High accuracy measurements of neutron induced cross sections on short-lived nuclei at the CERN n_TOF facility

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on behalf of the n_TOF Collaboration

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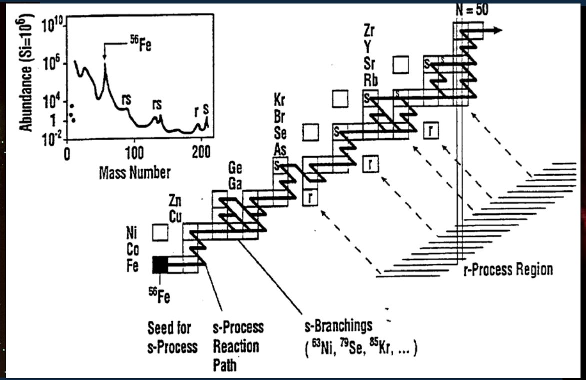
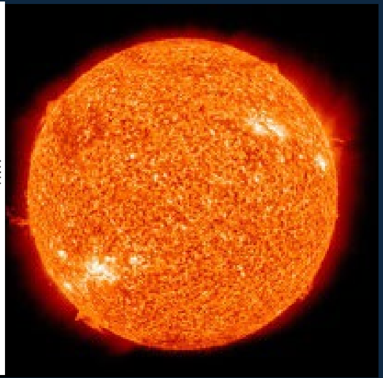
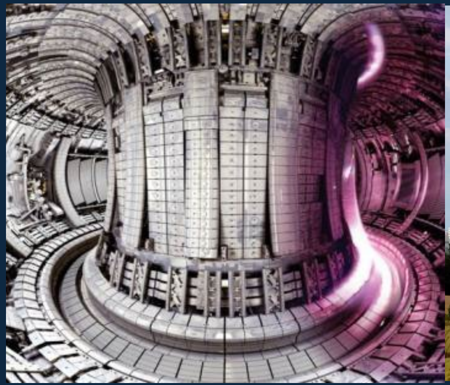
Neutron-induced reaction experiments provide data of paramount importance for

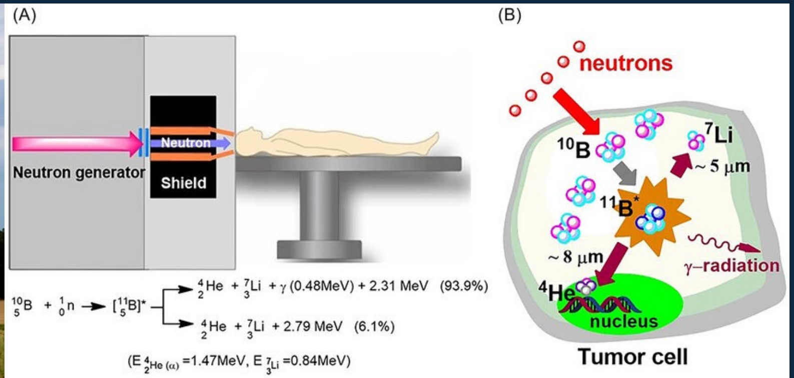
- **Nuclear astrophysics**
  - Stellar nucleosynthesis
  - Cosmocronology
  - Investigation of stellar environments
  - Primordial nucleosynthesis





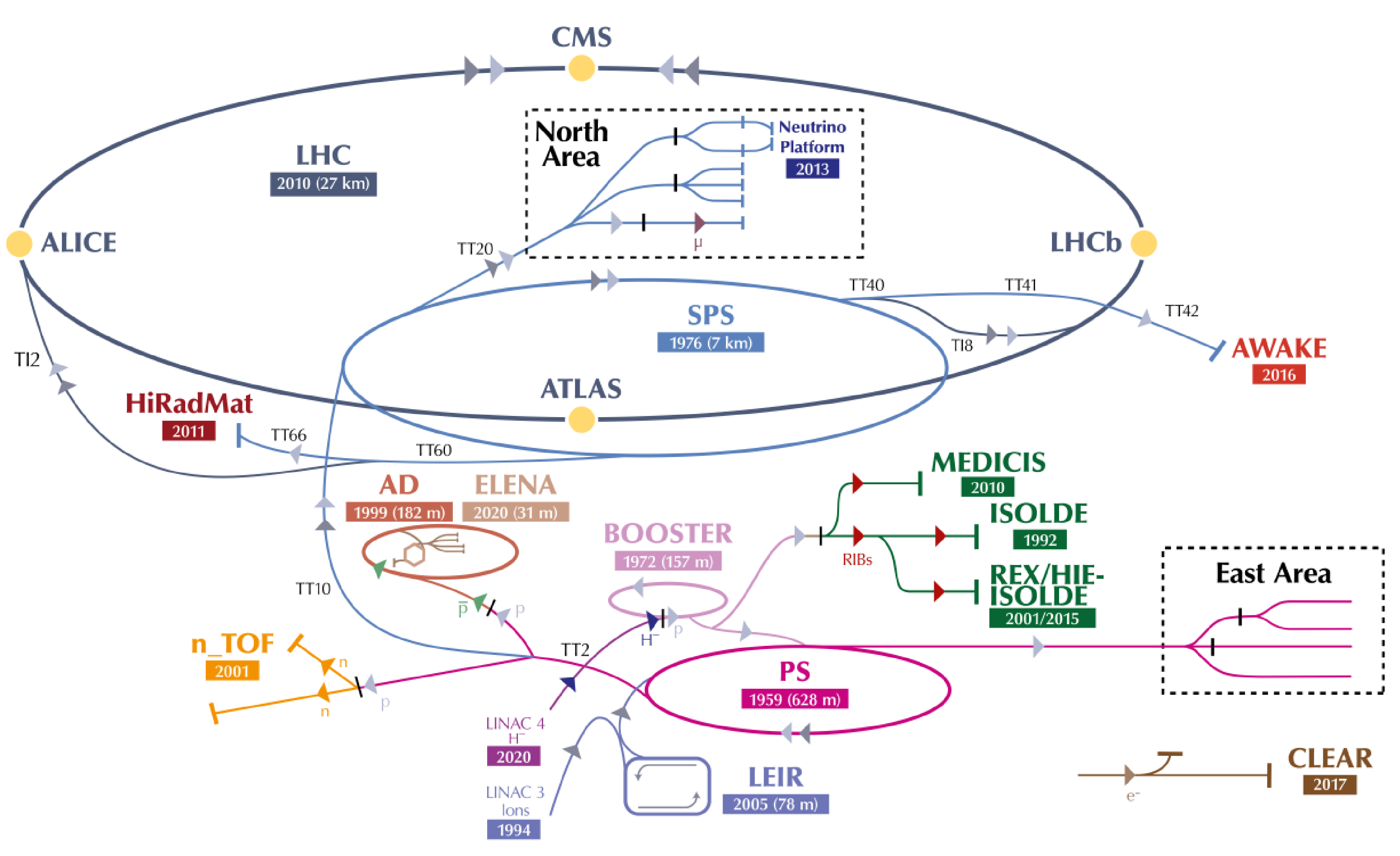
- Advanced nuclear technologies
  - Gen-IV reactors
  - Nuclear waste destruction
  - Fusion reactors
  - Space technologies
  - Nuclear medicine





- and basic nuclear science

The CERN **n**eutron **T**ime **of** **F**light facility



A collaboration made of

≈ 40 Institutes, 150 researchers, 20 PostDoc, 30 PhD students

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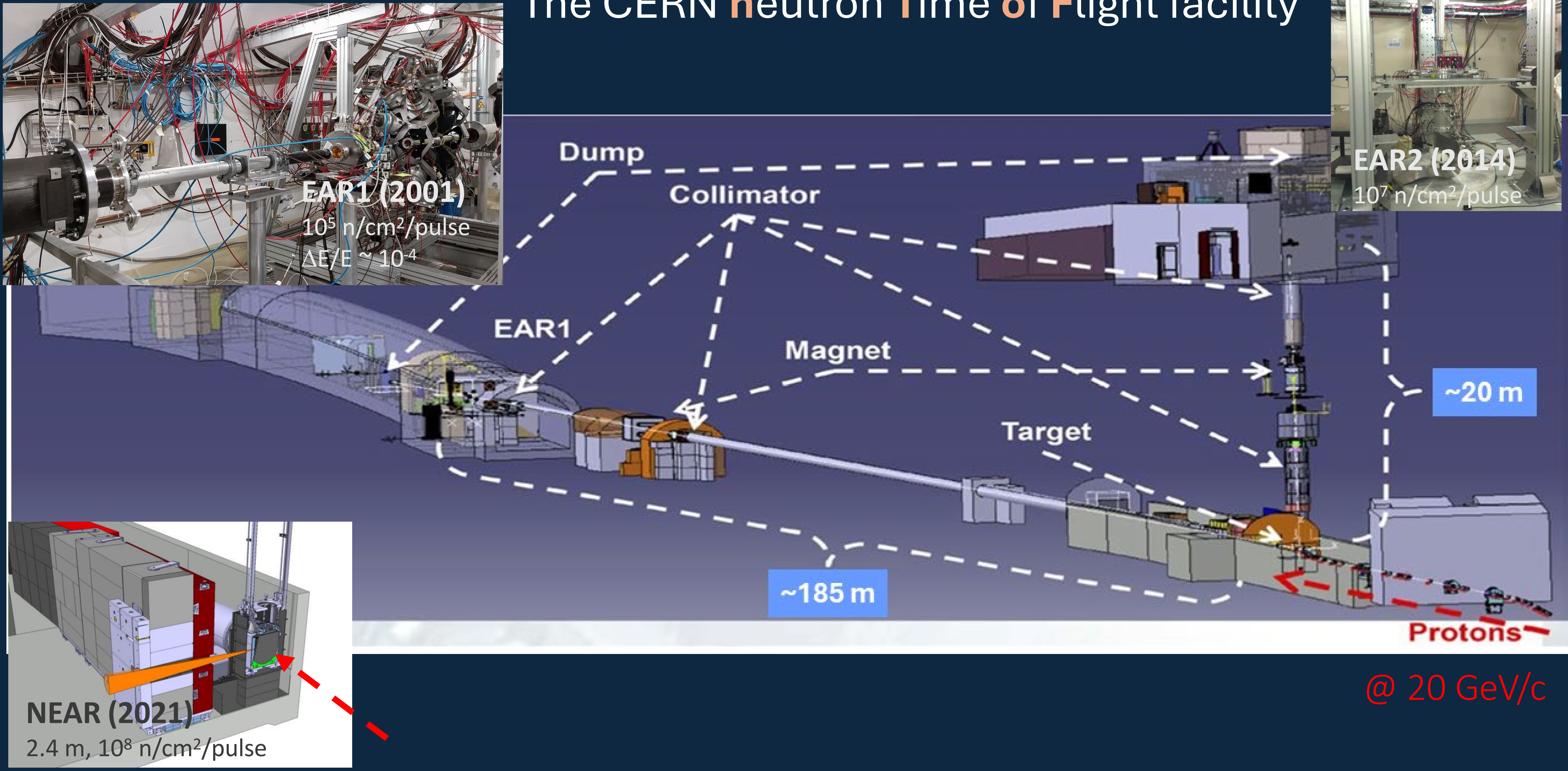
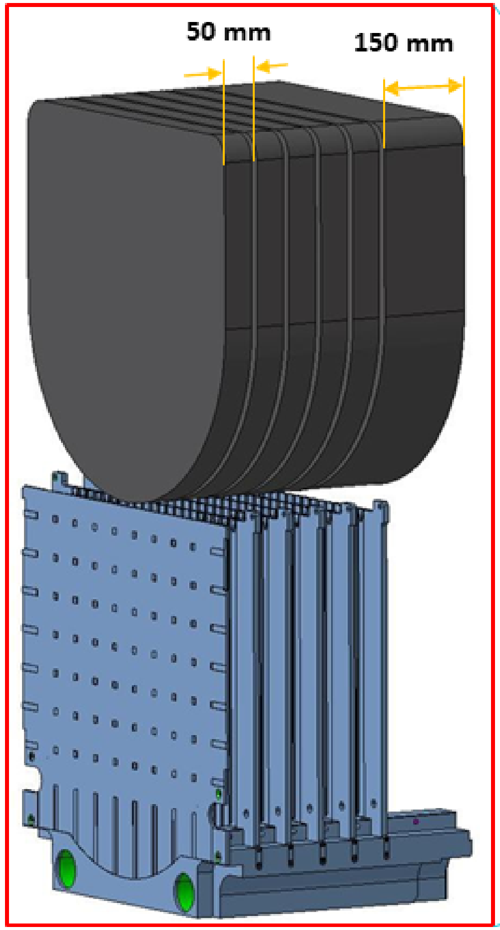
The CERN neutron Time of Flight facility

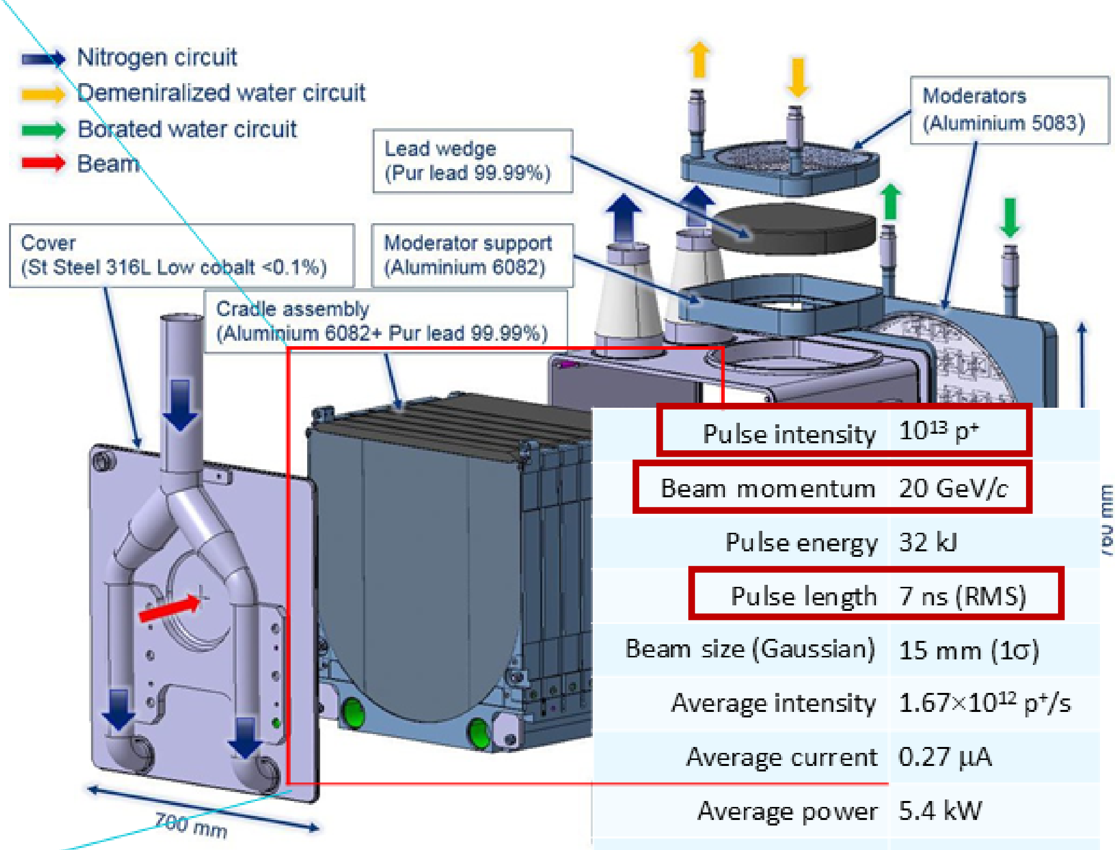


@ 20 GeV/c

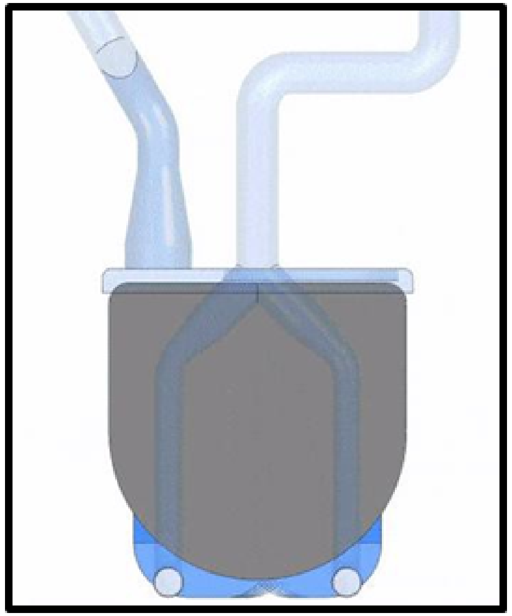
The spallation target

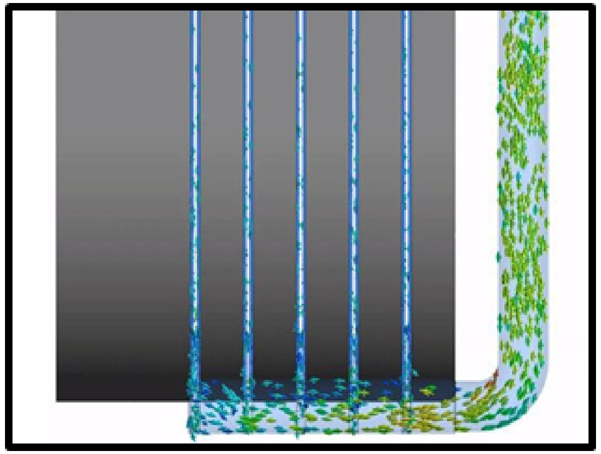


Al-6082-T6 supporting structure
(anti-creep and N_2 cooling channels)

