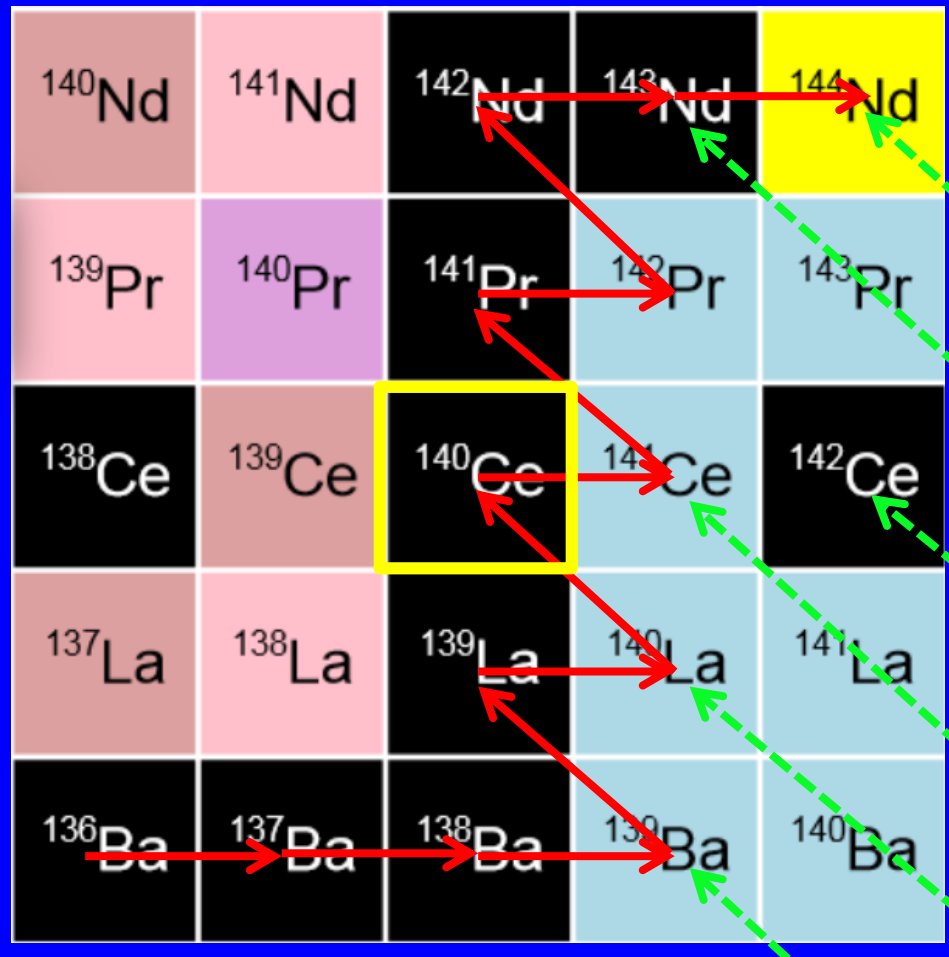


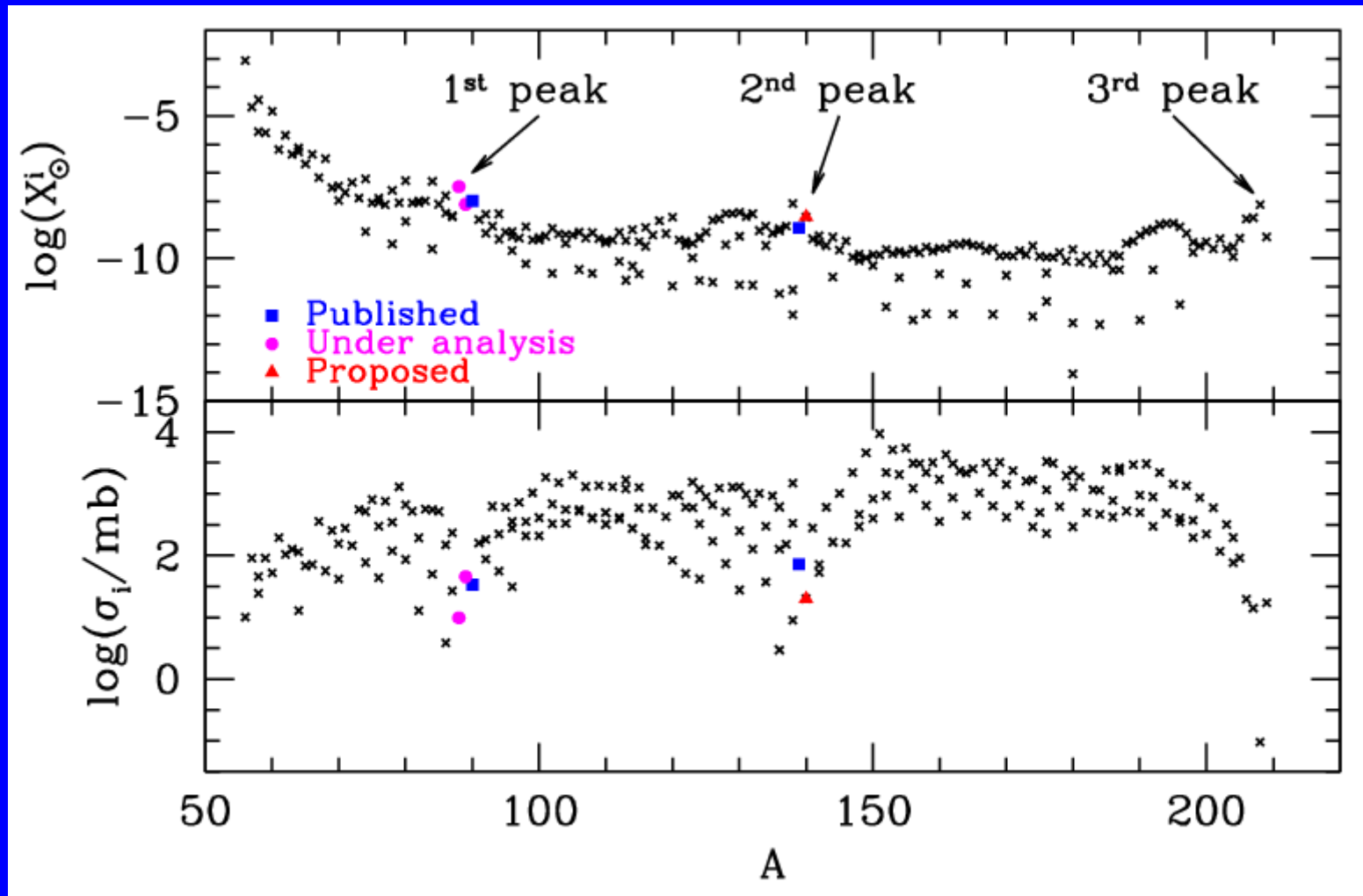
# The $^{140}\text{Ce}(n,\gamma)^{141}\text{Ce}$ reaction at n\_TOF-EAR1: a litmus test for theoretical stellar models.



→ s-process

-----> r-process

# The solar distribution and the s-process peaks



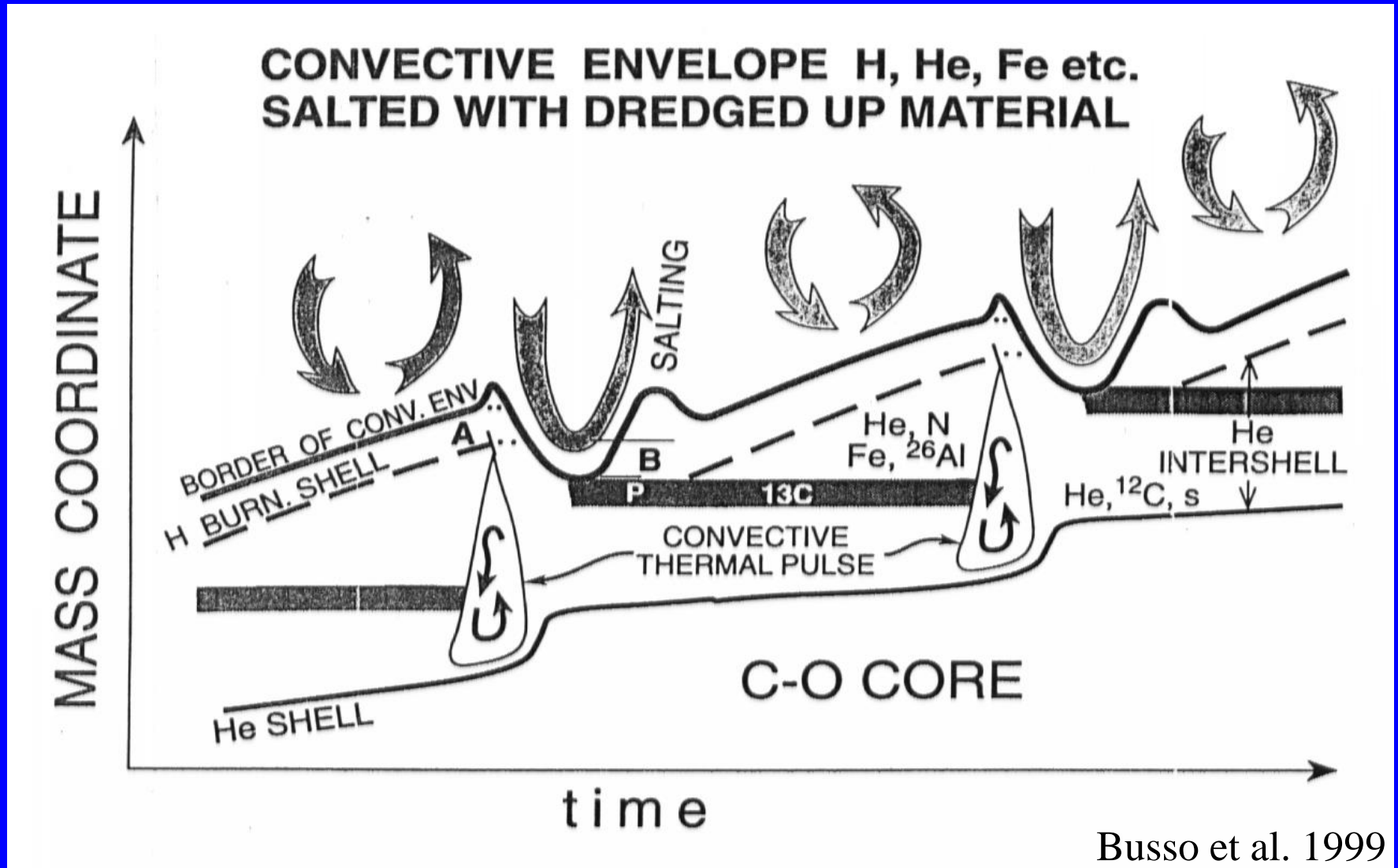
Magic nuclei are bottlenecks for the s-process nucleosynthesis

