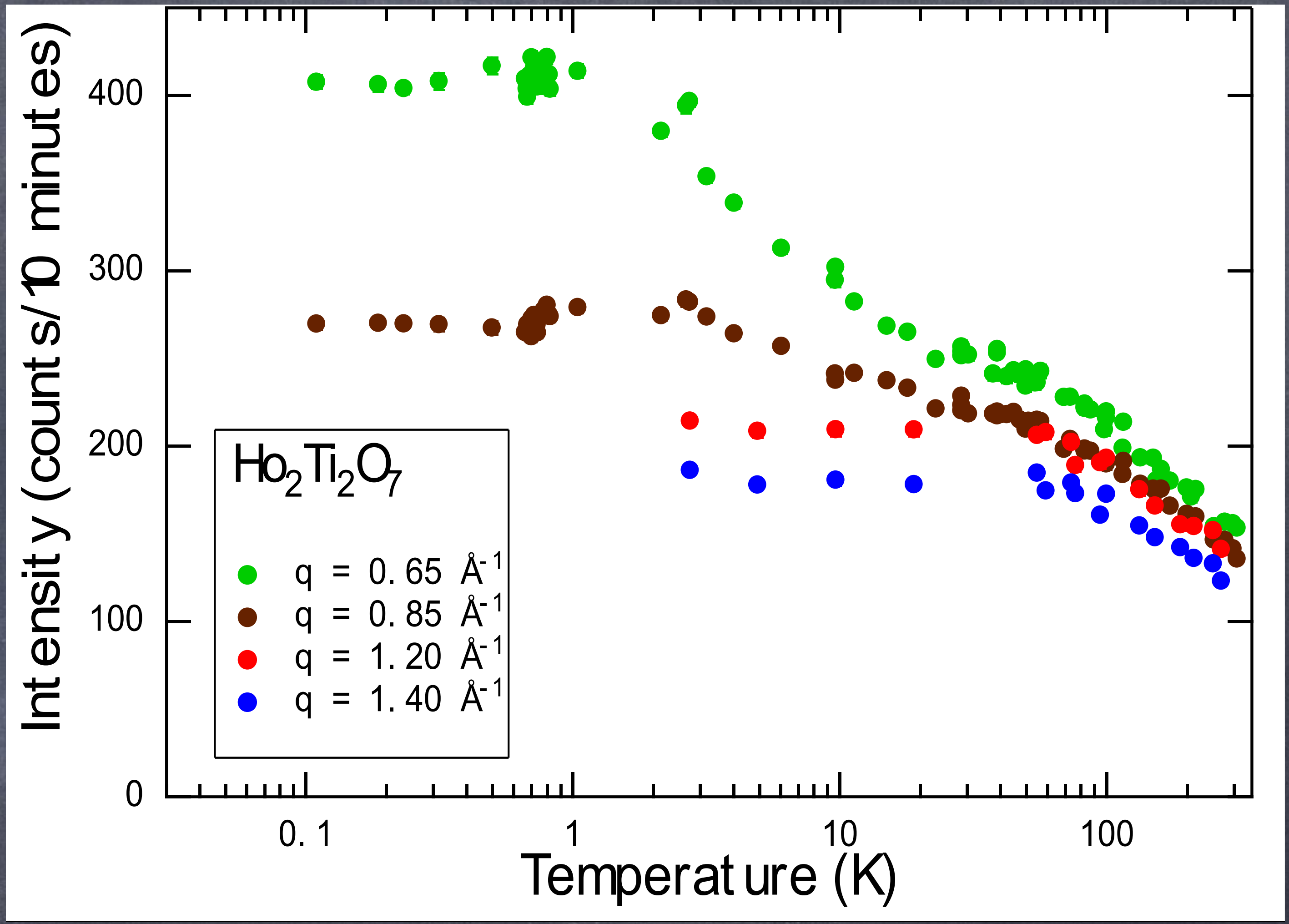


Not to be encouraged, but is at the heart of NSE



Sci Reports 8 16400 (2018)





J Phys Cond Matt 18 R231 (2006)

