Neutron spectroscopy of ^{26}Mg states: constraining the $^{22}Ne(\alpha,n)^{25}Mg$ reaction rate

Nicholas Pieretti on behalf of the n_TOF Collaboration

Department of Physics and Astronomy

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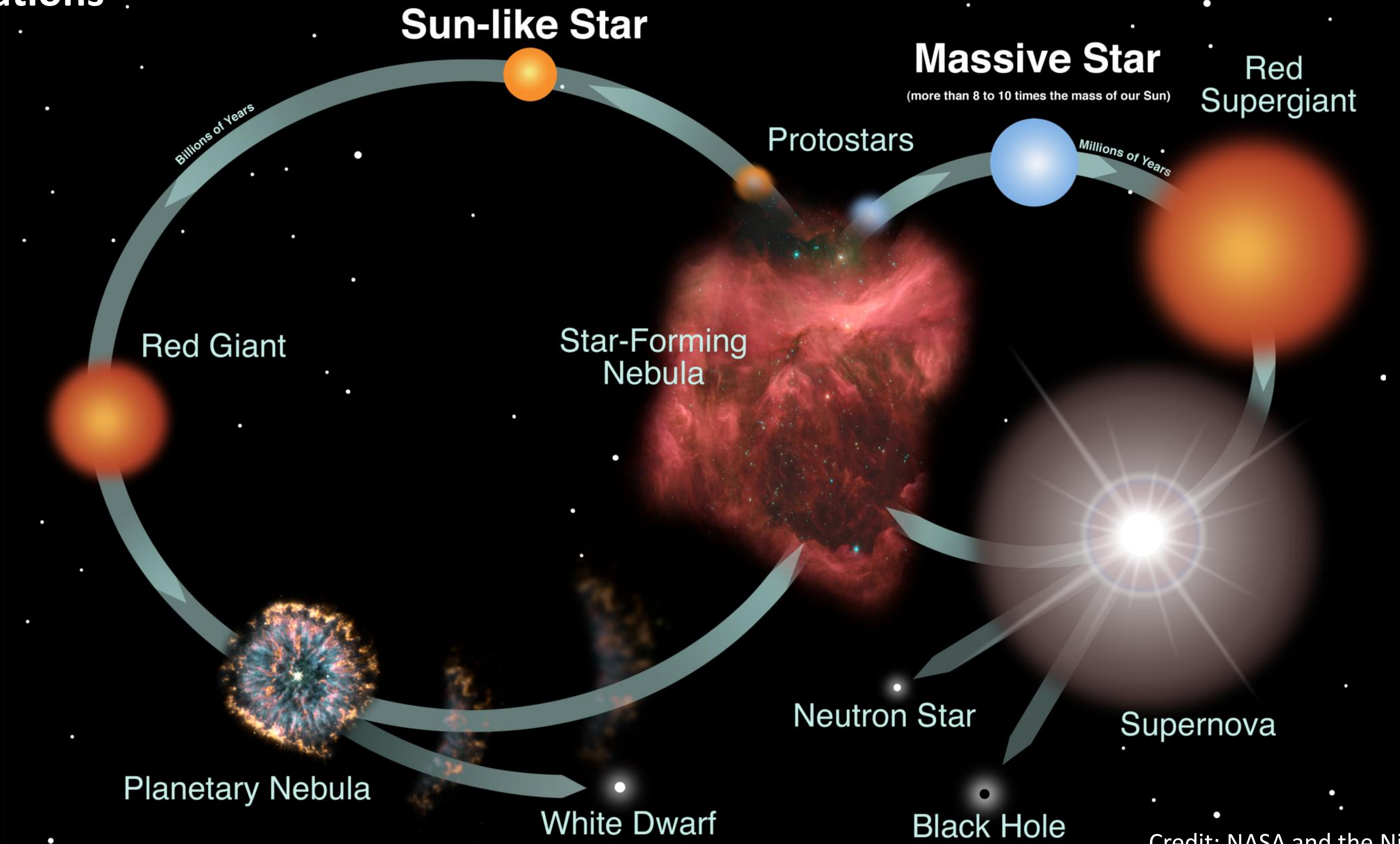
Motivations



Credit: NASA and the Night Sky Network

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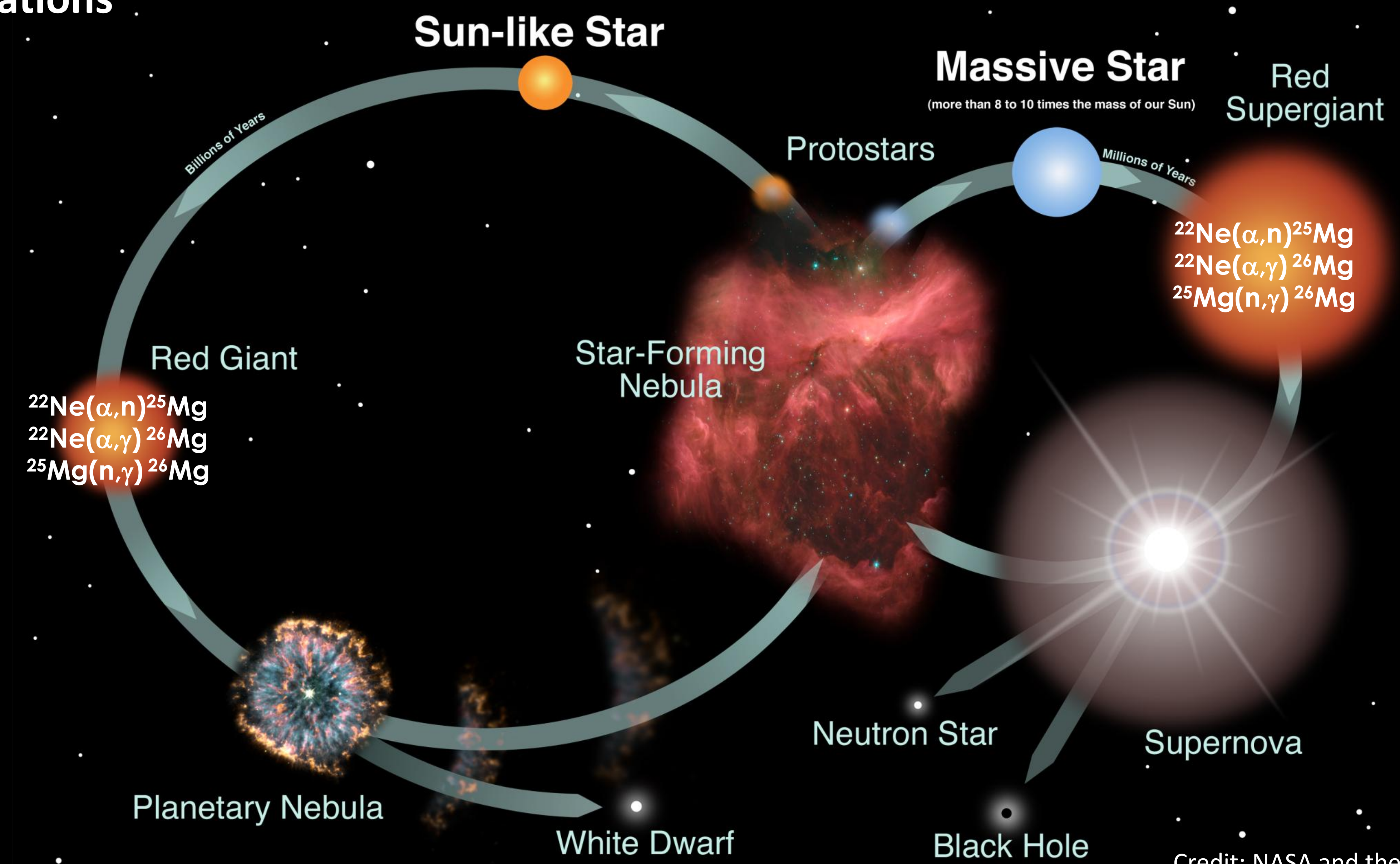

Credit: NASA and the Night Sky Network

Motivations

Neutron poison:

- ^{25,26}Mg are key **neutron poisons** during the s-process.
- They compete with ^{56}Fe (basic s-process seed) via **^{25,26}Mg(n,γ)**.

Constraints for ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg:

- **^{22}Ne(α,n)^{25}Mg**: primary **neutron source** in Red Giant stars
- Its reaction rate is very uncertain because of poor knowledge of **^{26}Mg states**.
- From neutron measurements the **energy** and **J^{π}** of **^{26}Mg** states can be deduced, together with Γ_{γ} and Γ_{n}.

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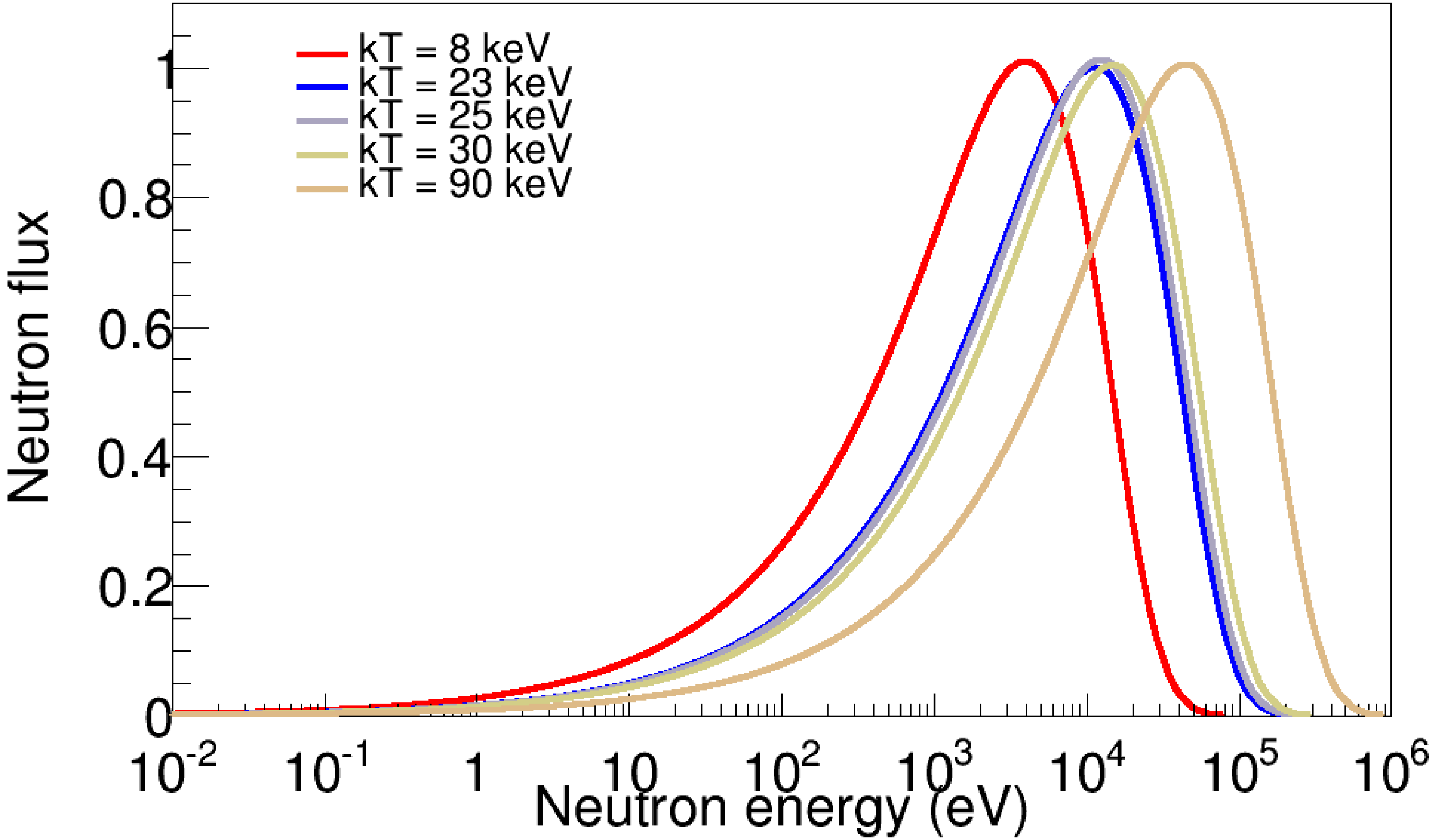
Measurement of $^{25}Mg(n,\gamma) \leftrightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

Stellar spectra: AGB (8, 23 keV) and Massive stars (25, 90 keV)



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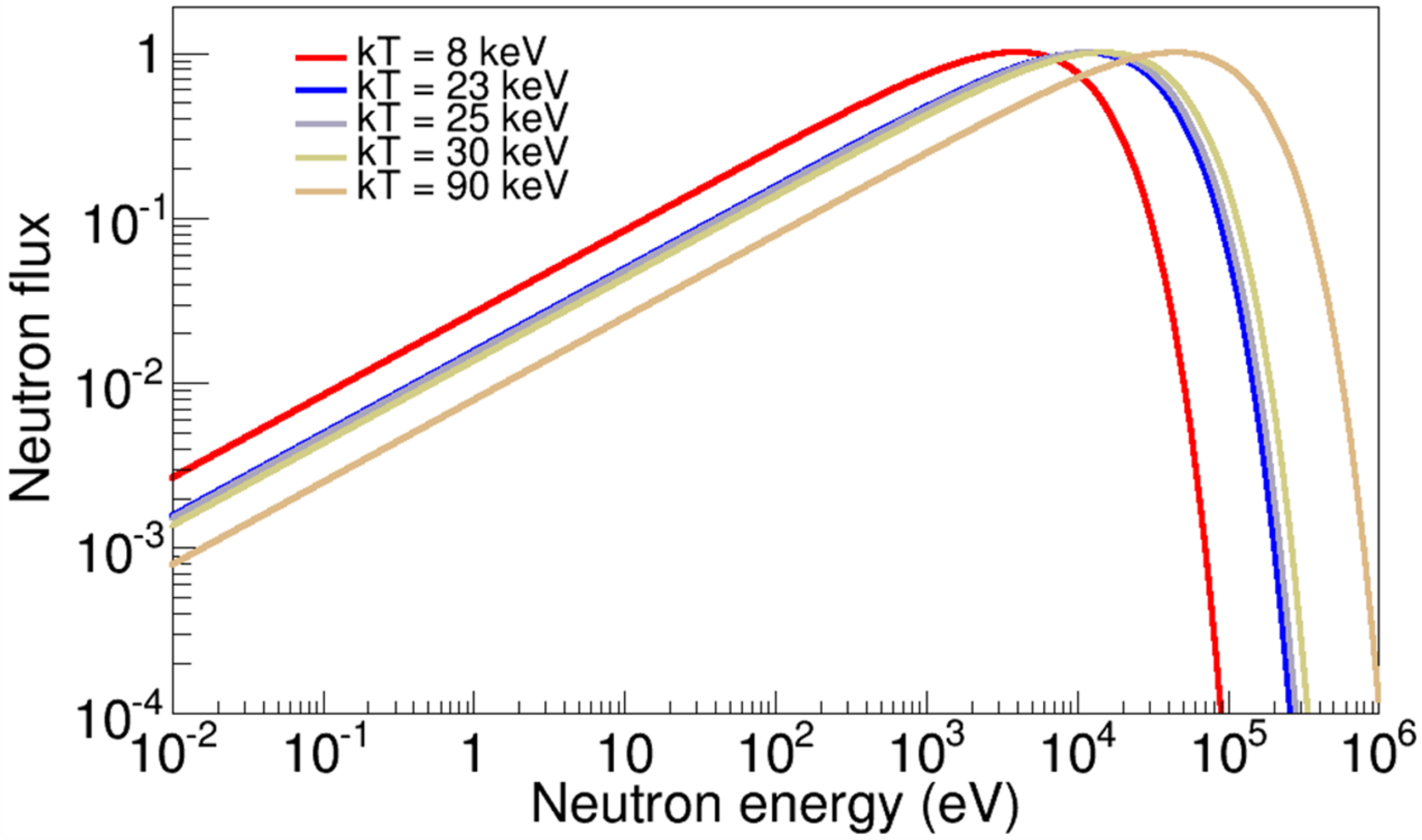

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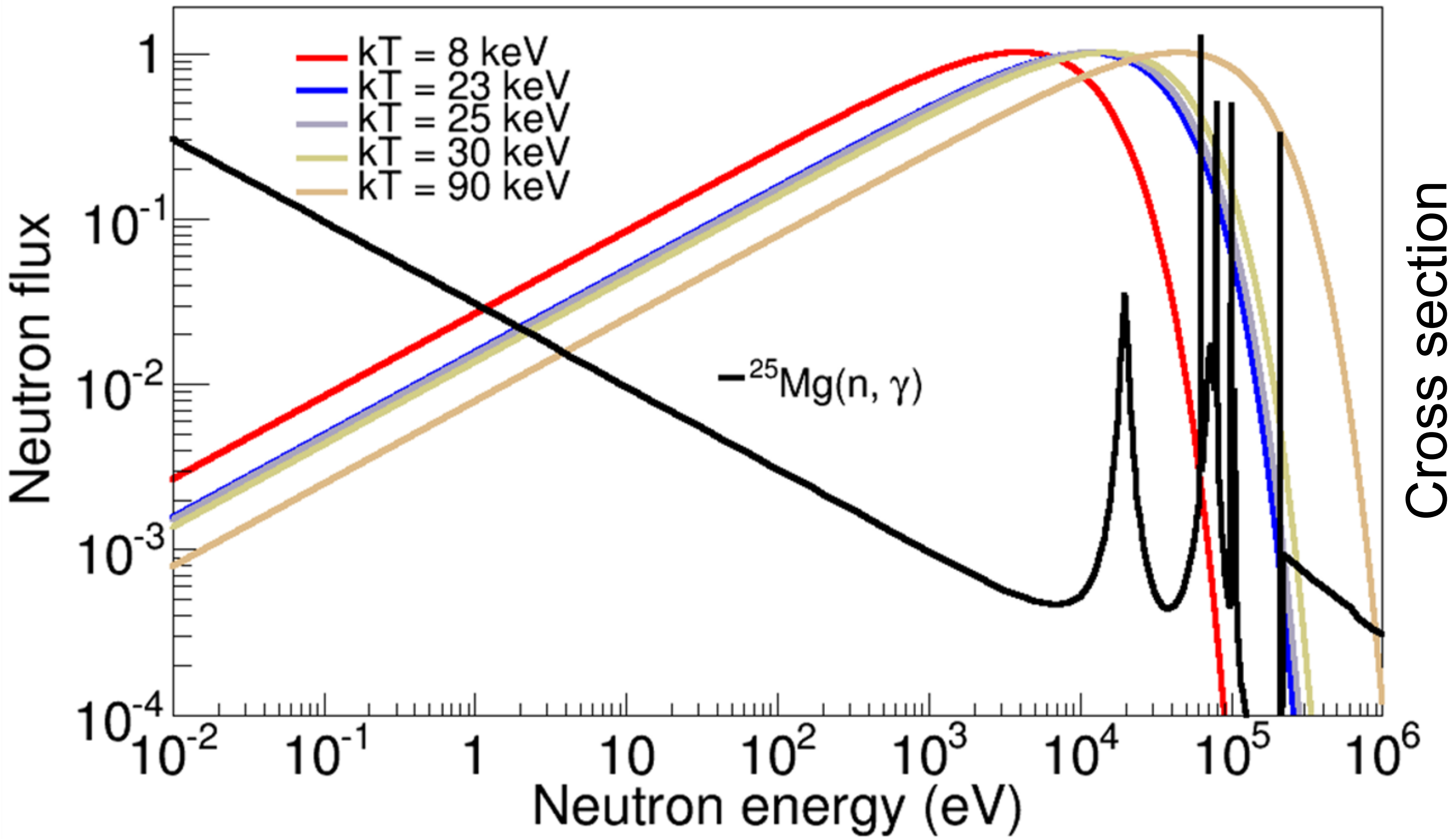


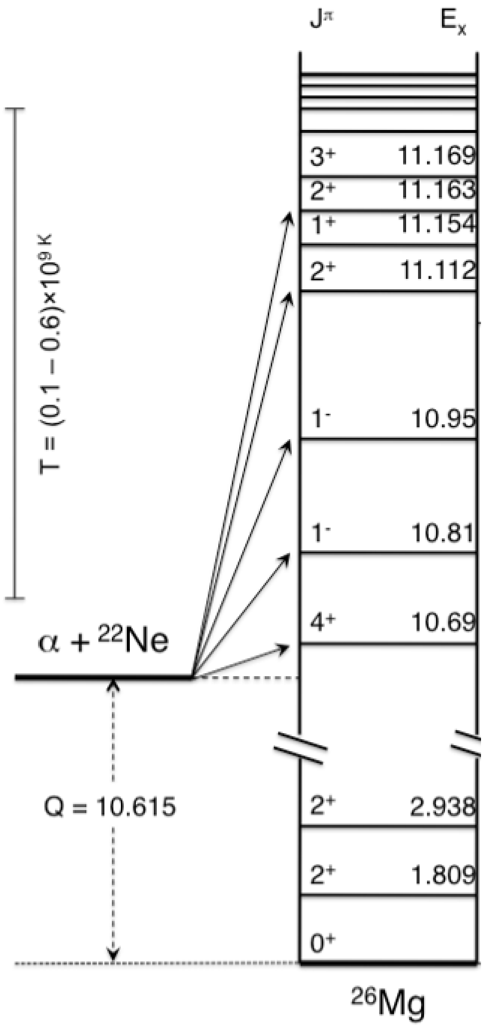
Measurement of $^{25}Mg(n,\gamma) \leftrightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

