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Measurement of the neutron capture cross section of the s-only ^{154}Gd isotope

Cristian Massimi

Department of Physics and Astronomy

On behalf of the n_TOF Collaboration

Outline

Motivation: Why? How? Where? When?

Data reduction (A. Mazzone)

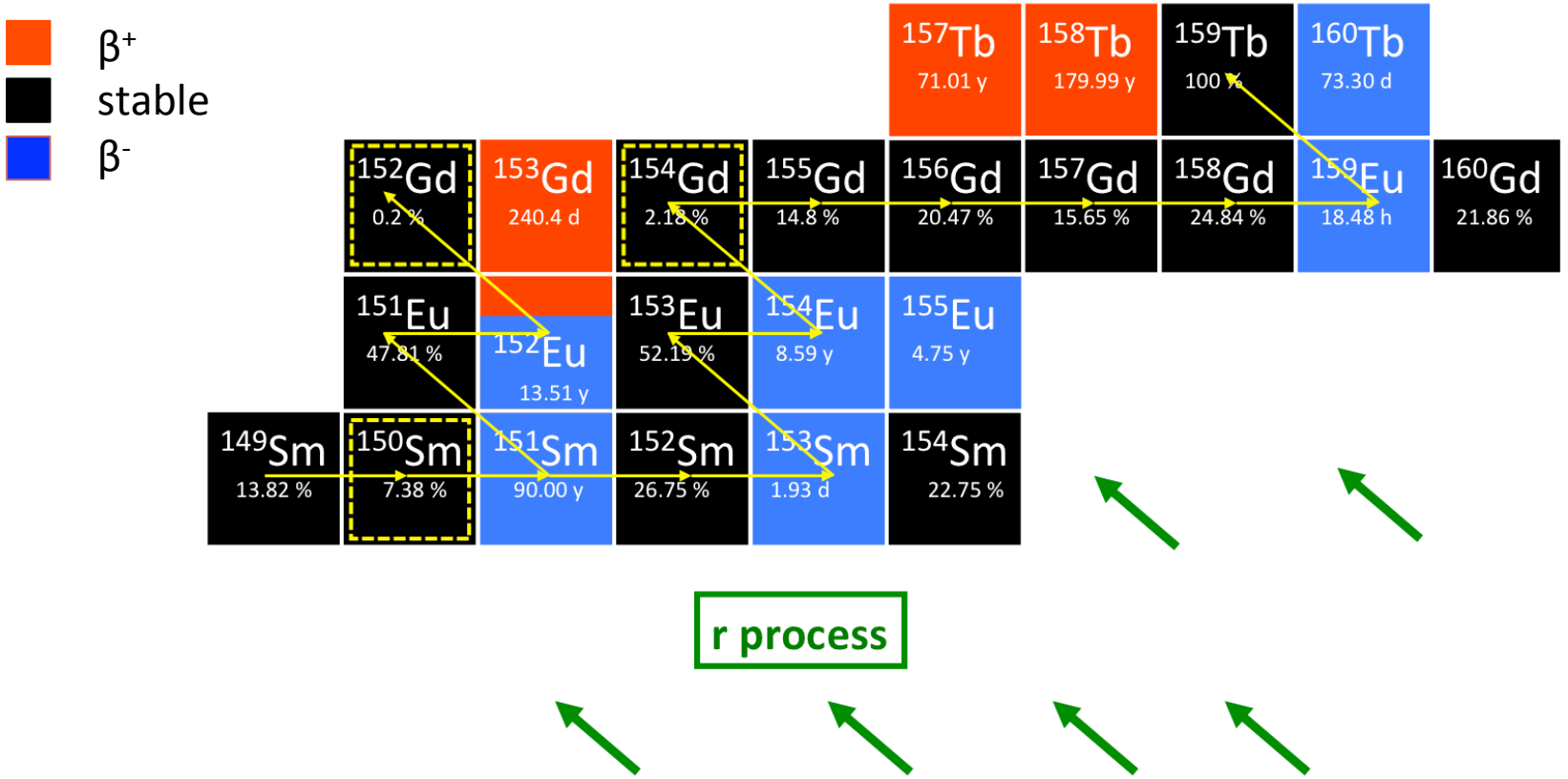
Study of the sample (R. Mucciola)

Analysis of:

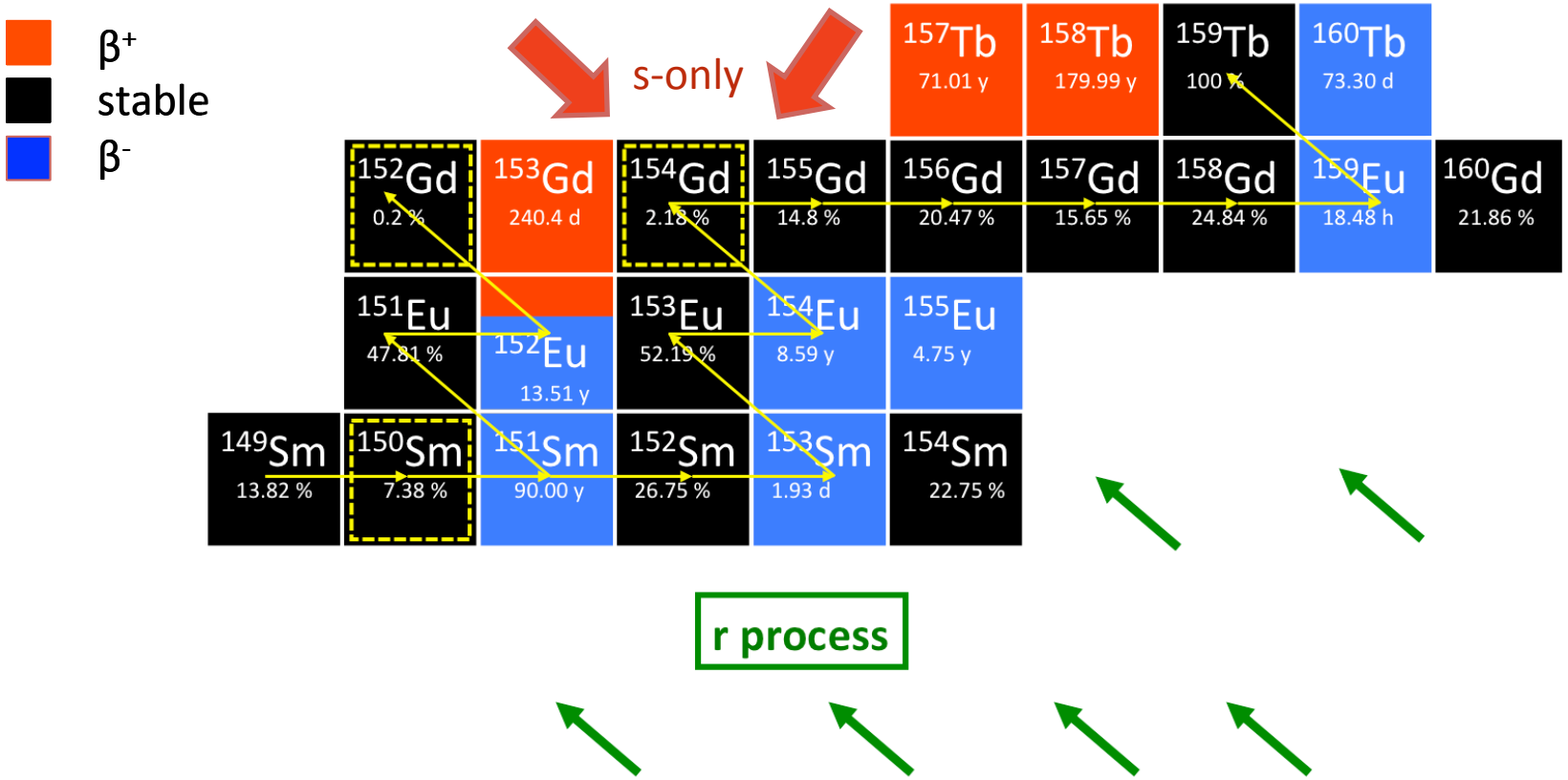
- Resolved Resonance Region (RRR) up to 2.7 keV
- Unresolved Resonance Region (URR) up to 200 keV
- HF calculation and extrapolation above 200 keV (**A. Mengoni**)

MACS & Results (M. Busso, S. Cristallo e D. Vescovi)

Why


β+
stable
β-
157Tb 71.01 y
158Tb 179.99 y
159Tb 100 %
160Tb 73.30 d
152Gd 0.2 %
153Gd 240.4 d
154Gd 2.18 %
155Gd 14.8 %
156Gd 20.47 %
157Gd 15.65 %
158Gd 24.84 %
159Eu 18.48 h
160Gd 21.86 %
151Eu 47.81 %
152Eu 13.51 y
153Eu 52.19 %
154Eu 8.59 y
155Eu 4.75 y
149Sm 13.82 %
150Sm 7.38 %
151Sm 90.00 y
152Sm 26.75 %
153Sm 1.93 d
154Sm 22.75 %
r process

Why



^{154}Gd s-only isotope: it can be produced only via s process because it is are shielded against the β-decay chains from the r-process region by the isobar samarium ^{154}Sm

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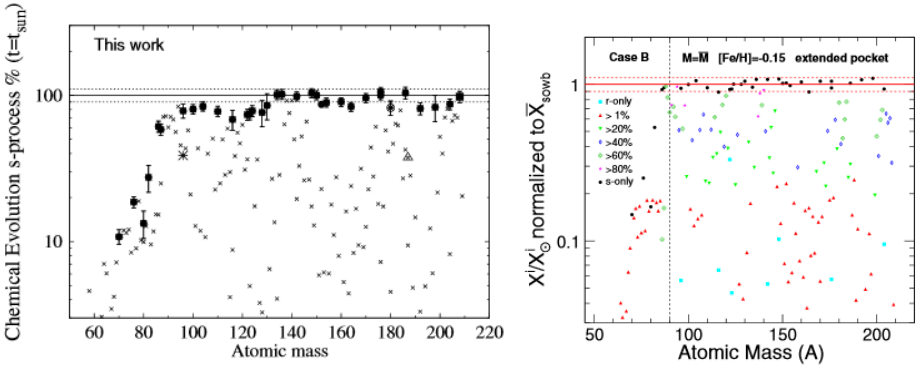
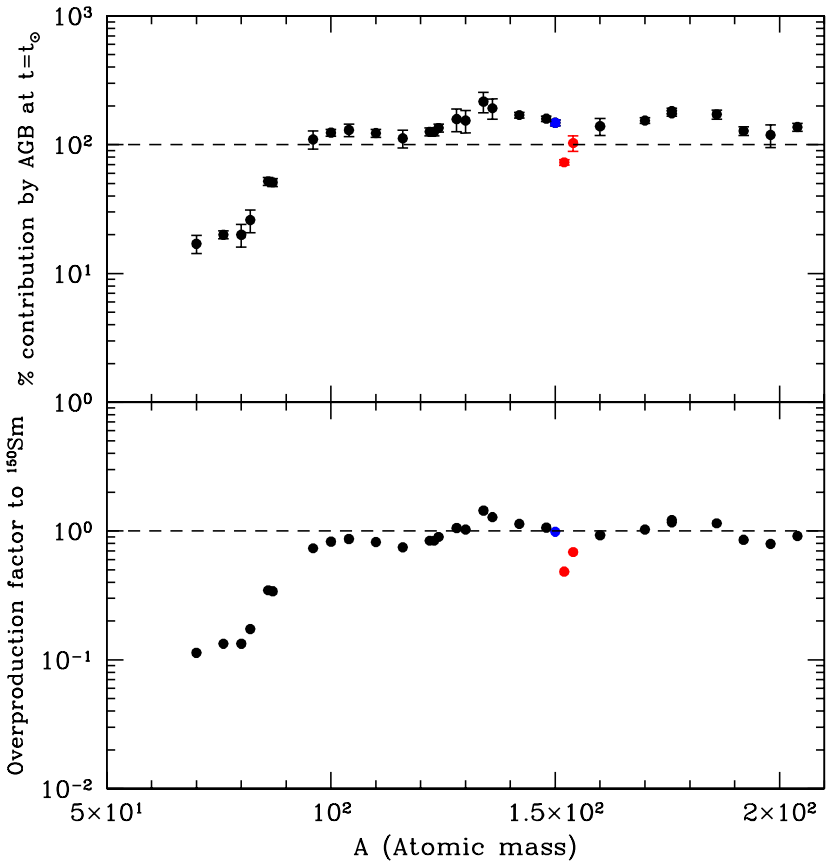
Why

3 very recent studies:





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

^{154}Gd s-only isotope: it can be produced only via s process because it is are shielded against the β-decay chains from the r-process region by the isobar samarium ^{154}Sm

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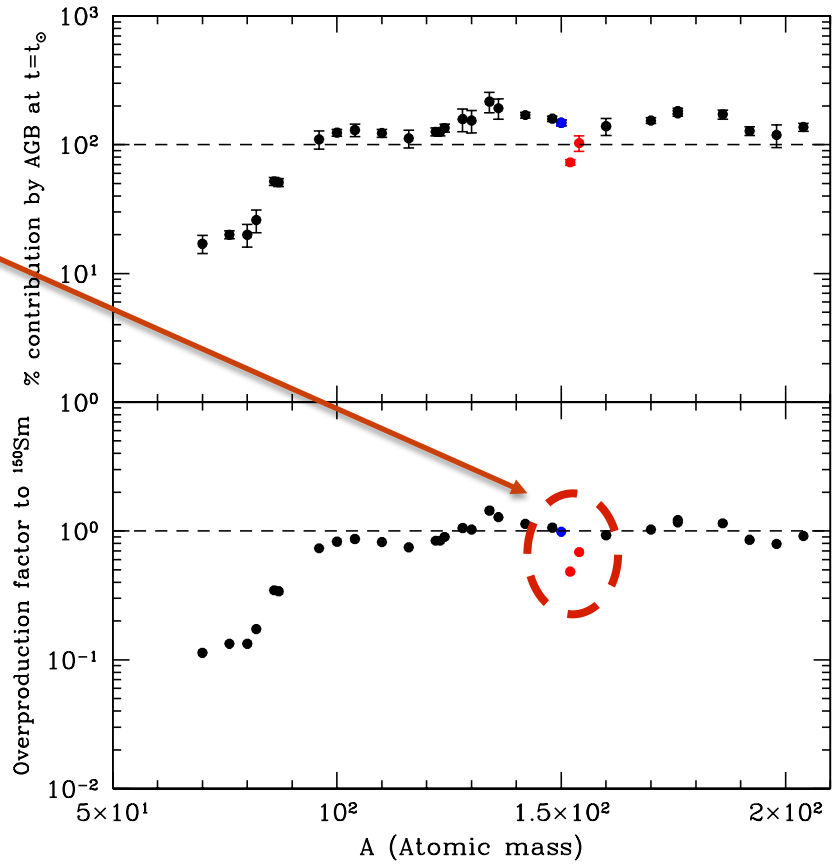
Why

3 very recent studies:

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

^{154}Gd s-only isotope: it can be produced only via s process because it is are shielded against the β-decay chains from the r-process region by the isobar samarium ^{154}Sm

