Probing explosive nucleosynthesis underground: recent LUNA measurements at the Bellotti IBF

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(on behalf of the LUNA Collaboration)

INFN - Laboratori Nazionali del Gran Sasso

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Direct measurements are challenging

$$Counting\ rate = beam\ flux \times target\ nuclei\ areal\ density$$

beam flux	10^{15} pps	(**150 μA** for 1^{+} beams)
target nuclei areal density	10^{19} atoms/cm^2	(often smaller)

Corbet's Couloir, *Jackson Hole Mountain Resort*

Direct measurements are challenging

$$Counting\ rate = beam\ flux \times target\ nuclei\ areal\ density \times cross\ section$$

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cross section	10^{-36} cm^2	(often smaller)

Corbet's Couloir, *Jackson Hole Mountain Resort*

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a few counts/day

Corbet's Couloir, *Jackson Hole Mountain Resort*

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a few counts/day

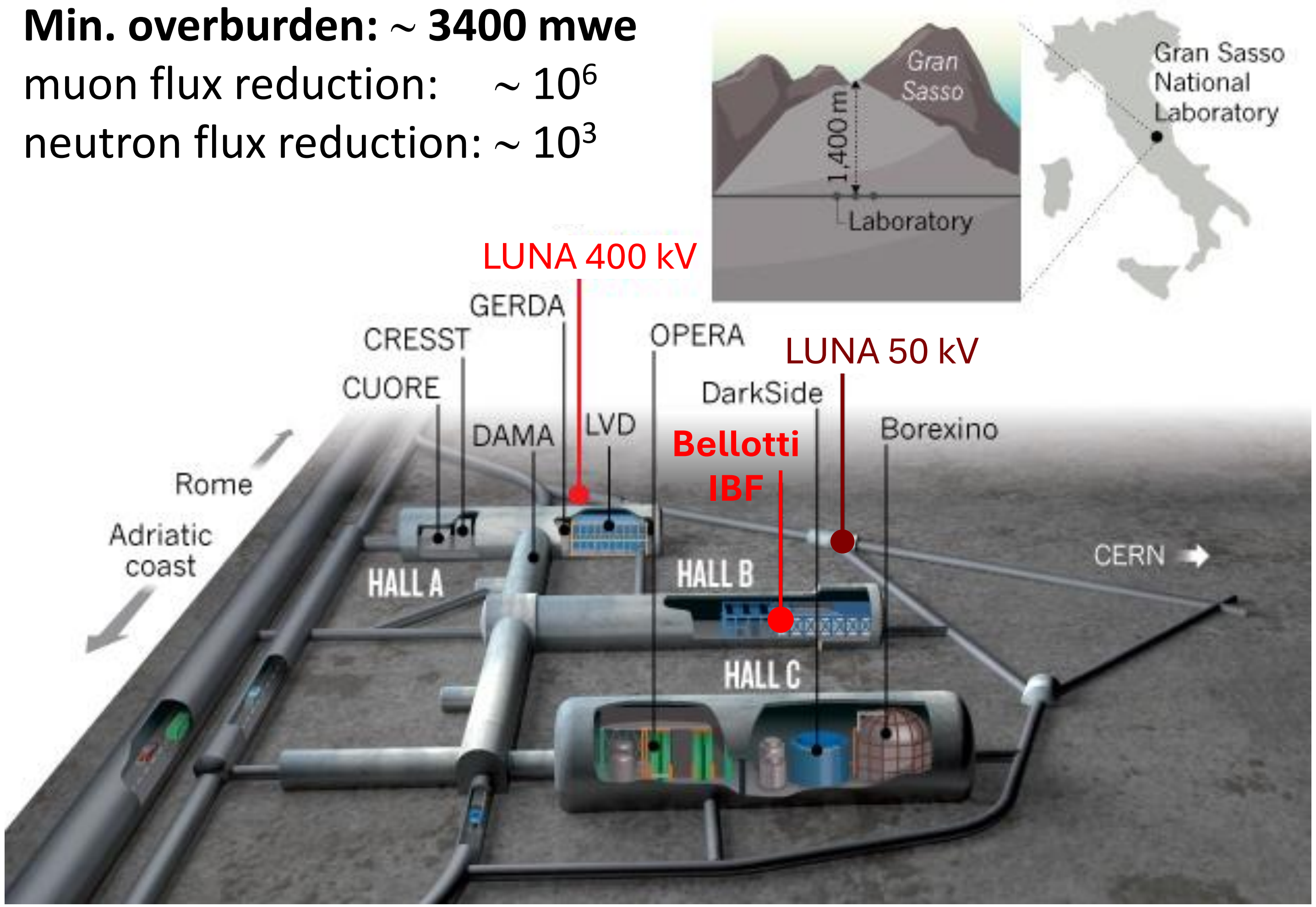
↓

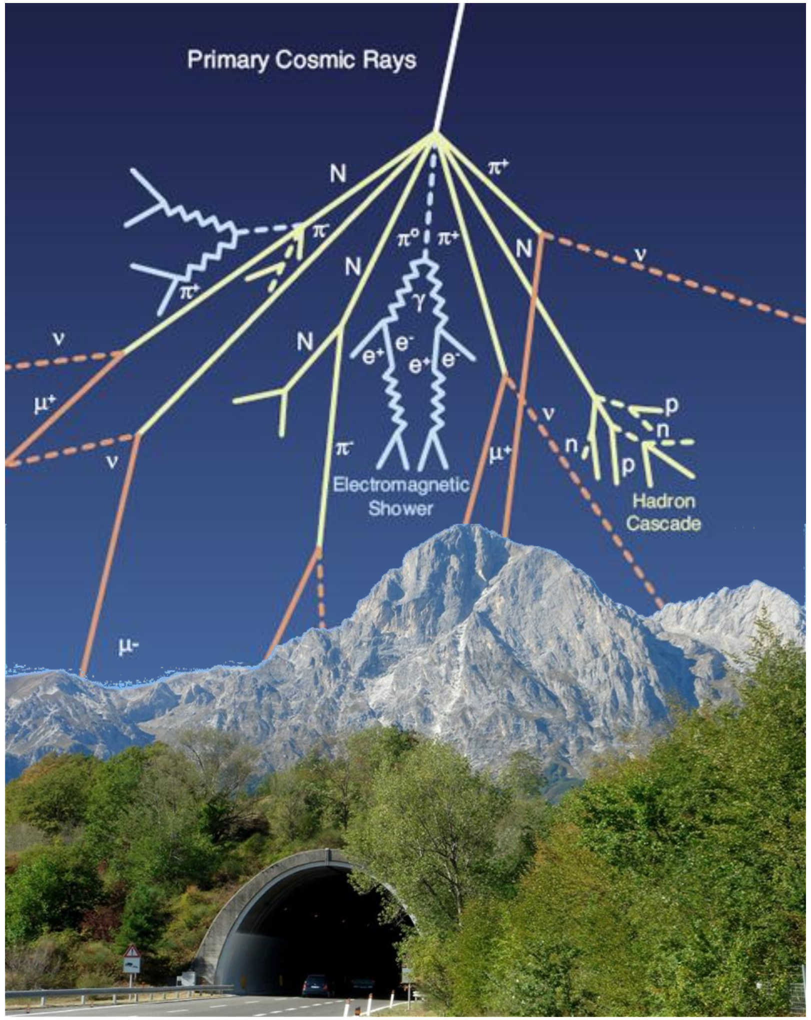
underground laboratories can shield our detectors!

