Neutron cross section measurements of astrophysical interest at CERN n_TOF

J. Lerendegui-Marco

19th Russbach School on Nuclear Astrophysics, 3-9 March 2024

Outline

- Neutron cross sections and nuclear astrophysics
- Stellar nucleosynthesis & neutron capture reactions
- Neutron capture cross section measurements at n_TOF
- Recent advances and highlights on (n,g) astrophysical measurements
- Future prospects for (n,g) astrophysics experiments at n_TOF

Neutron cross sections and nuclear astrophysics

Neutrons and nuclear astrophysics @ n_TOF

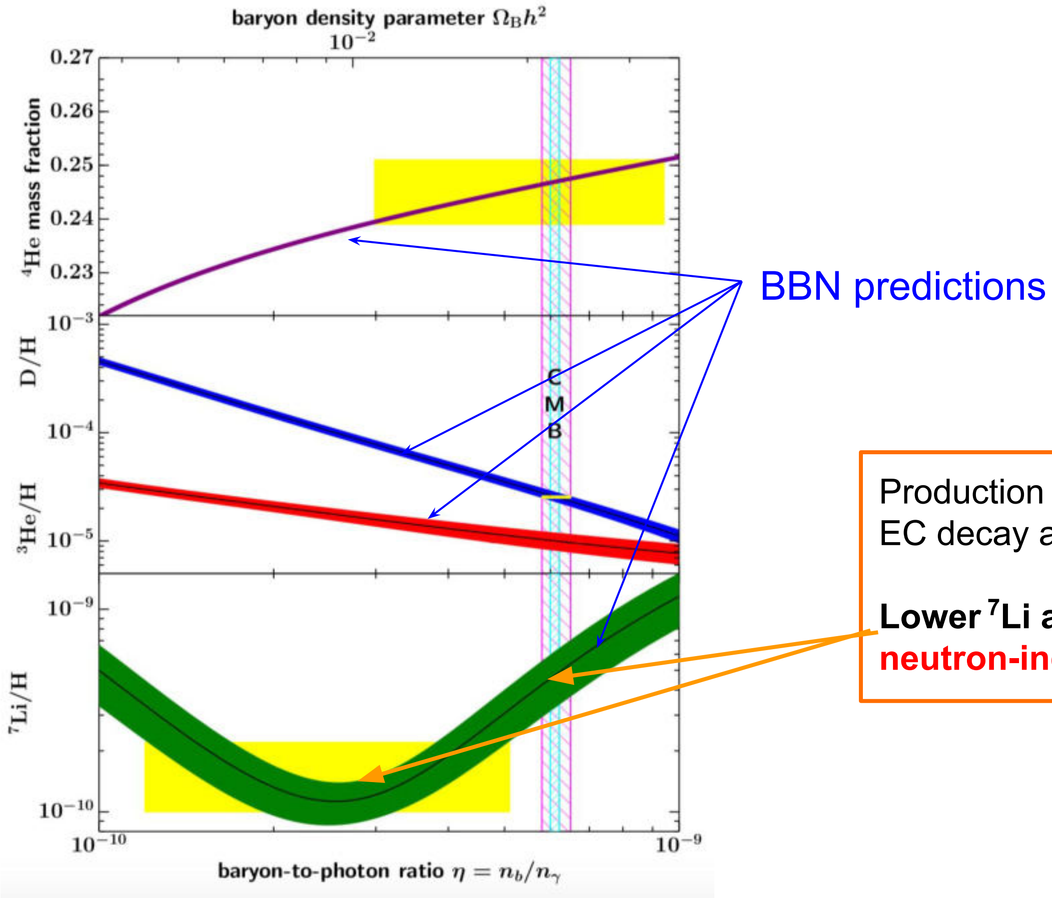
s-process: production of the majority of elements heavier than Fe.

BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

Neutron-induced reactions in Nuclear Astrophysics

Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.

Neutrons and nuclear astrophysics @ n_TOF



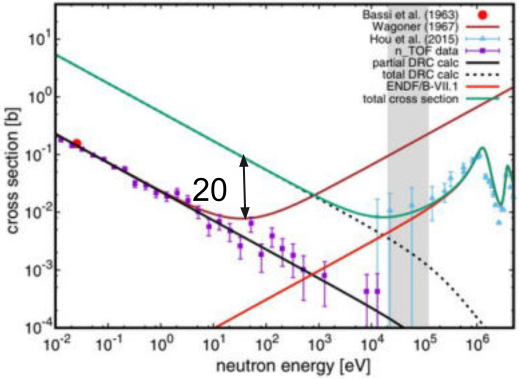
BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

Production of ^{7}Li: dominated by the ^{7}Be EC decay after the BBN.

Lower ^{7}Li abundance? A higher rate for **neutron-induced** reactions on 7Be?

PRL 117, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

$^{7}Be(n,\alpha)^{4}He$ Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

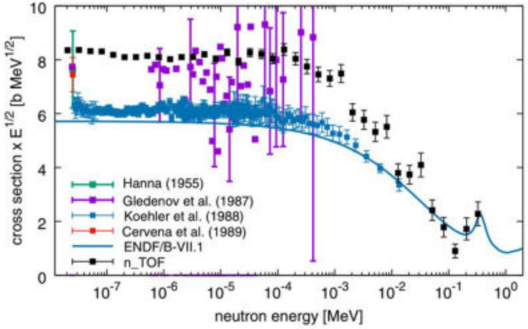


BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

PHYSICAL REVIEW LETTERS 121, 042701 (2018)

$^{7}Be(n,p)^{7}Li$ Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

- Be-7(n,a): x20 vs calculations of BBN below 100 eV
- Be-7(n,p): +40% vs previous at low En

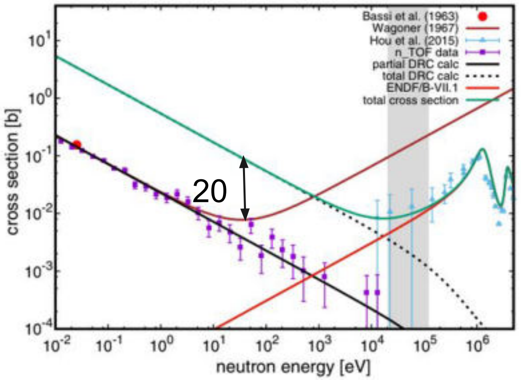


$^{7}Be(n,p)^{7}Li$ rate	η_{10}	Li/H yield
Cyburt (2004) rate [22]	6.09	5.46
This work [Eq. (3)]	6.09	5.26 ± 0.40
	5.8–6.6	4.73–6.23
Observations [1]		1.6 ± 0.3

Neutrons and nuclear astrophysics @ n_TOF

PRL 117, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

^{7}Be$(n,\alpha)^4$He Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN



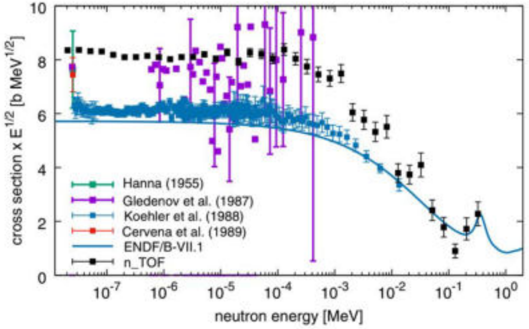
BBN and the Li-problem: Neutron cross sections are key to clarify the gross overestimate in BBN models of the primordial abundance of Lithium.

PHYSICAL REVIEW LETTERS 121, 042701 (2018)

^{7}Be$(n,p)^7$Li Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

^{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

- Be-7(n,a): x20 vs calculations of BBN
- Be-7(n,p): +40% vs previous at low En



Neutrons are not enough to solve the CLiP → Alternative physics or astromical scenarios

Neutrons and nuclear astrophysics @ n_TOF

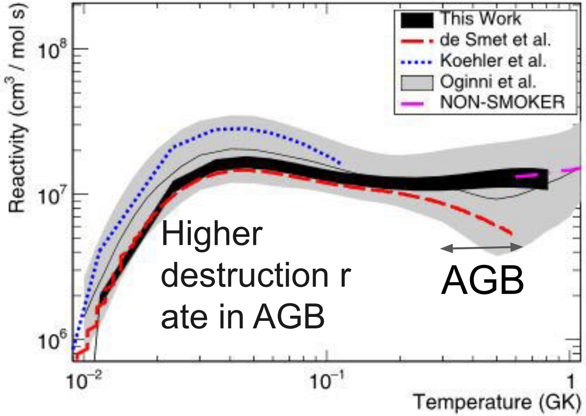
PHYSICAL REVIEW C **104**, L032803 (2021)

Letter

Destruction of the cosmic γ-ray emitter ^{26}Al in massive stars: Study of the key ^{26}Al(n, α) reaction

C. Lederer-Woods,[1,*] P. J. Woods,[1] T. Davinson,[1] A. Estrade,[1,†] J. Heyse,[2] D. Kahl,[1,‡] S. J. Lonsdale,[1] C. Paradela,[2]

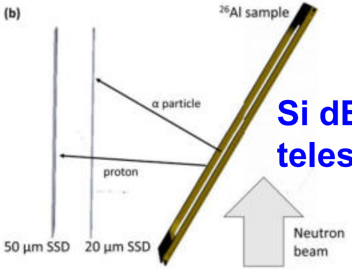
Neutron-induced destruction of the cosmic-ray emitter Al-26 (T1/2 = 0.7 Myr)



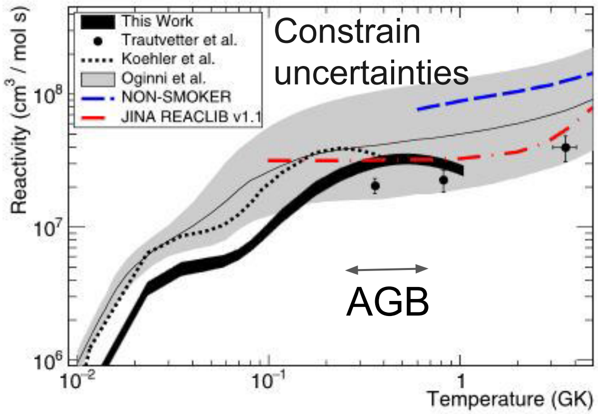
PHYSICAL REVIEW C **104**, L022803 (2021)

Letter

Destruction of the cosmic γ-ray emitter ^{26}Al in massive stars: Study of the key ^{26}Al(n, p) reaction



Si dE/E telescope



- Significant discrepancies in the Al-26 destruction rates.
- Impact in the Al-26 production in supernovae and AGB origin of our early solar system

Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.

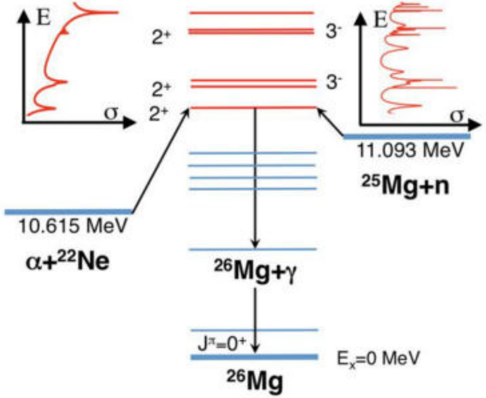
Next: extend>1 GK (Massive stars)

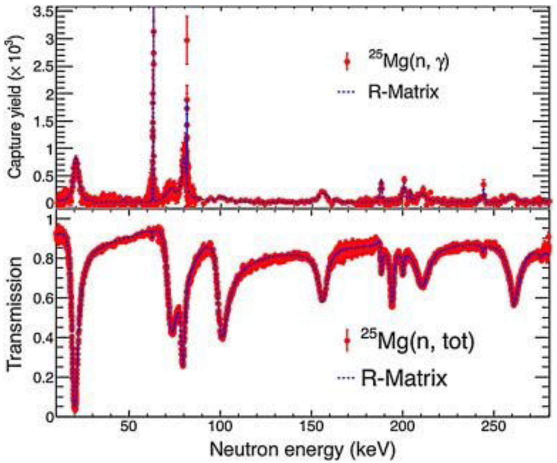
Neutrons and nuclear astrophysics @ n_TOF

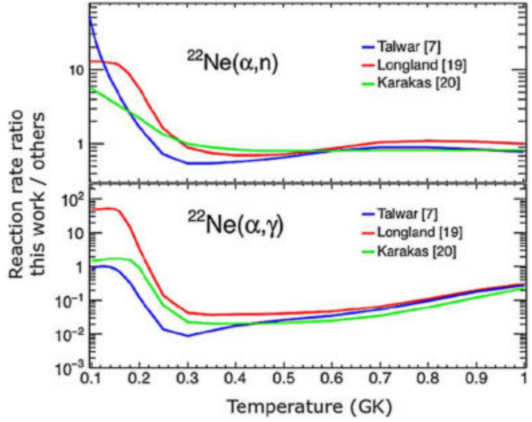
Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source ^{22}Ne$(\alpha,n)^{25}$Mg

C. Massimi[a,b,*], S. Altstadt[c], J. Andrzejewski[d], L. Audouin[e], M. Barbagallo[f], V. Bécares[g],

Neutron-spectroscopy to experimentally constrain the neutron source reaction 22Ne(α,n)25Mg

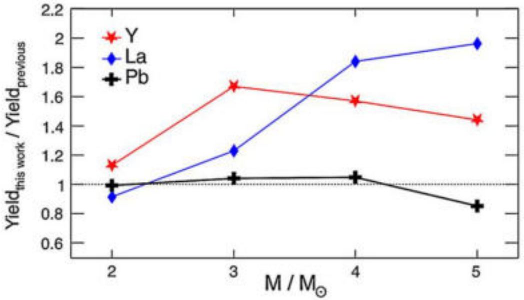




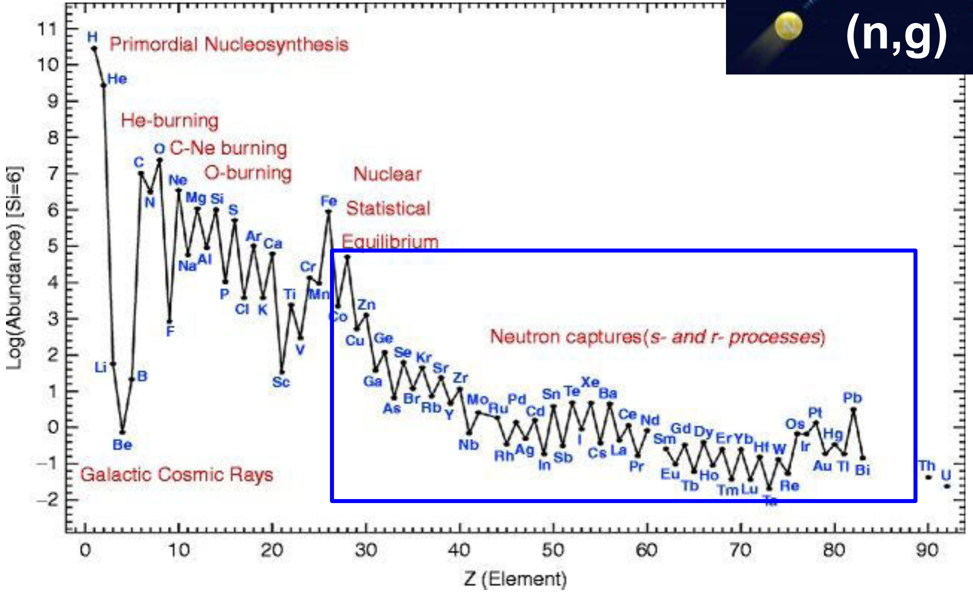


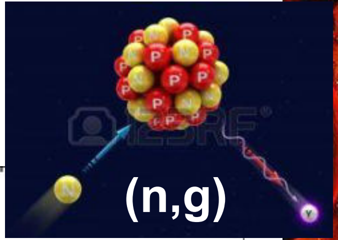
- R-matrix on (n,g) → parity assignment of the excited states in 26Mg
- 22Ne(a,n) rates enhanced at low temperature.
- Large impact in the AGB s-process abundances (2-5 M).

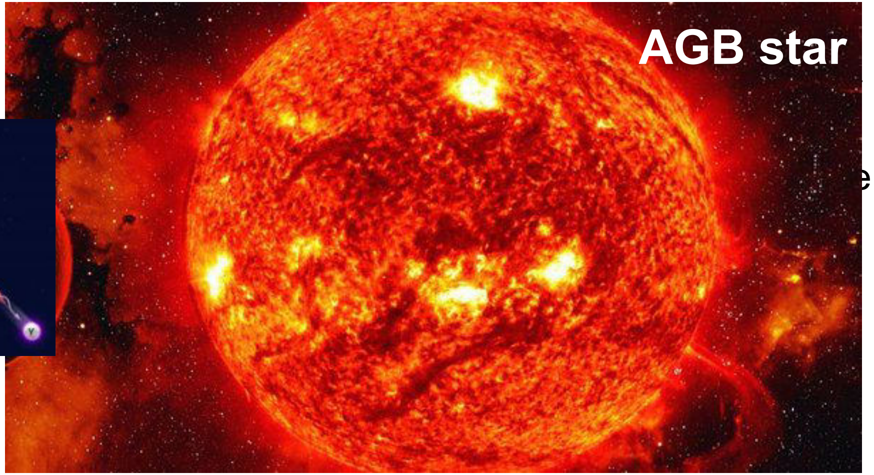
Neutron sources: neutron cross sections of light elements acting as neutron poison, or linked to stellar neutron sources.



s-process: production of the majority of elements heavier than Fe.





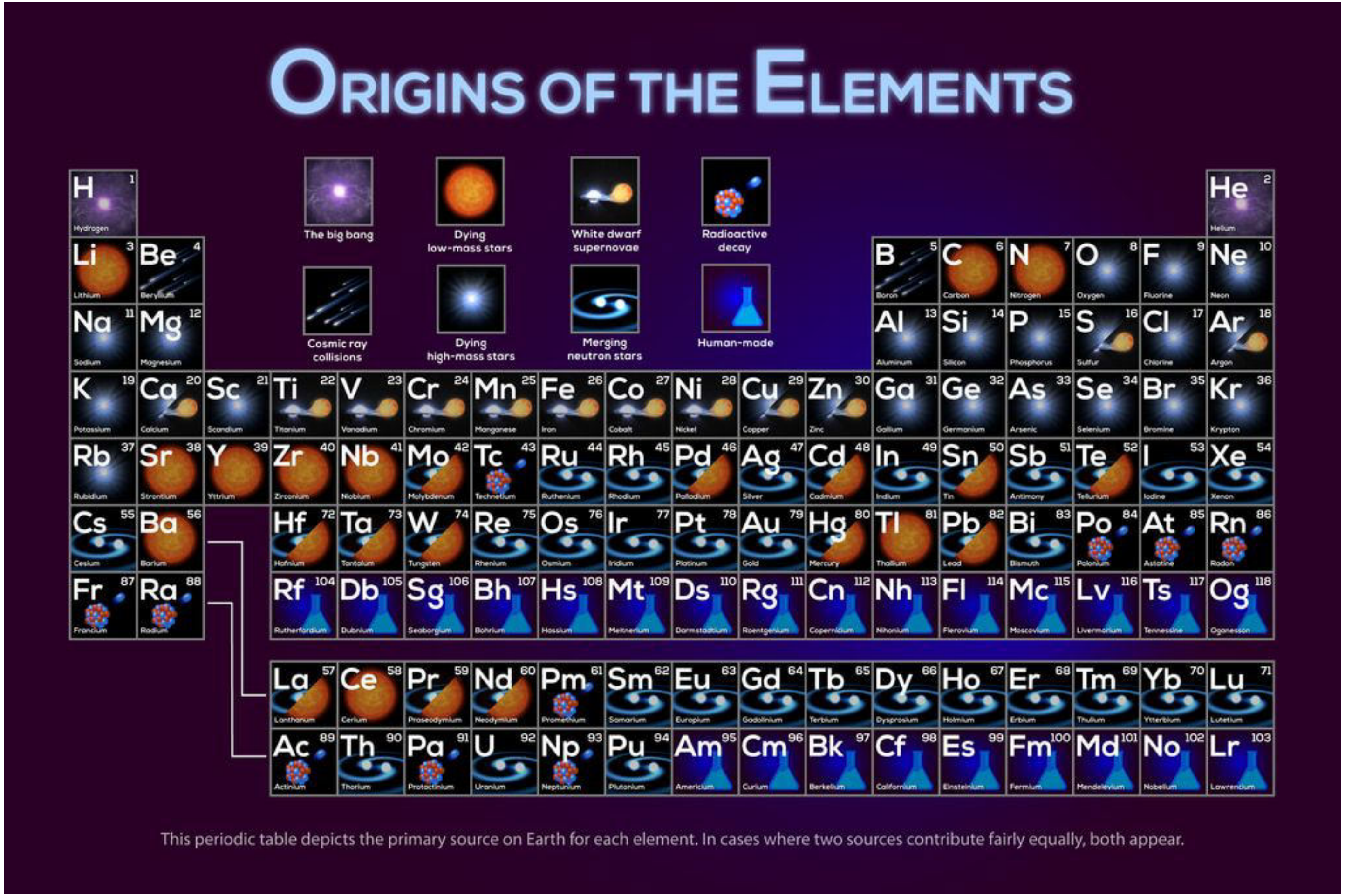


Most of the astrophysics experiments at n_TOF are on **neutron capture cross sections** of relevance for the s-process

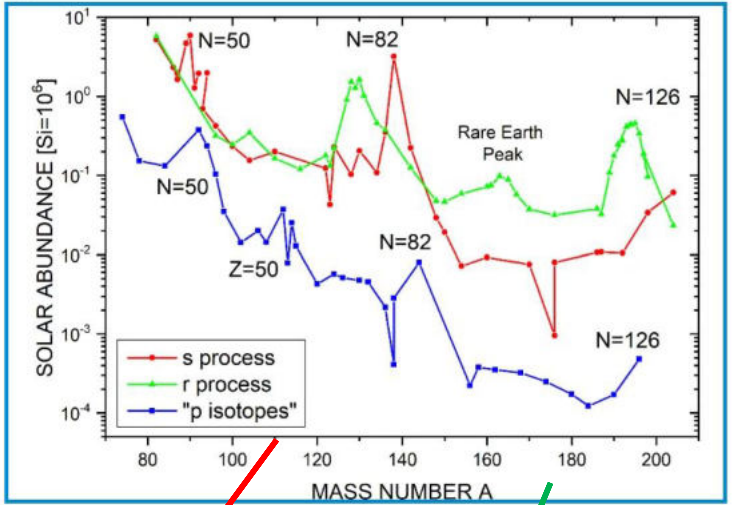
This lecture!

Stellar nucleosynthesis & neutron capture reactions

The synthesis of elements in stars



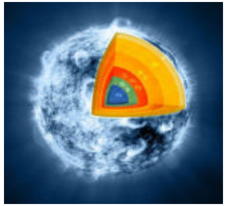
Stellar nucleosynthesis of heavy elements



s-process

$T = 10^8 - 10^9$ K

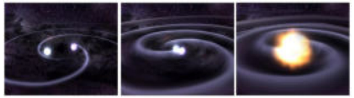
$N_n = 10^6 - 10^{12}\ cm^{-3}$

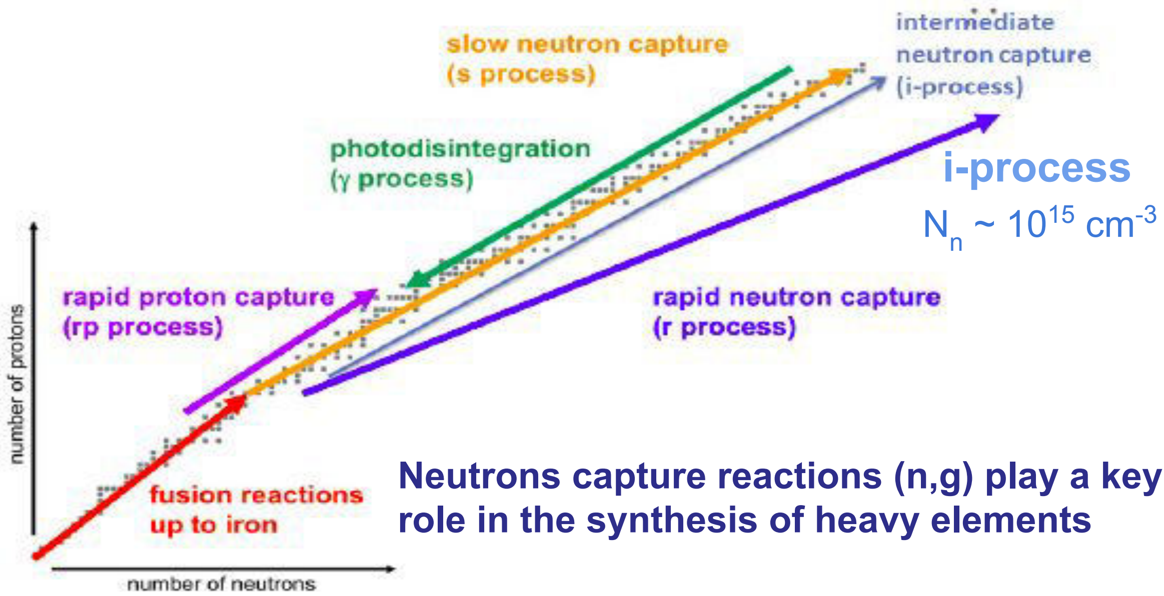


r-process

$T = 10^8 - 10^{10}$ K

$N_n = 10^{20} - 10^{27}\ cm^{-3}$



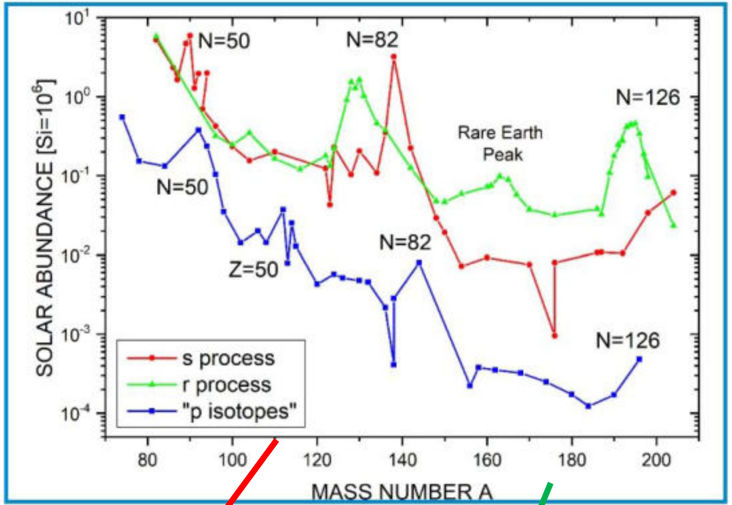


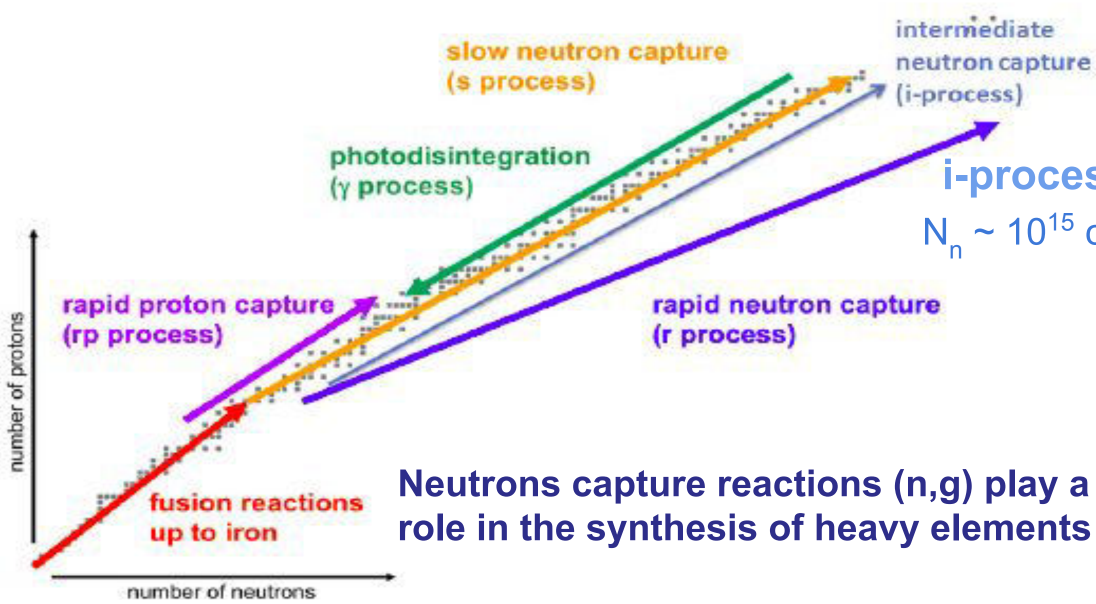
i-process

$N_n \sim 10^{15}\ cm^{-3}$

Neutrons capture reactions (n,g) play a key role in the synthesis of heavy elements

Stellar nucleosynthesis of heavy elements





i-process

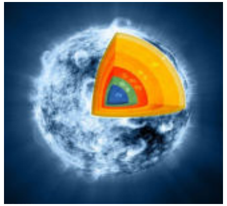
$N_n \sim 10^{15}$ cm^{-3}

Neutrons capture reactions (n,g) play a key role in the synthesis of heavy elements

s-process

$T = 10^8 - 10^9$ K

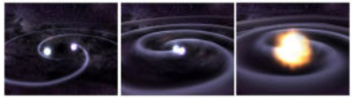
$N_n = 10^6 - 10^{12}$ cm^{-3}



r-process

$T = 10^8 - 10^{10}$ K

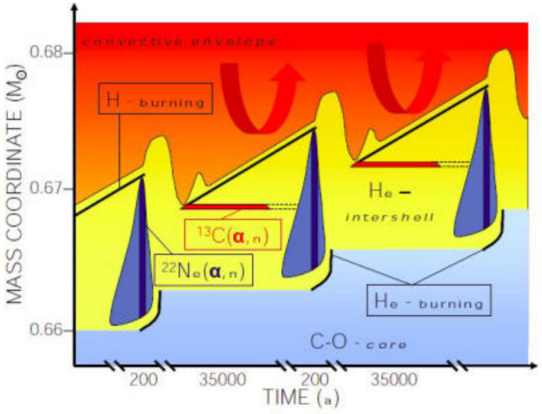
$N_n = 10^{20} - 10^{27}$ cm^{-3}

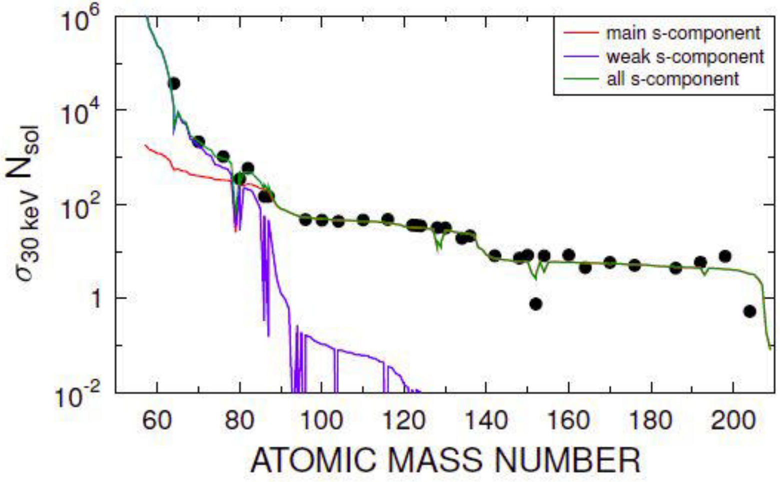


Experimental aim at n_TOF: measure stellar (n,g) cross sections of nuclei involved in the s-process (& i-process)

s-process nucleosynthesis: stellar sites

Thermally pulsing low-mass AGB stars





S-PROCESS COMPONENTS

MAIN S-PROCESS:

He shell burning phase in AGB STARS

$^{22}Ne(\alpha,n)$: 10^{12} n/cm³, kT ~30 keV

$^{13}C(\alpha,n)$: 10^{7} n/cm³, kT ~5 keV

90<A<209

WEAK S-PROCESS:

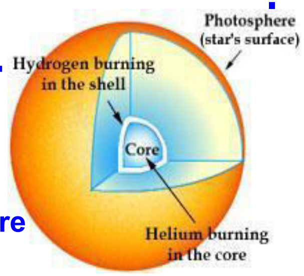
Massive stars

$^{22}Ne(\alpha,n)$

He core burning: 10^{6}n/cm³, kT ~25 keV

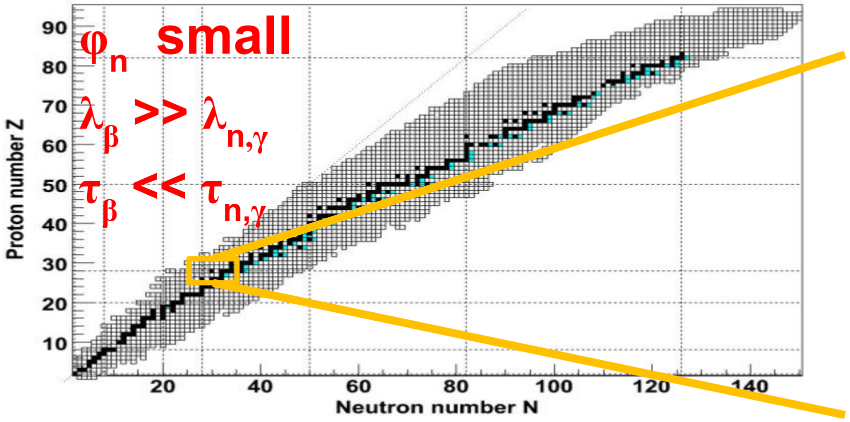
C-shell burning: 10^{12}n/cm³, kT ~90 keV