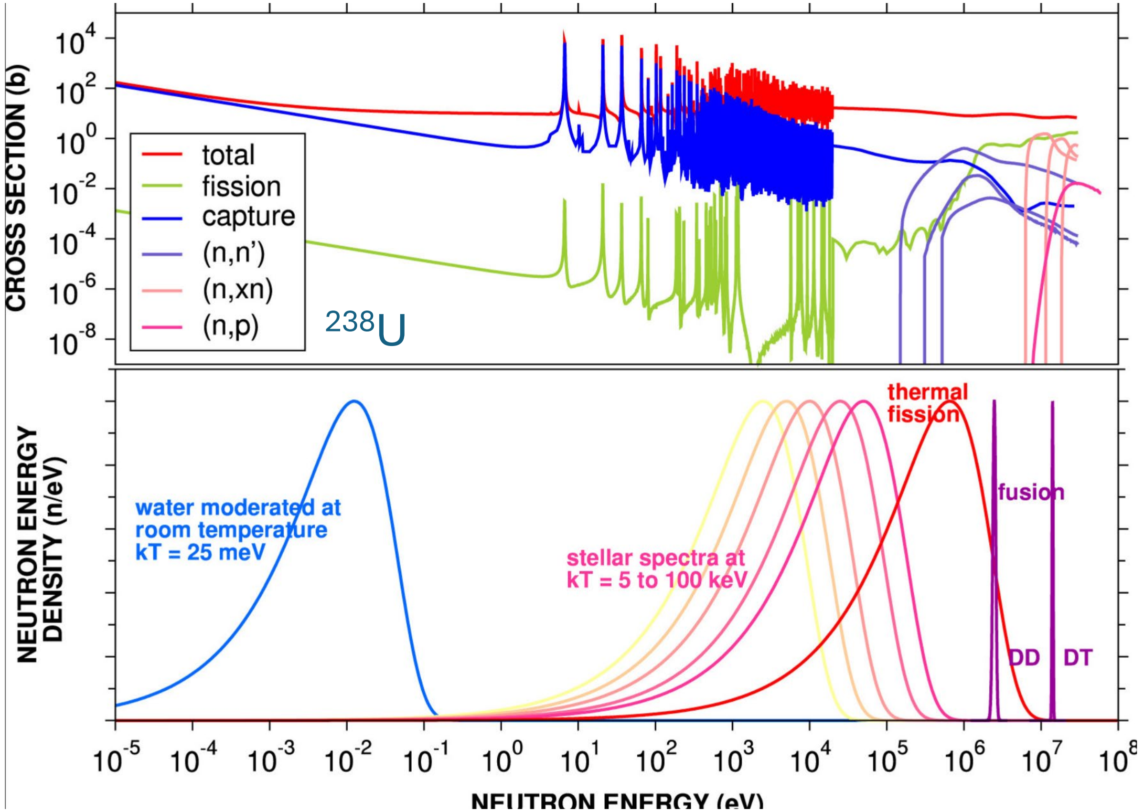


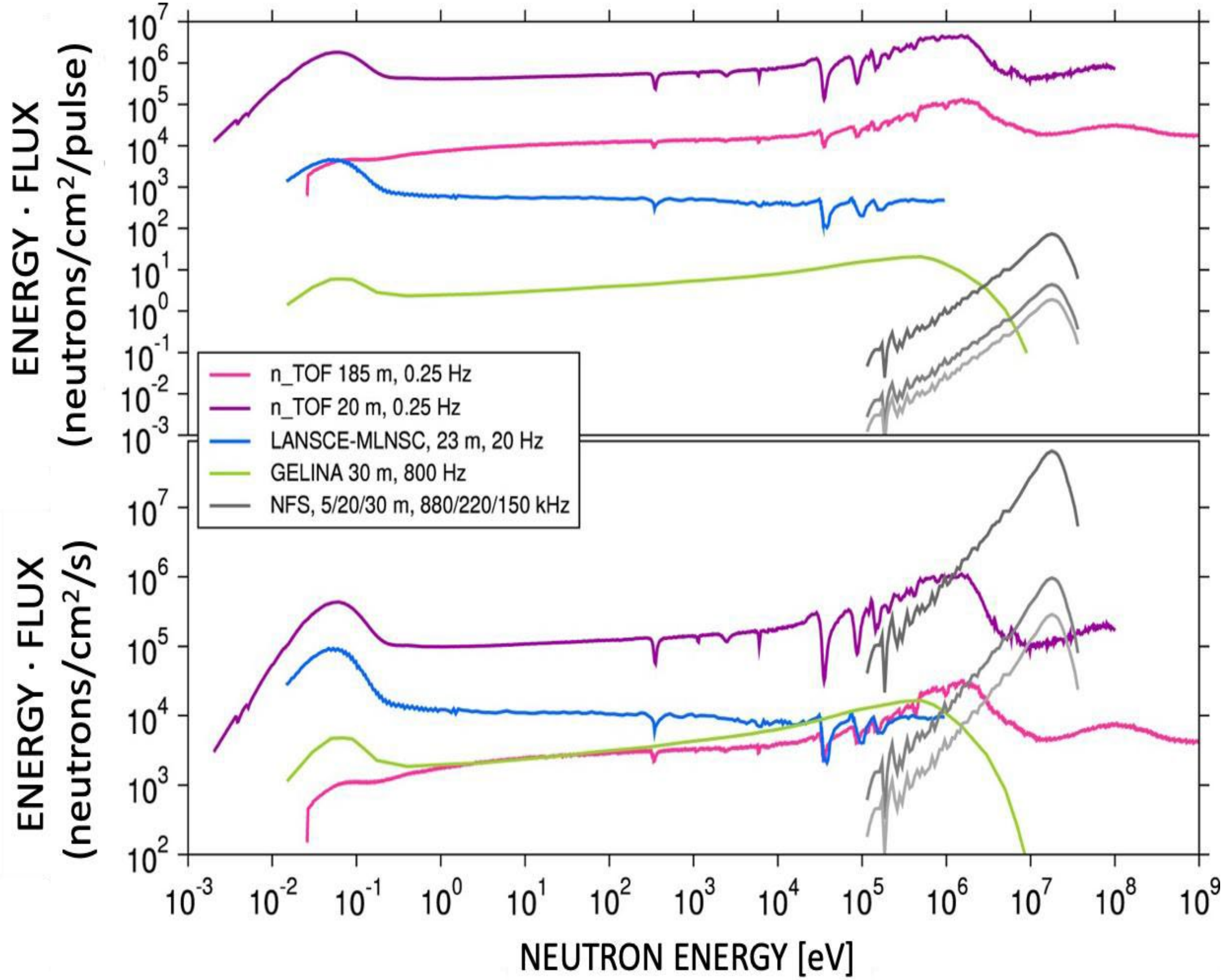
Pulse intensity	10^{13} p^+
Beam momentum	20 GeV/c
Pulse energy	32 kJ
Pulse length	7 ns (RMS)
Beam size (Gaussian)	15 mm (1σ)
Average intensity	1.67×10^{12} p^+/s
Average current	0.27 µA
Average power	5.4 kW
Peak current	91.3 A
Peak power	1.8 TW





Uniqueness of n_TOF



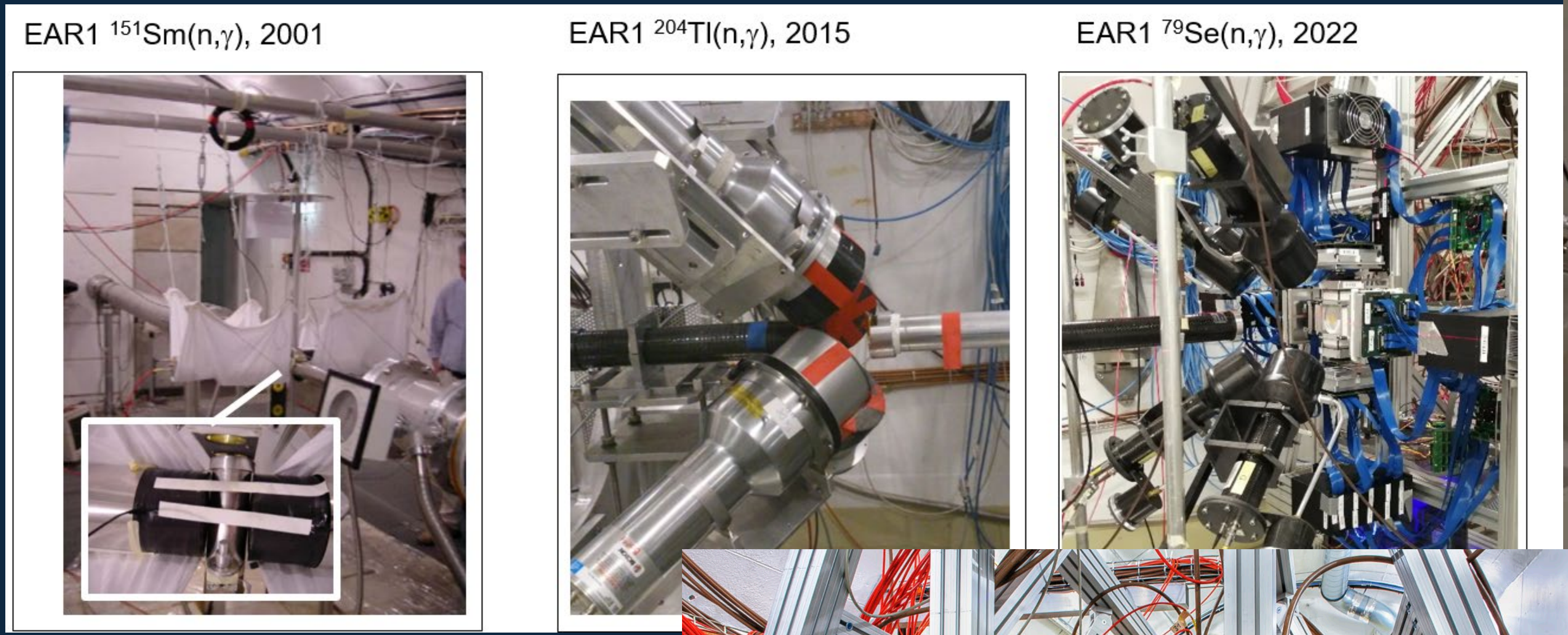


Progress in Particle and Nuclear Physics, **101**, 177 (2018)

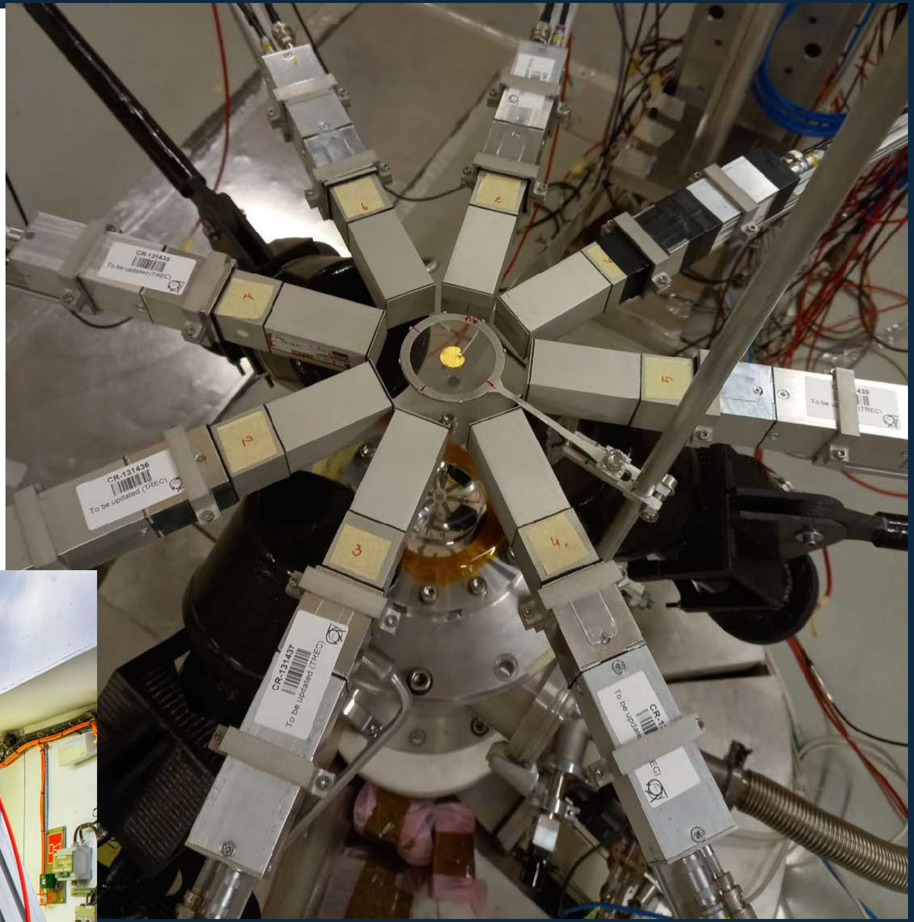
- Instantaneous intensity
- Energy distribution
- Time/neutron energy resolution

n_TOF features	***Translate in***
Broad neutron energy range (meV < E_n < GeV)	Measurement of neutron-induced cross sections in a wide energy range (meV-GeV)
High instantaneous flux (10^5-10^6 n/cm^2/bunch)	Measurement of small cross sections Measurements on samples available in small quantities (isotopically enriched samples) Measurements on radioactive samples (low intrinsic background)
Excellent energy resolution $\Delta E/E \approx 10^{-4}$ up to 100 keV	Resonance dominated cross section measurements
Low neutron sensitivity Low backgrounds	Accurate cross section measurements even for large $\boldsymbol{\sigma}_{el}/\boldsymbol{\sigma}_{capture}$

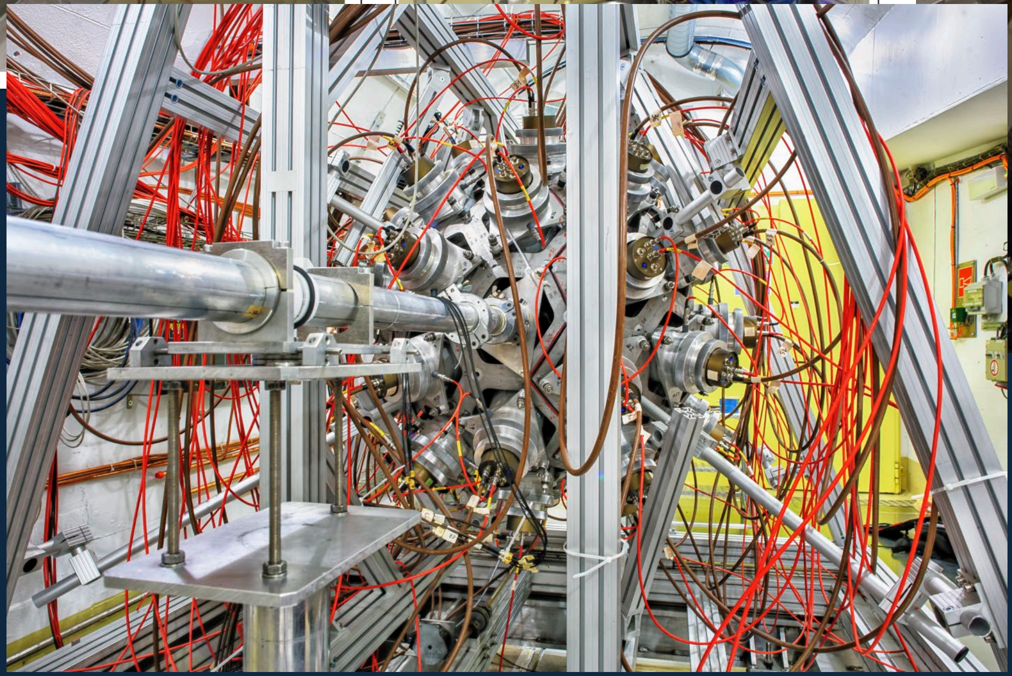
Experimental set-up – Neutron Capture measurements



