Basic Introduction to

Neutron Scattering

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Why Learn Neutron Scattering?

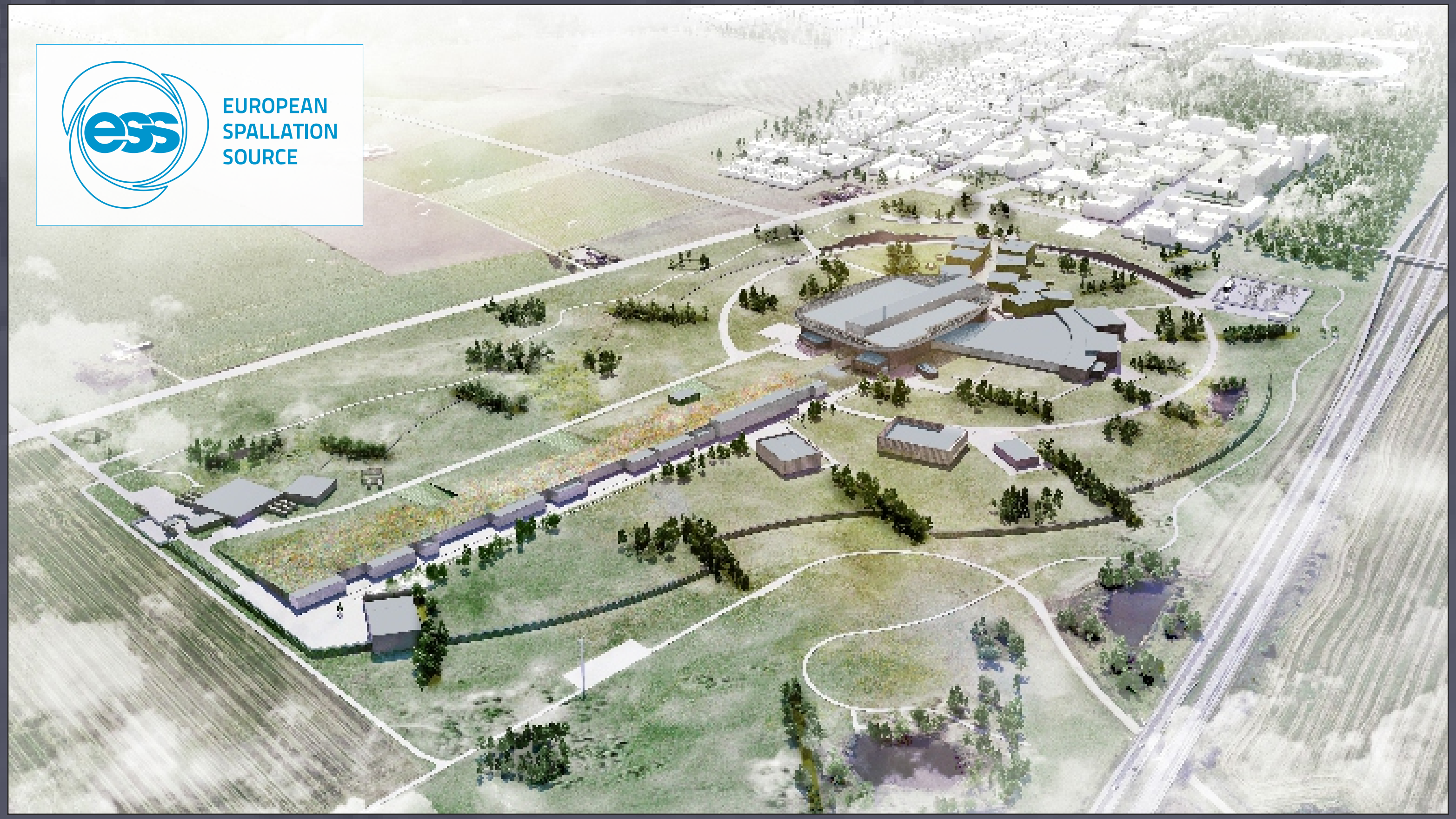
- Neutron scattering is one of the most versatile experimental techniques and is a useful tool for a broad range of scientific fields (materials science, condensed mattter physics, chemistry, biology, engineering, energy, ...)

- Many material properties can not be measured in any other way and modern condensed matter physics would in principle not exist without NS (magnetic structures, spin-fluctuations in superconductors, quantum magnetism etc.)

- Today's high-tech industry and everyday devices are using more complex materials i.e. NS is an invaluable tool for future applications (spintronics, green construction materials, energy cells, medical implants, catalysis...)

- Sweden hosts the state-of-the-art European Spallation Source (ESS), which will be the leading neutron source in the world.

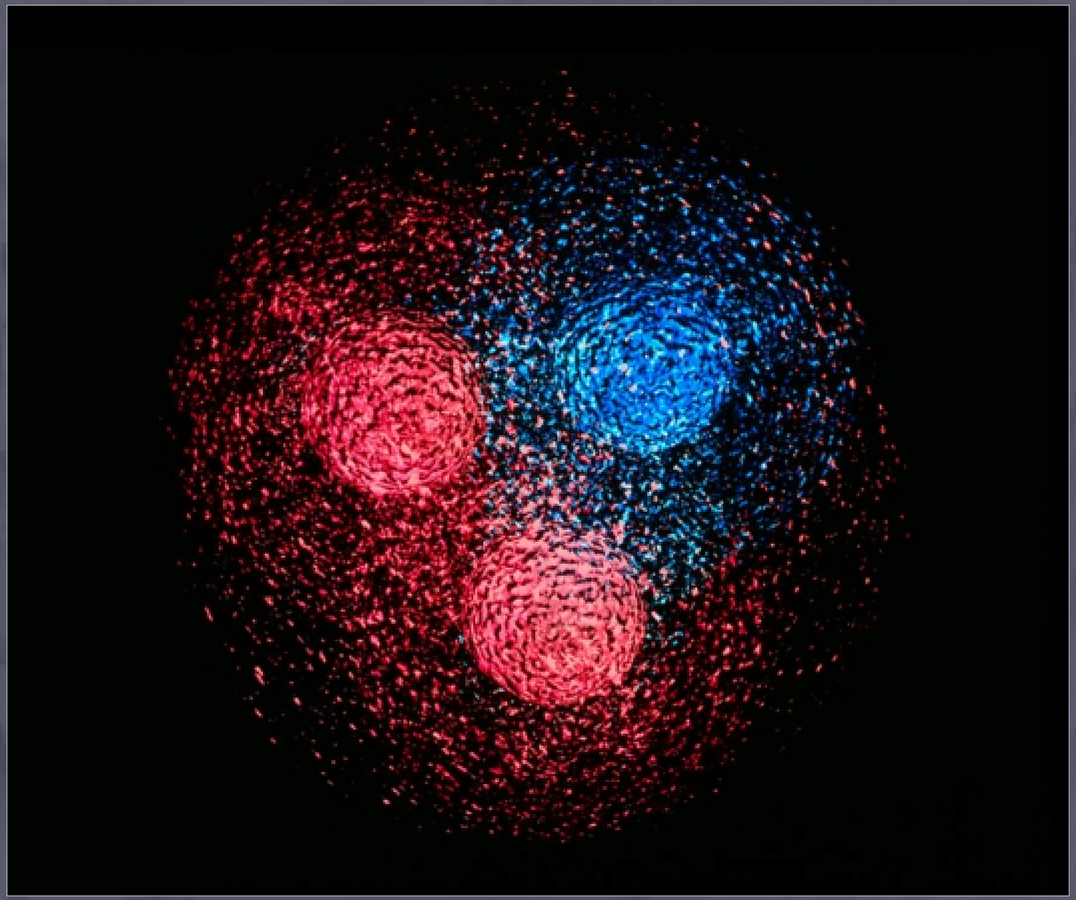
- From ~2025 there will be excellent possibilities for young scientists & industry to perform world-leading science & developments.

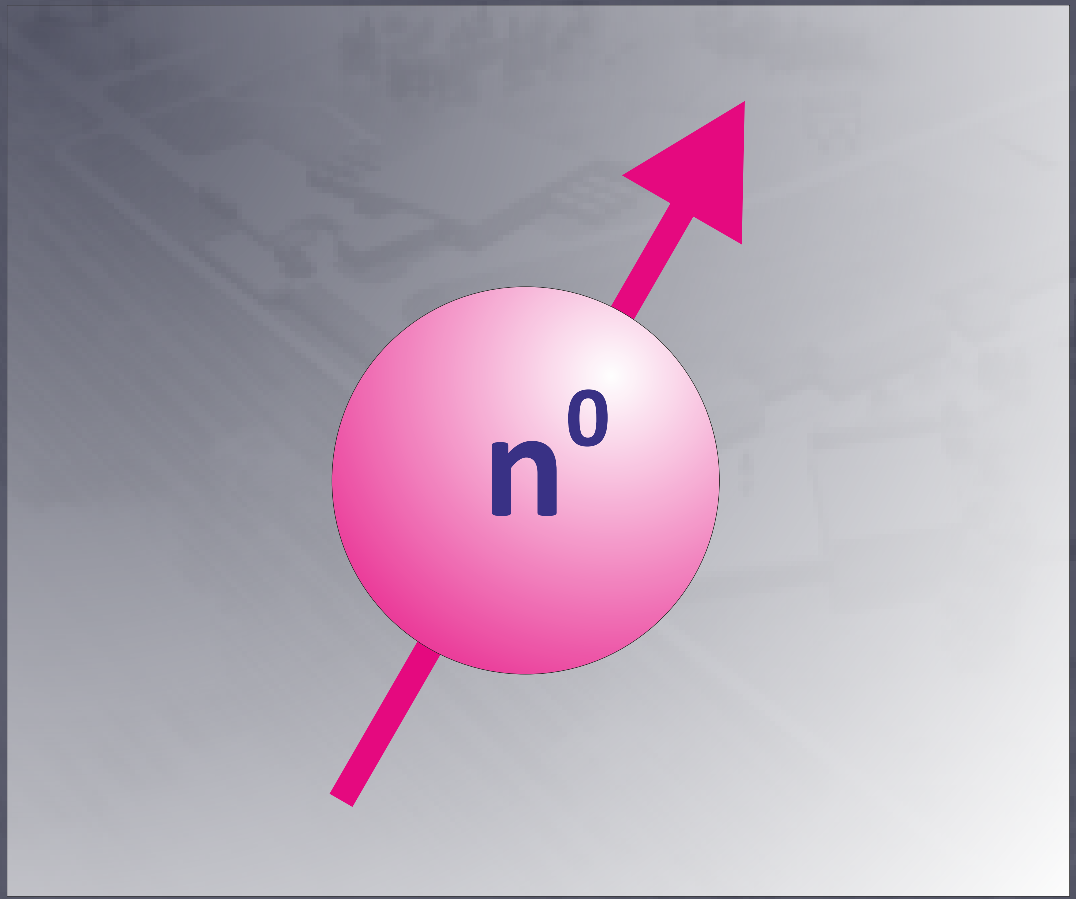


What is a Neutron (n^0)?

For particle physicists:

- A subatomic baryon particle of the hadron family.
- Consists of three quarks (2 down & 1 up) of different flavours held together by gluons.





For neutron scatterers:

- A neutral S = ½ particle used as an optimal tool to investigate microscopic / macroscopic materials / device properties.
- "Can show where atoms are and what they do" + magnetism

Neutron Properties

NEUTRAL

Charge = 0 → infinitely small electronic dipole moment, neutrons do not see charge!

HAS A SPIN

S = ½ → Initial state can be polarized & polarization of the final state can be analyzed!

HAS A MAGNETIC MOMENT

$\mu_{n0} = -1.913\ \mu_{Nuc}$ → neutrons can see magnetism !!!

RATHER STABLE

β-decays but lifetime τ = 881.5 seconds

(enough to survive the experiment!)

VERY SMALL

Confinement radius $R = 7 \times 10^{-14}$ m → All interactions are point-like!

'IDEAL' MASS

$m_{n0} = 1.675 \times 10^{-27}$ kg $\approx m_{p+} \approx 1840 \times m_{e-}$

PARTICLE- & WAVE-LIKE PROPERTIES

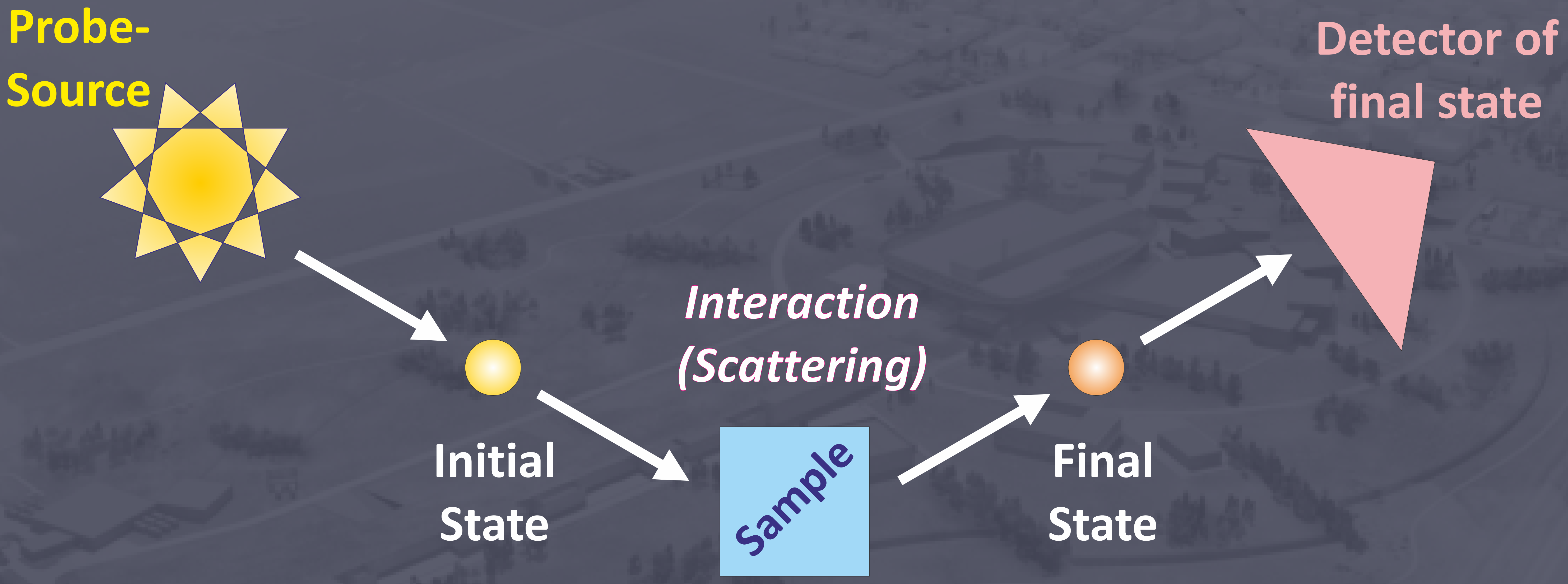
Dispersion relation: $E = \hbar k^2 / 2m \rightarrow \ldots$

$\lambda = 5$ Å → E = 3.3 meV

'Lingo'	E [meV]	λ [nm]
Cold	0.1–5	3–0.4
Thermal	5–100	0.4–0.1
Hot	100–500	0.1–0.04

Neutron wavelengths/energies are perfect for studying microscopic material properties i.e. condensed matter physics !!!

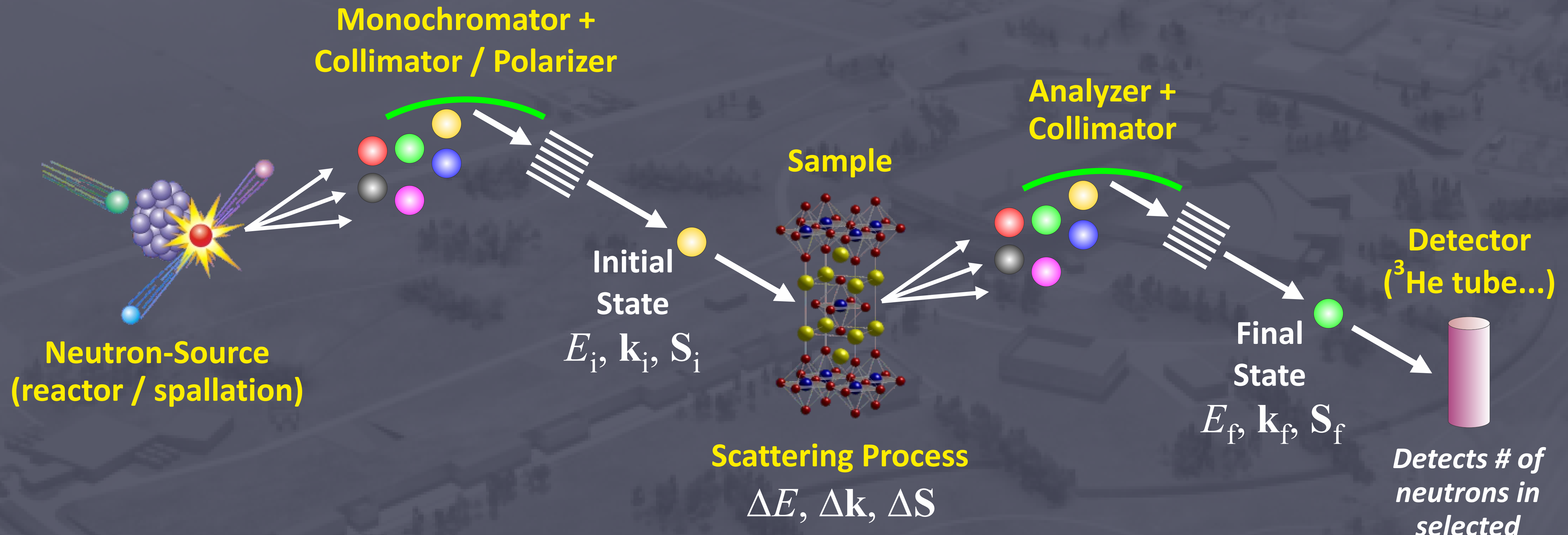
A Scattering Experiment



Remember that scattering methods provide statistically averaged information on structures rather than real-space pictures of particular instances !!!

The Neutron Scattering Experiment

- **Two problems:** **#1**: Can not easily manipulate initial state **#2**: Final state can not be measured directly
- **Solution**: Use 'filters' *e.g.* monochromator, collimators and analyzer

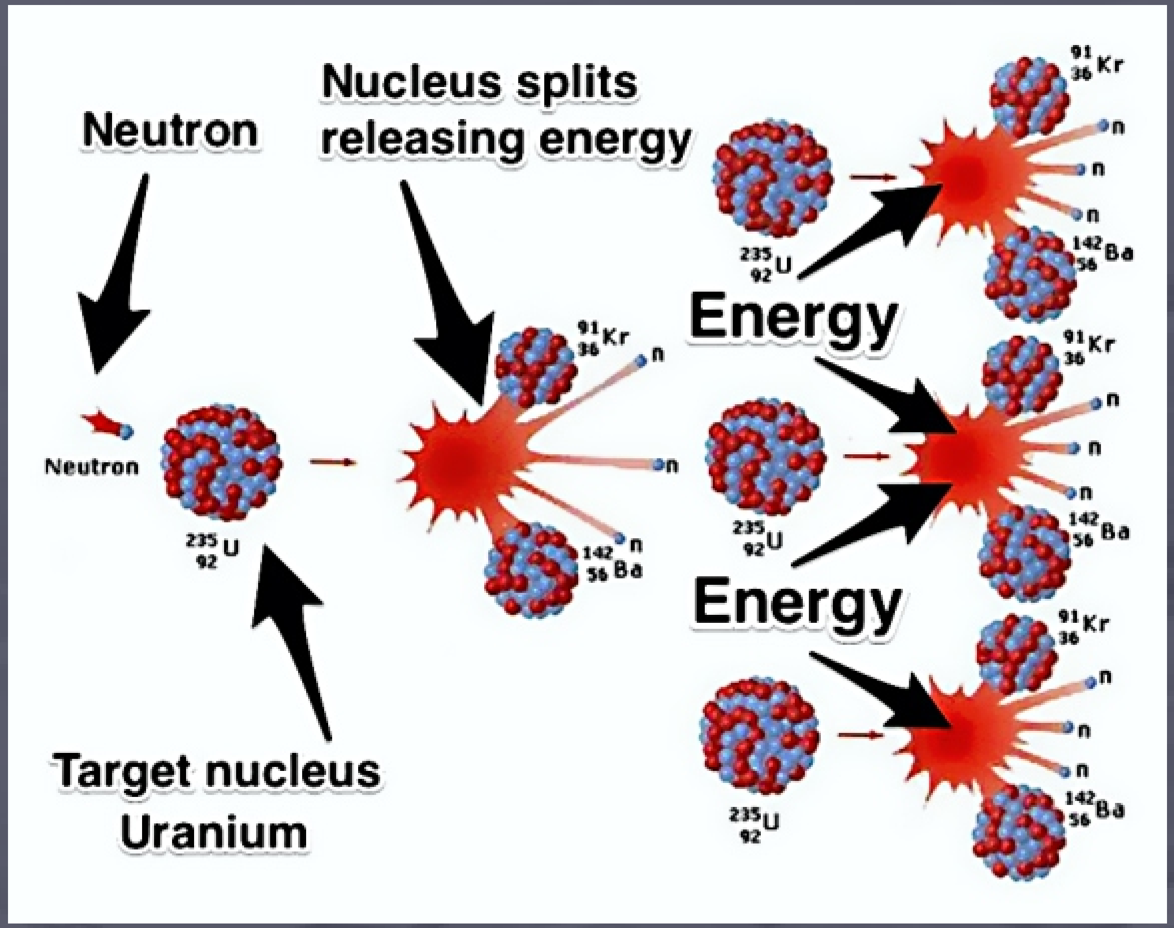


Unfortunately, most neutrons are wasted... twice → ESS !!!

- Traditionally (continuos sources), many experiments were performed by fixing initial state and scanning the selected final state. (TIME DEMANDING!)
- Modern pulsed sources with multi-detectors allow to measure 'everything' in one measurement.

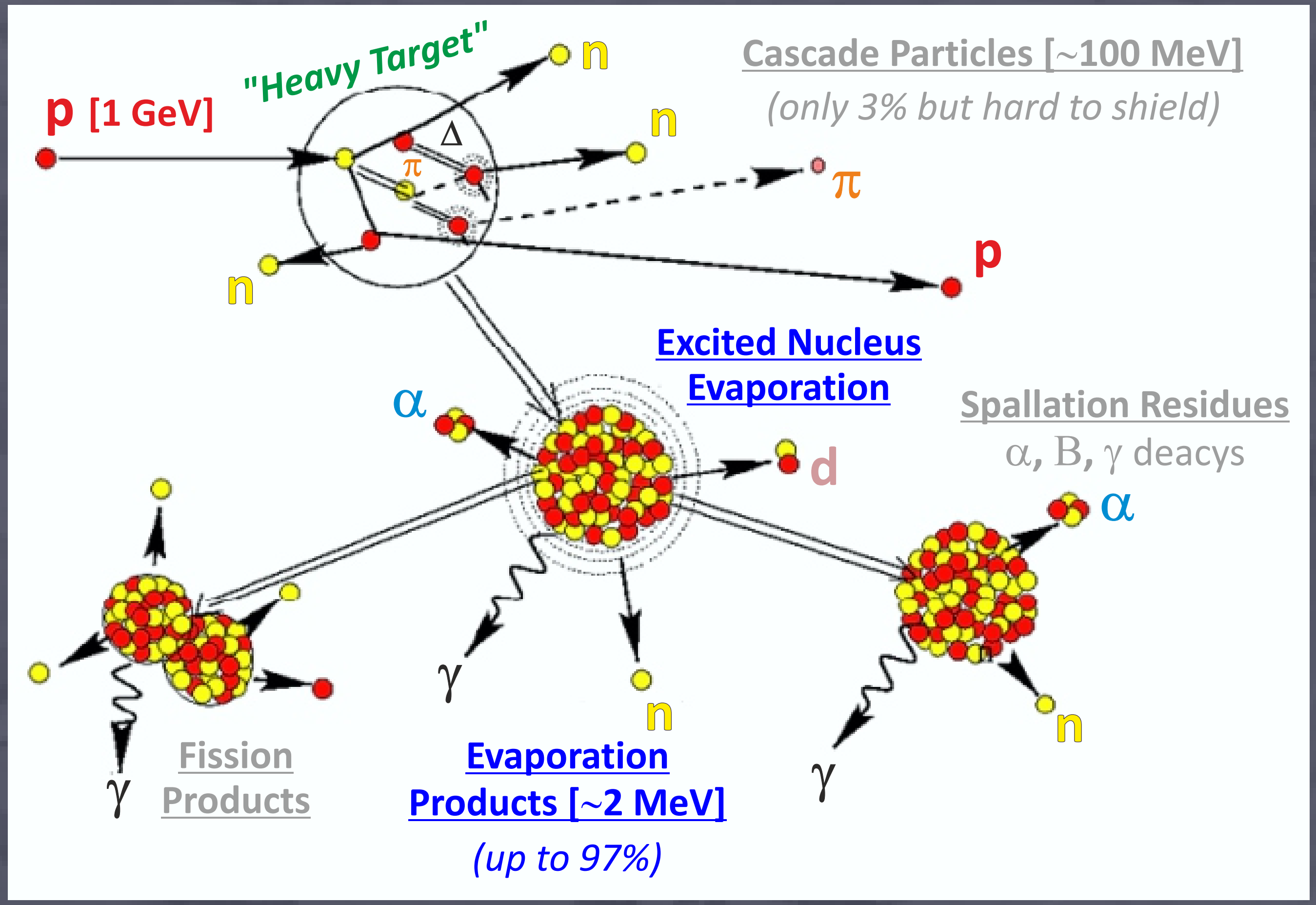
Neutron Production

Soon to be the past
Reactors (fission)



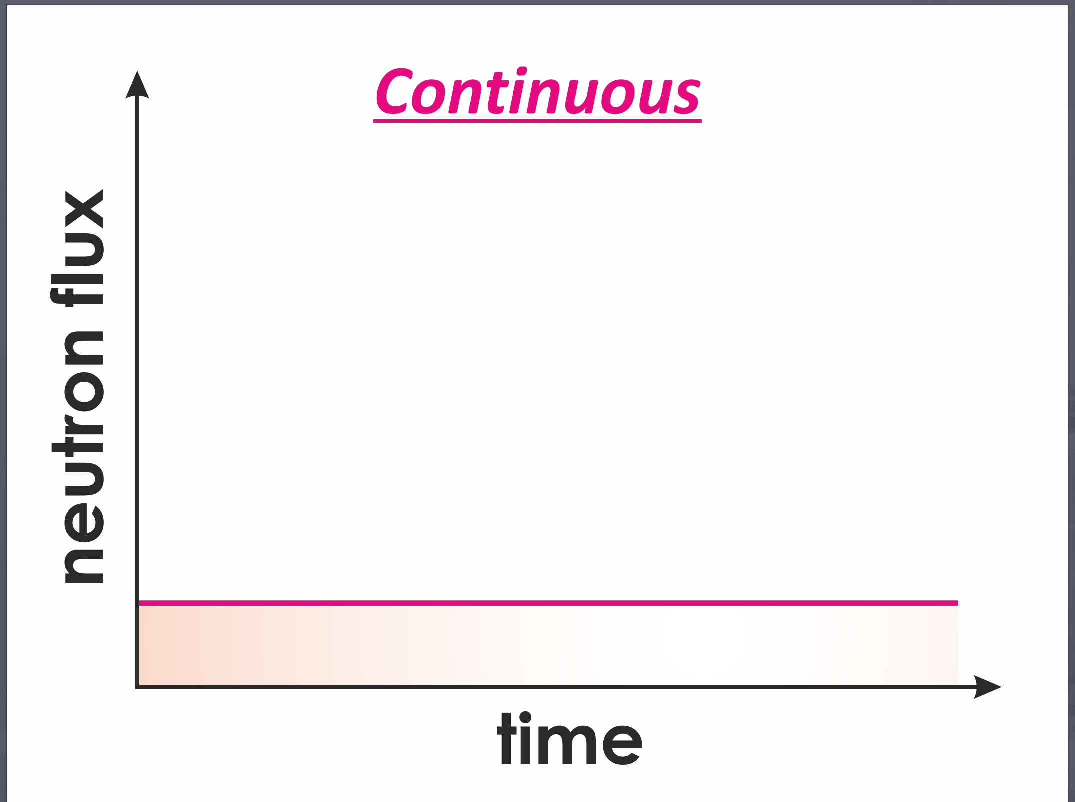
- Energy per neutron ~180 MeV
- High and continuous flux
- Waste a lot of neutrons in ToF
- Rare beam down, but if...
- Safety / Politics complicated

Future already here
Spallation Sources

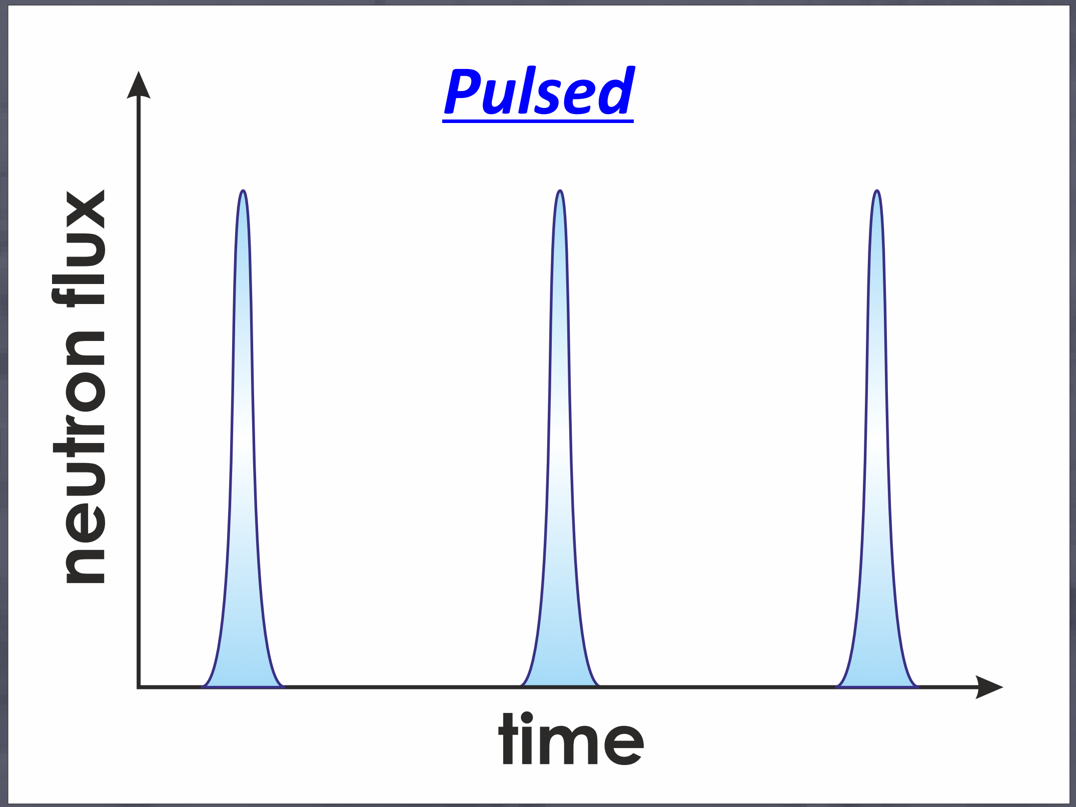


- Energy per neutron ~20 MeV
- 10 times higher brightness / unit heat
- "External power source" needed
- Beam dumps but quicker recovery (?)
- Safety / Politics much easier

Continuous vs. Pulsed Sources



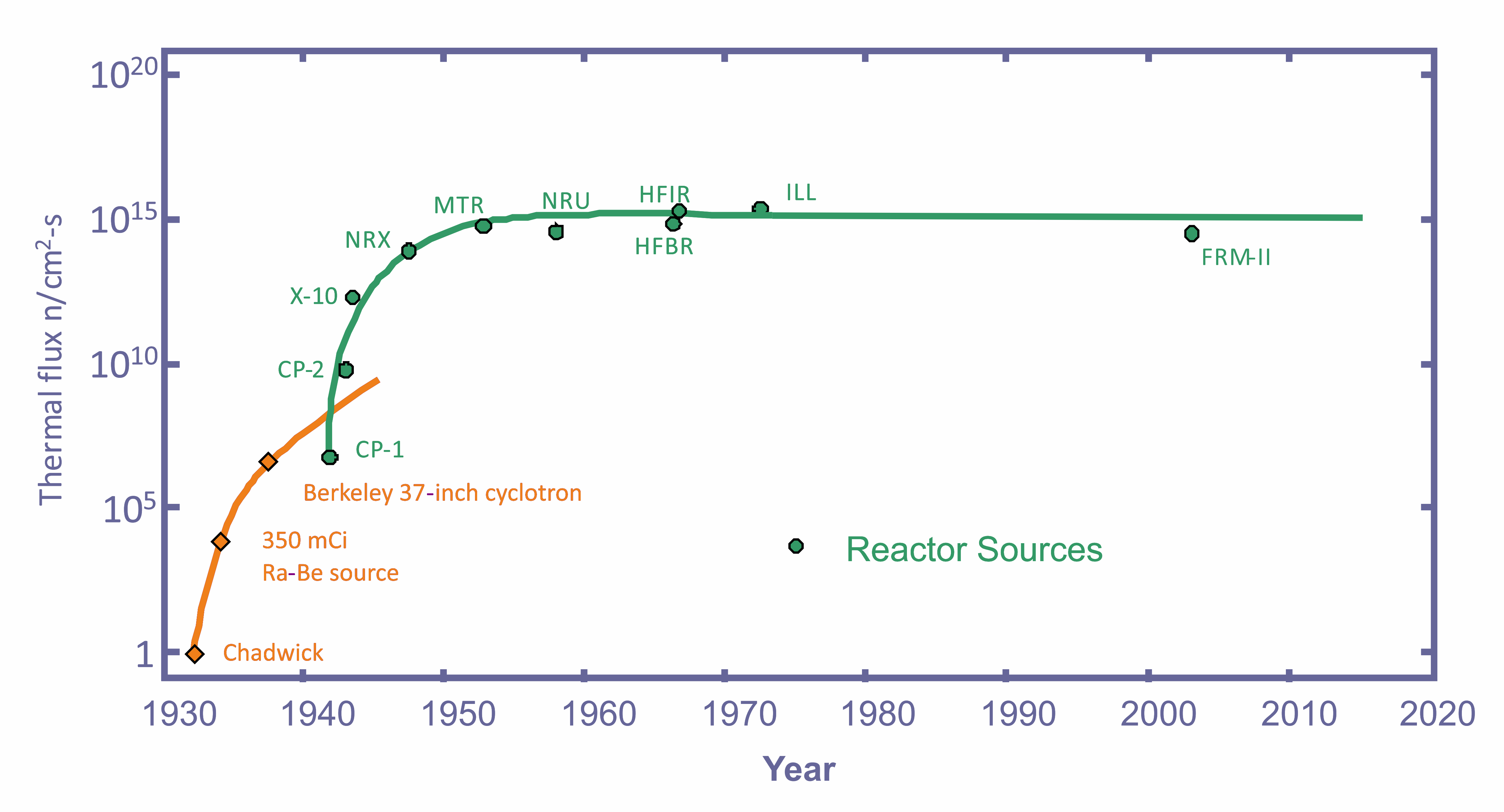
- Optimized for average flux
- Good enough for most applications
- Fission neutrons easier to shield
- Easy to build compact and simple instruments
- Simple electronics / data
- Tried and tested ('Old School')



- Optimized for peak flux and pulse shaping
- Better for most applications
- Cascade neutrons hard to shield
- Instruments long, advanced and expensive
- Very fast electronics and huge data sets
- Still developing ('The Future')

