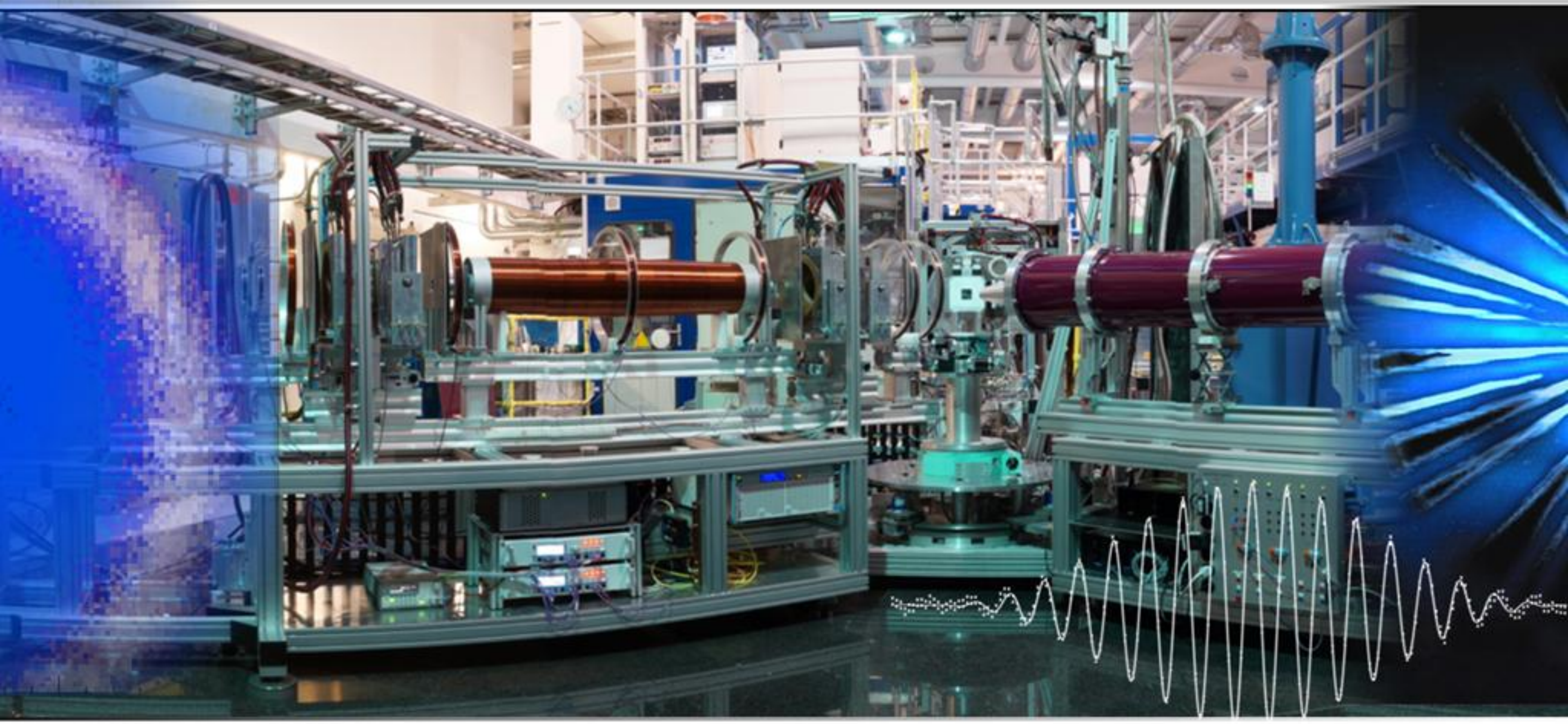
Neutron Detectors
probing nano and macro scales

Particle Physics Colloquium
April 18th 2019

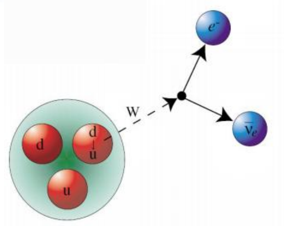
Physikalisches Institut

Rheinische Friedrich-Wilhelms Universität
Bonn

Markus Köhli
AG DESCH



Beta Asymmetry and CKM Matrix



$$H_\beta = H_{V,A}$$
$$= \bar{e}\gamma_\lambda(1-\gamma^5)\nu_e\bar{p}(g_V + g_A\gamma^5)\gamma^\lambda n$$

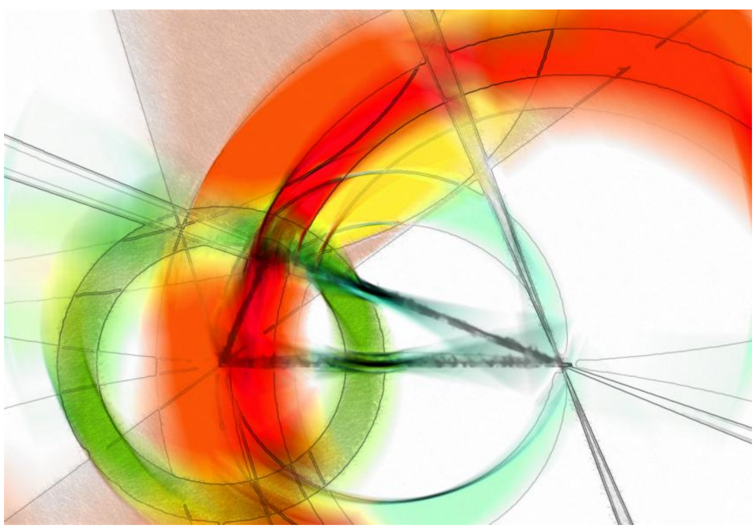
Vector (Fermi, ΔJ=0) → g_V

Axial Vector (Gamow-Teller, ΔJ=1) → g_A

$$\tau_n = \frac{1}{|V_{ud}|^2}\frac{4908.7 \pm 1.9\ \mathrm{s}}{(1+3\lambda^2)}$$

$$ft_n = \frac{2\pi^3\ln(2)\hbar^3}{m_e^5c^4}\cdot[|G_V|^2 + 3|G_A|^2]^{-1}$$

$$\lambda = |g_A/g_V|$$



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

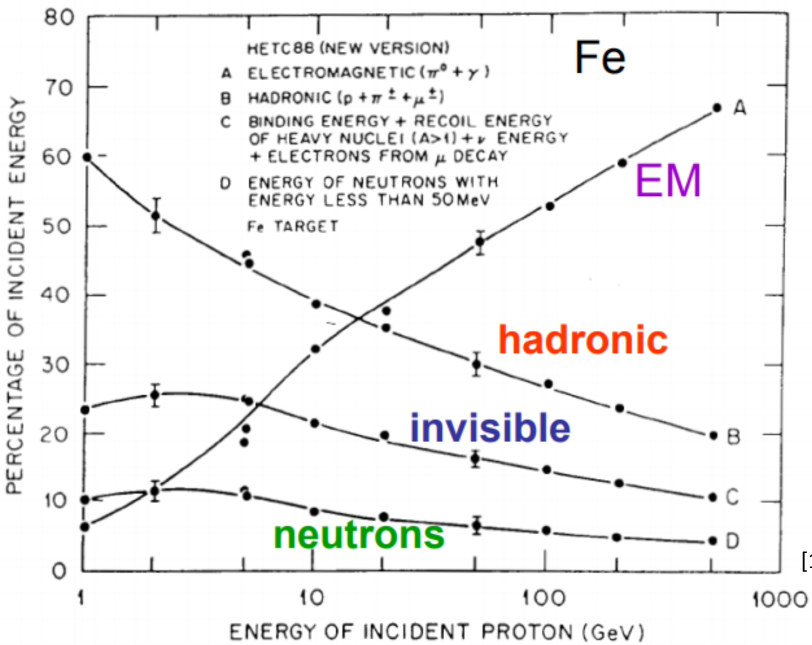
$$G_V\,(\Delta Y = 0) = G_F\cdot\cos(\theta_c);\ G_V\,(\Delta Y = 1) = G_F\cdot\sin(\theta_c)$$

Neutrons in Calorimeters

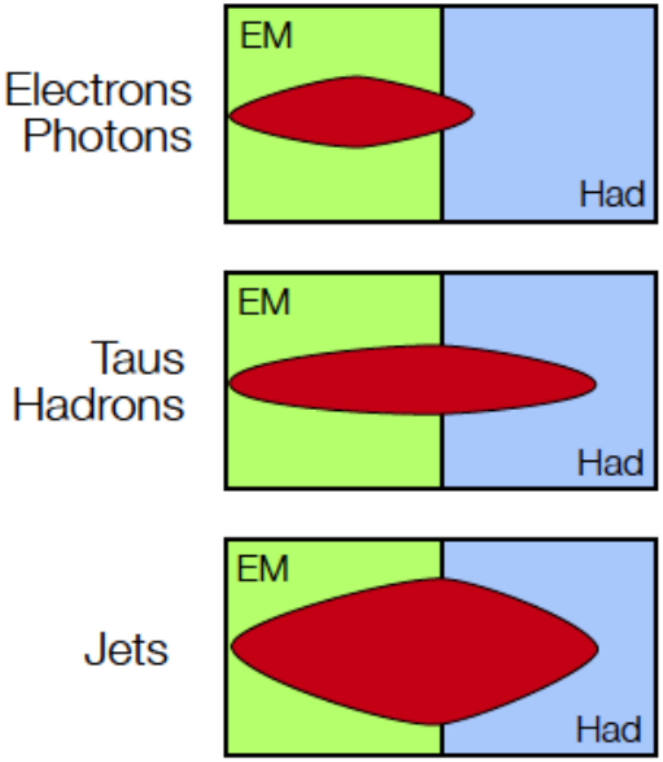
Deposited Energy

$$E_p = f_{em} e + (1 - f_{em}) h$$

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$



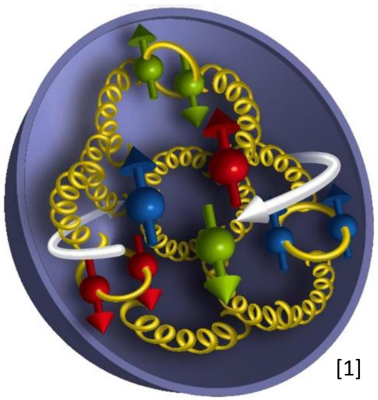
[1]



[2]

[1] Anderson, D.F. et. al. „Proceedings Of The First International Conference on Calorimetry In High Energy Physics"
[2] Schlepper, „Hadron Calorimeters" http://www.desy.de/~schleper/lehre/Det_Dat/SS_2018/06_lecture_calorimetry_HAD.pdf

Neutron Science Scales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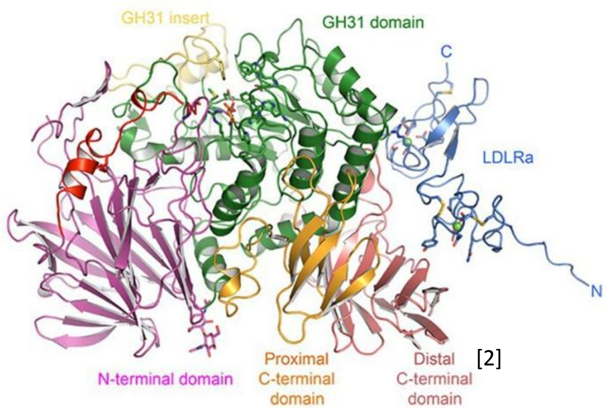
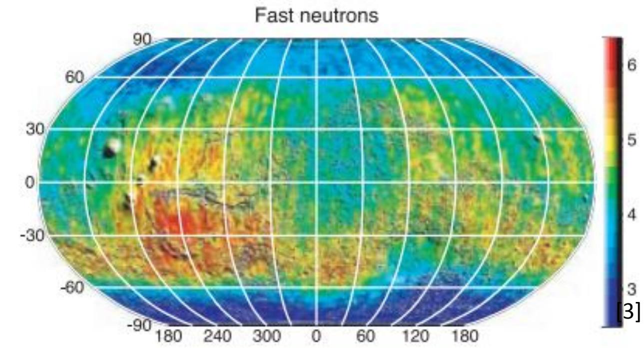


[2]



[3]

[1] BNL „2015's Top 10 Scientific Advances at Brookhaven National Laboratory"
[2] Caputo et al. „Structures of mammalian ER α-glucosidase II capture the binding modes of broad-spectrum iminosugar antivirals"
[3] Feldman, et al., "Global Distribution of Neutrons from Mars: Results from Mars Odyssey" Science (2002), pp 75-78

A talk of ~2 neutron lifetimes

- Neutron Detection Principles
- Rapid Growth of Detection Solutions
- Novel Neutron Detectors
- Neutron Physics Scales

Neutron Detection

- No charge
- „Low“ energies - as low as thermal ($k_B T$ = 25 meV)

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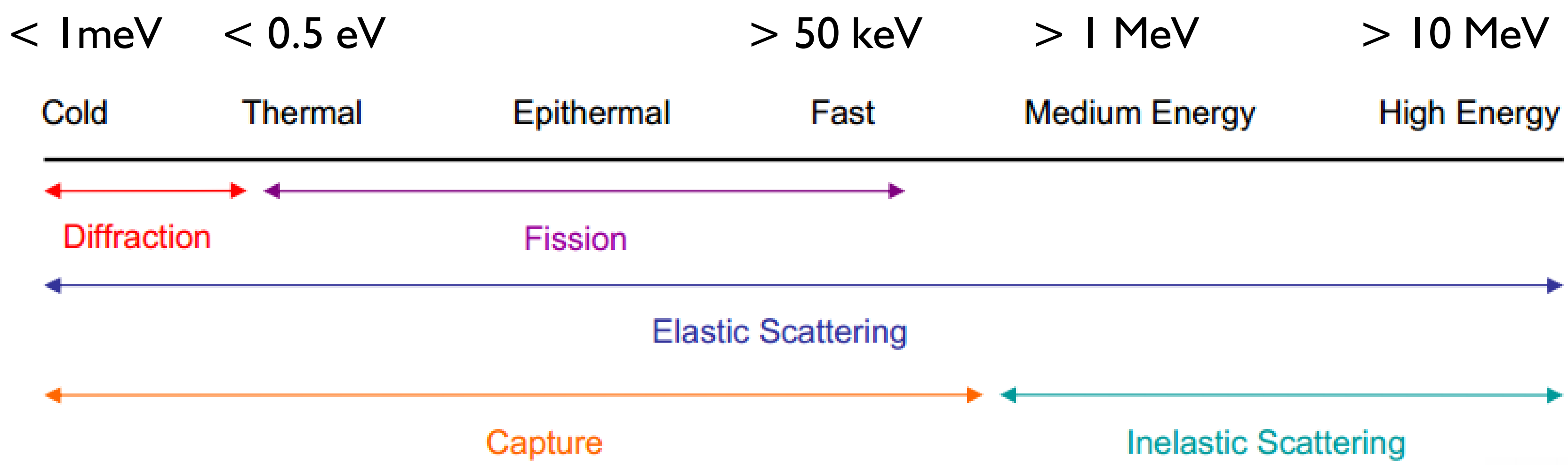

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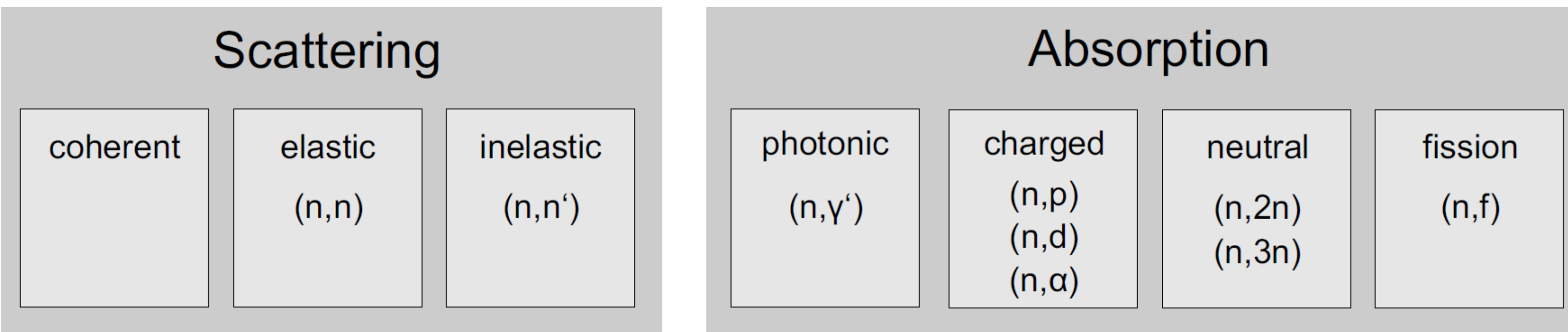

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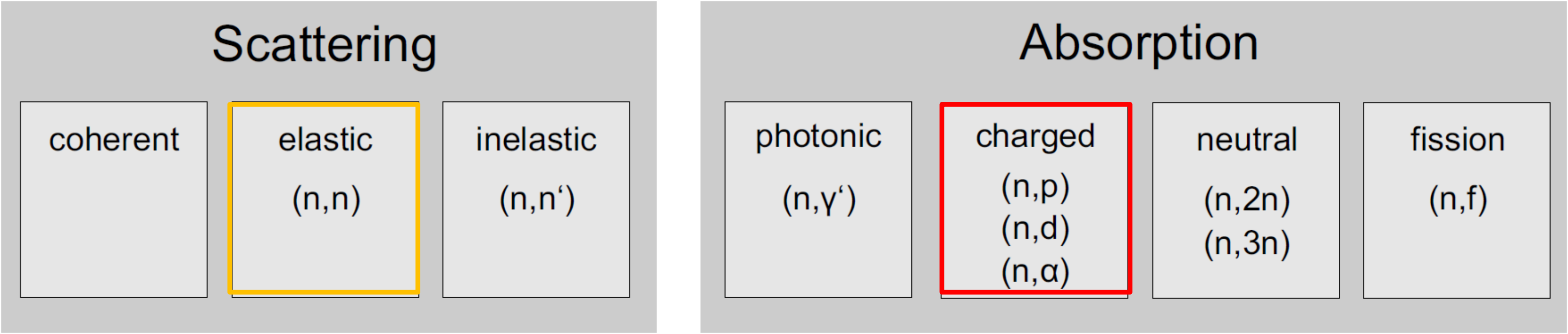
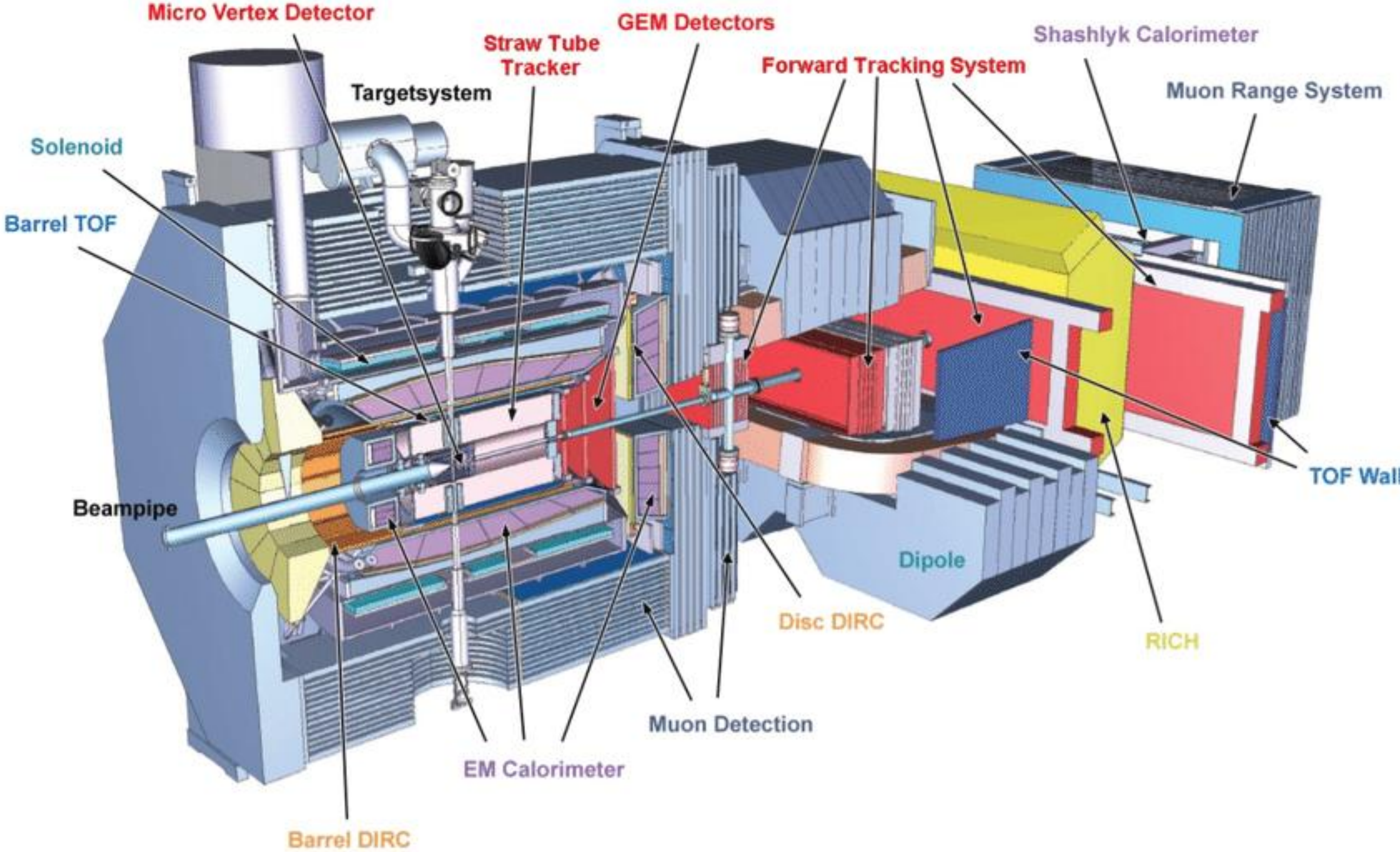


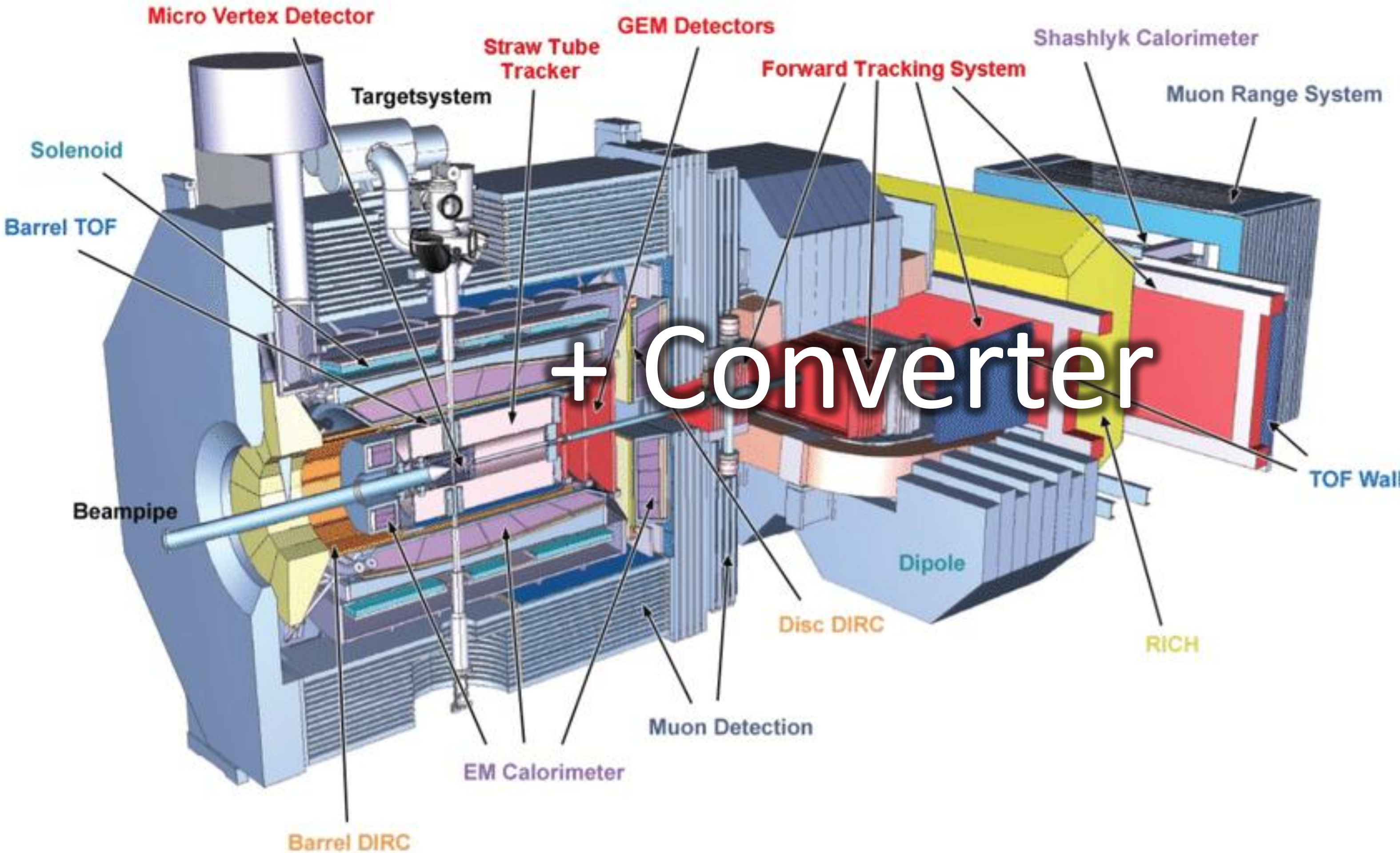
‚converters‘

Neutron Detection



W. Ikegami Andersson et al, „The PANDA Detector at FAIR", Journal of Physics: Conference Series 770 (2016) 012043

Neutron Detection



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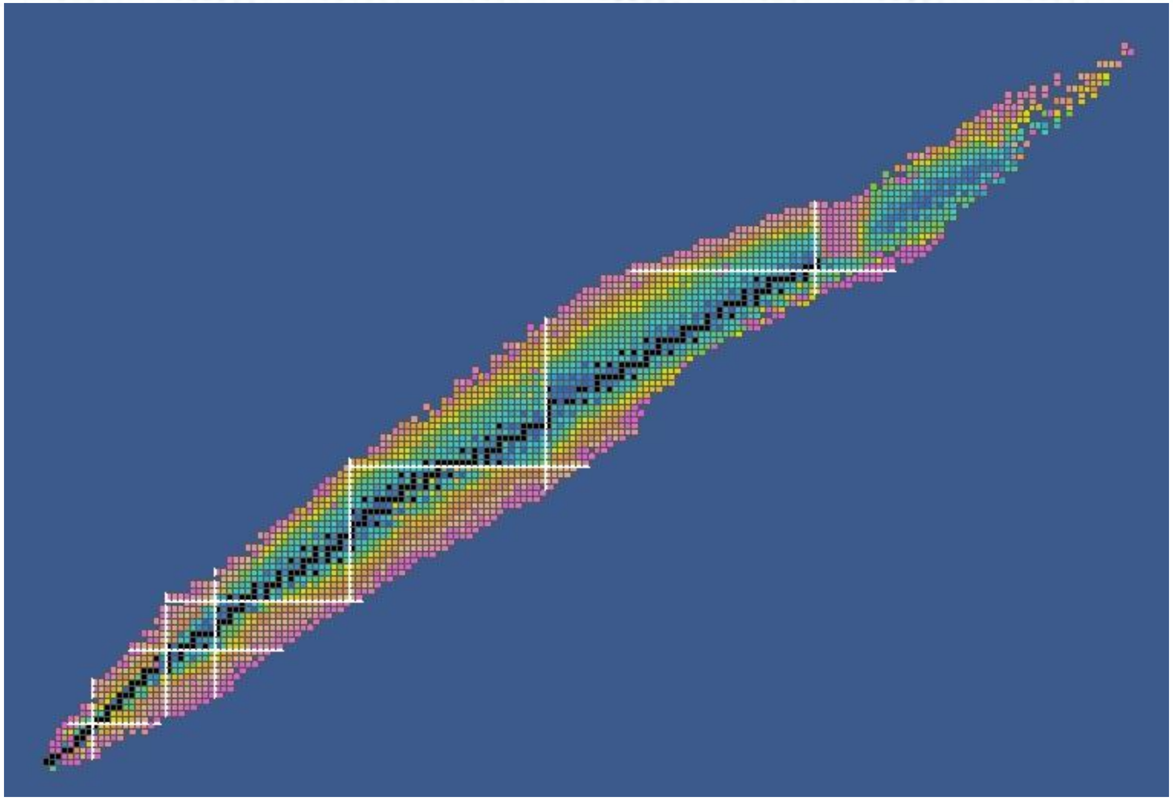
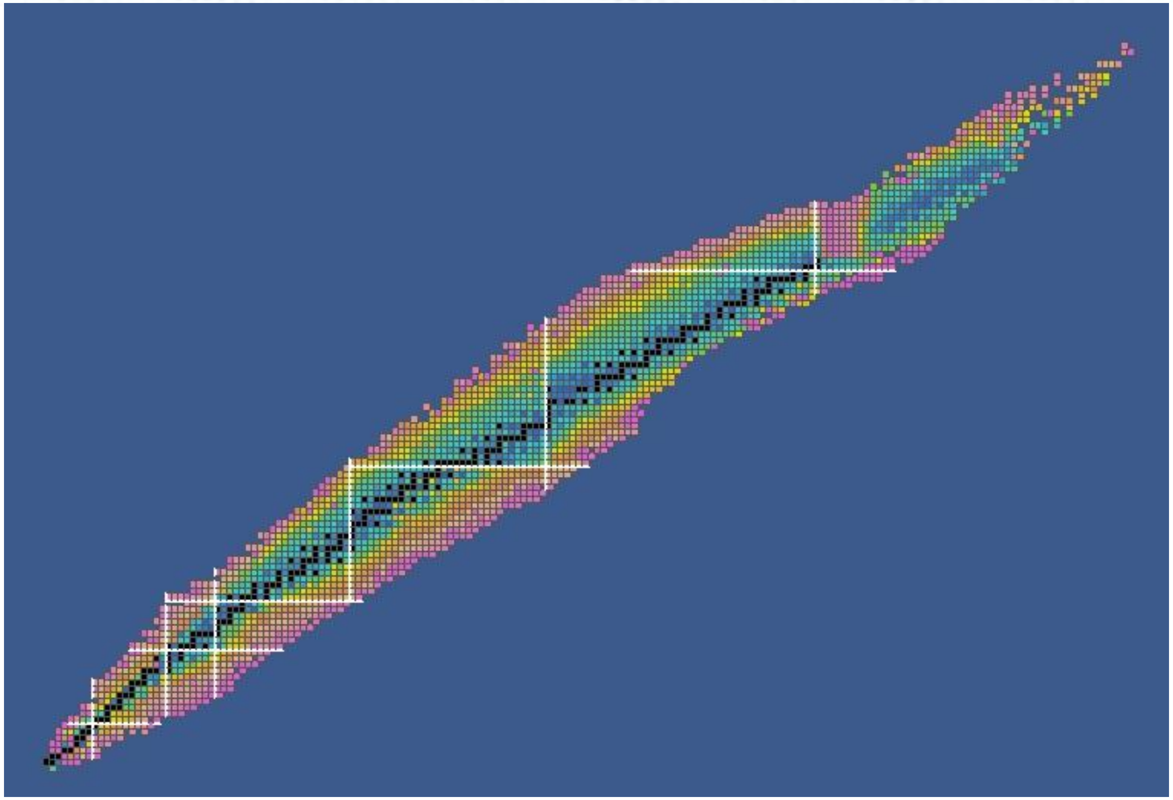
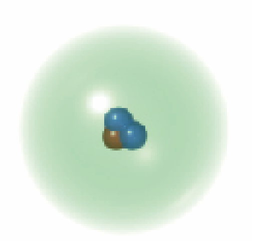
Neutron Detection



Img source: wikipedia

Neutron Detection

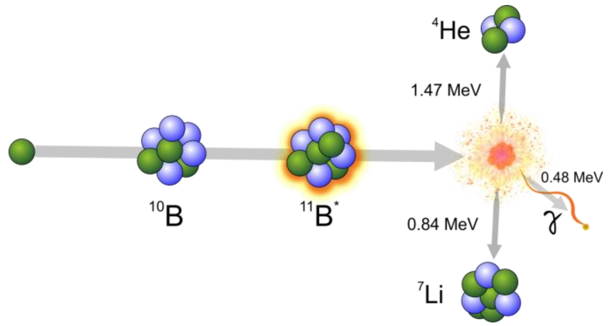




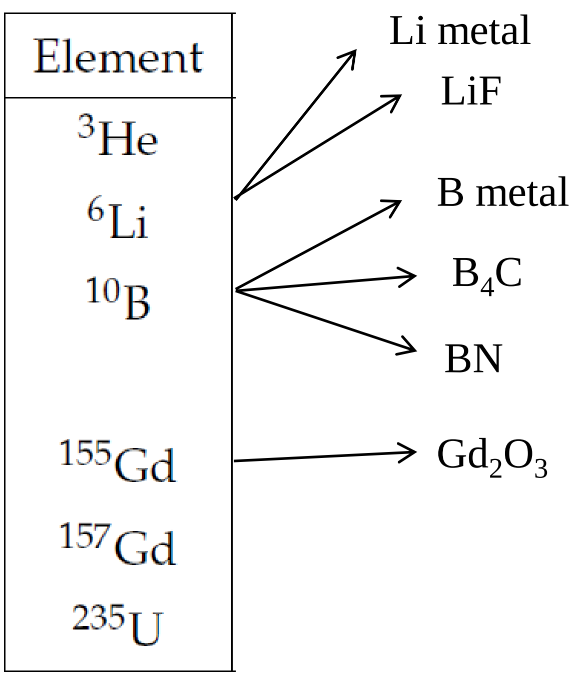
Img source: wikipedia

Neutron Converters

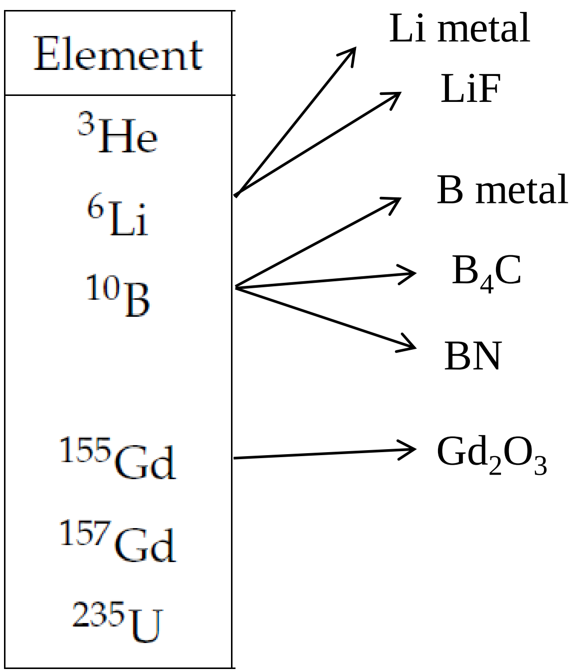
Element	Reaction	CS at 25.2 meV
^{3}He	$^3\mathrm{He}+\mathrm{n} \longrightarrow {}^3\mathrm{H}+764\,\mathrm{keV}\,\|+\mathrm{p}$	5327 b
^{6}Li	$^6\mathrm{Li}+\mathrm{n} \longrightarrow {}^3\mathrm{H}+\alpha+4.78\,\mathrm{MeV}$	940 b
^{10}B	$^{10}\mathrm{B}+\mathrm{n} \longrightarrow {}^7\mathrm{Li}+\alpha+2.79\,\mathrm{MeV}\ (6\,\%)$	3837 b
	$^{10}\mathrm{B}+\mathrm{n} \longrightarrow {}^7\mathrm{Li}^*+\alpha+2.31\,\mathrm{MeV}\ (94\,\%)$	
^{155}Gd	$^{155}\mathrm{Gd}+\mathrm{n} \longrightarrow {}^{156}\mathrm{Gd}+\gamma+e^-+(30-180)\,\mathrm{keV}$	61000 b
^{157}Gd	$^{157}\mathrm{Gd}+\mathrm{n} \longrightarrow {}^{158}\mathrm{Gd}+\gamma+e^-+(30-180)\,\mathrm{keV}$	254000 b
^{235}U	$^{235}\mathrm{U}+\mathrm{n} \longrightarrow$ fission fragments $+\,160\,\mathrm{MeV}$	584 b