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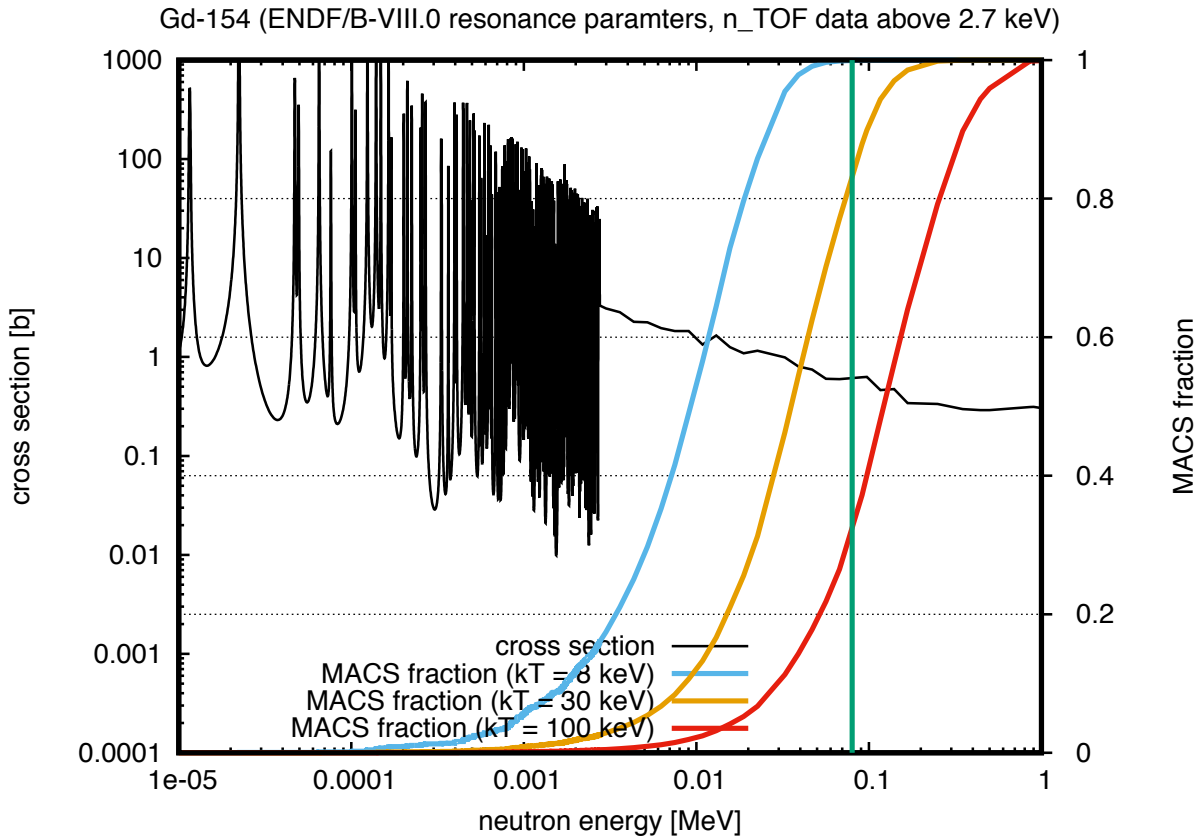
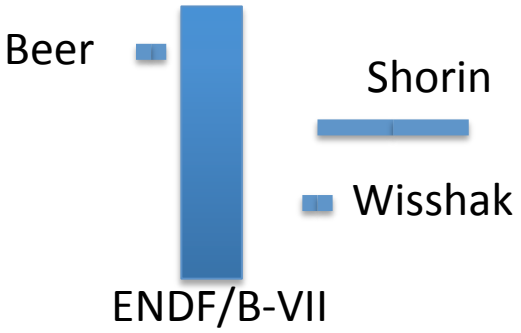
Why



Author / library	MACS @ 30 keV (mb)
ENDF/B-VII (2011)	953.3 +/- 37.0
JENDL-4.0 (2010)	992
JEFF-3.1 (2005)	862
Wisshak (1995)	**1028 +/- 12 → 1088**
Beer (1988)	**878 +/- 27**
Shorin (1974)	**1278 +/- 102 →1184**



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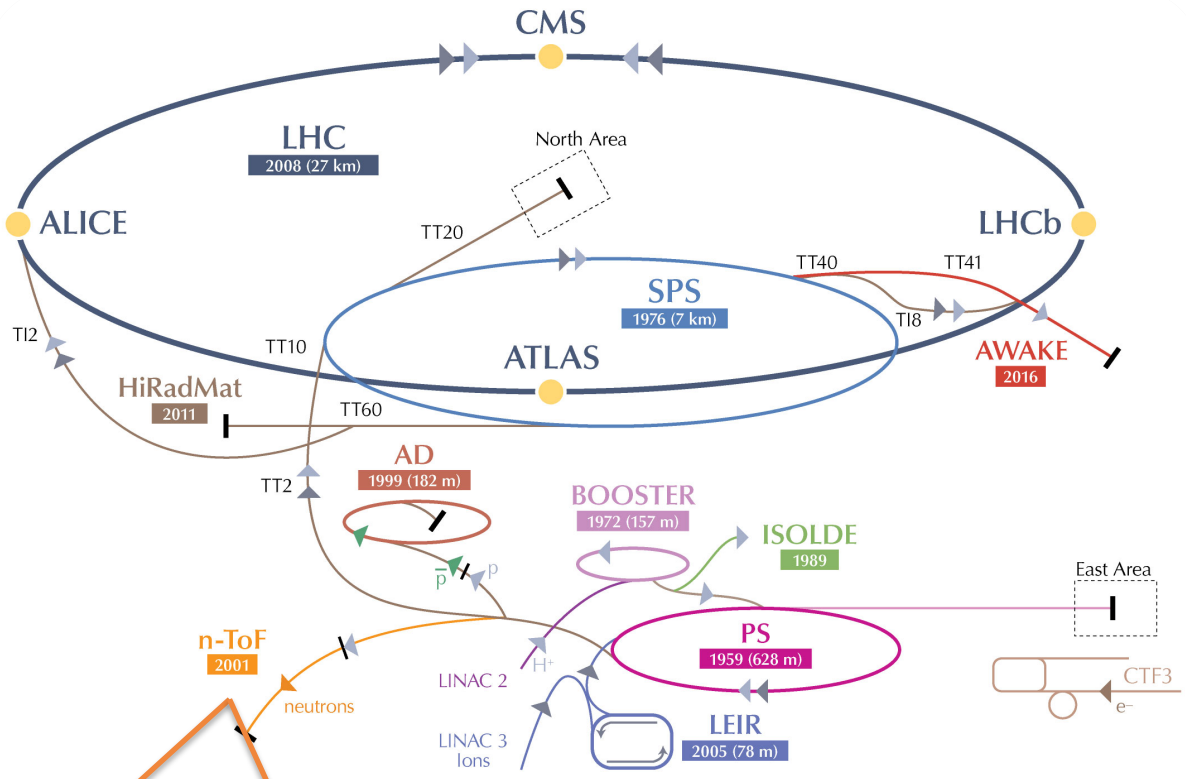
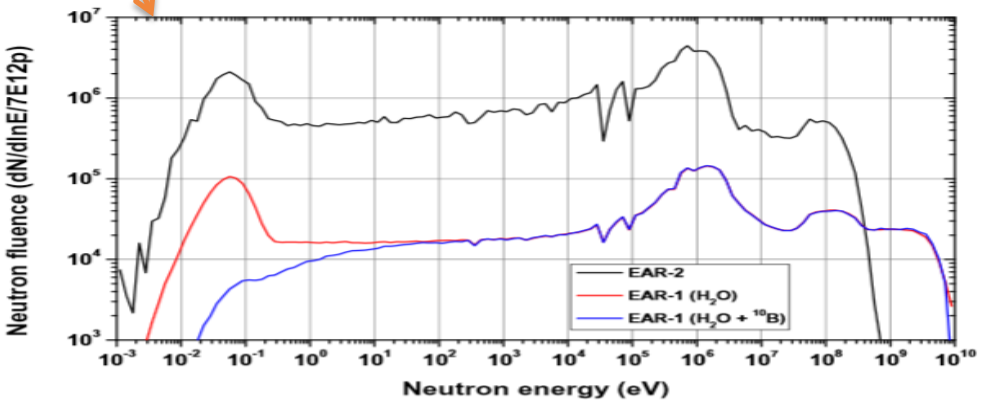
How, where, when



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



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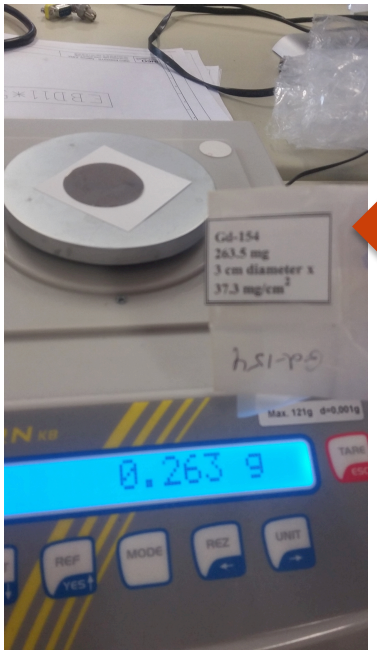
How, where, when



ORNL

0.263 g - 1.414E-4 a/b

metal disc

^{154}Gd ~ 66,78 %

main contaminant ^{155}Gd

~ 17.52%

Radius = 1.5 cm

GOODFELLOW

8.749 g

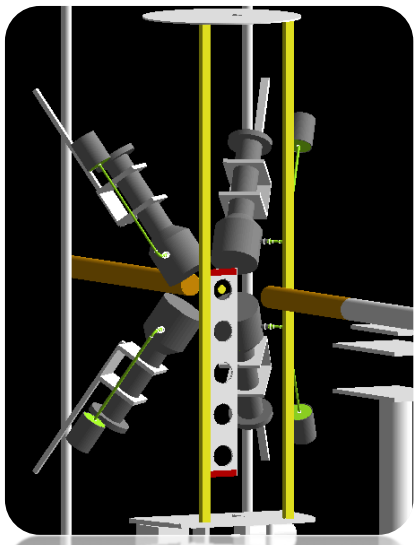
Natural Gd

99%

Measurement

14th August **2017**

10th September 2017

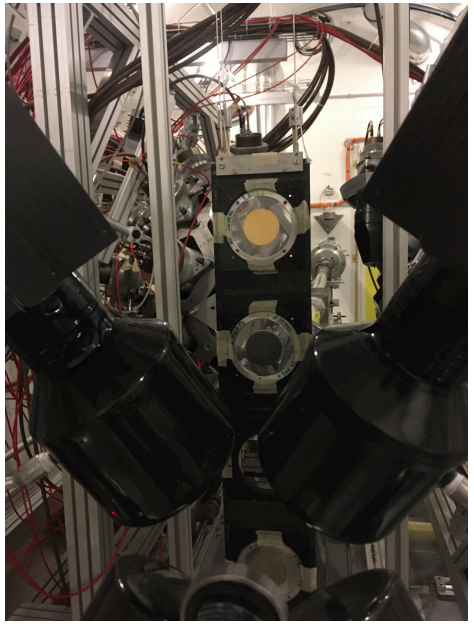


@ EAR1 (FP=184 m)

Total detection energy system:

- PHWT
- 4 C_6D_6 from LNL-INFN

Normalization and Background:
Au, Pb, Gd with FILTERS



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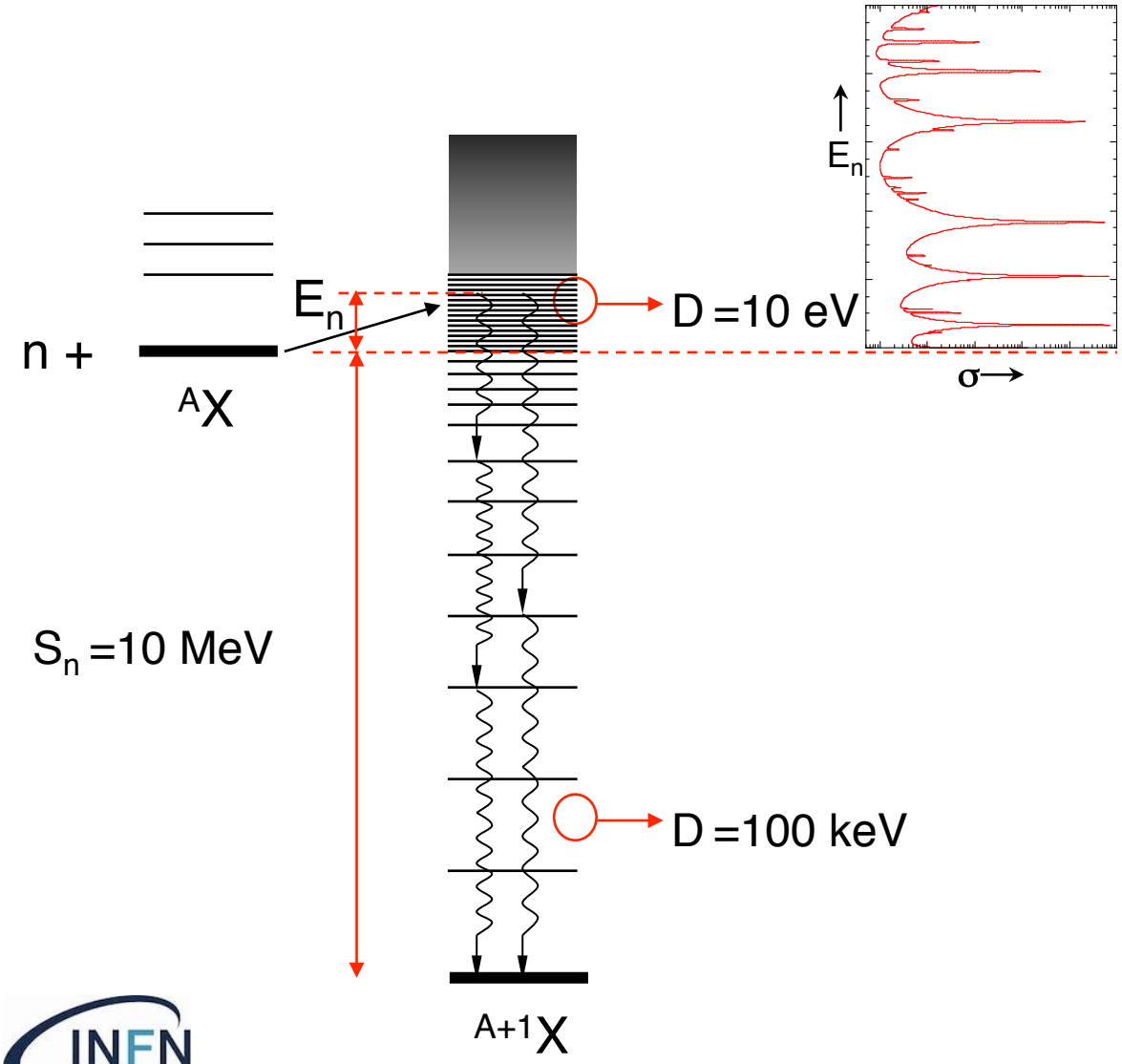
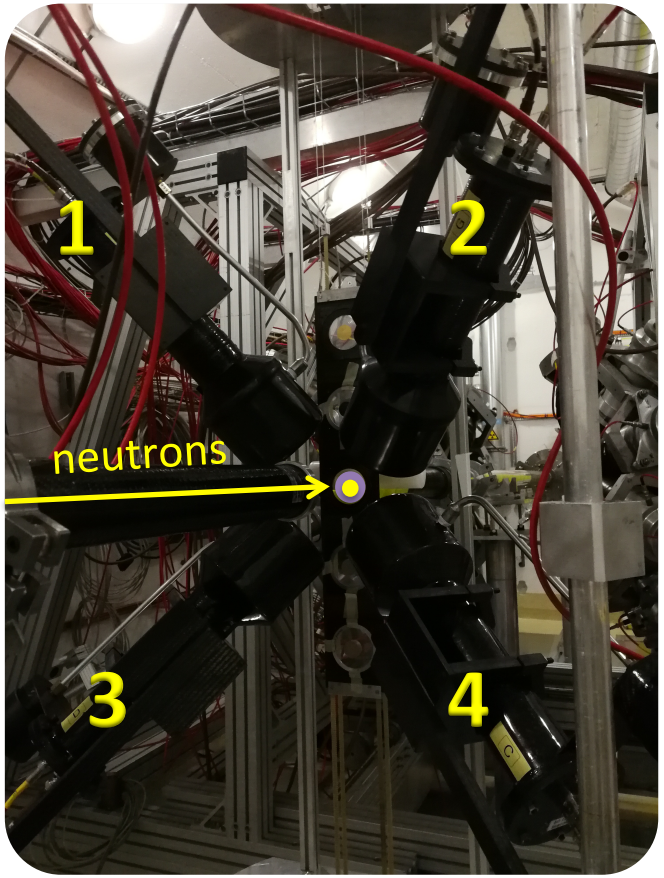
How, where, when