Historical Source Development

- Traditional reactor sources have reached a plateau since many years



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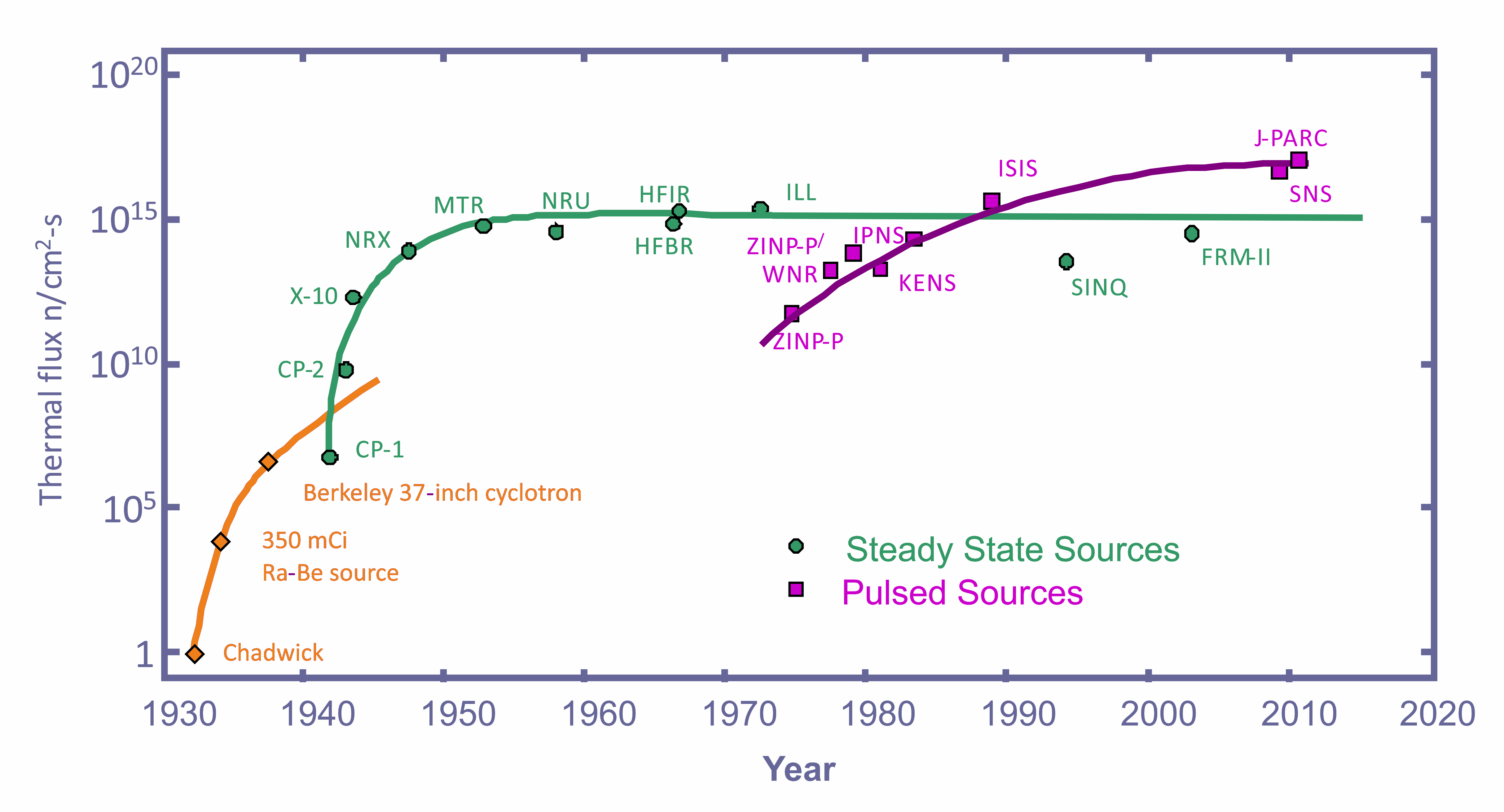

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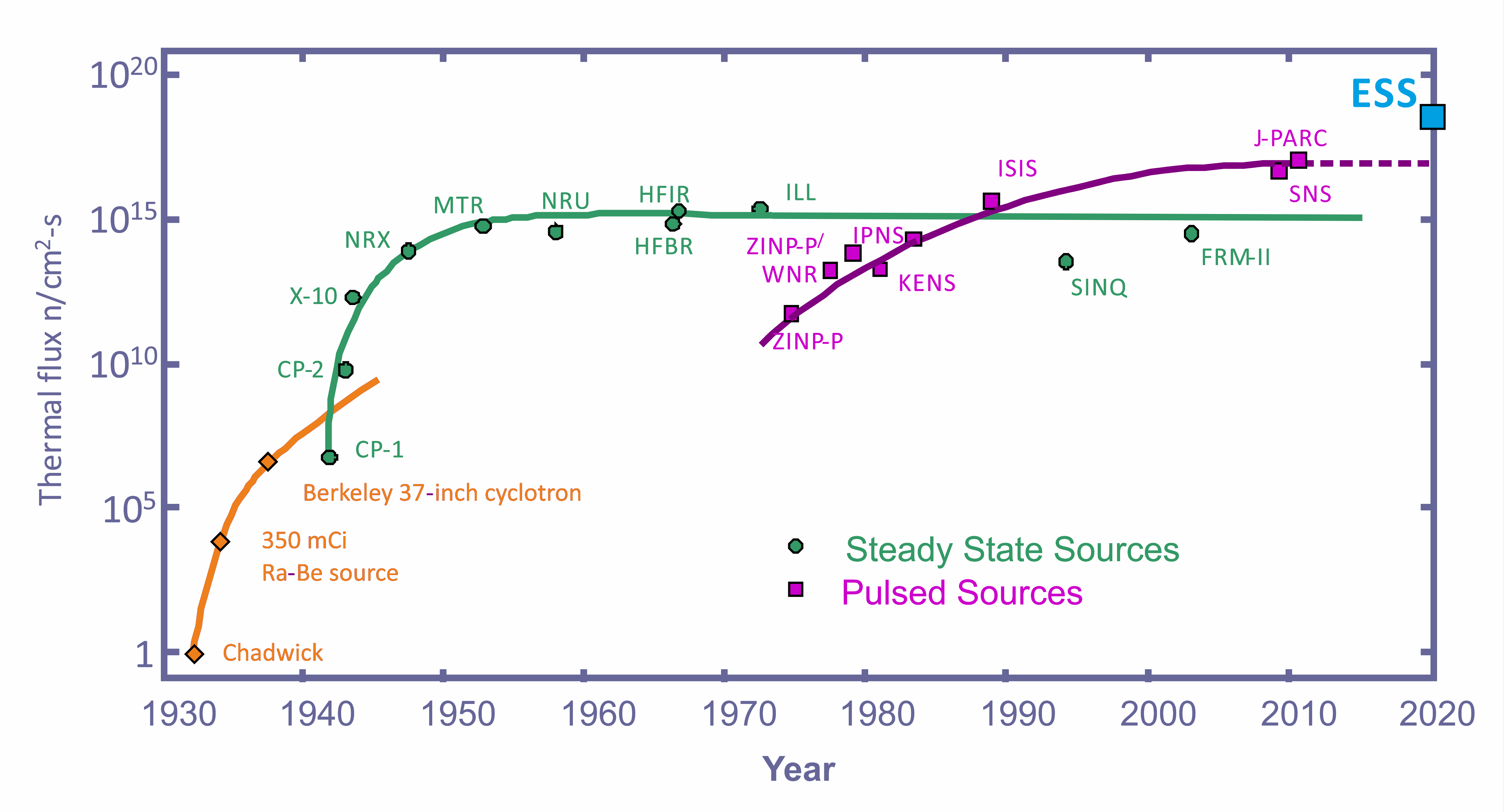
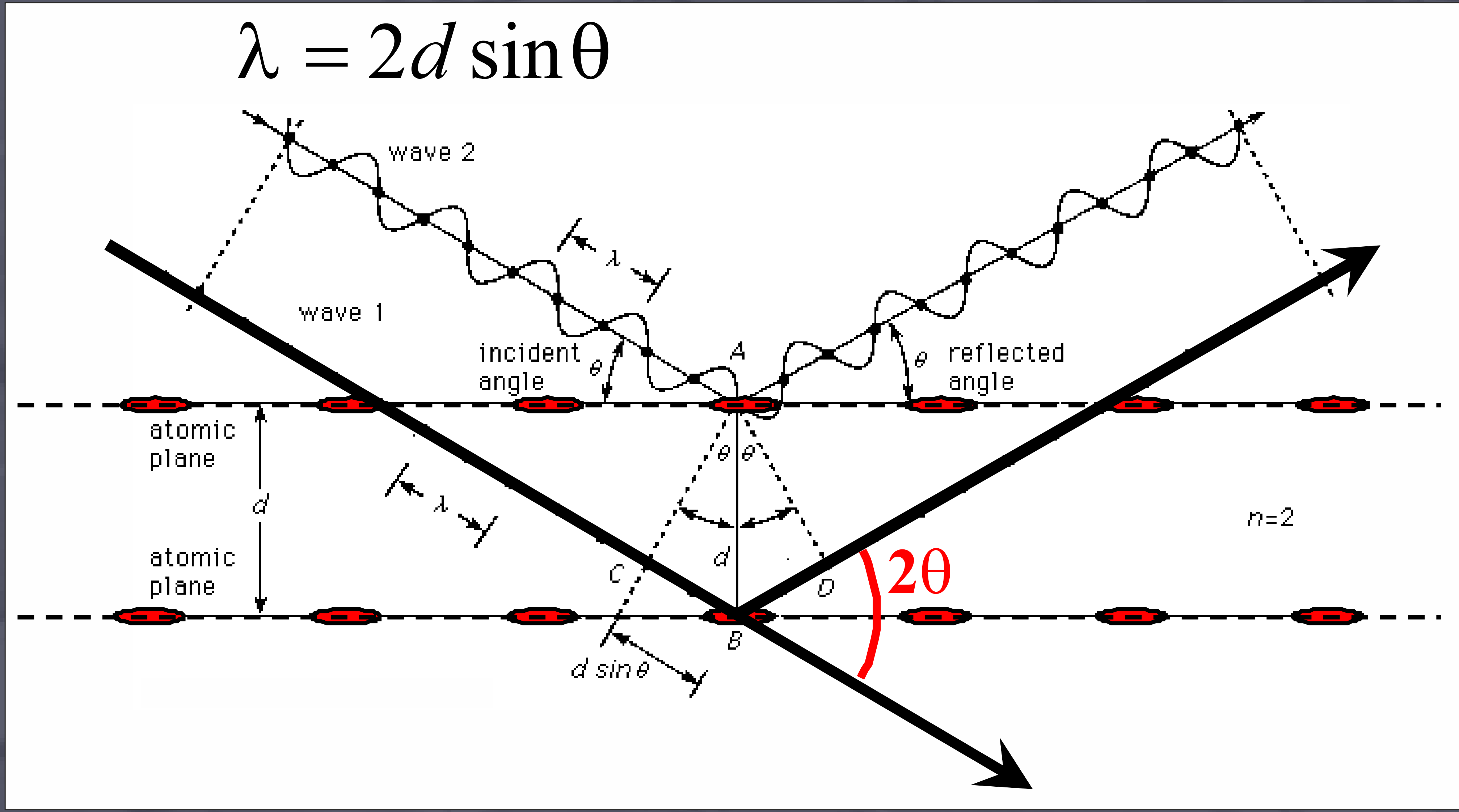


- Hope surpass such trend with new technological developments at ESS !!!

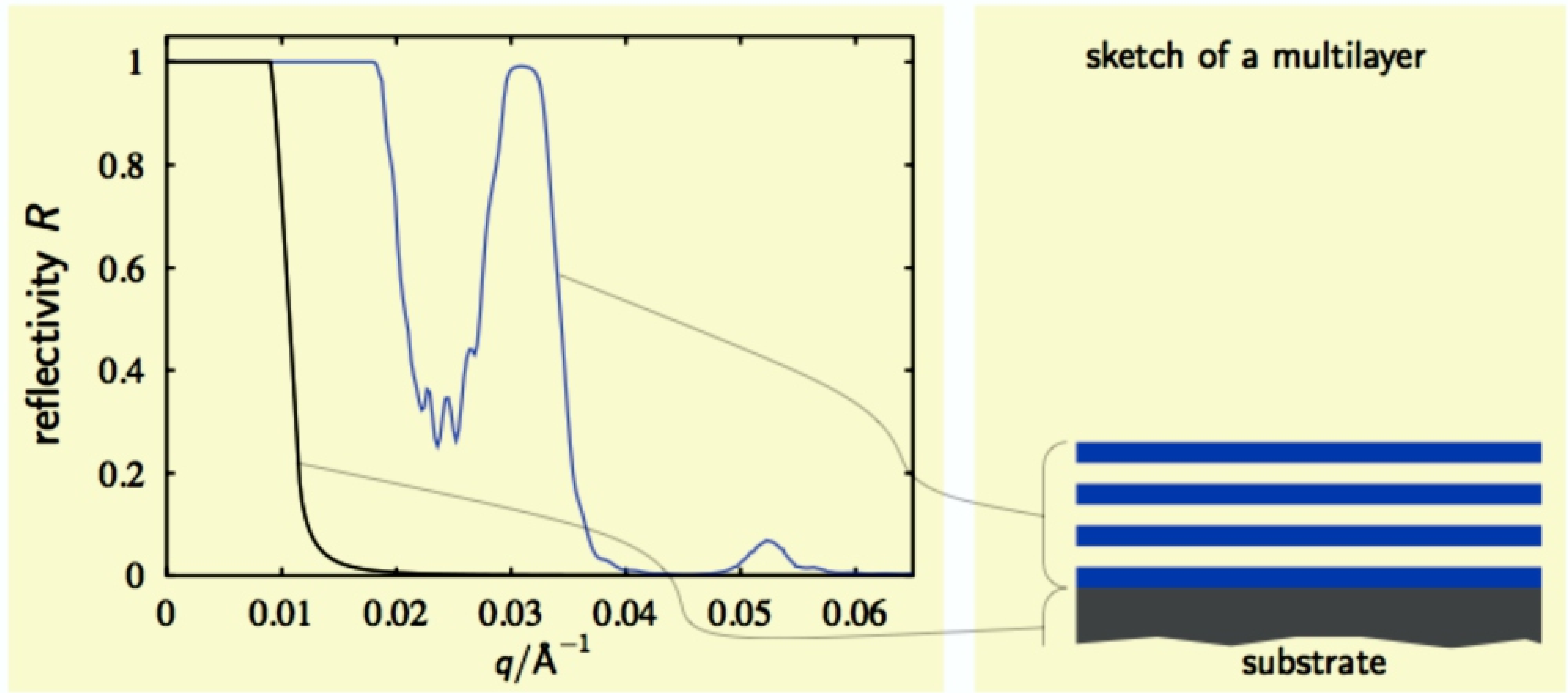
Neutron Guides

- Neutrons are neutral i.e. they are hard to manipulate
- However, neutrons can scatter *e.g.* on atomic planes (Bragg's Law)



Neutron Super Mirrors

- Use "artificial atomic planes" i.e. grow thin film multi-layers in order to guide the neutrons.
- Alternating layers of "transparent" (Ti) and reflecting (Ni) materials
- One set of multi-layers only scatter (reflect) a certain range of neutrons.



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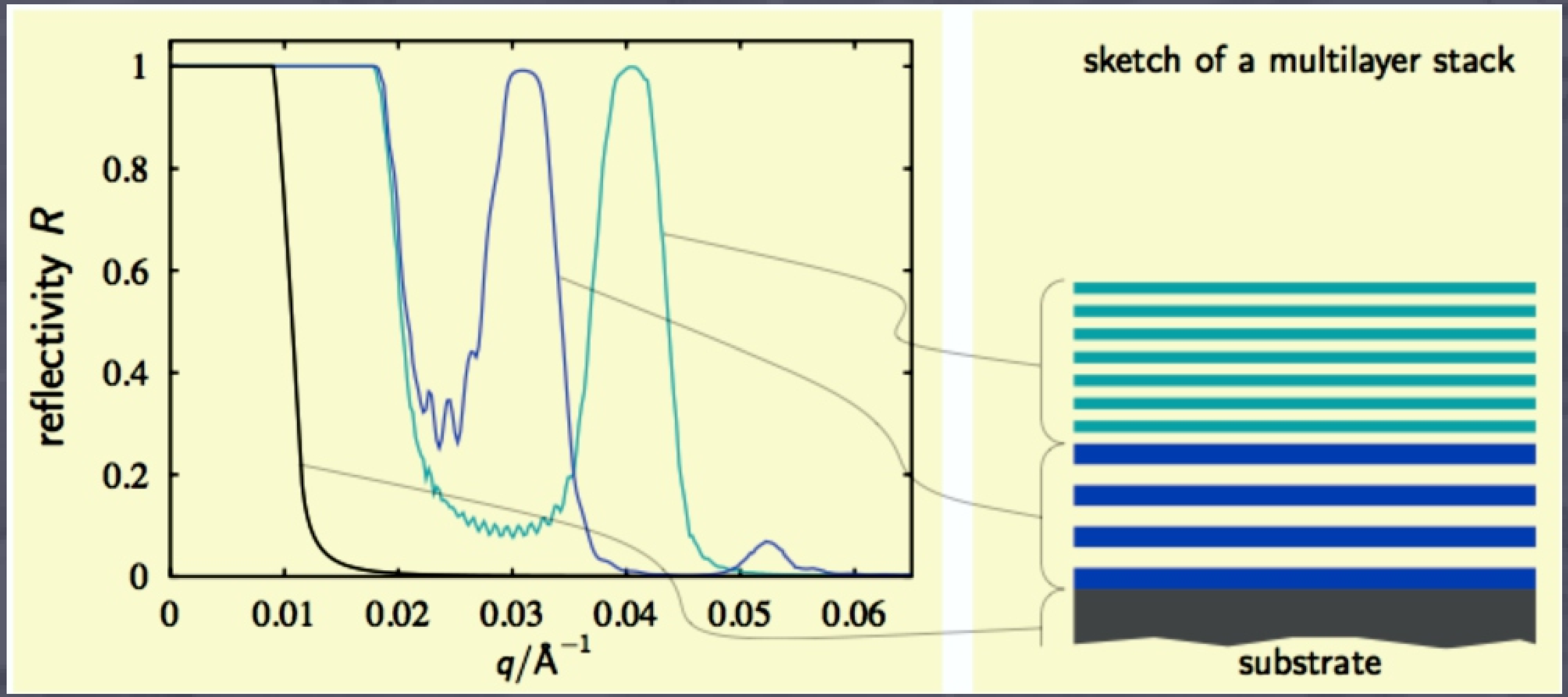

- So we grow several different multi-layers on top of each other in order to guide a broader band-width of neutrons.

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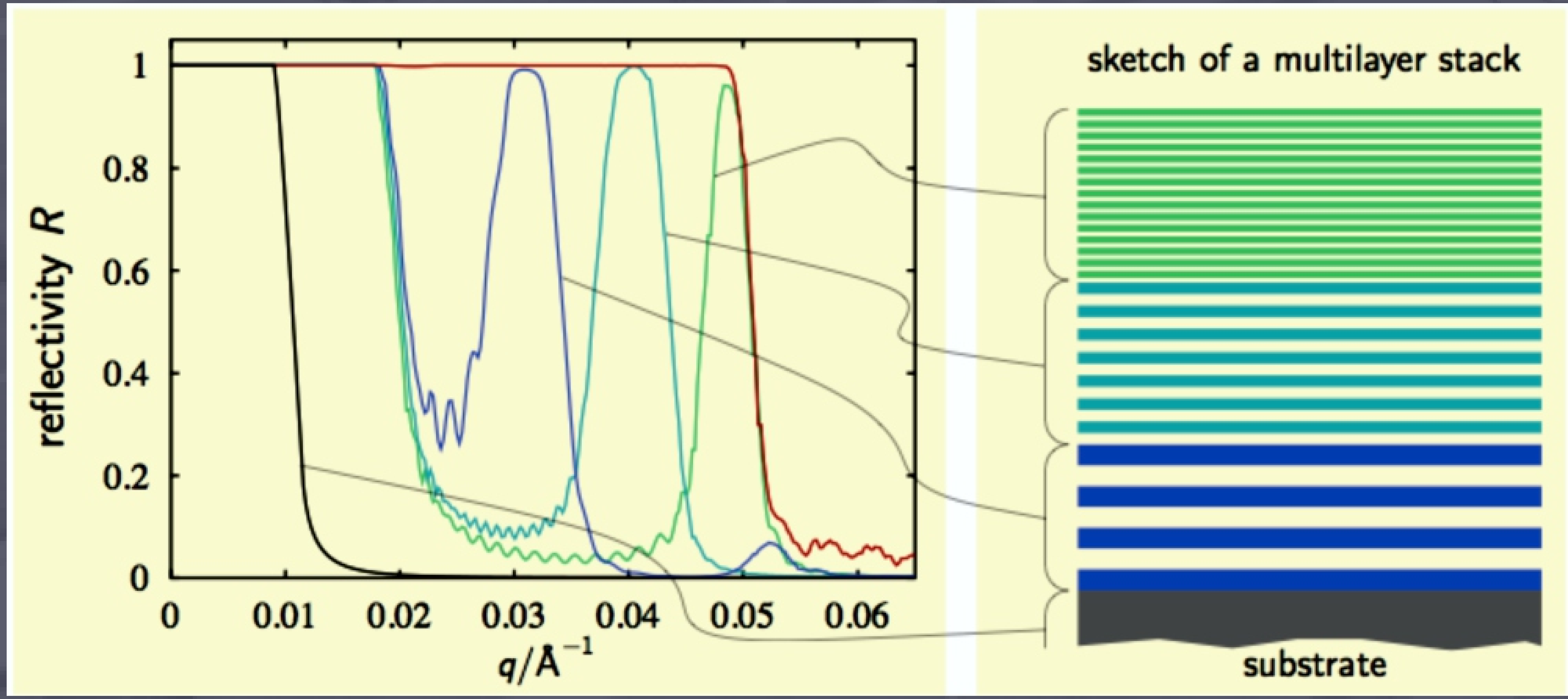

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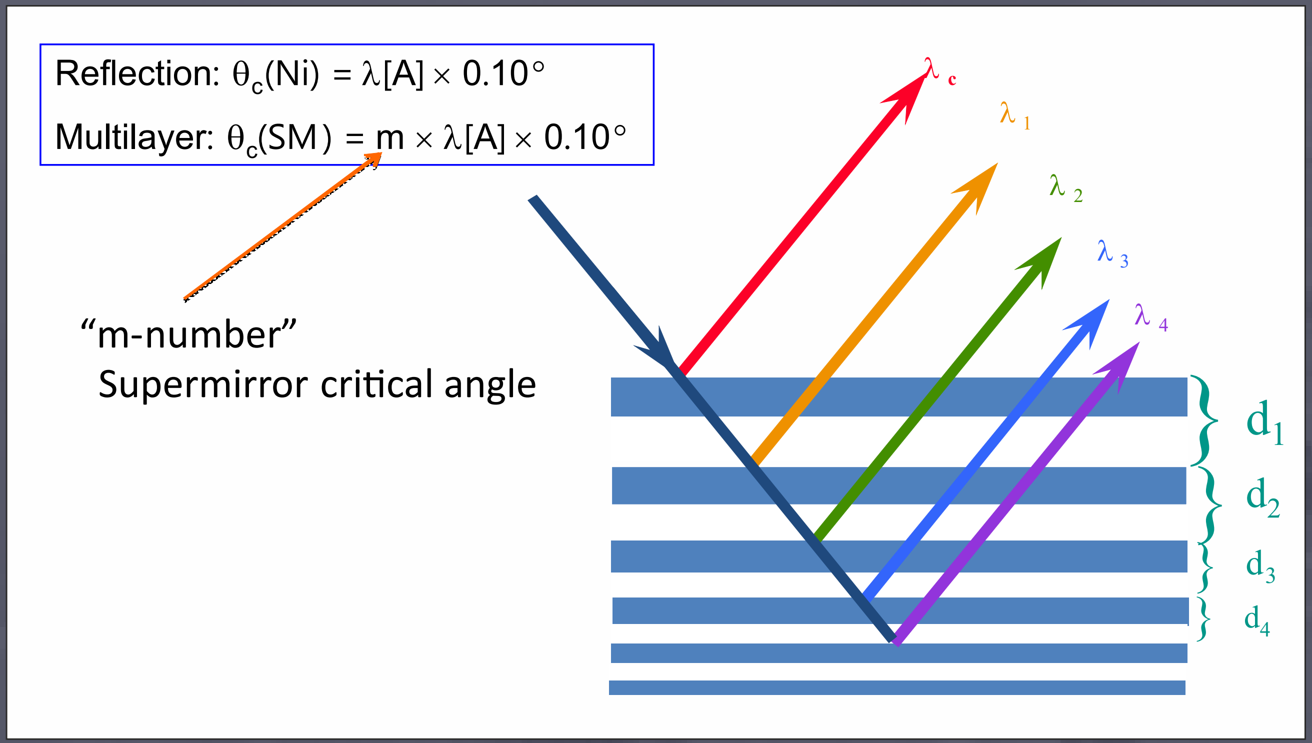
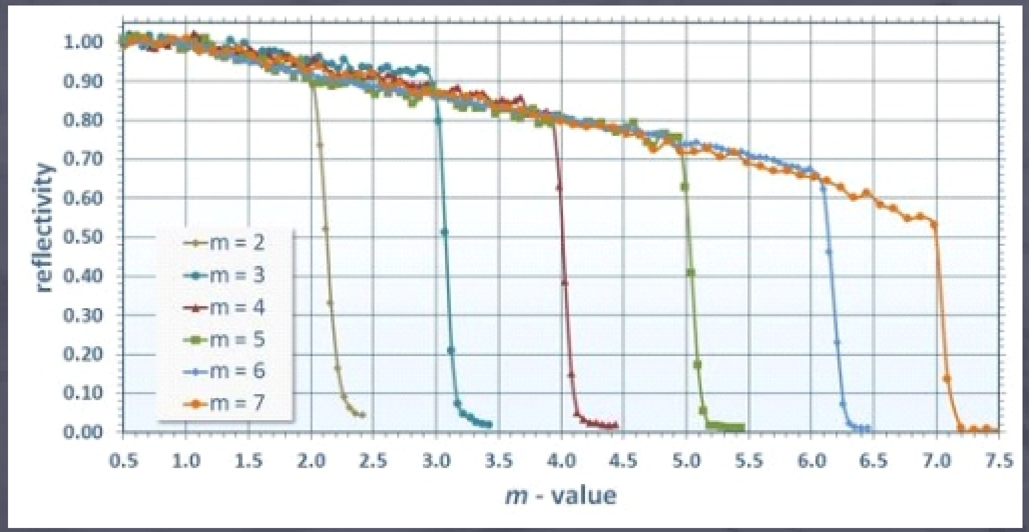
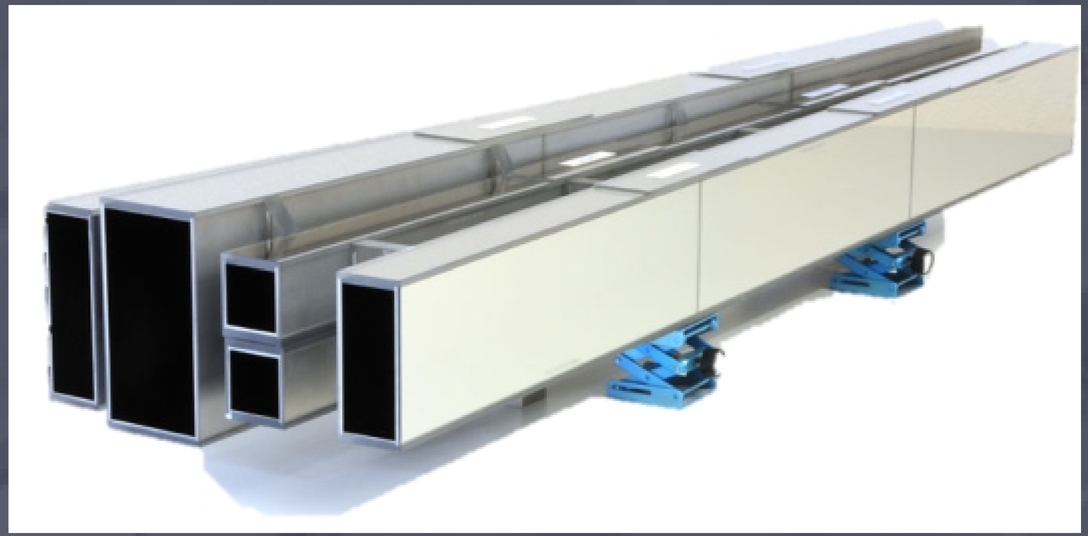
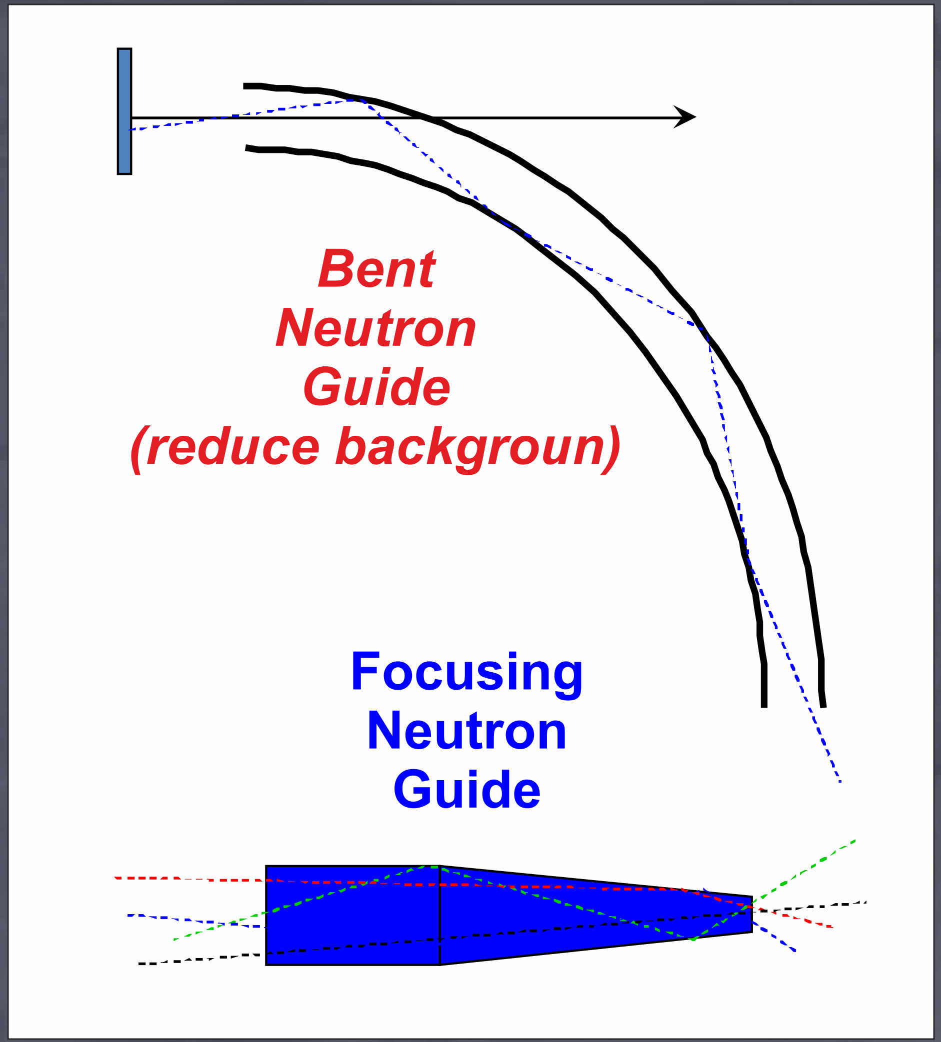
Neutron Super Mirrors





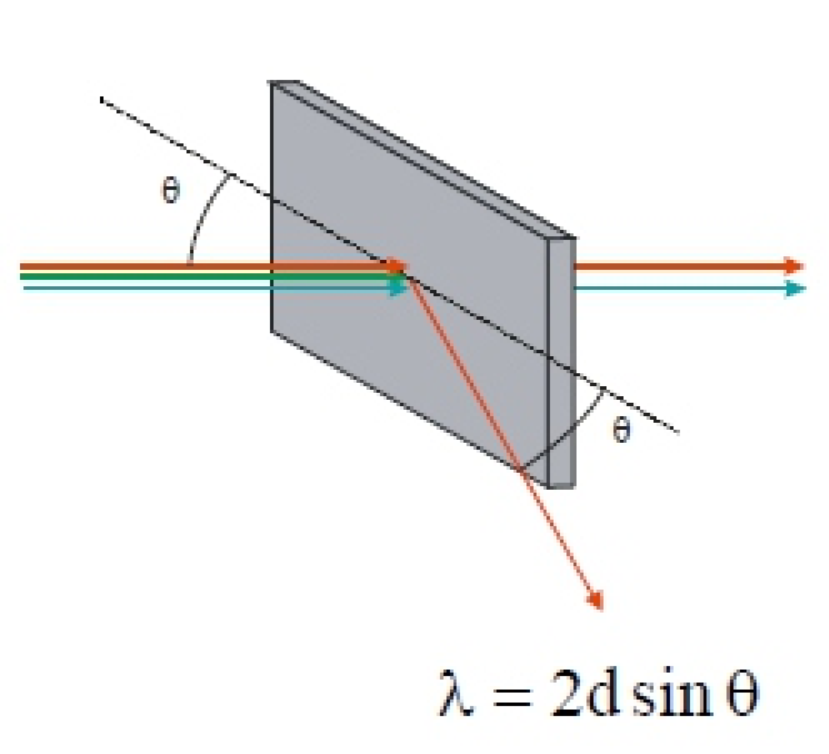




- **Neutron guides can also be focusing, "bending" (to reduce background) or even polarizing!**

Defining E: Crystal Monochromators

- Same idea as supermirrors but use single crystals of pure materials.
- Several very carefull co-aligned crystals are put together into a monochromator.
- Angle and crystal type selects the out-going neutron energy
- Can be made to also focus the beam.



Material	d-spacing
Ge [333]	1.089 Å
Be	1.79 Å
Cu [200]	1.807 Å
Si [111]	3.14 Å
Graphite/PG [002]	3.355 Å
Mica [002]	9.98 Å

Graphite [002]

Copper [200]

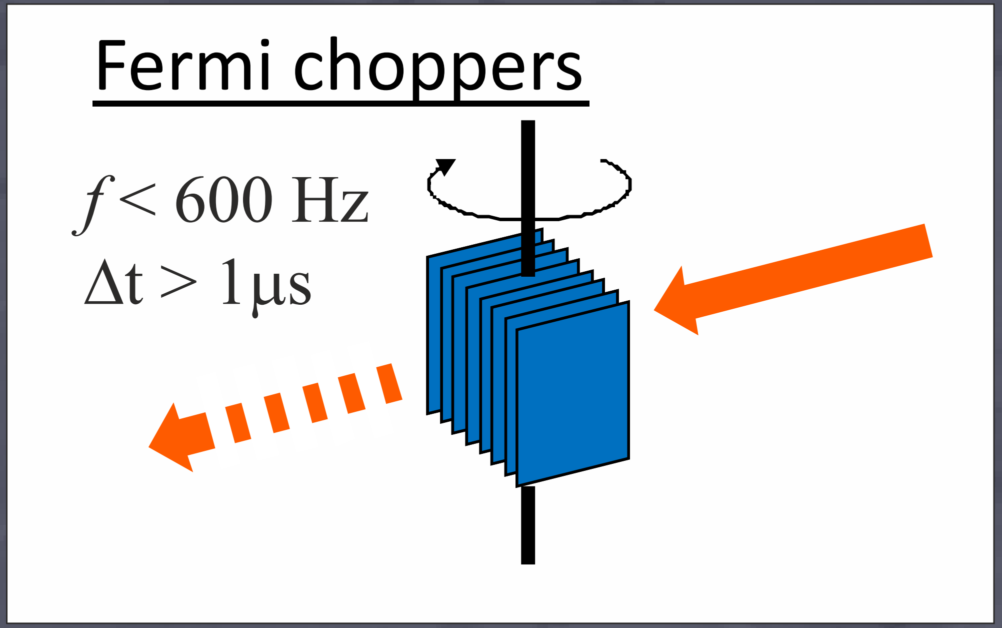
- Mainly used in the "old type" of reactor/continuous neutron sources.

Defining E/t: Neutron Choppers

- Another way to select neutron energy is to use so-called **choppers**.
- Simplest form is a spinning disc made out of a neutron absorbing material with a gap that works as a velocity selector.

Choppers =  **velocity selector**

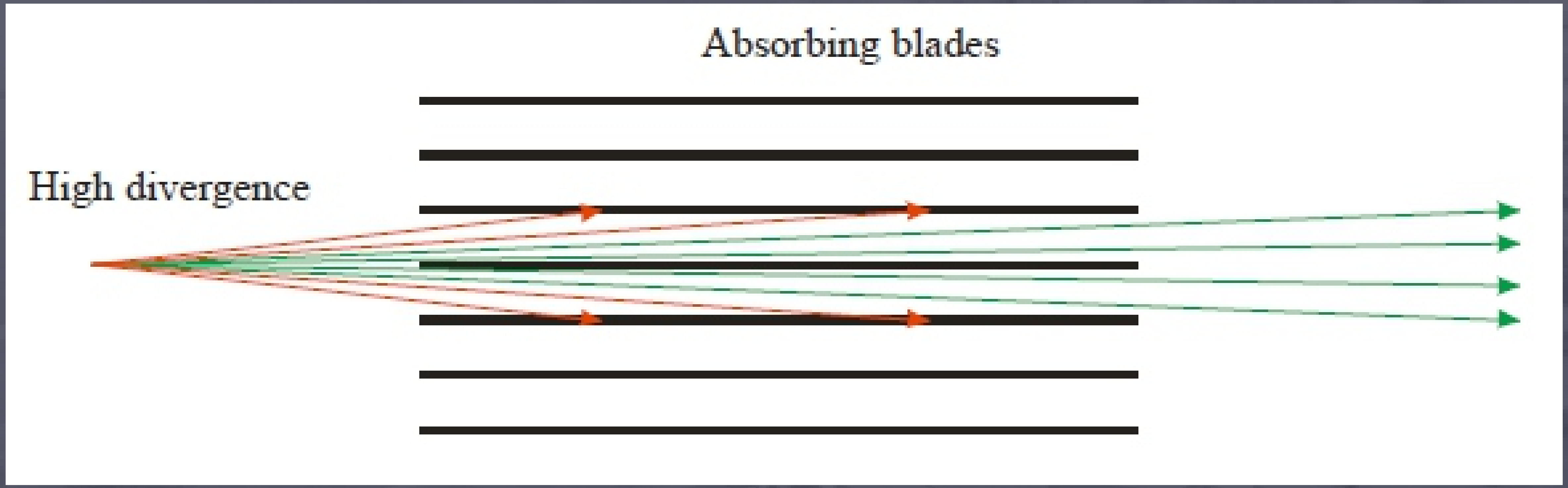
- Combining several choppers and controlling both their individual speed and phases allow to choose a narrow energy range (or several overtones)
- There are several other more complex chopper designs allowing to "shape" the neutron beam even more carefully.
- Can be used at any type of source but of course much more efficient for pulsed sources where "time = energy is used"



- ESS will have MANY MANY MANY choppers installed... will explain why a bit later in this lecture...

