# NEUTRONS AND THEIR INTERACTION WITH MATTER

## Overview

- History – neutrons and nuclear reactions
- Production – reactors and spallation sources
- Properties – as a particle and a probe
- Instruments – exploiting the probe to do science

# A BIT OF HISTORY

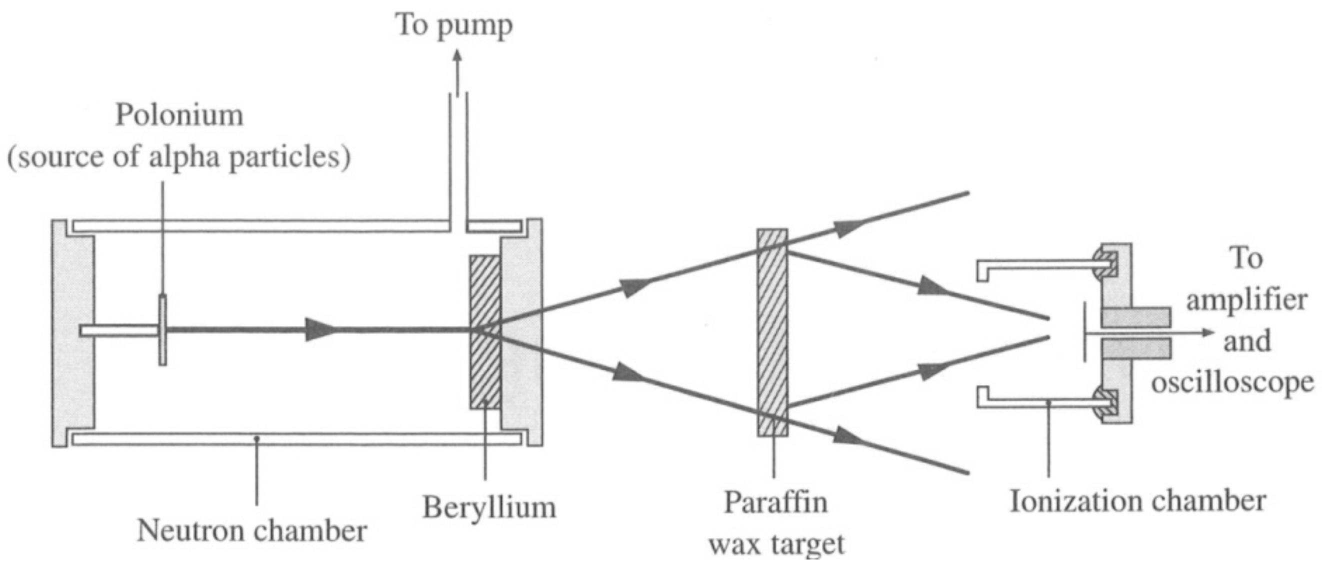
The neutron

- 1932: J. Chadwick, after work by others, discovers the 'neutron', a neutral but massive particle

$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

$$(m_{He} + m_{B})c^2 + T_{He} = (m_C + m_n)c^2 + T_C + T_n$$

$$m_n = 1.0067 \pm 0.0012 \text{a.m.u}$$




# A BIT OF HISTORY

## The nuclear reaction

- 1938: O. Hahn, F. Strassmann & L. Meitner discovered the fission of $^{235}U$ nuclei through thermal neutron capture
- 1939: H. v. Halban, F. Joliot & L. Kowarski showed that $^{235}U$ nuclei fission produced 2.4 $n^0$ on average – chain reaction
- 1942: E. Fermi & al. demonstrated first self-sustained chain reaction reactor

Chicago pile:
360T of graphite
50T of U and UO
0.5W power

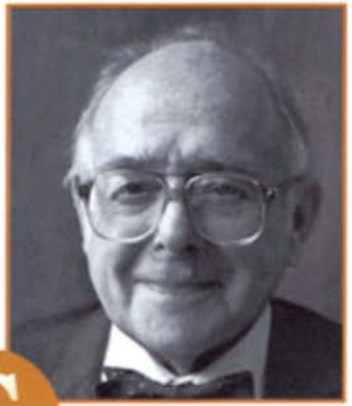
# NOBEL PRIZES, NEUTRONS AND THE ILL

Chadwick, Shull & Brockhouse

*James Chadwick*
*(1891 - 1974)*

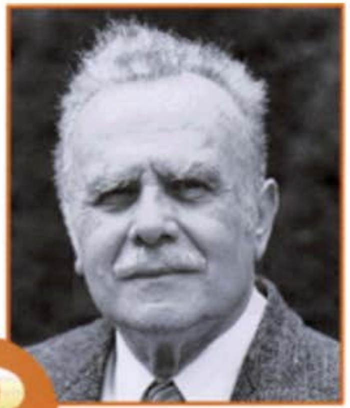
## The Nobel Prize in Physics 1994

**The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.**



S

**Clifford G. Shull**, MIT, Camebridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.



B

**Betram N. Brockhouse**, McMater University, Hamilton, Ontario, Canada, receives one half of the 1994 Nobel Prize in Physics for the development of neutron spectroscopy.

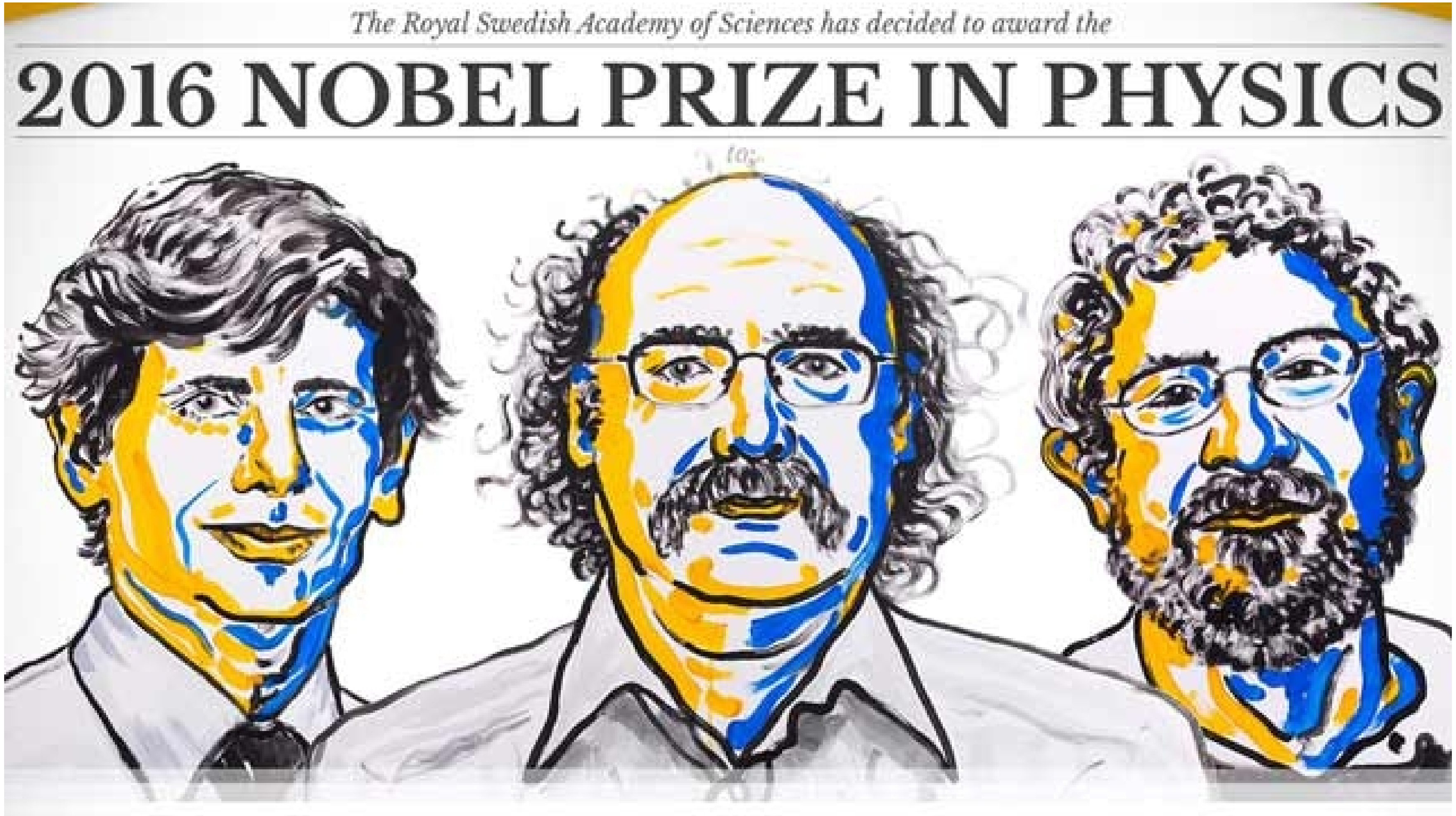
**Shull** made use of **elastic scattering** i.e. of neutrons which change direction without

**Brockhouse** made use of **inelastic scattering** i.e. of neutrons, which change

# NOBEL PRIZES, NEUTRONS AND THE ILL

# Nobel prizes, neutrons and the ILL

Haldane (1977 – 1981), Kosterlitz and Thouless for topological phase transitions and phases of matter (Electronic structure and excitation of 1D quantum liquids and spin chains)



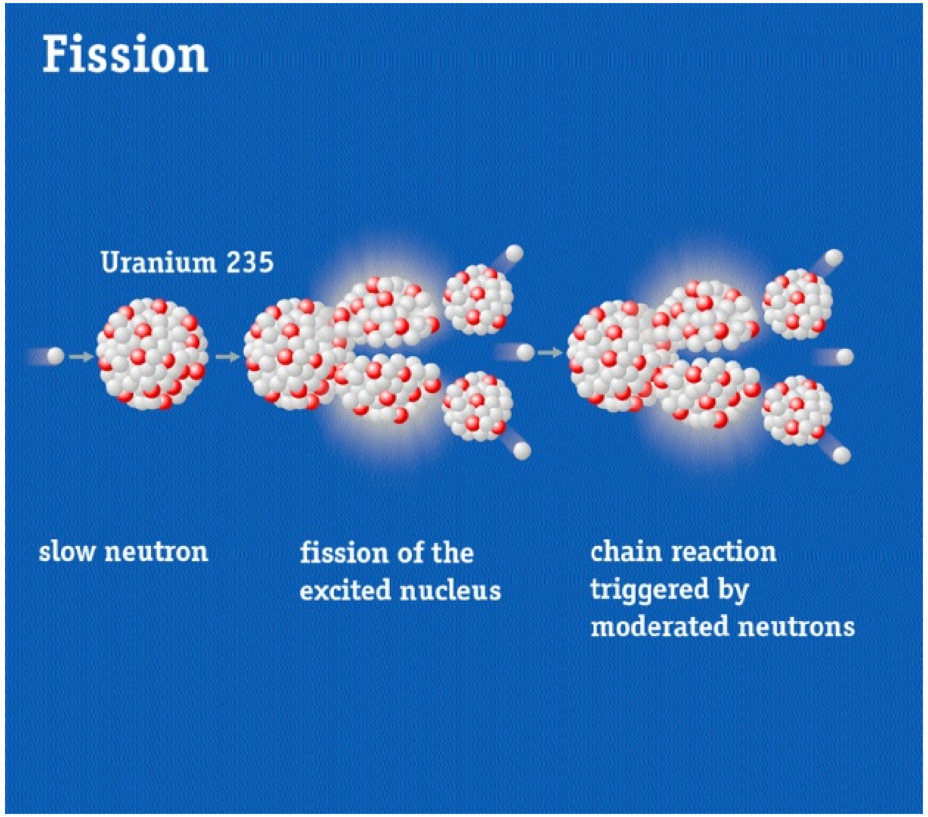



NEUTRONS FOR SOCIETY

# Neutron sources

## Fission reactors

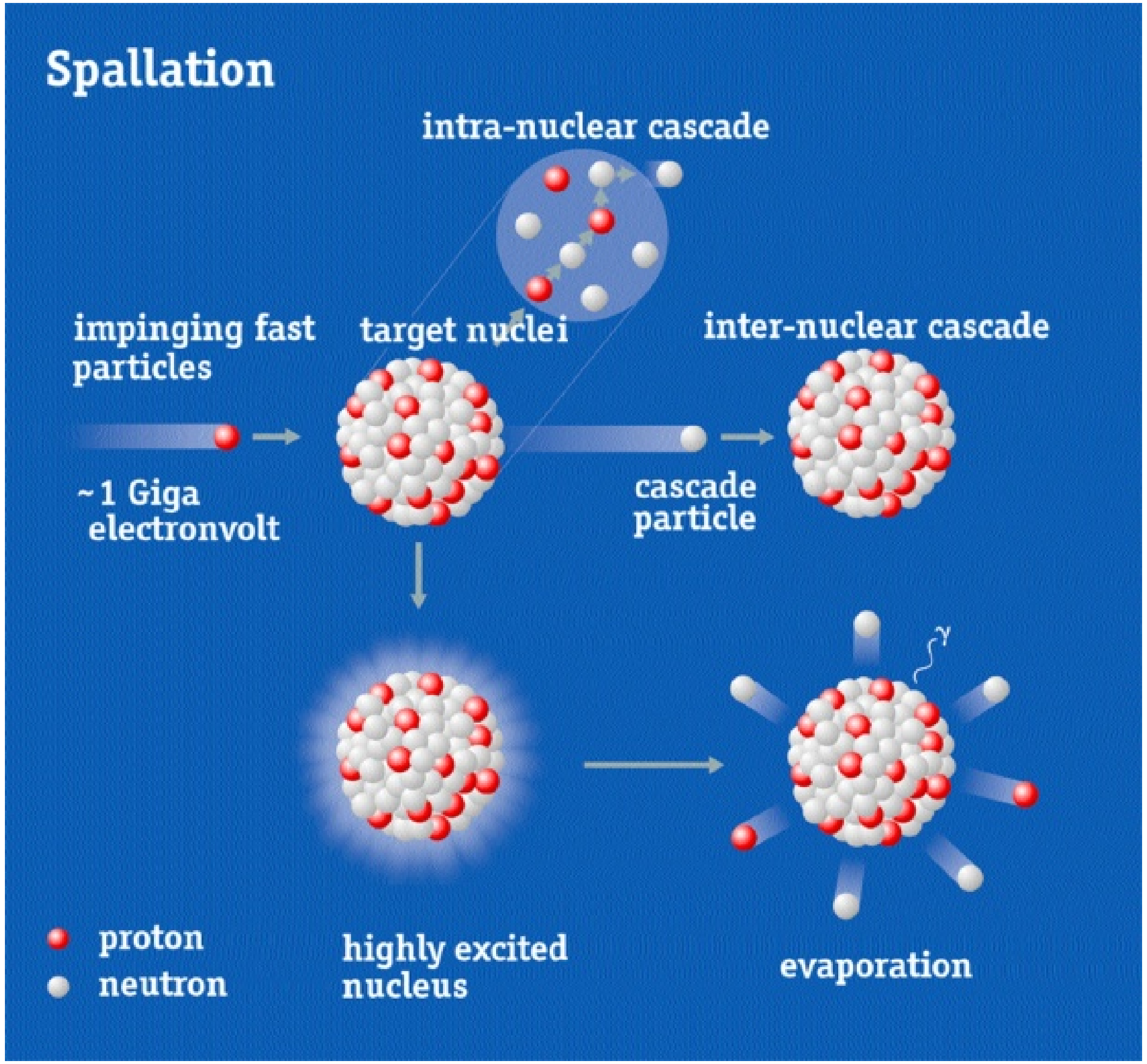
- Nuclear fission → chain reaction with excess neutrons (1n → 2.5n)
- Slow neutrons split U-235 nuclei
- Fission neutrons have MeV energies and need to be moderated (thermalized) to meV energies by scattering from water
- Thermalisation @ RT → *thermal* neutrons, @ 25K → *cold* neutrons and @ 2400 K → *hot* neutrons
- ILL – flux 1.5 x $10^{15}$ n/cm$^2$/s



# NEUTRON SOURCES

Spallation sources

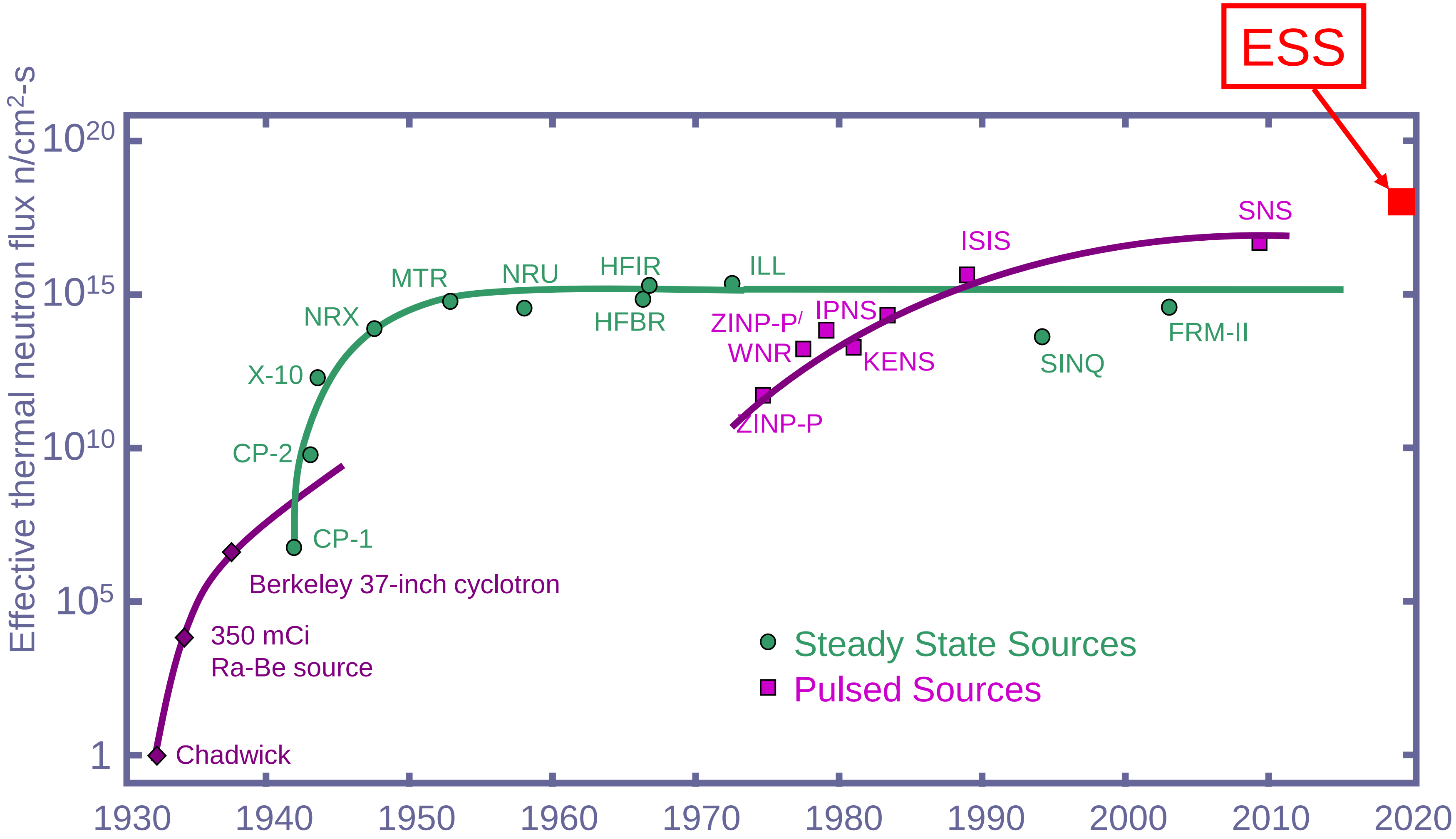
- Neutrons can be produced by bombarding heavy metal targets
- 2 GeV protons (90% speed-of-light) produce spallation – evaporation of ~30 neutrons