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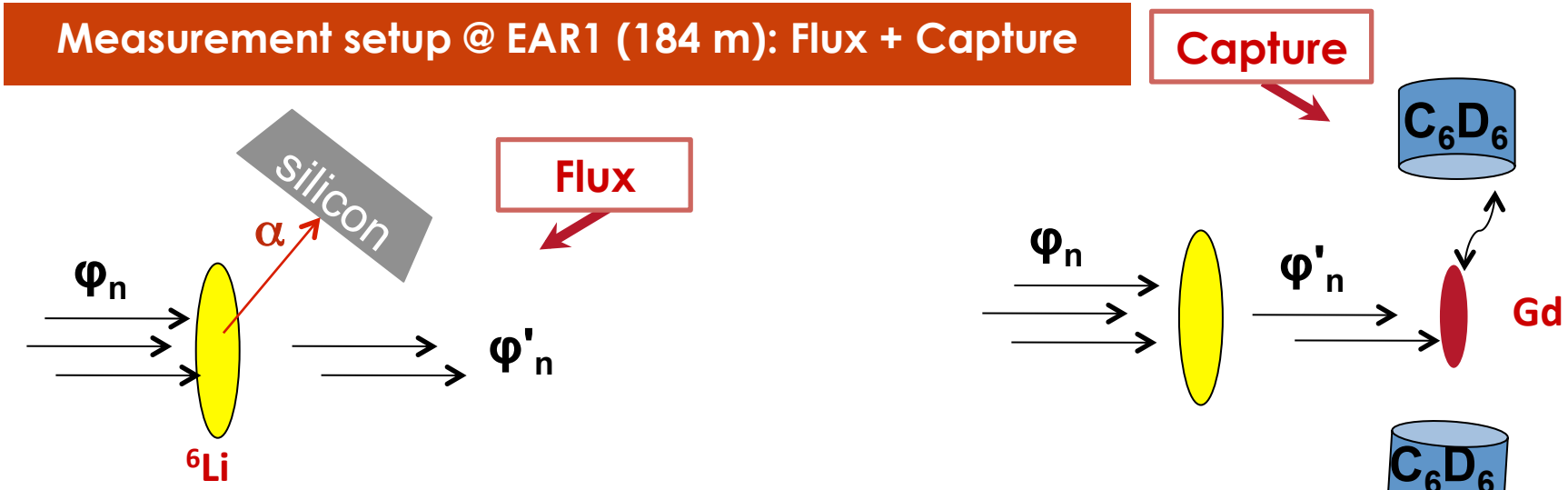
How, where, when

Measurement setup @ EAR1 (184 m): Flux + Capture



$$Y_n = \frac{C_n}{\varepsilon_n \Omega_n A_n \varphi_n}$$

$$Y_n = (1 - e^{-n\sigma_{tot}}) \frac{\sigma_\alpha}{\sigma_{tot}}$$

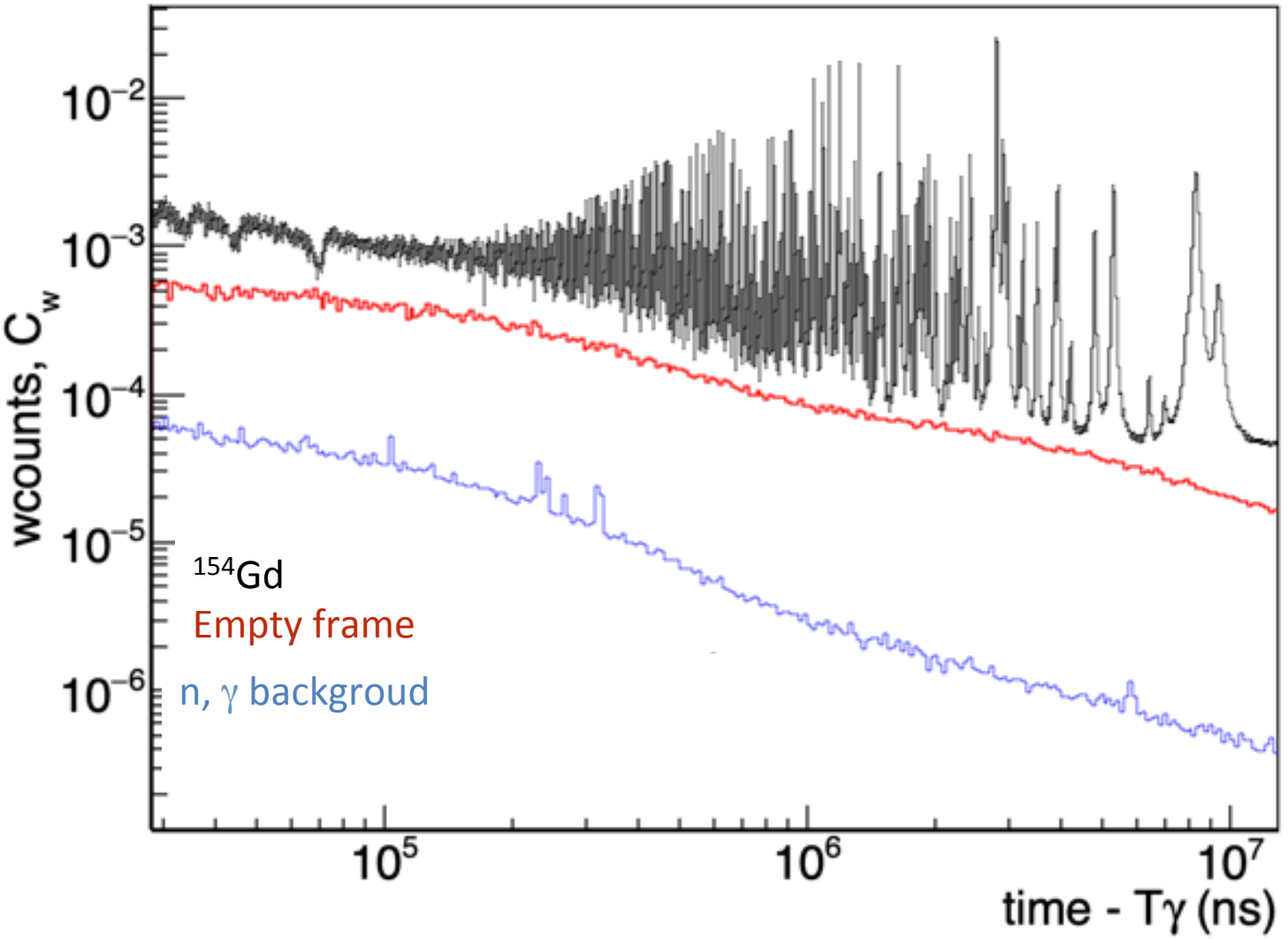
$$\varphi_n = \frac{C_n}{\varepsilon_n \Omega_n A_n Y_n}$$

$$Y_C = \frac{\varepsilon_n \Omega_n A_n}{\varepsilon_C \Omega_C A_C} \times \frac{C_W}{C_n} \times \frac{(1 - e^{-n\sigma_{tot}}) \frac{\sigma_\alpha}{\sigma_{tot}}}{e^{-n\sigma_{tot}}}$$

$$Y_C = N \times \frac{C_W}{C_n} \times \frac{Y_n}{e^{-n\sigma_{tot}}}$$

Data reduction

Background



Background = RED+BLUE curve

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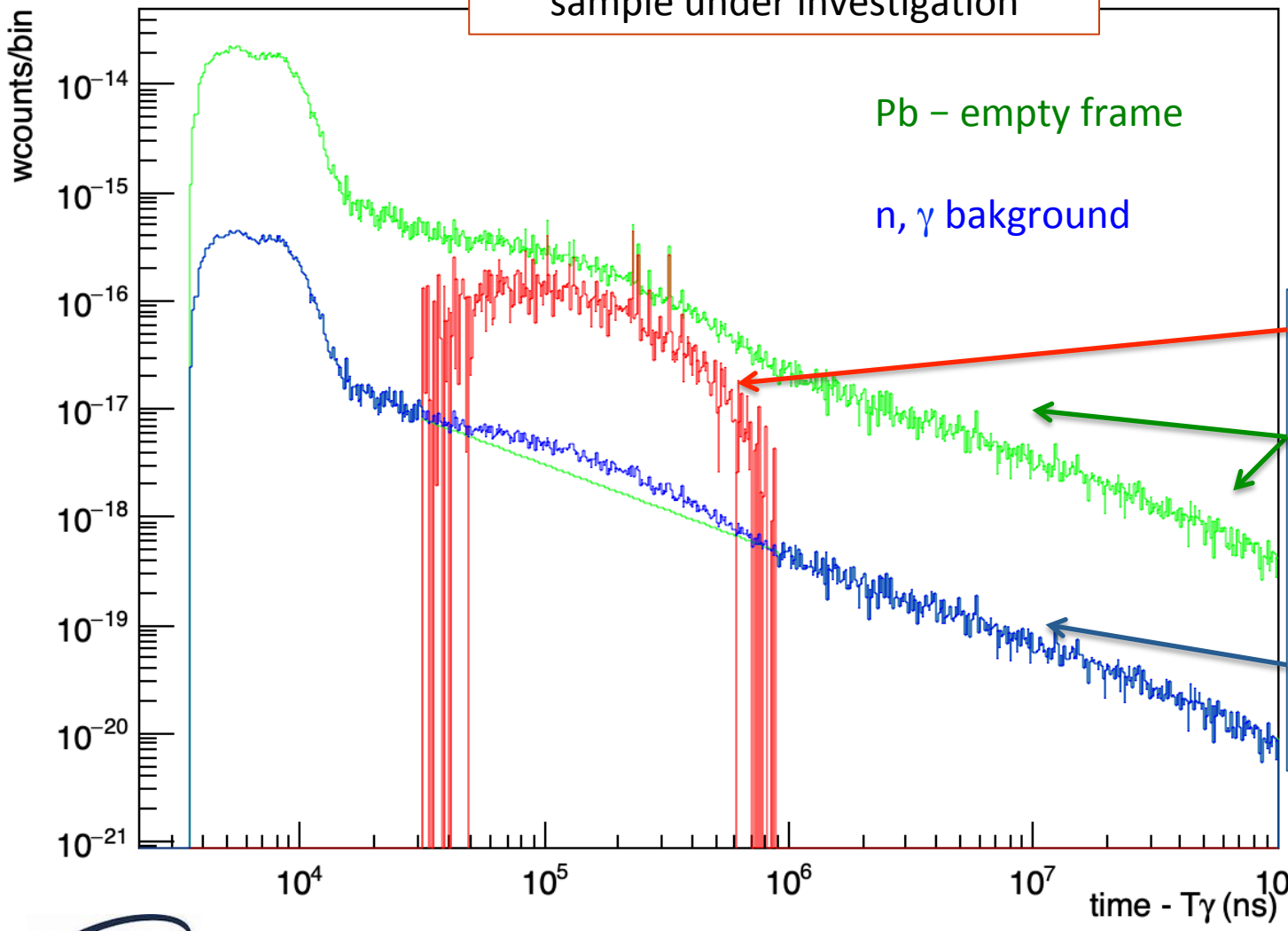
Data reduction

Background

In-beam γ-rays scaled to z of the sample under investigation



In-beam γ-rays

Sample-scattered neutrons

Total background (scaled to sample features)

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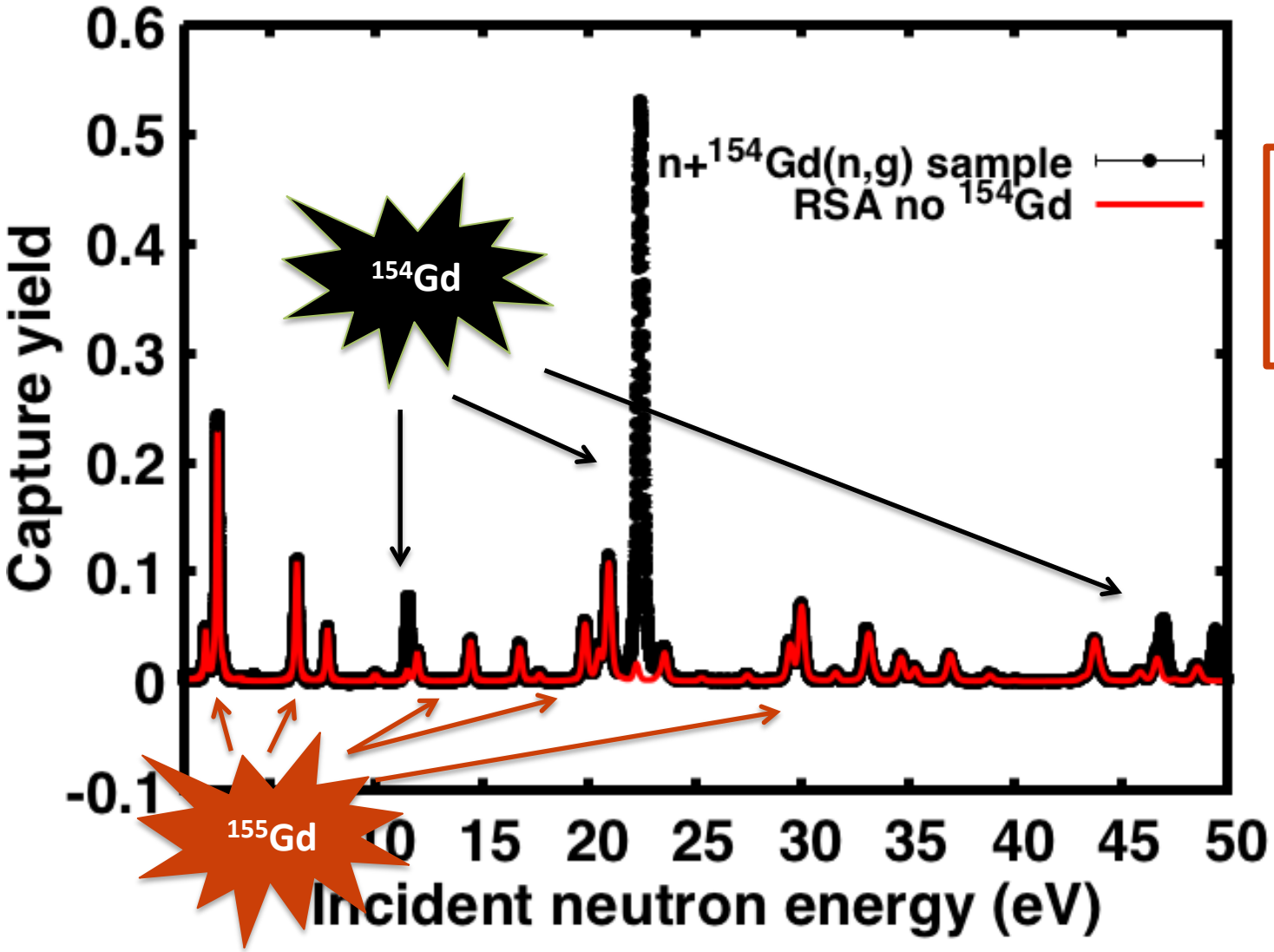
Data reduction