Defining "direction": Collimators

- **Slit collimators: of Al-plates with neutron absorbing coatings e.g. Gd**



- **Defined how accurate they are by 'minutes' (lower is better but more neutrons are lost = no free lunch!)**
- **Previously changed by hand, but now often controlled by motors/mechanics**
- **Also have radial collimators to avoid scattering from cylindrical sample environment (cryostats, magnets...)**

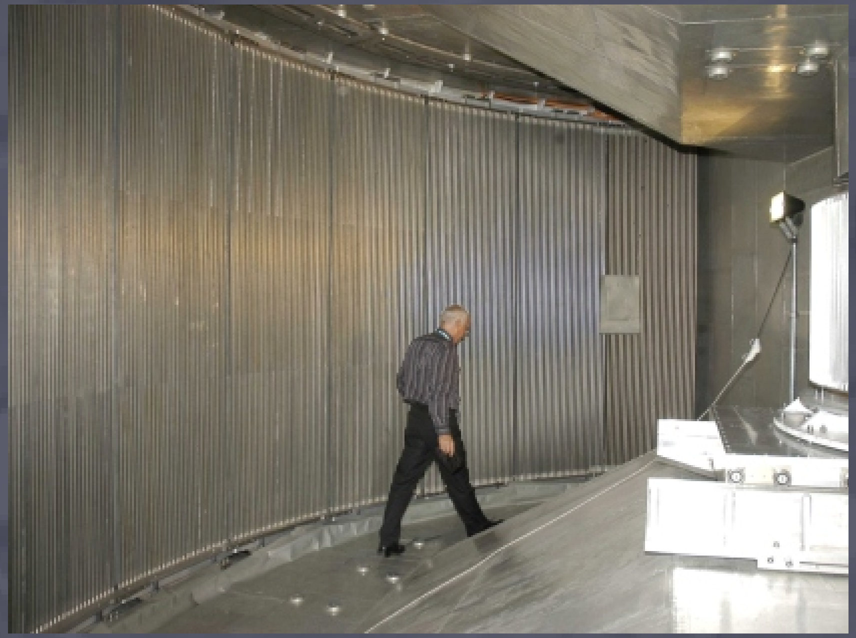
Detecting the Neutrons

- Neutral particle = hard to detect $\Rightarrow$ Need nuclear reaction.
- Two "old" technologies (^{3}He is most common):

^{3}He Tubes

$n + {}^{3}He \rightarrow {}^{1}P$ [570 keV] + ${}^{3}H$ [200 keV]

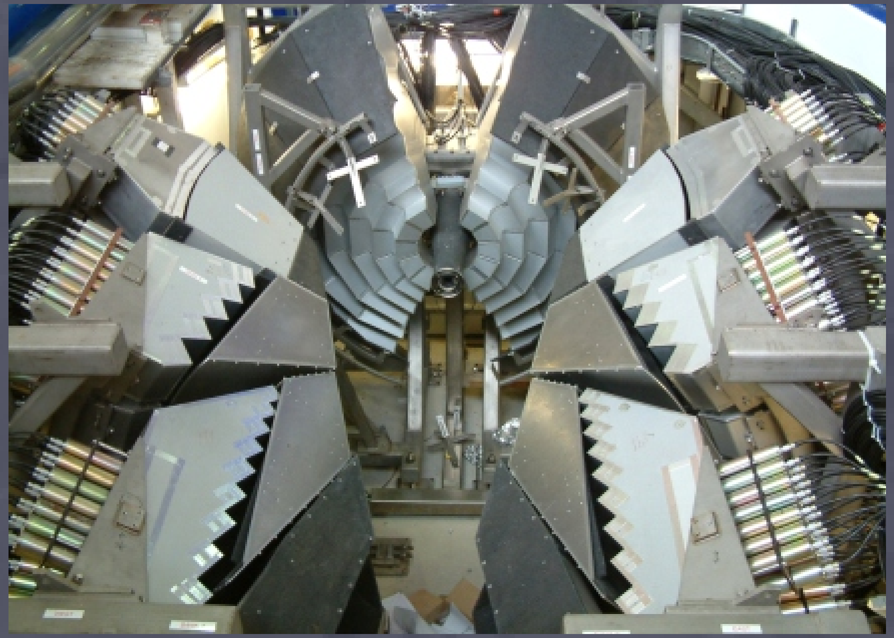
> 1mm resolution
High Efficiency
Low gamma sensitivity
Supply/cost problem!!!



Scintillators

$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79$ MeV

< 1mm resolution
Medium Efficiency
Some gamma sensitivity
Magnetic Field Sensitive!



- ESS would need about 25 000 liters of ^{3}He (2000 USD/liter = 500 MSEK!)

Detecting the Neutrons

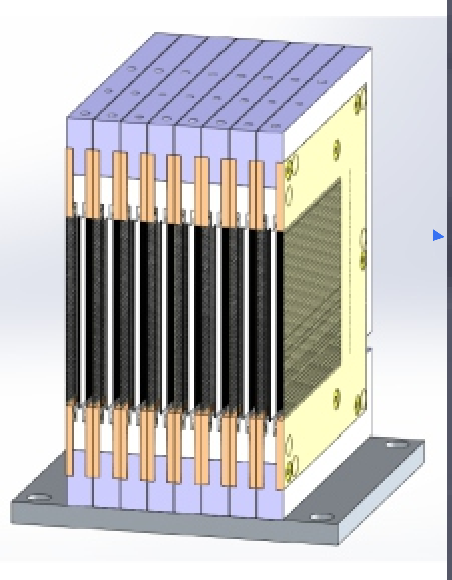
- New technology under development based on ^{10}B:

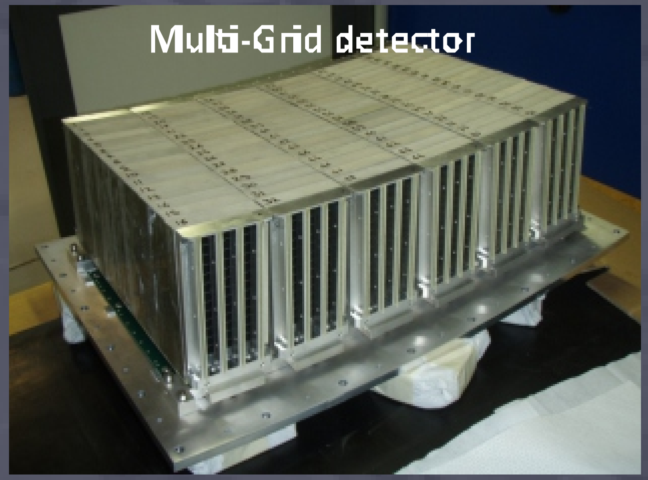
^{10}B Detectors

$n + {}^{10}B \rightarrow {}^{4}He\ [1.5\ meV] + {}^{7}Li\ [830\ keV] + \gamma$

<<< 1mm resolution
70% Efficiency of ^{3}He
10B is abundant (20% of natural B)
New Technology under development!!!

- ~1 μm thin solid ^{10}B-containing layer (α and 7Li need to exit) ⇒ only 5% efficiency ⇒ multi-layers and multisegment / blades





- Use $^{10}B_4C$ since it is mechanically, chemically & thermally very stable

- Big development program and production at LiU for ESS

Linköping University

The Neutron Scattering Experiment

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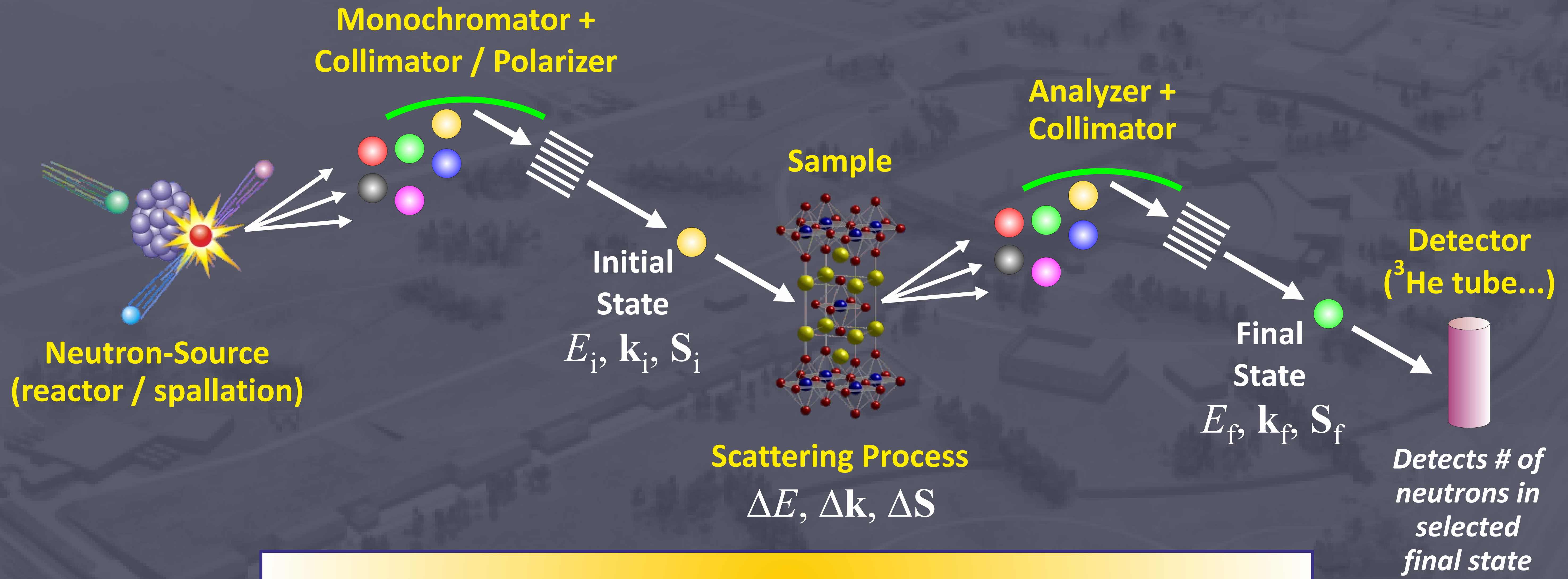
- **Solution**: Use ‘filters’ *e.g.* monochromator, collimators and analyzer



Unfortunately, most neutrons are wasted... twice → ESS !!!

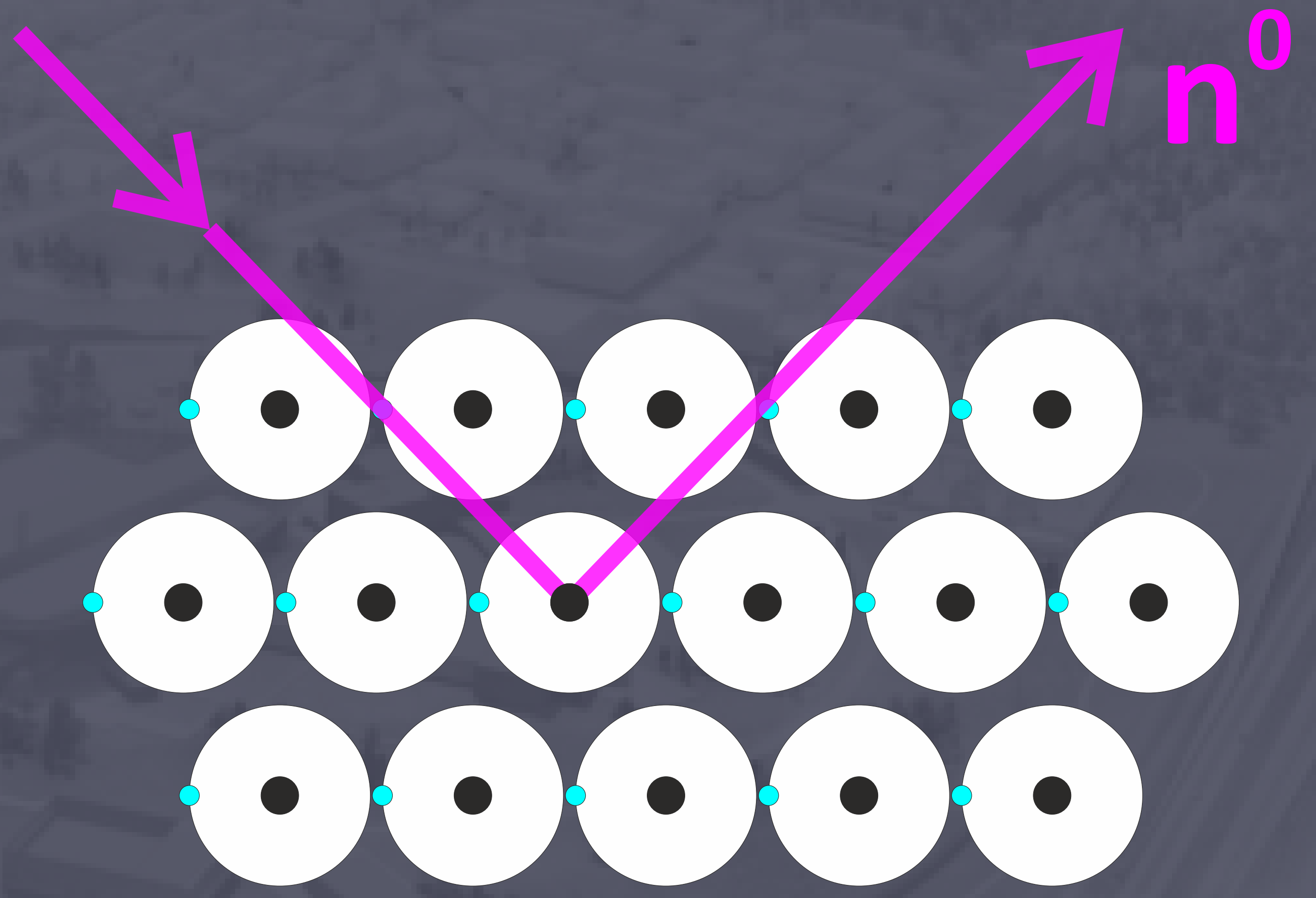
- Traditionally (continuos sources), many experiments were performed by fixing initial state and scanning the selected final state. (TIME DEMANDING!)
- Modern pulsed sources with multi-detectors allow to measure ‘everything’ in one measurement.

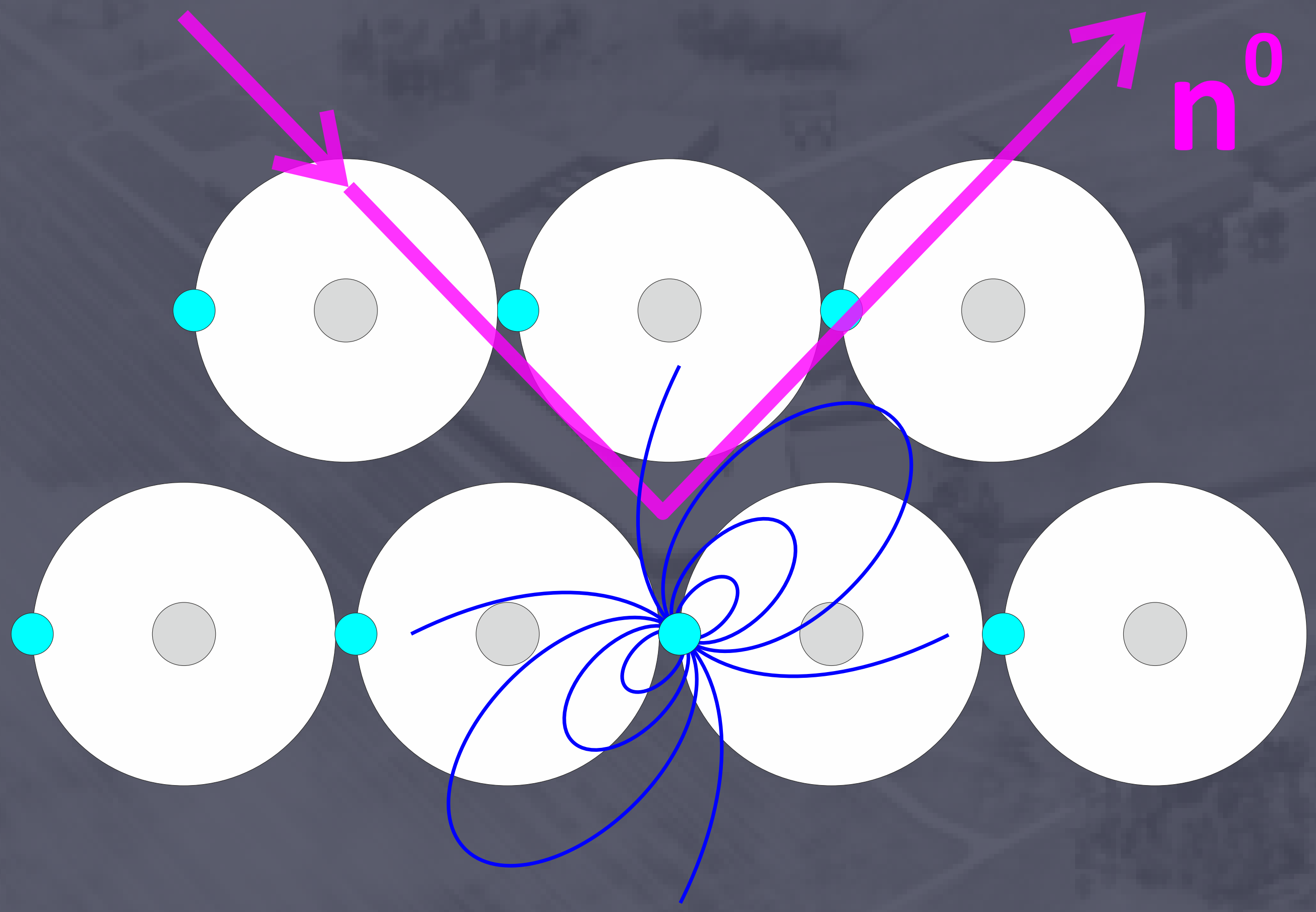
Neutron Interaction with Matter

- Neutrons interact strongly with atomic nuclei on a very short length scale (fm) = "point-like" interaction

- Neutrons see crystal structure, density correlations & excitations (*e.g.* lattice vibrations).

- *"Show us where atoms are and how they move"*





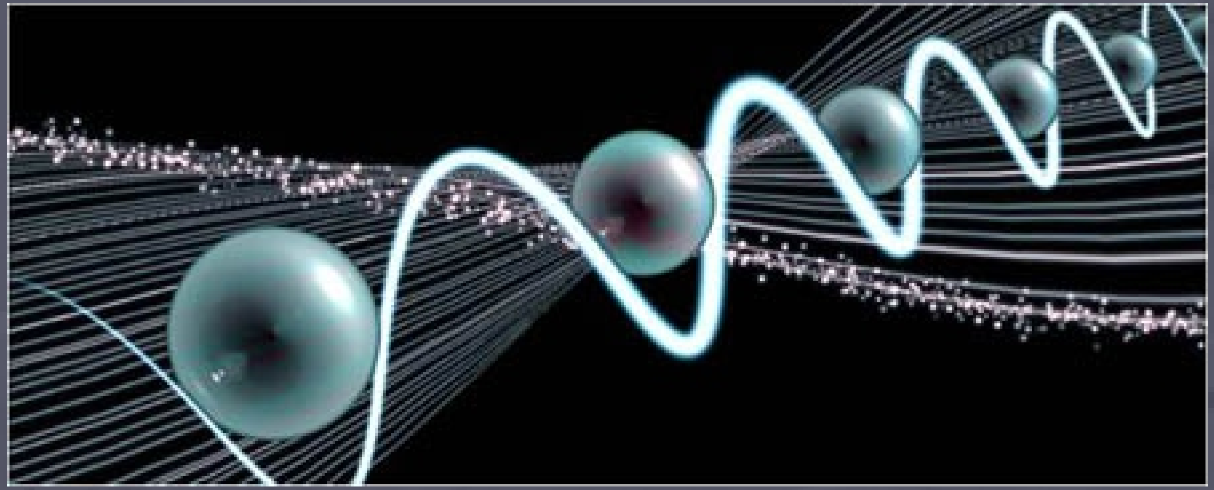
- Neutrons also interact with unpaired electrons via a weaker magnetic dipole interaction.

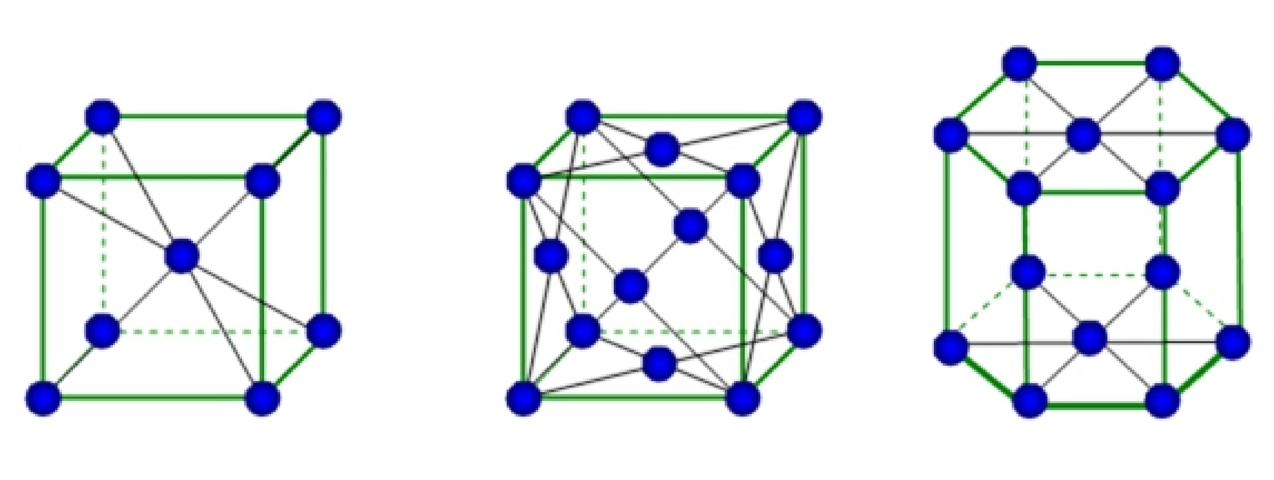
- Neutrons see magnetic structures, spin waves and other magnetic excitations.

- *"Show us how spins align and what they do"*

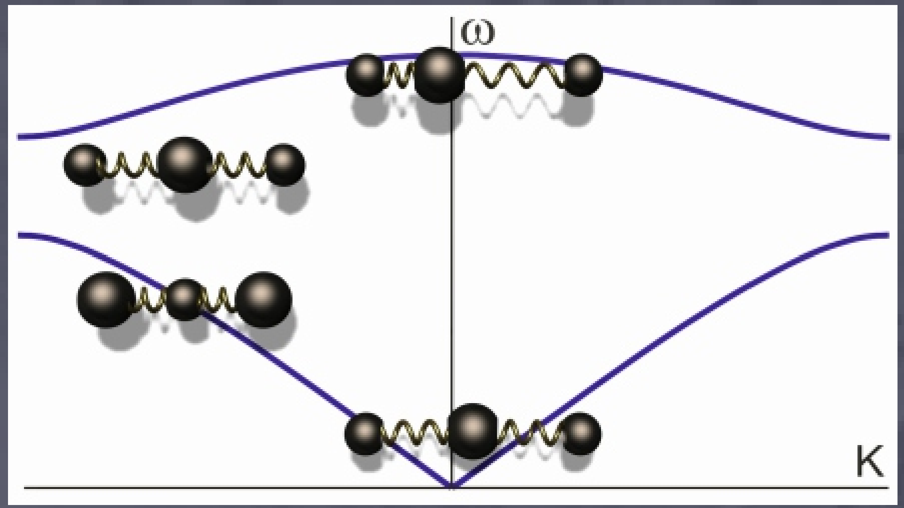
Why is NS Optimal for Probing Materials (I) ?

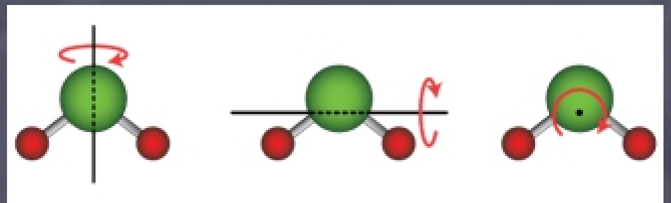
- Strong nuclear scattering AND magnetic scattering
- Neutron wave-length is approximately ”a few Ångström” (~1-30 Å)
- Same length-scale as interatomic distances = ideal probe for atomic lattices, molecules & spin-order!

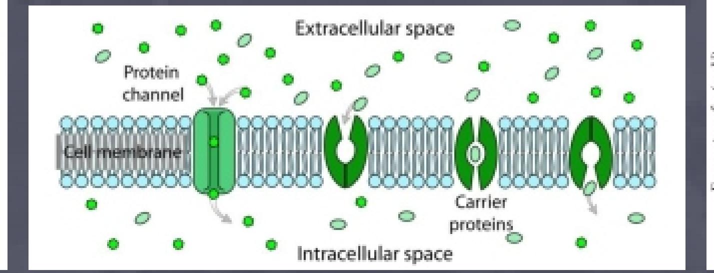


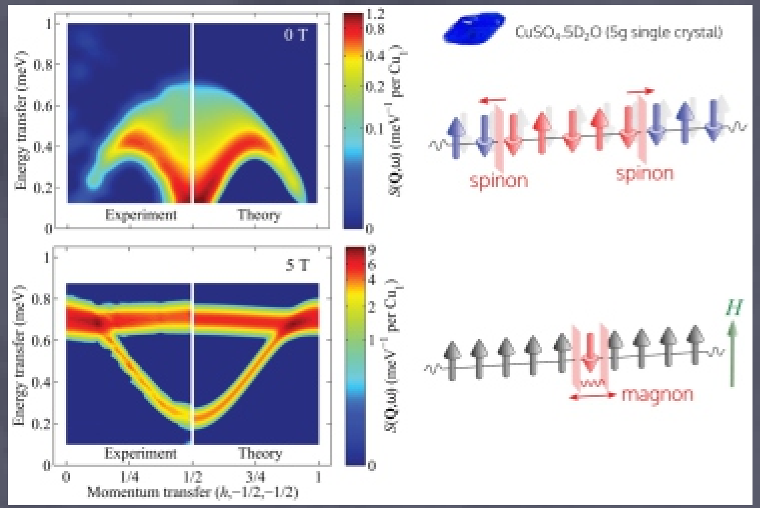


- Neutron mass yields that such wave-length equals an energy of 0.1 - 100 meV (’*chicken-egg*’)
- This energy-scale fits perfectly to many atomic/molecular/spin excitations: phonons, molecular dynamics, ion diffusion, magnetic spinwaves/magnons



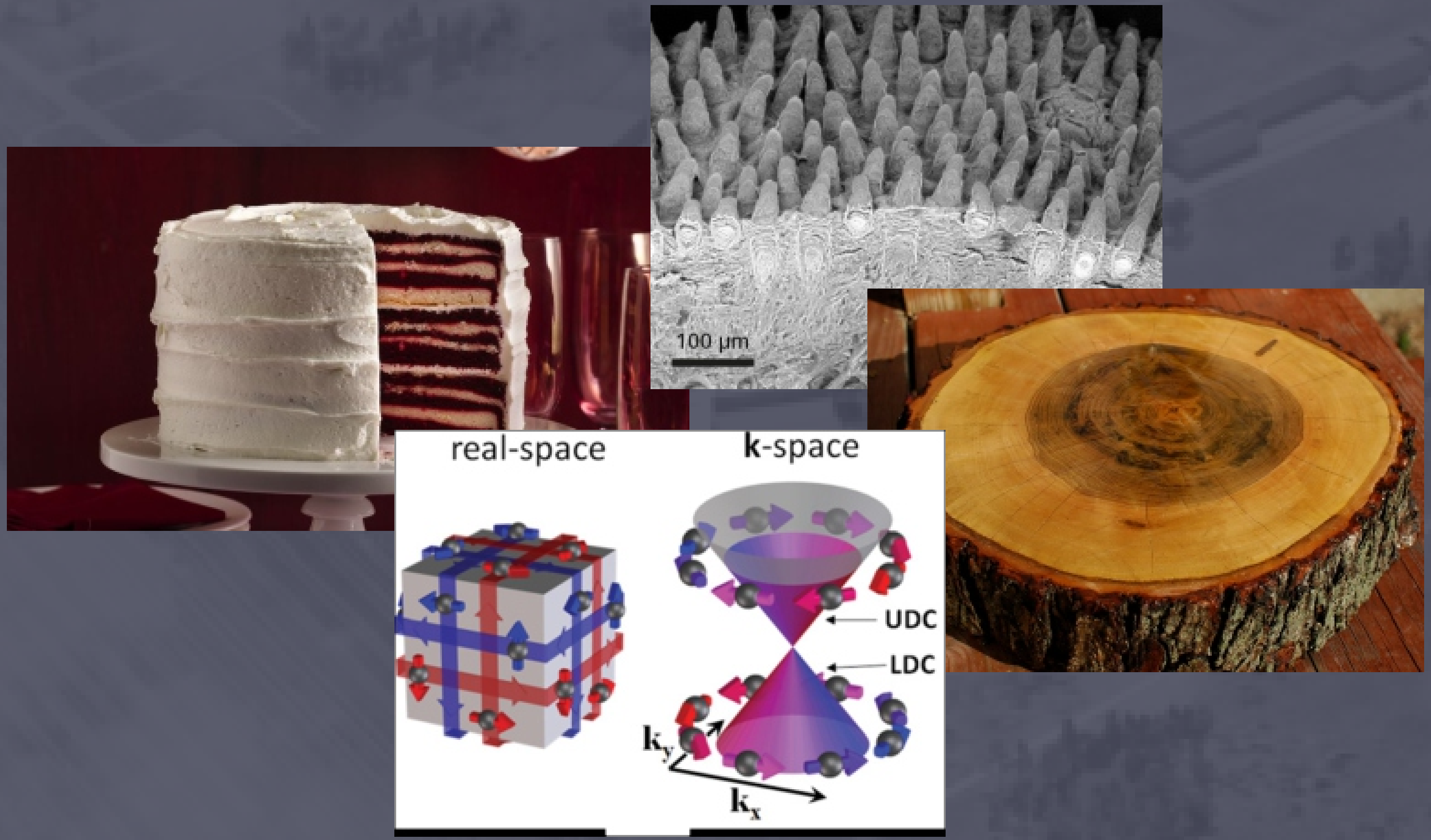


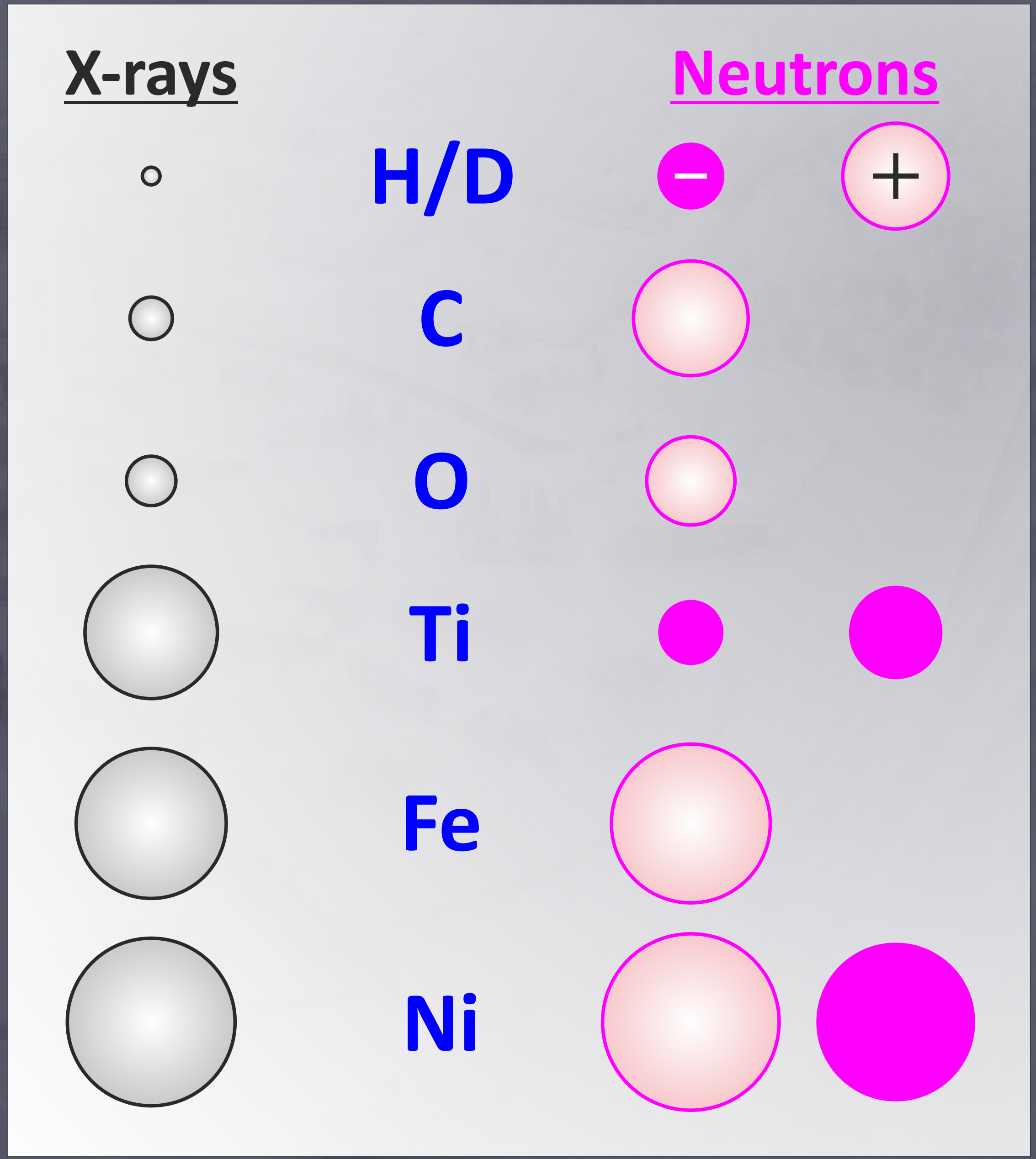




Why is NS Optimal for Probing Materials (II) ?

- Point-interaction with nuclei (not only e^-) →
- Possible to investigate also light elements, *e.g.* Hydrogen, which is more or less impossible with x-rays.
- Point-interaction → Q-independent form-factor (c.f. x-rays!)
- Neutral particle that penetrates → probe bulk (intrinsic material) properties as well as buried structures. [surface vs. bulk!!!]



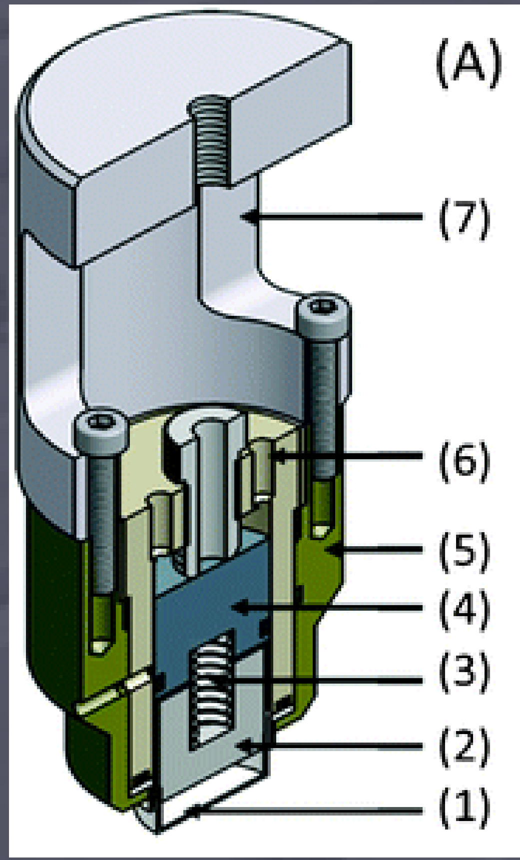


Scattering Strengths

- Some materials (*e.g.* Aluminium) are ‘transparent’ for neutrons → easy to make sample holders, containers for the experiment and also...

Why is NS Optimal for Probing Materials (III) ?