Polarized Analysis

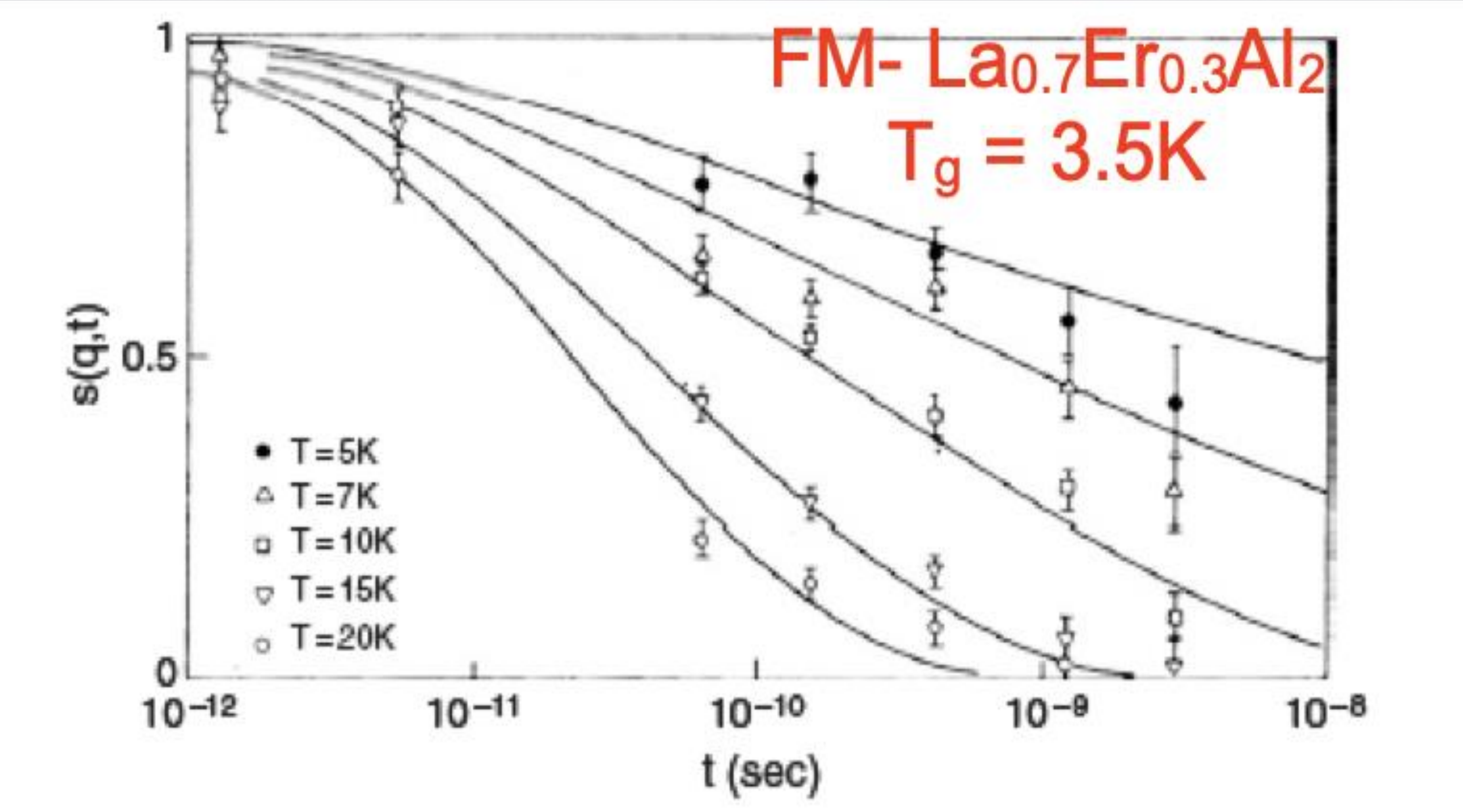
Rem. Barry on Wednesday

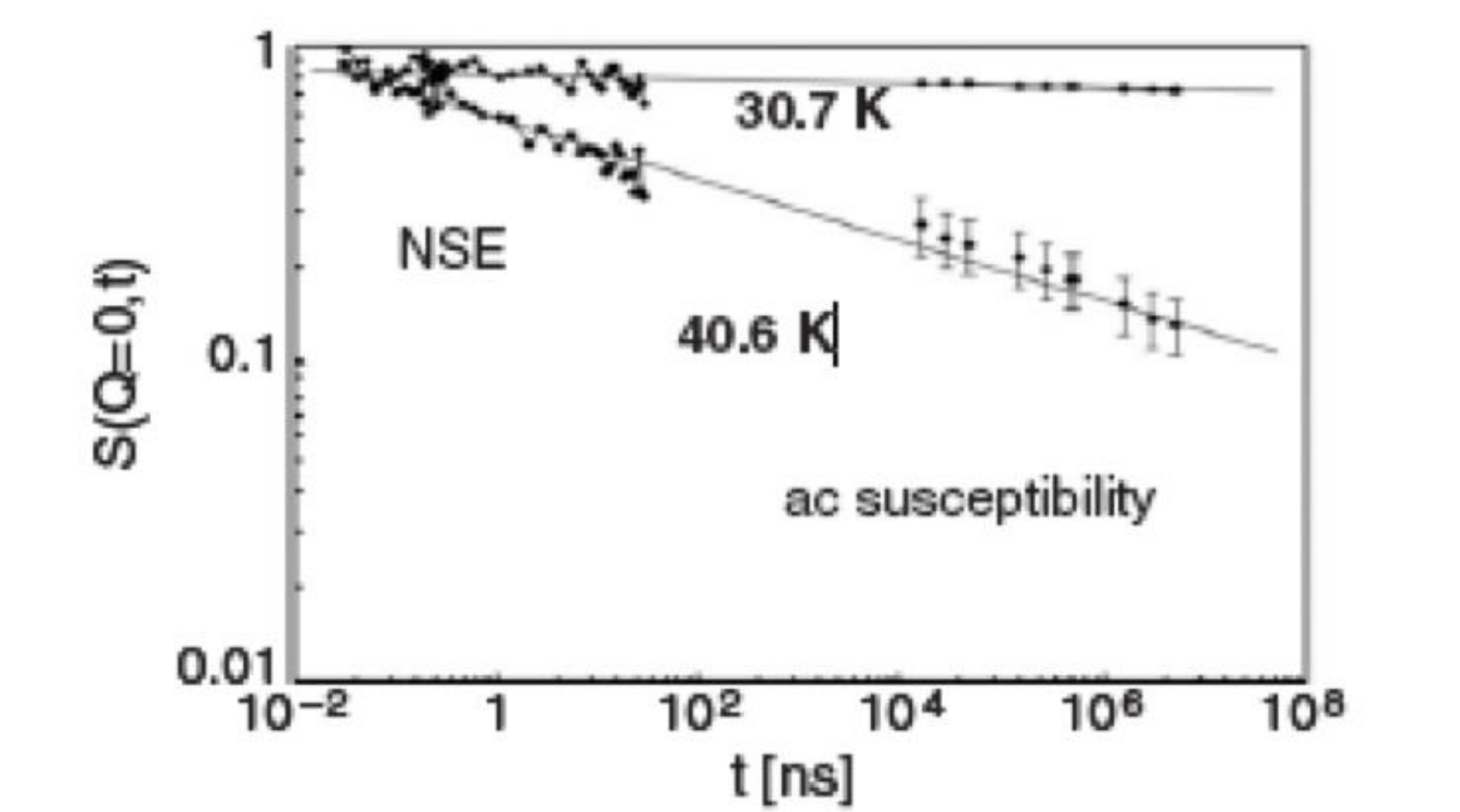
Spin Glasses

Disordered systems

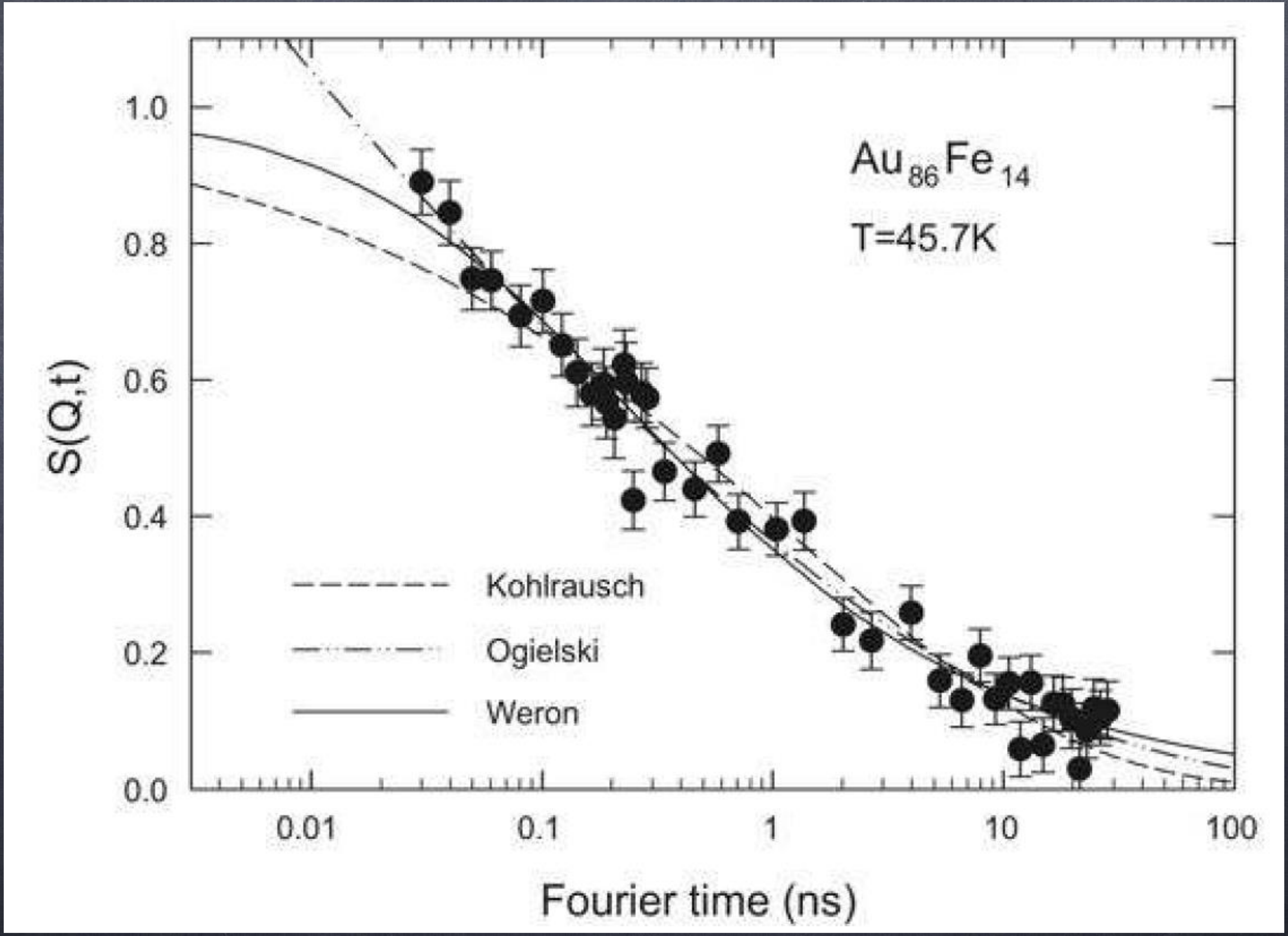
Mezei, Solid State Comm. 45, 411 (1983)

Pappas, Solid State Comm. 68 054431, 2003



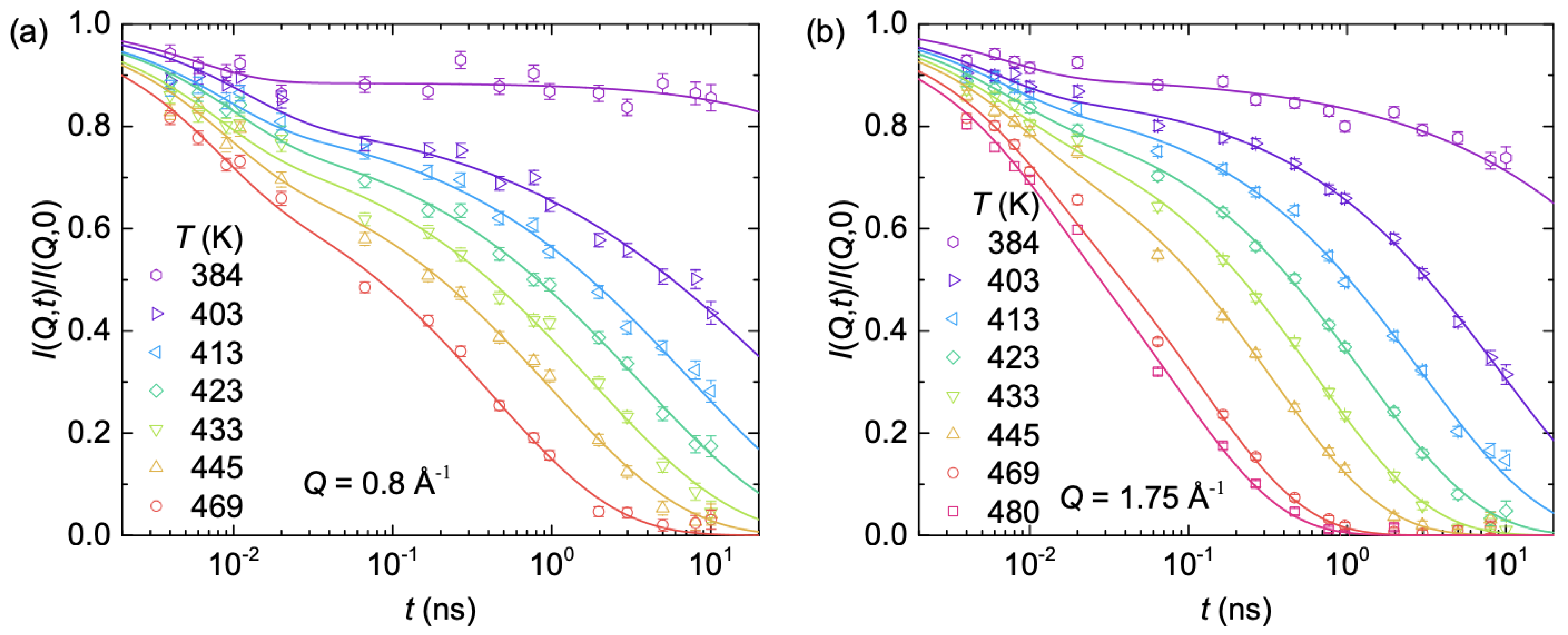


Spin Glasses



RM Pickup et al., PRL 102 097202 (2009)

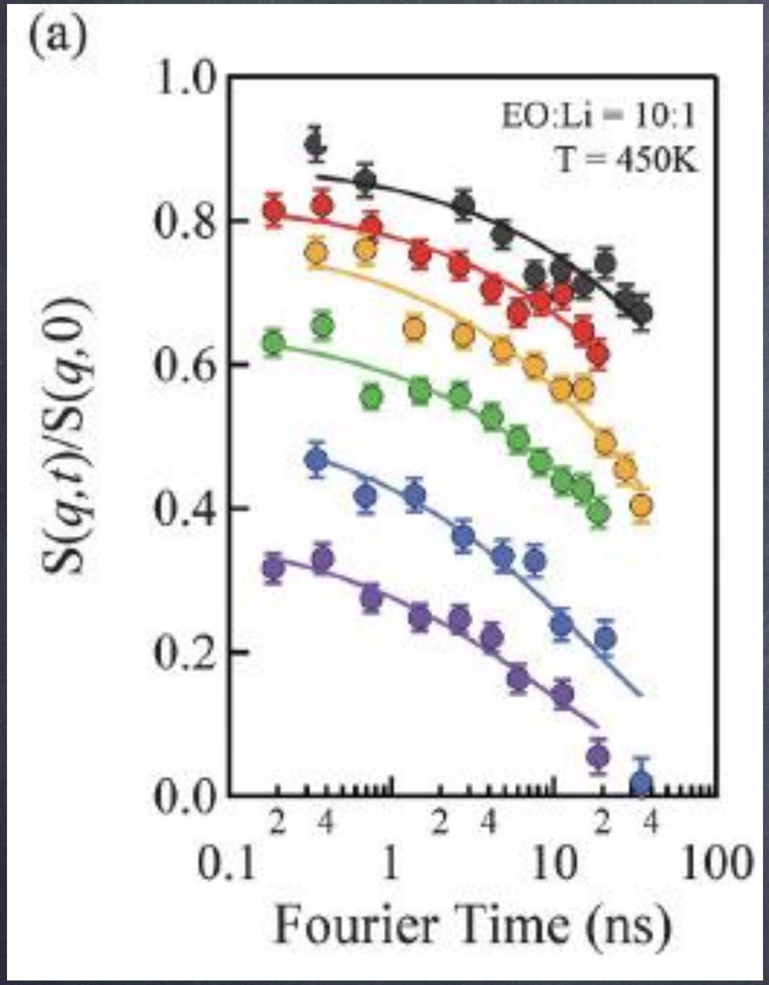
Glass forming Liquids



P. Luo … A. Faraone and YZ, Nature Comm. 13 2092 (2022)

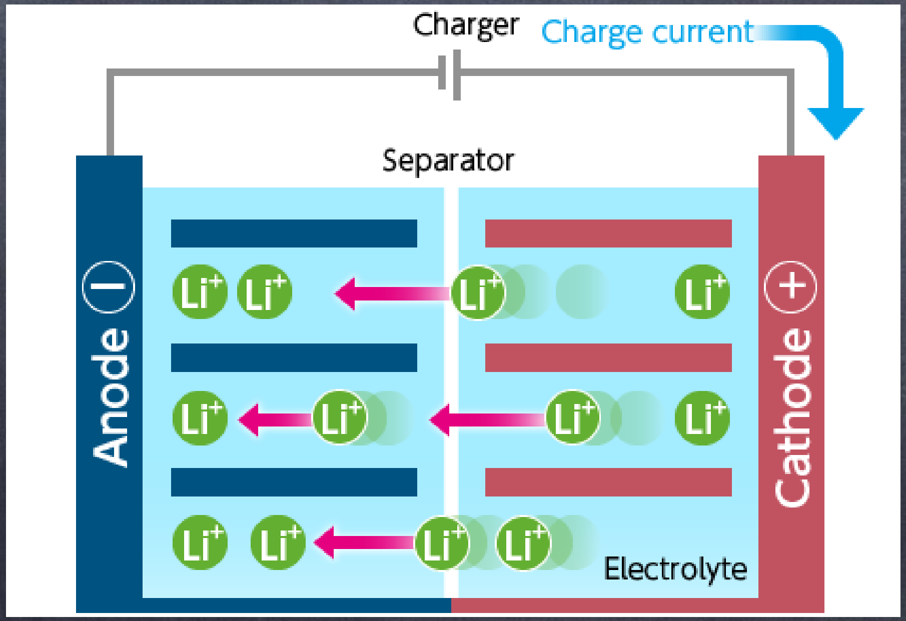
Multiple relaxation processes.

