Direct measurement of neutron capture on radioactive isotopes at CERN n_TOF

César Domingo Pardo

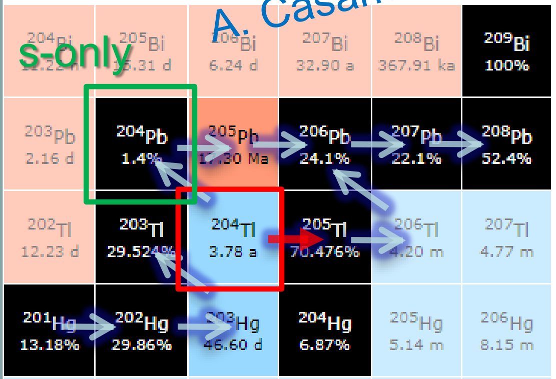
Nuclei in the Cosmos XVIII, Girona, 15-20 June, 2025

Why (n,γ) with unstable isotopes? and why direct measurements?

S-process branchings: Stellar models & conditions

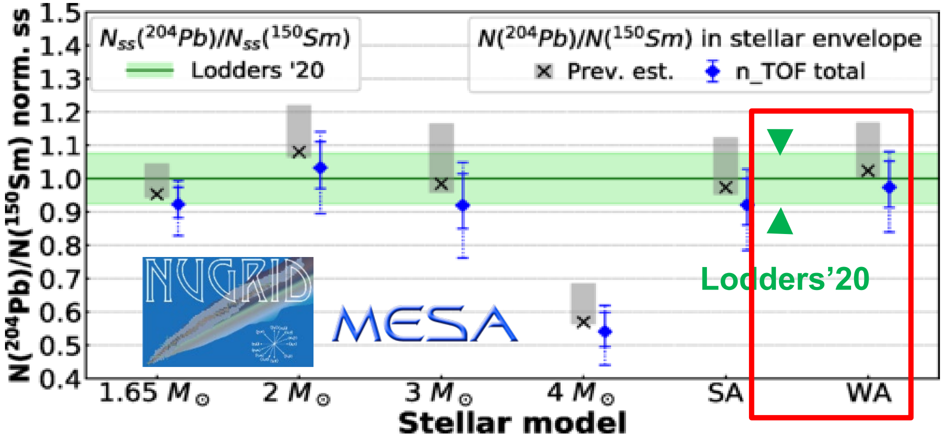
^{204}Tl(n,γ)

A. Casanovas talk, Monday!



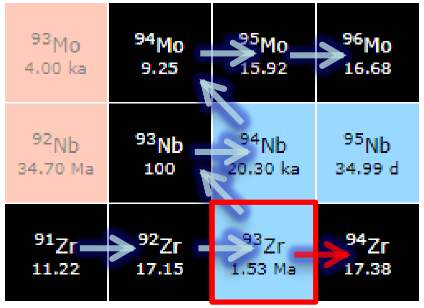
CI-Chondrites

Lodders, Space Sci. Rev. 217 (2021)

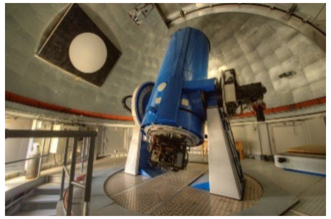


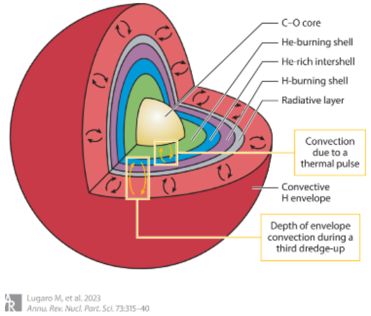
Casanovas-Hoste *et al.* Phys. Rev. Lett. **133** (2024)

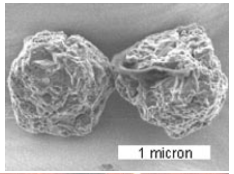
^{93}Zr(n,γ)

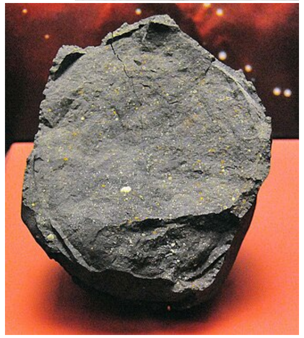


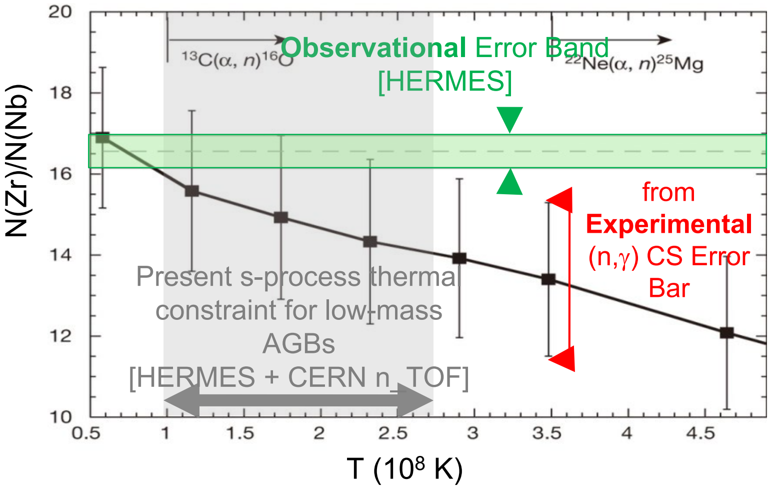
S-type stars











Neyskens et al., Nature 517 (2015)
Tagliente et al. Phys. Rev. C 87 (2013)

C-rich AGBs
Z=0.01-0.03
1 $M_\odot$ < M < 4 $M_\odot$
AGBs:

→ Stellar mass
→ Stellar metalicity
→ Rotation
→ ^{13}C pocket uncertainties

Lugaro et al. Ap. J. 593 (2003)
Lugaro et al. Ap. J. 780 (2014)
Liu et al. Ap. J. 865 (2018)
Lugaro et al. Annu. Rev. NPS (2023)

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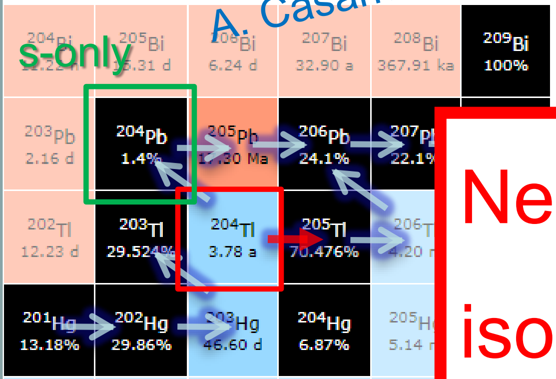

