INFN PTB ENEA

n + ^{63,65}Cu at n_TOF

rame + n = *ramen* 

(proposal INFN + ENEA in APRENDE)

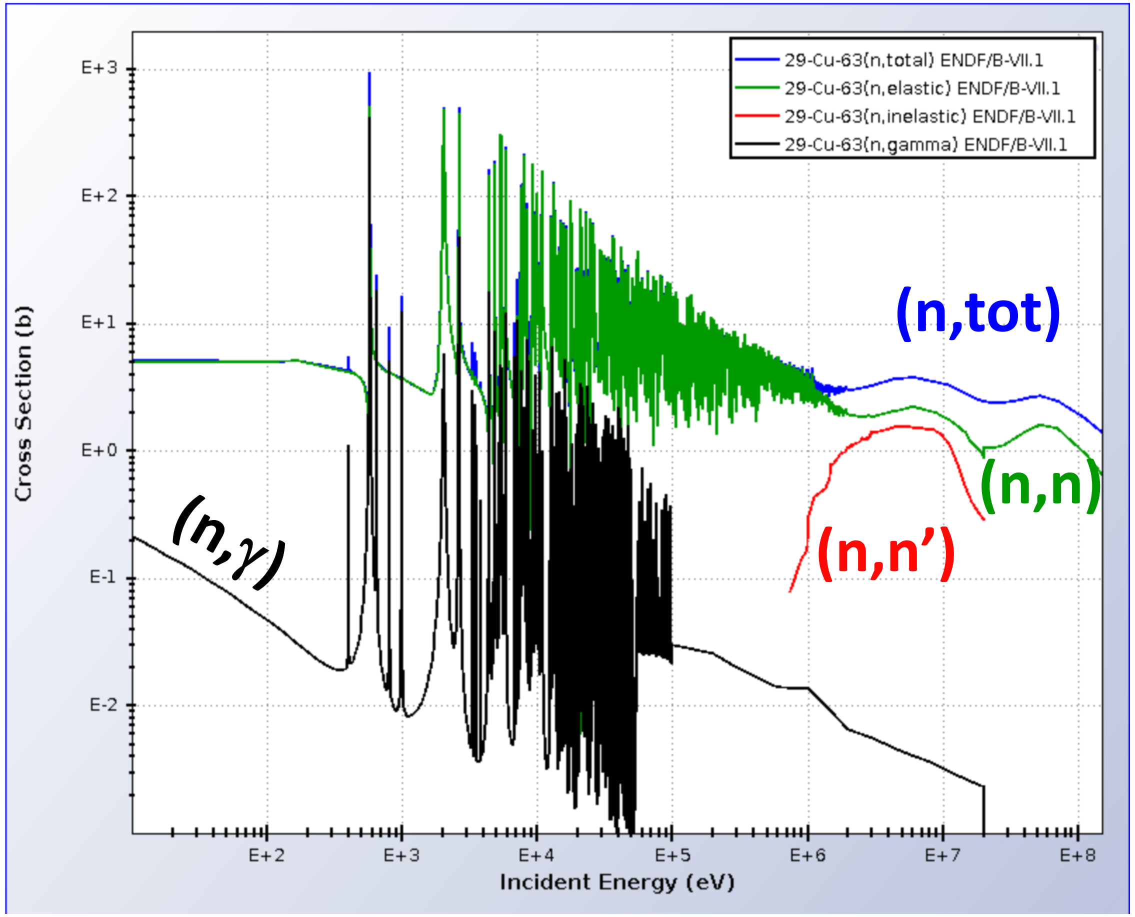
Copper is “Rame” in italian

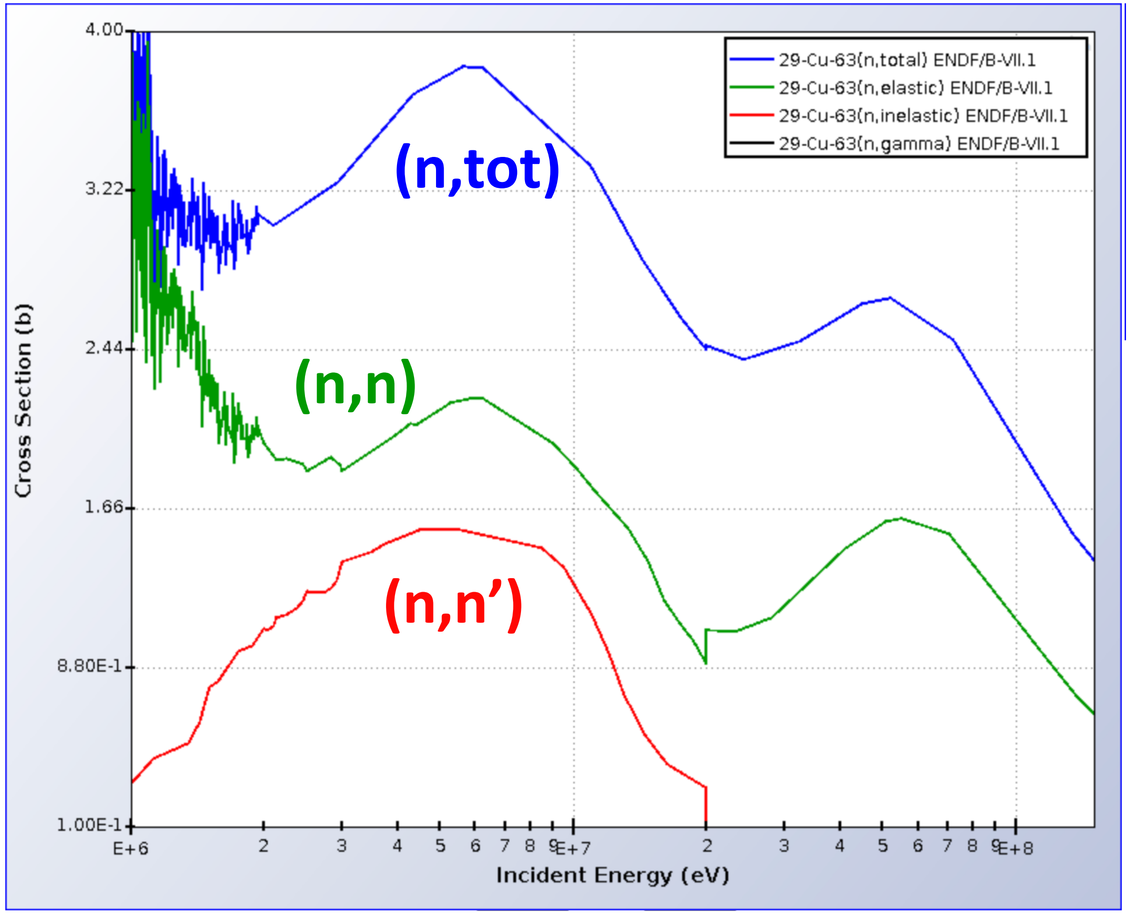
n + ^{63}Cu

Natural abundance:
^{63}Cu 69.2 %
^{65}Cu 30.8 %

$\sigma_n >> \sigma_\gamma$
$\sigma_{el} > \sigma_{inel}$

	Q-value (keV)
$^{63}Cu + n$	0
$^{64}Cu + \gamma$	7915.9 ± 0.6
$^{60}Co + \alpha$	1717.0 ± 0.6
$^{63}Ni + p$	715.4 ± 0.6





Scientific interest

- Nuclear Technology — Nucl. Techn.
- Nuclear Astrophysics — Nucl. Astro.

- ^{63}Cu and ^{65}Cu very **similar**
- ^{63}Cu presented here
- ^{65}Cu in backup slides

massimi@bo.infn.it

Nucl. Techn.

TAPIRO research reactor

TAratura Pila Rapida Potenza ZerO

- 5 kW power
- U-Mo fuel
- Core = 12 cm cylinder
- ^{235}U enrichment = 93.5%
- 4x10^{12} n/s

Nucl. Techn.

TAPIRO research reactor

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- 5 kW power
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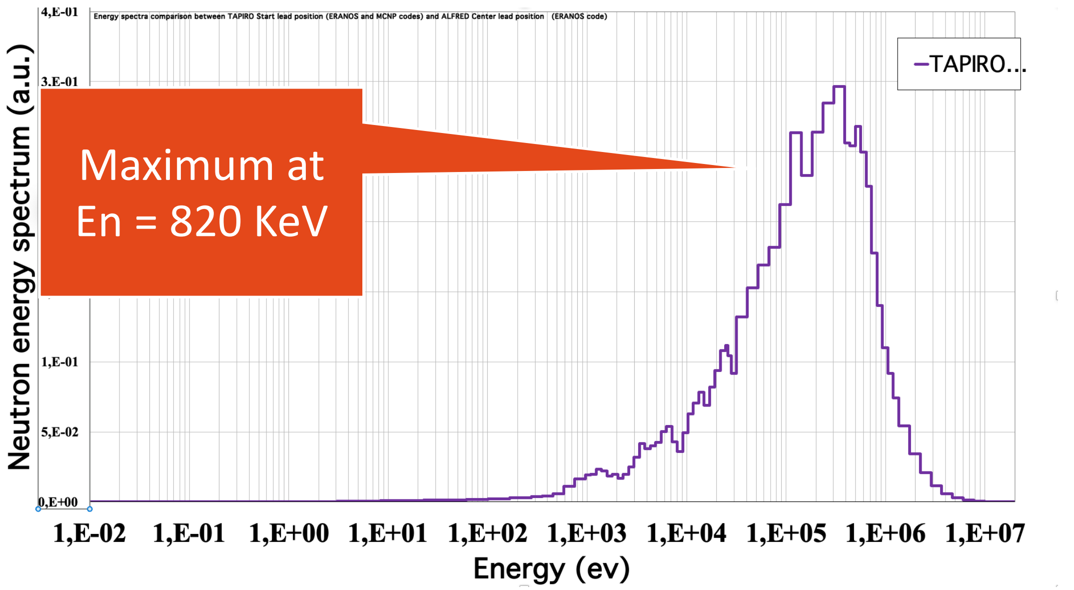
- Core = 12 cm cylinder
- ^{235}U enrichment = 93.5%
- 4x10^{12} n/s
- **FAST SPECTRUM**

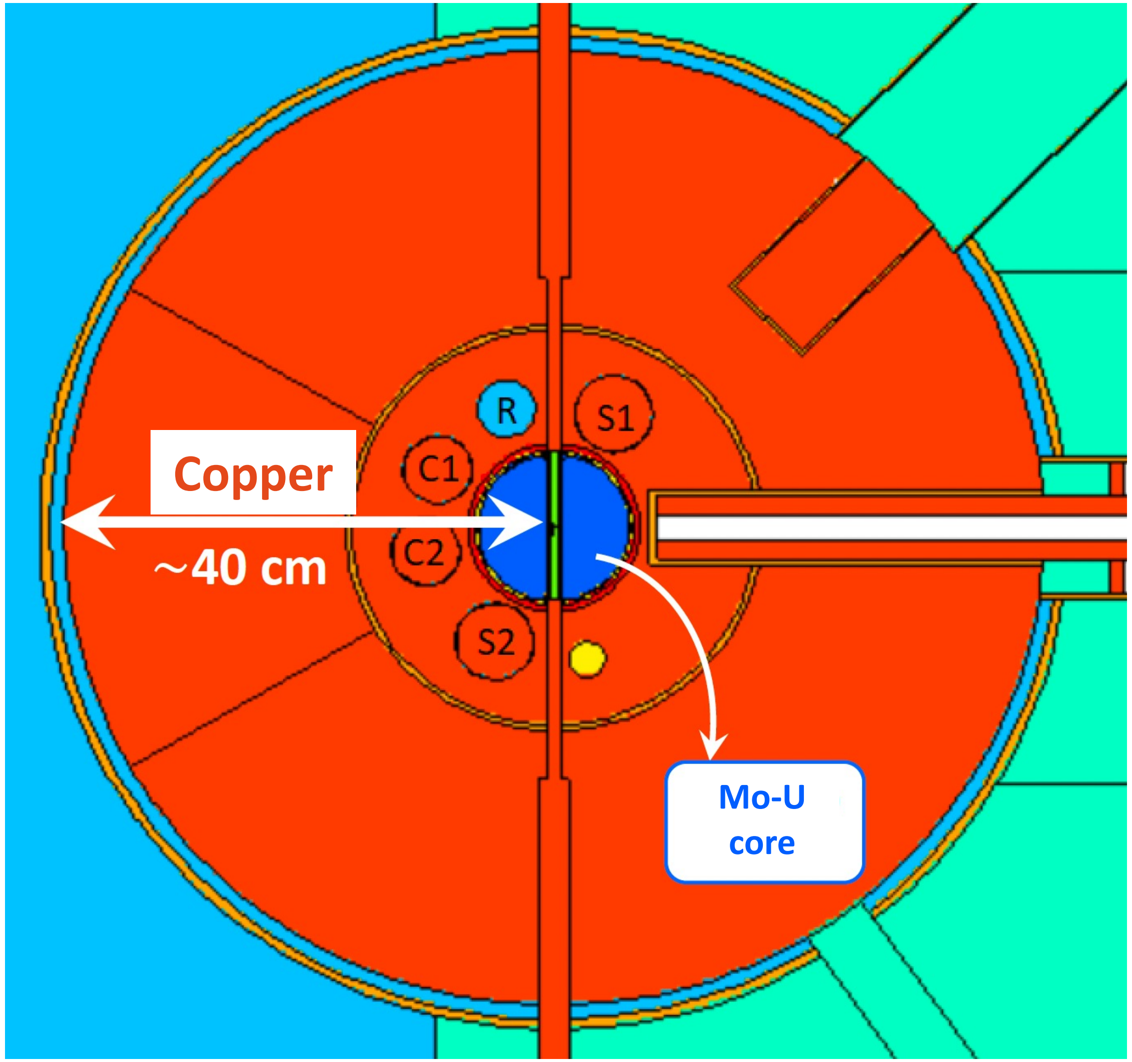
Evaluation benchmark

Material test



Nucl. Techn.

TAPIRO: MCNP study



ENDF/B-VIII.0 → k_{eff} = 1.00000

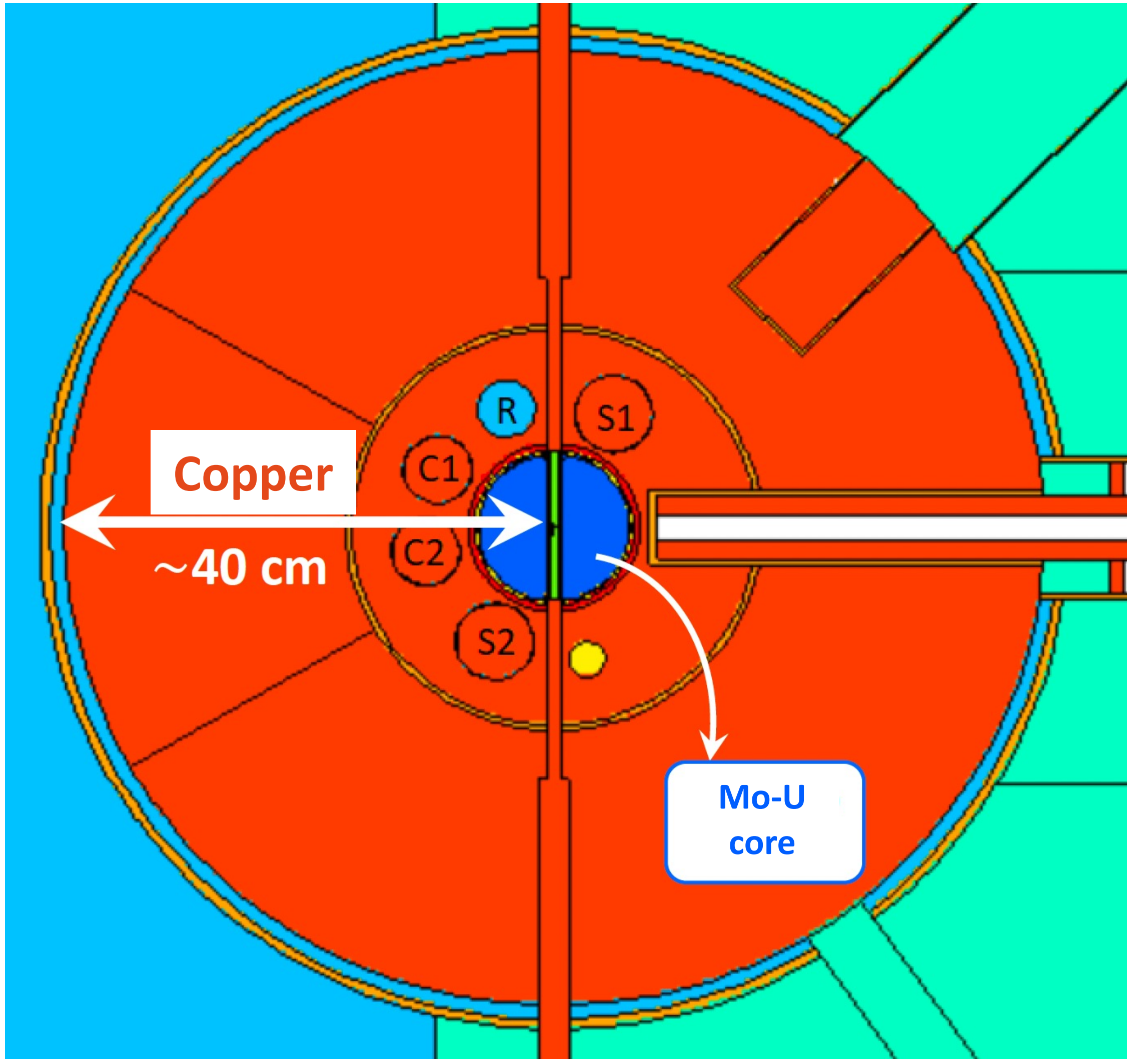
^{63}Cu

Evaluation	k_{eff}
JEFF3.3	1.00637 ± 0.00001
JENDL-5	1.00147 ± 0.00001
TENDL-2021	1.00102 ± 0.00001

^{65}Cu

Evaluation	k_{eff}
JEFF3.3	0.99980 ± 0.00001
JENDL-5	0.99782 ± 0.00001
TENDL-2021	1.00017 ± 0.00001

TAPIRO: MCNP study



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^{65}Cu

Evaluation	k_{eff}
JEFF3.3	0.99980 ± 0.00001
JENDL-5	0.99782 ± 0.00001
ENDL-2021	1.00017 ± 0.00001

Library effect
=
1.5 times the effect of a regulation rod !

massimi@bo.infn.it

Nucl. Techn.

