NEUTRONS FOR SCIENCE®

The Institut Laue Langevin
Global leadership in neutron science

EIROforum Serving European Science

european photon & neutron science campus

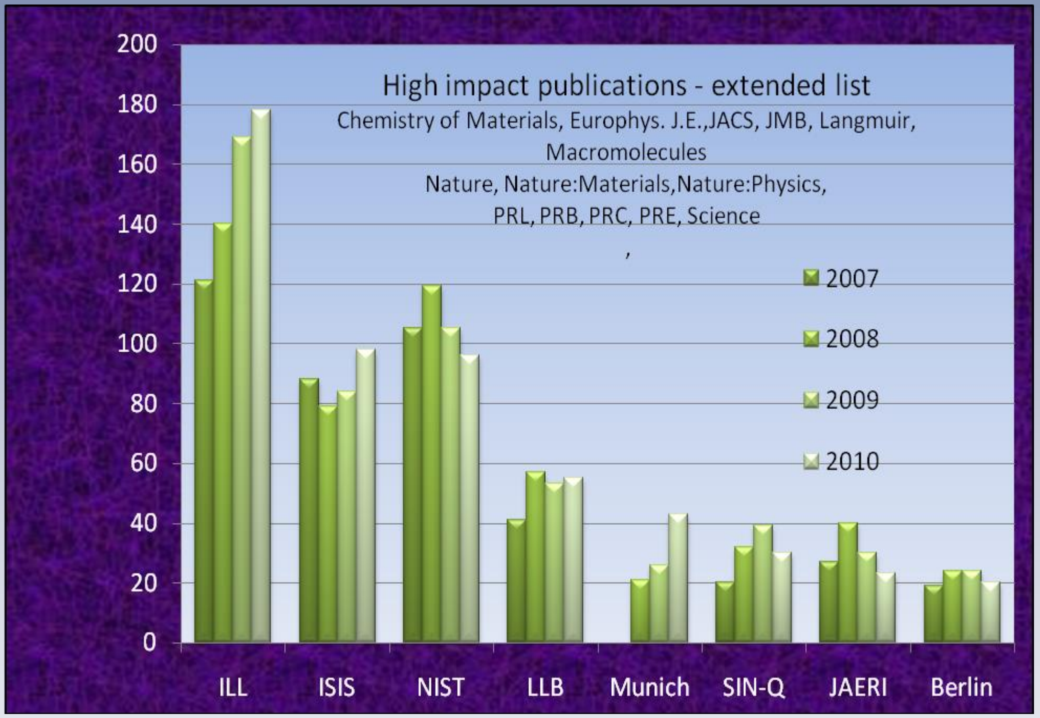
The Institut Laue Langevin At the service of the European neutron community

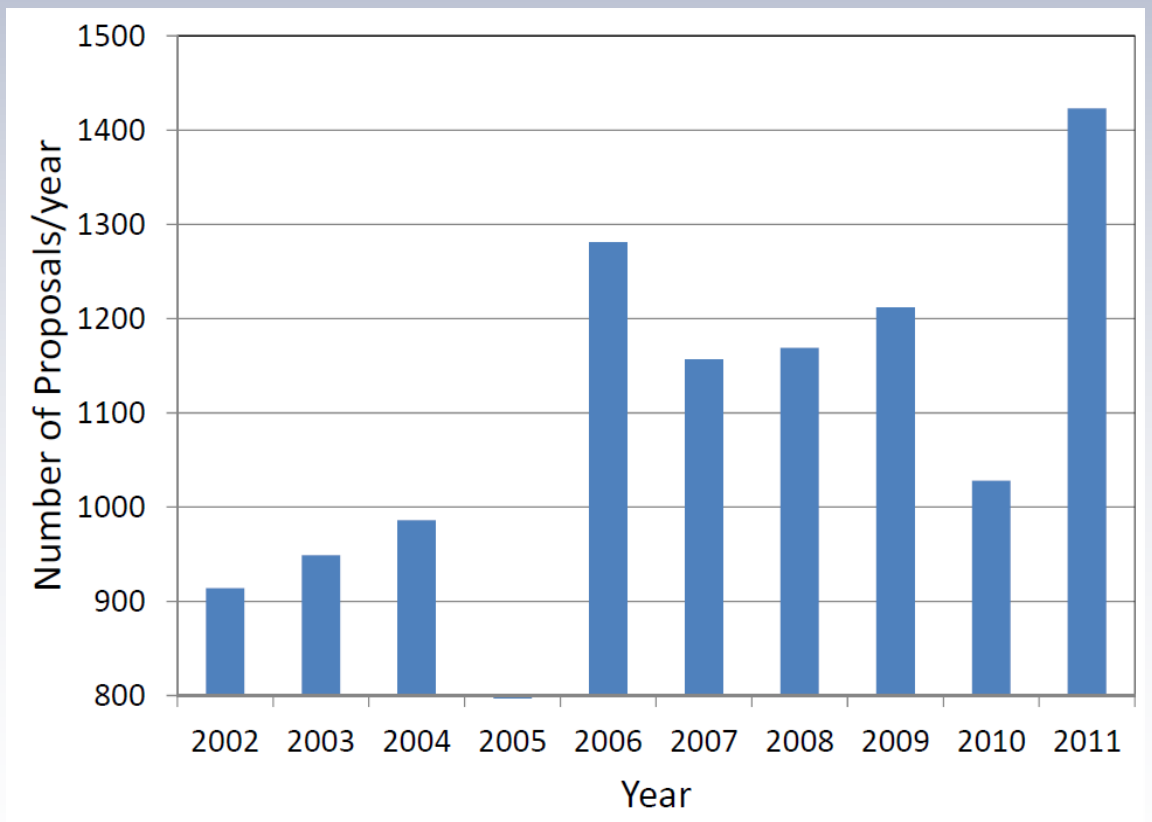
- Created in 1967.

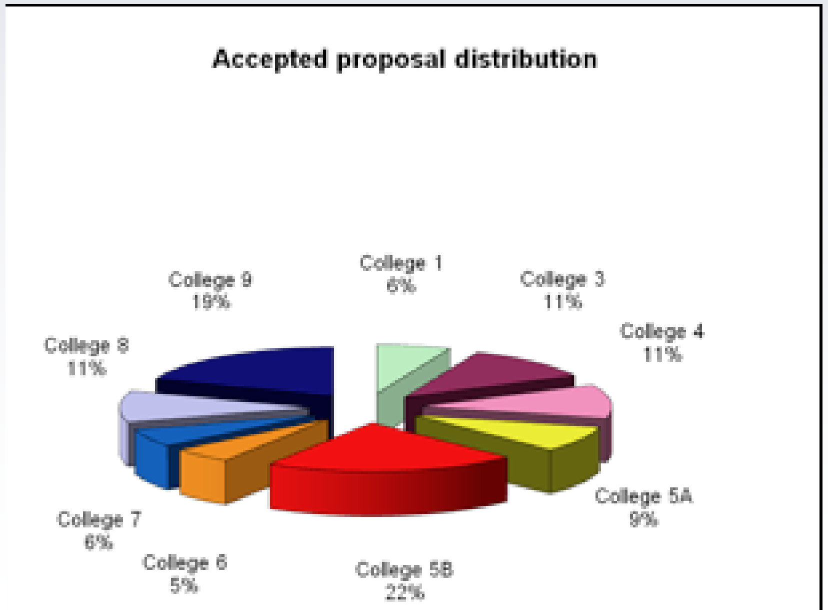
- 3 Associates (France, Germany and the United Kingdom)
- 11 scientific members
- A staff of 500 people
- An annual budget > 80 M€
- An investment share of 20 %

The Institut Laue Langevin: A reference in terms of knowledge creation within the neutron community

1400 peer reviewed proposals
2000 users
800 experiments
600 publications

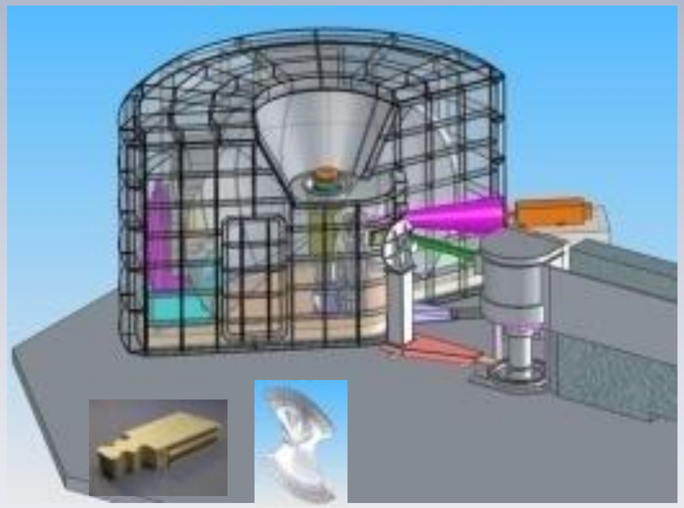


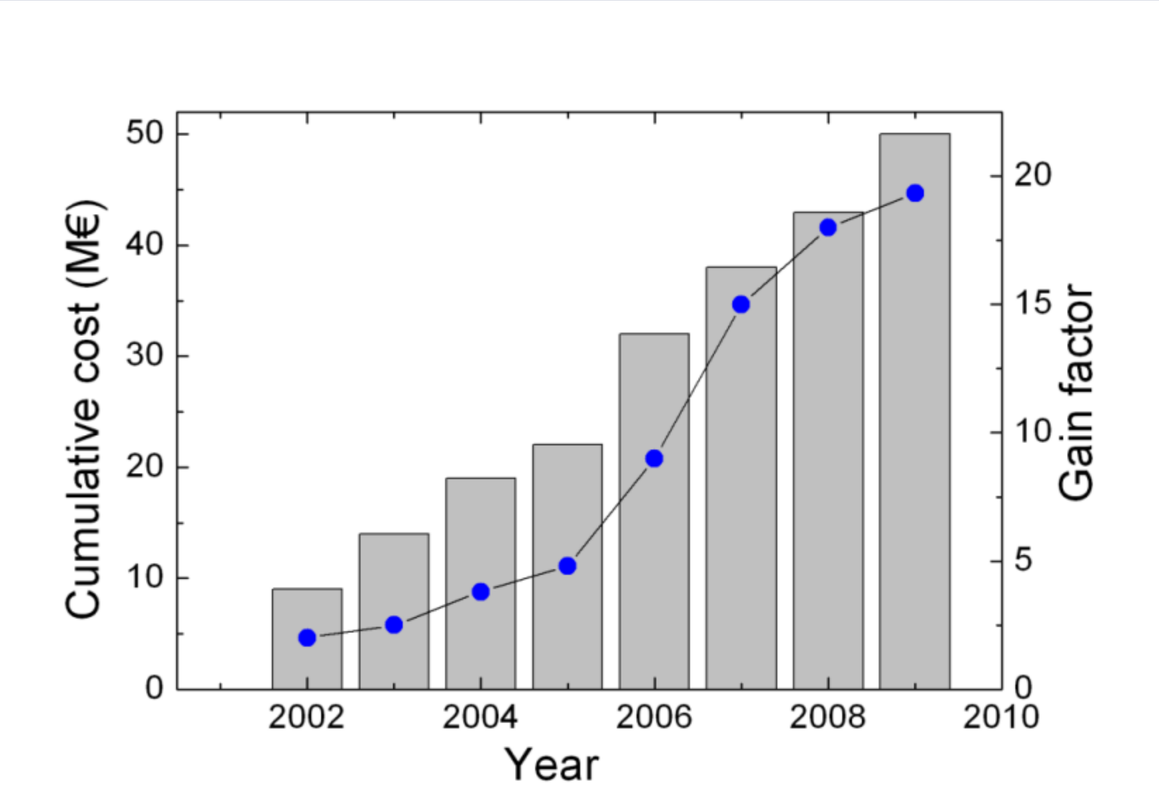


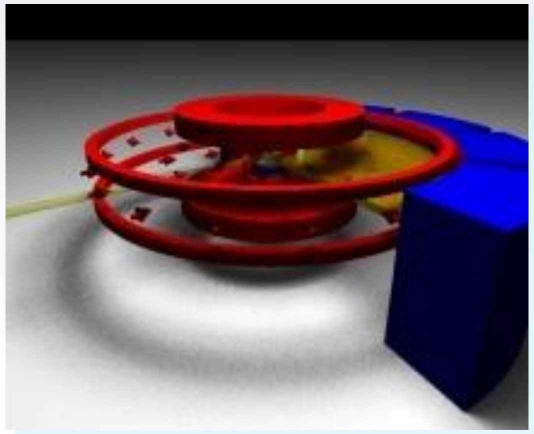


Continuous upgrading of the scientific infrastructure

- The « Millennium Programme » has allowed to increase the overall performance by a factor of 20.
- ILL-2020 is on ESFRI roadmap.





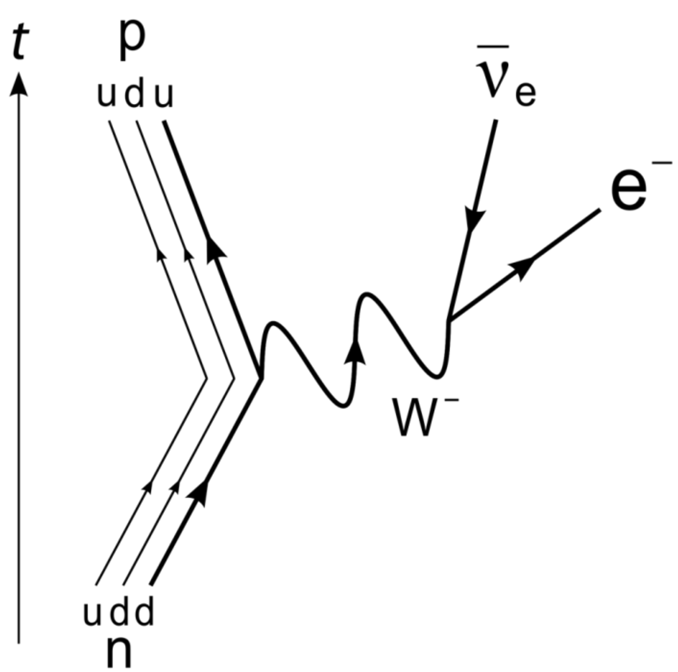


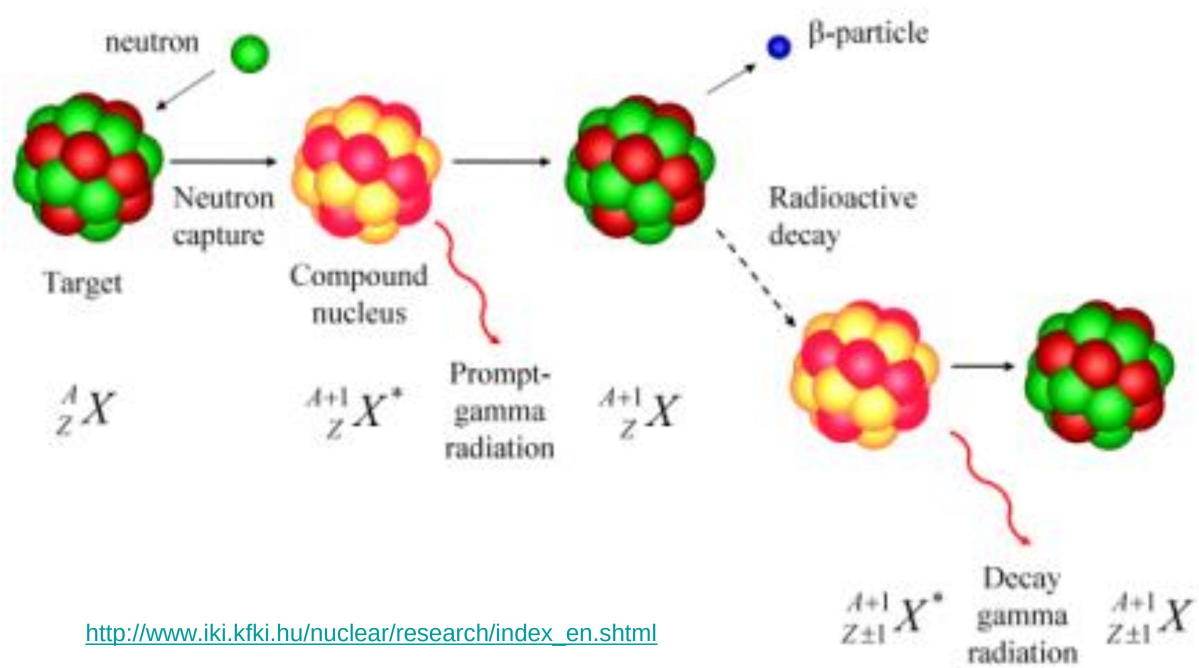
Science enabled by neutron sources

Helmut Schober
Institut Laue Langevin

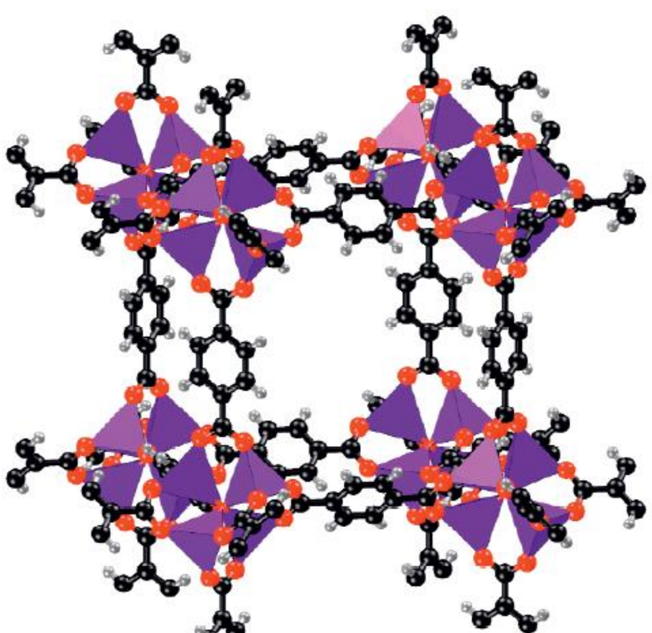
The neutron as probe of matter

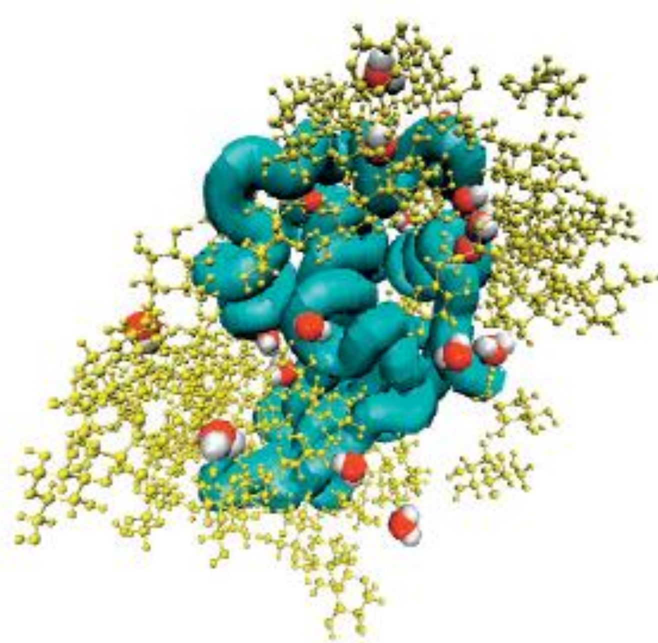
From the elementary particle to macroscopic objects

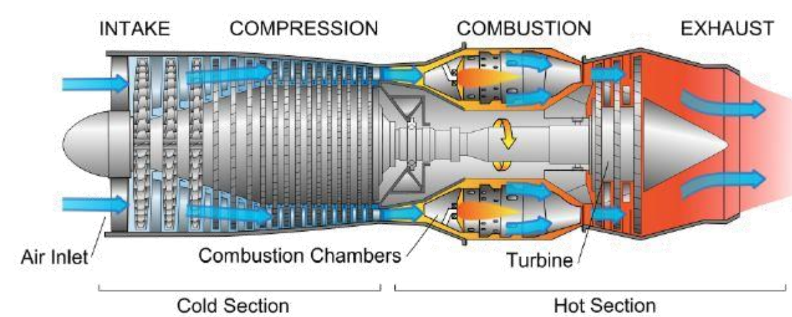




http://www.iki.kfki.hu/nuclear/research/index_en.shtml



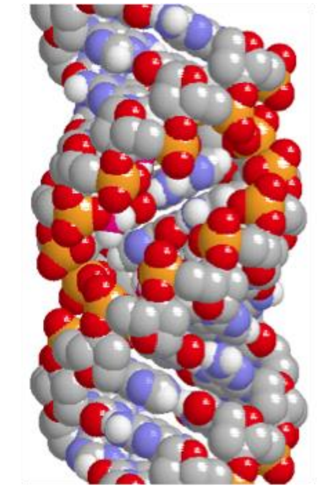




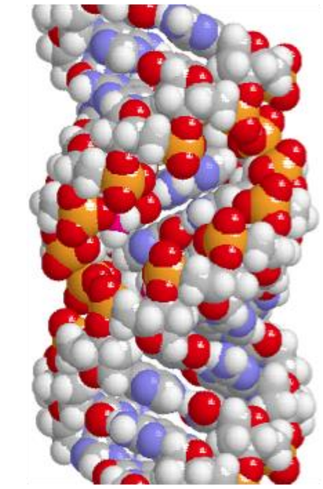
The decisive properties of the neutron

- Electrically neutral.
- Interacts with the nuclei via the strong interaction.
- Carries a magnetic moment.
- Possesses a mass slightly above that of the proton.

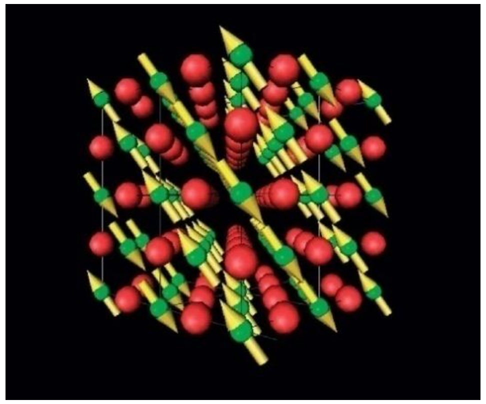
- Consequences:
  - Simple theoretical description (Born approximation).
  - Isotope specific contrast.
  - Gentle and deeply penetrating.
  - Extreme sensitivity towards magnetism.
  - Extremely sensitive to microscopic dynamics (fs to µs).

