NUCLEAR PHYSICS IN ASTROPHYSICS - CLUJ-NAPOCA

Nuclear Astrophysics deep underground: the LUNA experiment

Rosanna Depalo
for the LUNA Collaboration

University of Milano and INFN Milano

Istituto Nazionale di Fisica Nucleare

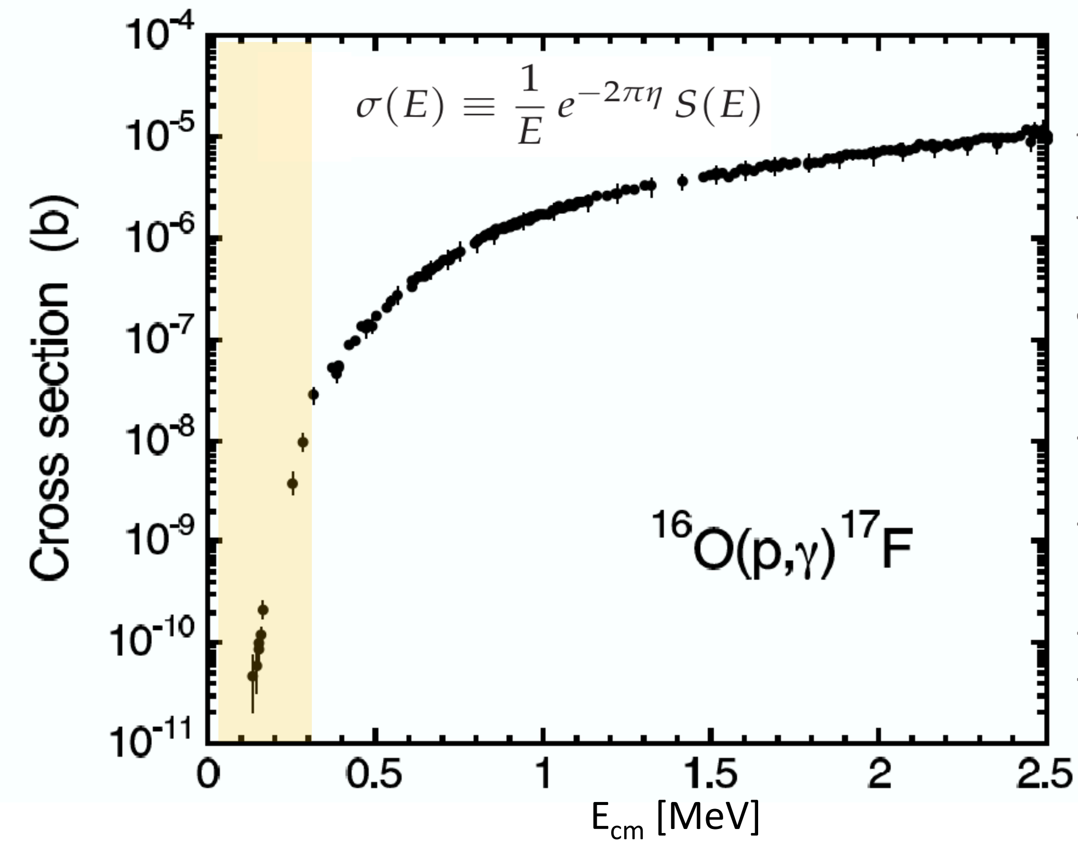
Charged-particle-induced reactions at astro energies

In most astrophysical scenarios, the kinetic energy of interacting nuclei is much lower than Coulomb repulsive potential:

→ Quantum-mechanical tunnelling enables reactions below the Coulomb barrier

→ The tunneling probability drops steeply with decreasing energy

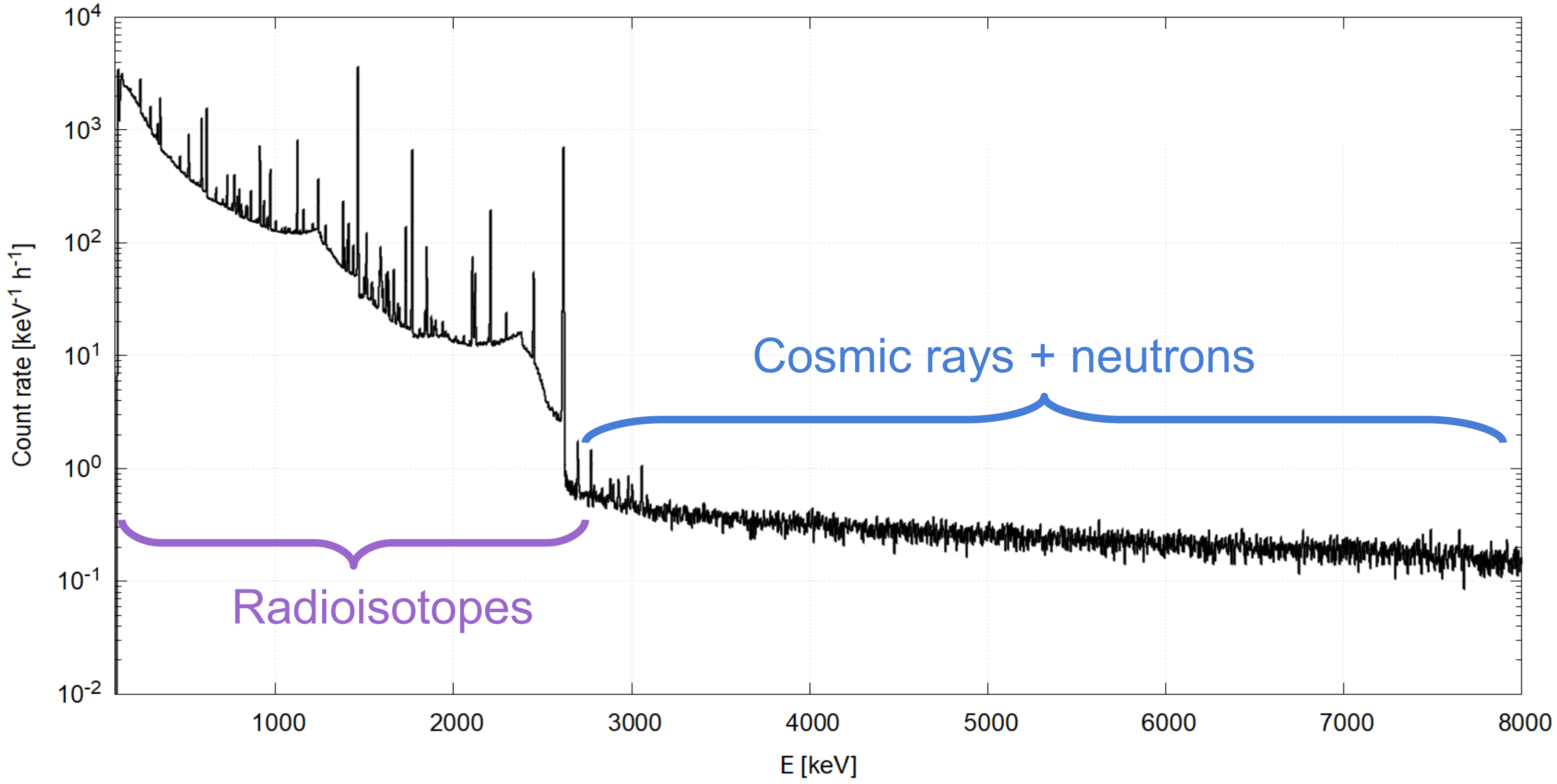
At astrophysical energies, the cross section can be extremely small (fb – nb) and **the reaction signal is easily lost in environmental background**.



Iliadis, Nuclear physics of stars (2007)

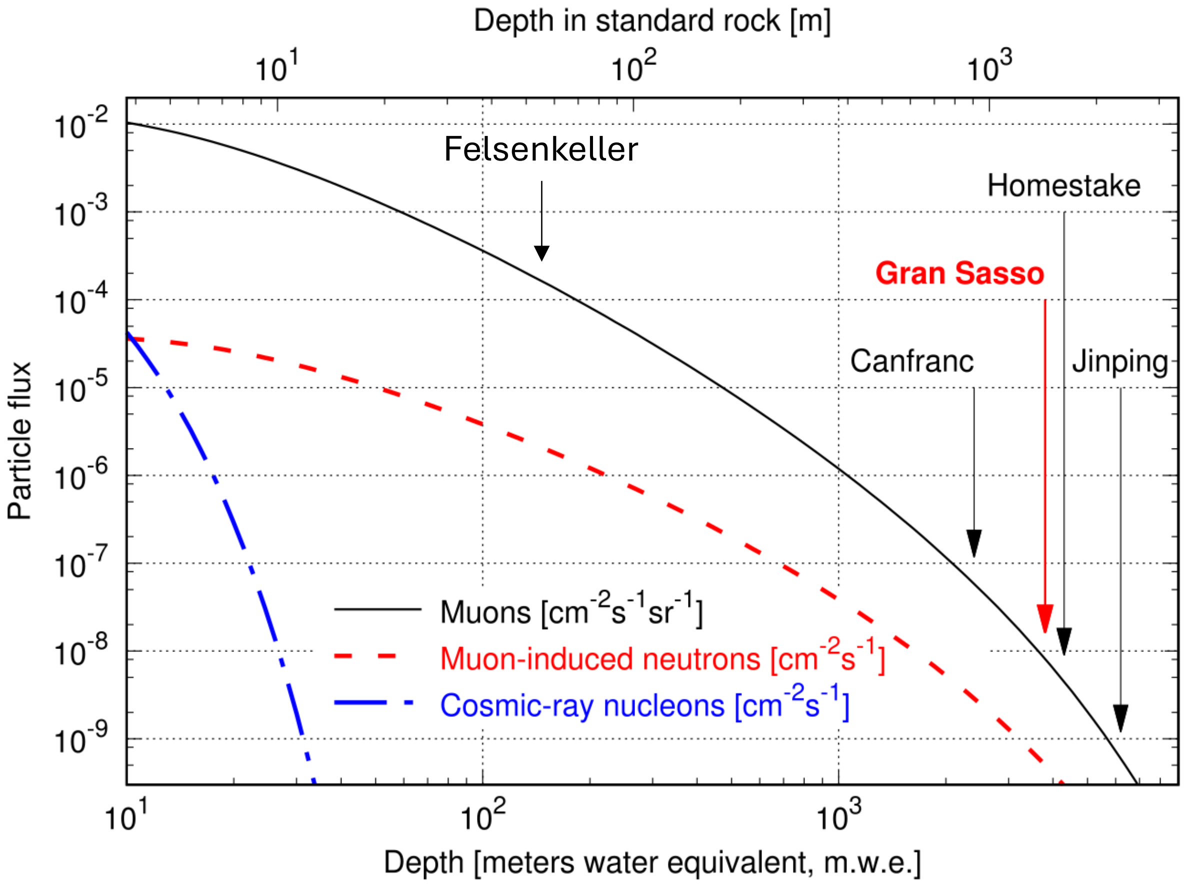
Environmental background

- **Environmental radioactivity**: $^{235,238}U$ and ^{232}Th chains and ^{40}K
- **Cosmic rays:** mainly muons at sea level
- **Neutrons from (α,n) and spallation**

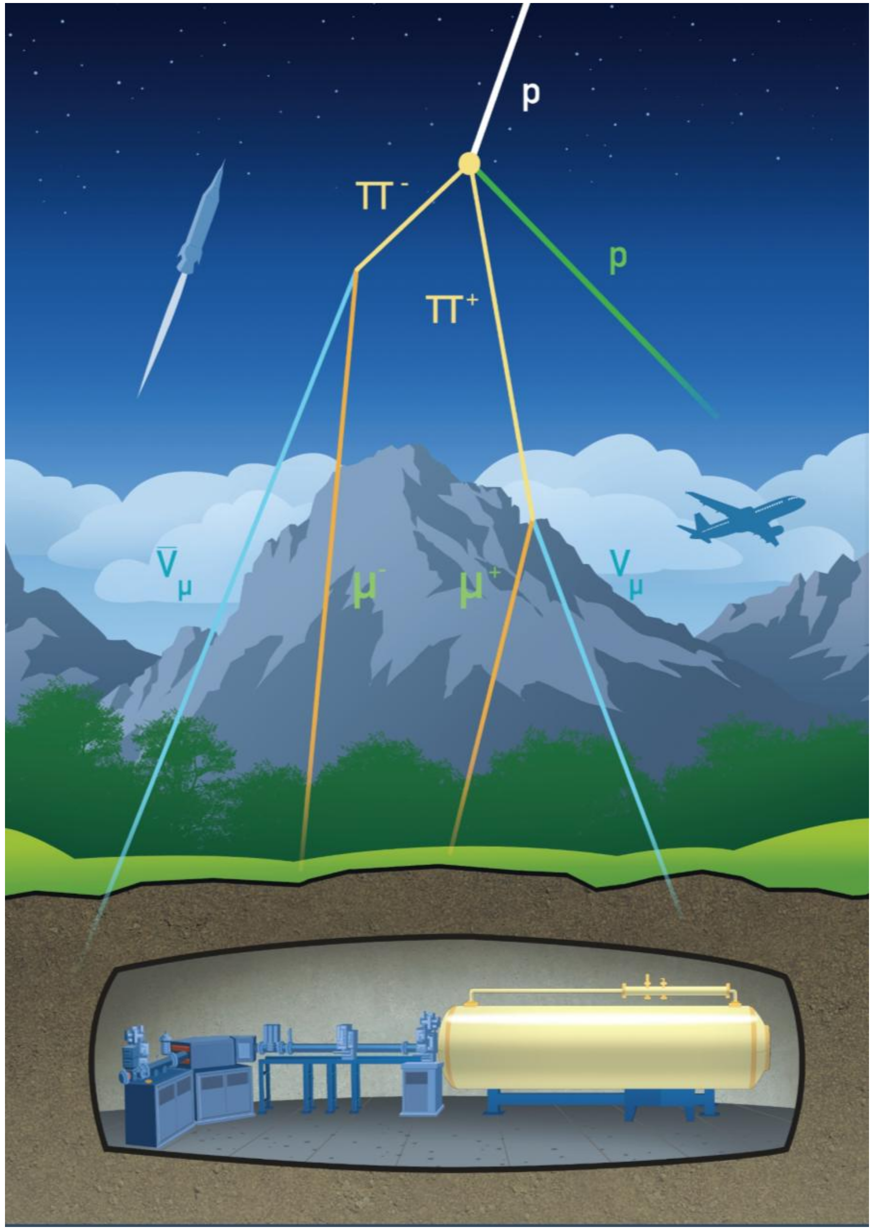


Why underground?

