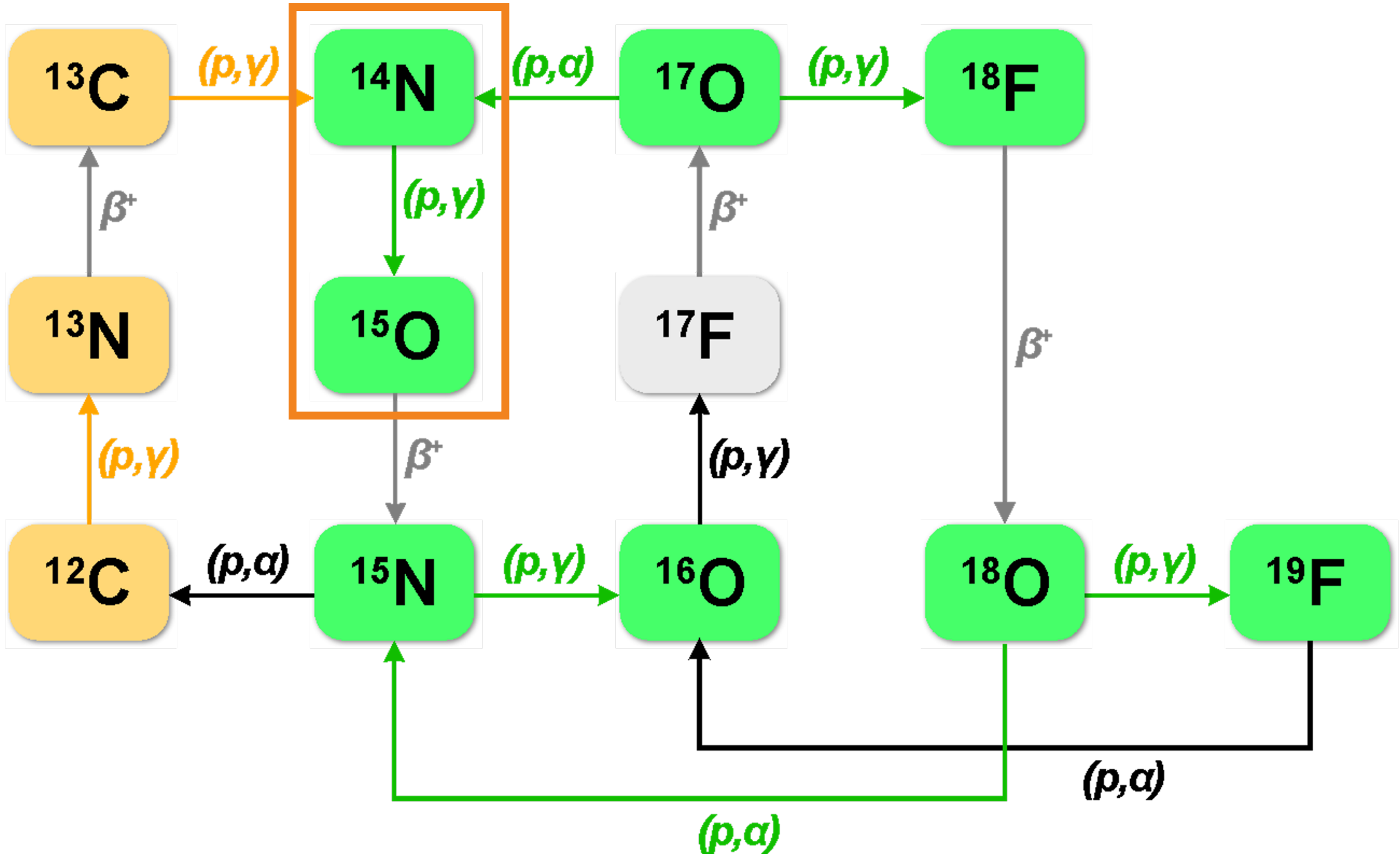
A renewed deep-underground measurement of the astrophysical key reaction $^{14}N(p,\gamma)^{15}O$ at LUNA

Alessandro Compagnucci

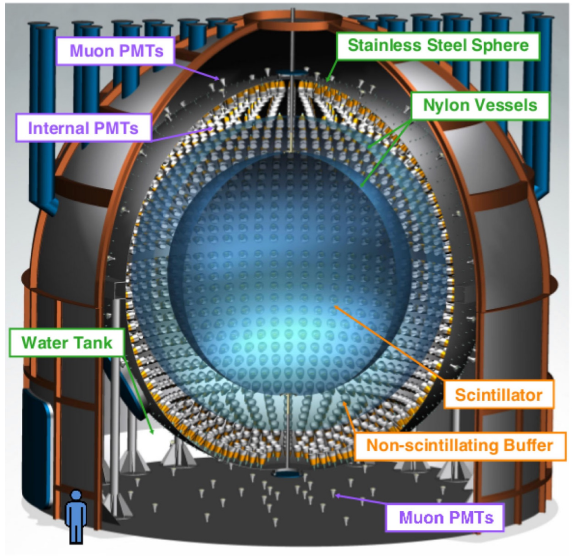
The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

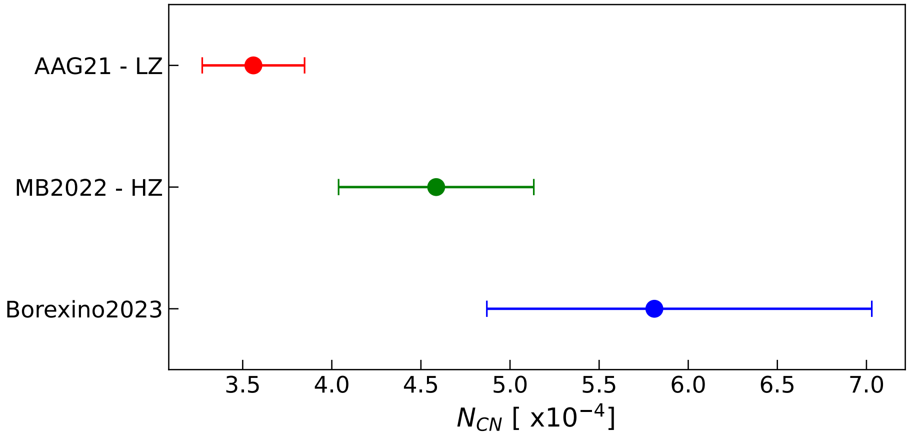
- The CNO Cycle is the main source of energy generation in massive main-sequence stars, accounts for **~1% in the Sun**.
- The $^{14}N(p,\gamma)^{15}O$ is the **slowest reaction of the CNO**, controls its speed and energy production rate.

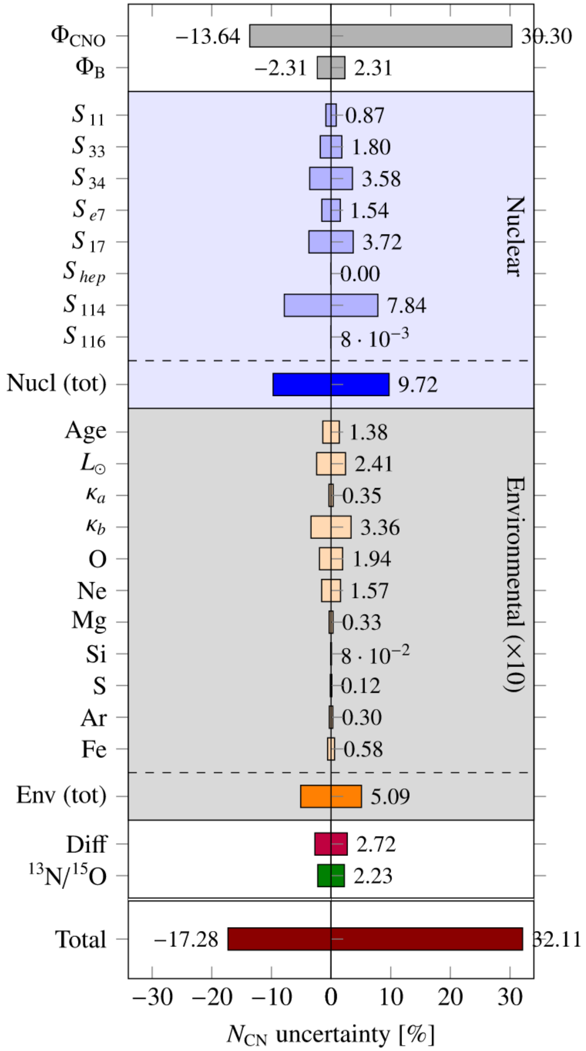


The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

- **Solar CNO neutrino flux** recently detected for the first time by Borexino (2020). → **Solar metallicity probe.**
- The result of Borexino disfavours "low metallicity" SSM prediction, **but large uncertainties** remains. After CNO Flux itself, biggest contribution to the uncertainty budget from $^{14}N(p,\gamma)^{15}O$ cross section.



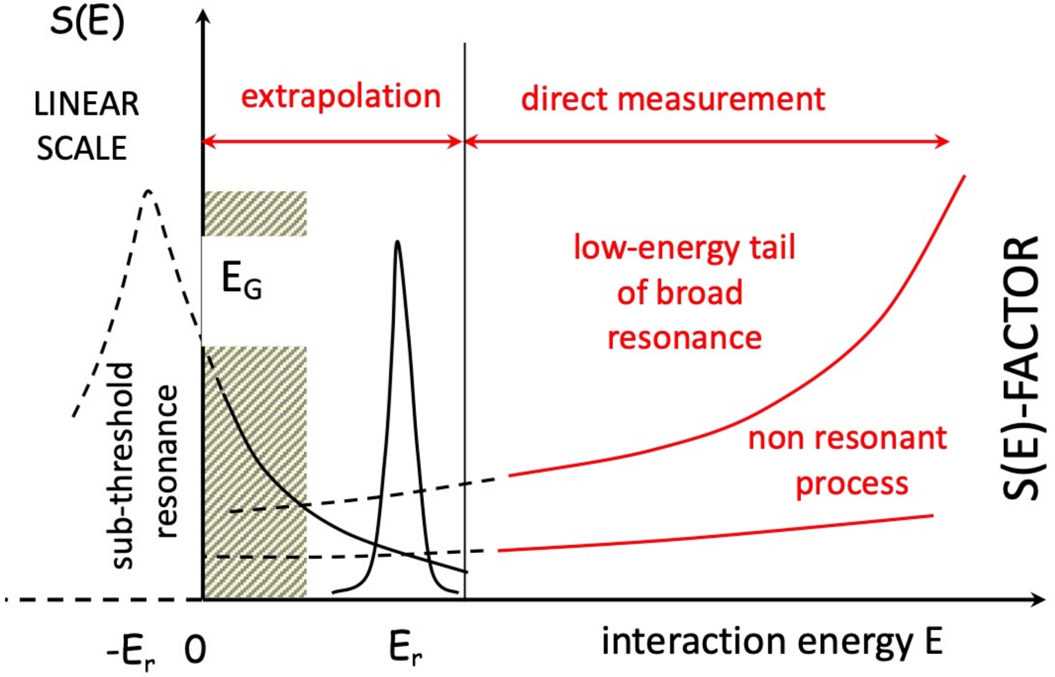


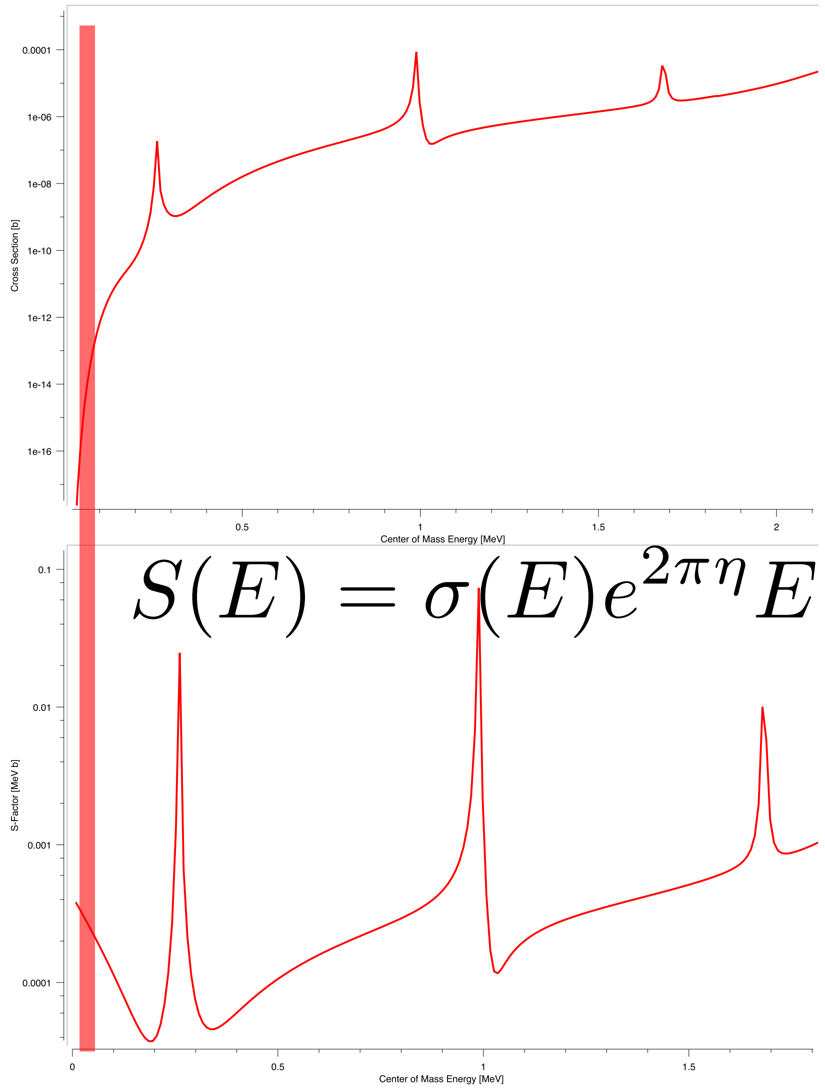


Appel et al. (2022)