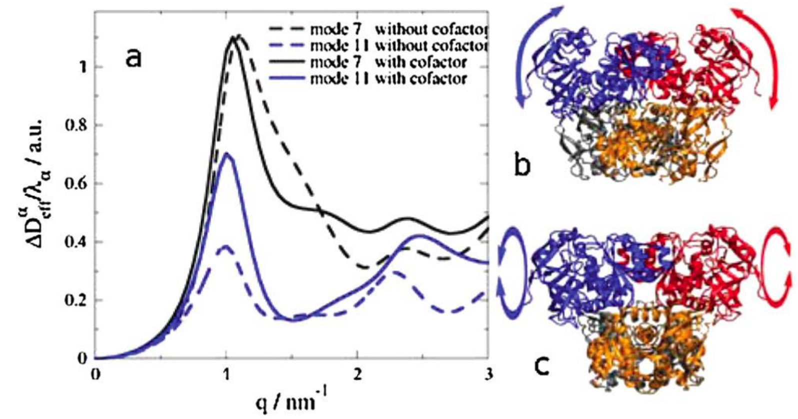


DNA without H



DNA with H



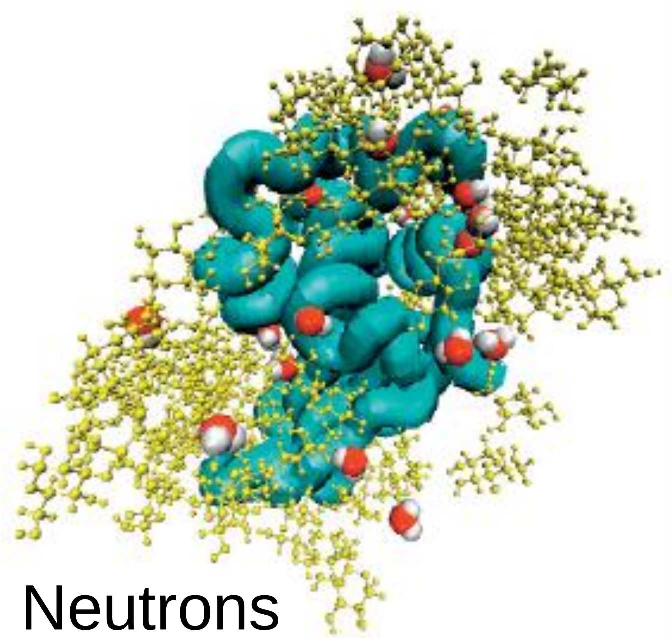


The specific case of scattering

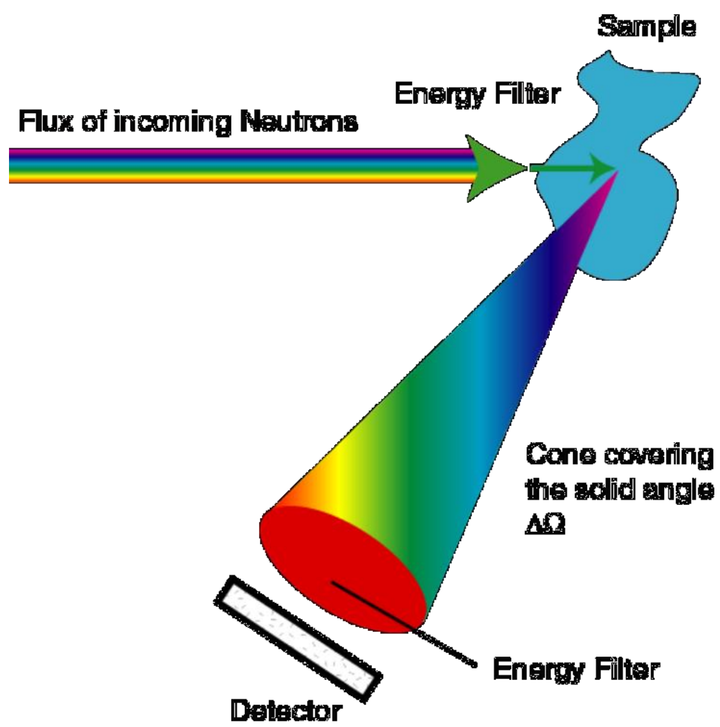
Neutron wavelength correspond to typical microscopic length scales in matter.

The corresponding neutron energies match very well the typical excitation energies of these objects.

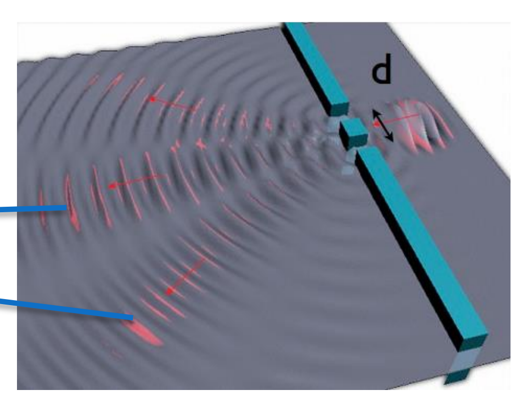
From 1000 nm and μs (~1 neV)



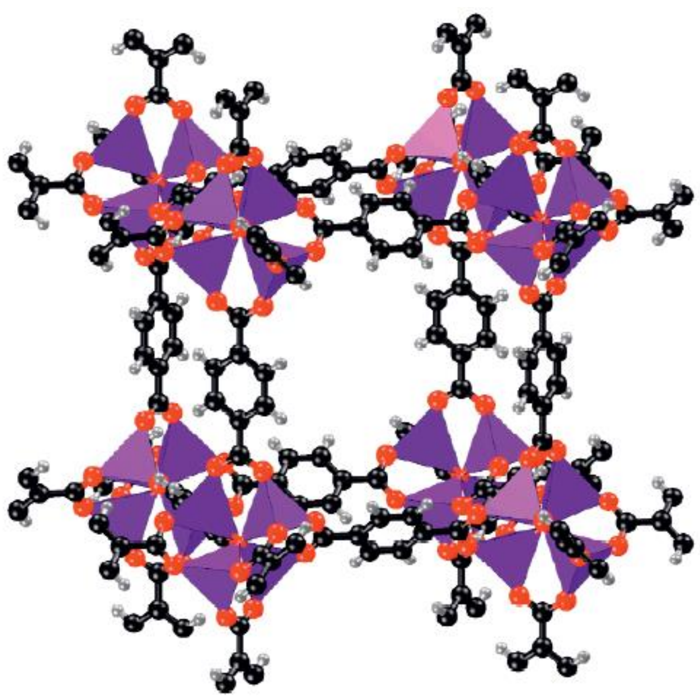
Cold Neutrons



$$\Delta\phi = \frac{\Delta y}{D} = \frac{\lambda}{d}$$



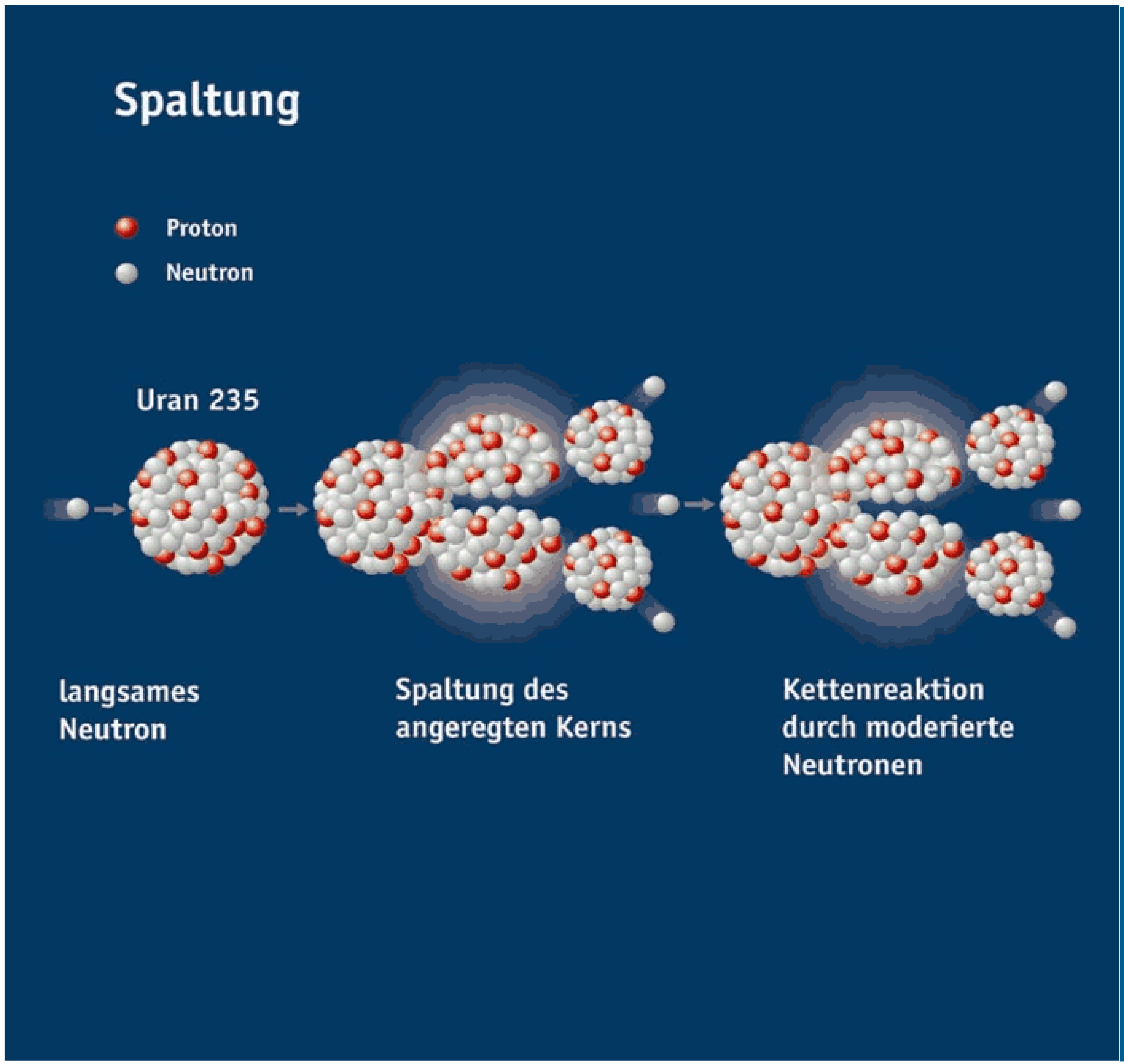
down to 0.001 nm and 10 fs (~500 meV)



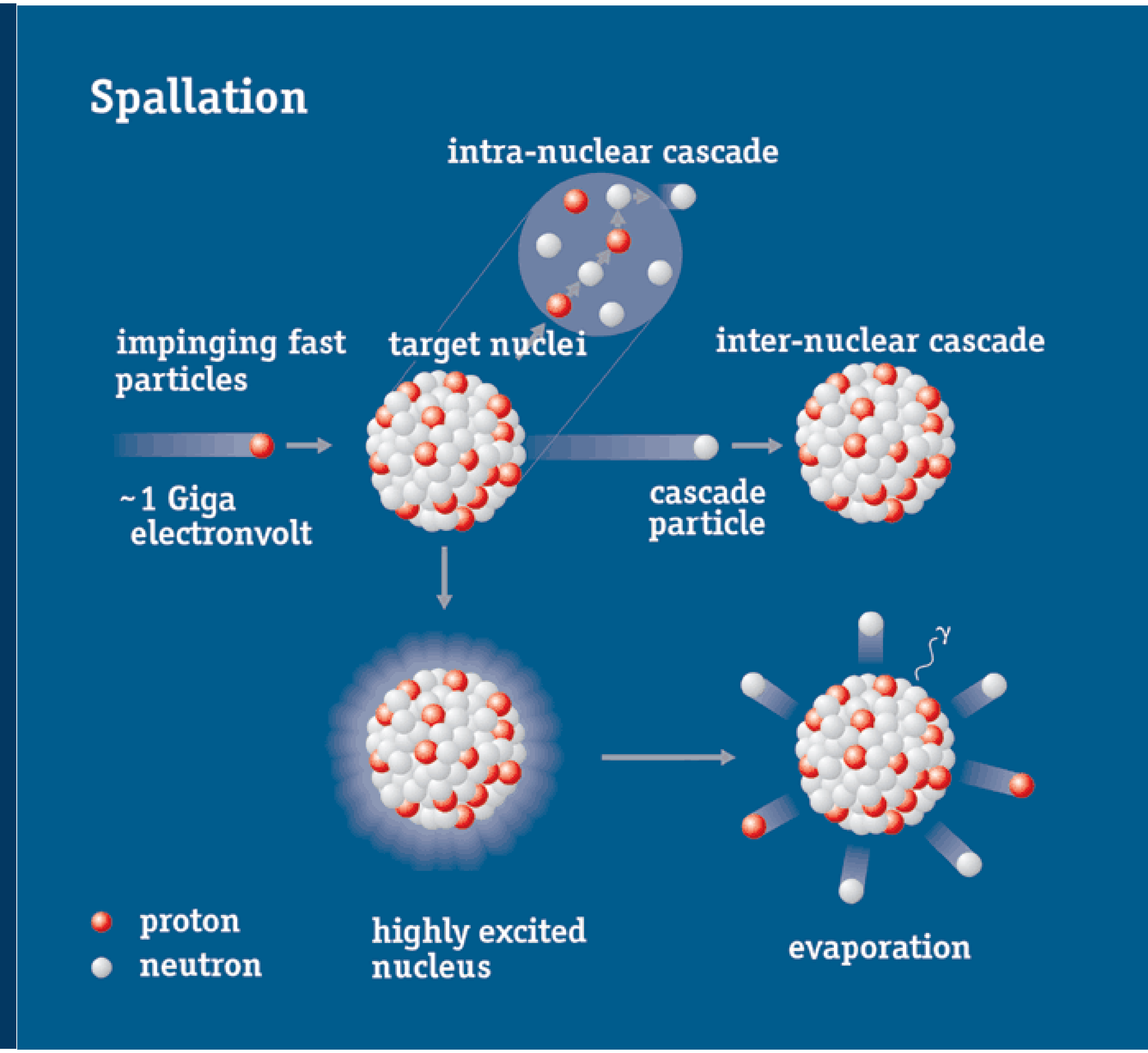
Hot Neutrons

How to produce free neutrons

Fission



Spallation



180 MeV/neutron for a reactor 20 MeV/neutron for a spallation source
A 1 MW spallation source creates at least the same costs as a 60 MW reactor

As produced neutrons have extremely high energies

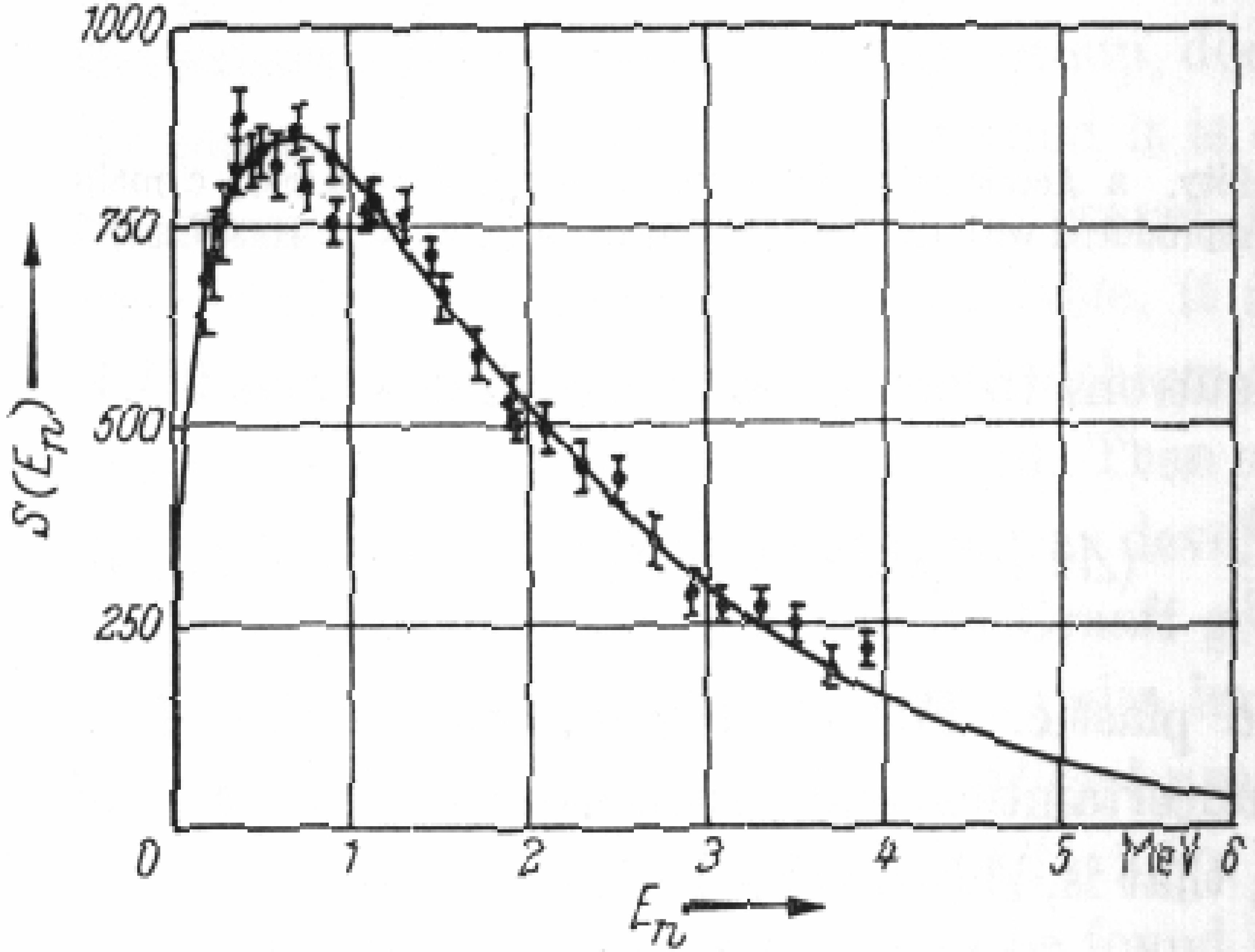
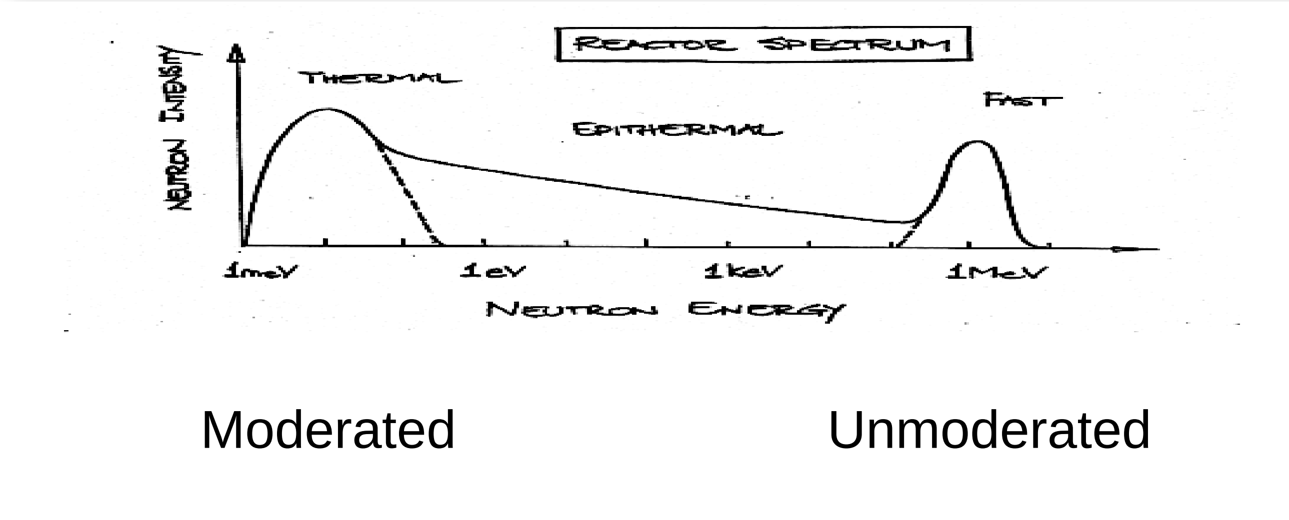


Fig. 2.6.1. The energy spectrum of neutrons produced in thermal neutron fission of U^{235}

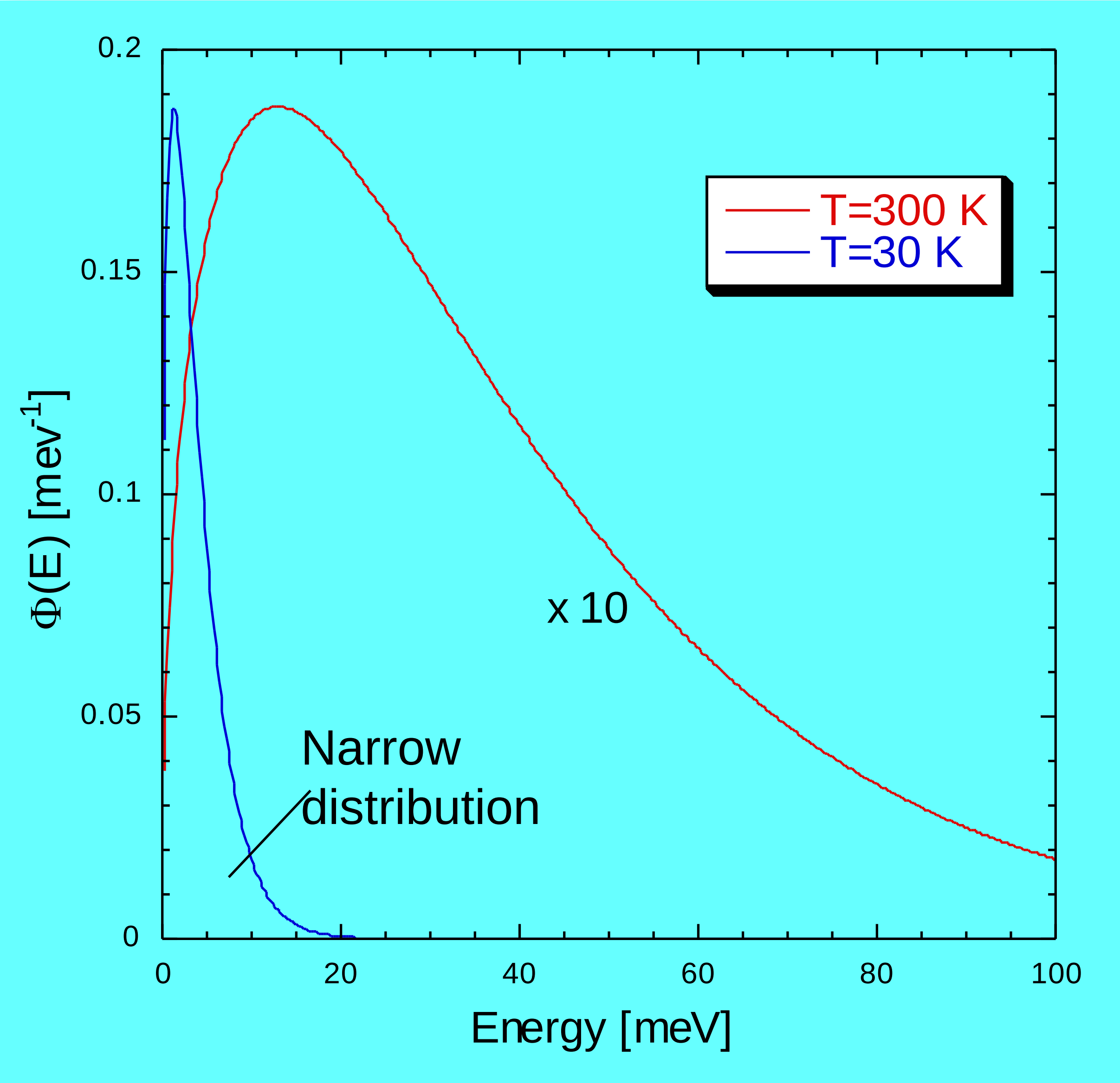
In the case of spallation the mean energies are even higher.