56<A<90

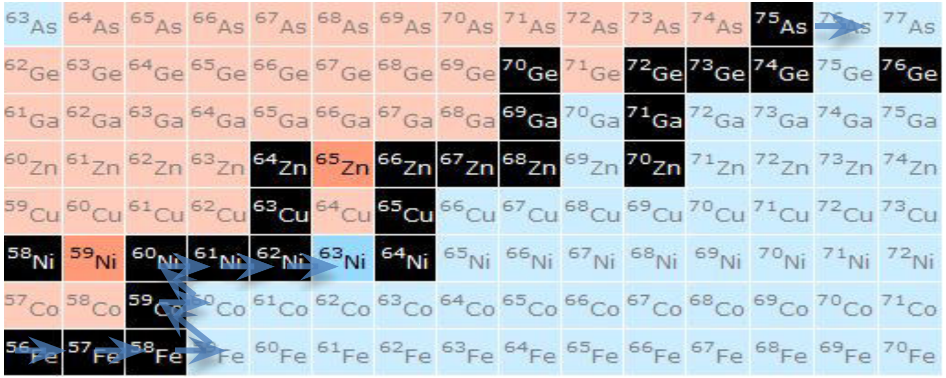


He-burning core Massive star

s-process nucleosynthesis path



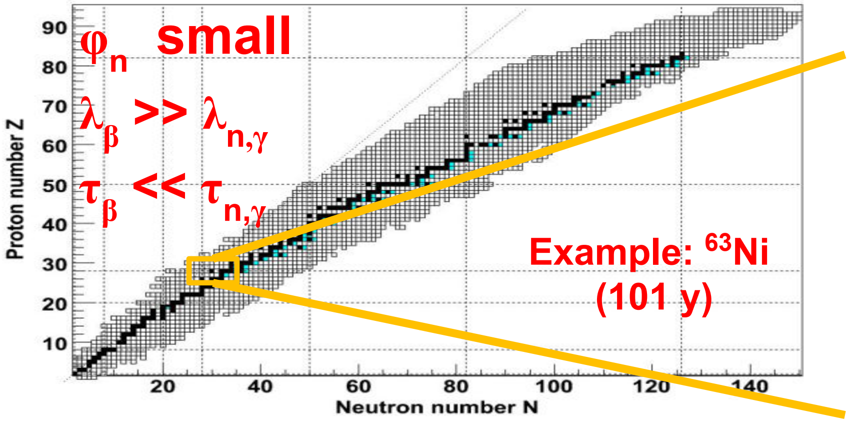
s-process: ~½ of the abundances A>56



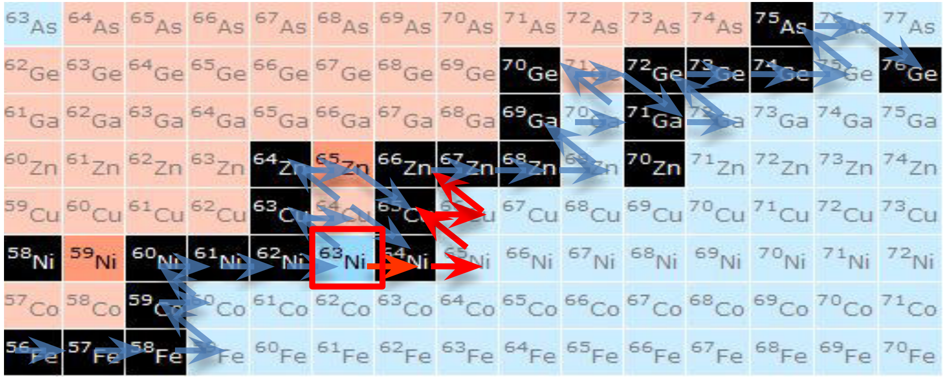
s-process: n capture + beta decay along stability valley

Stellar temp. kT = 5 - 90 keV

s-process nucleosynthesis path



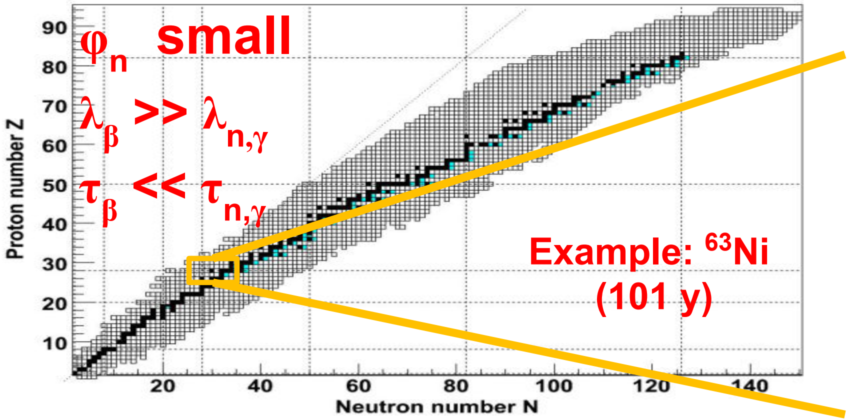
s-process: ~½ of the abundances A>56



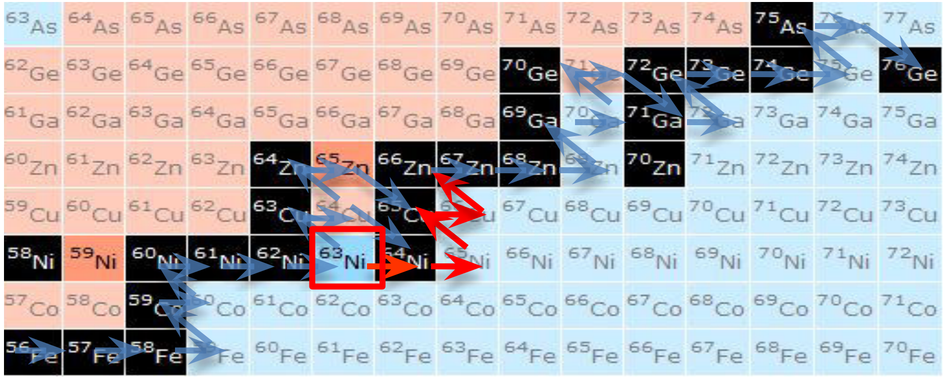
s-process: n capture + beta decay along stability valley

Stellar temp. kT = 5 - 90 keV

s-process nucleosynthesis path



s-process: ~½ of the abundances A>56



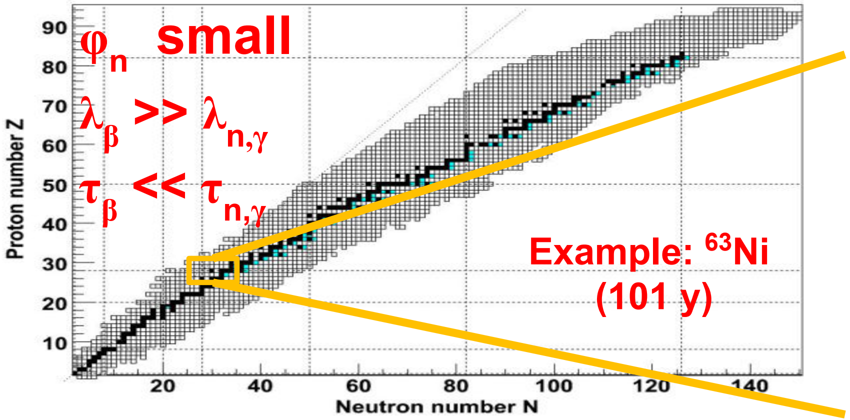
s-process: n capture + beta decay along stability valley

Stellar temp. kT = 5 - 90 keV

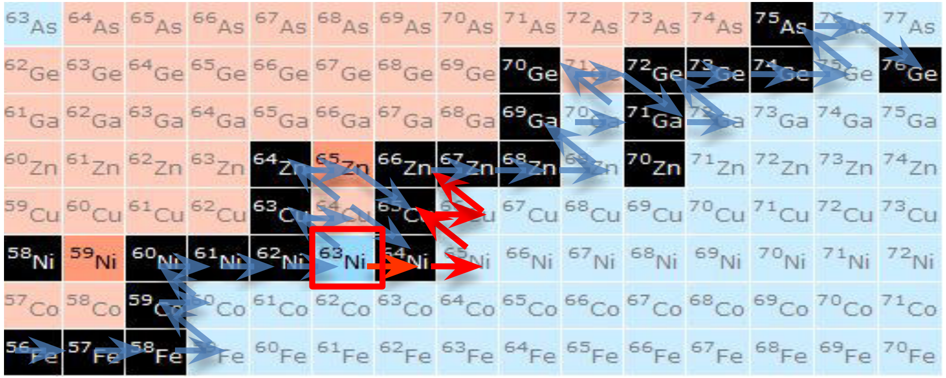
if λ_β is small
or φ_n increases
$\lambda_\beta \sim \lambda_{n,\gamma}$

BRANCHING POINTS:
$^{A}Z(n,\gamma)\ ^{A+1}Z$ competes with
$^{A}Z \rightarrow {}^{A}(Z+1) + \beta + \nu$

s-process nucleosynthesis path



s-process: ~½ of the abundances A>56



s-process: n capture + beta decay along stability valley

Stellar temp. kT = 5 - 90 keV

if λ_β is small
or φ_n increases
$\lambda_\beta \sim \lambda_{n,\gamma}$

BRANCHING POINTS:
$^{A}Z(n,\gamma)\ ^{A+1}Z$ competes with
$^{A}Z \rightarrow {}^{A}(Z+1) + \beta + \nu$

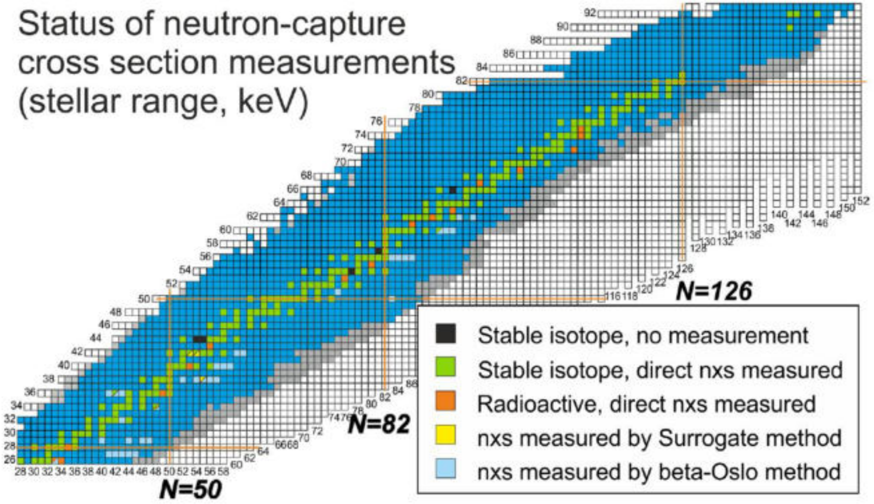
Branching points: Local abundance pattern → (n,γ) measurements provide tight constraints to stellar conditions

(n,γ) cross sections
are the key nuclear input

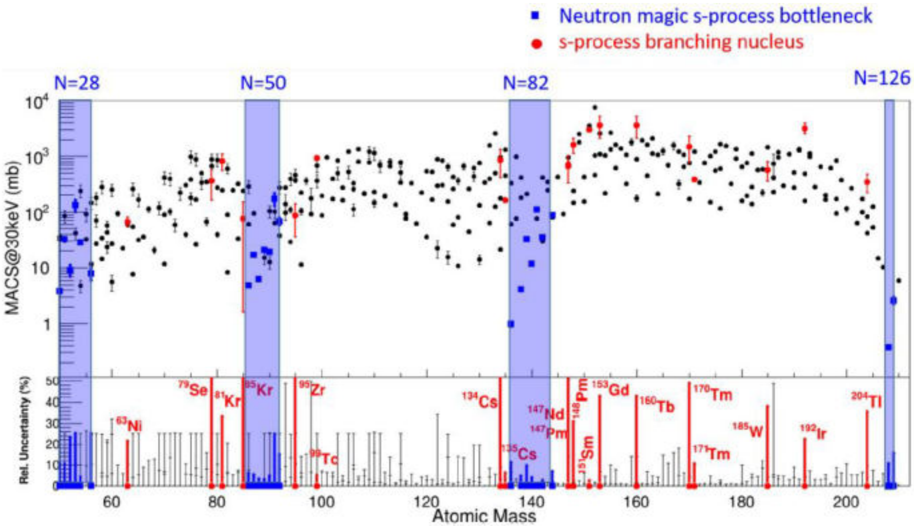
s-process: status of data on branching points

Key cases: branching points
$^{A}Z(n,\gamma)$ competes with β decay
(n,γ) cross sections→ conditions stellar enviroment

I. Dillmann et al., *Eur. Phys. J. A* **59**, 105 (2023).



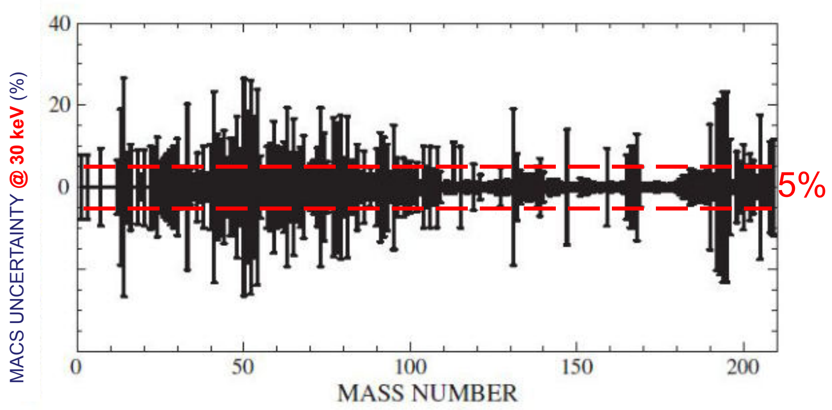
C. Domingo-Pardo et al. Eur. Phys. Jour. A, **59**, 8 (2023)



Challenging measurements:
Radioactive isotopes, low masses

Consequence:
Very little direct (n,g) data,
Very large uncertainties for most of them

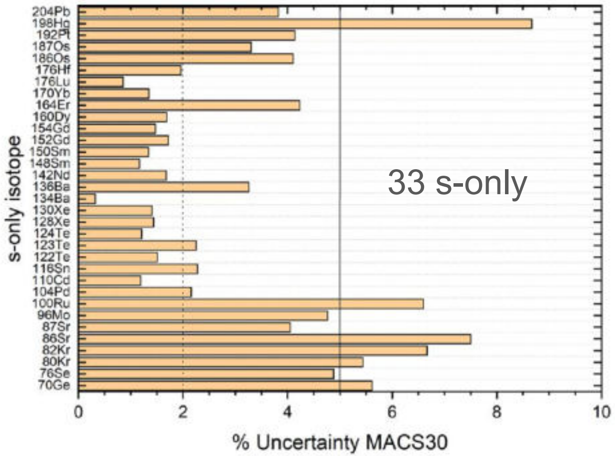
s-process: data needs on stable isotopes



F. Käppeler et al. Rev. Mod. Phys. (2011)

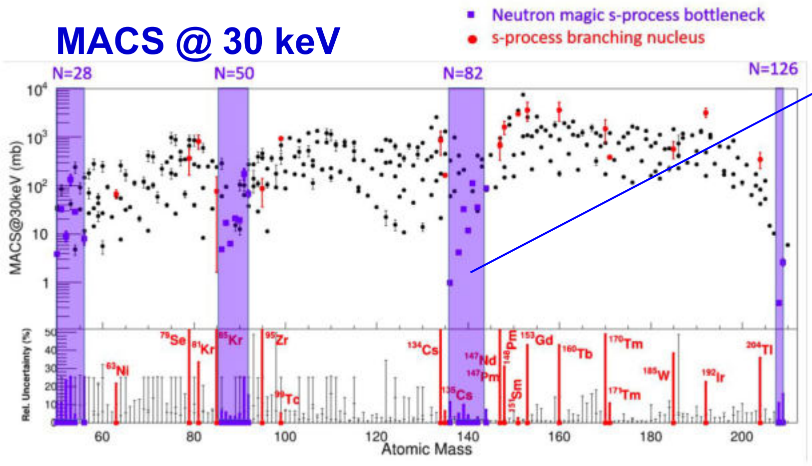
S-only isotopes:

Accuracy MACS down to 2% unc.



I. Dillmann et al. Eur. Phys. Jour. A (2023)

MACS @ 30 keV

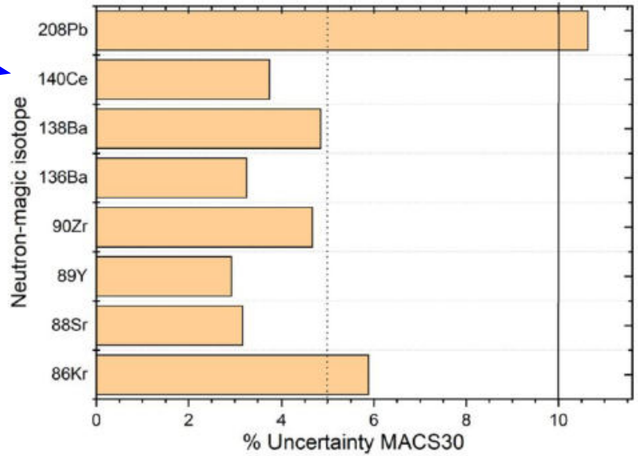


C. Domingo-Pardo et al. Eur. Phys. Jour. A (2023)

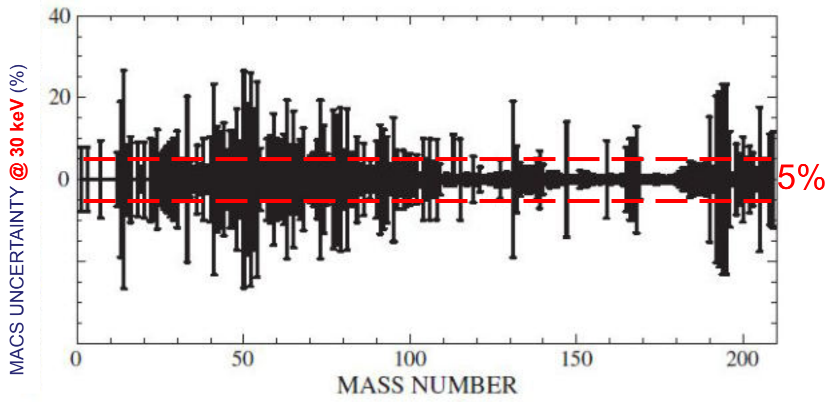
N-magic nuclei:

S-process bottlenecks

Very small (n,g) XS



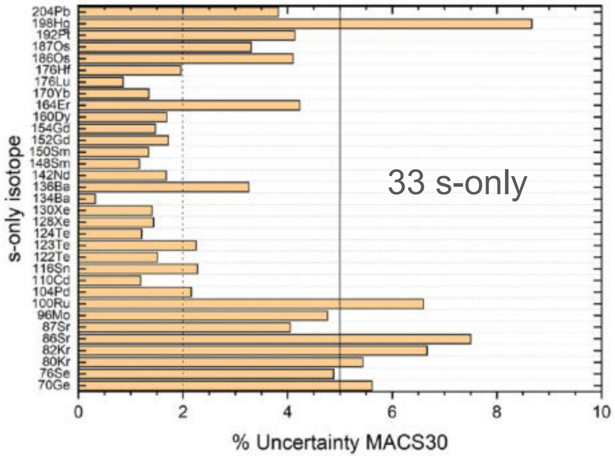
s-process: data needs on stable isotopes



F. Käppeler et al. Rev. Mod. Phys. (2011)

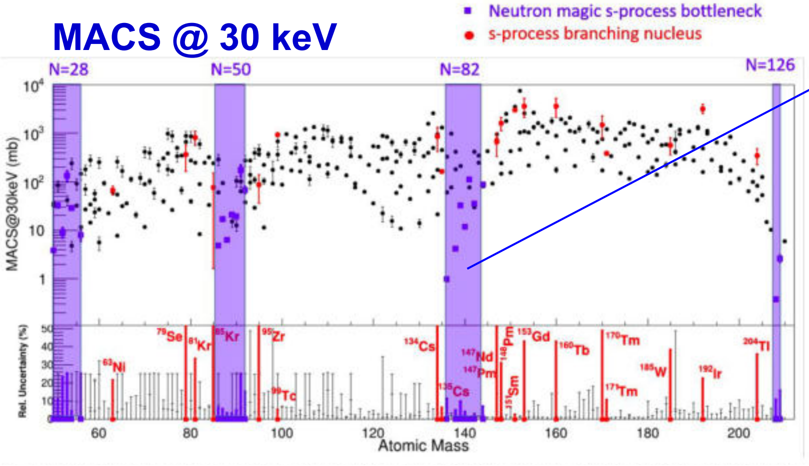
S-only isotopes:

Accuracy MACS down to 2% unc.



I. Dillmann et al. Eur. Phys. Jour. A (2023)

MACS @ 30 keV



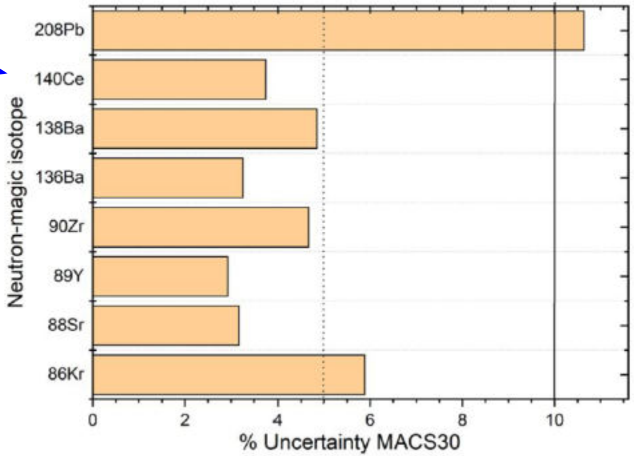
C. Domingo-Pardo et al. Eur. Phys. Jour. A (2023)

N-magic nuclei:

S-process bottlenecks

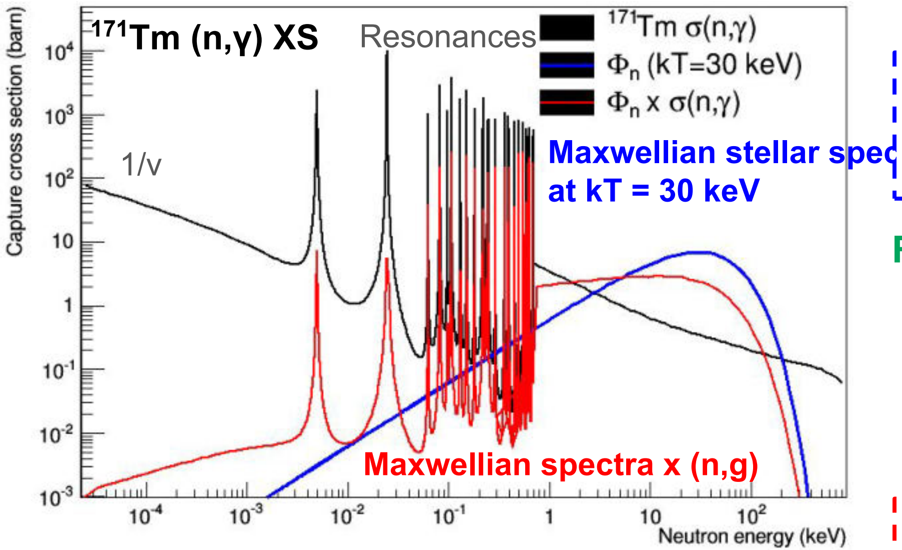
Very small (n,g) XS

High accuracy (n,g) data on stable nuclei also needed!



Neutron capture cross section measurements at n_TOF

Stellar (n,γ) cross sections: MACS



Maxwellian stellar spectra

$$\phi_{MB}(v)dv = \phi_{MB}(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

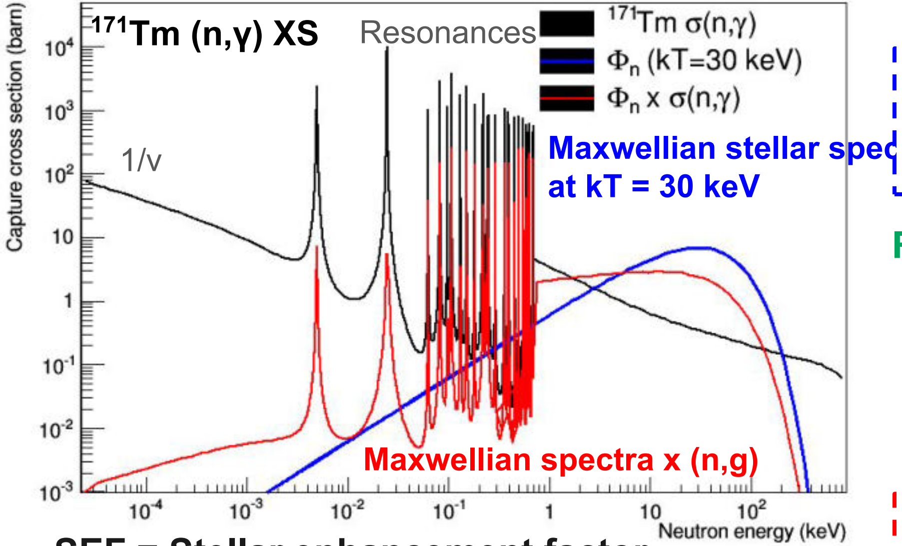
Reaction rate per particle pair

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

MACS = Maxwellian Averaged Cross Section

$$\mathrm{MACS} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

Stellar (n,γ) cross sections: MACS



SEF = Stellar enhancement factor

For some isotopes:

$$SEF(T) = \frac{\langle\sigma\rangle^{\text{star}}}{\langle\sigma\rangle_{kT}},$$

Maxwellian stellar spectra

$$\phi_{MB}(v)dv = \phi_{MB}(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

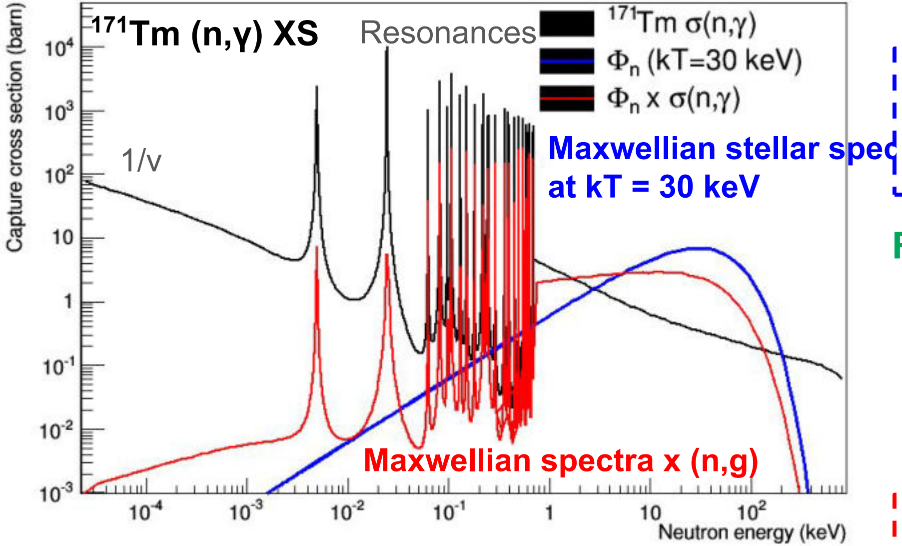
Reaction rate per particle pair

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

MACS = Maxwellian Averaged Cross Section

$$\text{MACS} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

Stellar (n,ɣ) cross sections: MACS



Maxwellian stellar spectra

$$\phi_{MB}(v)dv = \phi_{MB}(E)dE = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^{3/2}}\sqrt{E}e^{-\frac{E}{kT}}dE$$

Reaction rate per particle pair

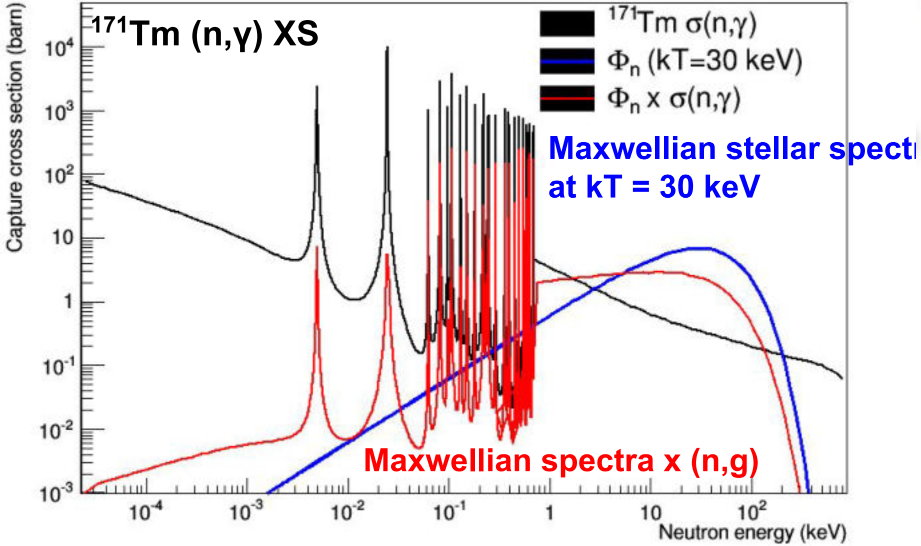
$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

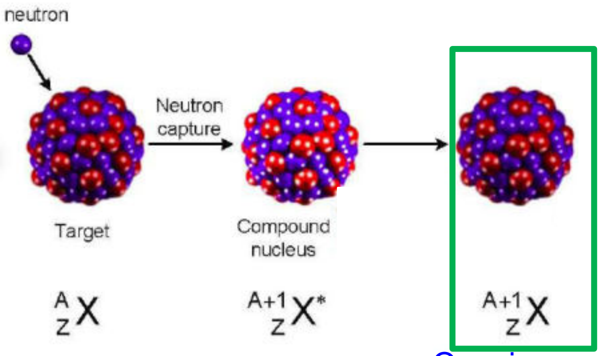
MACS = Maxwellian Averaged Cross Section

$$\text{MACS} = \frac{\langle\sigma v\rangle}{v_T} = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty E\sigma(E)e^{-\frac{E}{kT}}dE.$$

Is it possible to produce a Maxwellian spectra?
How do we measure energy-dependent cross sections?