Uncertainties in $^{14}N(p,\gamma)^{15}O$ cross section determination

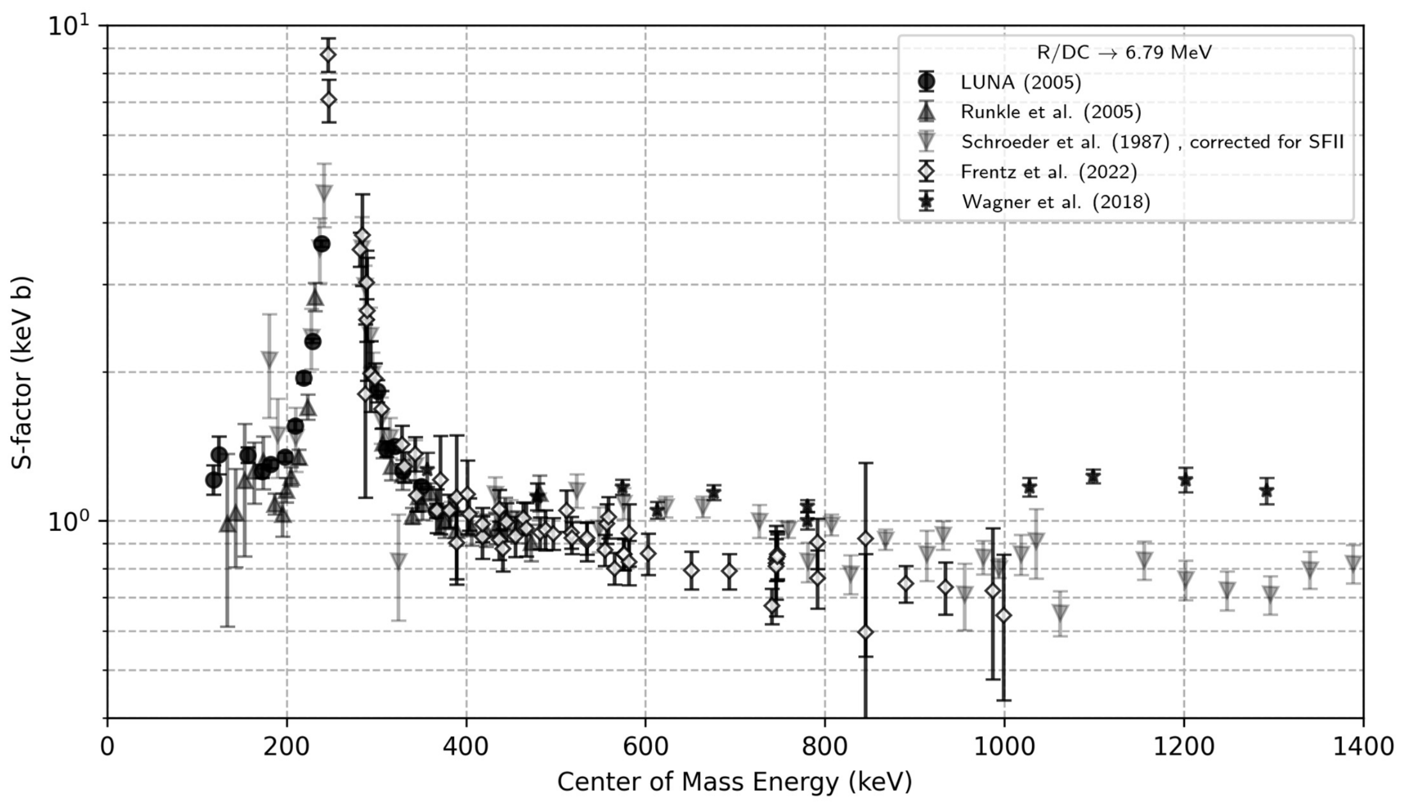
- The precise measurement charged-particle induced cross sections near stellar burning energy is challenging.