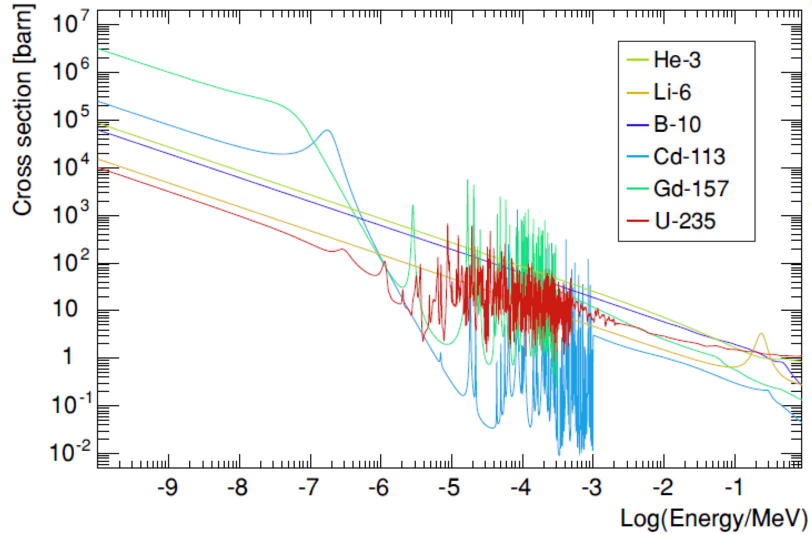


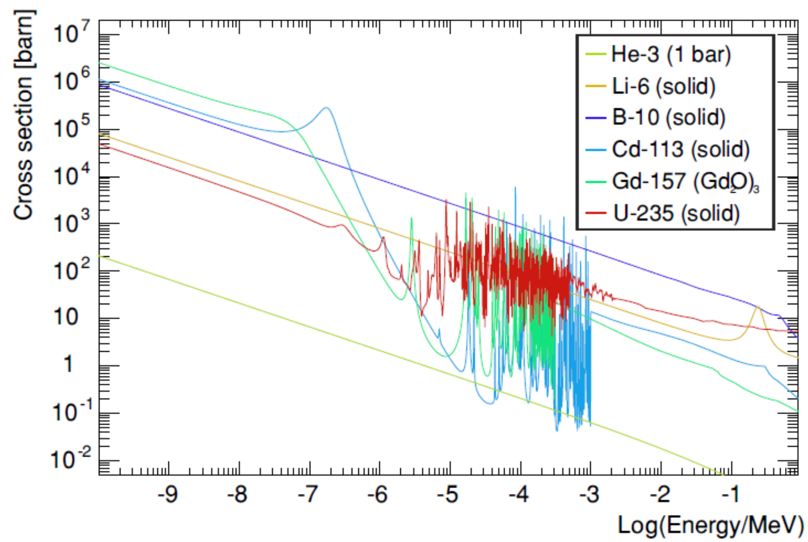
Neutron Converters



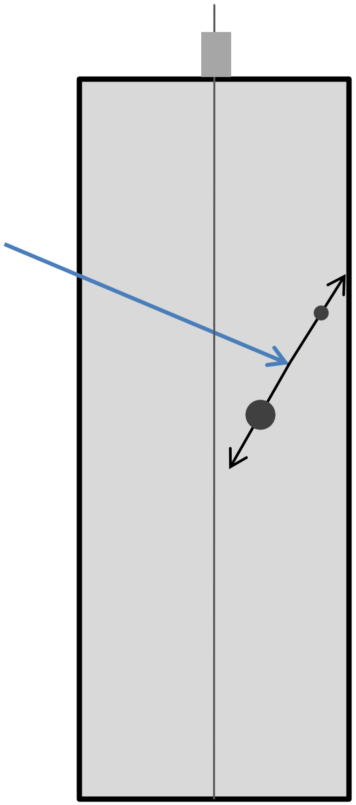
CS vs. absorption coefficient



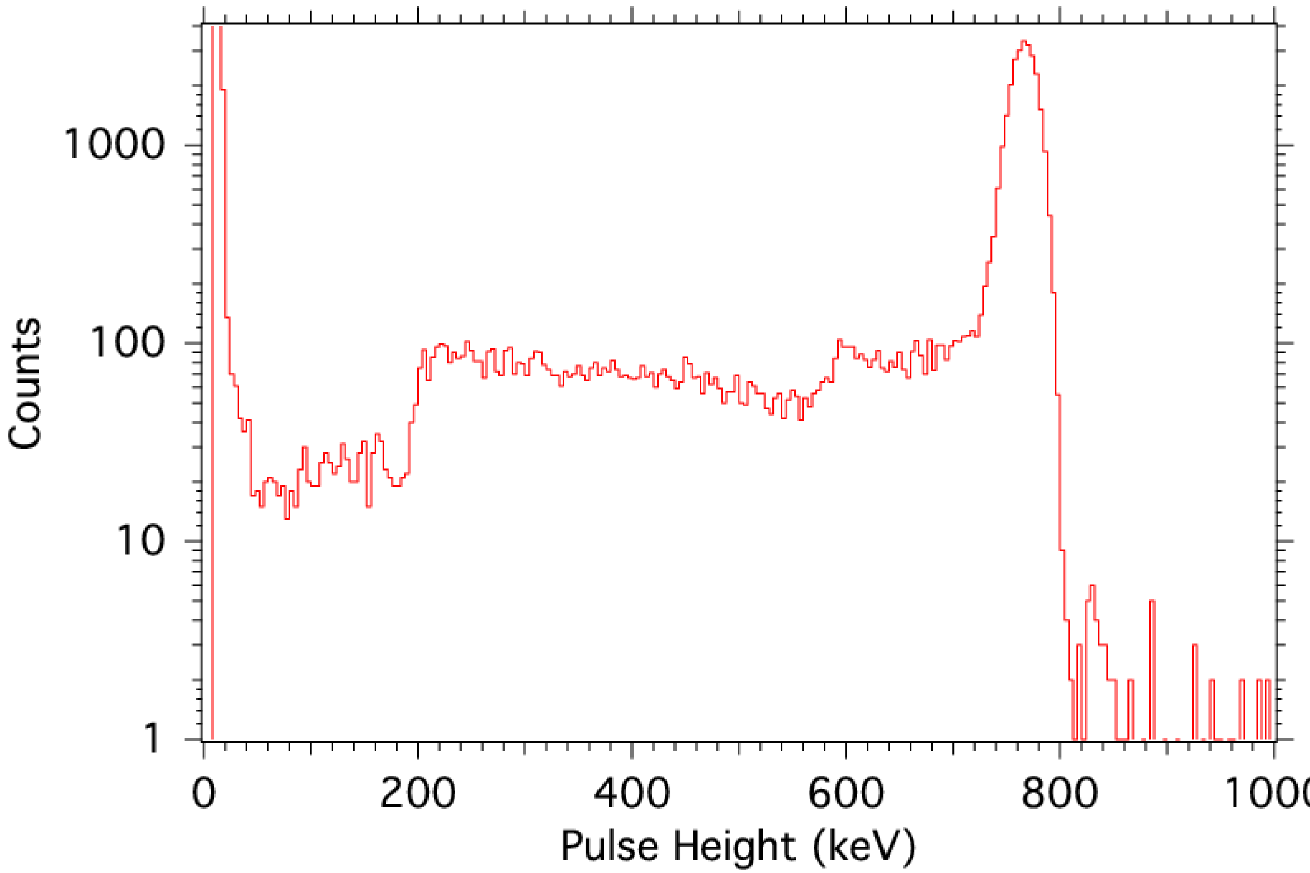




Conversion in ^{3}He

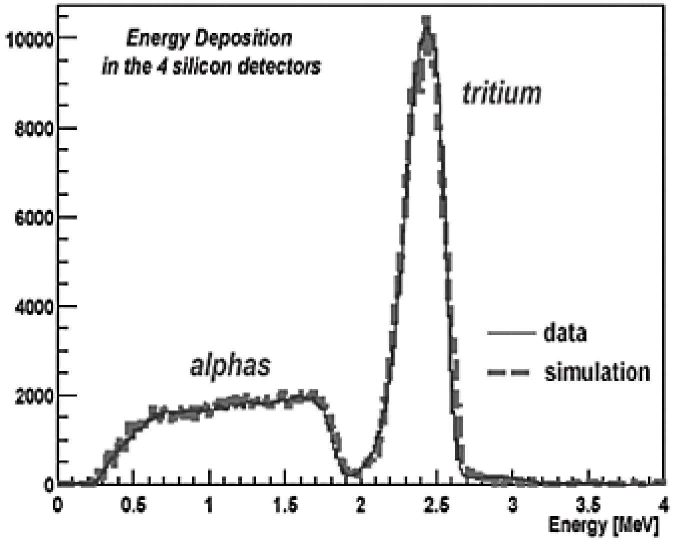


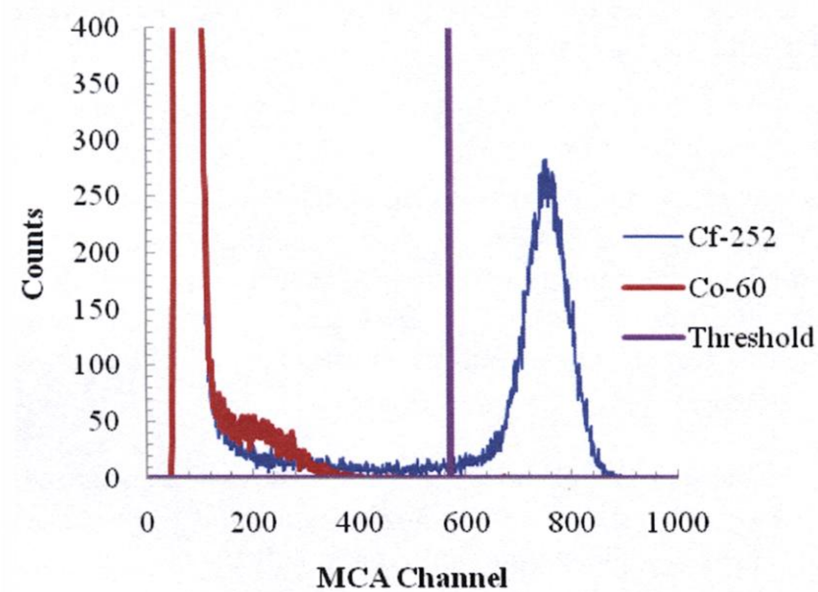
1“ 4 atm He-3

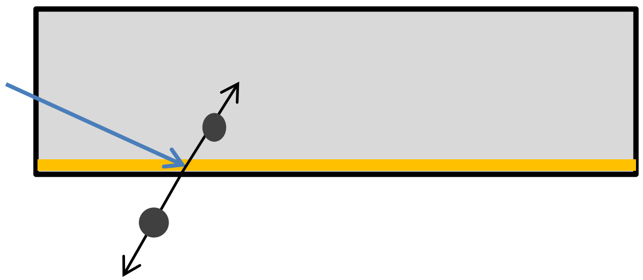


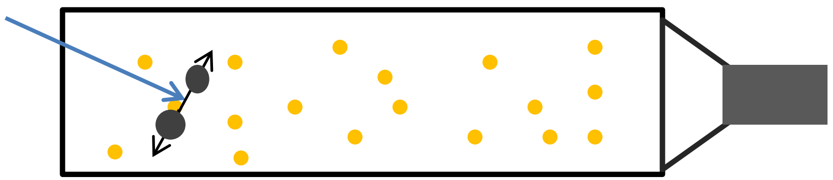
Langford et al., “Event Identification in 3He Proportional Counters Using Risetime Discrimination” arXiv:1212.4724v1

Conversion in ^{6}Li



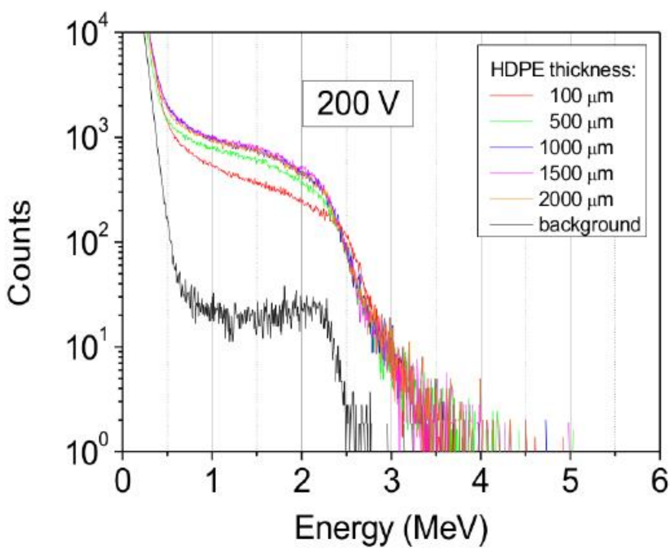






[1] P.F. Mastinu et al., "A low-mass neutron flux monitor for the n _TOF facility at CERN", Braz. J. Phys. vol.34 no.3, 2004
[2] M. Foster et al. "A Compact Neutron Detector Based on the use of a SiPM Detector", IEEE Nuc. Spring Symp., 2008

Fast Neutron Detector



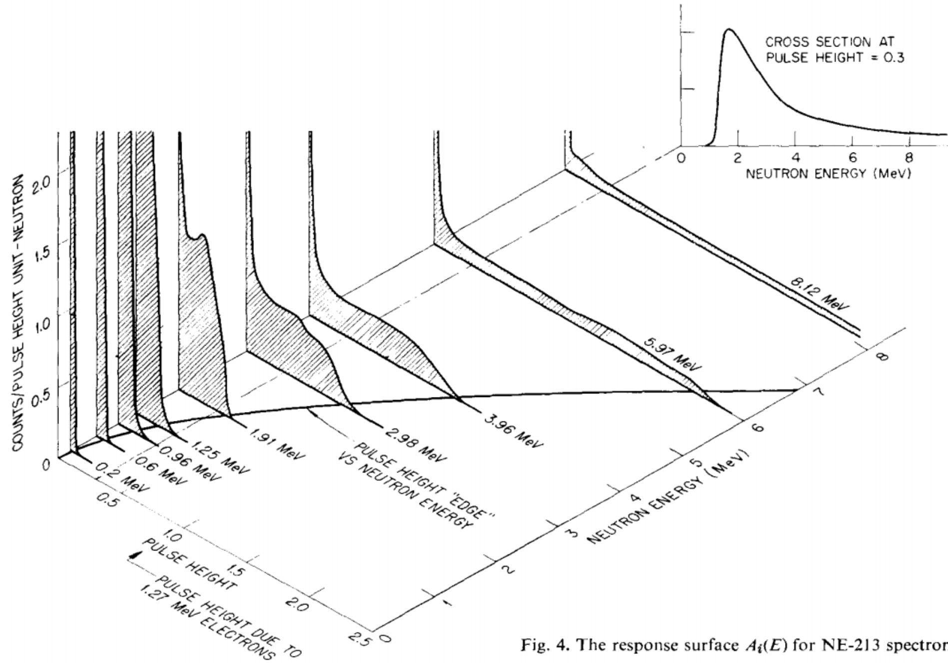
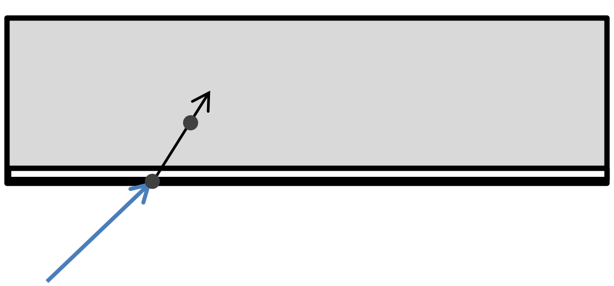
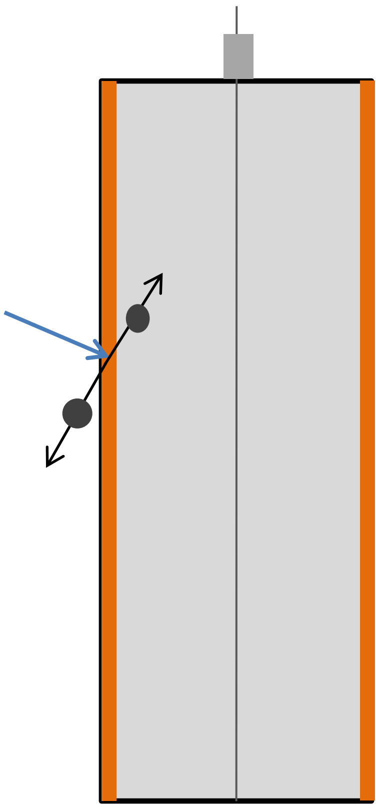


Fig. 4. The response surface $A_i(E)$ for NE-213 spectrometer.

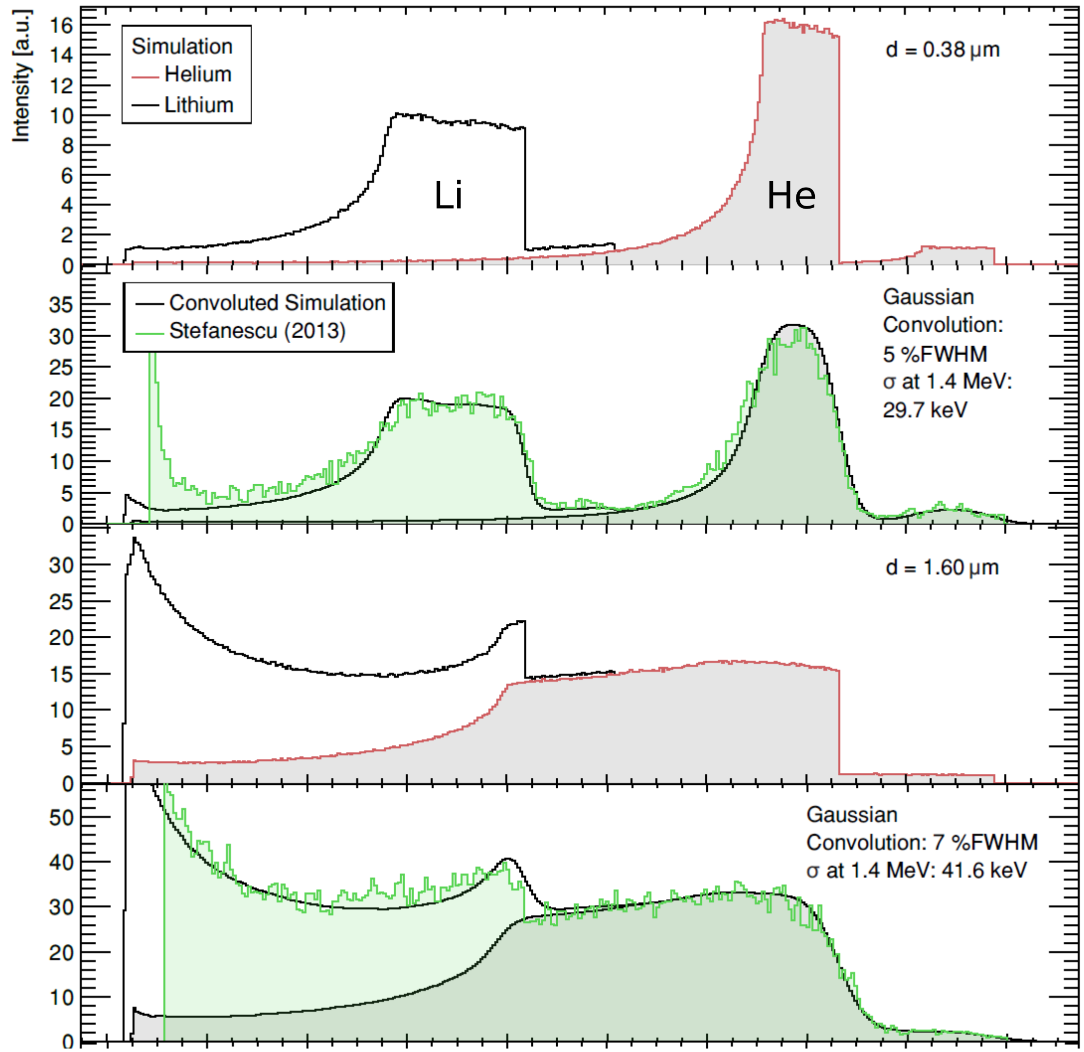


[1] A. Sagatova et al., "Semi-insulating GaAs detectors optimized for fast neutron detection", JINST 8 C03016
[2] W.R. Burrus and V.V. Verbinski, "Fast-Neutron Spectroscopy with thick organic scintillators", NIM 67 (1969), pp. 191-196

Conversion in ^{10}B



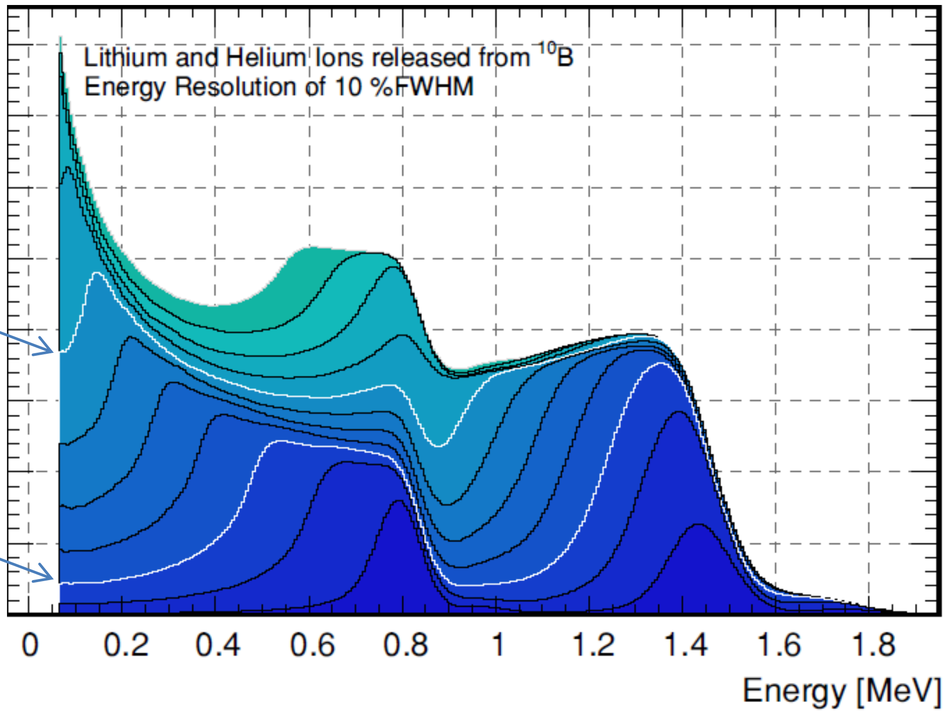
0.035 mm ^{10}B

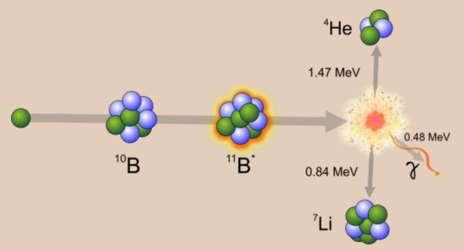


Conversion Products: Energy Spectra

thick converter

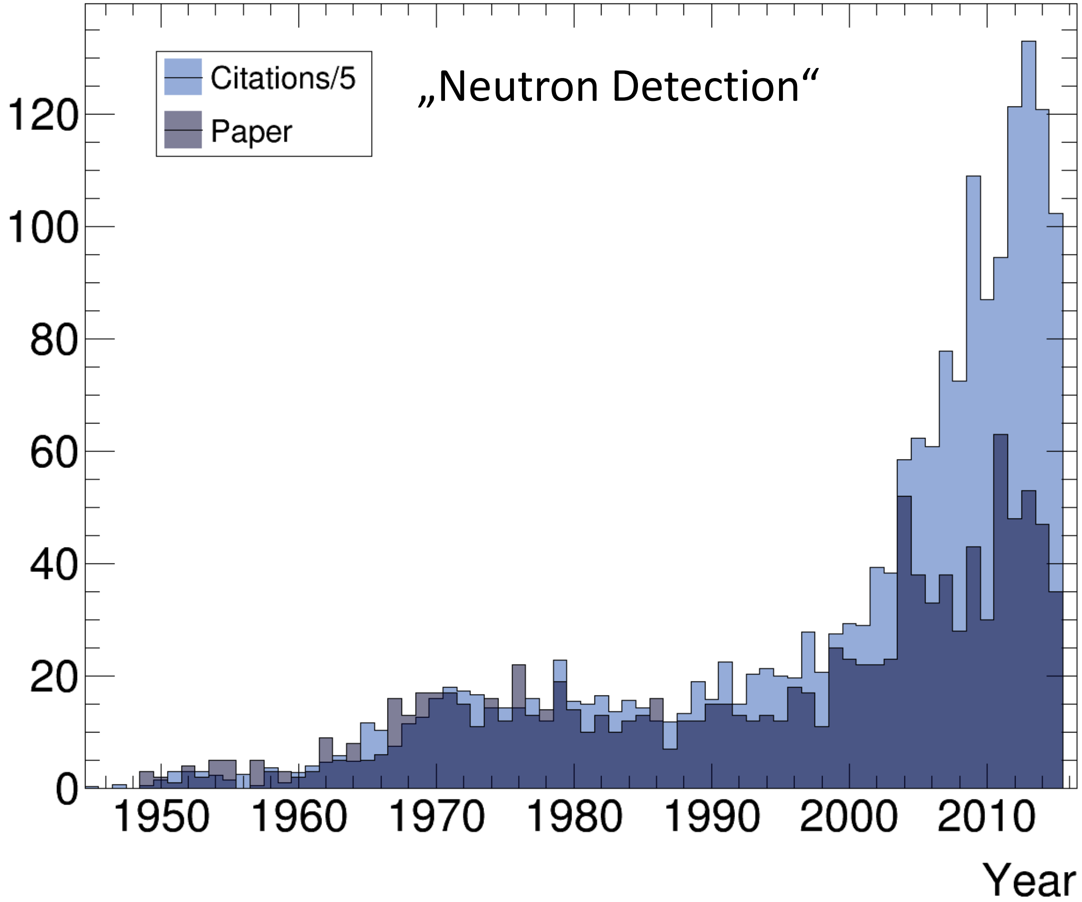
thin converter





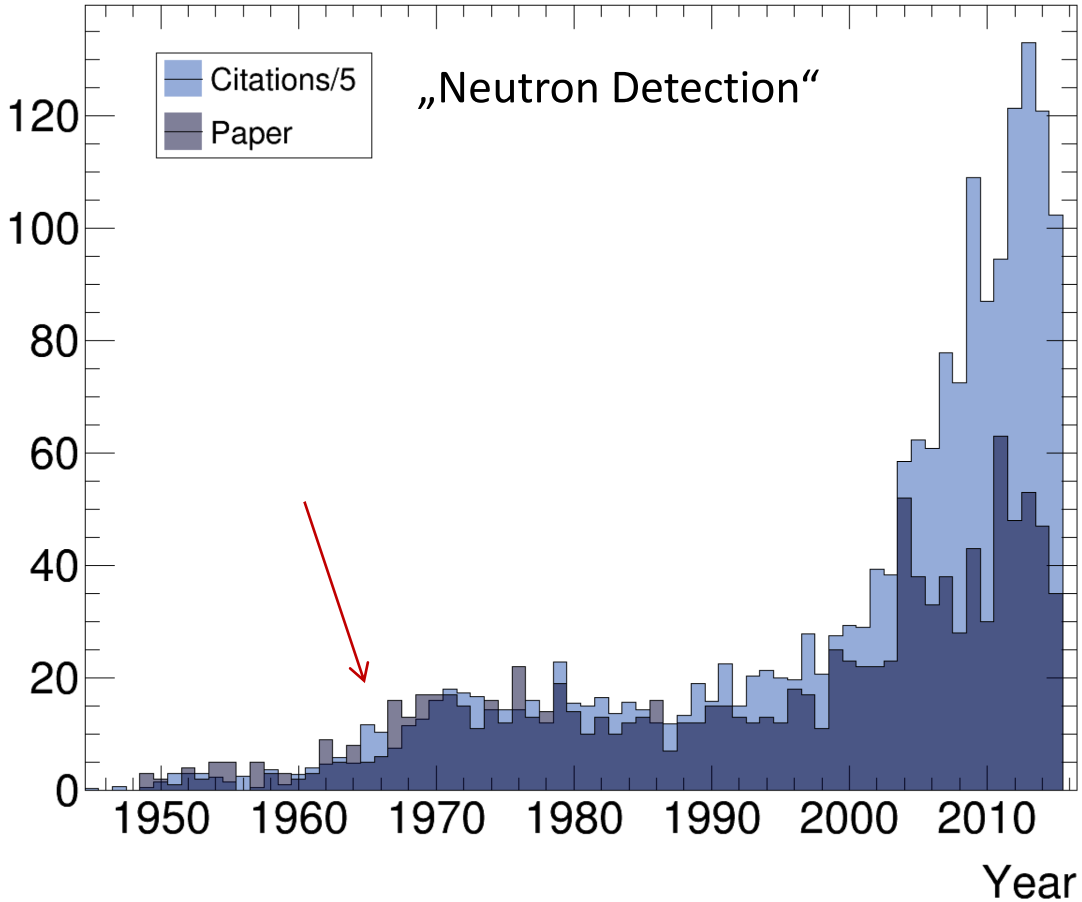
The rise and rise of citatation analysis

Neutron Detection Citatation Analysis



Web of Science Citation Reports

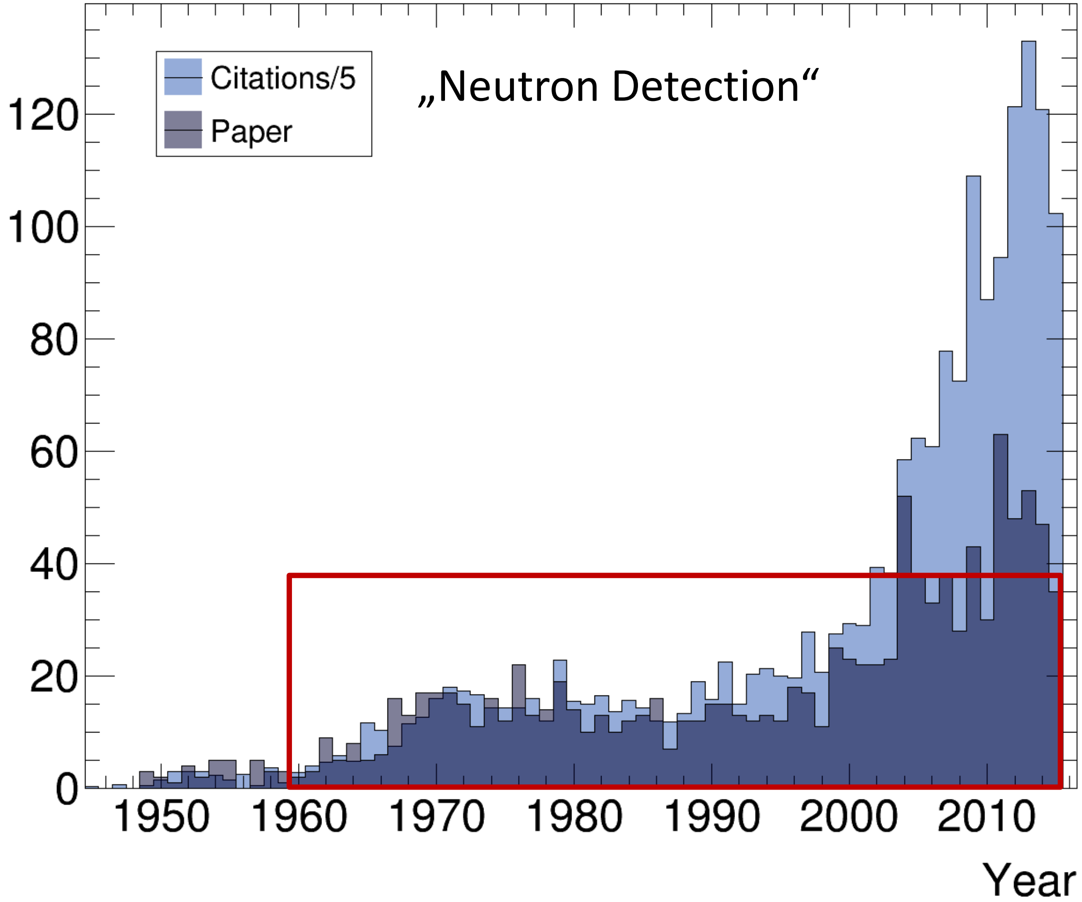
Neutron Detection Citatation Analysis



Web of Science Citation Reports


CNCS inelastic spectrometer, SNS

Neutron Detection Citatation Analysis



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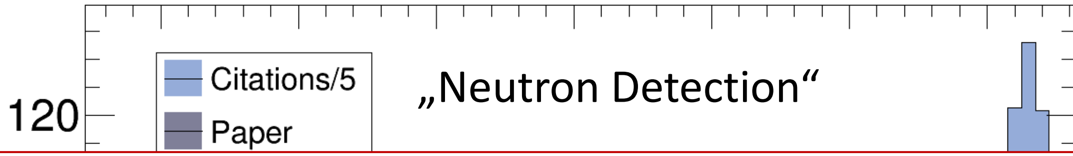
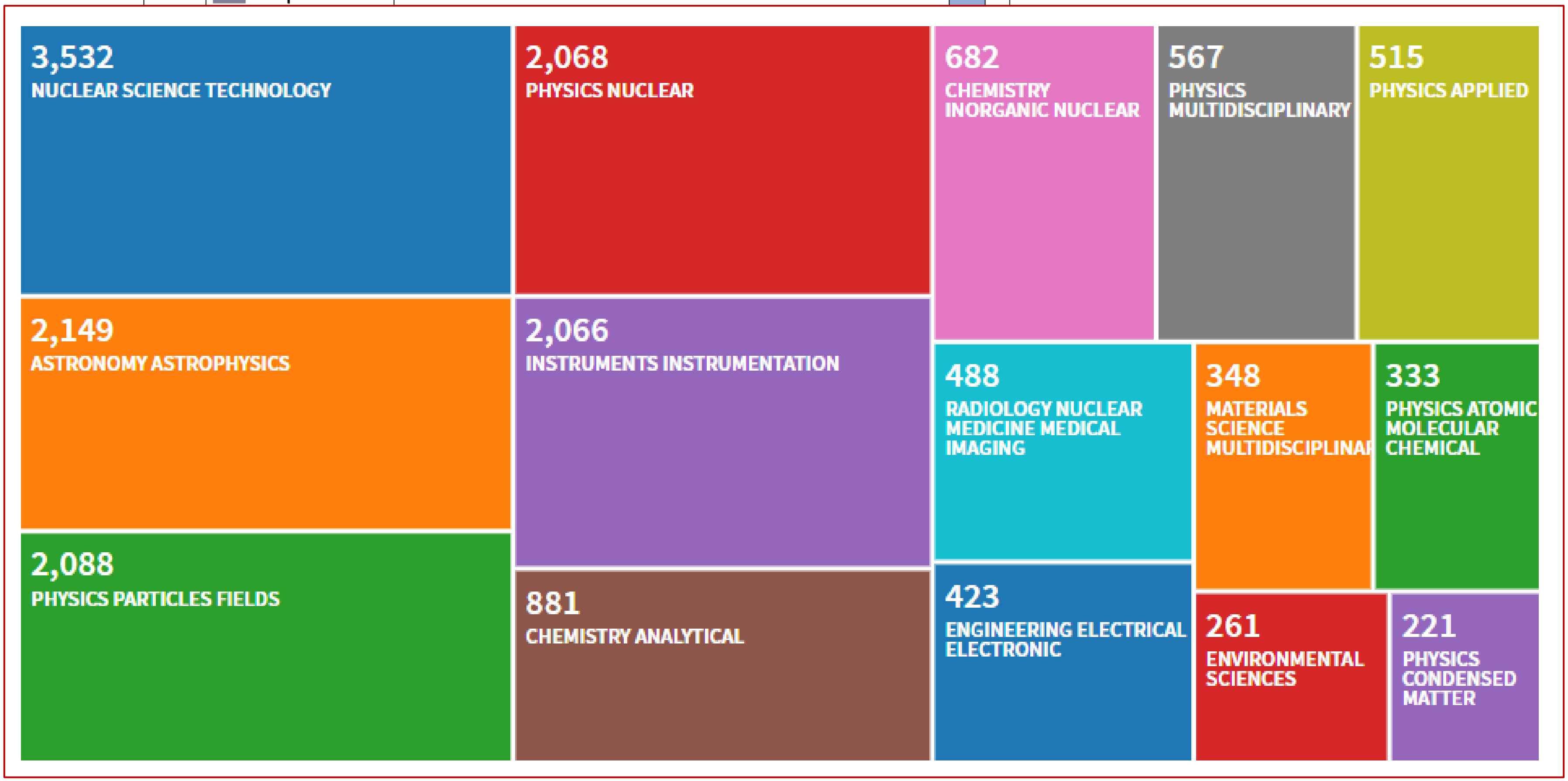