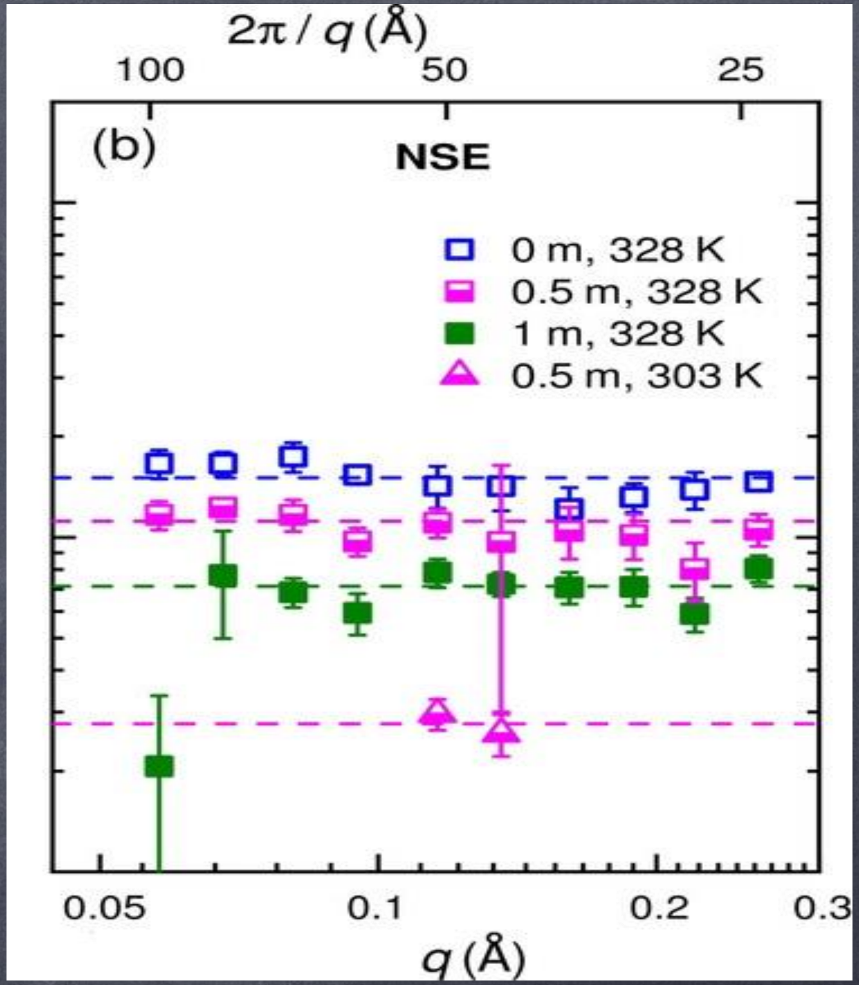
Electrolytes



C Do, et al PRL 111 018301 (2013)

Understanding the mechanisms of ionic diffusion is important for the design of new energy storage materials