Rocks can efficiently suppress cosmic ray flux

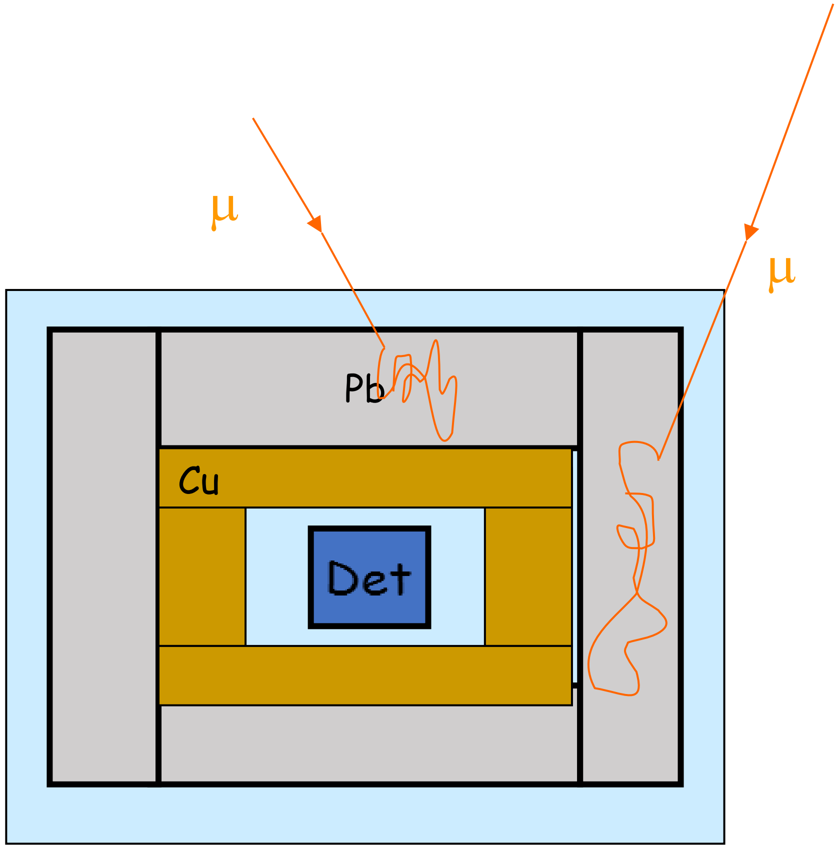


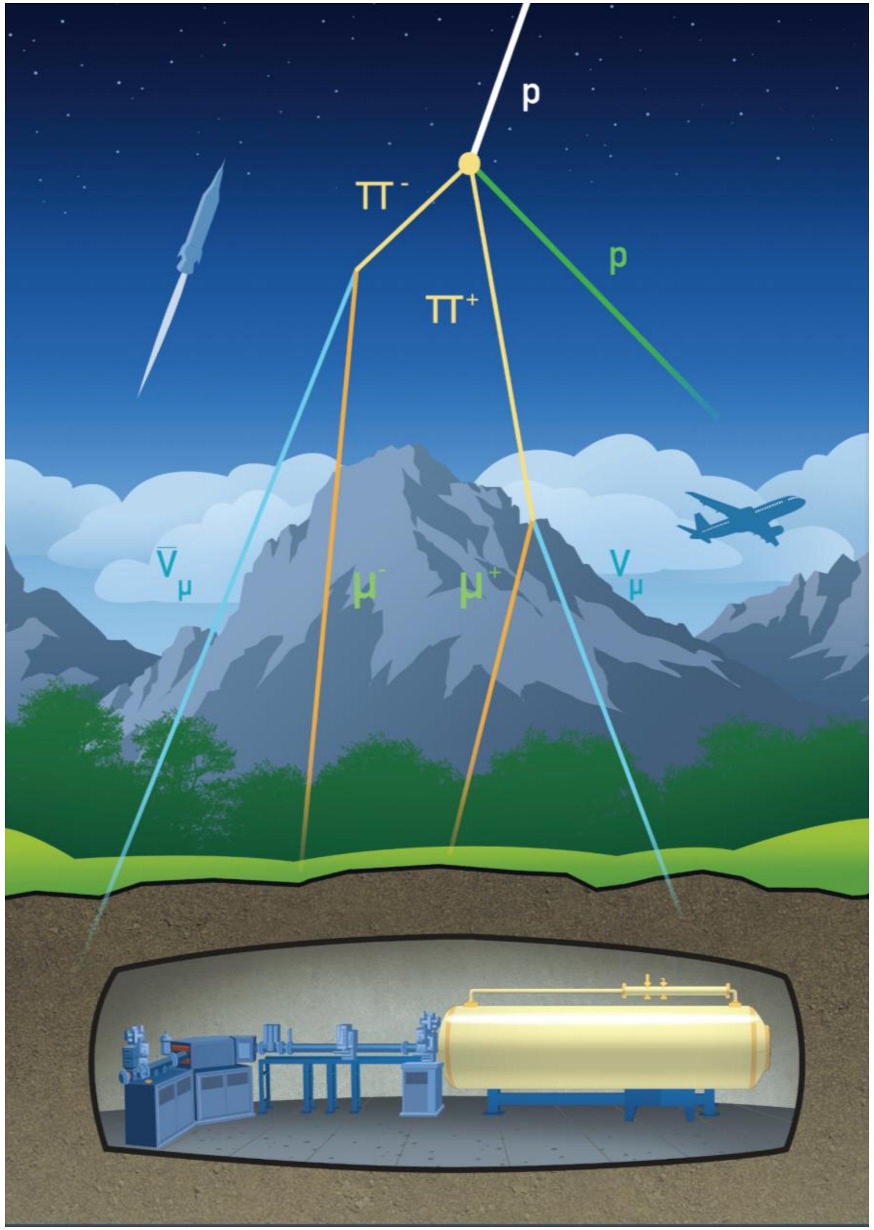
C. Broggini+, Prog. Part. Nuc. Phys. 98 (2018) 55–84



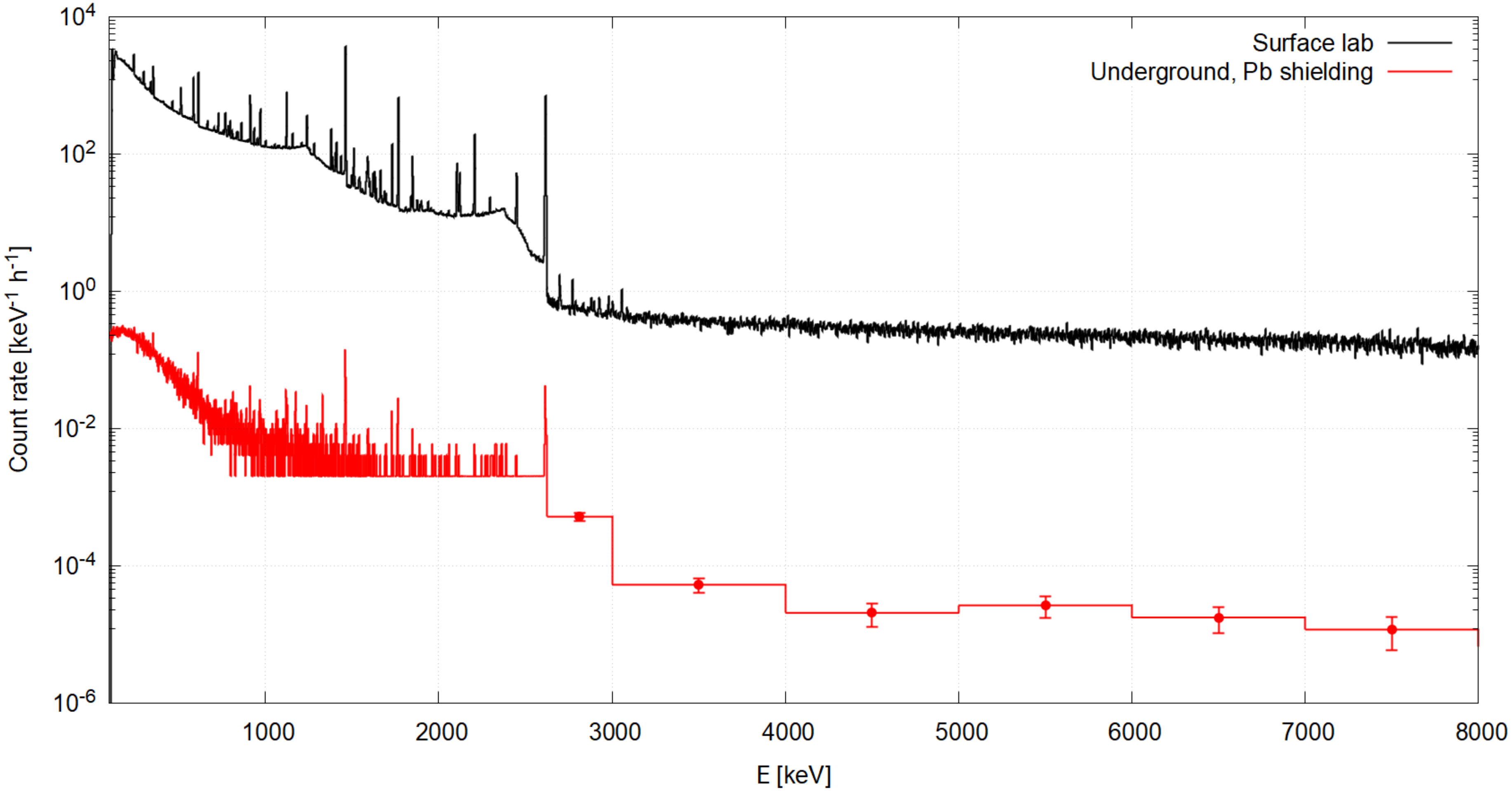
Why underground?

+ More effective passive shielding for Eγ < 3 MeV



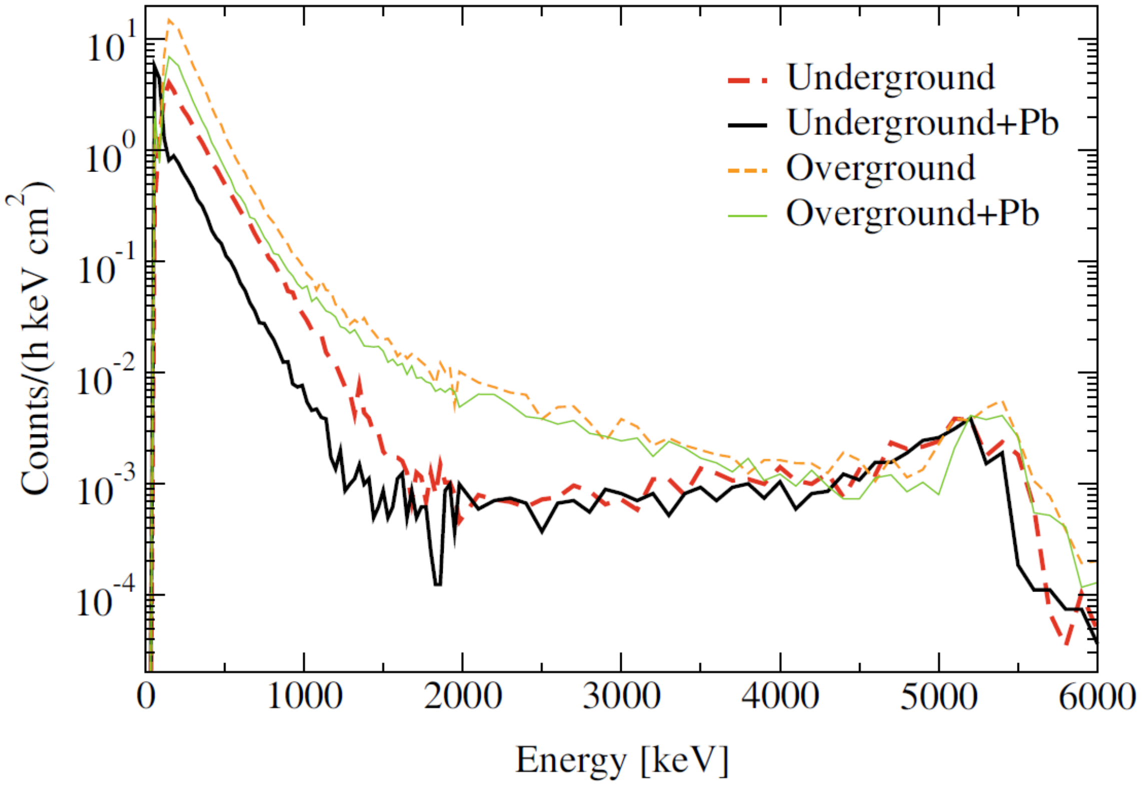


Why underground?



