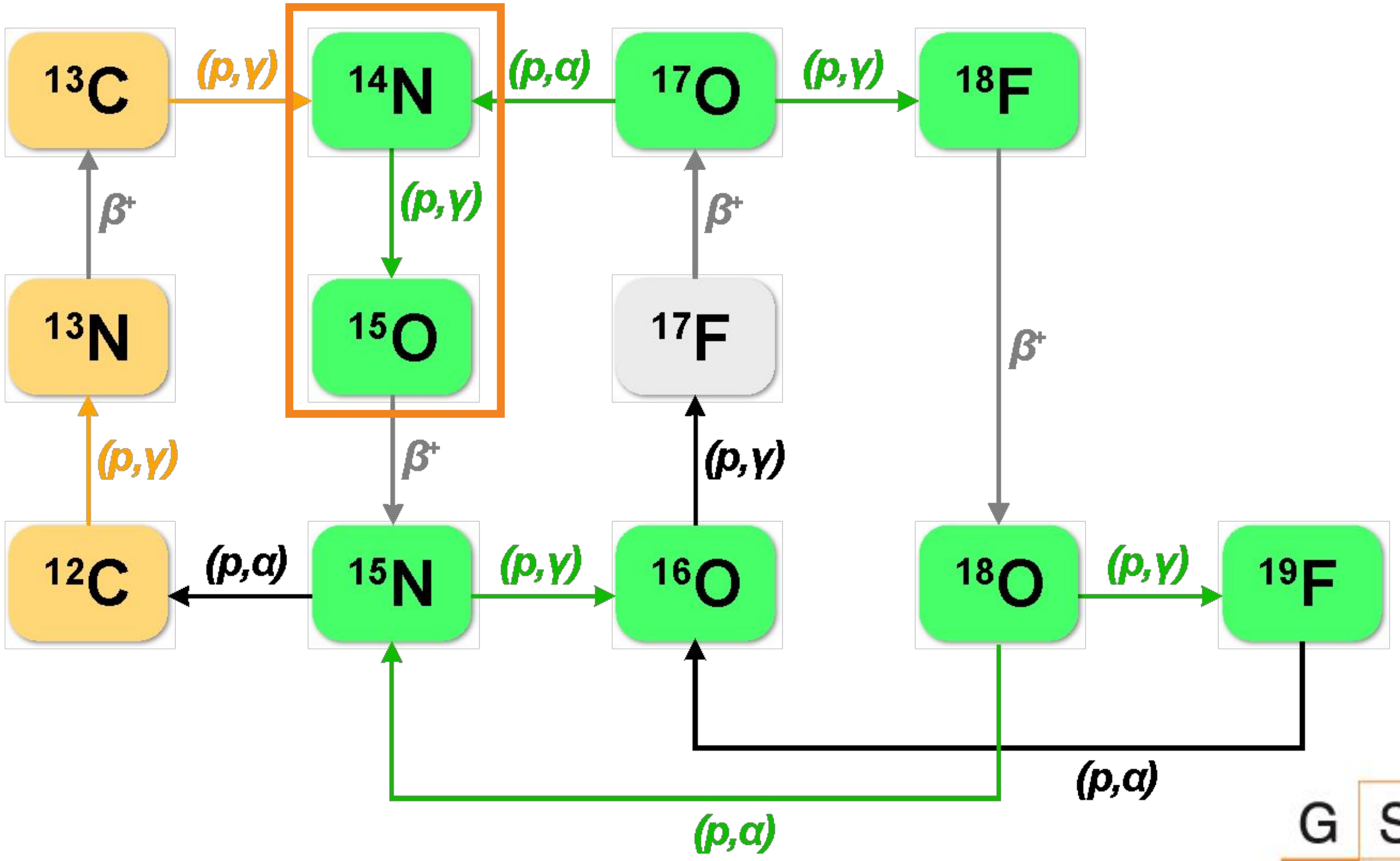
New results from the LUNA collaboration at the Bellotti Ion Beam Facility

Alessandro Compagnucci

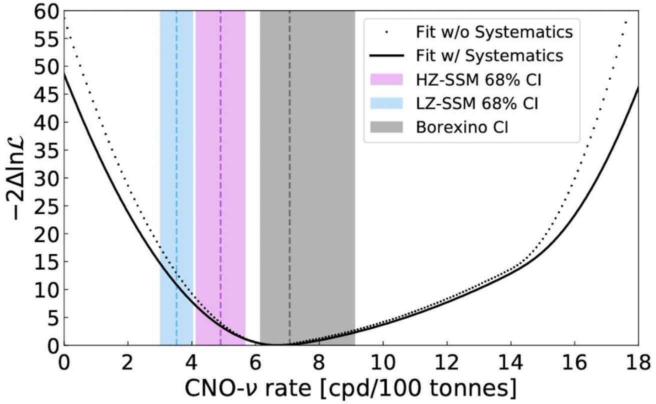
The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

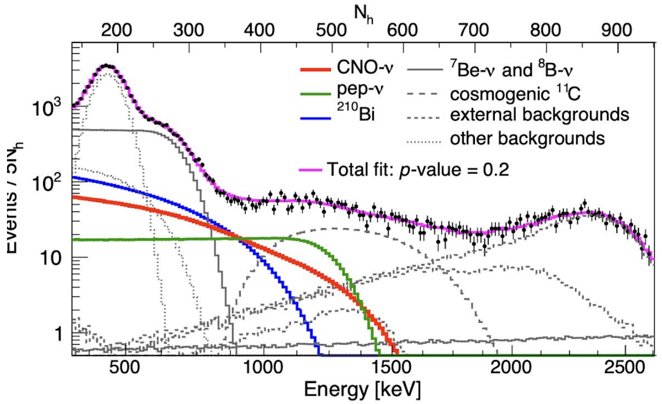
- The CNO Cycle is the main source of energy generation in massive main-sequence stars, accounts for **~1% in the Sun.**
- The $^{14}N(p,\gamma)^{15}O$ is the **slowest reaction of the CNO**, controls its speed and energy production rate.

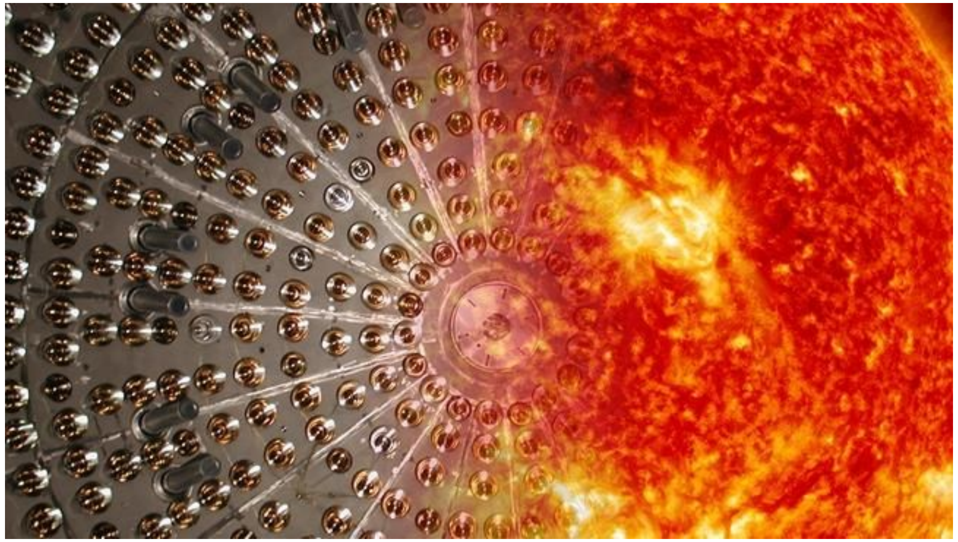


The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

- **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** still remains. After CNO Flux itself, biggest contribution to the uncertainty budget from $^{14}N(p,\gamma)^{15}O$ cross section.