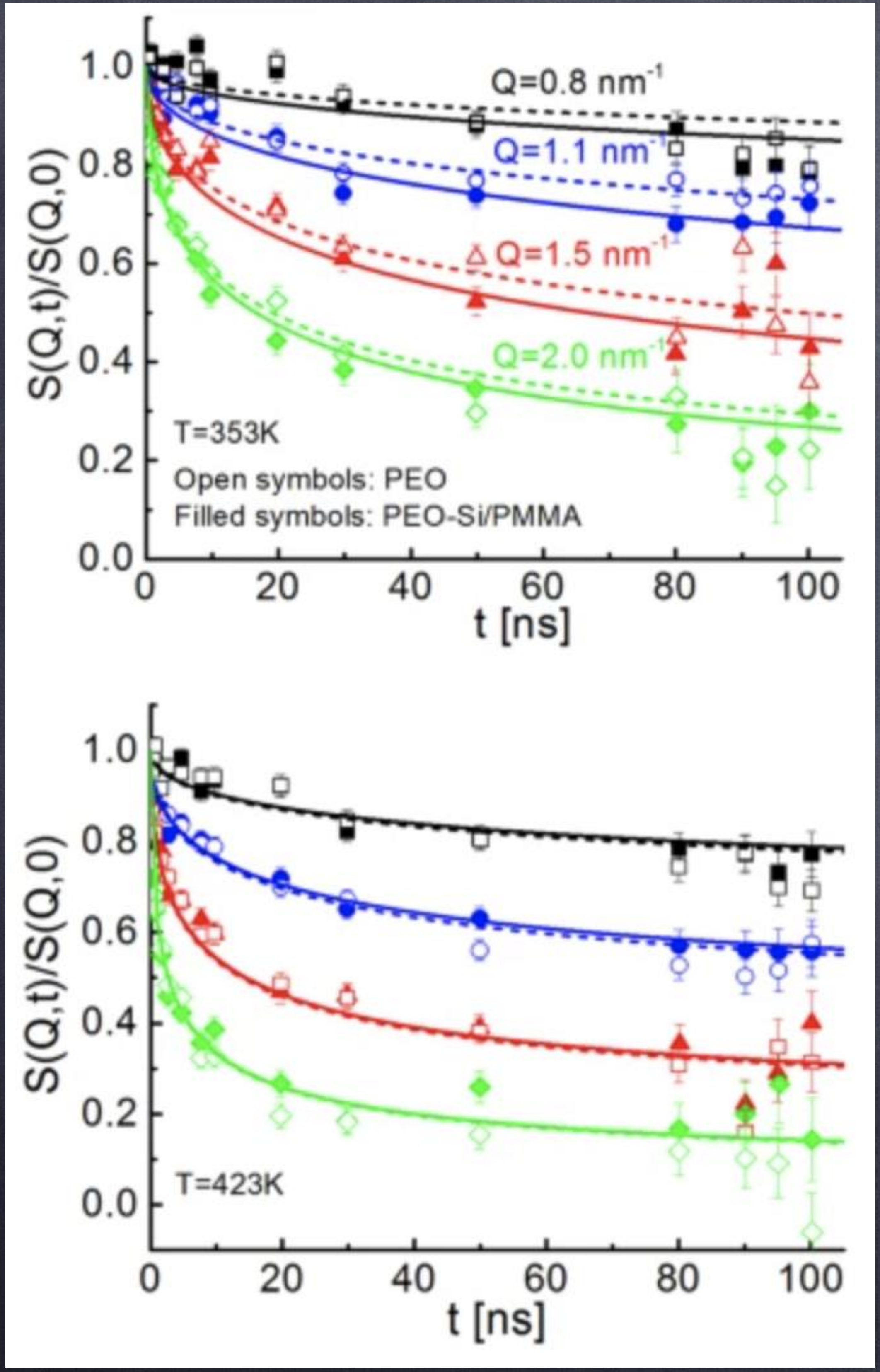


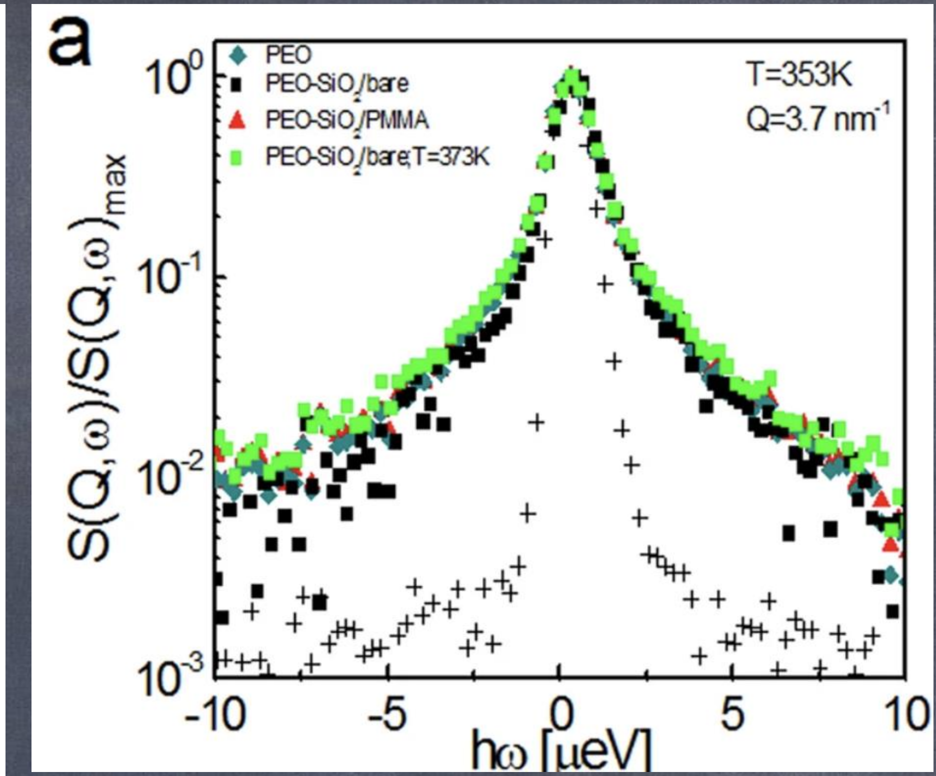


ChemSusChem, Vol 11, 3512-3523

Incoherent signal weak, Q dependence Critical

Nano Composites



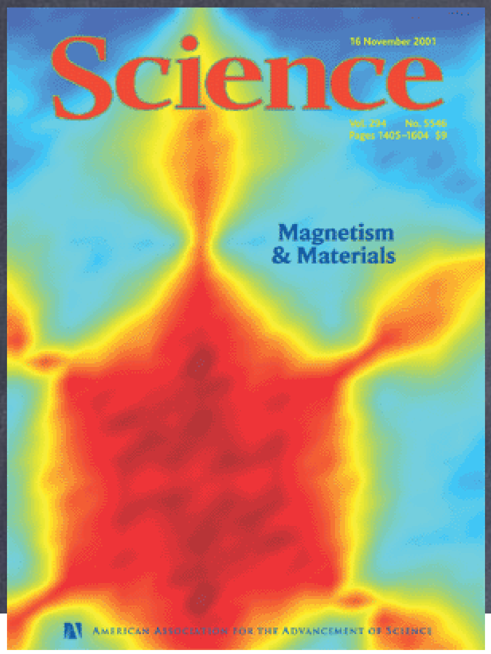


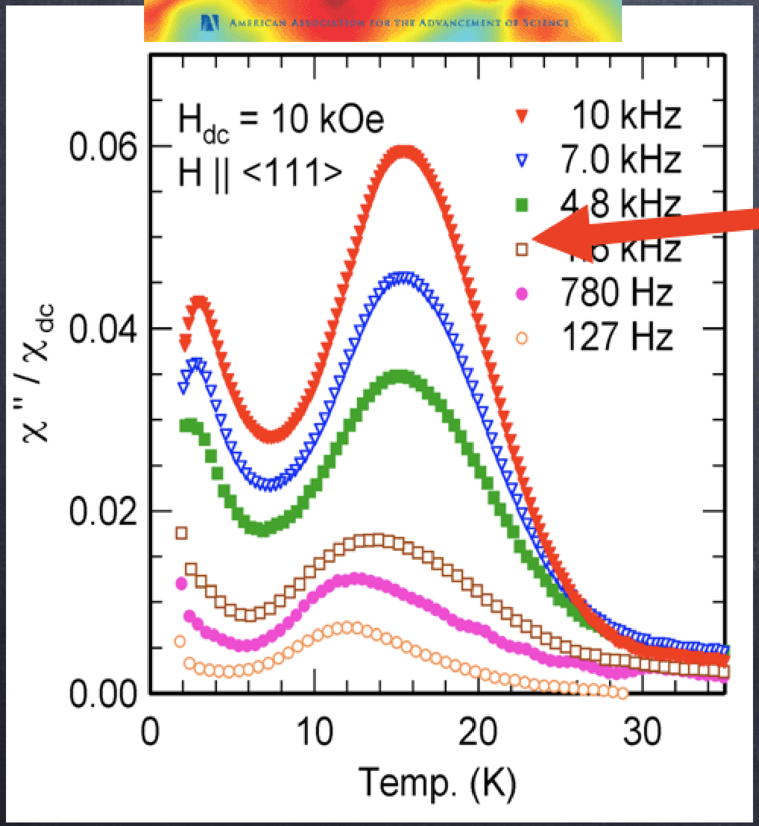
Taking advantage of selective isotope labeling of the chains, we studied the role of interfacial polymer on segmental and collective dynamics of the matrix chains

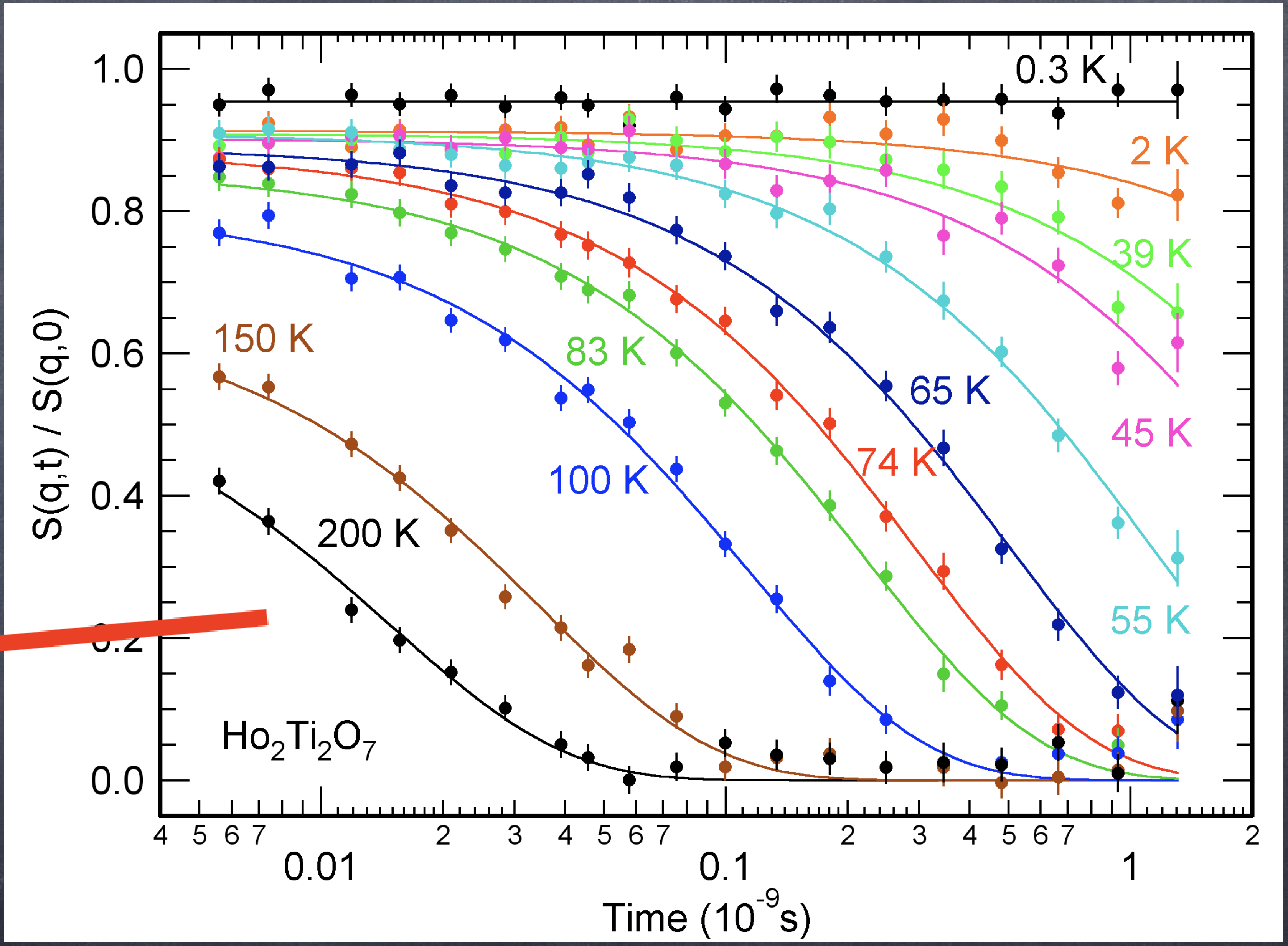
E. Senses, A. Faraone and Pinar Akcora, Scientific Reports (2016)

Spin ice

J Phys Cond Matt 15 L9 (2003)