Moderation is essential



- Thermal region: Maxwell Boltzmann distribution

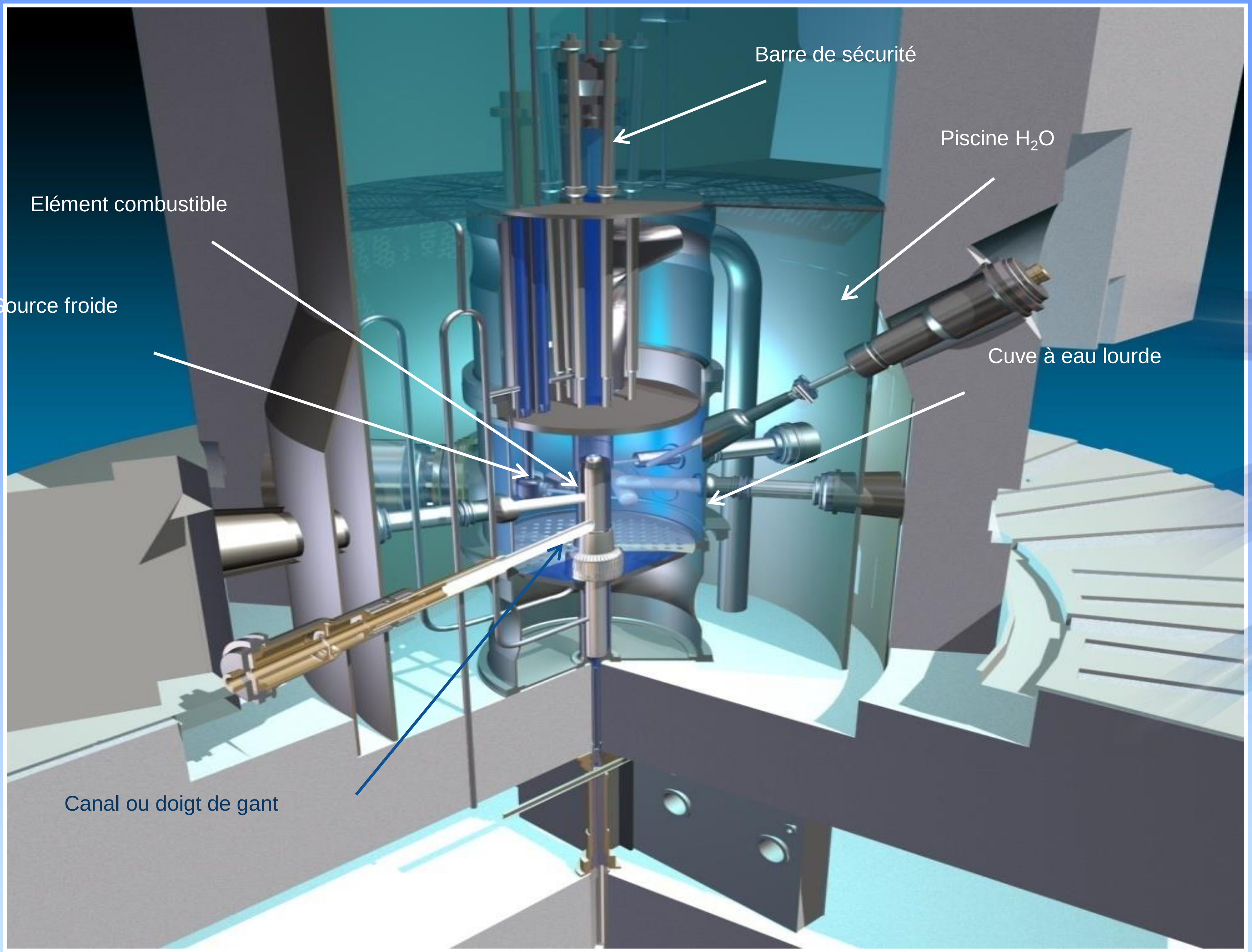
$$\Phi(E)dE = \Phi_{\text{thermal}} \frac{2}{\sqrt{\pi}} \frac{\sqrt{E}}{(k_b T)^{3/2}} \exp\left(-\frac{E}{k_b T}\right) dE$$



- Epithermal 1/E region
- Fast background
- Cold and Hot sources

Cold Neutrons	0.1-10 meV
Thermal Neutrons	10-100 meV
Hot Neutrons	100 - 500 meV
Epithermal Neutrons	> 500 meV

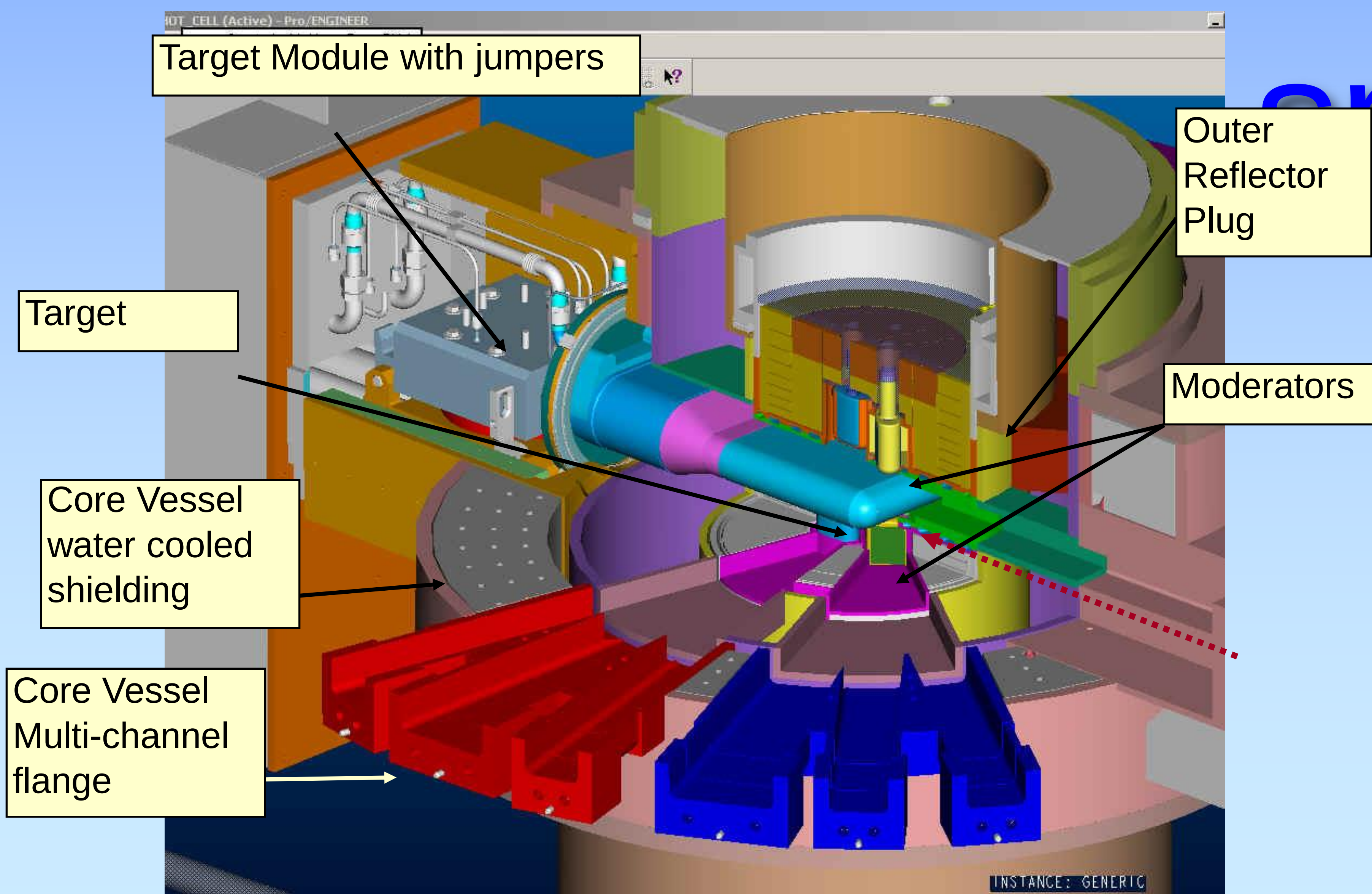
ILL continuous source



Courtesy B. Desbrière

Moderation via D_2O
Extraction via channels
UAl fuel element 93 % HEU

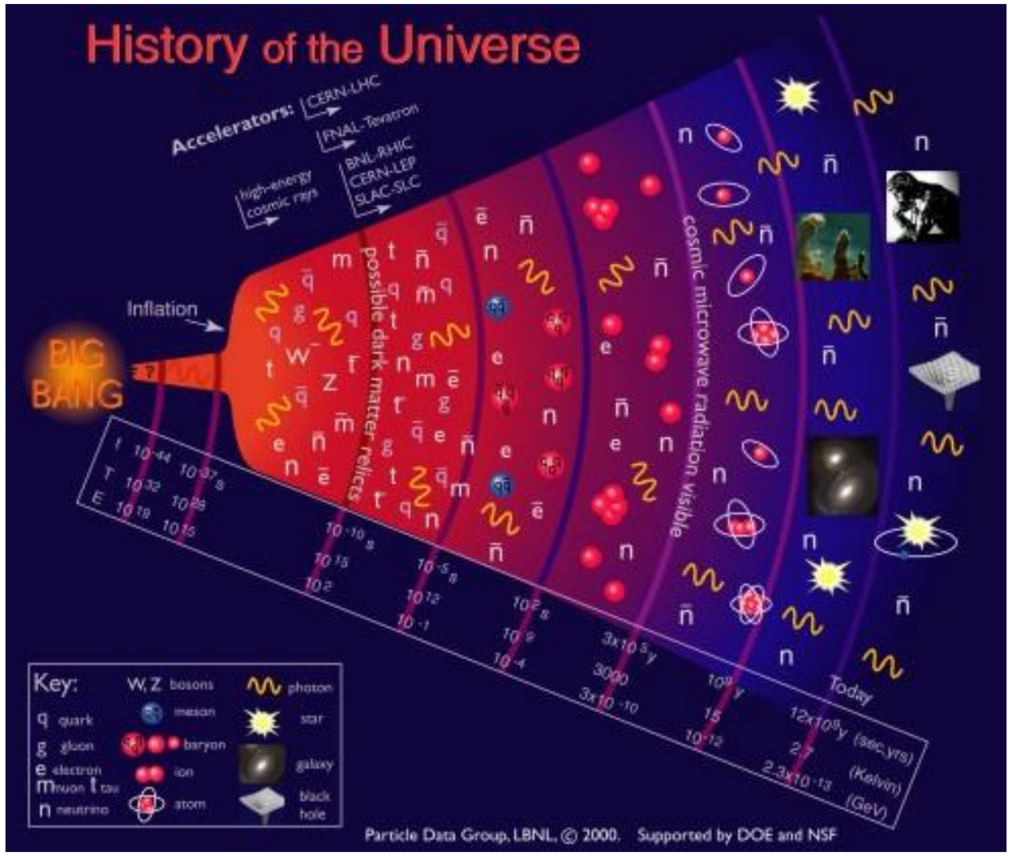
SNS Short pulse spallation




A short hike through the neutron landscape
I will try to cross as many vegetation zones as possible

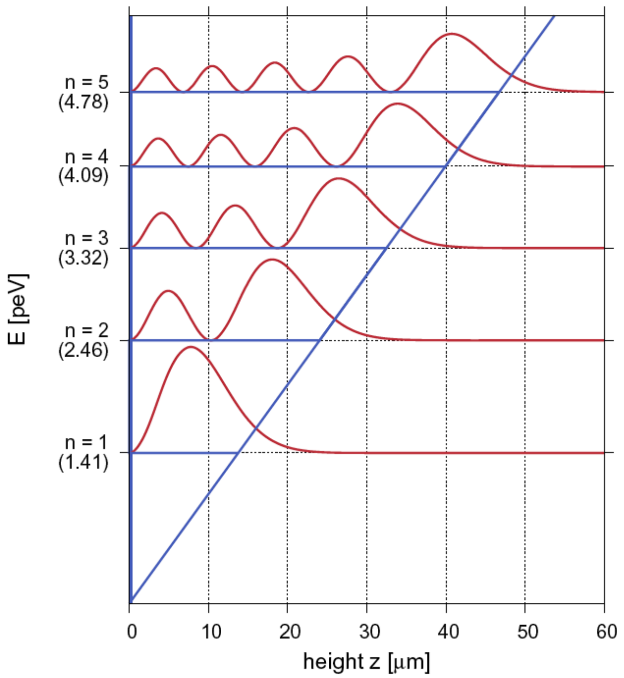
Let us start at the bottom

- There are two ways to penetrate the depths of matter:
  - higher energies,
  - higher precision.
- Neutrons are relevant for the later:
  - neutron lifetime,
  - β-decay asymmetries,
  - the neutron’s electric dipole moment,
  - neutrons as a gravitational probe.



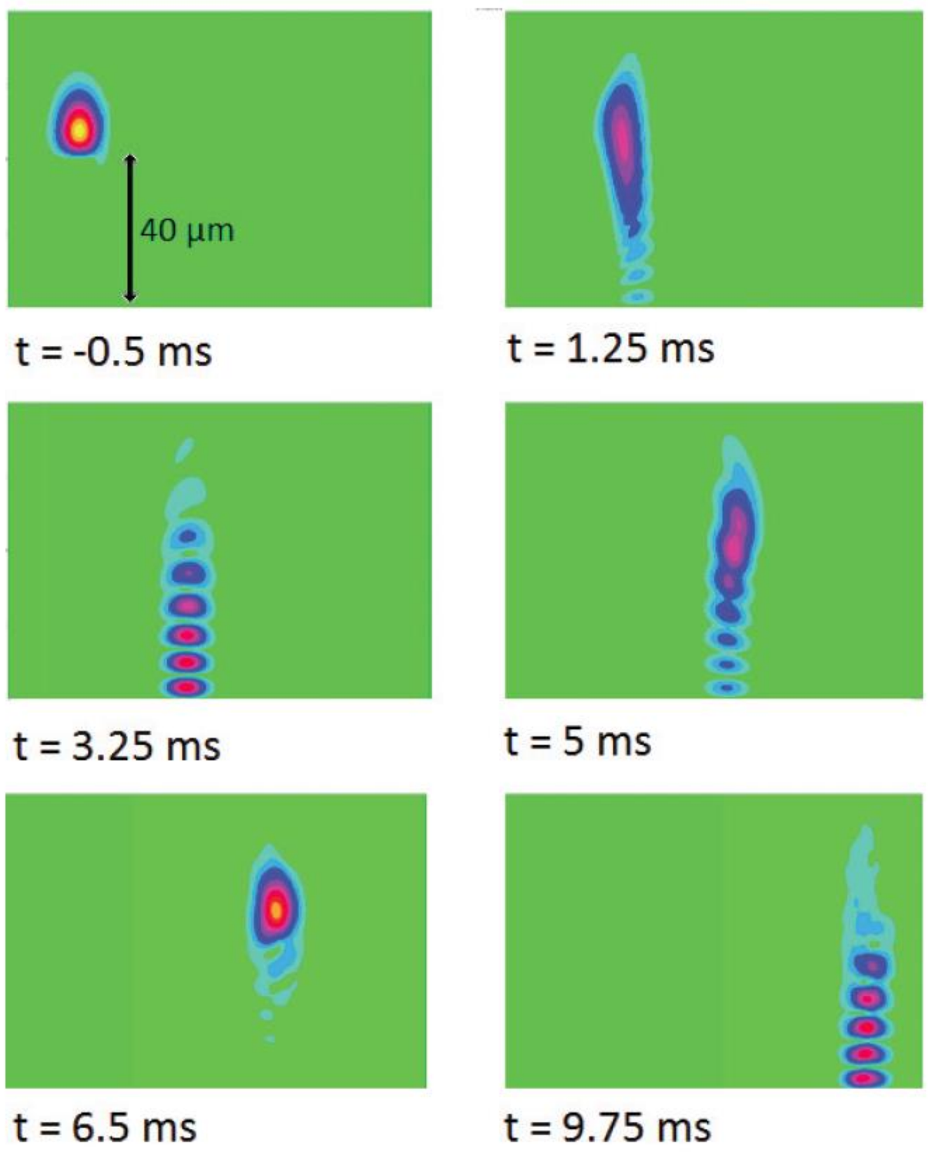
Gravitational forces at short distances

- Ultracold neutrons (E < 100 neV) are ideal quantum bouncers.
- As neutral elementary particles they do not stick to surfaces.



Jenke et al., Nature Physics 2011,
Abele und Rauch, New J. Phys. 2012

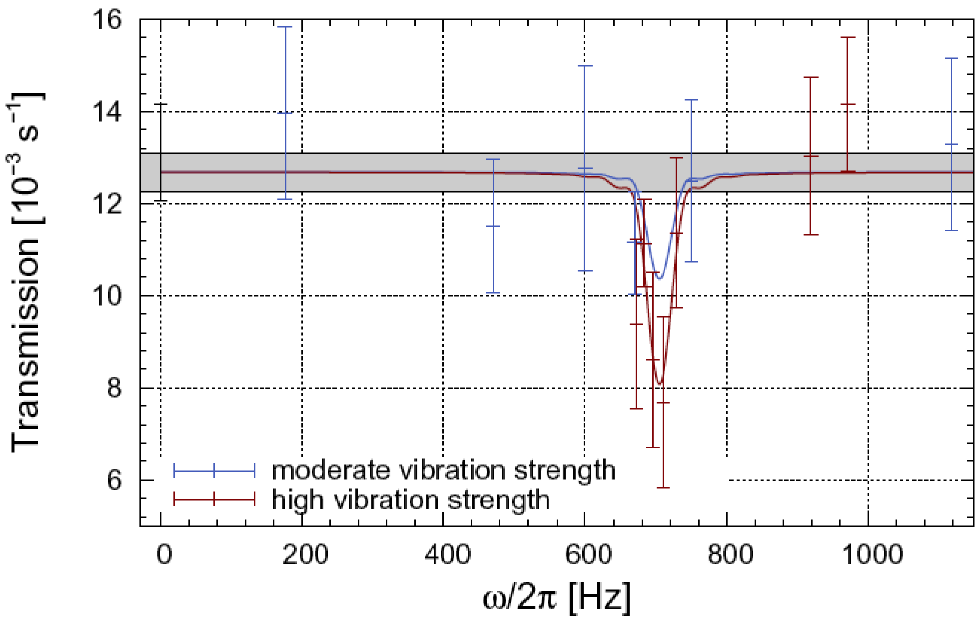
Quantum Bouncers

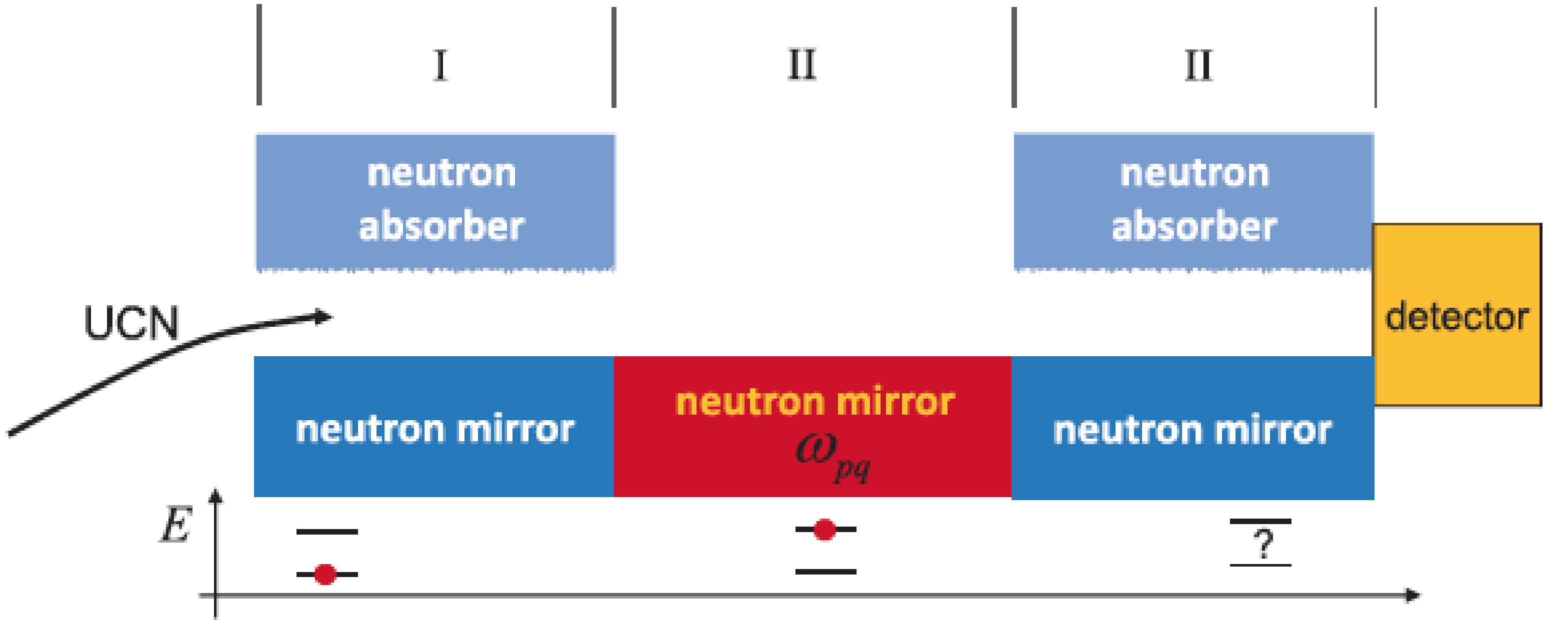


Precision measurements using resonance techniques

- Probing the gravitational potential on the µm scale with a precision of currently ΔE = 2×10^{-14} eV.
- Essential experiments to check for non-Newtonian corrections to the gravitational field.

