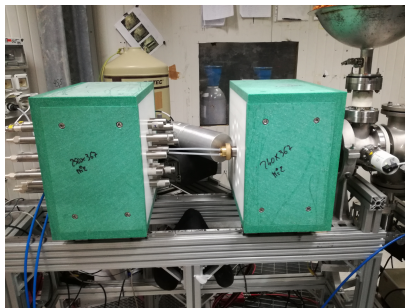
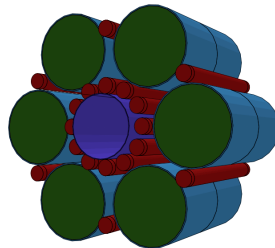


$^{13}\text{C}+\alpha$ and $^{22}\text{Ne}+\alpha$ at low energies



Andreas Best

INFN Naples

University of Naples "Federico II"



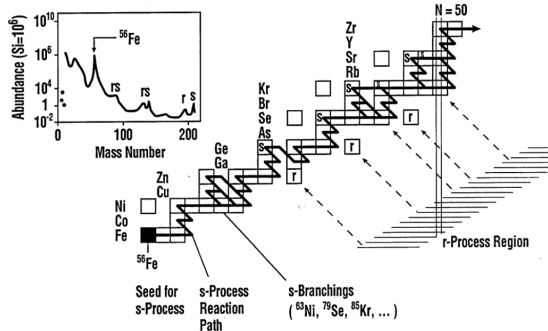
LUN



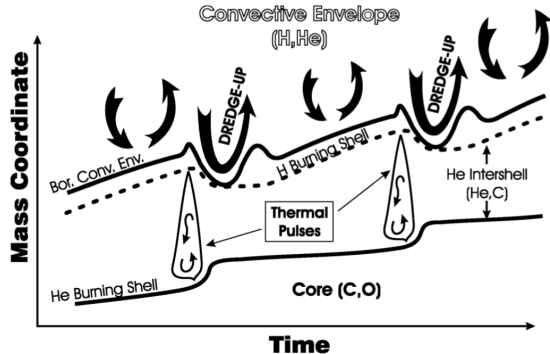
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$^{13}\text{C}(\alpha, n)^{16}\text{O}$ - main s



Kaeppler et al. 2011

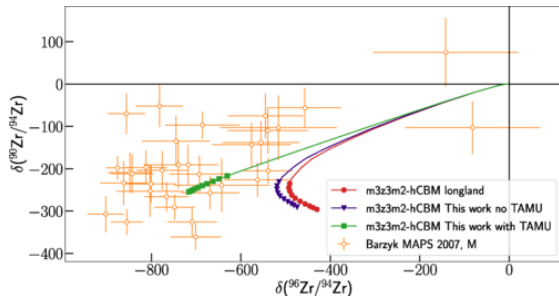


Straniero et al. 2006

- $\lambda_{(n,\gamma)} \ll \lambda_{\beta^-}$: nucleosynthesis follows valley of stability
- Takes place in “ ^{13}C pocket” in thermally pulsing AGB stars
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$ main neutron sources for s process
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$: $T \approx 90$ MK, energy range 140 - 230 keV
- Also possible neutron source for i-process (~ 280 MK, 285 - 510 keV)