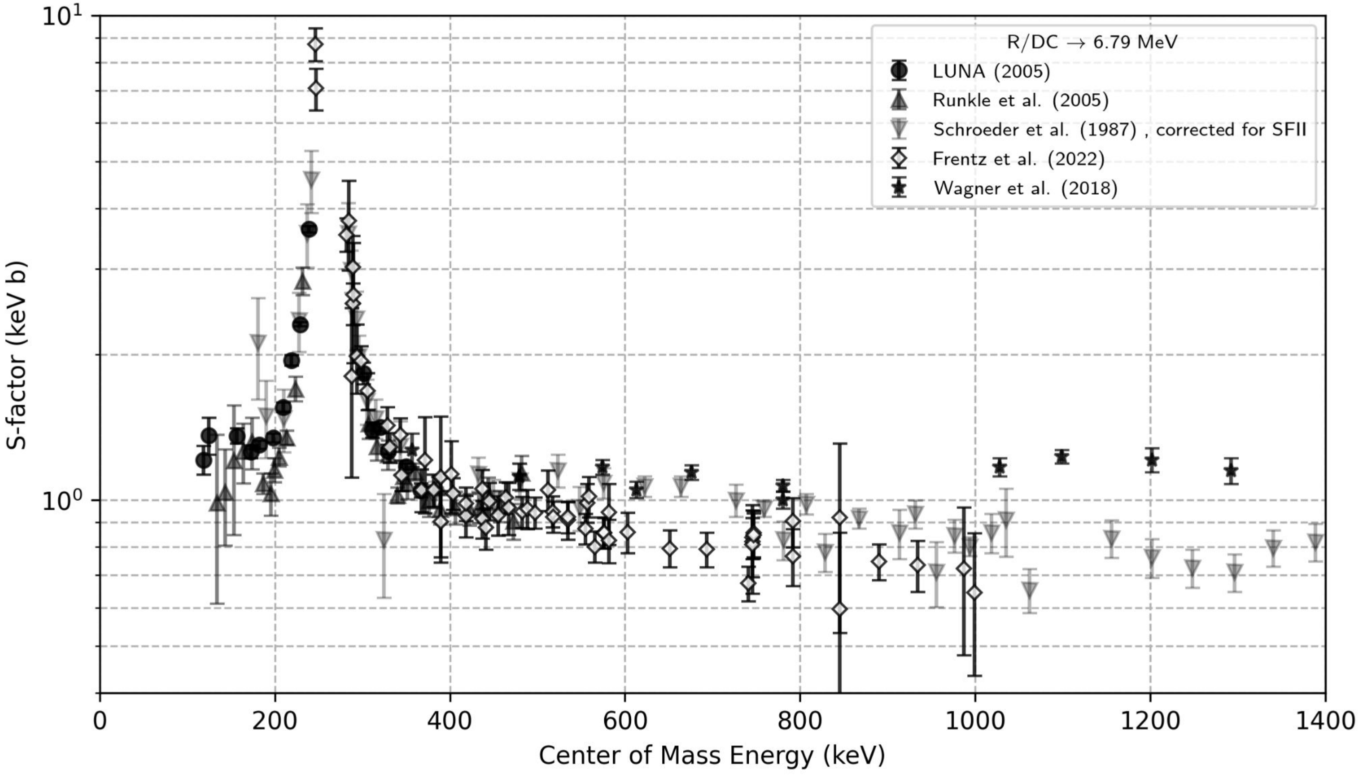


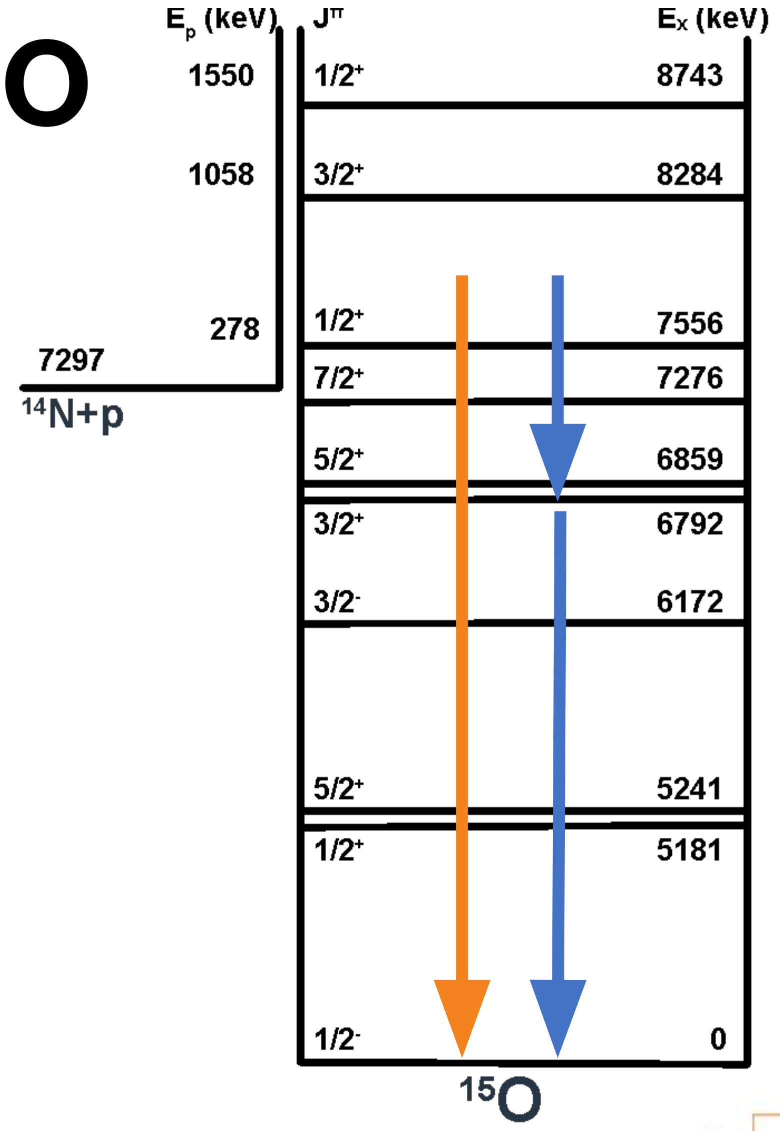


Appel, S. et al. (2022) PRL

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

- Transition to the **6.79 MeV** excited state of ^{15}O: A lot of consistent measurements in the low energy region