NEUTRONS FOR SOCIETY

# Neutron sources

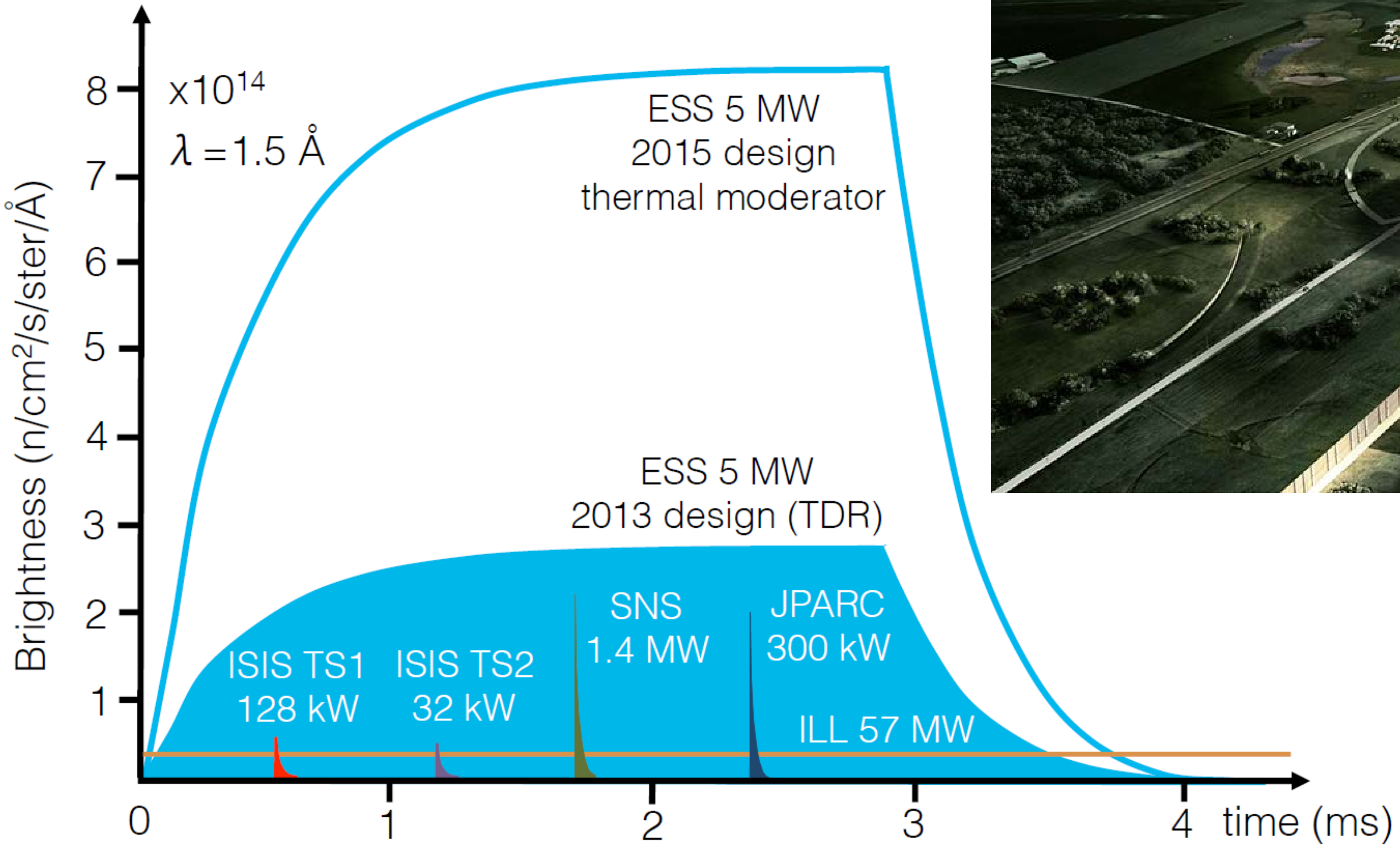



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

NEUTRONS FOR SOCIETY

# Continuous or pulsed beams

Integrated vs peak flux – ESS will have a time-integrated flux comparable to ILL

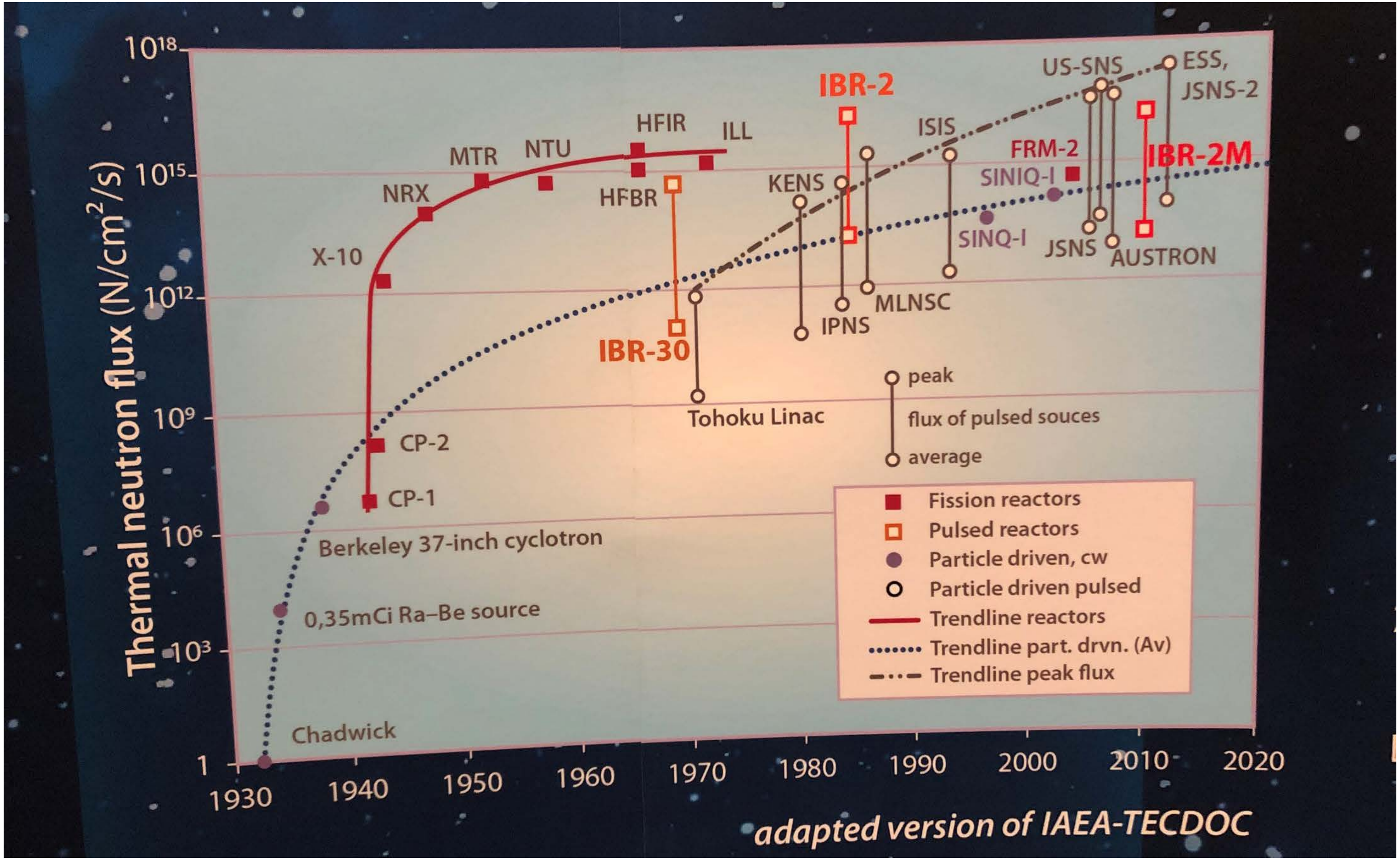





NEUTRONS FOR SOCIETY

# CONTINUOUS OR PULSED BEAMS

Integrated vs peak flux – ESS will have a time-integrated flux comparable to ILL





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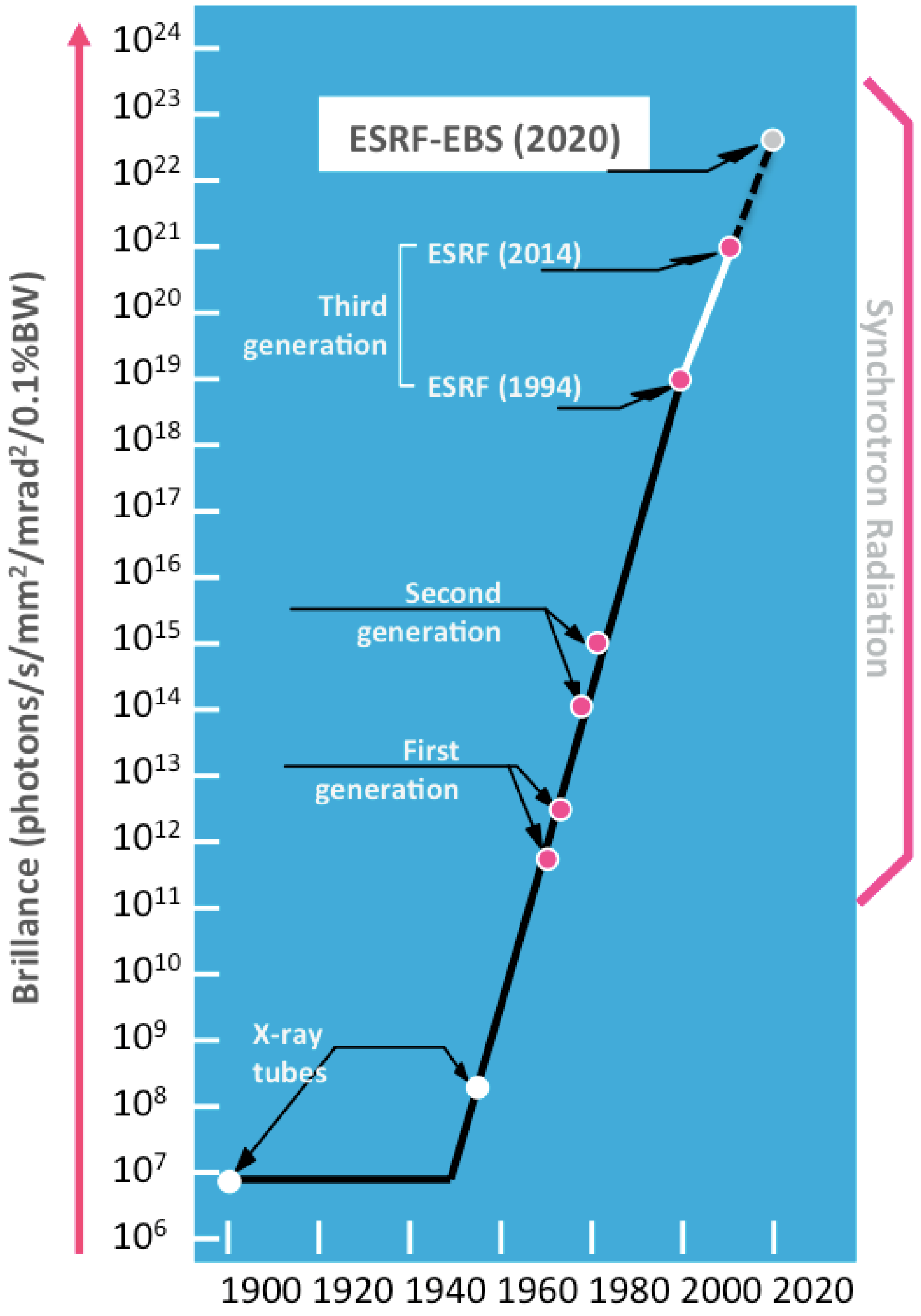
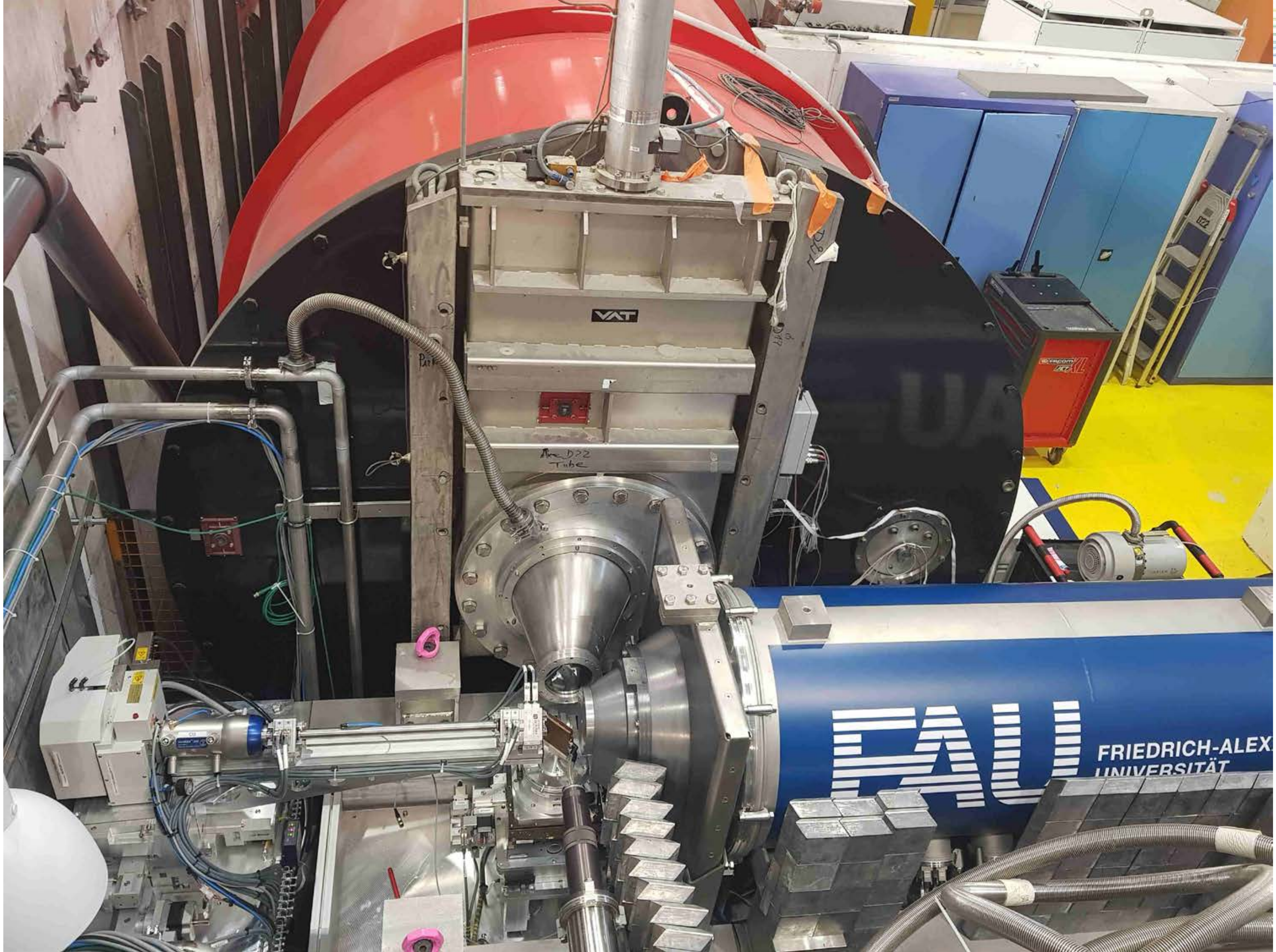
# N vs X

ESRF (hard X-rays)



# N & X



# The neutron

As a particle

- free neutrons are unstable: β-decay → proton, electron, anti-neutrino

  life time: 888 ± 1 sec or 880 ± 1 sec

- wave-particle duality: neutrons have particle-like and wave-like properties
- mass: $m_n$ = 1.675 x $10^{-27}$ kg = 1.00866 amu. (unified atomic mass unit)
- charge = 0
- spin =1/2
- magnetic dipole moment: $\mu_n = -1.9\ \mu_{N,}\ \mu_p = 2.8\ \mu_{N,}\ \mu_e \sim 10^3\ \mu_{n,}$
- velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

# The neutron

As a particle

- velocity (v), kinetic energy (E), temperature (T), wavevector (k), wavelength (λ)

$$E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2m_n = (h/\lambda)^2/2m_n$$

- Neutron energy determines velocity and therefore time-of-flight (*tof*) over a given distance i.e. *tof* → energy determination

$$tof = \frac{L}{v} = 253\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

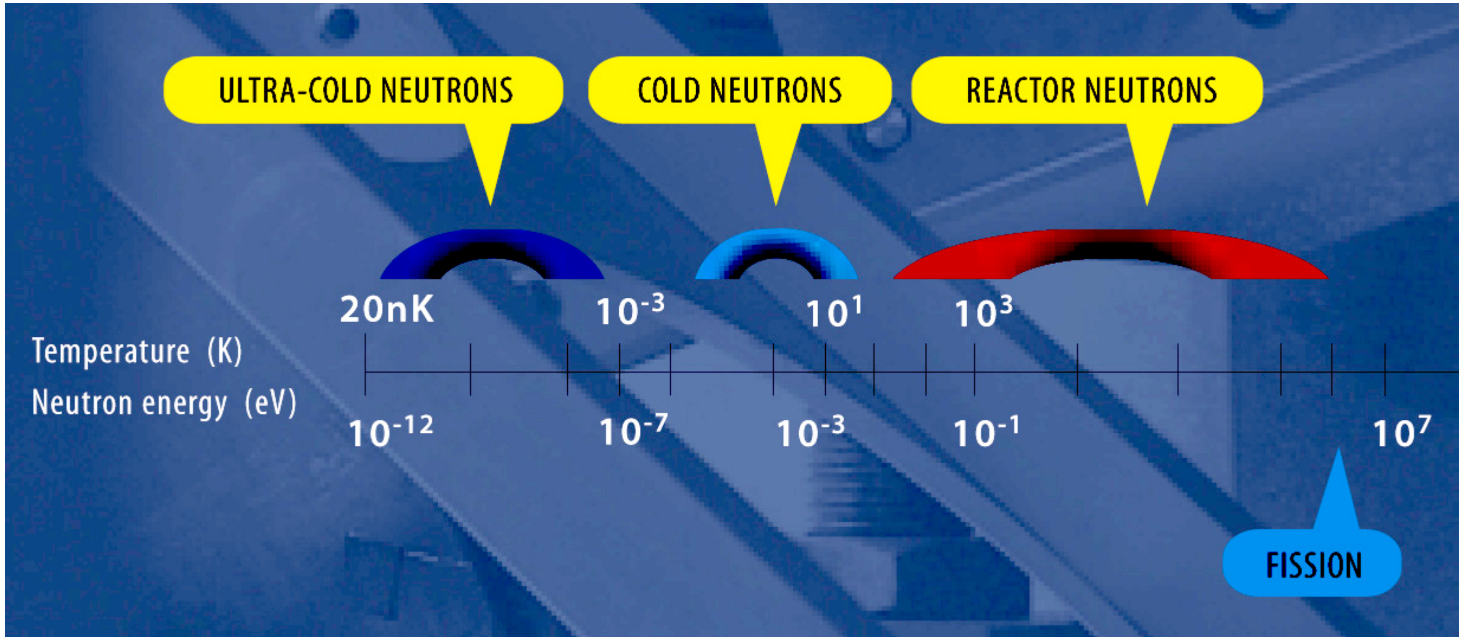


NEUTRONS FOR SOCIETY

# The neutron

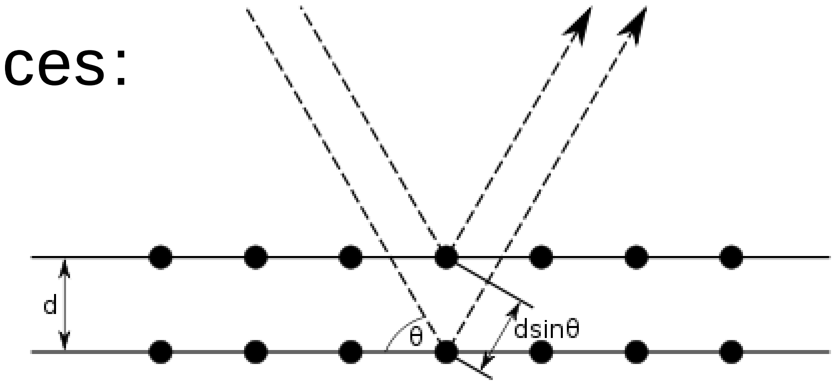
## As a probe

| | Energy | Temperature (K) | Wavelength (nm) | velocity (m/s) |
|---|---|---|---|---|
| Ultra cold neutrons | < 10 µeV | < 0.05 | > 30 | < 15 |
| Cold neutrons | 100 - 5000 µeV | 1 - 60 | 0.4 - 3 | 150 - 1000 |
| Thermal neutrons | 5 - 50 meV | 60 - 600 | 0.13 - 0.4 | 1000 - 4000 |
| Hot neutrons | 0.05 - 0.5 eV | 600 - 6000 | 0.04 - 0.13 | 4000 - 10000 |



# The neutron

As a probe




- Wavelengths on the scale of inter-atomic distances: *Å - nm* wavelengths to measure *Å* - $\mu m$ distances/sizes

$$n\lambda = 2d\sin\Theta$$

- Energies comparable to structural and magnetic excitations: *meV* neutrons to measure *neV – meV* energies
- Neutral particle – gentle probe, highly penetrating (e.g. 30 cm of Al), no radiation damage
- Magnetic moment (nuclear spin) probes magnetism of unpaired electrons (N.B. $\mu_e$ ~ 1000x $\mu_N$)

# THE NEUTRON

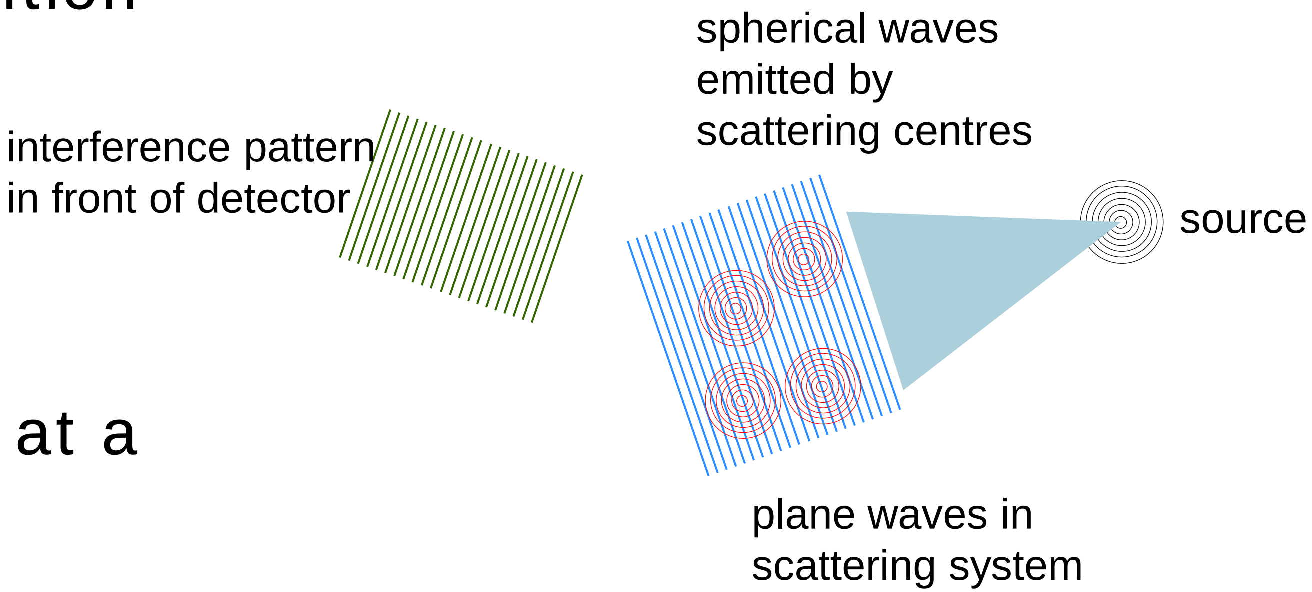
As a probe – interacting with matter – scattering from atoms