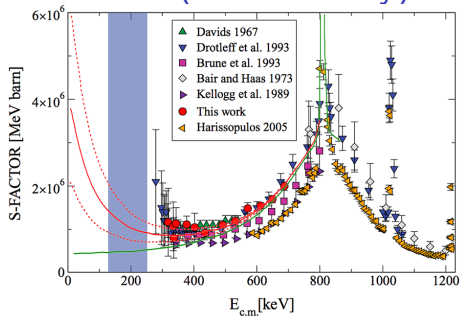


^{94}Mo 9.25 102 mb	^{95}Mo 15.92 292 mb	^{96}Mo 16.68 112 mb	^{97}Mo 9.55 339 mb	^{98}Mo 24.13 99 mb	^{99}Mo 2.75 d 240 mb, β^-
^{93}Nb 100 266 mb	^{94}Nb 20.30 ka 482 mb, β^-	^{95}Nb 34.99 d 310 mb, β^-	^{96}Nb 23.35 h β^-	^{97}Nb 1.20 h β^-	^{98}Nb 2.86 s β^-
^{92}Zr 17.15 33 mb	^{93}Zr 1.53 Ma 95 mb, β^-	^{94}Zr 17.38 26 mb	^{95}Zr 64.03 d 79 mb, β^-	^{96}Zr 2.8 10.7 mb	^{97}Zr 16.74 h β^-



- $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ contributes during late stages of main s process
- Determines branch point population
- Main source for weak s process
- Mg isotope observations in stellar atmospheres

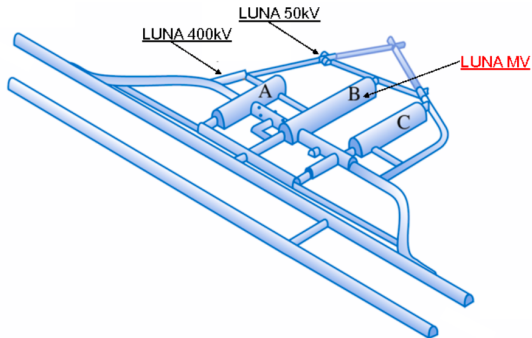
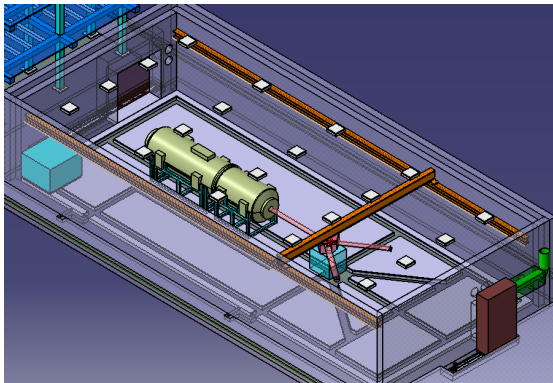
$^{13}\text{C}(\alpha, n)^{16}\text{O}$ state of the art (until recently)



Heil et al. 2008

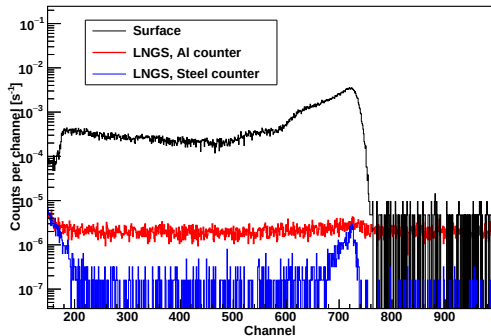
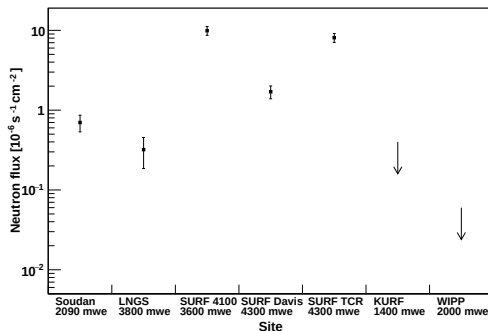
- Heil et al.: down to 317 keV, large uncertainties below 400 keV
- Drotleff et al.: $E_{cm,min} = 279$ keV, large uncertainties below 350 keV
- Environmental background
 - ▶ Heil 340 counts/hour
 - ▶ Drotleff 290 counts/hour
- At higher energies strong differences in normalization
- Trojan horse data anchor to ANC/high-energy c.s.

