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Neutron Cross Sections: Linking the Lab to the Cosmos

… and how to measure them

Michael Bacak (TU Wien, Austria)

Michael Bacak

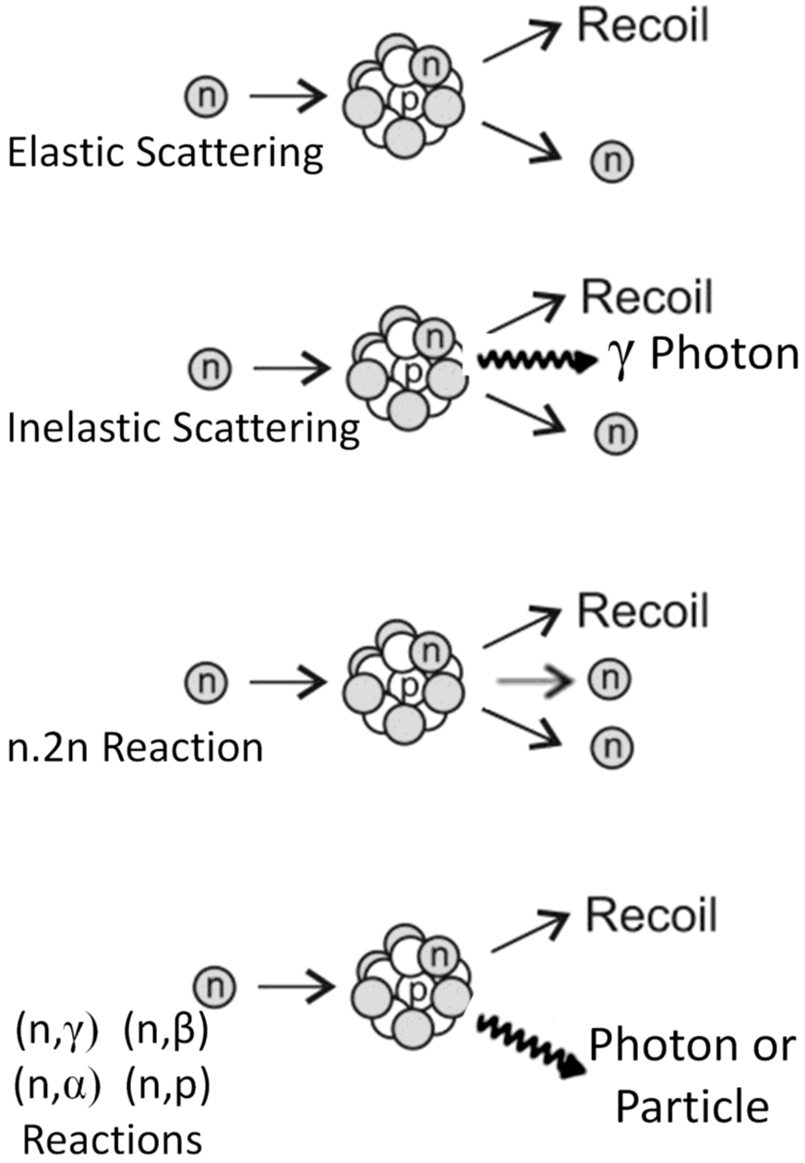
- 1989 @ Vienna
- Technical Physics BSc & MSc @ TU Wien (reactor neutrons)
- 2016-2019 PhD: ^{233}U(n,g) @ TU Wien & Université Paris-Saclay
  based at n_TOF/CERN
- 2019-2021: PostDoc @ PSI – neutron dark-field imaging
- 2021-2024: CERN Research Fellow & Run Coordinator @ n_TOF/CERN
- 2024-2026: MSCA Fellow @ TU Wien: developing instruments for (n,inl)/(n,xng) measurements at n_TOF via gamma-ray spectroscopy

Basics of neutron cross sections

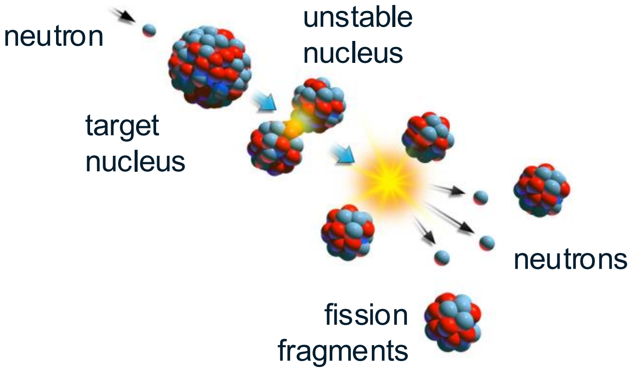
… and where they are needed

Basics: neutrons & matter

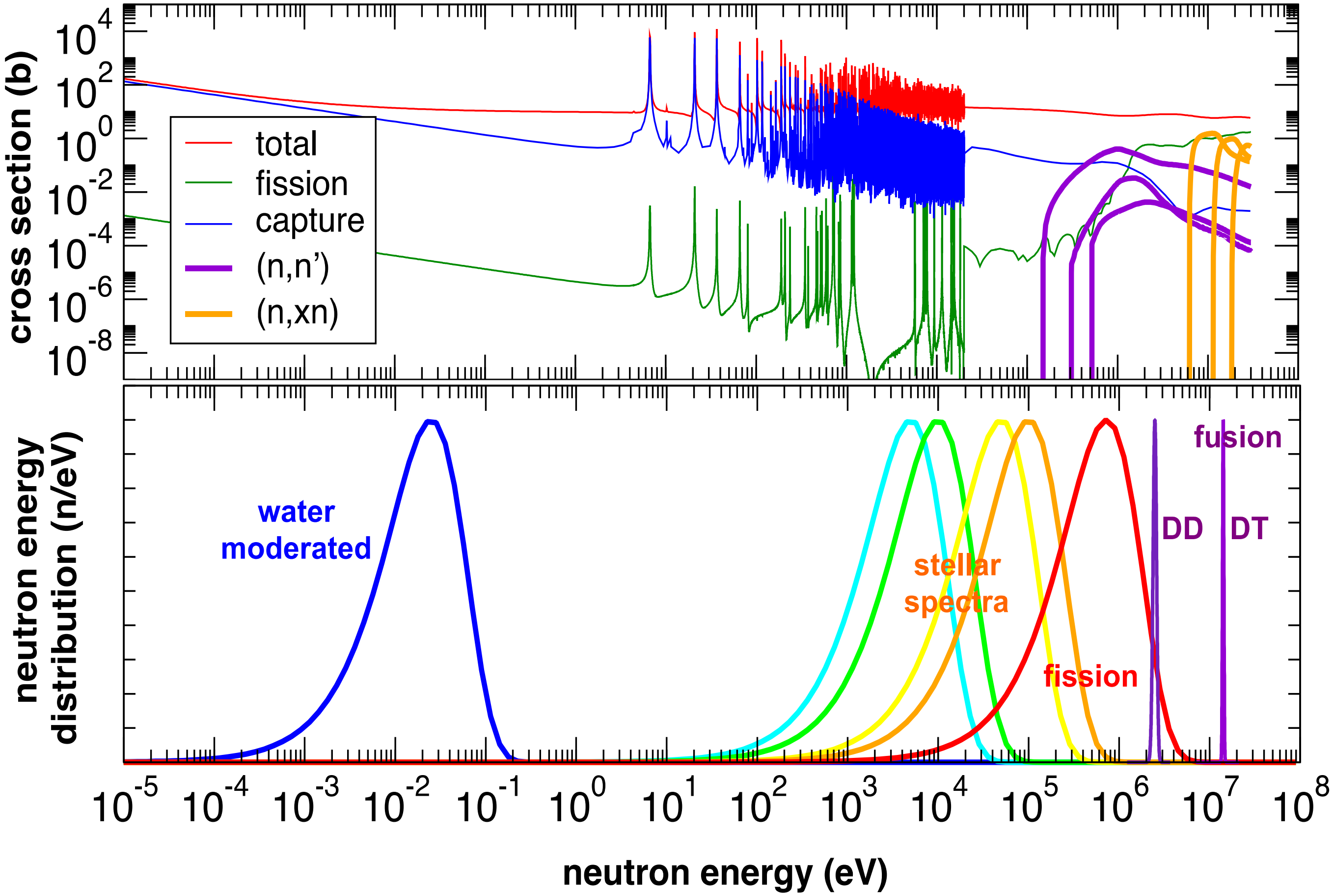
- Hadron, no electrical charge = interaction with nuclei
- Scattering or absorption → secondary radiation
- Cross section (XS): physical quantity representing the probability for an interaction to occur

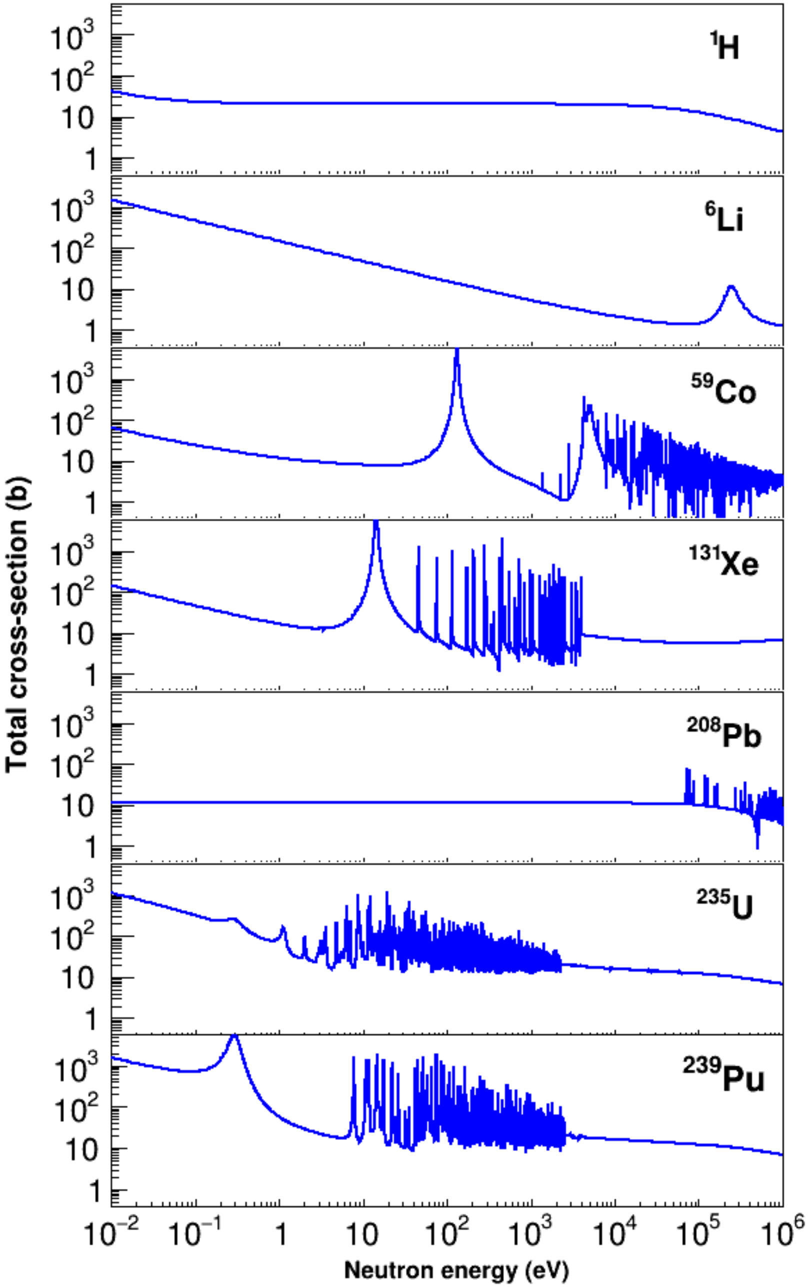


Fission (n,*f*)



Cross sections





Resonant XS structure reveals something about **nuclear physics** and makes **transport calculations** tricky

Nuclear data (including cross sections) are …

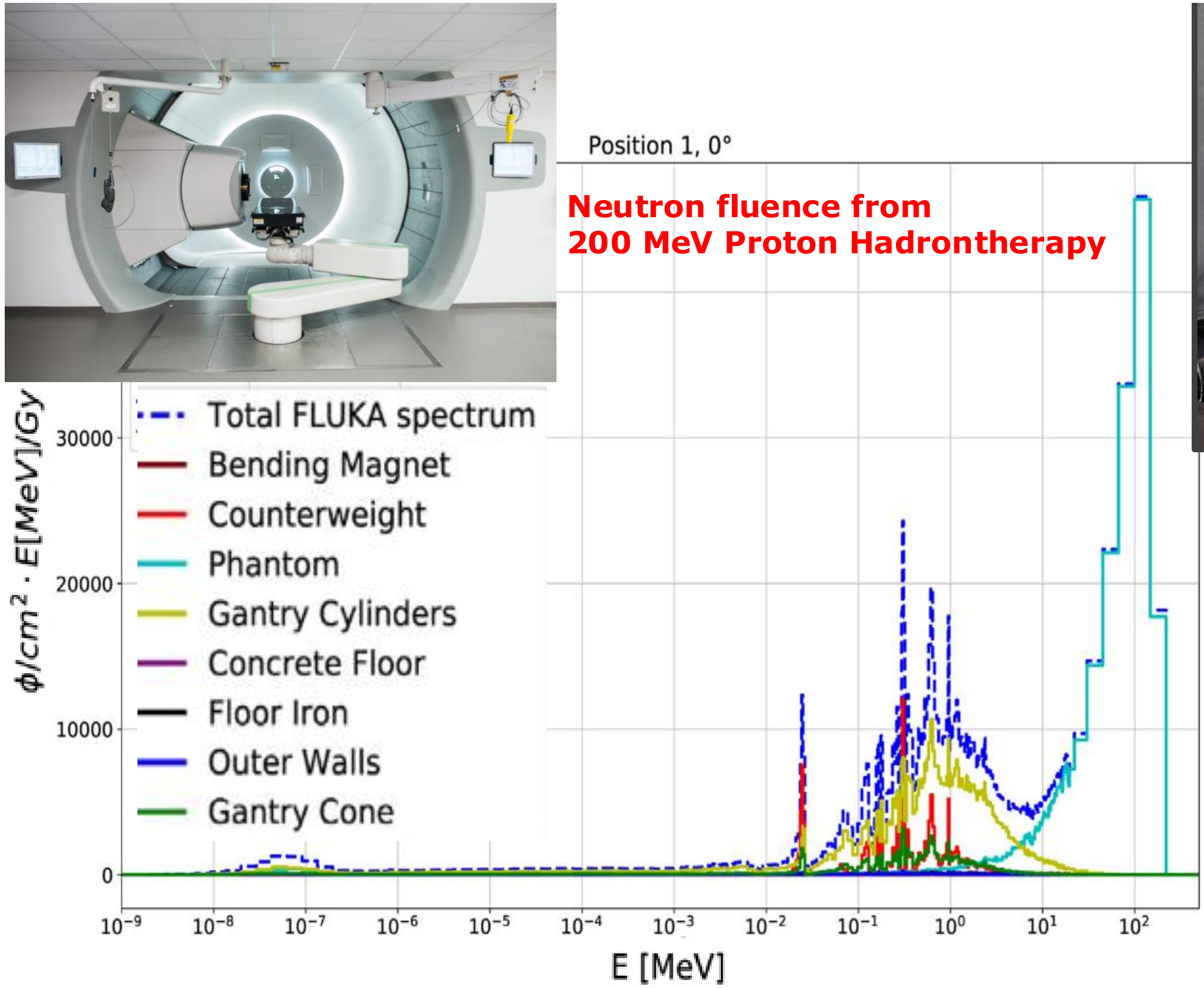
… the quantified properties of atomic nuclei and their interactions, expressed in numerical form so they can be used in calculations, simulations, and design of nuclear and physics systems.

They are the **bridge between nuclear physics** experiments/theory **and practical applications**:

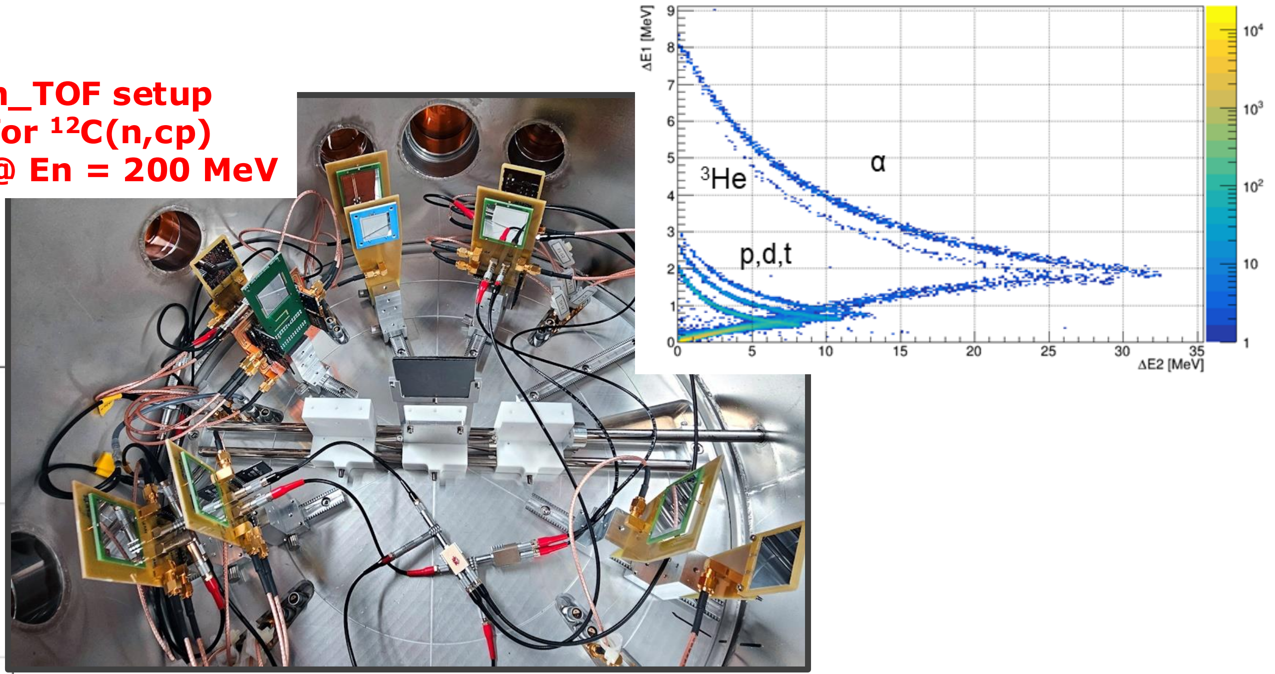
- Energy applications: fission and future fusion reactors
- Astrophysics
- Shielding
- Dosimetry
- Medical isotopes
- Safeguards
- Space applications and planetary exploration
- Geological surveys
- …

Medicine & radiobiology

Neutron fluence from 200 MeV Proton Hadrontherapy



n_TOF setup for $^{12}C(n,cp)$ @ En = 200 MeV



dose in an airplane

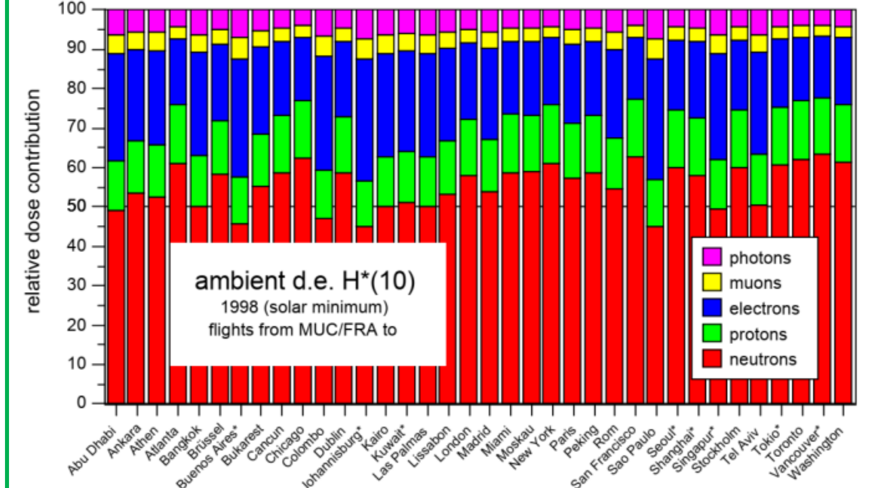
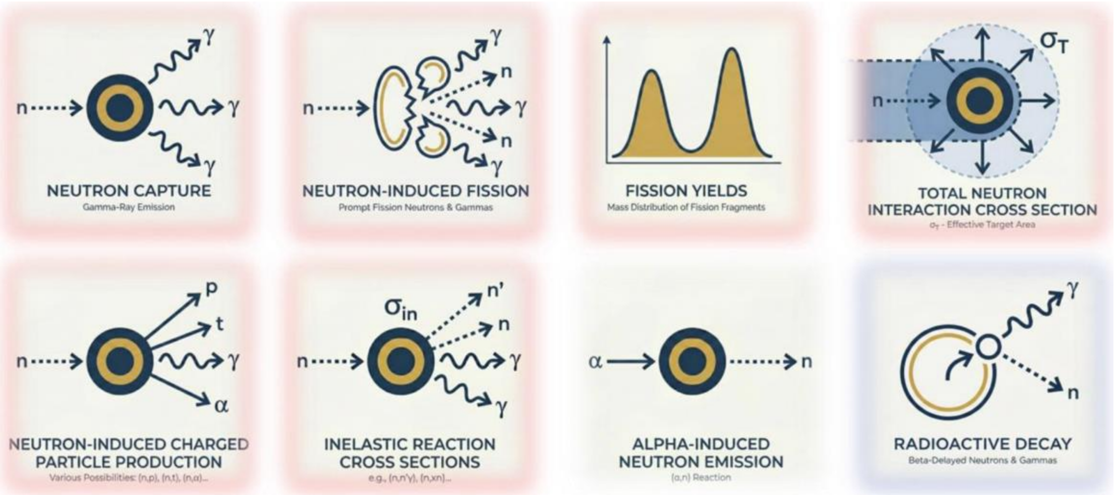
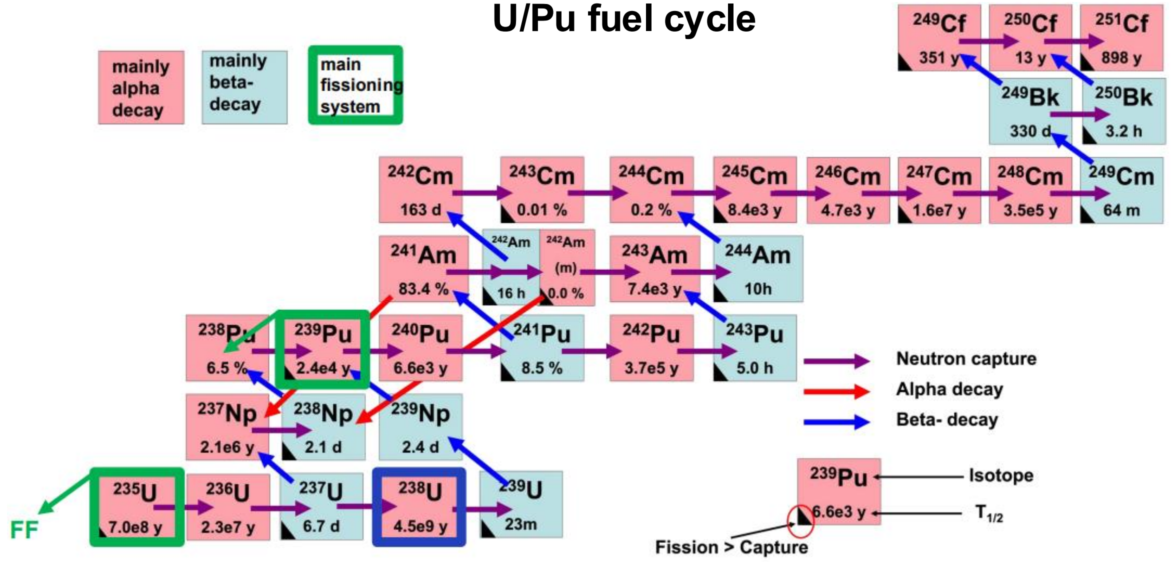


Figure II.6 Relative contribution to ambient dose equivalent for various destinations near solar minimum condition (1998) for 37000 ft flight altitude.

(Advanced) Nuclear Technologies



U/Pu fuel cycle



fission

Gen IV designs (SFR, LFR, MSR, VHTR) require data for high-energy (fast) neutrons and high temperatures.

Fast Reactors (SFR/LFR): ^{23}Na and ^{208}Pb/^{209}Bi

Molten Salt Reactors (MSR): complex salt chemistry (e.g., FLiBe), precursor drift effects, ^{35}Cl.