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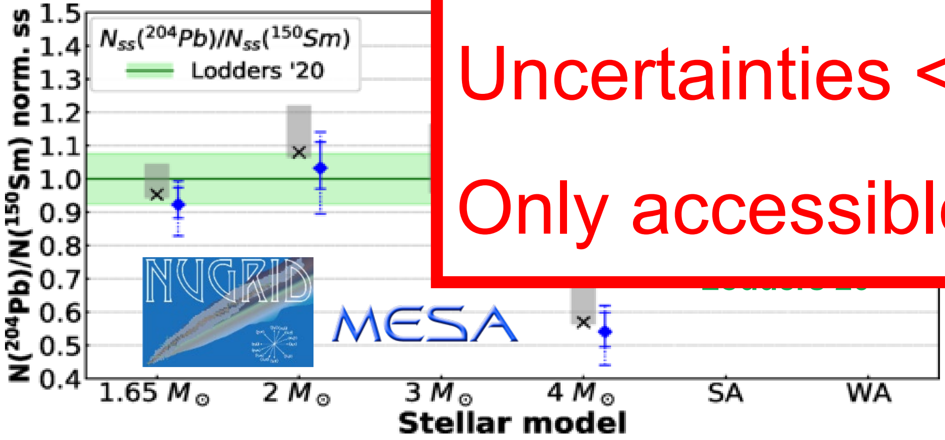

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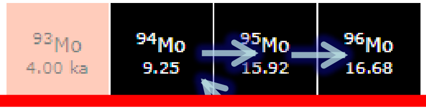
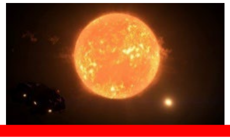
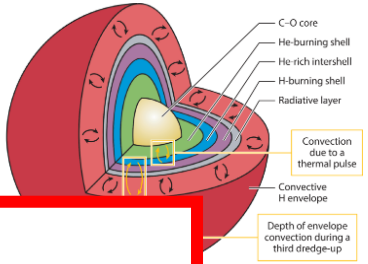
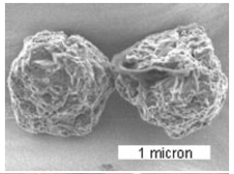
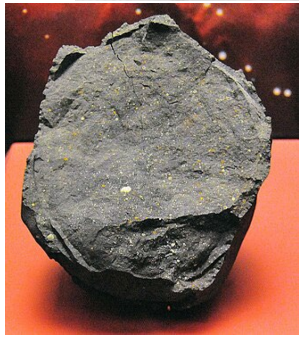






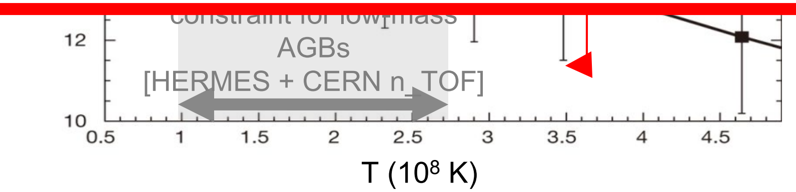




Neutron-capture experiments on unstable isotopes yield a wealth of information! But…

Uncertainties <20-30% are required!

Only accessible via direct (n,γ) measurements



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S-process branchings in the TOF lab: the roadmap

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

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

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Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, 76021 Karlsruhe, Germany

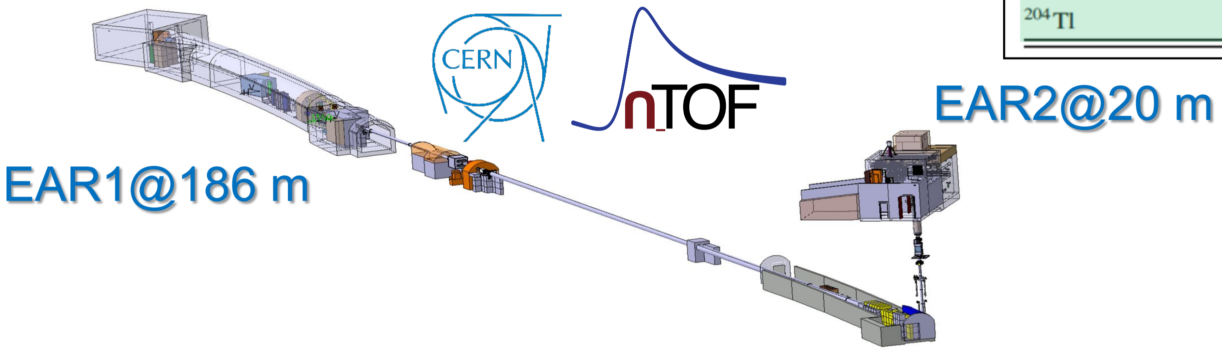
R. Gallino†
Dipartimento di Fisica Generale, Università di Torino I-101
INAF-Osservatorio Astronomico di Teramo, I-64100 Teram

S. Bisterzo‡
Dipartimento di Fisica Generale, Università di Torino, I-101

Wako Aoki§
National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

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

Talk: Adria Casanovas (Monday)
Poster#64 Emmanuel Seyi Odusina
Poster#99 Selin Berencioglu



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^{151}Sm ^{93}Zr ^{63}Ni ^{171}Tm ^{204}Tl ^{94}Nb ^{79}Se