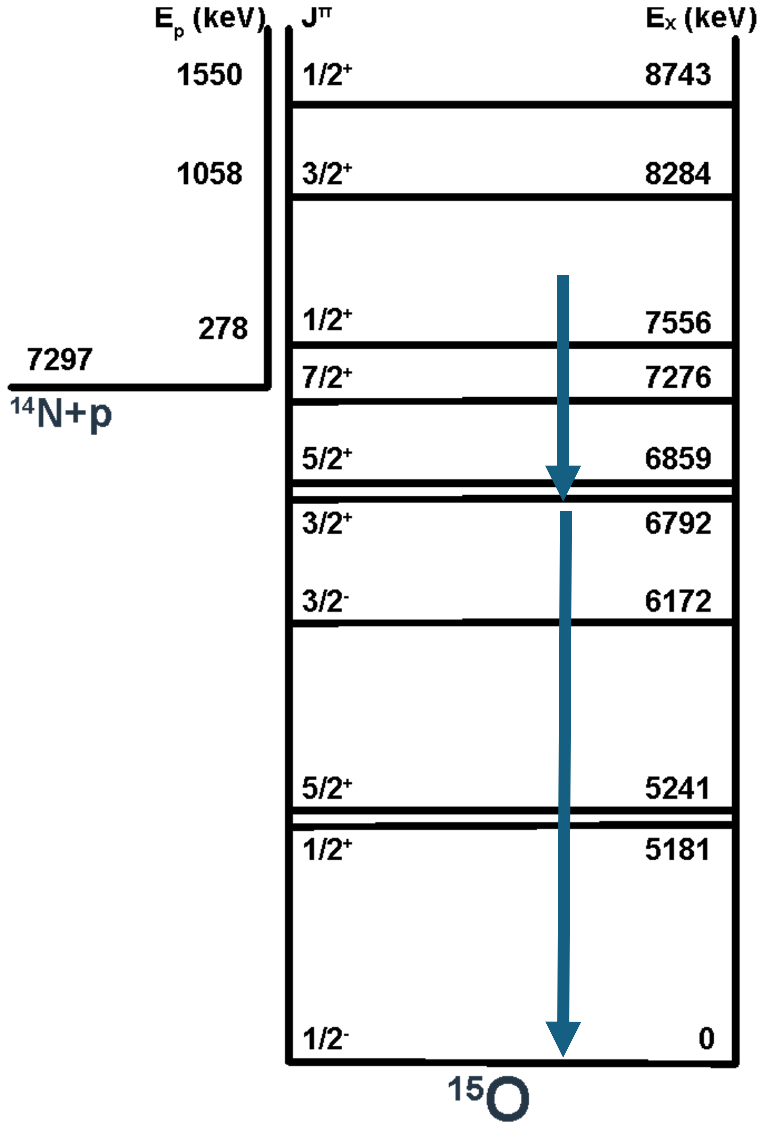




$$S(E) = \sigma(E)e^{2\pi\eta}E$$

Open issues with $^{14}N(p,\gamma)^{15}O$

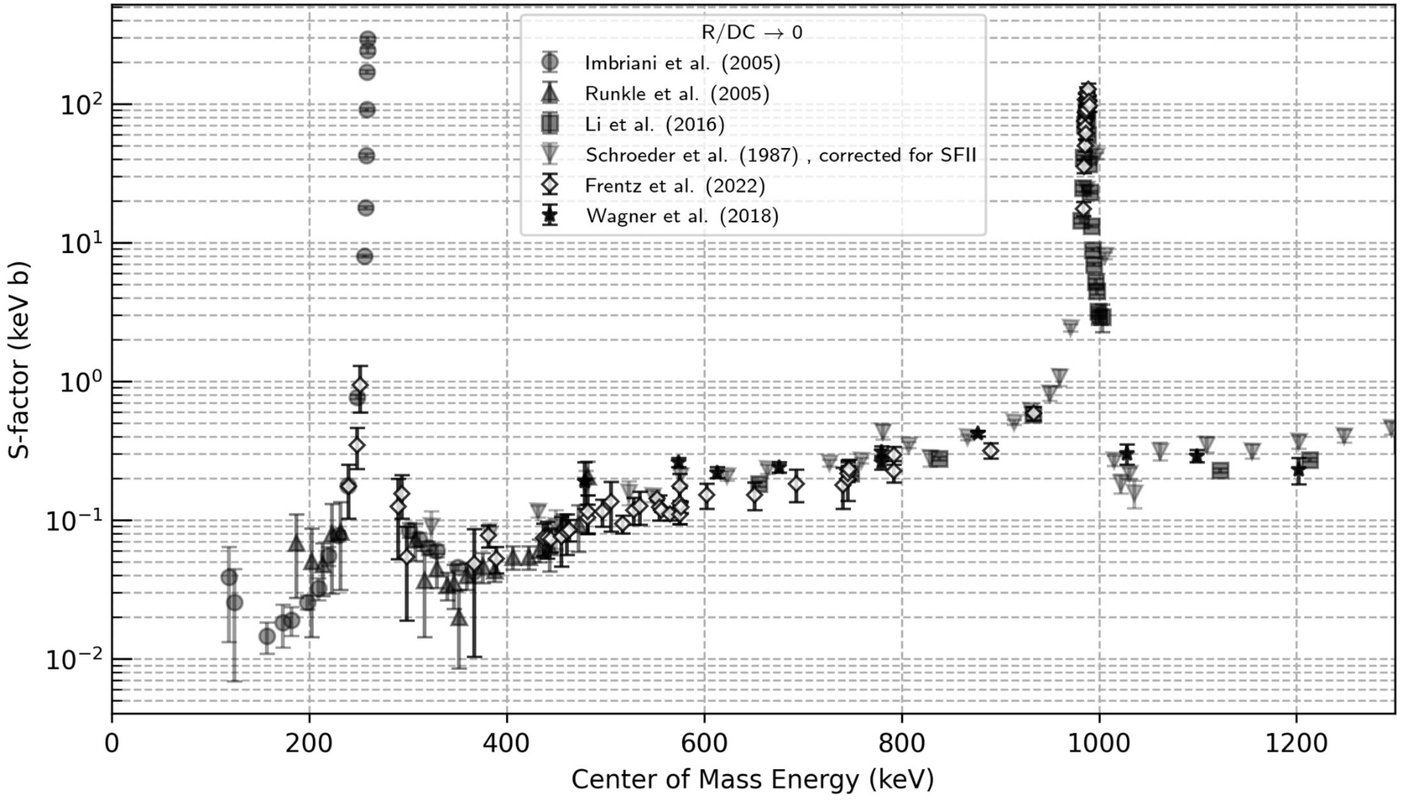


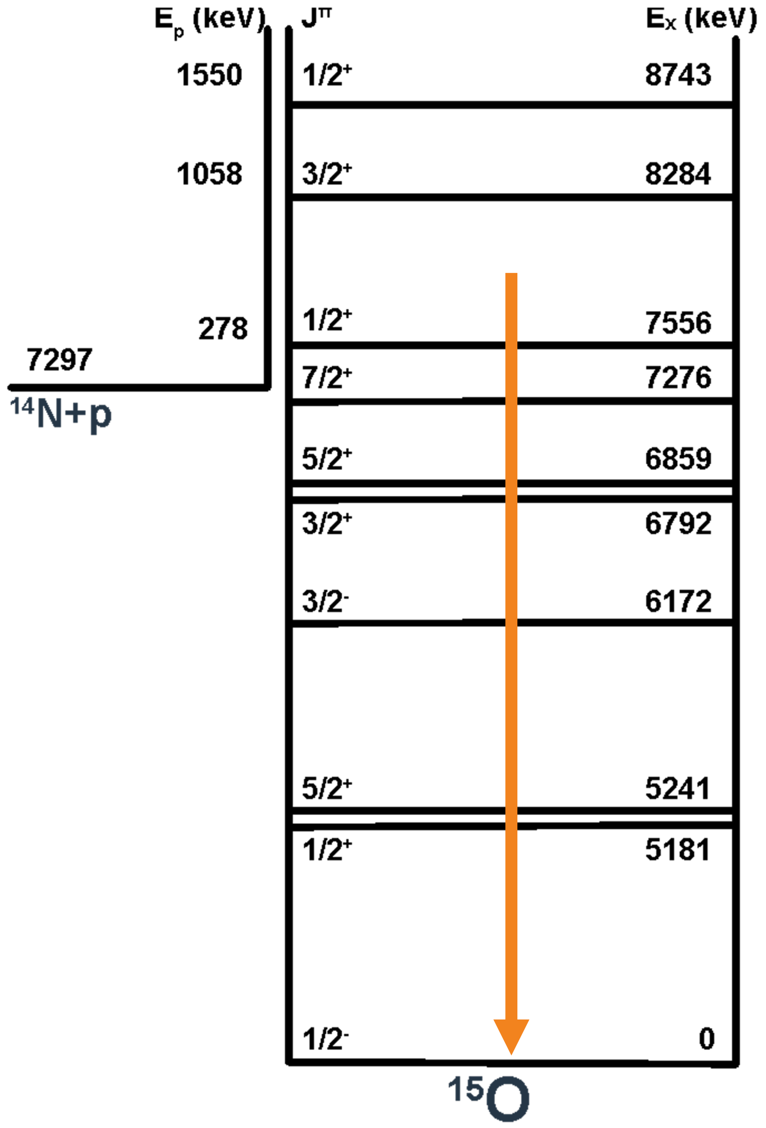


Transition to the **6.79 MeV** excited state of ^{15}O, most important contribution to the total cross section

Level scheme for ^{15}O

Open issues with $^{14}N(p,\gamma)^{15}O$





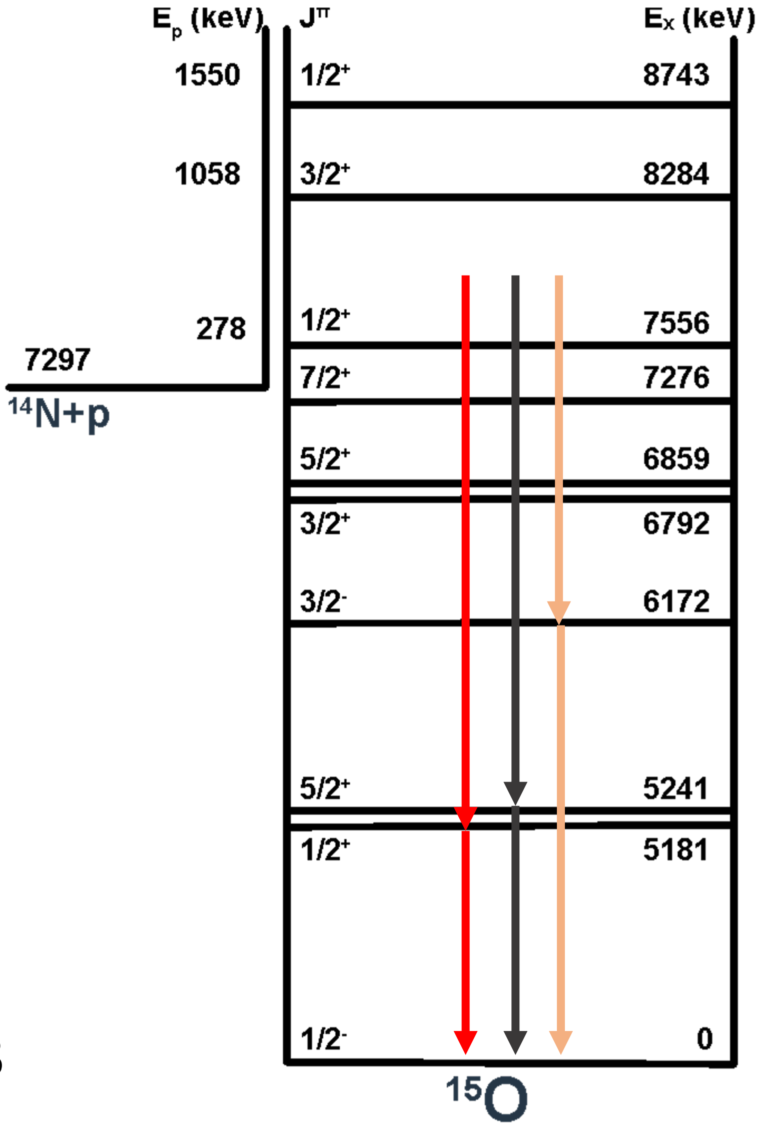
Level scheme for ^{15}O

Transition to the **ground state** of ^{15}O: Very difficult to reconcile all the measurements in a consistent picture.

Open issues with $^{14}N(p,\gamma)^{15}O$

Year	Reference	R/DC→0	R/DC→6.79	R/DC→6.17	Others	Total
2001	Angulo et al. [59]	$0.08^{+0.13}_{-0.06}$	1.63 ± 0.17	$0.06^{+0.01}_{-0.02}$	-	1.77 ± 0.20
2005	Runkle et al. [48]	0.49 ± 0.08	1.15 ± 0.05	0.04 ± 0.01	-	1.68 ± 0.09
2005	Imbriani et al. [47]	0.25 ± 0.06	1.21 ± 0.05	0.08 ± 0.03	0.07	1.61 ± 0.08
2008	Marta et al. [54]	0.20 ± 0.05	-	0.09 ± 0.07	-	1.57 ± 0.13
2011	Li et al. [2]	0.42 ± 0.04 (stat) $^{+0.09}_{-0.19}$ (sys)	1.29 ± 0.06 ± 0.06 (sys)	-	-	-
2016	Wagner et al. [50]	0.19 ± 0.01 (stat) ± 0.05 (sys)	1.24 ± 0.02 ± 0.11 (sys)	-	-	-
2022	Frentz et al. [49]	$0.33^{+0.16}_{-0.08}$	1.24 ± 0.09	0.12 ± 0.04	-	1.69 ± 0.13
2024	Chen et al. [60]	0.47 ± 0.04	1.25 ± 0.04	0.11 ± 0.02	0.09 ± 0.02	1.92 ± 0.08
2011	SF-II [18]	0.27 ± 0.05	1.18 ± 0.05	0.13 ± 0.06	0.08 ± 0.02	1.66 ± 0.12
2024	SF-III [12]	0.30 ± 0.11	1.17 ± 0.03	0.13 ± 0.05	0.078 ± 0.020	1.68 ± 0.14

New data for the other transitions R/DC → 6.17, 5.24, 5.18 are missing.



Level scheme for ^{15}O

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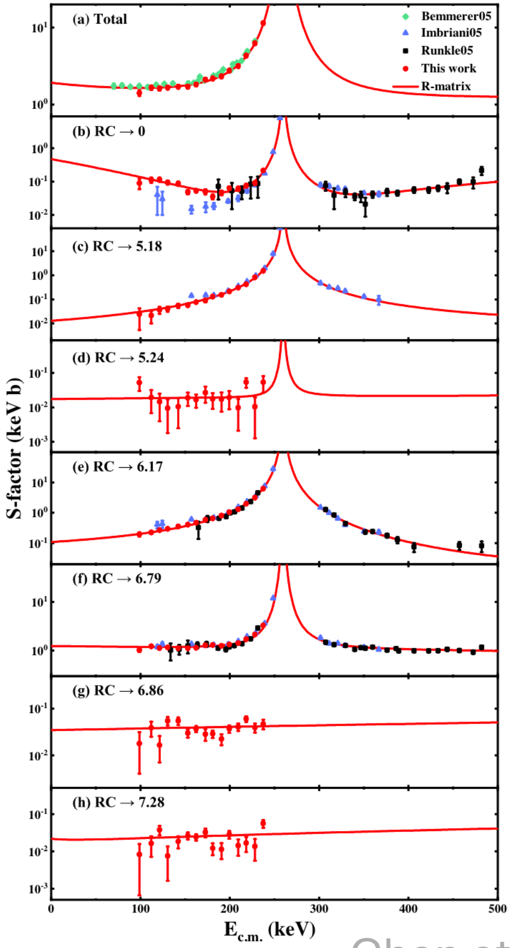
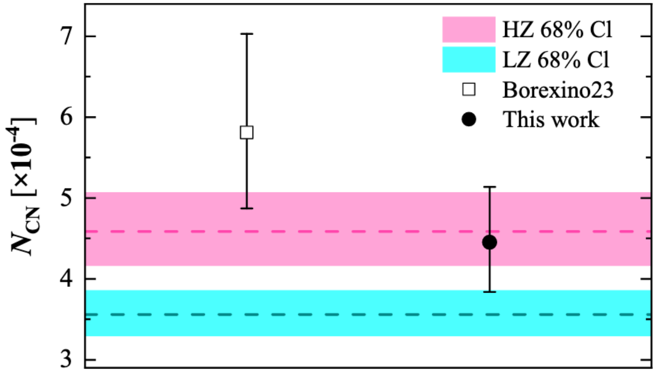
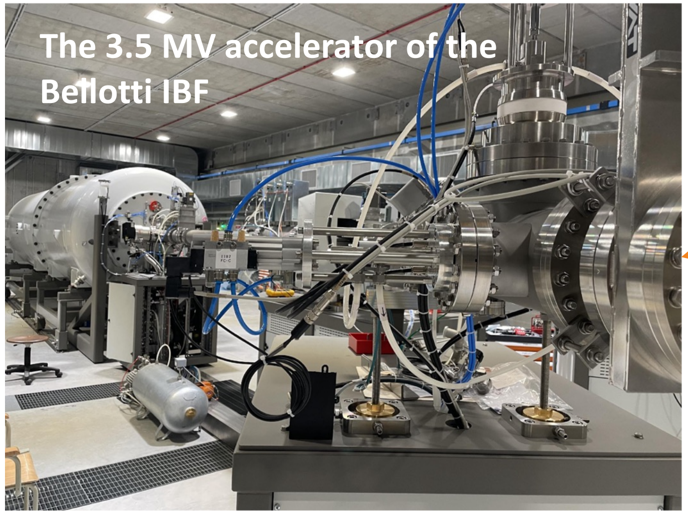


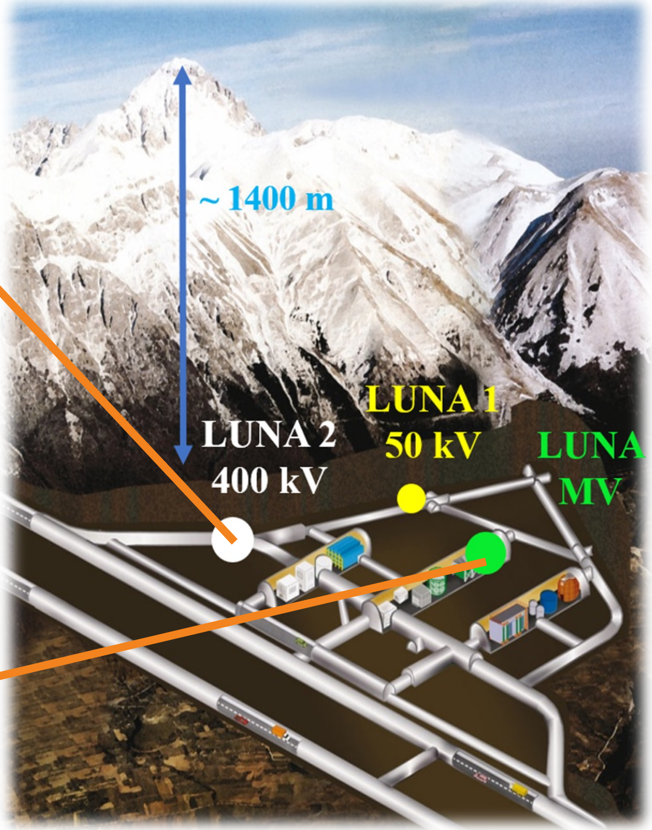
Chen et al. (2024)

