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Neutron capture reactions at the n_TOF facility at CERN

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GIANTS- IX Incontro dei Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale

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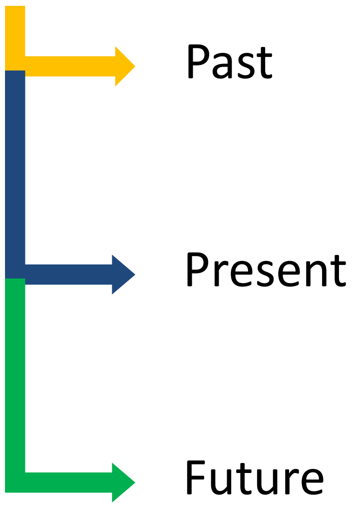
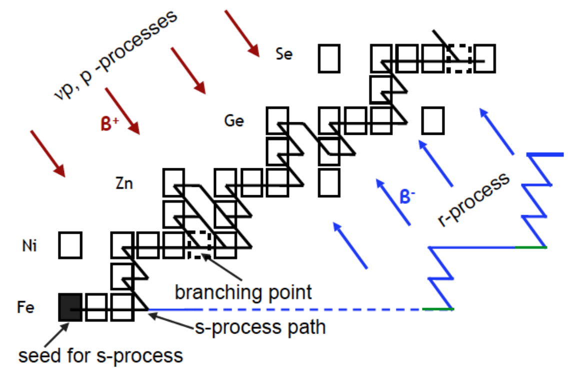
Summary

- The Physics Case: s-process Nucleosynthesis
- The n_TOF facility at CERN (time-line, main features, “*how-to*”)
- Experimental program on neutron capture reactions



Summary

- ~~The Physics Case: s-process Nucleosynthesis~~
- The n_TOF facility at CERN (time-line, main features, "*how-to*")
- Experimental program on neutron capture reactions
  - Past
  - Present
  - Future



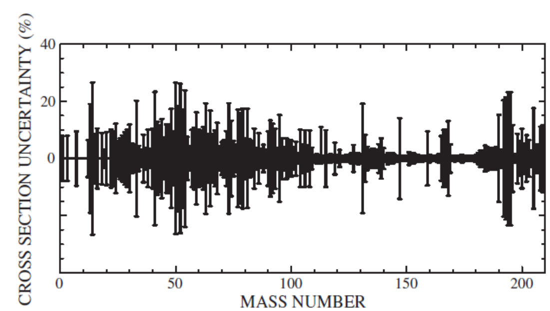
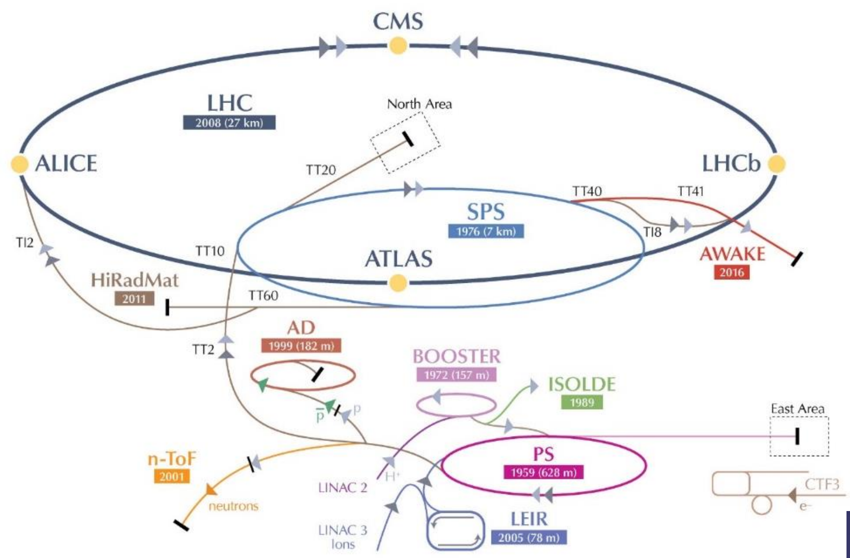
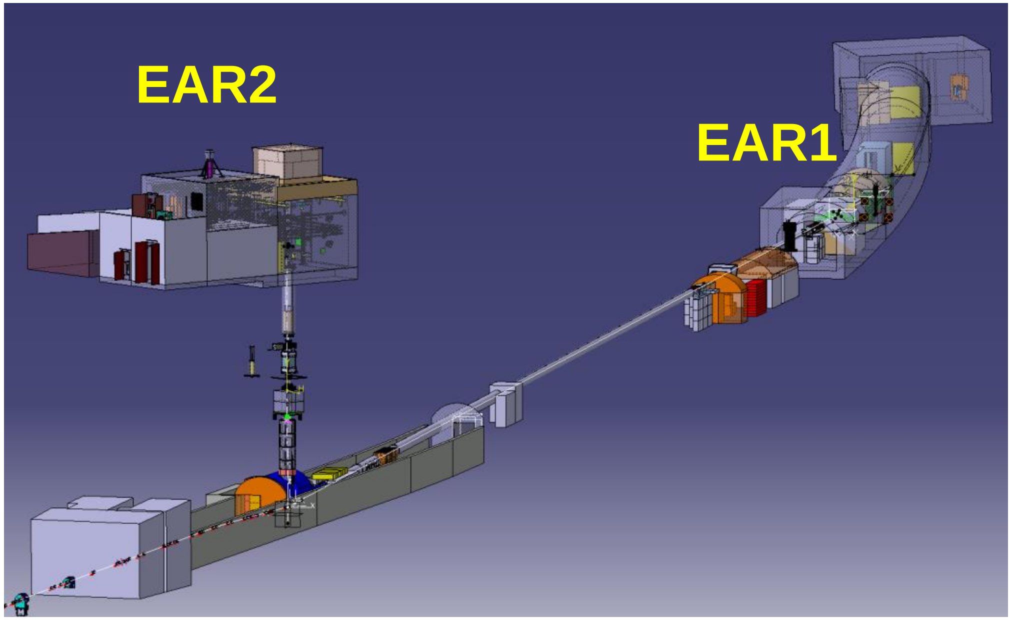


FIG. 6. Uncertainties of the stellar (n, γ) cross sections for *s*-process nucleosynthesis. These values refer to a thermal energy of $kT = 30$ keV, but may be considerably larger at lower and higher temperatures.

The n_TOF facility at CERN



- Neutron spallation source
- Pulsed neutron beam produced by the high energy proton beam



- Two beam lines **(180m e 20m)**
- **Two** experimental areas (**EAR1** and **EAR2**), <u>class A laboratories</u>

n_TOF Time-line

F. Gunsing et al (n_TOF Coll.), Eur. Phys. J. Plus (2016) 131: 371

1997 — 2017 …

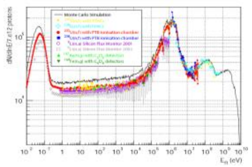
1997
Concept
by C.Rubbia
CERN/ET/Int. Note 97-19

May 1998
Feasibility
CERN/LHC/98-02+Add

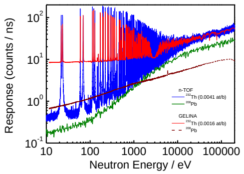
Aug 1998
Proposal submitted

1999
Construction started

2000
Commissioning



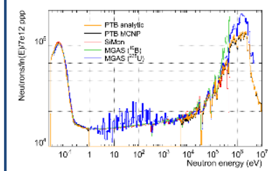
2001-2004
Phase I
Isotopes
Capture: 25
Fission: 11