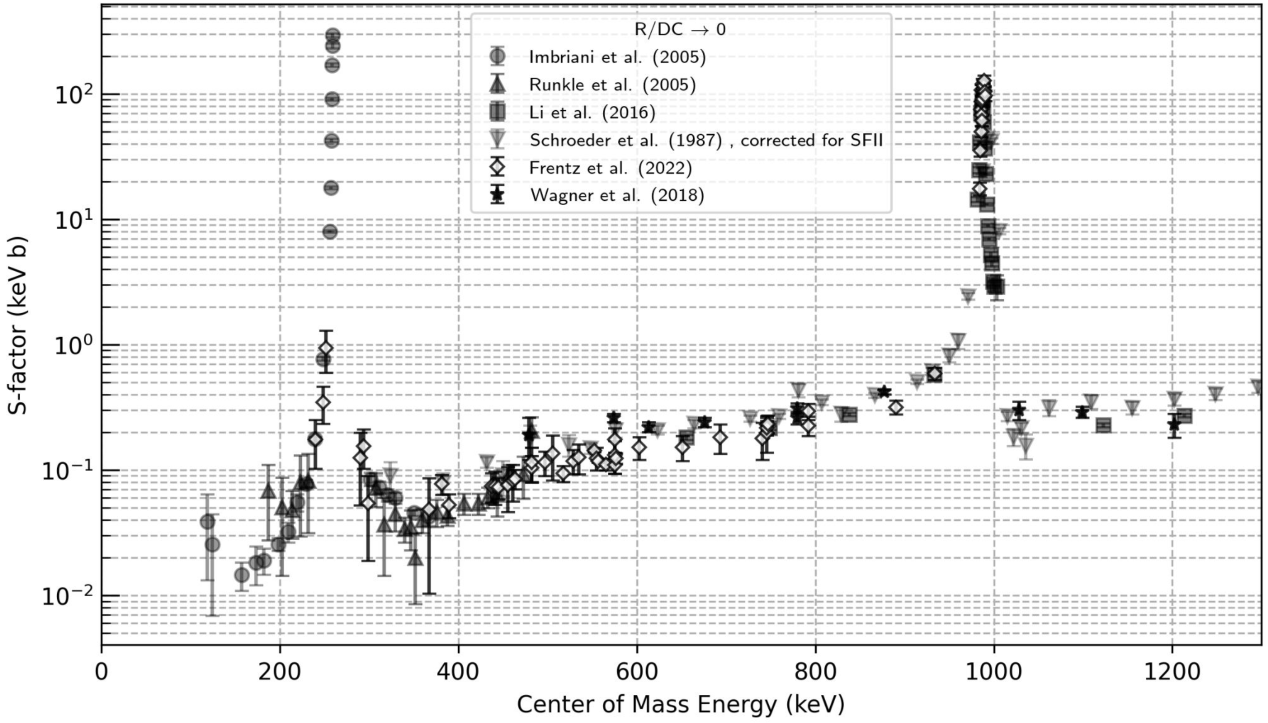


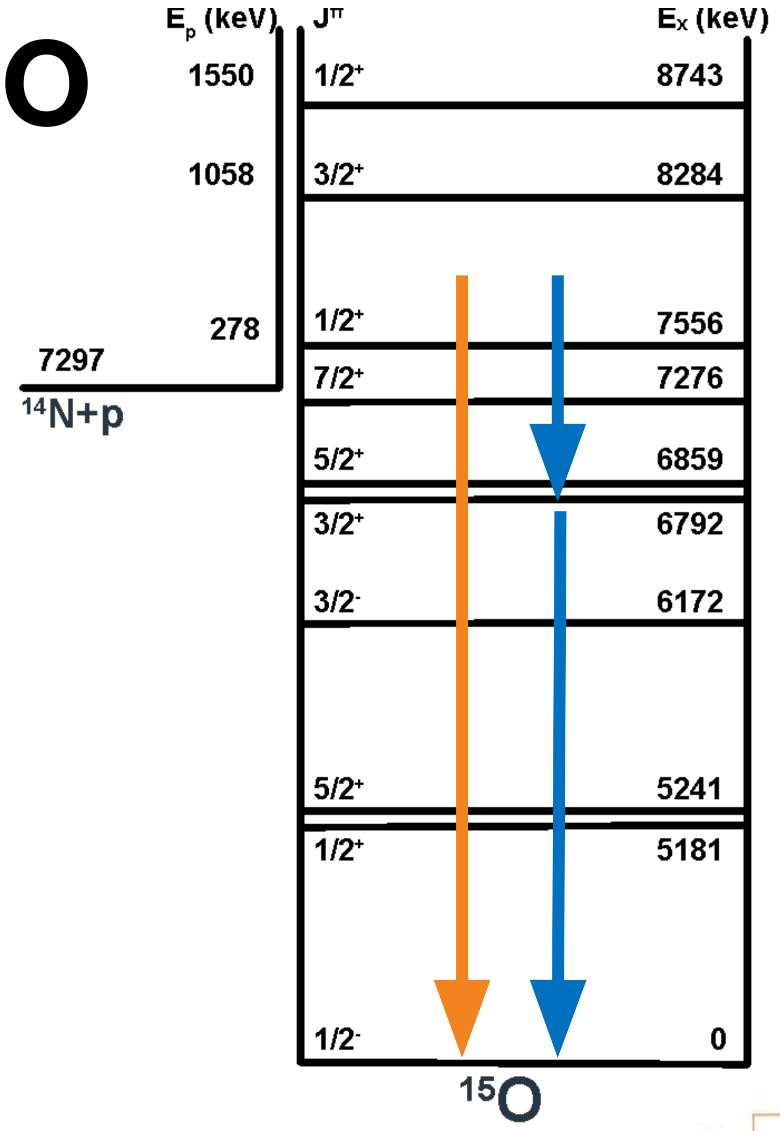


Level scheme for ^{15}O

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

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





Level scheme for ^{15}O

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

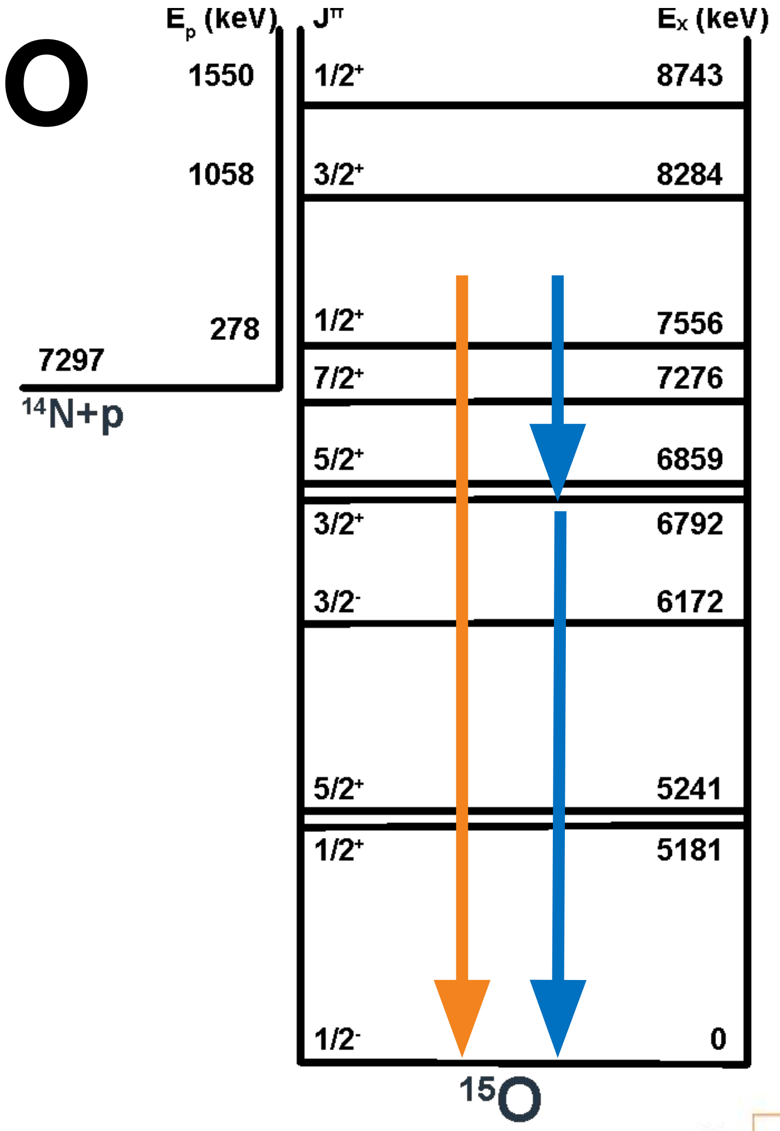
- The transition to the **6.79 MeV** excited state of ^{15}O and to the **ground state** are fairly well know but effected to problems with their extrapolations at low energies

TABLE I. A summary of zero energy S factors for the $^{14}N(p,\gamma)^{15}O$ reaction.

		Astrophysical S factor $S(0)$ (keV b)				
Year	Reference	R/DC → 0.00	R/DC → 6.792	R/DC → 6.172	Others[d]	Total
1987	Schröder *et al.* [9]	1.55 ± 0.34	1.41 ± 0.02	0.14 ± 0.05	0.1	3.20 ± 0.54
2001	Angulo *et al.*[a] [10]	$0.08^{+0.13}_{-0.06}$	1.63 ± 0.17	$0.06^{+0.01}_{-0.02}$	– –	1.77 ± 0.20
2003	Mukhamedzhanov *et al.* [16]	0.15 ± 0.07	1.40 ± 0.20	0.133 ± 0.02	0.02	1.70 ± 0.22
2004	Formicola *et al.* [17]	0.25 ± 0.06	1.35 ± 0.05 (stat) ± 0.08 (sys)	$0.06^{+0.01}_{-0.02}$[b]	0.04	1.7 ± 0.1 (stat) ± 0.02 (sys)
2005	Imbriani *et al.* [11]	0.25 ± 0.06	1.21 ± 0.05	0.08 ± 0.03	0.07	1.61 ± 0.08
2005	Runkle *et al.* [15]	0.49 ± 0.08	1.15 ± 0.05	0.04 ± 0.01	– –	1.68 ± 0.09
2005	Angulo *et al.* [18]	0.25 ± 0.08	1.35 ± 0.04	0.06 ± 0.02	0.04	1.70 ± 0.07 (stat) ± 0.10 (sys)
2006	Bemmerer *et al.* [13]	– –	– –	– –	– –	1.74 ± 0.14 (stat) ± 0.14 (sys)[c]
2008	Marta *et al.* [14]	0.20 ± 0.05	– –	0.09 ± 0.07	– –	1.57 ± 0.13
2010	Azuma *et al.* [19]	0.28	1.3	0.12	0.11	1.81
2011	Adelberger *et al.* [3]	0.27 ± 0.05	1.18 ± 0.05	0.13 ± 0.06	0.08	1.66 ± 0.08
2016	Li *et al.* [20]	0.42 ± 0.04 (stat) $^{+0.09}_{-0.19}$(sys)	1.29 ± 0.06 (stat) ± 0.06 (sys)	– –	– –	– –
2018	Wagner *et al.* [21]	0.19 ± 0.01 (stat) ± 0.05 (sys)	1.24 ± 0.02 (stat) ± 0.11 (sys)	– –	– –	– –
2022	This work	$0.33^{+0.16}_{-0.08}$	1.24 ± 0.09	0.12 ± 0.04	– –	1.69 ± 0.13

[a] R-matrix analysis on available data, not a measurement.
[b] Adopted from Angulo and Descouvemont [10].
[c] Measured S factor at 70 keV.

Frentz et al (2022)



Level scheme for ^{15}O

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

- Lack of recent data for the other transitions
  R/DC → 6.17, 5.24, 5.18 ...

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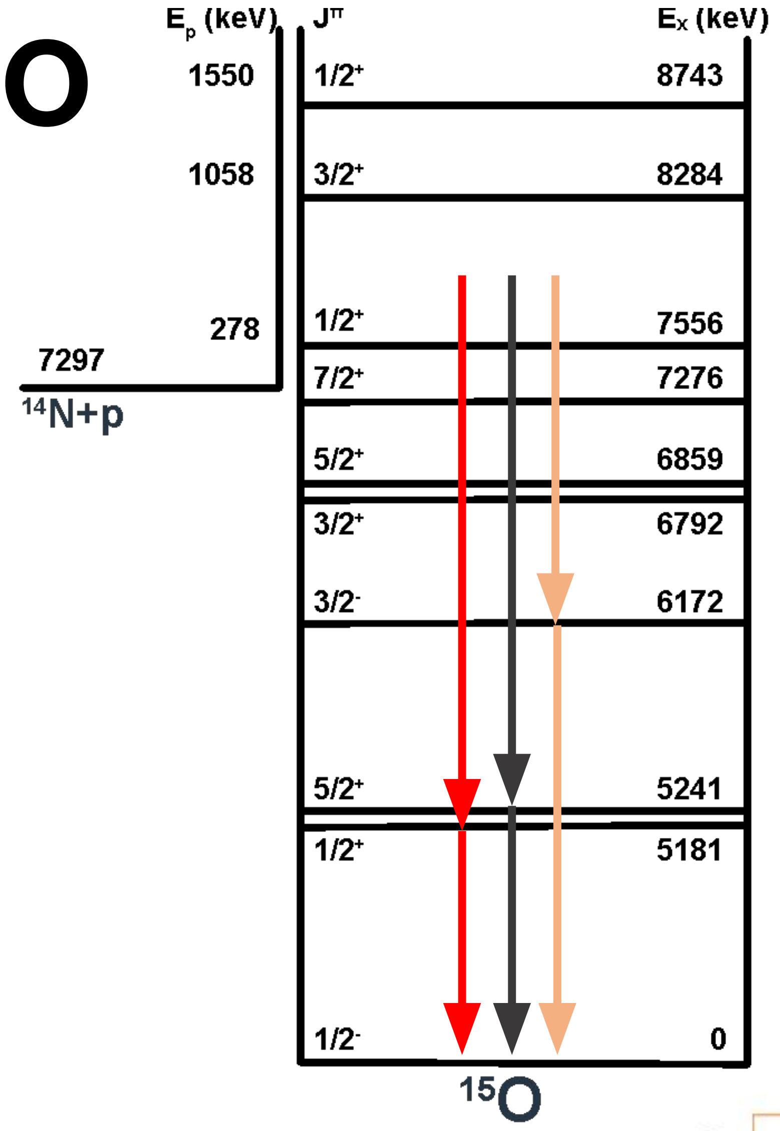
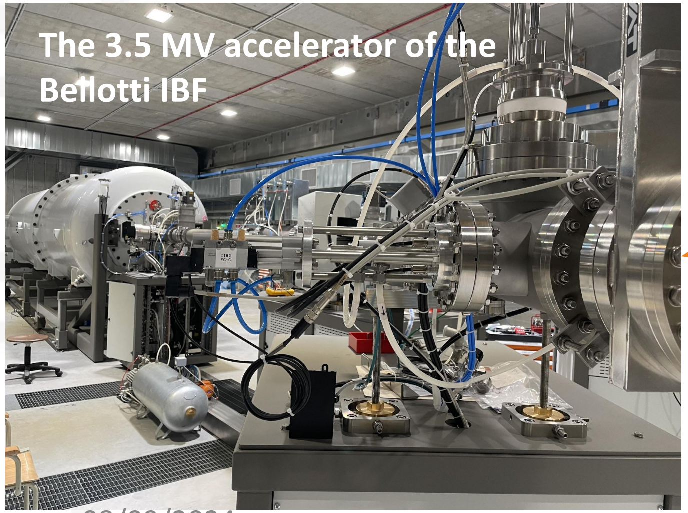
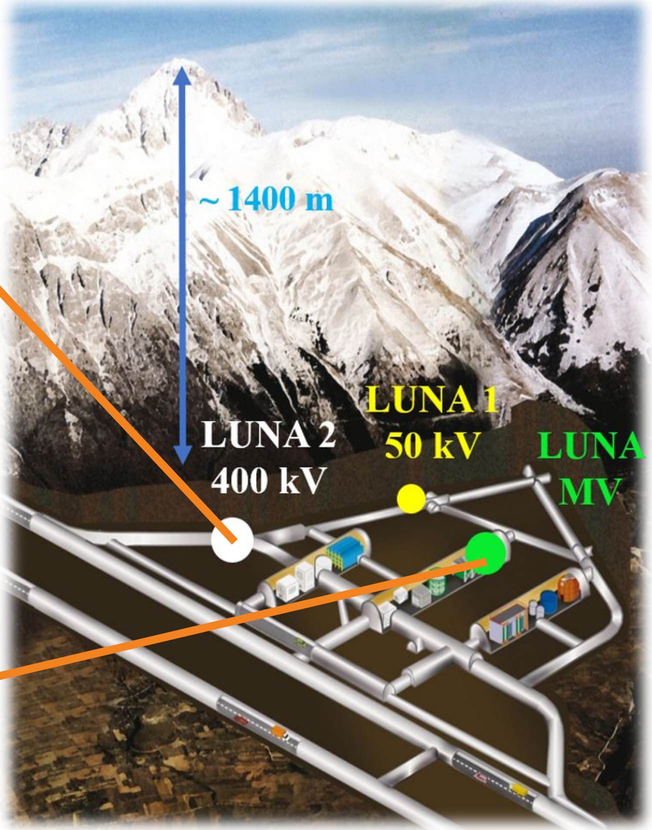
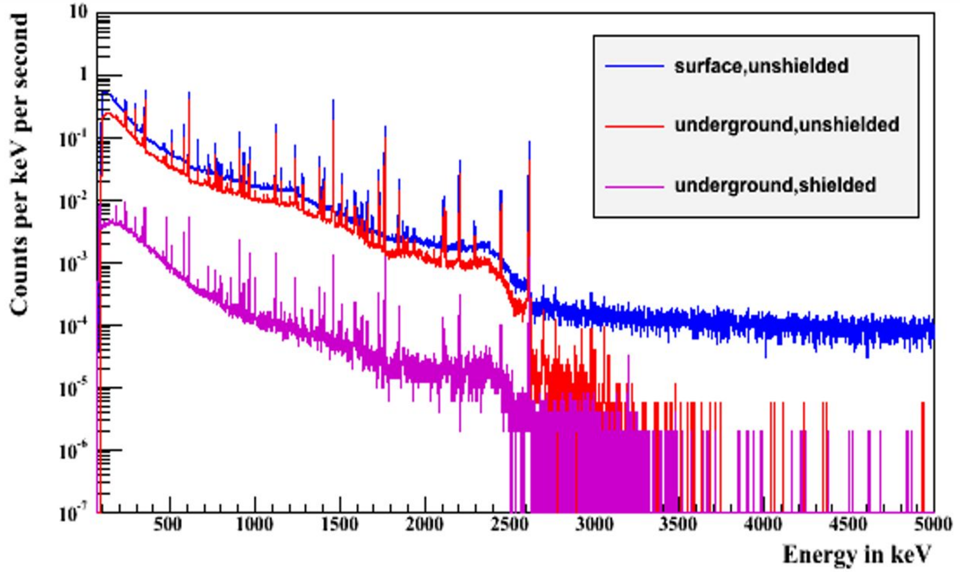