$\alpha + {}^{22}Ne$

α	$J^\pi = 0^+$
^{22}Ne	$J^\pi = 0^+$

Only **natural-parity states in ^{26}Mg** can participate in the **$^{22}Ne(\alpha,n)^{25}Mg$** reaction:

$J^\pi = 0^+, 1^-, 2^+, 3^-, 4^+$ …



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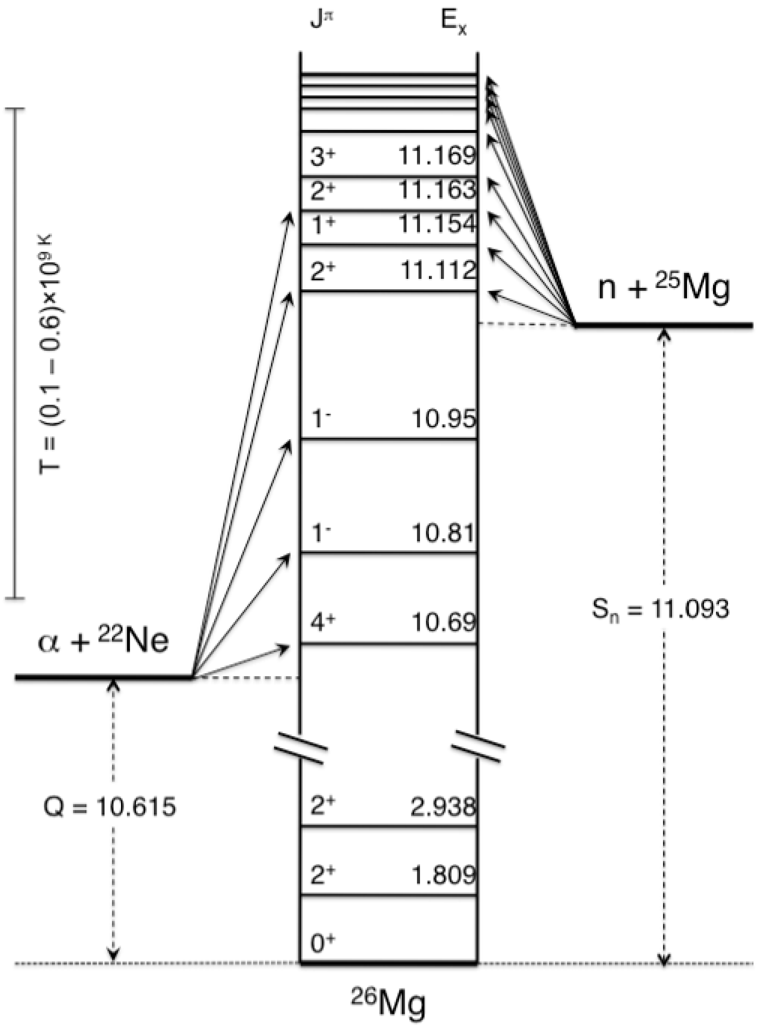

$n + {}^{25}Mg$

n	$J^\pi = 1/2^+$
^{25}Mg	$J^\pi = 5/2^+$

All **states in ^{26}Mg** can participate in the **$^{25}Mg(n,\gamma)^{26}Mg$** reaction:

$J^\pi = 0^+$, 0^-, 1^+, **1^-**, **2^+**, 2^-, …

nTOF

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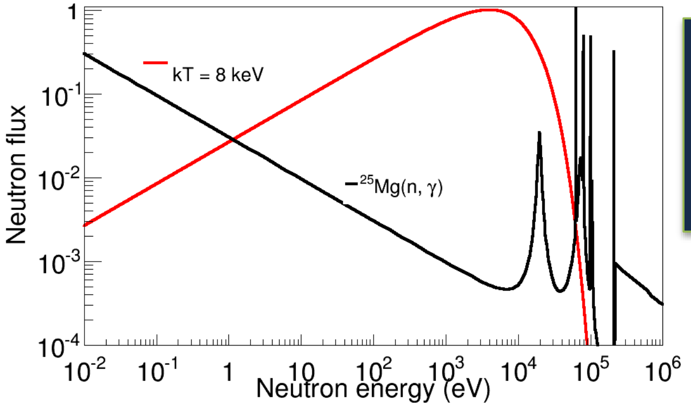
Neutron-induced reactions



For nuclear astrophysics, what is important is the **Maxwellian Averaged Cross-Sections (MACS)** at various **temperatures** (kT depends on stellar site).

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

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

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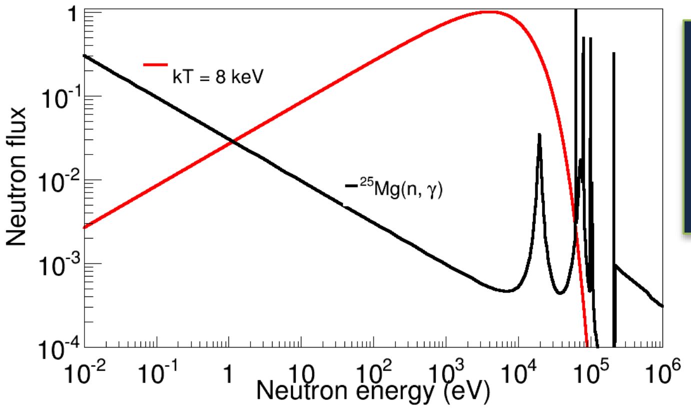

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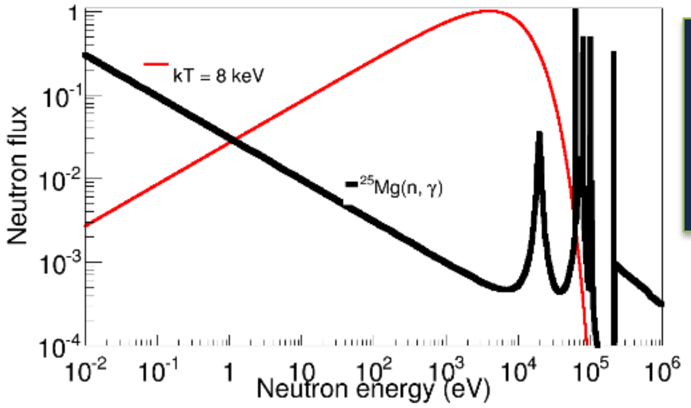
Two methods to determine MACS:

Neutron-induced reactions



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1. measurement of **energy dependent** neutron capture cross-sections → EAR1 & EAR2

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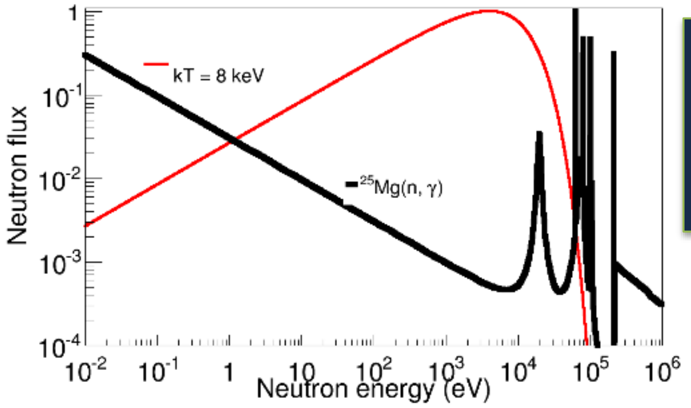

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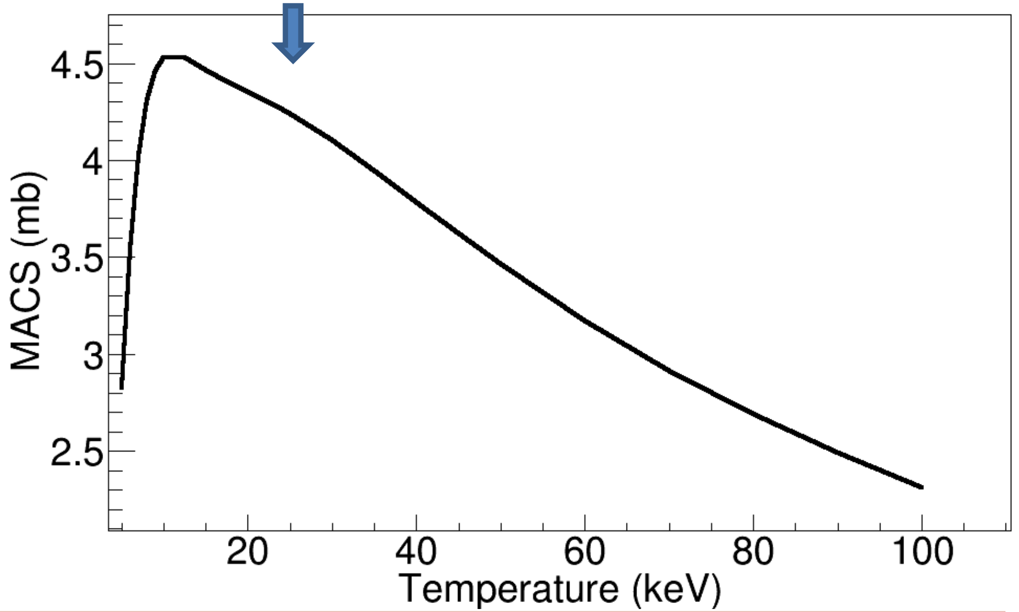

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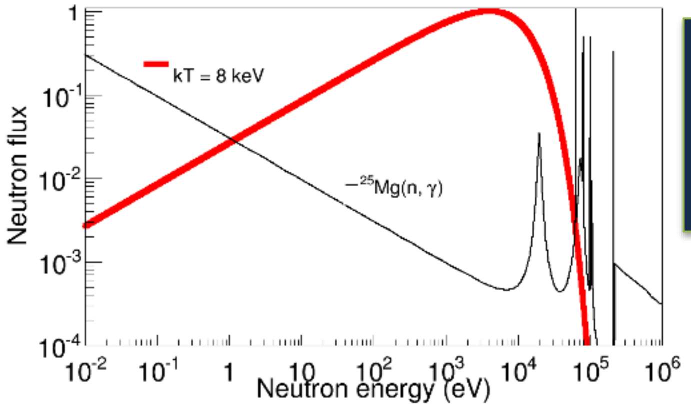

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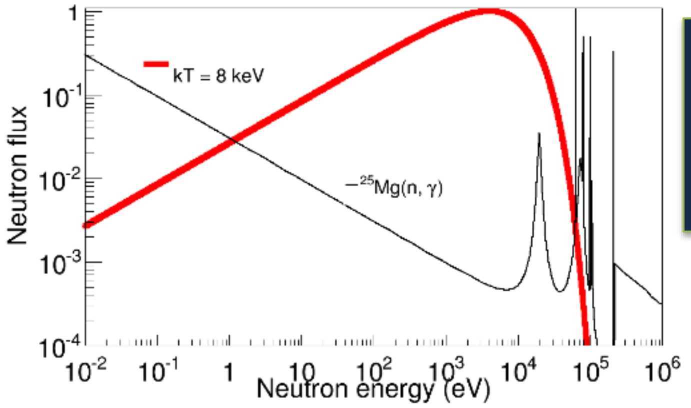
Two methods to determine MACS:

1. measurement of **energy dependent** neutron capture cross-sections → **EAR1 & EAR2**
2. **integral measurement** (energy integrated) using neutron beams with suitable energy → **NEAR**

Neutron-induced reactions



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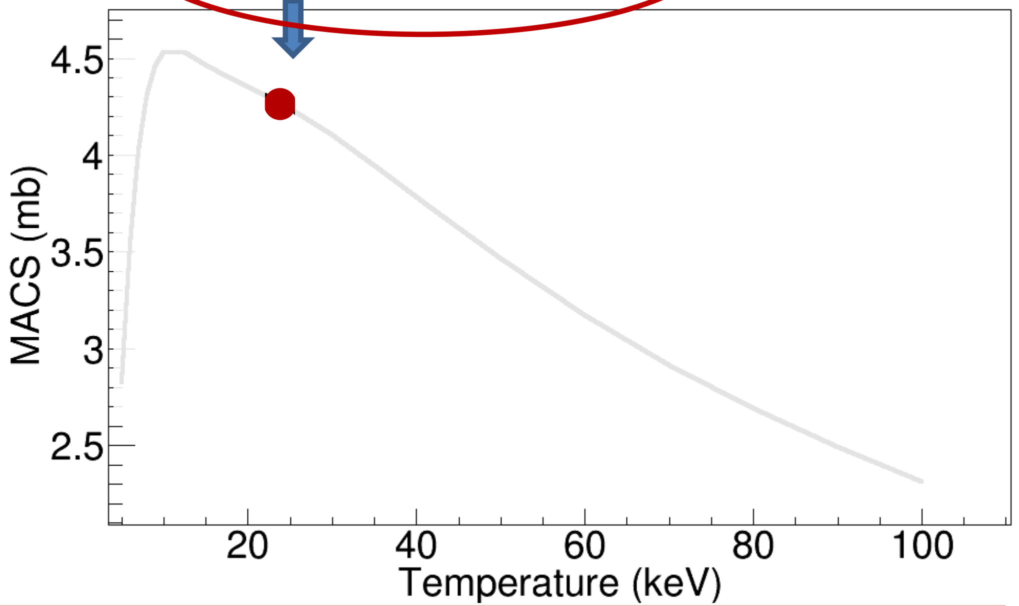

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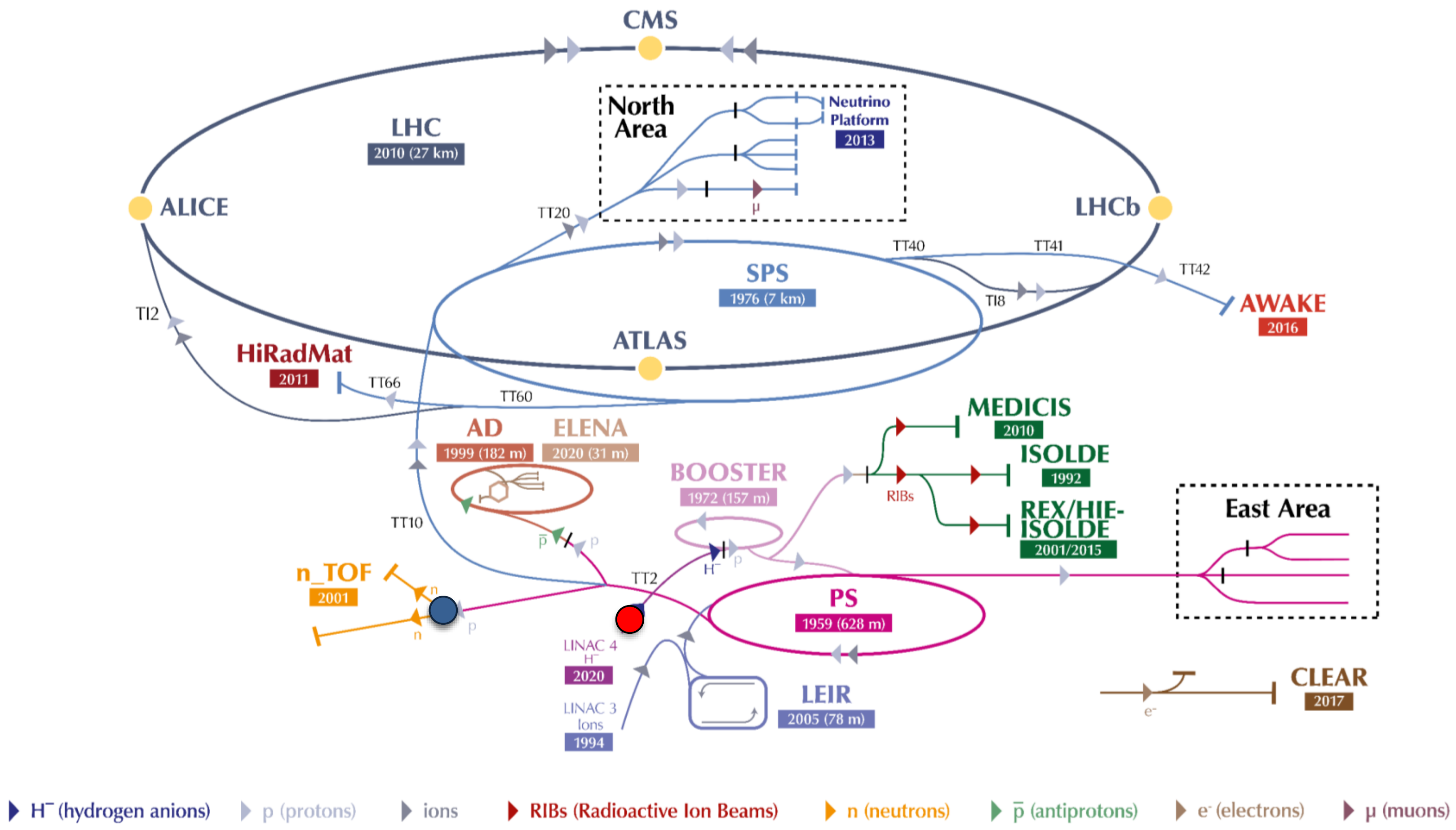
The CERN accelerator complex
Complexe des accélérateurs du CERN



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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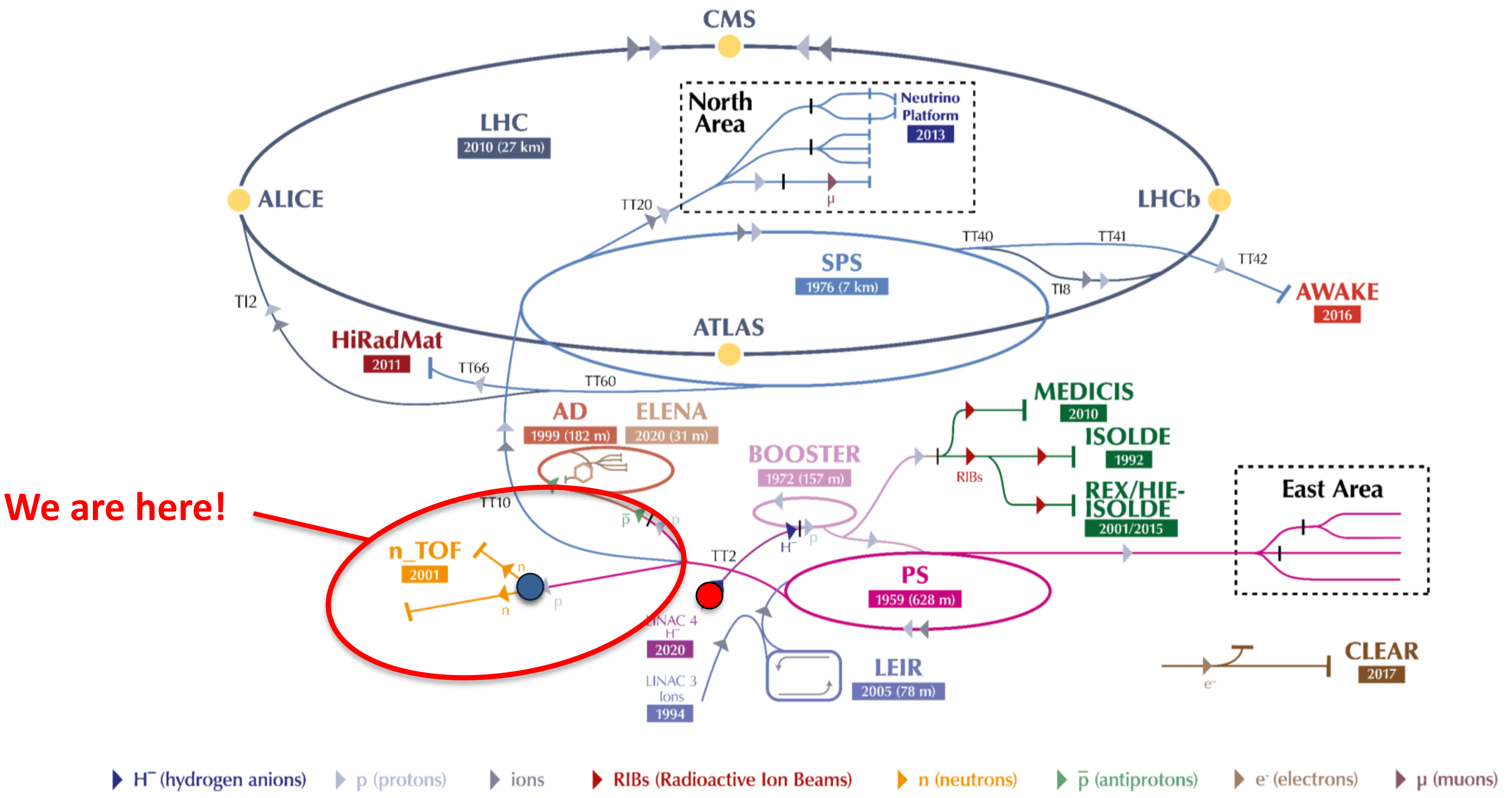

