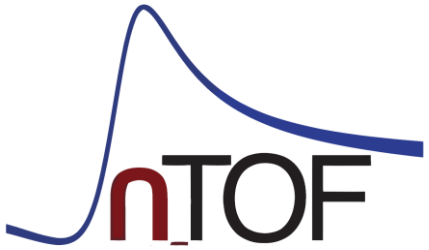
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA



European Nuclear Physics Conference 2025

22-26 September 2025, Caen, France

Measurement of ^{63,65}Cu neutron capture cross sections at the n_TOF facility

Nicholas Pieretti on behalf of the n_TOF Collaboration

Department of Physics and Astronomy, University of Bologna

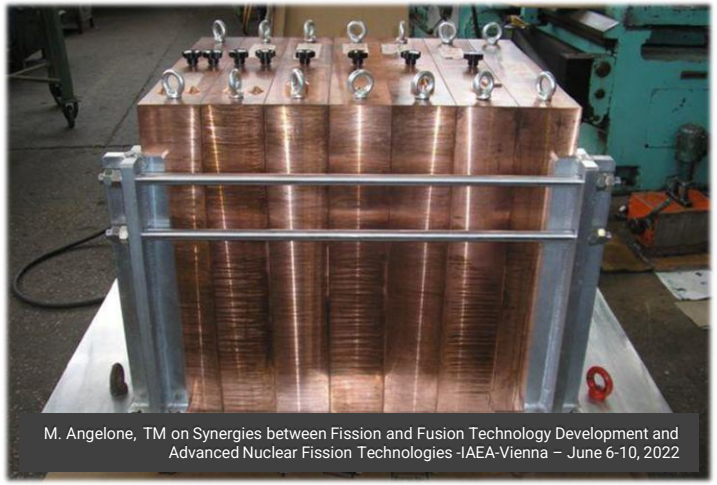
Why Copper?

Nuclear Fission Technologies

- Generation IV fast reactors
- Nuclear data and material testing at the ENEA TAPIRO research reactor
- S&U and representativeness tests revealed inadequacies in Cu cross section data

Other Fields

- Astrophysics: Cu nucleosynthesis scenarios to be determined, affecting also heavier elements abundances
- Fusion: Cu benchmark experiment at ENEA FNG for nuclear data validation



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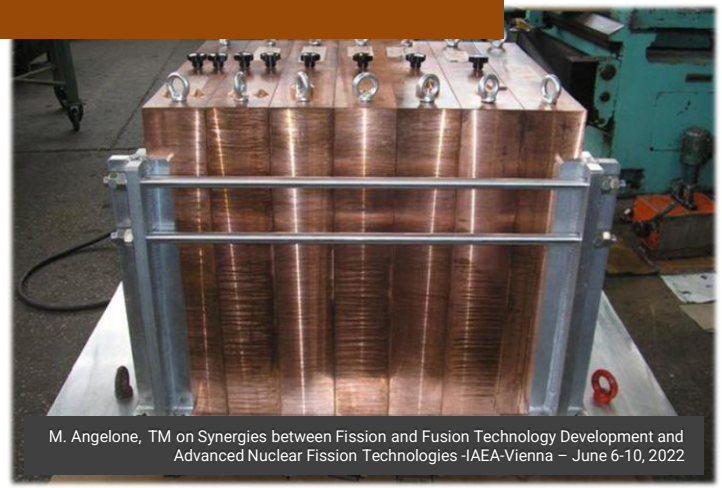
Need for better σ: (n,tot), (n, n), (n, γ), …

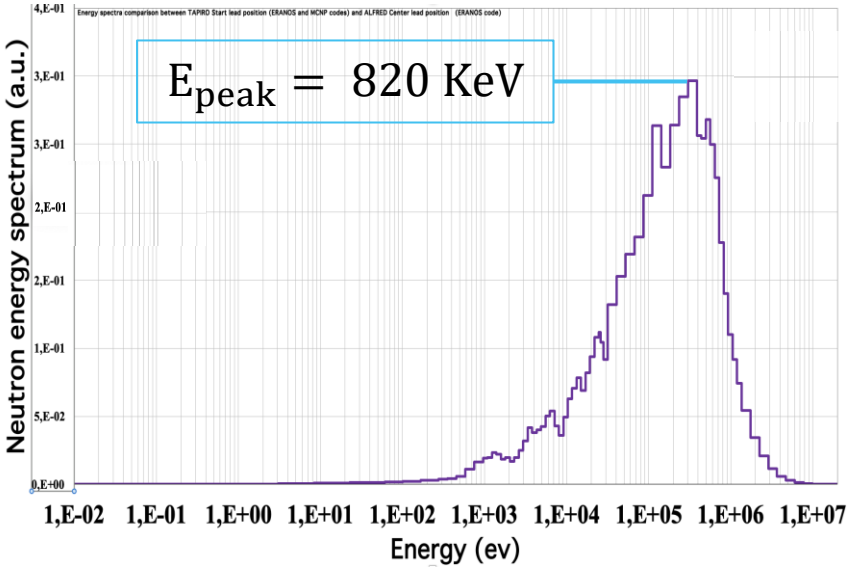


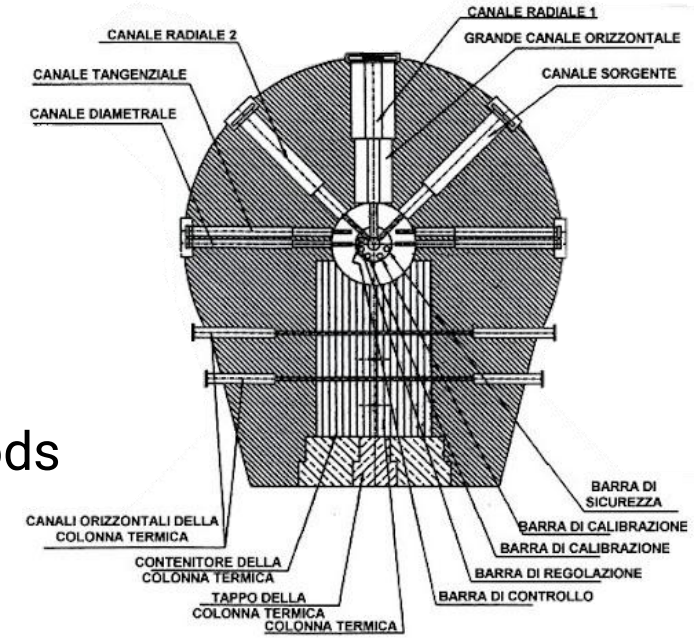
M. Angelone, TM on Synergies between Fission and Fusion Technology Development and Advanced Nuclear Fission Technologies -IAEA-Vienna – June 6-10, 2022

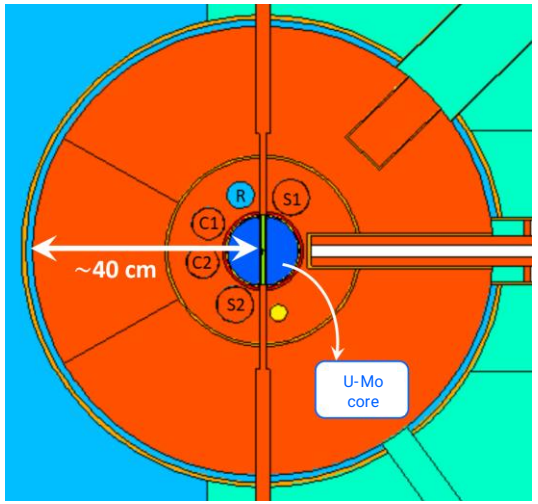
Why TAPIRO?

TAratura Pila Rapida Potenza ZerO:

- 5 kW power
- U-Mo fuel
- Core = 12 cm cylinder
- ^{235}U enrichment = 93.5%
- $4 \times 10^{12}\ \mathrm{n \cdot cm^{-2} \cdot s^{-1}}$
- Fast spectrum
- Cooling with He
- 4 experimental channels, 1 removable sector
- 5 rods (safety, calibration, regulation)
- Cu used as reflector, also in rods

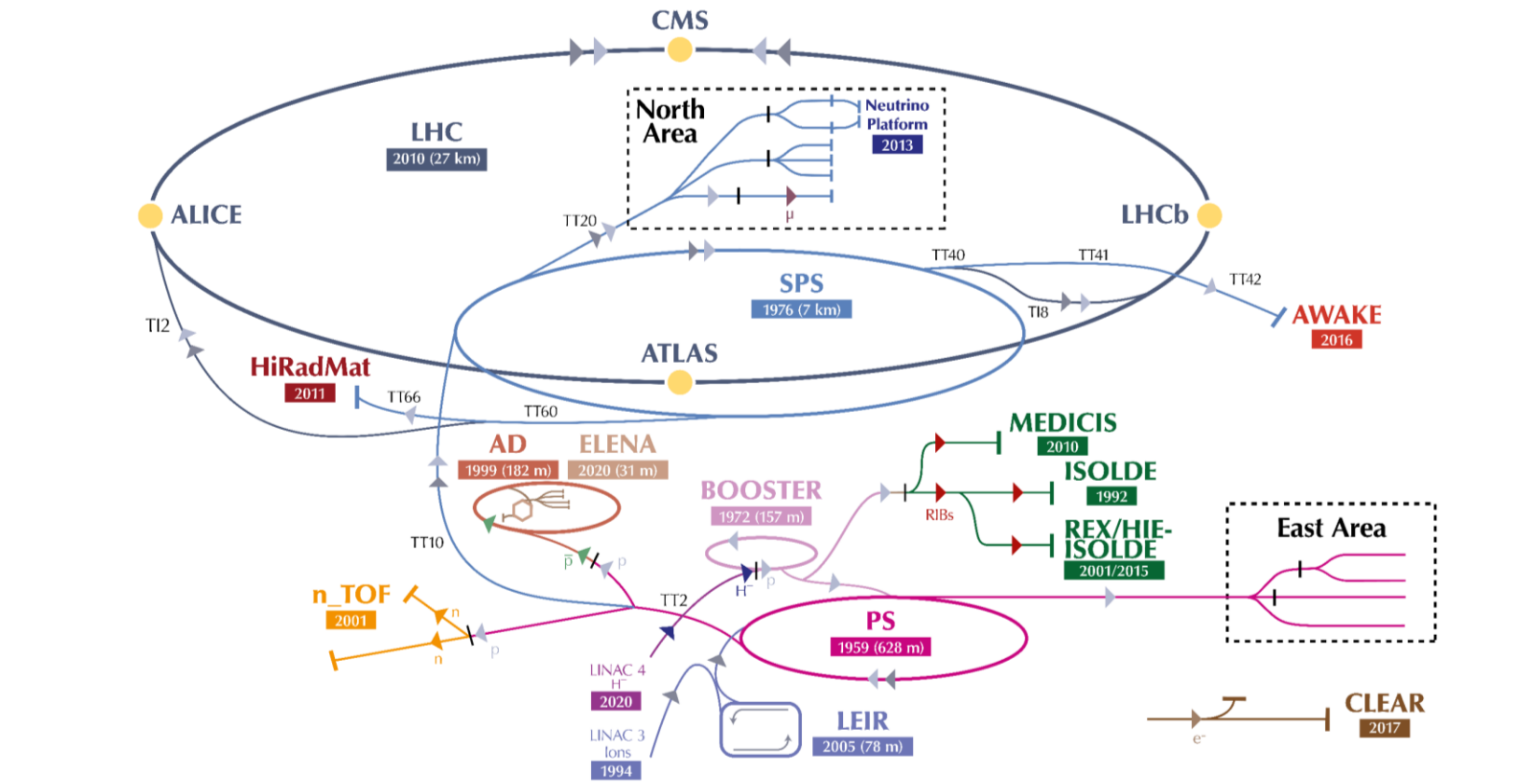






More details: A. Manna, DISRUPT, 15:30

The CERN accelerator complex
Complexe des accélérateurs du CERN



H⁻ (hydrogen anions) · p (protons) · ions · RIBs (Radioactive Ion Beams) · n (neutrons) · p̄ (antiprotons) · e⁻ (electrons) · μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

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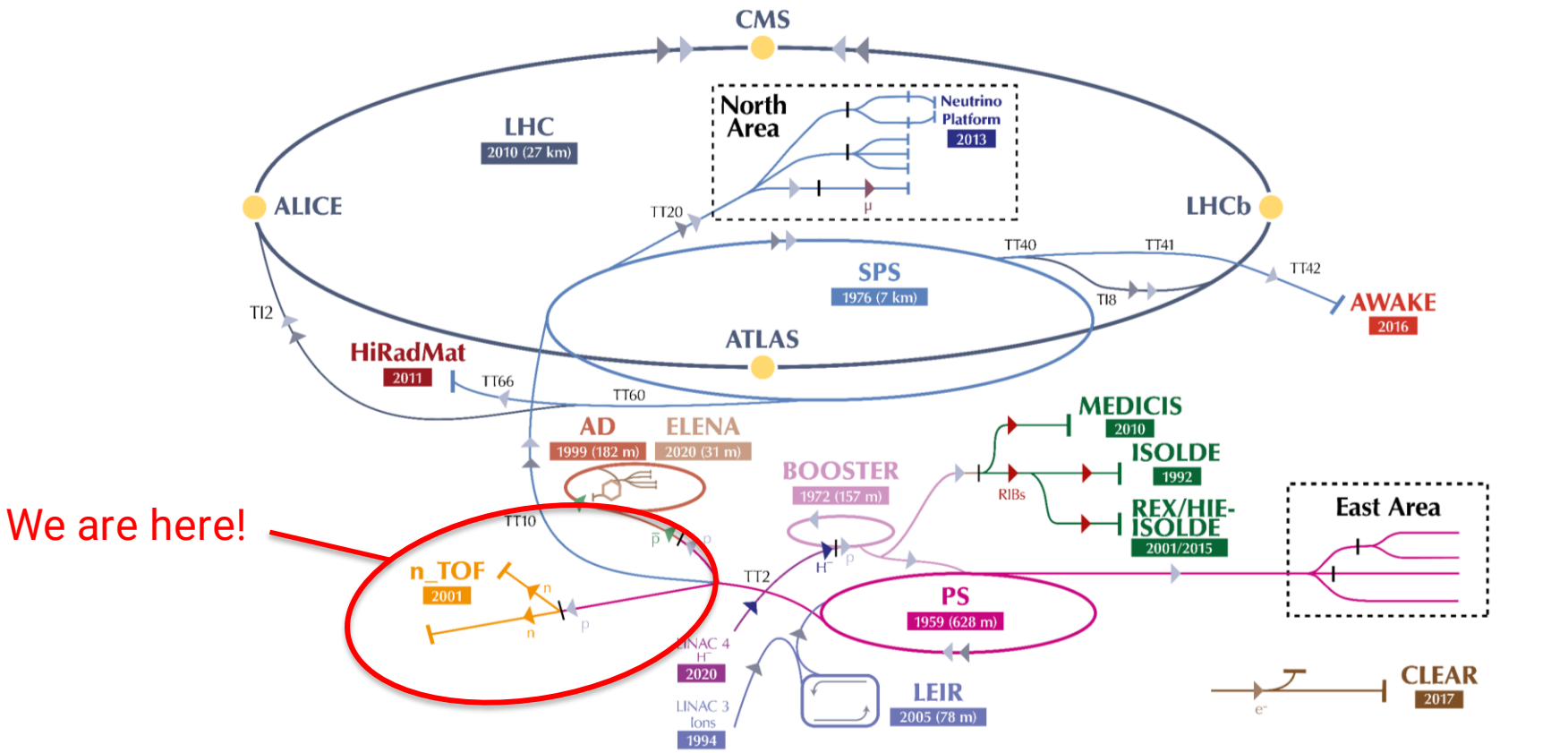

We are here!

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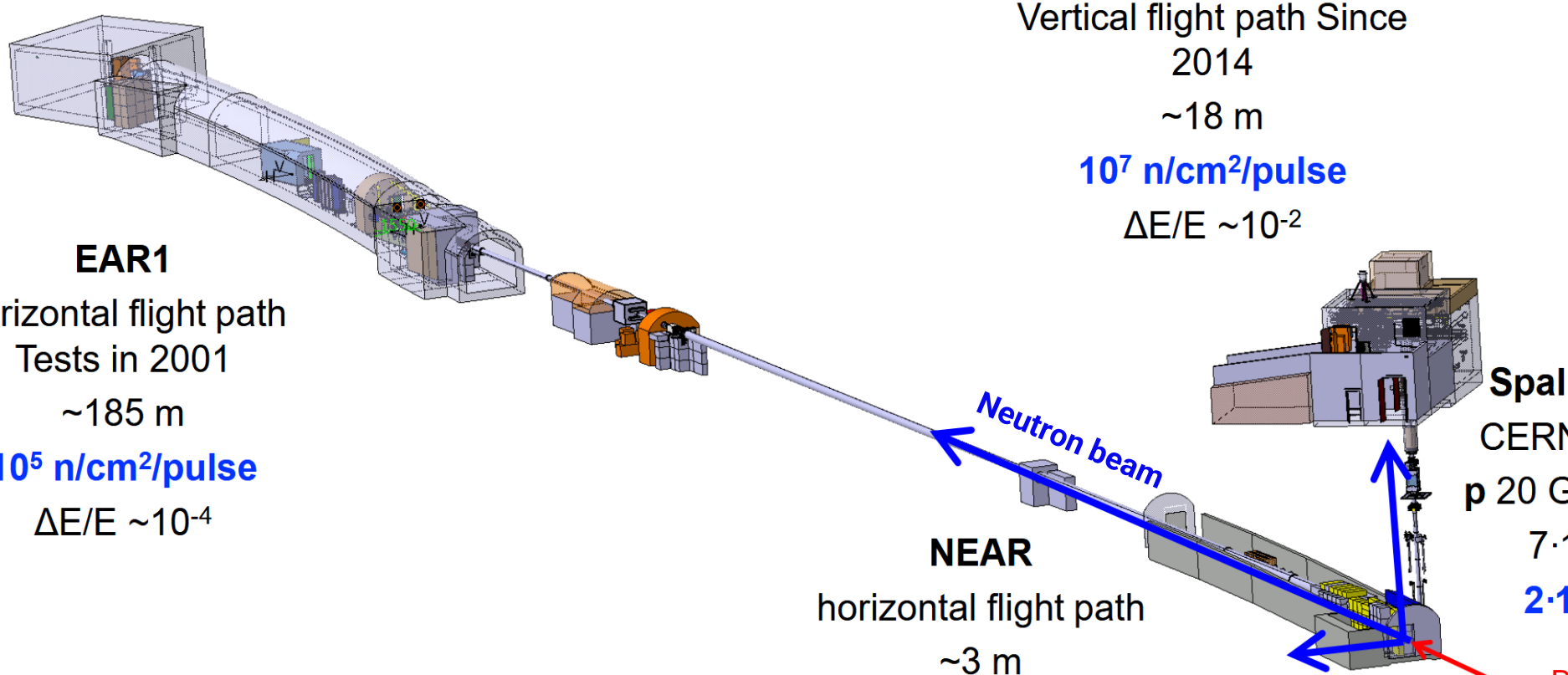
Why n_TOF?



EAR1
horizontal flight path
Tests in 2001
~185 m
10^5 n/cm²/pulse
ΔE/E ~10^{-4}

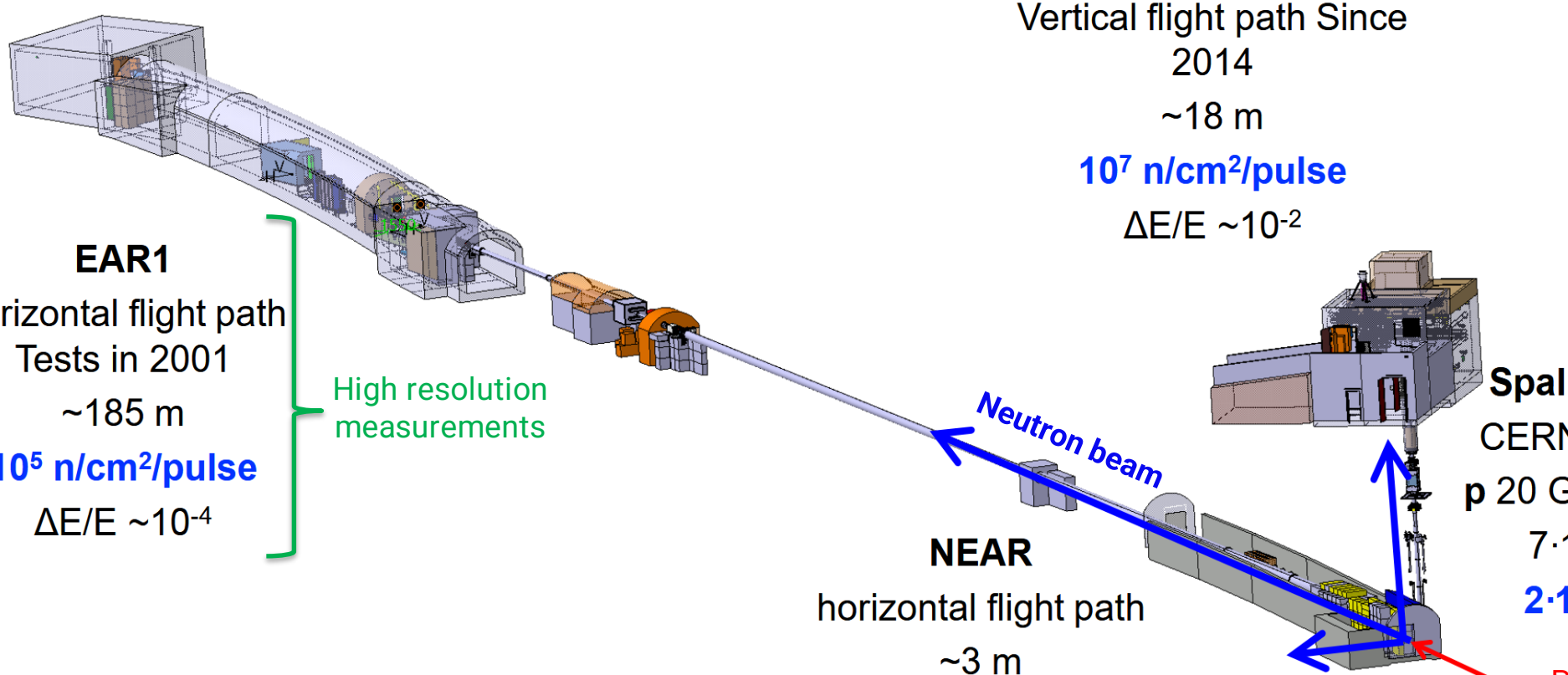
EAR2
Vertical flight path Since 2014
~18 m
10^7 n/cm²/pulse
ΔE/E ~10^{-2}

NEAR
horizontal flight path
~3 m
10^8 n/cm²/pulse

Spallation source
CERN PS @ 0.8 Hz
p 20 GeV/c, 7ns RMS
$7 \cdot 10^{12}$ p/pulse
$2 \cdot 10^{15}$ n/pulse

From E. Mendoza, APRENDE WP2-WP4 Workshop

Why n_TOF?