Web of Science Citation Categories



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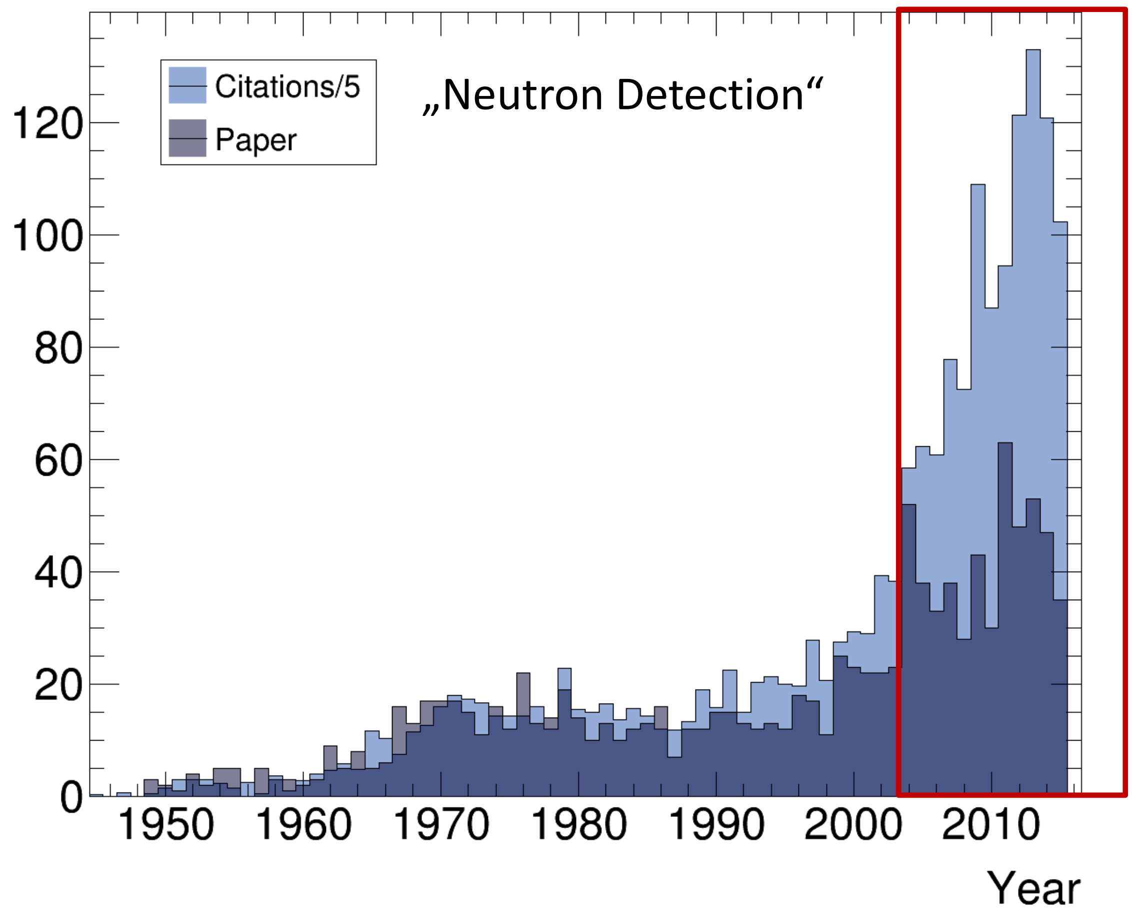
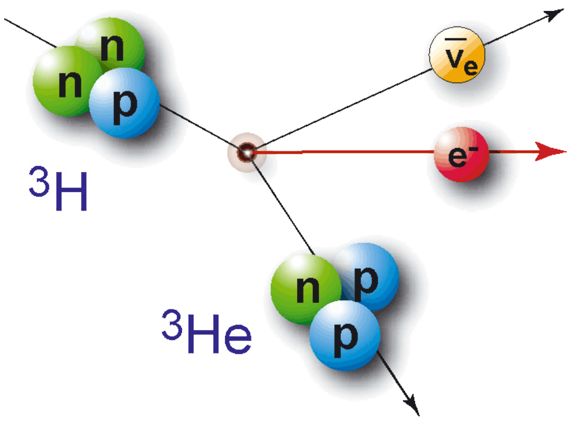


Web of Science Citation Reports

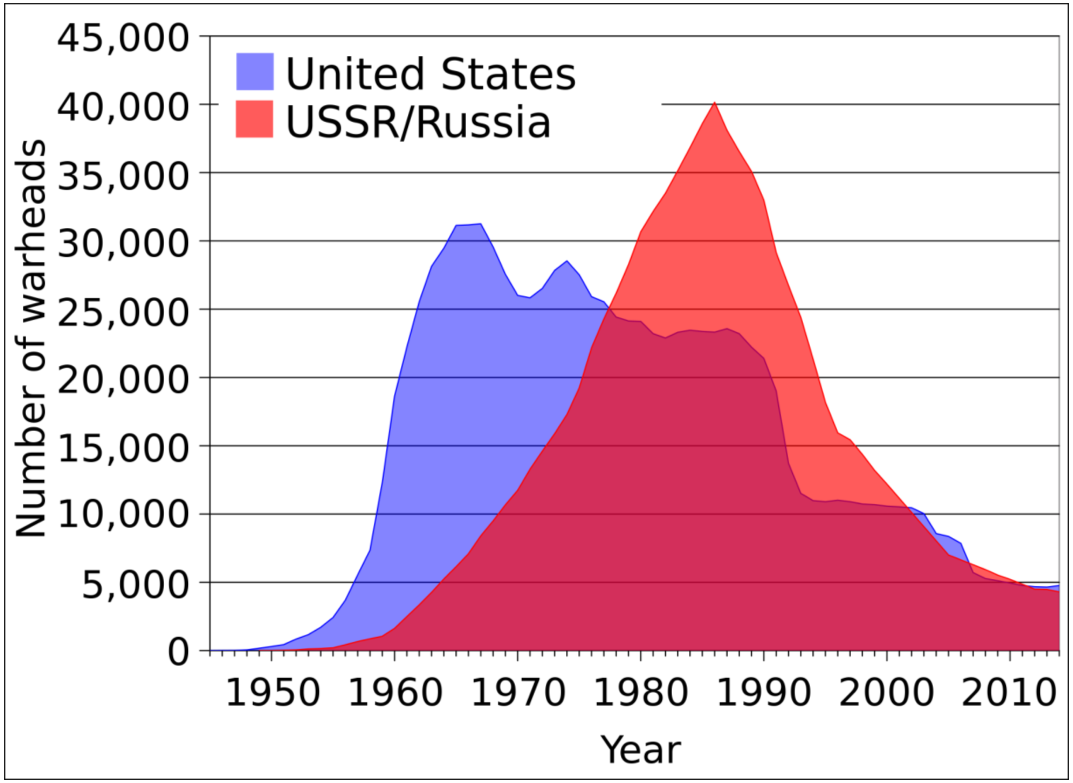
Titan II Rocket in Launch Silo, Arizona State Museum

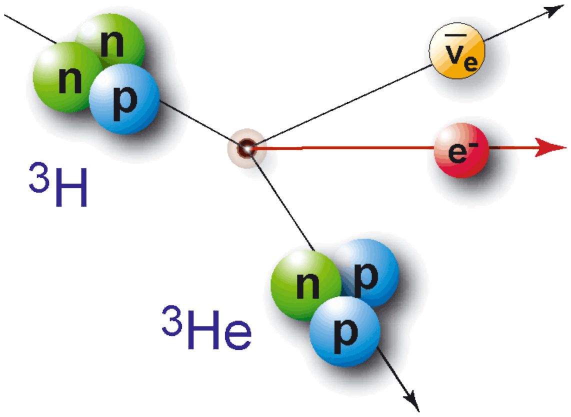
The Helium-3 Crisis



(12.3 years)

The Helium-3 Crisis

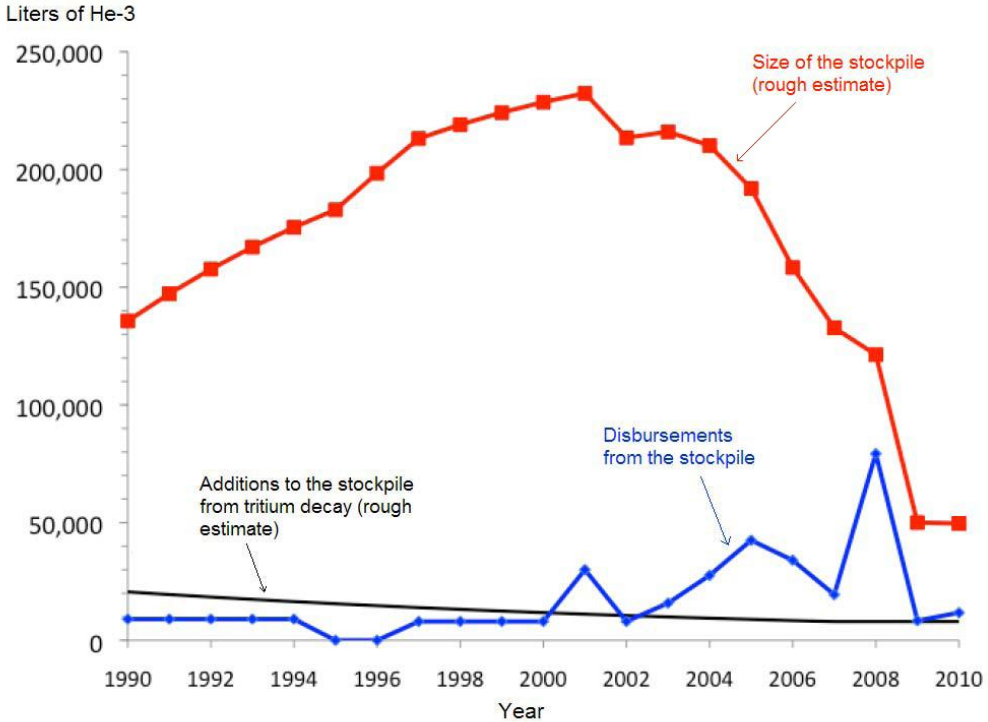




(12.3 years)

R. S. Norris and H. Kristensen, "Global nuclear stockpiles, 1945-2006," *Bulletin of the Atomic Scientists* 62, no. 4 (2006), 64-66

The Helium-3 Crisis



AAAS, Overview of Helium-3 Supply and Demand

[1] http://www.saphymo.com/photos/ecatalogue/116-2/access-control-clearance-monitors-rcp-radiological-control-for-pedestrian.jpg
[2] http://cits.uga.edu/uploads/1540compass/1540images/_compass750/RPM1.jpg

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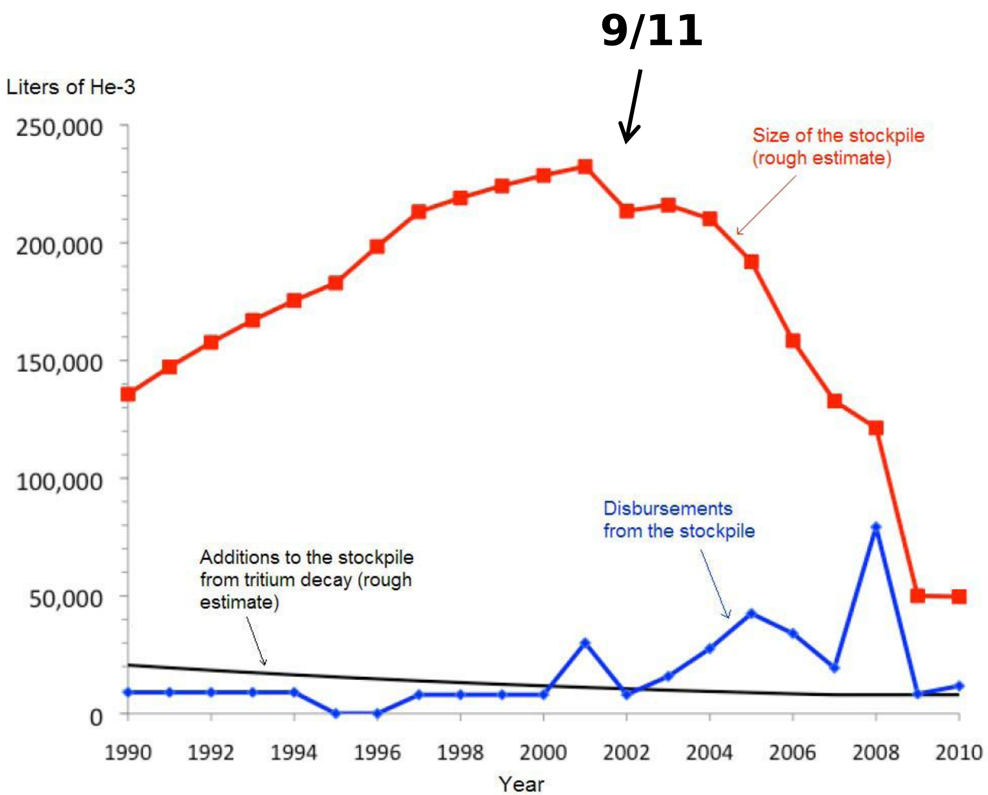

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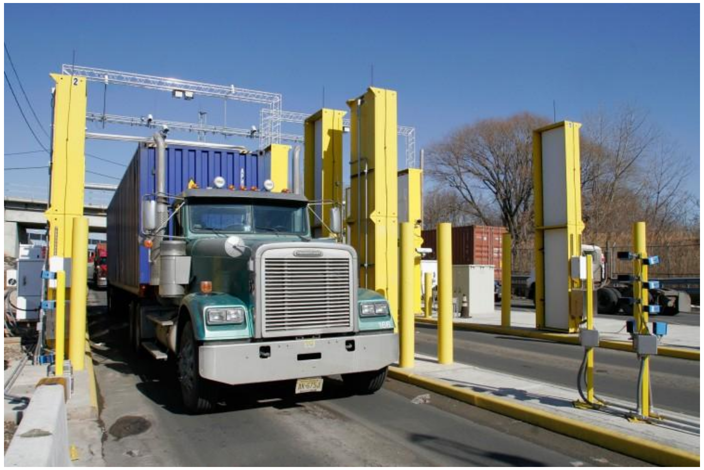

[2]

[1] http://www.saphymo.com/photos/ecatalogue/116-2/access-control-clearance-monitors-rcp-radiological-control-for-pedestrian.jpg
[2] http://cits.uga.edu/uploads/1540compass/1540images/_compass750/RPM1.jpg

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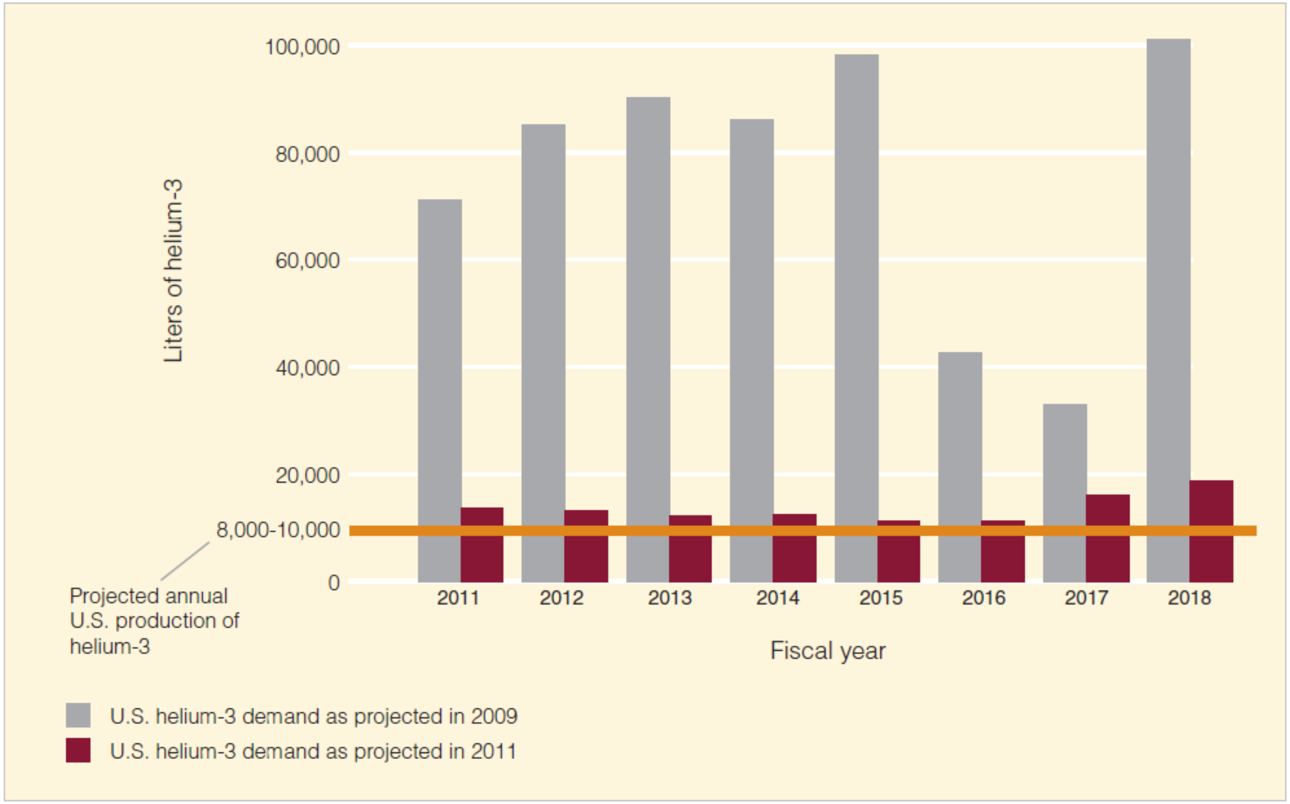
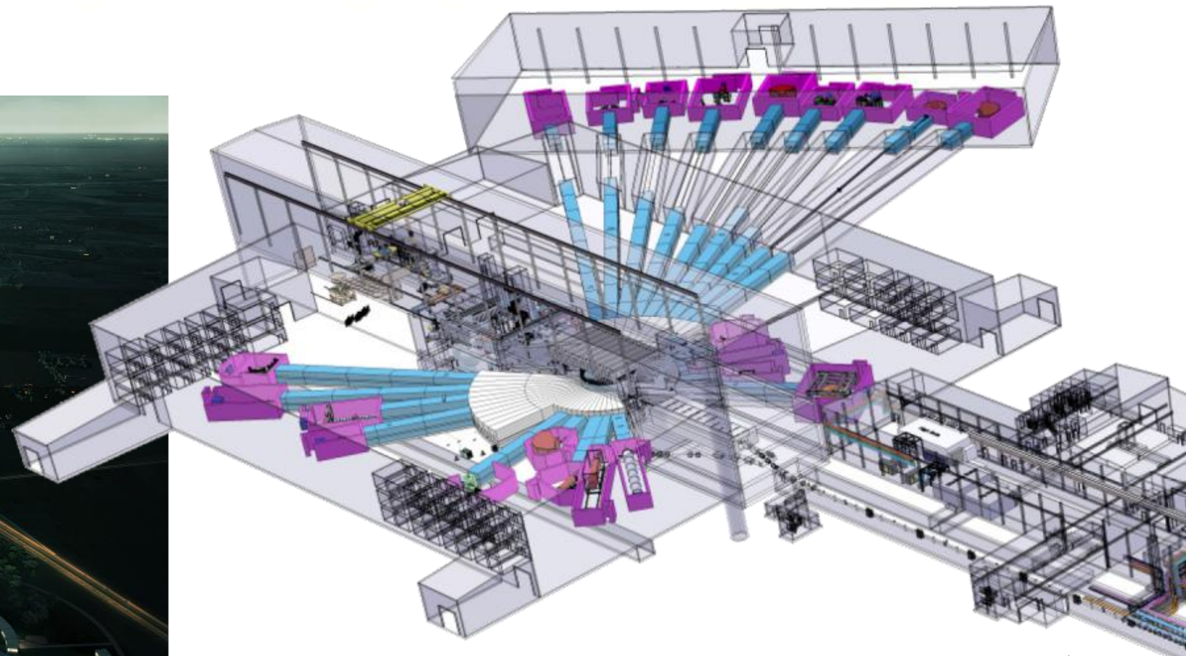


Figure 2.5 Helium-3 demand and annual U.S. production, 2011–18, as projected in 2009 and 2011.
Source: GAO analysis of information from the interagency policy committee.

„Neutron detectors - Alternatives to using helium-3“, GAO, 2011

The European Spallation Source

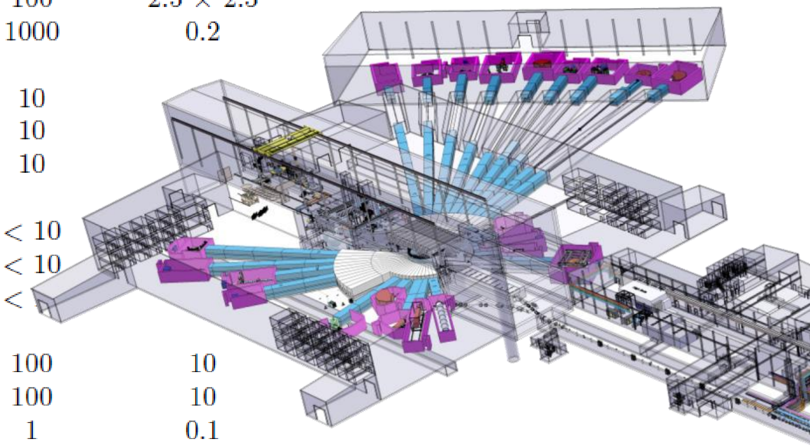
ESS TDR 2013
Lund, Sweden



Linear Accelerator
2 GeV
3 ms Pulse
62.5 mA

ESS Instrumentation

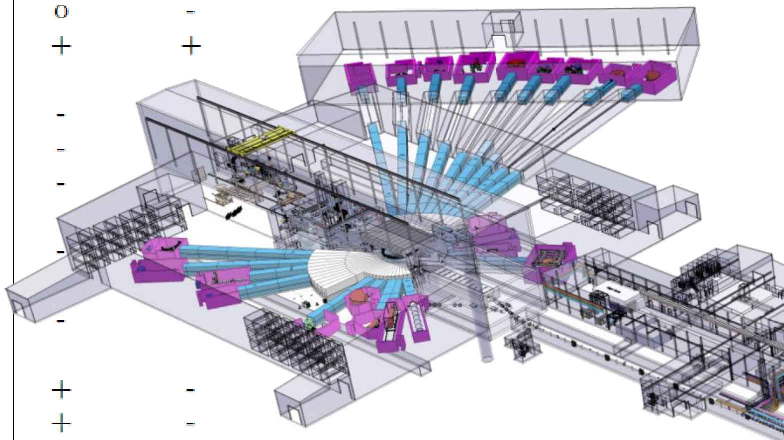
Instrument	Detector area [m^2]	Wavelength range [Å]	Time resolution [μs]	Spatial resolution [mm]
Multi-purpose imaging	0.5	1 - 20	1	0.001 - 0.5
General purpose polarised SANS	5	4 - 20	100	10
Broad-band small sample SANS	14	2 - 20	100	1
Surface scattering	5	4 - 20	100	10
Horizontal reflectometer	0.5	5 - 30	100	1
Vertical reflectometer	0.5	5 - 30	100	1
Thermal powder diffractometer	20	0.6 - 6	$<$ 10	2×2
Bi-spectral powder diffractometer	20	0.8 - 10	$<$ 10	2.5×2.5
Pulsed monochromatic powder diffractom.	4	0.6 - 5	$<$ 100	2×5
Material science & engineering diffractom.	10	0.5 - 5	10	2
Extreme conditions instrument	10	1 - 10	$<$ 10	3×5
Single crystal magnetism diffractometer	6	0.8 - 10	100	2.5×2.5
Macromolecular diffractometer	1	1.5 - 3.3	1000	0.2
Cold chopper spectrometer	80	1 - 20	10	
Bi-spectral chopper spectrometer	50	0.8 - 20	10	
Thermal chopper spectrometer	50	0.6 - 4	10	
Cold crystal-analyser spectrometer	1	2 - 8	$<$ 10	
Vibrational spectroscopy	1	0.4 - 5	$<$ 10	
Backscattering spectrometer	0.3	2 - 8	$<$	
High-resolution spin echo	0.3	4 - 25	100	10
Wide-angle spin echo	3	2 - 15	100	10
Fundamental & particle physics	0.5	5 - 30	1	0.1
Total	**282.6**			



ESS TDR 2013

ESS Instrumentation

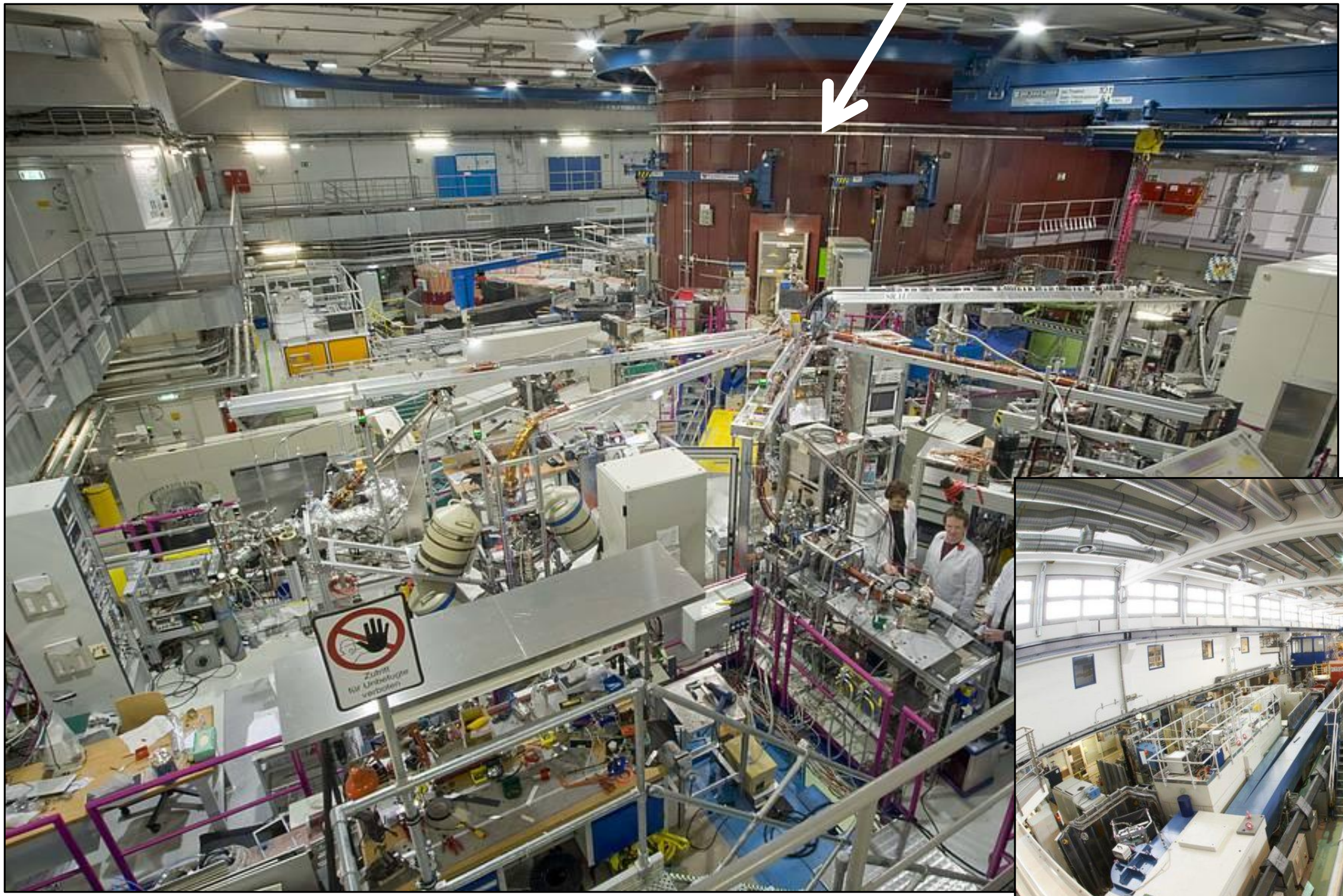
Instrument	Detector technology: ^{10}B thin films ⊥	^{10}B thin films ∥	Scintillators WSF	Scintillators Anger	^{3}He	Micropattern Rate	Micropattern Resolution
Multi-purpose imaging	-	-	-	-	-	o	+
General purpose polarised SANS	o	+	-	+	o	+	-
Broad-band small-sample SANS	o	+	-	+	-	+	-
Surface scattering	o	+	-	+	o	+	-
Horizontal reflectometer	-	o	-	+	+	o	-
Vertical reflectometer	-	o	-	+	+	o	-
Thermal powder diffractometer	o	+	+	-	-	o	-
Bi-spectral powder diffractometer	o	+	+	-	-	o	-
P-M powder diffractometer	o	+	+	-	-	o	-
MS engineering diffractometer	o	+	+	-	-	o	-
Extreme conditions diffractometer	o	+	+	-	-	o	-
Single crystal diffractometer	o	+	+	-	-	o	-
Macromolecular diffractometer	-	o	o	o	-	+	+
Cold chopper spectrometer	+	o	o	-	-	-	
Bi-spectral chopper spectrometer	+	+	o	-	-	-	
Thermal chopper spectrometer	+	+	+	-	-	-	
Cold crystal analyser spectrometer	-	o	-	+	+	-	
Vibrational spectrometer	-	o	-	o	+		
Backscattering spectrometer	-	o	-	+	+	-	
High-resolution spin echo	-	o	-	o	+	+	-
Wide-angle spin echo	-	o	-	o	+	+	-
Fundamental & particle physics	-	-	-	-	+	+	+



ESS TDR 2013

FRM Instrumentation

source



FRM Website of the Heinz-Maier-Leibnitz-Zentrum

Neutron Sources

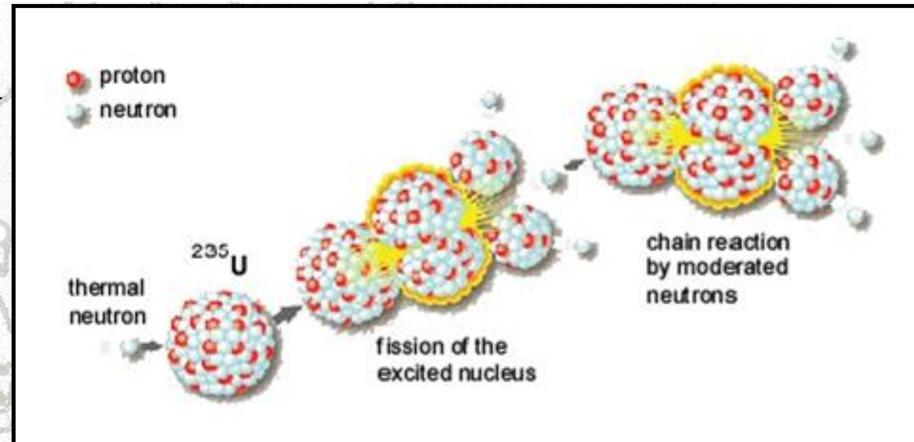
Neutron Sources

Fission Reactor

n + ^{235}U =

n + n + fragments

+ 180 MeV/n (heat)

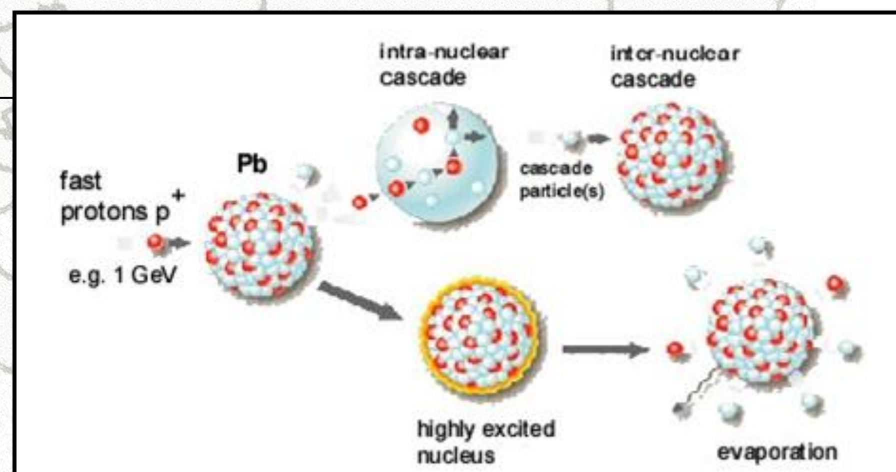


Spallation Source

p + heavy nucleus =

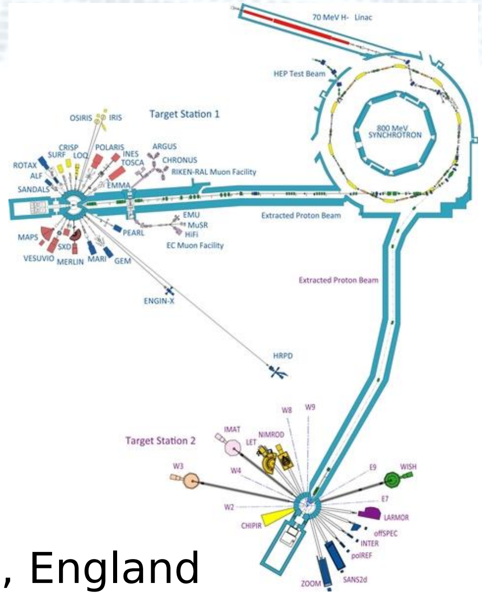
20~30 n + fragments

+ 30 MeV/n (heat)



C. Grupen and I. Buvat „Handbook of Particle Detection and Imaging", Springer, 2012

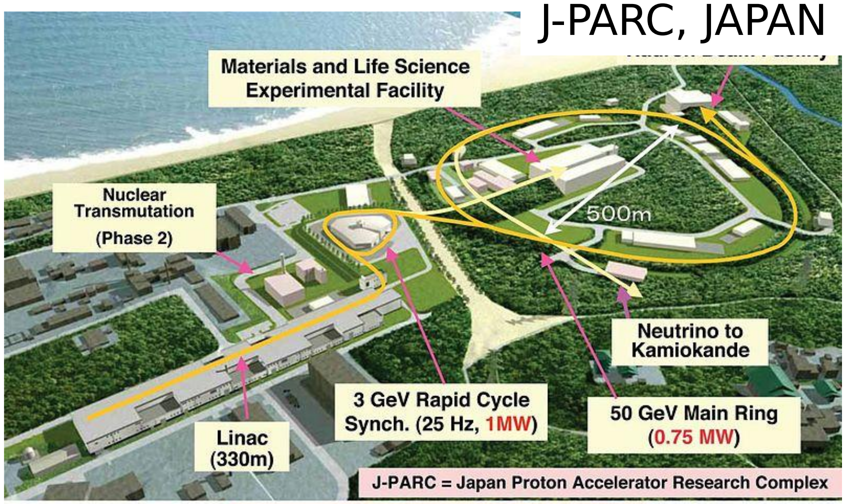
Spallation Neutron Sources



ISIS, England

T. O'Connor "UK science facility praised by international review", ISIS International Review (2013)
P-R. Kettle "Swiss Light Source set to be a world-class facility", CERN Courier (2002)

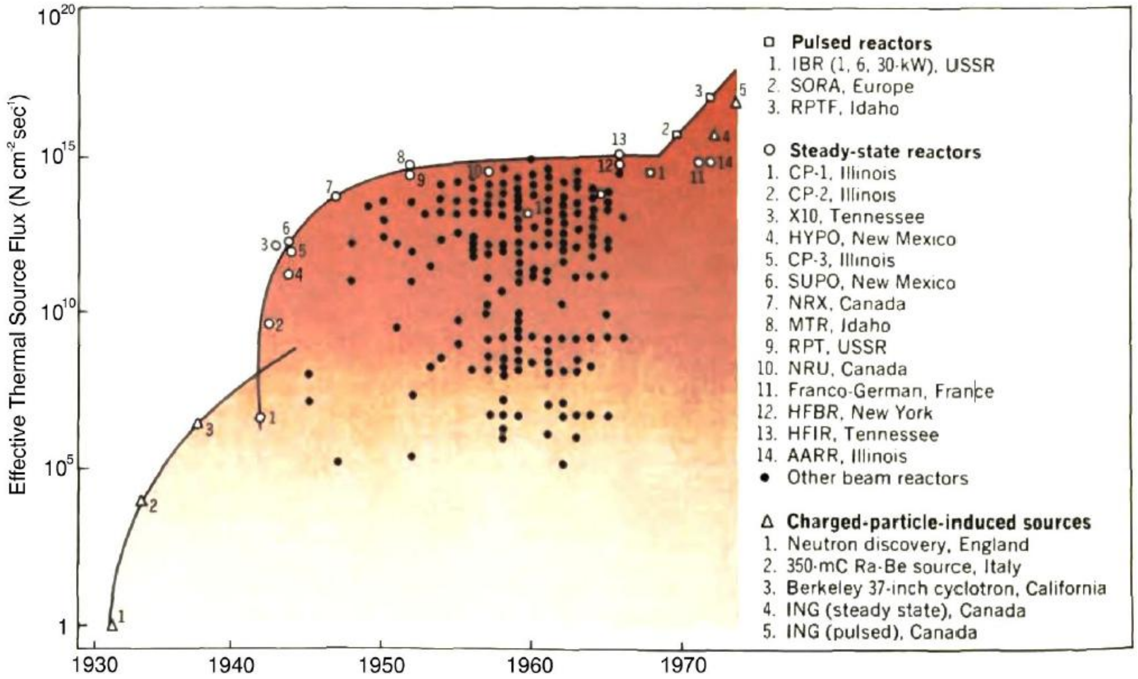
Created by John Jordan, Oak Ridge National Laboratory (wikimedia)
S. Nagamiya: "Introduction to J-PARC", Prog. Theor. Exp. Phys. (2012) 02B001