Resonance curve

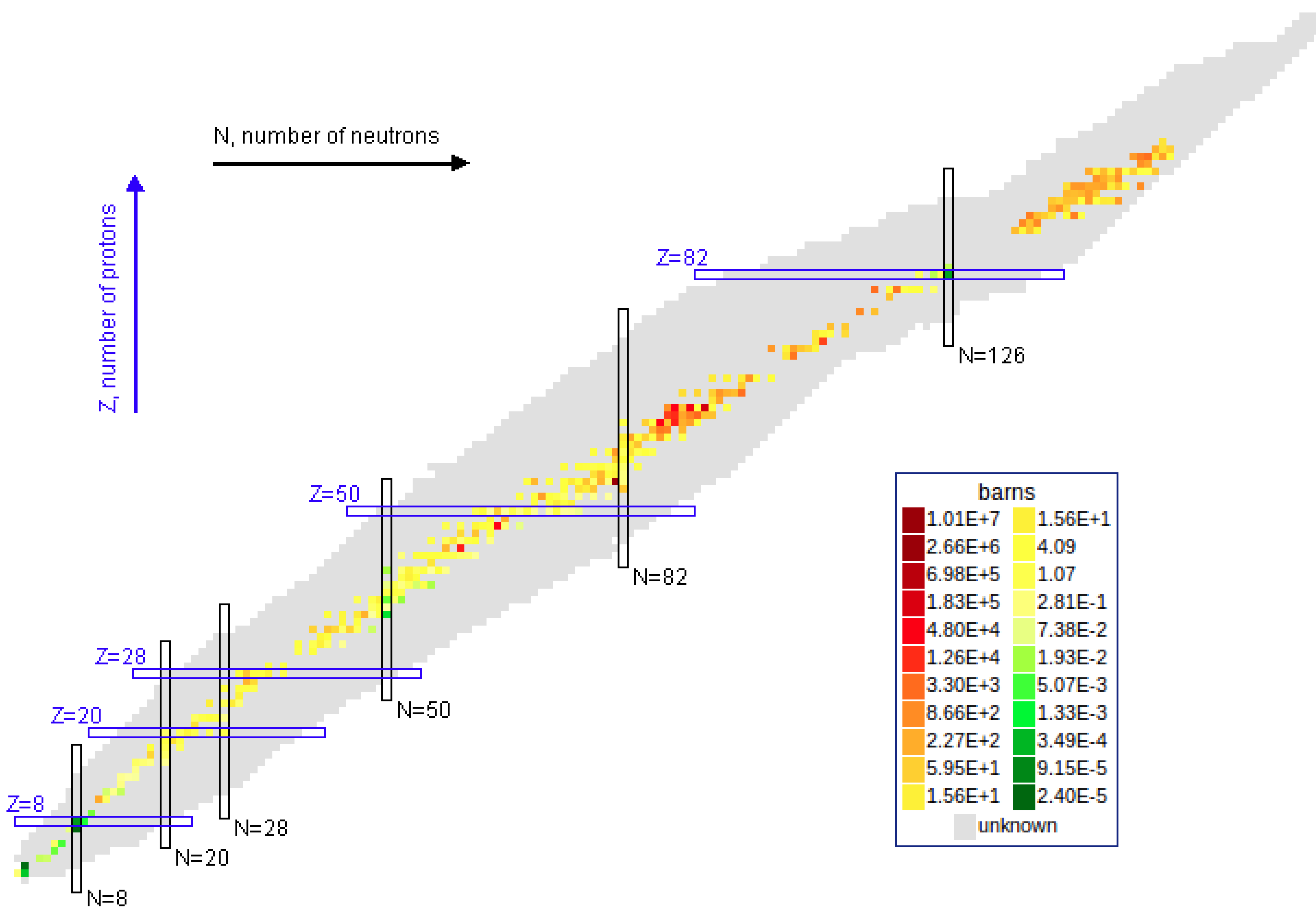


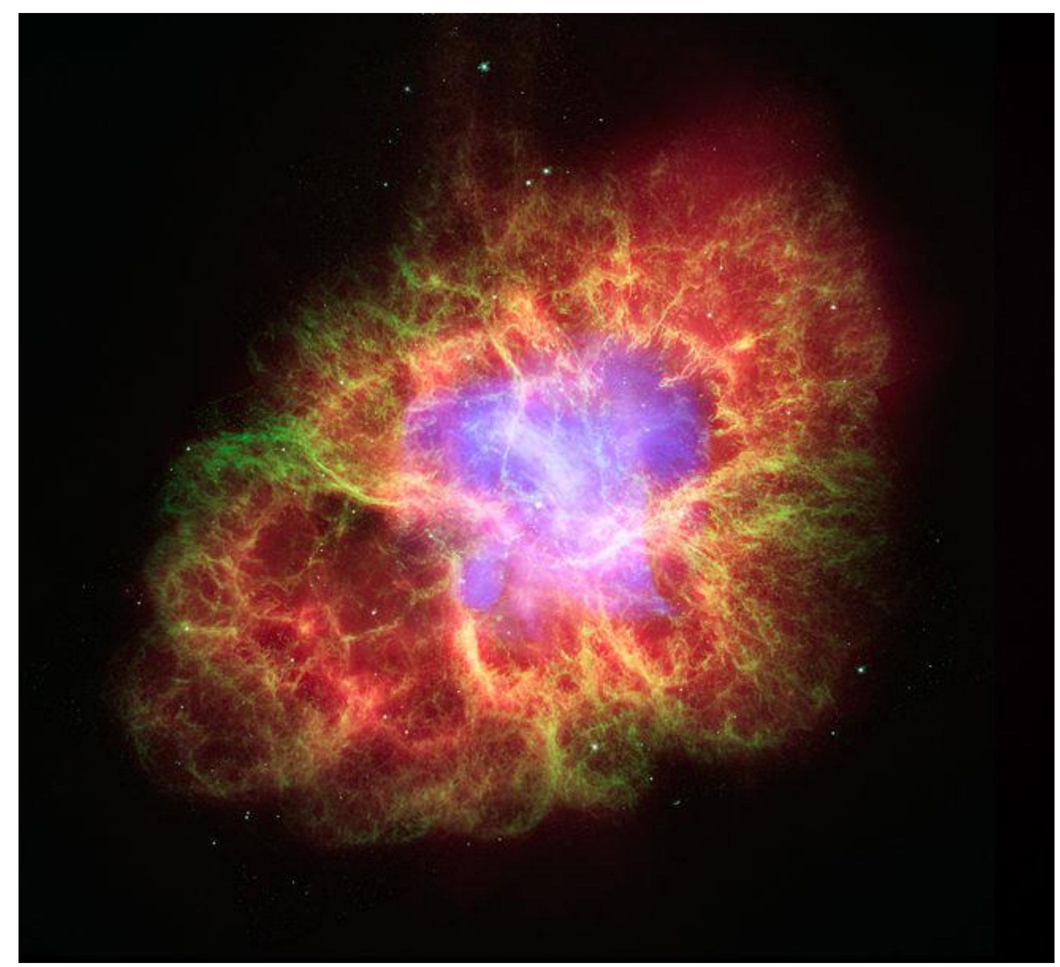


Jenke et al. Nature Physics 2011,
Abele und Rauch New J. Phys. 2012

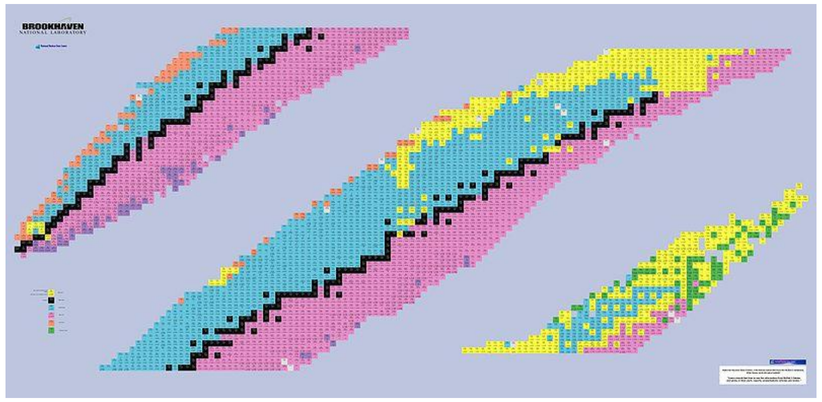
From the fundamental interactions to the nuclei

Neutron capture is ubiquitous in the universe.
At a neutron source it can be used in a controlled way to probe nuclear matter.

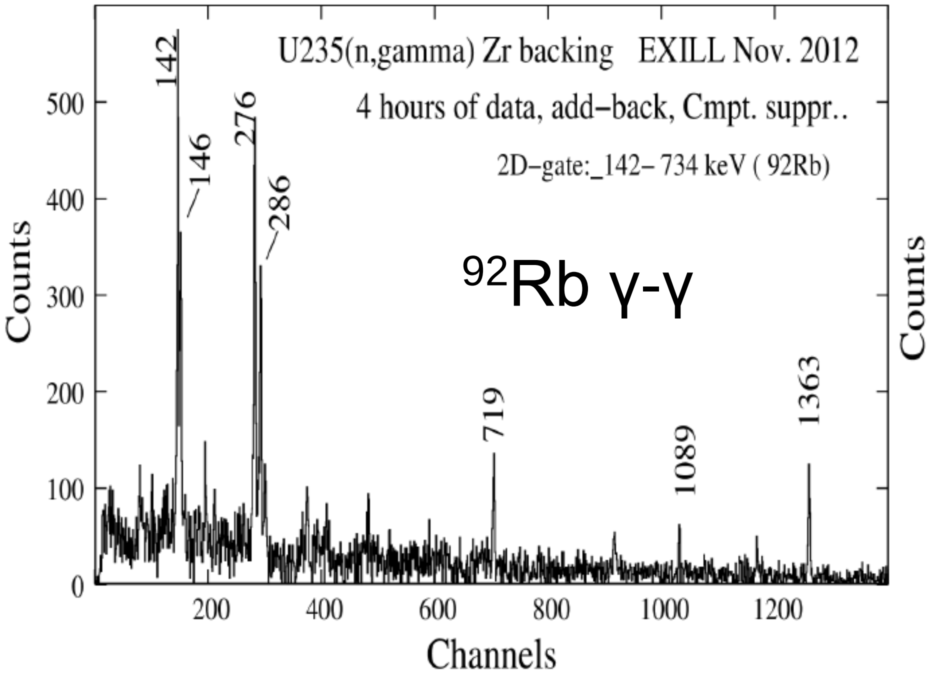




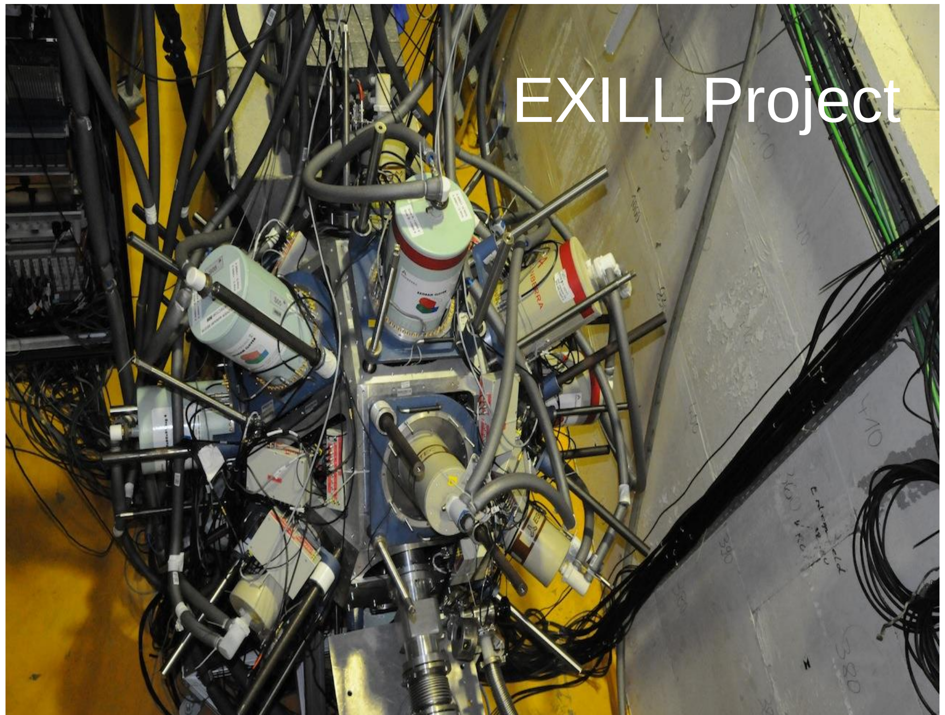
Observing nuclear processes



- Producing neutron reach isotopes via capture.
- Spectroscopic analysis of decay processes with or without simultaneous (Z/A) identification of decay products.
- Essential input for
- understanding nucleosynthesis,
- designing transmutation of radioactive materials,
- development of 4th generation reactors.
- Complementary to ion accelerators.

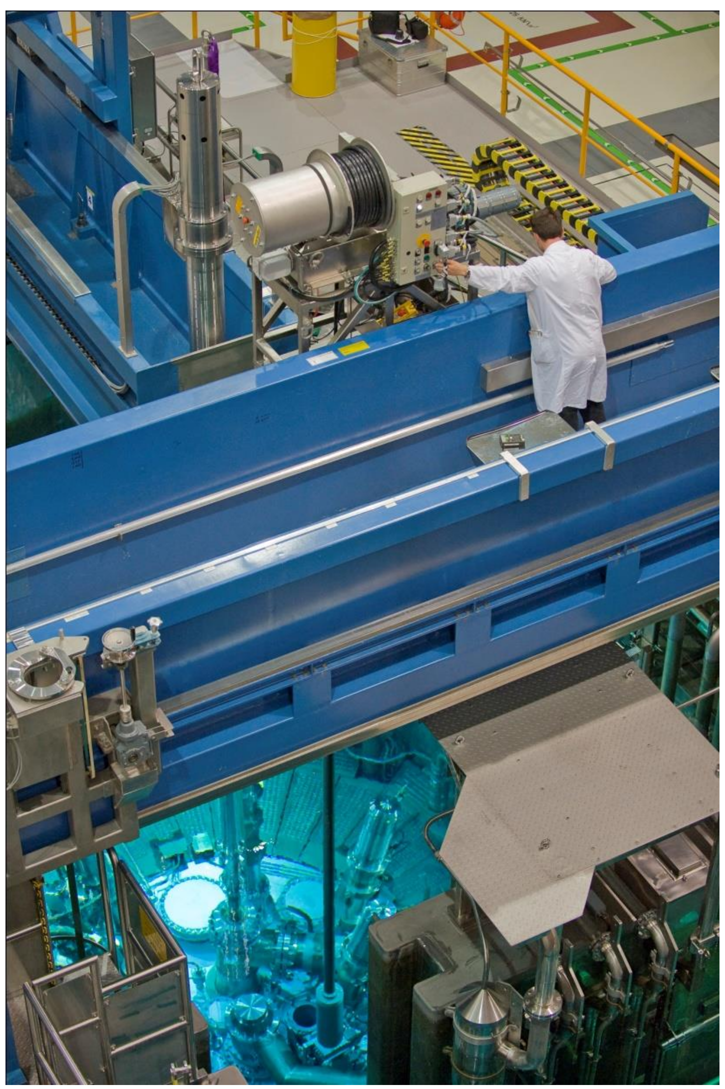


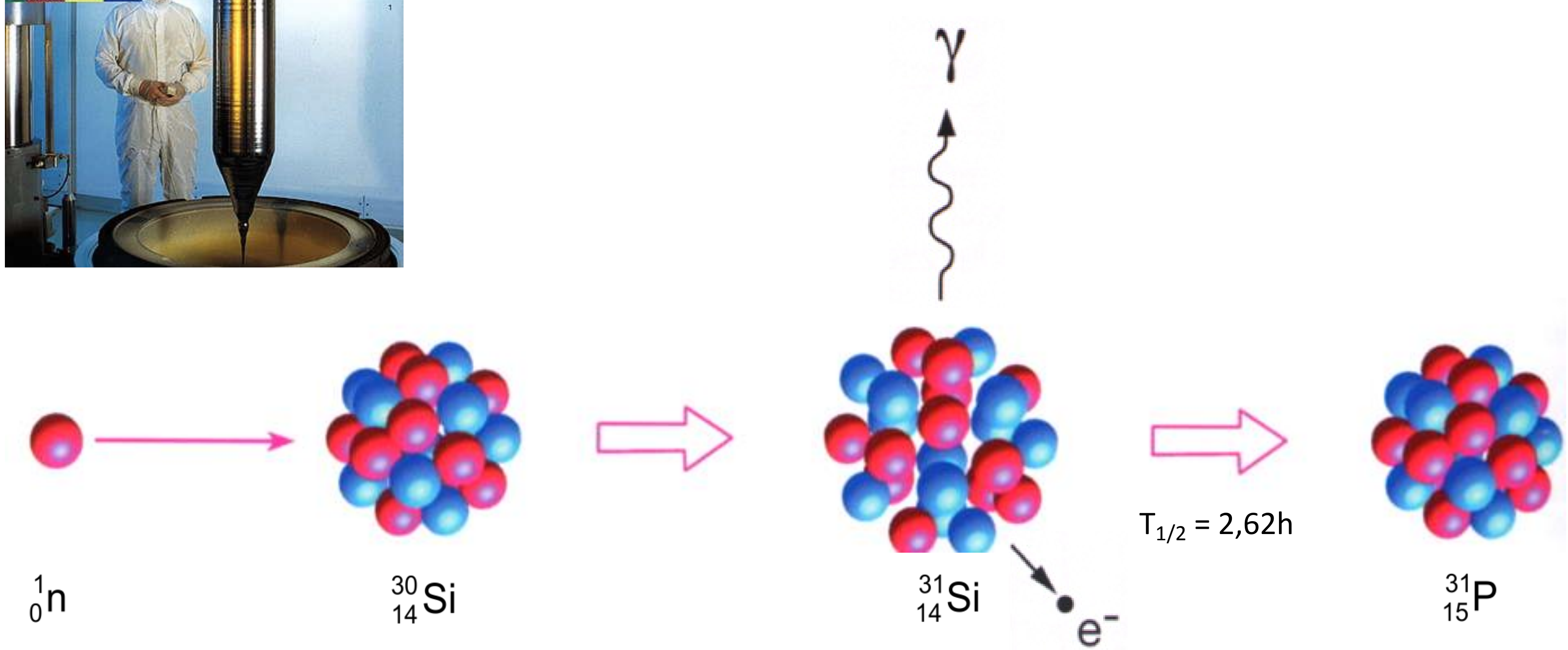
About 100 Terabyte of data await analysis by 40 research collaborations



Doping silicon for energy applications

15 tons of homogeneously n-doped silicon/year produced at FRM II (≈10% of world production)





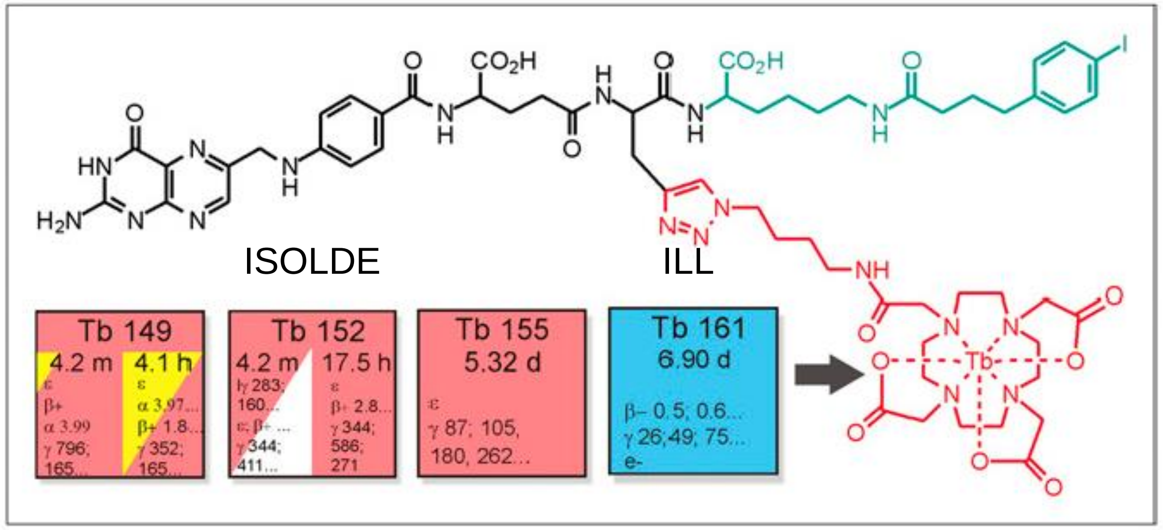
Radioisotopes for medicin

Müller et al. J. Nuclear Medcine 2012

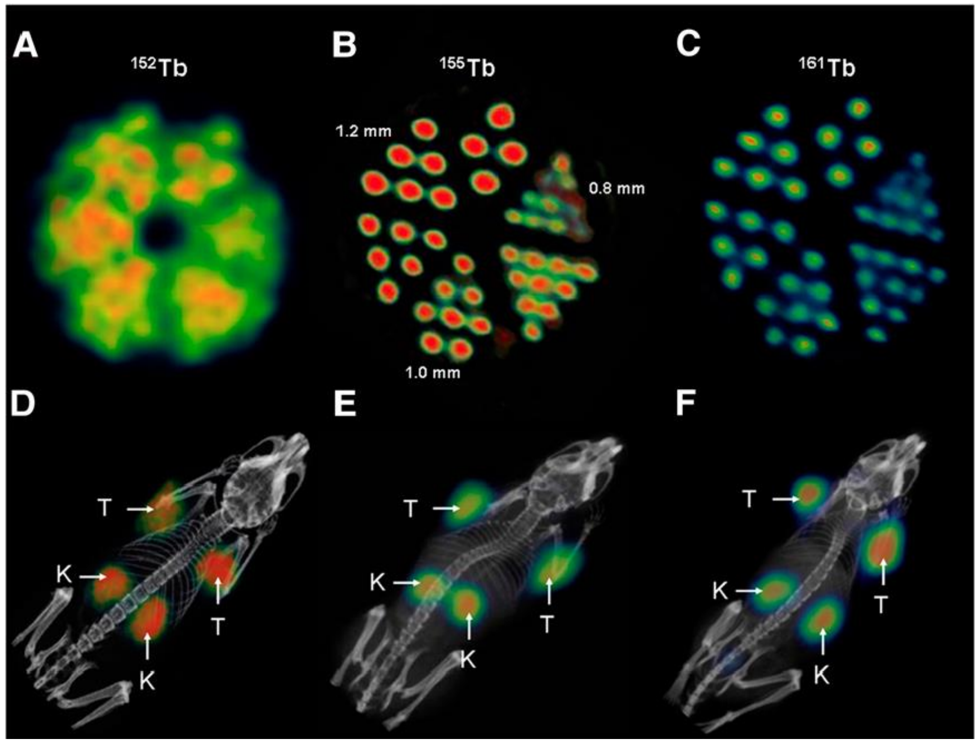
A collaboration between the Paul Scherrer Institute, CERN's ISOLDE facility, and the Institut Laue-Langevin

- Terbium radioisotopes possess excellent visualization and therapy efficiency.
- Terbium-161 is produced at FRM II or ILL for clinical purposes.