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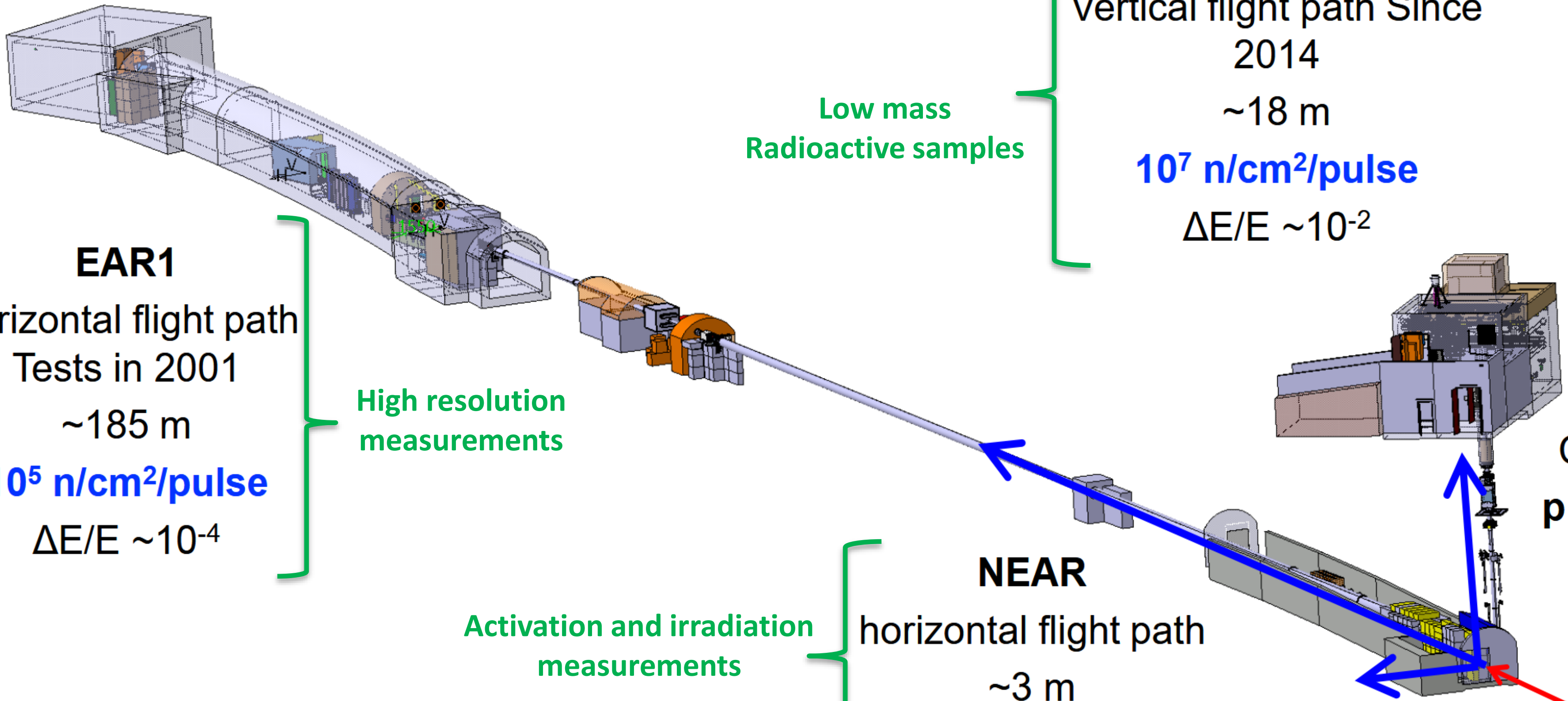
Why n_TOF?



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

Low mass
Radioactive samples

EAR1
horizontal flight path
Tests in 2001
~185 m
10^5 n/cm^2/pulse
ΔE/E ~10^{-4}

High resolution measurements

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

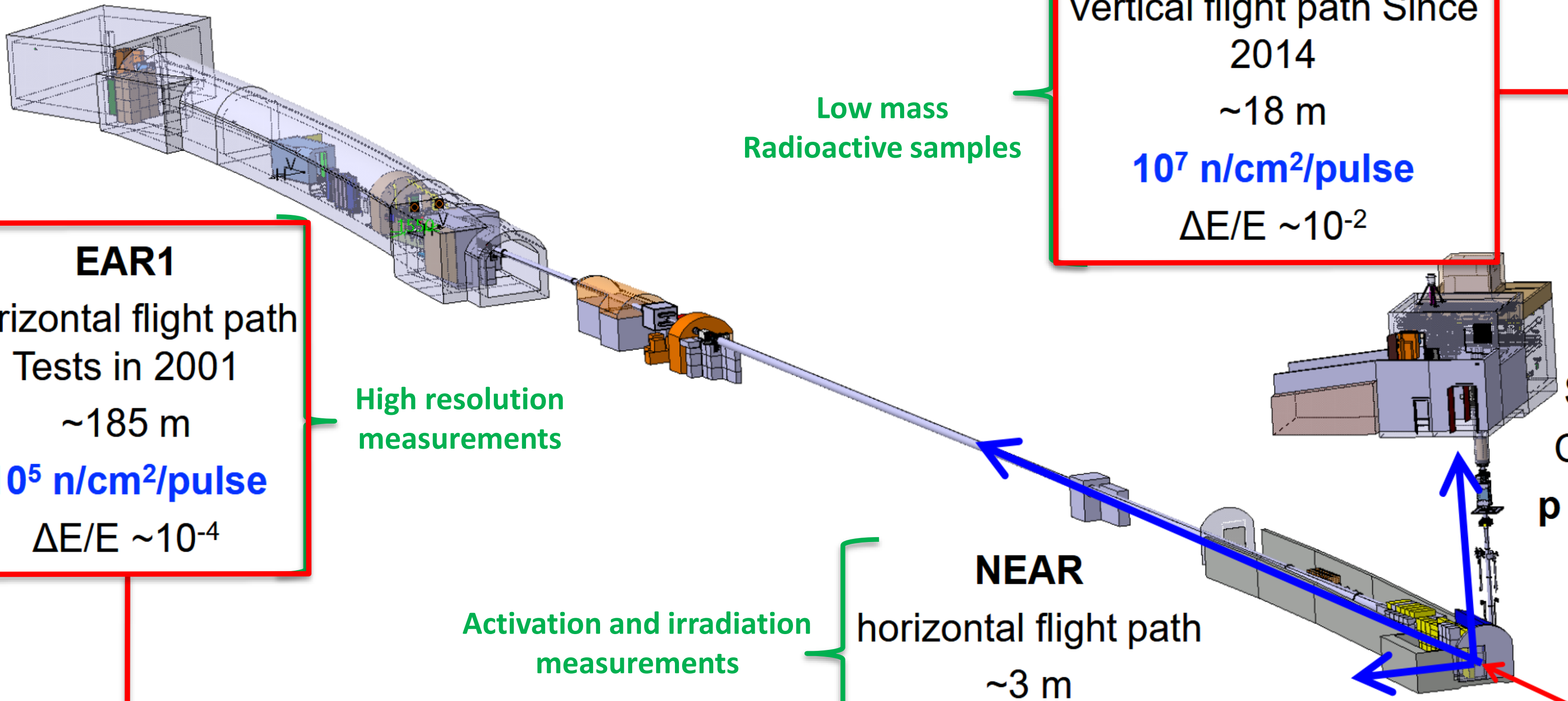
NEAR
horizontal flight path
~3 m
10^8 n/cm^2/pulse

Activation and irradiation measurements

Proton beam

From E. Mendoza, APRENDE WP2-WP4 Workshop

Why n_TOF?



From E. Mendoza, APRENDE WP2-WP4 Workshop

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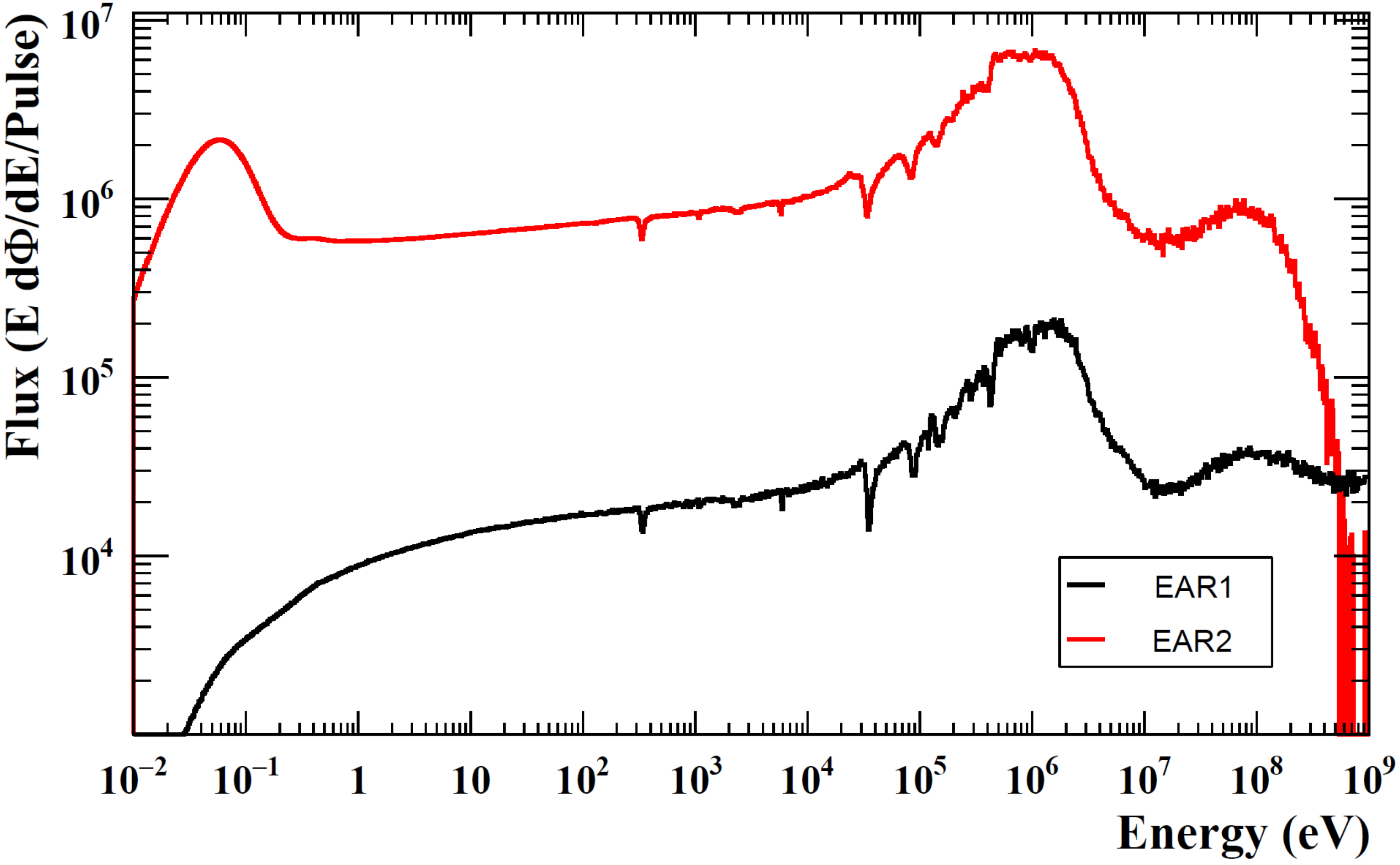
Why n_TOF?

- Wide energy range:
  $10 \text{ meV} \leq E_n \leq 1 \text{ GeV}$

- High current:
  8.5×10^{12} p/bunch
  $\rightarrow 10^6$ n/pulse

- Energy resolution at EAR1:
  $\frac{\Delta E_n}{E_n} = 0.03\% \ (1 \text{ eV})$
  $\frac{\Delta E_n}{E_n} = 0.5\% \ (1 \text{ MeV})$



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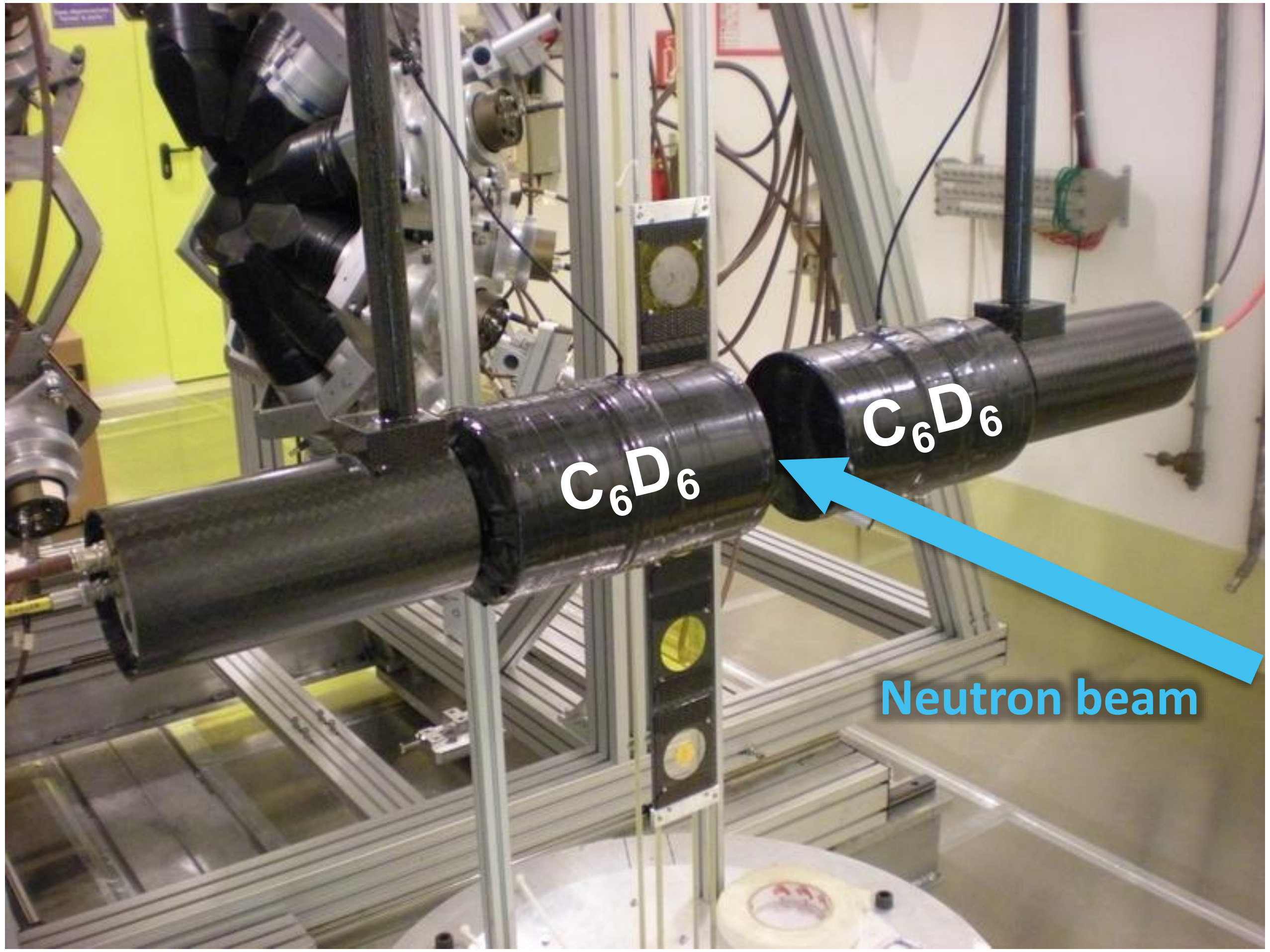
Previous measurements of ^{25}Mg(n,γ) at n_TOF

Capture setup:

- 2 C_6D_6 liquid scintillators
- Total Energy Detection System based on PHWT

Mg Sample:

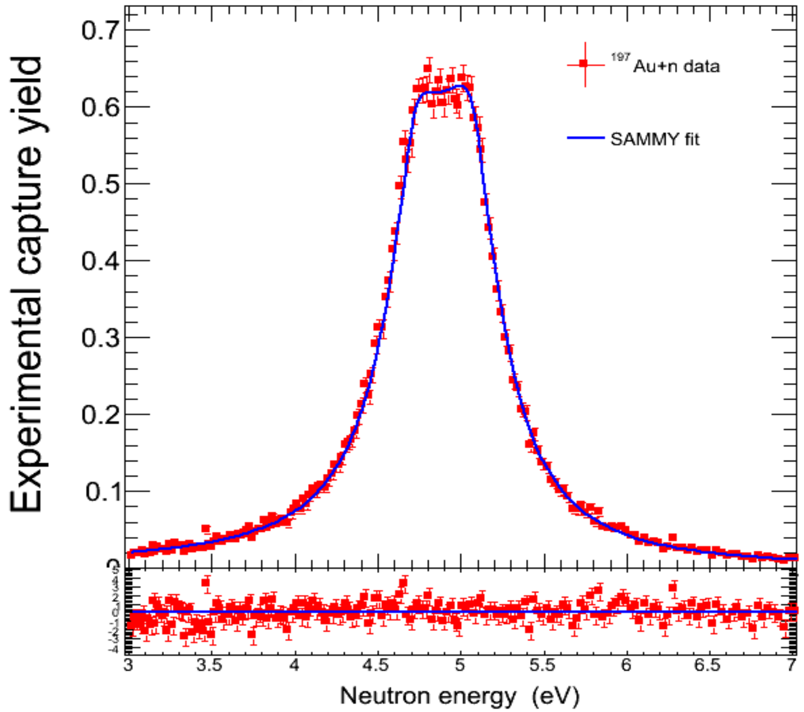
- 3.94 g, 2 cm diameter
- Enrichment 97.86 %
- 3.00×10^{-2} at/b

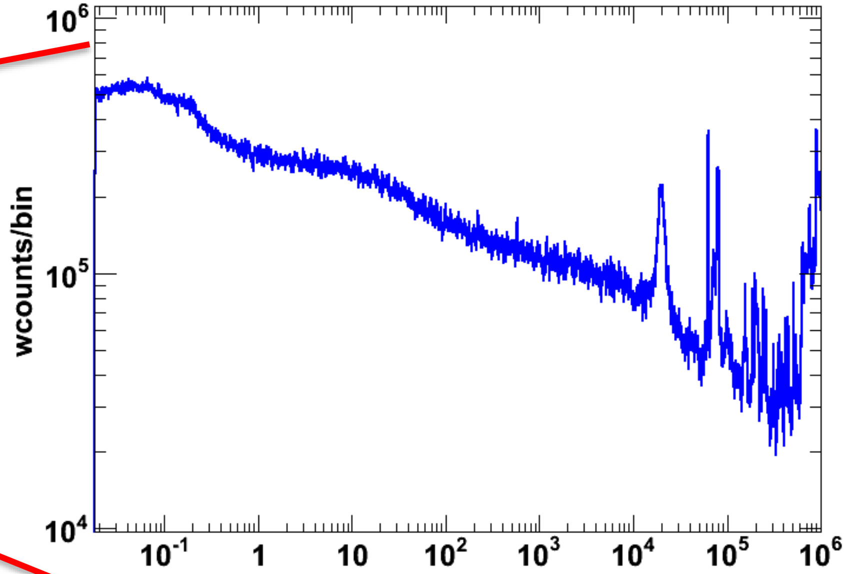


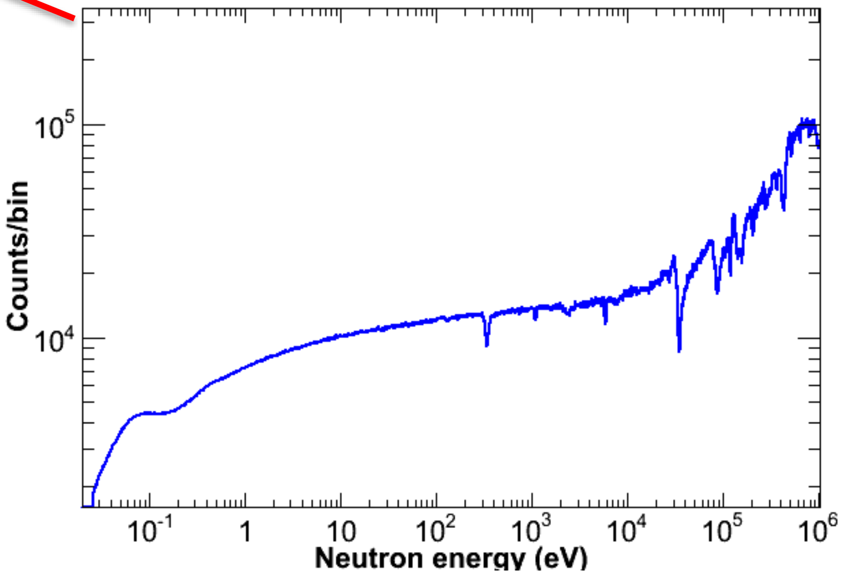
Previous measurements of ^{25}Mg(n,γ) at n_TOF