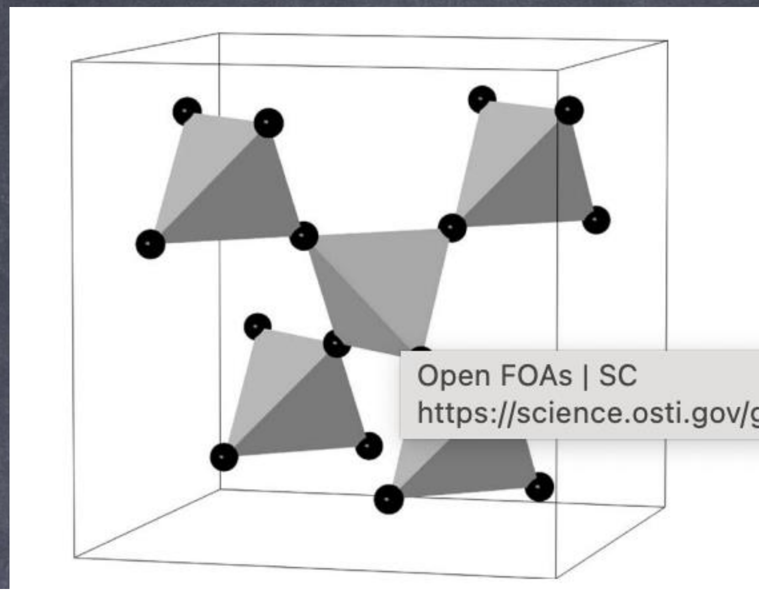


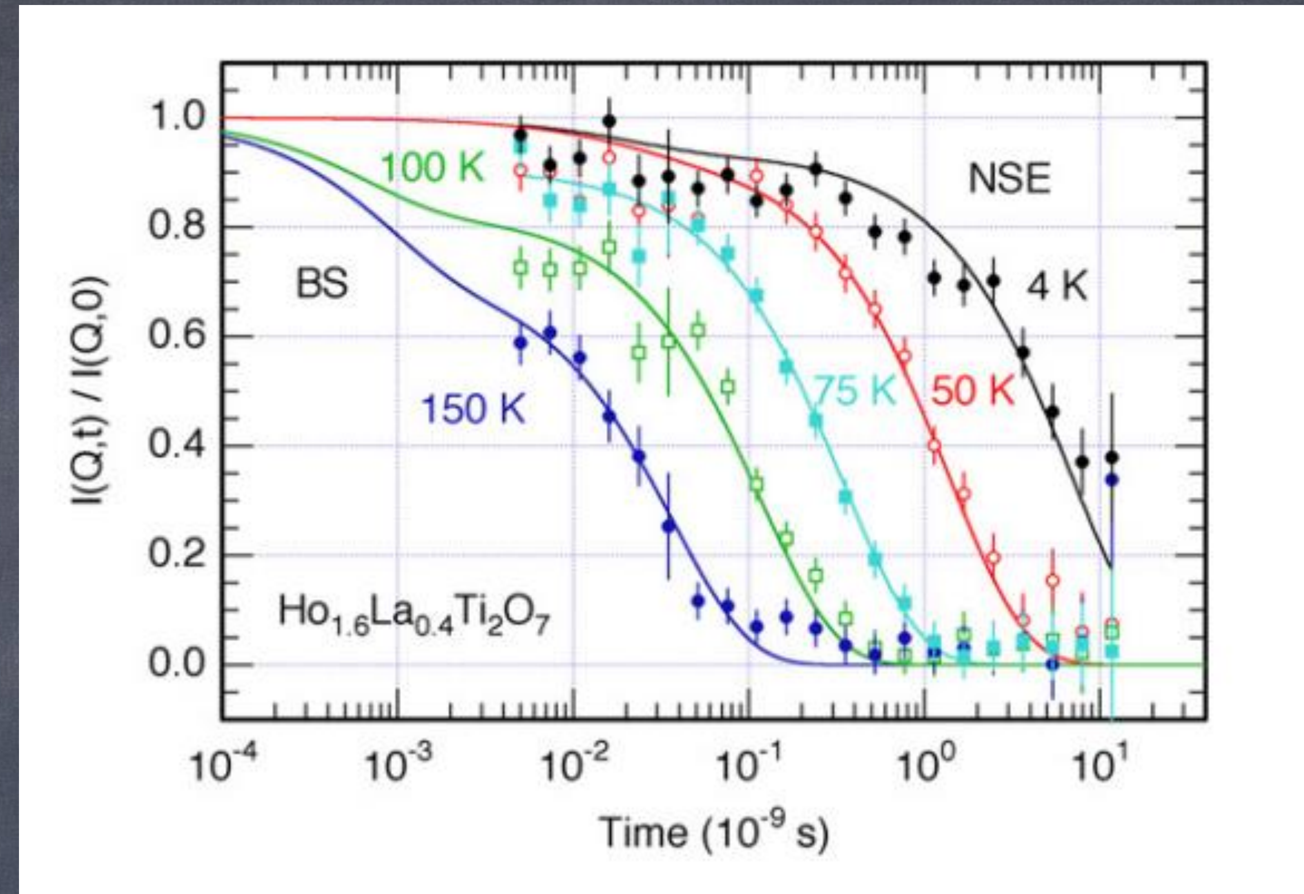


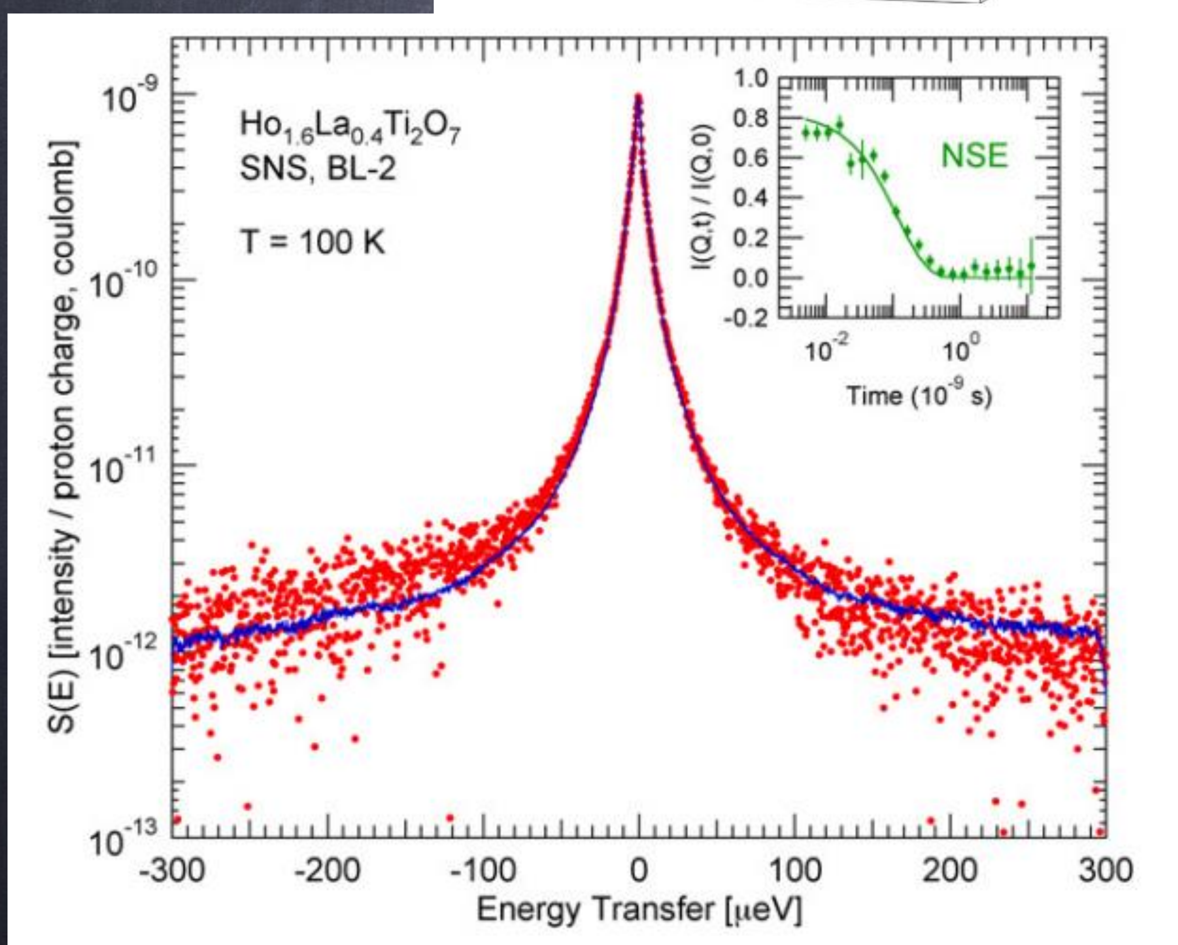


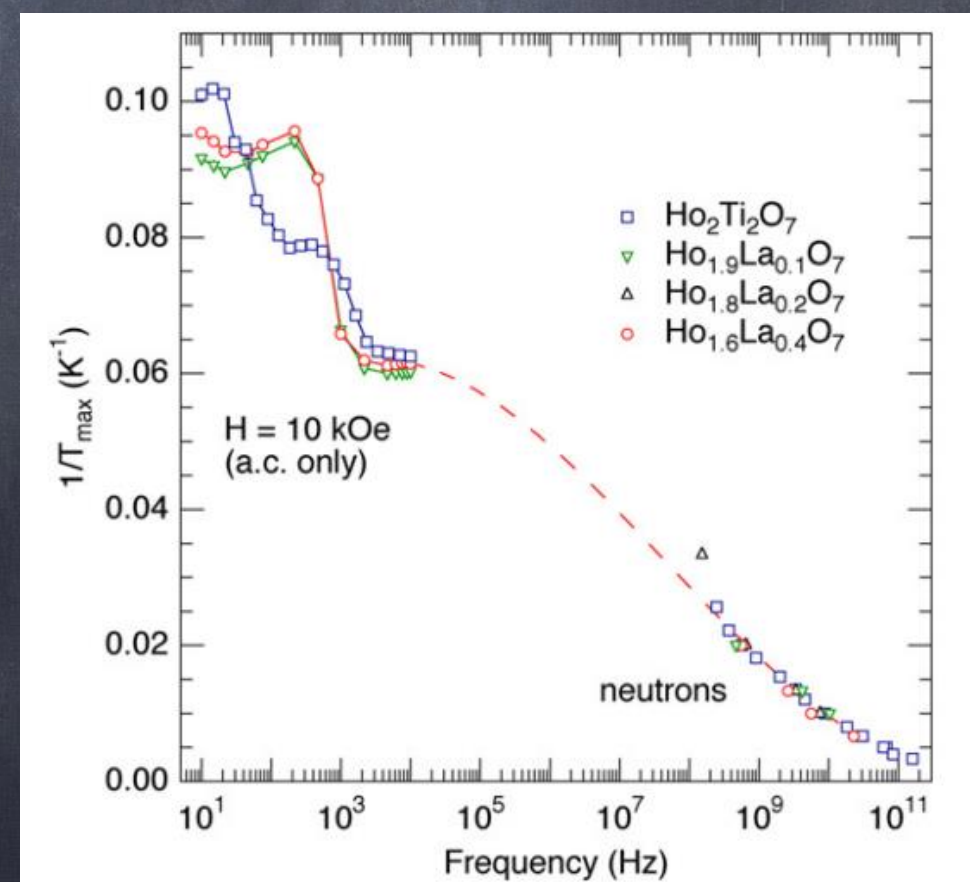
- Q and t dependence proved Nature paper wrong