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High resolution measurements

Neutron beam

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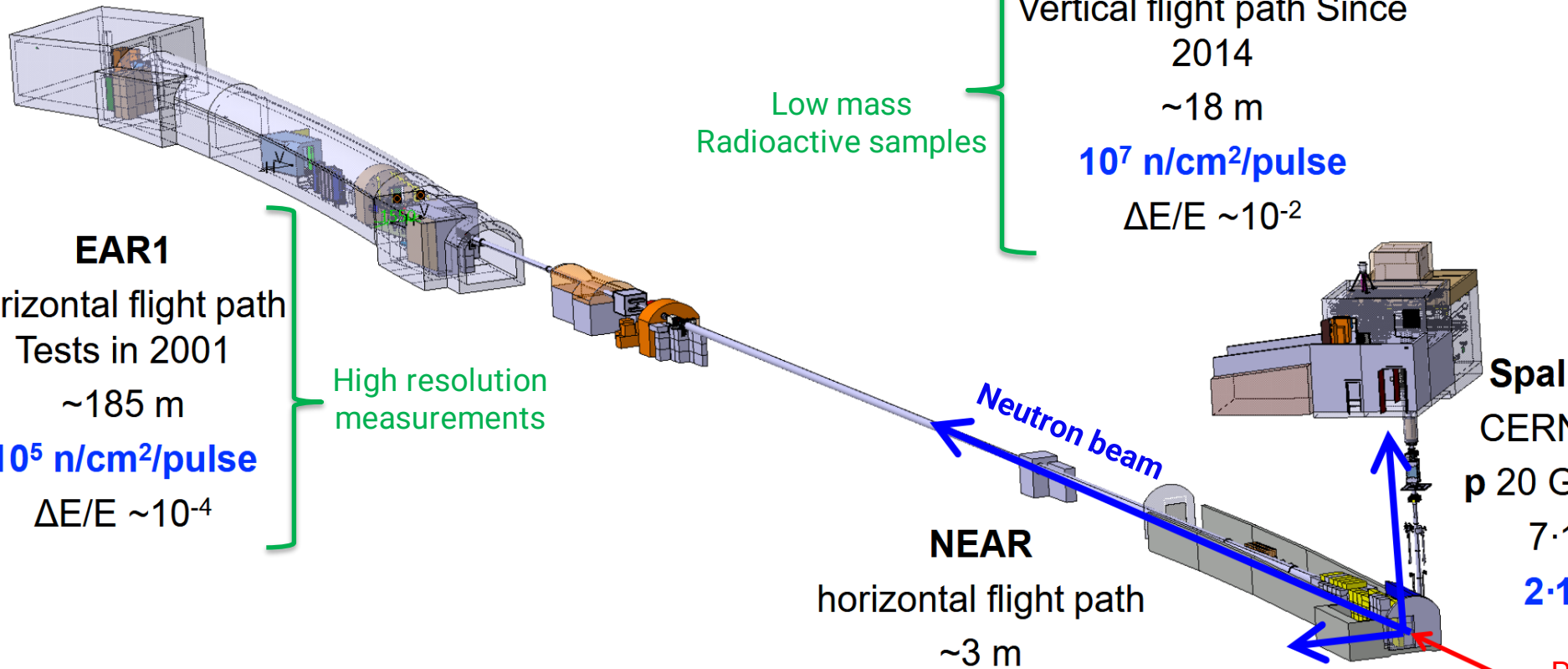

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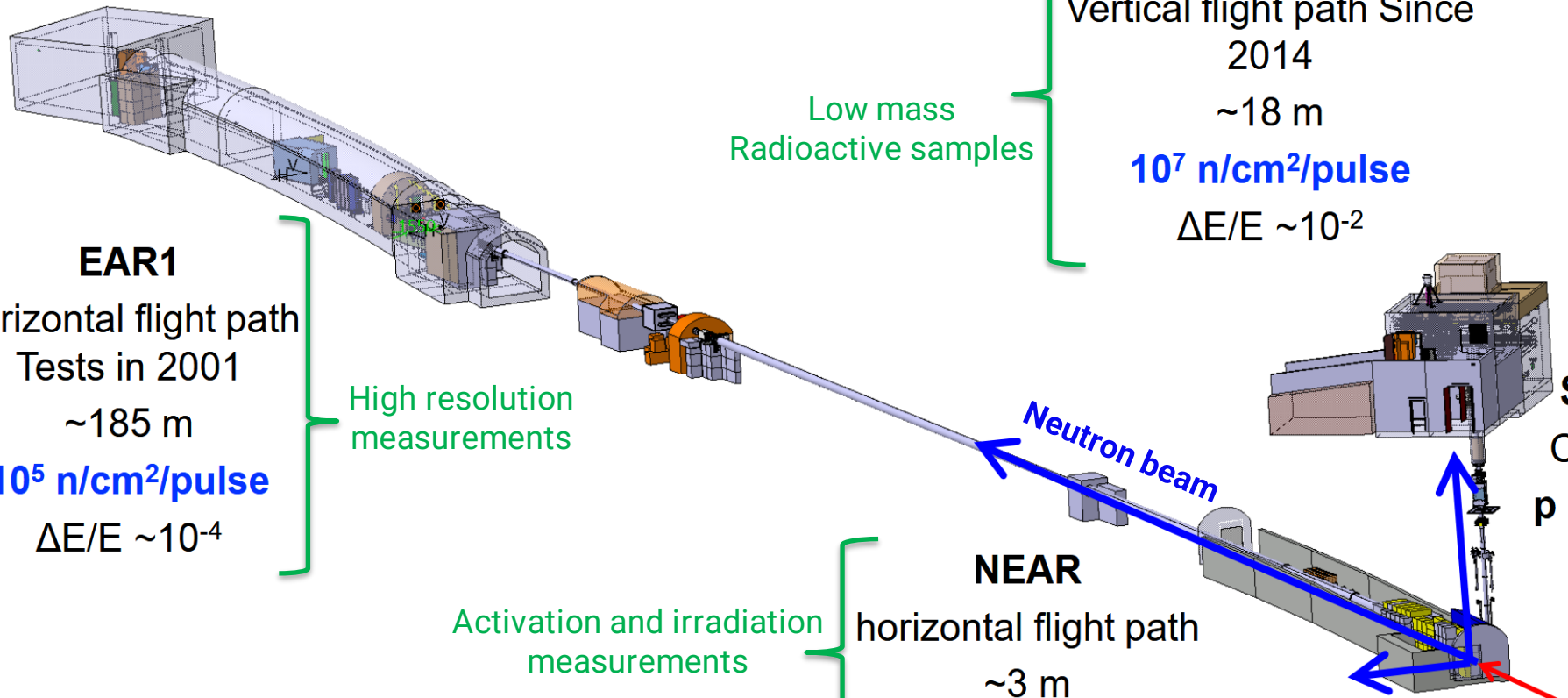

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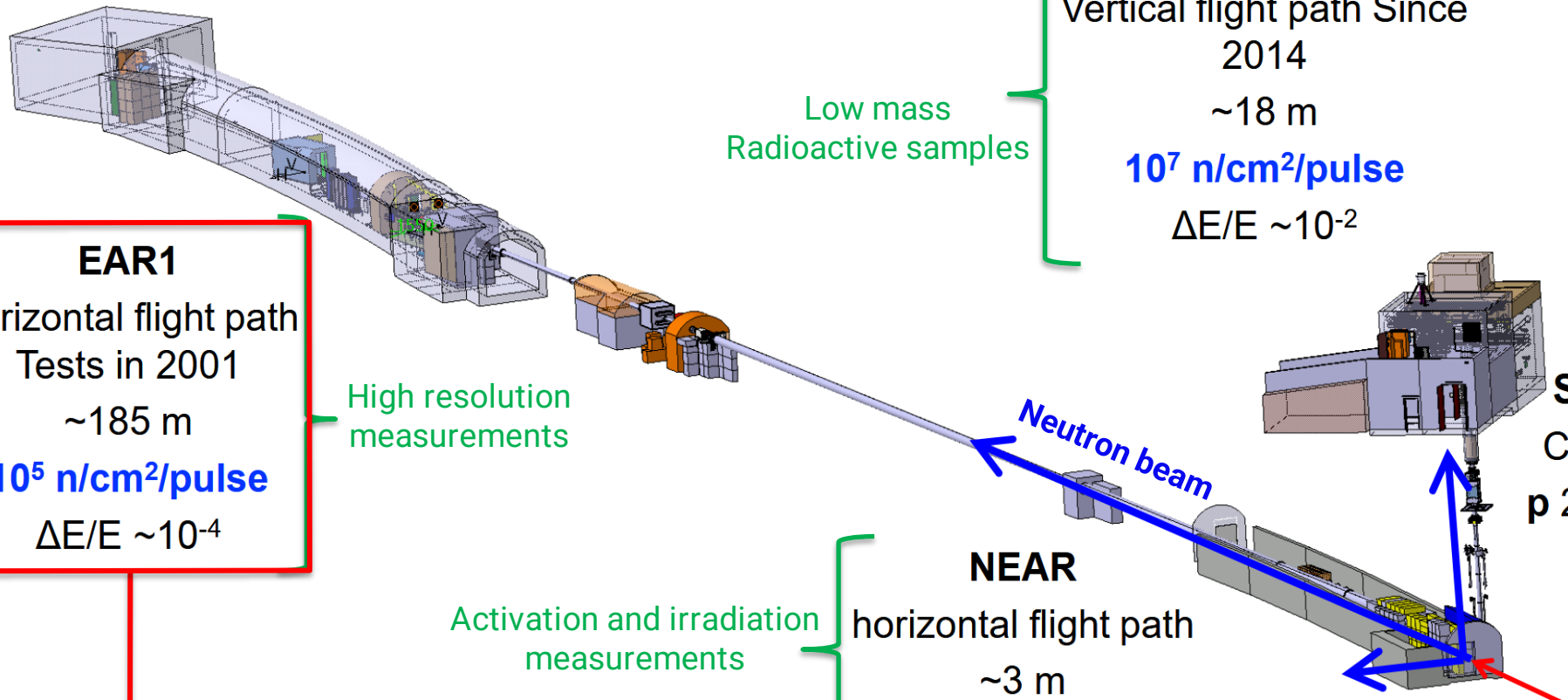

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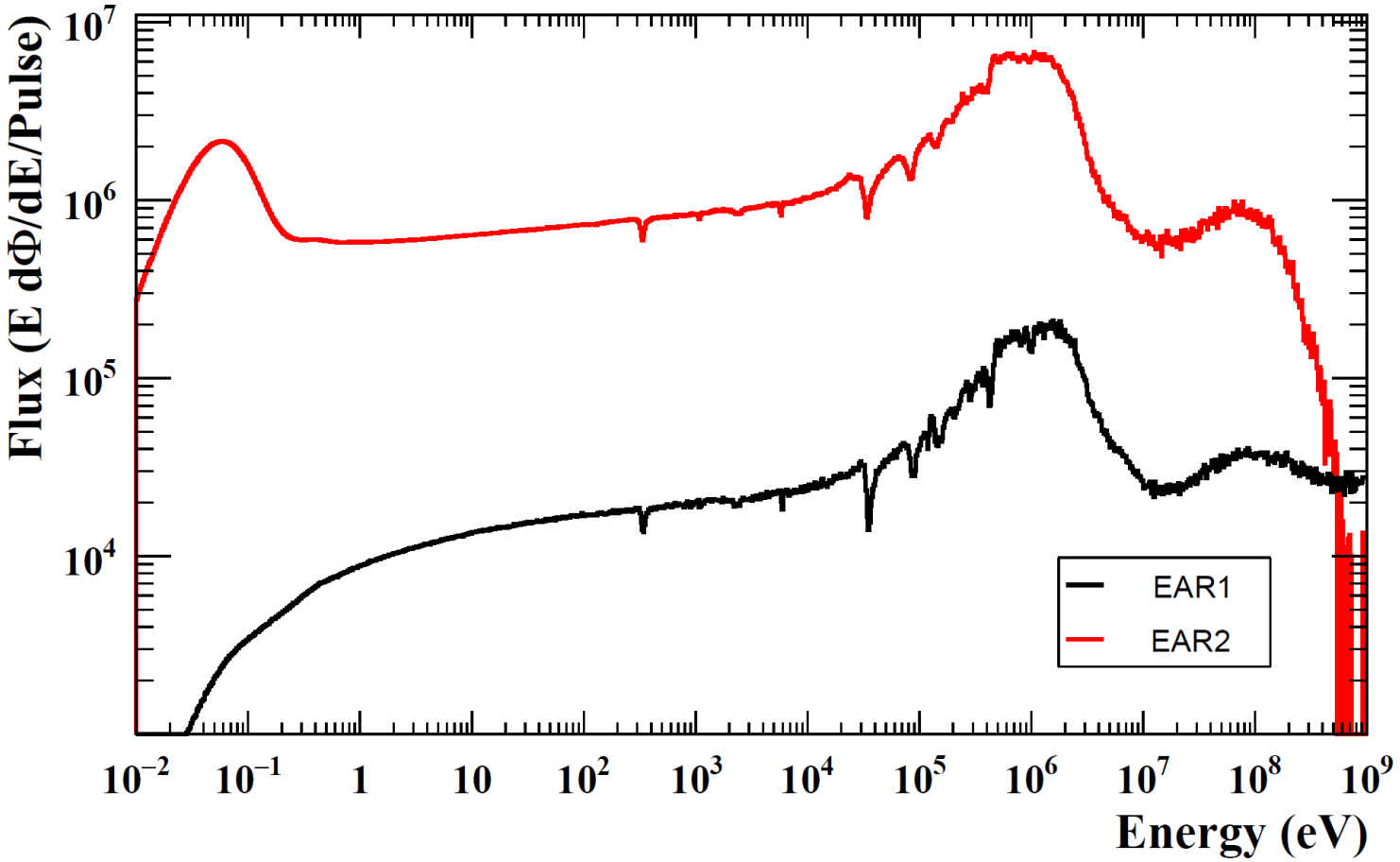
Why n_TOF?

- Wide energy range:
  $10\ \text{meV} \leq \text{E}_\text{n} \leq 1\ \text{GeV}$
- High current:
  8.5×10^{12} p/bunch
  $\rightarrow 10^{6}$ n/pulse
- Energy resolution at EAR1:
  $\frac{\Delta \text{E}_\text{n}}{\text{E}_\text{n}} = 0.03\%\ (1\ \text{eV})$
  $\frac{\Delta \text{E}_\text{n}}{\text{E}_\text{n}} = 0.5\%\ (1\ \text{MeV})$



Experimental campaign at n_TOF

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

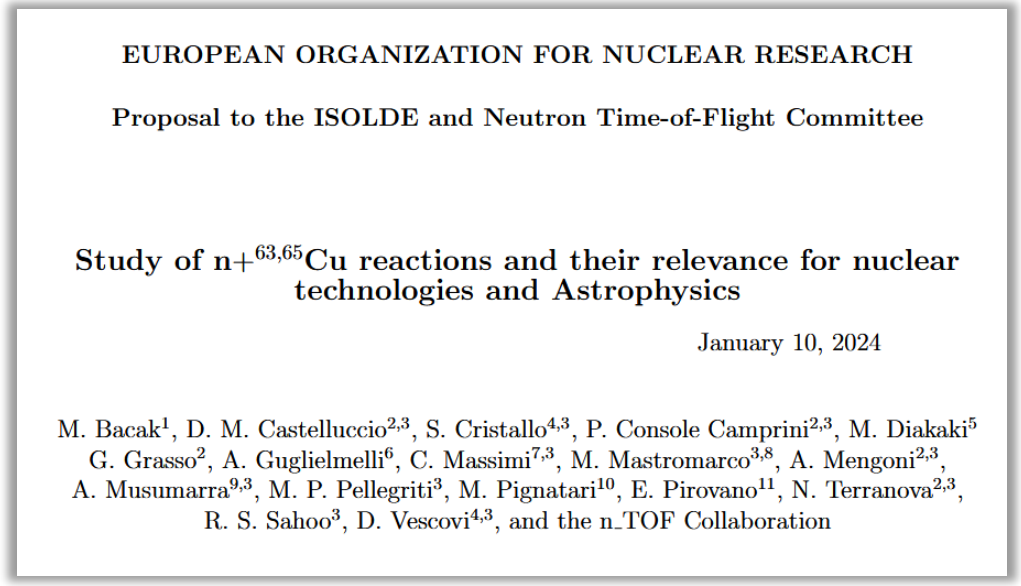
Study of n+^{63,65}Cu reactions and their relevance for nuclear technologies and Astrophysics

January 10, 2024

M. Bacak[1], D. M. Castelluccio[2,3], S. Cristallo[4,3], P. Console Camprini[2,3], M. Diakaki[5] G. Grasso[2], A. Guglielmelli[6], C. Massimi[7,3], M. Mastromarco[3,8], A. Mengoni[2,3], A. Musumarra[9,3], M. P. Pellegriti[3], M. Pignatari[10], E. Pirovano[11], N. Terranova[2,3], R. S. Sahoo[3], D. Vescovi[4,3], and the n_TOF Collaboration

Experiment	Sample	Protons	Comments
Capture	^{63}Cu	2.0×10^{18}	
Capture	^{65}Cu	2.0×10^{18}	
Capture	^{nat}Cu	0.3×10^{18}	EAR1 or EAR2
Capture	Empty-sample	0.2×10^{18}	background study
Capture	Pb	0.2×10^{18}	background study
Capture	C	0.2×10^{18}	background study
Capture	^{197}Au	0.1×10^{18}	normalization
Transmission	^{63}Cu	1.0×10^{18}	"Sample-in"
Transmission	^{65}Cu	1.0×10^{18}	"Sample-in"
Transmission	Empty-sample	1.0×10^{18}	"Sample-out"
		8.0×10^{18}	

Experimental campaign at n_TOF



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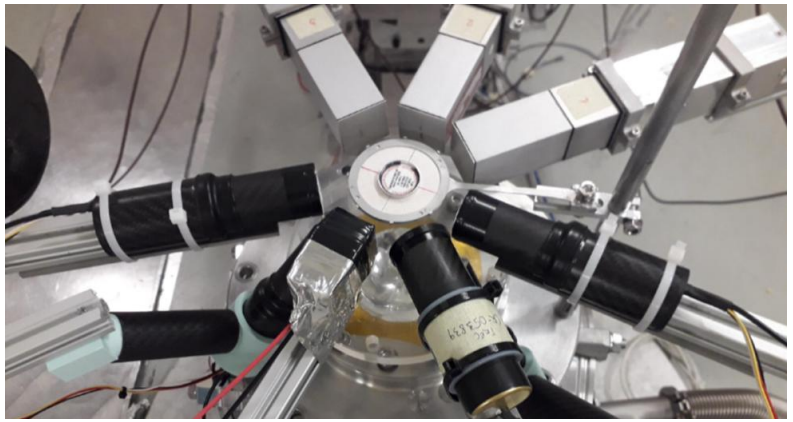
^{nat}Cu target

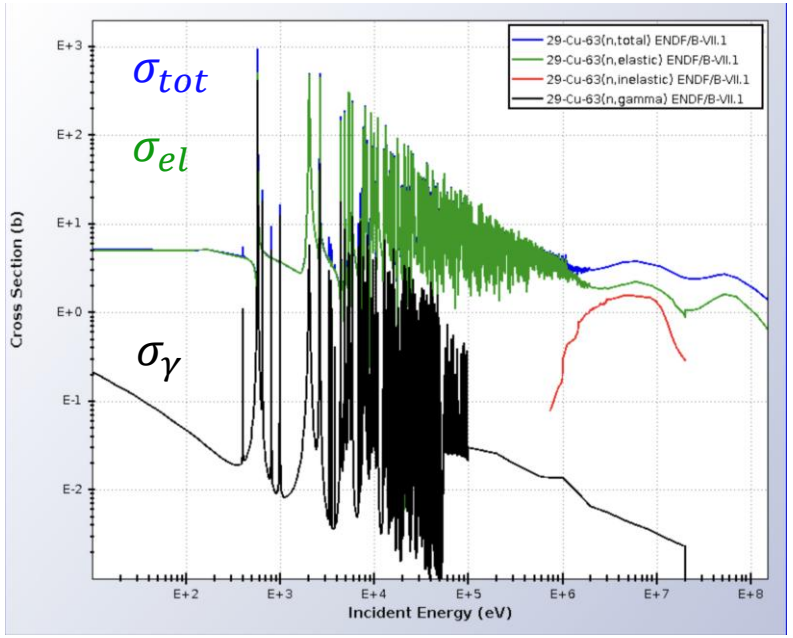
+ foreseen elastic and inelastic angular cross section measurements

Elastic and inelastic channels

- Very challenging measurements: see Letter of Intent INTC-I-274
- Test with eight stilbene scintillators
- Excellent:
  - n/γ discrimination
  - time performance
  - resolution
- C scattering cross section structures well reproduced
- Elastic cross section up to ~MeV can also be obtained from