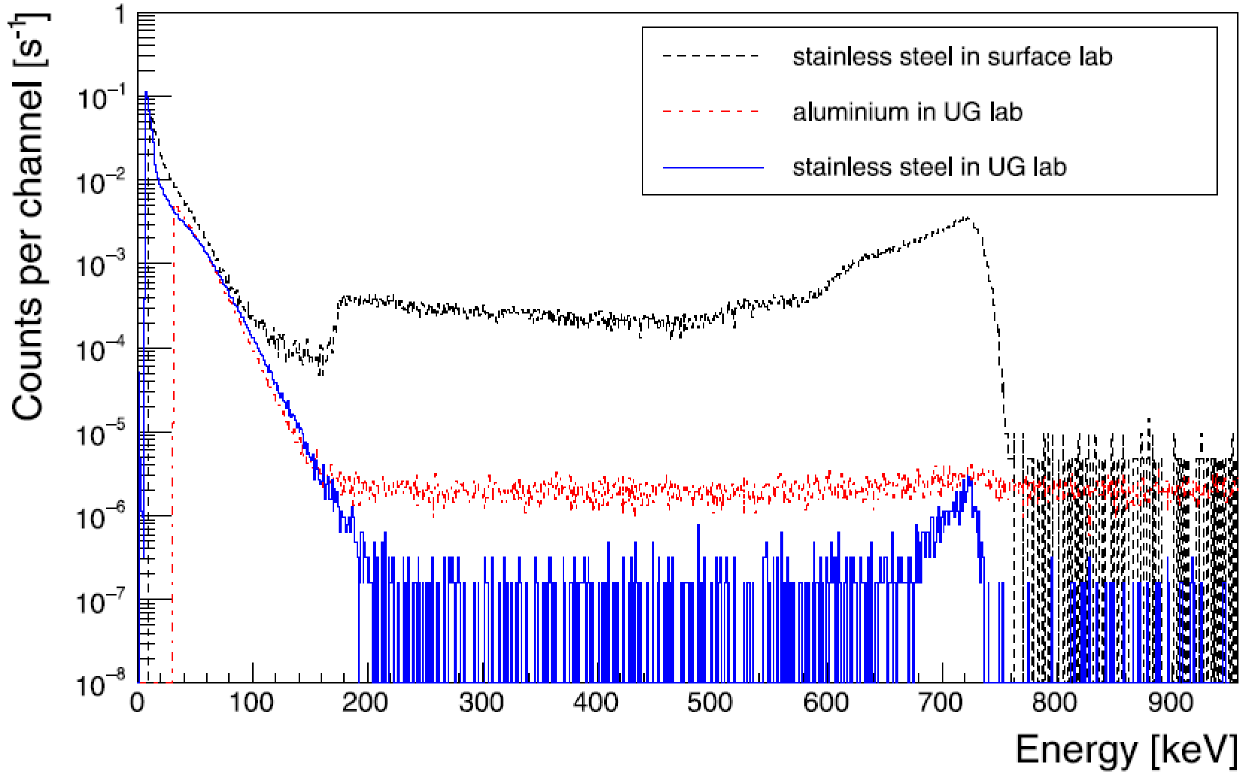
Why underground?

Si detectors



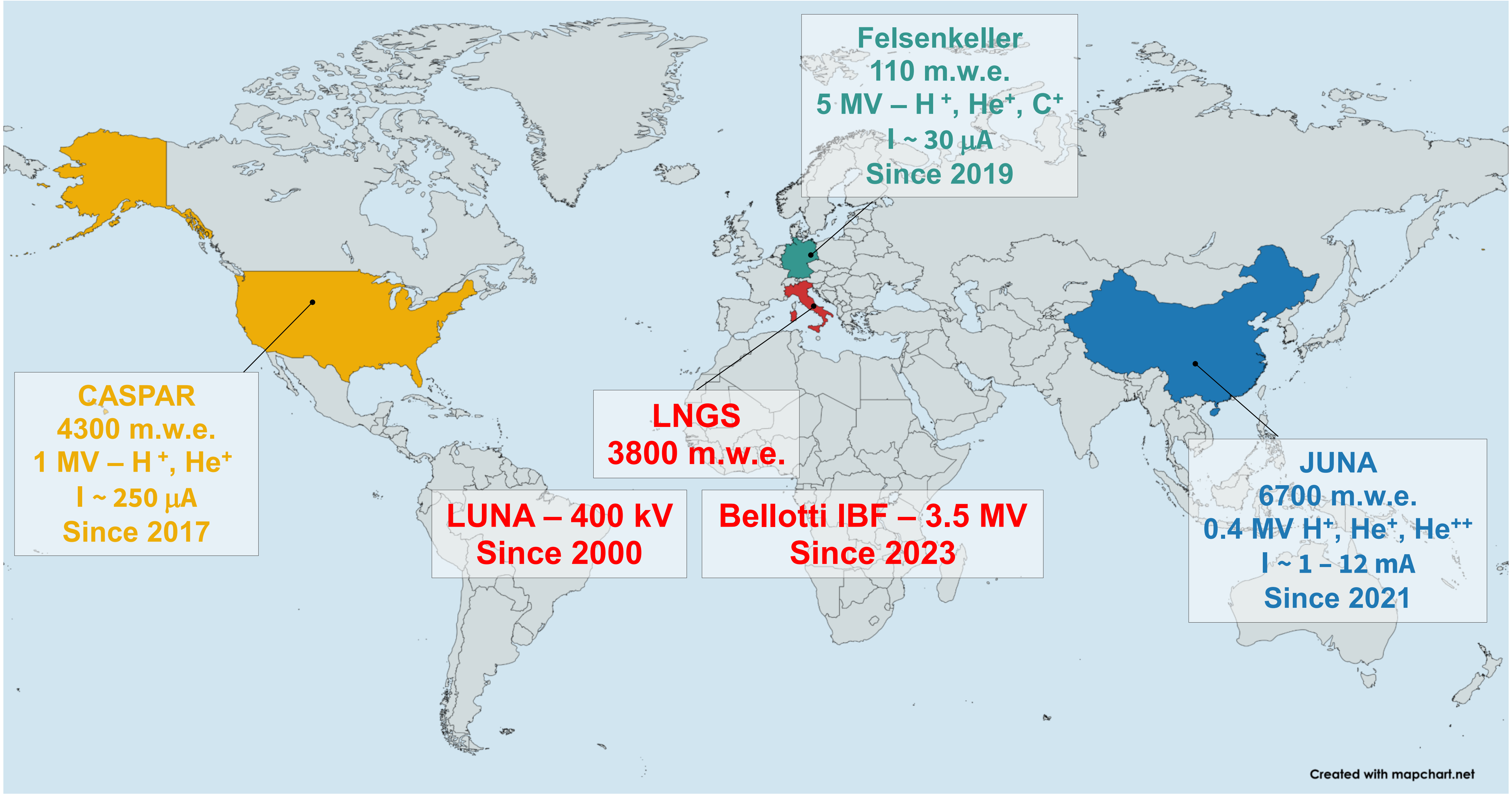
Bruno et al. EPJ A 51, 94 (2015)

^{3}He neutron counters



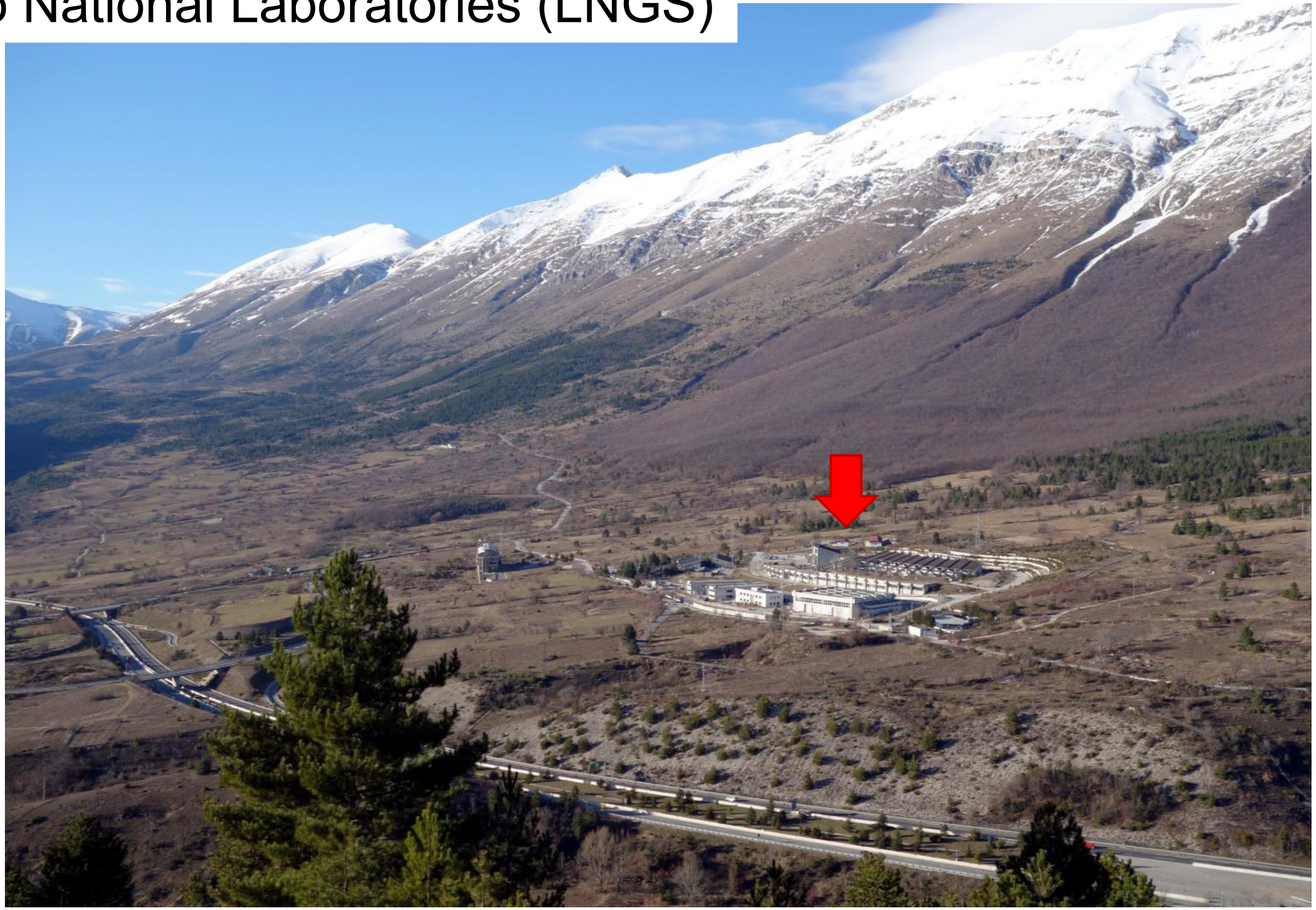
Csedreki et al. NIM A 994, 165081 (2021)

Underground Nuclear Astrophysics accelerators

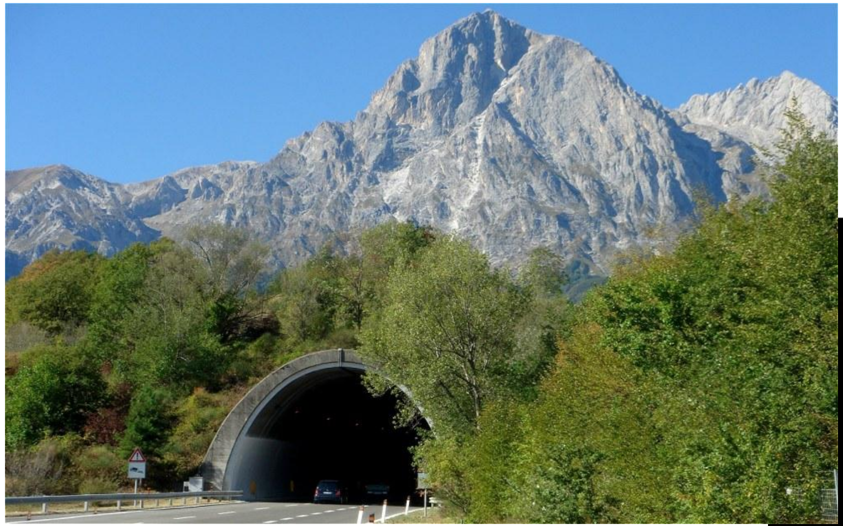


The Laboratory for Underground Nuclear Astrophysics

Gran Sasso National Laboratories (LNGS)