$N=50$  :  $^{88}\text{Sr}$ ,  $^{89}\text{Y}$ ,  $^{90}\text{Zr}$

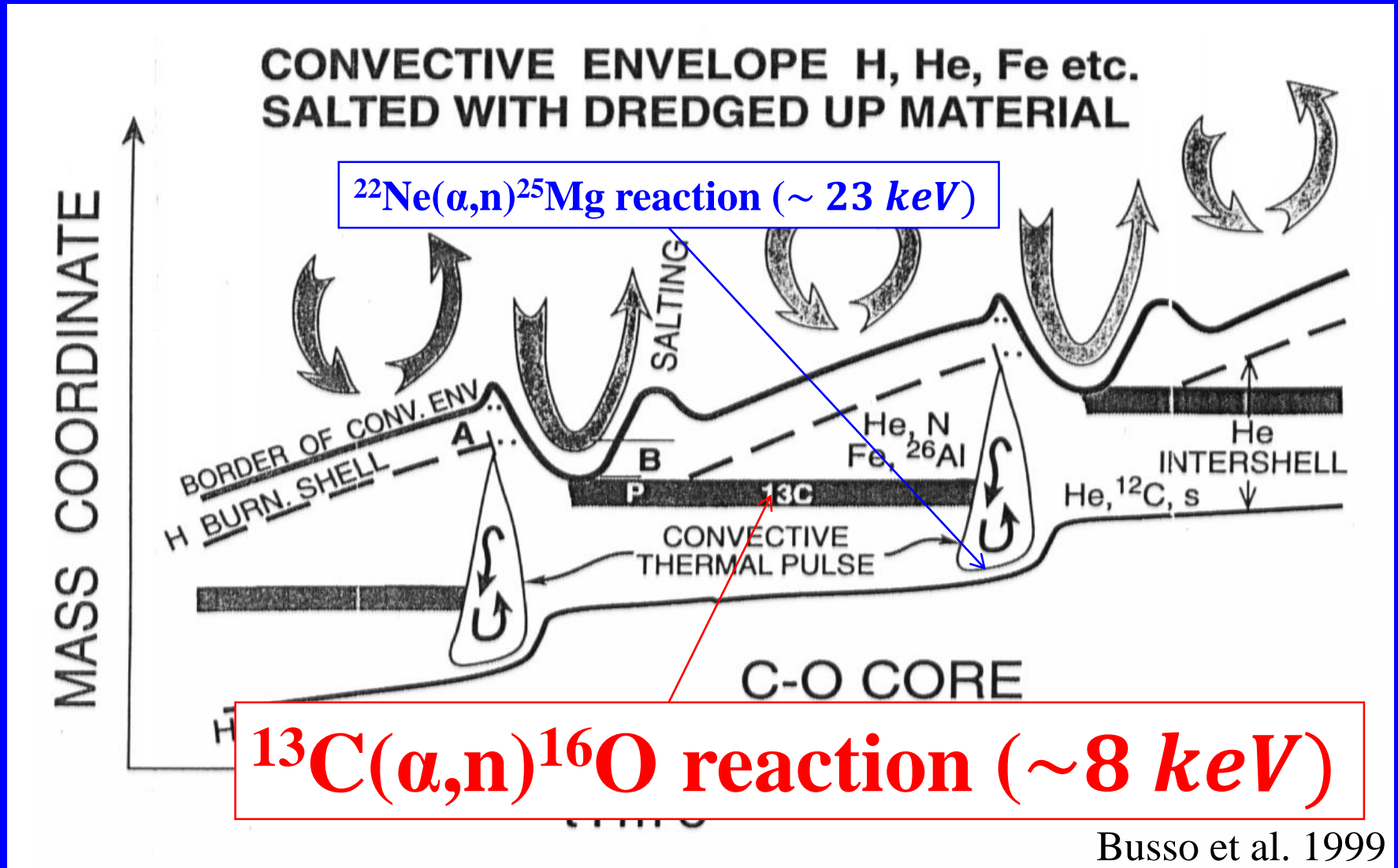
$N=82$  :  $^{138}\text{Ba}$ ,  $^{139}\text{La}$ ,  $^{140}\text{Ce}$ ,  $^{141}\text{Pr}$ ,  $^{142}\text{Nd}$

$N=126$  :  $^{208}\text{Pb}$

# The s-process in Asymptotic Giant Branch (AGB) stars

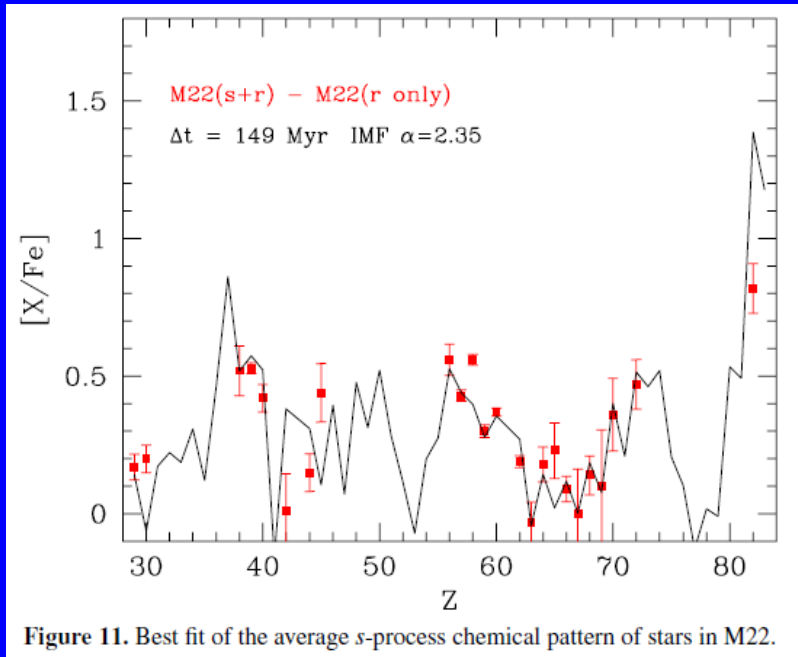


# The s-process in Asymptotic Giant Branch (AGB) stars

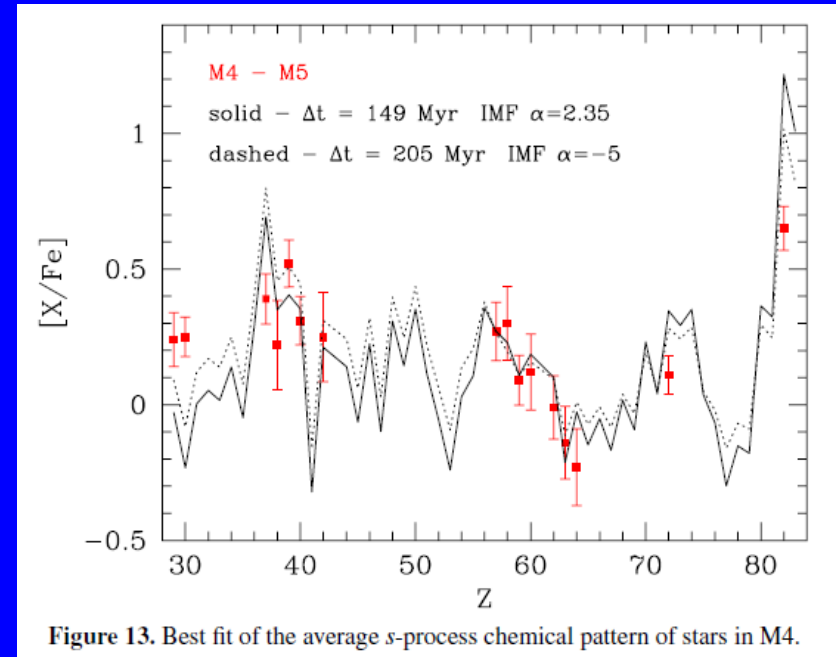


# The s-process in Globular Clusters

Roederer+ 2011 (6 stars)



Young+ 2008 (14 stars)



Straniero, Cristallo & Piersanti 2014

The pollution of AGB stars with a mass ranging between 3 to 6  $M_{SUN}$  may account for most of the features of the *s*-process enrichment of M4 and M22.

M22



M4

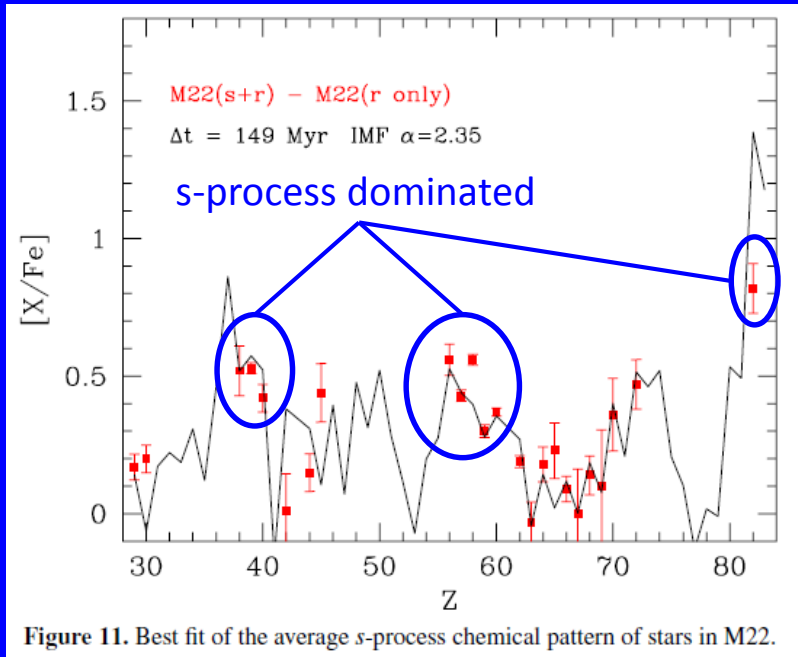


M5

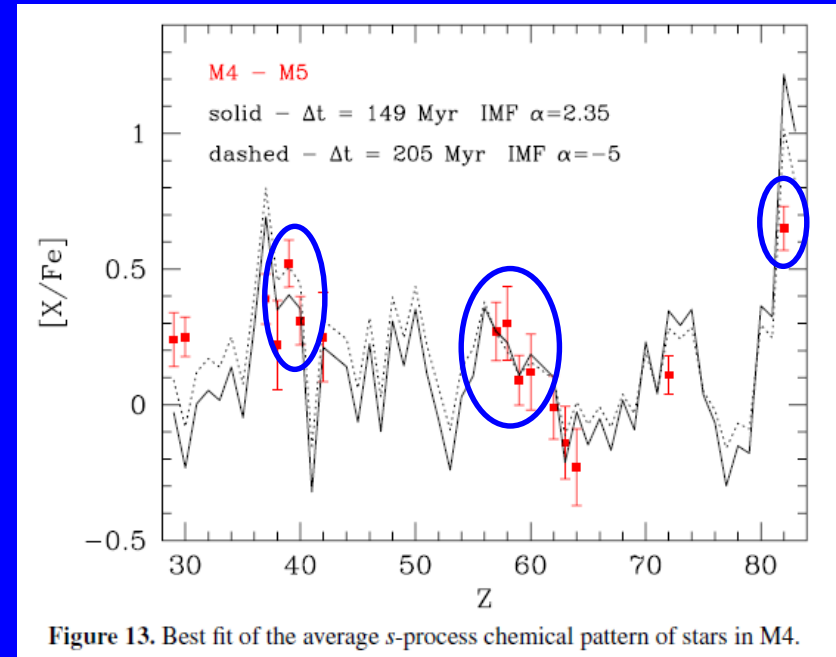


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M22



M4

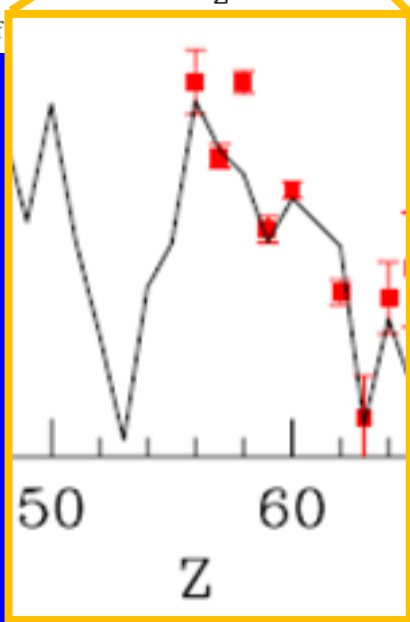
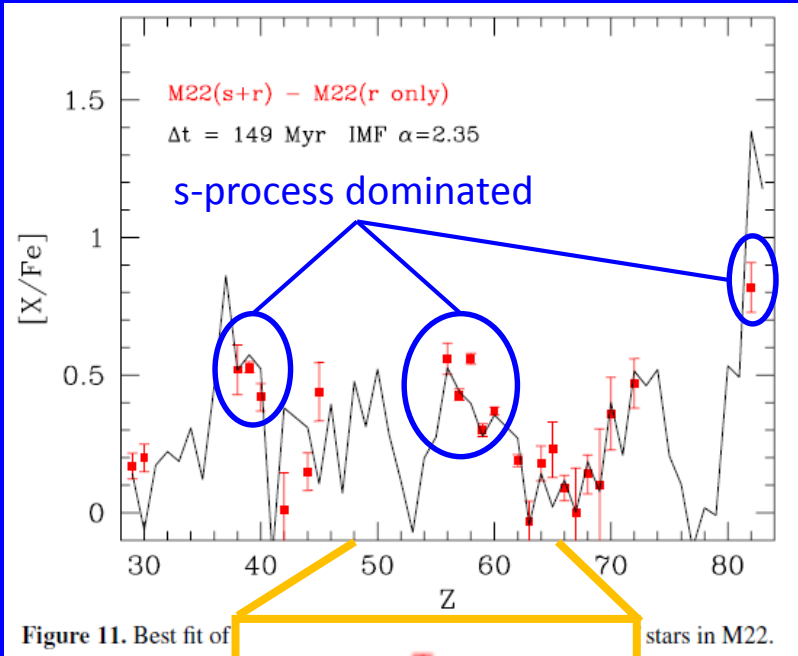