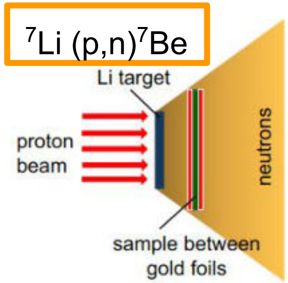
Stellar (n,γ) cross sections: beams & techniques

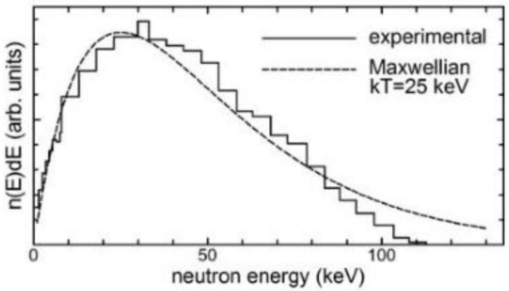




Activation: count product nuclei

Quasi-maxwellian @ 25 keV





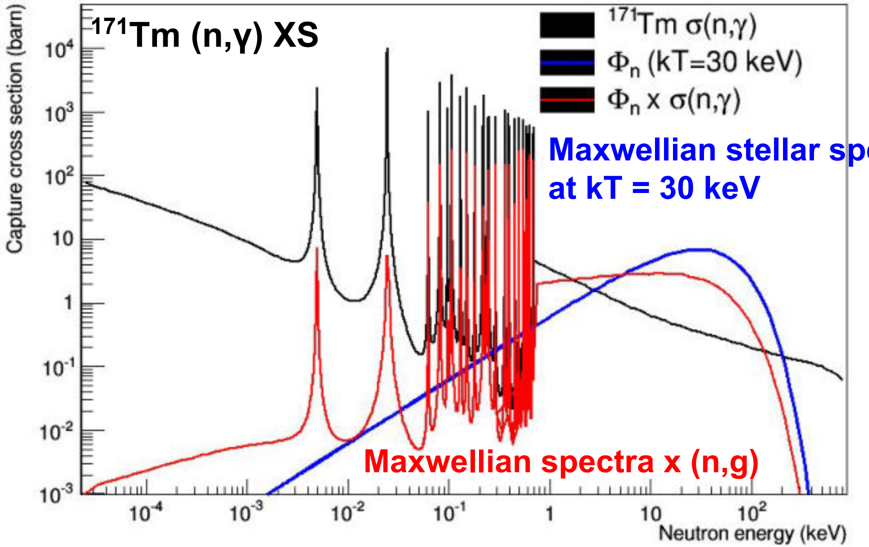
Ep=1912 keV

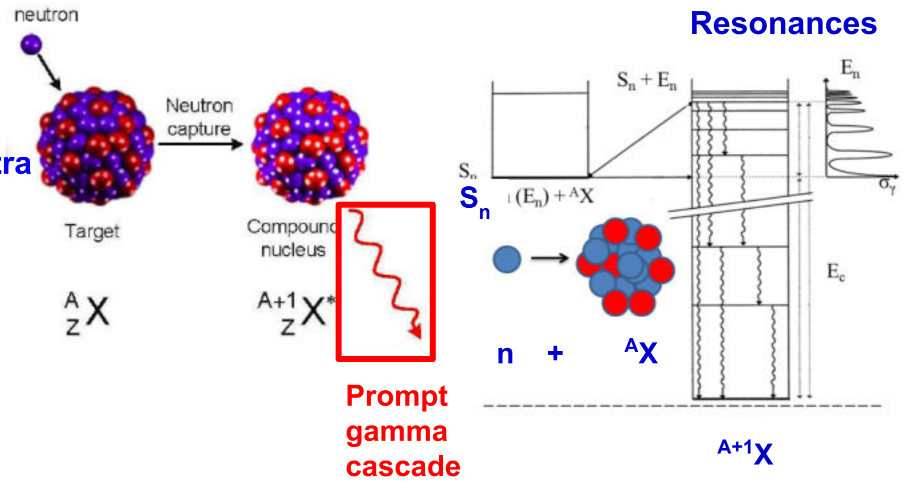
PHYSICAL REVIEW C **93**, 045803 (2016)

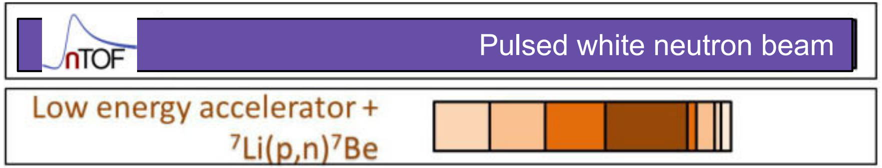
Low energy accelerator + $^{7}Li(p,n)^{7}Be$

Generate a "stellar" spectrum + measure directly the **MACS** via **activation (decay, MS, …)**

Stellar (n,γ) cross sections: beams & techniques



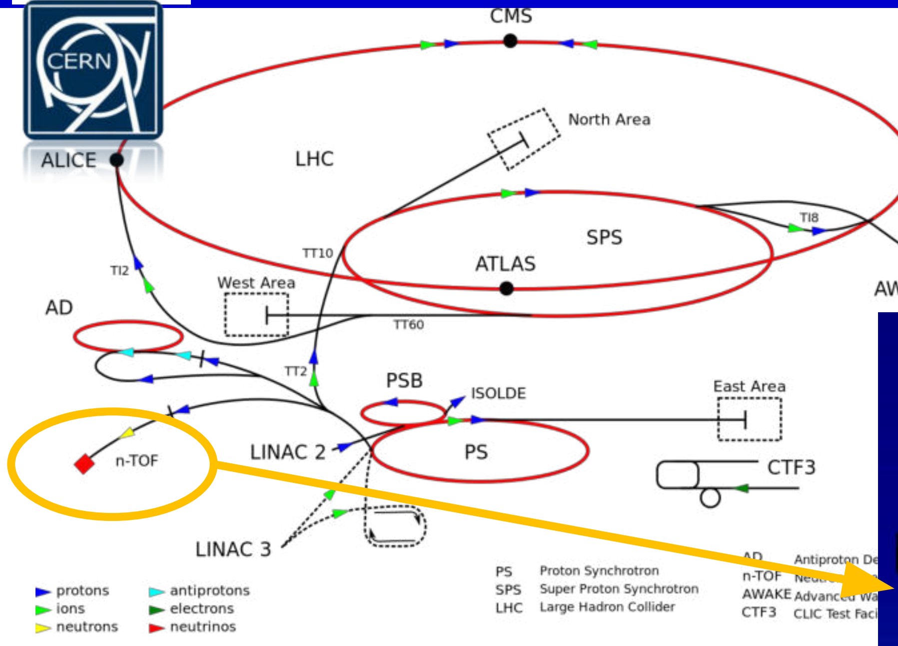




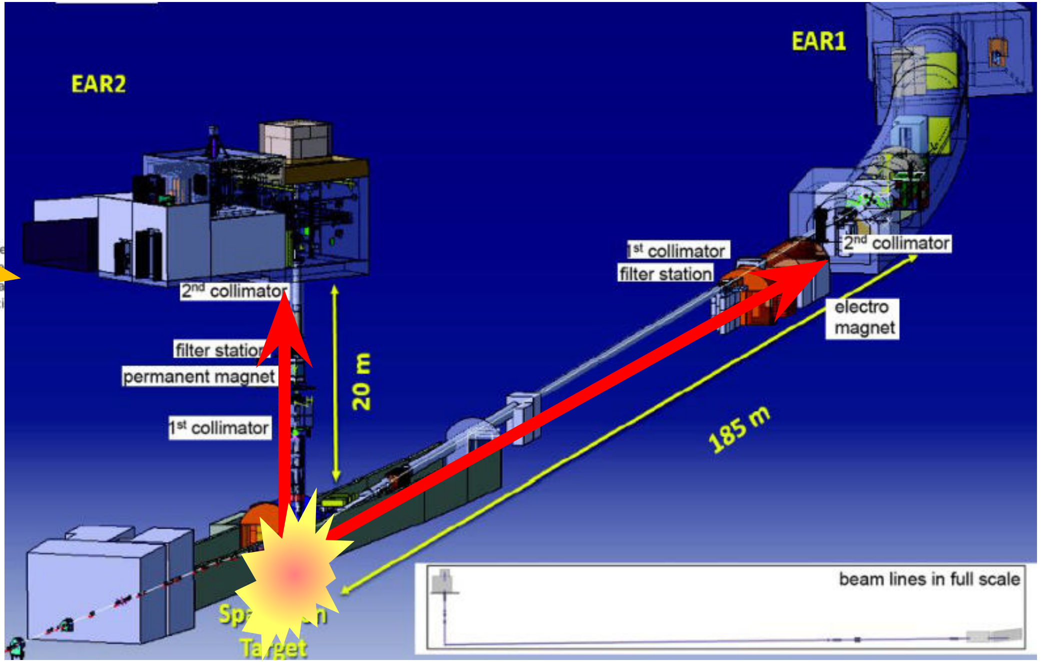
Measure the **emitted prompt-gamma radiation yield** as function the neutron energy:
Time-of-flight technique → Point wise XS

Generate a “stellar” spectrum + measure directly the **MACS** via **activation (decay, MS, …)**

The CERN n_TOF Facility

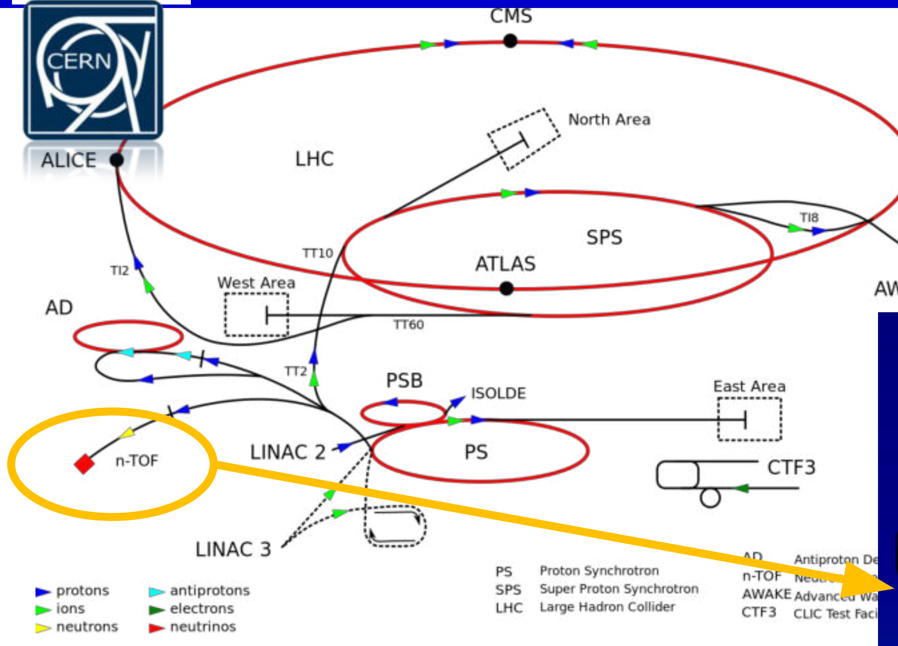


The n_TOF Collaboration
47 Research Institutions Europe & Asia.
124 researchers
+ 100 measurement
Nucl. Astrophysics, nuclear technologies, medical applications, basic nuclear research

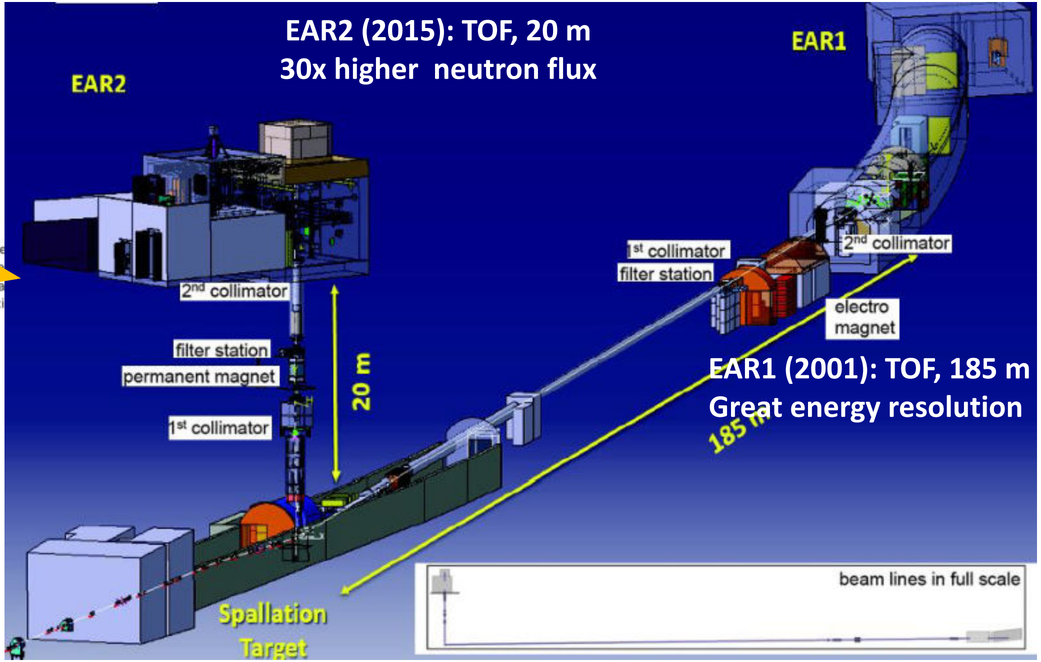


C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

The CERN n_TOF Facility



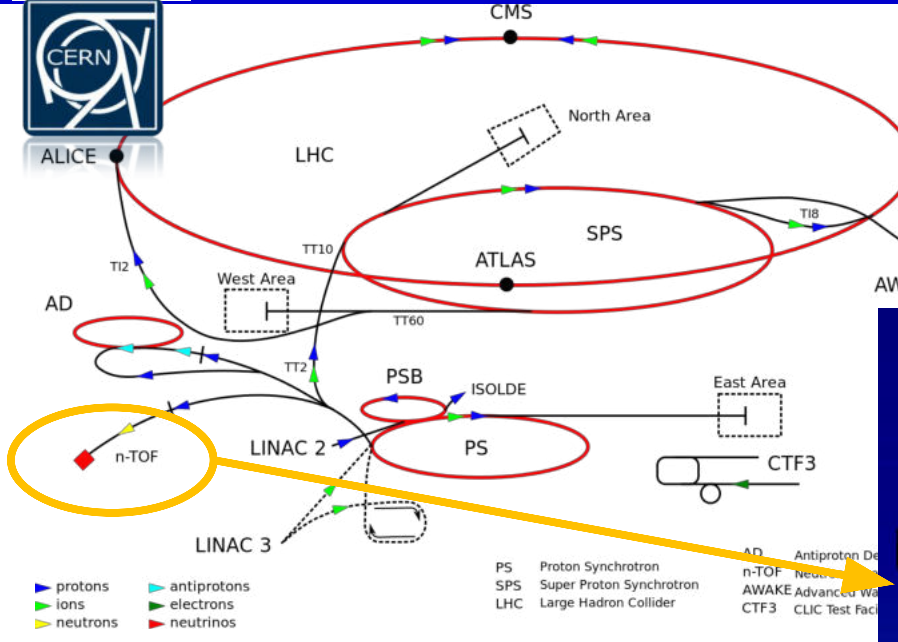
The n_TOF Collaboration
47 Research Institutions Europe & Asia.
124 researchers
+ 100 measurement
Nucl. Astrophysics, nuclear technologies, medical applications, basic nuclear research

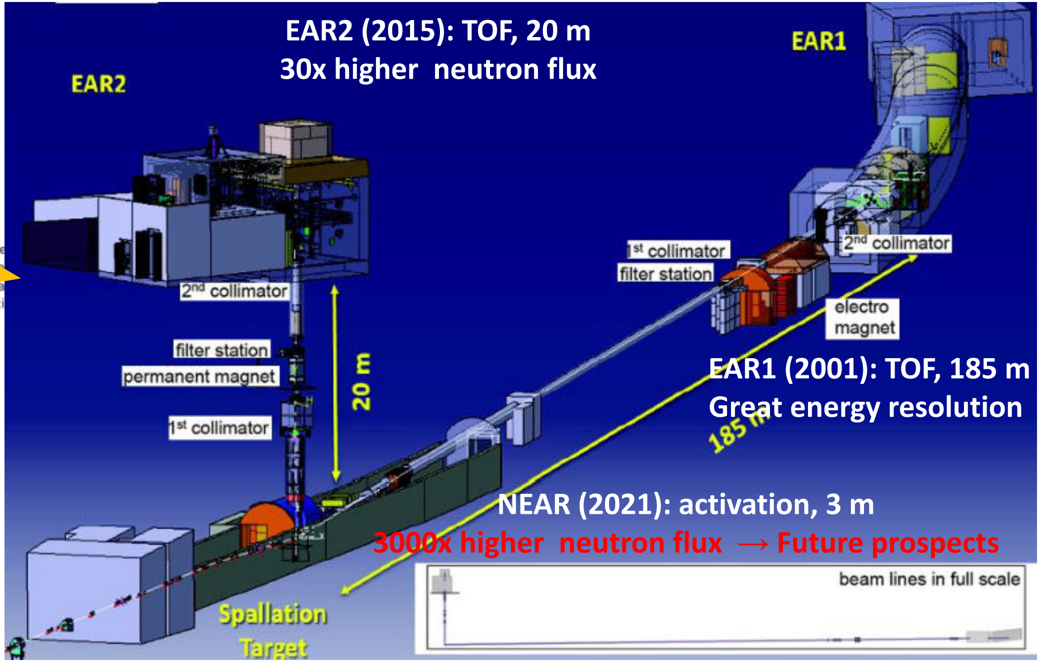


C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

The CERN n_TOF Facility

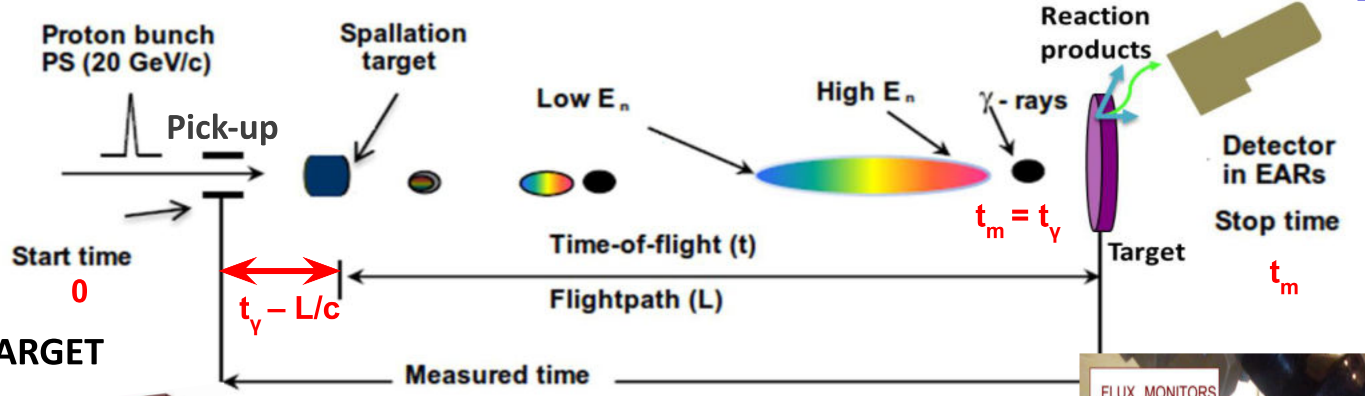
The n_TOF Collaboration
47 Research Institutions Europe & Asia.
124 researchers
+ 100 measurement
Nucl. Astrophysics, nuclear technologies, medical applications, basic nuclear research



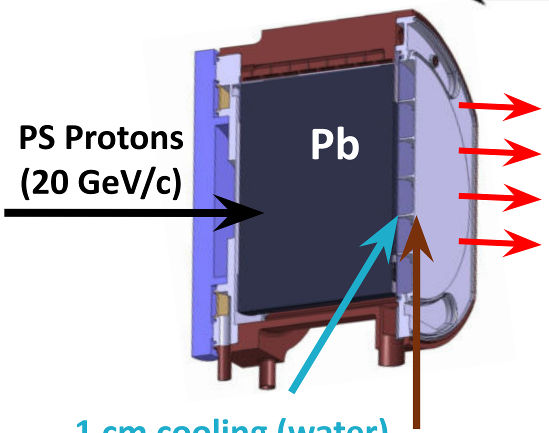


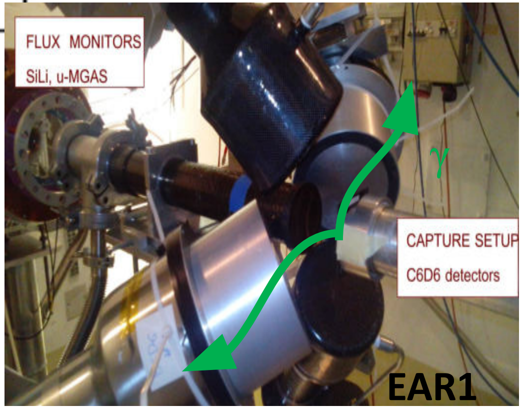
C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

The Time-of-flight technique



SPALLATION TARGET



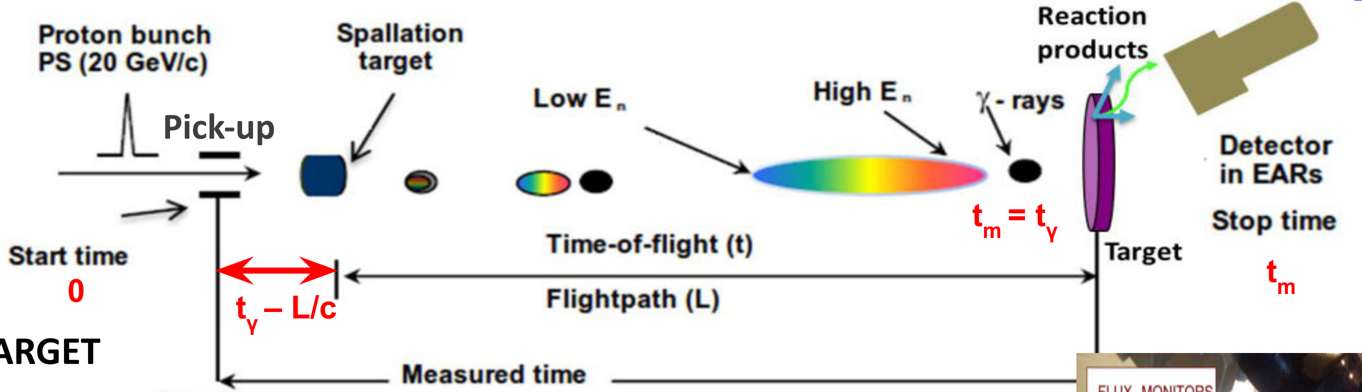


1 cm cooling (water)

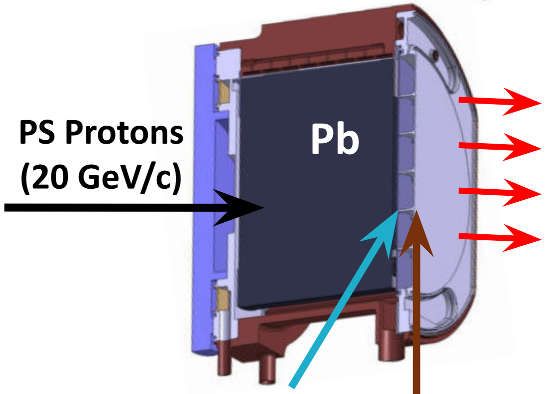
4 cm moderator (borated water)

Neutrons (meV to GeV)

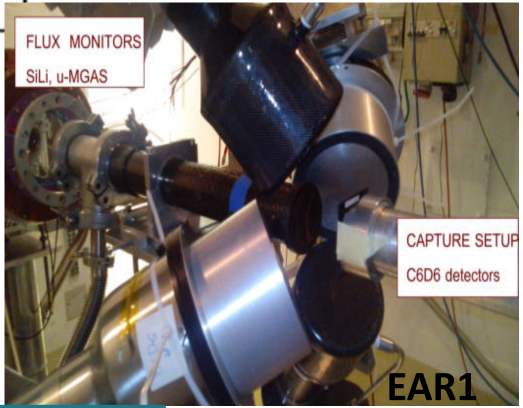
The Time-of-flight technique



SPALLATION TARGET



1 cm cooling (water)
4 cm moderator (borated water)
Neutrons (meV to GeV)



Time to energy conversion

$$E_n = \frac{1}{2}mv^2 = K^2\frac{L^2}{t^2}$$

Neutron time-of-flight

$$t = t_m - (t_\gamma - L/c)$$

Time reference: t_γ
Arrival of prompt γ-rays

(n,ɣ) measurements @ n_TOF: Capture yield

$$Y(E_n) = (1 - e^{-n_C \sigma_{tot}(E_n)}) \frac{\sigma_\gamma(E_n)}{\sigma_{tot}(E_n)} + Y_{MS}(E_n),$$

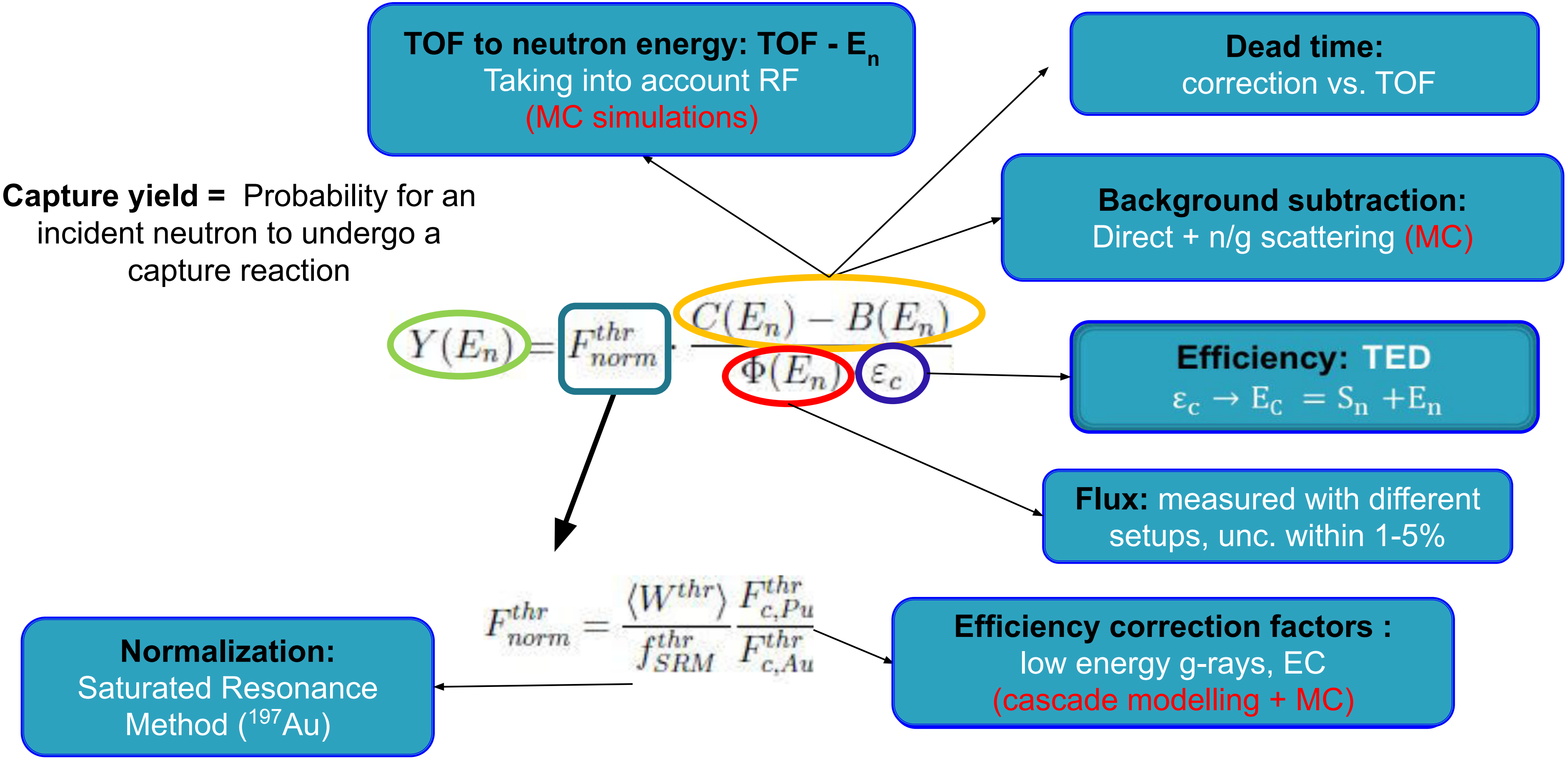
Theory

Capture yield = Probability for an incident neutron to undergo a capture reaction

$$Y(E_n) = F^{thr}_{norm} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n) \cdot \varepsilon_c}$$

Experimental

(n,ɣ) measurements @ n_TOF: Capture yield

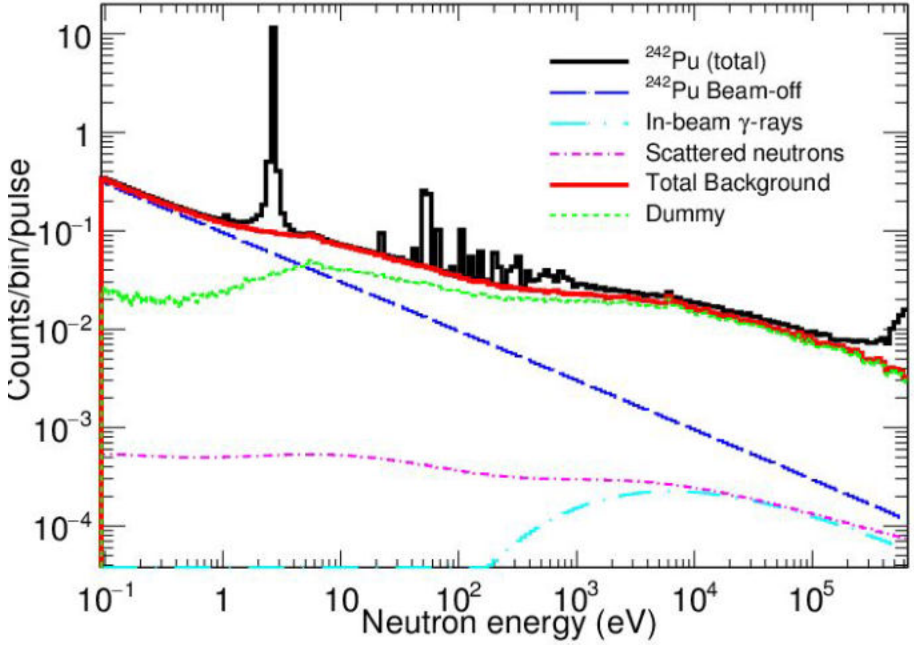


(n,γ) measurements @ n_TOF: Capture yield

$$Y(E_n) = F_{norm}^{thr} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n) \cdot \varepsilon_c}$$

Background subtraction:
Direct + n/g scattering

$$B_T = B_{dummy} + B_{off} + B_{off}^{Pu} + B_n^{Pu} + B_\gamma^{Pu}.$$



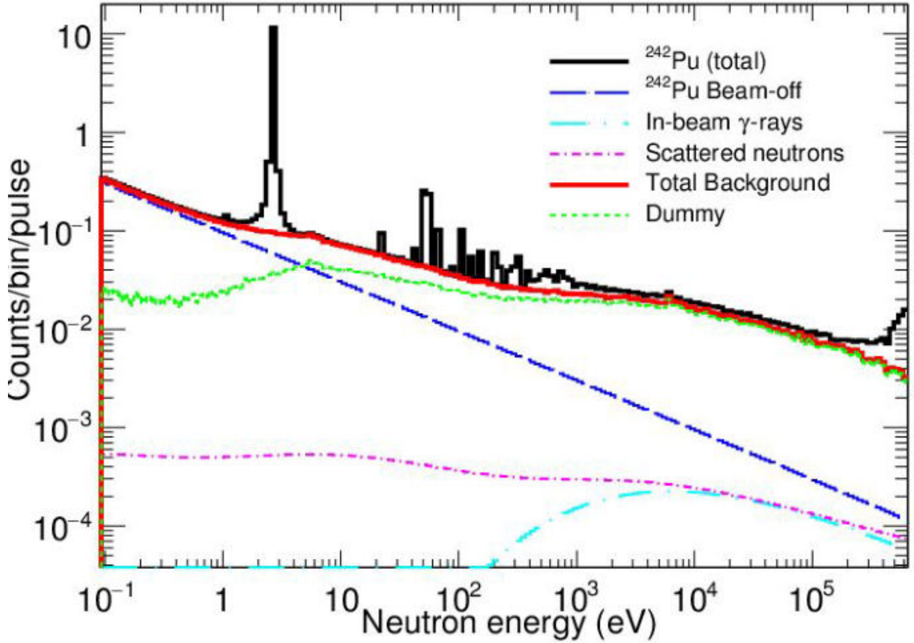
- Directly assessed with ancillary measurements:
  - *Dummy* (backings), *beam-off* (ambient)
- Indirectly estimated:
  - Neutrons and γ-rays scattered in the ^{242}Pu

(n,γ) measurements @ n_TOF: Capture yield

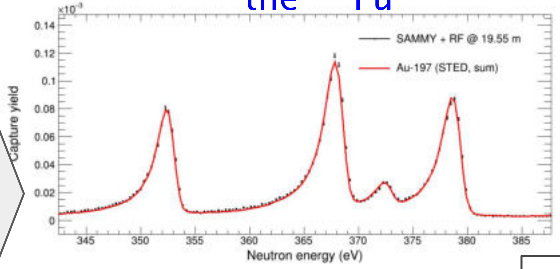
$$Y(E_n) = F_{norm}^{thr} \cdot \frac{C(E_n) - B(E_n)}{\Phi(E_n) \cdot \varepsilon_c}$$

Background subtraction:
Direct + n/g scattering

$$B_T = B_{dummy} + B_{off} + B_{off}^{Pu} + B_n^{Pu} + B_\gamma^{Pu}$$



- Directly assessed with ancillary measurements:
  - *Dummy* (backings), *beam-off* (ambient)
- Indirectly estimated:
  - Neutrons and γ-rays scattered in the ^{242}Pu



R-matrix analysis of (n,g) yield

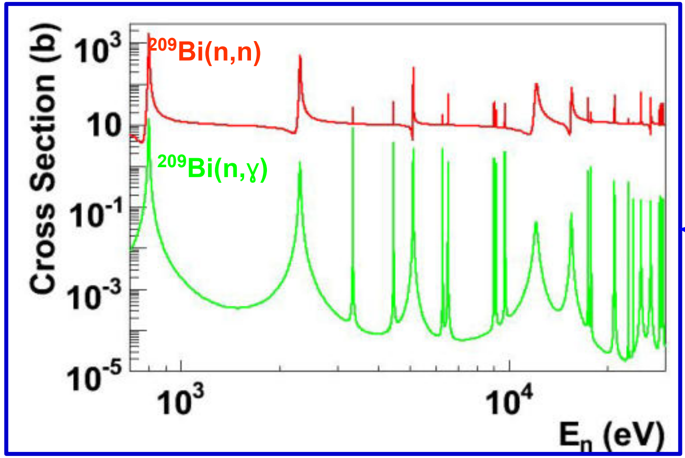
Goals R-Matrix:
Reconstruct cross section
Few parameters (E, J^P, Γ_n, Γ_γ, Γ_f)

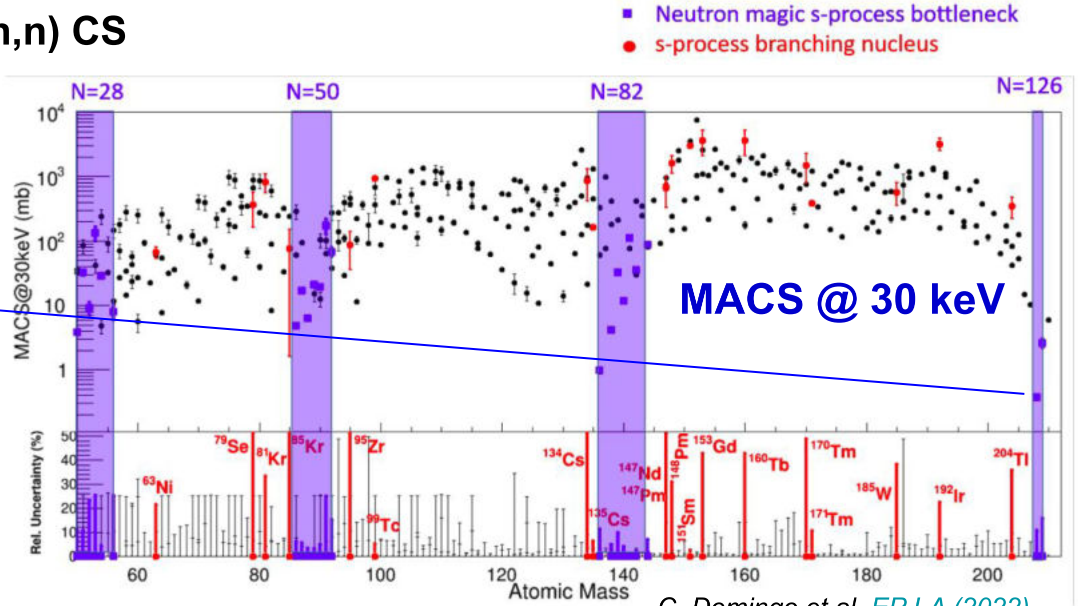
$$\sigma_x(E_c) = \pi\lambda^2 g \frac{\Gamma_n \Gamma_x}{(E_c - E_0)^2 + \frac{1}{4}\Gamma^2}$$

