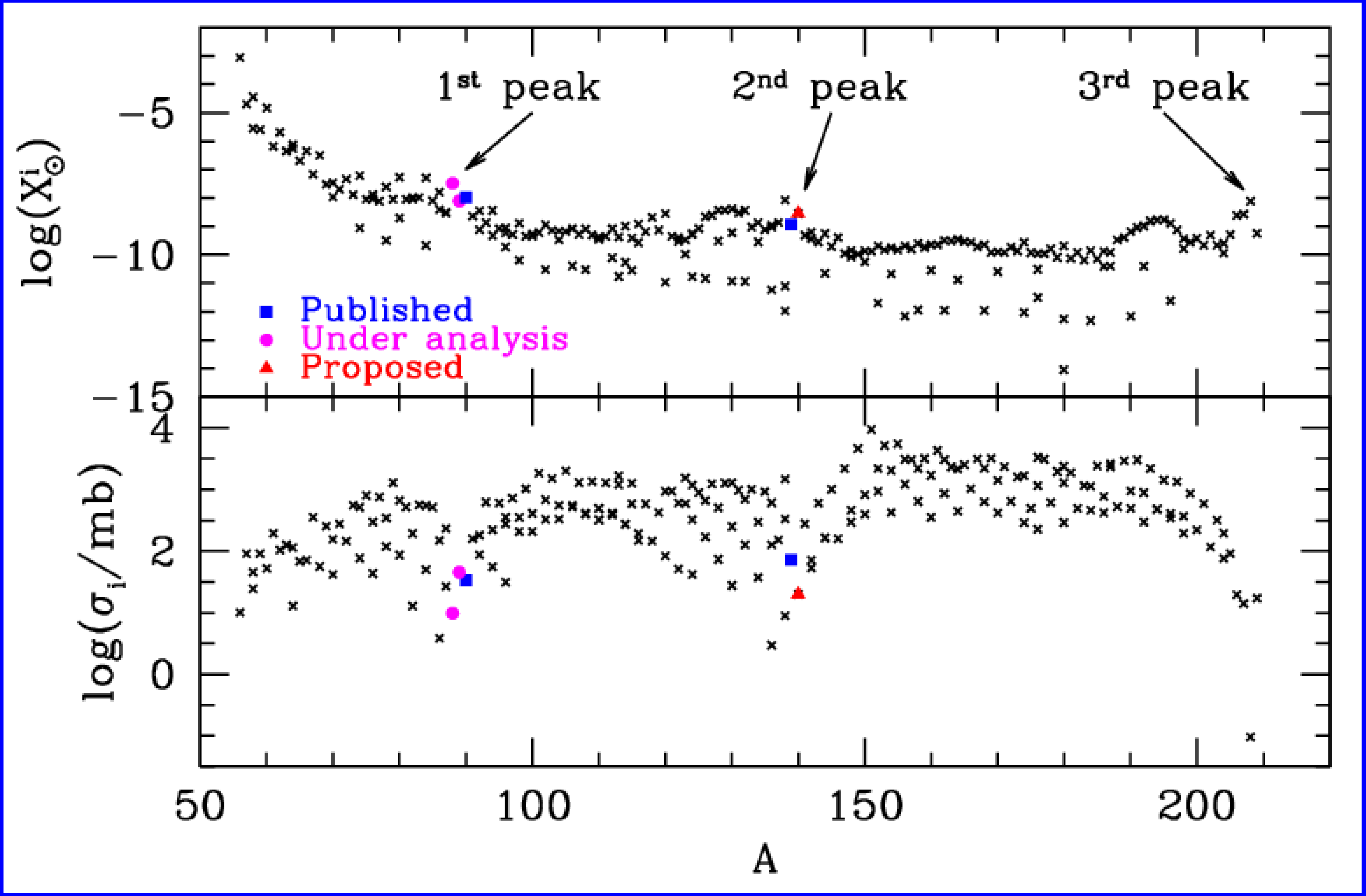
The $^{140}Ce(n,\gamma)^{141}Ce$ reaction at n_TOF-EAR1: a litmus test for theoretical stellar models.

(Preliminary) ABSTRACT

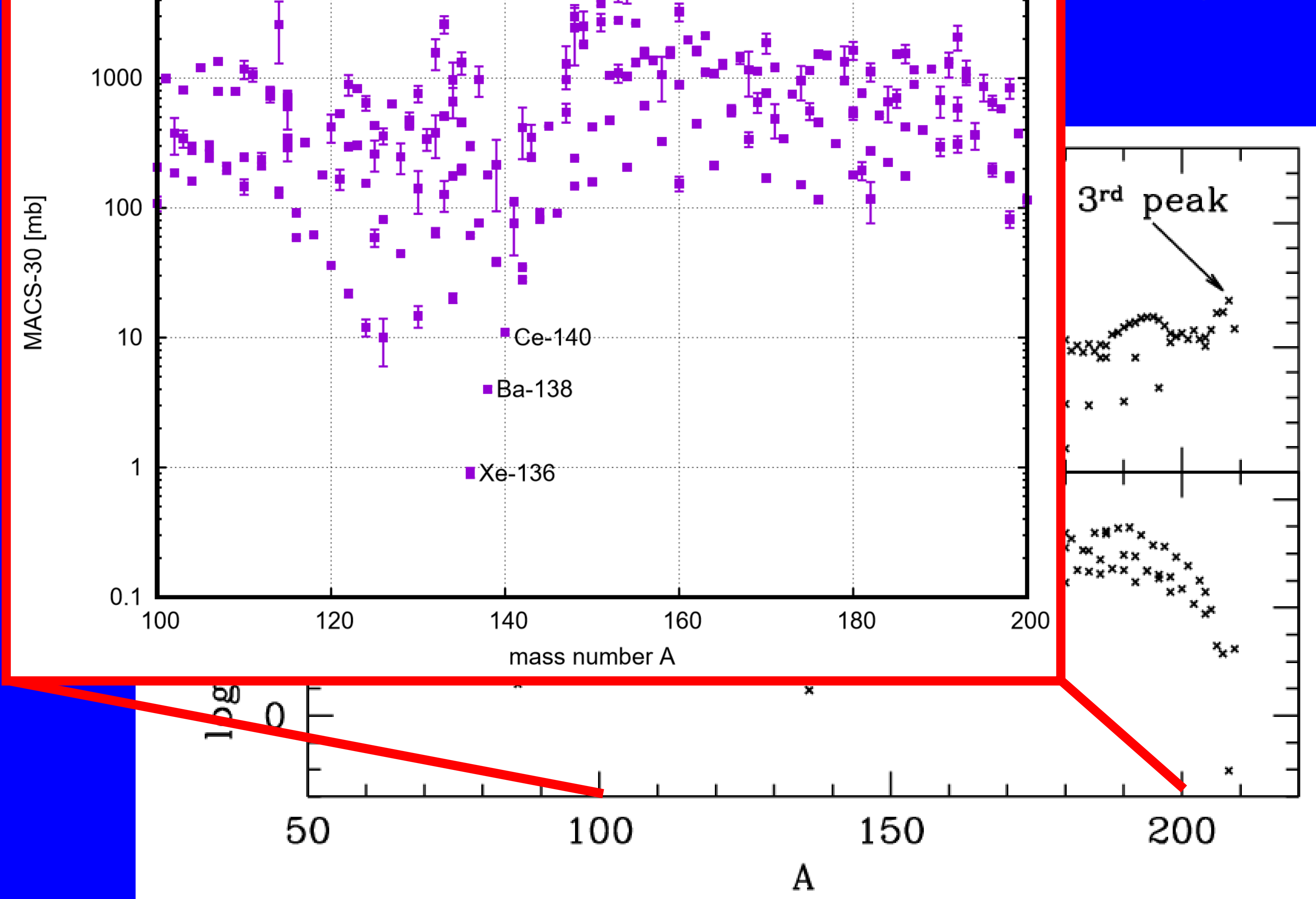
Evolutionary stellar models need nuclear input data as much accurate as possible. This holds in particular for nucleosynthesis calculations involving the production of nuclei heavier than iron. The case of ^{140}Ce (88% of solar cerium) is particularly interesting, because of its intrinsic closed shell nuclear structure. Cerium is mostly synthesized by the slow neutron capture process (the s-process). It has been carefully characterized in laboratory and observed in almost all stellar evolutionary phases. Currently, stellar models and observations of s-process enriched stars belonging to galactic globular clusters well agree for elements belonging to the 2nd s-process peak, apart from cerium. The re-evaluation of its neutron cross section is needed to verify the robustness of theoretical predictions, possibly solving the afore-mentioned discrepancy.

The solar distribution and the s-process peaks



Magic nuclei are bottleneck for the s-process nucleosynthesis

...cess peaks



Magic nuclei are bottleneck for the s-process nucleosynthesis

1^{st} s-process peak (N=50)

(^{86}Kr – ^{87}Rb) ^{88}Sr - ^{89}Y - ^{90}Zr

2^{nd} s-process peak (N=82)

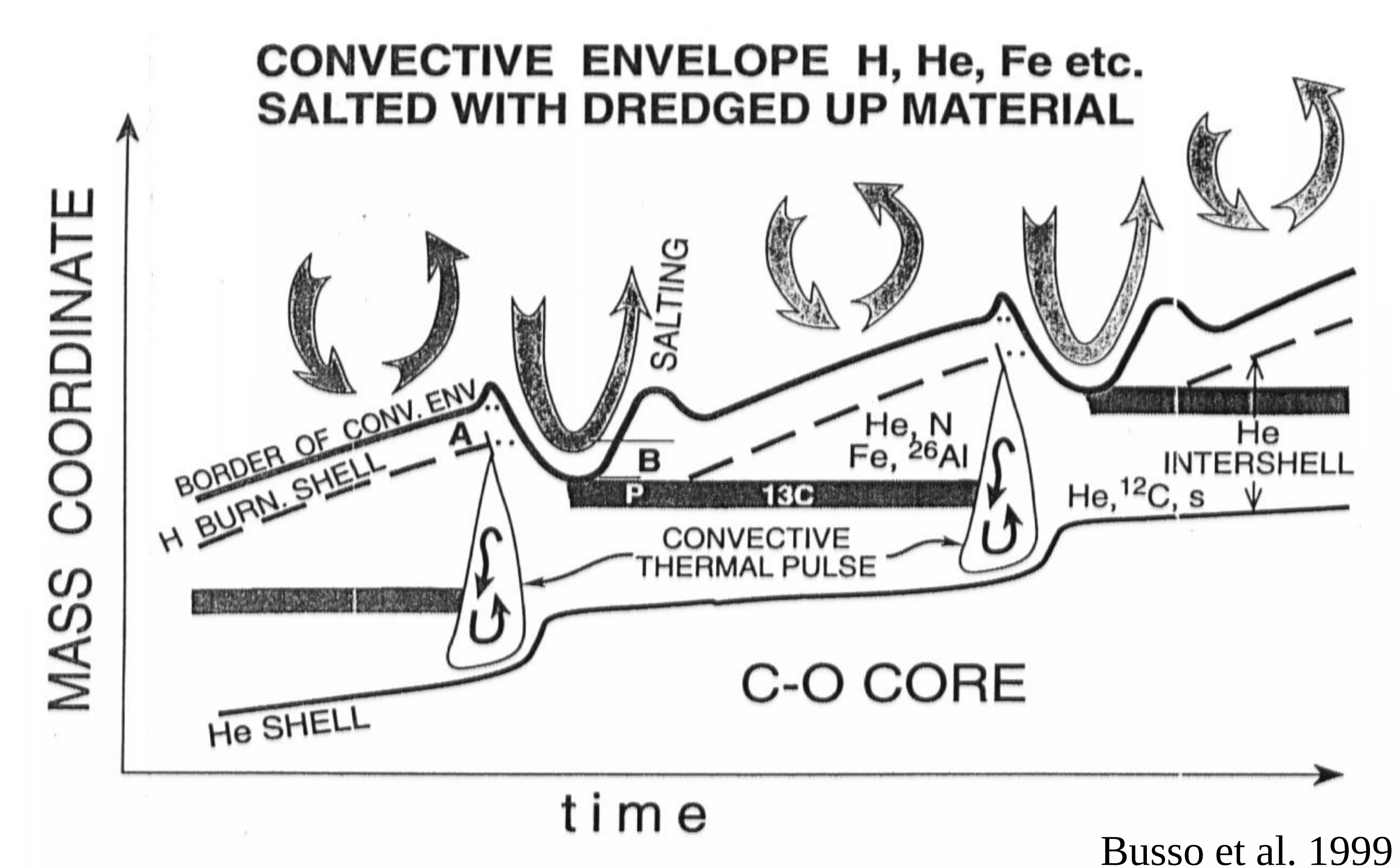
(^{136}Xe) ^{138}Ba - ^{139}La - ^{140}Ce – ^{141}Pr – ^{142}Nd (^{144}Sm)

3^{rd} s-process peak (N=126)