TAPIRO: **ERANOS** → S/U analysis

Sensitivity and Uncertainty (S/U) analysis was performed using the deterministic code ERANOS 2.3, for:

1. k_{eff} parameter
2. ratio of fission reaction rates U238/U235
3. ratio of fission r.r. Np237/U235

Nucl. Techn.

TAPIRO: **ERANOS** → S/U analysis

Sensitivity and Uncertainty (S/U) analysis was performed using the deterministic code ERANOS 2.3, for:

1. k_{eff} parameter — (n,n), (n,n'), (n,γ)
2. ratio of fission reaction rates U238/U235 — (n,n'), (n,n), (n,γ)
3. ratio of fission r.r. Np237/U235 — (n,n), (n,n'), (n,γ)

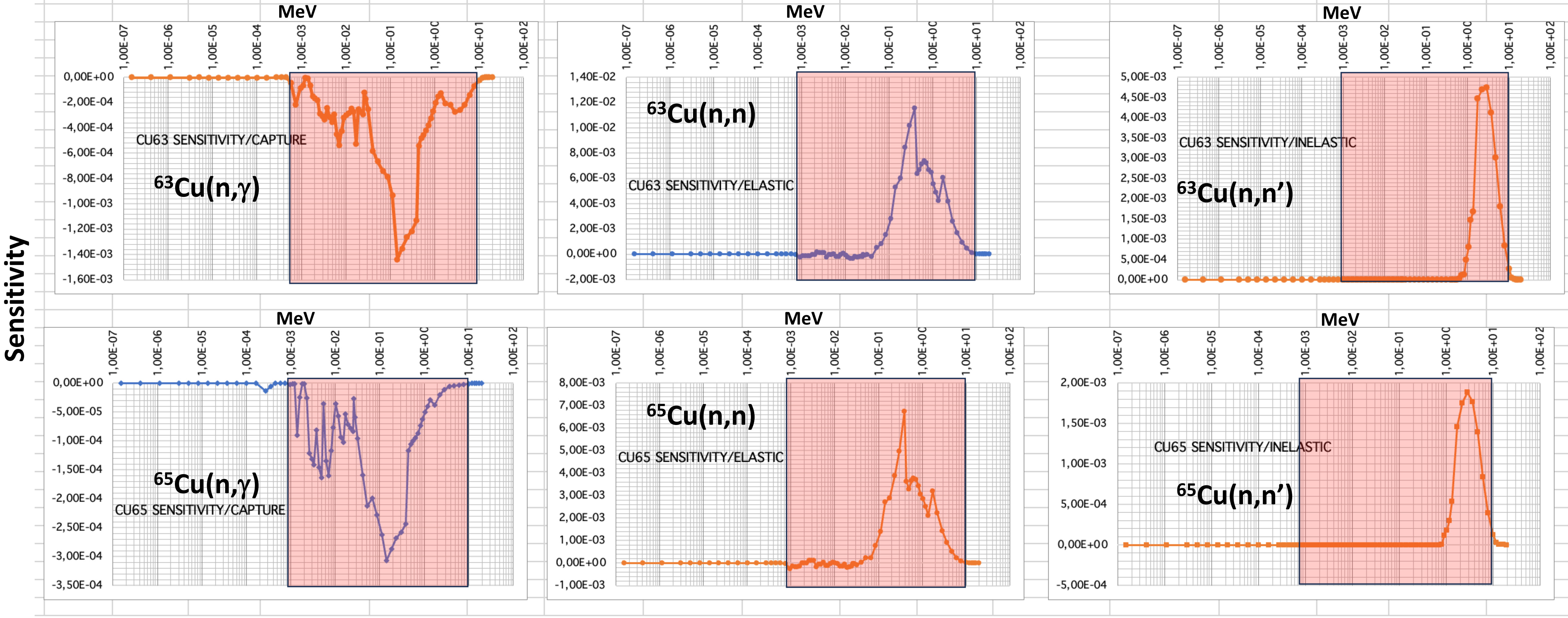
Relevant energy region

- **Elastic:** **50 keV < E_n < 5 MeV**
- **Inelastic** **1 MeV < E_n < 5 MeV**
- **Rad. capture:** **10 keV < E_n < 300 keV**

Nucl. Techn.

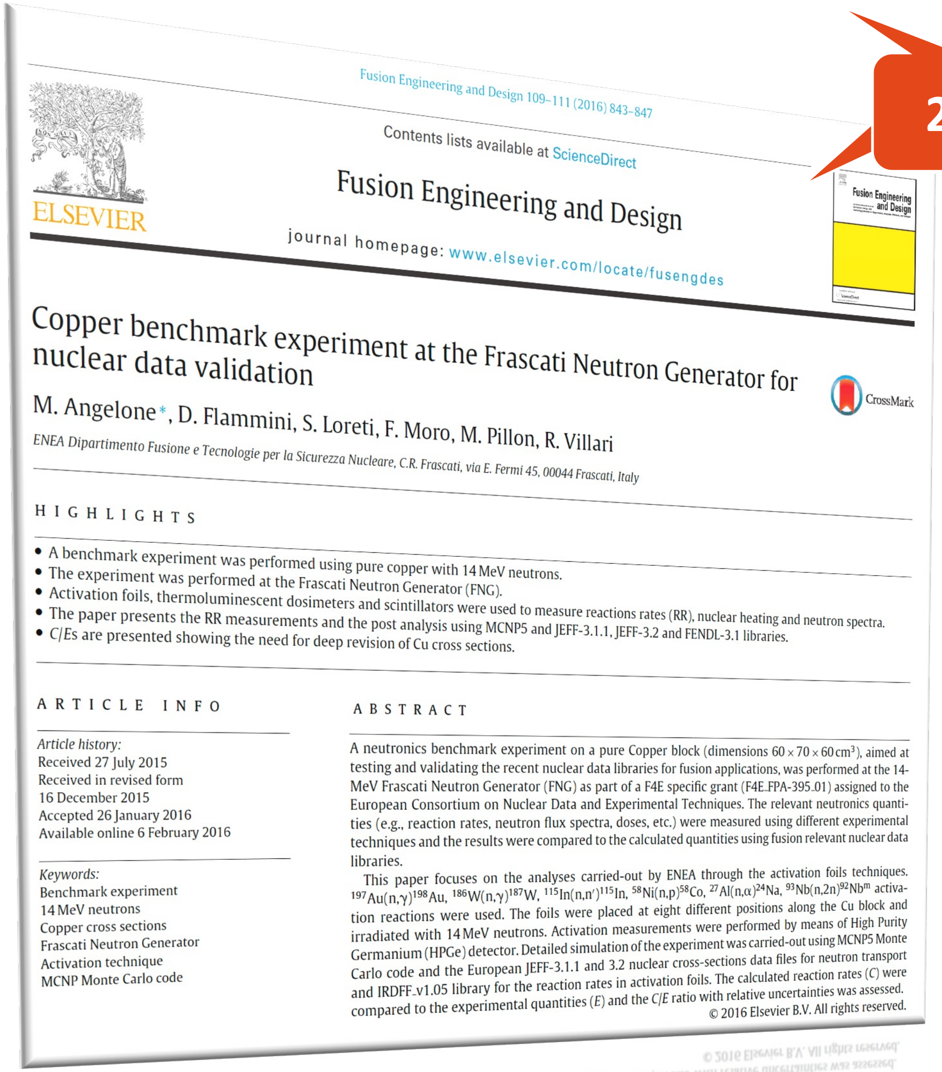
Example: k_{eff}

TAPIRO: **ERANOS** → S/U analysis



massimi@bo.infn.it

Fusion – study at FNG



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ELSEVIER

Copper benchmark experiment at the Frascati Neutron Generator for nuclear data validation

M. Angelone*, D. Flammini, S. Loreti, F. Moro, M. Pillon, R. Villari

ENEA Dipartimento Fusione e Tecnologie per la Sicurezza Nucleare, C.R. Frascati, via E. Fermi 45, 00044 Frascati, Italy

HIGHLIGHTS

- A benchmark experiment was performed using pure copper with 14 MeV neutrons.
- The experiment was performed at the Frascati Neutron Generator (FNG).
- Activation foils, thermoluminescent dosimeters and scintillators were used to measure reactions rates (RR), nuclear heating and neutron spectra.
- The paper presents the RR measurements and the post analysis using MCNP5 and JEFF-3.1.1, JEFF-3.2 and FENDL-3.1 libraries.
- C/Es are presented showing the need for deep revision of Cu cross sections.

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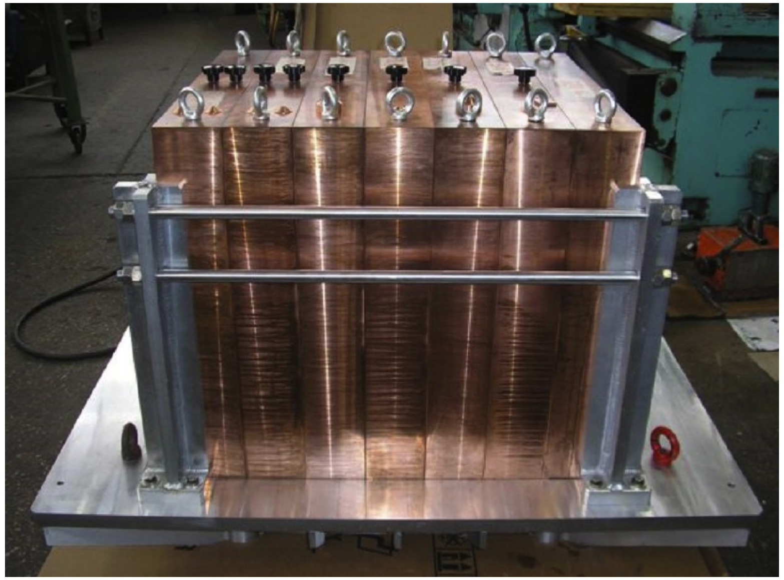
Activation technique
MCNP Monte Carlo code

ABSTRACT

A neutronics benchmark experiment on a pure Copper block (dimensions 60 × 70 × 60 cm^3), aimed at testing and validating the recent nuclear data libraries for fusion applications, was performed at the 14-MeV Frascati Neutron Generator (FNG) as part of a F4E specific grant (F4E-FPA-395-01) assigned to the European Consortium on Nuclear Data and Experimental Techniques. The relevant neutronics quantities (e.g., reaction rates, neutron flux spectra, doses, etc.) were measured using different experimental techniques and the results were compared to the calculated quantities using fusion relevant nuclear data libraries.

This paper focuses on the analyses carried-out by ENEA through the activation foils techniques. $^{197}Au(n,\gamma)^{198}Au$, $^{186}W(n,\gamma)^{187}W$, $^{115}In(n,n')^{115}In$, $^{58}Ni(n,p)^{58}Co$, $^{27}Al(n,\alpha)^{24}Na$, $^{93}Nb(n,2n)^{92}Nb^{m}$ activation reactions were used. The foils were placed at eight different positions along the Cu block and irradiated with 14 MeV neutrons. Activation measurements were performed by means of High Purity Germanium (HPGe) detector. Detailed simulation of the experiment was carried-out using MCNP5 Monte Carlo code and the European JEFF-3.1.1 and 3.2 nuclear cross-sections data files for neutron transport and IRDFF-v1.05 library for the reaction rates in activation foils. The calculated reaction rates (C) were compared to the experimental quantities (E) and the C/E ratio with relative uncertainties was assessed.



Conclusions

…

The present results call for a deep revision/re-evaluation of the copper cross sections. The new release JEFF-3.2 for Cu provided the highest disagreement in the C/E analysis and must be revised. To this end the results of the companion sensitivity/uncertainty post-analysis will help in identifying the main causes of uncertainty in the Cu cross sections. It worth to note that the largest discrepancy among the C/E values was observed for the thermal (capture) reactions suggesting problems and uncertainties in the ^{63,65}Cu capture and elastic cross sections at lower energy rather than at high energy.

Nucl. Astro.

How copper was produced?

Not clear! Candidates:

1. **Weak s process**
2. **SNIa**

The weak s-process requires:

- MACS @ kT= 25 keV
- MACS @ kT= 90 keV

^{62}Ga 116.00 ms β^+	^{63}Ga 32.40 s β^+	^{64}Ga 2.63 m β^+	^{65}Ga 15.20 m β^+	^{66}Ga 9.49 h β^+	^{67}Ga 3.26 d β^+	^{68}Ga 1.13 h β^+
^{61}Zn 1.48 m β^+	^{62}Zn 9.19 h β^+	^{63}Zn 38.47 m β^+	^{64}Zn 48.63 59 mb	^{65}Zn 243.63 d 162 mb, β^+	^{66}Zn 27.9 35 mb	^{67}Zn 4.1 153 mb
^{60}Cu 23.70 m β^+	^{61}Cu 3.33 h β^+	^{62}Cu 9.67 m β^+	^{63}Cu 69.17 94 mb	^{64}Cu 12.70 h β^+	^{65}Cu 30.83 41 mb	^{66}Cu 5.12 m β^-
^{59}Ni 75.99 ka 87 mb, β^+	^{60}Ni 26.223 30 mb	^{61}Ni 1.14 82 mb	^{62}Ni 3.634 22.3 mb	^{63}Ni 100.11 a 31 mb, β^-	^{64}Ni 0.926 8.7 mb	^{65}Ni 2.52 h β^-
^{58}Co 70.86 d β^+	^{59}Co 100 38 mb	^{60}Co 5.27 a β^-	^{61}Co 1.65 h β^-	^{62}Co 1.50 m β^-	^{63}Co 27.40 s β^-	^{64}Co 300.00 ms β^-
^{57}Fe 2.119 40 mb	^{58}Fe 0.282 12.1 mb	^{59}Fe 44.50 d β^-	^{60}Fe 1.50 Ma β^-	^{61}Fe 5.98 m β^-	^{62}Fe 1.13 m β^-	^{63}Fe 6.01 s β^-

Nucl. Astro.

How copper was produced?