Recent advances and highlights on (n,g) astrophysical measurements

Stellar (n,γ) TOF measurements: challenges

Nuclei with small (n,γ) and dominating (n,n) CS



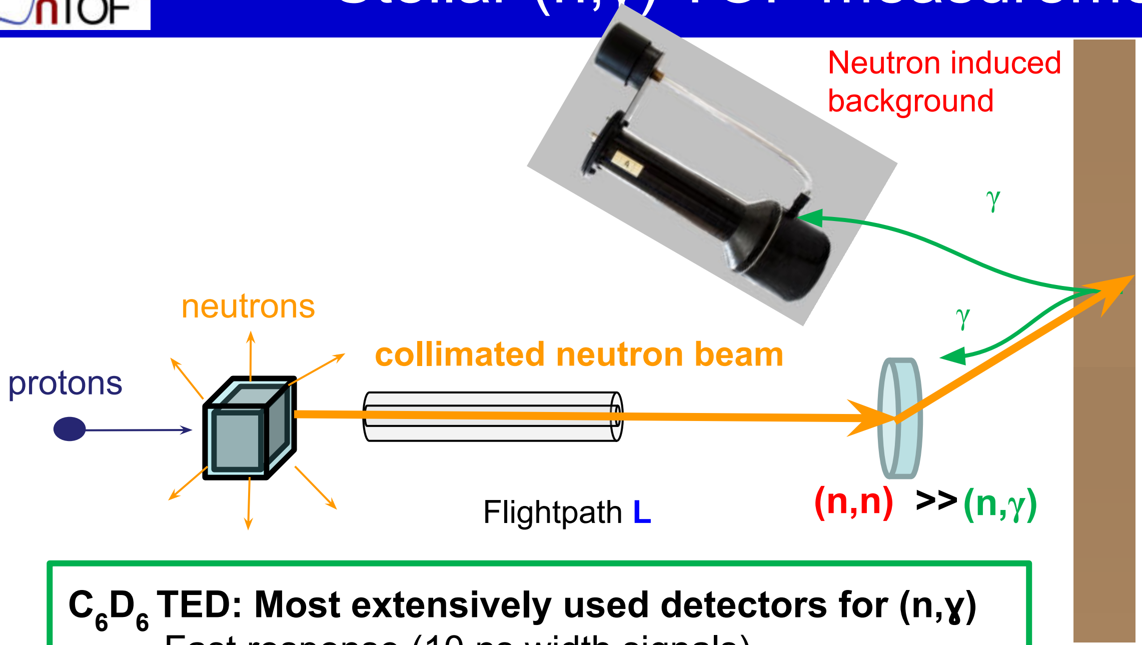


C. Domingo et al. EPJ-A (2022)

S-process bottlenecks (n-magic)

- Very small radiative CSs & (n,n) several orders of magnitude higher
- Consequence: Scattered-neutron background dominates
- **New detection systems with background rejection capabilities are required!**

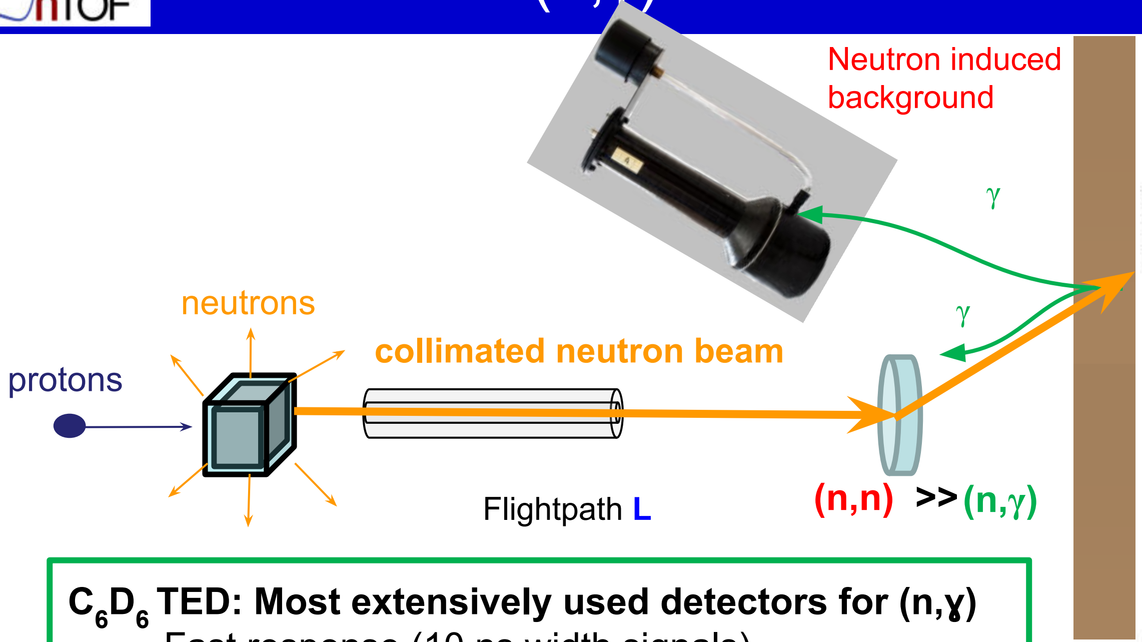
Stellar (n,γ) TOF measurements: challenges

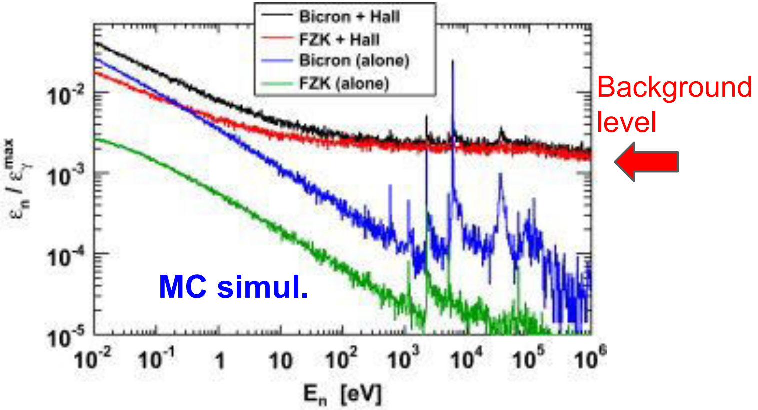


C_6D_6 TED: Most extensively used detectors for (n,γ)

- Fast response (10 ns width signals)
- Low neutron sensitivity

Stellar (n,γ) TOF measurements: challenges

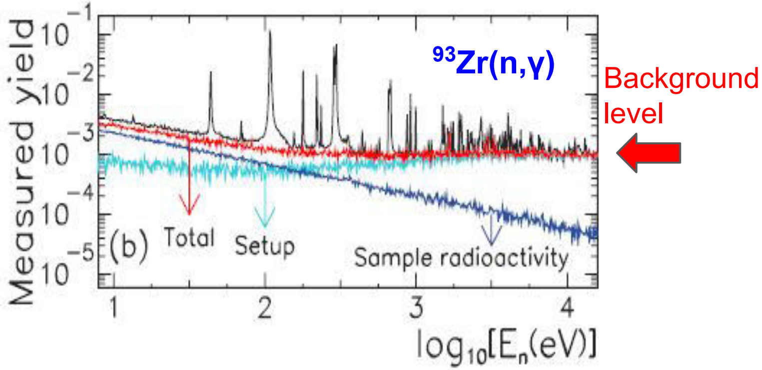




P. Zugec, et al., Nucl. Instrum. Methods A 760, 57 (2014);

PHYSICAL REVIEW C 87, 014622 (2013)

The $^{93}Zr(n,\gamma)$ reaction up to 8 keV neutron energy



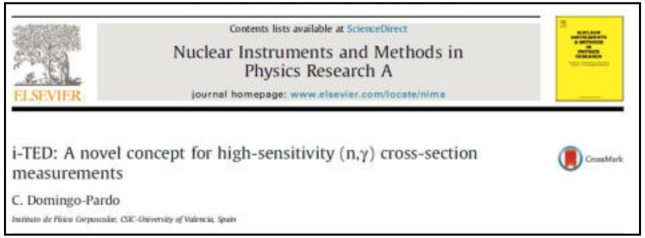
C_6D_6 TED: Most extensively used detectors for (n,γ)

- Fast response (10 ns width signals)
- Low neutron sensitivity

Limitation:

Poor background rejection capabilities.
In particular, background originated from neutron scattered in the sample

Stellar (n,γ) TOF measurements: solutions


Contents lists available at ScienceDirect

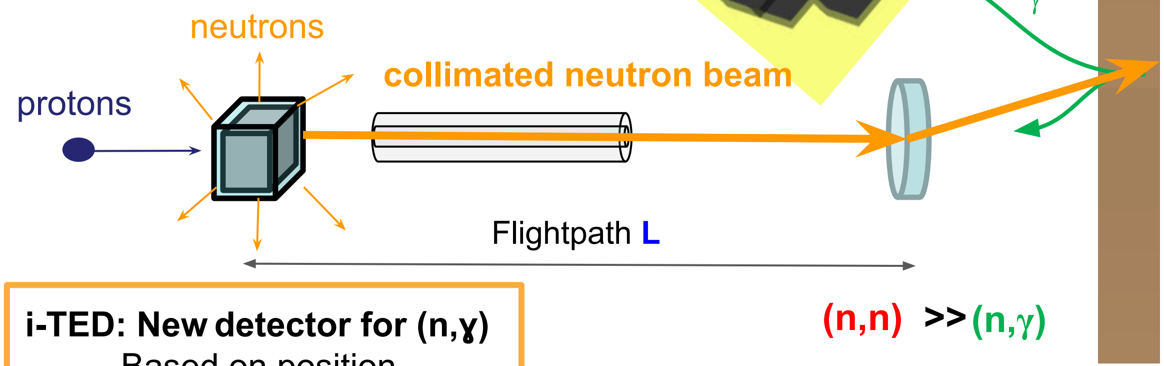
Nuclear Instruments and Methods in Physics Research A

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

i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements

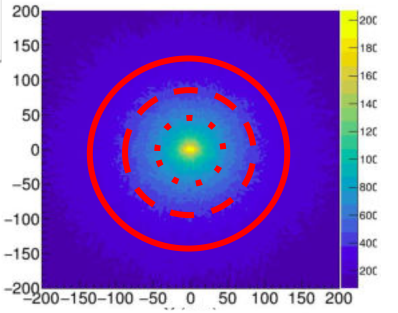
C. Domingo-Pardo

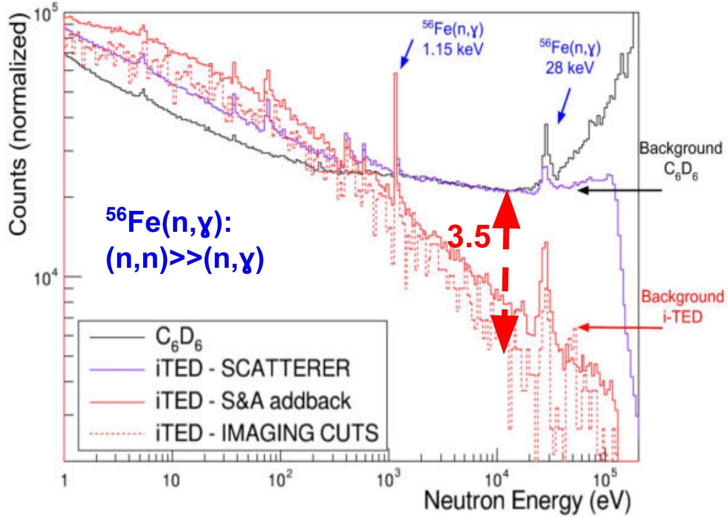
Instituto de Física Corpuscular, CSIC-University of Valencia, Spain



$$\theta = \arccos\left|1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)\right|$$

COMPTON IMAGING





Babiano-Suárez, V., *et al.* Eur. Phys. J. A **57**, 197 (2021)

i-TED: New detector for (n,γ)
- Based on position sensitive detectors
- Imaging capabilities

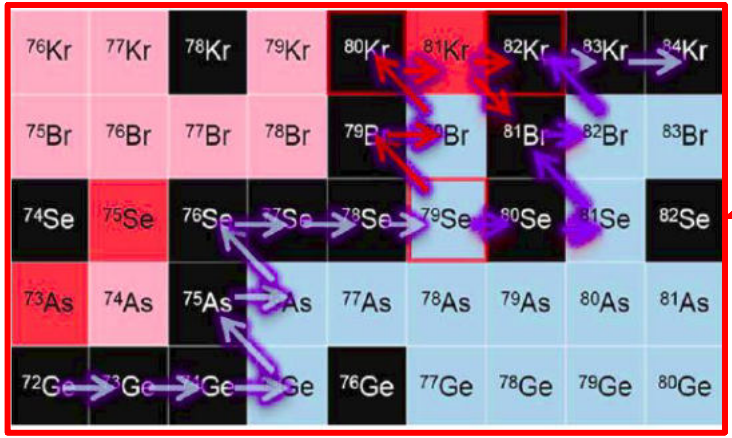
Solution: i-TED → Compton Imaging technique to reduce the neutron background and enhance the detection sensitivity

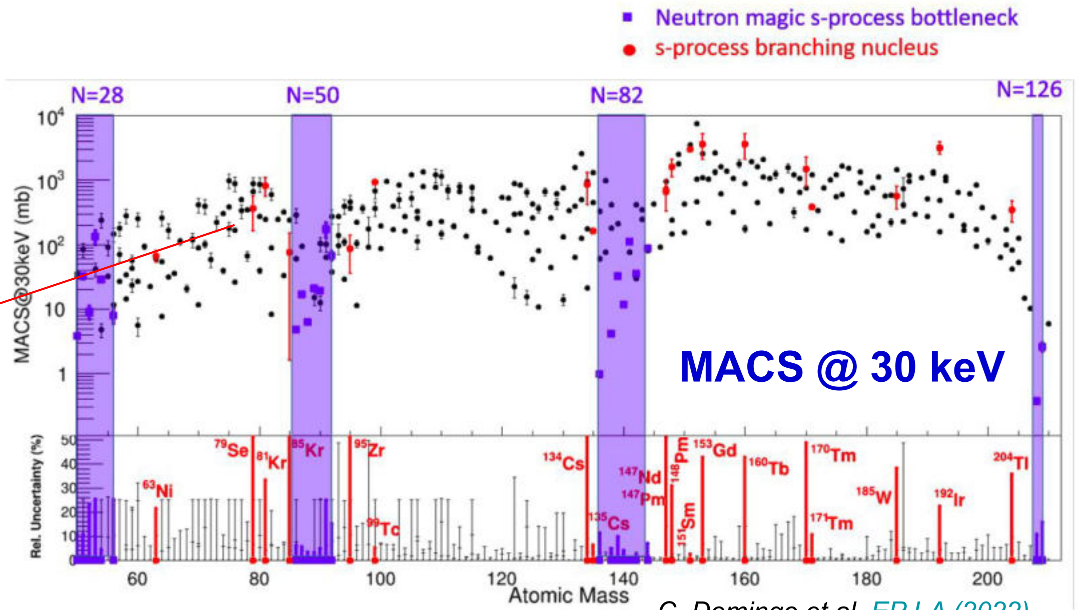
HYMNS
nucleosynthesis & MS evolution

European Research Council

Stellar (n,γ) TOF measurements: challenges

Radioactive nuclei





C. Domingo et al. EPJ-A (2022)

S-process branchings: very challenging measurements

- Unstable isotopes: Very small mass available & radioactive samples
- Consequences: High background from the activity and low (n,γ) counting rate
- **Higher instantaneous flux facilities & new detection systems are required!**

s-process branchings: highlights

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

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	C. Lederer *et al.*, *Phys. Rev. Lett.* **110,** 022501 (2013)
^{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	U. Abbondanno *et al.*, *Phys. Rev. Lett.* **93,** 161103 (2004)
^{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

F. Kaeppeler et al., *Rev. Mod. Phys* 83, 157 (2011)

21 key s-process branching points

Before 2015: only **2/21** of the key s-process isotopes measured by TOF

s-process branchings: highlights

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

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	C. Lederer *et al.*, *Phys. Rev. Lett.* **110**, 022501 (2013)
^{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	C.Guerrero *et al.*, Phys. Letters B, 797, 134809 (2019)
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	U. Abbondanno *et al.*, *Phys. Rev. Lett.* **93**, 161103 (2004)
^{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	C. Guerrero, J. Lerendegui-Marco et al., *Phys. Rev. Letters* **125**, 142701 (2020)
^{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	A. Casanovas, C. Domingo et al., *Phys. Rev. Letters (submitted)*

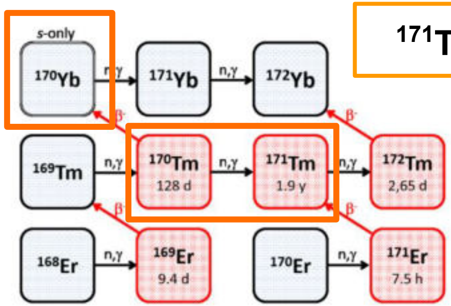
F. Kaeppeler et al., *Rev. Mod. Phys* 83, 157 (2011)

21 key s-process branching points

Before 2015: only **2/21** of the key s-process isotopes measured by TOF

2015-2018: **^{171}Tm, ^{204}Tl , ^{147}Pm** at **CERN n_TOF and/or LiLIT (activation)**

s-process branchings: highlights & limitations



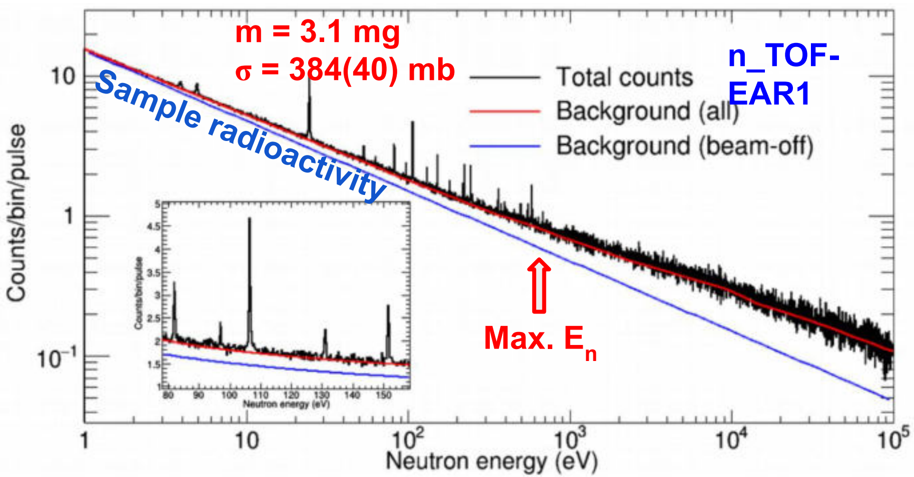
^{171}Tm(n,g)

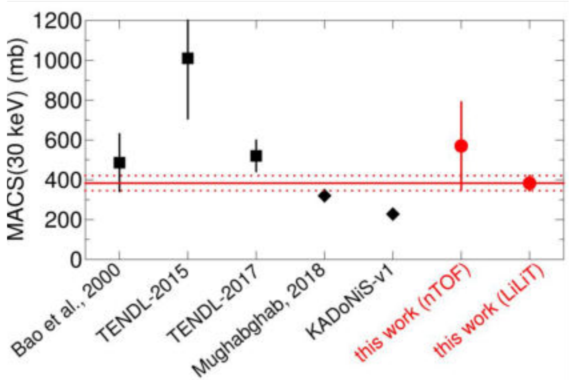
PHYSICAL REVIEW LETTERS

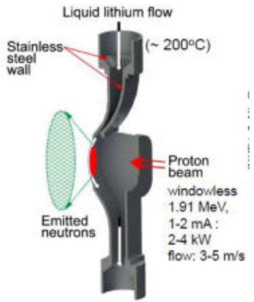
Neutron capture on the *s*-process branching point ^{171}Tm via time-of-flight and activation

C. Guerrero[1,2], J. Lerendegui-Marco[1], M. Paul[3], M. Tessler[4], S. Heinitz[5], C. Domingo-Pardo[6], S. Cristallo[7,8], R. Dressler[5], S. Halfon[4], N. Kivel[5], U. Köster[9], E. A. Maugeri[5], T. Palchan-Hazan[3], J. M. Quesada[1], D. Rochman[5], D. Schumann[5], L. Weissman[4], O. Aberle[10], S. Amaducci[26], J.

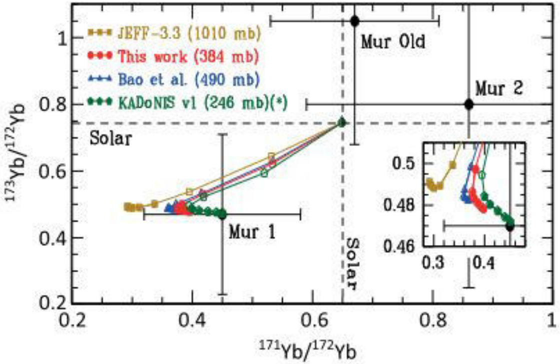
First TOF measurement ever! Combined TOF with activation MACS @ LiLIT





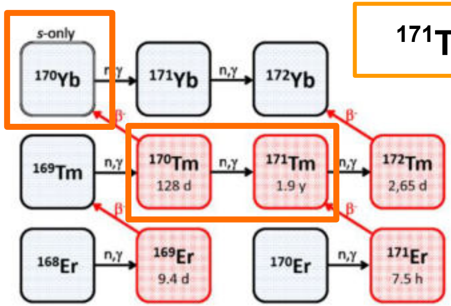


LiLIT



Yb-ratios from SiC grains: JEFF-3.3 large discrepancies

s-process branchings: highlights & limitations



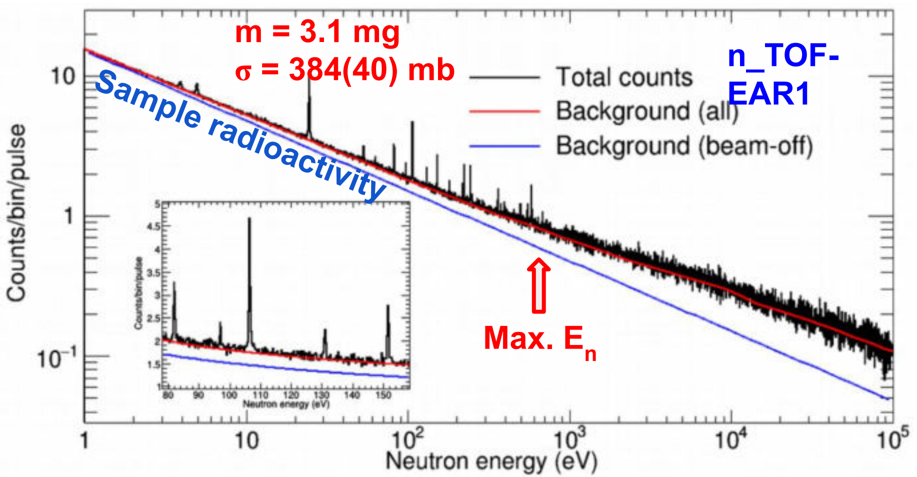
^{171}Tm(n,g)

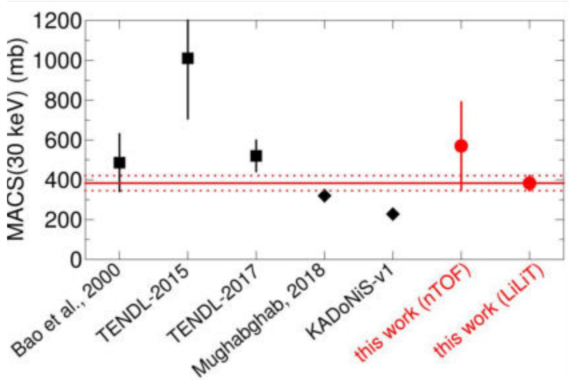
PHYSICAL REVIEW LETTERS

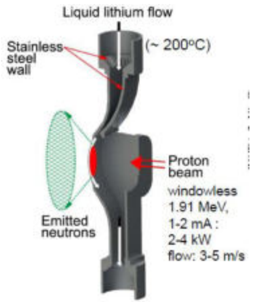
Neutron capture on the *s*-process branching point ^{171}Tm via time-of-flight and activation

C. Guerrero[1,2], J. Lerendegui-Marco[1], M. Paul[3], M. Tessler[4], S. Heinitz[5], C. Domingo-Pardo[6], S. Cristallo[7,8], R. Dressler[5], S. Halfon[4], N. Kivel[5], U. Köster[9], E. A. Maugeri[5], T. Palchan-Hazan[3], J. M. Quesada[1], D. Rochman[5], D. Schumann[5], L. Weissman[4], O. Aberle[10], S. Amaducci[26], J.

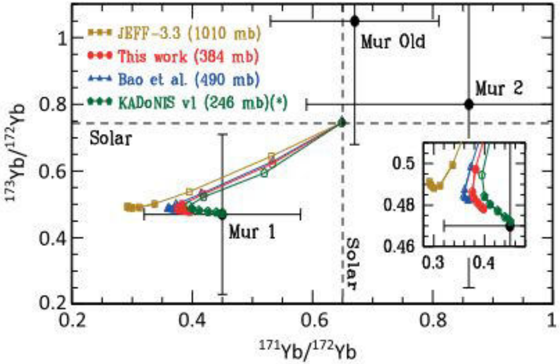
First TOF measurement ever! Combined TOF with activation MACS @ LiLIT







LiLIT



Yb-ratios from SiC grains: JEFF-3.3 large discrepancies (2Mo, Z=0.01)

Main limitation: Limited energy range via TOF due to sample activity background → **higher flux facilities required & new detectors with high CR capability**

s-process branchings: highlights & limitations

(in review)

PHYSICAL REVIEW LETTERS

Shedding light on the origin of the heaviest s-only isotope ^{204}Pb in the solar system

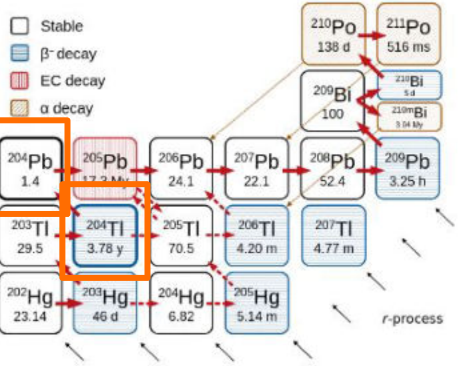
A. Casanovas-Hoste,[1,2,3] C. Domingo-Pardo,[2] J. Lerendegui-Marco,[4] C. Guerrero,[4] A. Tarifeño-Saldivia,[2]

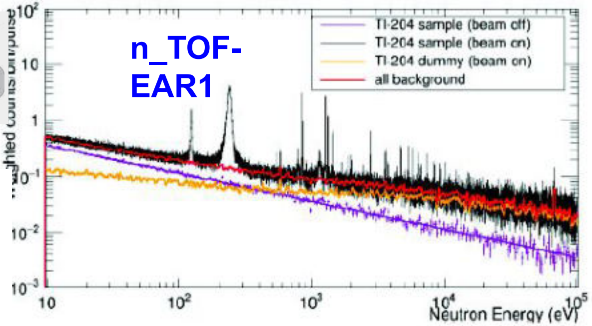
Tl-204(n,ɣ)

m = 9 mg
(+200 mg ^{203}Tl)
σ = 260(90) mb

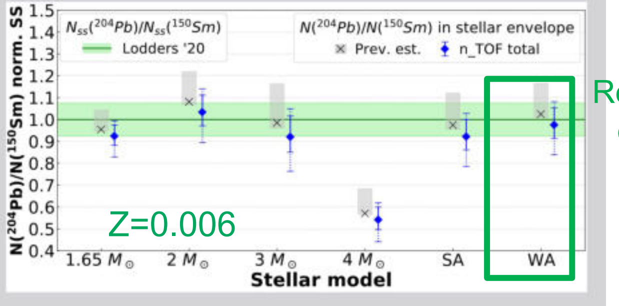
NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT PSI



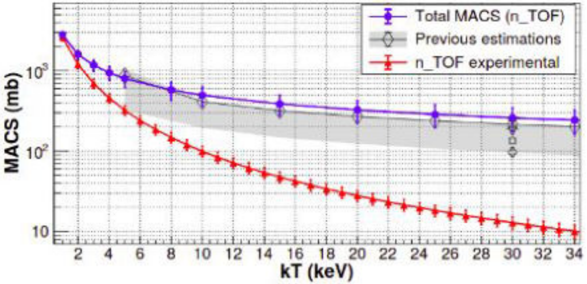


The neutron capture yield was measured by detecting the prompt de-excitation γ-rays emitted after each capture event, employing the standard setup at n_TOF of four C_6D_6 liquid scintillation detectors [42], which are optimized to minimize their neutron sensitivity [43]. Lead foils were placed on the detectors to reduce the impact of the γ-ray background arising from the ^{204}Tl decay. By



Reproduces experim. abund.

Relevant for the abundance of the heaviest s-only ^{204}Pb



First measurement of this cross section!
n_TOF Only

s-process branchings: highlights & limitations

Tl-204(n,γ)

m = 9 mg
(+200 mg ^{203}Tl)
σ = 260(90) mb

NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT

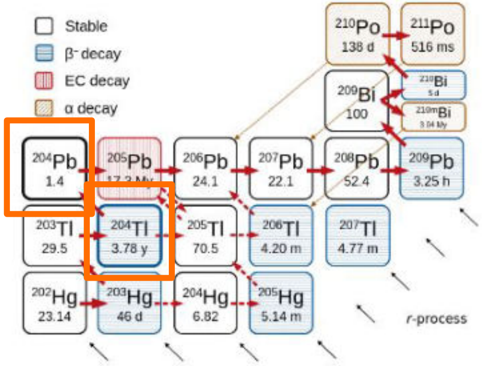
(in review)

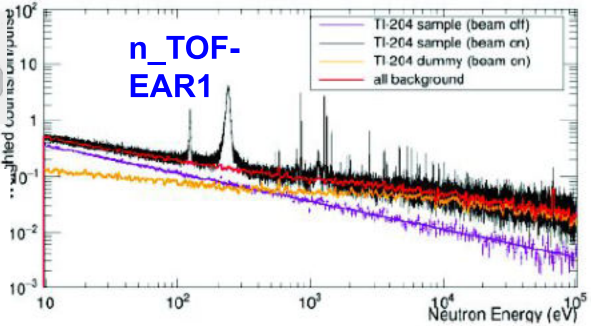
PHYSICAL REVIEW LETTERS

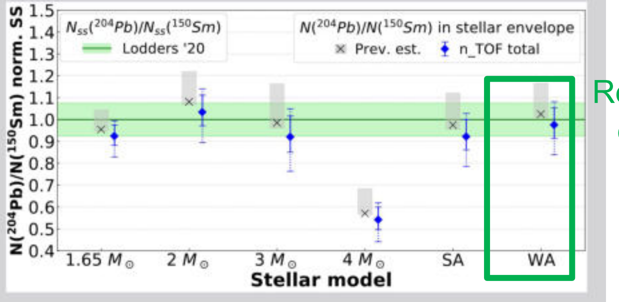
Shedding light on the origin of the heaviest s-only isotope ^{204}Pb in the solar system

A. Casanovas-Hoste,[1,2,3] C. Domingo-Pardo,[2] J. Lerendegui-Marco,[4] C. Guerrero,[4] A. Tarifeño-Saldivia,[2]

The neutron capture yield was measured by detecting the prompt de-excitation γ-rays emitted after each capture event, employing the standard setup at n_TOF of four C_6D_6 liquid scintillation detectors [42], which are optimized to minimize their neutron sensitivity [43]. Lead foils were placed on the detectors to reduce the impact of the γ-ray background arising from the ^{204}Tl decay. By

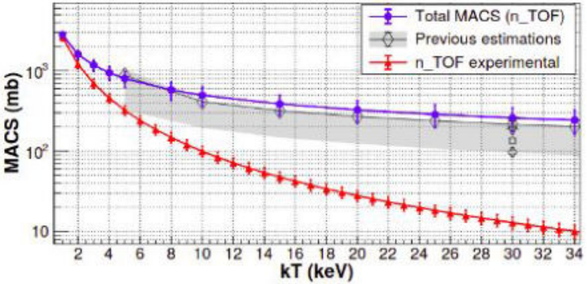






Reproduces experim. abund.