LUNA / MV campaigns



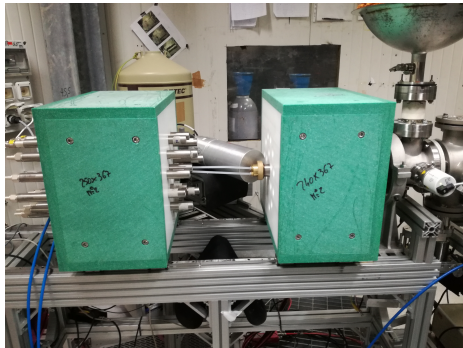
- Can cover 50 - 3500 keV with two accelerators
- Same setup(s) for both campaigns, energy overlap 350 - 400 keV
- Opportunity to calibrate using more reactions at higher energies
- p/α beam currents order of hundreds of μA
- MV opens possibility for inverse measurement $\rightarrow$ go lower in E?

Advantages of going underground



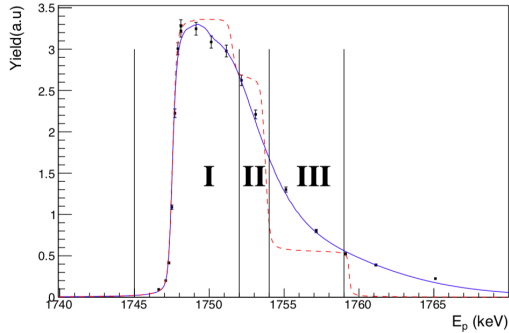
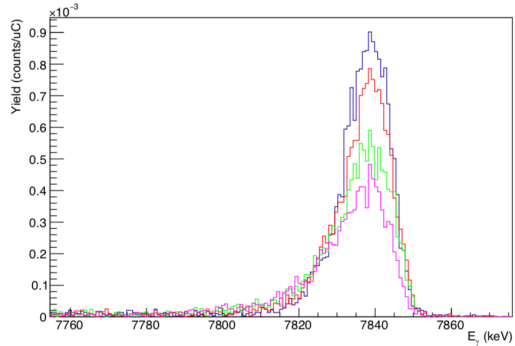
- Direct low-energy measurements limited by natural background
- LNGS $\approx$ 3400 m.w.e. underneath Gran Sasso mountain chain
- Cosmic-ray induced neutrons efficiently shielded against
- Residual flux from (α, n) and fission in rocks
- Neutron flux underground suppressed by $\approx$ 1000 w.r.t. surface

Setup - Detector



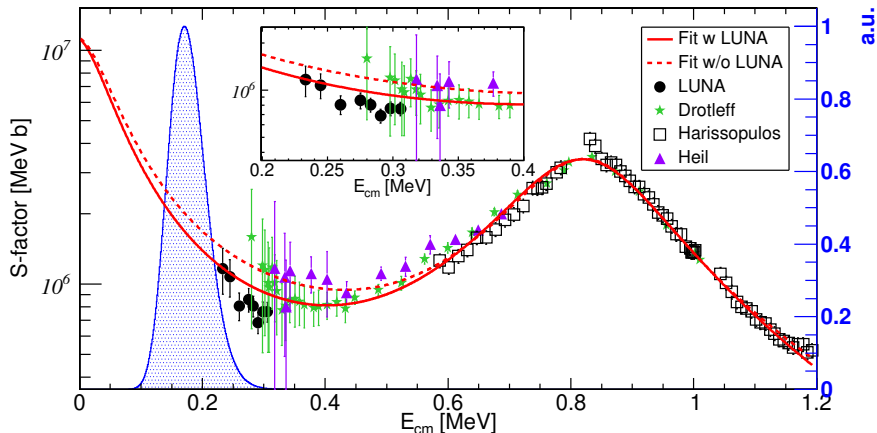
- 6×25 cm, 12×40 cm long, 10 bar ^3He counters in polyethylene
- Efficiency $\approx 30\%$ ($^{51}\text{V}(p,n)^{51}\text{Cr}$, AmBe)
- 2" 5% borated PE shielding
- 1-2 counts/hour total (internal+external) background
- Csedreki et al. NIM A A 994 (2021) 165081