- Neutron flux at reactor core
- $1.5 \times 10^{15}$ n/cm$^2$/s
- Flux at an instrument sample position
- $10^8$ n/cm$^2$/s

→ $10^{-6}$ n/μm$^2$/μs

→ $10^{-15}$ n/nm$^2$/ns

- On these time and length scales, neutrons are being scattered one at a time
- Need wave-particle duality of neutrons



# The neutron

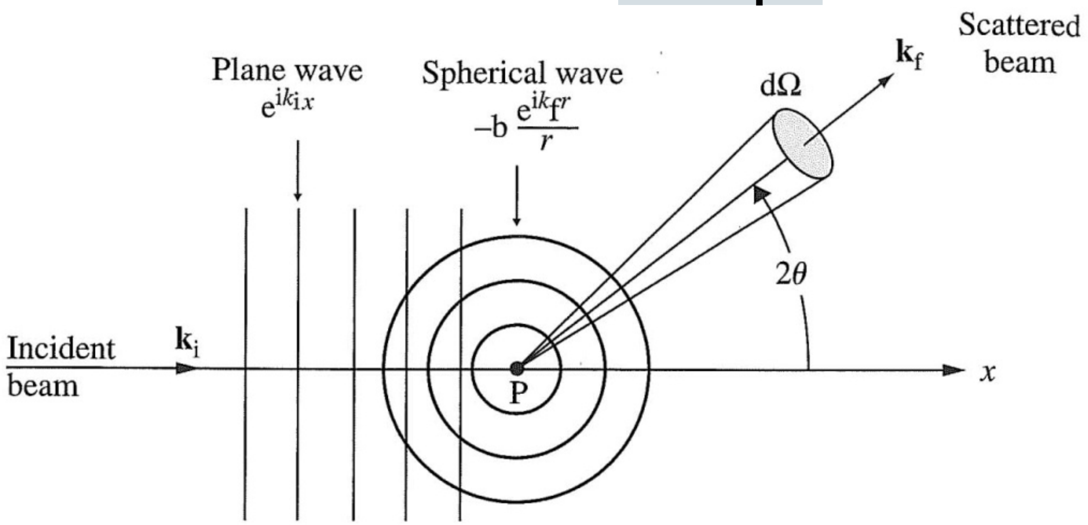
As a probe – interacting with matter – (elastic) scattering from a single fixed nucleus

- Nuclear size << neutron wavelength → point-like s-wave scattering
- *b* is the scattering length ('power') in *fm*
- #neutrons scattered per second per unit solid angle $\Omega$: $\Psi^2 r^2 d\Omega$

$$d\sigma / d\Omega = b^2$$

- $\sigma$ is the cross-section: $4\pi b^2$ (in barns)

$$-b\,\frac{e^{i\mathbf{k}_f.\mathbf{r}}}{r}$$




$$V(\mathbf{r}) = \frac{2\pi\hbar^2}{m_r}\, b\,\delta(\mathbf{r})$$

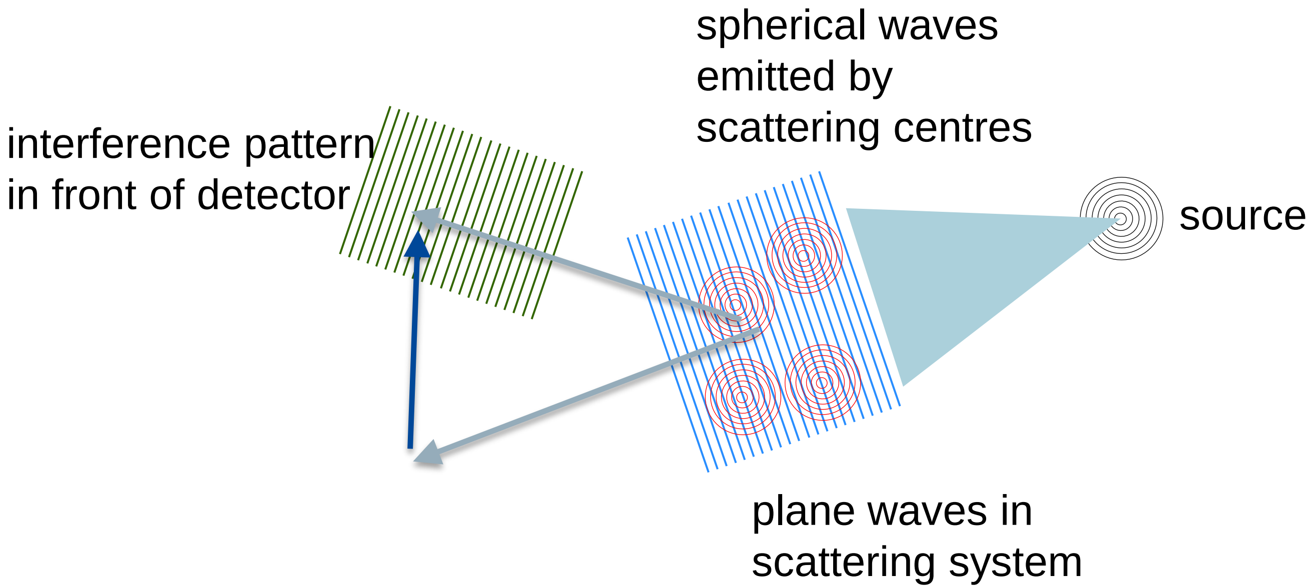
# The neutron

As a probe – interacting with matter – scattering from a set of nuclei

$$\frac{d\sigma}{d\Omega} = \sum_{j,k} b_j b_k e^{i\vec{Q}.\left(\vec{R}_j - \vec{R}_k\right)}$$

$$\vec{Q} = \vec{k}_f - \vec{k}_i$$

- *Q* is called momentum transfer
- *Q*-dependence (eg angle) gives info about atomic positions



# The neutron

As a probe – interacting with matter – scattering from a set of identical  nuclei – coherent and incoherent scattering

- Set of *N* similar atoms/ions – spins/isotopes are *uncorrelated* at different sites
- *b* depends on spin/isotope
- Average is ‹*b*›
- Incoherent scattering gives a *Q* independent background
- But it can be useful to probe the dynamics of single particles (later)

$$\frac{d\sigma}{d\Omega} = \langle b\rangle^2 \sum_{j,k} e^{iQ\cdot(R_j - R_k)} + \left(\langle b^2\rangle - \langle b\rangle^2\right)N$$

$$\sigma_{coh} = 4\pi\langle b\rangle^2 \qquad \sigma_{coh} = 4\pi b_{coh}{}^2$$

$$\sigma_{incoh} = 4\pi\left(\langle b^2\rangle - \langle b\rangle^2\right) \qquad \sigma_{incoh} = 4\pi b_{inc}{}^2$$

# THE NEUTRON

As a probe – interacting with matter – scattering from a set of identical nuclei – coherent and incoherent scattering

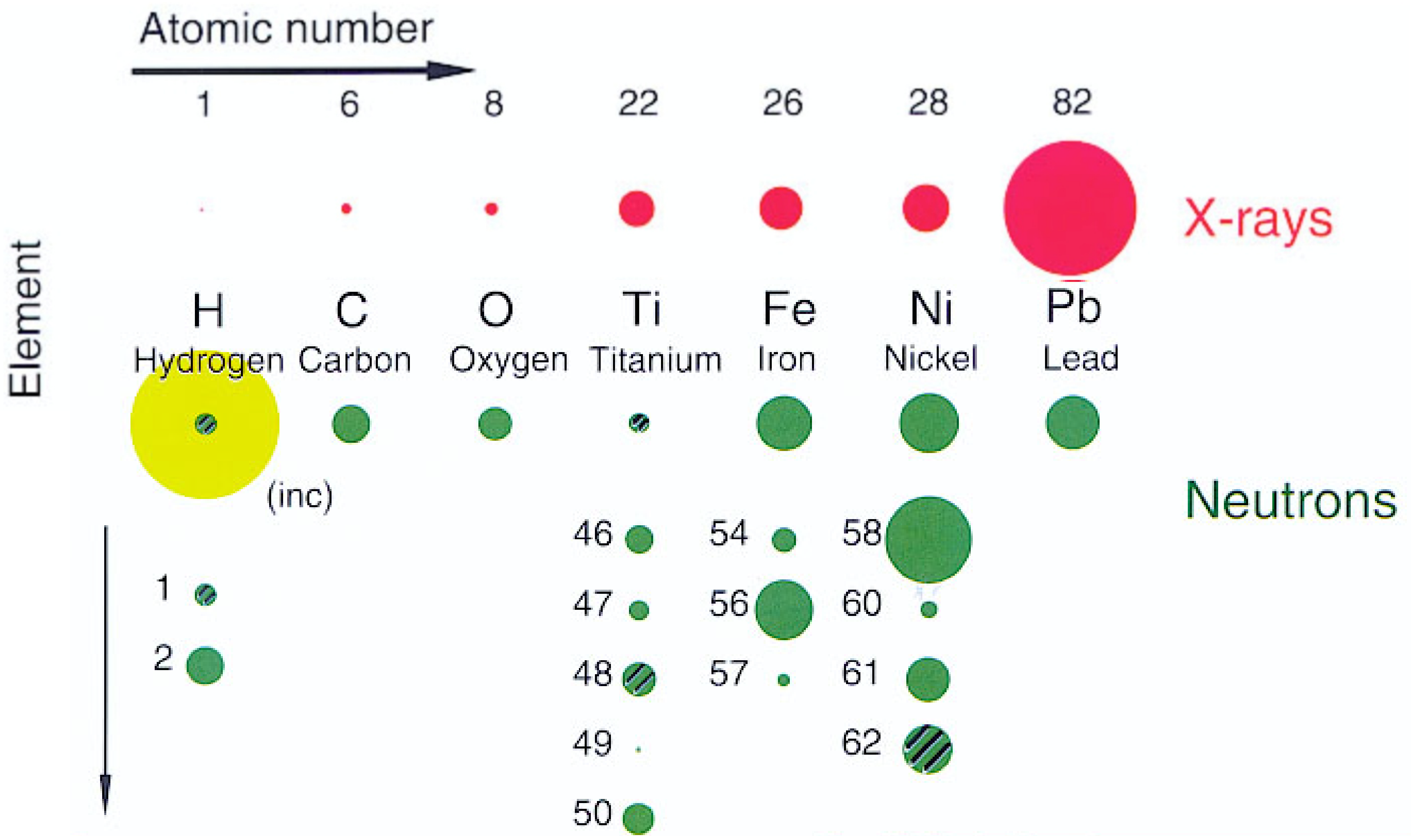
- If single isotope and zero nuclear spin, no incoherent scattering
- If single isotope and non-zero nuclear spin *I*
- nucleus+neutron spin: *I+1/2* and *I-1/2* scattering length $b^+$ and $b^-$
- To reduce incoherent scattering (background):
  - polarise nuclei and neutrons
  - use isotope substitution e.g. H→ D

$$\langle b \rangle = \frac{1}{2I+1}\left[(I+1)b^+ + Ib^-\right]$$

$$\langle b^2 \rangle - \langle b \rangle^2 = \frac{I(I+1)}{(2I+1)^2}\left(b^+ - b^-\right)^2$$

# The neutron

Scattering lengths
Light atoms
Contrast



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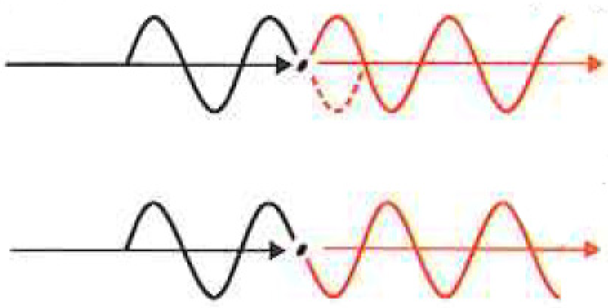
# The neutron

Scattering lengths can be positive or negative (nuclear physics)

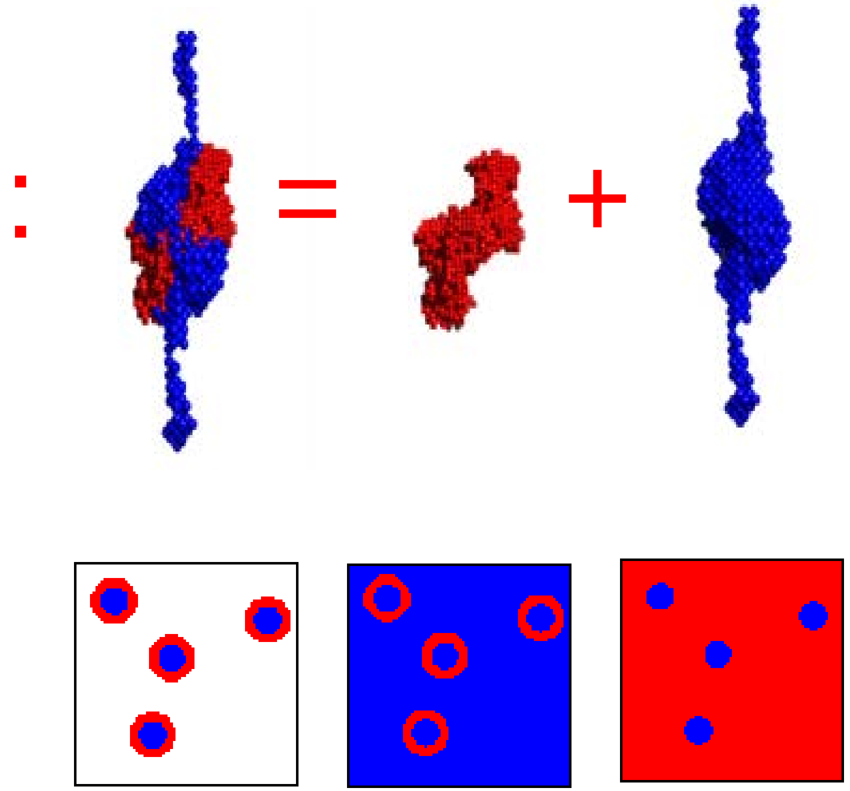
- Positive *b* (most nuclei): phase change
- Negative *b*: no phase change at scattering point

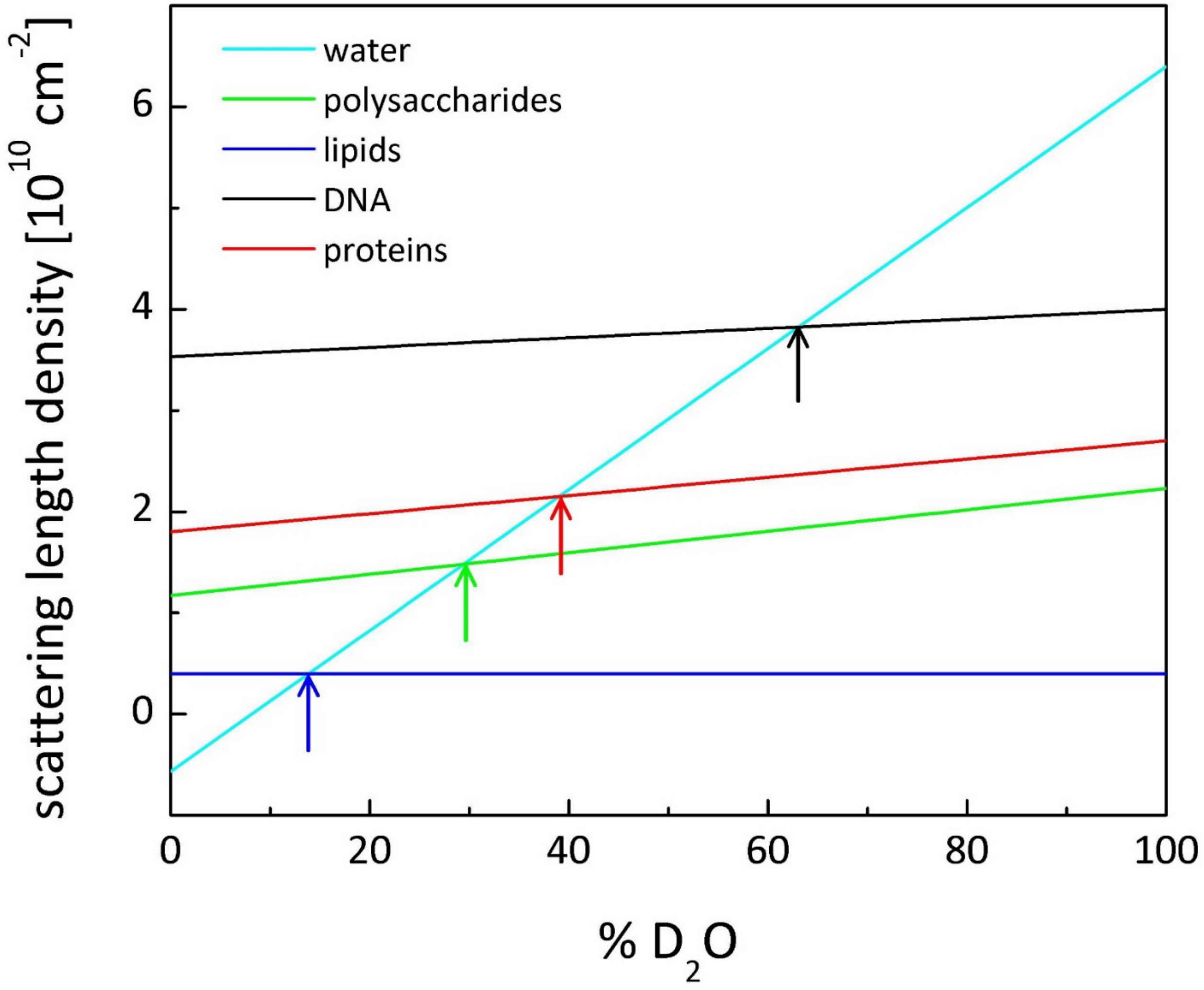


| ZSymbA | p or $T_{1/2}$ | I | $b_c$ | $b_+$ | $b_-$ | c | $\sigma_{coh}$ | $\sigma_{inc}$ | $\sigma_{scatt}$ | $\sigma_{abs}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **0-N-1** | **10.3 MIN** | **1/2** | **-37.0(6)** | **0** | **-37.0(6)** | | **43.01(2)** | | **43.01(2)** | **0** |
| **1-H** | | | **-3.7409(11)** | | | | **1.7568(10)** | **80.26(6)** | **82.02(6)** | **0.3326(7)** |
| 1-H-1 | 99.985 | 1/2 | -3.7423(12) | 10.817(5) | -47.420(14) | +/- | 1.7583(10) | 80.27(6) | 82.03(6) | 0.3326(7) |
| 1-H-2 | 0.0149 | 1 | 6.674(6) | 9.53(3) | 0.975(60) | | 5.592(7) | 2.05(3) | 7.64(3) | 0.000519(7) |
| 1-H-3 | 12.26 Y | 1/2 | 4.792(27) | 4.18(15) | 6.56(37) | | 2.89(3) | 0.14(4) | 3.03(5) | < 6.0E-6 |
| **2-He** | | | **3.26(3)** | | | | **1.34(2)** | **0** | **1.34(2)** | **0.00747(1)** |
| 2-He-3 | 0.00013 | 1/2 | 5.74(7) | 4.374(70) | 9.835(77) | E | 4.42(10) | 1.532(20) | 6.0(4) | 5333.0(7.0) |
| 2-He-4 | 0.99987 | 0 | 3.26(3) | | | | 1.34(2) | 0 | 1.34(2) | 0 |
| **3-Li** | | | **-1.90(3)** | | | | **0.454(10)** | **0.92(3)** | **1.37(3)** | **70.5(3)** |
| 3-Li-6 | 7.5 | 1 | 2.0(1) | 0.67(14) | 4.67(17) | +/- | 0.51(5) | 0.46(5) | 0.97(7) | 940.0(4.0) |
| 3-Li-7 | 92.5 | 3/2 | -2.22(2) | -4.15(6) | 1.00(8) | +/- | 0.619(11) | 0.78(3) | 1.40(3) | 0.0454(3) |