Level scheme for ^{15}O

Underground Nuclear Astrophysics at LUNA







The Bellotti Ion Beam Facility of LNGS

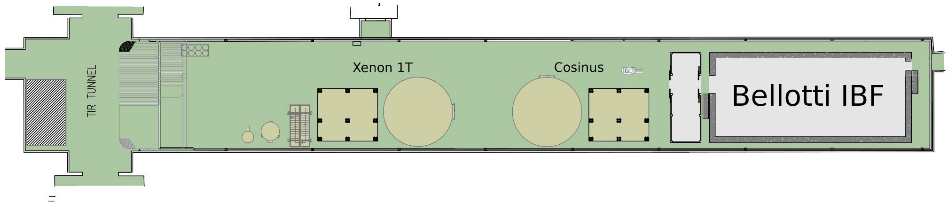
Inline Cockcroft Walton accelerator

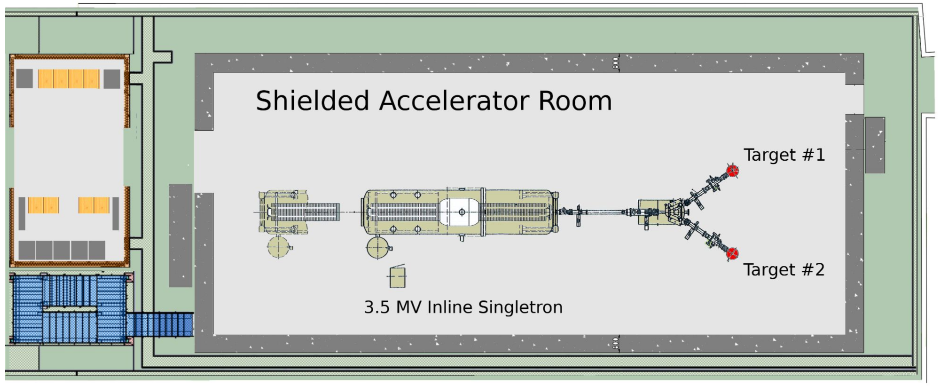
TERMINAL VOLTAGE: 0.3 – 3.5 MV

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

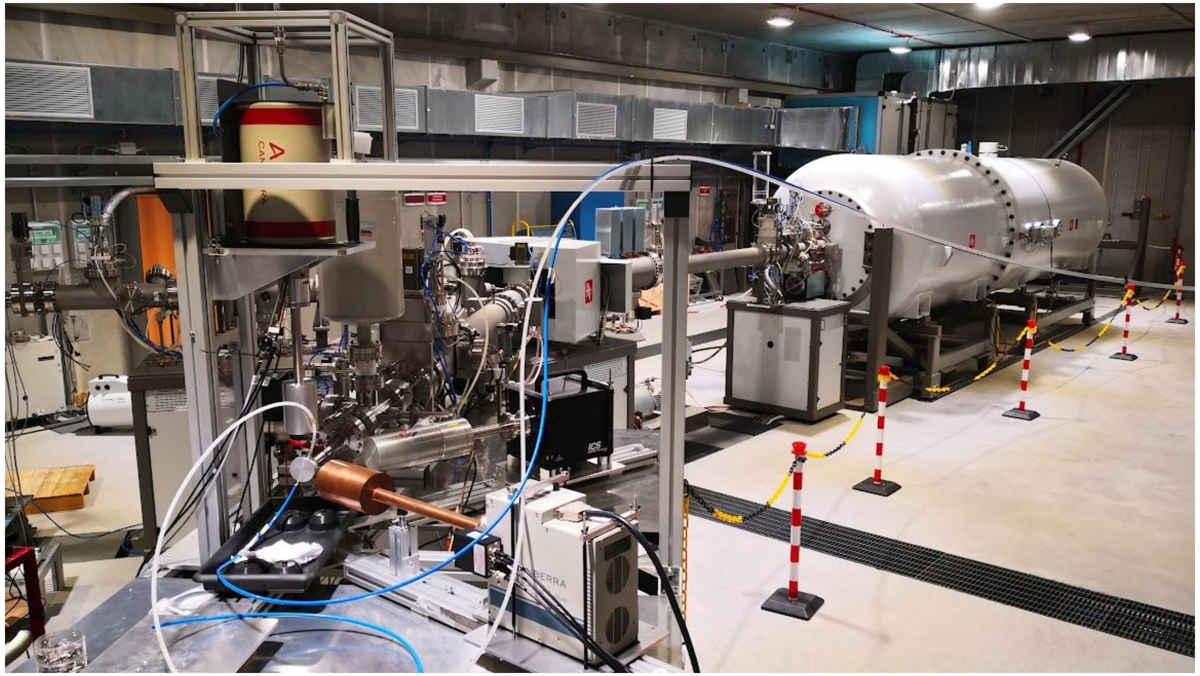
He^+ beam: 300 - 500 µA

C^+ beam: 100 - 150 µA

C^{++} beam: 50 pµA

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

- Low background measurement over a **wide-energy range**, in order 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

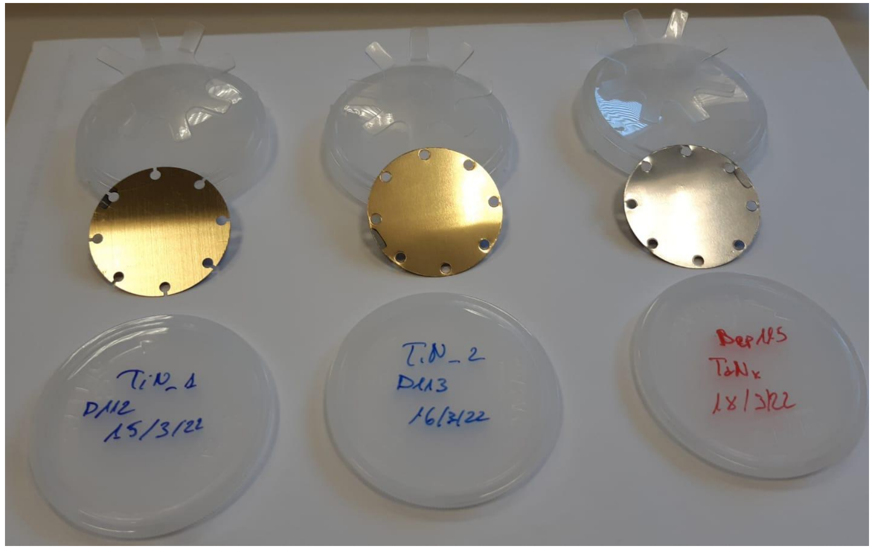


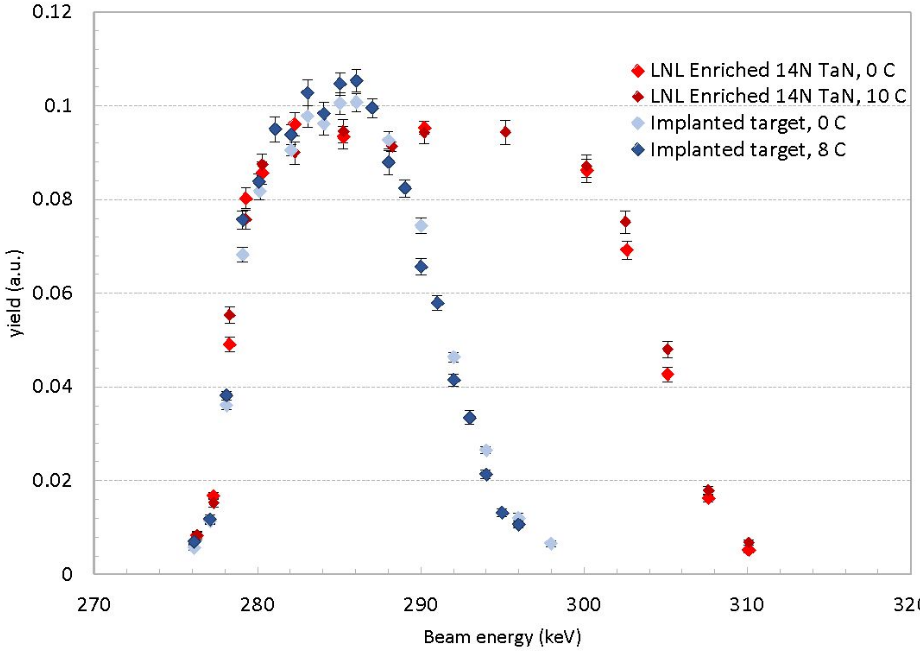
The $^{14}N(p,\gamma)^{15}O$ measurement at the Bellotti IBF