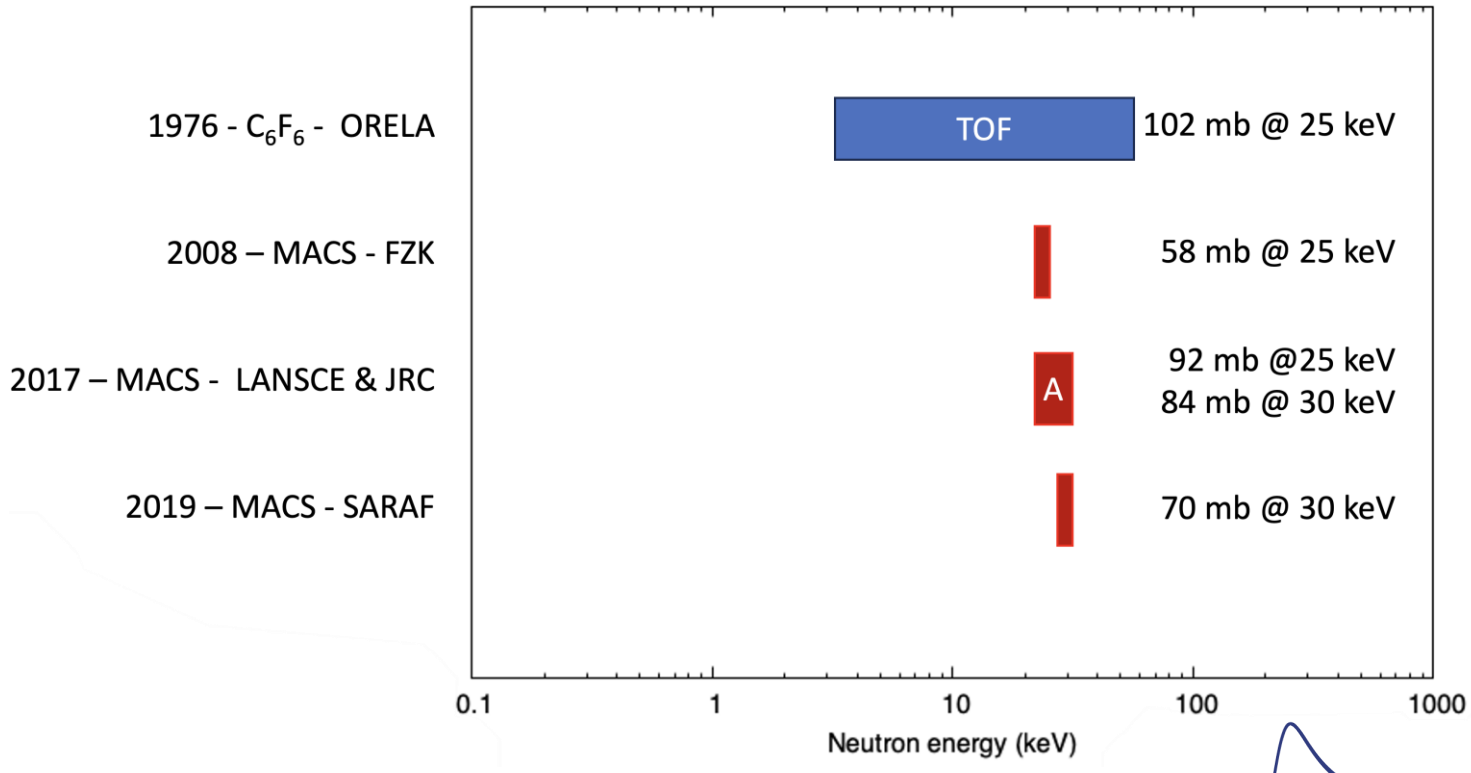
$$\sigma_{el} = \sigma_{tot} - \sigma_{\gamma}$$





Capture measurements of ^{63,65}Cu at n_TOF (2024)

- 2024: $^{63}\mathrm{Cu}(\mathrm{n},\gamma)$ and $^{65}\mathrm{Cu}(\mathrm{n},\gamma)$
- Measurements with $\mathrm{C_6D_6}$ detectors
- Resonance parameter extraction in the energy range of interest
  $E_n < 400$ keV, σ_γ below 3-5%



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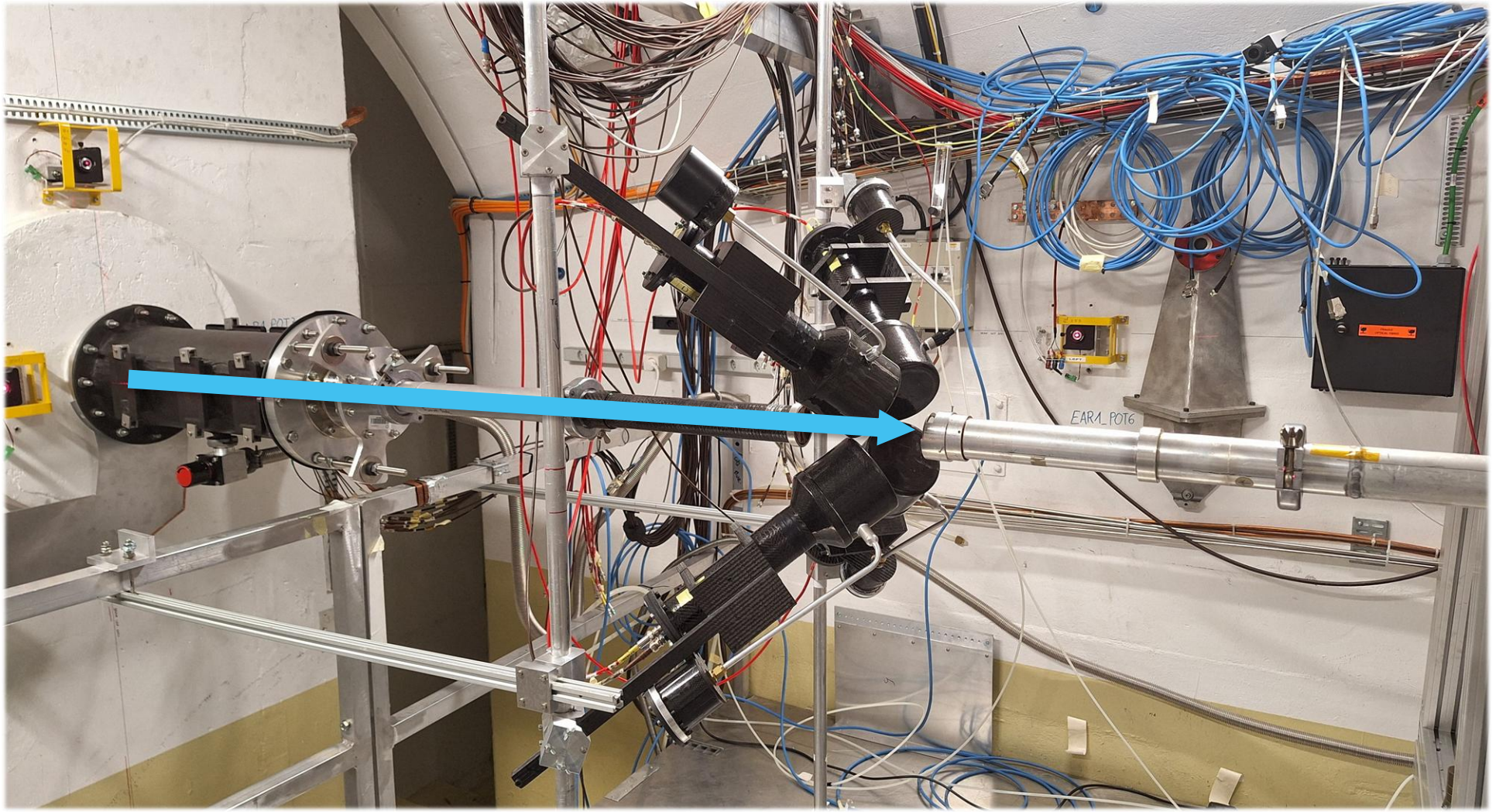

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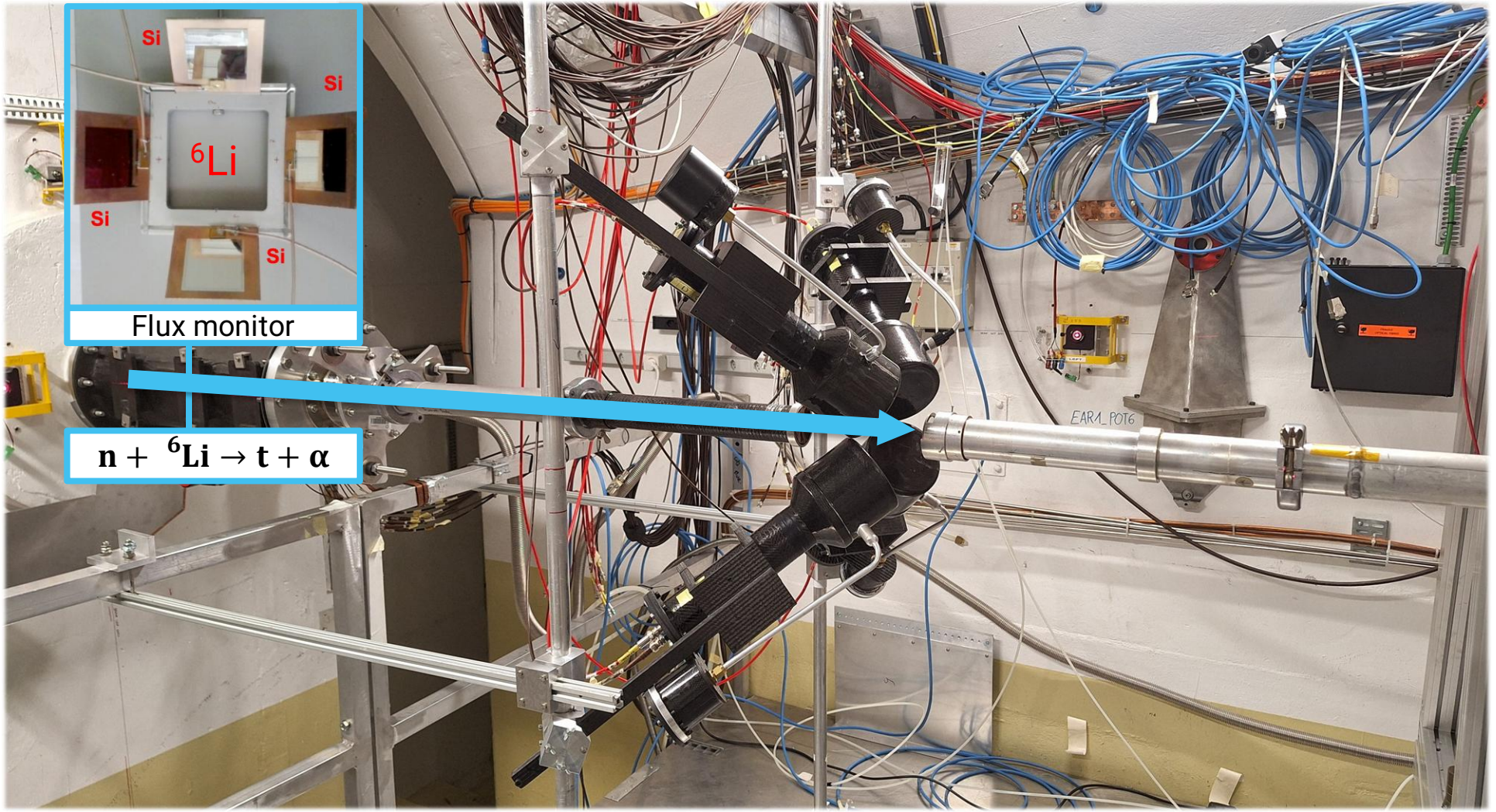

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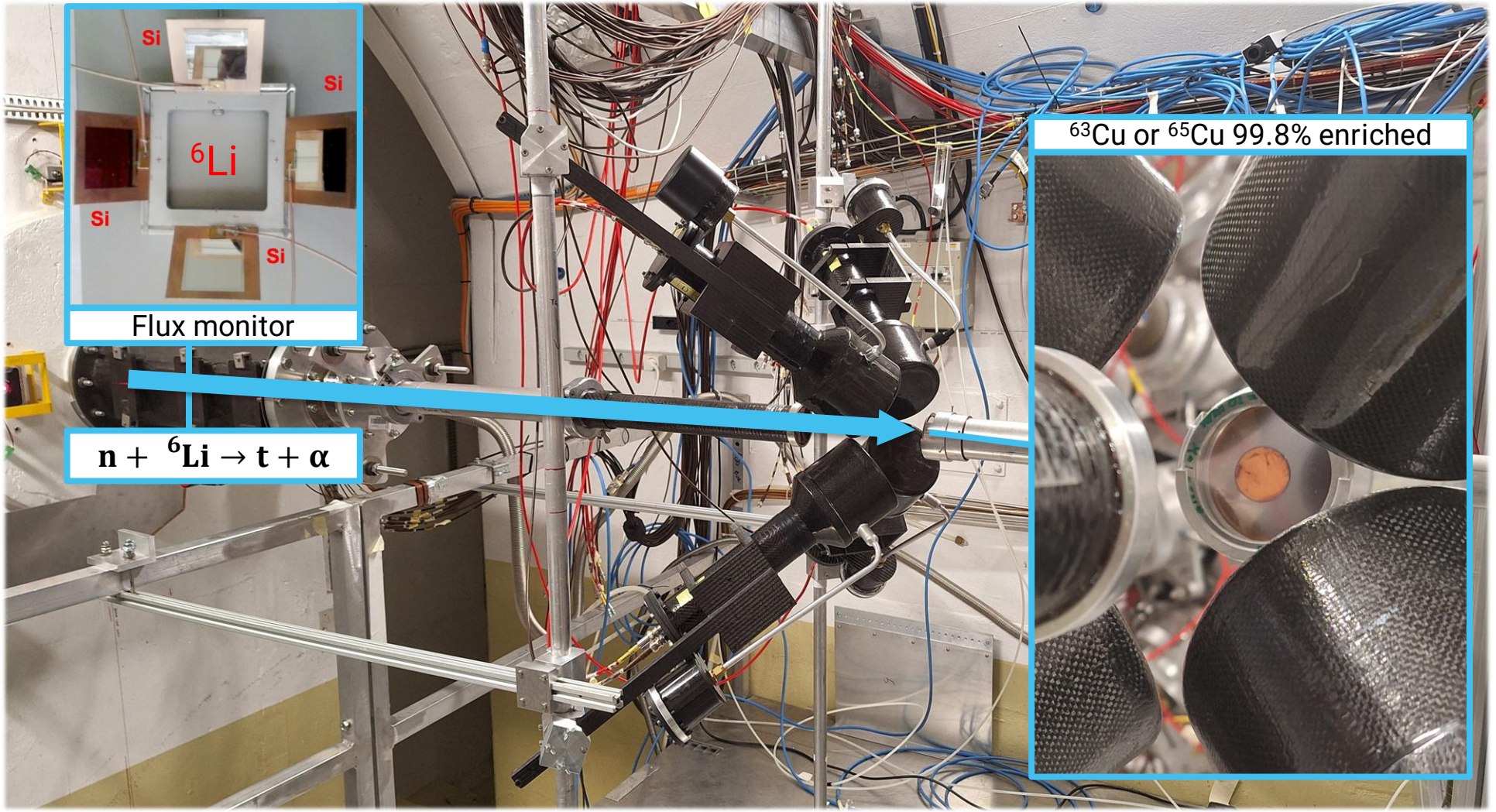

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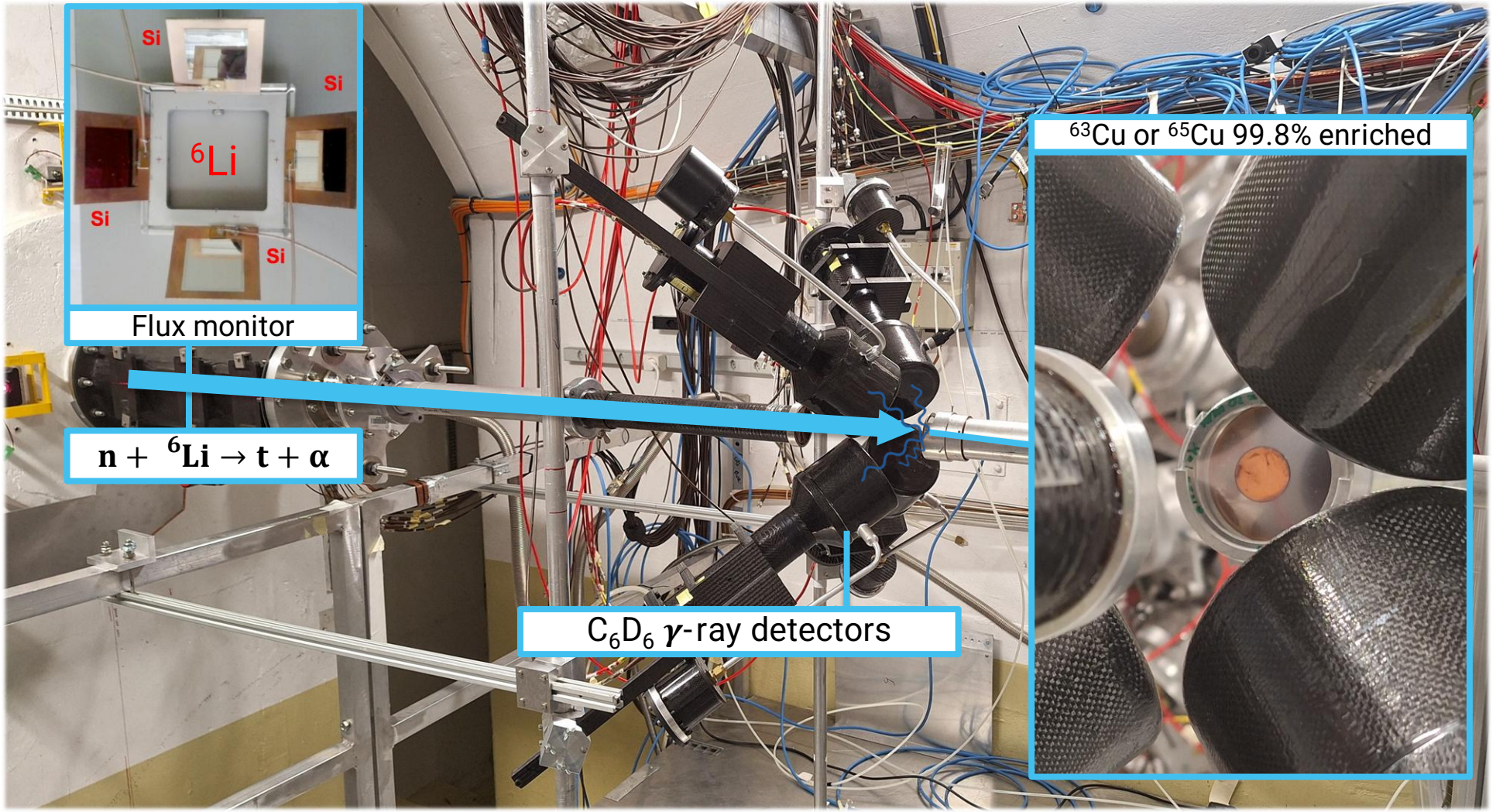

Capture measurements at n_TOF

Experimental capture yield

$$Y(E_n) = N\,\frac{C_w(E_n)}{\varphi_n(E_n)} \propto (1 - e^{-n\sigma_{tot}})\,\frac{\sigma_\gamma}{\sigma_{tot}}$$

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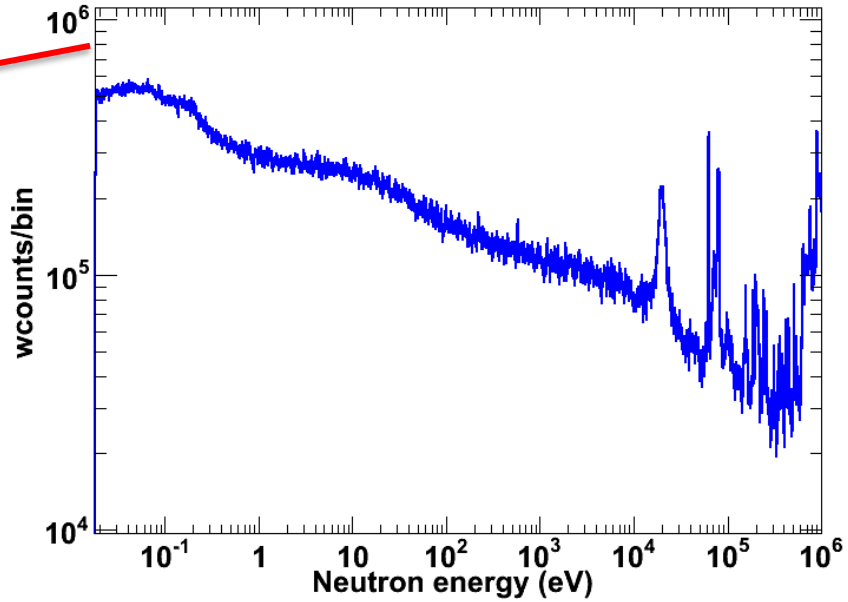