The Laboratory for Underground Nuclear Astrophysics

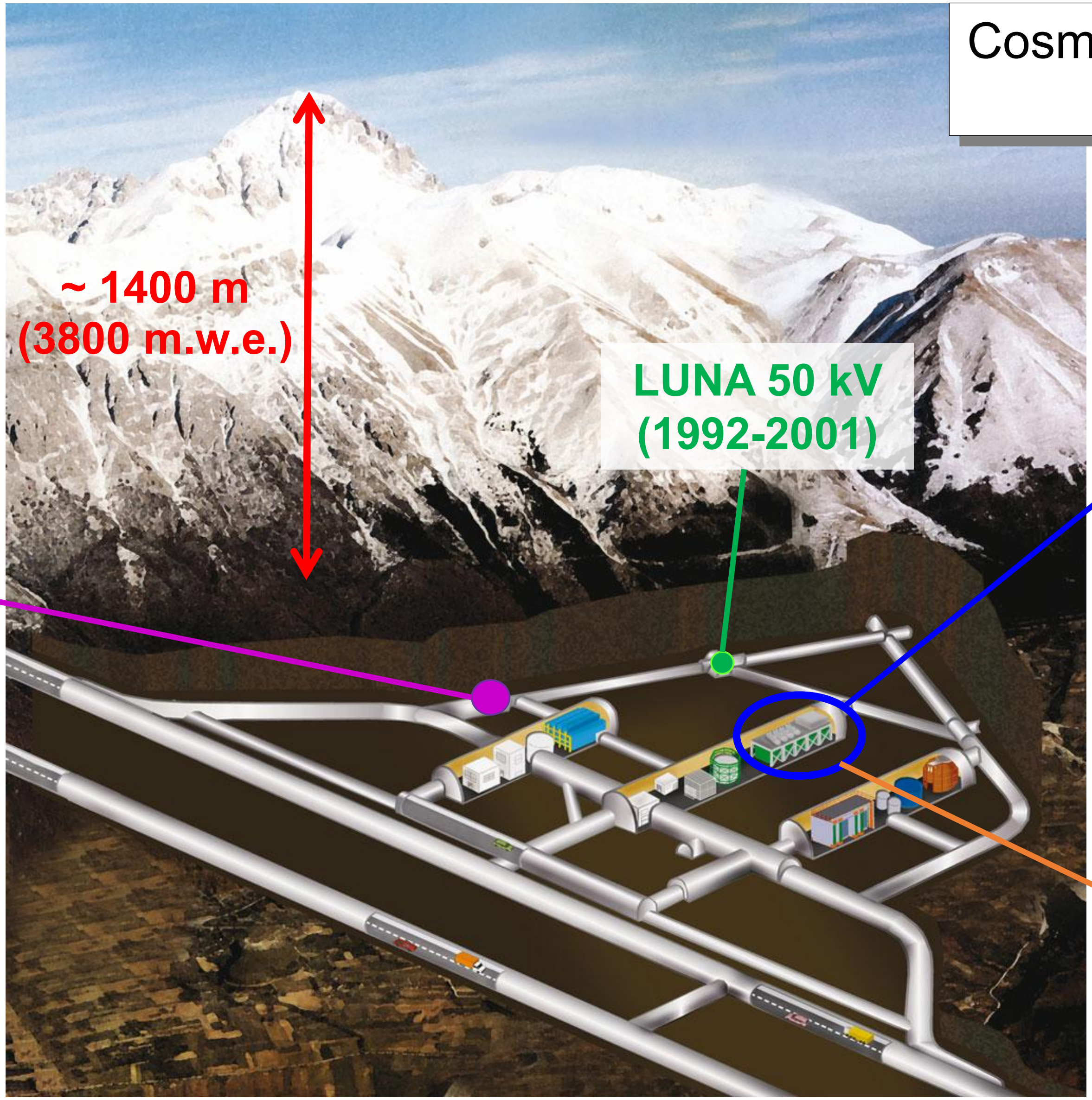


Virtual tour of LNGS
available on Google Maps

The Laboratory for Underground Nuclear Astrophysics

Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

LUNA 400 kV
(2000 → …)



Bellotti IBF – 3.5 MV
(2023 → …)

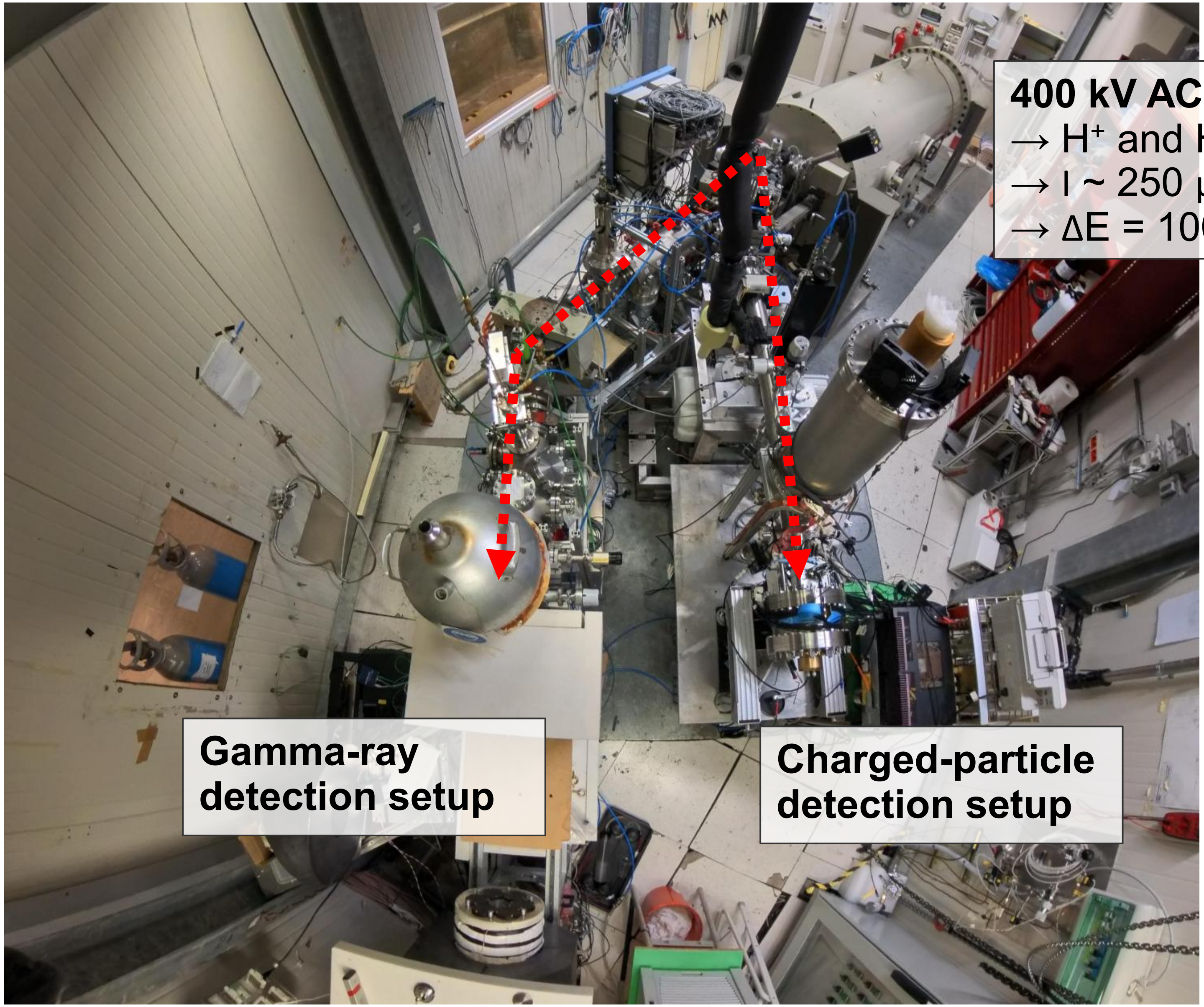
TALKS BY F. FERRARO, D. BASAK, T. CHILLERY

LUNA NOVA

European Research Council
Established by the European Commission

TALK BY D. BEMMERER

LUNA-400 kV



400 kV ACCELERATOR:
→ H^+ and He^+ beams
→ I ~ 250 μA
→ ΔE = 100 eV

Updates since last NPA conference

$^{21}Ne(p,\gamma)^{22}Na$ → Sidhu et al. Physical Review C **112**, L052801 (2025) ✓

$^{16}O(p,\gamma)^{17}F$ → Publication submitted ✓

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^{14}N(p,γ)^{15}O → Finalizing analysis

^{23}Na(p,α)^{20}Ne → Analysis in progress

^{19}F(p,γ)^{20}Ne → Analysis in progress

^{24}Mg(p,γ)^{25}Al → Analysis in progress

^{10}B(α,p)^{13}C, ^{10}B(α,d)^{12}C and ^{10}B(α,n)^{13}N → Data taking in progress

^{27}Al(p,α)^{24}Mg → Data taking in progress

Updates since last NPA conference

^{21}**Ne(p,γ)**^{22}**Na** → Sidhu et al. Physical Review C **112**, L052801 (2025) ✓

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^{14}**N(p,γ)**^{15}**O** → Finalizing analysis

^{23}**Na(p,α)**^{20}**Ne** → Analysis in progress

} THIS TALK

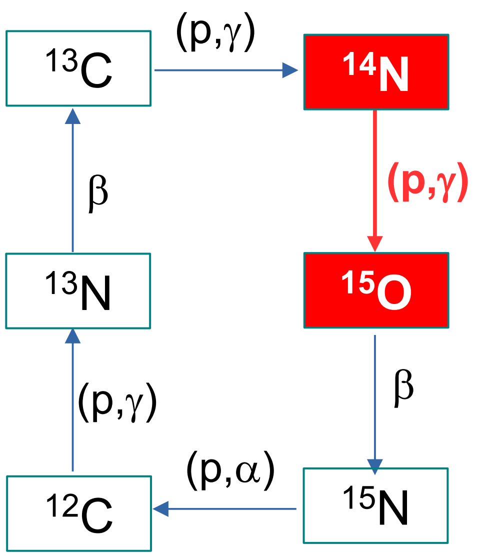
^{19}**F(p,γ)**^{20}**Ne** → Analysis in progress

^{24}**Mg(p,γ)**^{25}**Al** → Analysis in progress TALK BY G. SATURNO

^{10}**B(α,p)**^{13}**C,** ^{10}**B(α,d)**^{12}**C and** ^{10}**B(α,n)**^{13}**N** → Data taking in progress TALK BY M. ALIOTTA

^{27}**Al(p,α)**^{24}**Mg** → Data taking in progress POSTER BY S. MONTELLA

$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

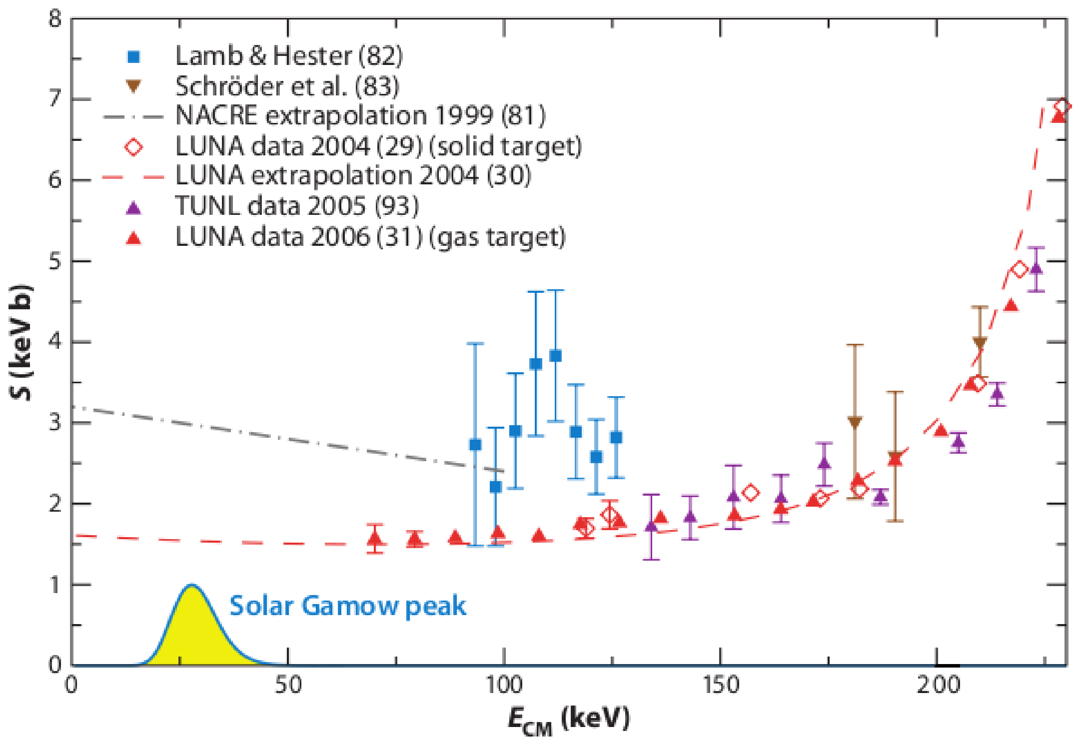


→ Determine age of the Universe from globular clusters

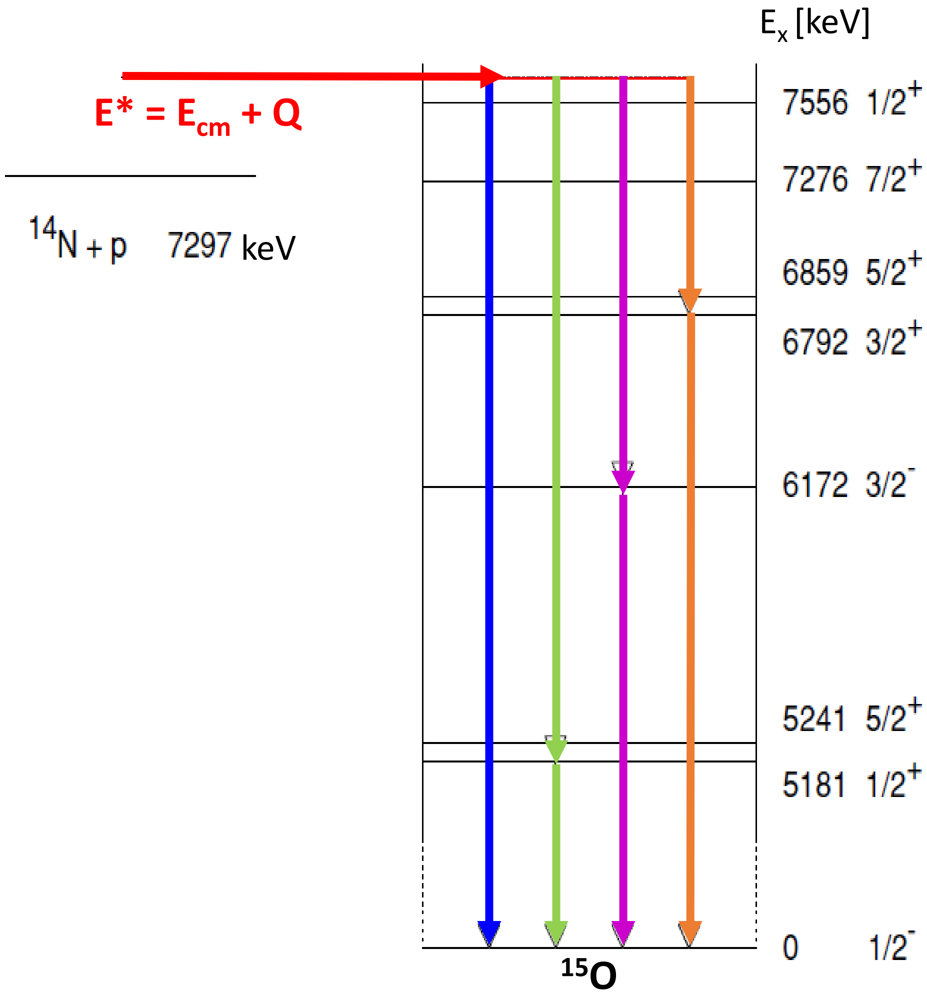
→ Use CNO neutrino flux to probe the interior of the Sun