# THE NEUTRON

Scattering lengths can be positive or negative
→ Contrast matching



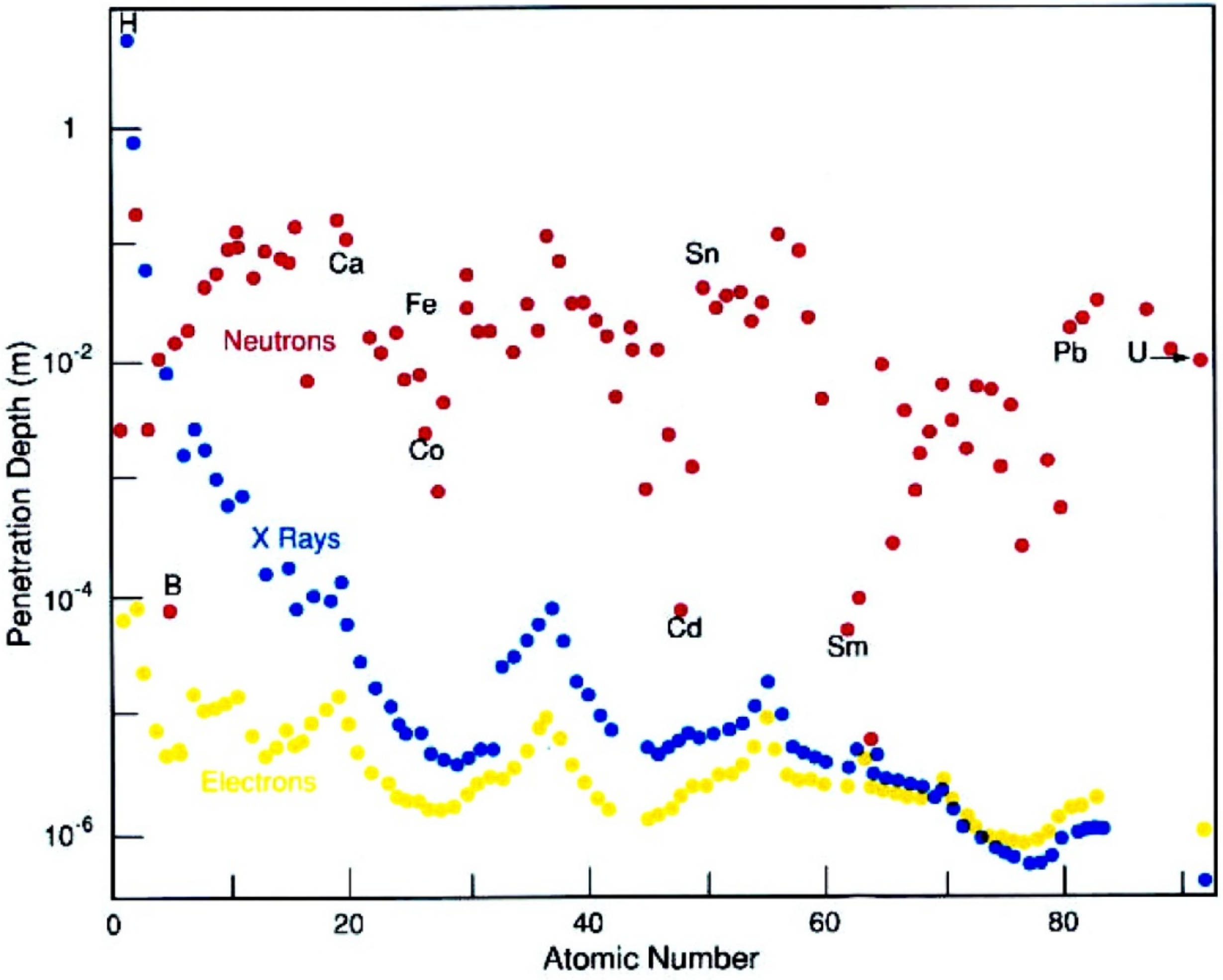


# The neutron

As a probe – interacting with matter - absorption

- Absorption – neutron capture
- Several strong absorbers:

  He, Li, B, Cd, Gd,…
- Isotope dependent – choose to your advantage



# The neutron

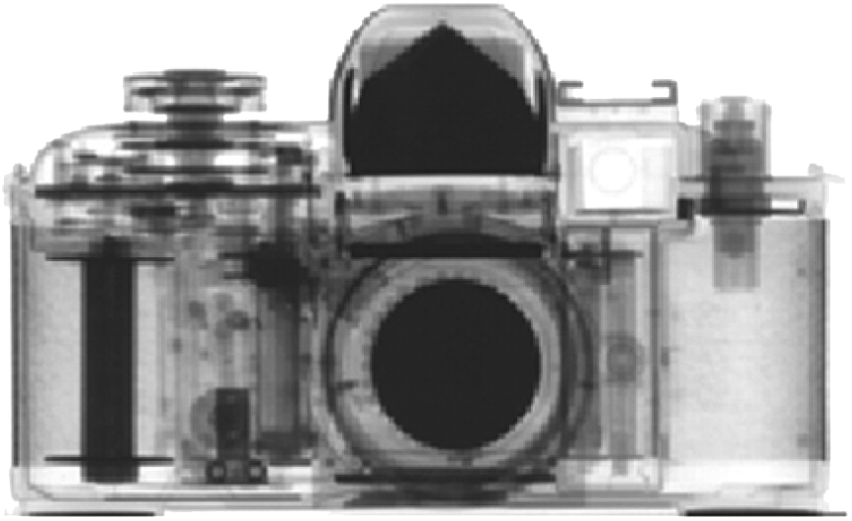
As a probe – interacting with matter - absorption - Neutron detection

- How to detect a weakly interacting, neutral particle?
- With a neutron absorber and measure the resulting signal

$$ {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + \mathrm{p} + 0.764\ \mathrm{MeV} $$

# THE NEUTRON

Scattering and absorption cause attenuation of a neutron beam → imaging



NEUTRONS

X-RAYS

# THE NEUTRON

Scattering and absorption cause attenuation of a neutron beam → imaging

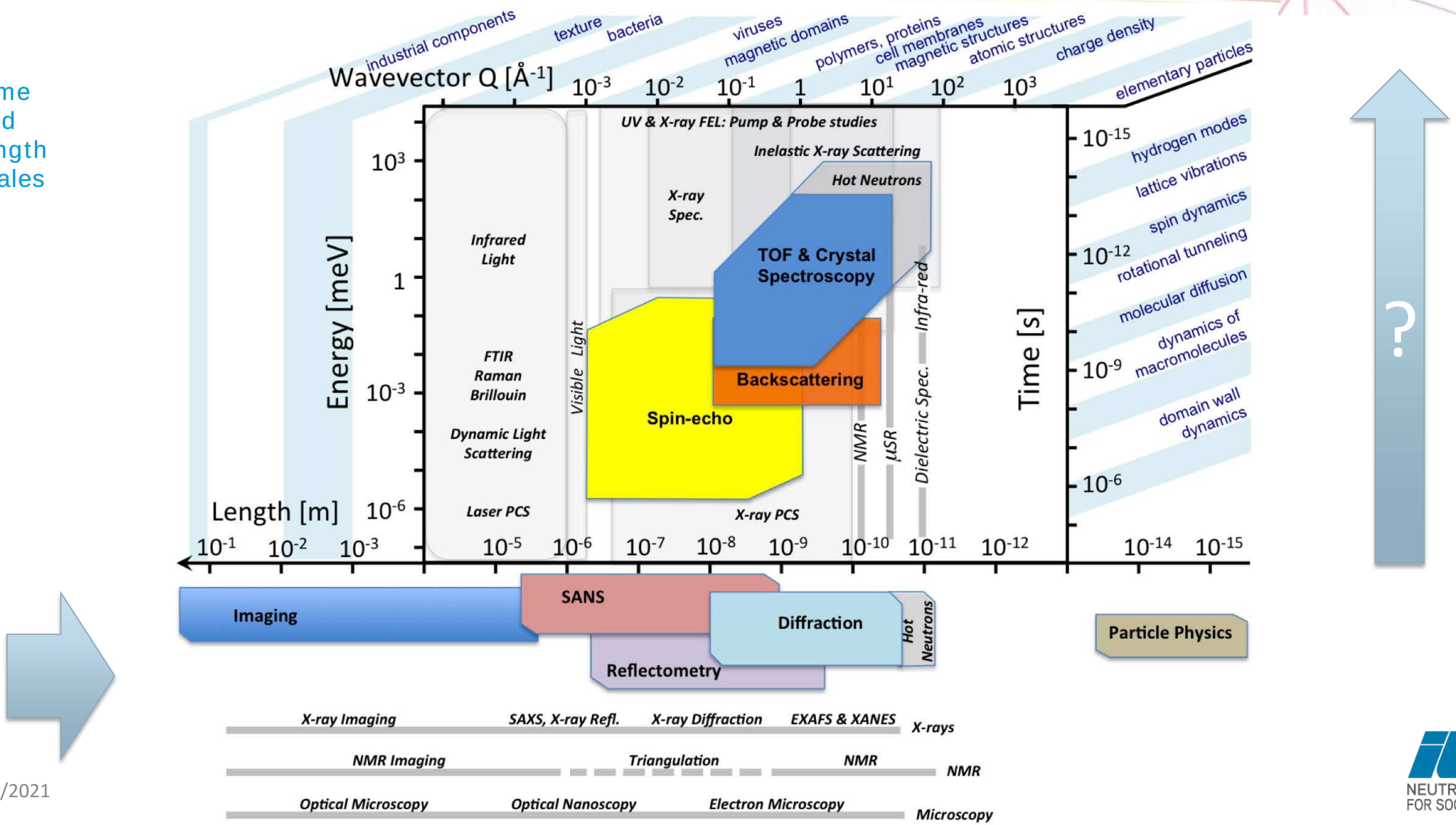
# THE NEUTRON

As a probe – interacting with matter - summary

- Interaction with nuclei:
  - short range interaction → angle independent scattering (no form factor)
  - scattering length can be positive or negative (→ contrast variation)
  - depends on isotope (→ selectivity) and nuclear spin
  - Coherent and incoherent scattering – strength and weakness
  - Scattering contrast different from X-rays, favours light atoms
- A gentle probe - meV neutron beam does not cause radiation damage like a ~10 keV photon beam (what about XFEL!)
- Magnetic moment probes magnetism of unpaired electrons

# INSTRUMENTS & SCIENCE

Time and length scales



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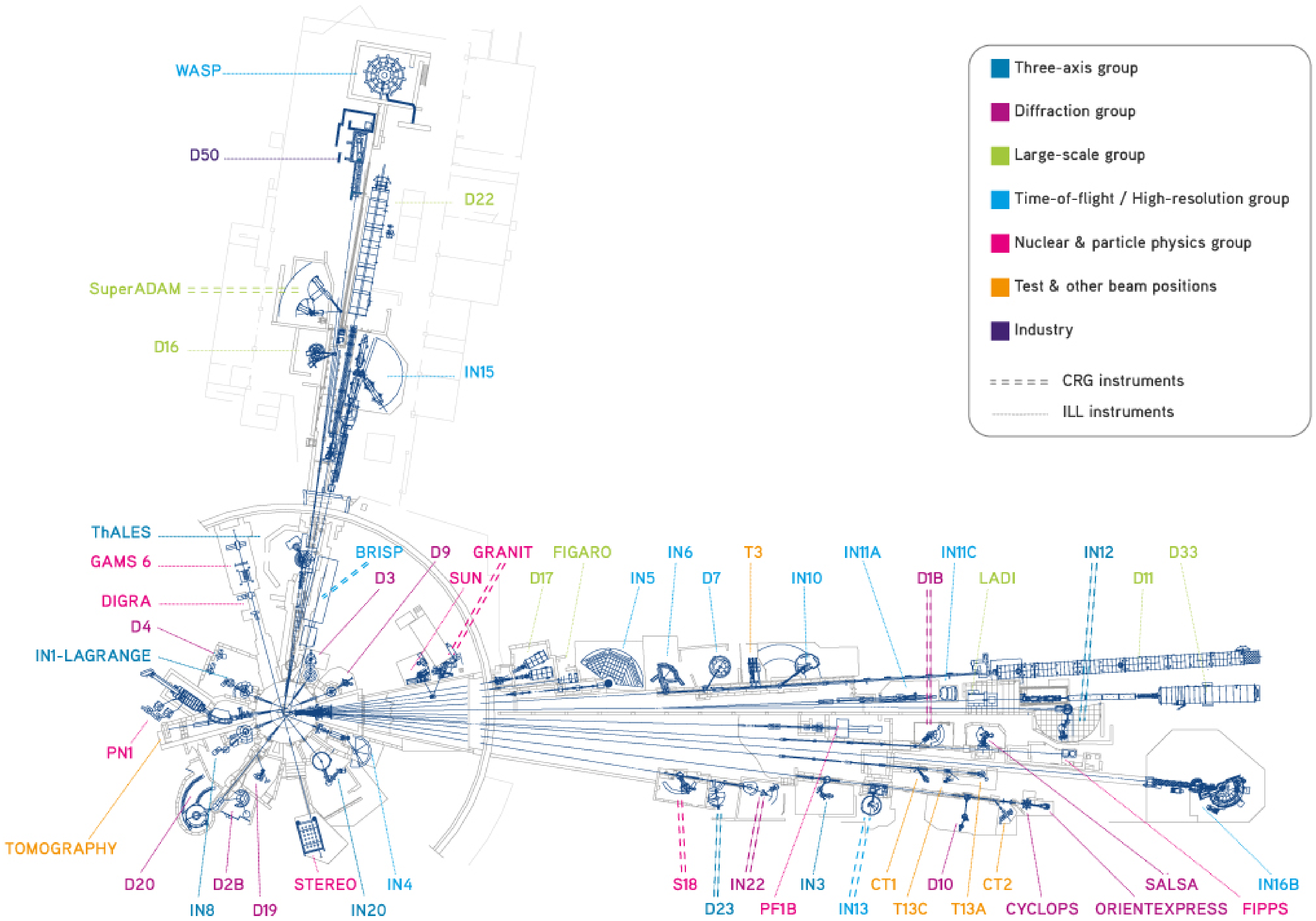
# The ILL's instrument suite




- Three-axis group
- Diffraction group
- Large-scale group
- Time-of-flight / High-resolution group
- Nuclear & particle physics group
- Test & other beam positions
- Industry
- = = = = = CRG instruments
- ········ ILL instruments

NEUTRONS FOR SOCIETY

# GENERAL EXPRESSION FOR SCATTERING FROM A COMPLEX SYSTEM

Deriving the general scattering function

Based on

- Born approximation – kinematic theory: neutron wavefunction un-perturbed inside sample
- Fermi's Golden Rule to calculate transitions of neutron (*k*) and system ($\lambda$) from initial and final state
- Hamiltonian to describe the system states ($\lambda$)

$$\frac{d\sigma}{d\Omega} = \frac{\sum_{k_f \, in \, d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f}}{\Phi \; d\Omega}$$

$$\sum_{k_f \, in \, d\Omega} W_{k_i,\lambda_i \to k_f,\lambda_f} = \frac{2\pi}{\hbar} \rho_{\mathbf{k}_f} \left| \langle \mathbf{k}_f \lambda_f | V | \mathbf{k}_i \lambda_i \rangle \right|^2$$

$$\left( \frac{d^2\sigma}{dE_f \, d\Omega} \right)_{\lambda_i \to \lambda_f} = \frac{k_f}{k_i} \left( \frac{m_n}{2\pi\hbar^2} \right)^2 \left| \langle \mathbf{k}_f \lambda_f | V | \mathbf{k}_i \lambda_i \rangle \right|^2 \delta\left( E_i - E_f + E_{\lambda_i} - E_{\lambda_f} \right)$$

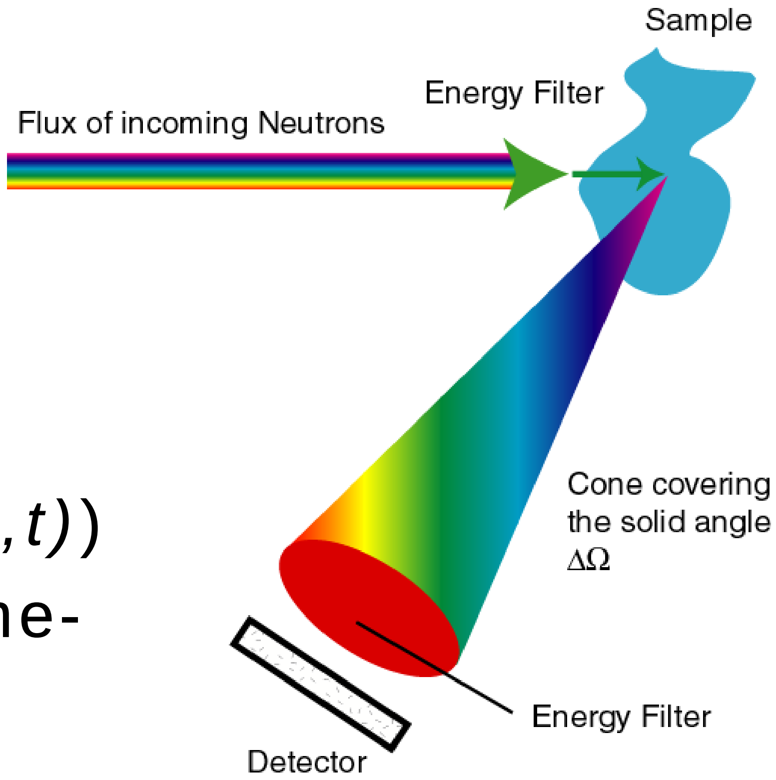
# General expressions for scattering from a set of moving atoms

Deriving the scattering function – end up with (after much algebra and manipulations!)

$$\left(\frac{d^2\sigma}{dEd\Omega}\right) = \frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk} b_j b_k \int_{-\infty}^{+\infty} \left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle \exp(i\omega t)\,dt$$

$$\left(\frac{d^2\sigma}{dEd\Omega}\right) = \frac{k_f}{k_i}\frac{1}{2\pi\hbar} S(\vec{Q},\omega)$$

- Experiment measures double differential cross-section which is simply related to $S(Q,\omega)$ (or $I(Q,t)$)
- $S(Q,\omega)$ is the double Fourier transform of the time-dependent pair-correlation function



# General expressions for scattering from a set of moving atoms

Deriving the scattering function – end up with – coherent & incoherent contributions

- For a simple system with a single element but different *b*'s

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{coh} = \frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{jk}\int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_k(t)\right\}\right\rangle \exp(-i\omega t)dt$$

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{incoh} = \frac{\sigma_{incoh}}{4\pi}\frac{k_f}{k_i}\frac{1}{2\pi\hbar}\sum_{j}\int_{-\infty}^{+\infty}\left\langle \exp\left\{-i\vec{Q}\cdot\vec{R}_j(0)\right\}\exp\left\{i\vec{Q}\cdot\vec{R}_j(t)\right\}\right\rangle \exp(-i\omega t)dt$$

- Scattering function determined by positions *R* of different atoms at different times *t*
- Incoherent scattering can be useful: it measures the correlation between the same atom at different times → single particle dynamics - diffusion

# General scattering experiment

Scattering triangle – handling Q and $\omega$

- $\boldsymbol{Q = k_f - k_i}$, $\hbar\omega = E_f - E_i$ ($E \sim k^2$, $k = 2\pi/\lambda$)

- Elastic scattering:

  vary $Q$ without changing $\omega$

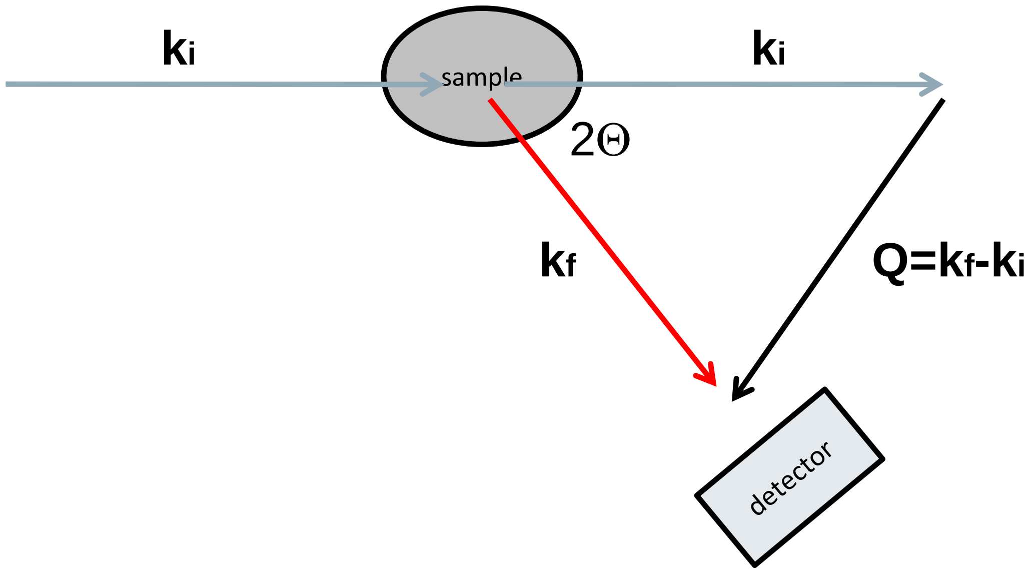
  $E_i = E_f$ vary $2\Theta$ (monochromatic)

  vary $|E|$ fix $2\Theta$ (t.o.f.)