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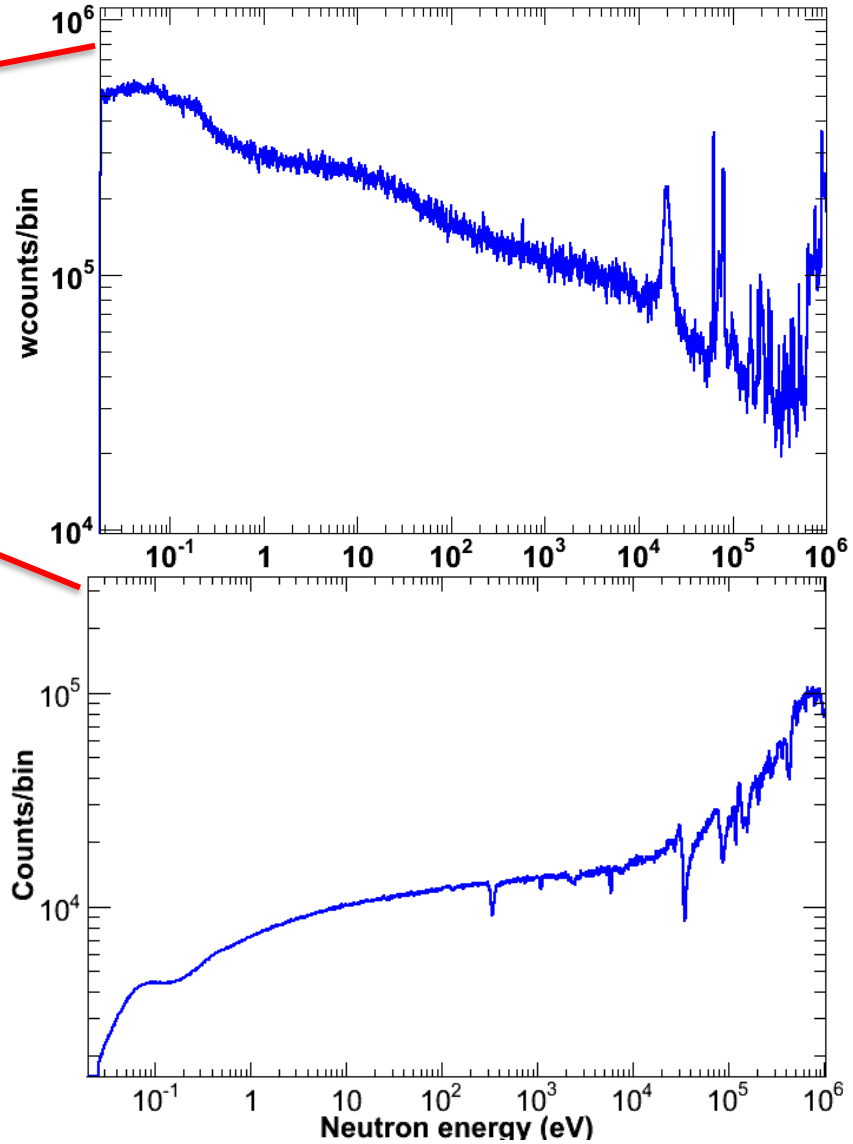

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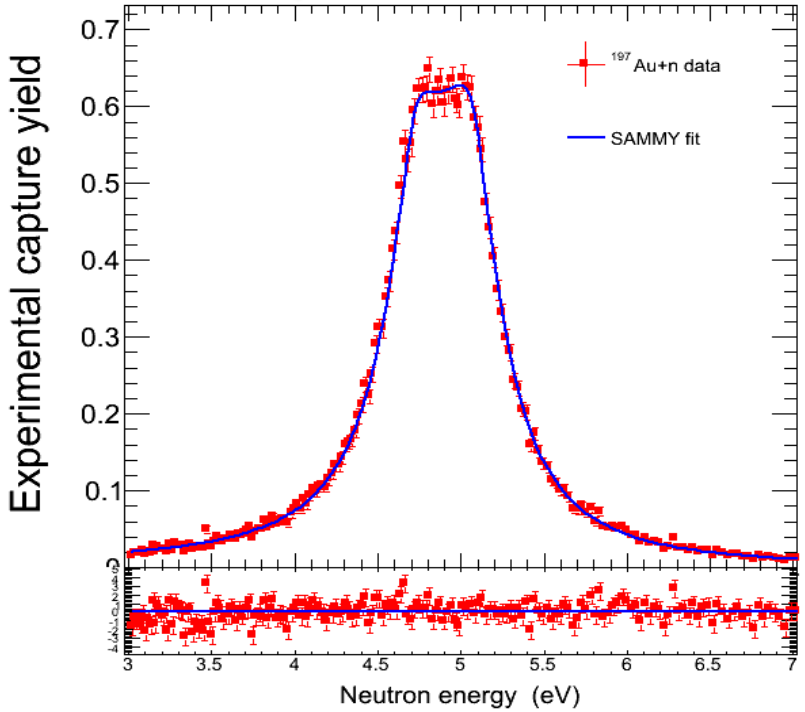
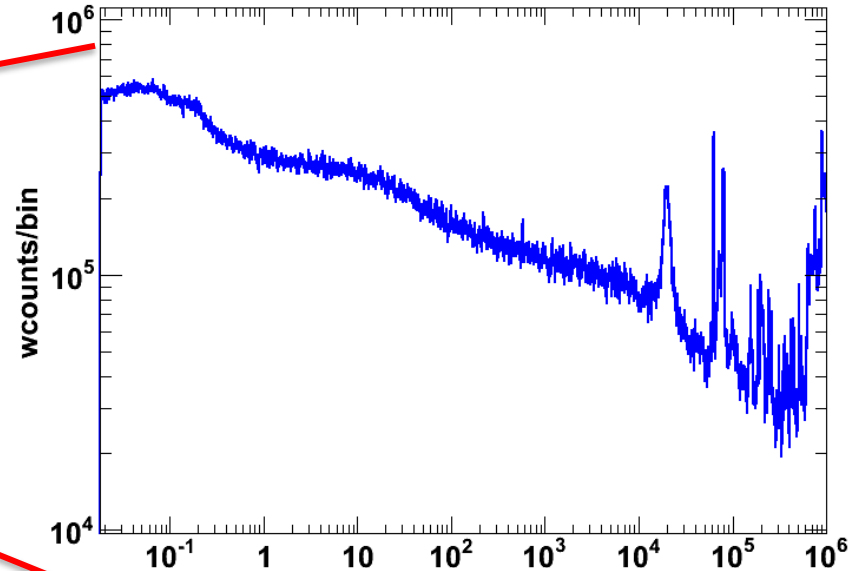
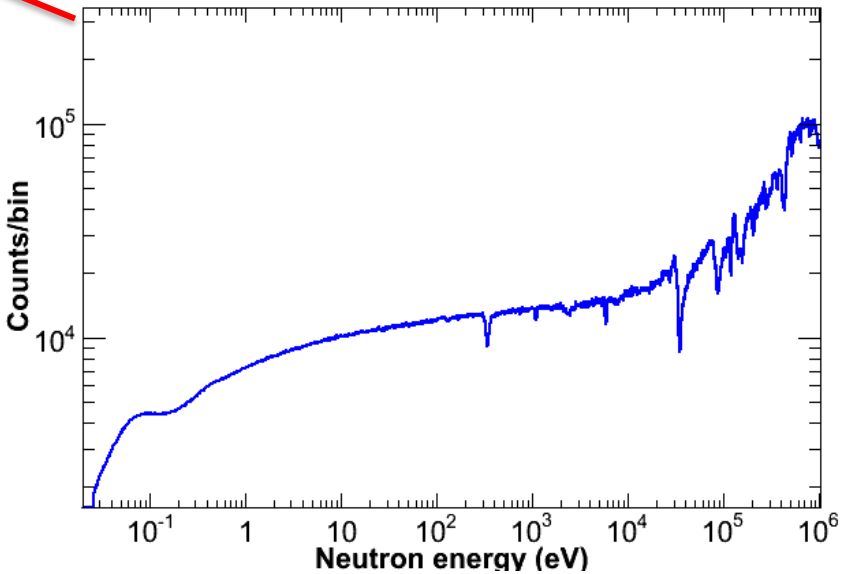


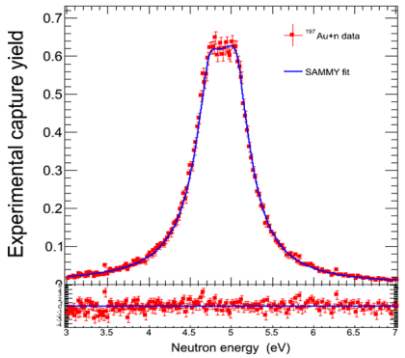


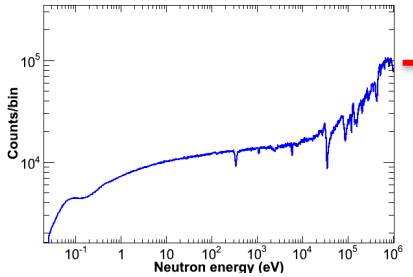


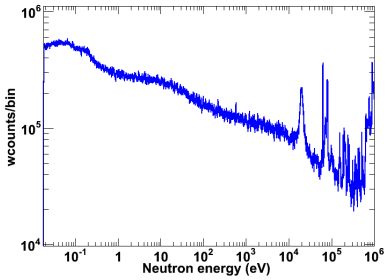
Capture measurements at n_TOF

Before $Y_{(n,\gamma)}$ lots of analysis steps:

1. pulse shape analysis
2. detector calibrations
3. detector resolution
4. MC of monoenergetic sources
5. Weighting Functions (WF)
6. physical cuts on spectra
7. normalization
8. neutron beam analysis
9. background subtraction
10. …







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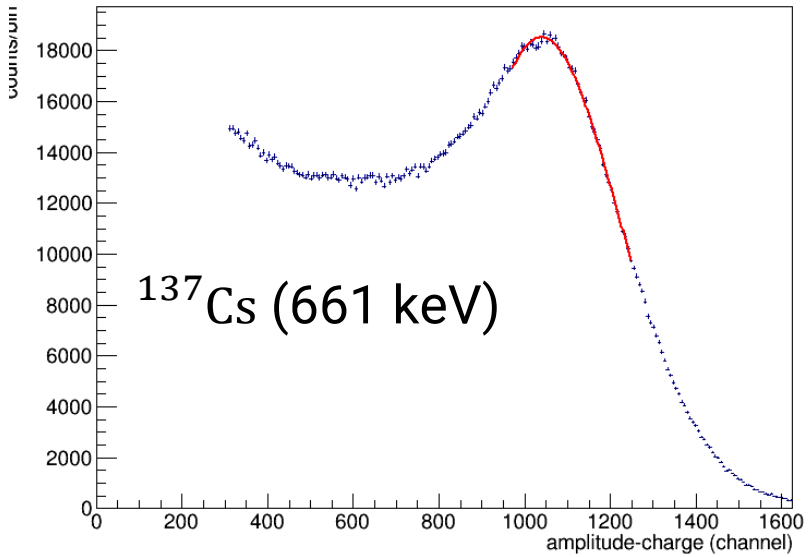
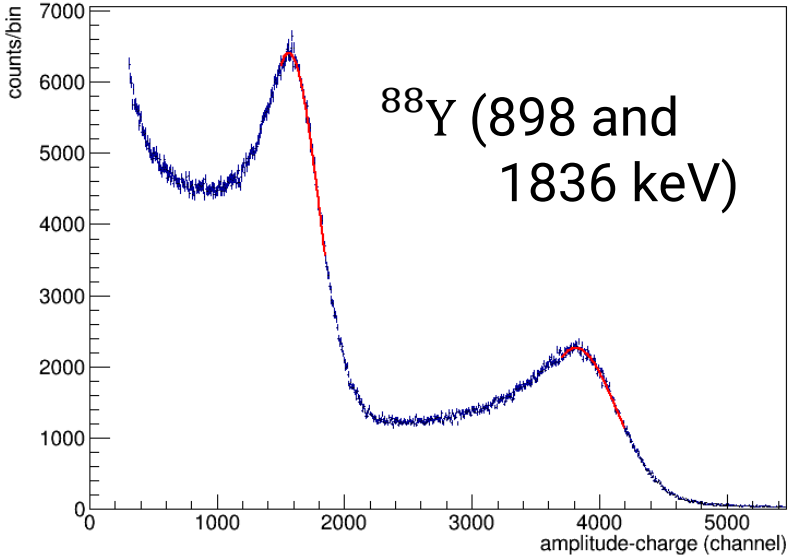
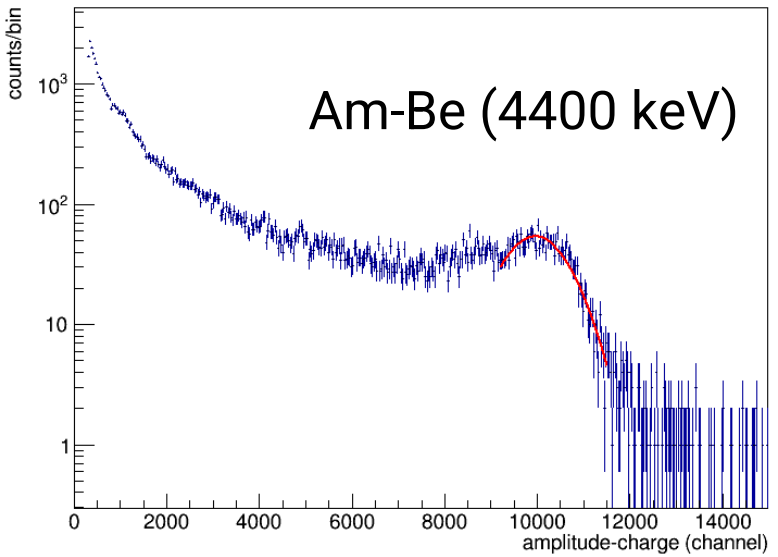
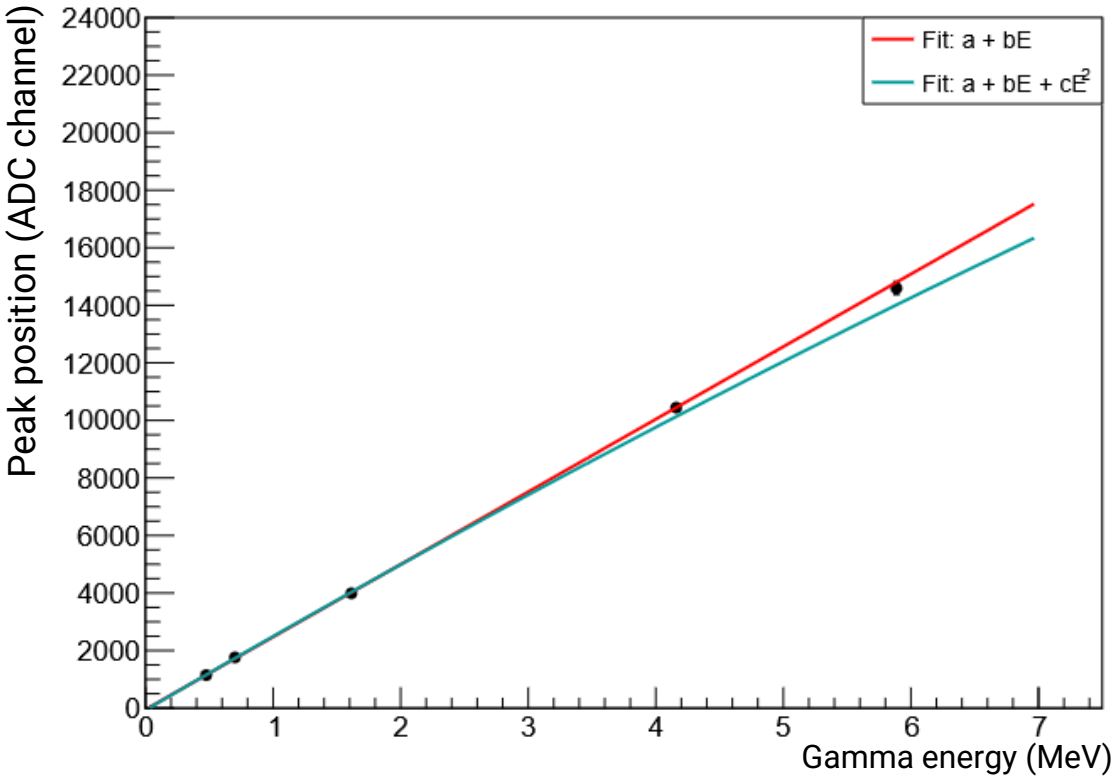