2004-2007
Upgrade

2008
New Target construction

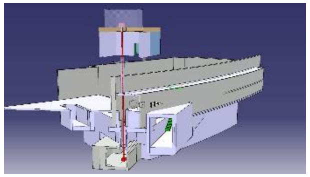
May 2009
Commissioning



2009 - 2012
Phase II
Isotopes
Capture: 14
Fission: 3
(n,cp): 2

2010
Upgrades:
Borated-H_2O
Second Line
Class-A

2011
EAR2
Design and Construction



July 2014
Commissioning of EAR-2

2014-2018
Phase III
Capture: 14
Fission: 4
(n,cp): 4

n_TOF Features

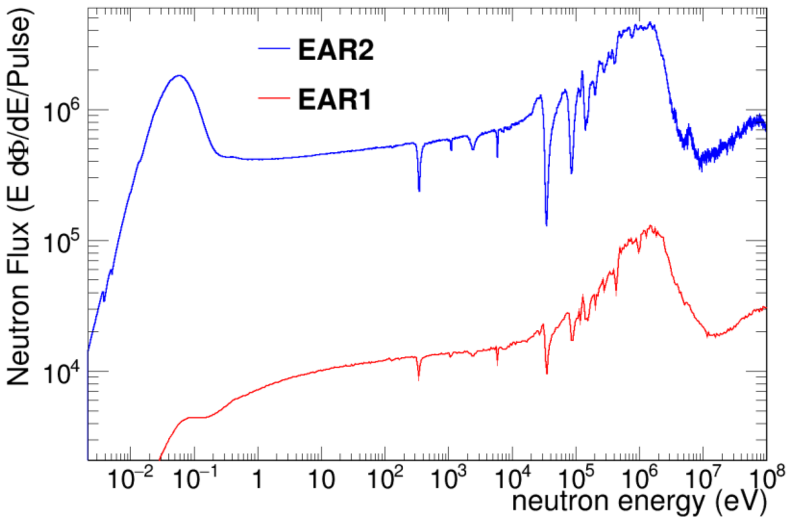
Advantages of the Proton Synchrotron beam: high energy, high peak current (7e12 ppp/7 ns)

High instantaneous neutron flux

(10^5 n/cm^2/pulse and 10^7 n/cm^2/pulse).

Very convenient for measurements of:

- radioactive isotopes,
- low cross sections,
- isotopes available in small quantities



Other features of the neutron beams:

- High **resolution in energy** *($\Delta E/E = 10^{-4}$ in EAR1 and $\Delta E/E = 10^{-3}$ in EAR2)*
- Wide **energy range** *(1 meV<E_n<1 GeV)*
- Low **repetition** rate(*< 0.8 Hz*) *(no wrap-around)*

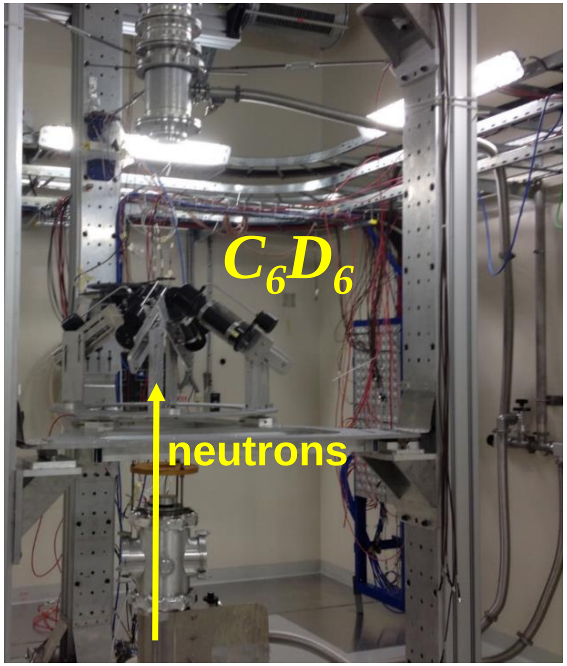
C. Guerrero et al (n_TOF Coll.), Eur. Phys. J. A (2013) 49: 27

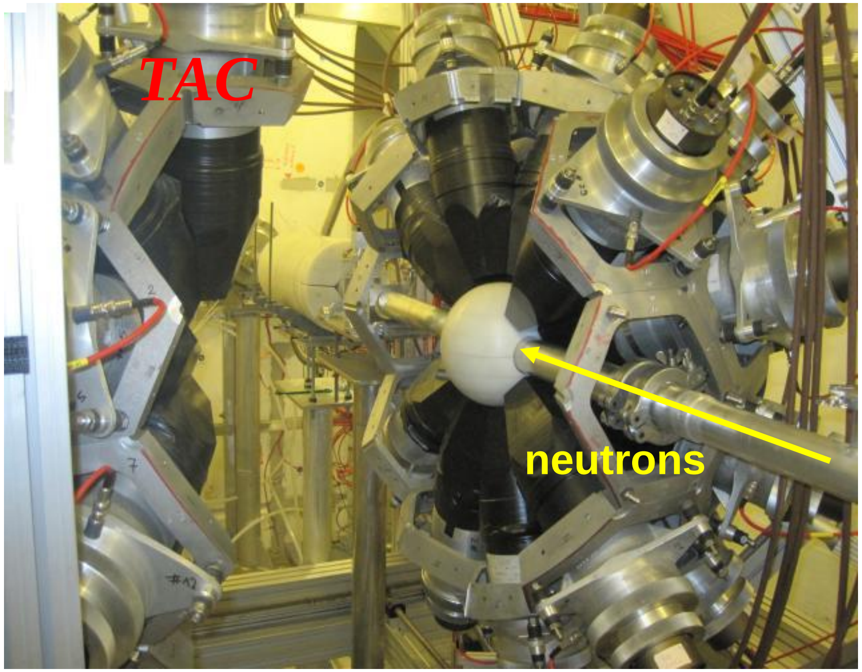
M. Barbagallo et al (n_TOF Coll.), Eur. Phys. J. A (2013) 49: 156

n_TOF capture measurements: An "How to"

Two systems (and two different techniques) were used at n_TOF to measure neutron capture cross sections:

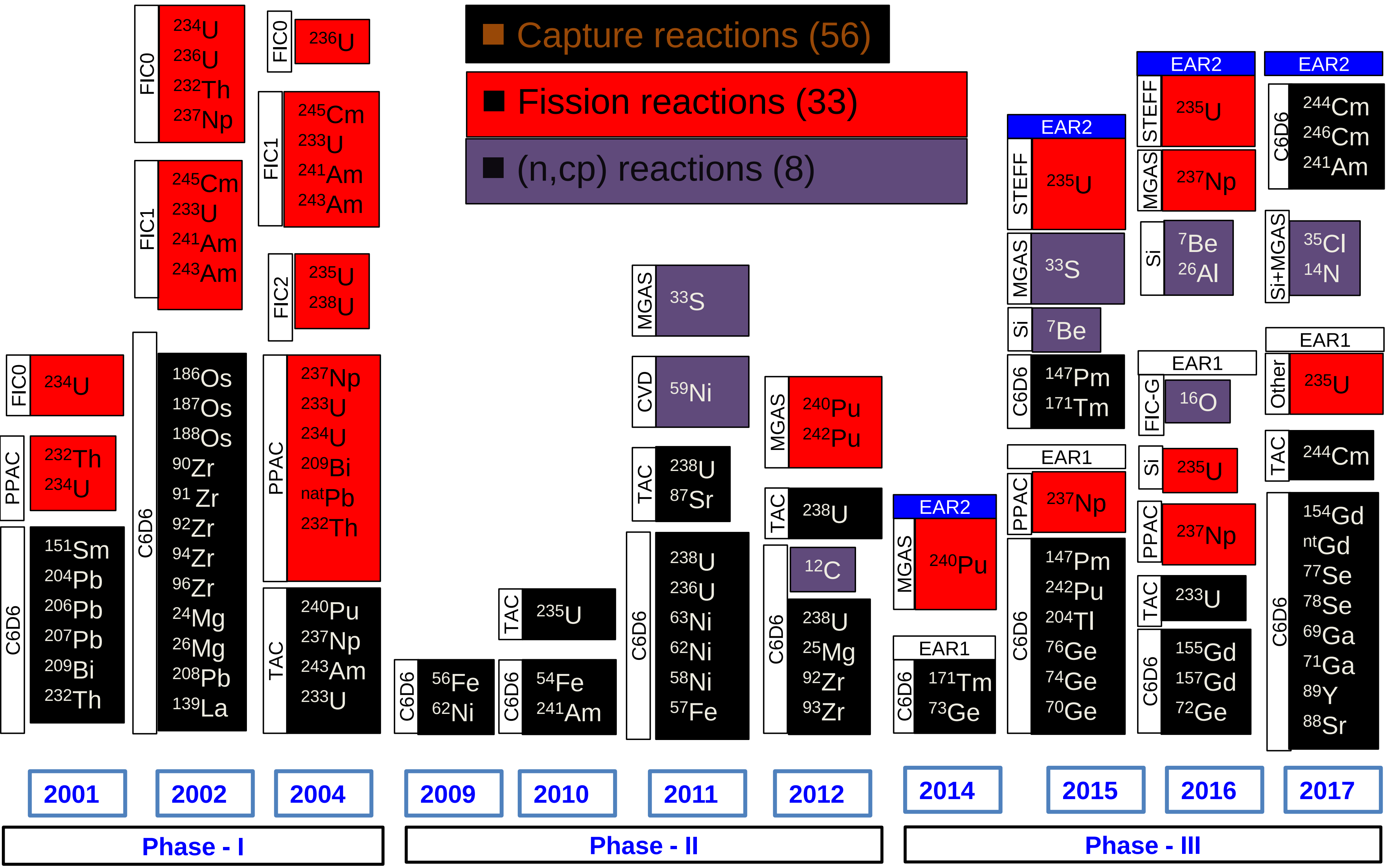
- Several C_6D_6 detectors → Total energy method
- A 4π BaF2 array (TAC) → Total absorption calorimetry