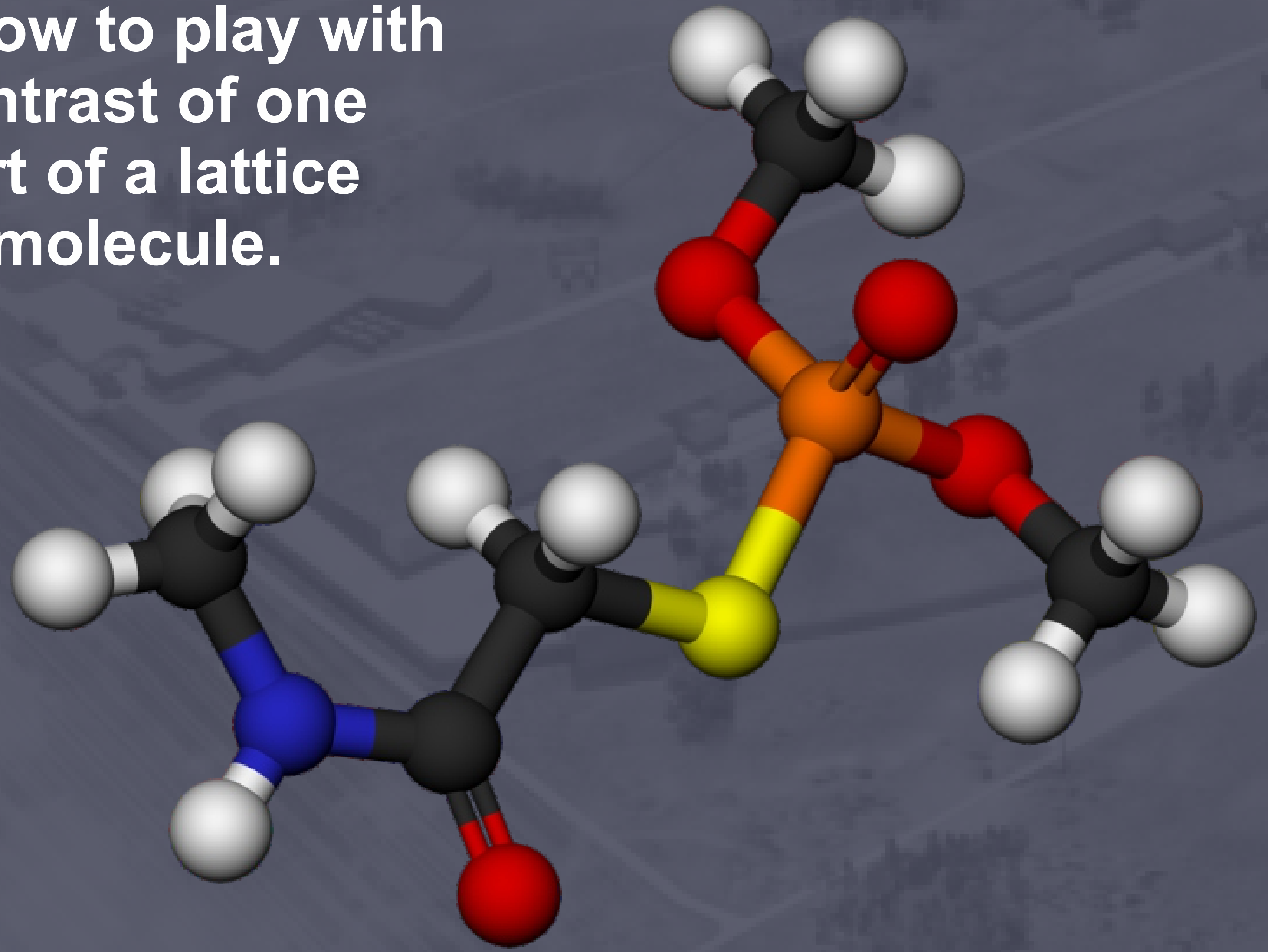
- Some materials (*e.g.* Aluminium) are 'transparent' for neutrons →
- Good materials for building sample environments (cryostats, magnets, pressure cells...).

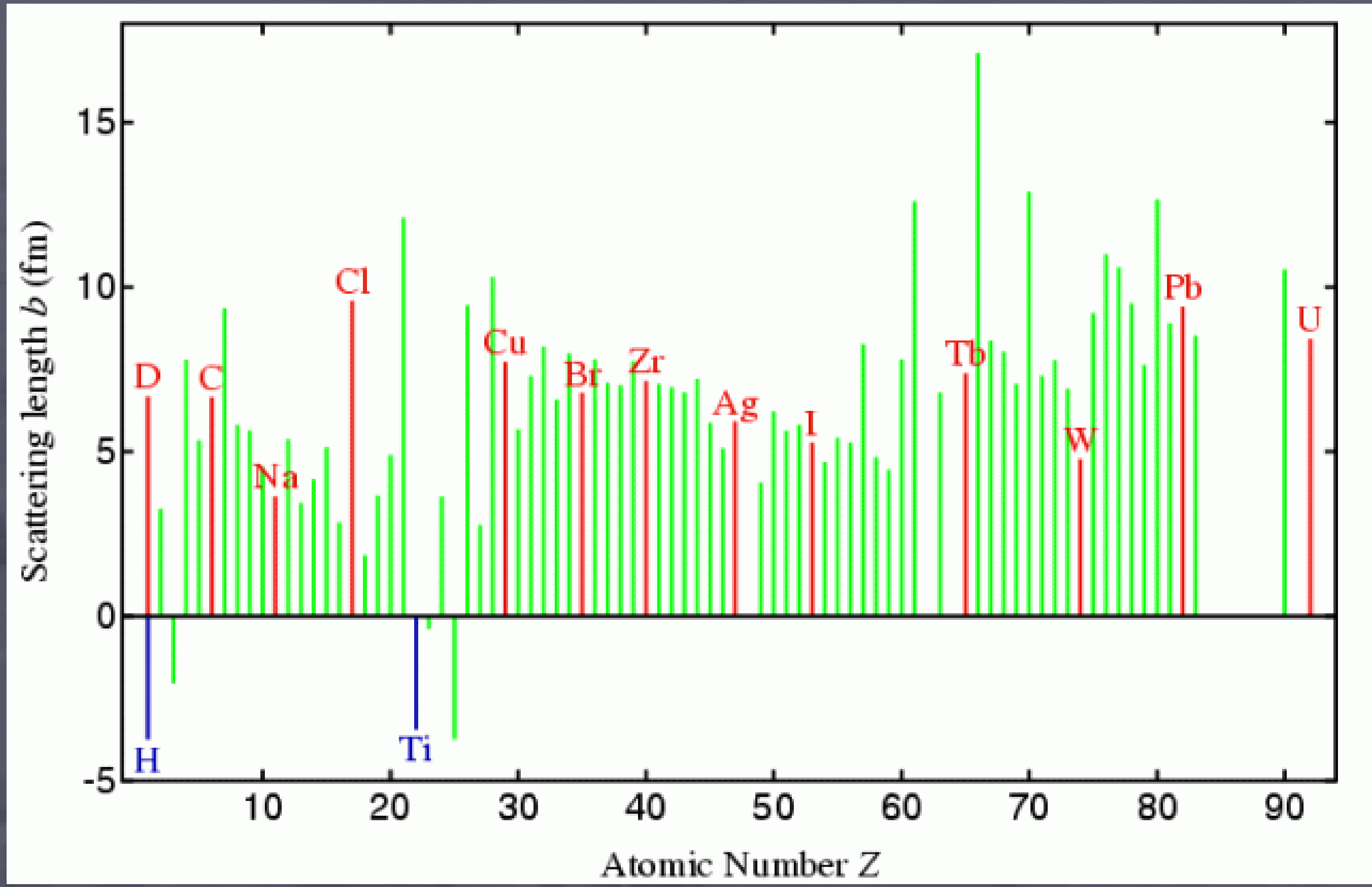


- Measurements under extreme conditions: low (T = 10 mK) & high (1500 K) temperatures, high pressures (P = 500 kbar) & magnetic fields (H = 27 T).
- Also opens the door to make in situ / in operando measurements of e.g. real batteries, flow cells, catalysis, engineering materials fatigue tests...

Isotope Sensitivity

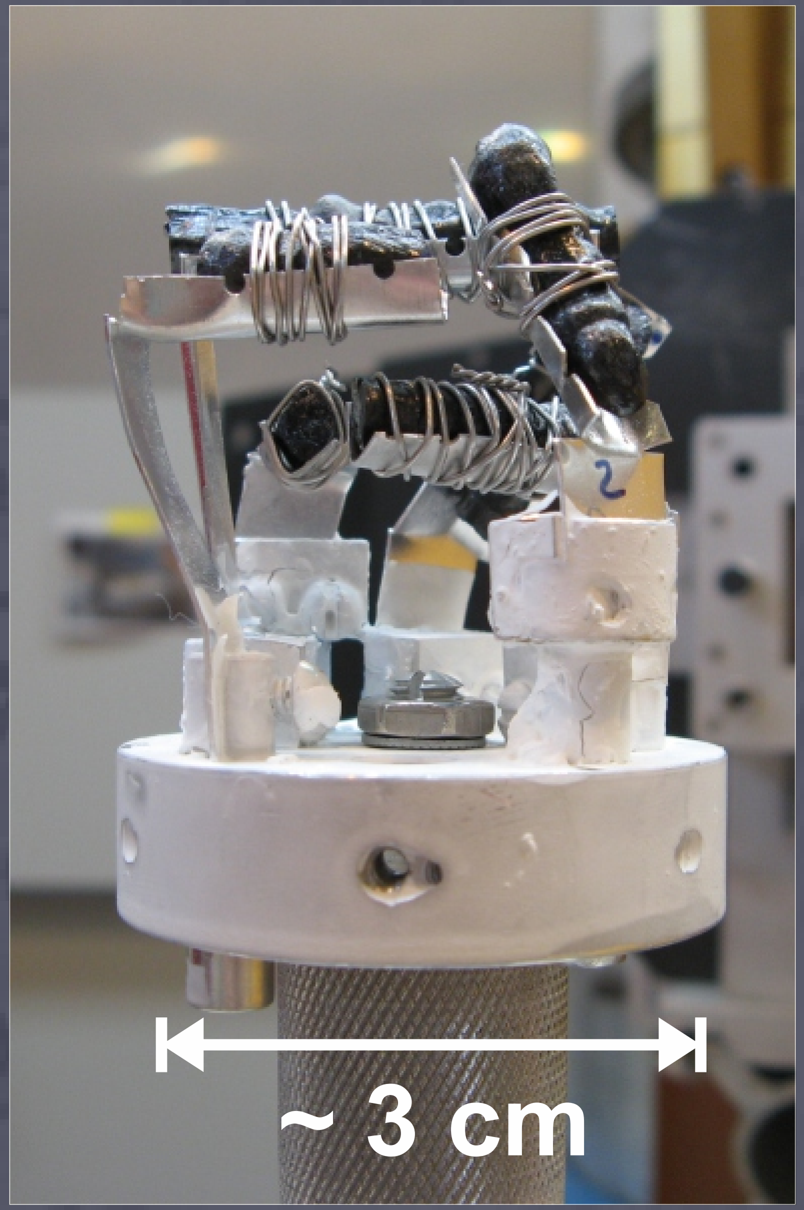
- **Isotopes of the same element have different scattering lengths (and absorption).**
- **Some of them even have different signs (phases) *e.g.* H / D or ^{6}Li / ^{7}L**
- **Allow to play with contrast of one part of a lattice or molecule.**





- **Isotopic labeling of a part of an organic/bio molecule by using deuterated reaction chemicals.**
- **Discern *e.g.* details regarding specific molecular dynamics.**
- **Can also play with contrast matching to remove background from a sample in solution (H_2O / D_2O)**

Drawbacks of Neutron Scattering



- Slow method, new high-brilliance neutron sources are needed (ESS) e.g. for INS/QENS studies or spectroscopic/time-resolved measurements.
- LARGE-scale facilities are needed to produce neutrons → very expensive and limited amount of experimental beamtime.
- Usually large samples are needed (several grams), which is a problem for *e.g.* single crystal samples (better with new sources).
- Some elements strongly absorbs neutrons (Eu, Cd).
- Neutral particle → technically hard to manipulate particle beam (focus, bend, accelerate and detect).

- Kinematic restrictions on Q for large energy transfers → Difficult to study excitations at higher (eV) energies (...RIXS !!!)
- Some samples gets highly activated in the neutron beam, which is hazardous and sometimes not 'practical'.

Elastic Neutron Scattering

- The aim of a NS experiment is to determine the probability that an initial neutron of wavevector k_i is scattered into a final state k_f .

- Intensity of the scattered neutrons is measured as a function of momentum transfer (Q) and energy transfer (E):

$$\mathbf{Q} = (\mathbf{k}_i - \mathbf{k}_f)$$

$$E = \hbar\omega = \hbar^2(\mathbf{k}_i^2 - \mathbf{k}_f^2) / 2m$$

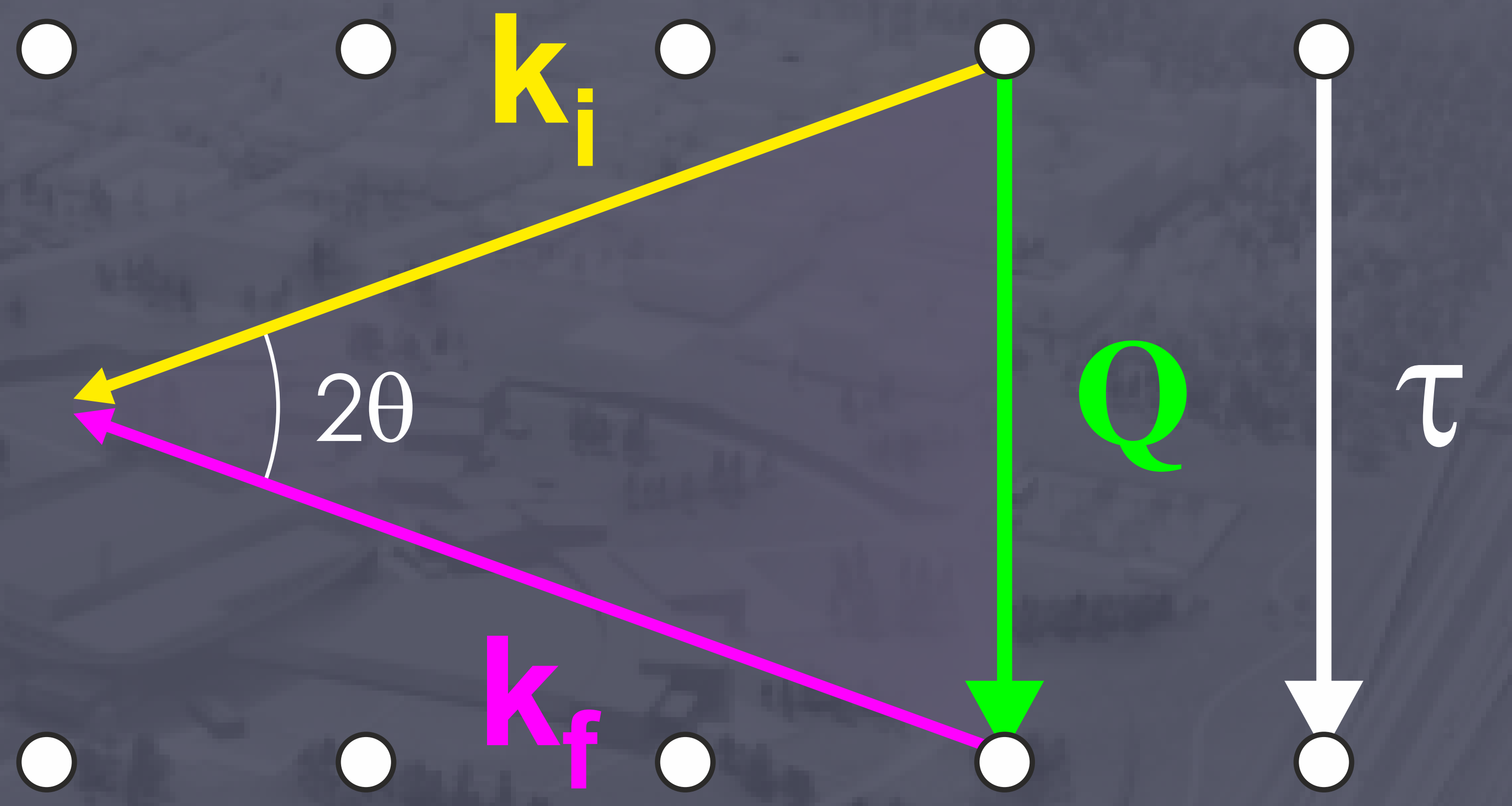
- These two equations describe the momentum and energy conservation of the neutron scattering process !!!

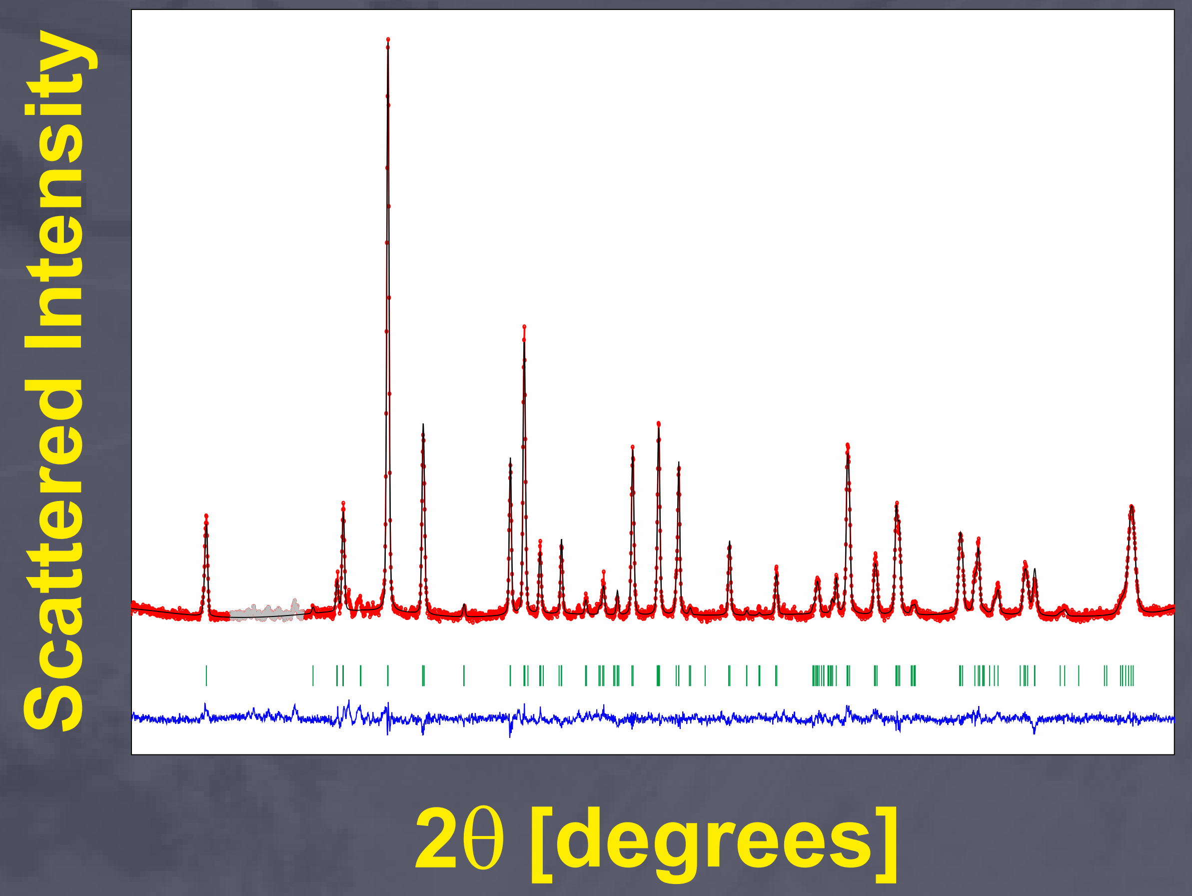
- If the scattering occurs without any loss/gain of neutron energy ($E = 0$ i.e. $|\mathbf{k}_i| = |\mathbf{k}_f|$) this is called Elastic Neutron Scattering:

Tells us about where atoms are and how spins align

Neutron Diffraction

- If the scattering vector $\mathbf{Q} = \tau$ where τ is a reciprocal lattice vector for a nuclear and/or magnetic lattice we obtain coherent elastic scattering.
- As for a normal XRD experiment this is done by performing θ / 2θ scans (2-axis instrument) using fixed & monochromatic incident neutron energy.
- According to the (hopefully) familiar Bragg's law, ($\lambda = 2d_{hkl} \sin\theta$) where θ allows $\mathbf{Q} = \tau$, a coherent Bragg peak appears in the diffraction pattern.
- By collecting large number of Bragg peaks combined with advanced data-analysis it is possible to very accurately refine the structure of a material
- Can be performed for both powder samples as well as single crystals.
- Compared to XRD sample mass is larger (order of a gram) and the measurement is slower [hour(s)]. **Modern sources → mg and minutes !!!**



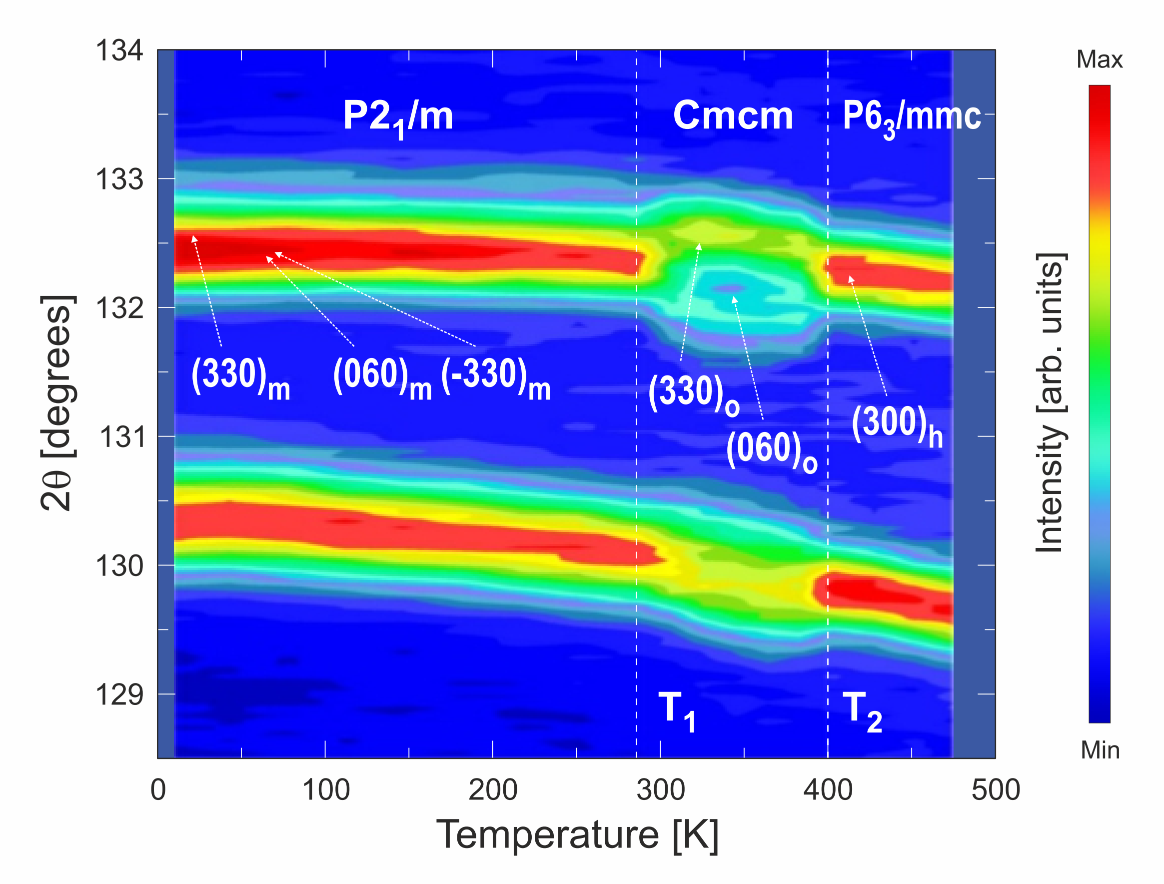


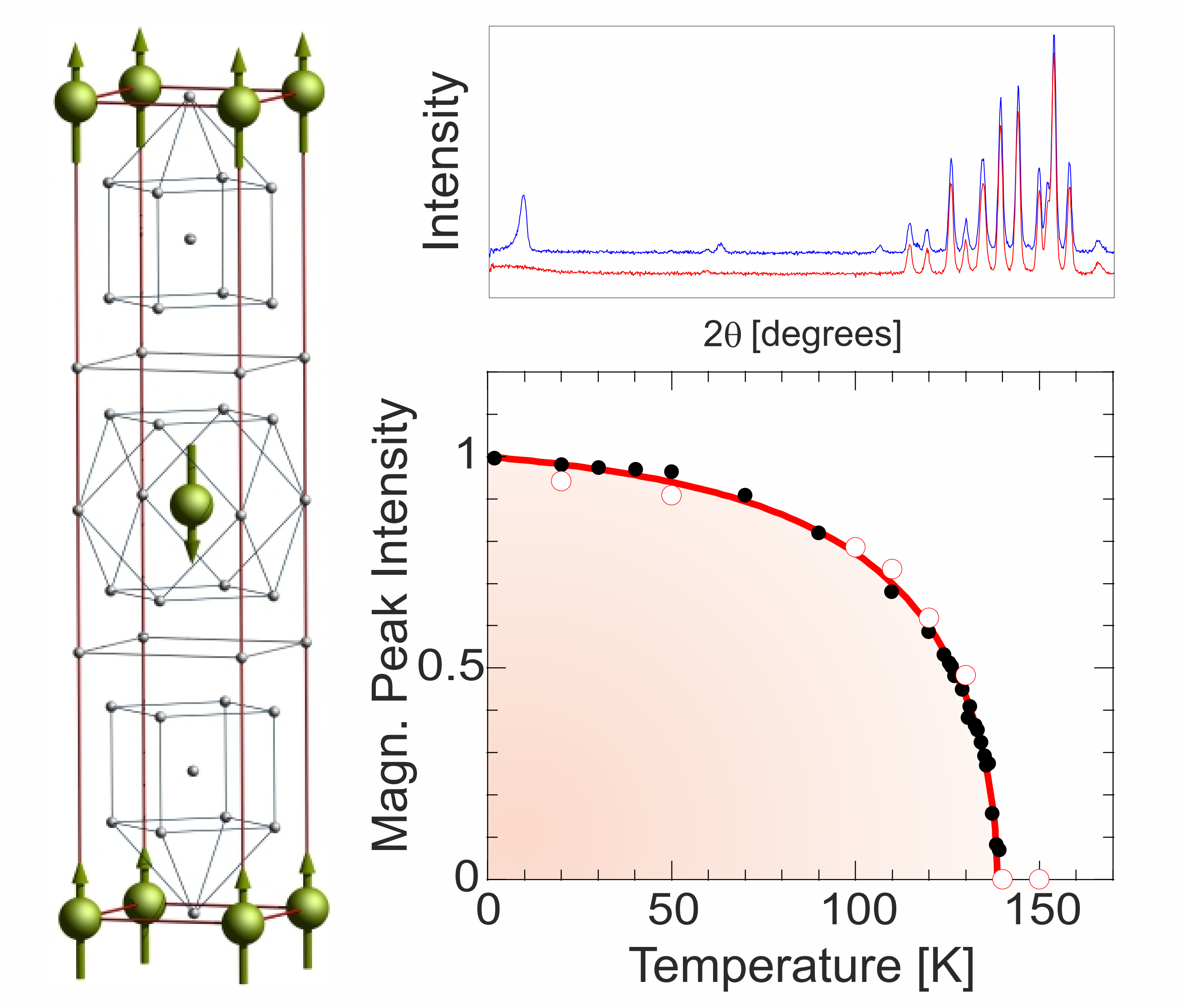
Neutron Diffraction Examples

Nuclear Diffraction

- Determination of & changes in atomic structure when a sublattice contains light atoms or under extreme conditions *e.g.*
  - Li/Na ions in battery materials
  - Hydrogen lattice sites in H-storage materials
  - High-P / low-T induced structural changes
  - Structure of organic materials (also H !)

Medarde, Phys. Rev. Lett. 110, 266401 (2013)





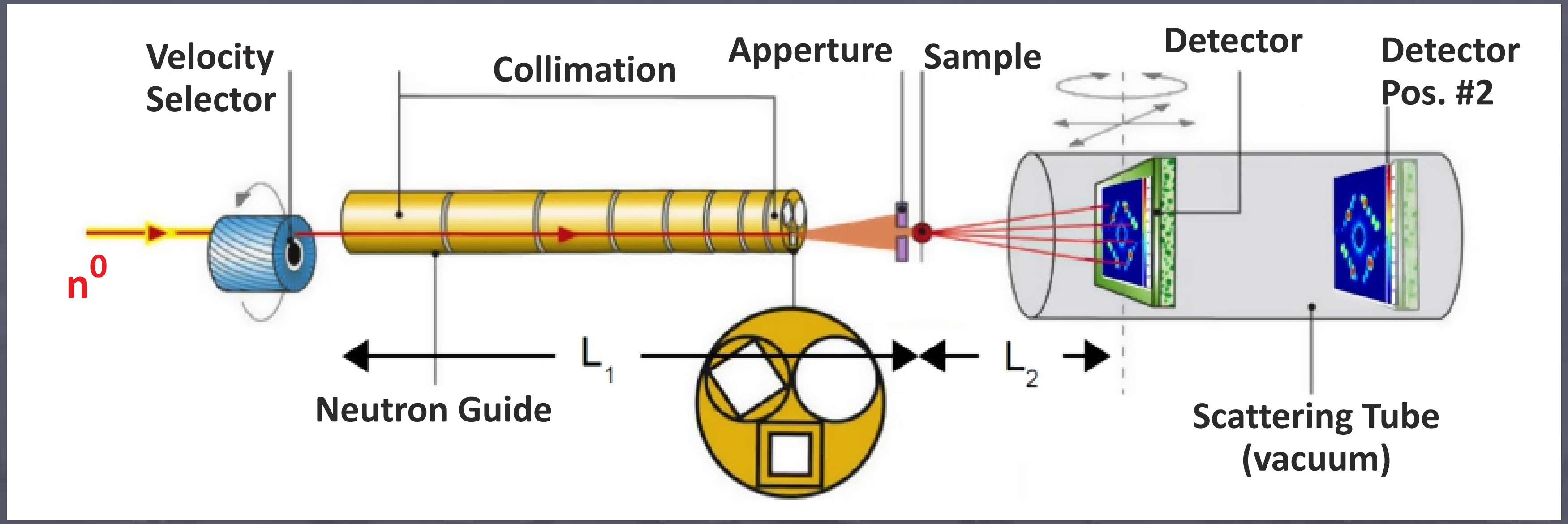
Magnetic Diffraction

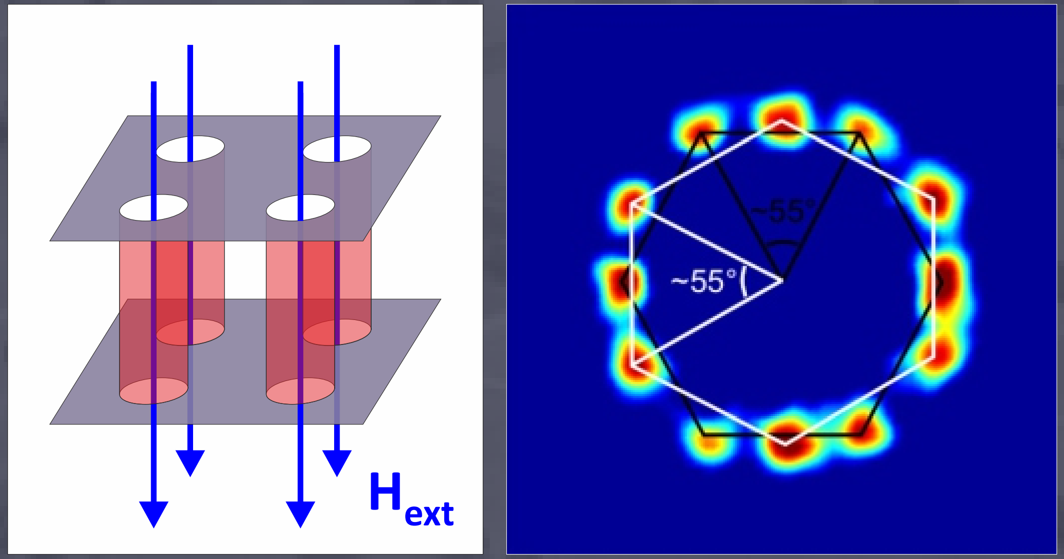
- Only available tool (!!!) to directly study magnetic order:
  - Determine complex spin-structures and size + direction of magnetic moment for spintronics, storage, novel materials...
  - Magnetic order parameters as a function of T/H to understand formation of spin order *e.g.* frustrated/quantum magnets.
  - Polarized diffraction allow to study AF + FM order

Other Elastic NS Techinques

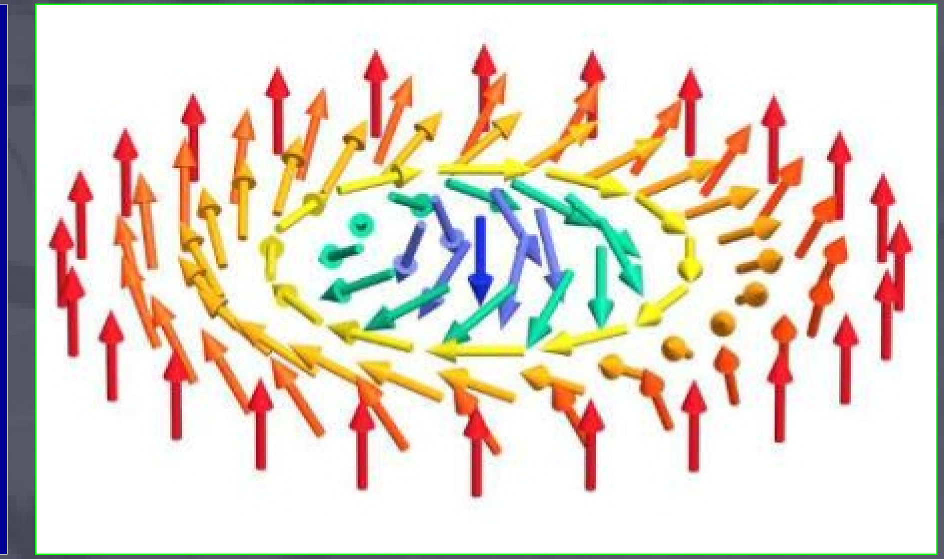
Small-Angle Neutron Scattering (SANS)

- Order/distribution of nm-µm sized objects
  - *Micelles in liquids, creep cavities in steel, ...*
  - Magnetic nano-particles
  - Flux-line (vortex) lattice in superconductors
  - Magnetic Skyrmions



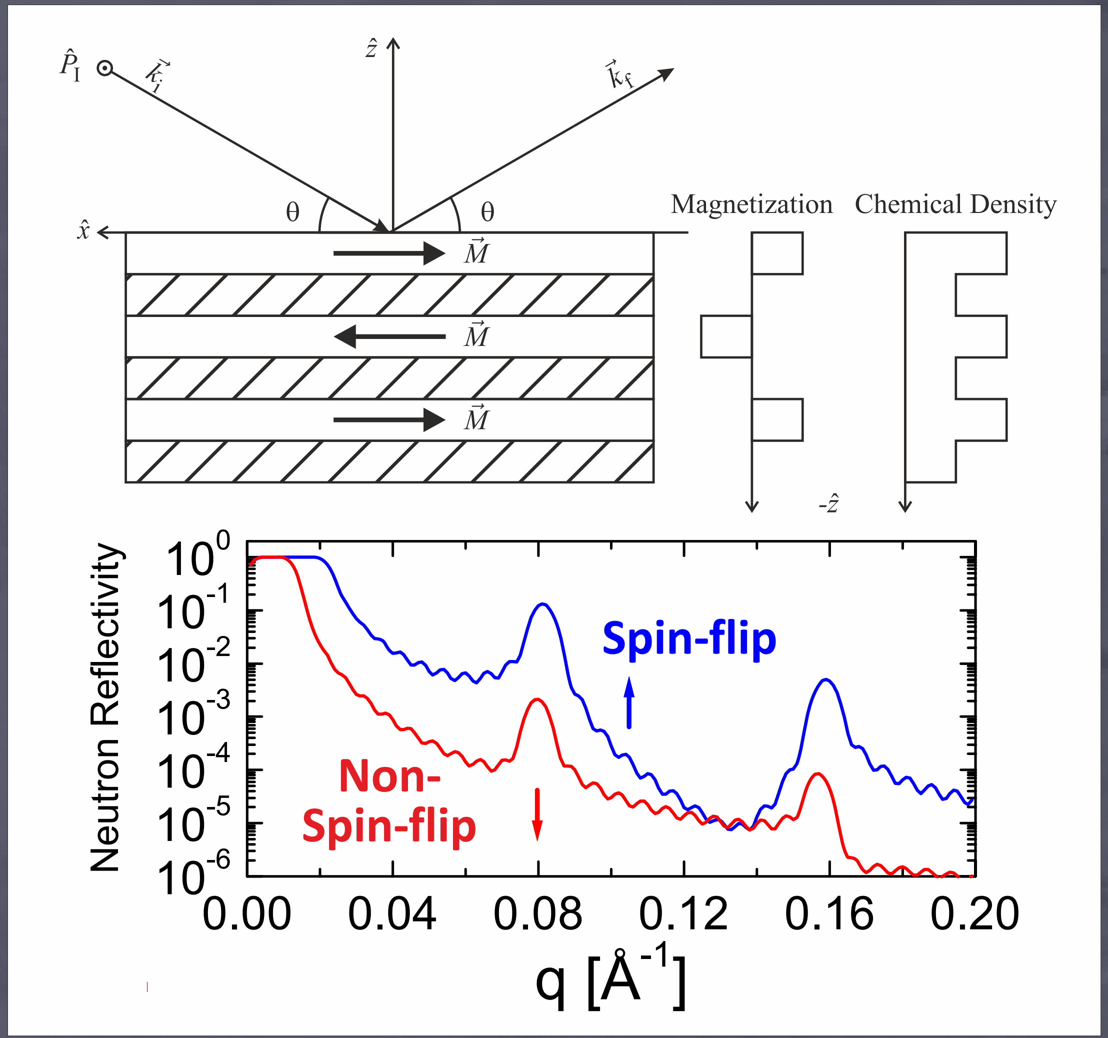


H. Kawano-Furukawa, Phys. Rev. B 84, 024507 (2011)



S. Mühlbauer, et al., Science 323, 915 (2009)

Neutron Reflectometry



- Determine film/layer thickness, roughness & structural interfaces
  - *Solid-liquid interfaces, spin coated polymer films, ...*
  - Magnetism in thin films and multilayers (magnetic storage...)
  - Magnetic coupling and ‘twisting’ in multi-layers (mag. / non-mag. / mag.)
  - Magnetic / Superconducting multi-layers (co-existing of SC and magnetism)
  - Spintronics in *e.g.* graphene and topological insulators