Experimental capture yield

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







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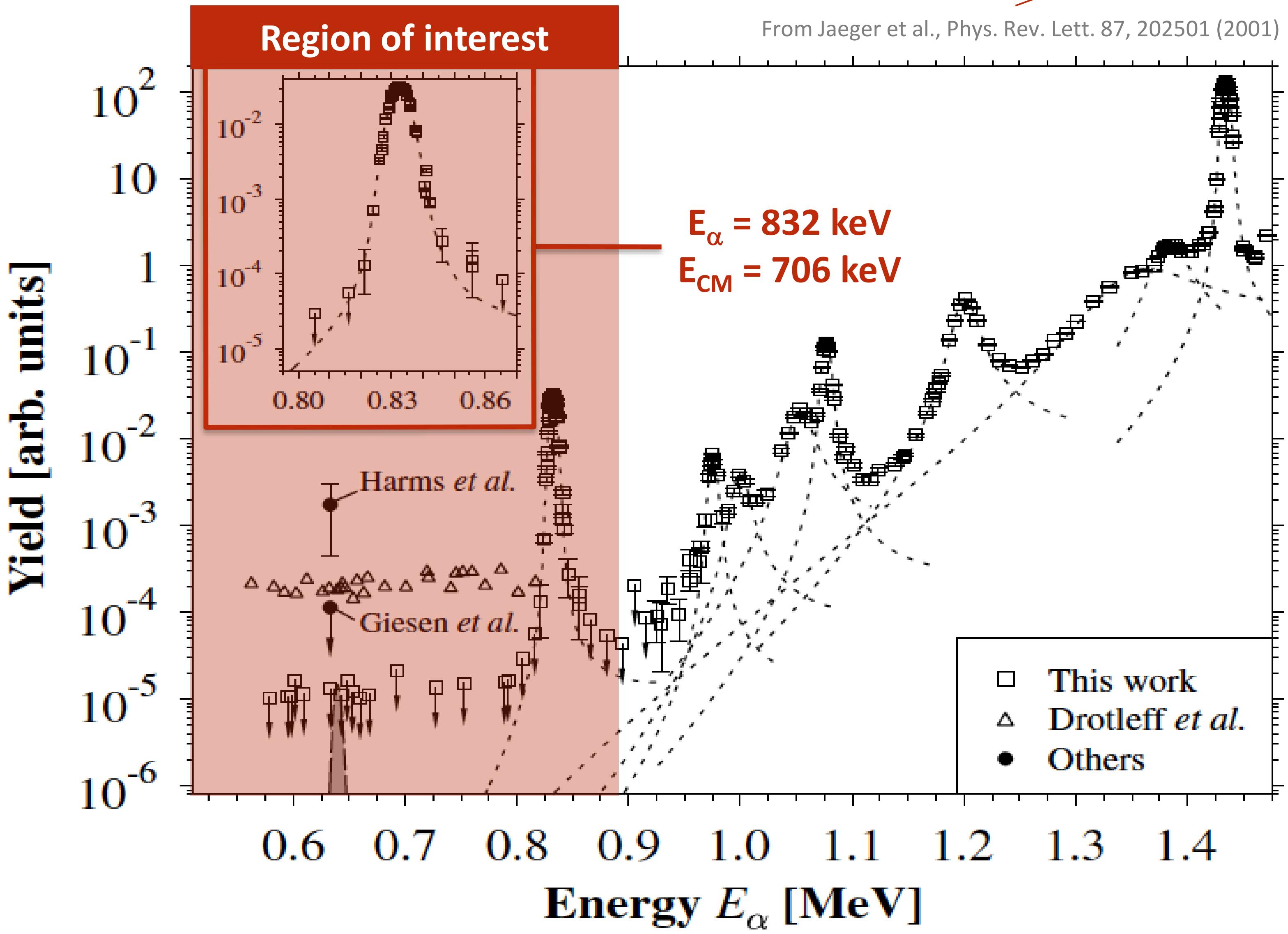
Measurement of ^{25}Mg(n,γ) ↔ ^{22}Ne(α,n)^{25}Mg

- Direct measurement of ^{22}Ne(α,n)^{25}Mg in Gamow Window
- 100-150 μA He^{+} beam incident on a ^{22}Ne gas jet target

Data in the literature

^{22}Ne(α,n)^{25}Mg



From Jaeger et al., Phys. Rev. Lett. 87, 202501 (2001)

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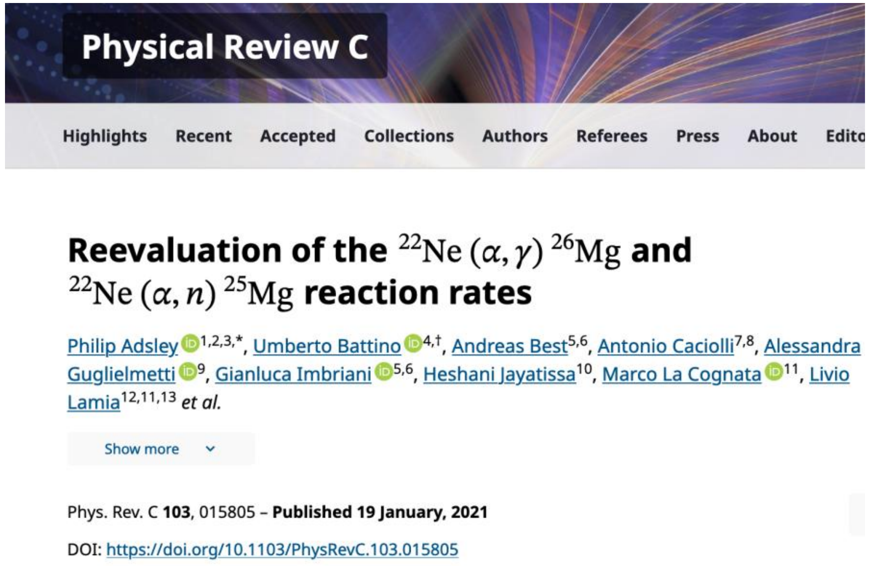
Stellar cross sections (MACS) for the s-process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Reevaluation of the ^{22}Ne (α,γ) ^{26}Mg and ^{22}Ne (α,n) ^{25}Mg reaction rates

Philip Adsley[1,2,3,*], Umberto Battino[4,†], Andreas Best[5,6], Antonio Caciolli[7,8], Alessandra Guglielmetti[9], Gianluca Imbriani[5,6], Heshani Jayatissa[10], Marco La Cognata[11], Livio Lamia[12,11,13] et al.

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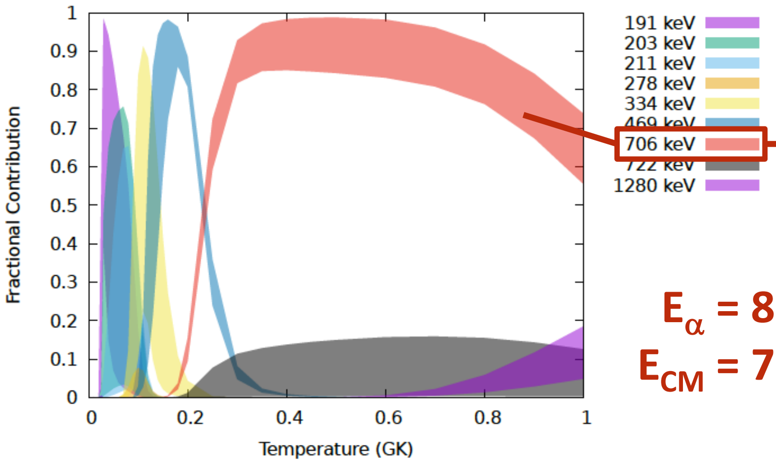
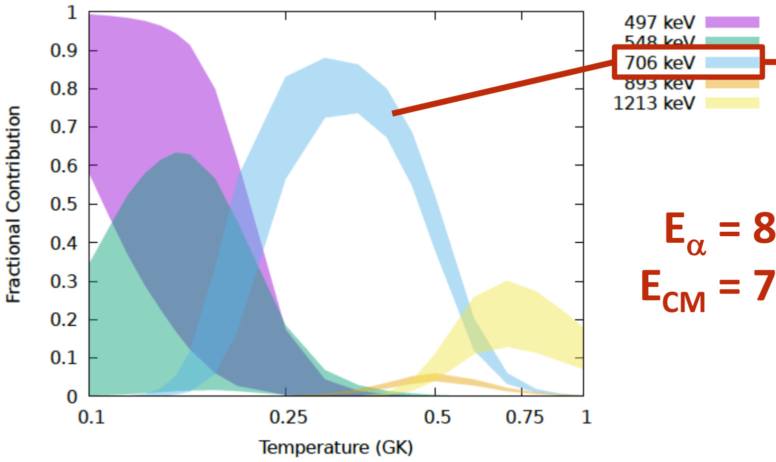
Phys. Rev. C **103**, 015805 – **Published 19 January, 2021**

DOI: https://doi.org/10.1103/PhysRevC.103.015805

FIG. 1. Fractional contributions of selected resonances to the (top) ^{22}Ne$(\alpha,\gamma)^{26}$Mg and (bottom) ^{22}Ne$(\alpha,n)^{25}$Mg reaction rates. These fractional contributions are for the recommended reaction rates, which incorporate the Texas A&M results. The shaded region gives the 68% coverage limit for the contribution of each resonance. Note that only the most significant resonances are included in the figure; the sum of the contributions may not reach 100% due to contributions from omitted resonances.



E_α = 832 keV
E_{CM} = 706 keV



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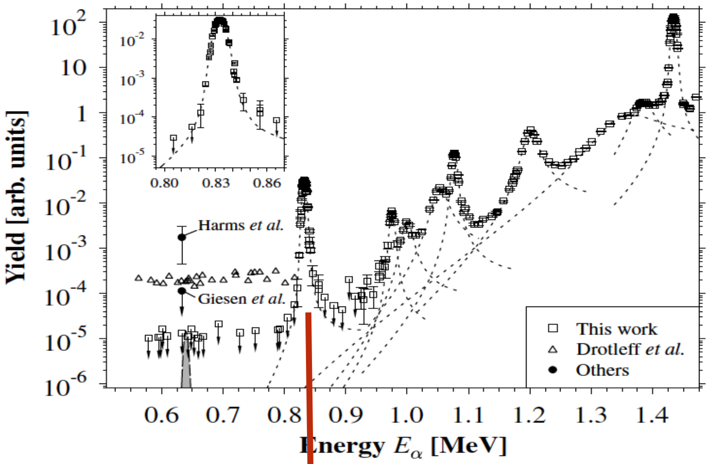
^{22}Ne$(\alpha$,n$)^{25}$Mg



E_α = 832 keV
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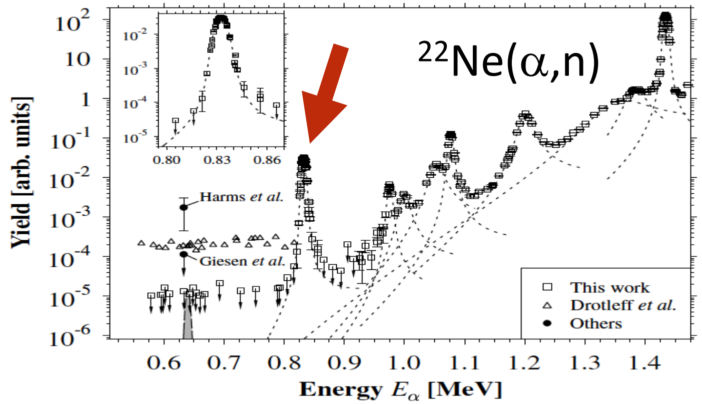
$^{25}Mg(n,\gamma)$ for neutron source reaction in stars



Resonance strength $^{22}Ne(\alpha,n)^{25}Mg$:

$$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

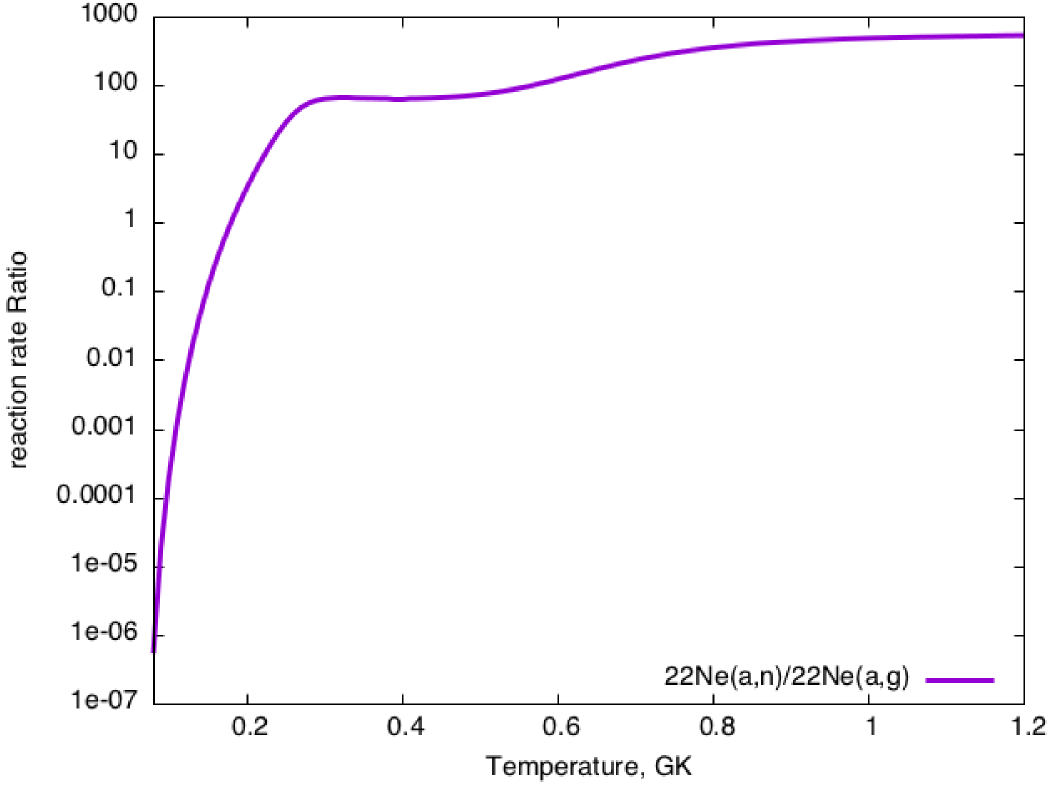
Resonance strength $^{22}Ne(\alpha,\gamma)^{26}Mg$:

$$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Resonance strength ratio and **Reaction rate ratio** independent of Γ_α

$^{22}Ne(\alpha,n)$ / $^{22}Ne(\alpha,\gamma)$



nTOF

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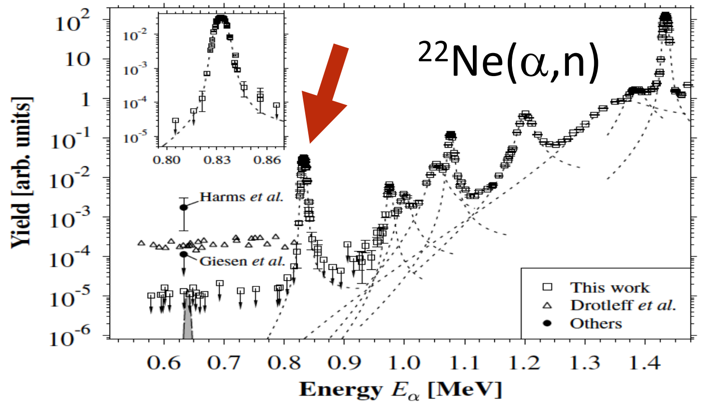

^{22}Ne(α,n) / ^{22}Ne(α,γ)

Resonance strength ^{22}Ne(α,n)^{25}Mg:

$$\omega_\alpha = g\,\Gamma_\alpha\Gamma_n / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

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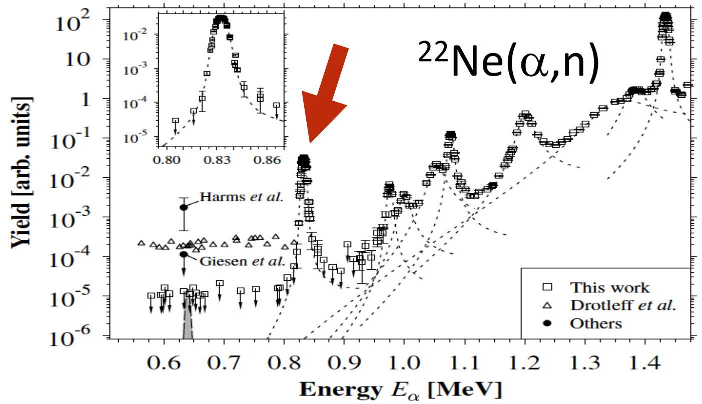
$$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Publication	YEAR	Result	comment
Shahina, PRC	2024	Γ_n / Γ_γ = 2.85(71)	ω_α res. strength
M. Wiescher, EPJA	2023	Γ_n = 0.4 - 1.0 eV Γ_γ = 1.33 eV	Re-evaluation
Y. Chen, PRC	2021	Γ_n = 0.4 eV Γ_γ = 1.33 eV	^{25}Mg(d,p)^{26}Mg transfer
S. Ota, PLB	2020	Γ_n / Γ_γ = 1.14(26)	transfer

^{25}Mg(n,γ) for neutron source reaction in stars



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$$\omega_\gamma = g\,\Gamma_\alpha\Gamma_\gamma / (\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)$$

$$\frac{\omega_\alpha}{\omega_\gamma} = \frac{\Gamma_n}{\Gamma_\gamma}$$

Neutron width Γ_n and γ-ray width Γ_γ can be deduced **from n + ^{25}Mg experiments**

$$\sigma_\gamma(E_n) = g\frac{\pi}{k_n^2}\frac{\Gamma_n\Gamma_\gamma}{(E_n - E_R)^2 + (\Gamma/2)^2}$$

^{25}Mg(n,γ) cross section

nTOF

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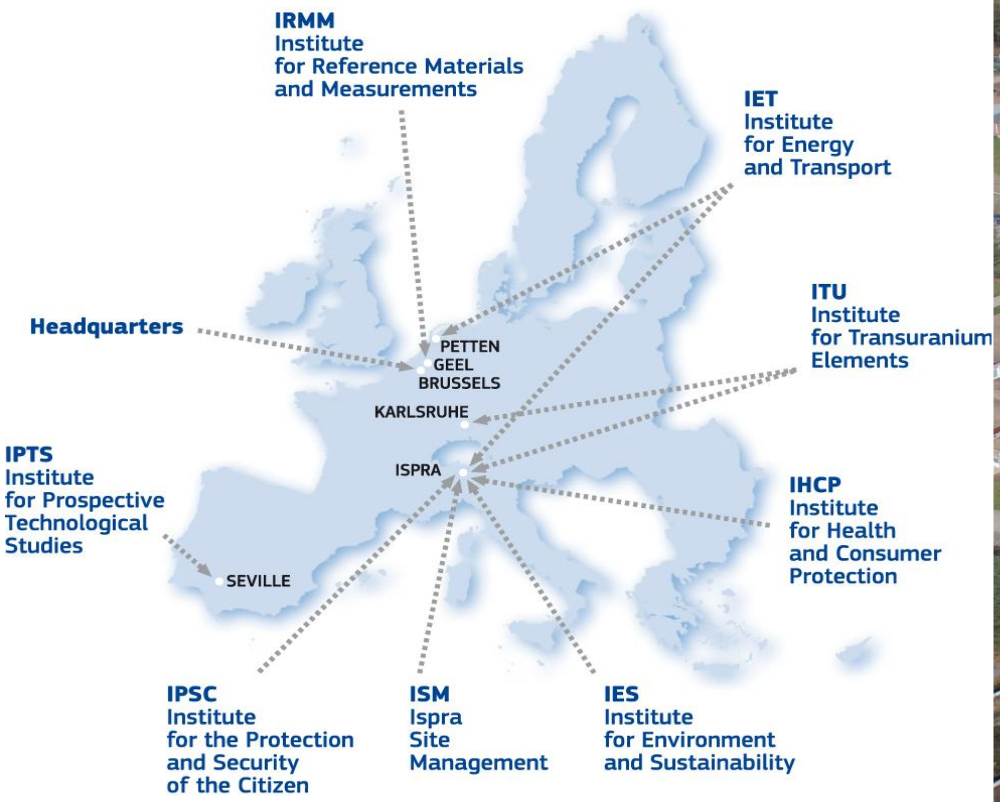
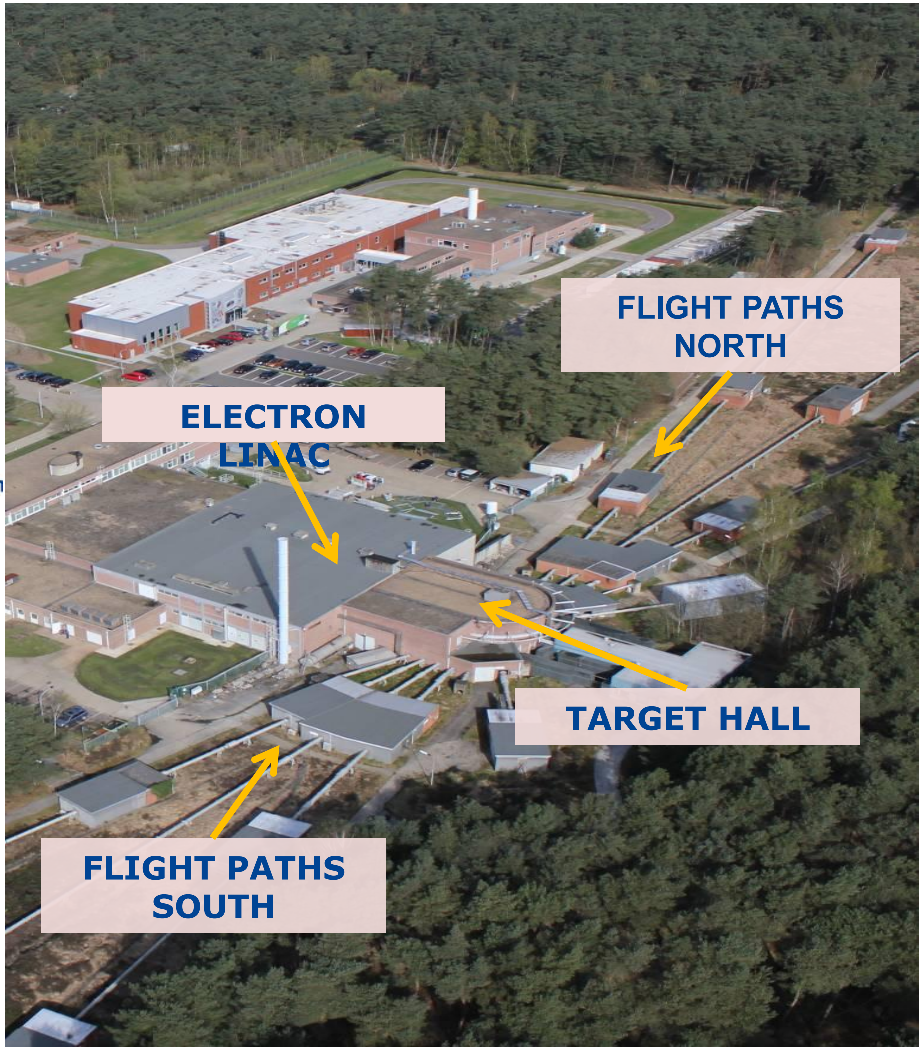
Measurement of $^{25}Mg(n,tot)$ @ GELINA