Measurement strategy



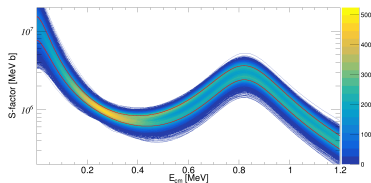
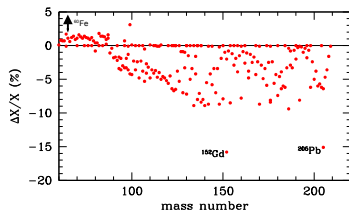
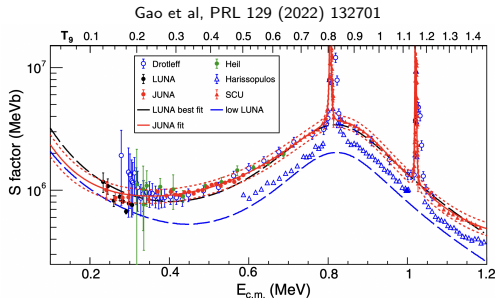
- Solid target (99 % ^{13}C on Ta) $\rightarrow$ degradation under beam
- Normally, use resonance yield profile to monitor target
- No ^{13}C resonances in LUNA 400 energy range!
- Switch to H^+ beam, measure $^{13}\text{C}(\text{p}, \gamma)$ gamma ray shape
- Ciani et al., EPJ A 56 (2020), 75

Results

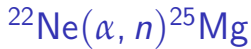
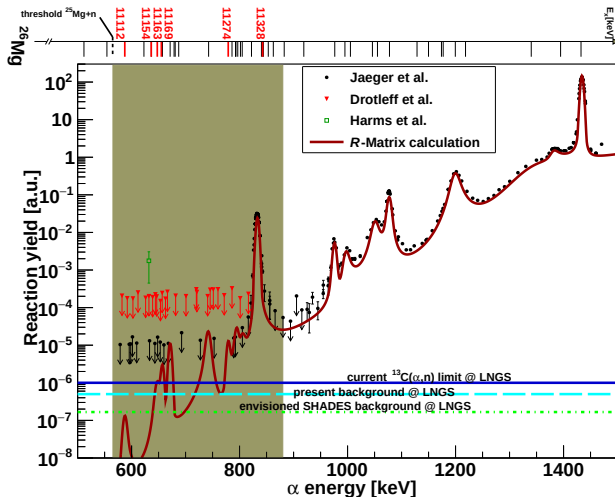


- Covered 235 - 300 keV, 50 keV lower than before
- ≈ 100 C for lowest point
- Ciani et al. PRL 127, 152701 (2021)

R matrix + astro



- Two normalizations: Harissopulos, Drotleff&Heil
- LUNA data kept fixed, others rescaled
- MC R matrix for combined reaction rate PDF
- **I have heard some rumours about the Avila et al. ANC?**



R matrix courtesy of R. J. deBoer, University of Notre Dame/JINA

- Capabilities on surface exhausted (20 years since last data)
- Current lowest data 2 reactions/minute
- Covered one resonance close to Gamow
- Many states that can contribute
- **300 keV of upper limits...**

