Nuclear Astrophysics at LUNA

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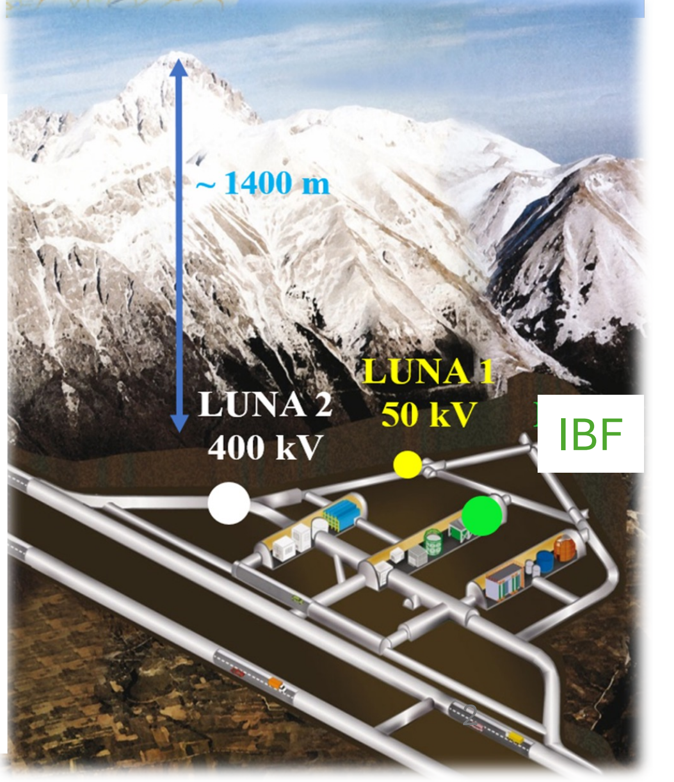
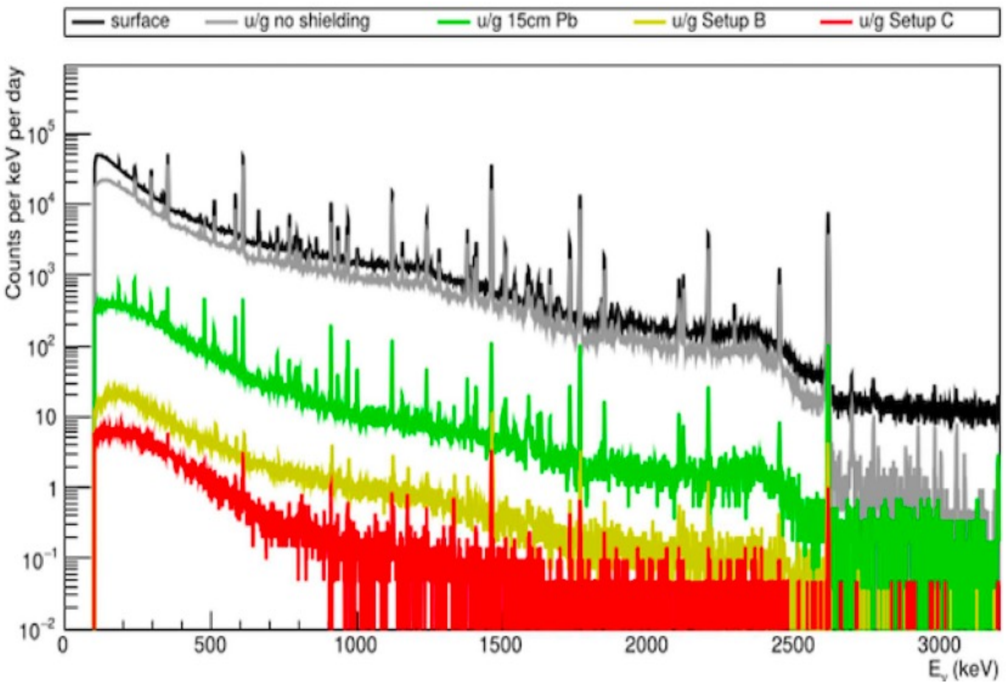
Laboratory for Underground Nuclear Astrophysics

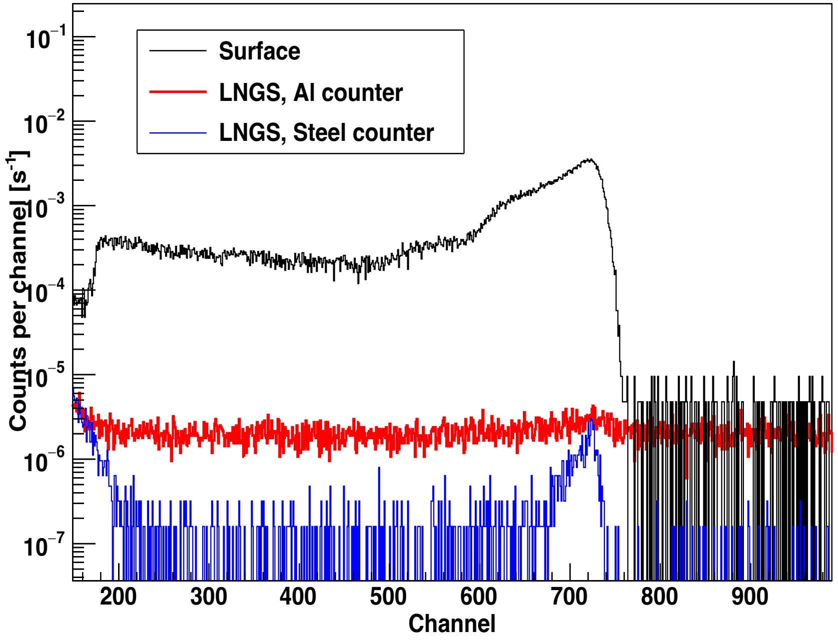
- Located in the Grand Sasso Laboratory of the Italian Institute for Nuclear Physics (LNGS-INFN)

- 1400 m (3800 m.w.e.) grant a background reduction by:
  - 6 orders of magnitude for muons
  - 3 orders of magnitude for neutrons

- Further background reduction using additional passive shielding (Lead, Copper, BPE) and ultrapure materials

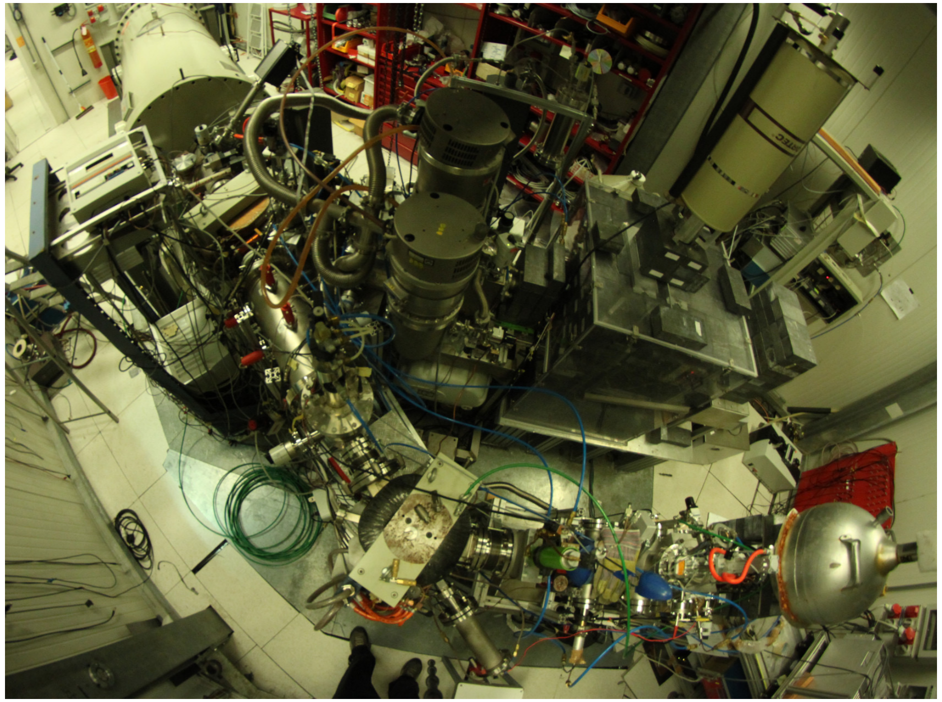






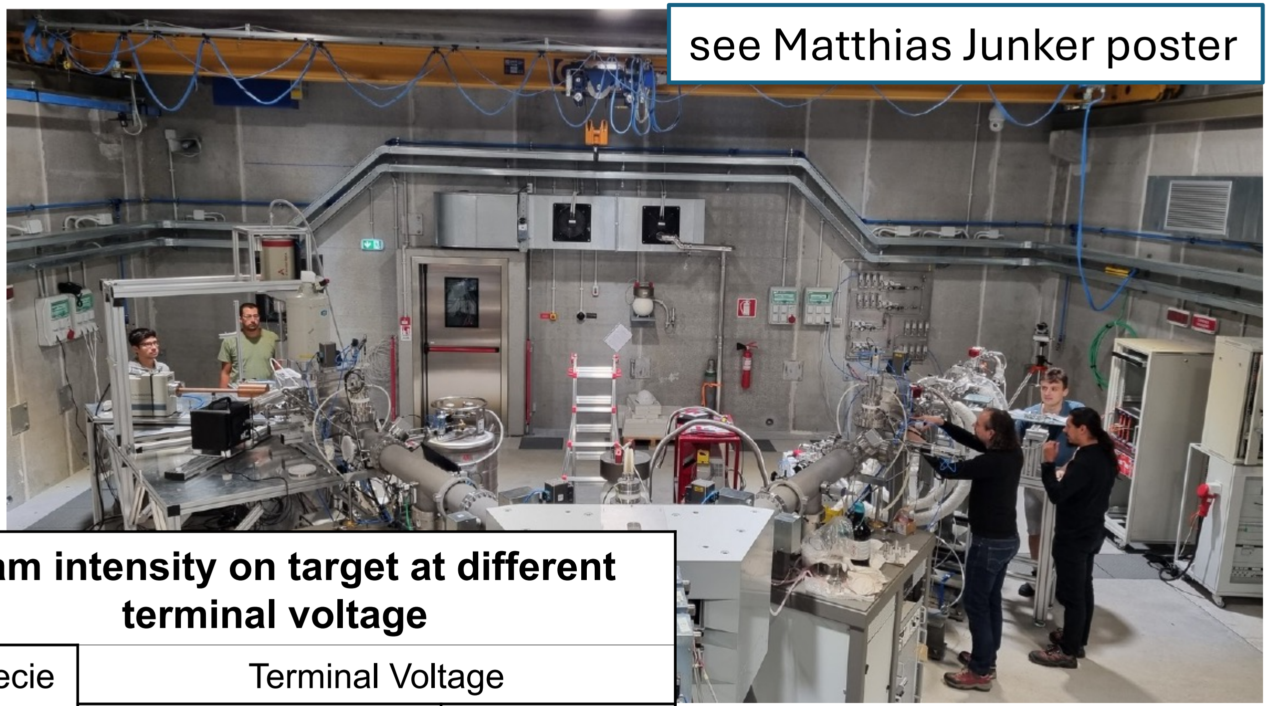
LUNA-400 and Ion Beam Facility «Bellotti»

Formicola et al. NIM A 507 (2003) 609–616



Beam energy (keV)		Beam intensity on target (uA)	
H+	He+	H+	He+
50-400	50-400	250	250

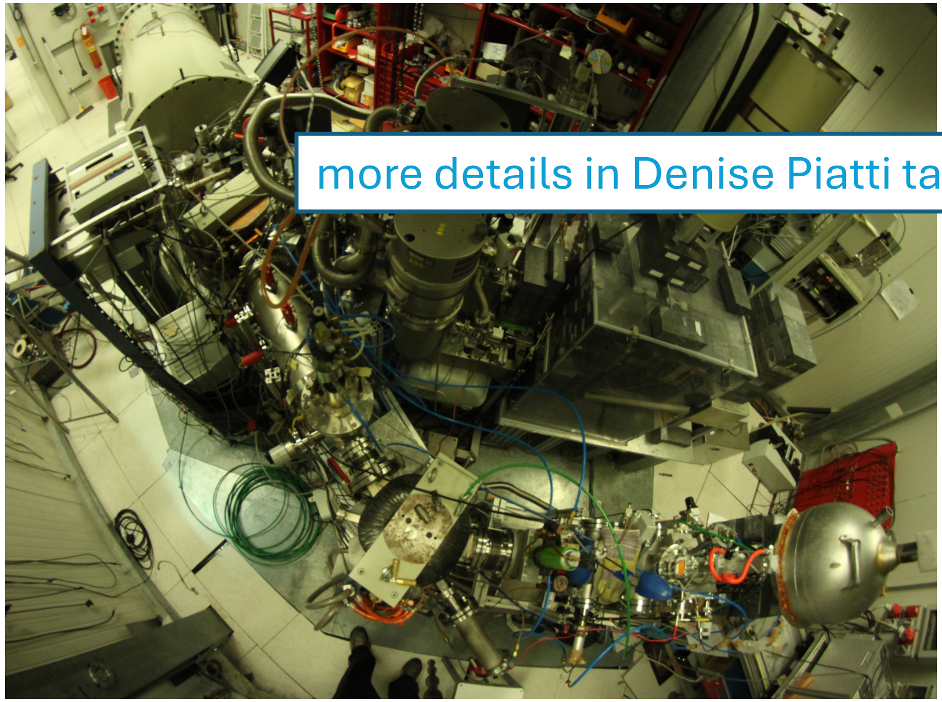
see Matthias Junker poster



Beam intensity on target at different terminal voltage		
Ion specie	Terminal Voltage	
	0.3 MV – 0.5 MV	0.5 MV - 3.5 MV
$^{1}H^{+}$	500 μA	1000 μA
$^{4}He^{+}$	300 μA	500 μA
$^{12}C^{+}$	100 μA	150 μA
$^{12}C^{+2}$	60 μA	100 μA
Number of beam lines		2
Terminal Voltage range		0.3 – 3.5 MV

- OSAT successfully concluded in **Spring 2023**
- First beam given to LUNA the **19th June 2023** for the commissioning of the machine by the study of the $^{14}N(p,\gamma)^{15}O$
- Presently under study $^{22}Ne(\alpha,n)^{25}Mg$

LUNA-400 and l



more details in Denise Piatti talk

Beam energy (keV)		Beam intensity on
H+	He+	
50-400	50-400	

more details in Antonio Caciolli talk

LUNA400 reaction list

- $^{2}H(p,\gamma)^{3}He$ - Mossa et al. Nature 587, 210-213 (2020)
- $^{6}Li(p,\gamma)^{7}Be$ - Piatti EPJ Web of Conferences 279, 11012 (2023)
- $^{10}B(\alpha,p)^{13}C$, $^{10}B(\alpha,d)^{12}C$ and $^{10}B(\alpha,n)^{13}N$ – planned for 2025
- $^{12,13}C(p,\gamma)^{13,14}N$ - Skowronski et al. PRL131, 162701 (2023)
- $^{13}C(\alpha,n)^{16}O$ - Ciani et al. 2021 PRL 127, 152701
- $^{14}N(p,\gamma)^{15}O$ - Imbriani et al. 2005 Eur. Phys. J. A 25, 455–466
  -> low energy resonance under measurement now
- $^{15}N(p,\gamma)^{16}O$ – LeBlanc et al. PRC **82**, 055804
- $^{16}O(p,\gamma)^{17}F$ - under measurement now
- $^{17}O(p,\gamma)^{18}F$ - Gesuè et al. PRL133, 052701 (2024)
- $^{17}O(p,\alpha)^{14}N$ - Bruno et al. PRL 117, 142502 (2016)
- $^{18}O(p,\gamma)^{19}F$ - Pantaleo et al. 2021 PRC104, 025802
- $^{18}O(p,\alpha)^{15}N$ - Bruno et al. PLB790, 237-242 (2019)
- $^{19}F(p,\gamma)^{20}Ne$ - planned for 2025
- $^{20}Ne(p,\gamma)^{21}Na$ - Masha et al. PRC 108, L052801 (2023)
- $^{21}Ne(p,\gamma)^{22}Na$ – Under analysis now
- $^{22}Ne(p,\gamma)^{23}Na$ - Takács PRC 109, 064627 (2024)
- $^{22}Ne(\alpha,\gamma)^{23}Na$ - Piatti et al. EPJ A 58, 194 (2022)
- $^{23}Na(p,\gamma)^{24}Mg$ - Boeltzig et al. PRC106, 045801 (2022)
- $^{23}Na(p,\alpha)^{20}Ne$ – under measurement now
- $^{24,25,26}Mg(p,\gamma)^{25,26,27}Al$ – Limata et al. PRC C 82, 015801 (2010)
  -> additional measurements in 2025