High Temperature (VHTR) demands accurate Thermal Scattering Laws (TSL)

Fuel Cycle Economics & Burnup Credit

Burnup Credit: reactivity reduction from fission products.

Decay Heat Prediction: packing in spent fuel casks.

Power Uprates: plants running at higher power without violating safety limits.

Small Modular Reactors (SMR)

The Physics of Leakage: reflectors like Be and steel.

Economic Sensitivity: factory serial production.

Transportability: Micro-reactors require optimized shielding.

Structural materials

New Alloys: accurate displacement cross-sections (dpa) to predict swelling and embrittlement,.

Activation: ^{56}Fe, ^{58}Ni… become radioactive.

New fuels

HALEU (High-Assay Low-Enriched Uranium) with 5–20% enrichment range, forcing regulators to use large safety margins.

Advanced Technology Fuels / Accident Tolerant Fuels (ATF):

SiC Cladding: thermal scattering data.

Uranium Silicide (U_3Si_2): thermal scattering data.

FeCrAl Cladding: Requires activation cross-sections for Fe and Cr.

Waste management

Minor Actinides (MA): transmutation of ^{239}Pu, ^{237}Np and ^{241,243}Am.

Shielding: Handling ^{244}Cm requires massive shielding.

Regulatory modernisation

BEPU Methodology: "Best Estimate Plus Uncertainty" (BEPU) approaches.

Covariance Matrices: Correlations for avoiding worst-case scenarios.

Licensing Advanced Designs: safety analyses based on well-characterized data.

fusion

Tritium breeding (fuel self-sufficiency). Fusion reactors must breed more tritium than they consume. Highly accurate nuclear data for lithium breeding reactions and neutron multipliers (Be, Pb) are critical.

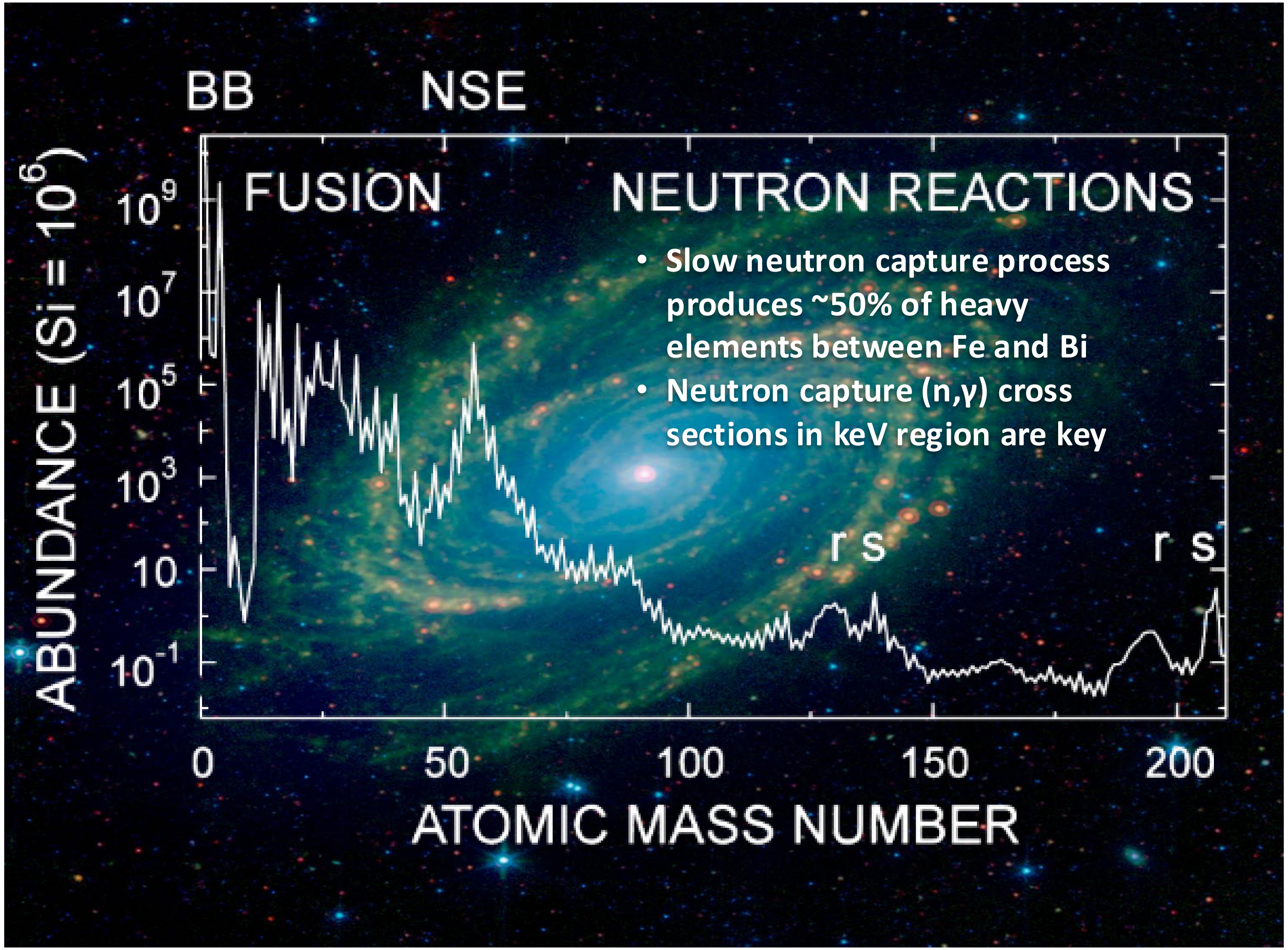
Radiation damage and material lifetime. High-energy fusion neutrons cause severe displacement damage and gas production (helium and hydrogen) in structural and plasma-facing materials. Reliable cross-sections are essential to predict swelling, embrittlement, and component lifetimes.

Shielding and magnet protection. Superconducting magnets are extremely radiation-sensitive. Accurate neutron and gamma transport data are needed to model deep shielding penetration and gamma heating, which directly affects magnet cooling and operational safety.

Safety, activation, and waste management. Reactor materials become activated. Precise activation data are required to predict decay heat, waste classification, and shutdown safety.

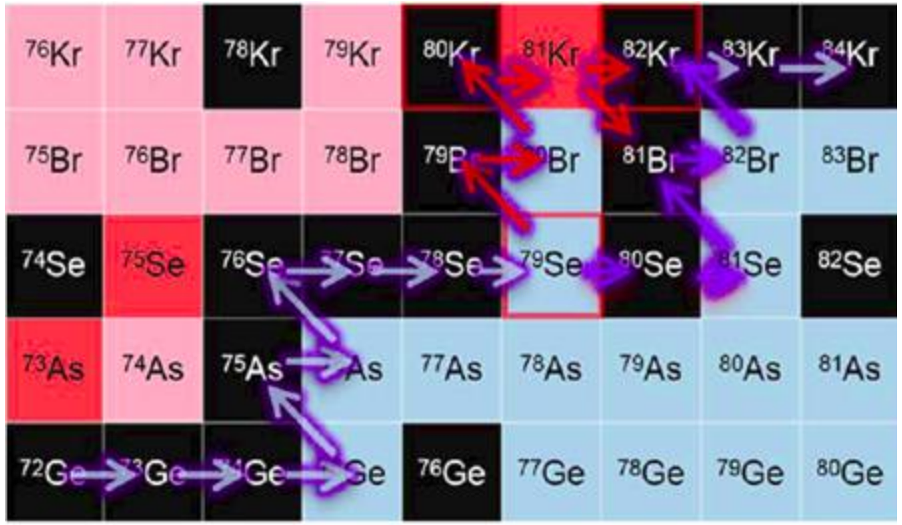
Advanced blanket concepts. Novel liquid breeders and coolants (e.g. FLiBe, Pb-Li) suffer from limited and uncertain neutronic and thermophysical data. Improving these datasets is essential to validate advanced blanket and cooling designs.

Nuclear Astrophysics – BB and Stellar Nucleosynthesis



- Slow neutron capture process produces ~50% of heavy elements between Fe and Bi
- Neutron capture (n,γ) cross sections in keV region are key

slow-process
& rapid-process

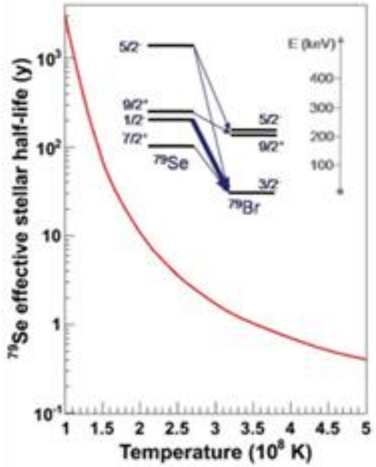


^{76}Kr	^{77}Kr	^{78}Kr	^{79}Kr	^{80}Kr	^{81}Kr	^{82}Kr	^{83}Kr	^{84}Kr
^{75}Br	^{76}Br	^{77}Br	^{78}Br	^{79}Br	^{80}Br	^{81}Br	^{82}Br	^{83}Br
^{74}Se	^{75}Se	^{76}Se	^{77}Se	^{78}Se	^{79}Se	^{80}Se	^{81}Se	^{82}Se
^{73}As	^{74}As	^{75}As	^{76}As	^{77}As	^{78}As	^{79}As	^{80}As	^{81}As
^{72}Ge	^{73}Ge	^{74}Ge	^{75}Ge	^{76}Ge	^{77}Ge	^{78}Ge	^{79}Ge	^{80}Ge

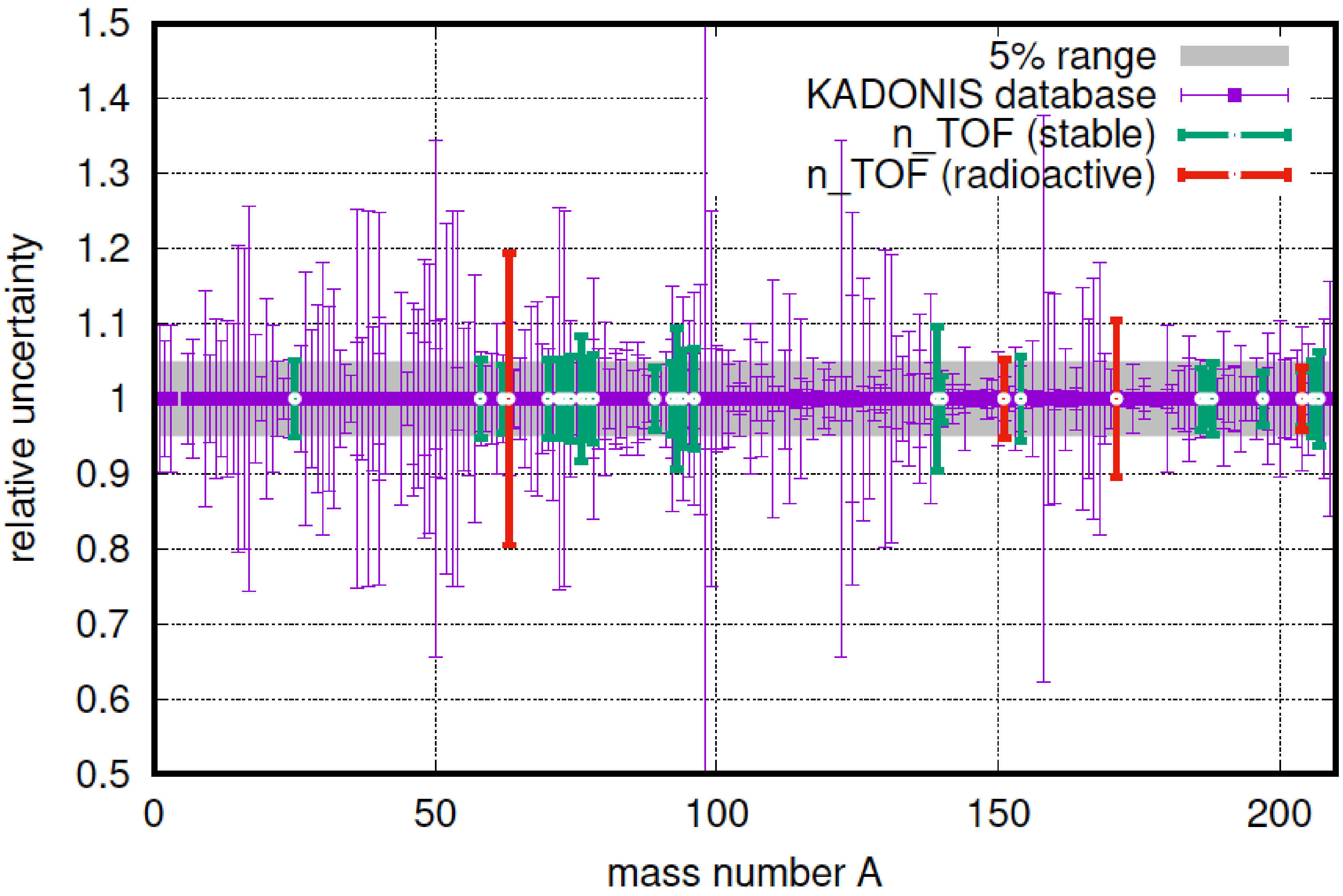
Not only abundance:

^{79}Se(n,ɣ): a stellar thermometer

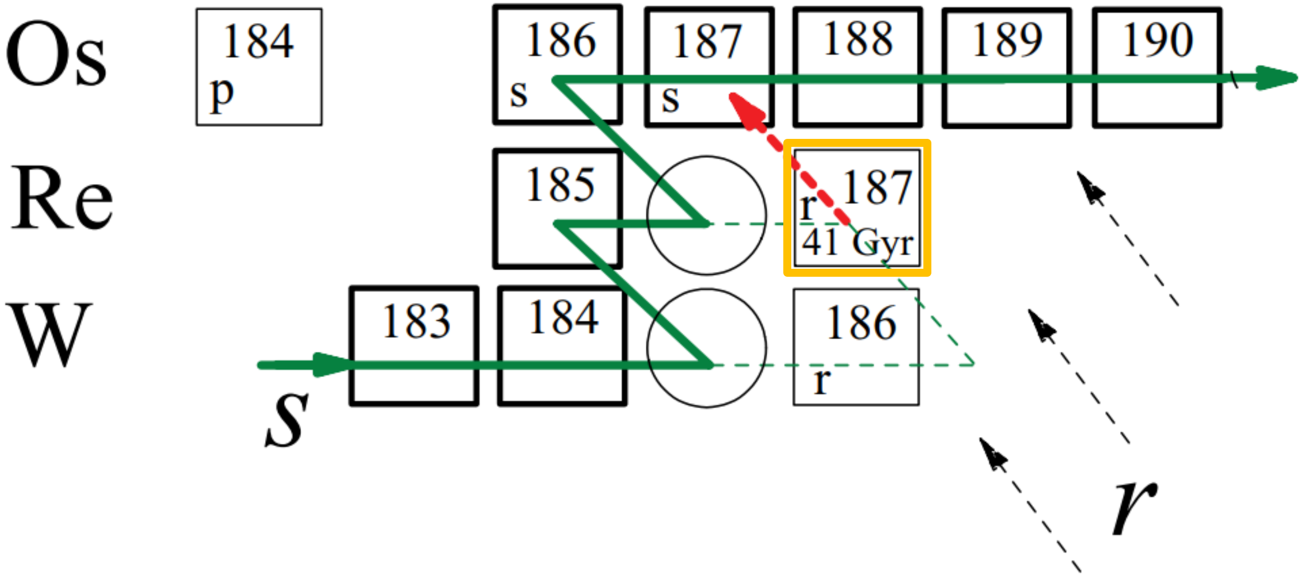
($T_{1/2,terr}$~3.10^5 y)



s-process (n,g) cross sections



Re-Os clock – ^{187}Re cosmochronometer



^{187}Re exclusively produced by r-process in supernova explosions in massive stars = fast/short life = clock started early after galaxy formation
→ chronometer for the formation of first galaxies

41.2 Gyr half-life provides radiogenic contribution to ^{187}Os abundance

Chronometer depends mostly on nuclear properties of the mother/daughter pair ^{187}Re/^{187}Os:

- ^{187}Re production through r-process starts at first galaxy formation
- ^{187}Os production through s-process & ^{187}Re decay (radiogenic contribution)
- **Observed ^{187}Os abundance – s-process component = radiogenic contribution**

$$N_c(^{187}\mathrm{Os}) = N_\odot(^{187}\mathrm{Os}) - N_s(^{187}\mathrm{Os})$$

Ingredients:

- S-process cross-sections in that region
- Mainly ^{186,187}Os(n,g) from eV to MeV (n_TOF)
- Stellar enhancement factors (SEF) due to thermally populated excited states: (n,n') cross-sections on ^{186,187}Os (Karlsruhe)

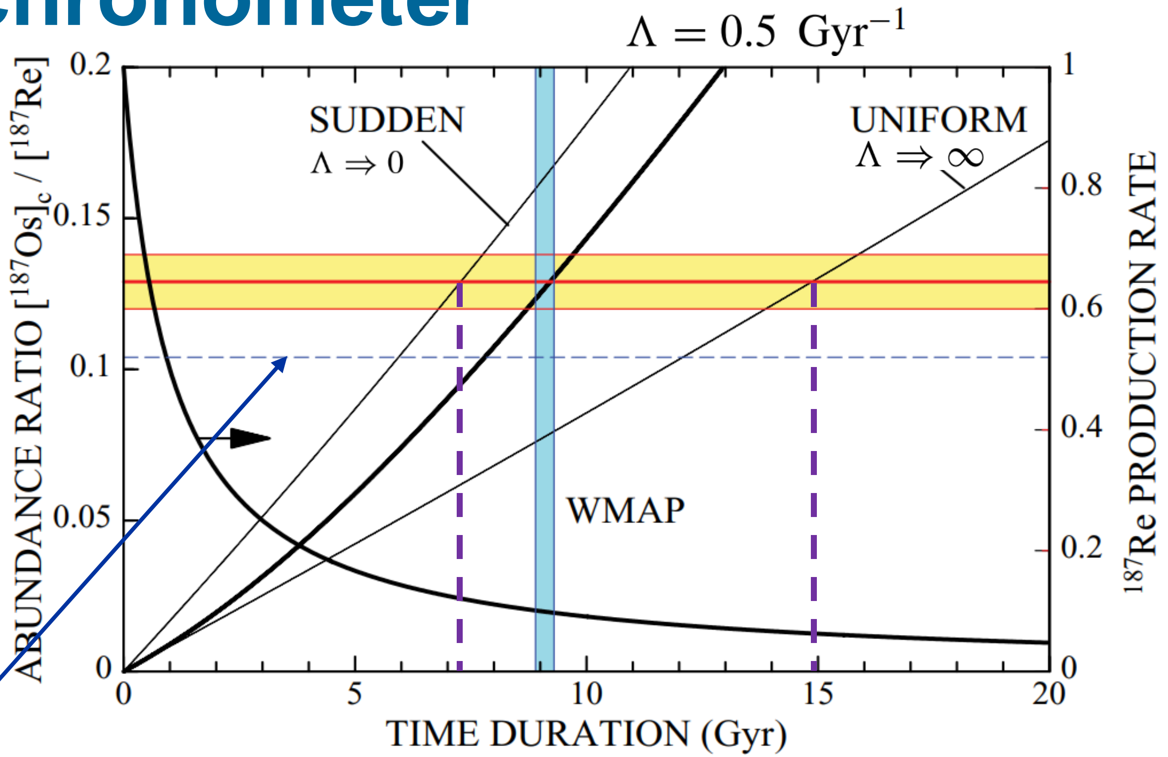
Uncertainties:

- Realistic model of galactic chemical evolution
- ~~Temperature dependence of the ^{187}Re half-life (GSI measurement on fully stripped ^{187}Re)~~
- ~~Minor s-process contribution to ^{187}Re~~

Re-Os clock – ^{187}Re cosmochronometer

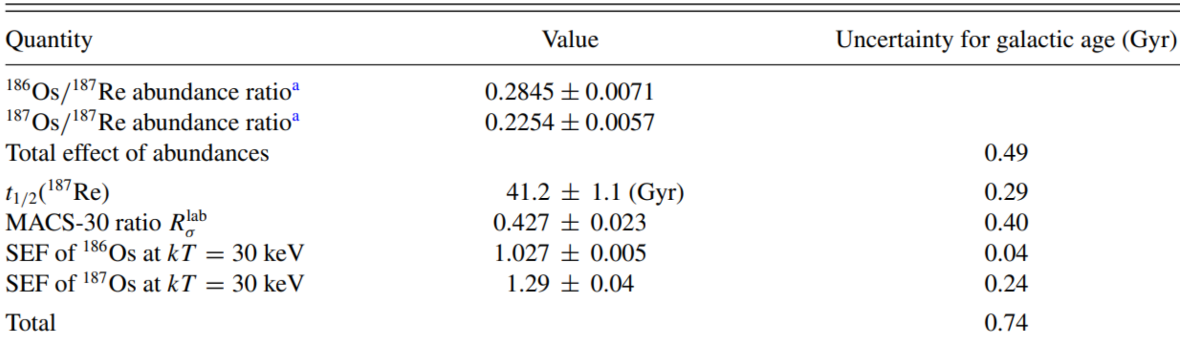
$$\frac{N_c(^{187}\mathrm{Os})}{N(^{187}\mathrm{Re})} = \left[\frac{\Lambda - \lambda}{\Lambda} e^{\Lambda t_0} \frac{1 - e^{-\Lambda t_0}}{1 - e^{-(\Lambda - \lambda) t_0}}\right] - 1$$

Λ and t0 time constant and duration of the r-process nucleosynthesis



before formation of solar system (4.65 Gyr)

Pre 2010 (n,g) and (n,n') measurements



Quantity	Value	Uncertainty for galactic age (Gyr)
^{186}Os/^{187}Re abundance ratio[a]	0.2845 ± 0.0071	
^{187}Os/^{187}Re abundance ratio[a]	0.2254 ± 0.0057	
Total effect of abundances		0.49
$t_{1/2}(^{187}\mathrm{Re})$	41.2 ± 1.1 (Gyr)	0.29
MACS-30 ratio R_σ^{lab}	0.427 ± 0.023	0.40
SEF of ^{186}Os at $kT = 30$ keV	1.027 ± 0.005	0.04
SEF of ^{187}Os at $kT = 30$ keV	1.29 ± 0.04	0.24
Total		0.74

K. Fujii et al., Physical Review C 82, 015804 (2010)

The Cosmological Lithium Problem

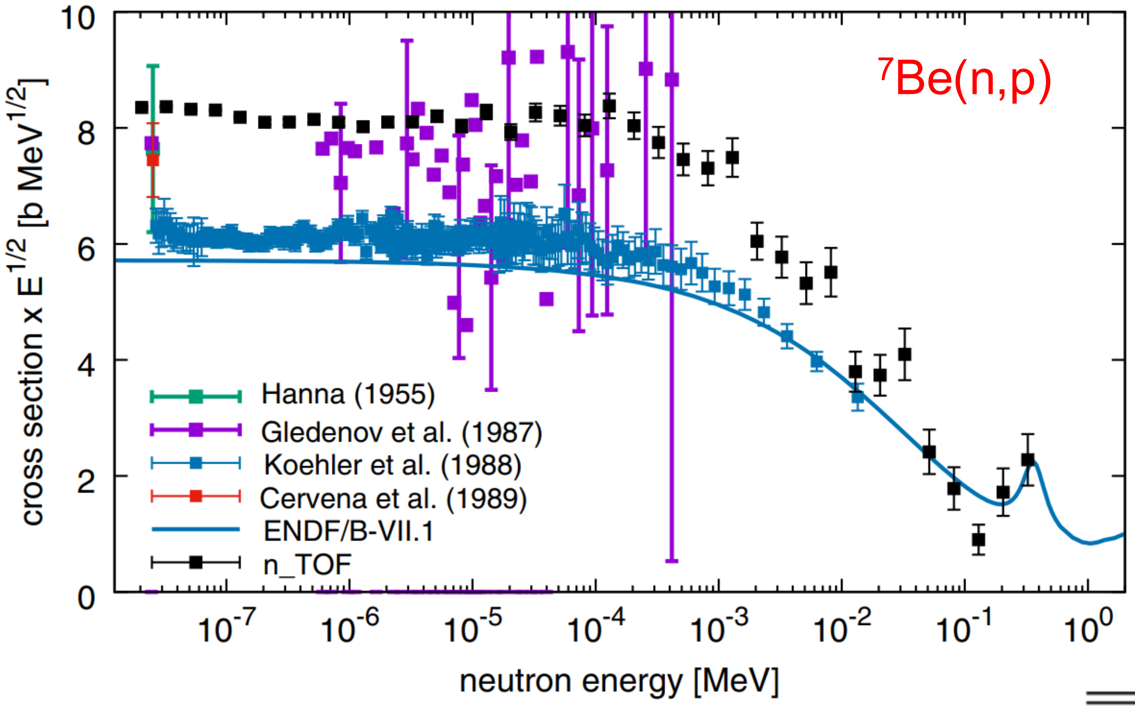
- Big Bang Nucleosynthesis = production of light elements.
  - Works well for D, ^{4}He
  - **Observed ^{7}Li abundance factor 3 smaller than predicted** – ***Missing ^{7}Li!***

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$

- Possible explanations involving:
  - astrophysics, astronomical observations, nonstandard cosmology, and new physics beyond the standard model physics
  - Numerous experiments with charged particles did not solve the issue

- **^{7}Be destruction via (n,a) and (n,p) possible** – data situation pre-2016:
  - **No data** in neutron energy region of interest (100s keV)
  - Inconsistent data below and when extrapolating (constrained via ^{7}Li(p,n)^{7}Be)
  - **Challenging measurement**:
    - ^{7}Be $t_{1/2}$ ~ 55 days
    - Sufficient material needs to be produced, refined and shaped (PSI > ISOLDE > PSI > n_TOF)

The Cosmological Lithium Problem



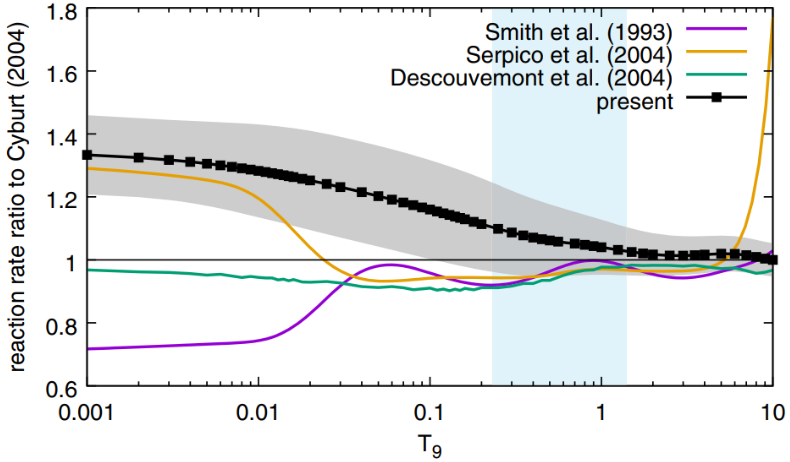
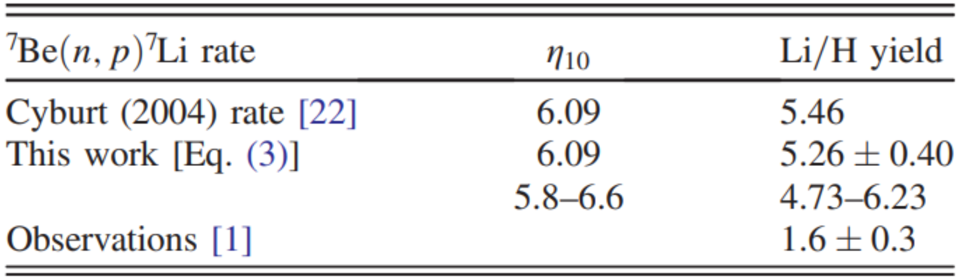


FIG. 3. Rates of the ^{7}Be$(n,p)^{7}$Li reaction relative to Cyburt [22]. The present result is shown with the associated error band, and the rates of Smith *et al.* [23], Serpico *et al.* [24], and Descouvemont *et al.* [25] are shown for comparison. The temperature range of BBN with a larger impact on the lithium yield is indicated by the vertical band.