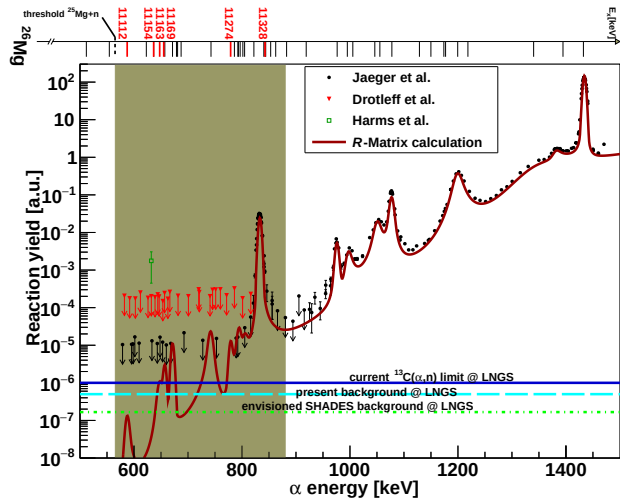
Low-energy states

Table 1. Properties of states in ^{26}Mg between the neutron threshold and the 832 keV resonance. Values taken from [15], except for the last row, which is from [14].

E_n [keV]	E_x [keV]	E_α [keV]	$J\pi$	Neutron width [eV]
19.92	11112	589	2+	2095
72.82	11163	649	2+	5310
79.23	11169	656	3-	1940
187.95	11274	779	2+	410
194.01	11280	786	3-	1810
243.98	11328	843 ?	?	171
235 [14]	11319	832	2+	Total width = 250 eV

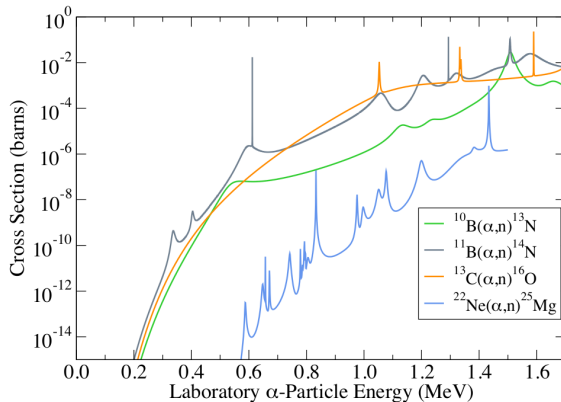
- Recent nTOF study of energies and neutron widths (Massimi et al. PLB 768 (2017), 1)
- 832 keV state still a bit unclear w.r.t. n/α channel, energy
- No α widths are known

What to do?



- Drastic background reduction
- Large beam current increase
- Suppression/identification of beam-induced background

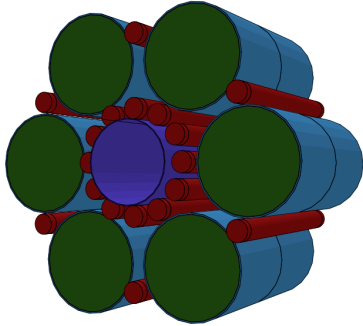
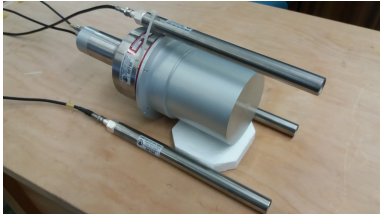
Beam-induced backgrounds



- Q-values:

- ▶ $^{22}\text{Ne} = -478$ keV
- ▶ $^{10}\text{B} = 1059$ keV
- ▶ $^{11}\text{B} = 158$ keV
- ▶ $^{13}\text{C} = 2216$ keV

Measurement strategy

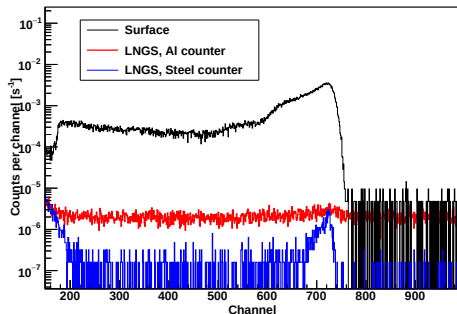
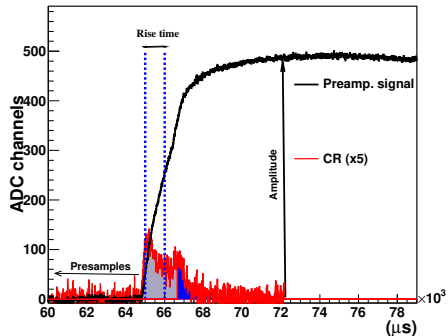