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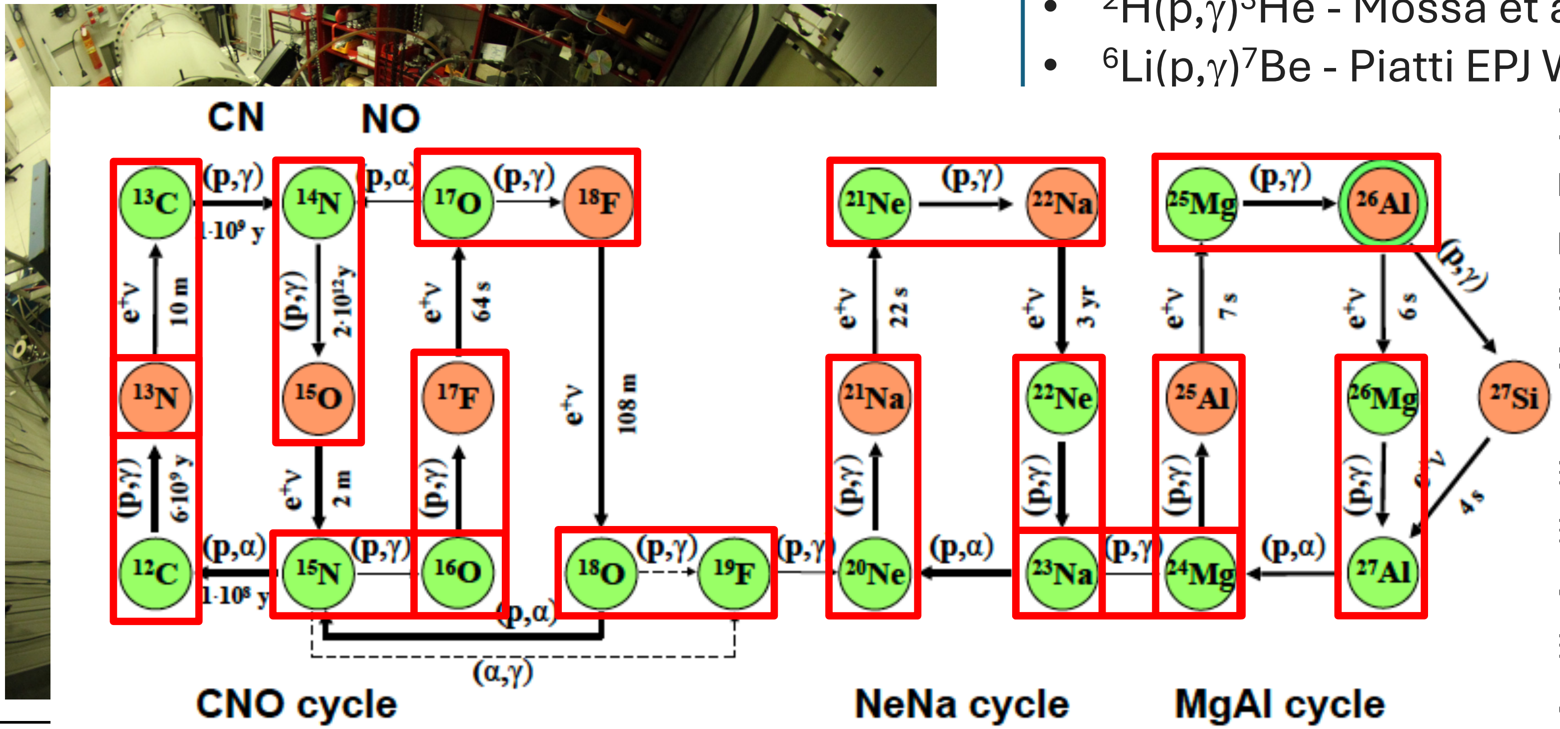
^{5}O

LUNA-400 and Ion Beam Facility «Bellotti»

Formicola et al. NIM A 507 (2003) 609–616



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- ^{21}Ne(p,γ)^{22}Na -
- ^{22}Ne(p,γ)^{23}Na - Ferraro et al. 2018 PRL121
  ^{22}Ne(α,γ)^{23}Na - Piatti et al. EPJ A 58, 194 (2022)
- ^{23}Na(p,γ)^{24}Mg - Boeltzig et al. PRC106, 045801 (2022)
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LUNA-400 and Ion Beam Facility «Bellotti»

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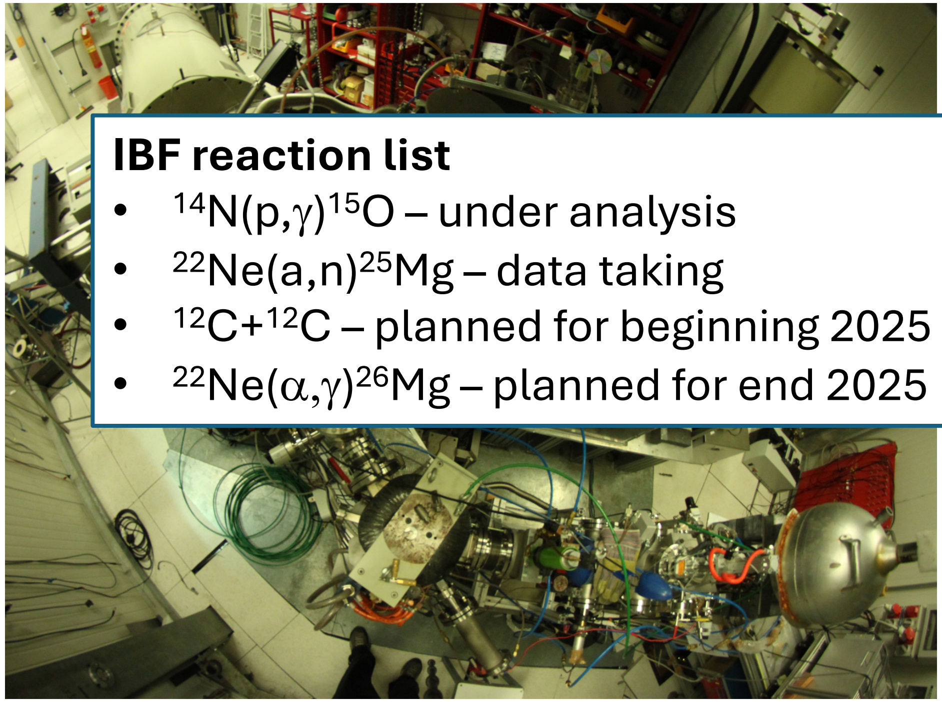

IBF reaction list

- $^{14}N(p,\gamma)^{15}O$ – under analysis
- $^{22}Ne(a,n)^{25}Mg$ – data taking
- $^{12}C+^{12}C$ – planned for beginning 2025
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ – planned for end 2025

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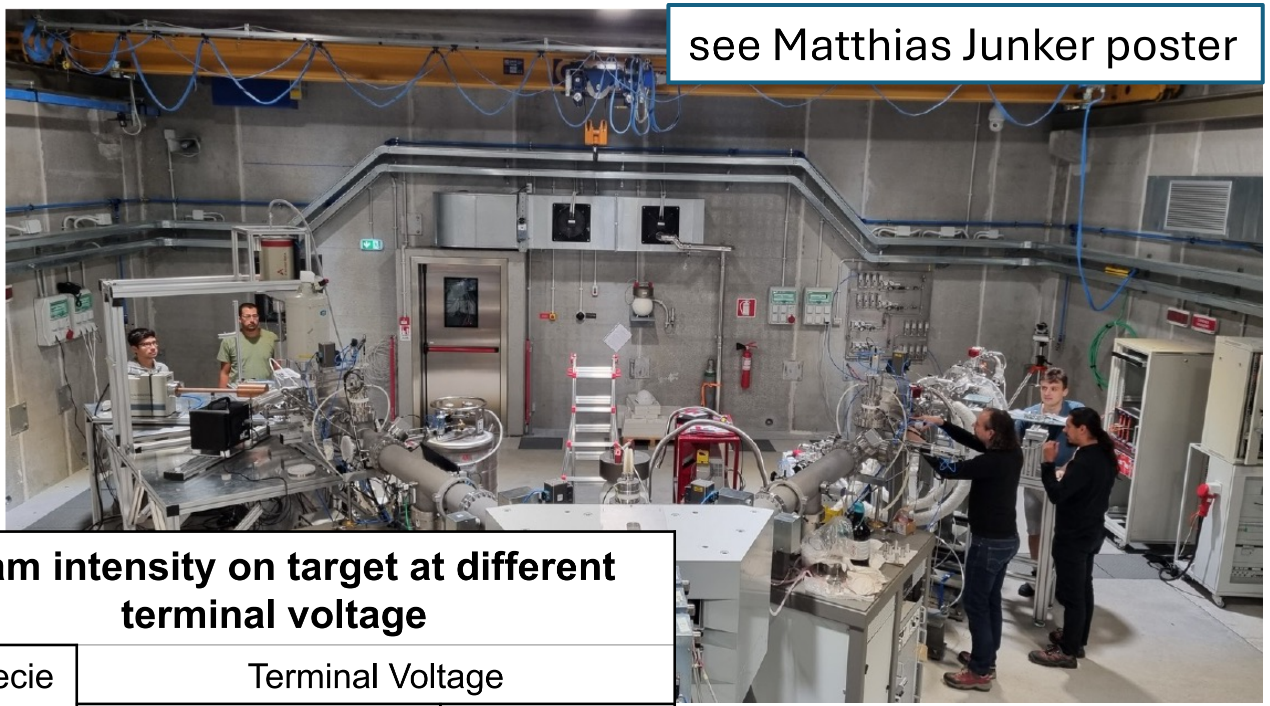
see Matthias Junker poster



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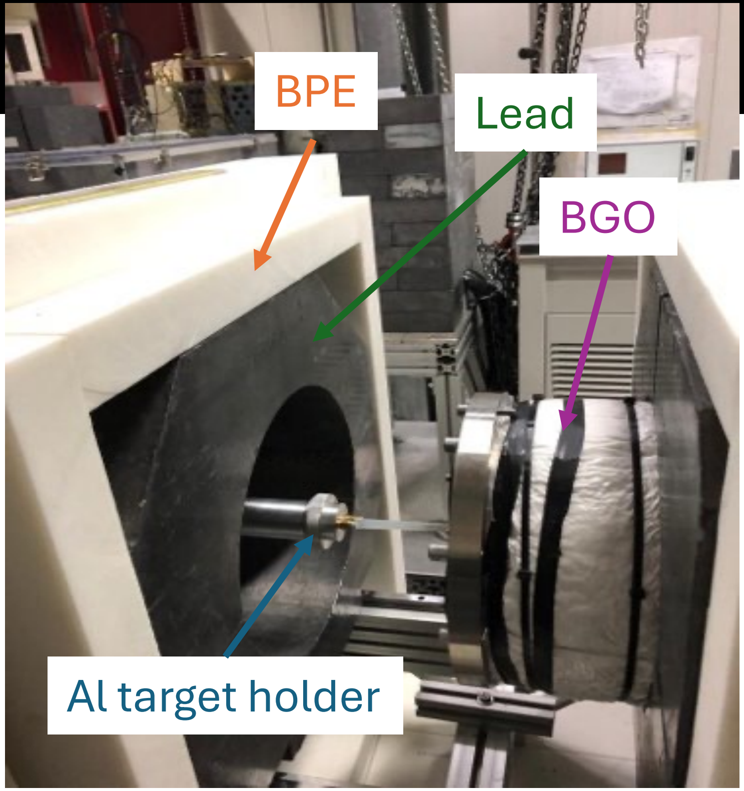
Gesuè et al. PRL133 (2024)

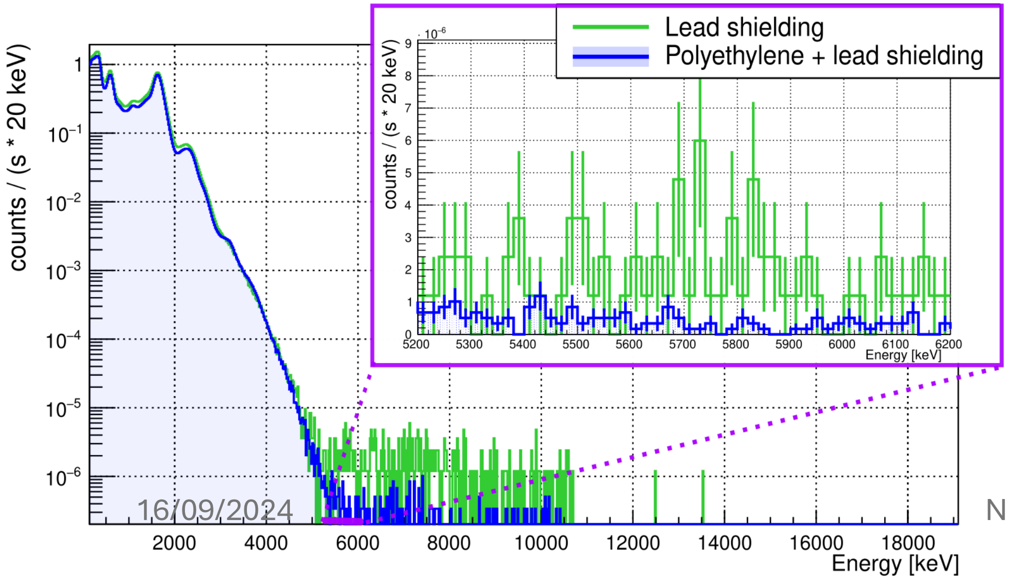


see Riccardo Maria Gesuè poster

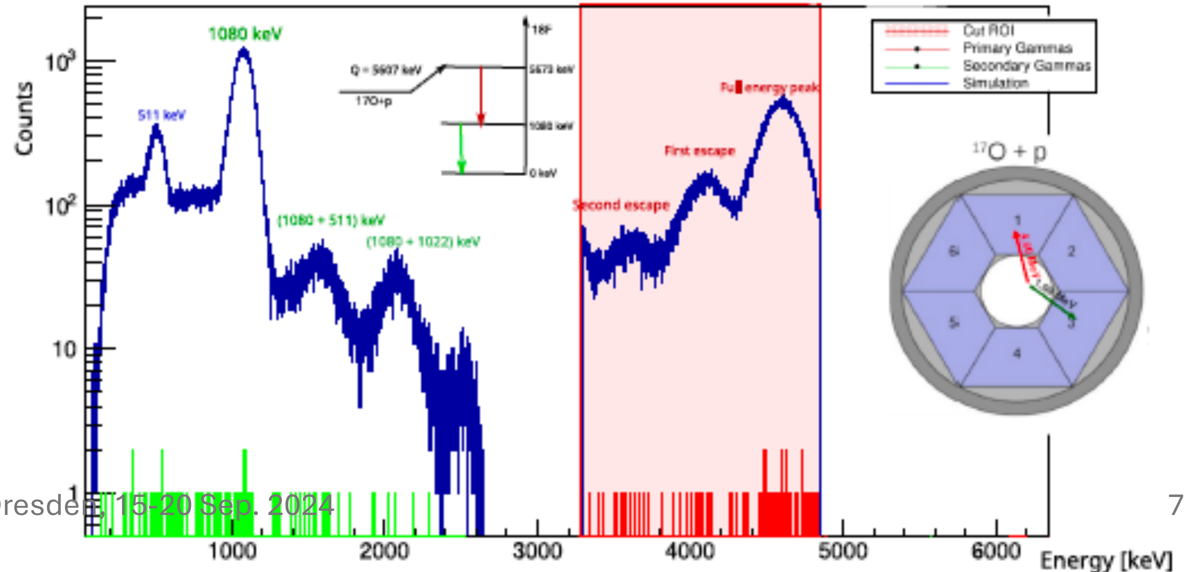
- 65 keV resonance direct measurement;
- 4π BGO detector, $Ta_2{}^{17}O_5$ enriched targets;
- passive (10 cm of lead + 4 cm of BPE) and active shielding (γ-ray coincidence) ; ***Skowronski et al. J. Phys. G 50, 045201 (2023)***
- 400 C (1 month of continuous beam operation) and about 100 counts.