Inelastic Neutron Scattering (INS)

- Intensity of the scattered neutrons is measured as a function of momentum transfer (**Q**) and energy transfer (*E*):

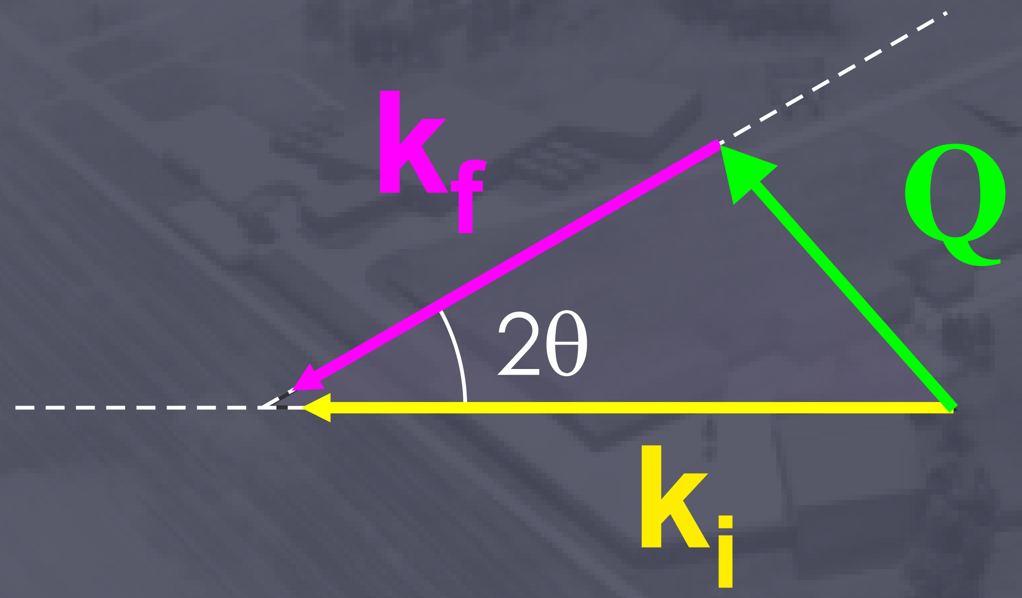
$$\mathbf{Q} = (\mathbf{k}_i - \mathbf{k}_f)$$

$$E = \hbar\omega = \hbar^2(\mathbf{k}_i^2 - \mathbf{k}_f^2) / 2m$$

- If the neutrons lose or gain energy in the scattering process ($E \neq 0$ i.e. $|\mathbf{k}_i| \neq |\mathbf{k}_f|$) this is called Inelastic Neutron Scattering (INS):

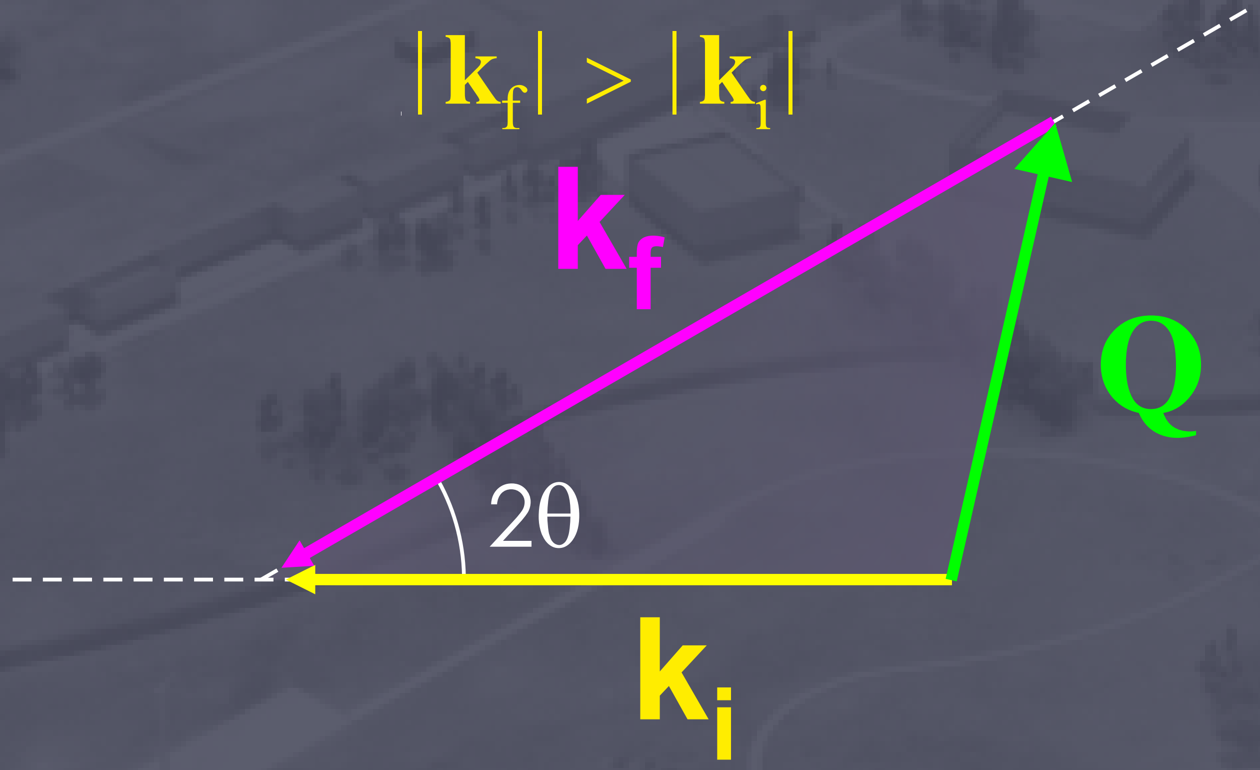
Neutron Loses Energy

$|\mathbf{k}_f| < |\mathbf{k}_i|$



Neutron Gains Energy

$|\mathbf{k}_f| > |\mathbf{k}_i|$

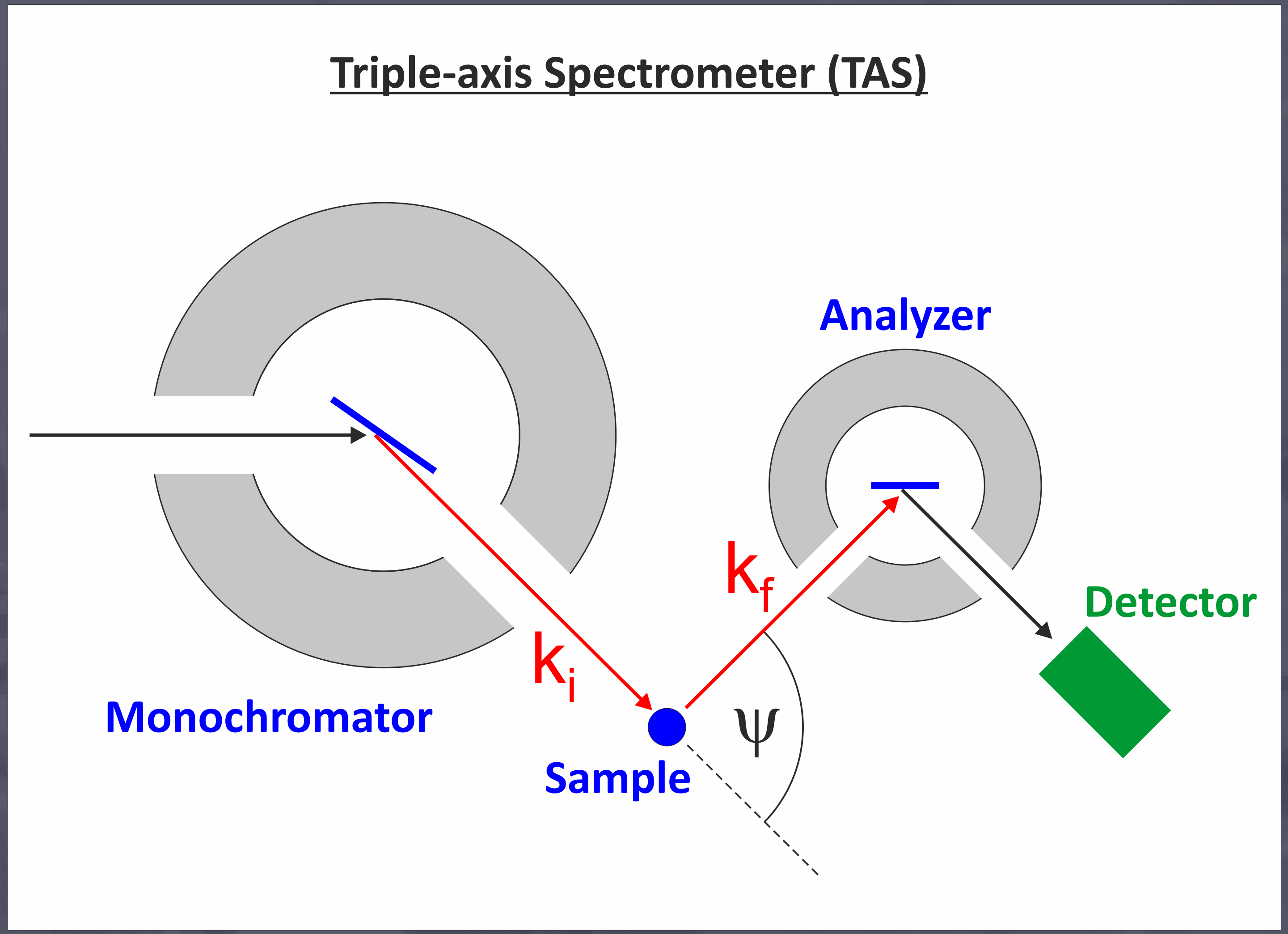


Tells us what the atoms & electron spins 'do'

- INS intensity is presented as the dynamic structure factor $S(Q,\omega)$, which in case of magnetic scattering equals the dynamic susceptibility $\chi''(Q,\omega)$.

Classic Triple-Axis Spectroscopy (TAS)

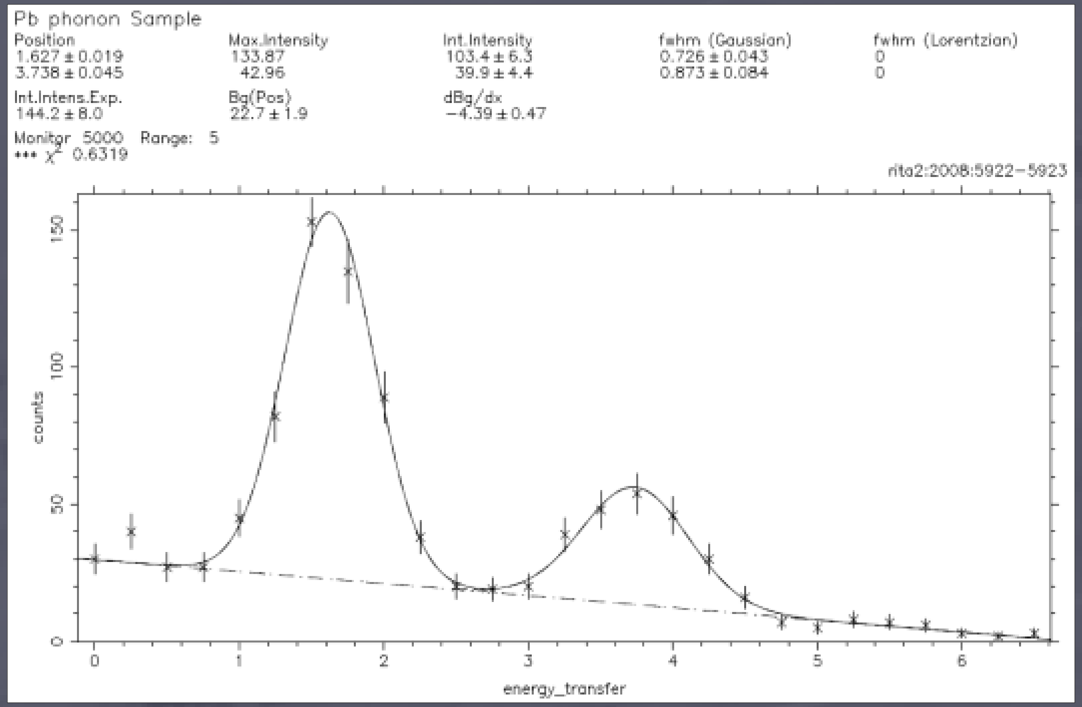
- Measure a single Q,E point at a time by using monochromators and "filters" to define initial state and to detect a specific final state.



- This is a very inefficient and slow method where most neutrons are wasted (twice) and it can take several minutes for one single data point.

Classic TAS: Data Acquisition & Analysis

- **Build up an excitation dispersion curve (E vs. Q) by acquiring 1D cuts (1 spectra) and fitting the peaks to give 1 or several points of the dispersion.**



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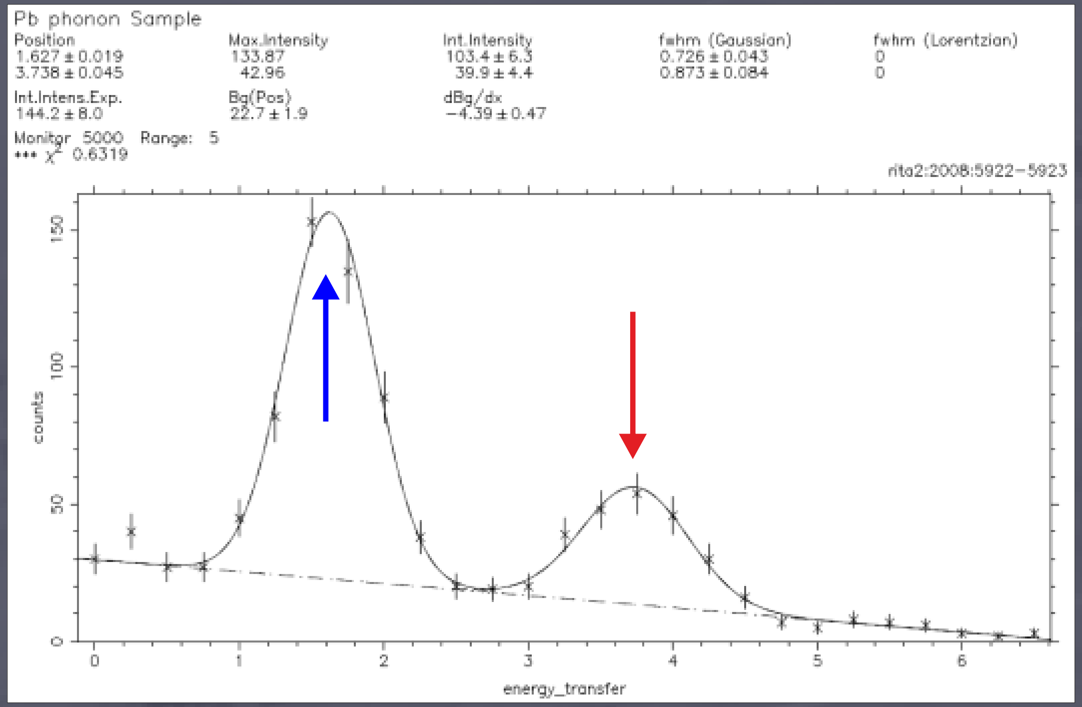

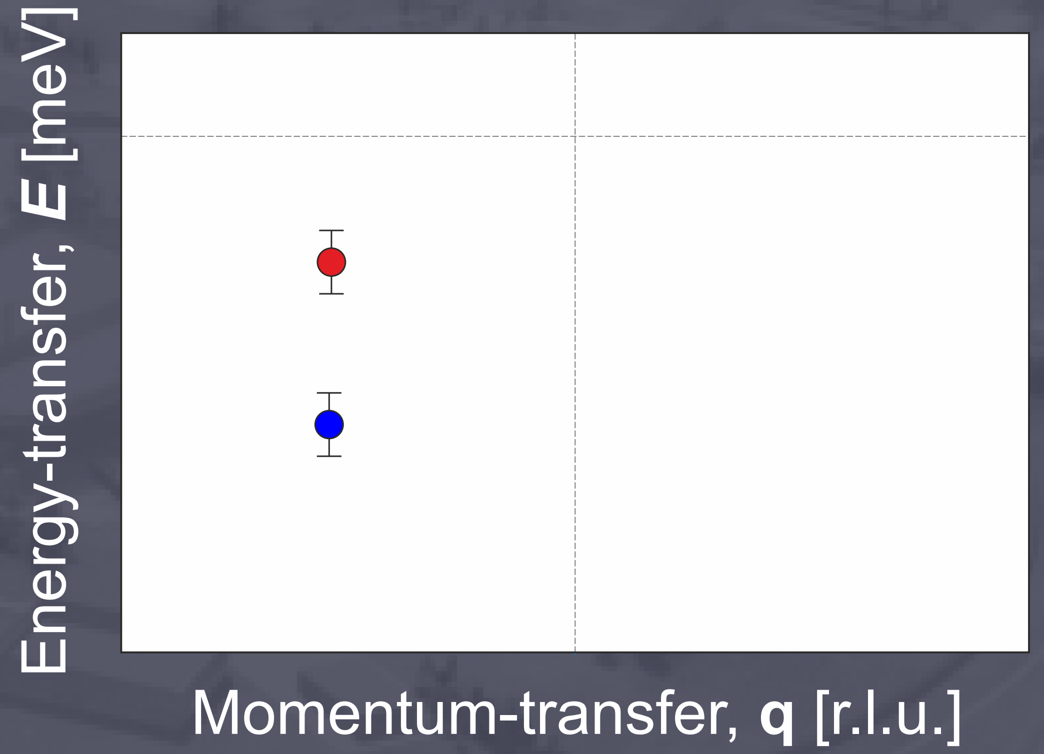

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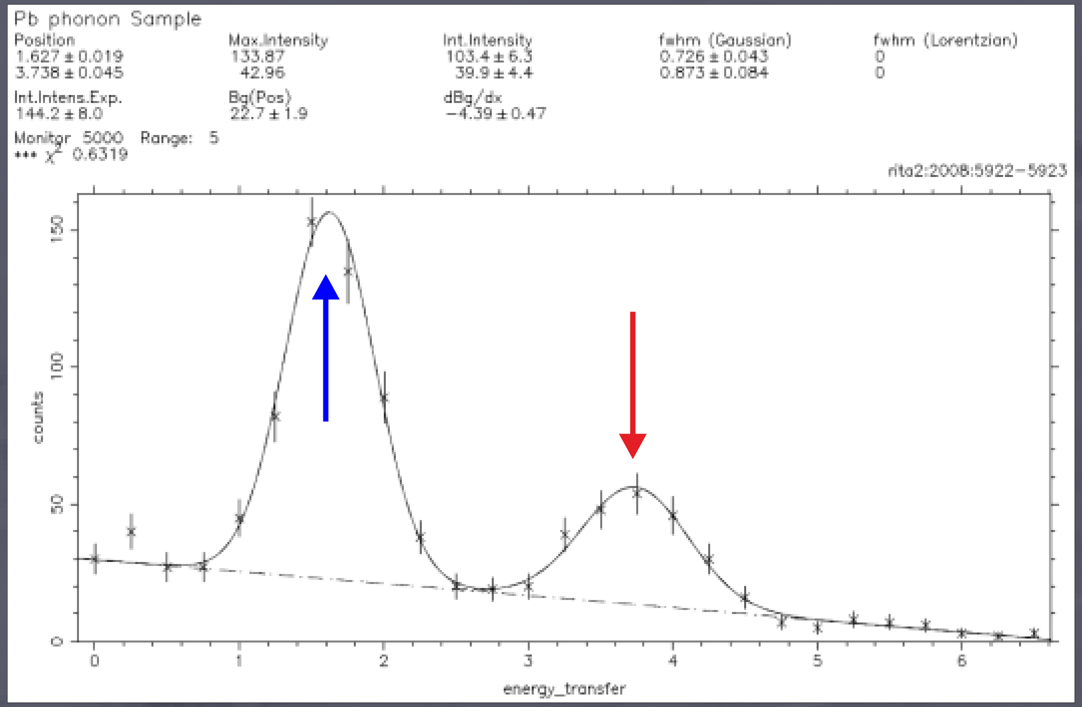

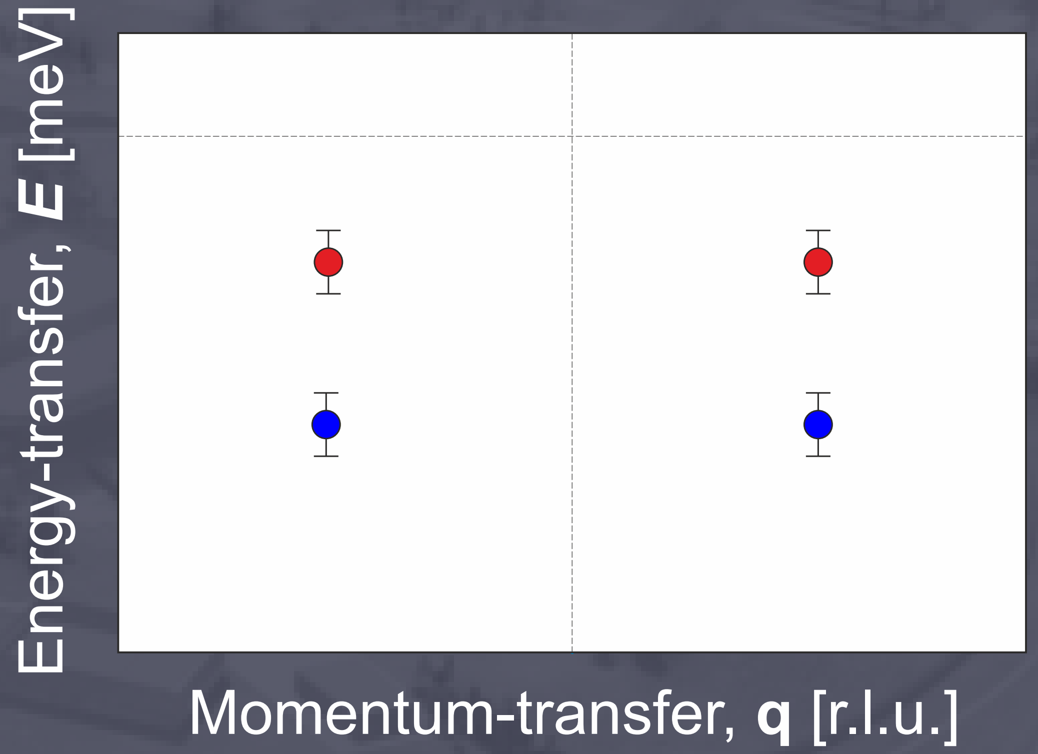

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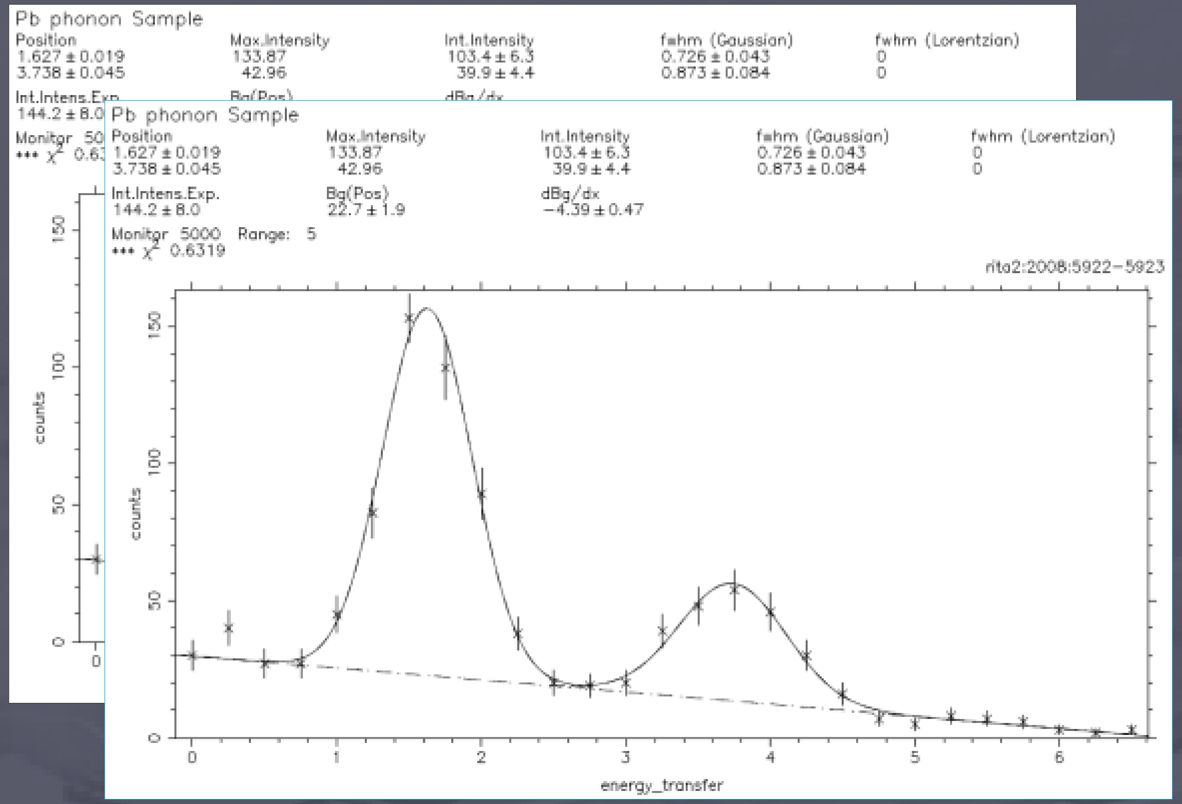

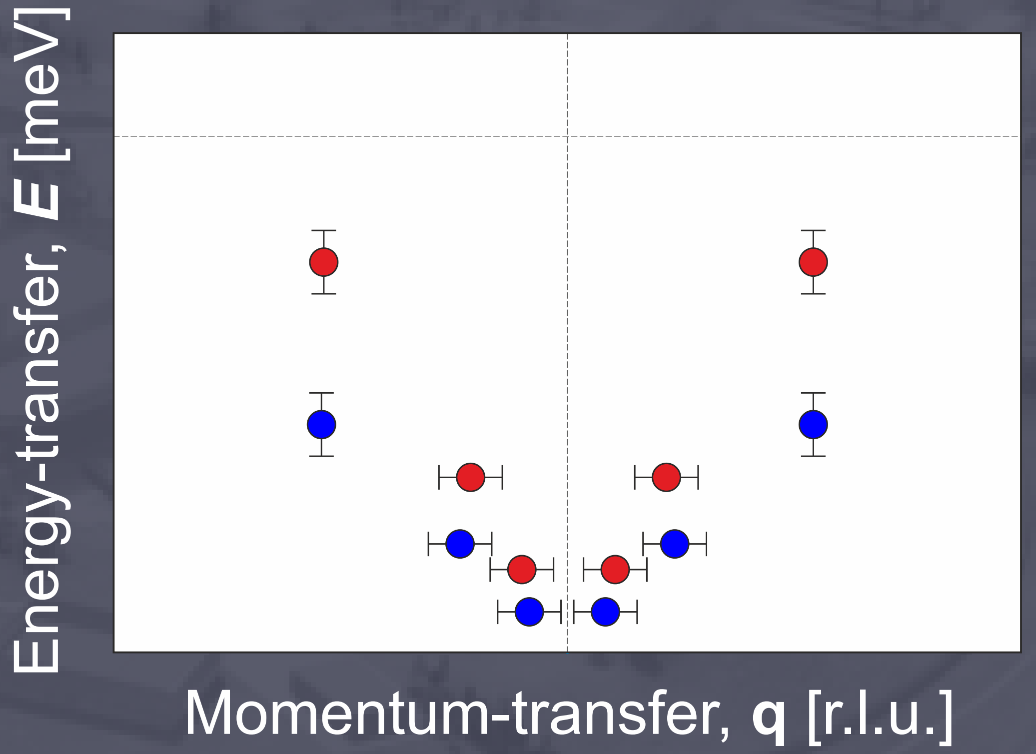

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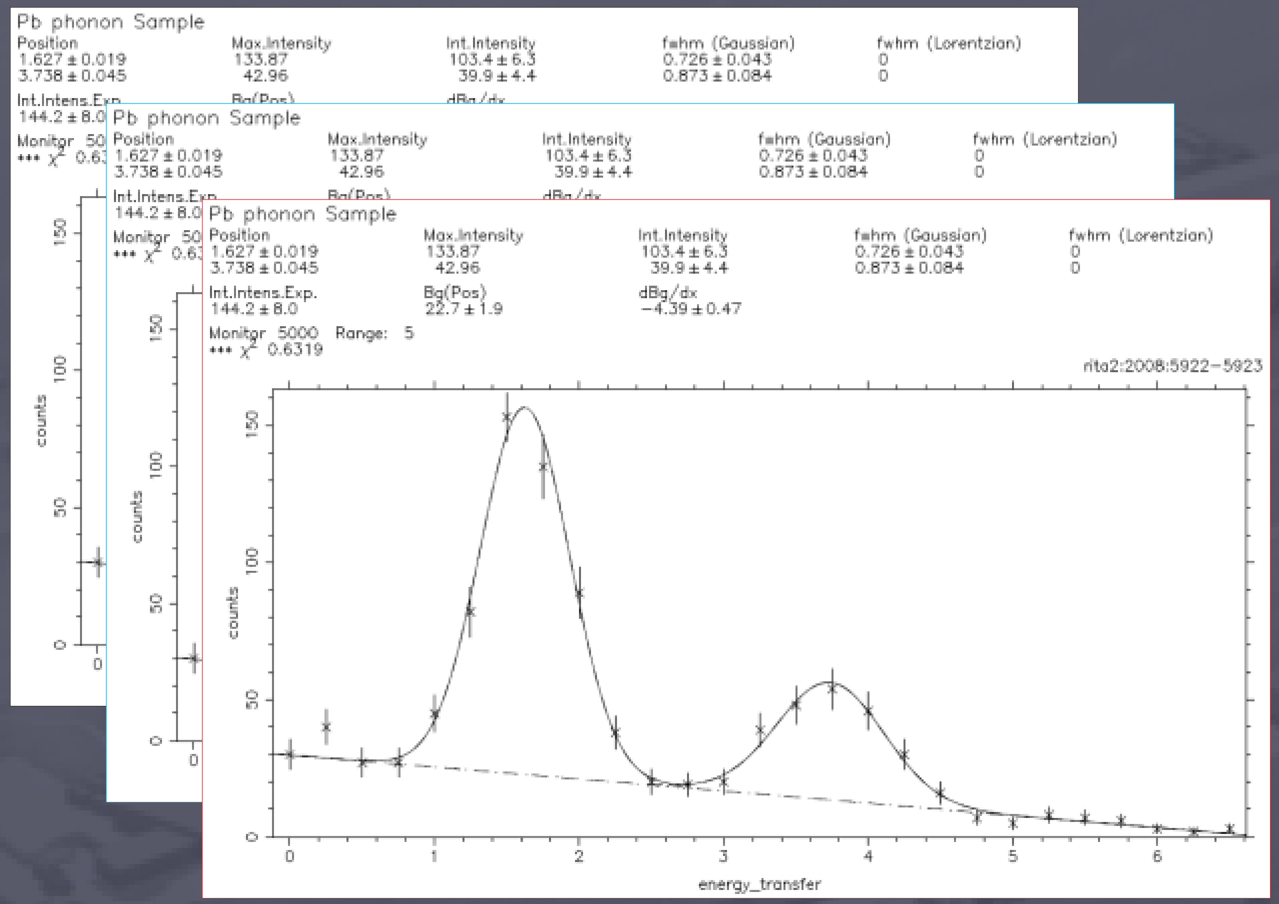

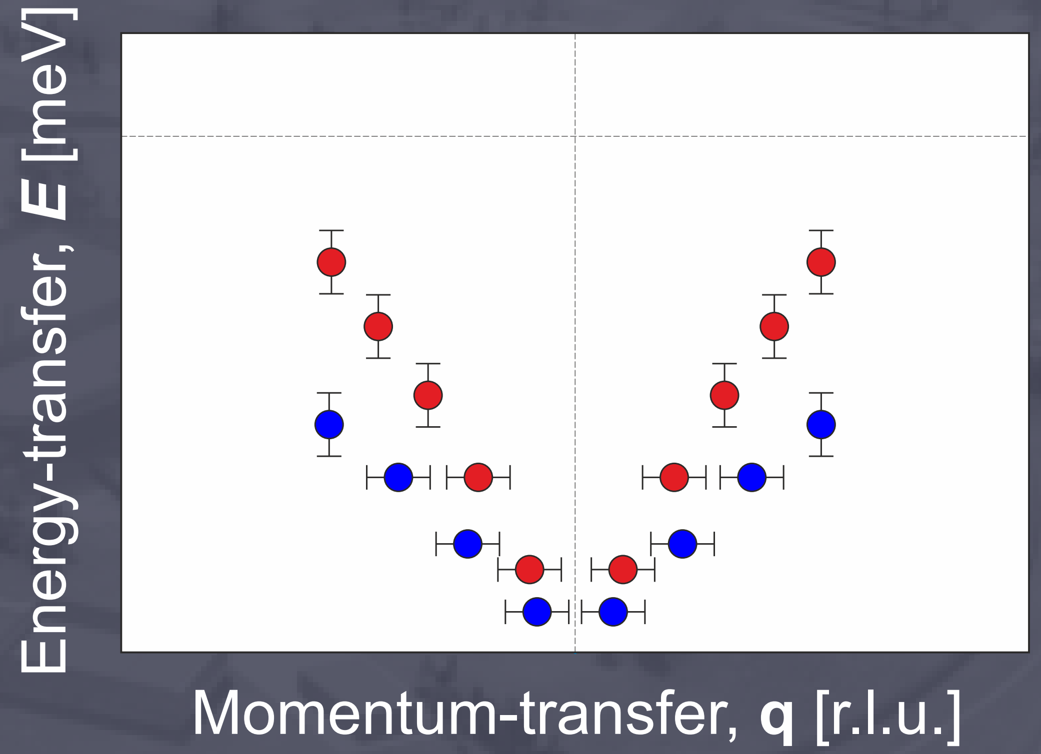

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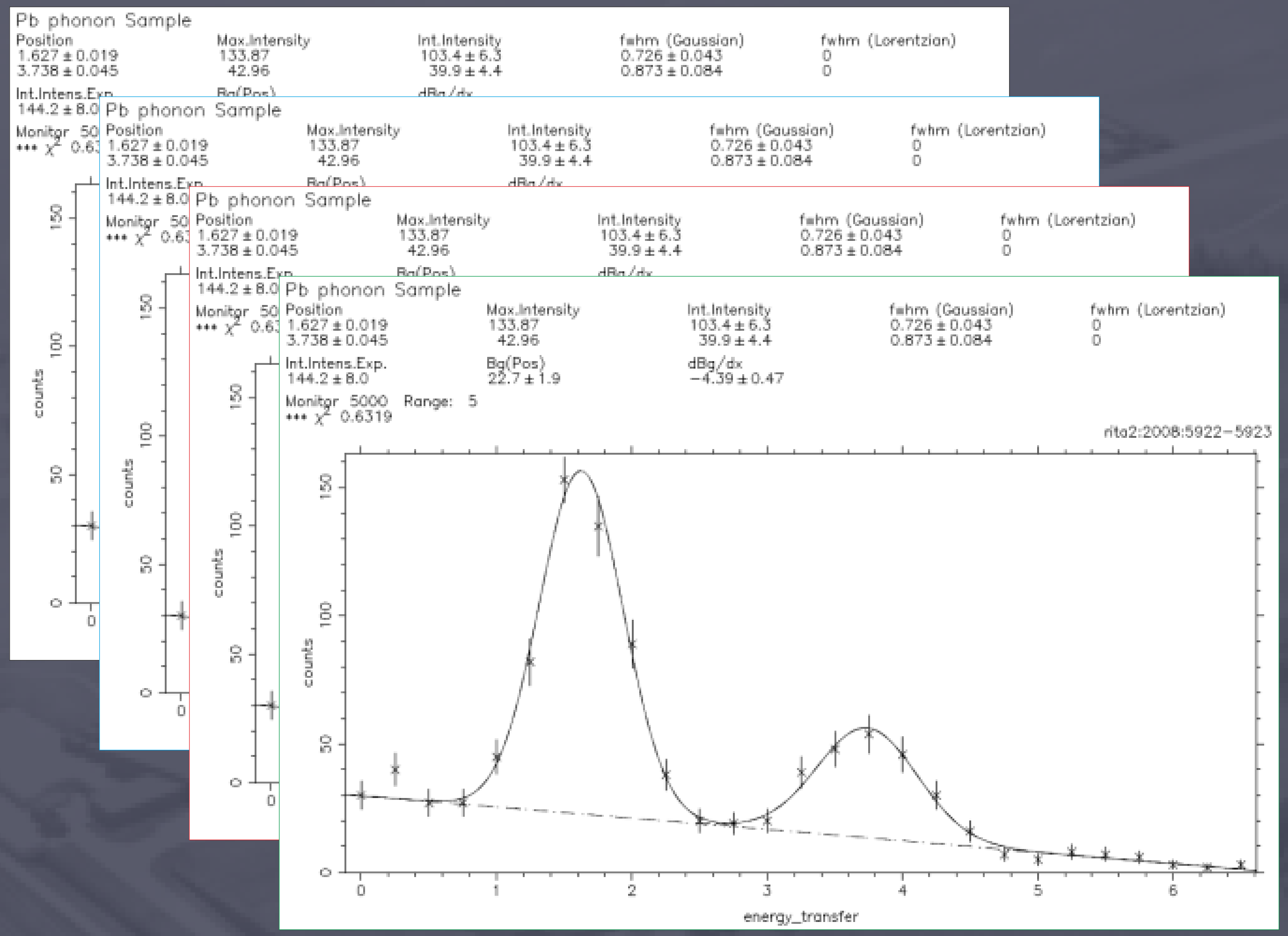