L. Damone et al., Phys. Rev. Lett. 121, 042701 (2018)
M. Barbagallo et al., Phys. Rev. Lett. 117, 152701 (2016)

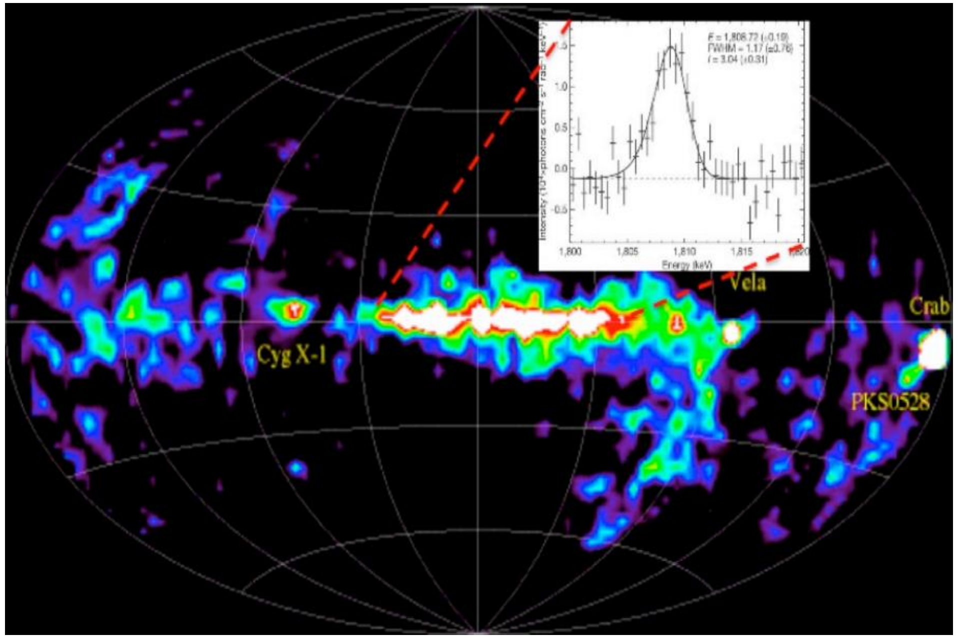


^{7}Be$(n,p)^{7}$Li rate	η_{10}	Li/H yield
Cyburt (2004) rate [22]	6.09	5.46
This work [Eq. (3)]	6.09	5.26 ± 0.40
	5.8–6.6	4.73–6.23
Observations [1]		1.6 ± 0.3

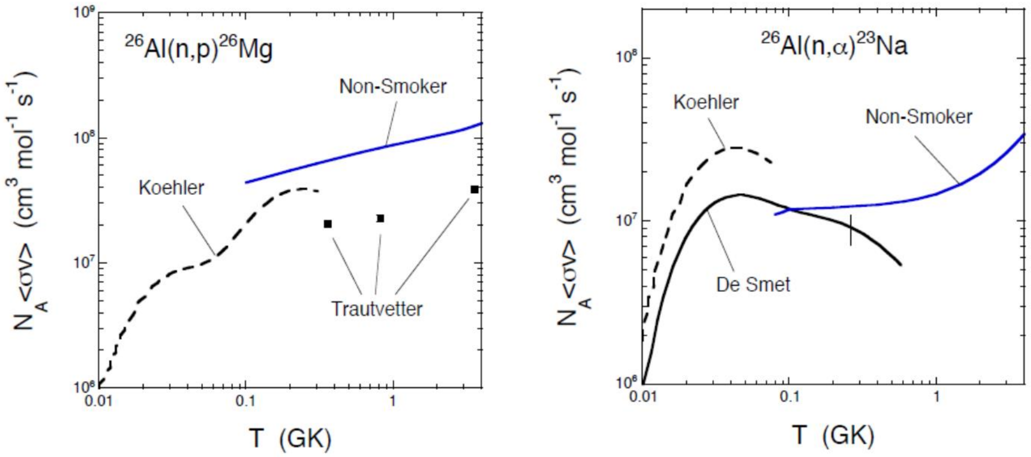
Destruction of ^{7}Be(n,a) and (n,p) is
not responsible for the missing ^{7}Li

^{26}Al – first cosmic/galaxy γ-ray emitter

R. Diehl, Nature 439, 45(2006)



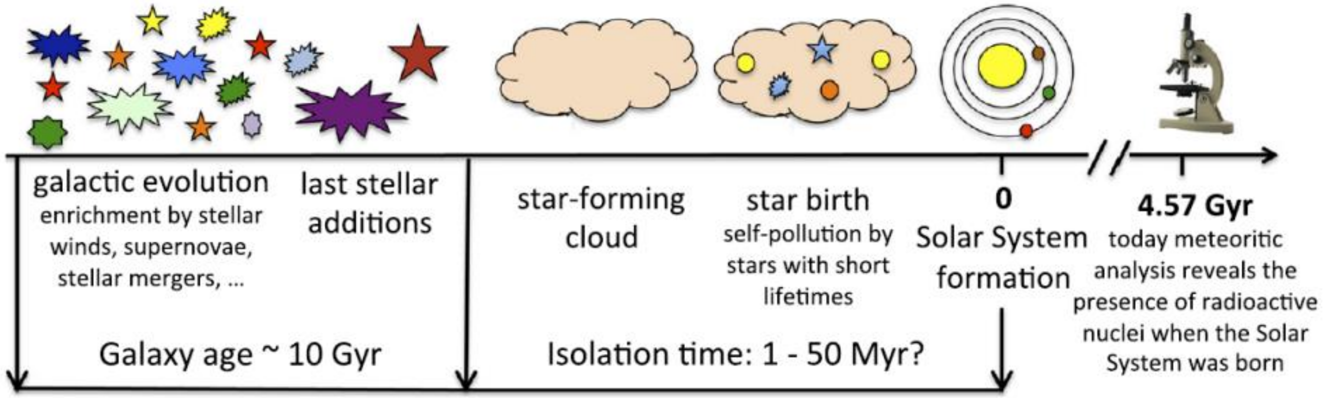
- Insights into star formation, stellar evolution and stellar explosions
- Detection via satellite telescopes & char. G-ray emission (1.8 MeV)
- Main origin: massive stars
- Abundance prediction strongly reliant on ^{26}Al(n,p) and (n,α)
- Existing data incomplete/discrepant
- Issue: sample!



C Iliadis et al., Ast. J. Supp. 193, 16 (2011)

^{41}Ca – pre-solar environment

- Insights into environment where the sun formed and the history of the solar proto-planetary disc

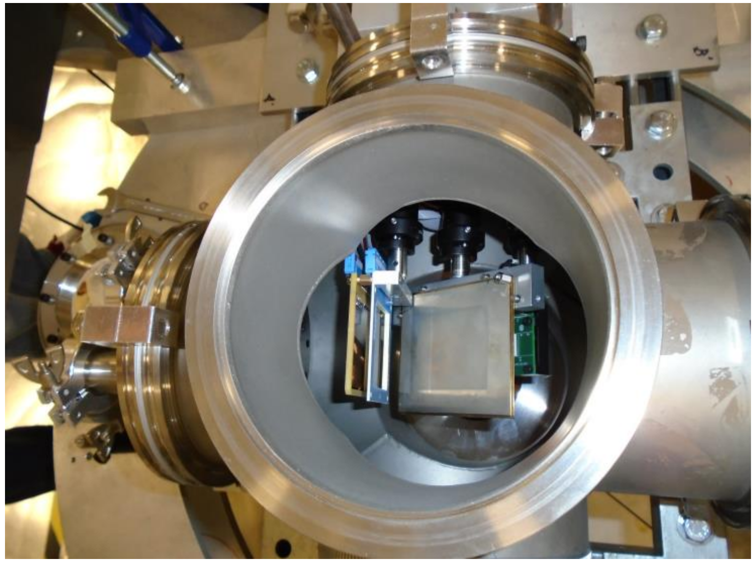


M. Lugaro, U. Ott, and A. Kereszturi. Radioactive nuclei from cosmochronology to ´ habitability. Progress in Particle and Nuclear Physics, 102:1–47, September 2018

- Main destruction: (n, α) and (n, p)

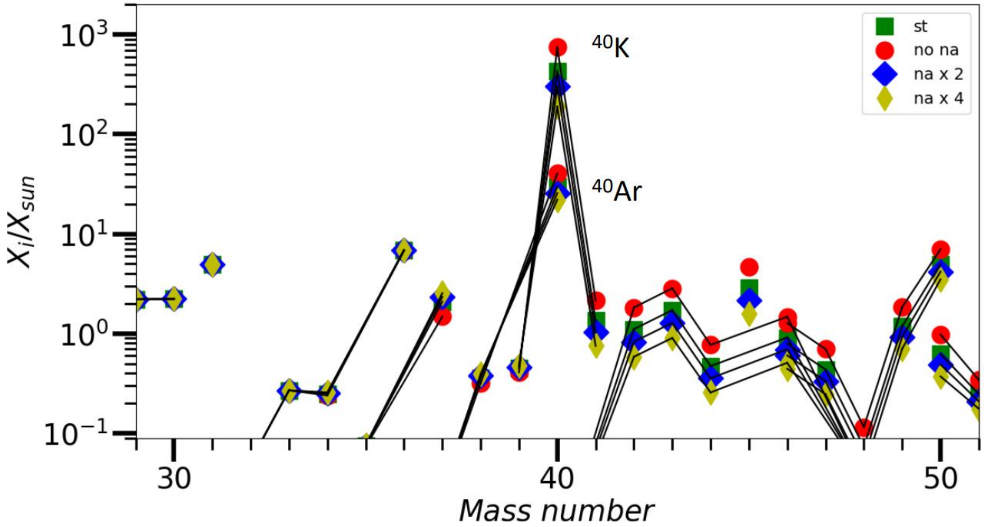
- Existing data incomplete

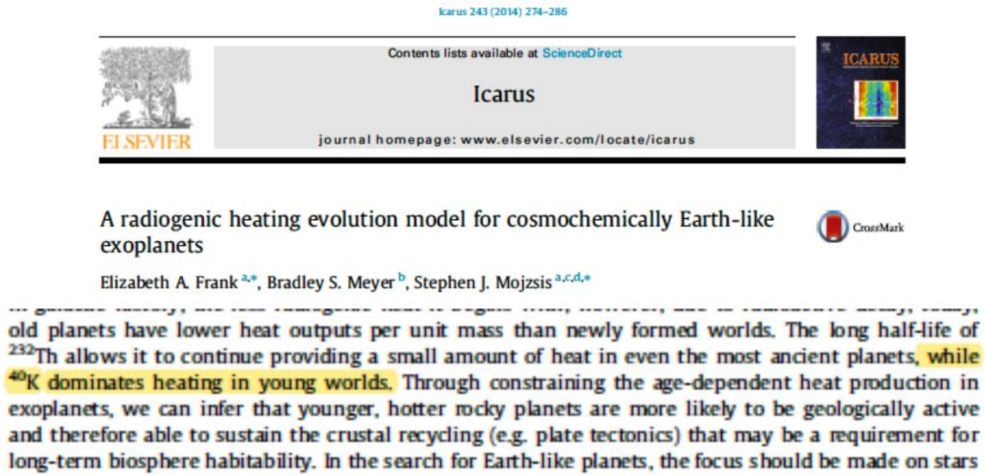
- Issue: sample (1e17 atoms) & statistics



^{40}K – heating young worlds

- Producing during oxygen burning and massive stars (s-process)
- Abundance important for radiogenic heating in earth like exoplanets (e.g. plate tectonics)
- Main destruction in s process: (n, α) and (n, p)
  - Impacting abundances around and beyond ^{40}K





Icarus 243 (2014) 274–286

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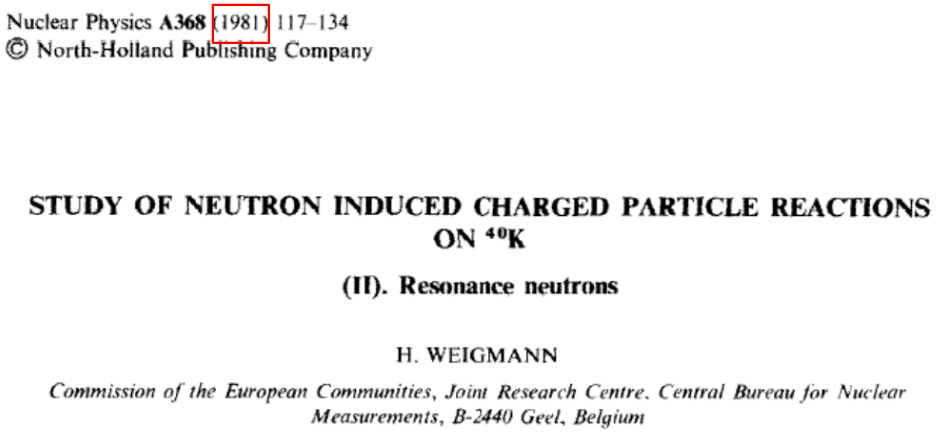
Icarus

journal homepage: www.elsevier.com/locate/icarus

A radiogenic heating evolution model for cosmochemically Earth-like exoplanets

Elizabeth A. Frank[a,*], Bradley S. Meyer[b], Stephen J. Mojzsis[a,c,d,*]

old planets have lower heat outputs per unit mass than newly formed worlds. The long half-life of ^{232}Th allows it to continue providing a small amount of heat in even the most ancient planets, while ^{40}K dominates heating in young worlds. Through constraining the age-dependent heat production in exoplanets, we can infer that younger, hotter rocky planets are more likely to be geologically active and therefore able to sustain the crustal recycling (e.g. plate tectonics) that may be a requirement for long-term biosphere habitability. In the search for Earth-like planets, the focus should be made on stars



Nuclear Physics **A368** (1981) 117–134
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STUDY OF NEUTRON INDUCED CHARGED PARTICLE REACTIONS ON ^{40}K

(II). Resonance neutrons

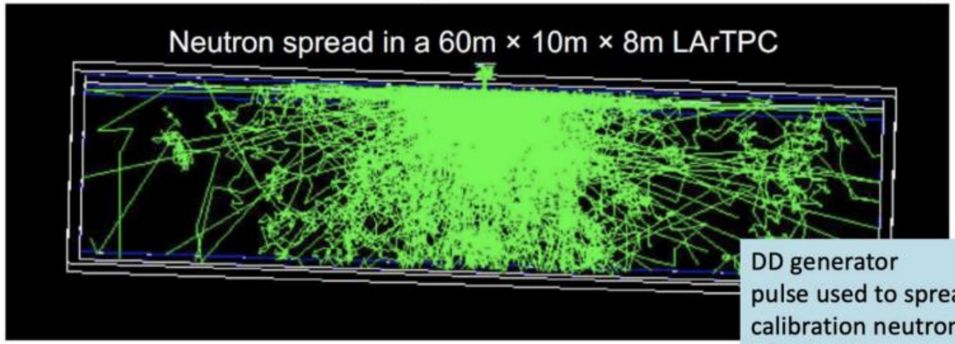
H. WEIGMANN

Commission of the European Communities, Joint Research Centre, Central Bureau for Nuclear Measurements, B-2440 Geel, Belgium

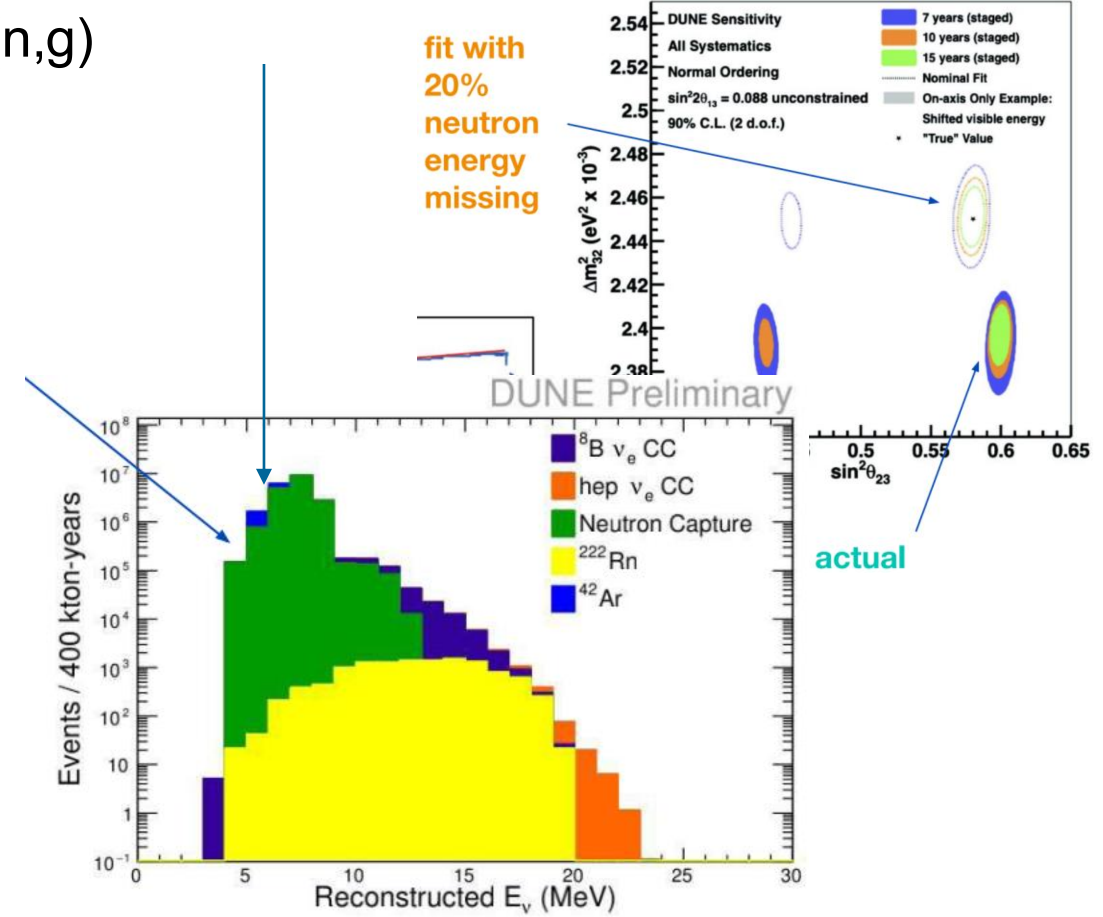
- Existing data incomplete (& old)
- Issue: sample

Ar(n,tot) – neutron transport in LAr detectors

- Liquid Argon (LAr) particle physics detectors for dark matter and neutrino, e.g. DUNE
  - Neutrons carry away a large fraction of energy; yields are model dependent
  - Modeling supernova and solar neutrino physics (reject neutrons)
  - Pulse Neutron Source for detector calibration via Ar(n,g)
    - Cross sections for neutron transport in LAr



DD generator pulse used to spread calibration neutrons Into DUNE



fit with 20% neutron energy missing

actual

- Significant gaps in the $\sigma_{(n,tot)}$
  - around 57 keV at a cross section minimum (max. free path length)
  - No data at 50-100 MeV
    & above 100 MeV uncertainties

Measuring neutron cross-sections

… in a wide energy range

… with excellent energy resolution

… with high precision

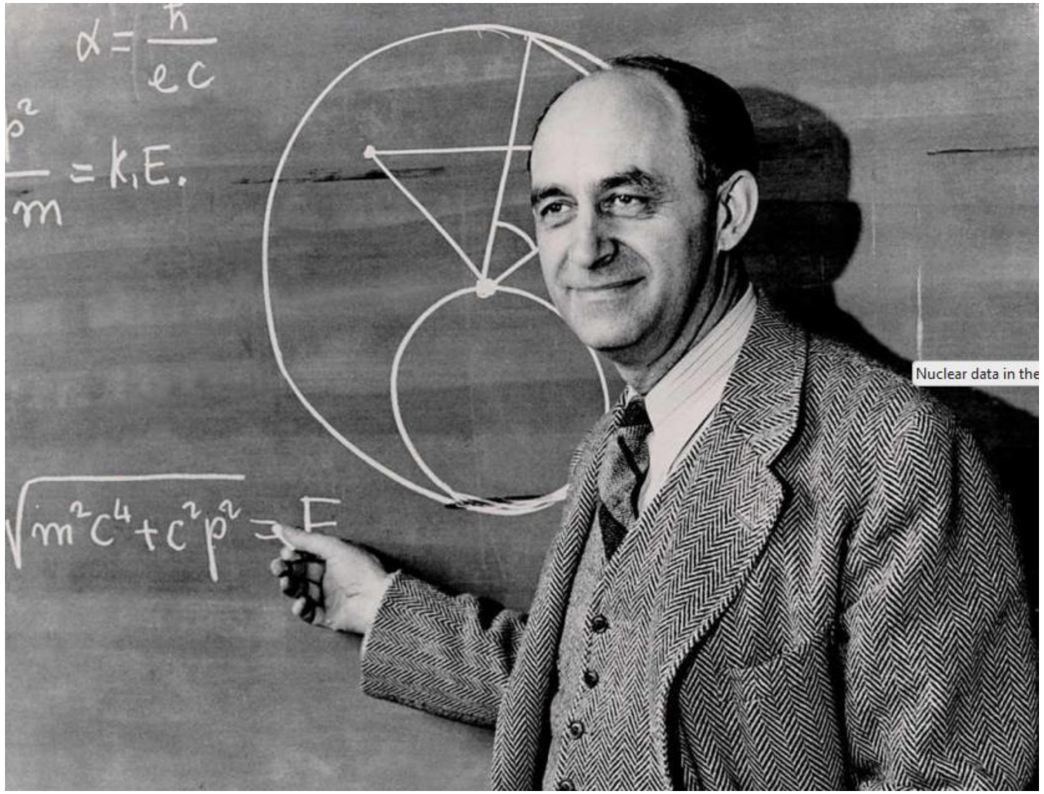
Ingredients needed:

- *Neutrons*
- *Detectors*
- *Samples*
- *Motivated scientists*

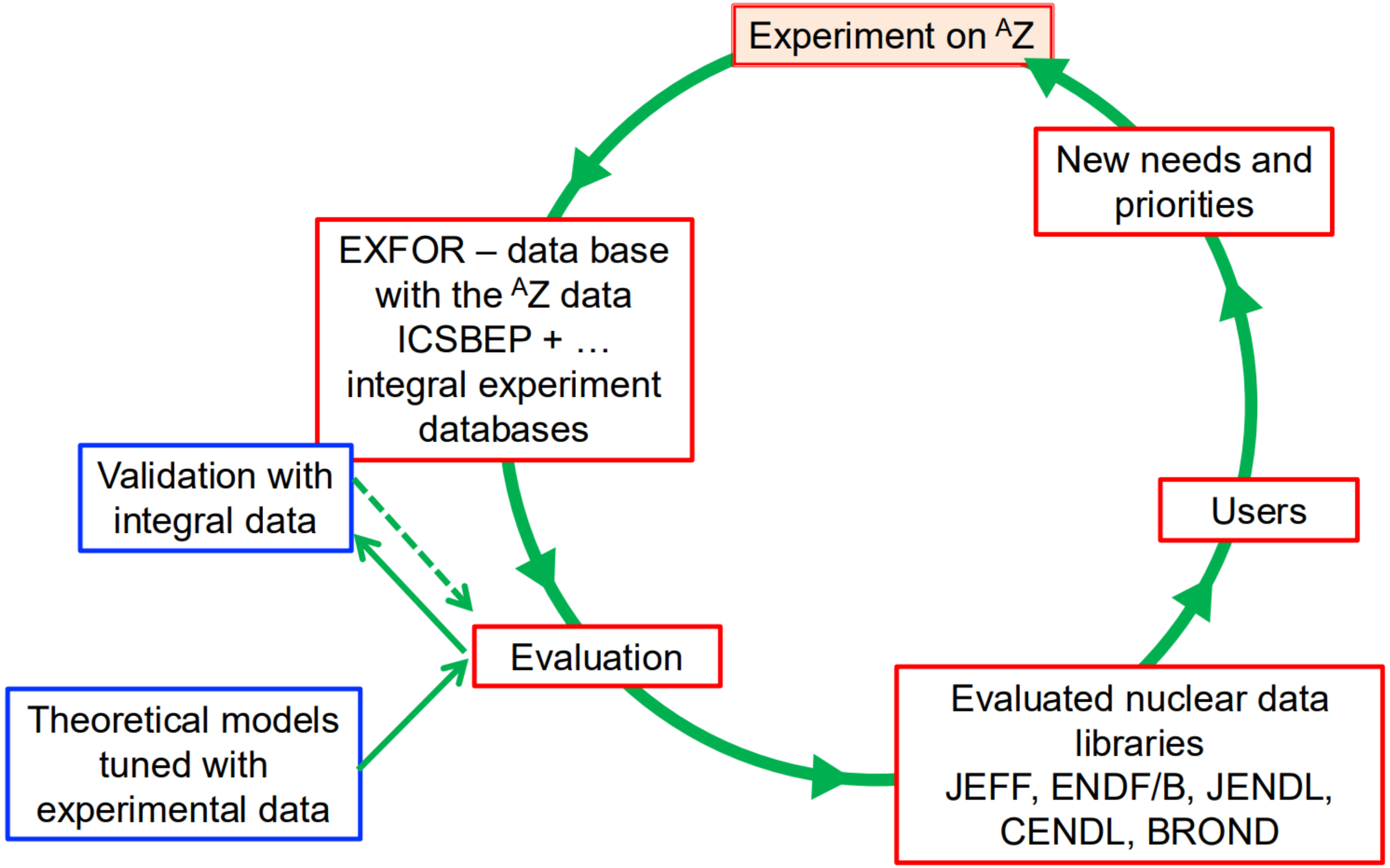
Nuclear data in the Fermi era…

“In the early days of the Manhattan Project when an unknown cross section was needed, the procedure for obtaining a value for it was simple. You went and asked Fermi. Invariably he would refuse to hazard a guess. The next step, so the story goes, was to recite slowly a long string of numbers, and if one of the numbers produced a gleam in Fermi's eye - that was the value to use!“

H. Goldstein (talk at Atomenergie, Sweden, September 1953)



Nuclear data in the post Fermi era…


Experiment on ^AZ

New needs and priorities

EXFOR – data base with the ^AZ data ICSBEP + … integral experiment databases

Users

Validation with integral data

Evaluation

Theoretical models tuned with experimental data

Evaluated nuclear data libraries JEFF, ENDF/B, JENDL, CENDL, BROND

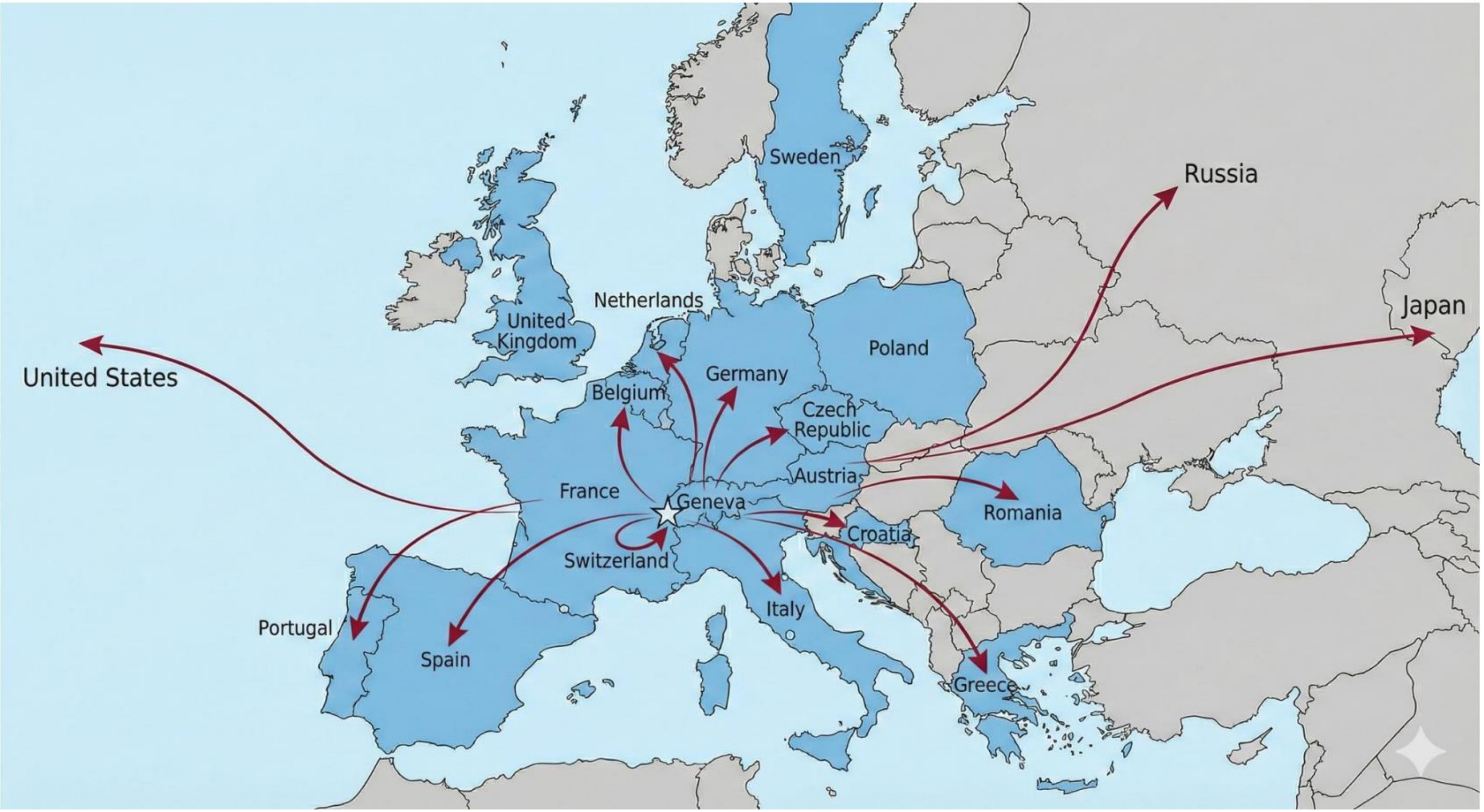
Several measurements on the same isotopes and reaction channels are needed to reduce the uncertainties, mostly due to uncontrolled systematics.

Priorities are compiled by the international agencies IAEA and NEA/OCDE, and different expert groups:

IAEA: https://www-nds.iaea.org/
HPRL: https://www.oecdnea.org/jcms/pl_68746/hprlapp

The neutron Time-Of-Flight n_TOF Collaboration (2001)

… the world's largest collaboration in the $\sigma_{(n,x)}$ field



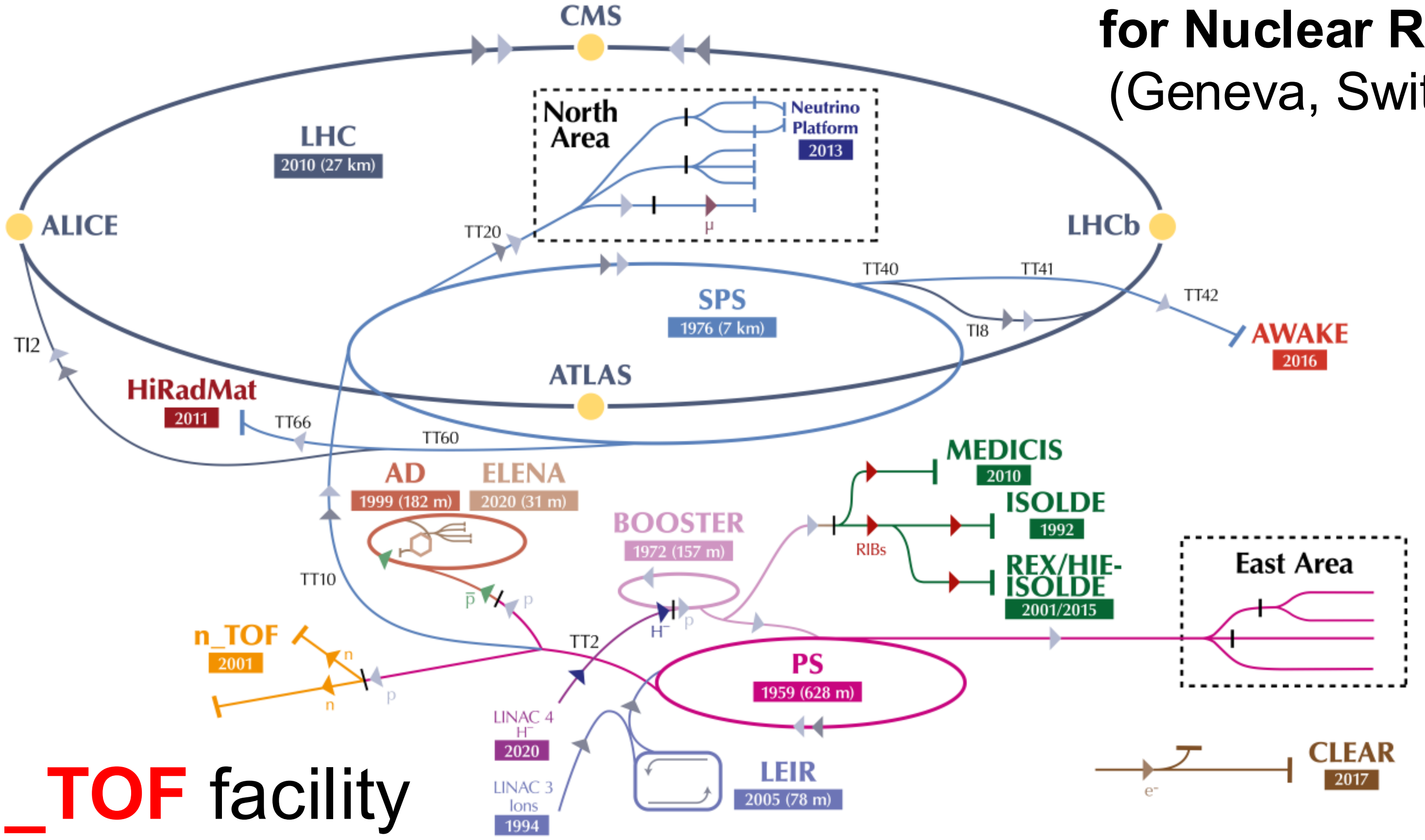
152 scientists
(33 students)
43 different institutes
19 countries

Training new generations of neutron physicists in Europe and several in the USA

Excellent links to other European infrastructures and facilities

n_TOF @ CERN

CERN: European Organization for Nuclear Research
(Geneva, Switzerland)



n_TOF facility
(2001)

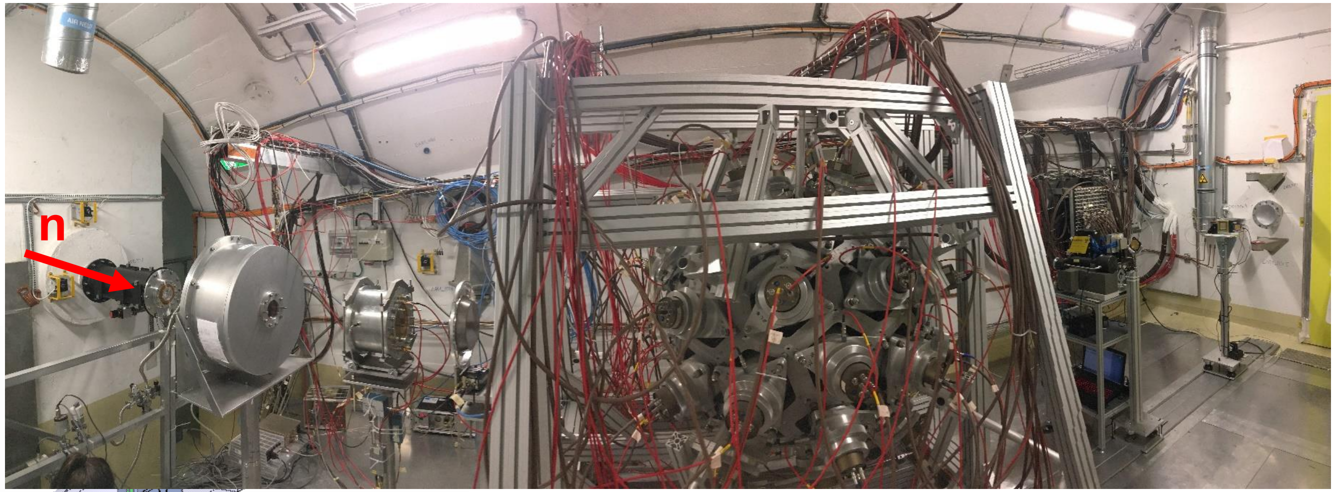
Being at CERN:

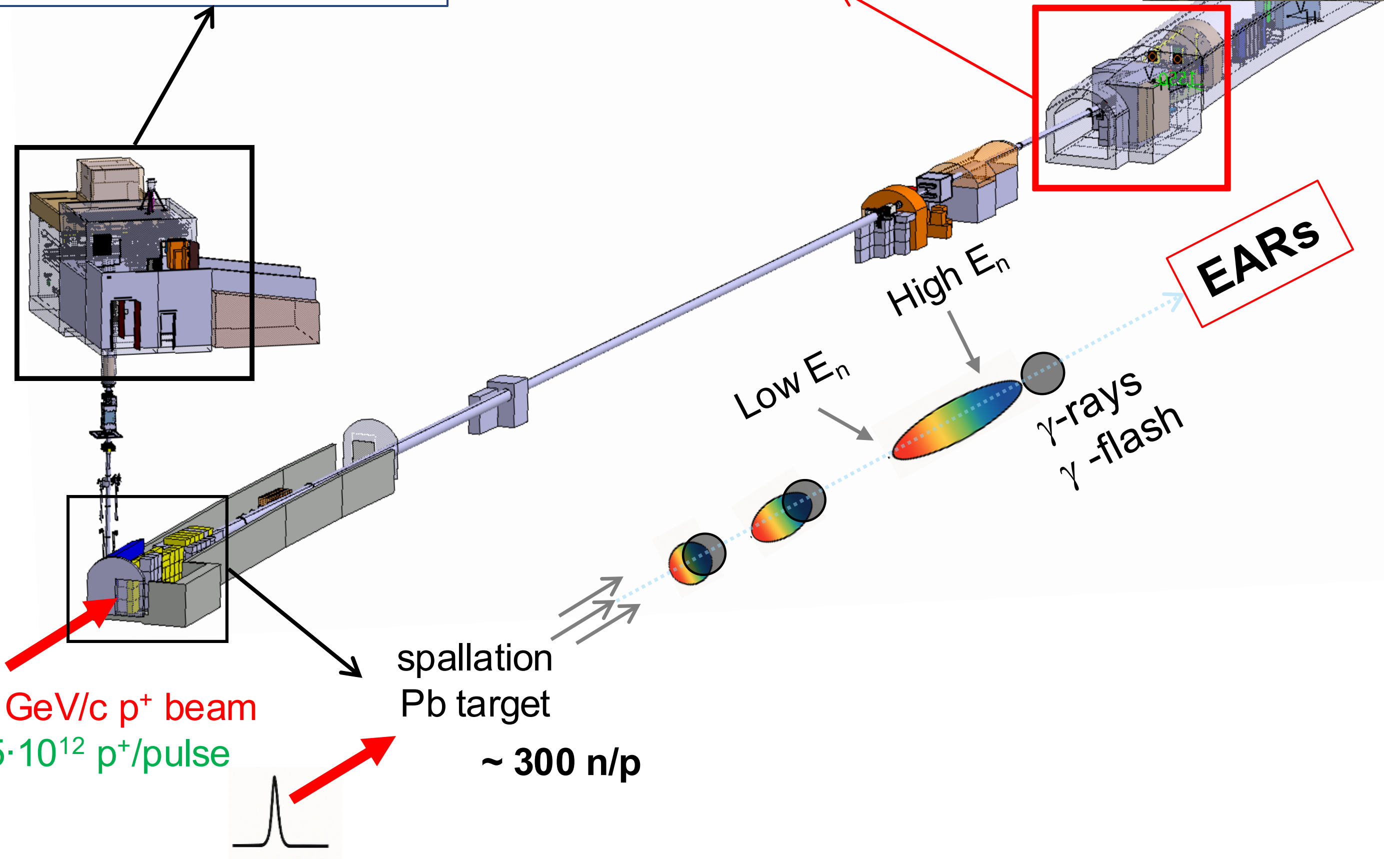
- Accelerator infrastructure & expertise
- Computing capabilities: fully digitized experiment since 25 years
- Complementary facilities: ISOLDE, hot labs, irradiation stations

n_TOF facility

Experimental **AR**ea **2**
since 2014 @ 20m
meV – 350 MeV
$\Delta E/E \sim 10^{-3}$-10^{-2}

Experimental **AR**ea **1**
@ 185 m
few meV – 1 GeV
$\Delta E/E \sim 10^{-3}$ @ 1 MeV
3e5 n/cm^2/pulse





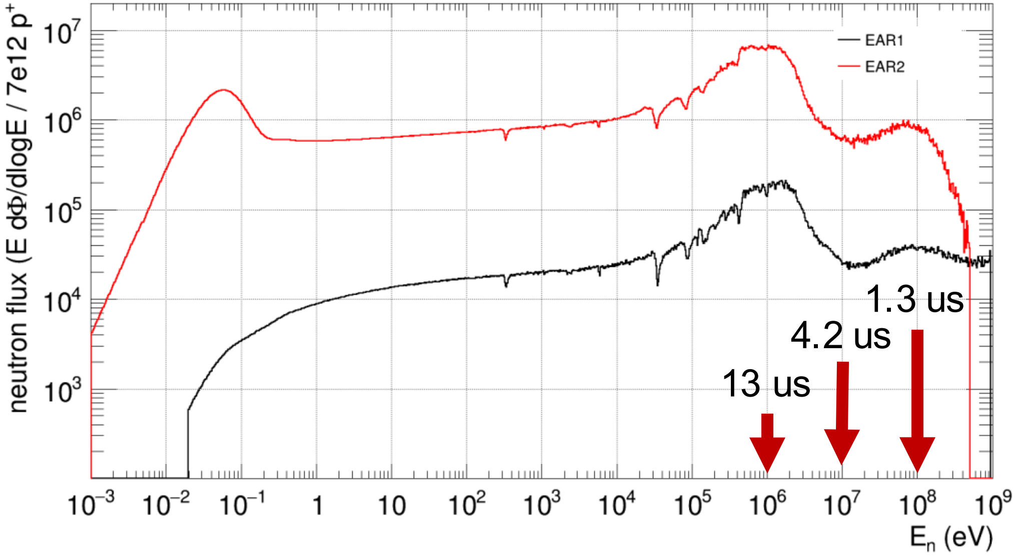
spallation
Pb target

~ 300 n/p

20 GeV/c p$^+$ beam
8.5·10^{12} p$^+$/pulse

time-of-flight technique:

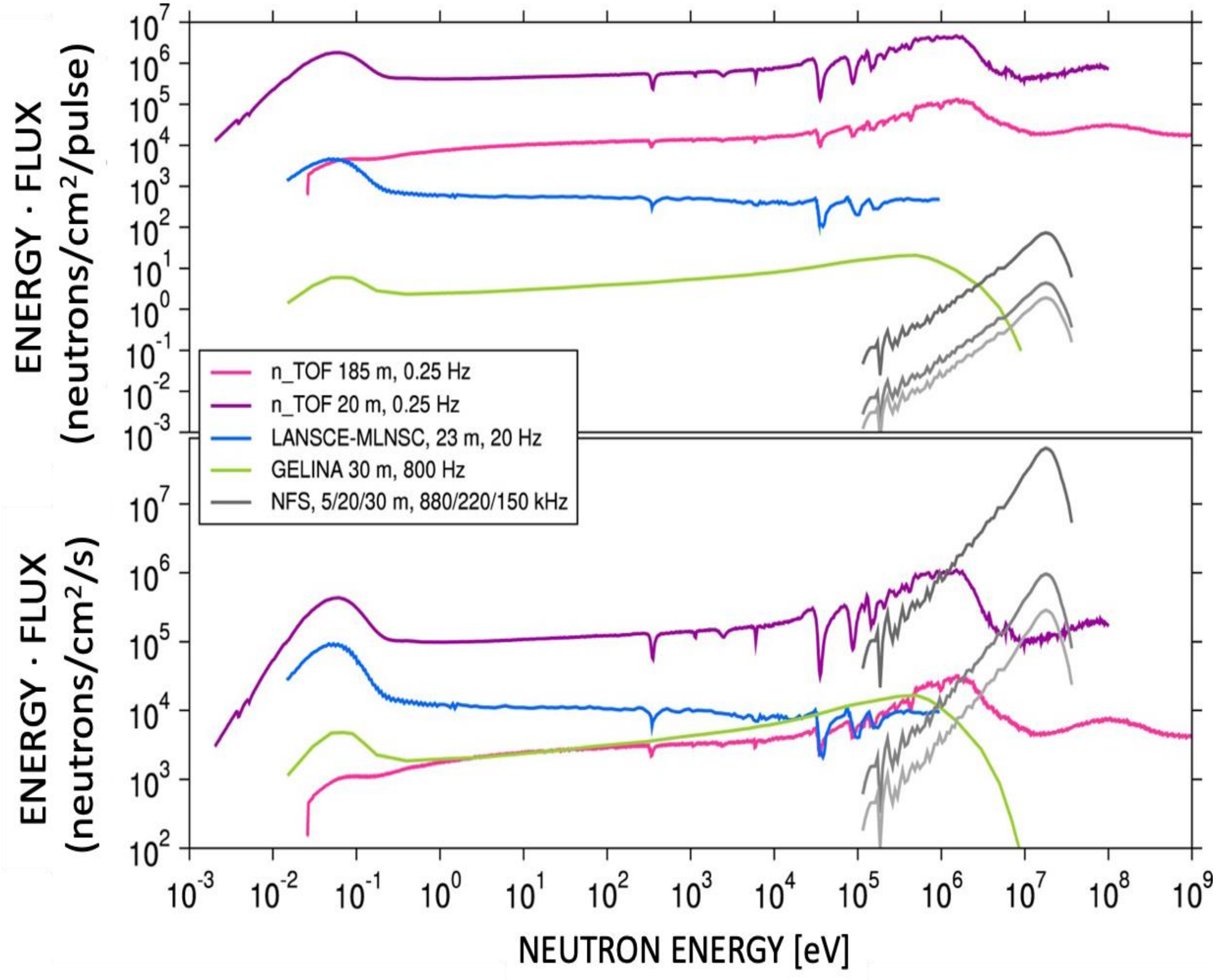
$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right) \qquad \beta = \frac{v_n}{c} = \frac{\mathrm{L}}{c\ \mathrm{TOF}}$$