$$\omega\gamma = (34^{7sta}{}_{3sys})\ peV$$

4x background reduction in the ROI



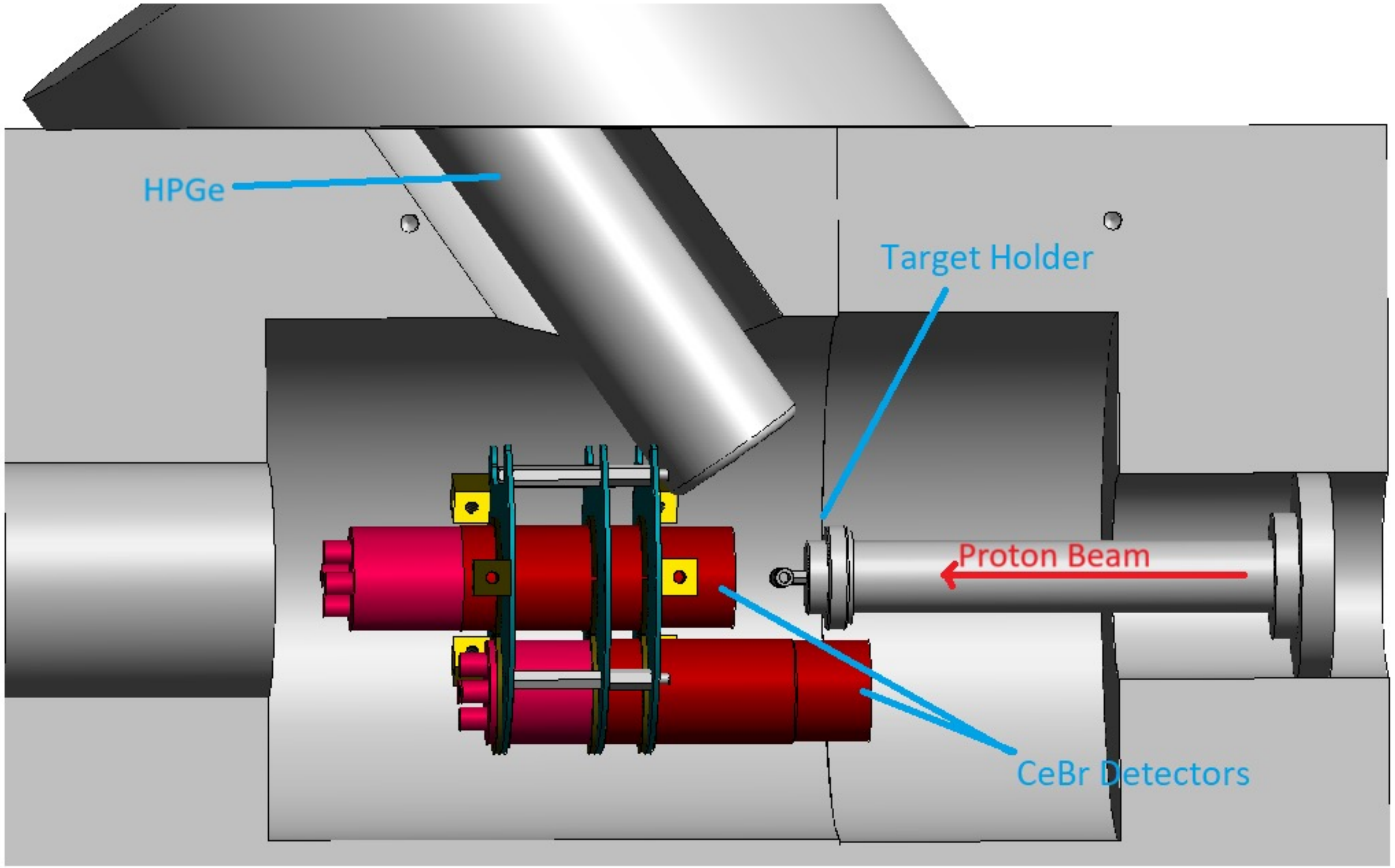
Transition to 1081keV



$^{16}O(p,\gamma)^{17}F$

Prompt gamma detection setup

- Prompt Gamma - HPGe at 55°, $CeBr_3$ scintillators at 0° and 90°
- Activation – Segmented BGO with nearly 4π coverage
- Both setups enclosed within thick lead shielding
- Ta_2O_5 targets, natural



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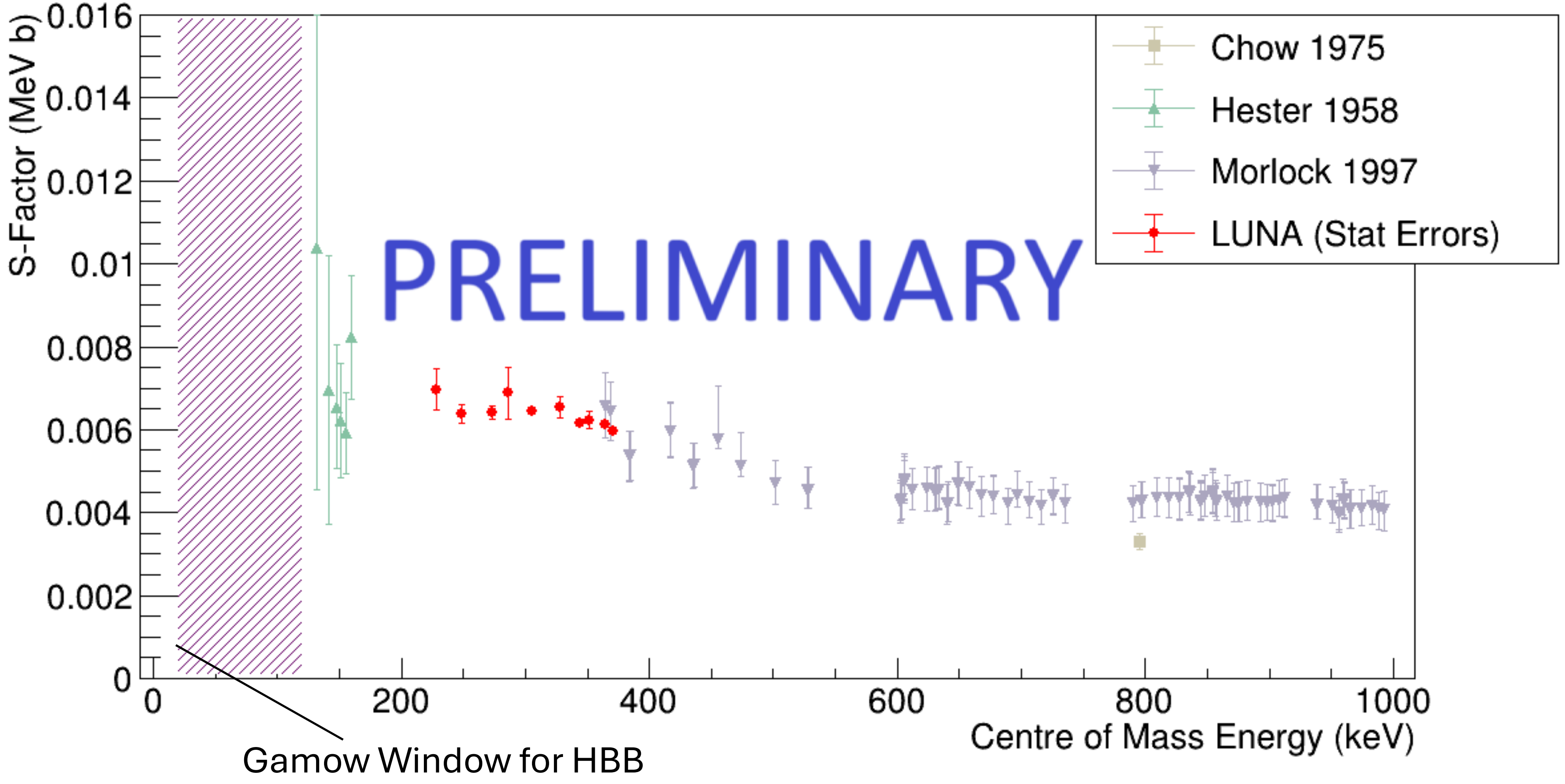
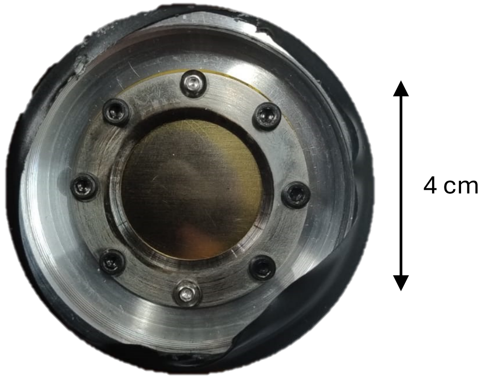


Study of the $^{14}N(p, \gamma)^{15}O$ reaction

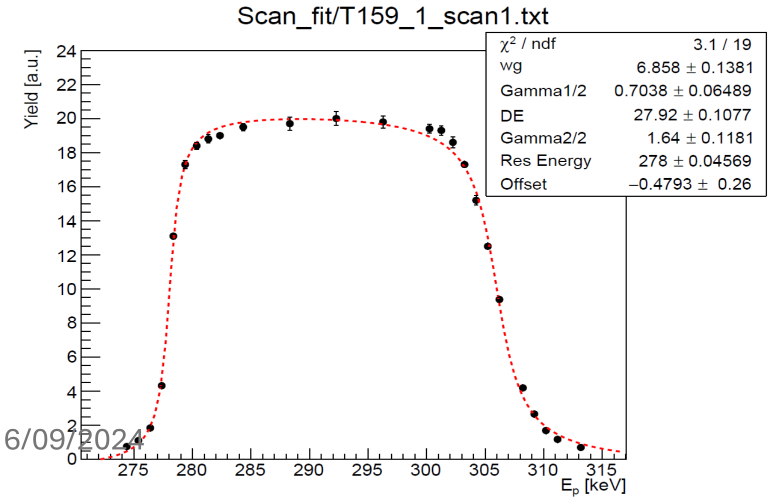
see Giulia Gosta poster

Solid Targets

TiN sputtered targets (70 – 140 nm)+ Ti inter-layer + Ta backing produced @ LNL

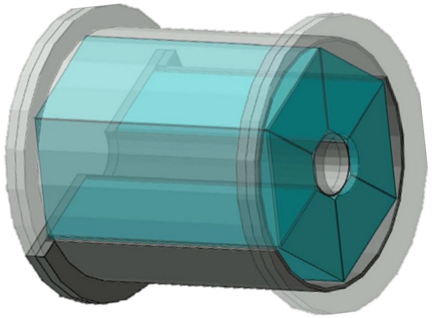


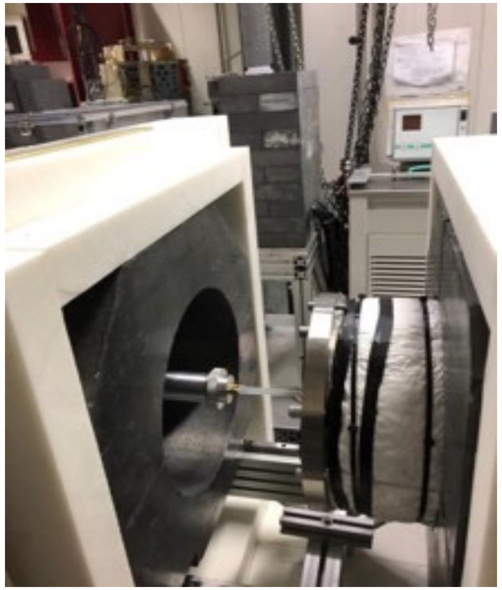
every day we performed a scan of the 278 keV resonance to monitor target stability