^{62}Ga 116.00 ms β^+	^{63}Ga 32.40 s β^+	^{64}Ga 2.63 m β^+	^{65}Ga 15.20 m β^+	^{66}Ga 9.49 h β^+	^{67}Ga 3.26 d β^+	^{68}Ga 1.13 h β^+
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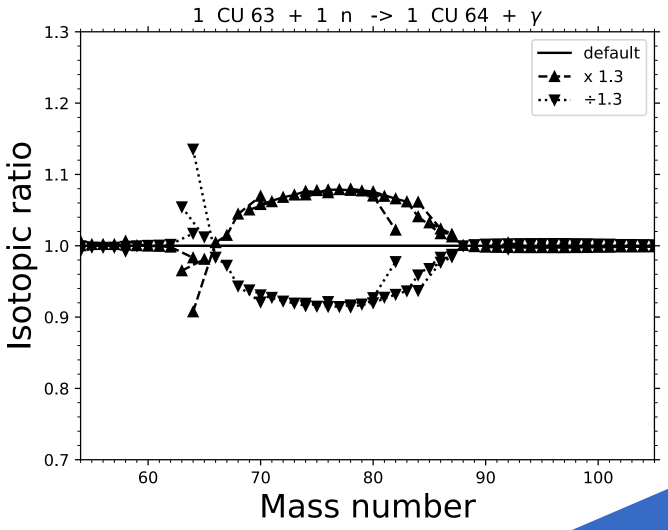
^{58}Co 70.86 d	^{59}Co 100	^{60}Co 5.27 a	^{61}Co 1.65 h	^{62}Co 1.50 m	^{63}Co 27.40 s	^{64}Co 300.00 ms

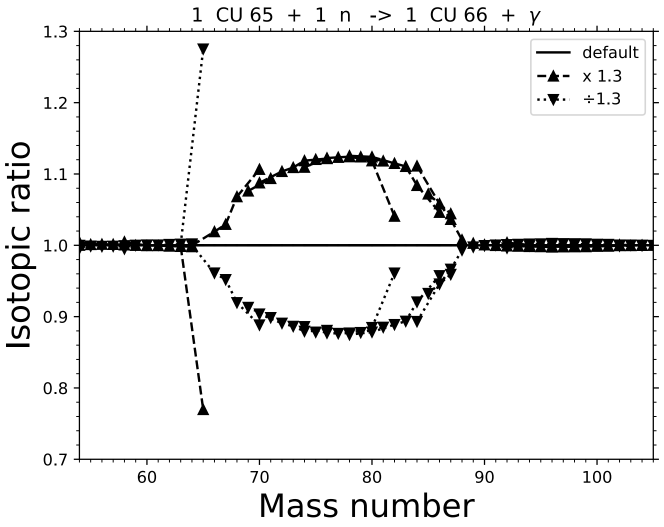
Not clear! Candidates:

1. **Weak s process**
2. **SNIa**

The weak s-process requires:

- MACS @ kT= 25 keV
- MACS @ kT= 90 keV



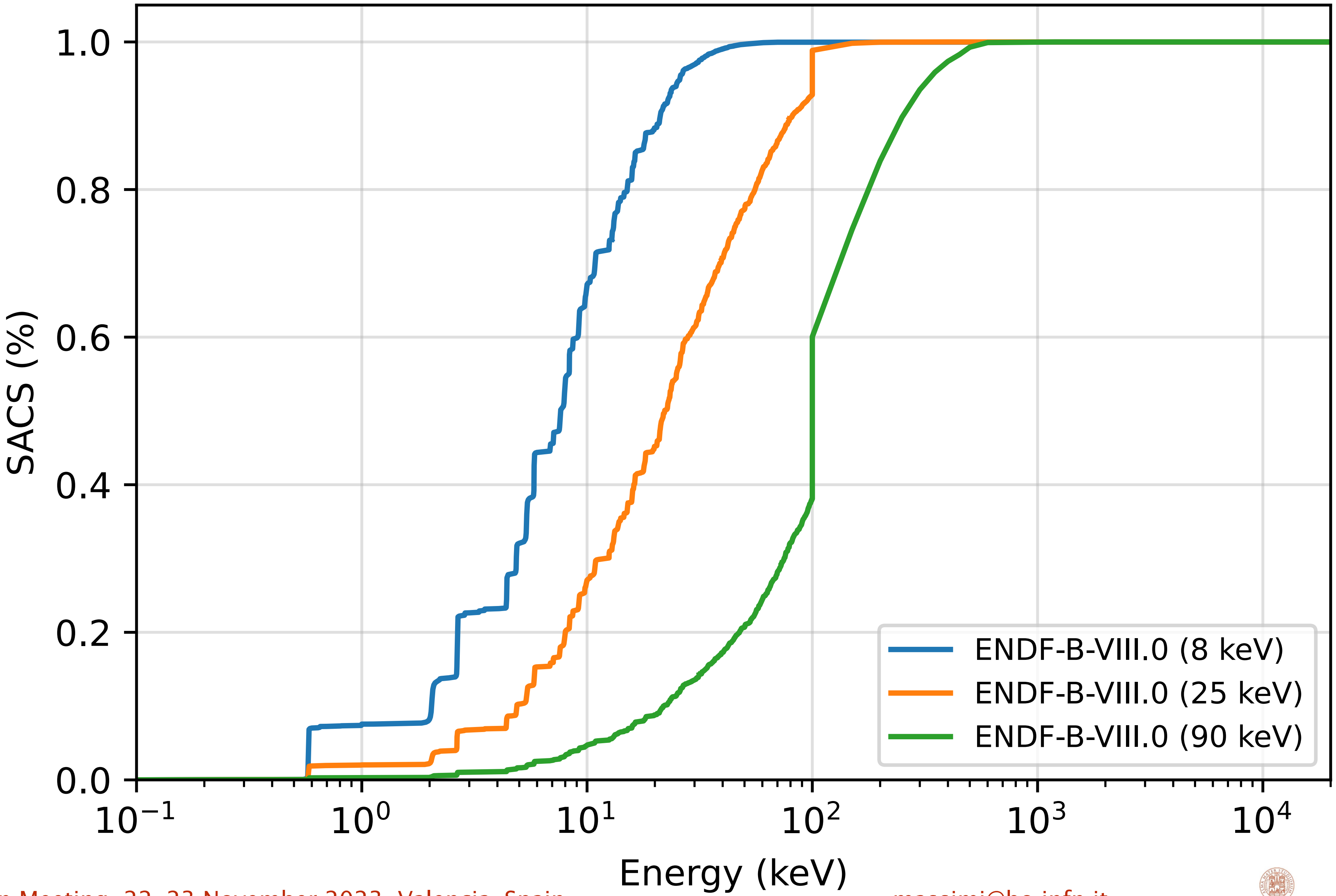


Impact of ^{63,65}Cu(n,γ) cross sections

Nucl. Astro.

$^{63}Cu(n,\gamma)$

% MACS



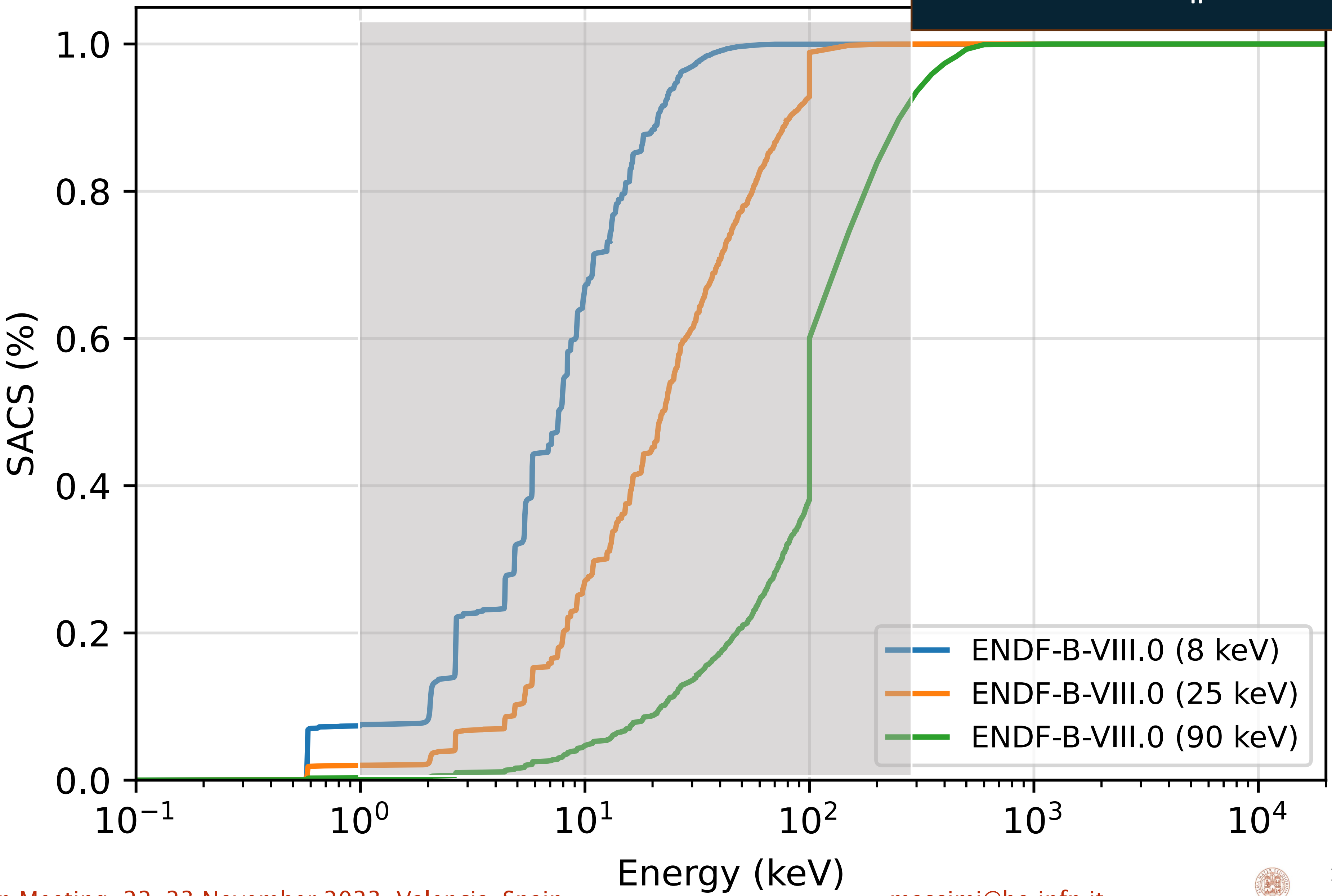
$^{63}Cu(n,\gamma)$

Nucl. Astro.

Relevant energy region

1 keV < E_n < 300 keV

% MACS



Nucl. Astro.

$^{63}Cu(n,\gamma)$

View Maxwellian-Averaged (n,g) Cross Section

Isotope 63Cu Show

(Examples: Ba138, Ta180m, Se.)

Karlsruhe Astrophysical Database of Nucleosynthesis in Stars • KADoNiS

Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{63}Cu\ (n,\gamma)^{64}Cu$$

Total MACS at 30keV: 60.1 ± 6.2 mb

Cross sections do not include stellar enhancement factors!

History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	60.1 ± 6.2	-	-
0.3	55.6 ± 2.2	-	-
0.0	94 ± 10	-	-

(Version 0.0 corresponds to Bao et al.)

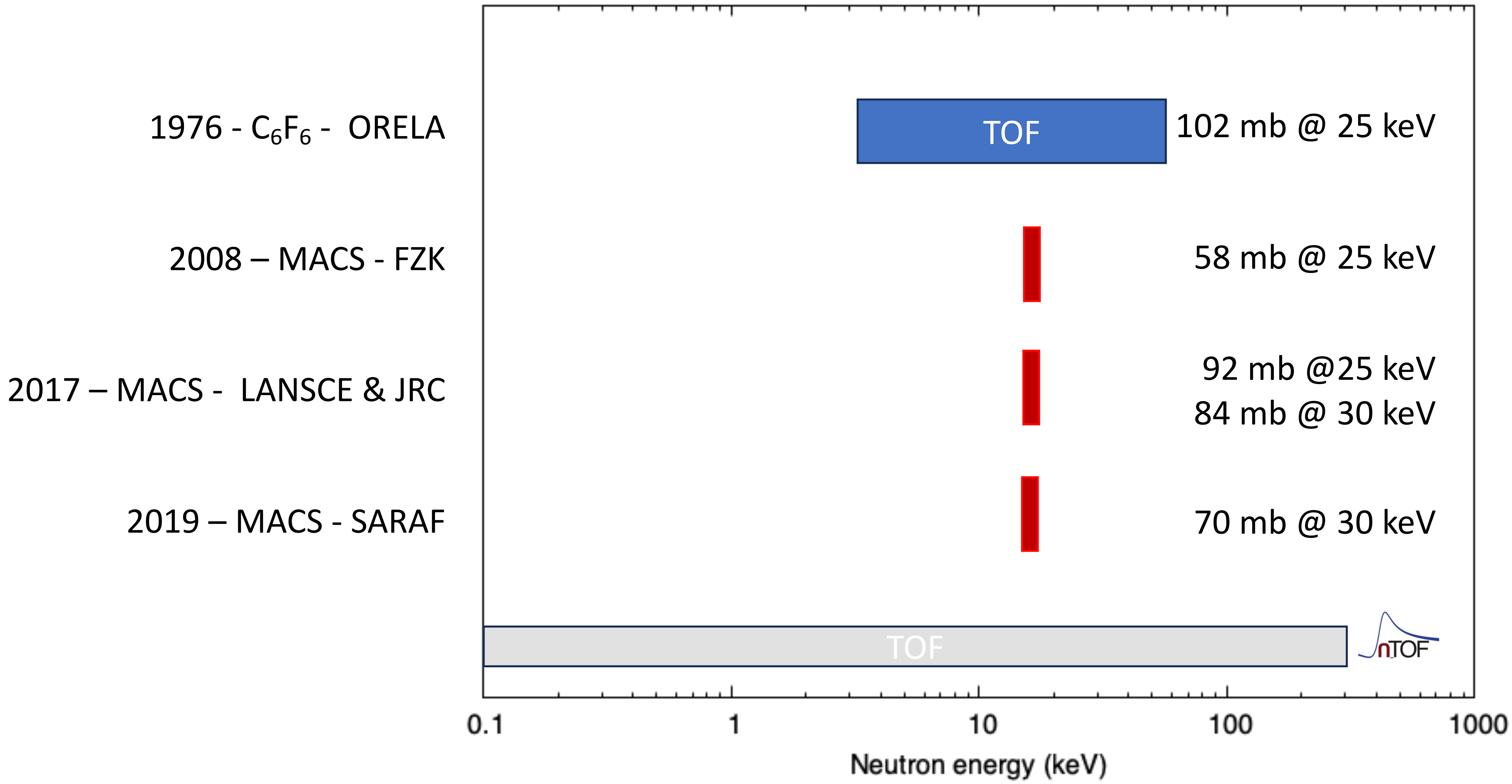
Comment

New rec. value is from HKU08, renormalized by 632 mb/586 mb = 1.0785, and recalculated with normalized energy dependencies of tendl15,endfb71,jendl40. Uncertainty is the deviation between different evaluations plus 4% exp. uncertainty from HKU08. **Note the large deviation between the activation measurement and the TOF measurements. More investigation needed!**
Last review: April 2017

Nucl. Astro.