Joint Project between KEK and JAEA

High Flux Sources

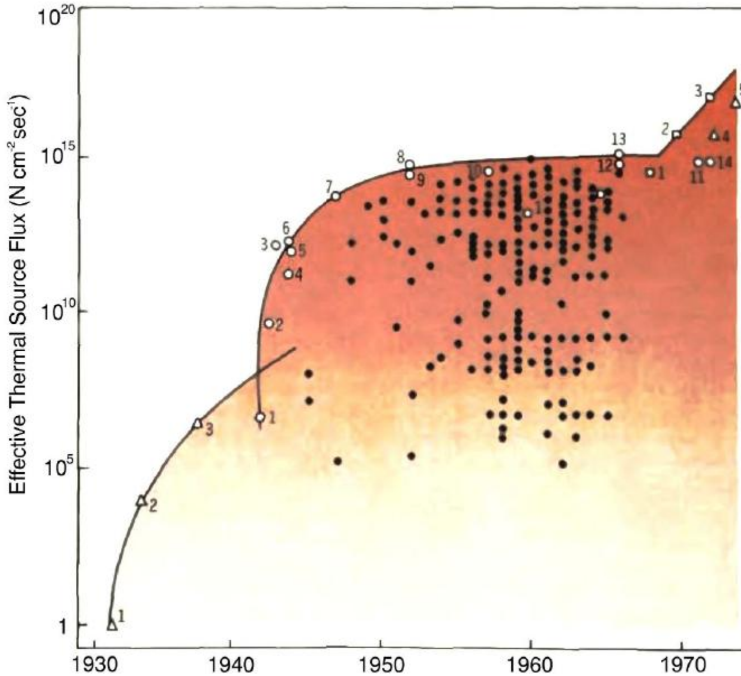
„Brugger“ Plot [1]

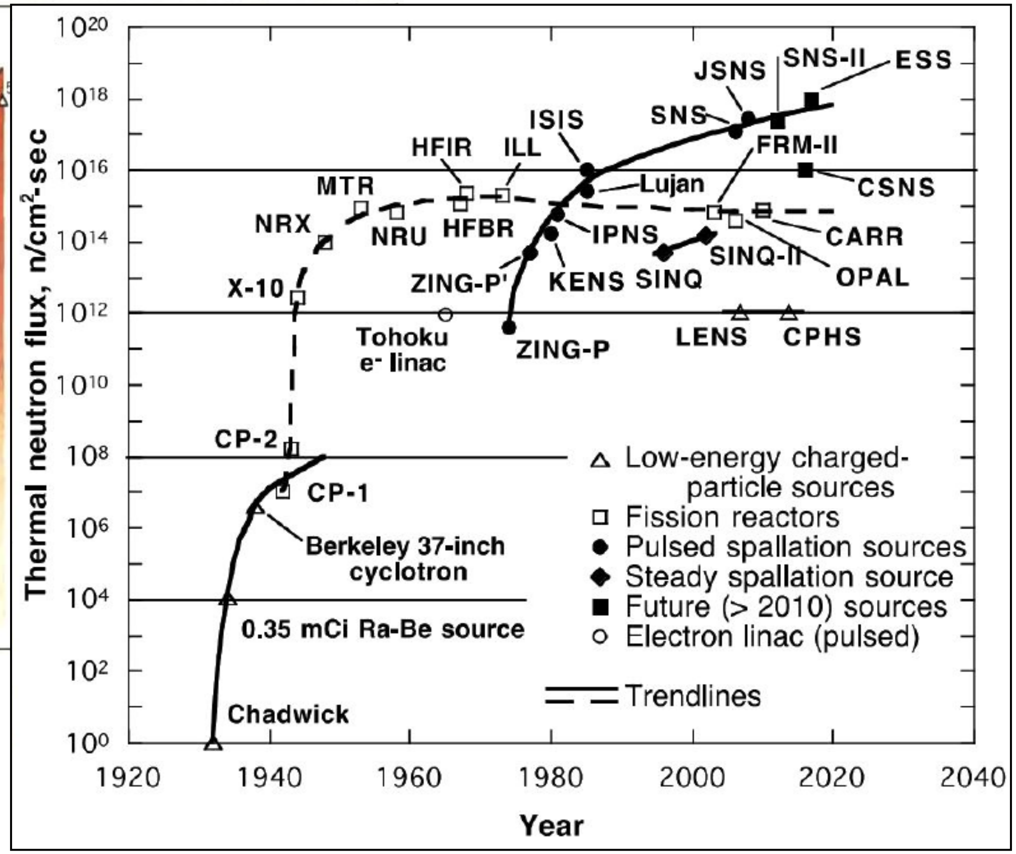


[1] R.M. Brugger, “We need more intense thermal-neutron beams.” In: Physics Today 21(12) (1968), pp. 23–30.
[2] J.M. Carpenter and W.B. Yelon, „2. Neutron Sources.” In: Neutron Scattering. Vol. 23. Methods in Experimental Physics, 1986, pp. 99–196.

High Flux Sources

„Brugger“ Plot [1]



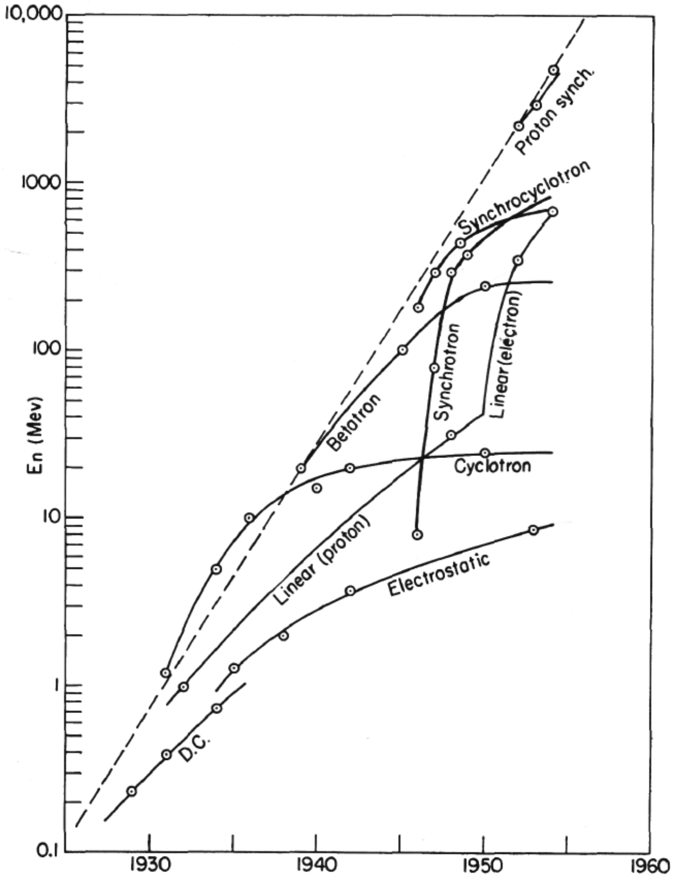


[2]

[1] R.M. Brugger, “We need more intense thermal-neutron beams.” In: Physics Today 21(12) (1968), pp. 23–30.
[2] J.M. Carpenter and W.B. Yelon, „2. Neutron Sources.” In: Neutron Scattering. Vol. 23. Methods in Experimental Physics, 1986, pp. 99–196.

High Flux Sources

„Livingston“ Plot [1]

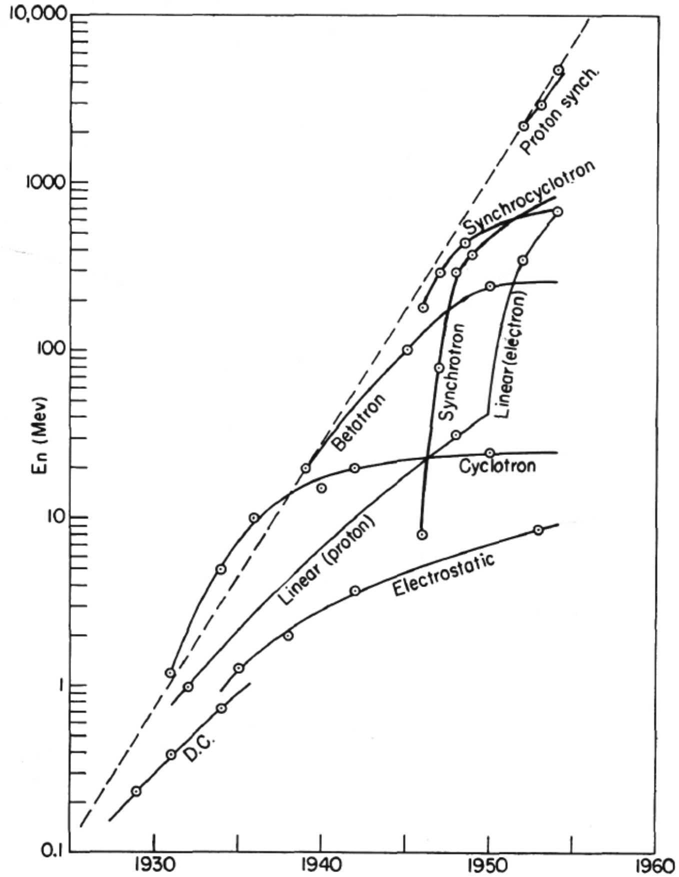


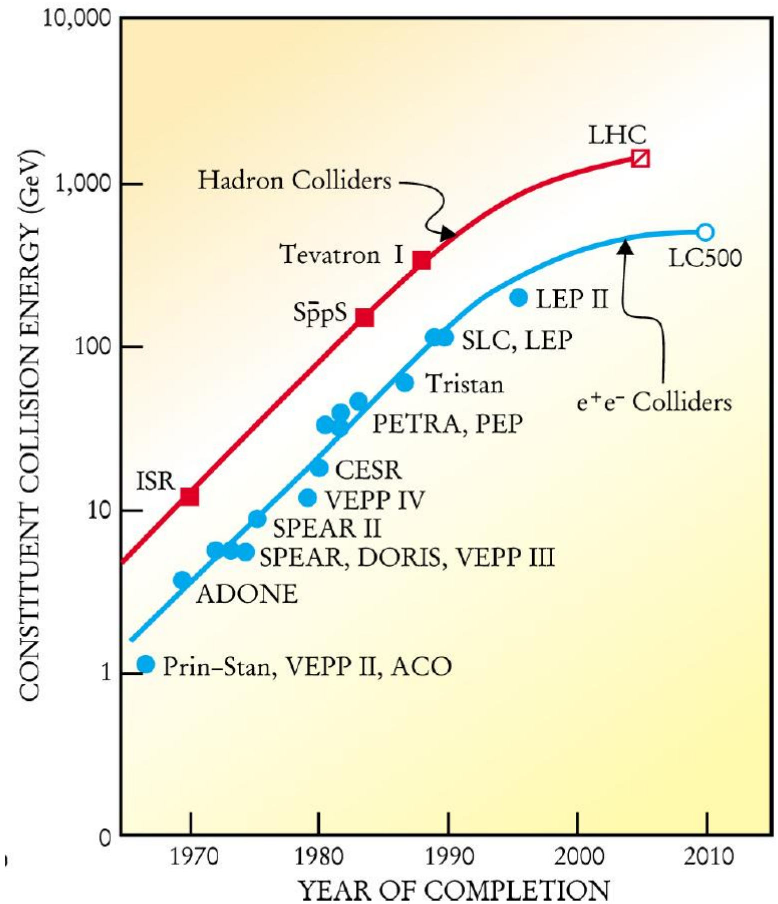
[1] Livingston, M.S. “High-energy accelerators. Interscience tracts on physics and astronomy”. 1954.

[2] Tigner, M. “Does Accelerator-Based Particle Physics Have a Future?” In: Physics Today 54(1) (2001), pp. 36–40.

High Flux Sources

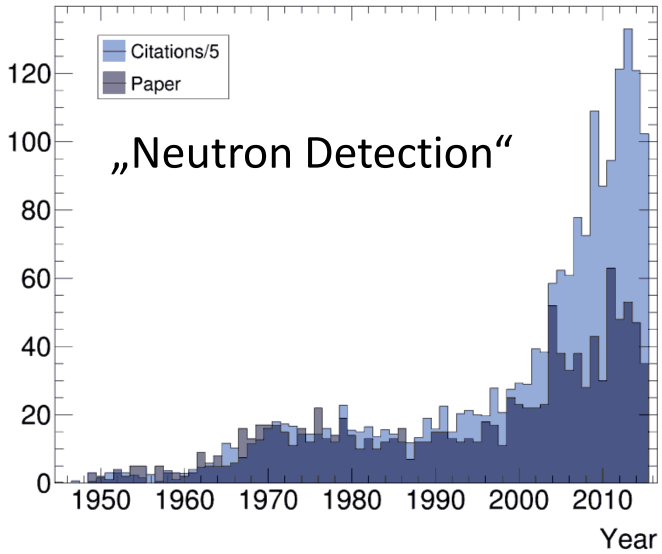
„Livingston" Plot [1]

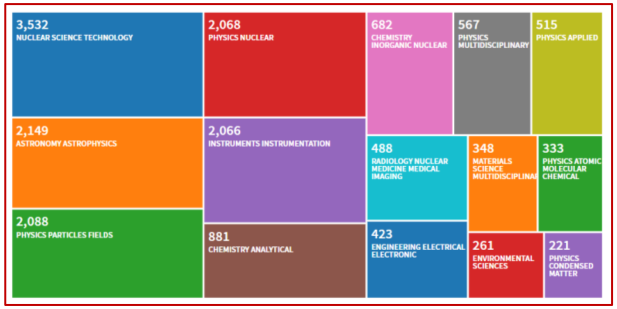


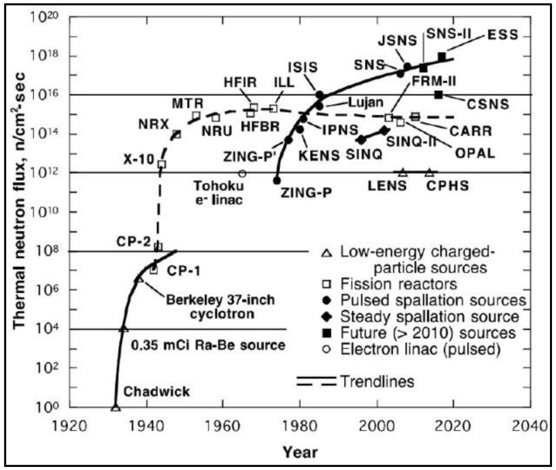


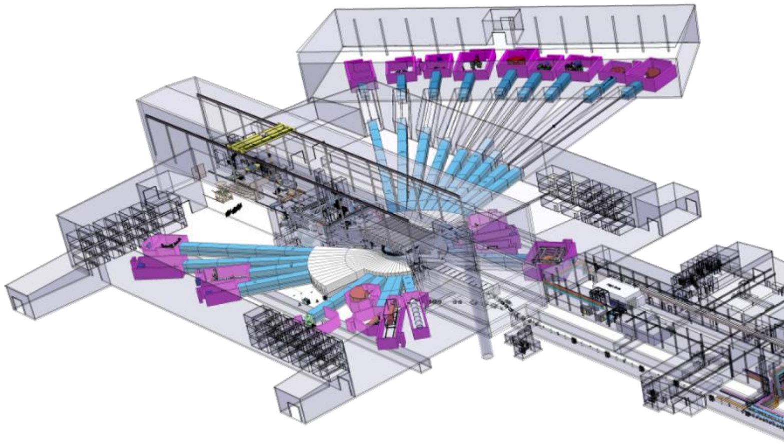
[1] Livingston, M.S. "High-energy accelerators. Interscience tracts on physics and astronomy". 1954.
[2] Tigner, M. "Does Accelerator-Based Particle Physics Have a Future?" In: Physics Today 54(1) (2001), pp. 36–40.

Neutron Detection Citatation Analysis

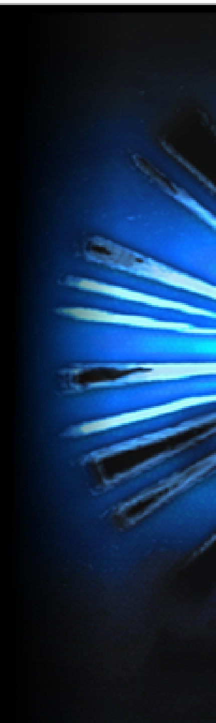




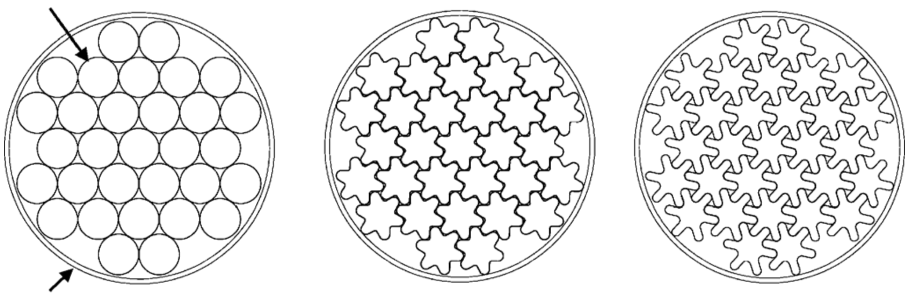


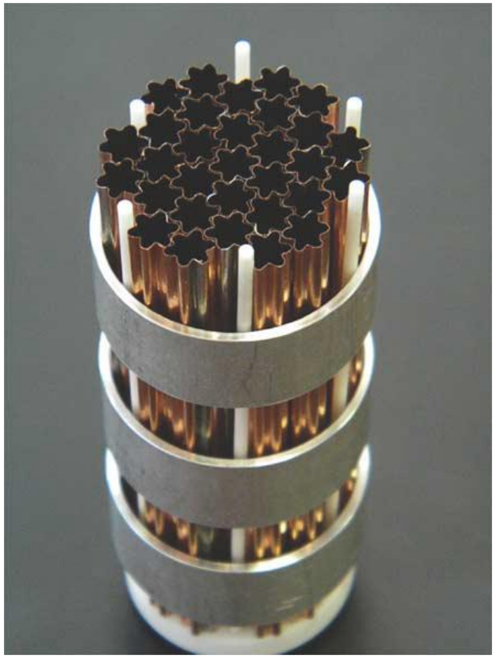


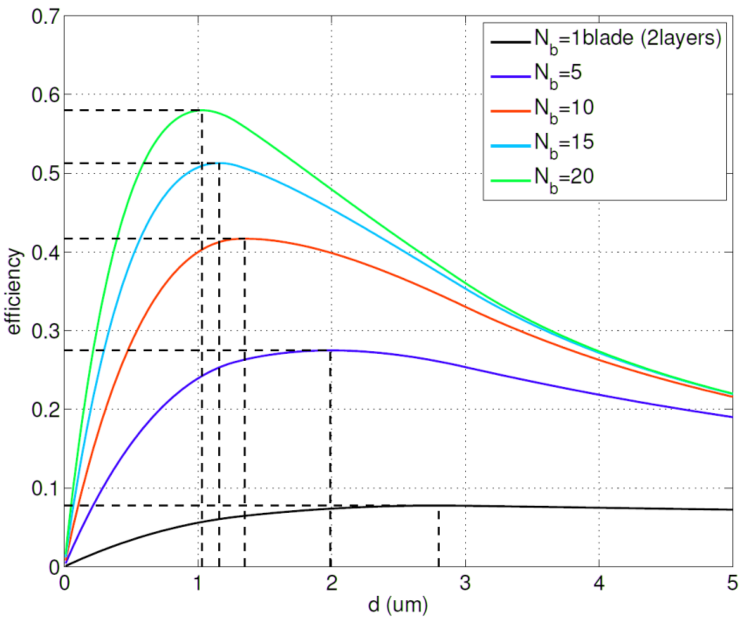
Alternative detection technologies



New Detectors – Tube Replacement



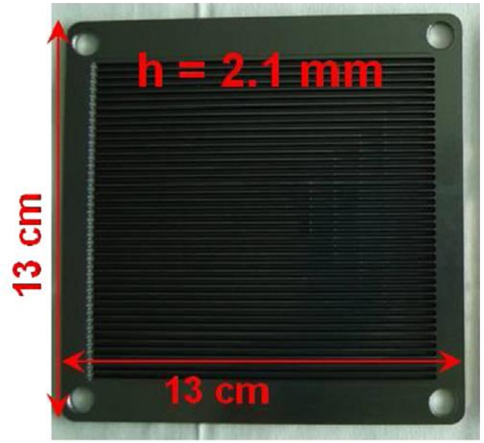


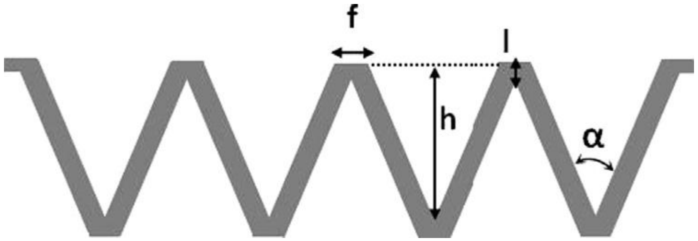


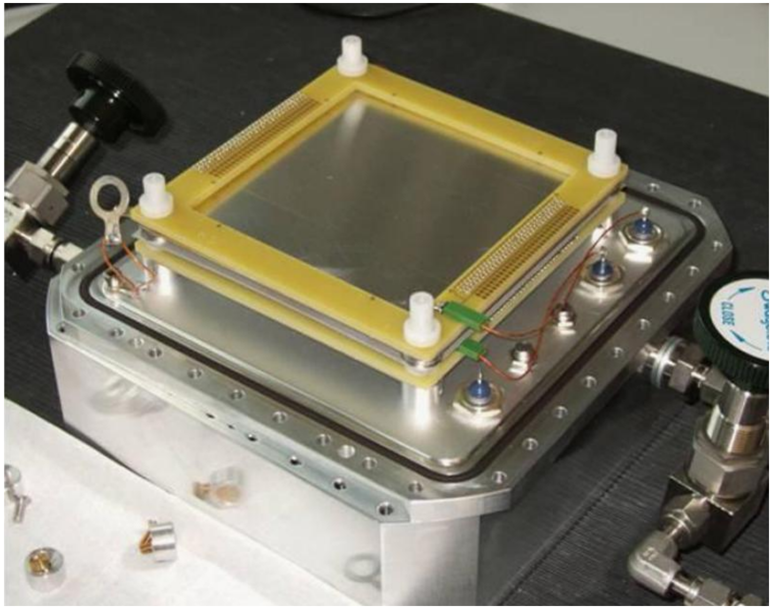
[1] F. Piscitelli, "Boron-10 layers, Neutron Reflectometry and Thermal Neutron Detectors", PhD Thesis 2014

[2] J. L. Lacy et al., "The Evolution of Neutron Straw Detector -Applications in Homeland Security", IEEE Transactions on Nucl. Science, 60,2,2013

New Detectors – Cathode Structures

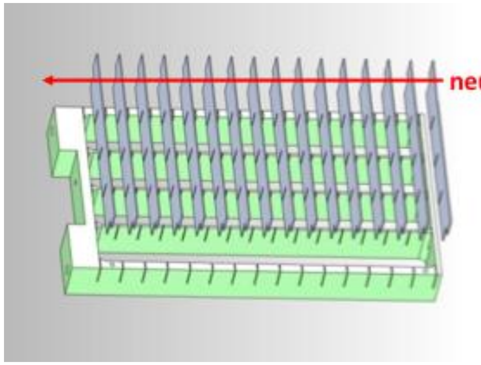


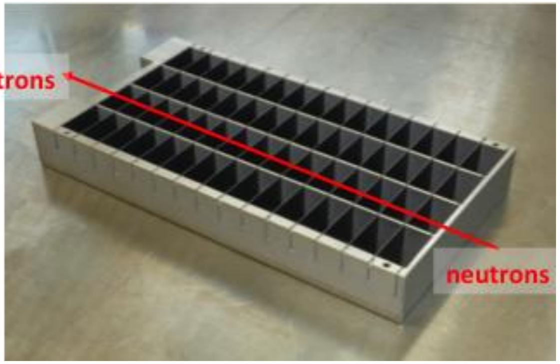


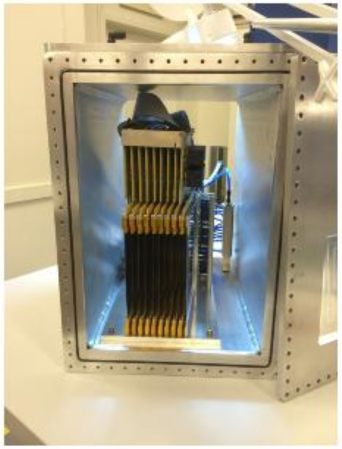


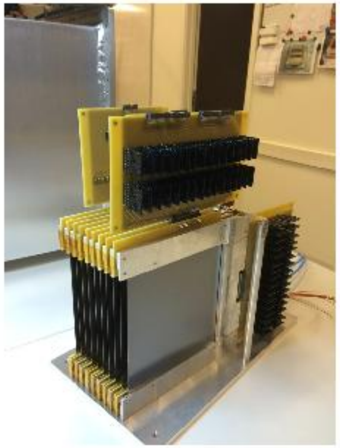
I. Stefanescu et al., „Development of a novel macrostructured cathode for large-area neutron detectors based on the 10B-containing solid converter“, NIMA 727, 2013

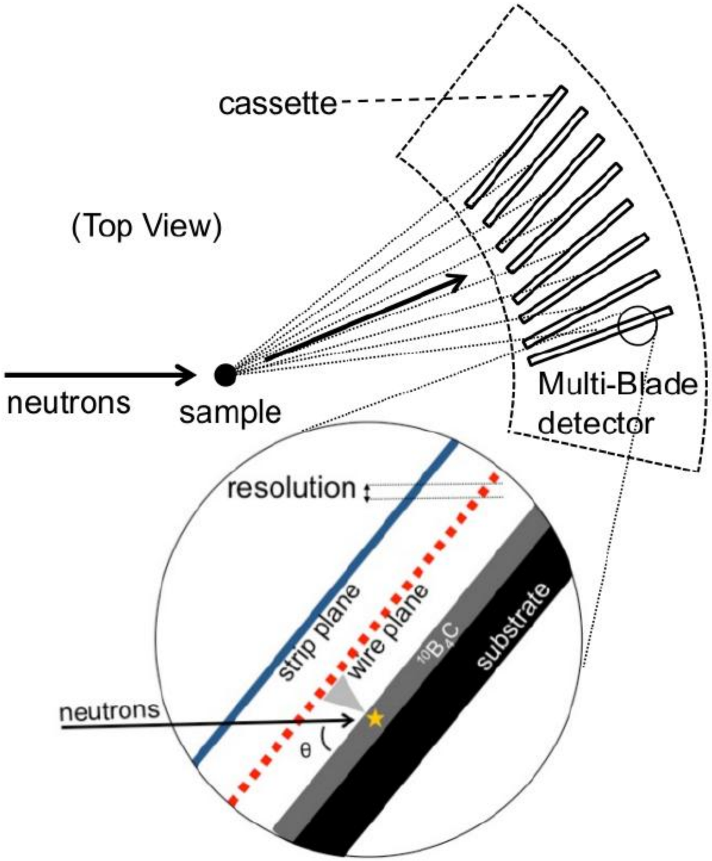
New Detectors – He-3 Replacements





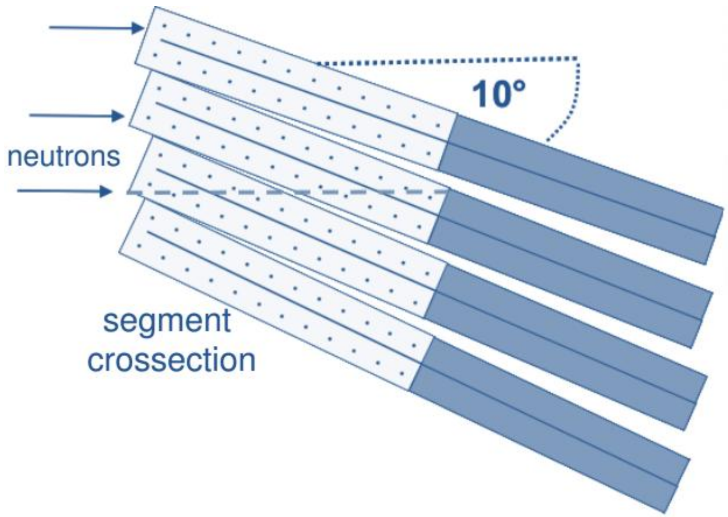


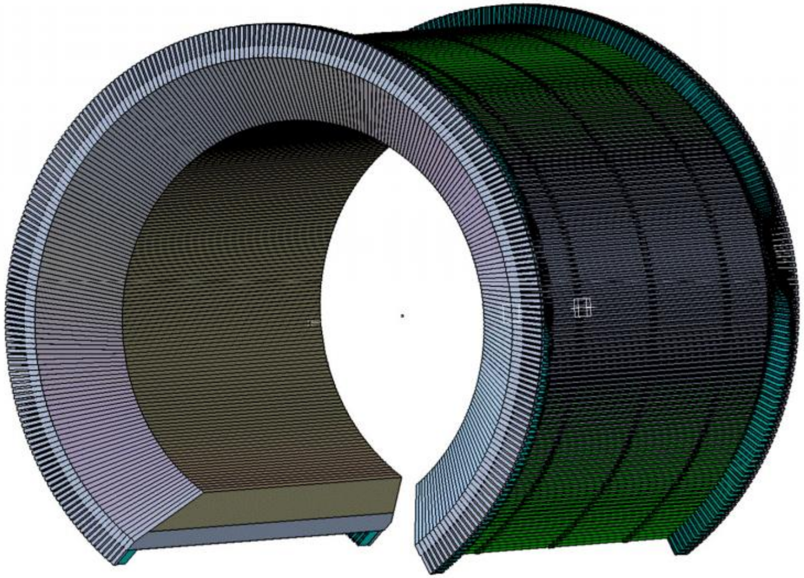


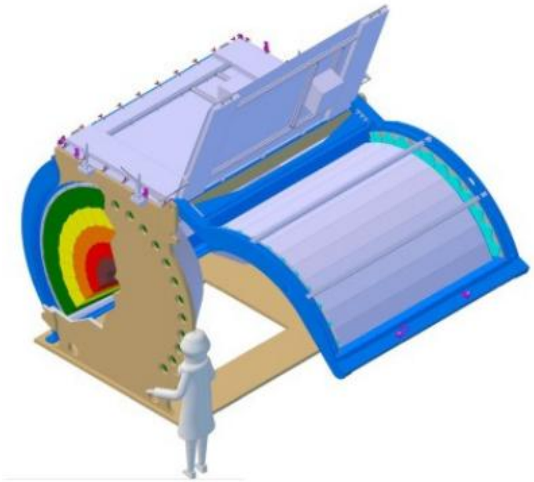


F. Piscitelli et al., “Novel Boron-10-based detectors for Neutron Scattering Science” arXiv:1501.05201v1

New Detectors – He-3 Replacements



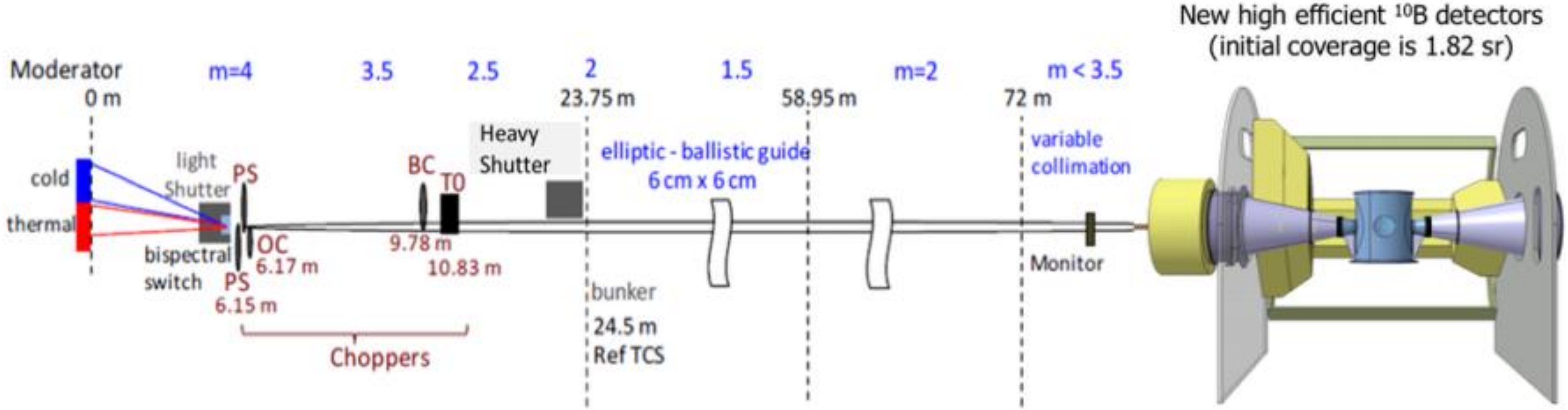


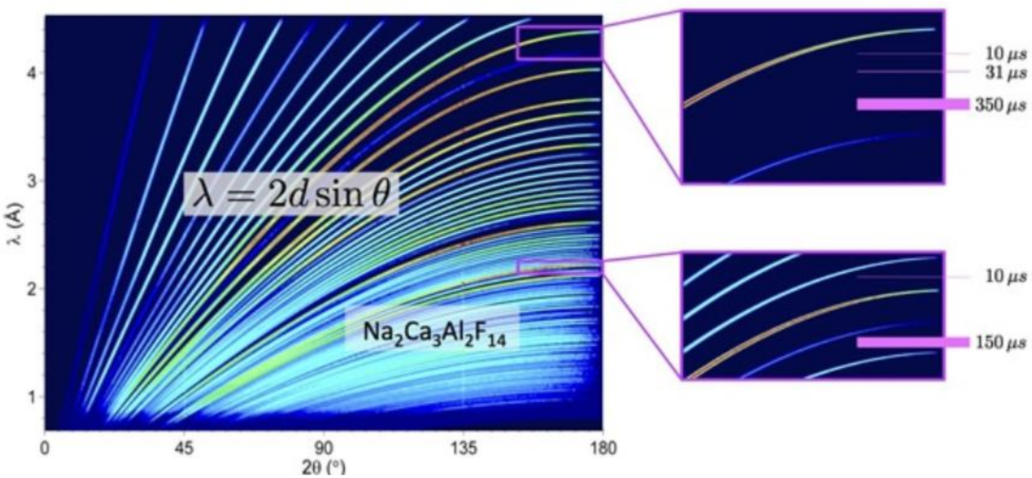


Ch. J. Schmidt, “The 10B-based Jalousie Neutron Detector”, DENIM 2015

New Detectors – He-3 Replacements

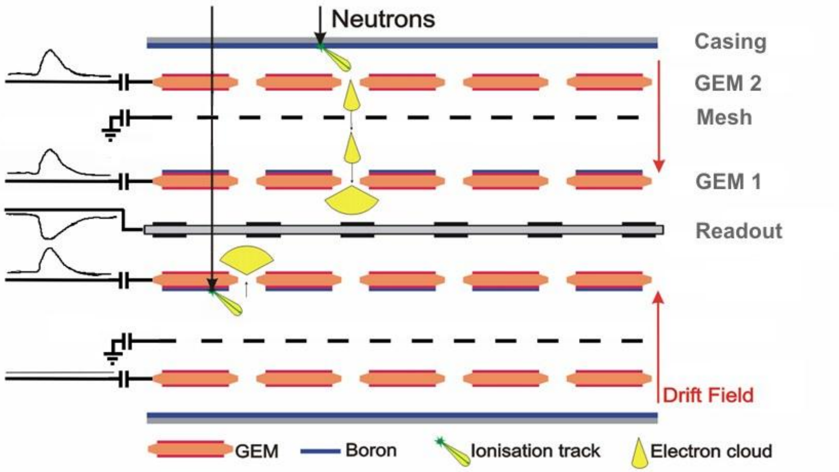
DREAM @ ESS: Bispectral Powder Diffractometer

