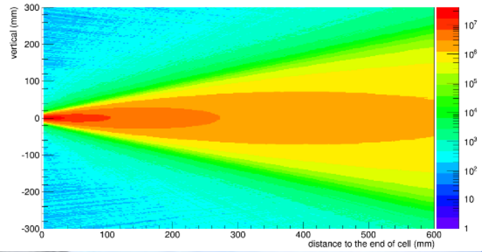
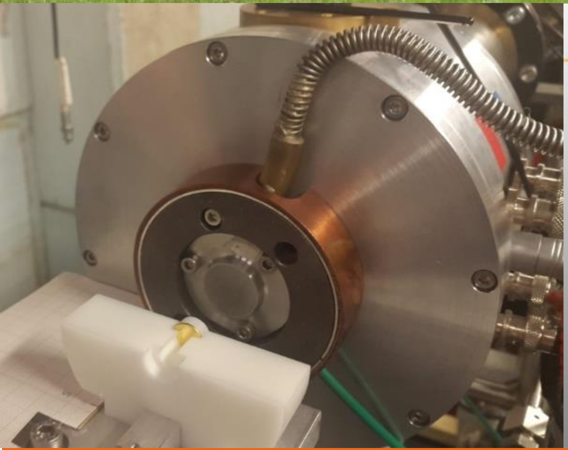
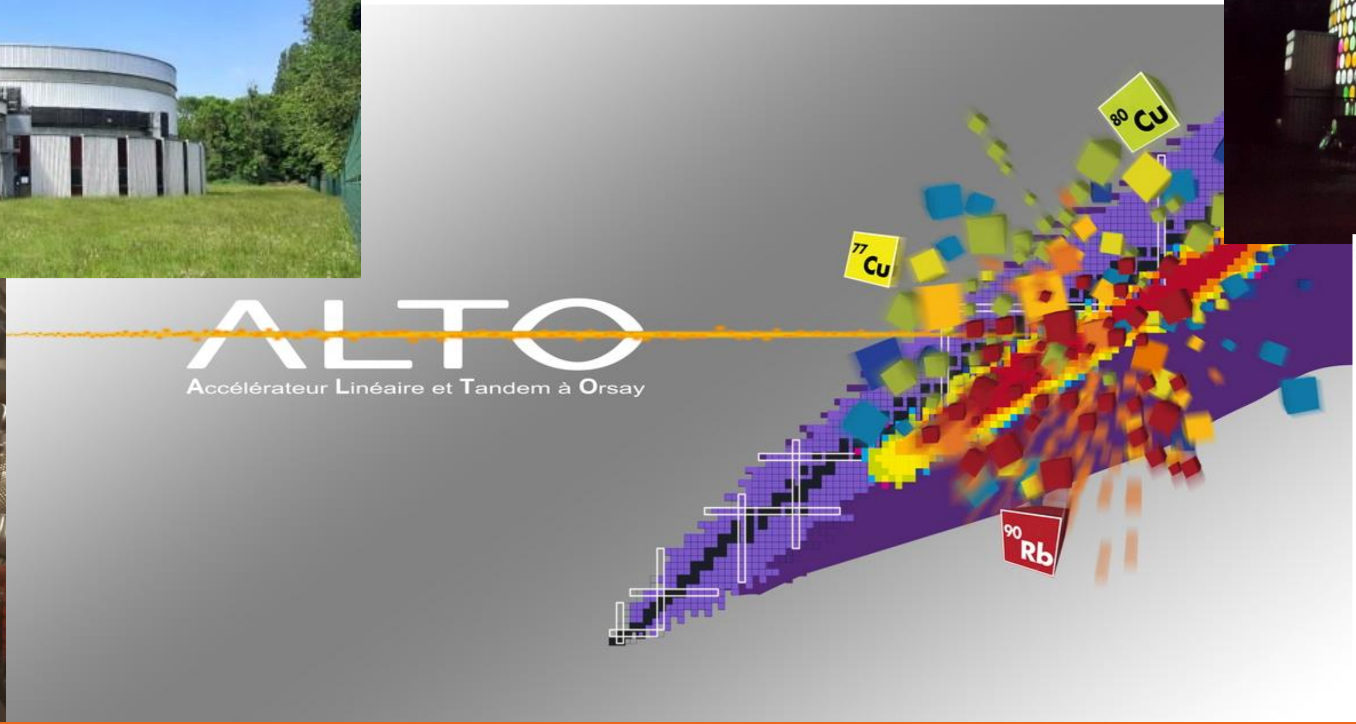
The LICORNE inverse kinematic neutron source

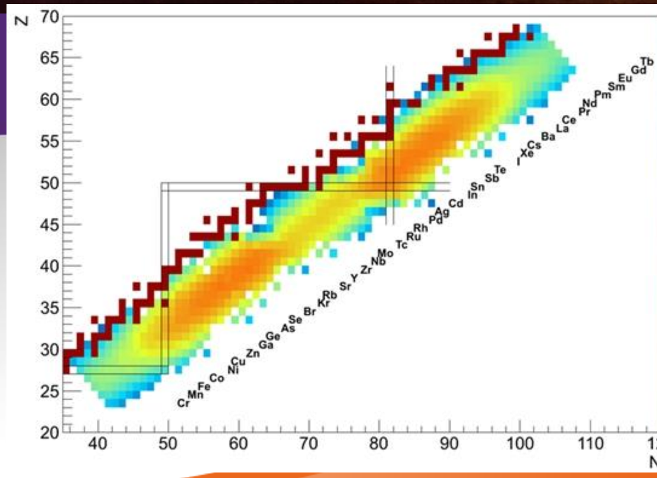


Development and perspectives

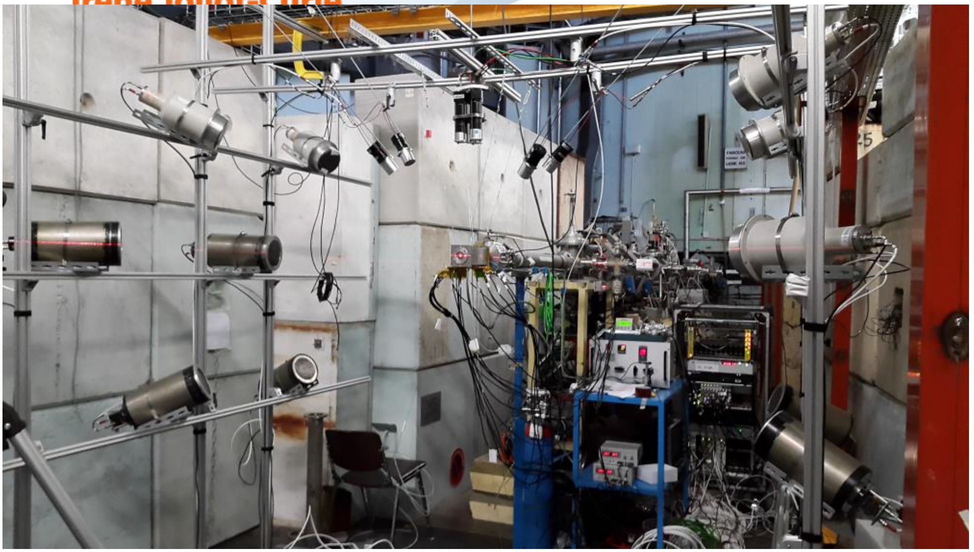
J.N. Wilson, IJC Lab Orsay

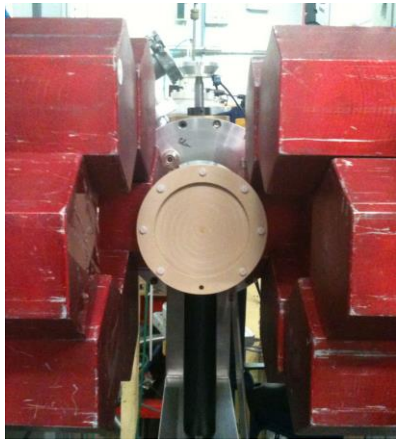






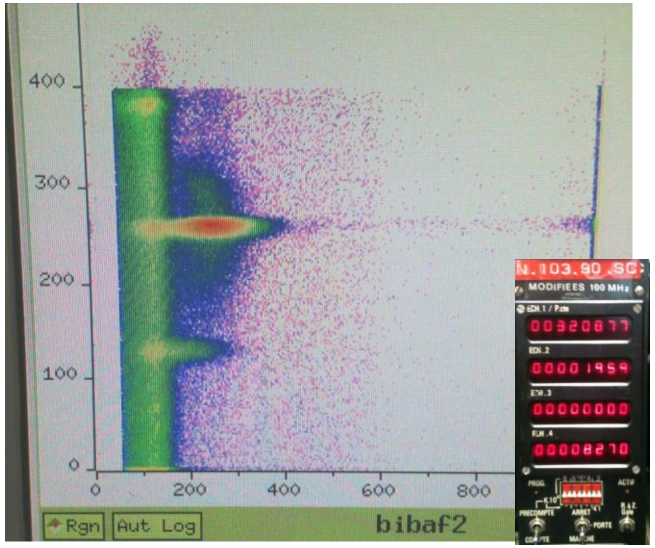
10 years of LICORNE@ALTO

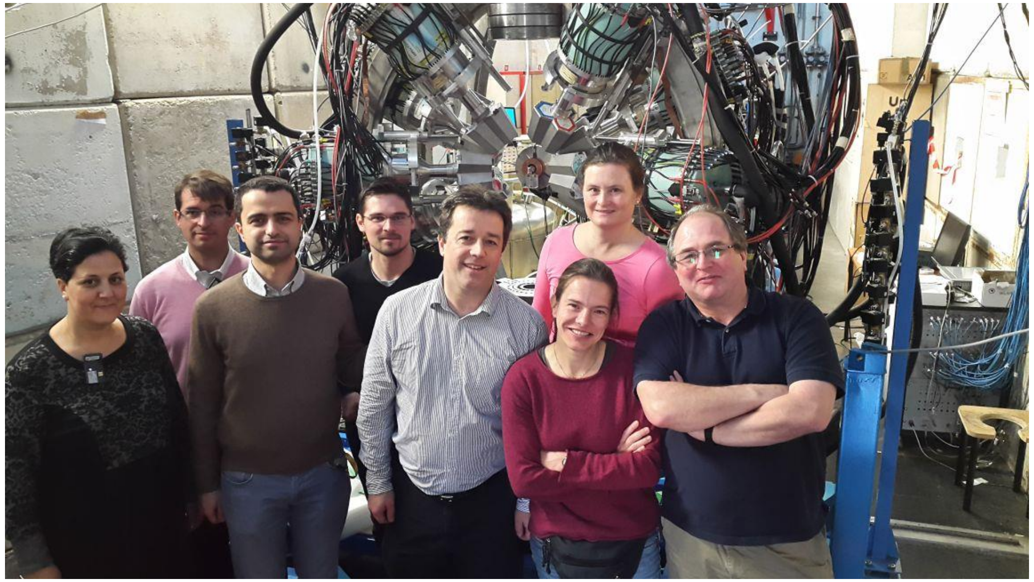




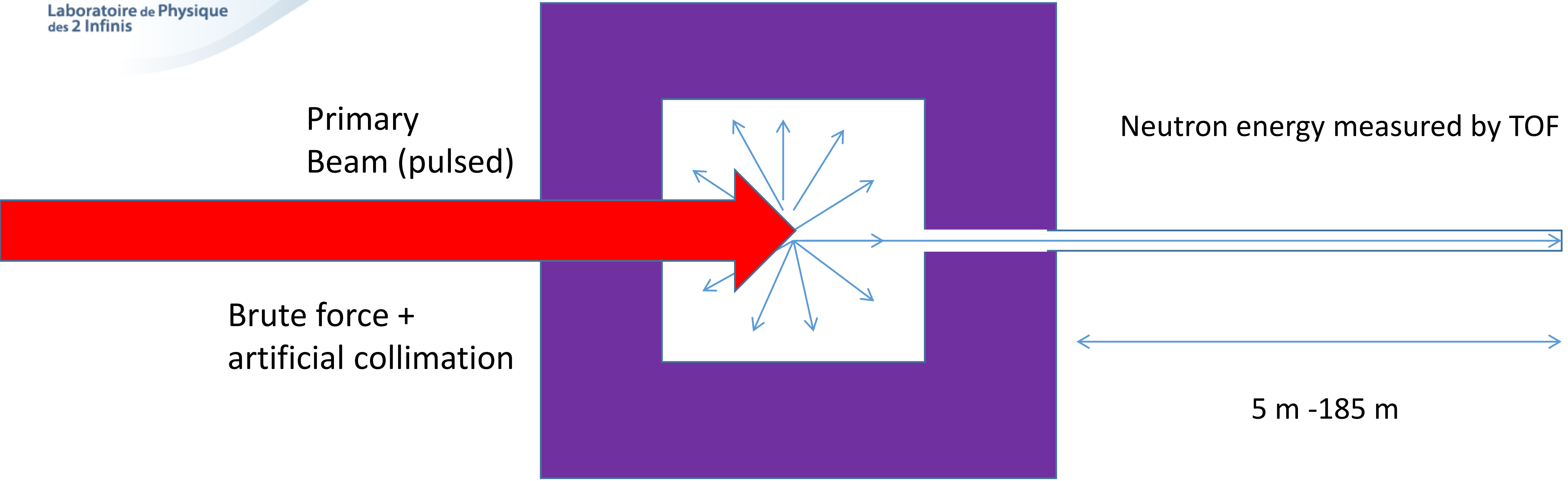
- Study of prompt emission in fission
- Fast neutron tomography
- Dark matter TPC tests

(33 publications, 8 Ph.D theses since 2013)





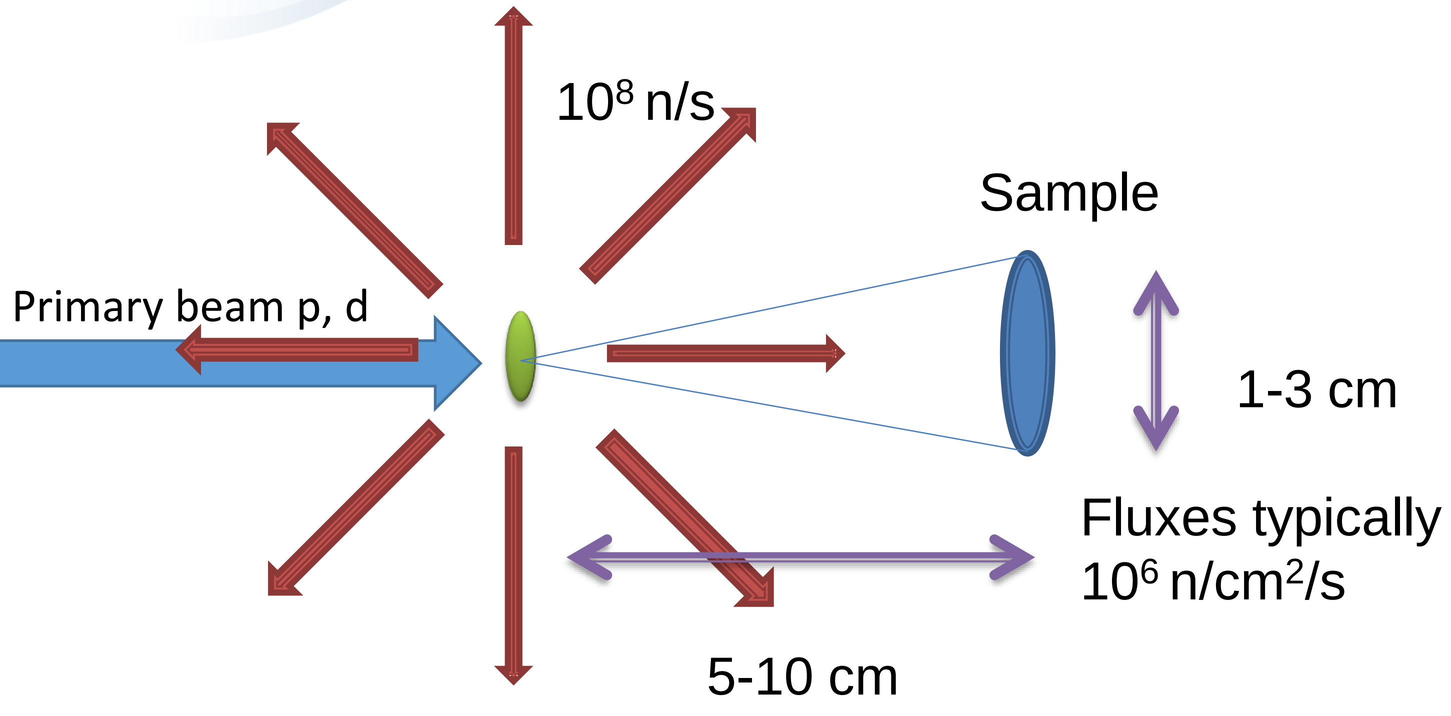
Accelerator based neutron sources (white sources)



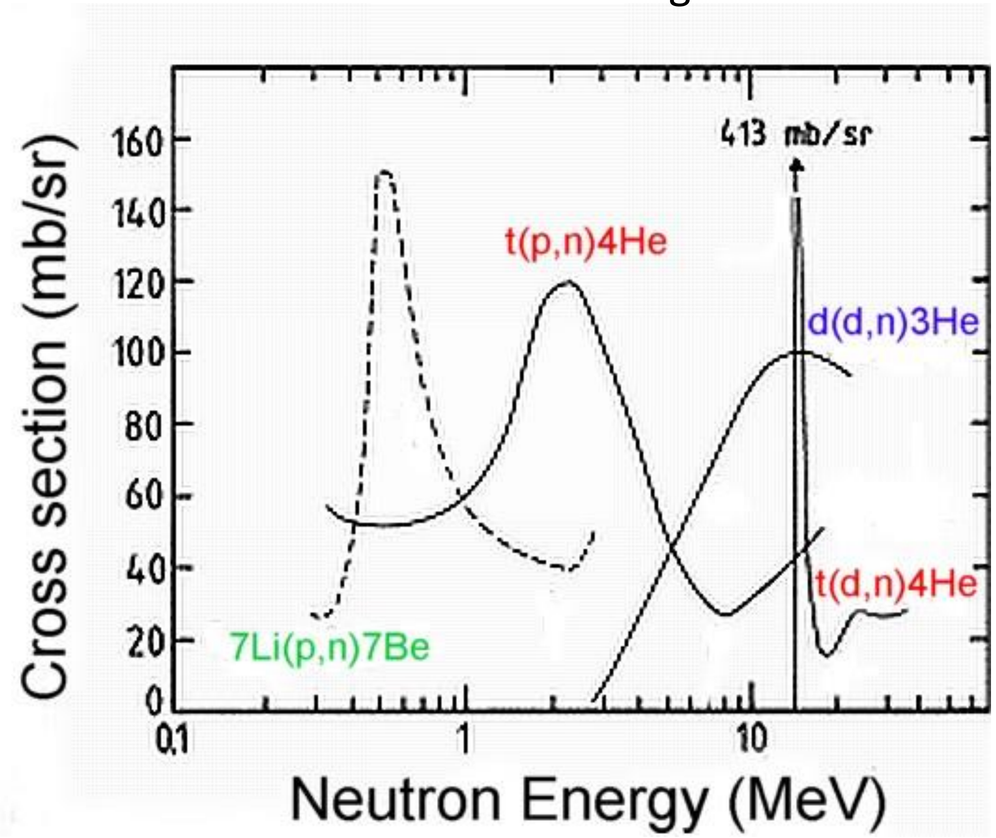
Lab	beam	reaction	n/s	Sample distance
Gelina (Geel)	100uA e- (100 MeV)	Photofission 238U	10^{13}	10 – 50 m
nTOF (CERN)	100uA p (24 GeV)	Pb spallation	10^{15}	185 m
NFS (Spiral2)	1mA deuterons	Breakup 9Be	10^{13}	5 - 20 m

Thick target

Accelerator based neutron sources (mono-energetic)

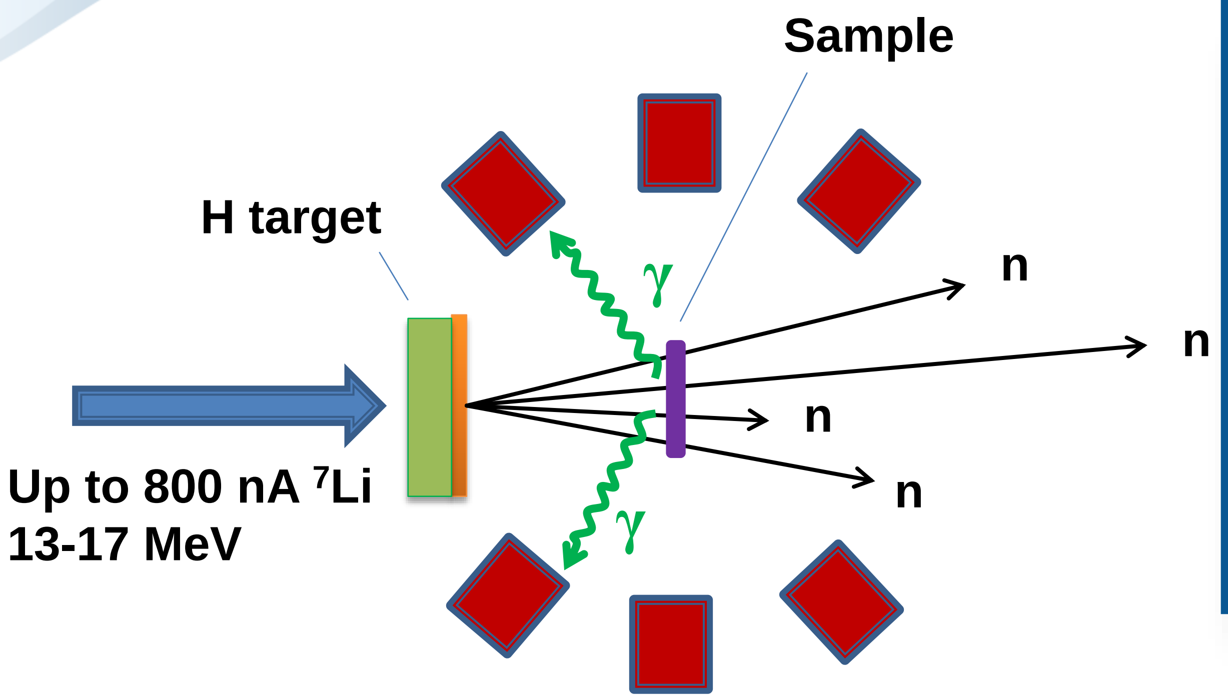


Direct reactions on light nuclei



- Typically over 99% of neutrons ''wasted''
- Wasted neutrons contribute to the room background
- Placement of sensitive detectors impossible without heavy shielding