^{208}Pb – ^{209}Bi

↗ Z=82

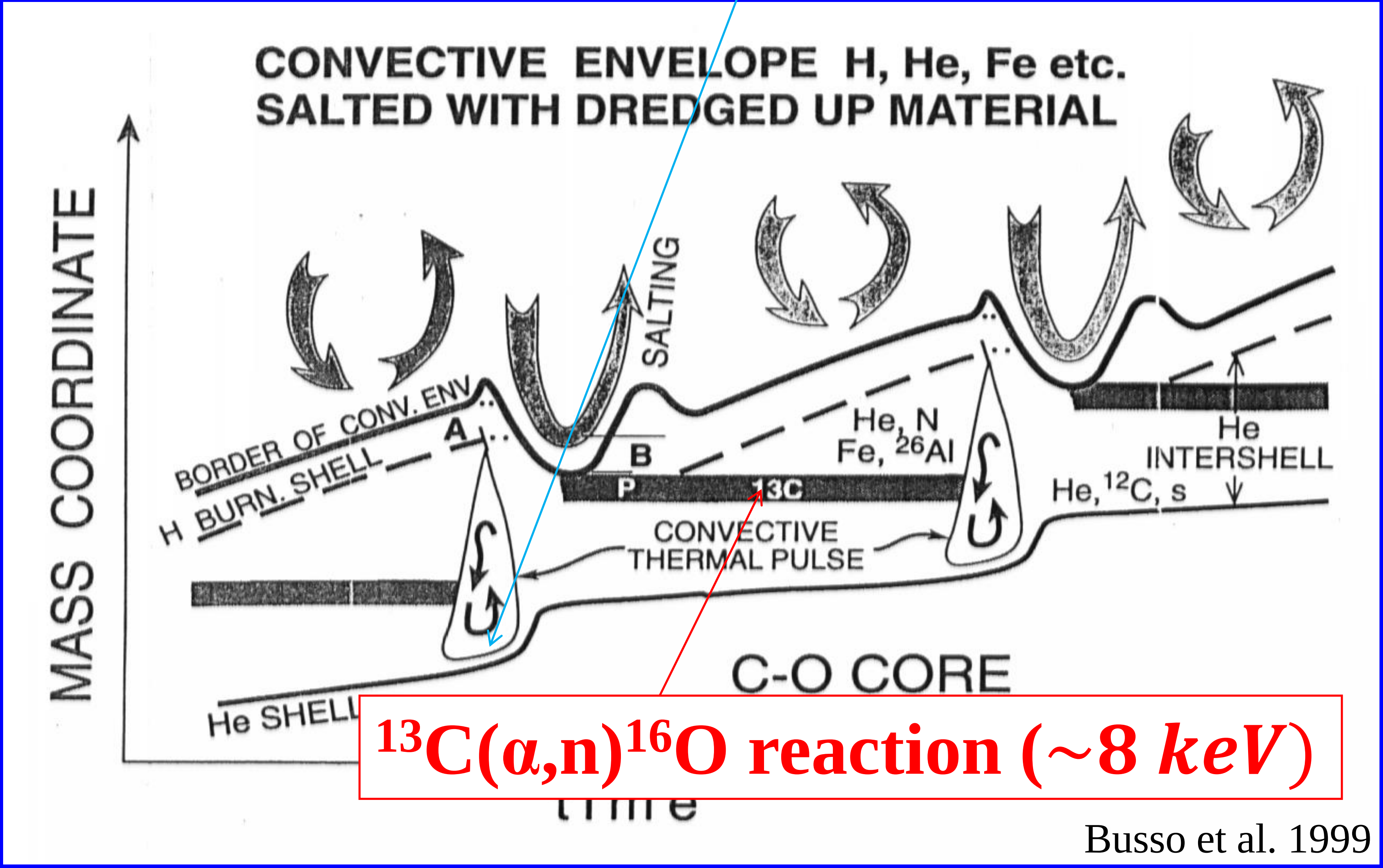
The s-process in AGB stars



Busso et al. 1999

The s-process in AGB stars

$^{22}Ne(\alpha,n)^{25}Mg$ reaction (~ 23 keV)



$^{13}C(\alpha,n)^{16}O$ reaction (~8 keV)

Busso et al. 1999

The s-process in Globular Clusters

Roederer+ 2011 (6 stars)

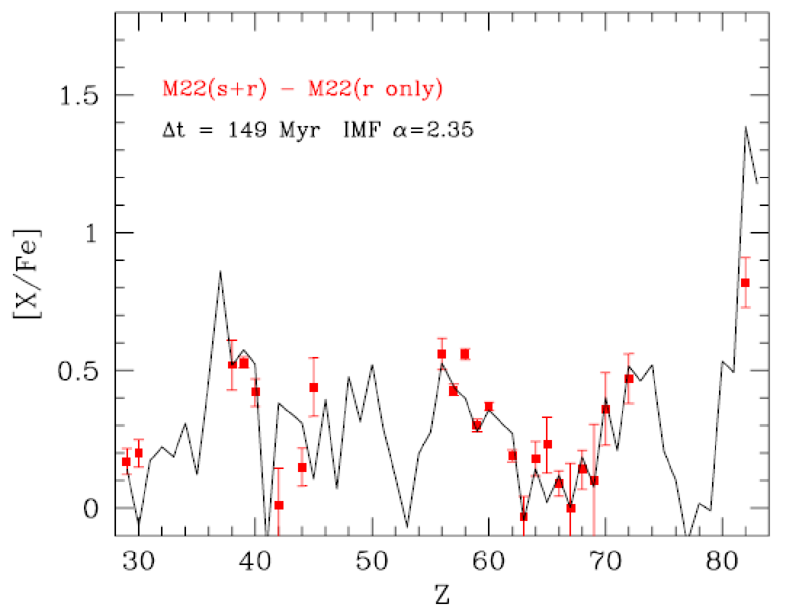


Figure 11. Best fit of the average s-process chemical pattern of stars in M22.

Young+ 2008 (14 stars)

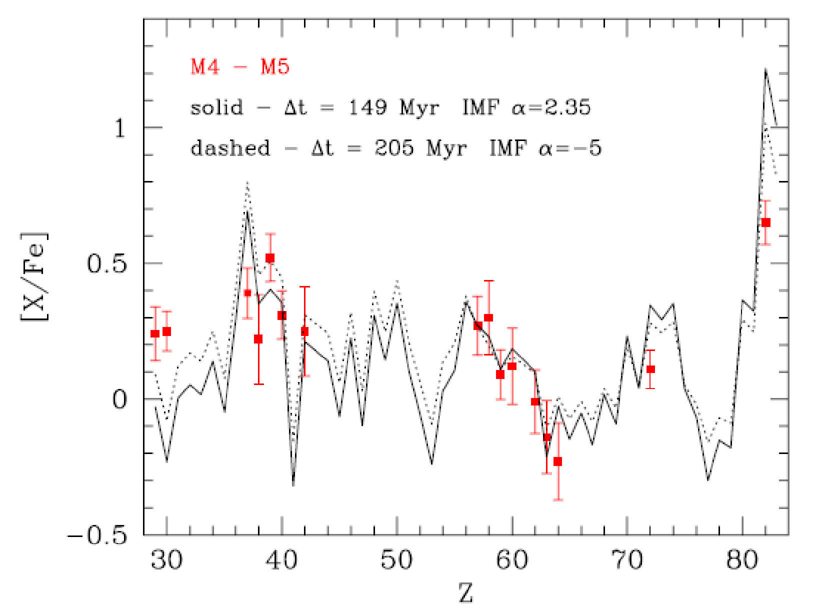


Figure 13. Best fit of the average s-process chemical pattern of stars in M4.

Straniero, Cristallo & Piersanti 2014

Hot low metallicity Main Sequence stars: reliable observations

The pollution of asymptotic giant branch (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.

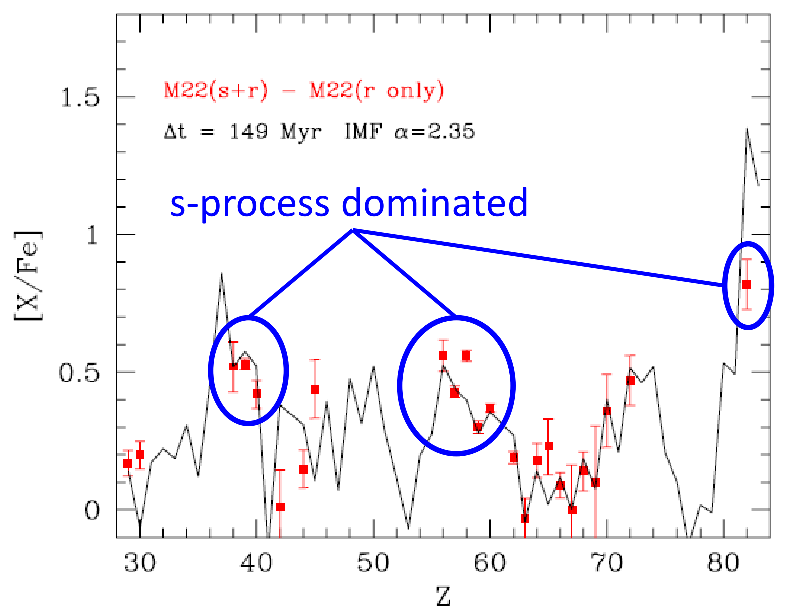
M22

M4

M5

The s-process in Globular Clusters

Roederer+ 2011 (6 stars)



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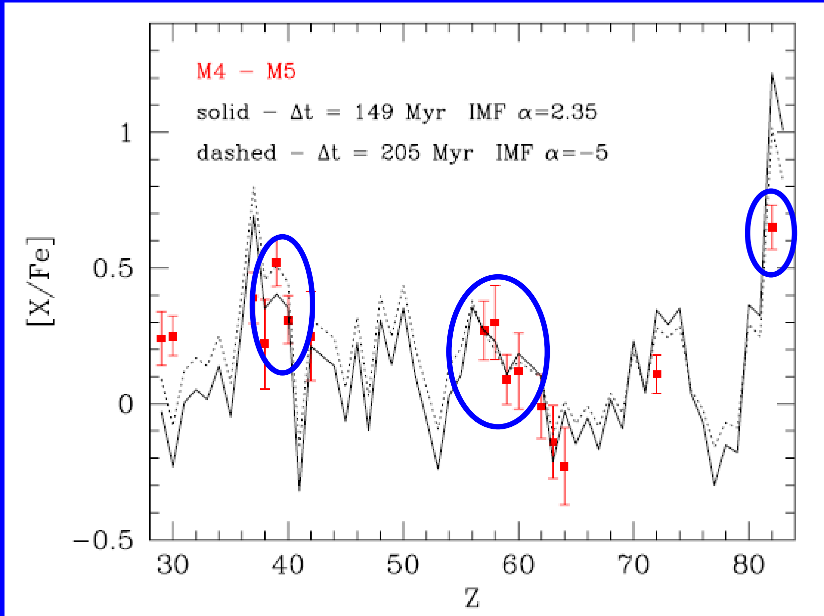


Figure 13. Best fit of the average *s*-process chemical pattern of stars in M4.

Straniero, Cristallo & Piersanti 2014

Hot low metallicity Main Sequence stars: reliable observations

The pollution of asymptotic giant branch (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.

s-process contributions:

Sr 97%
Y 92%
Zr 96%

Ba 89%
La 71%
Ce 81%
Pr 52%
Nd 57%

Pb 87%

The s-process in Globular Clusters

Roederer+ 2011 (6 stars)

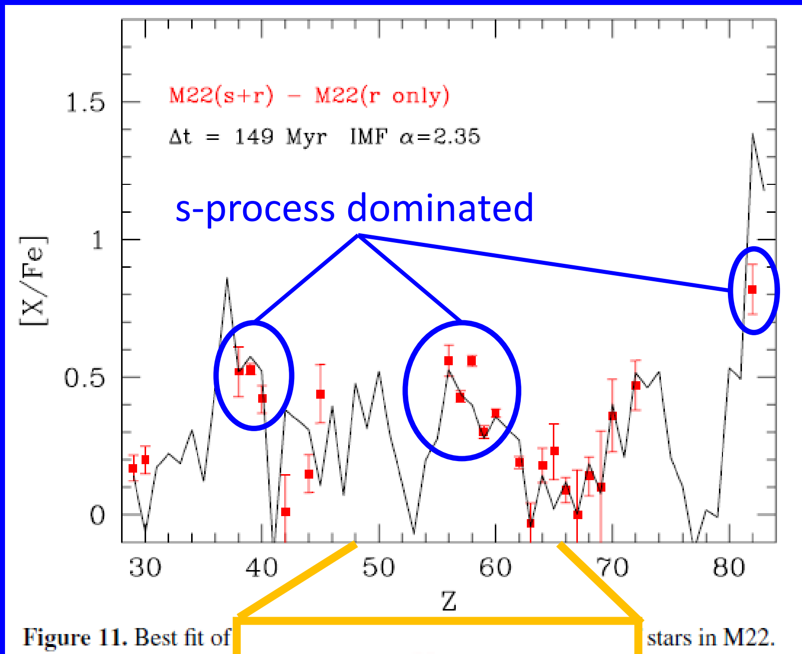
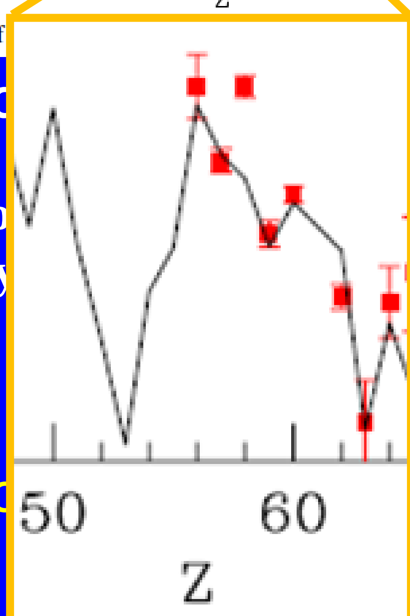


Figure 11. Best fit of ... stars in M22.