- Single HPGe at 55° in close geometry, **excitation function**. **(June 2023)**
- Three HPGe detectors, **angular distribution**.
  55°-135°-90° + 0°-120°-90°
  (Oct. 2023 - under progress)

Solid Targets

- **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 14N+p resonance scans.
- **Implanted targets**: Produced at IST, Lisbon. Tested for stability up to 15 C.





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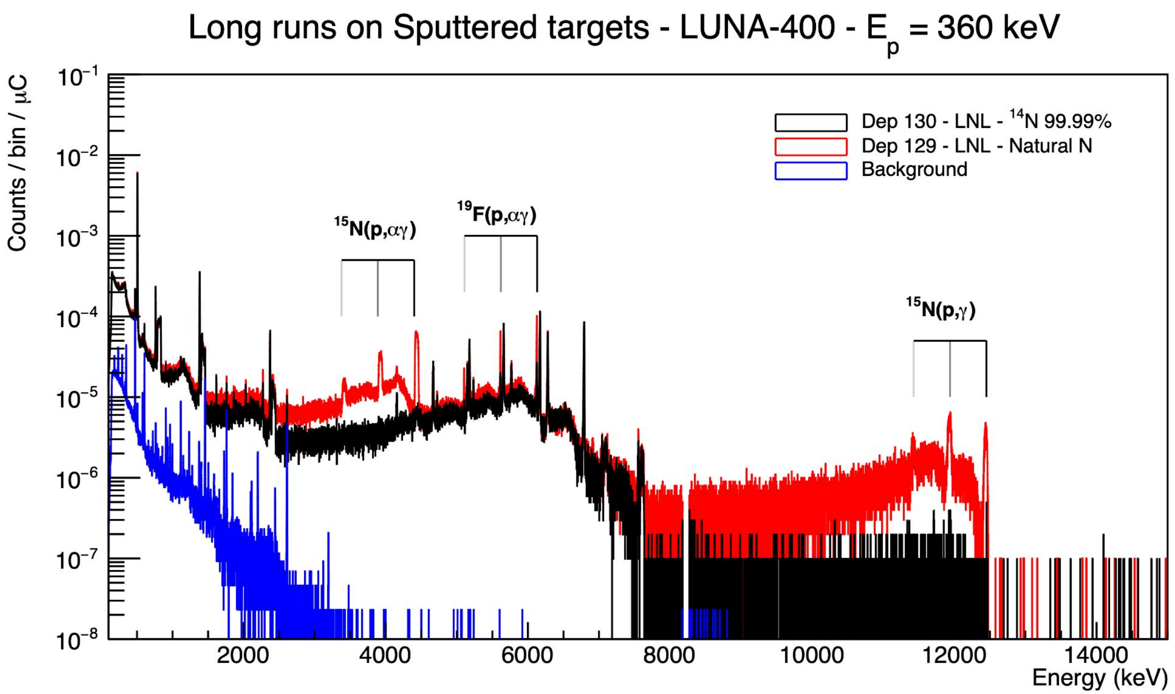
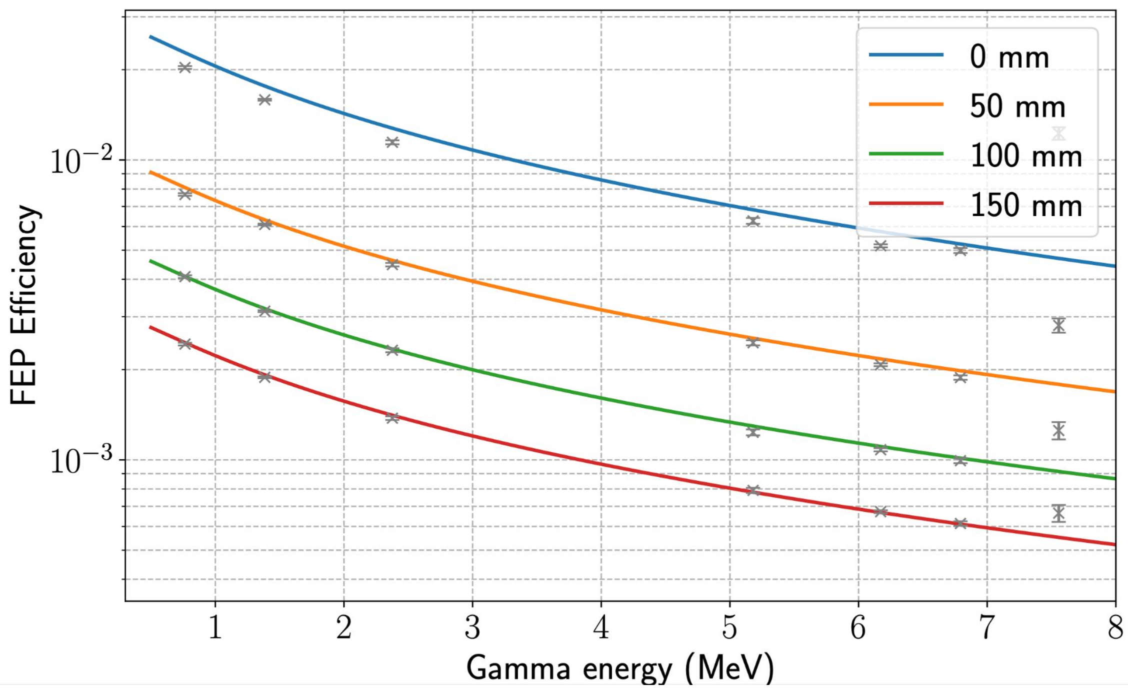


Efficiency characterization for the HPGe detector

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



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

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

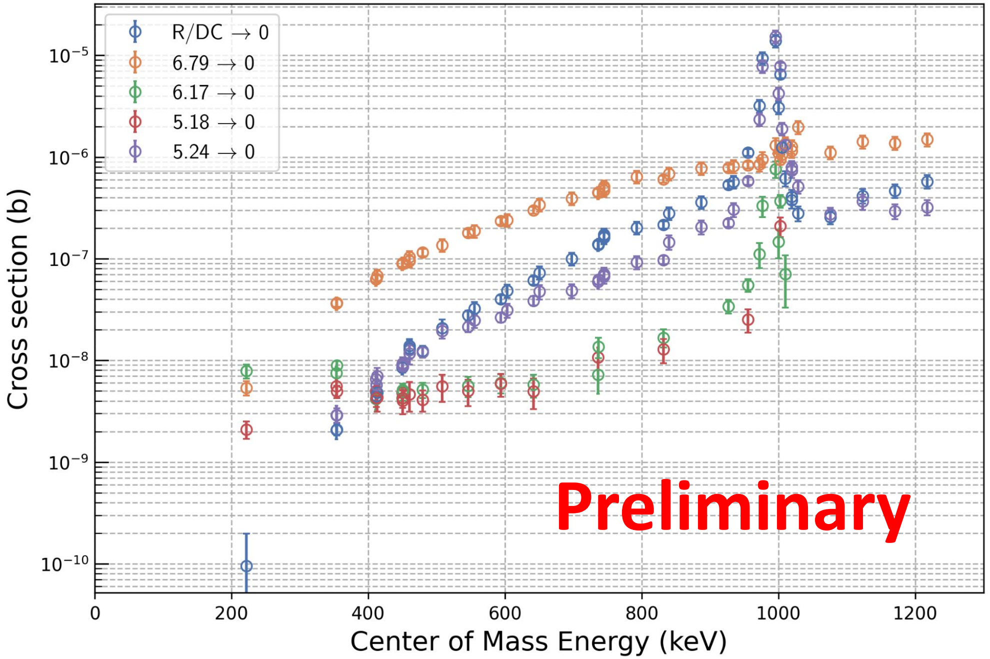
$$Y_{i_{sec}} = Rb_i\varepsilon_{fe}(E_{i_{sec}})(1-\varepsilon_{tot}(E_{i_{pri}}))\,,$$