C_6D_6 and their upgrading



Segmented Total Energy Detectors



The Total Absorption Calorimeter
Made of 40 BaF2 crystals
4π geometry

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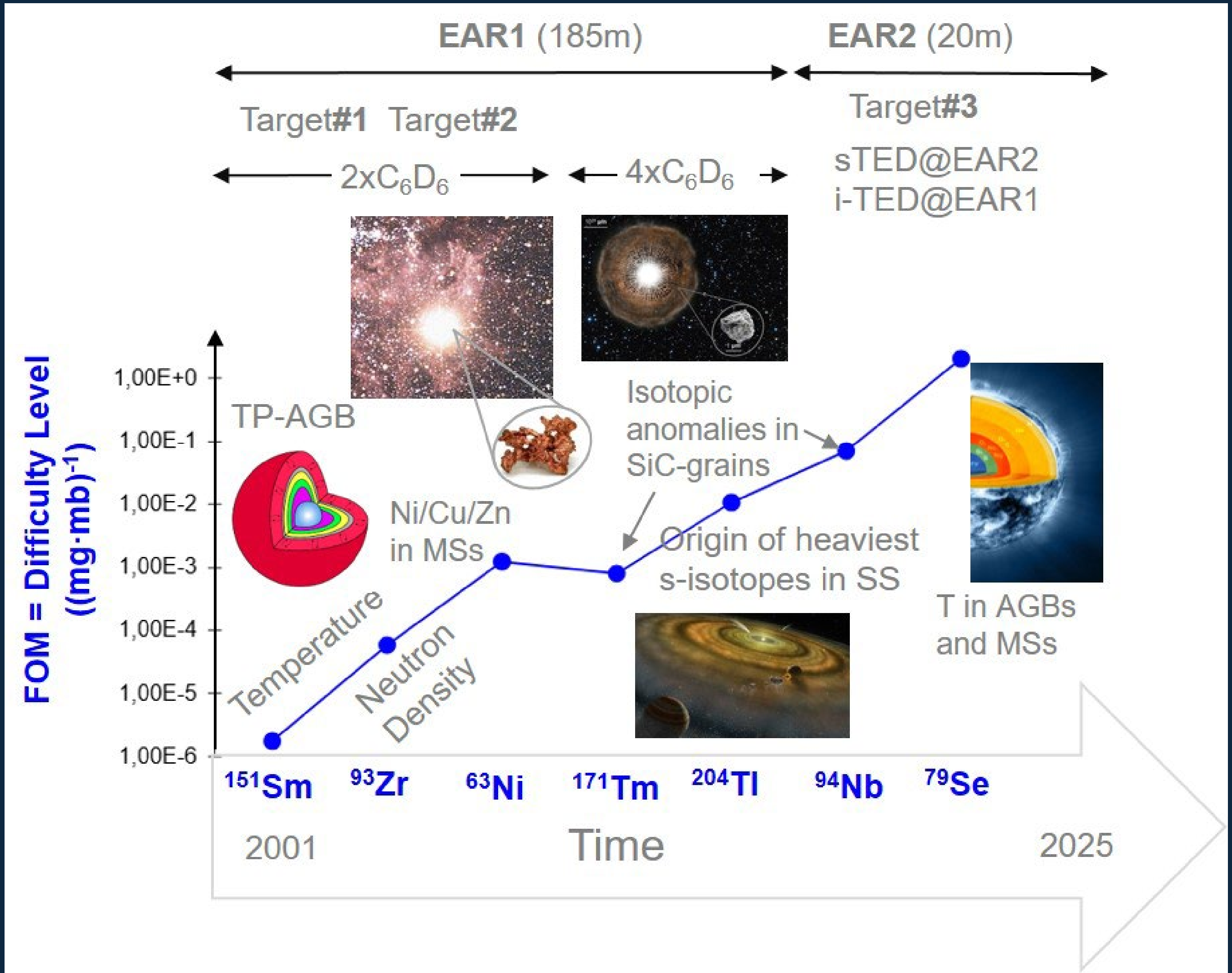
Increasing performances

$$\text{FOM} = \frac{1}{m \cdot f \cdot \sigma}$$

Royalties to
Cesar Domingo-Pardo



^{151}Sm

Mass m = 200 mg

Enrichment factor f = 0.9

Capture cross section at 30 keV, σ=3b

^{79}Se

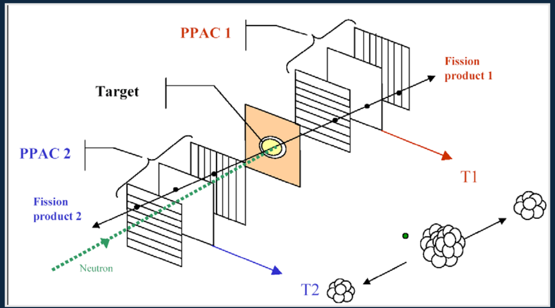
m = 2.7 mg

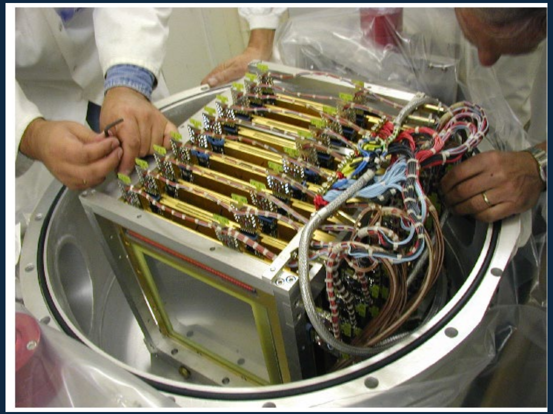
f = 7x10^{-4}

σ = 0.2 b

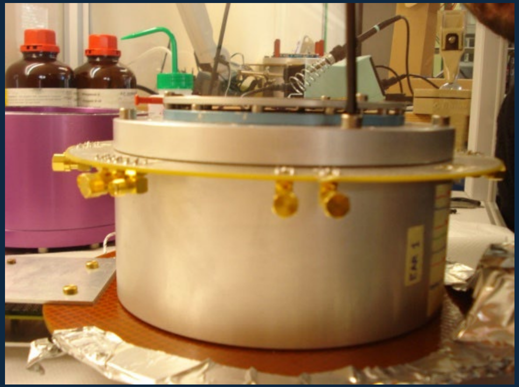
Experimental set-up – Neutron induced Fission measurements

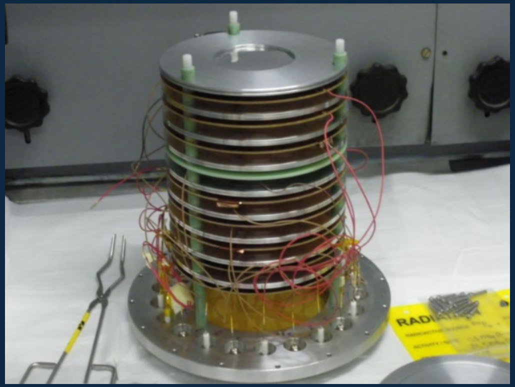
Parallel Plate Avalanche Chamber (PPAC)



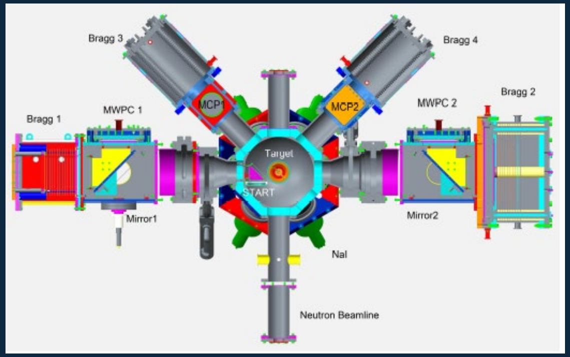


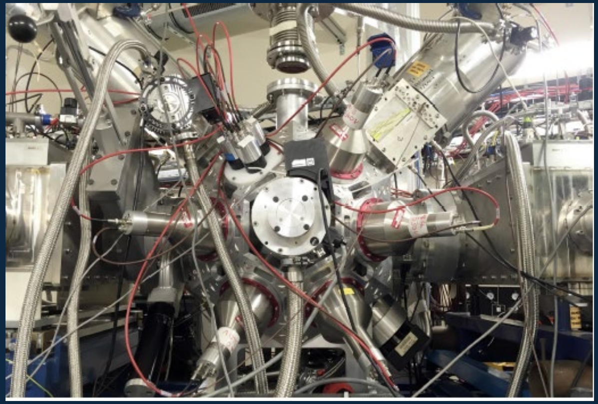
MicroMegas



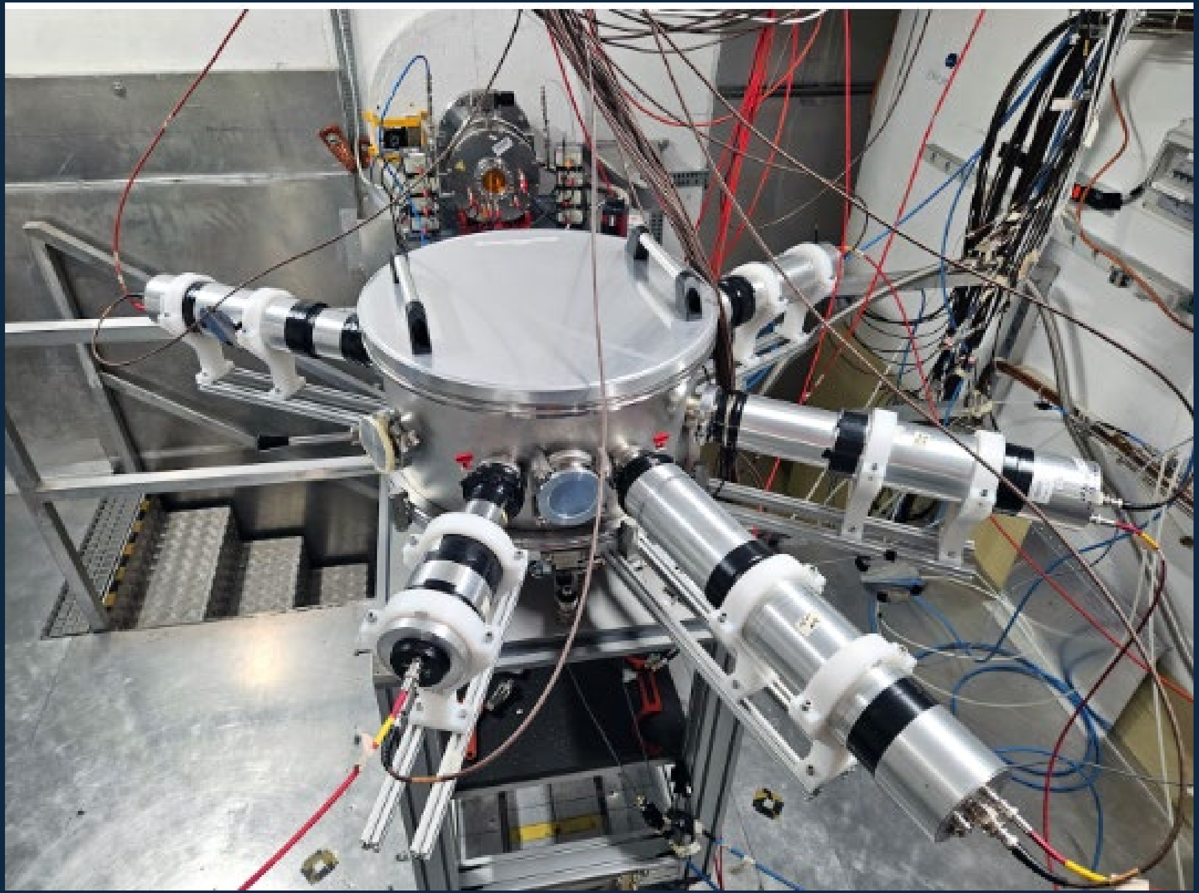


STEFF
Spectrometer for Exotic Fission Fragments

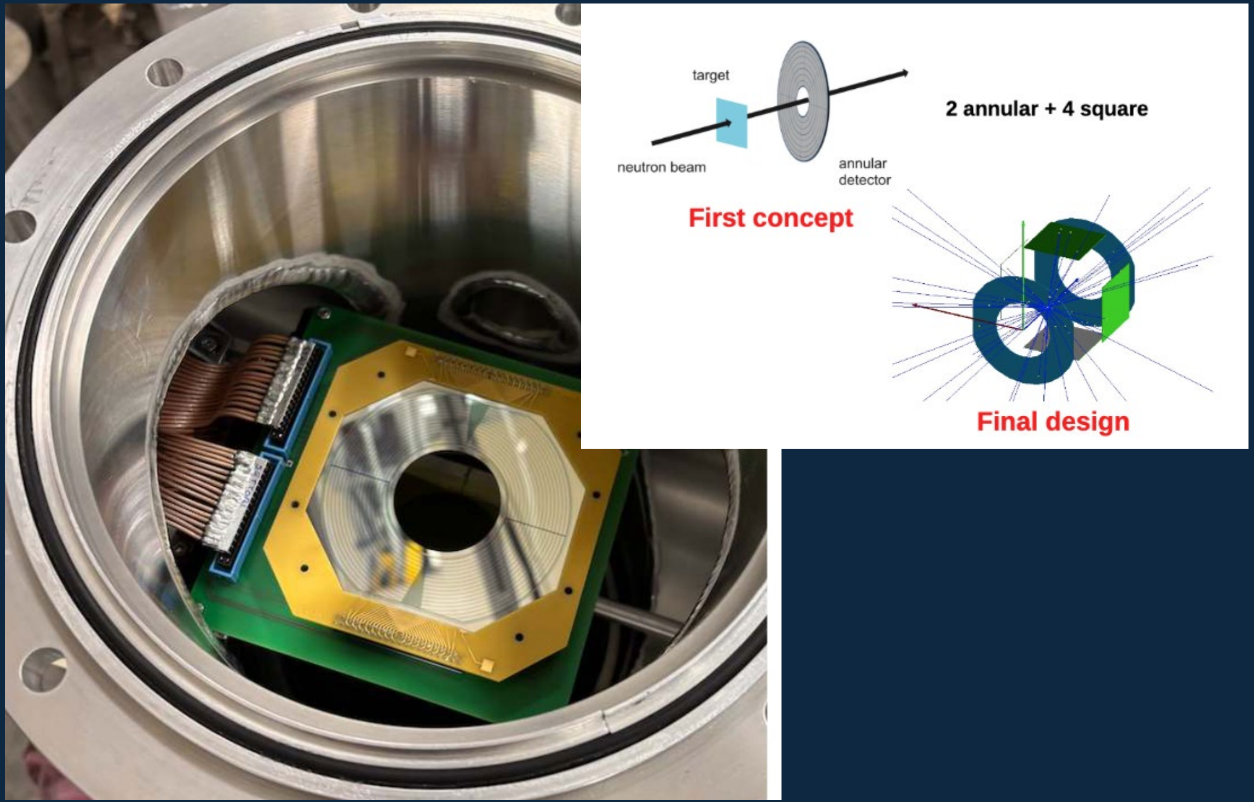




Experimental set-up – Light charged particles in the exit channel of the reaction