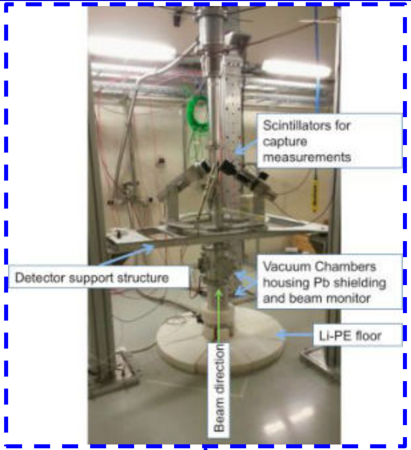
Relevant for the abundance of the heaviest s-only ^{204}Pb

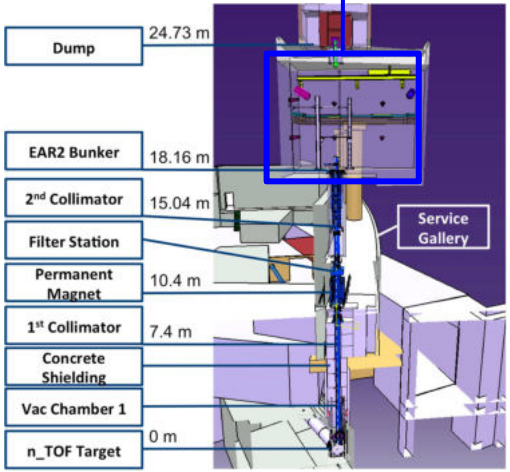


First measurement of this cross section!
n_TOF Only

Main limitations: Limited energy range due to mass, purity of the sample and background due to the sample activity →
Higher flux facilities and high purity samples are required

Stellar (n,γ) TOF measurements: solutions



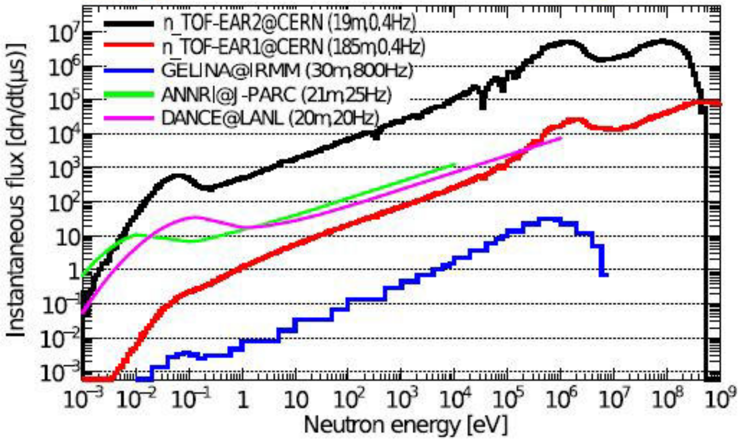


n_TOF EAR2 (20 m, vertical)

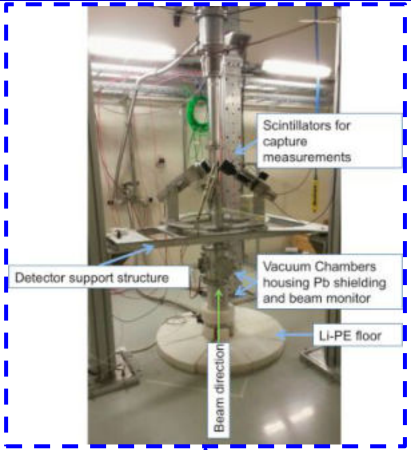
- Since **2015**: >10 (n,γ) measurements

Key features:

- **x300** higher **instantaneous flux**
- Low mass / **radioactive samples**



Stellar (n,γ) TOF measurements: solutions

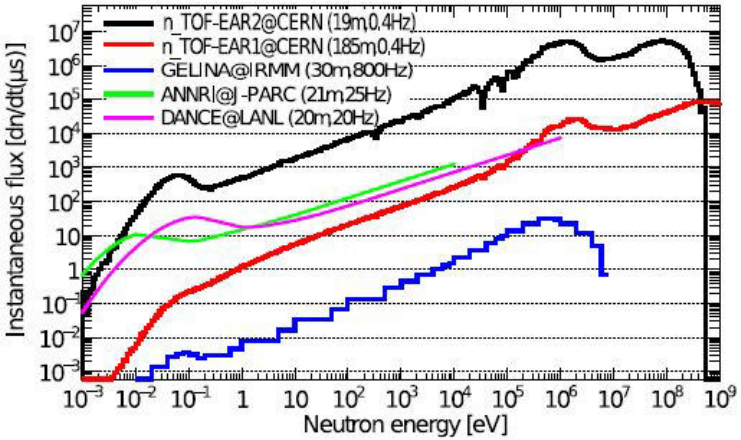


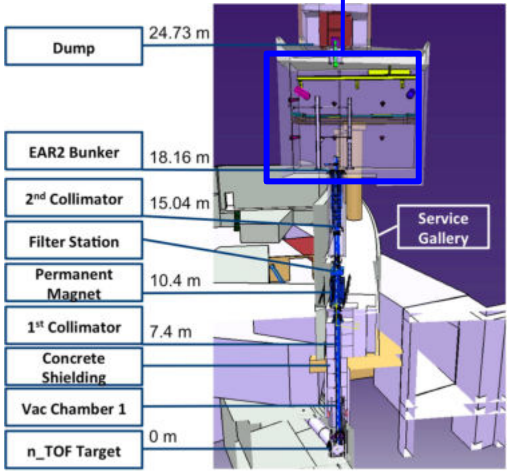
n_TOF EAR2 (20 m, vertical)

- Since **2015**: >10 (n,γ) measurements

Key features:

- **x300** higher **instantaneous flux**
- Low mass / **radioactive samples**



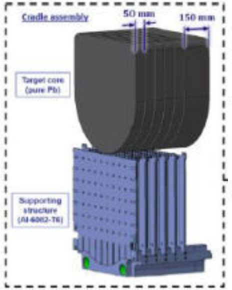


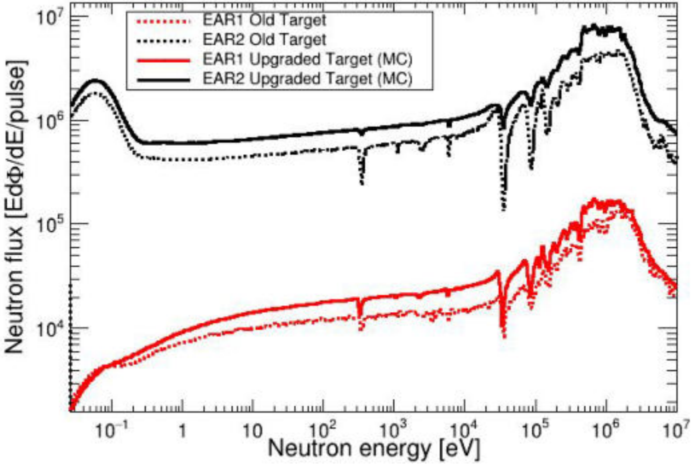
New spallation target

- Replaced in 2021

Key features:

- EAR2: 30-50% higher flux & improved energy resolution





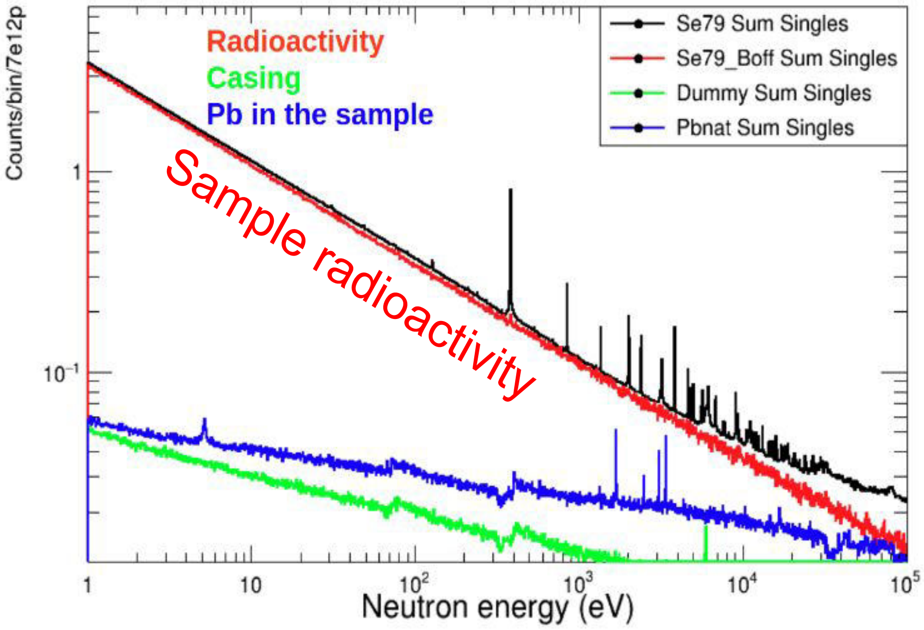
Stellar (n,γ) TOF measurements: solutions

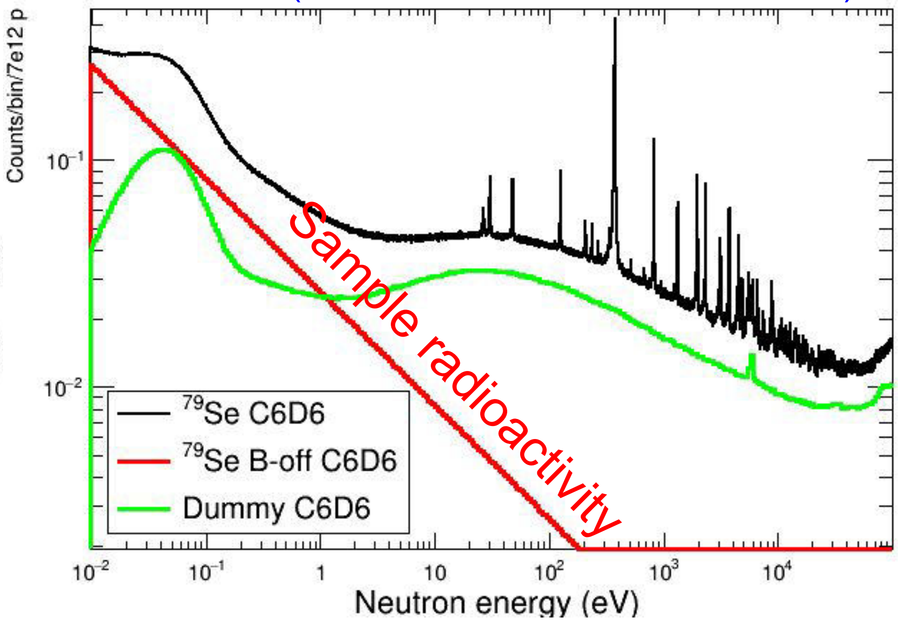
n_TOF EAR1

$^{79}Se(n,\gamma)$

n_TOF EAR2

(x300 instantaneous flux of EAR1)





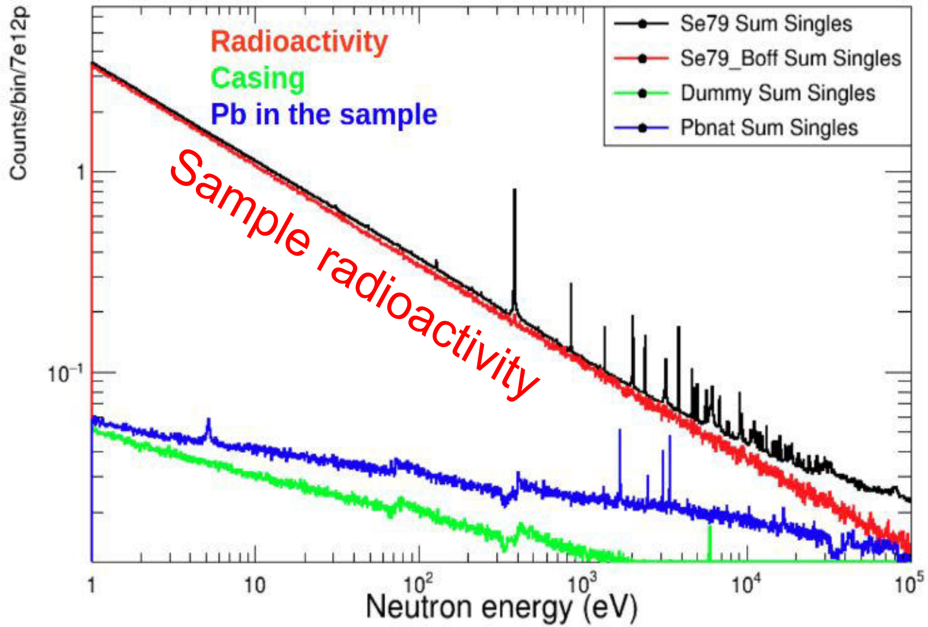
Stellar (n,γ) TOF measurements: solutions

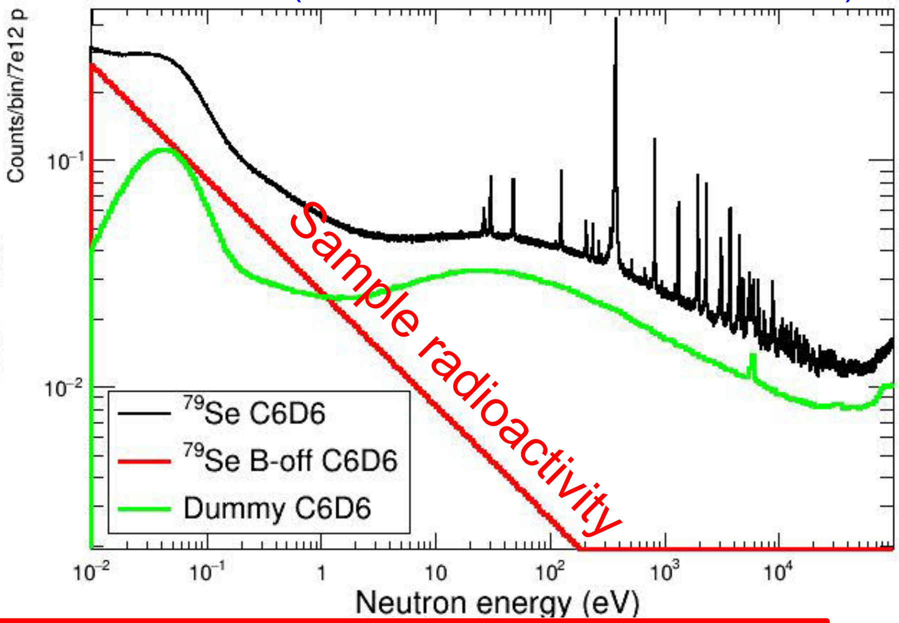
n_TOF EAR1

$^{79}Se(n,\gamma)$

n_TOF EAR2

(x300 instantaneous flux of EAR1)





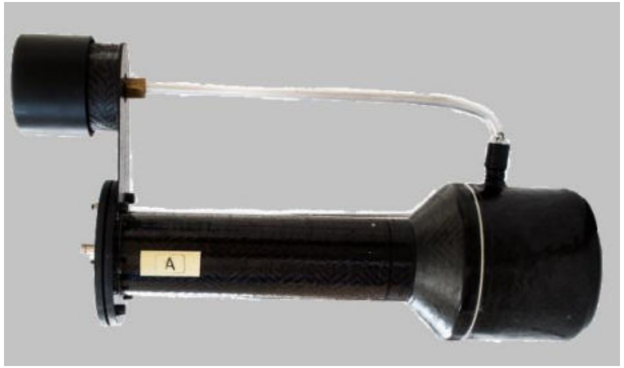
Higher instantaneous flux is a solution for unstable isotopes… BUT also a challenge

- High flux at EAR2 (even higher after target upgrade) → Counting rate limit of detectors
- High instantaneous flux facilities →**New detector systems are required!**

sTED: segmented (n,g) detectors at EAR2

State-of-the-art detectors:
Limited at the high-flux EAR2 by C. rates >=10MHz

State-of-the art C_6D_6 TED



0.6-1 L Liquid Scintillator Cells

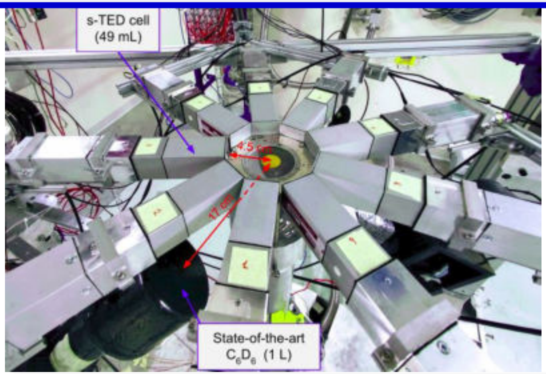
V. Alcayne , EPJ Web of Conferences **284**, 01043 (2023)

Solution:
Segmentation of the volume

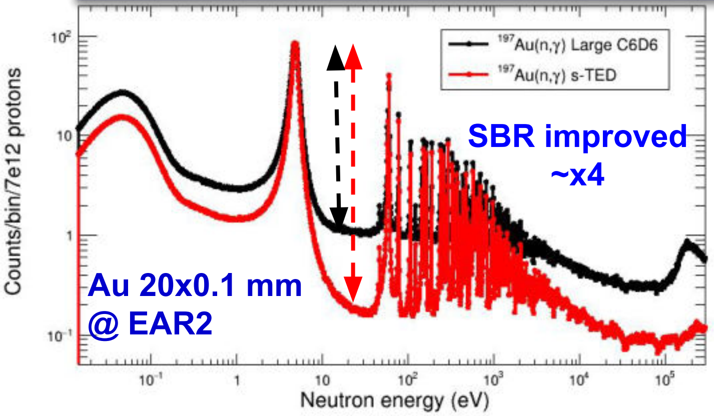
Segmented (s)TED

9 cells of 0.05 L
(factor **15-20 reduction**)

s-TED cells in ring configuration
for optimized efficiency and SBR



J. Balibrea, EPJ Web of Conferences **279**, 06004 (2023)

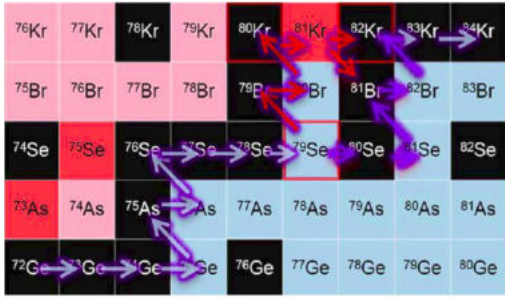


GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Stellar (n,γ) highlights after the latest upgrades

^{79}Se(n,γ)

m = 2.7 mg (+3g of PbSe)
σ = 263 mb

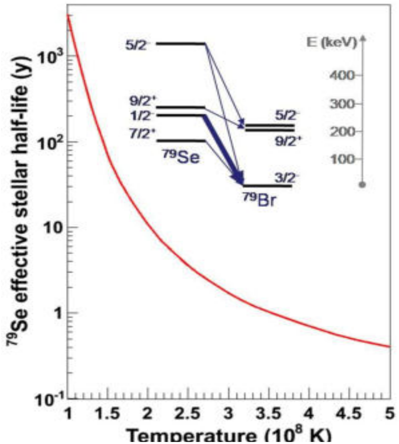


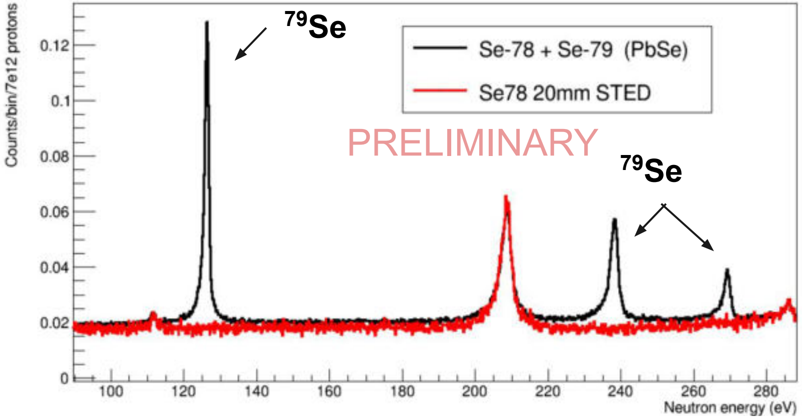
NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT

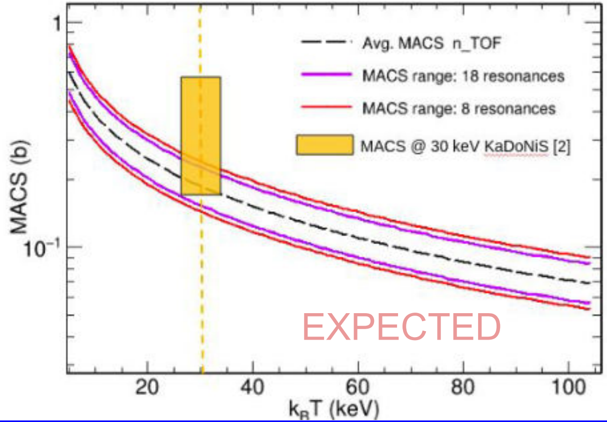
^{79}Se(n,γ): branching suited for thermal conditions stellar medium→ strong thermal dependence of the beta decay rate

First measurement ever!





^{79}Se(n,γ):
10-15 Resonances analyzed Via R-Matrix



Lerendegui-Marco, J. et al., EPJ Web Conf. 279, 13001 (2023).

MACS from Hauser-Feshbach XS in the URR

Future prospects for (n,g) astrophysics experiments at n_TOF

19th Russbach School on Nuclear Astrophysics, 3-9 March 2024

(n,g) on s-process branchings: state-of-the art

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

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	C. Lederer *et al.*, Phys. Rev. Lett. **110,** 022501 (2013)
^{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
^{147}Pm	2.6234	β^-, 0.225	C.Guerrero *et al.*, Phys. Letters B, 797, 134809 (2019)
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	U. Abbondanno *et al.*, Phys. Rev. Lett. **93,** 161103 (2004)
^{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	C. Guerrero, J. Lerendegui-Marco et al., Phys. Rev. Letters **125**, 142701 (2020)
^{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	A. Casanovas, C. Domingo et al., Phys. Rev. Letters (submitted)

F. Kaeppeler et al., Rev. Mod. Phys 83, 157 (2011)

21 key s-process branching points

Significant progress in the last decade but still many measurements not feasible, in particular (n,g) via TOF
→**What are the current limits?**

Before 2015: only **2/21** of the key s-process isotopes measured by TOF

2015-2018: ^{171}**Tm**, ^{204}**Tl**, ^{147}**Pm** at **CERN n_TOF and/or LiLIT (activation)**

Very recent progresses: ^{79}**Se**

(n,g) on s-process branchings: state-of-the art

Towards more unstable s-process branching point isotopes: radioactive → challenges

1. Difficult to produce in sizable quantities→ **Low capture/background ratio in TOF measurements**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background for **standard measuring techniques.**

Example: $^{147}Pm(n,\gamma)$

m = 85 ug
σ = 826 mb

n_TOF lowest mass record at that point!

C.Guerrero, M. Tessler, M. Paul, J. Lerendegui., Phys. Letters B, 797, 134809 (2019)

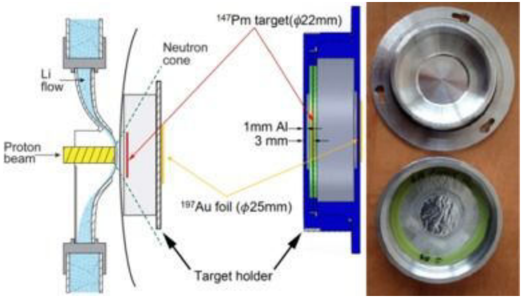
measurement features the smallest mass (85 μg) ever measured at the n_TOF facility. The mass was unexpectedly small due to the deviations in the assumed value for the thermal capture cross section of ^{146}Nd (seed irradiated at ILL). For this reason n_TOF-EAR2 was chosen over EAR1, featuring the highest instantaneous neutron flux among time-of-flight facilities worldwide [25]. The small mass just allowed to clearly measure the three largest resonances (see left panel of Figure 4) and identify ten

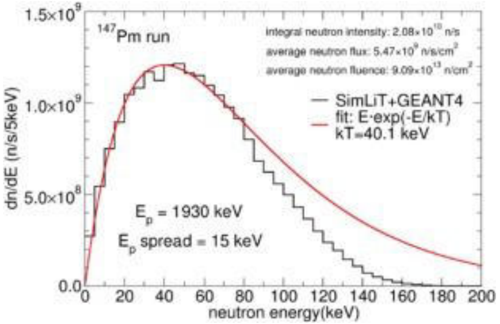
TOF measurement not fully successful due to limited mass

Only MACS via activation with a stellar spectra at LiLiT was feasible

MACS @ 30 keV

	$\langle\sigma(^{147\to148g}Pm)\rangle_{30\ keV}$	$\langle\sigma(^{147\to148m}Pm)\rangle_{30\ keV}$
This work	469(50) mb	357(27) mb
Reifarth et al.*	332(64) mb	419(58) mb





(n,g) on s-process branchings: state-of-the art

Towards more unstable s-process branching point isotopes: radioactive → challenges

1. Difficult to produce in sizable quantities→ **Low capture/background ratio in TOF measurements**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background for **standard measuring techniques.**

Example: $^{147}Pm(n,\gamma)$

measurement features the smallest mass (85 μg) ever measured at the n_TOF facility. The mass was unexpectedly small due to the deviations in the assumed value for the thermal capture cross section of ^{146}Nd (seed irradiated at ILL). For this reason n_TOF-EAR2 was chosen over EAR1, featuring the highest instantaneous neutron flux among time-of-flight facilities worldwide [25]. The small mass just allowed to clearly measure the three largest resonances (see left panel of Figure 4) and identify ten

m = 85 ug
σ = 826 mb

n_TOF lowest mass record at that point!

Current Limit TOF (n,g): 5e17-1e18 atoms

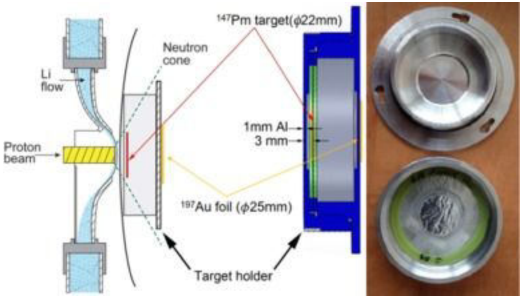
TOF measurement not fully successful due to limited mass

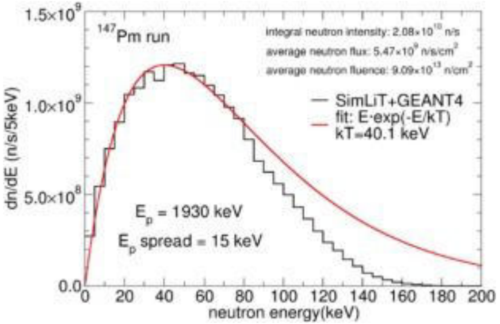
Only MACS via activation with a stellar spectra at LiLiT was feasible

C.Guerrero, M. Tessler, M. Paul, J. Lerendegui., Phys. Letters B, 797, 134809 (2019)

MACS @ 30 keV

	$\langle\sigma(^{147\to148g}Pm)\rangle_{30\ keV}$	$\langle\sigma(^{147\to148m}Pm)\rangle_{30\ keV}$
This work	469(50) mb	357(27) mb
Reifarth et al.*	332(64) mb	419(58) mb



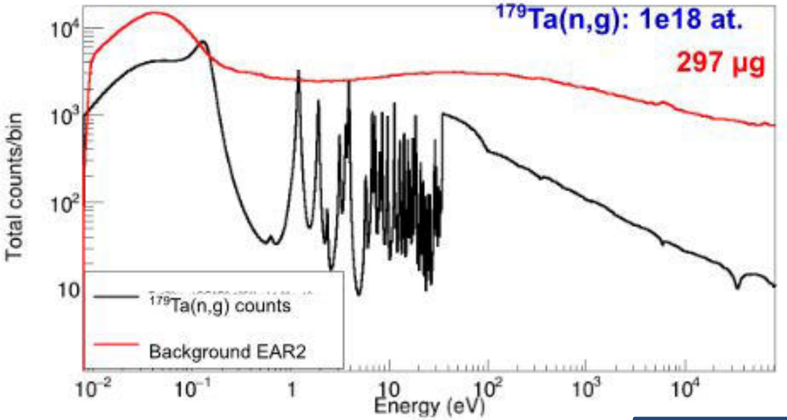


(n,g) on s-process branchings: current limits of TOF

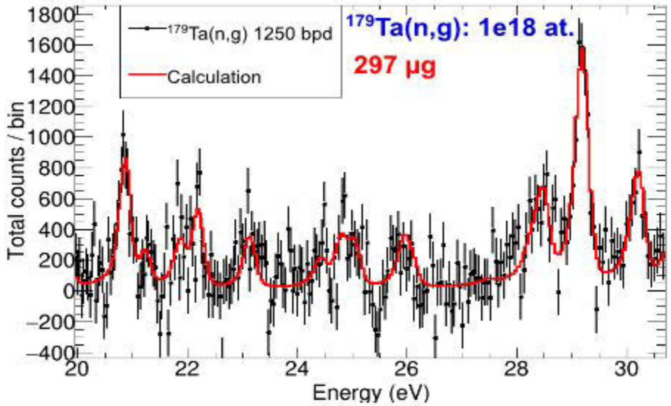
Towards more unstable s-process branching point isotopes: radioactive → challenges

1. Difficult to produce in sizable quantities→ **Low capture/background ratio in TOF measurements**
2. Activity implies a considerable **radiation hazard.**
3. Activity represents an intense source of background for **standard measuring techniques.**

(n,g) vs background



Expected (n,g) yield with ~45 days of measurement



Current Limit TOF (n,g): 5e17-1e18 atoms

J. Lerendegui-Marco et al., EPJ-WOC (2023)
arXiv:2310.15714

"First-time" key s-process branching that could be feasible:

- Eu-155, Ta-179, W-185 (low g-ray background)
- **Mass required for TOF → Activity 5 - 100 GBq!**

Isotope	Mass(ug)	Natoms	Activity (Gbq)
Eu-155	257.390	1.00E+18	4.70E+00
Ta-179	297.243	1.00E+18	1.21E+01
W-185	307.207	1.00E+18	1.07E+02

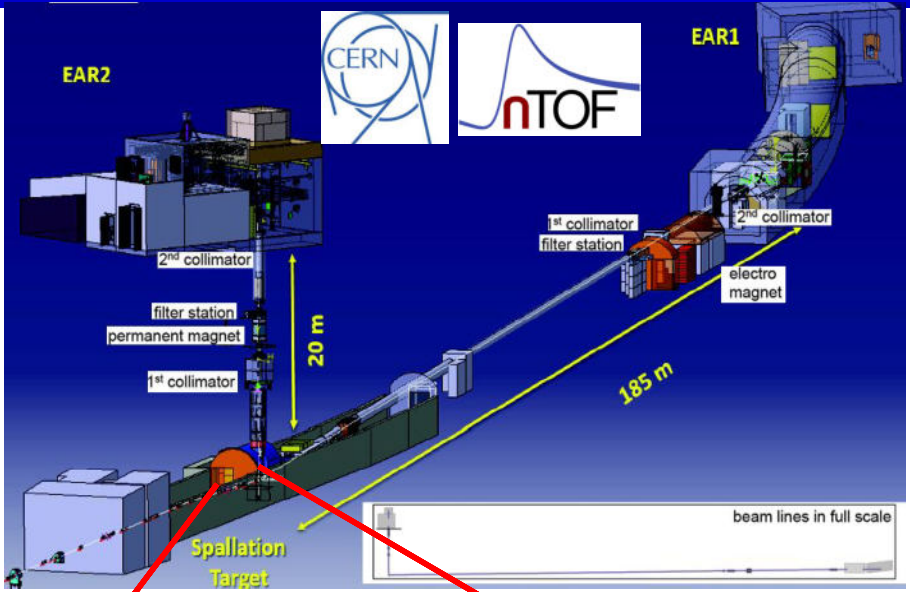
High flux facility for activation: n_TOF-NEAR

Physics at the n-TOF NEAR station (2021):
@ 3 m from spallation target

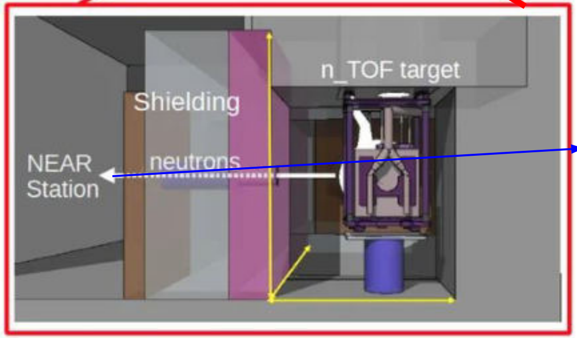
- High flux (x~100 EAR2 outside the collimator)
- Activation measurements
- Small mass
- Unstable isotopes

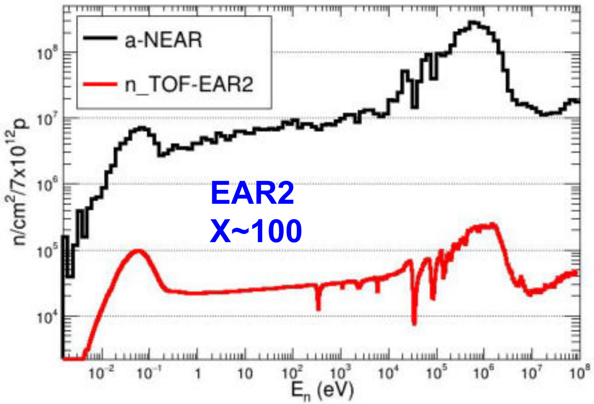
e.g. s-branchings and i-process not accessible via TOF

- Irradiation facility for electronics & materials

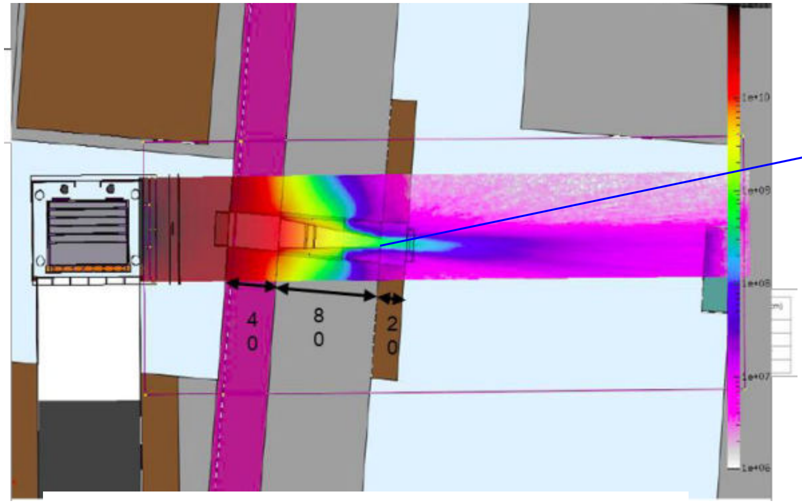


NEAR

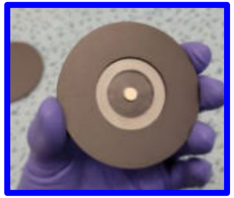




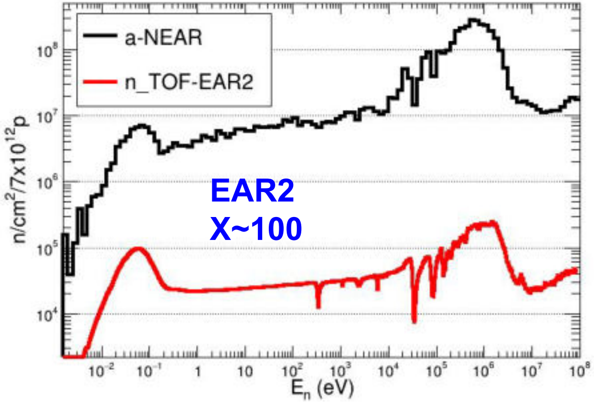
Stellar (n,g) activation measurements at NEAR