$^{63}Cu(n,\gamma)$

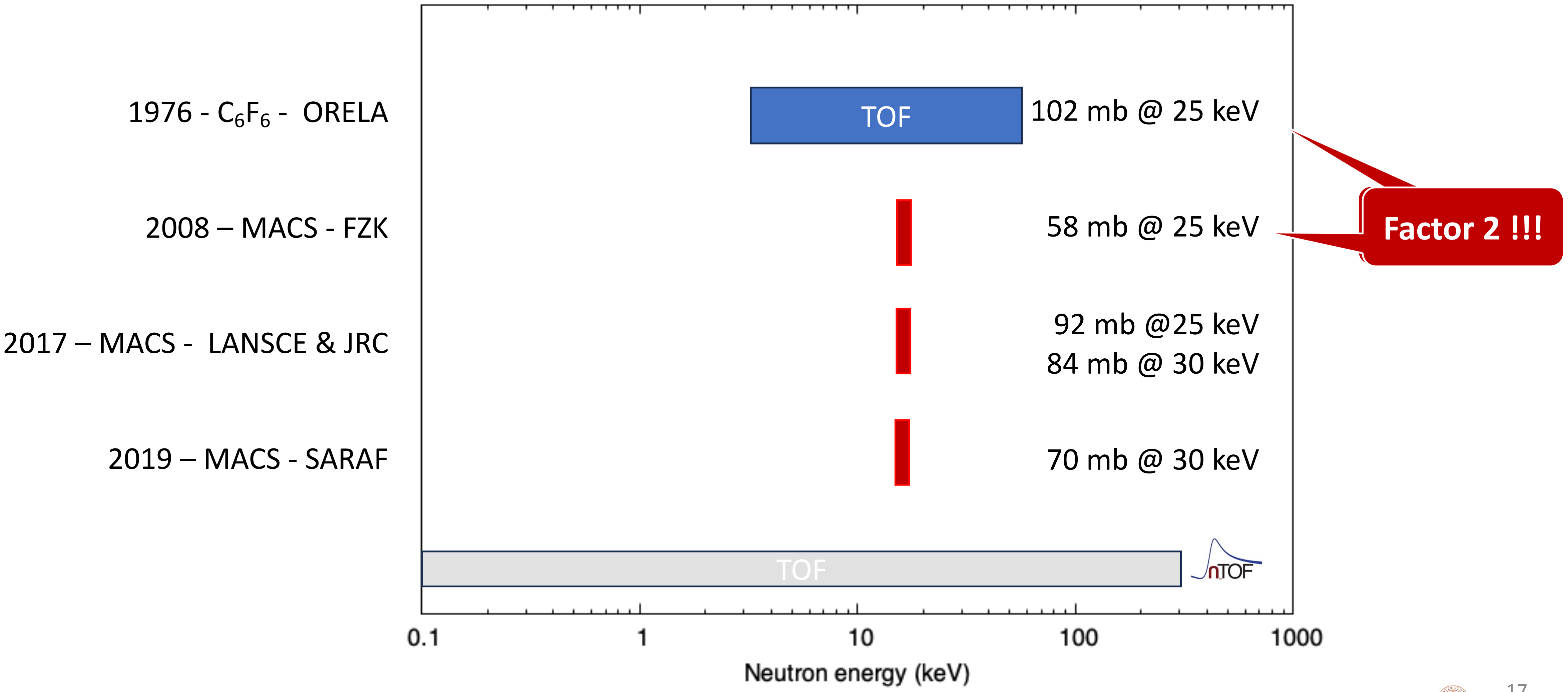
E_n < 300 keV



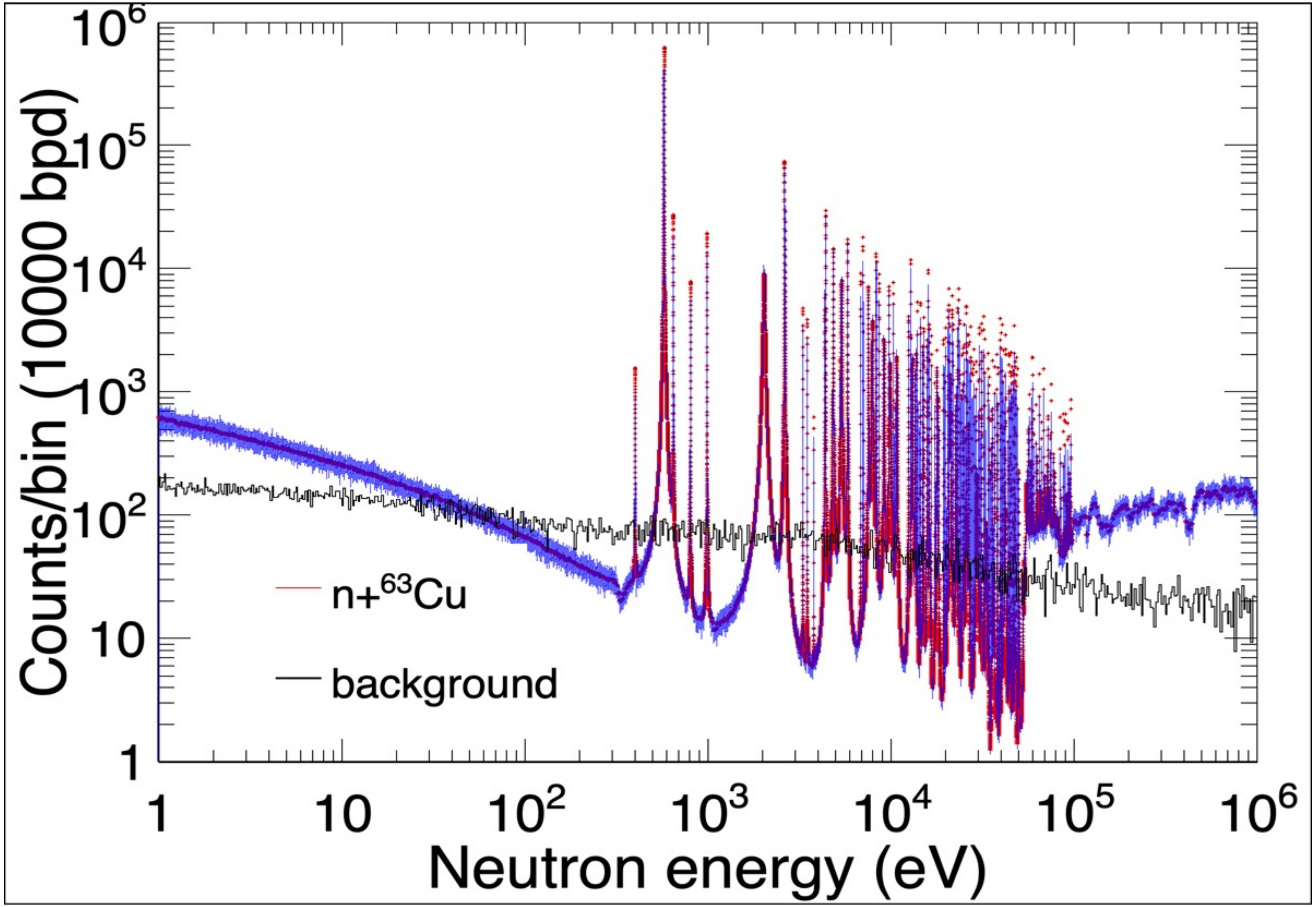
Nucl. Astro.

$^{63}Cu(n,\gamma)$

$E_n < 300$ keV



(n,γ) @ EAR 1

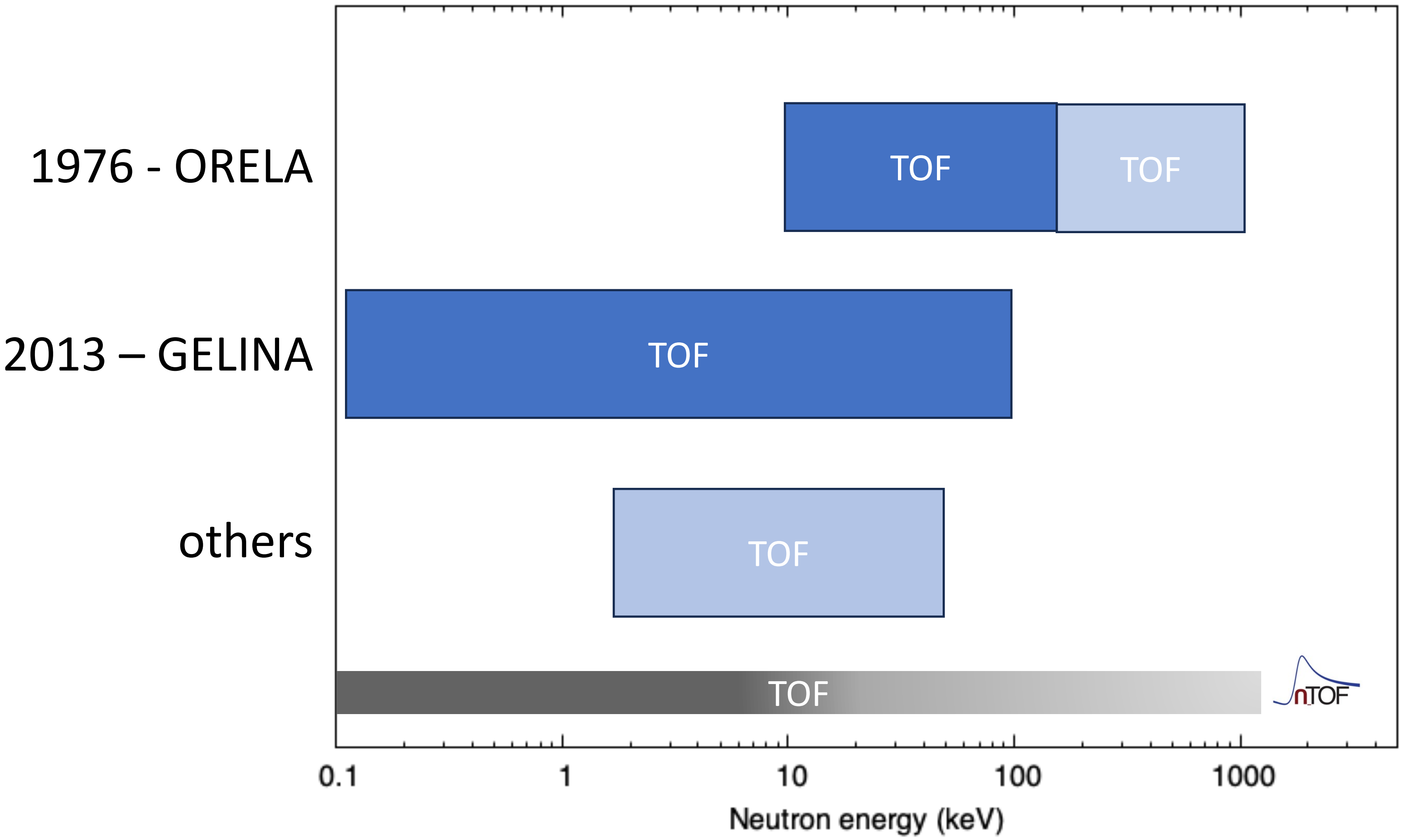


- 4 C_6D_6
- Radius = 1 cm
- Mass = 2 g
- $3x10^{18}$ protons

Nucl. Techn.

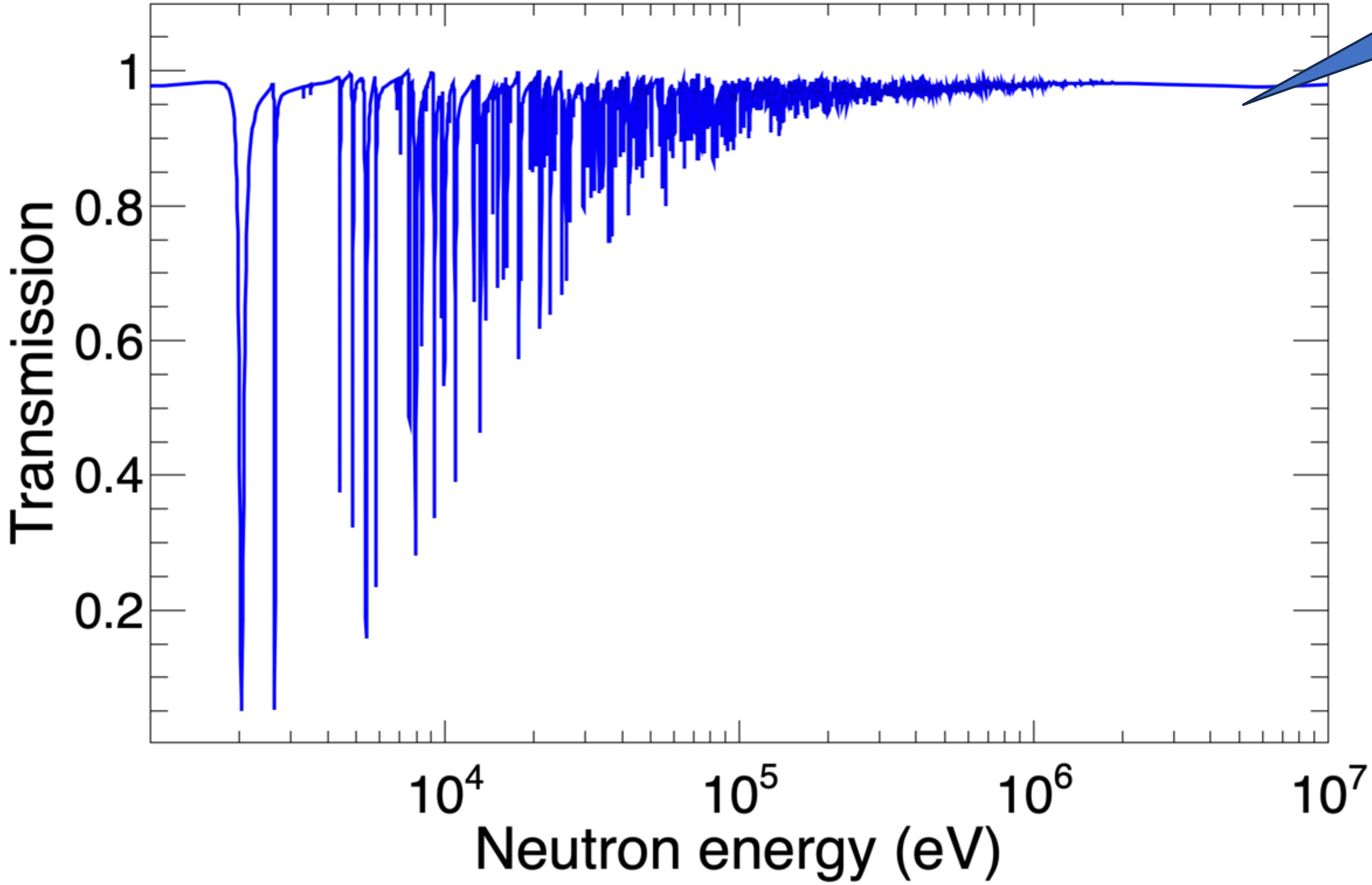
$^{63}Cu(n,tot)$

$E_n < 5$ MeV



(n,tot) @ EAR 1

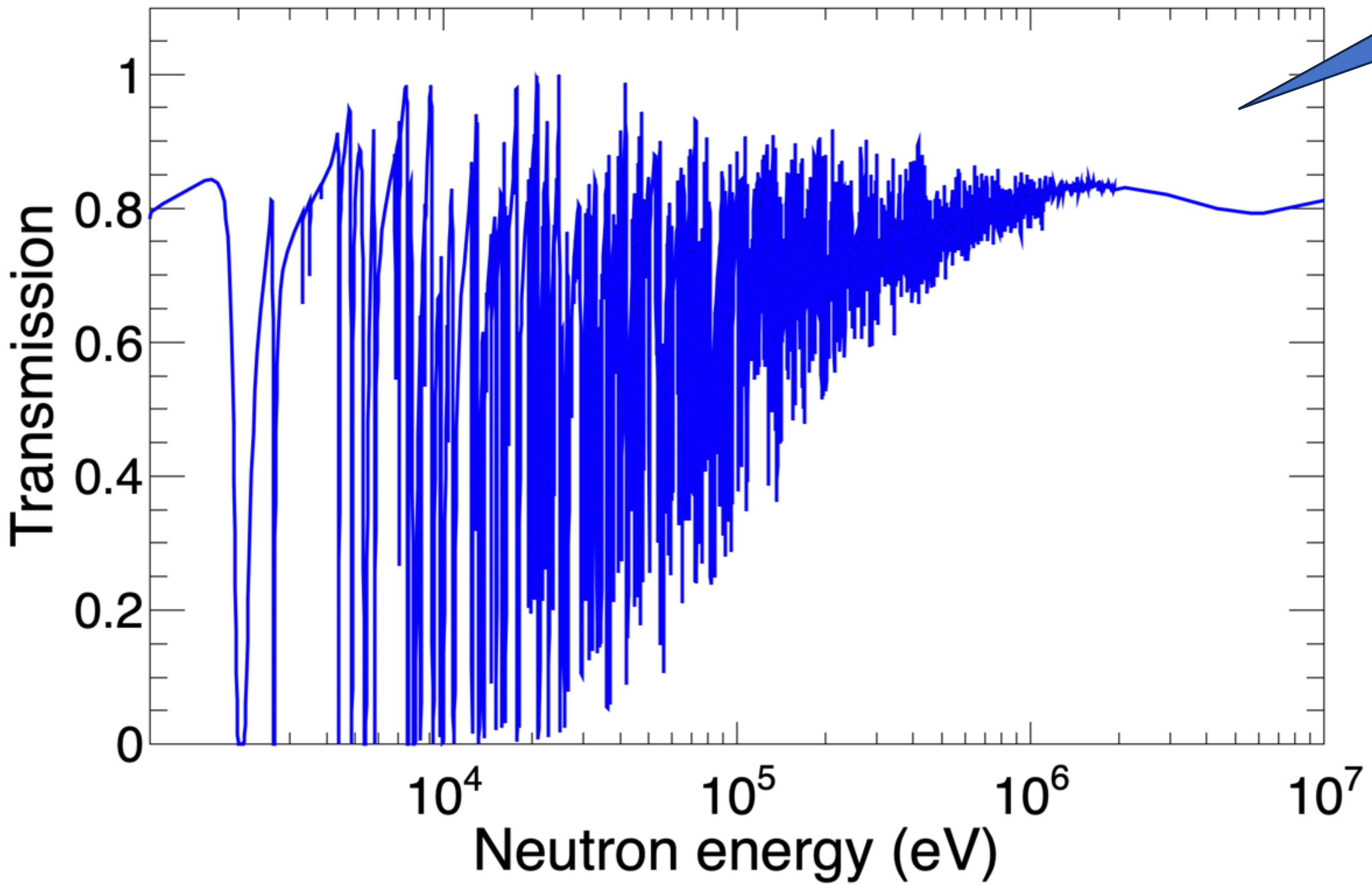
Mass should be 10 times larger !!!