Corbet's Couloir, *Jackson Hole Mountain Resort*

Underground laboratories

Min. overburden: ~ 3400 mwe
muon flux reduction: ~ 10^6
neutron flux reduction: ~ 10^3





"Explosive" measurements performed by LUNA

Motivation	Reaction	Past	Present	Future
^{18}F and the 511 keV emission in the first hours of nova	$^{17}O(p,\gamma)^{18}F$	LUNA 400 kV		
^{15}N abundance in novae emissions and grains	$^{15}N(p,\gamma)^{16}O$	LUNA 400 kV		
Sodium production in nova and 1275 keV line of ^{22}Na	$^{20}Ne(p,\gamma)^{21}Na$ $^{21}Ne(p,\gamma)^{22}Na$ $^{22}Ne(p,\gamma)^{23}Na$	LUNA 400 kV LUNA 400 kV LUNA 400 kV		
^{26}Al ground state, and the nova share of the 1809 keV emitters	$^{24}Mg(p,\gamma)^{25}Al$ $^{25}Mg(p,\gamma)^{26}Al$	LUNA 400 kV LUNA 400 kV		
^{27}Al destruction in nova	$^{27}Al(p,\gamma)^{28}Si$ $^{27}Al(p,\alpha)^{24}Mg$		LUNA 400 kV LUNA 400 kV	
Carbon ignition: thermonuclear supernovae and superbursts	$^{12}C+^{12}C$		**Bellotti IBF**	**Bellotti IBF**
Neutron source: weak s process and explosive shell burning	$^{22}Ne(\alpha,n)^{25}Mg$ $^{22}Ne(\alpha,\gamma)^{26}Mg$	**Bellotti IBF** LUNA 400 kV	 **Bellotti IBF**	

I will focus on **LUNA measurements at the Bellotti Ion Beam Facility**

Bellotti Ion Beam Facility

Inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.2 – 3.5 MV

Beam energy reproducibility: 0.01% TV or 50V

Beam energy stability: 0.001% TV / h

Beam current stability: < 5% / h

H^+ beam: 500 - 1000 μA

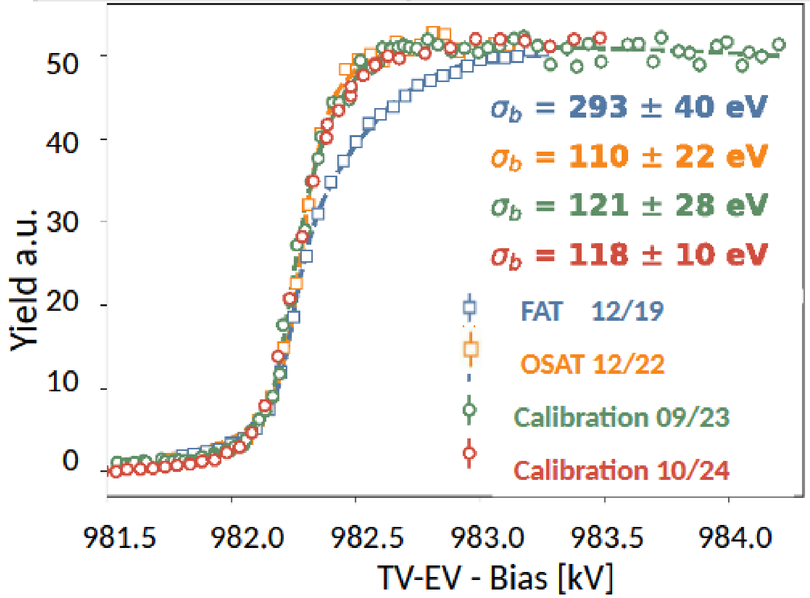
He^+ beam: 300 - 500 μA

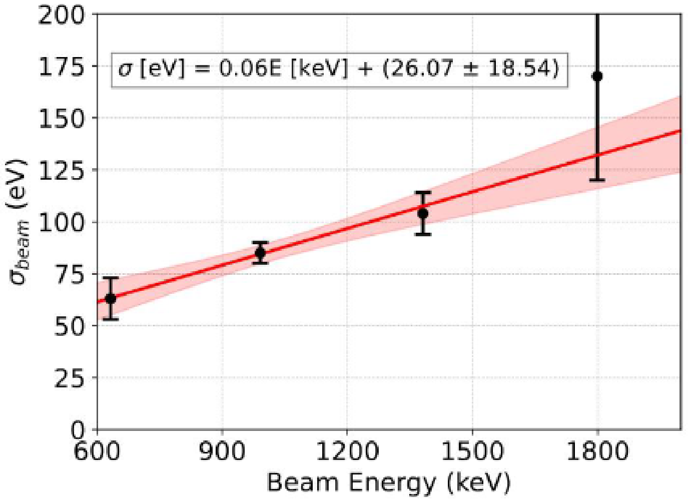
C^+ beam: 100 - 150 μA

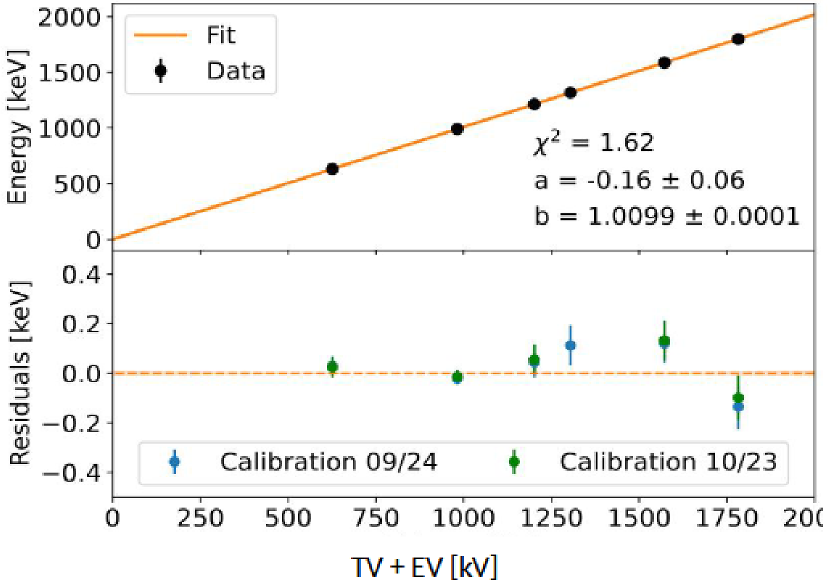
C^{++} beam: 50 pμA

Beam Energy calibration and stability using $^{27}Al(p,\gamma)$ resonances

$E_{r,\,lab}$ (keV)	Γ (eV)
632,23 ± 0.04	6,7 ± 0.5
991,86 ± 0.03	70 ± 10
1213,08 ± 0.06	< 100
1317,14 ± 0.07	35 ± 4
1587,49 ± 0.08	< 200
1799,75 ± 0.09	450 ± 60