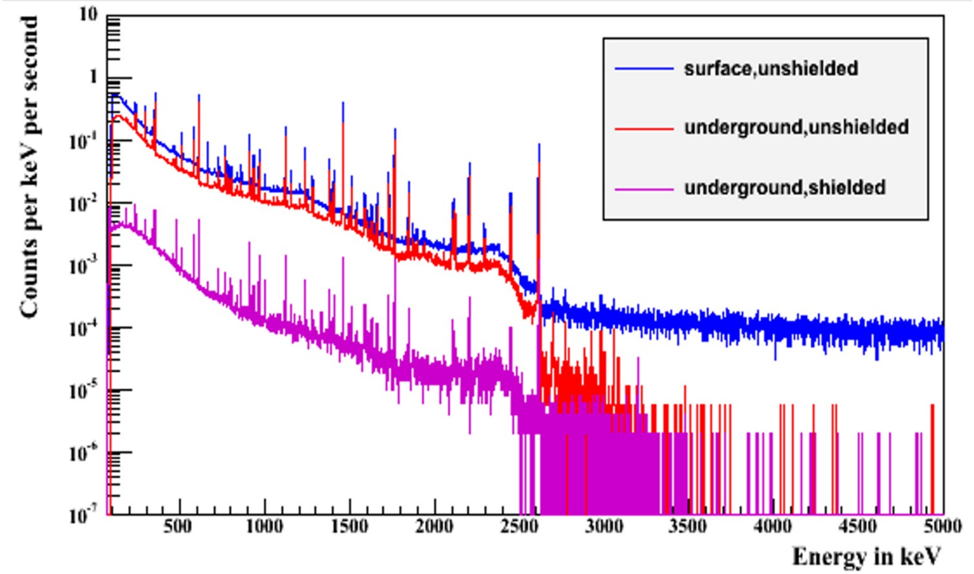


- **Solar Fusion III**: $S_{114}(0) = 1.68 \pm 0.14$ keV b, increased uncertainty since SFII recommendation.
- **Chen et al.** : Ep = 110 - 260 keV, all transition reported, $S_{114}(0) = 1.92 \pm 0.08$ keV b

Underground Nuclear Astrophysics at LUNA

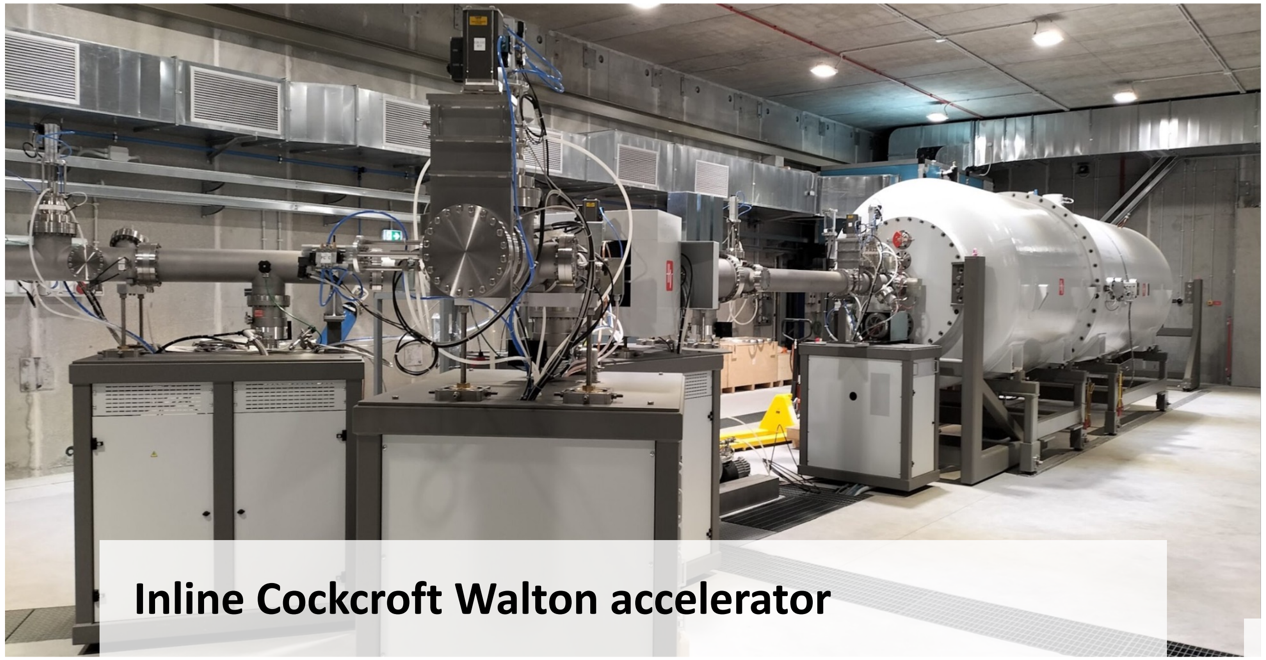






LUNA

The Bellotti Ion Beam Facility of LNGS



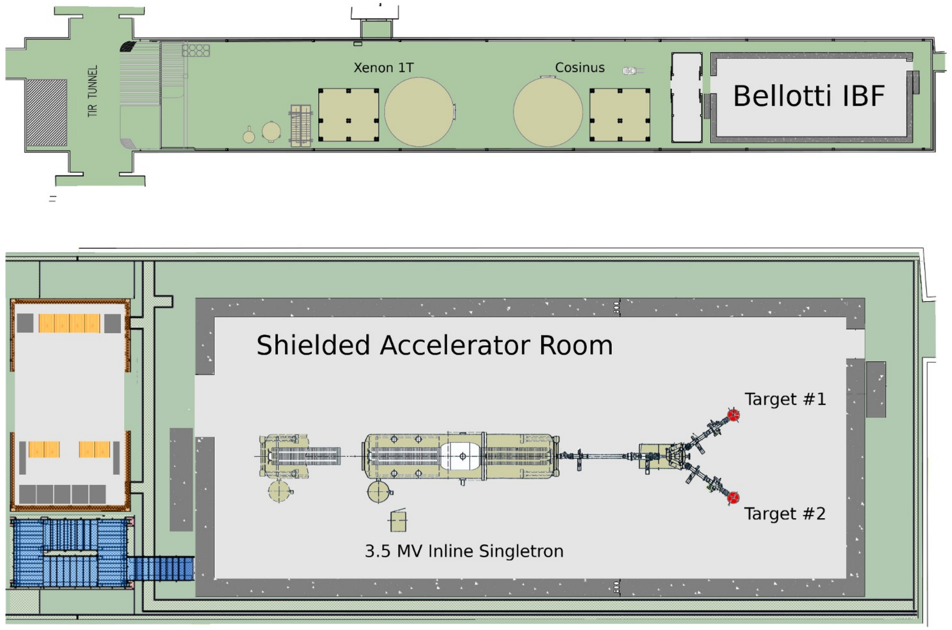
Inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.3 – 3.5 MV

Beam energy reproducibility: 0.01% TV or 50V

Beam energy stability: 0.001% TV / h

Beam current stability: < 5% / h



courtesy of M. Junker

H^+ beam: 500 - 1000 μA

He^+ beam: 300 - 500 μA

C^+ beam: 100 - 150 μA

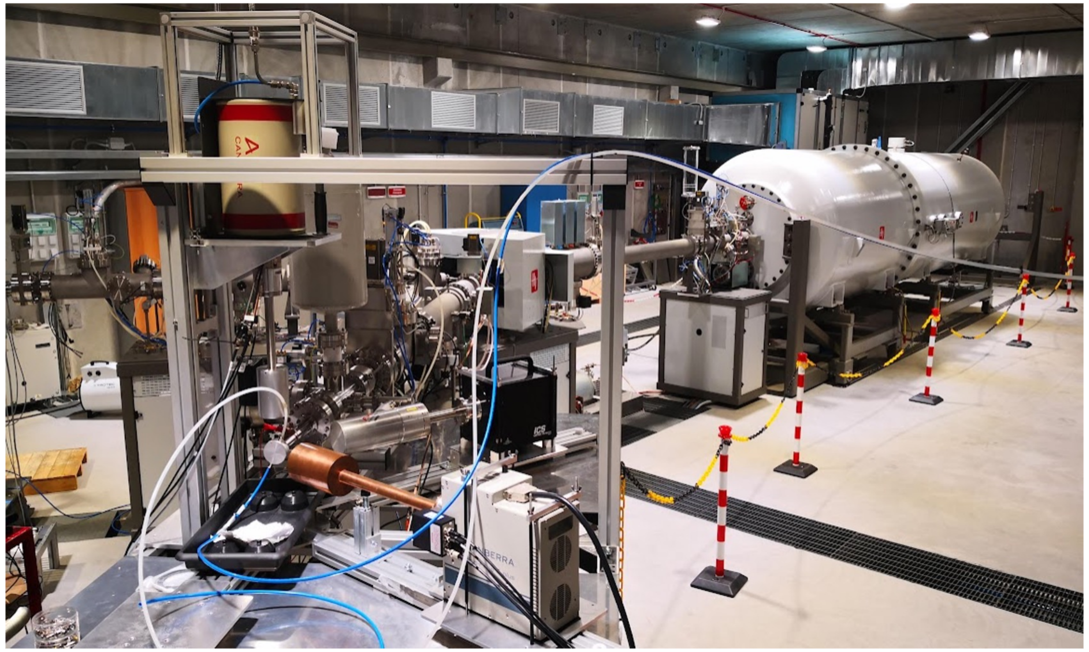
C^{++} beam: 50 pμA

$^{14}N(p,\gamma)^{15}O$ measurement at the Bellotti IBF

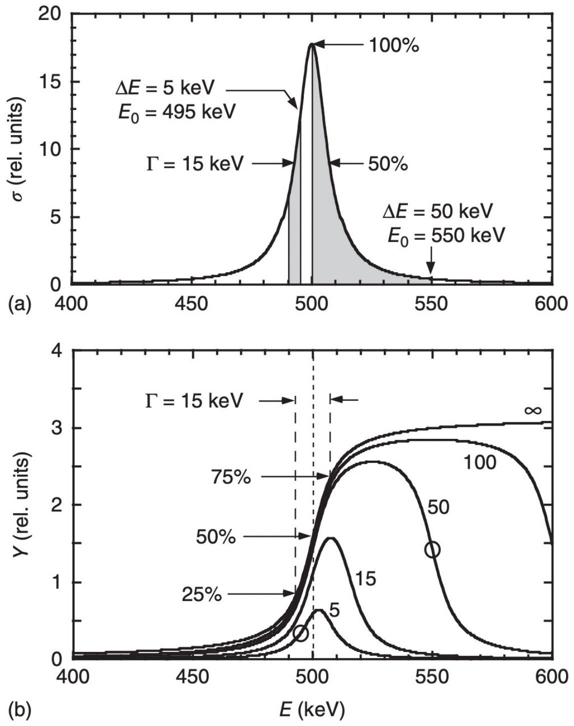
- Low background measurement over a **wide-energy range**, to address the existing issues in the extrapolations
- **Angular distribution**
- Measuring **weaker transitions**
- Pilot LUNA project at the
- new facility

→ Verifying the **performance of the accelerator**

→ **Energy calibration** campaign ancillary to the measurements



Energy calibration of the Bellotti IBF



From Iliadis C. "Nuclear physics of the stars"

$$Y = k \int dE' \int dE f(E, Eres, \Gamma) N(E, E', \sigma_{tot})$$

$f(E, Eres, \Gamma)$: Breit Wigner function that describes the resonance at E_{res} and with a width of Γ

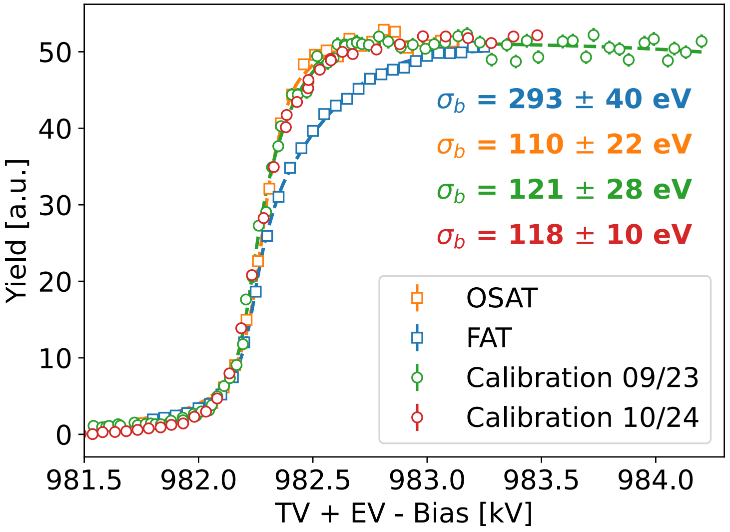
$N(E, E', \sigma_{tot})$: Gaussian function that convolutes the cross section

