Neutron Spectroscopy 2: high resolution spectrometers

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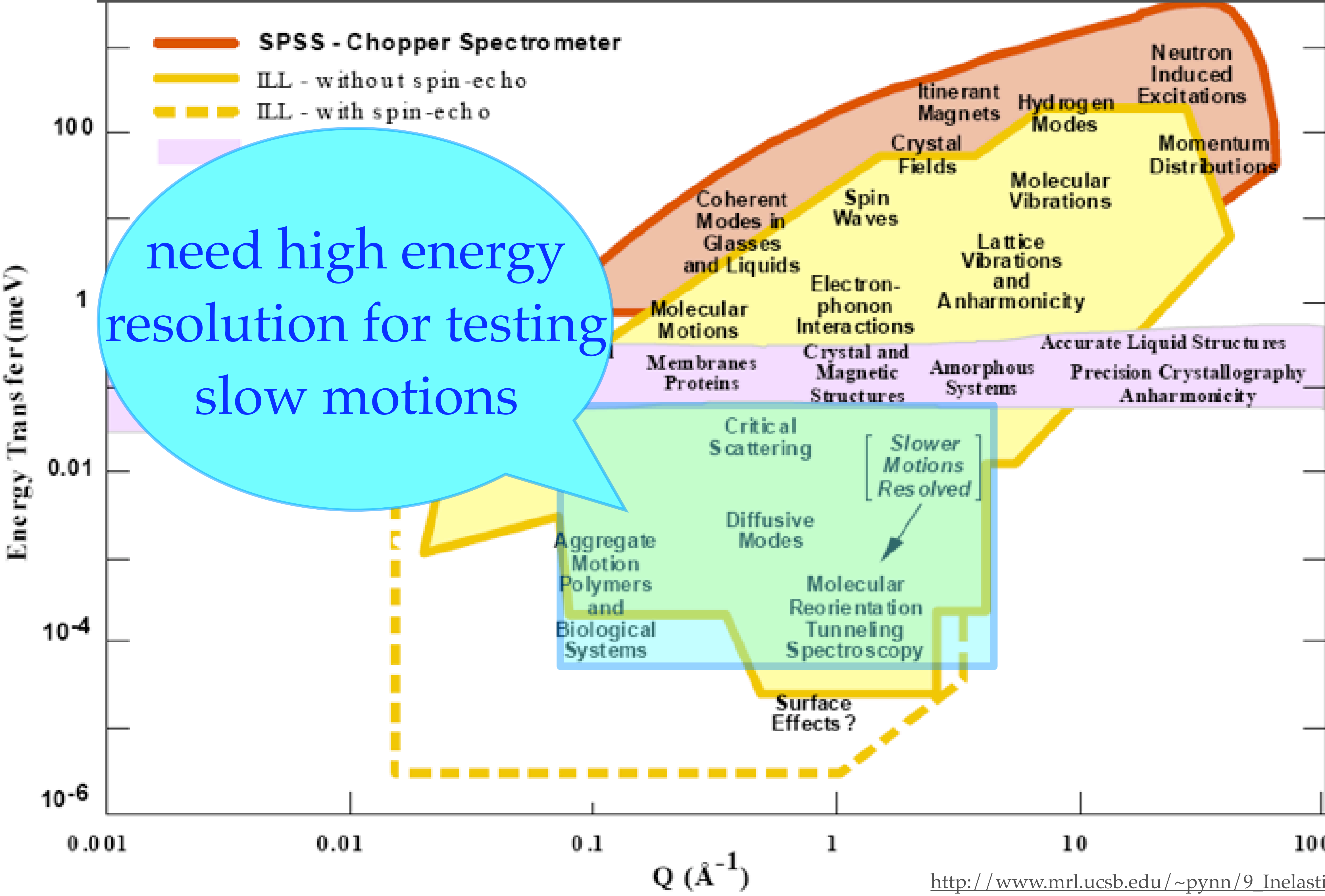
NEUTRONS
FOR SCIENCE

content

- why do we need high resolution neutron spectroscopy?
- how to achieve the best energy resolution
  - in time-of-flight spectroscopy
  - in crystal spectroscopy
  - in neutron spin echo
- some applications
  - slow diffusion processes
    - translational-, jump-, rotational diffusion
  - spectroscopy of local motions
    - EISF
    - quantum tunnelling

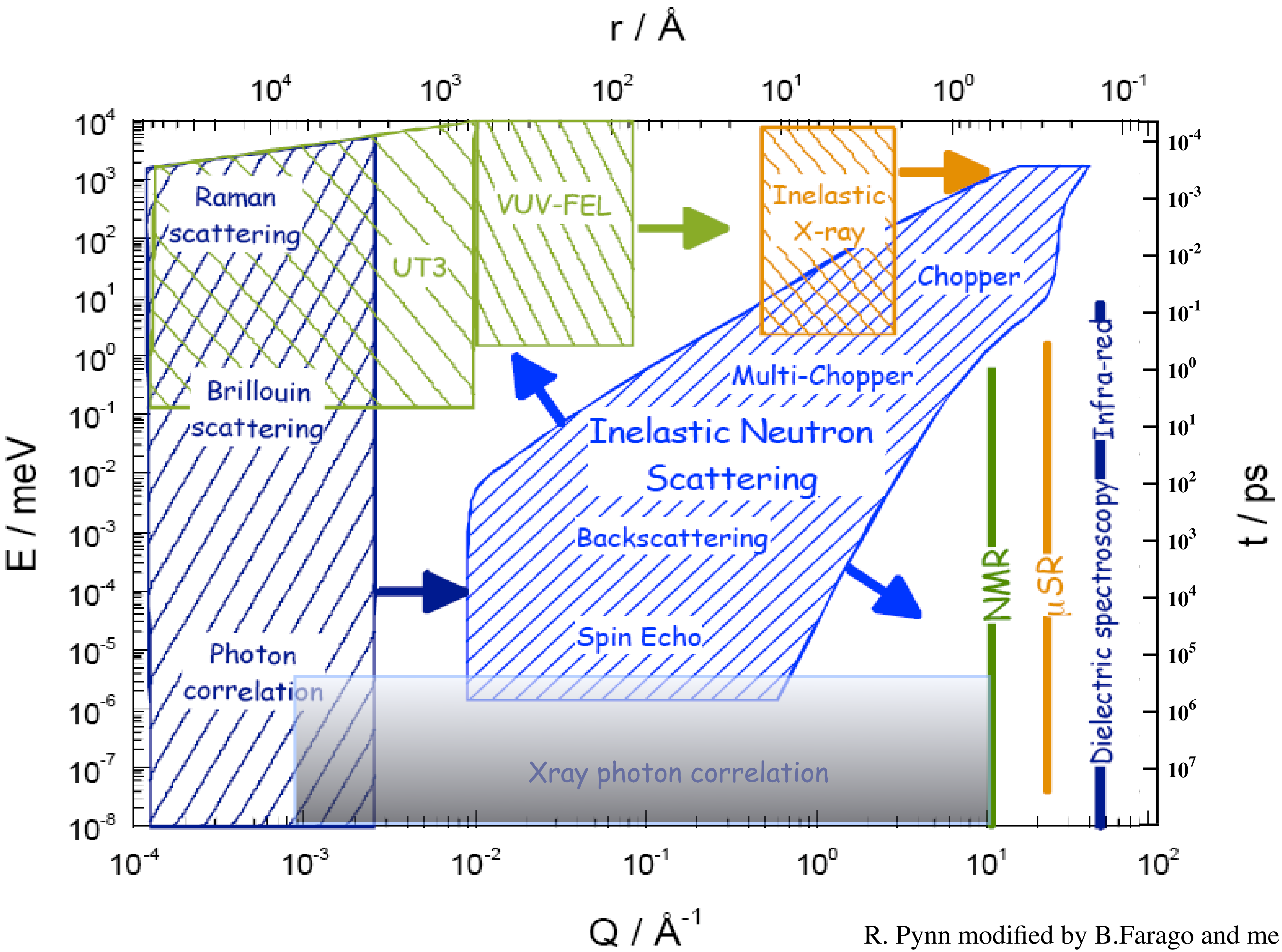
SCIENTIFIC APPLICATIONS IN CONDENSED MATTER MAP



need high energy resolution for testing slow motions

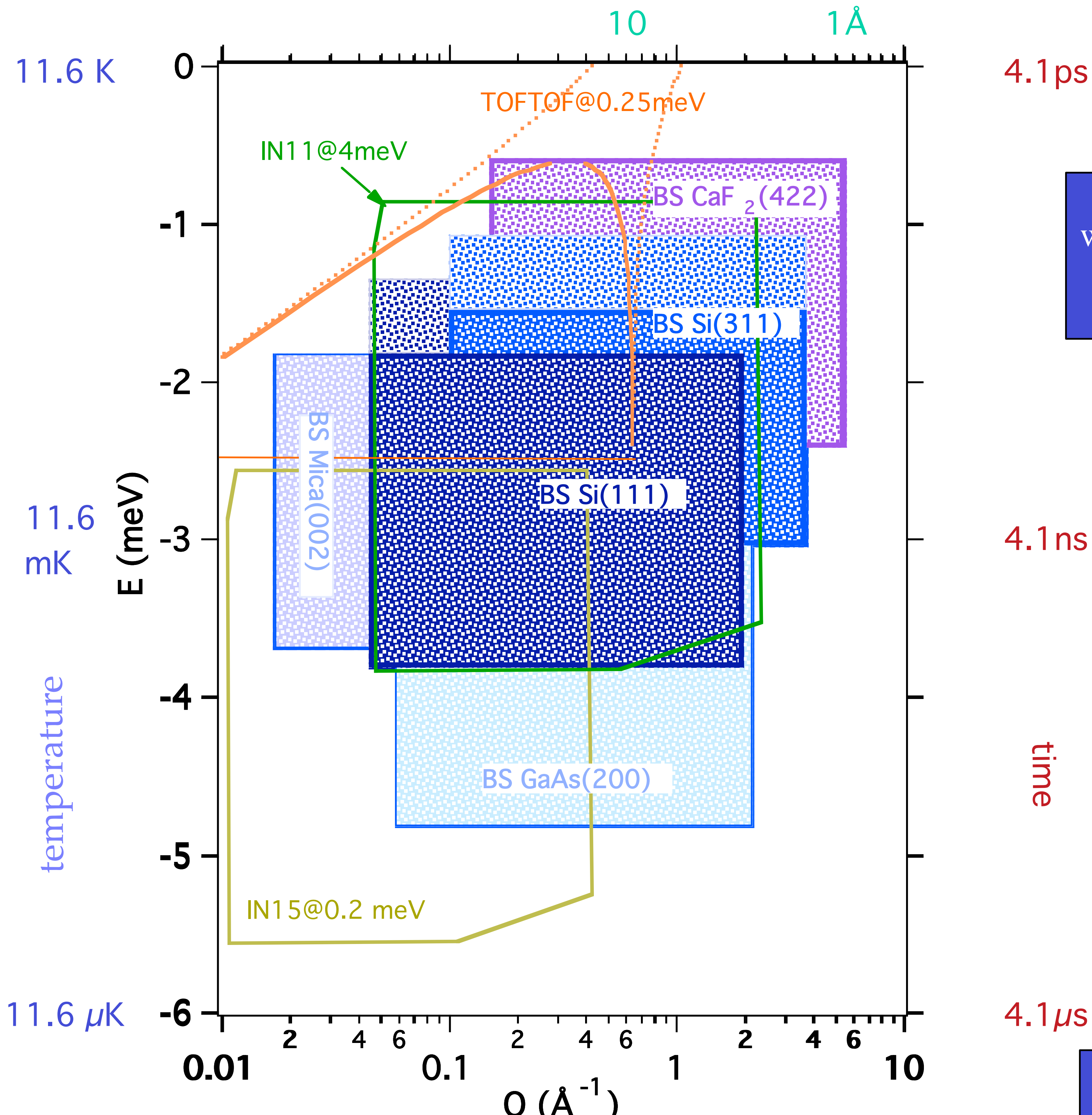
http://www.mrl.ucsb.edu/~pynn/9_Inelastic.pdf

SPECTROSCOPY MAP



R. Pynn modified by B.Farago and me

High energy resolution Map



$E = h\nu$
with: h=4.136 meVps
$\Rightarrow$1THz : 4.1meV
$\Rightarrow$ 1meV : 4.1ps

elastic scattering:
$Q=4\pi/\lambda\sin(\Theta)$

density correlation functions - pair correlation function

T. Springer, 'Quasielastic Neutron Scattering for the Investigation of Diffusive Motions in Solids and Liquids', Springer Tracts in Modern Physics 64, 1972

for a classical system in terms of a microscopic particle density function:

$$G(\mathbf{r},t) = \frac{1}{N}\int < \rho(\mathbf{r}' - \mathbf{r}, 0)\rho(\mathbf{r}', t) > d\mathbf{r}'$$

i.e. auto-correlation function of the particle density

asymptotic behaviour:

$$G^{\infty}(\mathbf{r}) = \lim_{\mathbf{r},t\to\infty} G(\mathbf{r},t) = \frac{1}{N}\int \bar{\rho}(\mathbf{r}' - \mathbf{r})\bar{\rho}(\mathbf{r}')d\mathbf{r}'$$

liquid:

$$G^{\infty}(\mathbf{r}) = \bar{\rho} = \frac{N}{V}$$

density correlation functions - self correlation function

T. Springer, ‘Quasielastic Neutron Scattering for the Investigation of Diffusive Motions in Solids and Liquids’, Springer Tracts in Modern Physics 64, 1972

define average probability per volume to find particle i at r′:

$$p_i(\mathbf{r}^{'}) =< \delta[\mathbf{r}^{'} - \mathbf{r}_i(t)] >$$

asymptotic behaviour:

$$G_s^{\infty}(\mathbf{r}) = \frac{1}{N}\sum_{i=1}^{N}\int p_i(\mathbf{r}^{'} - \mathbf{r})p_i(\mathbf{r}^{'})d\mathbf{r}^{'}$$

liquid:

$$\lim_{t\to\infty} G_s^{\infty}(\mathbf{r},t) = \frac{1}{V}$$

thus: $G_s^{\infty}(\mathbf{r}) \longrightarrow 0$ for $V \longrightarrow \infty$

but not if V is finite: EISF!

assume identical scattering particles (drop index i)

$$G_s^{\infty}(\mathbf{r}) = \int p(\mathbf{r}^{'} - \mathbf{r})p_{(}\mathbf{r}^{'})d\mathbf{r}^{'}$$

and separate **G**$_s$ in decaying and stationary part:

$$G_s^{'}(\mathbf{r},t) = \underline{G_s(\mathbf{r},t)} - \underline{G_s^{\infty}(\mathbf{r})}$$

elastic incoherent structure factor:

$$S_{inc}^{el}(\mathbf{Q}) = \int \exp\{-i(\mathbf{Q}\mathbf{r})\}G_s^{\infty}(\mathbf{r})d\mathbf{r} = |\int \exp\{-i(\mathbf{Q}\mathbf{r})\}p(\mathbf{r})d\mathbf{r}|^2$$

density correlation functions - self correlation function

T. Springer, 'Quasielastic Neutron Scattering for the Investigation of Diffusive Motions in Solids and Liquids', Springer Tracts in Modern Physics 64, 1972

elastic **coherent** structure factor:

$$S^{el}_{coh}(\mathbf{Q}) = |\int \exp\{-i(\mathbf{Qr})\}\rho(\mathbf{r})d\mathbf{r}|^2$$

"... diffraction from different particles distributed in space... "

elastic **incoherent** structure factor:

$$S^{el}_{inc}(\mathbf{Q}) = |\int \exp\{-i(\mathbf{Qr})\}p(\mathbf{r})d\mathbf{r}|^2$$

"... diffraction of the neutron wave on the probability distribution in space of an individual particle spread over a finite volume... "
(thermal cloud due to vibrations, rotations, tunneling, ...)

thus we need high energy resolution in neutron spectroscopy, because

- of its suitable time resolution for some dynamic phenomena at the proper length scale
- it is in some cases the unique method, often it is complementary to other spectroscopic techniques (time & spatial probe)

content

- ☑ why do we need high resolution neutron spectroscopy?
- how to achieve the best energy resolution
  - in time-of-flight spectroscopy (Toby Perring)
  - in crystal spectroscopy
  - in neutron spin echo (Ross Stewart)
- some applications
  - slow diffusion processes
    - translational-, jump-, rotational diffusion
  - spectroscopy of local motions
    - EISF
    - quantum tunnelling

TOF-resolution

- fore more see talk by Toby Perring

- the art is to keep $\Delta t/t_{elastic}$ small
- short pulses: (fast choppers with narrow slits; multi-choppers, counter rotating...)
- long flight path
- ......
- long wavelength / slow neutrons - but then Q is limited (elastic Q: $4\pi/\lambda \sin(\Theta)$)use of modern multi-chopper

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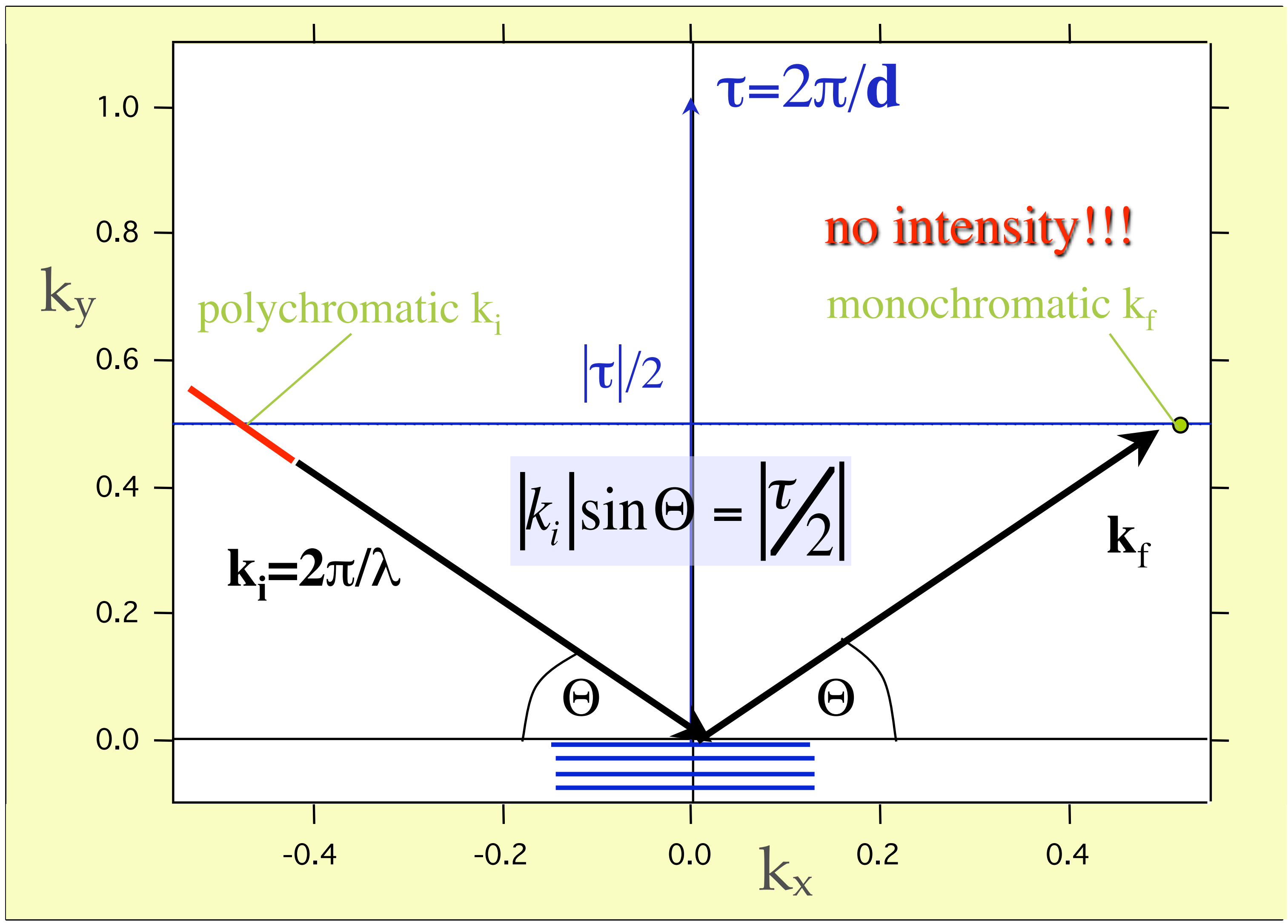
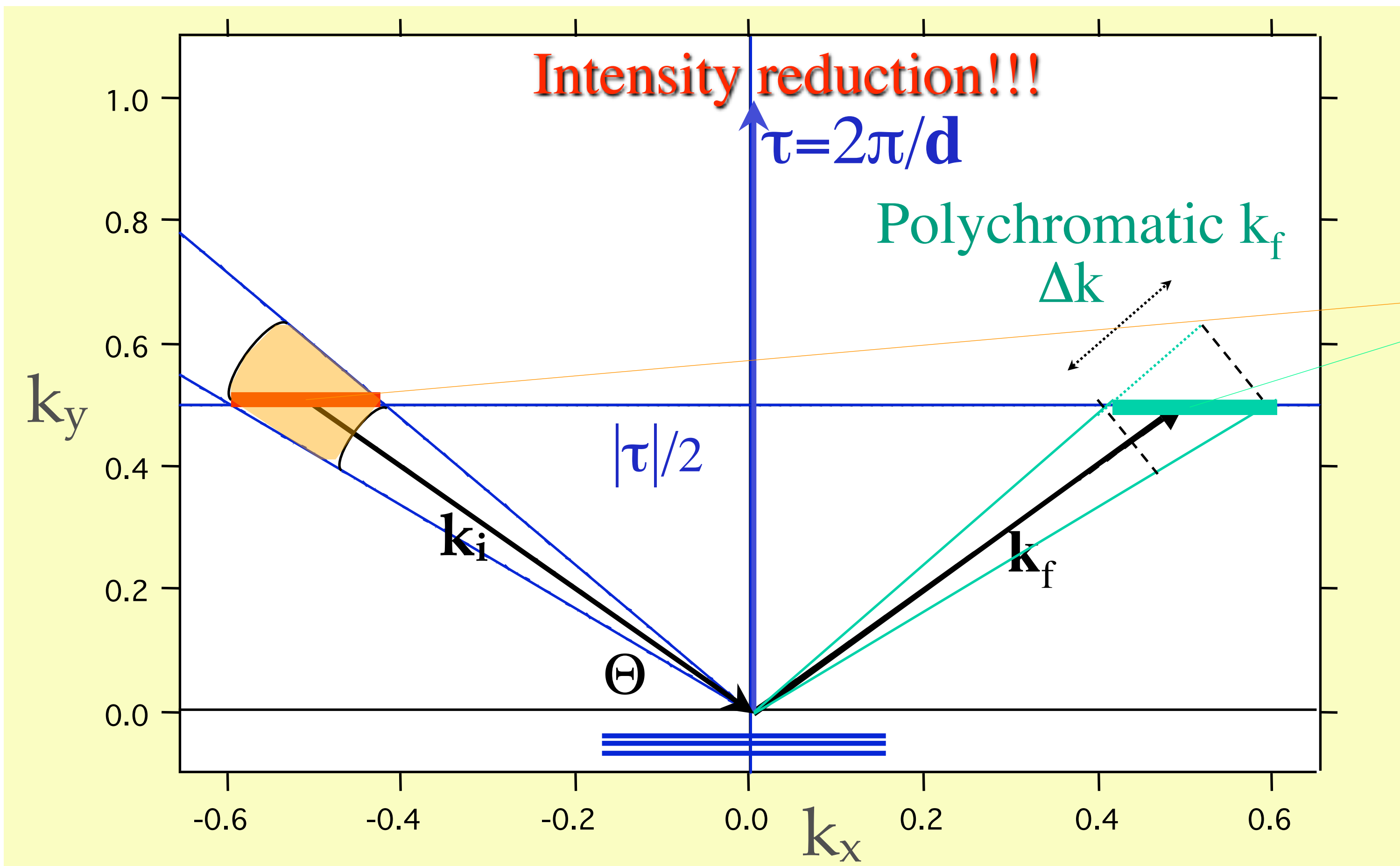
ENERGY RESOLUTION FROM A PERFECT CRYSTAL