Spin ice





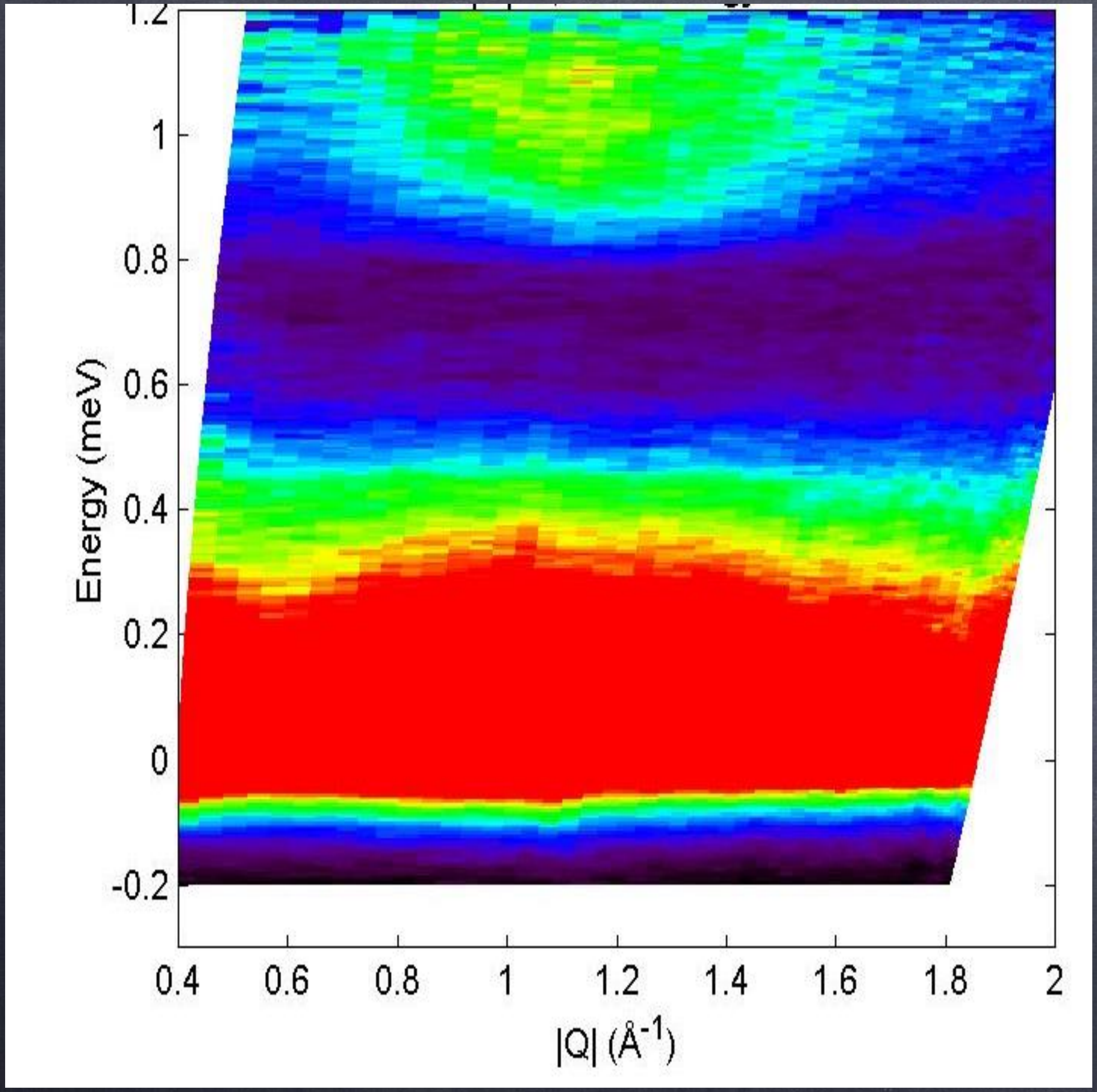


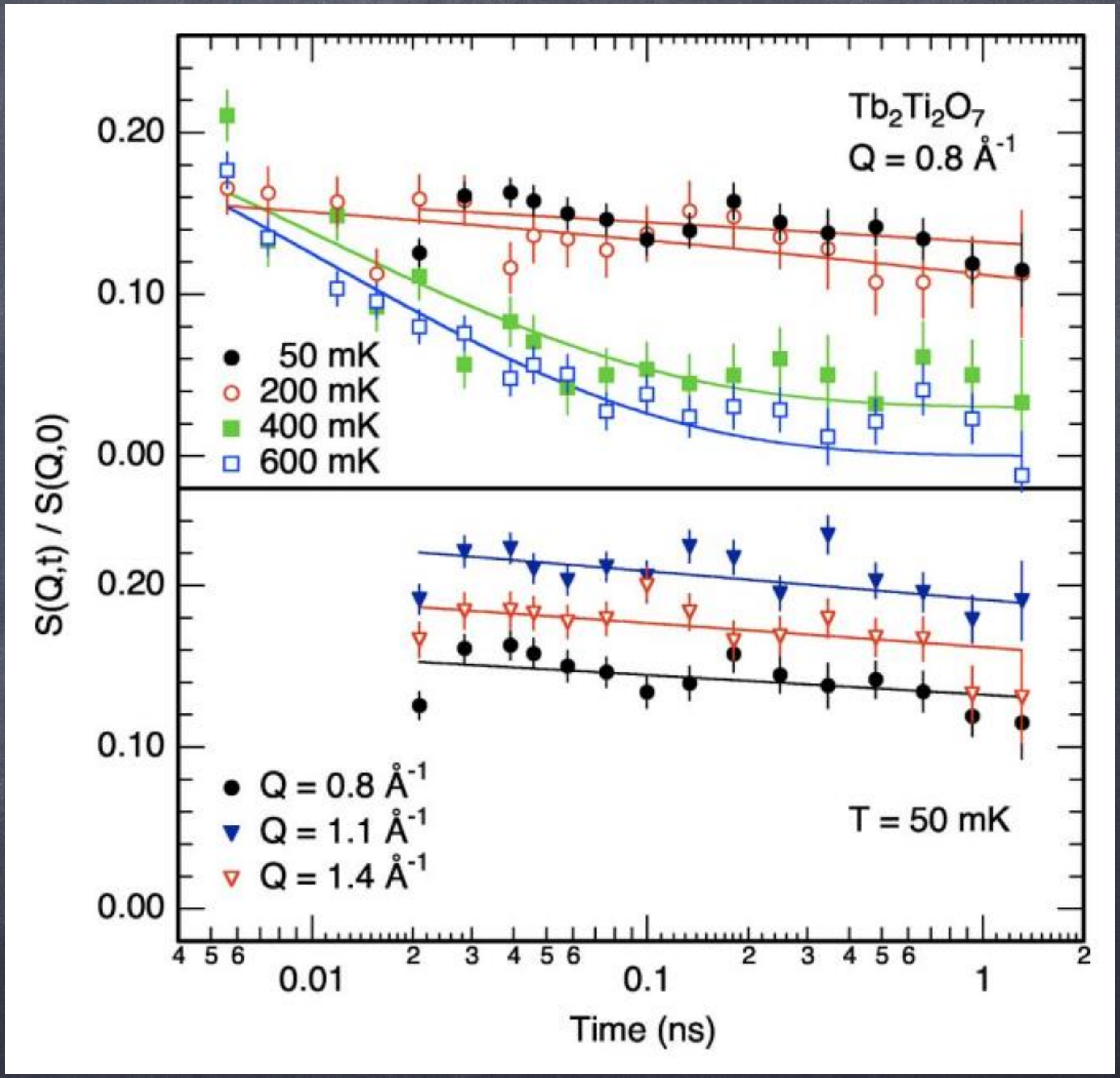


J Phys Cond Matt 20 235206 (2008)

Thank you

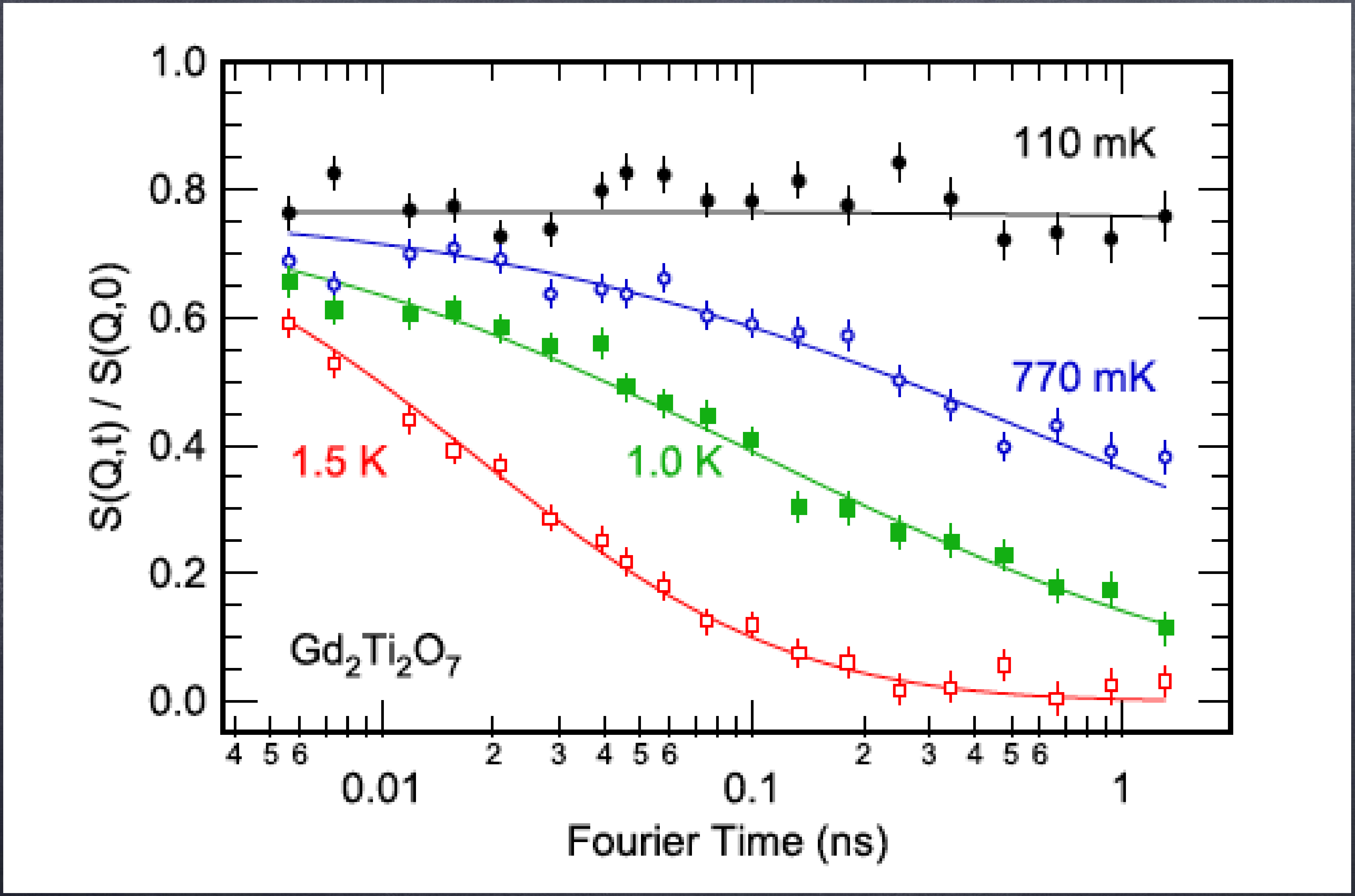
Magnetism – Spin Liquid





JSG *et al.*, Phys Rev B, 68, 180401 (R) 2003

Magnetism - Partial Order at 700 mK



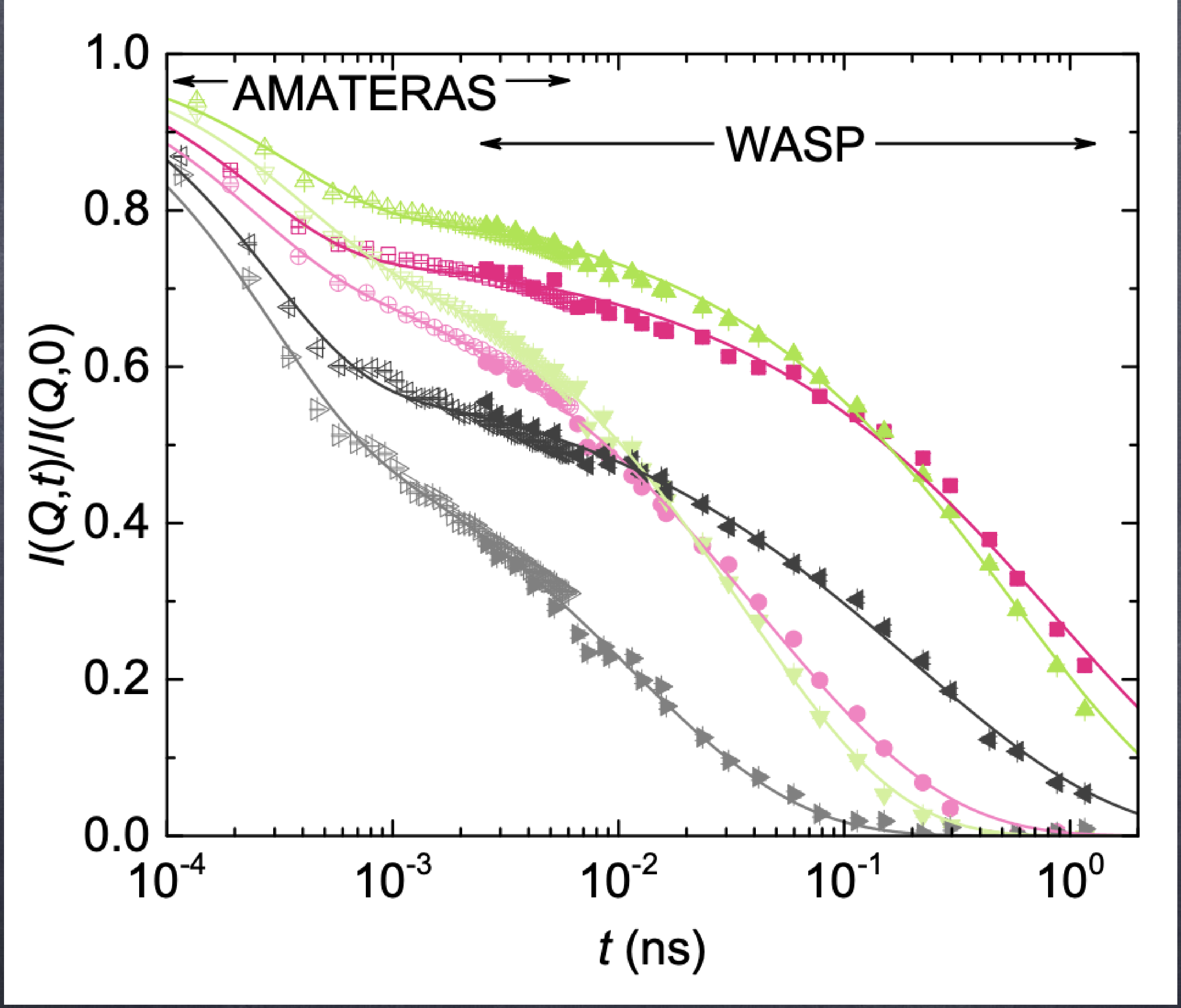
J Phys Cond Matt 18 R231 (2006)