Neutron production in inverse kinematics



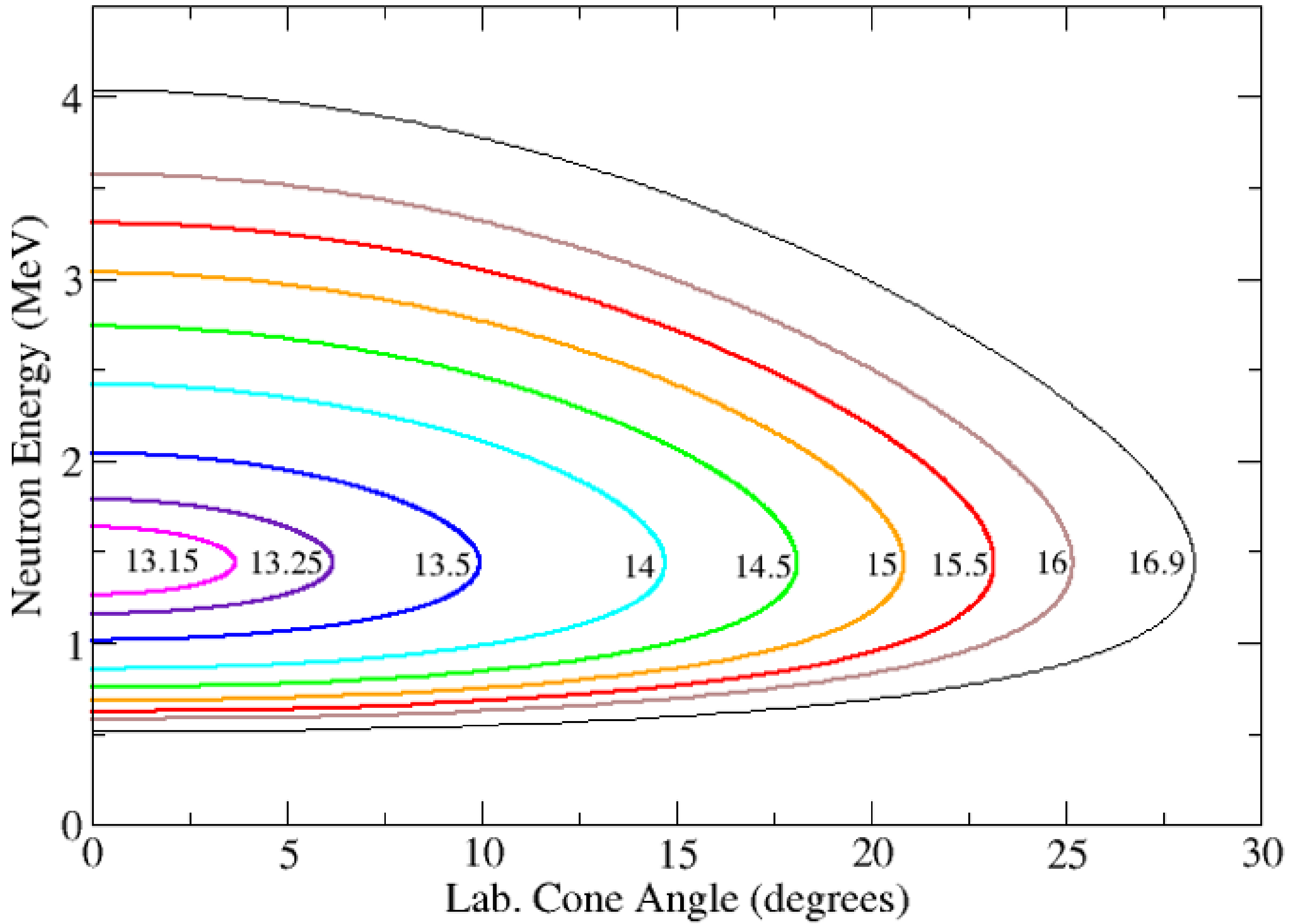
ALTO 15 MV
Tandem accelertor

Lithium Inverse Cinematiques ORsay NEutron source

- p(^{7}Li,^{7}Be)n reaction in inverse kinematics
- Kinematic focusing increases flux by a factor of 10 - 30
- Low room background, since highly non-isotropic emission
- Quasi-monoenergetic fast neutrons between 0.5 and 4 MeV

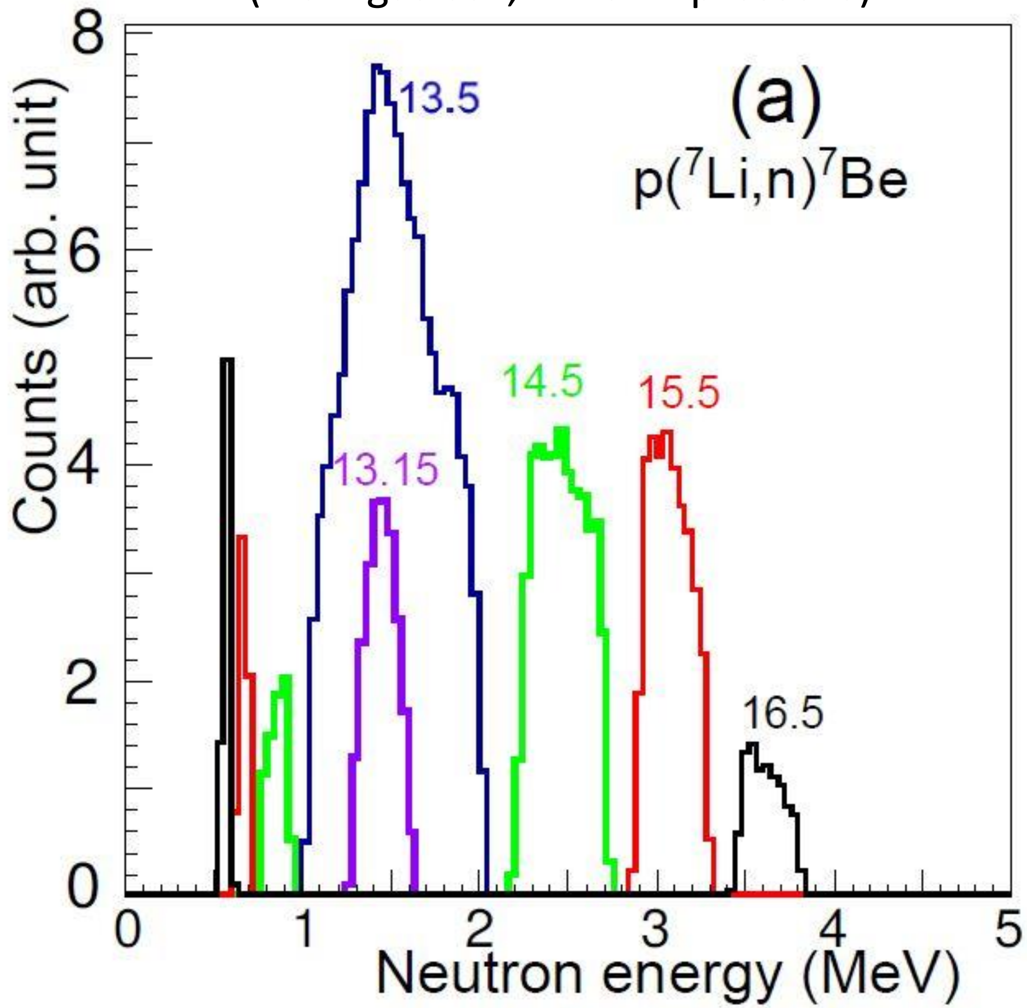
LICORNE: Quasi-monoenergetic mode

Varying the ^7Li beam energy and H_2 target thickness allow control of the neutron spectrum

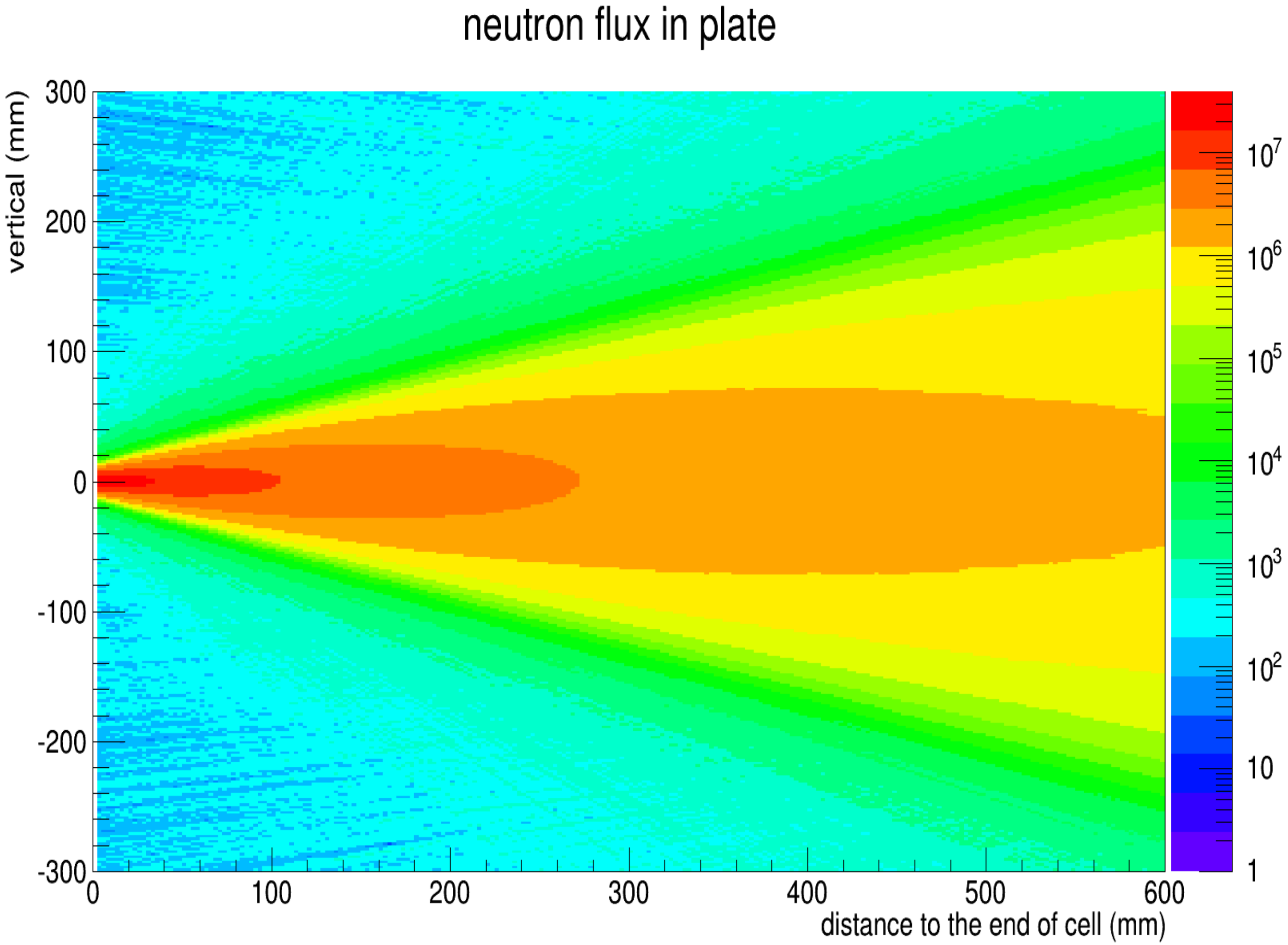


"Thin" H_2 target

(2 cm gas cell, 1.1 atm pressure)



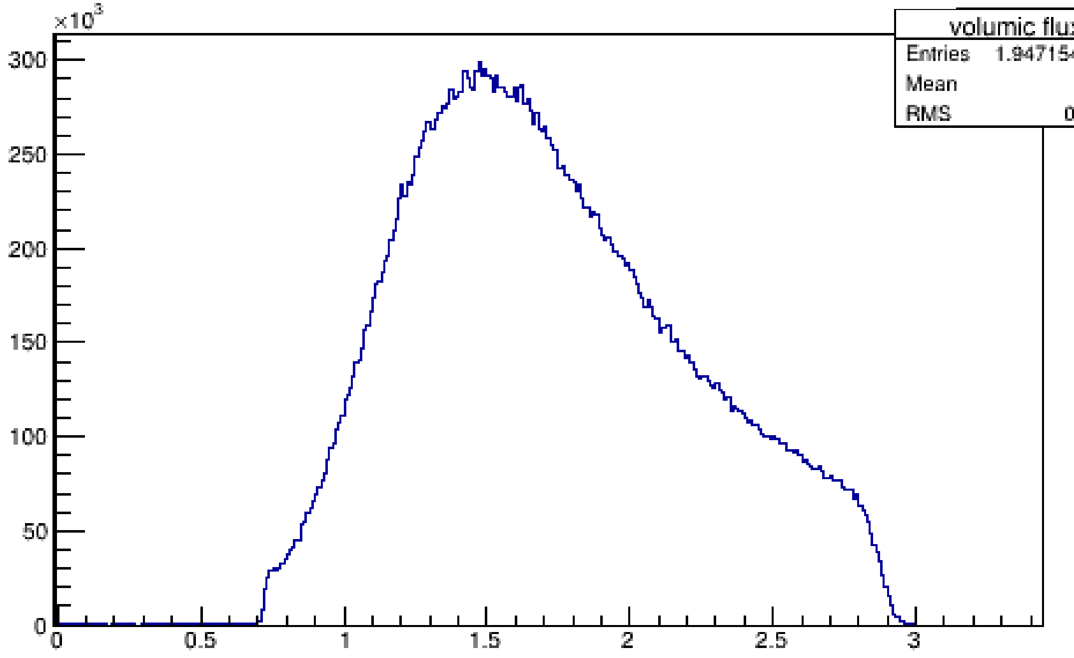
LICORNE: White source mode



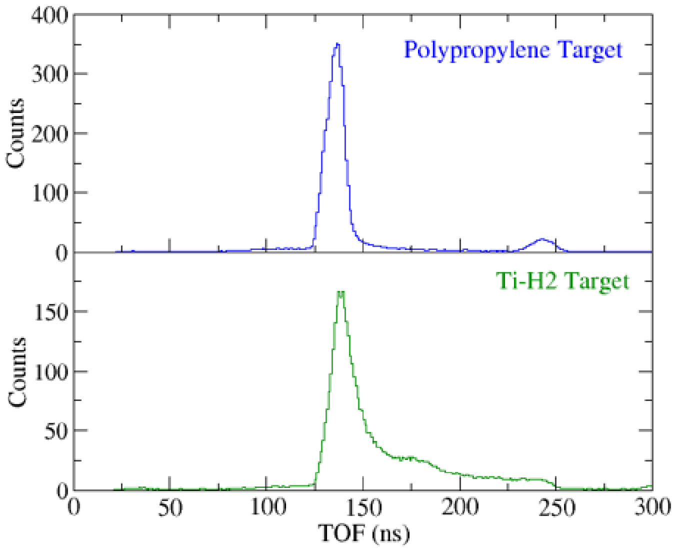
Thick H_2 target

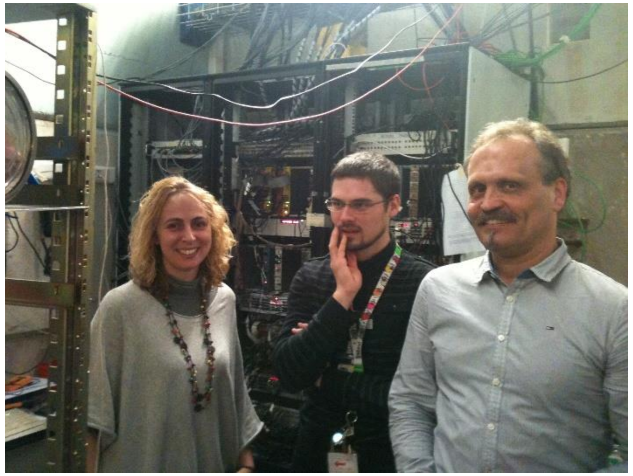
(3.5 cm gas cell, 1.6 atm pressure)

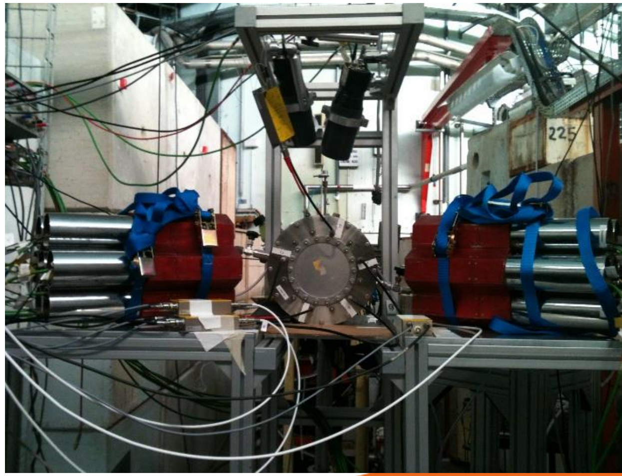
Neutron spectrum at zero degrees



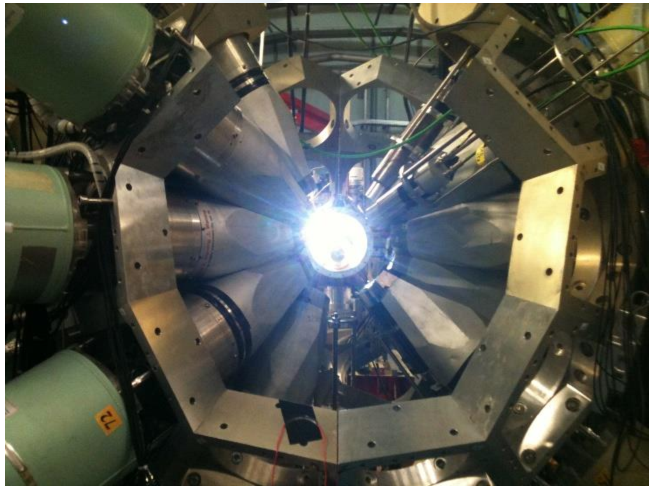
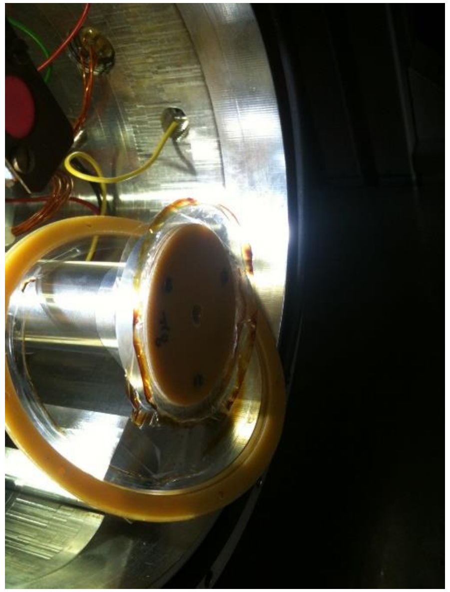
LICORNE development (2012 – 1014)



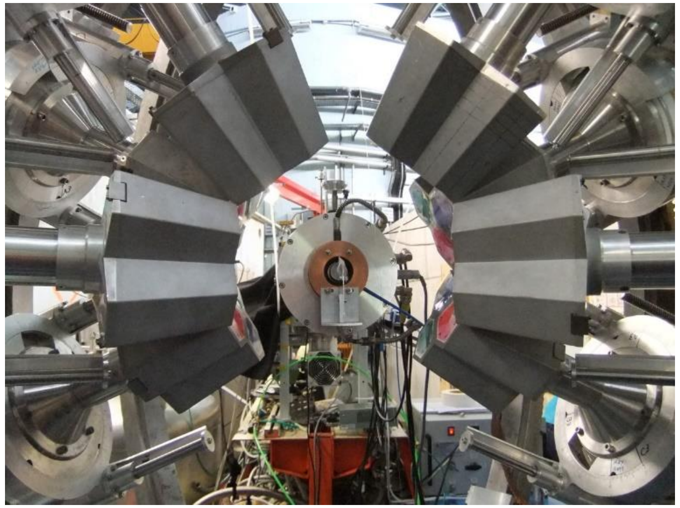


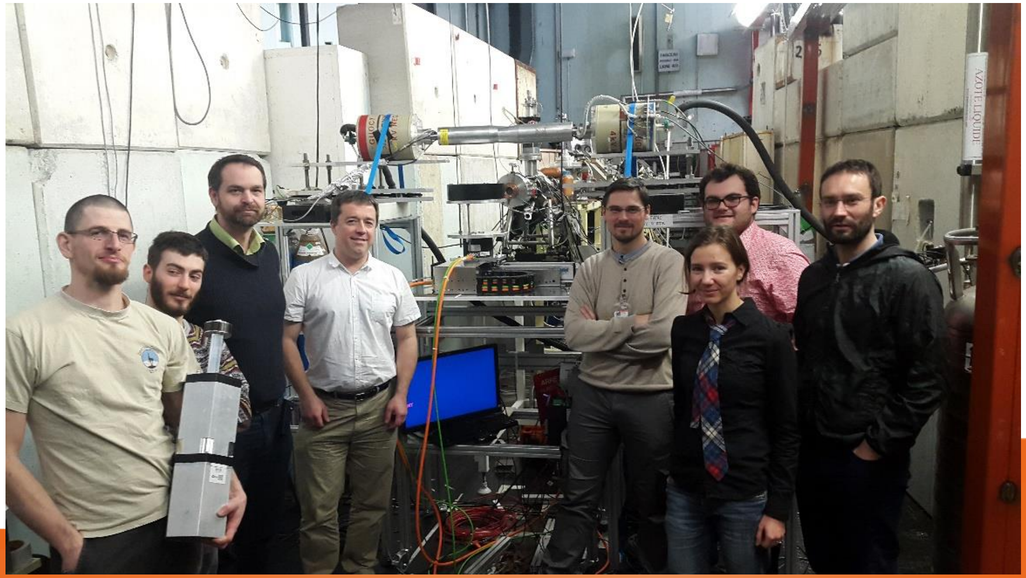


LICORNE development (2014 – 2016)

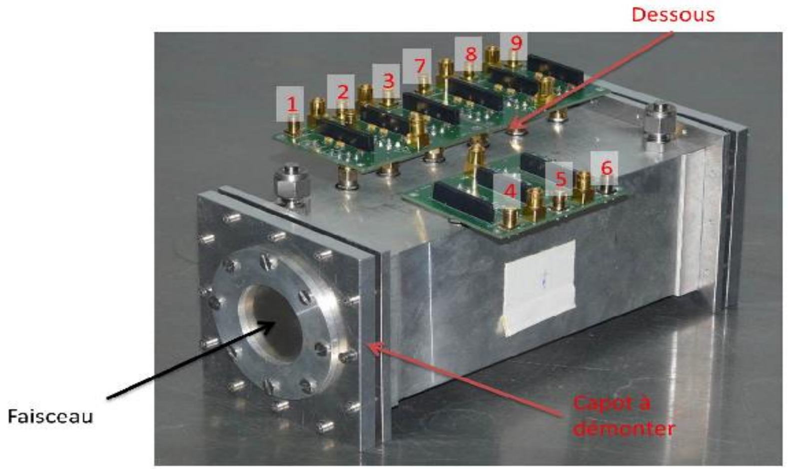
Flux
>10^7 n/s

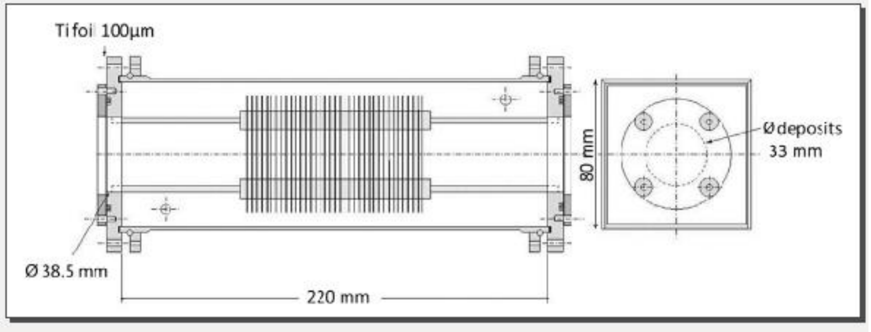





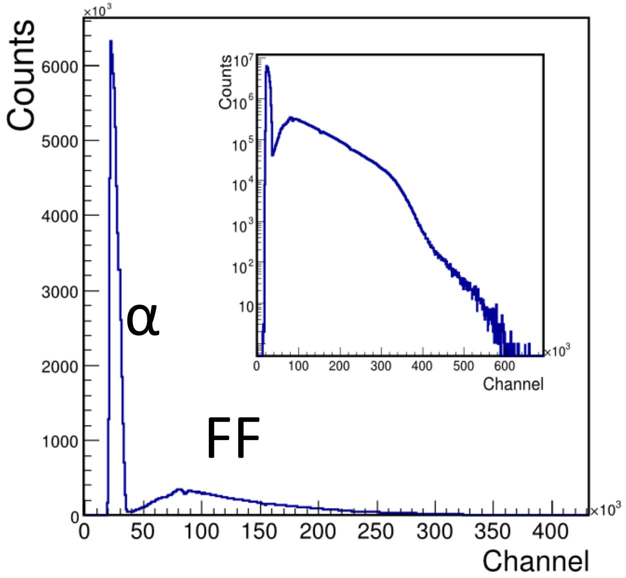
Coupling neutron beams with Ionization chambers

CEA/DAM ^{238}U chamber





- Good alpha-fission fragment discrimination: <2%
- Good Time resolution: <1ns
- Efficiency: ~100%
- 360mg ^{238}U in 72 deposits



Fission– alpha discrimination

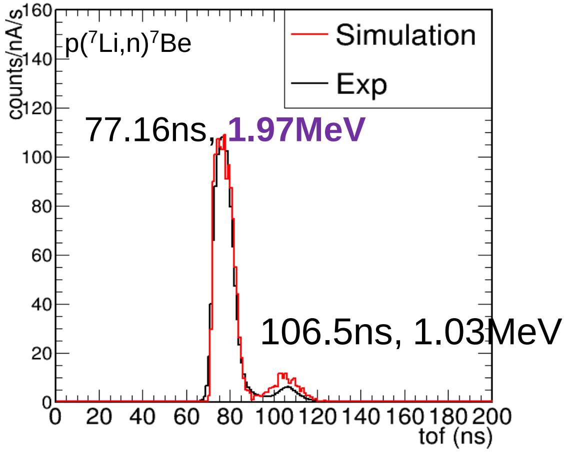
Ionisation chamber, JRC-Geel
S. Oberstedt et al.