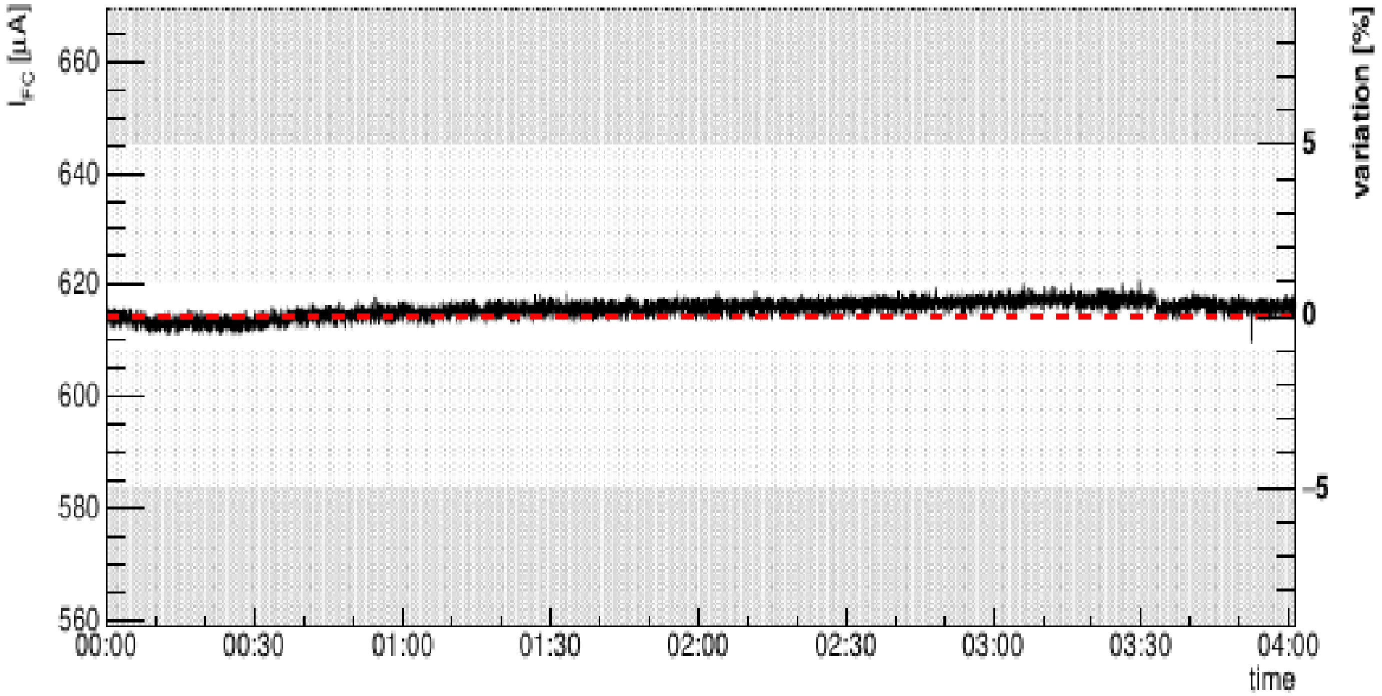
A. Compagnucci (GSSI & LNGS), J. Skowronski (Padova)

Beam current stability of the 3.5 MV Singletron

Maximum deviation of beam intensity: ≤ 5% / h

Credits: Matthias Junker

α beam	
Beam energy	1 MeV
Beam Intensity on target	615 μA
Test duration	4 h
Beam current variation	≤ 1 %/h



More information in

Sen *et al.*, https://doi.org/10.1016/j.nimb.2018.09.016

Junker *et al.*, https://doi.org/10.3389/fphy.2023.1291113

On Site Acceptance Test LNGS 2022/2023

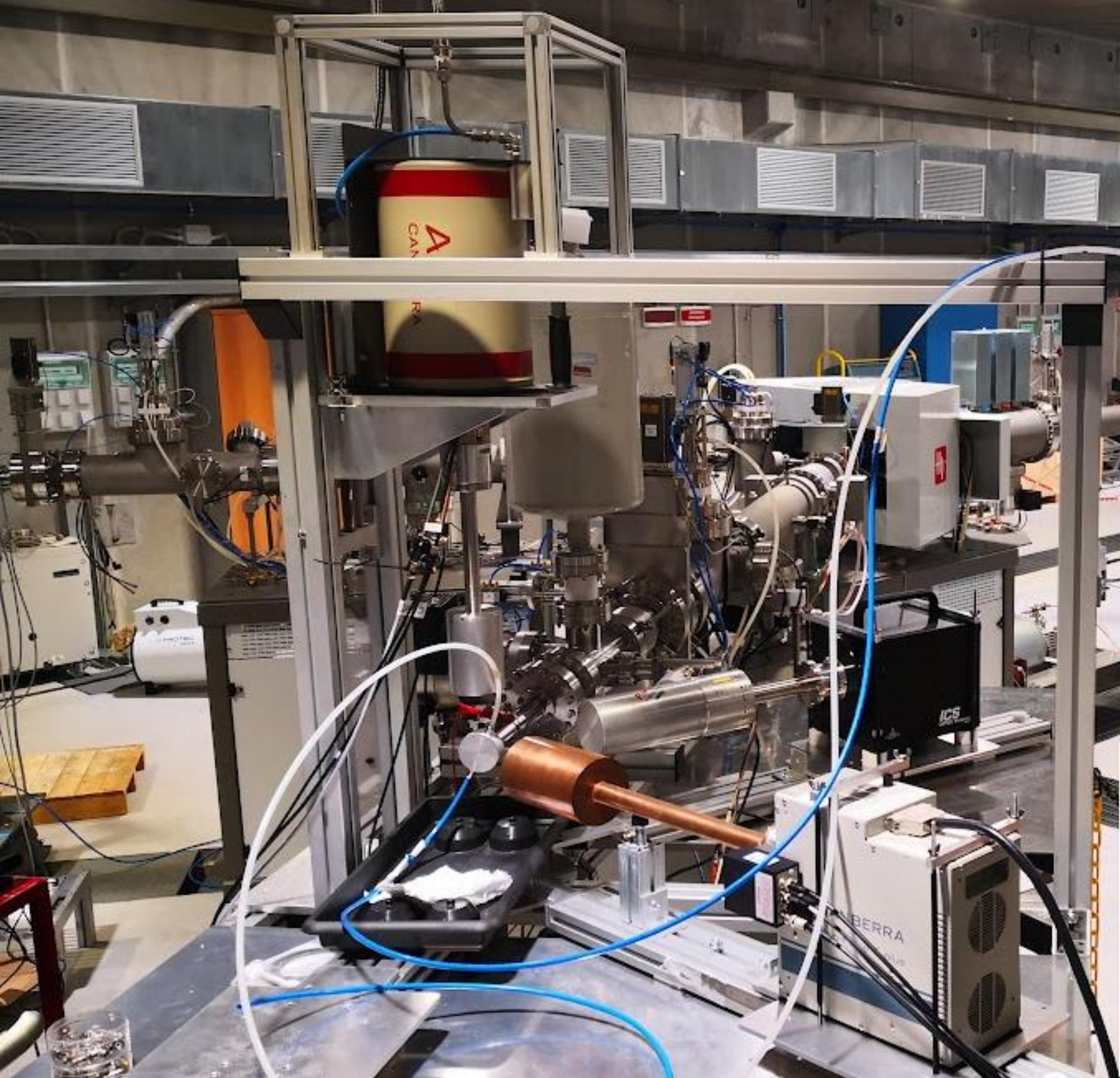
LUNA at the Bellotti Ion Beam Facility

$^{14}N(p,\gamma)^{15}O$ → writing ongoing → perfect **commissioning measurement,** useful for **calibration** purposes too