A cutting-edge technology for detection of γ rays is mandatory for high accuracy measurements

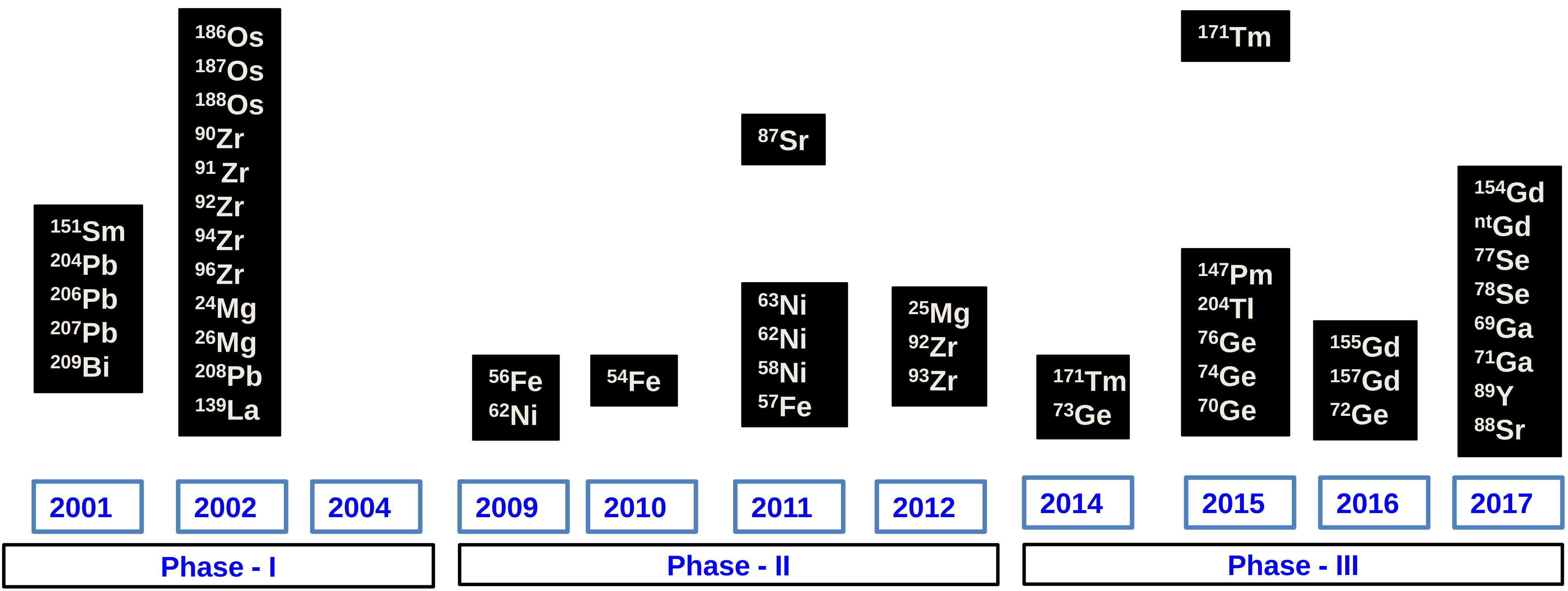
n_TOF at glance



n_TOF at glance

Nearly 50 (n,γ) reaction of interest for Nuclear Astrophysics studied at n_TOF so far:

- Branching points isotopes
- Abundancies in pre-solar grains
- Magic nuclei and end-points
- Seed-isotopes
- Cosmo-Cronometer



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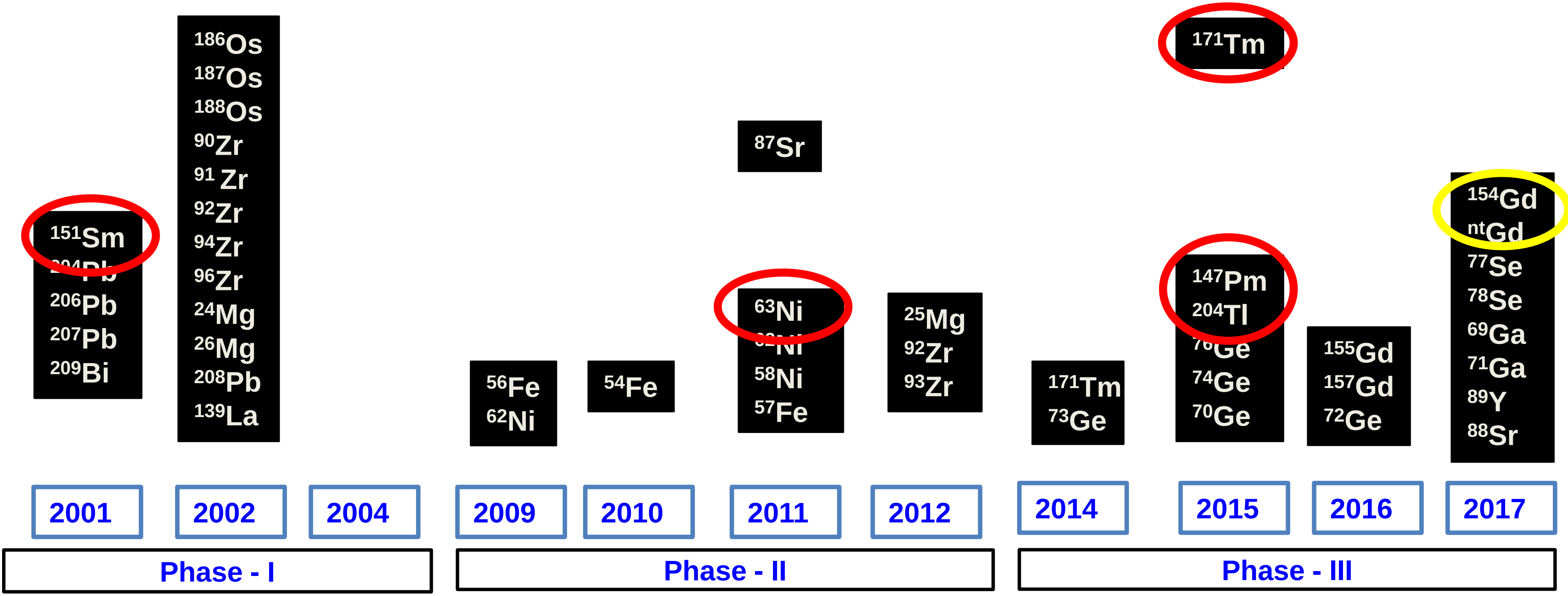
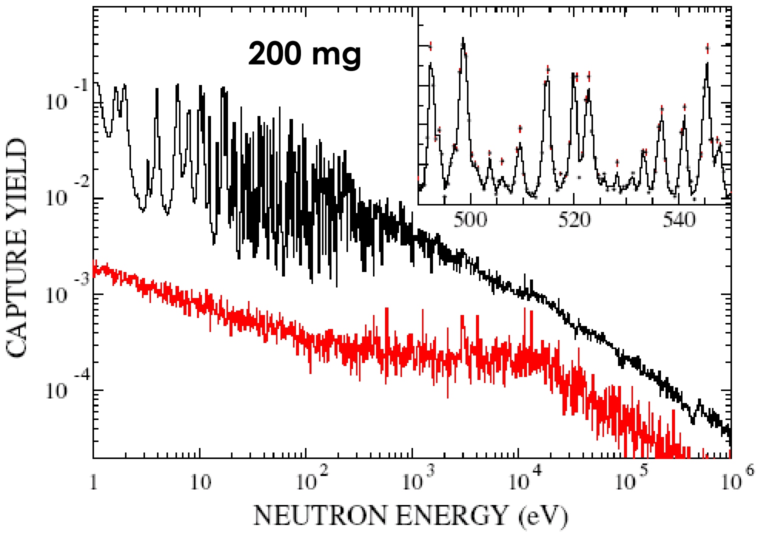
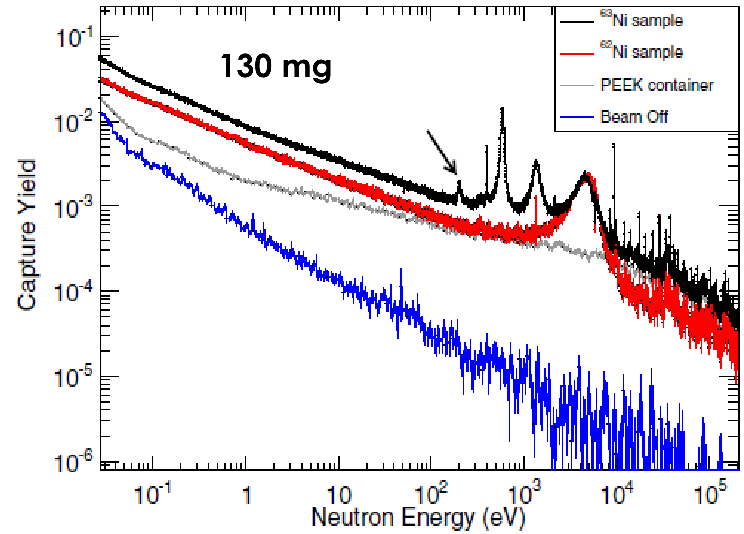