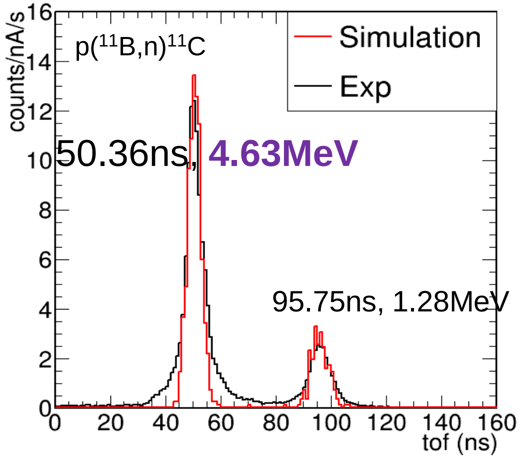
J. Taieb et al, Nuclear Instruments and Methods in Physics Research A 833 (2016) 1-7

Prompt fission gamma ray spectra measurements

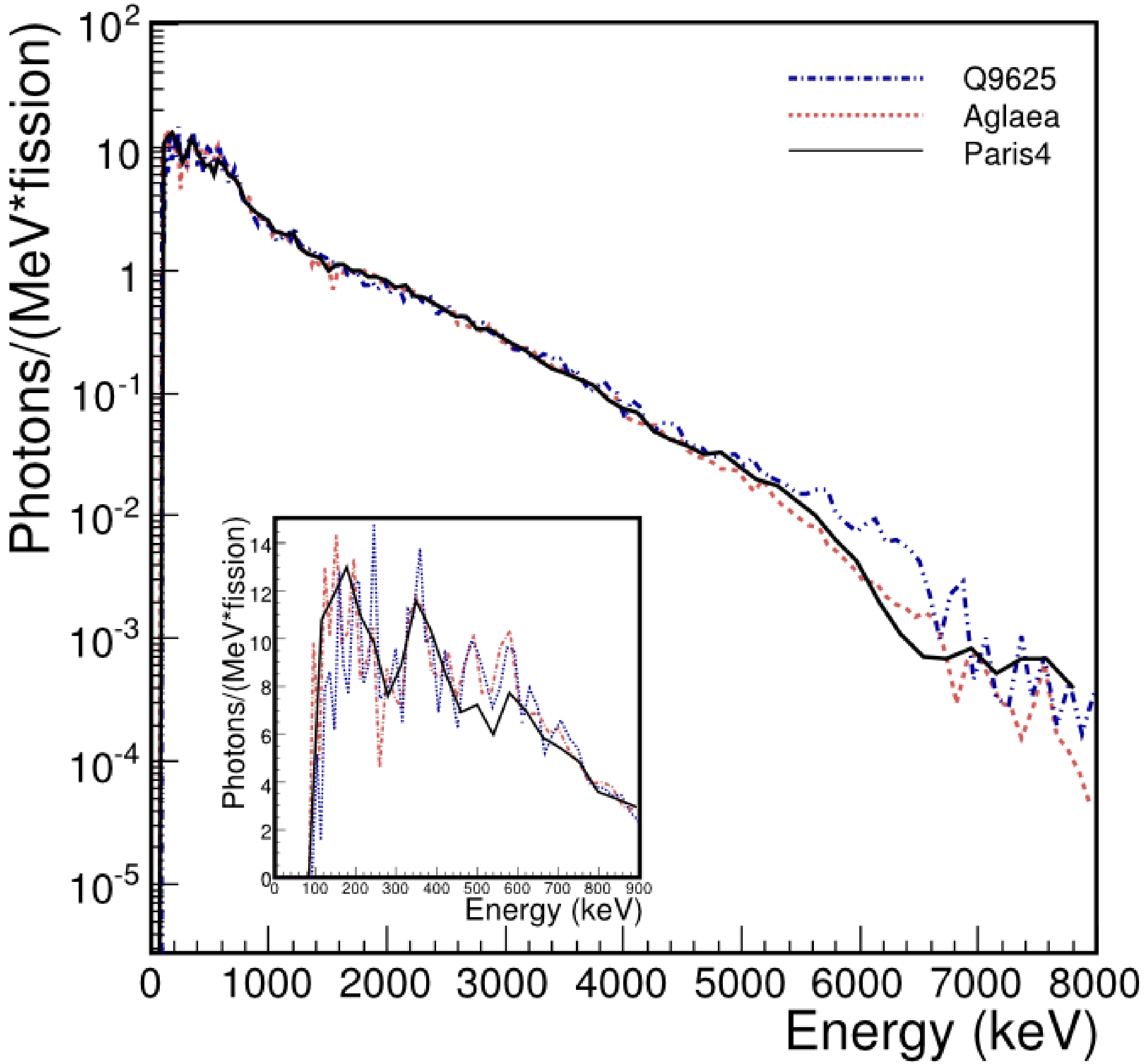
Use of the first PARIS cluster

Measurementrs at two neutron energies





Prompt fission gamma ray spectra measurements



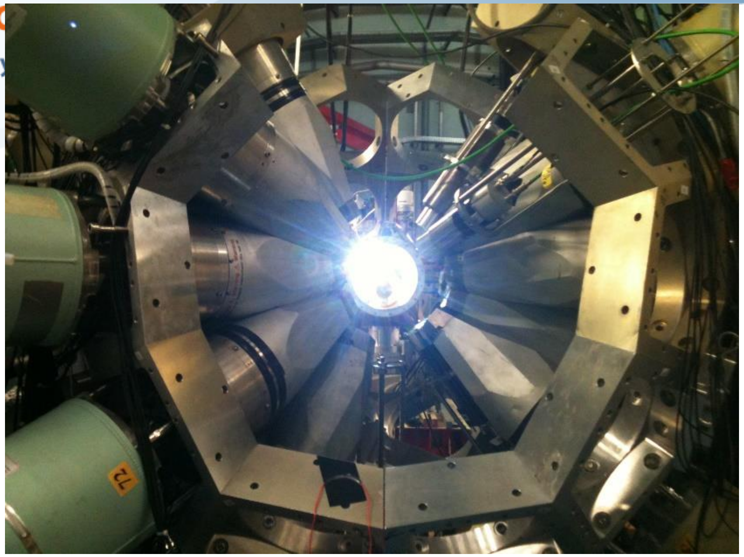
Prompt γ-ray characteristics from 235U(n, f) at En= 1.7 MeV
A. Oberstedt, M. Lebois, S. Oberstedt, L. Qi & J. N. Wilson, Eur. Phys. J. A 56 (2020) 236

Potential of prompt γ-ray emission studies in fast-neutron induced fission: A first step
L. Qi, C. Schmitt, et al. Eur. Phys. J A 56:98 (2020)

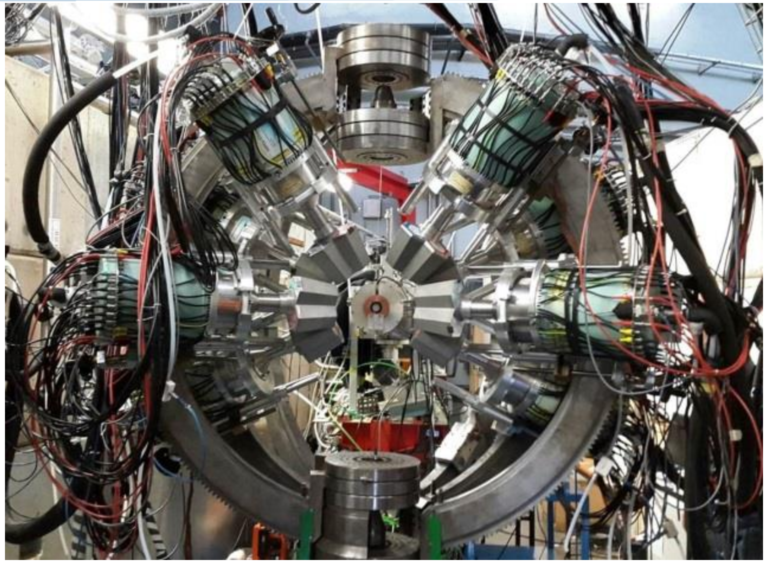
Statistical study of the prompt-fission γ-ray spectrum for 238U(n, f) in the fast-neutron region
L. Qi, M. Lebois, J. N. Wilson, et al., Phys. Rev. C 98, 014612 (2018)

Comparative measurement of prompt fission γ-ray emission from fast-neutron-induced fission of 235U and 238U
M. Lebois et al. Phys. Rev. C92, 034618 (2015)

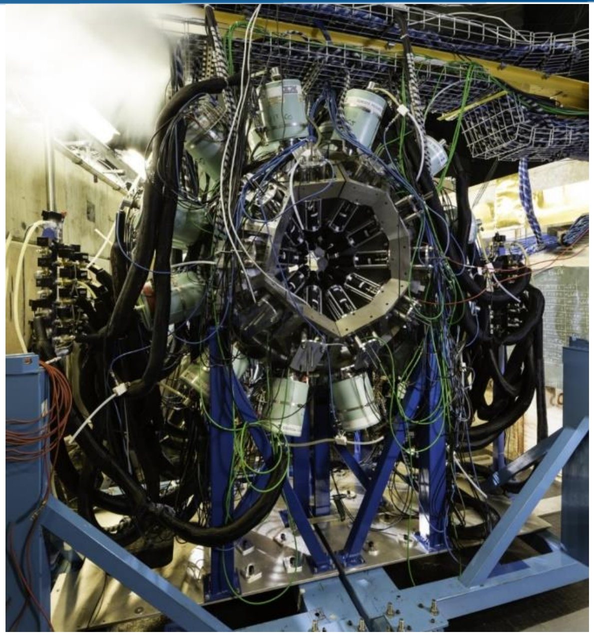
Coupling LICORNE to gamma ray spectrometers



Orgam (2015)

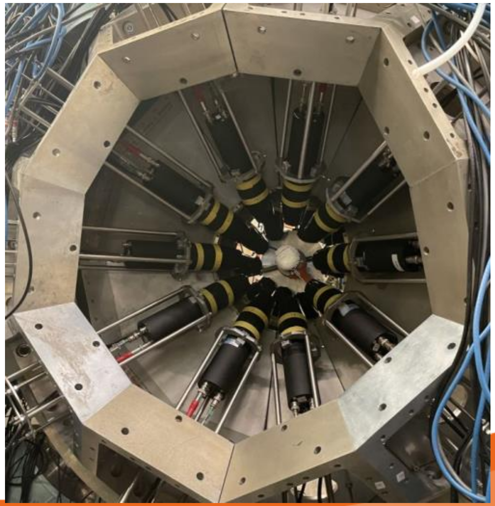


Miniball (2017)



Nu-Ball1 (2018)

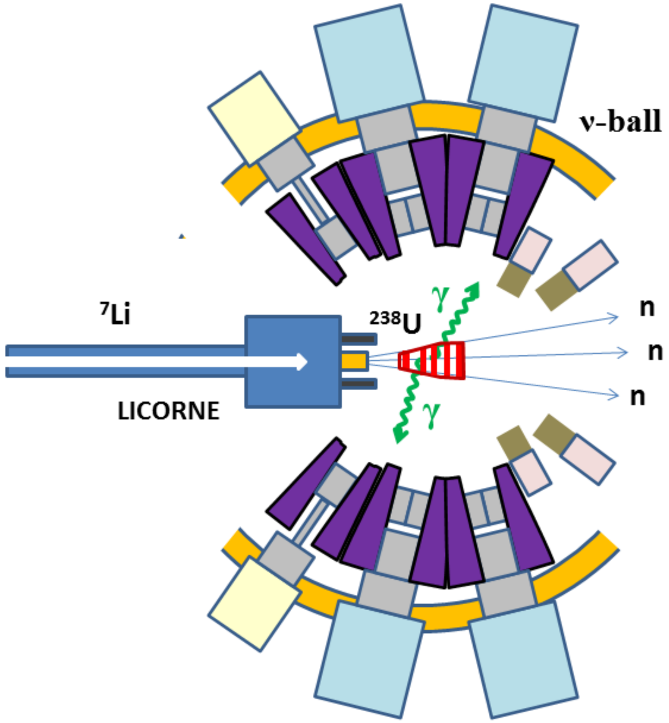
Nu-Ball1 (2018)

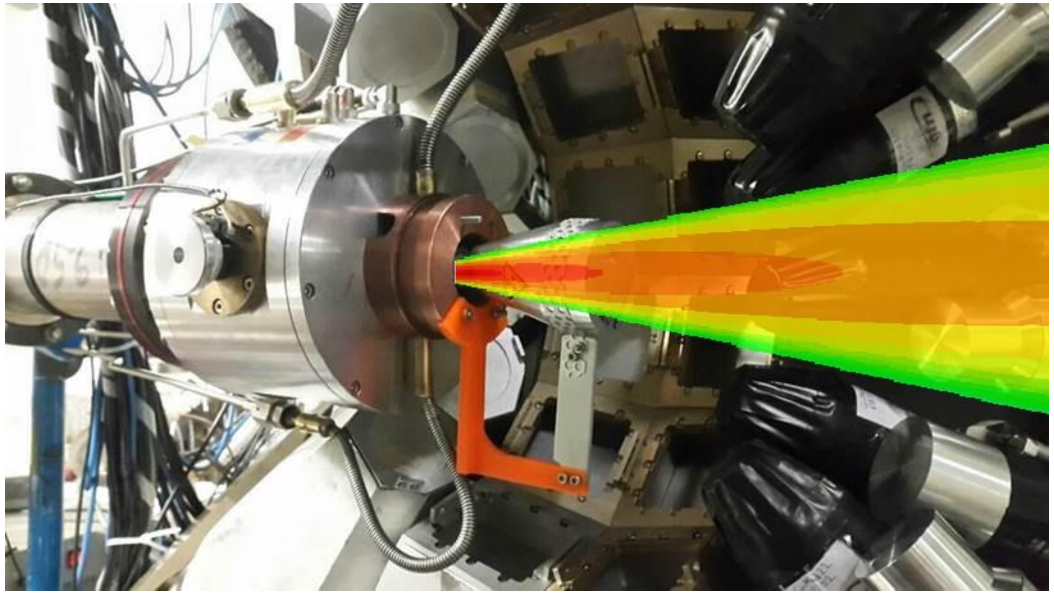


Nu-Ball2 (2022)

LICORNE/ν-ball coupling principle

LICORNE: The unique inverse kinematics neutron source of the ALTO facility





Primary beam
(200ns – pulsed)
2 x 10^{11} /s

^{7}Li (16 MeV)

100 nA

Gas target

H_2

3 x 10^{20} atoms/cm^2

Secondary beam
2 x 10^{7} /s

1.5 MeV neutrons

Samples
up to 10^{5} fissions/s

^{238}U
^{232}Th
~100 g

Applications

- Detector calibrations for Direct Dark Matter Search (DS50)

The Dual-Phase TPC

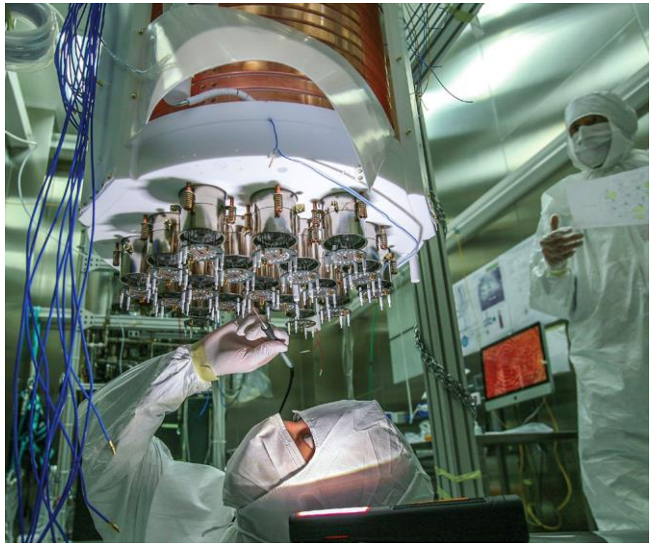
- 50 kg active mass of UAr
- 19 top + 19 bottom R11065 HQE 3'' PMTs
- 36 cm height, 36 cm diameter
- Low field of 0.2 kV/cm drift

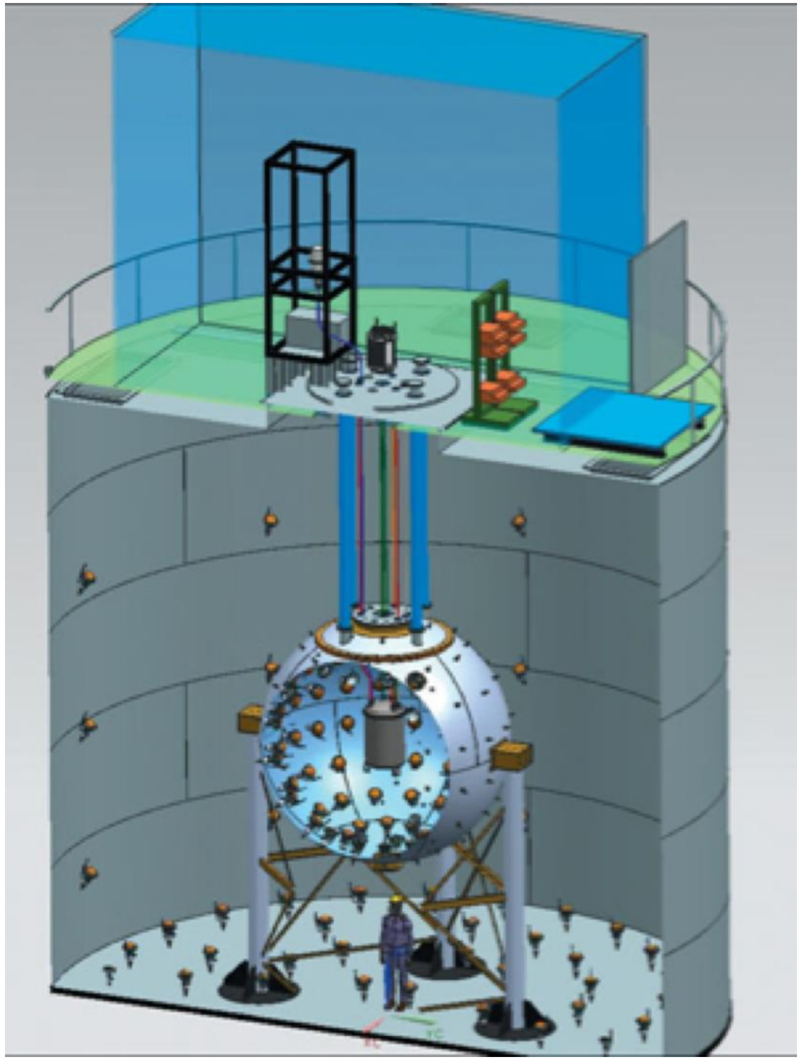
Liquid Scintillator Veto against neutrons

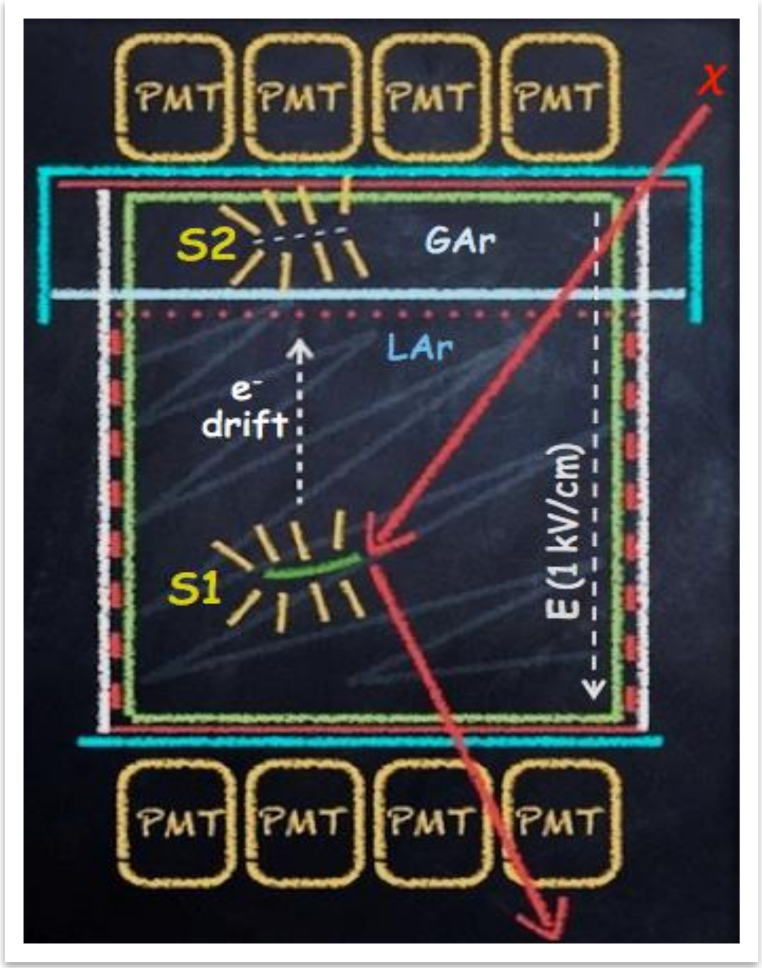
- 4 m diameter sphere
- Boron-loaded: 1:1 PC and TMB
- 110 8" PMTs
- LY ~ 500 pe/MeV