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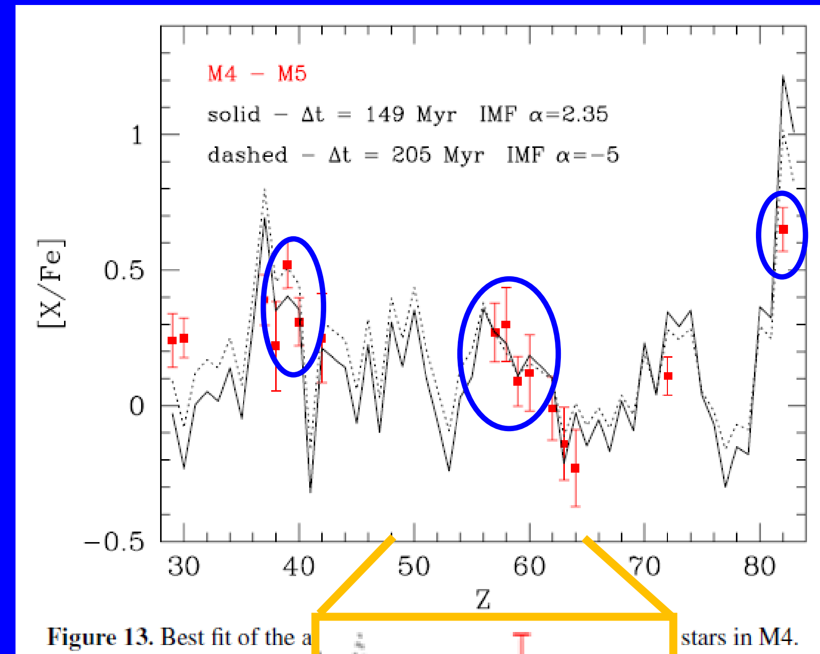
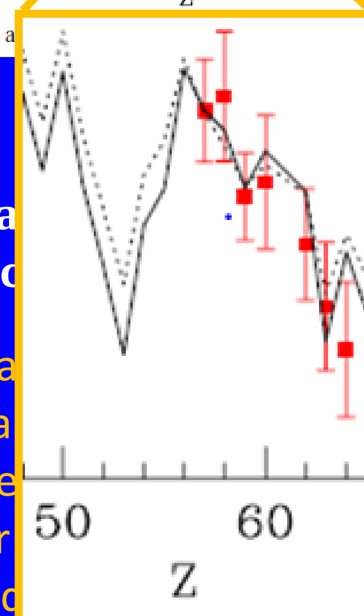


Figure 13. Best fit of the a ... stars in M4.



Straniero, C ... 014

The pollutio ... nt branch (AGB) stars with a ... tween 3 to 6 M_{SUN} may ... of the features of the *s*-proc ... f M4 and M22.

s-pro ... ons:

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Ba
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Nd

Cerium

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

→ (n,γ)

↖ β^- decay

Cerium

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(n,γ)

β^- decay

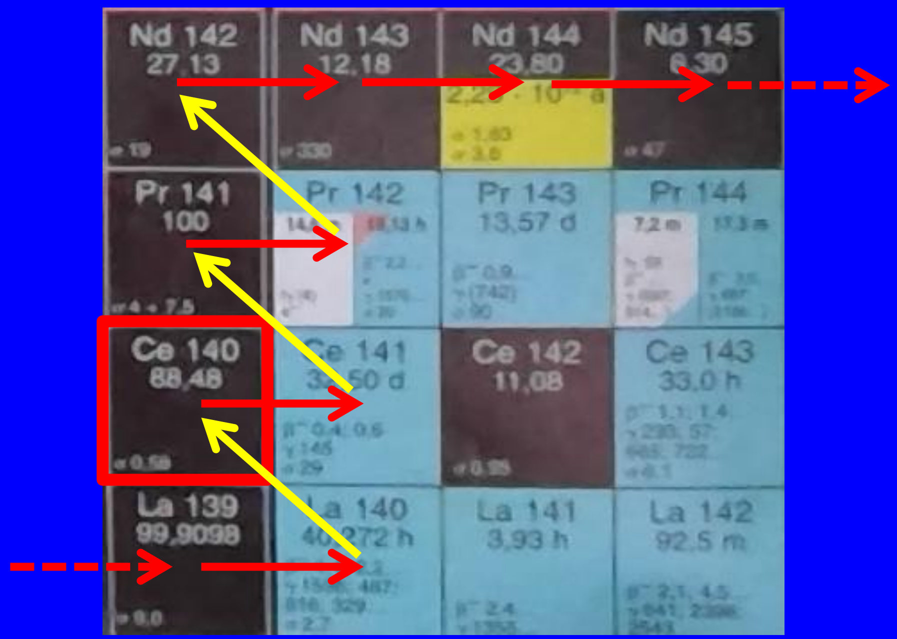
Its production channel has already been explored by the n_TOF collaboration (Terlizzi+ 2007)

Cerium

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

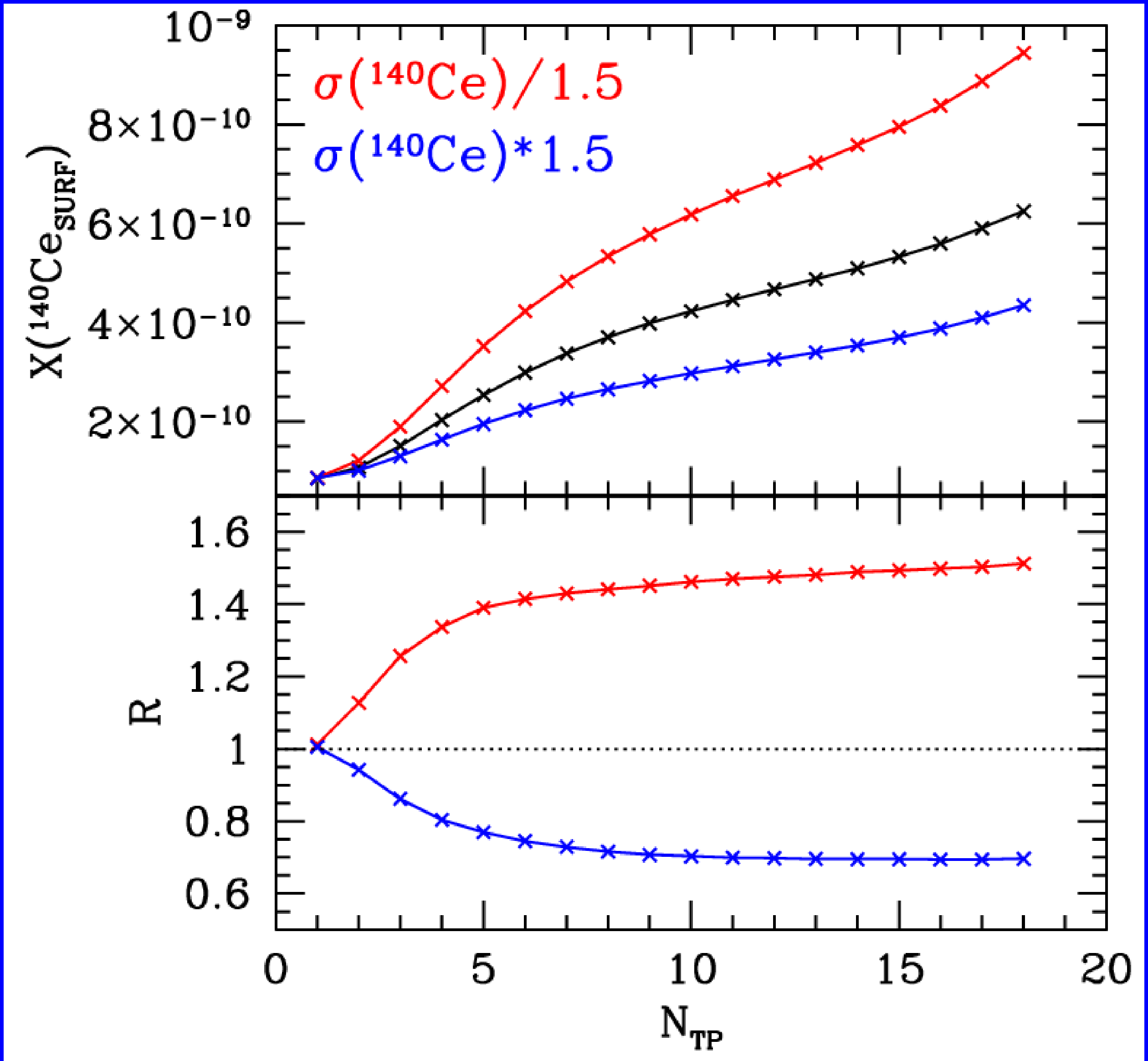
→ (n,γ)

↖ β$^-$ decay



Cerium has been observed in all evolutionary phases (MS,RGB, AGB) at various metallicities. Most of its lines, however, are blended (less problematic at low metallicities). Its **oscillator strengths** have been determined precisely by Lawler+ 2009 (oscillator strenghts express the probability of absorption or emission of electromagnetic radiation in transitions between energy levels).

Stellar nucleosynthesis

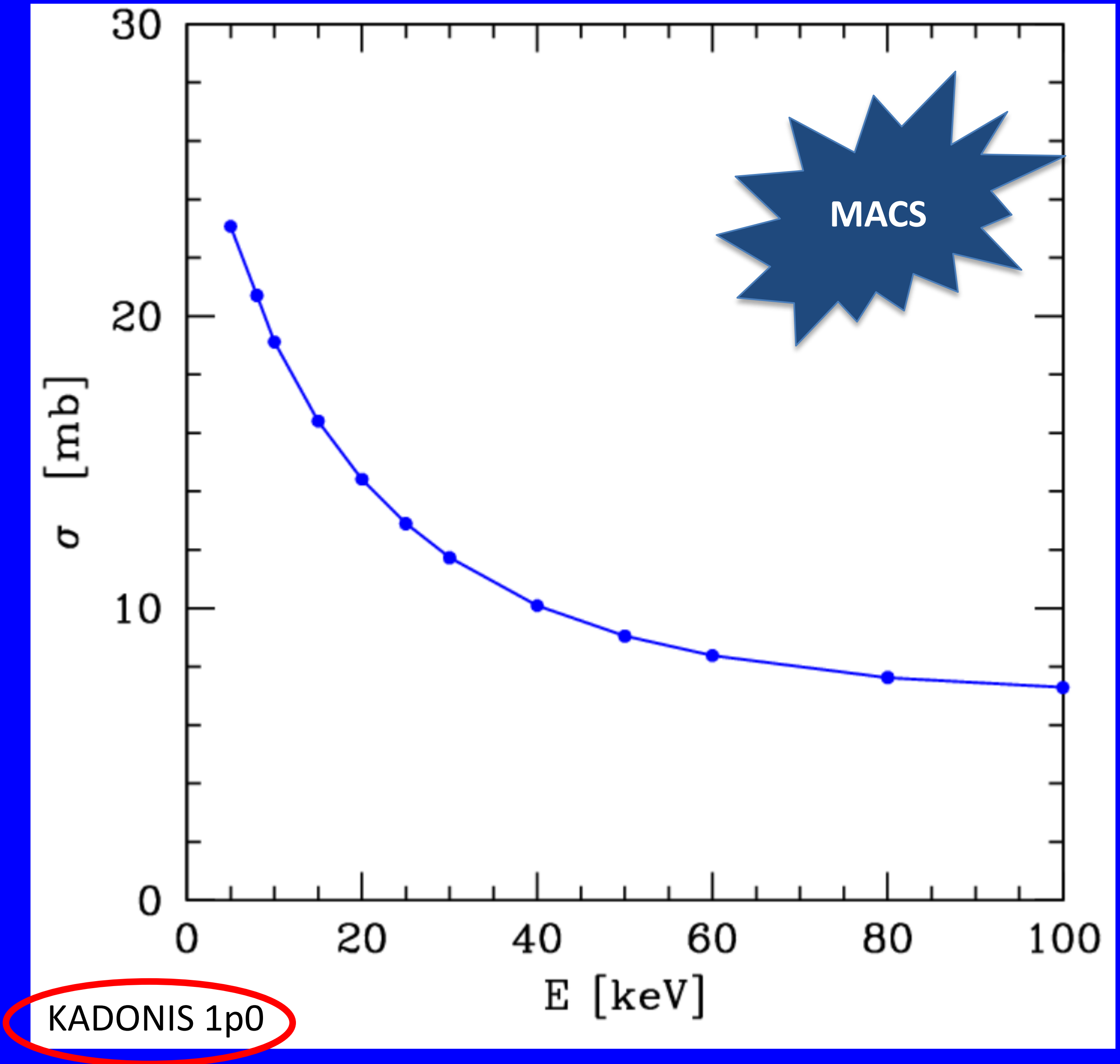


Stellar surface abundances

Surface ratio with respect to standard (Bao&Kappeler 2000)

FUNS $M=4\ M_{SUN}$ [Fe/H]=-1.67

^{140}Ce neutron capture cross section (I)



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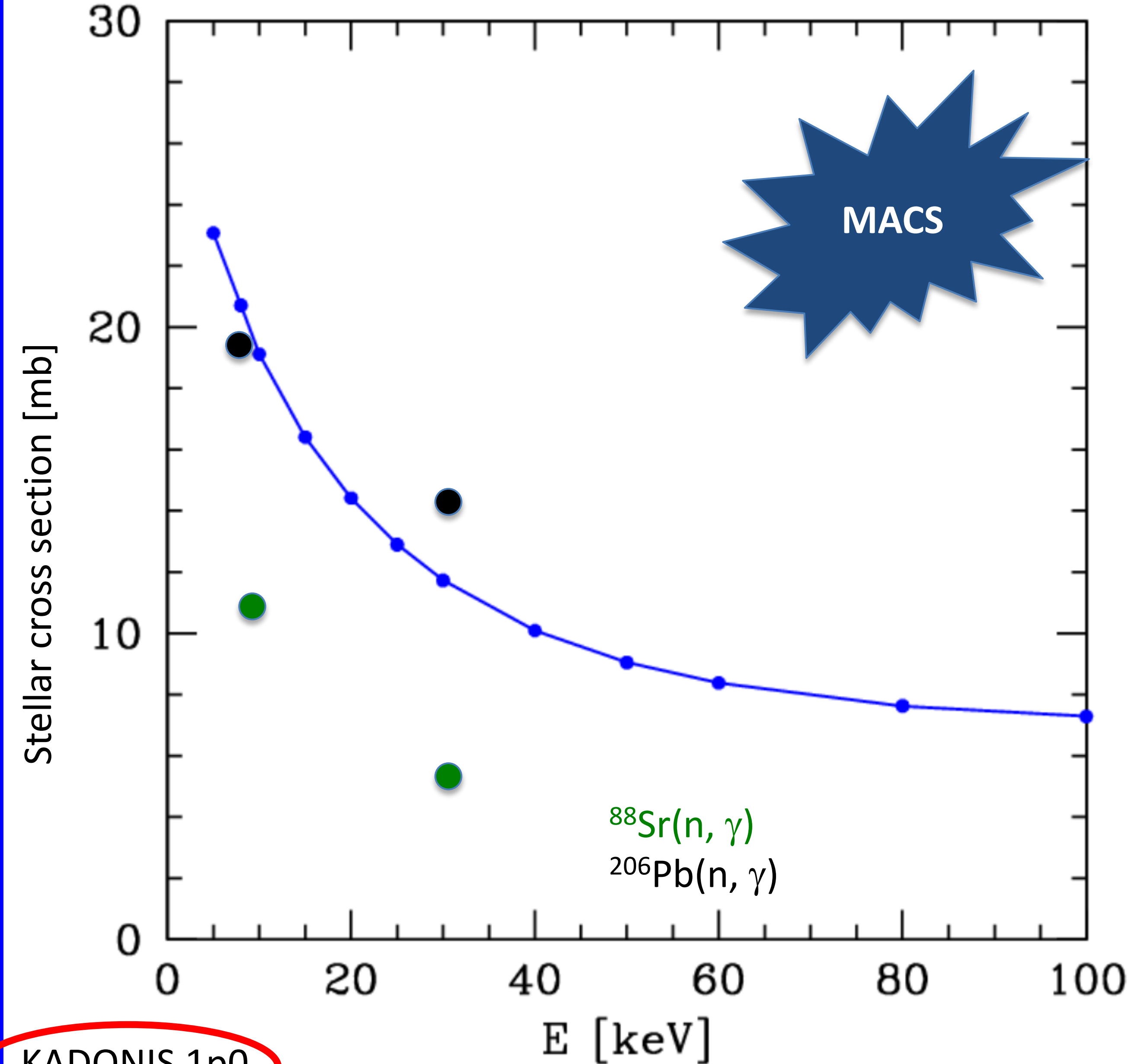