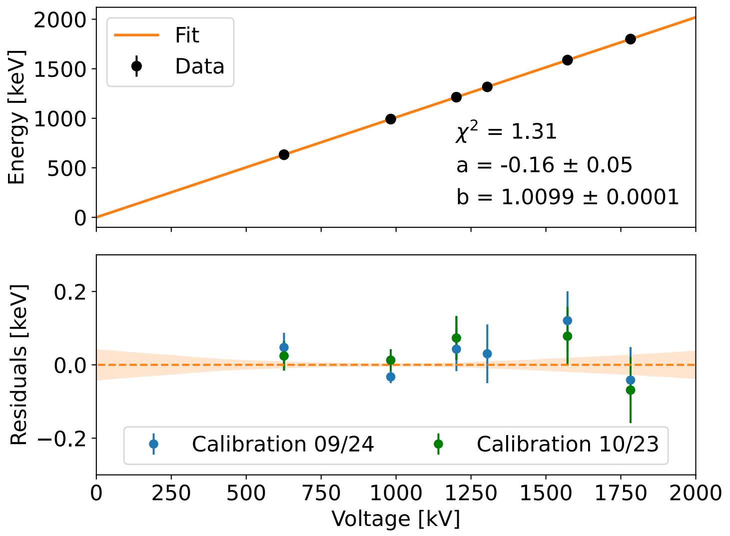
$$\sigma_{tot} = \sqrt{\sigma^2_{stragg}(E) + \sigma^2_{dopp} + \sigma^2_{beam}}$$

σ_{stragg}: calculated with the ERYA-Profiling code, see Nucl. Instrum. Methods Phys. Res. B 502 (2021) 142–149

$\sigma_{dopp} = \sqrt{\frac{m_p E_p k_b T}{m_T}}$: same definition as **Formicola et al. (2003)** (LUNA 400kV calibration)

E_{res} (kV)	Γ (eV)	σ_{beam} (eV)	σ_{dopp} (eV)
982.341 ± 0.006	70	118 ± 10	47



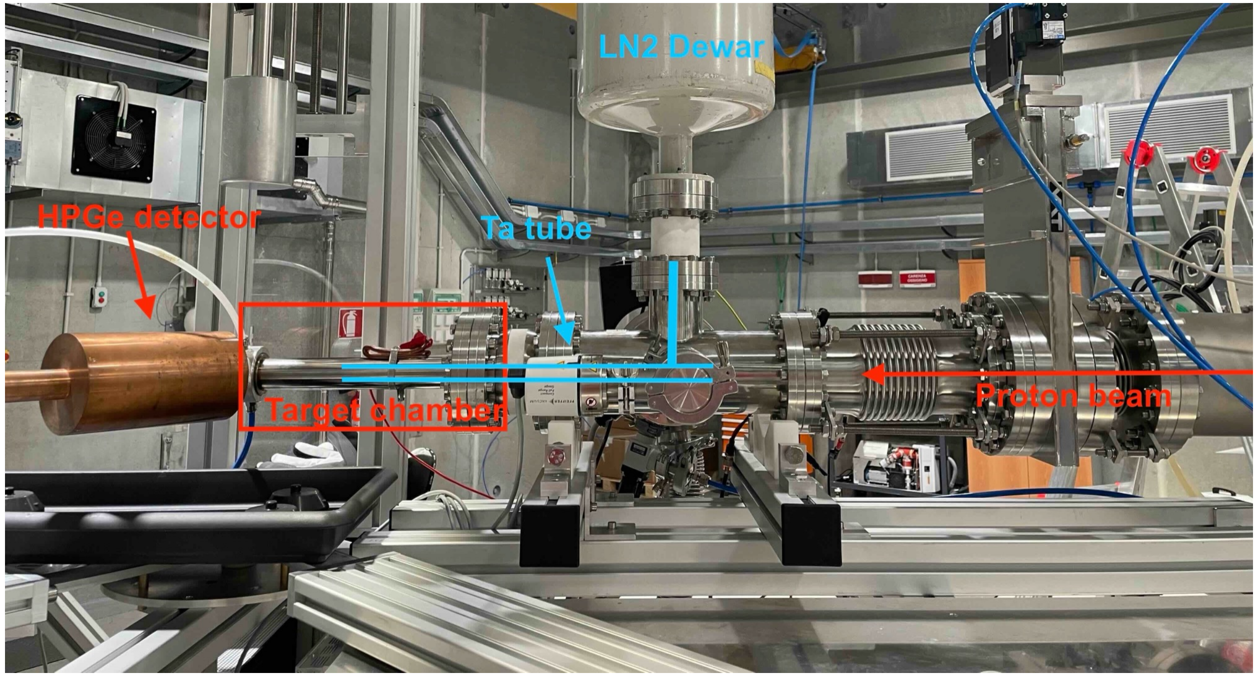


$^{14}N(p,\gamma)^{15}O$ measurement at the Bellotti IBF

- Single HPGe at 55° in close geometry, **excitation function**. (June 2023)
- Three HPGe detectors, **angular distribution**.

  55°-135°-90° + 0°-120°-90°

  (Oct. 2023 - Oct 2024)



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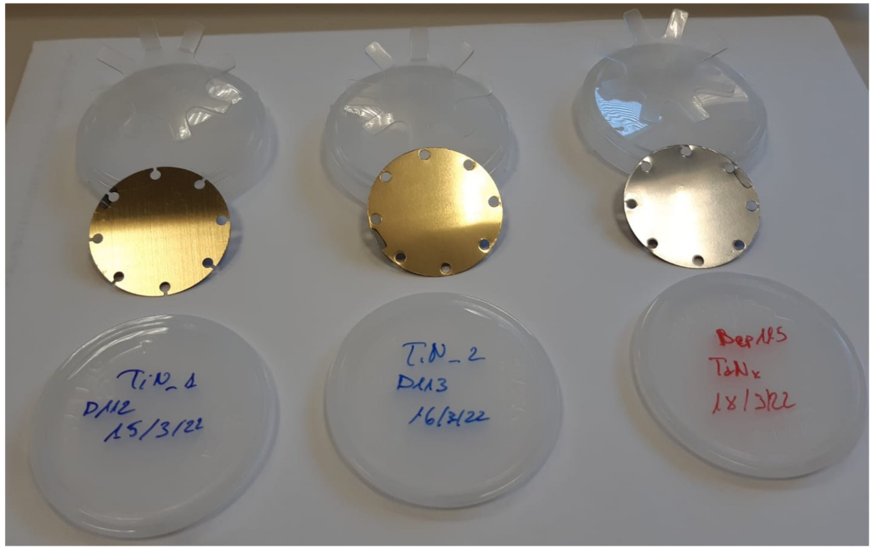
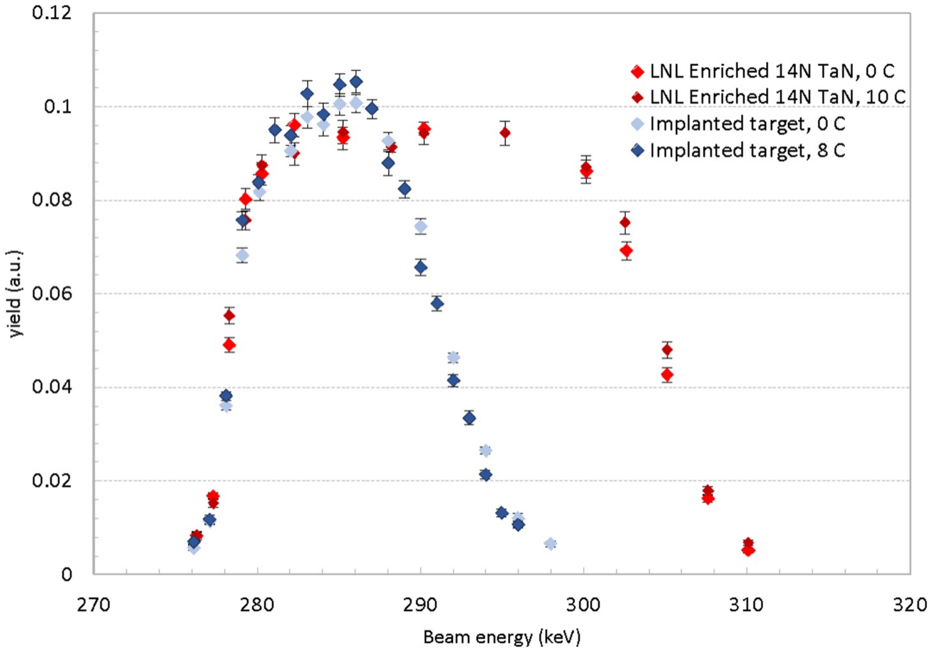
Solid targets

- **Sputtered TaN targets**: Produced at LNL. Enriched (99.99%) 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.





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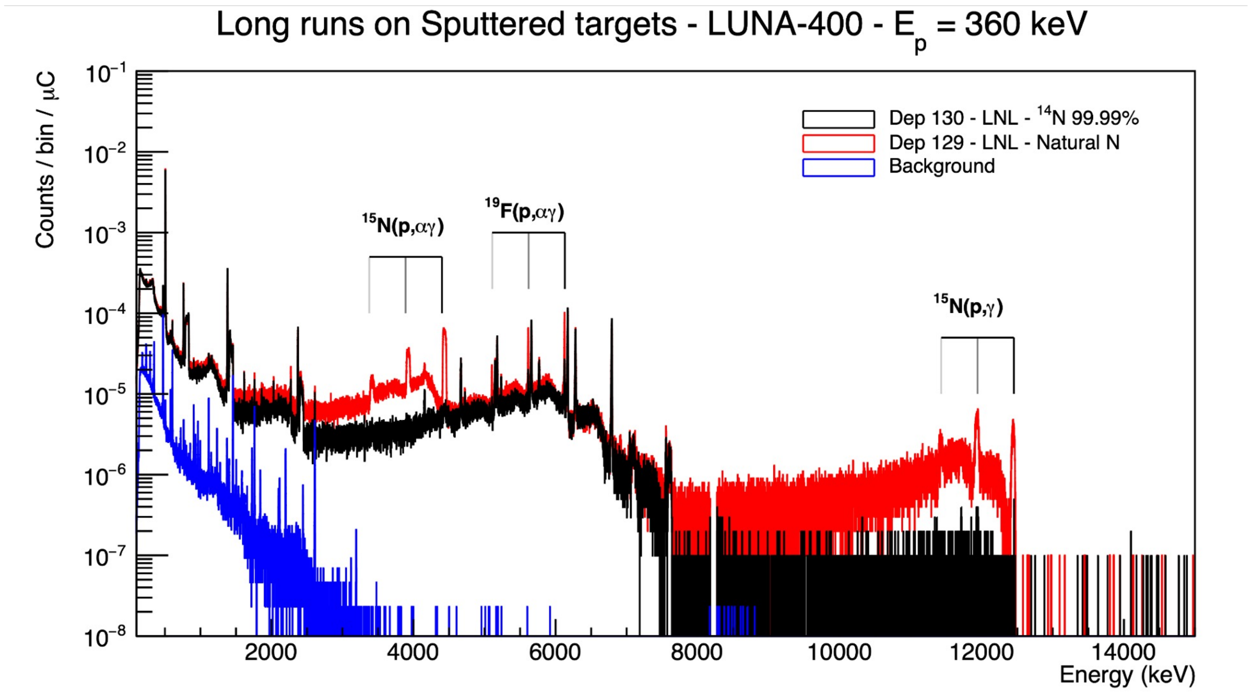
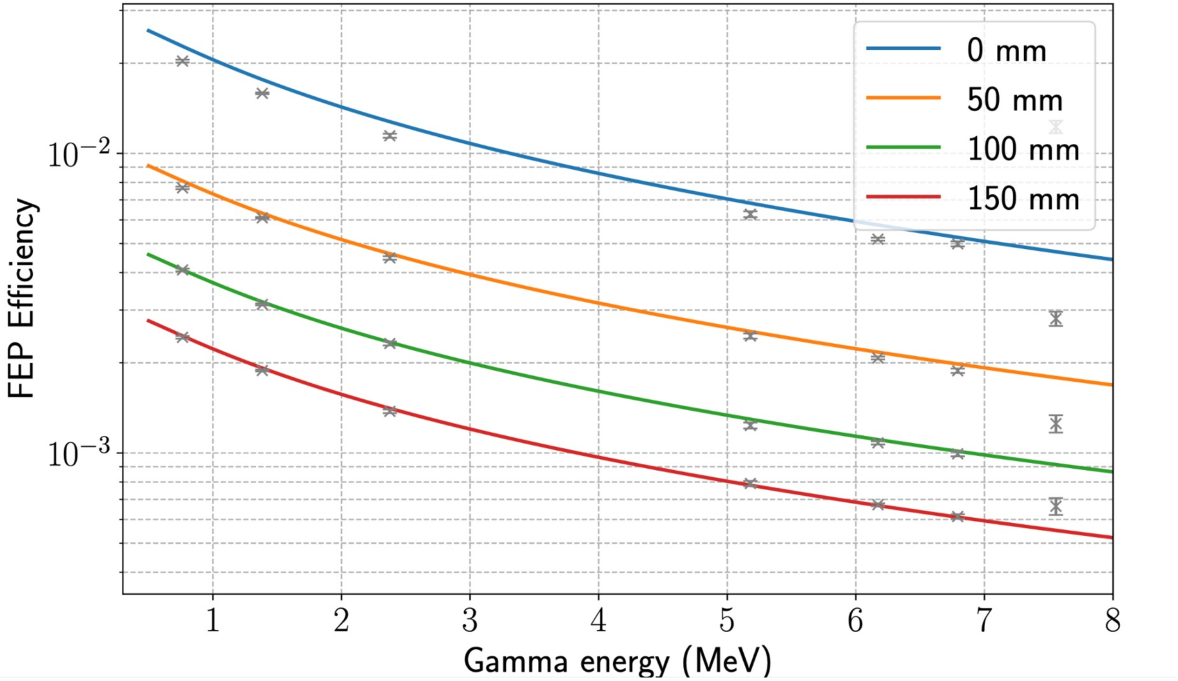