- Need to measure very low event rates
- Require some sort of energy sensitivity
- Hybrid detector array: ^3He counters & liquid scintillator
- High efficiency + energy sensitive
- Gas target for long, uninterrupted runs



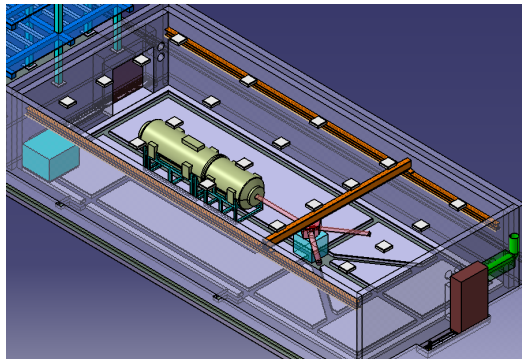
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Background reduction



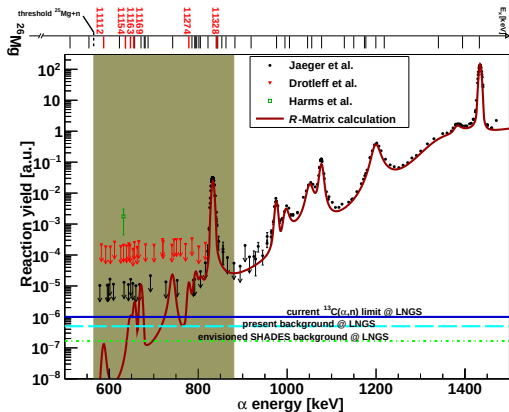
- Deep underground @ LNGS: Suppression of (thermal) neutron background by > 1000
- Additional clean detector material & PSD
- Extended gas target with enriched ^{22}Ne
- Coincidence/Anticoincidence
- Total background < 1 count/hour

Top-of-the-line accelerator



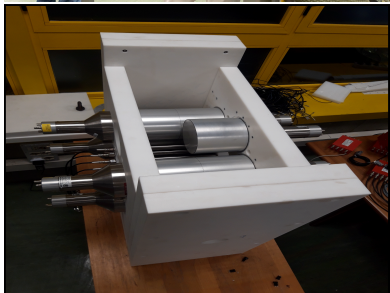
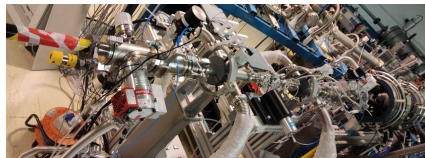
- Specifically designed to fit nuclear astrophysics needs
- Reaction rates of $< 1/\text{hour}$:
 - ▶ Beam current ($\approx 5 \times$ Jaeger et al.): push signal-noise ratio
 - ▶ Current stability: measurements of the order of weeks
 - ▶ Energy stability: must not drift over long periods
- 300 - 3500 kV: cover entire astrophysical energy range

Goals



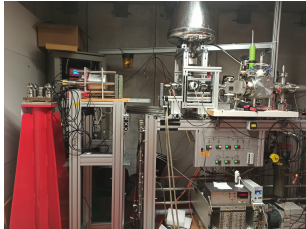
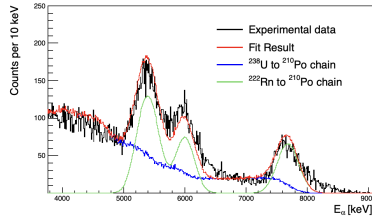
- Cover from threshold to 3.5 MeV
- > two orders of magnitude improvement
- Comprehensive R matrix analysis
- Perform nucleosynthesis calculations with new data