normalization



Most of the structures are due to contaminants

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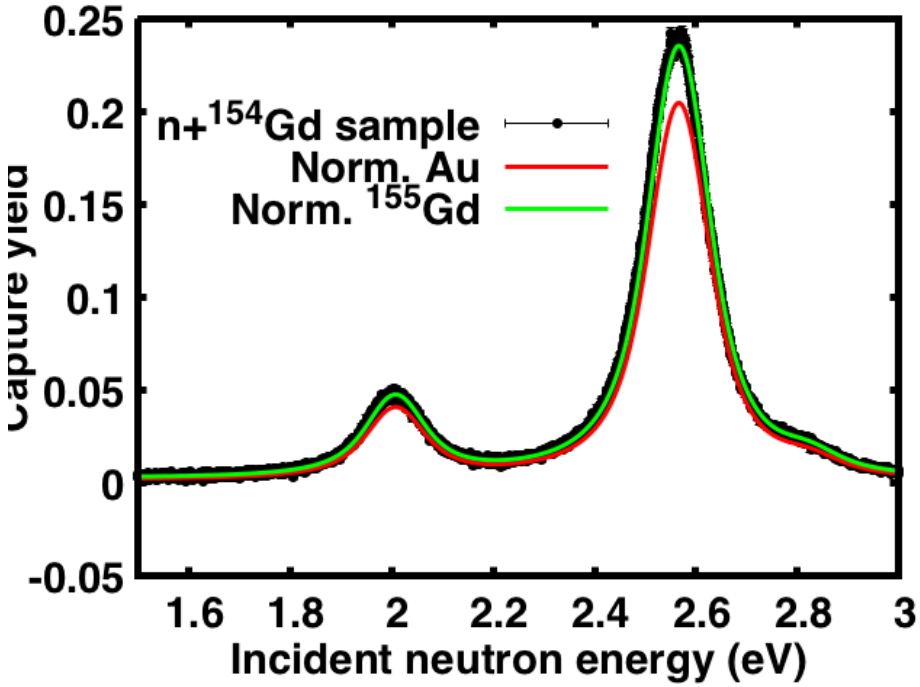
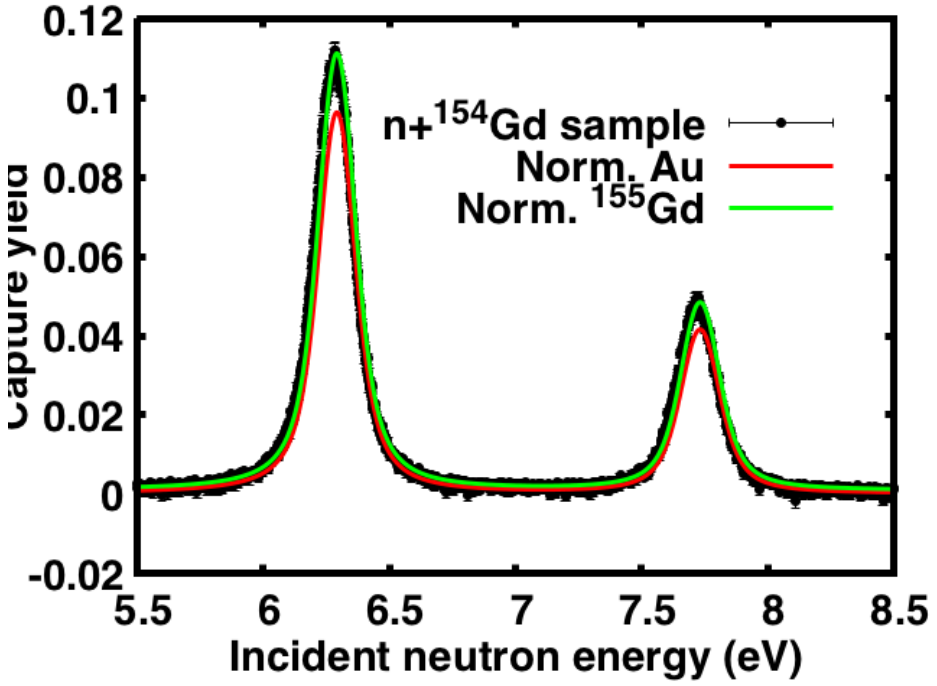
Data reduction



Normalization



method	Normalization
Au	0.865
^{155}Gd (17.5%) in ^{154}Gd sample	0.95-0.97
^{155}Gd (**20.2%**) in ^{154}Gd sample	0.865

- Different WFs
- Different discrimination levels
- Different upper cuts
- Normalization (SiMom, protons)

Were checked… what else?

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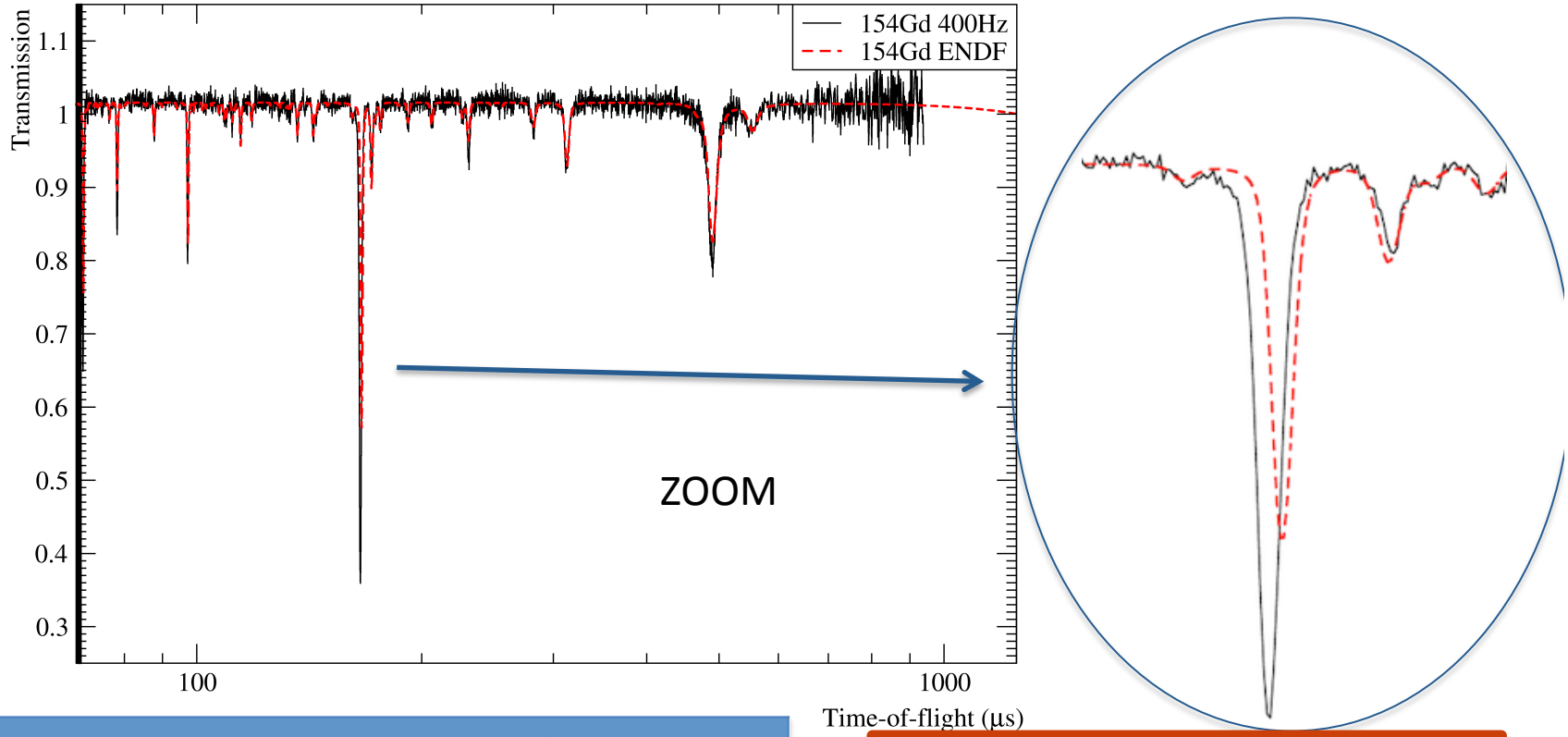
Study of the sample

Transmission at GELINA



method	Normalization
Au	0.865
^{155}Gd (17.5%) in ^{154}Gd sample	0.95-0.97
^{155}Gd (**20.2%**) in ^{154}Gd sample	0.865

TRANSMISSION:

- **N = 0.89±0.04**
- ^{155}Gd (**20.1%**) in ^{154}Gd sample

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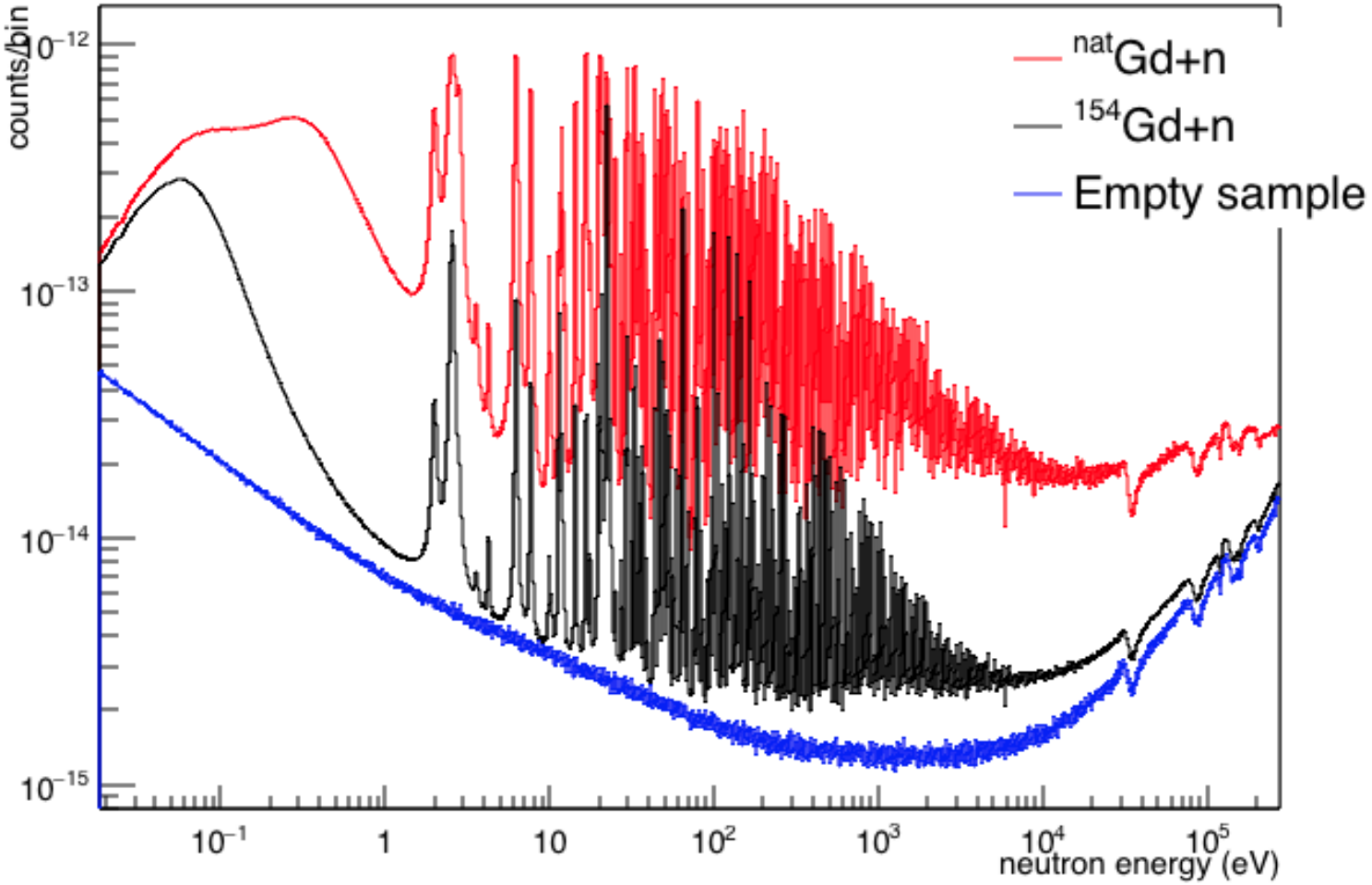
Resonance analysis