Cherenkov Water Detector

- 11 m diam. x 10 m
- 80 PMTs

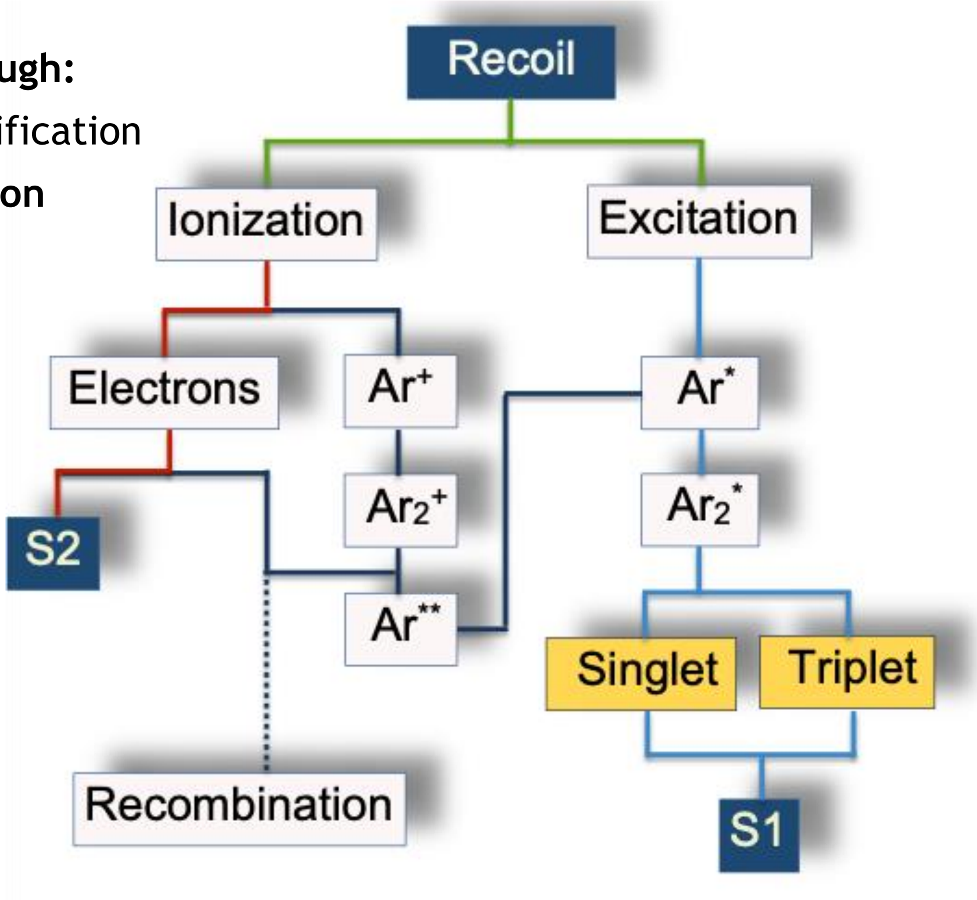






Particle discrimination **through:**

- Accurate 3D **position** identification
- **Multiple-scattering rejection**
- **S2/S1 ratio**
- S1 **PSD** (if available)



The DS-50 high-mass search

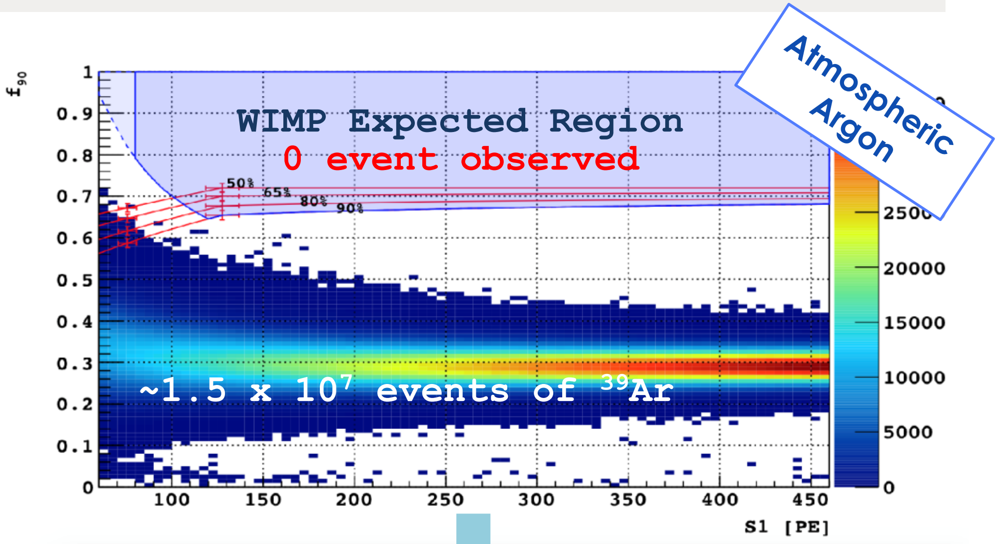
LAr scintillation times:

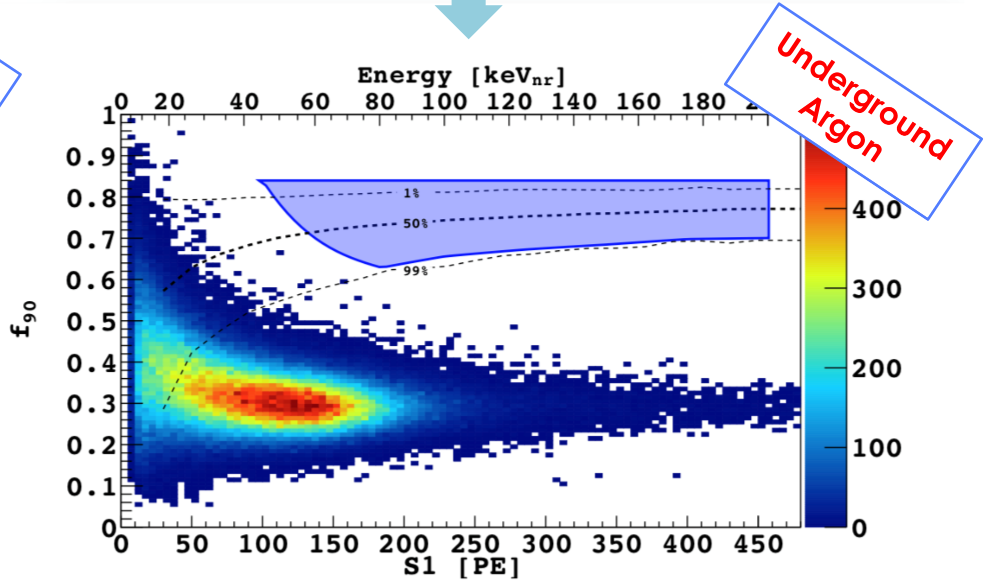
- singlet ~ 6 ns
- Triplet ~ 1600 ns

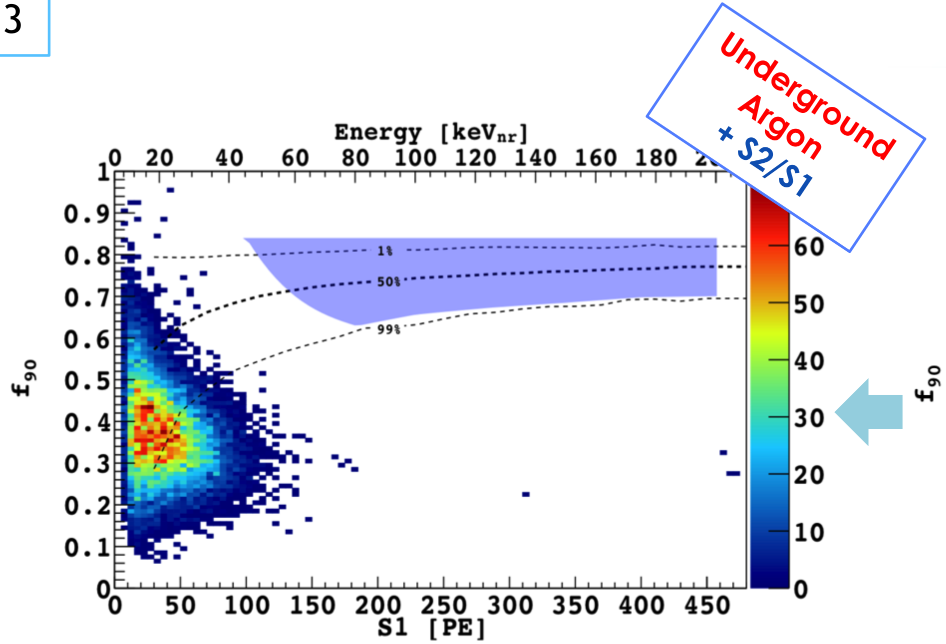
Singlet-to-triplet ratios:

- Nuclear recoils ~ 0.7
- Electron recoils ~ 0.3

Very distinctive (and unique) signatures to separate electron recoils from nuclear recoils







Background-free over more than 530 days!

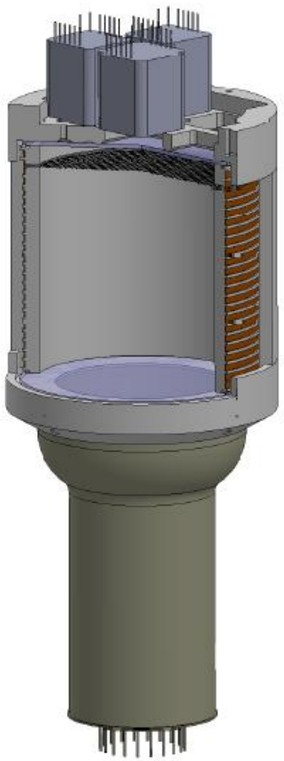
ARIS: Dark Matter Search, Liquid Argon TPC irradiation

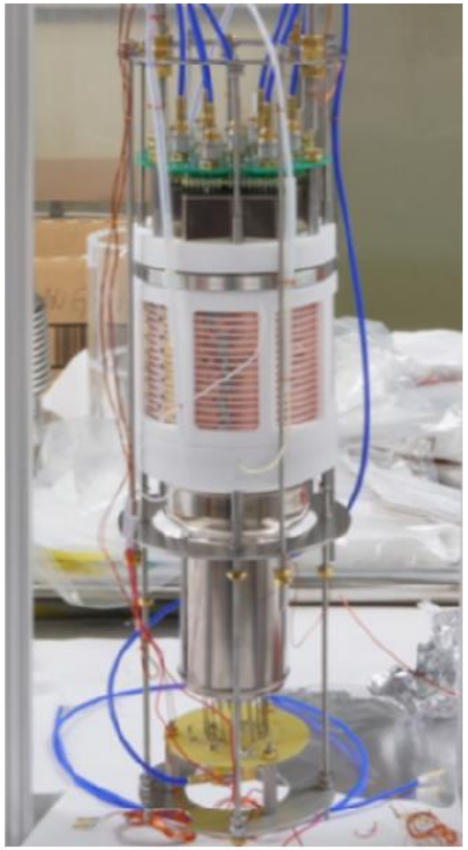
Measurement of the liquid argon energy response to nuclear and electronic recoils

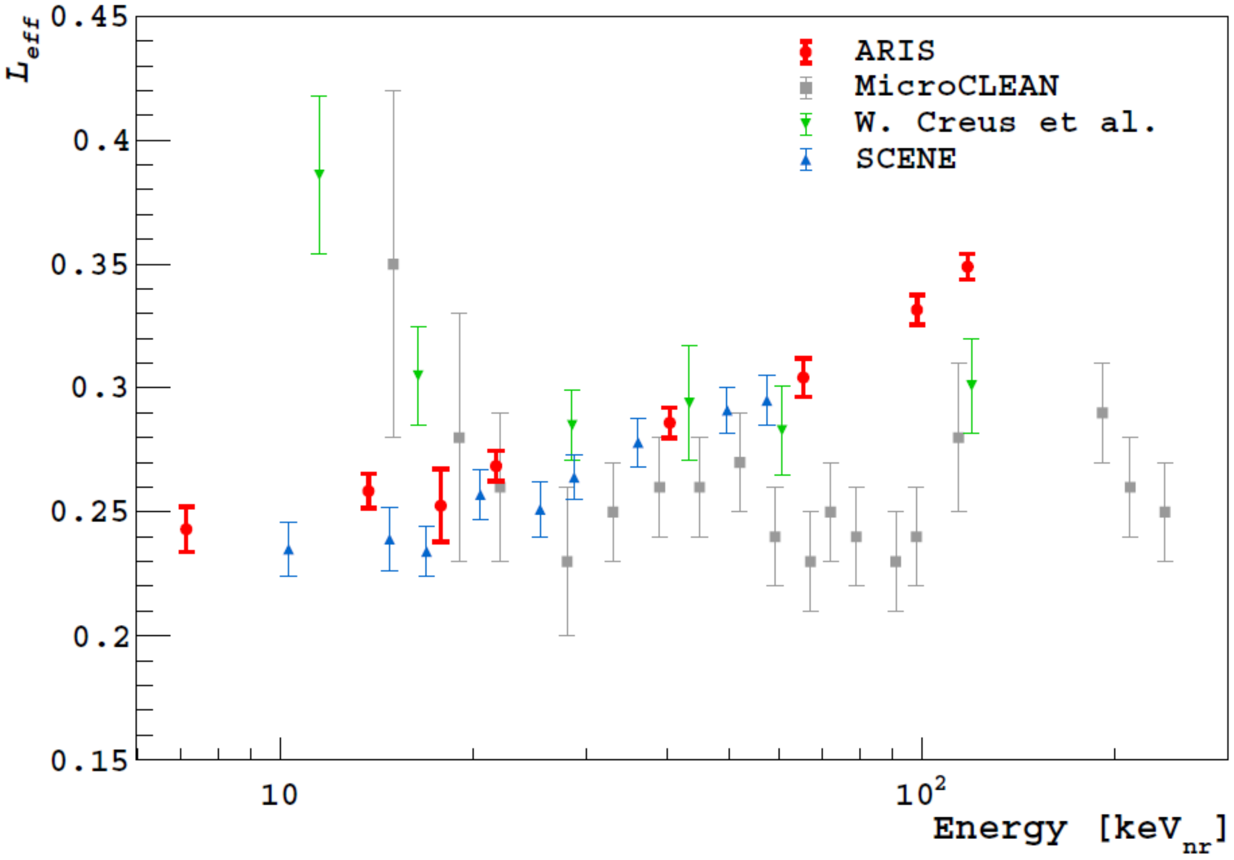
P. Agnes, et al. Phys. Rev. D 97, 112005 (2018)

- Dark matter search liquid Argon detector prototype
- Neutrons used as a proxy for WIMPS

→ Characterisation of the detection properties via nuclear recoils and sensitivity limits







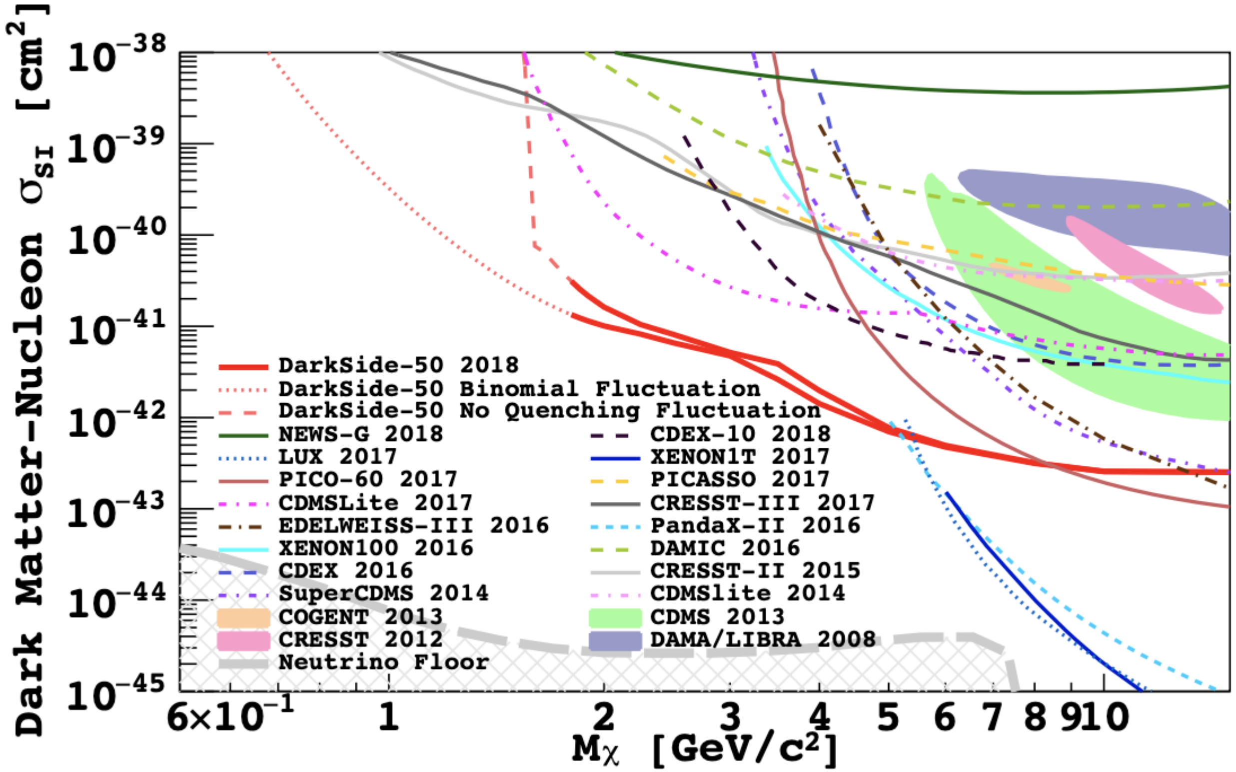
The DS-50 low-mass search in brief

- **2018** First results on light dark matter candidates with liquid argon using the ionization channel:
  - DarkSide-50, Phys. Rev. Lett. 121 (2018) 081307
  - DarkSide-50, Phys. Rev. Lett. 121, 111303 (2018)

- **2019** End of the DarkSide-50 data taking

- **2021** Measurement of the LAr ionization response down to the sub-keV with DarkSide-50
  - DarkSide-50, Phys.Rev.D 104 (2021) 8, 082005

- **2022** Re-analysis of the DarkSide-50 dataset
  - DarkSide-50, arxiv:2207.11966 (2022)
  - DarkSide-50, arxiv:2207.11967 (2022)
  - DarkSide-50, arxiv:2207.11968 (2022)

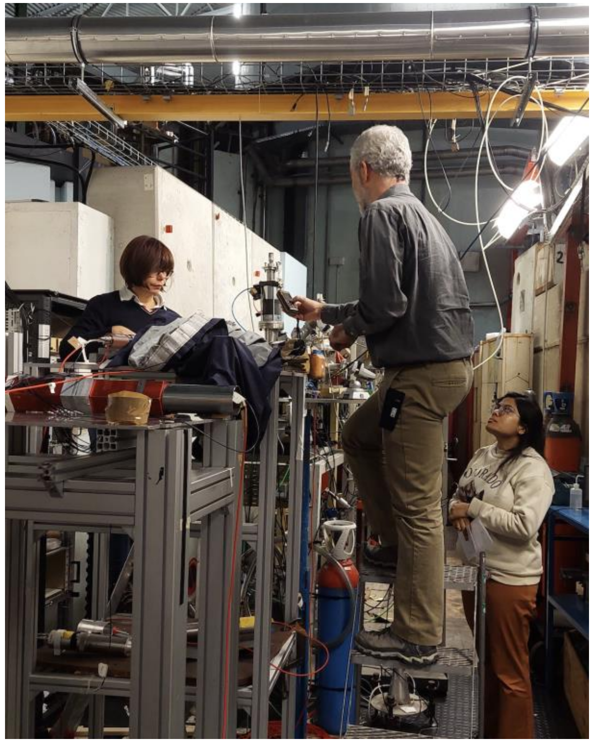


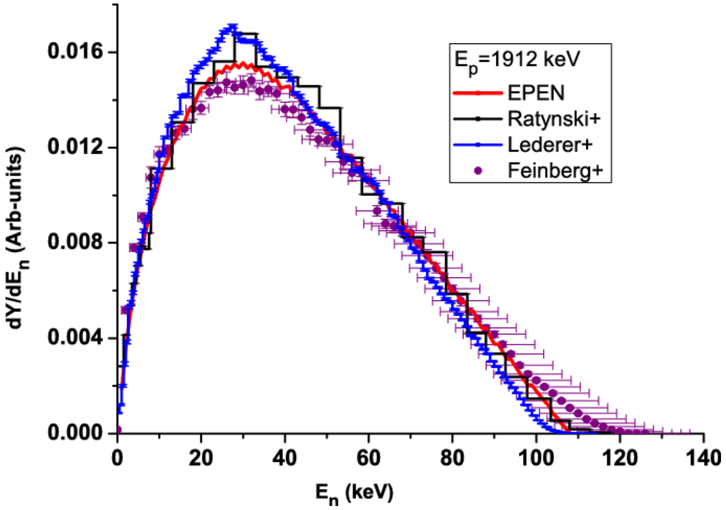
BLEND (I-SI-39): Feasibility study to calibrate noble liquid TPCs with O(100 keV) neutron beam

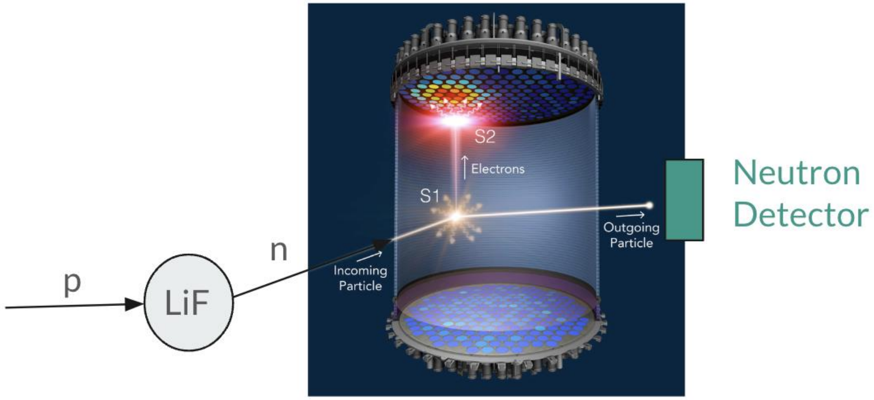
6 UT - 11-13 December 2023

8 participants on site from France (APC, IJCLab, CPPM) Italy (GSSI, LNS), US (VirginiaTech)

Test in preparation for calibration of liquid argon/xenon response to O(< 1 keV) nuclear recoils for future direct dark matter experiments (ARIS-like)