- Quasi/in-elastic scattering:

  vary $\omega$, normally $Q$ will also change

  vary $E_i$ or $E_f$ and/or $2\Theta$



## Generic instrument

Energy selection

- How to measure the energy of a neutron beam?
- Or, how to monochromate a beam?
- Measure $\lambda$ with Bragg reflection

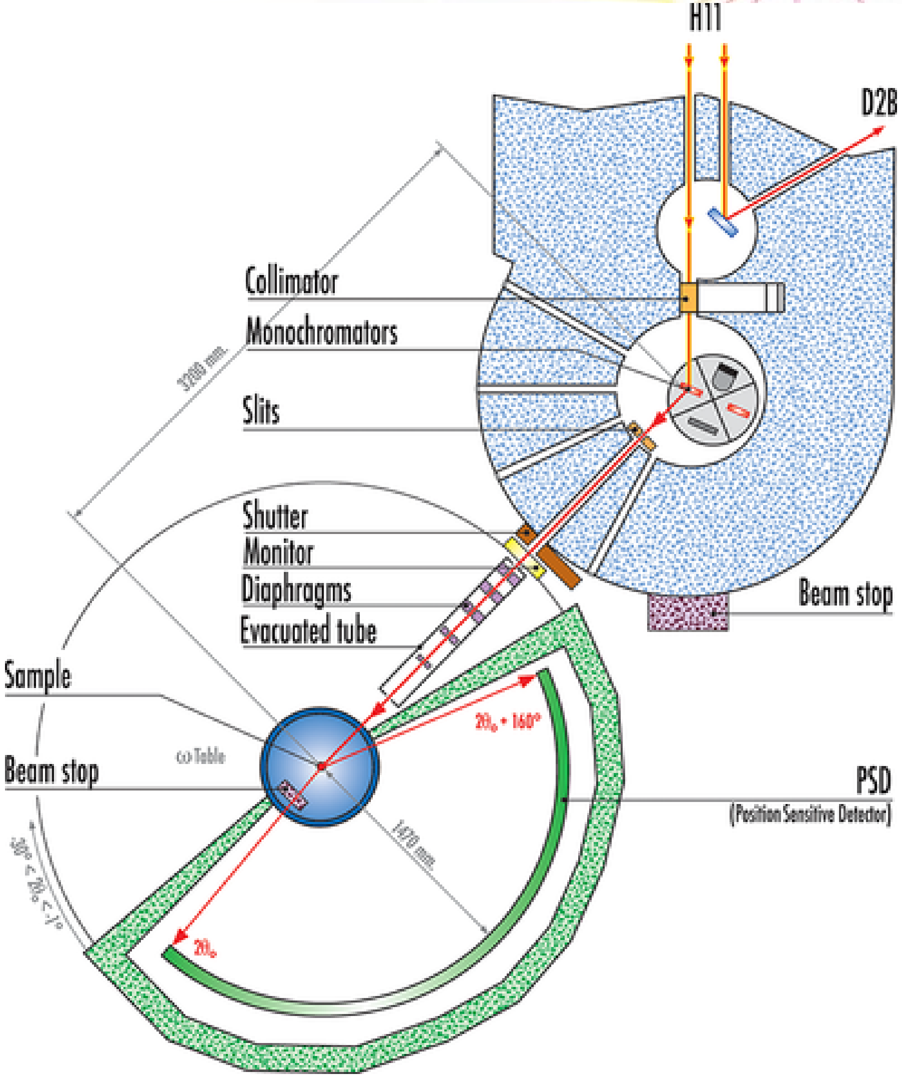
  $n\lambda = 2d\sin\Theta$

  $d$ = distance between scattering planes
- Use neutron *t.o.f.* (or precession of neutron magnetic moments in a magnetic field)

$$tof = \frac{L}{v} = 253\mu\sec\cdot\lambda\left[\overset{o}{A}\right]\cdot L[m]$$

# DIFFRACTION

Instruments (don't measure the final energy!) – D2b & LADI



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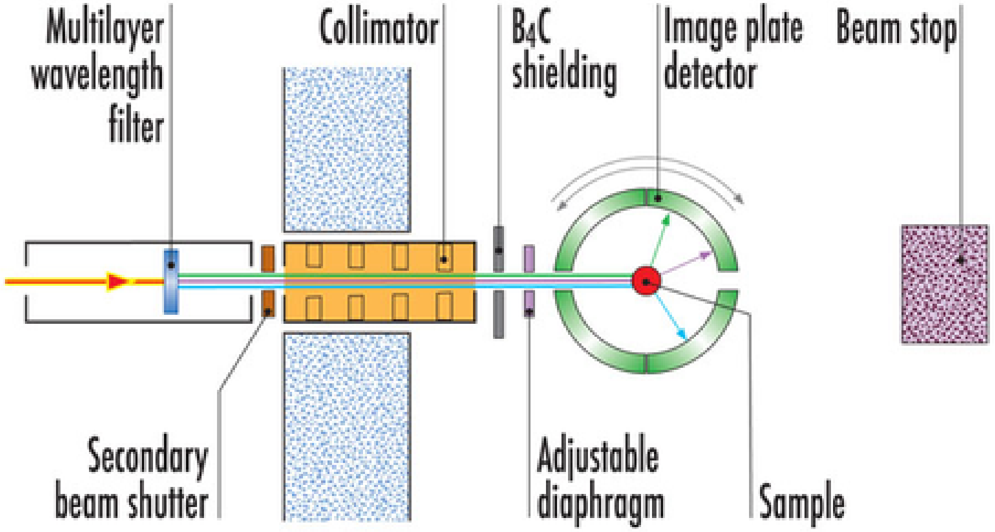
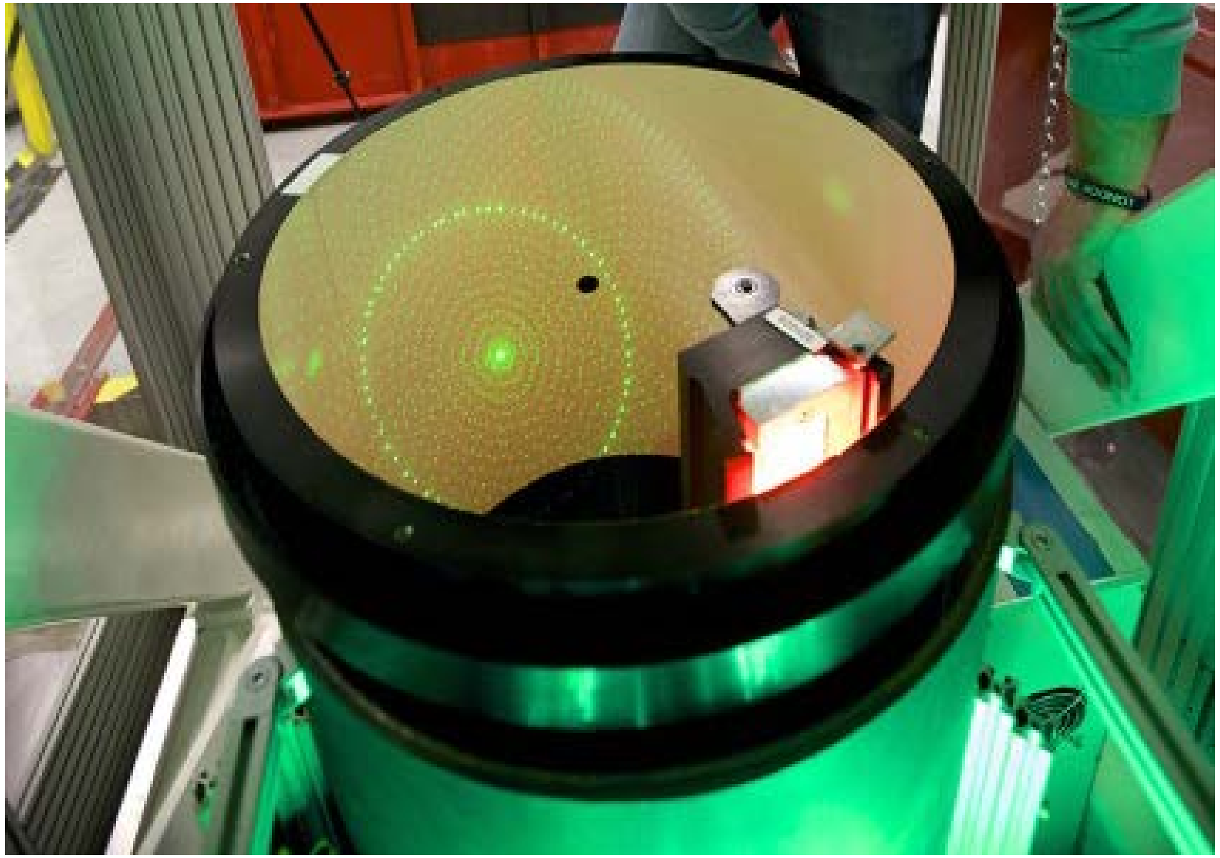
# DIFFRACTION

Example – Formation and properties of ice XVI obtained by emptying a type sII clathrate hydrate

# DIFFRACTION

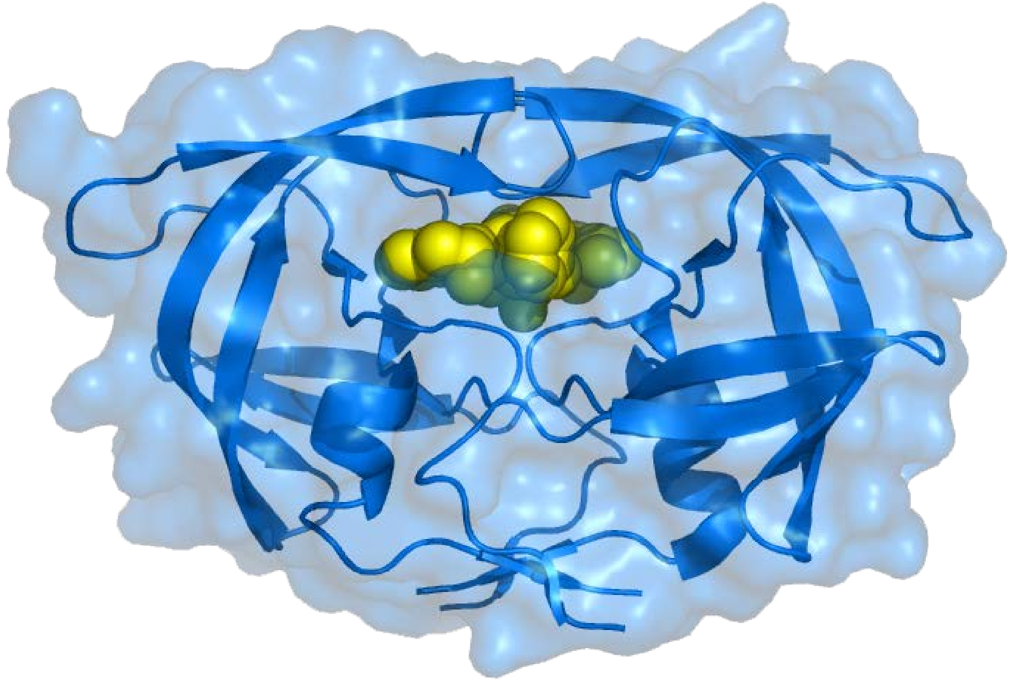
## Instruments (don’t measure the final energy!) – D2b & LADI

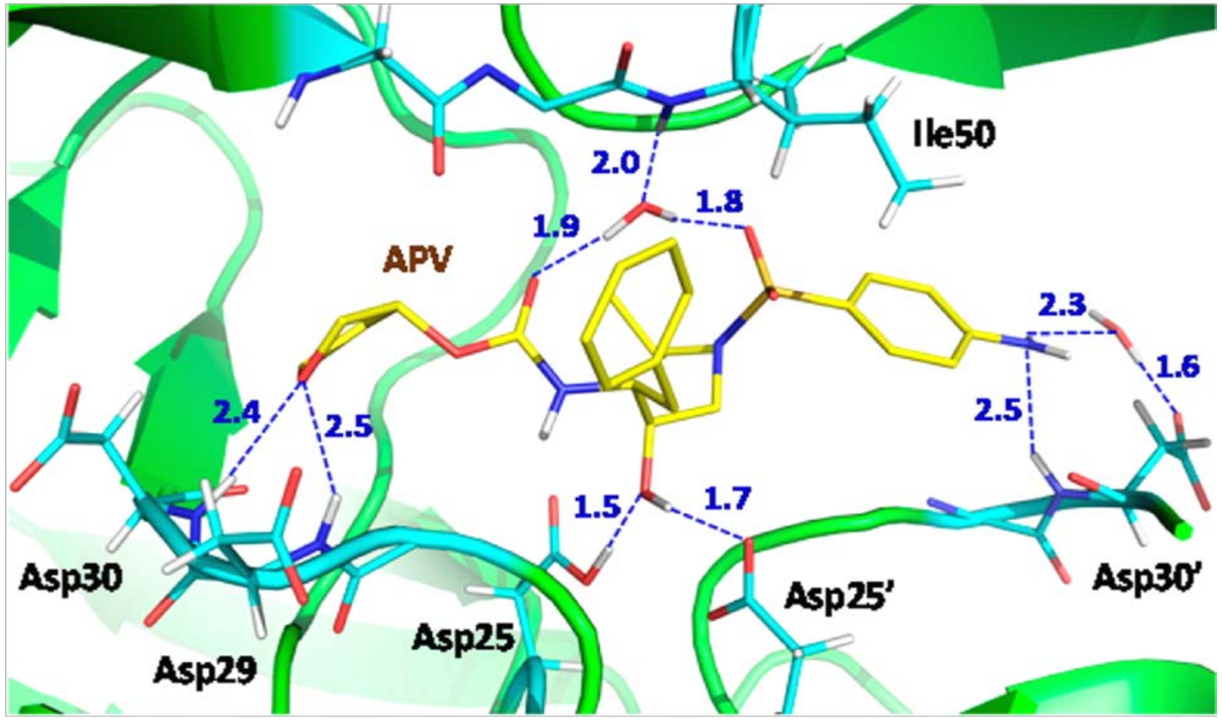


# DIFFRACTION

Example – Improving drug design: HIV-1 Protease in complex with clinical inhibitors (sample ~50 μg)





# Spectroscopy – time / frequency domain

Simplified expressions for the scattering function – coherent scattering

In previous scattering expressions

$R = R_0 + \delta R(t)$

For normal modes: $\delta R(t)$ → displacement vectors **e** & frequencies $\omega$

Coherent scattering - Phonons:

- Short range coupling gives long range correlations
- Dispersion as a function of ***q*** (or wavelength) – guitar string!

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{coh\pm1} = \frac{\sigma_{coh}}{4\pi}\frac{k_f}{k_i}\frac{(2\pi)^3}{v_0}\frac{1}{2M}\exp(-2W)\sum_s\sum_\tau\frac{\left(\vec{Q}\cdot\vec{e}_s\right)}{\omega_s}\langle n_s + 1/2 \pm 1/2\rangle$$

$$\times\delta(\omega \mp \omega_s)\delta\left(\vec{Q} \mp \vec{q} - \vec{\tau}\right)$$



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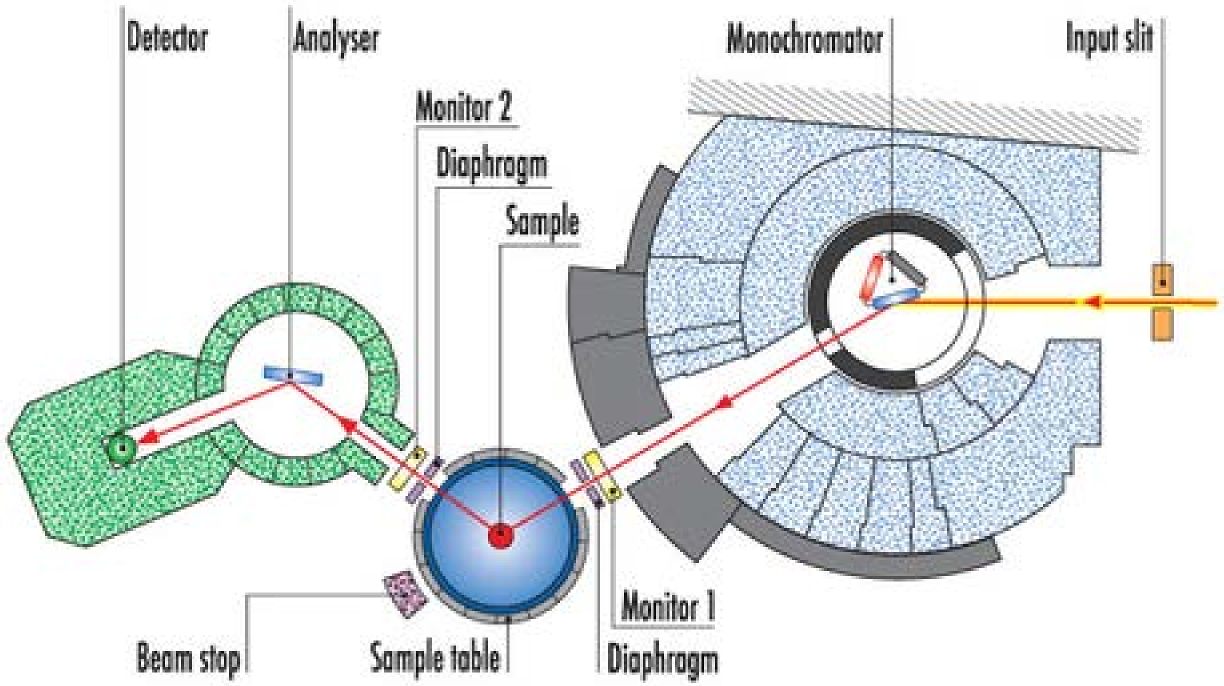
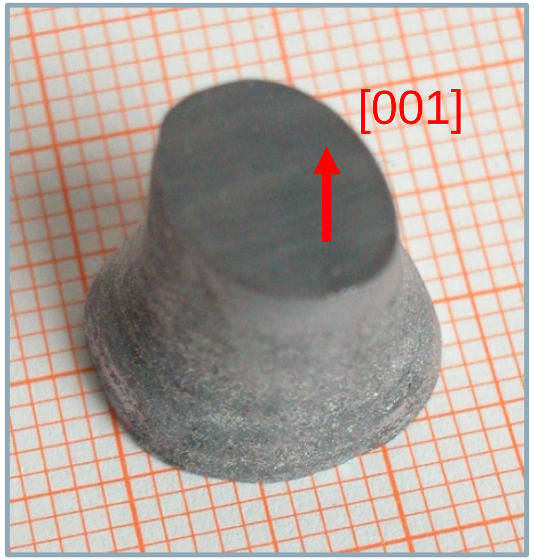
# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

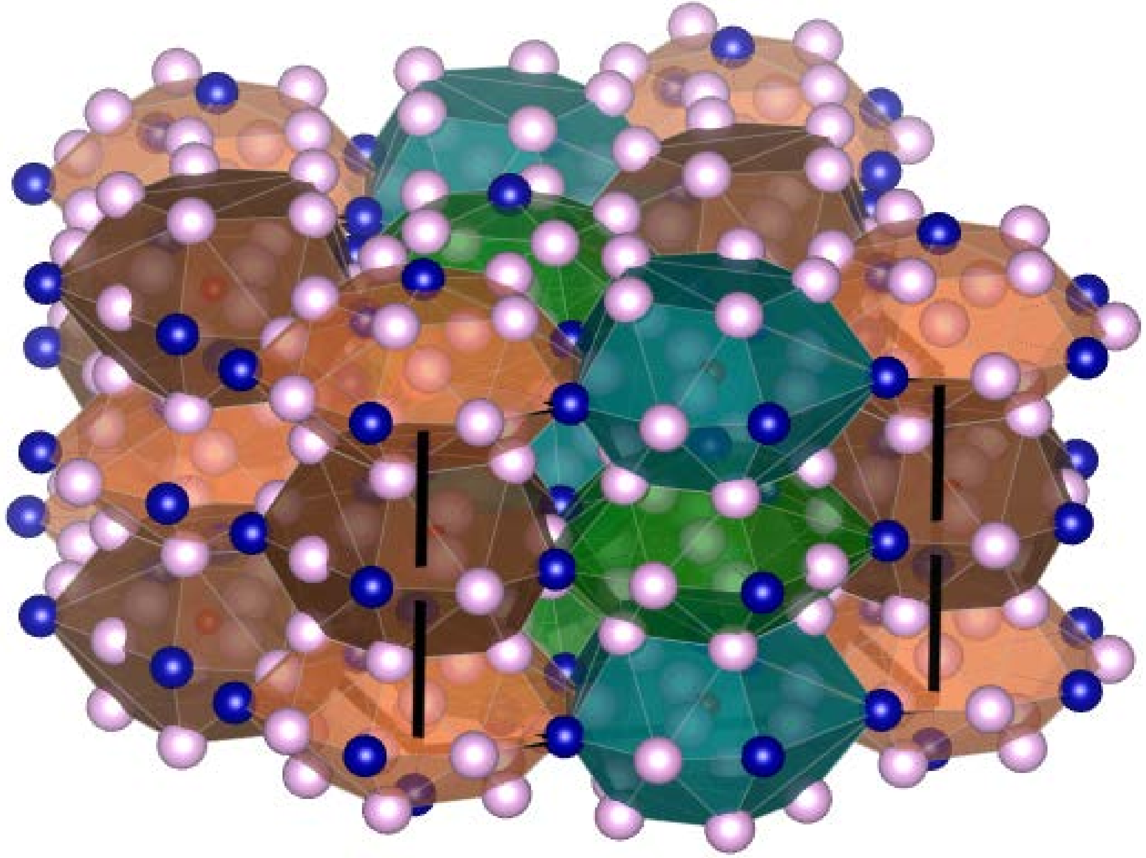
Instruments – varying $k_i$ & $k_f$ – TAS, TOF




# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

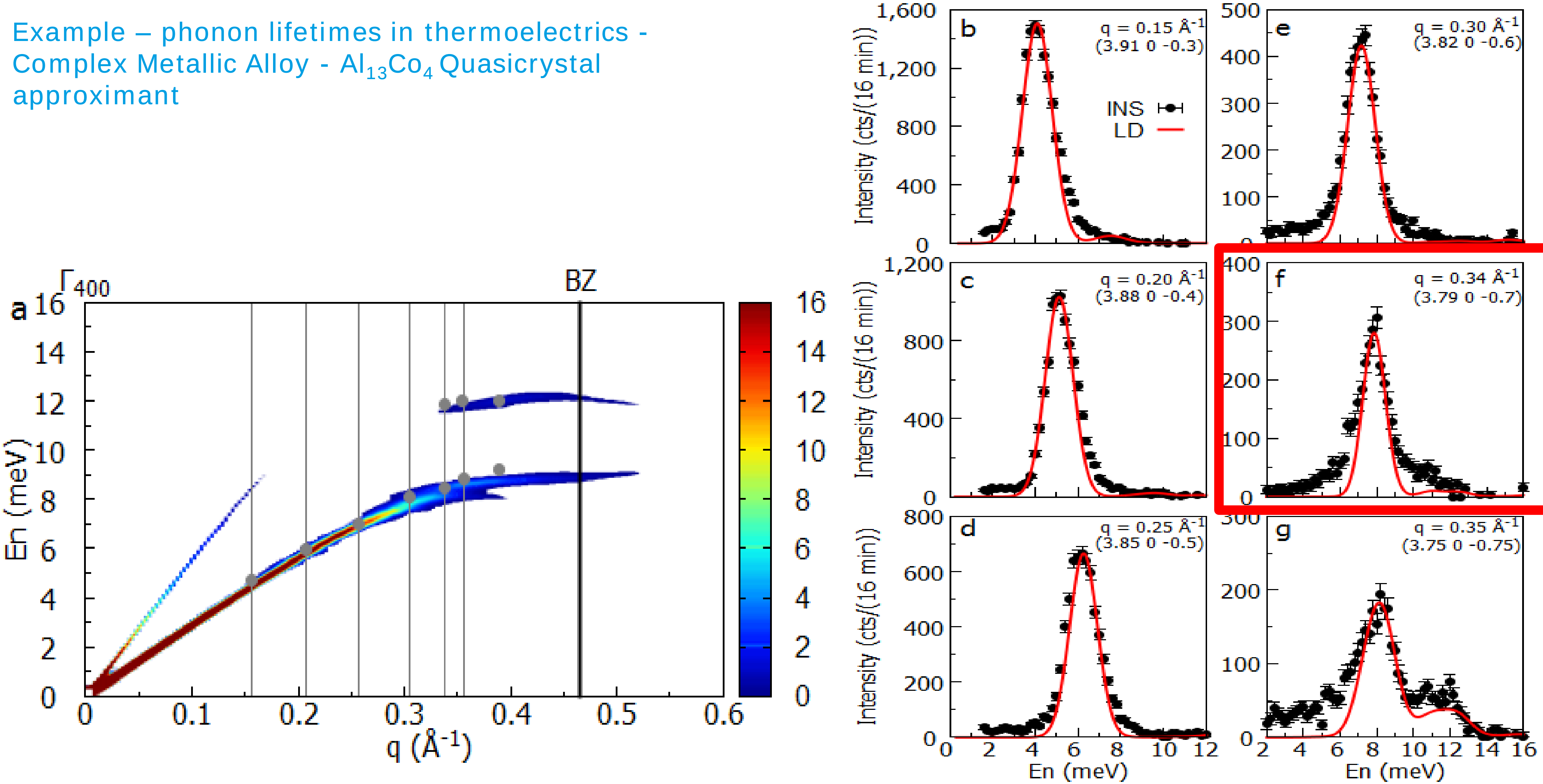
Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant



# Spectroscopy – time / frequency domain

Example – phonon lifetimes in thermoelectrics - Complex Metallic Alloy - $Al_{13}Co_4$ Quasicrystal approximant



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# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

Simplified expressions for the scattering function – incoherent scattering

In previous scattering expressions

$$R = R_0 + \delta R(t)$$

For normal modes: $\delta R(t)$ → displacement vectors **e** & frequencies $\omega$

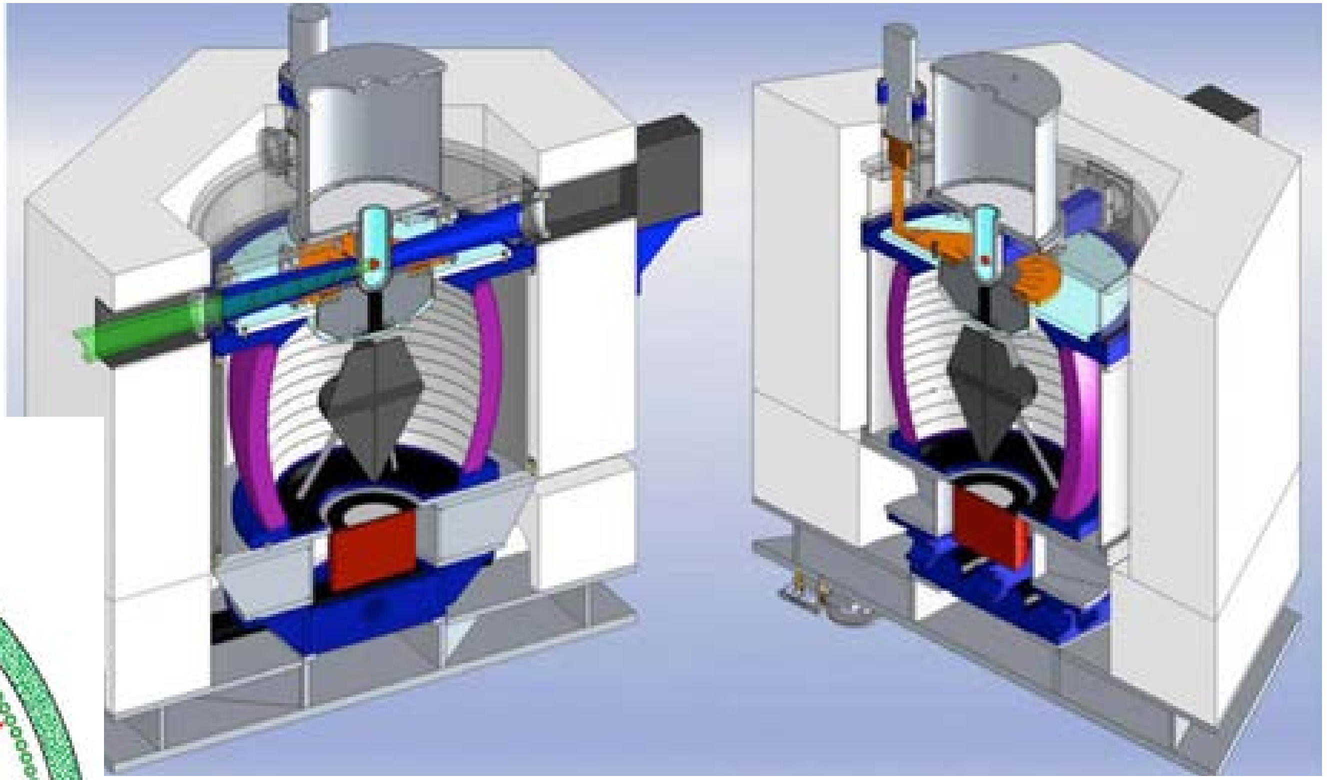
Incoherent scattering - Internal (molecular) modes:

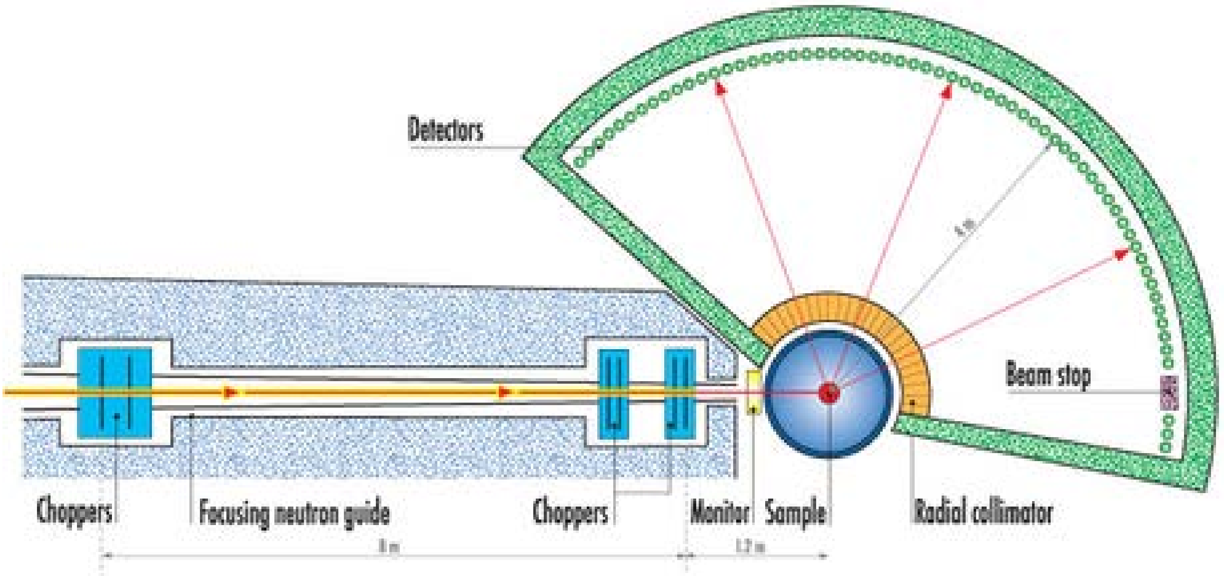
- No long range correlations due to weak coupling
- No dispersion

$$\left.\frac{d^2\sigma}{d\Omega dE_f}\right)_{incoh\pm1} = \frac{k_f}{k_i}\sum_s \delta(\omega \mp \omega_s)\frac{\langle n_s + 1/2 \pm 1/2\rangle}{2\omega_s}\sum_r \frac{(\sigma_{incoh})_r}{4\pi}\frac{1}{M_r}\left|\vec{Q}\cdot\vec{e}_r\right|^2 \exp(-2W_r)$$