$^{22}Ne(\alpha,n)^{25}Mg$ → analysis ongoing → erc SHADES
Scintillator-^{3}**He** **A**rray for **D**eep-underground **E**xperiments on the **S**-process

$^{12}C+^{12}C$ → data taking ongoing → MUR CaBS
Carbon Burning in Stars

$^{22}Ne(\alpha,\gamma)^{26}Mg$ → starting in October → MUR EASγ
Experimental and **A**strophysical **S**tudy of the $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction



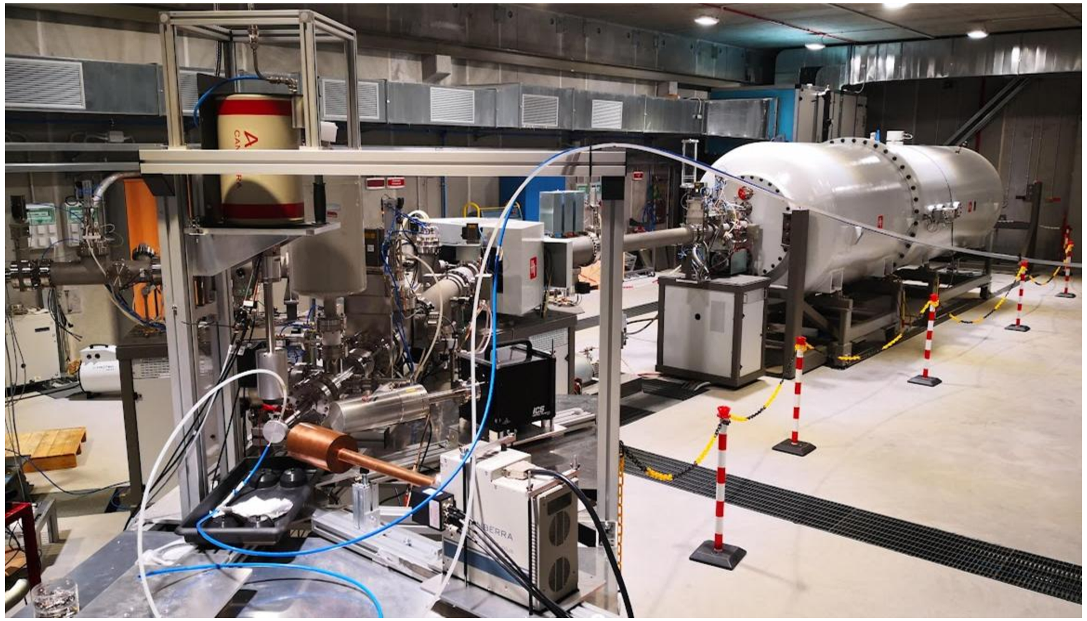
$^{14}N(p,\gamma)^{15}O$

3 High-Purity Germanium detectors allow for

- very high energy resolution
- close/far geometry
- reduced summing-in effect
- sensitivity to angular distribution

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

Credits: Alessandro Compagnucci

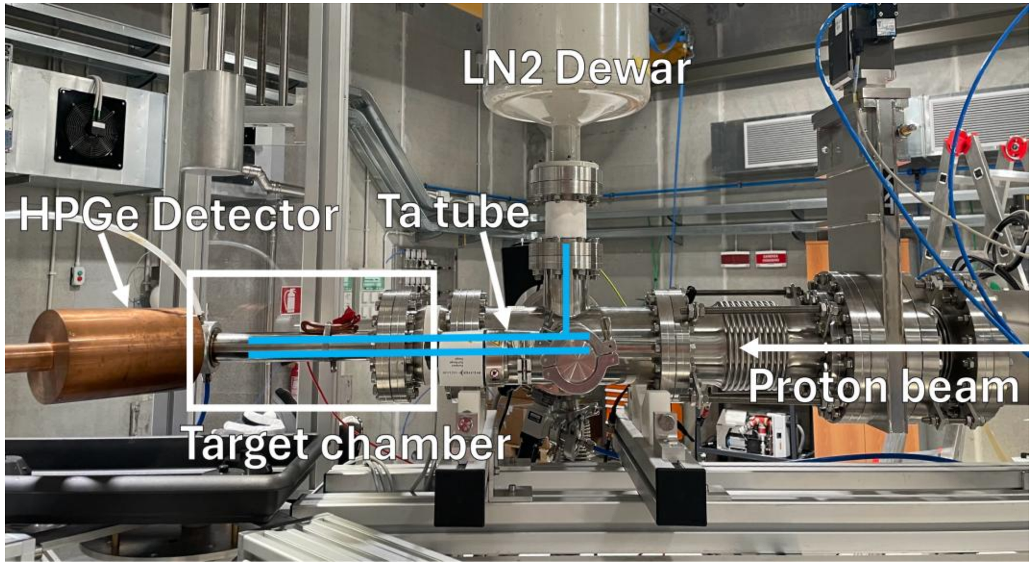


SETUP

- Single HPGe at 55° in close geometry, excitation function
- Three HPGe detectors on goniometric table
- (55°-135°-90° + 0°-120°-90°)
- Solid, enriched ^{14}N targets

GOALS

- Accelerator **commissioning**
- Cross-section measurements over a **wide-energy range**
- **Angular distribution** measurements
- Measure **weak transitions**