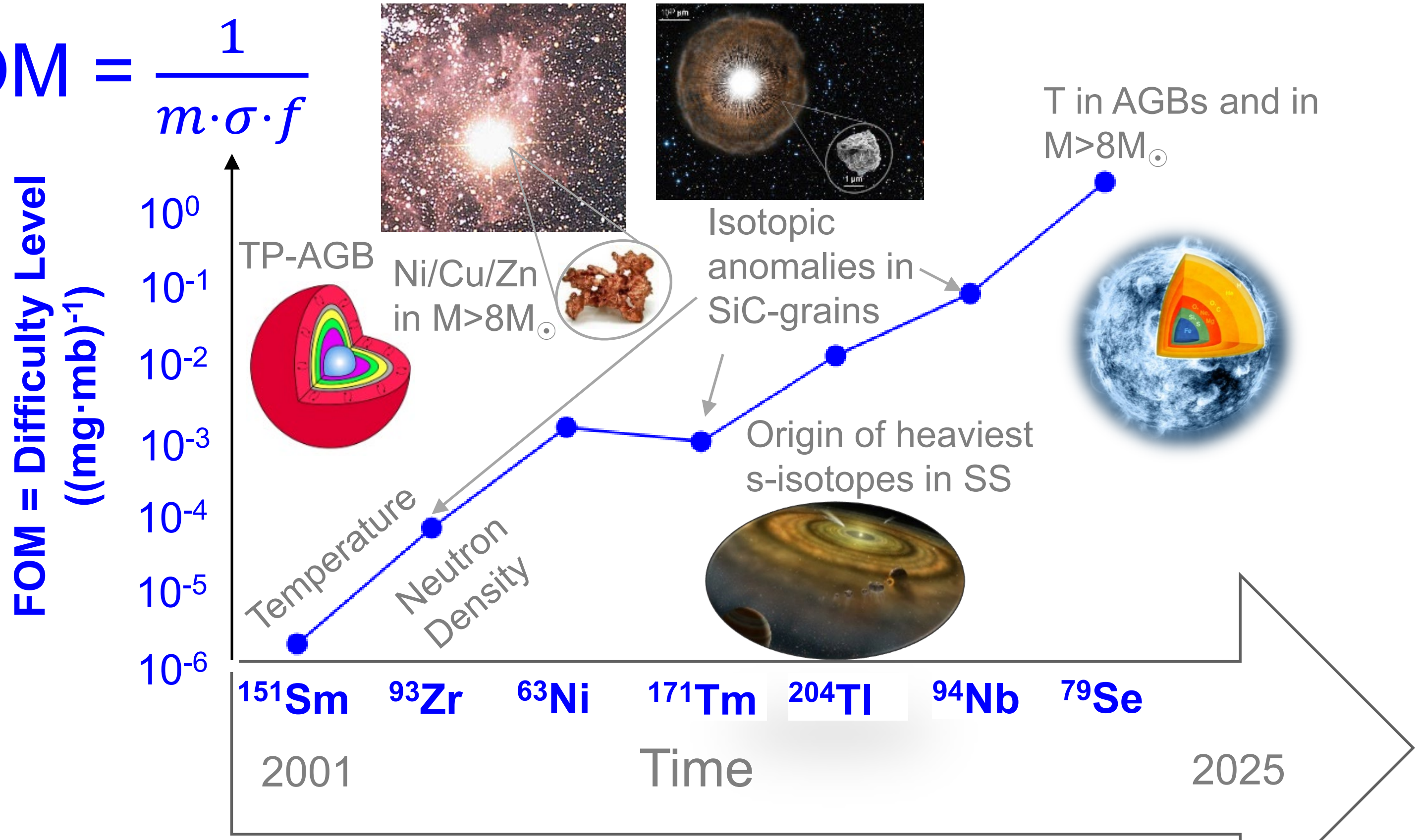
2001 Time 2025

^{151}Sm
m = 200 mg
f = 0.9
σ=3b at 30keV

^{79}Se
m = 2.7 mg
f = 7x10^{-4}
σ=0.2 b at 30kev

S-process branchings in the TOF lab: the efforts

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



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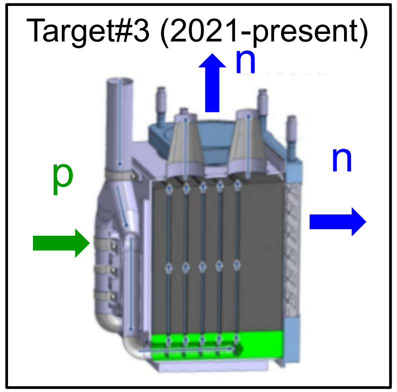

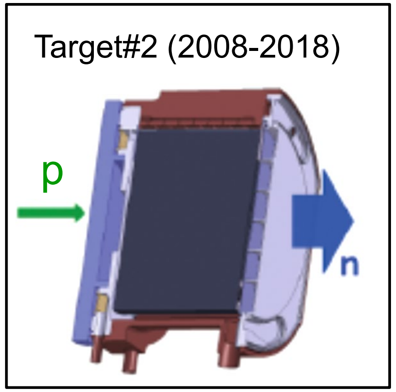

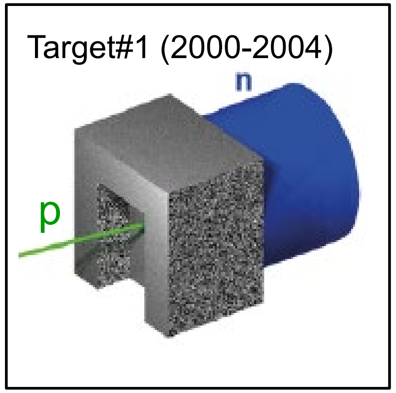

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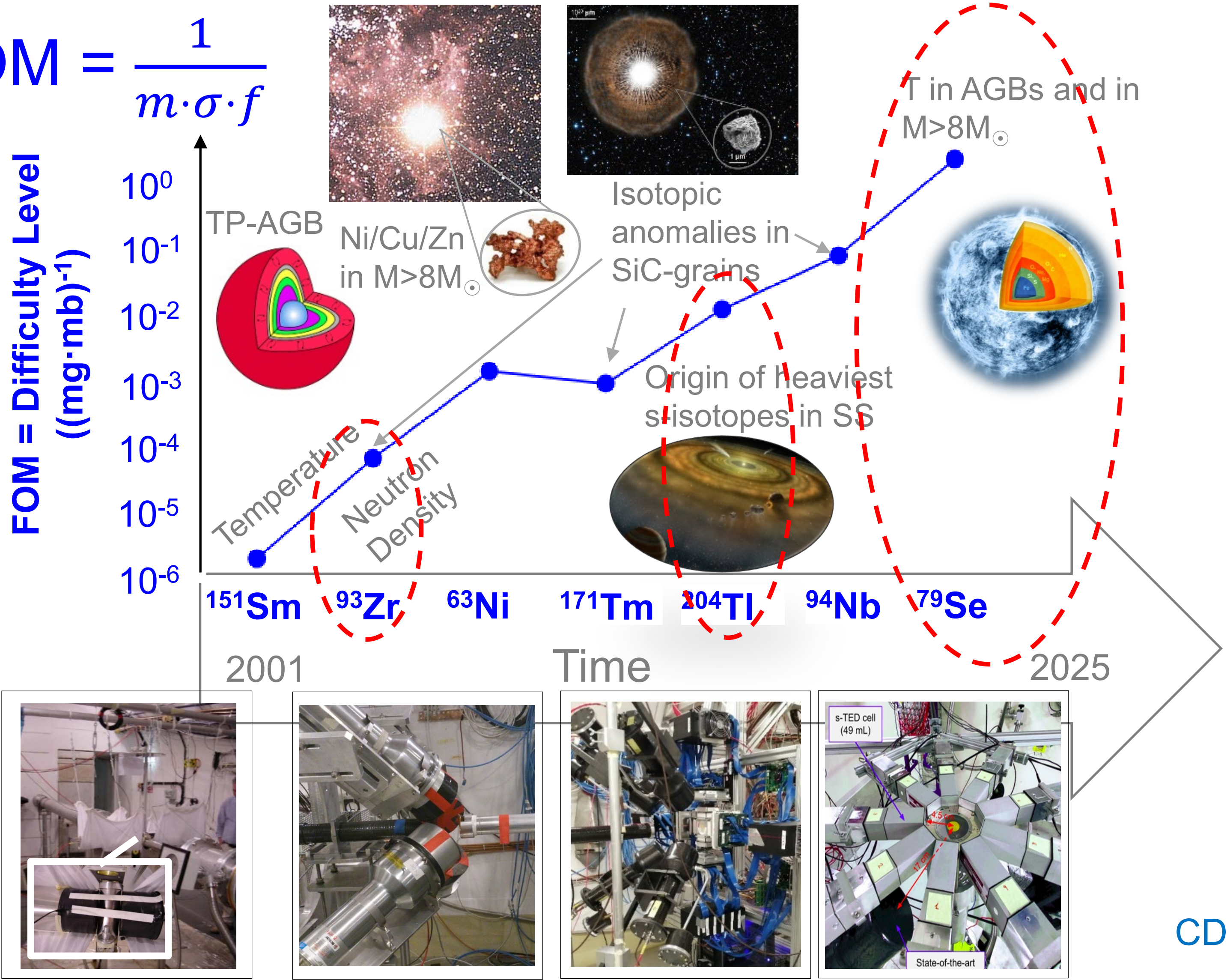
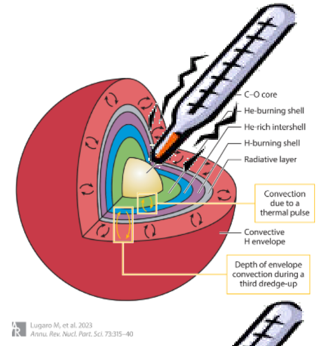
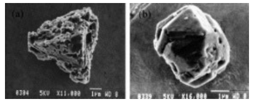
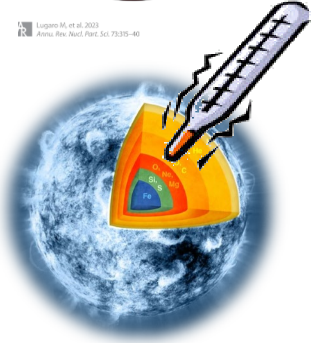