# Spectroscopy – time / frequency domain

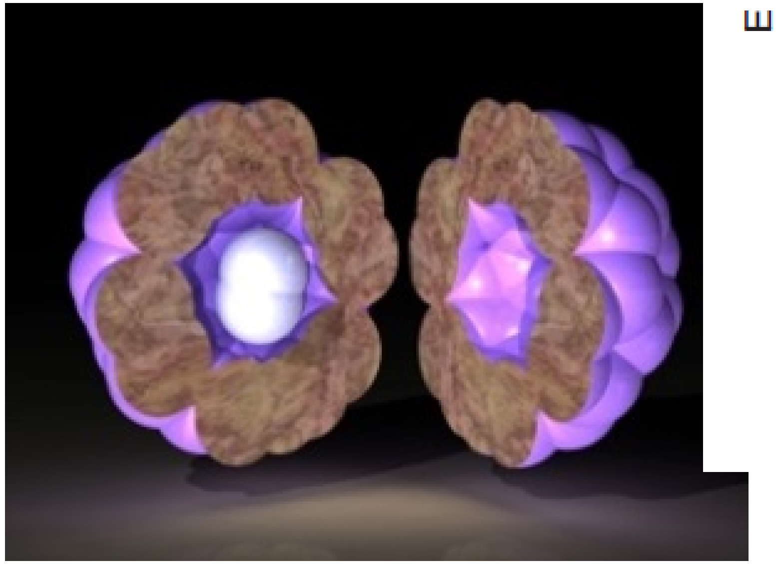
Instruments – TOF, Lagrange

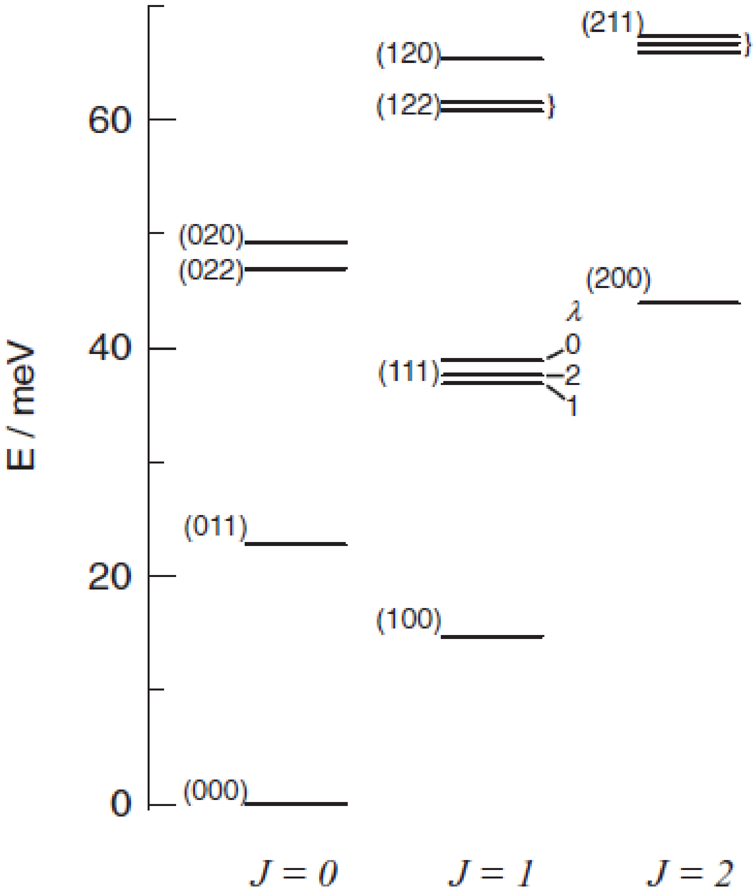


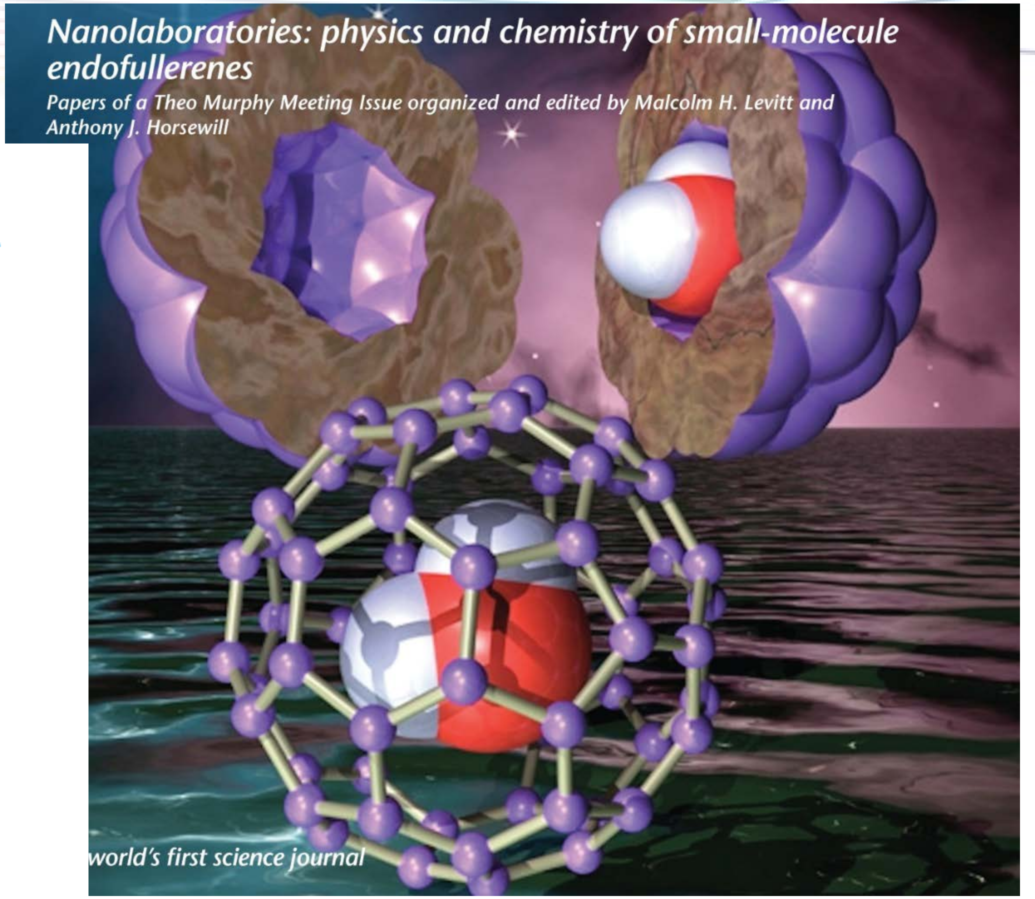


# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

Example – endofullerenes

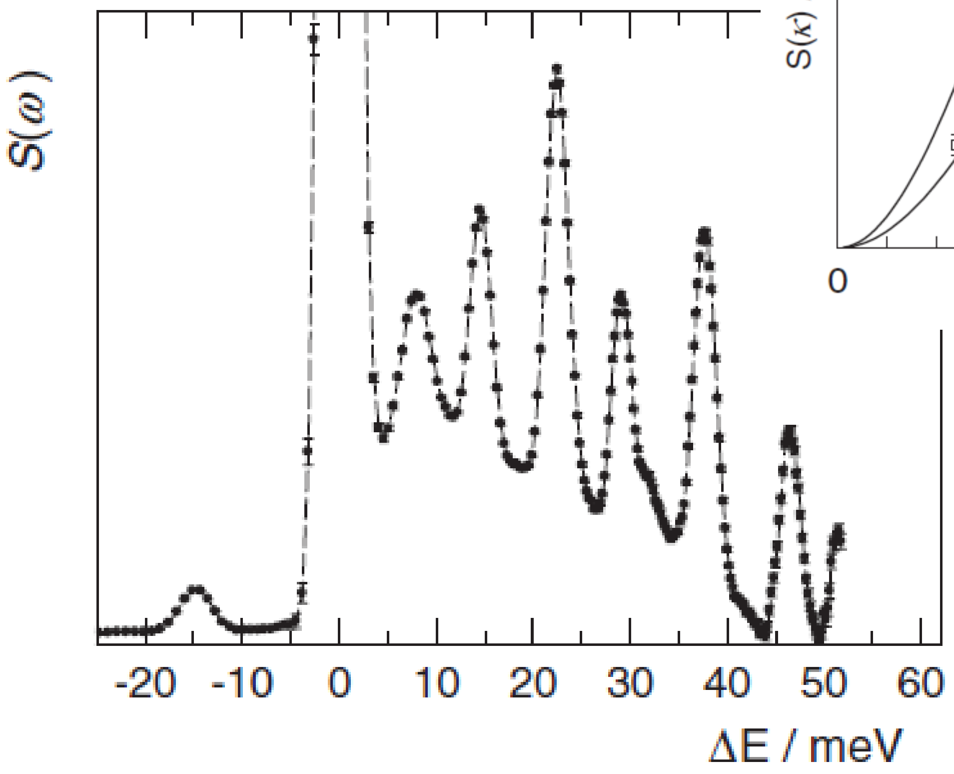


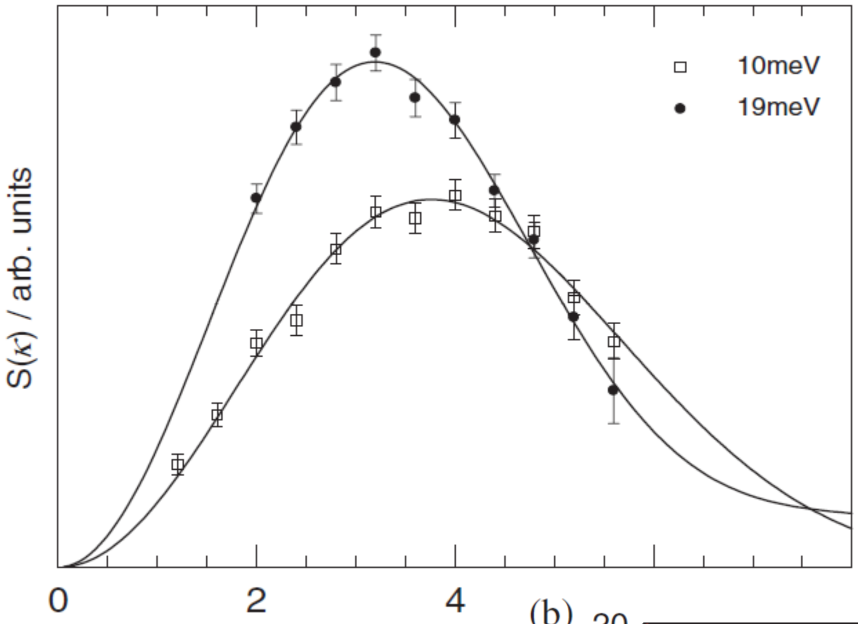


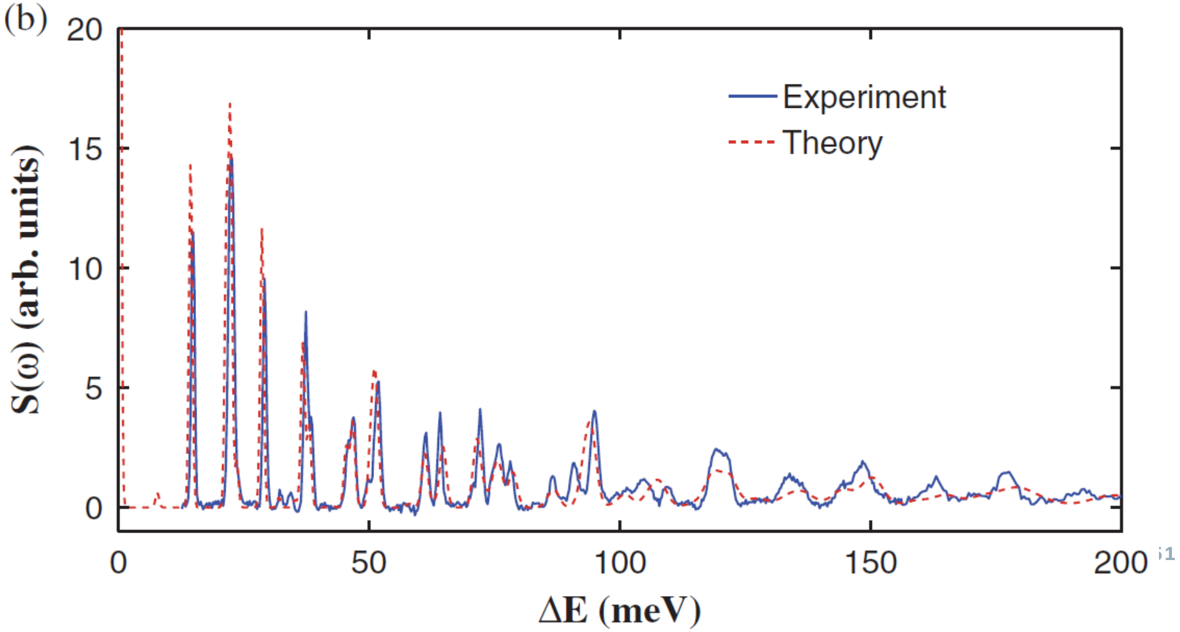



# Spectroscopy – time / frequency domain

Example – endofullerenes

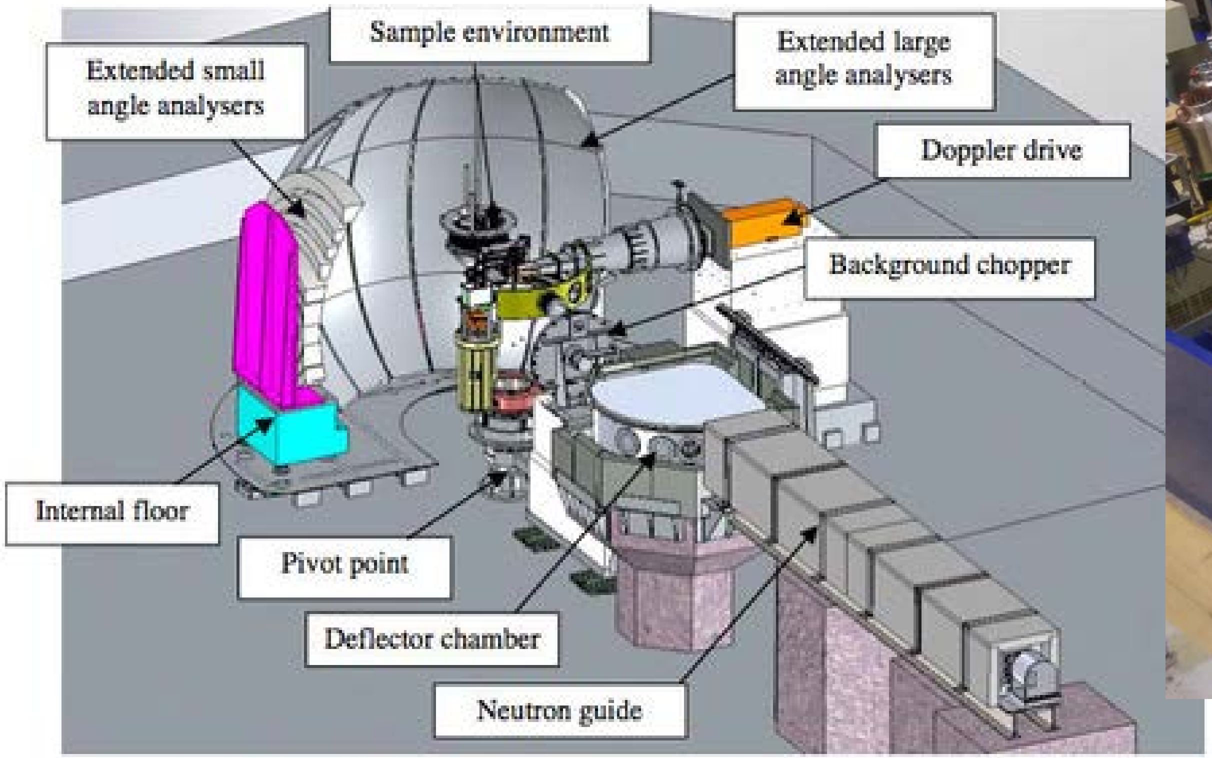


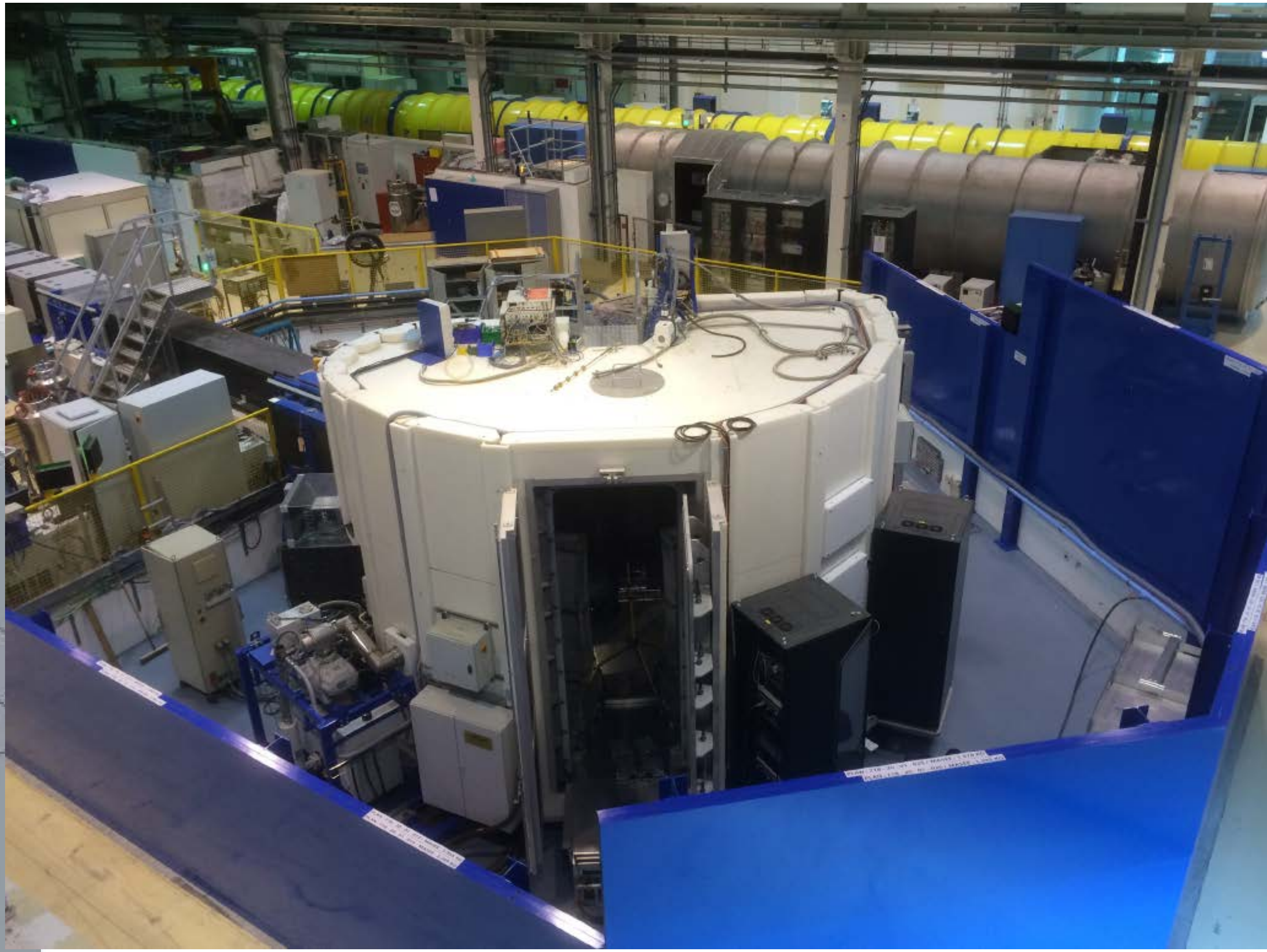



# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

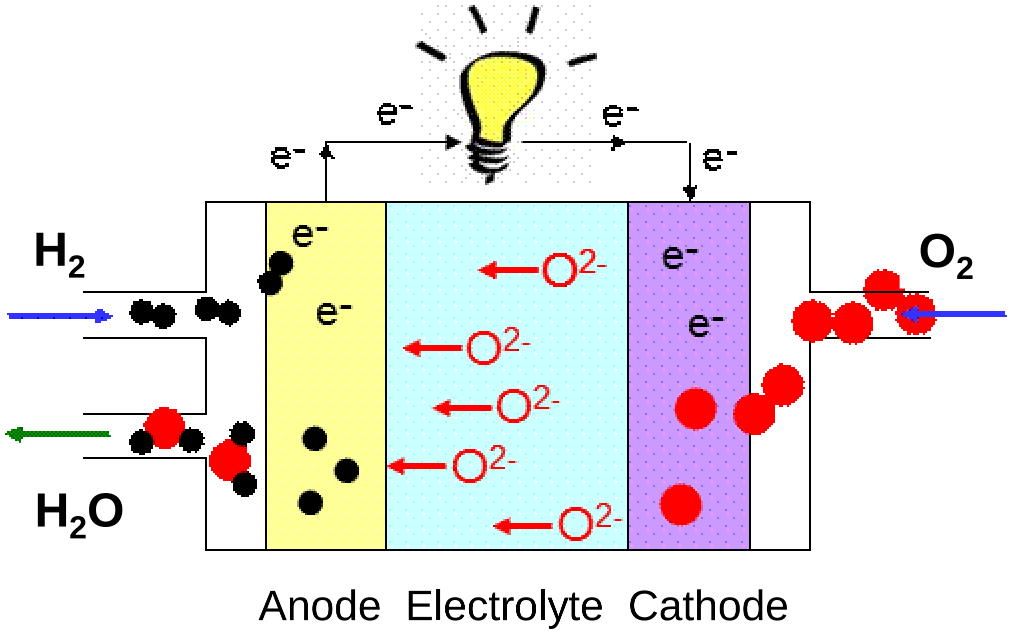
Instruments – Back-Scattering

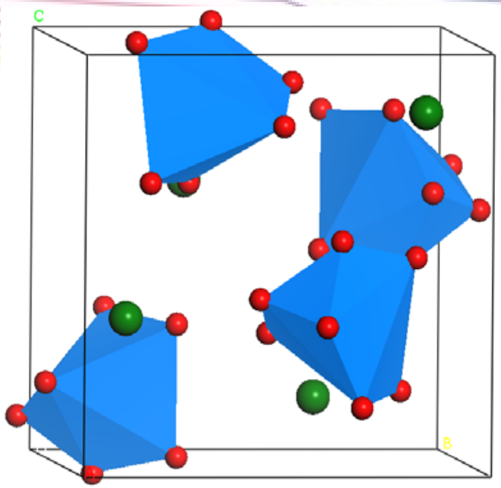


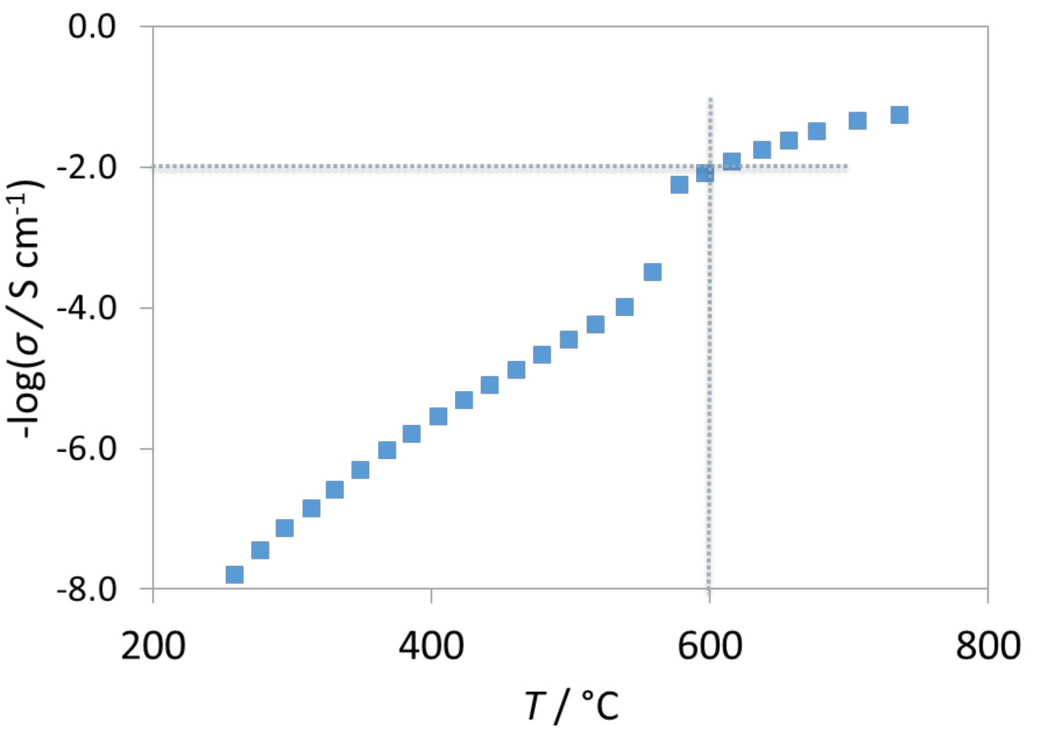



# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

Example – oxide ion conductors





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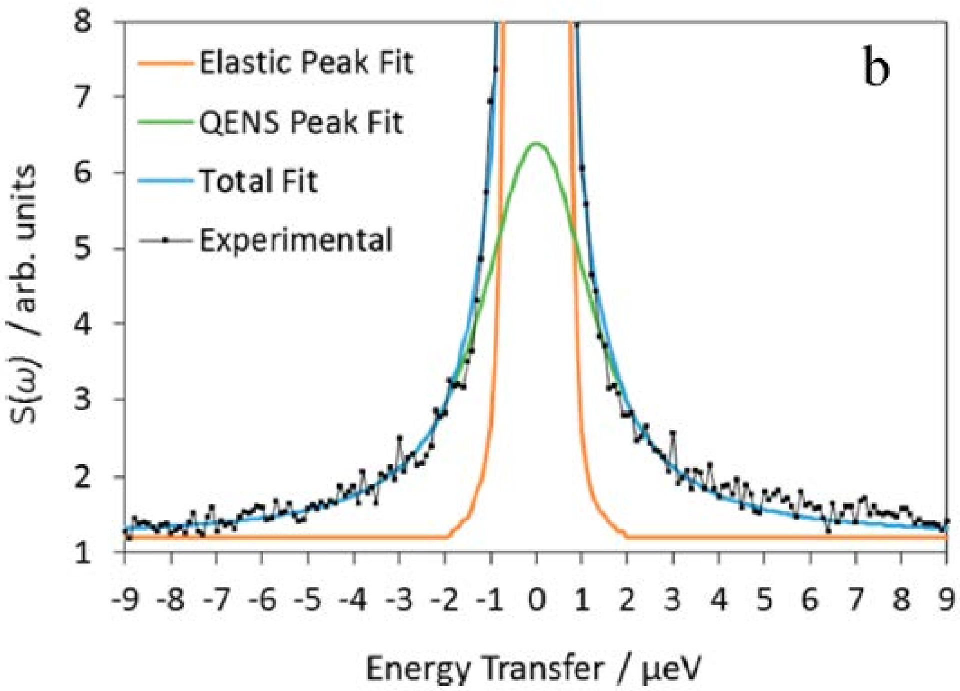
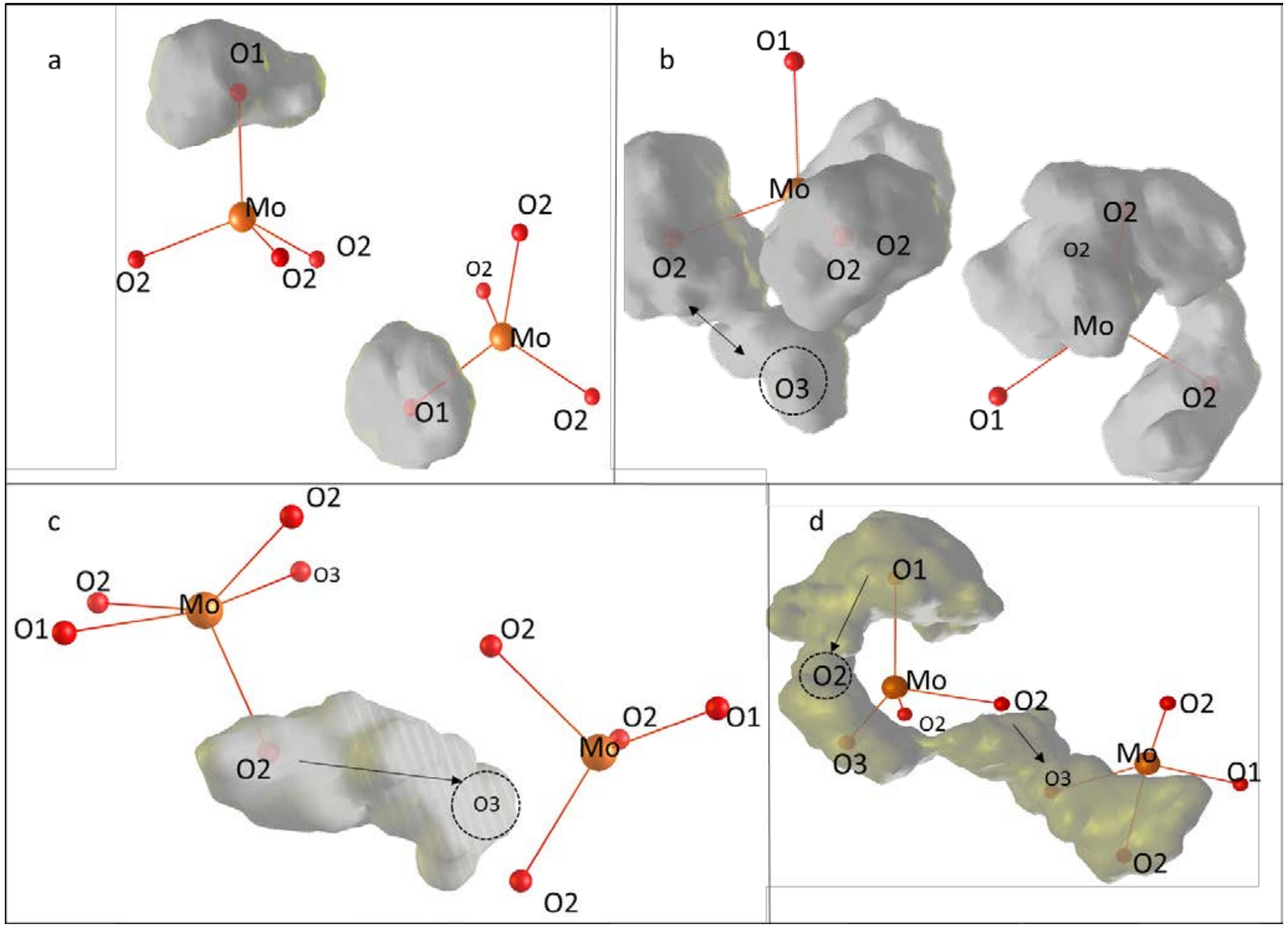
# SPECTROSCOPY – TIME / FREQUENCY DOMAIN

Example – oxide ion conductors



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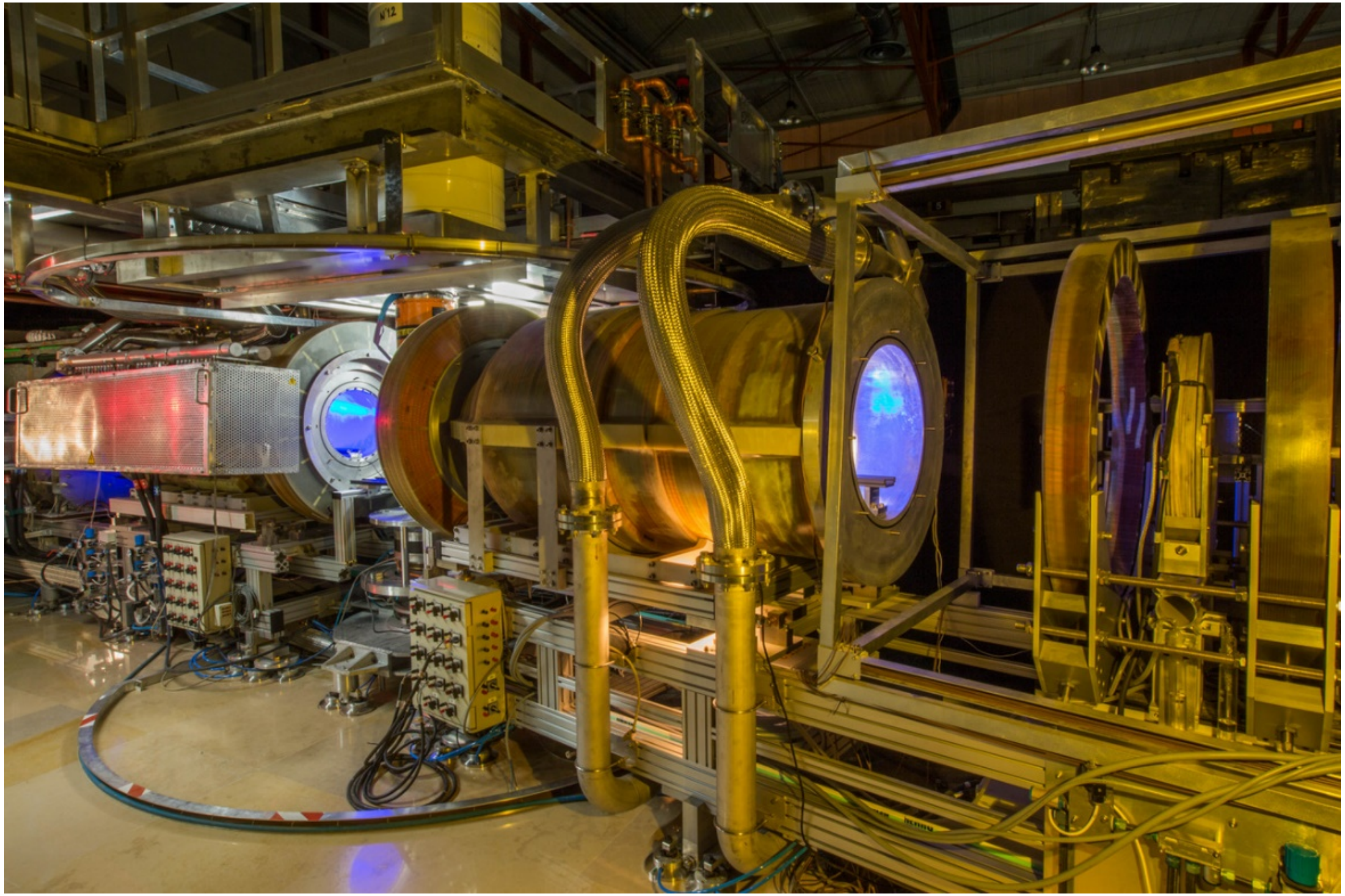
# SPECTROSCOPY – SPIN ECHO