PTB

PTB
^{235}U fission chamber

(n,tot) @ EAR 1



20 grams

PTB
^{235}U fission chamber

^{63,65}Cu(n,n)

50 keV < E_n < 5 MeV

- Transmission (@ n_TOF)
- p-stil (elastic angular sistribution): 1 MeV < E_n < 10 MeV

Addendum in the future?

$^{63,65}Cu(n,n')$

$1\ \text{MeV} < E_n < 10\ \text{MeV}$

- HPGe/LaBr @ EAR1

Addendum in the future?

Conclusion:

- Ramen: an intriguing physics case! (we have just proposed a new entry in HPRL)

- next INTC (february): capture and transmission @ EAR1 using 10^{19} protons
  - 6×10^{18} Protons for $^{63}Cu(n,\gamma)$ and $^{65}Cu(n,\gamma)$
  - 4×10^{18} Protons for $^{63}Cu(n,tot)$ and $^{65}Cu(n,tot)$

- Measurements performed in 2 years (*e.g.* ^{63}Cu in 2024 and ^{65}Cu in 2025)

- Other reacions in dedicated addendum (if possible)

Acknowledgement:

- ERANOS Sensitivity studies by **Donato Maurizio Castelluccio**
- MCNP caluclations by **Patrizio Console Camprini**
- Massive stars sentitivity study by **Marco Pignatari**

Backup

^{63}Cu

TOF - DANCE

List of all available values

original	renorm.	year	type	Comment	Ref
84.0 ± 7.8		2017	c	TOF; W Spall., Au	WBC17
60.3 ± 2.4 kT= 25keV	60.1	2016	r	VdG, Act., Au:RaK88 corrected by 632/586= 1.0785; en. dep. from endfb71,jendl40,tendl15	HKU08
60.3 ± 2.4 kT= 25keV	55.6 ± 2.2	2008	c	VdG, Act., Au:RaK88; en. dep. from Bao00	HKU08
94 ± 10		1977	r	Linac, TOF, ^{6}Li, Au:Sat., Recalc. inc[illegible]. data of Alt75 at 50 < E(n) < 300 keV	PGM77
56 ± 7 E(n)= 25 (5) keV		1979	c	F.N.B., Act., 1/v(E), ^{127}I:832 mb [illegible]5 keV)	AJB79
21		1970	c	Sb-Be, Act., 1/v(E), Au:640 mb [illegible] keV)	ChP70

Attivazione - FZK

TOF - ORELA

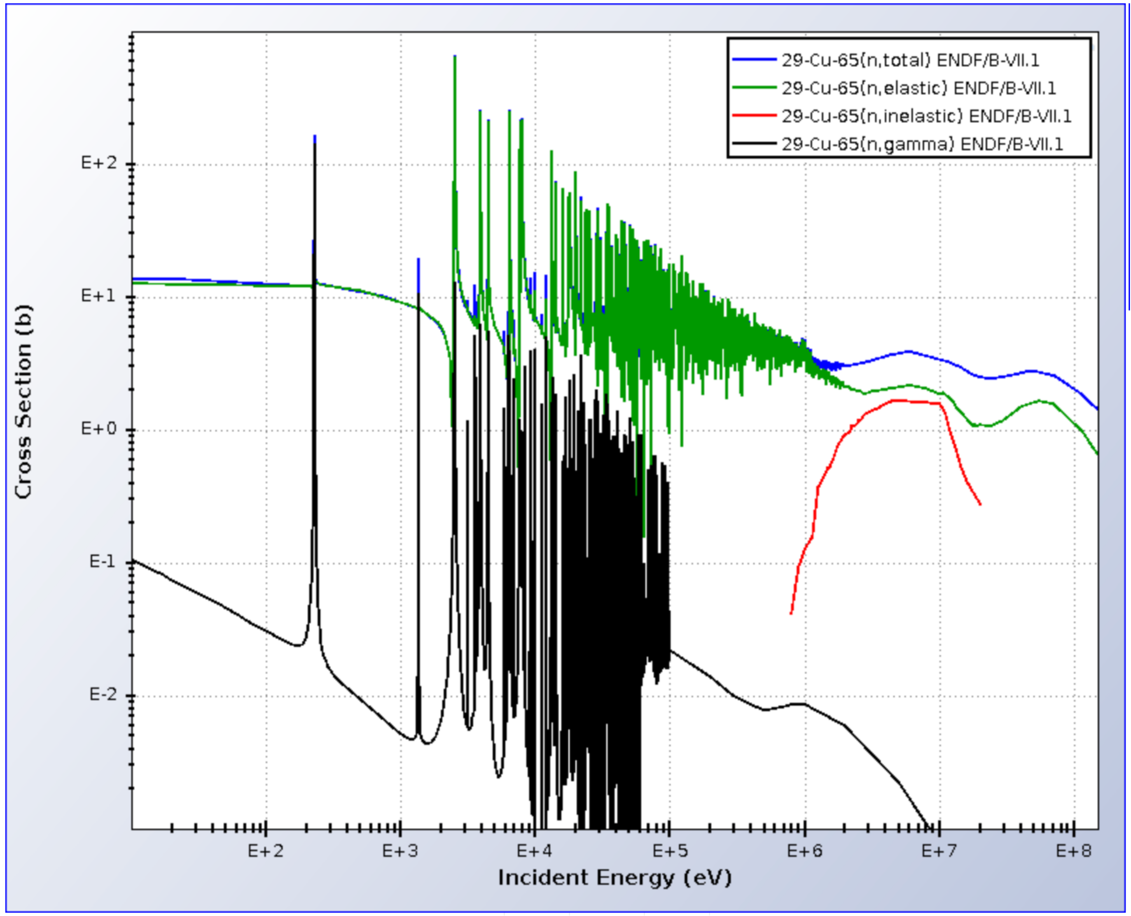
Natural abundance 30.9%

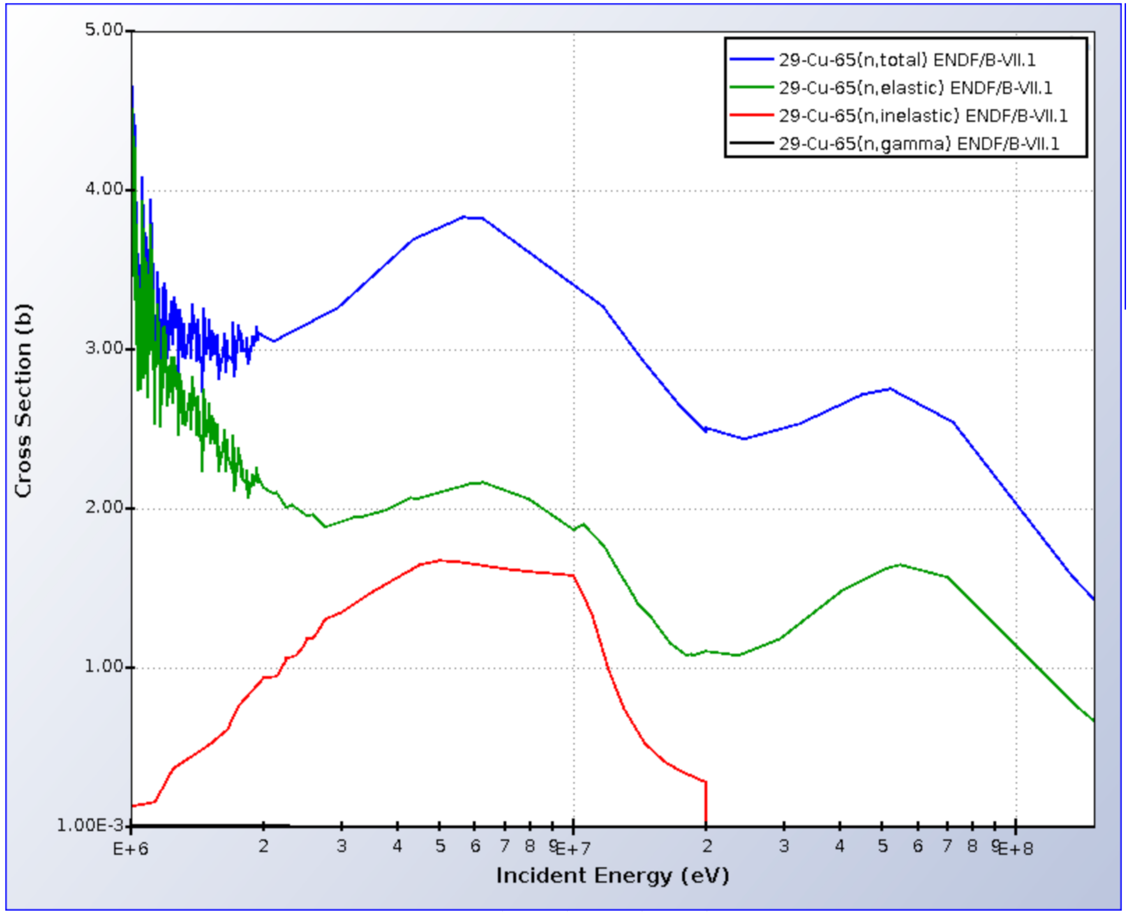
n + ^{65}Cu

$\Gamma_n >> \Gamma_\gamma$

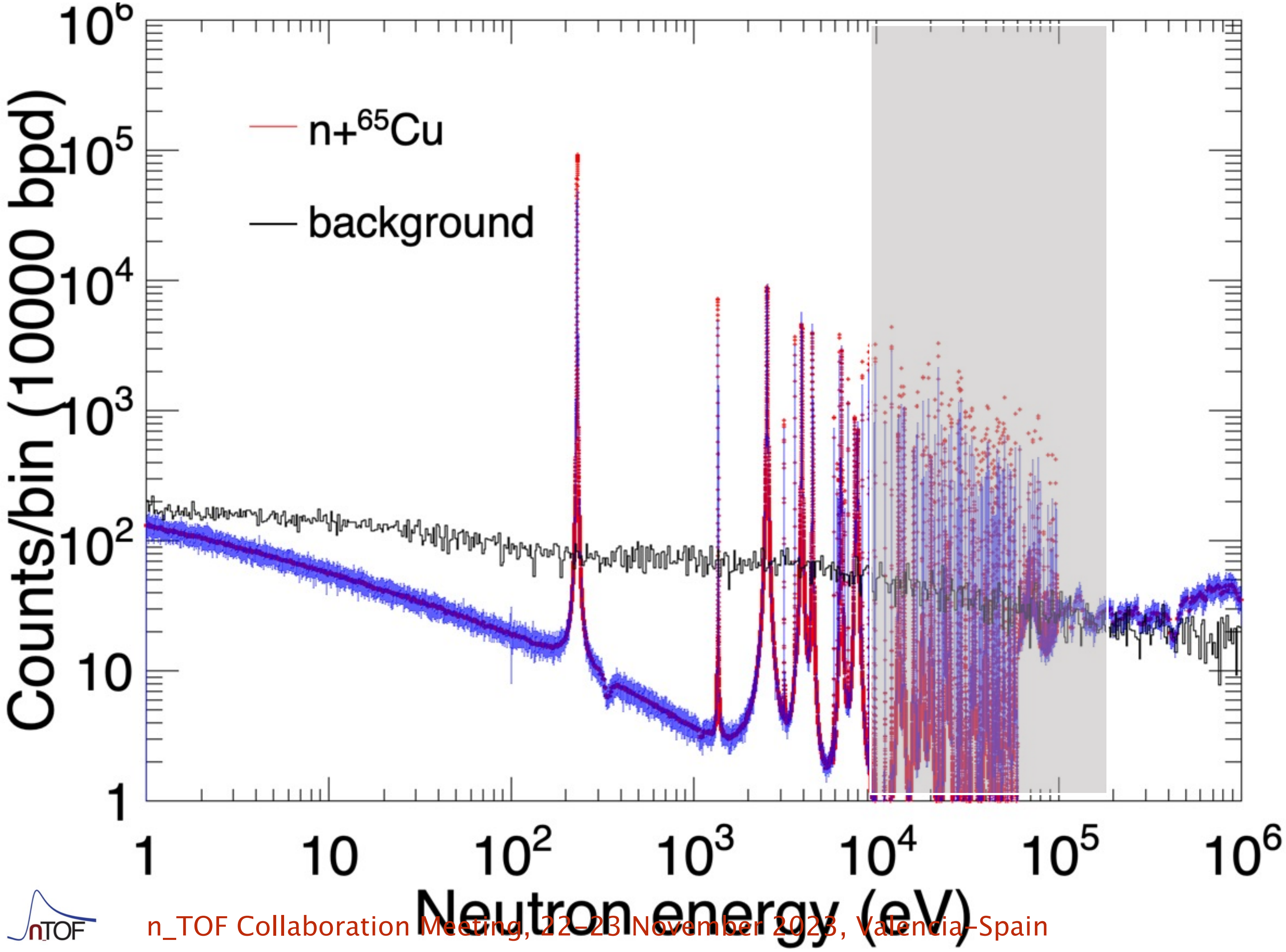
$\sigma_{el} > \sigma_{anel}$

	Q-value (keV)
$^{65}Cu + n$	0
$^{66}Cu + \gamma$	7065.9 ± 0.9
$^{62}Co + \alpha$	-193 ± 18
$^{65}Ni + p$	-1355.5 ± 0.8