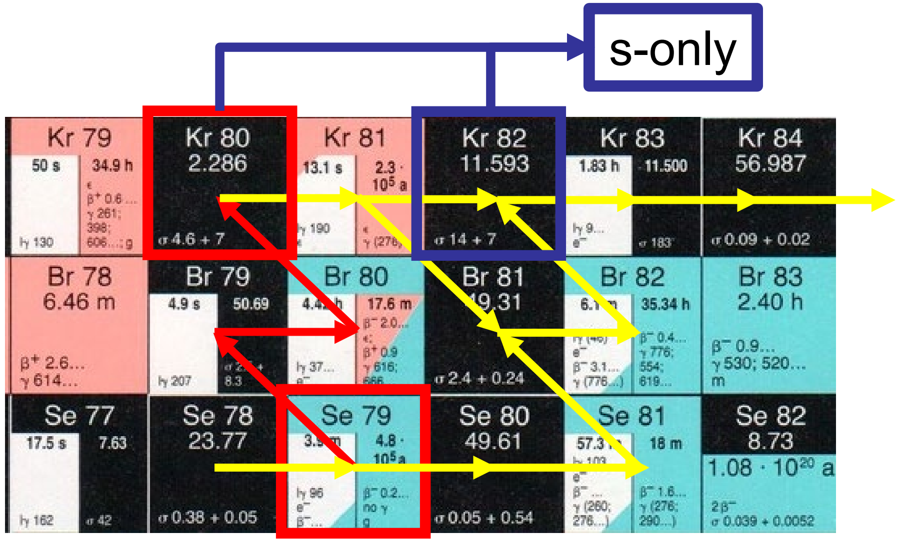
CDP et al. EPJ-A 61 (2025)

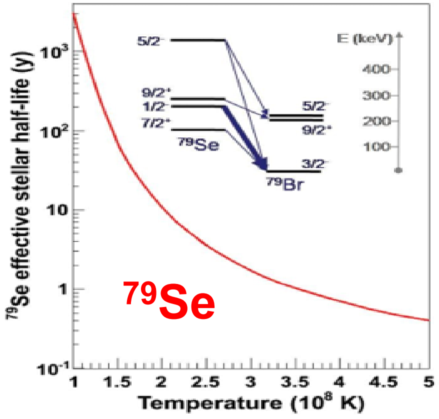
The ^{79}Se(n,γ) stellar thermometer

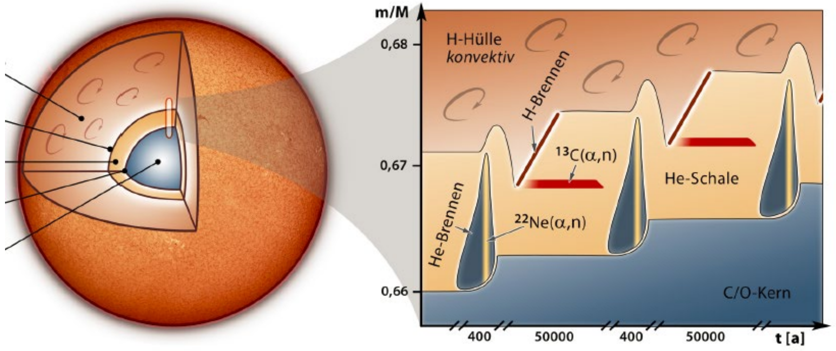












1.0 g of ^{78}Se

2.8 g of ^{208}Pb

220 °C

1.0 g of ^{78}Se

2.8 g of ^{208}Pb

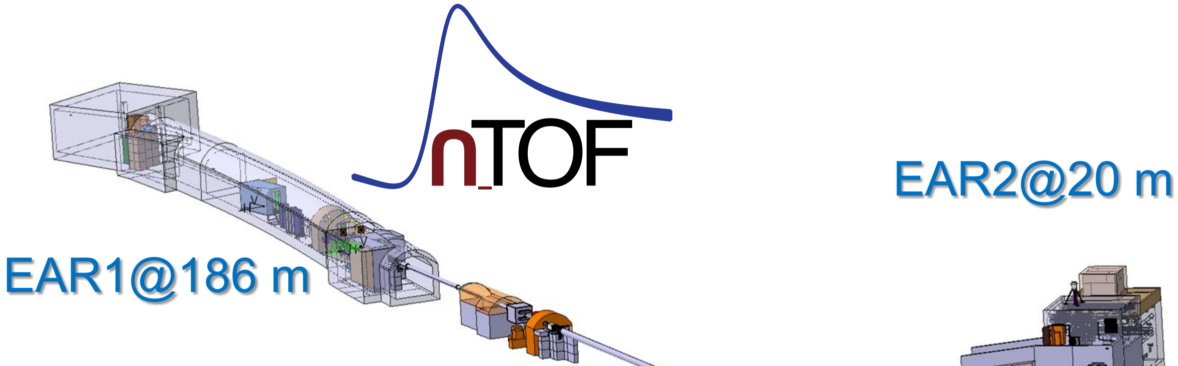
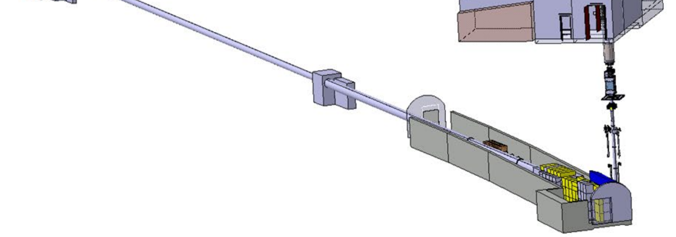
2.6 mg of ^{79}Se