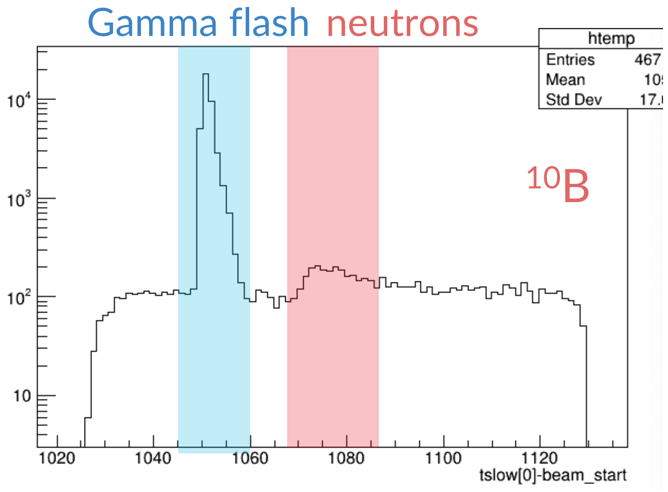




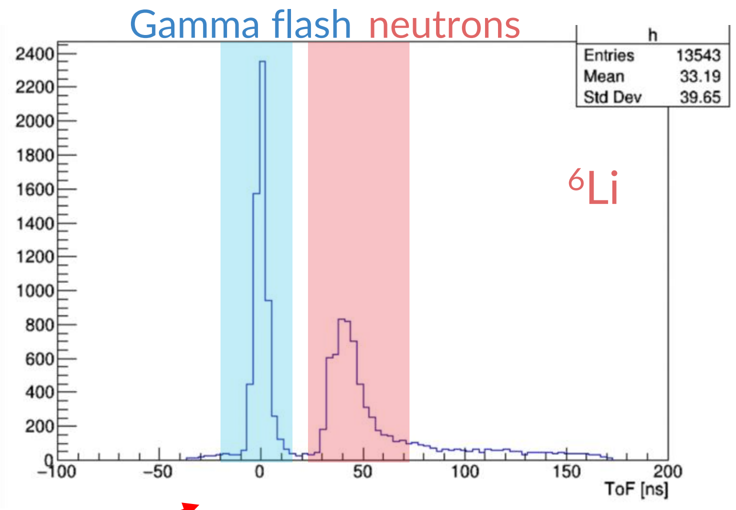


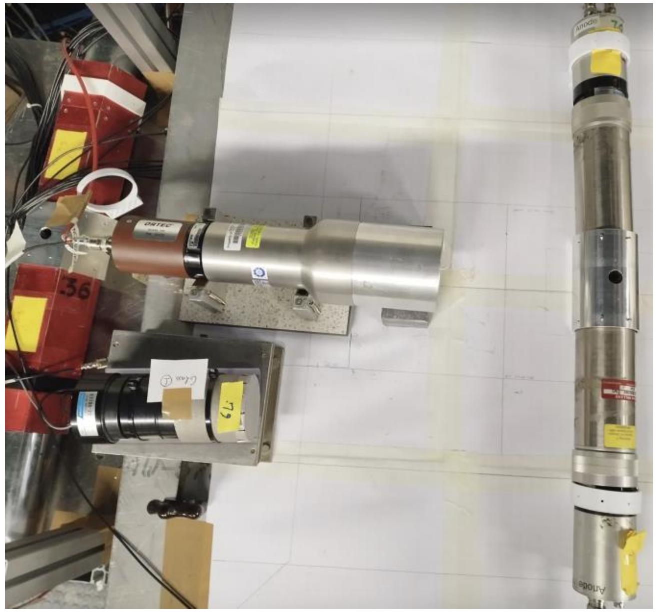
Dual-goal:

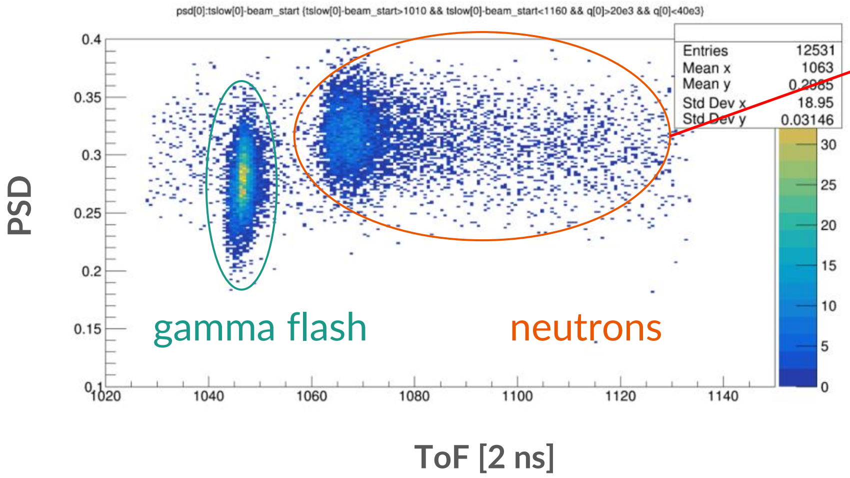
- **testing "low-background" neutron beam**
  - characterizing neutron flux and distribution from $^7Li(p,n)^7Be$ at 2.1 - 2.4 MeV (1-5 nA)
  - check gamma rate and evaluate possible shielding: under evaluation with MC
- **testing ^{10}B-BaF_2 and ^6Li glass for ToF detection**

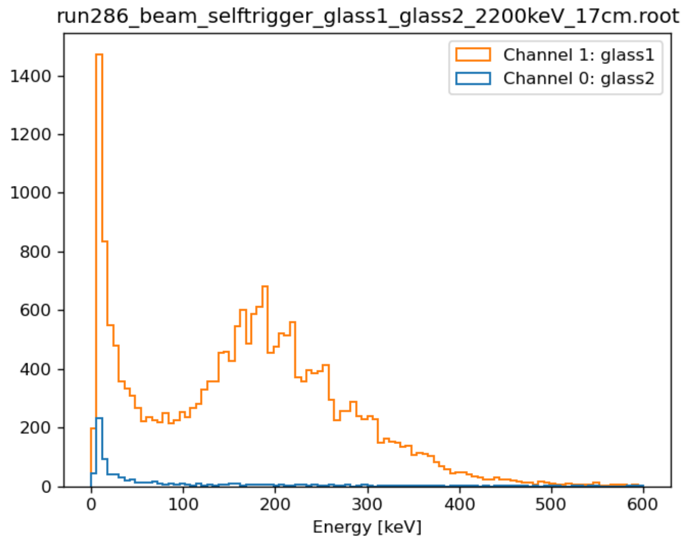


- Detection with ^{10}**B** dominated by gamma background
- Detection with ^{6}**Li-glass** almost **background-free** (time resolution ~ 2.4 ns)









Characterization of neutron flux in progress

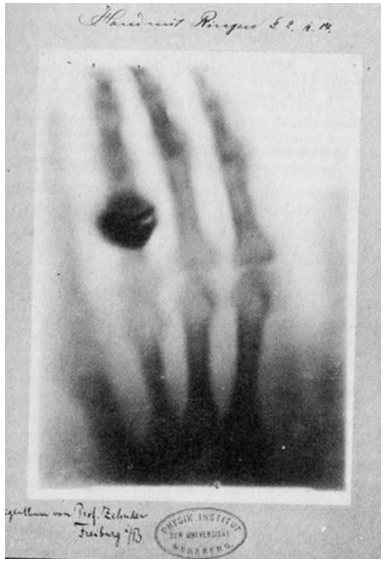
Applications

- Fast neutron tomography

X-rays for imaging applications

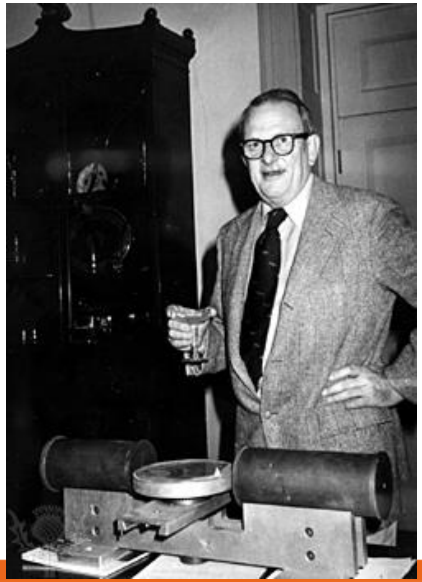
First x-ray Images

Willhelm Röntgen (1895)
1st ever Nobel Prize (1901)



First x-ray Computed Tomographic Images

Allan M. Cormack &
Godfrey N. Hounsfield
Nobel Prize in Medicine (1979)



Why fast neutron tomography?

X-ray tomography is a mature technology and currently a multi-billion dollar industry

Complimentarity between x-rays and neutrons

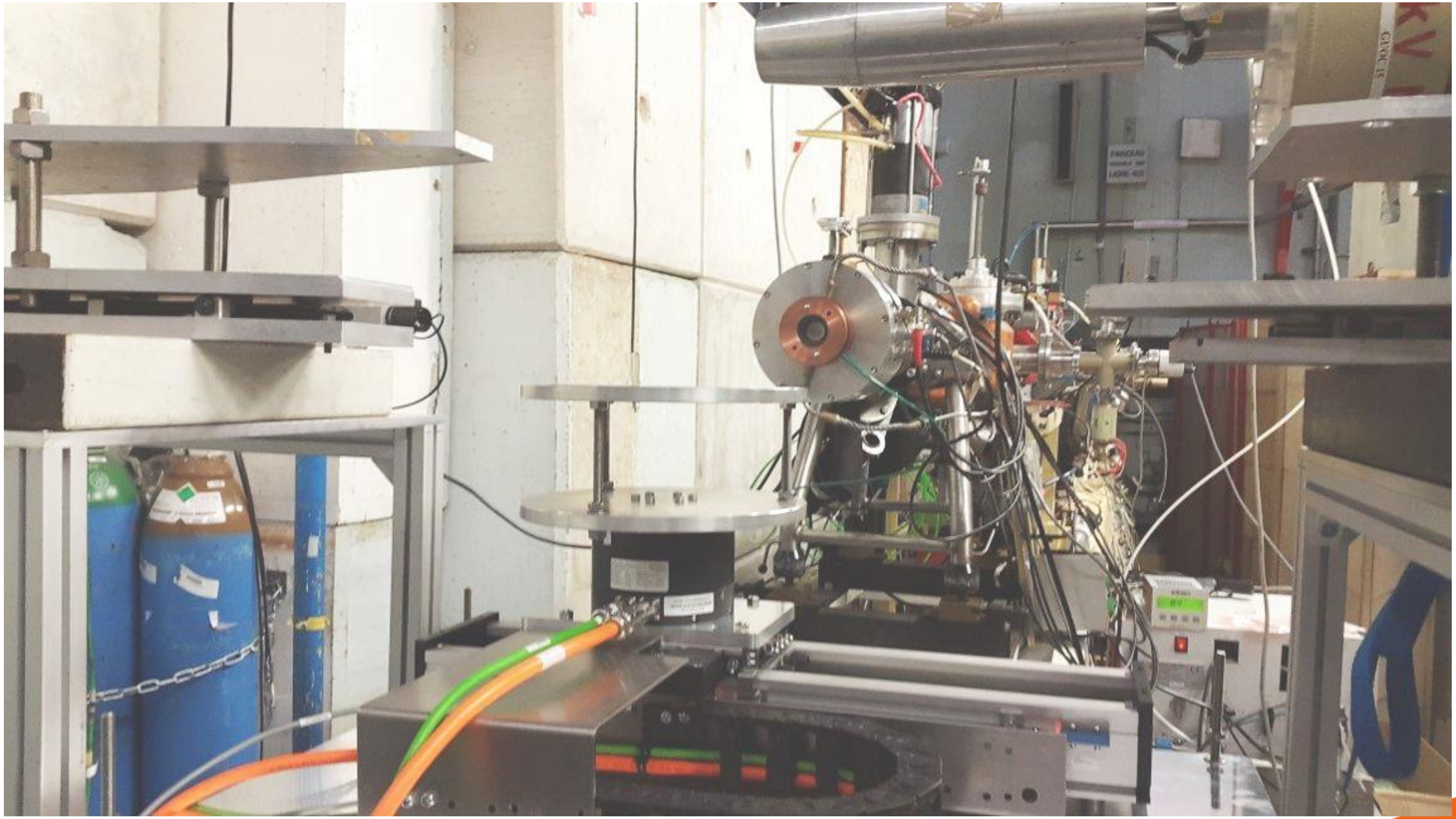
X-rays are strongly absorbed by high-Z materials but pass easily through low-Z materials
Fast neutrons penetrate high-Z materials but are easily scattered by low-Z materials

Potential Applications

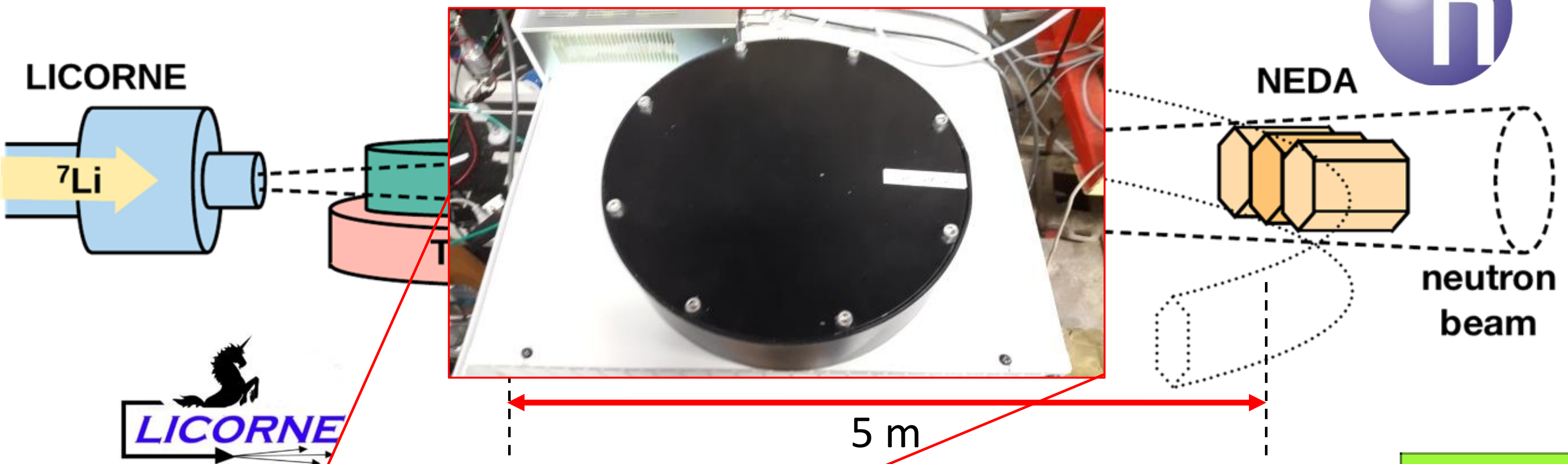
- ❑ Border/airport security (e.g. detection of explosives in suitcases)
- ❑ Nuclear Industry: Characterisation of nuclear waste packages
- ❑ Cultural Heritage: Imaging inside precious artifacts and objects
- ❑ Precision quality control for industry
- ❑ Non destructive characterization of geological samples (e.g. Metorites)

Courtesy of BAM, Berlin

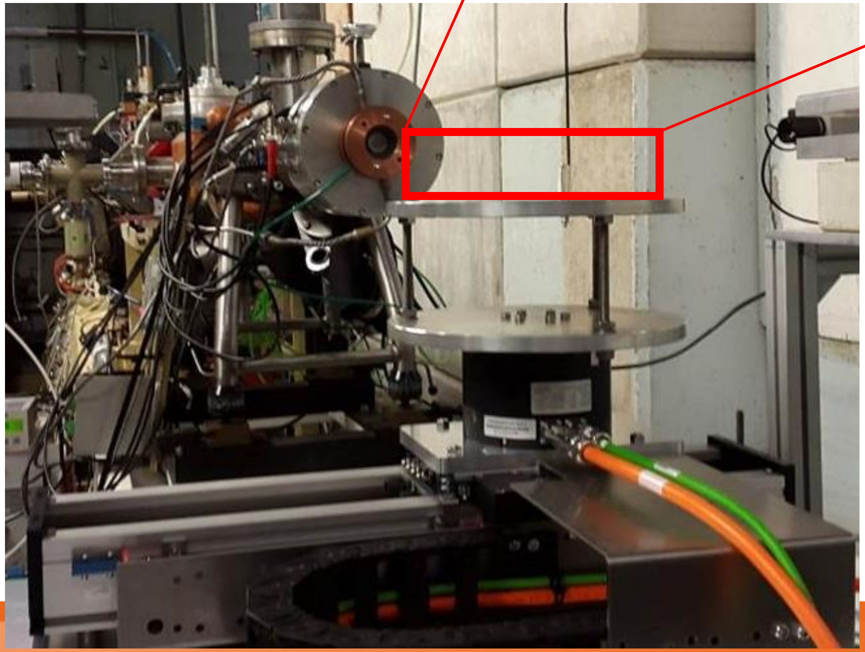
Fast neutron tomography with LICORNE @ ALTO

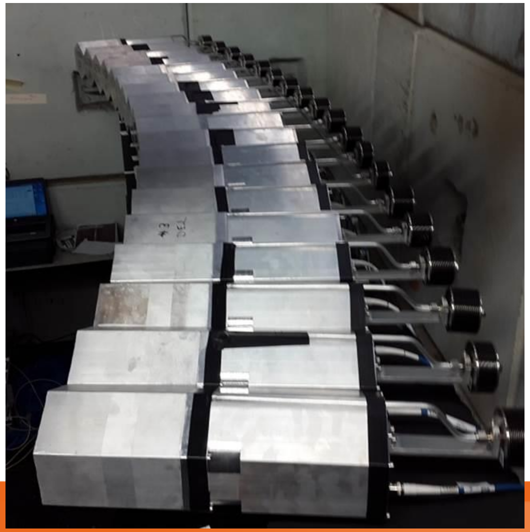


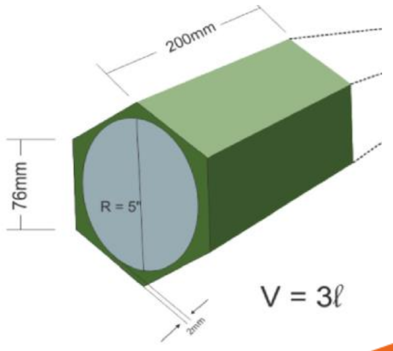
Fast neutron tomography with LICORNE @ ALTO