M5

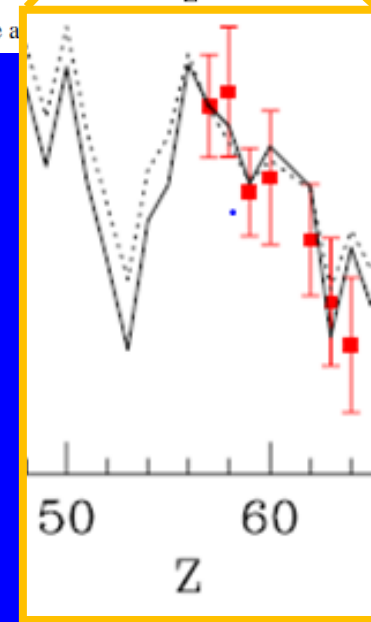
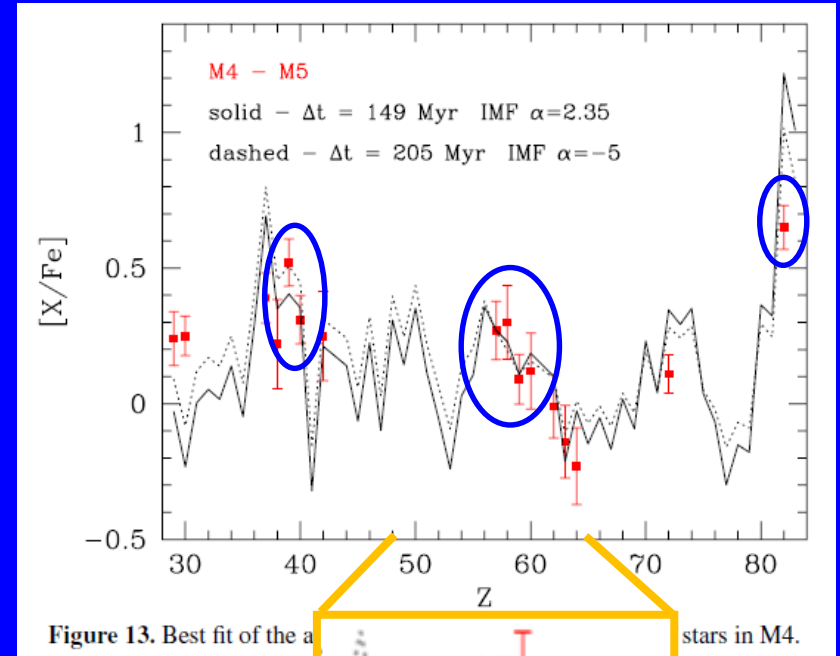


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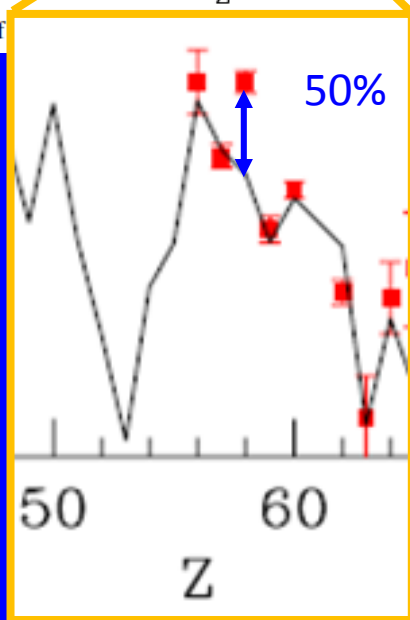
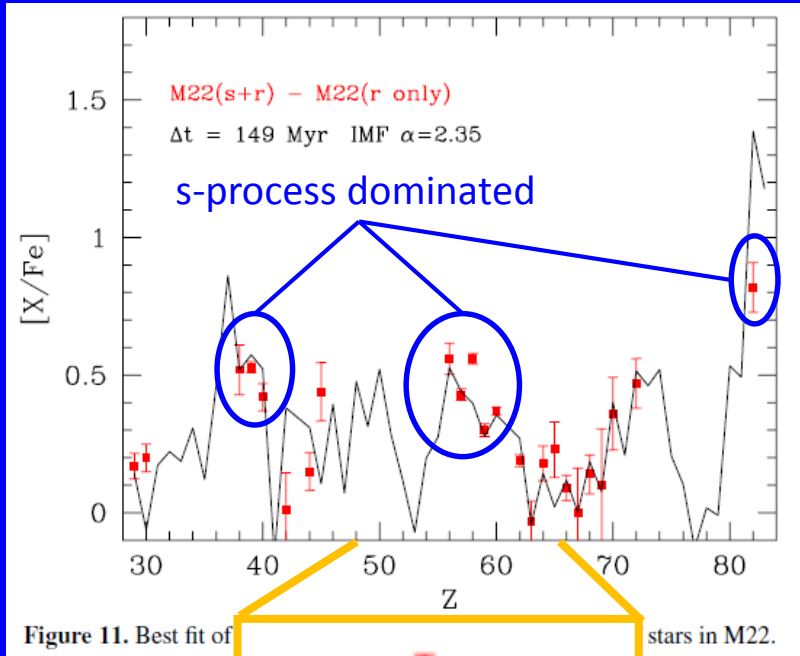


Young+ 2008 (14 stars)

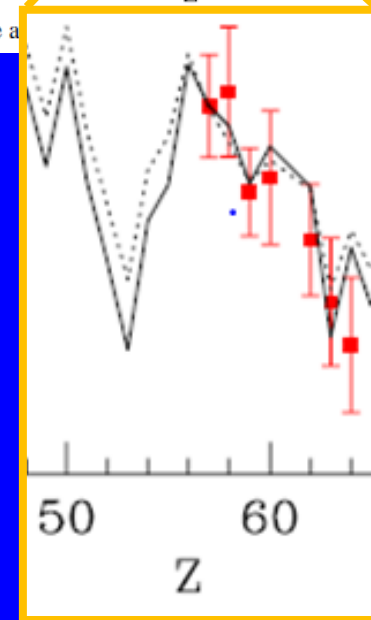
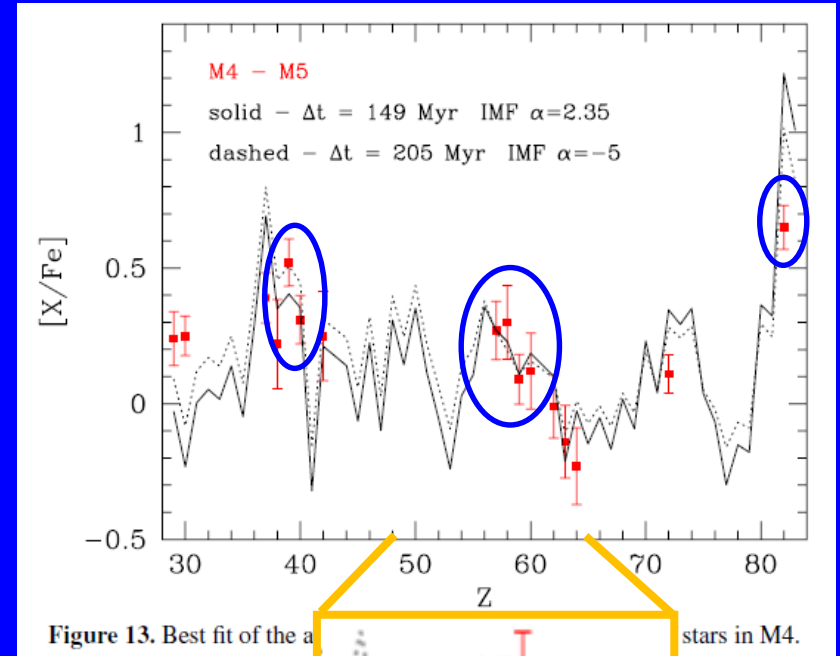


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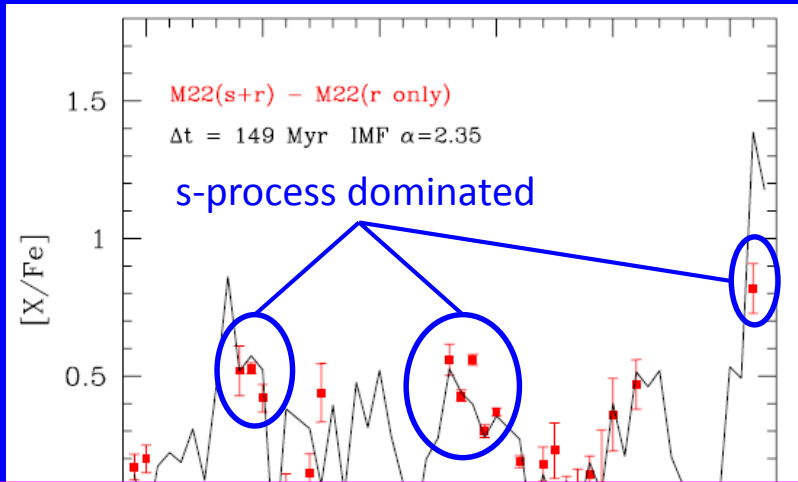
Young+ 2008 (14 stars)



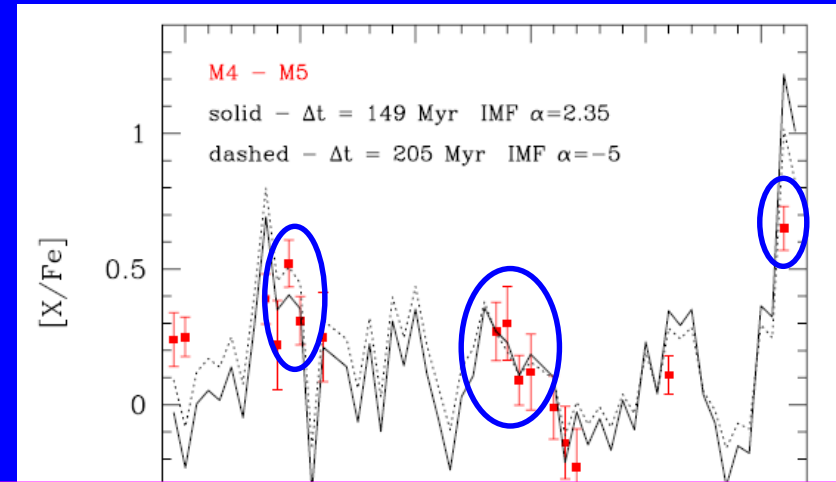


# The s-process in Globular Clusters

Roederer+ 2011 (6 stars)



Young+ 2008 (14 stars)



1. From the observational point of view, data relative to Ce are very robust.
2. Stellar models uncertainties affect the average absolute values of the three peaks and their relative ratios.
3. Within a single peak the relative distribution is determined by *nuclear inputs*.

# Cerium

$^{140}\text{Ce}$  is the most abundant cerium isotope (88%)

→ (n,γ)  
↖ β<sup>-</sup> decay

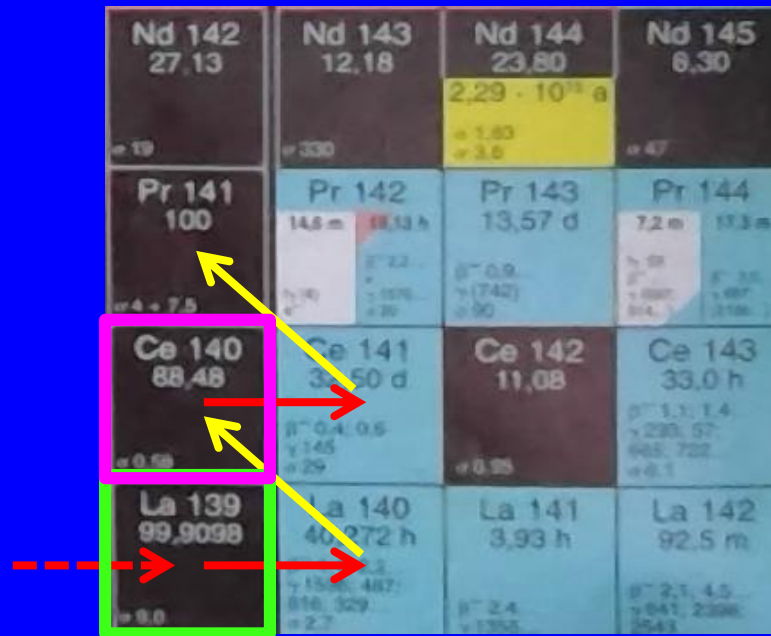


Its production channel has already been explored by the n\_TOF collaboration (Terlizzi+ 2007)