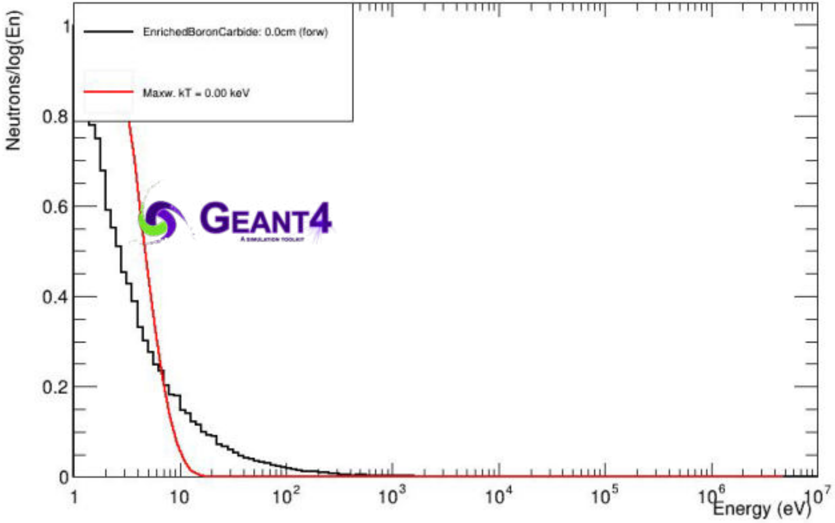
R&D contract ITC-UJI



$^{10}B_4C$ Filters :
Different Stellar temperatures
kT:0.1~500 keV



White neutron beam filtered →quasi-"Stellar"

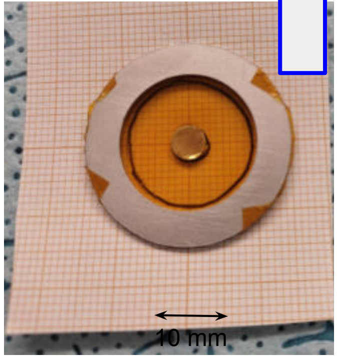


N. Patronis et al., [arXiv (submitted to EPJ-C, 2023)]

Stellar (n,g) activations at NEAR: Present

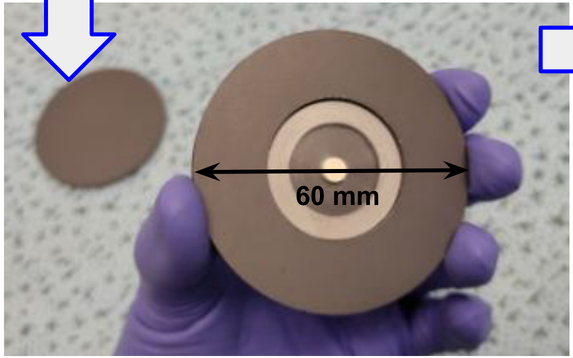
MACS measuring capability benchmark:
E. Stamati et al.,
CERN-INTC-2022-008;
INTC-P-623 (2022)

2) Irradiation at NEAR:
One long irradiation (~1 week)



1) Sample preparation:
5 mm sample
on 30mm diam Al ring

3) Access to NEAR (6h) + manual transport to decay station (~h)

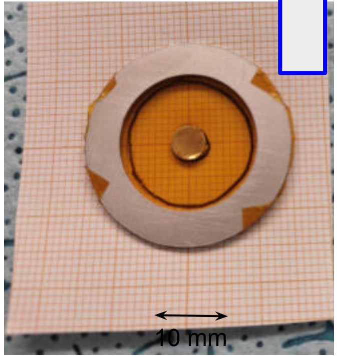


4) Decay measurement at GEAR: HPGe decay station

Eff @ 3 cm:
1.6% @818keV

Stellar (n,g) activations at NEAR: Present

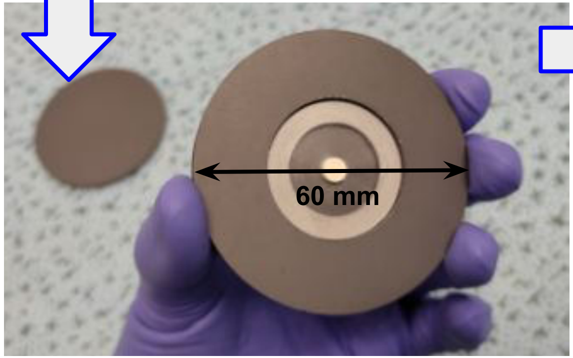
MACS measuring capability benchmark:
E. Stamati et al.,
CERN-INTC-2022-008;
INTC-P-623 (2022)



1) Sample preparation:
5 mm sample
on 30mm diam Al ring

2) Irradiation at NEAR:
One long irradiation (~1 week)

3) Access to NEAR (6h) + manual transport to decay station (~h)



4) Decay measurement at GEAR: HPGe decay station

Eff @ 3 cm:
1.6% @818keV

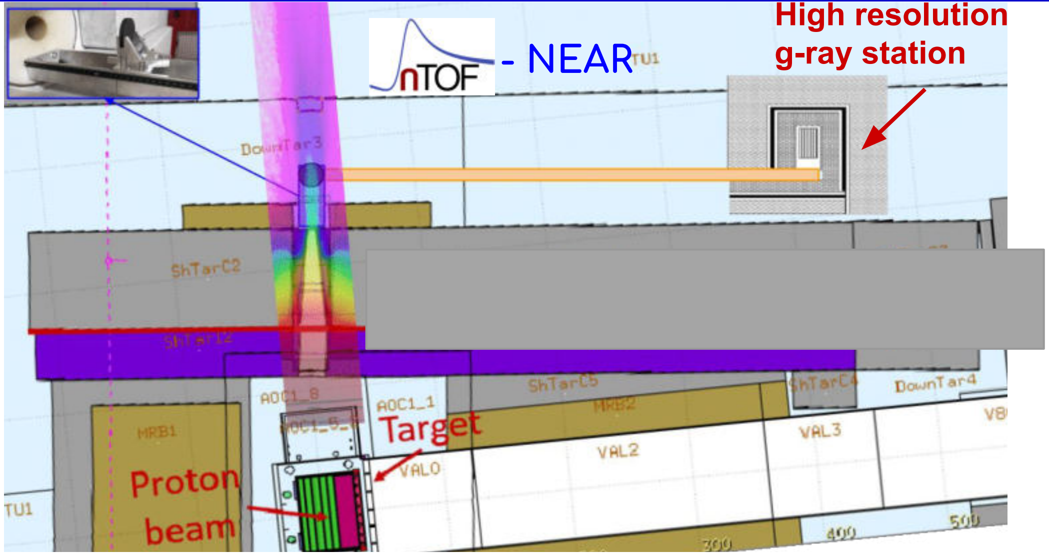
Main limitations:

- Not able to measure activation with short lived (s, min) (n,g) products
- Impossible to activate short lived (hours-days) targets

Prospects stellar (n,g) at NEAR: CYCLING

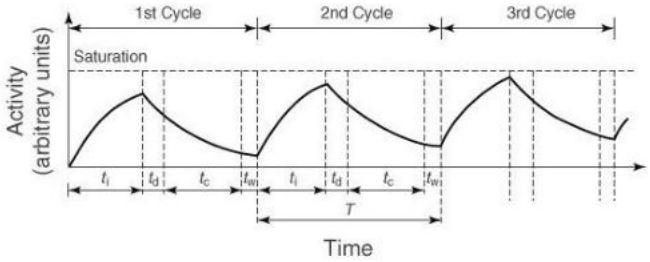
CYCLING @ NEAR: CYCLIc activation for (N,G) measurements

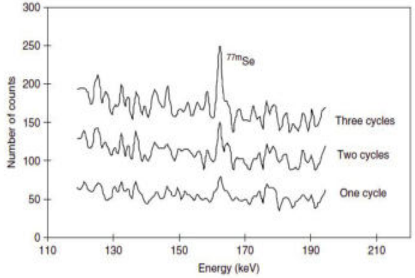
- Allows: activation with short lived (s, min) (n,g) products
- Especially interesting for unstable isotopes.
- Well suited to the rep. Rate (>0.8Hz) of n_TOF



Interesting cases for astrophysics:

- s-process/AGB: ^{107,109}Ag(n,γ), ^{26}Mg(n, γ), ^{50}Ti(n,γ), ^{19}F(n, γ), ^{60}Fe(n, γ)
- i-process: ^{137}Cs(n,γ), ^{144}Ce(n,γ), ^{132}Te(n,γ),...





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

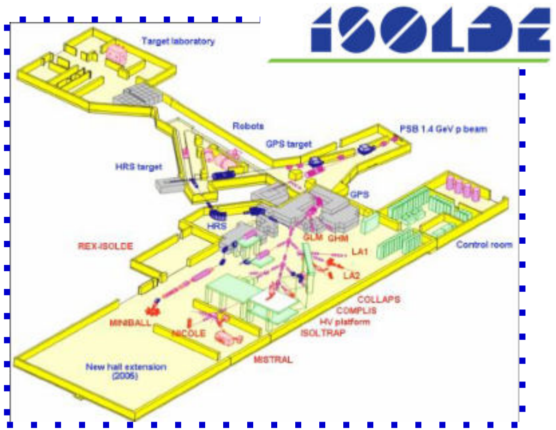
J. Lerendegui, M. Bacak *CERN-INTC-2022-018 ; INTC-I-241*.

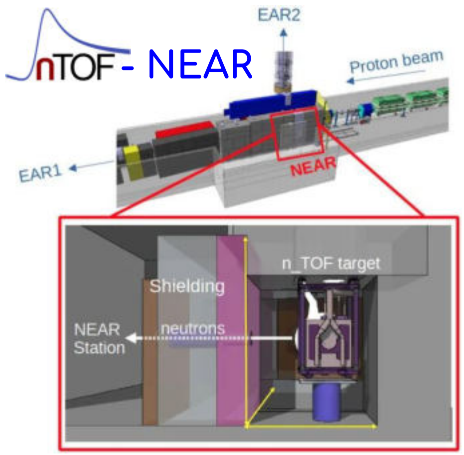
H. Beer, et al., Nucl. Inst. Meths. 337, 2–3 (1994)

Prospects stellar (n,g) at NEAR: Synergy ISOLDE

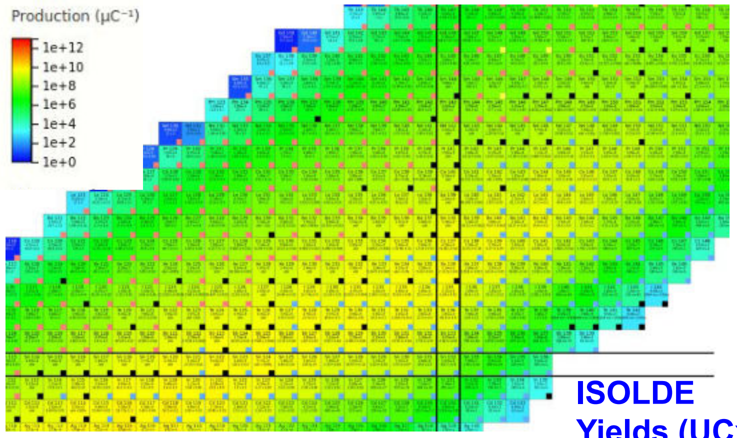
Goal:(n,g) on many unstable isotopes s and i- processes→ **(still) unfeasible via TOF**

Alternative: Produce samples of relevant unstable nuclei at **ISOLDE** & measure MACS at **NEAR**



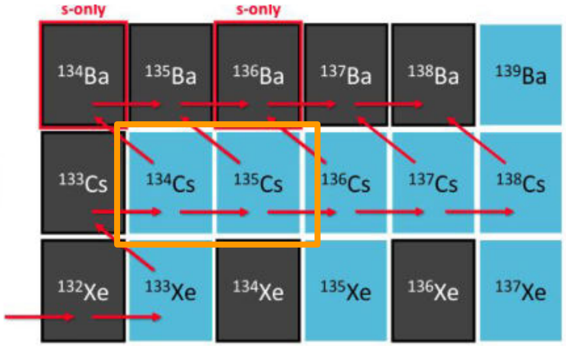


- **ISOLDE - NEAR (w/ CYCLING) :**
- smaller production yields & shorter-lived isotopes would be accessible
- **Examples:**
  - 59Fe, 134Cs, **135Cs**, 148Pm, 154Eu, 155Eu, 160Tb, 170Tm, and 181Hf (s-process),
  - Cs-137, Ce-144, 66Ni, 72Zn (i-process)



ISOLDE Yields (UCx)

Synergy NEAR-ISOLDE for stellar (n,g): ^{135}Cs



Collab with INFN-Padova

(n,g) via activation at NEAR:

- Capability to tune the energy spectrum
- *MACS* in a wider range (1 keV-300 keV) of interest for astrophysics

Cross section (mb)	n_TOF irradiation time	Activation measurement time	$\beta-\gamma$ coincidences at 818.5 keV	Neutron flux (neutrons/s/cm^2)	^{135}Cs atoms needed
160 ± 10	40 days	39 days	200	$5.4 \cdot 10^7$	$2.4 \cdot 10^{15}$

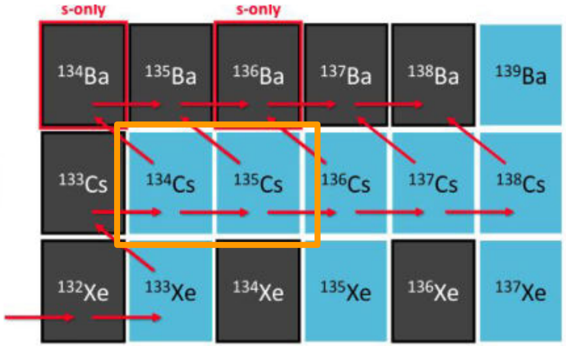
Table 1: Summary of the data used for the calculation

^{135}Cs

→ Among the **21 key s-nuclei** listed in Kaeppeler, *Rev. Mod. Phys* 83, 157 (2011)

Palmerini et al. (2021).: ***Ba isotopic ratios*** *sensitive to* ***^{135}Cs(n,γ)*** + ***Temp. dependence*** *β−decay rates*

Synergy NEAR-ISOLDE for stellar (n,g): ^{135}Cs



(n,g) via activation at NEAR:

- Capability to tune the energy spectrum
- *MACS* in a wider range (1 keV-300 keV) of interest for astrophysics

Collab with INFN-Padova

Cross section (mb)	n_TOF irradiation time	Activation measurement time	$\beta-\gamma$ coincidences at 818.5 keV	Neutron flux (neutrons/s/cm^2)	^{135}Cs atoms needed
160 ± 10	40 days	39 days	200	$5.4 \cdot 10^7$	$2.4 \cdot 10^{15}$

Table 1: Summary of the data used for the calculation

^{135}Cs → Among the **21 key s-nuclei** listed in Kaeppeler, *Rev. Mod. Phys* 83, 157 (2011)

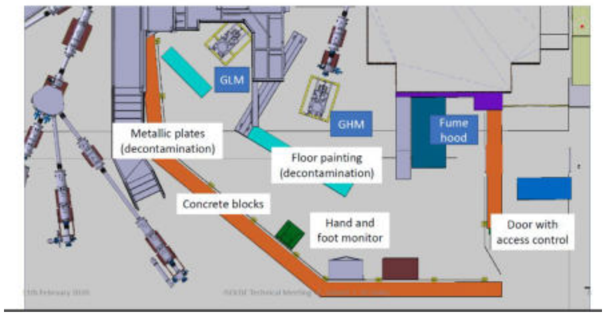
Palmerini et al. (2021).: ***Ba isotopic ratios** sensitive to* ***^{135}Cs(n,γ)*** *+* ***Temp. dependence*** *β−decay rates*

Production of a ^{135}Cs sample at ISOLDE for (n,γ) activation measurements at n_TOF-NEAR

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

Molten La metal:
8.5e9 at/μC

Target	Required Days[a]
Molten La	4.4
U carbide	15.4
La carbide	28.5



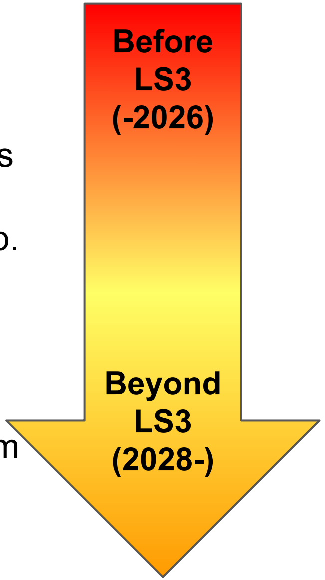
Stellar (n,γ): future projects/ideas @ n_TOF

GENERAL AIM: Enhancing the capabilities for new physics
Focusing on (n,g) measurements on unstable nuclei relevant for astrophysics:

TOF Measurements on lower mass unstable (s-process):

- Improve CR capability, efficiency & sensitivity (higher segmentation, larger arrays, solid scintillators, …)
- Improve signal-to-background: New shieldings and collimator for EAR2 or modification of EAR2 with walls and ceiling further from setup.
- High purity samples (RITU project, PSI)
- Beamline looking to moderator and/or new beamlines (backwards): less background from high energy neutrons
- Higher intensity per pulse & higher rep. rate with similar t-resolution.

Current spallation target



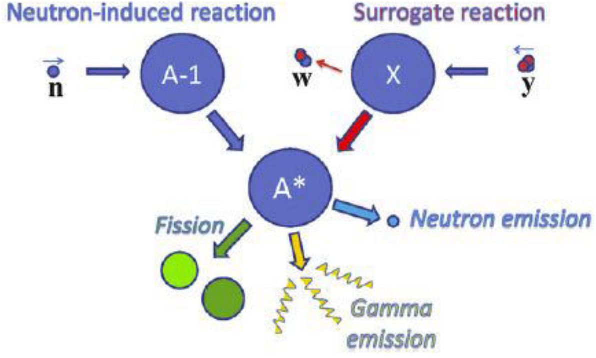
New spallation target

NEAR: activations on short-lived isotopes (s/i-process)

- Installation of NEAR moderator (target) → Improve SACS/MACS
- Cycling: Rabbit system NEAR-ISR and (if feasible) decay station at NEAR.
- Activations inside the target shielding (factor x100 flux) → Rabbit system.
- Strengthen Synergy ISOLDE-NEAR for sample production and combined direct - surrogate reactions.
- Average intensity x10 higher with worse t-resol (suitable only for NEAR).

Future of stellar (n,γ) beyond n_TOF

SURROGATE REACTIONS



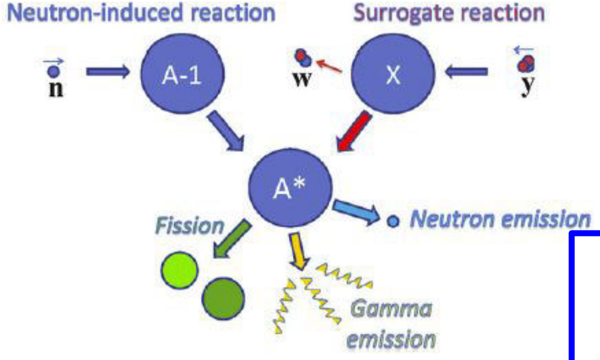
PHYSICAL REVIEW LETTERS **122,** 052502 (2019)

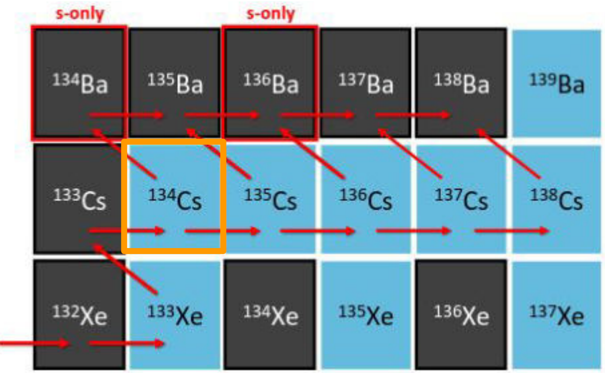
Towards Neutron Capture on Exotic Nuclei: Demonstrating $(d,p\gamma)$ as a Surrogate Reaction for (n,γ)

A. Ratkiewicz,[1,2,*] J. A. Cizewski,[2] J. E. Escher,[1] G. Potel,[3,4] J. T. Harke,[1] R. J. Casperson,[1]

Future of stellar (n,γ) beyond n_TOF

SURROGATE REACTIONS





Temperature-sensitive s-branching

No TOF (High activity) + No activation

PHYSICAL REVIEW LETTERS **122**, 052502 (2019)

Towards Neutron Capture on Exotic Nuclei: Demonstrating (*d,pγ*) as a Surrogate Reaction for (*n,γ*)

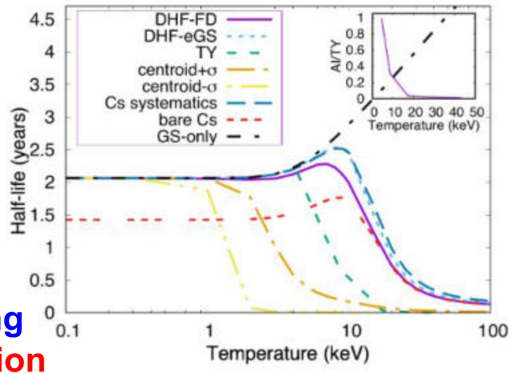
A. Ratkiewicz,[1,2,*] J. A. Cizewski,[2] J. E. Escher,[1] G. Potel,[3,4] J. T. Harke,[1] R. J. Casperson,[1]

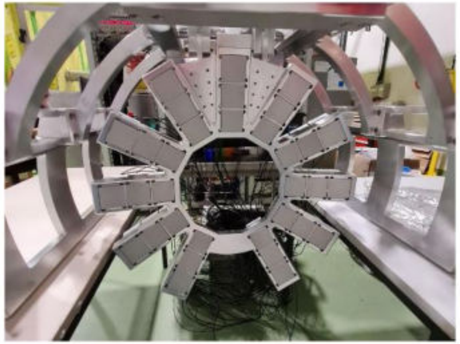
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of neutron capture cross section on ^{134}Cs through surrogate reaction (d,pγ) at ISS

January 10, 2024





Surrogate reaction Inverse kinematics

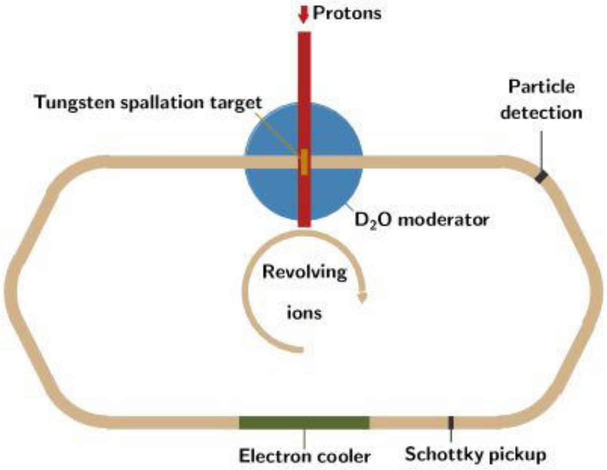
^{134}Cs beam @ ISOLDE + CD_2 target

ISOLDE Solenoid

Future idea: complement (n,g) at NEAR (low En) + (d,pg) at ISS-ISOLDE

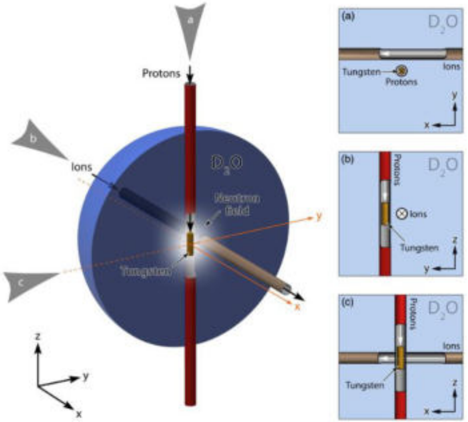
Future of stellar (n,γ) beyond n_TOF

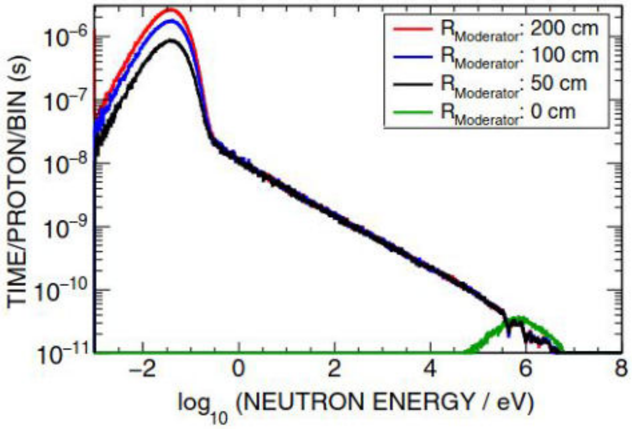
DIRECT (N,G) IN INVERSE KINEMATICS



Measurements of neutron-induced reactions in inverse kinematics and applications to nuclear astrophysics

René Reifarth[1,a], Yuri A. Litvinov[2], Anne Endres[1], Kathrin Göbel[1], Tanja Heftrich[1], Jan Glorius[1,2], Alexander Koloczek[1,2], Kerstin Sonnabend[1], Claudia Travaglio[3,4], and Mario Weigand[1]





DIRECT reaction Inverse kinematics

Exotic ion-beam ring

\+ Neutron target

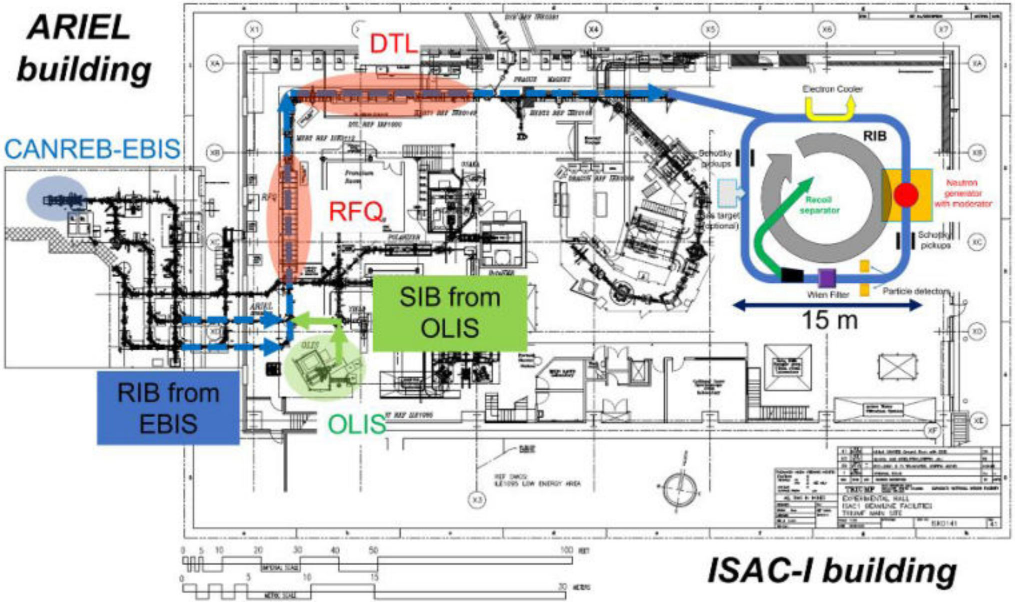
\+ **Spallation + moderation**

Neutron target facility @ LANL

DIRECT (N,G) IN INVERSE KINEMATICS

– *s*-process: ^{134}Cs ($t_{1/2}$ = 2.06 y), ^{147}Nd ($t_{1/2}$ = 11 d), ^{148}Pm ($t_{1/2}$ = 5.37 d), ^{153}Gd ($t_{1/2}$ = 240.4 d), ^{160}Tb ($t_{1/2}$ = 72.3 d), ^{170}Tm ($t_{1/2}$ = 128.6 d), and ^{204}Tl ($t_{1/2}$ = 3.78 y).

– *i*-process: ^{66}Ni ($t_{1/2}$ = 54.6 h), ^{75}Ga ($t_{1/2}$ = 126 s), ^{135}I ($t_{1/2}$ =6.58 h), ^{141}Ba ($t_{1/2}$ = 18.27 m), and ^{141}La ($t_{1/2}$ = 3.92 h).



DIRECT reaction Inverse kinematics Exotic ion-beam ring

+ Neutron target
  + Spallation + moderation
  + **Neutron generators: "gas target"**

TRISR @ ARIEL-TRIUMF

I. Dillmann et al. Eur. Phys. Jour. A (2023)

https://arxiv.org/pdf/2312.11859.pdf

Summary

- **Accurate neutron capture CS** are key **the s-process of stellar nucleosynthesis,** for validating and constraining stellar nucleosynthesis models**.**

- **Stellar (n,g) measurements at n_TOF**
  - Stellar magnitude of interest: MACS
  - At n_TOF: high resolution cross-section vs En by means of time-of-flight technique in a very wide energy range.

- **Recent highlights at n_TOF for stellar (n,g):**
  - **Higher instantaneous luminosity:** Higher flux beam-line (EAR2) + neutron source upgrade.
  - **New detection systems**: high count rate of new facilities / n-induced background .
  - Several **s-process branchings measured for the first time** in the last decade.

- **Future perspectives:**
  - **Towards more unstable isotopes (s-process & i-process)** → **Current limit for TOF: signal-to-background**

  - **Future:**
    - **NEAR**: New high flux facility for MACS activation measurements + **CYCLING**: access short-lived.
    - **Synergy NEAR & ISOLDE**: Produce low mass samples of unstable isotopes + MACS via activation
    - Complement direct (n,g) with surrogate reactions + new facilities (neutron targets + RIB)

HYMNS

European Research Council

High sensitivitY Measurements of key stellar Nucleo-Synthesis reactions

+ Info: https://hymnserc.ific.uv.es/public_documents

Grant FJC2020-044688-I funded by:

MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea NextGenerationEU

Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

Thank you for your attention!

Grant CIAPOS/2022/020 funded by:

GENERALITAT VALENCIANA

UNIÓ EUROPEA
Fons Social Europeu
L'FSE inverteix en el teu futur

CERN

nTOF

ILL NEUTRONS FOR SCIENCE

PAUL SCHERRER INSTITUT PSI

VNIVERSITAT DE VALÈNCIA

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

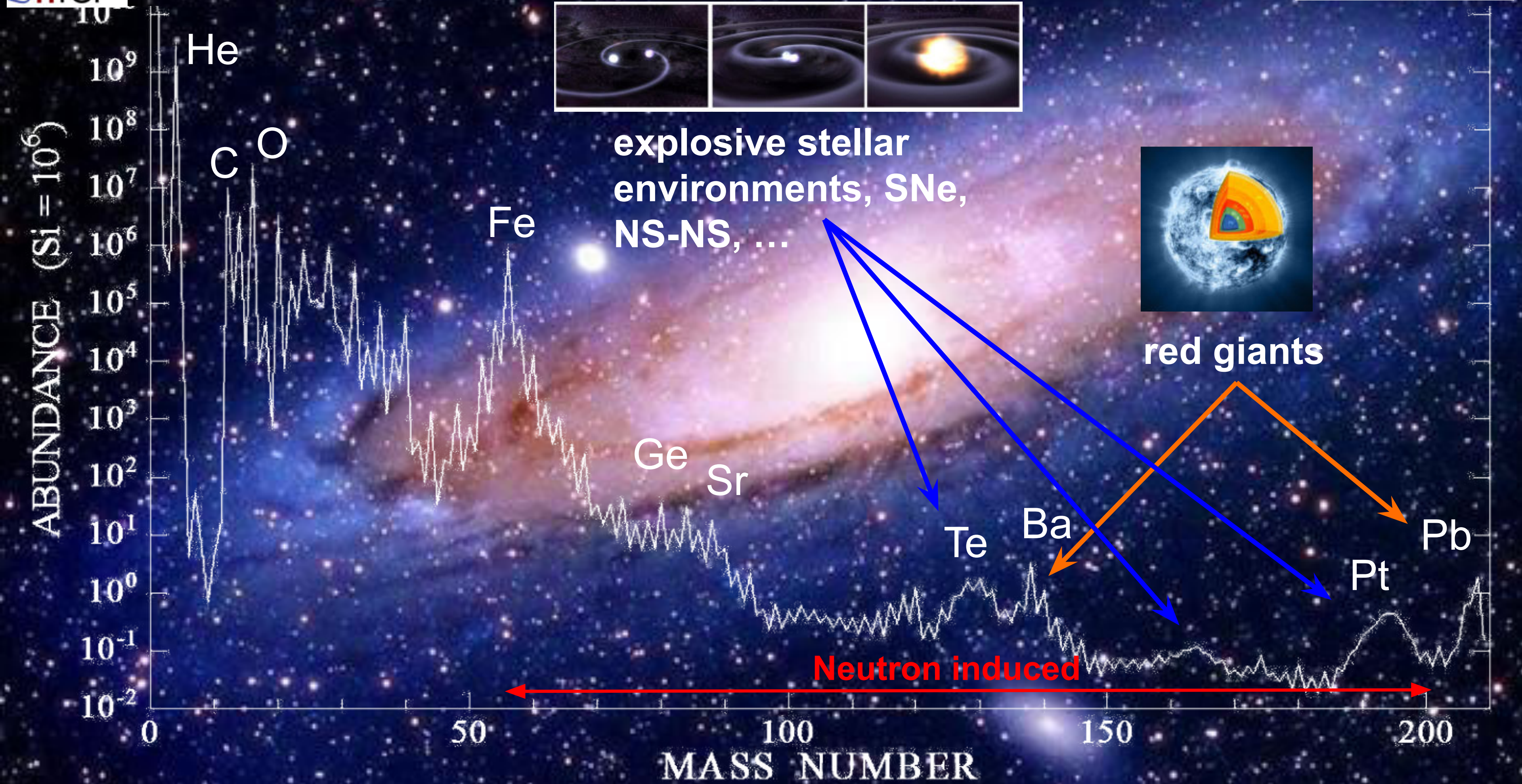
IFIC INSTITUT DE FÍSICA CORPUSCULAR

BACK-UP SLIDES

J. Lerendegui-Marco

19th Russbach School on Nuclear Astrophysics, 3-9 March 2024

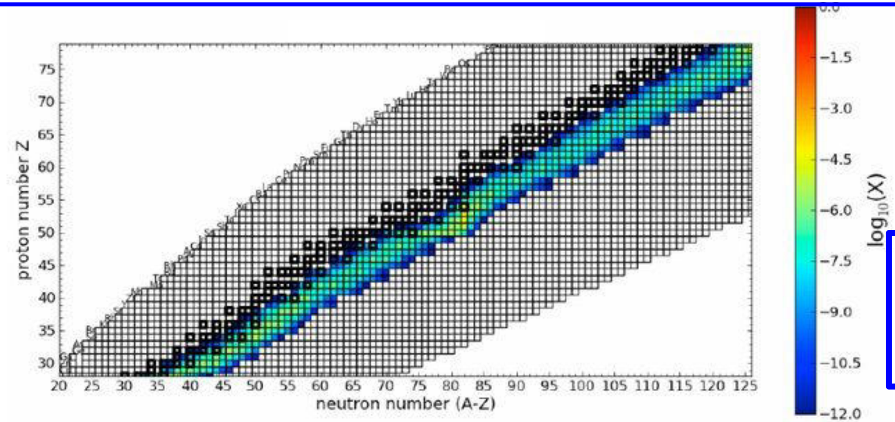
Stellar nucleosynthesis of heavy elements

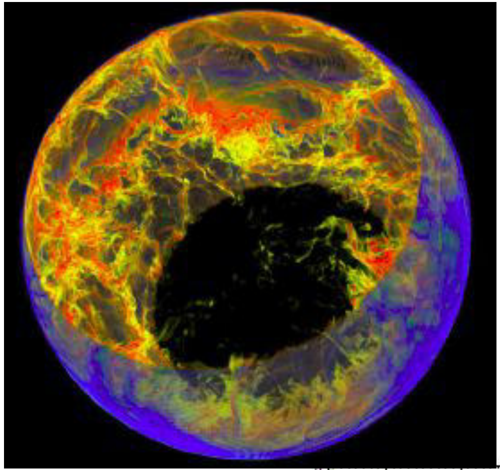


i- process nucleosynthesis: stellar site and path

Stellar Explanation:
Convective-reactive nucleosynthesis episodes →Proton ingestion in the C-shell → Neutron densities 10^{15} n/cm³

i-process path:
Conditions between the s- and r- process, the reaction occurs a few mass units away from the valley of stability.