KADONIS 1p0

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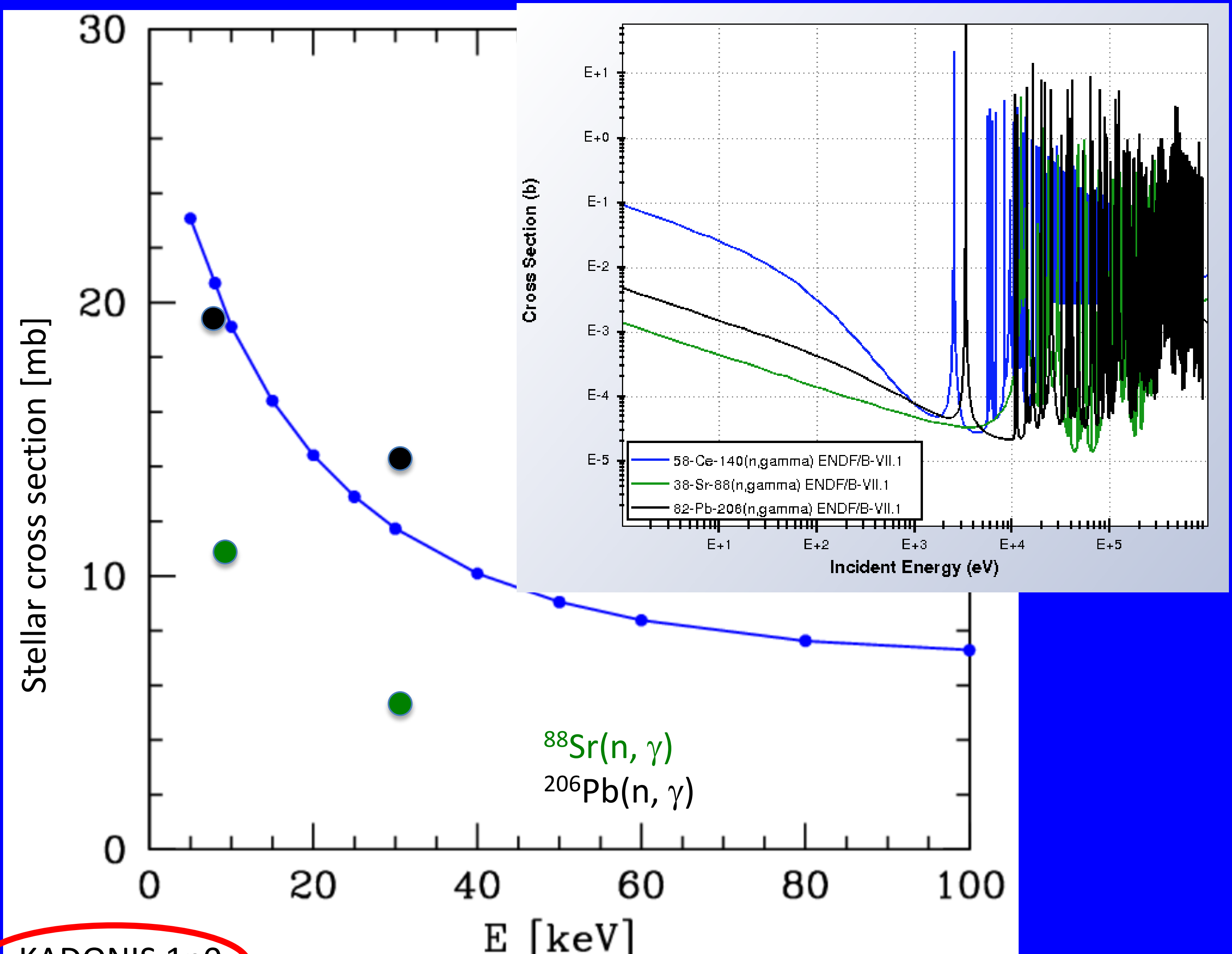
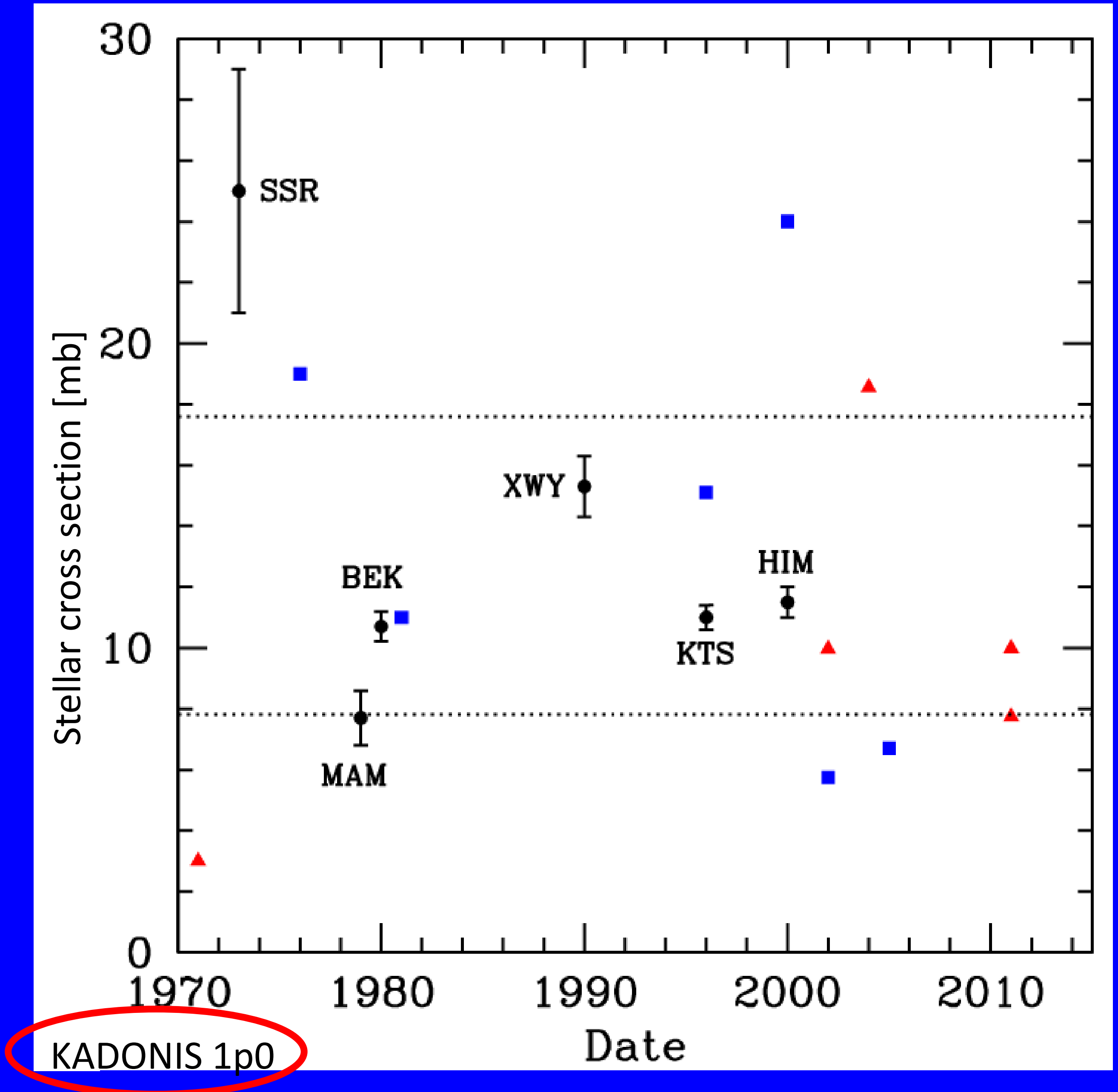


KADONIS 1p0

^{140}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)
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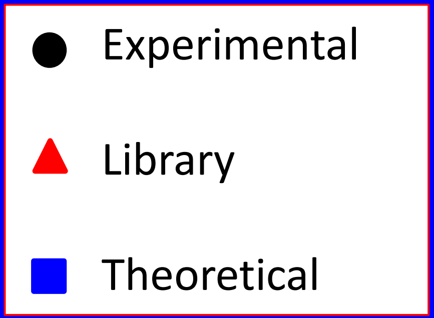

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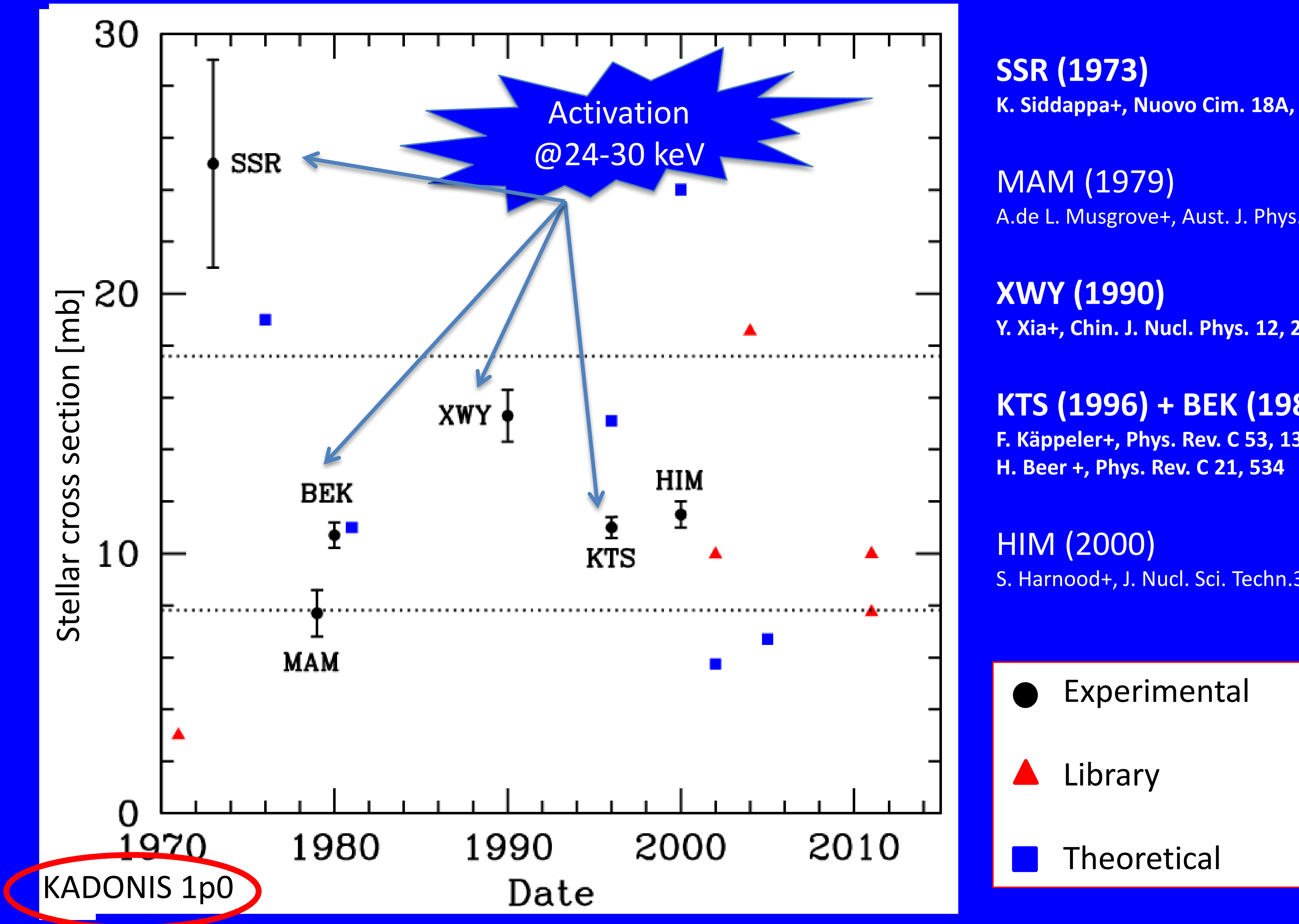