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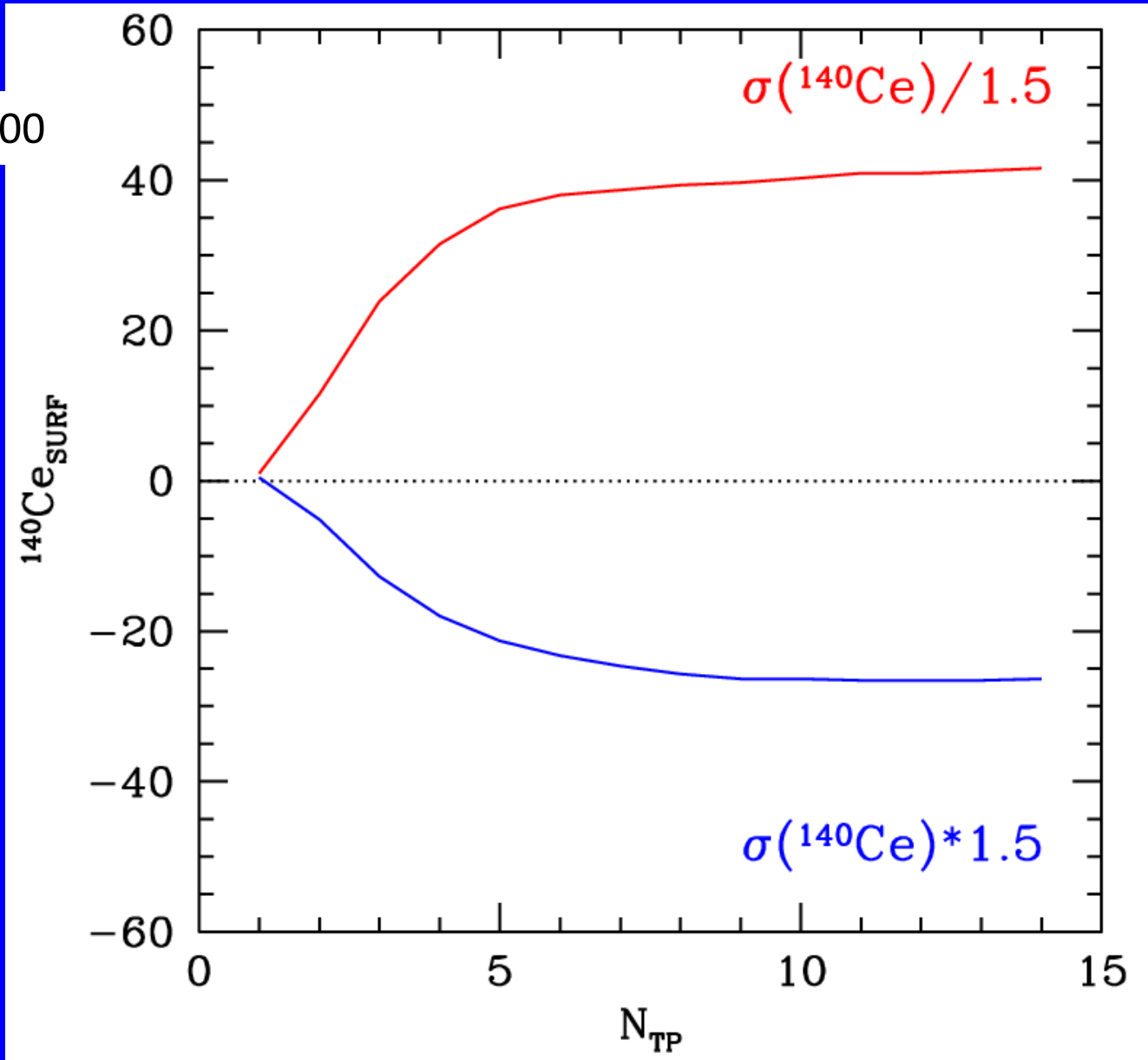
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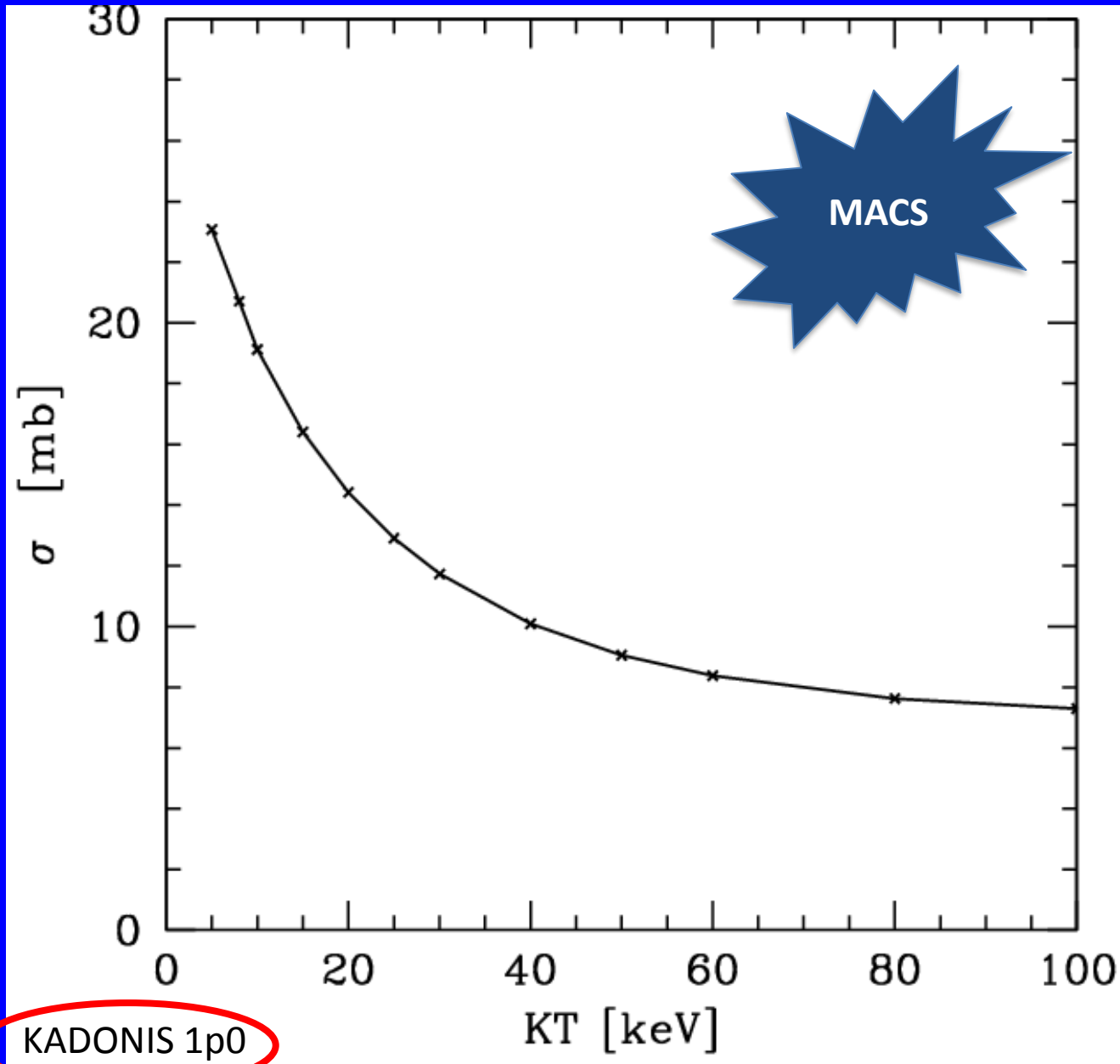
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# Expected variations on a theoretical AGB model ( $M=4 M_{\text{SUN}}$ )