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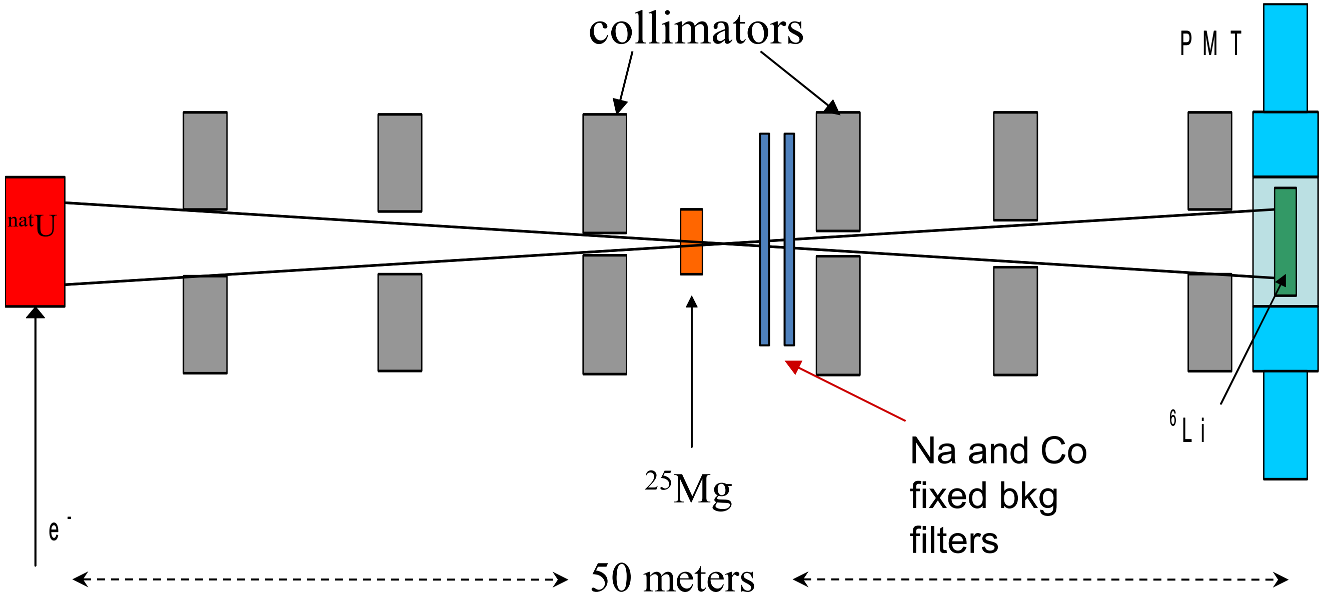

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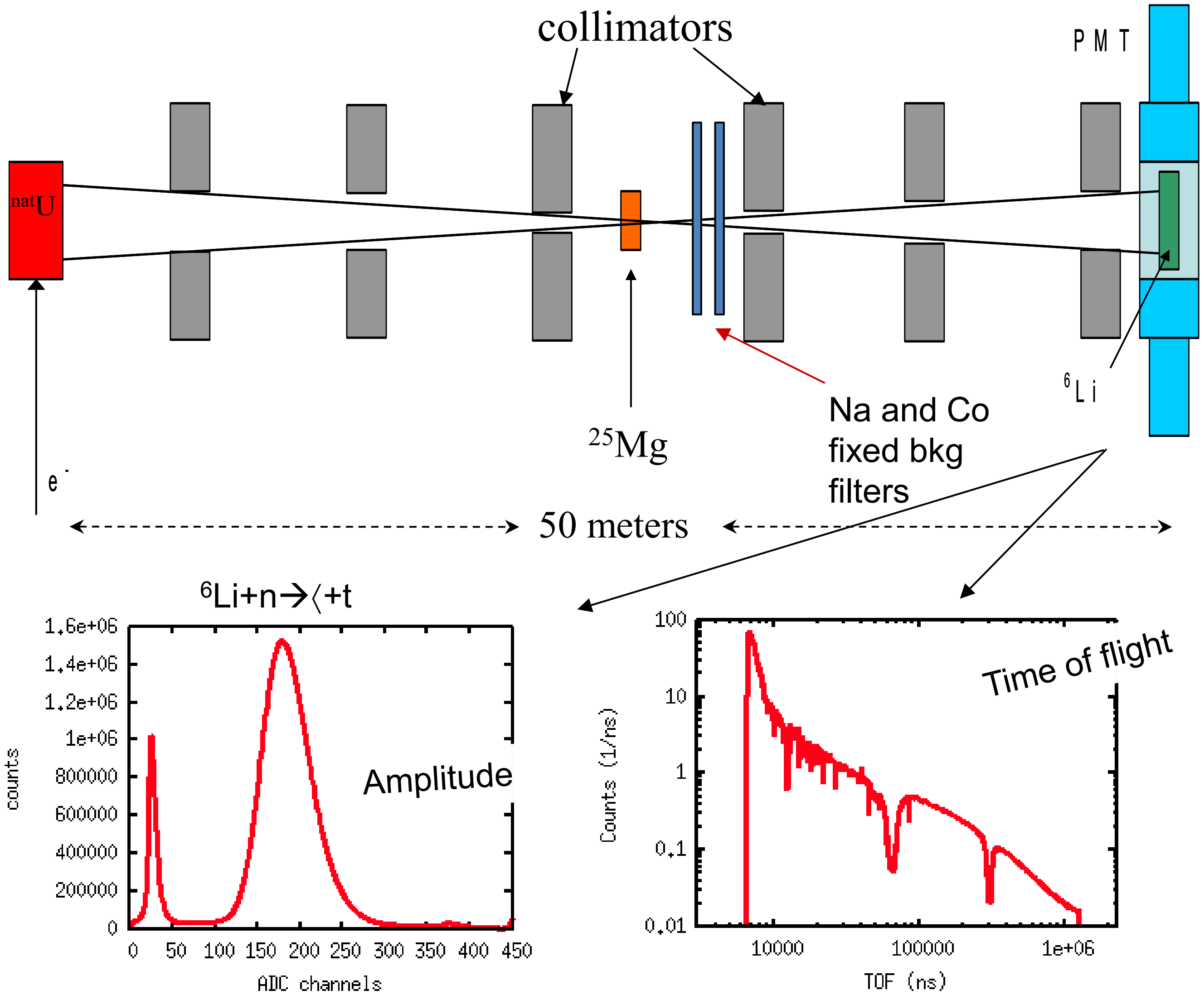
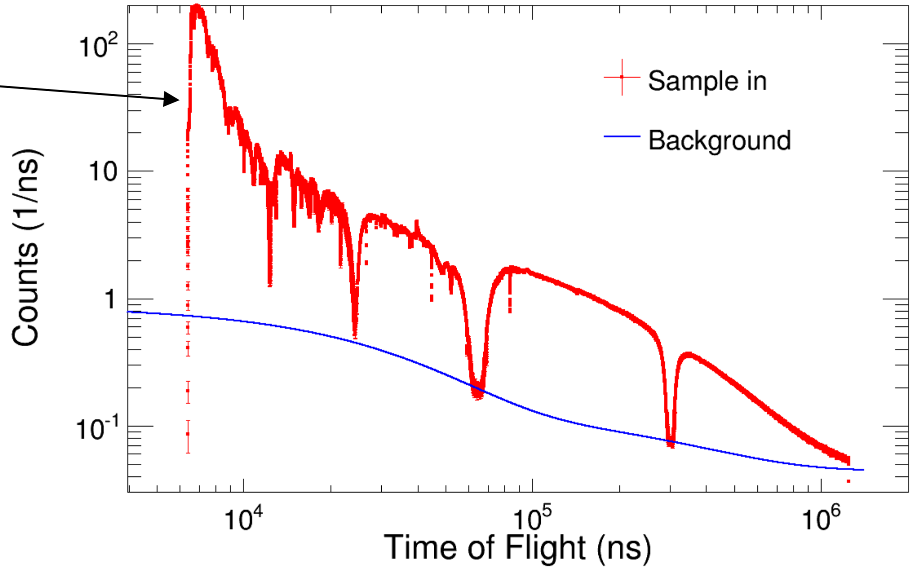
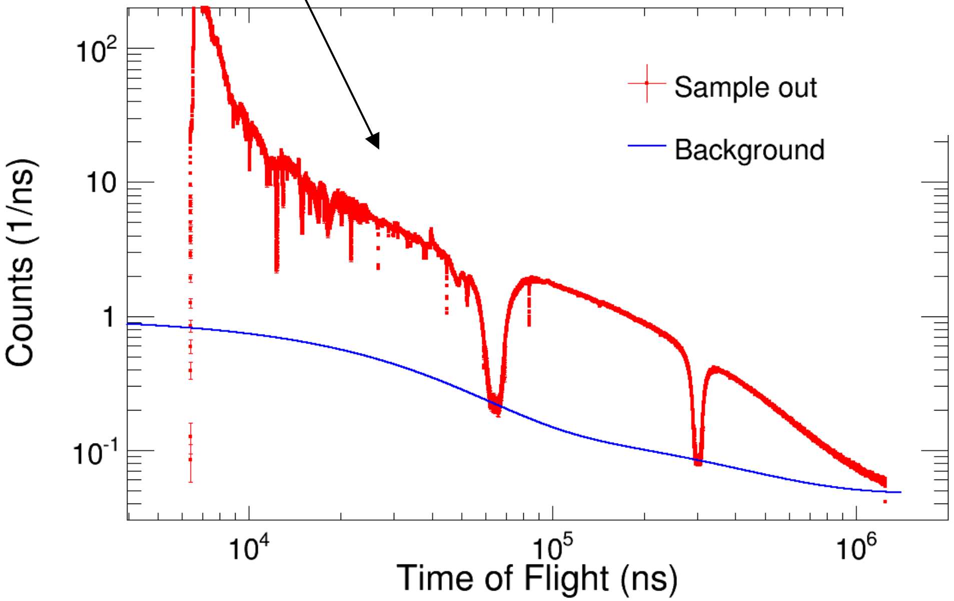


Transmission setup:
- 2 ^{6}Li-glass scintillators

Measurement of ^{25}Mg(n,tot) @ GELINA

$$T = \frac{C_{in}}{C_{out}} \propto e^{-n\,\sigma_{tot}}$$





Background determined by **black resonance** technique:

$$B(t) = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t} + b_3 e^{-\lambda_3 (t+t_0)}$$

P. Schillebeeckx, *et al.*, Nucl. Data Sheets **113** (2012) 3054

nTOF

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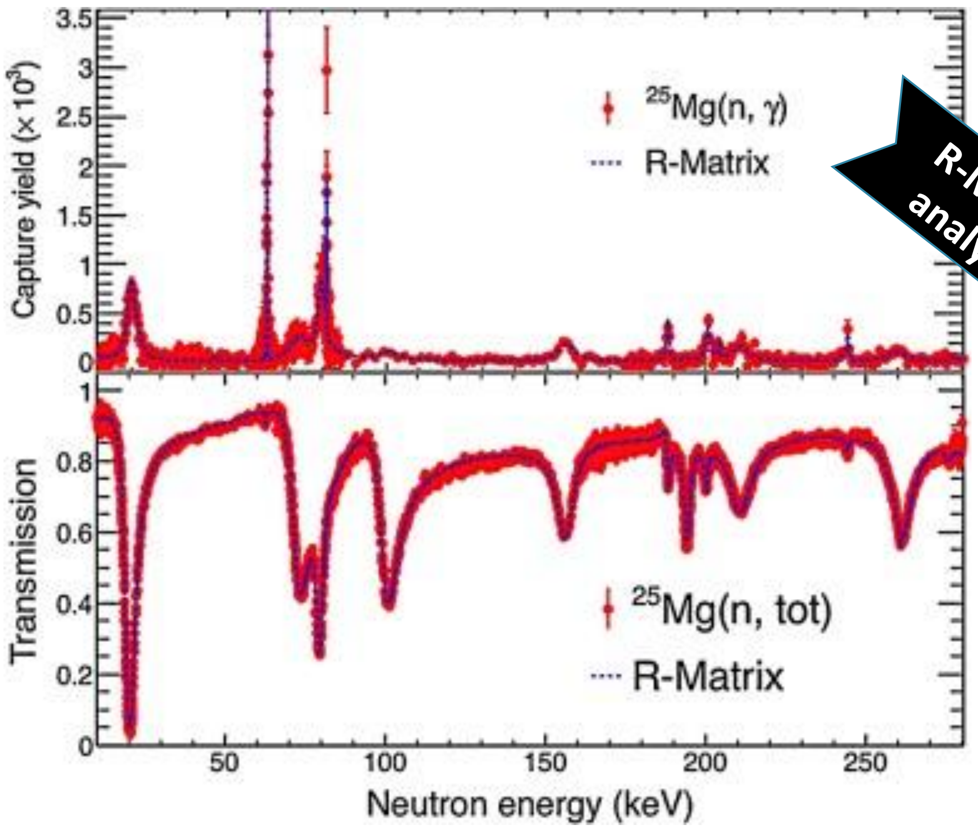
^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
C Massimi *et al.*, Phys. Lett. B **768**, 1 (2017)



R-Matrix analysis

E_n (keV)	E_x (keV)	E_α^{Lab} (keV)	J^π ($\hbar$)	Γ_γ (eV)	Γ_n (eV)
19.92(1)	11112	589	2^+	1.37(6)	2095(5)
62.73(1)	11154		1^+	4.4(5)	7(2)
72.82(1)	11163	649	2^+	2.8(2)	5310(50)
79.23(1)	11169	656	$3^{-(a)}$	3.3(2)	1940(20)
81.11(1)	11171			5(1)	1 – 30
100.33(2)	11190		3^+	1.3(2)	5230(30)
155.83(2)	11243		2^-	4.7(5)	5950(50)
187.95(2)	11274	779	2^+	2.2(2)	410(10)
194.01(2)	11280	786	$3^{-(a)}$	0.3(1)	1810(20)
199.84(2)	11285		2^-	4.8(4)	1030(30)
203.88(4)	11289			0.9(3)	3 – 20
210.23(3)	11295		2^-	6.6(6)	7370(60)
243.98(2)	11328	843	$2^{+(b)}$	2.2(3)	171(6)
260.84(8)	11344			1.0(2)	300 – 3900
261.20(2)	11344		> 3	3.0(3)	6000 – 9000

Energy, J^π, Γ_γ, Γ_n

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^{25}Mg(n,tot) and ^{25}Mg(n,γ) R-Matrix analysis

C Massimi *et al.*, Phys. Rev. C **85**, 044615 (2012)
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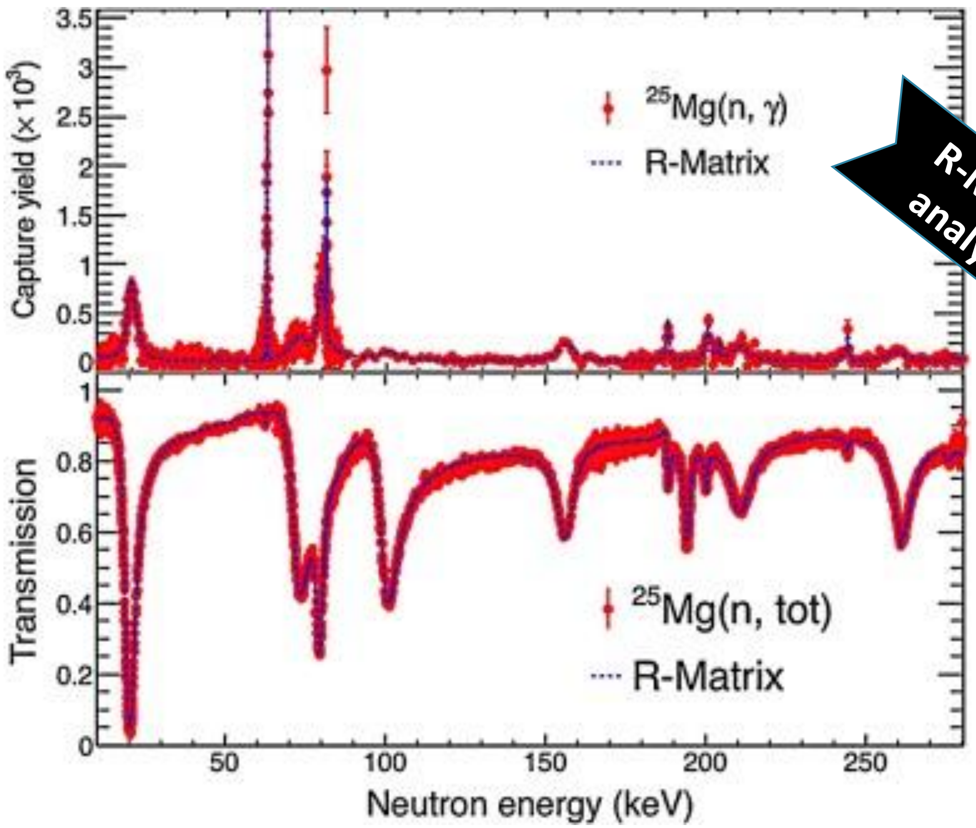