reciprocal space representation
- perfectly collimated white beam

ENERGY RESOLUTION FROM A PERFECT CRYSTAL AND DIVERGENT BEAM

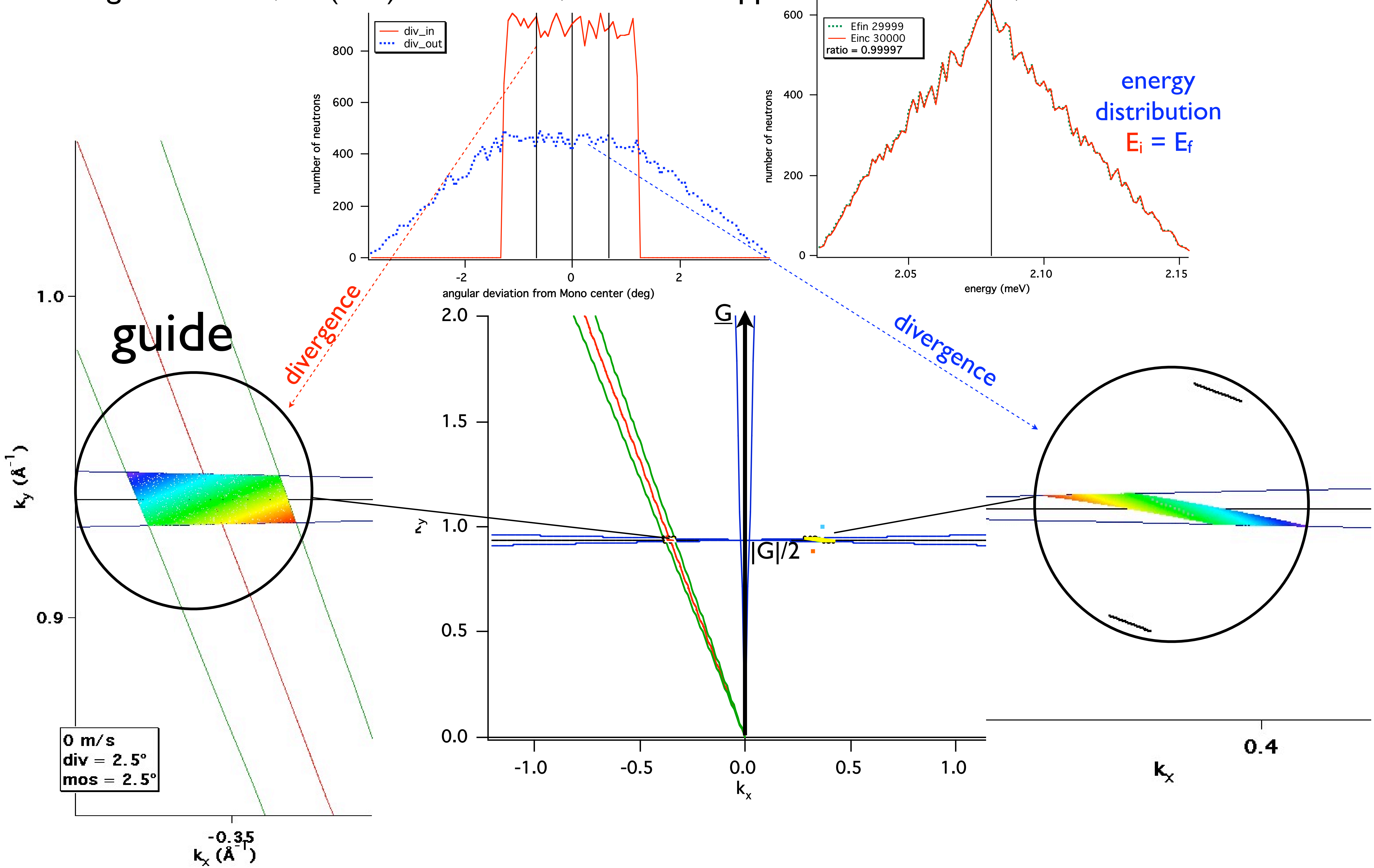


reciprocal space presentation
- open collimation and nearly white beam

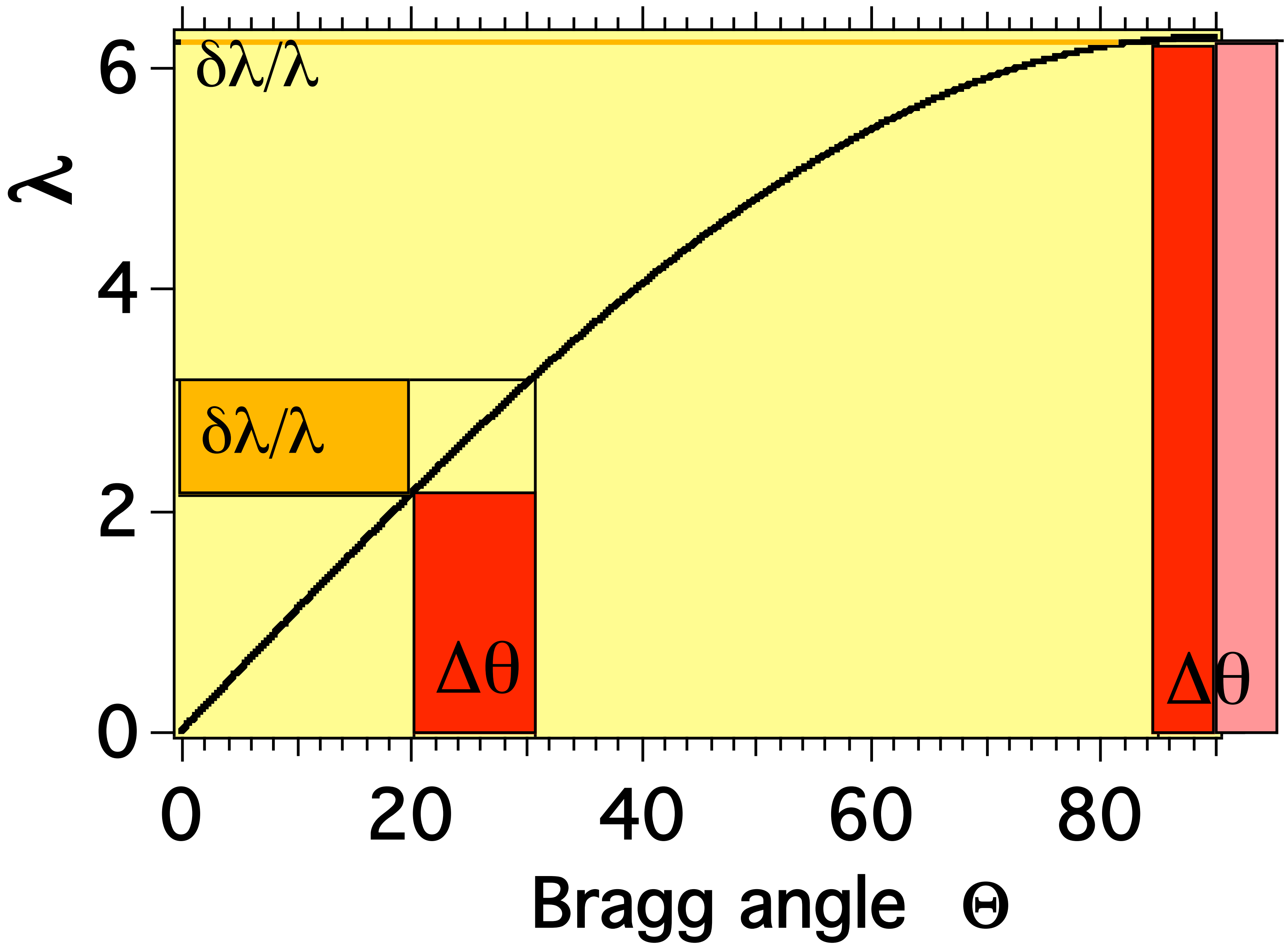
- intensity proportional phase space element
- the better the energy resolution, the lower the intensity
- energy resolution & divergence are coupled and depend on Θ

mosaic crystal

guide: m=2.0; PG(002) mosaic 2.5°; distance chopper $d_{D1\text{-}ch}$=2140mm; focus width 50mm



ENERGY RESOLUTION AND DIVERGENCE



$$\text{Bragg's law}: \quad 2d \sin\Theta = n\lambda$$

differentiate:

$$2\Delta d \sin\theta + 2d\cos\theta\Delta\theta = \Delta\lambda$$

or:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta d}{d} + \cot\theta\Delta\theta$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta k}{k} = \frac{\Delta E}{2E} \quad \text{and} \quad \frac{\Delta d}{d} = \frac{\Delta\tau}{\tau}$$

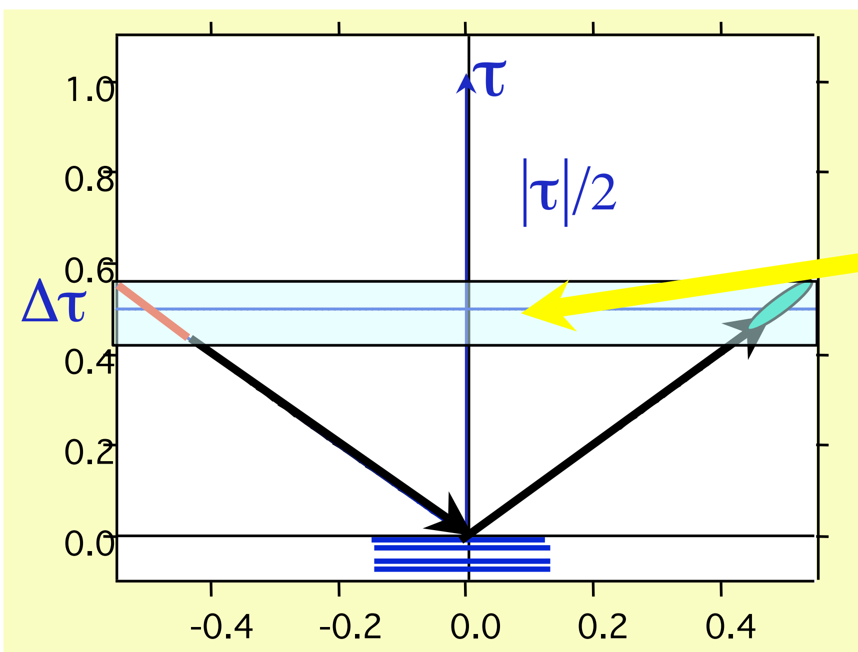
$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\tau}{\tau} + \frac{\Delta\theta^2}{8} + \frac{\Delta\varepsilon^2}{4}$$

$\varepsilon = \text{deviation from BS}$

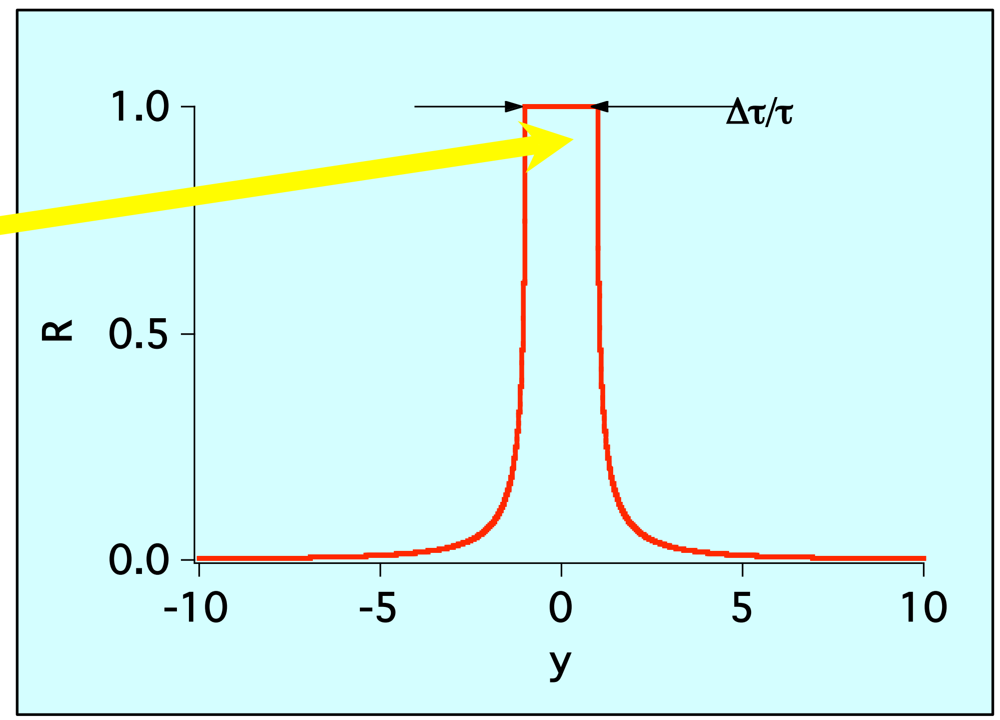
$\Delta\theta = \text{beam divergence}$

- **energy resolution improves towards backscattering**
- **decoupling of divergence and energy resolution**

REFLECTIVITY OF CRYSTALS IN DYNAMIC SCATTERING THEORY



Darwin curve



- **primary extinction** leads to finite energy resolution for perfect crystals

$$R = \begin{cases} 1 & \text{for } |y| \le 1 \\ \left(|y| - \sqrt{y^2 - 1}\right)^2 & \text{for } |y| > 1 \end{cases}$$

How large is the primary extinction for a BS-crystal?

$$\frac{\Delta\tau}{\tau} = \frac{16\pi F_\tau N}{\tau^2}$$

N=number density of unit cells

F= structure factor

$$F_\tau = \sum_{sites\ i\ in\,cell} b^i_{coh} \cdot DWF_i \cdot \exp(-i\vec{Q}\vec{R}_i)$$

for neutrons:

$$\Delta E = 2E\frac{\Delta\tau}{\tau}$$

$$\boxed{\Delta E} = 2\frac{\hbar^2\left(\frac{\tau}{2}\right)^2}{2m}\frac{16\pi F_\tau N}{\tau^2} = \boxed{\frac{\hbar^2}{m}4\pi F_\tau N}$$

Typical backscattering monochromators:

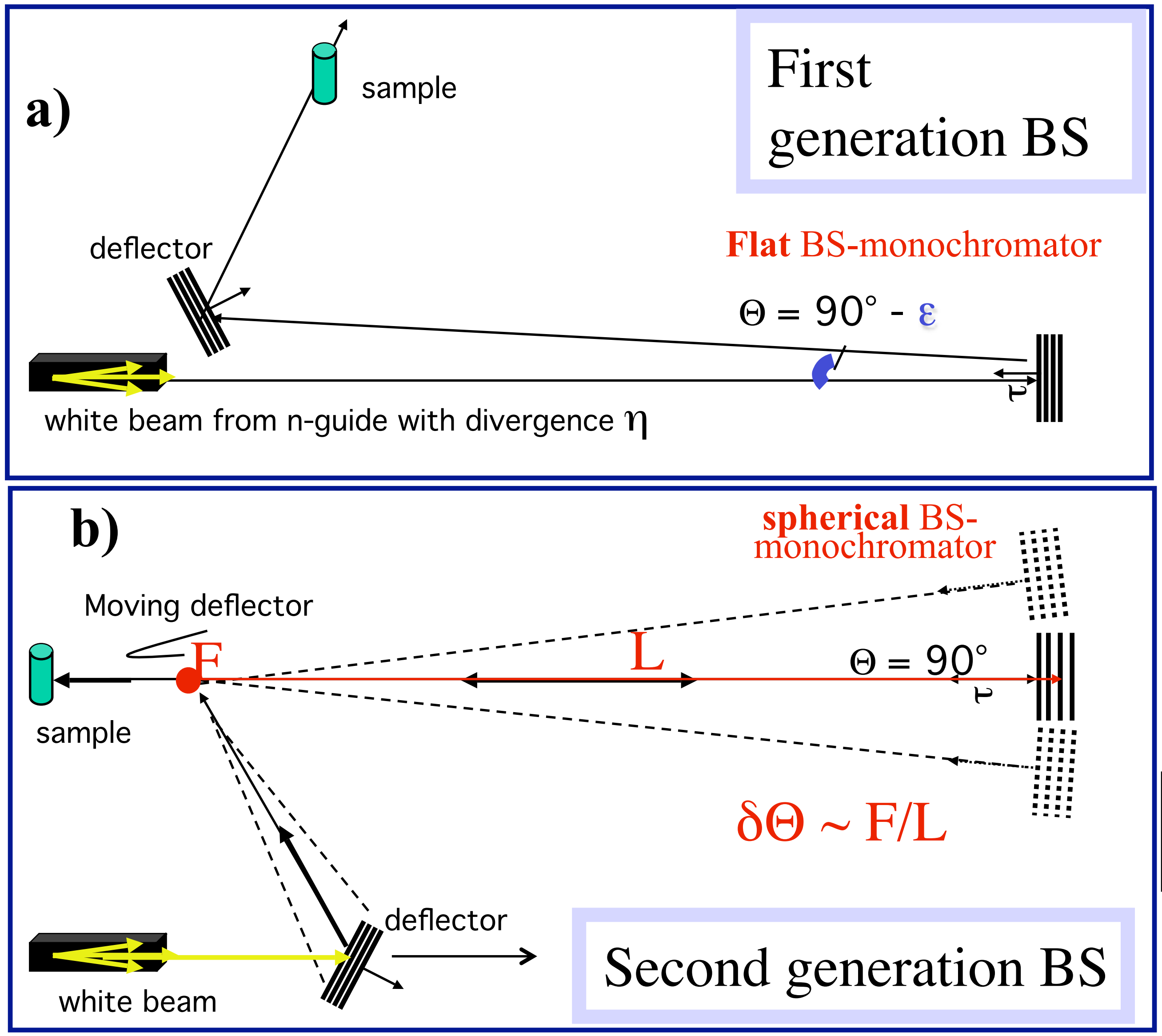
Crystal plane	$\frac{\Delta\tau}{\tau}$	ΔE_{ext} (μeV)	λ (Å) for Θ = 90°
Si (111)	$1.86.10^{-5}$	0.077	6.2708
Si (311)	$0.51.10^{-5}$	0.077	3.2748
Ca F_2 (111)	$1.52.10^{-5}$	0.063	6.307
Ca F_2 (422)	$0.54.10^{-5}$	0.177	2.23
Ga As (400)	$0.75.10^{-5}$	0.153	2.8269
Ga As (200)	$0.157.10^{-5}$	0.008	5.6537
Graphite (002)	$12.10.10^{-5}$	0.44	6.70

http://www.ill.fr/YellowBook/IN16/BS-review/index.htm

- energy resolution independent of order of reflection (for same F)
  - this is different for X-rays
- extremely small crystal contribution (other resolution contributions for TOF or 3X-spectrometers much larger)

