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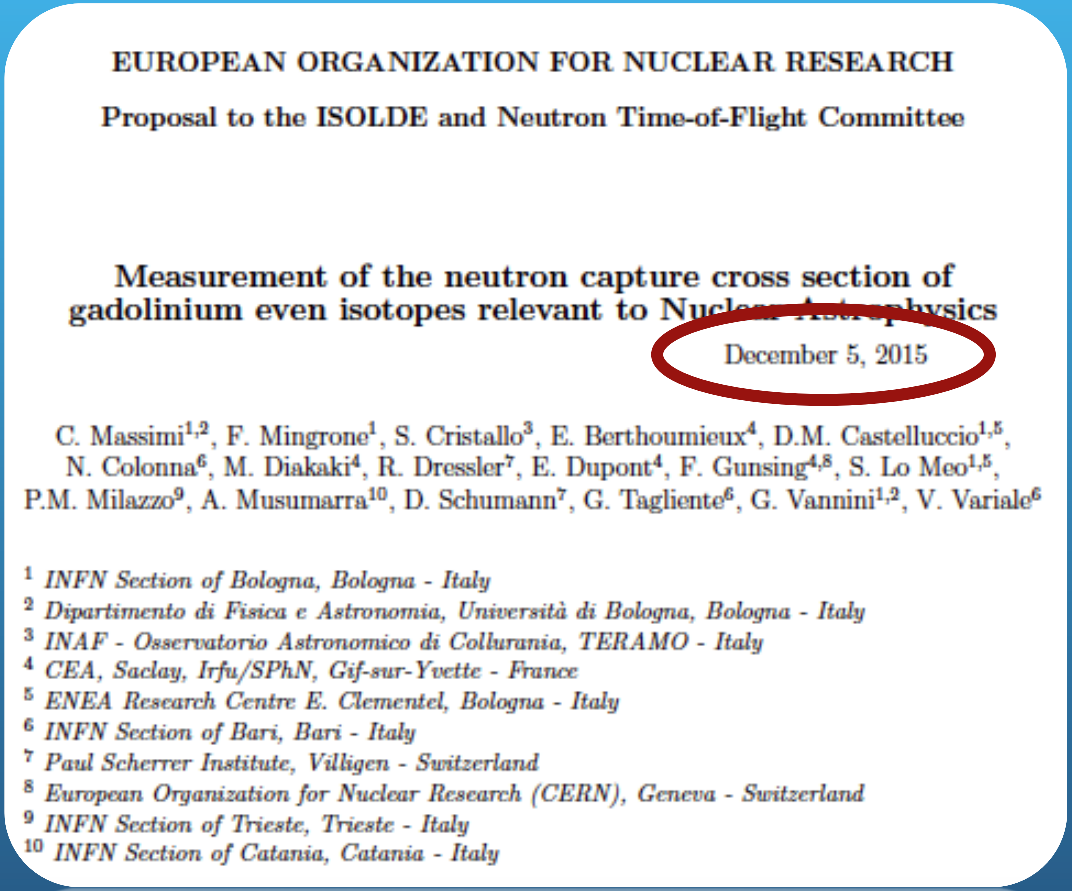
Measurement of the ^{154}Gd neutron capture cross-section at n_TOF, and its astrophysical implications

Annamaria Mazzone
INFN Bari / CNR-IC
on behalf of the n_TOF Collaboration

2018 European Nuclear Physic Conference

September 6, Bologna

The Proposal



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the neutron capture cross section of gadolinium even isotopes relevant to Nuclear Astrophysics

December 5, 2015

C. Massimi[1,2], F. Mingrone[1], S. Cristallo[3], E. Berthoumieux[4], D.M. Castelluccio[1,5],
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P.M. Milazzo[9], A. Musumarra[10], D. Schumann[7], G. Tagliente[6], G. Vannini[1,2], V. Variale[6]

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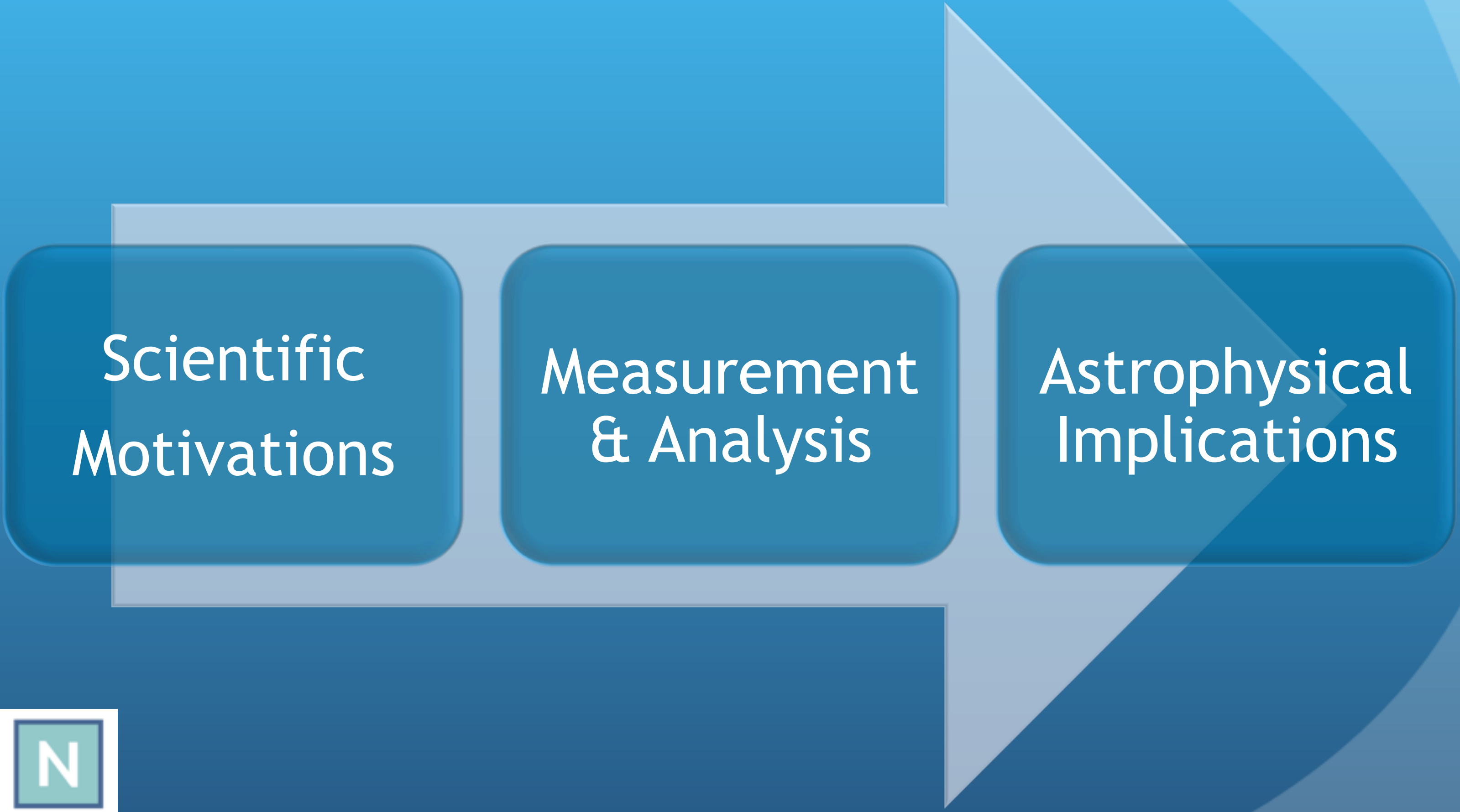
Outlines



Scientific Motivations

Measurement & Analysis

Astrophysical Implications

Outlines

Scientific Motivations

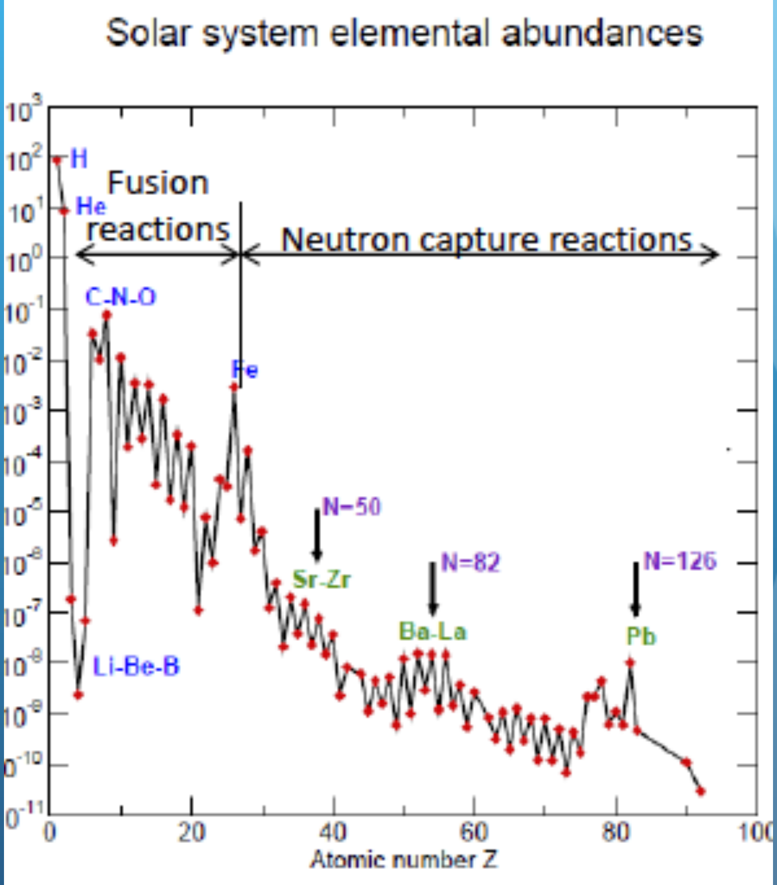
Measurement & Analysis

Astrophysical Implications

Solar Nucleosynthesis

Chemical elements beyond Iron are synthesized via neutron capture reactions in stars