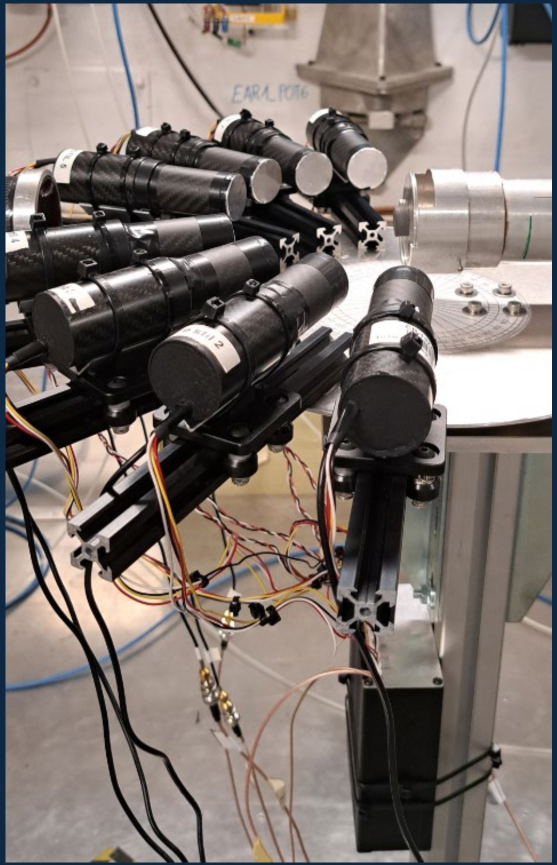


The DDX chamber
ΔE stage - Silicon detectors
E stage – Plastic scintillators

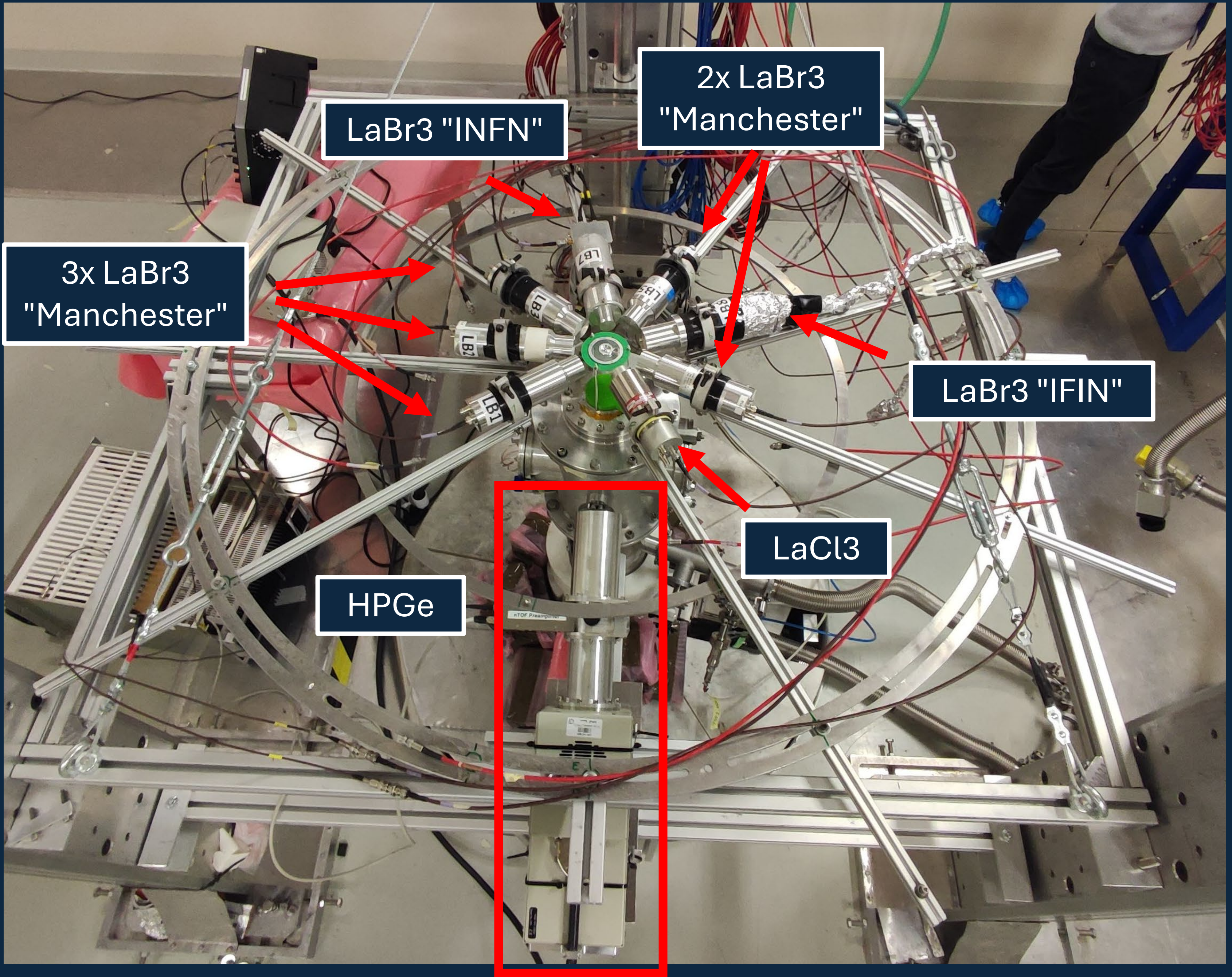


DSSSD
Annular Double-Sided Silicon Strip Detector

Experimental set-up
(n, n' γ) measurements

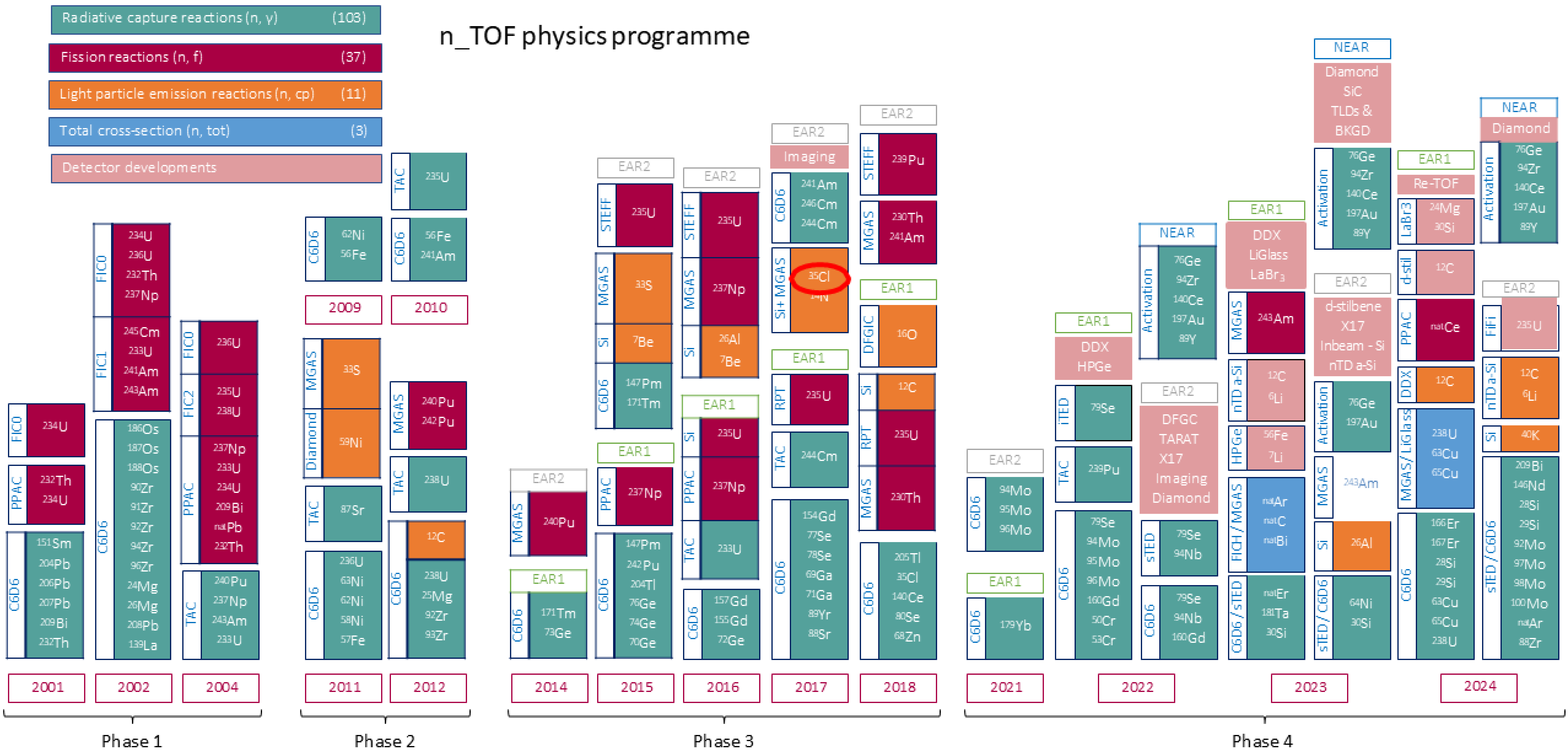


Stilbene detectors



$LaBr_3$ detectors

A long history

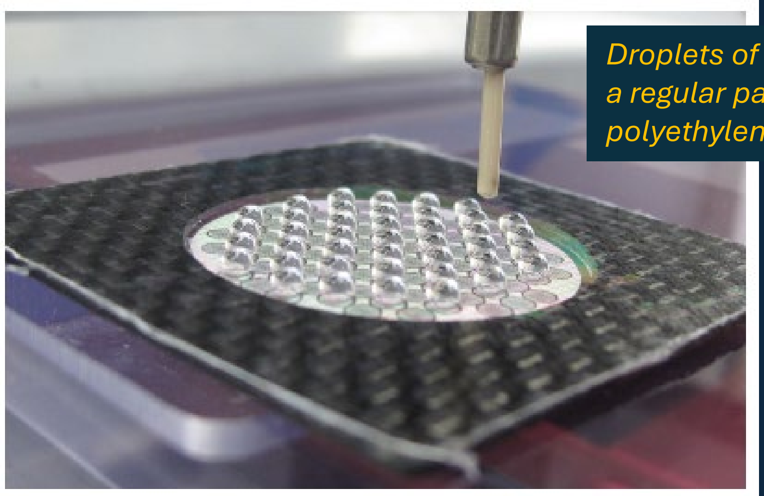


^{7}Be

$T_{1/2}$ = 53.2 days

M ≈ 10 µg

Activity = 13 GBq/µg



Droplets of a 7Be-loaded solution deposited in a regular pattern on a 0.6 µm-thick low-density polyethylene foil

The 7Be samples material were produced at PSI,

by radiochemical separation of ^{7}Be from the SINQ cooling water.

Separated material was then implanted on an Al backing at CERN-ISOLDE

and immediately afterwards irradiated at n_TOF

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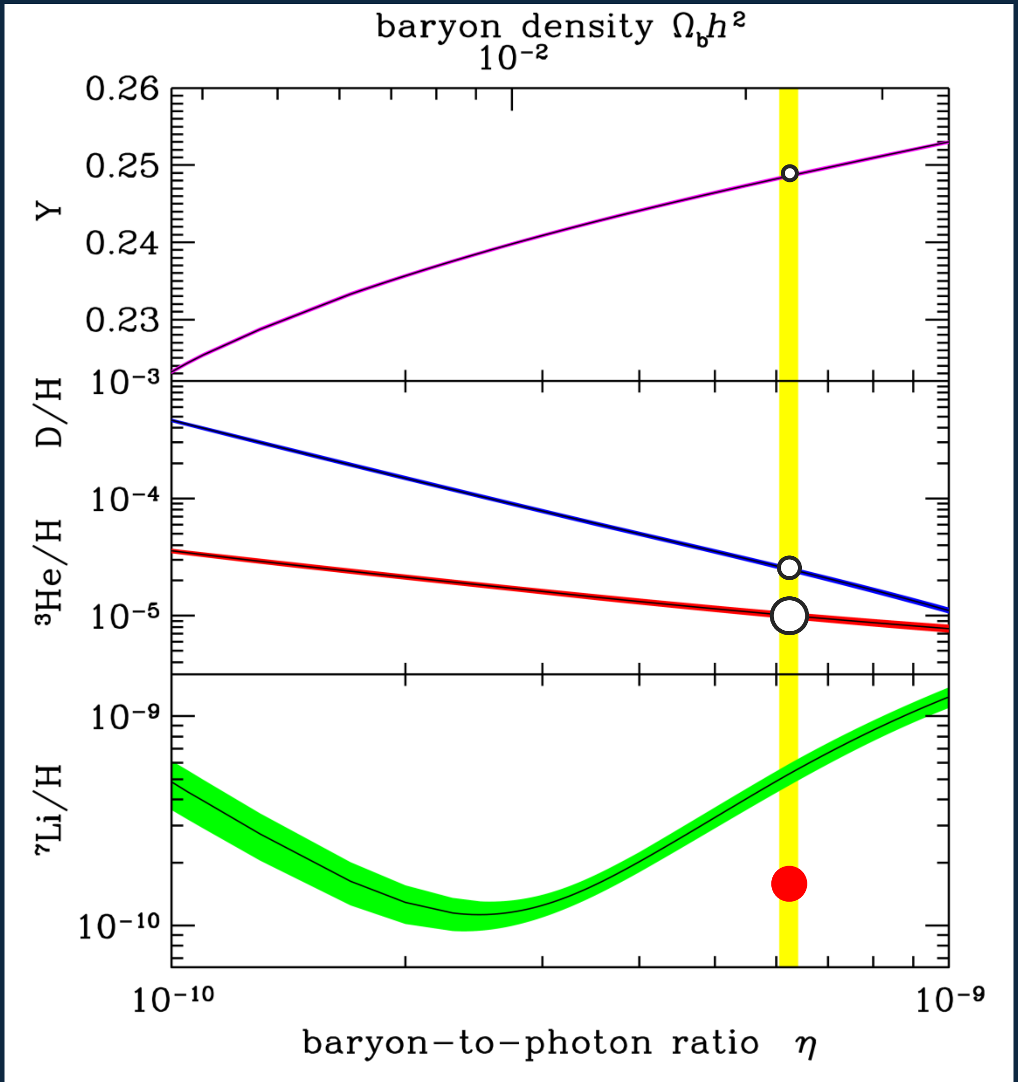
PRIMORDIAL NUCLEOSYNTHESIS

Big Bang Nucleosynthesis (BBN), together with Cosmic Microwave Background Radiation, is one of the cornerstones for Big Bang Theory.

BBN gives the sequence of nuclear reactions leading to the synthesis of light elements in the early stage of Universe (0.01-1000 sec)

BBN is a parameter free theory,
being the **cross-sections** of reactions involved the only input to the theory.

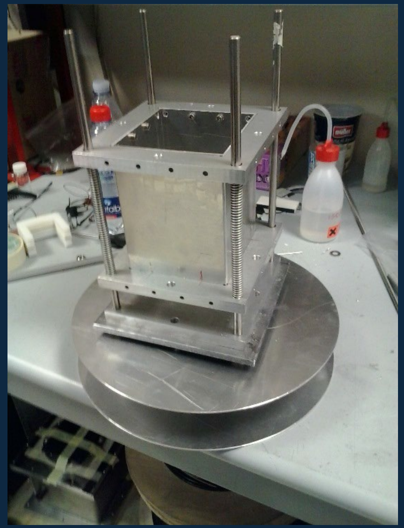
BBN successfully predicts the abundancies of light elements, i.e. D and ^{3}He.

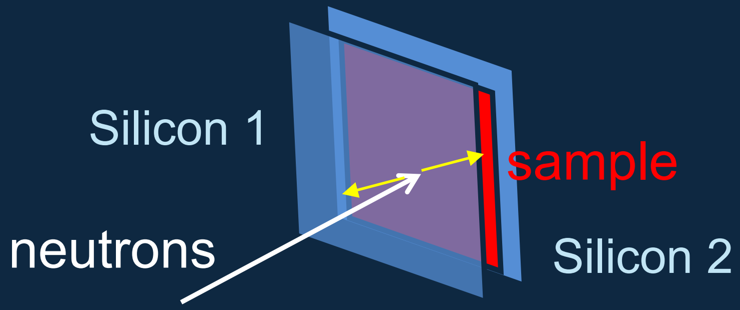


A large discrepancy between the predicted abundance of ^{7}Li and value inferred by measurements is present.