HOW TO GET THE SAMPLE AND DETECTOR OFF FROM PRIMARY BEAM?

generic primary spectrometer concepts:



example IN10:
$\varepsilon = 0.3°$
$\eta = 1.2°$

$\Delta E_{div} \sim 0.24 \mu eV$
$\Delta E_{ext} \sim 0.08 \mu eV$

divergence and extinction not matched,
But divergence and deviation from BS

IN16:
F~2.7cm
L=200cm

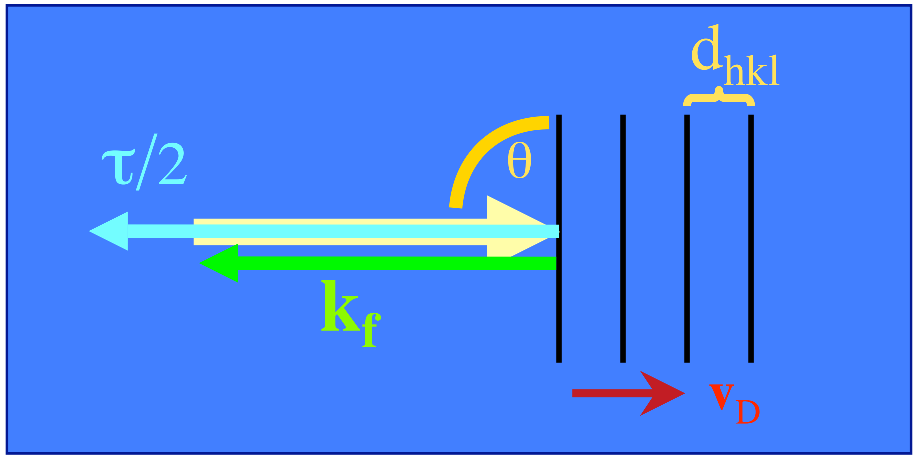
$\Delta E_{div} \sim 0.09 \mu eV$
$\Delta E_{ext} \sim 0.08 \mu eV$

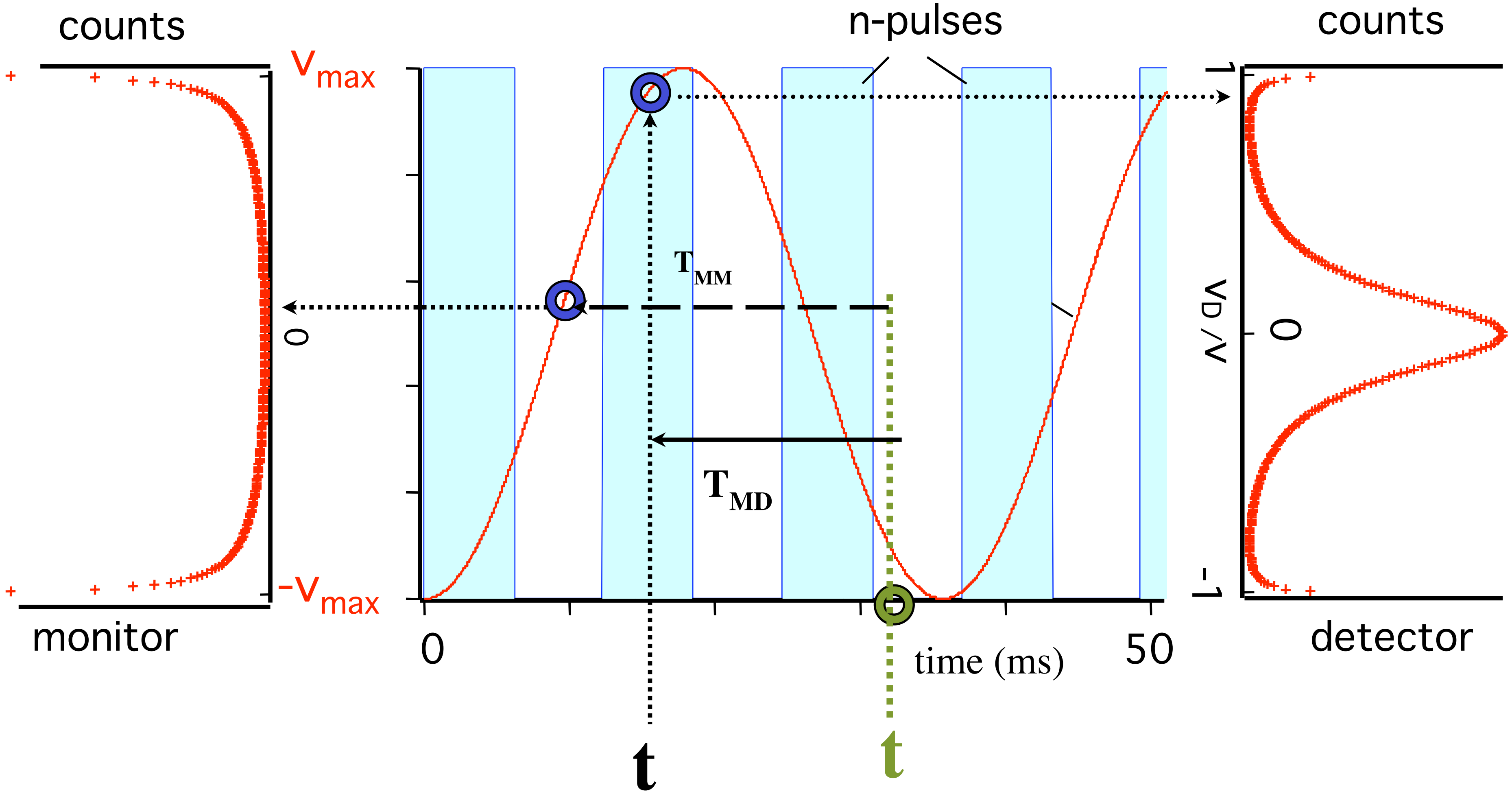
matched

HOW TO SCAN THE ENERGY AND REMAIN IN BS?

1) Doppler motion of the monochromator:

$$\frac{\delta E_D}{E_i} \approx 2\frac{v_D}{v_i}$$



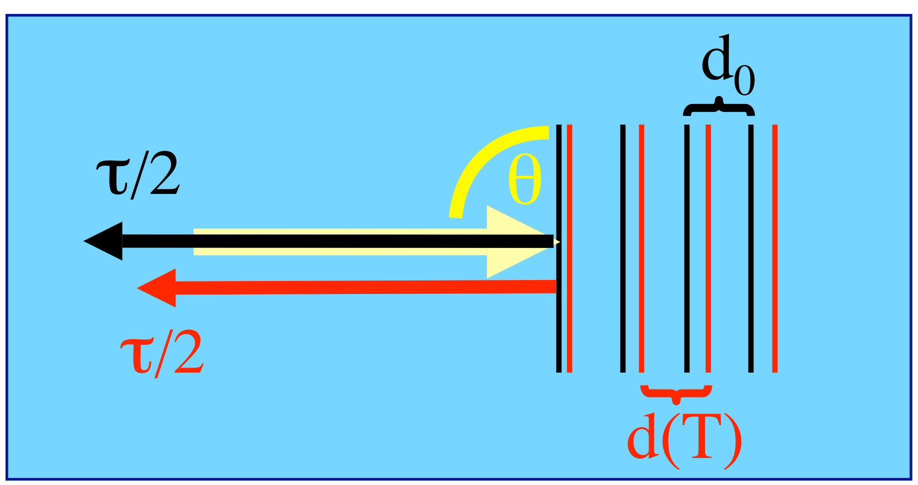


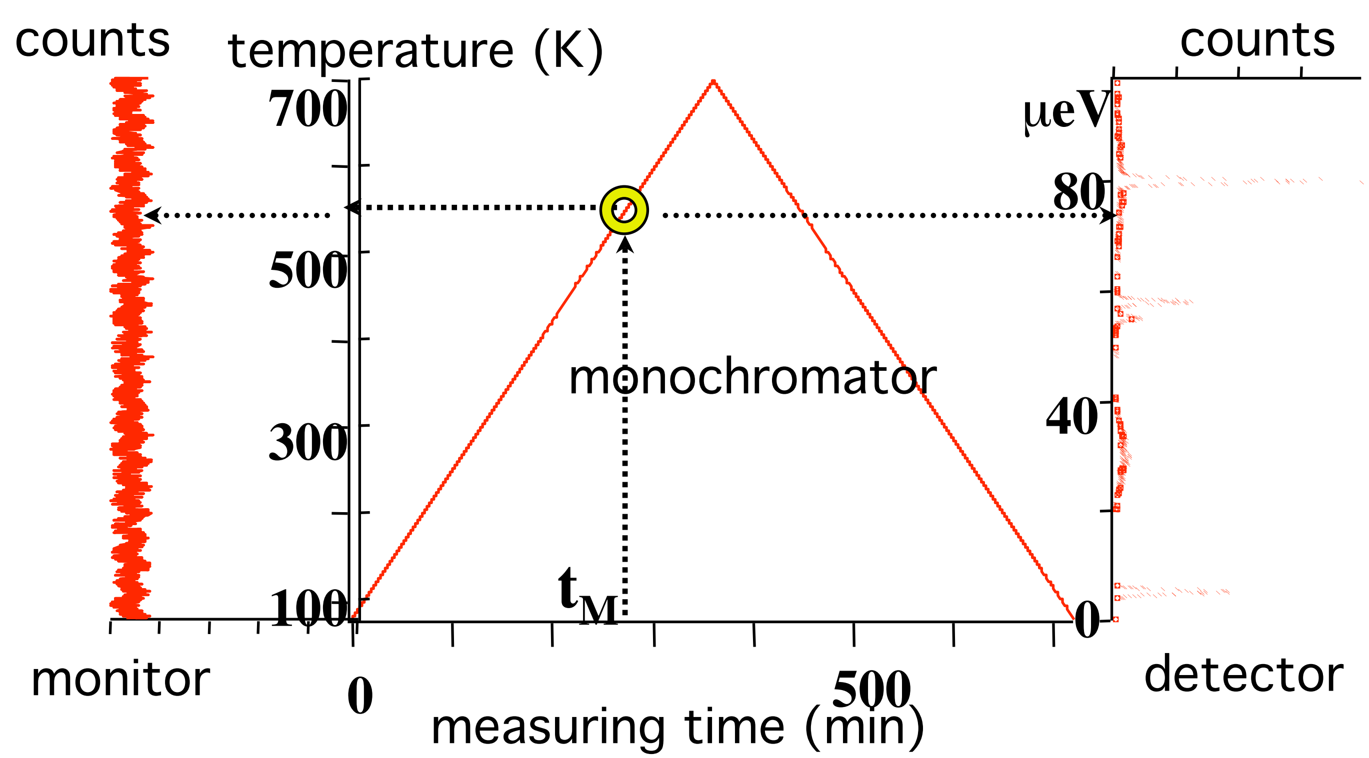
HOW TO SCAN THE ENERGY AND REMAIN IN BS? (2)

2) Change of the monochromator temperature = change of lattice distance :

$$d(T) = d_0\,(1 + \alpha\,T + O(2)\ldots).$$

$$\frac{\delta E}{E_i} = \frac{\delta d(T)}{d_0}$$

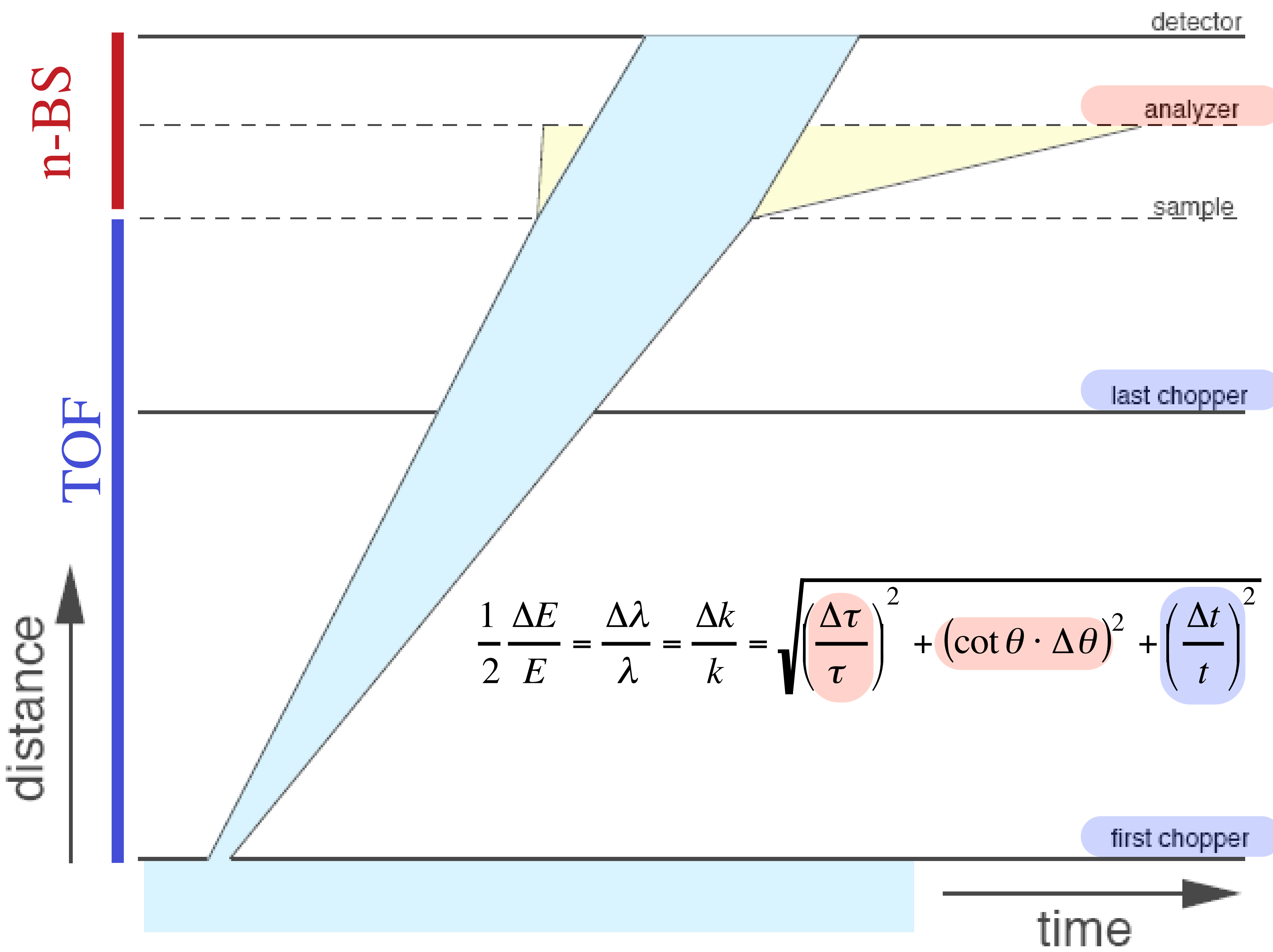




IN16 - reactor cold neutron backscattering instrument

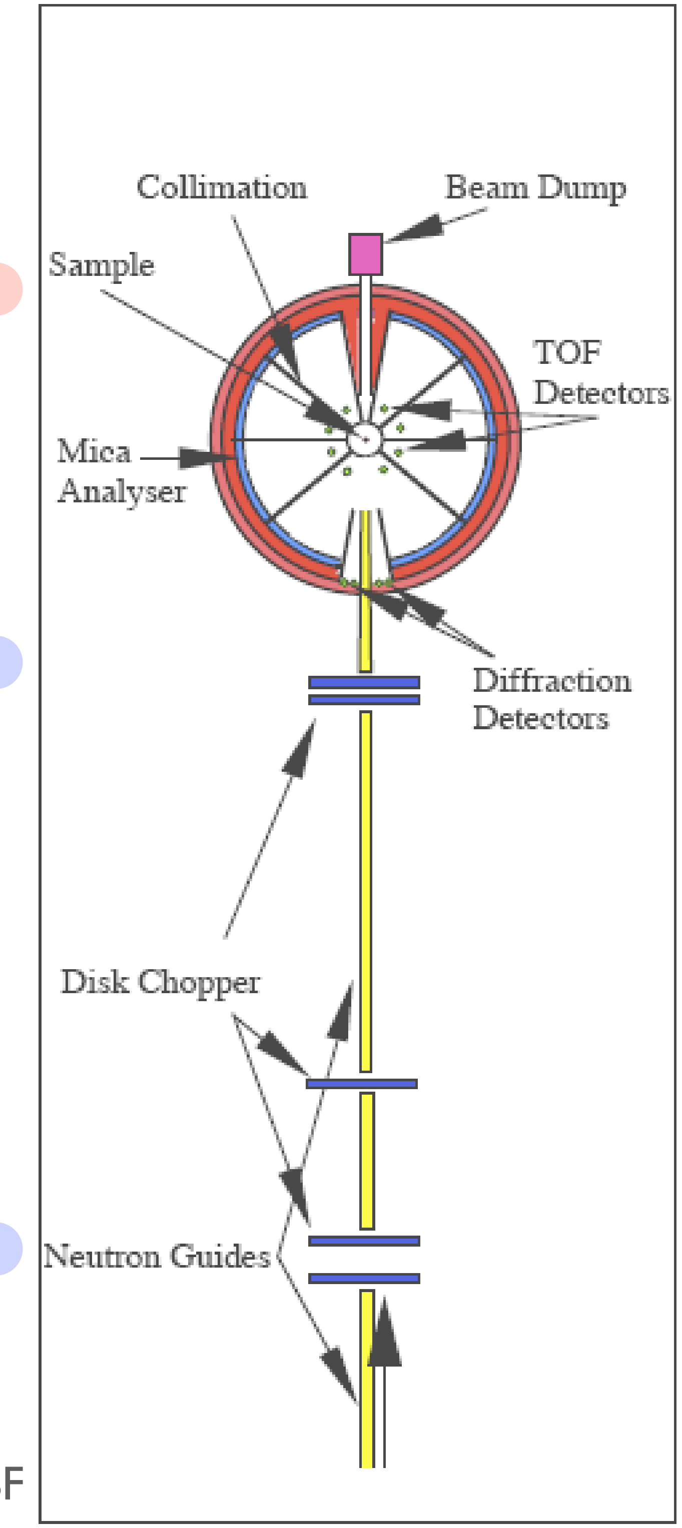
Inverted TOF spectrometers near backscattering

examples: IRIS-IRIS, MARS-PSI, BASIS-SNS



$$\frac{1}{2}\frac{\Delta E}{E} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta k}{k} = \sqrt{\left(\frac{\Delta\tau}{\tau}\right)^2 + \left(\cot\theta\cdot\Delta\theta\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

from Allenspach, PSI; modified BF



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Neutron Spinecho

fore more see talk by Ross Stewart

Echo condition:

$$\int_{\pi/2}^{\pi} B_1 d\ell = \int_{\pi}^{\pi/2} B_2 d\ell$$

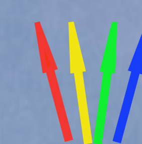
The measured quantity is: $S(q,t)/S(q,0)$

where

$$t \propto \lambda^3 \int B d\ell$$

For elastic scattering: $$\varphi_{tot} = \frac{\gamma B_1 l_1}{v_1} - \frac{\gamma B_2 l_2}{v_2} = 0$$

For omega energy exchange: $$\varphi_{tot} = \frac{\hbar\gamma B l}{m v^3}\omega + o\left(\left(\frac{\omega}{1/2 m v^2}\right)^2\right)$$



The probability of omega energy exchange: $$S(q,\omega)$$

The final polarization: $$\langle\cos\varphi\rangle = \frac{\int \cos(\frac{\hbar\gamma B l}{m v^3}\omega) S(q,\omega) d\omega}{\int S(q,\omega) d\omega} = S(q,t)$$