Tb-CM09



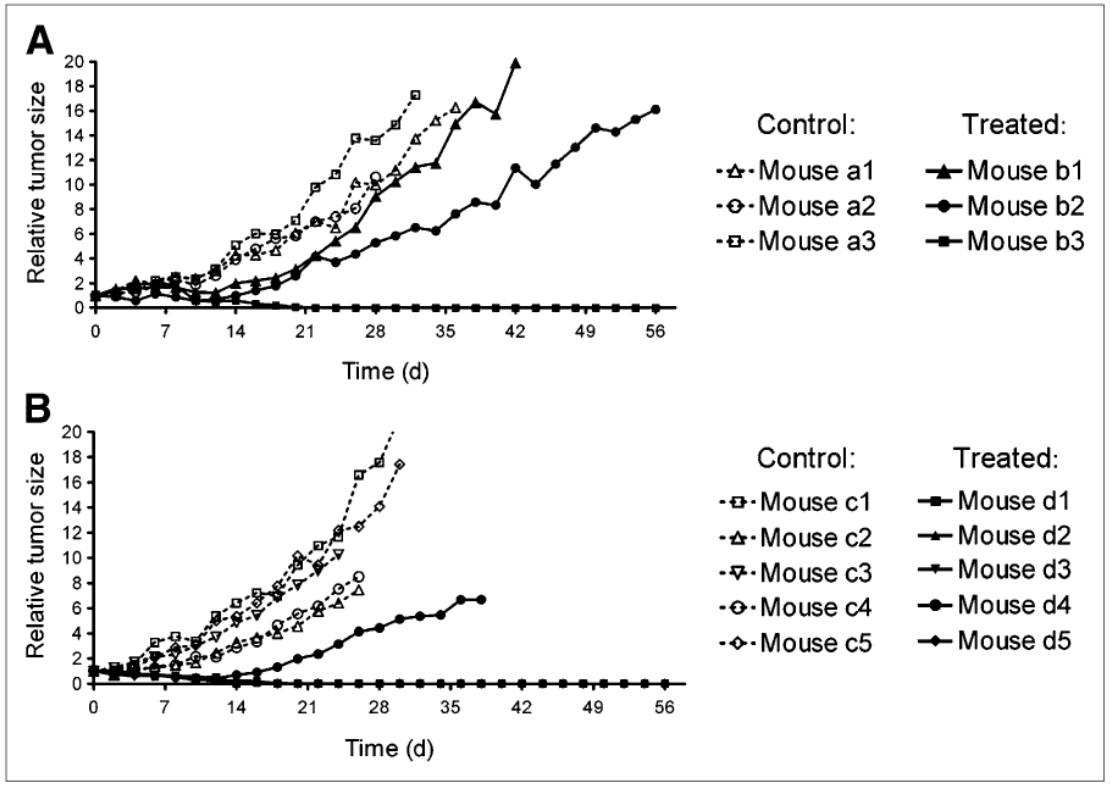
Diagnoses



Positron emission tomography

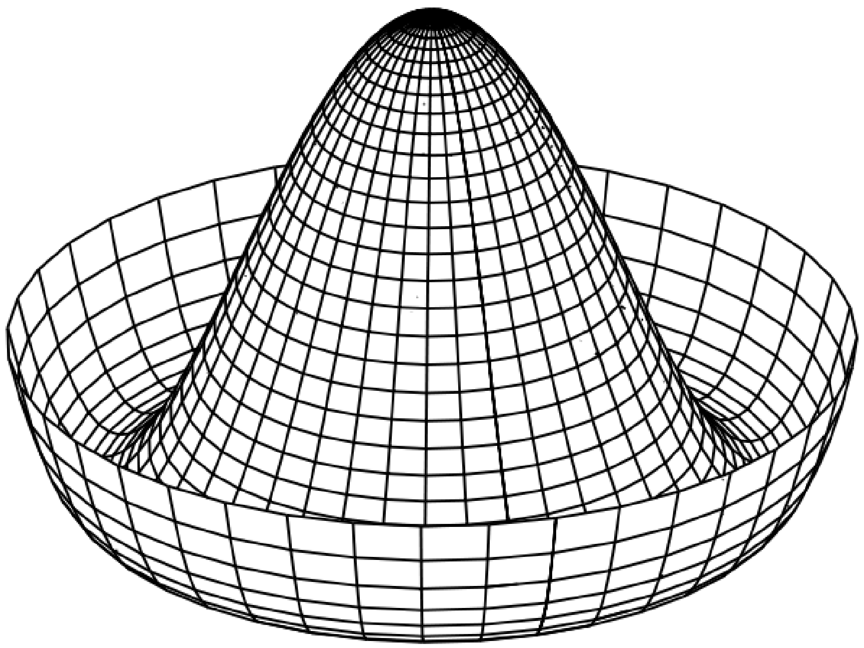
Single photon emission computed tomography

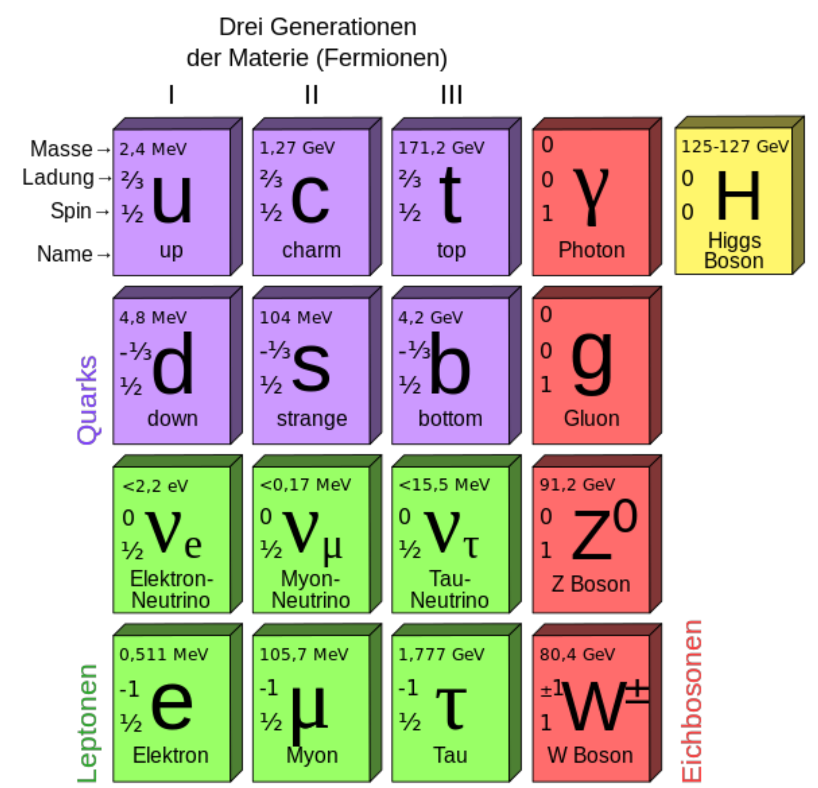
Therapy



From the nuclei to the solid
The Anderson-Higgs mechanism

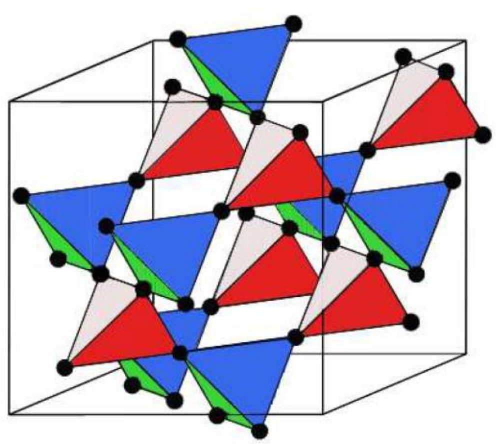
- Gauge theories are the backbone of physics.
- This leads to broken symmetries and massless Nambu-Goldstone particles.
- The Anderson Higgs Mechanism couples the gauge bosons to Nambu-Goldstein particles and thus provides mass.
- Applications: Standard model of particle physics, superfluidity and superconductivity.

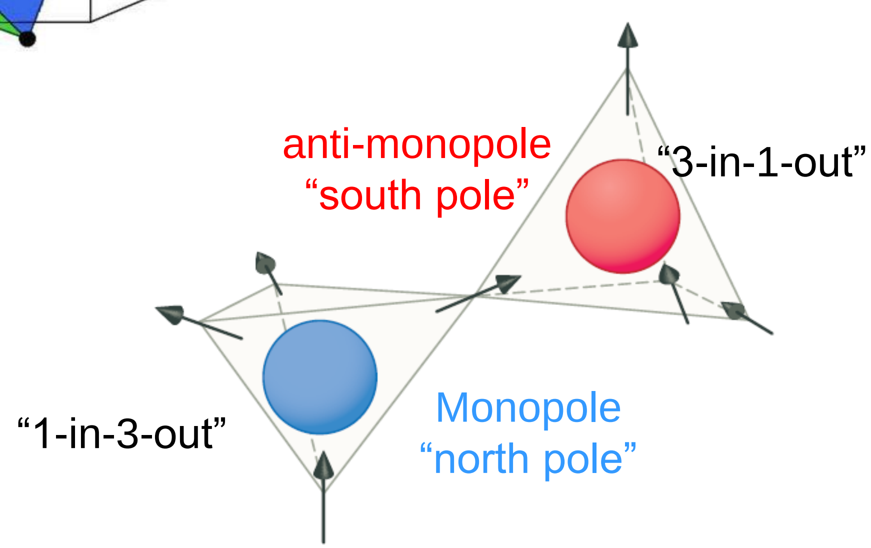


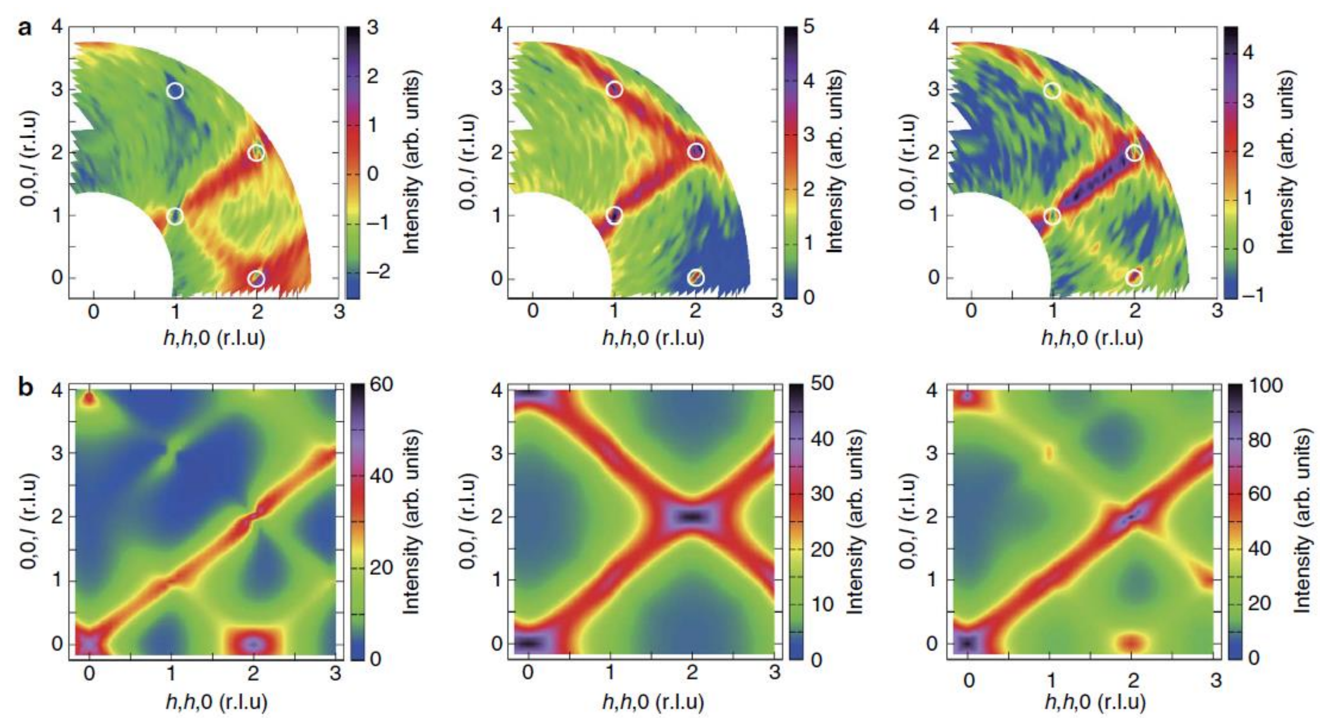


Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$

- Magnetic frustration leads to defects that behave like a liquid of magnetic monopoles interacting via a Coulomb interaction.





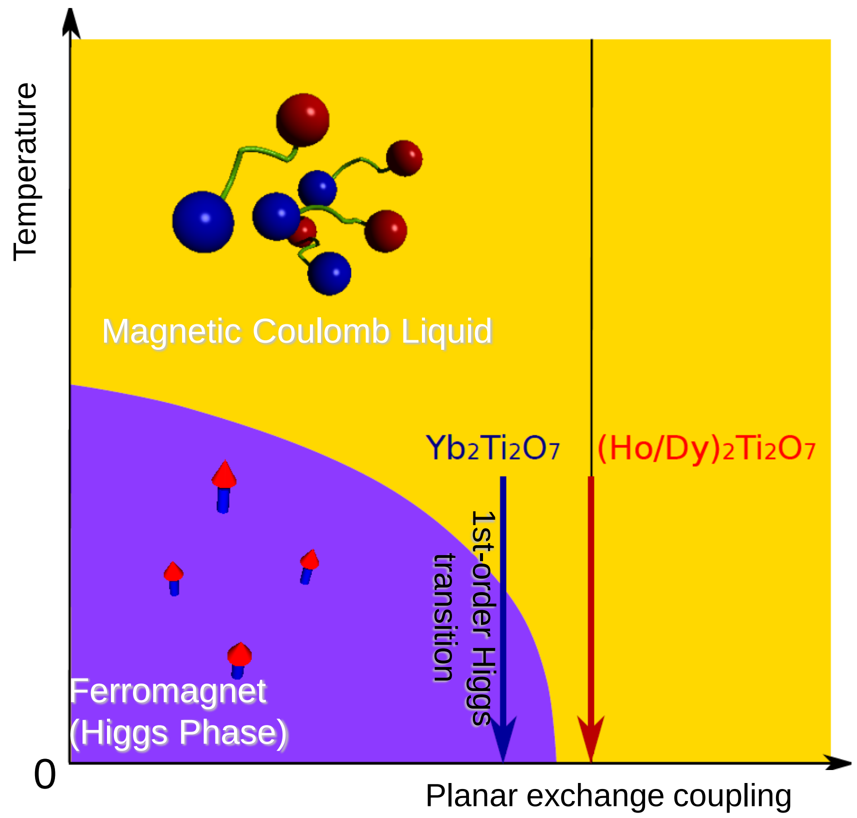


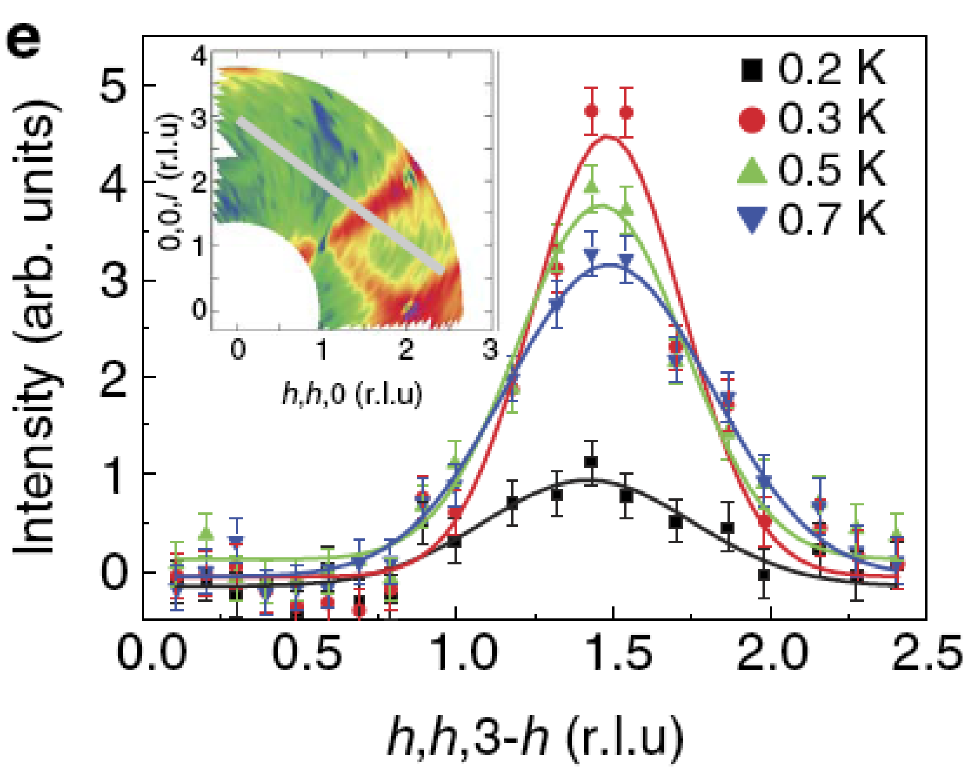
Neutrons observe the ground state directly

Chang et al. Nature Communications 2012

Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$

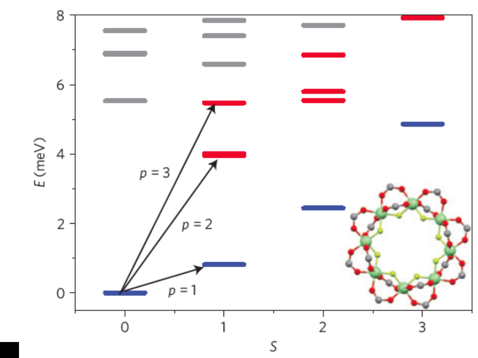
- Below 210 mK we find a ferromagnet with "anticipated" energy gap.
- This is analogous to creating a massive gauge particle.



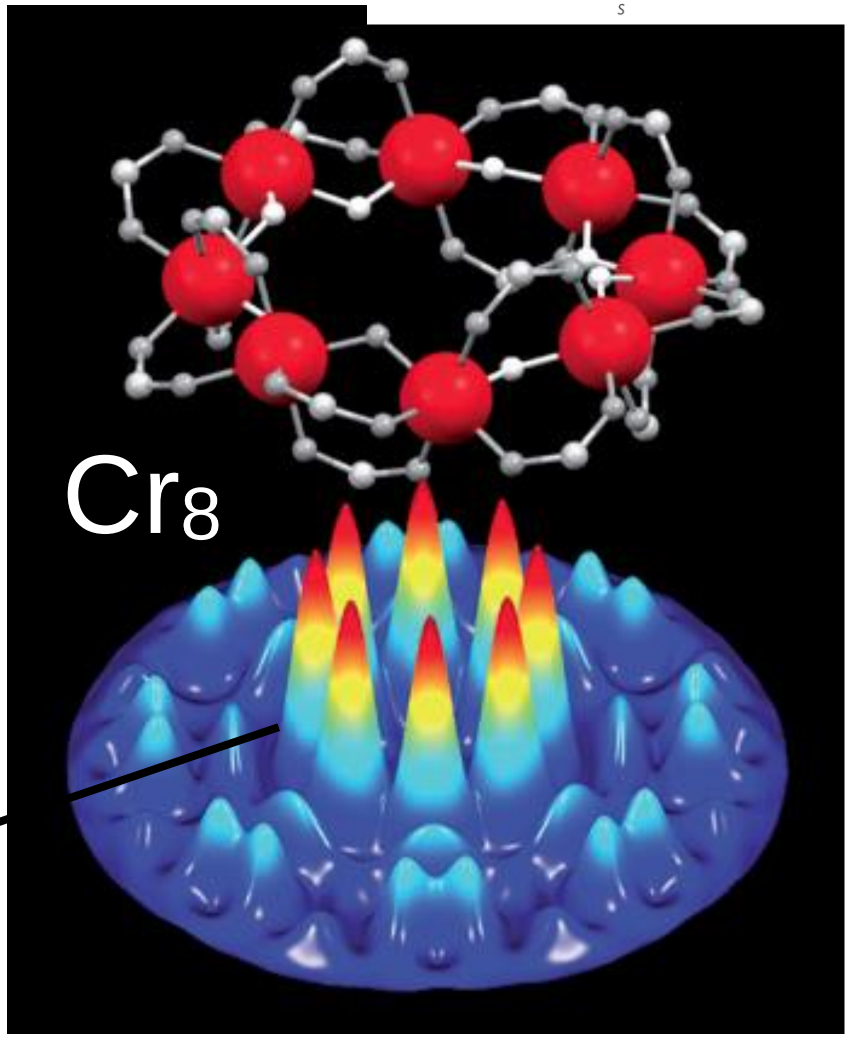


Chang et al. Nature Communications 2012

The successful marriage of chemistry and magnetism



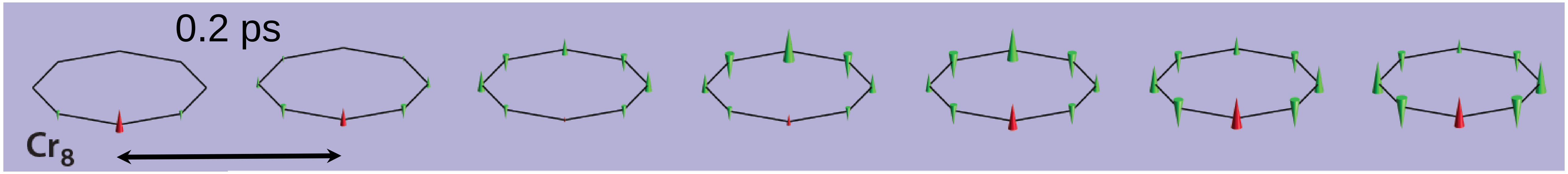
- Modern chemistry allows to specifically design molecular magnets.
- Neutron spectroscopy on single crystals gives Fourier images of coherent spin excitations.
- This allows to directly calculate the spin dynamics.
- Potential for spintronics and quantum computing.