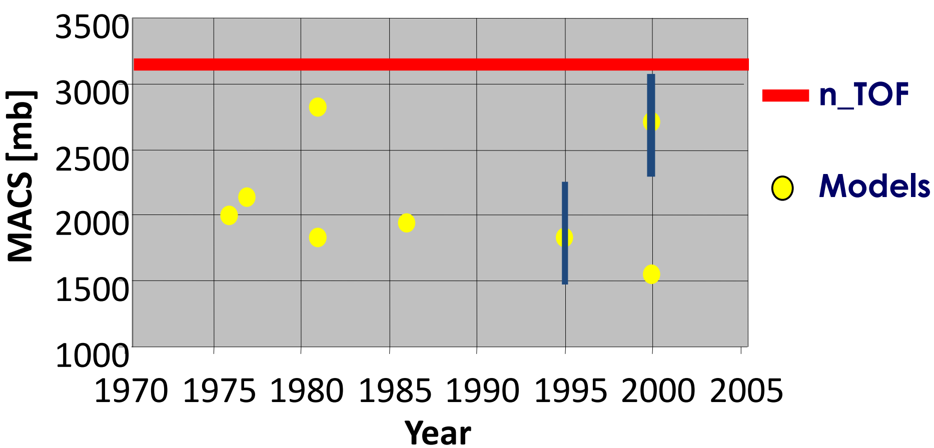
The past (fraction of)

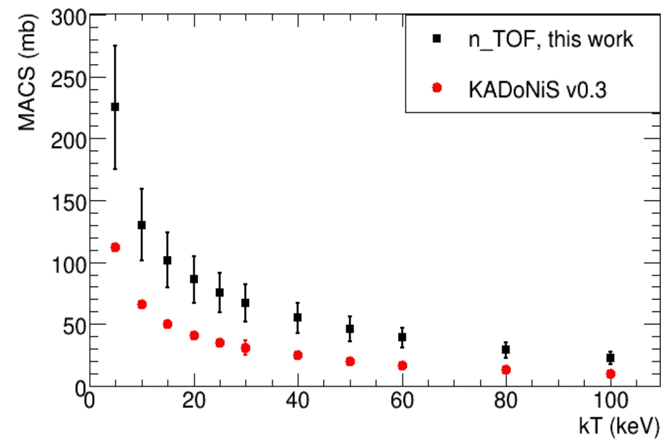
^{151}Sm ($t_{1/2}$=93 y), determines **abundance** of **$^{152,154}Gd$**



^{63}Ni ($t_{1/2}$=100 y) **first branching point** determines **abundance** of **$^{63,65}Cu$**







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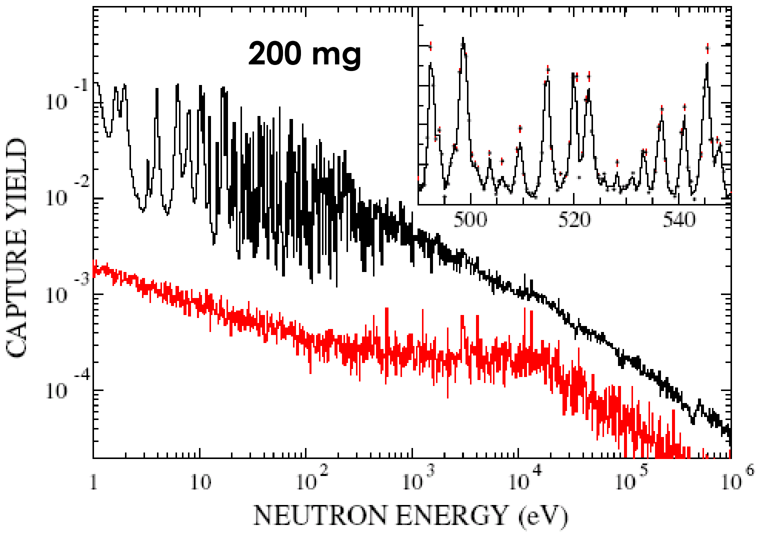

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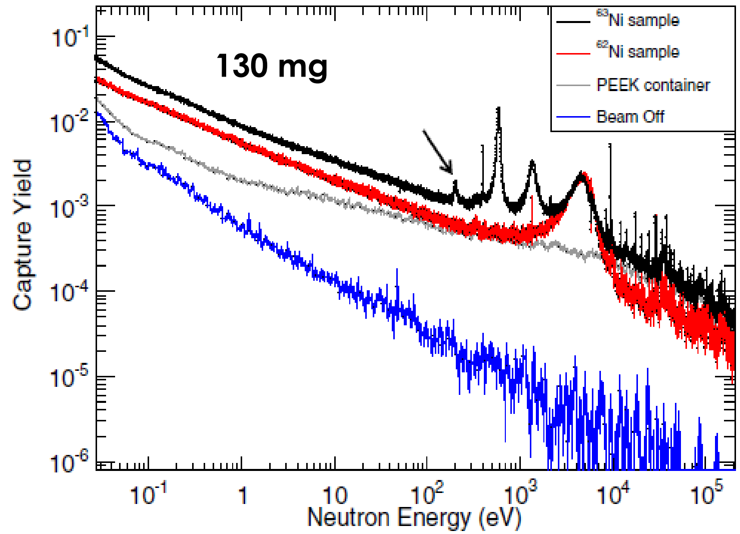

First, strong evidence of thermal pulsing in AGB stars.