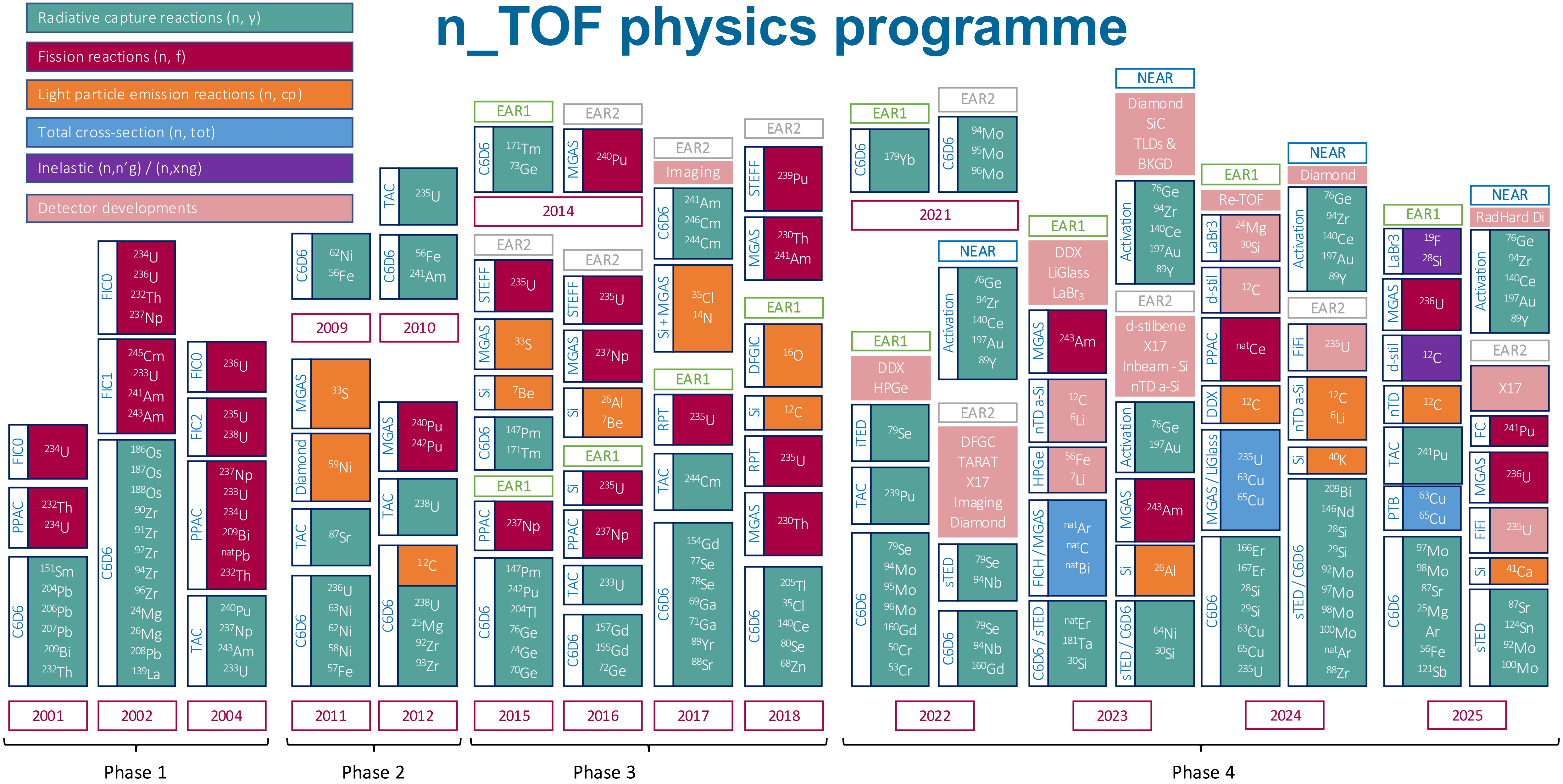
n_TOF uniqueness

Neutron Physics with particle accelerators
N. Colonna, F. Gunsing, and F. Käppeler
Progress in Particle and Nuclear Physics, **101**, 177 (2018)

- Instantaneous neutron intensity
- Wide neutron energy spectrum
- Time/neutron-energy resolution
- Proximity to ISOLDE, PSI & ILL



n_TOF physics programme



Radiative capture reactions (n, γ)
Fission reactions (n, f)
Light particle emission reactions (n, cp)
Total cross-section (n, tot)
Inelastic (n,n'g) / (n,xng)
Detector developments

2001
- FIC0: ^{234}U
- PPAC: ^{232}Th ^{234}U
- C6D6: ^{151}Sm ^{204}Pb ^{206}Pb ^{207}Pb ^{209}Bi ^{232}Th

2002
- FIC0: ^{234}U ^{236}U ^{232}Th ^{237}Np
- FIC1: ^{245}Cm ^{233}U ^{241}Am ^{243}Am
- C6D6: ^{186}Os ^{187}Os ^{188}Os ^{90}Zr ^{91}Zr ^{92}Zr ^{94}Zr ^{96}Zr ^{24}Mg ^{26}Mg ^{208}Pb ^{139}La

2004
- FIC0: ^{236}U
- FIC2: ^{235}U ^{238}U
- PPAC: ^{237}Np ^{233}U ^{234}U ^{209}Bi ^{nat}Pb ^{232}Th
- TAC: ^{240}Pu ^{237}Np ^{243}Am ^{233}U

Phase 1

2009
- C6D6: ^{62}Ni ^{56}Fe

2010
- TAC: ^{235}U
- C6D6: ^{56}Fe ^{241}Am

2011
- MGAS: ^{33}S
- Diamond: ^{59}Ni
- TAC: ^{87}Sr
- C6D6: ^{236}U ^{63}Ni ^{62}Ni ^{58}Ni ^{57}Fe

2012
- MGAS: ^{240}Pu ^{242}Pu
- TAC: ^{238}U
- C6D6: ^{12}C ^{238}U ^{25}Mg ^{92}Zr ^{93}Zr

Phase 2

2014
- EAR1
  - C6D6: ^{171}Tm ^{73}Ge
- EAR2
  - MGAS: ^{240}Pu

2015
- EAR2
  - STEFF: ^{235}U
  - MGAS: ^{33}S
  - Si: ^{7}Be
  - C6D6: ^{147}Pm ^{171}Tm
- EAR1
  - PPAC: ^{237}Np
  - C6D6: ^{147}Pm ^{242}Pu ^{204}Tl ^{76}Ge ^{74}Ge ^{70}Ge

2016
- EAR2
  - STEFF: ^{235}U
  - MGAS: ^{237}Np
  - Si: ^{26}Al ^{7}Be
- EAR1
  - Si: ^{235}U
  - PPAC: ^{237}Np
  - TAC: ^{233}U
  - C6D6: ^{157}Gd ^{155}Gd ^{72}Ge

2017
- EAR2
  - Imaging
  - C6D6: ^{241}Am ^{246}Cm ^{244}Cm
  - Si + MGAS: ^{35}Cl ^{14}N
- EAR1
  - RPT: ^{235}U
  - TAC: ^{244}Cm
  - C6D6: ^{154}Gd ^{77}Se ^{78}Se ^{69}Ga ^{71}Ga ^{89}Yr ^{88}Sr

2018
- EAR2
  - STEFF: ^{239}Pu
  - MGAS: ^{230}Th ^{241}Am
- EAR1
  - DFGIC: ^{16}O
  - Si: ^{12}C
  - RPT: ^{235}U
  - MGAS: ^{230}Th
  - C6D6: ^{205}Tl ^{35}Cl ^{140}Ce ^{80}Se ^{68}Zn

Phase 3

2021
- EAR1
  - C6D6: ^{179}Yb
- EAR2
  - C6D6: ^{94}Mo ^{95}Mo ^{96}Mo

2022
- EAR1
  - DDX HPGe
  - iTED: ^{79}Se
  - TAC: ^{239}Pu
  - C6D6: ^{79}Se ^{94}Mo ^{95}Mo ^{96}Mo ^{160}Gd ^{50}Cr ^{53}Cr
- NEAR
  - Activation: ^{76}Ge ^{94}Zr ^{140}Ce ^{197}Au ^{89}Y
- EAR2
  - DFGC TARAT X17 Imaging Diamond
  - sTED: ^{79}Se ^{94}Nb
  - C6D6: ^{79}Se ^{94}Nb ^{160}Gd

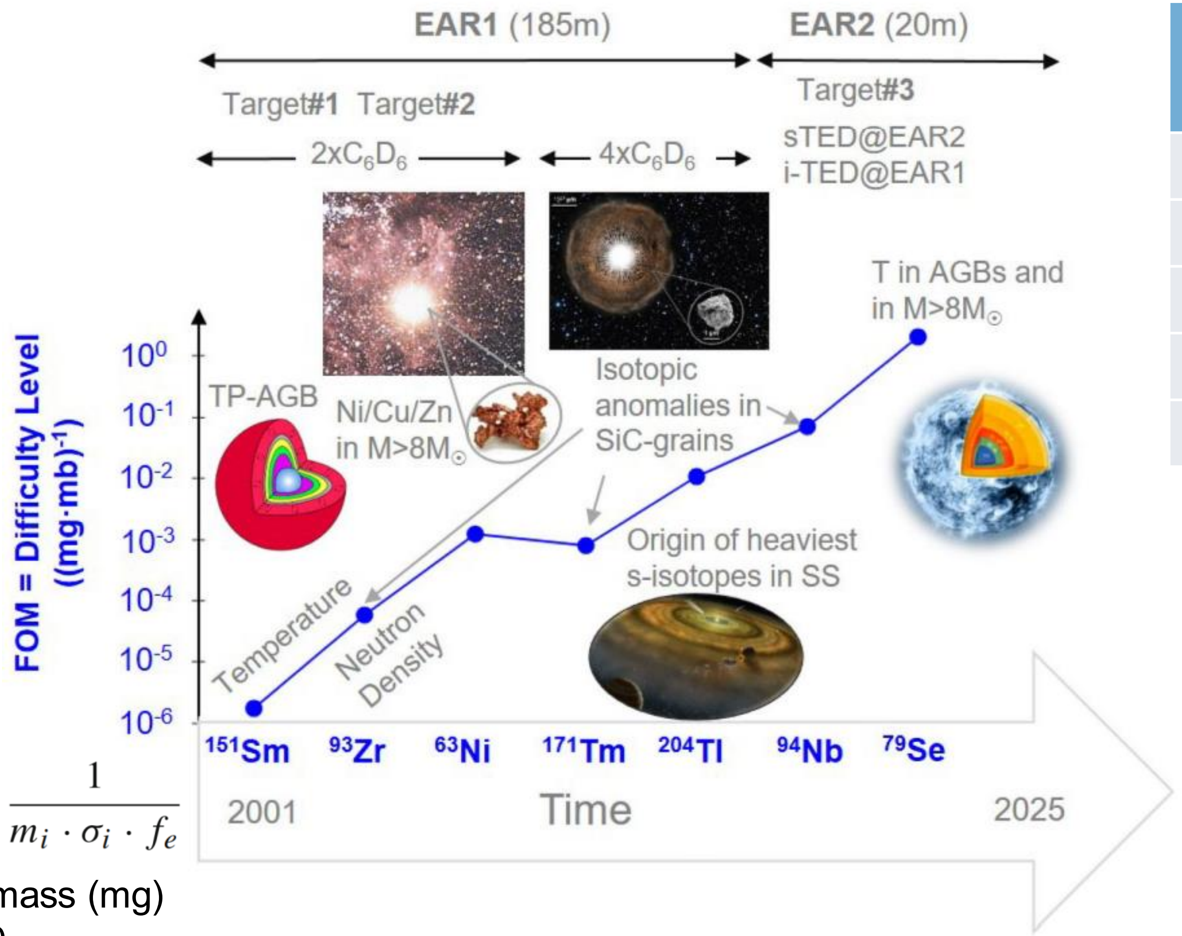
2023
- EAR1
  - DDX LiGlass LaBr$_3$
  - MGAS: ^{243}Am
  - nTD a-Si: ^{12}C ^{6}Li
  - HPGe: ^{56}Fe ^{7}Li
  - FICH / MGAS: ^{nat}Ar ^{nat}C ^{nat}Bi
  - C6D6 / sTED: ^{nat}Er ^{181}Ta ^{30}Si
- NEAR
  - Diamond SiC TLDs & BKGD
  - Activation: ^{76}Ge ^{94}Zr ^{140}Ce ^{197}Au ^{89}Y
- EAR2
  - d-stilbene X17 Inbeam - Si nTD a-Si
  - Activation: ^{76}Ge ^{197}Au
  - MGAS: ^{243}Am
  - Si: ^{26}Al
  - sTED / C6D6: ^{64}Ni ^{30}Si

2024
- EAR1
  - Re-TOF
  - LaBr3: ^{24}Mg ^{30}Si
  - d-stil: ^{12}C
  - PPAC: ^{nat}Ce
  - DDX: ^{12}C
  - MGAS / LiGlass: ^{235}U ^{63}Cu ^{65}Cu
  - C6D6: ^{166}Er ^{167}Er ^{28}Si ^{29}Si ^{63}Cu ^{65}Cu ^{235}U
- NEAR
  - Diamond
  - Activation: ^{76}Ge ^{94}Zr ^{140}Ce ^{197}Au ^{89}Y
- EAR2
  - FiFi: ^{235}U
  - nTD a-Si: ^{12}C ^{6}Li
  - Si: ^{40}K
  - sTED / C6D6: ^{209}Bi ^{146}Nd ^{28}Si ^{29}Si ^{92}Mo ^{97}Mo ^{98}Mo ^{100}Mo ^{nat}Ar ^{88}Zr

2025
- EAR1
  - LaBr3: ^{19}F ^{28}Si
  - MGAS: ^{236}U
  - d-stil: ^{12}C
  - nTD: ^{12}C
  - TAC: ^{241}Pu
  - PTB: ^{63}Cu ^{65}Cu
  - C6D6: ^{97}Mo ^{98}Mo ^{87}Sr ^{25}Mg Ar ^{56}Fe ^{121}Sb
- NEAR
  - RadHard Di
  - Activation: ^{76}Ge ^{94}Zr ^{140}Ce ^{197}Au ^{89}Y
- EAR2
  - X17
  - FC: ^{241}Pu
  - MGAS: ^{236}U
  - FiFi: ^{235}U
  - Si: ^{41}Ca
  - sTED: ^{87}Sr ^{124}Sn ^{92}Mo ^{100}Mo

Phase 4

TOF measurements “difficulty level” & challenges



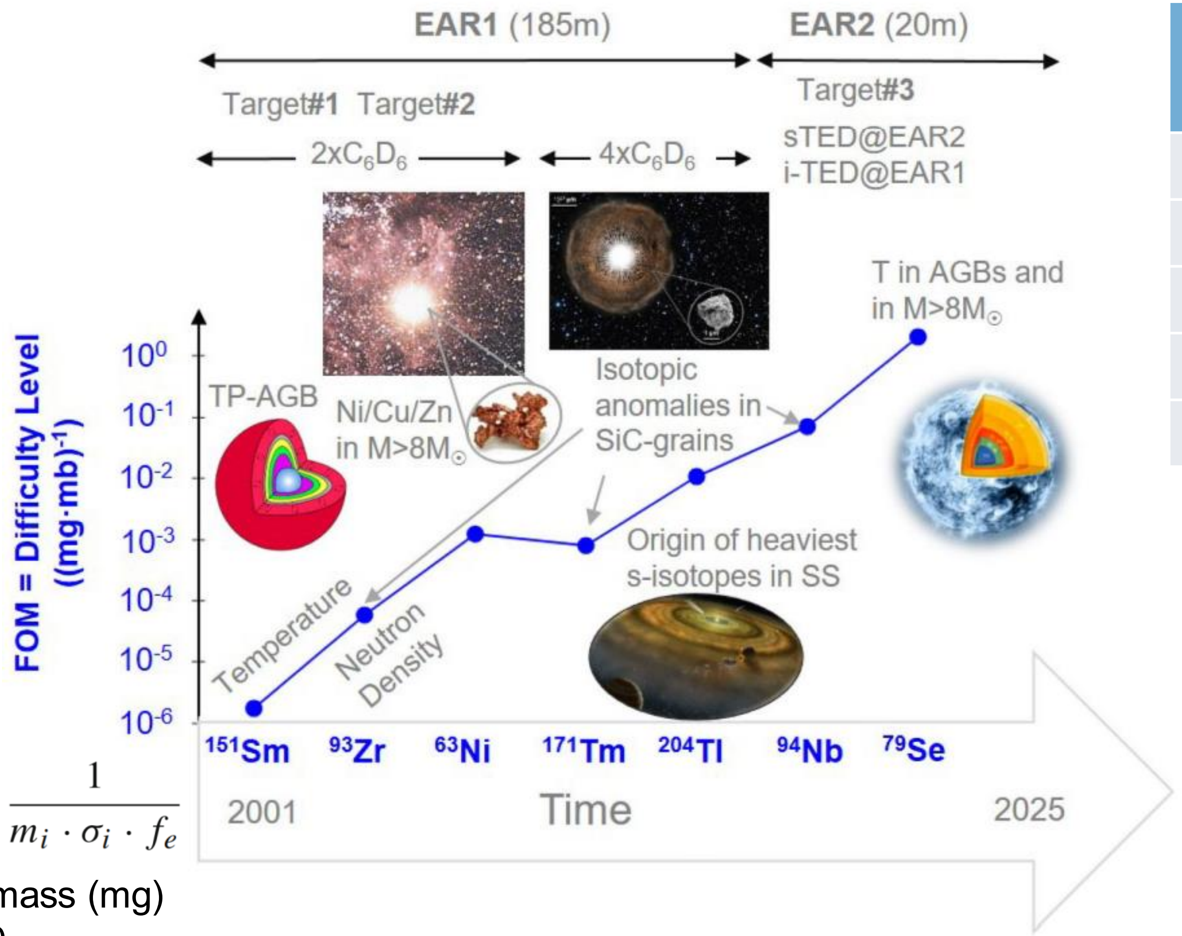
$$FOM = \frac{1}{m_i \cdot \sigma_i \cdot f_e}$$

isotope mass (mg)
MACS30
Isotope enrichment

C. Domingo-Pardo et al., Eur. Phys. J. A 61, 105 (2025)

isotope	$t_{1/2}$ (y)	#atoms (1e19)	activity (GBq)	f	MACS30 (mb)
^{151}Sm	94.6	80	156	0.9	3100
^{63}Ni	101	100	240	0.1	67
^{204}Tl	3.78	2.7	150	0.04	260
^{94}Nb	2.00E+04	0.9	0.01+0.01	0.01	
^{79}Se	3.30E+05	2	0.04	0.0007	

TOF measurements “difficulty level” & challenges



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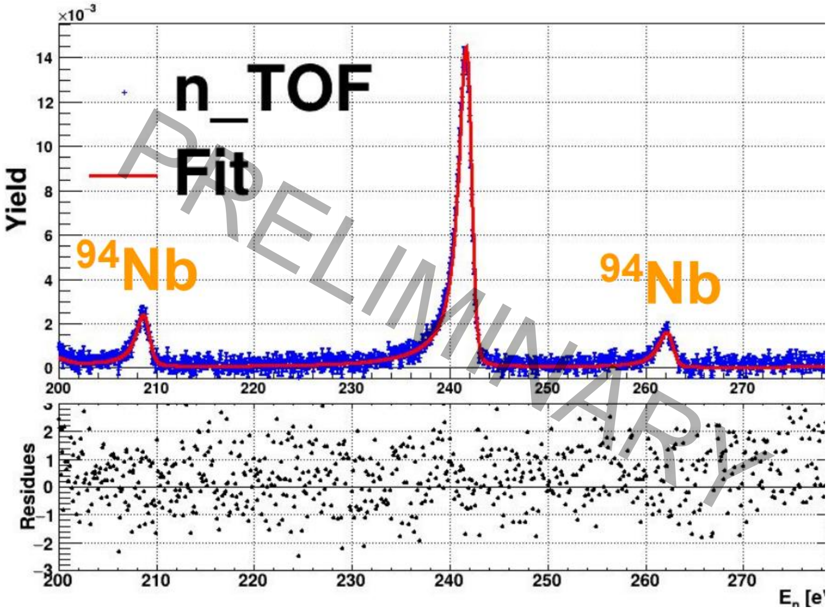
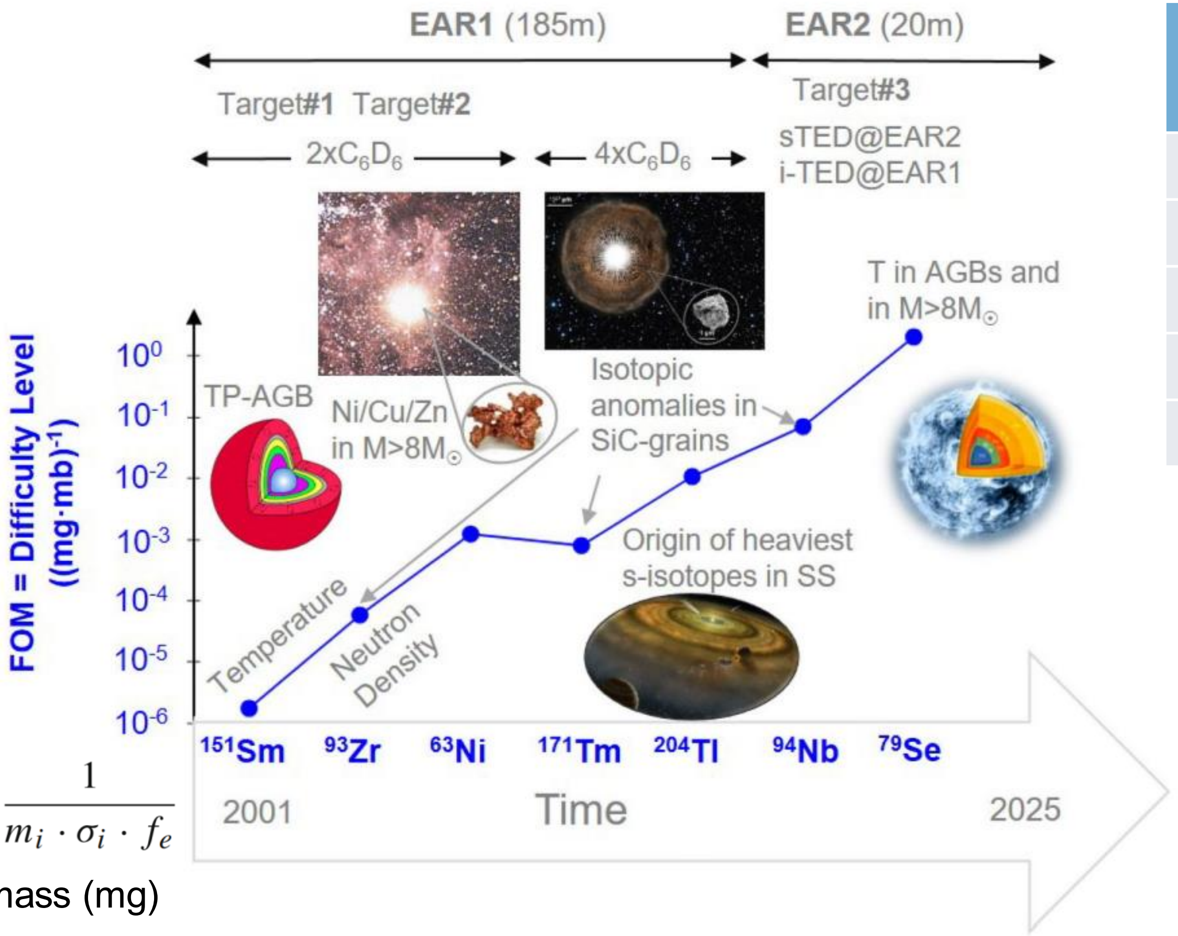
^{79}Se	3.30E+05	2	0.04	0.0007	