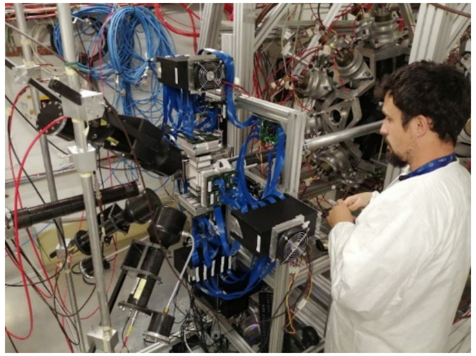
1.6 MBq of ^{60}Co

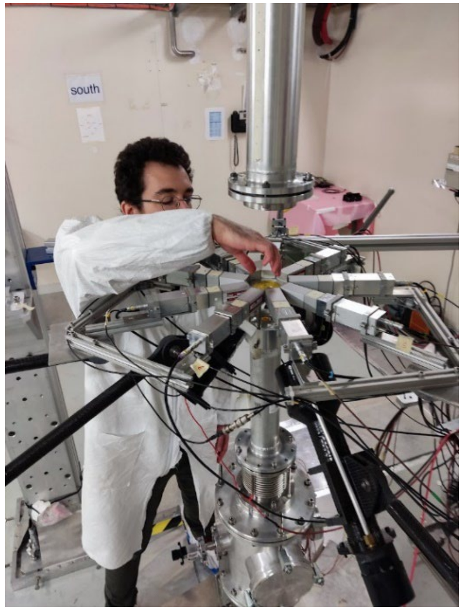
5 MBq of ^{75}Se

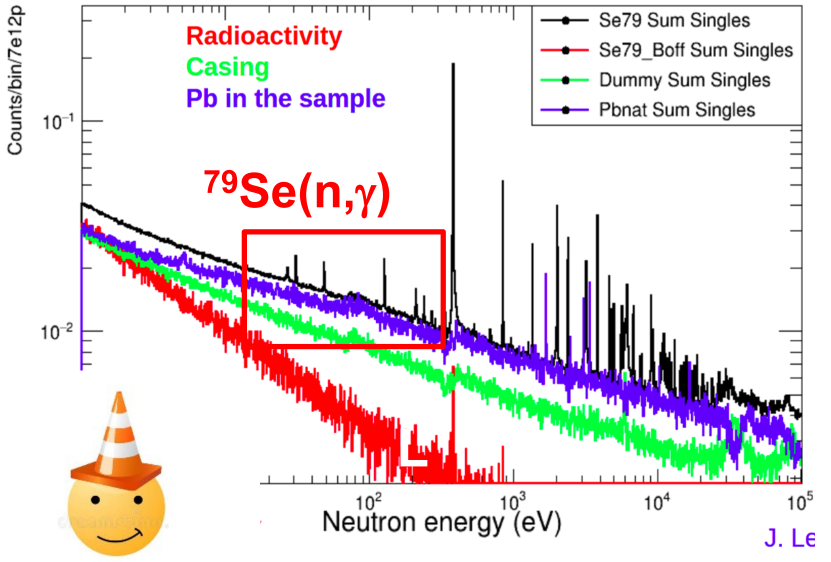
Sample itself was the main challenge!

s-process temperature via the ^{79}Se branching

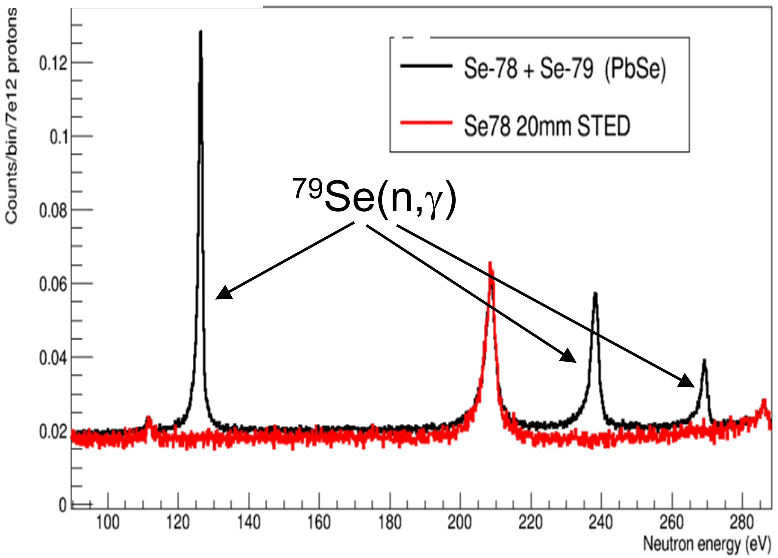





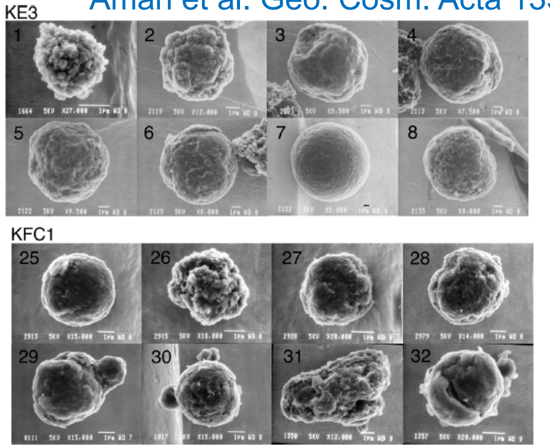


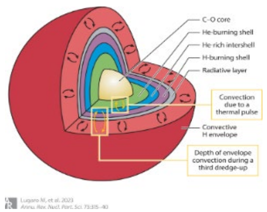


WORK IN PROGRESS



Amari et al. Geo. Cosm. Acta 133 (2014)





Future improvements:

→ Dedicated separators? Target laboratories? Other ideas for improving sample quality?…

→ Alternative direct techniques?

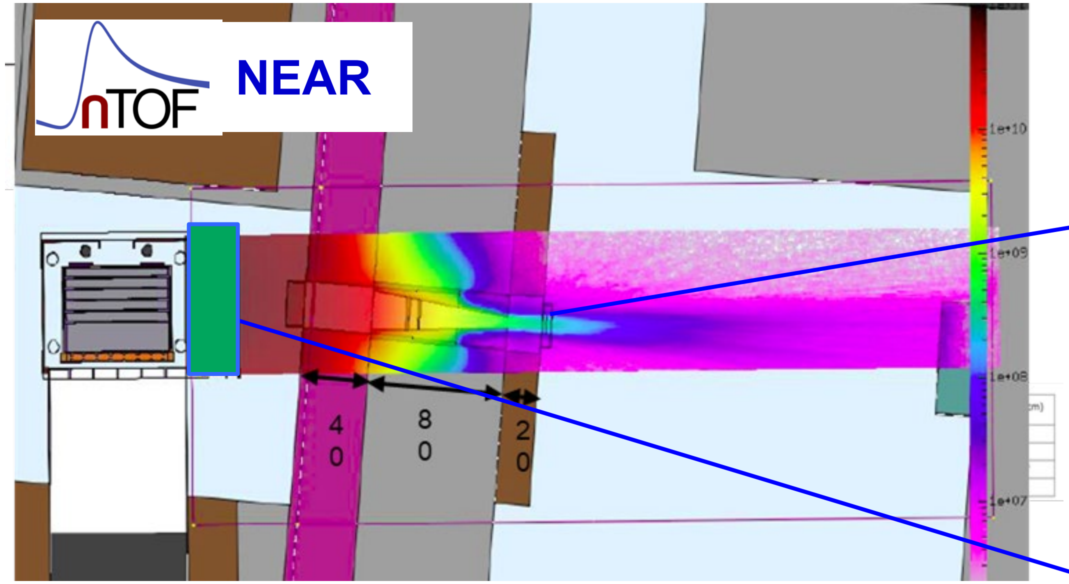
Lerendegui-Marco, et al., EPJ Web Conf. 279 (2023)

Outline

- Why unstable isotopes? and why direct (n,γ) measurements?
- Recent (n,γ) measurements with unstable isotopes at CERN n_TOF
- Plans for future direct (n,γ) measurements on s- and i-process isotopes
- Long-term perspectives for direct (n,γ) measurements on short-lived nuclei
- Summary & Outlook

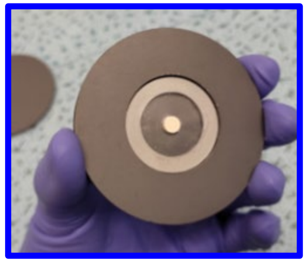
Activation at NEAR: several MACS possible!

n_TOF NEAR: (n,g) activations with very high flux (x~100 EAR2): small masses, unstable isotopes



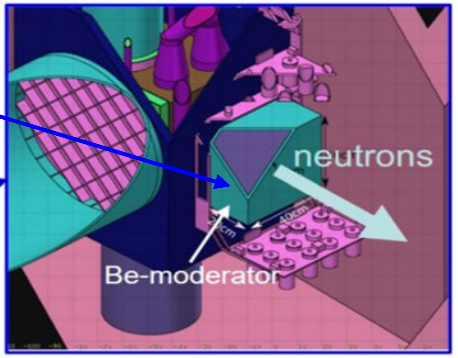
9×10^8 n/cm^2/pulse → **Mass limit ~ 10^{15} atoms**