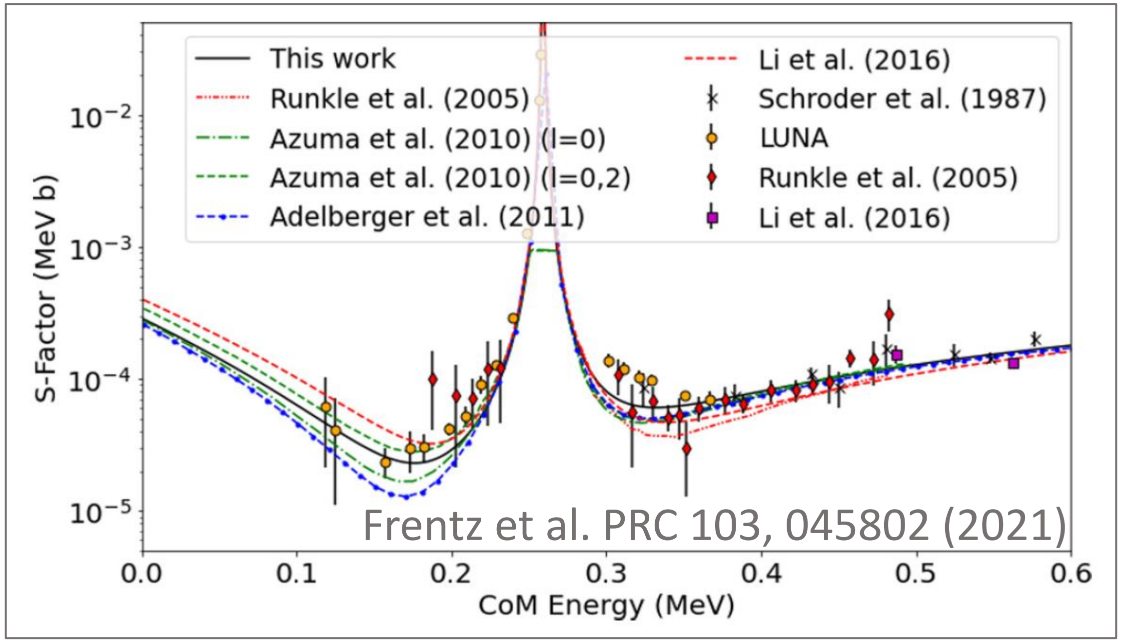
$^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO cycle

It determines the overall rate of the cycle



$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle





Solar Fusion III Rev. Mod. Phys. 97, 3 (2025)

Transition	$S_{114}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr → 0	0.30 ± 0.11	37%	This review
tr → 6.79	1.17 ± 0.03	2.9%	This review
tr → 6.17	0.13 ± 0.05	38%	Adelberger *et al.* (2011)
tr → 5.18	0.010 ± 0.003	30%	Adelberger *et al.* (2011)
tr(5.24) → 0	0.068 ± 0.020	30%	Adelberger *et al.* (2011)
R-matrix sum	1.68 ± 0.13[a]	7.6%	
Additional system uncertainty[b]		3.5%	
Total	1.68 ± 0.14	8.4%	

$^{14}N(p,\gamma)^{15}O$ reaction: Experiment

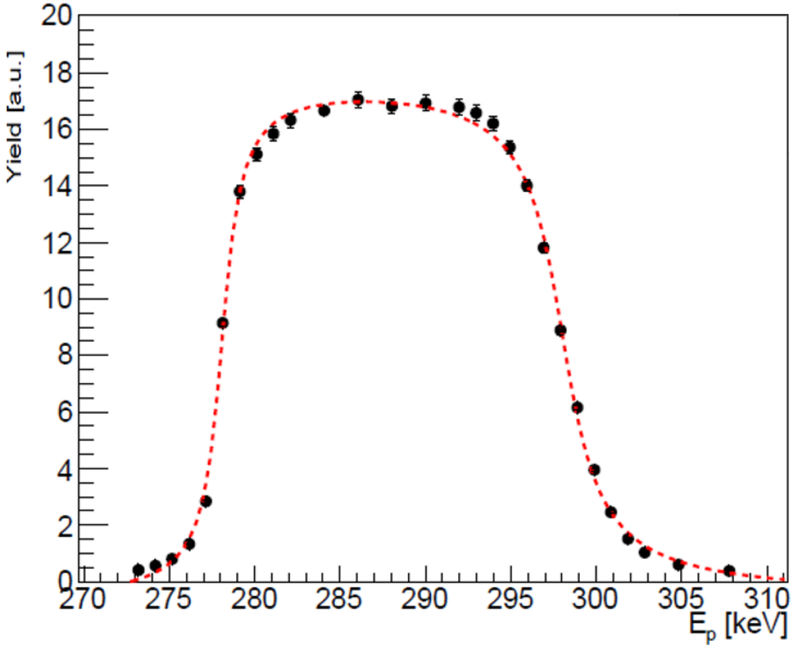
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA
Ministero dell'Università e della Ricerca
Finanziato dall'Unione europea
NextGenerationEU

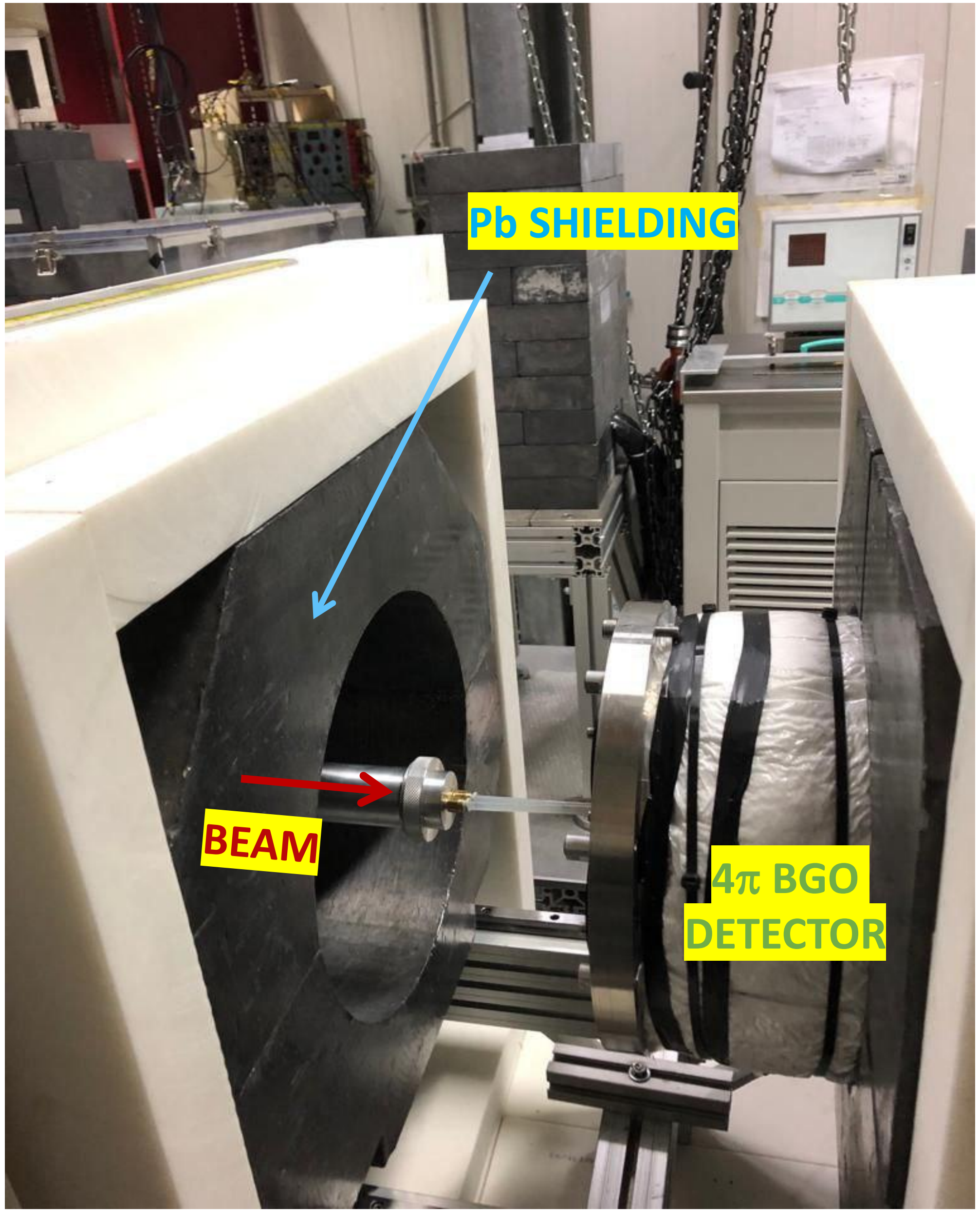
GOAL: measure partial cross sections down to $E_{cm} \approx 100$ keV

Solid Targets TiN sputtered targets (thickness 70 – 140 nm) on Ta backing produced at LNL

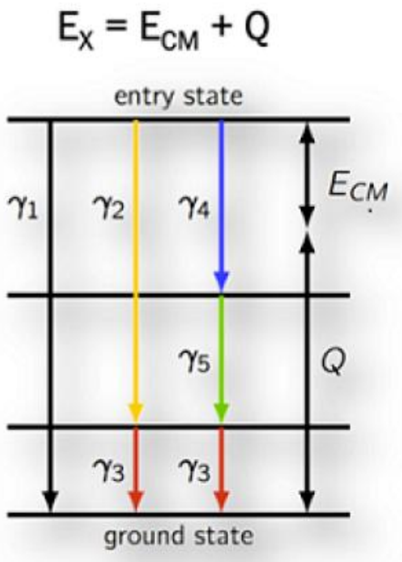
4π-BGO detector (6 crystals) + 10 cm lead shielding.

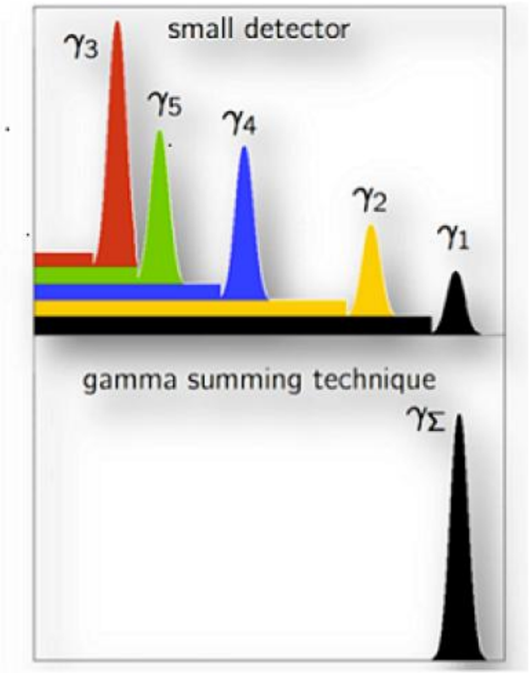
Target characterization through periodic scan of the 278 keV resonance