RRR



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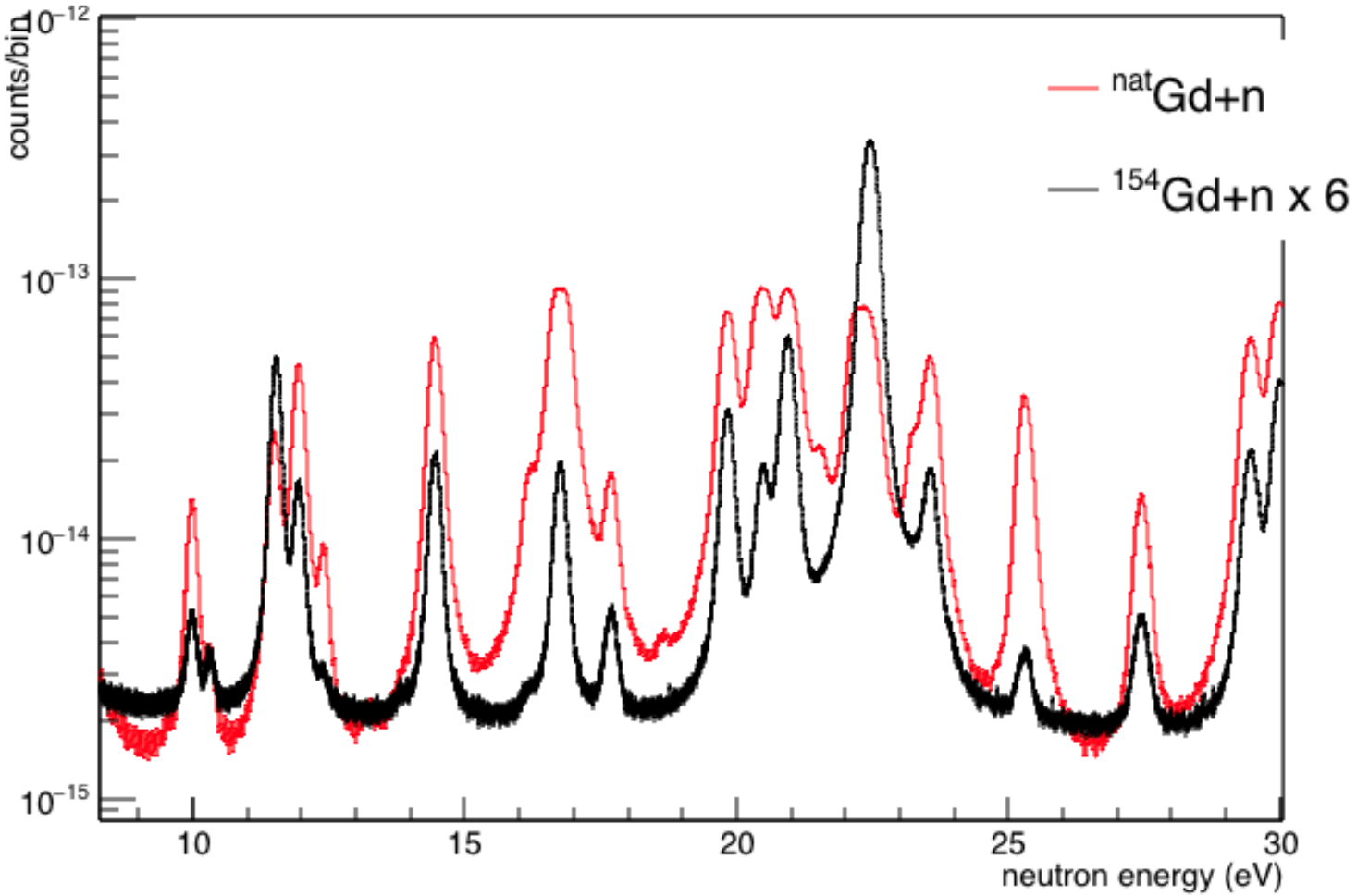
Resonance analysis

RRR



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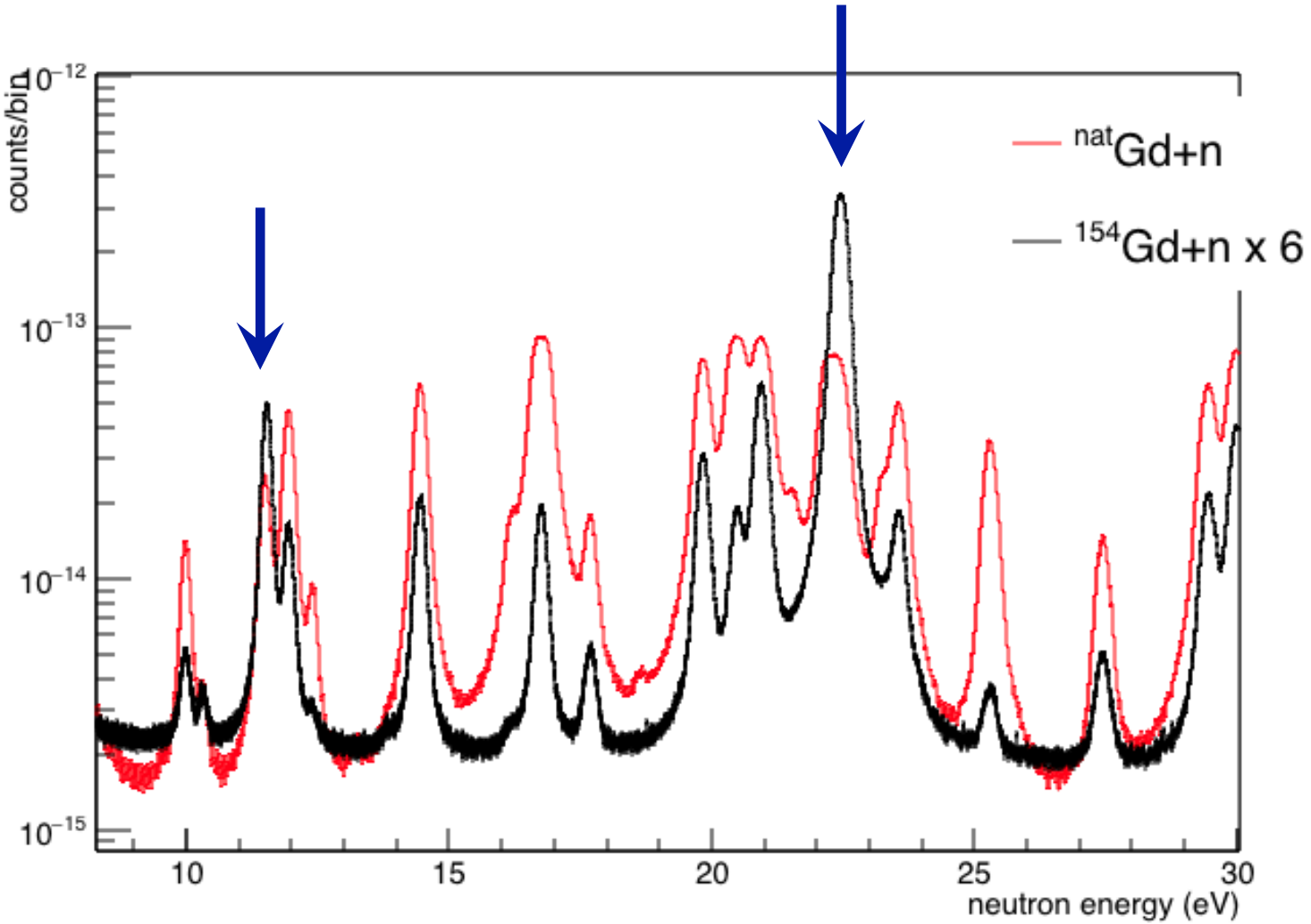
Resonance analysis

RRR



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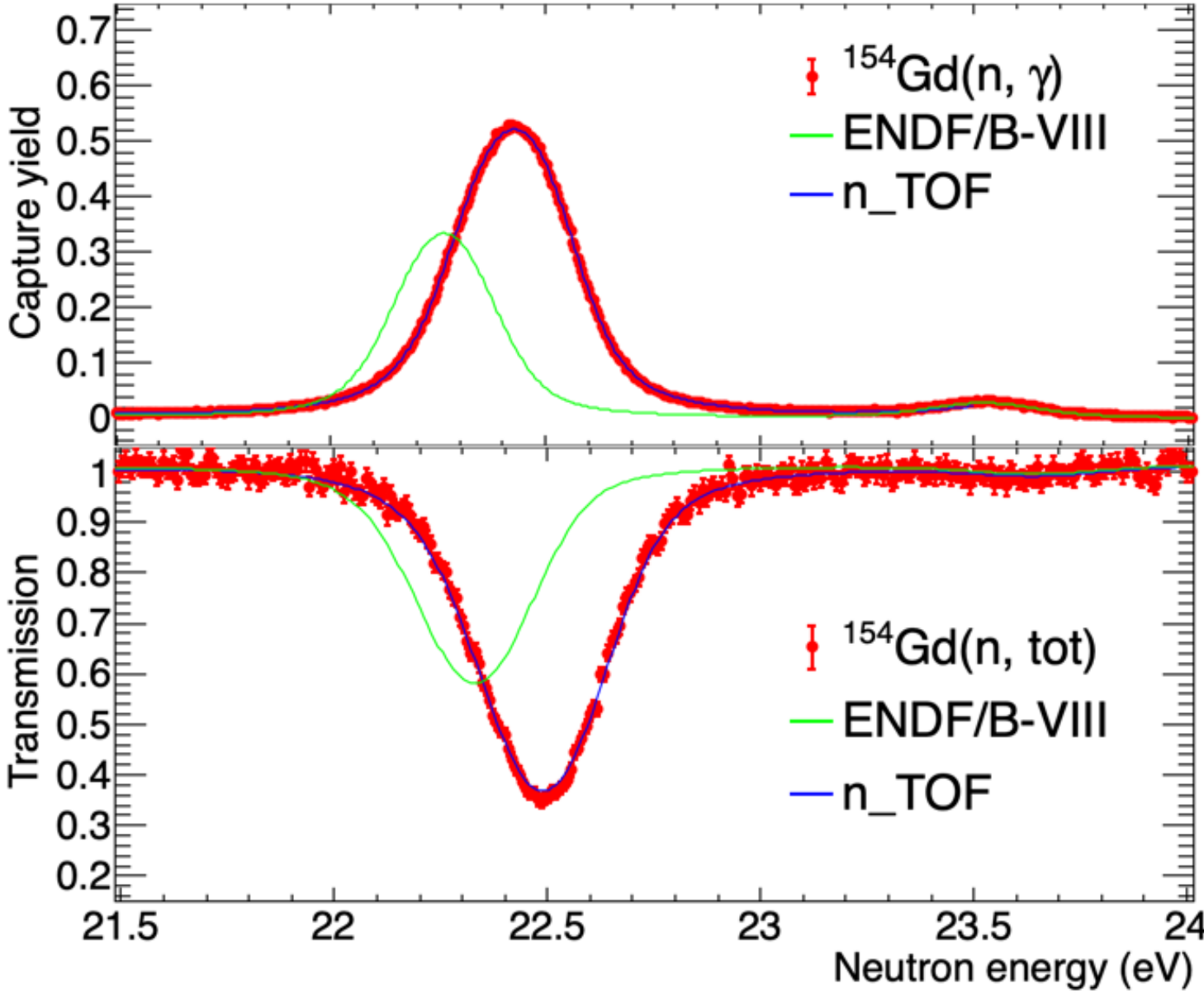
Resonance analysis

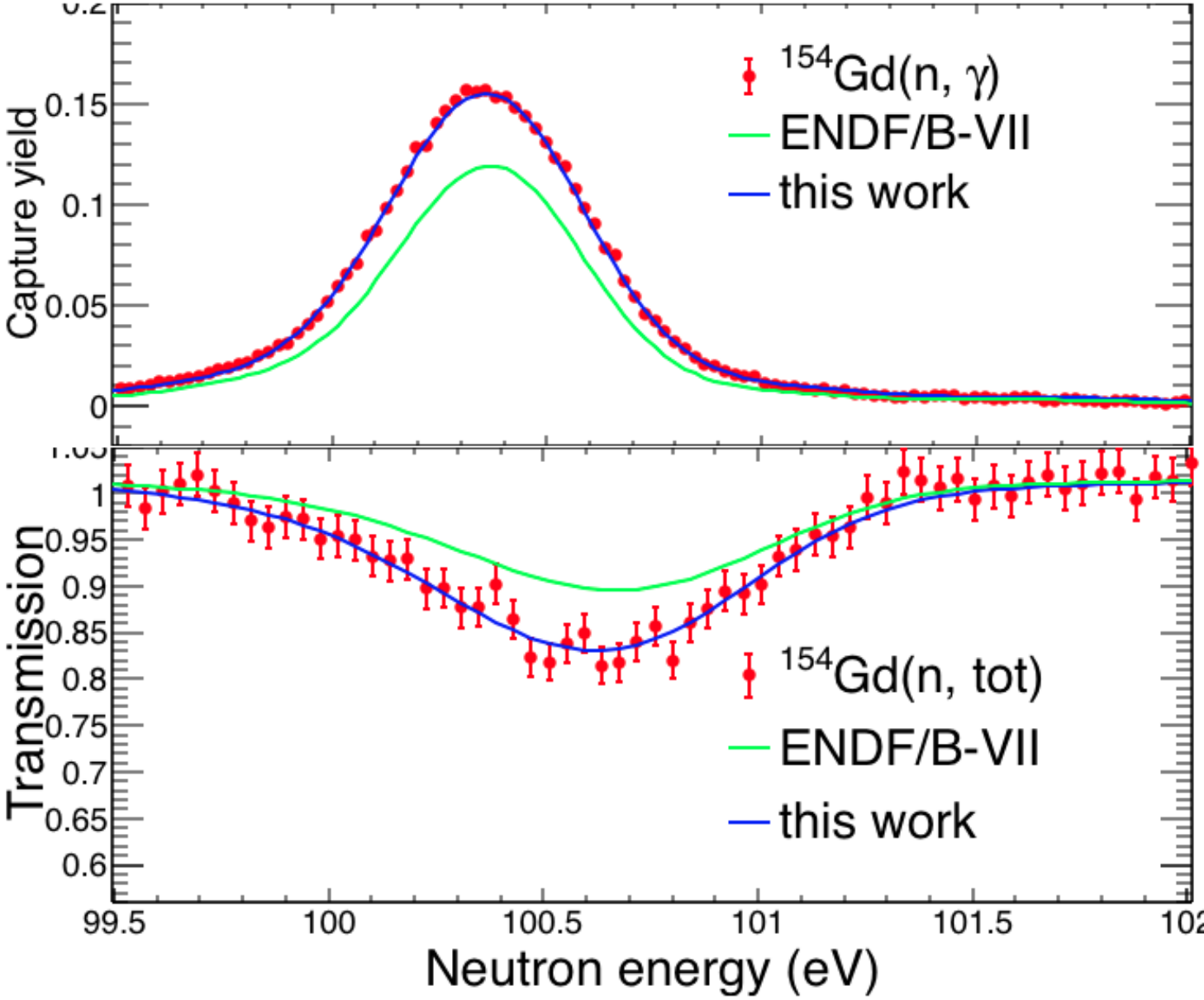
^{154}Gd(n,γ)