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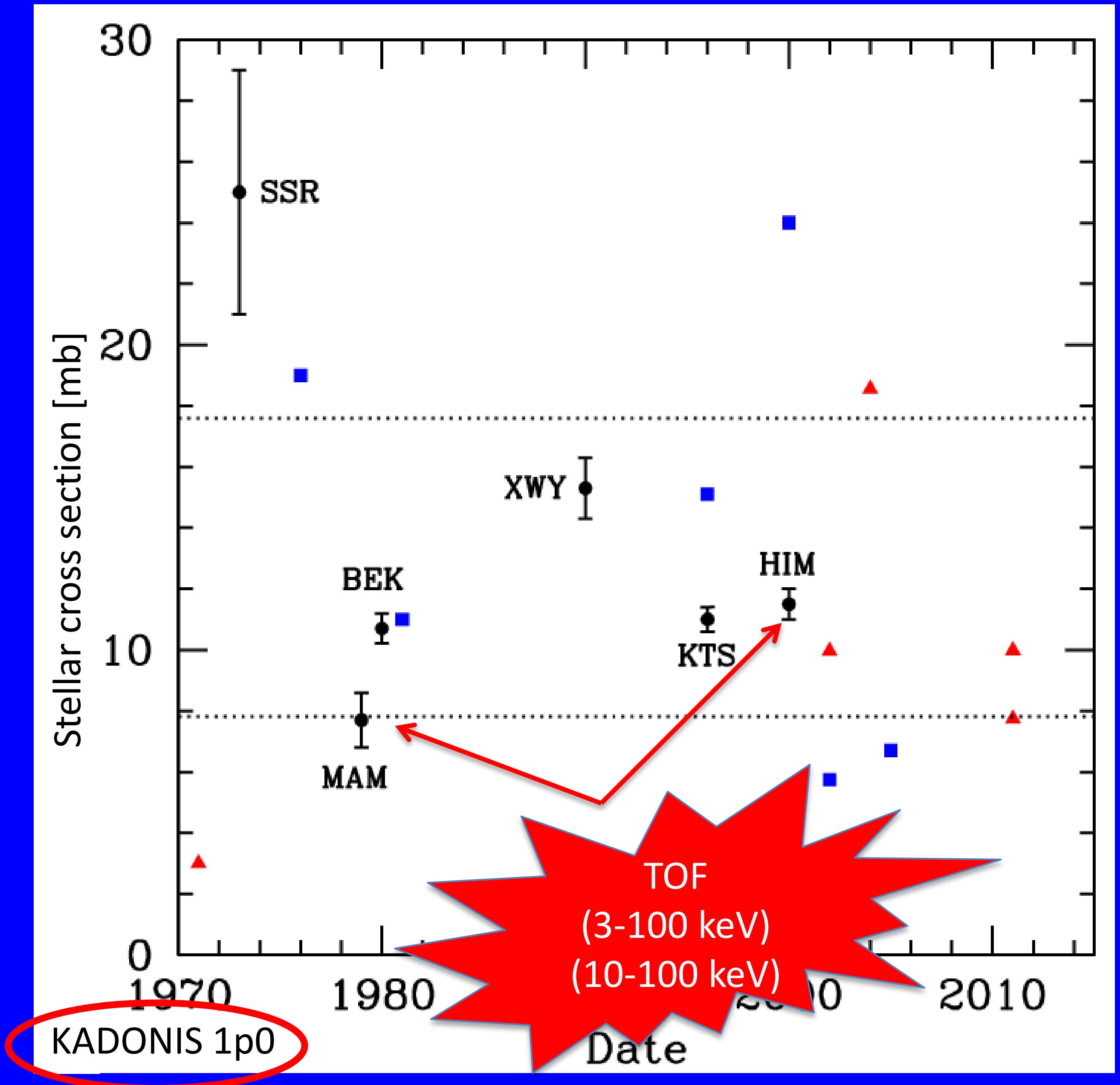

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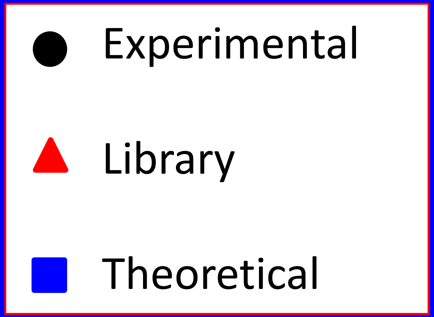
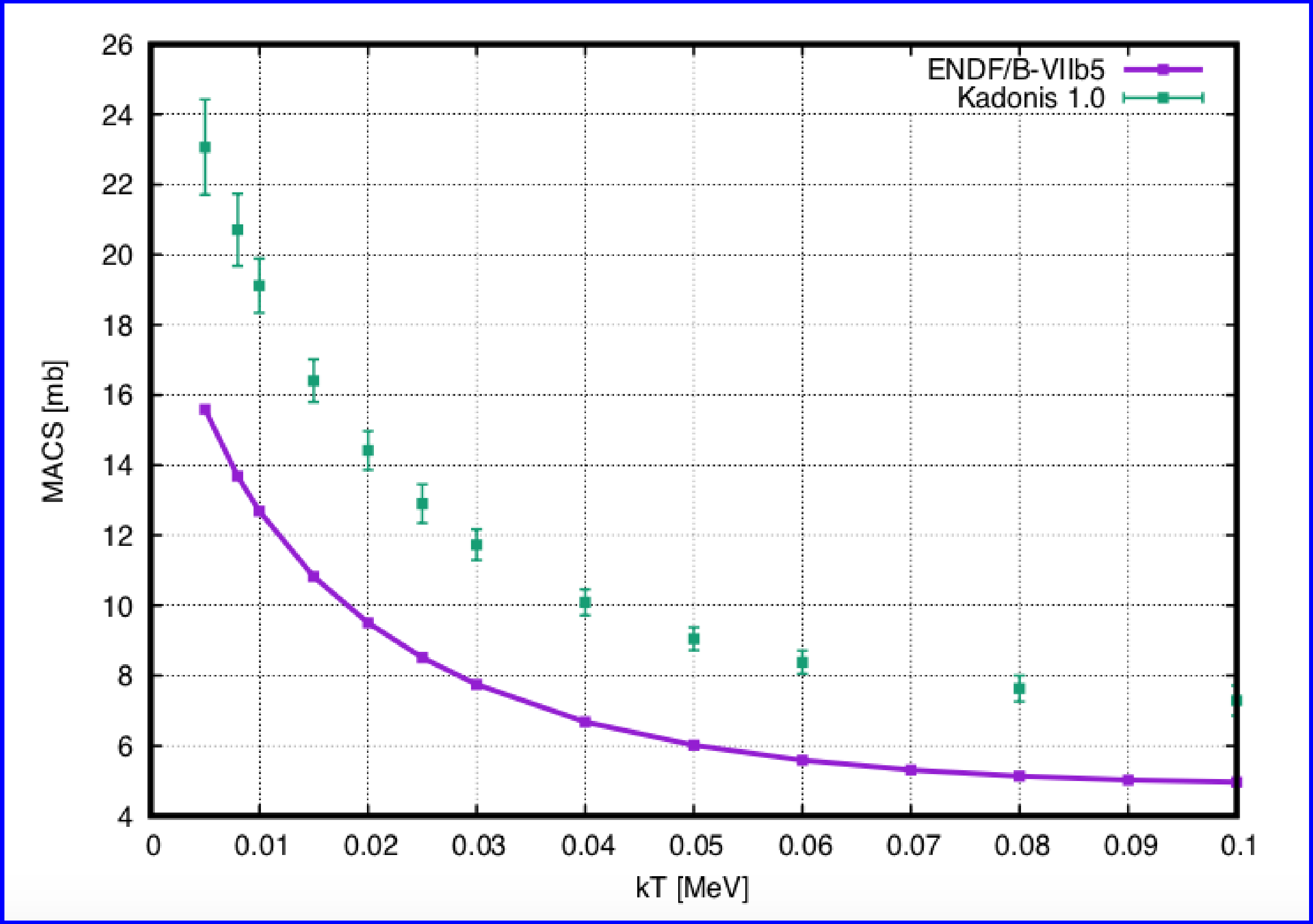


^{140}Ce neutron capture cross section (III)



EVALUATIONS:

Capture ORELA 40 m, C_6F_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 ^{nat}Ce
E_n < 60 keV
Ohkubo, jaeri report 1993

Capture (preliminary) 1974
En<65 keV

by Hacken (Columbia)

not published

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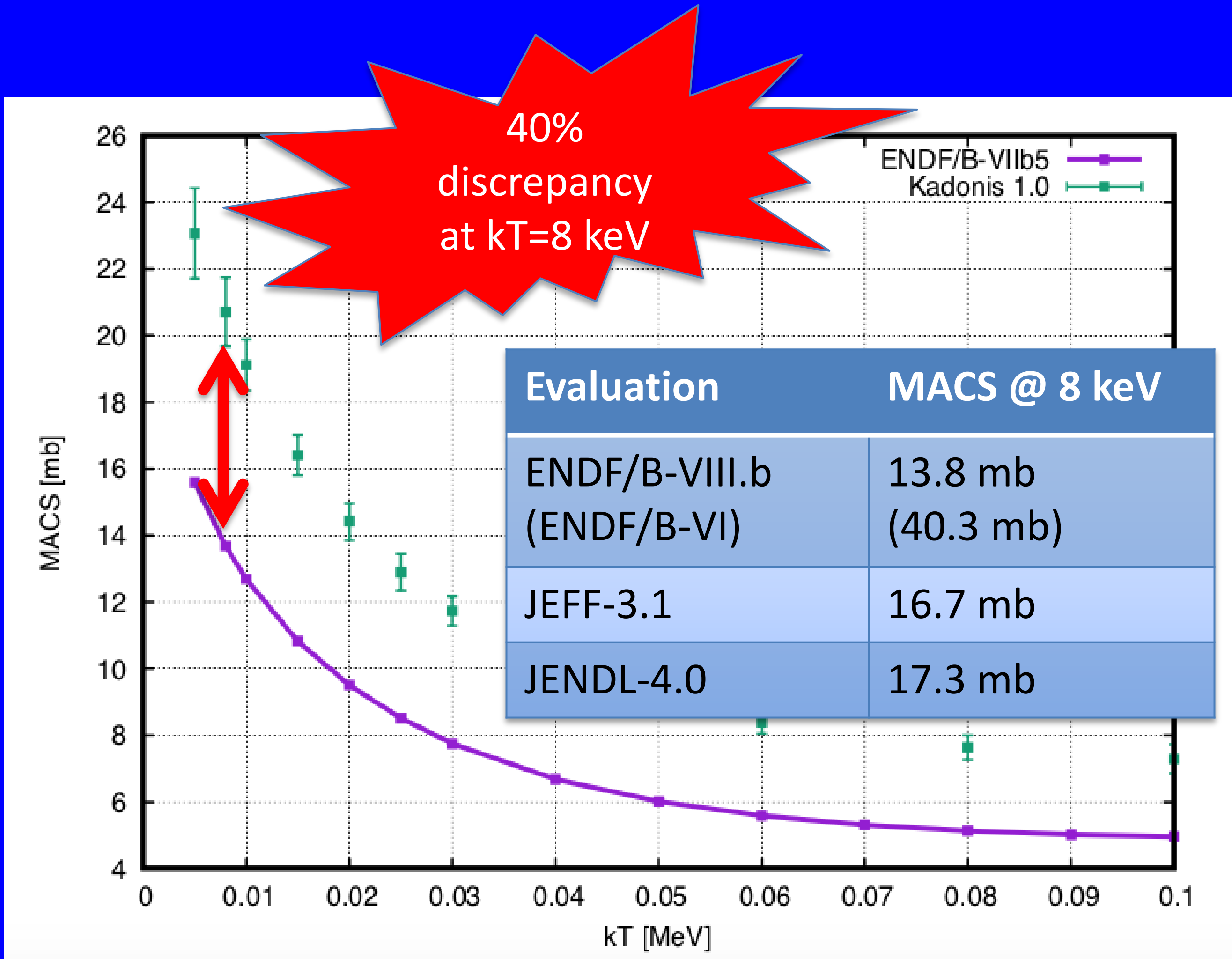

Evaluation	MACS @ 8 keV
ENDF/B-VIII.b (ENDF/B-VI)	13.8 mb (40.3 mb)
JEFF-3.1	16.7 mb
JENDL-4.0	17.3 mb