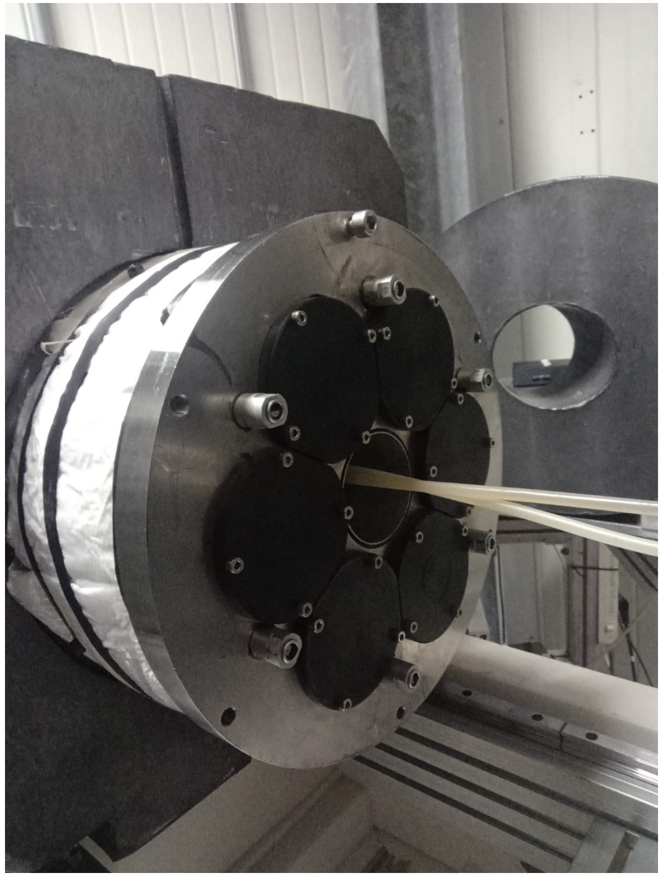


Detectors

4π-BGO + 10 cm-thick lead shielding all around



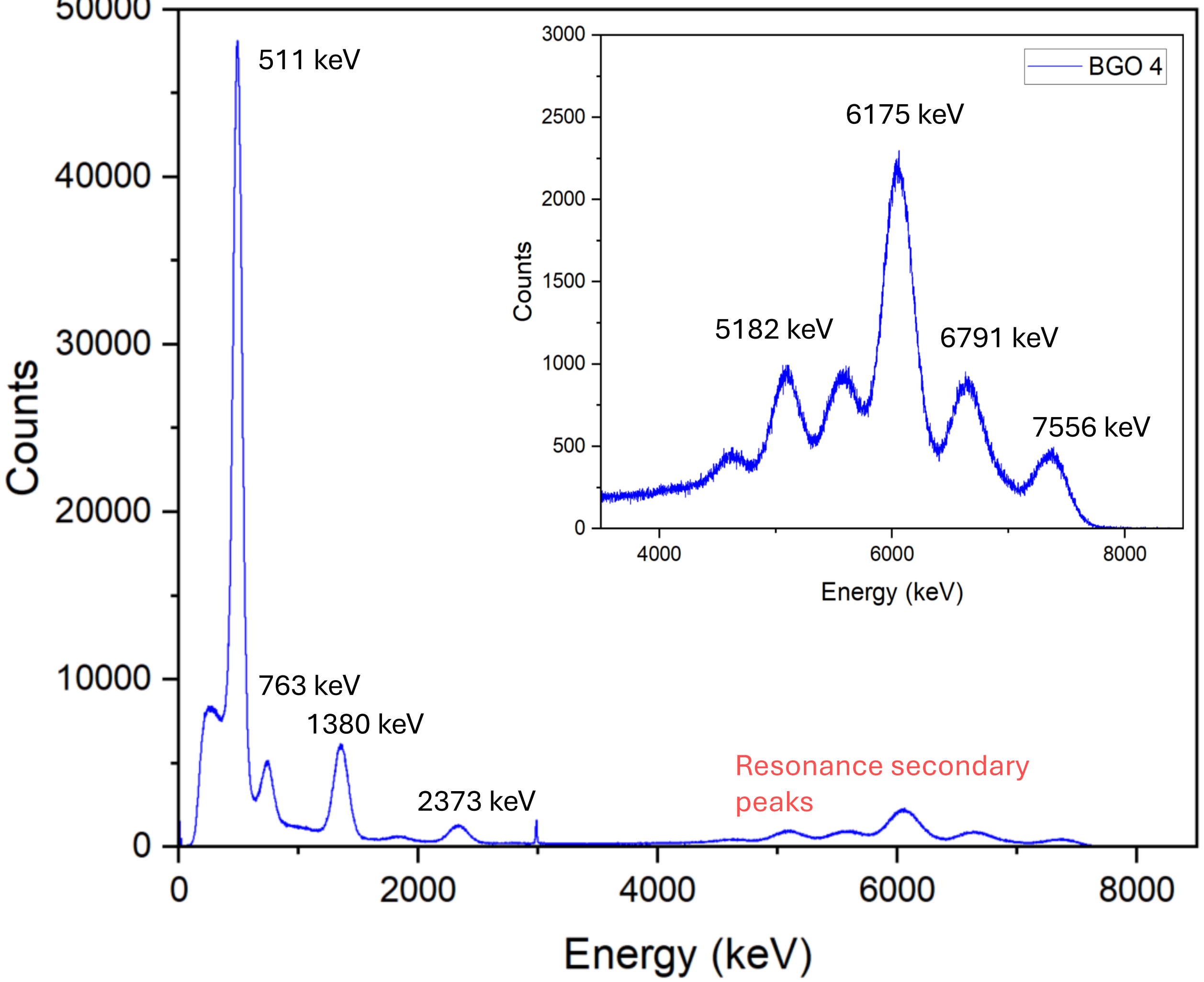


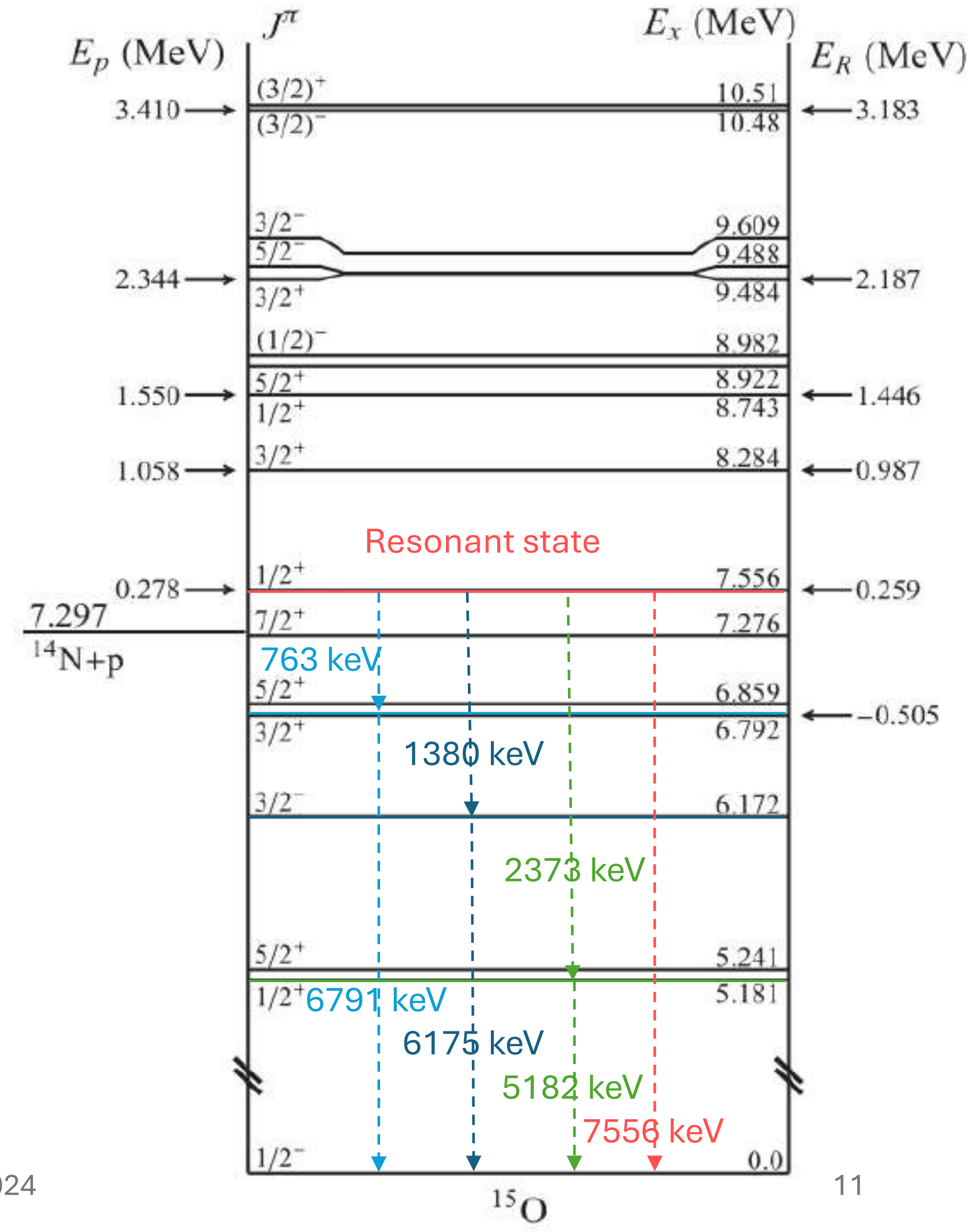


Study of the $^{14}N(p, \gamma)^{15}O$ reaction

see Giulia Gosta poster

Singles spectrum on E_p = 278 keV resonance





Study of the $^{14}N(p,\gamma)^{15}O$ reaction

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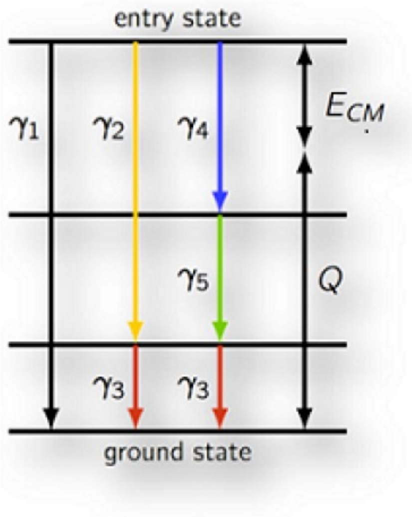
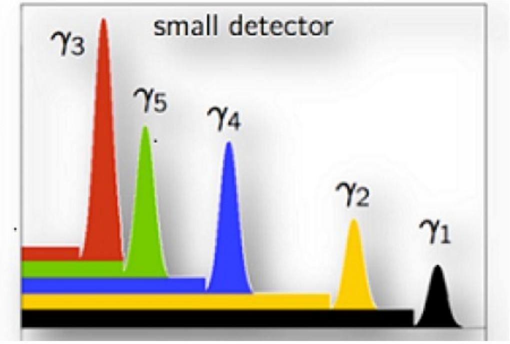
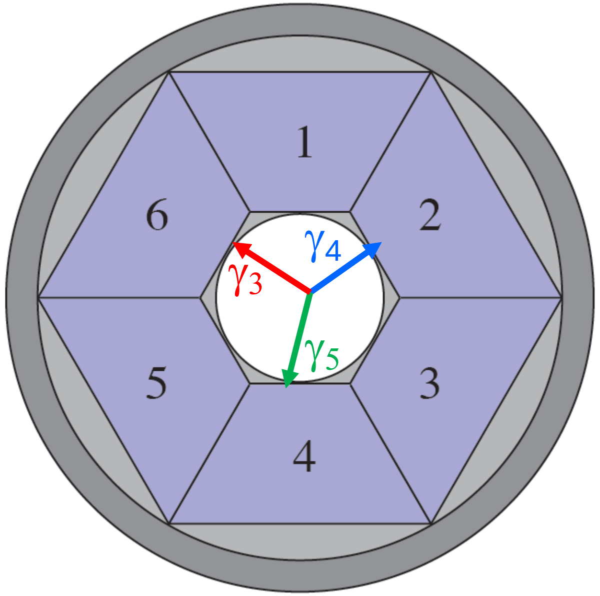
Analysis procedure: add-back spectrum

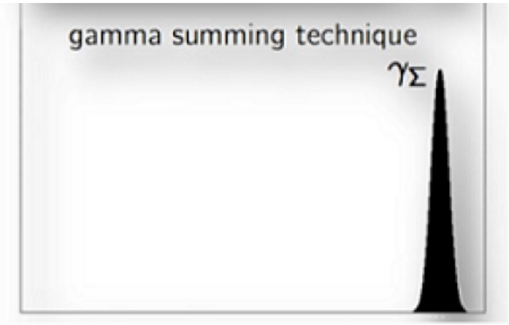
The energy of all events in time coincidence in any of the 6 BGO segments is summed