TOF measurements “difficulty level” & challenges



$$FOM = \frac{1}{m_i \cdot \sigma_i \cdot f_e}$$

isotope mass (mg)
MACS30
Isotope enrichment

C. Domingo-Pardo et al., Eur. Phys. J. A 61, 105 (2025)

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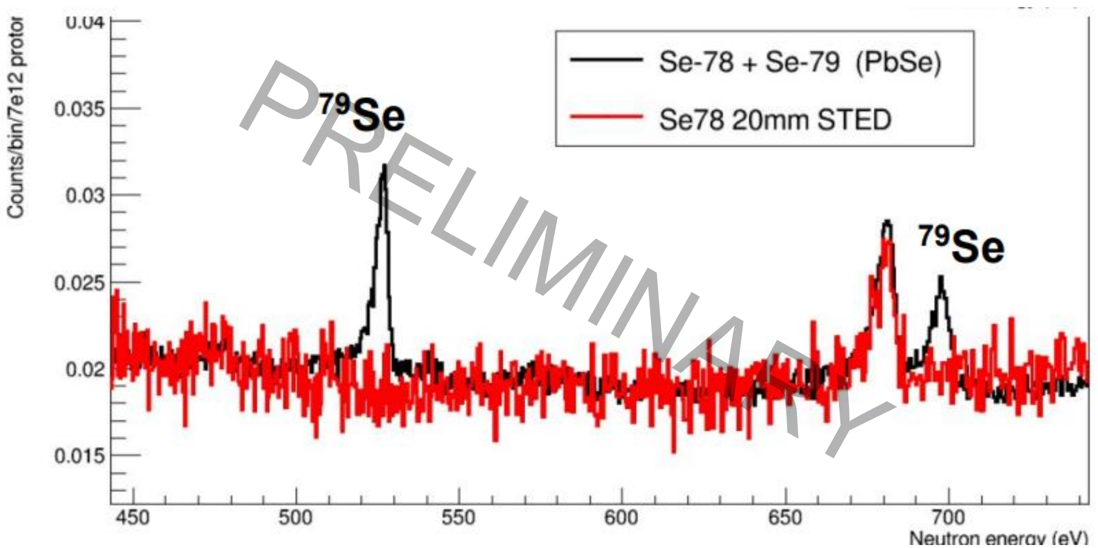
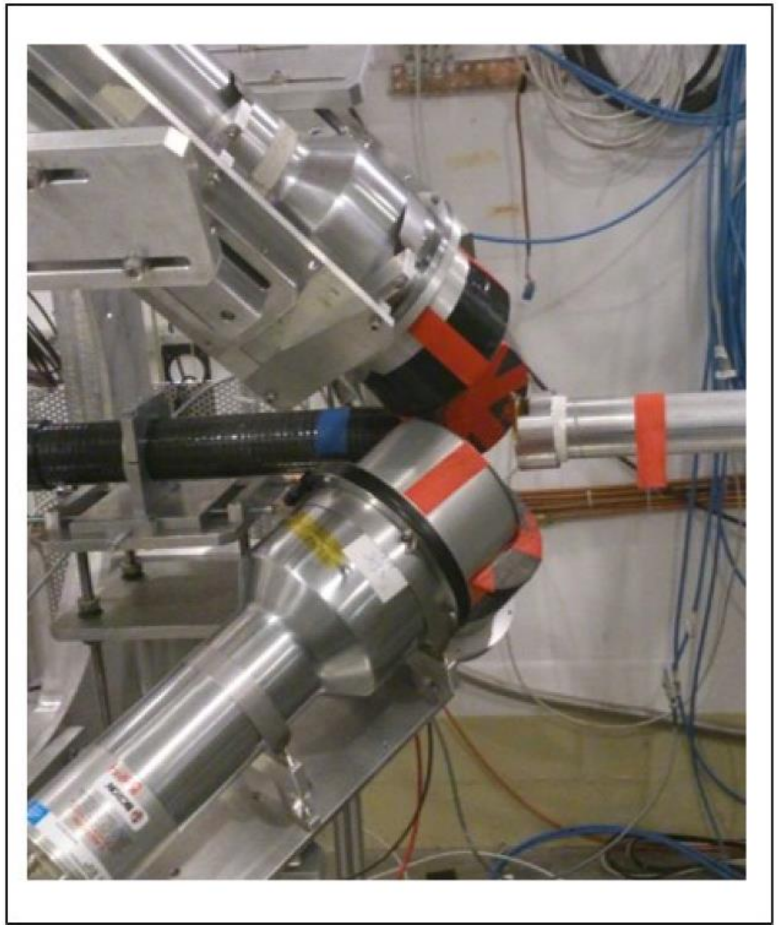
^{79}Se	**3.30E+05**	**2**	**0.04**	**0.0007**	



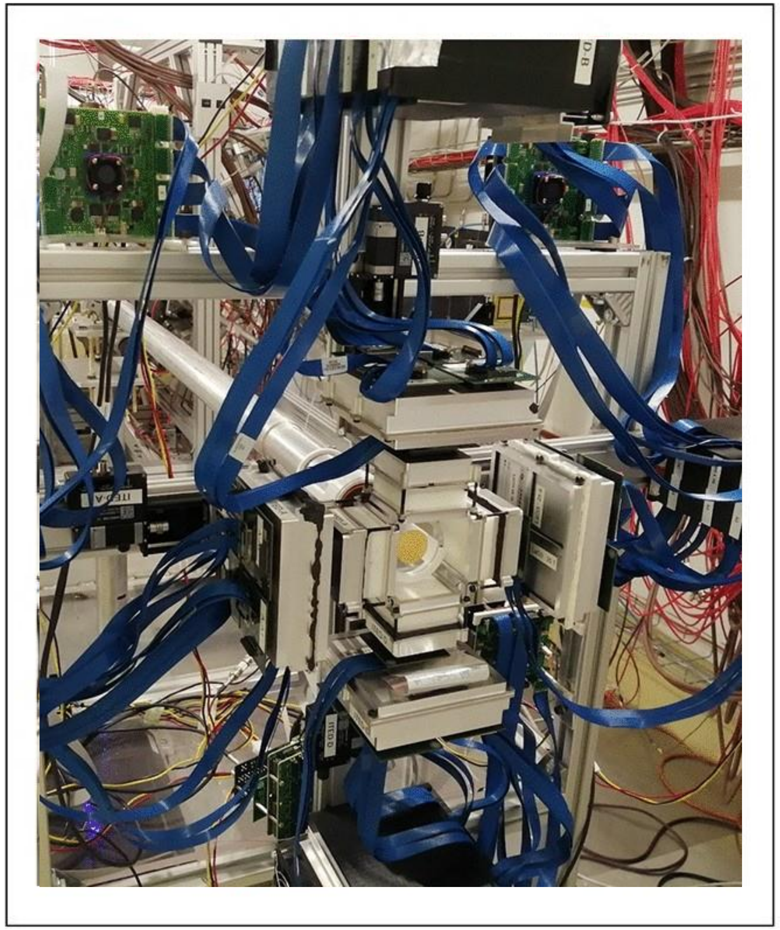
Associated detector development

EAR1 ^{151}Sm(n,γ), 2001

EAR1 ^{204}Tl(n,γ), 2015



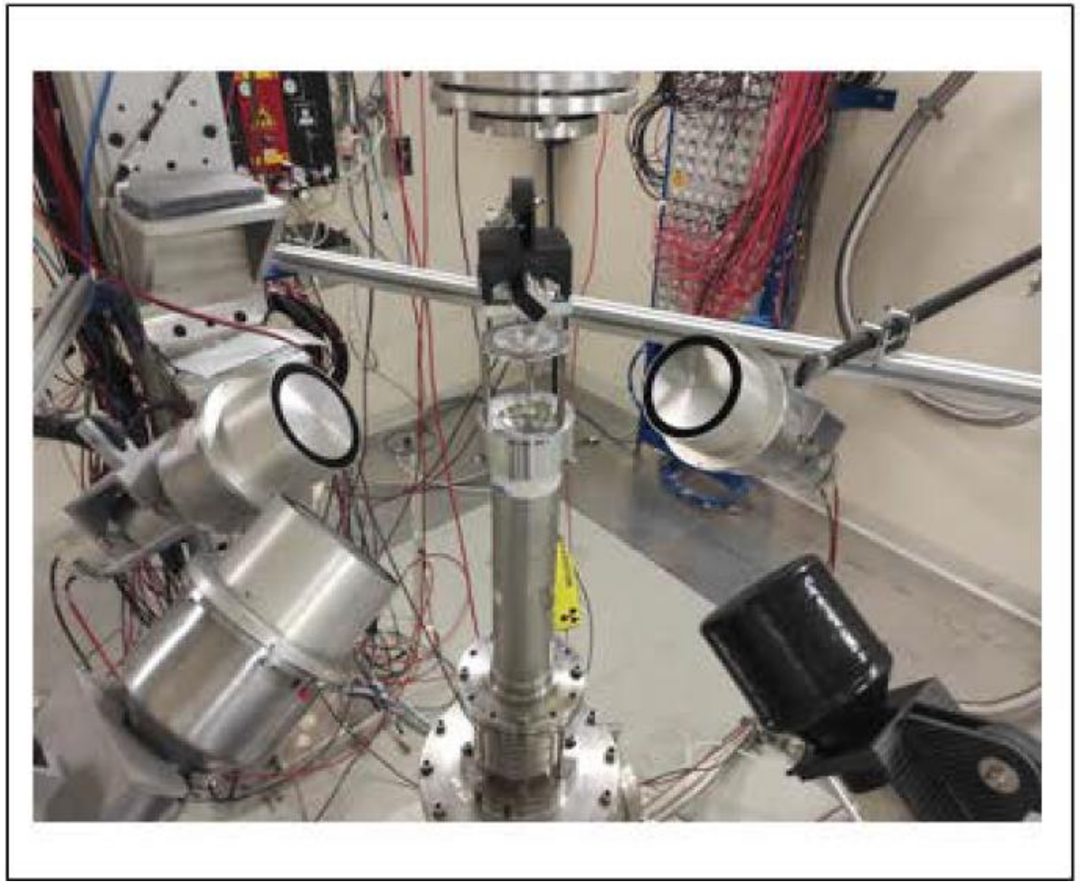
EAR1 ^{79}Se(n,γ), 2022



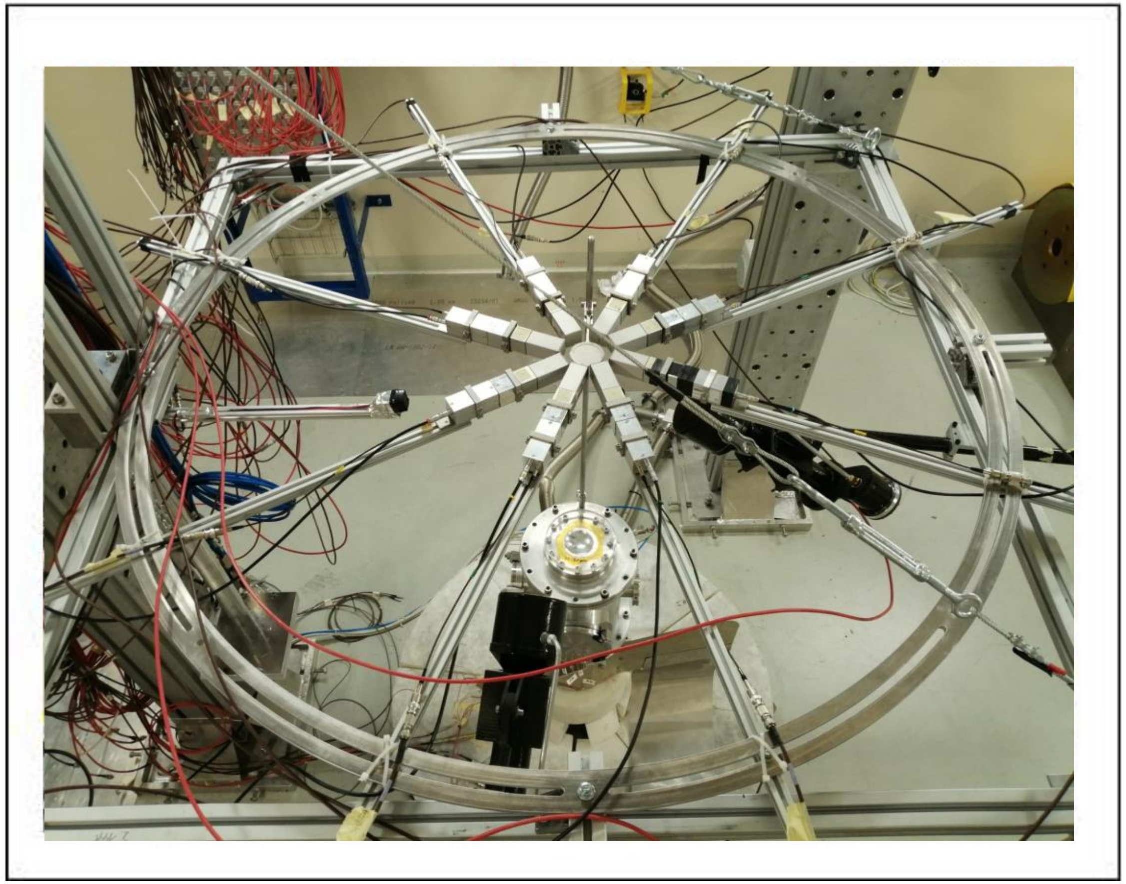
C. Domingo-Pardo et al., Eur. Phys. J. A 59, 8 (2023)

Still not enough reactions >> shorter flight path

EAR2, 2015

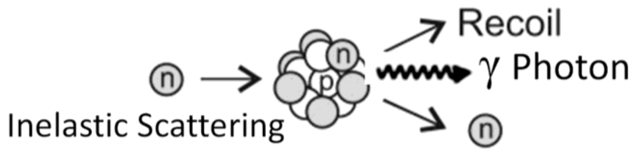


EAR2 ^{79}Se(n,γ) ^{94}Nb(n,γ), 2022



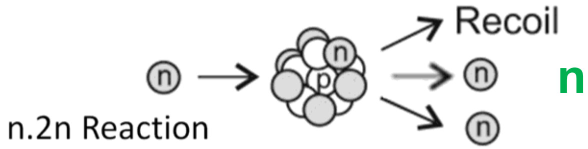
C. Domingo-Pardo et al., Eur. Phys. J. A 59, 8 (2023)

(n,n‘g) and (n,xng) @ n_TOF



characteristic γ-rays

100s keV to 200 MeV



neutron multiplication
10s to 200 MeV

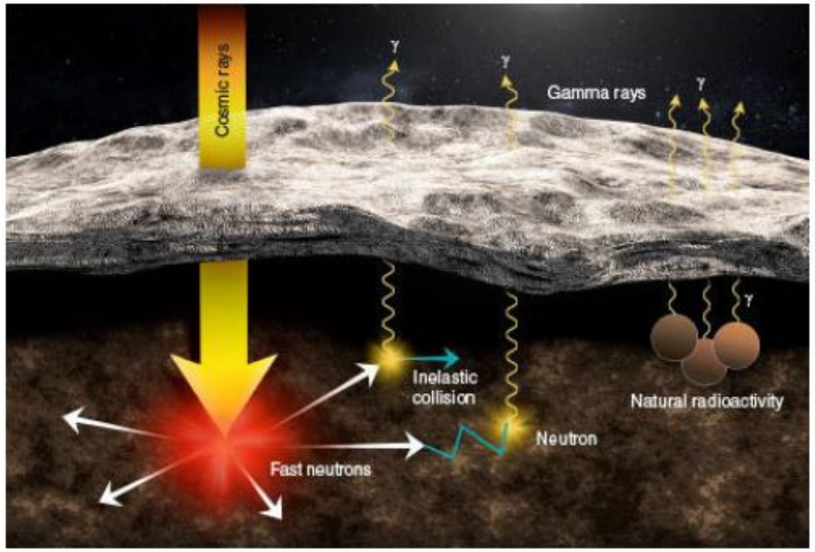


Photo credit: L. Casonhua, “Mini” Device Set to Analyze Mysterious Psyche, (2019). https://str.llnl.gov/2019-05/burks

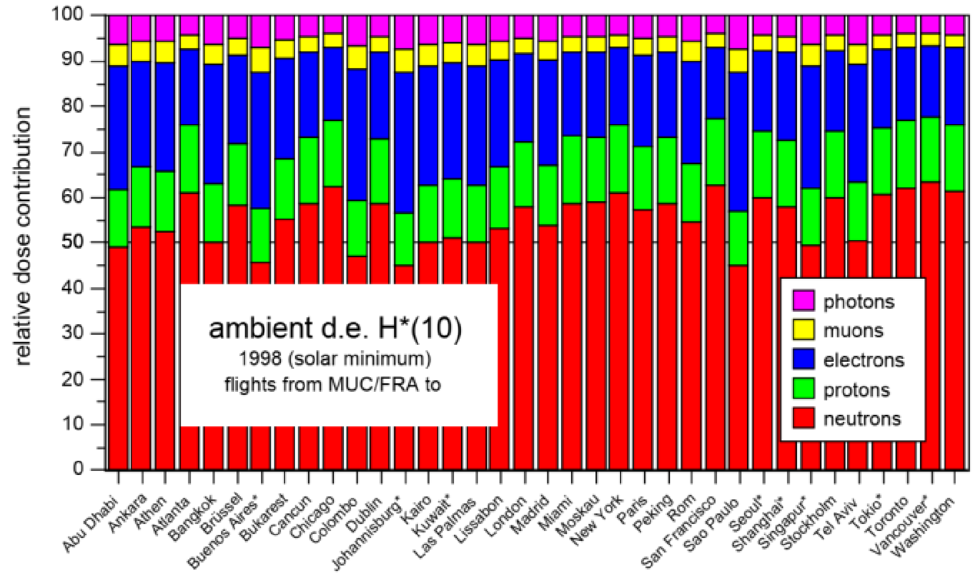


Figure II.6 Relative contribution to ambient dose equivalent for various destinations near solar minimum condition (1998) for 37000 ft flight altitude.

Neutron transport in matter - applications:

- Radiobiology (aviation, hadron therapy, shielding, …)
- Nuclear energy (fast & fusion)
- Neutron damage in materials/electronics
- Space exploration
- Detectors (neutrino)
- …

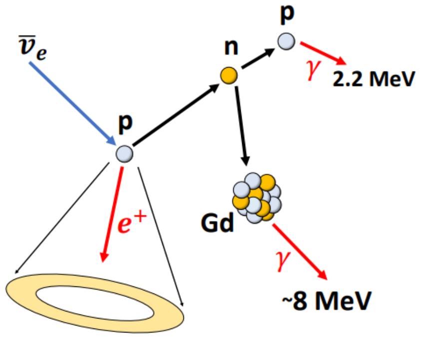
Fundamental nuclear physics (collective excitations)

Ingredients for a measurement:

- Spectroscopic n and/or γ-detectors
- A fast/HE neutron source

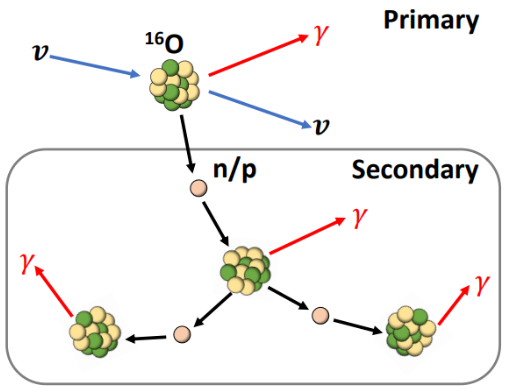
^{16}O(n,γ-production) and Super-Kamiokande

- Transport of neutrino interaction products in water
- Neutron tagging implemented in 2008 + gadolinium in 2020 → helps with background



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

Inverse-beta decay (IBD)
primary e+ and delayed n
(gamma signal)



$$\nu(\bar{\nu}) + {}^{16}\mathrm{O} \to \nu(\bar{\nu}) + {}^{15}\mathrm{O} + \gamma + \boxed{\mathrm{n}}$$
$$\nu(\bar{\nu}) + {}^{16}\mathrm{O} \to \nu(\bar{\nu}) + {}^{15}\mathrm{N} + \gamma + \mathrm{p}$$

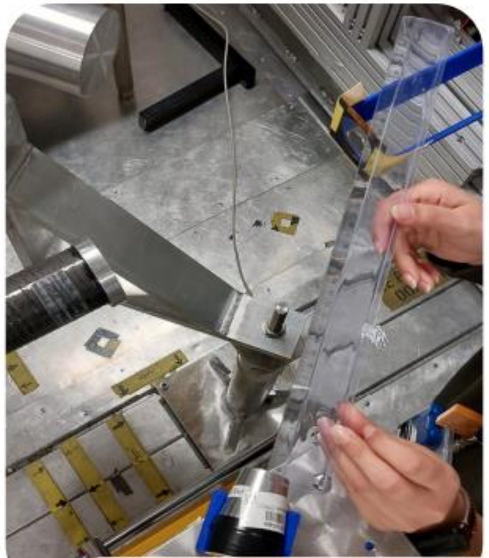
Surviving background reactions:
neutral current quasi-elastic (NCQE)
due to atmospheric neutrinos

Issue with uncertainties in background due to subsequent interaction of the reaction products (neutron) within O(100 ns)

Energy	Parent (J^π)	Physics process
7.12 MeV	$^{16}\mathrm{O}(1^-)$	$^{16}\mathrm{O}(n,n')^{16}\mathrm{O}^*$
6.92 MeV	$^{16}\mathrm{O}(2^+)$	$^{16}\mathrm{O}(n,n')^{16}\mathrm{O}^*$
6.32 MeV	$^{15}\mathrm{N}(\frac{3}{2}^-)$	$^{16}\mathrm{O}(n,np)^{15}\mathrm{N}^*$
6.13 MeV	$^{16}\mathrm{O}(3^-)$	$^{16}\mathrm{O}(n,n')^{16}\mathrm{O}^*$
5.27 MeV	$^{15}\mathrm{N}(\frac{5}{2}^+)$	$^{16}\mathrm{O}(n,n')^{16}\mathrm{O}^*$ then $^{16}\mathrm{O}^* \to {}^{15}\mathrm{N}^* + p$, or $^{16}\mathrm{O}(n,np)^{15}\mathrm{N}^*$
4.44 MeV	$^{12}\mathrm{C}(2^+)$	$^{16}\mathrm{O}(n,n')^{16}\mathrm{O}^*$ then $^{16}\mathrm{O}^* \to {}^{12}\mathrm{C}^* + \alpha$, or $^{16}\mathrm{O}(n,n\alpha)^{12}\mathrm{C}^*$
3.68 MeV	$^{13}\mathrm{C}(\frac{3}{2}^-)$	$^{16}\mathrm{O}(n,\alpha)^{13}\mathrm{C}^*$
2.31 MeV	$^{14}\mathrm{N}(0^+)$	$^{16}\mathrm{O}(n,2np)^{14}\mathrm{N}^*$
2.30 MeV	$^{15}\mathrm{N}(\frac{7}{2}^+)$	$^{16}\mathrm{O}(n,np)^{15}\mathrm{N}^*$

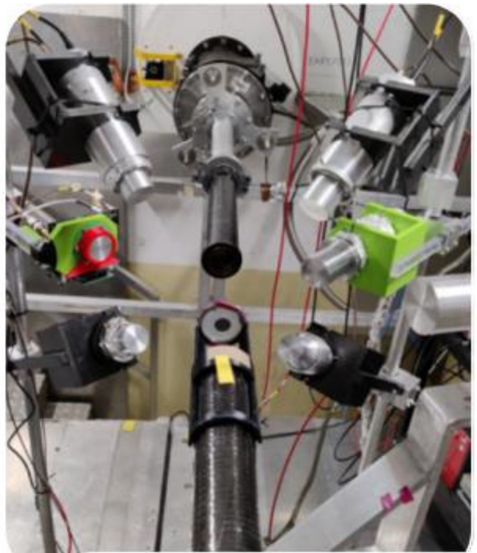
Simulations to estimate wrongly identified NCQE as IBD
13%/20% systematic uncertainty due to neutron nuclear data
→ **requires neutron XS, i.e. ^{16}O(n,g-prod) from MeV to 200 MeV**