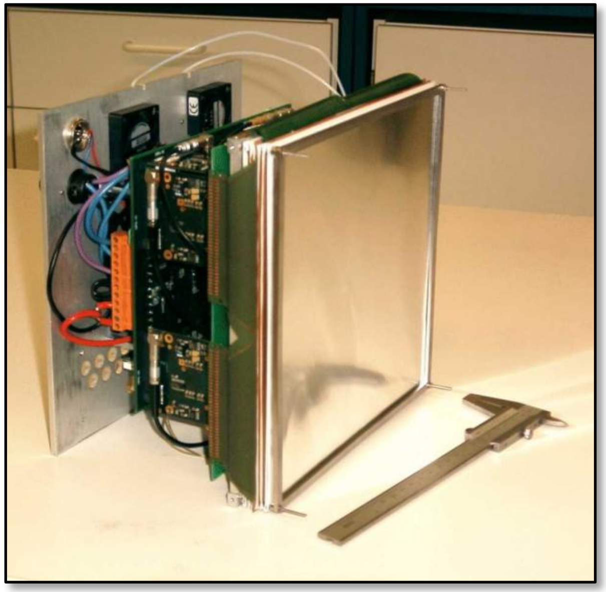


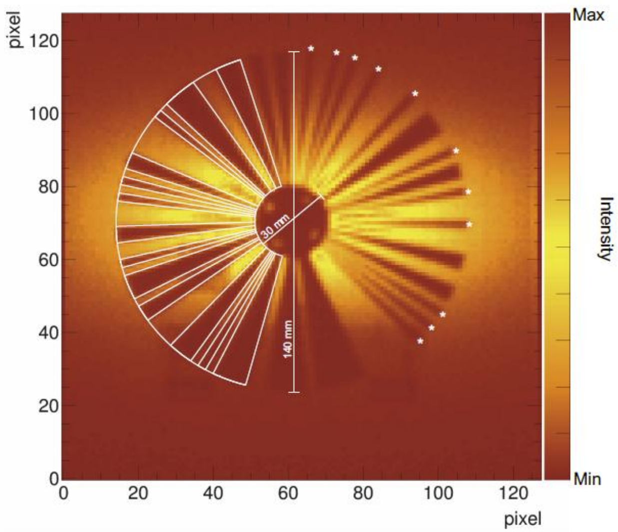


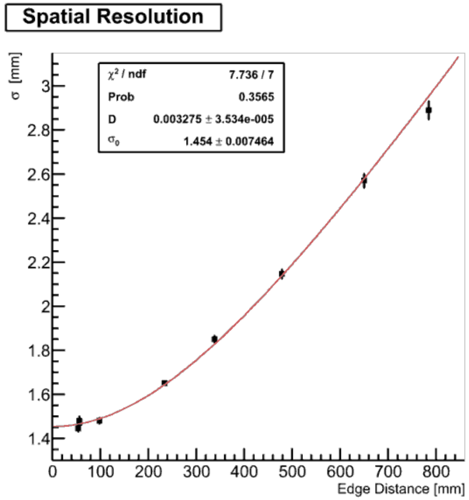
https://europeanspallationsource.se/instruments/dream

New Detectors – CASCADE



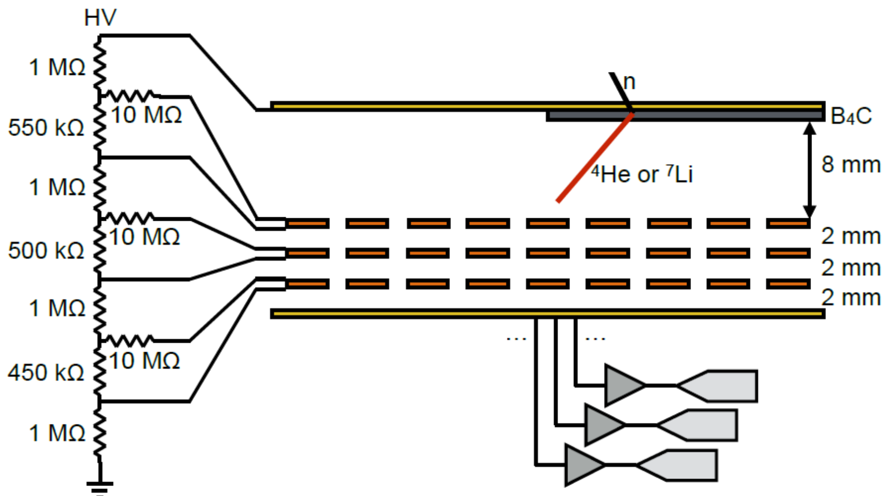


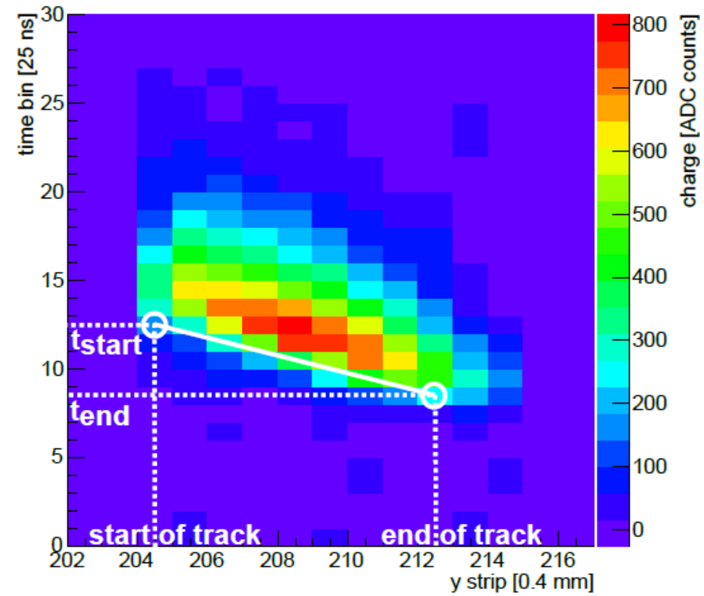


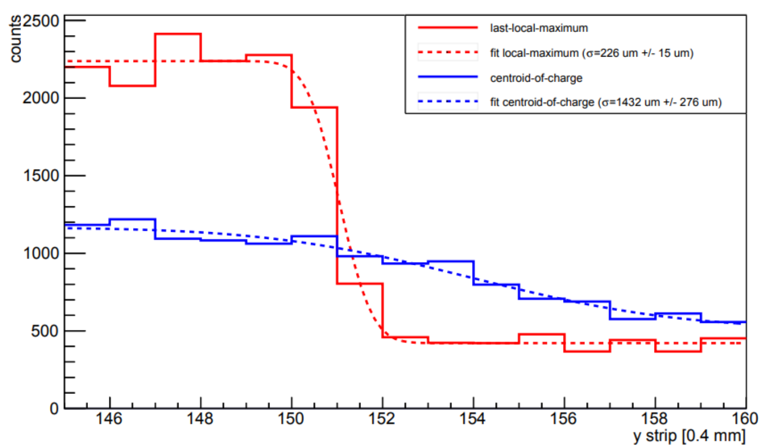


Spatial Resolution σ (1.4) mm

New Detectors – Time Projection







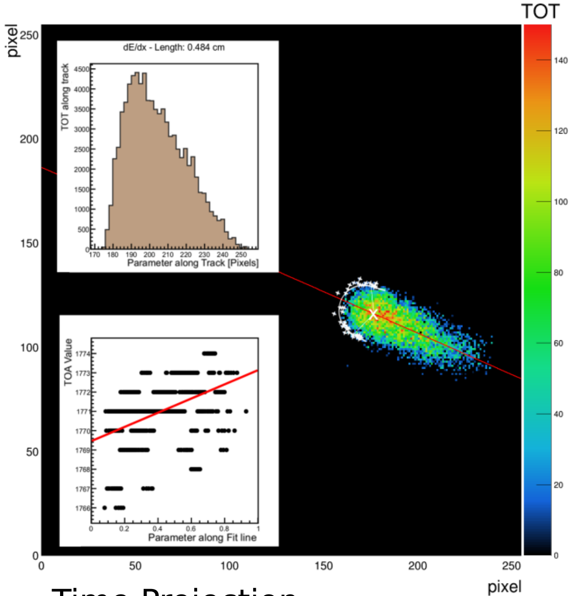
Spatial Resolution σ
~ (200) µm

D. Pfeiffer et al., "The muTPC Method: Improving the Position Resolution of Neutron Detectors Based on MPGDs", 2015 arXiv:1501.05022v1

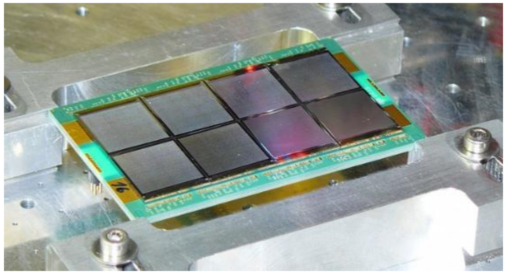
D. Pfeiffer et al., "First measurements with new high-resolution gadolinium-GEM neutron detectors" JINST 11 (2016) P05011

New Detectors – Time Projection

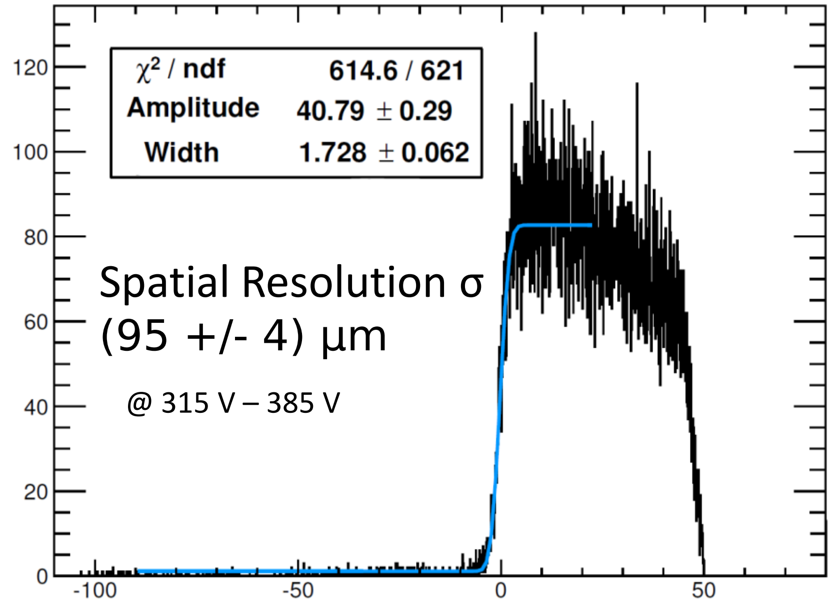
Spatial Projection

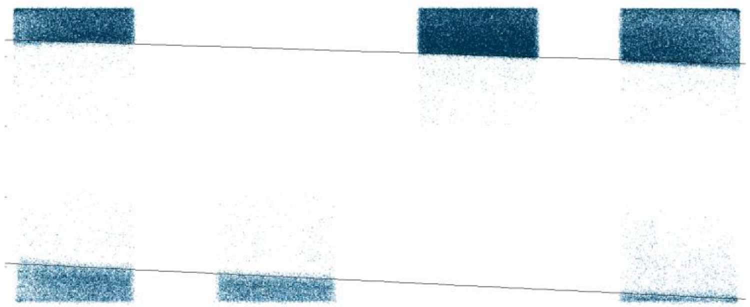


Time Projection

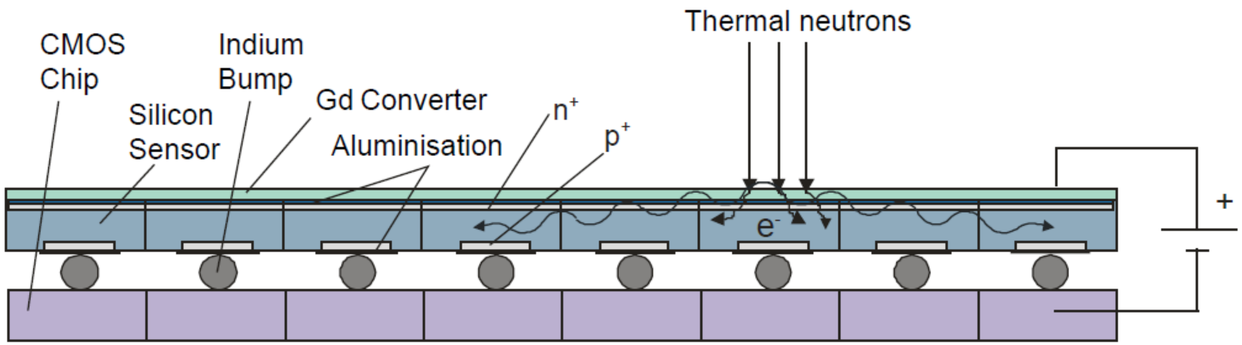


Edge Projection





New Detectors – Gd Imaging



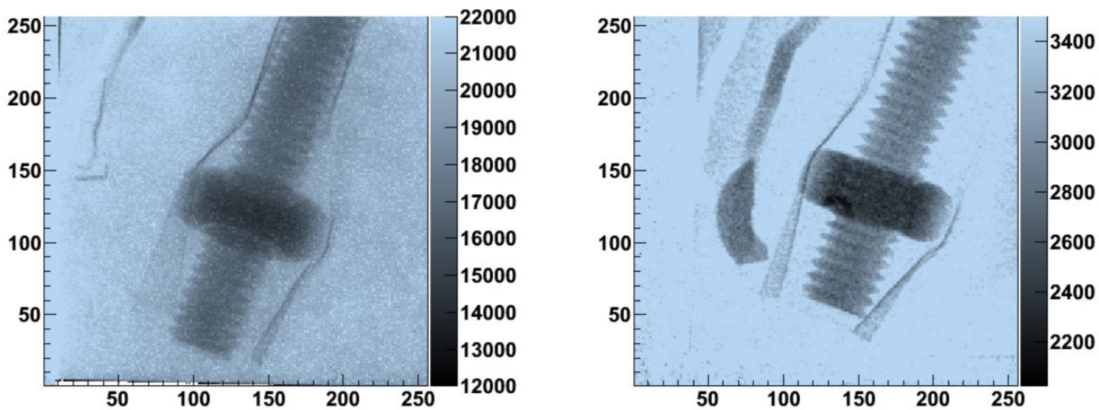


Figure 13. Neutron images of a screw and nut: left image a 240 sec. exposure with a Gd converter, right image a 120 sec. exposure with a 10-B converter.

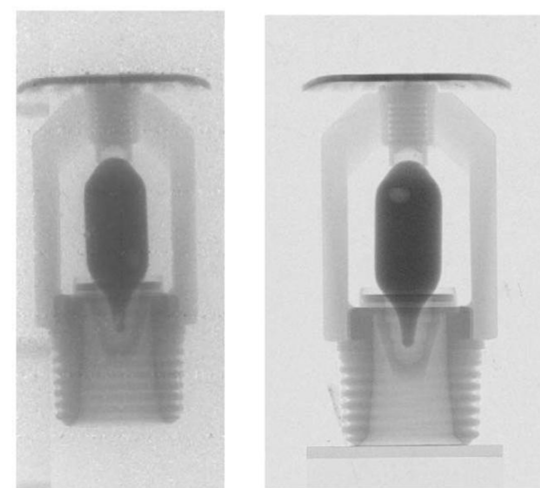
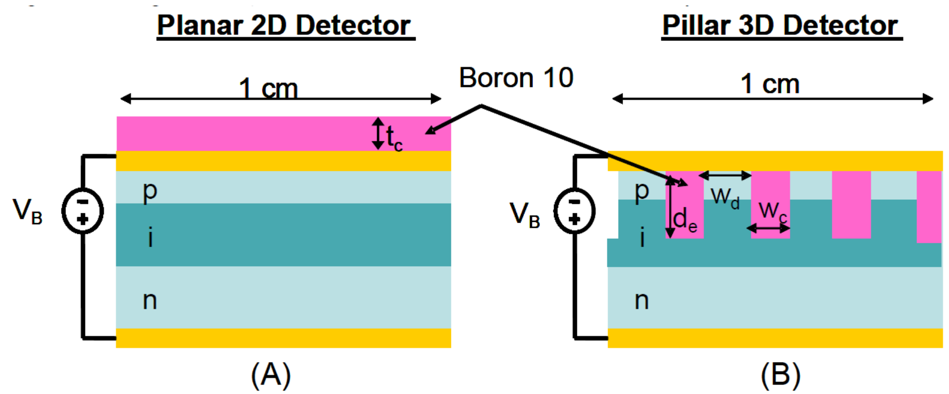
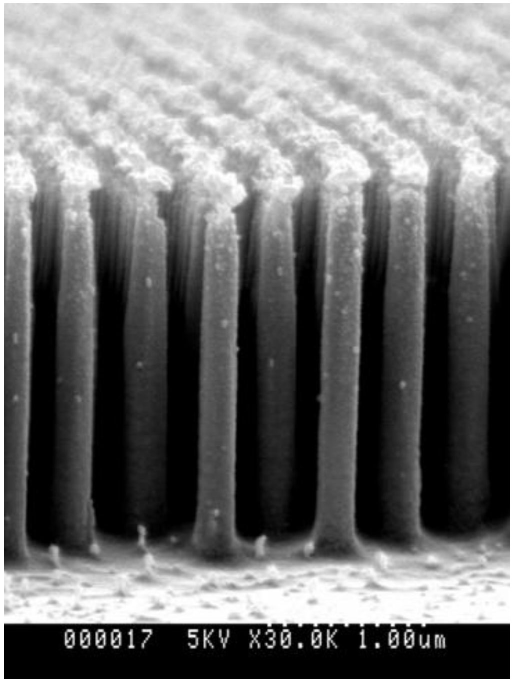


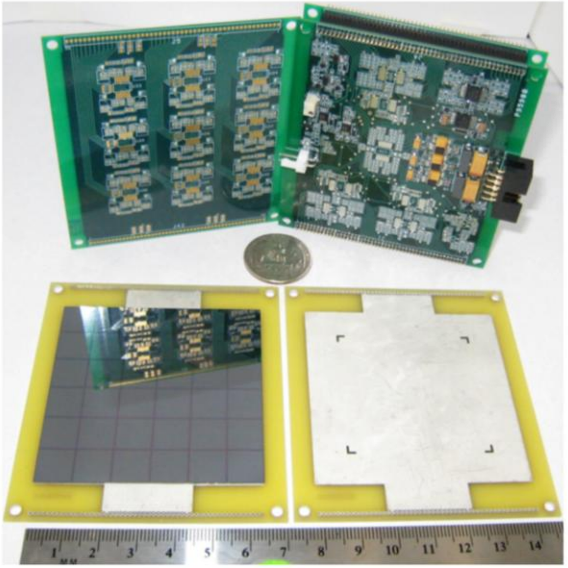
Fig. 7. Radiography image of a sprinkler nozzle made with different imaging systems, PILATUS (left), imaging plate (right).

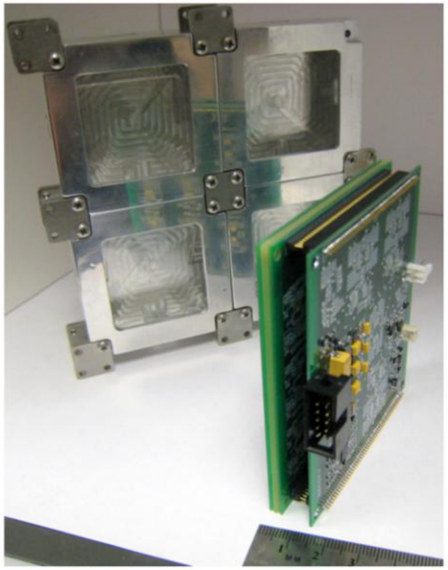
E. Lehmann et al., “Neutron imaging—detector options and practical results”, NIM A 531, 2004
E. Lehmann et al., “Neutron imaging — Detector options in progress ”, JINST, 2011

New Detectors – 3D Silicon



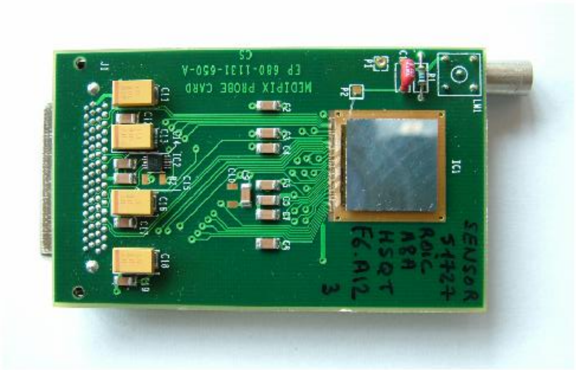






R.J. Nikolic et al. “Roadmap for High Efficiency Solid-State Neutron Detectors“, Barry Chin Li Cheung Publications, 15
D.S. McGregor et al., „High-efficiency microstructured semiconductor neutron detectors that are arrayed, dual-integrated, and stacked “, Applied Radiation and Isotopes 70, 2012

New Detectors – MediPix/TimePix



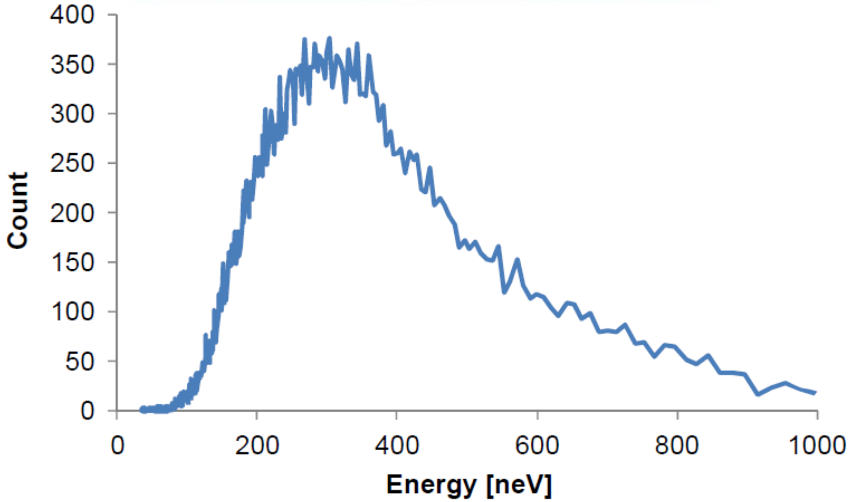
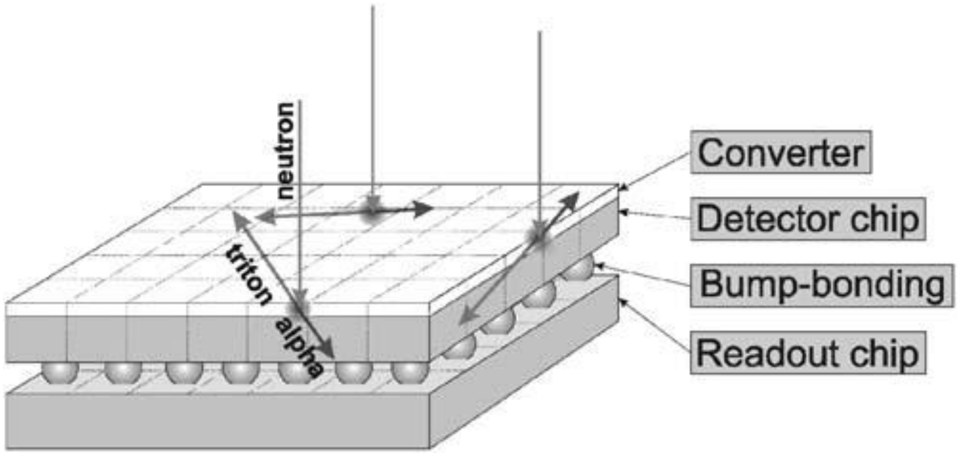
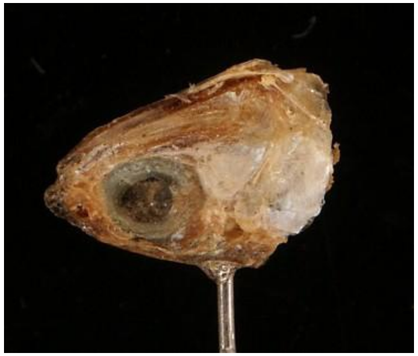
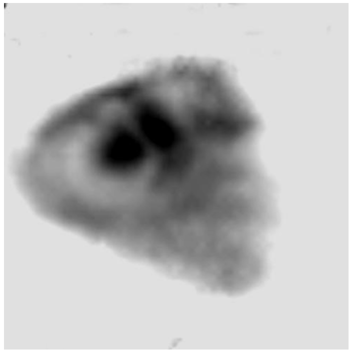


Fig. 2. Energy spectrum of UCN beam.





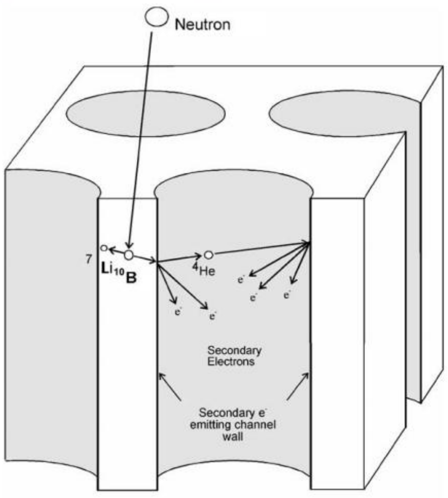


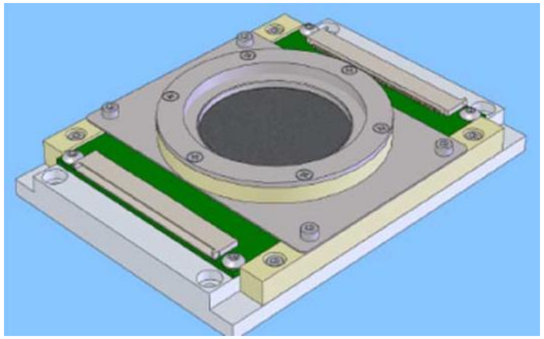
J. Uhrt et al., "Single Neutron Pixel Detector Based on Medipix-1 Device", 2004
„Performance of a pixel detector suited for slow neutrons", 2005
„3D Neutron Detectors", 2007,
„ Position-sensitive spectroscopy of ultra-cold neutrons with Timepix pixel detector ", 2009

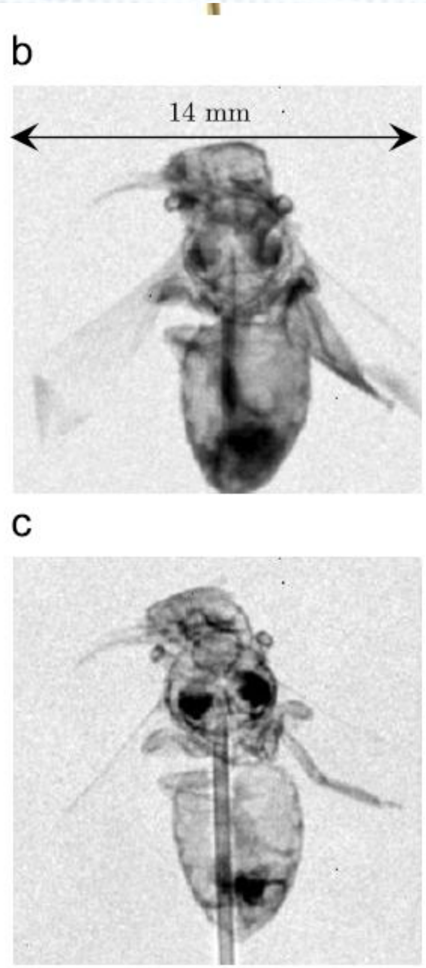
New Detectors – MediPix/TimePix

2003	Single neutron pixel detector based on Medipix-1 device	(IEEE)
2005	Spatial resolution of Medipix-2 device as neutron pixel detector	(NIMA)
2004	Properties of the single neutron pixel detector based on the Medipix-1	(NIMA)
2005	Properties of neutron pixel detector based on Medipix-2 device	(IEEE)
2006	Neutron imaging with Medipix-2 chip and a coated sensor	(NIMA)
2008	Detection of fast neutrons with the Medipix-2 pixel detector	(IEEE)
2008	High-resolution UV, alpha and neutron imaging with the Timepix CMOS readout	(NIMA)
2009	Neutron Detector Based on Timepix Pixel Device with Micrometer Spatial Resolution	(SPIE)
2009	A coated pixel device TimePix with micron spatial resolution for UCN detection	(NIMA)
2009	High-resolution neutron radiography with microchannel plates: Proof-of-principle experiments at PSI	(NIMA)
2010	Fast neutron detector based on TimePix pixel device with micrometer spatial resolution	(IEEE)
2010	Monte-Carlo simulation of fast neutron detection using double-scatter events in plastic scintillator and Timepix	(IEEE)
2011	Design, Implementation and First Measurements with the Medipix Neutron Camera in CMS	(arxiv)
2011	Detection of fast neutrons with particle tracking detector Timepix combined with plastic scintillator	(Rad. Meas.)
2011	High-resolution strain mapping through time-of-flight neutron transmission diffraction with a microchannel plate neutron counting detector	(Strain)
2011	A high resolution neutron counting sensors in strain mapping through a transmission bragg edge diffraction	(IEEE)
2012	A highly miniaturized and sensitive thermal neutron detector for space applications	(AIP)
2012	High resolution neutron counting detectors with microchannel plates and their applications in neutron radiography, diffraction and resonance absorption imaging	(Neutron News)
2012	Neutron radiography with sub-15 µm resolution through event centroiding	(NIMA)
2013	Directional detection of fast neutrons by the Timepix pixel detector coupled to plastic scintillator with silicon photomultiplier array	(IOP)
2014	Fast Neutron Dosimeter using the pixelated detector TimePix	(Rad. Prot. Dos.)
2014	Position sensitive detection of neutrons in high radiation background field	(Rev. Sci. Instrum.)
2014	Characterization of Timepix Detector Coated with 10B4C Film for High Resolution Neutron Imaging	(Proc. ICATPP)
2014	Dosimetry measurements using Timepix in mixed radiation fields induced by heavy ions; comparison with standard dosimetry methods	(J. Radiat. Res.)
2014	Time-of-flight measurement of fast neutrons with Timepix detectors	(JInst)
2014	Fast Sensors for Time-of-Flight Imaging Applications	(Phys. Chem.)
2015	Time-resolved neutron imaging at ANTARES cold neutron beamline	(JInst)
2016	Development and characterization of high-resolution neutron pixel detectors based on Timepix read-out chips	(JInst)
2016	Improved fast neutron detector based on timepix and plastic scintillating converter	(IEEE)
2017	Real-time Crystal Growth Visualization and Quantification by Energy-Resolved Neutron Imaging	(Sci. Rep.)
2017	Evaluation of Wavelength-Dependent Detection Efficiency of Neutron-Sensitive Microchannel Plate Detector	(Sensors and Mat.)
2018	Neutron Imaging with Timepix Coupled Lithium Indium Diselenide	(J. Imaging)
2018	Energy-Resolved Neutron Imaging for Reconstruction of Strain Introduced by Cold Working	(J. Imaging)
2018	Towards high-resolution neutron imaging on IMAT	(IOP)
2018	Asic developments for radiation imaging applications: The medipix and timepix family	(NIMA)

New Detectors - MCP



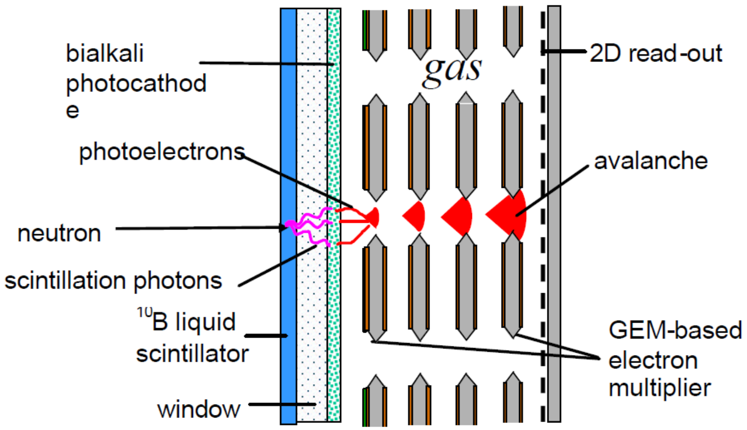


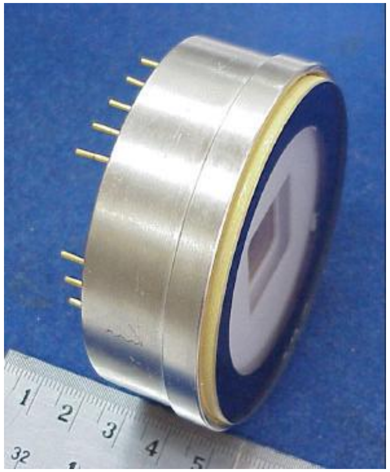


A. Tremsin et al., “High-resolution neutron radiography with microchannel plates: Proof-of-principle experiments at PSI”, NIM A, 605, 2009
A. Tremsin et al., „Efficiency optimization of microchannel plate (MCP) neutron imaging detectors. I. Square channels with 10B doping“, NIM A, 539, 2005

Fig. 3. Photograph (a) and neutron radiographic images of a bee; (b) thermal neutron beamline NEUTRA, acquisition time 15 min; (c) cold neutorn beamline ICON, acquisition time 3 min. The edges of the hypodermic needle show some diffraction enhancement.