N. Patronis et al., [arXiv (submitted to EPJ-A, 2025)]



$^{10}B_4C$ Filters

Different Stellar temperatures kT:0.1~500 keV

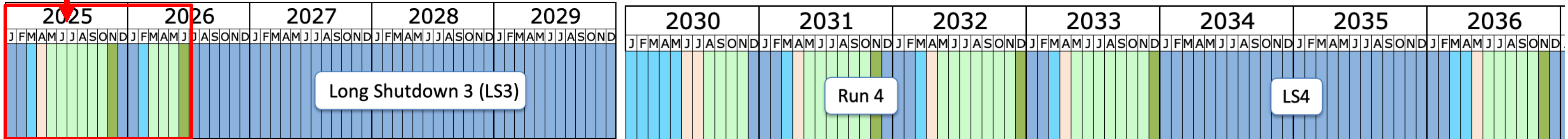


Be / $Al_2 0_3$ moderator

Poster#237: Jorge Lerendegui
Poster#85: Pablo Pérez Maroto

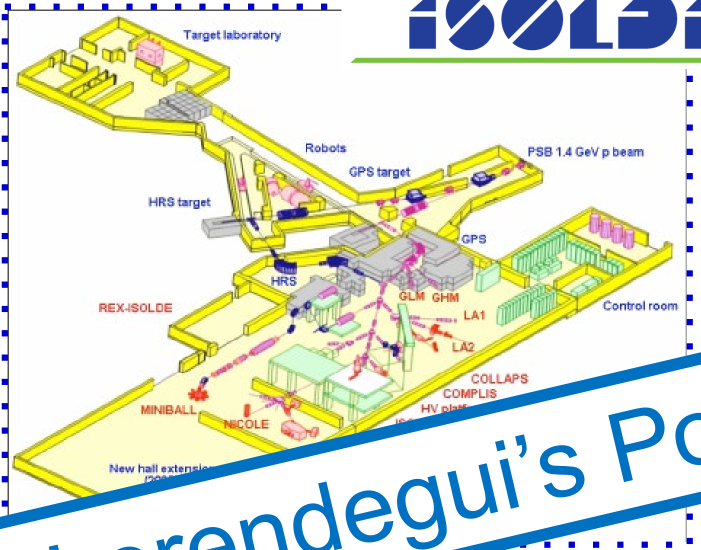
We are here

TOF @ EAR(1+2) + Activation @ NEAR

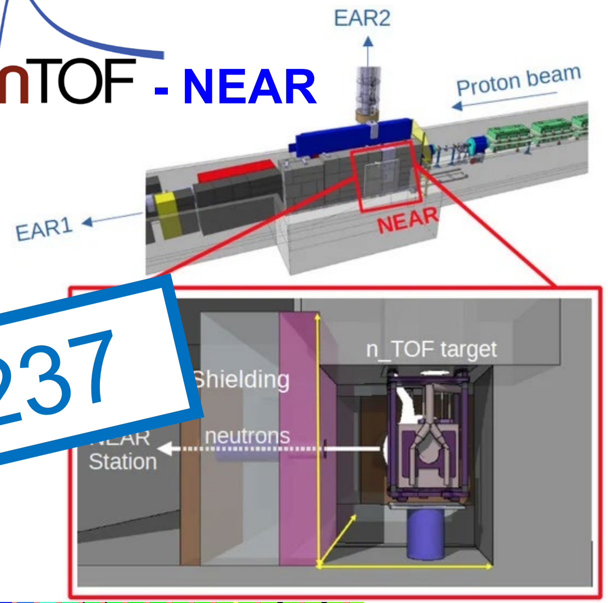


Activation at NEAR: synergy with ISOLDE for radio-isotopically pure samples!

Goal: Produce samples of relevant unstable nuclei at **RIB** & measure MACS at **high-flux facility**

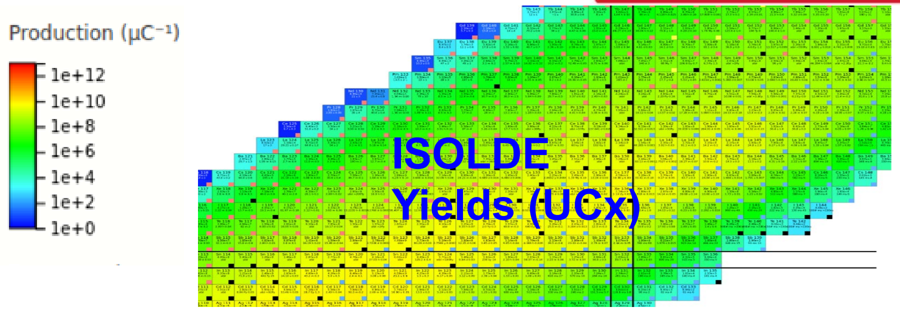


ISOLDE + nTOF - NEAR



Jorge Lerendegui's Poster#237

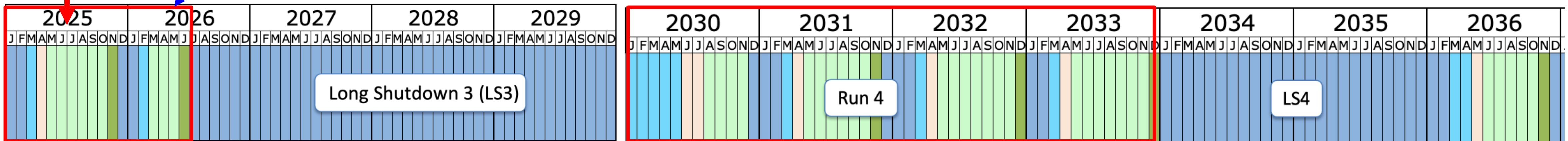
- **Example at CERN: ISOLDE + n_TOF-NEAR**
- **High flux + proximity**: Smaller m... would be accessible
- **Examples:**
  - 59Fe, 134Cs, 135Cs, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, and 181Hf (s-process),
  - Cs-137, Ce-144, 66Ni, 72Zn (i-process)