Strong constraints on Cu, Ni and Zn production in massive stars and subsequent supernovae

U. Abbondanno et al., Phys Rev. Lett. 93, 161103 (2004)

C. Lederer et al., Phys. Rev. Lett. 110, 022501, (2013)

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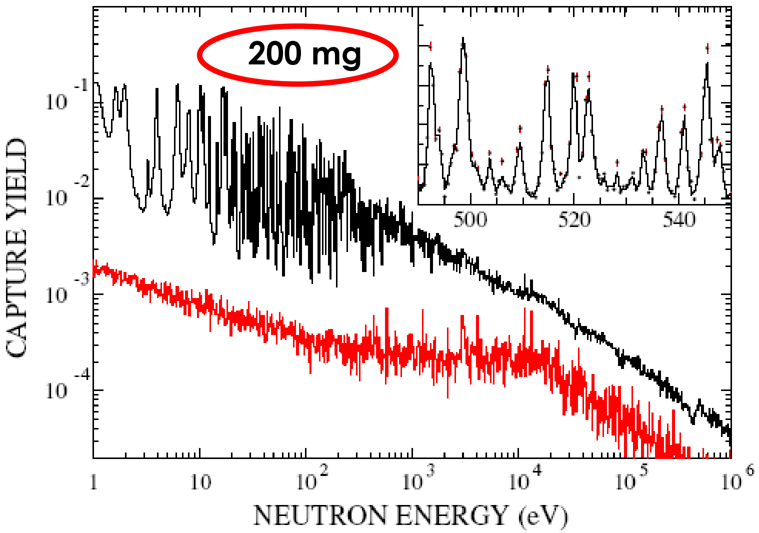

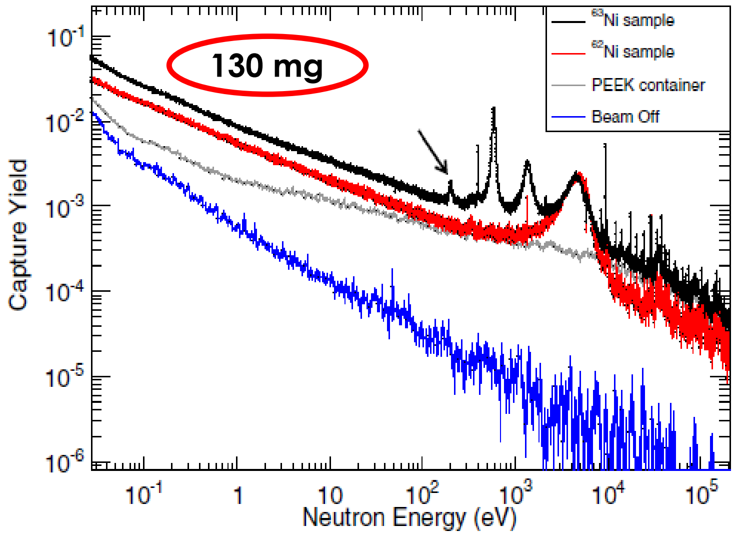

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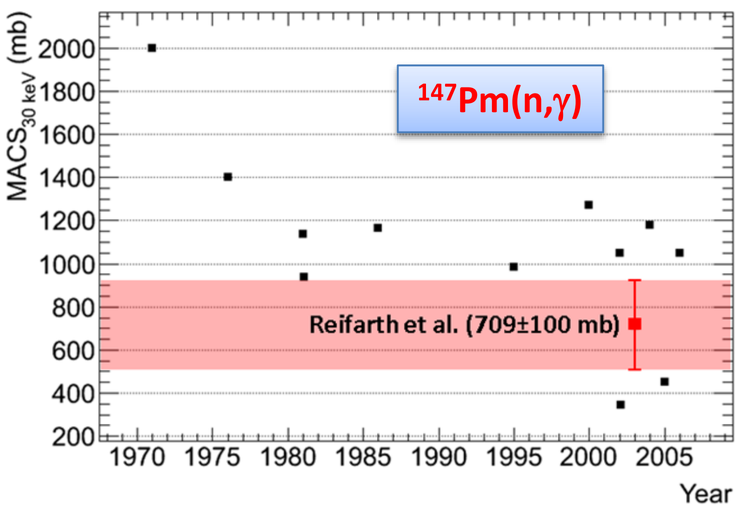

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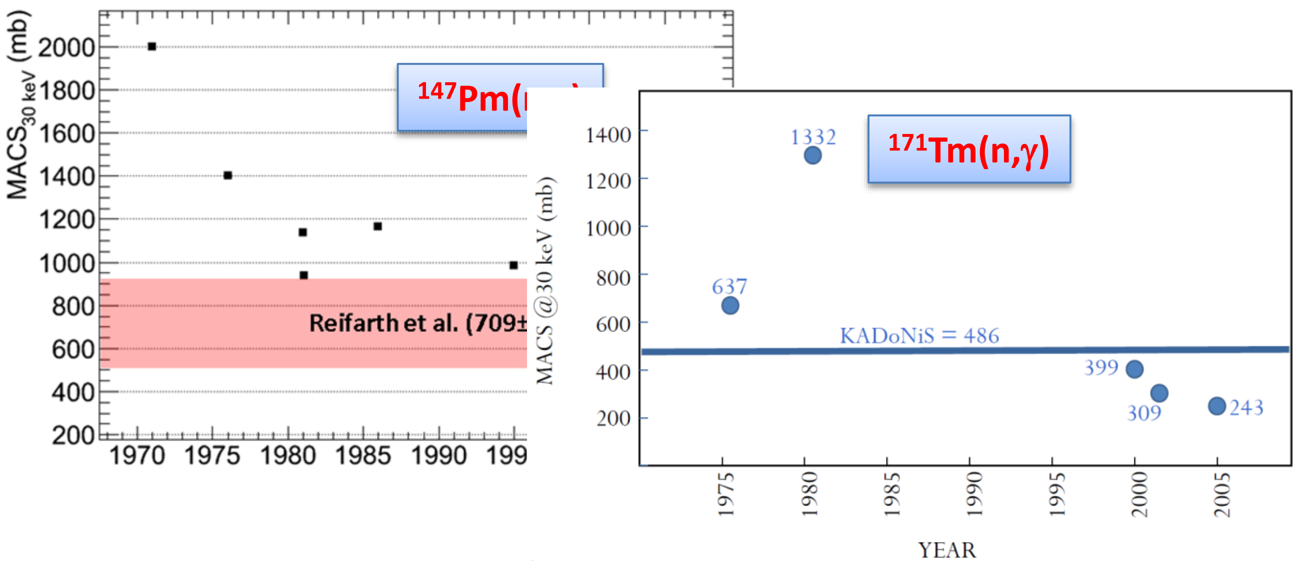