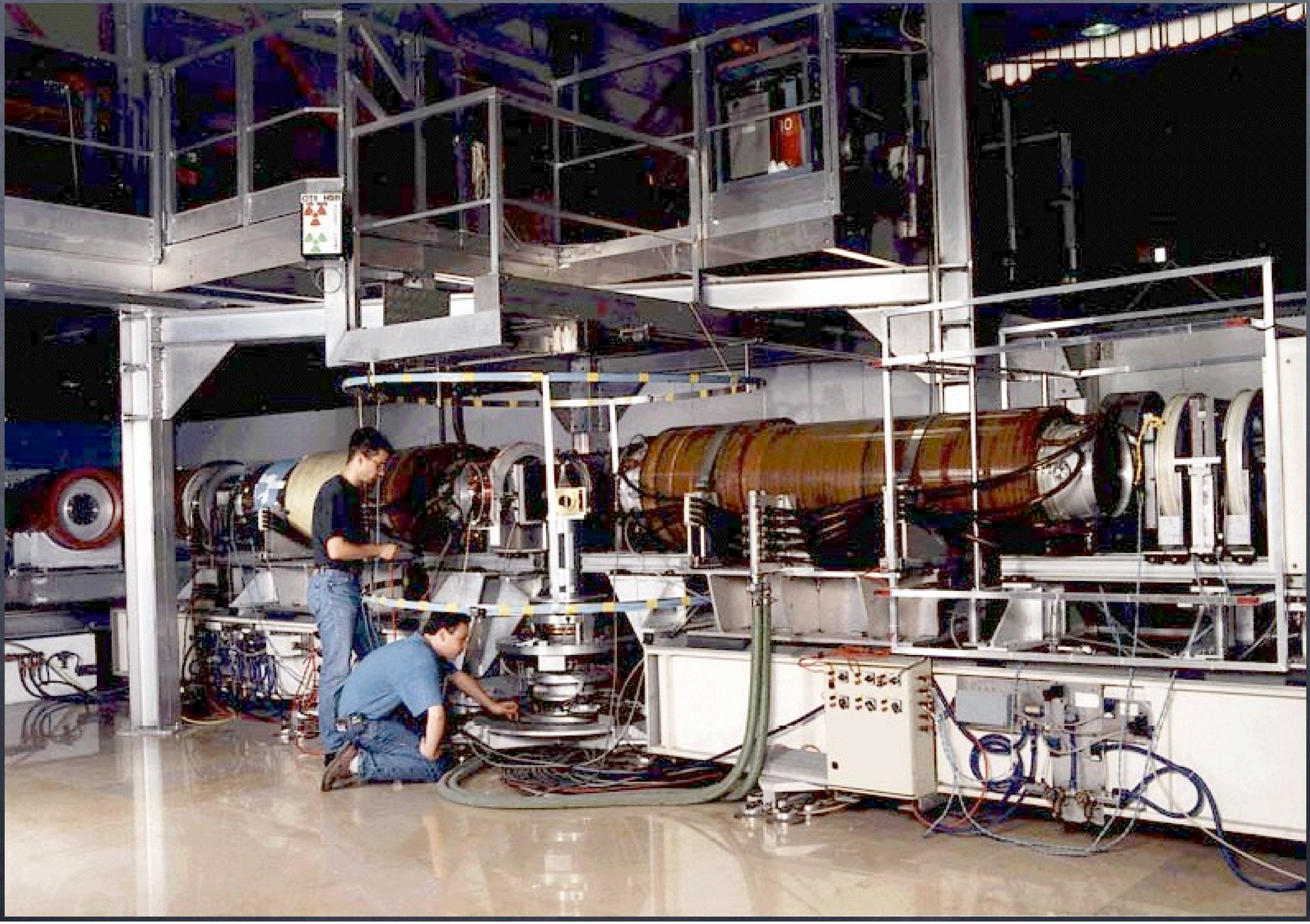
from Bela Farago, ILL

NSE

In15 the fat

Fourier time (in nsec):

8Å		10Å		16Å		20Å	
t min	t max	t min	t max	t min	t max	t min	t max
0.12	26.3	0.34	51.5	0.8	174	1.4	300



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applications of high resolution spectroscopy

- low frequency inelastic spectroscopy
  - tunneling spectroscopy
  - hyperfine interaction
  - ^{4}He excitation spectrum (roton)
  - aerogels & fractons
- quasielastic spectroscopy
  - Diffusion in metals, alloys, intercalation compounds, hydrogen in metals, fuel cells, membranes
  - Dynamics in polymers and biological systems
  - Dynamics of the phase transition and glass transition in molecular glasses and spin glasses
  - Atomic and molecular motion on surfaces and in confinement
  - Critical scattering near phase transitions
  - Dynamics of liquid crystals and liquids
  - Dynamics of hydrogen bonds
  - rotations of molecules, confinement

density correlation functions - self correlation function

T. Springer, ‘Quasielastic Neutron Scattering for the Investigation of Diffusive Motions in Solids and Liquids’, Springer Tracts in Modern Physics 64, 1972

define average probability per volume to find particle i at r′:

$$p_i(\mathbf{r}^{'}) =< \delta[\mathbf{r}^{'} - \mathbf{r}_i(t)] >$$

asymptotic behaviour:
$$G_s^{\infty}(\mathbf{r}) = \frac{1}{N}\sum_{i=1}^{N}\int p_i(\mathbf{r}^{'}-\mathbf{r})p_i(\mathbf{r}^{'})d\mathbf{r}^{'}$$

liquid:
$$\lim_{t\to\infty} G_s^{\infty}(\mathbf{r},t) = \frac{1}{V}$$

thus $\boxed{G_s^{\infty}(\mathbf{r}) \to 0 \quad \text{for} \quad V \to \infty}$

but not if V is finite: EISF!

reminder

assume identical scattering particles (drop index i)

$$G_s^{\infty}(\mathbf{r}) = \int p(\mathbf{r}^{'} - \mathbf{r})p_(\mathbf{r}^{'})d\mathbf{r}^{'}$$

and separate **G_s** in decaying and stationary part:

$$G_s^{'}(\mathbf{r},t) = \underline{G_s(\mathbf{r},t)} - \underline{G_s^{\infty}(\mathbf{r})}$$

elastic incoherent structure factor:

$$S_{inc}^{el}(\mathbf{Q}) = \int \exp\{-i(\mathbf{Qr})\}G_s^{\infty}(\mathbf{r})d\mathbf{r} = |\int \exp\{-i(\mathbf{Qr})\}p(\mathbf{r})d\mathbf{r}|^2$$

high energy/time resolution needed!

typical incoherent scattering law

$$S_{inc}(\mathbf{Q},\omega) = A_0(\mathbf{Q})\delta(\omega) + (1 - A_0(\mathbf{Q}))\mathbf{L}(\mathbf{Q},\omega)$$

elastic, EISF
stationary part

quasi-elastic
decaying part

for a given Q: $$\int_{-\infty}^{\infty} S_{inc}(\mathbf{Q},\omega)d\omega = 1$$

$$EISF = \frac{S_{inc}^{el}(\mathbf{Q})}{S_{inc}^{el}(\mathbf{Q}) + S_{inc}^{qel}(\mathbf{Q})}$$

simple incoherent scattering law:

isotropic translational diffusion

no stationary part -> no elastic scattering,

time space

$$S_{inc}(\mathbf{Q},t) = \exp(-DQ^2 t)$$

relaxation rate ***|τ| = 1/(DQ²)***

energy space

$$S_{inc}(Q,\omega) = \frac{1}{\pi}\frac{DQ^2}{\omega^2 + (DQ^2)^2}$$

Lorentzian with energy width

HWHM = Γ/2 = ħDQ²

D=self diffusion constant [m²/s]

*D~exp(-**E_a**/kT)*

$$Q = 1\mathring{A}^{-1} : D = \frac{\Gamma\pi}{hQ^2} = \frac{\Gamma[\mu eV]\pi}{4.136[\mu eV ns]10^{16}[cm^2]} \approx \frac{3}{4}\Gamma[\mu eV]\cdot 10^{-7}\frac{cm^2}{s}$$

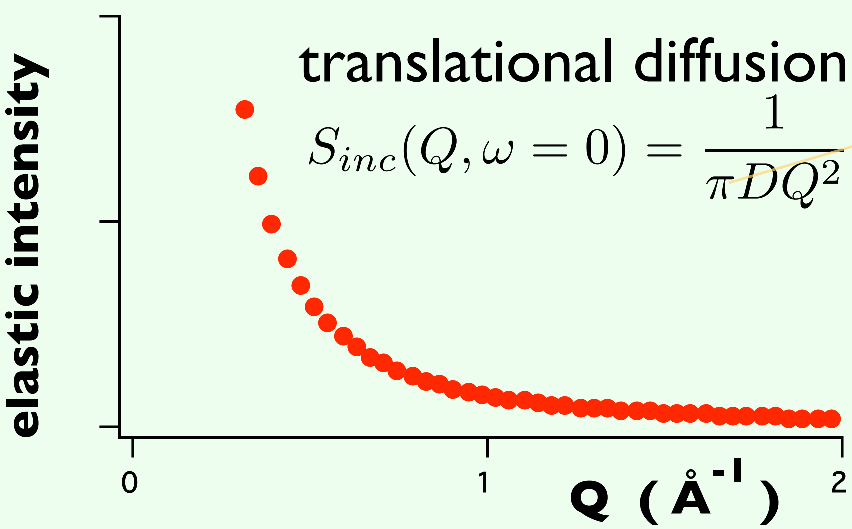
example:
D(H_2O @ RT) ~ 2 10^{-5} cm²/s
FWHM ~ 270 μeV @ 1Å^{-1}; τ=5ps
FWHM ~ 2.7 μeV @ 0.1Å^{-1}; τ=50ps
=> TOF dynamic range

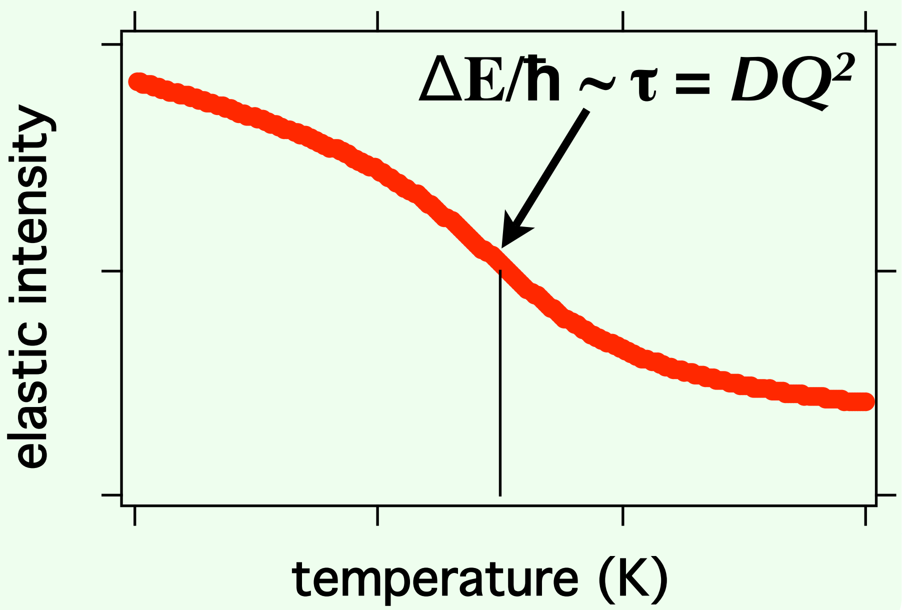
simple incoherent scattering law:

isotropic translational diffusion

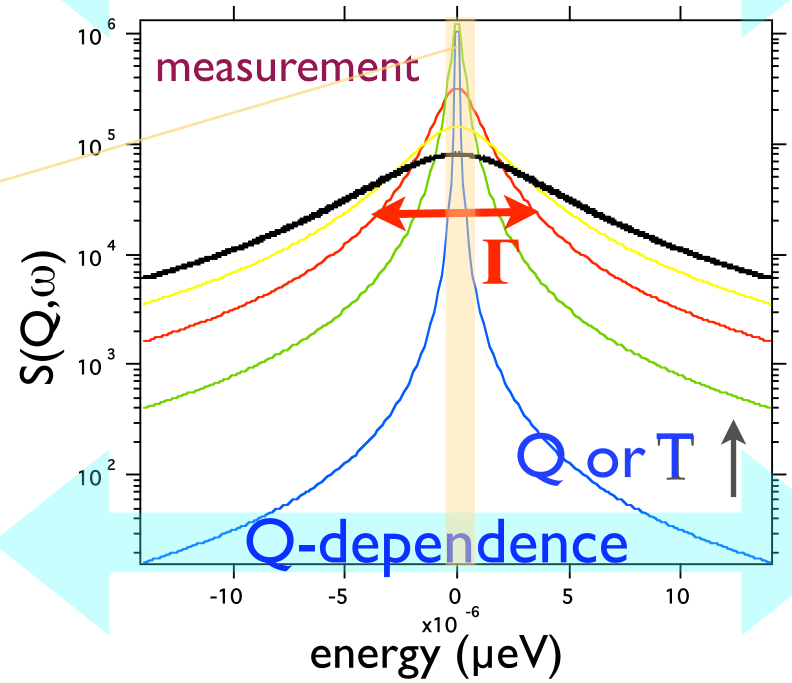
no stationary part -> no elastic scattering

e.g. elastic scans on BS

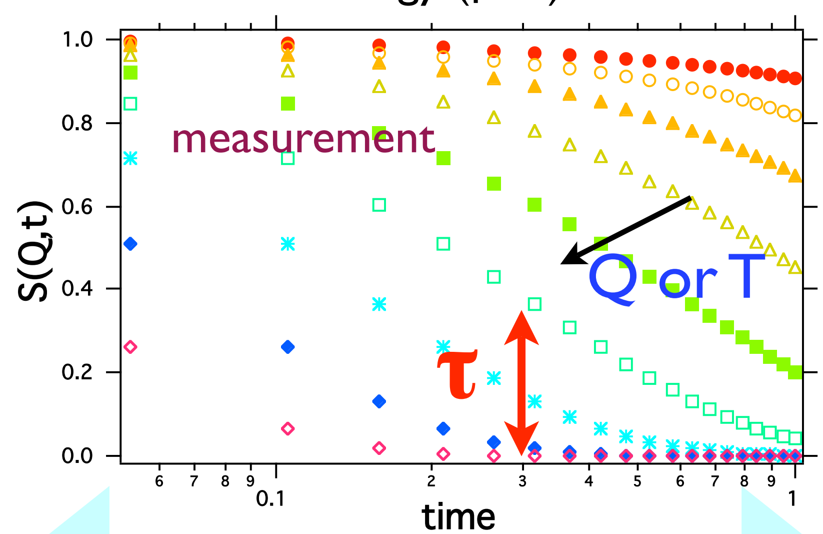




line shape



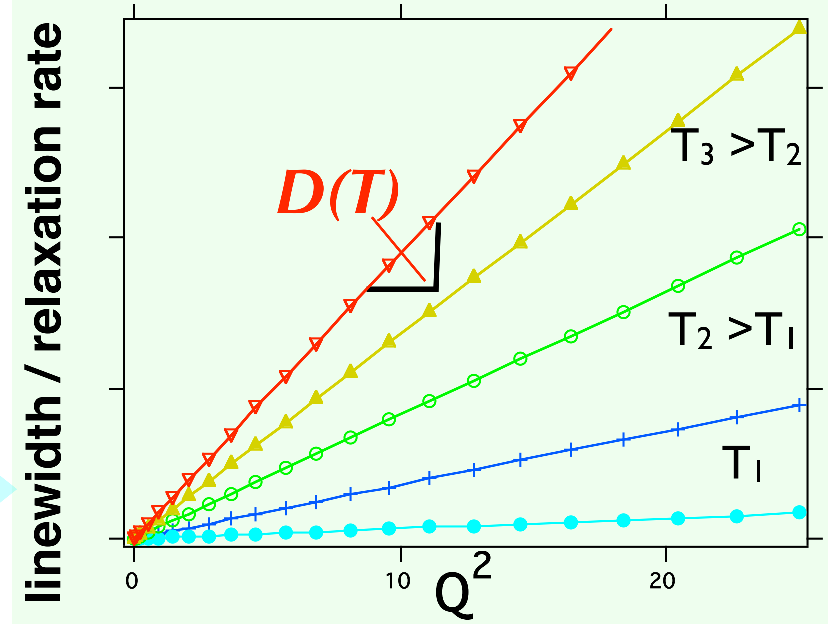
Q-dependence

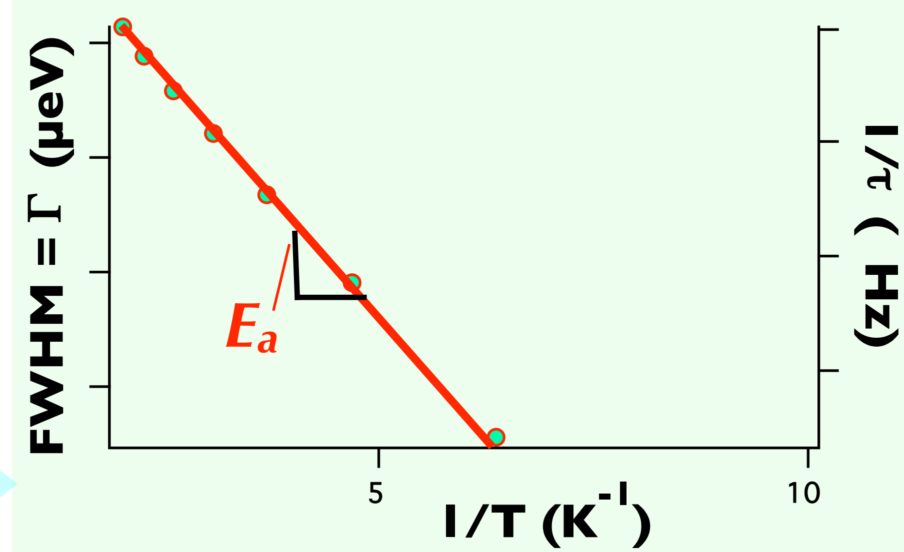


T-dependence

t- or E-spectroscopy on NSE or TOF, BS

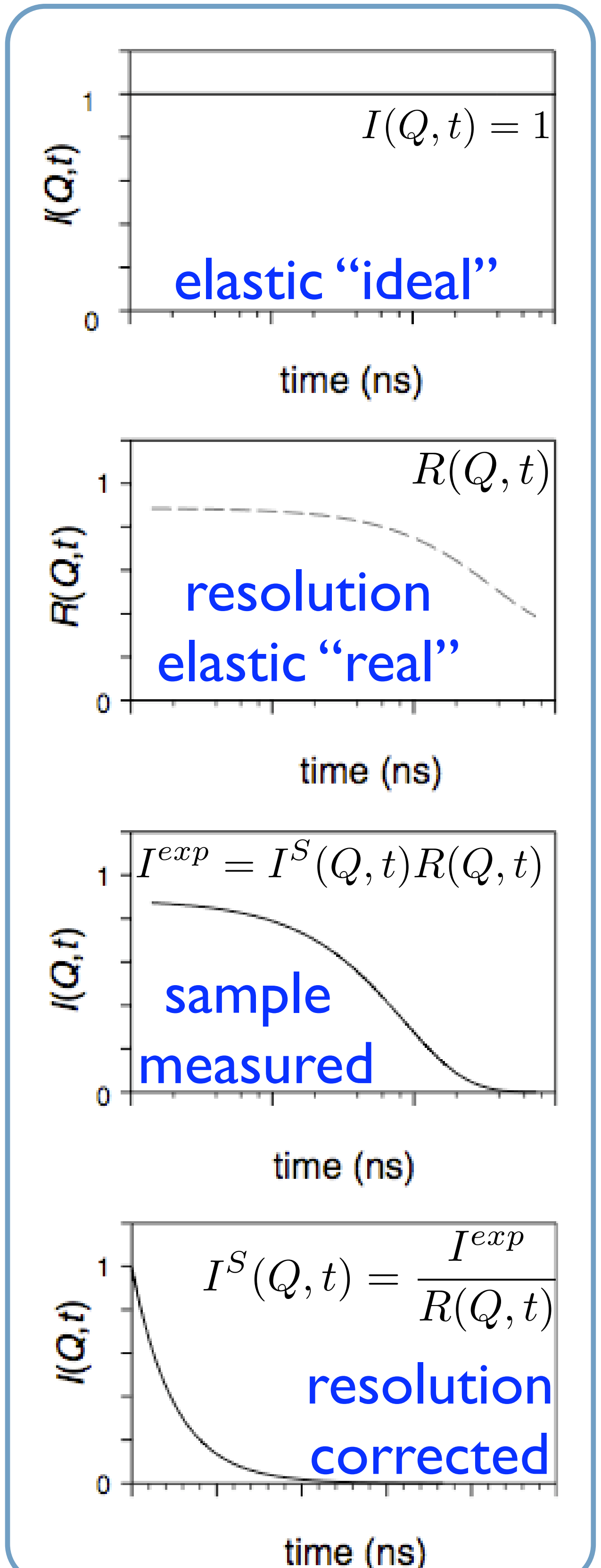
Lorentzian with $\Gamma/2 = \hbar DQ^2 = \hbar/|\tau|$





simple coherent scattering law:

transport diffusion - example experiment



neutron spin echo

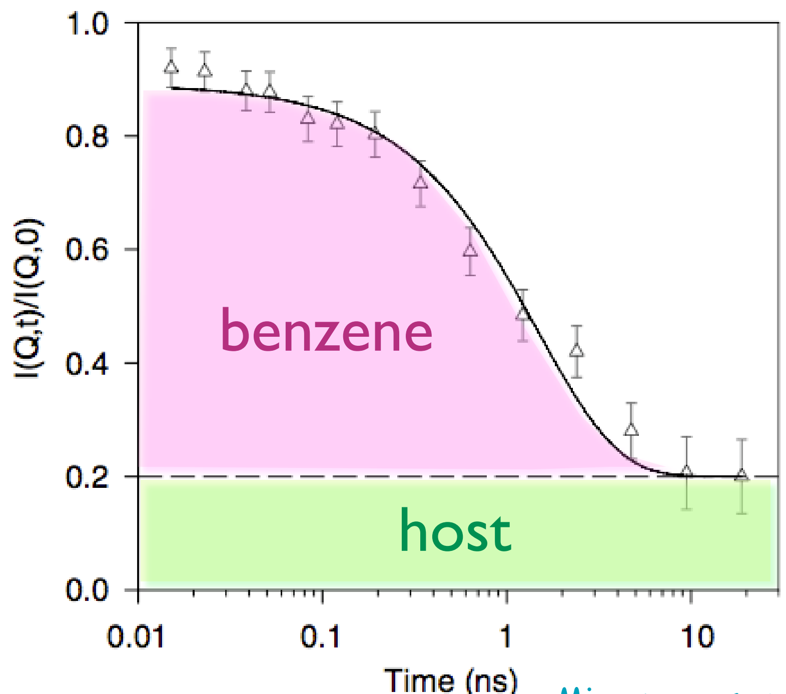


Fig. 6. Normalized intermediate scattering function obtained for benzene in NaY zeolite (1 molecule per supercage, on average, $T = 475$ K, $Q = 0.3$ Å^{-1}). The fraction of the intensity due to the zeolite is represented as a dashed line.