$E_X = E_{CM} + Q$



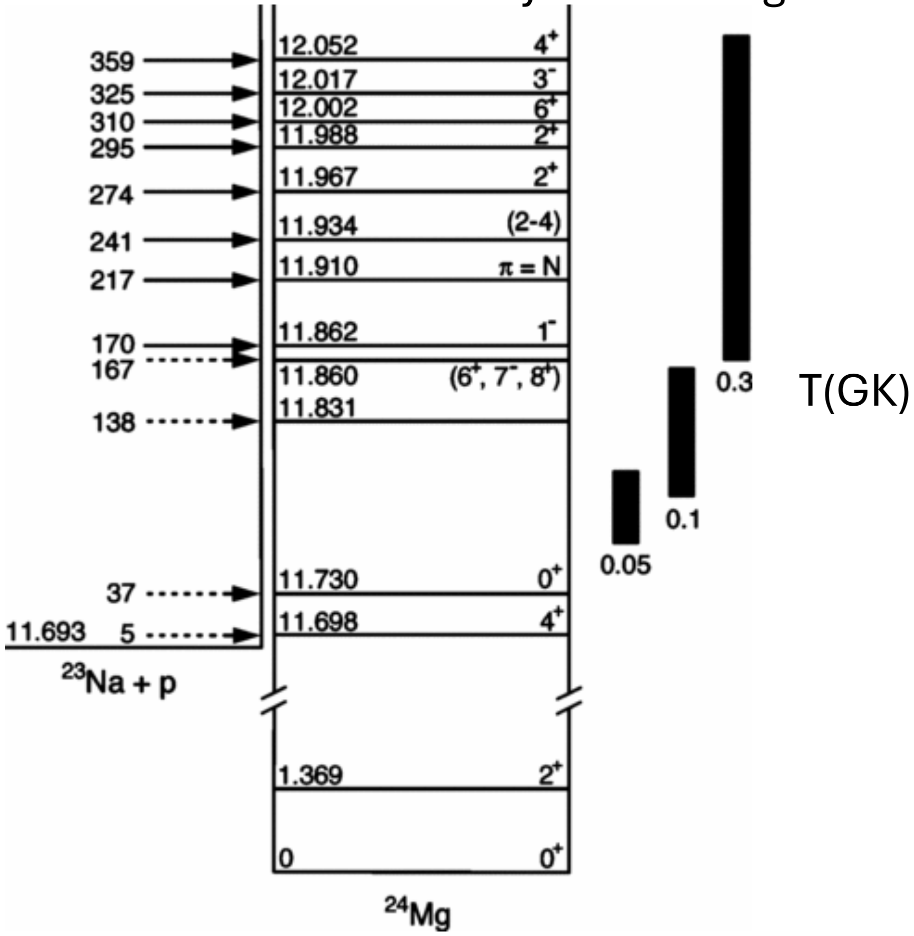


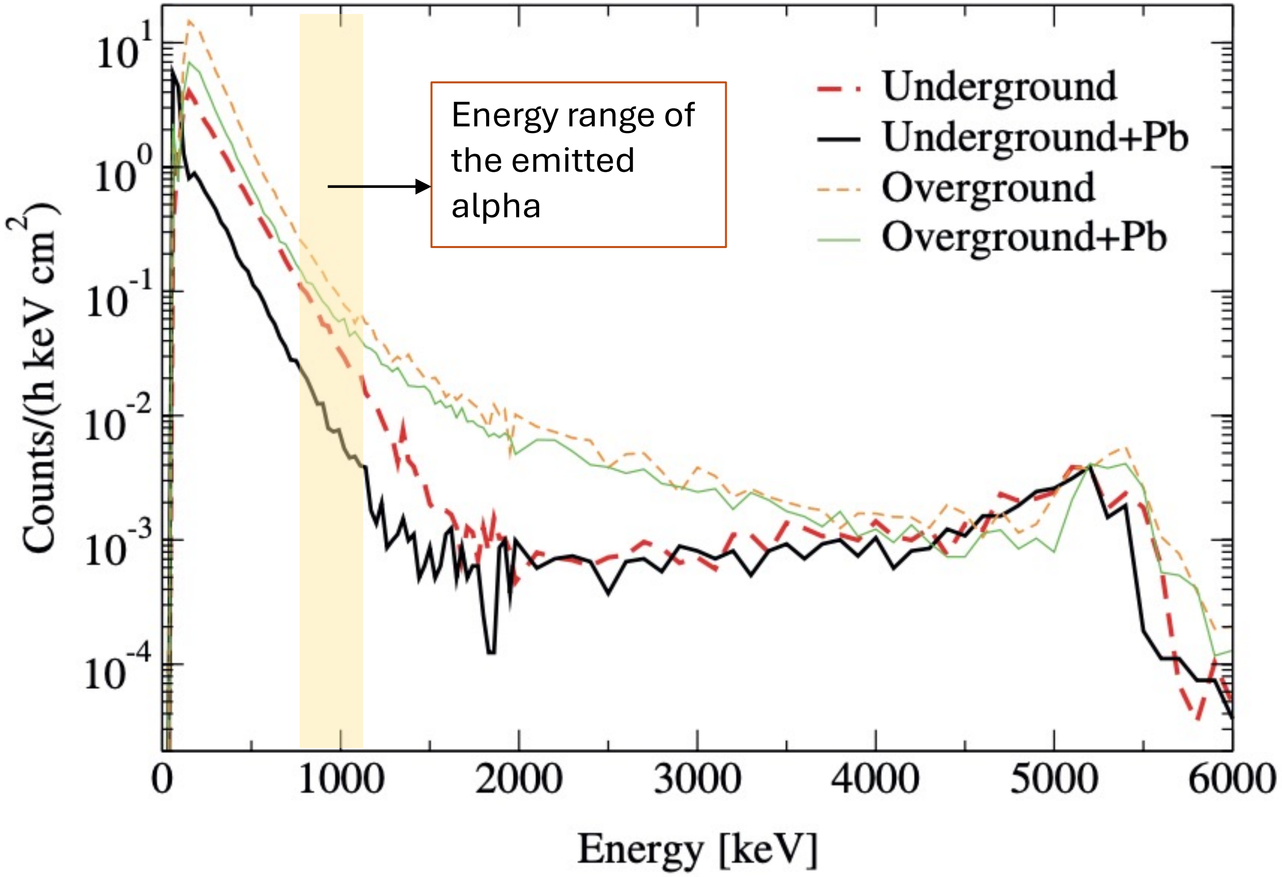




$^{23}Na(p,\alpha)^{20}Ne$

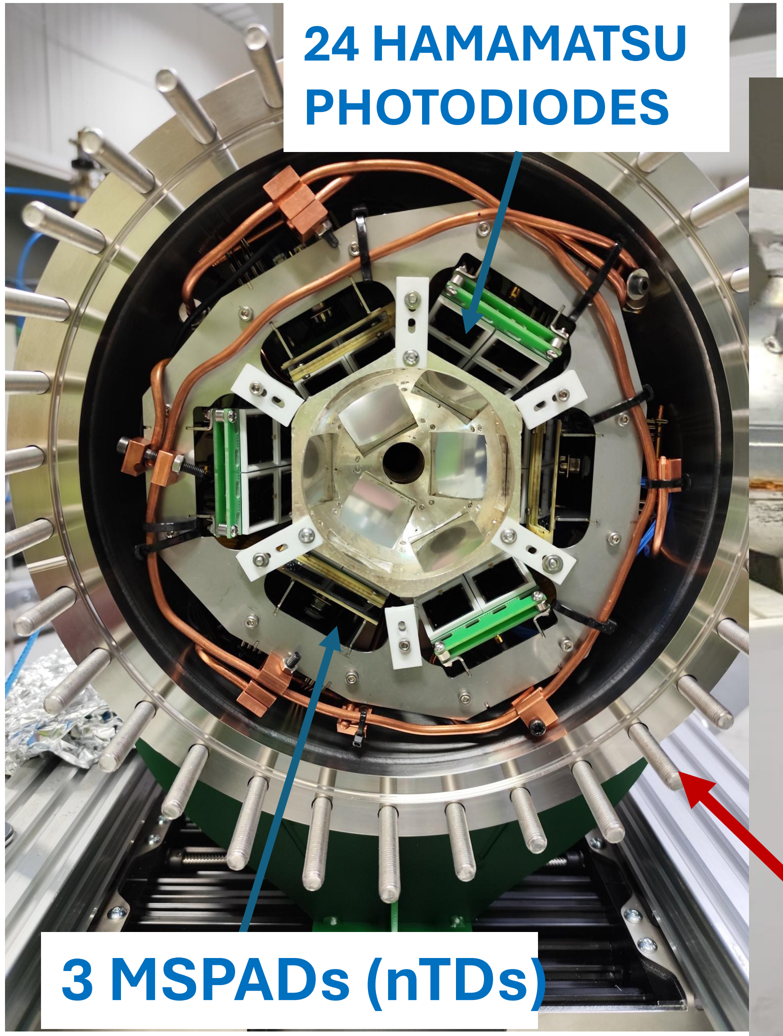
ERC-ELDAR
burning questions on the origin of Elements in the Lives and Deaths of stARts
PI Carlo Bruno – University of Edinburgh

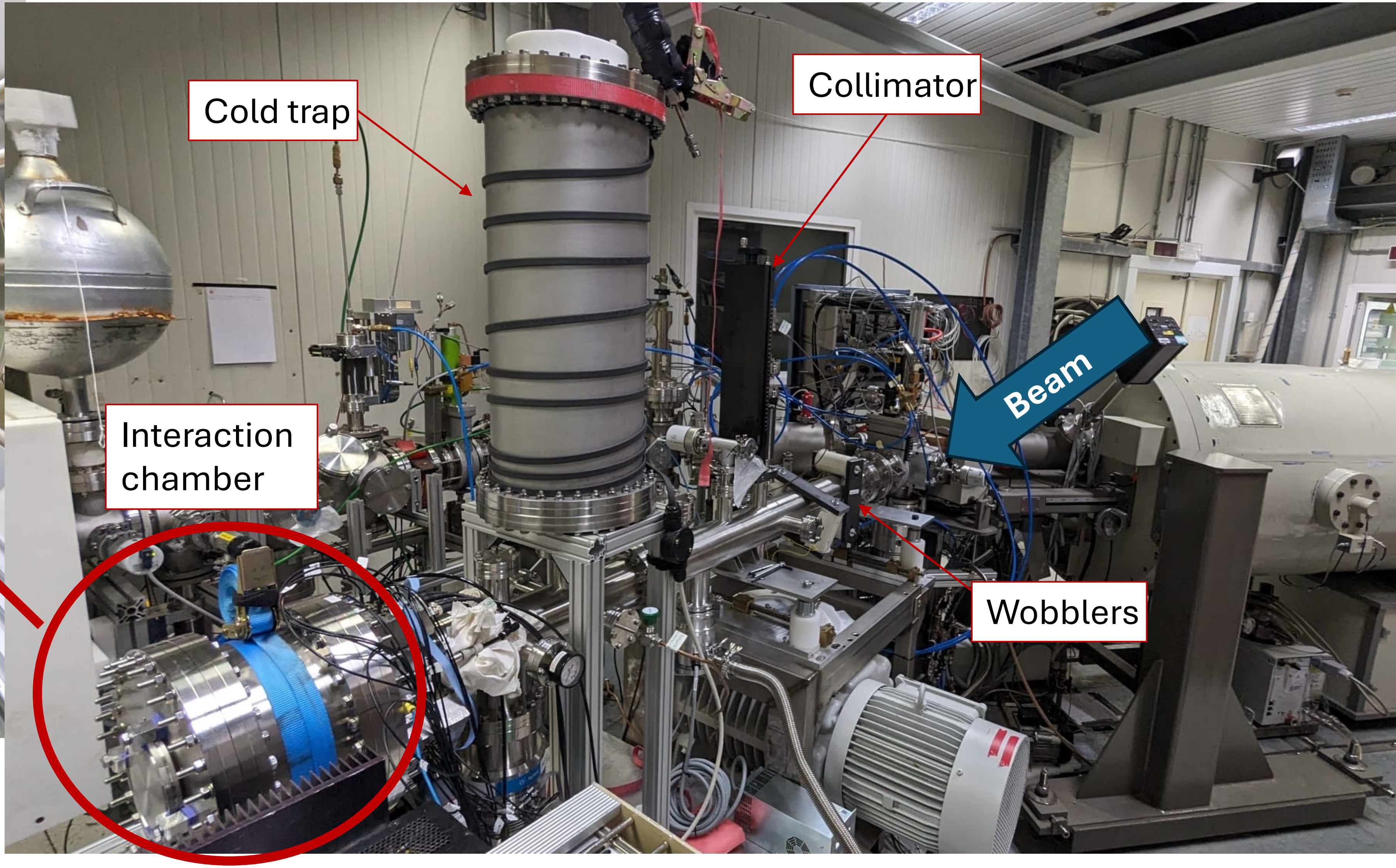




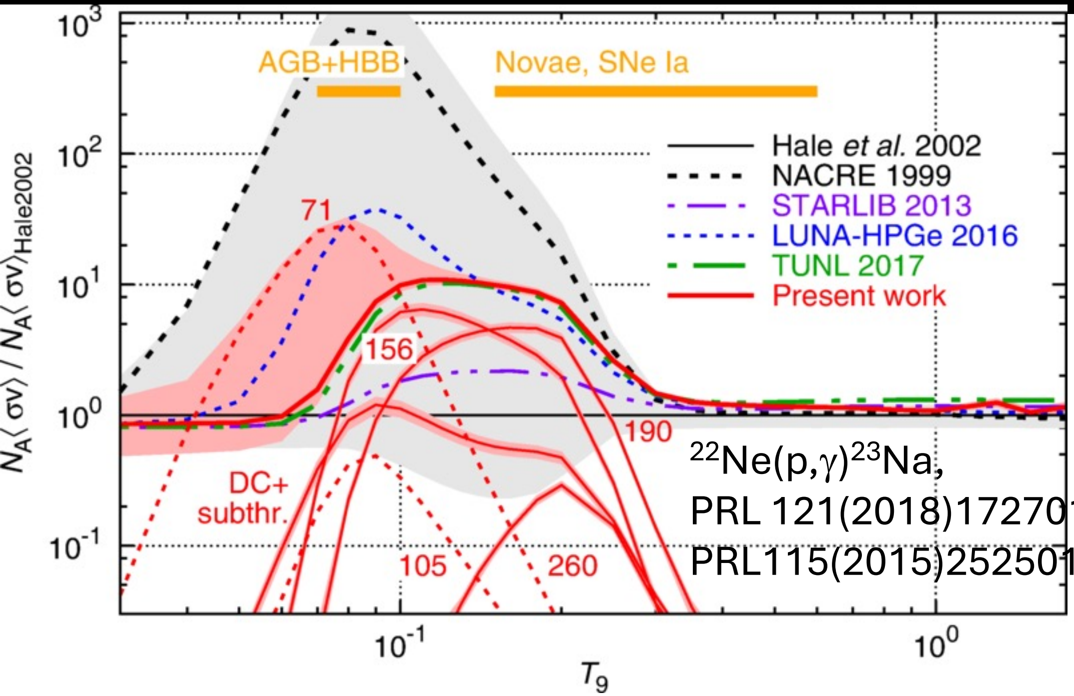
E_r [keV]	J^π	$\omega\gamma$ [eV]
37	0^+	$< 3.3 \times 10^{-20}$
138	? (l_p=0)	$< 1.6 \times 10^{-6}$
	? (l_p=1)	$< 7.5 \times 10^{-8}$
	? (l_p=2)	$< 2.8 \times 10^{-9}$
	? (l_p=3)	$< 5.4 \times 10^{-11}$
167	$(6,7,8)^+$	? (negligible)
170	1^-	$(23 \pm 5) \times 10^{-3}$

Only **tentative upper limits** to the resonance strength have been placed, depending on the value of the **unknown proton momentum transfer l_p.**

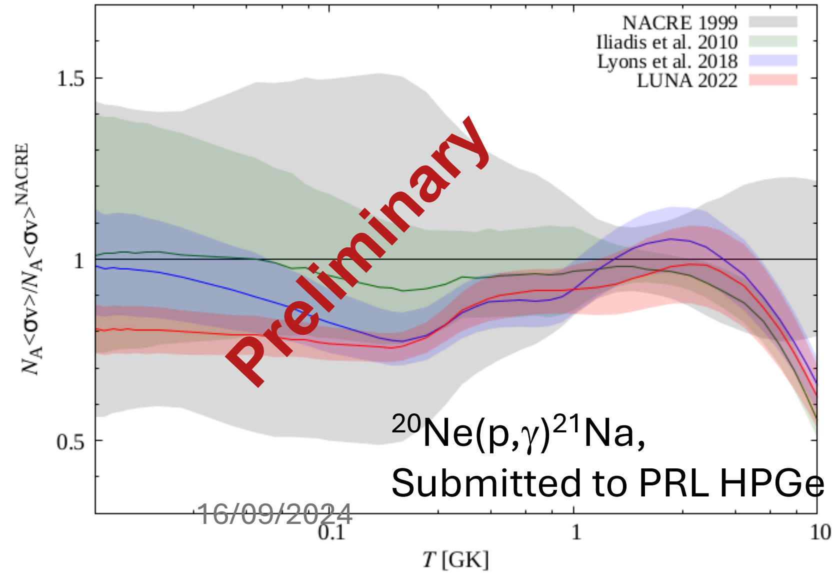

24 HAMAMATSU PHOTODIODES
3 MSPADs (nTDs)

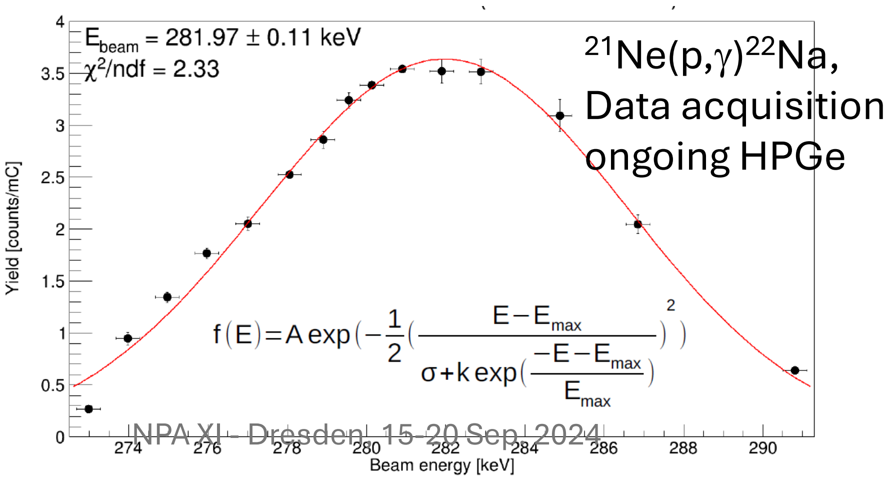

Cold trap
Collimator
Beam
Interaction chamber
Wobblers

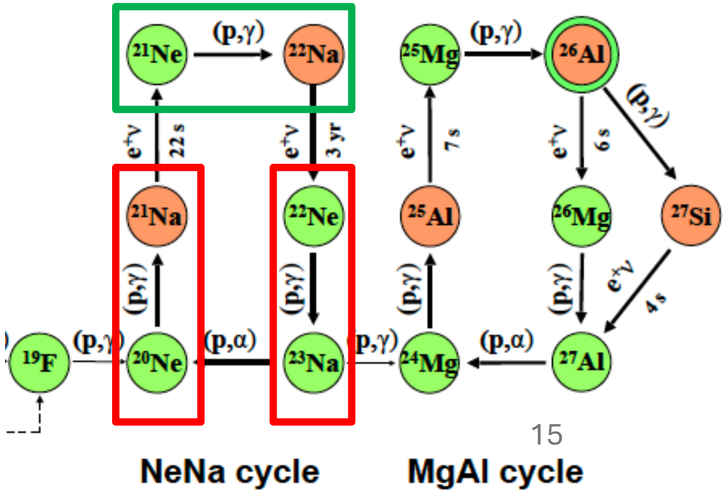
$^{20,22}Ne\ (p,\gamma)^{21,23}Na$ at LUNA400



- We have directly measured several low energy state belonging to $^{22}Ne(p,\gamma)^{23}Na$, $^{20}Ne(p,\gamma)^{23}Na$ and $^{21}Ne(p,\gamma)^{22}Na$;
- Using gas target, lead shielding, BGO and HPGe detectors;
- We reduced the rate uncertainties enormously improving the knowledge of the NeNa cycle