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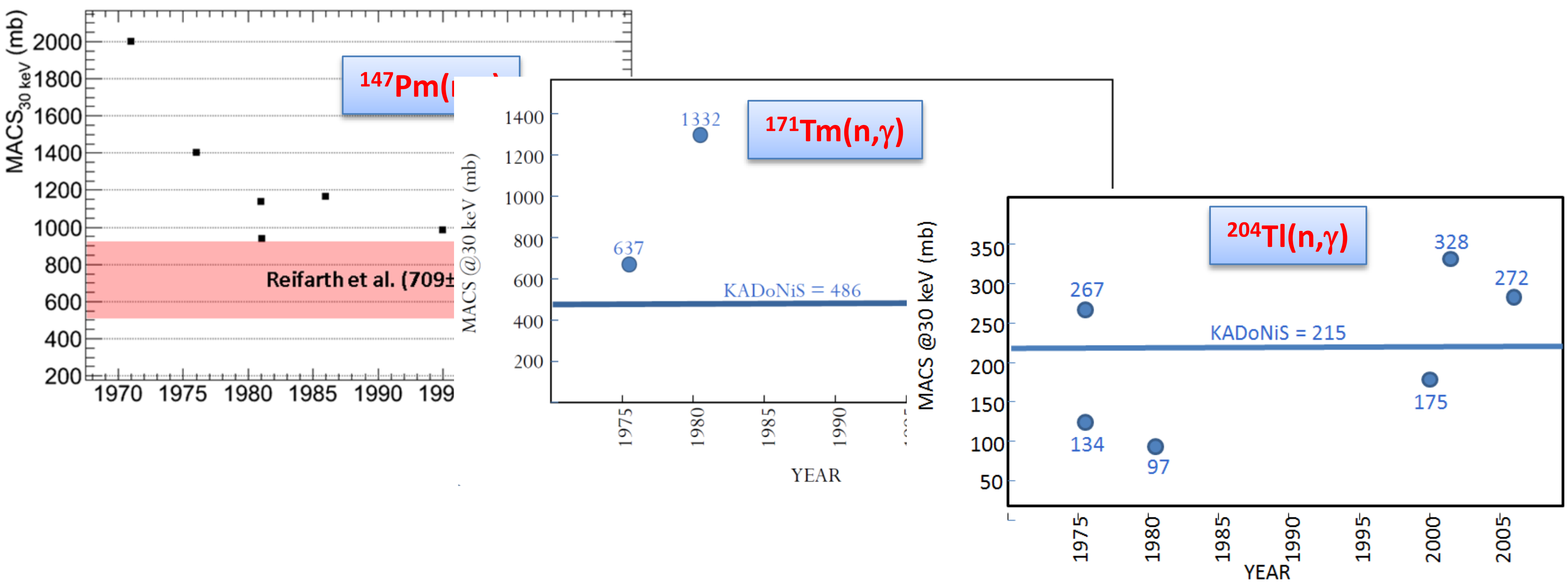
^{204}Tl ($t_{1/2}$=3.8 y) capture cross-section affects the ^{205}Pb/^{205}Tl ratio and the s-only isotope ^{204}Pb.



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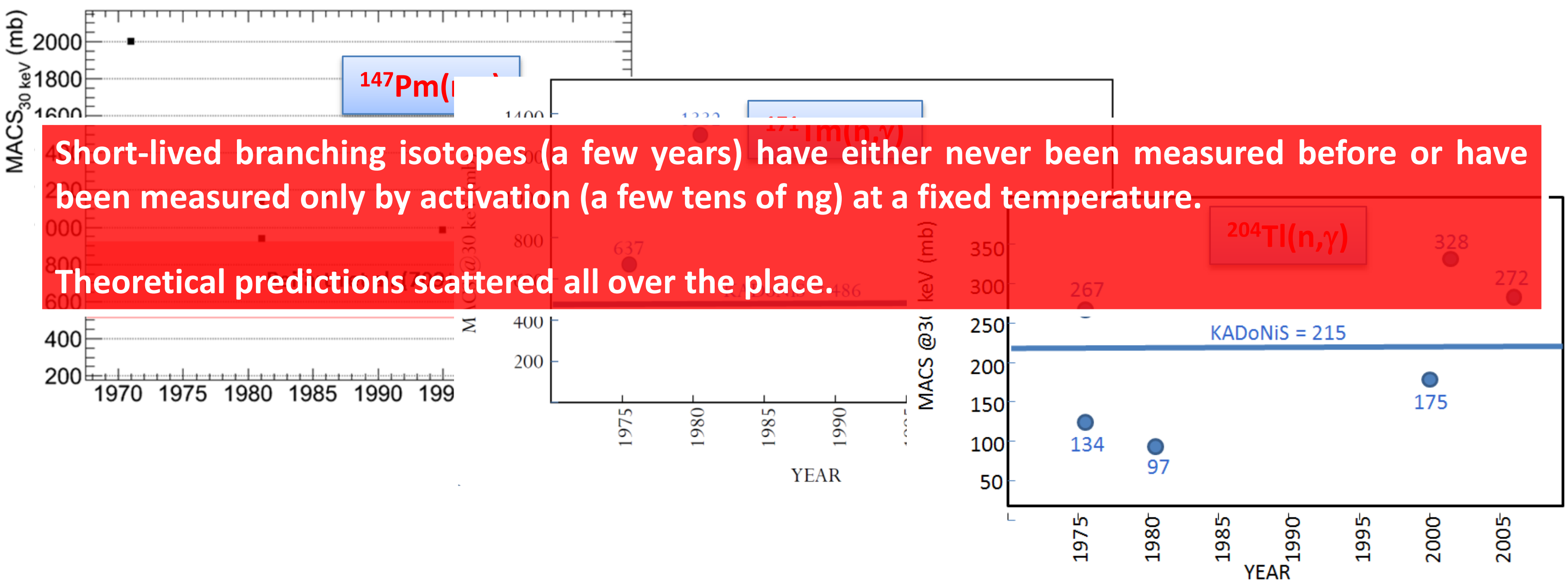


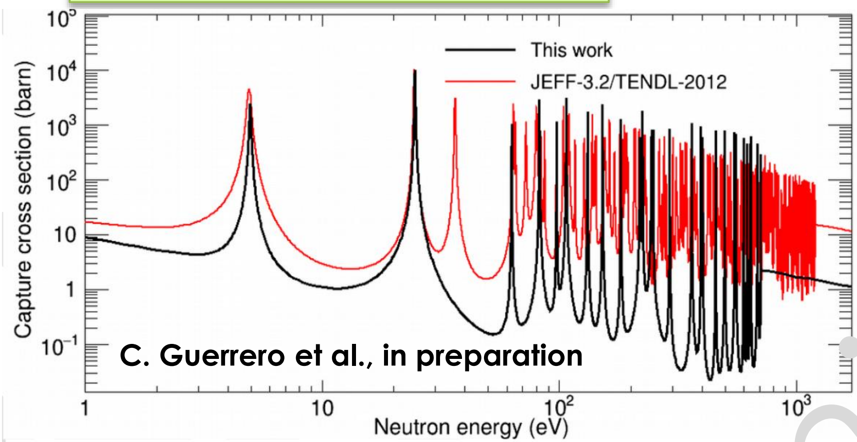
Short-lived branching isotopes (a few years) have either never been measured before or have been measured only by activation (a few tens of ng) at a fixed temperature.

Theoretical predictions scattered all over the place.

The present (fraction of)

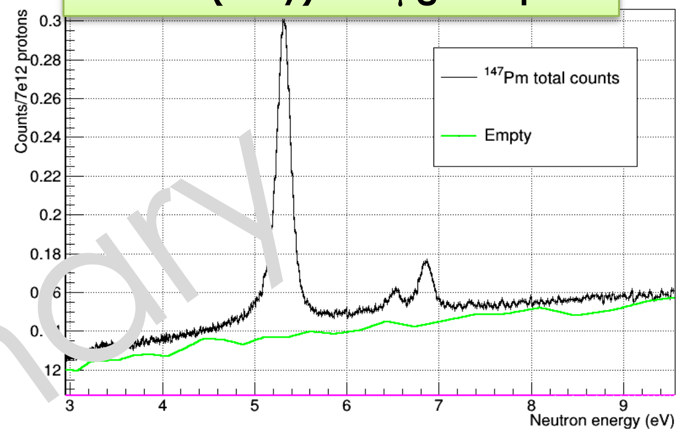
Isotope production by **neutron irradiation at @ ILL** (^{146}Nd(n,γ)^{147}Nd(β), ^{170}Er(n,γ)^{171}Er (β), ^{203}Tl(n,γ) ^{204}Tl)
Chemical separation and **sample preparation** @ PSI