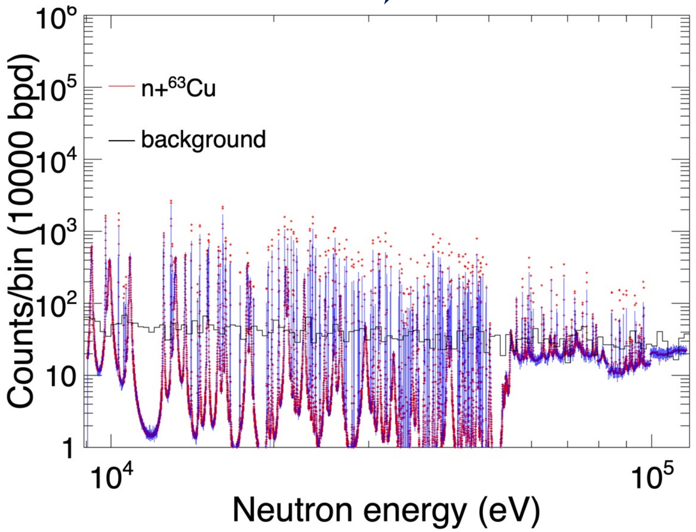




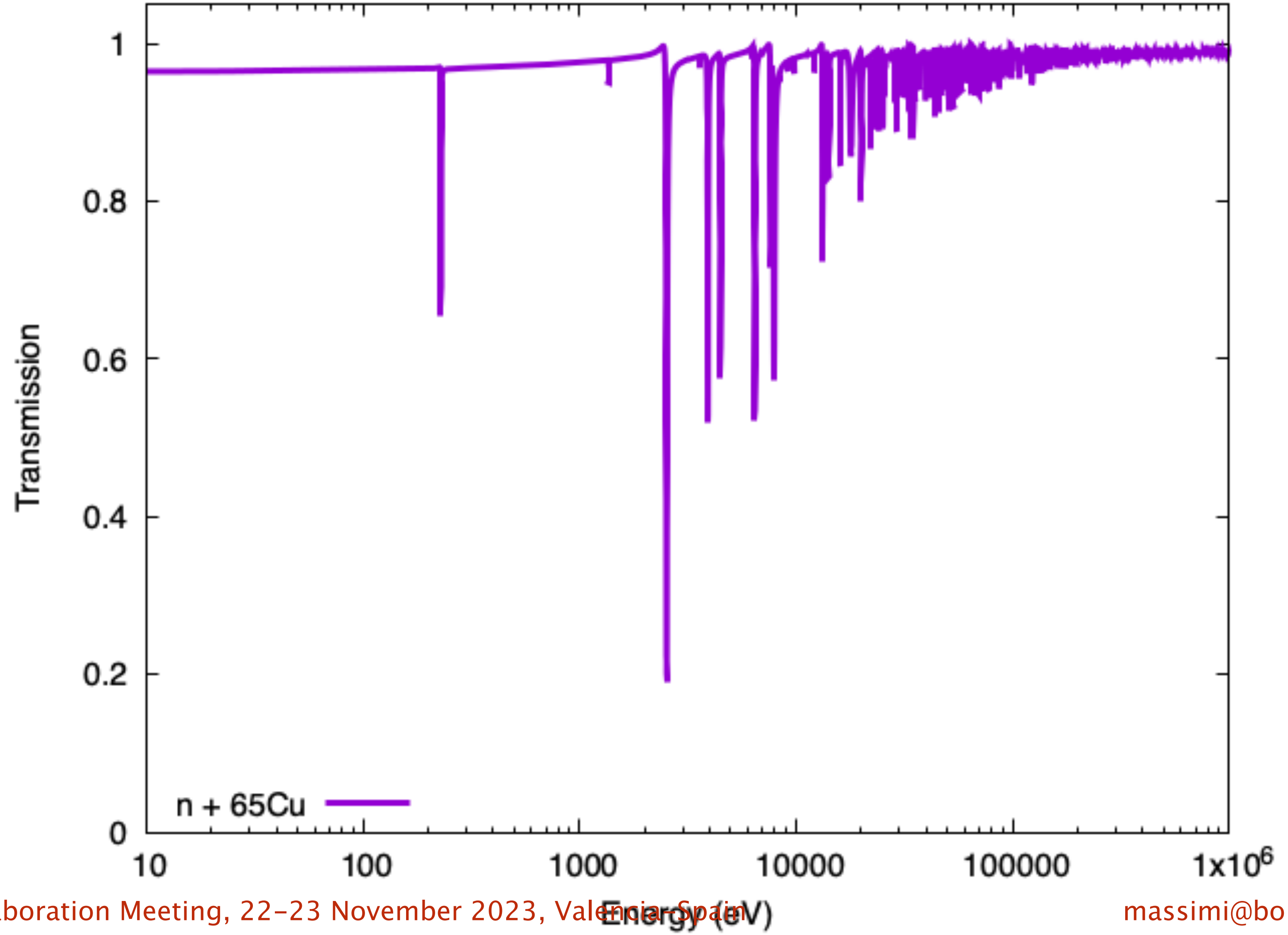
(n,γ) @ EAR 1, 4 C_6D_6, Ø = 3 cm, mass = 2 g



4x10[18] p



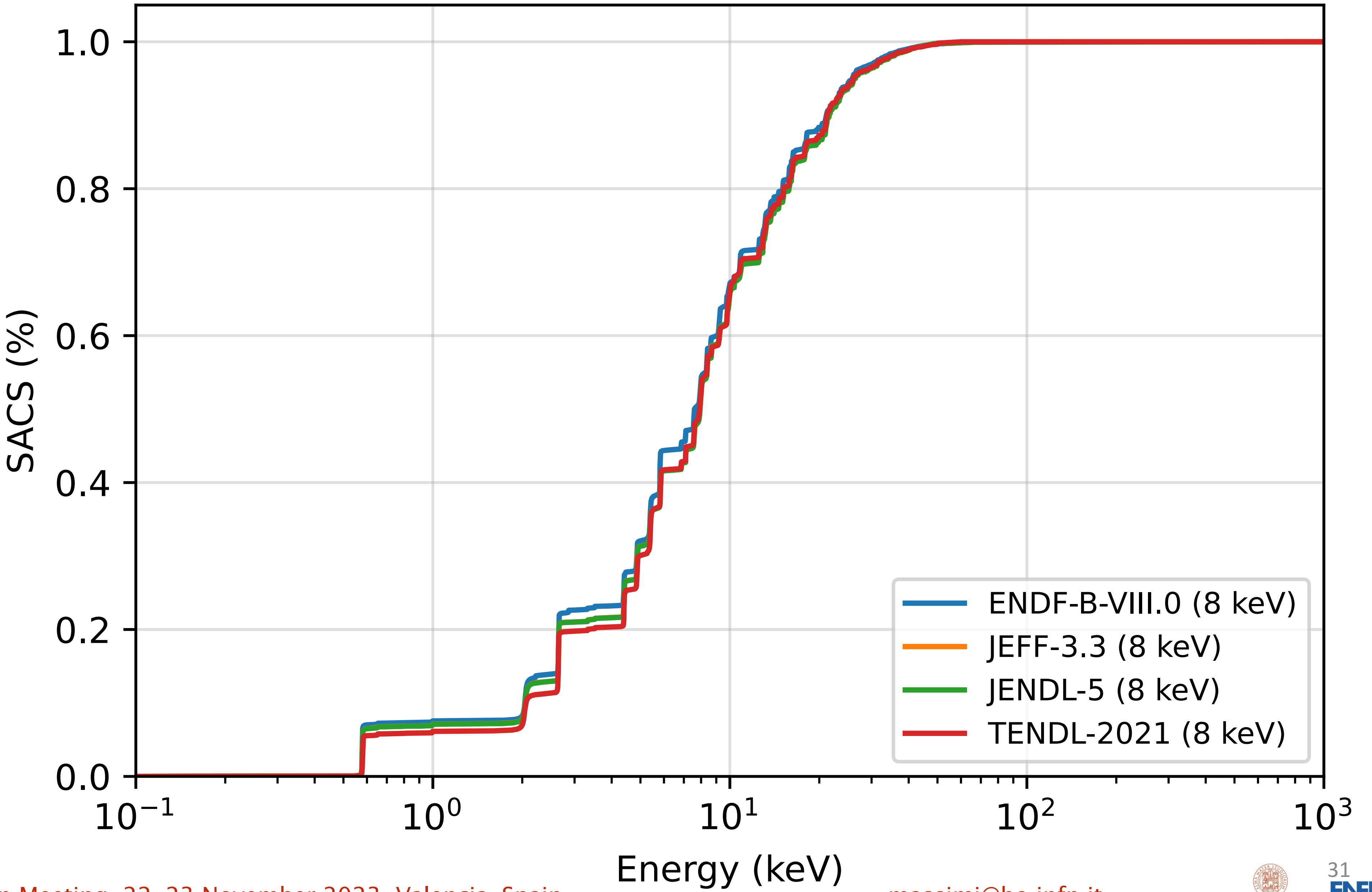
(n,γ) @ EAR 1, 4 C_6D_6, Ø = 3 cm, mass = 2 g



Nucl. Astro.

kT = 8 keV

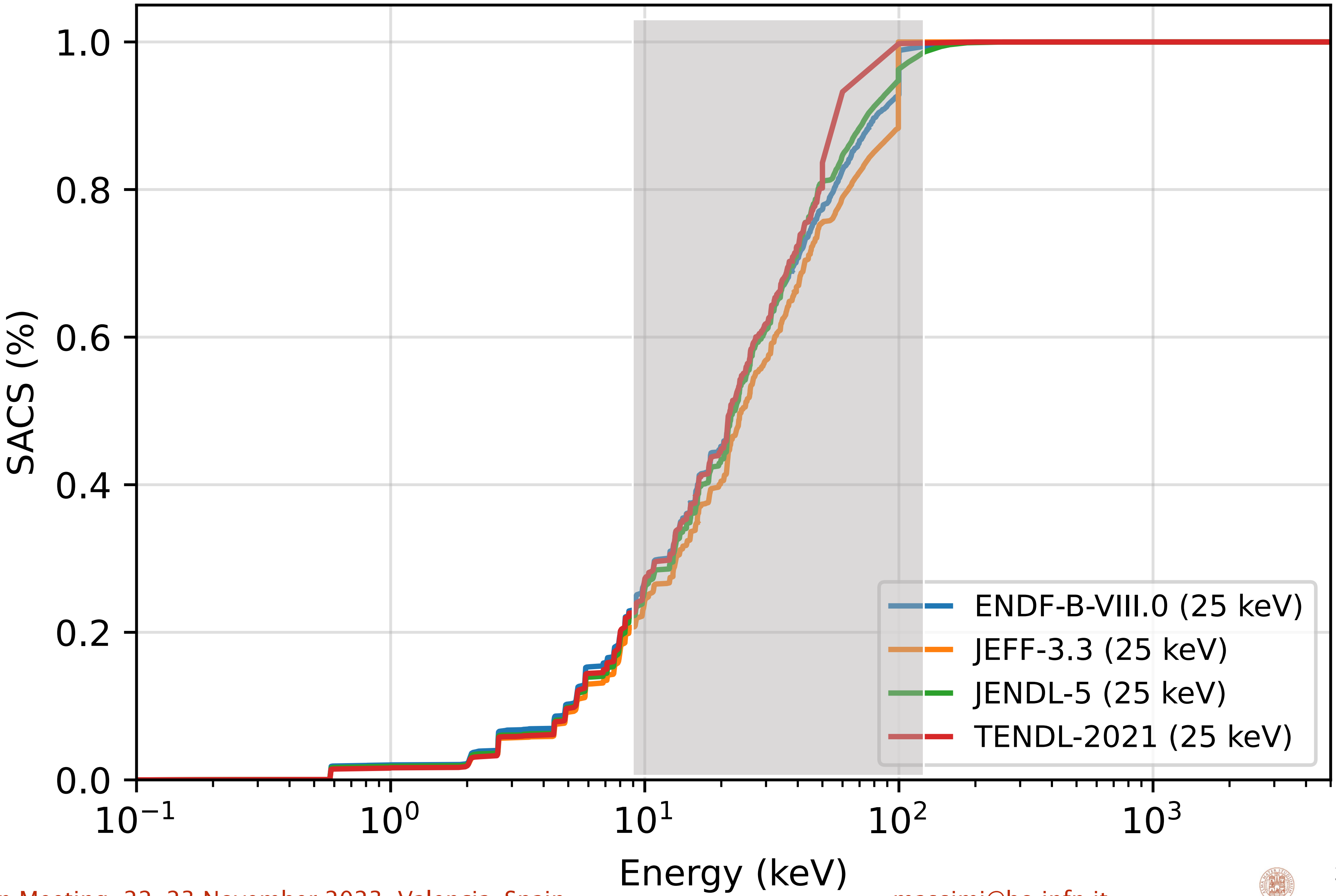
^{63}Cu



Nucl. Astro.

kT = 25 keV

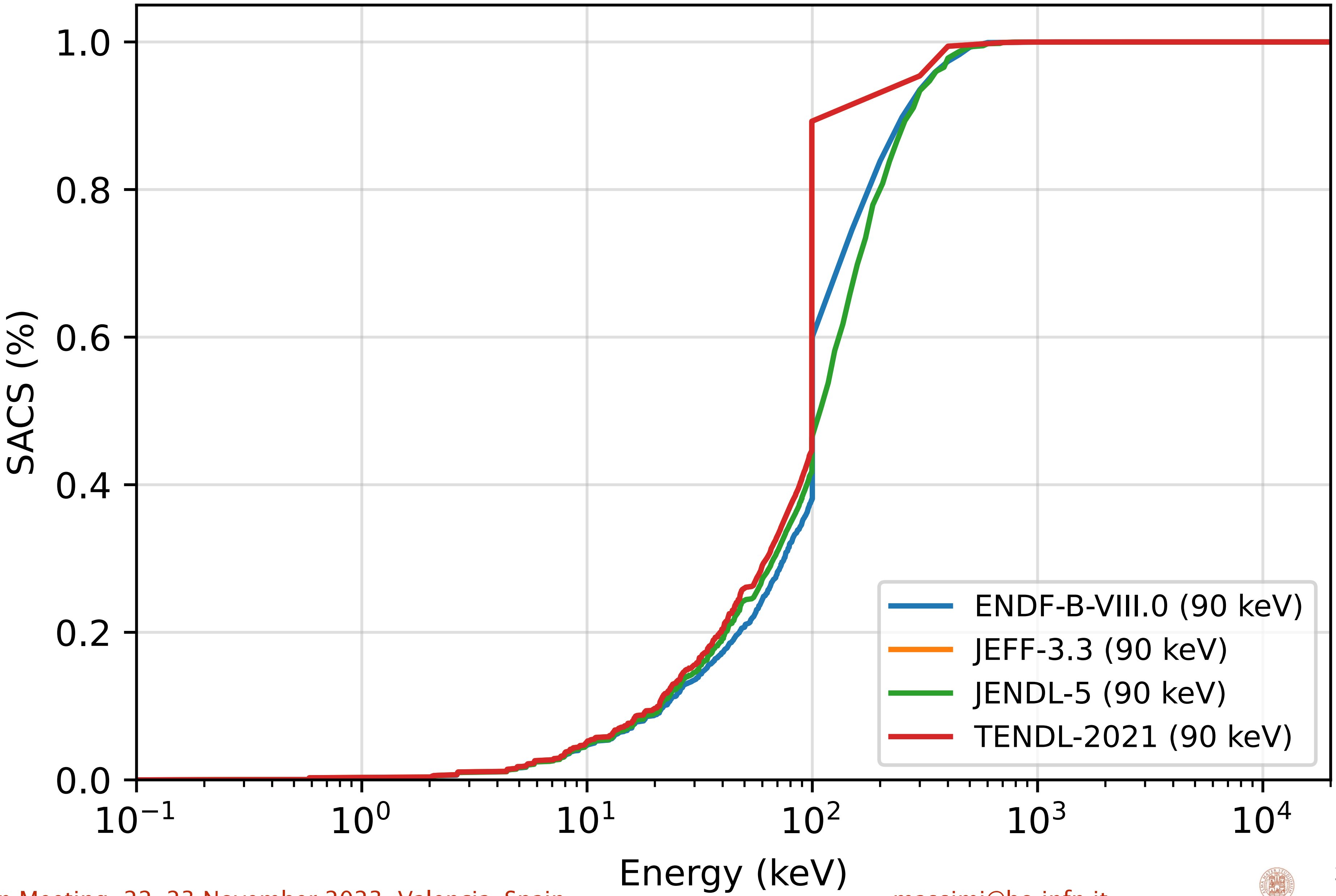
^{63}Cu



Nucl. Astro.