Cosmological Lithium problem (CLiP)

The abundance of ^{7}Li is essentially determined by the production and destruction of ^{7}Be.
(≈95% of primordial ^{7}Li is produced from the electron capture decay of ^{7}Be)

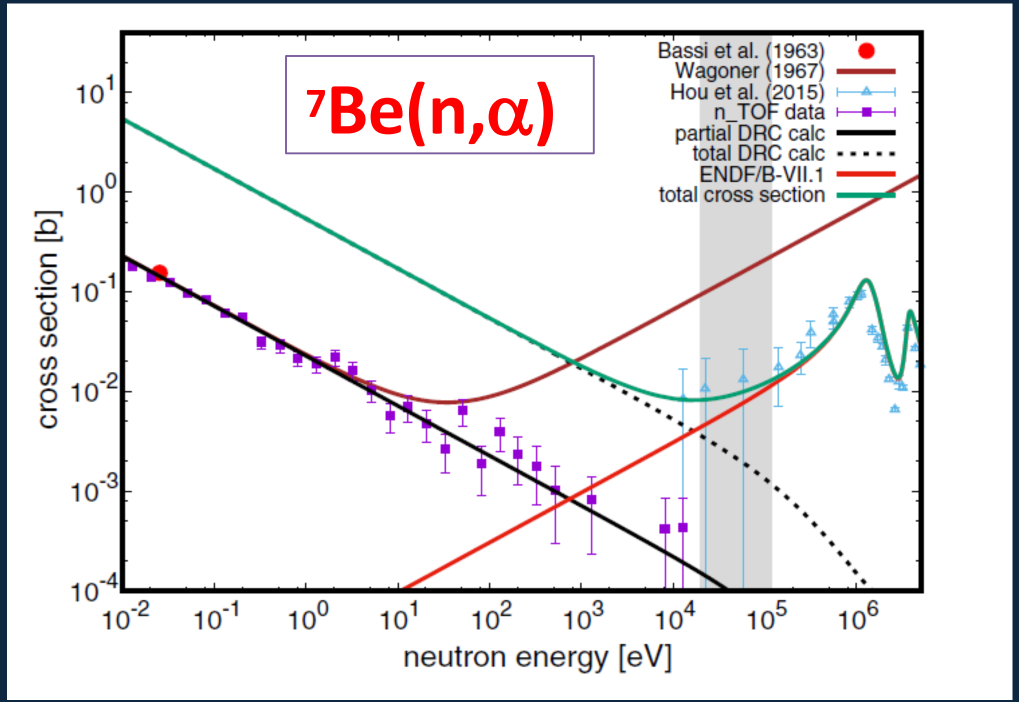




Sandwich of silicon detectors
<u>directly inserted in the beam</u>

Detection of both α particles (E≈9 MeV)
[Coincidence technique allows a strong rejection of background]

Before the measurement at EAR2 n_TOF
Only an experimental point was available in the literature
@ 25 meV
(P. Bassi et al., Il Nuovo Cimento XXVIII, 1049 (1963))



^{171}Tm

$T_{1/2}$ = 1.92 years

M ≈ 3.6 mg

^{204}Tl

$T_{1/2}$ = 3.78 years

M ≈ 11 mg

Stable isotopes (^{170}Er, ^{203}Tl) irradiated at the high-flux reactor at ILL, Grenoble
(60 days at 1.5×10^{15} n/cm^2/s)

Preparation of samples at the PSI
[with an enrichment of 1.8% (^{171}Tm) and 5.3% (^{204}Tl)]

and measurements at n_TOF

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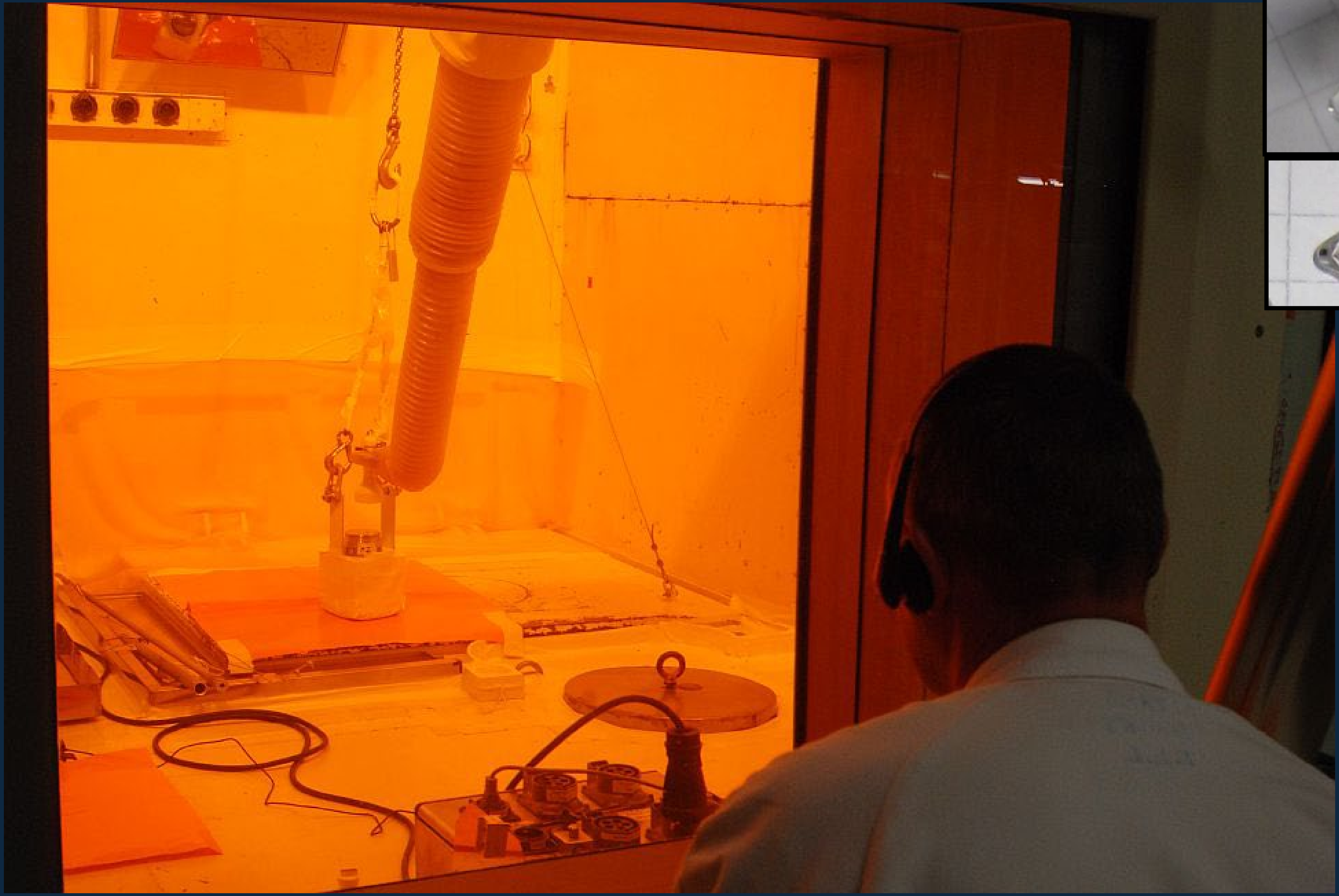


171Tm
6


204Tl

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

The *s* process: Nuclear physics, stellar models, and observations

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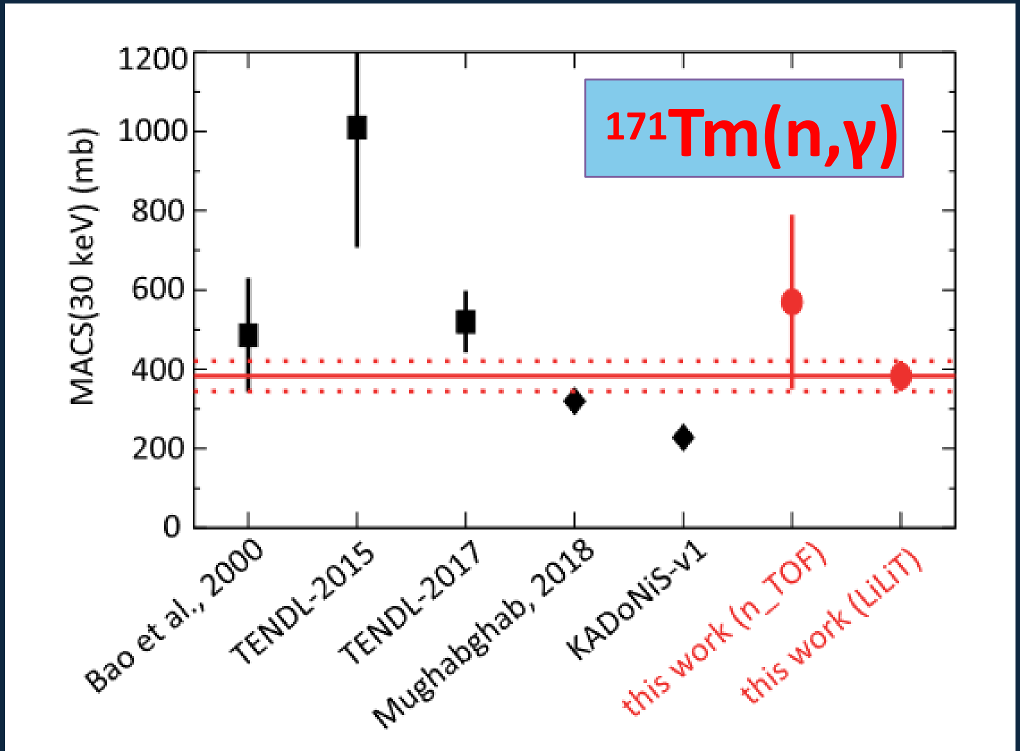
Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and neutron density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

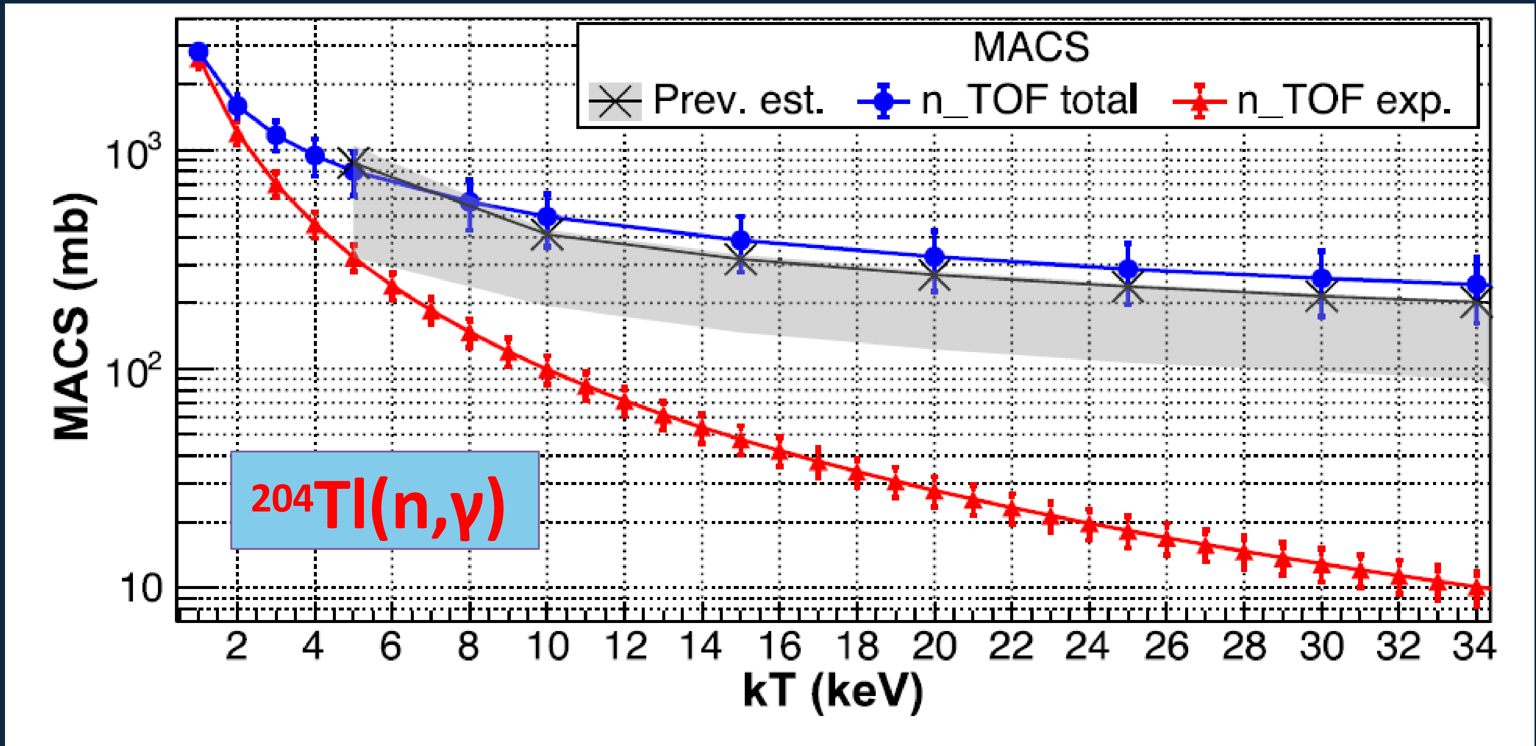
STELLAR NUCLEOSYNTHESIS

The result of experiment at EAR1 n_TOF provided the first ever set of resonance parameters

Extracted MACS at the s-process temperatures of kT ≈ 8 keV and kT ≈ 30 keV , are about 3% lower and 20% higher, respectively, than the corresponding theoretical values widely used in nucleosynthesis simulations.
New data report to the agreement with the ^{204}Pb abundance measured in the solar system.



C.Guerrero et al., Physical Review Letters **125** 142701 (2020)



A.Casanovas-Hoste et al., Physical Review Letters **133** 052702 (2024)

^{88}Zr

$T_{1/2}$ = 83 days

M ≈ 1.7 µg

Activity = 1.1 GBq/µg

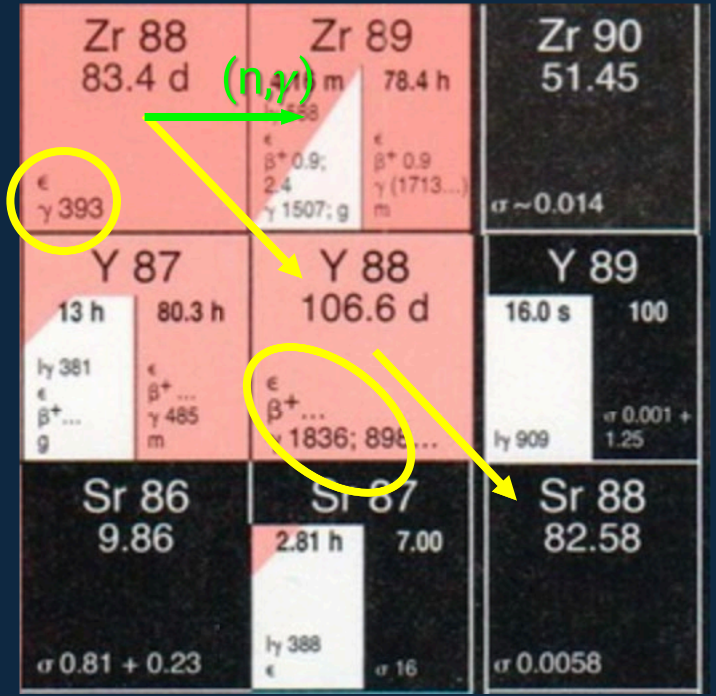
Production of sample materials at LANL

05 AUG 2024 LANL separation

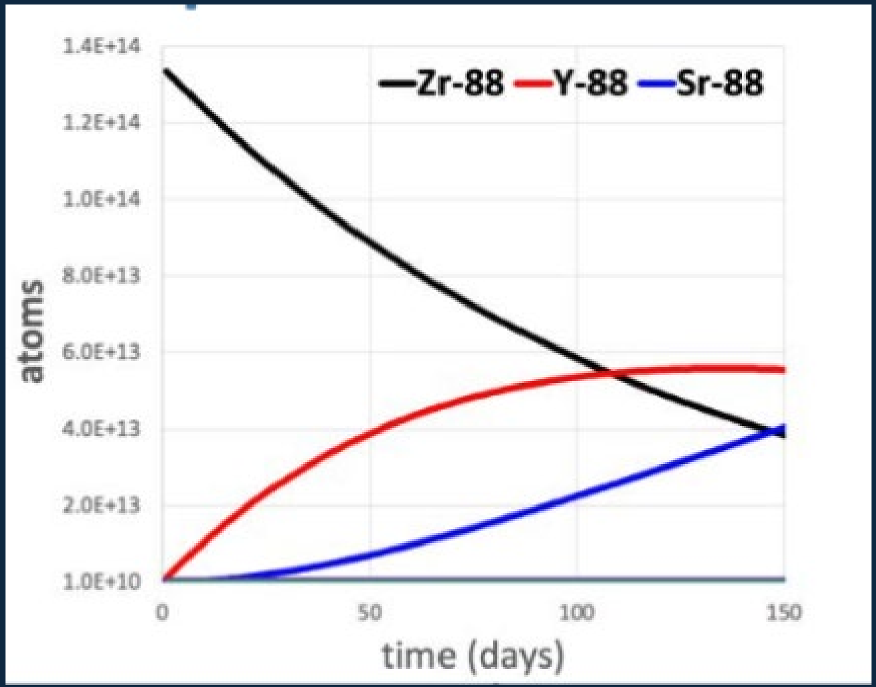
12 AUG 2024 receipt at PSI, handling and preparation of the sample

16 AUG 2024 begin irradiation at EAR2 n_TOF

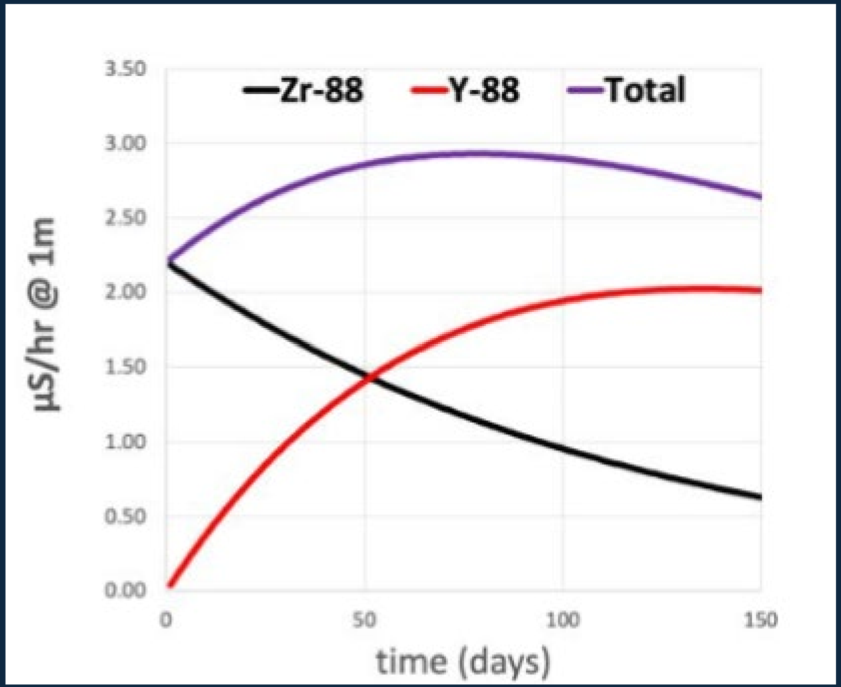
Surprisingly large neutron capture cross section (expected ≈ 10 barn, measured ≈ 800 kbarn)