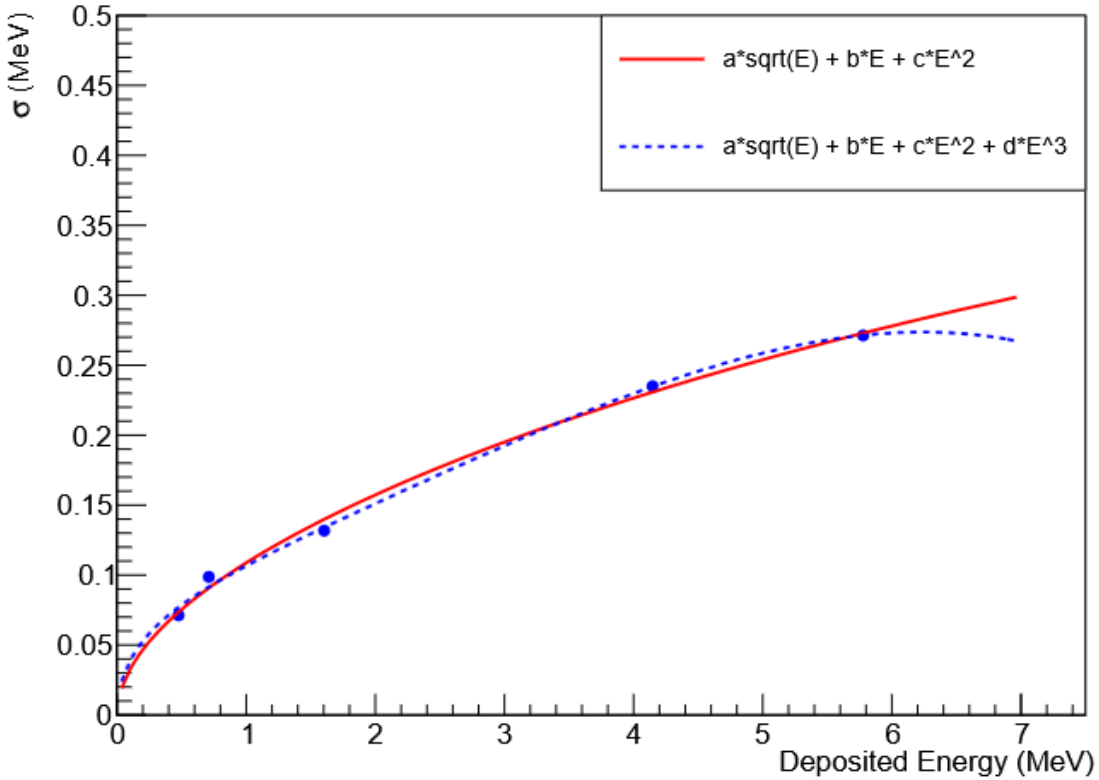




Peak fits for monoenergetic γ-ray sources

Capture measurements at n_TOF

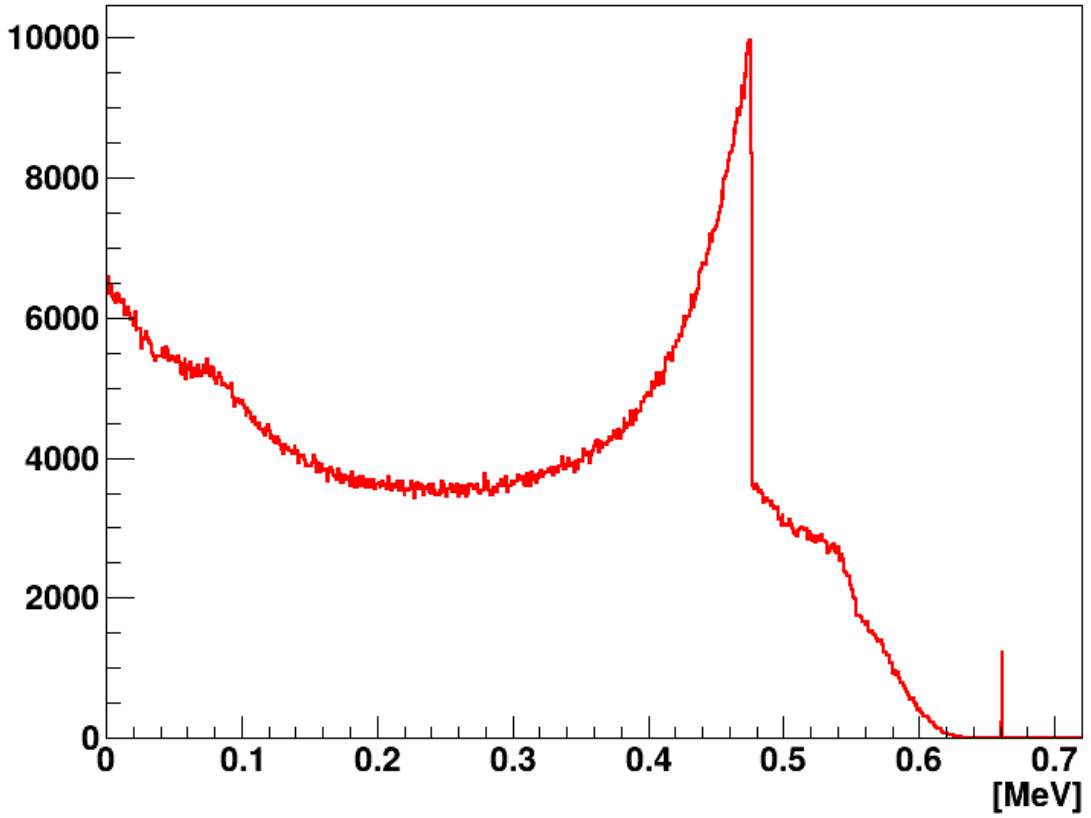




Calibration curve and resolution for C_6D_6 detectors

Capture measurements at n_TOF

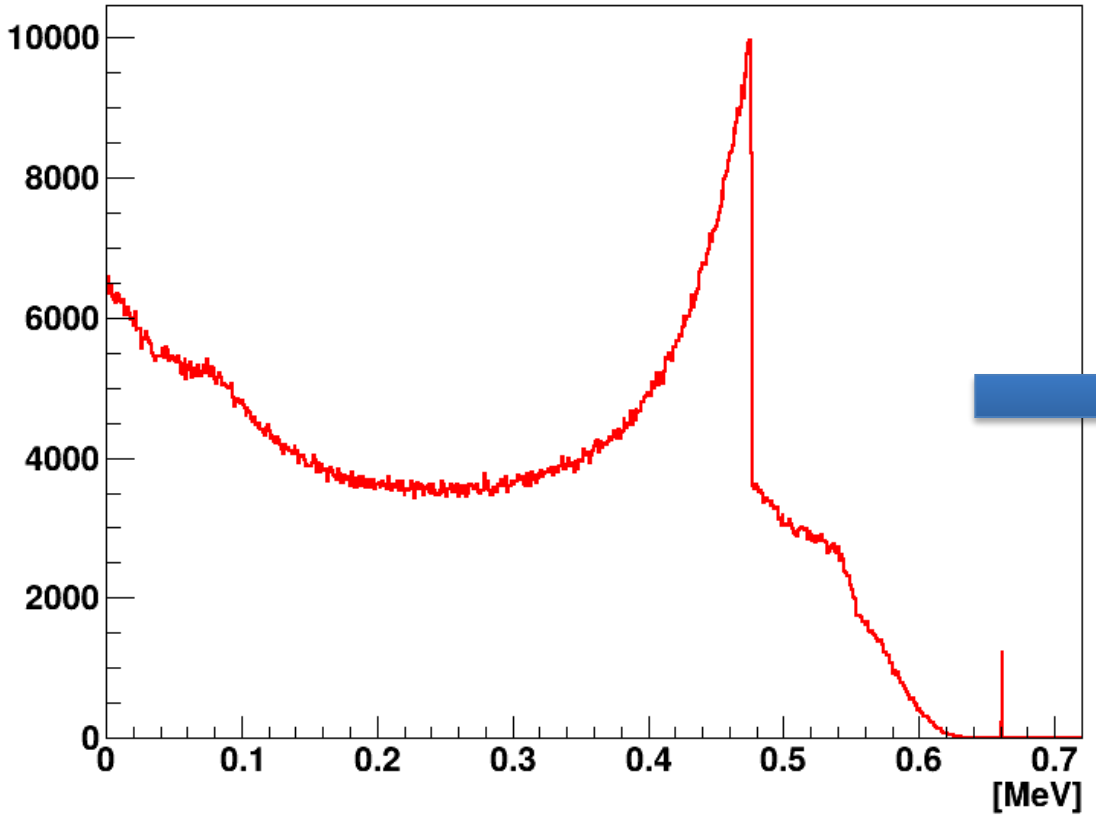
Monte Carlo



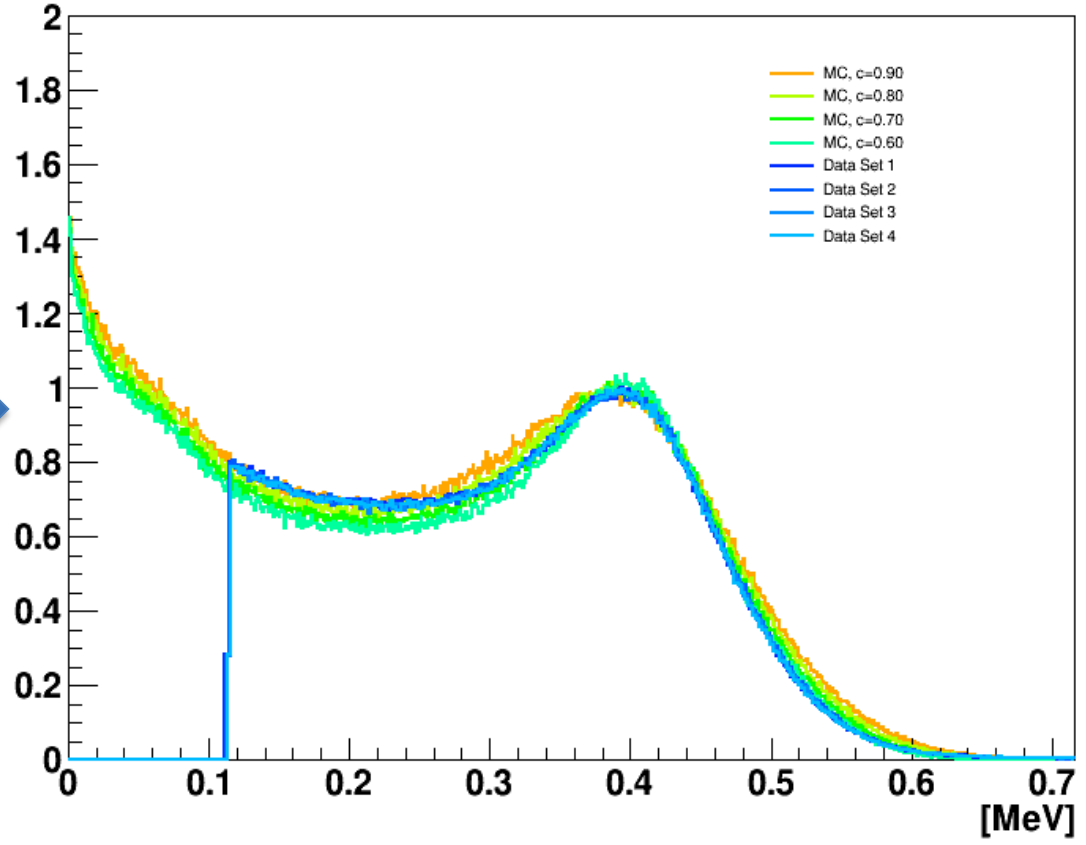
From P. Console Camprini

Capture measurements at n_TOF

Monte Carlo

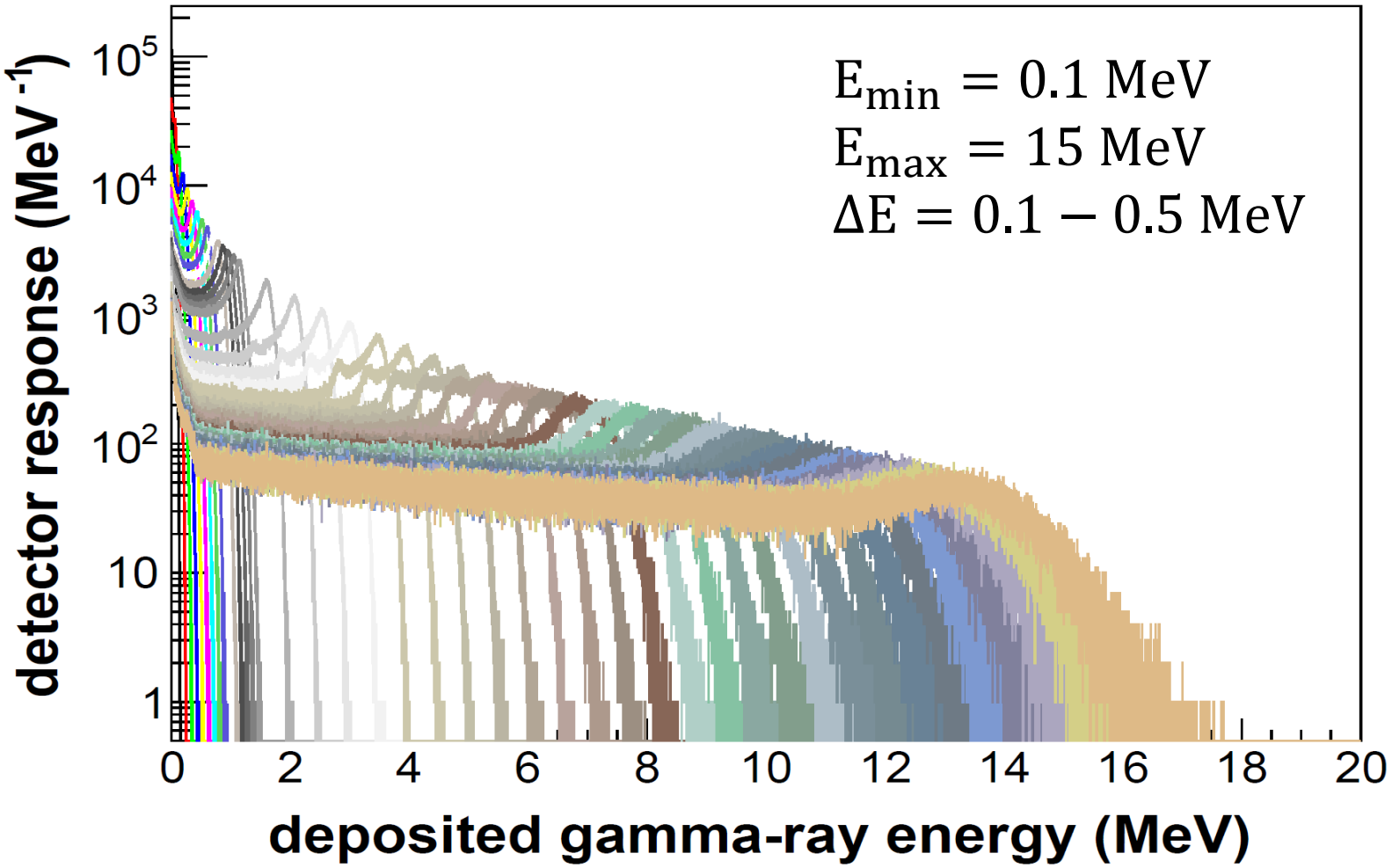


Smearing and comparison

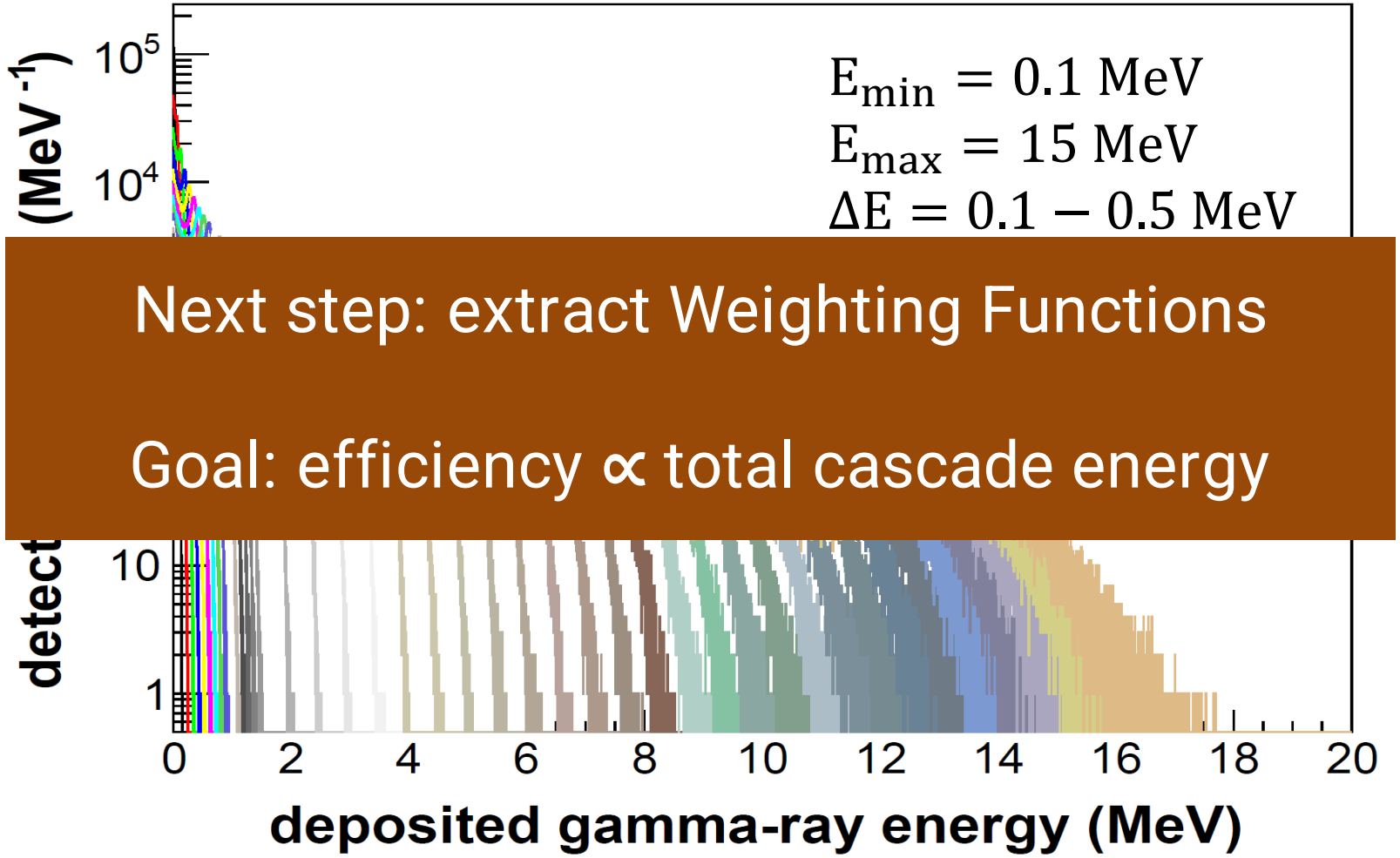


From P. Console Camprini

Capture measurements at n_TOF



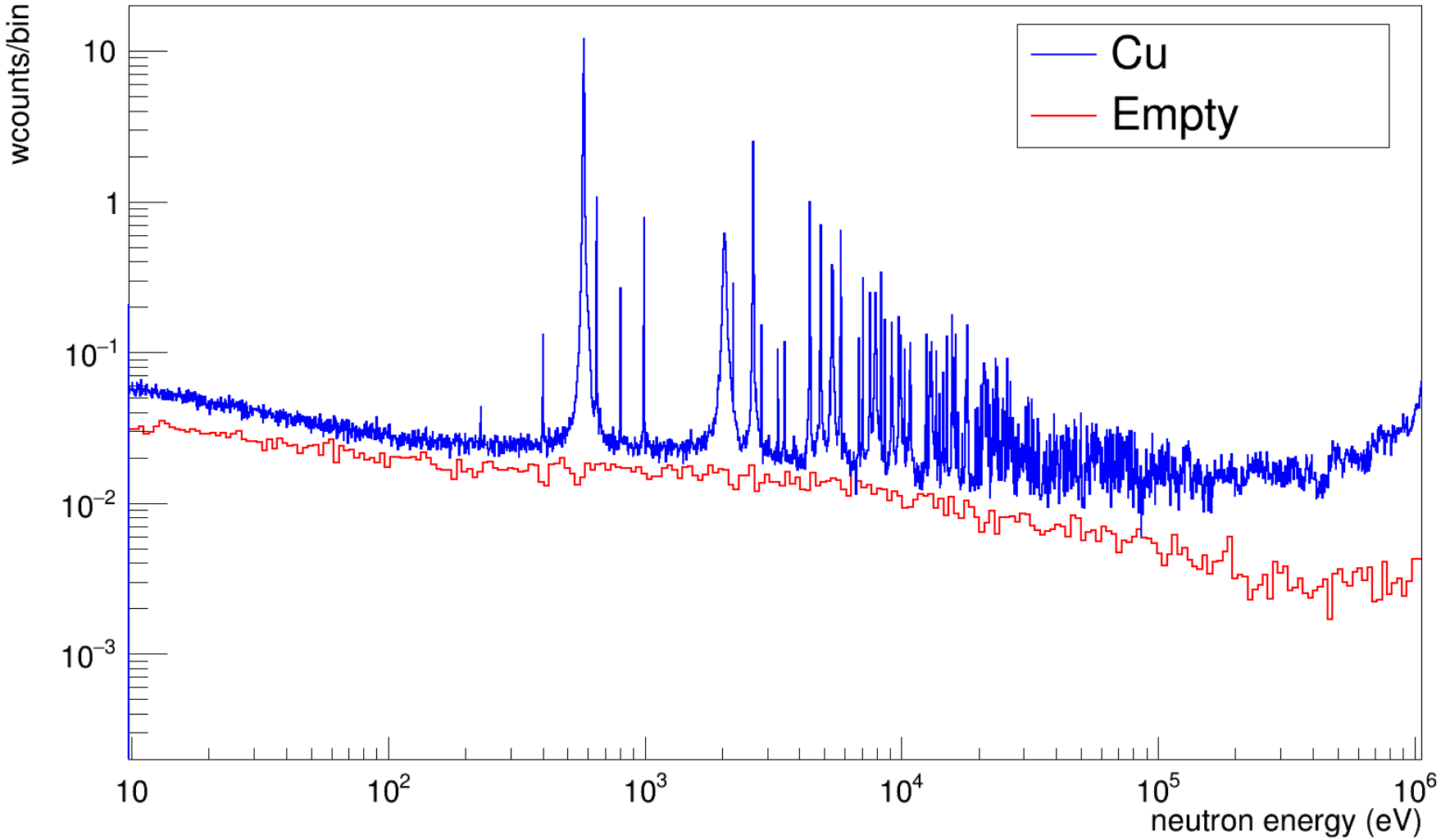
Capture measurements at n_TOF



Next step: extract Weighting Functions

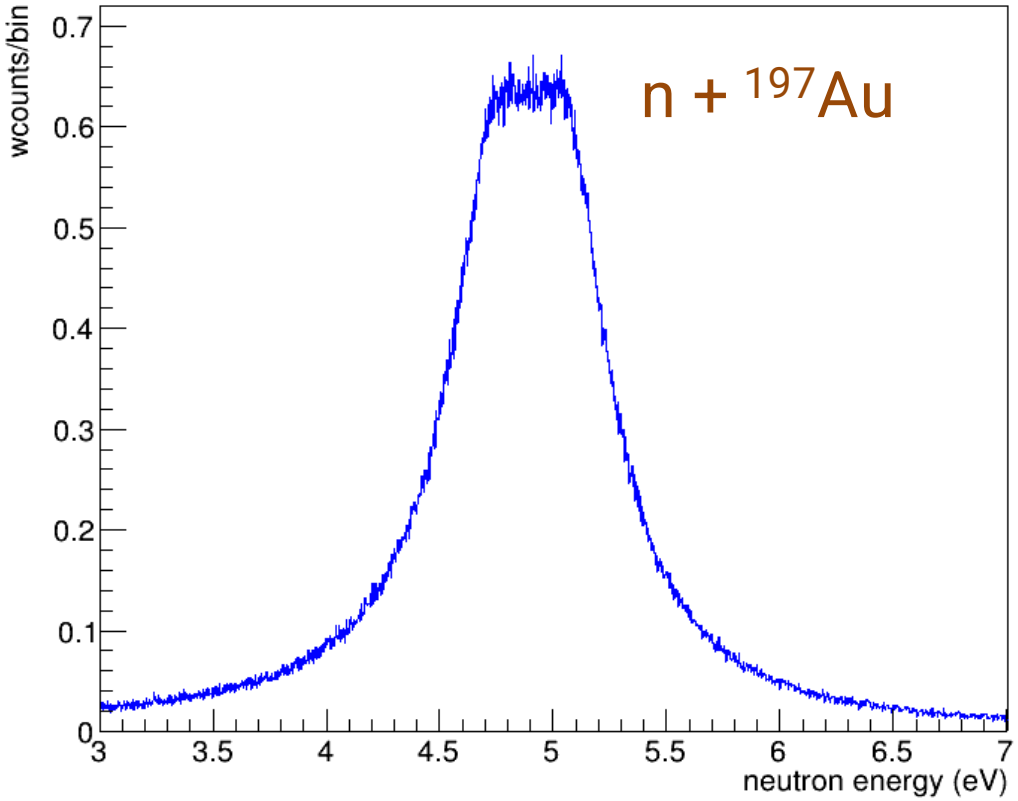
Goal: efficiency ∝ total cascade energy

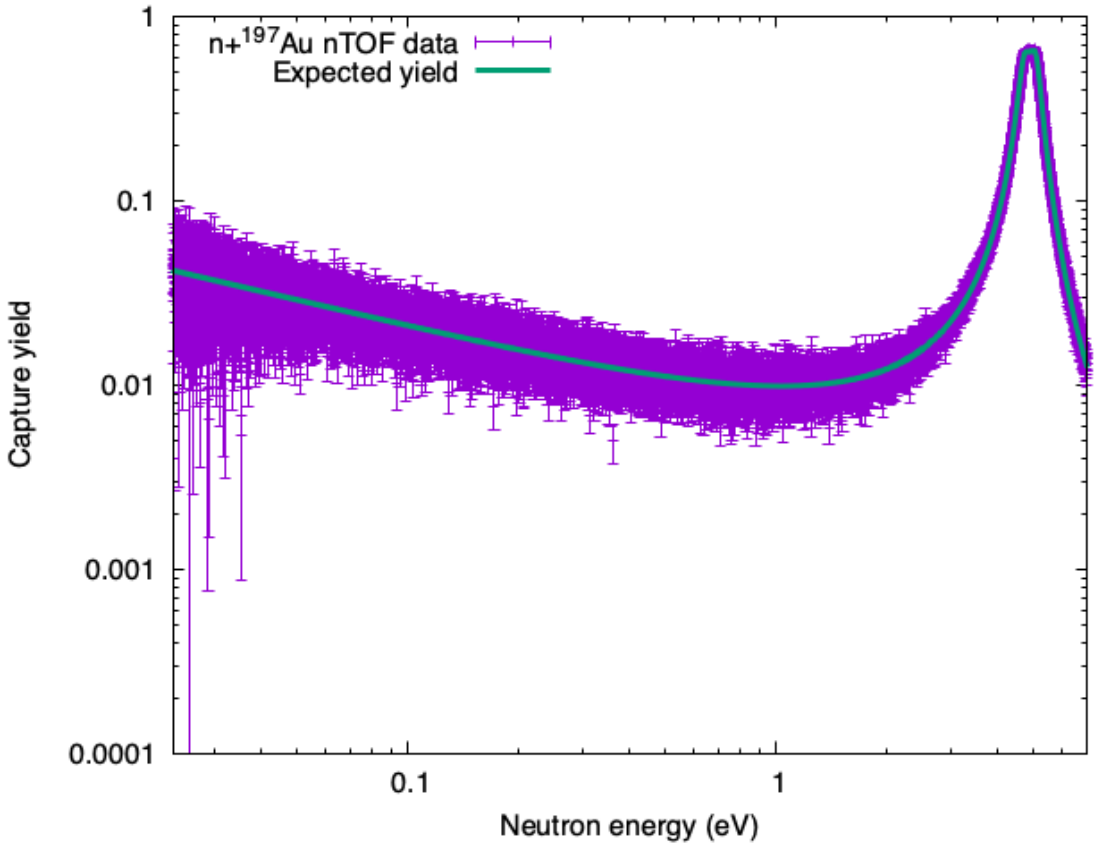
Capture measurements at n_TOF



Weighted Spectra

Capture measurements at n_TOF

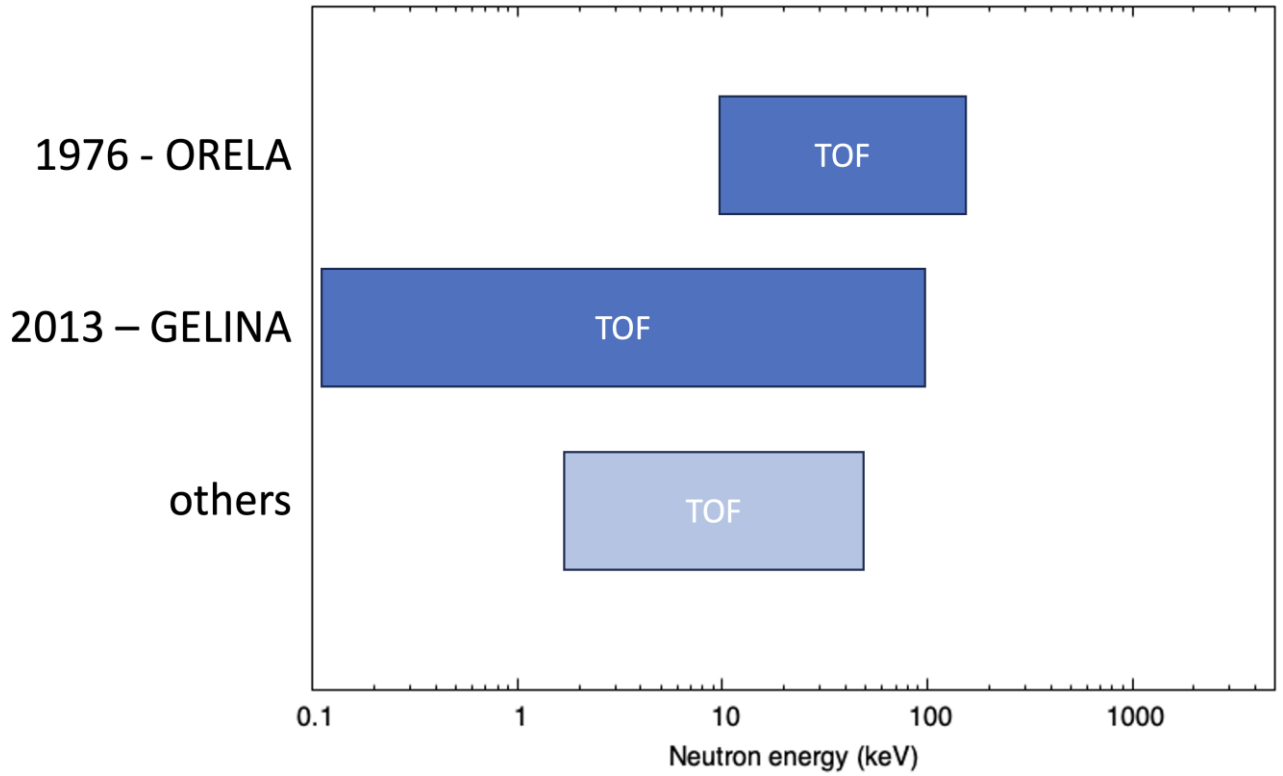




Normalization & more quality checks

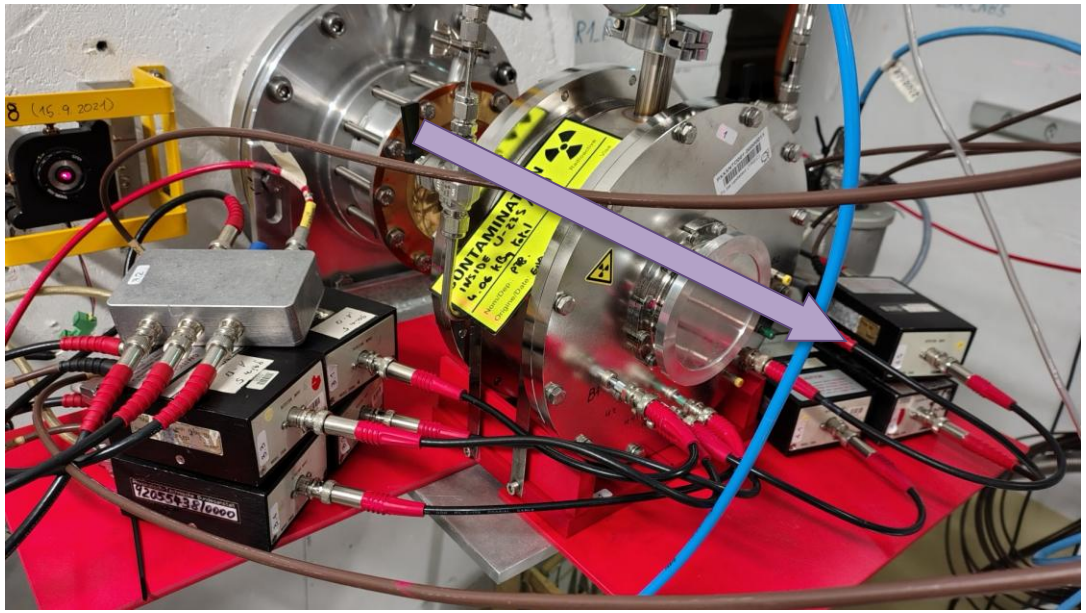
Transmission measurement of ^{nat}Cu at n_TOF (2025)

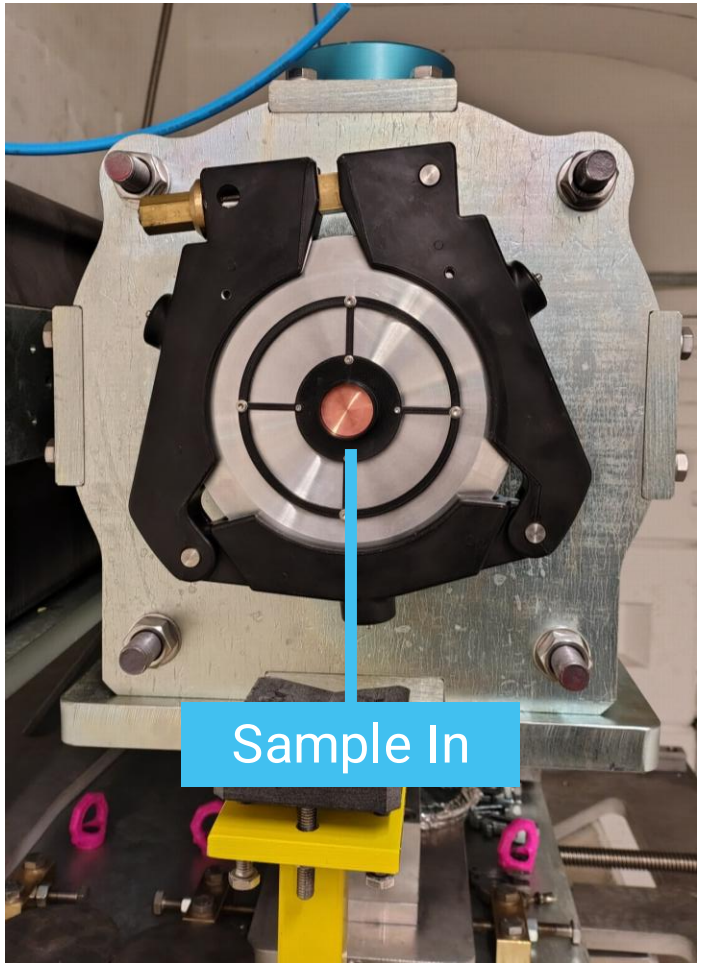