For those still awake

- NSE studies dynamics in the ps to ns time range (4 orders of magnitude in time!), over lengthscales from tens of Ås to fractions of an Å. It covers the largest lengthscales and longest timescales of all neutron spectrometers.
- NSE works in the time domain. The instrumental resolution can be simply divided out.
- **Exploit the time and length scales accessible to NSE only, isotope effect and/or full PA analysis**
- NSE works by encoding the neutron speed in its spin state. Do not depolarize the neutron beam.

- NSE is count limiting. Large samples and/or significant scattering intensities are required.
- Good knowledge intense scattering, from other neutron techniques

The Future
Glass forming liquids



Fantastic Background and calibration of two instruments, incredible error bars.

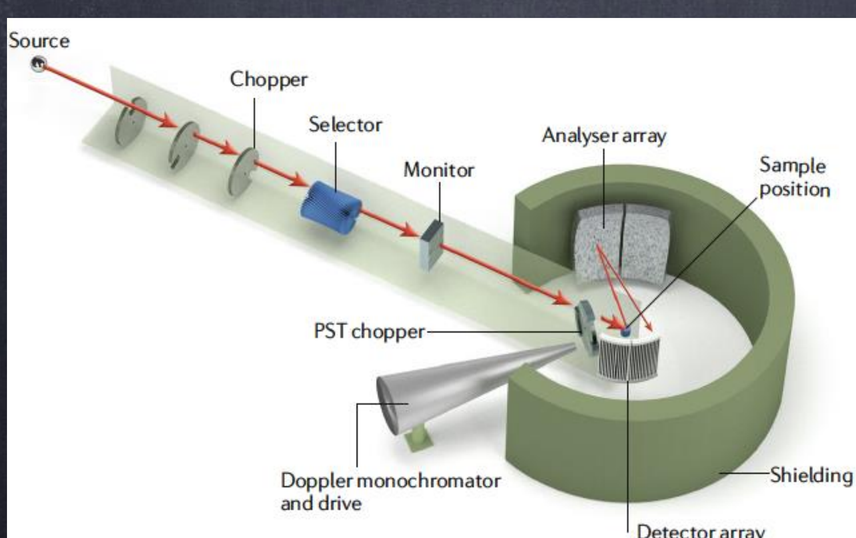

thank you
danke
謝謝
ngiyabonga
рахмат
teşekkür ederim
gracias
merci
obrigado
dziękuję
bedankt
спасибо
Баярлалаа
go raibh maith agat
mochchakkeram
sukriya
kop khun krap
terima kasih
grazie
arigatô
takk
dakujem
мерси
감사합니다
ありがとう
ευχαριστώ
tapadh leat
mahalo
хвала
asante
manana
obrigada
tenki
murakoze
chokrane
mamnun
дякую
trugarez
shukriya
mercé
dhanyavadagalu
diolch
rahmet
tanemirt
xièxie
sulpáy
taiku
dank je
misaotra
matondo
paldies
grazzi
welalin
tack
spas
mersi
kia ora
barka
vinaka
спасибі
blagodaram
faafetai lava
kiitos
dankie
dhanyavad
nanni
nandri
hvala
gràcie
bayarlalaa
maururuu
köszönöm
enkosi
chnorakaloutioun
gratias ago
gràcies
dankon
aciu
akun
djiere dieuf
tau
sobodi
dėkuji
mèsi
sagolun
didi madloba
najis tuke
kam sah hamnida
rahmat

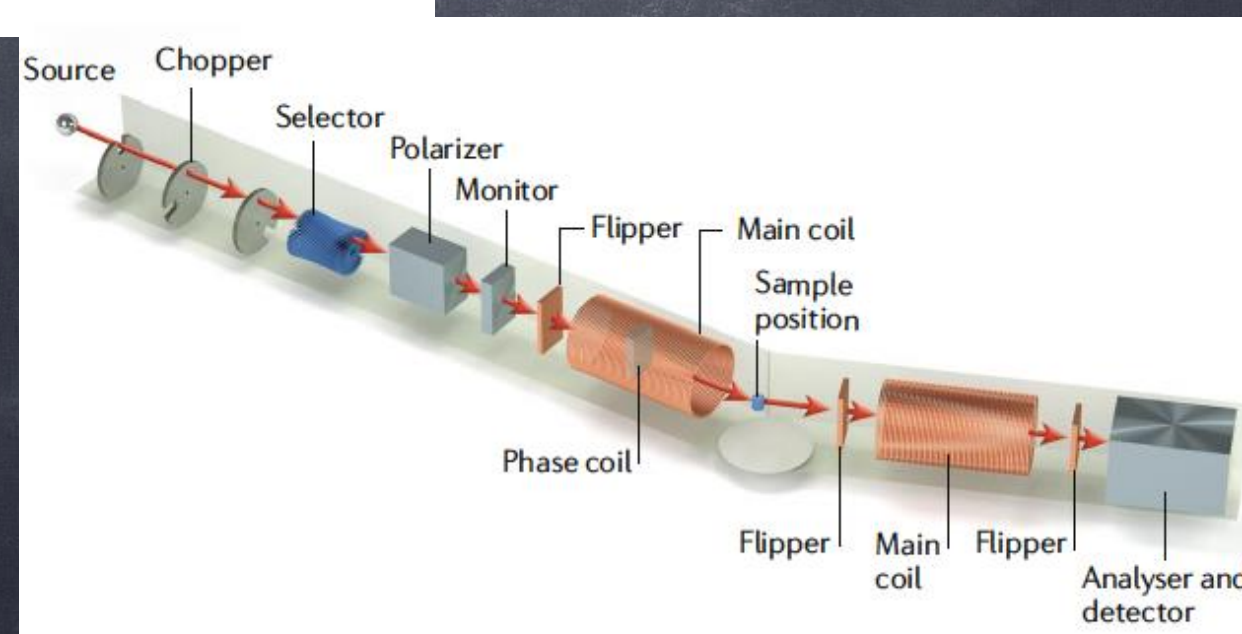
Nature Reviews Physics, 2, 103-116 (2020)

High-resolution neutron spectroscopy using backscattering and neutron spin-echo spectrometers in soft and hard condensed matter

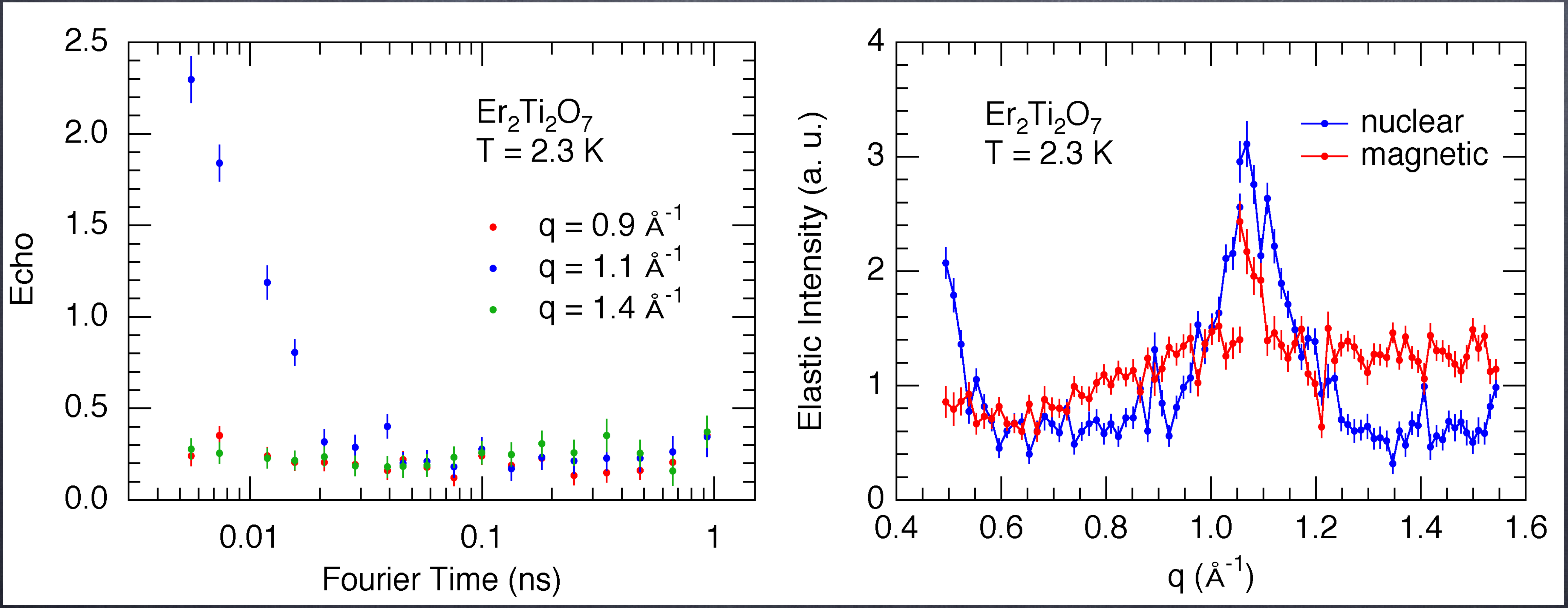
Jason S. Gardner[1], Georg Ehlers[2], Antonio Faraone[3] and Victoria García Sakai[4]*

Abstract | The instruments best suited to performing high-energy-resolution neutron spectroscopy are spin-echo spectrometers and backscattering spectrometers. The development of these experimental techniques dates back almost half a century, and most major neutron scattering facilities operate mature spectrometers of one or both classes. Recent advances in instrumentation and neutron sources are enhancing their performance and expanding their capabilities, with the objective of enabling researchers to tackle new and more complex problems. In this Technical Review, we assess the current state of the art in high-energy-resolution neutron spectrometers, showcasing their role in the study of nanoscale dynamics in soft and biological materials, as well as disordered magnets.