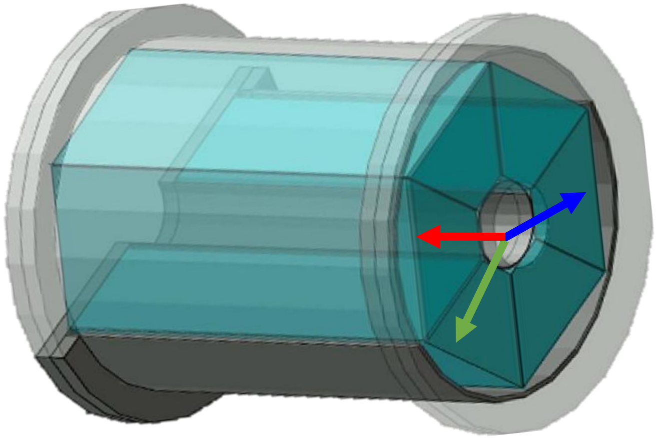


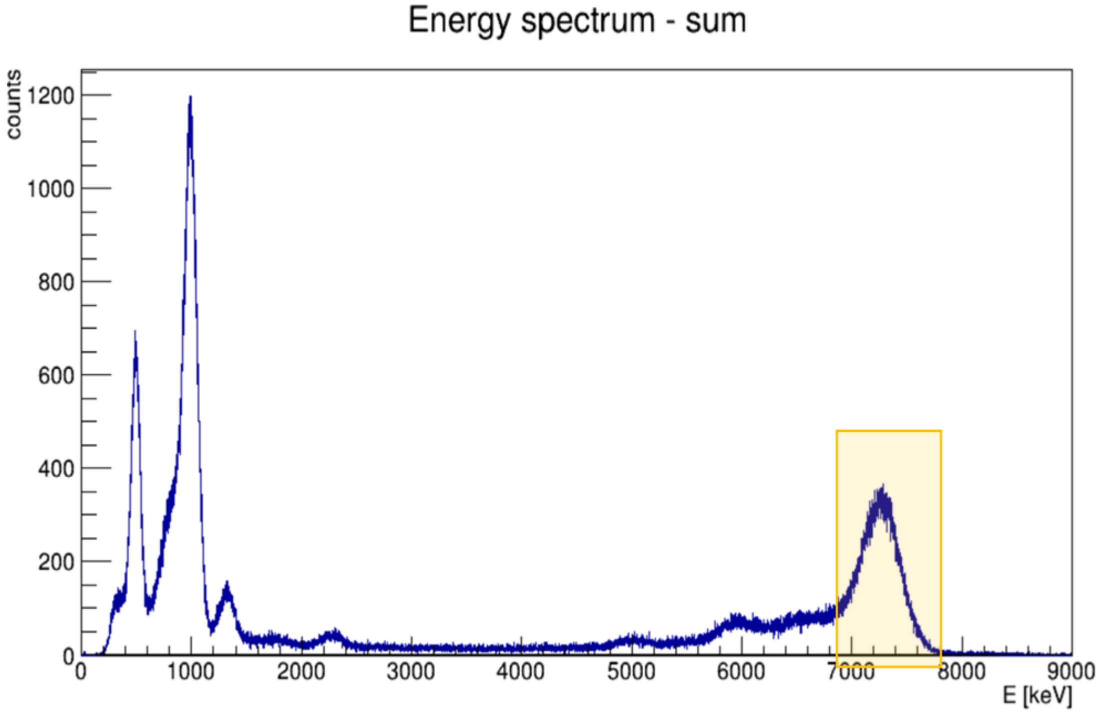


$^{14}N(p,\gamma)^{15}O$ reaction: Analysis technique









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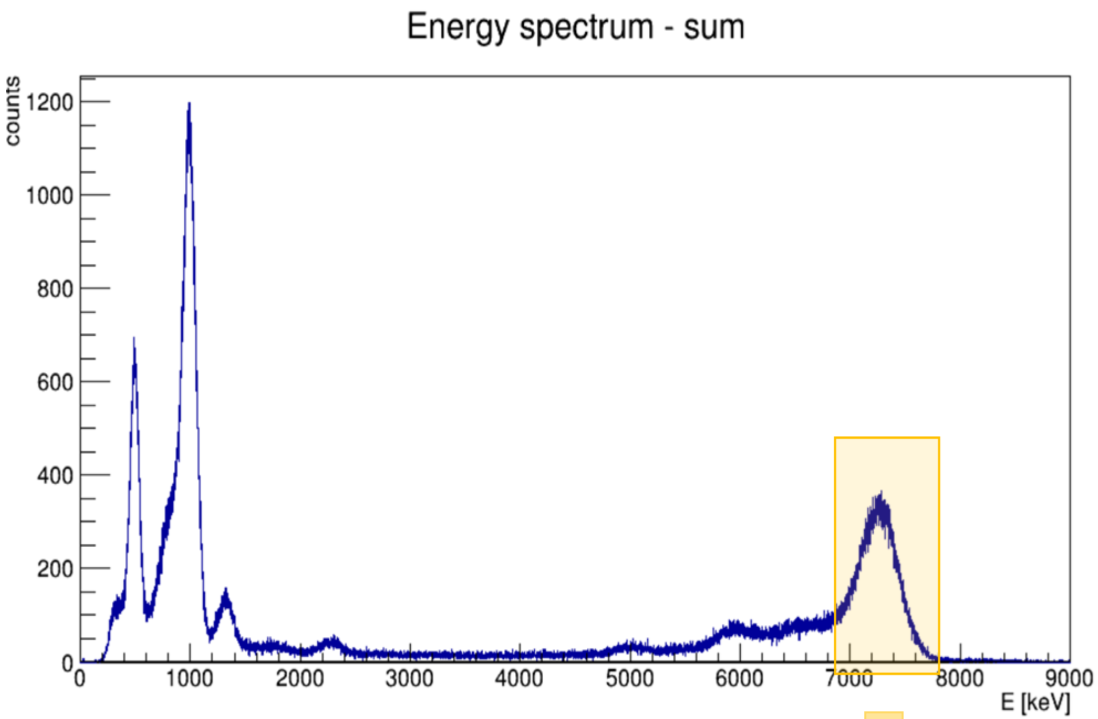
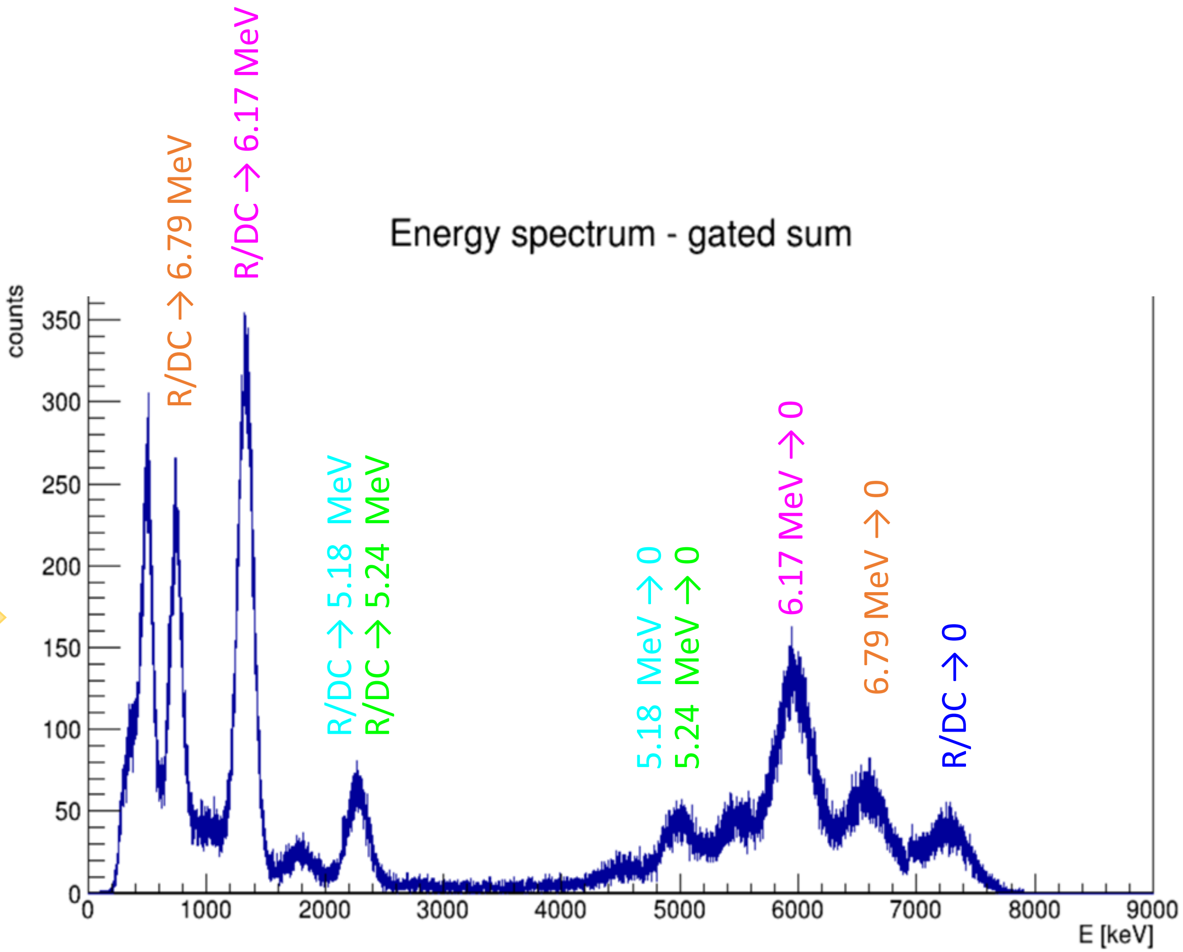
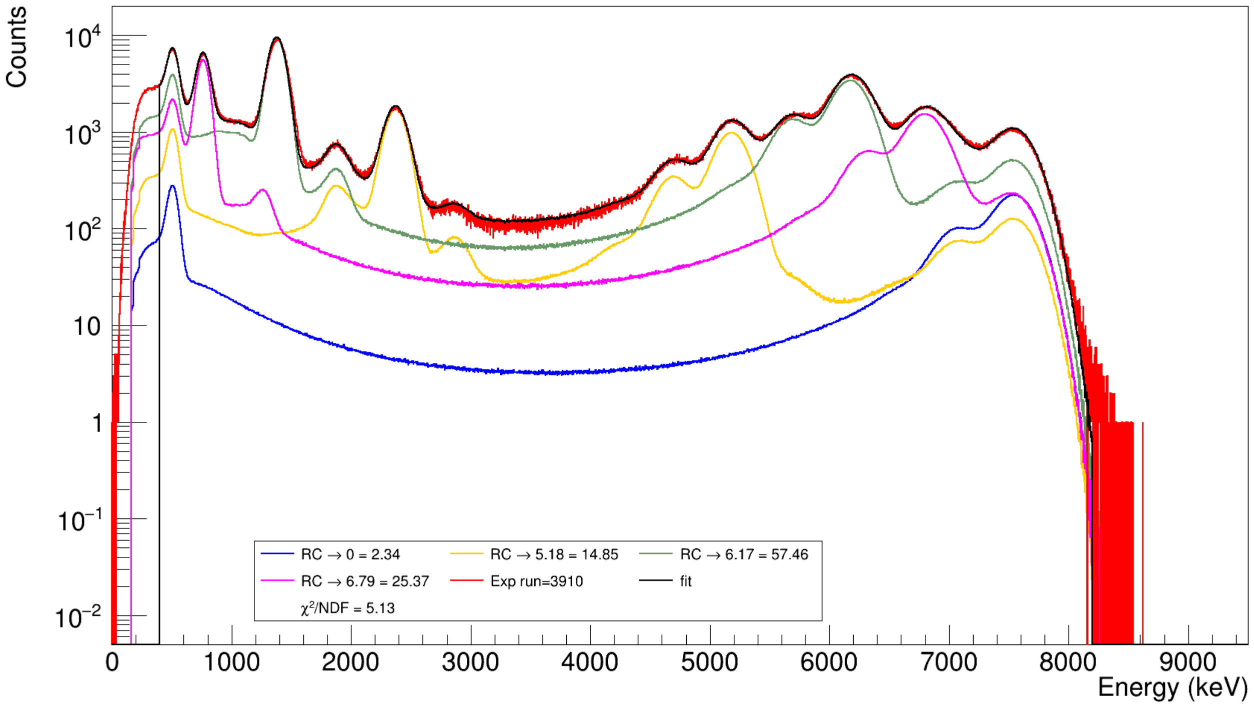




Gated spectrum fitted as a linear sum of simulated template spectra for each of the gamma cascades

$^{14}N(p,\gamma)^{15}O$ reaction: Results

Analysis technique tested on 278 keV resonance



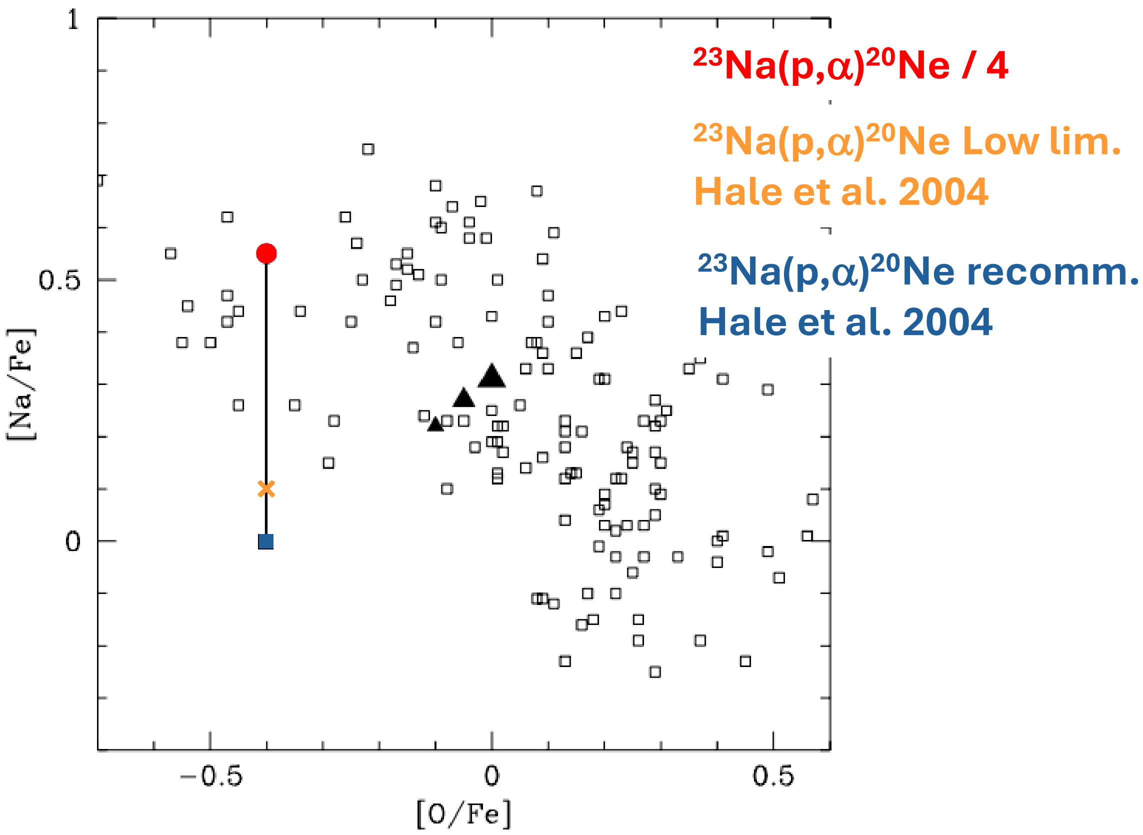
Transition	Branching [%]	
	This work	Daigle et al. 2006
R → 0	$2.3 \pm 0.3_{stat}$	1.5 ± 0.3
R → 5.18 MeV	$14.5 \pm 0.1_{stat}$	16.9 ± 0.4
R → 5.24 MeV	-	0.22 ± 0.07
R → 6.17 MeV	$57.4 \pm 0.3_{stat}$	58.4 ± 0.3
R → 6.79 MeV	$25.0 \pm 0.3_{stat}$	23.0 ± 0.3
R → 6.86 MeV	$0.82 \pm 0.04_{stat}$	0.14 ± 0.04

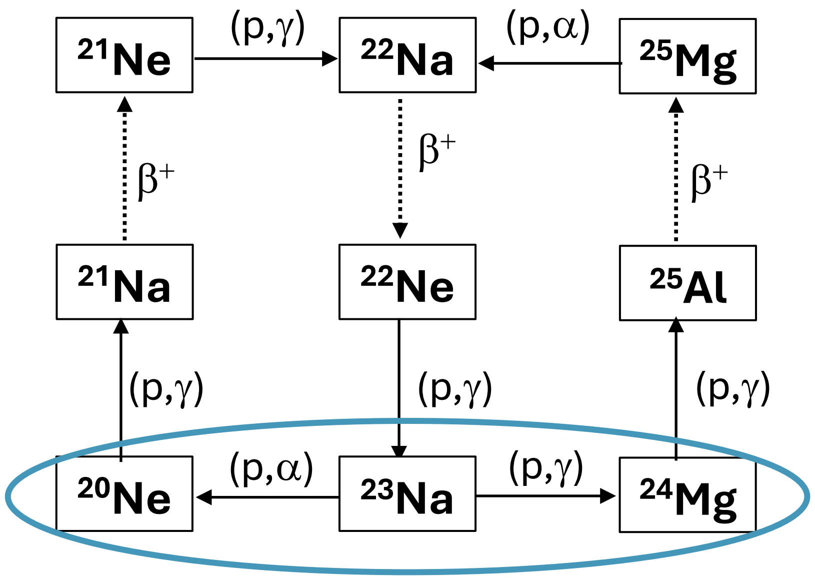
$\omega\gamma = (12.73 \pm 0.01_{stat} \pm 0.98_{syst})$ meV
SF III value: $\omega\gamma = (12.9 \pm 0.5)$ meV

^{23}Na(p,α)^{20}Ne reaction: Motivation

Stellar models need extensive tuning to reproduce observed abundances in GCs. The ^{23}Na(p,α)^{20}Ne reaction affects sodium abundance, and hence the observed **Na-O anti-correlation** pattern.