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

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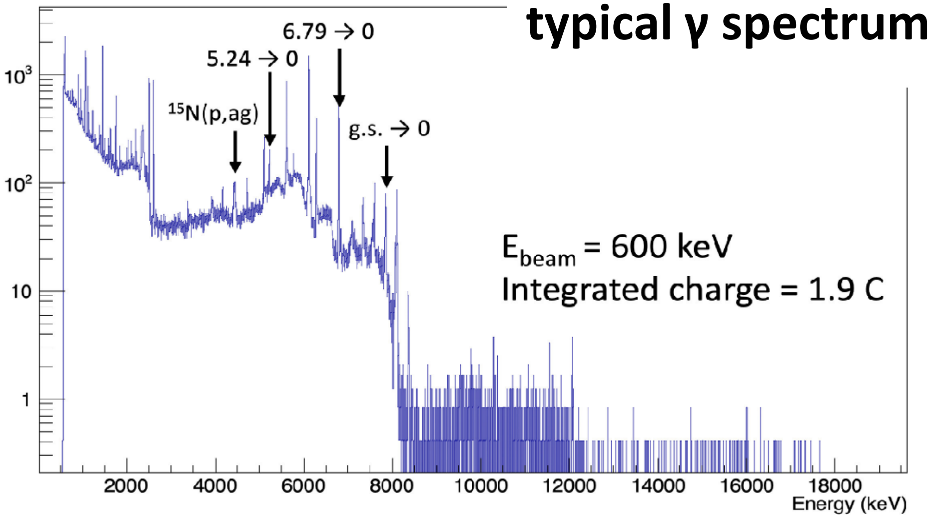
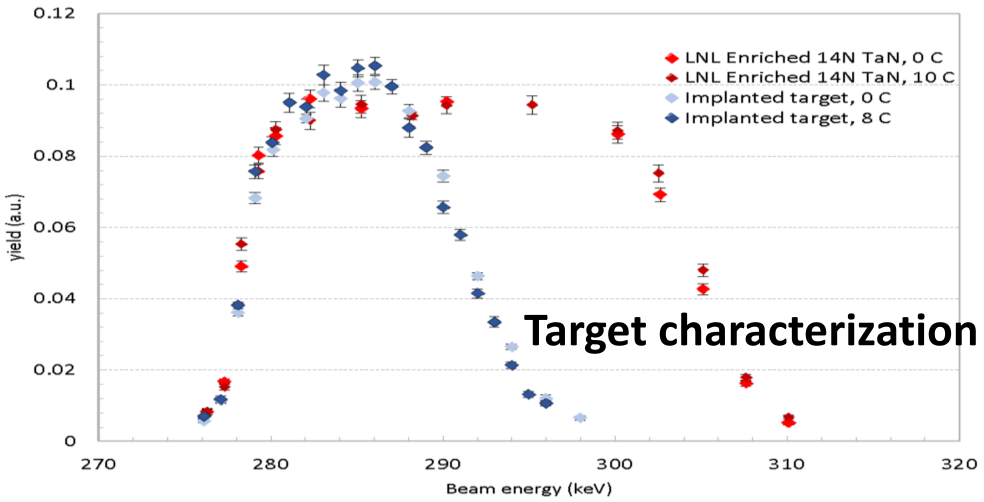
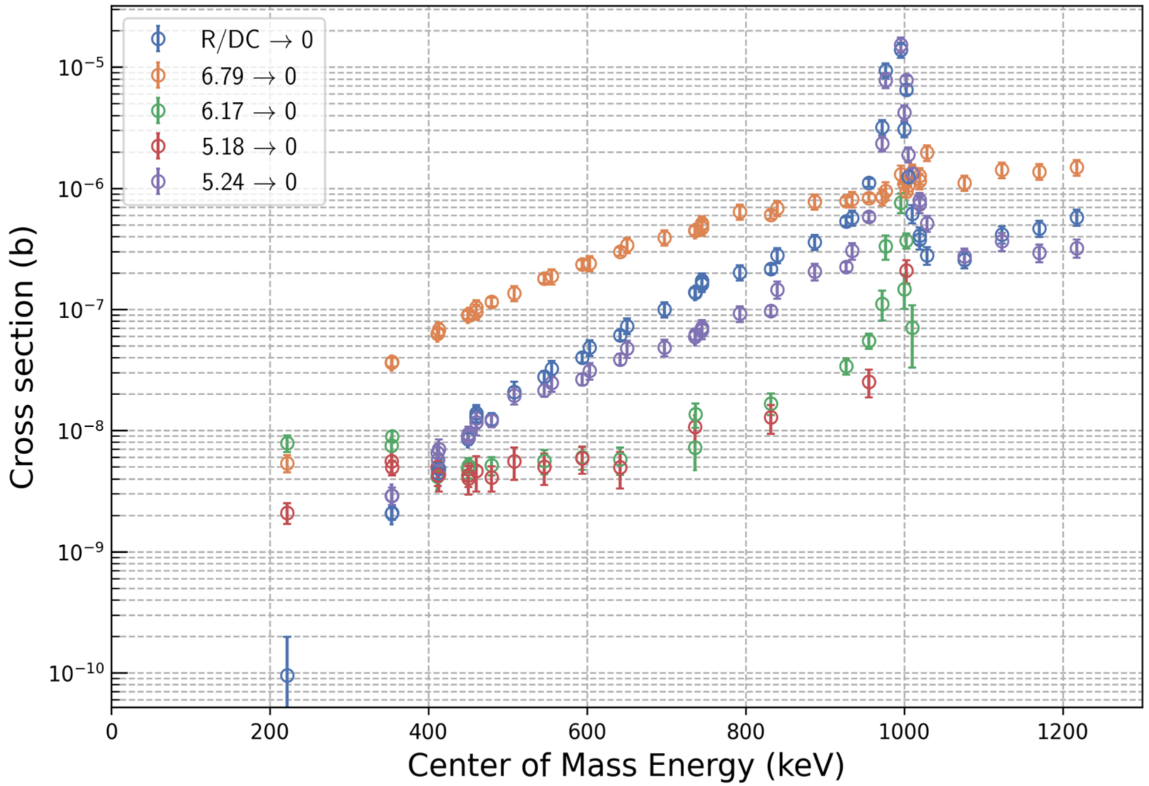
typical γ spectrum