- ≈½ by the s-process
- ≈½ by the r-process

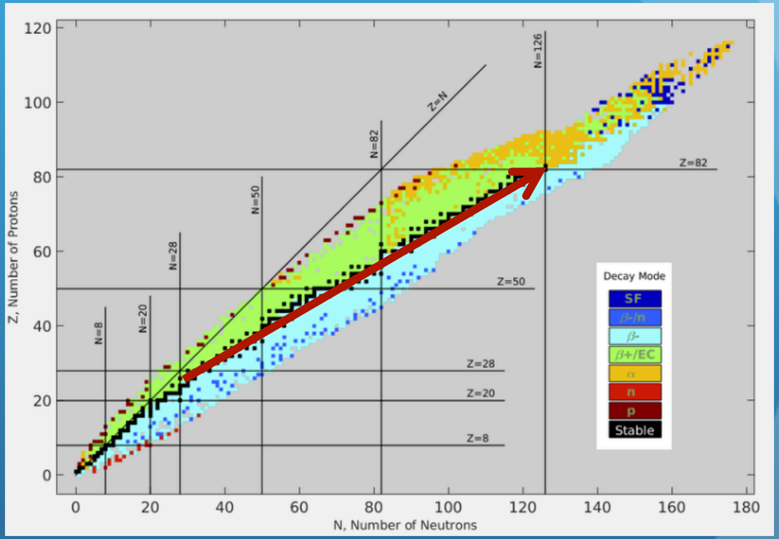


Solar system elemental abundances

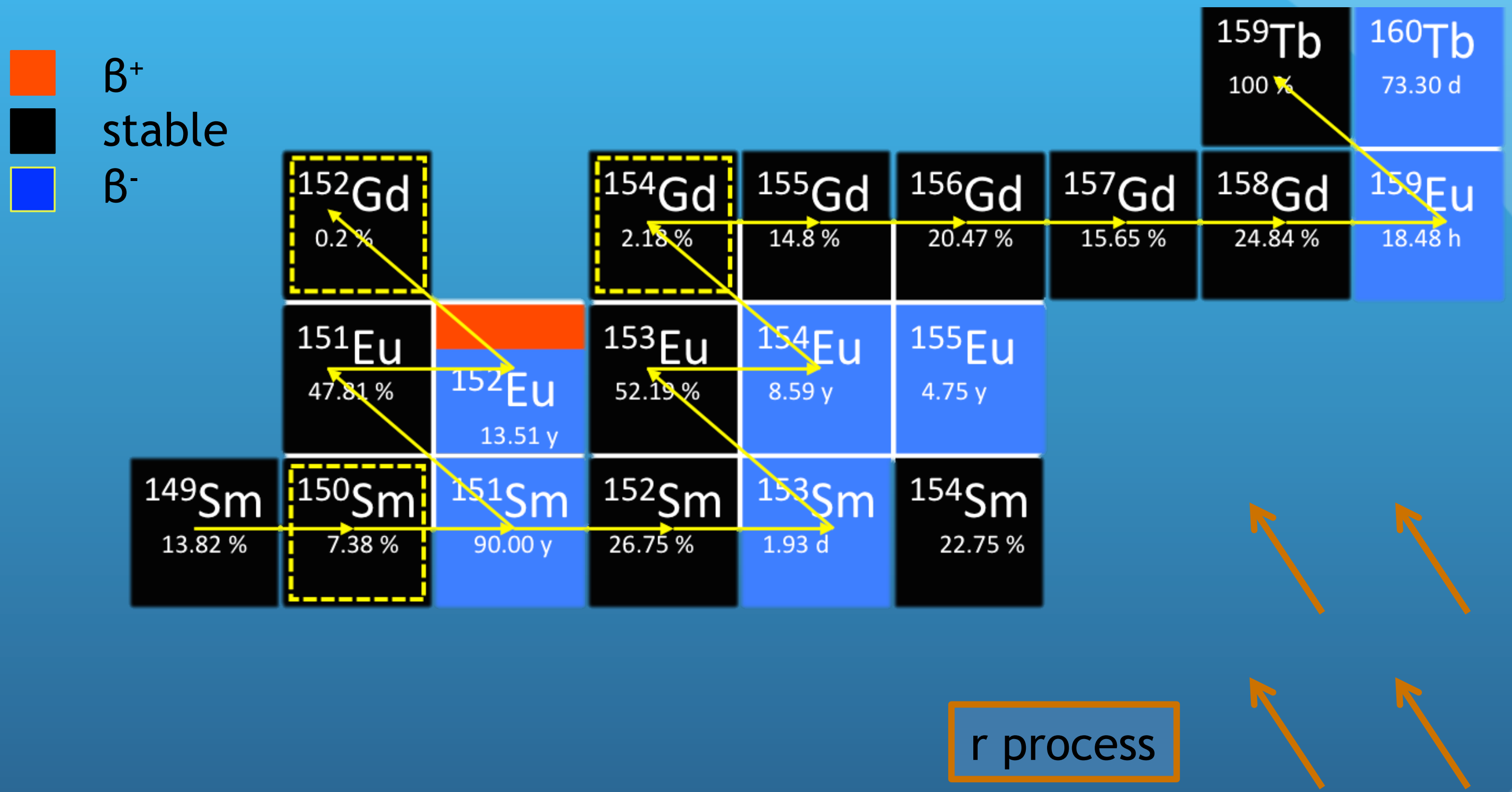
s-Process

- The time scale for n capture reactions being much slower than for beta-decays implies that the reaction path follows the stability valley

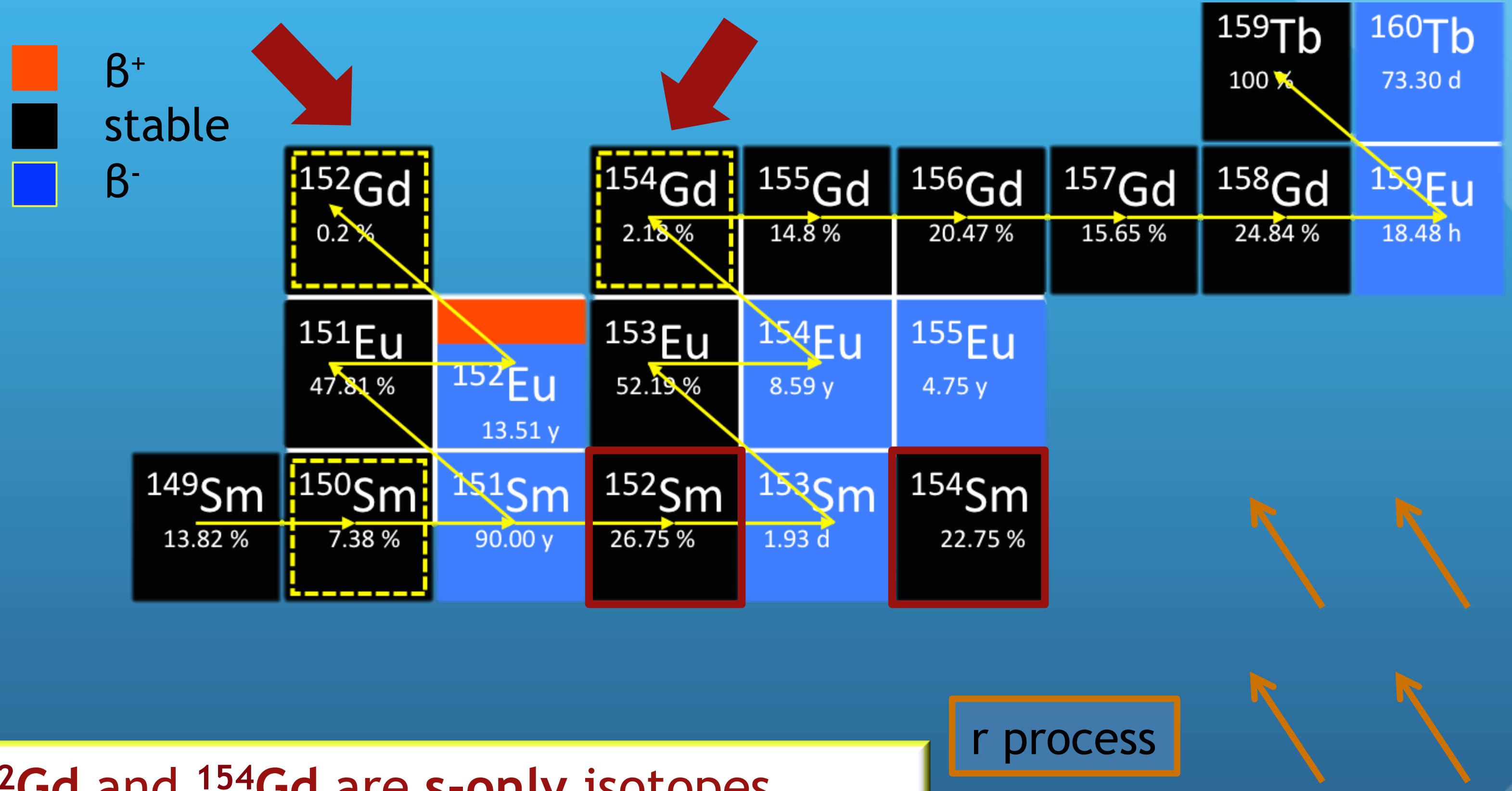
- **Low-mass Asymptotic Giant Branch (AGB)** stars are the sites for the main component of the s-process, for elements between strontium and lead.



Motivations



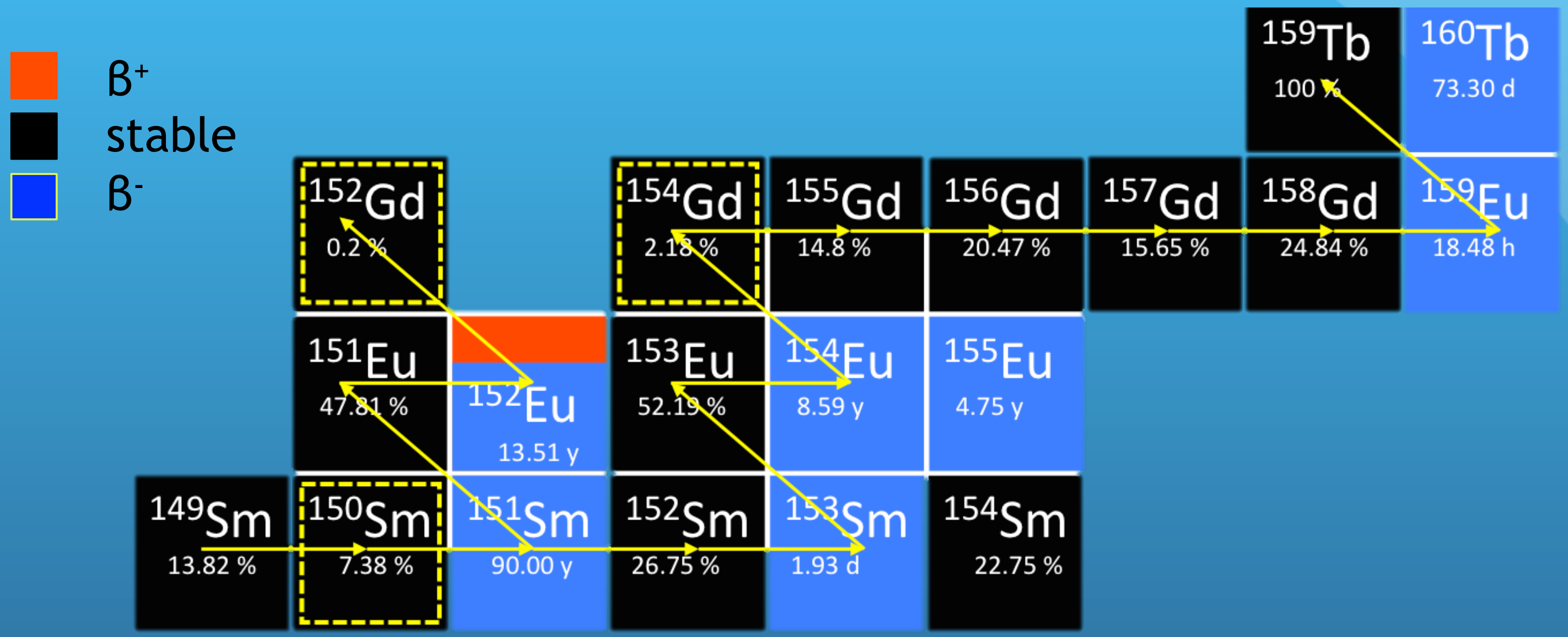
Motivations



^{152}Gd and ^{154}Gd are s-only isotopes

They can be produced only via s-process because they are shielded against the β-decay chains from the r-process region by the isobars samarium