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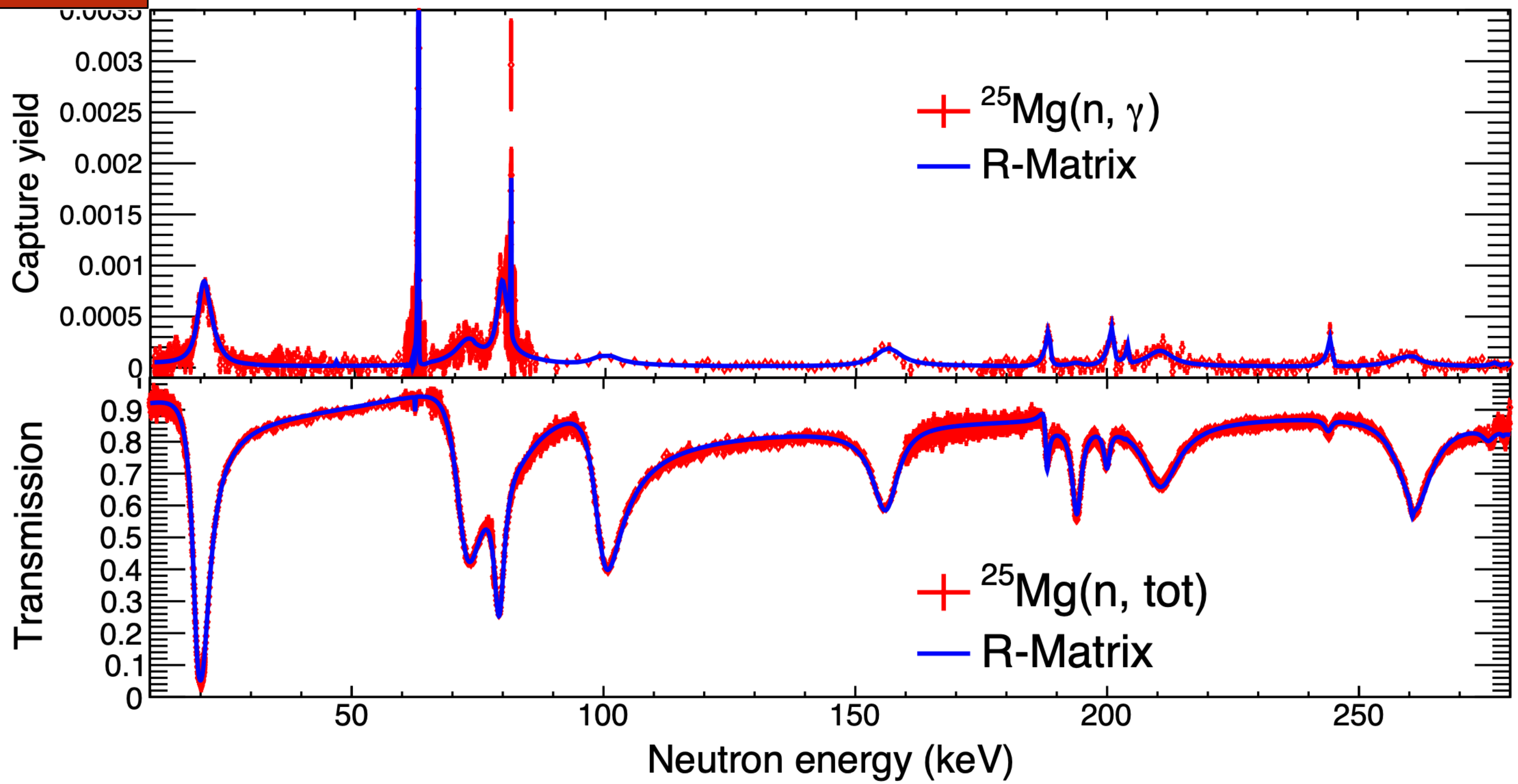
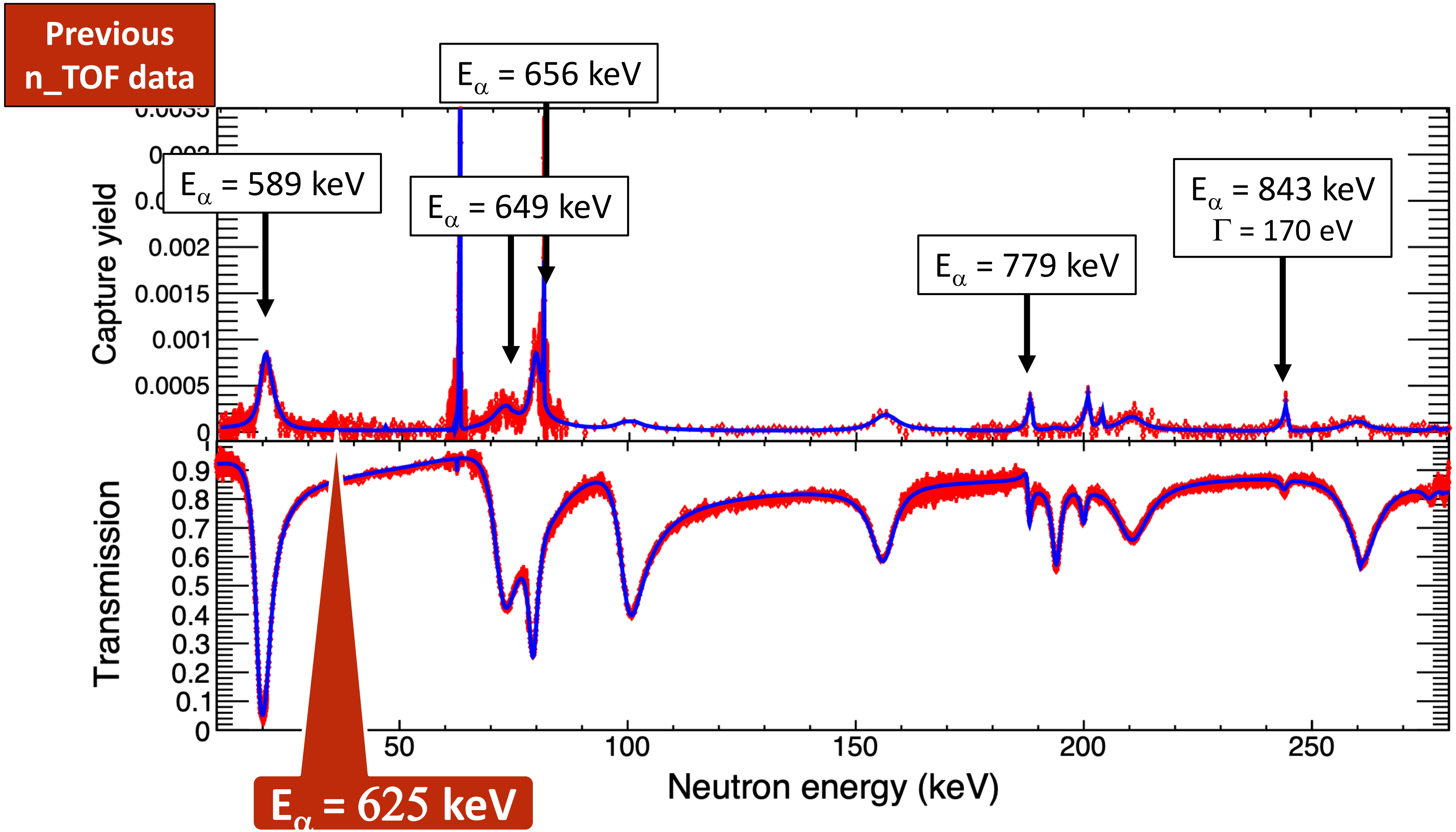
Energy, J^π, Γ_γ, Γ_n

^{25}Mg(n,γ) for neutron source reaction in stars

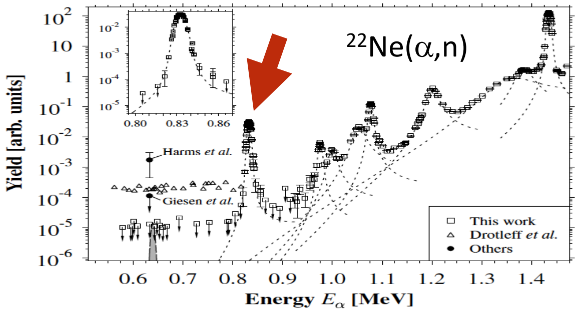
Previous n_TOF data

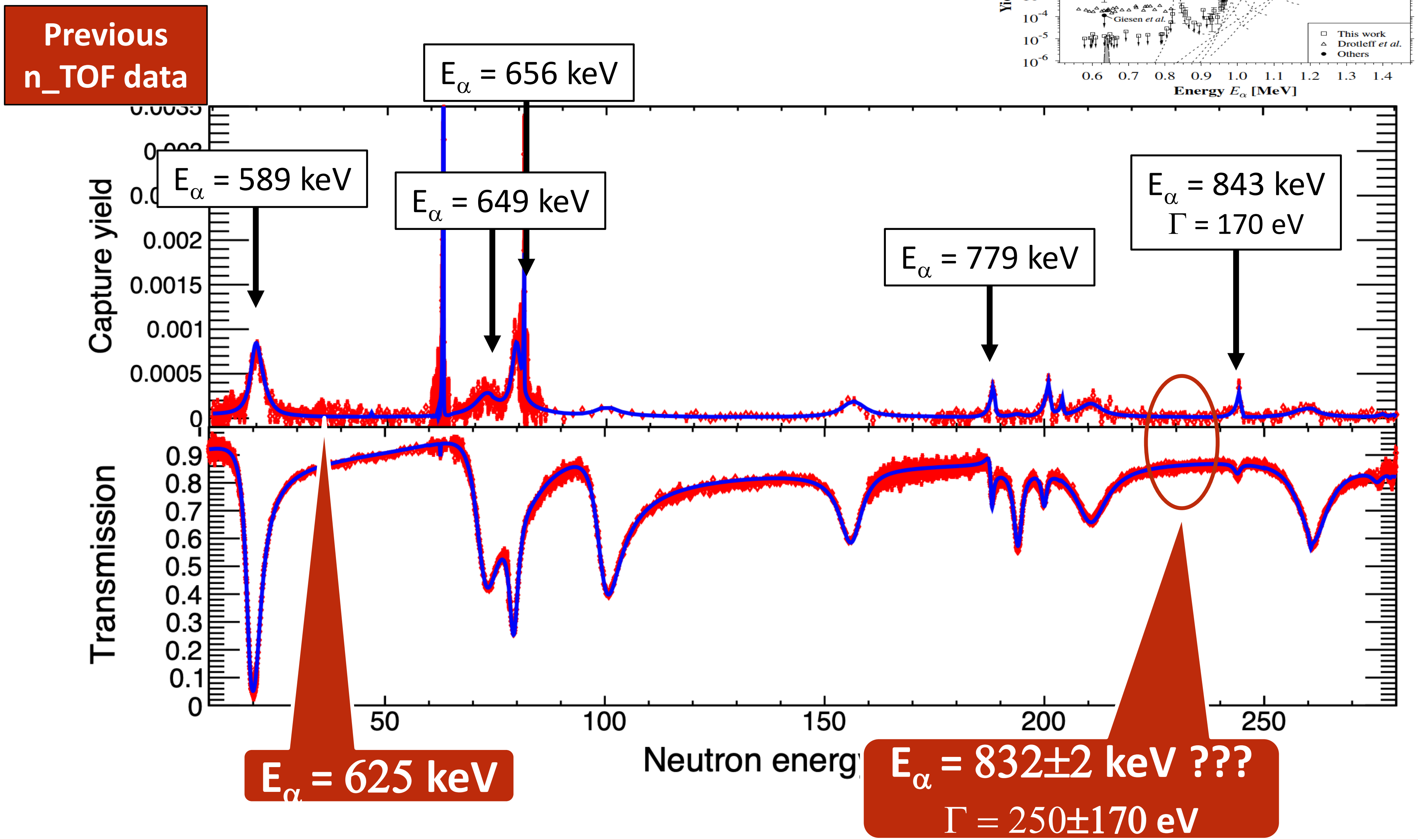


^{25}Mg(n,γ) for neutron source reaction in stars



^{25}Mg(n,γ) for neutron source reaction in stars





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Conclusions…?

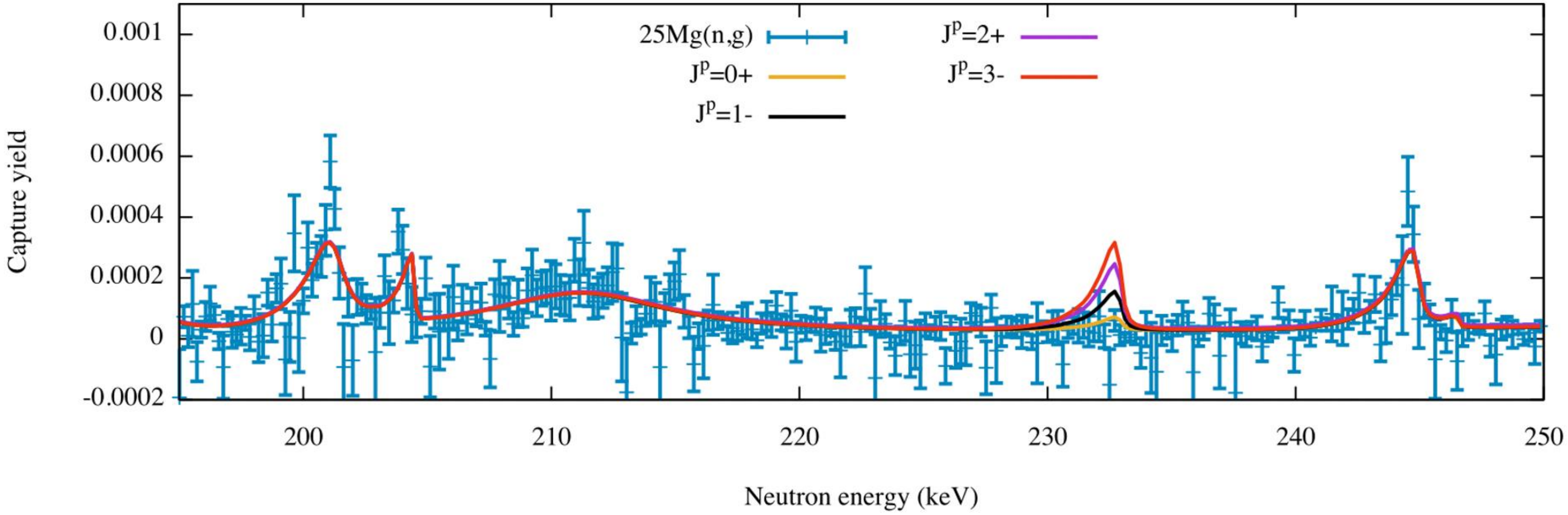
- ^{22}Ne(α,n) and (α,γ) represent a long-standing "problem" in nuclear astrophysics
- Measurements of ^{25}Mg(n,tot) and ^{25}Mg(n,γ) were performed at the GELINA facility and the n_TOF facility, respectively, to study excited states in ^{26}Mg

- Simultaneous resonance shape (R-Matrix) analysis of capture and transmission resulted in:
  - accurate ^{25}Mg(n,γ) cross section;
  - **energy** and **J$^{\pi}$** determination of ^{26}Mg levels: evidence for natural states;
  - constraints for the competing ^{22}Ne(α,γ) reaction;
  - doubts on the **E_{α} = 832 keV** resonance.

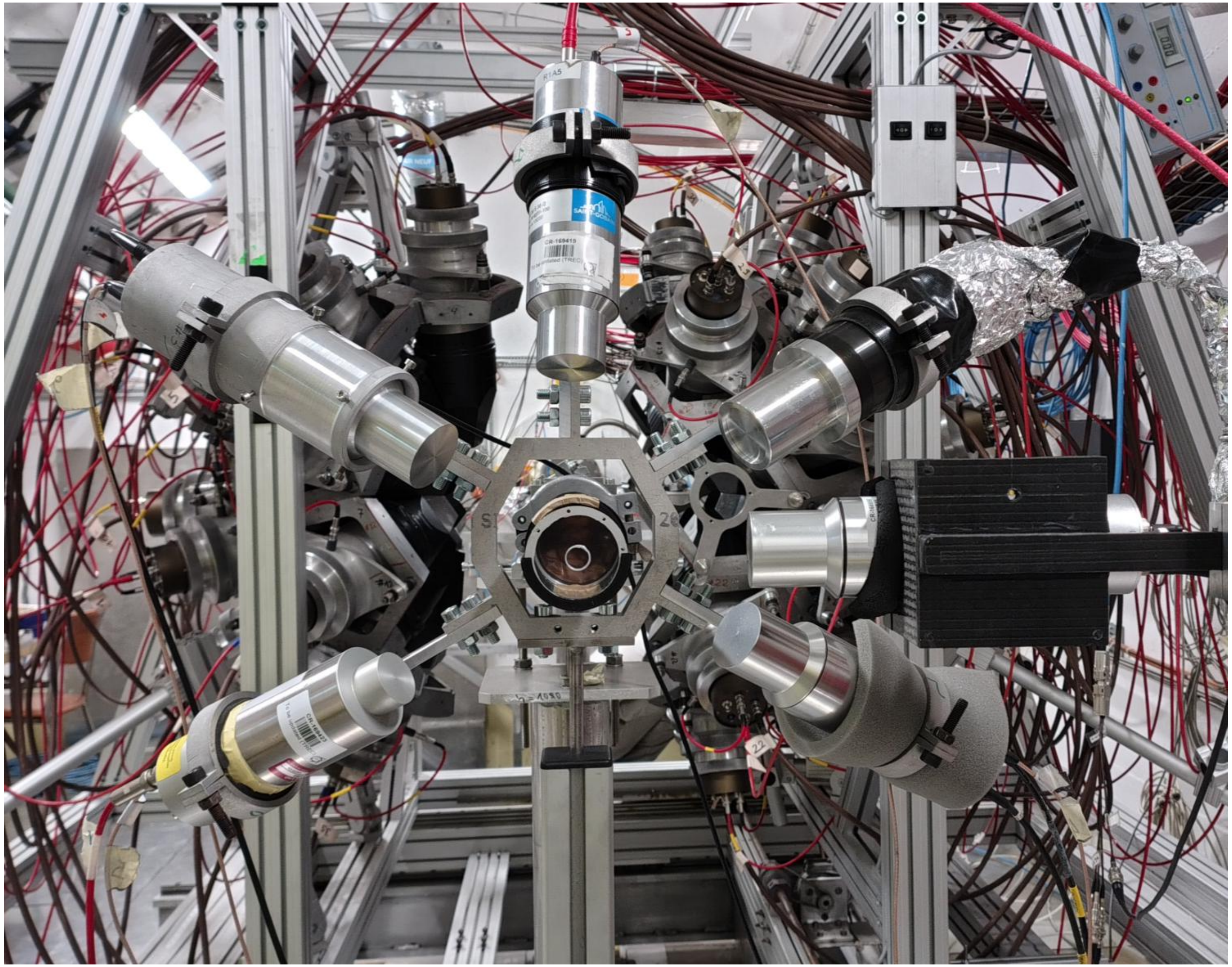
Proposal: $^{25}Mg(n,\gamma)^{26}Mg$ @ n_TOF

Our proposal is to **repeat the measurement in EAR1** with a factor 4 higher statistics and with some improvements:

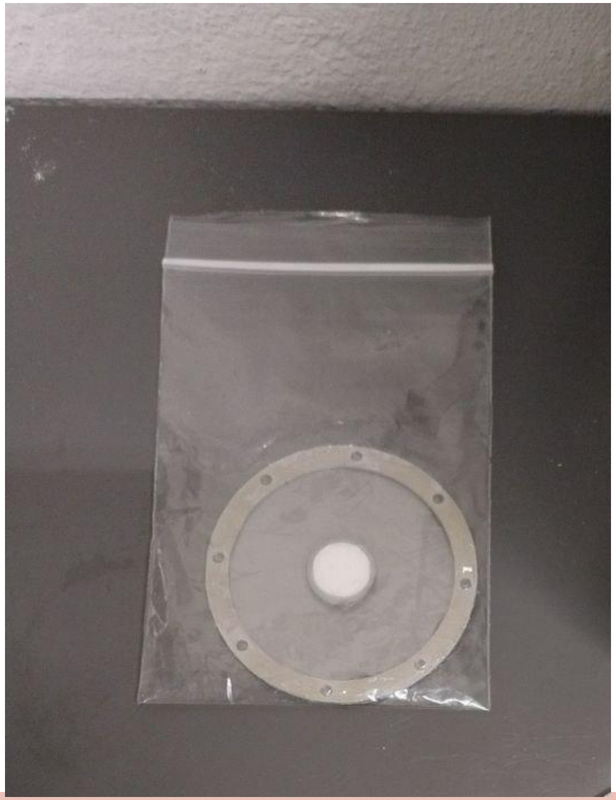
- Combined use of $LaBr_3$ and C_6D_6 detectors
- Use of a thicker enriched ^{25}Mg sample
- Combine with a capture measurement in EAR2



Proposal: ^{25}Mg(n,γ)^{26}Mg @ n_TOF



- More protons (4×10^{18})
- Thicker Mg sample



Acknowledgments

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

Thank you for your attention!