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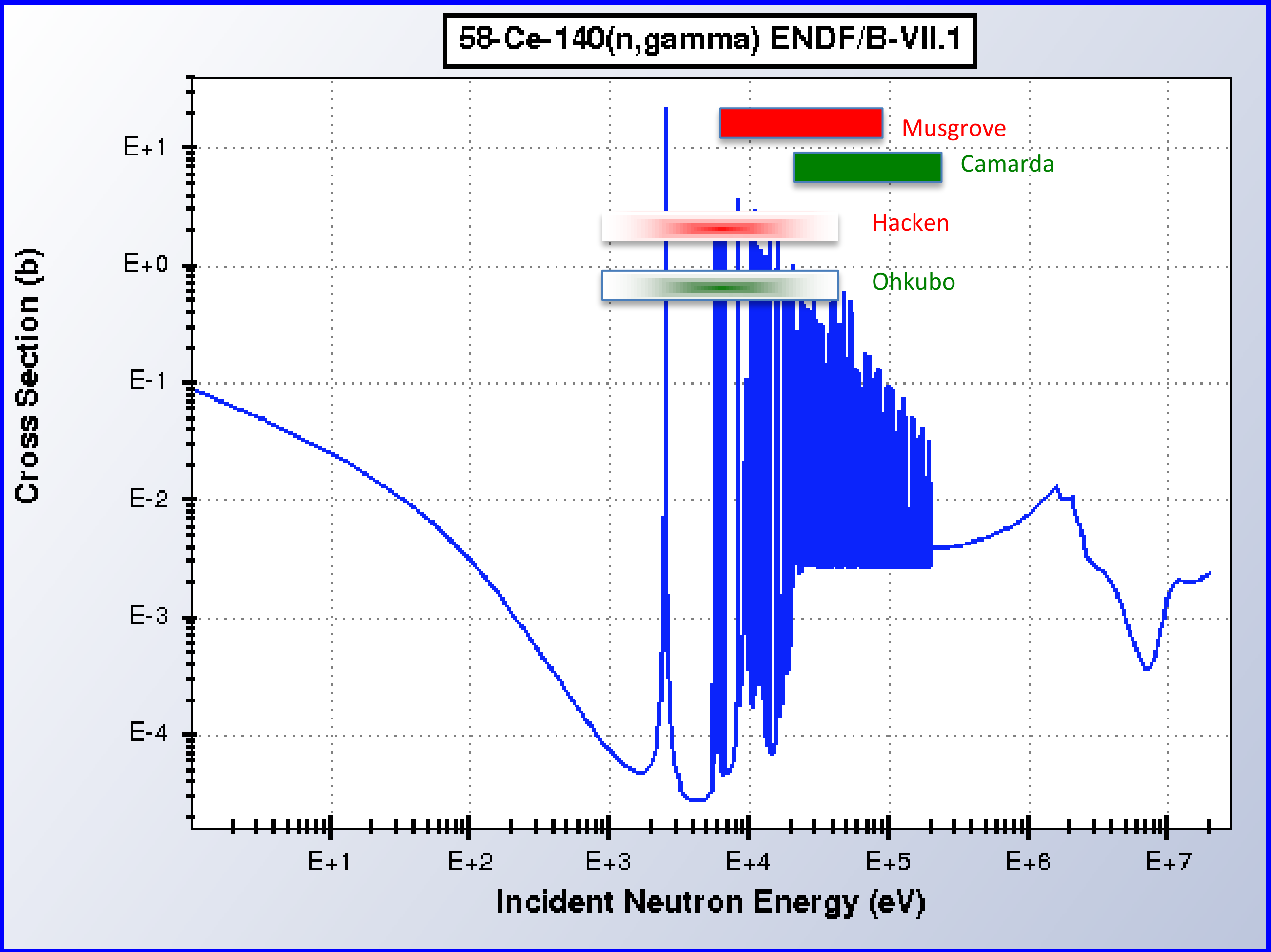

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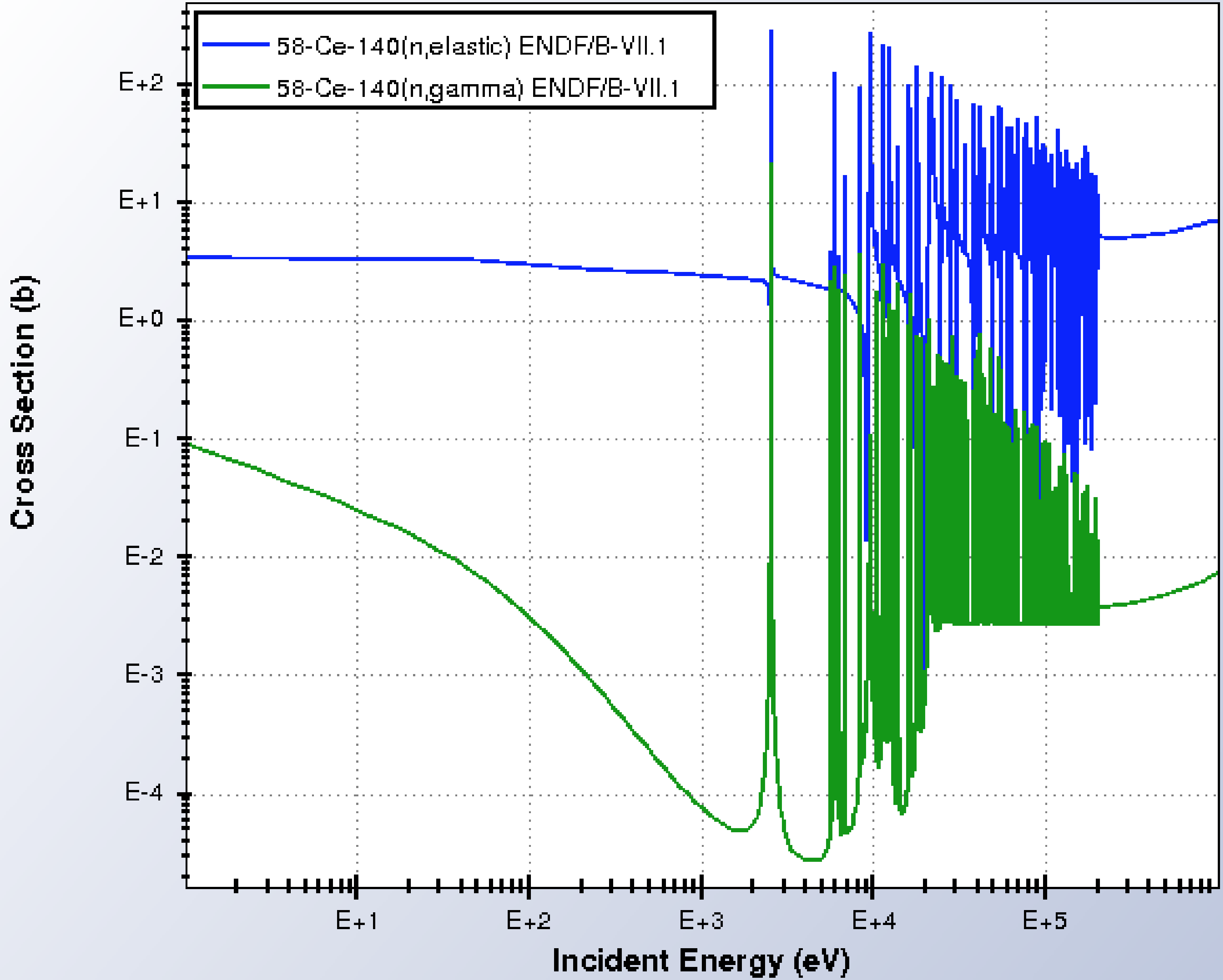
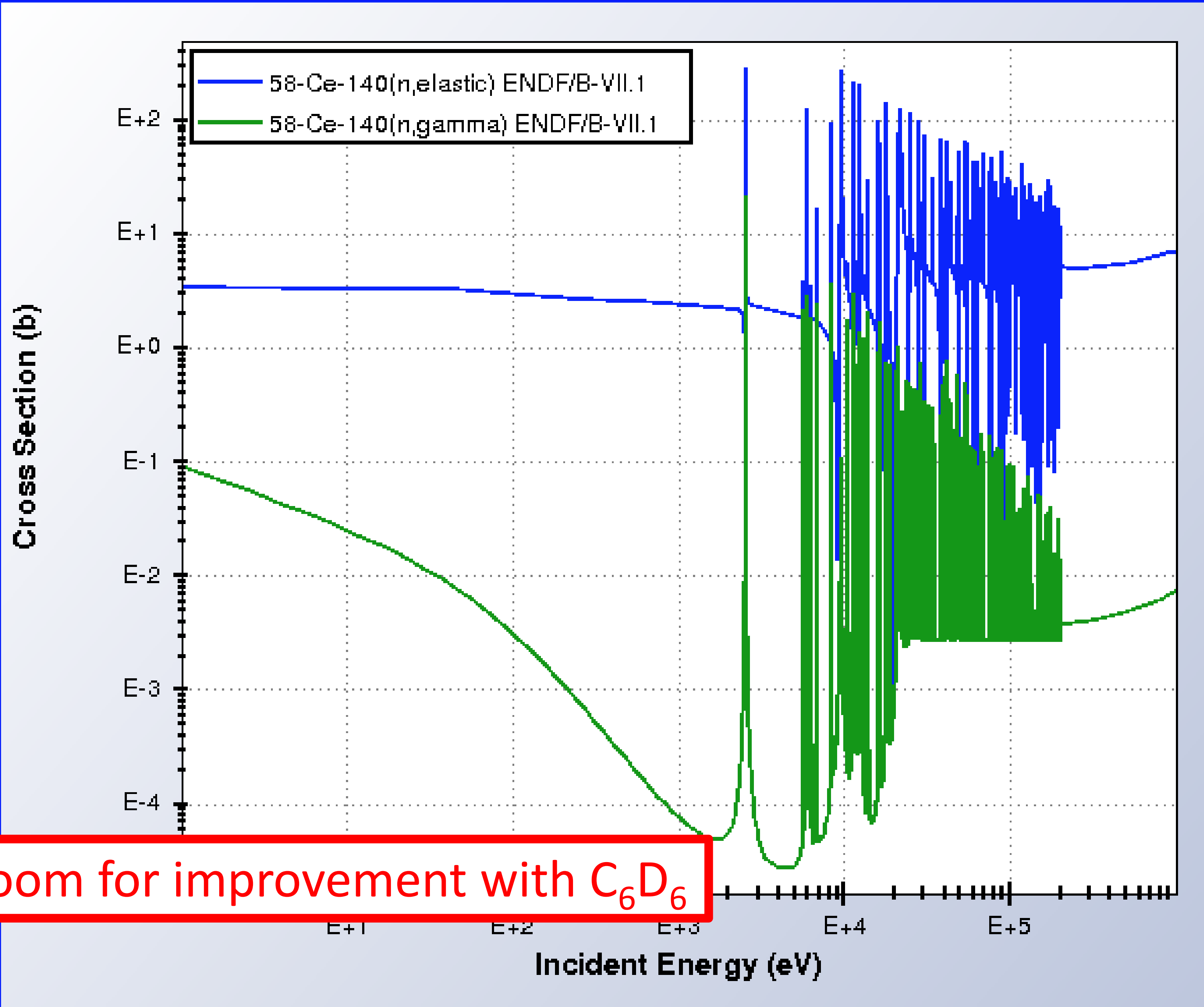


58-Ce-140(n,elastic) ENDF/B-VII.1
58-Ce-140(n,gamma) ENDF/B-VII.1
Cross Section (b)
E+2
E+1
E+0
E-1
E-2
E-3
E-4
E+1
E+2
E+3
E+4
E+5
Incident Energy (eV)



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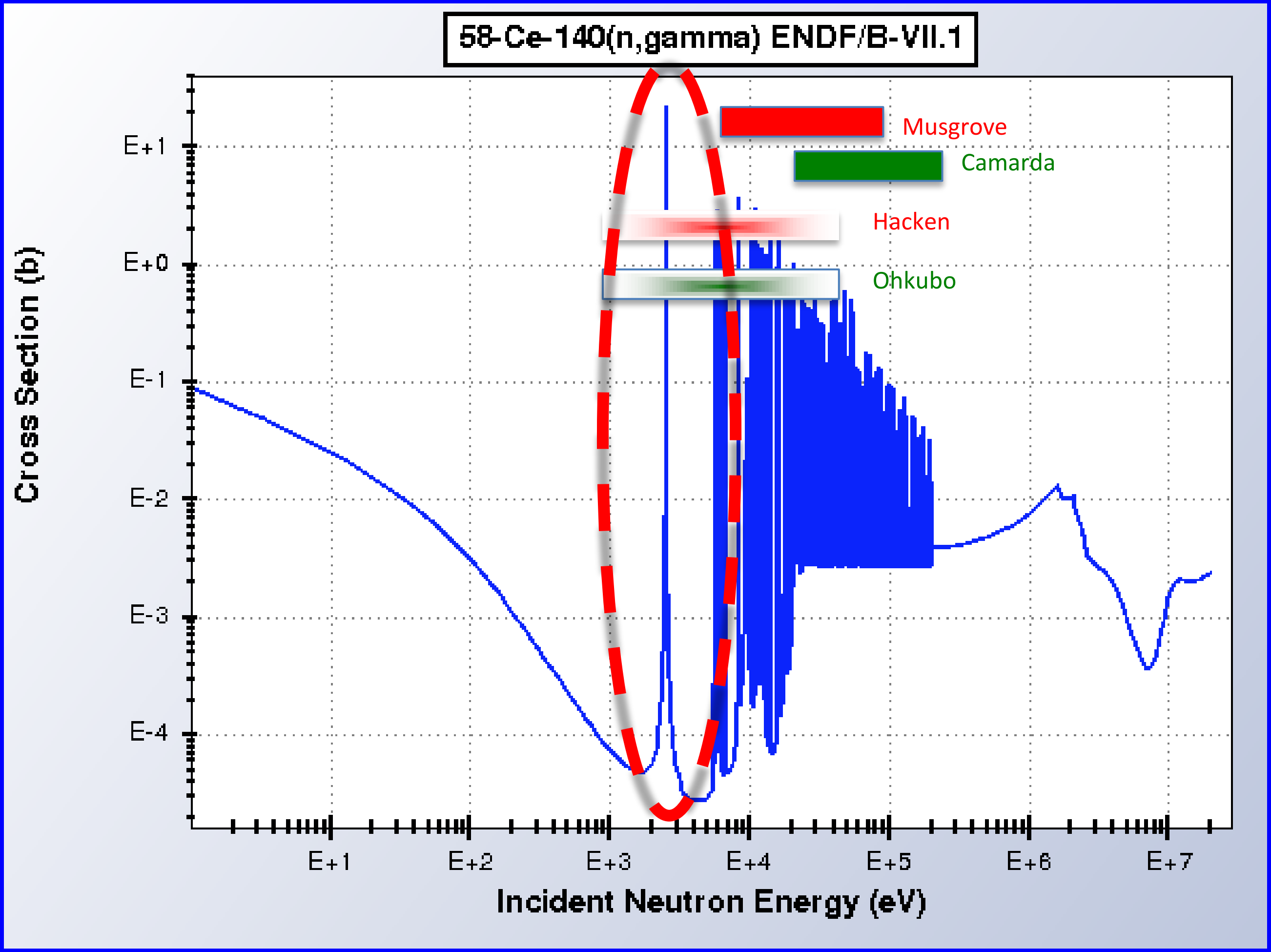
E+2
E+1
E+0
E-1
E-2
E-3
E-4
Cross Section (b)
E+1
E+2
E+3
E+4
E+5
Incident Energy (eV)
Room for improvement with C6D6