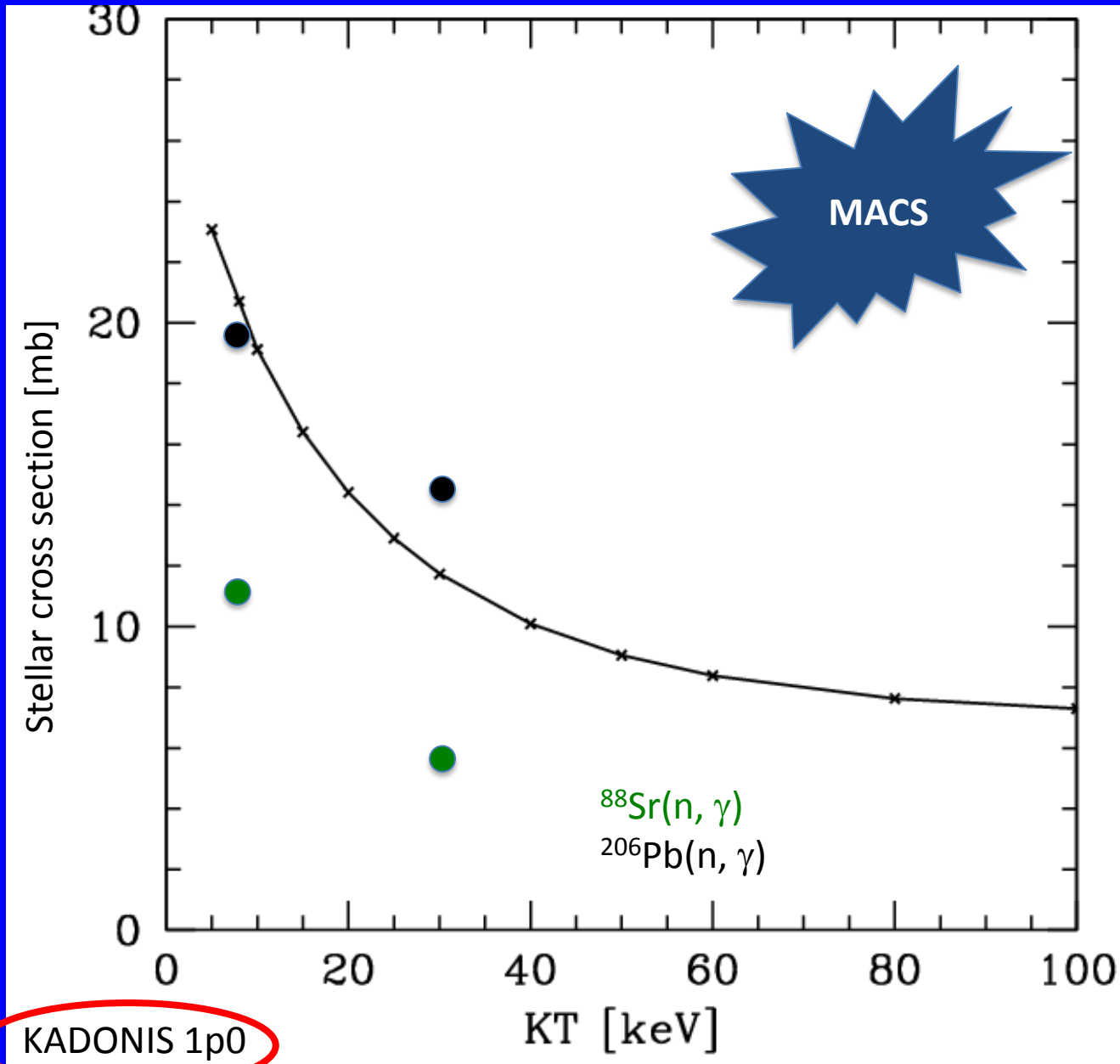
(Case-REF)/REF\*100



# $^{140}\text{Ce}$ neutron capture cross section (I)

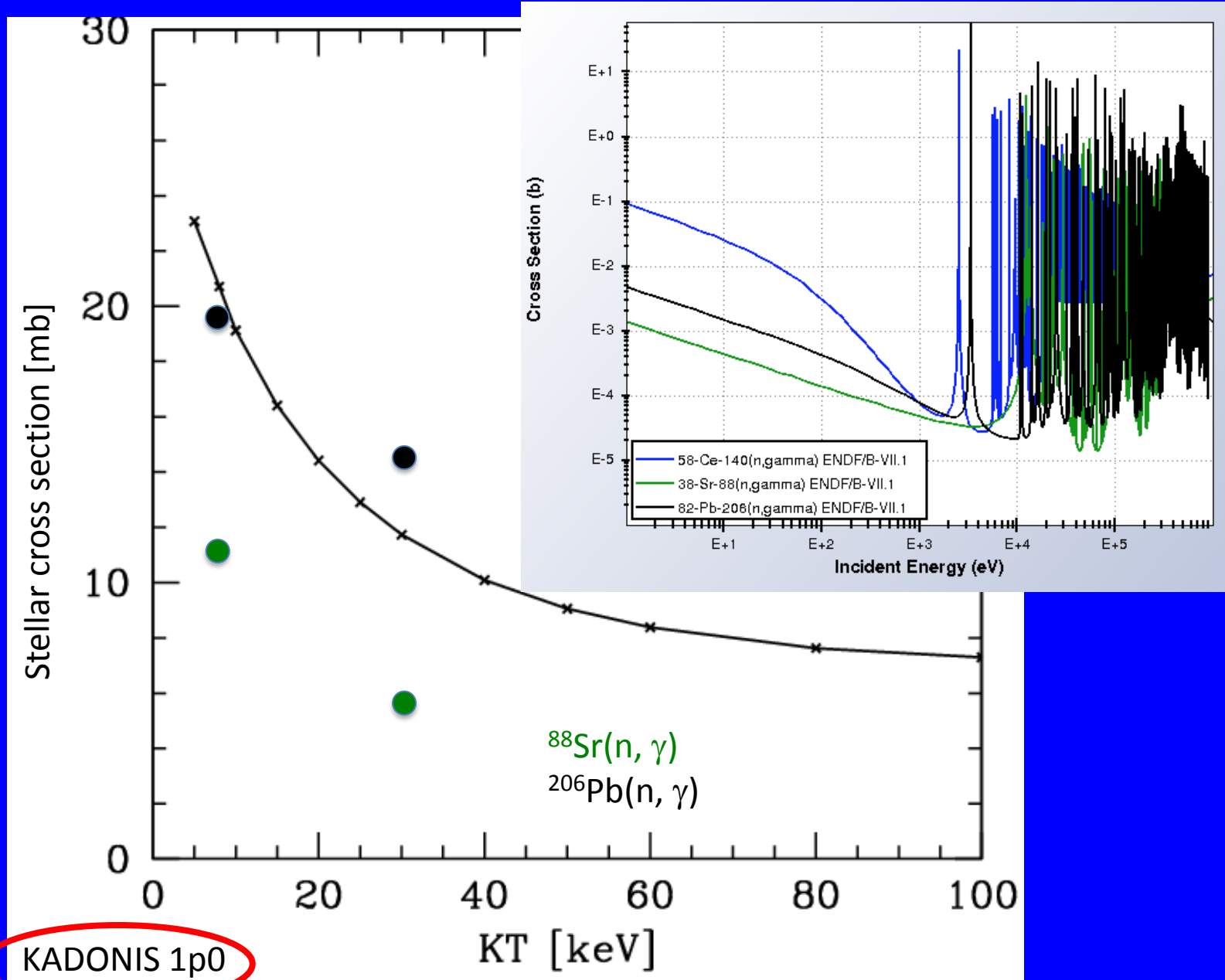


# $^{140}\text{Ce}$ neutron capture cross section (I)

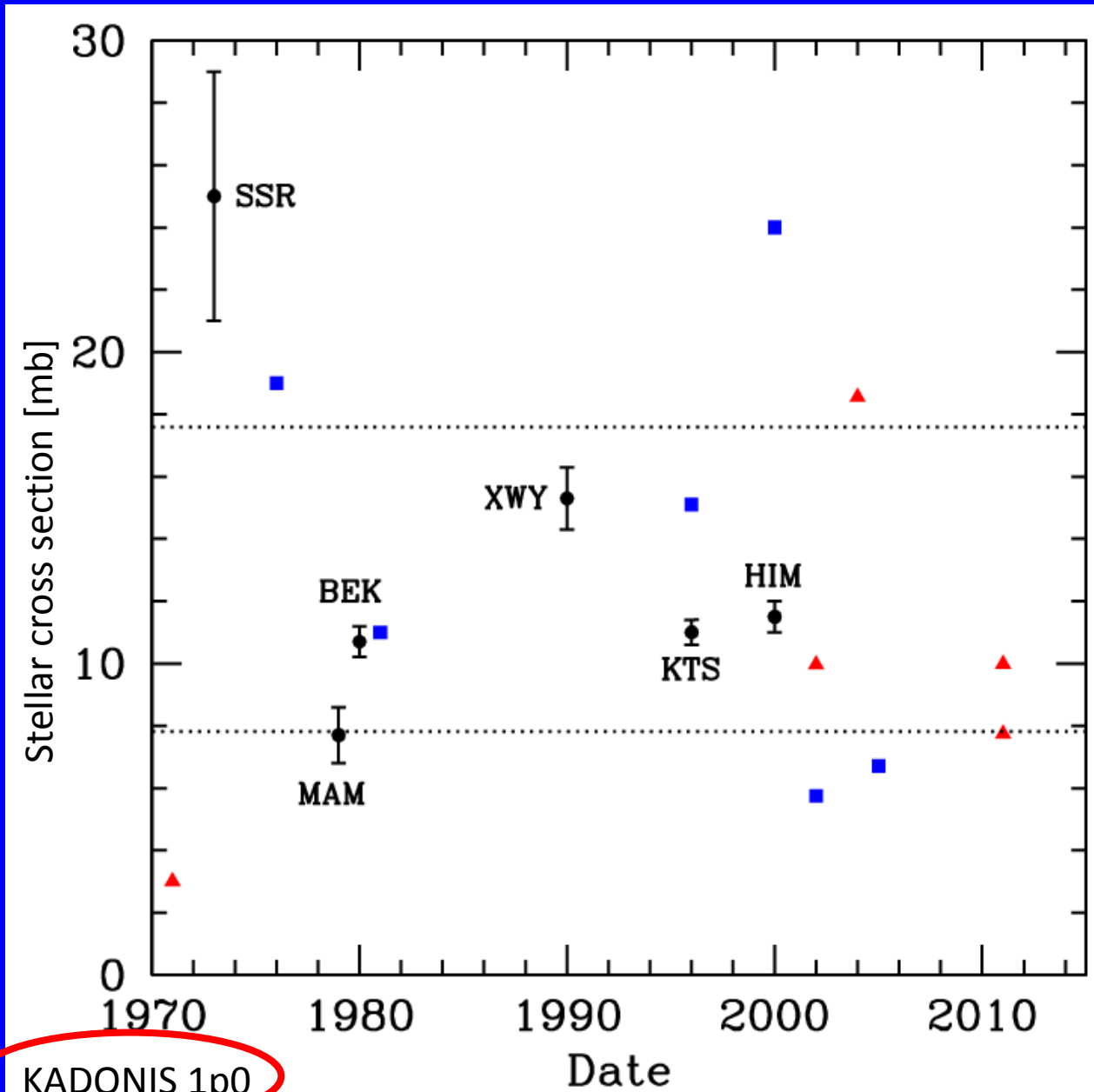


KADONIS 1p0

# $^{140}\text{Ce}$ neutron capture cross section (I)



# $^{140}\text{Ce}$ neutron capture cross section (II)



SSR (1973)

K. Siddappa+, Nuovo Cim. **18A**, 48

MAM (1979)

A.de L. Musgrove+, Aust. J. Phys. **32**, 213

XWY (1990)

Y. Xia+, Chin. J. Nucl. Phys. **12**, 261

KTS (1996) + BEK (1980)

F. Käppeler+, Phys. Rev. C **53**, 1397

H. Beer +, Phys. Rev. C **21**, 534

HIM (2000)