First Use of **NEDA** with FASTER

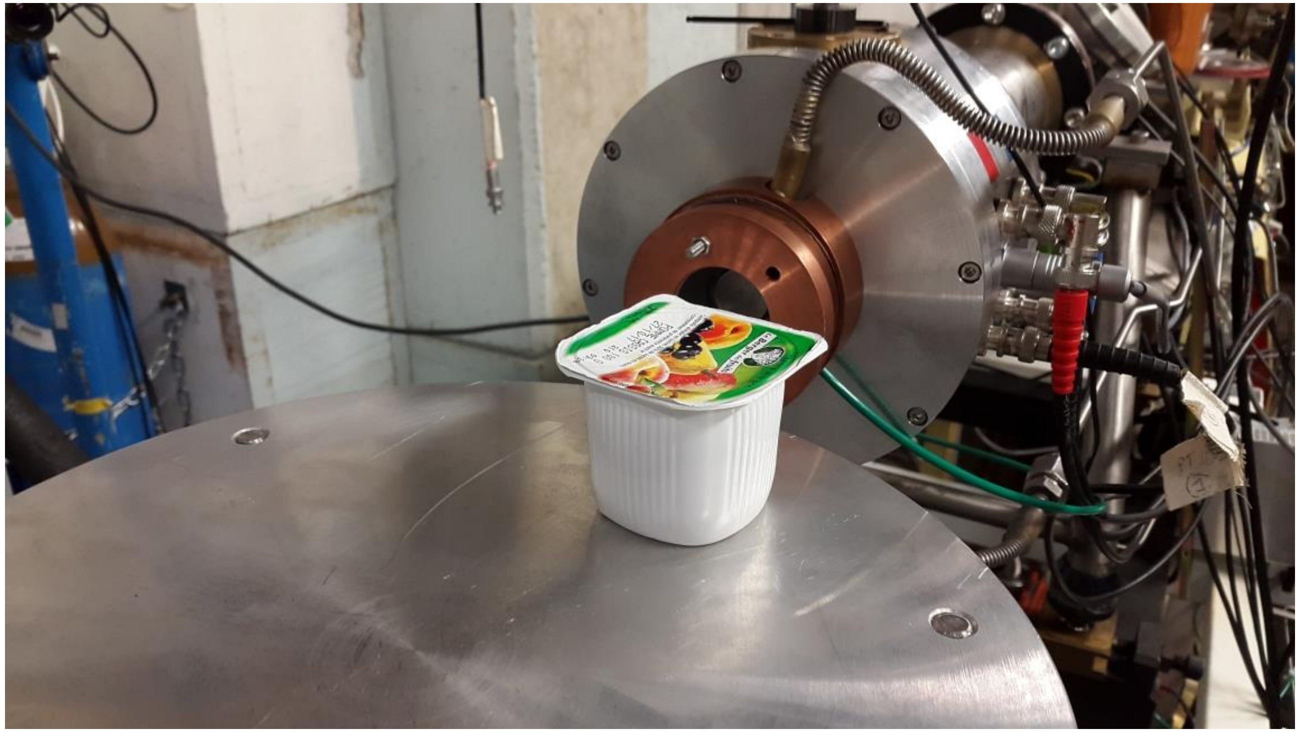


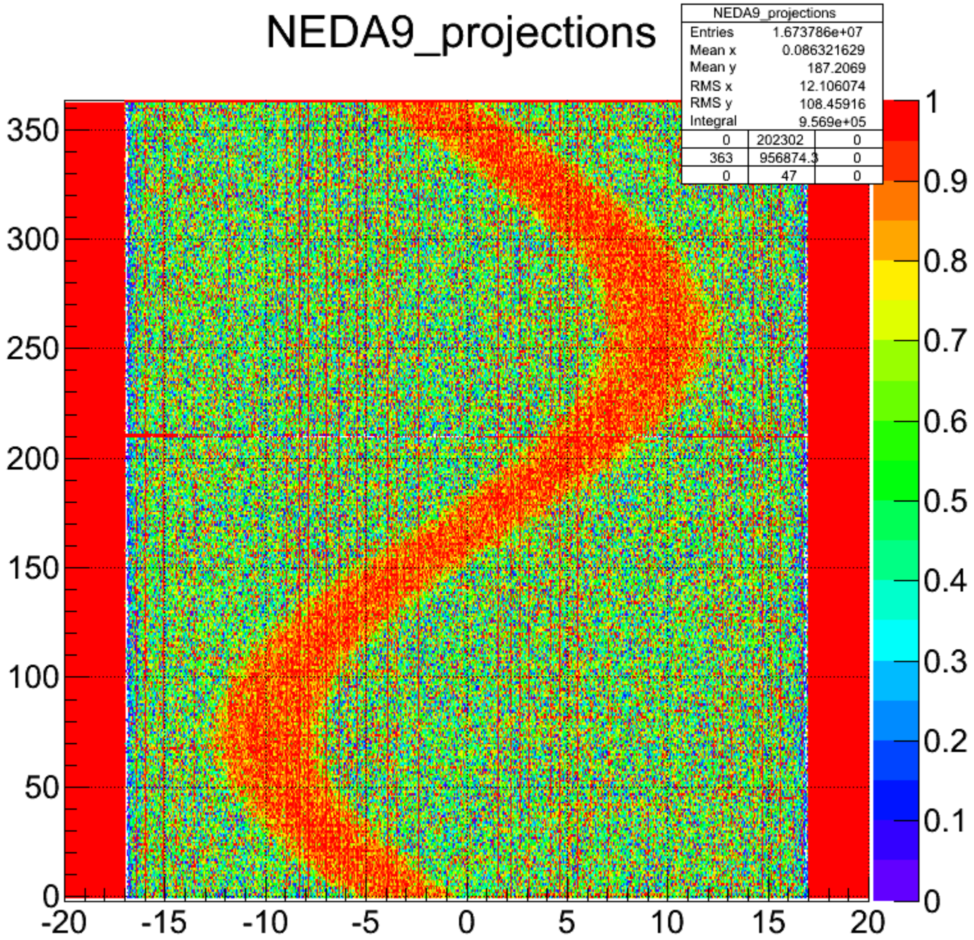




BC501A

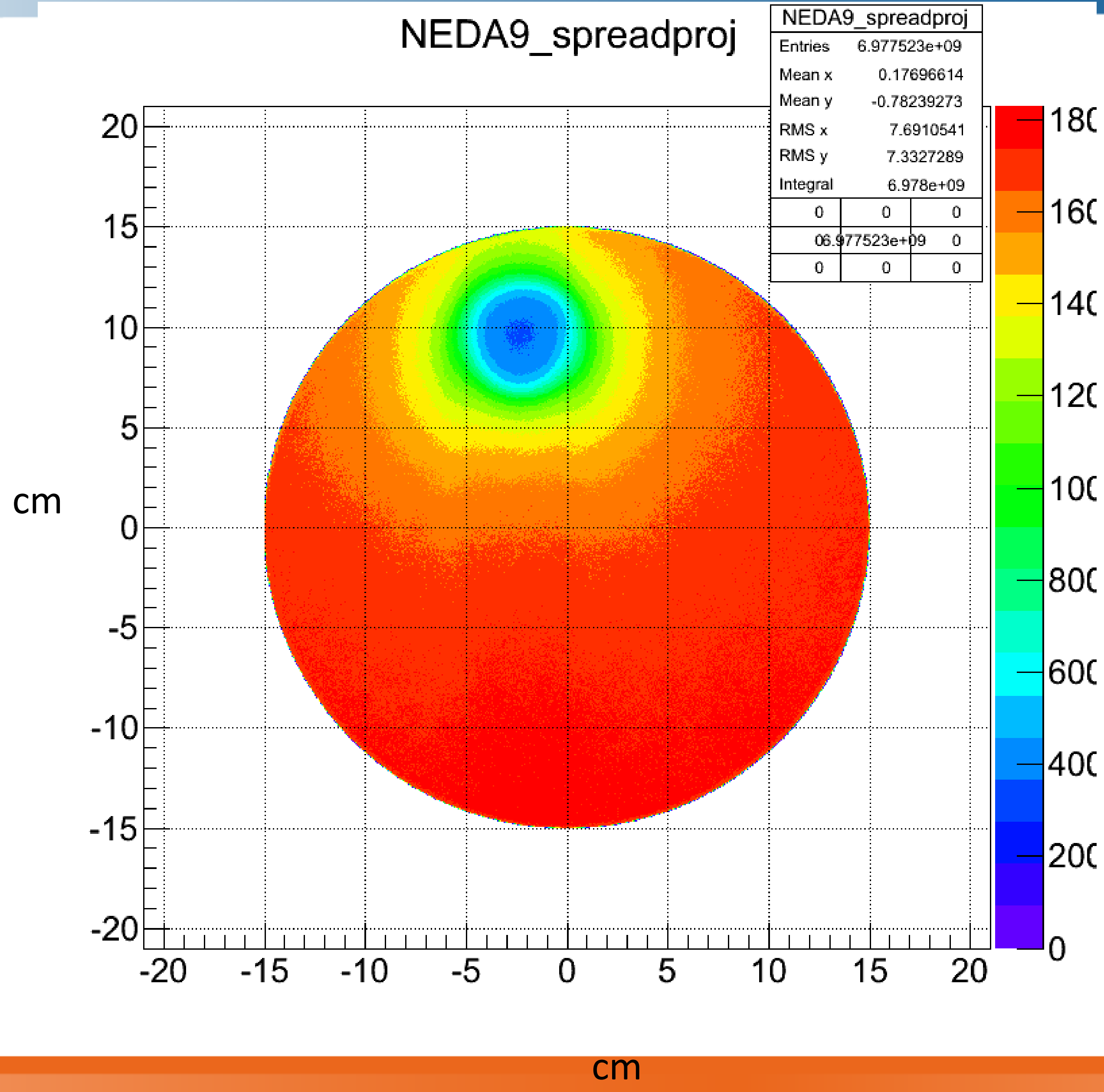
Fast neutron tomography: Simple objects





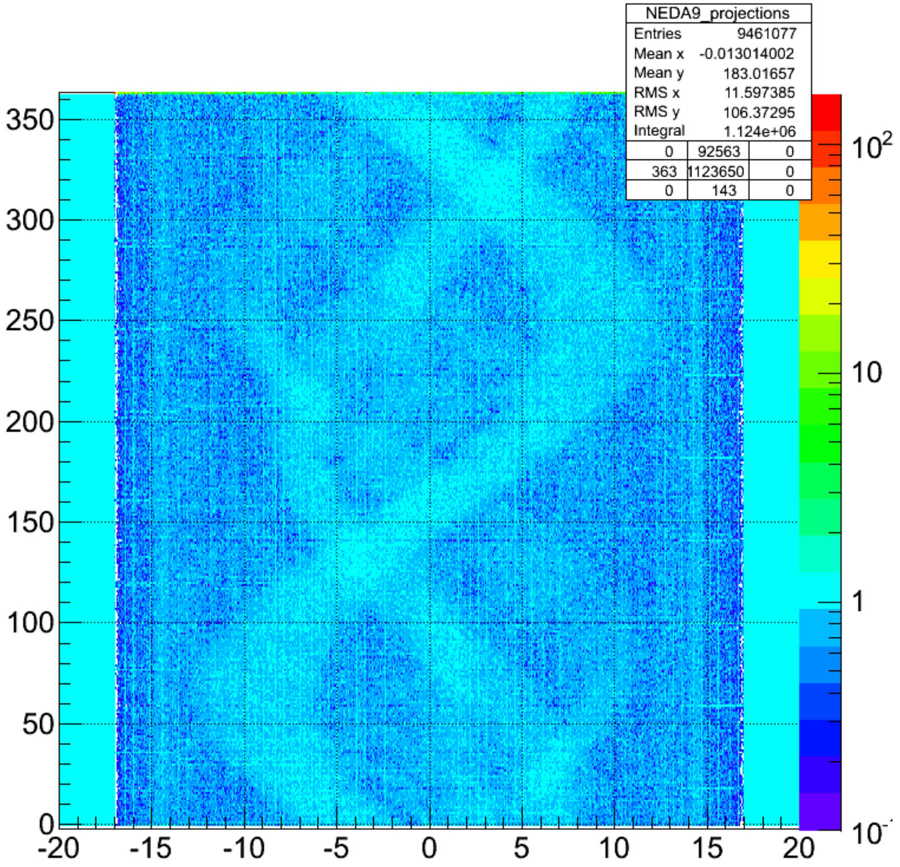
Courtesty of B. Wasilewska

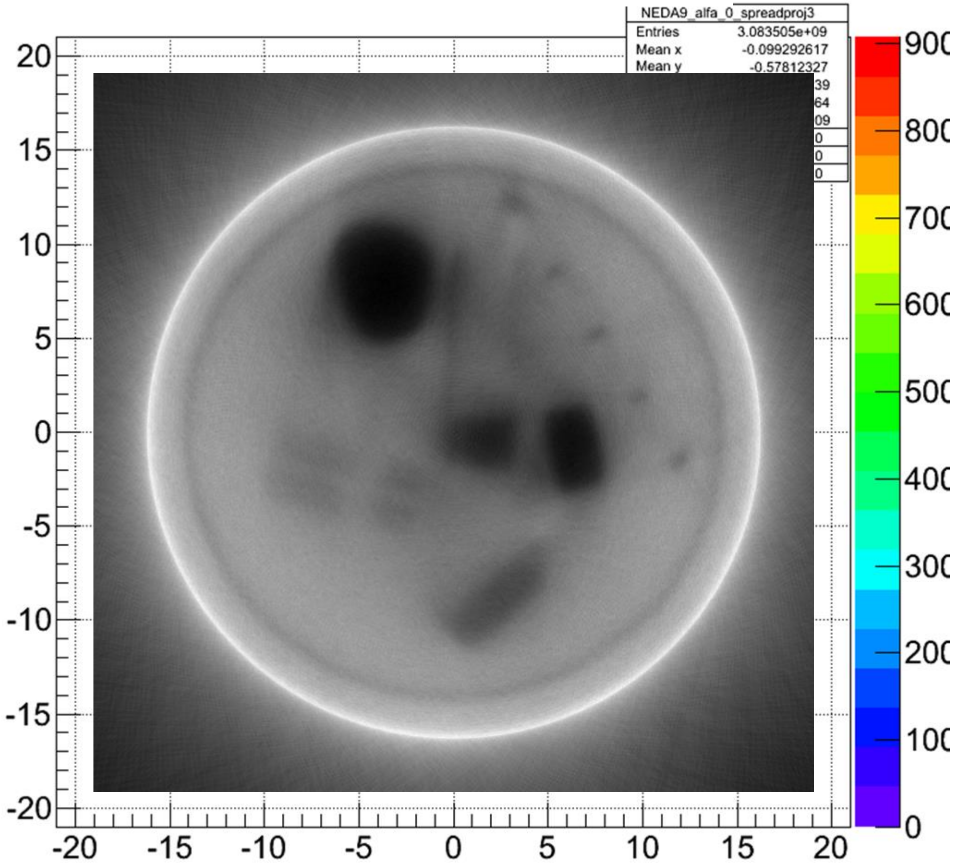
Fast neutron tomography: Reconstruction simple objects



Courtesty of B. Wasilewska

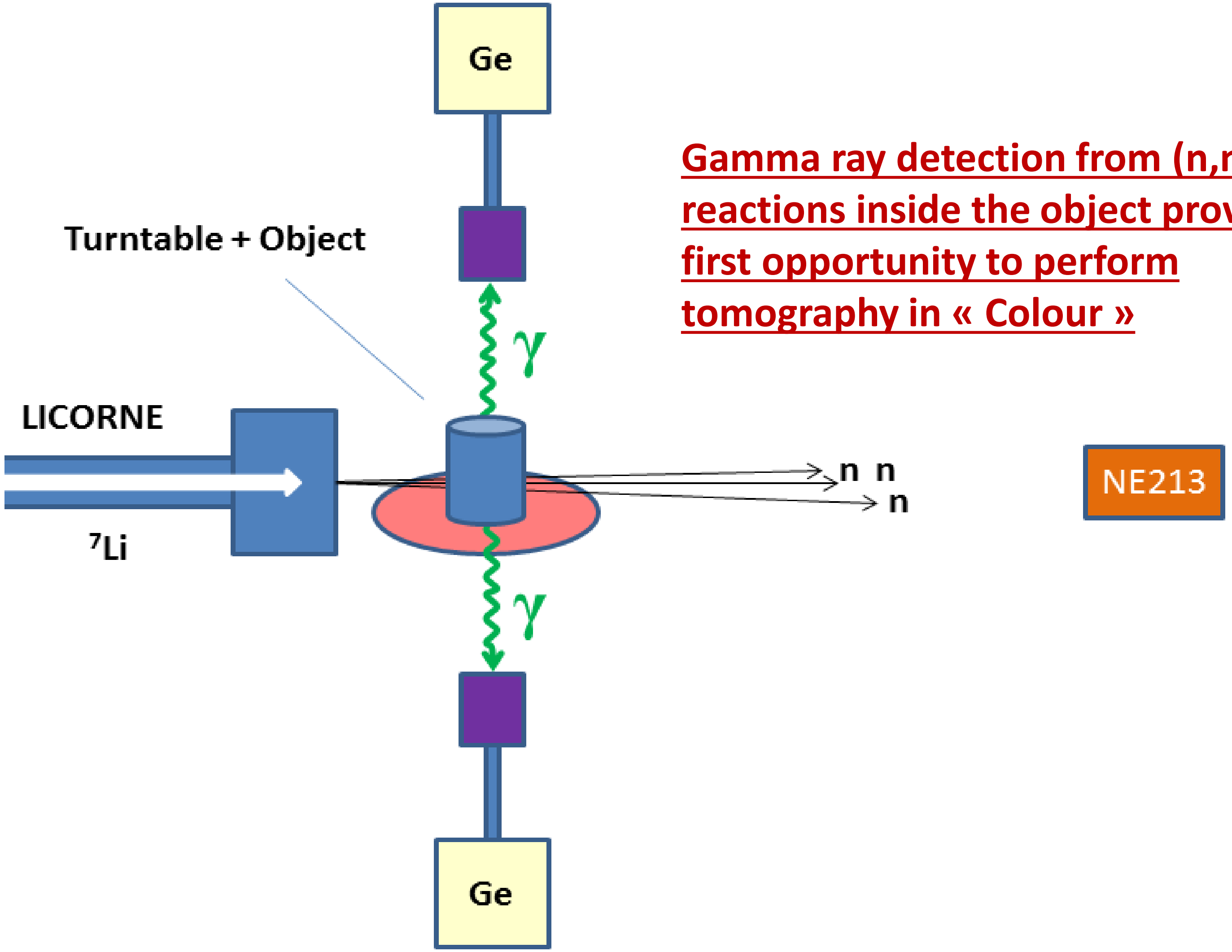
Fast neutron tomography: Reconstruction complex objects





Courtesty of B. Wasilewska

COLOUR tomography with fast neutrons



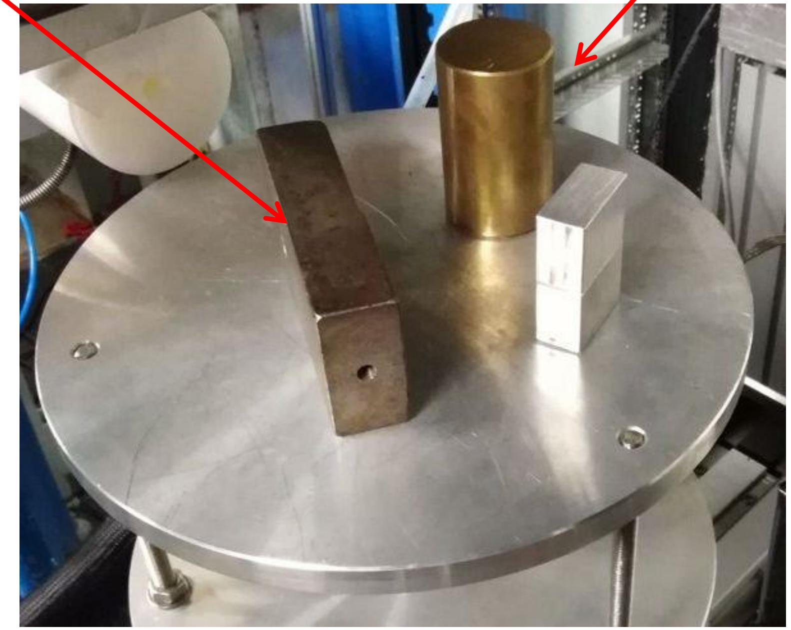
Gamma ray detection from (n,n'γ) reactions inside the object provide the first opportunity to perform tomography in « Colour »

Colour tomography with fast neutrons

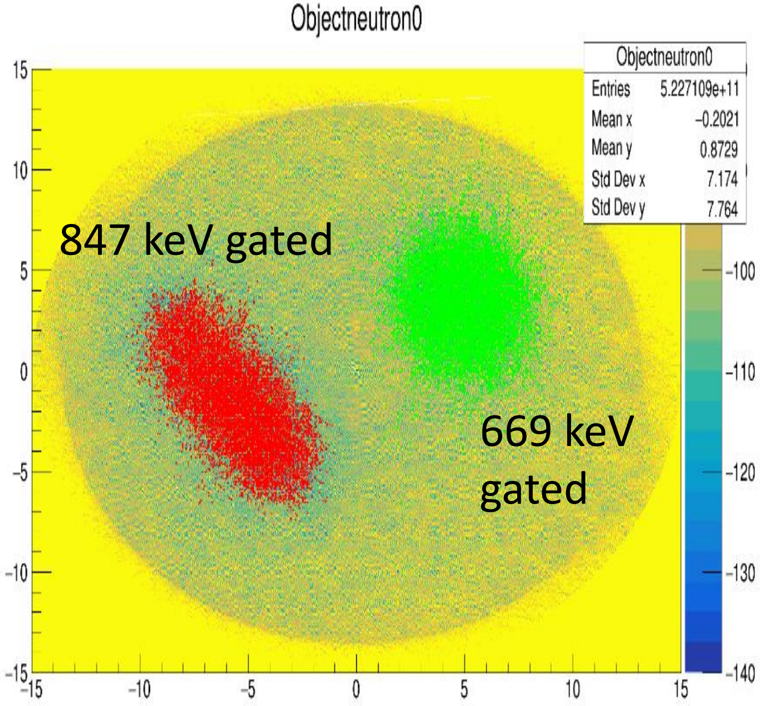
Brass cylinder

Fe block

Optical image



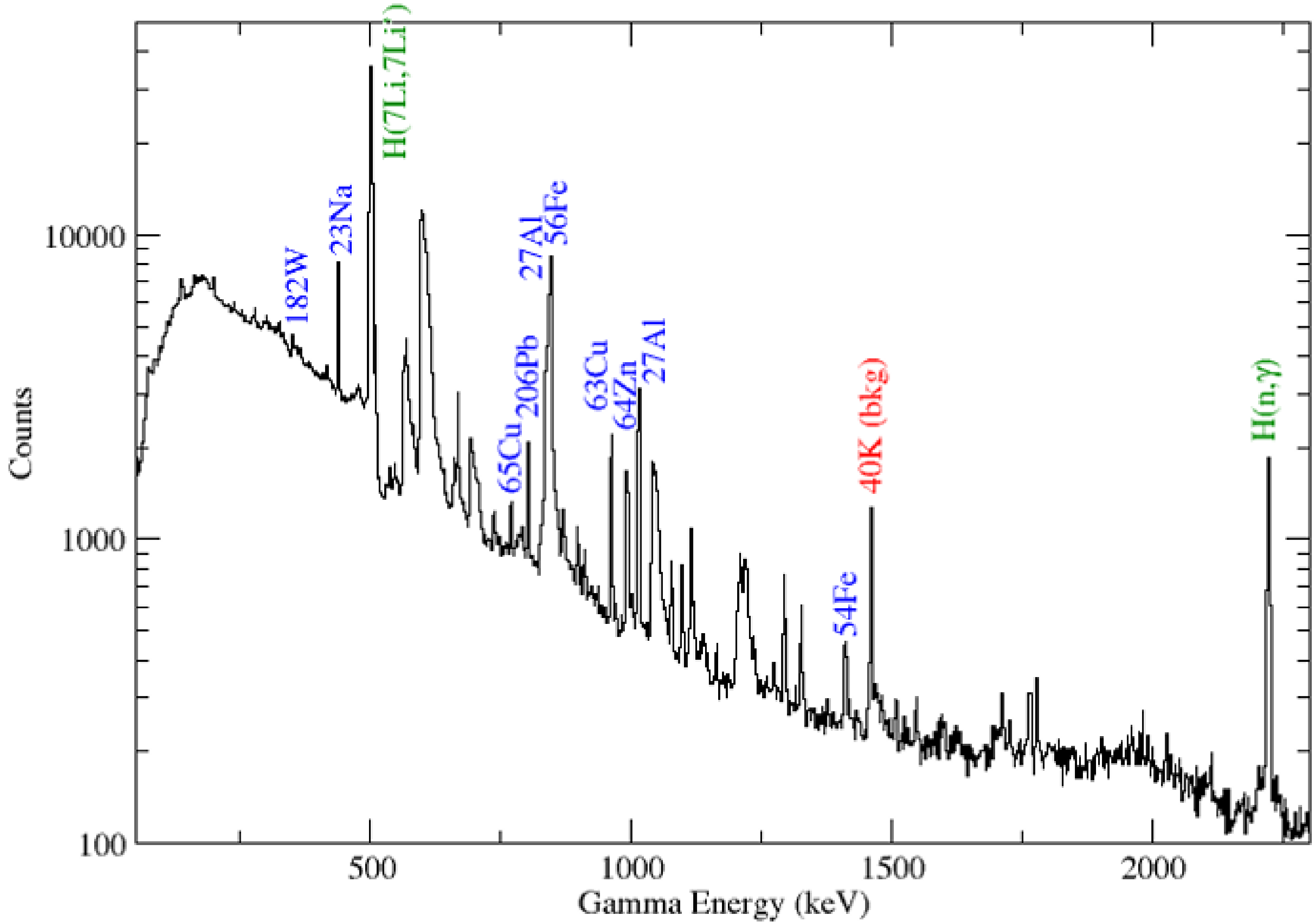
Partial colour image



Fast neutron colour tomographic "painting"

Iron block
Brass cylinder
Salt jar
Aluminium block
Lead block
Tungsten collimator
Germanium half-cylinder

Fast neutron colour tomographic "painting"

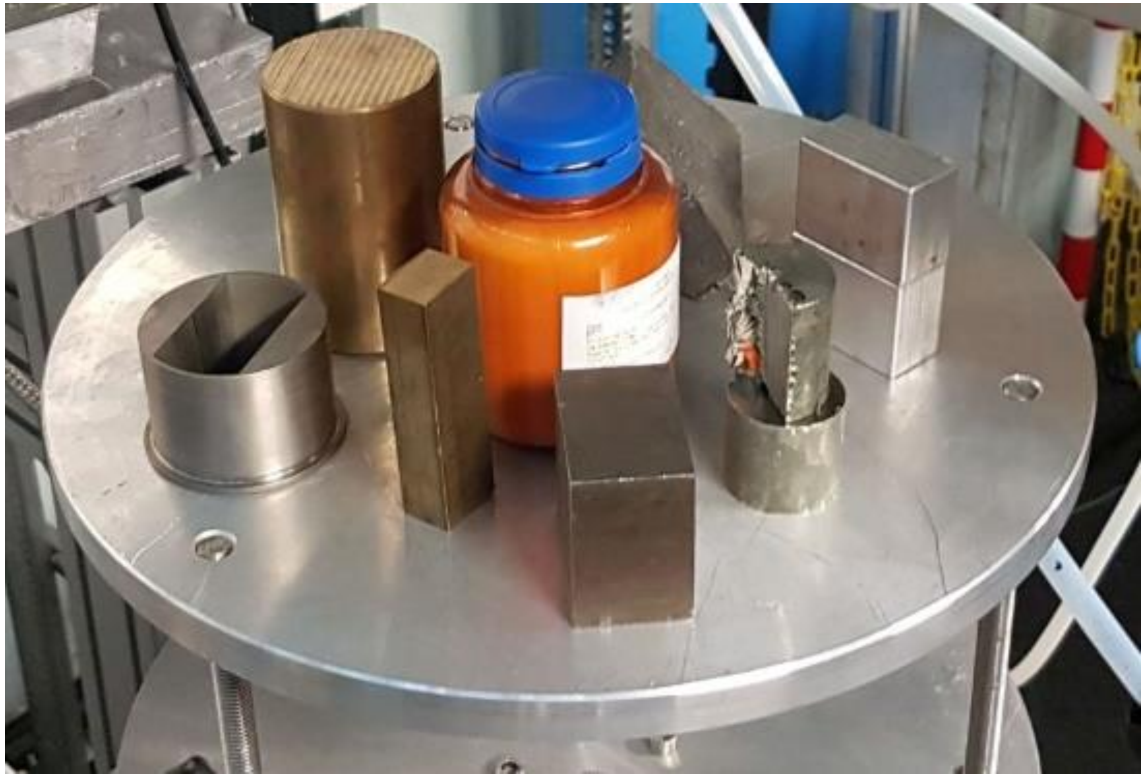


Gamma lines from:

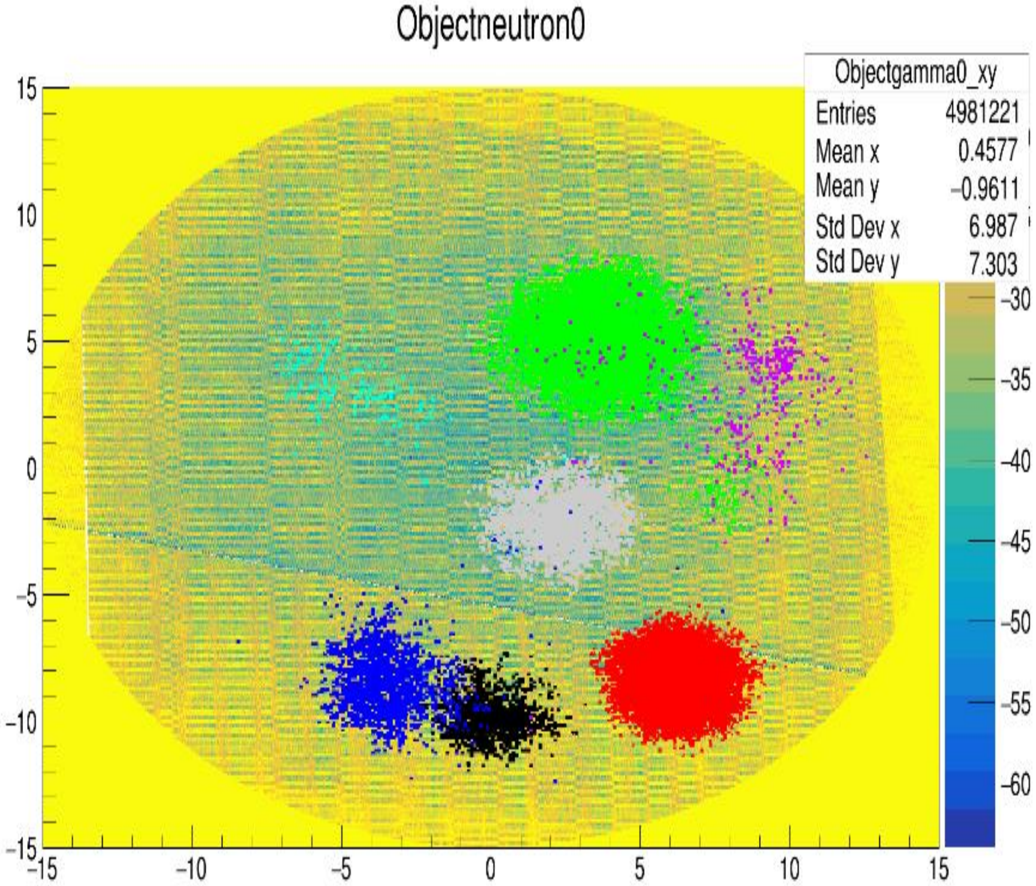
54,56Fe
63,65Cu
64Zn
23Na
27Al
206Pb
182W

Fast neutron colour tomographic "painting"

Optical image



Reconstructed colour image

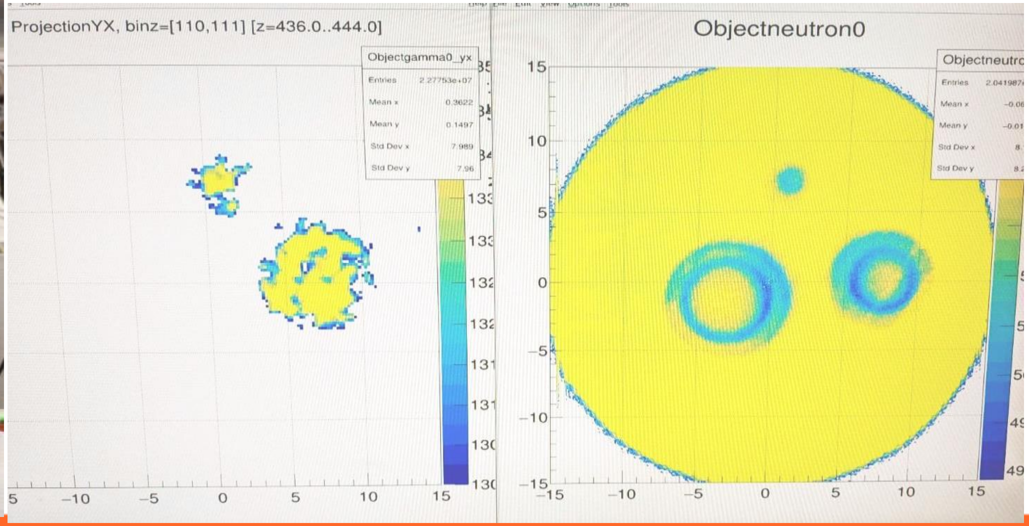


November 2023 : Colour fast neutron tomography (2)

[Collaboration: IJC Lab/ U. York, UK]

- New improved setup with « pencil beam » collimation
- 10 simple and complex objects imaged (3h/object) at high intensity
- Neutron images (attenuation) *and* colour gamma images
- Gammas produced from (n,n') on object isotopes
- Expected spatial resolutions of 2 mm and 8 mm for n and γ respectively
- Detailed analysis ongoing

Online n and γ images



Basic image reconstruction online from object sinograms

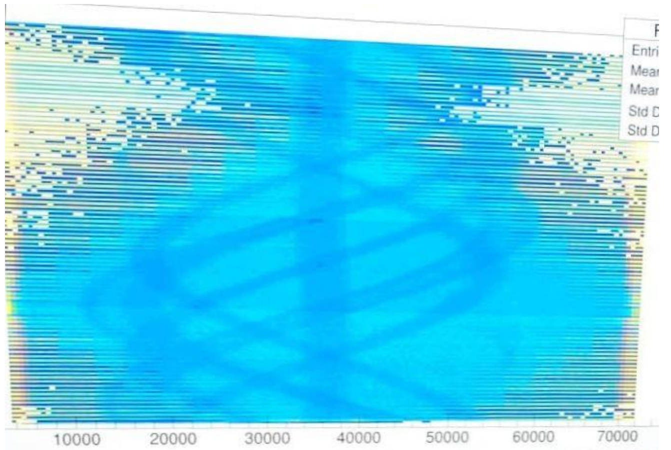


Table x-position

Future Applications

- *Directional* thermal neutron beams for solid state physics

THERMAL NEUTRON PRODUCTION FOR MATERIALS SCIENCE

« Troisième génération »

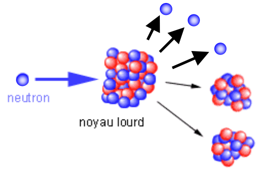
1950… **1980…** **2010…**

- **Reactor**

Fission

Coeur = 0.1 m^3

Modérateur D_2O ~ $1m^3$



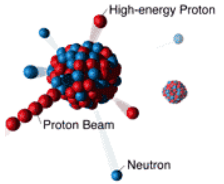
NEUTRONS FOR SOCIETY

- **Spallation sources**

Proton ~GeV

Cible = 4 litres

Modérateur ~ 1 L (couplage faible)



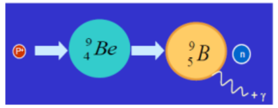
EUROPEAN SPALLATION SOURCE

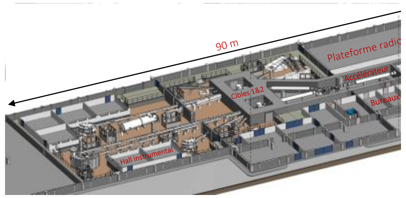
- **Low energy nuclear reactions**

Proton ~MeV

Cible = 0.05 litres

Moderateur ~ 1 litre (couplage 90%)





ICONE

Neutrons for Materials Sciences

25 MeV/80 mA protons

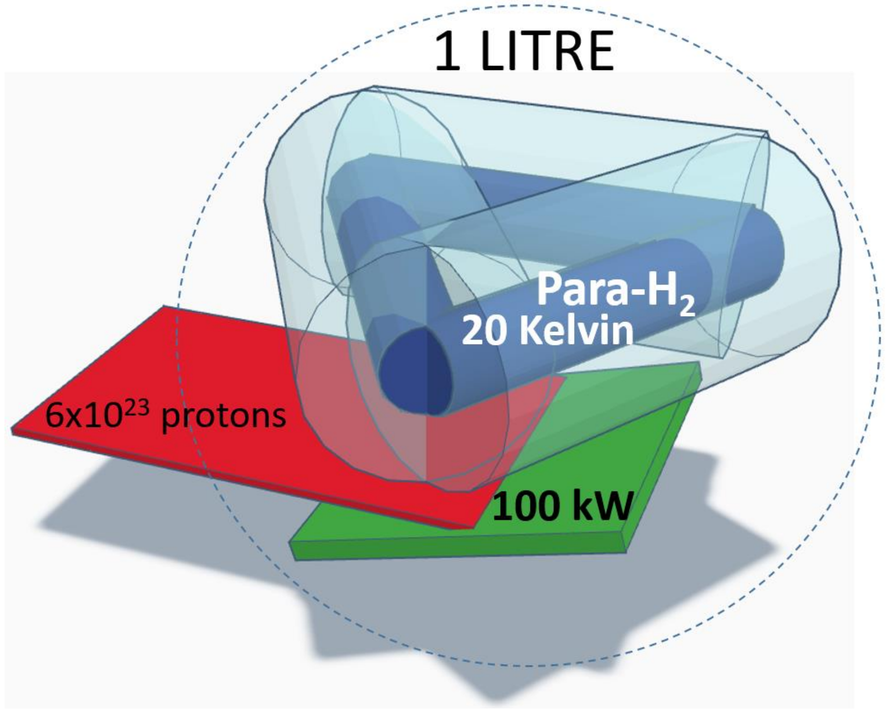
The baseline goal is to offer performances equivalent to a medium power research reactor or spallation source

PROJECT NEEDS

- **Neutron scattering experiments for condensed matter need thermal neutrons (26 meV) and cold neutrons (4 meV)**

- **Step 1: Production of fast neutrons (1-2 MeV)**
- **Step 2: Water moderation (légère, H2O)**
- **Step 3: Moderation with para-hydrogene**

- **Sur ICONE, l'objectif est de construire un ensemble Cible – Modérateur très compacte (1litre) Pour maximiser la densité de neutrons**

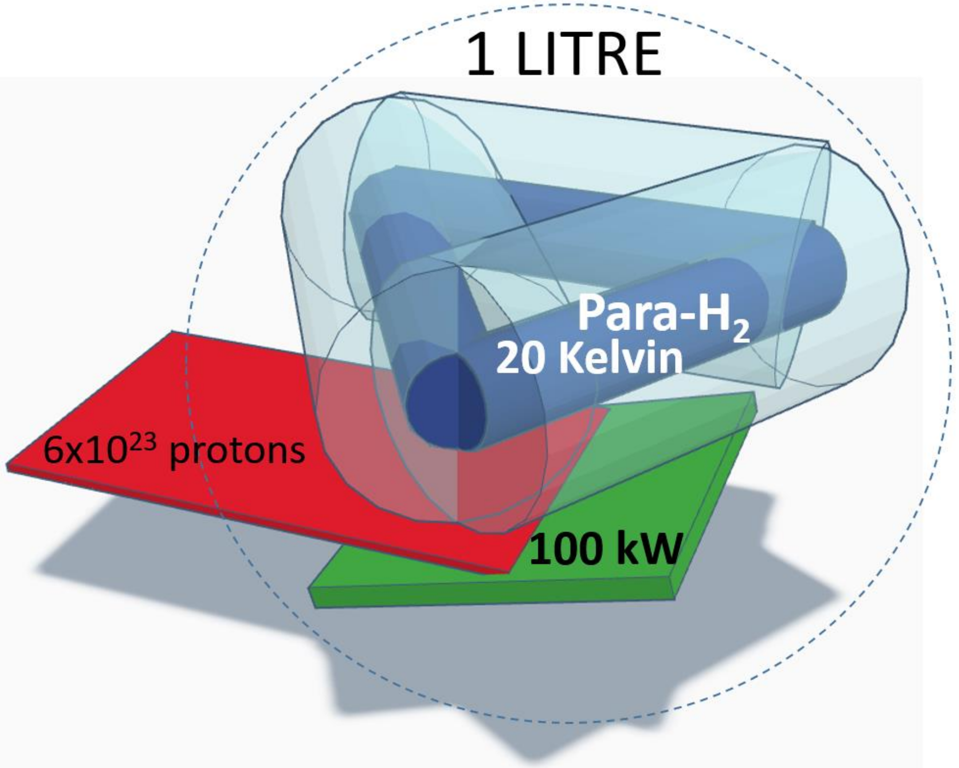


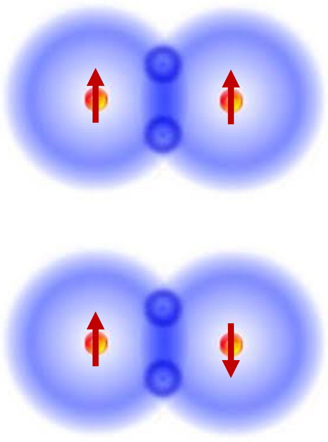
MODERATORS

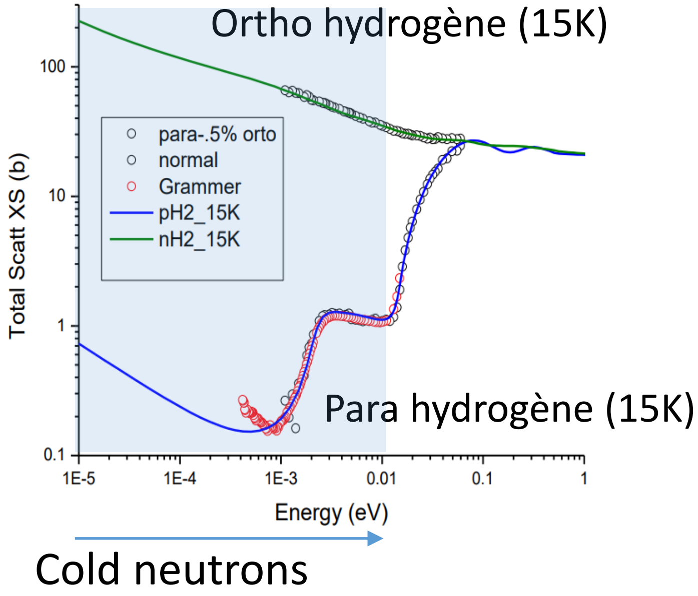
During the R&D of the ESS,
→ Emergence of the concept of a *directional* moderater

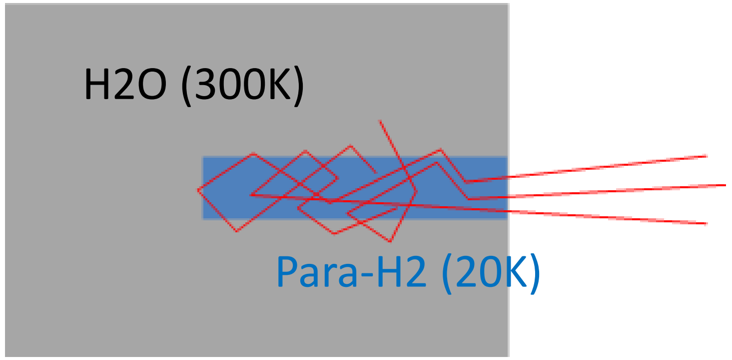
Passage d'une géométrie 3D (volume)
→ Géométrie 2D (→ ESS)
→ Géométrie 1D (tubes, ICONE, HBS)

→ Use of the special properties of para-hydrogen



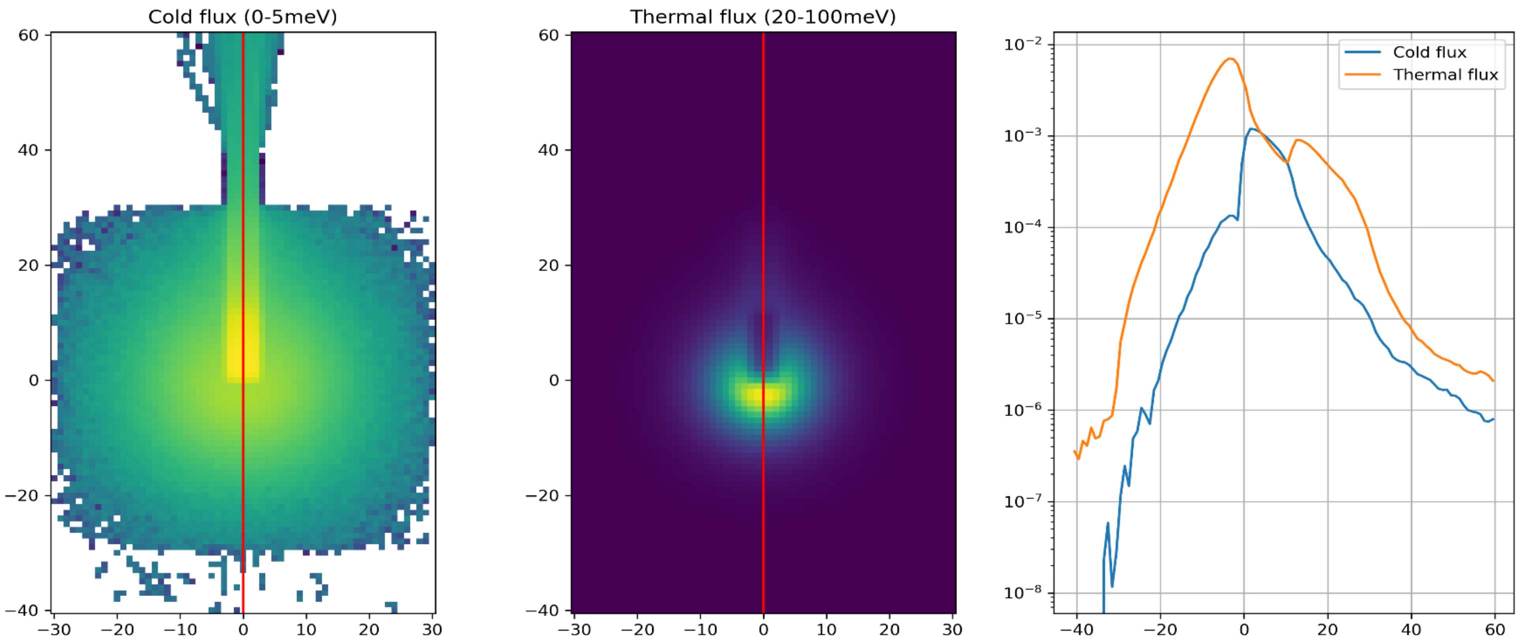






Quand les neutrons se thermalisent et que leur énergie passe sous 10meV ils peuvent sortir librement du modérateur parce que le para-H2 devient transparent aux neutrons et ils sont émis dans une direction utile

Objective: Demonstrate the real performance of a directional moderator using LICORNE@ALTO

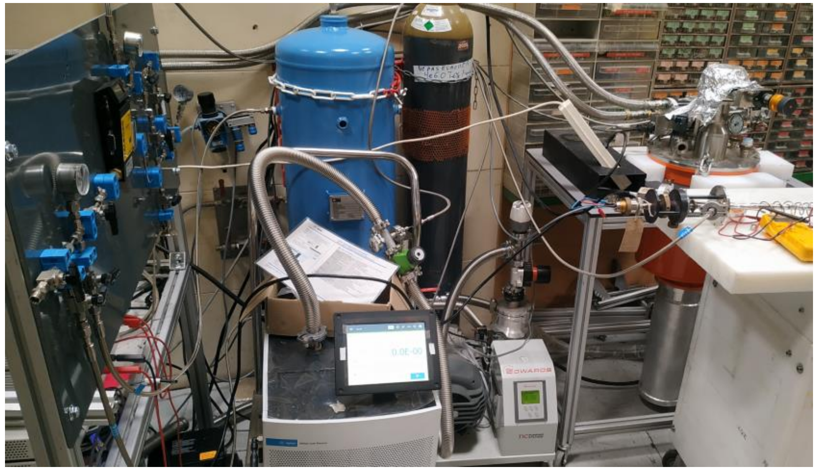


Current Status : Cryostat under construction / test

Cryostat + cryogénérateur

Condenser and cell (test geometry)

Moderation cell
(en aluminium dans la version finale)



Other cryogenic equipment

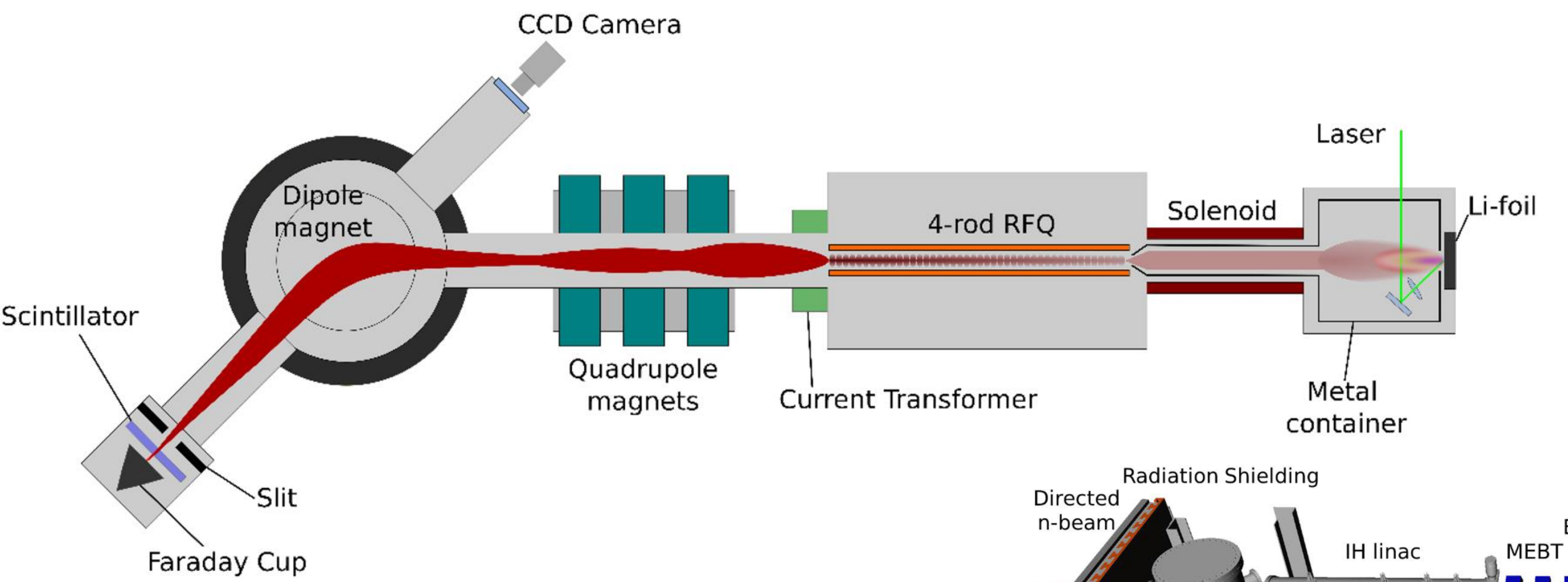
Future Applications

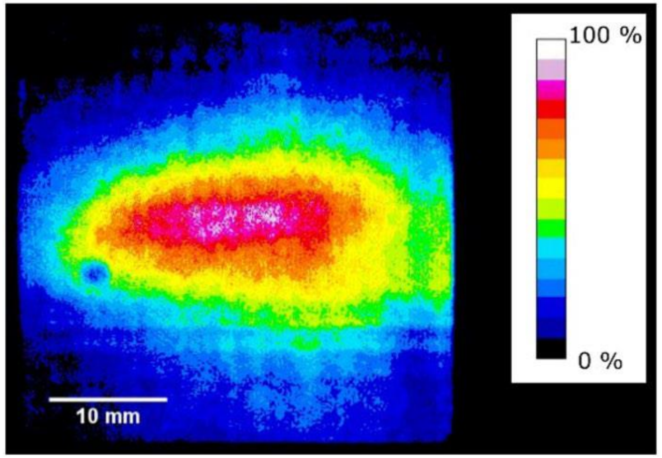
- Development of a very high intensity “Super-LICORNE?”