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Credits:

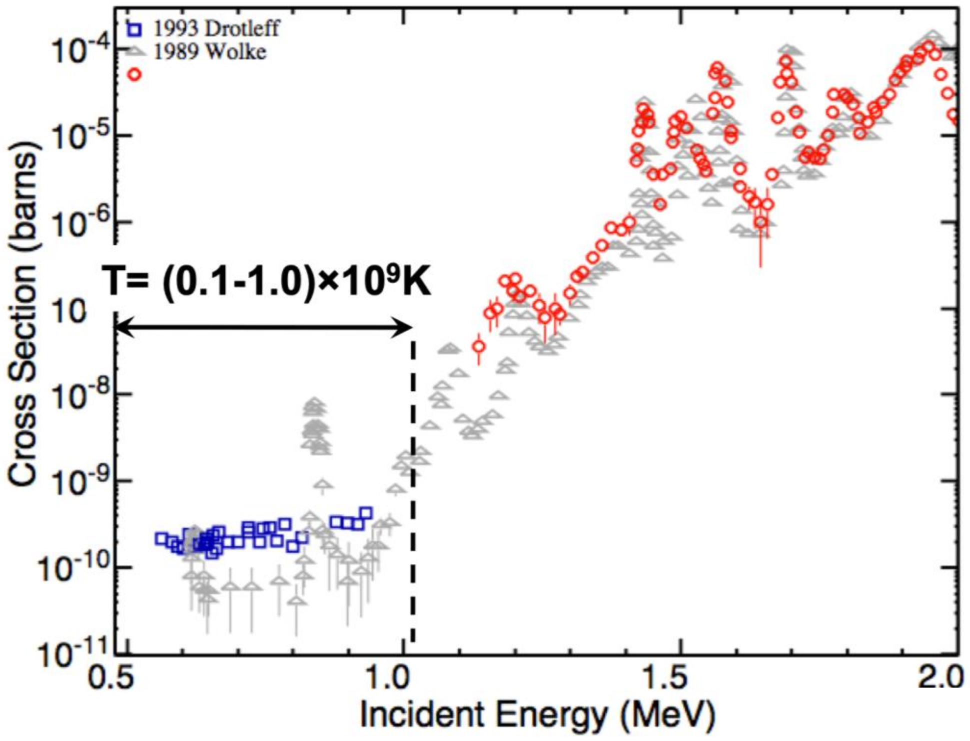
Motivations

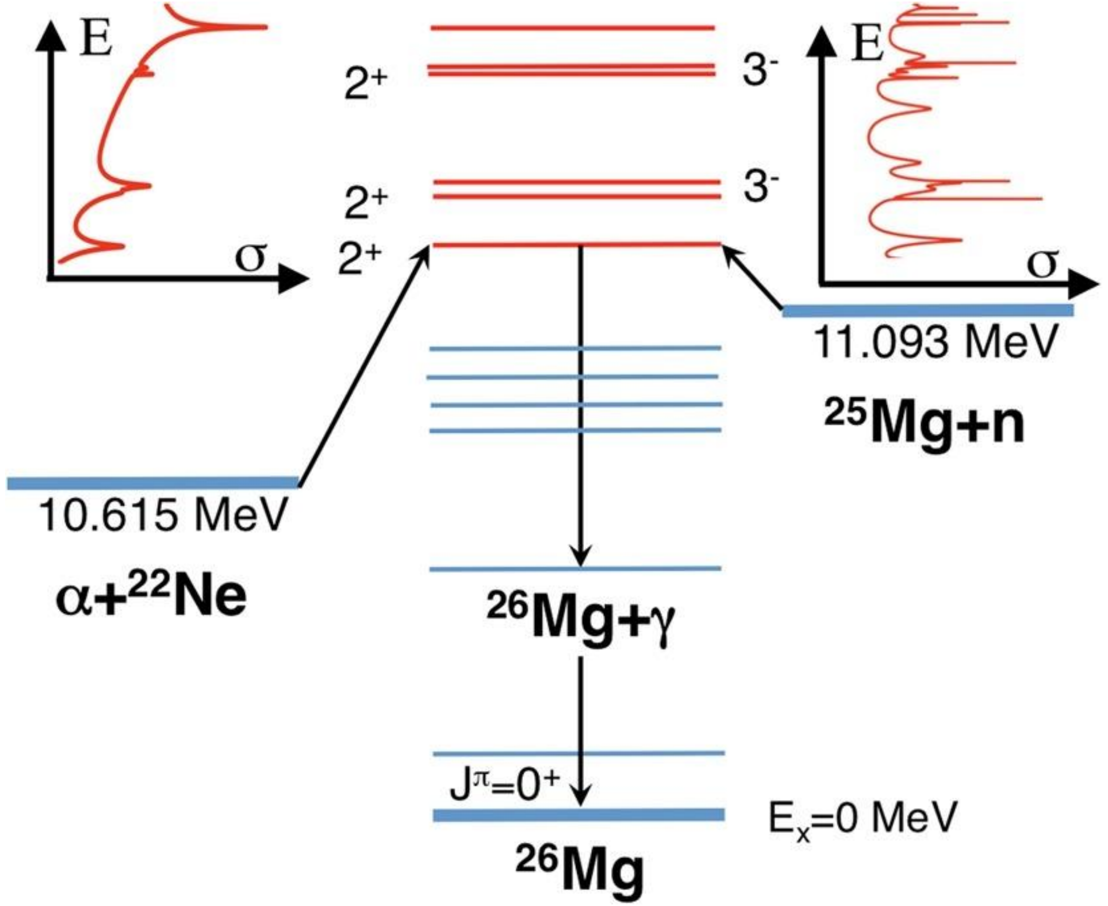
- NEUTRON POISON:
  - ^{25,26}Mg are the most important neutron poisons due to neutron capture on Mg stable isotopes, i.e. **^{25,26}Mg(n,γ),** in competition with neutron capture on ^{56}Fe (the basic s-process seed for the production of heavier isotopes).

- CONSTRAINTS for ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg:
  - ^{22}Ne(α,n)^{25}Mg is one of the most important neutron source in Red Giant stars. Its reaction rate is very uncertain because of the poorly known property of the states in ^{26}Mg. From neutron measurements the energy, **J^{π}** and **energy** of **^{26}Mg** states can be deduced, in addition to Γ_{γ} and Γ_{n}.

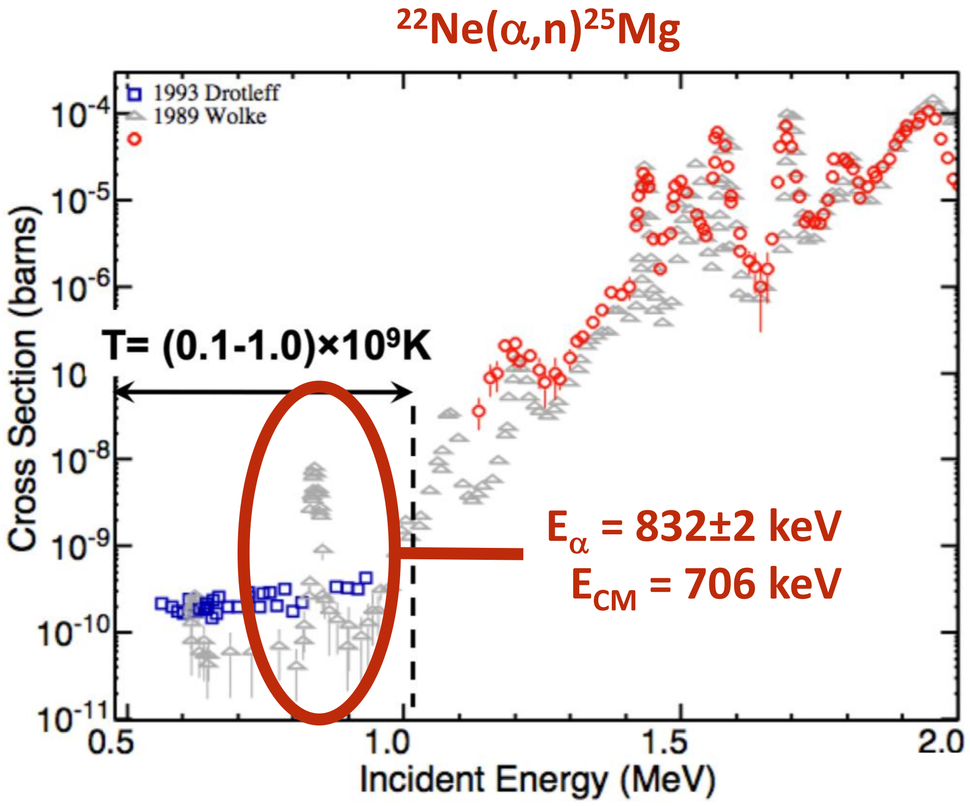
Measurement of $^{25}Mg(n,\gamma) \leftrightarrow {}^{22}Ne(\alpha,n)^{25}Mg$

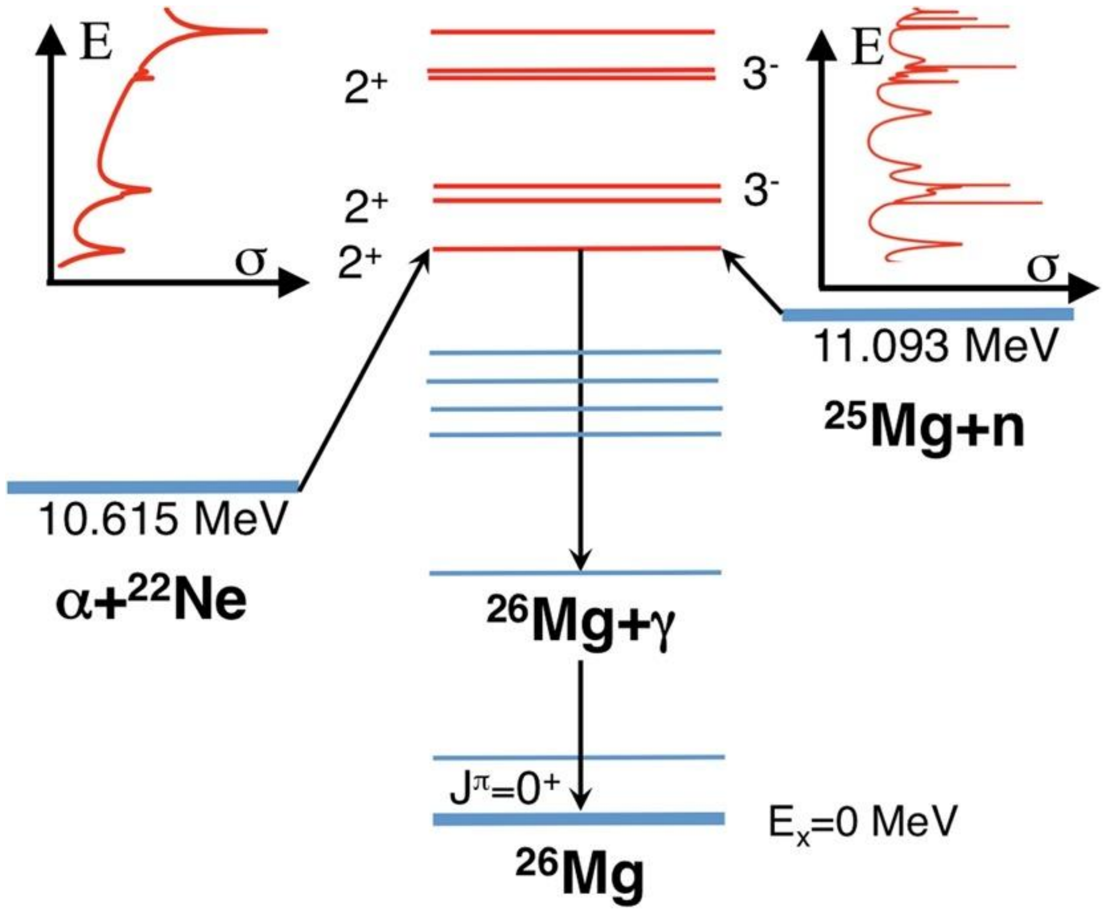
$^{22}Ne(\alpha,n)^{25}Mg$





Measurement of $^{25}Mg(n,\gamma) \leftrightarrow {}^{22}Ne(\alpha,n)^{25}Mg$





- ^{26}Mg levels via n + ^{25}Mg
- $^{25}Mg(n,\gamma)$ is not conclusive enough, **need for other reaction channels**

Extra slides

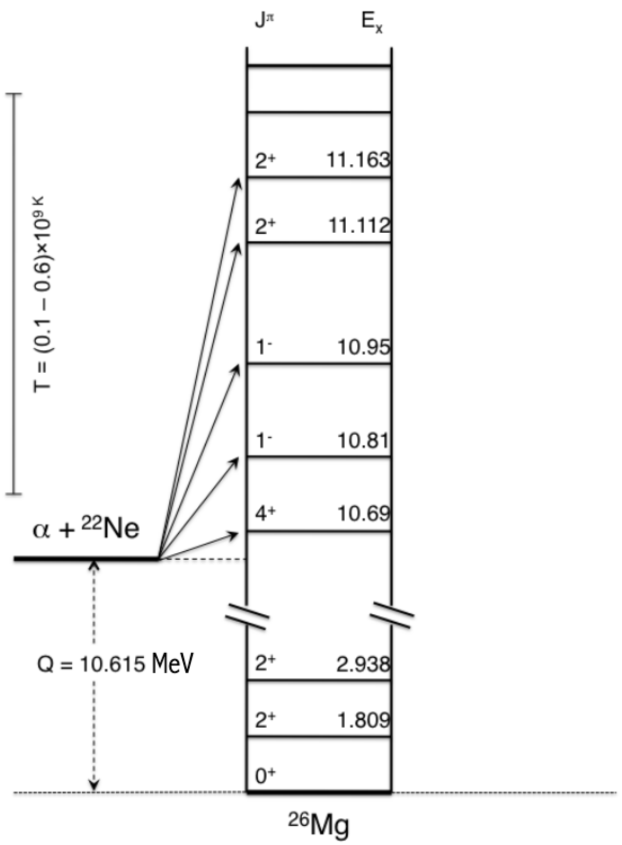
Constraints for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

Element	Spin/ parity
^{22}Ne	0^+
^{4}He	0^+

$$\vec{J} = \underbrace{\vec{I} + \vec{i}}\, + \vec{\ell}$$

$$\vec{J} = 0 + \vec{\ell}$$

Only **natural-parity** (0^+, 1^-, 2^+, 3^-, 4^+, …) **states in ^{26}Mg** can participate in the $^{22}Ne(\alpha,n)^{25}Mg$ reaction



Extra slides

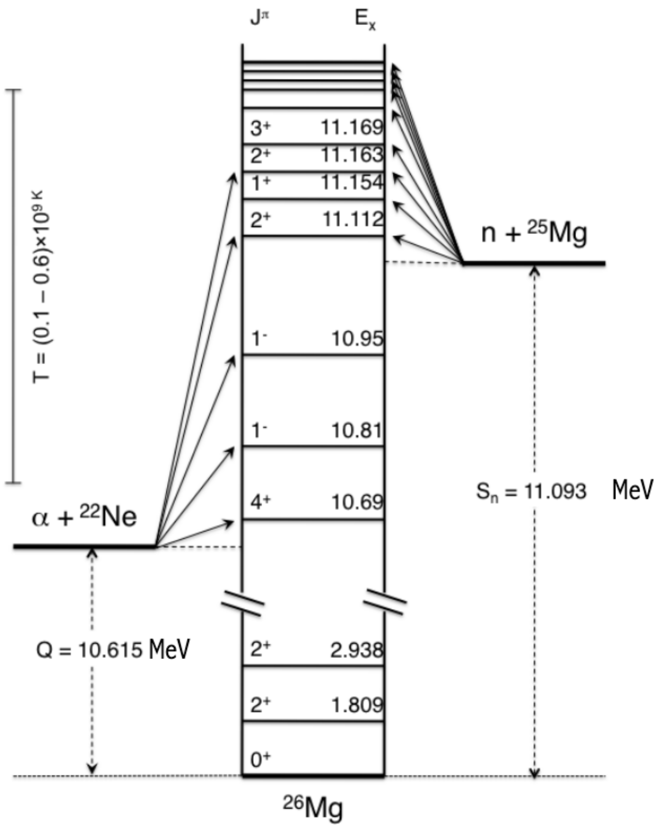
Constraints for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction

Element	Spin/ parity
^{25}Mg	$5/2^+$
n	$1/2^+$

$$\vec{J} = \vec{I} + \vec{i} + \vec{\ell}$$

$$\vec{J} = 2 + \vec{\ell} \qquad \vec{J} = 3 + \vec{\ell}$$

s-wave → J^π= **2⁺**, 3^+
p-wave → J^π= **1⁻**, 2^-, **3⁻**, 4^-
d-wave → J^π= **0⁺**, 1^+, **2⁺**, 3^+, **4⁺**, 5^+
States in ^{26}Mg populated by $^{25}Mg(n,\gamma)$ reaction

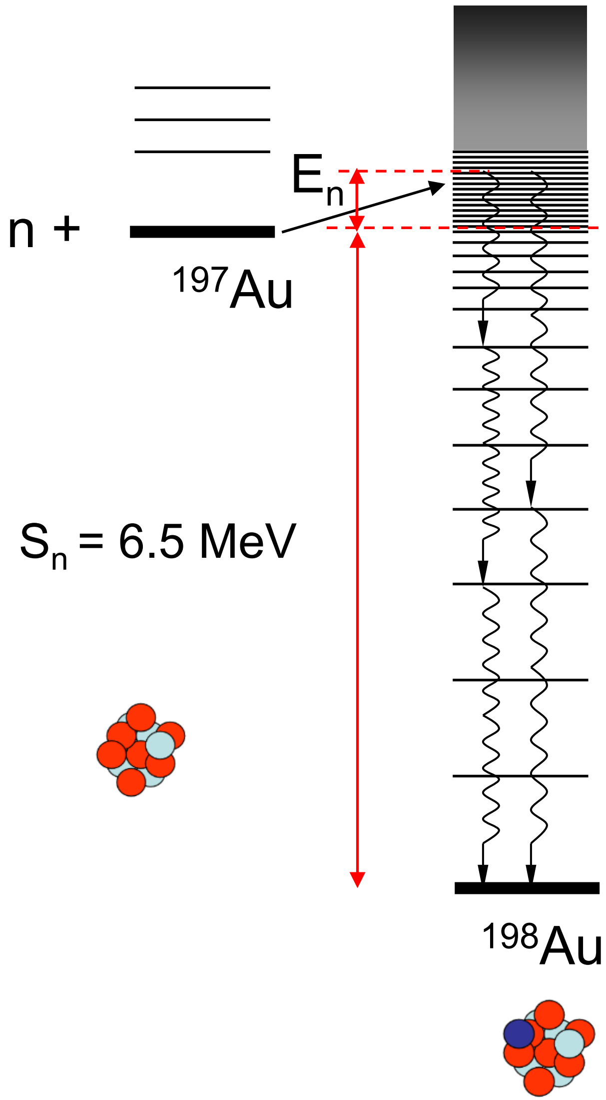


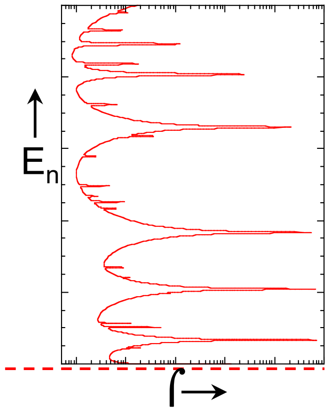
The n_TOF facility

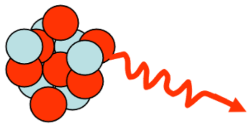
The advantages of n_TOF are a direct consequence of the characteristics of the **PS proton beam**: **high energy, high peak current, low duty cycle.**

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)

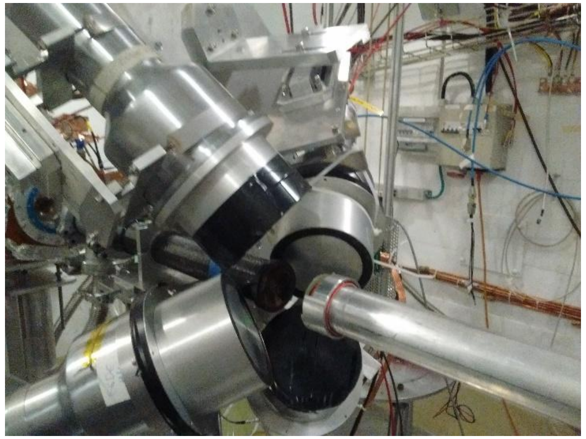




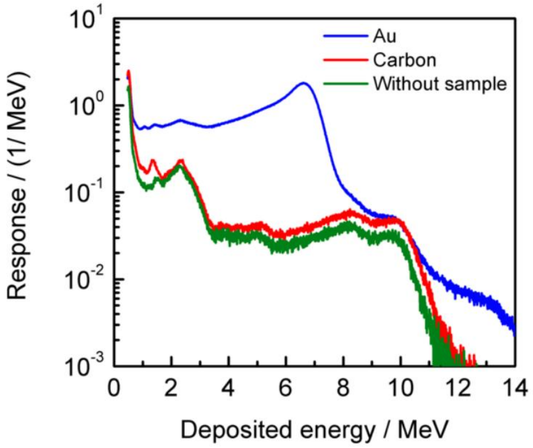


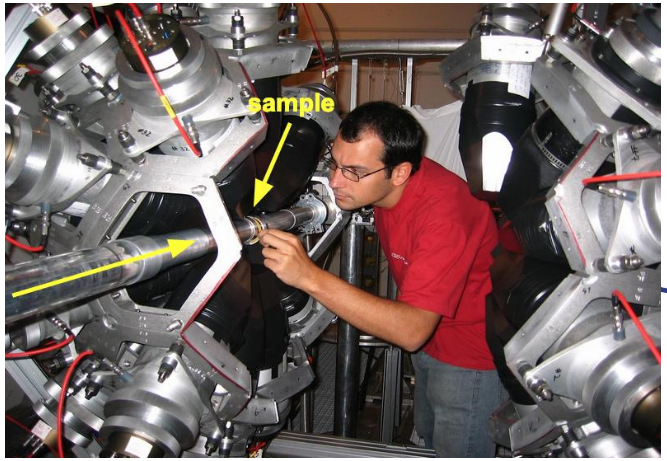
The C_6D_6 Total Energy Detectors (TED)