S. Harnood+, J. Nucl. Sci. Techn. **37** 740

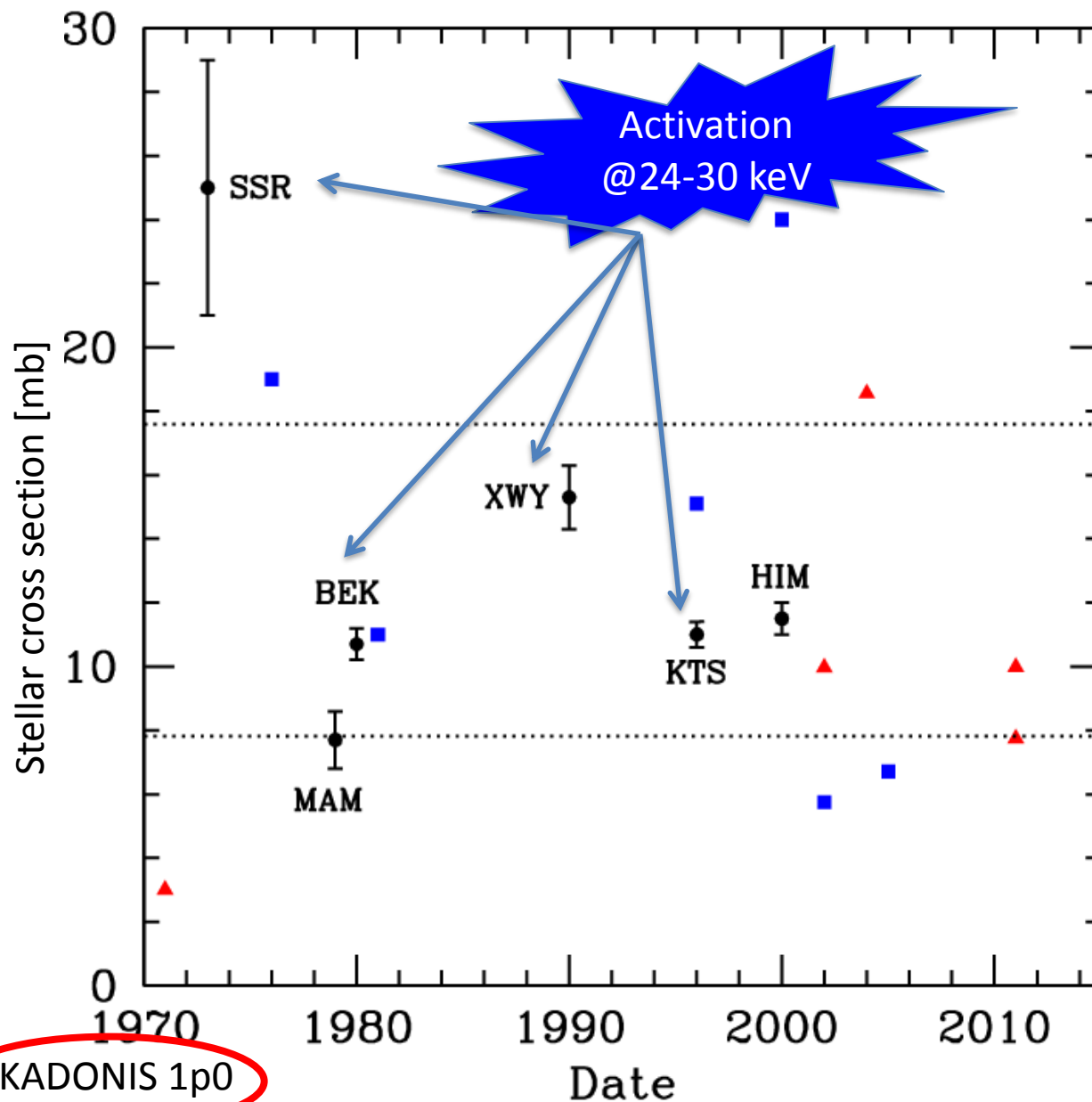
● Experimental

▲ Library

■ Theoretical



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**SSR (1973)**

K. Siddappa+, *Nuovo Cim.* 18A, 48

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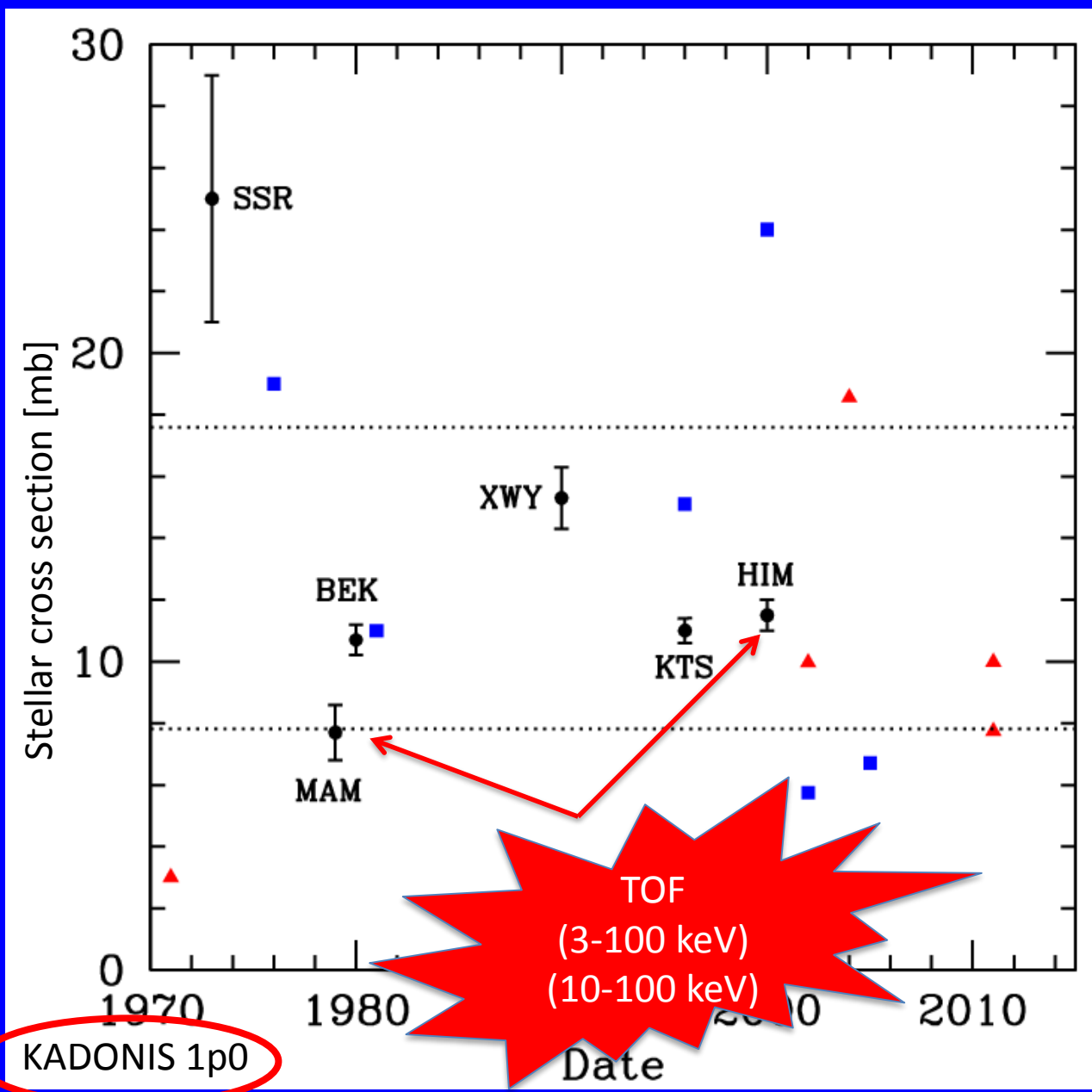
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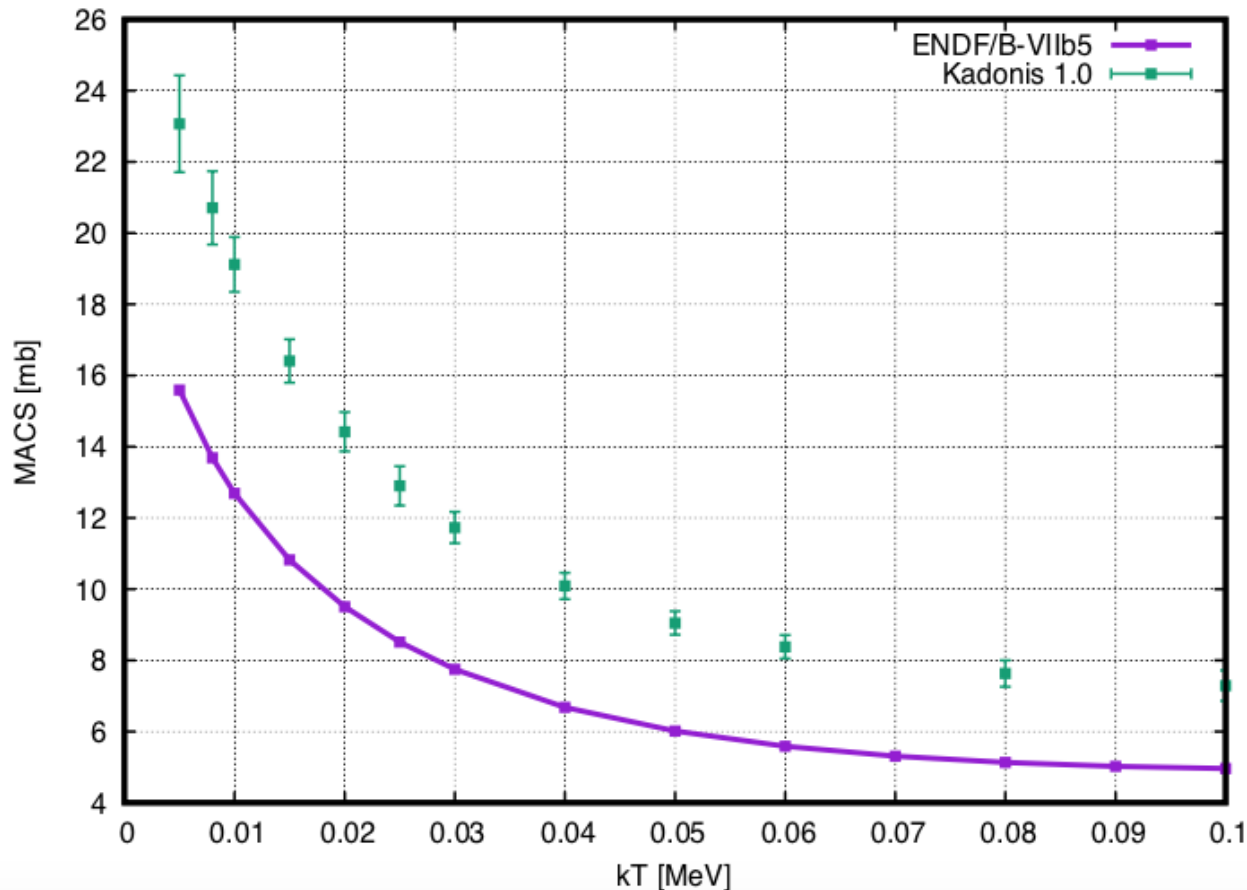
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- Experimental
- ▲ Library
- Theoretical

# $^{140}\text{Ce}$ neutron capture cross section (III)



## EVALUATIONS:

Capture ORELA 40 m,  $\text{C}_6\text{F}_6$   
 **$5 < E_n < 100$  keV**

A.de L. Musgrove+, Aust. J. Phys. 32, 213

Transmission RPI 250 m

**$20 < E_n < 60$  keV**

H. S. Camarda. PRC 18, 1254

Transmission JAERI  $^{140}\text{Ce}$

**$E_n < 60$  keV**

Ohkubo, jaeri report 1993

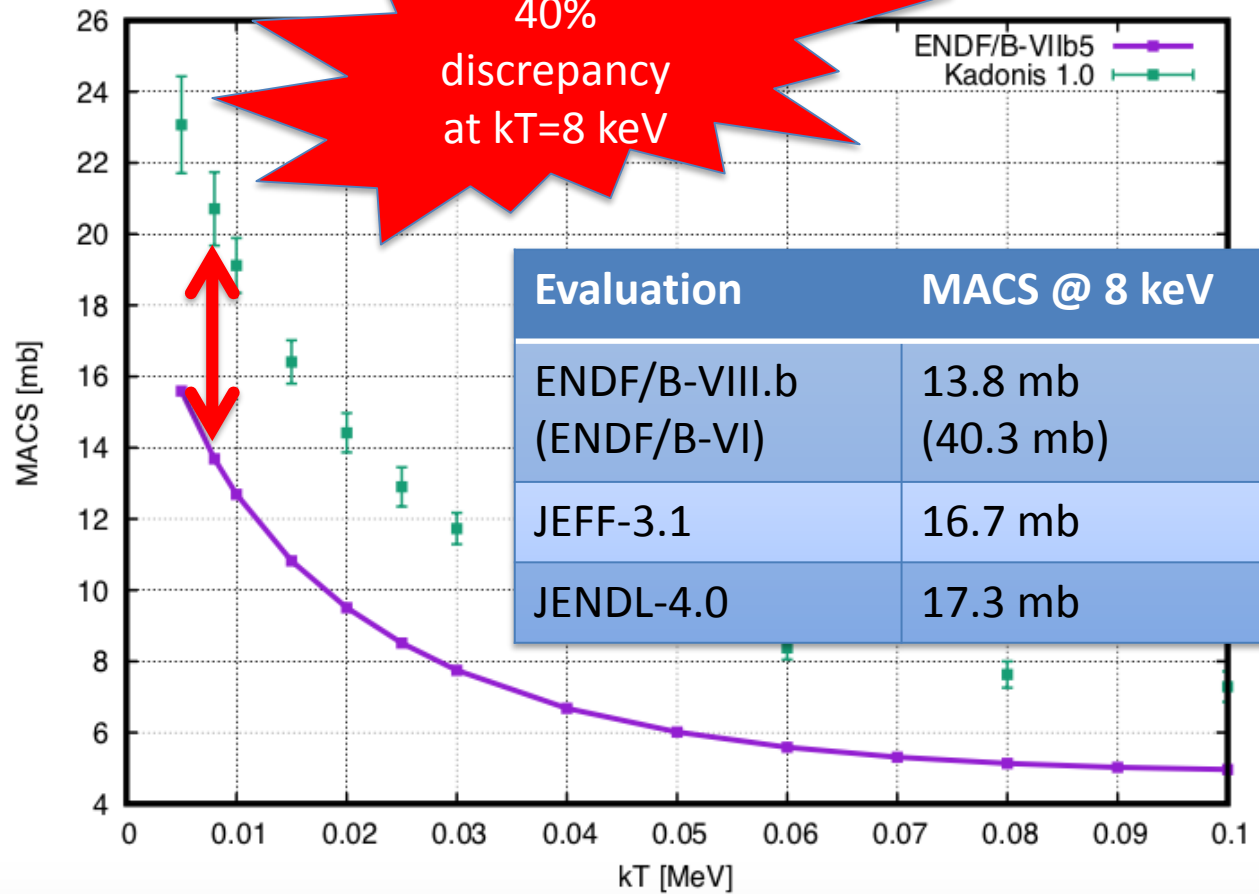
Capture (preliminary) 1974

**$E_n < 65$  keV**

by Hacken (Columbia)