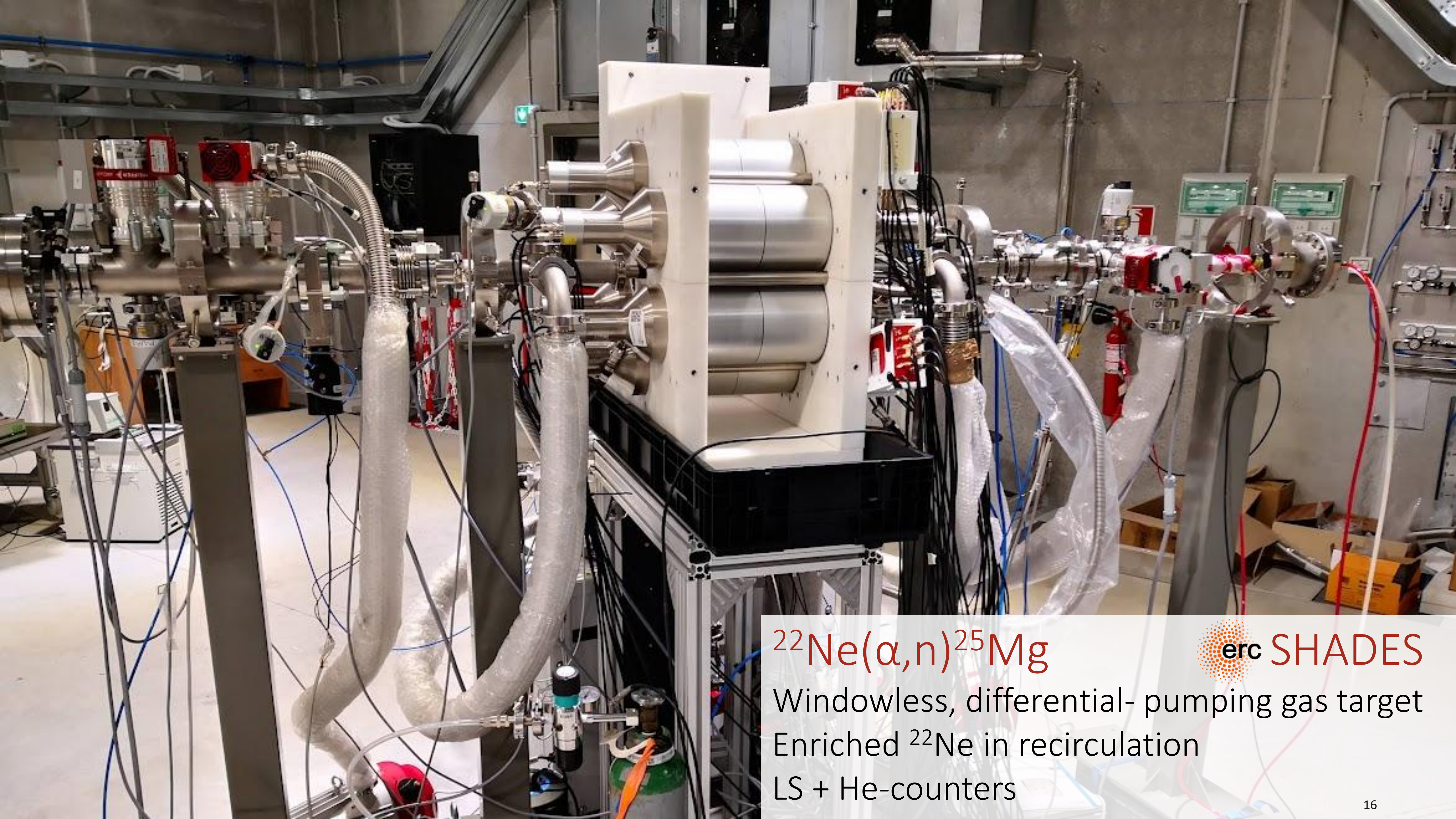


Target characterization

See the talk by Jakub Skowronski to have an idea what these data imply!



See paper on target preparation, characterization and first results: Compagnucci et al. EPJA **61**, 191 (2025)



^{22}Ne(α,n)^{25}Mg

erc SHADES

Windowless, differential- pumping gas target

Enriched ^{22}Ne in recirculation

LS + He-counters

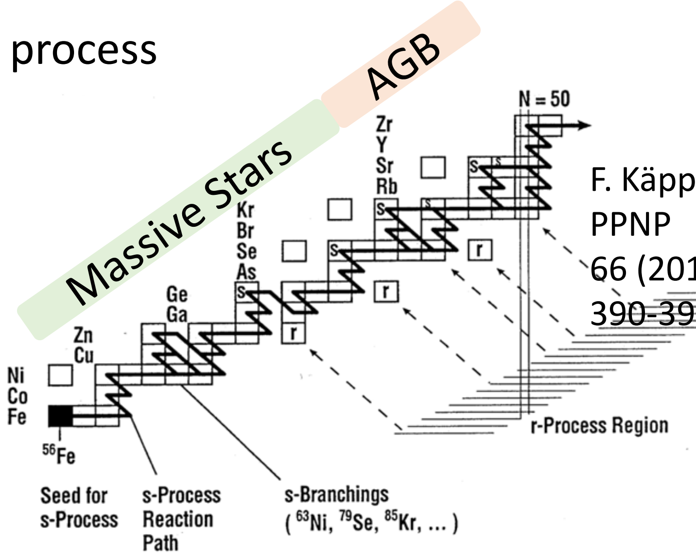
$^{22}Ne(\alpha,n)^{25}Mg$

Credits: Thomas Chillery

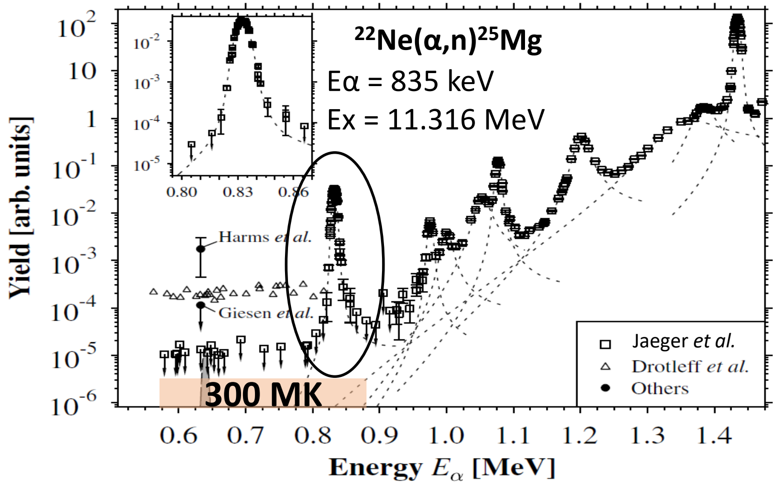
- ½ of elements heavier than Fe produced in slow neutron-capture (*s*-) process
- **Massive Stars**
  - Convective He core and C shell burning, 0.25 – 1 GK
  - Weak *s*-process component
- Asymptotic Giant Branch **(AGB) stars** ($M/M_\odot$ = 1.5 – 3)
  - He-rich inter-shell region
  - Main and strong *s*-process components
- Dominant neutron sources: **$^{22}Ne(\alpha,n)^{25}Mg$** and $^{13}C(\alpha,n)^{16}O$

BUT:
$$^{22}Ne(\alpha,n)^{25}Mg \leftrightharpoons {}^{22}Ne(\alpha,\gamma)^{26}Mg$$