165 (3 new) resonances up to 2.7 keV

Resonance analysis

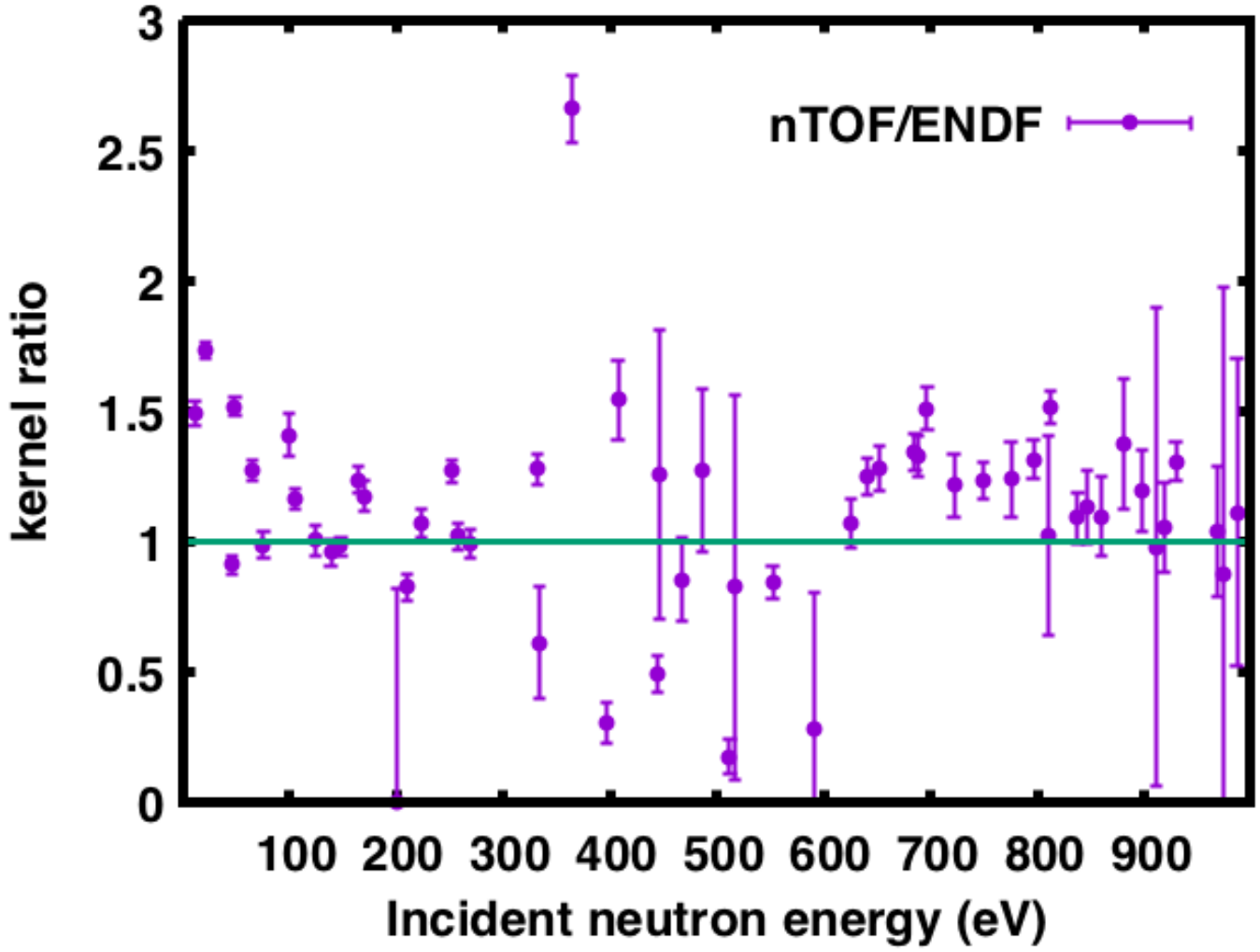
^{154}Gd(n,γ)



165 (3 new) resonances up to 2.7 keV

Resonance analysis

$^{154}Gd(n,\gamma)$



165 (3 new) resonances up to 2.7 keV

Sizable differences

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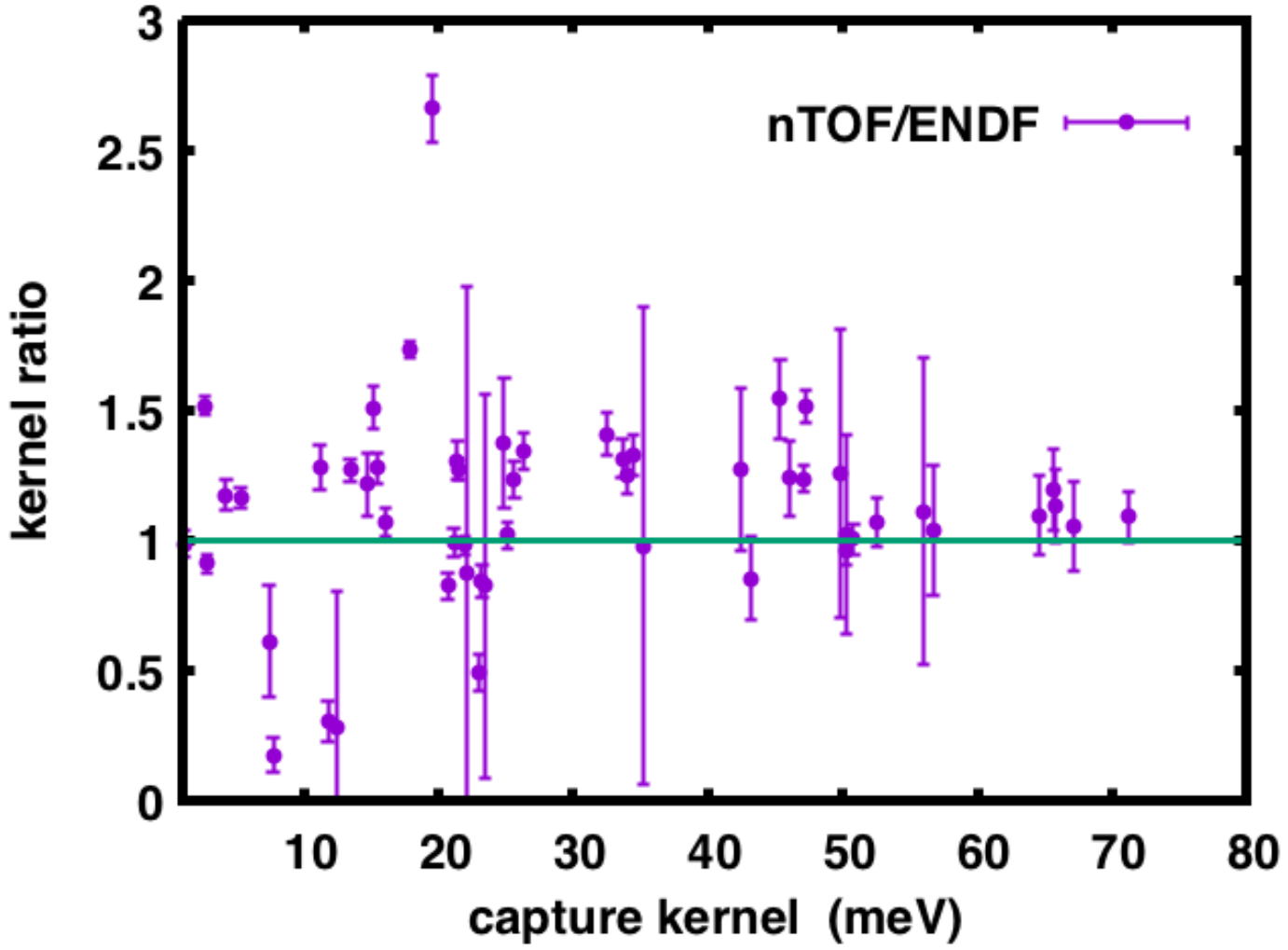
Resonance analysis

^{154}Gd(n,γ)



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Sizable differences

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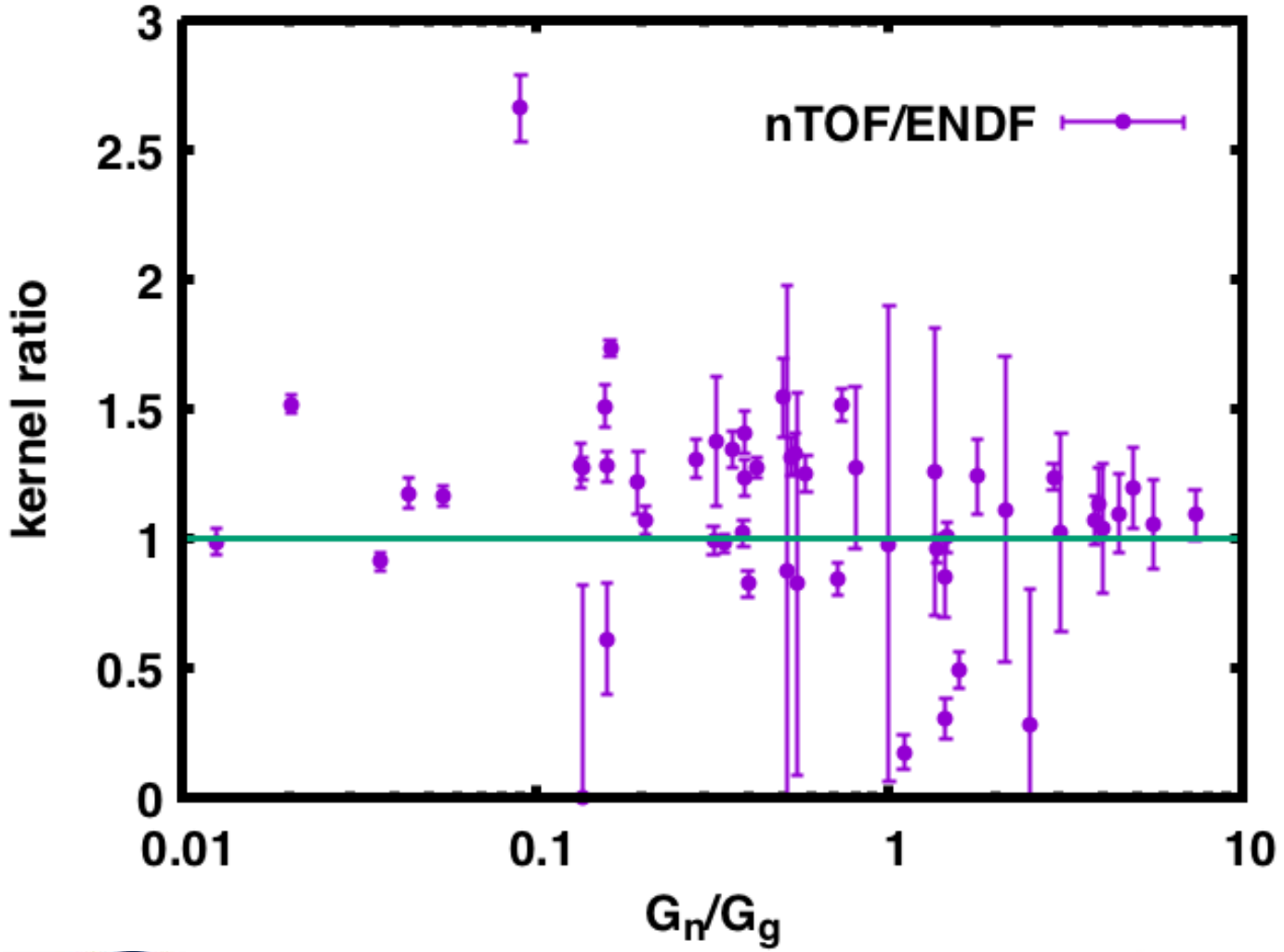
Resonance analysis

^{154}Gd(n,γ)



165 (3 new) resonances up to 2.7 keV

Sizable differences

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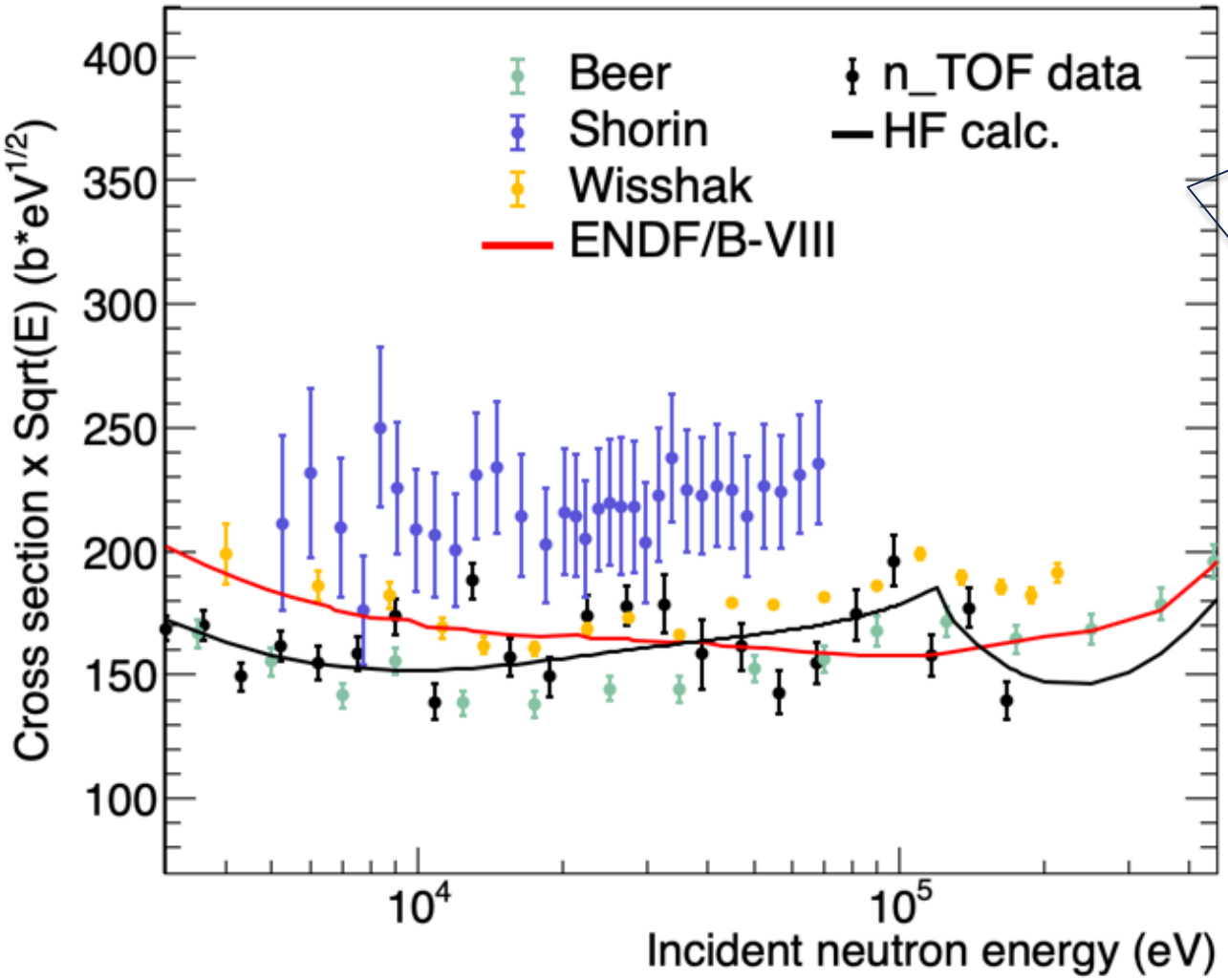
Analysis