Motivations



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Proof of galactic chemical evolution (GCE) models

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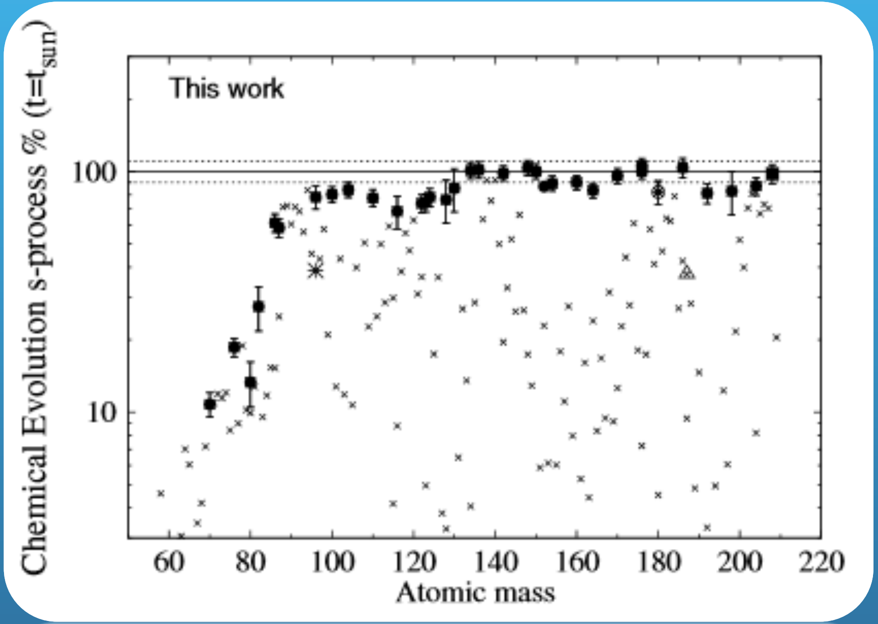
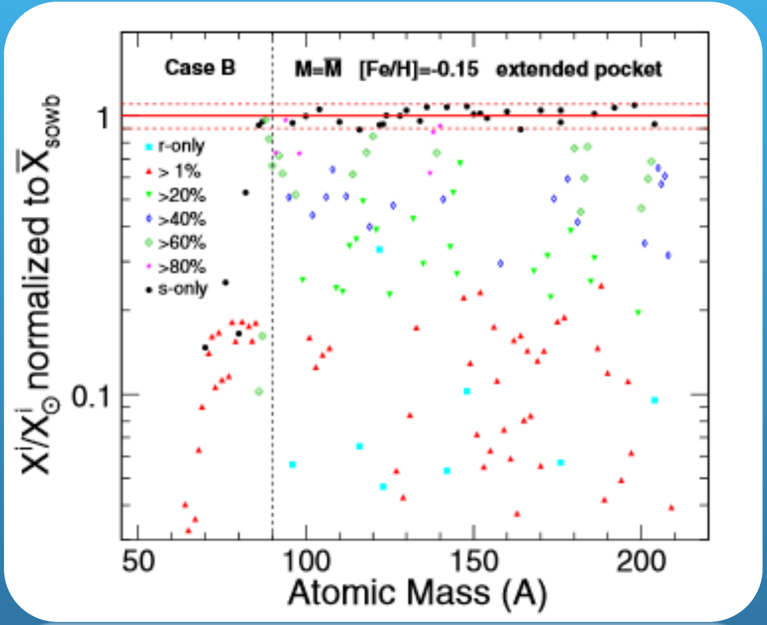
3 Recent Independent Studies…



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

3 Recent Independent Studies…



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

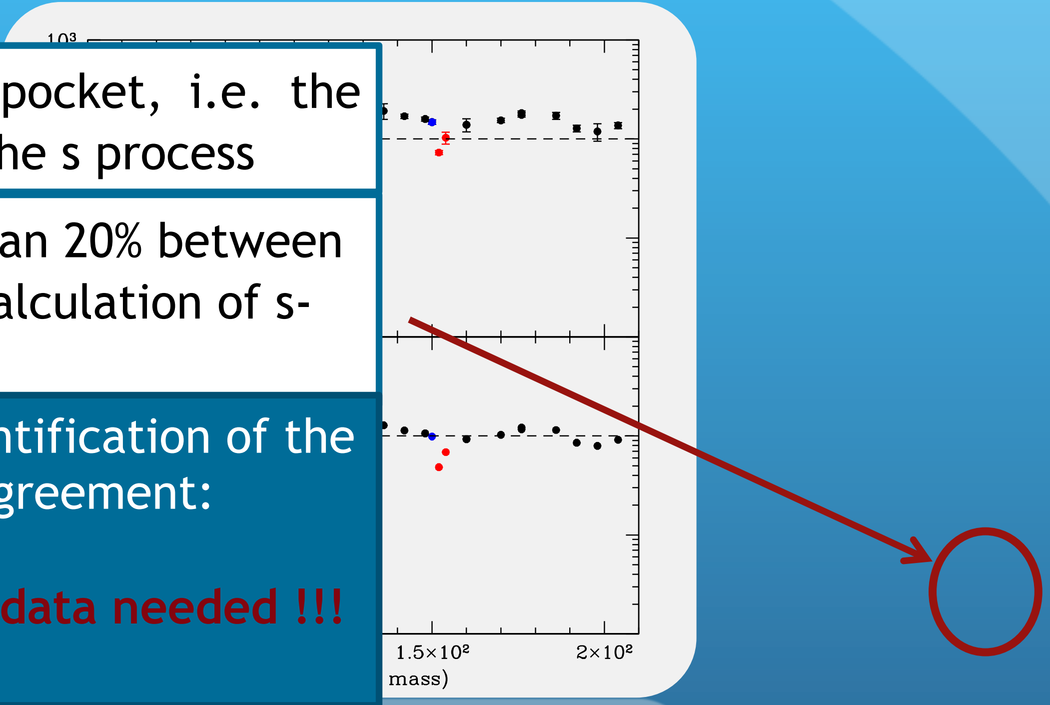
3 Recent Independent Studies…

Constraints for the ^{13}C pocket, i.e. the main neutron source of the s process

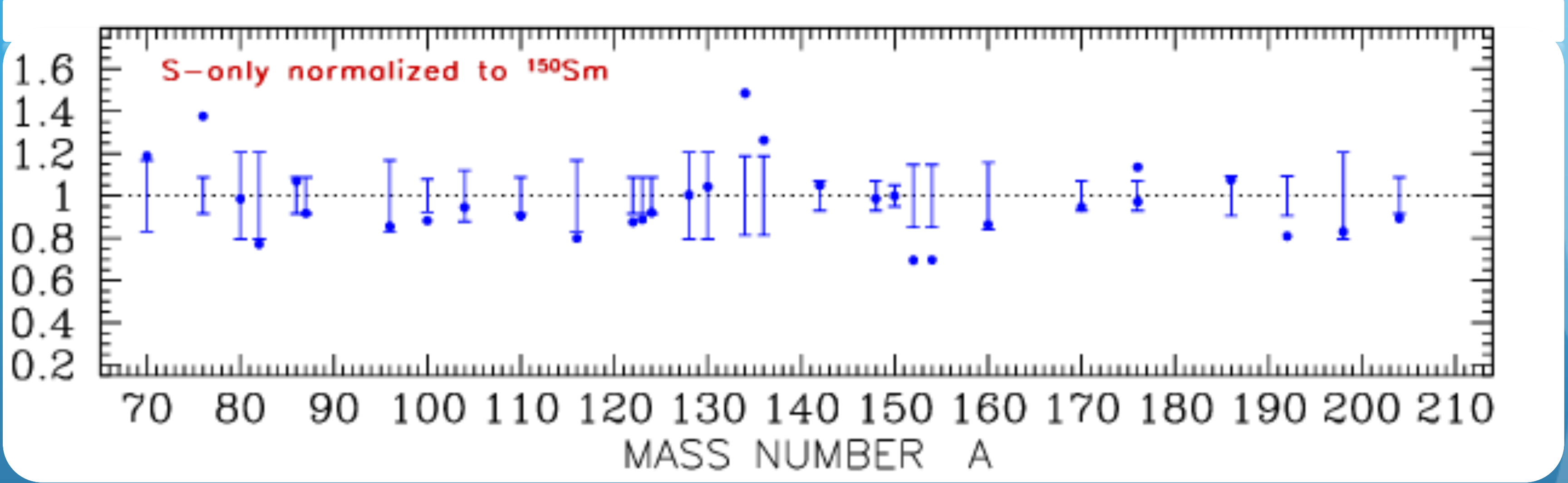
Disagreement of more than 20% between observation and model calculation of s-process abundances

So far, no conclusive identification of the causes of the disagreement:

more accurate nuclear data needed !!!