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

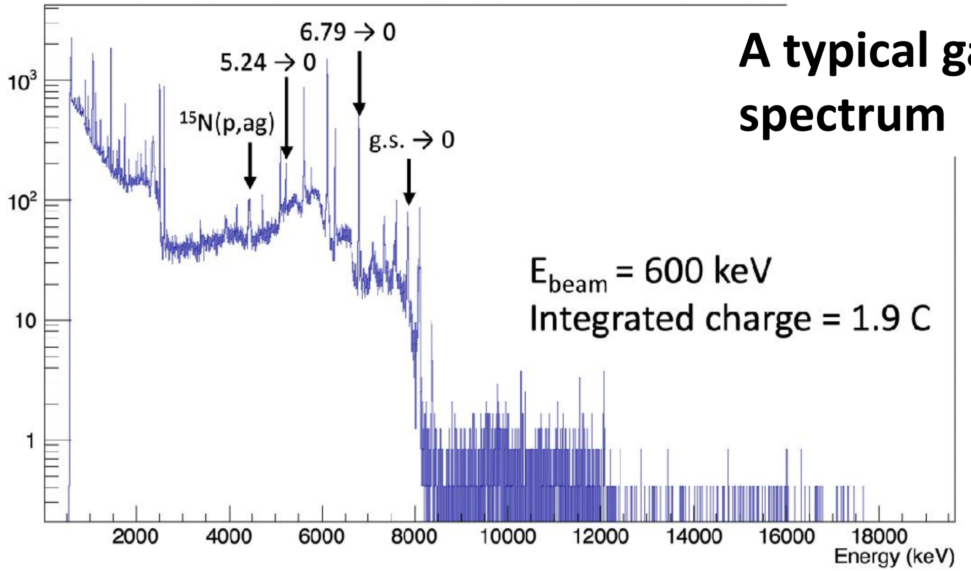
$$\varepsilon_{fe}(d) = \frac{1-e^{\frac{d+d_0}{1+\beta\sqrt{E_\gamma}}}}{(d+d_0)^2}\,.$$

Preliminary results

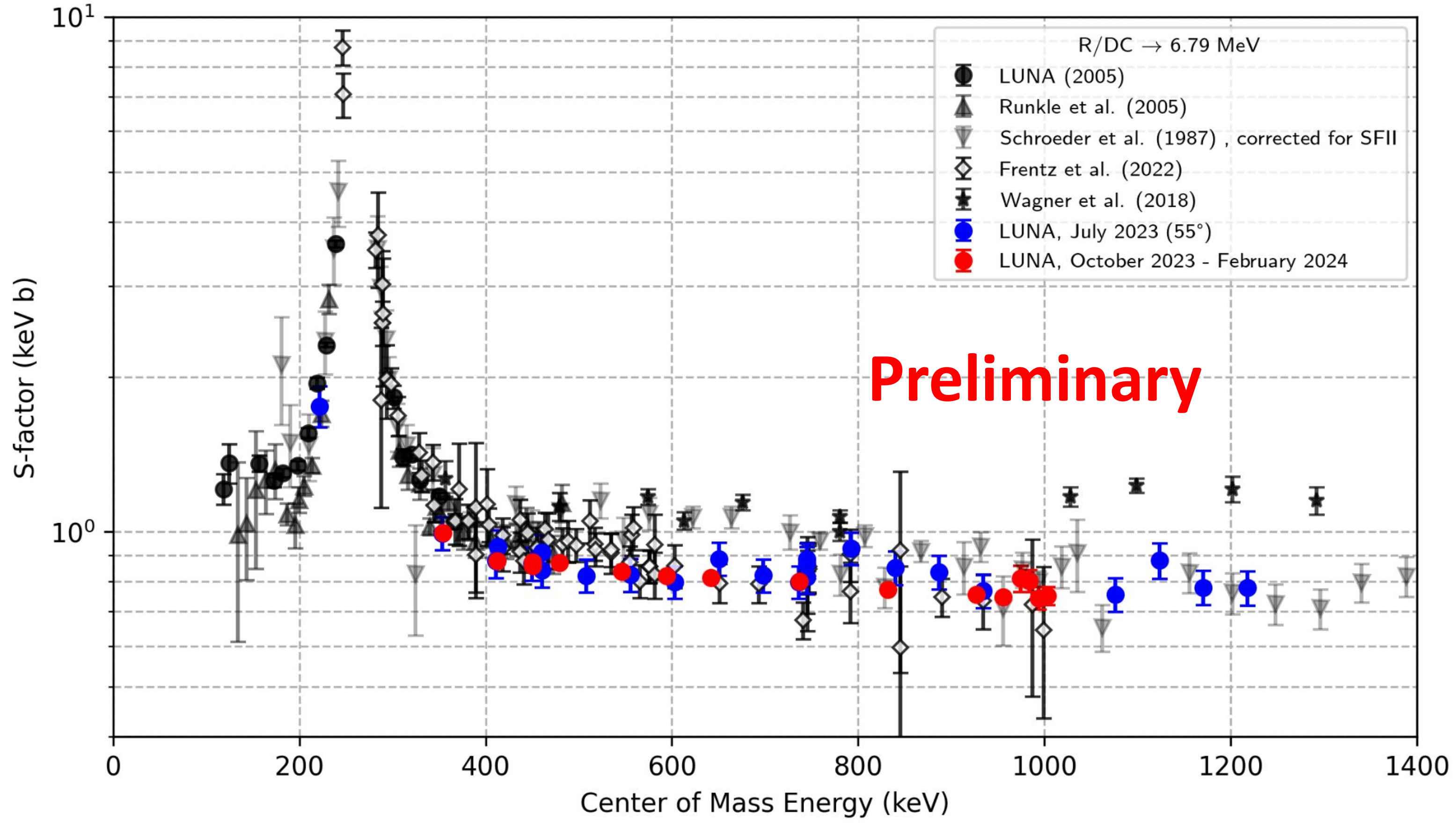
- Excitation function measurement **(June 2023)**:
  - **0.25-1.3 MeV** in 50 keV steps,
  - 55° HPGe at 5 cm from target,
  - Total charge collected: **38 C** (up to 300 µA).
- Angular distribution measurement **(October 2023 - February 2024)**
  - **0.4 - 1.1 MeV** in 100 keV steps
  - 3 HPGe detectors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