Towards g-spectroscopy @ n_TOF



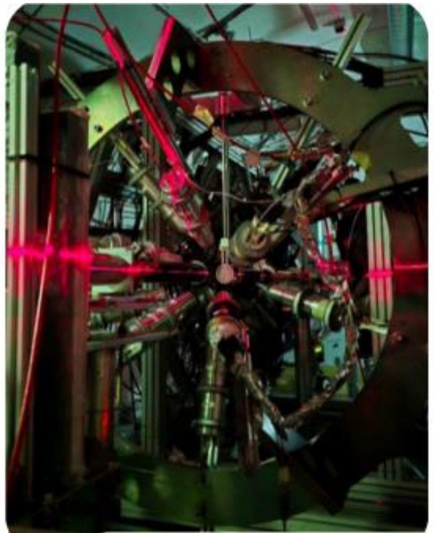
2023

- Parasitic tests
- Different approaches



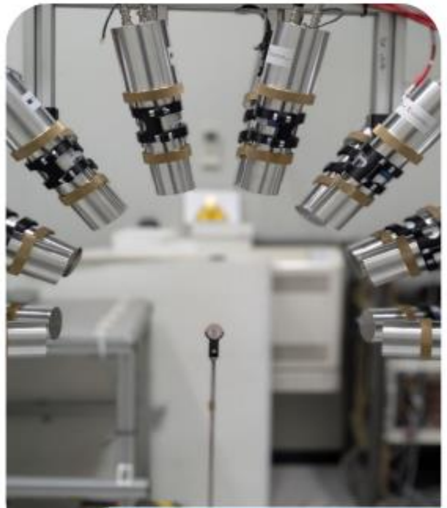
2024

- ^{24}Mg LOI
- Two runs
- First (n,inl) xs



2025

- ^{19}F(n,n’)
- ^{28}Si(n,n’)
- New frame for 10 det



2026

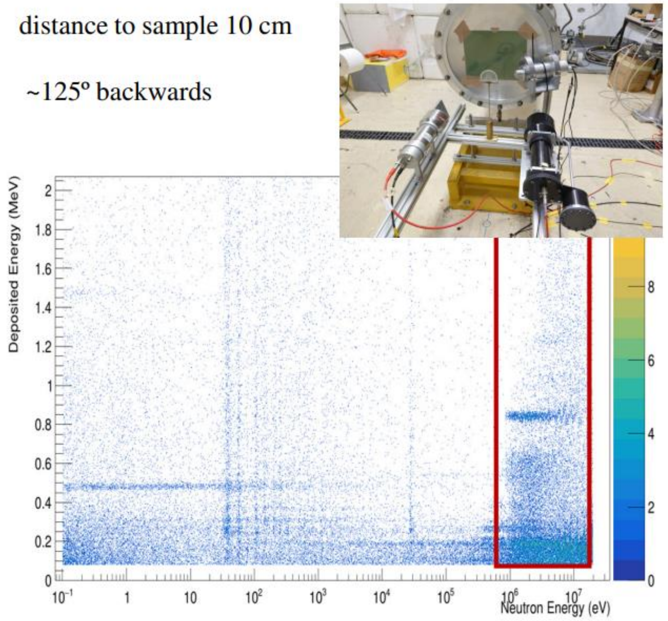
- ^{10}B(n,α_1)
- +16 CIEMAT detectors

First tests & investigations

- Gamma-spectroscopy based on $LaBr_3$ & HPGe
- Parasitic & dedicated tests to investigate different hardware with beam

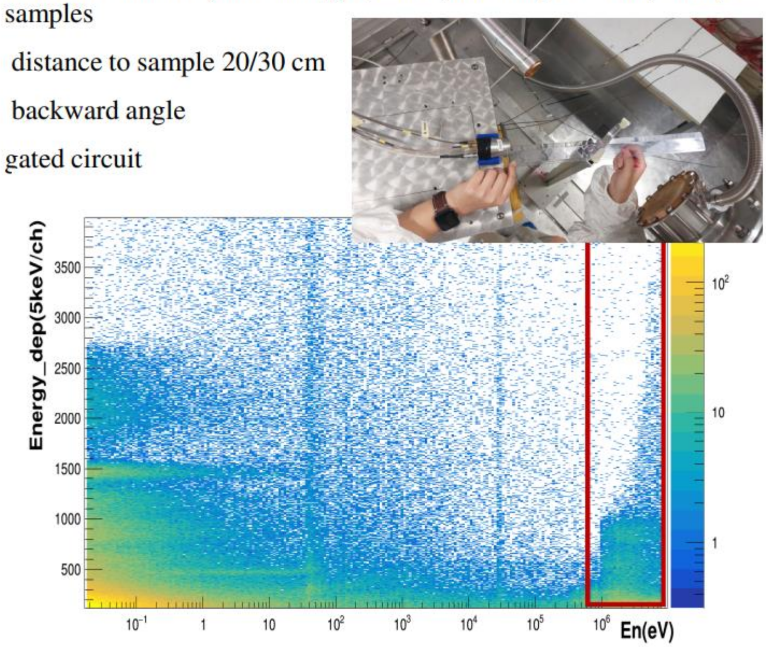
Photomultiplier tube (INFN PMT)

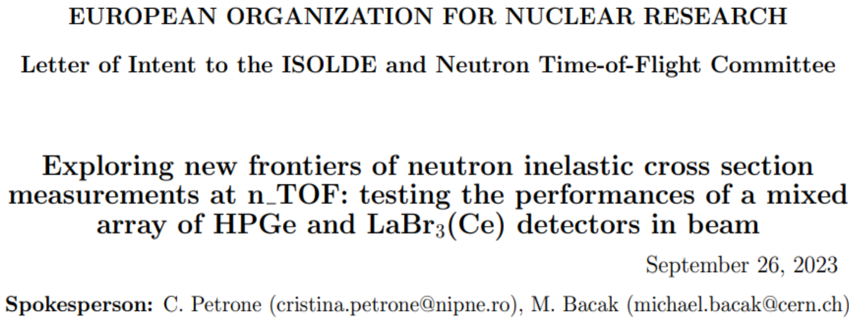
- 1inch cylindrical crystal & ^{56}Fe sample (0.85mm)
- distance to sample 10 cm
- ~125° backwards



Silicon photomultiplier (SiPM)

- 1.5 inch conical crystal damaged, ^{56}Fe (0.85mm) & ^{62}Ni (1 mm) samples
- distance to sample 20/30 cm
- backward angle
- gated circuit





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Exploring new frontiers of neutron inelastic cross section measurements at n_TOF: testing the performances of a mixed array of HPGe and $LaBr_3$(Ce) detectors in beam

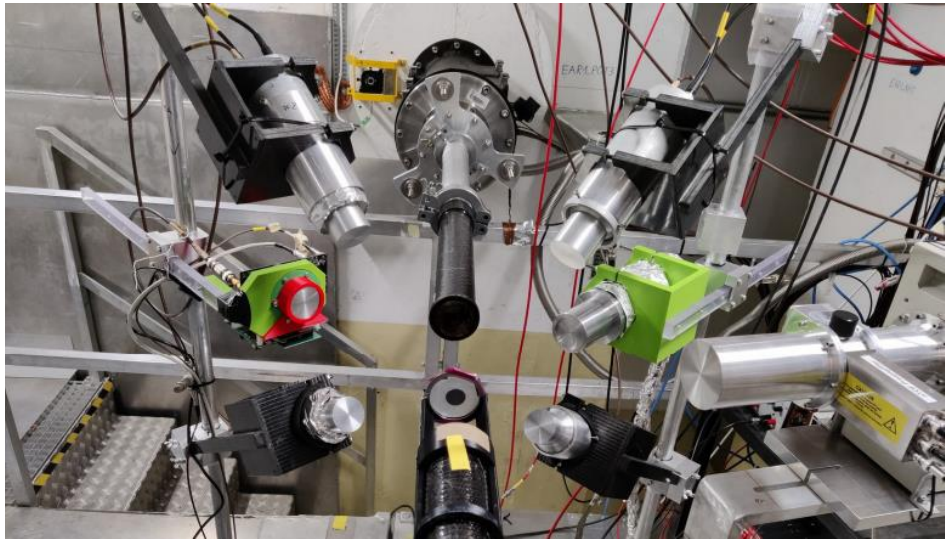
September 26, 2023

Spokesperson: C. Petrone (cristina.petrone@nipne.ro), M. Bacak (michael.bacak@cern.ch)

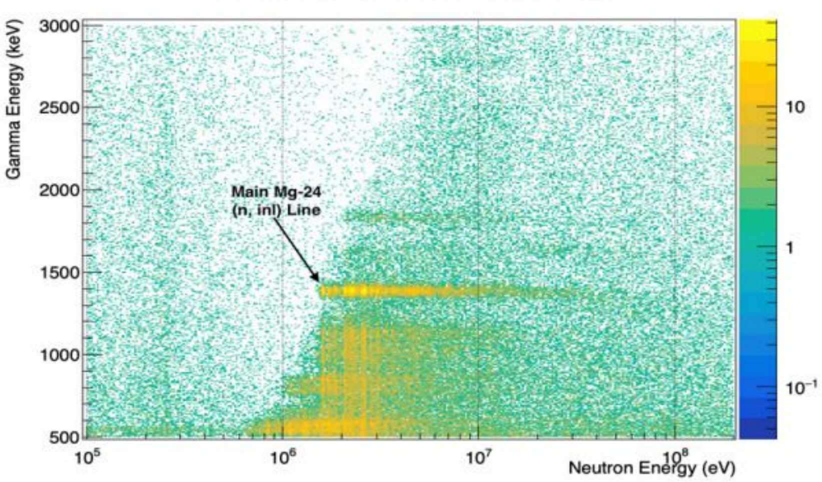
Transition to a real setup – hardware investigation

Finding/Developing hardware for beam conditions:

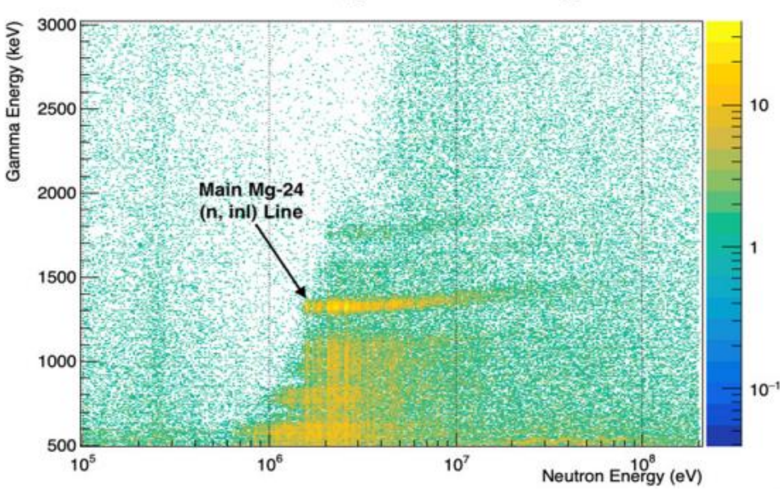
- **100 kHz without gain drifts**
- **Nominal energy resolution (~3% FWHM @ 662 keV)**



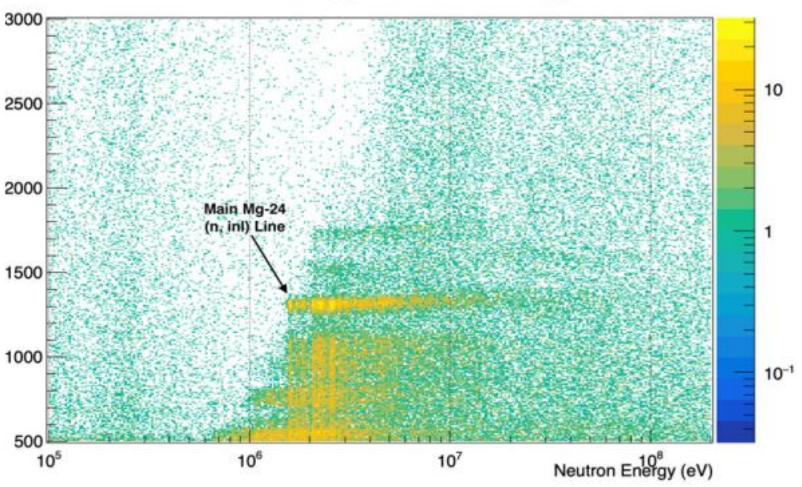
IFIN-HH Detector


Gamma Energy vs Neutron Energy

INFN Detector


Gamma Energy vs Neutron Energy

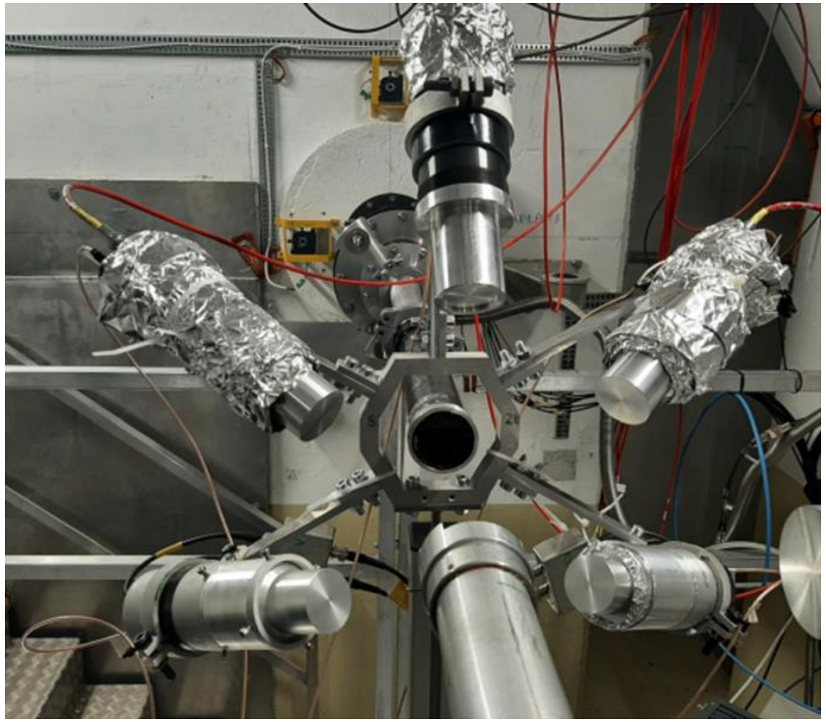
UoM Detector

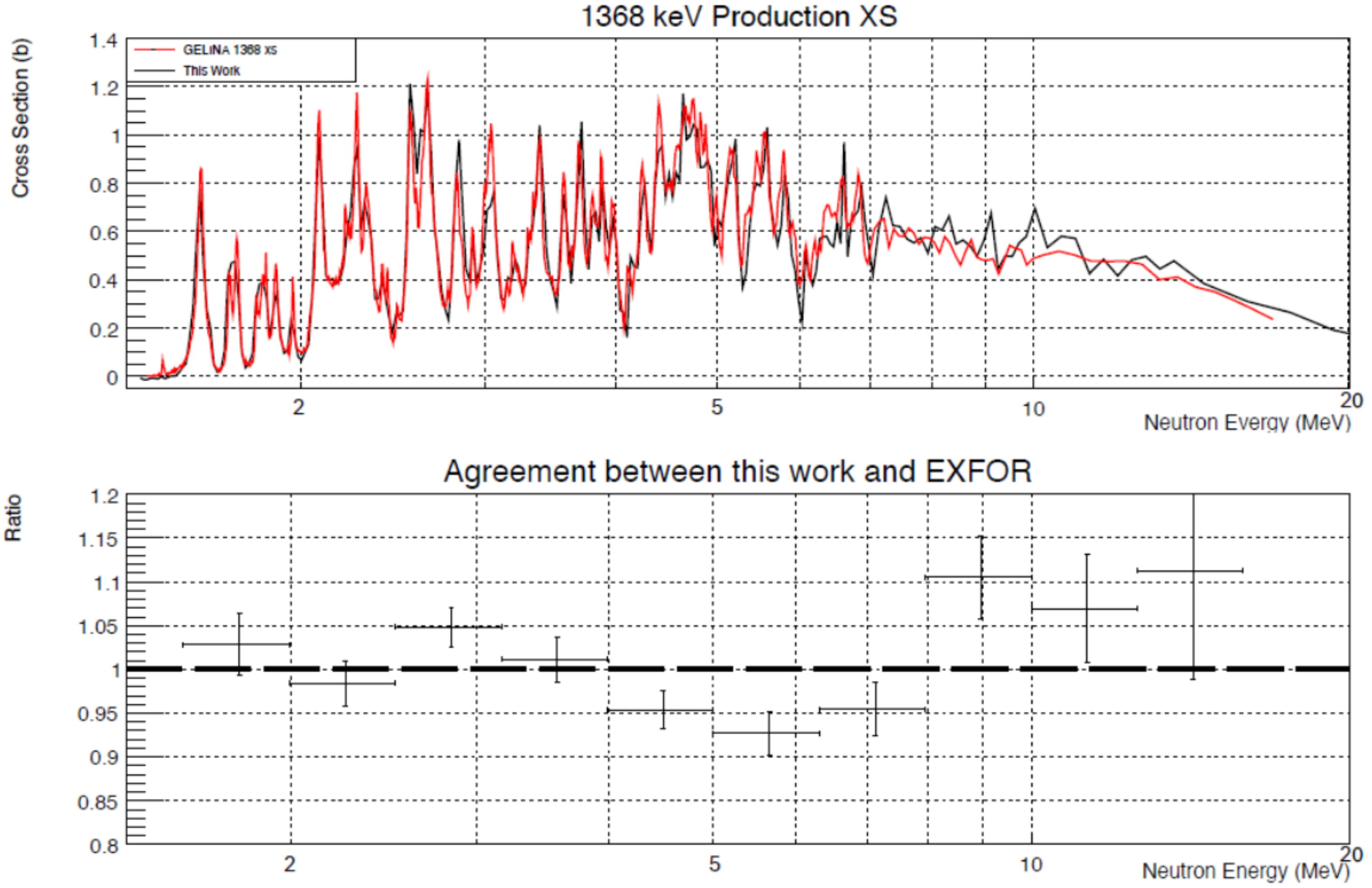

Gamma Energy vs Neutron Energy

First physics benchmark – ^{24}Mg(n,n‘g)

^{24}Mg(n,inl) benchmark: high quality reference data

- 5 well performing detectors
- A sample
- 5 days of statistics

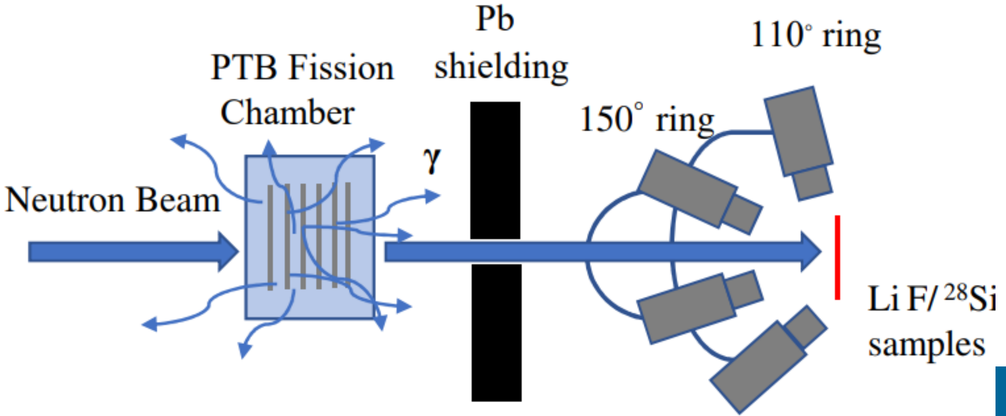


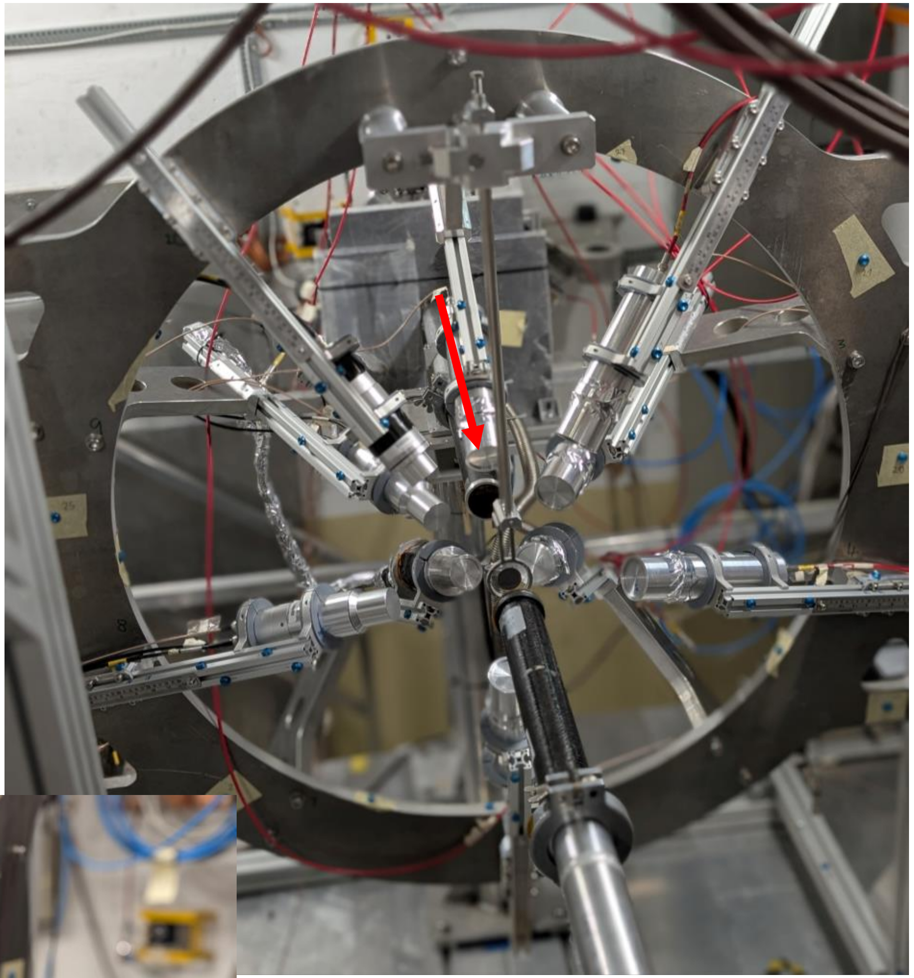


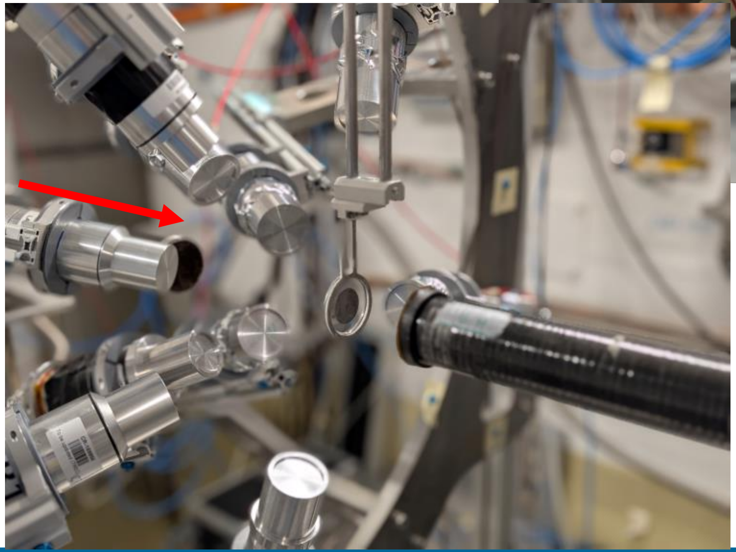
^{24}Mg(n,inl) M. Birch *et al.*

Towards an full array

- Developed by teams from TU Wien + IFIN-HH (Romania) + INFN (Italy) + Uni Manchester (UK)
- Dedicated Detector Configuration:
  - 10 $LaBr_3(Ce)$ detectors
  - Two rings @ 110° and 150°
  - Beam monitor
  - Shielding
- Two physics cases:
  - $^{19}F(n,n')$ FLiBe molten salt coolant
  - $^{28}Si(n,n')$ space exploration studies