Decrease of sample mass Vs t



Increase of activity Vs t



➡ Signal to background ratio (SBR) decreases Vs t

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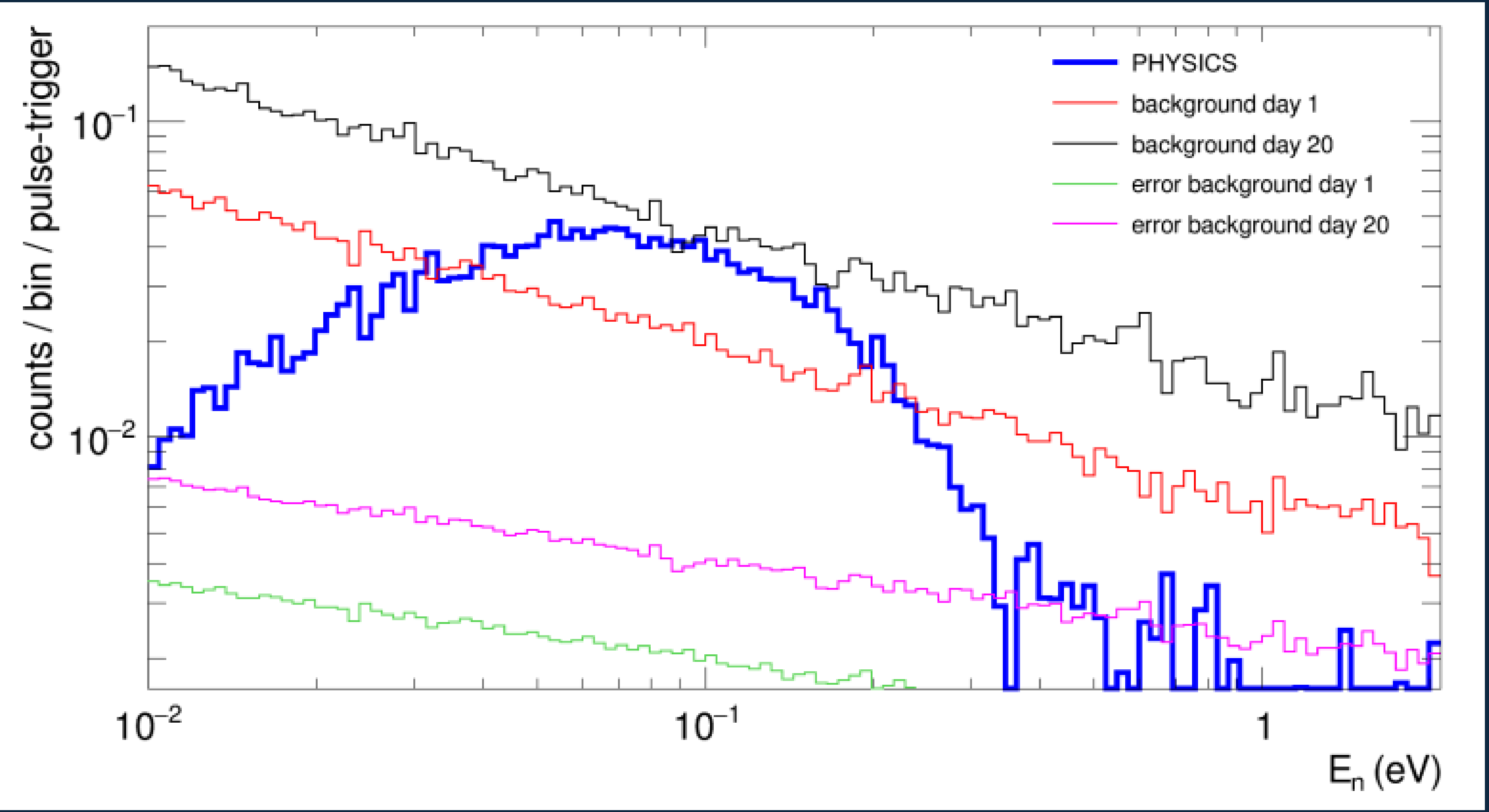
Measurement was possible thanks to

- the high instantaneous neutron flux and
- excellent neutron energy resolution



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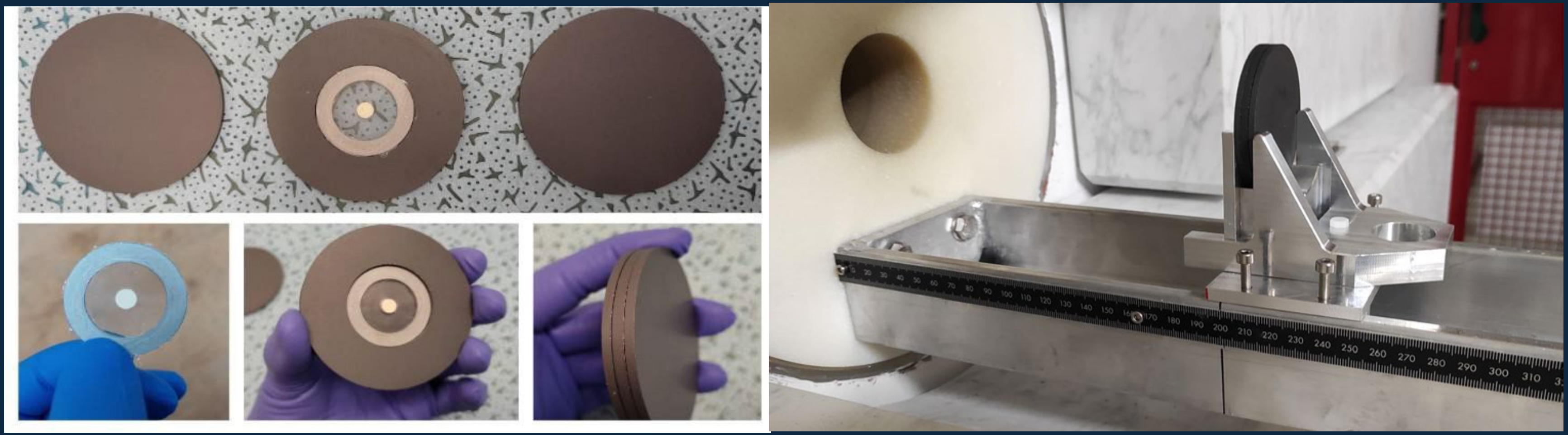
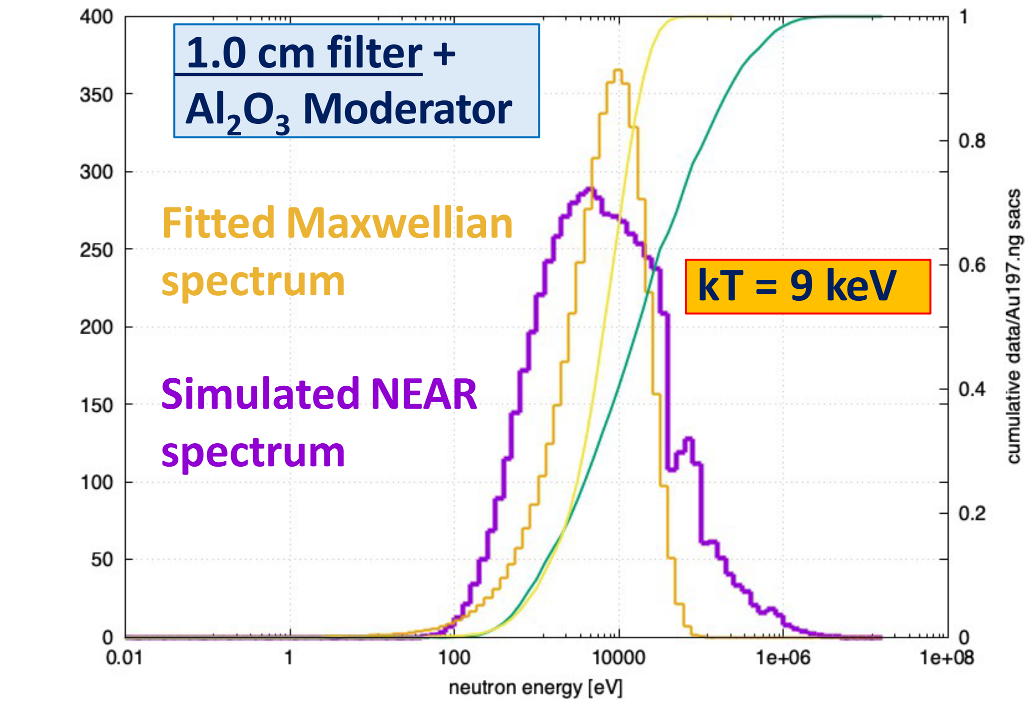
Activation measurements at the NEAR station

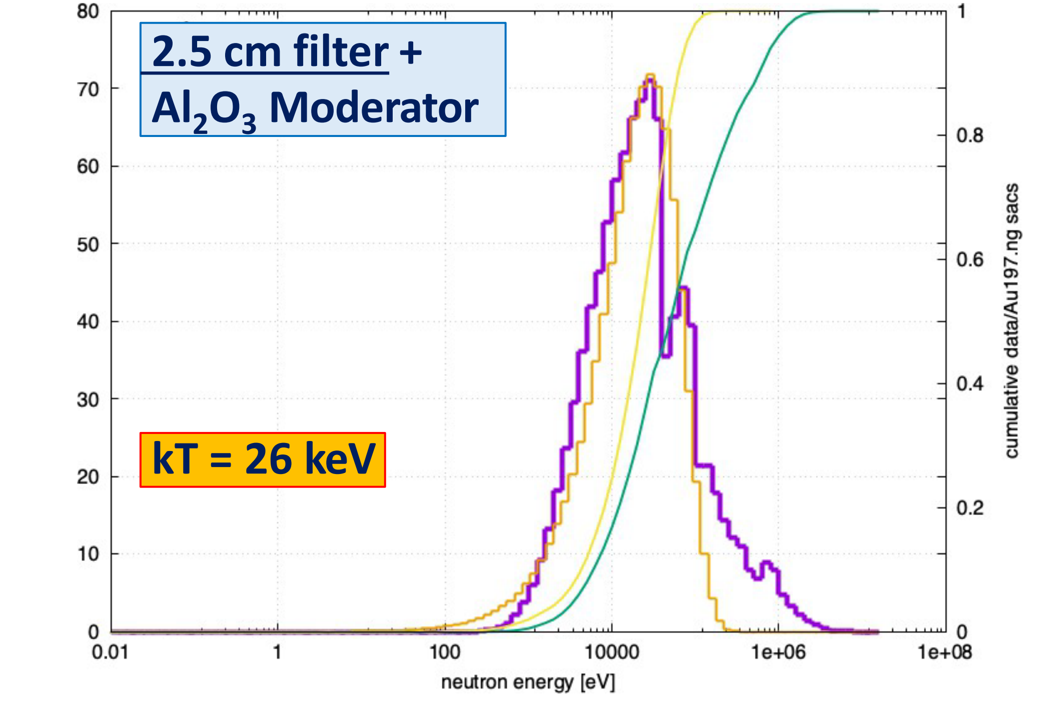


Feasibility tests on

^{197}Au, ^{76}Ge, ^{94}Zr, ^{109}Ag, ^{140}Ce

Special beam tailoring with **$^{10}B_4C$ filters** to mimic stellar spectra

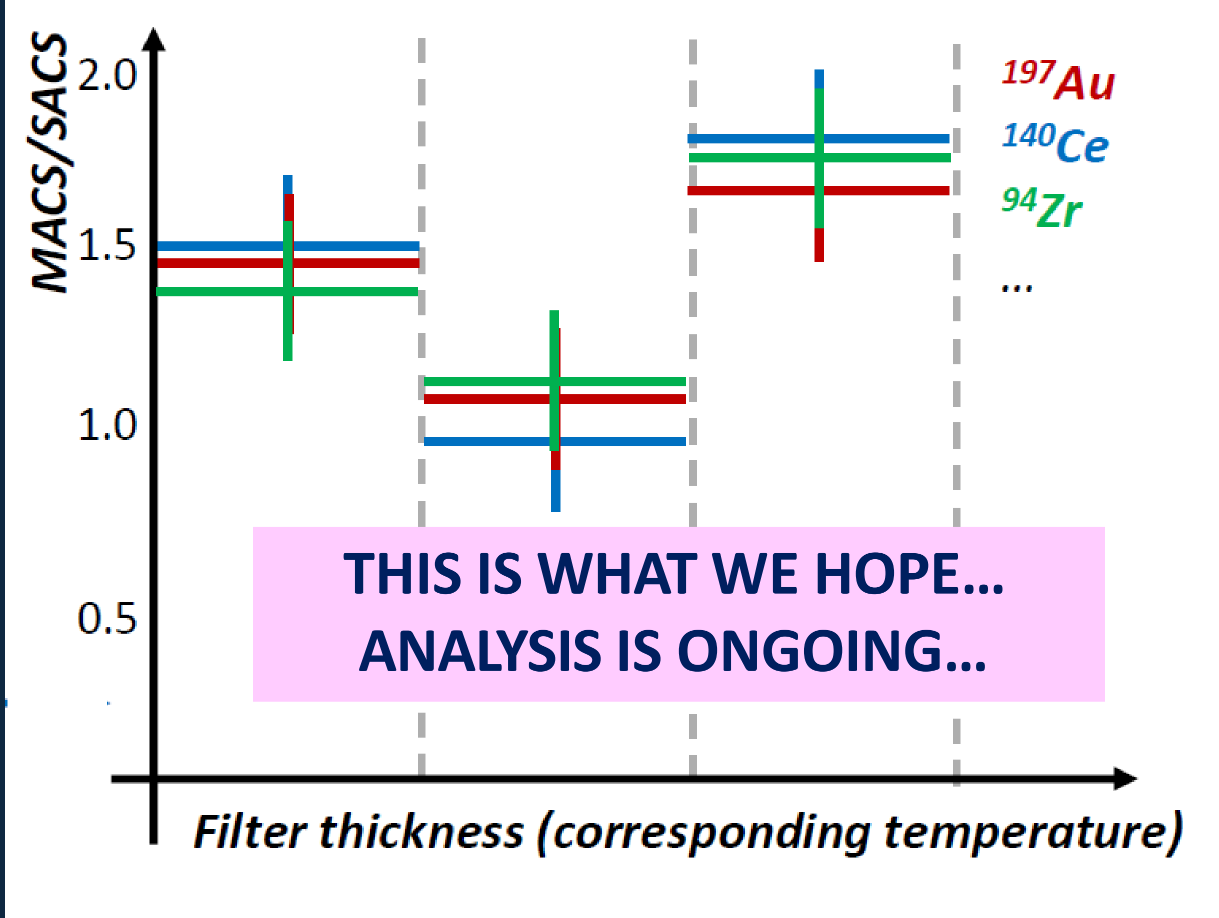




Activation measurements at the NEAR station

Measurements provide SACS *(Spectral Average CS)*
Need to estimate a correction factor to convert
SACS to MACS (*Maxwellian Averaged CS*)

Measuring SACS and
comparing to calculated MACS.