Energy resolved scattering intensity

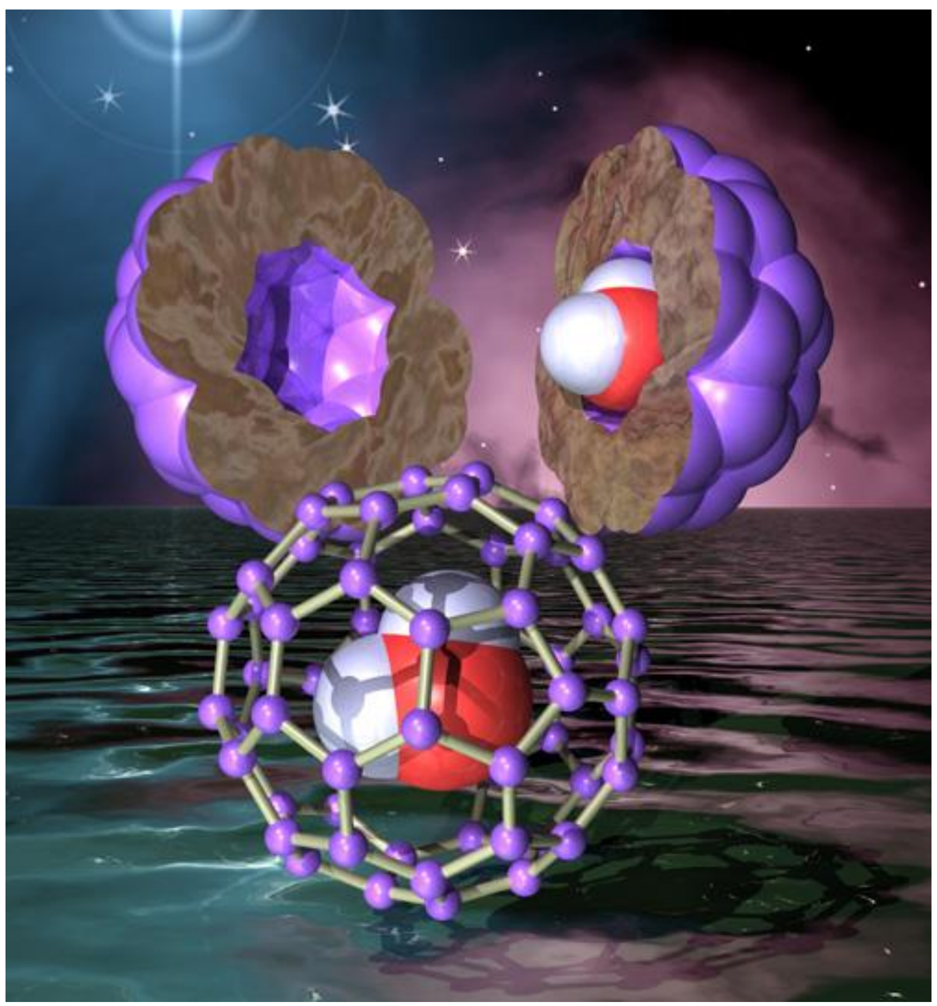
Barker et al. Nature Physics 2012

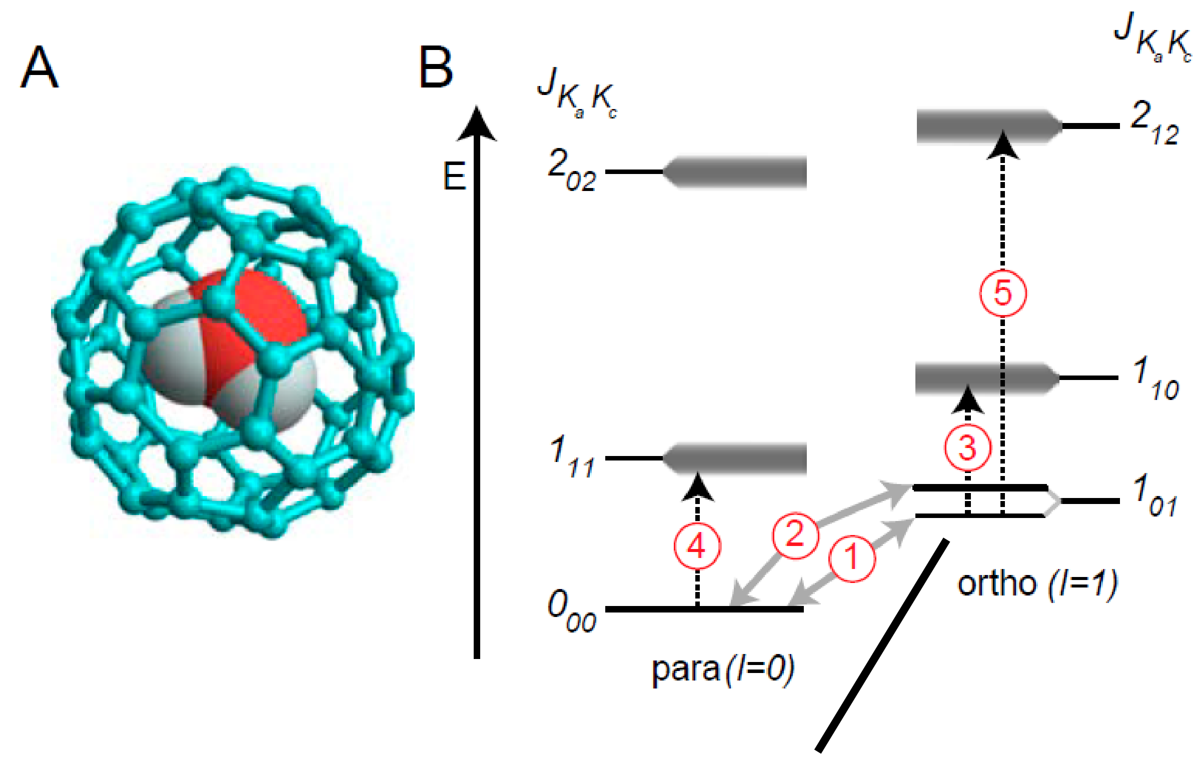
0.24 g von $Cr_8F_8[(O_2CC(CD_3)_3]_{16}$



Molecular surgery

- Modern chemistry allows us performing physics in a nano-lab.

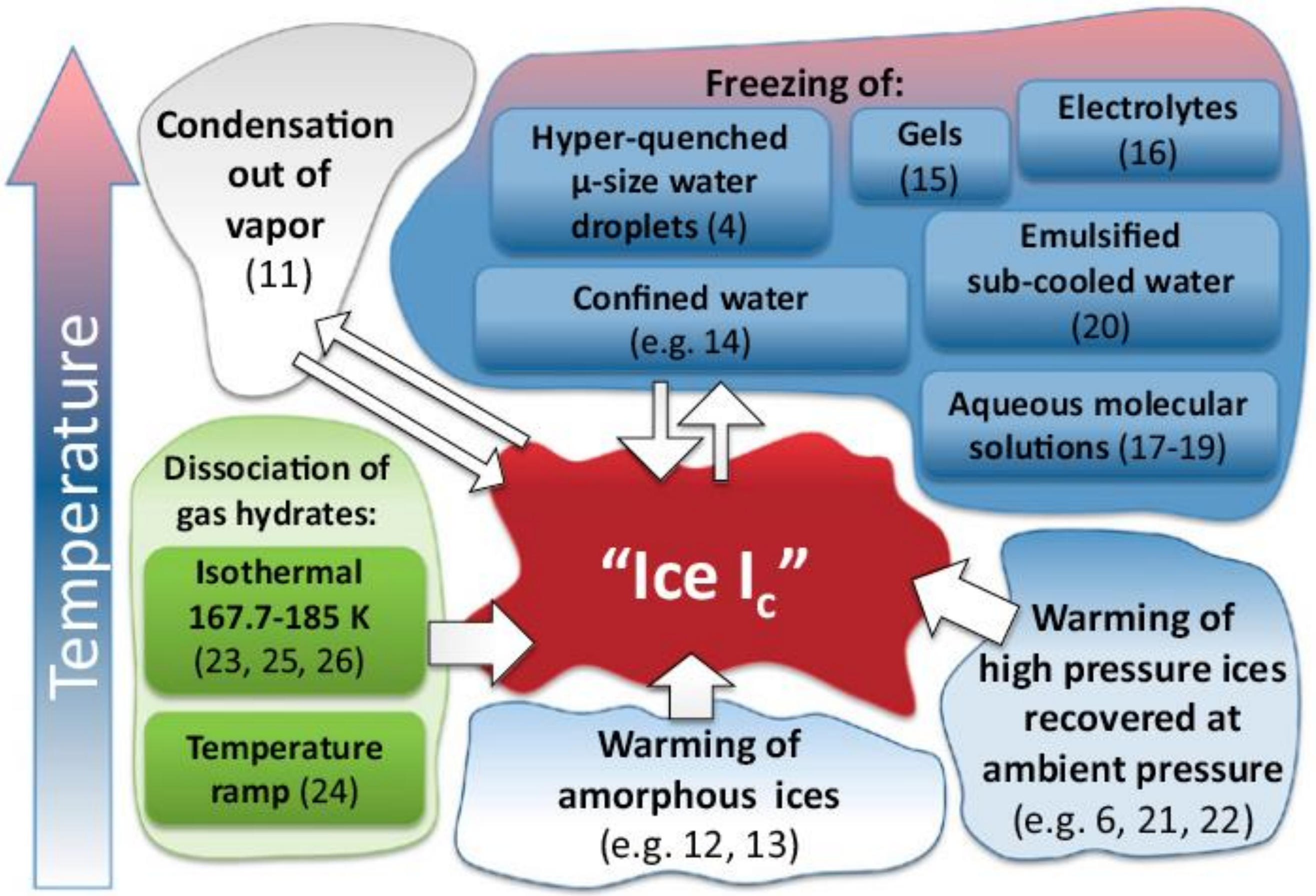


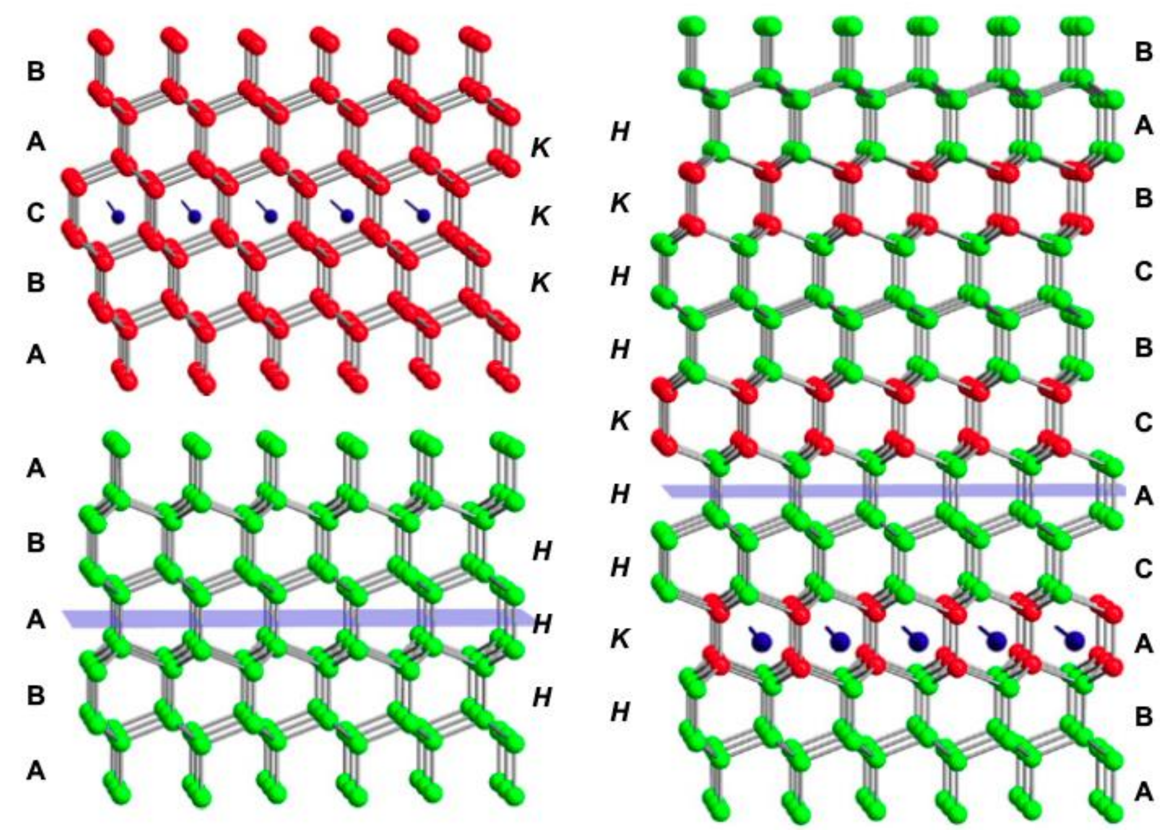


Transition is in principle forbidden.
Cages deformed?
Ferroelectric phase?

Beduz *et al*, PNAS 109 (2012) 12894-12898

Neutrons investigate the crystalline state



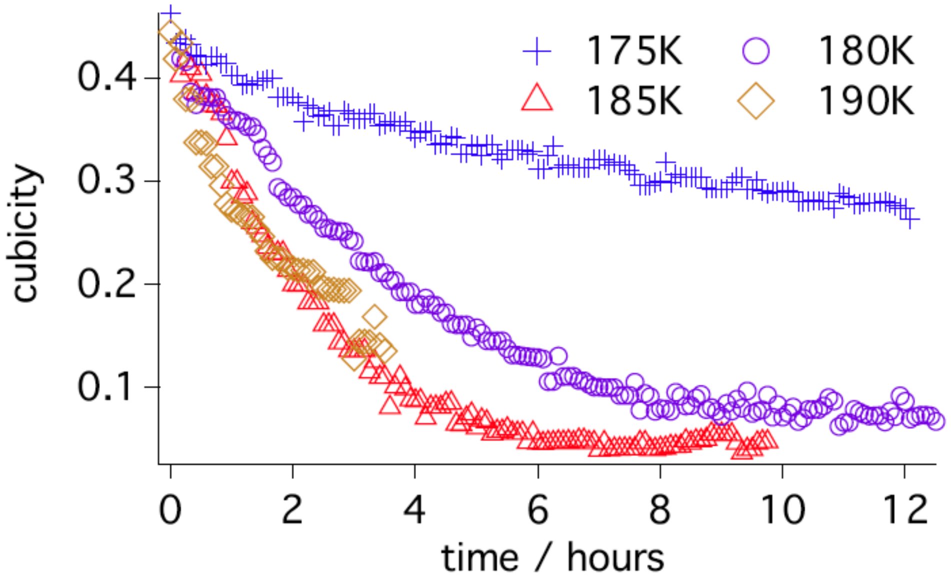


Neutrons are particularly good when it comes to light elements like H,D and Li.

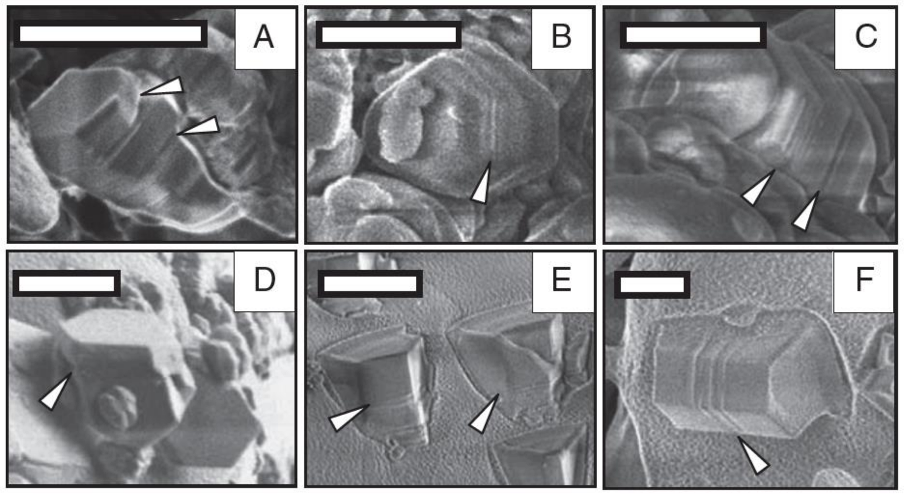
W. Kuhs. et al, PNAS 2012

A contribution to climate models

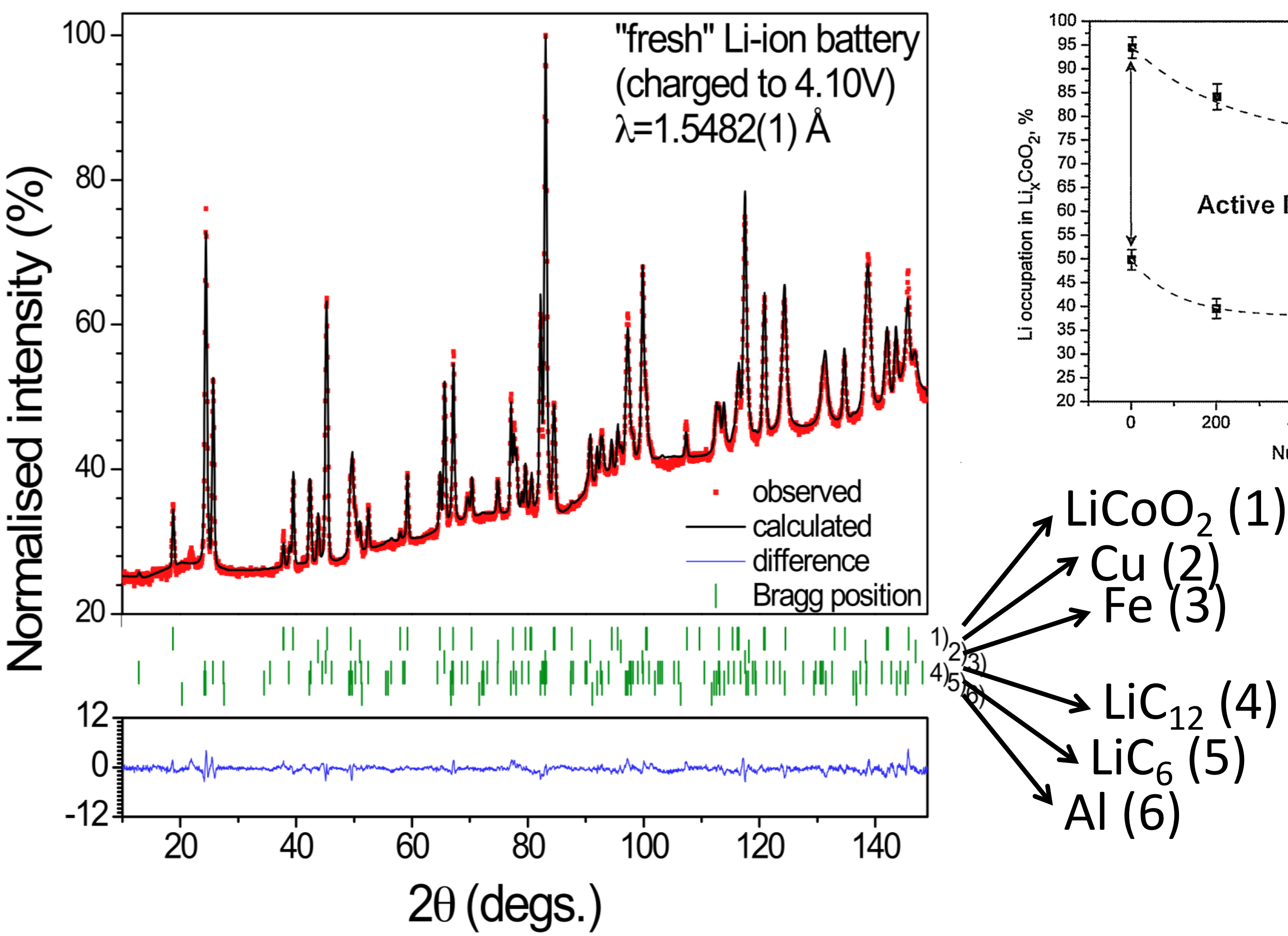
- Exact monitoring of transition dynamics from cubic to hexagonal ice.
- Size and surface quality of crystallites extracted.
- Results constitute important input into models of
  - ice formation (including clathrates),
  - reflection of light in the atmosphere,
  - chemistry of the atmosphere.

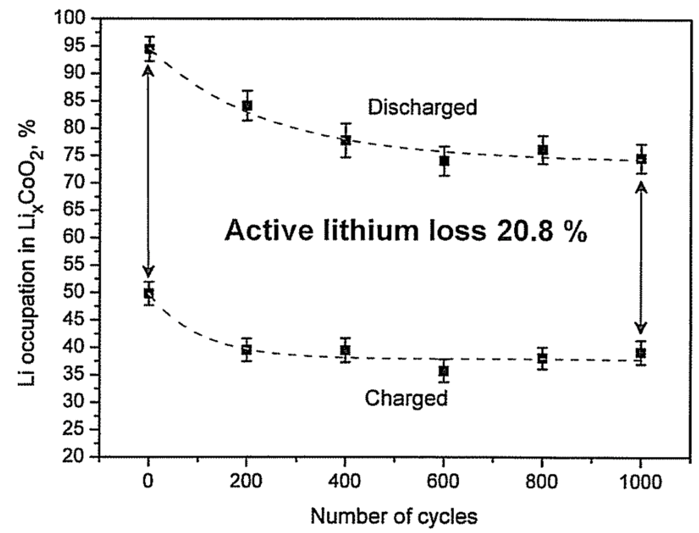


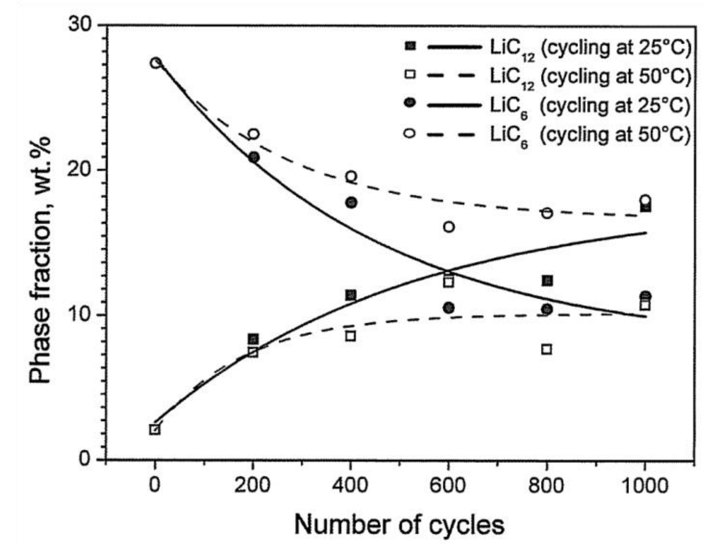
W. Kuhs. et al, PNAS 2012



Following chemical processes in batteries



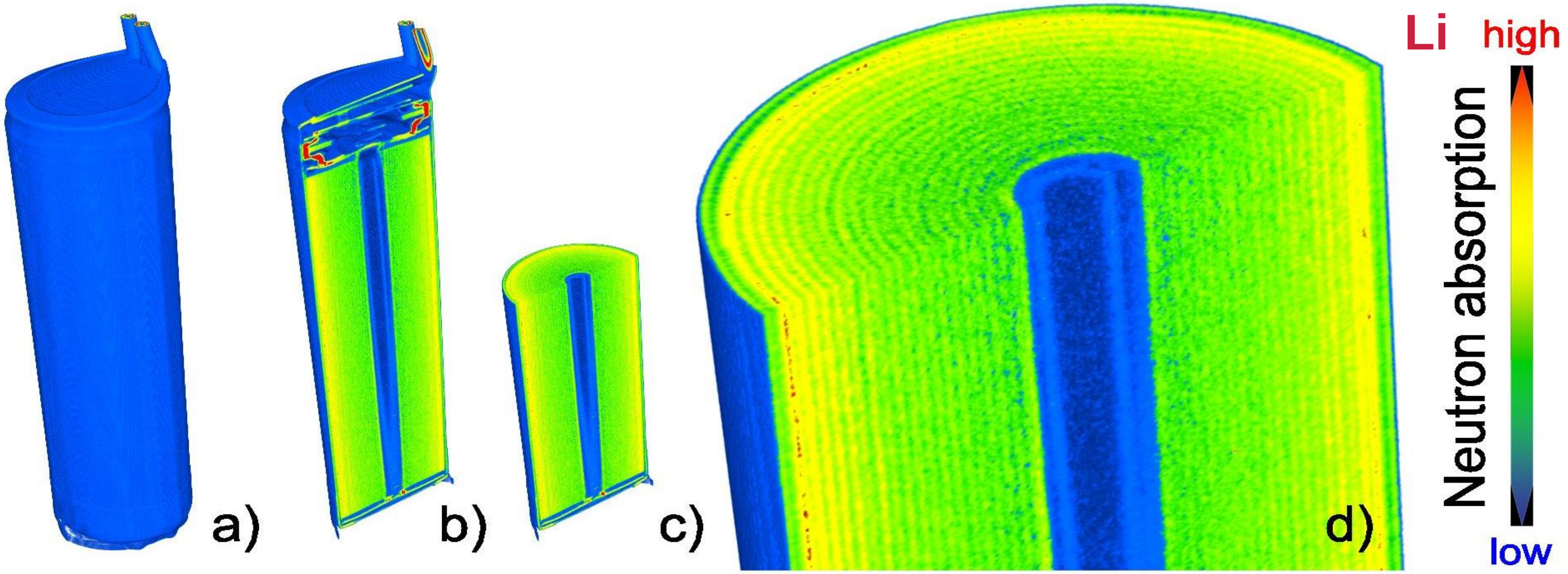




- In-situ diffraction is possible.
- Cycling leads to creation of LiC_6 at the carbon anode.
- This loss of Li leads to a loss of capacitance.