^{140}Ce neutron capture cross section (III)



EVALUATIONS:

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Capture (preliminary) 1974
En<65 keV
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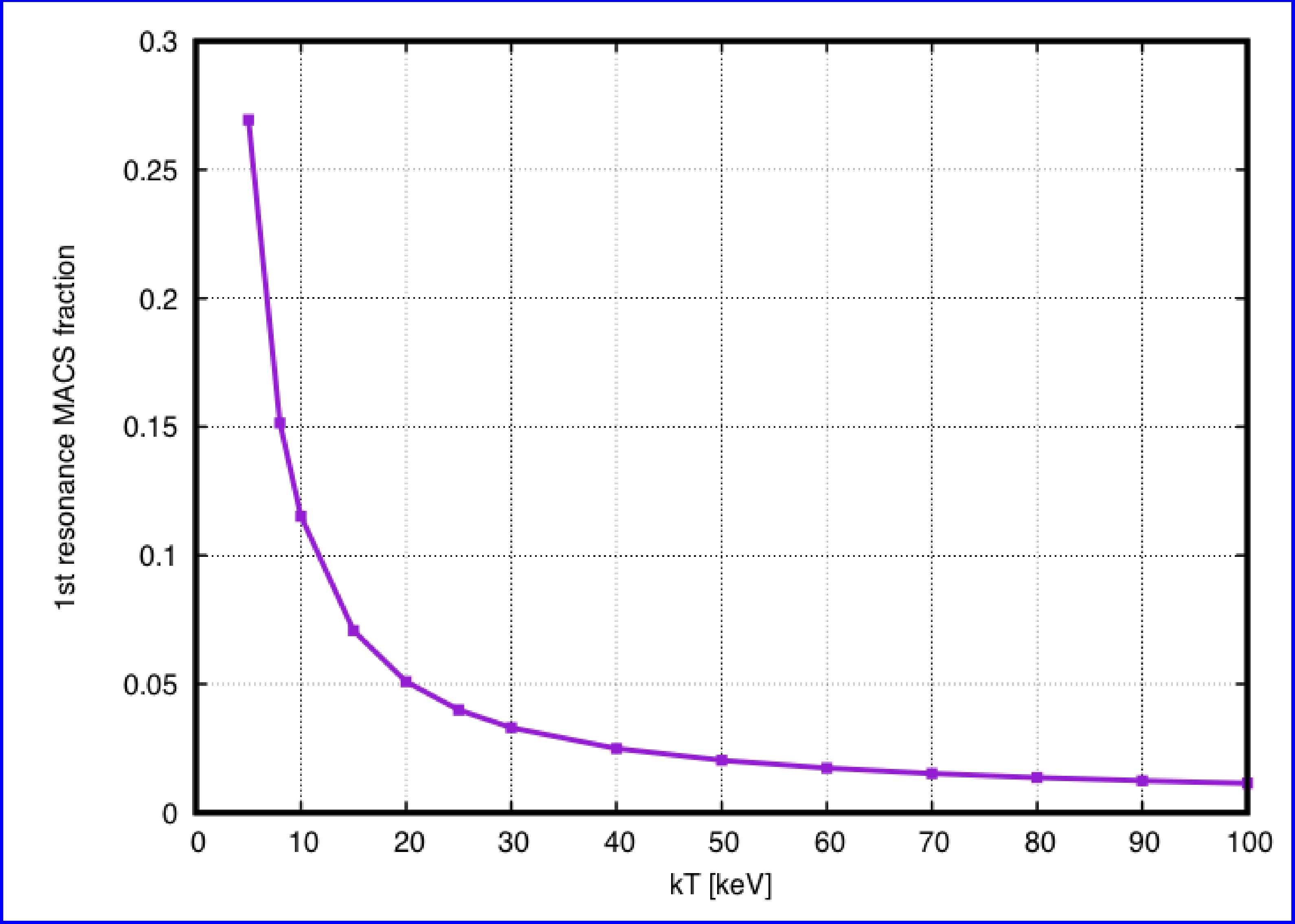
not published

$E \sim 2{,}5\ keV$

^{140}Ce neutron capture cross section (III)



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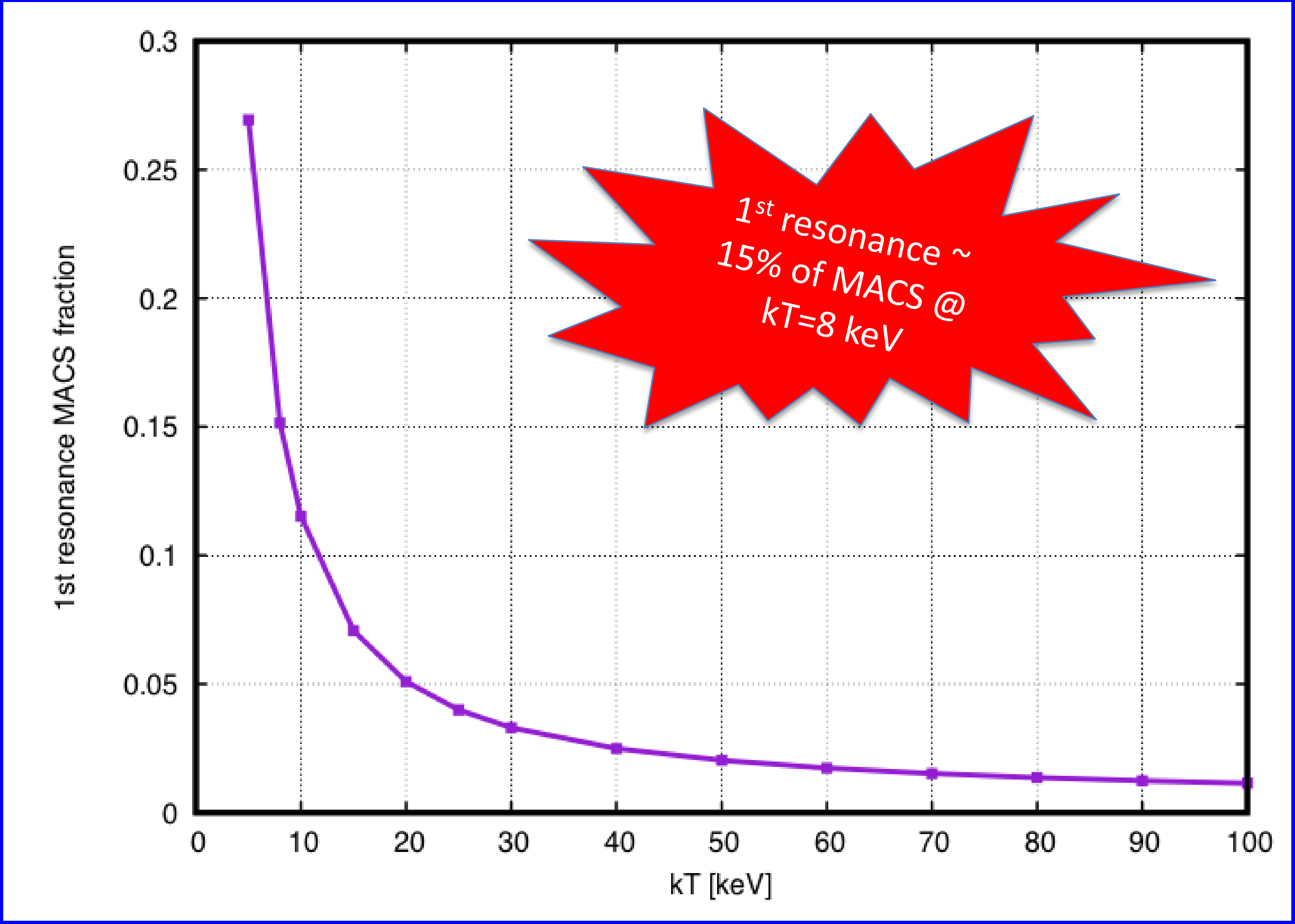
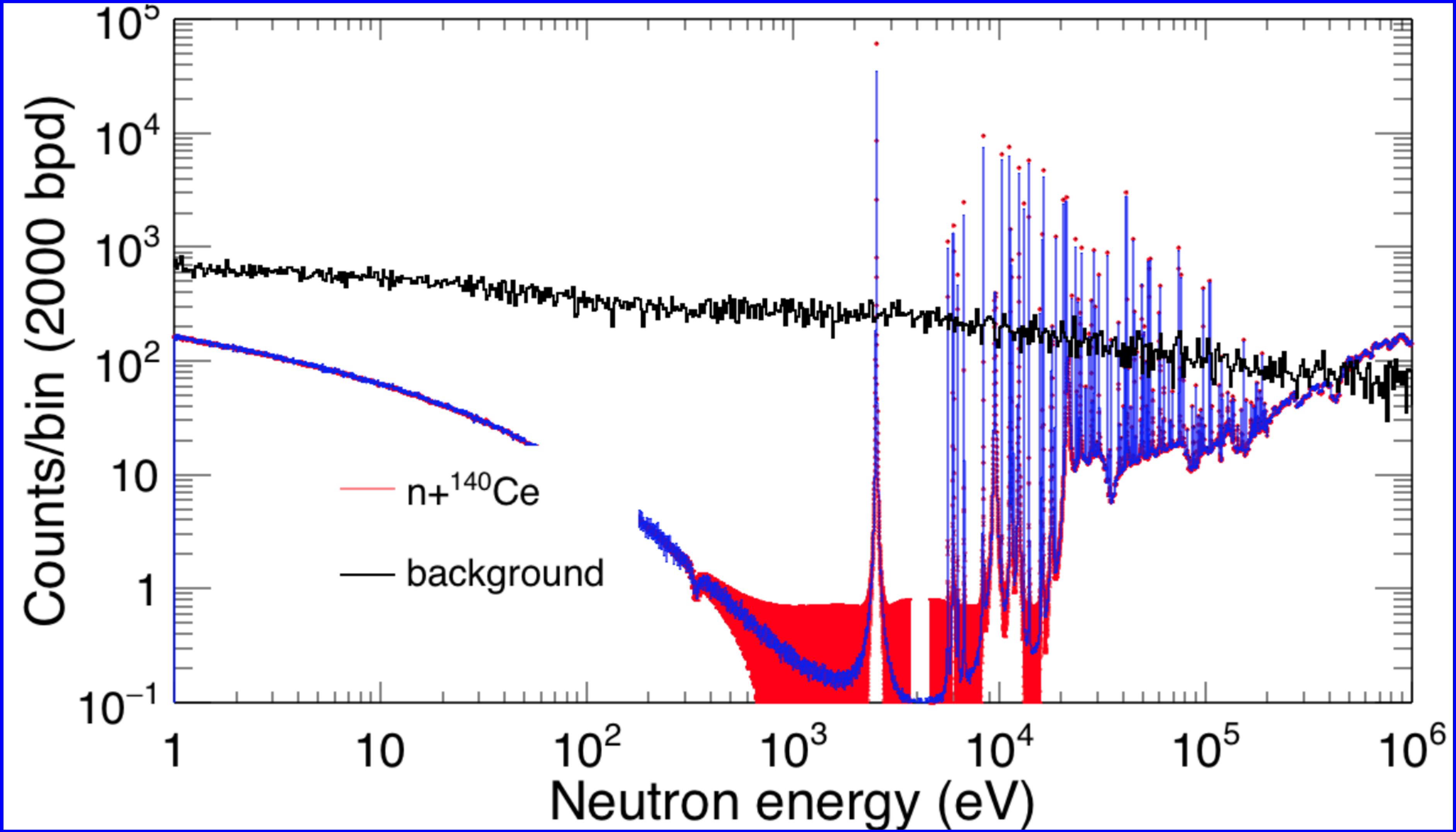