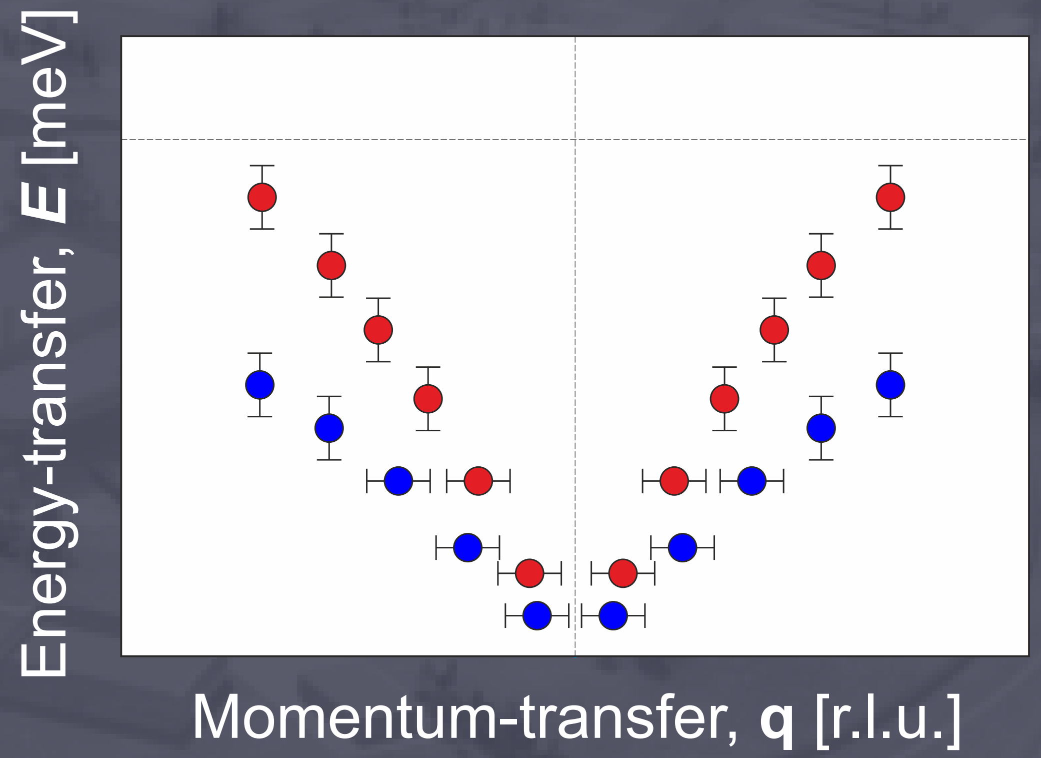

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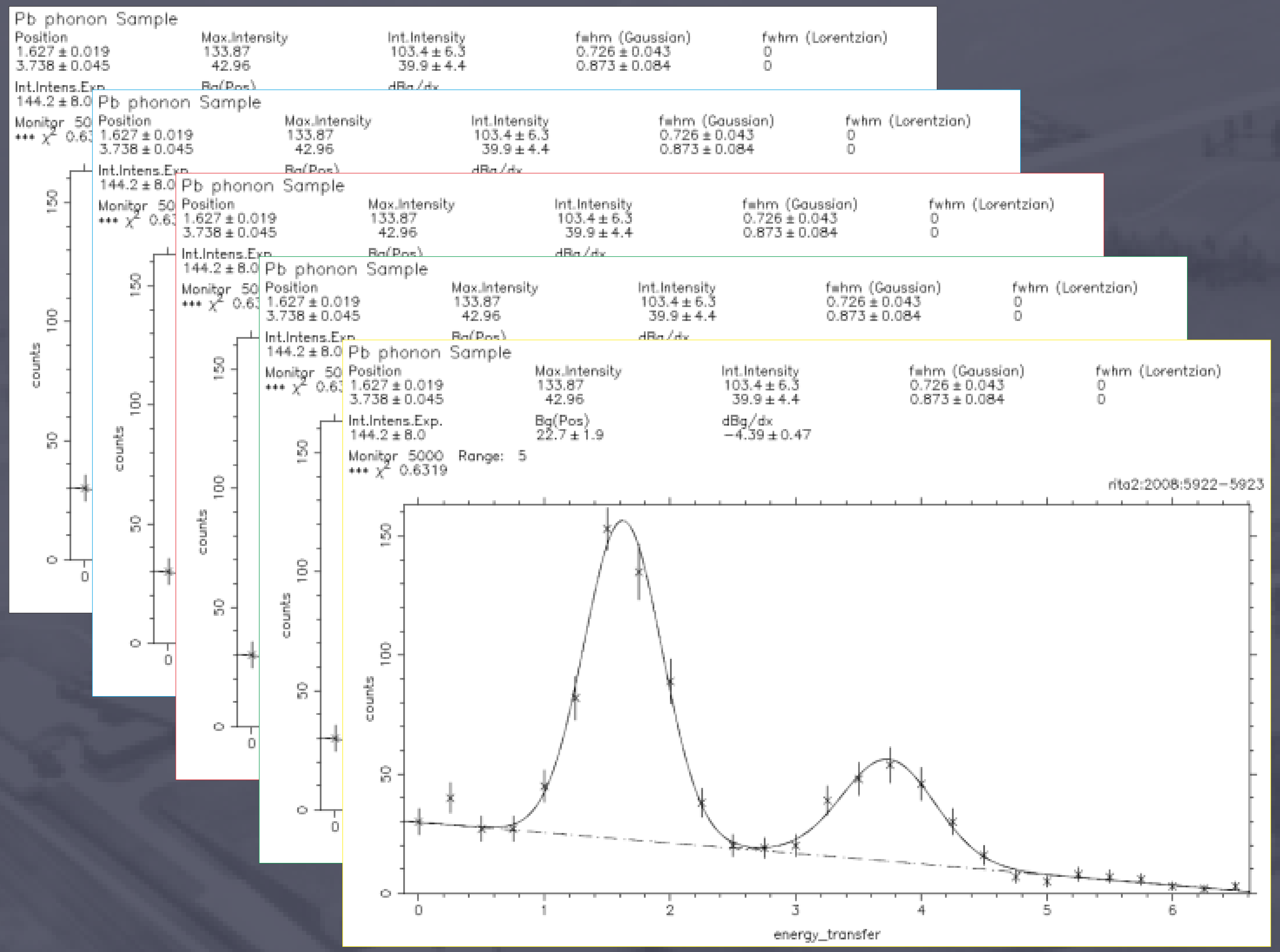

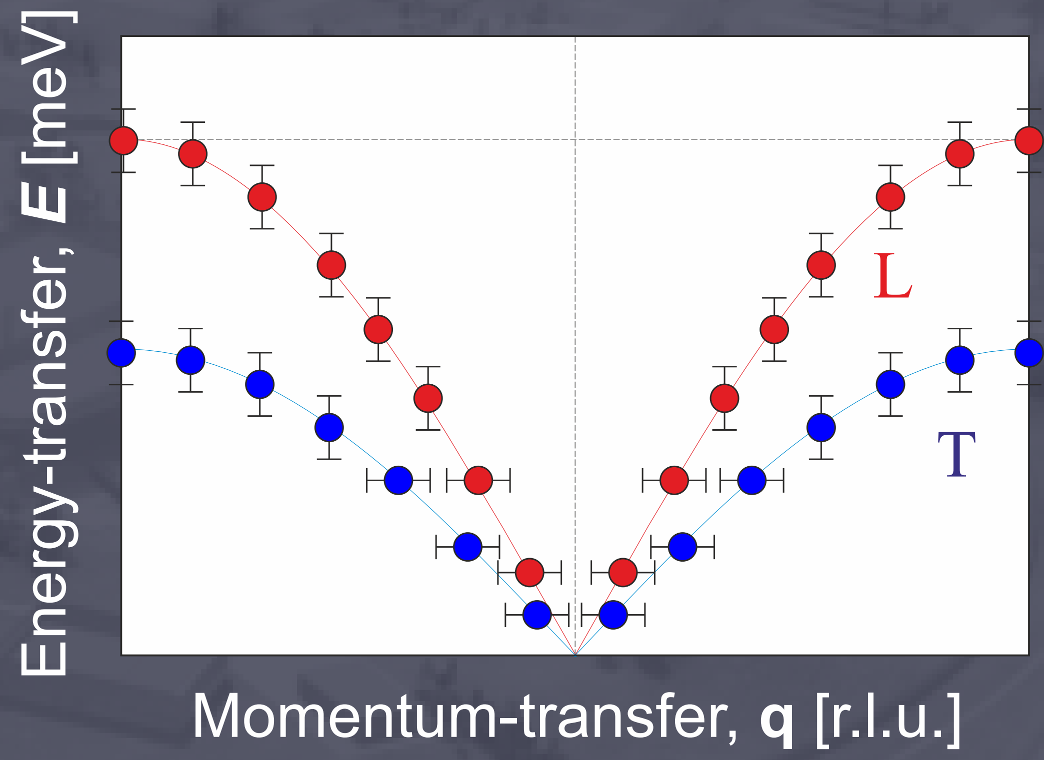

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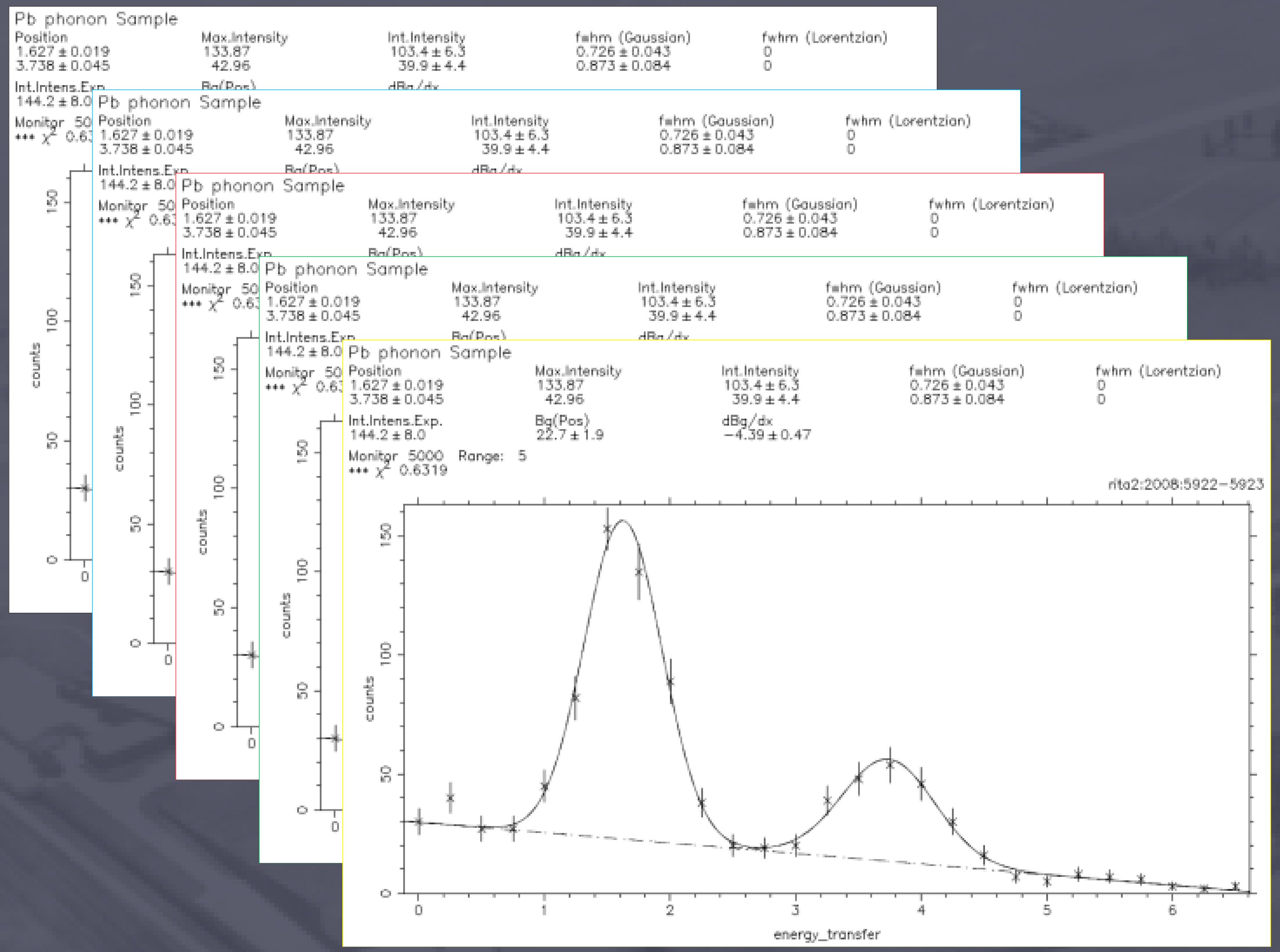

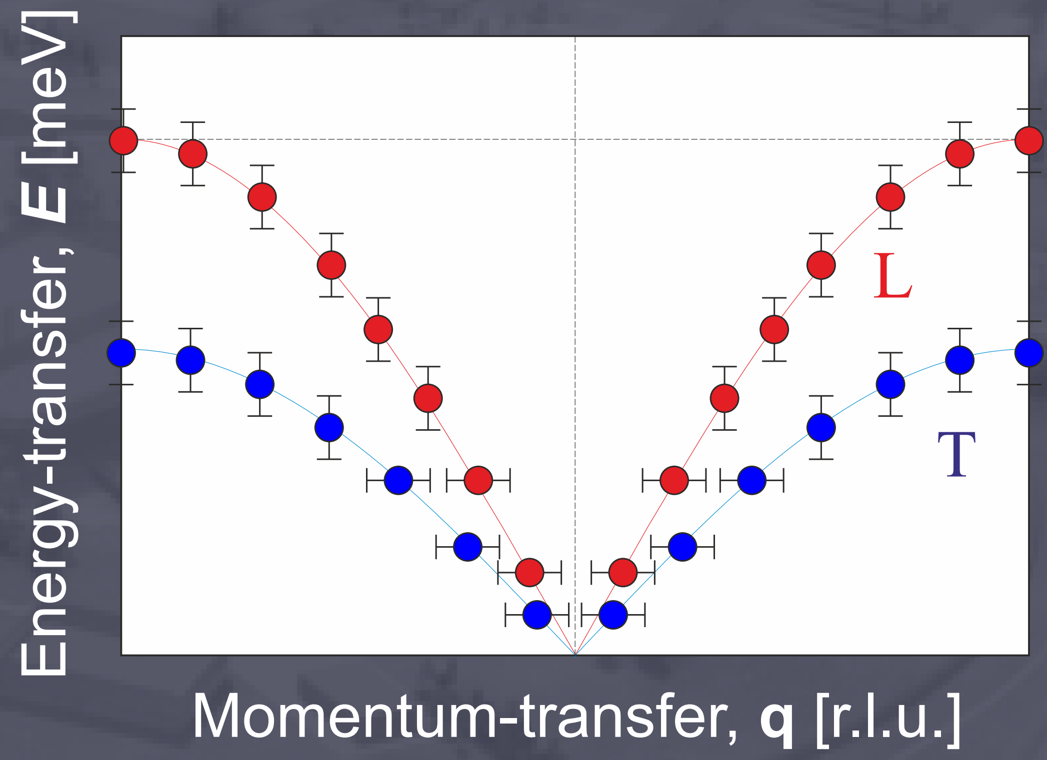

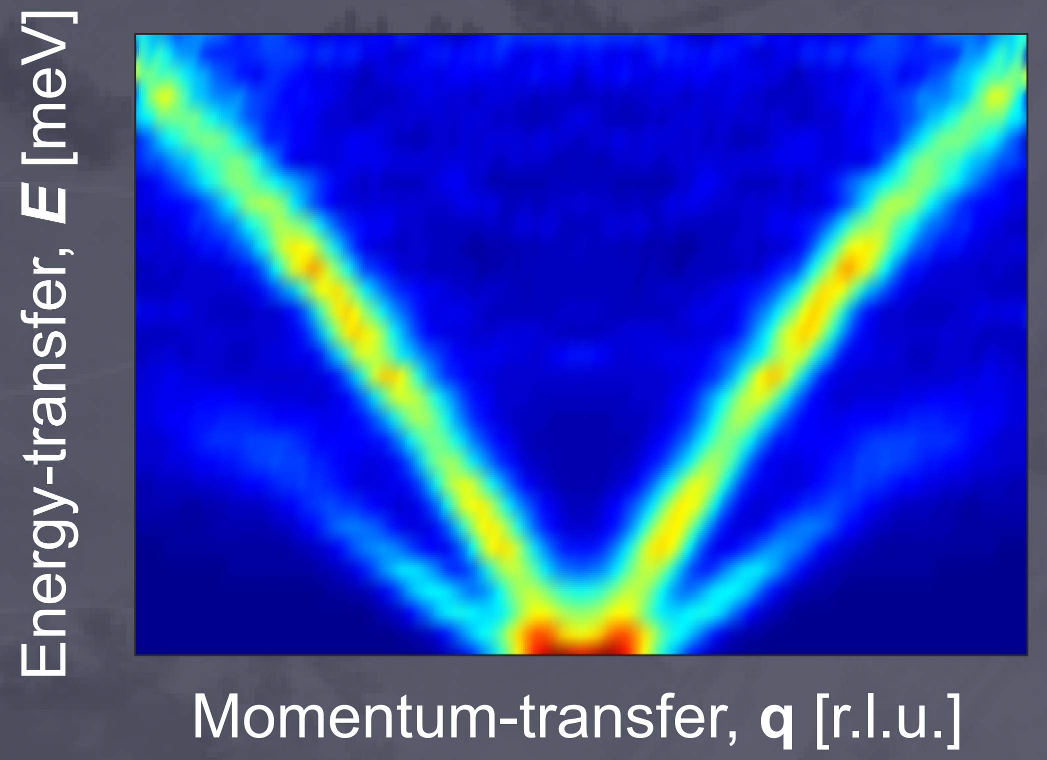

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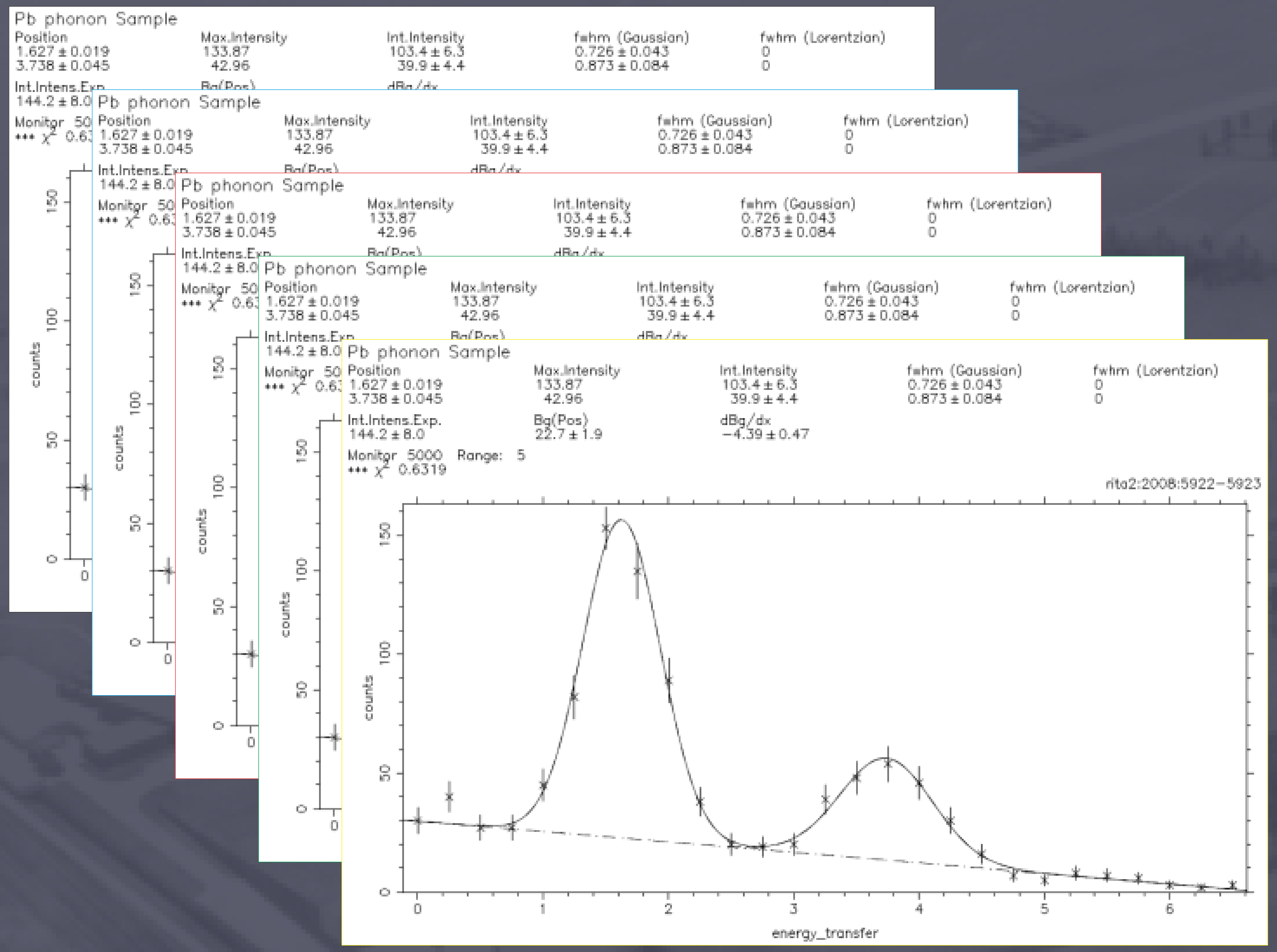
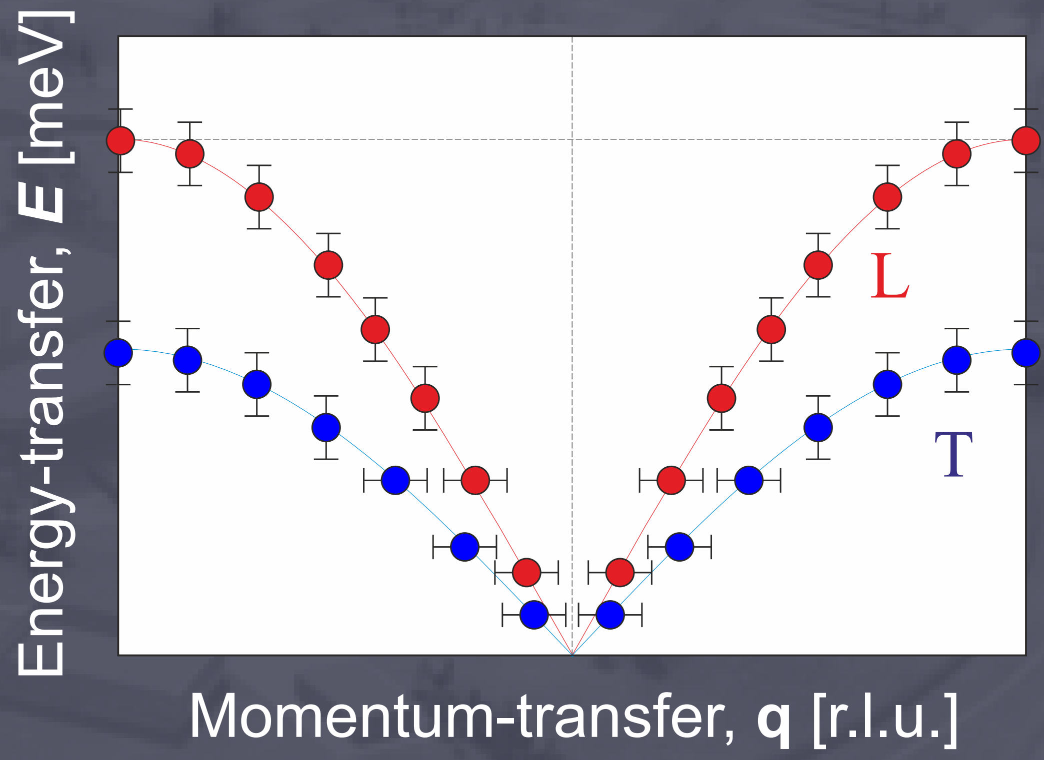
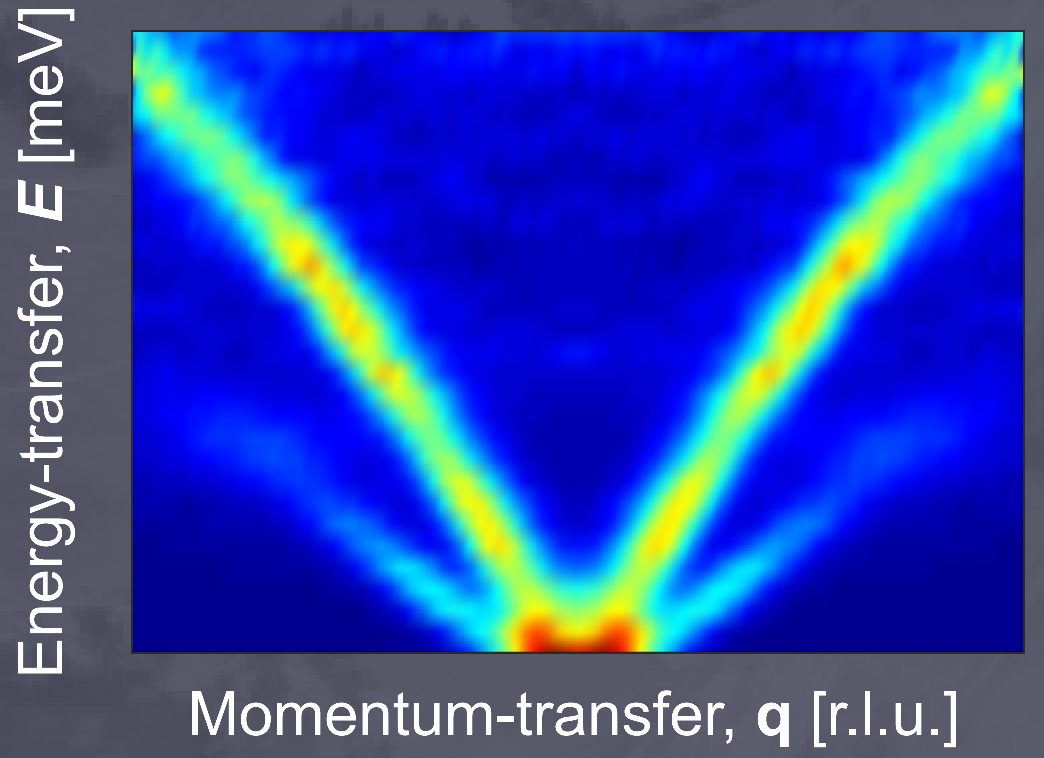


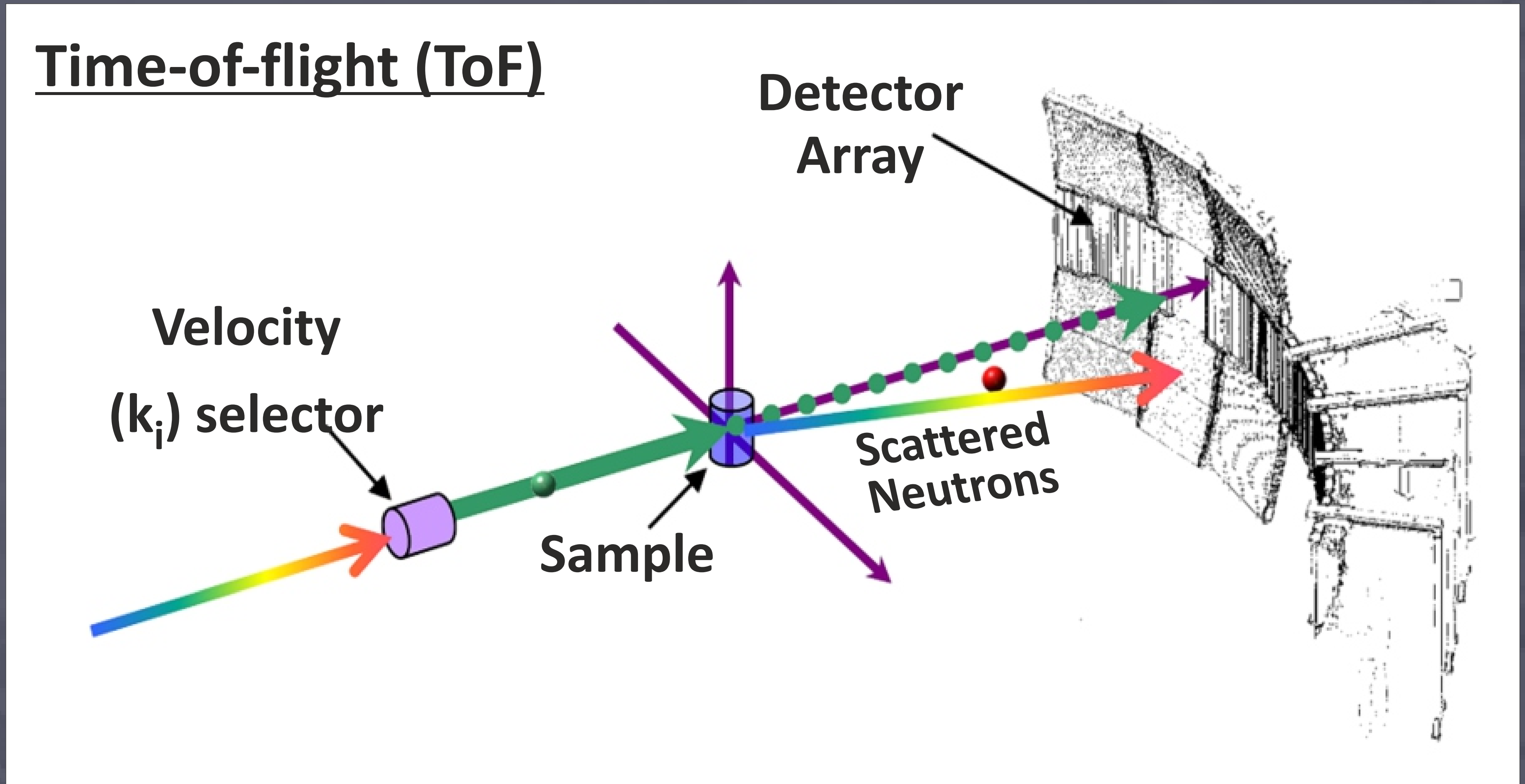


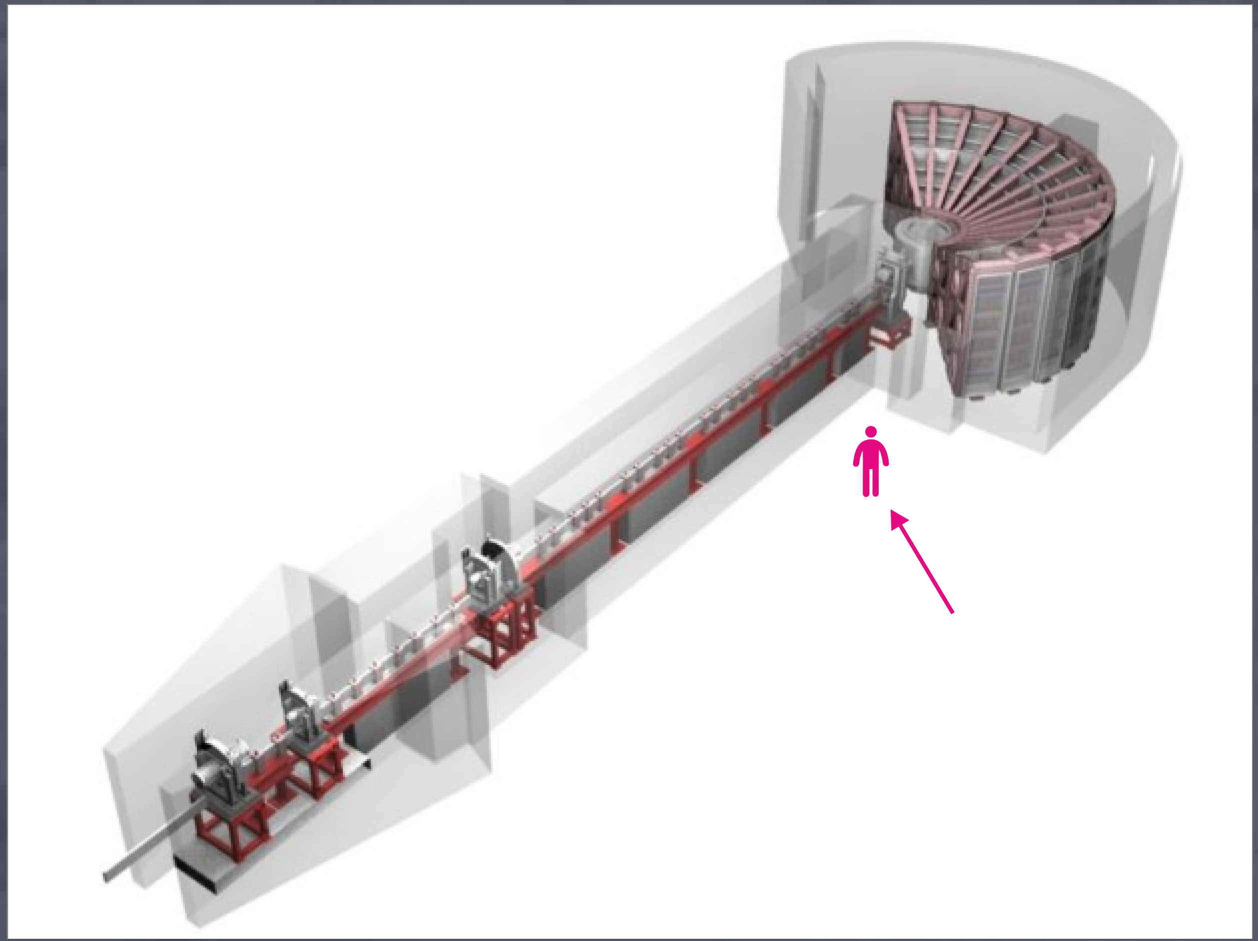


- **Online data analysis is made in 1 minute while scanning next point. Full analysis is done in 1 hour/spectra. Total data volume 100 kbyte acquired in 5 days (magnetic).**

Modern INS: Time-of-Flight (ToF)

- Modern time-of-flight instruments (on modern pulsed sources) have huge detector banks.