AND:
Large uncertainties in these stellar rates; 0.2 – 0.3 GK

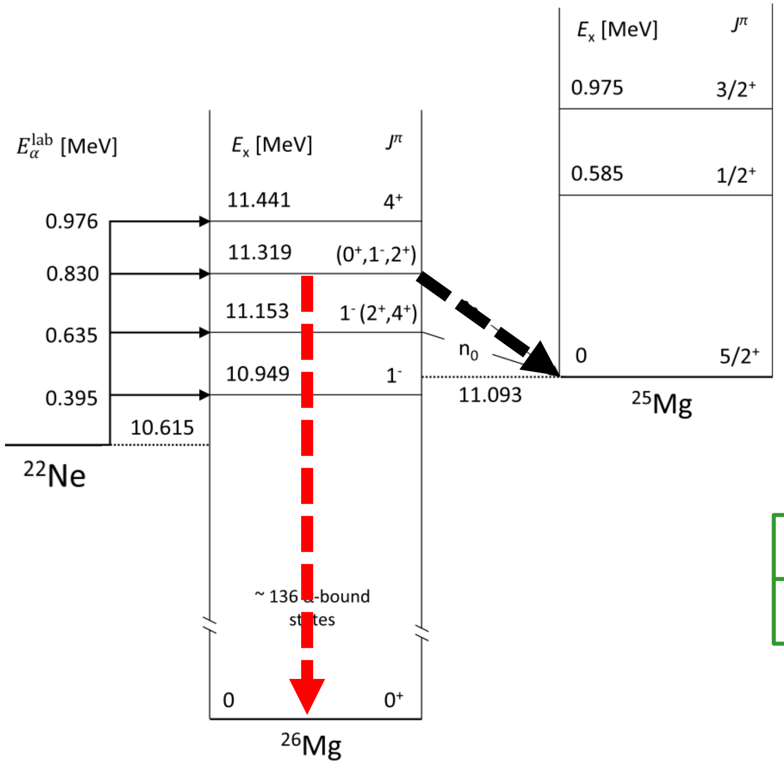


F. Käppeler, PPNP 66 (2011) 390-399

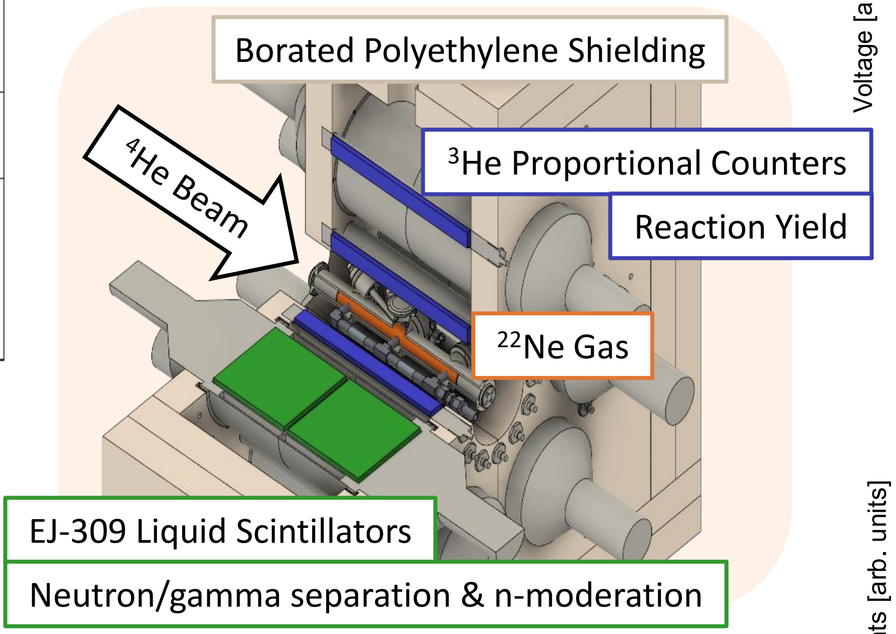


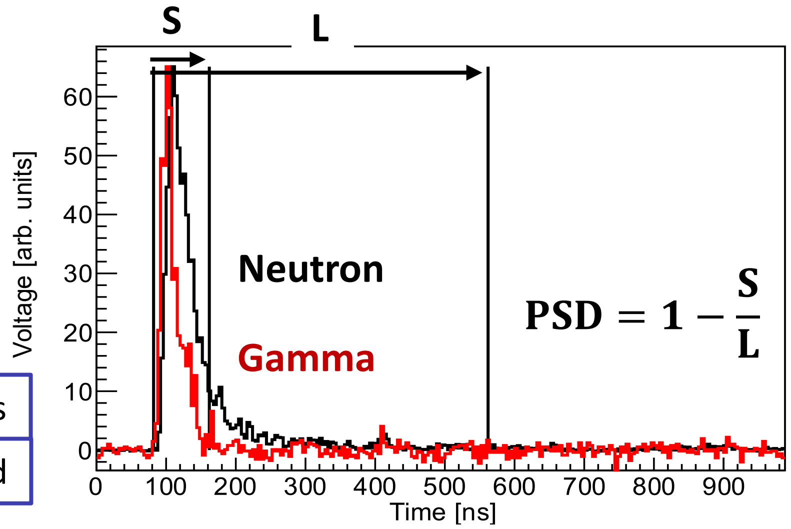
M. Jaeger *et al.* PRL 87 (2001) 202501

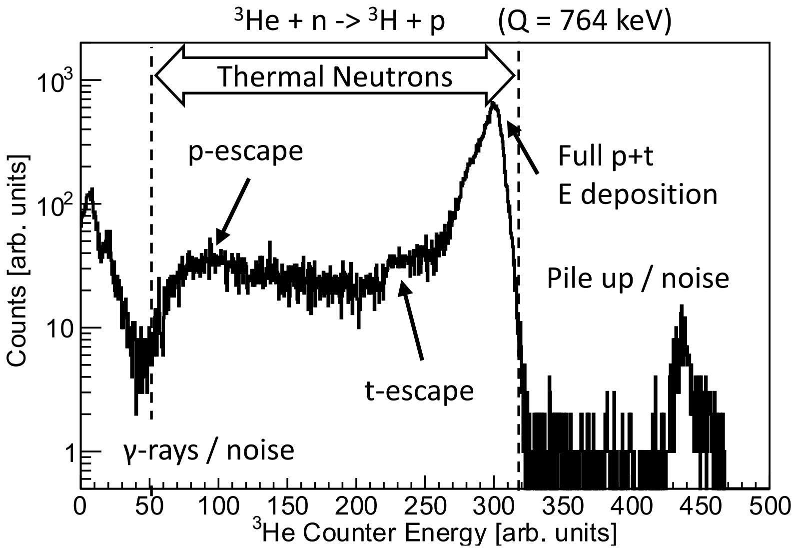
$^{22}Ne(\alpha,n)^{25}Mg$



Best et al. (2025)