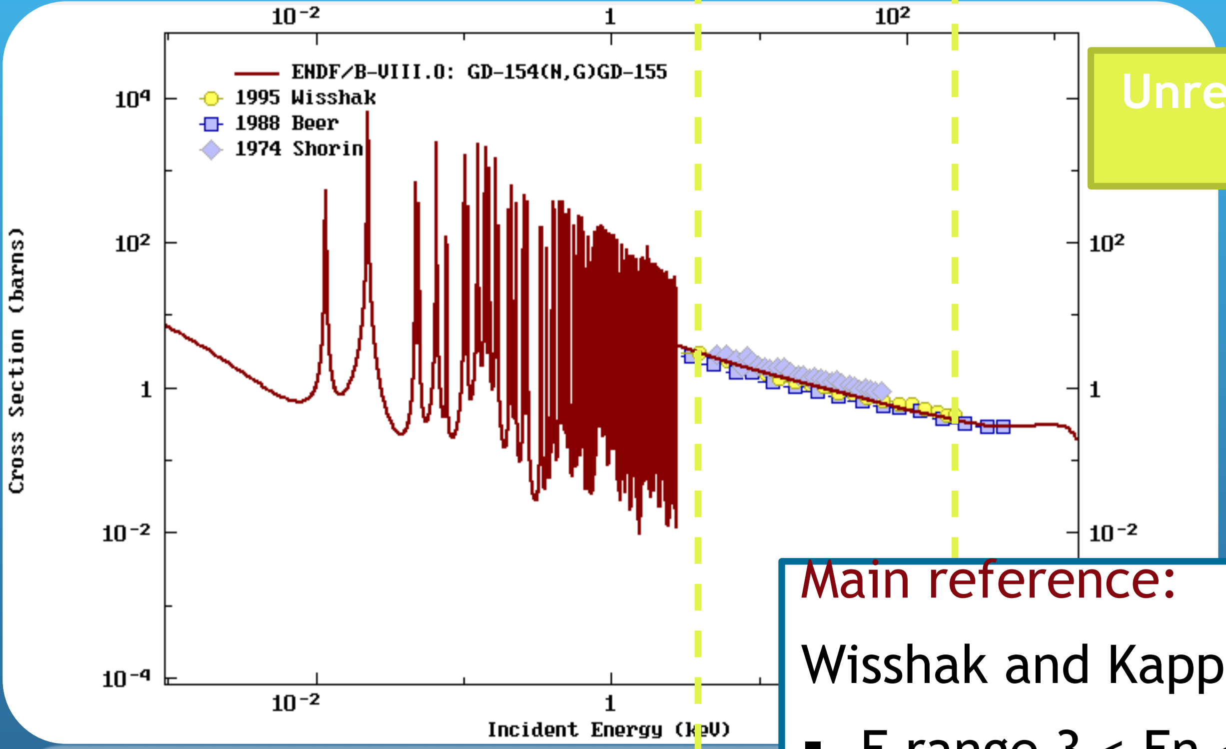


S. Cristallo, *et al.*,
The Astrophysical Journal 801 (2015) 53



Prantzos, N., et al., MNRAS, 476 3432 (2018)

Gd Data In Literature



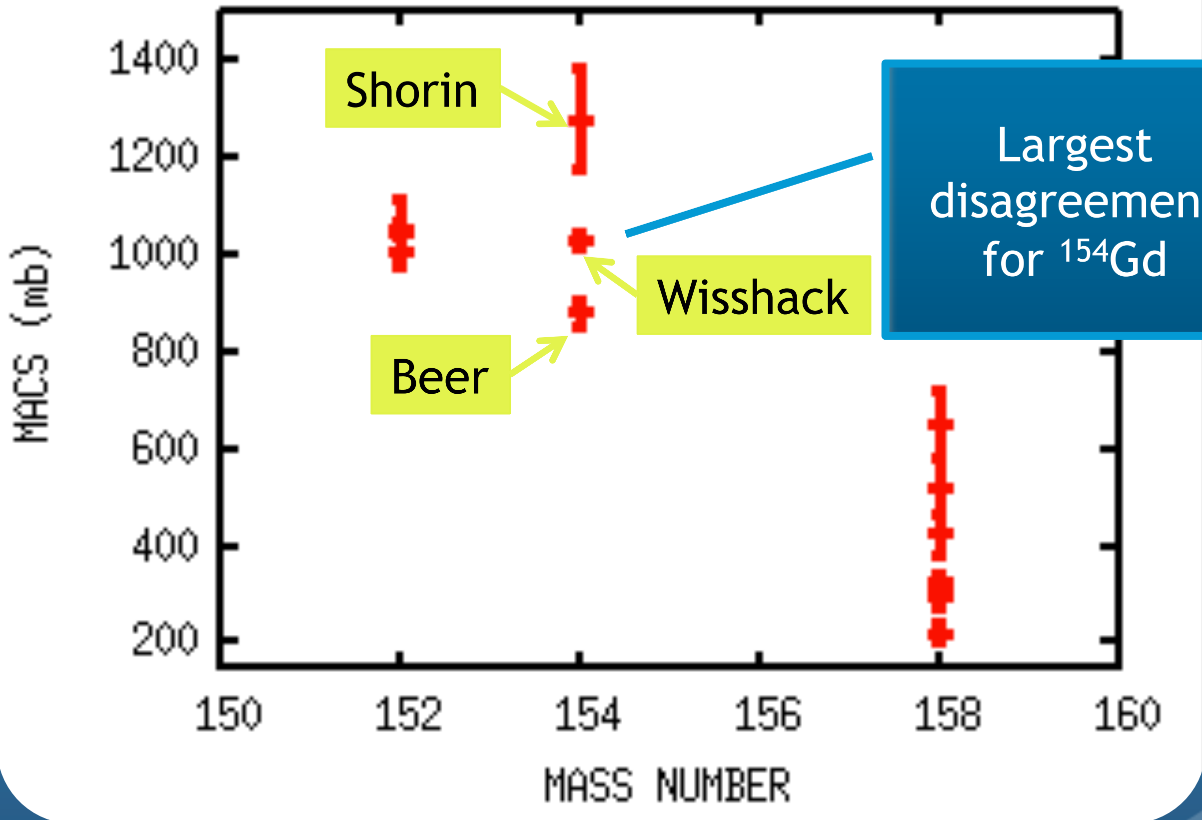
Unresolved Resonance Region

Main reference:

Wisshak and Kappeler

- E range 3 < En < 200 keV
- 4π BaF2 detector
- The error is of about 1%

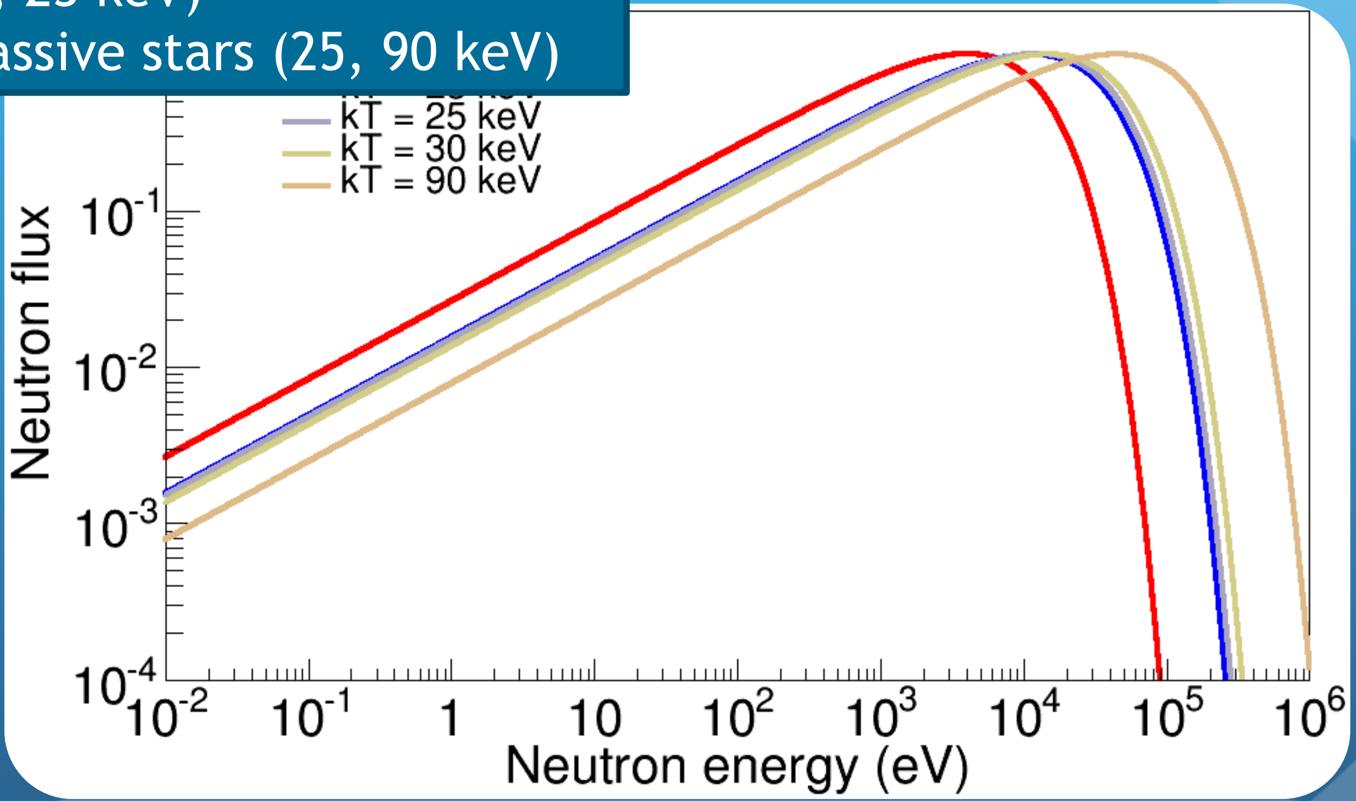
MACS



Largest disagreement for ^{154}Gd

The n_TOF project

Stellar spectra:
AGB (8, 23 keV)
and Massive stars (25, 90 keV)



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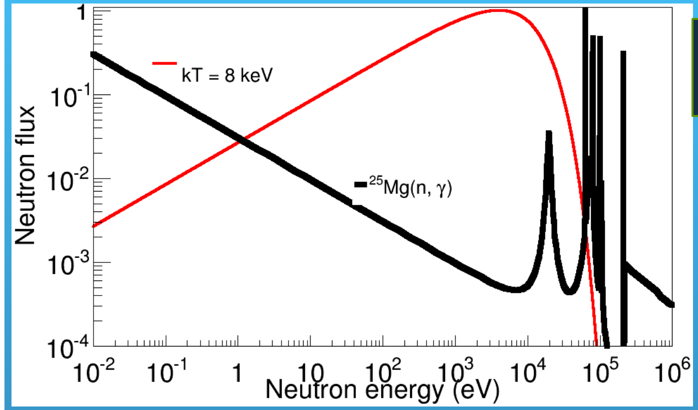
The n_TOF project

Istituto Nazionale di Fisica Nucleare



For Astrophysical applications it is important to determine Maxwellian Averaged Cross-Sections (MACS), for various temperatures (kT depends on stellar site).