H. Jobic, Theodorou
Microporous and Mesoporous Materials 102 (2007) 21

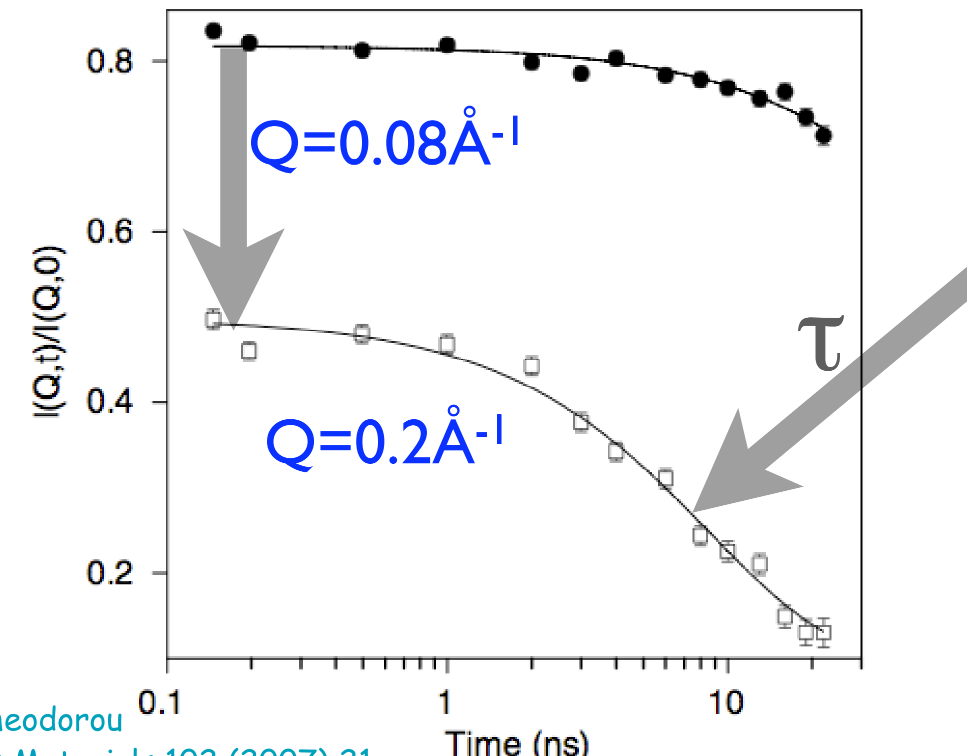
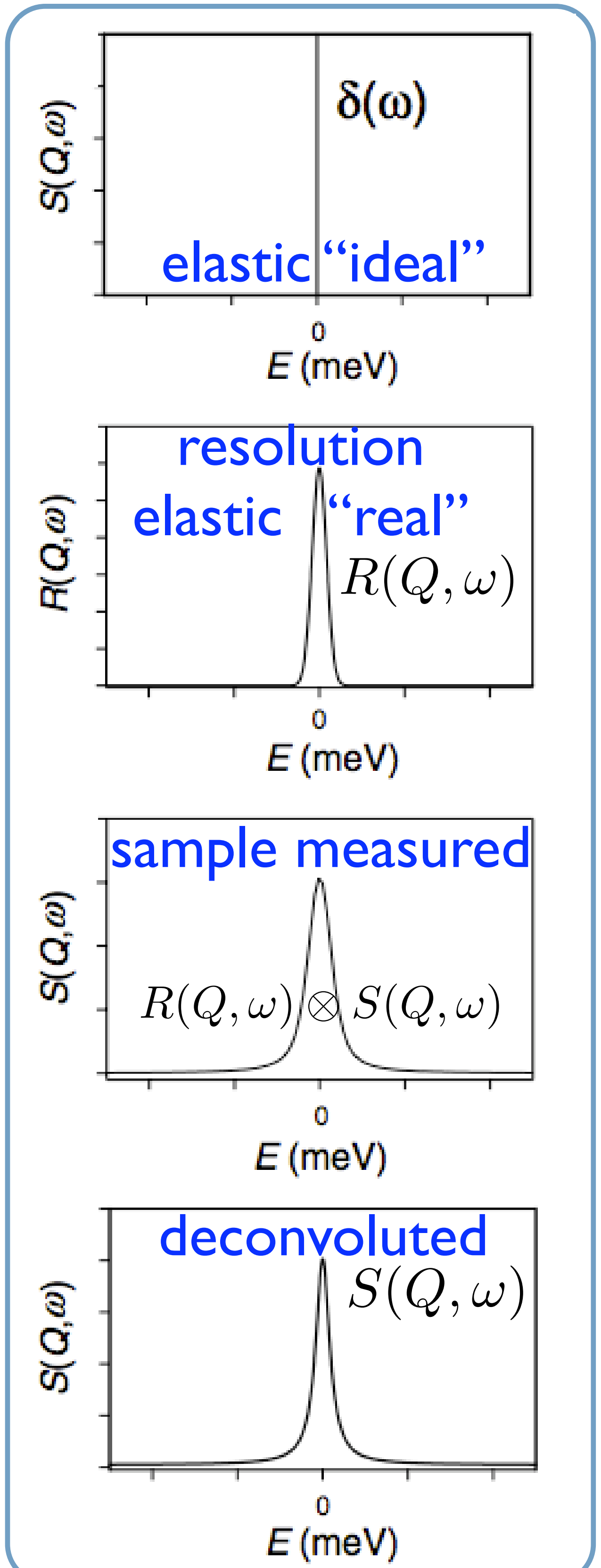


Fig. 7. Normalized intermediate scattering functions obtained for isobutane in silicalite-1 at 550 K, for two different Q values: (●) 0.08 Å^{-1}, (□) 0.2 Å^{-1}.

NSE best for coherent scattering
incoherent: 1/3 'signal' on 2/3 background
wide dynamic range: important for line-shape studies
best time resolution
difficult for partially deuterated samples with similar relaxation times

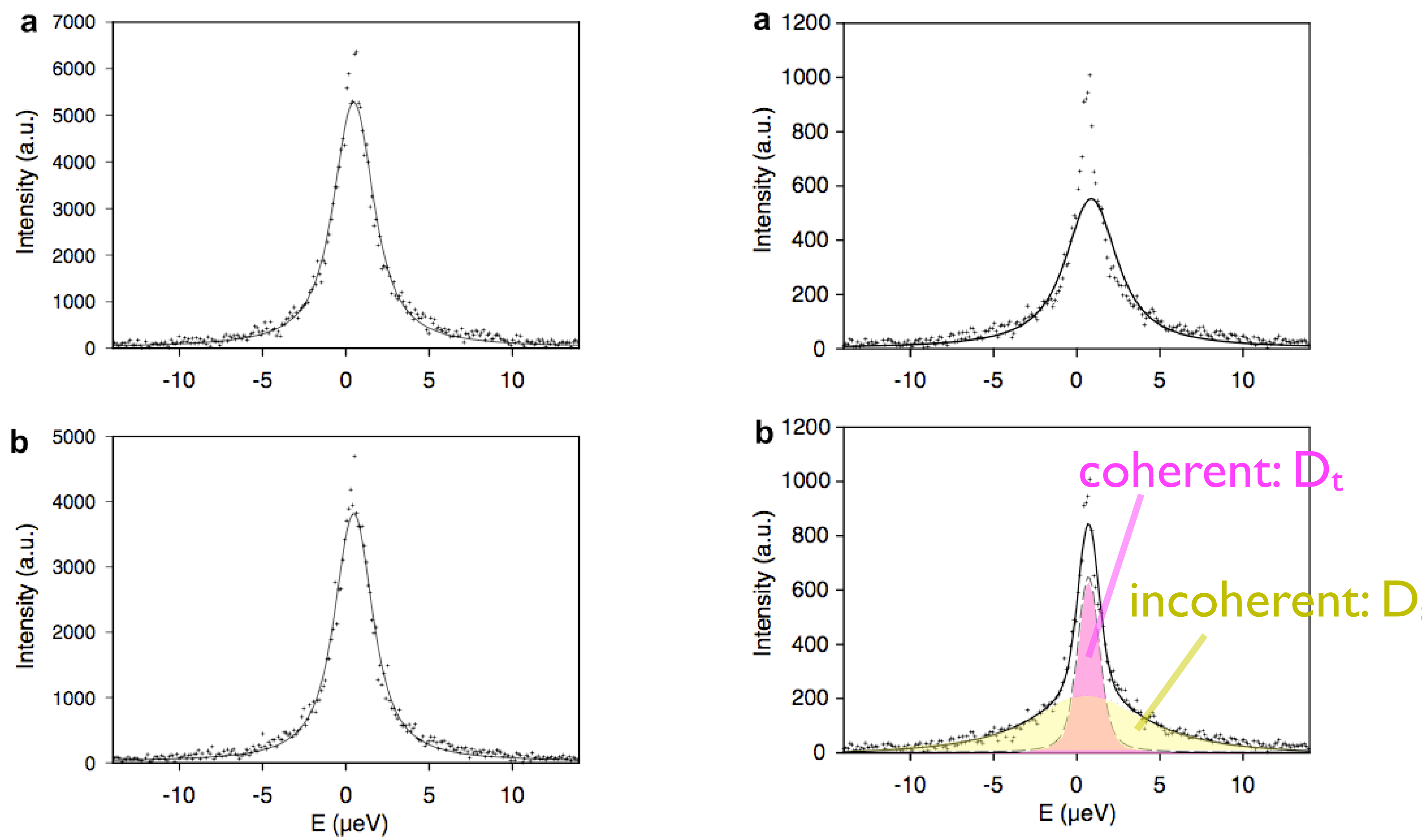
simple incoherent scattering law:

translational diffusion - D_s and D_t



example from neutron backscattering at reactors

H. Jobic, D.N. Theodorou / Microporous and Mesoporous Materials 102 (2007) 21–50



best for very low frequency inelastic excitations; good for quasielastic

best for incoherent scattering, but possible for partially deuterated (knowledge of $S_i(Q)$ needed)

narrow dynamic range, but combined by FT with TOF as wide as NSE

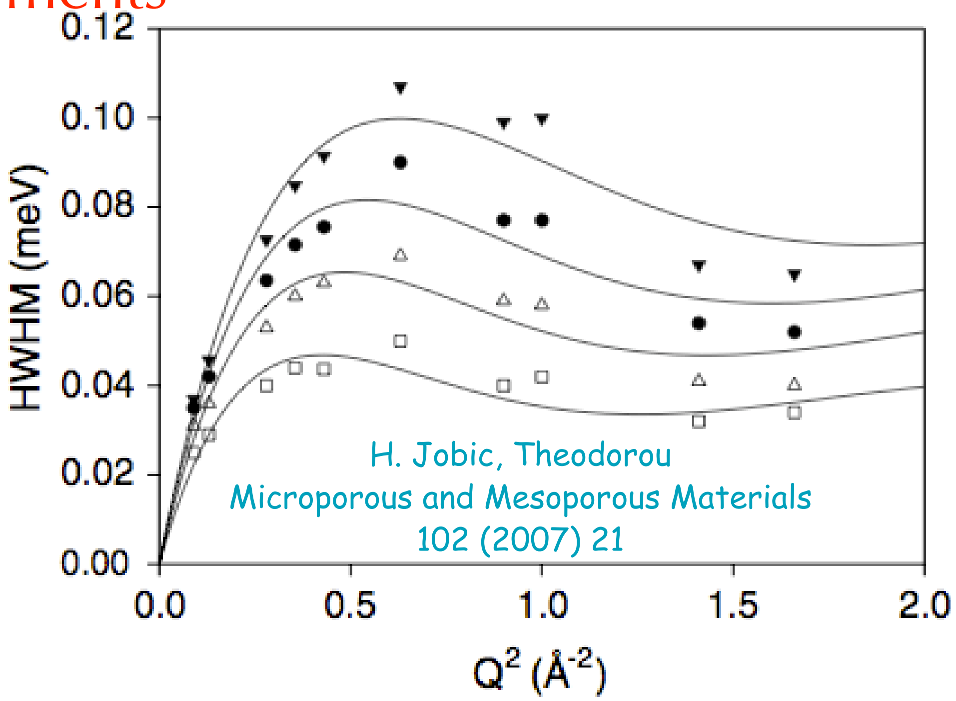
best energy resolution

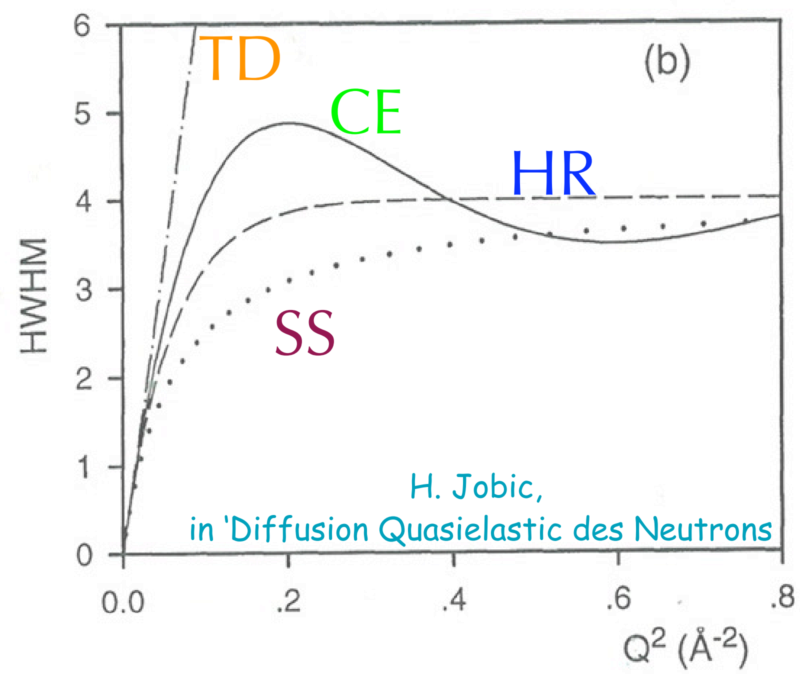
diffusion models

deviations from (Fick's law) translational diffusion at larger Q

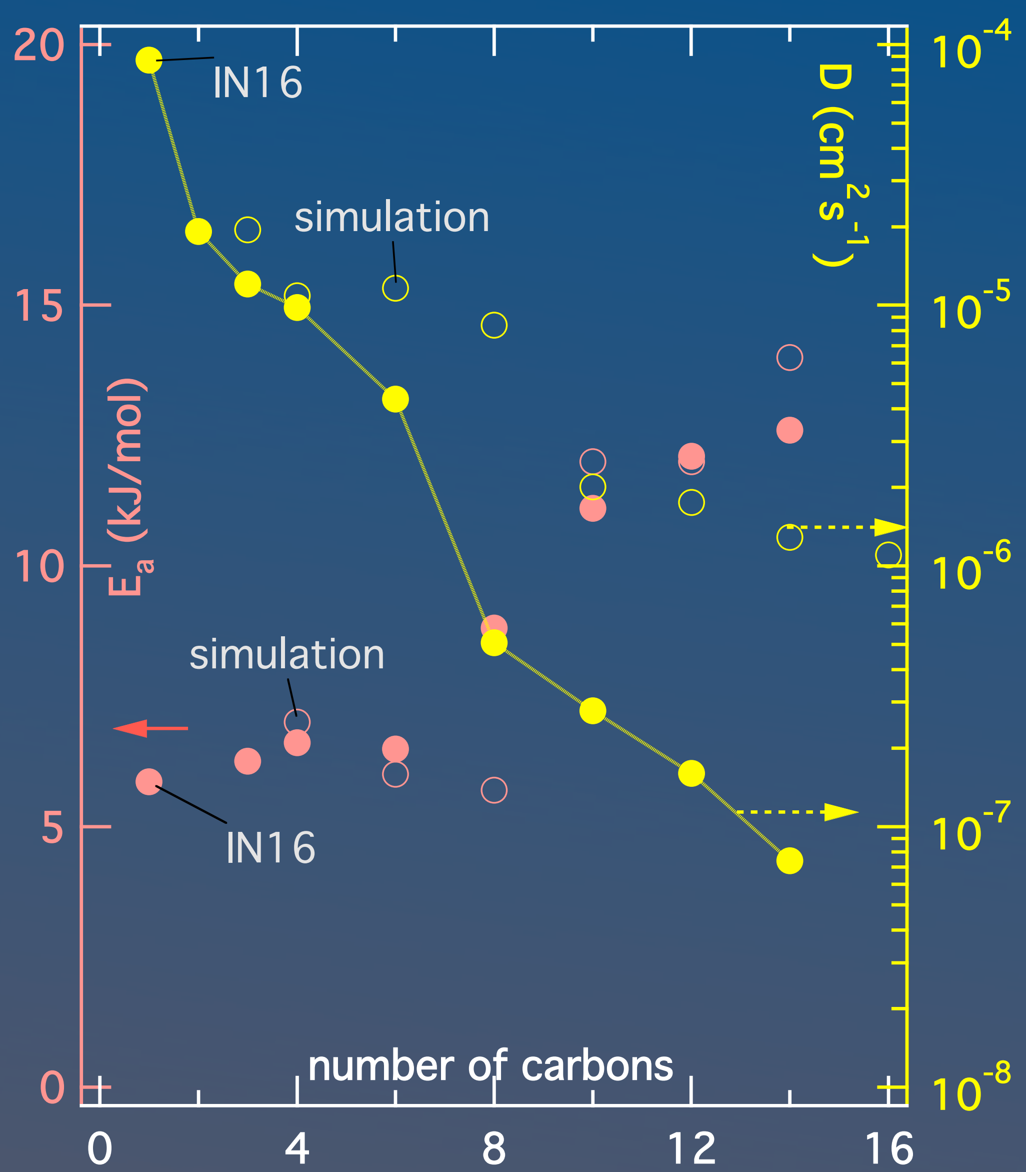
example from TOF instruments

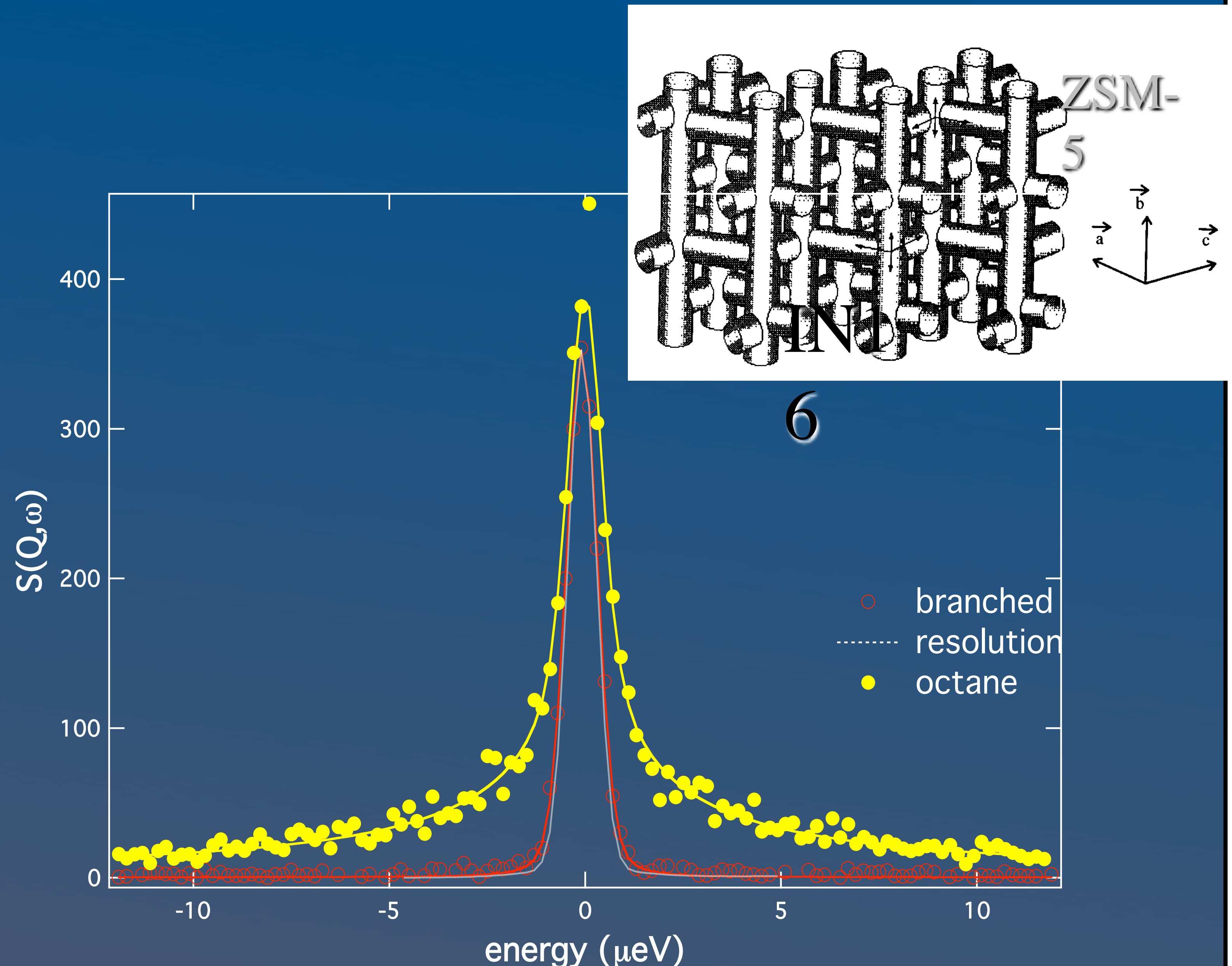
- continuous / translational diffusion
- jump diffusion models:
  - Chudley-Elliott: HWHM is Q-dependent
  - Singwi-Sjölander
  - Hall-Ross
- anisotropic diffusion models
- diffusion in lower dimensions





diffusion of alkanes in zeolites





See e.g. Hervé Jobic, J.Mol.Catalysis A:Chemical 158,(2000),135

- studies as a function of chain length, branching, loading of alkanes

⇒fit of Chuddley-Elliott type jump models; wide Q-range needed

simple incoherent scattering law:

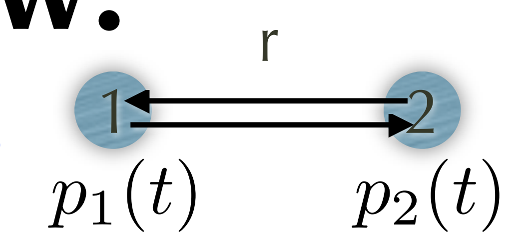
- jump models

see e.g.: - M. Bée, 'Quasielastic Neutron Scattering'

local motions -> Q-independent linewidth & EISF

- jumps between 2,3,4,...n (non-)equivalent sites
  - rotational diffusion on a circle
  - diffusion on a sphere
- diffusion inside a sphere, cylinder,...

simple incoherent scattering law:



- two site jump among equivalent sites

stationary part -> elastic scattering

$$I(\mathbf{Q},t) = A_0(\mathbf{Q}) + A_1(\mathbf{Q}))exp(-\frac{2t}{\tau})$$

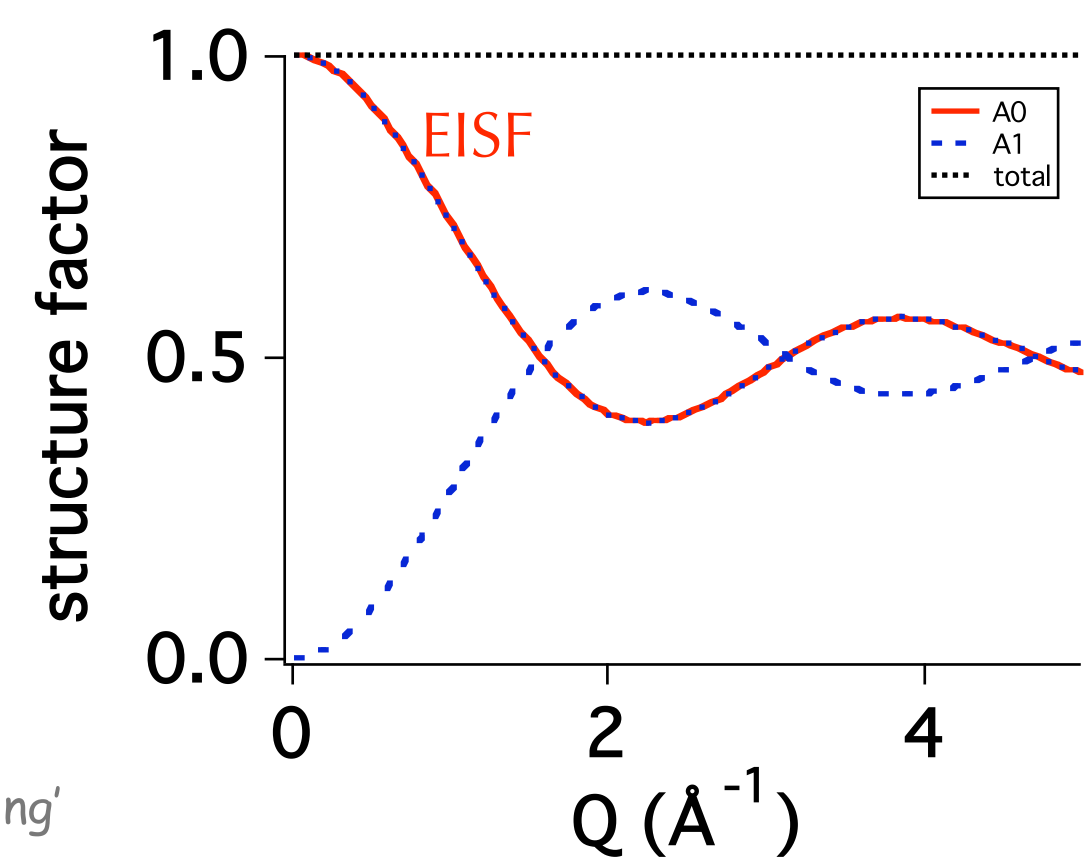
$$S_{inc}(\mathbf{Q},\omega) = A_0(\mathbf{Q})\delta(\omega) + A_1(\mathbf{Q})\frac{1}{\pi}\frac{2\tau}{4+\omega^2\tau^2}$$

structure factors after powder averaging:

EISF: $A_0(Q) = [1 + j_0(Qr)]/2$

$A_1(Q) = [1 - j_0(Qr)]/2$

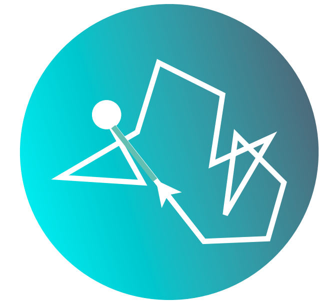
j_0 = 0-th order spherical Besselfct.



see e.g. M. Bée, 'Quasielastic Neutron Scattering'

simple incoherent scattering law:

- free diffusion inside a sphere



stationary part -> elastic scattering

Volino F., Dianoux A.J. , Mol. Phys. 41, 271-279 (1980)

$$S(q,\omega) = A_0^0(q)\,\delta(\omega) + \frac{1}{\pi}\sum_{\ell,n}(2\ell+1)A_n^\ell(q)\,\frac{\left(x_n^\ell\right)^2 D/R^2}{\left[\left(x_n^\ell\right)^2 D/R^2\right]^2+\omega^2}$$

$$A_0(Q) = \left(\frac{3j_1(Qa)}{Qa}\right)^2 \text{ and } j_1(x) = \frac{sin(x)}{x^2} - \frac{cos(x)}{x}$$ spherical Besselfct. of 1st order

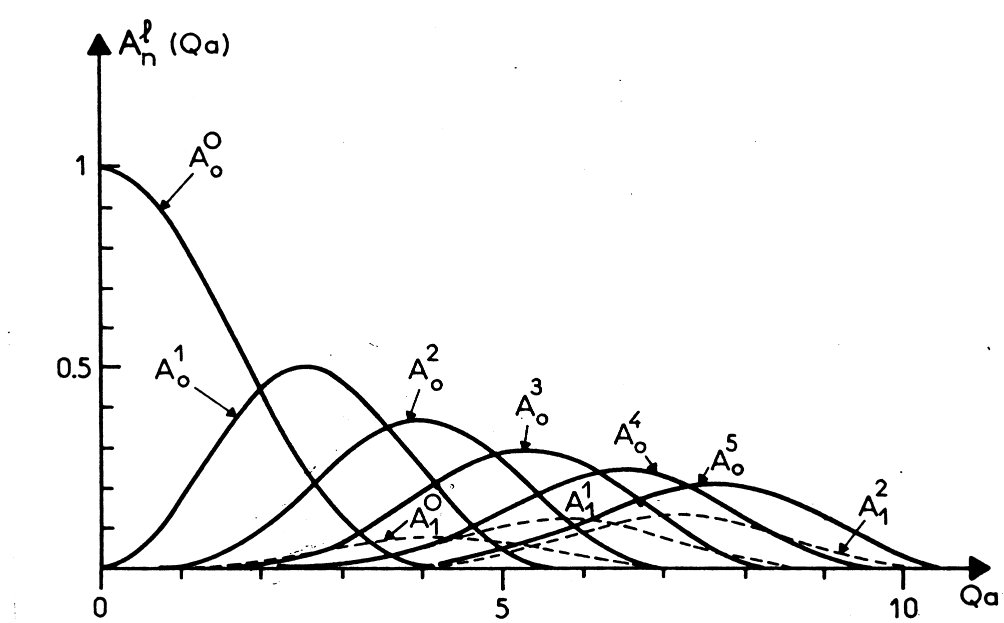


Figure 1. Variation of the first incoherent structure factors $A_n^l(Q)$ versus Qa (31–32) for diffusion inside an impermeable sphere of radius a. The elastic incoherent structure factor (EISF) is $A_0^0(Q)$.

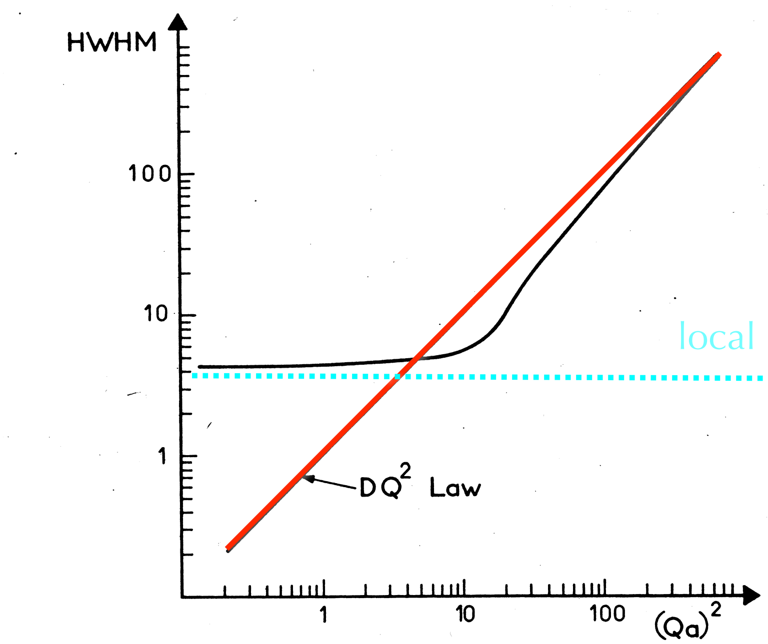
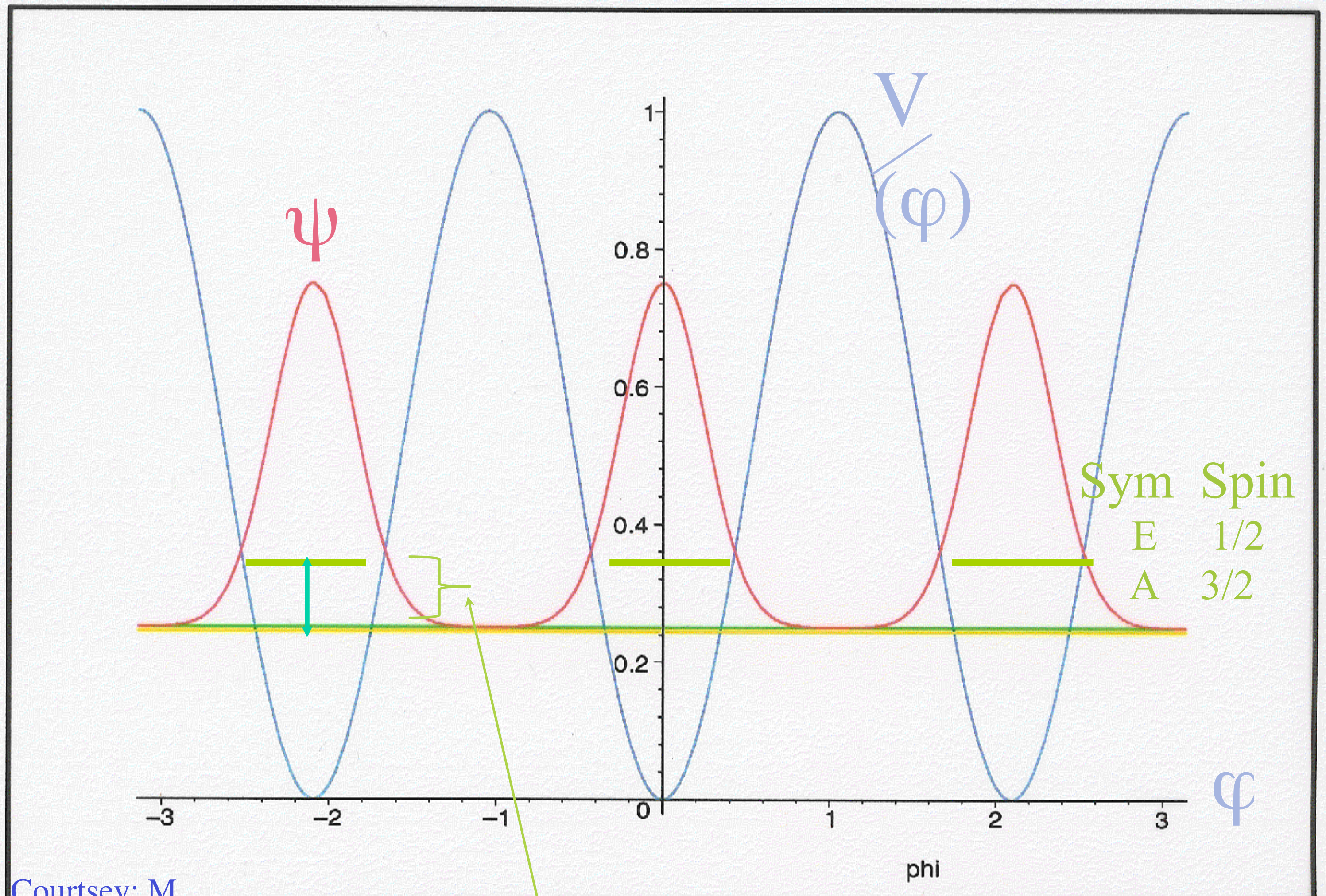


Figure 2. Variation of the half width at half maximum (HWHM) of the broadened component of the scattering law for diffusion inside a sphere of radius a, (33), expressed in D/a^2 energy units, versus $(Qa)^2$. The HWHM of the DQ^2 law is also represented. In the present units, its value is $(Qa)^2$.

Rotational tunneling

Single particle model: environment=potential $V(\varphi)$



Courtesy: M. Prager

$|123>$ $|231>$ $|312>$

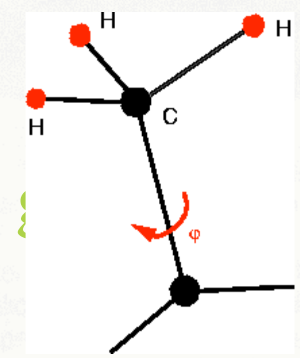
Extreme sensitivity: $\hbar\omega_t \sim e^{-\alpha V(\varphi)}$

Rotational Tunneling and Neutron Spectroscopy: A Compilation

M. Prager
Institut für Festkörperforschung des Forschungszentrums Jülich, D-52425 Jülich, FRG

A. Heidemann
Institut Laue-Langevin, B.P. 156, F-38042 Grenoble, France

1d rotor e.g.: CH_3



1 tunnel transition; doublet ground state (A,E)

3d rotors:

CH_4, NH_4

5 sub-states (A,3T,E)

more complex tunneling spectra

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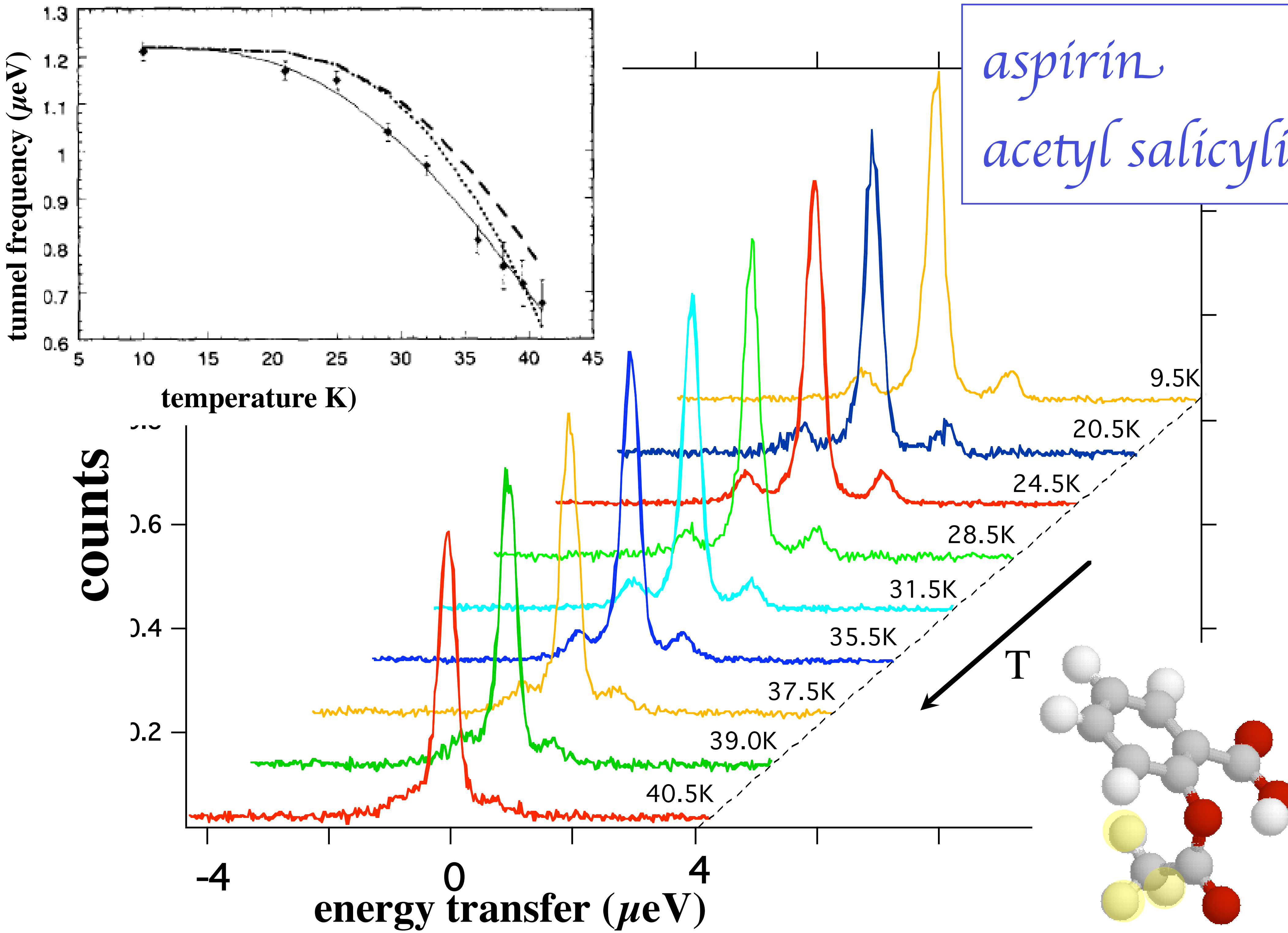
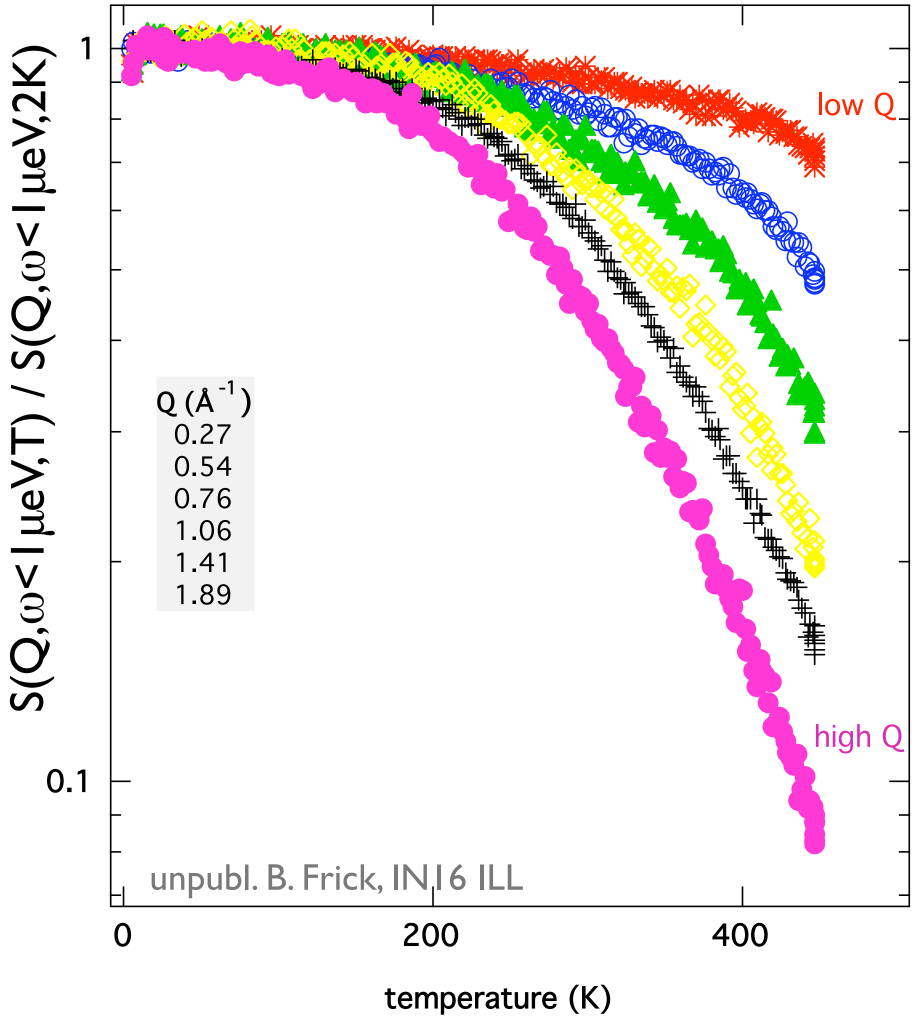
methyl group tunneling