Count rate @ EAR1 – 4 g ^{140}Ce



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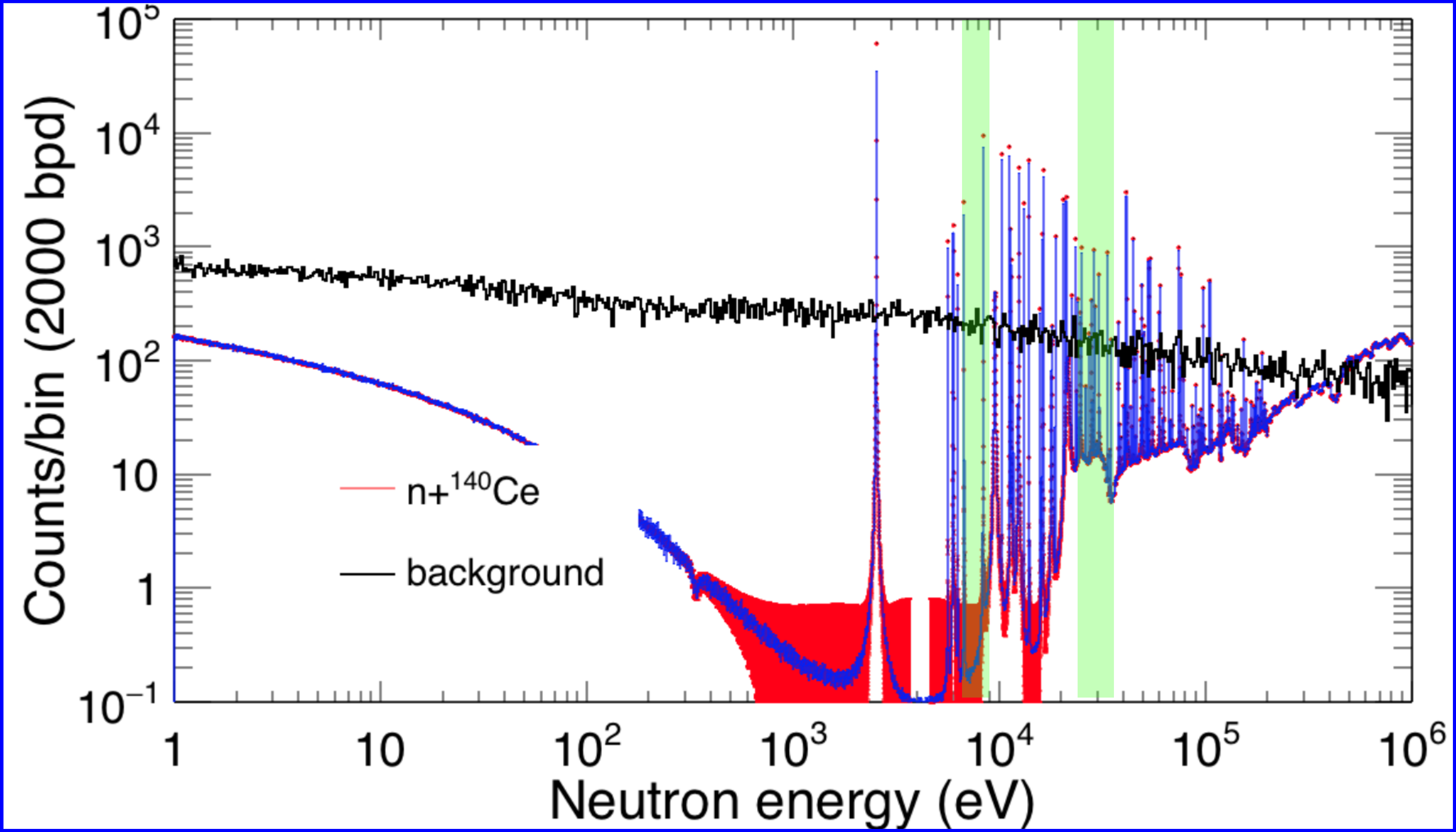
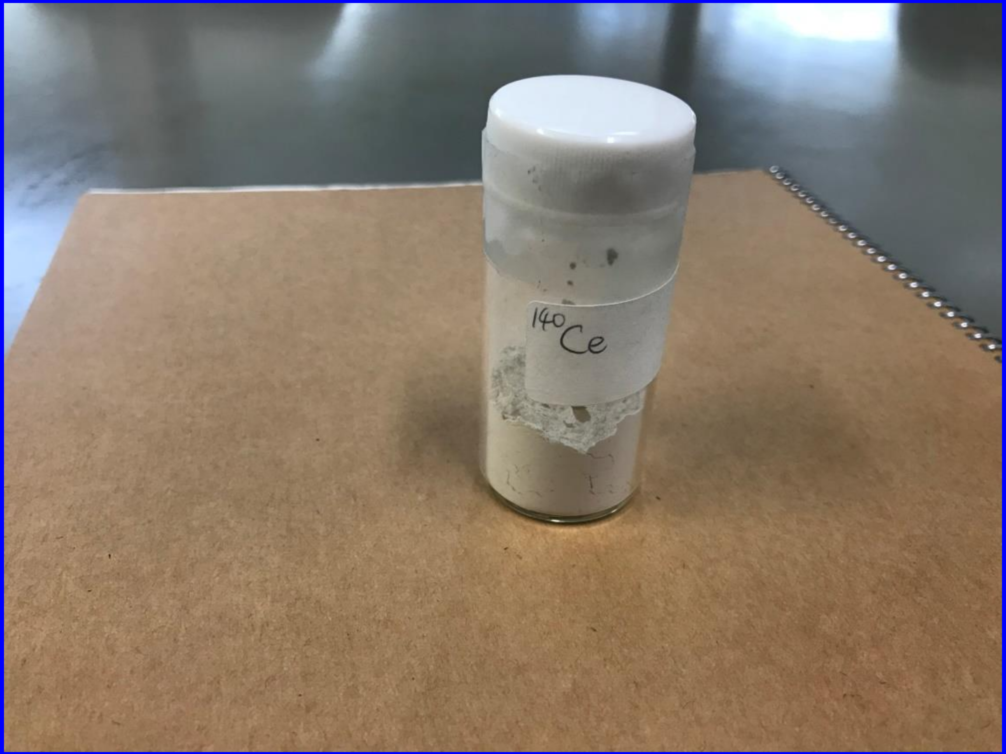


Oak Ridge Natioanl Laboratory: 4gr → 26040 ε
Approved by III commission INFN (2018 budget): 5000 ε

BUT…

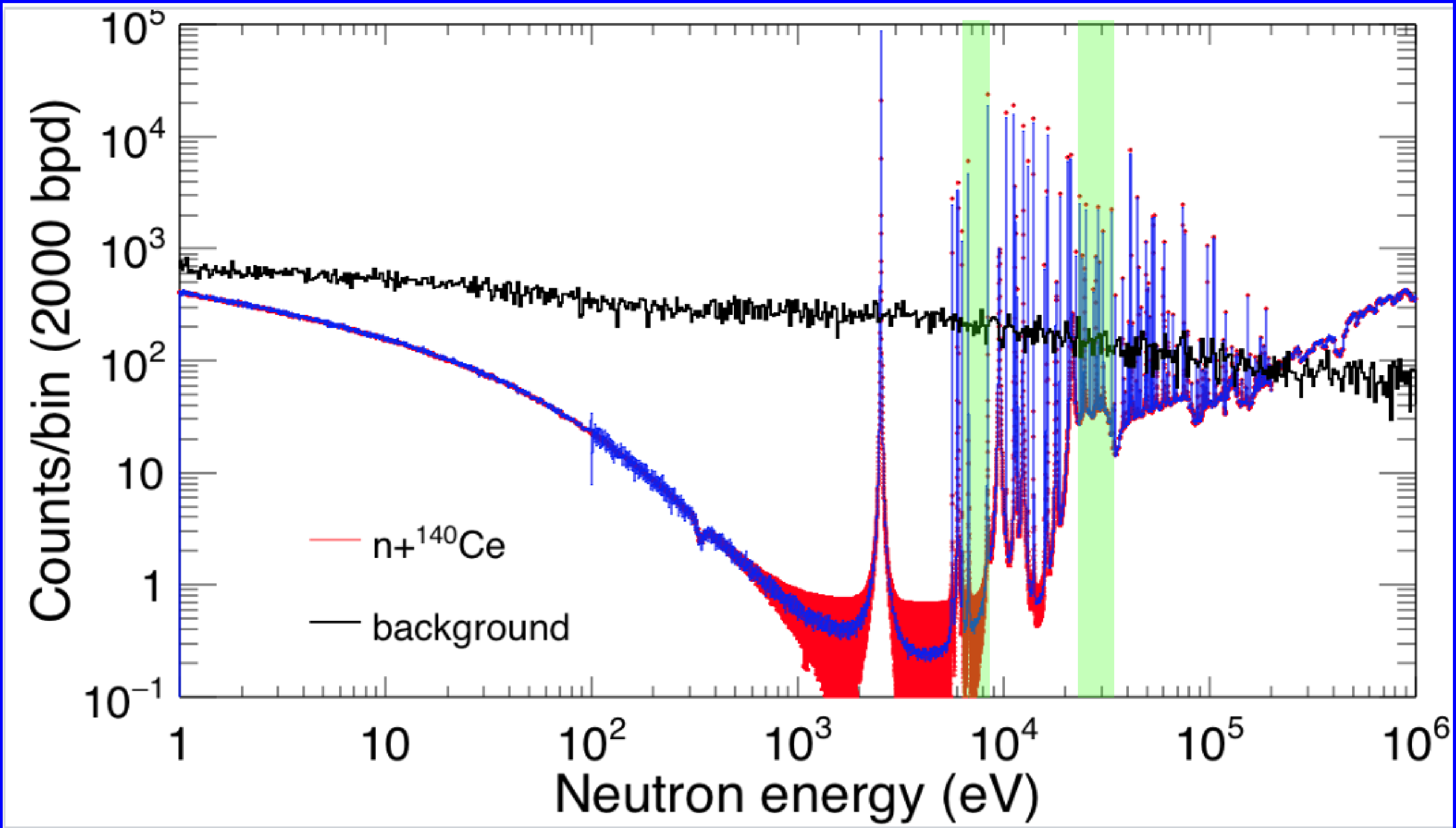
Measurement of keV-Neutron Capture Cross Sections and Capture Gamma-Ray Spectra of ^{140}Ce and ^{141}Pr

Suhe HARNOOD , Masayuki IGASHIRA , Tetsuro MATSUMOTO , Satoshi MIZUNO & Toshiro OHSAKI



10 gr of CeO_2

Count rate @ EAR1 – 10 g ^{140}Ce



Conclusions

- ^{140}Ce is a magic nucleus (88% os solar cerium), mostly synthesized by the s-process (81% of Galactic cerium). It has been observed in all evolutionary phases and metallicities.
- Heavy-element abundances in s-rich galactic Globular Clusters show good agreement with theoretical AGB models for elements belonging to the 2nd s-process peak…apart from cerium!
- MACS at AGB energies are higly uncertain due to lack of experimental data:
  - 2 transmission experiments in literature (^{nat}Ce was used, energy region does not cover the whole region of interest, En>20 keV)
  - 1 capture experiment in literature (C_6F_6 as capture detector, not well suited for this measurement: $\Gamma_n >> \Gamma_\gamma$)
  - No capture data below 5 keV reported in literature (just one unpublished report)!
- <u>**Clear need of accurate capture data on ^{140}Ce**</u>

- n_TOF can provide capture data in the energy region of interest:
  - Low cross section → $3x10^{18}$ protons
  - Resonances in the keV region → EAR1
  - $\Gamma_n >> \Gamma_\gamma$ → C_6D_6

Conclusions

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- He … ood ag … nd s- pr…
- MA…
  - … does
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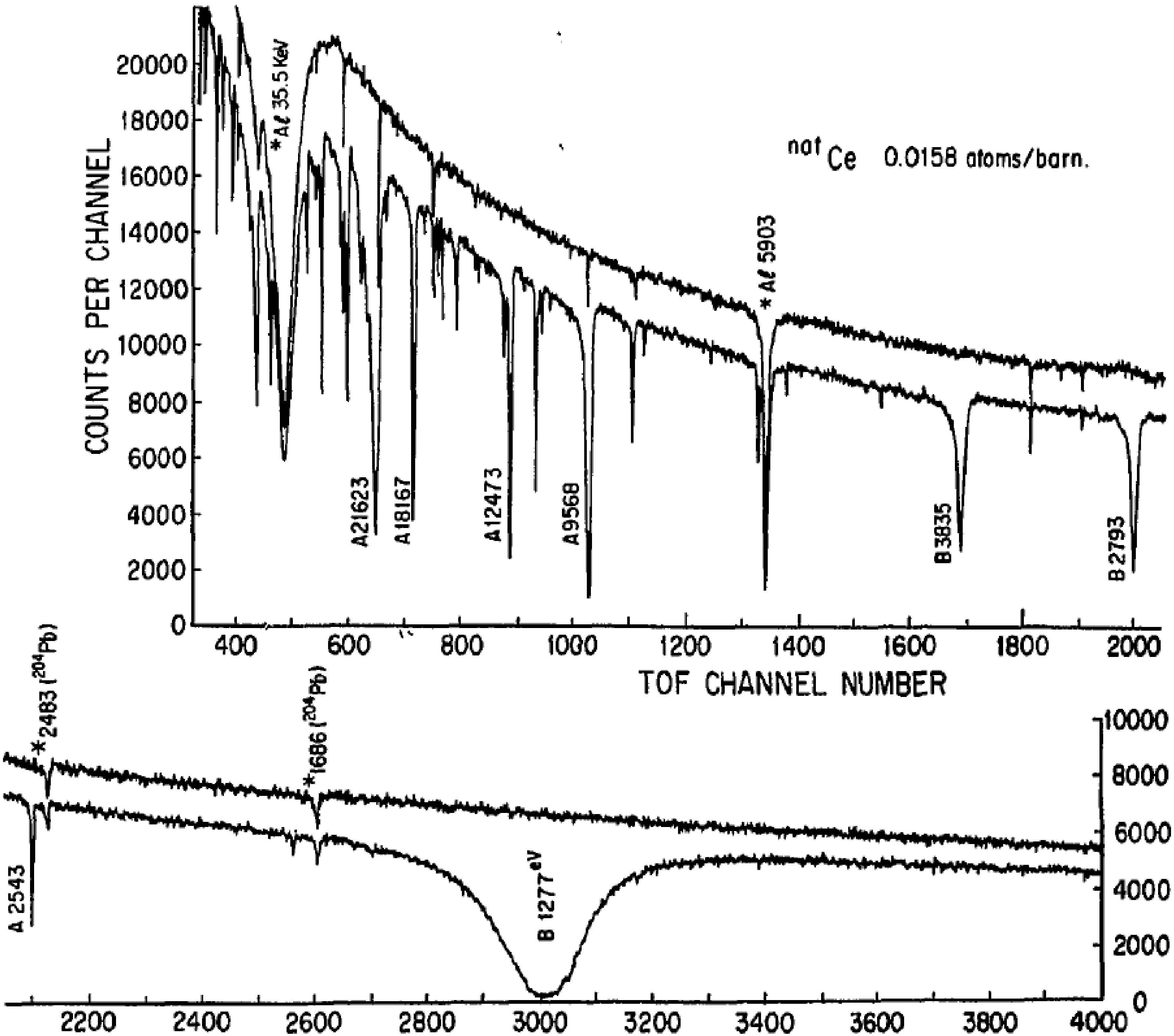
- **Clear need of accurate capture data on ^{140}Ce**

Why this measurement:

a) New cross section → new stellar evaluations

b) Confirmed cross section → blending problem in stellar spectra

- n_TOF can provide capture data in the energy region of interest:
  - Low cross section → $3x10^{18}$ protons
  - Resonances in the keV region → EAR1
  - $\Gamma_n >> \Gamma_\gamma$ → C_6D_6



COUNTS PER CHANNEL
TOF CHANNEL NUMBER
natCe 0.0158 atoms/barn.
*Al 35.5 KeV
*Al 5903
A21623
A18167
A12473
A9568
B3835
B2793
*2483 (204Pb)
*1686 (204Pb)
A 2543
B 1277 eV