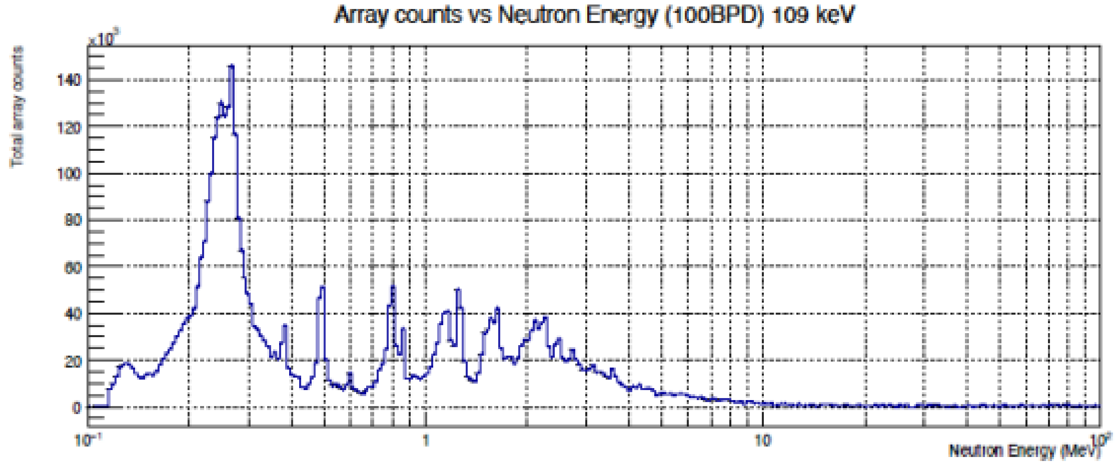


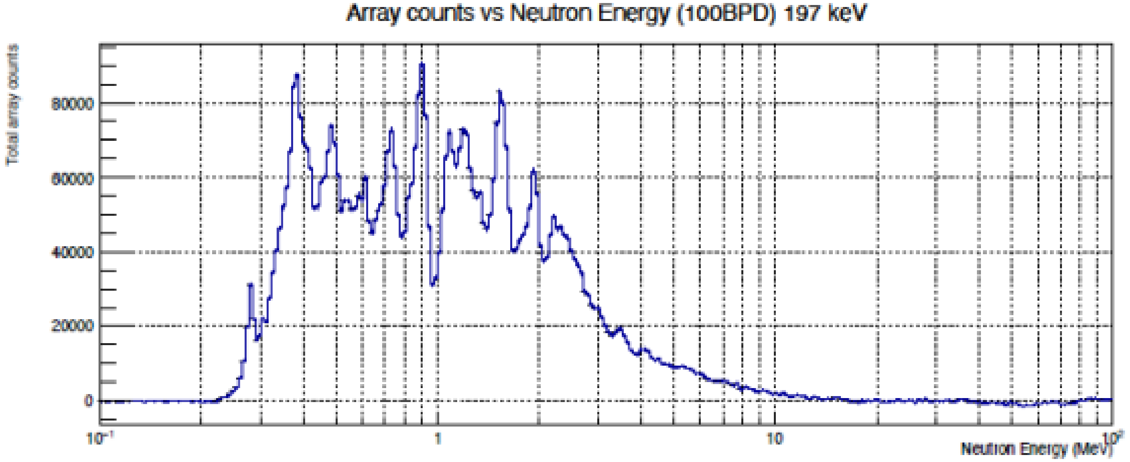




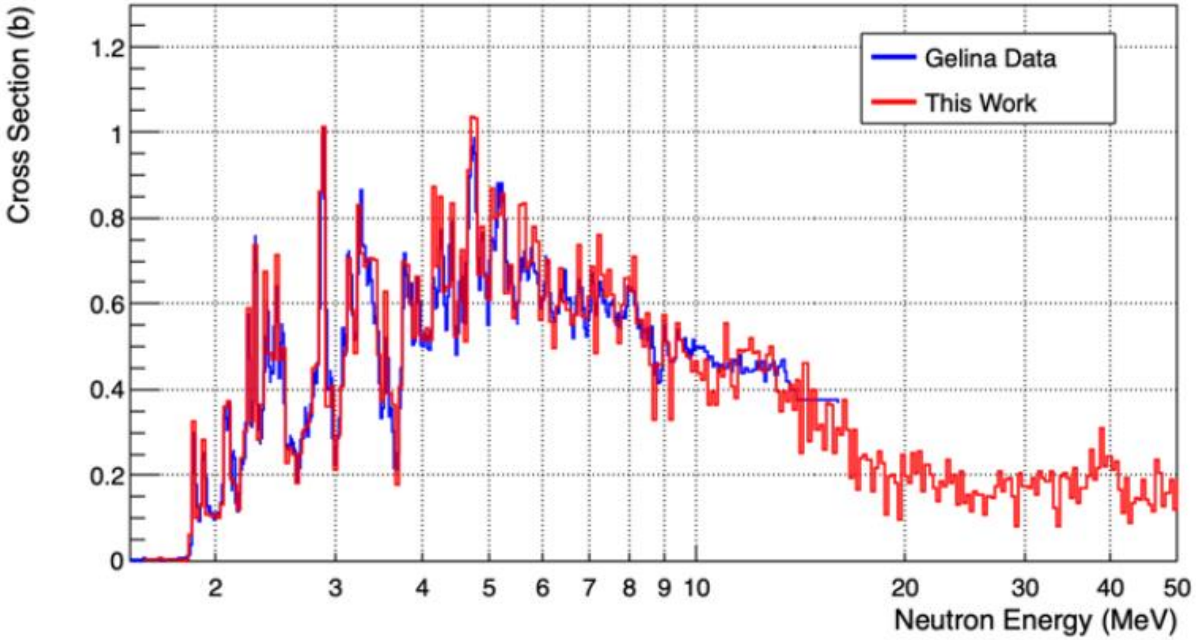
^{19}F(n,n‘) & ^{28}Si(n,n‘)

^{19}F(n,n’)





^{28}Si(n,n’)

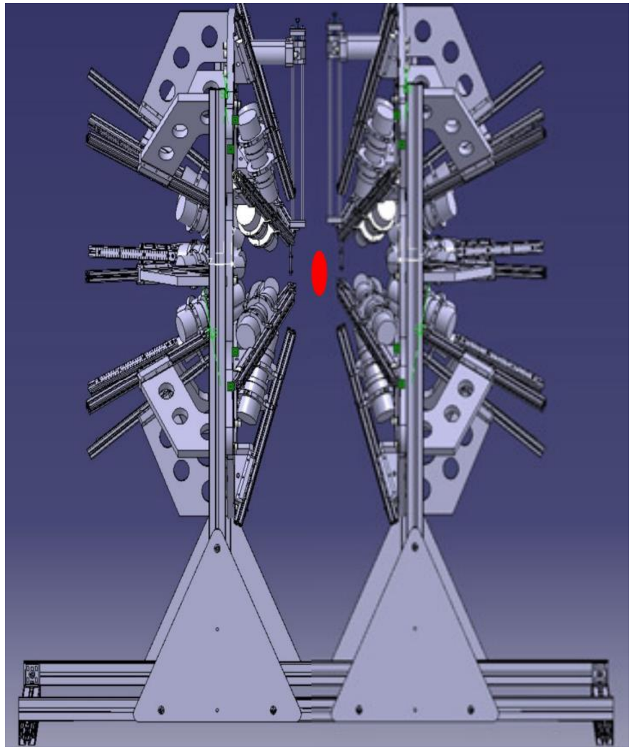


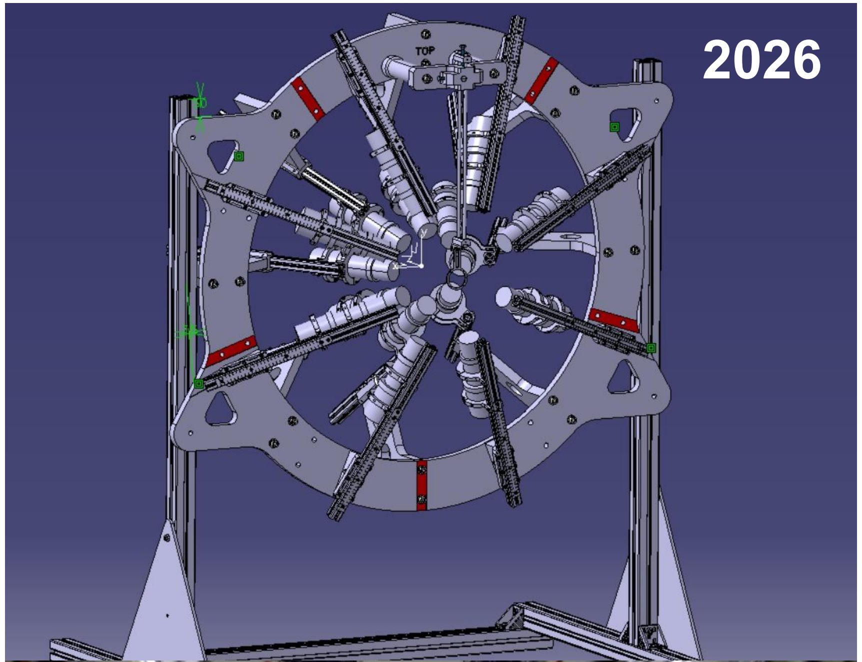
BRAINS for (n,n‘g) and (n,xng)

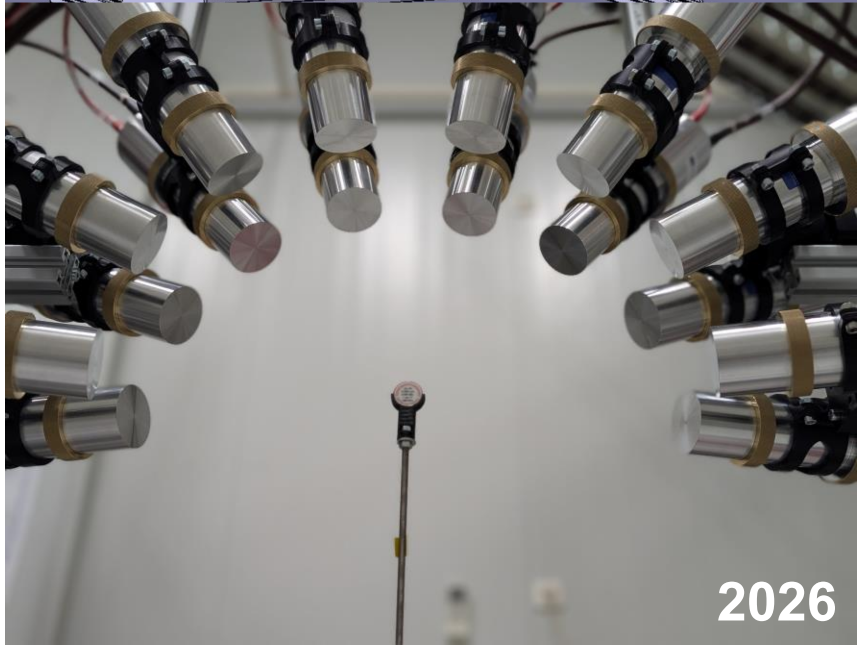
- **BR**illiance **A**rray for **I**n-beam **N**eutron reactions **S**tudies

- New standard configuration for 16 detectors / hemisphere
- +16 detectors from CIEMAT (Spain)
- Total 28 detectors available

- Outlook:
  - ^{10}B(n,$\alpha_1\gamma$) (Aug 2026)
  - Forward hemisphere?
  - Inelastic XS: ^{16}O, ^{12}C, ^{209}Bi, $^{90-94}$Zr
  - (n,xn) on ^{63,65}Cu, ^{56}Fe
  - Fission studies
  - Capture ?
  - …




2026


2026

Summary

- Neutron nuclear data, especially cross sections, are of interest in
  - Nuclear technology, astrophysics and medicine
  - Fundamental research – improve neutron transport simulations (e.g. backgrounds)
  - Detector design: single event failures in electronics / radiation damage to materials

- Higher precision nuclear data / neutron cross sections are required by new technologies & applications & modelling tools in various energy regions

- TU Wien @ n_TOF:
  - Is a founding member of the largest collaboration measuring $\sigma_{(n,x)}$
  - Developing new instruments for broadening the physics programme via (n,n’) and (n,xng) and beyond

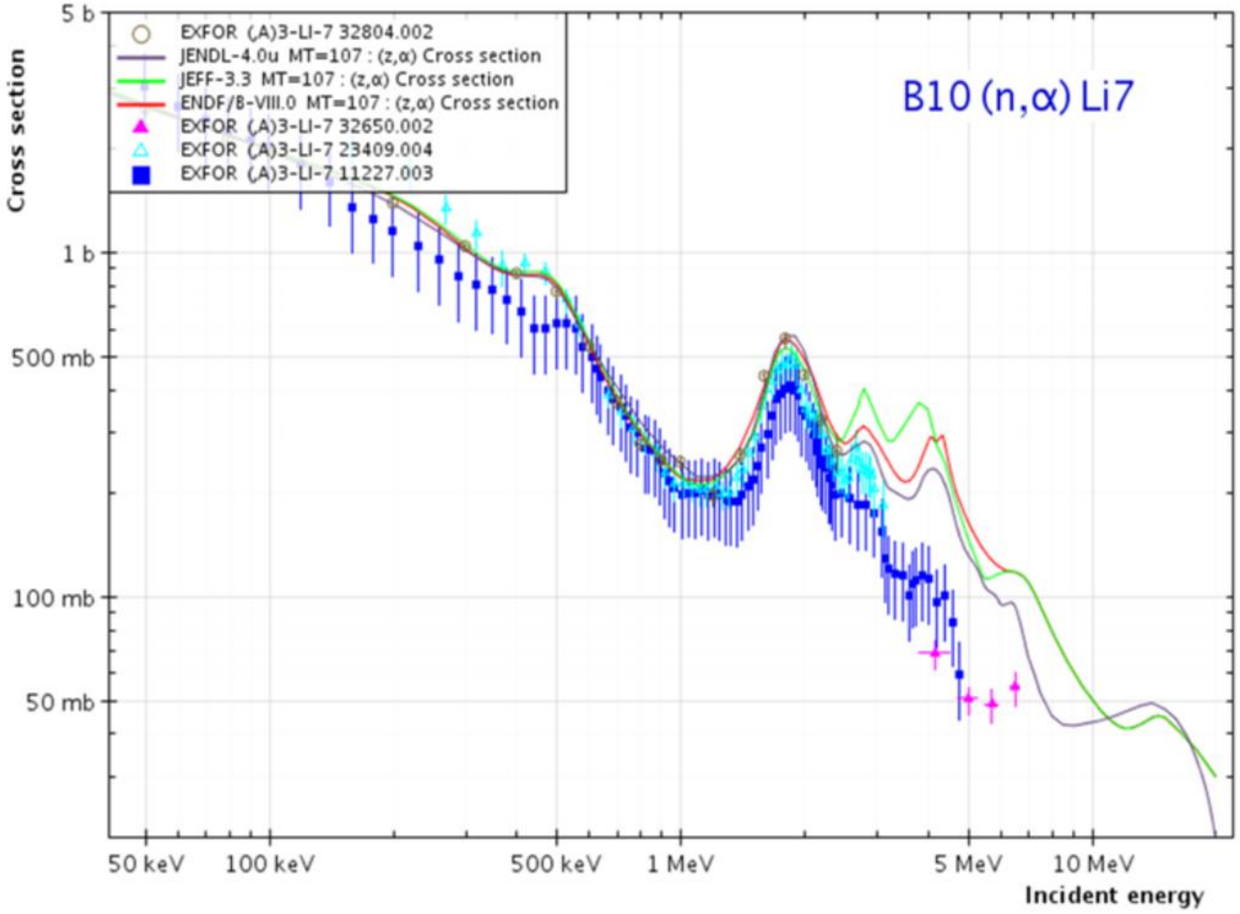
Beyond (n,inl) – ^{10}B(n,$\alpha_1\gamma$) standard

- ^{10}B(n,a) cross section is a well-established standard from thermal energies up to 1 MeV

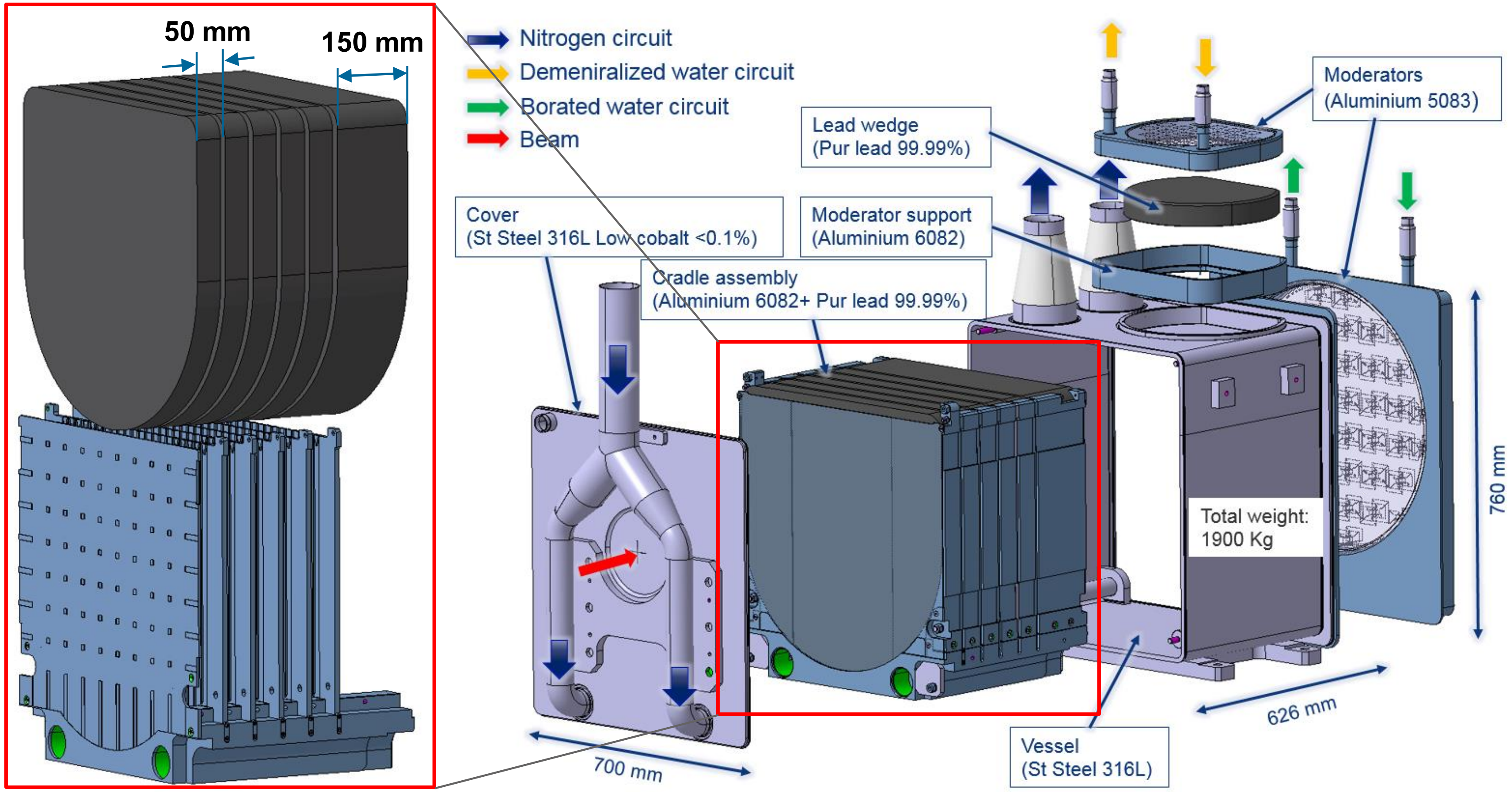
- Many data exist

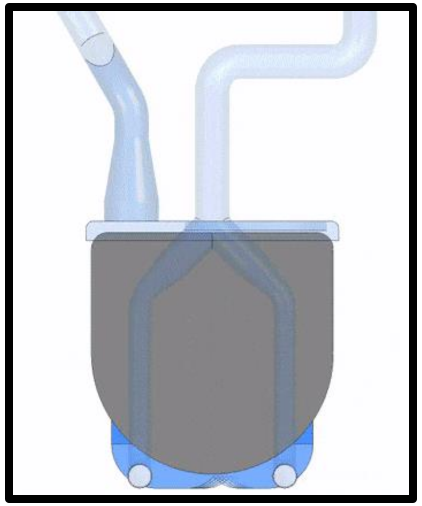
- Beyond 1 MeV data discrepant
  - Reason: particle-leaking effect when measuring the charged particle
  - To avoid: measure the 478 keV gamma in (n,$\alpha_1\gamma$)

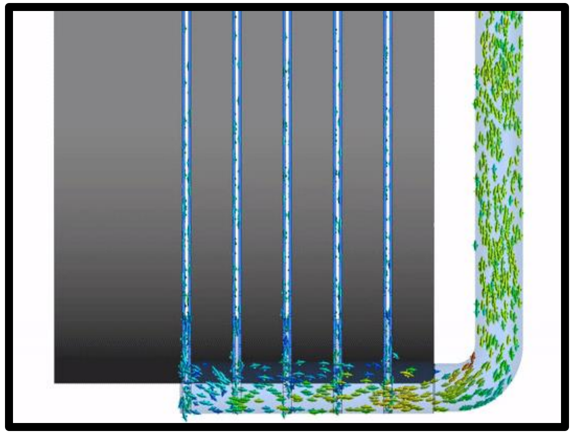
- Also used in Boron Neutron Capture Therapy – 478 keV gamma used for dose delivery monitoring



n_TOF spallation target







Al-6082-T6 supporting structure (anti-creep and N_2 cooling channels)

N_2 gas cooling to avoid Pb corrosion and contamination of the cooling circuit

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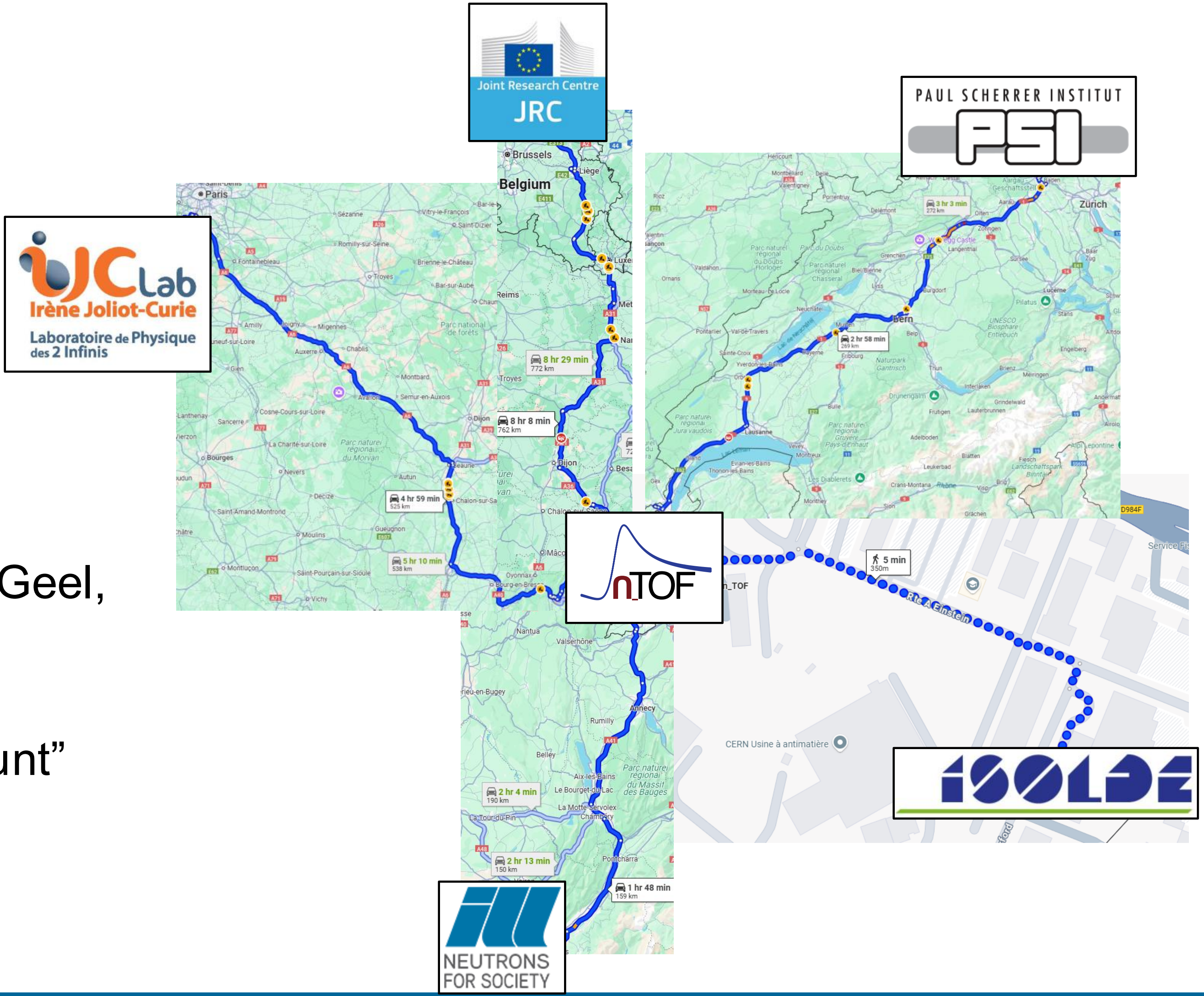
The heart of Europe

- Some of the highest impact physics cases (^{79}Se, ^{94}Nb, $^{239+241}$Pu, ^{88}Zr, ^{243}Am, …)
- No sample = no measurement
- Collaboration with ISOLDE, GRC Geel, PSI, ILL, IJClab & others is crucial
- “Omnes viae ~~Romam~~ n_TOF ducunt” … all roads lead to …



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