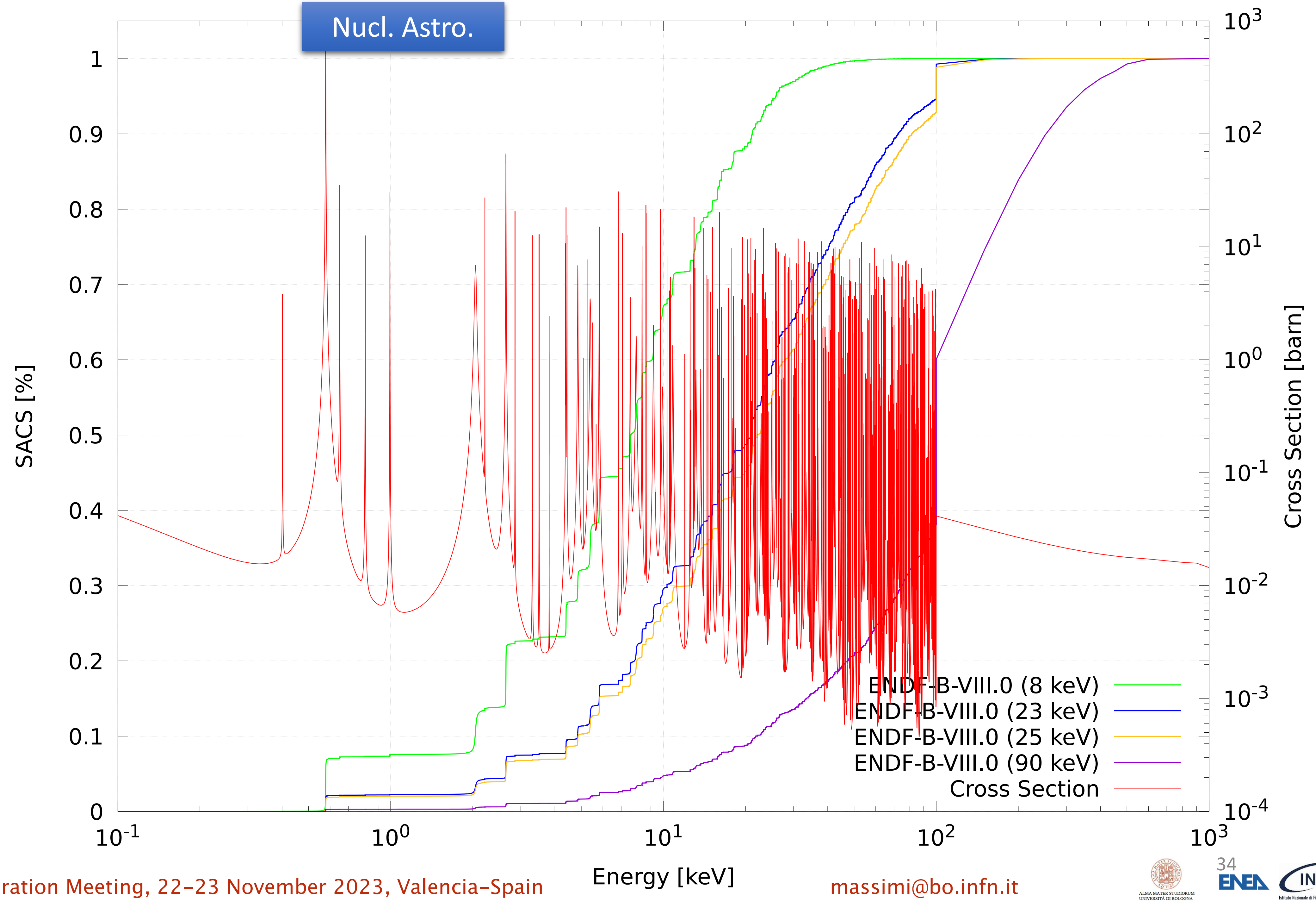
kT = 90 keV

^{63}Cu



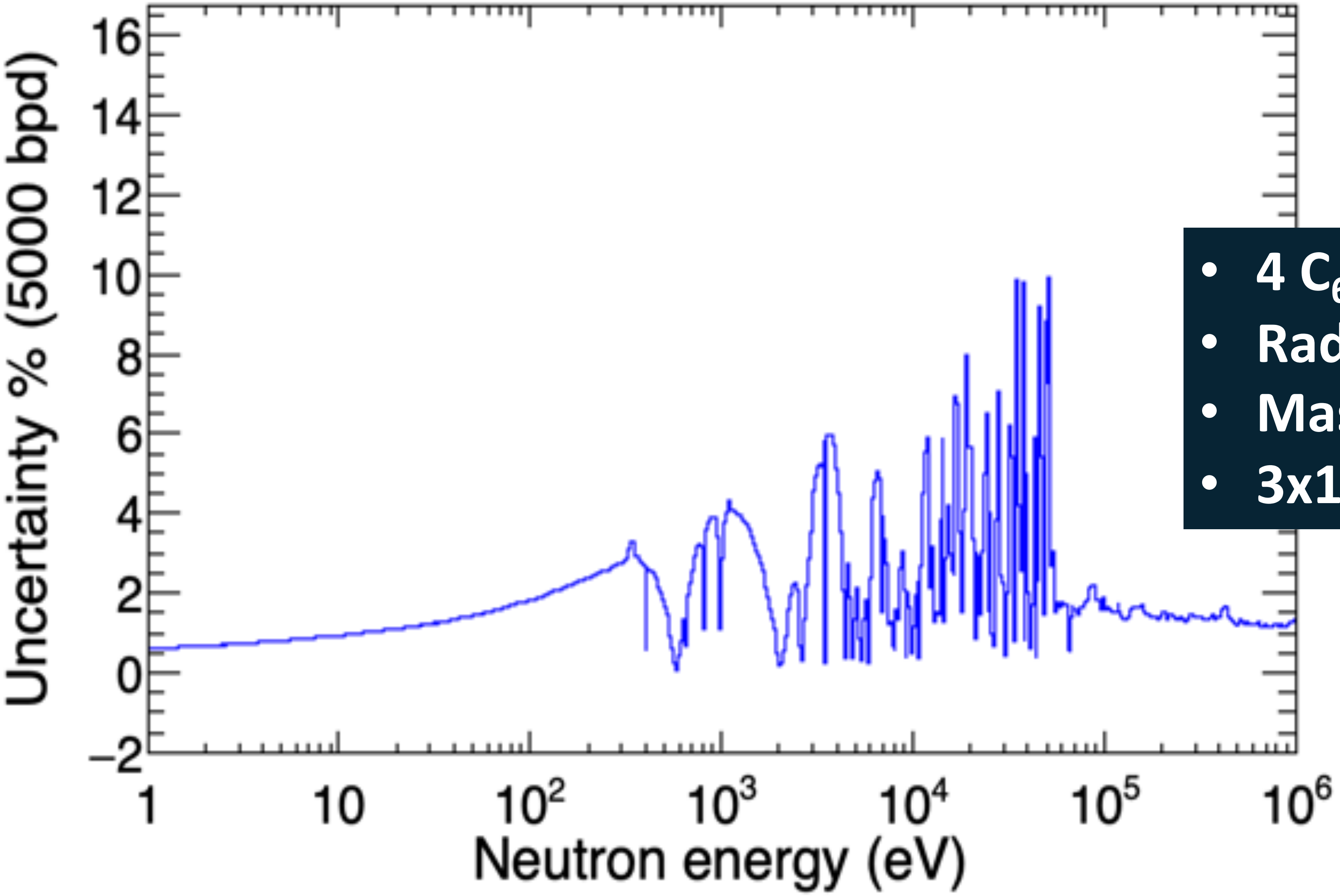
Nucl. Astro.

^{63}Cu



Nucl. Astro.

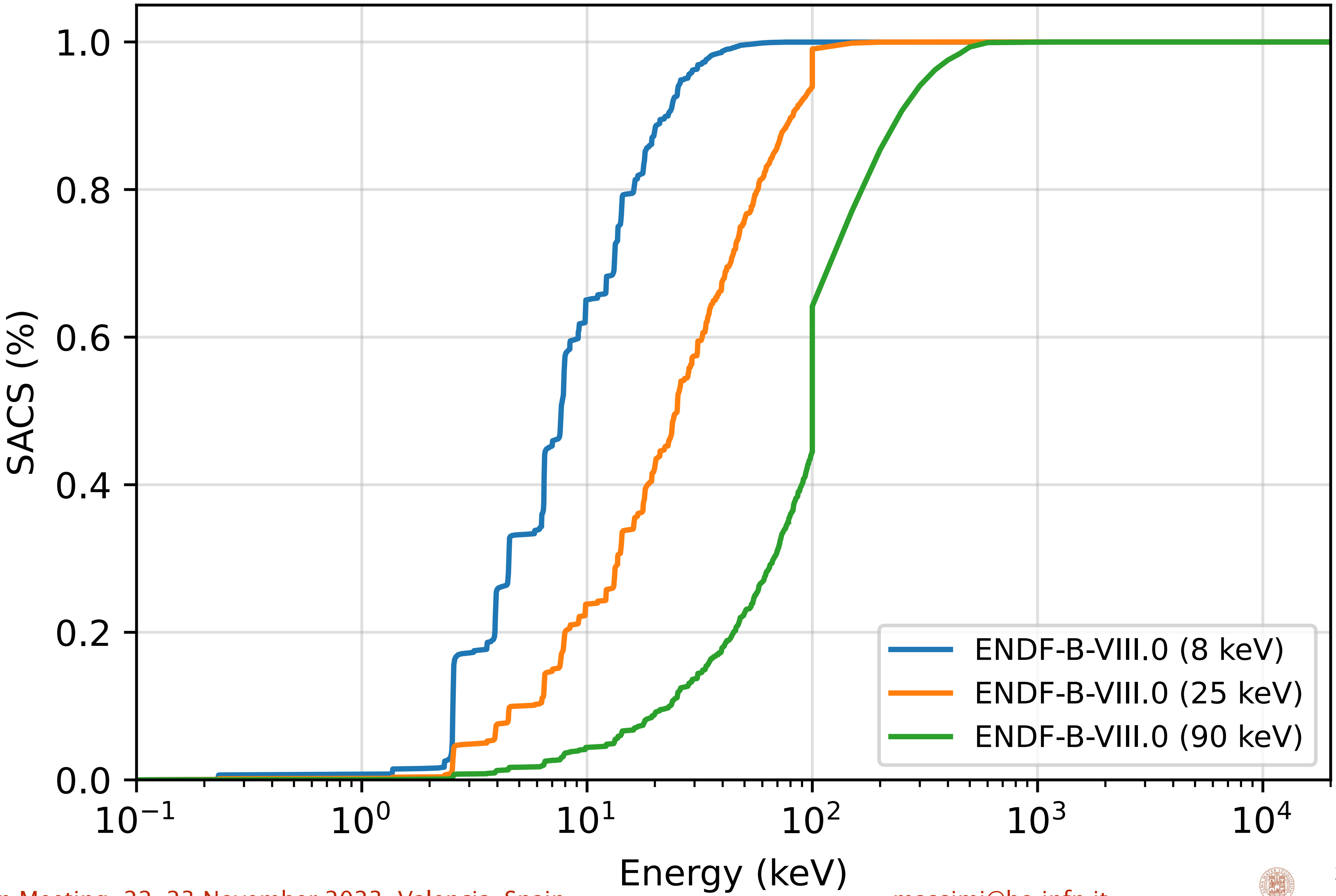
^{63}Cu



- 4 C_6D_6
- Radius = 2 cm
- Mass = 2 g
- $3x10^{18}$ protons

Nucl. Astro.

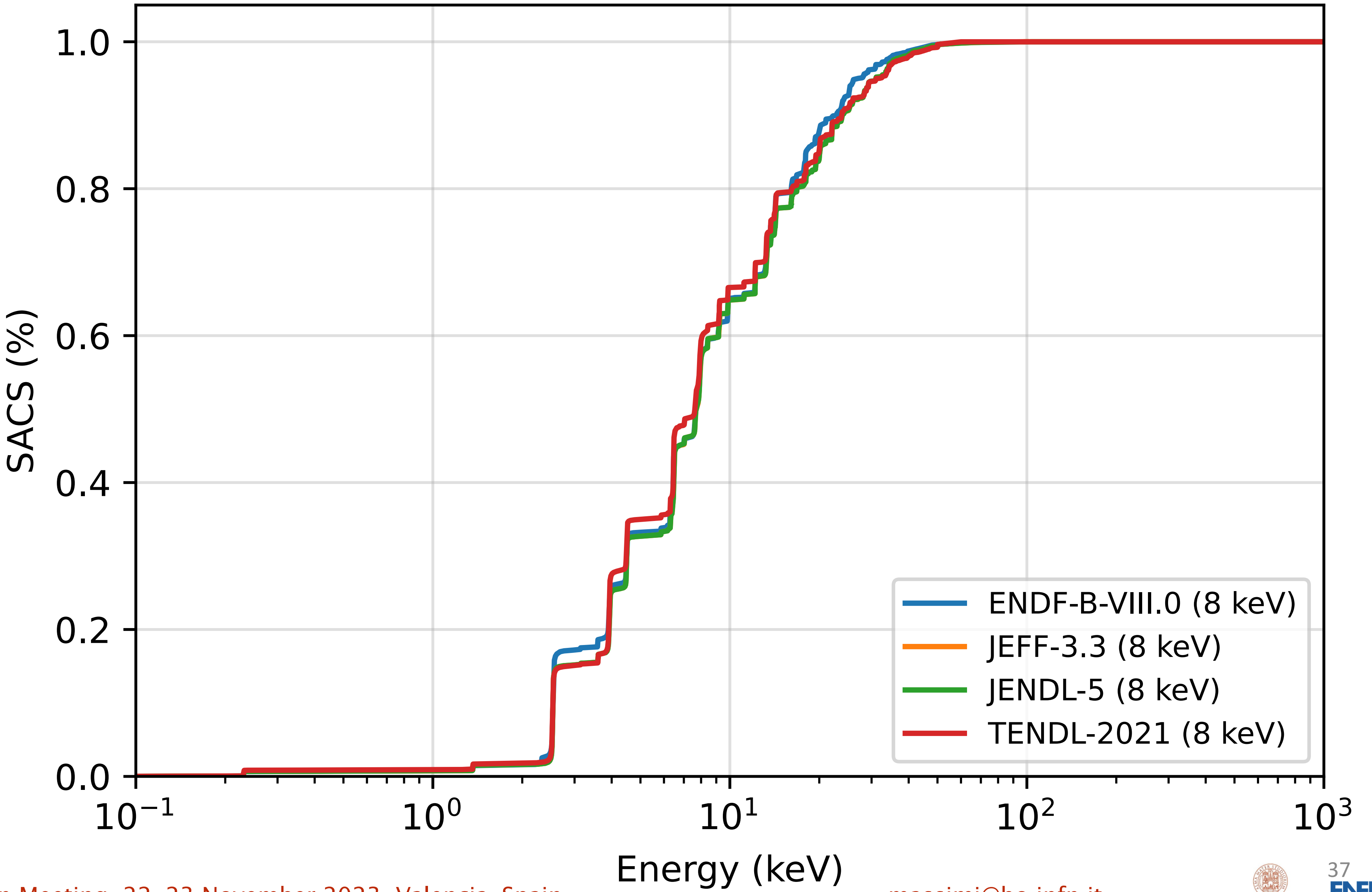
^{65}Cu



Nucl. Astro.

kT = 8 keV

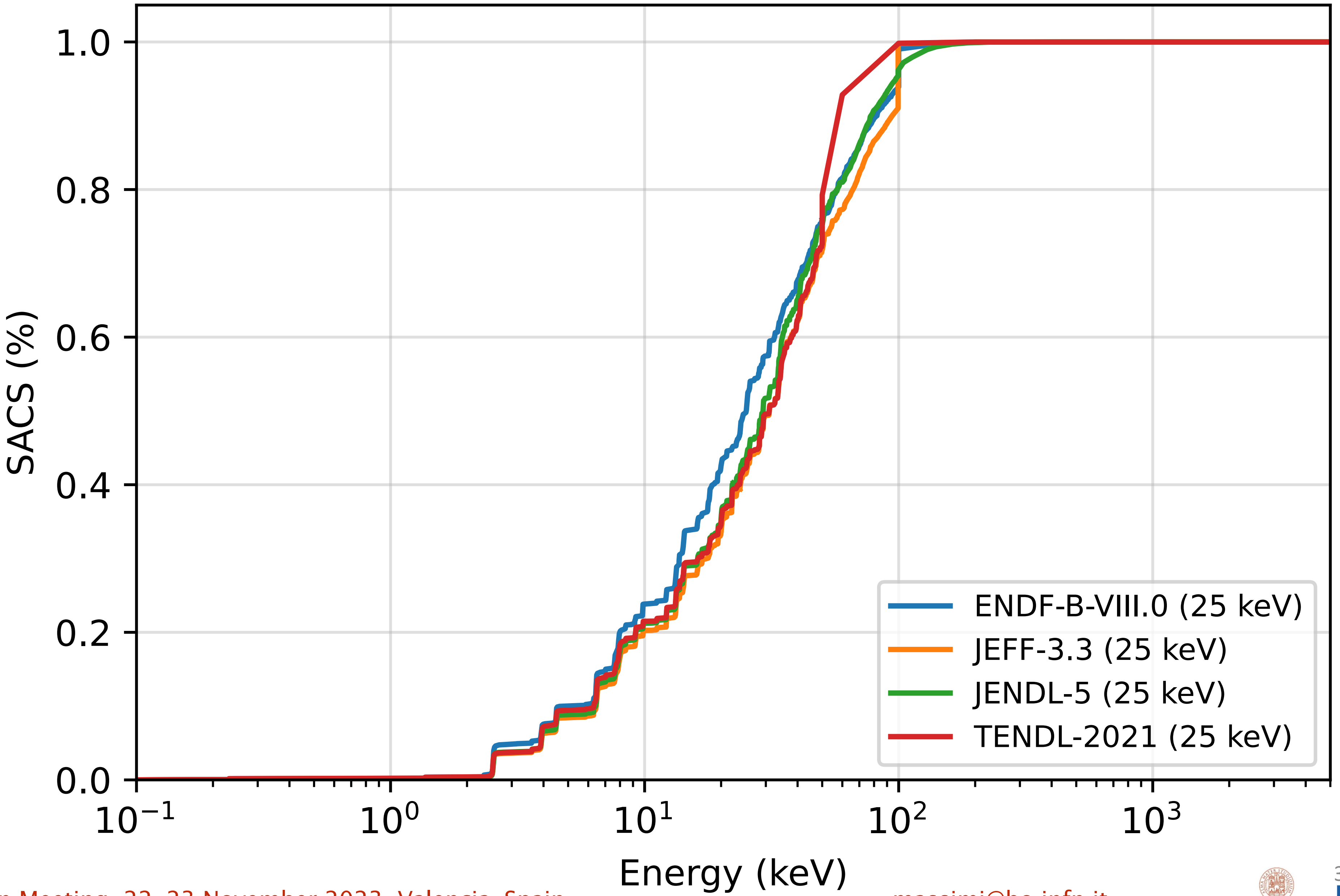
^{65}Cu



Nucl. Astro.