Reaction rate (cm^{-3}s^{-1}): $r = N_A N_n v\sigma(v)$

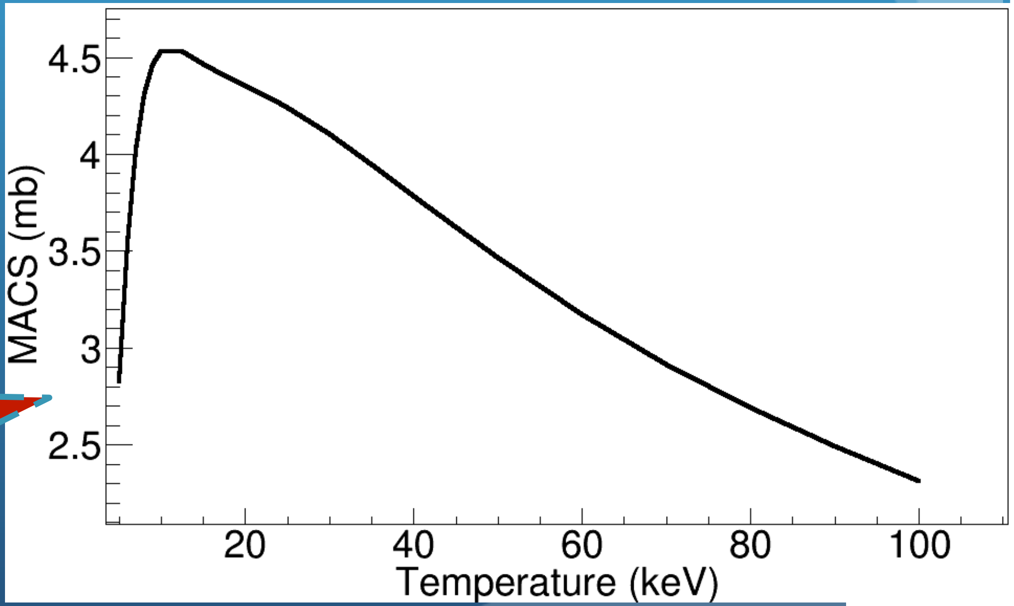
$$\rightarrow r = N_A N_n \langle \sigma \cdot v \rangle$$

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

Two methods are used to determine MACS:

1. measurement of **energy dependent** neutron capture cross-sections;

n_TOF@
CERN



Outlines

- Scientific Motivations
- Measurement & Analysis
- Astrophysical Implications

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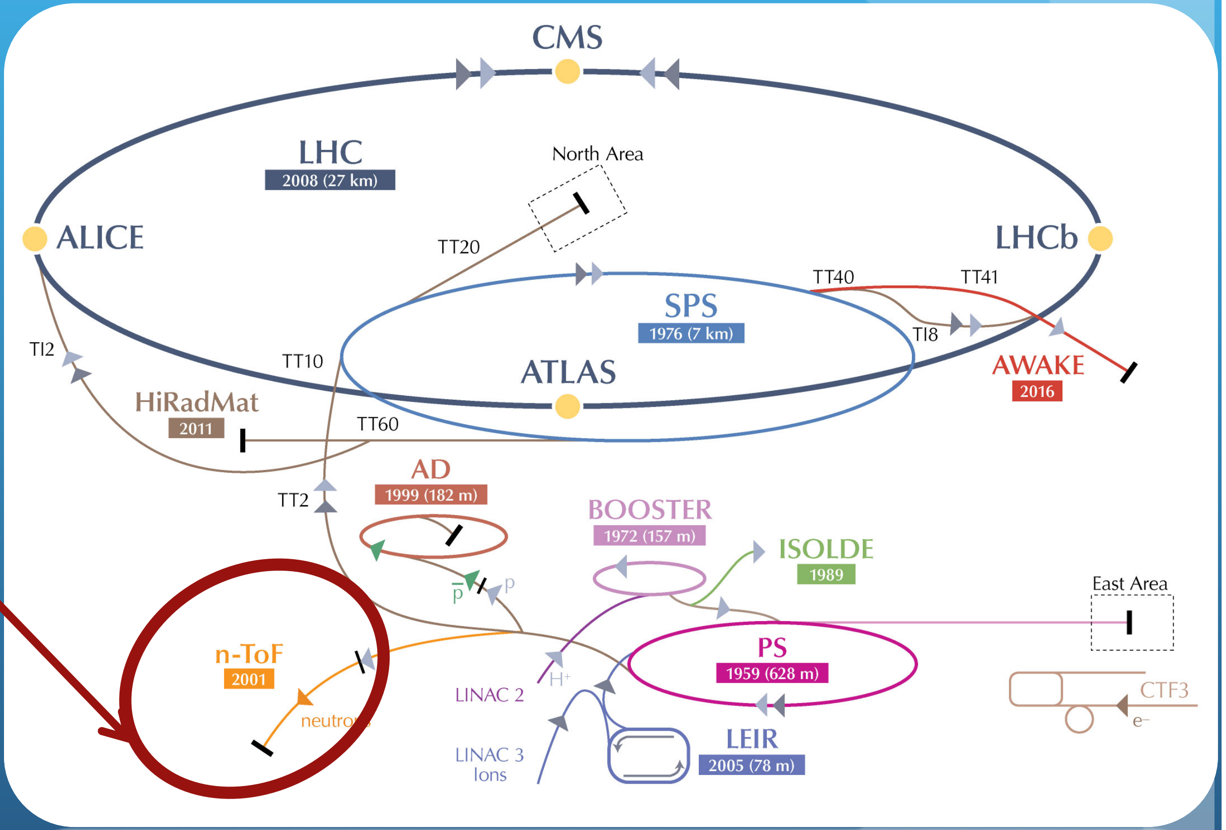
The n_TOF project

Neutron Time-Of- Flight facility: **n_TOF**



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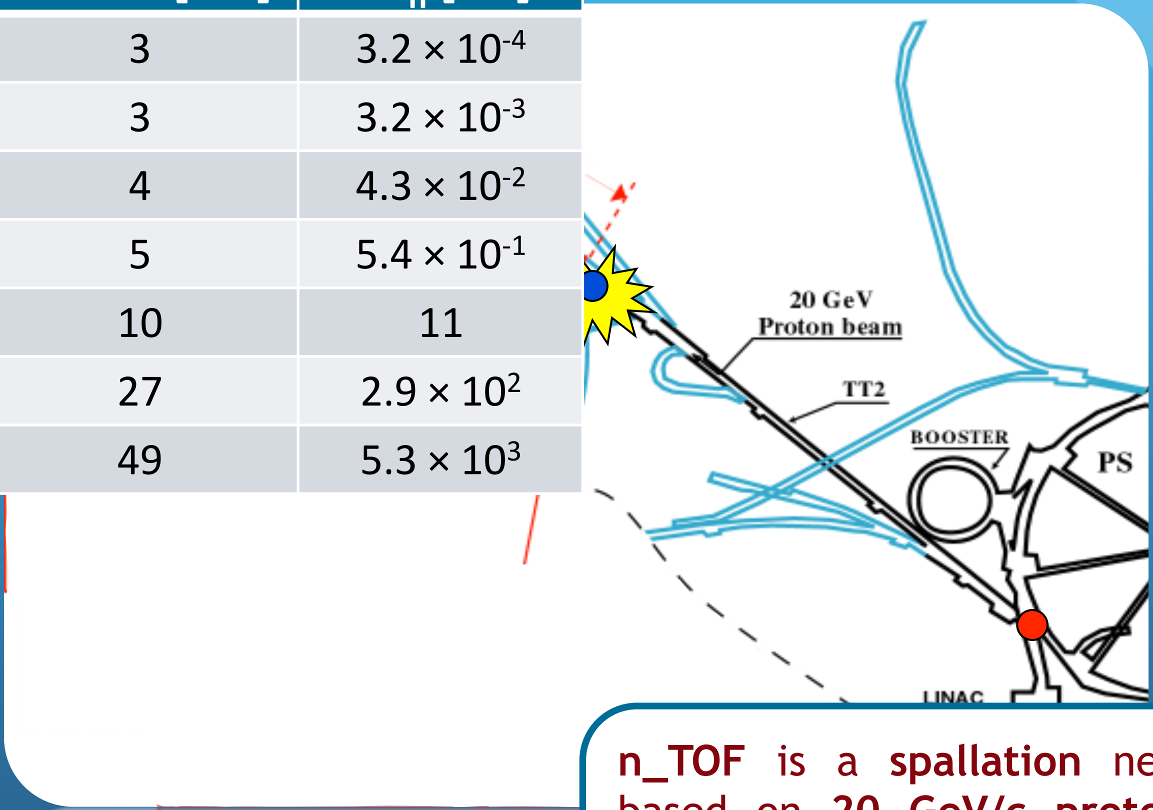
The n_TOF project

E_n [eV]	FWHM [cm]	ΔE_n [eV]
1	3	3.2×10^{-4}
10	3	3.2×10^{-3}
10^2	4	4.3×10^{-2}
10^3	5	5.4×10^{-1}
10^4	10	11
10^5	27	2.9×10^2
10^6	49	5.3×10^3



n_TOF is a **spallation** neutron source based on **20 GeV/c protons** from the CERN PS hitting a **Pb block** (~300 neutrons per proton and ~ 7×10^{12} ppp).