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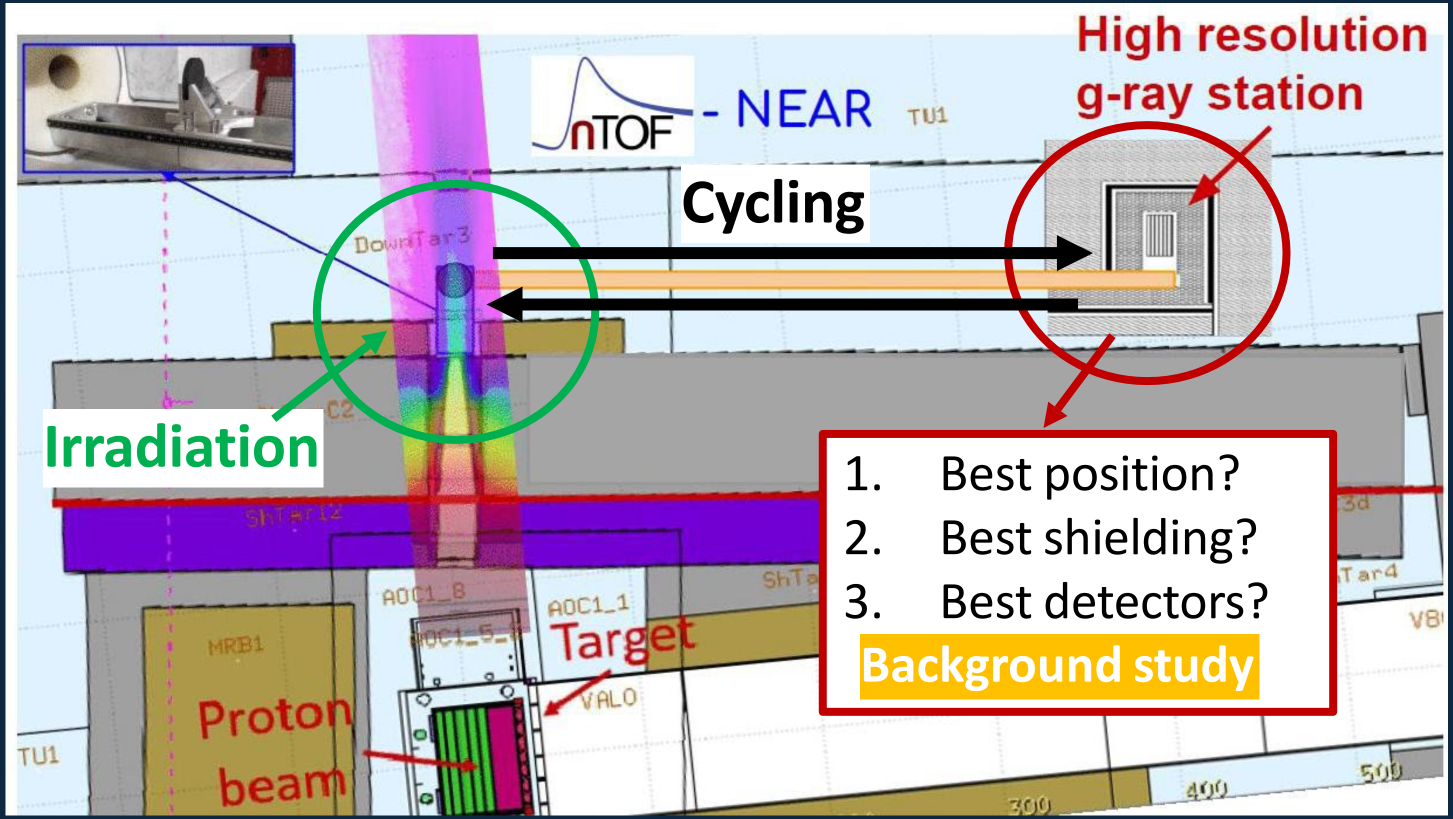
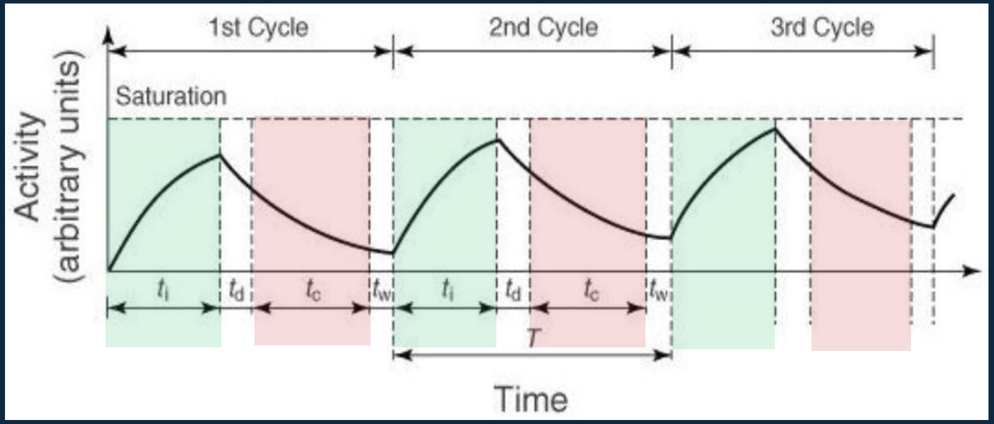
Cycling at the NEAR station

Measurement of short-lived products is now prevented by **6h** cooldown to access the Area



J. Lerendegui et al, CERN-INTC-2022-018 / INTC-I-241 (2022)



Cyclic **Irradiation** and **Activation Measurements** in a decay station inside NEAR. In principle would allow the measurements of isotopes with half lives of minutes

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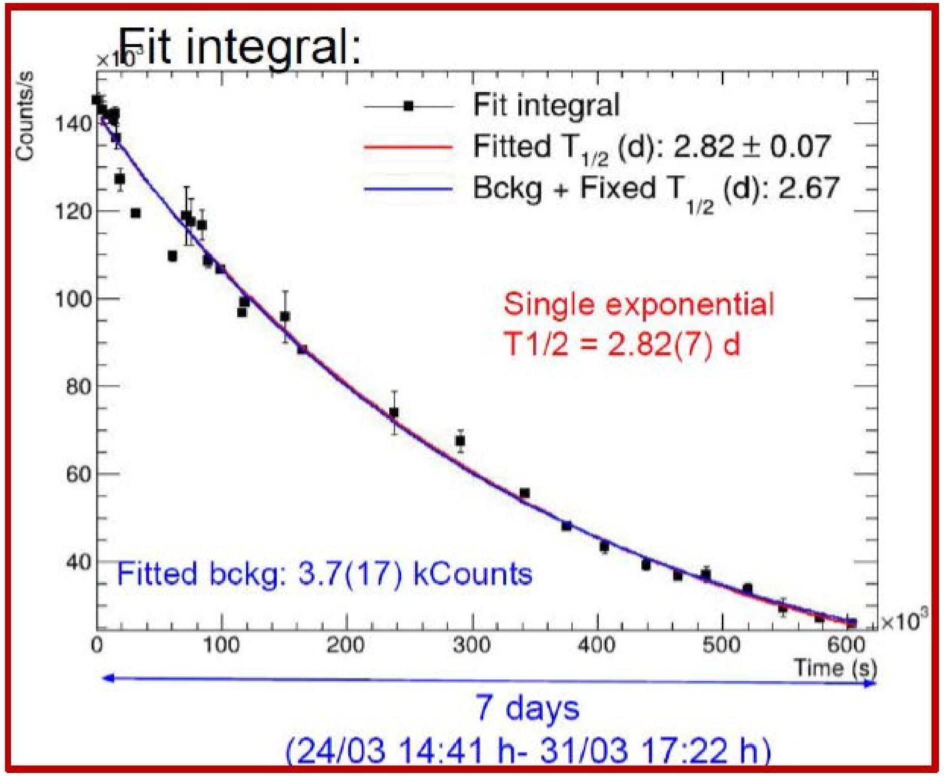
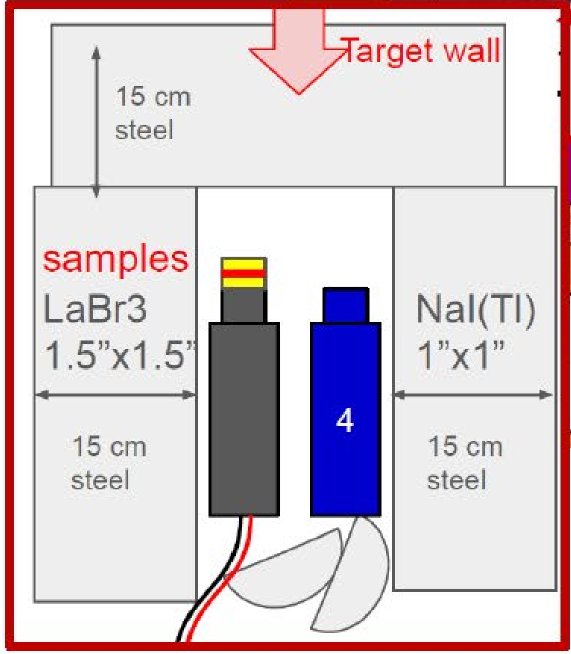
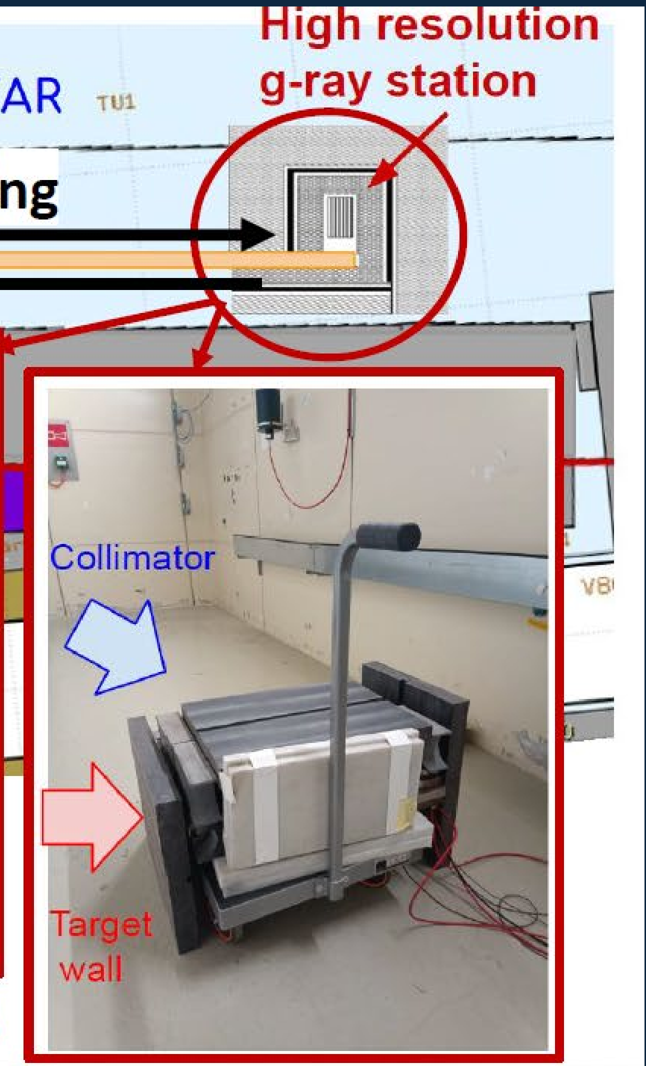
Cycling at the NEAR station

A first test has been performed in 2025, using a Au sample
Improvements for a reduction of background and
to manage gain shift are needed.





Pictures and plot from J. Lerendegui



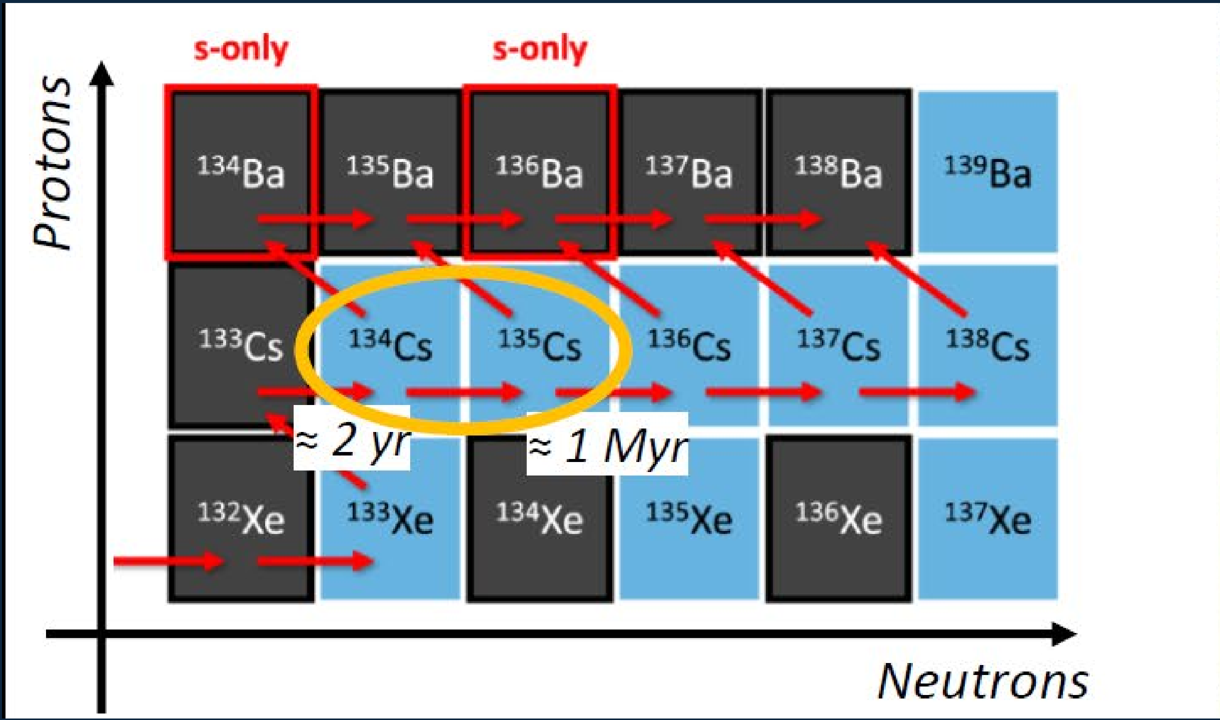
Sinergy inside CERN complex

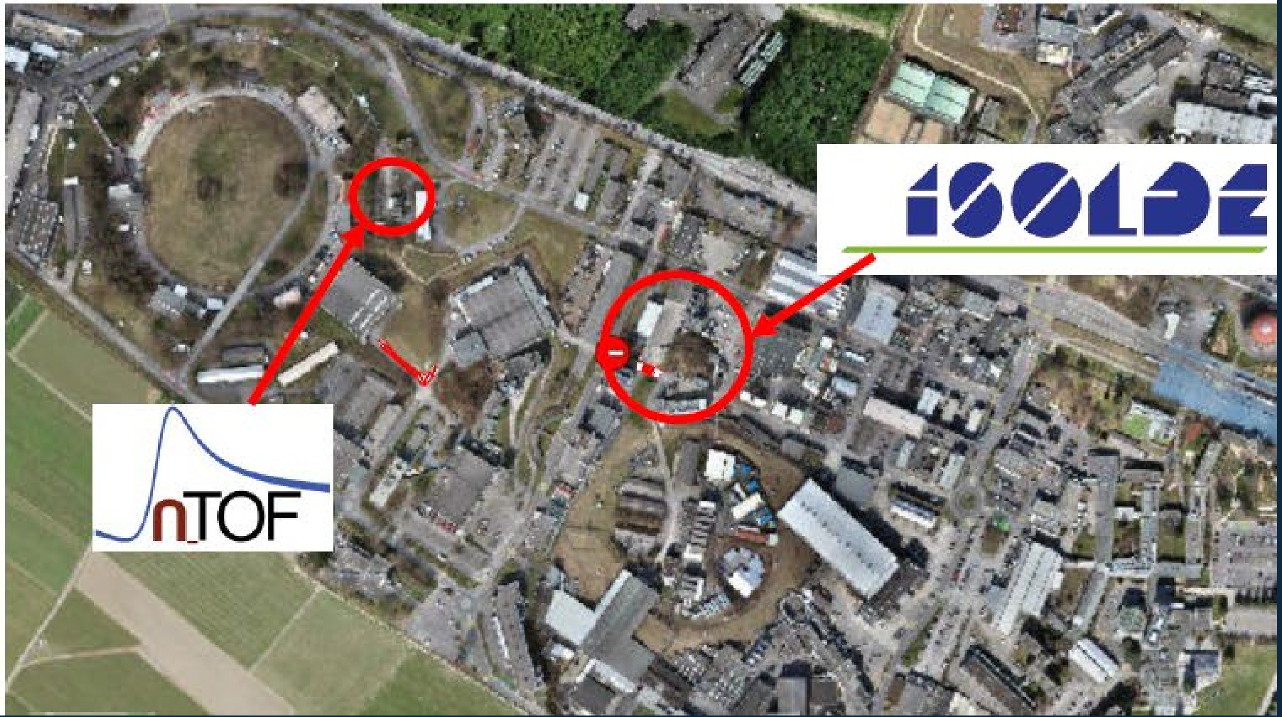
Irradiation of radioactive isotopes requires $\Delta t_{production\text{-}irradiation}$ **< lifetime**

Walking distance between NEAR and ISOLDE

There is a chance to produce and irradiate radioactive samples down to days.