A. Senyshyn (FRM II), H. Ehrenberg (IFW, FZK), K. Nikolowski (IFW)

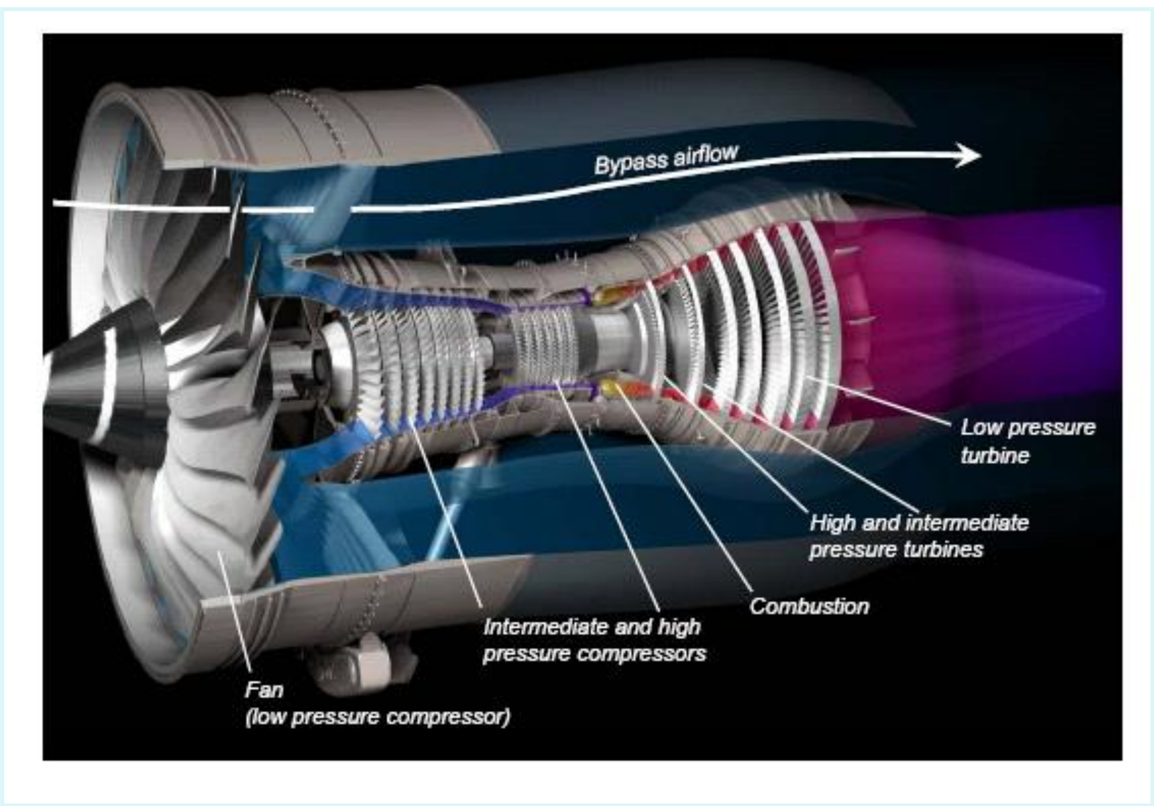
Following the chemical changes in batteries: Images in real space.

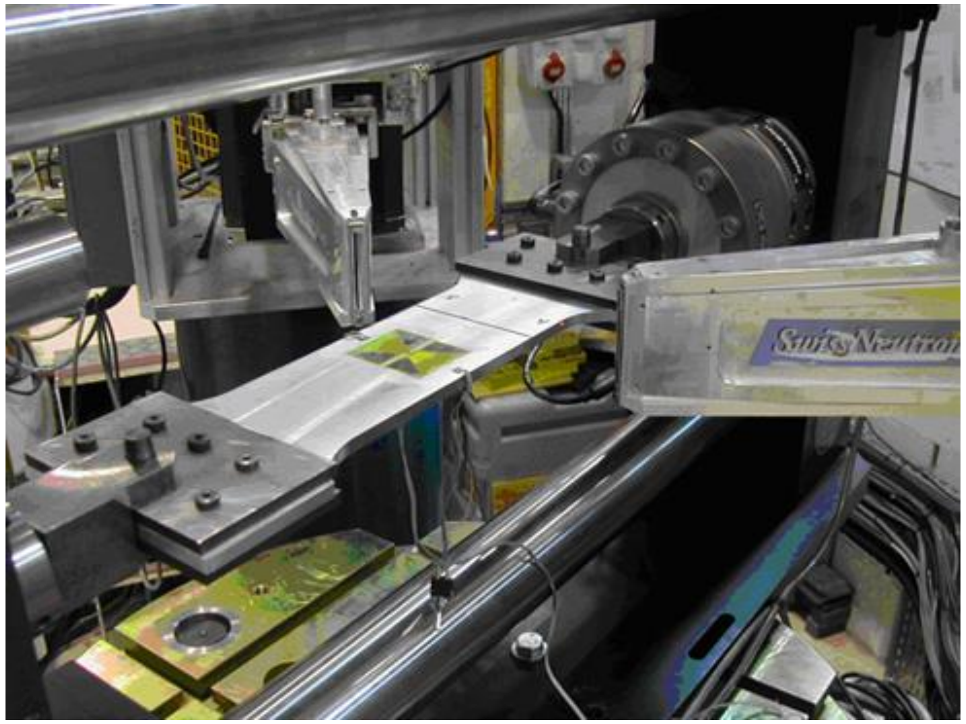


- Commercial 18650 Li-Ion Batterie, reconstructed from neutron tomography.
- Different colors symbolize the Li concentration.

A. Senyshyn, M.J.Mühlbauer, H. Ehrenberg, ANTARES

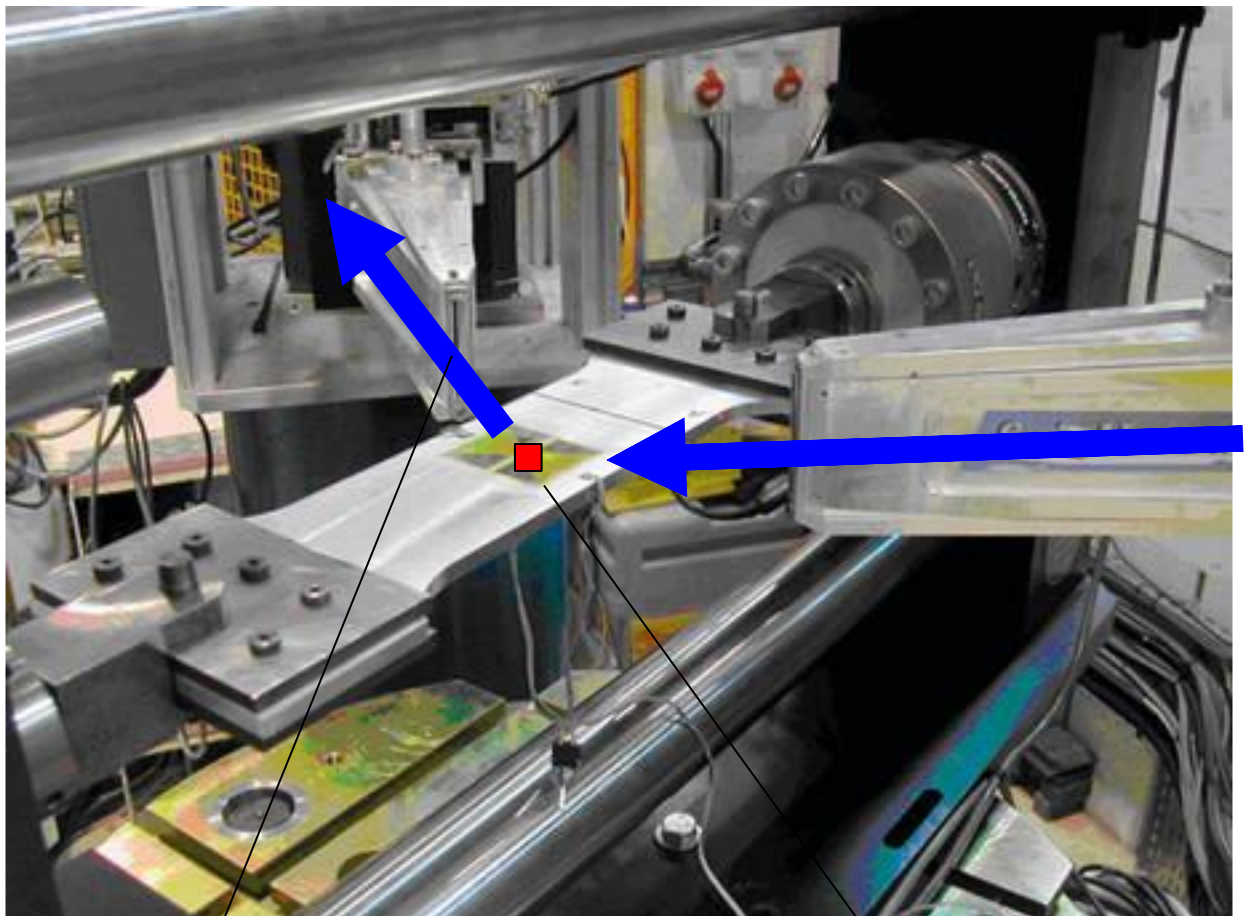
Remaining at macroscopic length scales: Strain and stress in materials

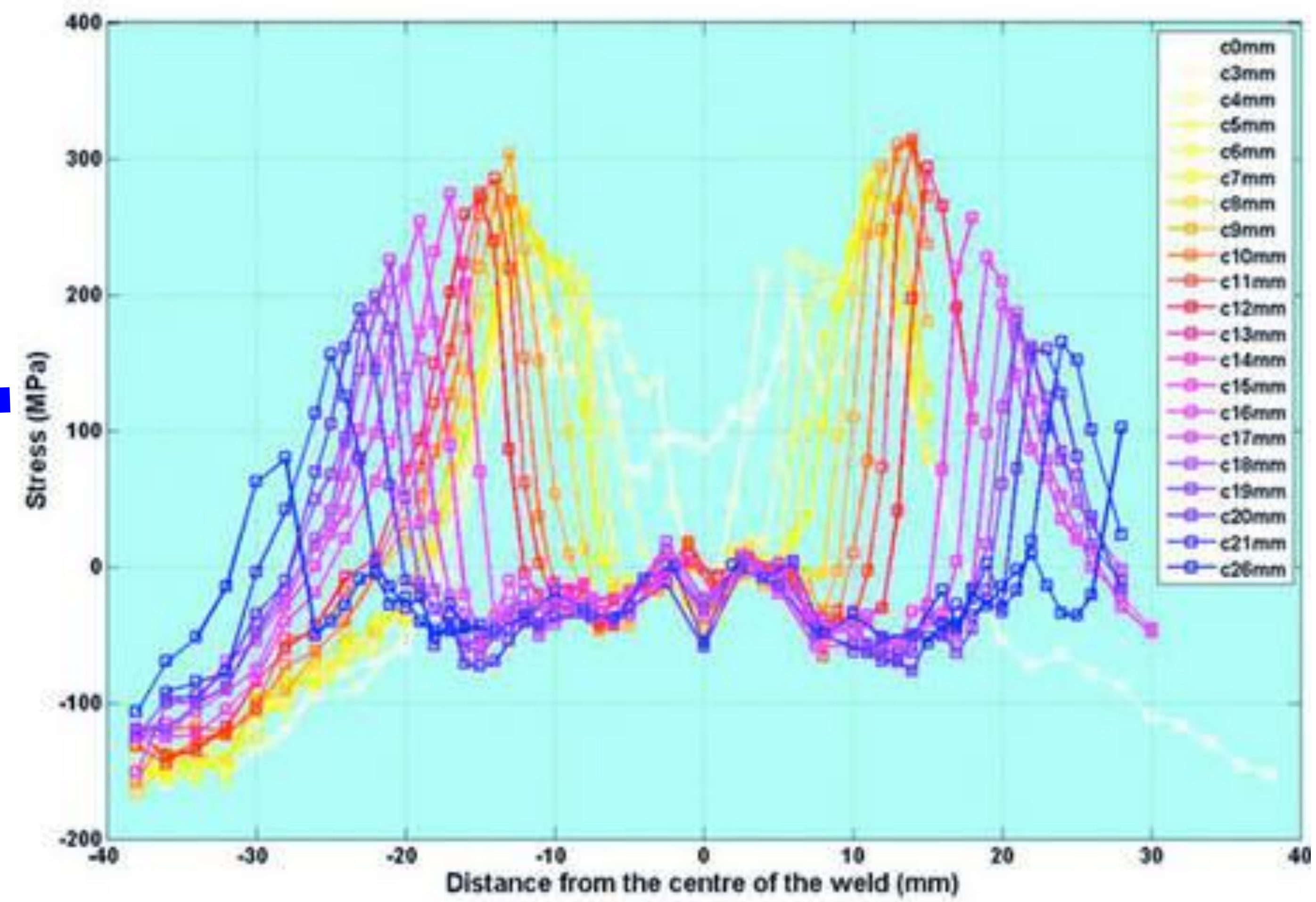




- Efficiency often comes at the price of more severe operating conditions.
- This leads to stress in the materials.
- Neutrons provide direct access to strain with ideal gauge volume and deep penetration.

An Example:
Fatigue crack growth in a weld.





gauge volume

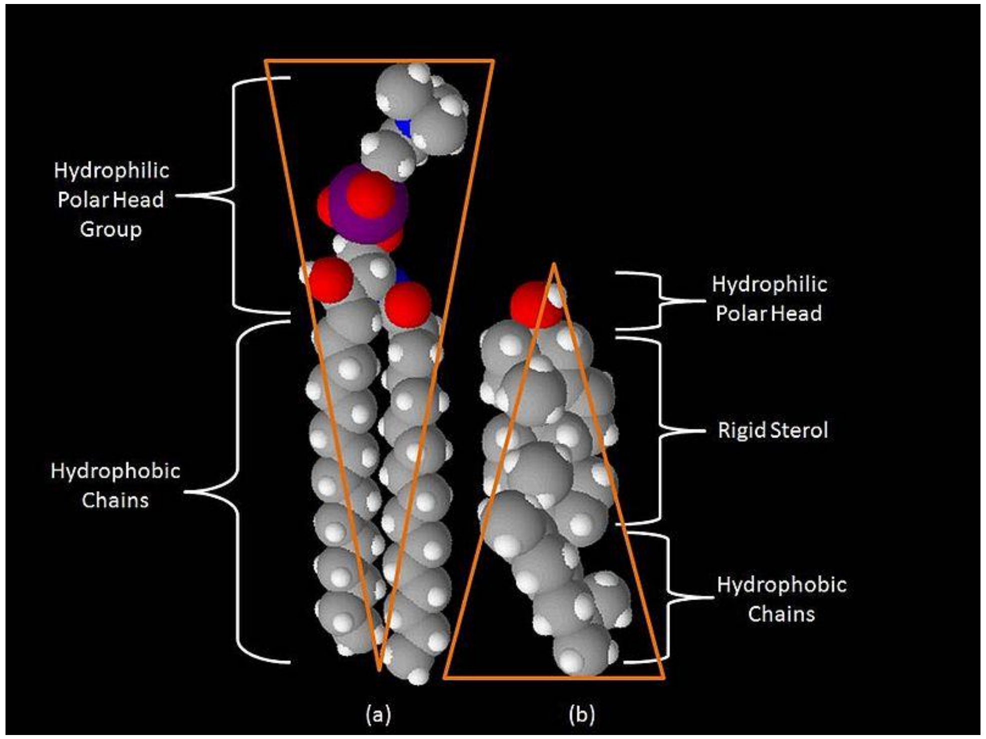
Neutrons

- In total the weld was subjected to over 100,000 fatigue cycles.
- The figure shows the variation of residual stress in the weld with crack length c.
- Linear elastic fracture mechanics are valid for the assessment of fatigue performance.

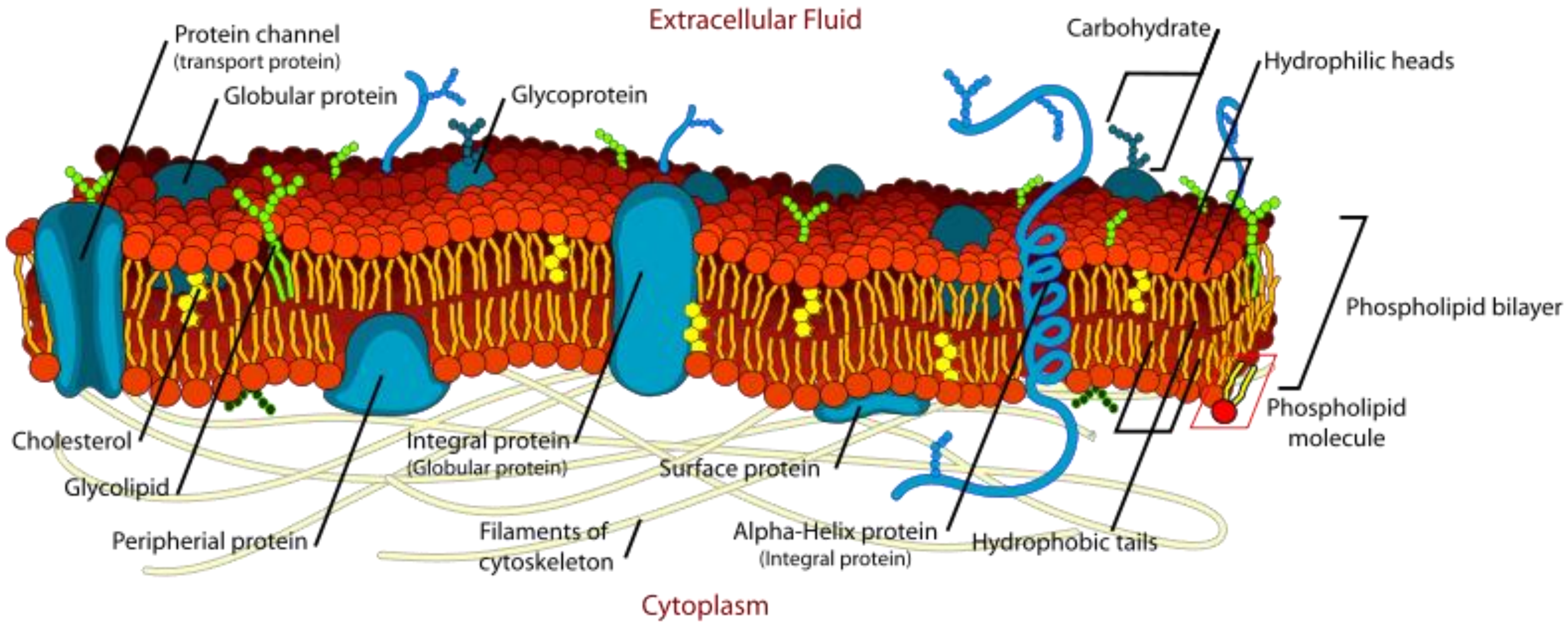
Going a further step up: The supramolecular level

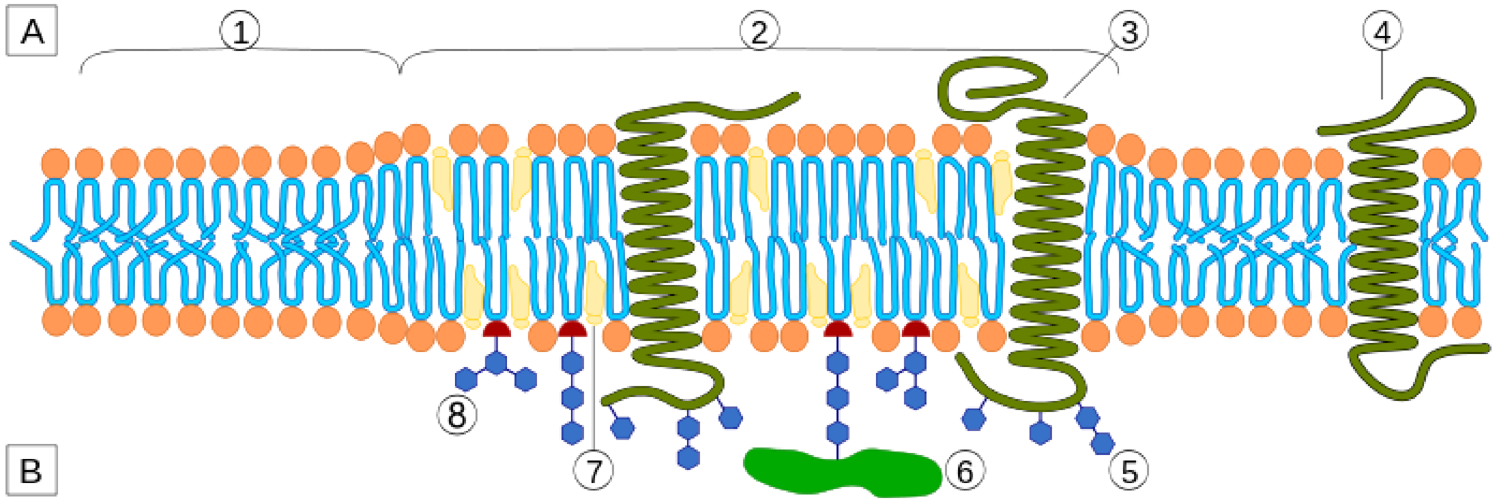
Lipid rafts are essential for the functions of the cell membrane.

How are these rafts stabilized?