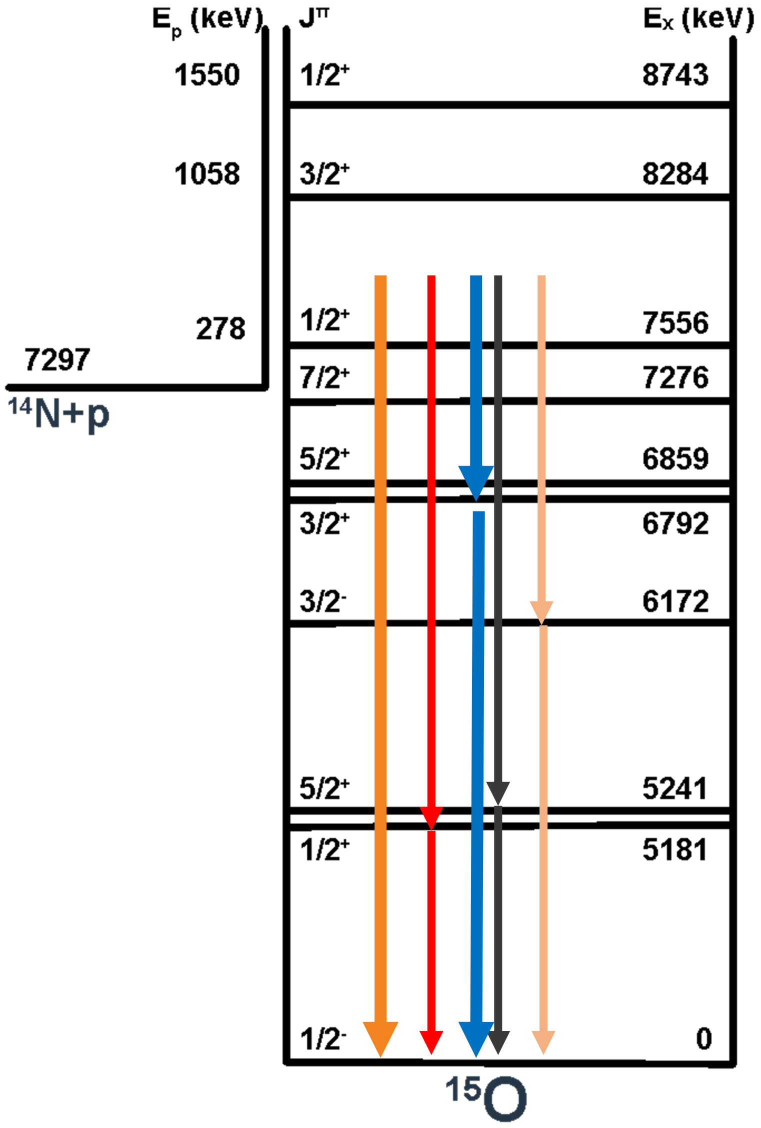






$^{14}N(p,\gamma)^{15}O$ @IBF-LNGS

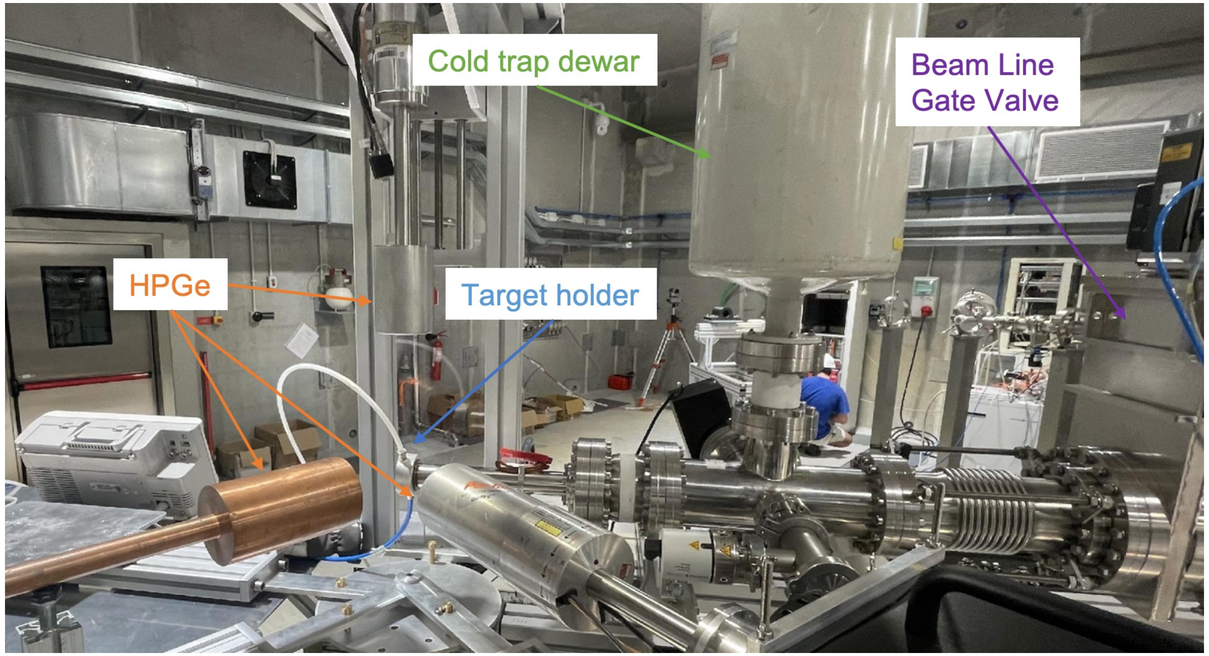
- Transition to the **6.79 MeV** excited state of ^{15}O: A lot of consistent measurements in the low energy region
- Transition to the **ground state** of ^{15}O: Very difficult to reconcile all the measurements in a consistent picture.
- The transition to the **6.79 MeV** excited state of ^{15}O and to the **ground state** are fairly well know but effected to problems with their extrapolations at low energies
- Lack of recent data for the other transitions R/DC → 6.17, 5.24, 5.18 ...

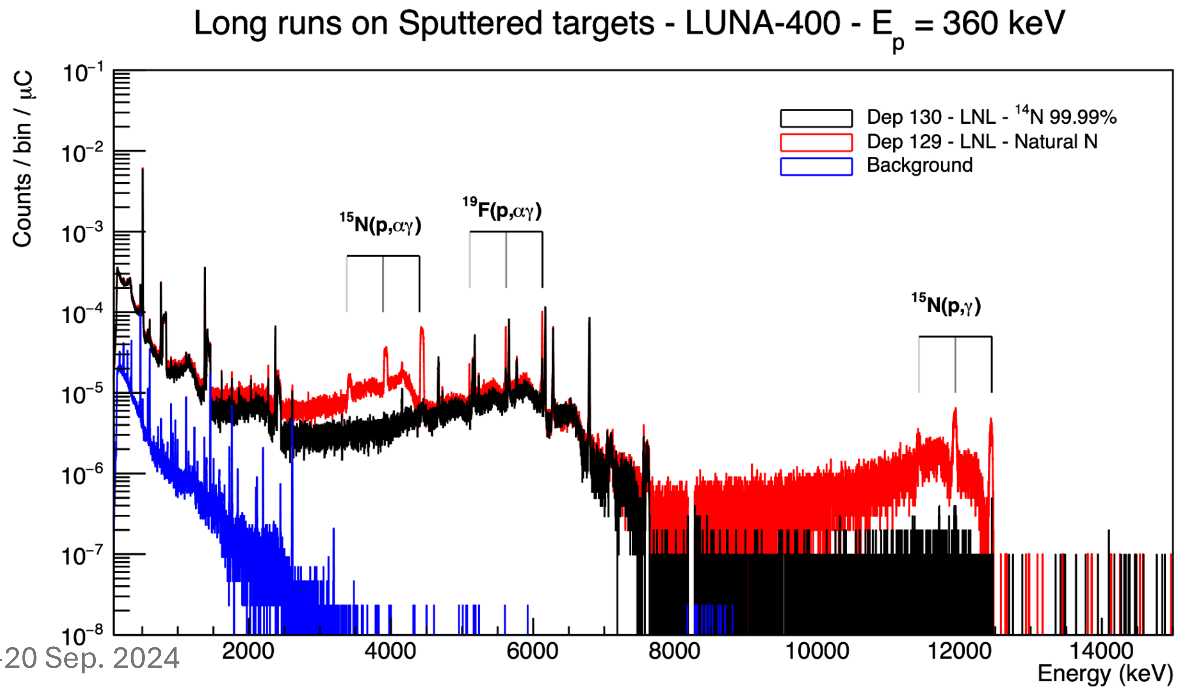


Level scheme for ^{15}O

$^{14}N(p,\gamma)^{15}O$ @IBF-LNGS

- Single HPGe at 55° in close geometry, **excitation function** **(June 2023)**
- Three HPGe detectors, **angular distribution** 55°-135°-90° + 0°-120°-90° **(Oct. 2023 - under progress)**
- **Sputtered TaN targets**: Produced at LNL. Enriched (99.95%) nitrogen gas. Tested for stability up to 40 C. Characterization via RBS and on-site using 278 keV ^{14}N+p resonance scans
- **Implanted targets**: Produced at IST, Lisbon. Tested for stability up to 15 C

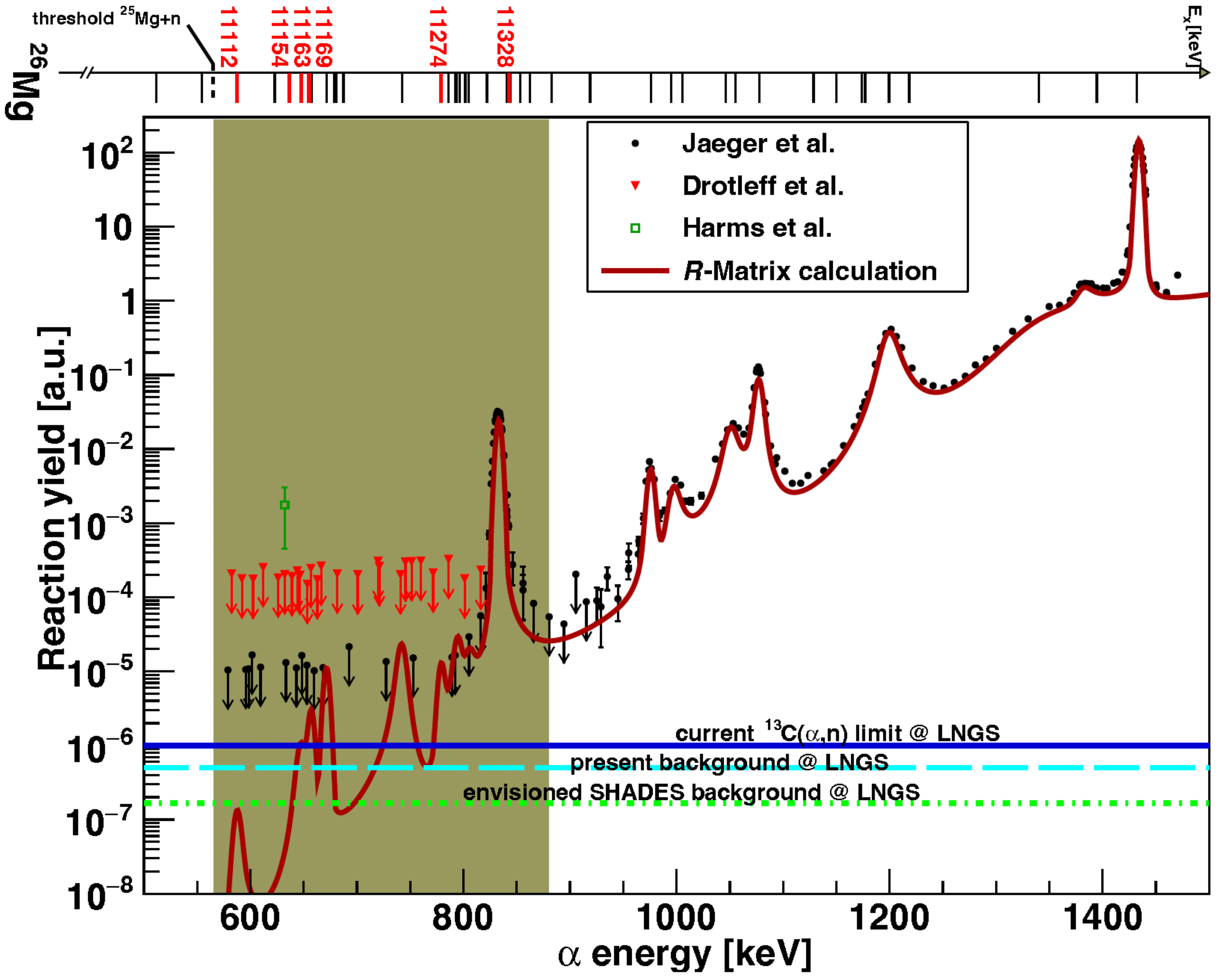




$^{22}Ne(\alpha, n)^{25}Mg$

ERC-SHADES

see Thomas Chillery and Daniela Mercogliano posters

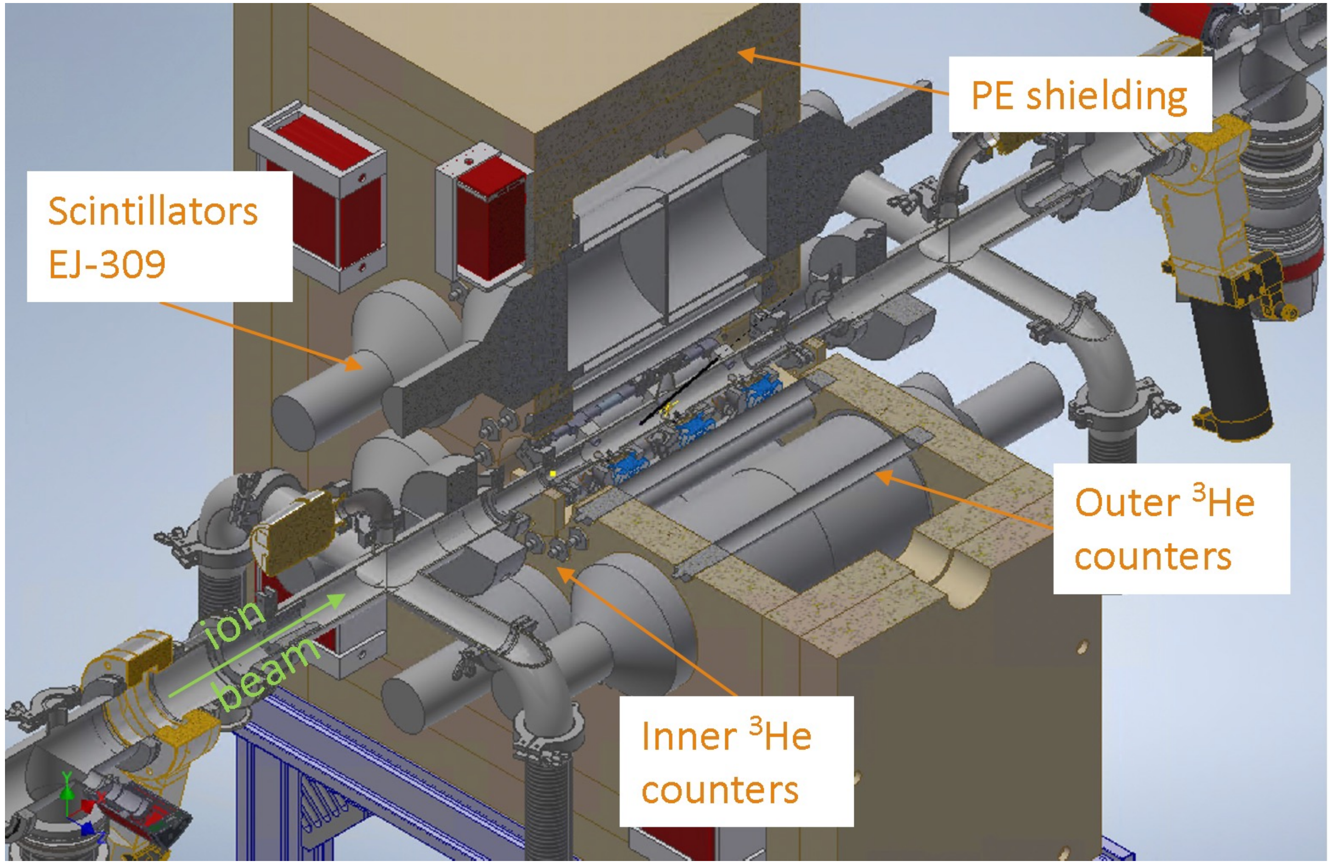


R matrix courtesy of R. J. deBoer, University of Notre Dame/JINA

- 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. . .**
- **We can measure 1-2 reaction/hour**