$^{154}Gd(n,\gamma)$

URR



Correction for multiple scattering

Capture yield

$$\sigma_\gamma = f_{MS} \times Y / n$$

Sample area density

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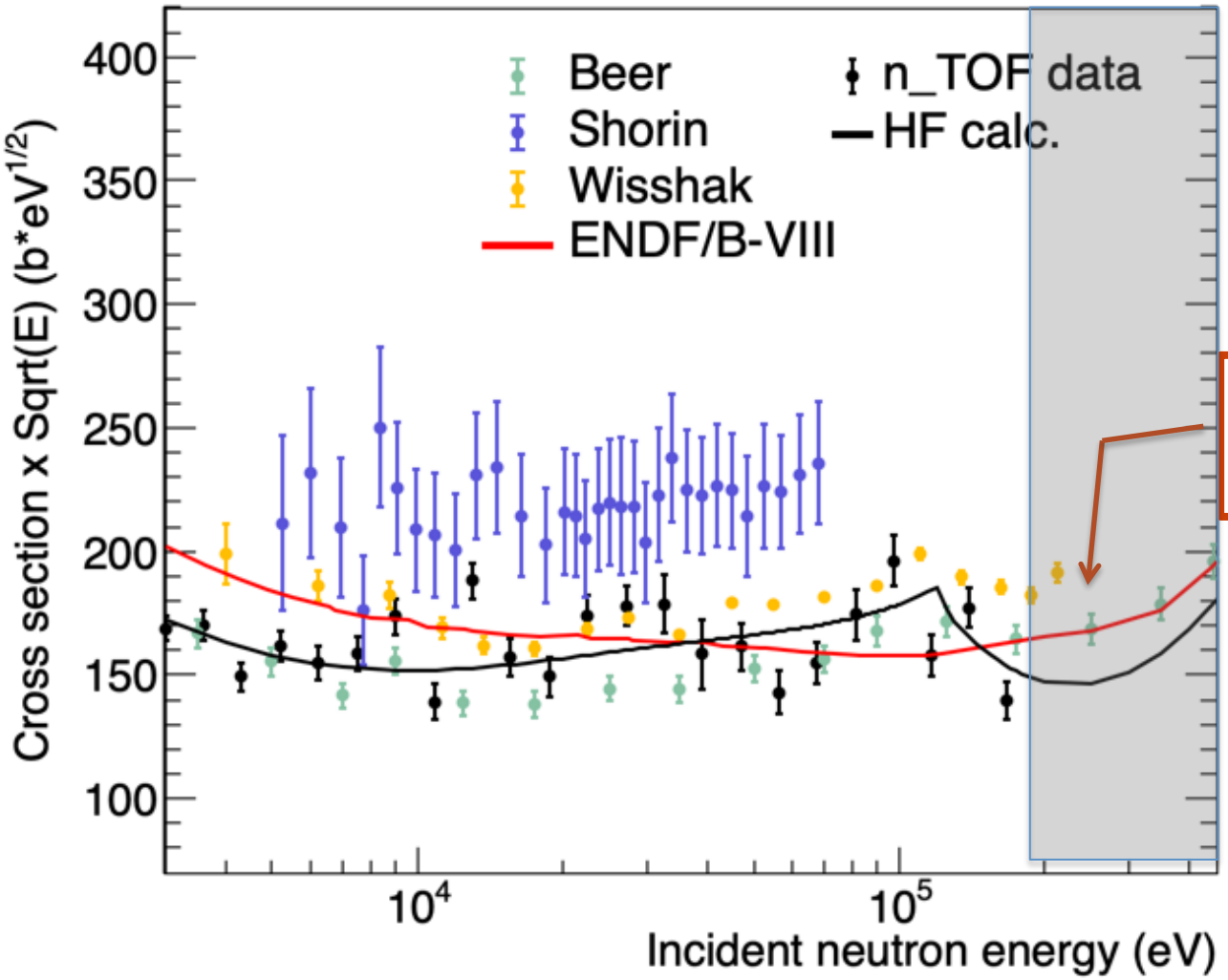
Analysis

$^{154}Gd(n,\gamma)$



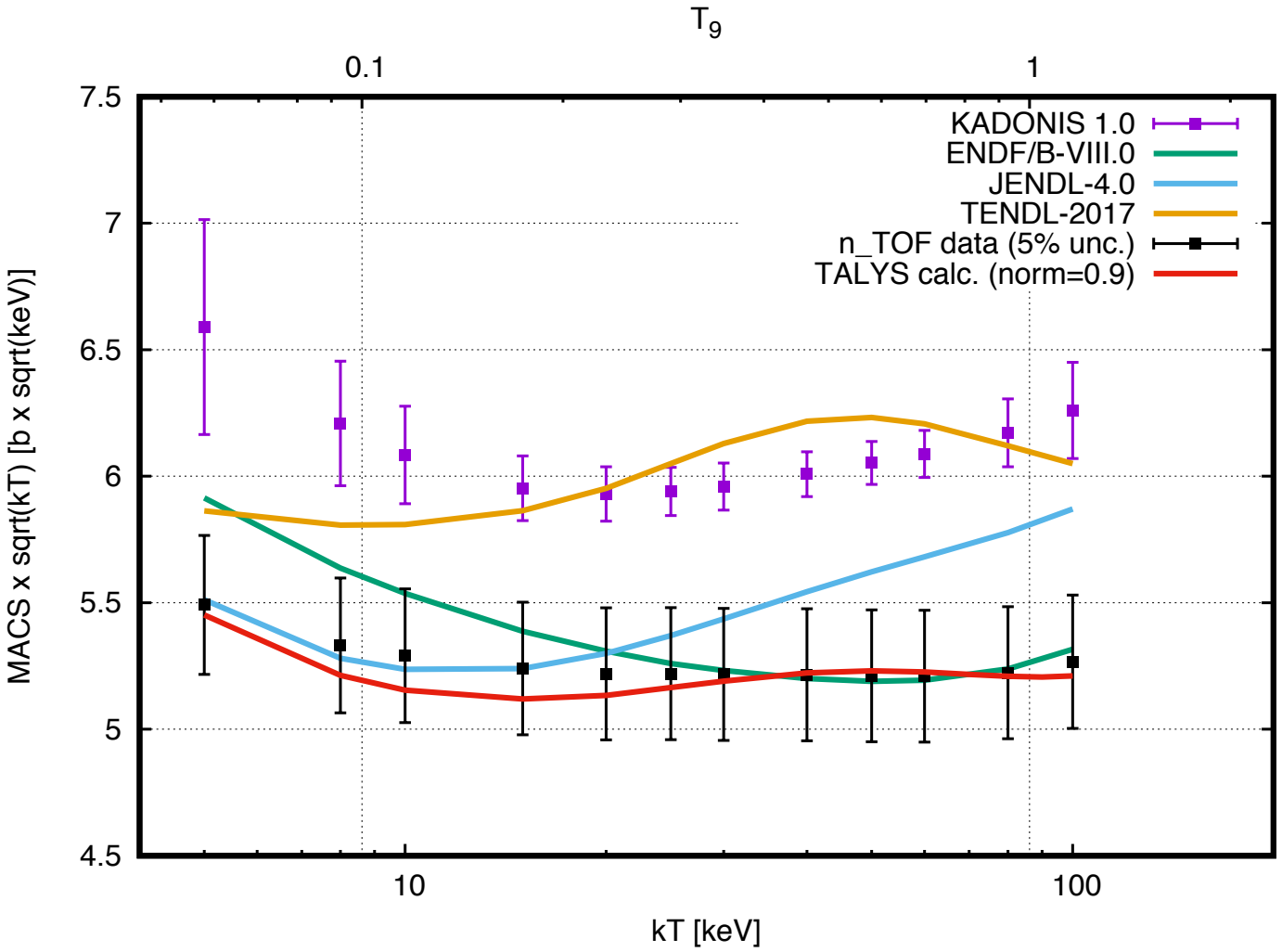
Hauser-Feshback calculation to extrapolate at $\mathbf{E_n > 200\ keV}$

$$\langle \sigma_c \rangle = \frac{\pi g_c}{k_c^2} (1 - \mathrm{Re} \langle S_{cc} \rangle)$$

Calculation based on average resonance parameters: Γ_γ, D_0, s_0

Analysis

MACS
Maxwellian Averaged Cross Section



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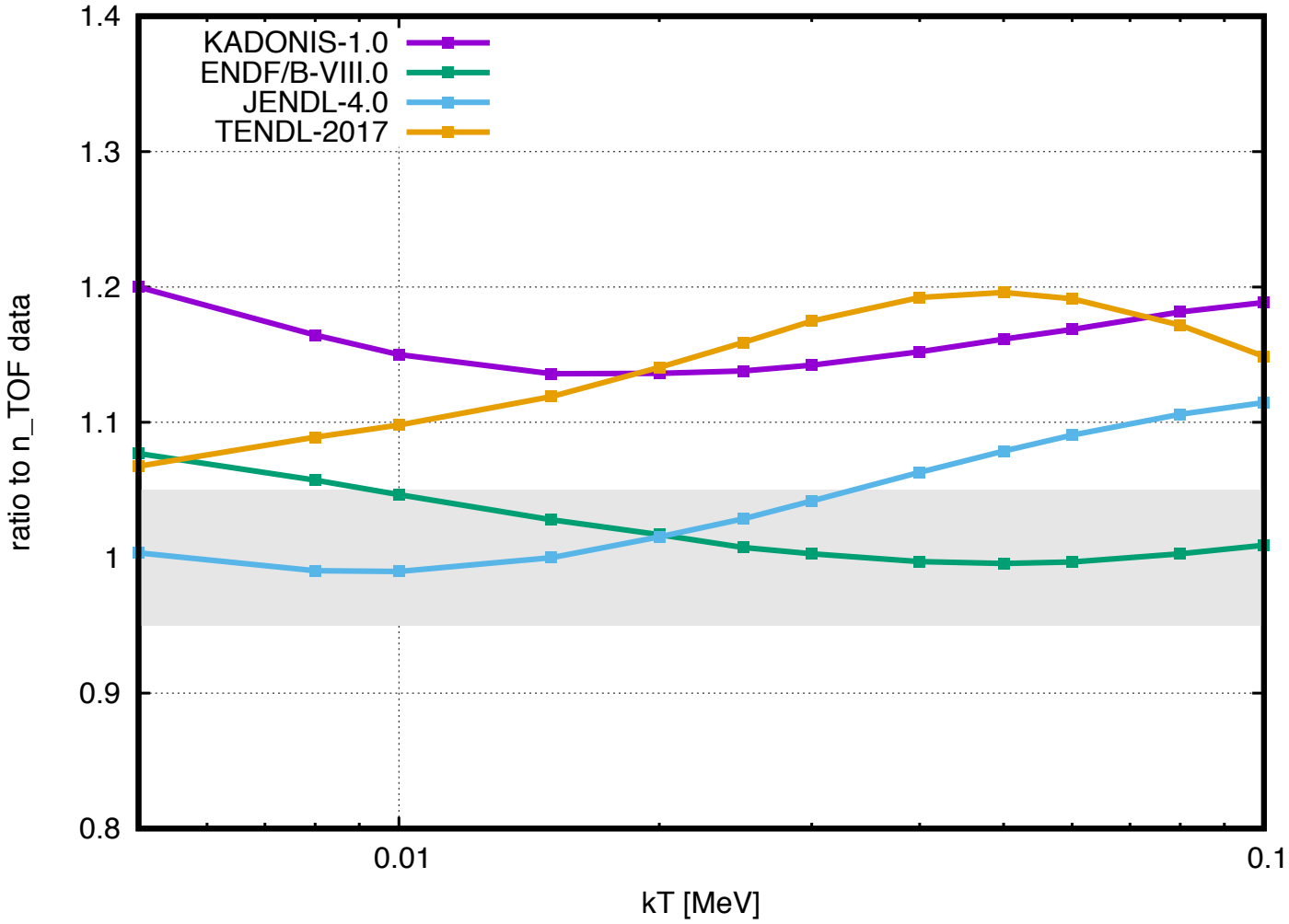
Analysis

MACS
Maxwellian Averaged Cross Section



Results & conclusions

- **n+^{154}Gd → ^{155}Gd + γ** studied at n_TOF from ~1 eV to 200 keV + extrapolation at higher energy with HFSM
- Crucial/auxiliary **Transmission** experiment at GELINA
- **MACS** (uncertainty ~7%) in the region of interest to s process is **10-20% lower** than **KADoNiS**
- **Preliminary** model calculation: impact on s-only ^{154}Gd isotope: its s-process nucleosynthesis is **enhanced** ~ 6%

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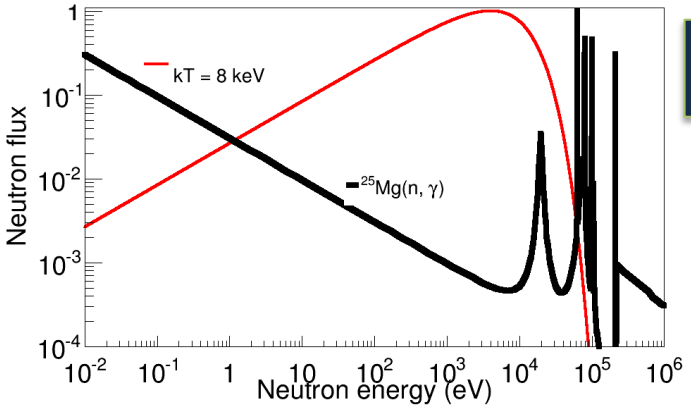
Cristian Massimi

Department of Physics and Astronomy

cristian.massimi@unibo.it

www.unibo.it

MACS



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

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

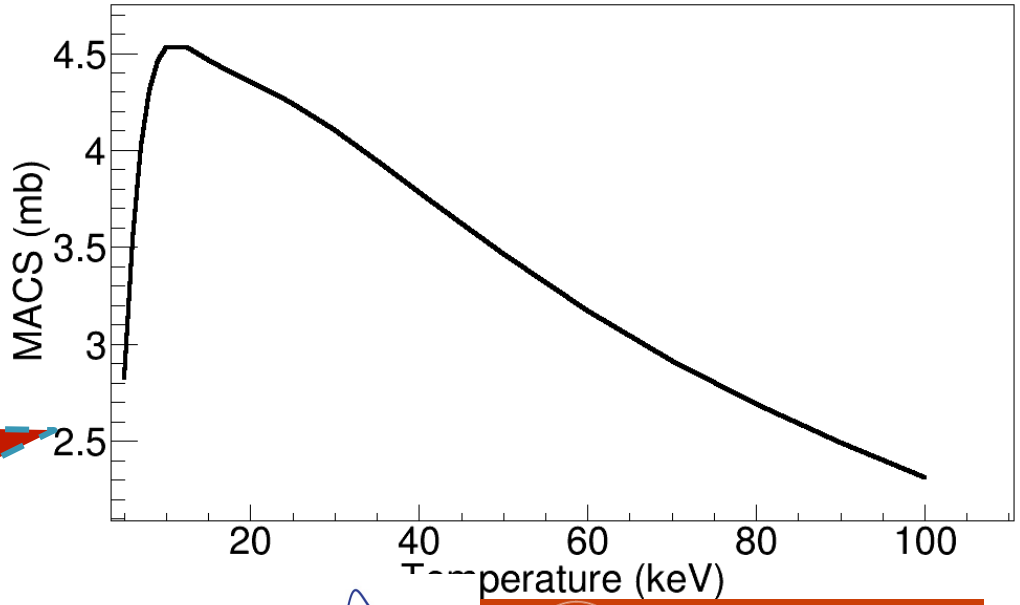
$$\rightarrow r = N_A N_n \langle \sigma \cdot v \rangle$$

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

Two methods are used to determine MACS:

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

n_TOF@ CERN



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Literature RRR

Isotope	Facility	Energy	Enrichment	Capture Detector	Transmission?
^{152}Gd	ORELA DUBNA	< 2.6 keV < 235 eV	32% 36%	C_6F_6 NaI	yes yes
^{154}Gd	Nevis Lab ORELA DUBNA	< 1 keV < 2.6 keV < 224 eV	66 %	C_6F_6 NaI	yes yes
^{158}Gd	Nevis Lab DUBNA	< 10 keV < 2.4 keV		NaI	yes