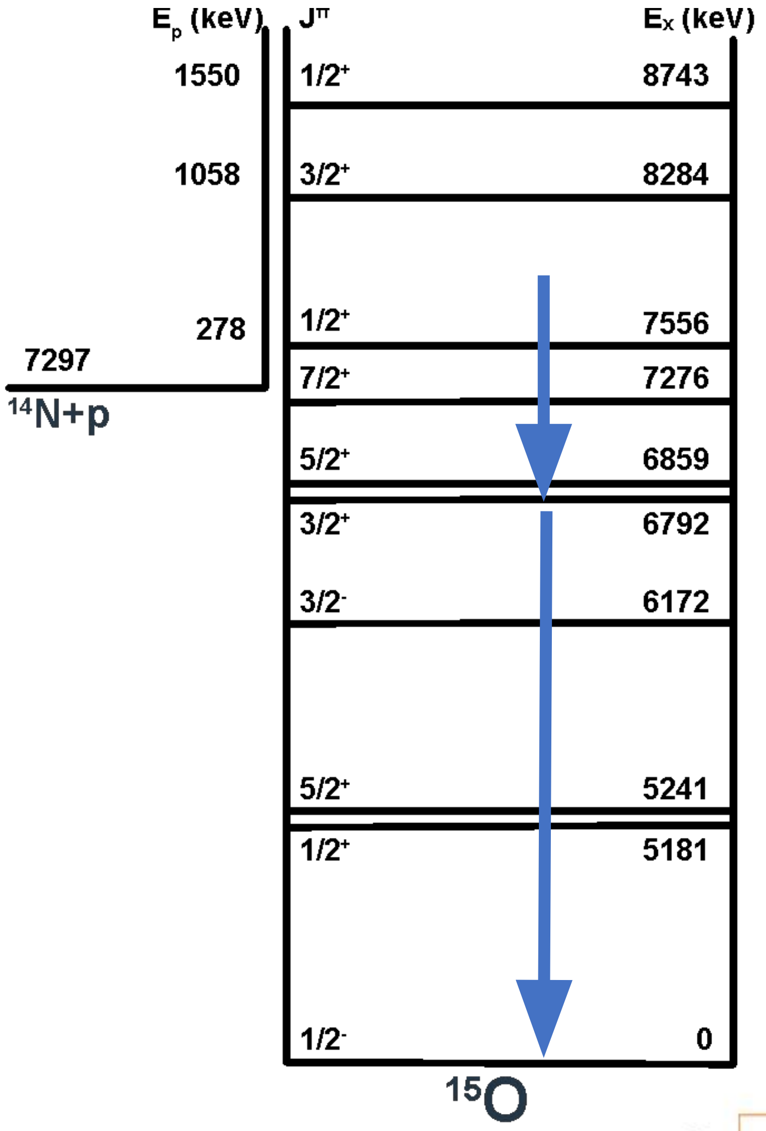


A typical gamma-ray spectrum



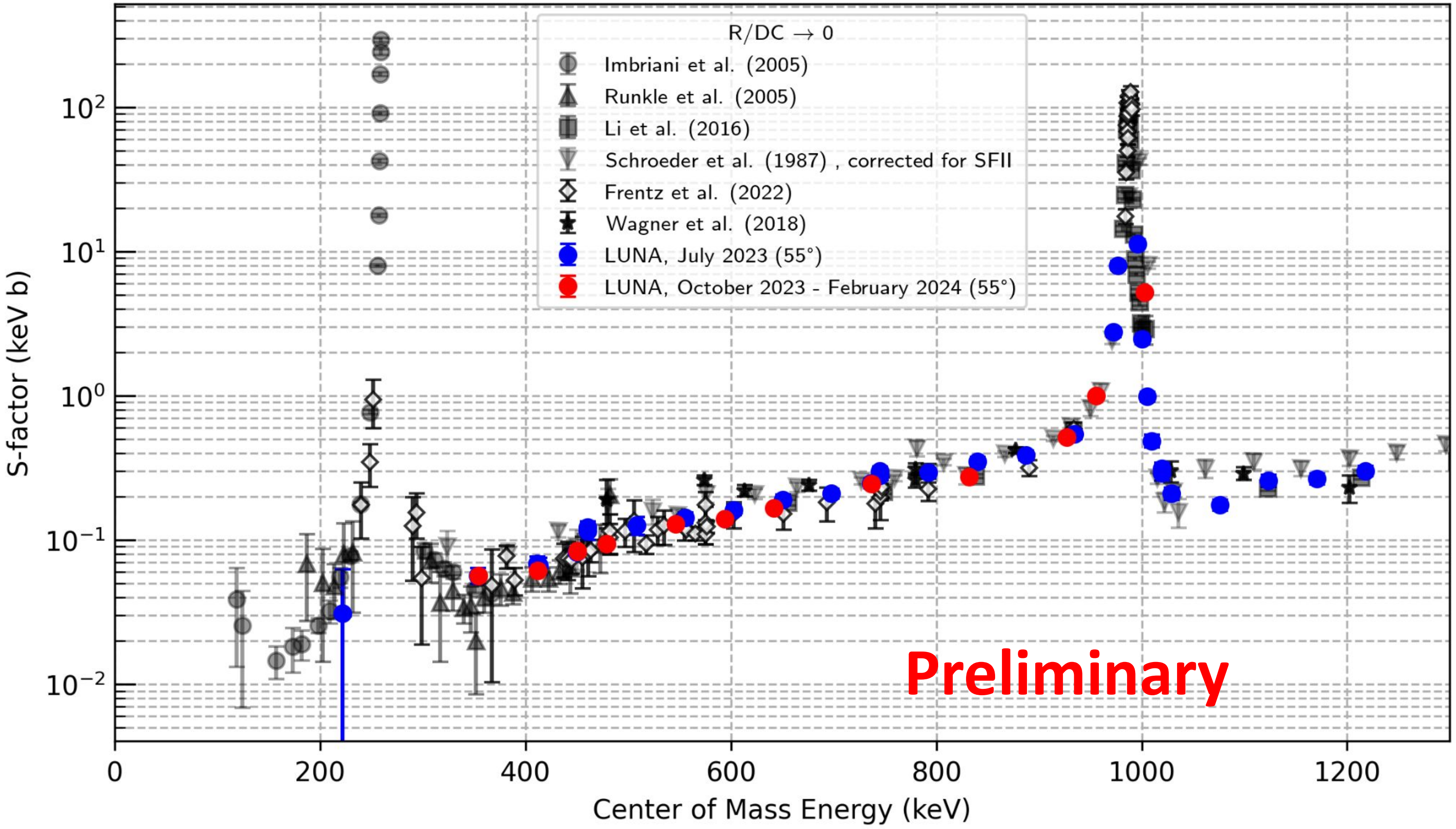
S-factor: R/DC → 6.79 MeV

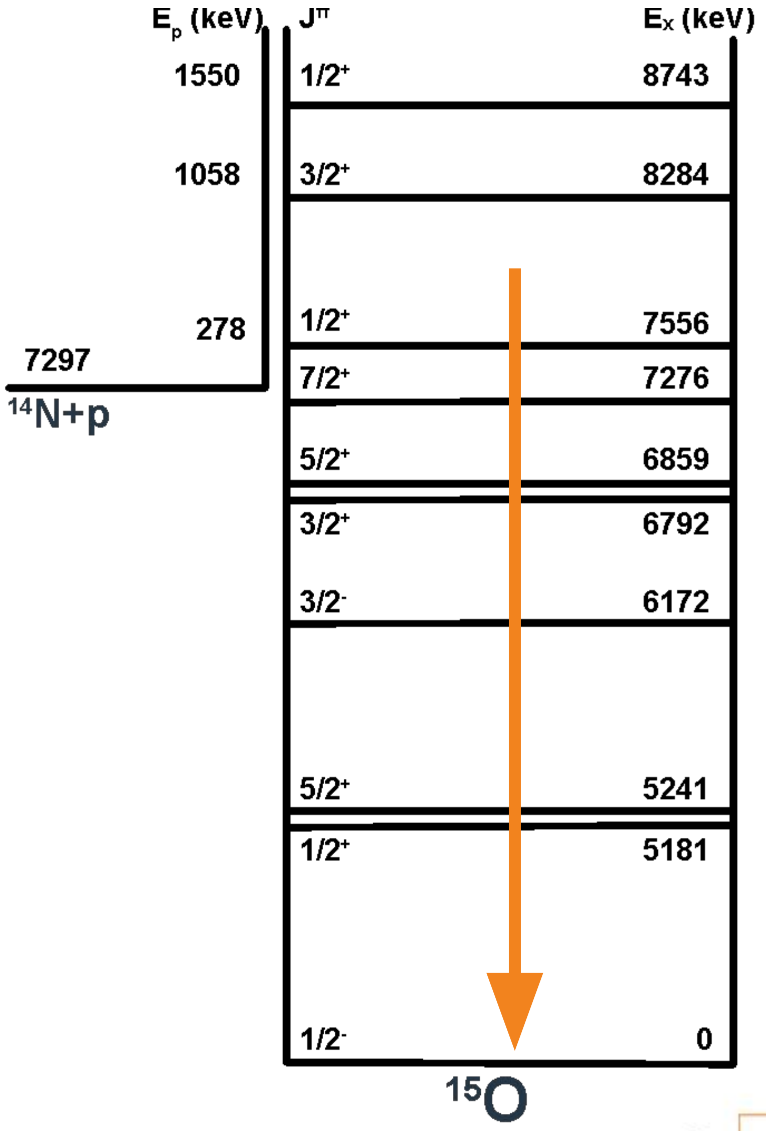




Level scheme for ^{15}O

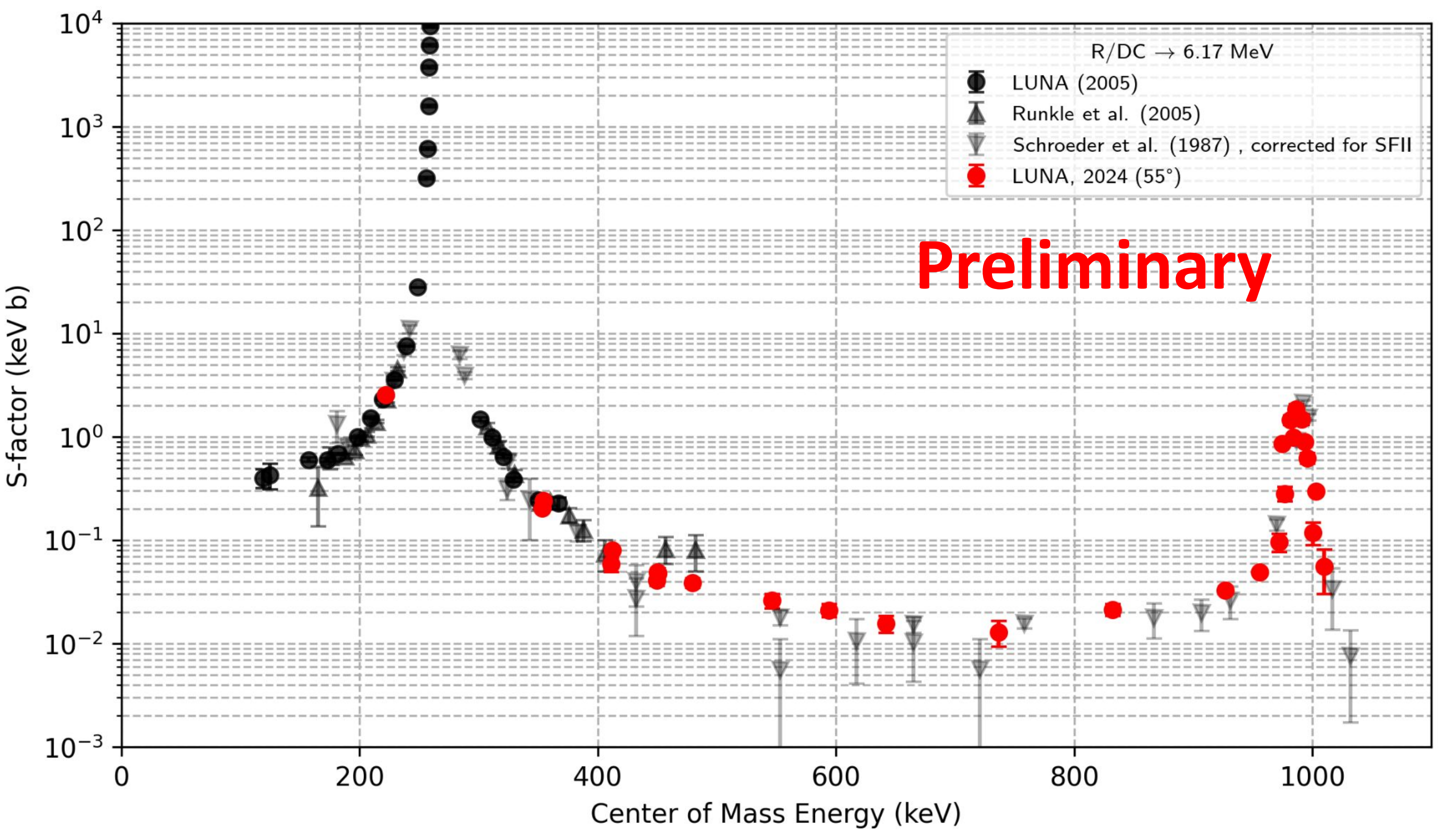
S-factor: R/DC → ground state

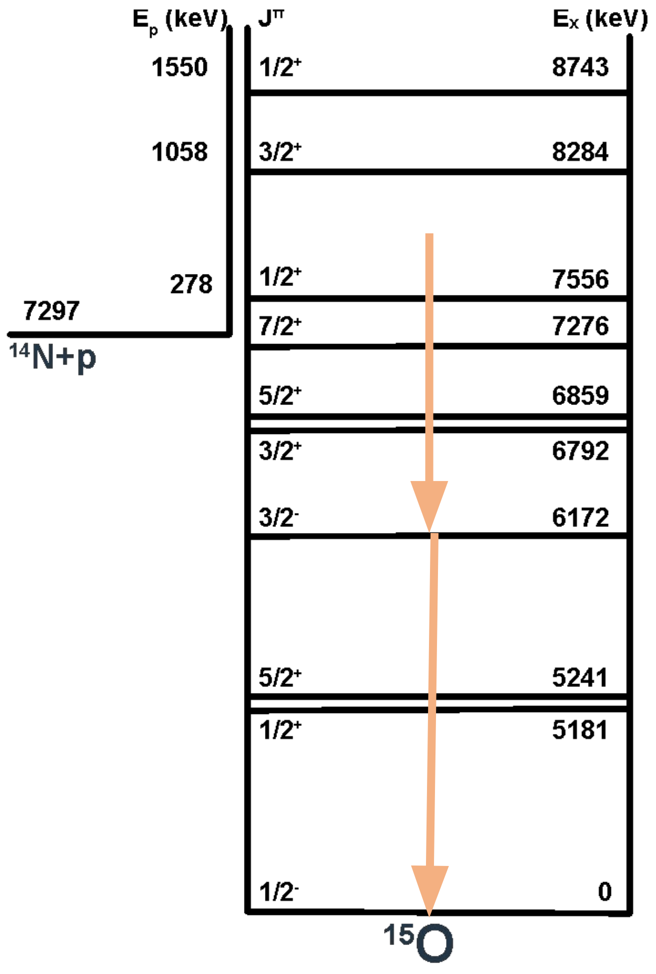




Level scheme for ^{15}O

S-factor: R/DC → 6.17 MeV

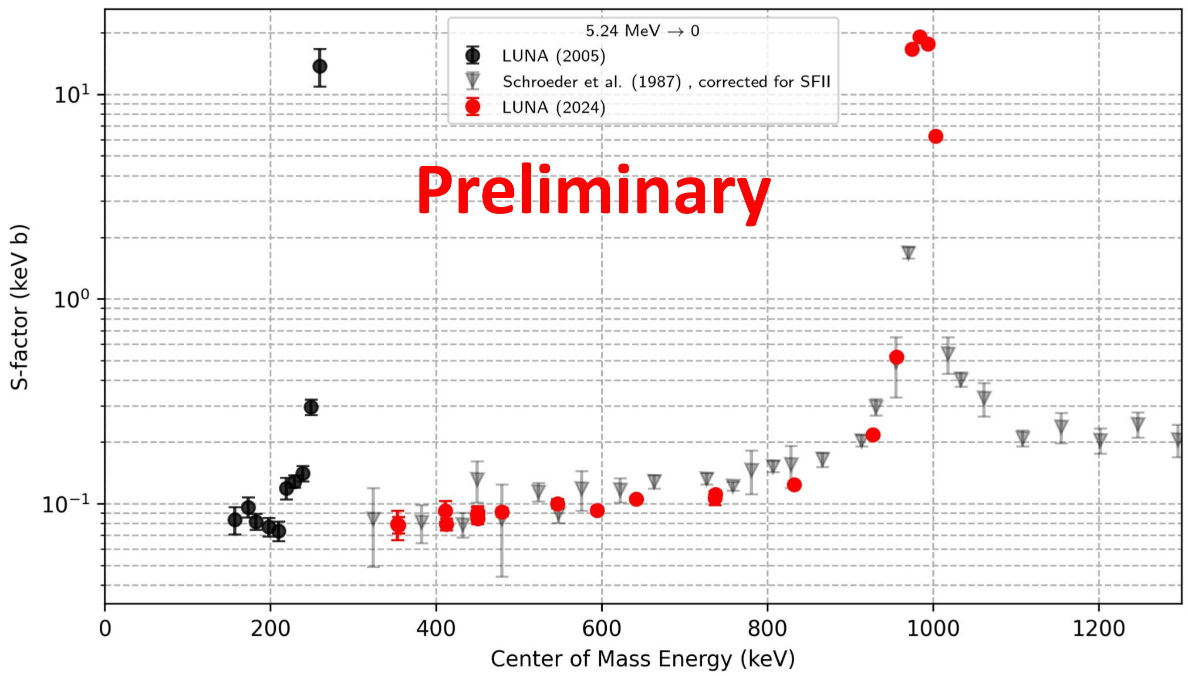


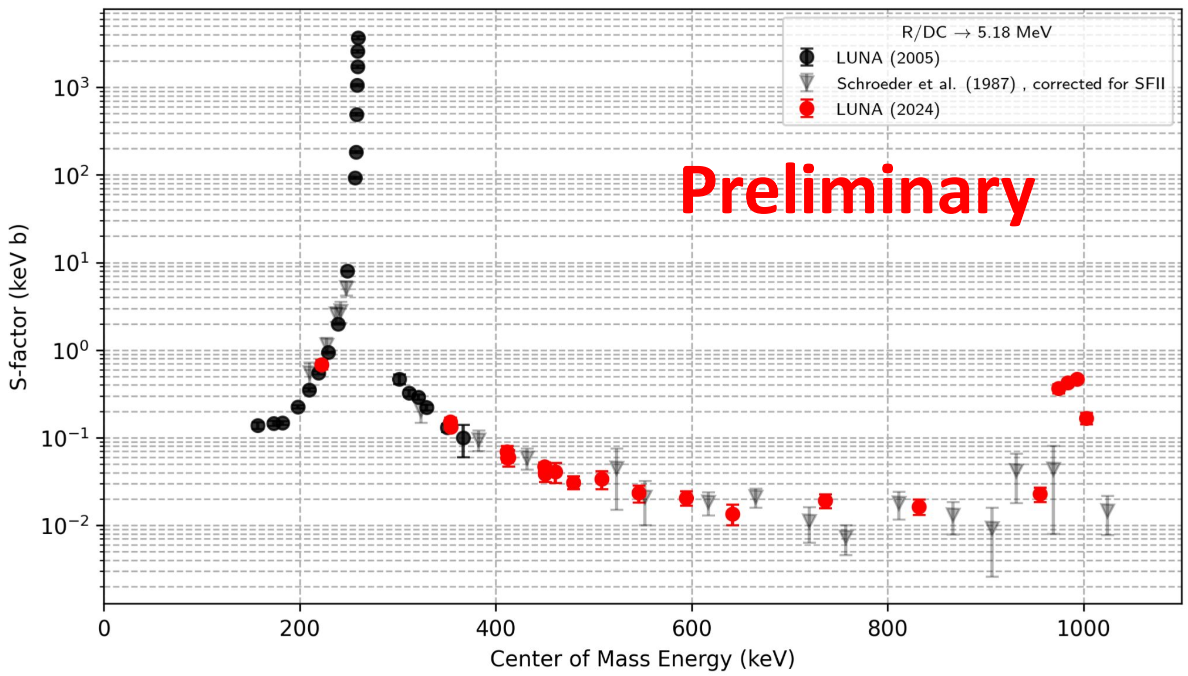


Level scheme for ^{15}O