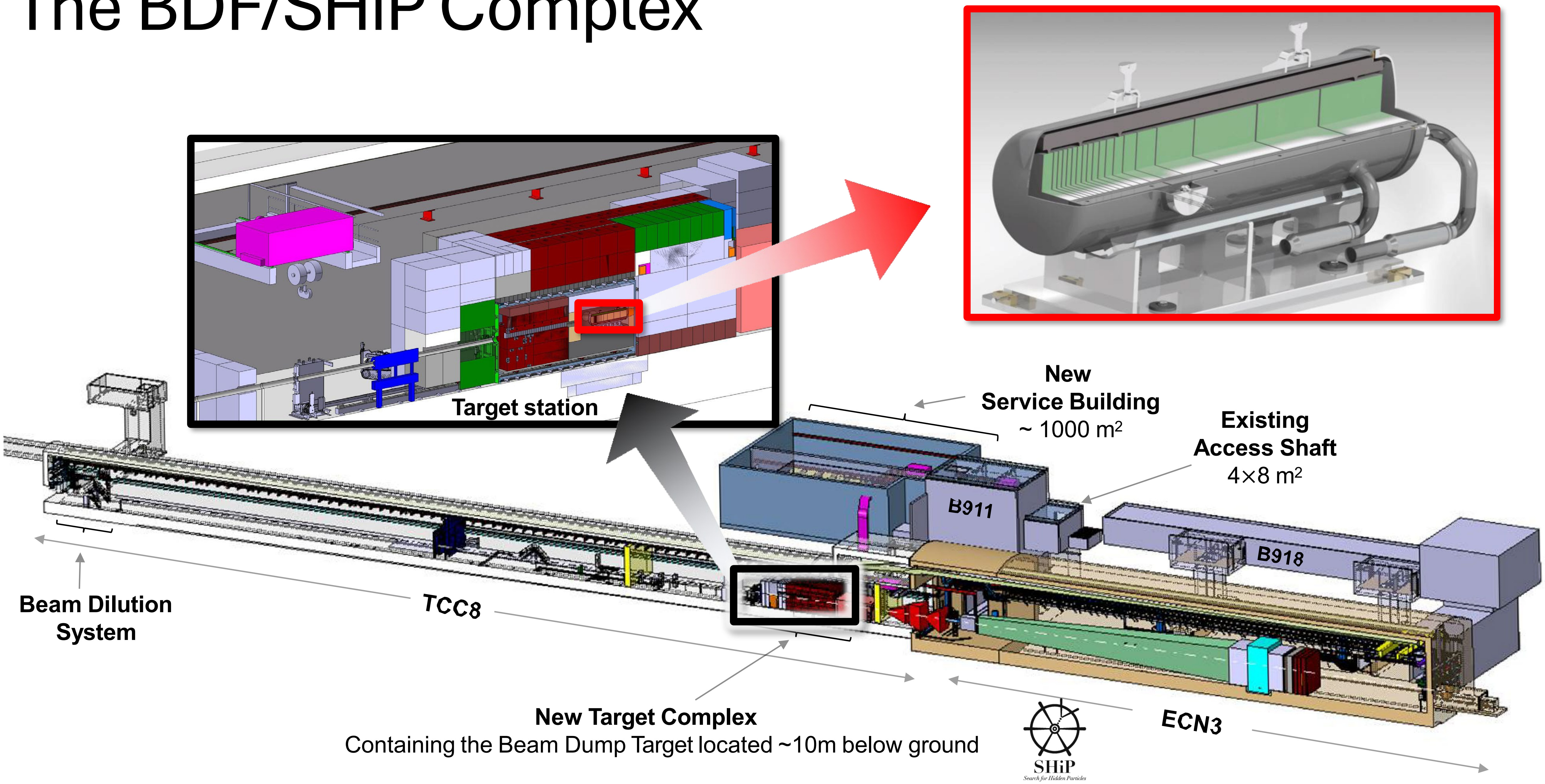
[First candidate ^{135}Cs]



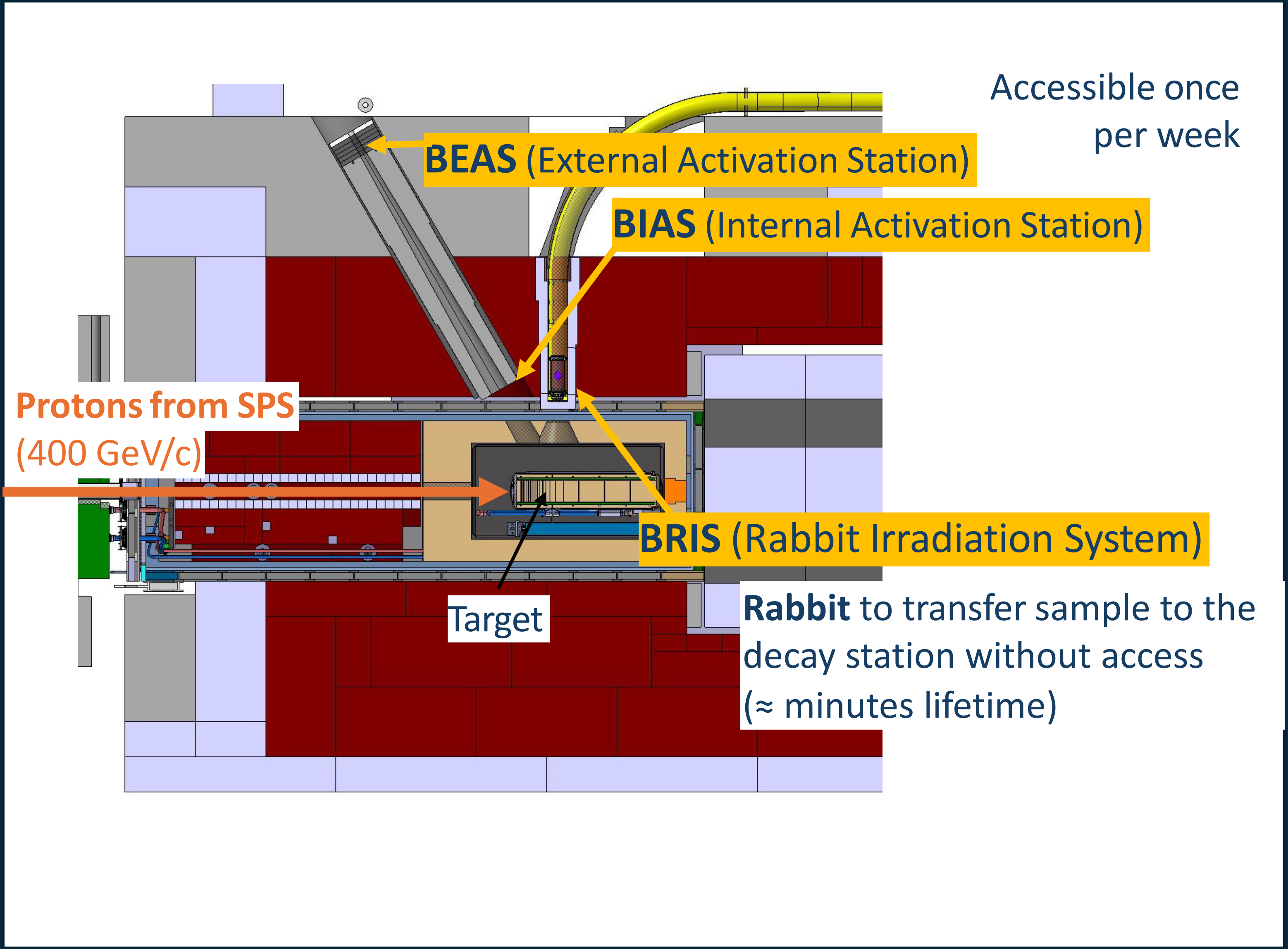


J. Lerendegui et al, CERN-INTC-2022-040 / INTC-P-641 (2022)

The BDF/SHiP Complex



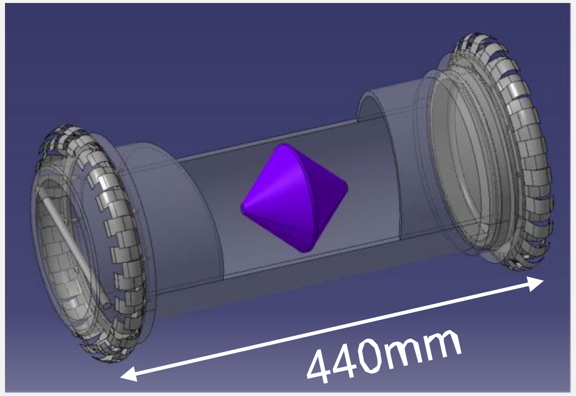
n_ACT@BDF


Accessible once per week
BEAS (External Activation Station)
BIAS (Internal Activation Station)
Protons from SPS (400 GeV/c)
BRIS (Rabbit Irradiation System)
Target
Rabbit to transfer sample to the decay station without access (≈ minutes lifetime)

BRIS

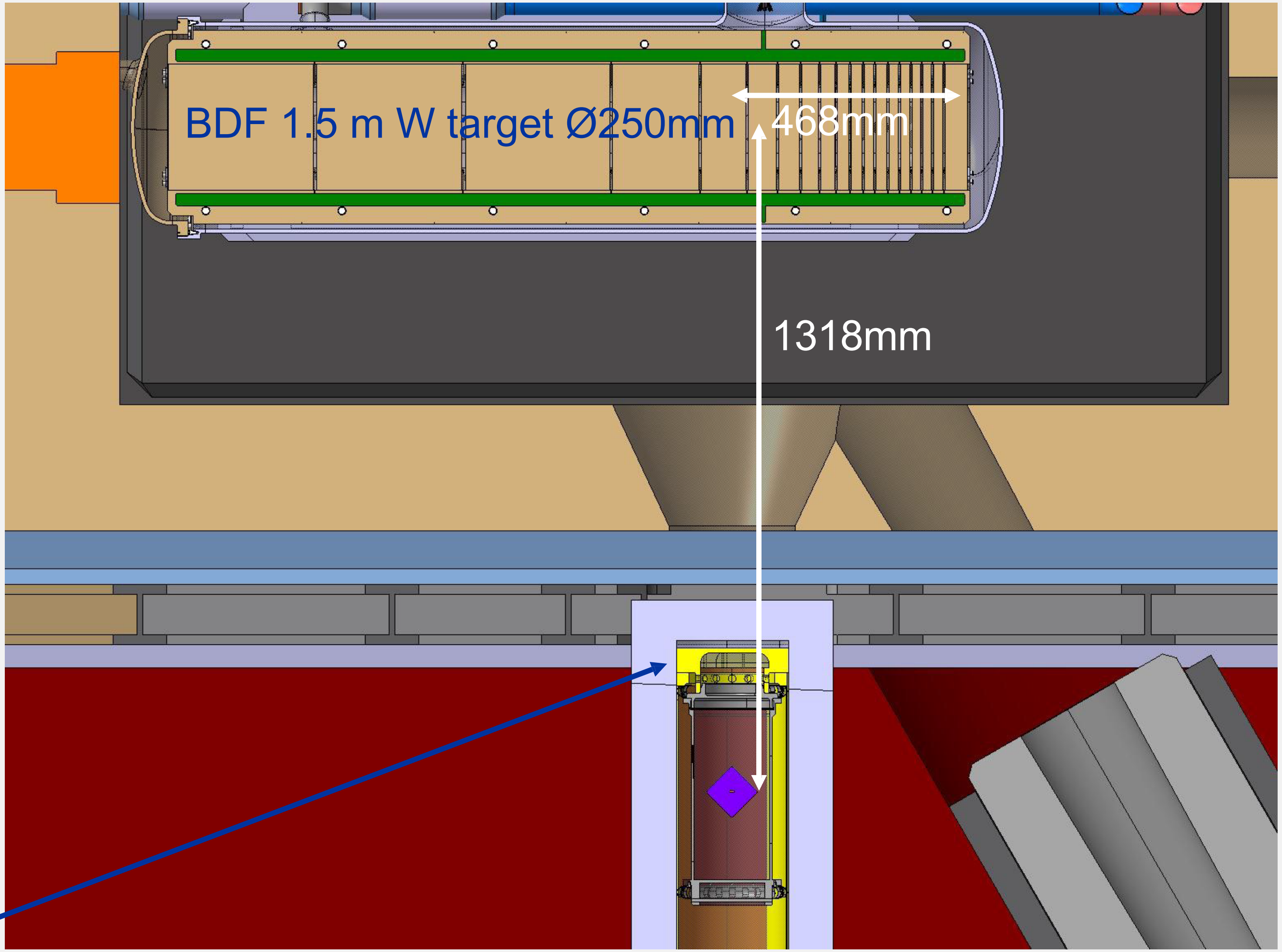
Equipped with a Rabbit system

BRIS Capsule
External Diameter: 200mm



Internal: ø 150mm x 360mm
Maximum weight ~1 kg
Polyethylene, Aluminium, Carbon fibre

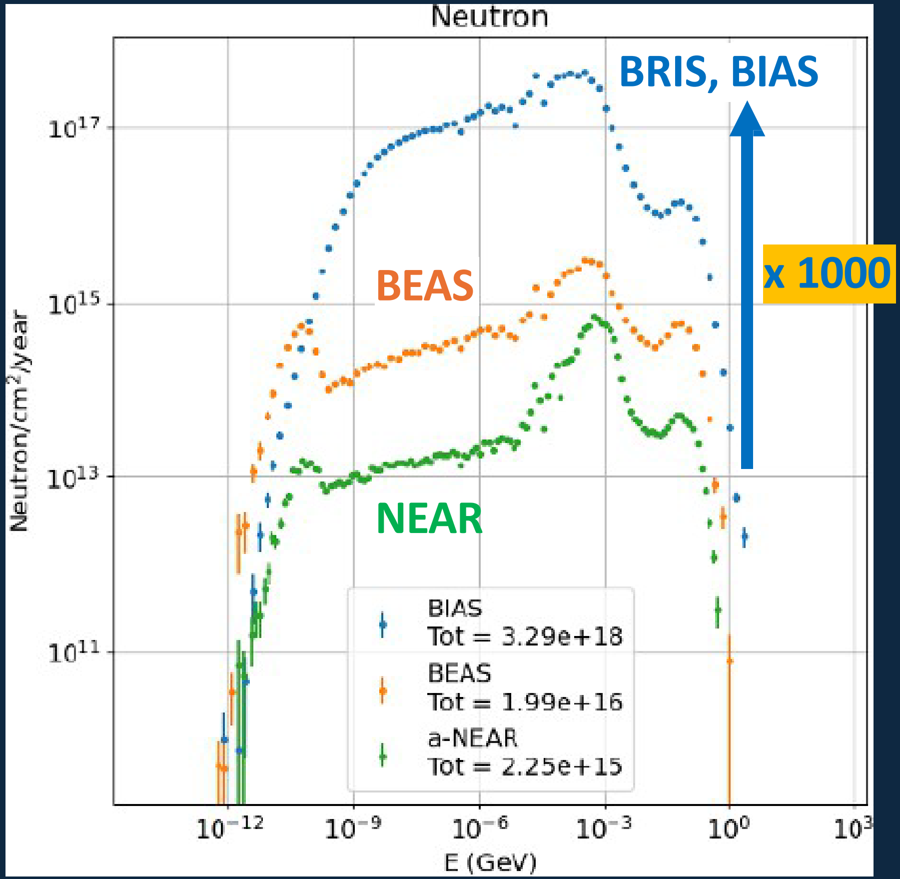
Independence from BDF/SHiP operation



Moderator installed around irradiation station

n_ACT@BDF

Nominal Design Parameter	
Beam type	proton
Beam momentum [GeV/c]	400
Beam pulse intensity [$\times 10^{13}$ p]	4.0
Spill length [s]	7.2
Beam pulse power [kW]	2560
Average beam power [kW] (7.2 s)	356
POT [$\times 10^{20}$ p over 15 years]	6.0



HEP experiment, approved & funded
Operation **start ~2031**

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Expression of Interest to the SPS and PS Experiments Committee

Neutron Activation Station at the SPS Beam Dump Facility (BDF)

October 18, 2024

- ✓ High selectivity of activation measurements (no enriched material required in most cases)
- ✓ High sensitivity due to highest flux (small amount of material needed, no need of separation from prompt BG signals)
- ✓ Possibility to measure short-lived products (if rabbit installed)

Summary

Neutron induced cross sections on several radioactive isotopes have been measured at the CERN n_TOF facility.

Some of them show half-lives up to hundreds of days and were available in very low amount of mass (μg)

Decisive is the collaboration between laboratories for production and preparation of samples
(CERN-Isolde, JRC, ILL, LANL, PSI)
matched to the uniqueness of the neutron beams performances.

In parallel to time-of-flight measurements studies to apply the activation technique are running (at the NEAR station).

Taking profit of the future BDF high flux challenging measurements are envisaged.

Along 24 years of activity more than 150 experimental data sets have been produced, published and disseminated
https://twiki.cern.ch/twiki/bin/view/NTOFPublic/DataDissemination

Full list of n_TOF publications: https://twiki.cern.ch/NTOFPublic/ListOfPublications

Cheers!

Expanding the n_TOF physics programme any collaboration, idea, challenge is warmly welcome.