Experimental area at **185 m** and **18.5 m.**

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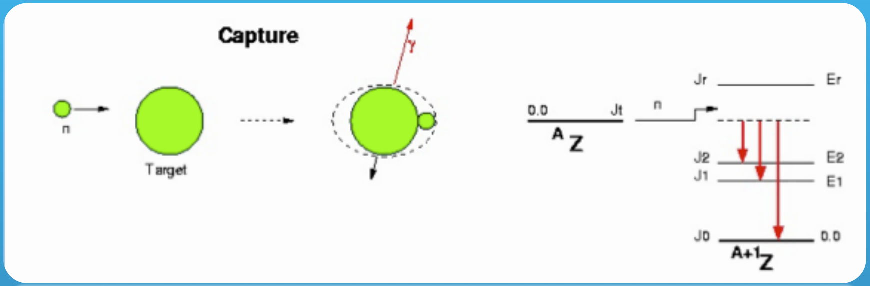
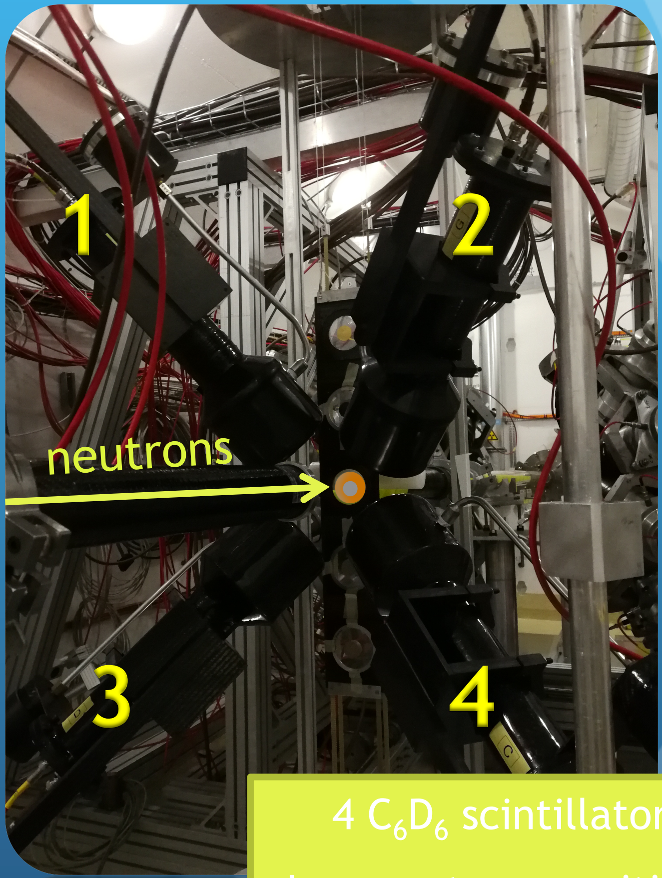
Experimental Set-Up



Capture reactions are measured by detecting γ-rays emitted in the de-excitation process



4 C_6D_6 scintillators

Low neutron sensitivity

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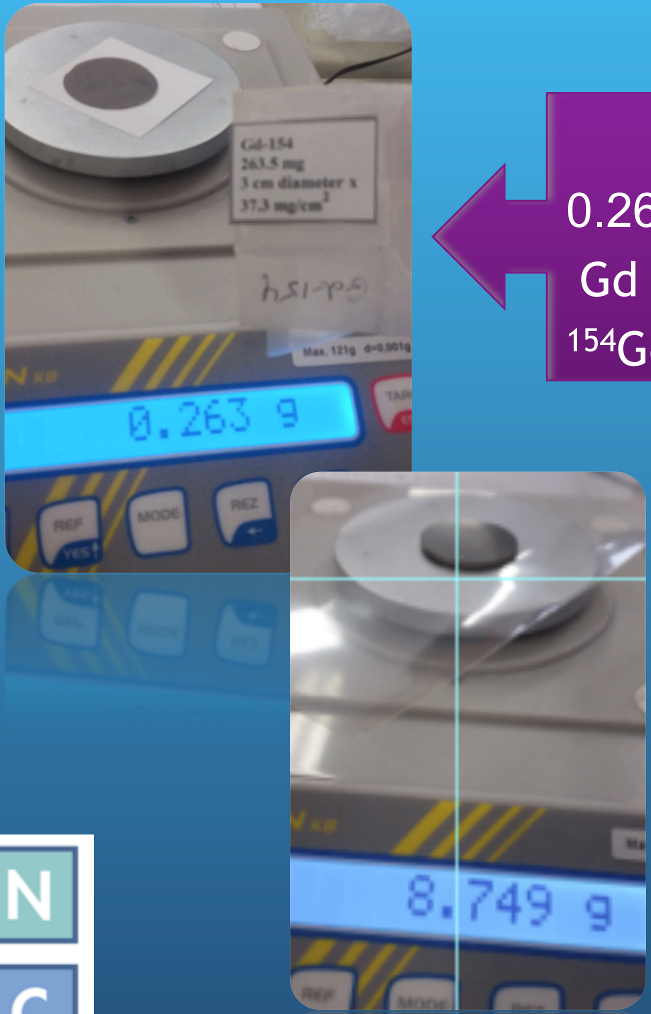
nTOF

Gd Samples



ORNL
0.263 g
Gd metal
^{154}Gd ~ 66,78 %

GOODFELLOW
8.749 g
Natural Gd
99%

Radius = 1.5 cm

EuNPC

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n-capture Gd Campaing

Isotope	Protons	note
^{197}Au	4×10^{16}	Cyclic – after calibration
^{154}Gd	1.88×10^{18}	
^{nat}Gd	2.3×10^{17}	
Carbon	4×10^{16}	From ^{88}Sr and ^{89}Y campaign
Lead	1.2×10^{17}	
Empty	3.5×10^{17}	
Others	2.0×10^{17}	Filters bkg

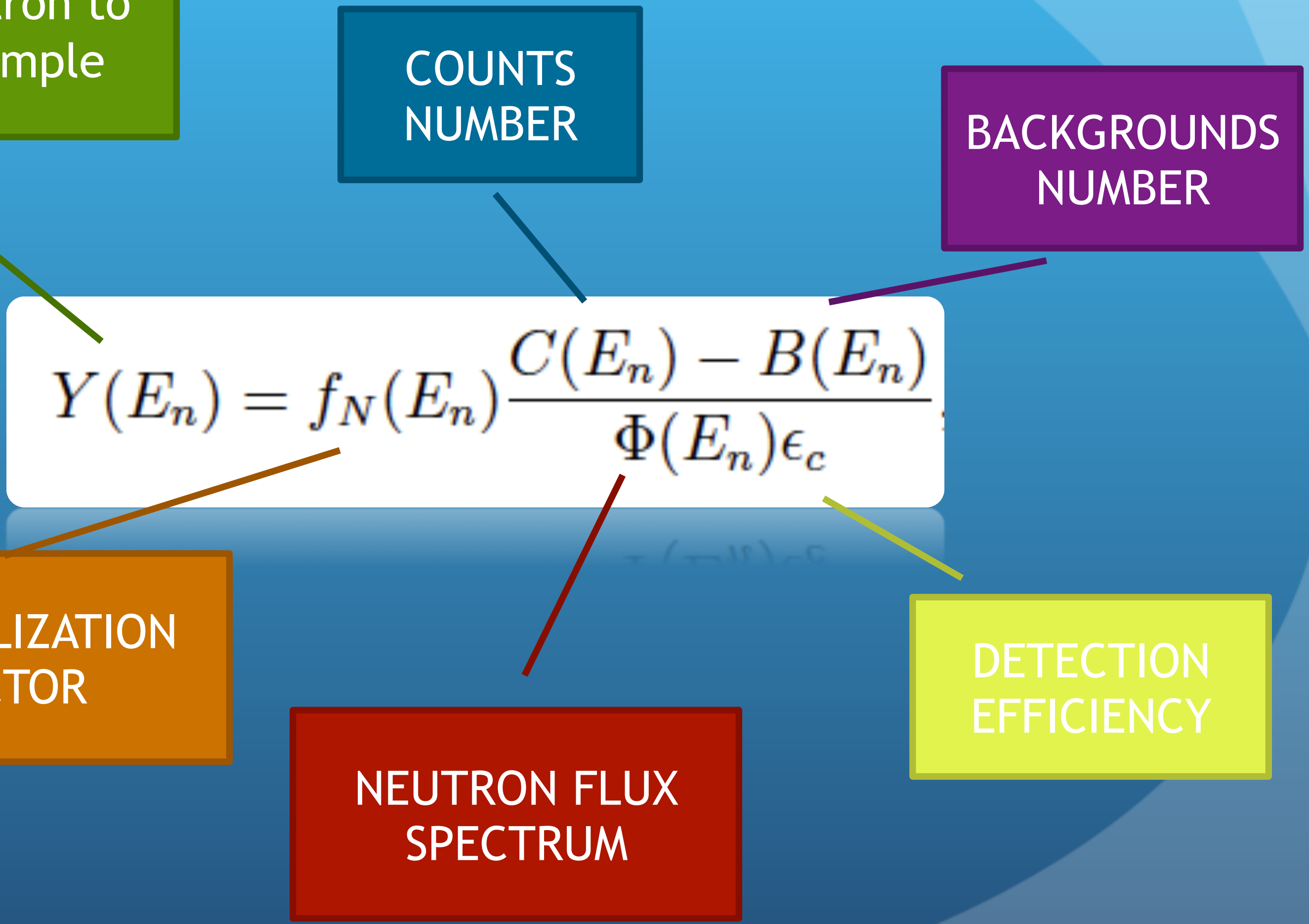
2.6×10^{18}

Full calibration (^{137}Cs, ^{88}Y, Am-Be and Cm-C composite γ-ray source) every week !!!

14th August 2017
10th September 2017

Data Analysis

NEUTRON CAPTURE YIELD: probability for a neutron to be captured in the sample



COUNTS NUMBER

BACKGROUNDS NUMBER

$$Y(E_n) = f_N(E_n)\frac{C(E_n) - B(E_n)}{\Phi(E_n)\epsilon_c}$$

NORMALIZATION FACTOR

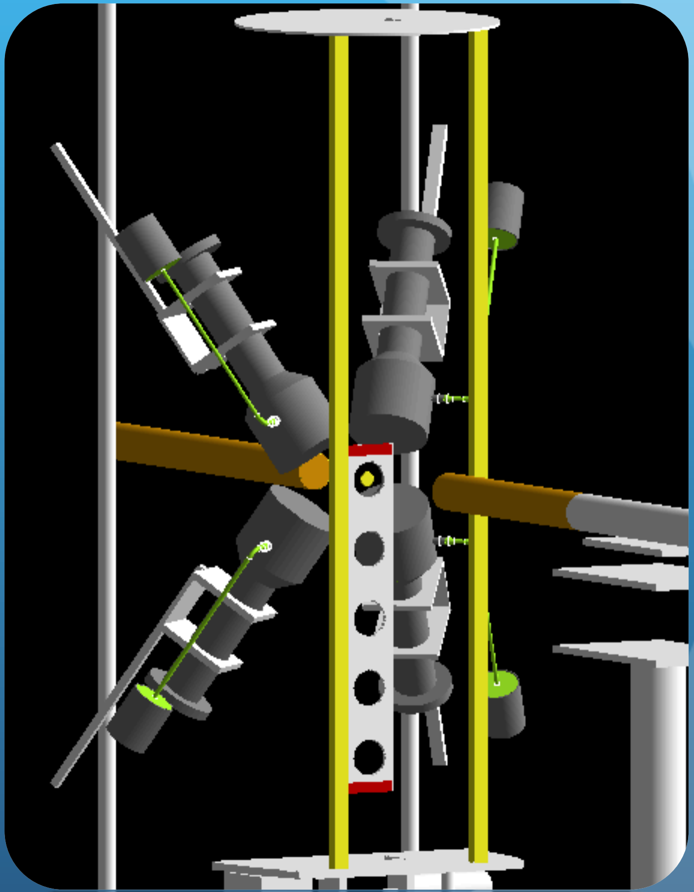
NEUTRON FLUX SPECTRUM

DETECTION EFFICIENCY

Detection Efficiency

ε_C was calculated using the Pulse Height Weighting Technique (PWHT)

- ε_C independent of the unknown decay pattern
- $\varepsilon_C = \Sigma\varepsilon_\gamma = E_c = S_n(^{155}Gd)+E_n$, where En is negligible for the eV neutrons of interest.