not  
published

# $^{140}\text{Ce}$ neutron capture cross section (III)



40% discrepancy at  $kT=8$  keV

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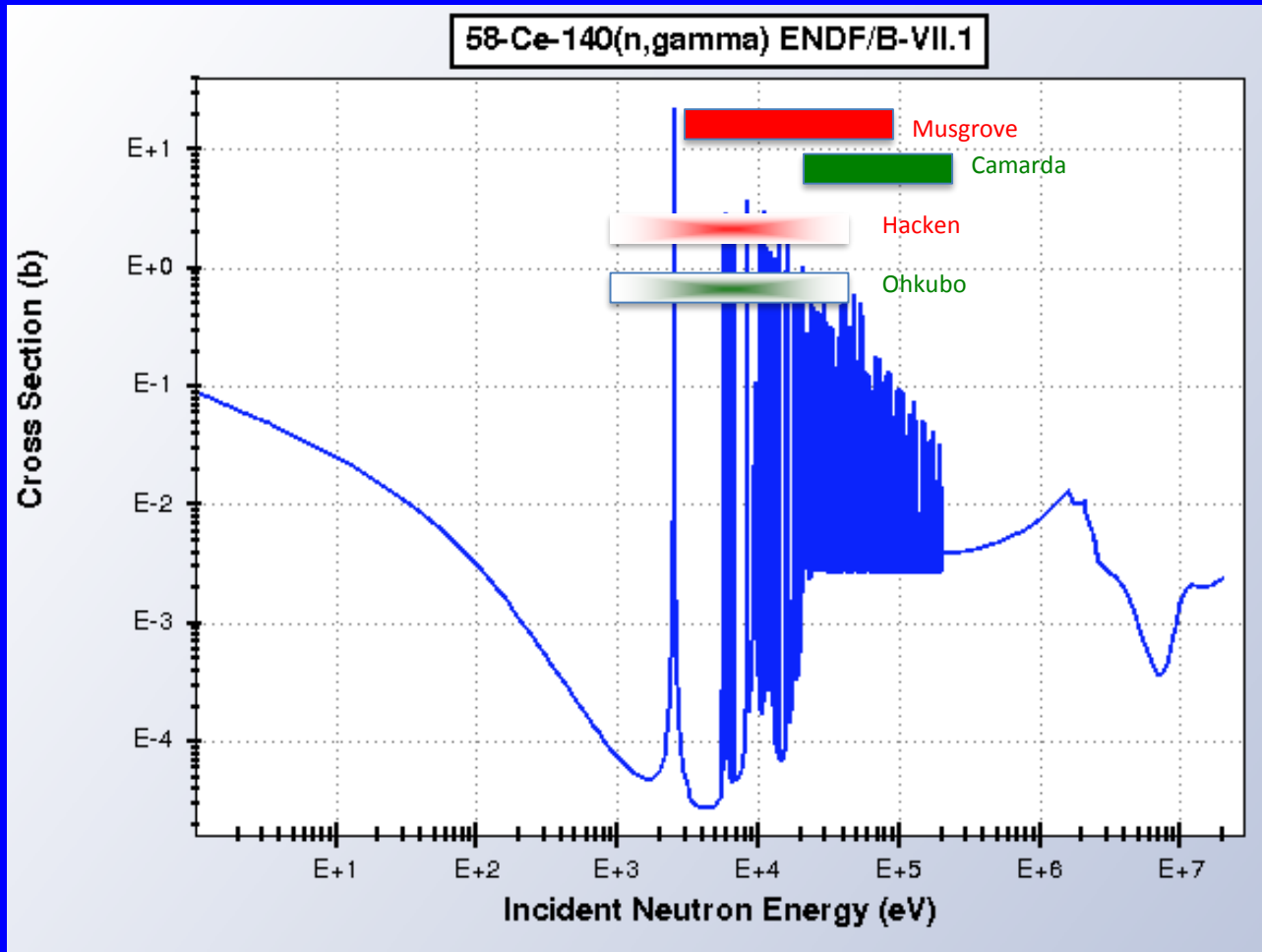
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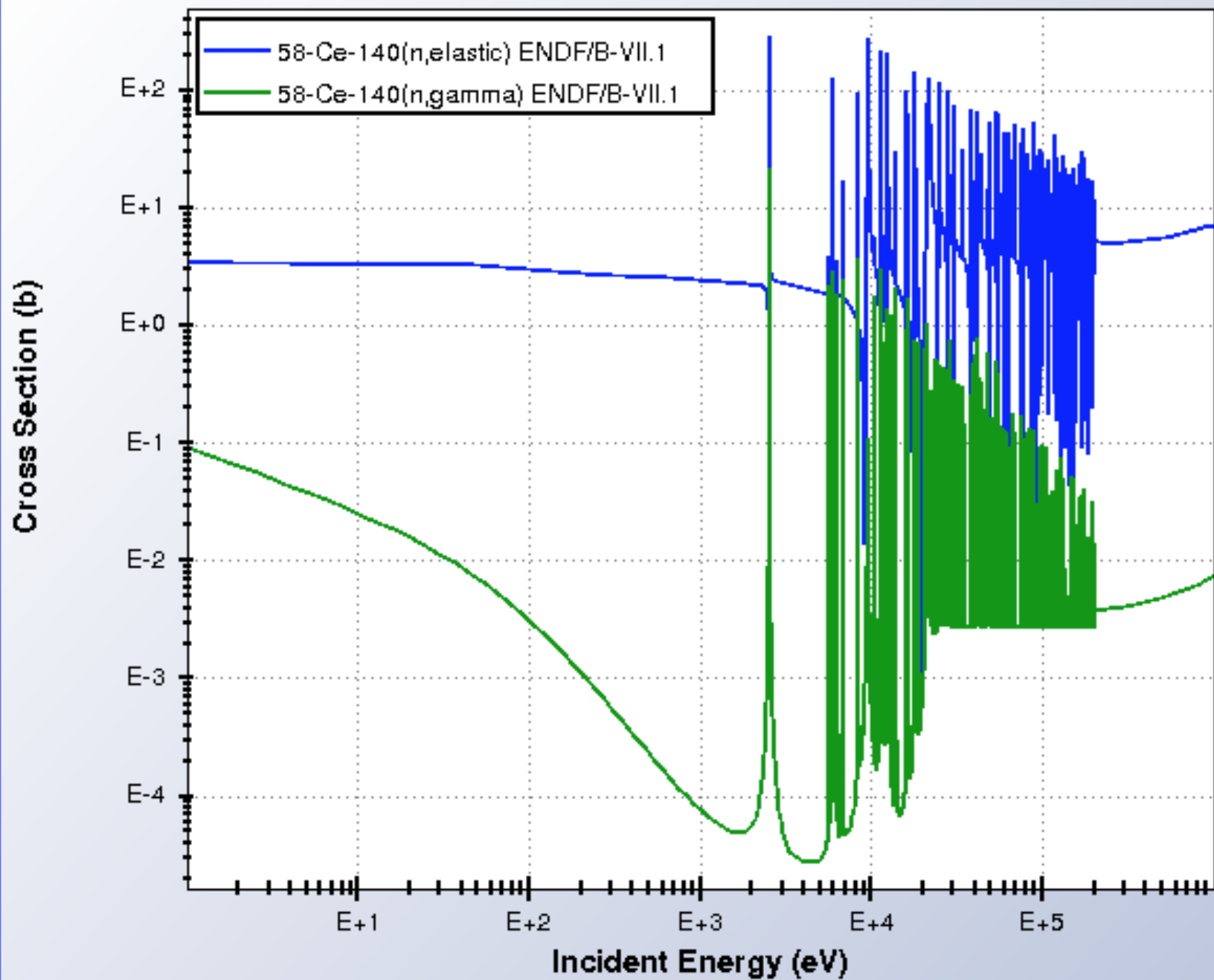
Ohkubo, jaeri report 1993

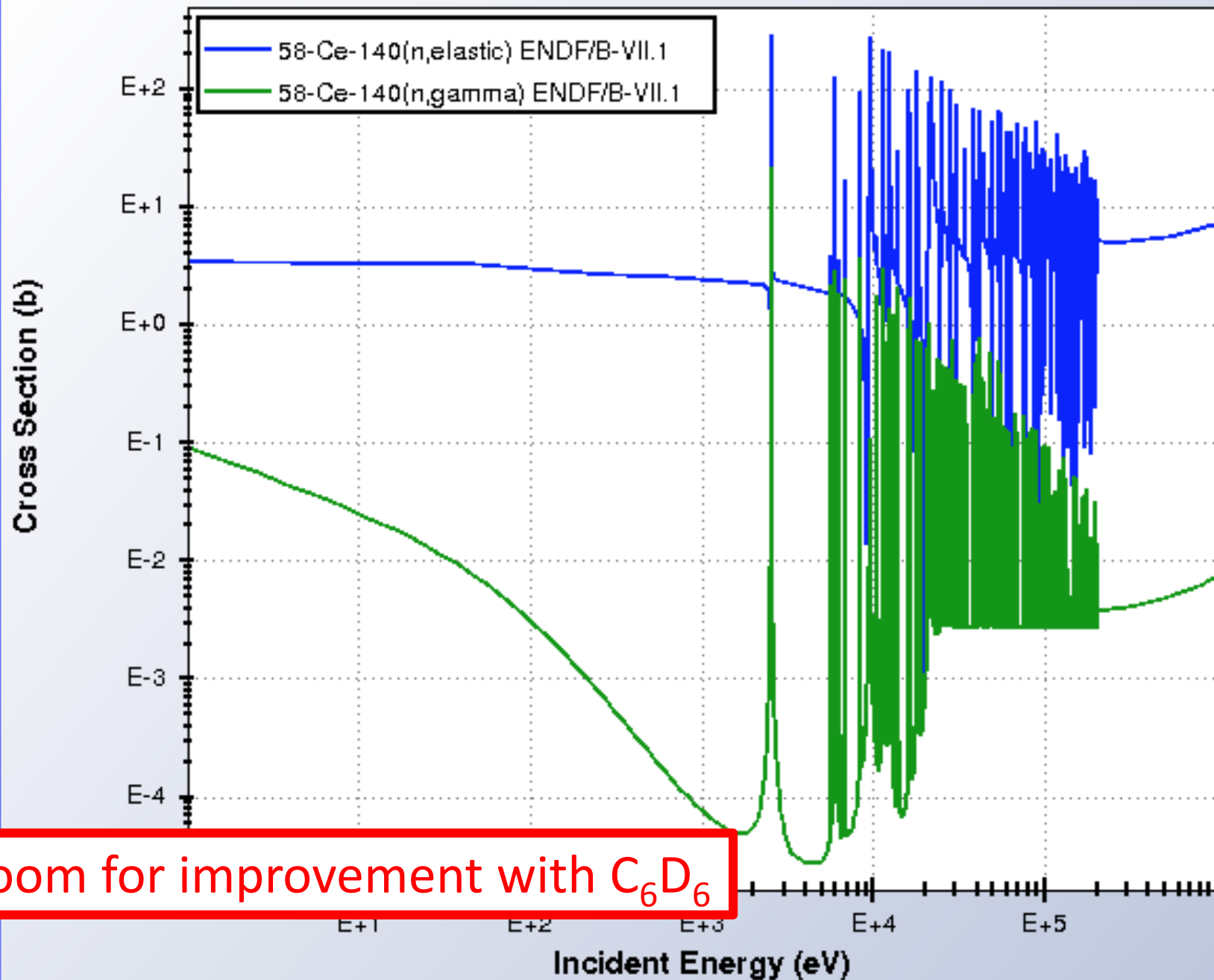
Capture (preliminary) 1974

$E_n < 65 \text{ keV}$

by Hacken (Columbia)

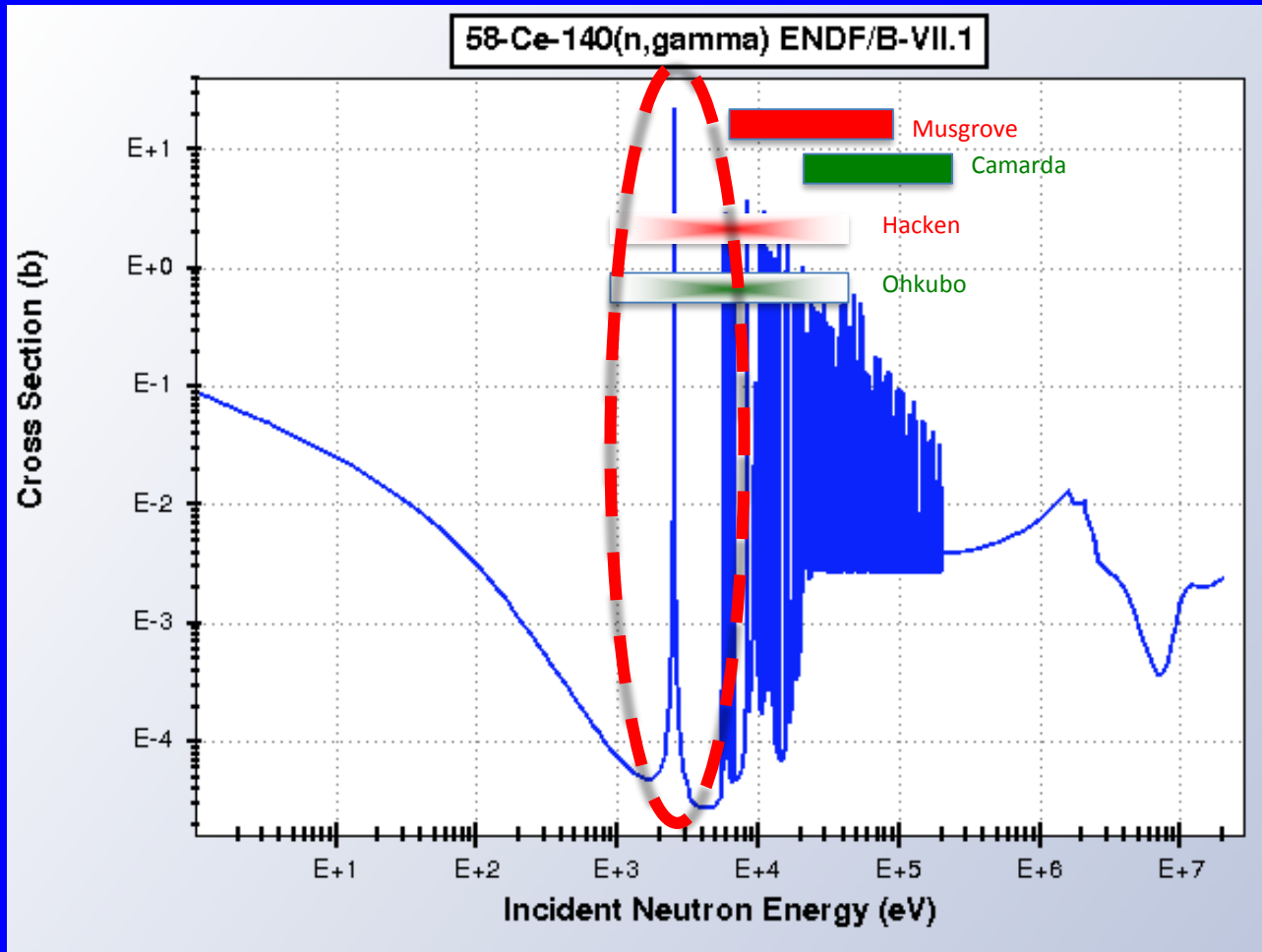
not  
published





Room for improvement with  $C_6D_6$

# $^{140}\text{Ce}$ neutron capture cross section (III)



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Capture ORELA 40 m,  $\text{C}_6\text{F}_6$