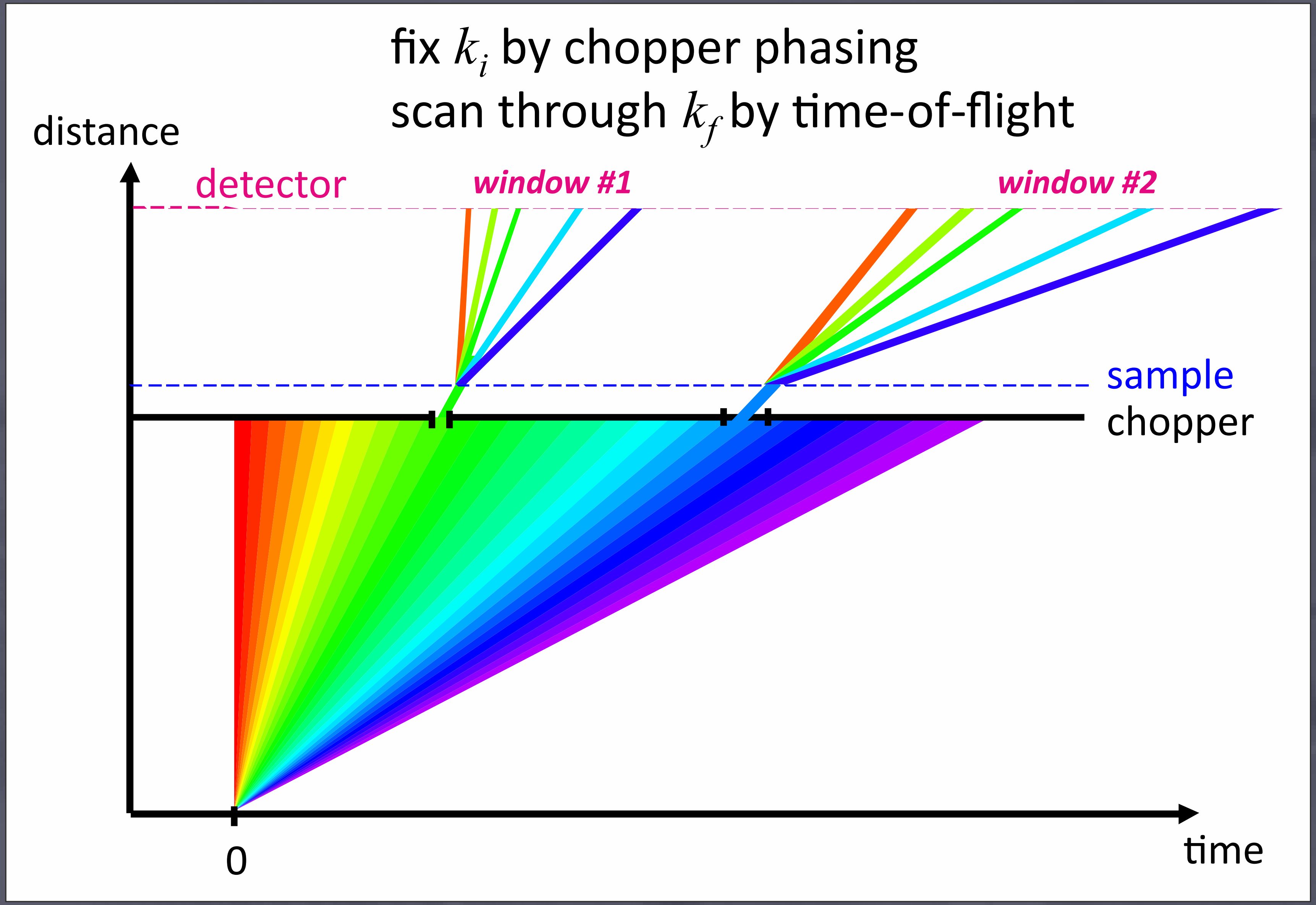


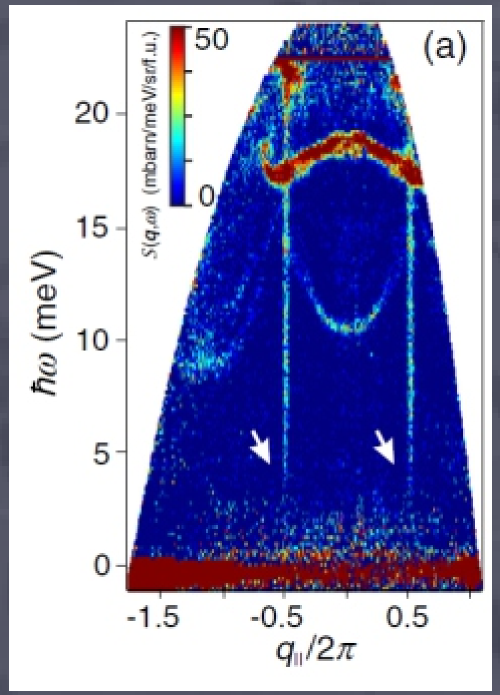


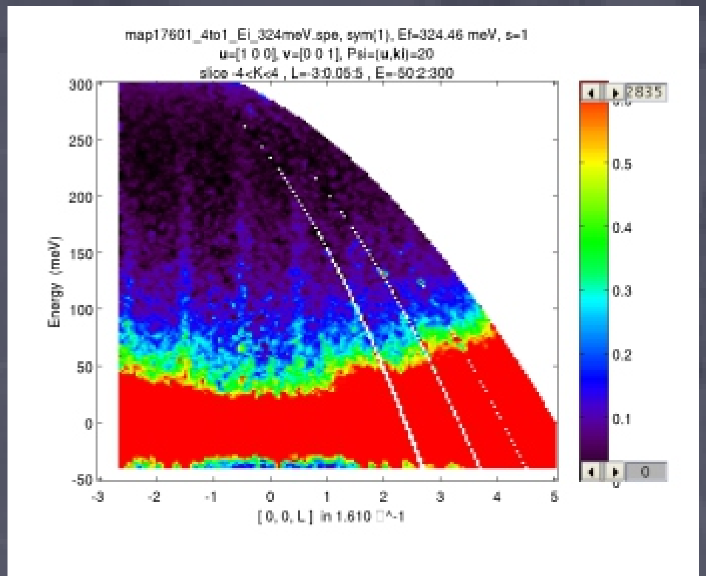
- Data come out as a 3D/4D matrix with a huge number of measured Q-points (qx, qy, qz). Each point is also resolved in energy-transfer... and H, T, E, P !!!
- Raw data files are 100 GB or even several TB
- Data collection can be a few days,while data analysis months or even years (first perform the experiment and then the PhD project).

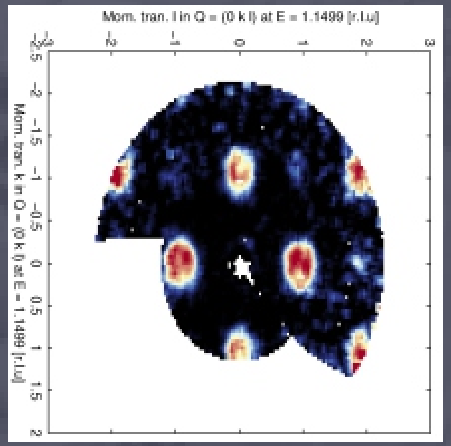
Multiple Time/Energy Windows

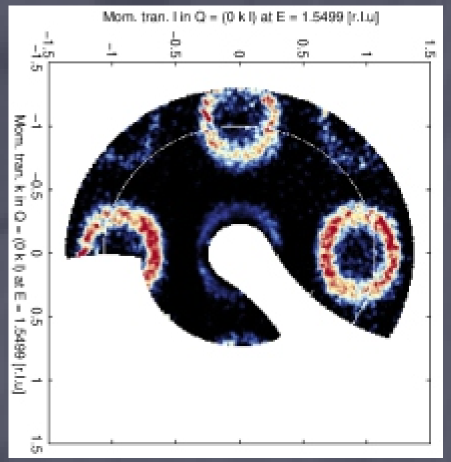
- By clever tuning of several chopper speeds and phases it is possible to gain several neutron energies in one single frame i.e 2 or 3 complete data sets simultaneously (high-resolution zoom + lower-resolution overview).

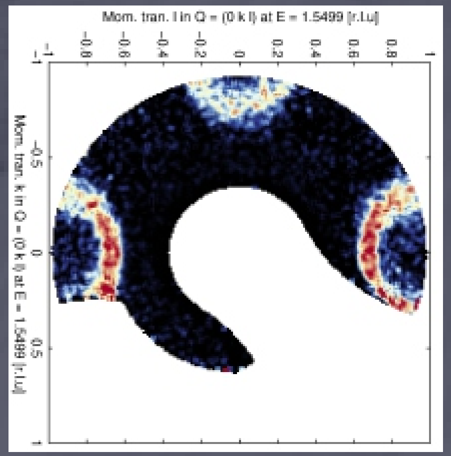






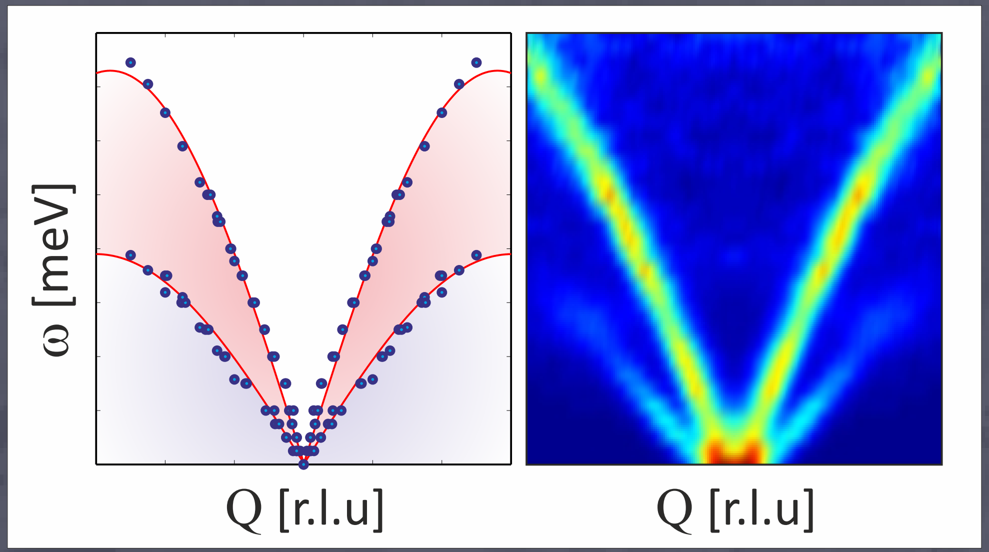






- Very efficient use of produced neutrons (much larger fraction of scattered neutrons are collected/counted (i.e. data).

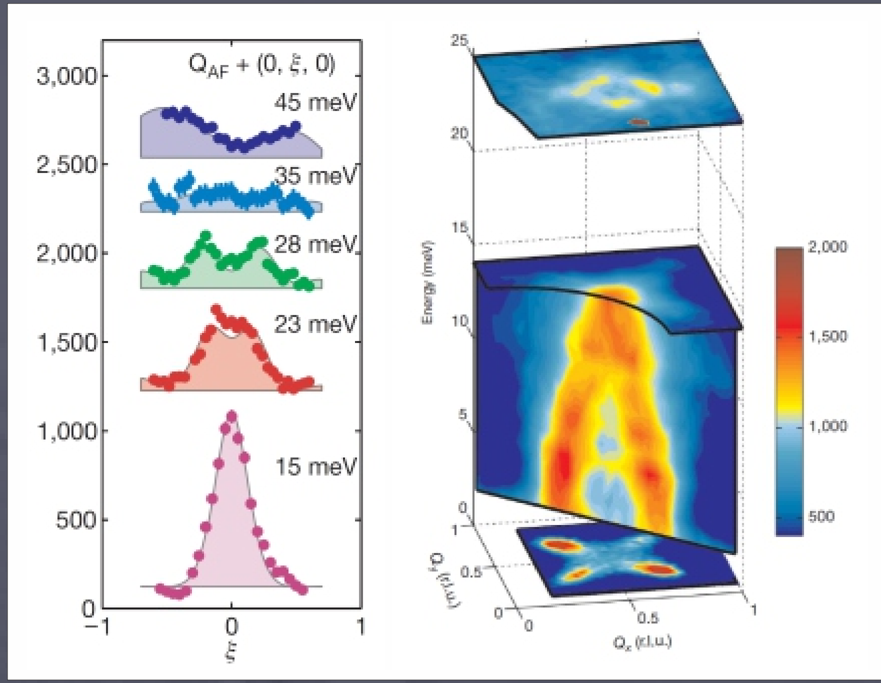
INS: Examples



NUCLEAR EXCITATIONS

- Lattice vibrations i.e. **phonons** have traditionally been extensively investigated (*e.g.* cooper-pair formation in conventional superconductors)

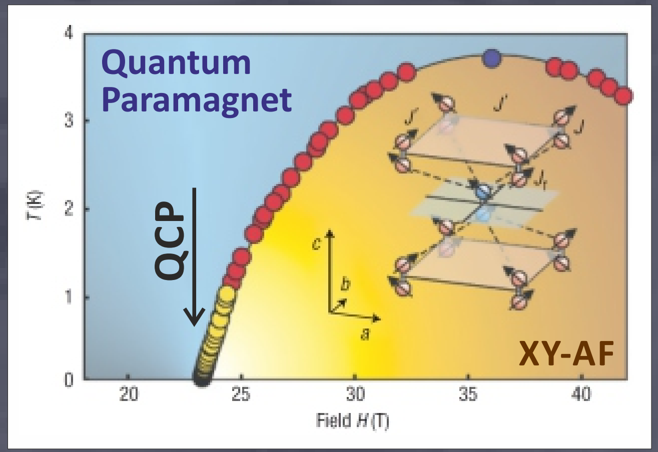
Boothroyd, Nature 471, 341 (2011)

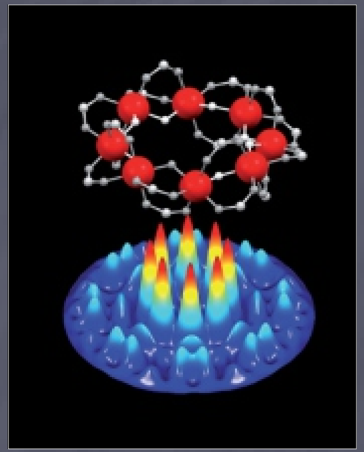


HIGH-TEMPERATURE SUPERCONDUCTIVITY

- HTSC emerges from AF parent compounds. INS has shown that **spin excitations** remain even in the SC phase.

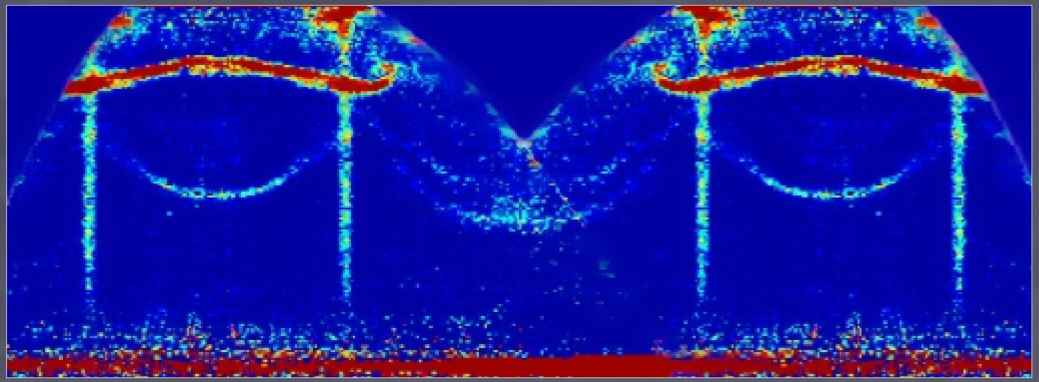
GIAMARCHI, Nature Physics 4, 198 (2008)





MAGNETISM

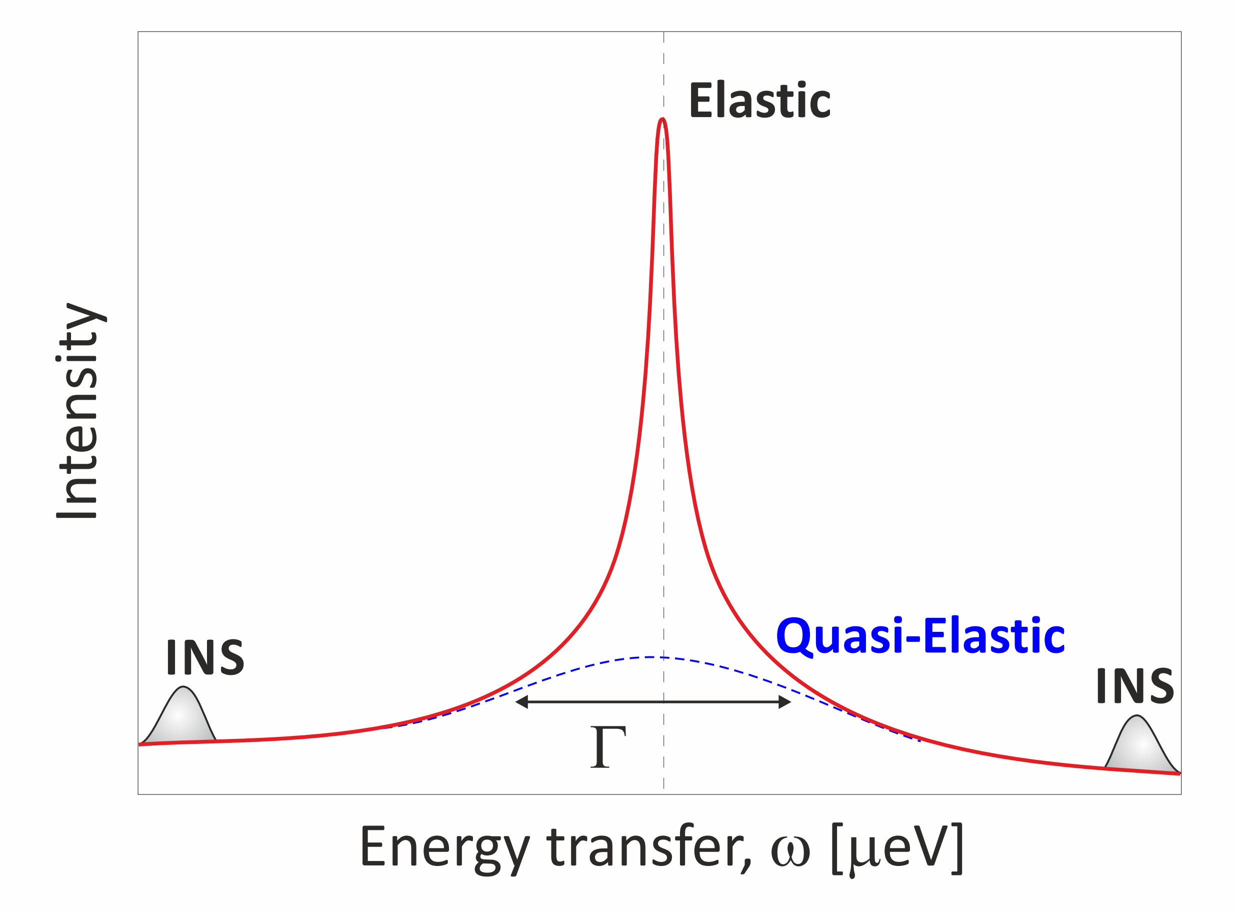
- **Spin-wave/magnon** mapping in exotic magnets (triangular frustration, square lattice AF etc.)
- Induce magnetic order by pressure, external field (**Bose Einstein Condensation and QCP** in quantum/molecular magnets).



Simutis, Phys. Rev. Lett. 111, 067204 (2013)

Quasi-Elastic Neutron Scattering (QENS)

- QENS is a ‘sub-genre’ of INS dealing with $\omega_{max} \approx \pm 2$ meV using high-resolution [μeV]
- QENS signal/line-width (Γ) supply info on particle/ion/molecular diffusion and/or dynamics on a 0.1–100 nm & ps–ns scale. Temperature dependence give activation energy (E_a) and Q-dependence information on geometry of the diffusion process (continuous, jump, rotation...).



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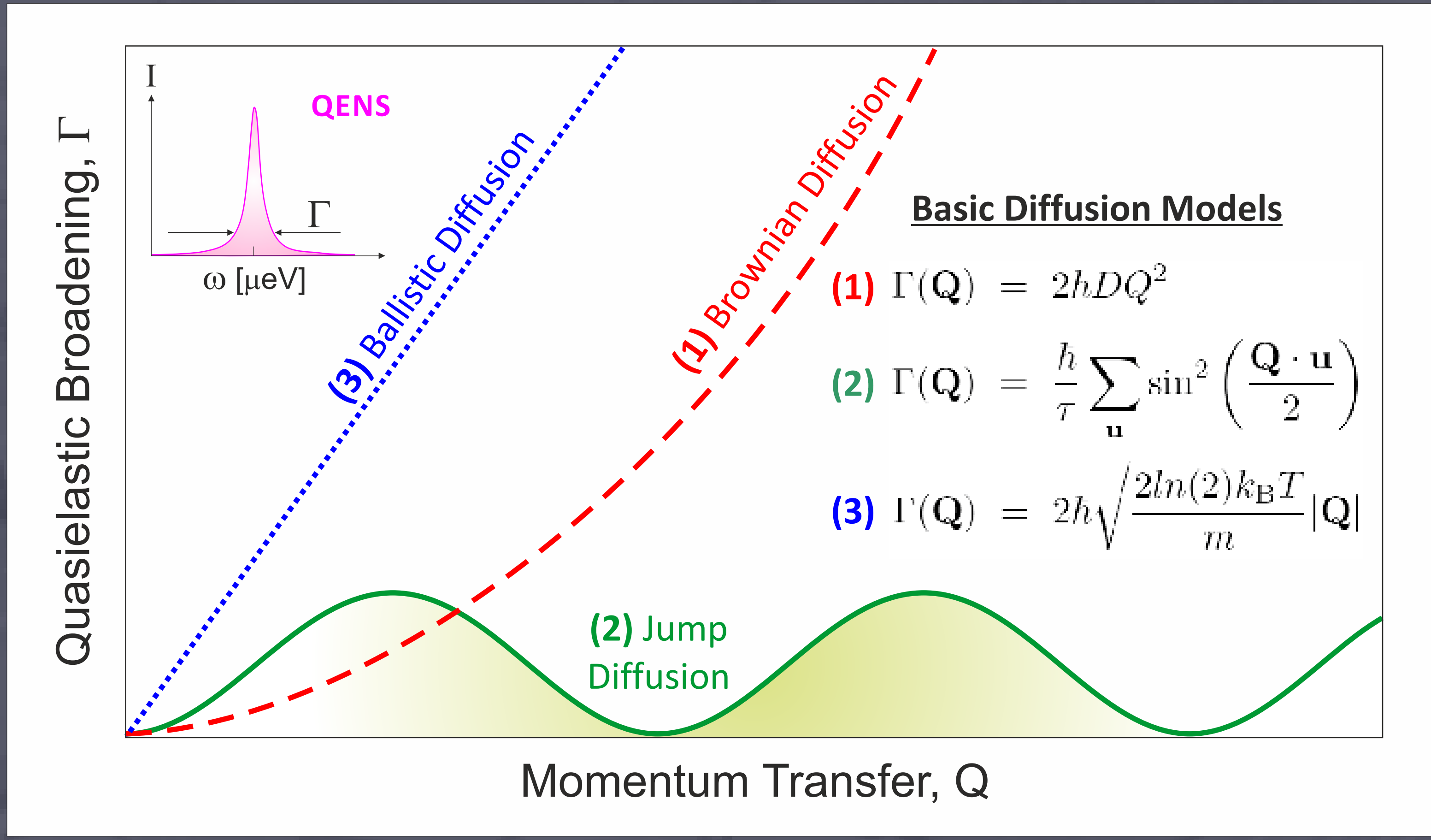

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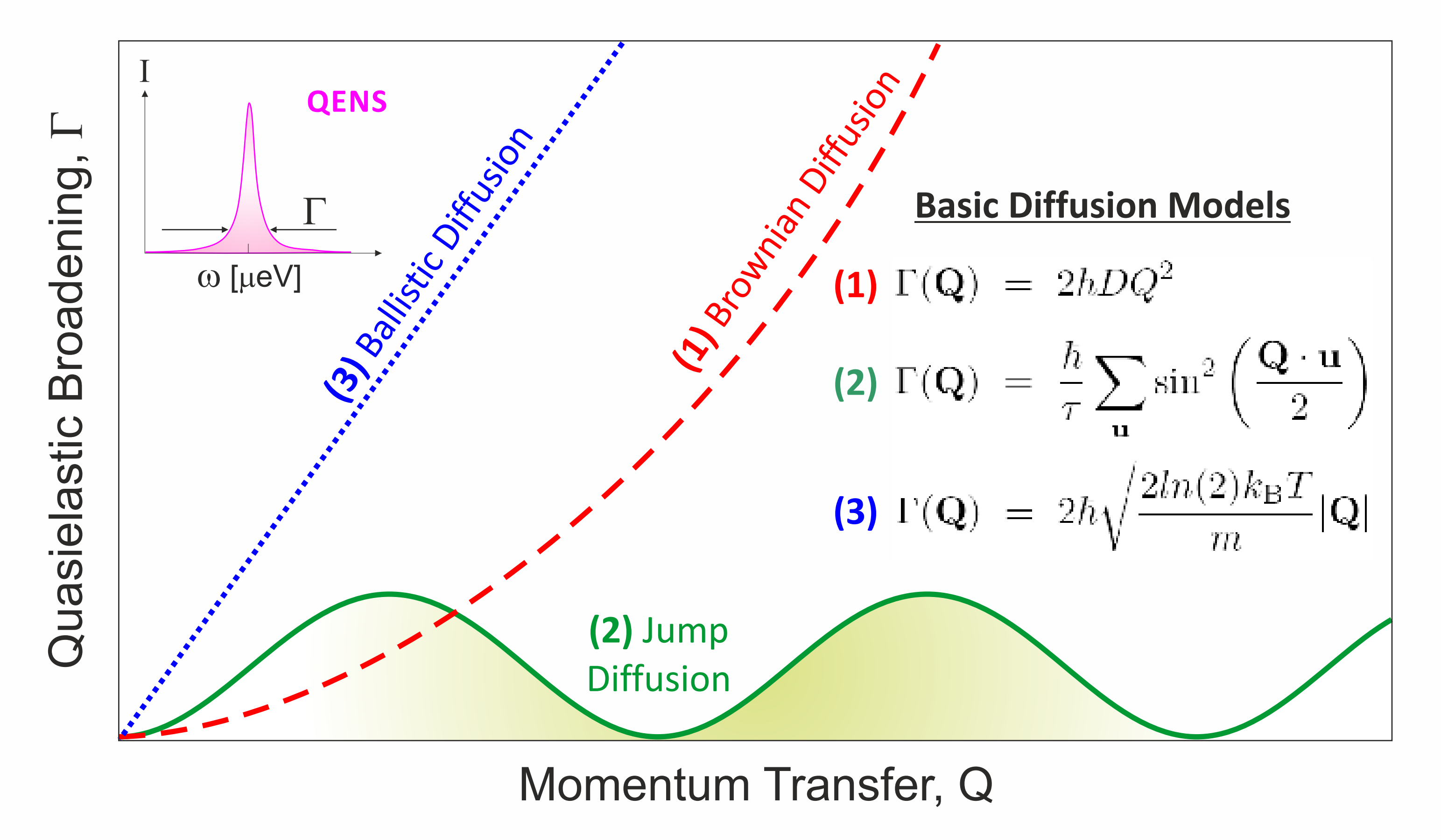
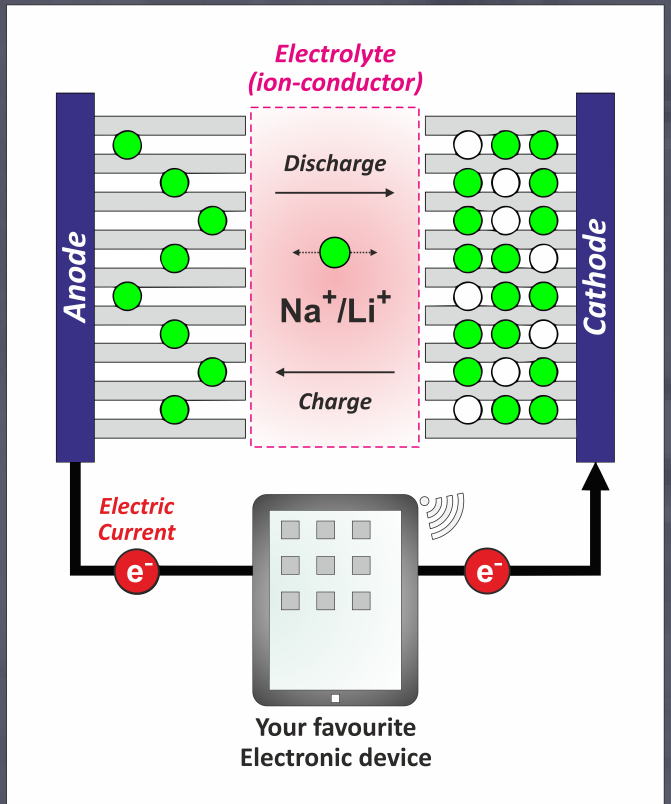
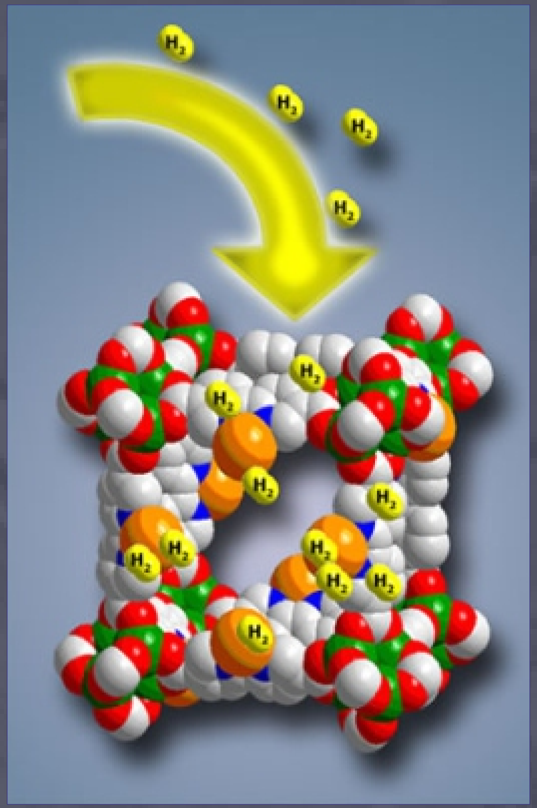
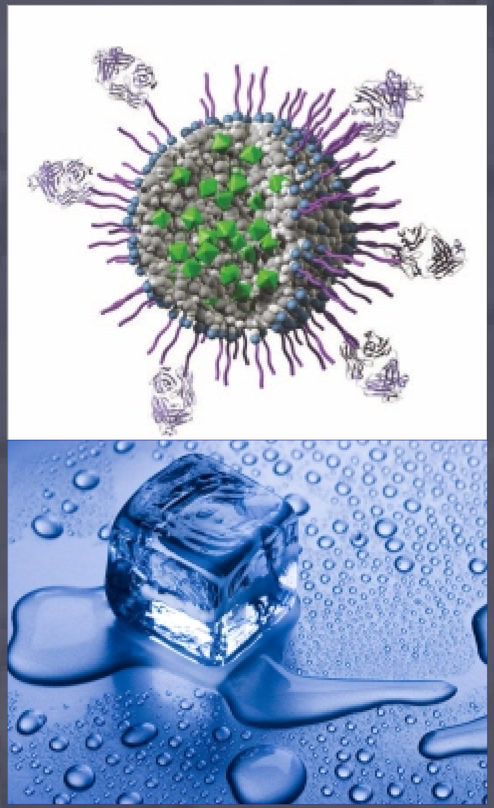






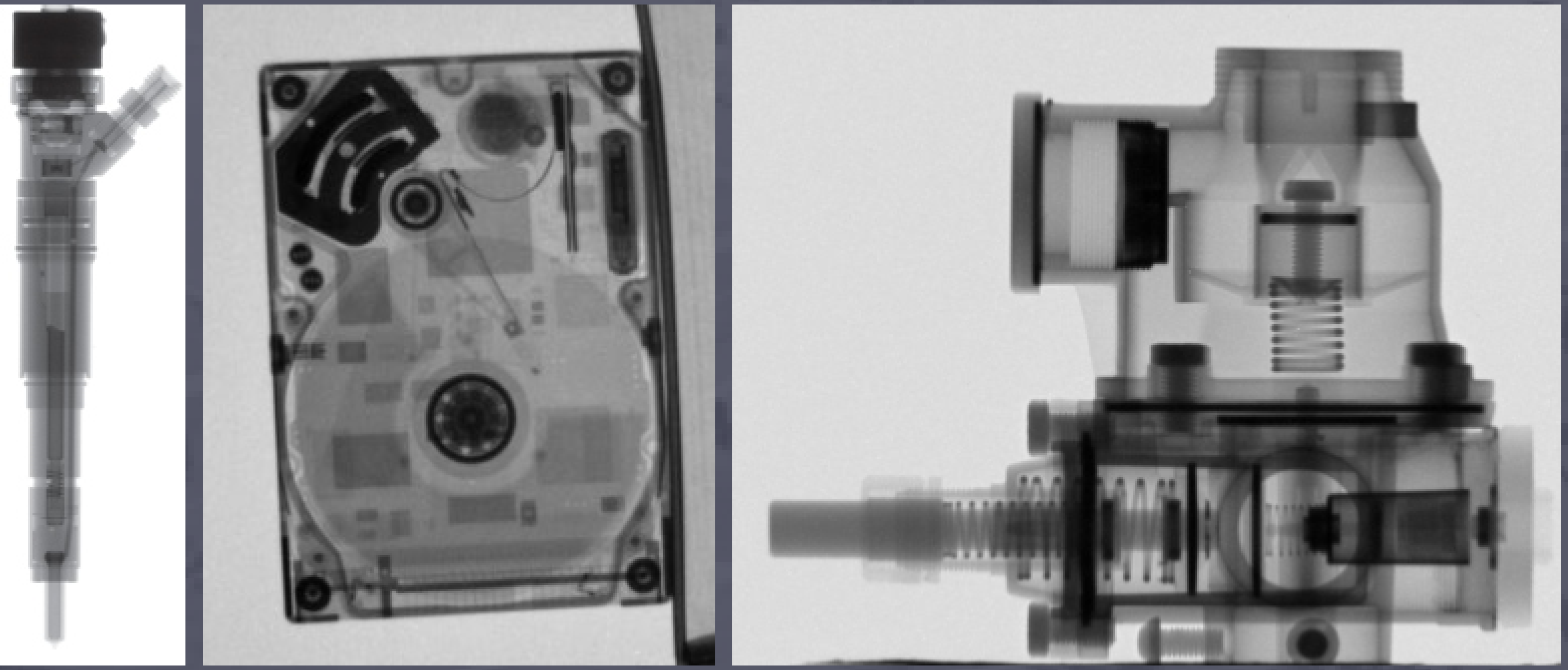


- Molecular dynamics (bond rotations...) and dyamics in bio / life-science
- Fluid dynamics including e.g. confined liquids and melting processes
- Energy materials including e.g. battery, hydrogen storage and fuel cells.

Neutron Imaging

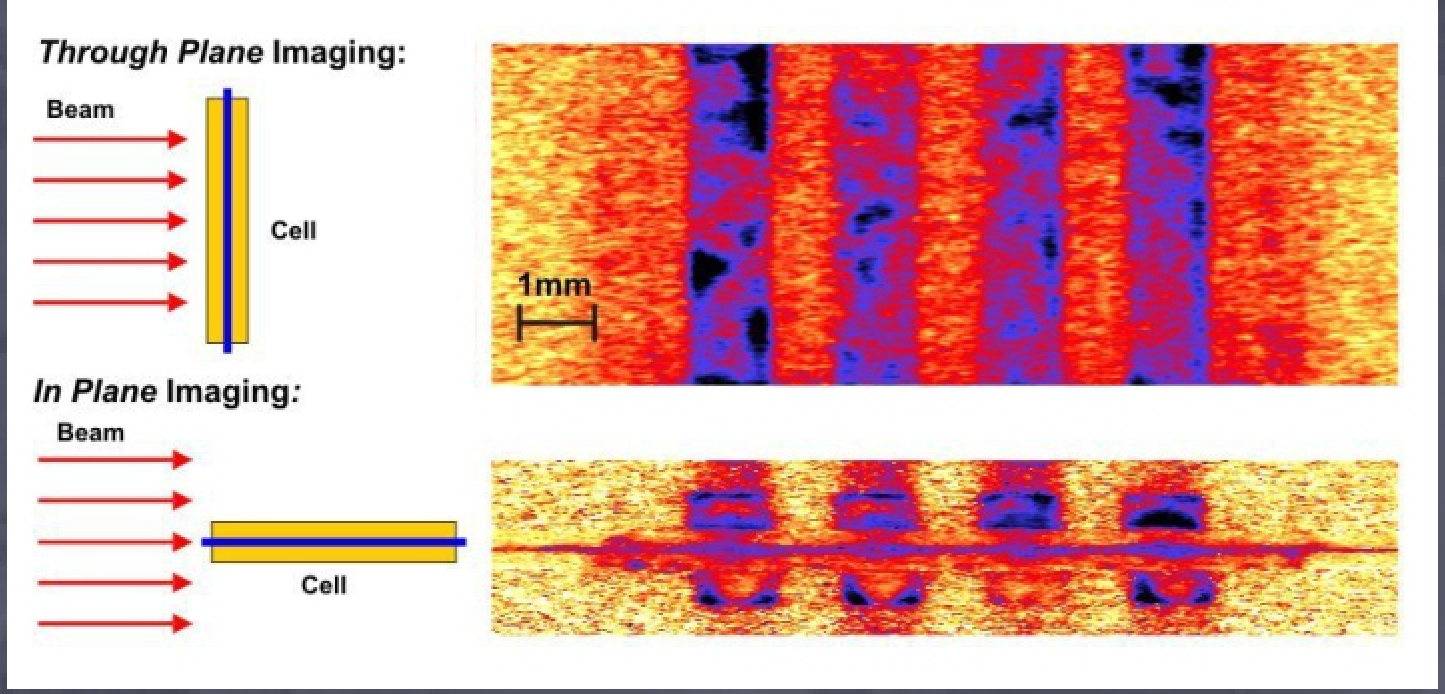
- Similar to an X-ray radiography but technically not a scattering technique
- Resulting image is based on the neutron attenuation properties of the different parts of the imaged object.
- Due to the different interaction mechanism of neutrons and X-rays with matter, neutrons delivers complementary information.
- Spatial resolution is on the order of micro-meter, but this is continuously being improved.