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

S-factor: R/DC → 5.24/5.18 MeV





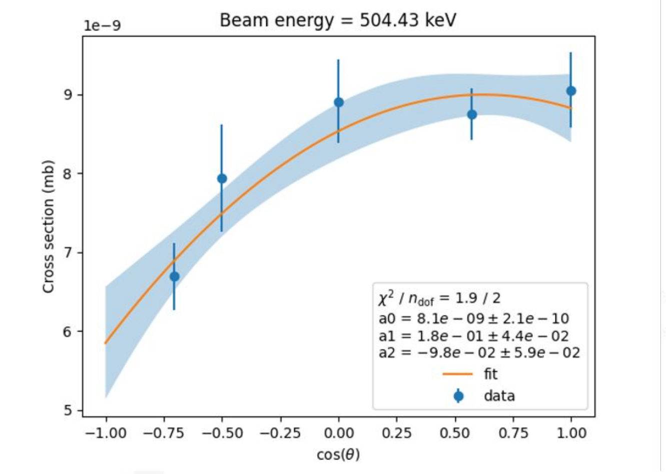
First new measurement since Schroeder et al (1987) in this energy range!

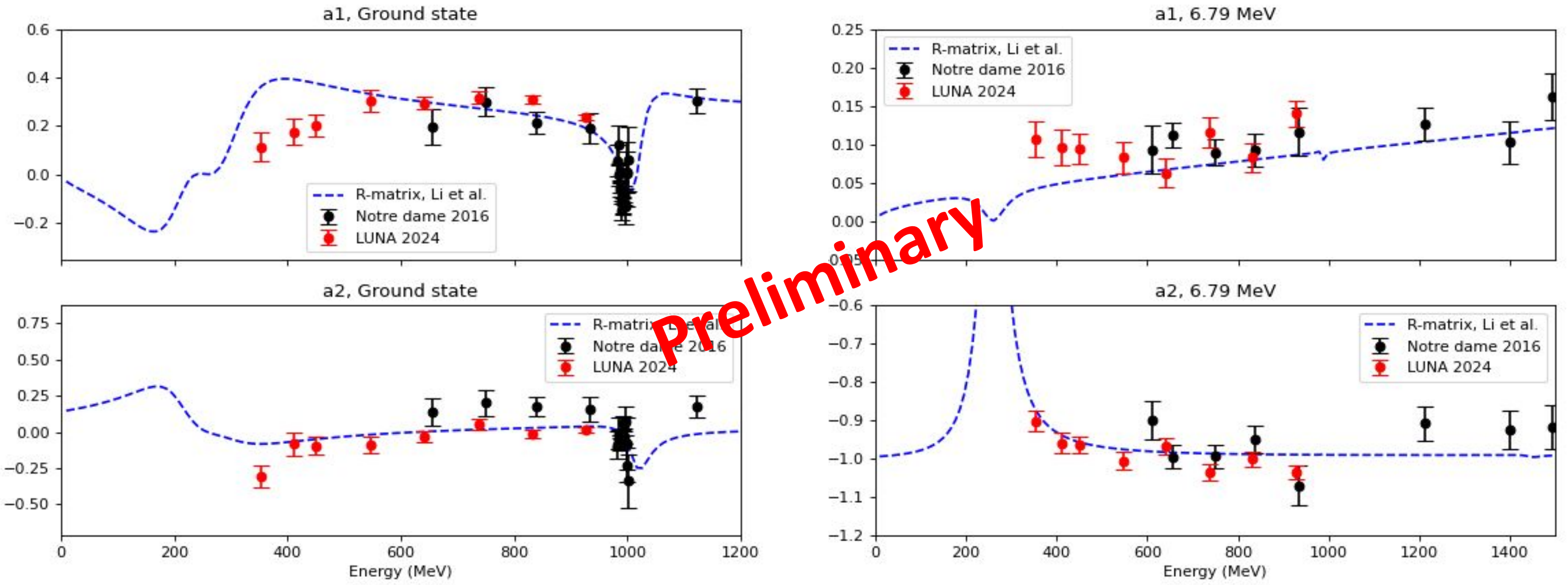
Angular distributions

- 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$\rightarrow$ 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 still underway, to be completed in 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.lngs.infn.it