C_6D_6 scintillators at 135°



The BaF_2 Total γ-ray Absorption Detector

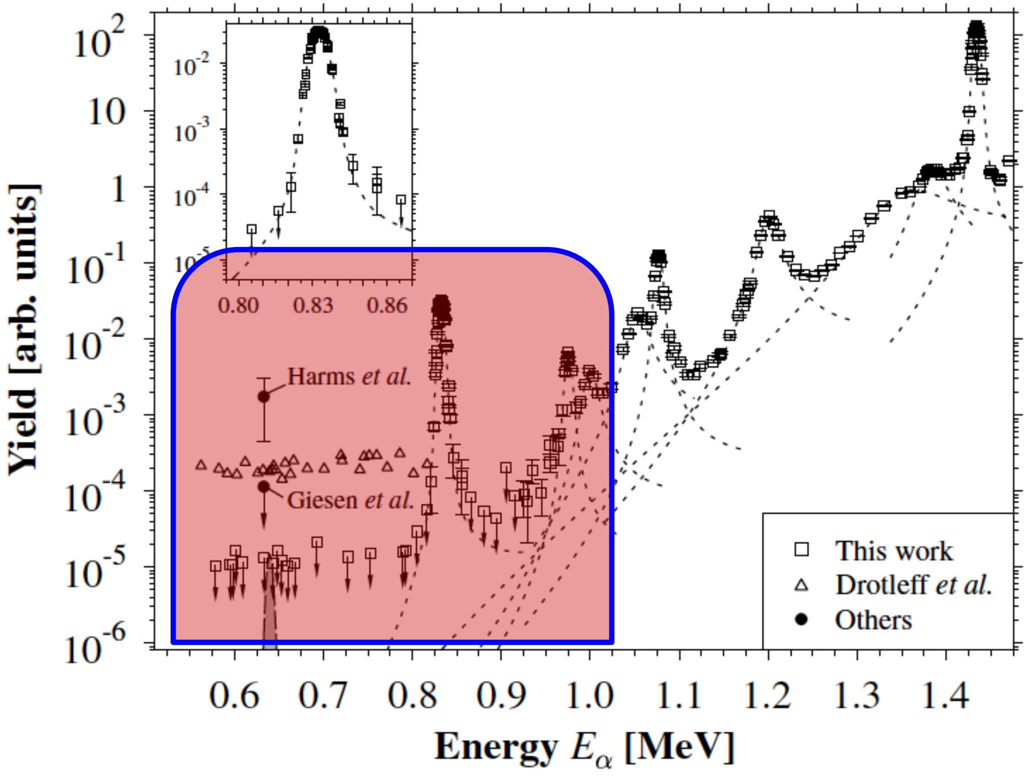


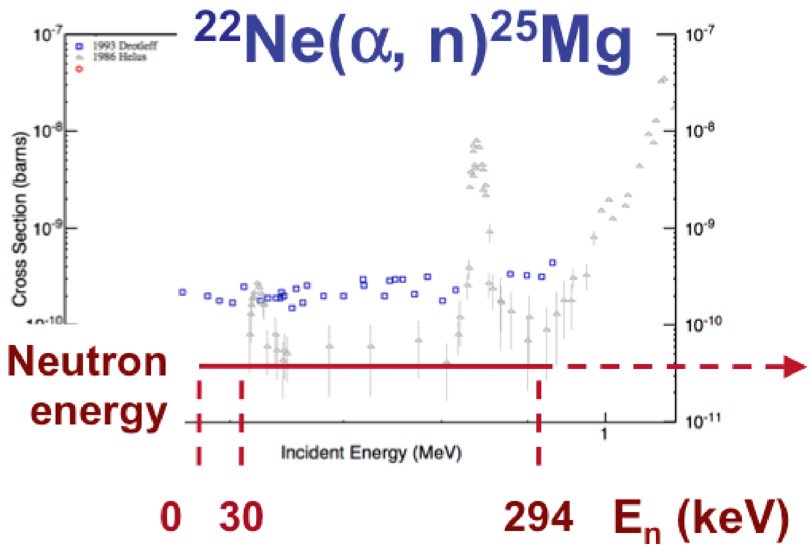


nTOF

Extra slides

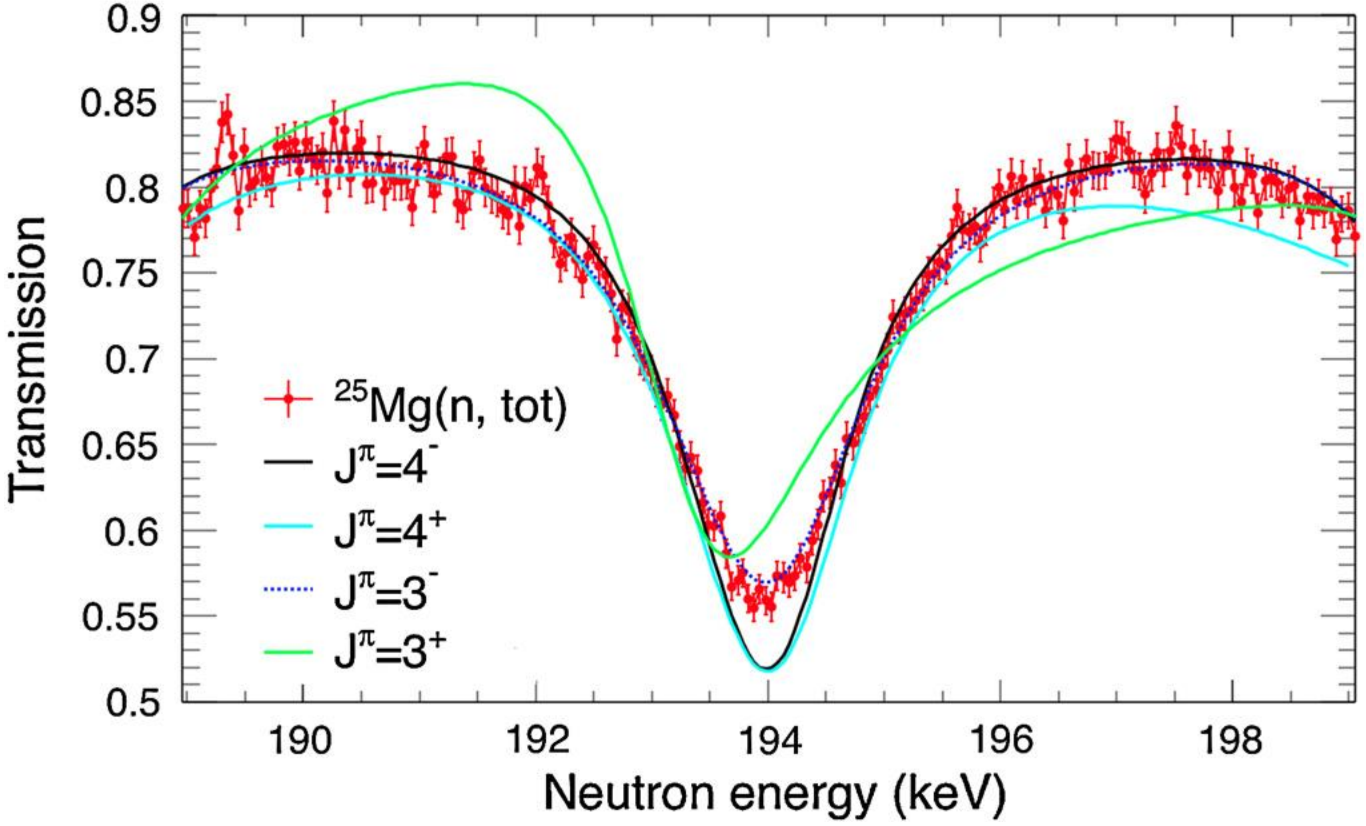
M. Jaeger, *et al.*, Phys Rev. Lett. **87** (2001) 20

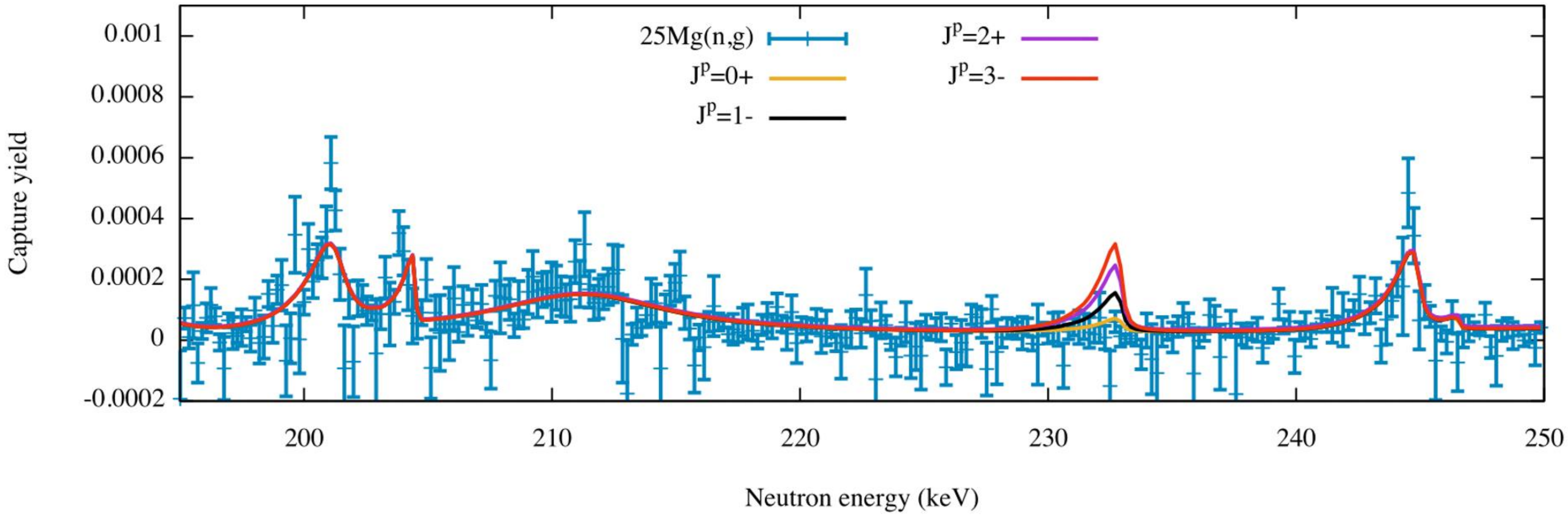




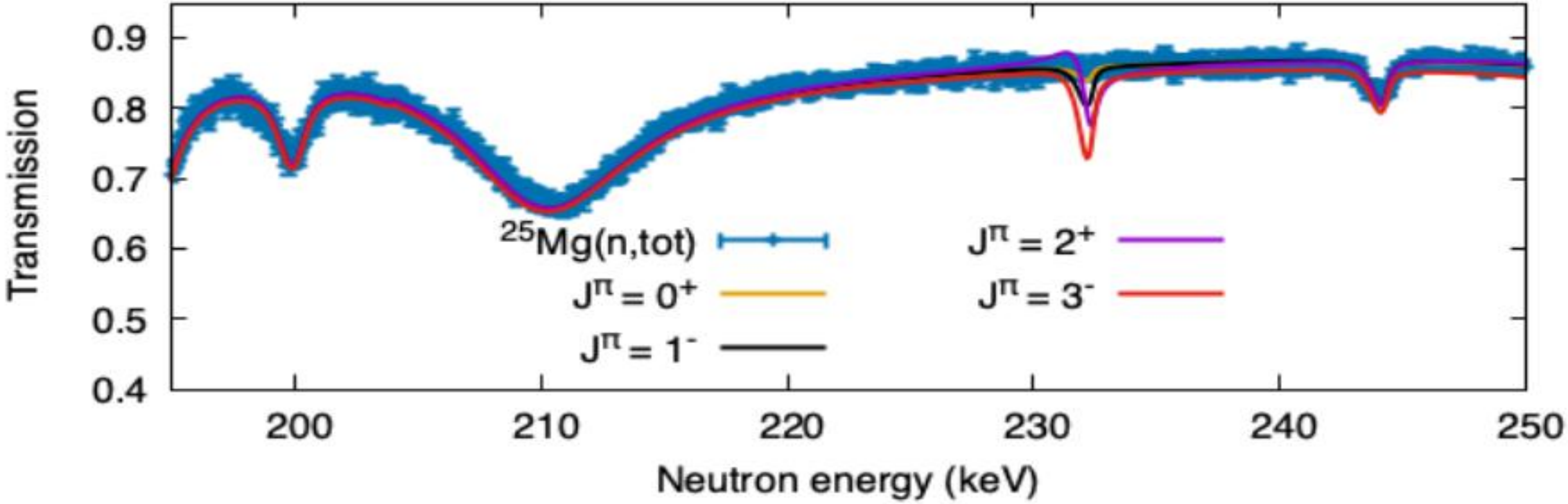
Measurement of ^{25}Mg(n,tot) @ GELINA

Example of the sensitivity to Spin and Parity J^{π}



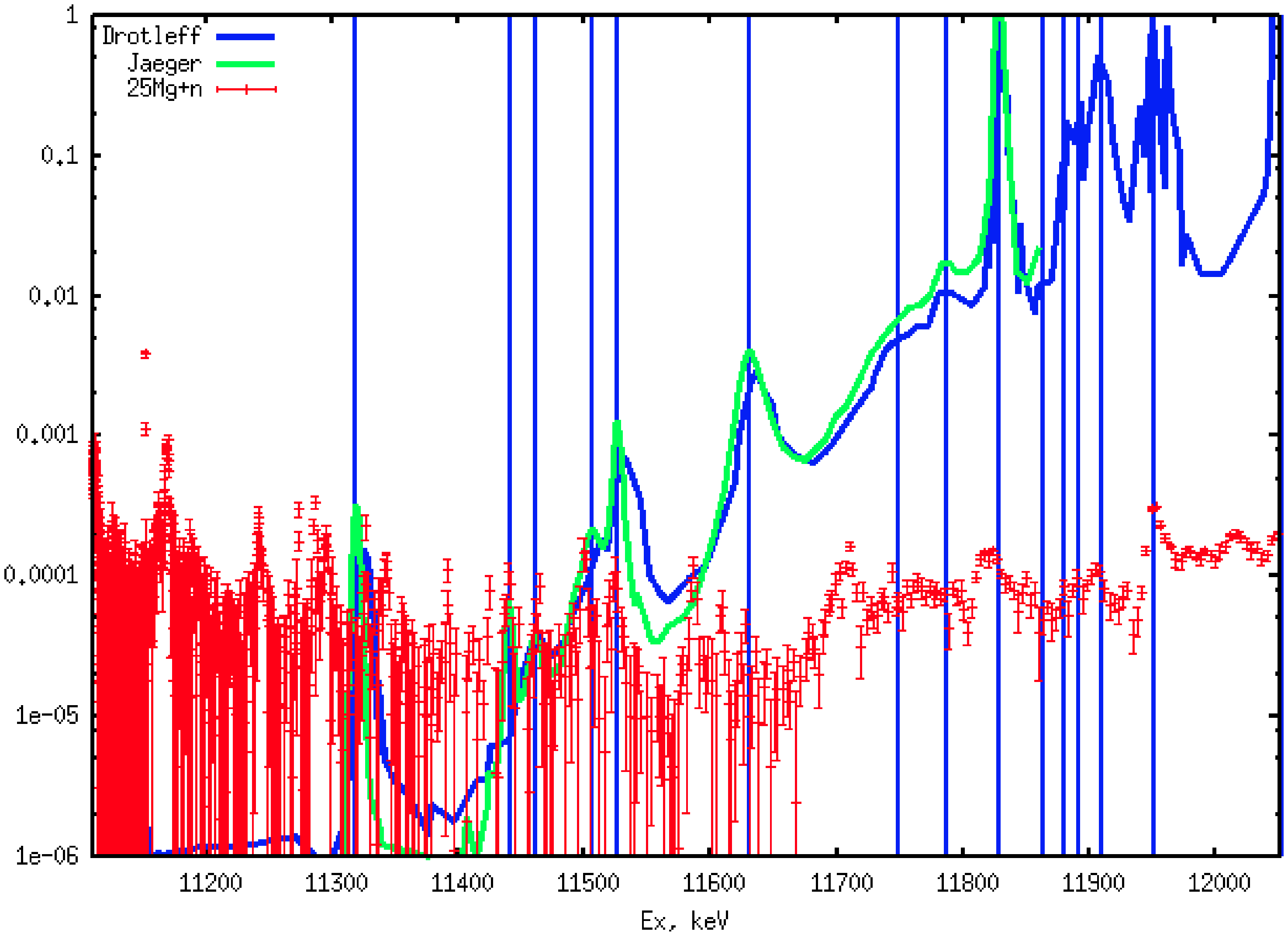


Capture yield
0.001
0.0008
0.0006
0.0004
0.0002
0
-0.0002
200
210
220
230
240
250
Neutron energy (keV)
25Mg(n,g)
Jp=0+
Jp=1-
Jp=2+
Jp=3-

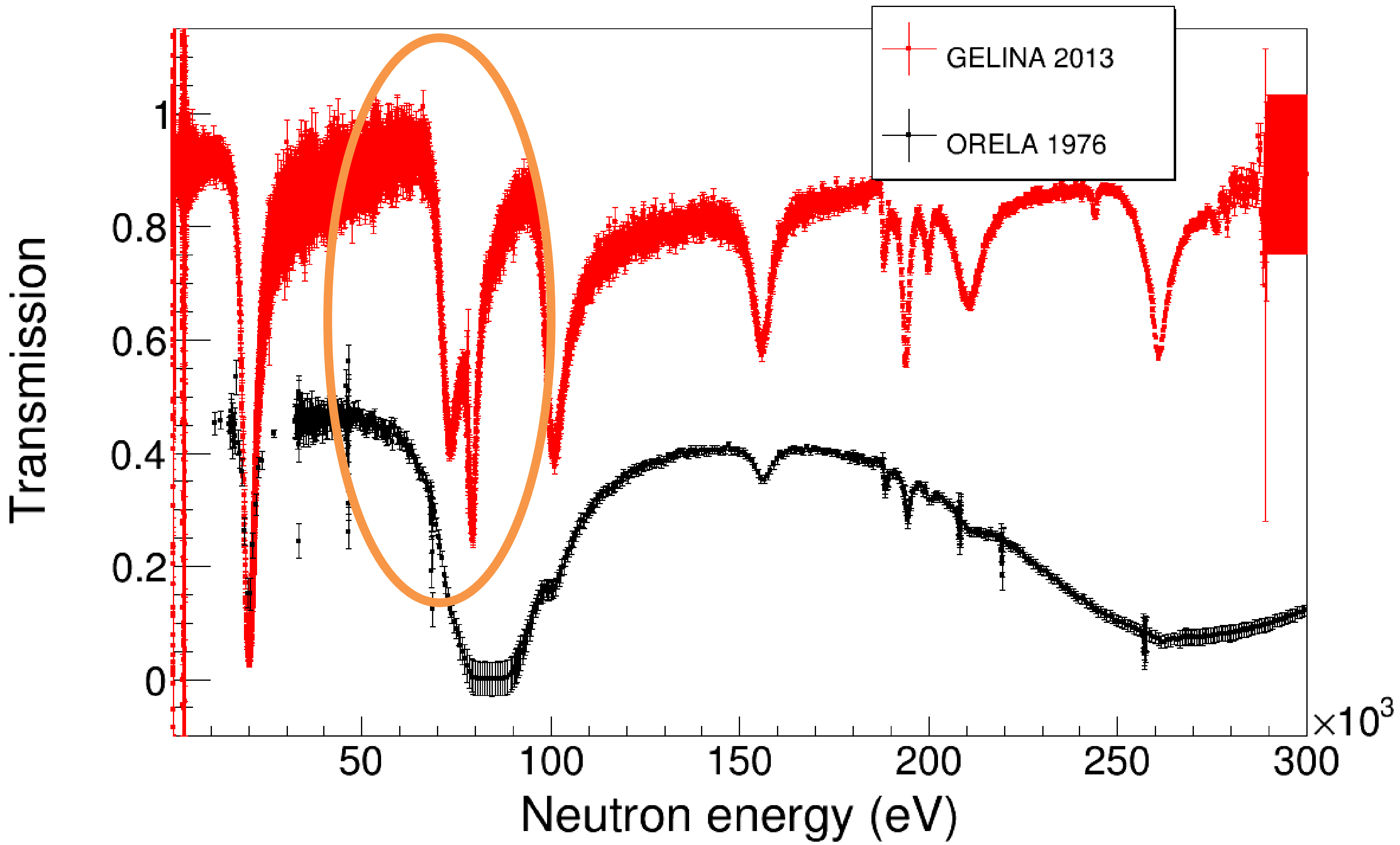


Transmission
0.9
0.8
0.7
0.6
0.5
0.4
200
210
220
230
240
250
Neutron energy (keV)
25Mg(n,tot)
Jπ = 0+
Jπ = 1-
Jπ = 2+
Jπ = 3-

Extra slides



Extra slides



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