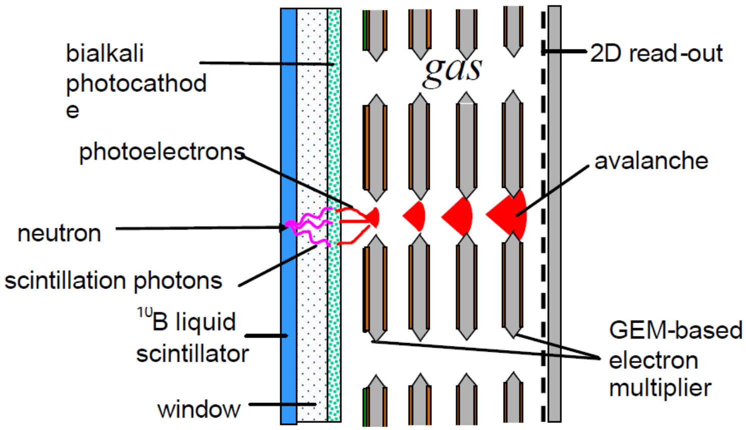
New Detectors – GEM + Scintillation

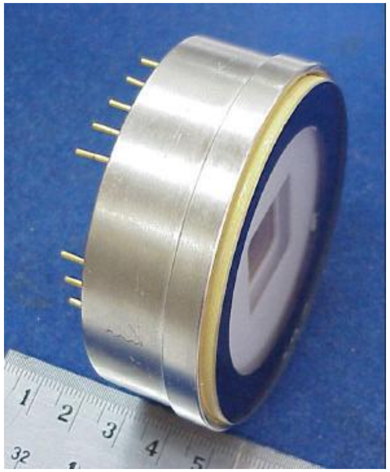




D. Vartsky et al., “Large Area Imaging Detector for Neutron Scattering Based on Boron-Rich Liquid Scintillator”, NIMA 504, 2003

New Detectors – GEM + Scintillation



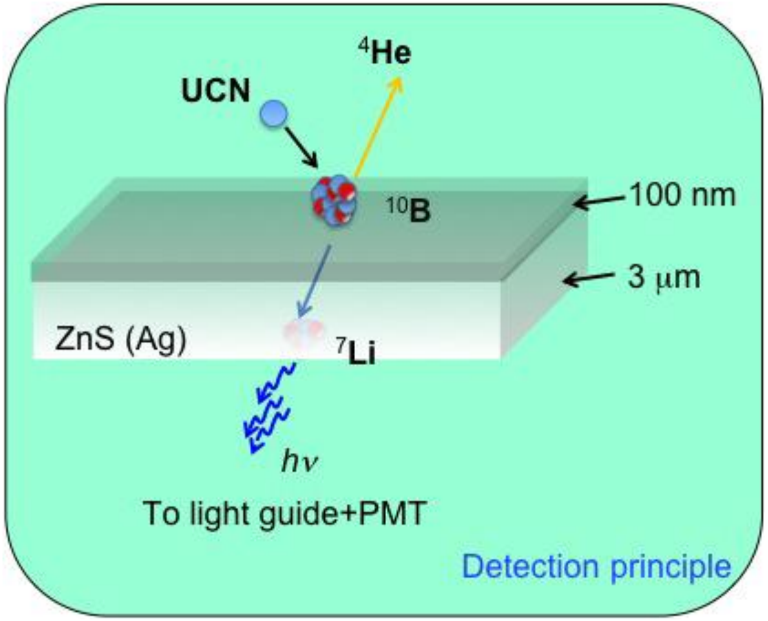


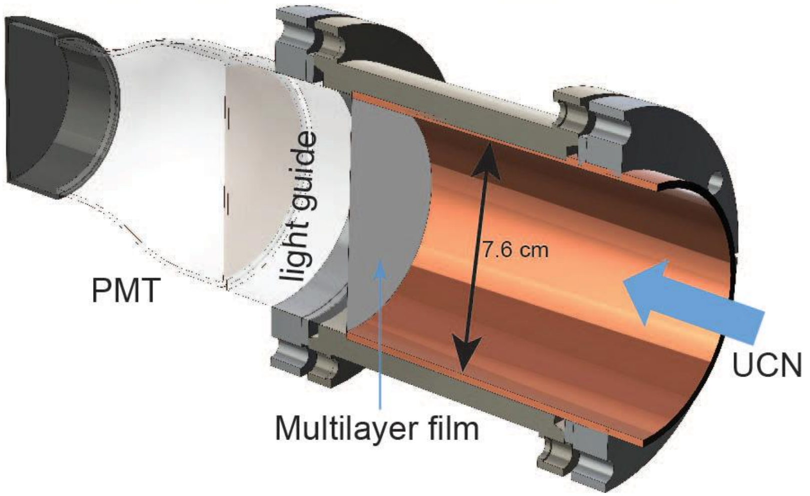
Other technologies:

- ^{10}B aerosol
- ^{10}B aerogel
- ^{6}LiF saturated foam
- ^{10}BN nanotubes
- h-BN epilayers
- BGaN epilayers
- ^{3}He gaseous scintillation

D. Vartsky et al., "Large Area Imaging Detector for Neutron Scattering Based on Boron-Rich Liquid Scintillator", NIMA 504, 2003

New Detectors – GEM + Scintillation

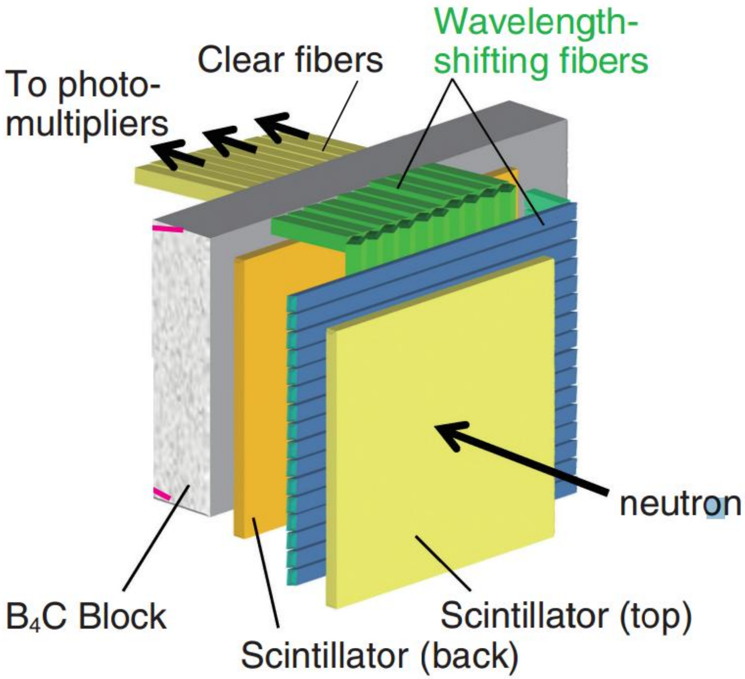


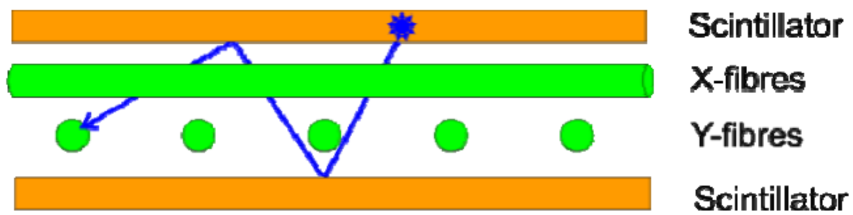


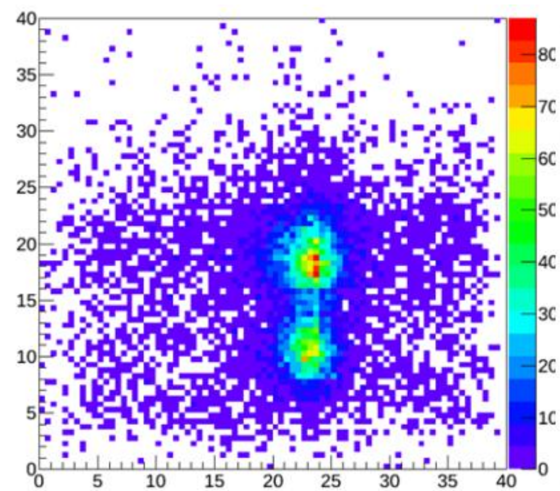
^{10}B-Coated ZnS screen

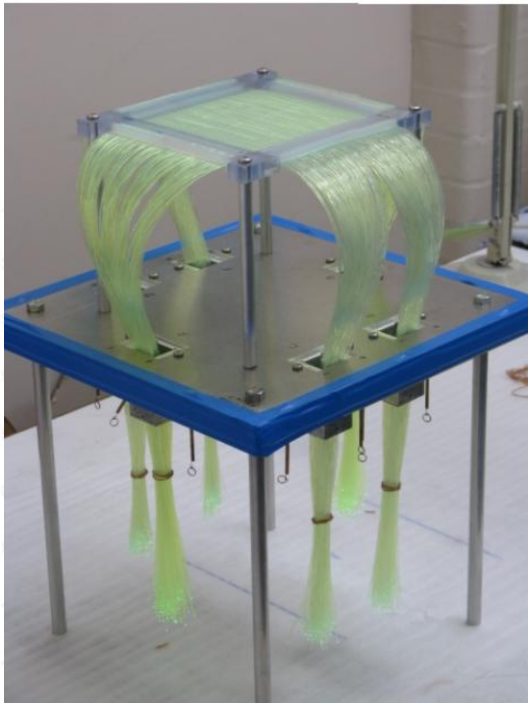
Z. Wang et al., "A multilayer surface detector for ultracold neutrons", arXiv:1503.03424v3

New Detectors - WLSF



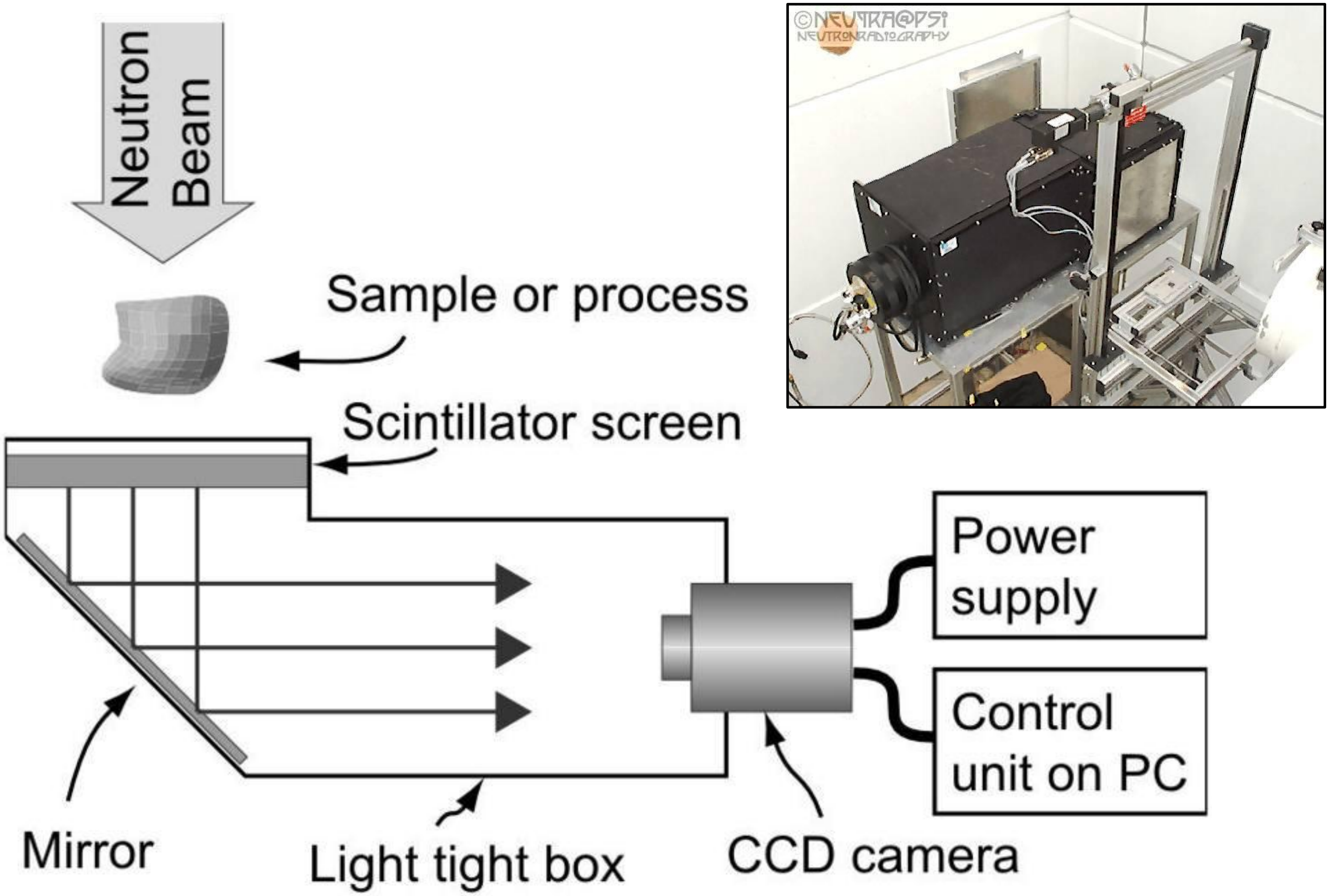






J. Sykora, “WLSF detector status and future plans at ISIS”, 2013
R. Engels “Status WLSF Neutron Detector Prototype from FZJ”, 2012
Nakamura, T. et al., “A Large-Area Two-Dimensional Scintillator Detector with a Wavelength-Shifting Fibre Readout for a Time-of-Flight Single-Crystal Neutron Diffractometer”, NIM A, 686, issue 1, 2012.

New Detectors - Imaging

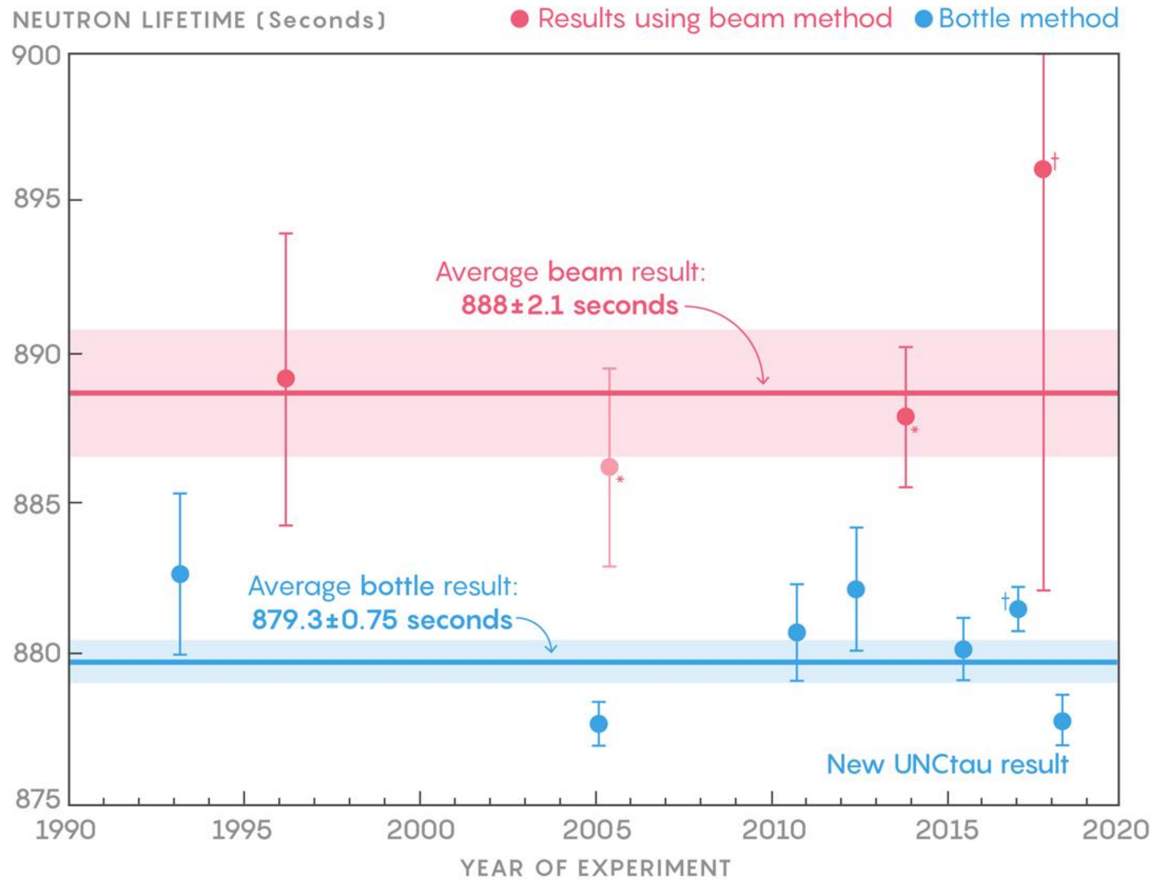


PSI Website „Neutron Imaging“
https://www.psi.ch/de/niag/neutron-imaging-detectors

Neutron Physics across the scales

(detection)

Neutron Lifetime

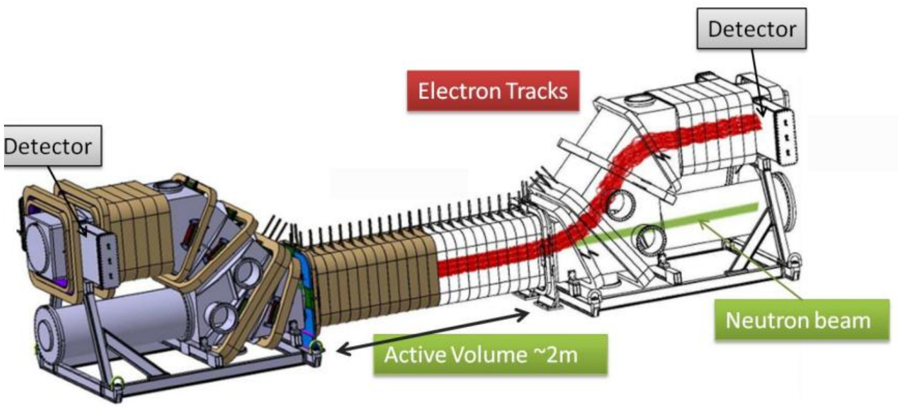


*Nico result (2005) was superseded by an updated and improved result, Yue (2013);
†Preliminary results

https://www.quantamagazine.org/neutron-lifetime-puzzle-deepens-but-no-dark-matter-seen-20180213/

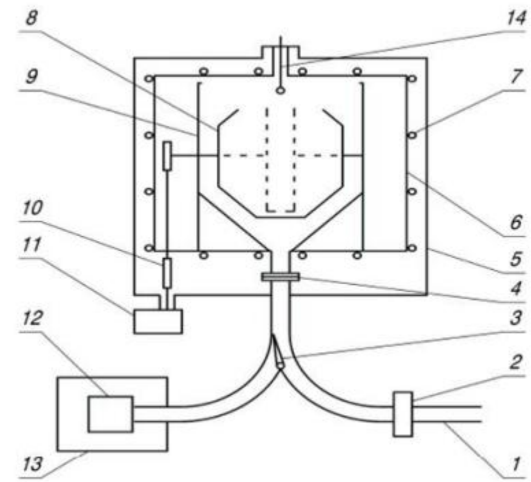
Neutron Lifetime

Inbeam



[1]

Bottle



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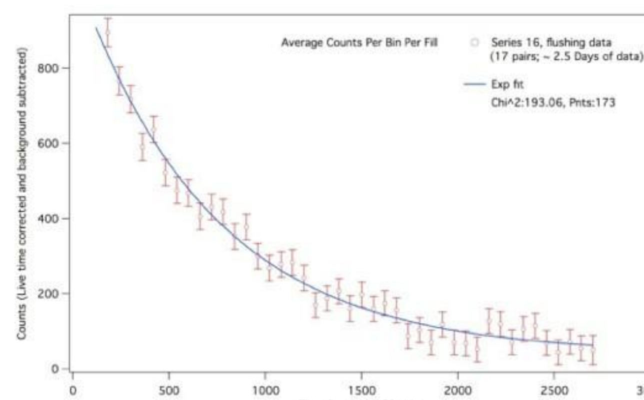
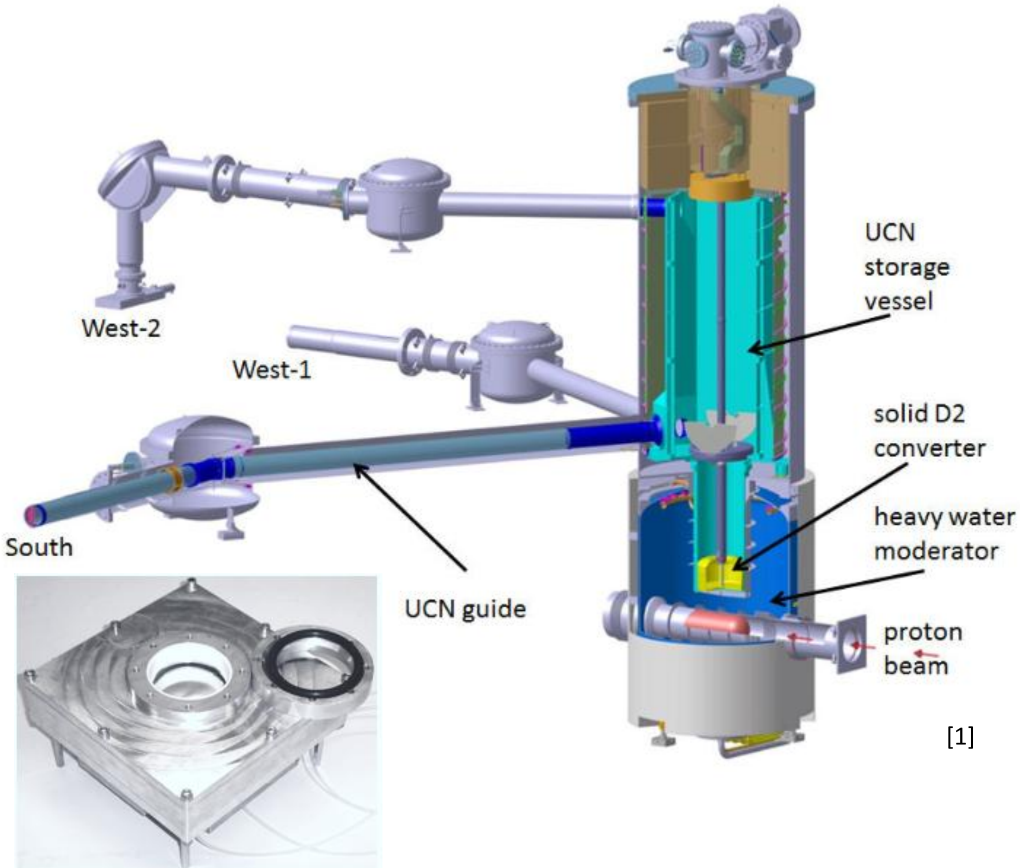


[3]

[1] B. Märkisch, personal communication
[2] A.P. Serebrov et al., Phys. Lett. B 605 (2005) 72
[3] P.R. Huffman et al. "Progress Towards Measurement of the Neutron Lifetime Using Magnetically Trapped Ultracold Neutrons", Proceedings of the PANIC: Particles and Nucleii International Conference (2006)

Neutron Lifetime



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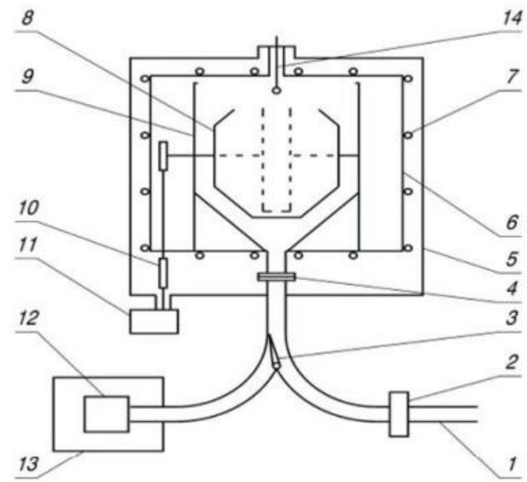

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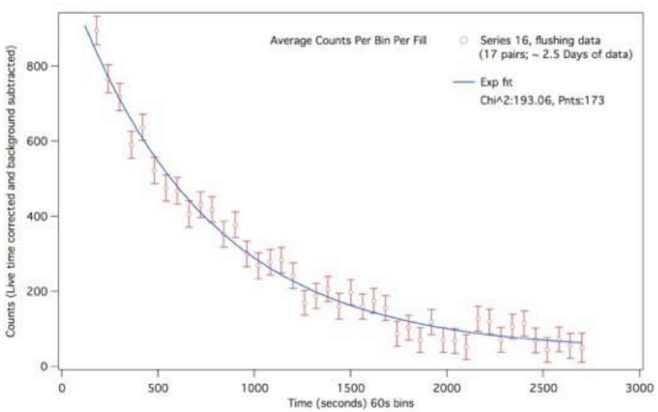
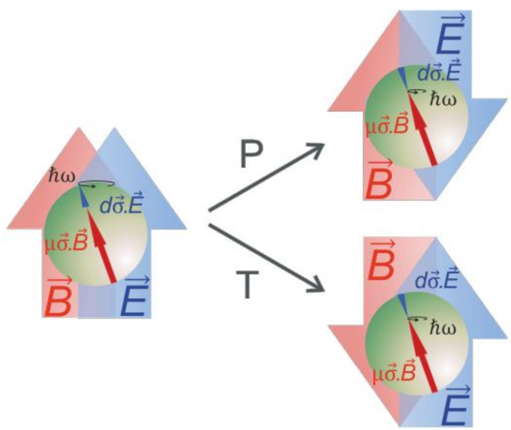


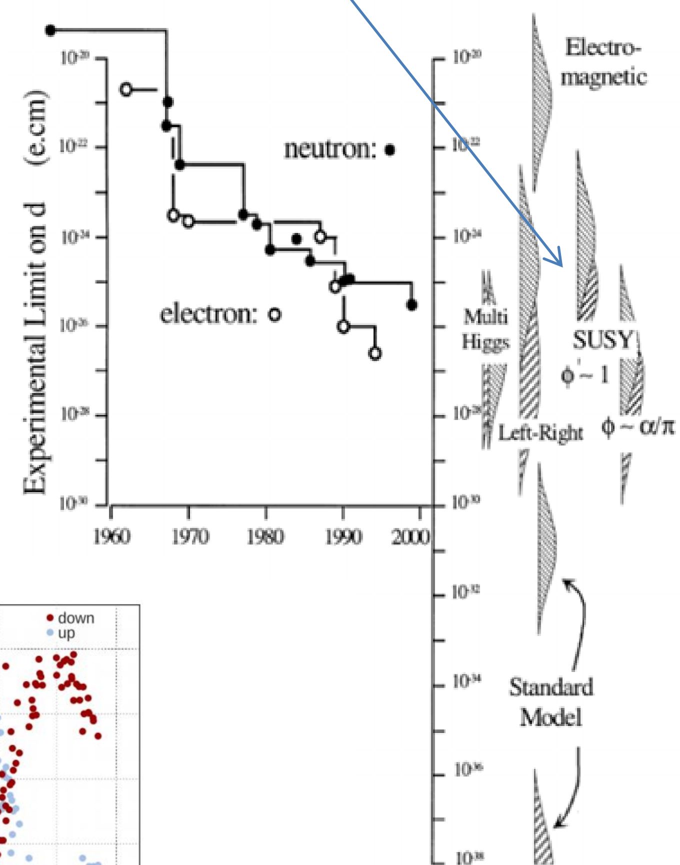
[3]

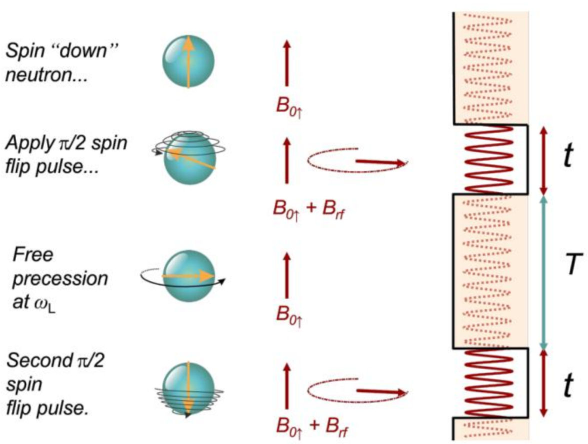
[1] https://www.psi.ch/ucn/ultracold-neutron-source-ucn
[2] A.P. Serebrov et al., Phys. Lett. B 605 (2005) 72
[3] P.R. Huffman et al. "Progress Towards Measurement of the Neutron Lifetime Using Magnetically Trapped Ultracold Neutrons", Proceedings of the PANIC: Particles and Nucleii International Conference (2006)

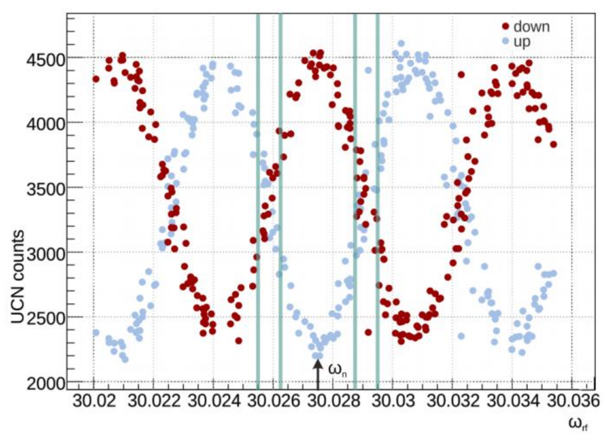
Electric Dipole Measurement

$$d_n \sim \left(\frac{300\,\mathrm{GeV}}{\Lambda_{\mathrm{SUSY}}}\right)^2 \sin\phi_{\mathrm{CP}} \times 10^{-24} e\cdot\mathrm{cm},$$



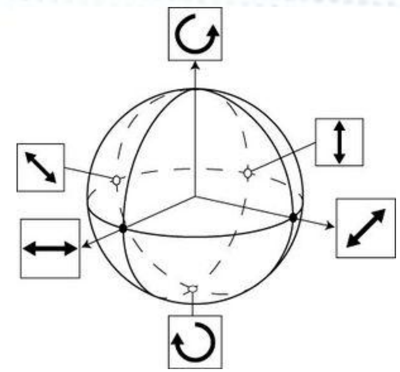


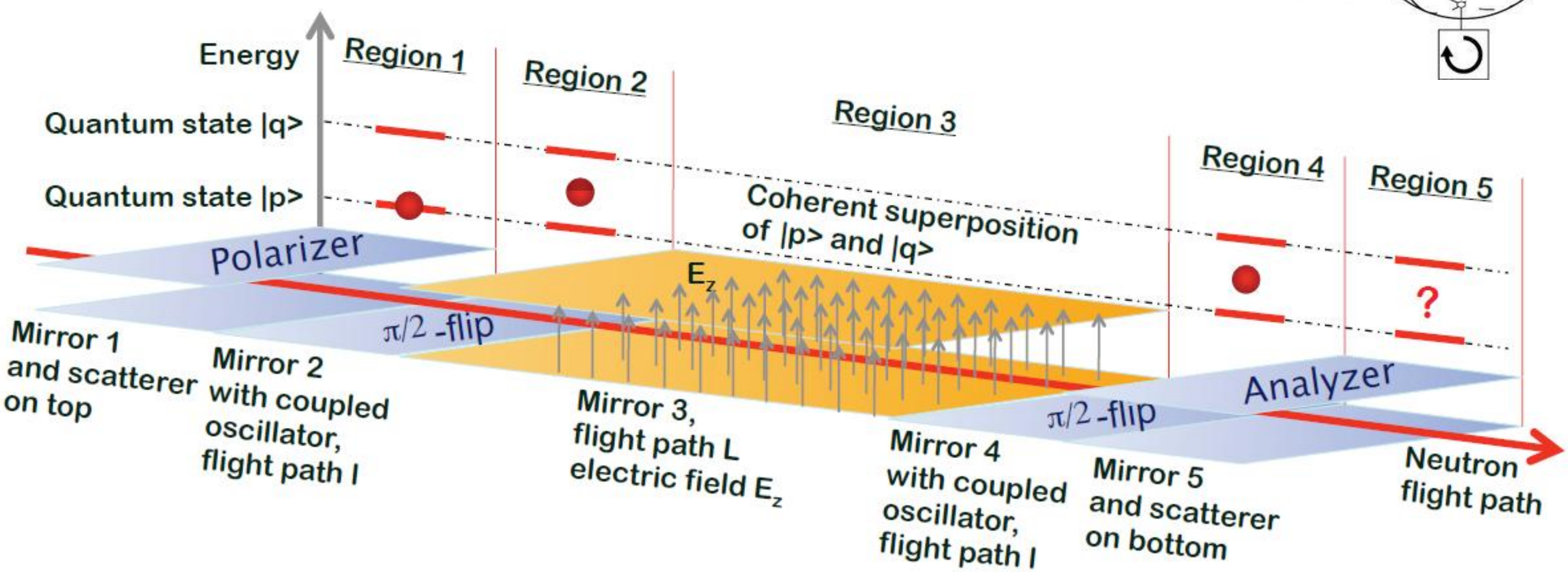




P. Schmidt-Wellenburg "The quest to find an electric dipole moment of the neutron" (2017)
arXiv: 1607.06609

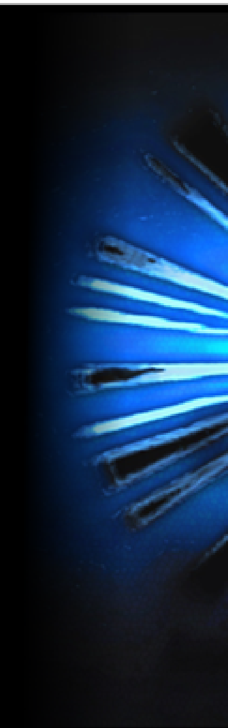
Neutron Charge Measurements



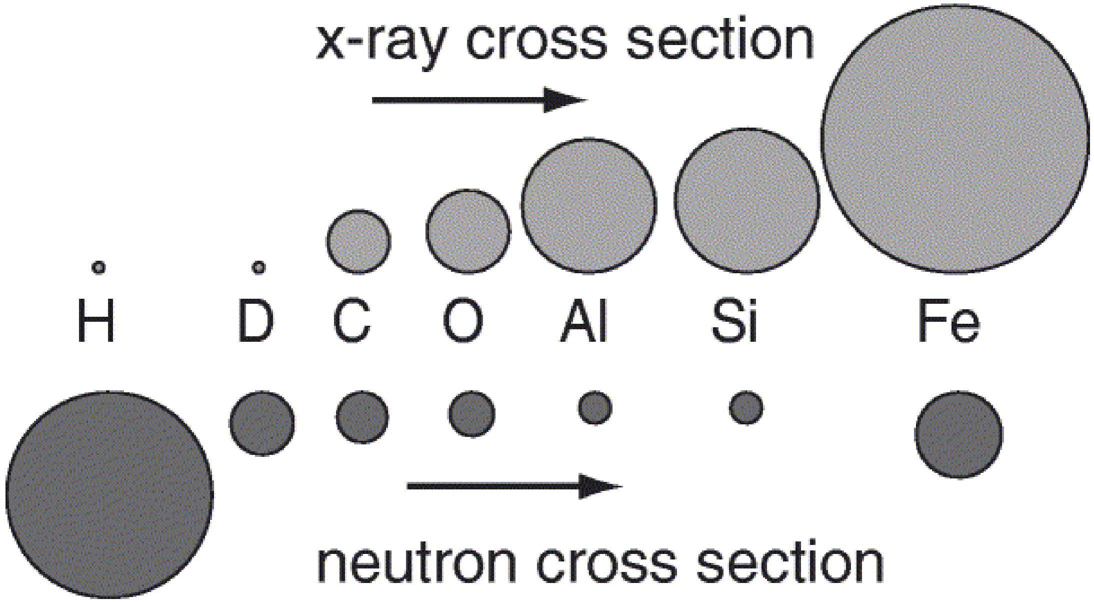


H. Abele et al. “High Precision Experiments with Cold and Ultra-Cold Neutrons“ (2014)

Materials Science



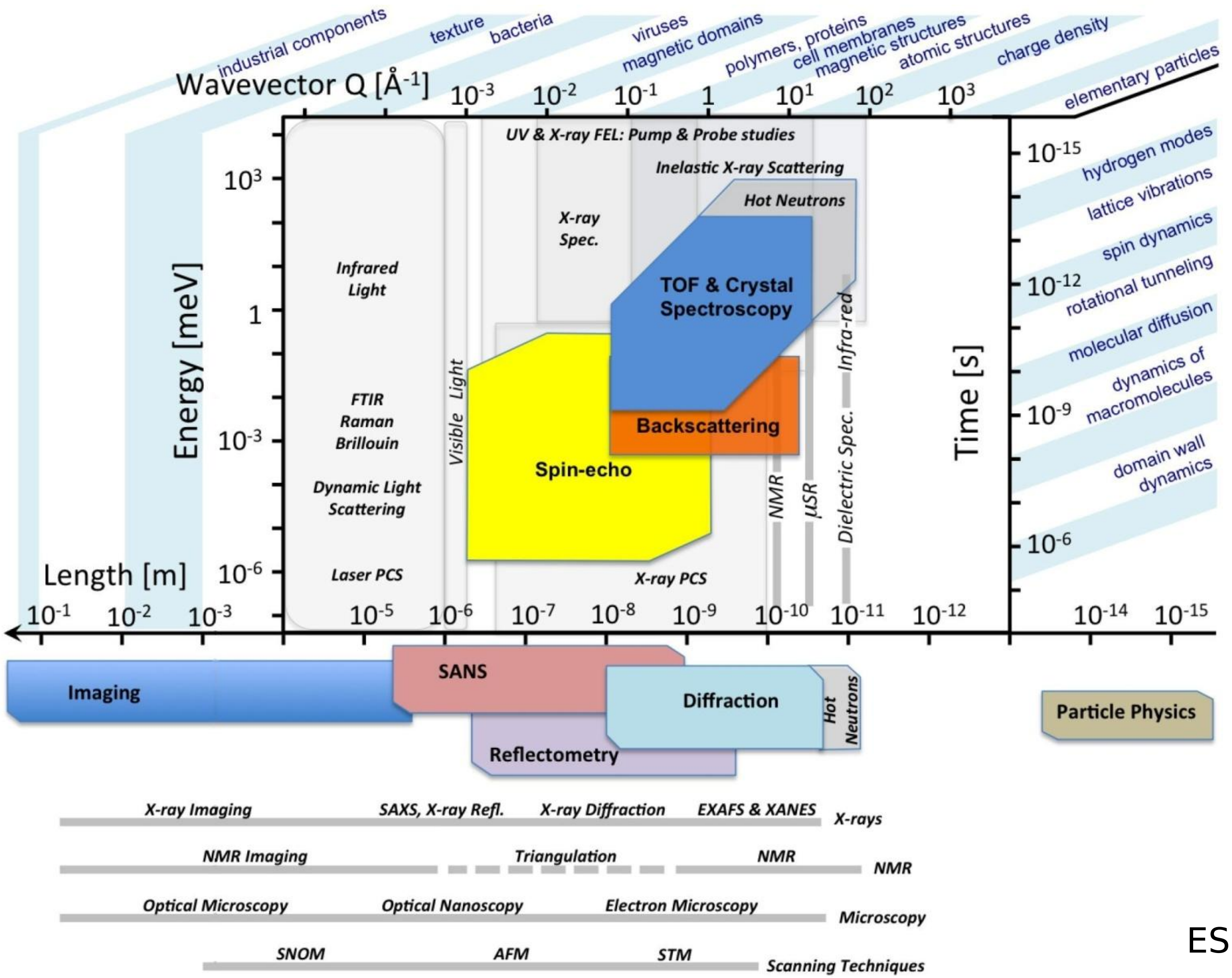
Spin Echo - MIEZE



- **X-Ray** cross section depends on Z
- **neutron** cross section varies over periodic table and isotopes (!)