Sphingomyelin (a) and Cholesterol (b)



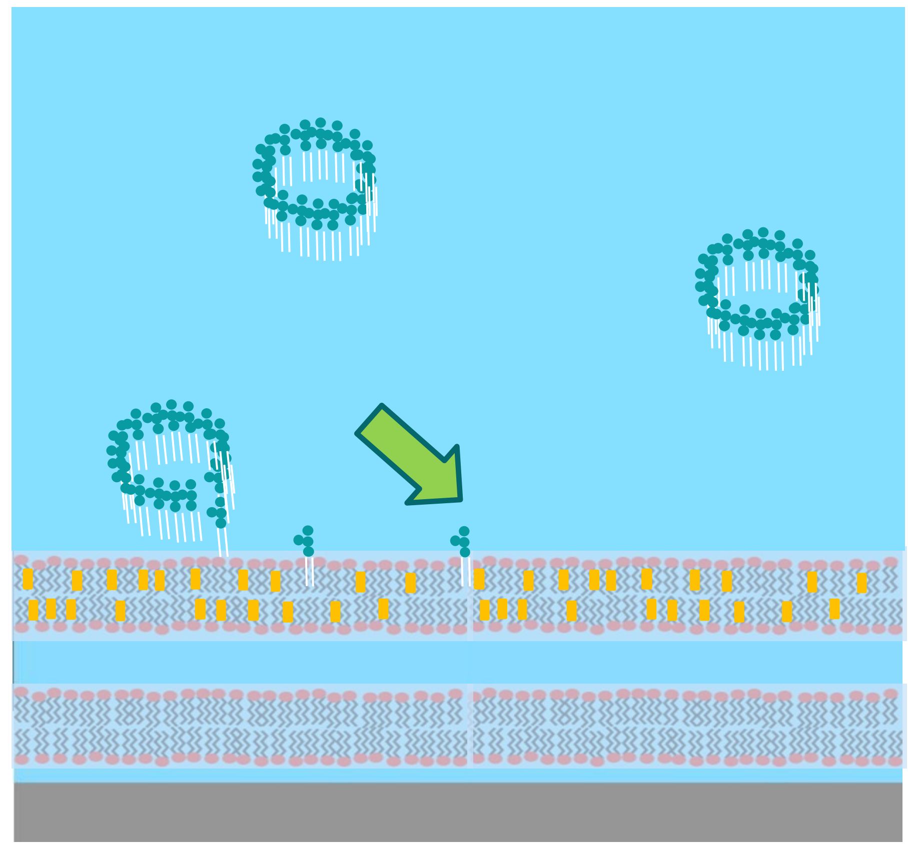


Rondelli et al. BBA (2012), Fragneto

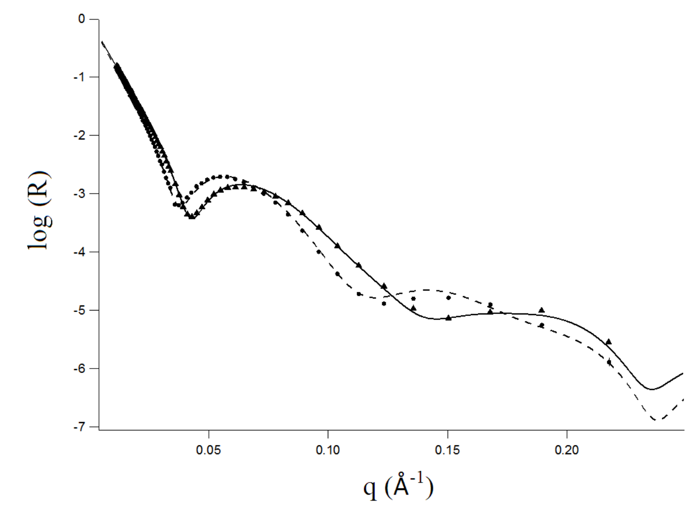
The supramolecular level: membranes

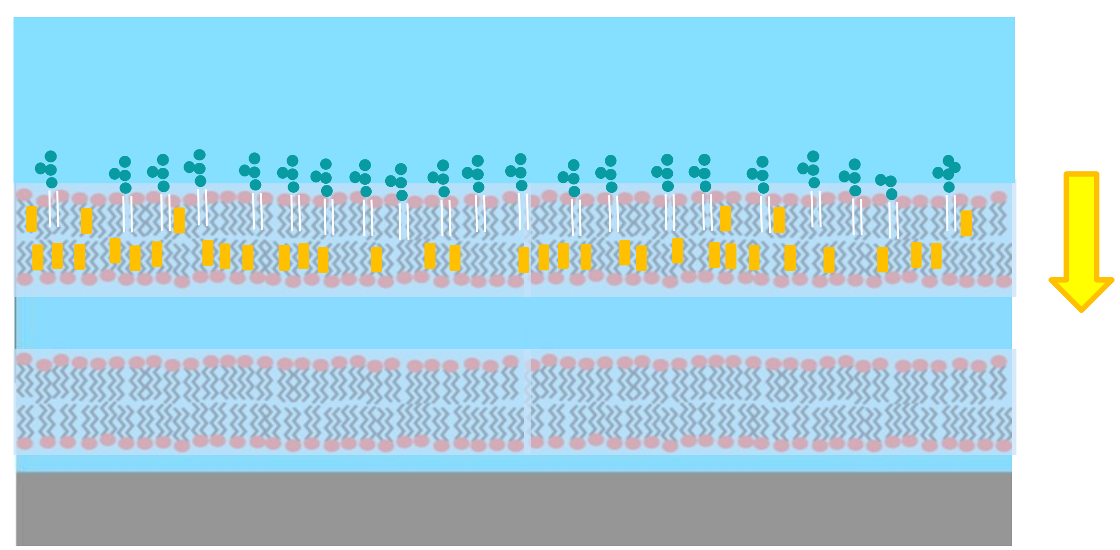
Structural correlation are observed between glycosphingolipis and cholesterol creating an asymmetric structural unit across the membrane that may influence local structural properties of rafts.

Rondelli et al. BBA (2012), Fragneto

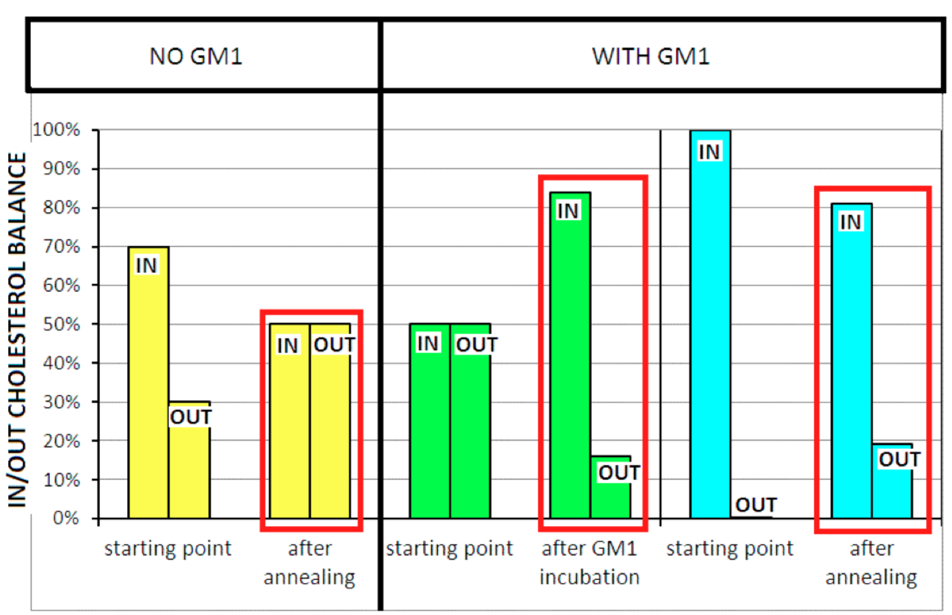


Ganglioside GM1 penetrates into the outer layer of the free floating membrane.

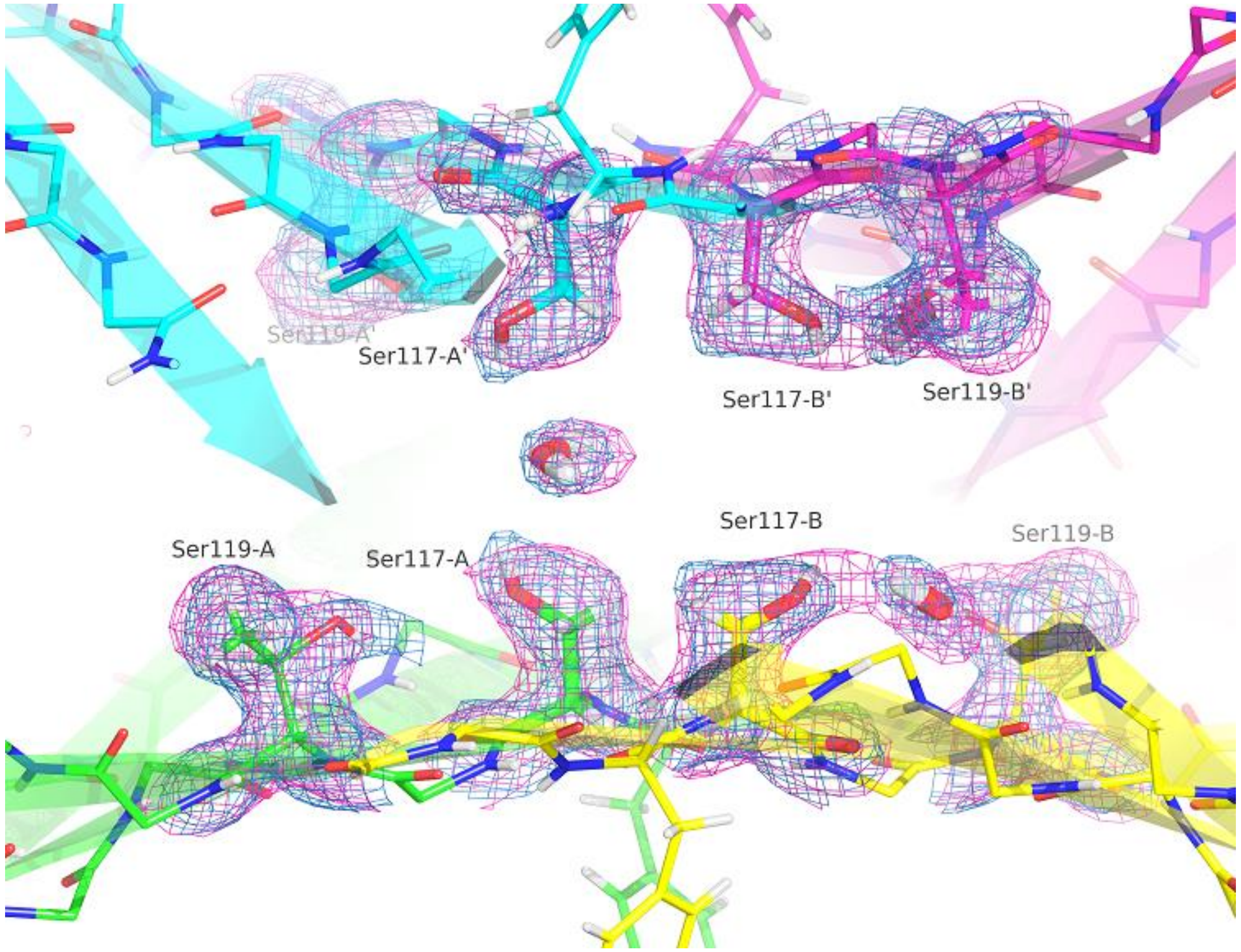




Cholesterol migrates to the opposite leaflet.



Biology at the service of medicine.

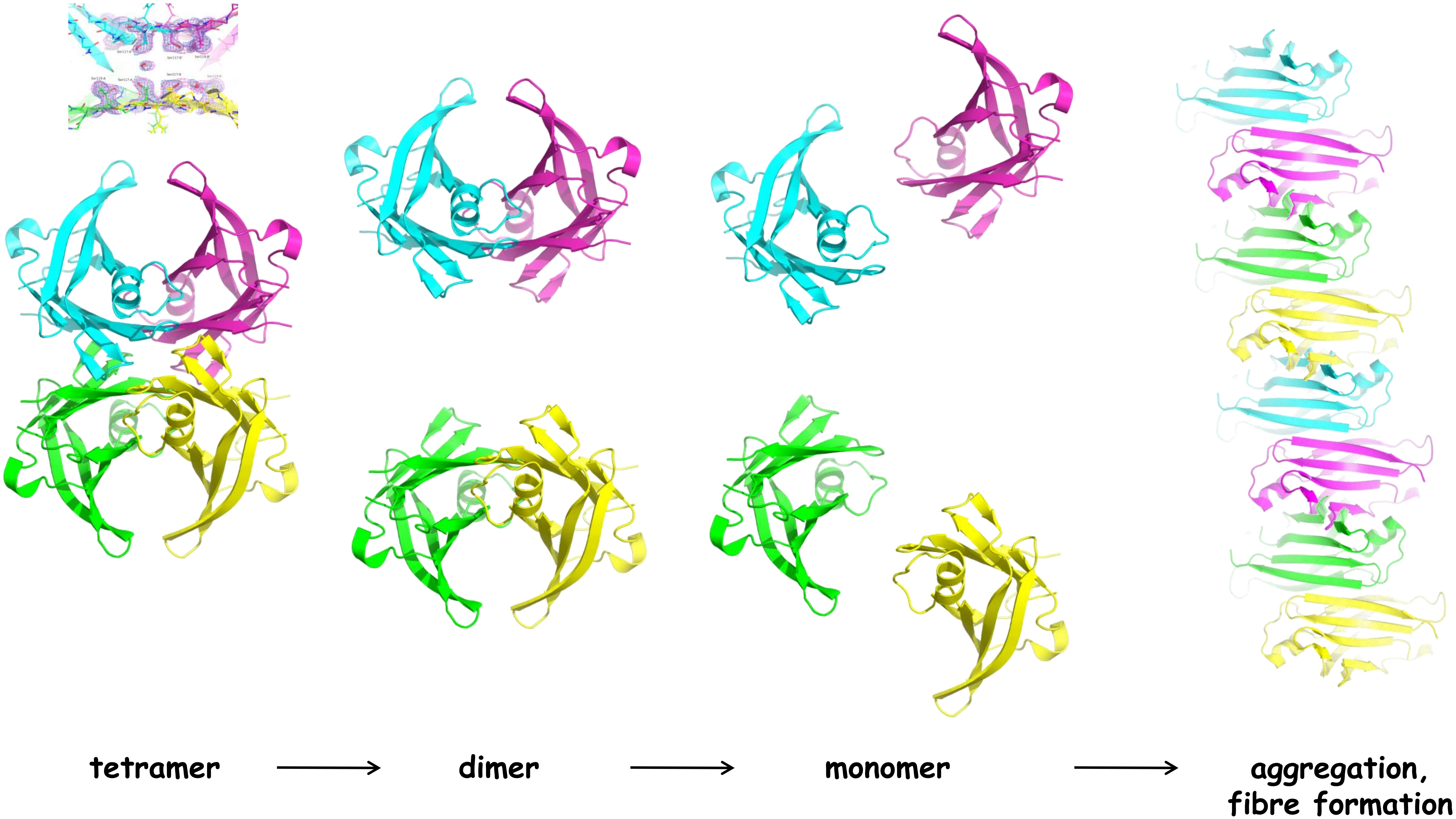


Transthyretin (**TTR**) is a serum and cerebrospinal fluid carrier of the thyroid hormone thyroxine (T4) and retinol binding protein bound to retinol.

T. Forsyth et al., unpublished

- Highly symmetric center of homo tetramer.
- The side chains of the four Ser-117 residues create a barrier between the two docking sites of the hormone.
- Neutrons show differences in the orientation of the binding of the G-deuterium in the A- and B-chains in addition to an isolated water molecule.

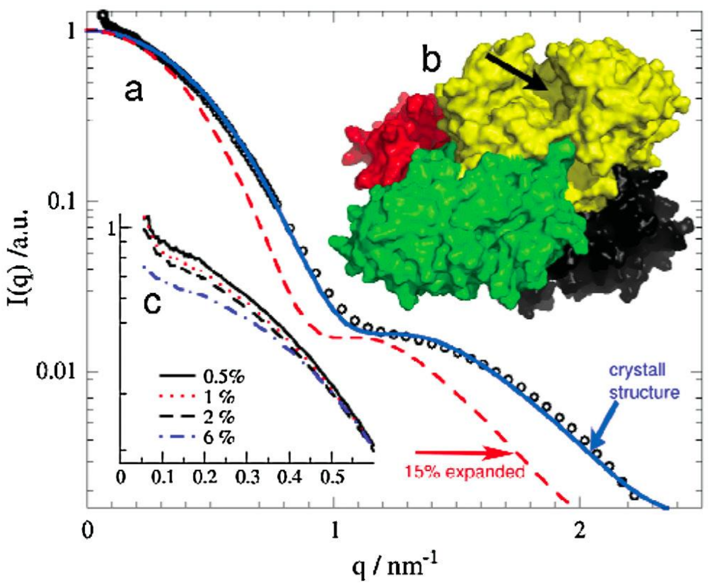
Biology at the service of medicine.



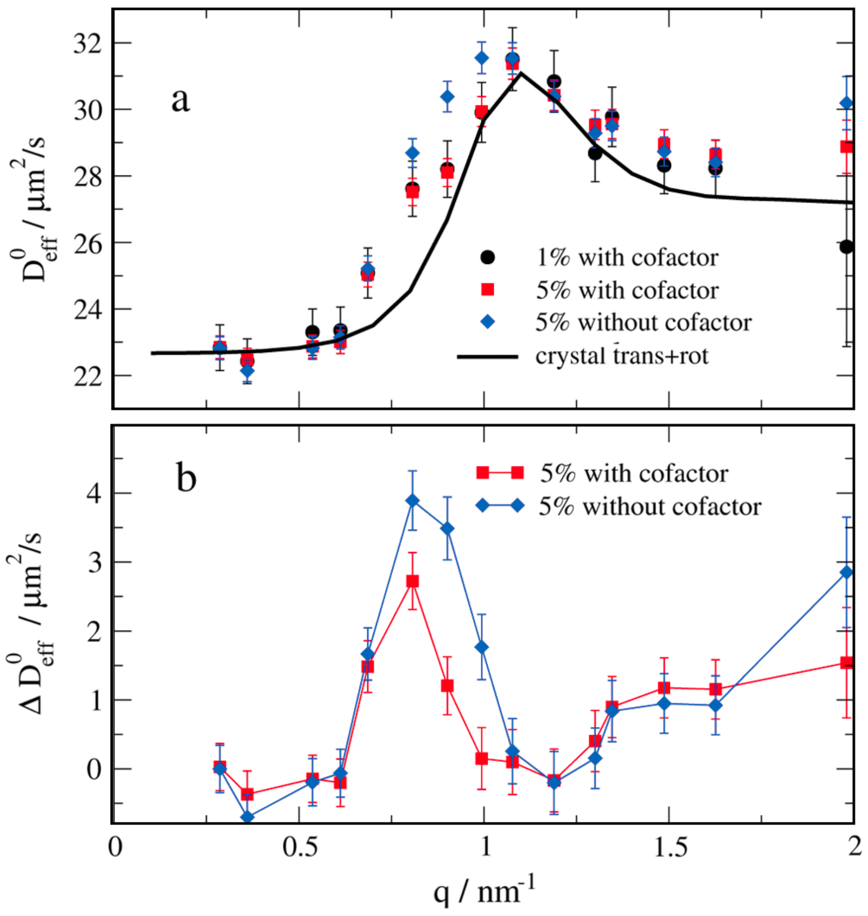
- **Amyloids** are insoluble fibrous protein aggregates.
- Abnormal accumulation of amyloid fibrils in organs may lead to **amyloid**osis, and may play a role in various neurodegenerative disorders.

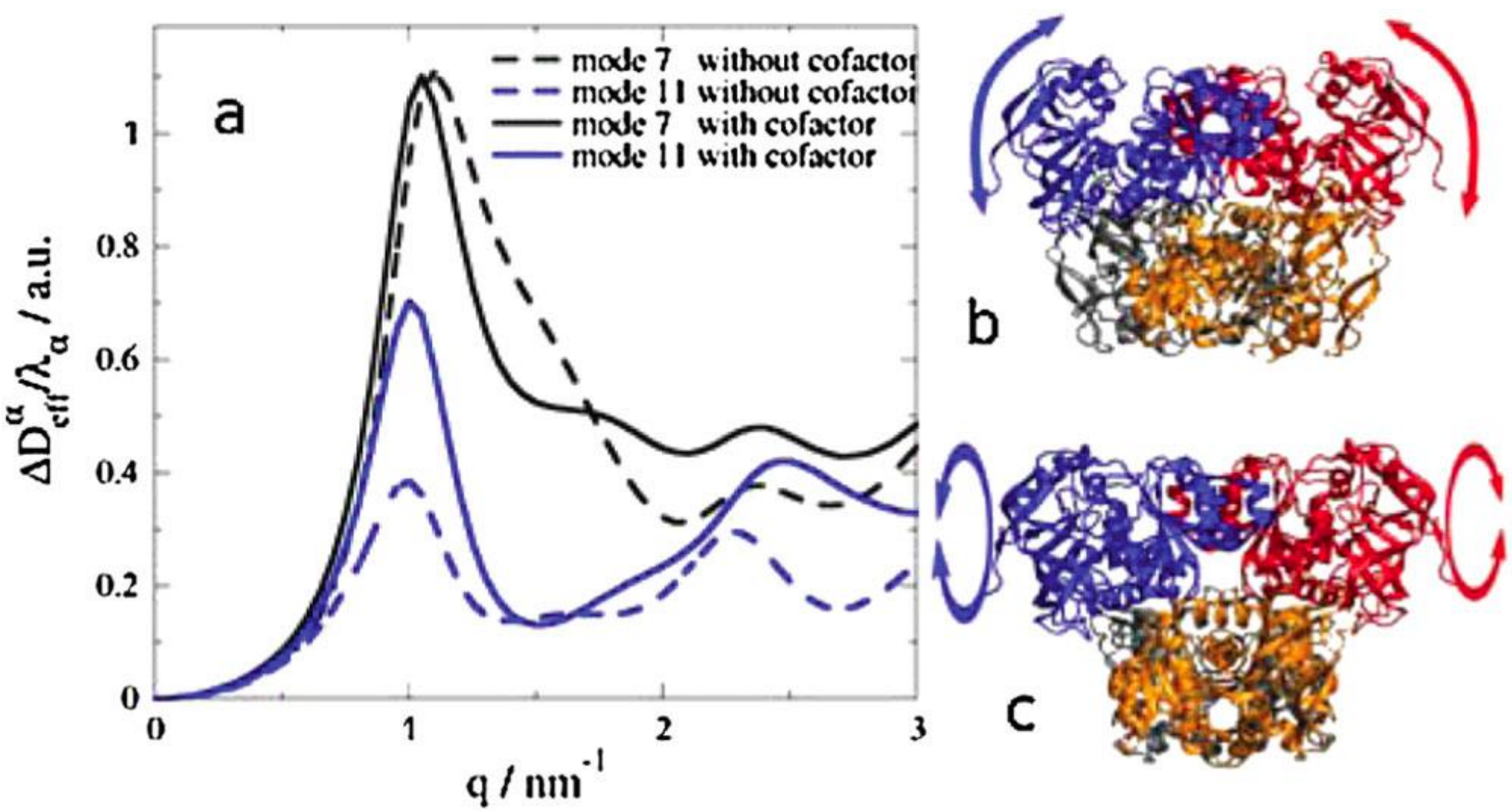
T. Forsyth et al., unpublished

Biological function equally is exploiting fast dynamics



Biehl, et al. Physical Review Letters, 101(13):138102 (4 pp.), 2008.
Correlated Interdomain Motion in Alcohol Dehydrogenase





I hope you enjoyed the walk!