- 2025: $^{\mathrm{nat}}\mathrm{Cu}(\mathrm{n},\mathrm{tot})$
- Measurements with ^{235}U-loaded fission chamber
- Resonance parameter extraction in the energy range of interest
  $E_n < 5$ MeV, σ_{tot} below 3-5%
- Target: σ_{tot} uncertainty below 5% for $E_n < 100$ keV with 100 bpd

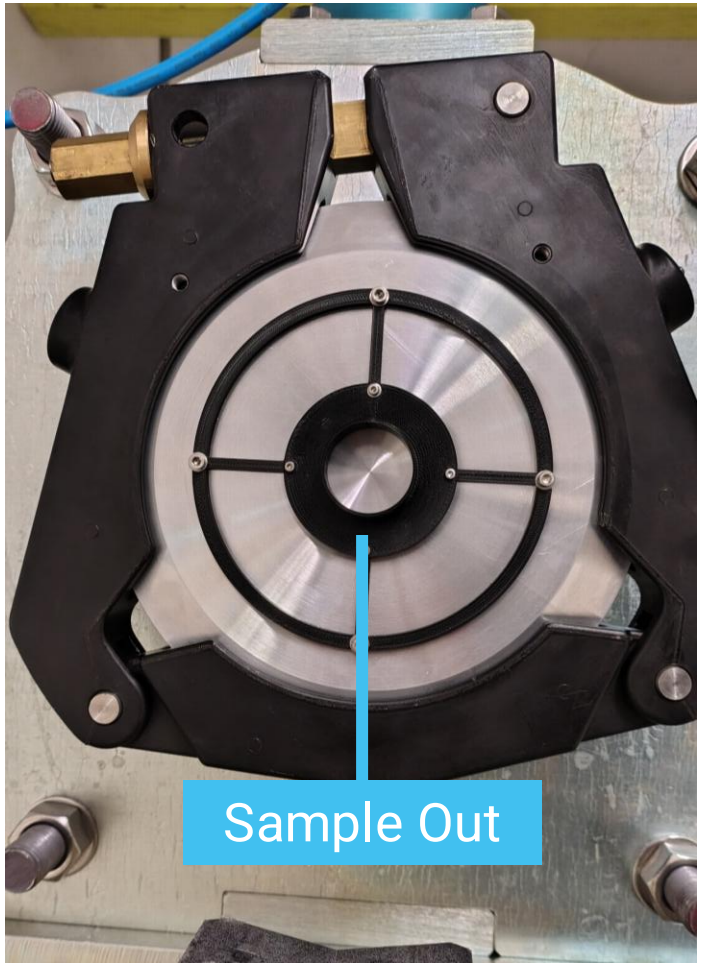


Transmission measurement of ^{nat}Cu at n_TOF (2025)

- PTB LMFC: fission chamber loaded with six ^{235}U foils, one empty for background studies
- Target in transmission station:
  Sample In vs Sample Out measurements → σ_{tot}

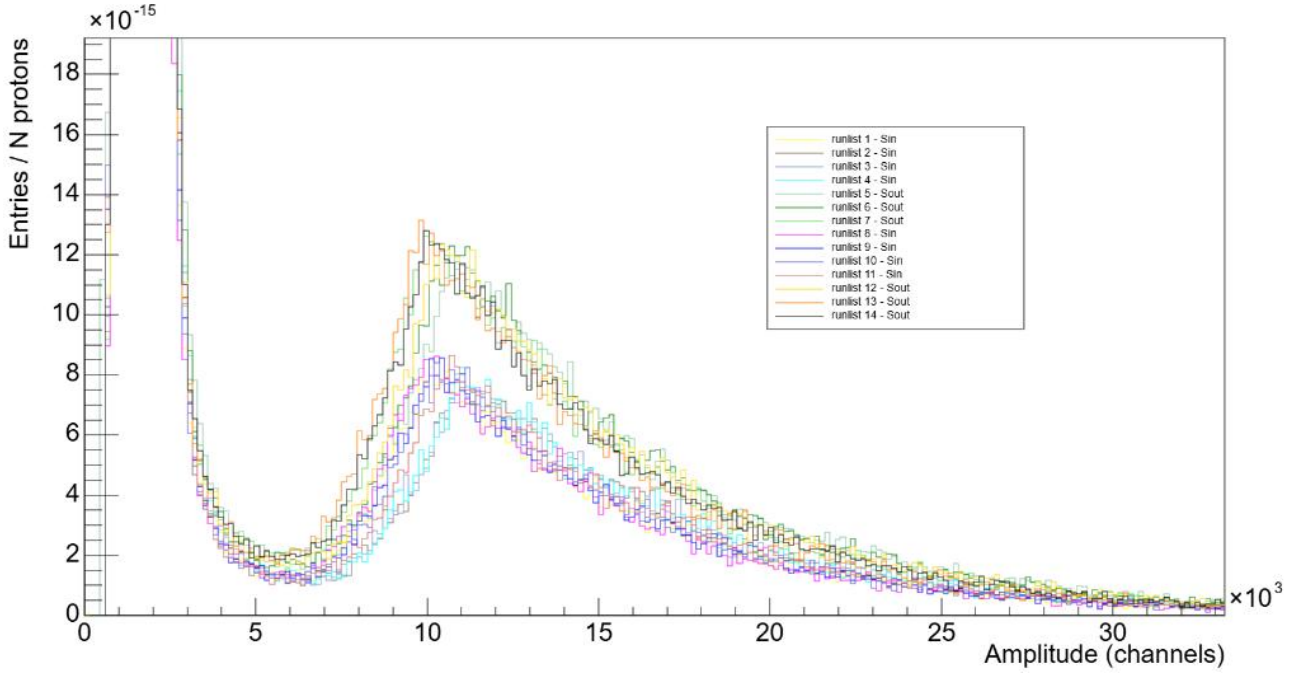


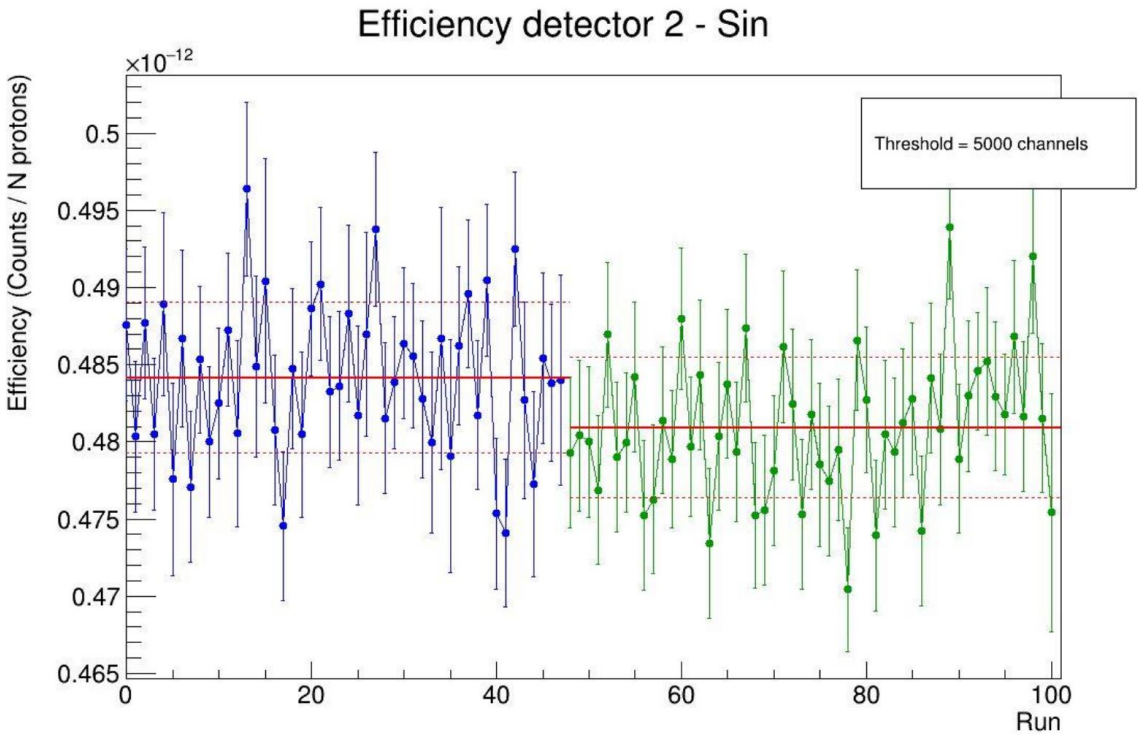




Transmission measurements at n_TOF

- 6 different & independent channels + 1 empty
- 2 sets of Sample-in & Sample-out
- 1-month data taking → check for stability of signal shape, gain, etc.

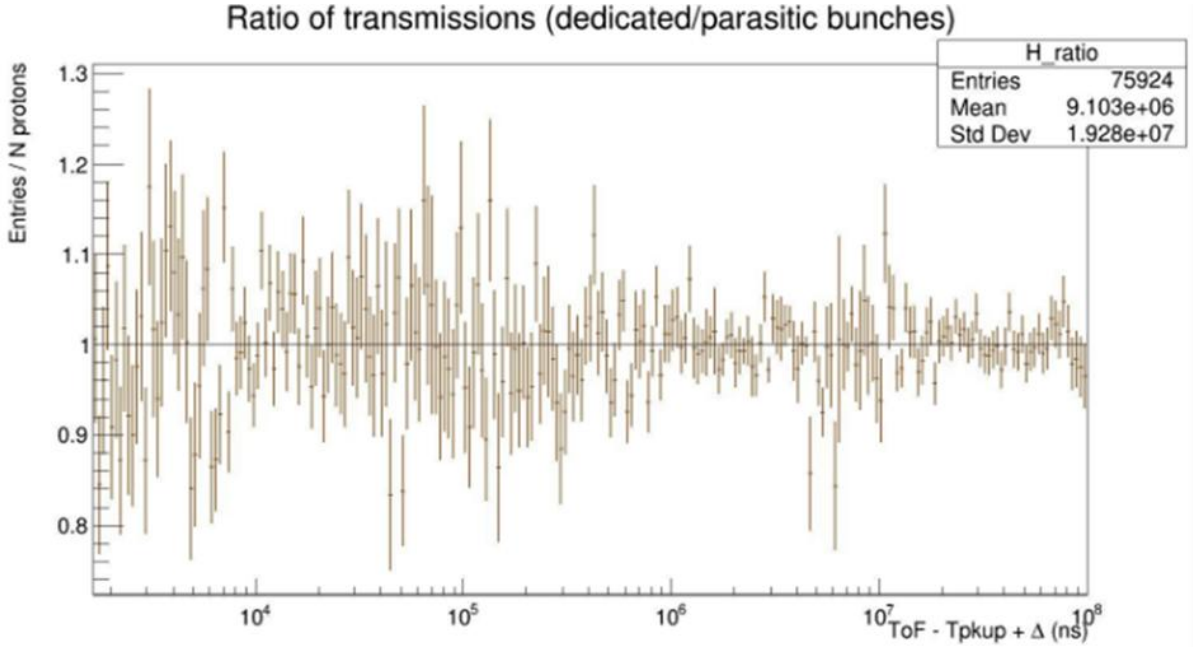


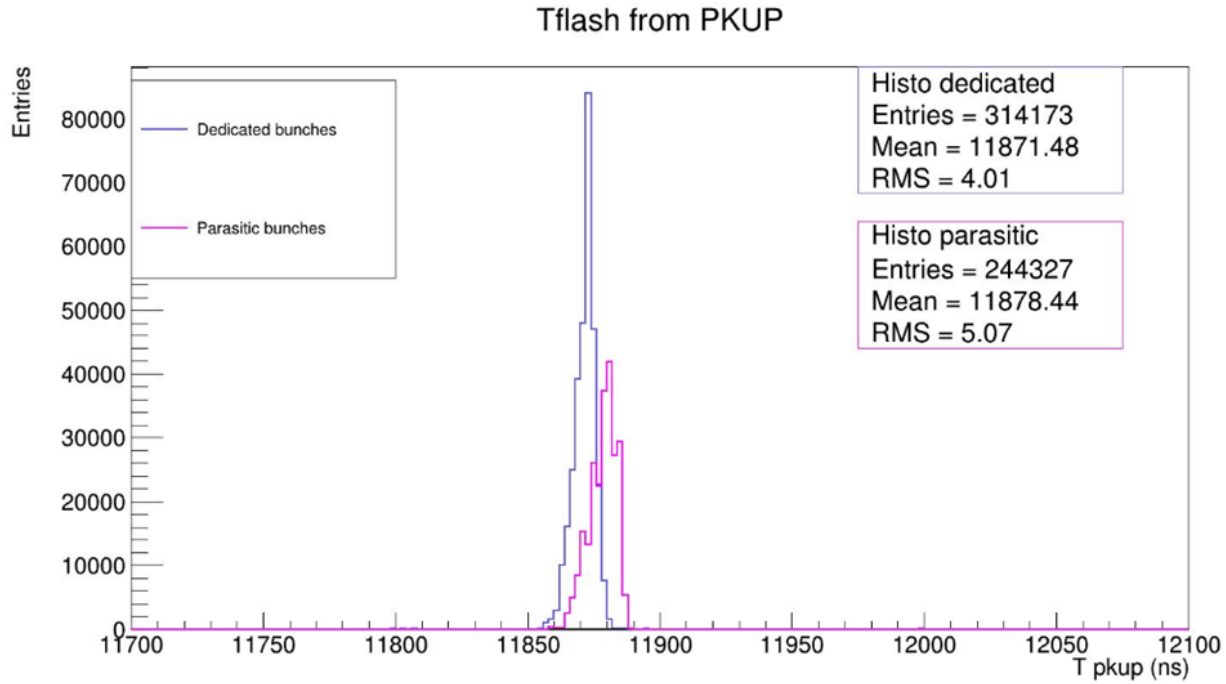


From A. Berardi Master's Thesis work

Transmission measurements at n_TOF

- Optimization of Pulse Shape Analysis
- Calibration of γ-flash time
- Detector stability analysis
- Selection cuts and efficiency studies
- Study of parasitic/dedicated bunches