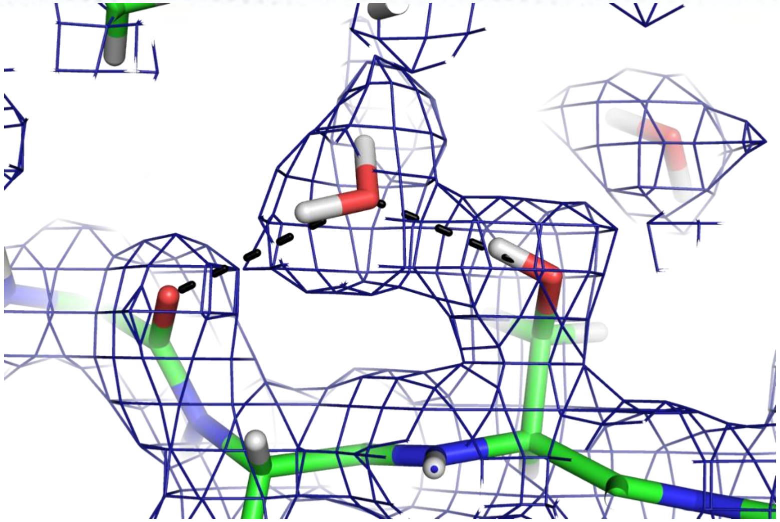
Y. A. Gandomi et al., “Critical Review—Experimental Diagnostics and Material Characterization Techniques Used on Redox Flow Batteries”, Journal of The Electrochemical Society 165(5) (2018), A970-A1010

Spin Echo - MIEZE

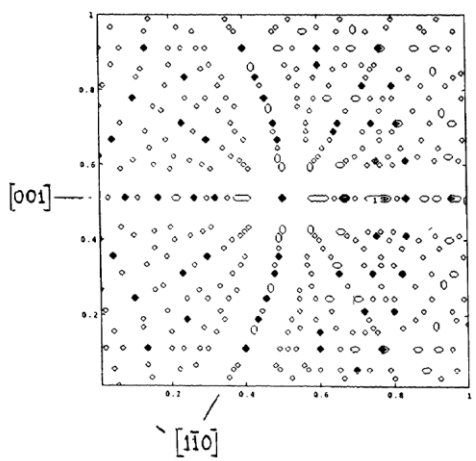


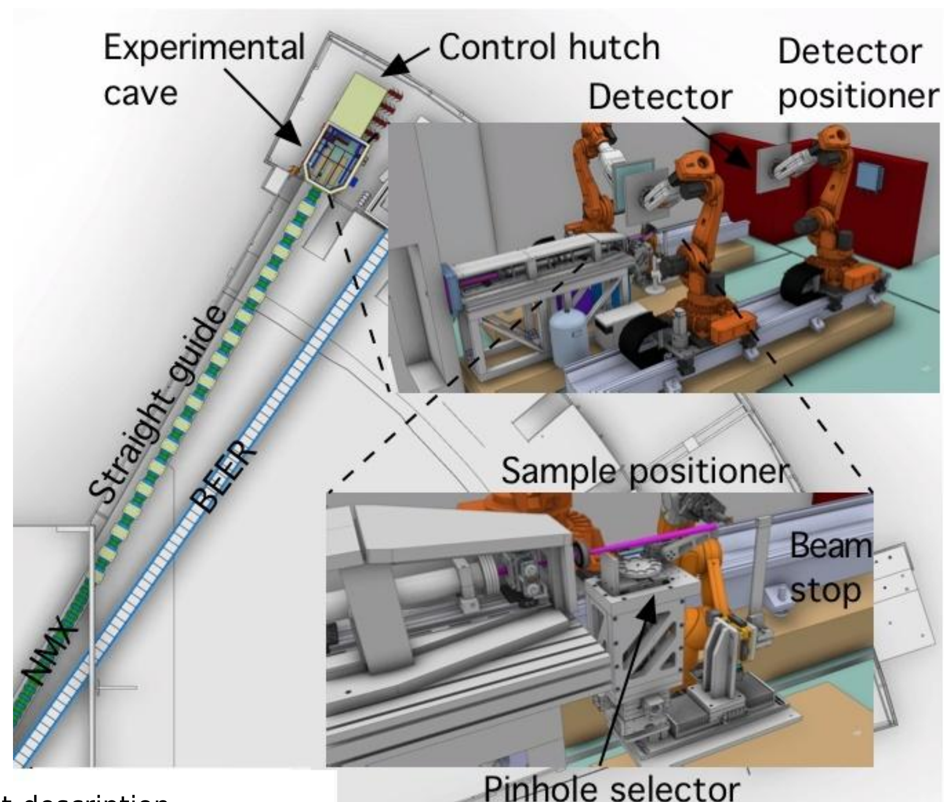
ESS TDR, 2013

NMX @ ESS



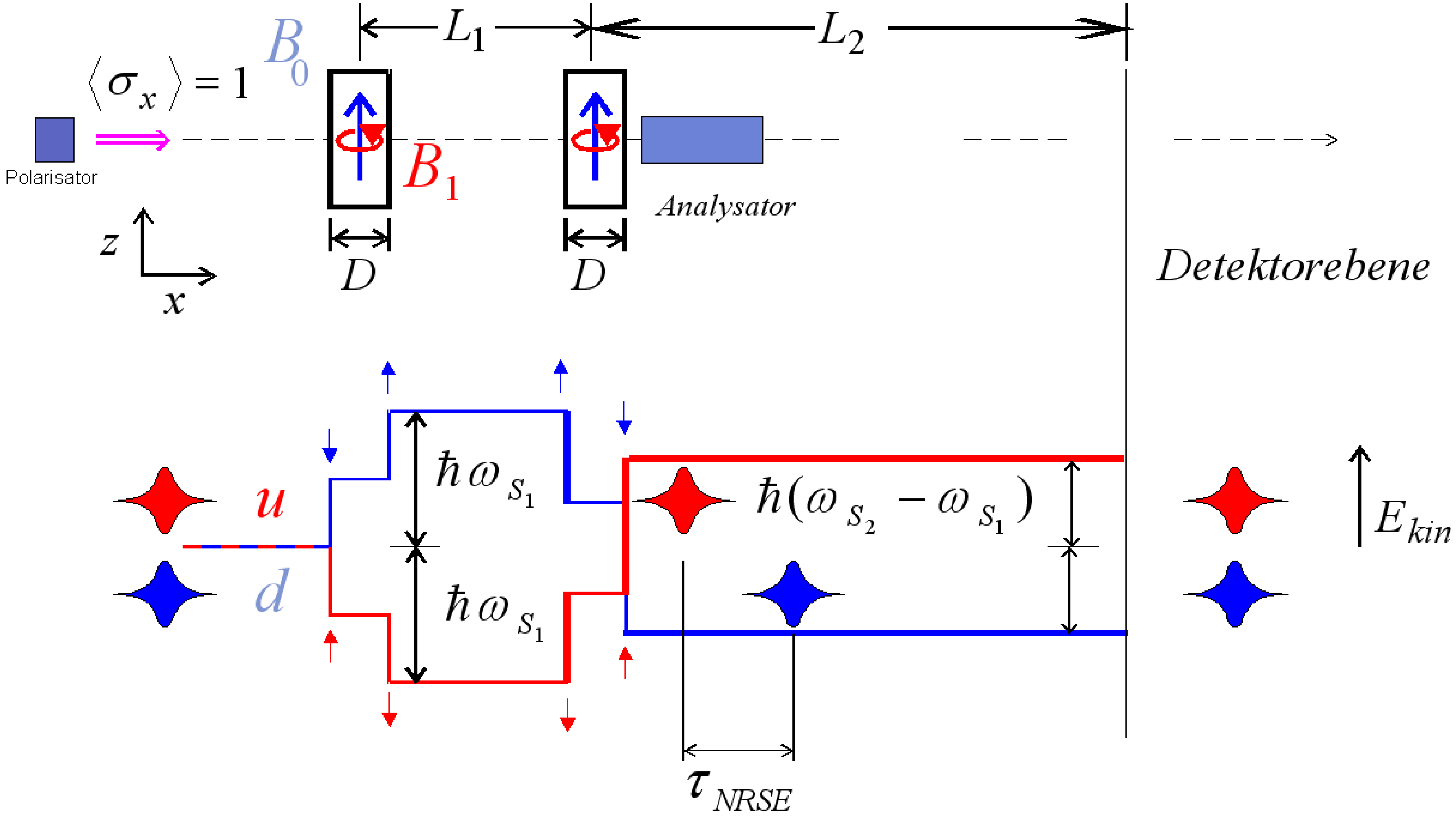
quasi-Laue time-of-flight (TOF)
single crystal diffractometer



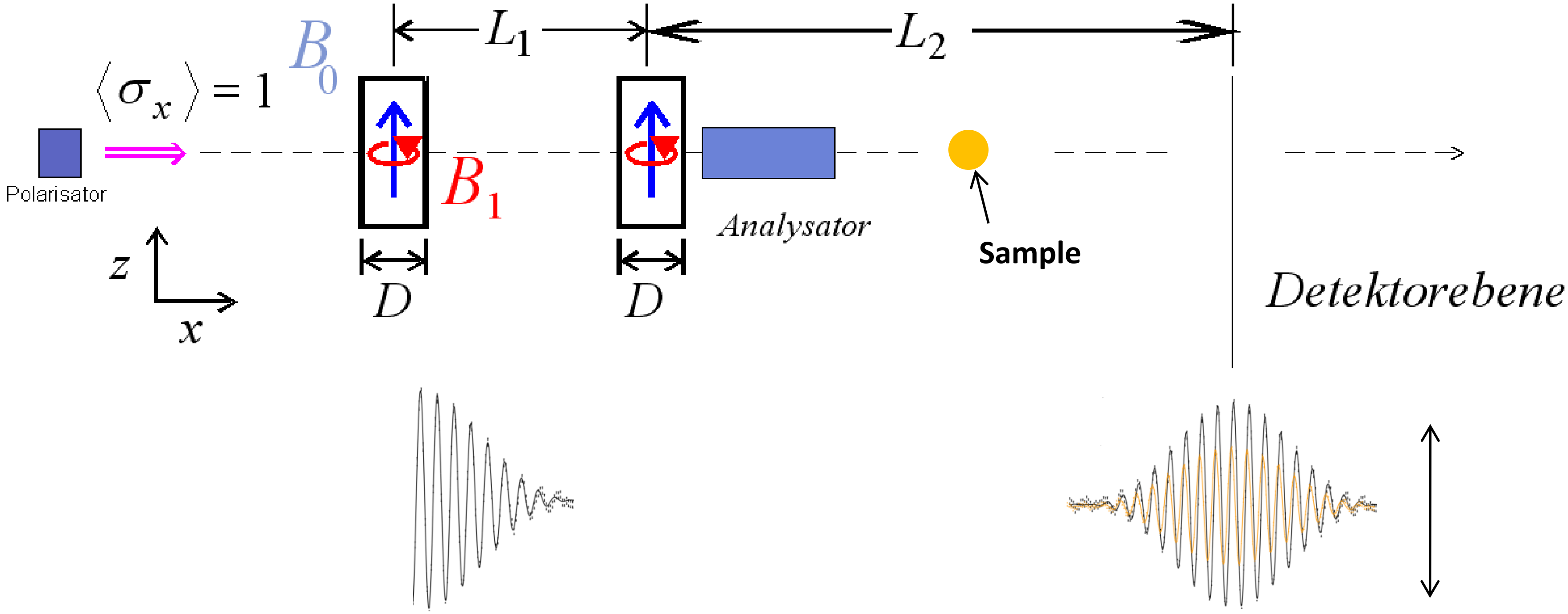


https://europeanspallationsource.se/instruments/nmx#instrument-description
C. Wilkinson amd M.S. Lehmann „Quasi-Laue neutron diffractometer“, NIMA310 (1991), 411-415

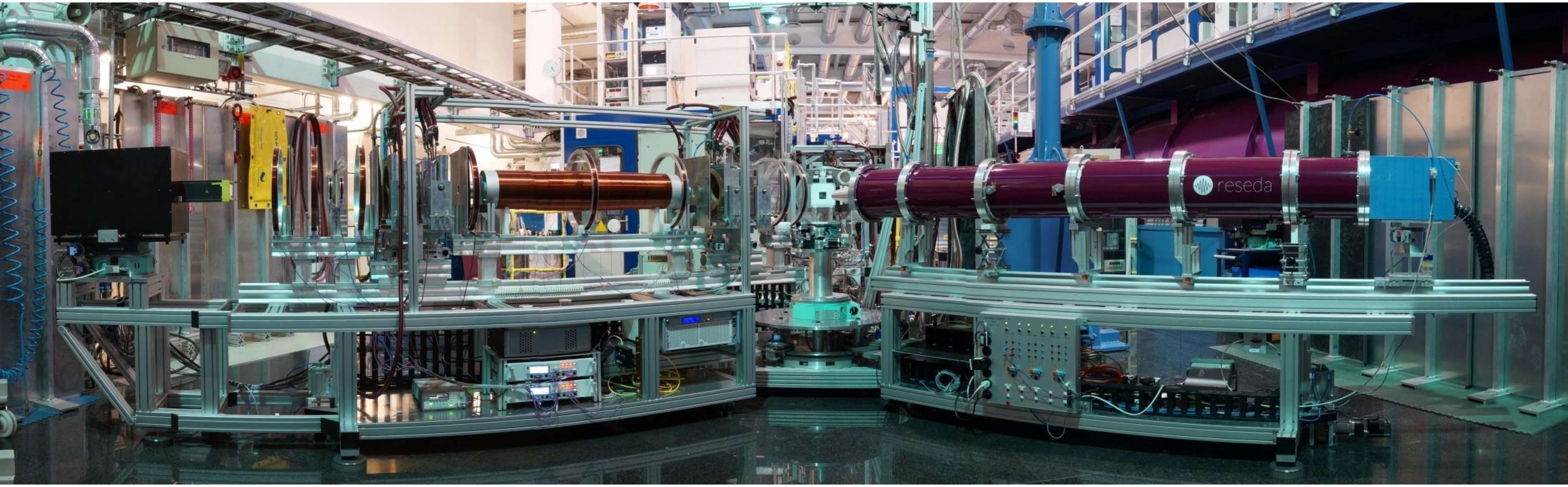
Spin Echo - MIEZE



Spin Echo - MIEZE

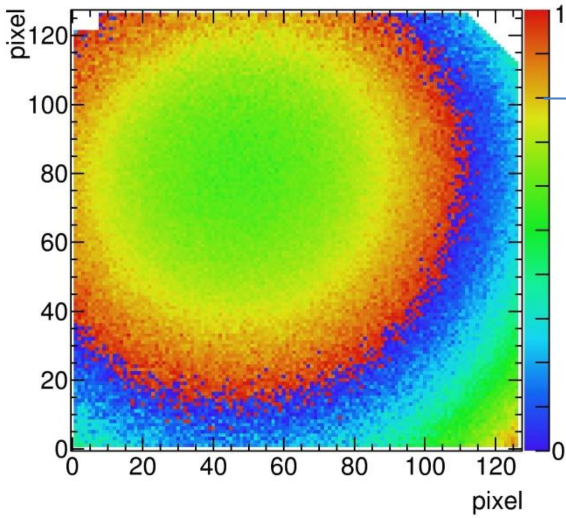


RESEDA, FRMII: spectrometer arms
3 – 15 Å @ 11% FWHM

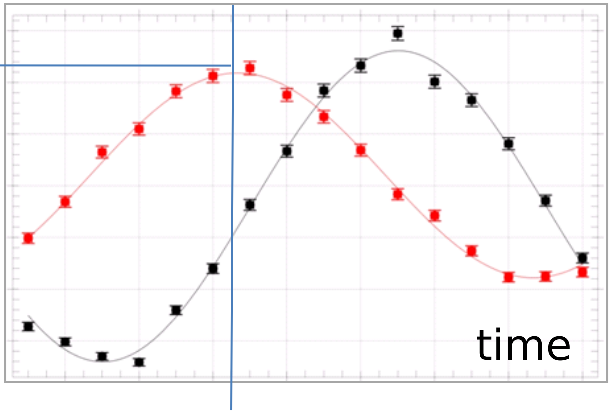


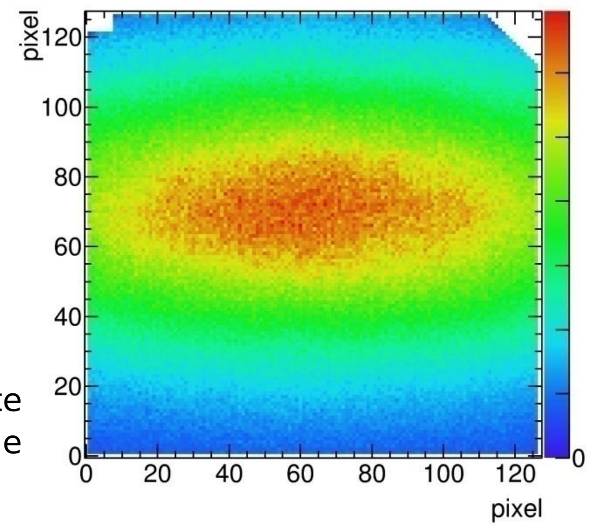
C. Franz, personal communication

Spin Echo Measurements

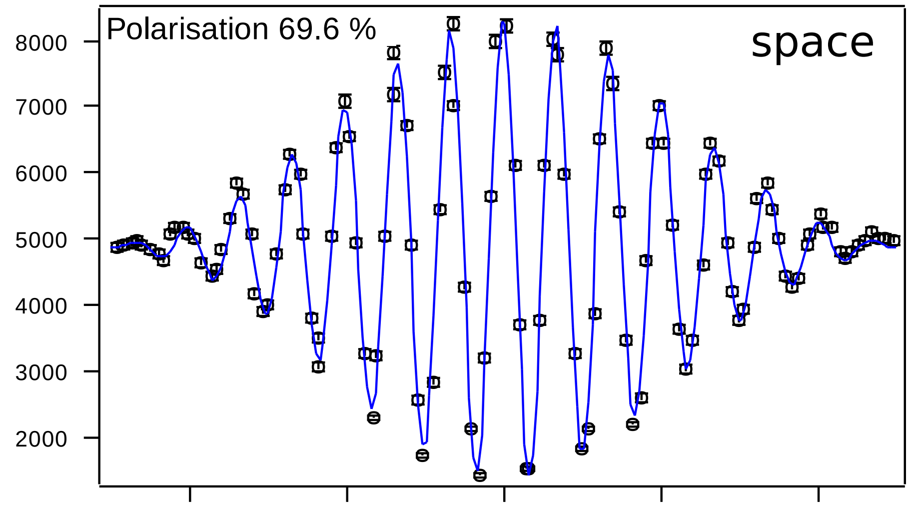


100 kHz x16



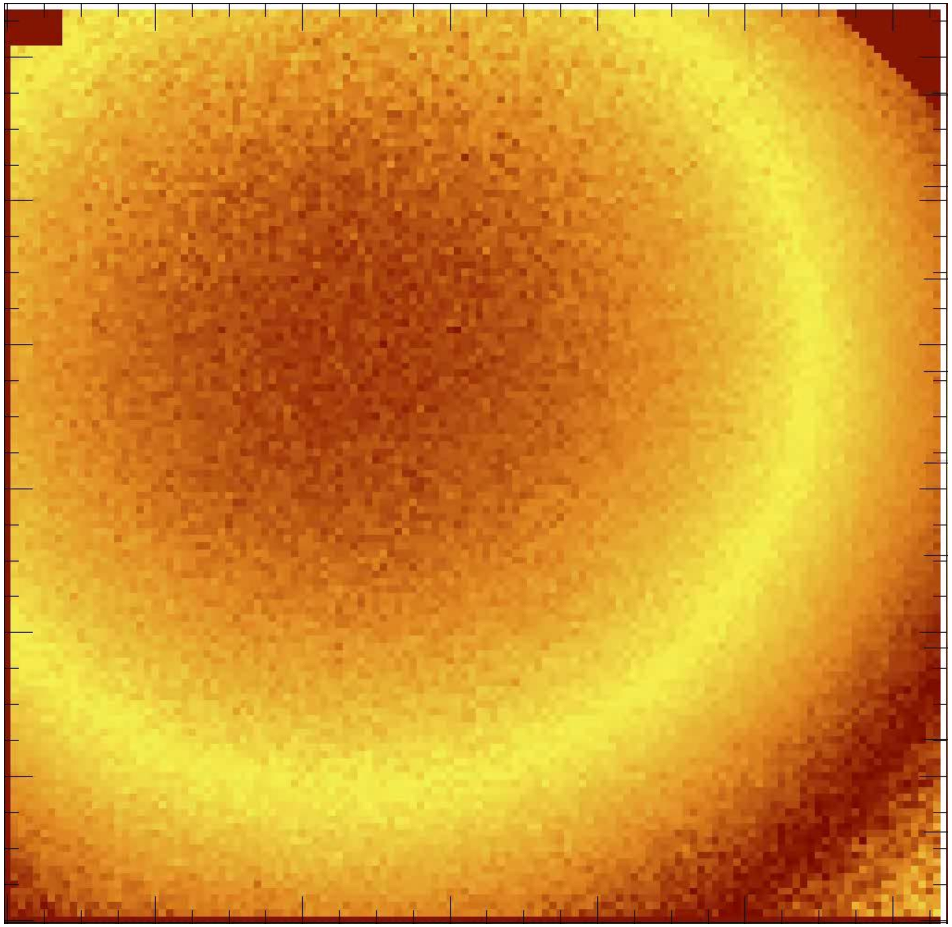


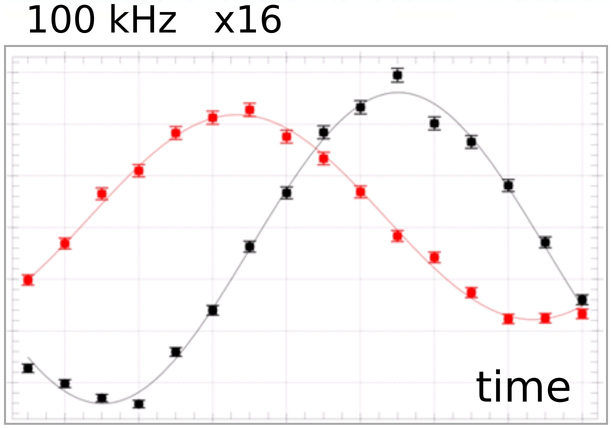
Graphite Sample



Typical Spin Echo group

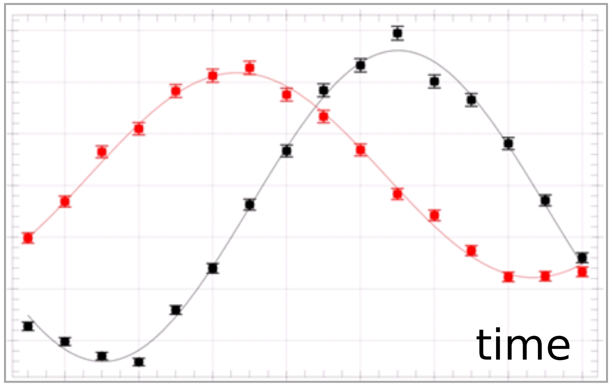
Spin Echo Measurements

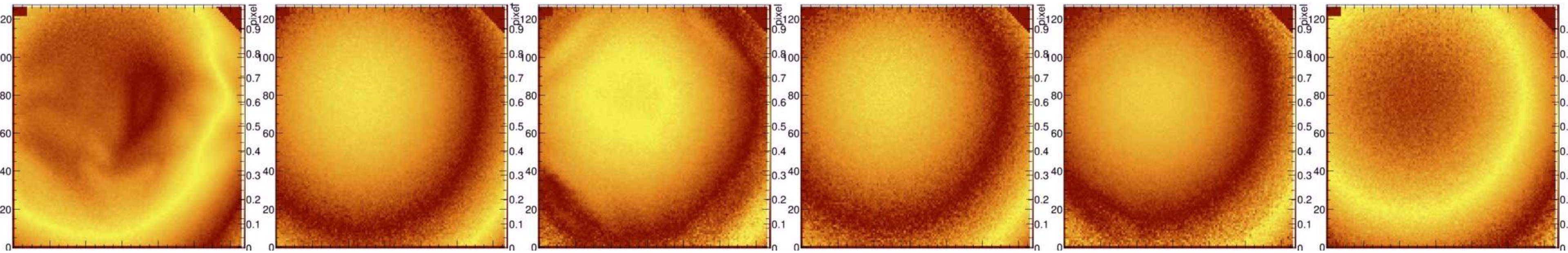


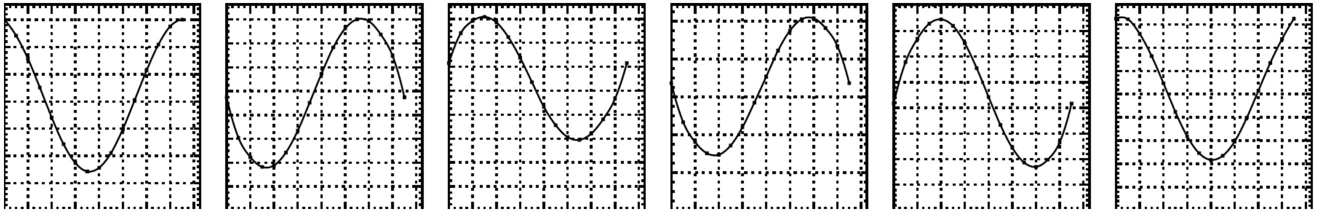


Spin Echo Measurements

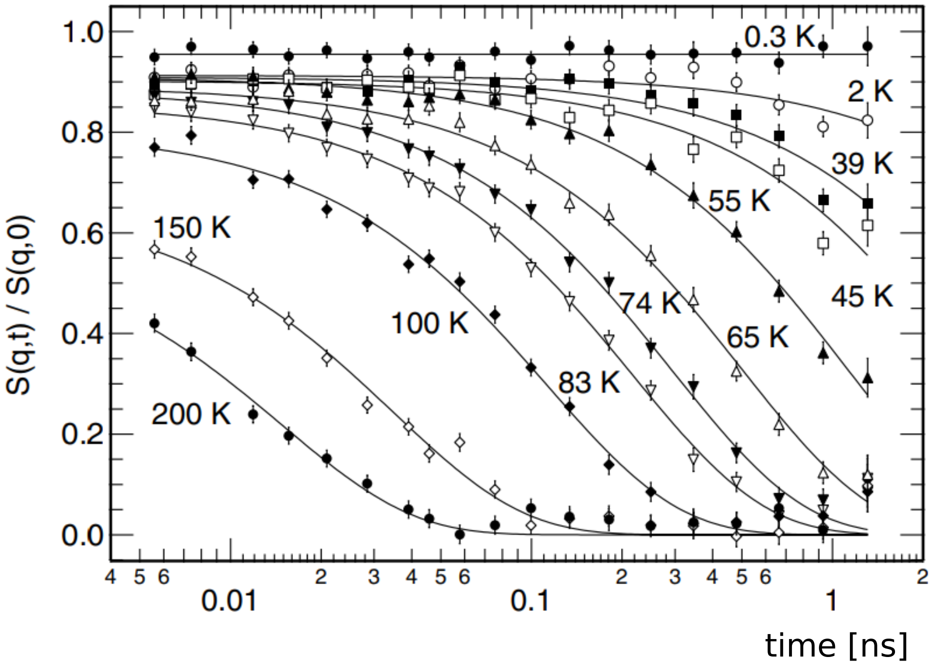
100 kHz x16







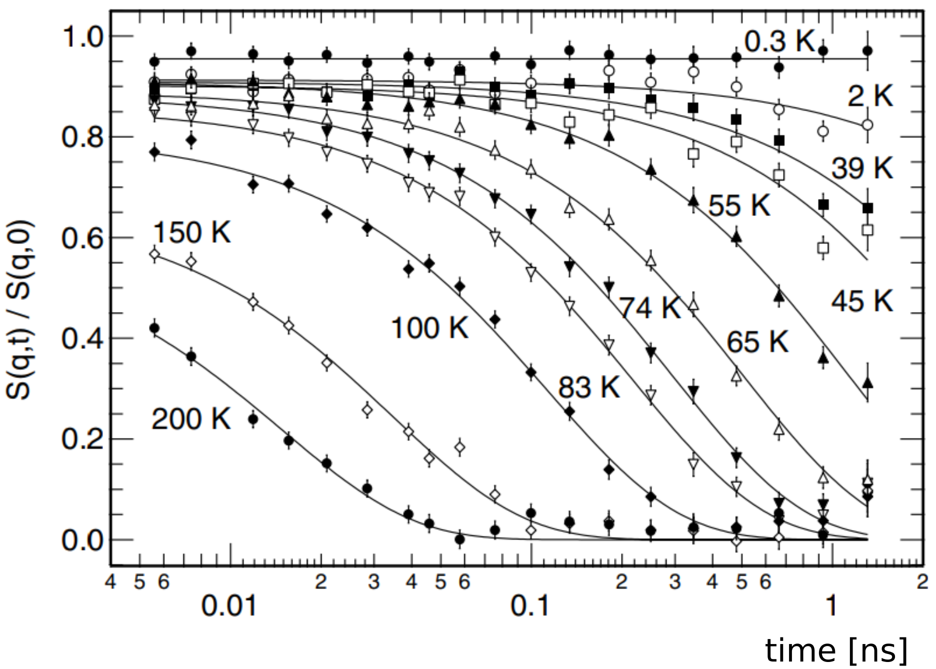
Spin Excitations: Ferromagnets



[1]

[1] G. Ehlers, et al. “Evidence for two distinct spin relaxation mechanisms in 'hot' spin ice Ho2 Ti2 O7” J. Phys.: Condens. Matter 16 (2004), S635
[2] C. Castelnovo, et al., “Magnetic monopoles in spin ice” Nature 45 (2008), 42-45
[3] M. Ruminy, et al. “Phonon-mediated spin-flipping mechanism in the spin ices Dy2Ti2O7 and Ho2Ti2O7”, PRB 95 (2017), 060414

Spin Excitations: Ferromagnets



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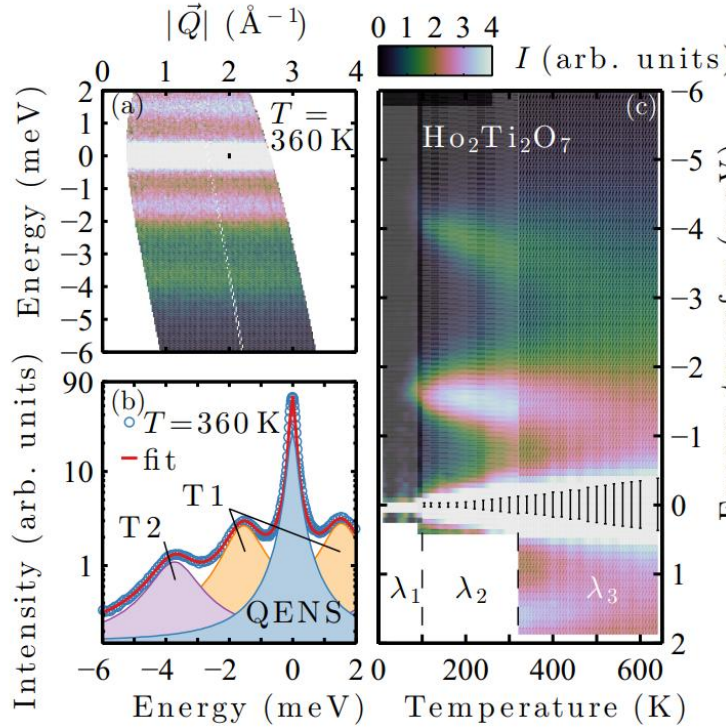
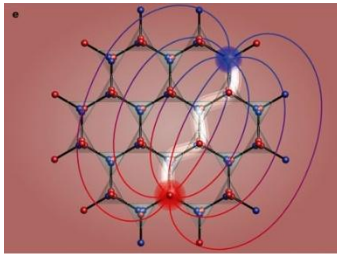


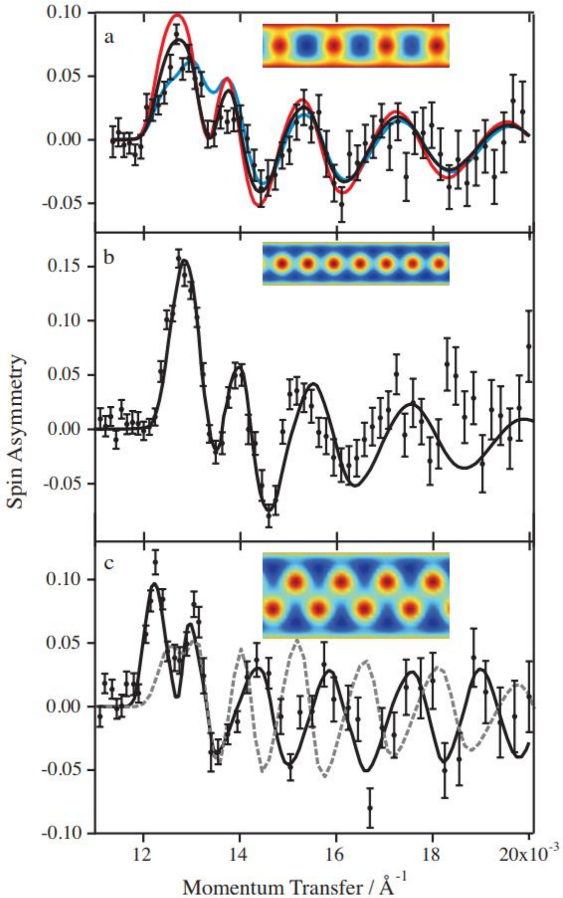
[3]


[2]

[1] G. Ehlers, et al. “Evidence for two distinct spin relaxation mechanisms in 'hot' spin ice Ho2 Ti2 O7” J. Phys.: Condens. Matter 16 (2004), S635
[2] C. Castelnovo, et al., “Magnetic monopoles in spin ice” Nature 45 (2008), 42-45
[3] M. Ruminy, et al. “Phonon-mediated spin-flipping mechanism in the spin ices Dy2Ti2O7 and Ho2Ti2O7”, PRB 95 (2017), 060414

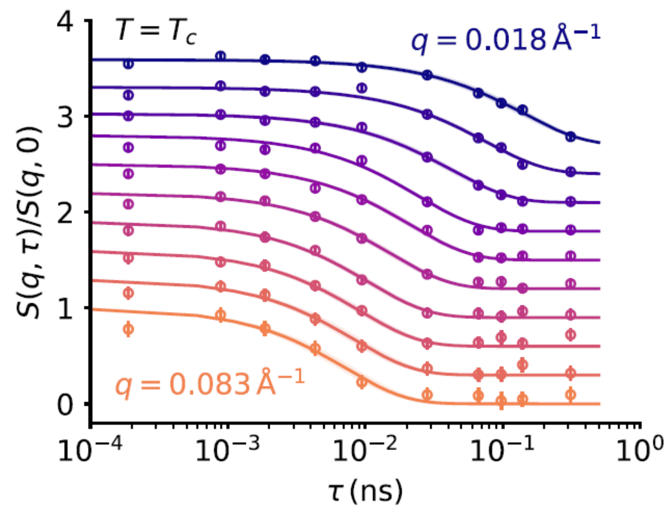
Superconductors

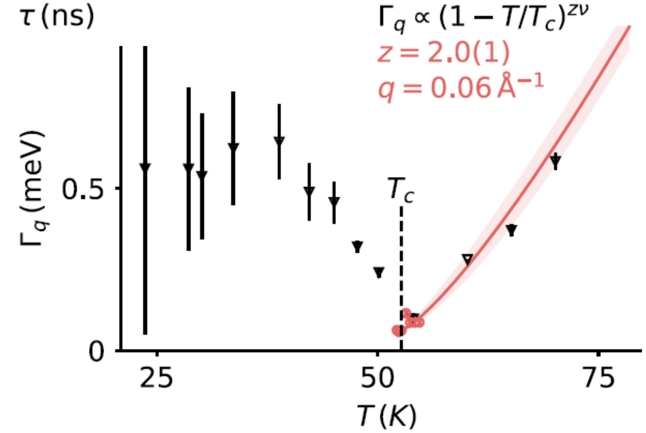
magnetic flux density



A.J. Drew, et al. “Using spin-polarized neutron reflectivity to probe mesoscopic vortex states in a Pb thin-film superconductor”, PRB 80 (2009), 134510