kT = 25 keV

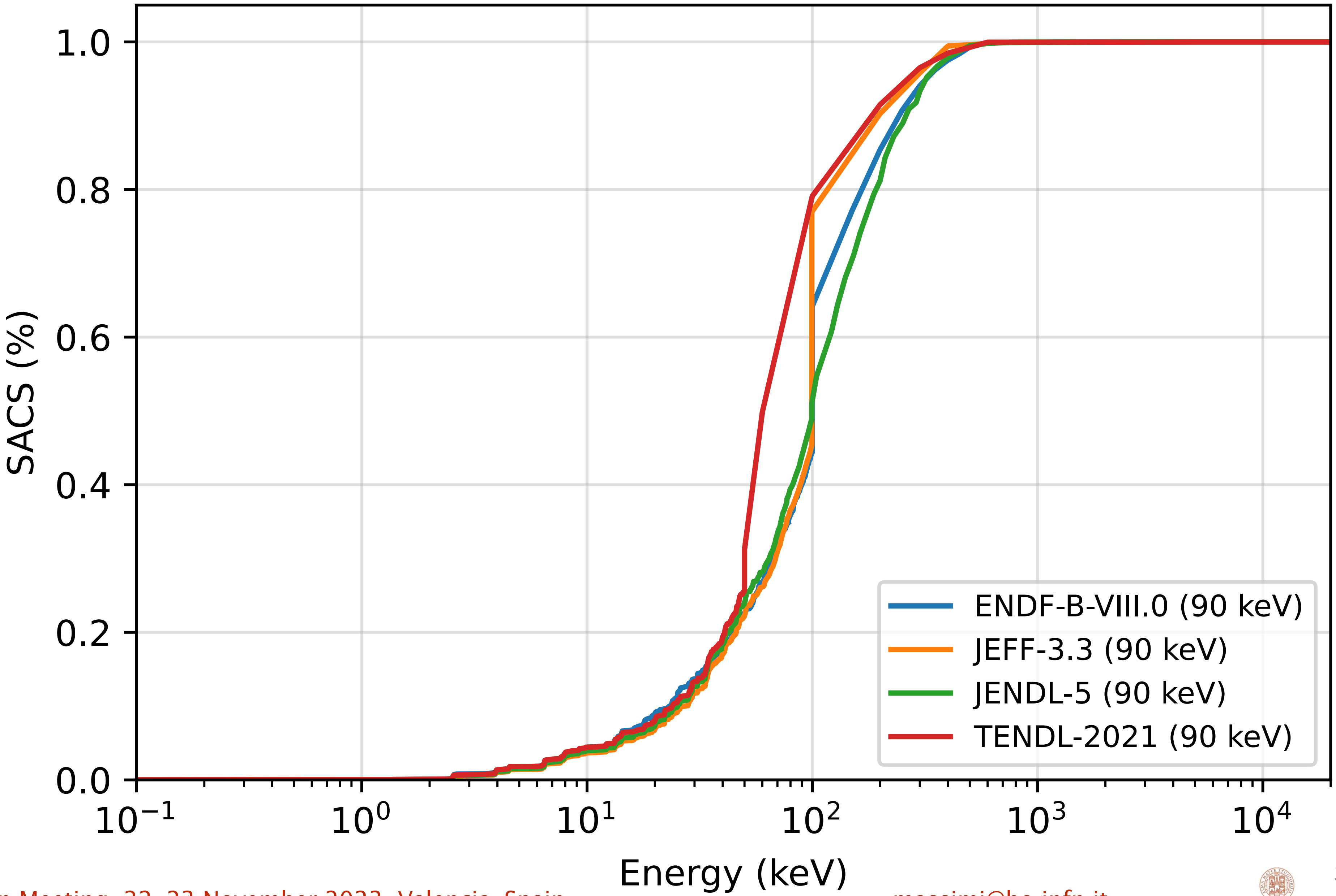
^{65}Cu



Nucl. Astro.

kT = 90 keV

^{65}Cu



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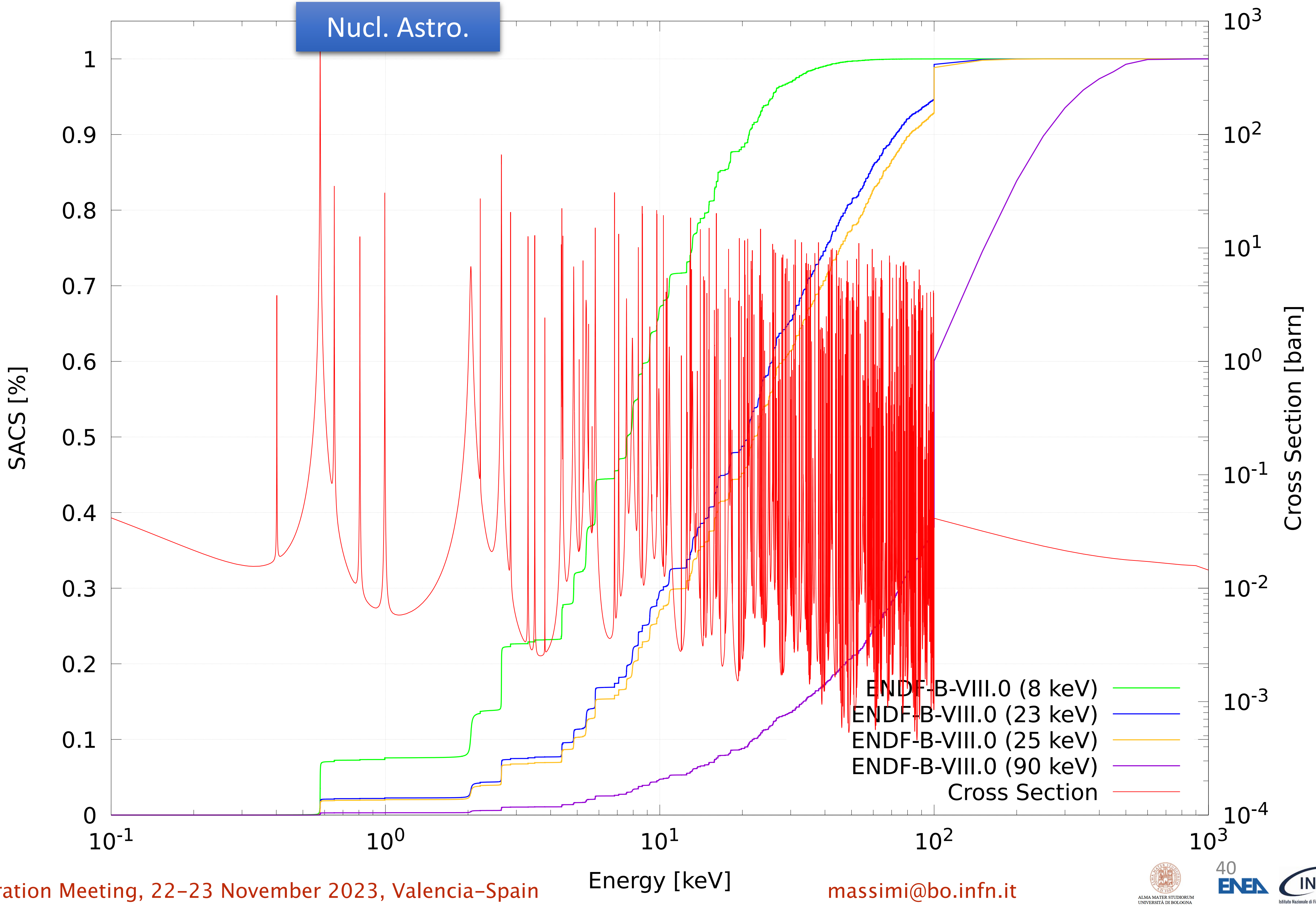
Nucl. Astro.

^{65}Cu



Nucl. Astro.

^{65}Cu

▼ Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{65}Cu\ (n,\gamma)^{66}Cu$$

Total MACS at 30keV: 31.2 ± 1.7 mb

Cross sections do not include stellar enhancement factors!

▼ History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	31.2 ± 1.7	-	-
0.3	29.8 ± 1.3	-	-
0.0	41 ± 5	-	-

(Version 0.0 corresponds to Bao et al.)

▼ Comment

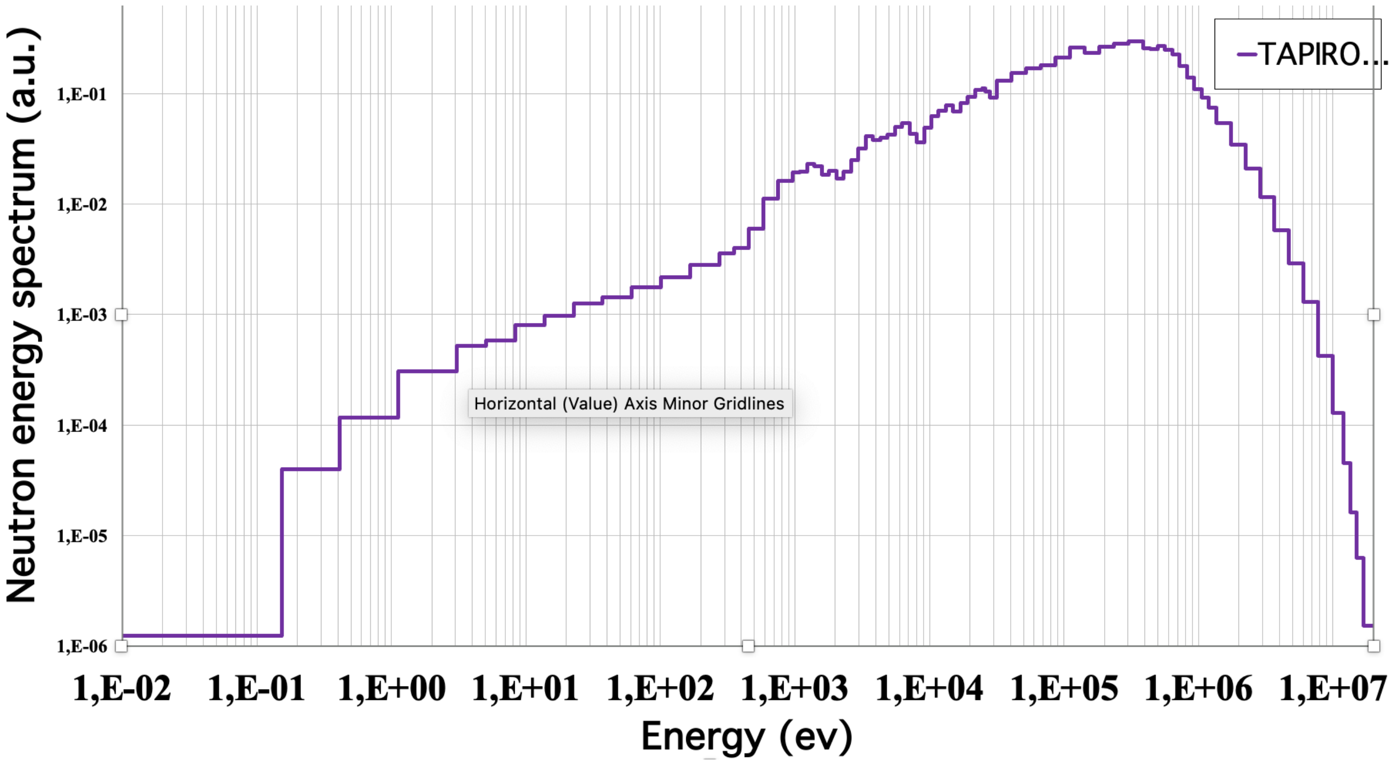
New rec. value is from HKU08, renormalized by 632 mb/586 mb = 1.0785, and recalculated with normalized energy dependencies of tendl15,endfb71,jendl40. Uncertainty is the deviation between different evaluations plus 4.3% exp. uncertainty from HKU08.
Last review: June 2016

^{65}Cu

▼ **List of all available values**

original	renorm.	year	type	Comment	Ref
32.0 ± 1.4 kT= 25 keV	31.2	2016	r	VdG, Act., Au:RaK88 corrected by 632/586= 1.0785; en. dep. from endfb71,jendl40,tendl15	HKU08
32.0 ± 1.4 kT= 25 keV	29.8 ± 1.3	2008	c	VdG, Act., Au:RaK88; en. dep. from bao00	HKU08
41 ± 5		1977	r	Linac, TOF, ^{6}Li, Au:Sat., Recalc. incl. data of PGM77 at 0 < E(n) < 50 keV (k= 0.9507) and data of GaK76 at 50 < E(n) < 400 keV	PGM77,GaK76

Tecnologie nucleari: TAPIRO



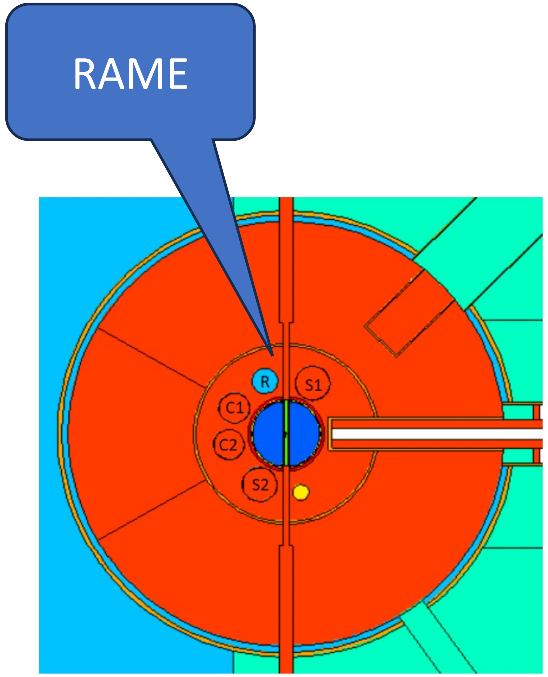
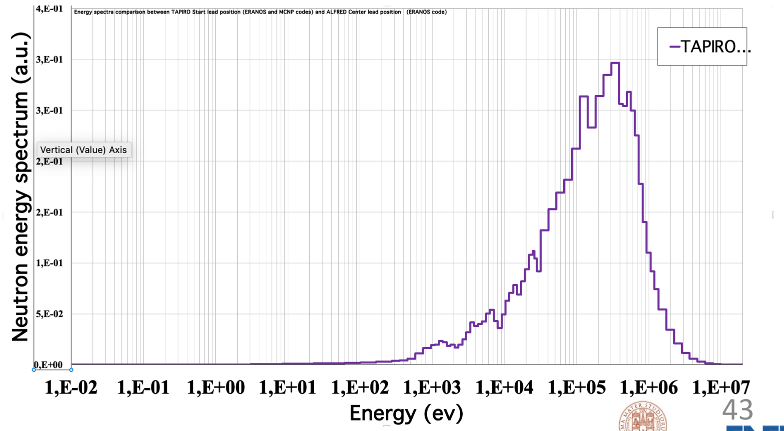


Figura 2.25: Sezione del reattore TAPIRO realizzata grazie al programma VISED. Nella figura si possono osservare in arancione il riflettore in rame, che si estende per un diametro di circa 80 cm, e in blu il nocciolo, costituito dalla lega di uranio e molibdeno, con diametro pari a 12 cm. Sono inoltre evidenti le 5 barre: 1 di regolazione (R), 2 di controllo (C1 e C2) e 2 di sicurezza (S1 e S2).

Tipico spettro di fissione, con massimo a E_n=820 keV
Ideale per studi di reattori veloci:

- test di materiali
- Validazione di dati nucleari



Backup