J. Lerendegui, S. Carollo et al., CERN-INTC-2022-040; INTC-P-641

We are here

TOF @ EAR(1+2) + Activation @ NEAR



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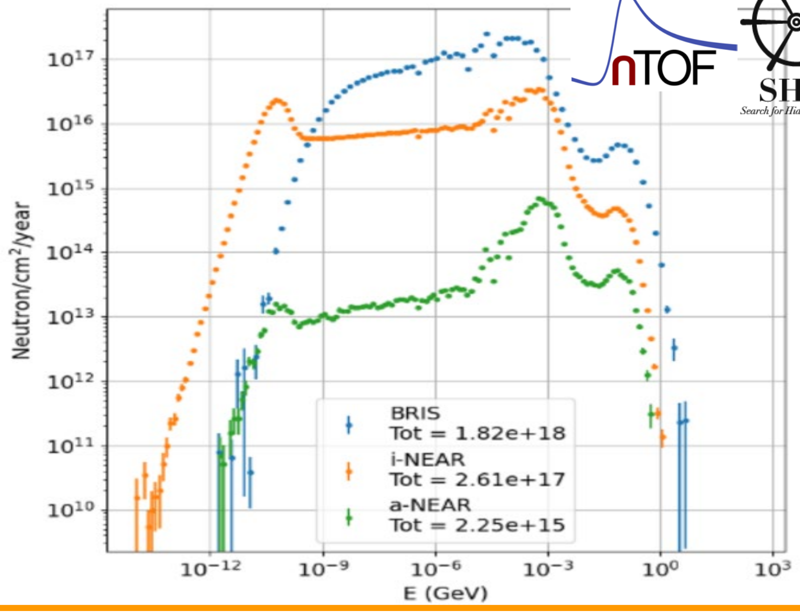
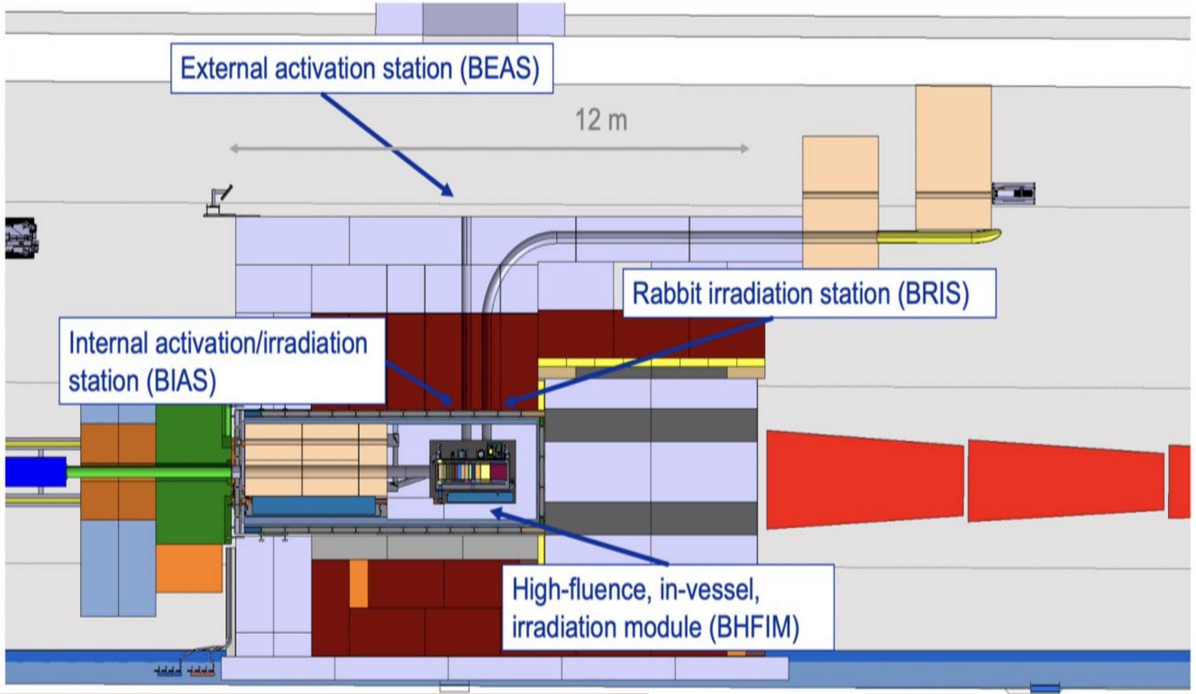
Long-term future: brighter neutron flux facilities at CERN



Flux (**a-NEAR x1000**) + fast rabbit (T1/2>=min-h)

Activation facility n_Act @ BDF/SHIP (SPS,CERN) (>2030)

C. Lederer et al. (n_TOF collaboration)
CERN-SPSC-2024-027 ; SPSC-EOI-023 (2024)

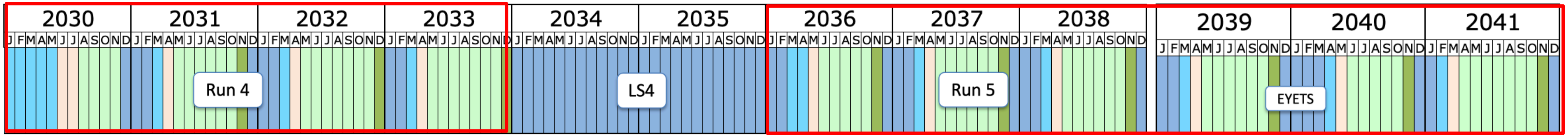


- TOF → Limited by sample quantity and quality (10^{18} atoms)
- Activation → Limited by sample activity (for decay measurement)

New techniques?

TOF @ EAR(1+2) + Activation @ NEAR

TOF @ EAR(1+2) + Activation @ NEAR + n_ACT

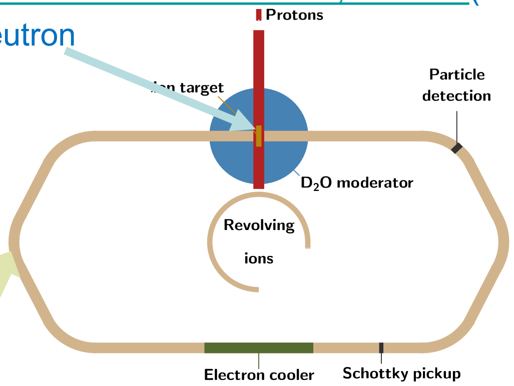


Changing the game. Direct (n,γ) reactions in inverse kinematics

- Novel approaches: neutron-sources & rings (LANL, TRIUMF)

Reifarth et al. Phys. Rev. Accel. Beams **20**, 044701 (2017)

Spallation neutron source



Storage Ring

RIB Facility

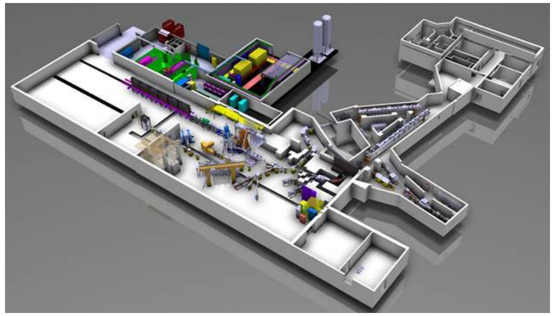
→ Proof-of-concept n-target ongoing @ Los Alamos, Cooper et al., JPCS 2743 (2024)

→ LE-customized Storage Ring @ TRIUMF, Dillmann et al. EPJ-A (2023)

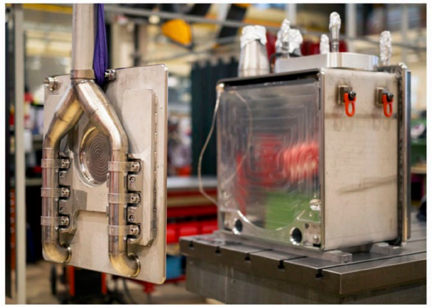
→ **Why not at CERN?**

Proof-of-concept developments on both the **neutron-target**, the **ion-storage** and the **detection** methods are of great importance!