Experiment

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

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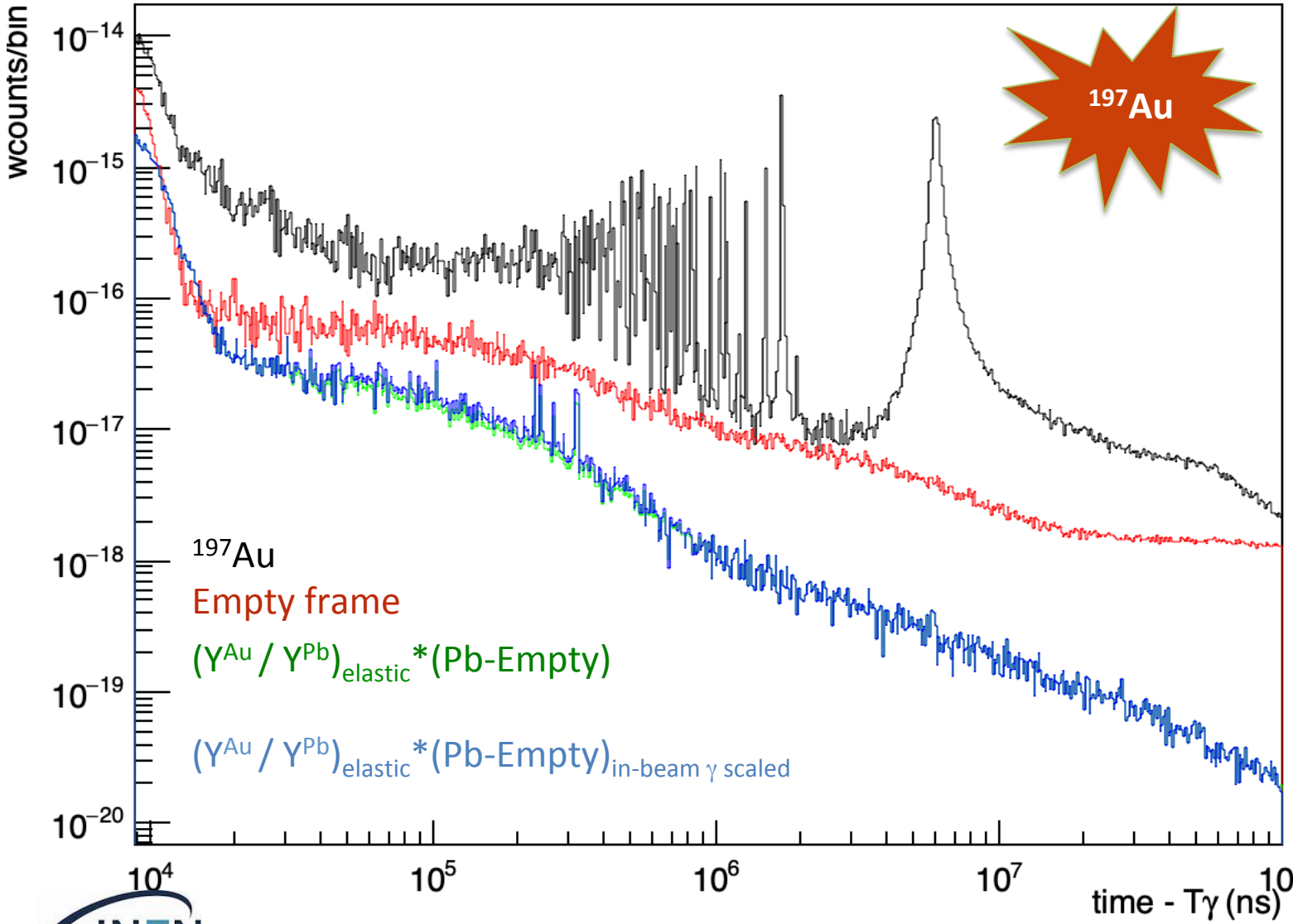
Data reduction

Background



Background = RED+BLUE curve

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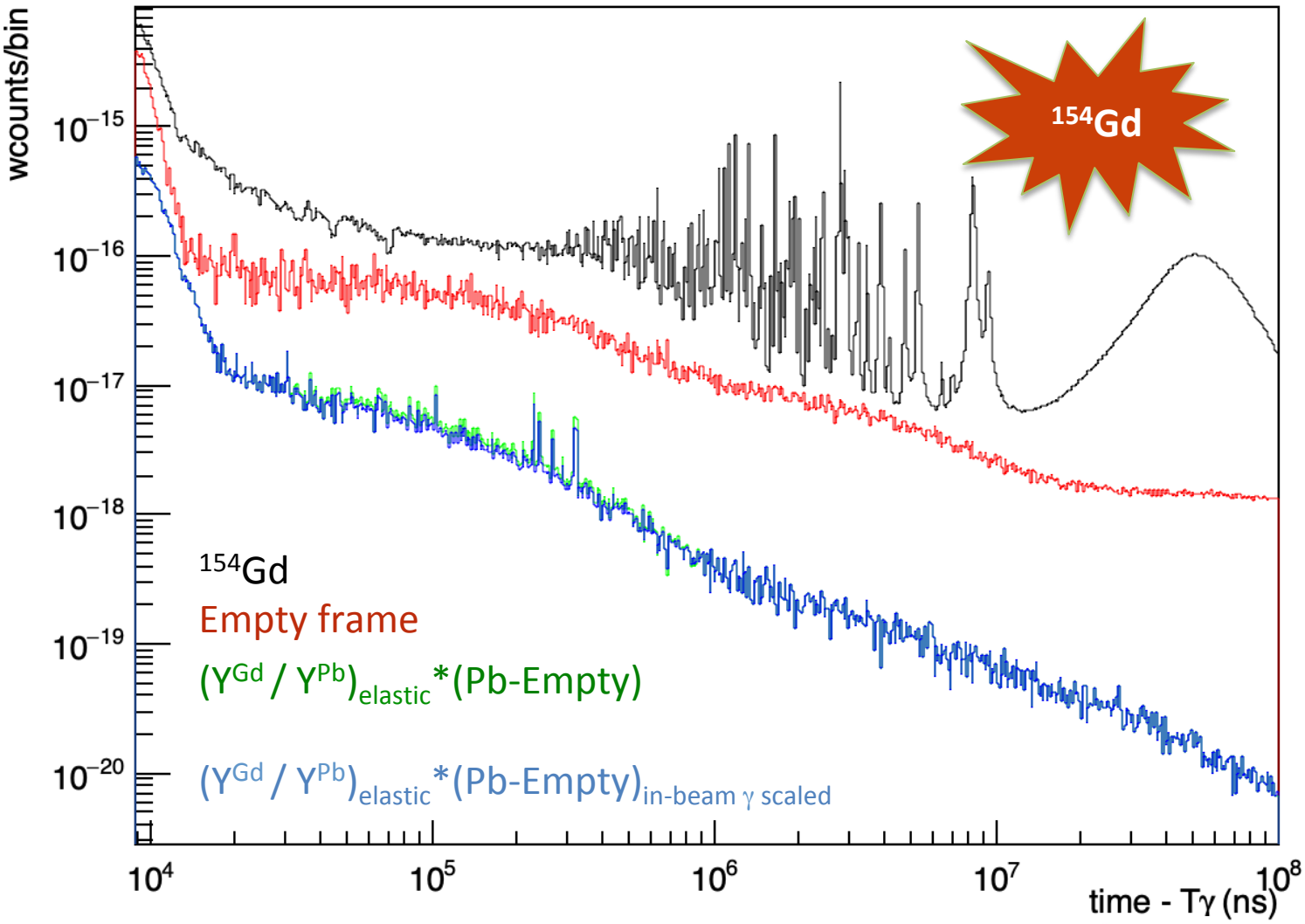
Data reduction

Background



Background = RED+BLUE curve

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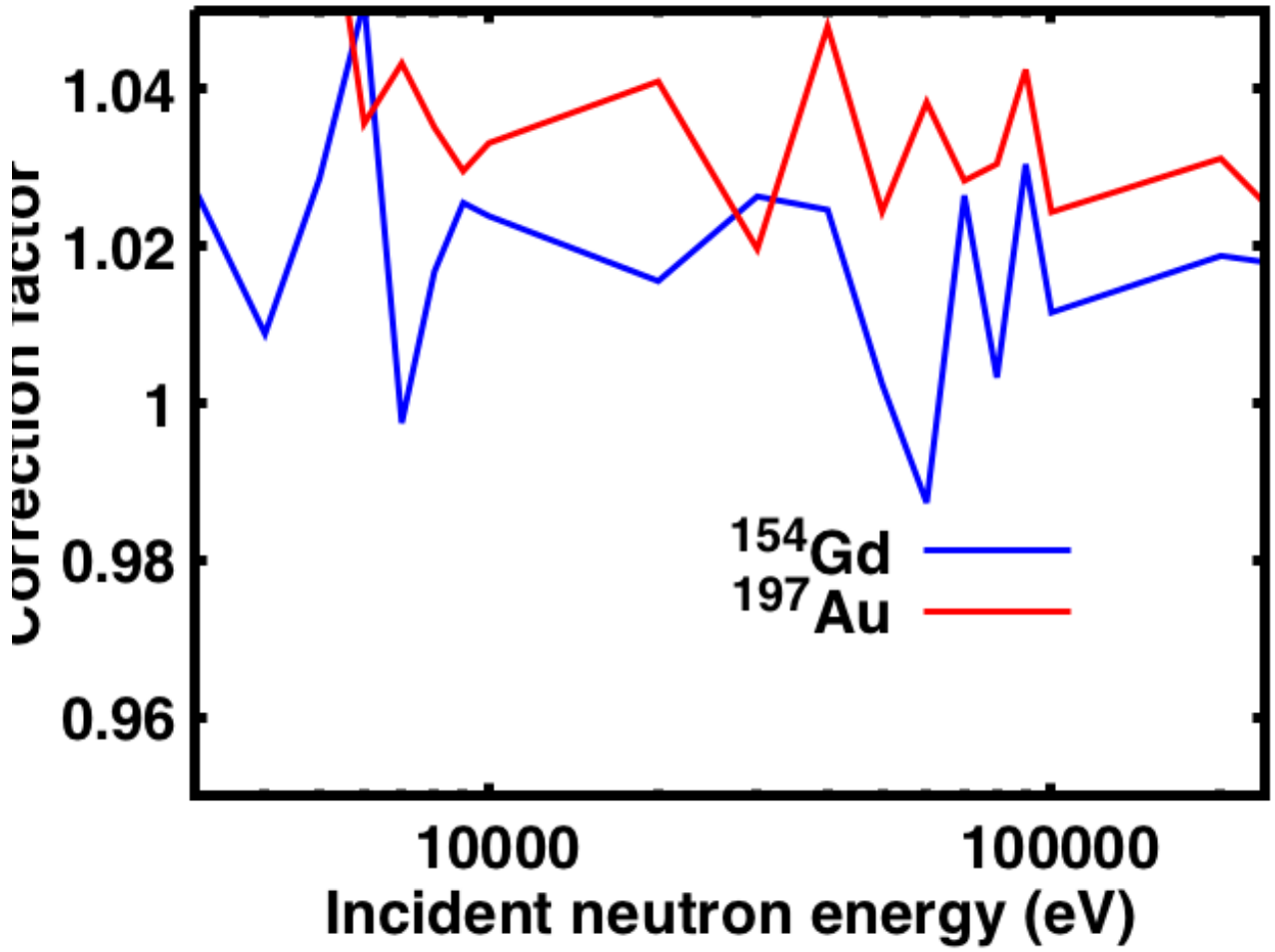
Data reduction

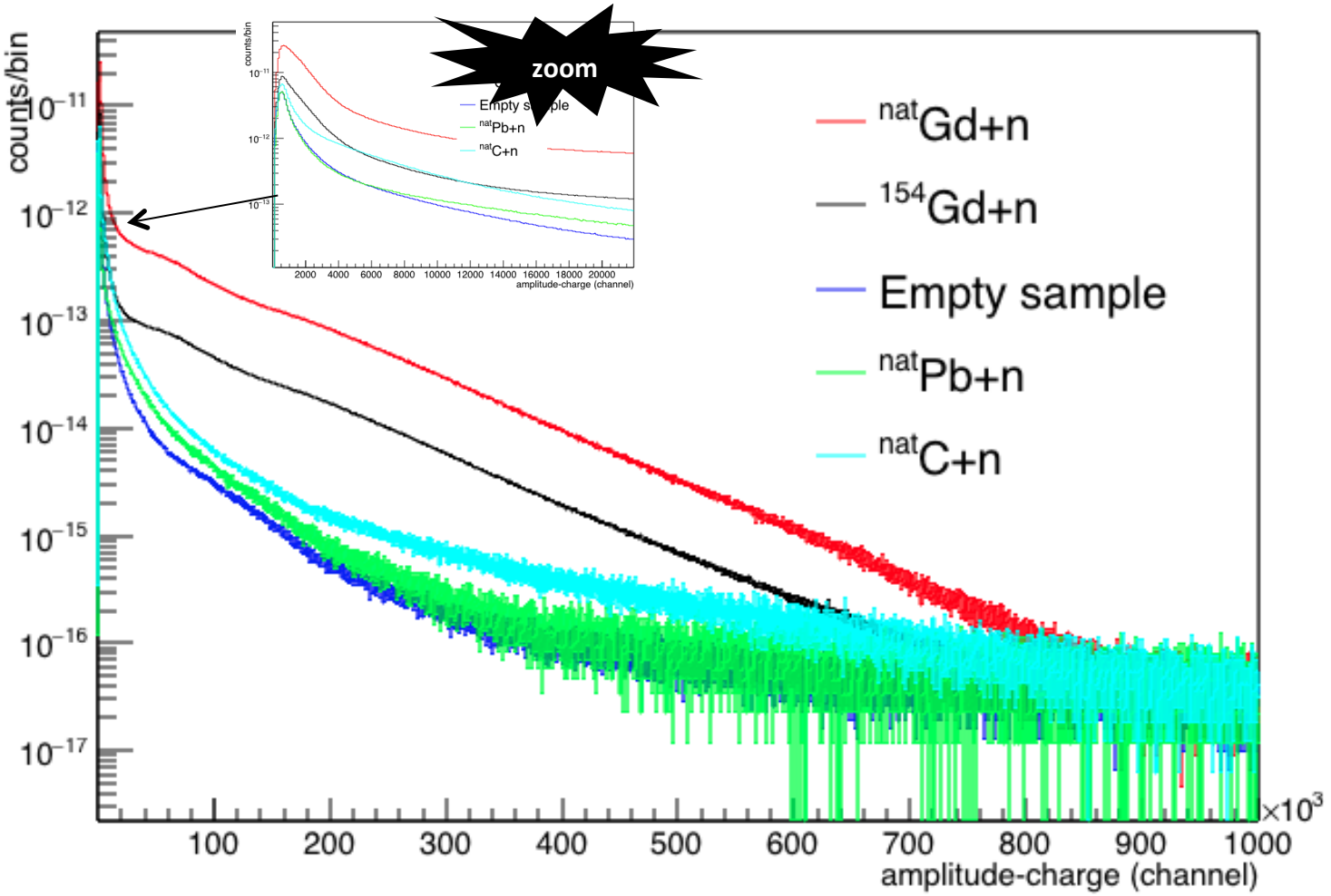
Multiple scattering



~ negligible correction in the URR for ^{154}Gd

Data reduction

Multiple scattering



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