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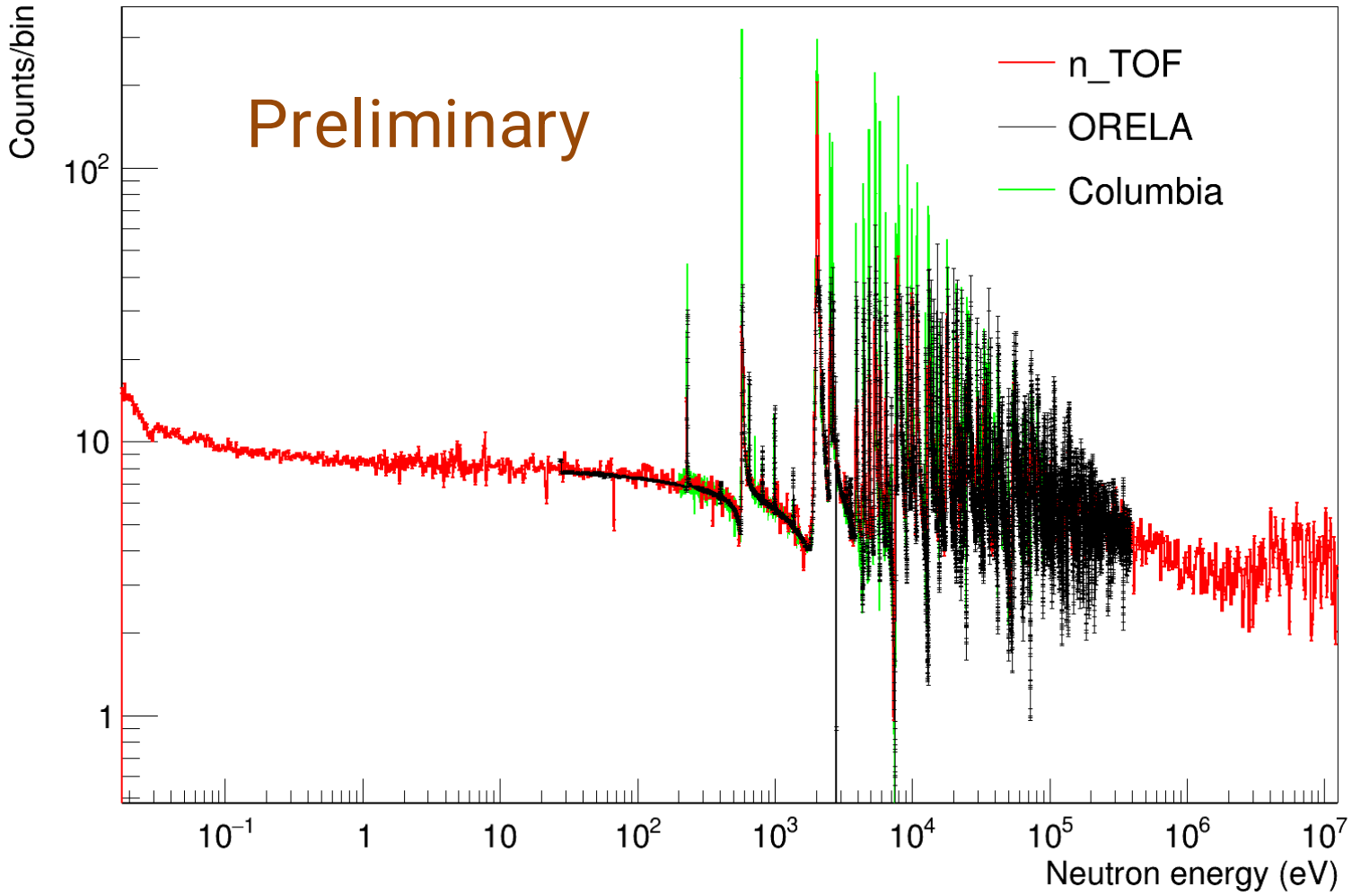
Transmission measurement at n_TOF



Conclusions

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  - ^{63,65}Cu(n,γ), 2024
  - ^{nat}Cu(n,tot), 2025
  - ^{63,65}Cu(n,n), ^{63,65}Cu(n,n'), 2026?

Conclusions

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- High-precision measurements at n_TOF EAR1, CERN
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  - ^{63,65}Cu(n,γ), 2024
  - ^{nat}Cu(n,tot), 2025
  - ^{63,65}Cu(n,n), ^{63,65}Cu(n,n'), 2026?
- Analysis ongoing, promising preliminary results

Acknowledgments

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 (EURO-LABS).

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Thank you for your attention!

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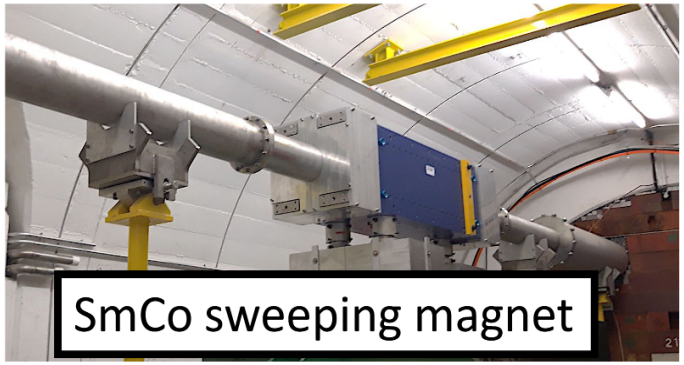
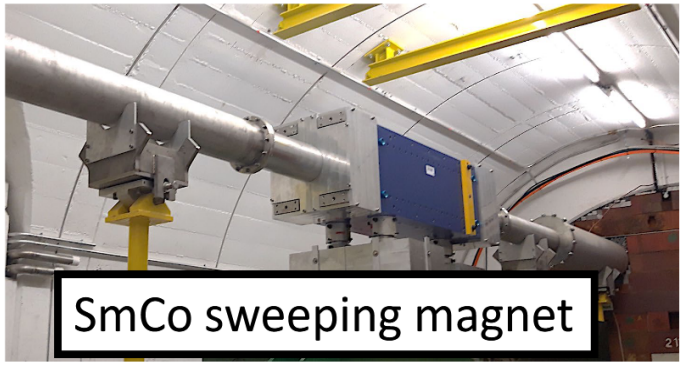
Why EAR1?



From N. Patronis, IAEA-CN301-154

Why EAR1?



From N. Patronis, IAEA-CN301-154

Uncertainties in a capture experiment

M. Mastromarco *et al.*, Eur. Phys. J. A (2019) 55: 9

Table 3. Summary of the correlated uncertainties in the ^{155}Gd(n, γ) and ^{157}Gd(n, γ) cross section measurements.

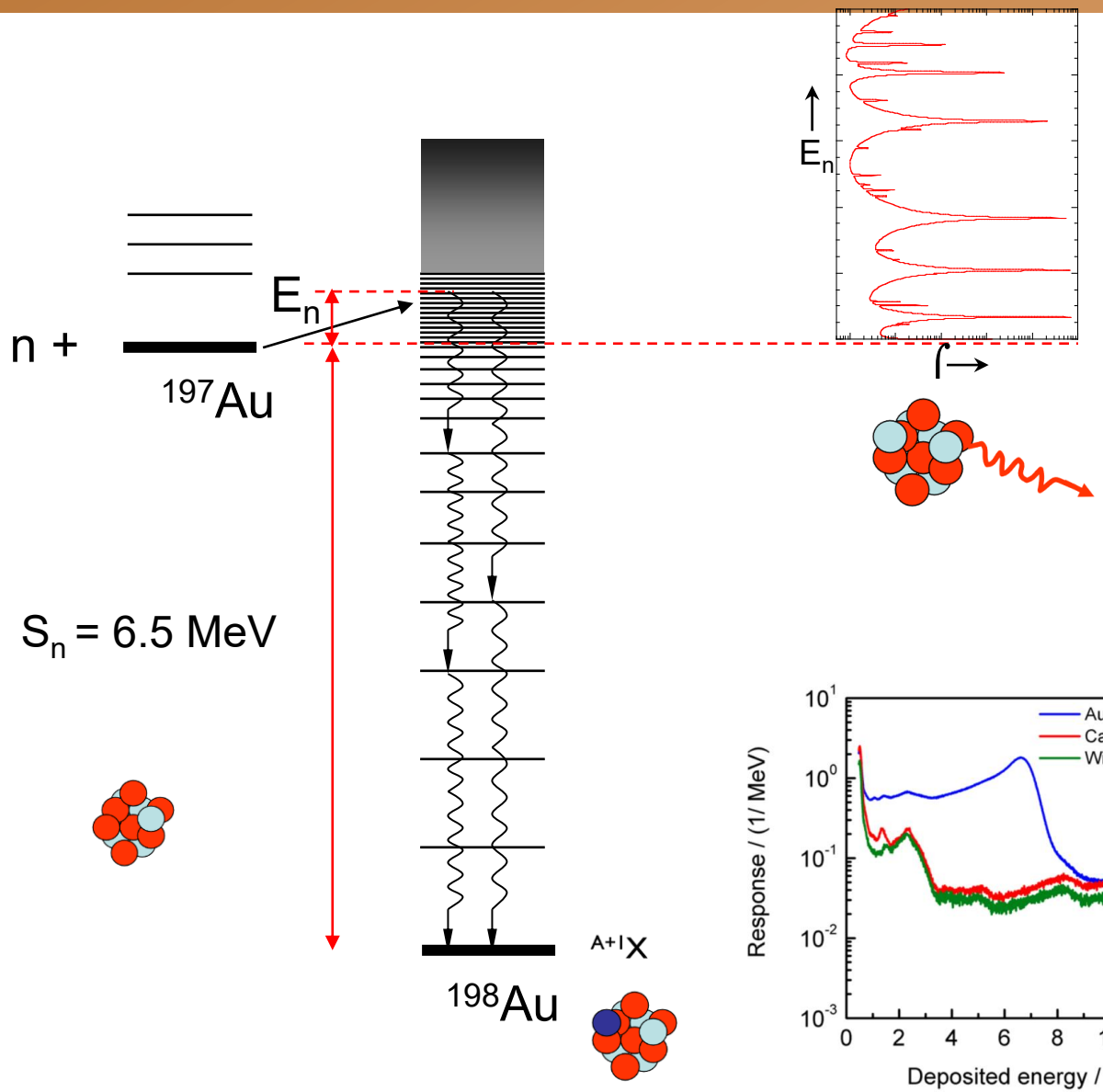
Source of	^{155}Gd(n, γ)		^{157}Gd(n, γ)	
uncertainty	near thermal	resonance region	near thermal	resonance region
Normalization	1.2%	1.2%	1.2%	1.2%
PHWT	1.5%	1.5%	1.5%	1.5%
Background	1.4%	$\approx$ 1%	1.0%	$\approx$ 1%
BIF	1.5%		1.5%	
Flux	1.0%	1.0%	1.0%	1.0%
Sample mass	1.0%	$<$ 0.2%	2.1%	$<$ 0.2%
Temperature		1%		1%
Total	3.2%	2.6%	3.5%	2.6%

The n_TOF facility

The advantages of n_TOF are a direct consequence of the characteristics of the PS proton beam: high energy, high peak current, low duty cycle.

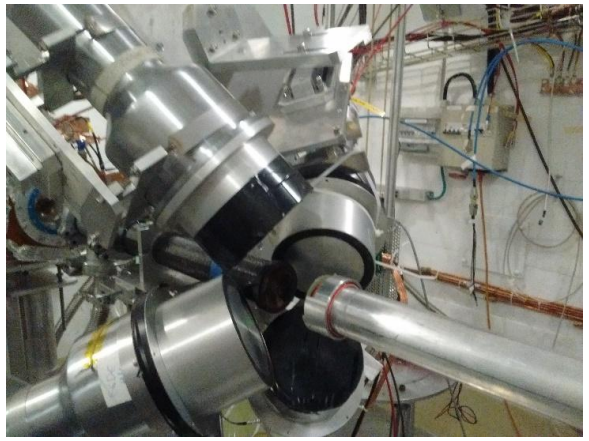
proton beam momentum	20 GeV/c
intensity (dedicated mode)	~ 10^{13} protons/pulse
repetition frequency	1 pulse/1.2s
pulse width	6 ns (rms)
n/p	300
lead target dimensions	80x80x60 cm^3
cooling & moderation material	N_2 & (H_2O + ^{10}B)
moderator thickness in the exit face	5 cm
neutron beam dimension in EAR-1 (capture mode)	2 cm (FWHM)

Extra slides: (n,γ)

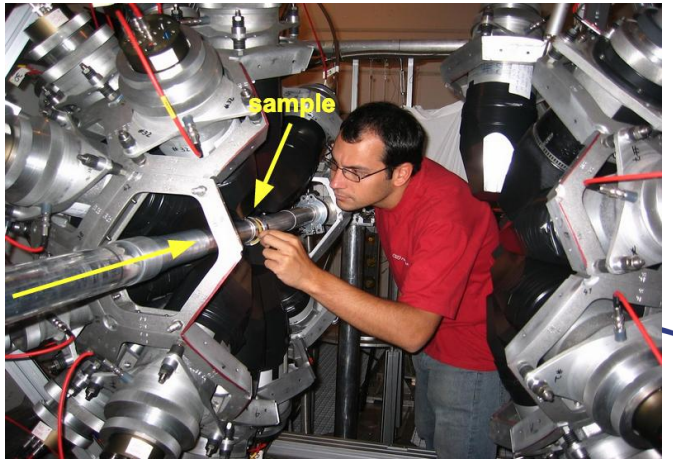


The C_6D_6 Total Energy Detectors (TED)

C_6D_6 scintillators at 135°



The BaF_2 Total γ-ray Absorption Detector

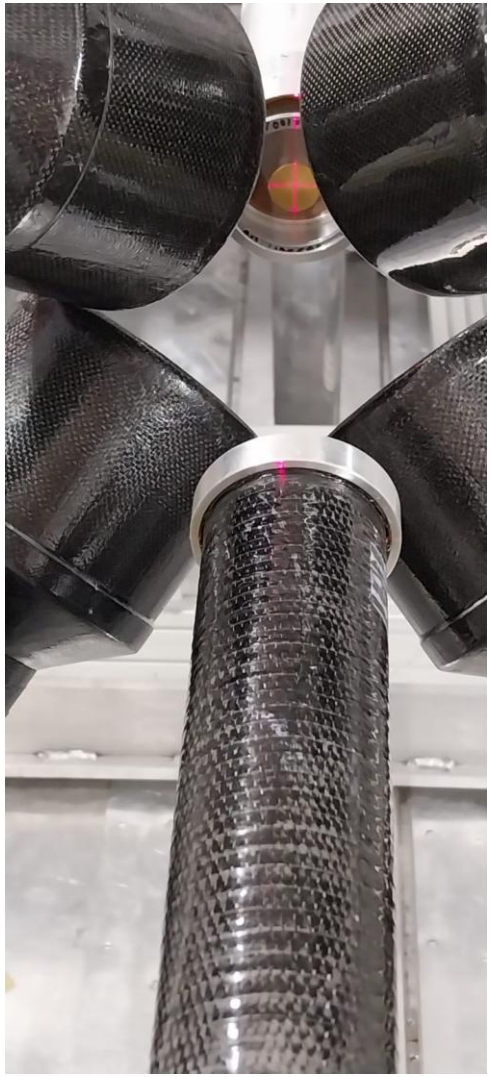


Capture measurements at n_TOF

- Final capture yield:

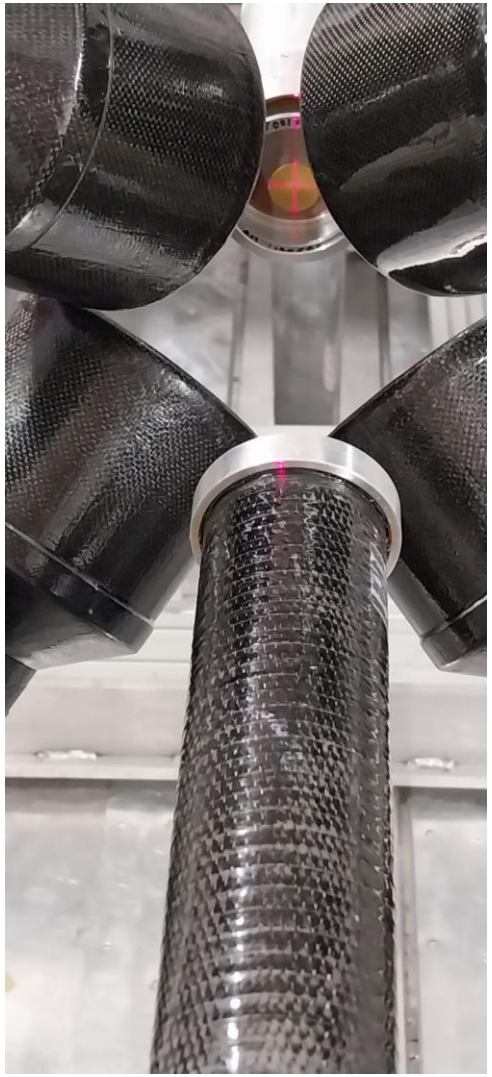
$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$

  - $C(E_n)$: number of counts in the detector
  - $B(E_n)$: background
  - $\varepsilon(E_n)$: detection efficiency
  - $\phi(E_n)$: # of neutrons impinging on target
- Before $Y_{(n,\gamma)}$ lots of analysis steps are needed:
  - pulse shape analysis
  - detector calibrations
  - physical cuts on spectra
  - PHWT
  - neutron beam analysis
  - background subtraction (!)
  - ...



Capture measurements at n_TOF

- The C_6D_6 detectors use the Total Energy Detection (TED) principle + Pulse Height Weighting Technique (PHWT) to obtain precise capture data.
- TED: capture events are measured base on total γ-ray cascade energy, independently of the de-excitation path of compund nucleus
- PHWT: detector response is corrected through an energy-dependent weighting factor to make efficiency proportional to total cascade energy
- C_6D_6 offer fast timing and low neutron sensitivity



Stellar cross sections (MACS) for the s- process

Some cross sections measured in 2001 - 2024

- Branching point isotopes:

  ^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{203}Tl, ^{79}Se

- Abundances in presolar grains:

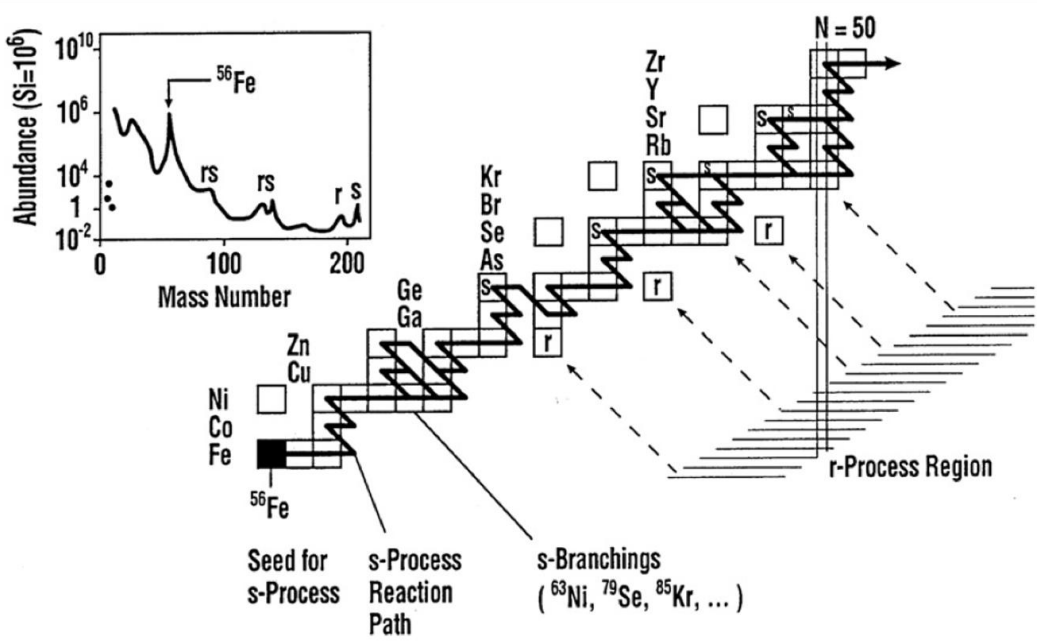
  ^{28,29,30}Si, ^{91,92,93,94,96}Zr, ^{94,96}Mo, ^{146}Nd

- Magic Nuclei and end-point:

  ^{139}La, ^{140}Ce, ^{90}Zr, ^{89}Y, ^{88}Sr, ^{204,206,207,208}Pb, ^{209}Bi

- Seeds isotopes:

  ^{54,56,57}Fe, ^{58,60,62,64}Ni, ^{59}Ni(n,a)