Spin fluctuations UGe_2





Haslbeck, et. al “Ultrahigh-resolution neutron spectroscopy of low-energy spin dynamics in UGe2”, PRB 99 (2019), 014429

On the
Macro Scales

Neutron imaging

Courtesy: PSI

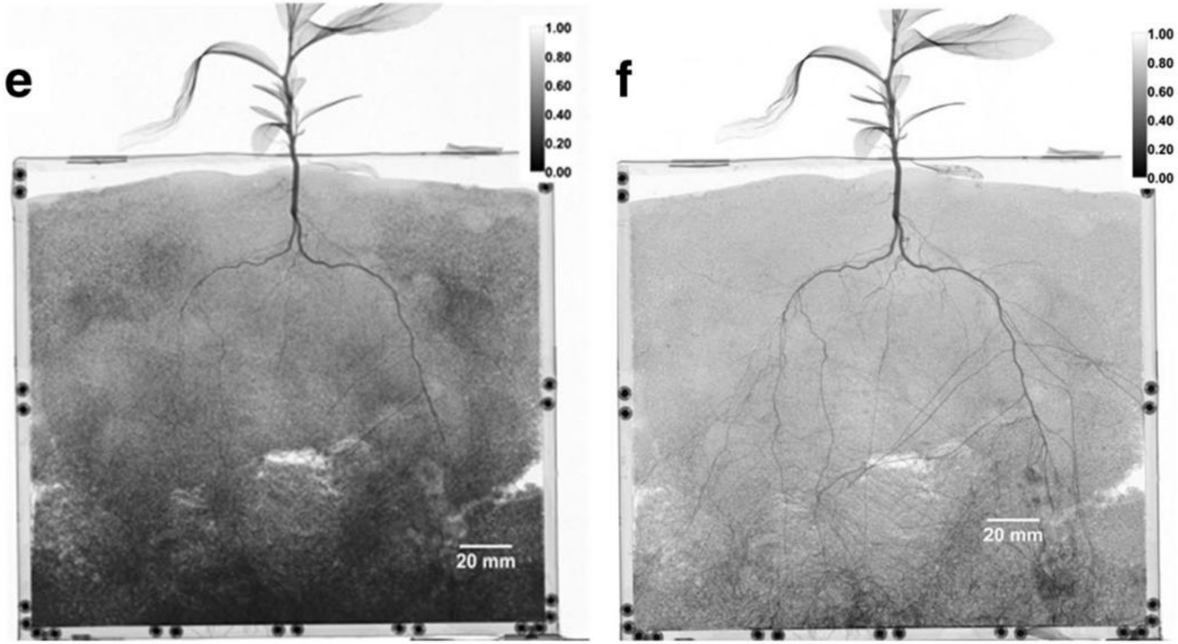
Neutron imaging

Artifacts of cultural heritage

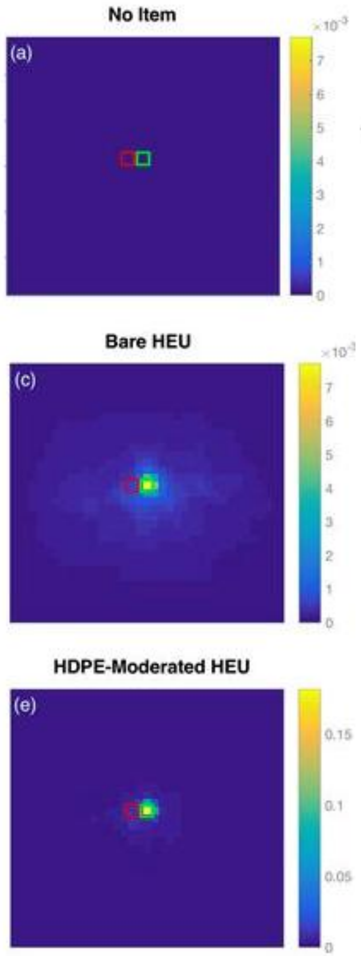
E. Lehmann "Neutron imaging — Detector options in progress", Journal of Instrumentation 6(01) (2011) C01050

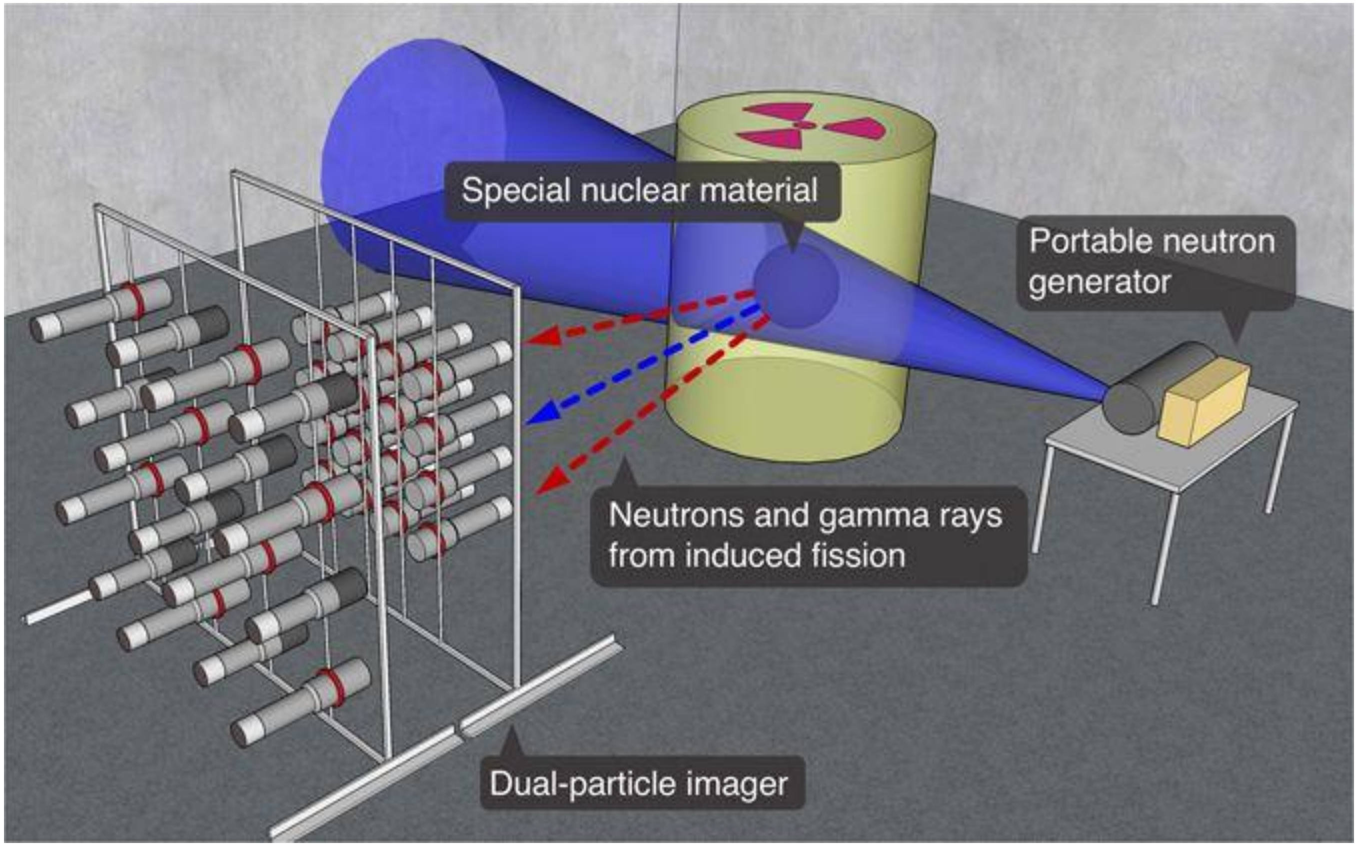
I. Dhiman, et al. "Quantifying root water extraction after drought recovery using sub-mm in situ empirical data", Plant Soil 424(1-2) (2018), 73-89

Water uptake in plants



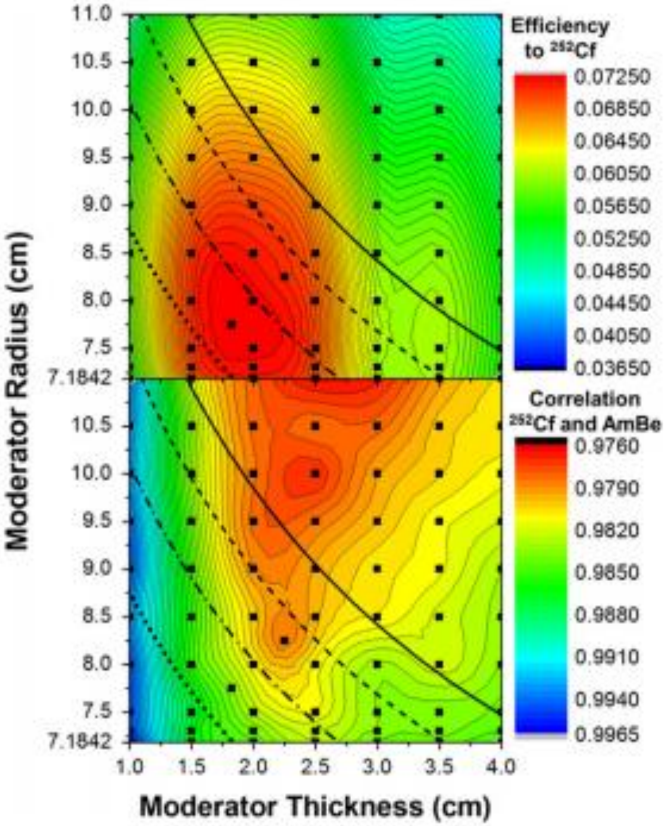
Non-proliferation

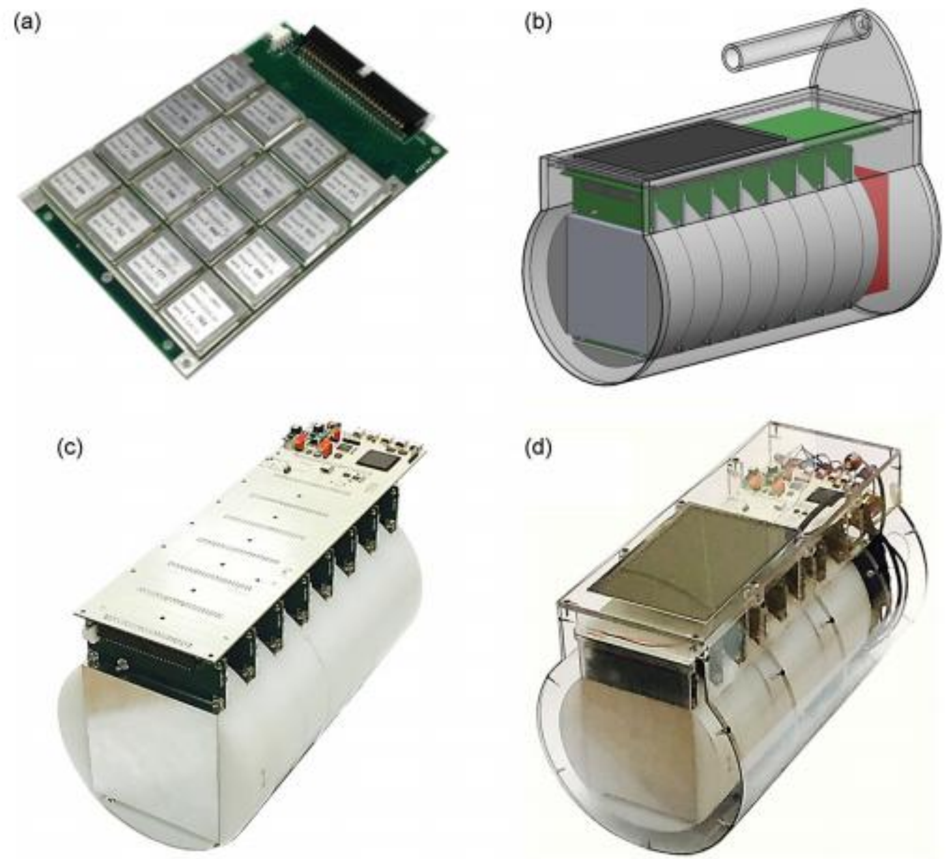




M.C. Hamel et al. "Active neutron and gamma-ray imaging of highly enriched uranium for treaty verification", Scientific Reports 7 (2017), 7997

Non-proliferation II

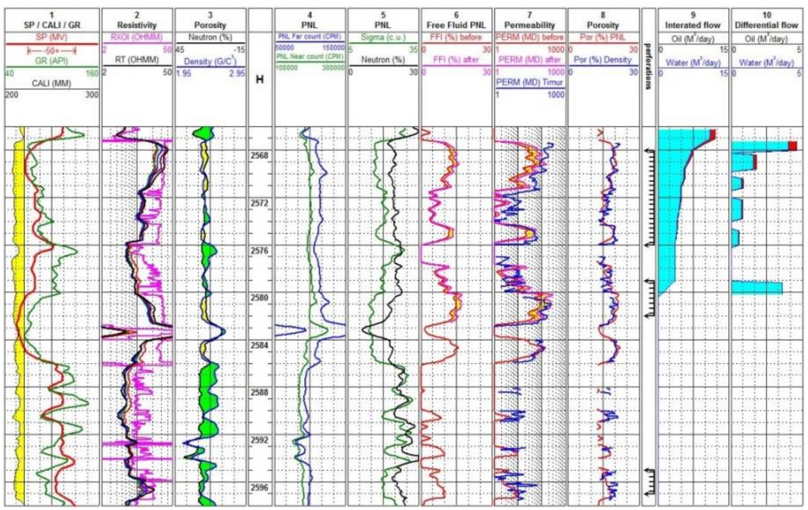




C.B. Hoshor et al. “A portable and wide energy range semiconductor-based neutron spectrometer”, NIM A 803 (2015), 68-81

Neutron Porosity determination

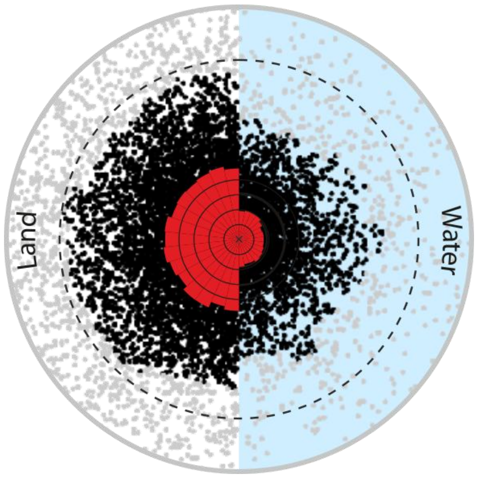
Downhole tool

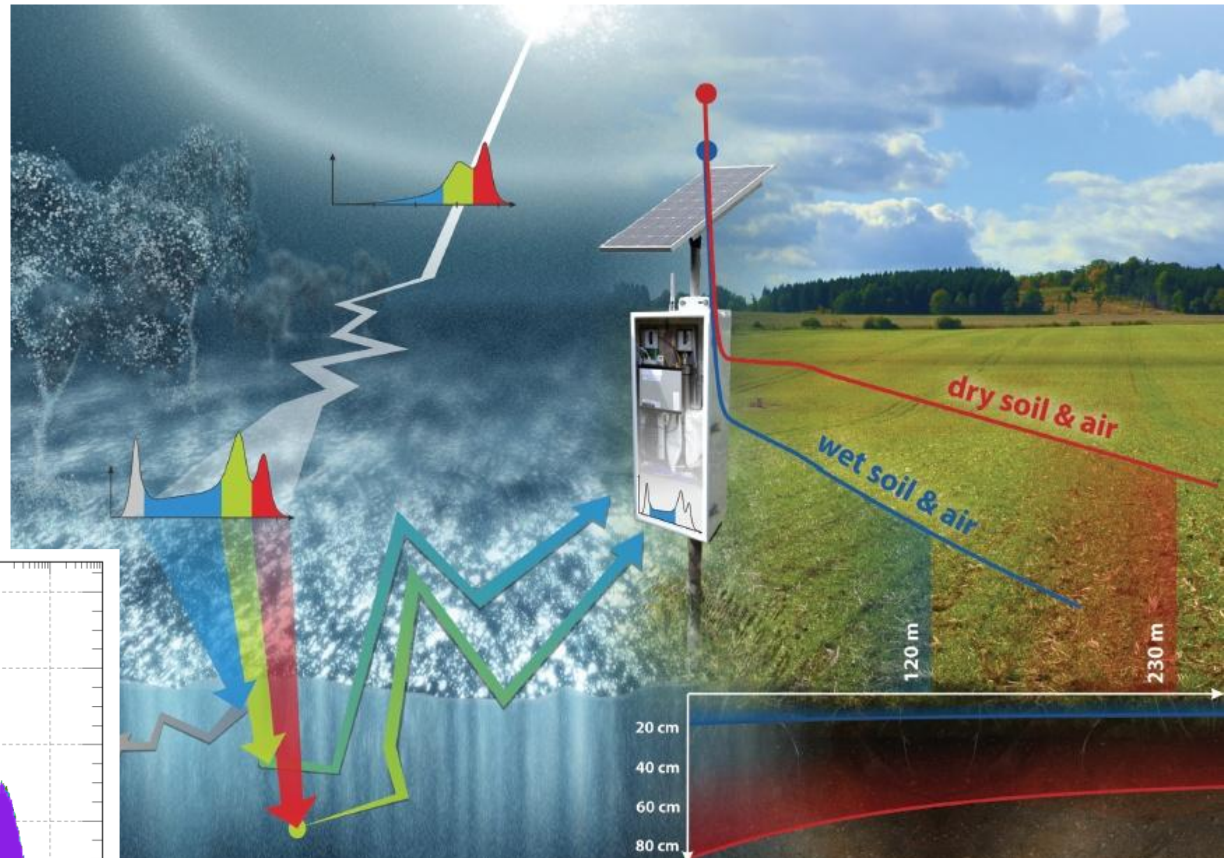


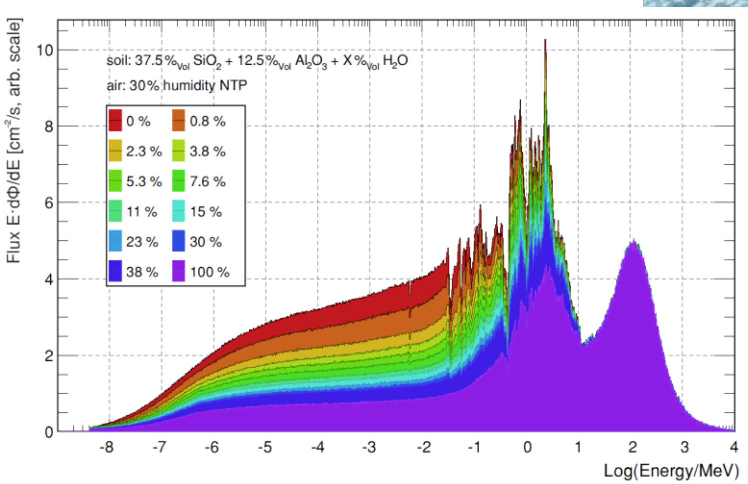
Troxler probe

https://www.apnga.com/industry-info/gauge-basics/
http://www.kngf.org/library/article/article.php?ID=2248

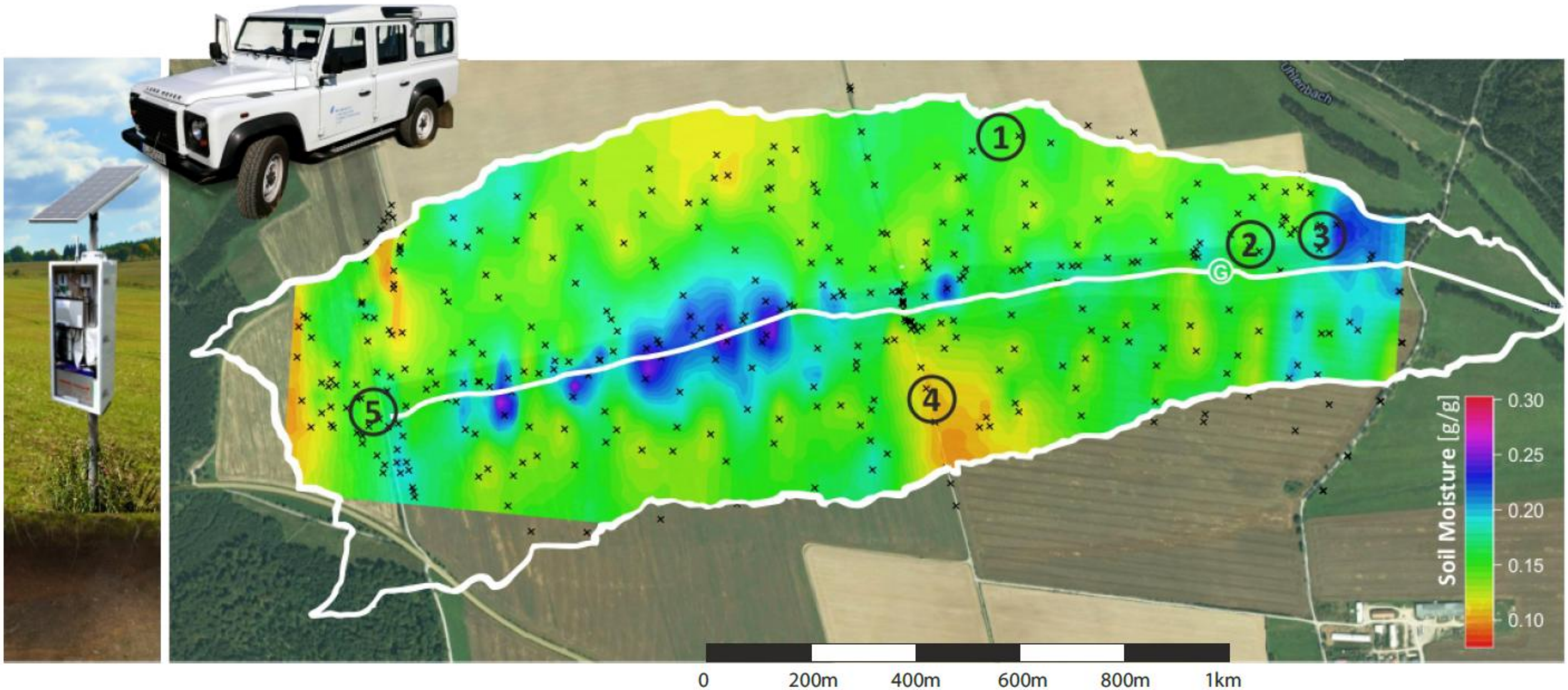
Cosmic-Ray Neutron Sensing



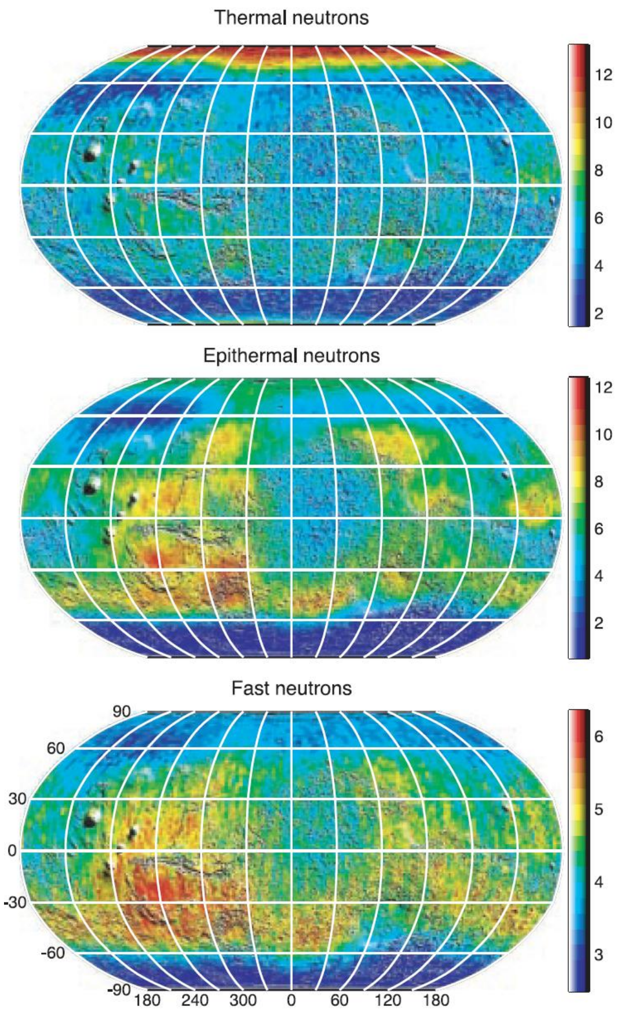




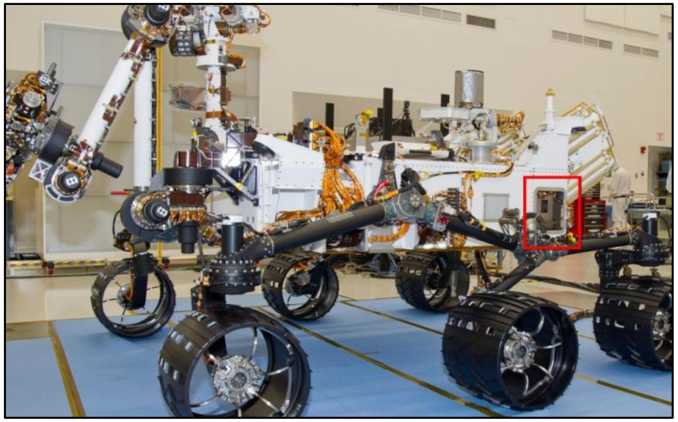
Cosmic-Ray Neutron Sensing

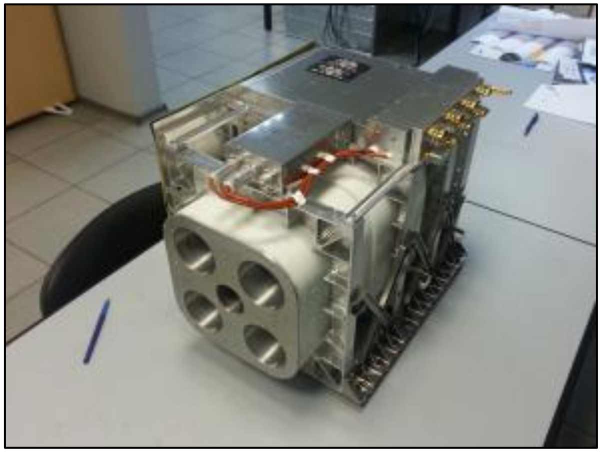


Water on Mars



Curiosity Rover

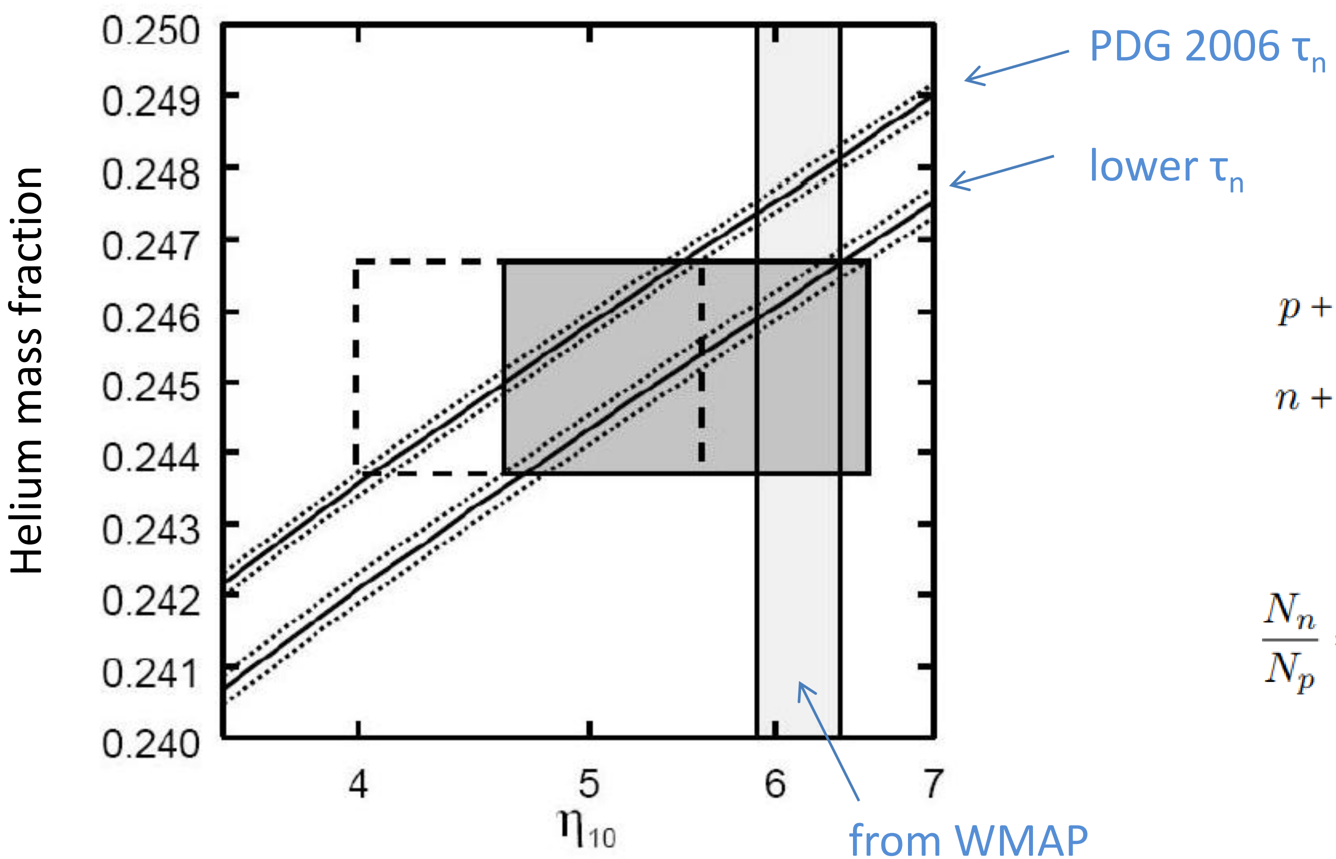




Trace Gas Orbiter

W.C. Feldman, et. Al „Global Distribution of Neutrons from Mars: Results from Mars Odyssey“, Science 297 (5578) (2002), 75-78.
http://exploration.esa.int/mars/48523-trace-gas-orbiter-instruments/?fbodylongid=2217
https://www.nasa.gov/mission_pages/msl/news/msl20111020.html

Nucleosynthesis



Baryon fraction

$$p + e^- \rightleftharpoons n + \nu_e$$

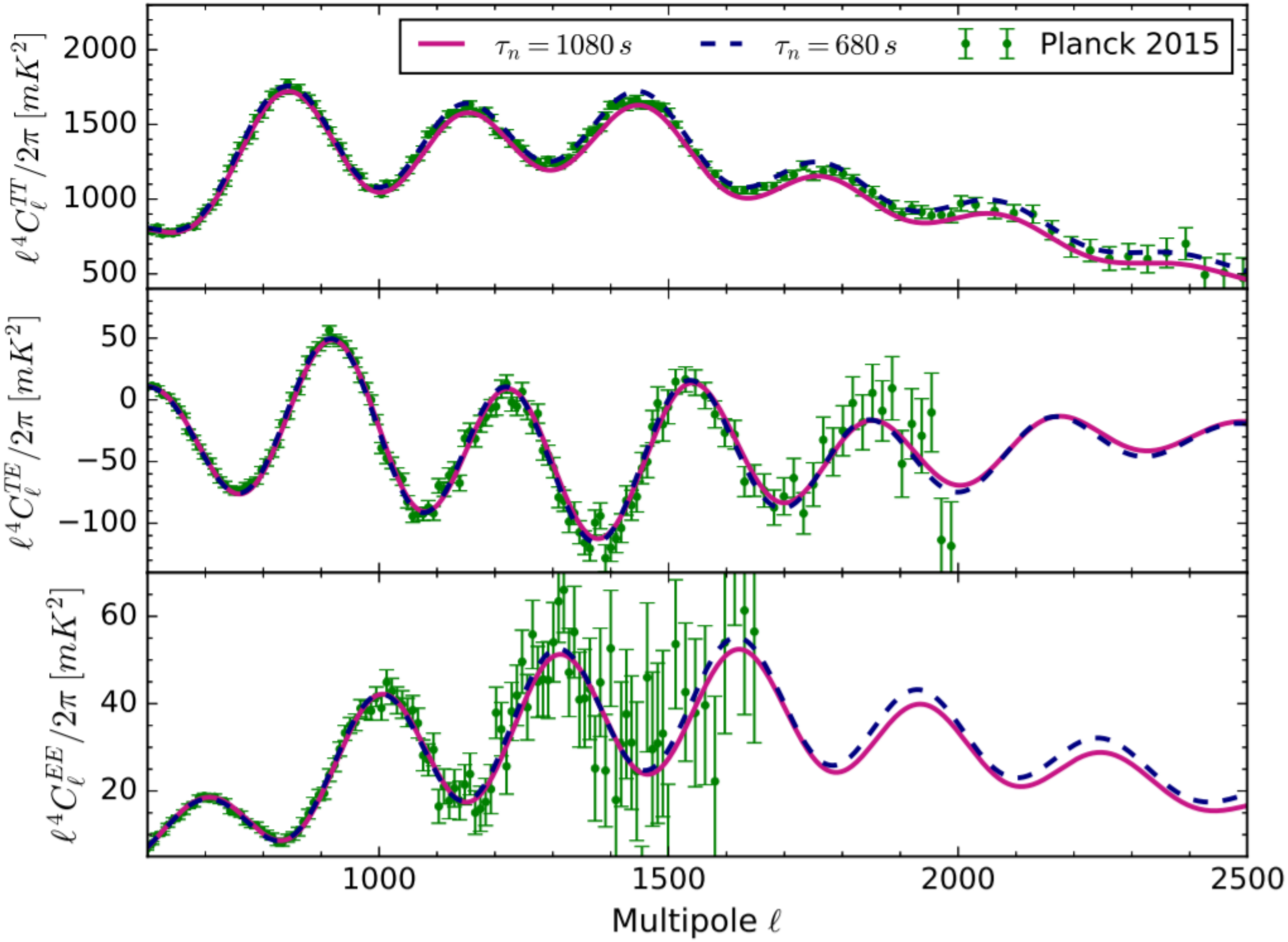
$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$\frac{N_n}{N_p} = \exp\left(-\frac{\Delta m}{T_f}\right)$$

pp fusion (…CNO cycle)

A. P. Serebrov et al., Phys. Lett. B 605 (2005) and S. Paul " The Puzzle of Neutron Lifetime" arXiv:0902.0169v2 (2009)

Nucleosynthesis



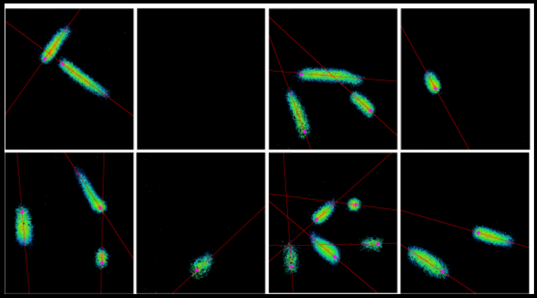
L. Salvati et al. „ Cosmological constraints on the neutron lifetime“, JCAP03(2016)055

Novel Neutron Detectors

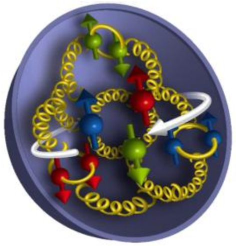
derived from developments of particle physics

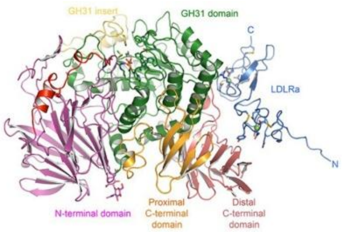
Boron-10 as the dominant alternative

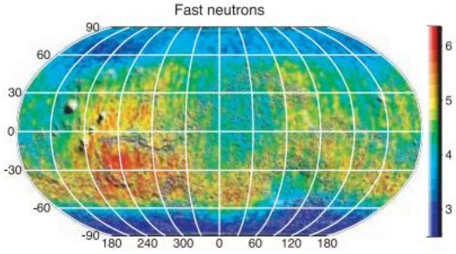
high rate, spatially and time resolved detectors, especially for the ESS



Neutron Science Scales







Neutron Detectors
probing nano and macro scales

Particle Physics Colloquium
April 18th 2019

Physikalisches Institut

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Rheinische Friedrich-Wilhelms Universität Bonn

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