Brookhaven National Lab Developments (2022-)

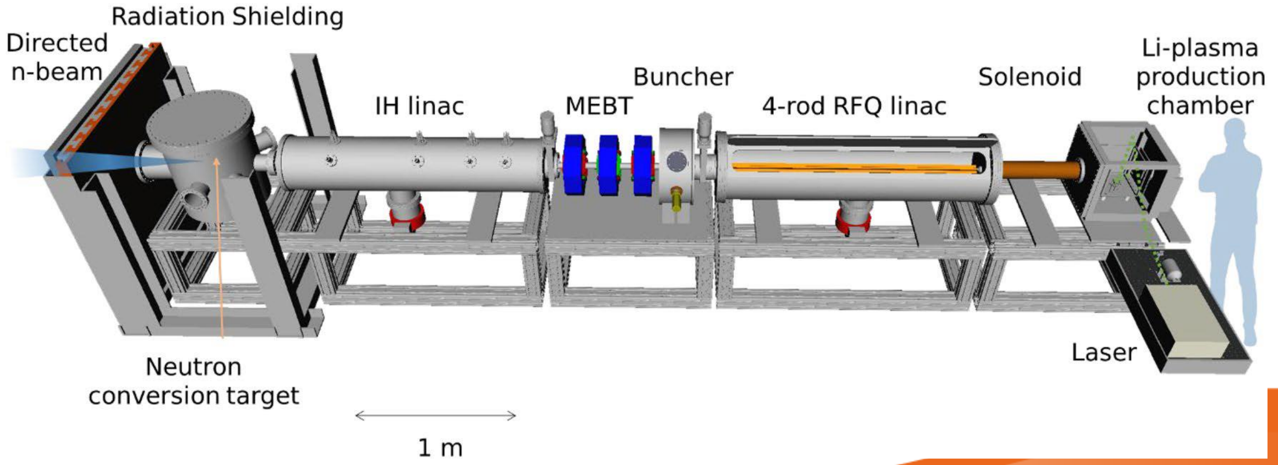
Demonstration of an intense lithium beam for forward-directed pulsed neutron generation

M. Okamura et al. Nature Scientific Reports 12 14016 (2022)





Li beam, 35 mA !!!



Neutron converter is still in the design phase

Thank you for your attention!

LICORNE publications (2013 – 2017)

14) Studies of fission fragment yields via high-resolution γ-ray spectroscopy
J.N. Wilson, M. Lebois, L. Qi, et al., Proceedings of the Theory-4 international workshop, Varna, Bulgaria (2017)
13) Neutron-rich isotopes from 238U(n,f) and 232Th(n,f) studied with the nu-ball spectrometer coupled to the LICORNE neutron source
J.N. Wilson, M. Lebois , and L. Qi, Proceedings of the FISSION-2017 international conference, Chamrousse (2017)
12) Anomalies in the charge yields of fission fragments from the 238U(n,f) reaction
J.N. Wilson, M. Lebois, L. Qi et al.,, Phys. Rev. Lett. 118, 222501 (2017)
11) Production and study of neutron-rich nuclei using the LICORNE directional neutron source
J.N. Wilson, M. Lebois, L. Qi et al., Proceedings of the Zakopane international conference, Acta Physica Polonica B Vol.48 395 (2017)
10) Studies of γ-ray emission in the fission process with LICORNE
M. Lebois, J.N. Wilson, et. al , Proceedings of the CNR*15 international conference , EPJ Web of Conferences 122, 01010 (2016)
9) Comparative measurement of prompt fission gamma-ray emission from fast neutron induced fission of 235U and 238U
M. Lebois, J.N. Wilson, et al, Phys. Rev. C 92 034 618 (2015)
8) Prompt Emission in Fission Induced with Fast Neutrons
J.N. Wilson, M. Lebois, P. Halipré, S. Oberstedt, A. Oberstedt, Physics Procedia, Volume 64, Pages 107–113 (2015)
7) Future research program on prompt gamma-ray emission in nuclear fission
S. Oberstedt, R. Billnert, F. -J. Hambsch, M. Lebois, A. Oberstedt and J. N. Wilson , Eur. Phys. J. A, 51 12 (2015) 178
6) Development of a kinematically focused neutron source with the p(7Li,n)7Be inverse reaction
M. Lebois, J.N. Wilson, P. Halipre, B. Leniau, I. Matea, A. Oberstedt, S. Oberstedt, D. Verney, Nucl. Instrum. Meth. A 735 46 (2014)
5) The LICORNE neutron source and measurements of prompt gamma rays emitted in fission
J.N. Wilson, M. Lebois, et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
4) Prompt fission gamma-rays from fast neutron-induced fission of 238U, 232Th and 235U with LICORNE
M. Lebois, J.N. Wilson et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
3) Measurements of prompt gamma-rays from fast-neutron induced fission with the LICORNE directional neutron source
J.N. Wilson, M. Lebois, P. Halipre, A. Oberstedt, S. Oberstedt, Proceedings of the final ERINDA meeting, CERN, Geneva (2013)
2) The LICORNE neutron source
J.N. Wilson, M. Lebois et al., Proceedings of the International Conference, FISSION2013, Caen, France (2013)
1) Nuclear Research with Quasi Mono-Energetic Neutrons at the IPNO LICORNE Facility
S. Oberstedt, J.N. Wilson, R. Billnert, G. Georgiev, P. Halipre, M. Lebois, B. Leniau, J. Ljungvall, I. Matea, A. Oberstedt, D. Verney, International Atomic Energy Agency (IAEA), Proceedings technical meeting IAEA-F1-TM-42752 (2013)

95 users from 34 different institutions in 13 different countries

LICORNE publications (2018 – 2024)

Statistical study of the prompt-fission γ-ray spectrum for 238U(n, f) in the fast-neutron region
L. Qi, M. Lebois, J. N. Wilson, et al., Phys. Rev. C 98, 014612 (2018)
Measurement of the liquid argon energy response to nuclear and electronic recoils, P. Agnes, et al., Phys. Rev. D 97, 112005 (2018)
Precision gamma-ray spectroscopy of fast-neutron-induced fission with the nu-ball spectrometer
J.N. Wilson and M. Lebois, Nuclear Physics News, Nupecc, Vol 28. No. 4 p29 Dec. (2018)
Neutron-rich isotopes from 238U(n,f) and 232Th(n,f) studied with the nu-ball spectrometer coupled to the LICORNE neutron source
J.N. Wilson, M. Lebois, and L. Qi, EPJ Web of Conferences 193, 04010 (2018)
Studies of fission fragment yields via high-resolution γ-ray spectroscopy, J.N. Wilson, M. Lebois, L. Qi, et al., EPJ Web of Conferences 169, 00030 (2018)
Prompt fission gamma-ray emission spectral data for 239Pu(n,f) using fast directional neutrons from the LICORNE neutron source
L Qi et al. EPJ Web of Conferences 169, 00018 (2018)
Boutique neutrons advance 40Ar/39Ar geochronology, D. Rutte et al., Science Advances, Vol5. No.9 (2019)
Isomer Spectroscopy and Sub-nanosecond Half-live Determination in 178W Using the NuBALL Array, M. Rudigier et al., Acta Phys. Pol. B 50, 661 (2019)
The ν-Ball Campaign at ALTO, M. Lebois et al. Acta Phys. Pol. B 50, 425 (2019)
Spectroscopy of neutron-induced reactions with the nu-ball spectrometer, N. Jovancevic et al. Acta Phys. Pol. B 50, 297 (2019)
Multi-quasiparticle sub-nanosecond isomers in 178W, M. Rudigier, P.M. Walker, R.L. Canavan, et al., Phys. Lett. B 801 (2020) 135140
Prompt and delayed spectroscopy of the neutron-rich 94Kr and observation of a new isomer, R-B. Gerst et al., Phys. Rev. C 102, 064323 (2020) γ-ray **Spectroscopy of 85Se Produced in 232Th Fission,** E. Adamska et al., Acta Phys. Pol. B 51, 843 (2020)
Prompt γ-ray characteristics from 235U(n, f) at En= 1.7 MeV, A. Oberstedt, M. Lebois, S. Oberstedt, L. Qi & J. N. Wilson, Eur. Phys. J. A 56 (2020) 236
Half-life measurements in 164,166Dy using γ–γ fast-timing spectroscopy with the ν-Ball spectrometer
R.L. Canavan, M. Rudigier, P.H. Regan, et al., Phys. Rev. C 101, 024313 (2020)
Potential of prompt γ-ray emission studies in fast-neutron induced fission: A first step, L. Qi, C. Schmitt, et al. Eur. Phys. J A 56:98 (2020)
The ν-Ball spectrometer, M. Lebois, N. Jovančević, D. Thisse, R. Canavan, D. Étasse, M. Rudigier, J.N. Wilson, Nucl. Instrum. and Meth. in Phys. Res. A 960, 163580 (2020)
First lifetime investigations of N>82 iodine isotopes: The quest for collectivity, G. Häfner et al., Phys. Rev. C 104, 014316 (2021)
Characterization of the scintillation time response of liquid argon detectors for dark matter search, P. Agnes et al., Journal of Instrumentation 16 P11026 (2021) **Angular momentum generation in nuclear fission,** J.N. Wilson et al., Nature 590, p566–570 (2021)
Spectroscopy and Lifetime Measurements in 134,136, 138Te Isotopes and Implications for the Nuclear Structure beyond N = 82
G. Hafner, R. Lozeva, et al., Phys. Rev. C 103 (2021) 034317
Study of N = 50 gap evolution around Z = 32: new structure information for 82Ge, D. Thisse, M. Lebois, et al., Eur. Phys. J. A (2023) 59:153
Examination of how properties of a fissioning system impact isomeric yield ratios of the fragments, D. Gjestvang et al., Phys. Rev. C 108 (2023) 064602

95 users from 34 different institutions in 13 different countries

The ν-Ball collaboration

IJC Lab, CEA DAM
Subatech, CENBG, IPHC,
GANIL, LPC Caen

University of Surrey, NPL
University of Manchester

IFJ-PAN Krakow
University of Warsaw

University of Novi Sad

University of Oslo

TU Darmstadt
IFK- Koln

University of Milano
INFN Legnaro

JRC-Geel
Leuven

University of Madrid
IFIC Valencia

ELI-NP, Bucharest

University of Sofia

Riken

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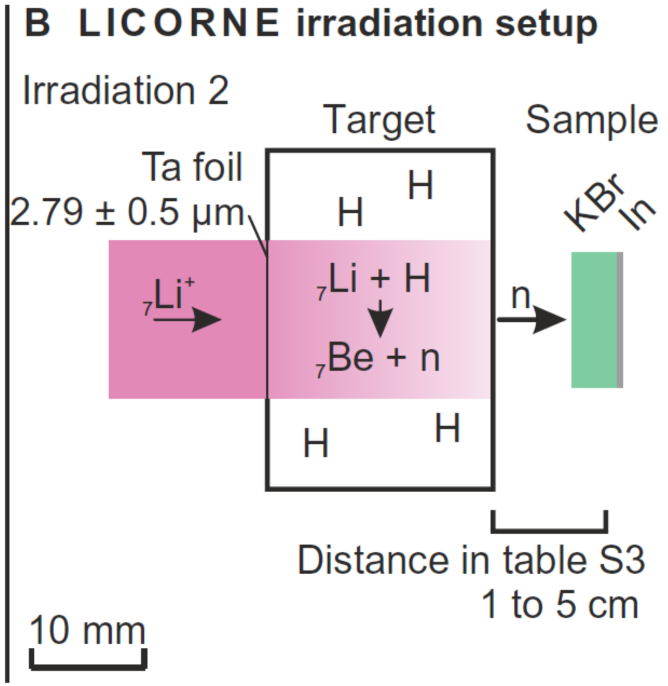
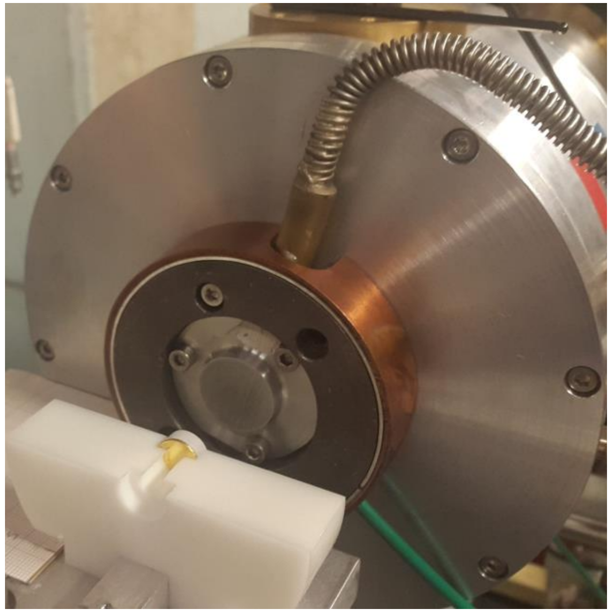
Geochronology: Measurement of $^{39}K(n,p)^{39}Ar$ cross section

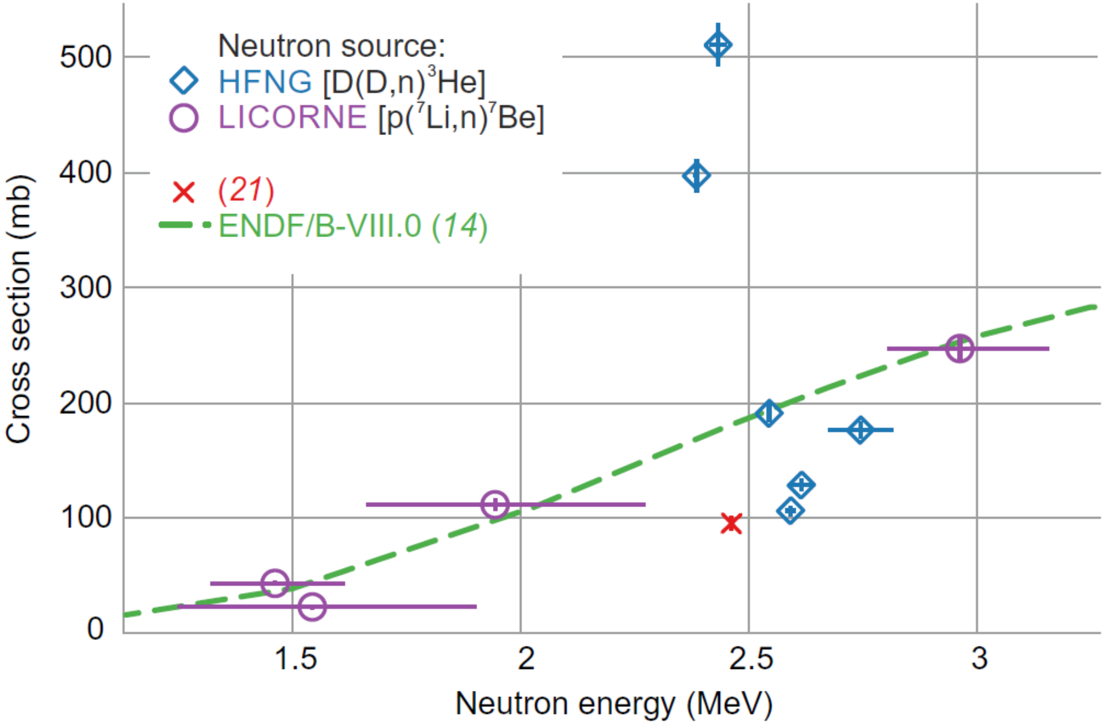
Boutique neutrons advance 40Ar/39Ar geochronology D. Rutte et al. Science Advances, Vol5. No.9 (2019)

$T_{1/2}$ (^{40}K) = 1.25 x 10^9 years Geochronological dating method for old rocks -> build up of ^{40}Ar daughter

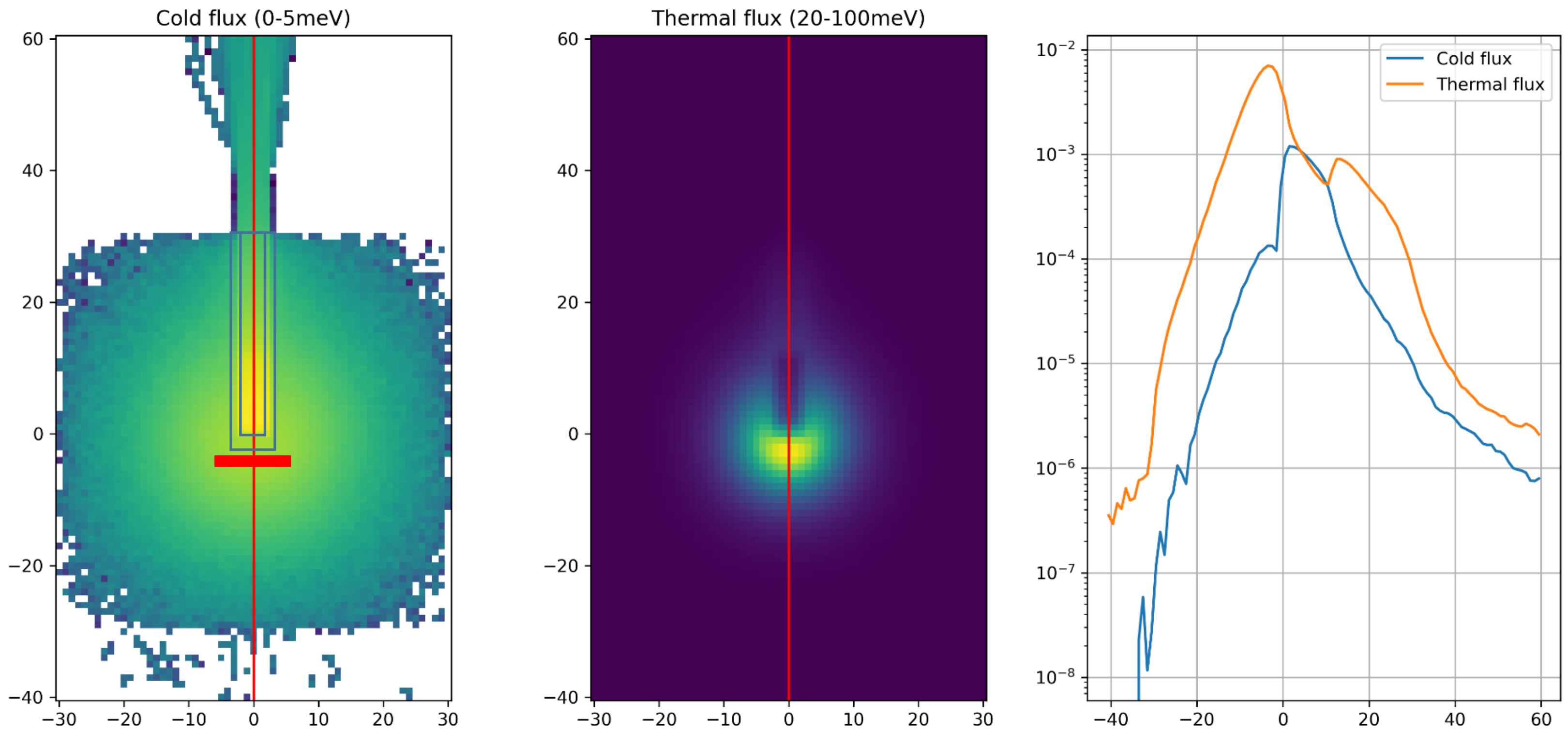
Accelerator based neutron irradiations broaden the applicability of the dating method to fine-grained materials



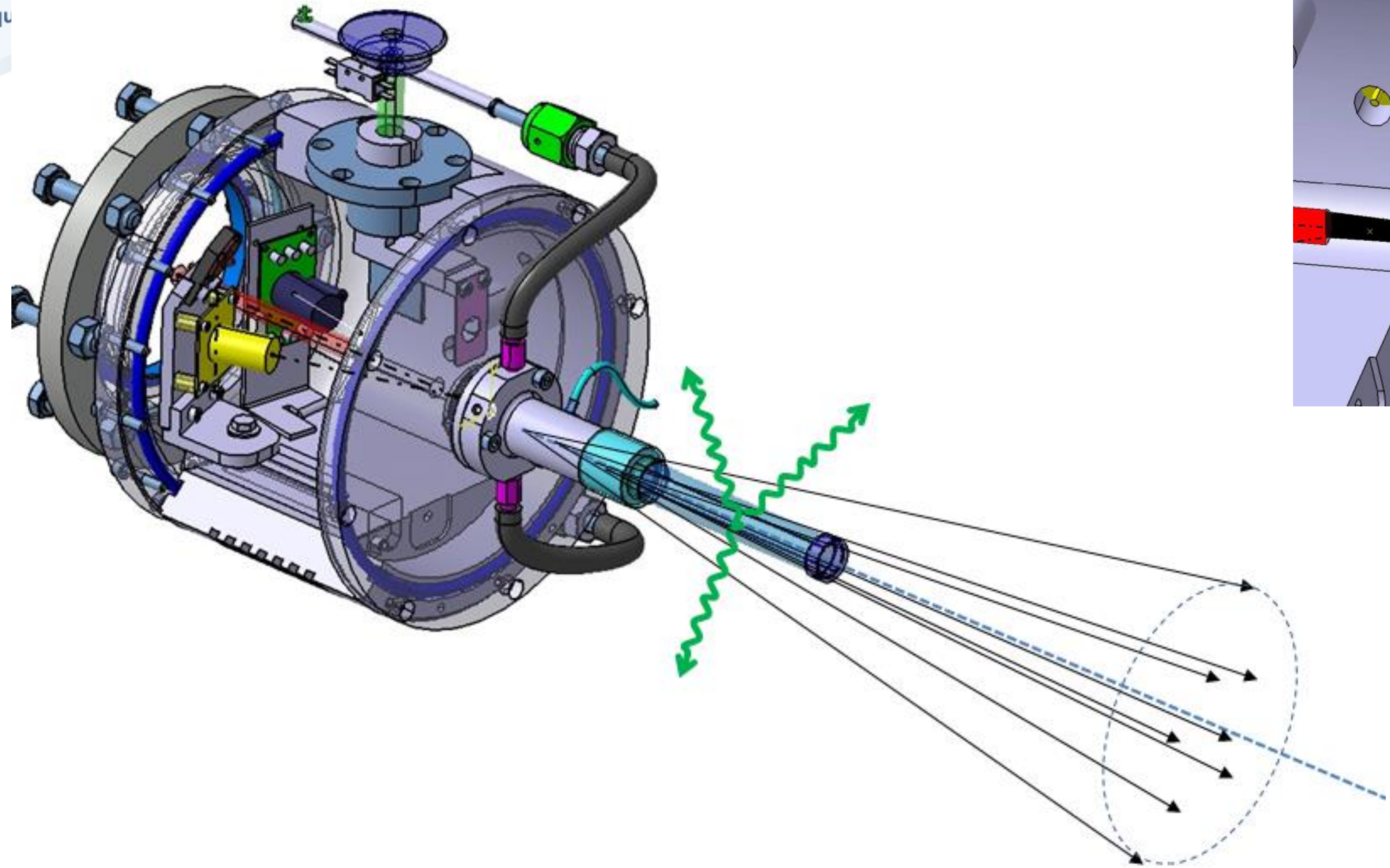


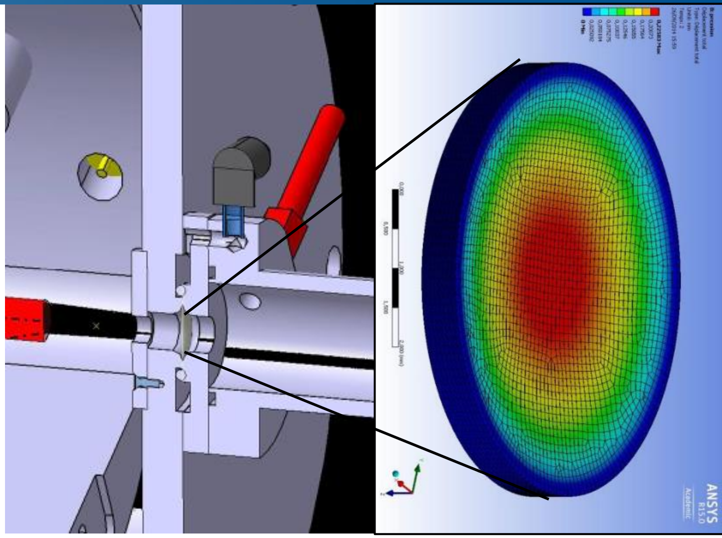


Simulations Monte-Carlo



LICORNE (H_2 gas version) chamber design 2014





Thin Ta window

- Separates vacuum and up to 2 atm hydrogen
- Cooling circuit to maintain window temperate and avoid melting