Efficiency characterization for the HPGe detector

- **Efficiency calibration** using ^{137}Cs, ^{60}Co and ^{14}N+p 278 keV resonance
- Reaction data have been corrected for summing effects



$$Y_{gs} = R\left(b_{gs}\varepsilon_{fe}(E_{gs}) + \sum_i b_i\varepsilon_{fe}(E_i^{sec})\varepsilon_{fe}(E_i^{pri})\right),$$

$$Y_{i_{pri}} = Rb_i\varepsilon_{fe}(E_{i_{pri}})(1-\varepsilon_{tot}(E_{i_{sec}})),$$

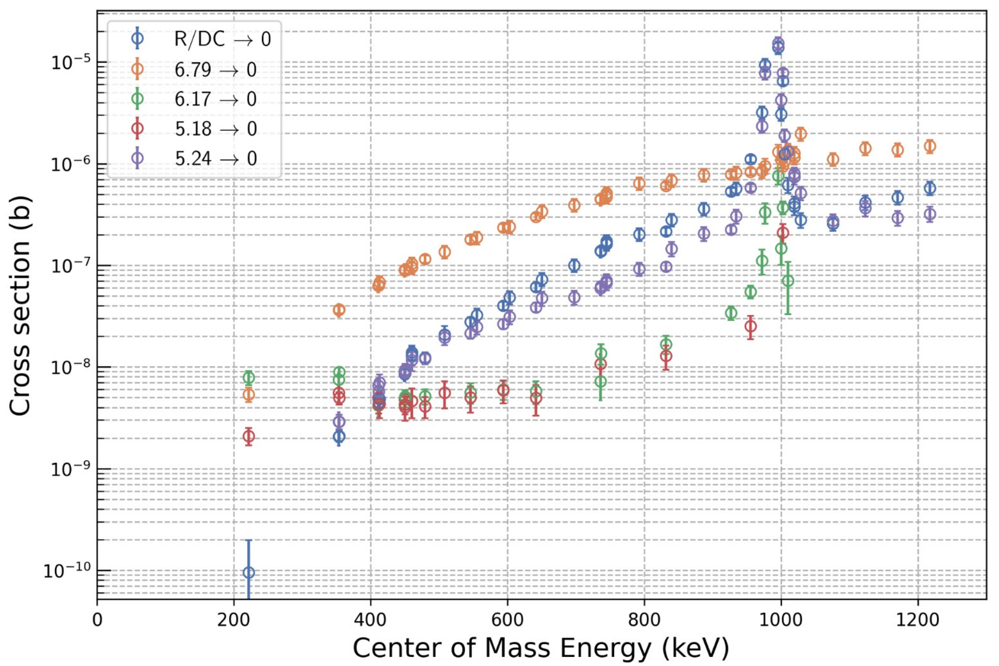
$$Y_{i_{sec}} = Rb_i\varepsilon_{fe}(E_{i_{sec}})(1-\varepsilon_{tot}(E_{i_{pri}})),$$

$$\ln(\varepsilon_{fe}) = a + b\ln(E_\gamma) + c[\ln(E_\gamma)]^2,$$

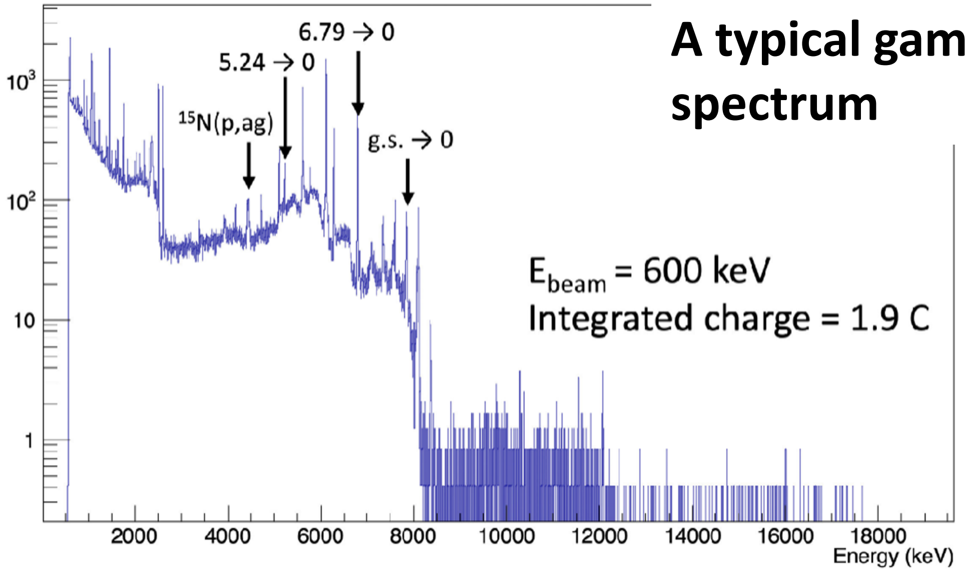
$$\varepsilon_{fe}(d) = \frac{1-e^{\frac{d+d_0}{1+\beta\sqrt{E_\gamma}}}}{(d+d_0)^2}.$$

Results

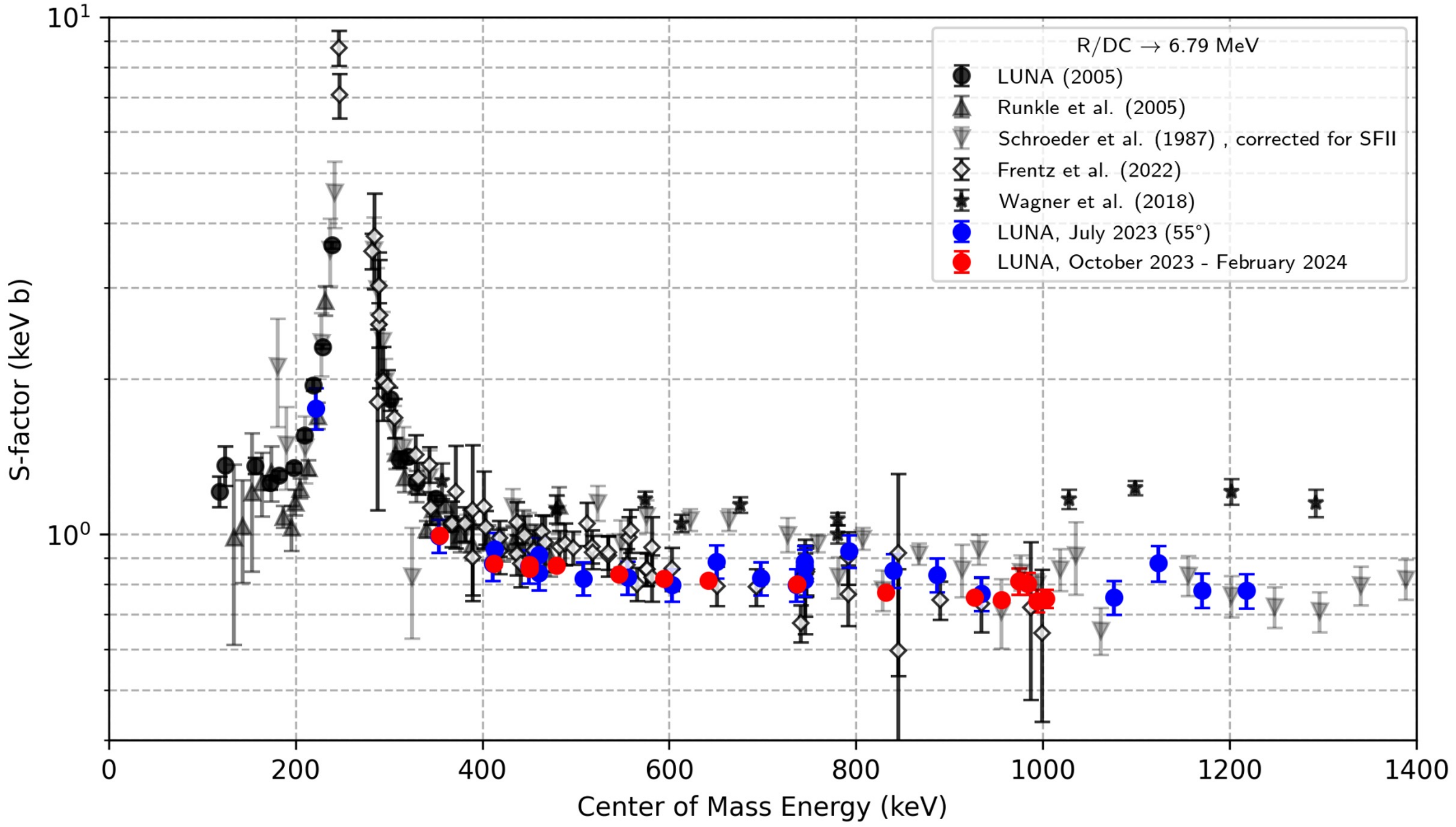
- Excitation function measurement **(June 2023)**:
  - **0.25-1.3 MeV** in 50 keV steps,
  - 55° HPGe at 5 cm from target,
  - Total charge collected: **38 C** (up to 300 μA).
- Angular distribution measurement **(October 2023 - February 2024)**
  - **0.4 - 1.1 MeV** in 100 keV steps
  - 3 HPGe detectors 15 cm from target
  - Total charge collected: **150 C**