3D simulation Convective-reactive

i-process path: few mass units away on the neutron rich side

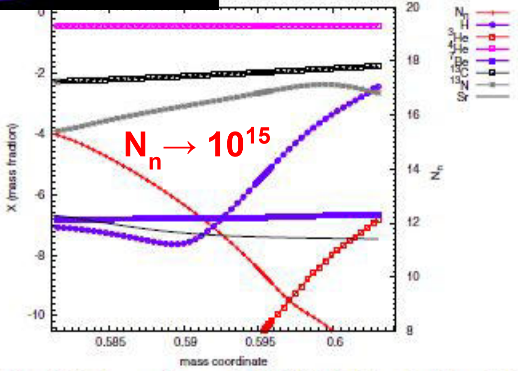


Figure 7. Abundance profiles snapshot (RUN103), just before the mixing split is imposed, demonstrates the simultaneous action of nucleosynthesis and mixing on similar timescales.

CONVECTIVE–REACTIVE PROTON–^{12}C COMBUSTION IN SAKURAI'S OBJECT (V4334 SAGITTARII) AND IMPLICATIONS FOR THE EVOLUTION AND YIELDS FROM THE FIRST GENERATIONS OF STARS

Falk Herwig[1,10], Marco Pignatari[1,2,3,10], Paul R. Woodward[4], David H. Porter[5], Gabriel Rockefeller[6,7,10], Chris L. Fryer[6,7,10], Michael Bennett[8,10], and Raphael Hirschi[8,9,10]

i- process nucleosynthesis: (n,g) cross sections

The intermediate neutron capture process

I. Development of the *i*-process in low-metallicity low-mass AGB stars

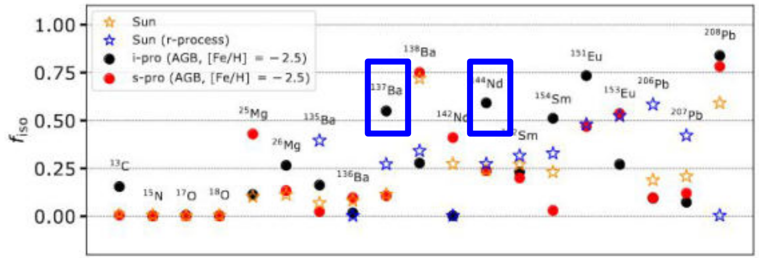
A. Choplin, L. Siess, and S. Goriely

The impact of (n,γ) reaction rate uncertainties on the predicted abundances of i-process elements with $32 \leq Z \leq 48$ in the metal-poor star HD94028

John E. McKay,[1,2†] Pavel A. Denissenkov,[1,3★†] Falk Herwig,[1,3★†] Georgios Perdikakis[3,4,5] and Hendrik Schatz[3,5,6†]

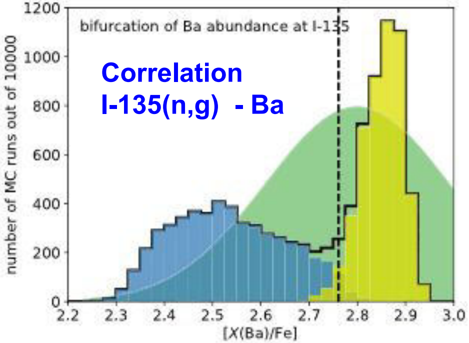
The impact of (n,γ) reaction rate uncertainties of unstable isotopes on the *i*-process nucleosynthesis of the elements from Ba to W

Pavel A. Denissenkov,[1,2,3★†] Falk Herwig,[1,2★†] Georgios Perdikakis[2,4,5] and Hendrik Schatz[2,5,6†]



Signatures of i-process: Ba-137, Nd-144→
^{137}Cs(**30 y**)(n,γ) , ^{144}Ce(**285 d**) (n,γ) compete with decay

Very high impact (n,g) in i-process abundances:
^{66}Ni(**55h**)(n,γ),^{72}Zn(**46.5h**)(n,γ),^{75}Ga(**2.10m**)(n,γ), ^{135}I(**6.6h**)(n,g)



Reaction		Element
^{66}Ni	54.6 h	Zn Ge As
^{72}Zn	46.5 h	Ge
^{75}Ga	2.10 m	As

Element	Reaction	
Ba	^{135}I	6.6 h

(n,g) for i-process: involves n-rich nuclei → even more challenging than s-process

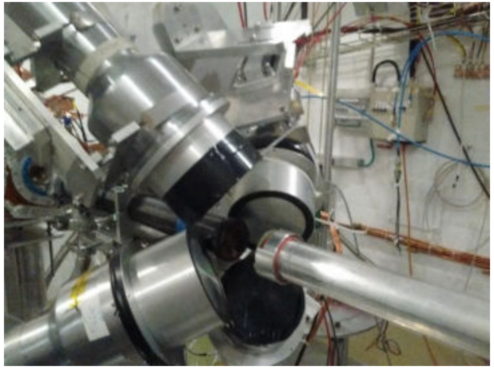
1. Very low masses →Often have to be produced in **exotic beam facilities**
2. **Half-life is for most of them too short (minutes-hours)** to allow a (weeks or months) measurement.
3. **Very high flux facilities** & very sensitive **experimental techniques**

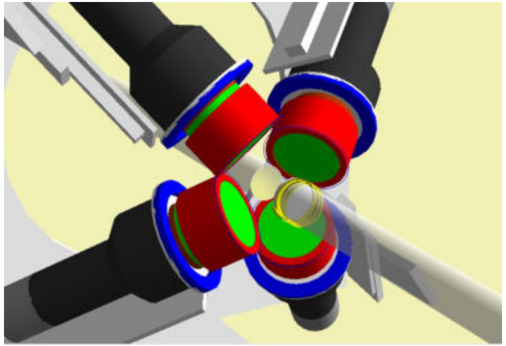
(n,ɣ) measurements @ n_TOF

	TAC	C_6D_6 TED
Advantages	Good background rejection High efficiency High resolution	Low neutron sensitivity Simple set-up Fast detectors
Drawbacks	Neutron sensitive Slow detectors: pile-up problems Complex detector (42 crystals)	Poor background rejection Low efficiency Software manipulation (PHWT) needed

Not able to measure in the keV range of astrophysical interest (dead time)

Usual setup for stellar (n,ɣ) measurements





State-of-the art for measurements in the astrophysical range of interest (1 - 100 keV):

- Fast response (10 ns width signals)
- Low neutron sensitivity

C_6D_6 TED

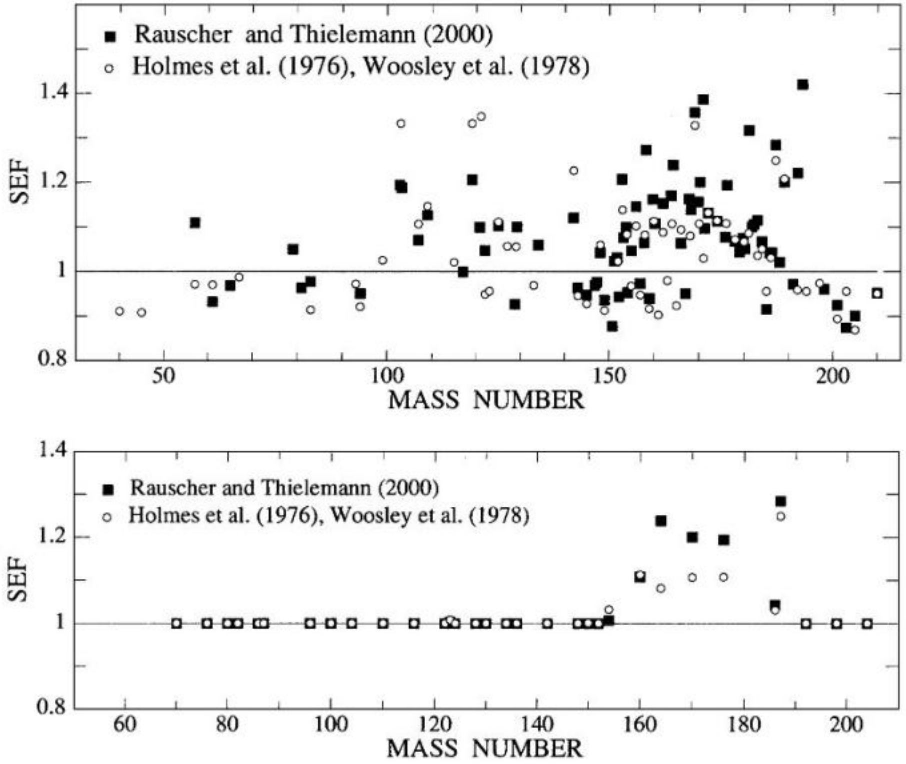
+ PHWT

Limitations:

- Background in the keV range due to dominant neutron scattering
- Limited by maximum count rate in high flux facilities such as n_TOF-EAR2

Solutions:
Recent progresses!

SEF

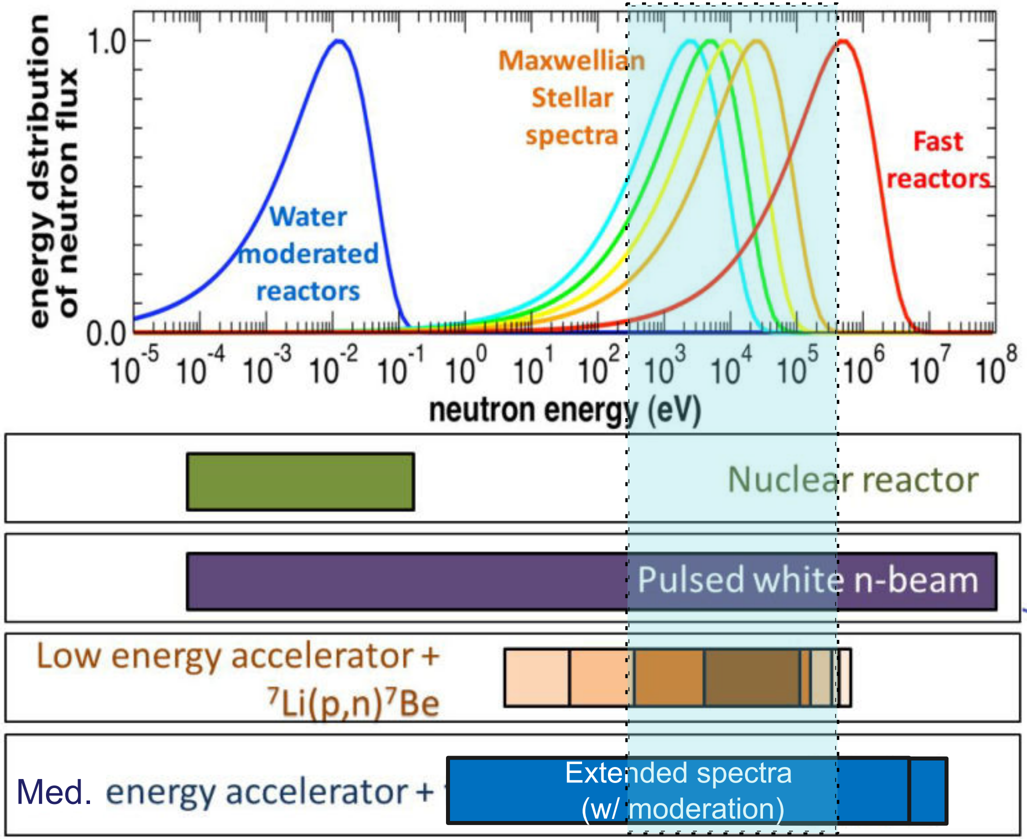


- 25% of all isotopes involved in the s process show SEF corrections of more than 2%.

- Significant corrections are to be expected for odd and/or deformed nuclei with excited states well below 100 keV.

- s-only isotopes little affected, except for the mass region 160 < A <190

Stellar (n,ɣ) cross sections: neutron beams



Stellar (n,ɣ) cross sections:
Energy range of interest
E_n = 500 eV - 300 keV

Complementary
neutron facilities & techniques

ILL, BRR, FRM-II,...

n_TOF, LANL, JRC-Geel, ..

HISPANoS- CNA, LiLIT, FRANZ

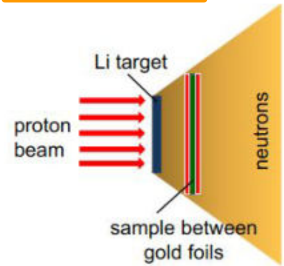
NFS, IFMIF-DONES?

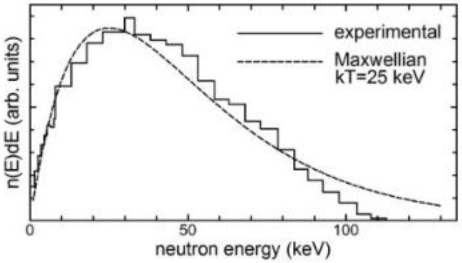
MACS via activation: “stellar” neutron beams

Low E (MeV) proton accelerators

$^{7}Li\ (p,n)^{7}Be$

Quasi-maxwellian @ 25 keV

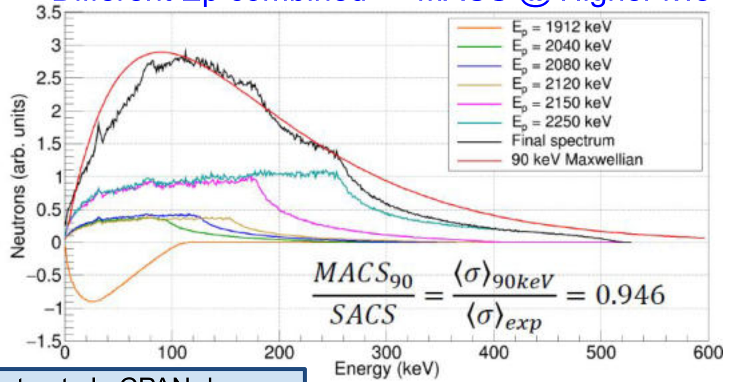




Ep=1912 keV

PHYSICAL REVIEW C **93**, 045803 (2016)

Different Ep combined → MACS @ Higher kTs

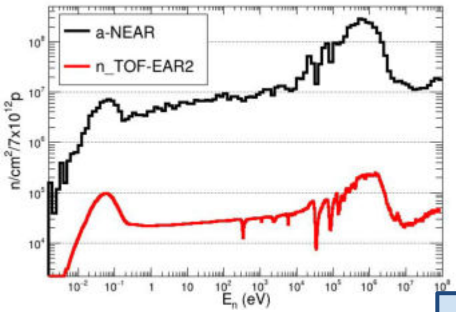


P. Perez-Maroto et al., CPAN days

Med/High energy accelerator (~10MeV - ~GeV)

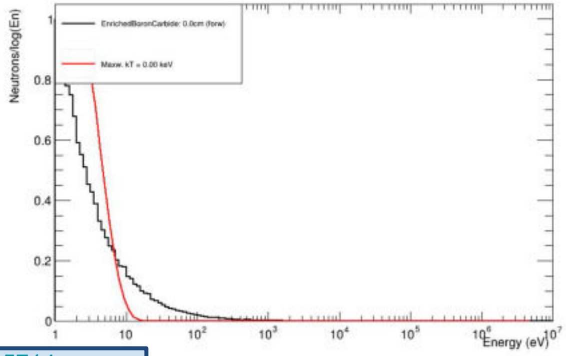
Target + moderator

White neutron beam



Moderating + Filtering assembly

Neutron energy shaping → MACS @ different kTs



J. Lerendegui-Marco et al., arXiv:2310.15714

Relevance of the branching at ^{79}Se

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

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

→ One of the **21 key s-nuclei** listed in: Kaeppeler, *Rev. Mod. Phys* 83, 157 (2011)

Temperature and $T_{1/2}$ of ^{79}Se

PHYSICAL REVIEW C VOLUME 38, NUMBER 1 JULY 1988

β-decay rate of ^{79m}Se and its consequences for the *s*-process temperature

N. Klay and F. Käppeler
Institut für Kernphysik III, Kernforschungszentrum Karlsruhe, D-7500 Karlsruhe, Federal Republic of Germany
(Received 21 December 1987)

The branching ratio between internal electromagnetic transitions and β^- decays of the isomer ^{79m}Se was determined experimentally. Extremely clean samples of ^{78}Se were activated with thermal neutrons at a high-flux reactor. A mini-orange-Si (Li) detection system was used to measure β^- particles and conversion electrons immediately after neutron irradiation. For the β^- decay we obtain $\log ft = 4.70^{+0.10}_{-0.09}$. Our present result was used to recalculate the temperature dependence of the effective β^- half-life of ^{79}Se in the stellar interior. In combination with the half-life deduced from a quantitative branching analysis, we obtain a possible temperature range between 182 and 295 million degrees for the weak component of the *s* process.

Nevertheless, the effective stellar half-life at temperatures above 200 million degrees is not changed by the assumed lower limit for the ground state half-life. This leads to the rather strange consequence that, at present, we know the stellar life time of ^{79}Se at a fixed temperature much better than its terrestrial one.

weak *s*-process component to range between 182 and 295 million degrees. **Need of improved cross sections**

The related uncertainty is mainly due to the uncertainty for the effective stellar half-life deduced from the σN systematics which can only be reduced by improved cross section measurements. The present experimental uncer-

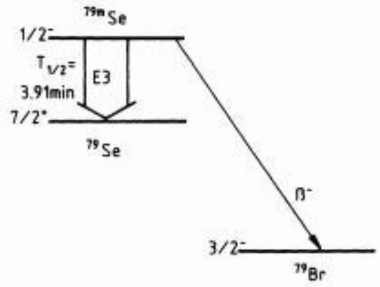


FIG. 1. Decay scheme of ^{79m}Se.

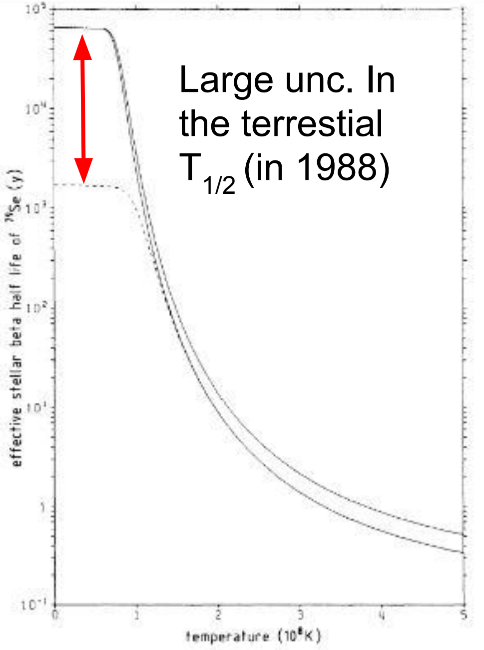


FIG. 7. Stellar half-life of ^{79}Se as a function of temperature. The error band reflects the uncertainty of our measurement. The dashed line refers to $\log ft = 8.5$ for the ground state decay.

Experimental measurement of the logft of the beta decay of the ^{79m}Se state at 96 keV, thermally populated at stellar temperatures

Branching at ^{79}Se: Kr abundances

Published: 22 November 1990

Meteoritic silicon carbide: pristine material from carbon stars

Roy S. Lewis, Sachiko Amari & Edward Anders

All five noble gases in interstellar silicon carbide grains have grossly non-solar isotopic and elemental abundances that vary with grain size but are strikingly similar to calculated values for the helium-burning shell of low-mass carbon stars. Apparently these grains formed in carbon-star envelopes, and were impregnated with noble gas ions from a stellar wind. Meteoritic SiC provides a detailed record of nuclear and chemical processes in carbon stars.

AGB Stars

The Kr isotopic ratios have been measured in bulk SiC acid residues providing details on AGB stars evolved prior to the formation of the Solar System.

Presolar grain measurements give the **most precise data** currently available on s-process nucleosynthesis (at least one order of magnitude better than spectroscopic observations)

ELSEVIER

Geochimica et Cosmochimica Acta

Volume 58, Issue 1, January 1994, Pages 471-494

Interstellar grains in meteorites: II. SiC and its noble gases

Roy S Lewis, Sachiko Amari *, Edward Anders †

interstellar SiC, isolated from the Murchison C2 chondrite. All are mixtures of a highly anomalous component bearing the isotopic signature of the astrophysical s-process and a more normal component, generally solar-like but with anomalies of up to 30% in the heavy isotopes. As these two components strikingly resemble predictions for the He-burning shells and envelopes of red giant carbon stars, it appears that the SiC grains are pristine circumstellar condensates from such stars. A number of elemental and isotopic ratios (such as $K^{80}K^{82}$ and $K^{86}Kr^{82}$) vary with grain size, suggesting that the SiC comes from carbon stars representing a range of masses, metallicities, temperatures, and neutron densities.

Branching at ^{79}Se: Kr abundances

Published: 22 November 1990

Meteoritic silicon carbide: pristine material from carbon stars

Roy S. Lewis, Sachiko Amari & Edward Anders

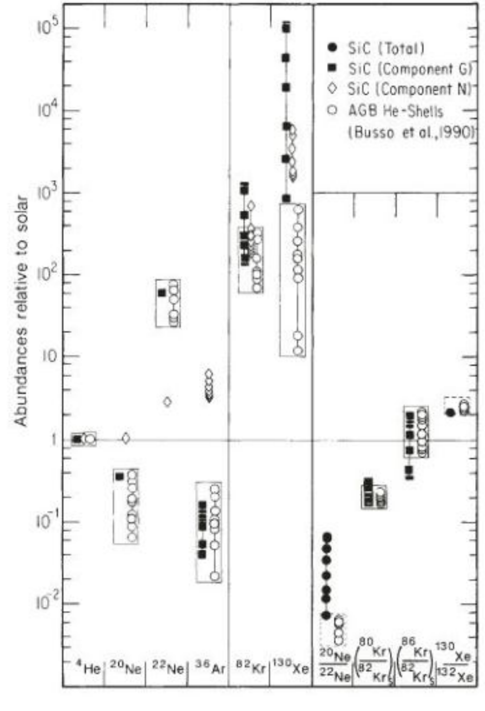


FIG. 3 Right, isotope ratios of SiC and AGB-star He shells, normalized to

AGB Stars

release temperature of the gas on heating or combustion[7,8]. The variations of ^{80}Kr and ^{86}Kr reflect branching of the s-process at their radioactive progenitors, ^{79}Se and ^{85}Kr (ref. 7). These branchings depend sensitively on neutron density and temperature in the s-process region[7,12], and thus can provide clues about the stars in which the Kr was formed. What we would

TABLE 1 Noble gases in SiC size fractions from Murchison chondrite

Sample	Size (μm)	^{3}He/^{4}He ×10^{-4}	^{20}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{84}Kr/^{82}Kr	^{130}Xe/^{132}Xe	$(^{80}Kr/^{82}Kr)_s$	$(^{86}Kr/^{82}Kr)_s$
KJA	0.05–0.1	1.32 (18)	0.9075 (10)	0.1927 (5)	3.702 (24)	0.3532 (10)	0.0597 (67)	0.621 (44)
KJB	0.1–0.2	2.00 (10)	0.8933 (3)	0.1919 (1)	3.603 (6)	0.3602 (4)	0.0586 (16)	0.695 (24)
KJC	0.2–0.3	1.48 (7)	0.6345 (3)	0.1907 (2)	3.693 (10)	0.3604 (6)	0.0526 (27)	1.145 (19)
KJD	0.3–0.5	1.16 (6)	0.4582 (5)	0.1935 (1)	3.769 (8)	0.3558 (5)	0.0490 (25)	1.733 (23)
KJE	0.5–0.8	0.81 (4)	0.2977 (5)	0.2051 (2)	3.756 (11)	0.3465 (10)	0.0451 (21)	2.363 (34)
KJF	0.8–1.5	0.56 (3)	0.2001 (2)	0.2210 (5)	3.776 (21)	0.3291 (22)	0.0365 (37)	2.710 (71)
KJG	1.5–3	0.53 (5)	0.1556 (2)	0.2313 (6)	3.915 (21)	0.2716 (28)	0.0336 (72)	2.872 (62)
KJH	3–5		0.0979 (19)	0.2090 (23)	4.500 (87)	0.1606 (52)	0.055 (58)	
Solar[21]		1.42	13.7	0.188	4.988	0.1643		
He-Shell, Range*			0.05–0.084	0.57–1.25	2.2–2.6	0.39–0.44		
He-Shell, Typical		0	0.0808	0.74	2.55	0.485†		

Very accurate 80Kr/82Kr abundances ratios

^{79}Se sample: a collaborative effort

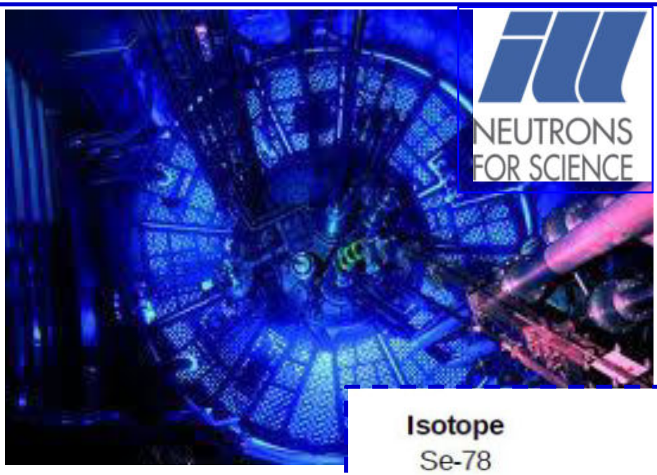
~15x4mm

PSI: $^{208}Pb^{78}Se$ alloy to avoid low melting point

CERN: Encapsulated in e-welded 6N Al+

~17x6mm

ILL: ~3 mg of ^{79}Se via ^{78}Se(n,ɣ)



Isotope	Mass (g)
Se-78	1.064
Se-79	0.003
Pb-208	2.838
Al-27	1.0244

PSI: Characterized active contaminants

Isotope	Activity (Mbq)
Se-79	4.33E-01
Se-75	5.66E+00
Ag-110m	2.04E-01
Zn-65	2.33E-01
Co-60	1.40E+00

gamma emmiters (Se-75, Ag-110m, Zn-65, Co-60)

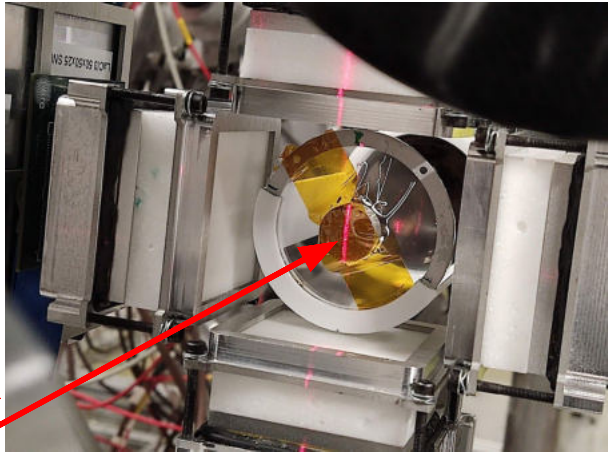
^{79}Se sample: a collaborative effort

~15x4mm

PSI: ^{208}Pb^{78}Se alloy to avoid low melting point

CERN: Encapsulated in e-welded 6N Al+

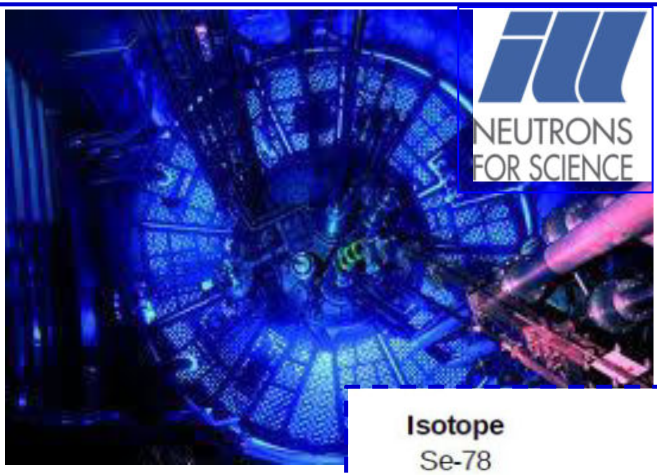
~17x6mm



n-beam

Sample in the beam of n_TOF-EAR1

ILL: ~3 mg of ^{79}Se via ^{78}Se(n,γ)



Isotope	Mass (g)
Se-78	1.064
Se-79	0.003
Pb-208	2.838
Al-27	1.0244

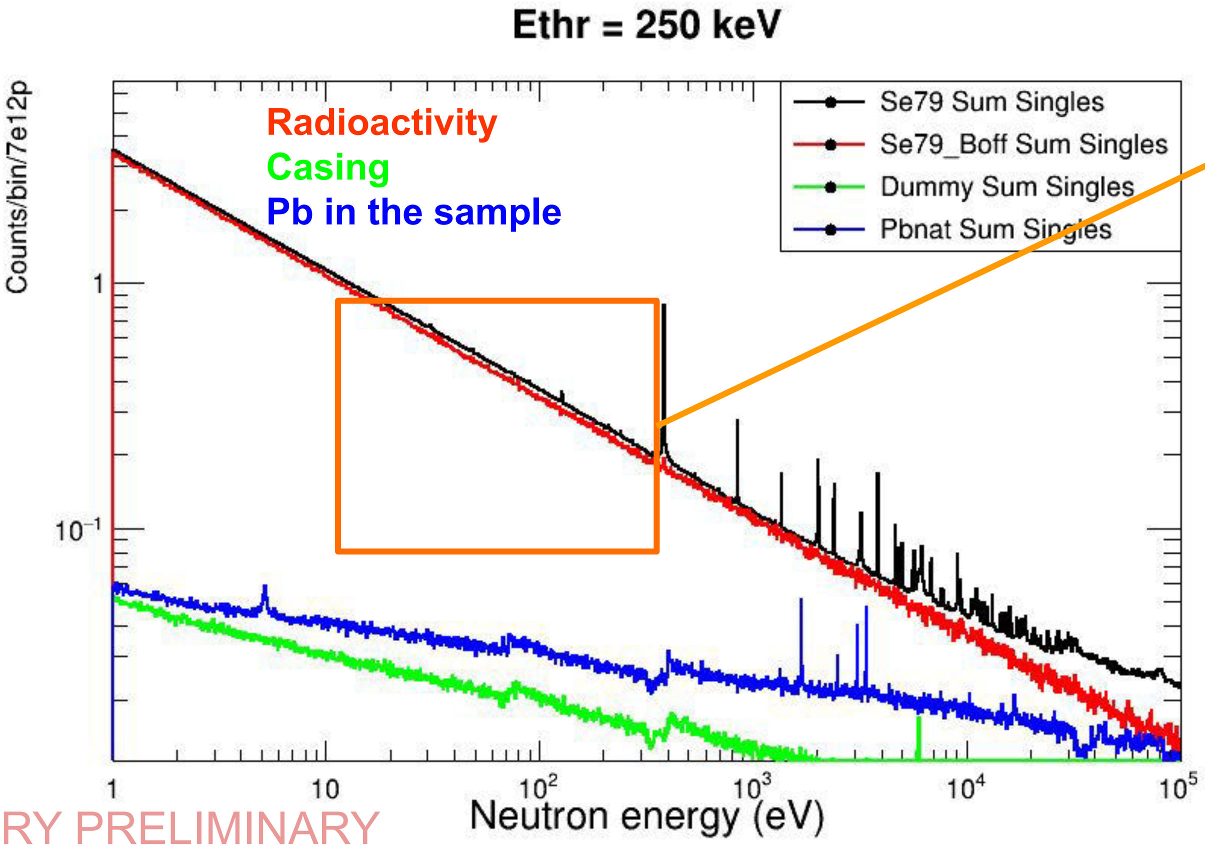
PSI: Characterized active contaminants

Isotope	Activity (Mbq)
Se-79	4.33E-01
Se-75	5.66E+00
Ag-110m	2.04E-01
Zn-65	2.33E-01
Co-60	1.40E+00

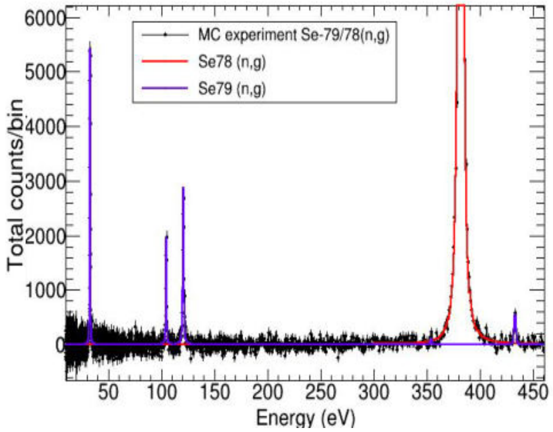
gamma emmiters

Preliminary results: i-TED in singles and Ethr

Count rate vs background components



First candidates for **resonances of Se-79** start to be visible on top of the background