Ventura, D'Antona, A&A 457, 995–1001 (2006)

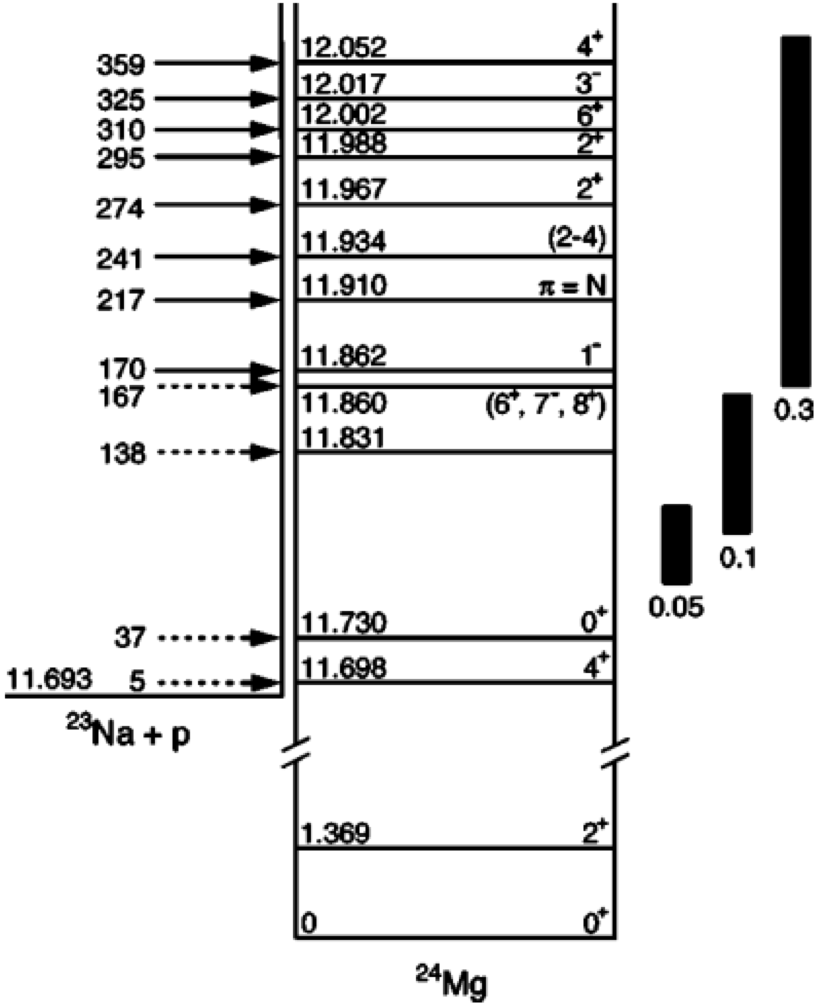




NeNa cycle, hydrogen burning in high-temperature environments ($T \geq 50$ MK)

$^{23}Na(p,\alpha)^{20}Ne$ reaction: State of the art

Several resonances contribute to astrophysical reaction rate. **Uncertainty ~20 – 40%**
[Iliadis et al. NPA *841 (2010) 31–250*]

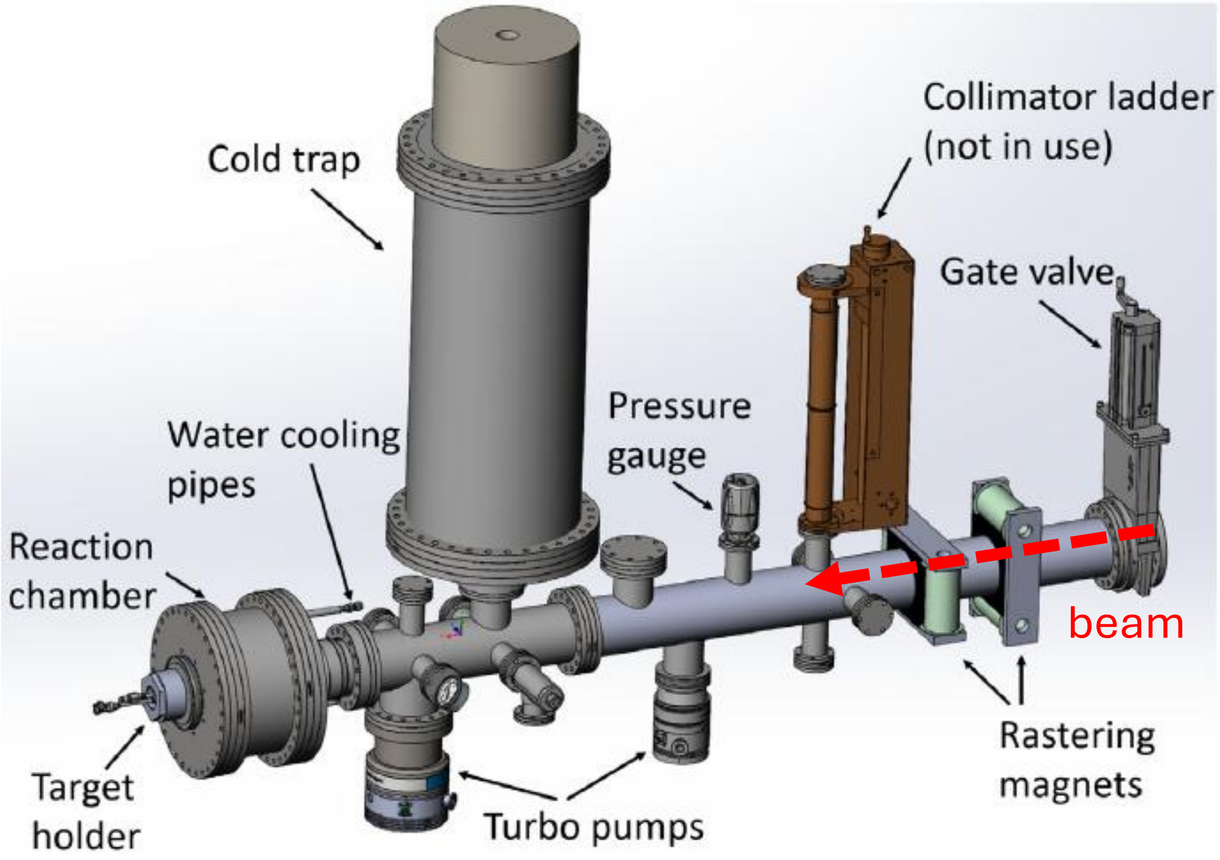


Hale et al. PRC 70, 045802 (2004)
**Boeltzig et al. PLB 795, 122 (2019)

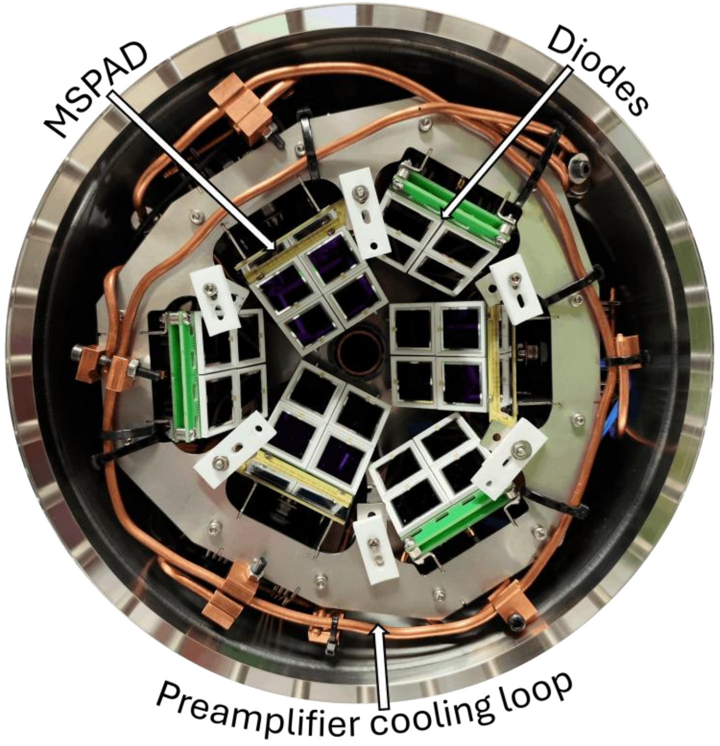
E_{cm} [keV]	J^{π}	$\omega\gamma$ [eV]	
		(p,γ)	(p,α)
133 -138*	?	$1.46^{+0.58}_{-0.53} \cdot 10^{-9}$ **	$< 2.8 \cdot 10^{-9}$
170	1-	$(1.2 \pm 0.4) \cdot 10^{-9}$	$(2.3 \pm 0.4) \cdot 10^{-5}$
217	N	$(2.7 \pm 1.4) \cdot 10^{-9}$	$(5.4 \pm 1.3) \cdot 10^{-5}$
241	3+	$(4.82 \pm 0.82) \cdot 10^{-4}$ **	< 0.1
274	2+	$< 5 \cdot 10^{-4}$	$(3.5 \pm 0.4) \cdot 10^{-2}$

*Marshall et al. PRC 104, L032801 (2021)

$^{23}Na(p,\alpha)^{20}Ne$ reaction: Experimental setup



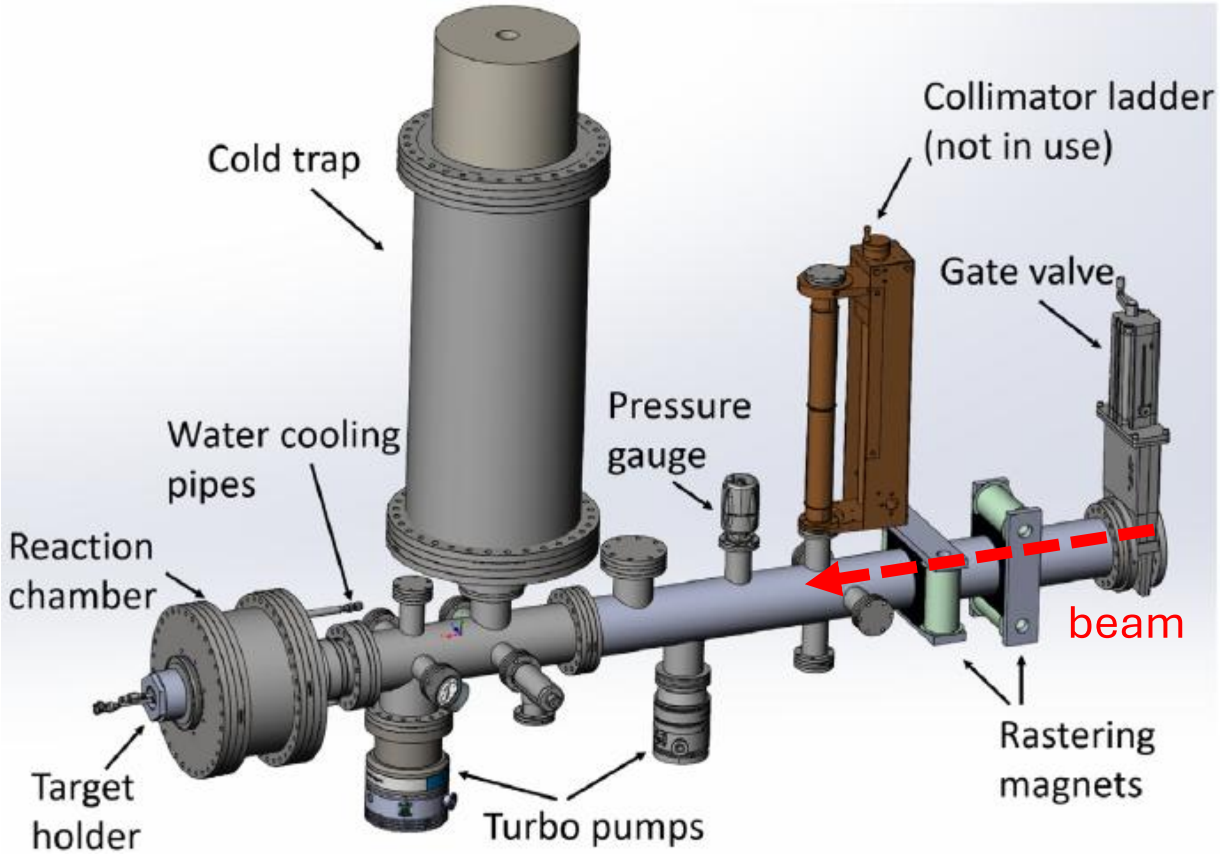
- 4 detection angles 102° < θ < 155°
- ~10% geometric efficiency