Non-destructive testing of mechanical components

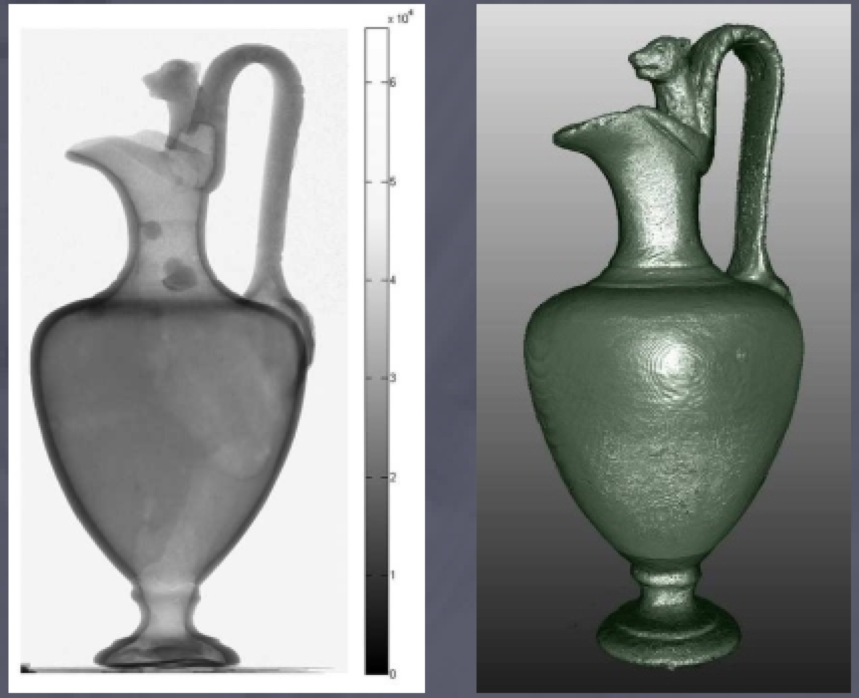


Root-system of plants

Stroboscopic measurement of water distribution in a stacked hydrogen PEM fuel-cell

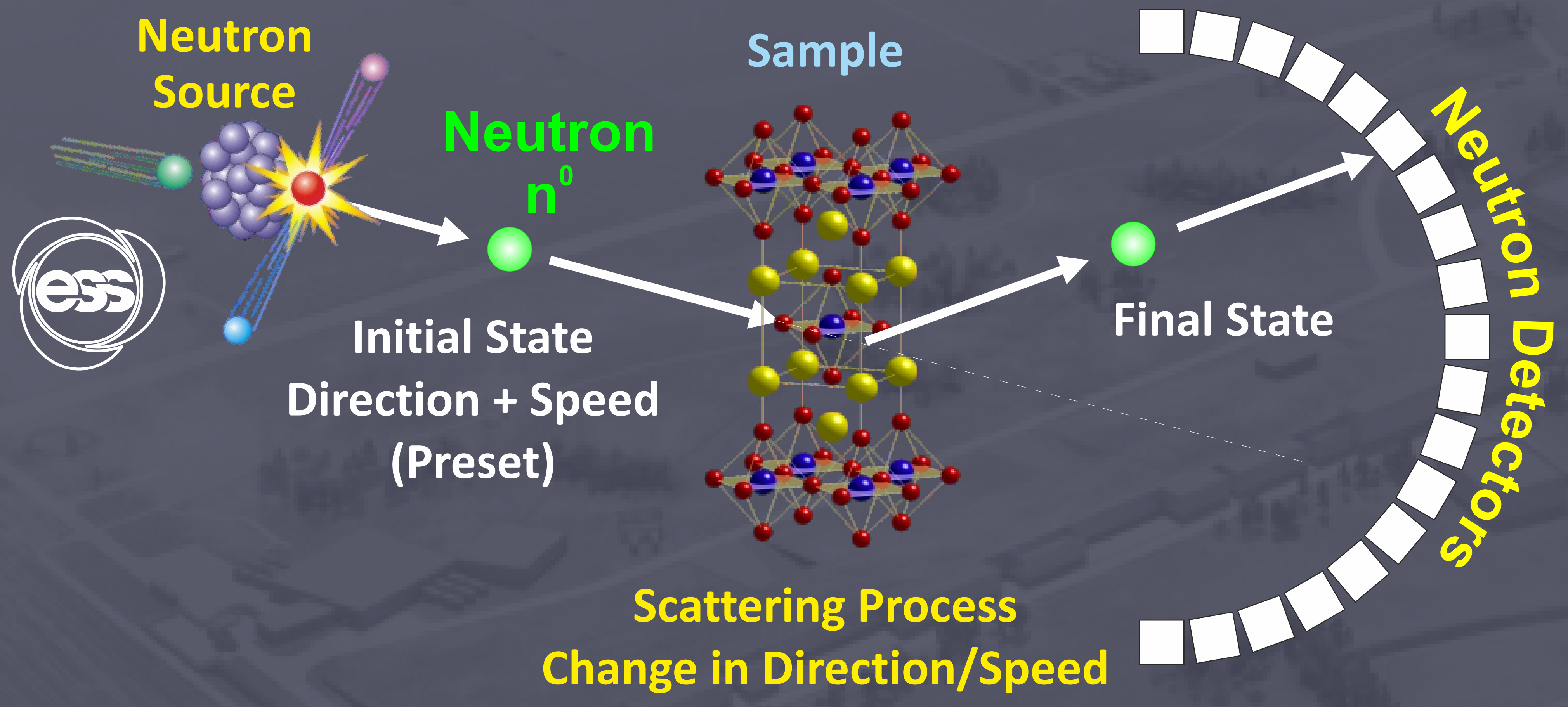


Radiography / Tomography of archeological artefacts

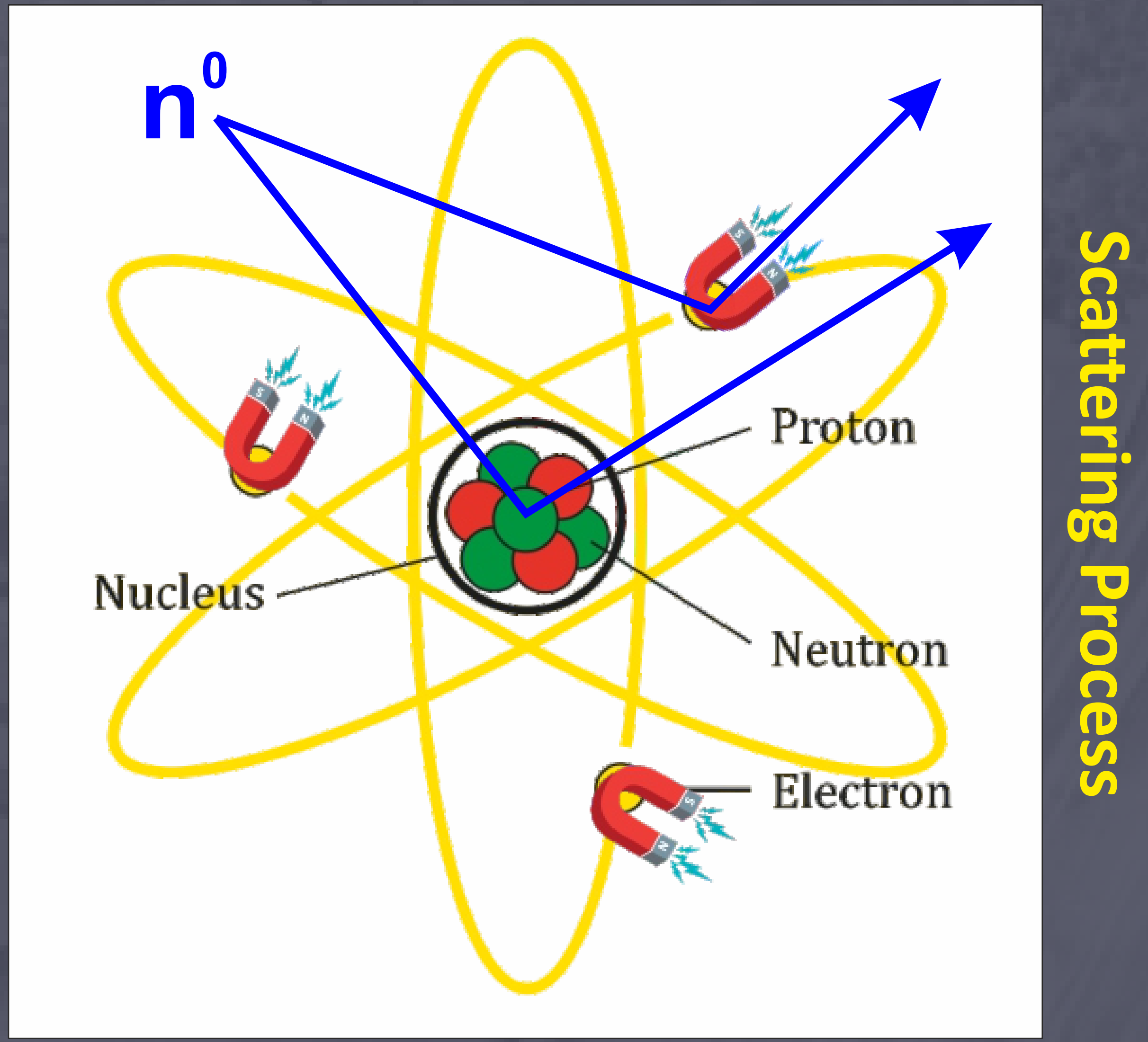


Neutron Scattering 101

- Neutron is a subatomic (very small) particle without charge (i.e. neutral) but with a magnetic moment (spin = 1/2).



Neutrons interact with both atomic nucleus and electron spins (magnetism) of the atoms



"Elastic Neutron Scattering"

Only detect change in direction/angle

Tells us about where atoms are and how spins align

"Inelastic Neutron Scattering"

Detect change in direction/angle + speed/energy

Tells us what the atoms and electron spins 'do'

Atomic Structure & Dynamics + Magnetism

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Neutron Sources of the World

http://www.neutrons.se/

http://www.neutronsources.org/

http://www.ncnr.nist.gov/nsources.html

EUROPE

ILL, Grenoble, France
ISIS/RAL, UK
SINQ, PSI, Switzerland
FRM-II, Germany

BER II, HZB, Berlin, Germany (closed !!!)
LLB, Saclay, France (closed !!!)
IFE, Kjeller, Norway (closed !!!)

OTHER EXAMPLES

HFIR/SNS, Oak Ridge, USA
J-PARC, Japan
ANSTO, Bragg Institute, Australia

UNDER CONSTRUCTION

Lund, Sweden — EUROPEAN SPALLATION SOURCE

Dongguan, China — SNS

European Spallation Source (ESS)

- European flagship project constructed in Lund with 15 member countries & Sweden as host
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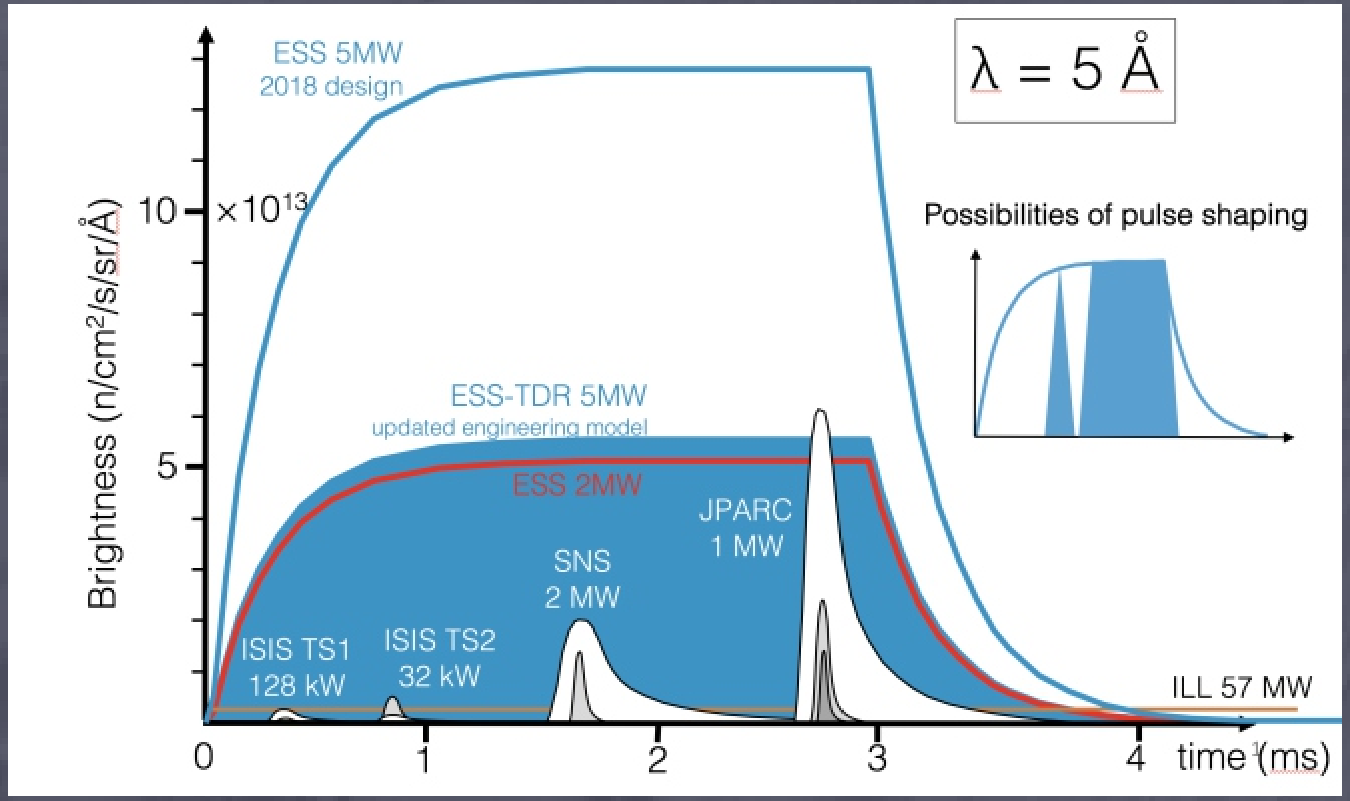
- Neutrons and then user operation expected ~2025...

ESS: A world-leading Neutron Facility

- ESS will clearly be the world's most intense neutron source
- But all technical aspects are "better": moderators, detectors wave-guides = also more efficient use of produced neutrons
- First 15 instruments are on average ×20 better (at 2 MW) than best existing instruments. But some ultimately ×250 !!!
- Now: measure for 20 or 250 days → ESS: measure 1 day !!!



- The result is that we can measure faster and/or study much smaller samples.
- "Game changer" for many many fields *e.g.* protein crystallography, quantum materials, energy, ...
- In situ/operando studies will strongly benefit with better time-resolution and lower background
- Extreme conditions much easier, where we can push the limit + use multiple conditions!
- Measurements of dynamics (inelastic + QENS = spectroscopy) will have a new world to explore
- Completely new way of conducting neutron scattering (J-PARC/SNS show a teaser...)

"The instrument suite of the European Spallation Source" – Nuclear Inst. and Methods in Physics Research, A 957, 163402 (2020)

ESS Construction Phase

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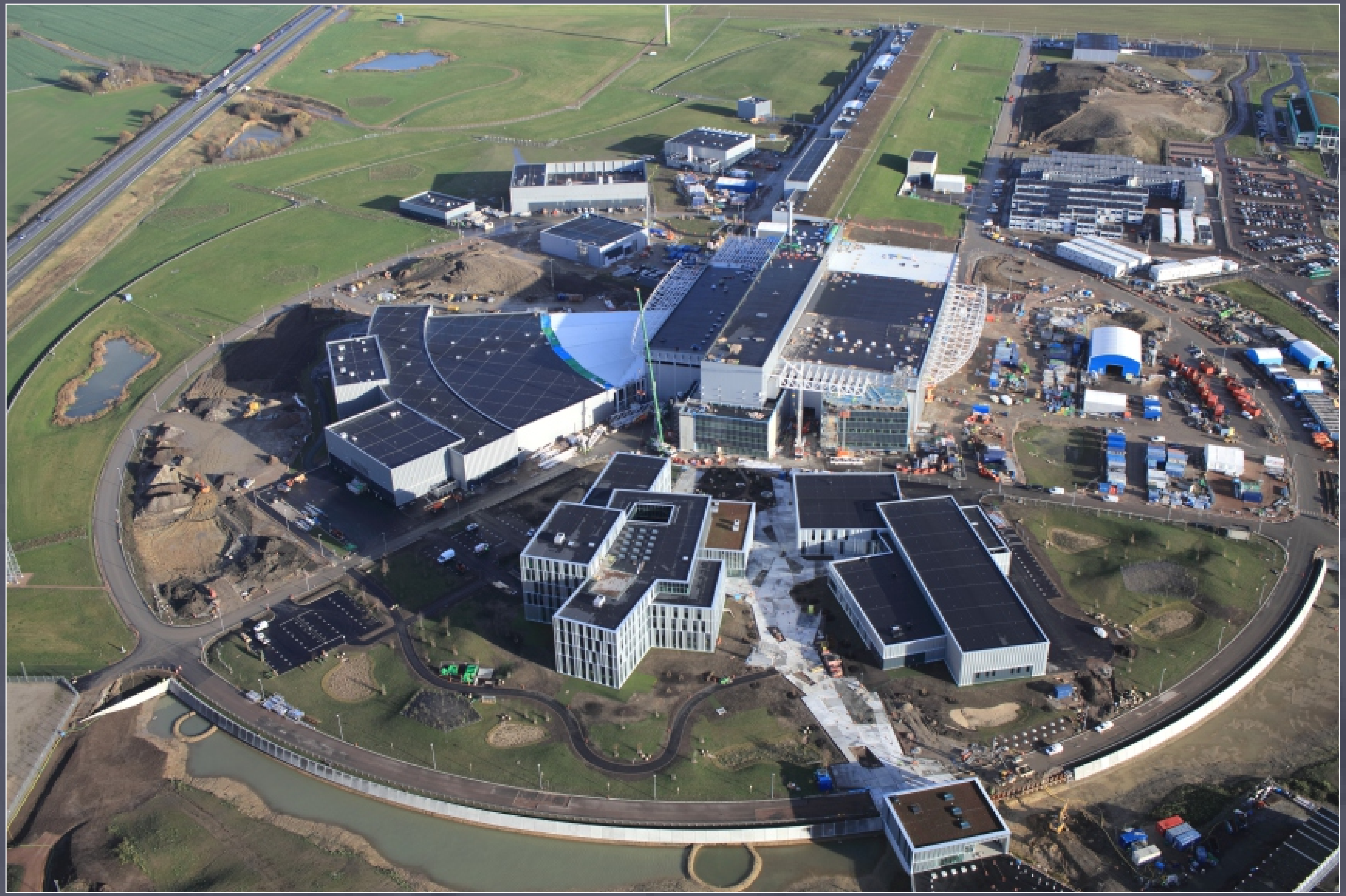
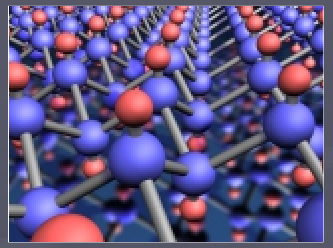
January 2021 (~80% Complete)

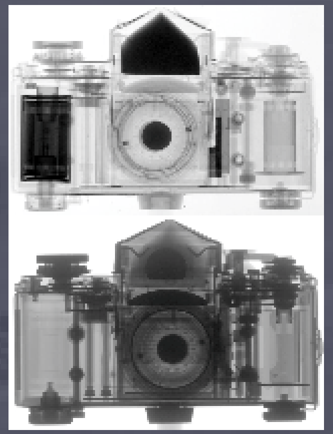


EUROPEAN
SPALLATION
SOURCE

Neutrons & X-rays

- Neutron and X-ray scattering techniques are complementary to each other.
- Together they create a very powerful experimental tool-box for a wide range of research fields.





- Deduce complex crystallographic structures that contains atoms visible/unvisible by X-rays and neutrons, respectively.
- Connection between changes in magnetic spin structure and very subtle structural transitions.
- Contrast variation in imaging/tomography techniques.
- Covering different inelastic energy ranges for excitation studies using INS and RIXS.

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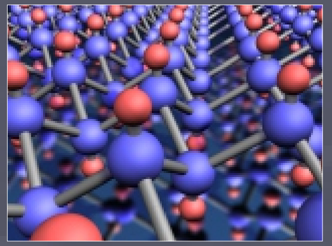

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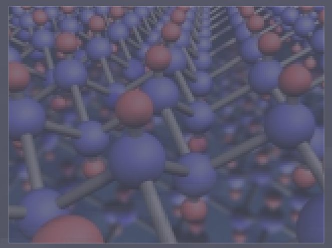
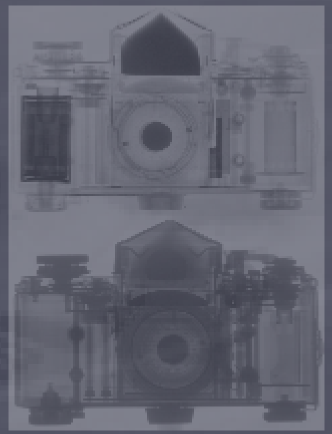

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Swedish Beamline @ PETRA III

Neutrons vs. X-rays

NEUTRONS	X-RAYS
Low Intensity	High Intensity
Slow Measurement	Fast Measurement
Bulk properties	Not always bulk properties
Extreme Conditions /In operando	"Difficult"
No beam damage	Potential beam damage (bio/organic)
Access to light elements Isotope Sensititive / Labelling	No access to light elements or Isotope labelling (especially H/D)
Better energy resolution	Worse energy resolution
Direct access to magnetism	No direct access to magnetism
Difficult to manipulate beams	Easy to manipulate beams

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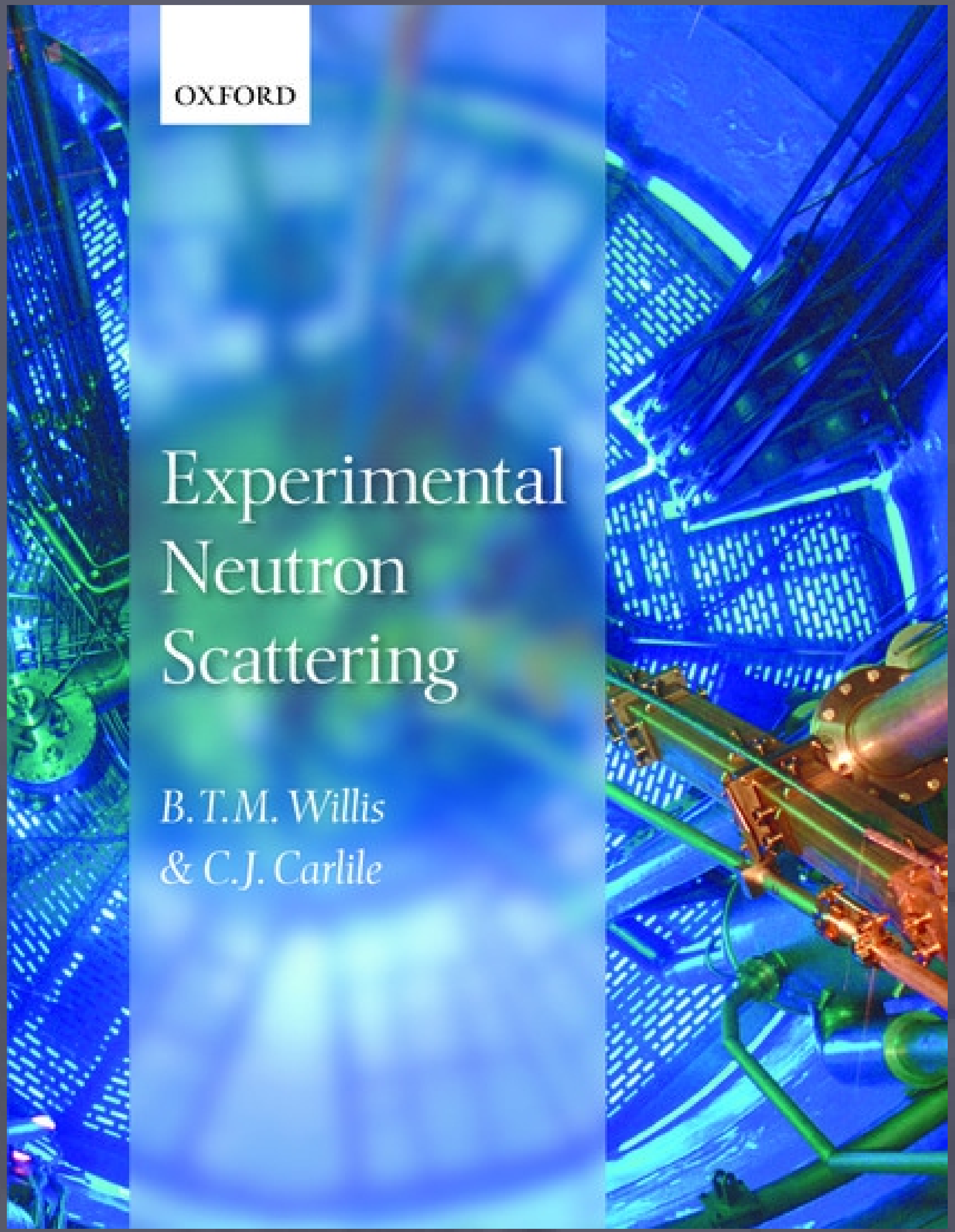
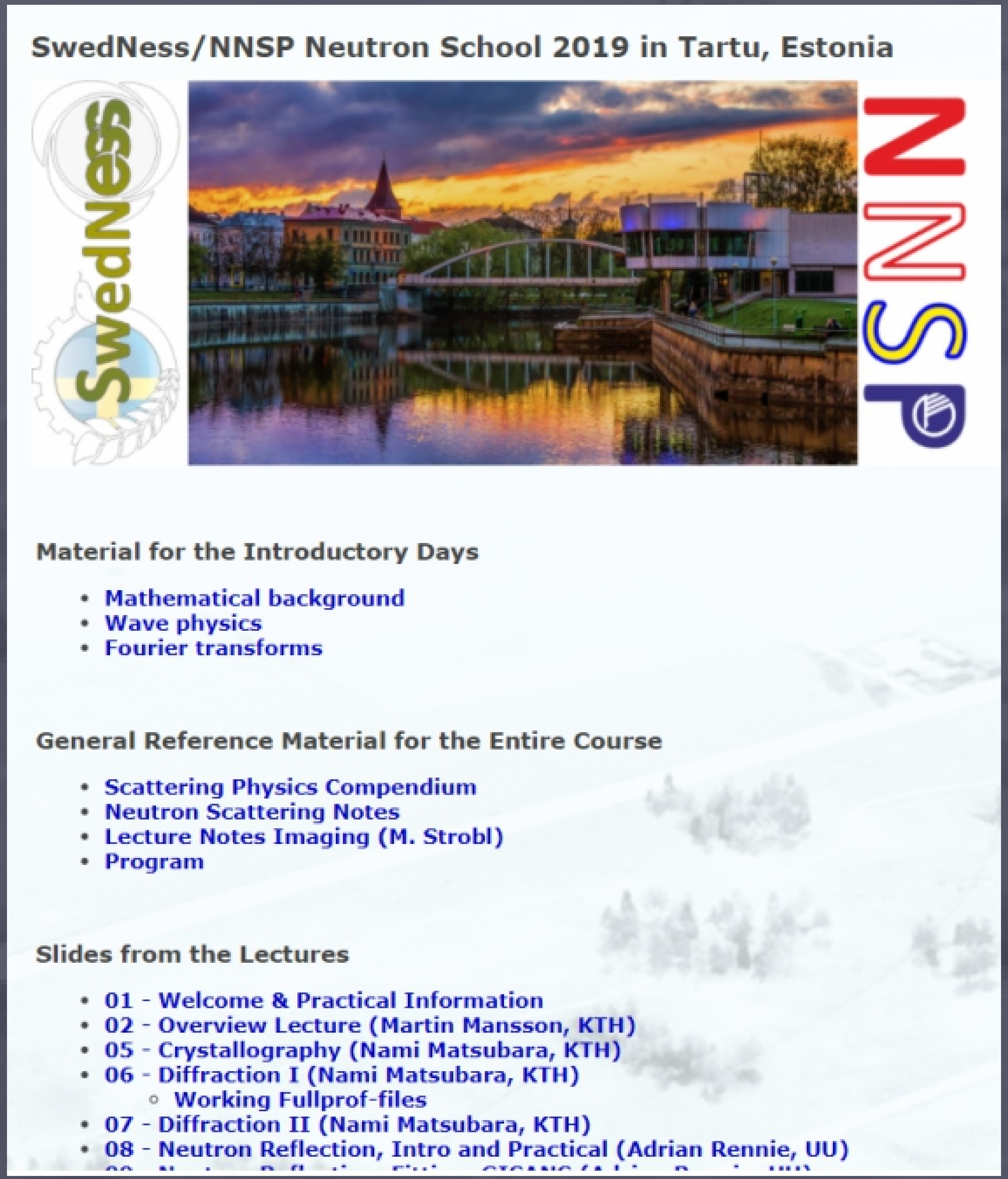
How to Practically do Neutron (X-ray) Experiments

- Have an idea for how neutrons can help your research
- Talk to an expert (*e.g.* send me an e-mail: condmat@kth.se)
- Consider your sample!!! (available size/mass, crystal/powder/thin film).
- Think about if you sample contains elements with low scattering or high absorption
  http://www.ncnr.nist.gov/resources/n-lengths/
- Select appropriate source and instrument for your experiment (check deadlines!)
- Contact instrument responsible to discuss experiment (>1 week before you submit proposal!)
- Write a proposal and apply for beamtime at your selected neutron source/instrument
- Cross your fingers and wait for the review committee + in some cases ”national quota”
- If you obtain beamtime start to prepare your experiments well advance
  (align crystals, manufacture sample holders etc.)
- Check necessary paperwork at source and perform the mandatory ”safety training”
- If you plan to do experiments at different sources with same samples: consider activation of your samples (active sample transport is complicated and expensive!)

Neutron References

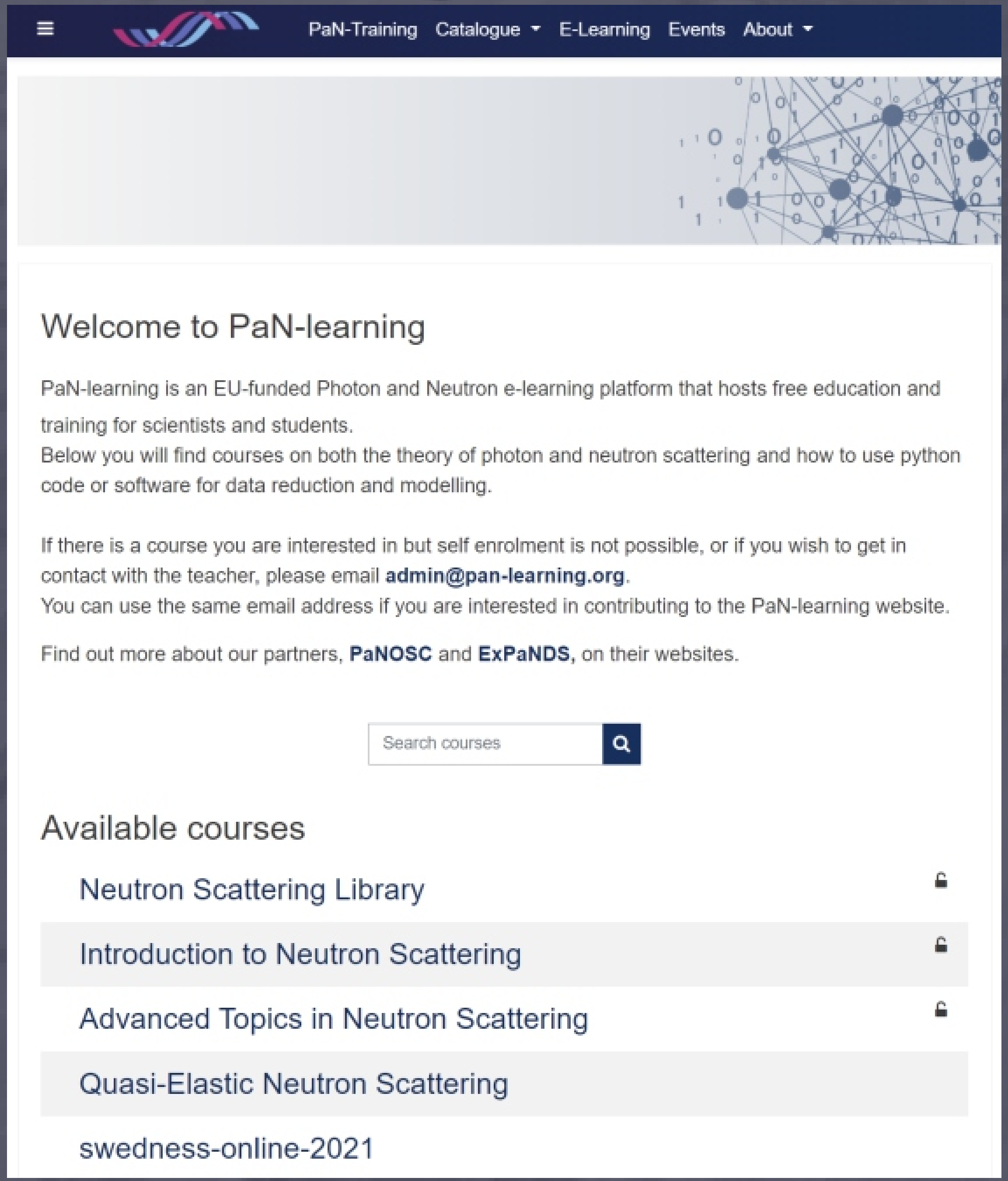


Experimental Neutron Scattering
B. T. M. Willis and C. J. Carlile
Oxford University Press (2013)
ISBN-13: 978-0199673773



http://www.neutrons.se/Tartu2020/

http://www.SwedNess.se



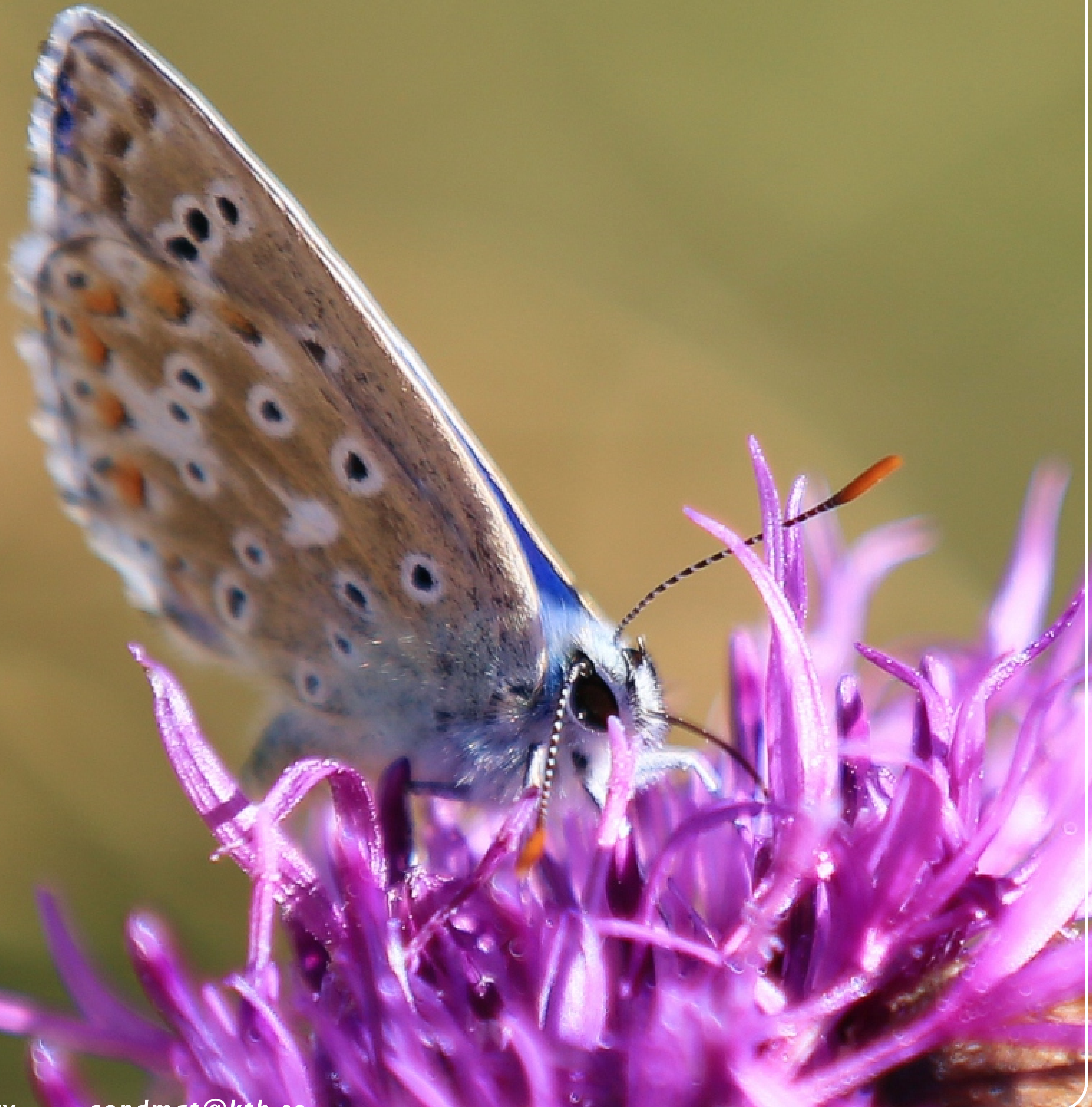
https://pan-learning.org/

Conclusions

- Neutron scattering is the most versatile & poweful experimental technique for studying intrinsic material properties.
- Tell us where atoms are and how spins align (elastic)
- Tell us how atoms and spins move / excitations (inelastic)
- The world's most intense neutron source, ESS, is currently being built in Sweden (Lund), user operation starts ~2025.
- Governments & funding agencies now put a lot of funding for strengthening the neutron scattering community.
- ESS + MAX IV + PETRA III = Great Opportunities !!!

Acquiring experience and expertise in neutron scattering will be favorable for science/industry and a career in the North !!!

Thank You for Your Attention !!!



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