CERN ISOLDE + nTOF



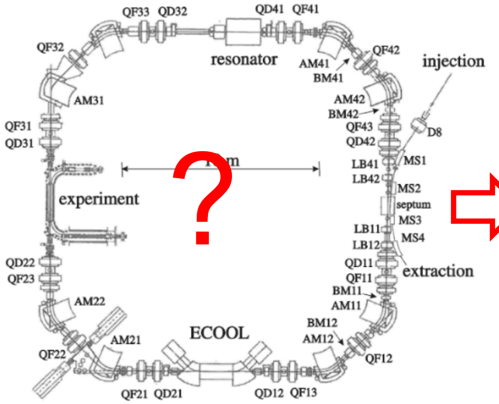
+

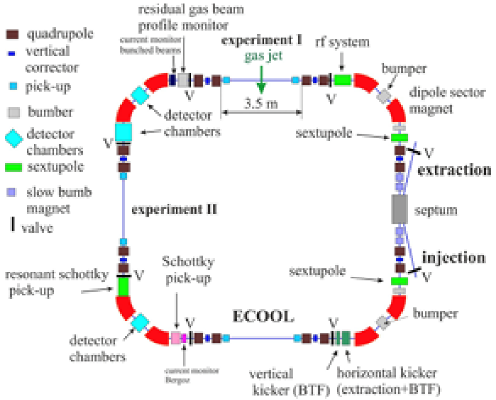


M. Grieser et al., Eur. Phys. J Spec. Top. 207 (2012)

+ RING?

+

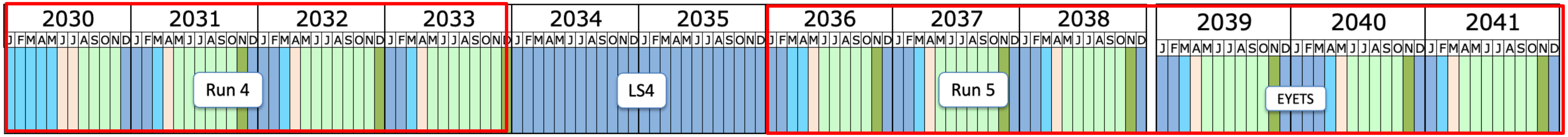




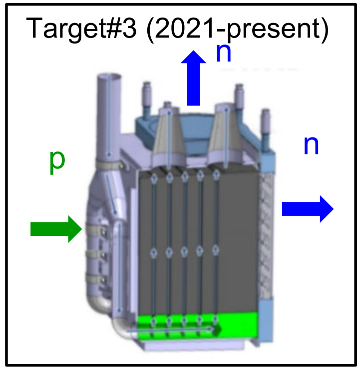
→ISR Project (LS4+?)

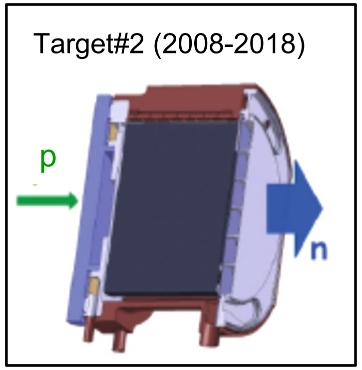
TOF @ EAR(1+2) + Activation @ NEAR

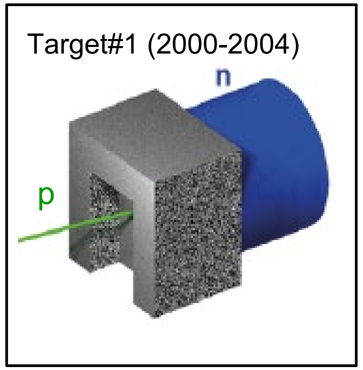
TOF @ EAR(1+2) + Activation @ NEAR + n_ACT + Inverse kin.?

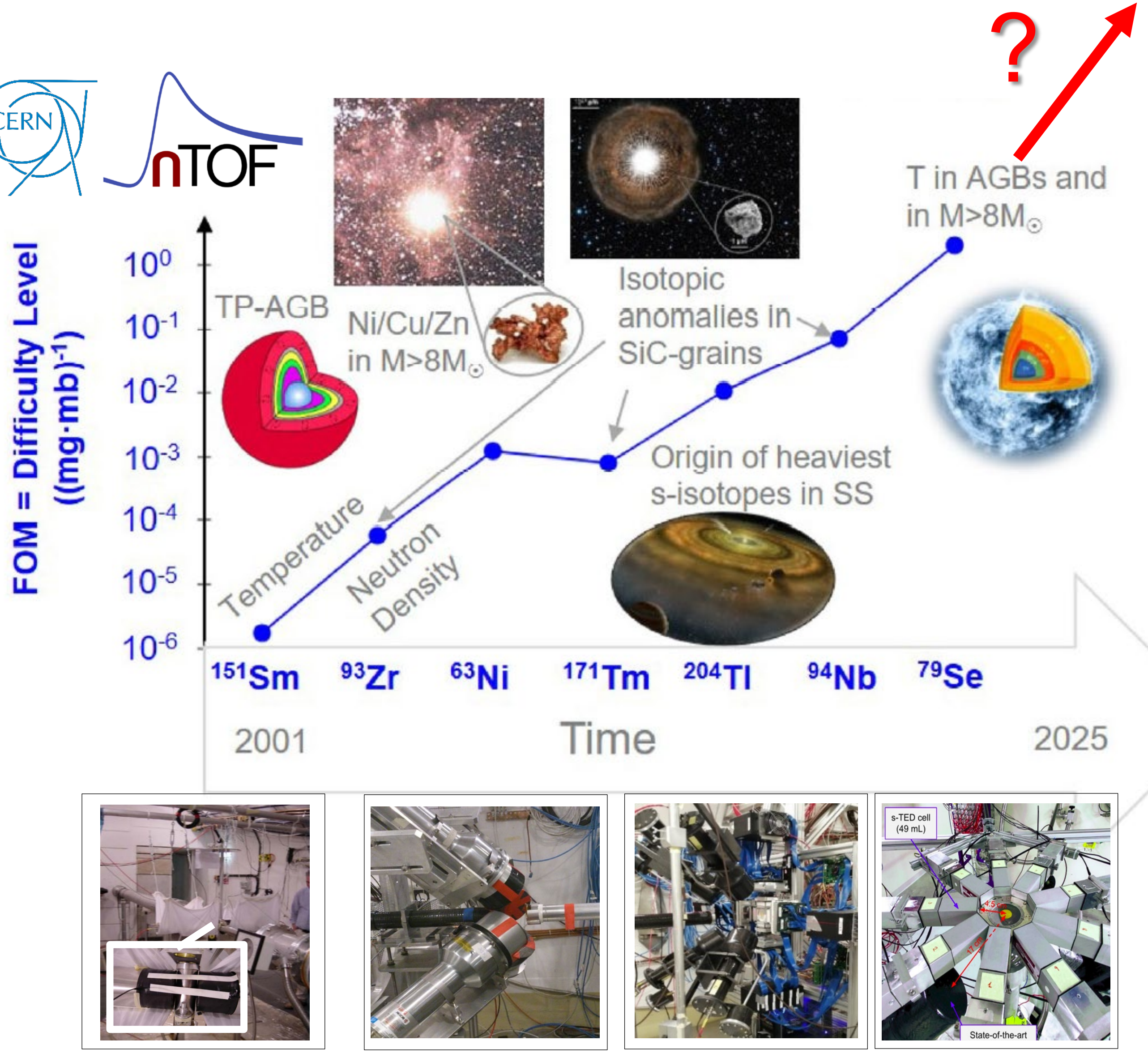


Summary & outlook









- Complementary (n,γ) activation at brighter facilities: NEAR & n_ACT-BDF
- Improve sample production:
  - Synergy with ISOLDE
  - Dedicated separators, etc
  - New ideas?

- Novel direct techniques in inverse kinematics
- Proof-of-concept developments for the neutron target, rings and detection methods

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The n_TOF Collaboration

Thanks for your attention!