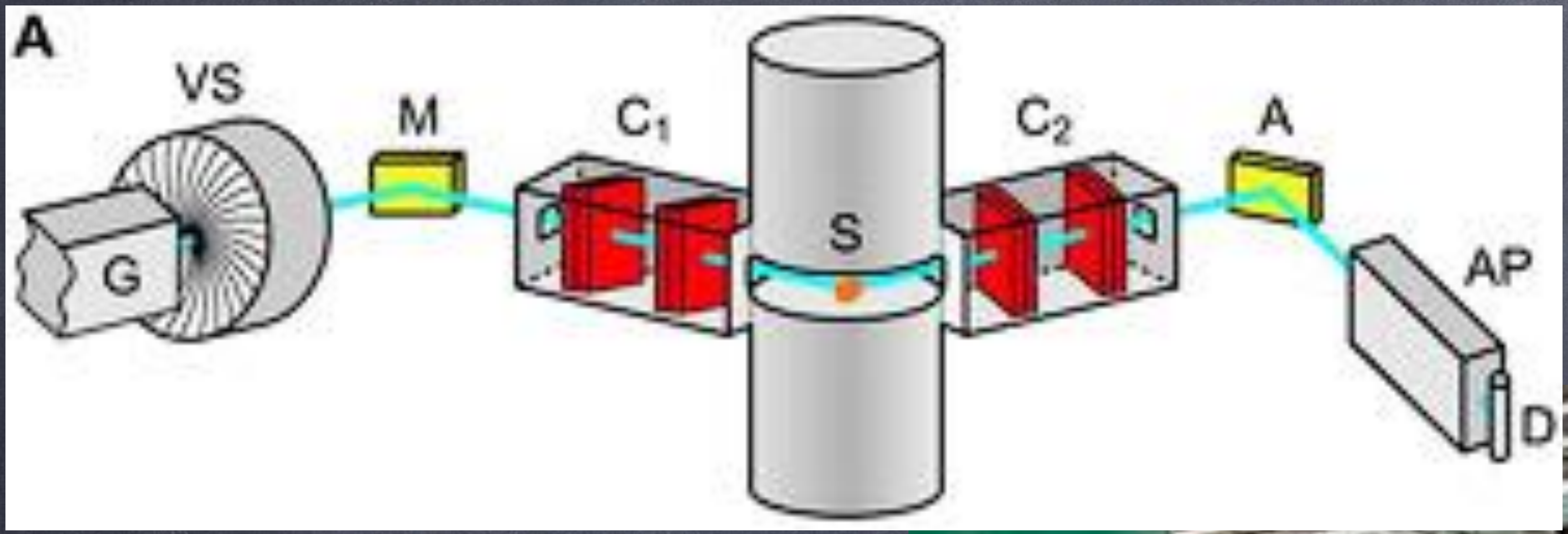


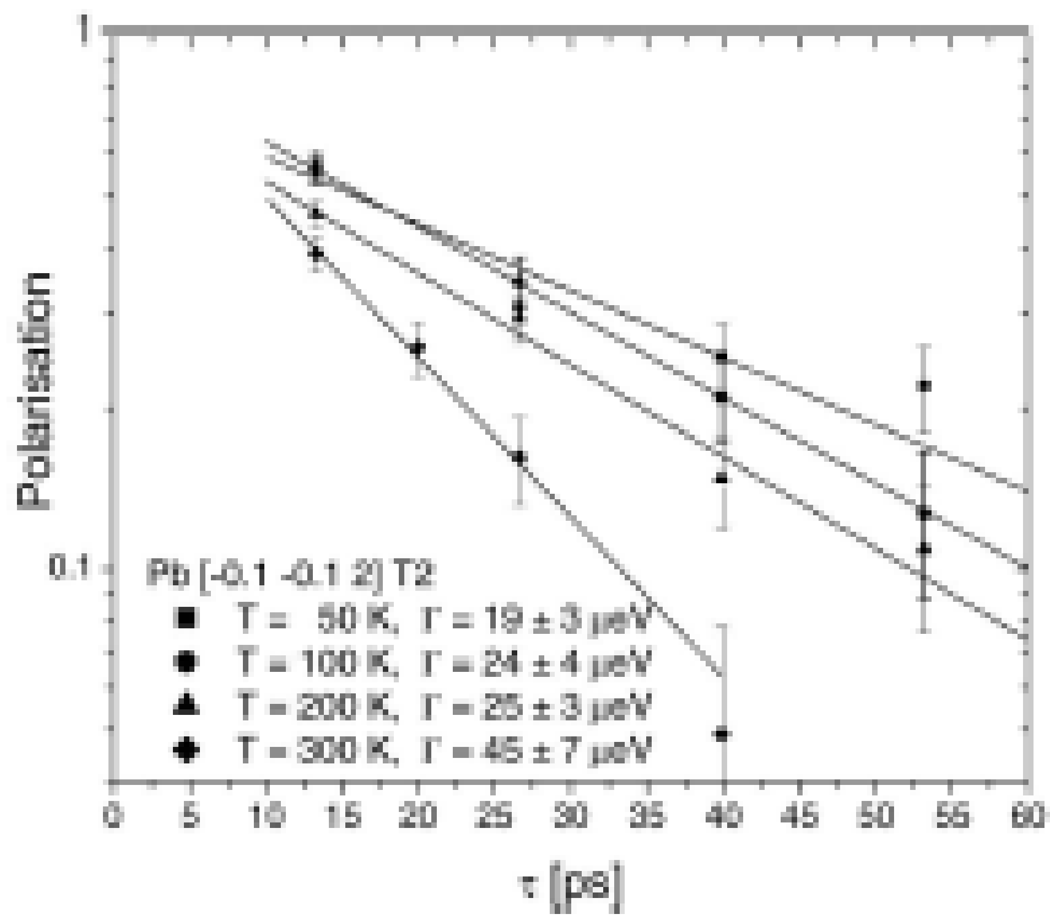


The NSE Spurions - Direct Echo

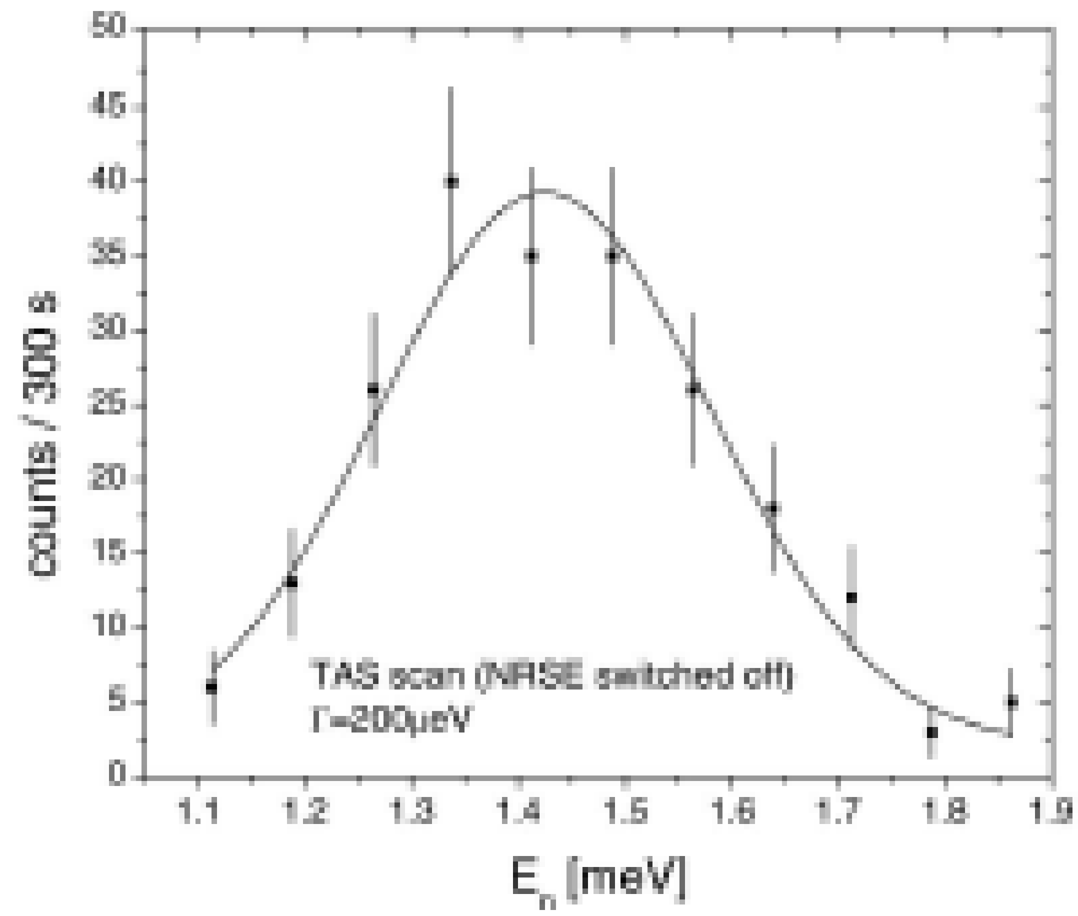


NSE on TAS





Adding NSE shows the intrinsic width is approximately 25 μeV



Good TAS data with an extracted linewidth From Lead of 200 μeV

xyz Polarization Analysis - Equations

case	non spin flip (“up”)	spin flip (“down”)
$\vec{p} \parallel \vec{x}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m \cdot (1 - p \cdot \cos^2\alpha)$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m \cdot (1 + p \cdot \cos^2\alpha)$
$\vec{p} \parallel \vec{y}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m \cdot \left(1 - p \cdot \sin^2\alpha\right)$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m \cdot \left(1 + p \cdot \sin^2\alpha\right)$
$\vec{p} \parallel \vec{z}$	$\sigma_n \frac{1+p}{2} + \frac{1}{2}\sigma_m$	$\sigma_n \frac{1-p}{2} + \frac{1}{2}\sigma_m$

$$\sigma_m = \frac{2}{p} \cdot \left(-\sigma_x^{\mathrm{up}} - \sigma_y^{\mathrm{up}} + 2 \cdot \sigma_z^{\mathrm{up}}\right)$$

$$\sigma_m = \frac{2}{p} \cdot \left(\sigma_x^{\mathrm{down}} + \sigma_y^{\mathrm{down}} - 2 \cdot \sigma_z^{\mathrm{down}}\right)$$