aspirin
acetyl salicylic acid

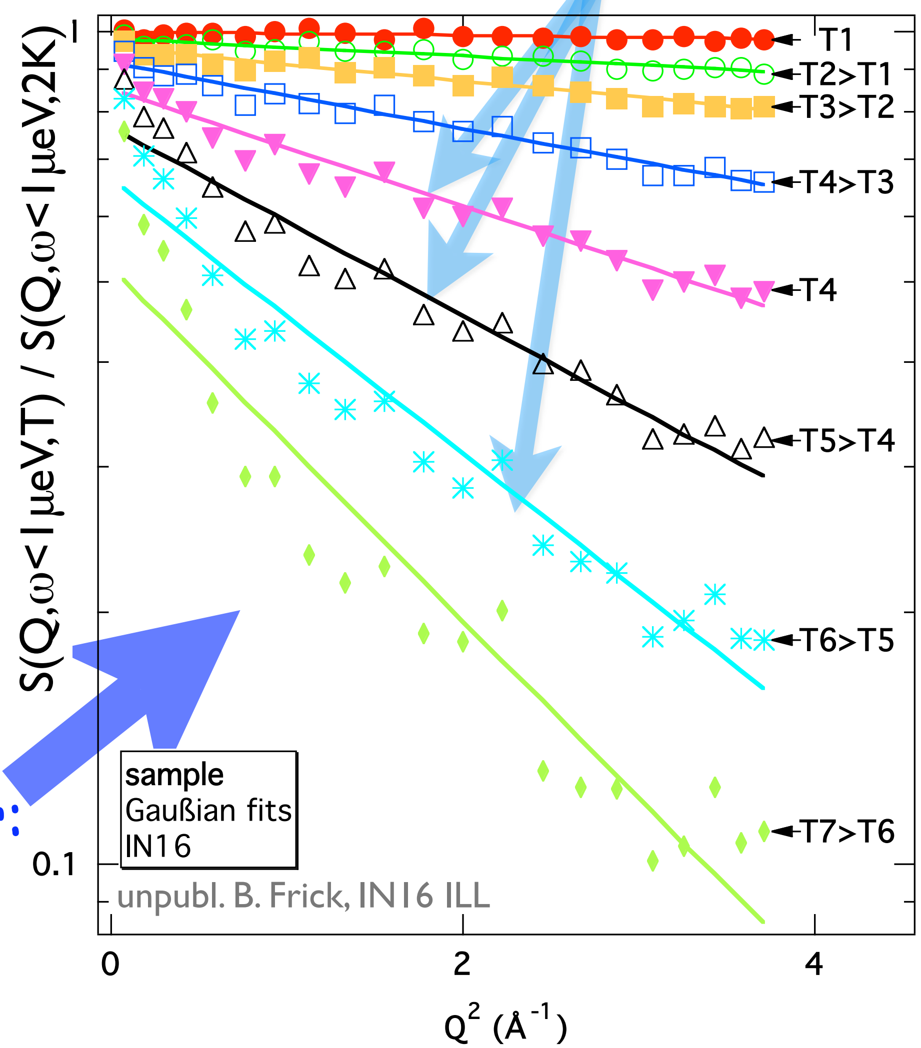


elastic scans

- and “Gaussian” behaviour

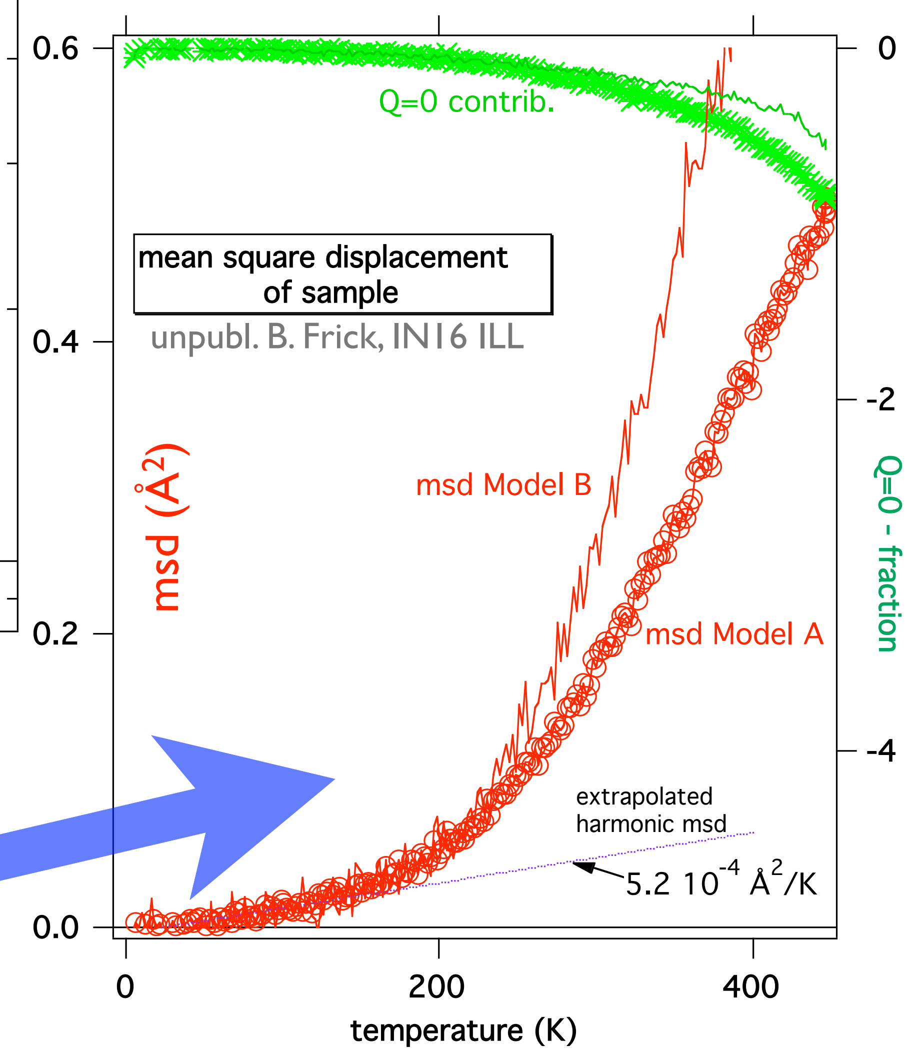


clear deviations from linear behaviour:
at T~T4 onset of anharmonic motion, formfactor etc.

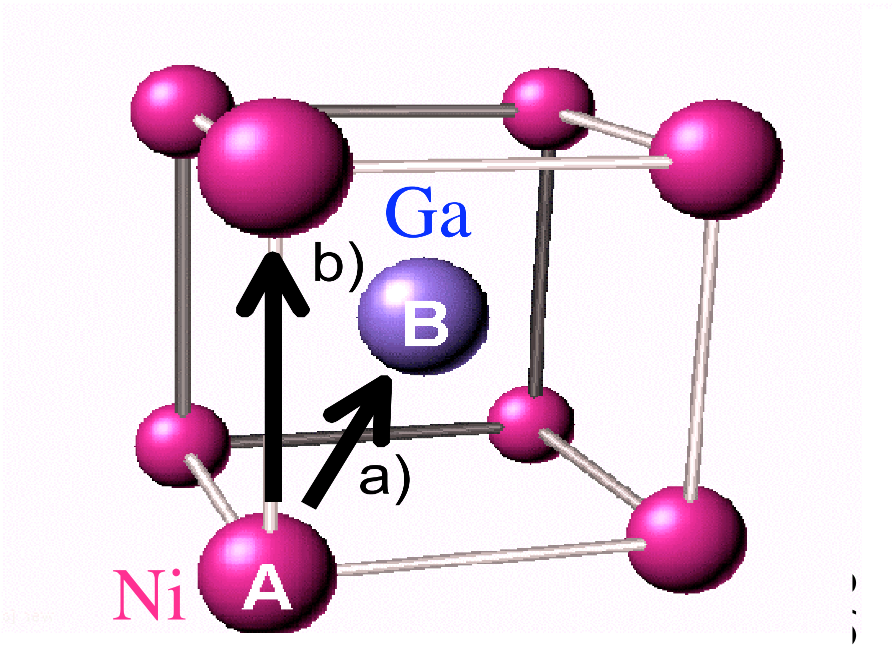


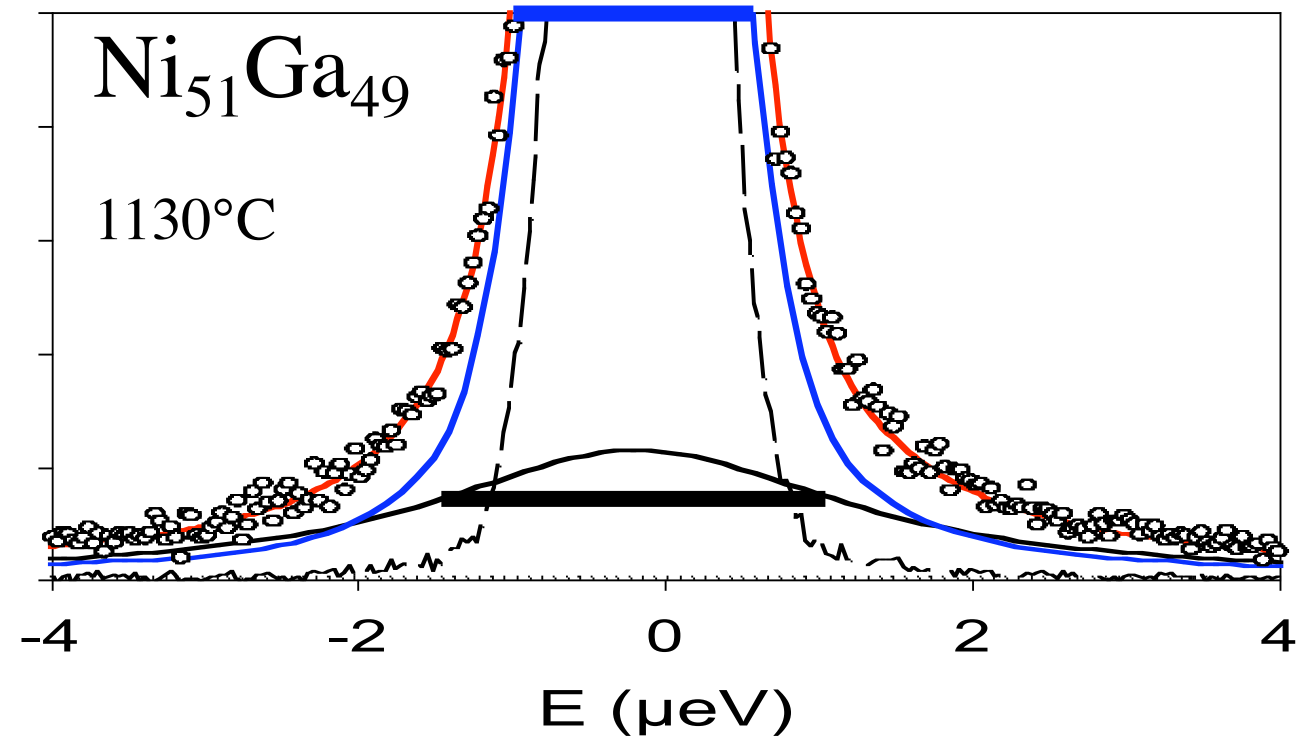
check for Gaussian behaviour:
linear in $\ln(I/I_0)$ vs Q^2

calculate mean squared displacement:

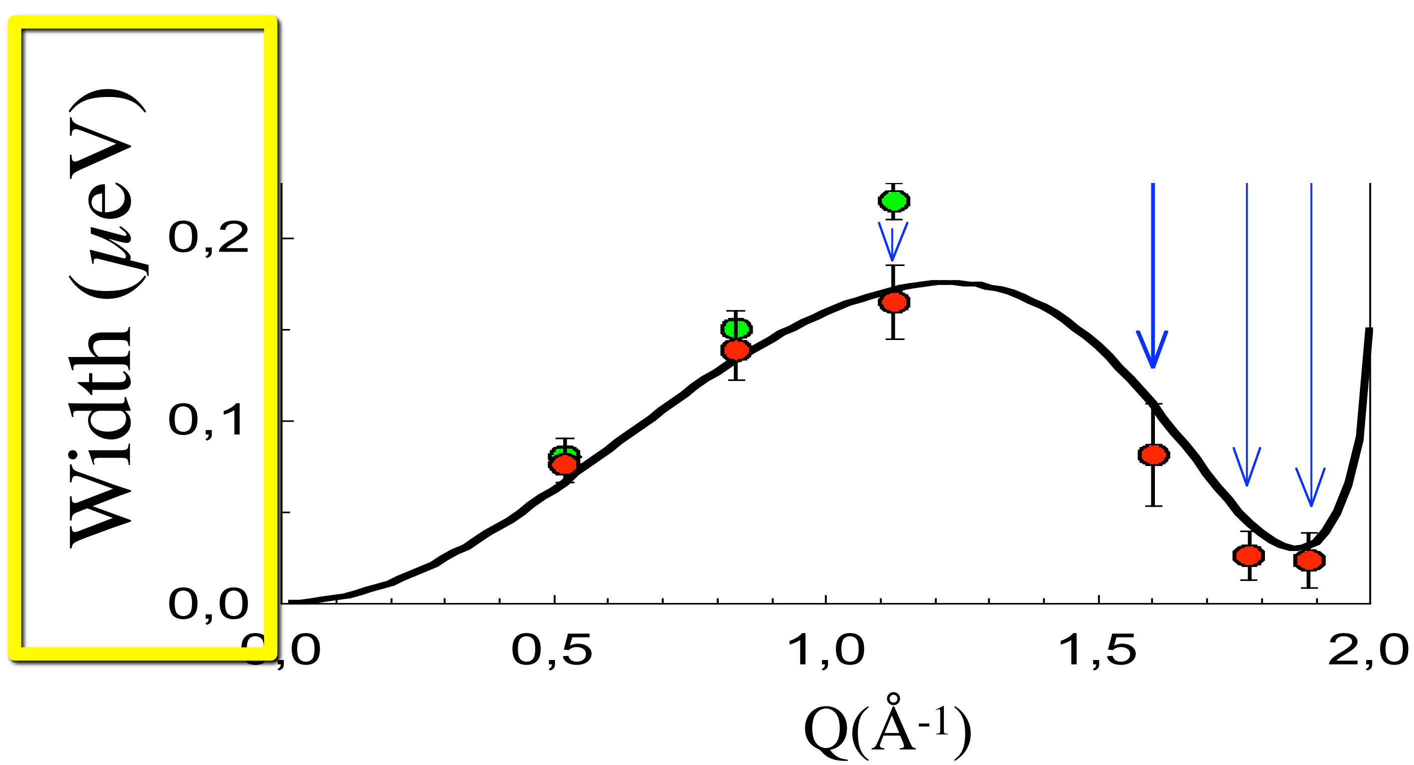


jump diffusion in single crystals





Using single crystals diffusion constants and jump vector can be determined.



Kaisermayr et al.; ILL Annual report 2000
Kaisermayr et al., PRB, 63 (2001)