^{171}Tm (1.9 y) - 3.6 mg sample



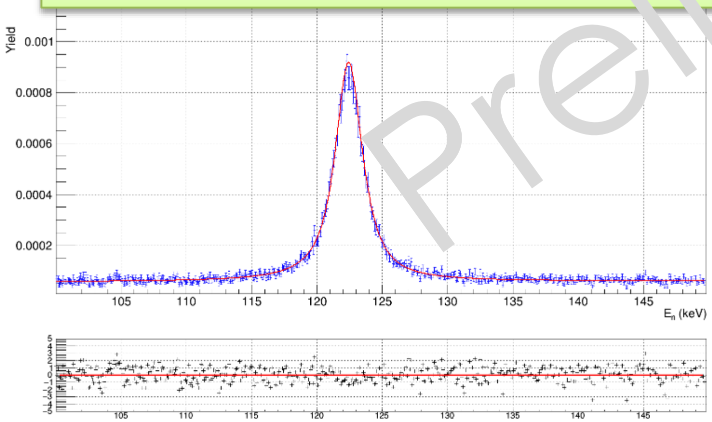
C. Guerrero et al., in preparation

^{147}Pm (2.6 y) - 80 μg sample



J. Lerendegui et al., in preparation

^{204}Tl (3.8 y) – 11 mg sample (210 GBq)



A. Casanovas et al., in preparation

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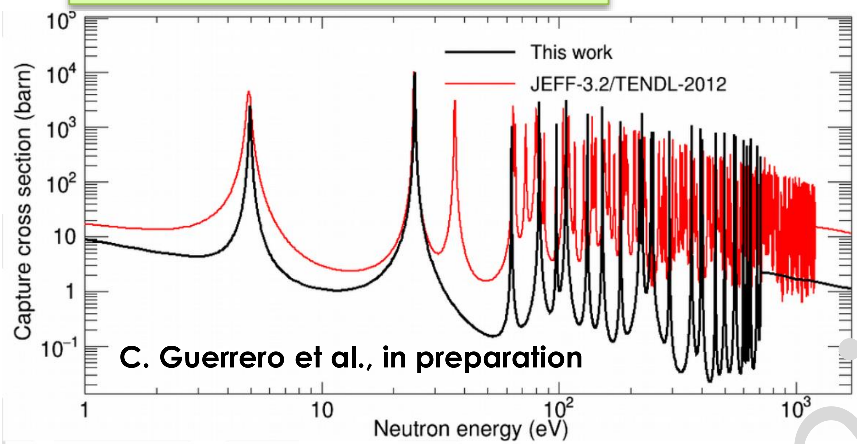

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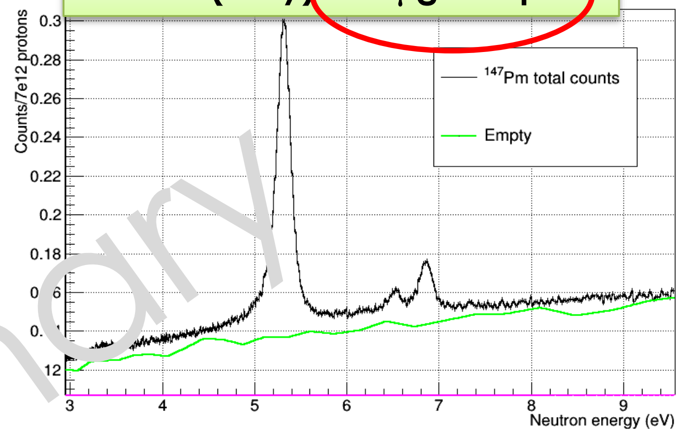

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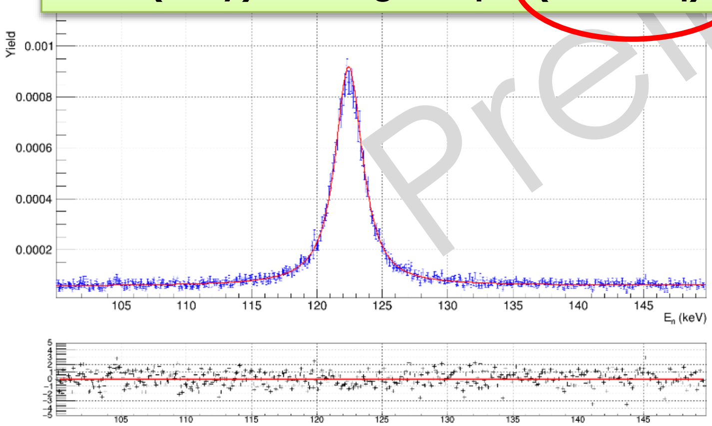

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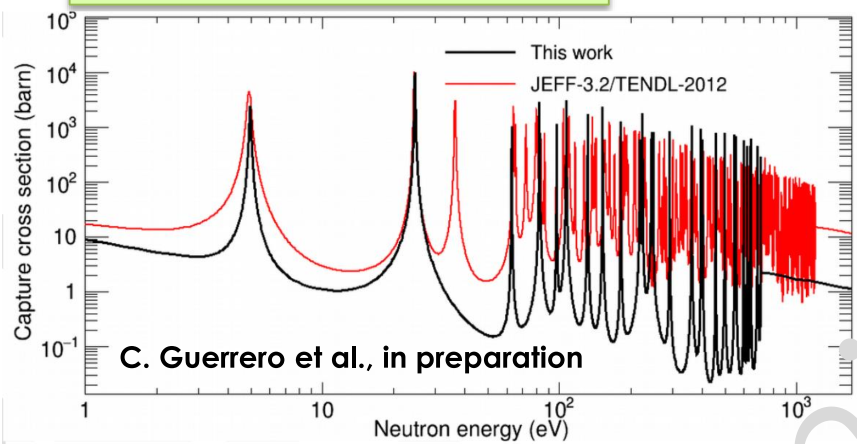

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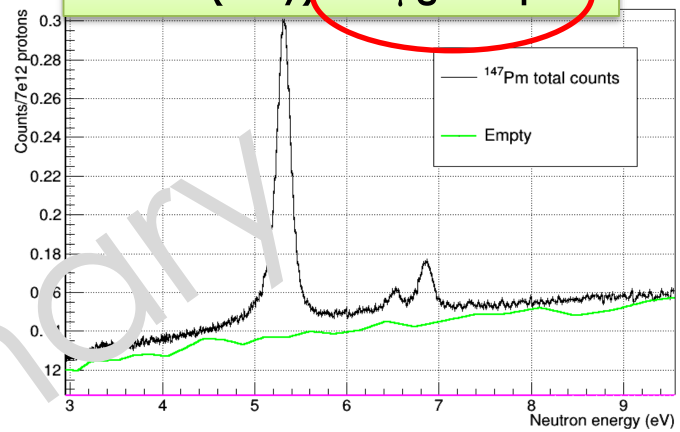

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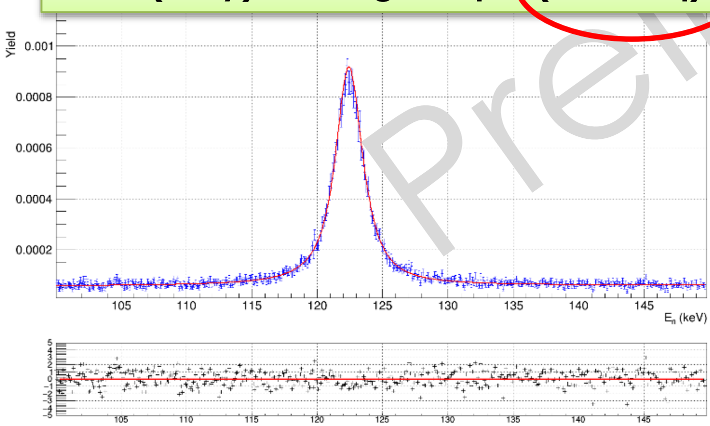


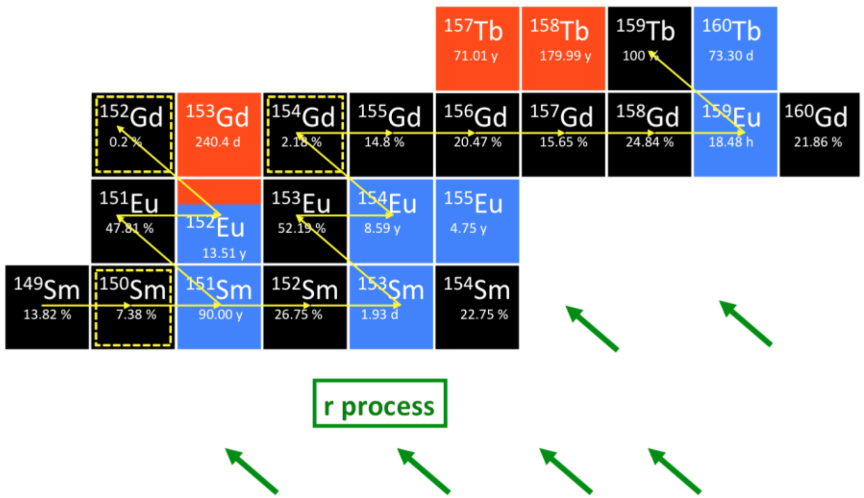
A. Casanovas et al., in preparation

Preliminary

Preliminary results indicate **important differences** in the MACS relative to calculations and (very few) previous integral measurements.