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

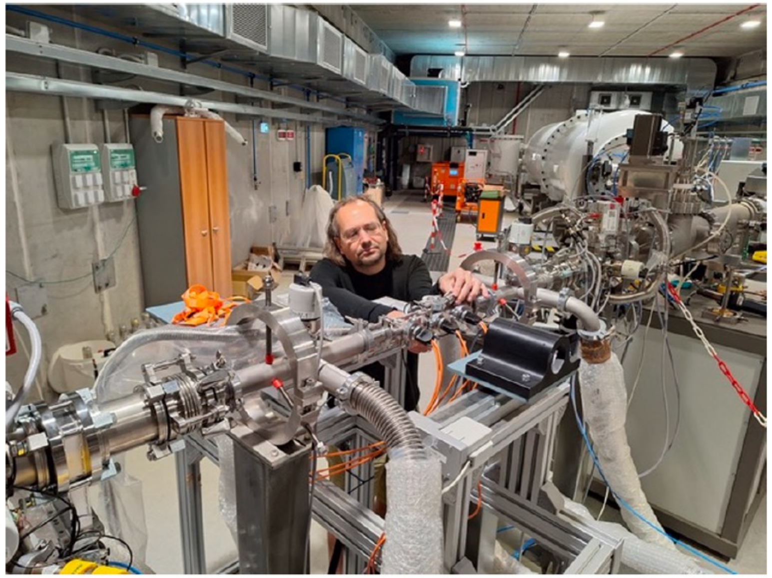
see Thomas Chillery and Daniela Mercogliano posters

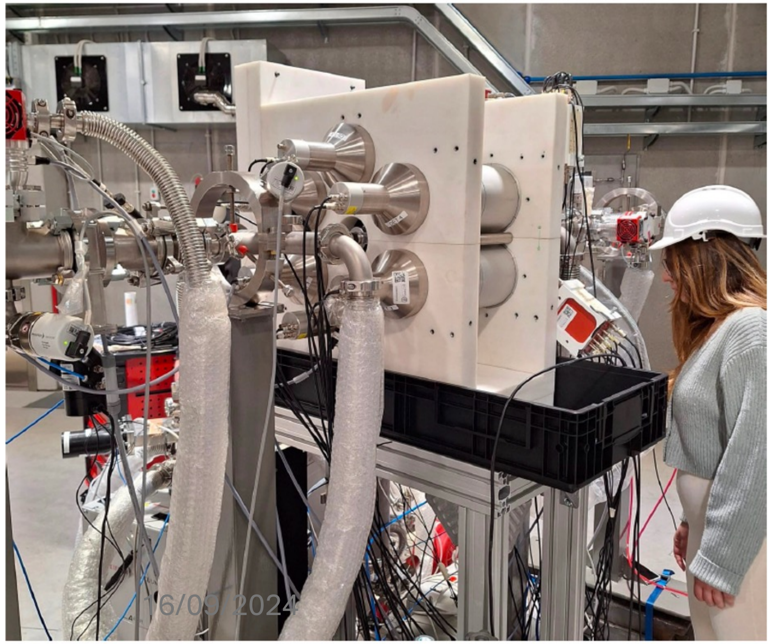


- ERC-SHADES - Scintillator-^{3}He Array for Deep underground Experiments on the S-process (PI Andreas Best, Università di Napoli “Federico")
- ^{3}He counter-EJ-309 liquid scintillator array suppression possible BIB
- High purity recirculated ^{22}Ne gas target
  -> Al sealing, scrubber, Ta coated surfaces, Si industry grade pumps, enriched ^{22}Ne

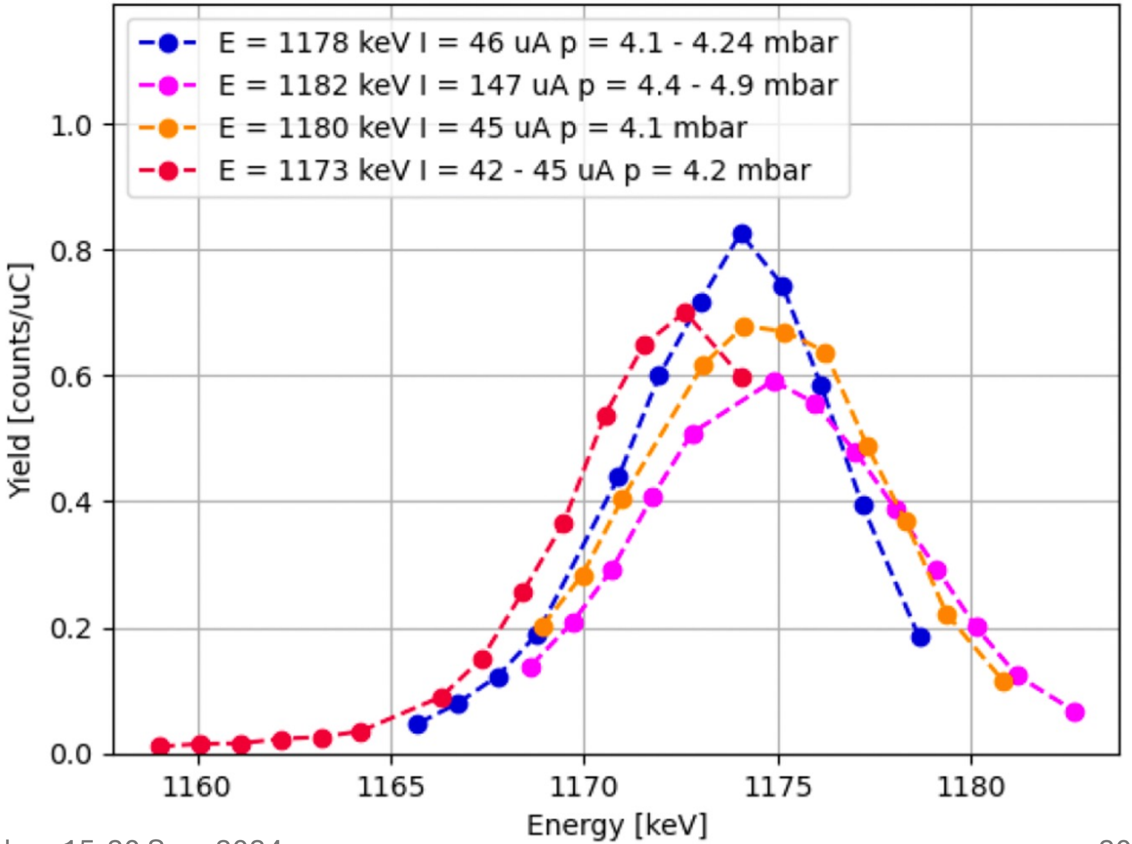
$^{22}Ne(\alpha, n)^{25}Mg$

see Thomas Chillery and Daniela Mercogliano posters





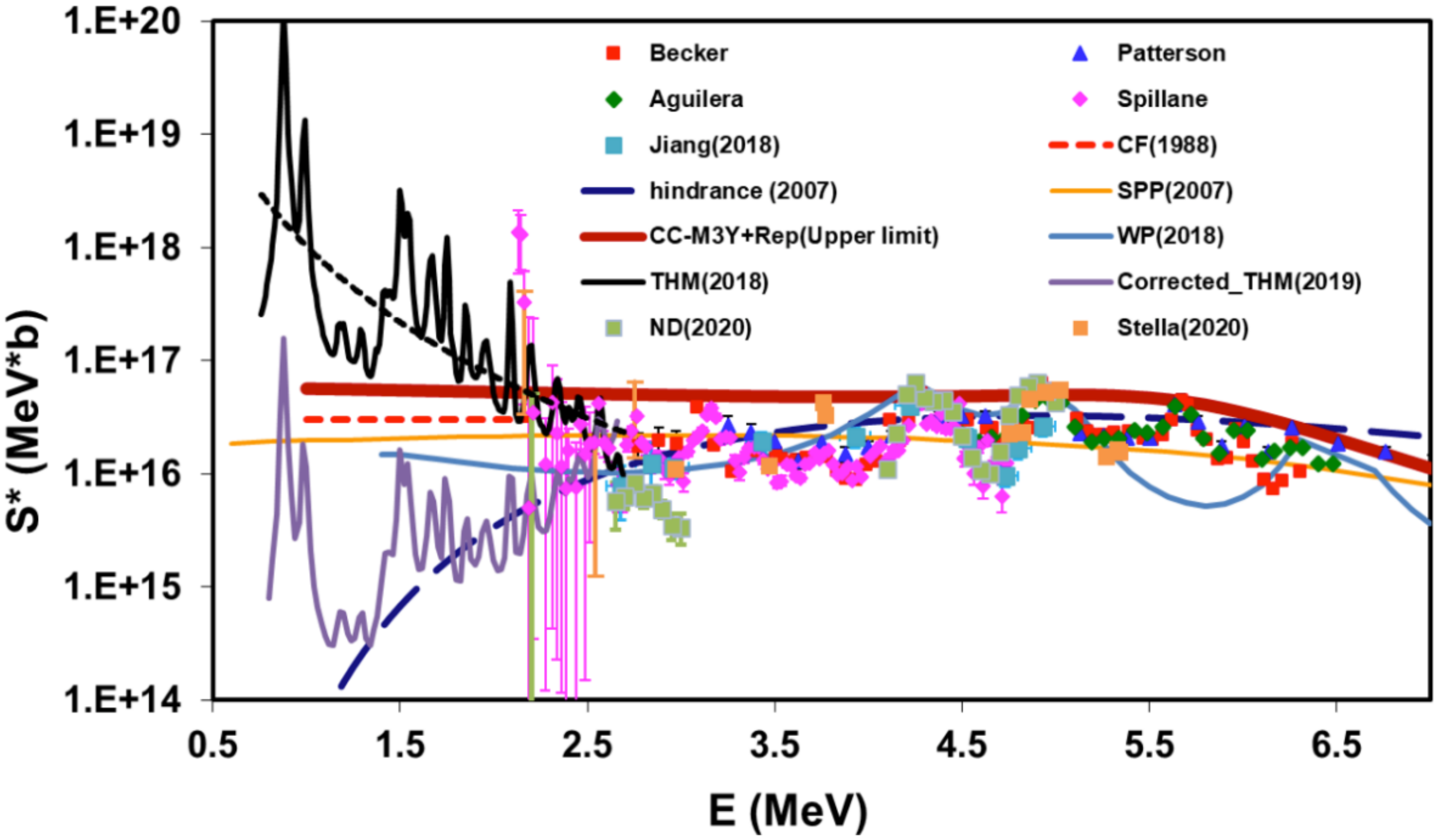
- Array intrinsic background characterization completed
  Ananna et al. 2024 NIM A 1060, 169036
- Array energy calibration performed at Frankfurt University in 2023
- Gas target characterization completed, under analysis
- Data taking Oct-Nov 2024, Feb 2025



The $^{12}C+^{12}C$ state of the art

see Riccardo Gesuè and Steffen Turkat posters

- Several datasets and models
- Direct measurements above 2.1 MeV (large scattering, large uncertainties)
- Only indirect measurements below 2.1 MeV (problems with normalization and other discrepancies)
- Very large uncertainty below 2.5 MeV
- Presence of several states at low energies



The $^{12}C+^{12}C$ study via γ detection

see Riccardo Gesuè and Steffen Turkat posters

$^{12}C+^{12}C \rightarrow ^{20}Ne + \alpha$ Q = 4.62 MeV

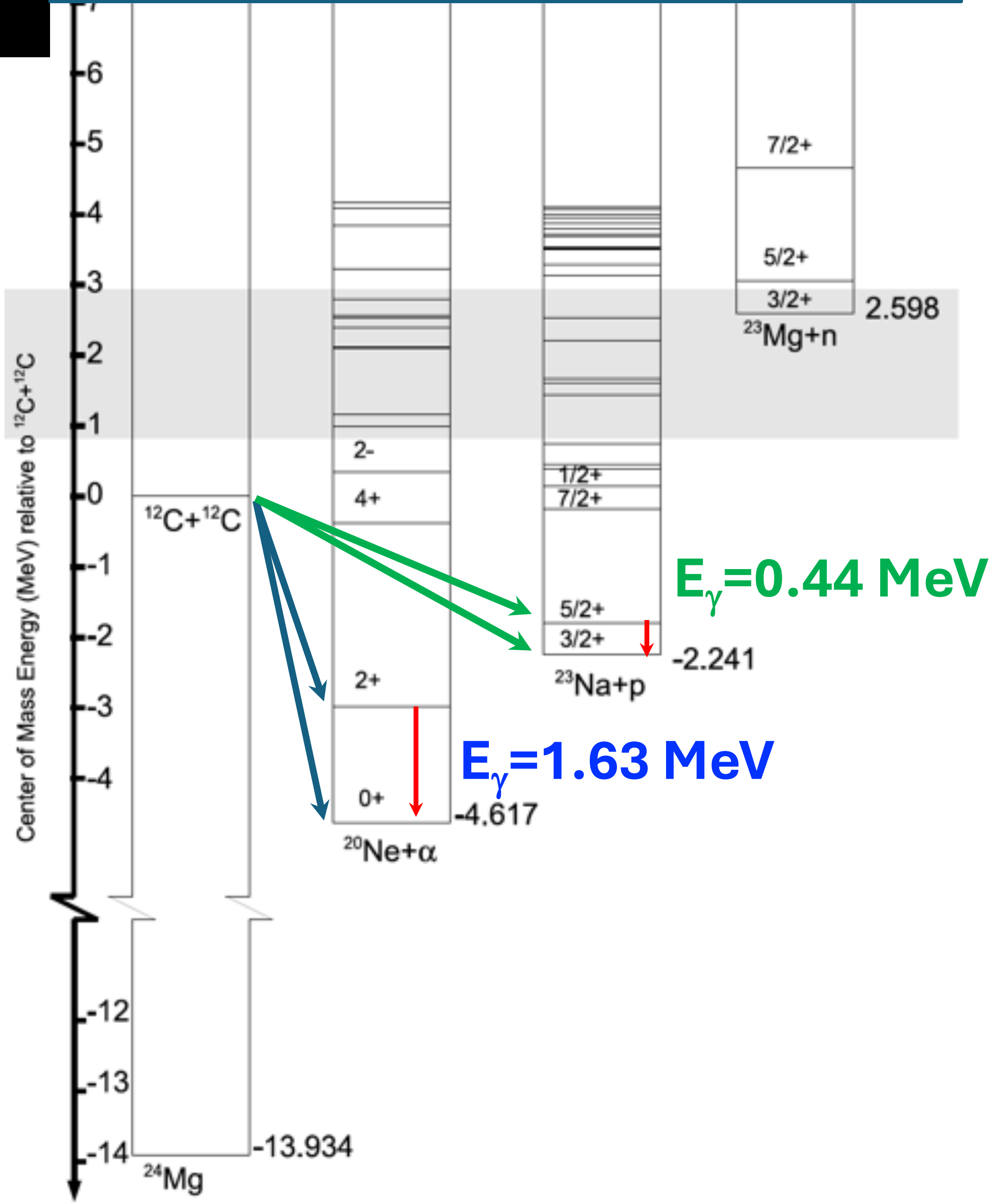
γ-rays and α particles energies for excited states for $^{12}C(^{12}C, \alpha)^{20}Ne$ (Q = 4.617 MeV)