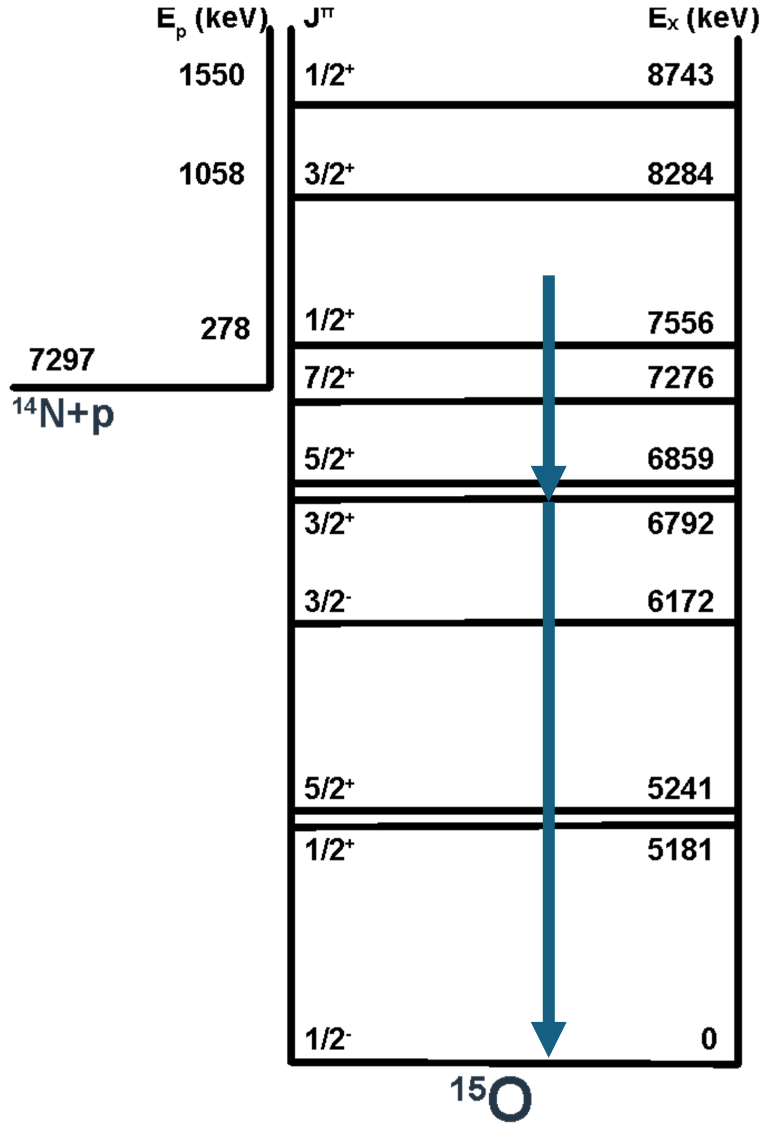


A typical gamma-ray spectrum



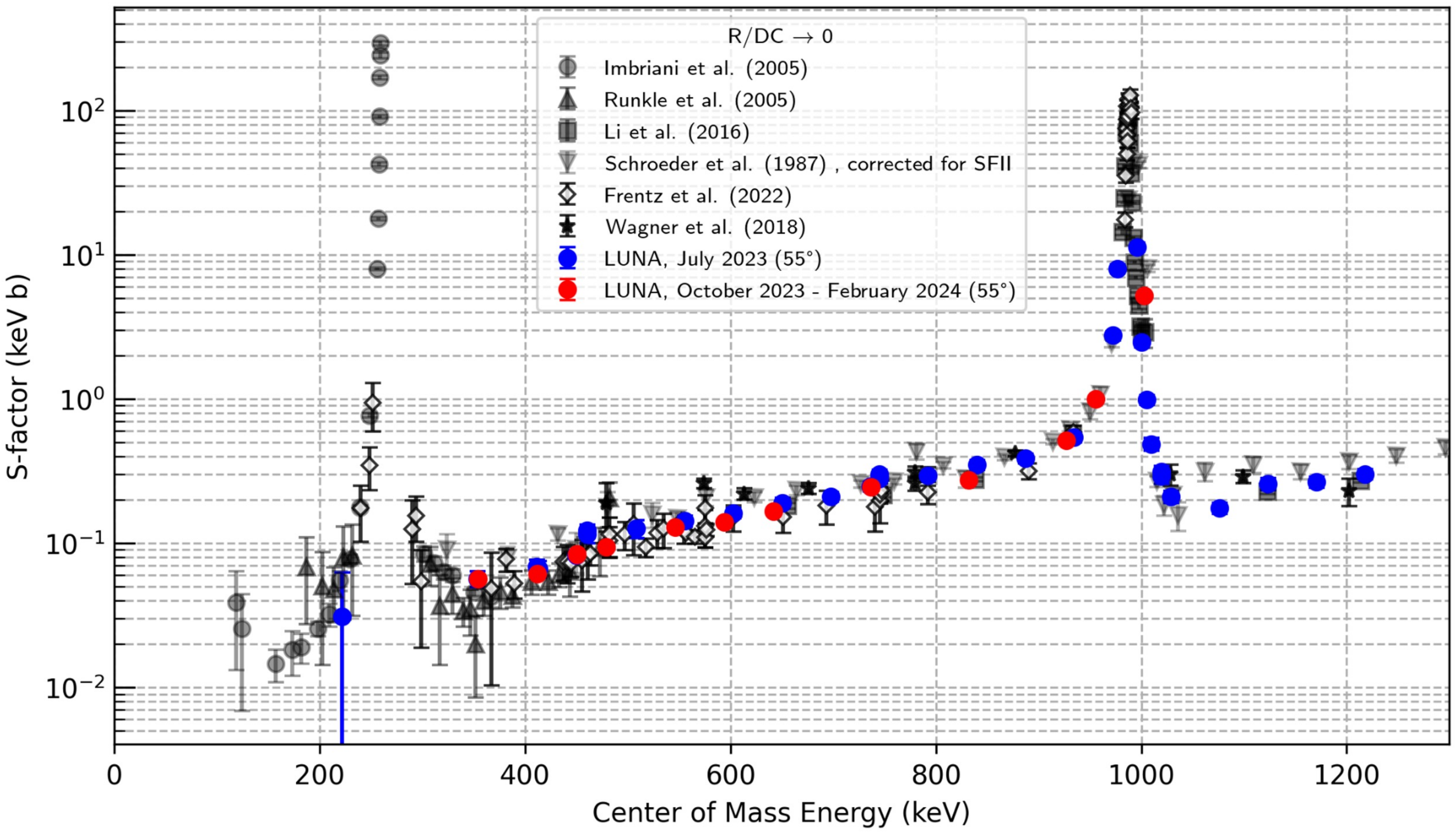
S-factor: R/DC → 6.79 MeV

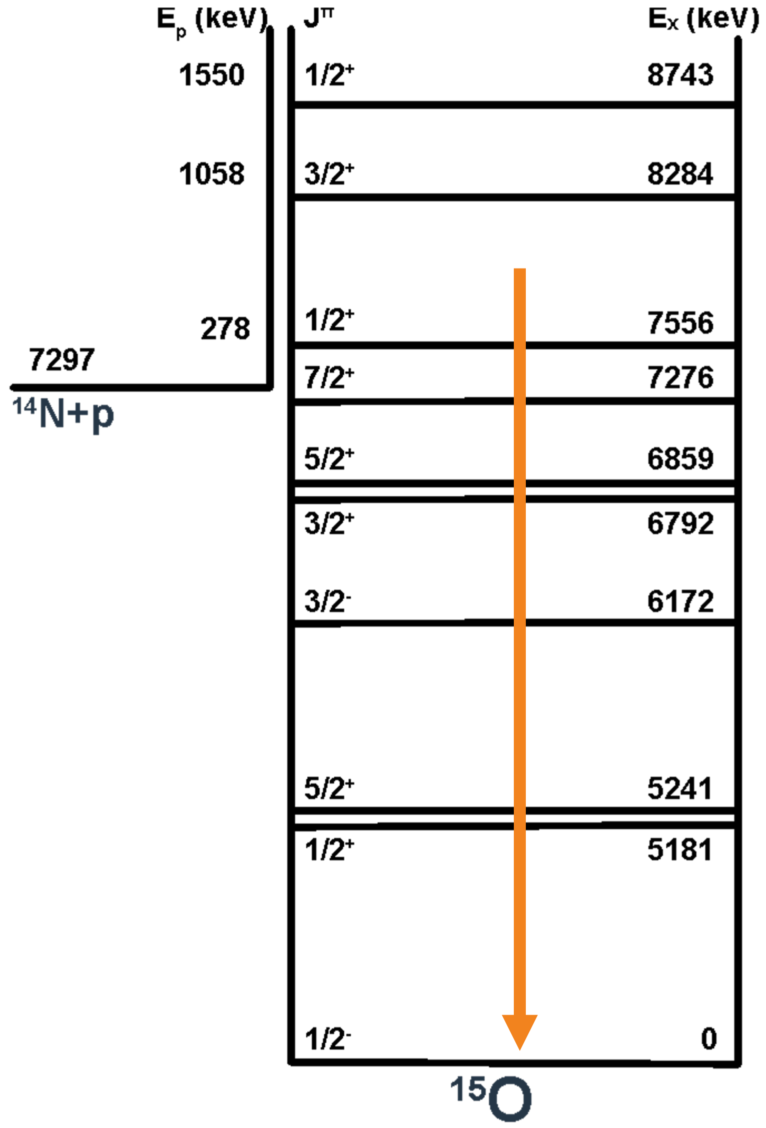




Level scheme for ^{15}O

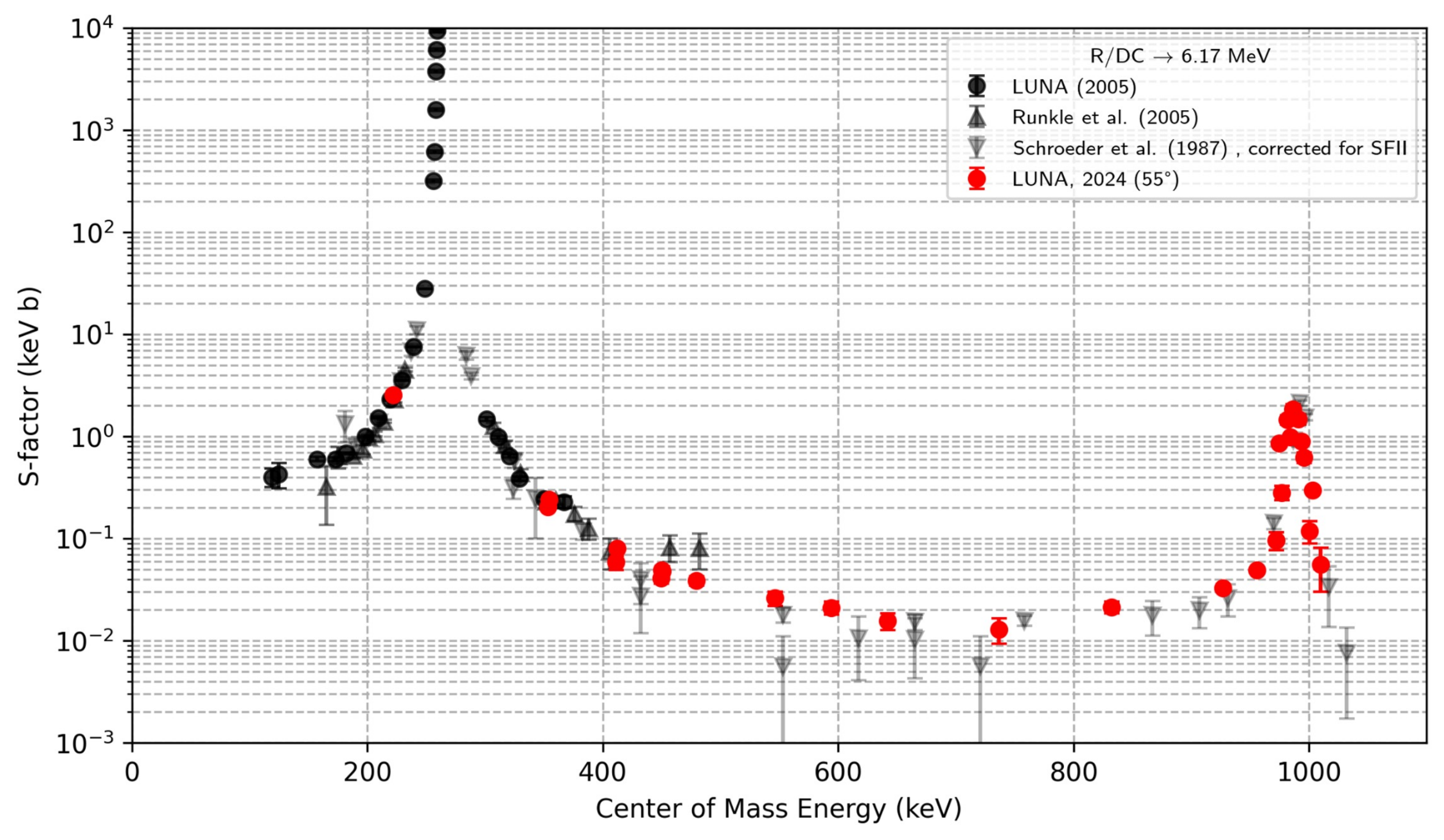
S-factor: R/DC → ground state

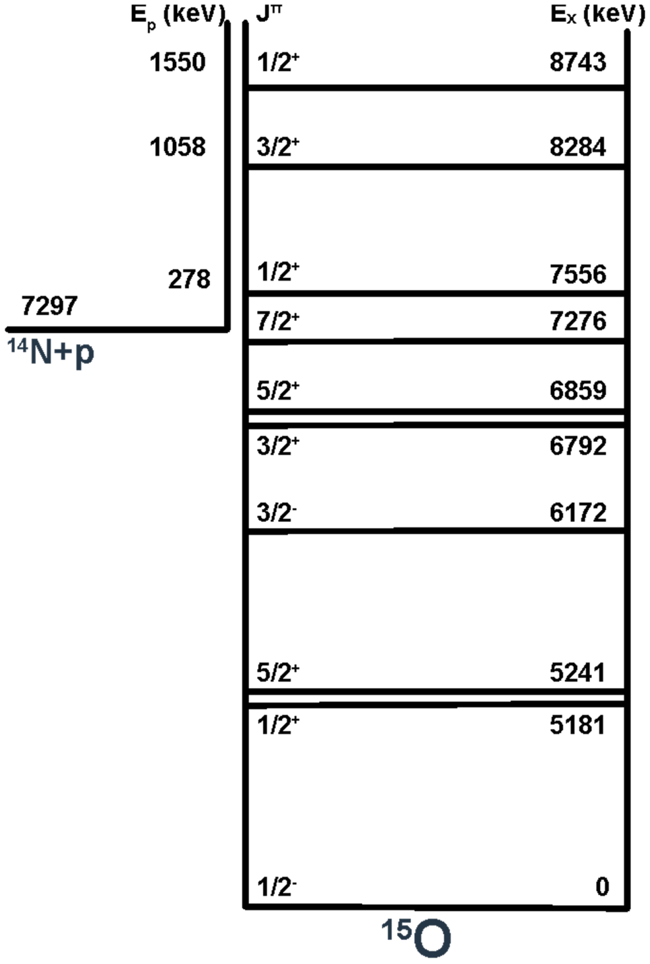




Level scheme for ^{15}O

S-factor: R/DC → 6.17 MeV

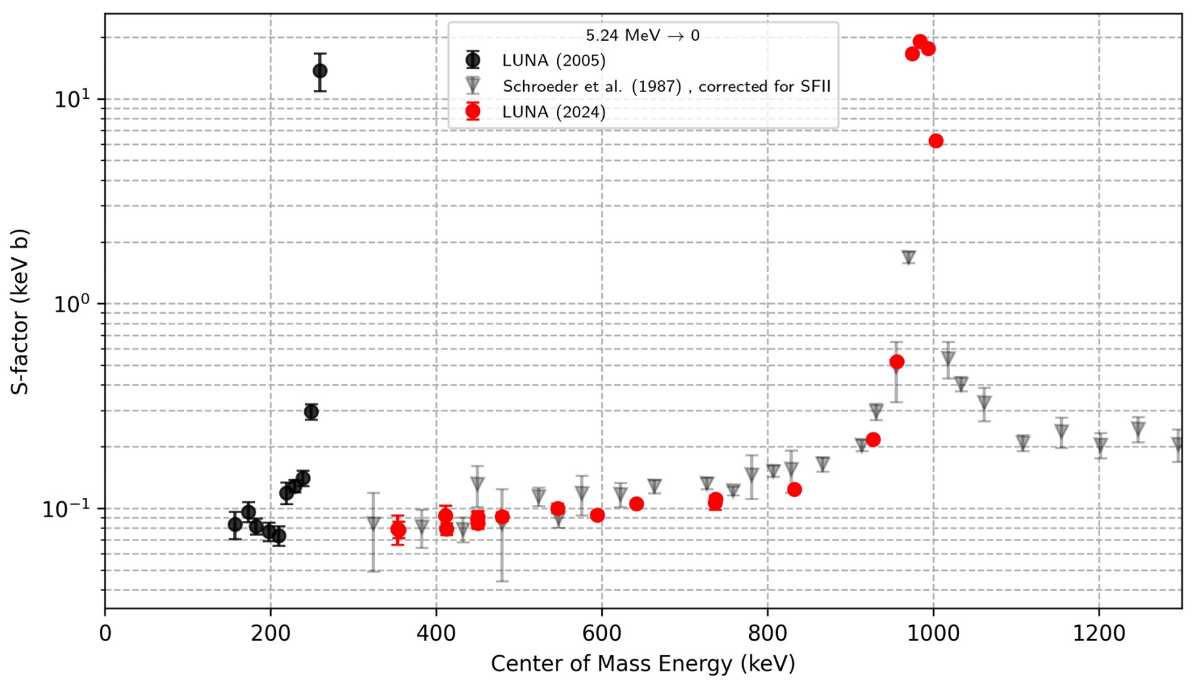


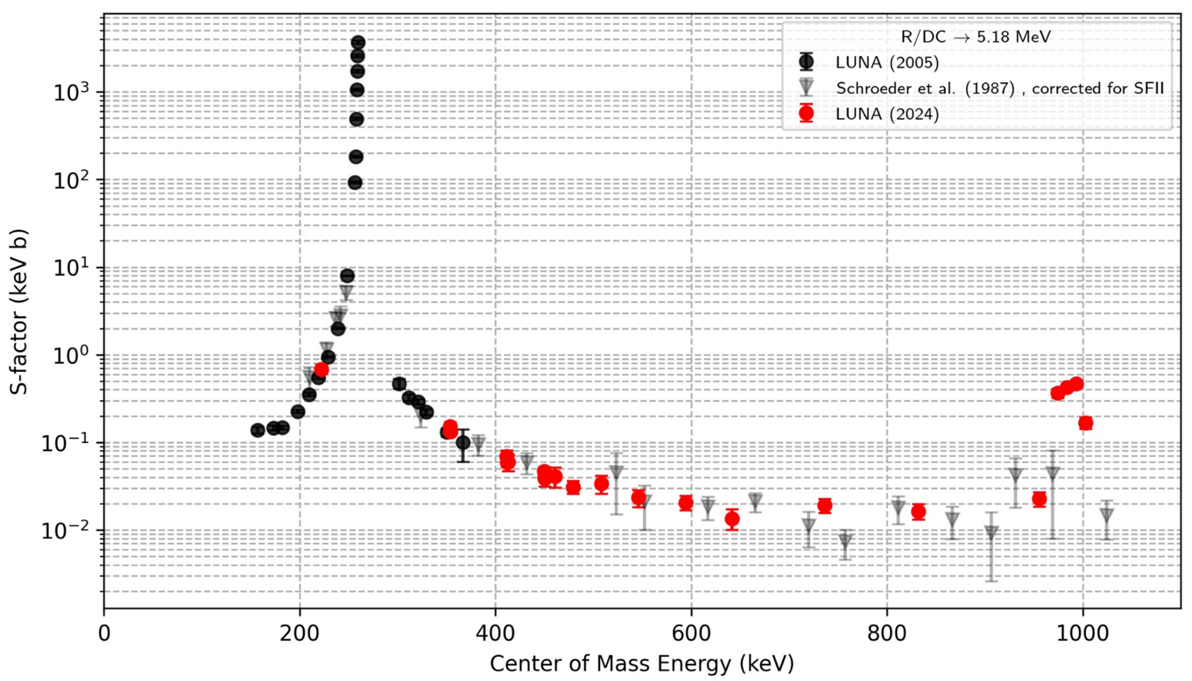


Level scheme for ^{15}O

First new measurement since Schroeder et al (1987) in this energy range!

S-factor: R/DC → 5.24/5.18 MeV





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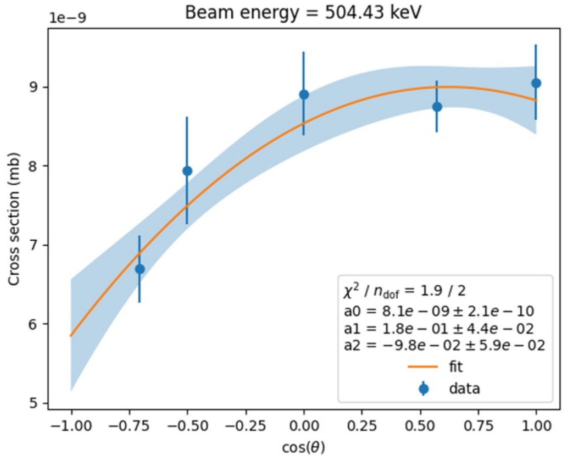
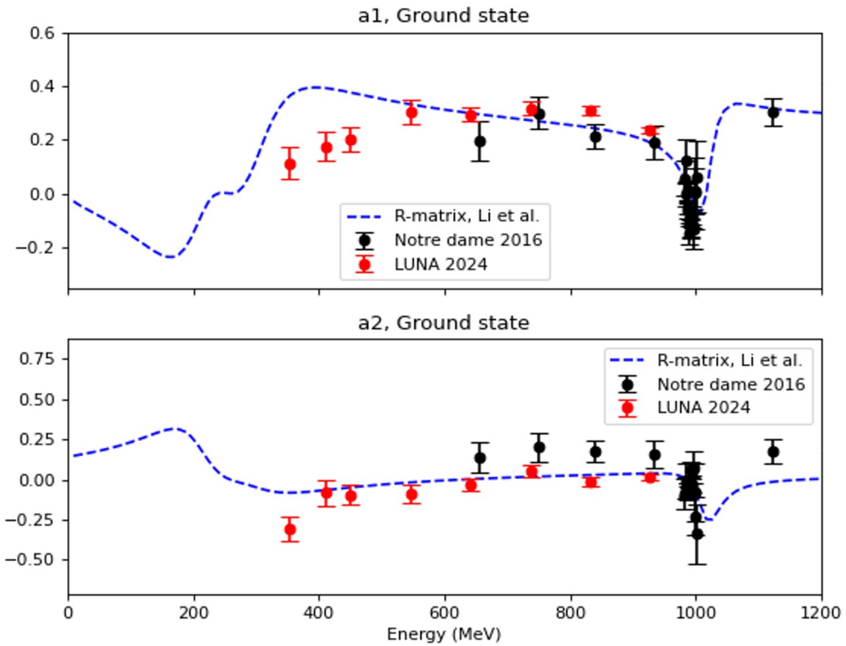
Angular distributions

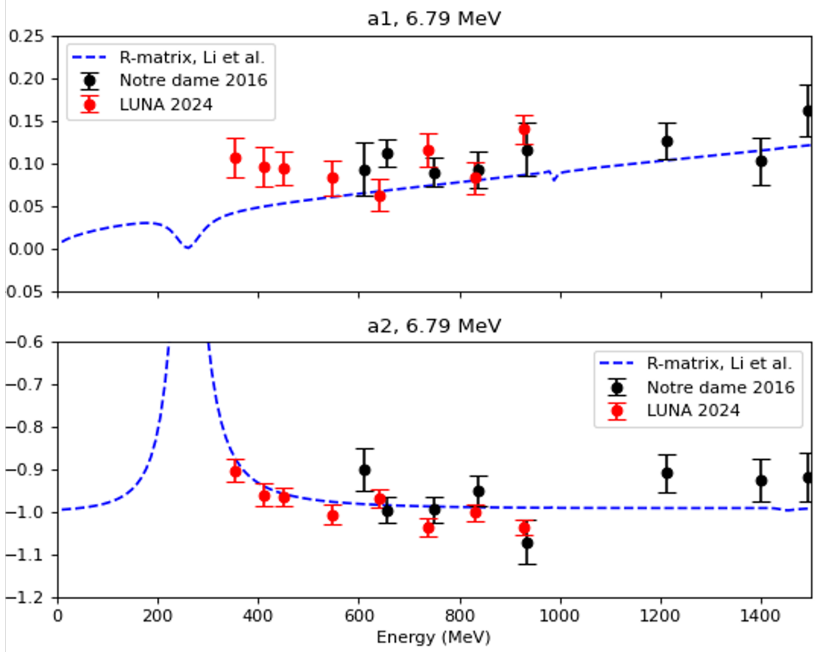
- angular distributions fit for a1 and a2 for the R/DC→ 6.79 MeV and ground state, down to 400 keV.

$$W(\theta) = a_0(1 + \sum_{i=1}^{n} a_i Q_i P_i(\cos\theta))$$

Example fit







Conclusion and outlook

- Cross section data for the astrophysical key reaction $^{14}N(p,\gamma)^{15}O$ have been collected in the energy range **0.25 - 1.3 MeV**.
- **Angular distributions** have been measured for the two most important transition R/DC→ 6.79 MeV and g.s. down to 400 keV.
- We measured most of the **weaker transitions**, many of them not observed by previous authors of recent publications.
- Data taking completed October 2024. Multi-channel **R-matrix** analysis started.
- New low energy measurement has also started @ LUNA-400 with the SOCIAL project.

Thank you for your attention!

The LUNA collaboration

LUNA

luna.lngs.infn.it