PRL 98, 215503 (2007) PHYSICAL REVIEW LETTERS week ending 25 MAY 2007

IRIS-example

Nature of the Bound States of Molecular Hydrogen in Carbon Nanohorns

F. Fernandez-Alonso,[1,*] F. J. Bermejo,[2,†] C. Cabrillo,[2]

PG(002) δE=8.8μeV

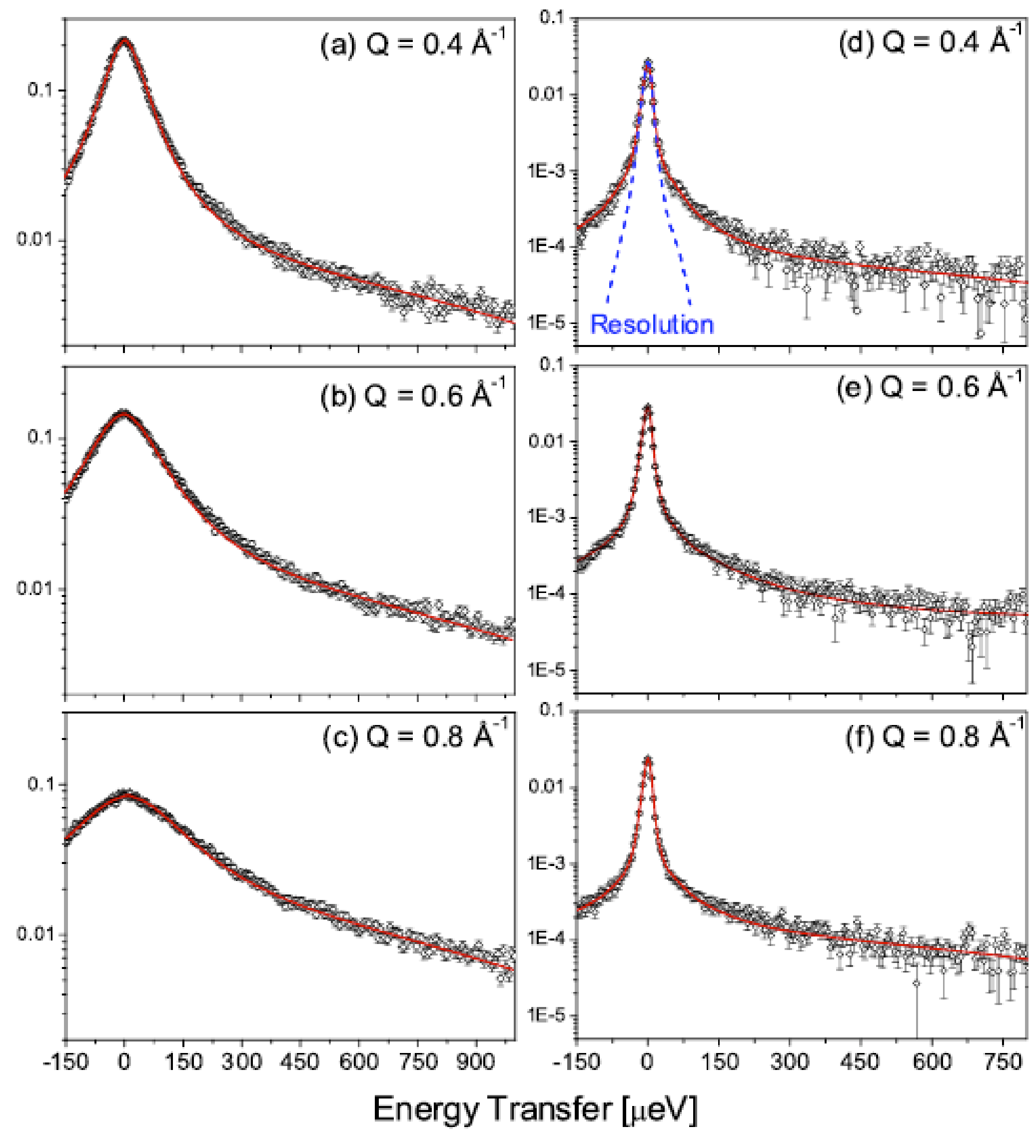
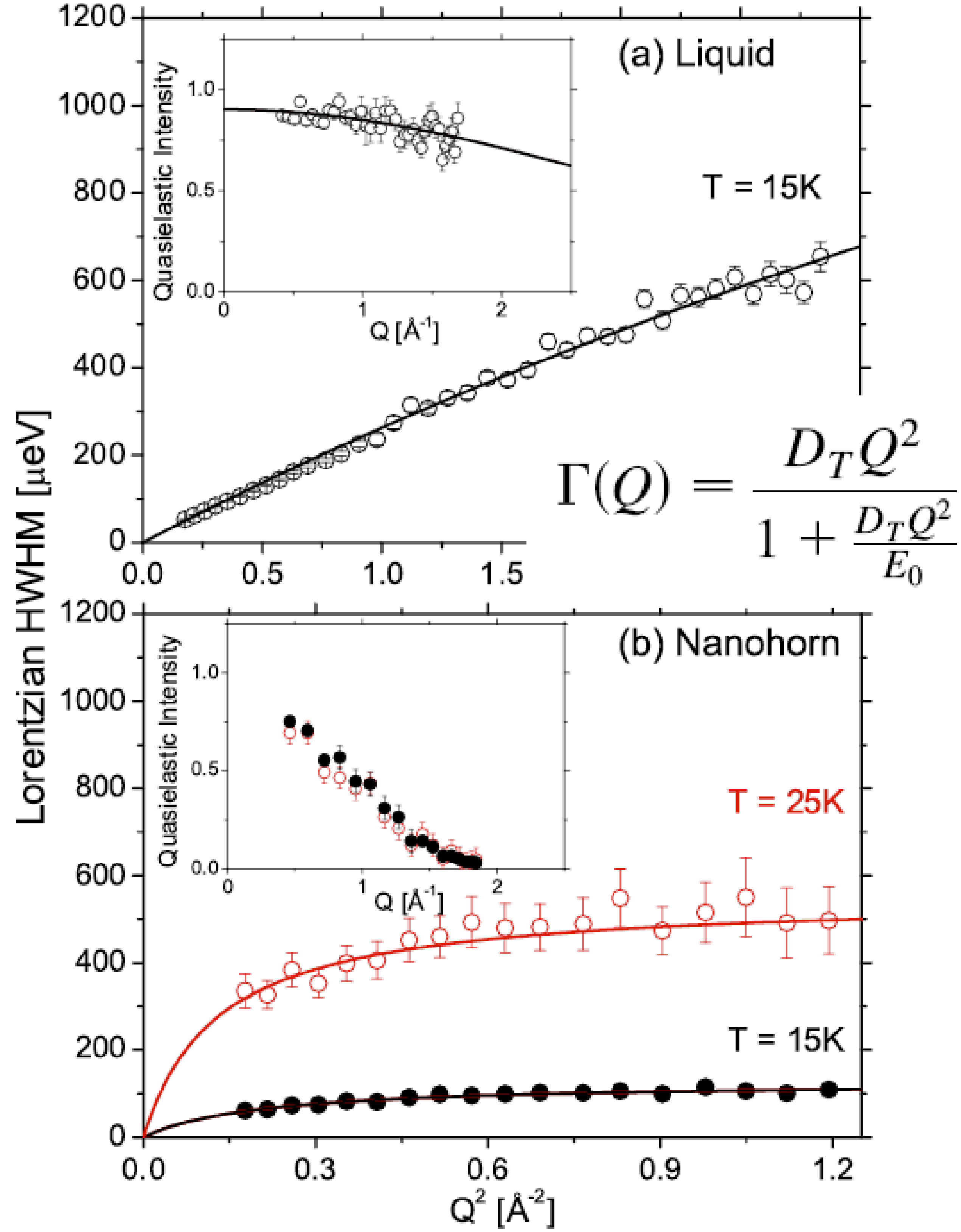
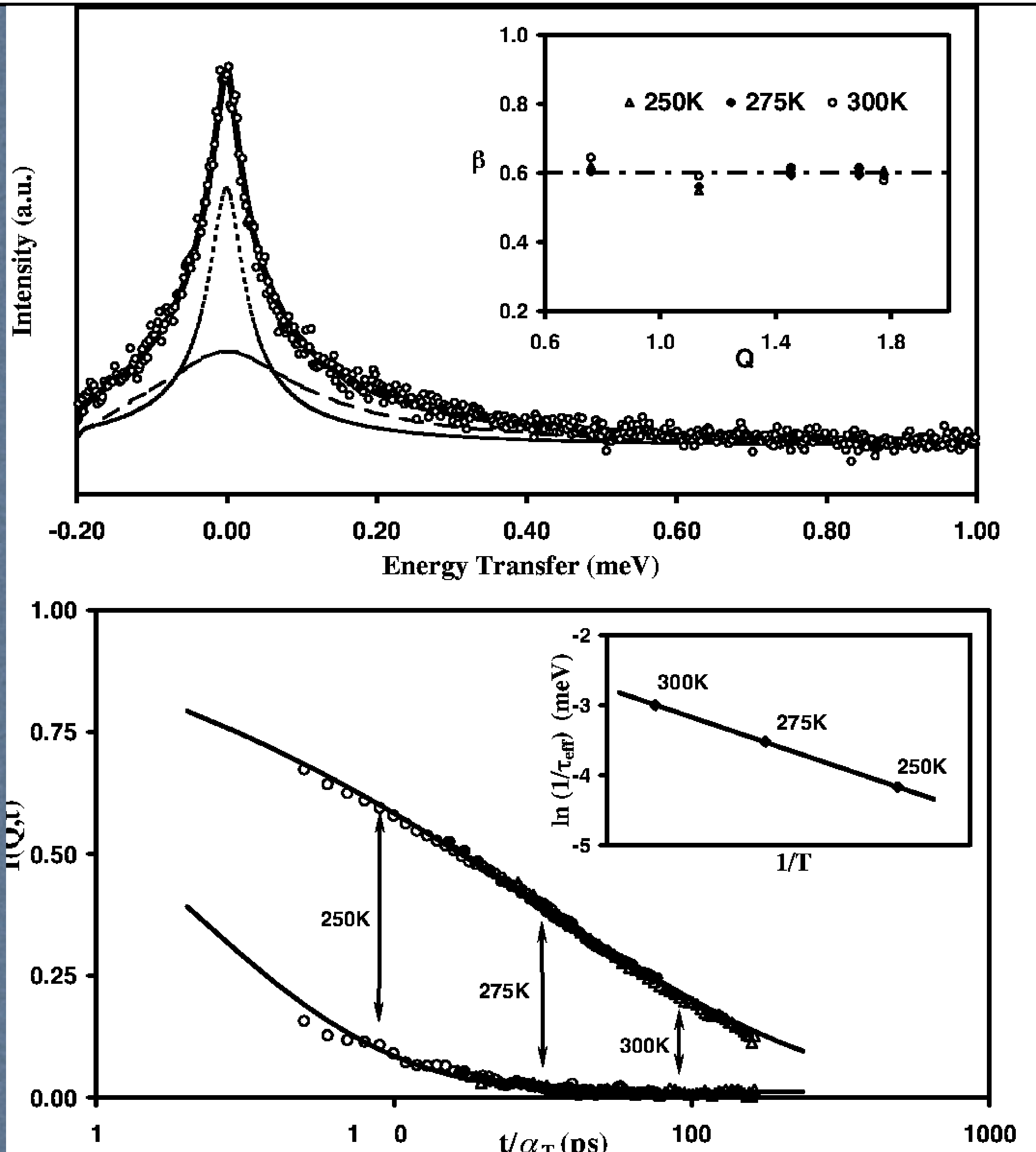


FIG. 1 (color online). QENS spectra at various wave vectors Q for the bulk liquid (a)–(c) and H_2-NH samples (d)–(f) at $T = 15$ K. The solid lines are model fits to the data. The narrow line in (d) represents the instrumental energy resolution.



$$\Gamma(Q) = \frac{D_T Q^2}{1 + \frac{D_T Q^2}{E_0}}$$

more complex relaxation patterns: e.g. polymers



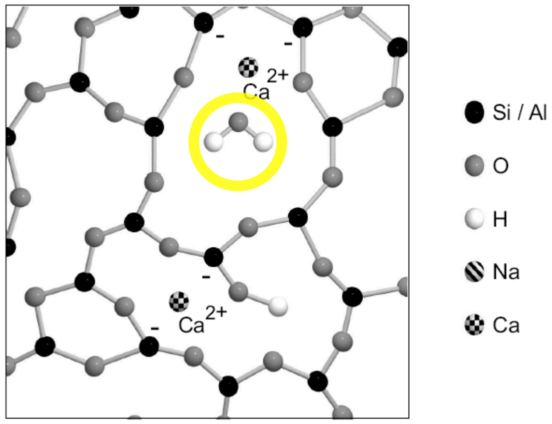
IRIS

V. Arrighi, F. Ganazzoli, C. H. Zhang, S. GagliardiPhysical Review Letters **90**(2003).

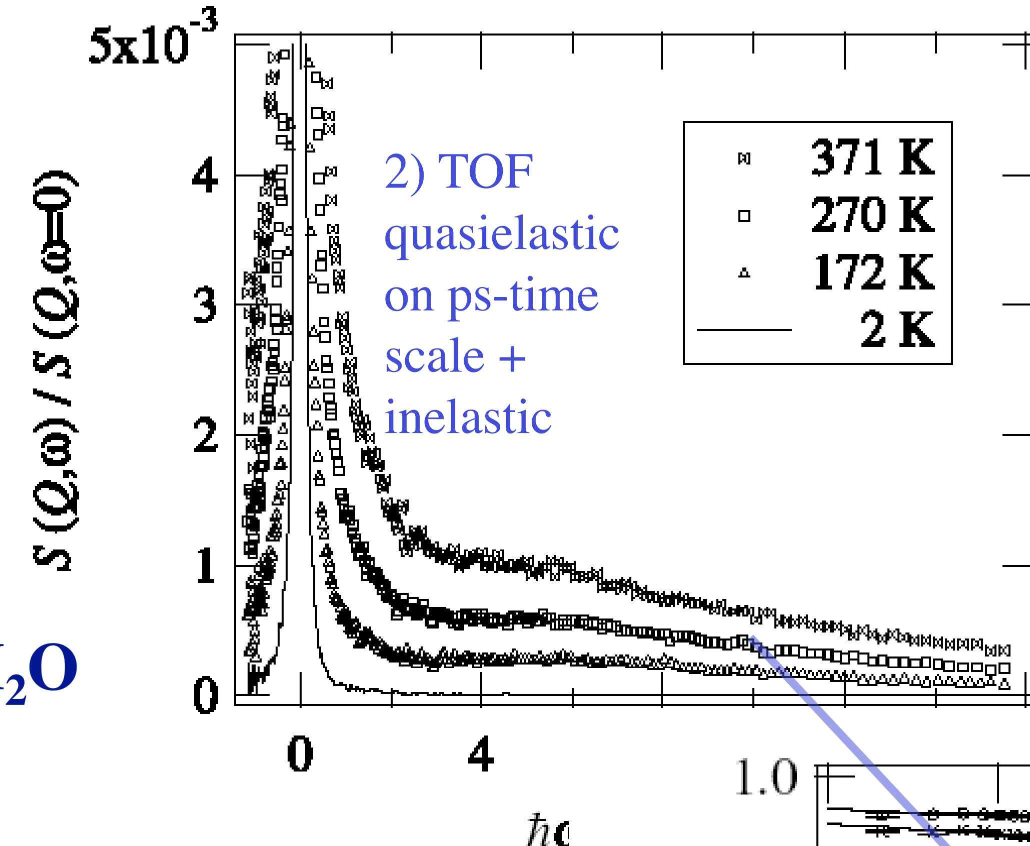
combination of TOF and BS

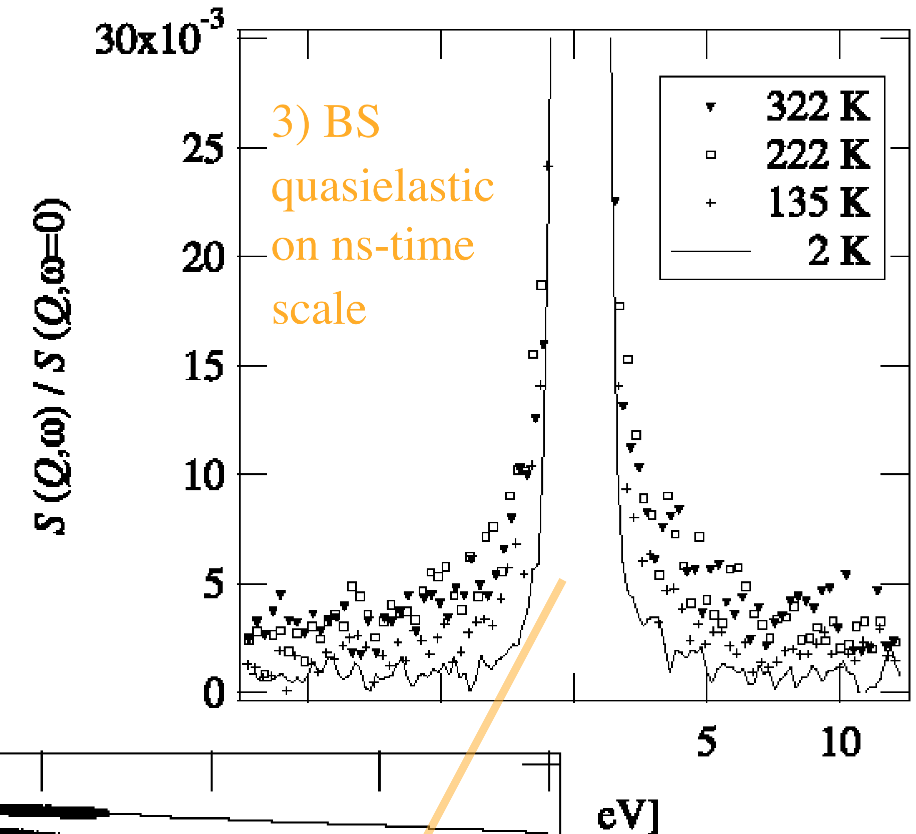
IN6 / IN16

- an example from geoscience

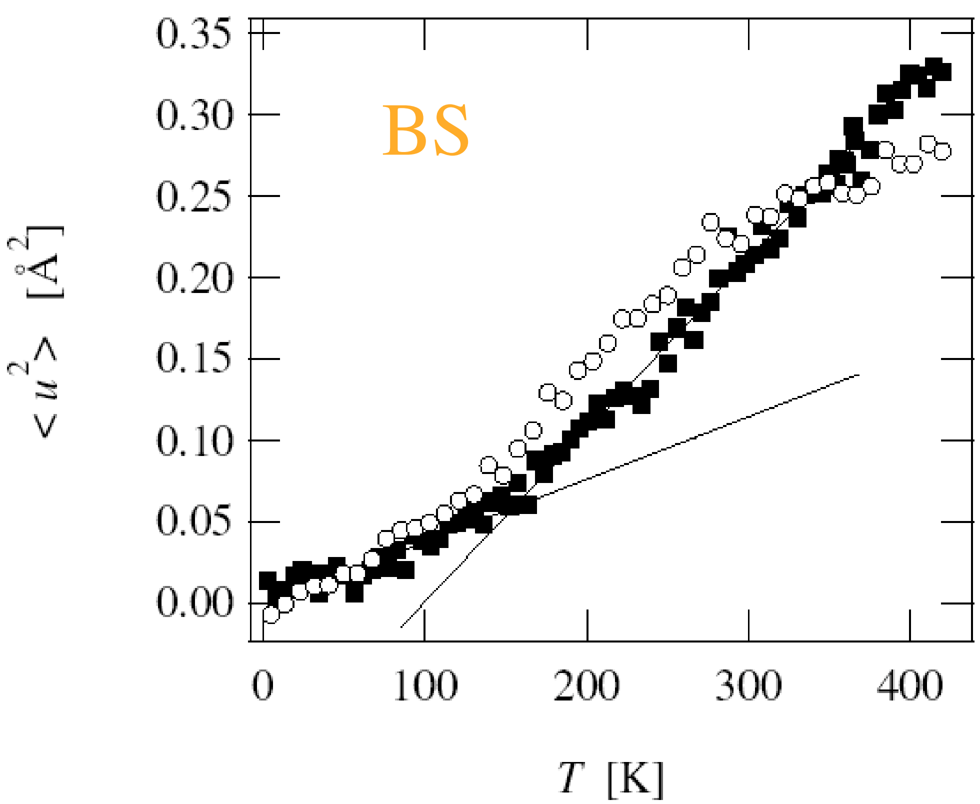


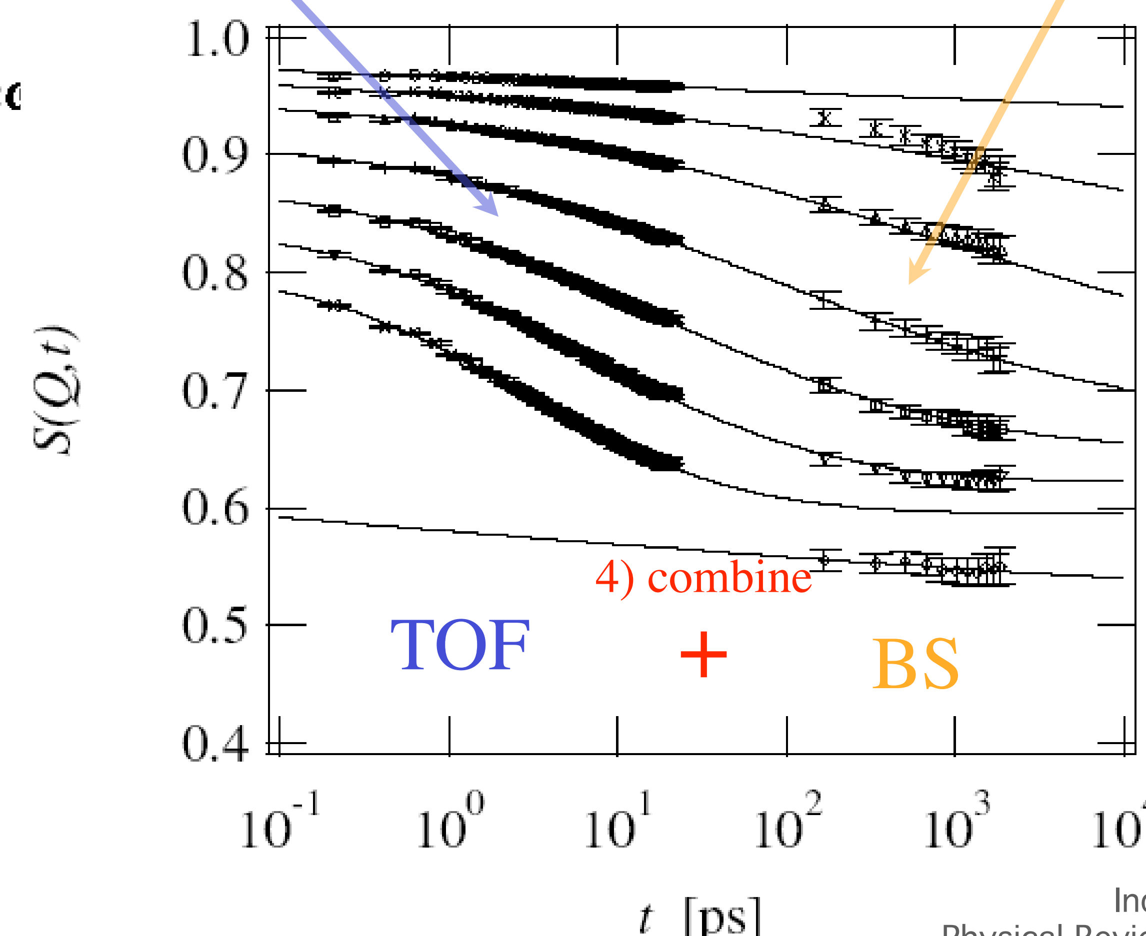
H$_2$O dynamics in $Ca_{0.5}AlSi_3O_8$+8%H_2O





1) overview from elas





Indris, S. et al.,
Physical Review B 71, 64205 (2005).

thank you for your attention

some literature:

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T. Springer, 'Quasielastic Neutron Scattering for the Investigation of Diffusive Motions in Solids and Liquids', Springer Tracts in Modern Physics 64, 197

M. Bée, 'Quasielastic Neutron Scattering Principles and Applications in Solid State Chemistry, Biology and Material Science', Adam Hilger, Bristol 1988

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diffusion in zeolites: H. Jobic, Theodorou, Microporous and Mesoporous Materials 102 (2007) 212

confinement studies: e.g. 'Int. Workshop on Dynamics in Confinement', Eur. Phys. J. - ST 141 (2007)

D. Richter, M. Monkenbusch, A. Arbe, J. Colmenero, Neutron Spin Echo in Polymer Systems, Advances in Polymer Science 174