Energy selection - precession of neutron magnetic moments in a magnetic field (depends on t.o.f. in B)



# SPECTROSCOPY – SPIN ECHO

# Magnetism

Structure and dynamics – double differential cross-section

As for interactions with nuclei but

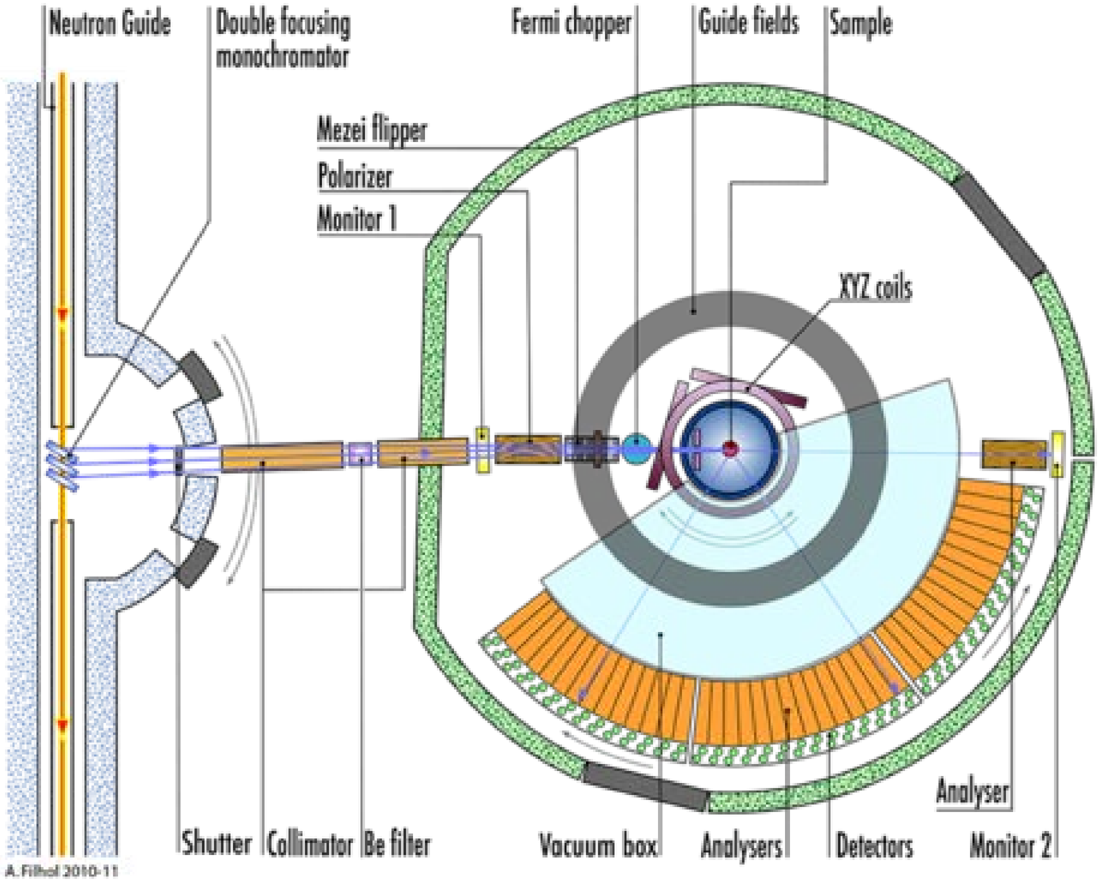
- Neutron spin probes local magnetic fields due to electron spin and orbital contribution
- Atomic form factor – scattering from an atom is angular dependent due to electron cloud
- No incoherence effects
- N.B. $\sigma$ and $V$ in these equations

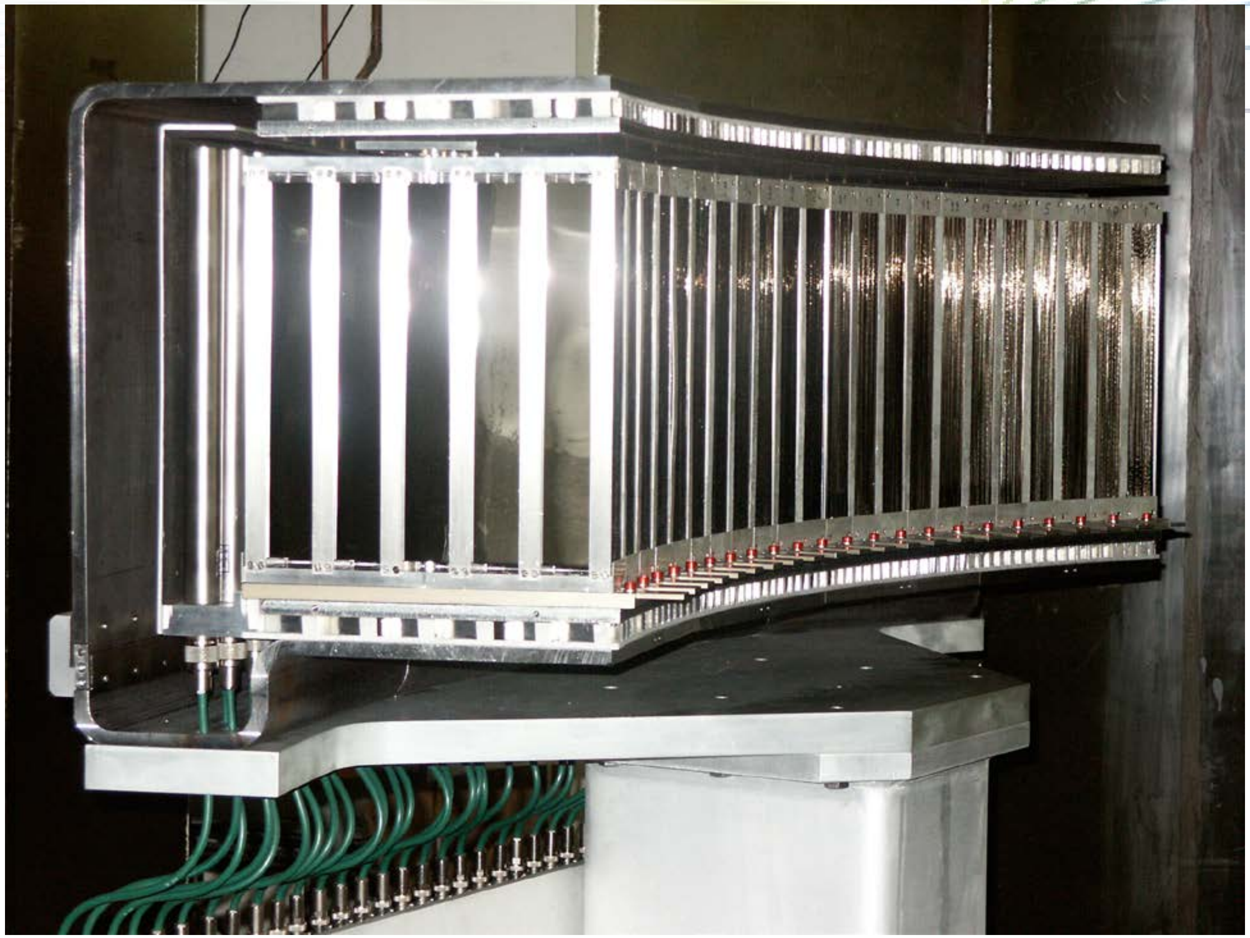
$$V_m = -\mu_n \cdot B = -\frac{\mu_0}{4\pi}\gamma\mu_N 2\mu_B\left\{curl\left(\frac{s\times R}{R^2}\right)+\frac{1}{\hbar}\frac{p\times R}{R^2}\right\}$$

$$\left(\frac{d^2\sigma}{dE_f d\Omega}\right)_{\sigma_i\lambda_i\to\sigma_f\lambda_f} = \frac{k_f}{k_i}\left(\frac{m_n}{2\pi\hbar^2}\right)^2 \left|\langle k_f\sigma_f\lambda_f|V_m|k_i\sigma_i\lambda_i\rangle\right|^2 \delta\left(E_i - E_f + E_{\lambda_i} - E_{\lambda_f}\right)$$

# Magnetism

Polarised neutrons – separate nuclear and magnetic signals
& more precise information on magnetic structures



- Measure 2, 6 or 10 polarised scattering channels: u→u (non spin flip) and d→u (spin flip) in the simplest case

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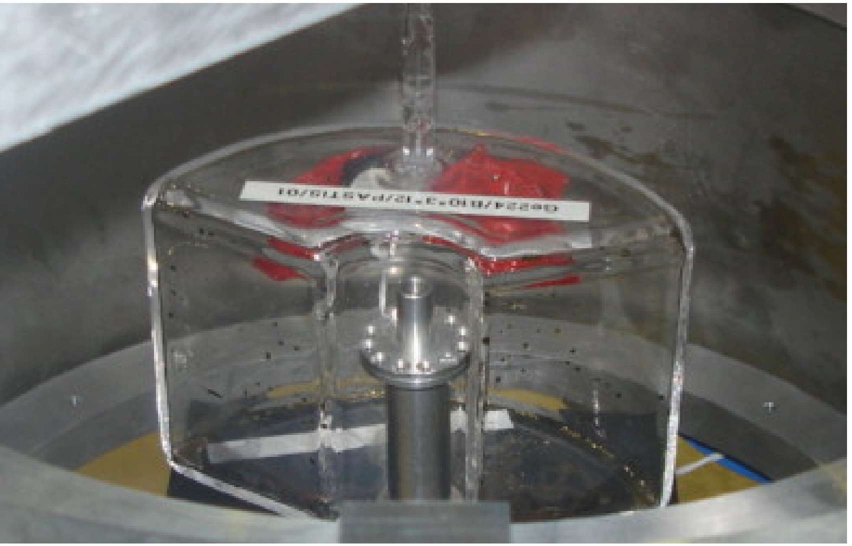
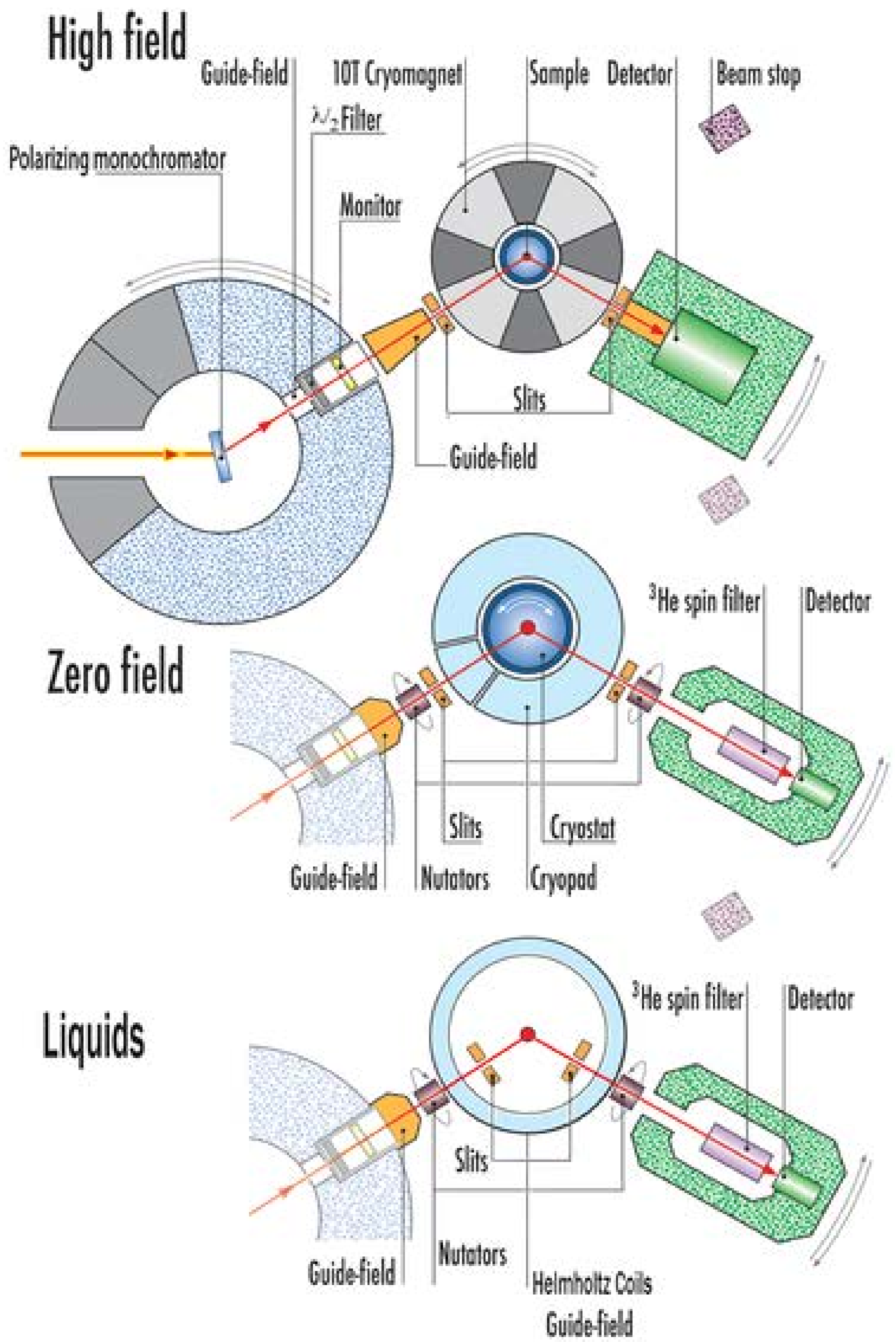
# MAGNETISM

Polarised neutrons – separate nuclear and magnetic signals
& more precise information on magnetic structures

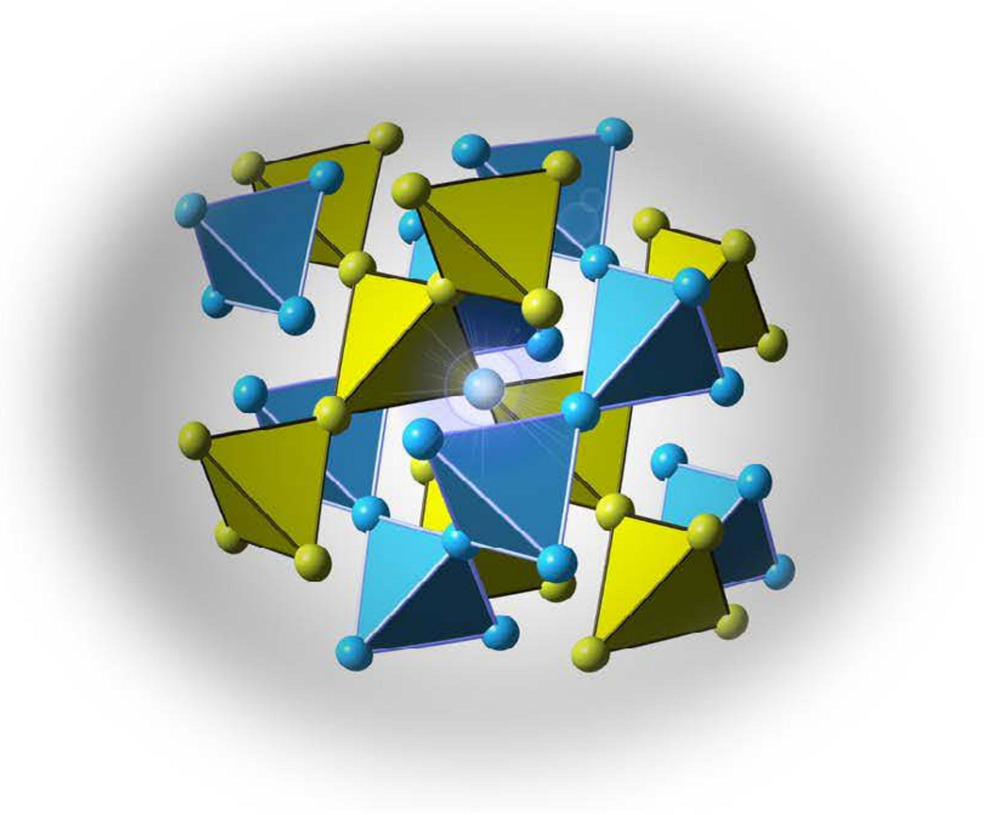
- Polarised (optically pumped) 3He selectively absorbs one neutron spin state – more versatile polariser
- Cryopad allows full control of incident and scattered neutron polarisation – spherical polarimetry





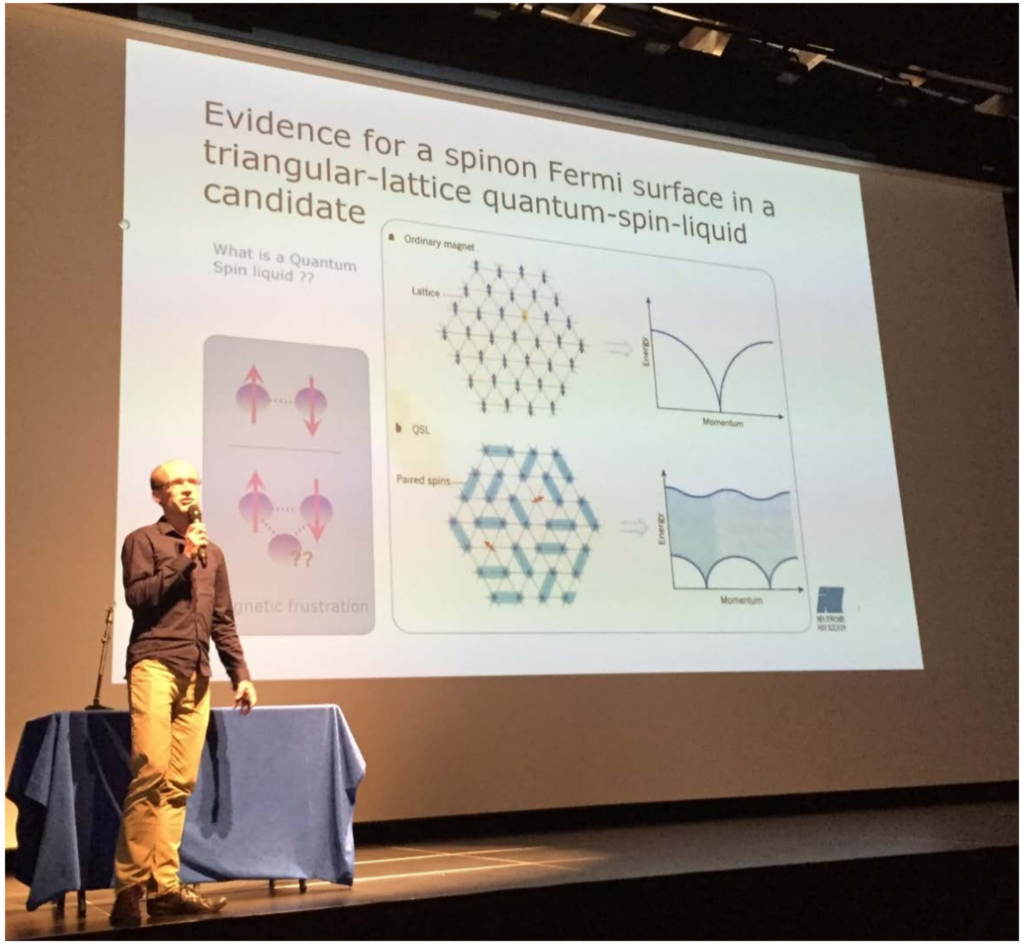
# MAGNETISM

Example – Ground state selection under pressure in the quantum pyrochlore magnet $Yb_2Ti_2O_7$



# Magnetism

Example – How do electrons/spins organise in a triangular lattice? Spins pair into quantum-mechanical bonds and fluctuate…






NEUTRONS FOR SOCIETY

# Summary – key messages

The neutron

- Is Highly penetrating
- Interacts with nuclei – favourable for light atoms (H, Li, O,...)
- Incoherent scattering is ideal for proton dynamics
- Isotopes provide selectivity – contrast matching
- Interacts with unpaired electrons – magnetism
- Probes 15 orders of magnitude in length & 10 in time

Neutron sources have relatively low intensity and are only available in large scale facilities – ILL, ISIS, PSI, FRM2 in Europe, SNS & NIST in US

# ADDITIONAL READING

Search the web! Plus...

- *Introduction to the Theory of Thermal Neutron Scattering*
- G.L. Squires  Reprint edition (1997) Dover publications ISBN 04869447

- *Experimental Neutron Scattering*
- B.T.M. Willis & C.J. Carlile (2009) Oxford University Press ISBN 978-0-19-851970-6

- *Neutron Applications in Earth, Energy and Environmental Sciences*
- L. Liang, R. Rinaldi & H. Schober Eds Springer (2009) ISBN 978-0-387-09416-8

- *Methods in Molecular Biophysiscs*
- I.N. Serdyuk, N. R. Zaccai & J. Zaccai Cambridge University Press (2007) ISBN 978-0-521-81524-6

- *Thermal Neutron Scattering*
- P.A. Egelstaff ed. Academic Press (1965)

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# VERCORS

# Chartreuse



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# Mont Blanc