E_X (MeV)	Jp	Main γ transitions (MeV)		ID	$E_{\alpha-max}$ (MeV) (E^{CM} = 2 MeV)
0.0	0^+			α_0	8.6
1.63	2^+	*1.63 → 0* **1.63**		α_1	6.8

$^{12}C+^{12}C \rightarrow ^{23}Na + p$ Q = 2.24 MeV

γ-rays and p particles energies for excited states for $^{12}C(^{12}C, p)^{23}Na$ (Q = 2.241 MeV)

E_X (MeV)	Jp	Main γ transitions (MeV)		ID	E_{p-max} (MeV) (E^{CM} = 2 MeV)
0.0	$3/2^+$			p_0	5.3
0.44	$5/2^+$	0.44 → 0 **0.44**		p_1	4.8



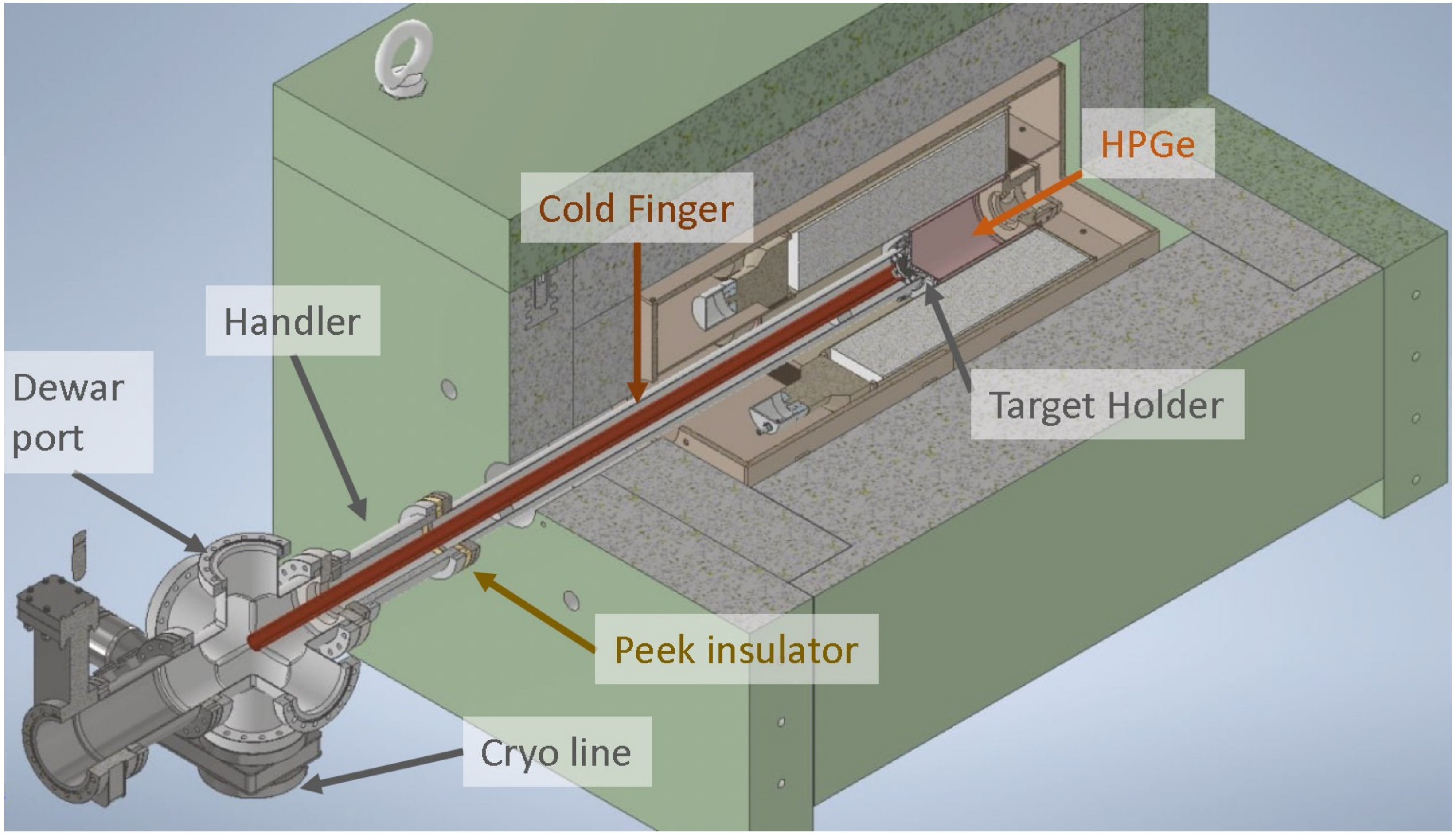
The $^{12}C+^{12}C$ preparation

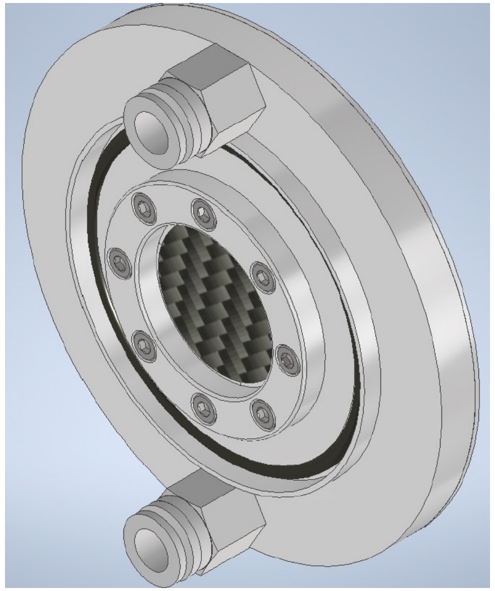
see Riccardo Gesuè and Steffen Turkat posters

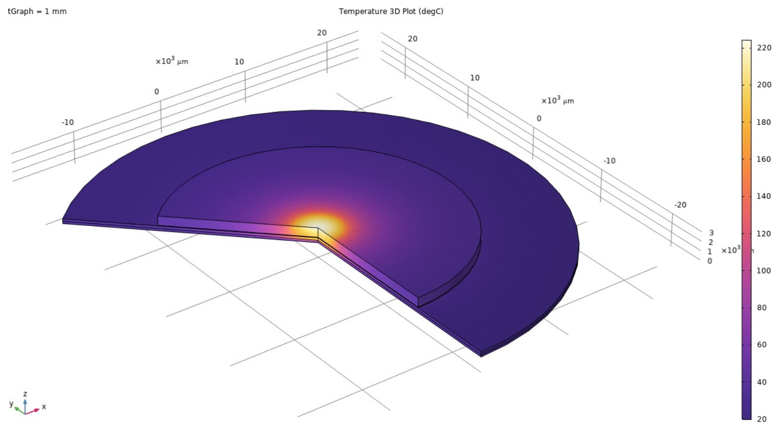
Preliminary targets stability tests performed in the Felsenkeller laboratory in Dresden

Graphite, HPGO – cooling system, expected temperature (thermometric, thermic calculations)

Measurement performed with HPGe at 0° close geometry and NaI array for Compton suppression







The $^{12}C+^{12}C$ preparation

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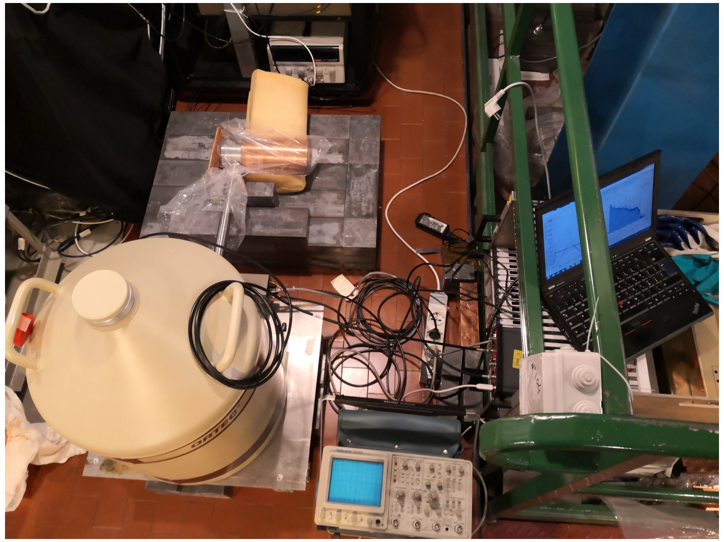
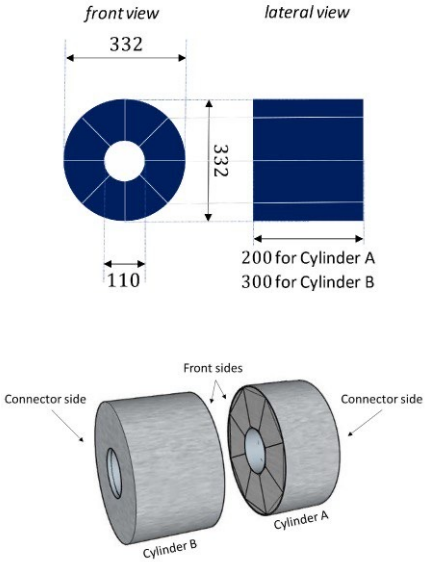
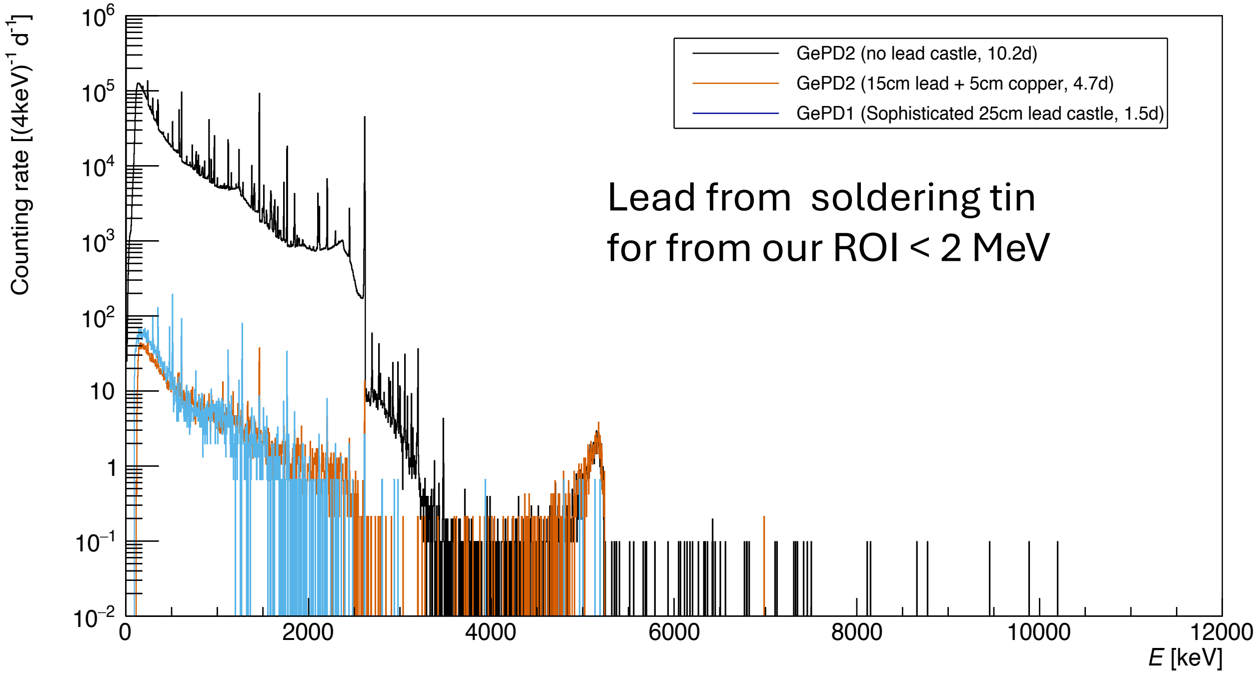
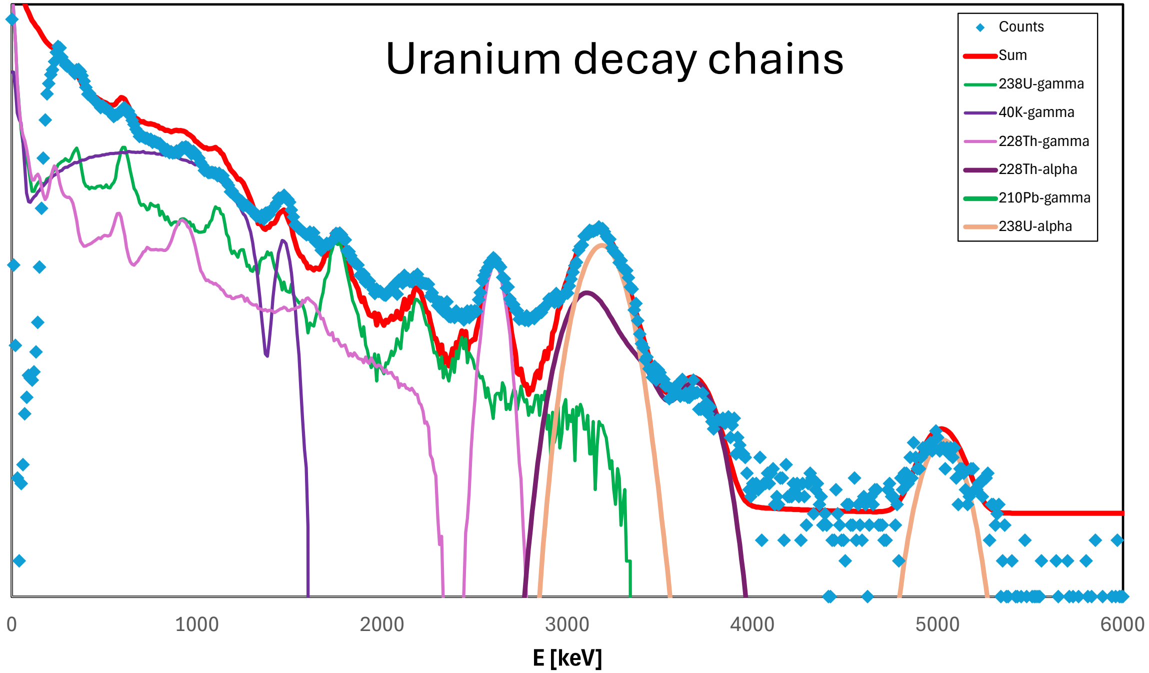




HPGe and NaI scintillator detectors intrinsic background and efficiency tests just performed at LNGS. Data analysis ongoing.





The $^{12}C+^{12}C$ preparation

see Riccardo Gesuè and Steffen Turkat posters

- Setup design completed, parts procured. Now under installation on surface in LNGS for testing.
- First beam for further target tests planned for Dec 2024
- First half of 2025 devoted to setup mounting
- Second half 2025 devoted to first data taking

Outlooks

LUNA 400 future program

- $^{10}B(\alpha,p)^{13}C$ - $^{10}B(\alpha,d)^{12}C$ - $^{10}B(\alpha,n)^{13}N$ - whole 2025
  ERC-NUCLEAR - NUclear Clustering Effects in Astrophysical Reaction
  PI Marialuisa Aliotta, University of Edinburgh
- $^{19}F(p,g)^{20}Ne$ – first half of 2025
- $^{24}Mg(p,g)^{25}Al$ – second half of 2025

LUNA MV future program at IBF (under PAC revision)

- $^{12}C+^{12}C$ – whole 2025
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ – second half of 2025

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Thank you for your attention

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