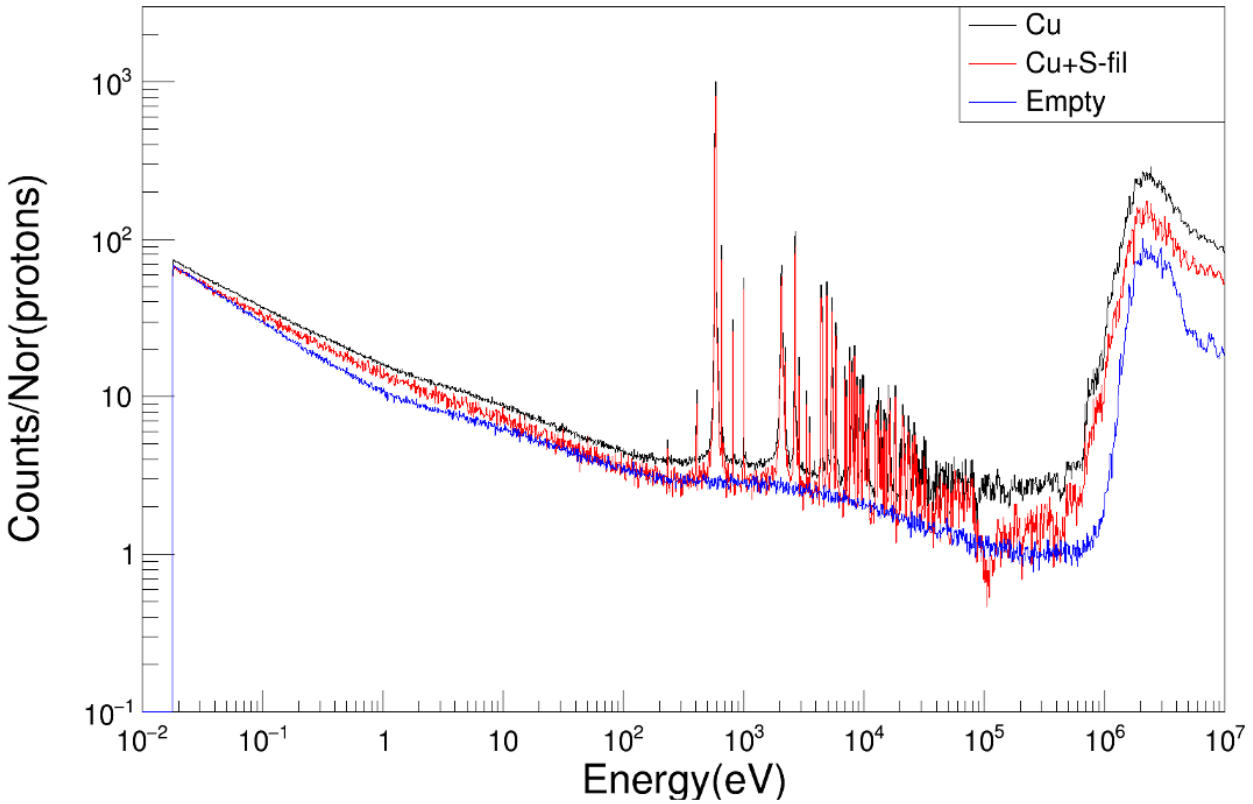
- Isotopes of special interest:

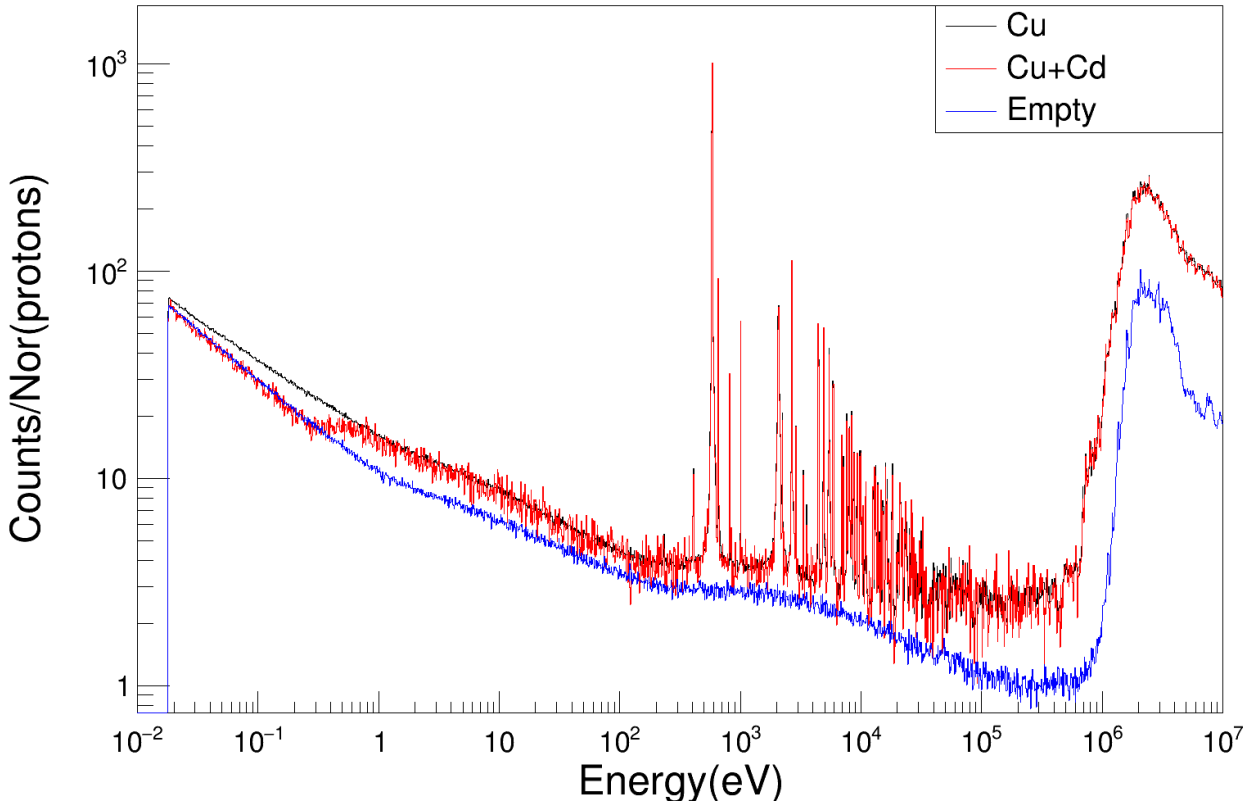
  ^{186,187,188}Os (cosmochronometer),^{197}Au (reference cross section), ^{24,25,26}Mg, ^{33}S(n,a), ^{14}N(n,p), ^{35}Cl(n,p), ^{26}Al(n,p), ^{26}Al(n,a) (neutron poison), ^{154}Gd (s-only isotopes), ^{40}K(n,p), ^{40}K(n,a), ^{63,65}Cu, ^{93,94}Nb, ^{68}Zn, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{77,78,80}Se (weak component), ^{155,157,160}Gd, ^{7}Li(n,p), ^{7}Li(n,a) BBN

- Neutron Sources ^{22}Ne(a,n)^{25}Mg and ^{13}C(a,n)^{16}O:

  n+^{25}Mg, n+^{16}O

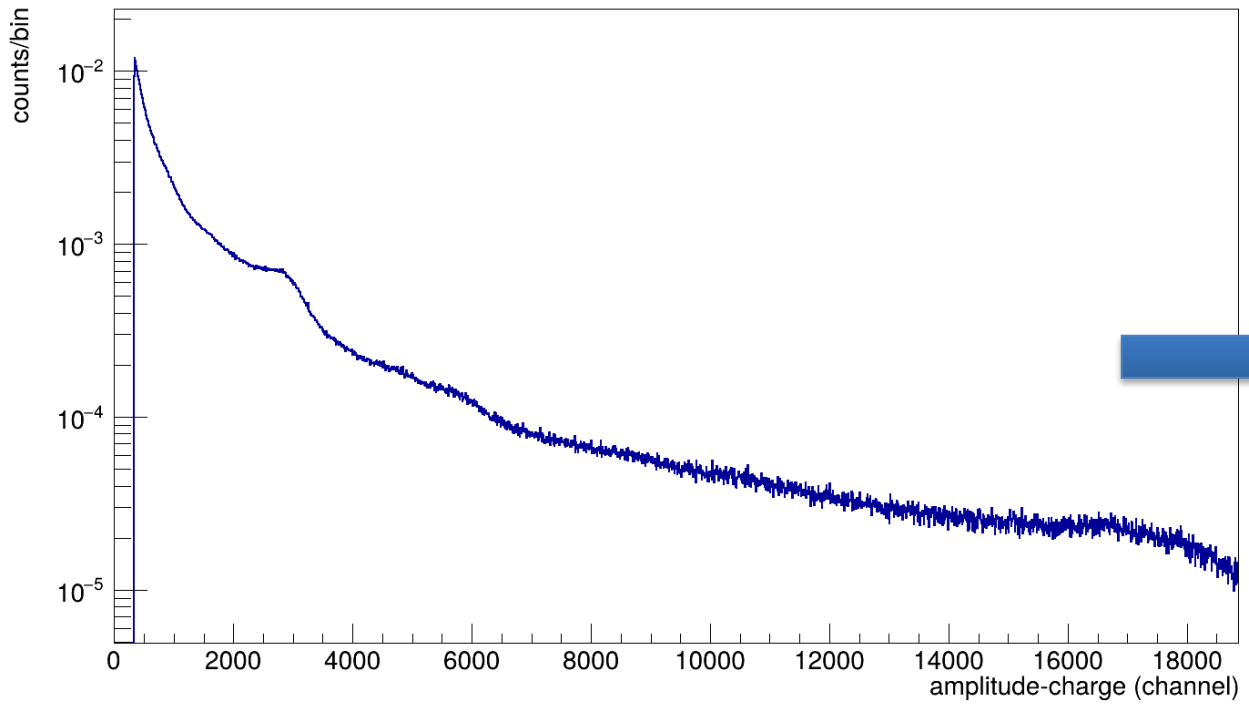
Capture measurements at n_TOF

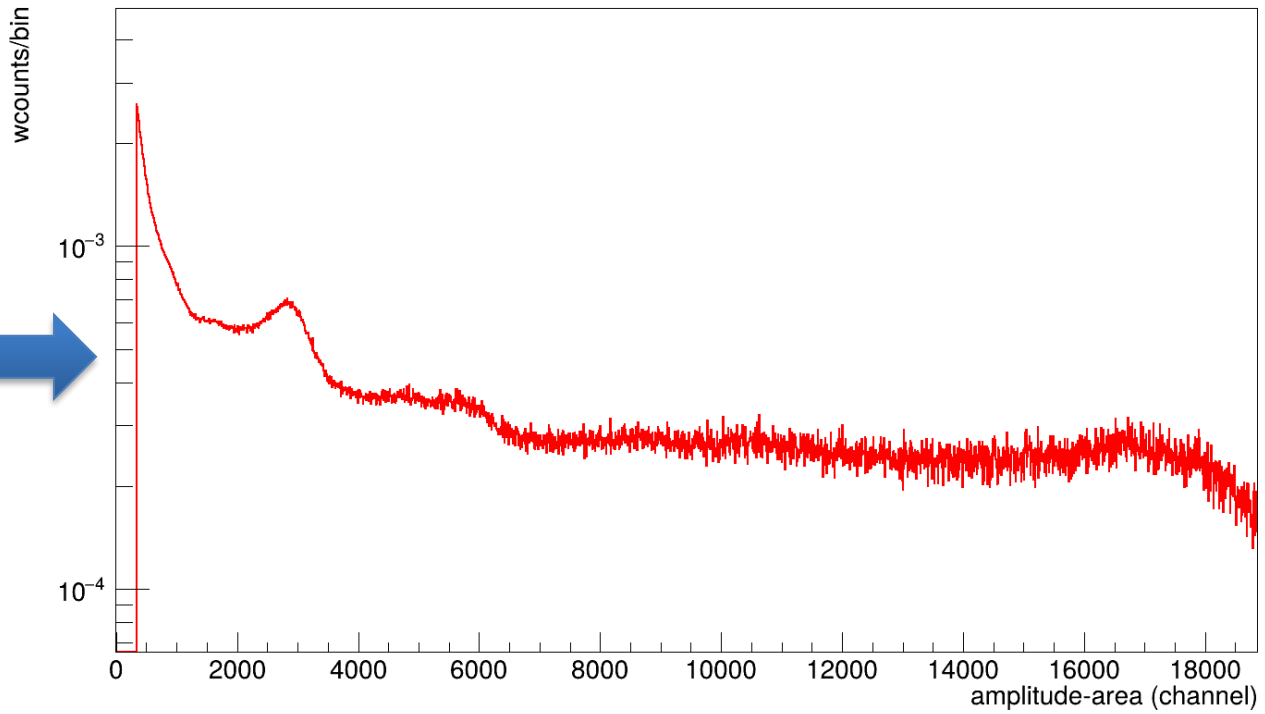




Filters for background studies

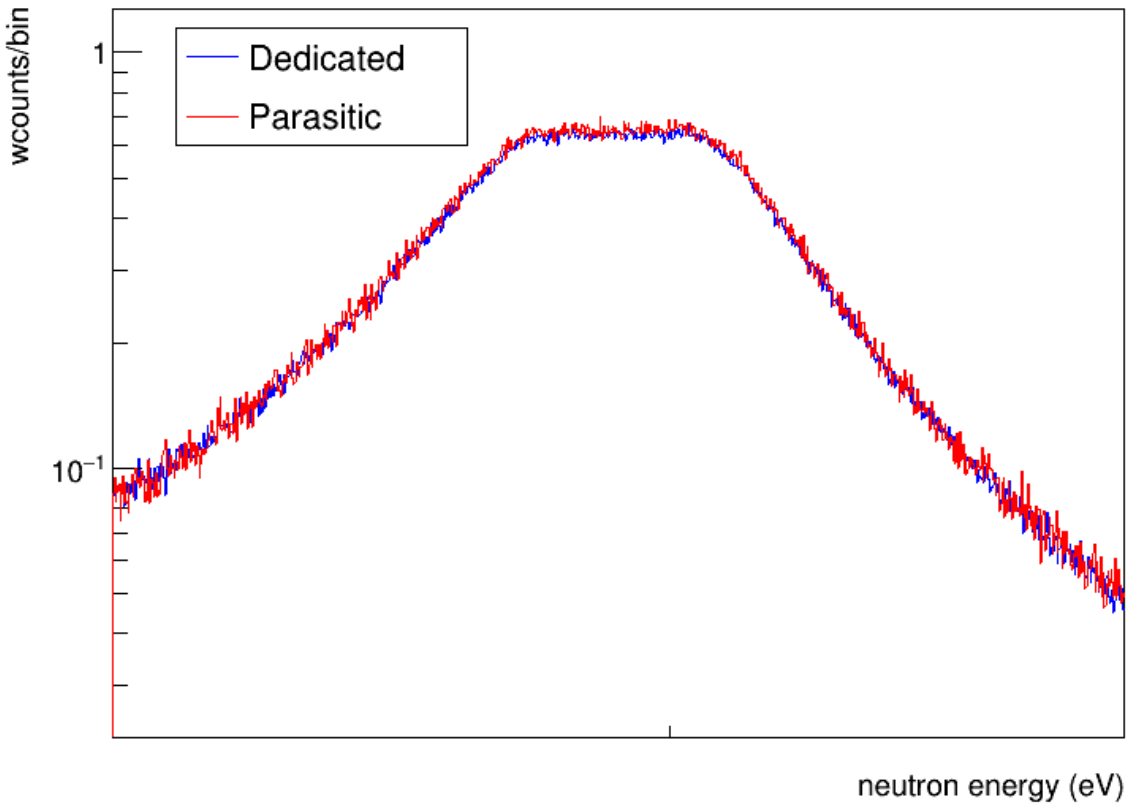
Capture measurements at n_TOF

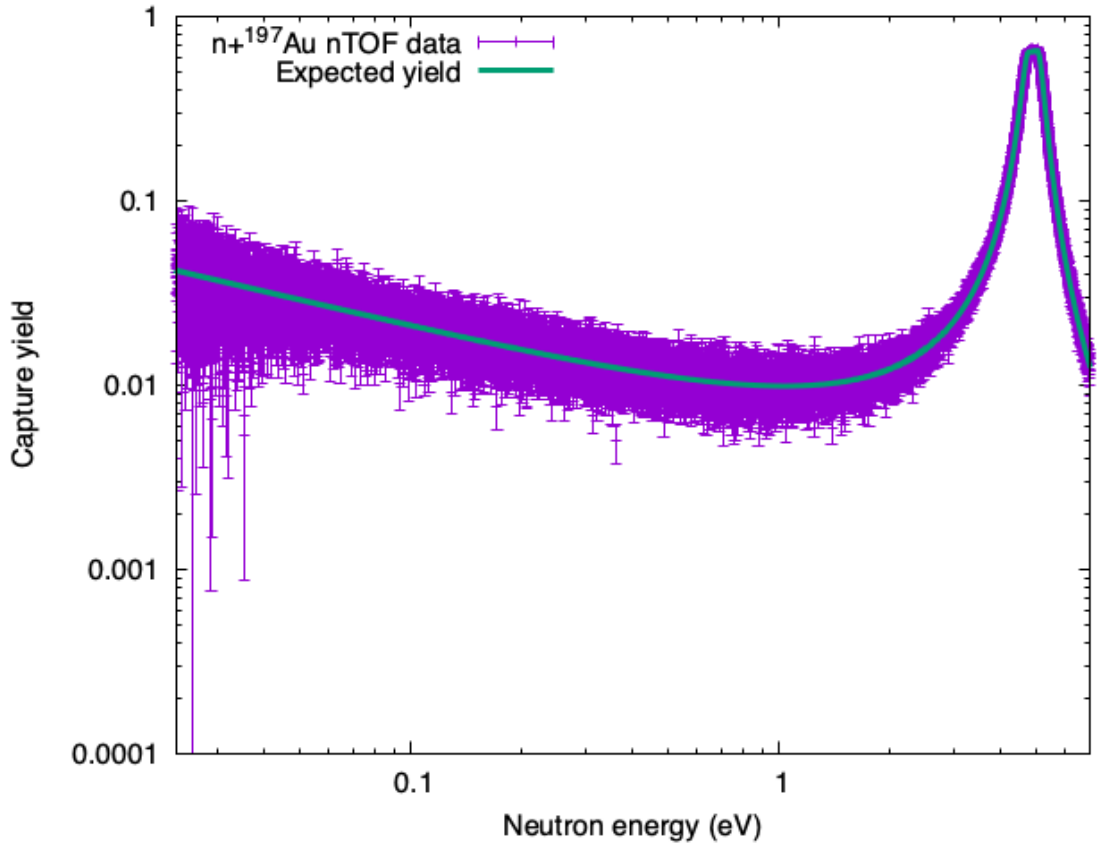




Weighted Spectra

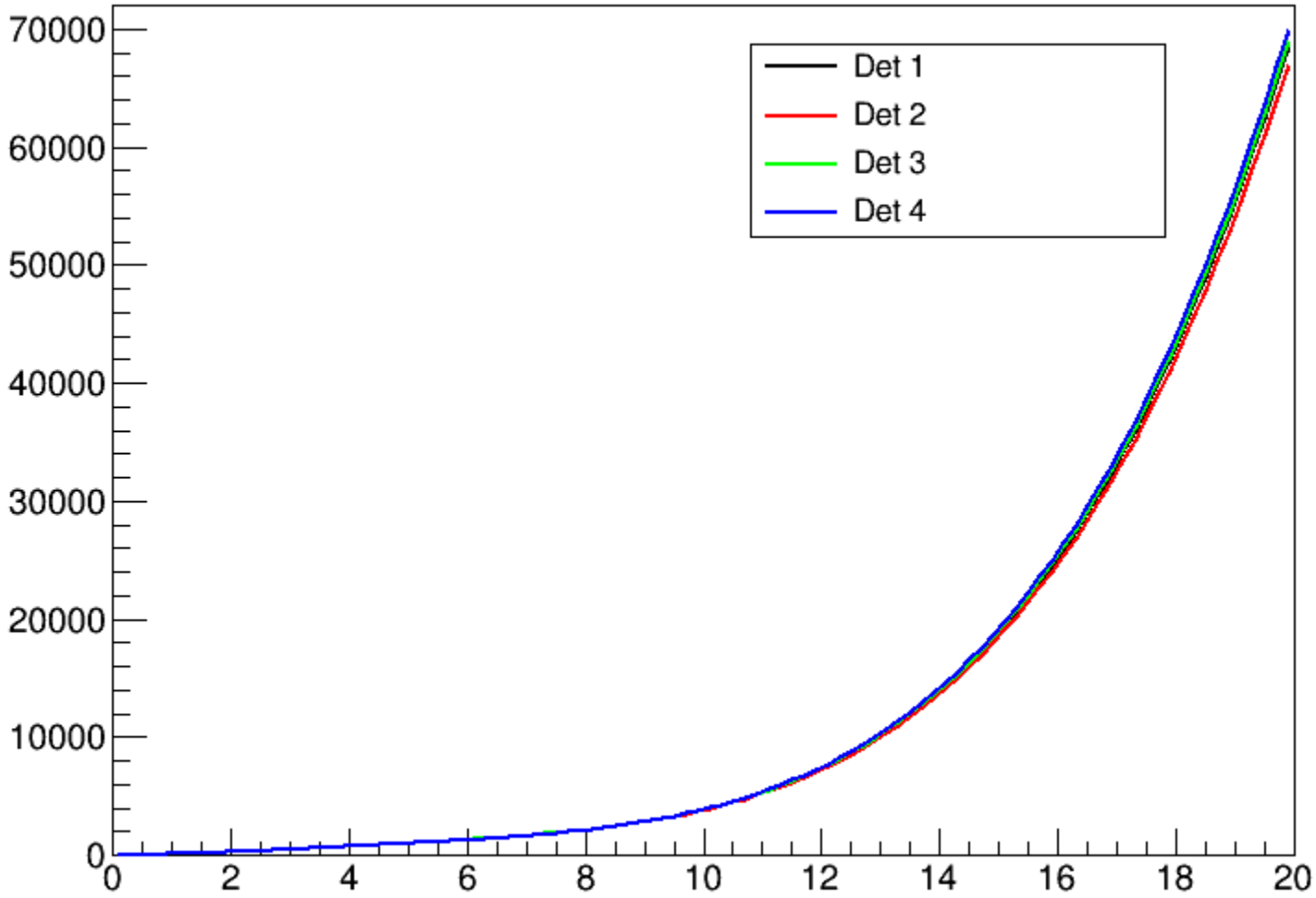
Capture measurements at n_TOF





Normalization & more quality checks

Capture measurements at n_TOF



Weighting Functions