Status I

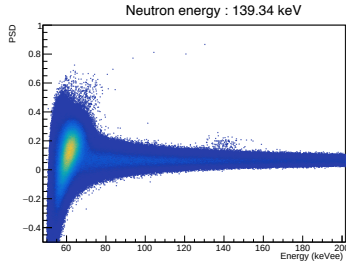


- 5(+1)-year, since February 2020
 - ▶ Target+detector assembled
 - ▶ 1st target characterisation at CIRCE
 - ▶ Detector background investigated
 - ▶ DAQ development underway
 - ▶ Detector characterisation at FRANZ
- Assembly at LNGS in July
- Underground campaign at LUNA MV
- Data evaluation and astrophysical impact - collaboration with M. Pignatari/Budapest

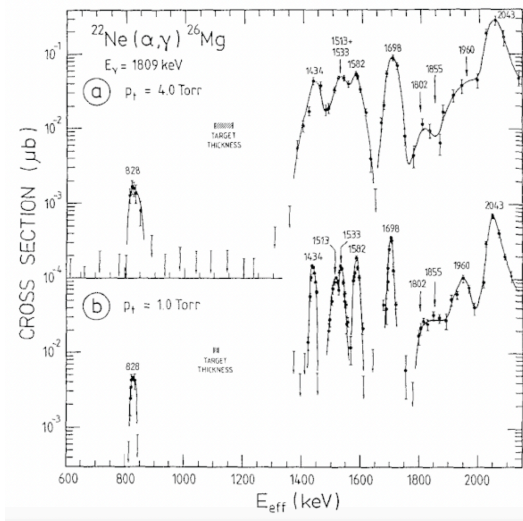
Status II



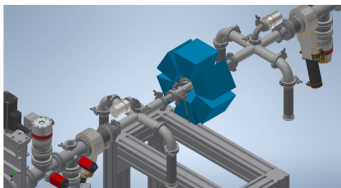
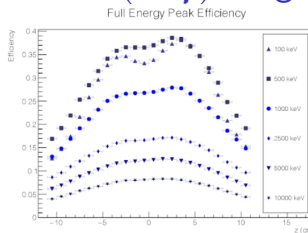
- Detector background investigated - ready to submit
- Detector characterisation at FRANZ - under analysis



$^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$



- Direct data Wolke et al. 1989 (!)
- Some remeasurements of 830 keV res (TUNL)
- CASPAR + LUNA few new upper limits
- Vast terra incognita to explore

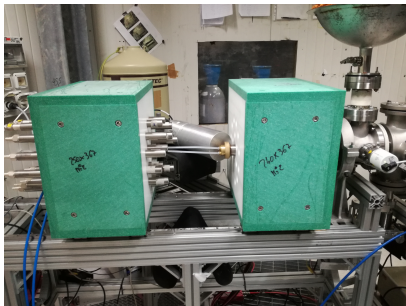
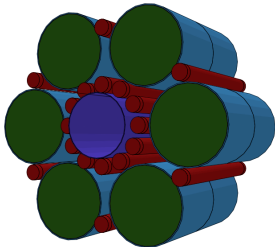
Experimental and Astrophysical Study of $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ 

- MUR project started 1. December 2022 - 4 years
- Synergize with ERC setup
- High-efficiency γ -detection array
- Map out cross section of (α, γ) channel
- O. Straniero + astro postdoc for stellar analysis

C. Ananna, A. Best, G. Imbriani, A. di Leva, D. Mercogliano, M. Junker, M. Pignatari, D. Rapagnani, O. Straniero + ???



Summary



- Good times for s process
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$
 - ▶ Wealth of new data, low-E, high-E
 - ▶ Global R matrix analysis in planning
- $^{22}\text{Ne}(\alpha, [n, \gamma])^{25,26}\text{Mg}$
 - ▶ Steady influx of indirect data
 - ▶ Push direct cross section towards Gamow energy with SHADES/EAS γ
 - ▶ Installation starting in July, beam in fall 2023 (n channel)