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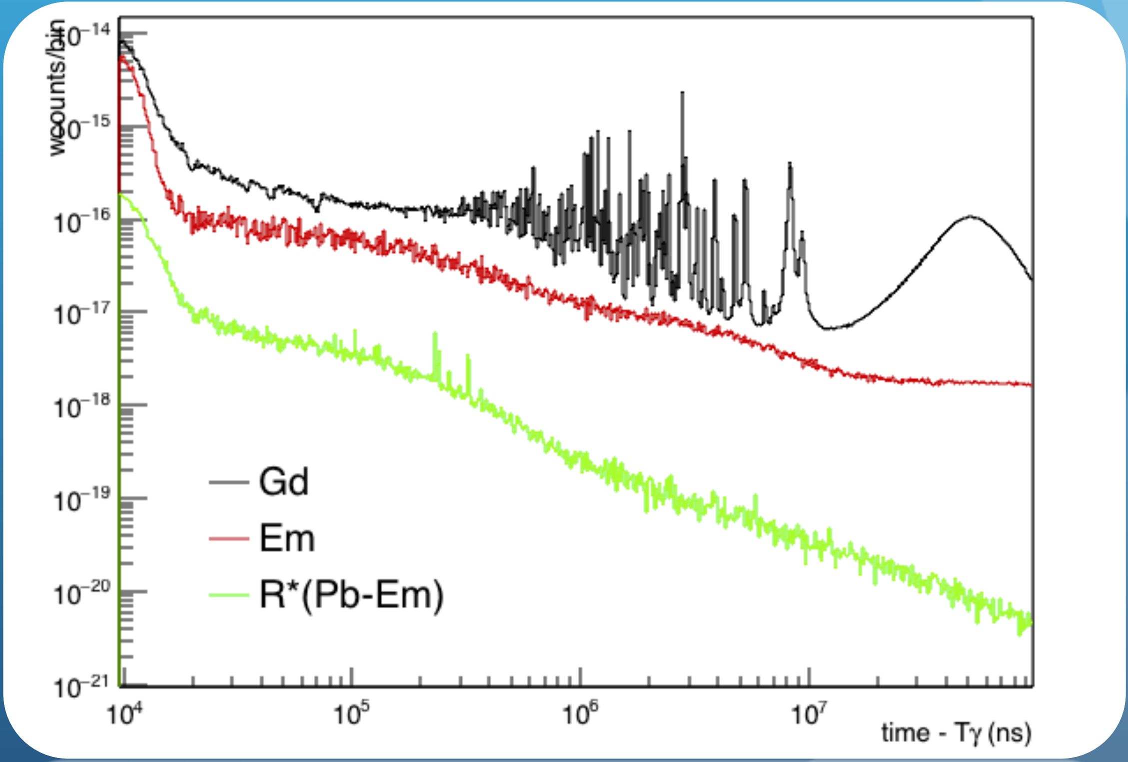
nTOF

Background Subtraction

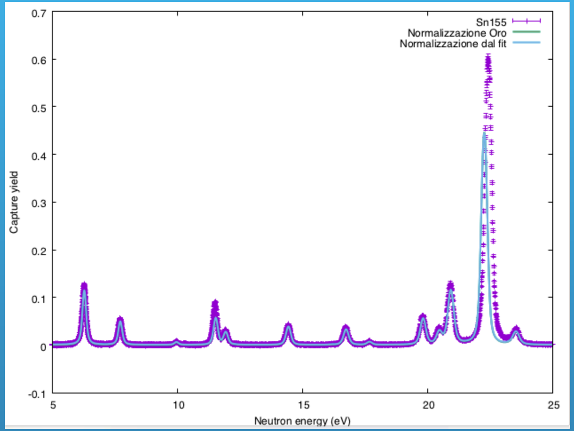
- Beam related background ➔ Empty Frame
- Scattered neutrons in the sample ➔ Pb Sample

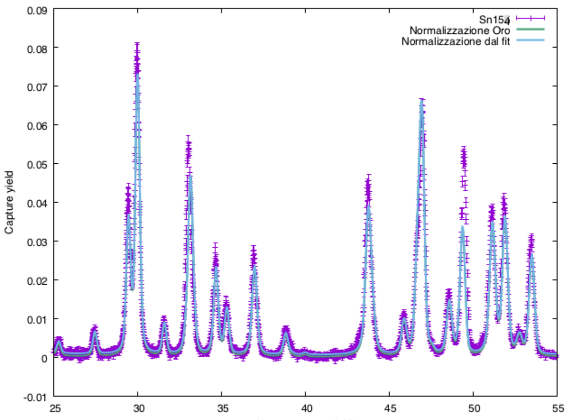


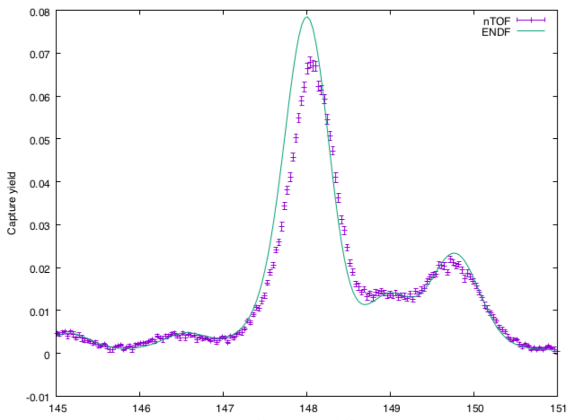
EuNPC

Resonance Shape Analysis

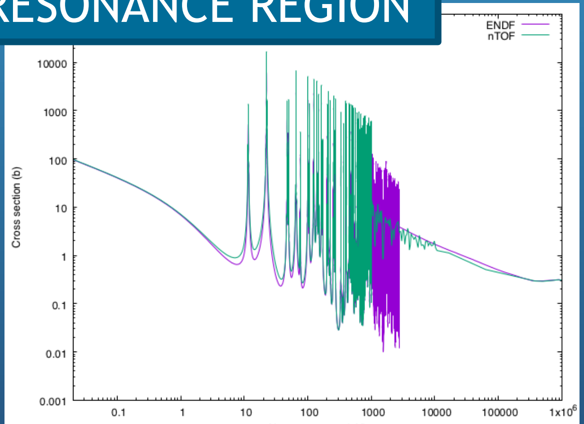
RESOLVED RESONANCE REGION







UNRESOLVED RESONANCE REGION

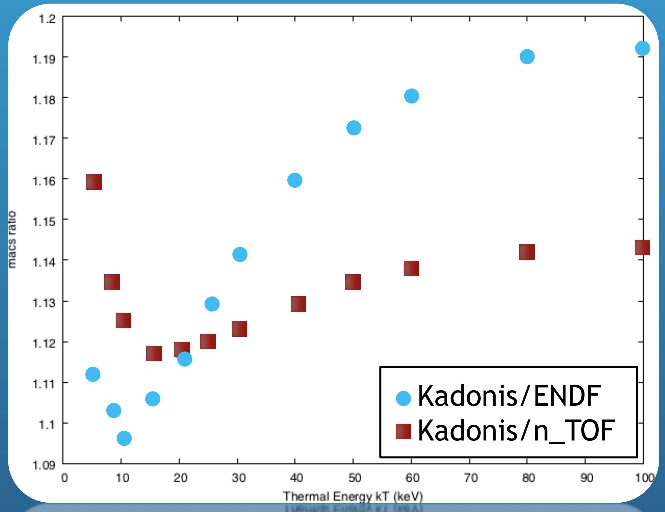


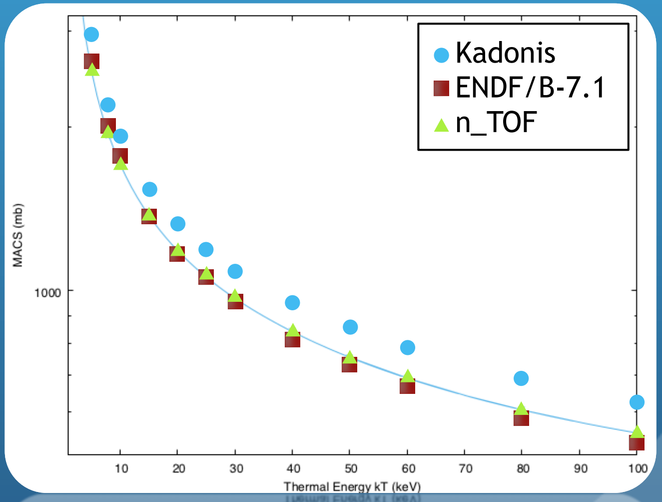
Contributes for the 80% to the MACS calculation

Maxwellian Averaged Cross Section (MACS)