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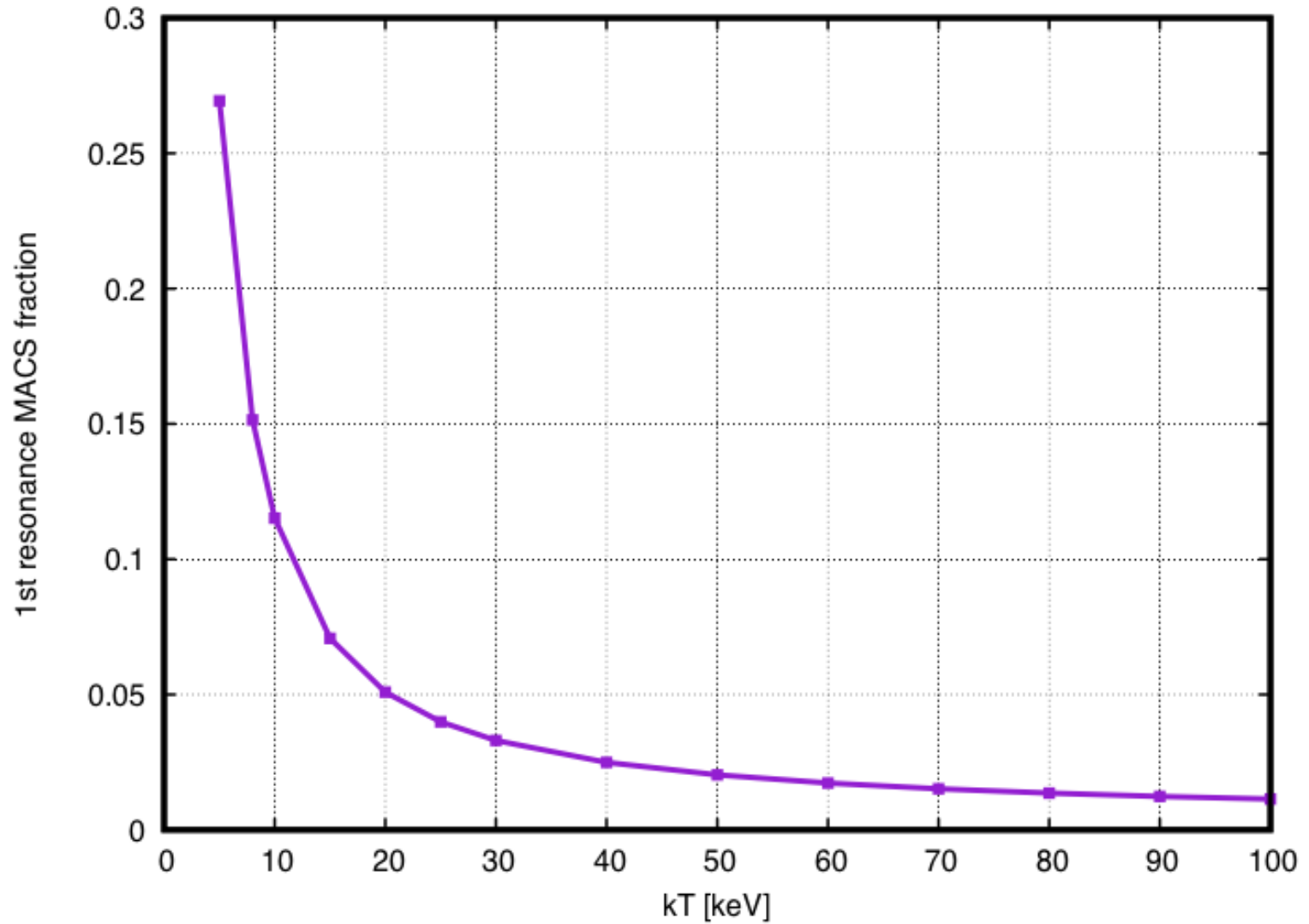
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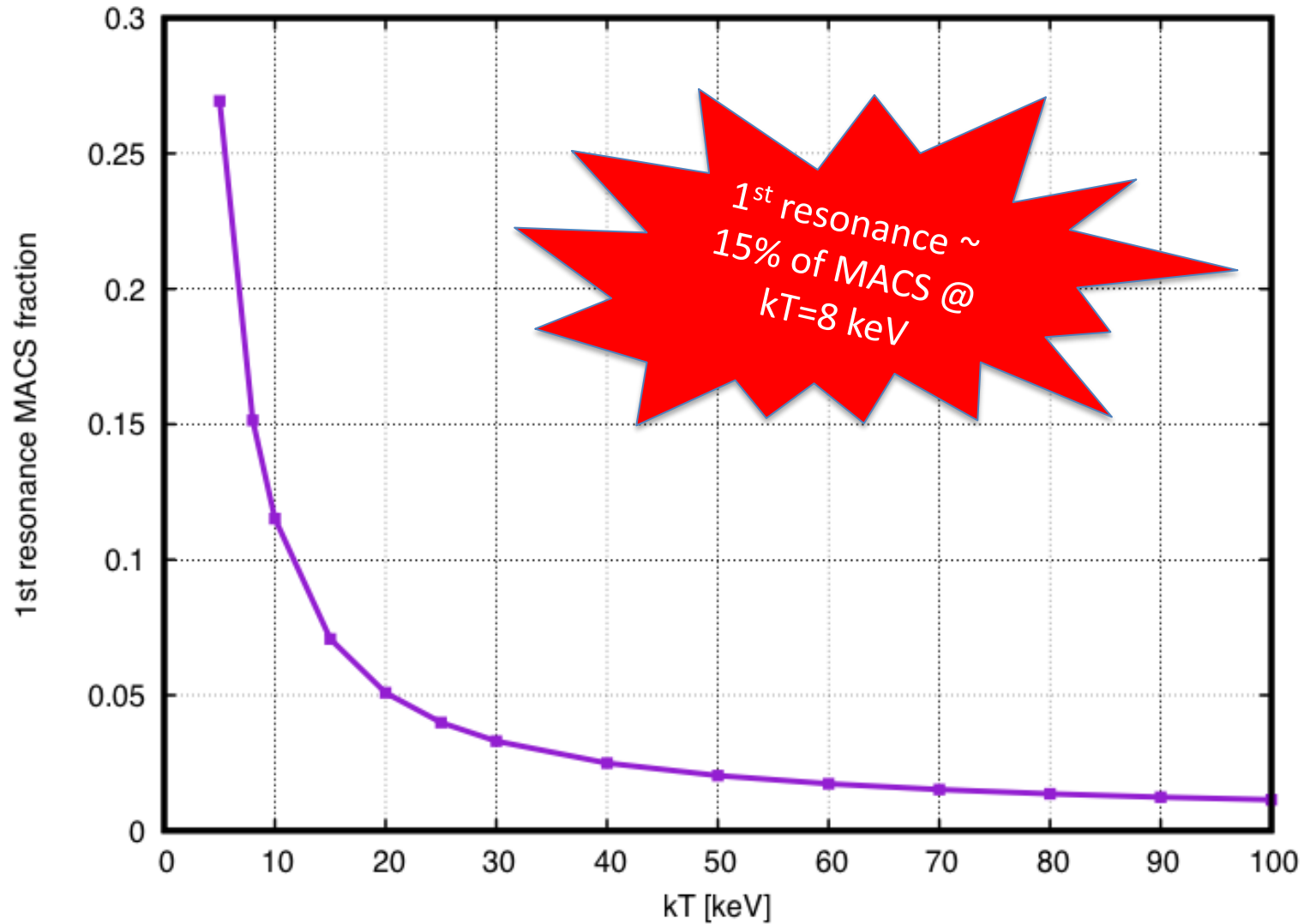
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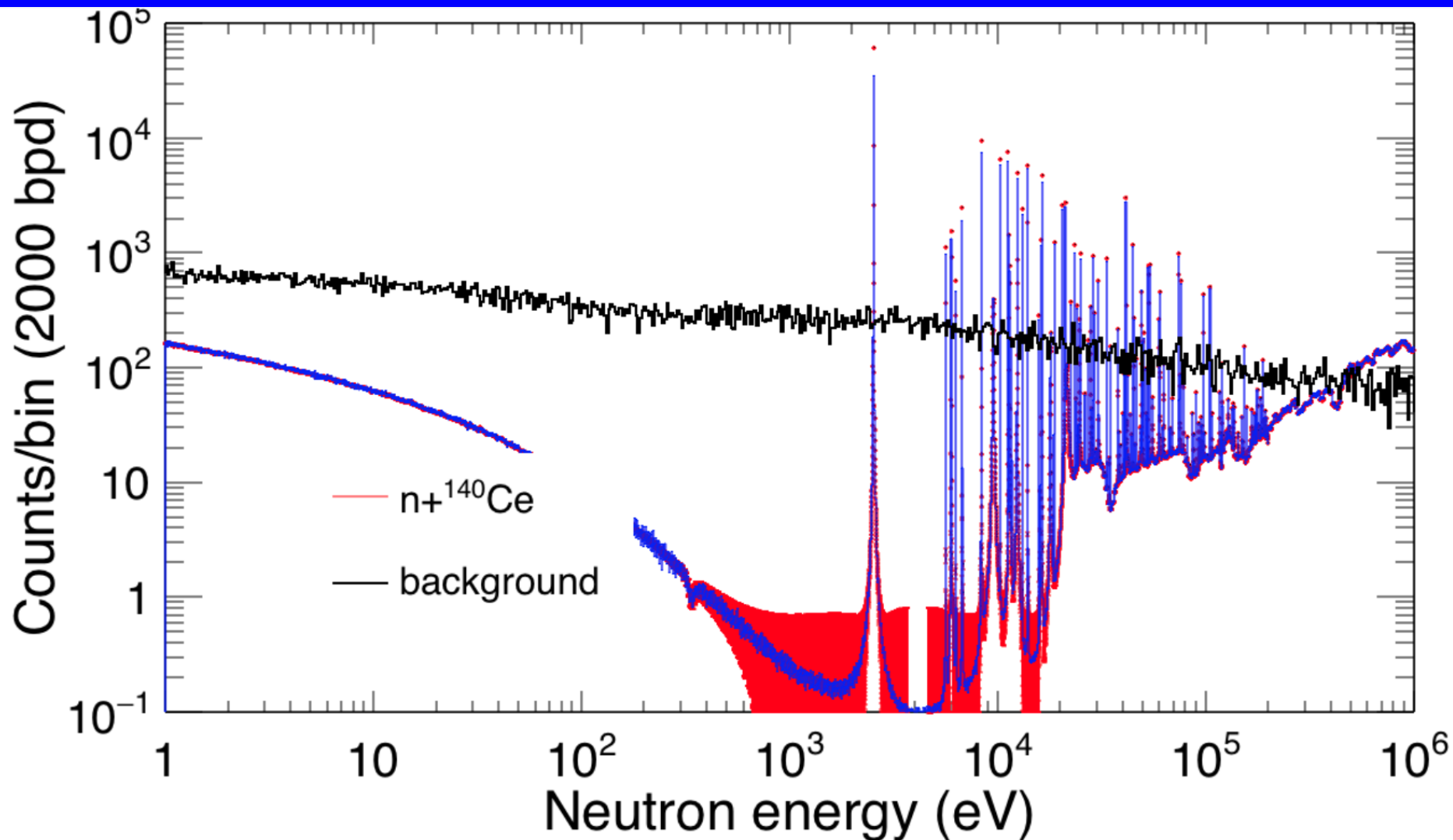
# $^{140}\text{Ce}$ neutron capture cross section (III)



# $^{140}\text{Ce}$ neutron capture cross section (III)



# Count rate @ EAR1 – 4 g $^{140}\text{Ce}$



# Conclusions

- $^{140}\text{Ce}$  is a magic nucleus (88% of solar cerium), mostly synthesized by the s-process (81% of Galactic cerium).
- Heavy-element abundances in s-rich galactic Globular Clusters show good agreement with theoretical AGB models for elements belonging to the 2<sup>nd</sup> s-process peak...apart from cerium!
- MACS at AGB energies are highly uncertain due to lack of experimental data:
  - 2 transmission experiments in literature ( $^{\text{nat}}\text{Ce}$  was used, energy region does not cover the whole region of interest,  $E_n > 20$  keV)
  - 1 capture experiment in literature ( $\text{C}_6\text{F}_6$  as capture detector, not well suited for this measurement:  $\Gamma_n \gg \Gamma_\gamma$ )
  - No capture data below 5 keV reported in literature (just one unpublished report)!
- **Clear need of accurate capture data on  $^{140}\text{Ce}$**
- n\_TOF can provide capture data in the energy region of interest:
  - Low cross section  $\rightarrow 2.9 \times 10^{18}$  protons
  - Resonances in the keV region  $\rightarrow$  EAR1
  - $\Gamma_n \gg \Gamma_\gamma \rightarrow \text{C}_6\text{D}_6$