The present (fraction of)

^{154}Gd and ^{156}Gd isotopes are of particular interest because their pure s-process origin allows to check the robustness of stellar models in galactic chemical evolution (GCE) models (^{13}C pocket).



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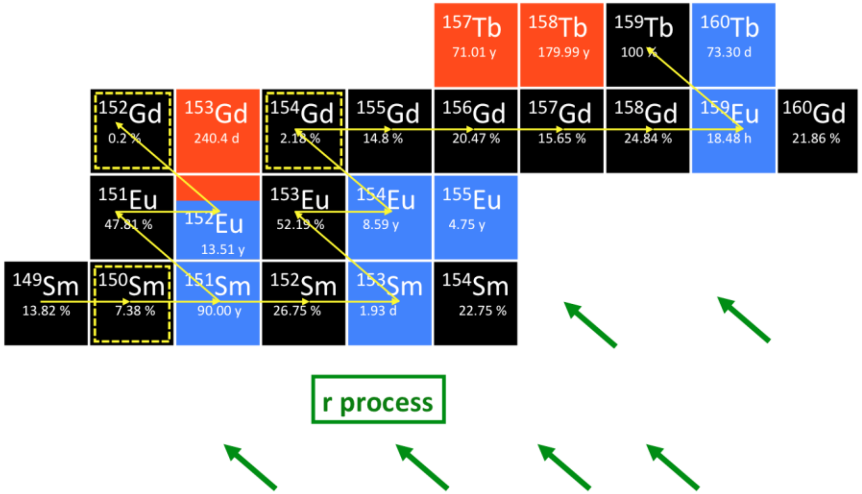
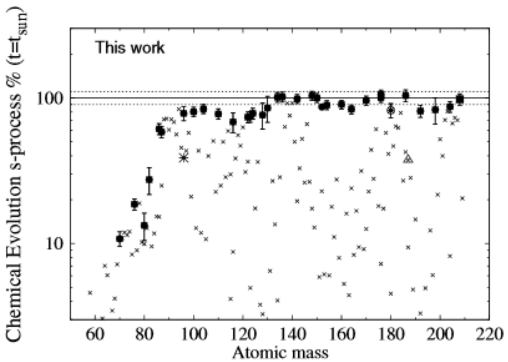
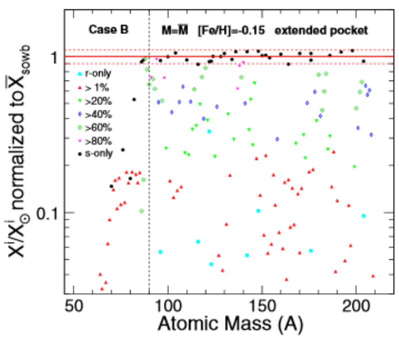
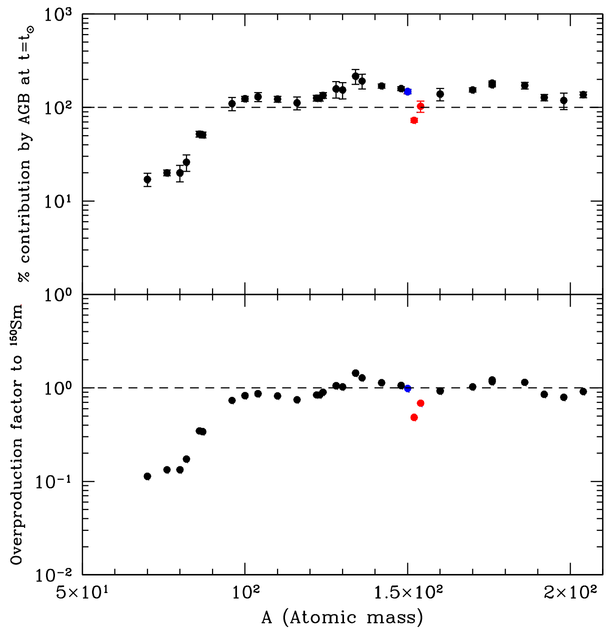


Disagreement of more than 20% between observation and model calculation of s-process abundances







S. Bisterzo, *et al.,* The Astrophysical Journal **787** (2014) 10

C. Trippella, *et al.,* The Astrophysical Journal **787** (2014) 41

S. Cristallo, *et al.,* The Astrophysical Journal **801** (2015) 53

The present (fraction of)

To date a systematic study of all isotopes has never been carried out in the energy region from thermal to about 1 MeV. Accuracy so far limited by:

- The detector used in these experiments, which in some cases suffered from high neutron sensitivity
- The experimental determination of the neutron flux, which might have been biased in some previous measurements
- The lack of information on the cross section of impurities
- The enrichment of the samples and their quality in terms of canning and other material needed for the container.

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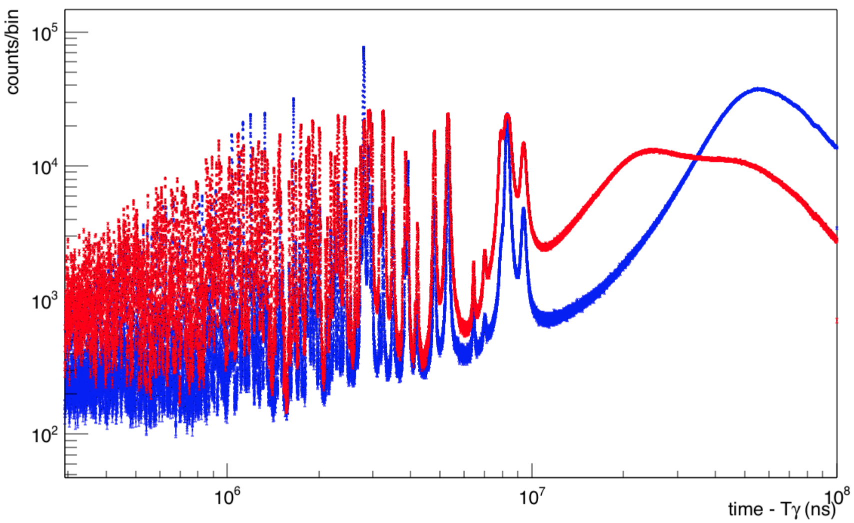
Measurement at n_TOF-EAR1 of $^{152,154,155,156,157,158,160}Gd(n,\gamma)$

+

A priori and a posteriori sample characterization



use of an array of C_6D_6 detectors. The objective is to determine stellar cross sections with overall uncertainty below 5% for thermal energies up to about $kT = 100$ keV. In total 3.3×10^{18}

Conclusions and Perspectives

- There is need of **accurate new data** on neutron cross-section for **Nuclear Astrophysics.**
- The combination of **excellent resolution, unique brightness and low background** allows to collect at n_TOF high-accuracy data, in some cases for the first time ever.
- **Since 2001,** n_TOF@CERN has provided an important contribution on many capture cross section measurements for stellar nucleosynthesis. **Stay tuned for new results..**
- **A second experimental area (EAR2)** at 20 m flight path has recently made possible to perform very challenging measurements of interest for Nuclear Astrophysics, **on short-lived radionuclides, on sub-mg samples, and on low cross section reactions.**
- **A new spallation target will be installed before 2020, for the experimental program in Nuclear Astrophysics (and more) in the next decade.**