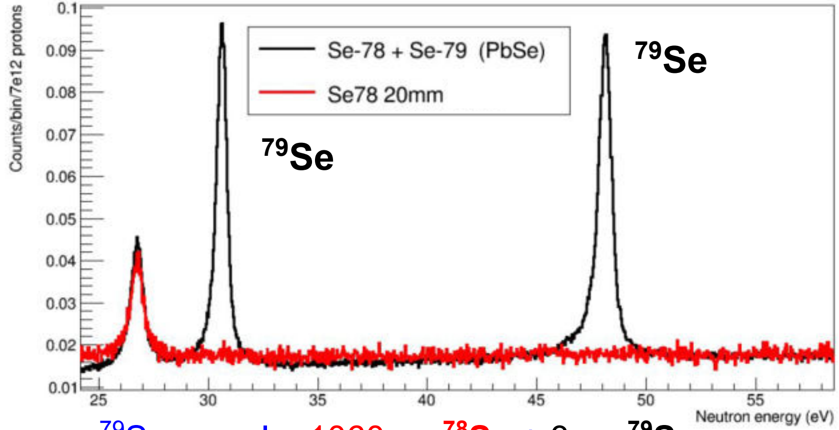
Proposal: first resonances of Se-79 expected @ 10-100 eV

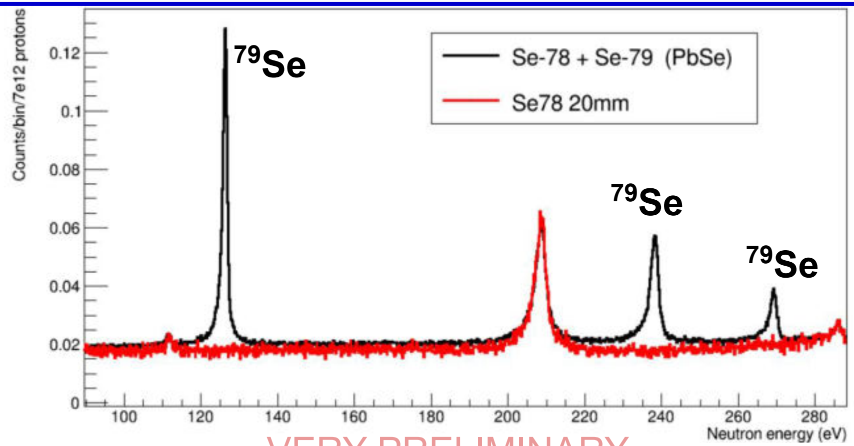
VERY PRELIMINARY

$^{79}Se(n,\gamma)$: first results

10-15 Resonances of Se-79 **First ever measured!**

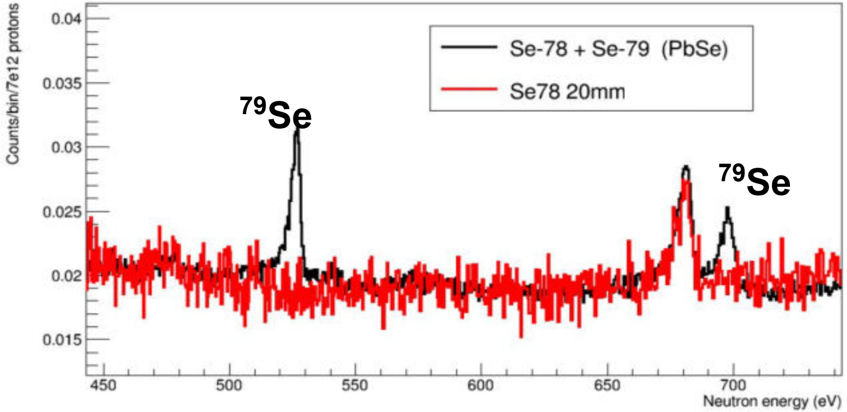
- **Se-79+Se-78 sample** vs **Se-78 sample**

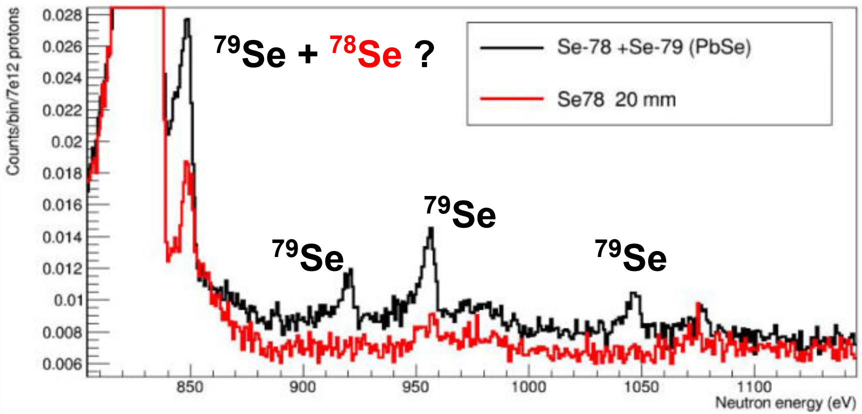




^{79}Se sample: 1060mg ^{78}Se + 3mg ^{79}Se

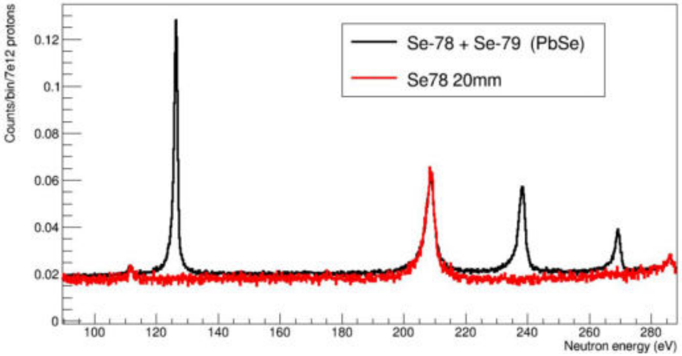
VERY PRELIMINARY





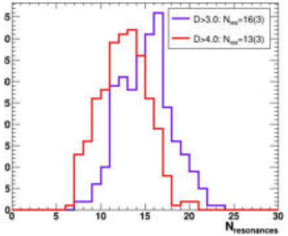
^{79}Se(n,γ): expected results

Experimental RRR: (s-wave Avg. Par.)



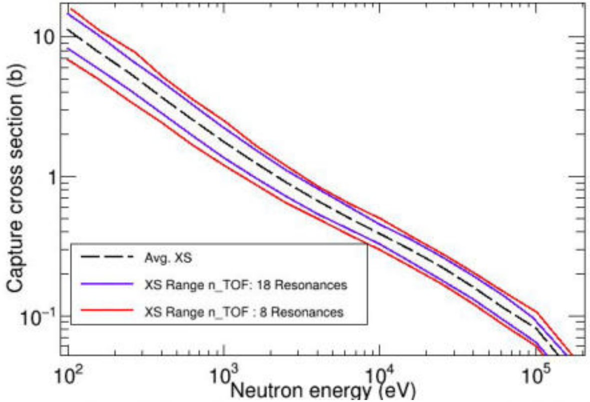
R-Matrix

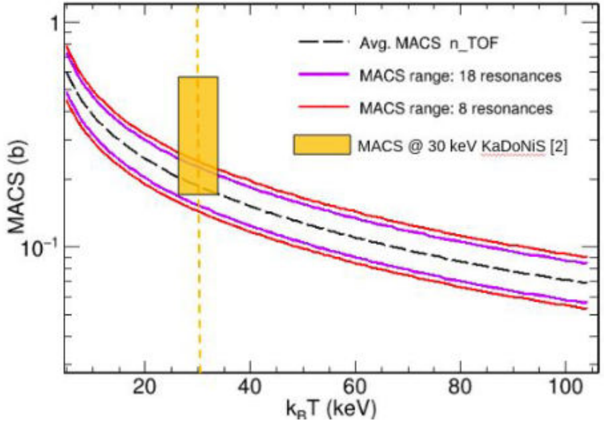
Measured: 10-15 resonances



Uncertainty D_0,S_0 ~ $\mathrm{sqrt}(N_{res})$

Hauser-Feshbach (FITACS): CS in the URR





- MACS @30 keV: 20-26% unc (from avg. par. only)
- Stellar enhancement Factor = 1 at 8, 30 keV
- **Direct stringent constraint for the thermal conditions of AGB and MSs**

MACS @ different kT: Constrain **theor. calculations in KaDoNiS** (@ 30 keV)

Same method for ^{171}Tm(n,γ): C. Guerrero, J. Lerendegui-Marco et al., **Phys. Rev. Letters 125**, 142701 (2020).

B4C filters & expected average kT

Calculations of the commissioning campaign (E. Stamati)

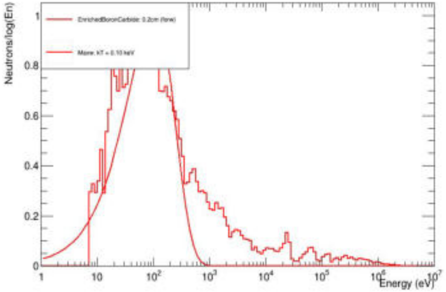
- 2.5 mm = 0.15 keV
- 5 mm = 0.88 keV
- 7.5 mm = 2.37 keV
- 10 mm = 27.7 keV

Good agreement up to 7.5 mm

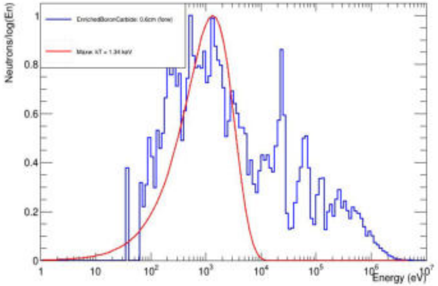
10 mm: significantly different → method to determine kT?
Better → SACS/MACS→1

Own Geant4 simulations

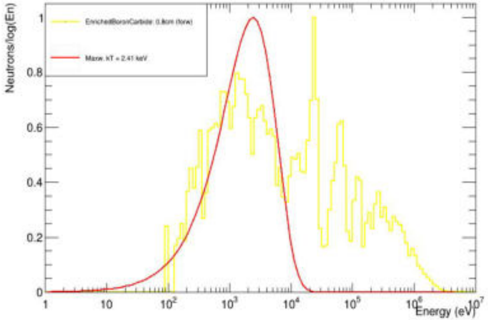
2mm = 0.10keV



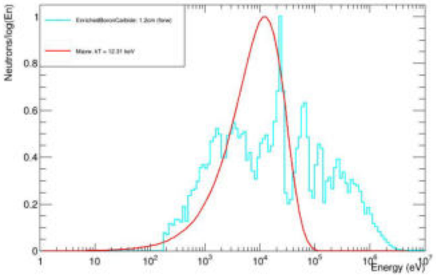
6mm = 1.34keV



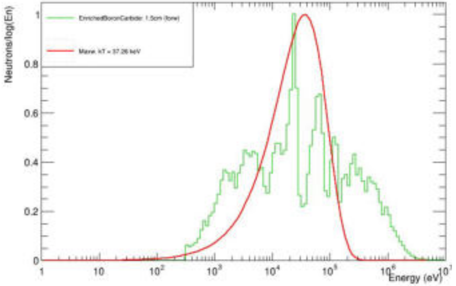
8mm = 2.4keV



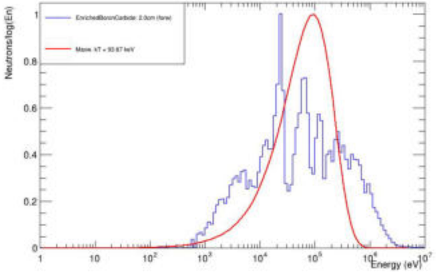
12 mm = 12 keV



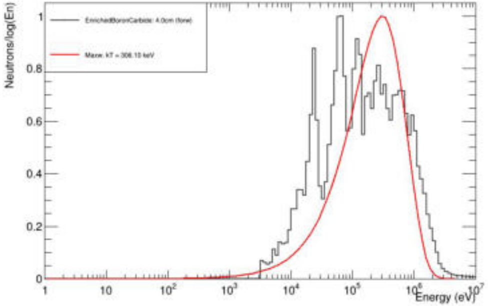
15 mm = 27 keV



20 mm = 91 keV

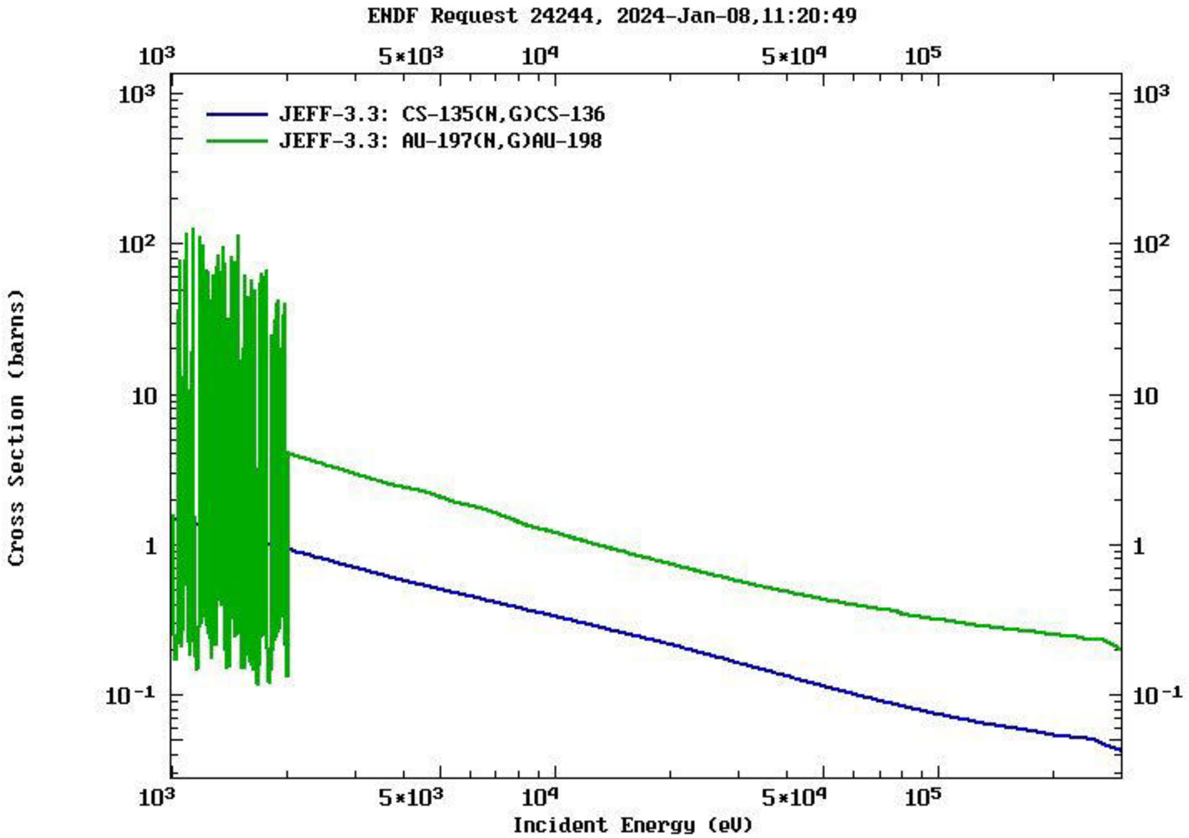


40 mm = 306keV



SACS to MACS: Au-197

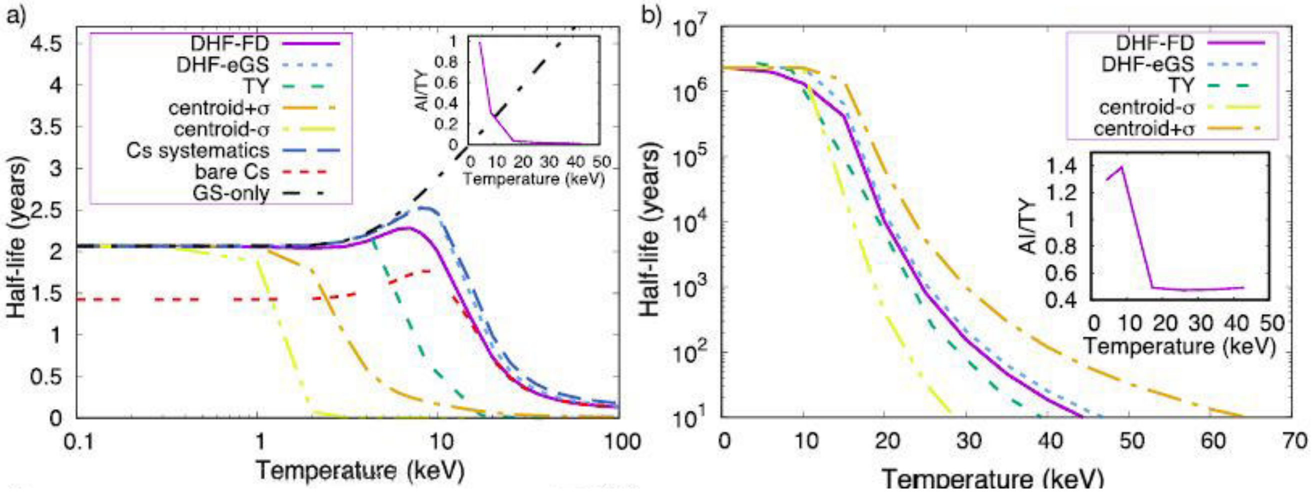
- Very similar shape of the cross section
- No large resonances in any of the isotopes
- MACS/SACS expected to be not very different.
- Shape of the cross sections can be used to improve the accuracy

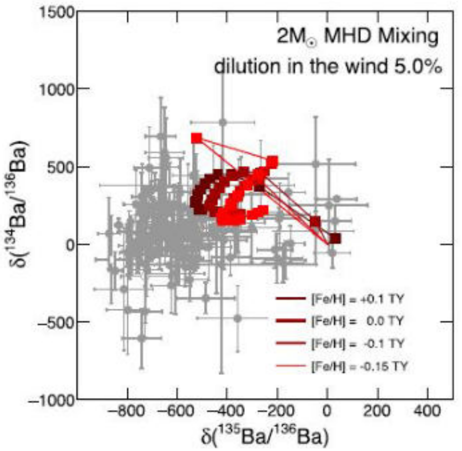


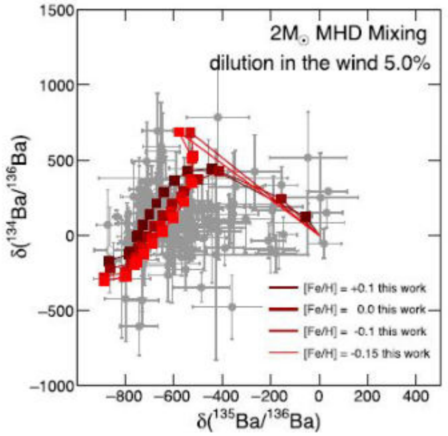
^{134}Cs, ^{135}Cs: T-dependence β-decay

Theoretical Estimate of the Half-life for the Radioactive ^{134}Cs and ^{135}Cs in Astrophysical Scenarios

Simone Taioli[1,2], Diego Vescovi[3], Maurizio Busso[4,5], Sara Palmerini[4,5,10], Sergio Cristallo[5,6], Alberto Mengoni[7,8], and Stefano Simonucci[5,9]







Agreement with the data improves with New beta decay rates of both ^{134,135}Cs

^{134}Cs, ^{135}Cs: Relevance s-process

Presolar Grain Isotopic Ratios as Constraints to Nuclear and Stellar Parameters of Asymptotic Giant Branch Star Nucleosynthesis

Sara Palmerini[1,2], Maurizio Busso[1,2], Diego Vescovi[2,3], Eugenia Naselli[4], Angelo Pidatella[4], Riccardo Mucciola[1,2], Sergio Cristallo[2,5], David Mascali[4], Alberto Mengoni[6,7], Stefano Simonucci[2,8], and Simone Taioli[9,10,11]

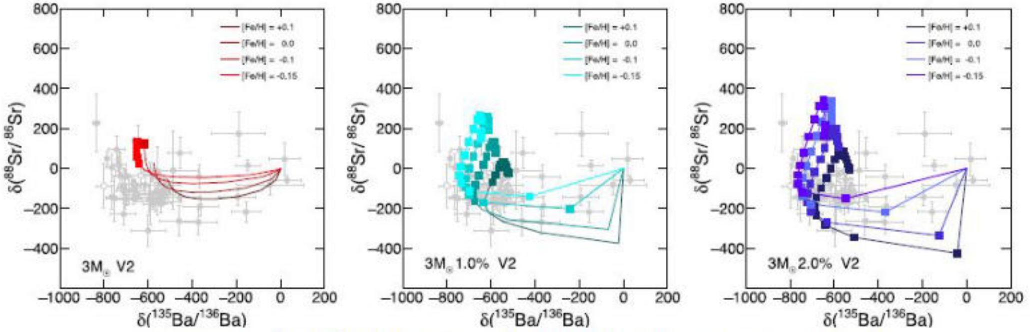


Figure 13. Same as Figure 12, but for the test models V2, with tentatively modified nuclear inputs (see Section 3).

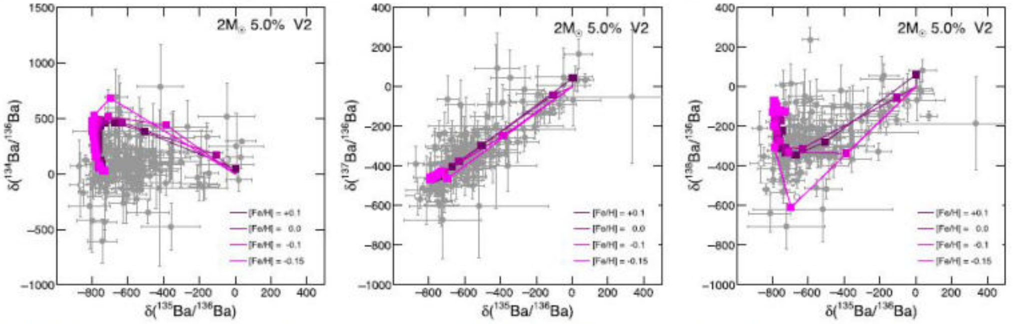


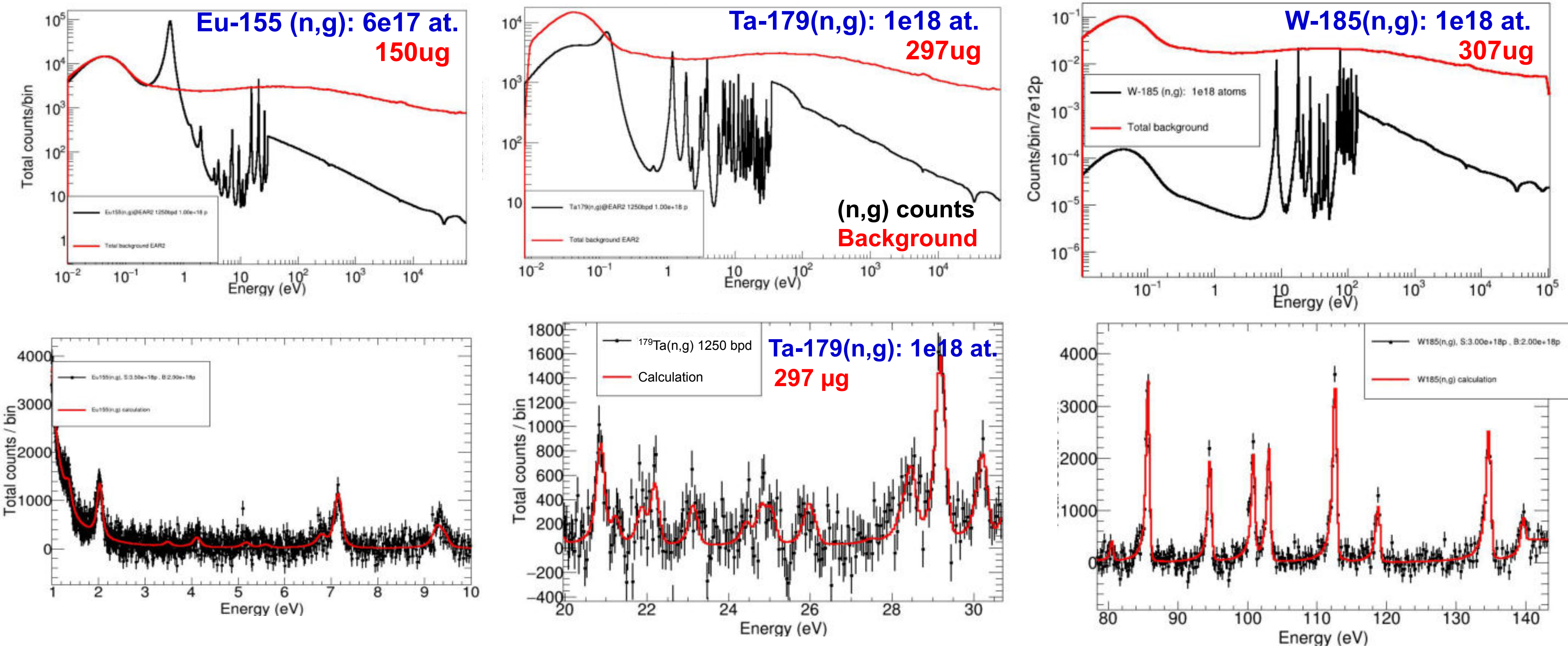
Figure 19. A comparison of model predictions from a representative case of 2 $M_\odot$ models (full lines with heavy dots) with SiC data for various Ba isotopes and with the the choice V2 for nuclear parameters, including revisions for the ^{134}Cs decay, as illustrated in Section 4. The meaning of the symbols is the same as in previous figures. The three panels represent the composition of winds with 5% of He-shell material added.

Sr/Ba ratios:
A longer half-live of 135Cs at 30 keV or **variations in the ^{135}Cs(n,g)cross section** will improve the agreement with the data

Ba-ratios separately:
Revision of the capture cross sections of Cs-isotopes would improve the agreement

TOF (n,g) on s-process branchings: feasibility limit

Estimated results in the upgraded **n_TOF-EAR2** with the **best sensitivity achieved so far with the STEDs**

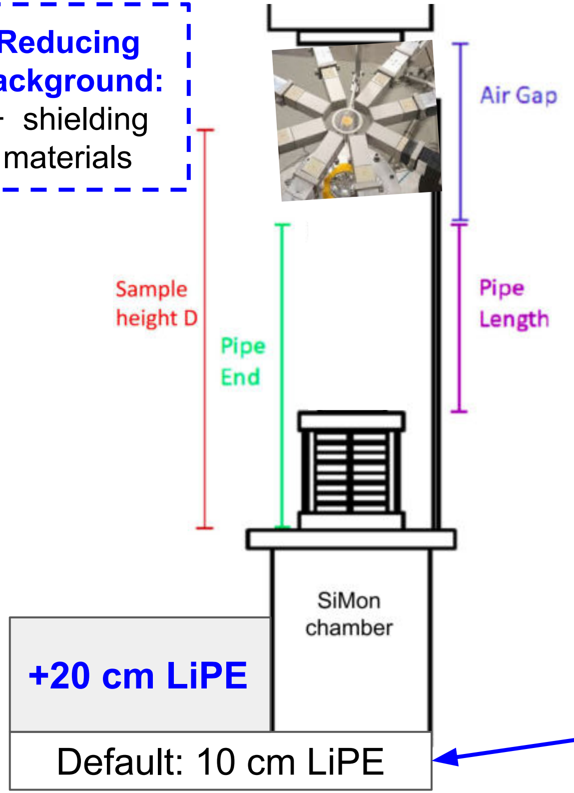


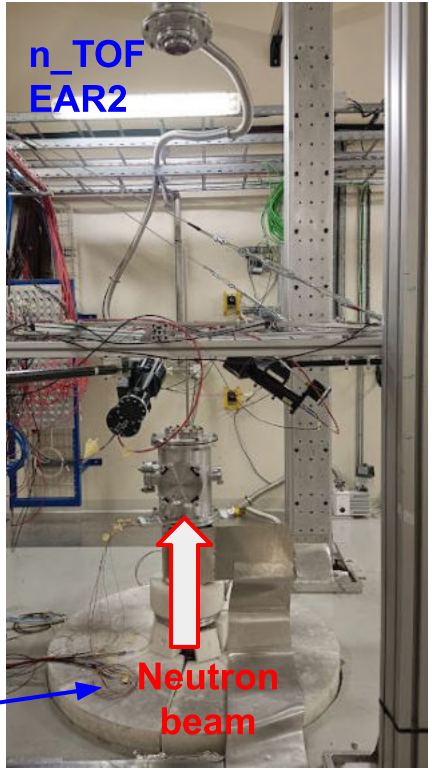
Limit: ~1e18 atoms (too high) currently required →We need **complementary techniques** → **ACTIVATION**!

Future: optimizing n_TOF-EAR2

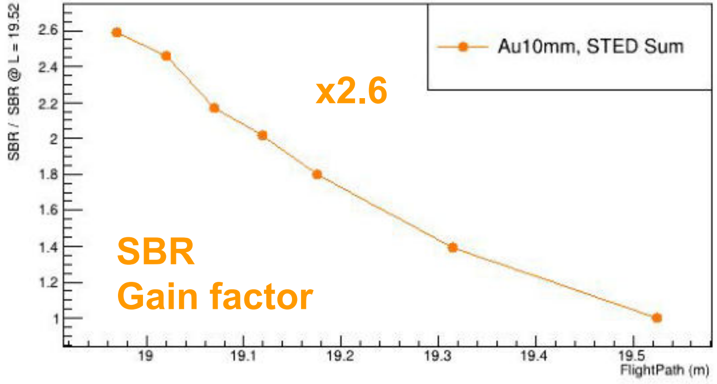
Short term: Optimization campaigns **at EAR2 & new ideas to improve the SBR for future experiments**

Reducing background:
+ shielding materials





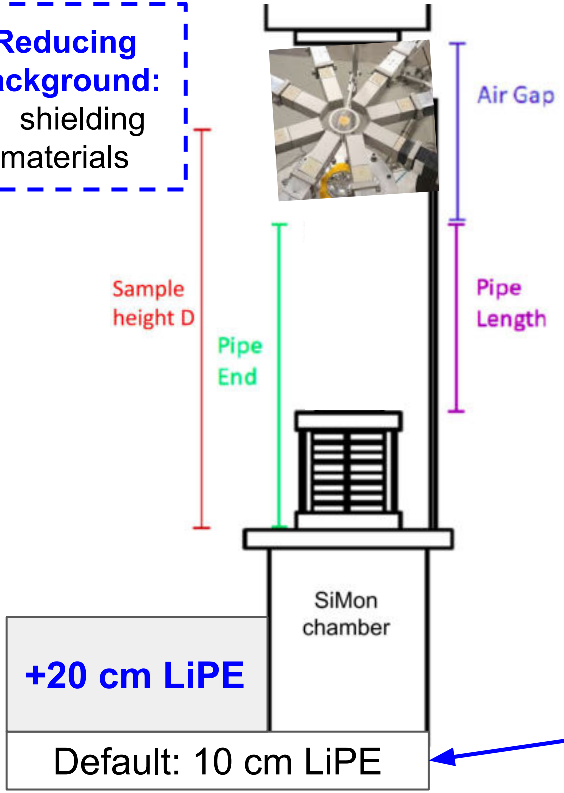
SBR Gain of a factor >2
by lowering 60cm the setup!

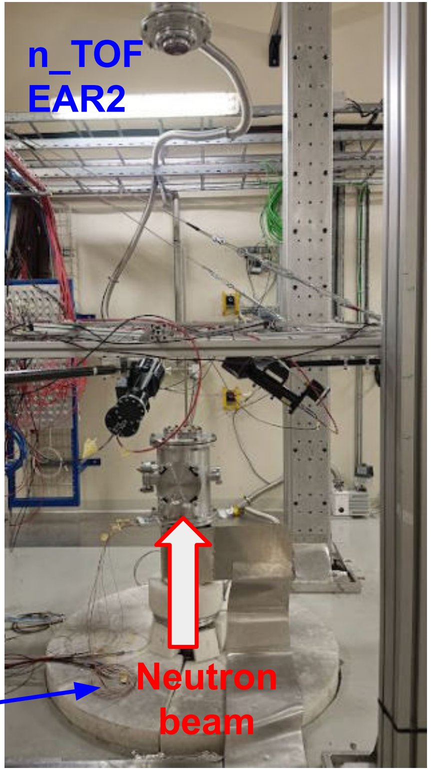


Future: optimizing n_TOF-EAR2

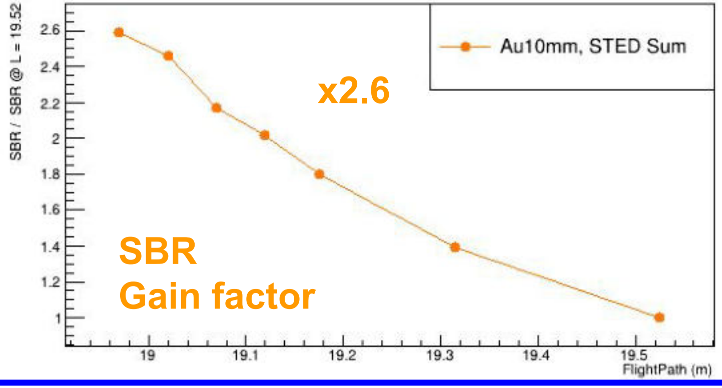
Short term: Optimization campaigns **at EAR2 & new ideas to improve the SBR for future experiments**

Reducing background:
\+ shielding materials





SBR Gain of a factor >2
by lowering 60cm the setup!



Long term:

- Change collimator design
- Upgraded experimental area (n-absorbers, enlarged: walls & floor further from beam)
- Avoid fastest neutrons: "look" only to moderator, new backwards TOF line