For more details on the setup, see:

Barbieri et al. NIM A 1092, 171767 (2026)

$^{23}Na(p,\alpha)^{20}Ne$ reaction: Experimental setup



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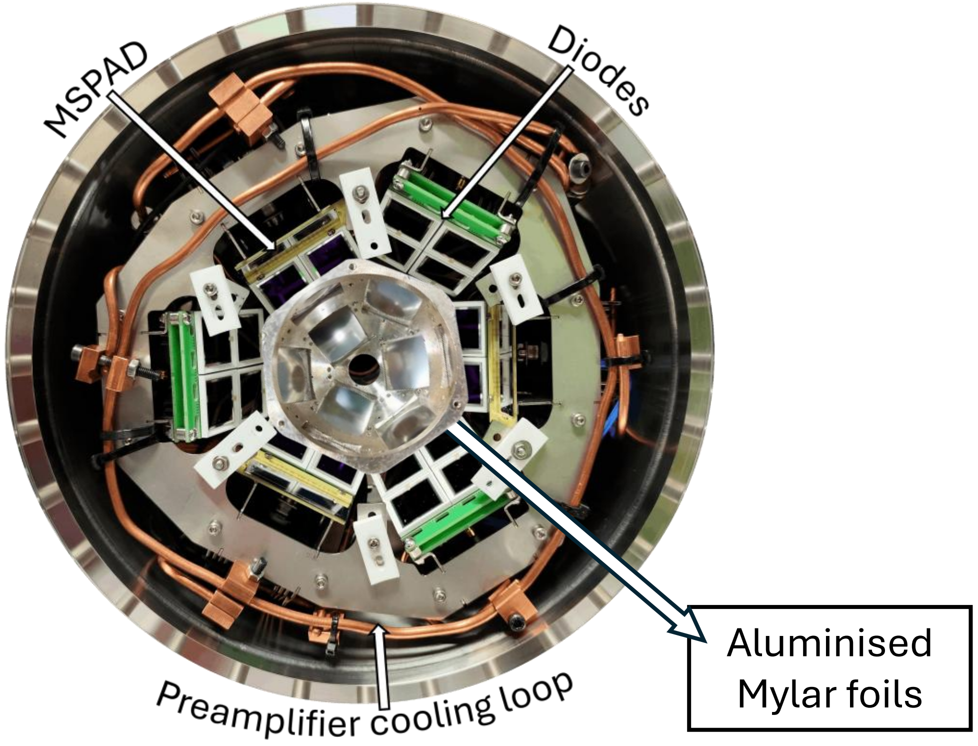
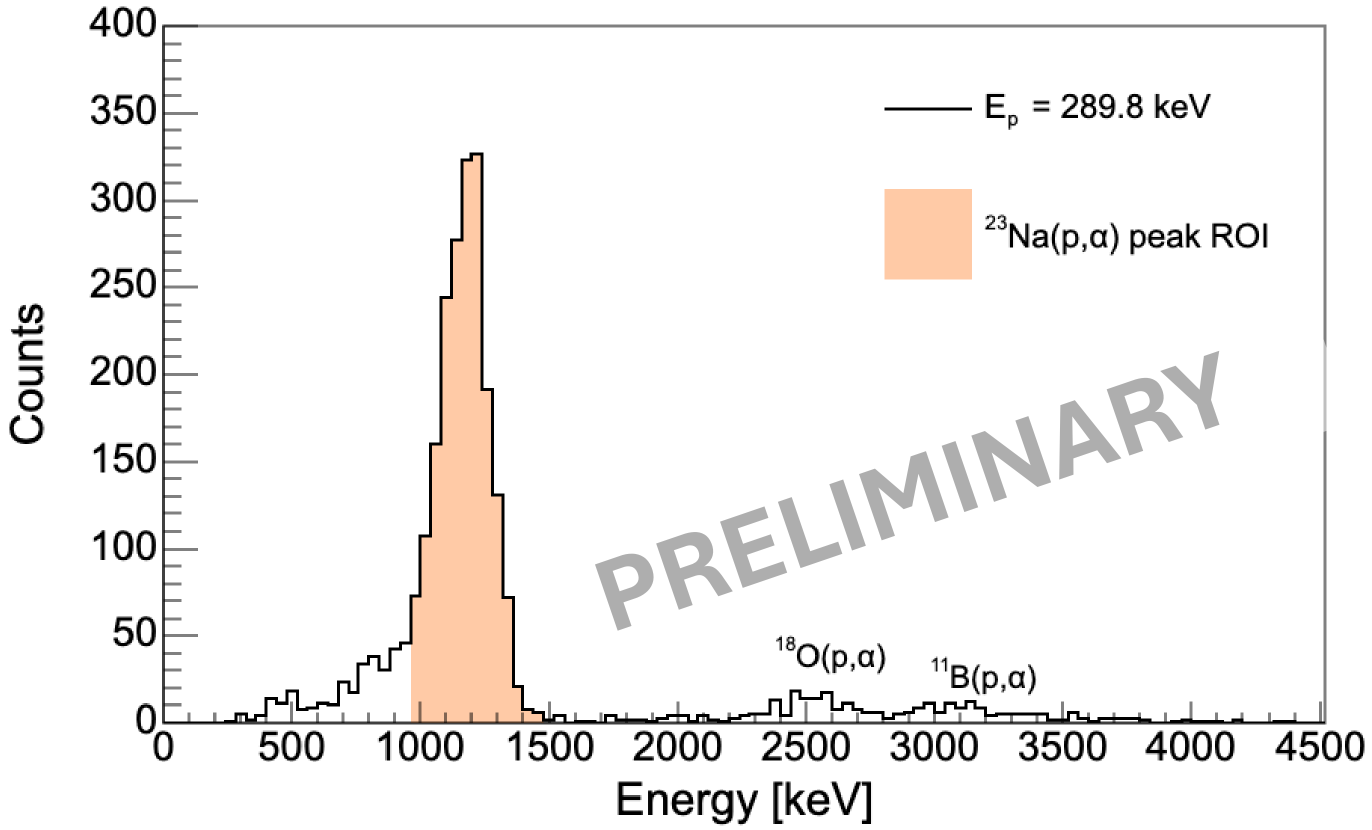
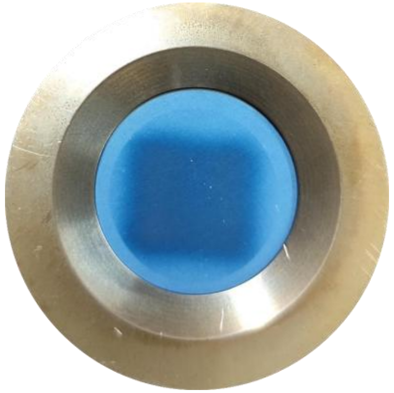
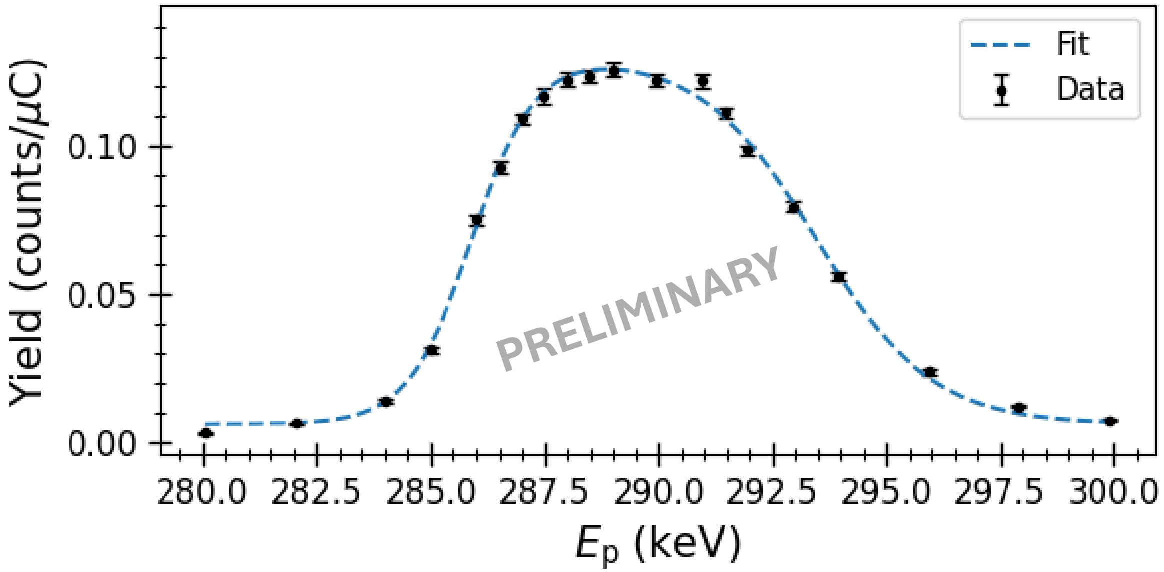


$^{23}Na(p,\alpha)^{20}Ne$ reaction: 274 keV resonance



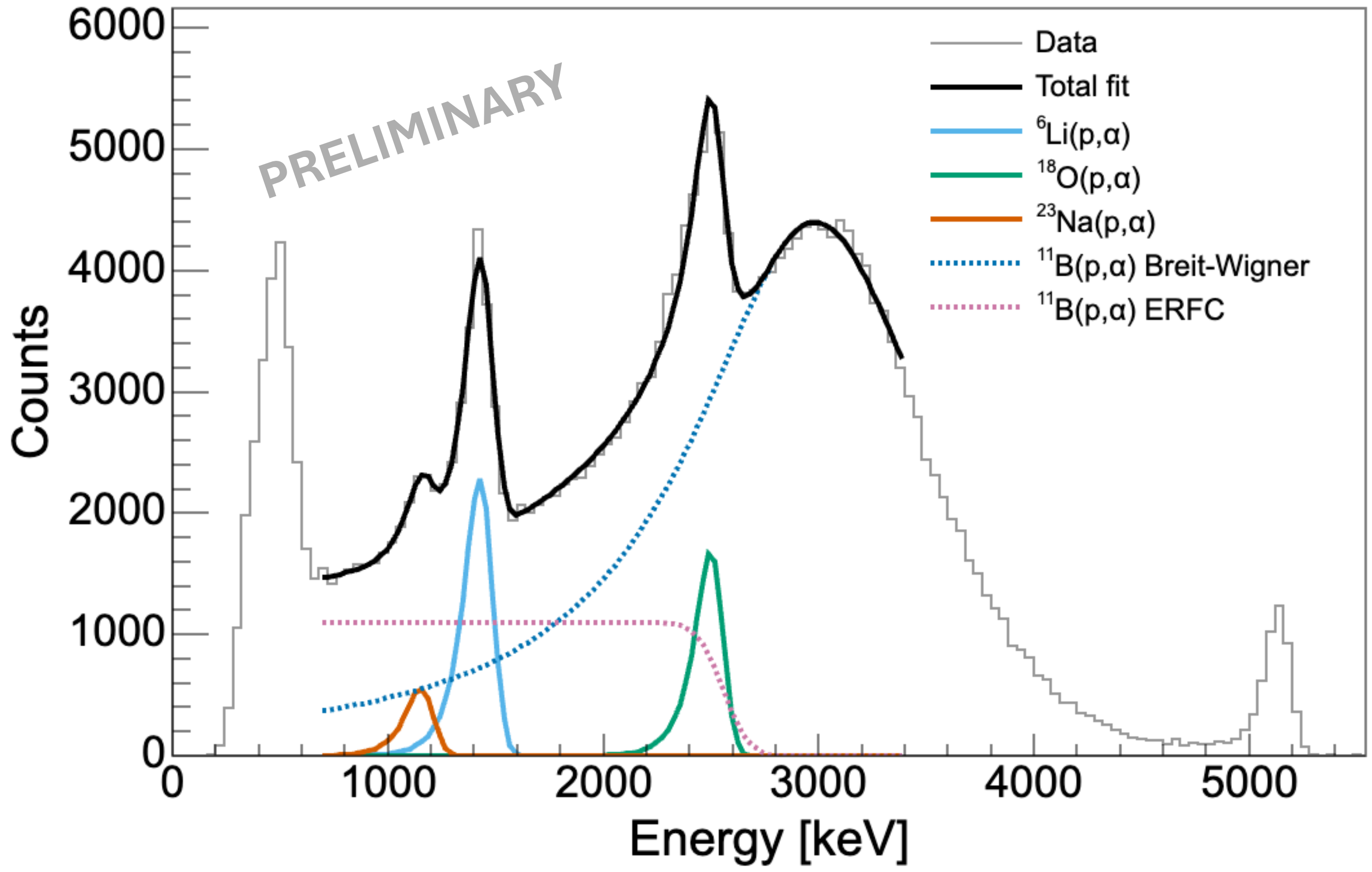
- **Target scans** performed on $Na_xNb_yO_z$ **sputtered** targets.





- **Resonance strength** agrees with literature values, with **reduced uncertainties.**
- **angular distribution** in agreement with literature.

$^{23}Na(p,\alpha)^{20}Ne$ reaction: 170 keV resonance



- For the lower energy resonances, **contaminants** affect the sodium ROI.
- **Resonance strength** extracted from **fits** and found in agreement with literature, with reduced uncertainties.

ANALYSIS IN PROGRESS for the (much weaker)
138 keV resonance

THANK YOU!

LUNA COLLABORATION:

INFN - LNGS/GSSI, L'AQUILA, Italy D. Basak, F. Ferraro, R. Gesuè, M. Junker, G. Saturno
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