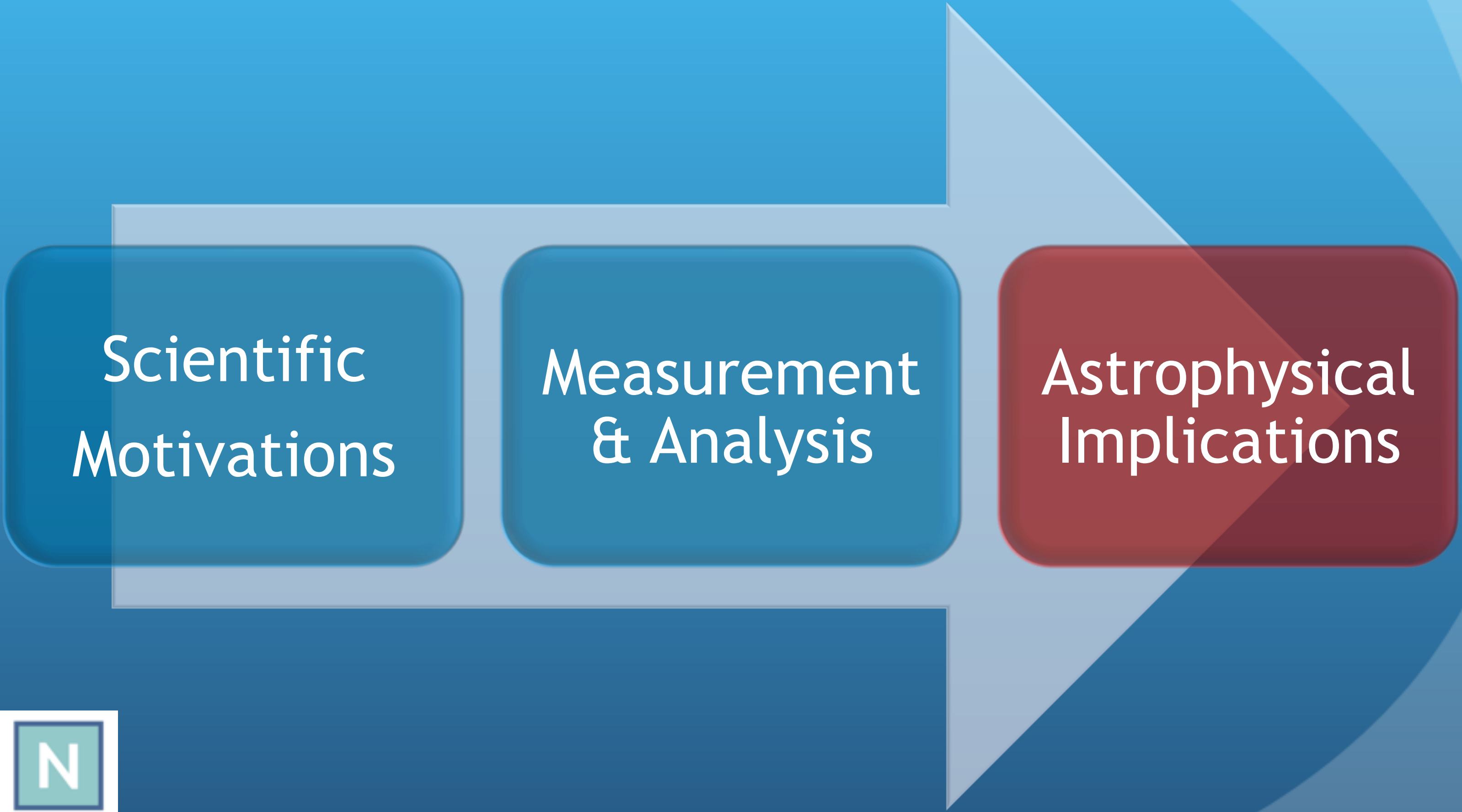
$$MACS = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^2}\cdot\int_0^{\infty} E\sigma(E)\cdot\exp\left(-\frac{E}{kT}\right)\mathrm{d}E$$

Cross section averaged
on a maxwellian distributi





Outlines



- Scientific Motivations
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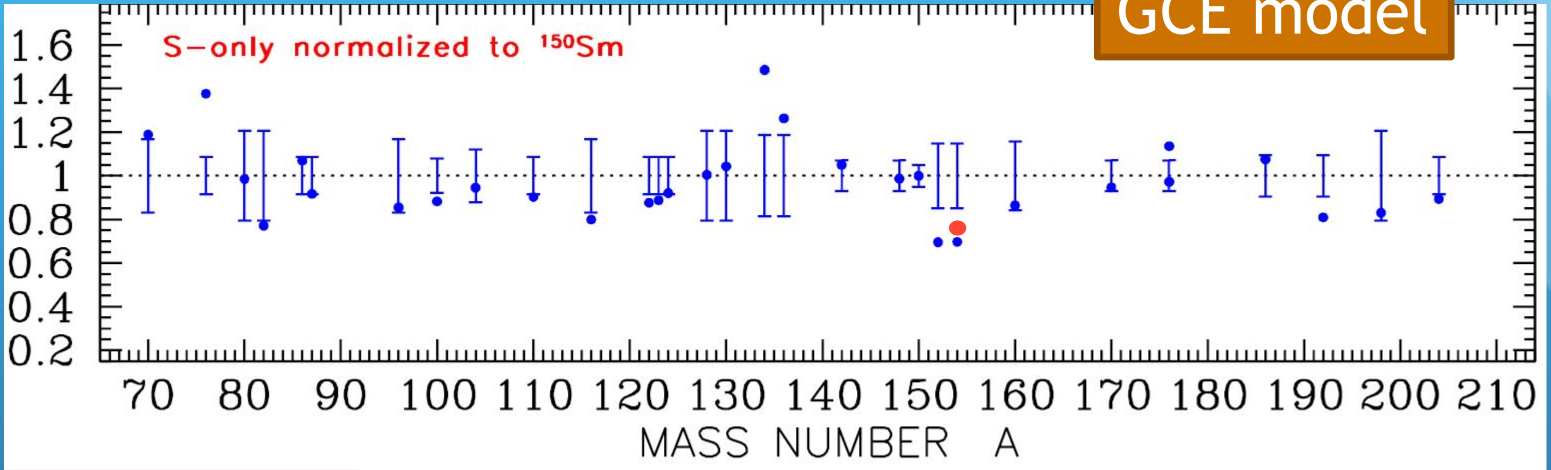
First Results

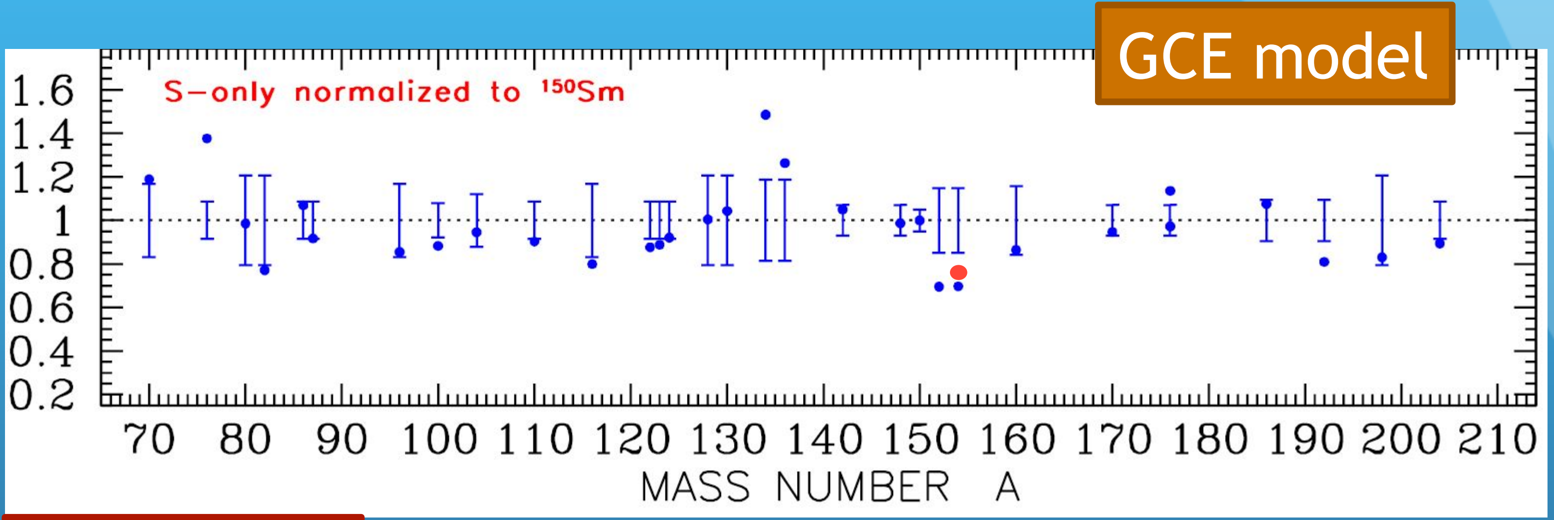
GCE model



Prantzos, 2018

- M=1.5 Msun Production(154Gd)=+9%
- M=2.0 Msun Production(154Gd)=+5%
- M=3.0 Msun Production(154Gd)=+4%

First Results

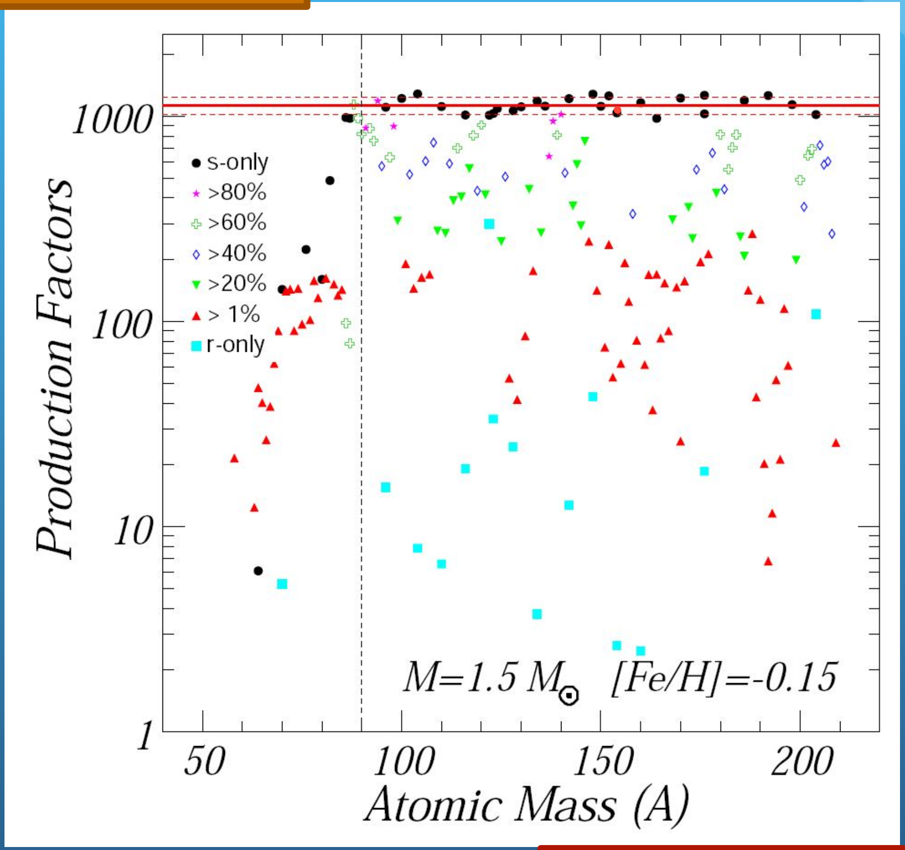


Prantzos, 2018

5% increments not justify the 40% model discrepancy

Gd cross section is not the solution

Single stellar model



Trippella, 2016

Conclusion

- The cross section of Gd154 was calculated in the energy range (1meV -100keV)
- The evaluated MACS is 15-10% lower than that obtained in KADONIS 1.0 starting from the CS (Wisshak 1995) with an error of 1% but in a narrow energy range.
- The strength of n_TOF is the large energy range it can cover (meV-GeV) -> it's possible calculate the cross section in a large energy range.

Outlook

- 1) study the production cross section of ^{153}Eu(n,γ)154Eu that ß- decays in ^{154}Gd
- 2) change the main neutron source mechanism into the FRUITY models

Neutron flux