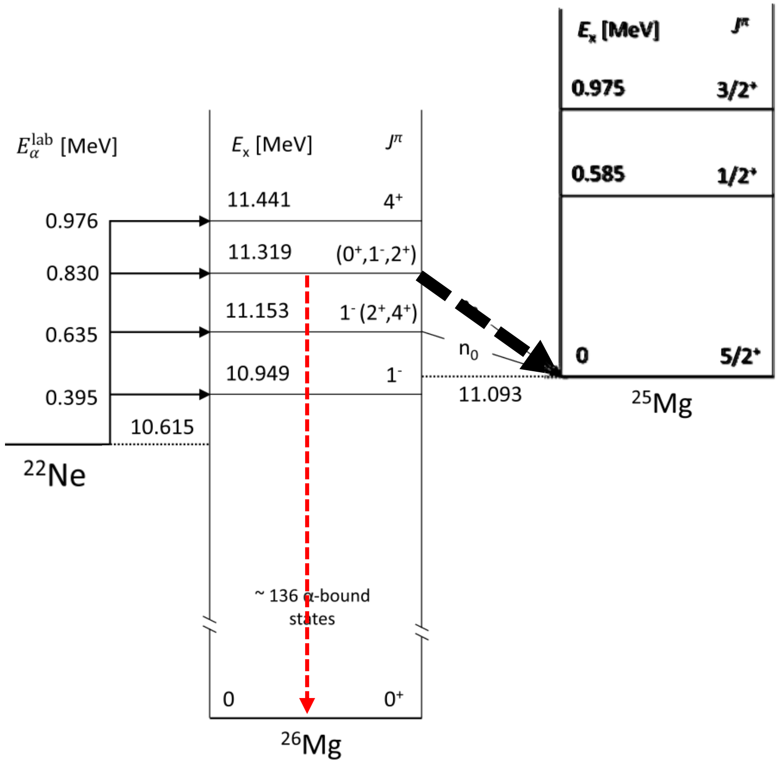




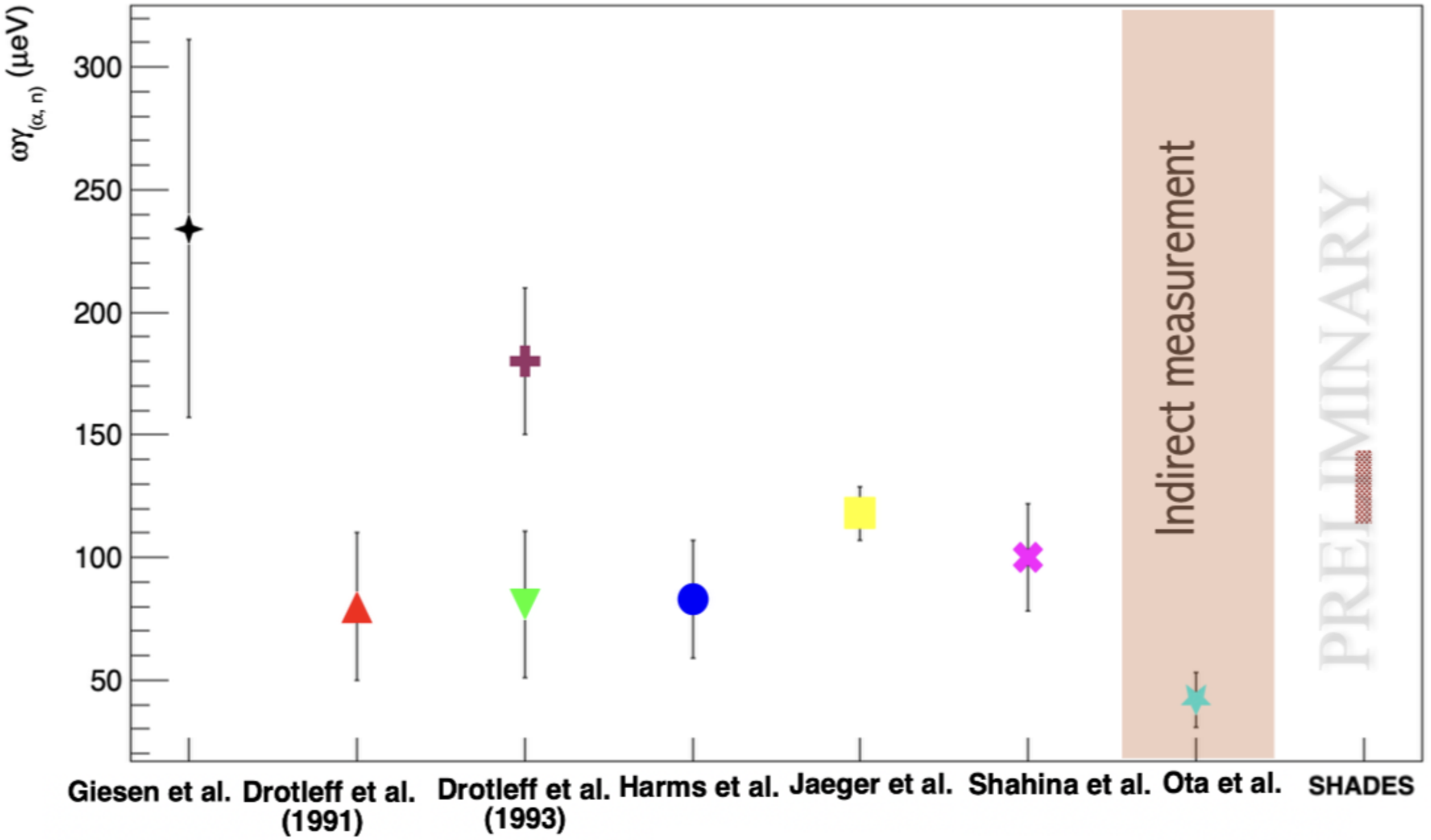
Credits: Marianna Vagnoni

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

A lot more details in the talk by Thomas Chillery



Best et al. (2025)



Credits: Marianna Vagnoni, Thomas Chillery

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

6-fold NaI detector allows for

- high detection efficiency
- coincidence analysis

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

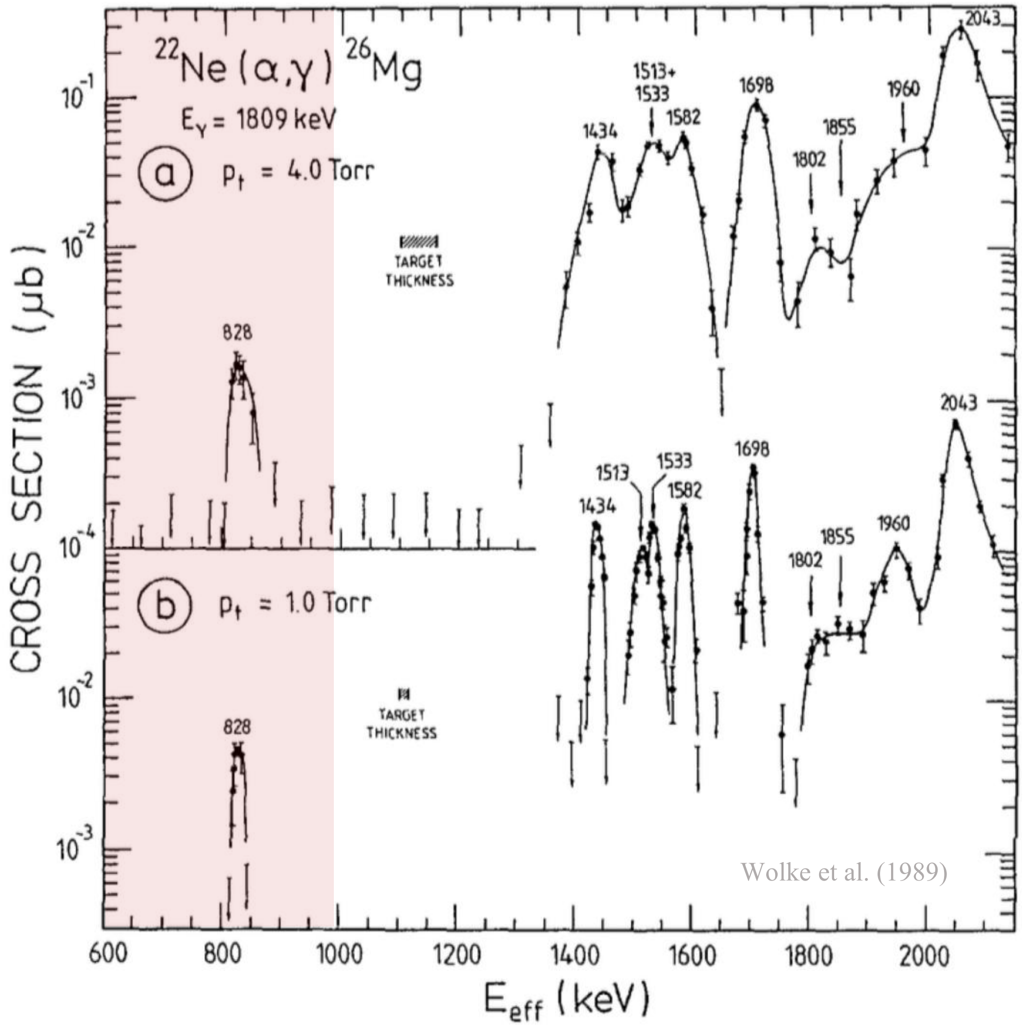
Together with the $^{22}Ne(\alpha,n)^{25}Mg$, the $^{22}Ne(\alpha,\gamma)^{26}Mg$ determines the neutron production rate for the weak s-process taking place in the thermal pulses

The weak *s-process* is both a direct product of the star and a seed for the explosion, so the ^{22}Ne branching enters the final yields twice!
[Pignatari, M., Roberti, L. & Jiao, T., *Eur. Phys. J. A* 62, 143 (2026)]

studied via direct and indirect measurements (also by LUNA [5])

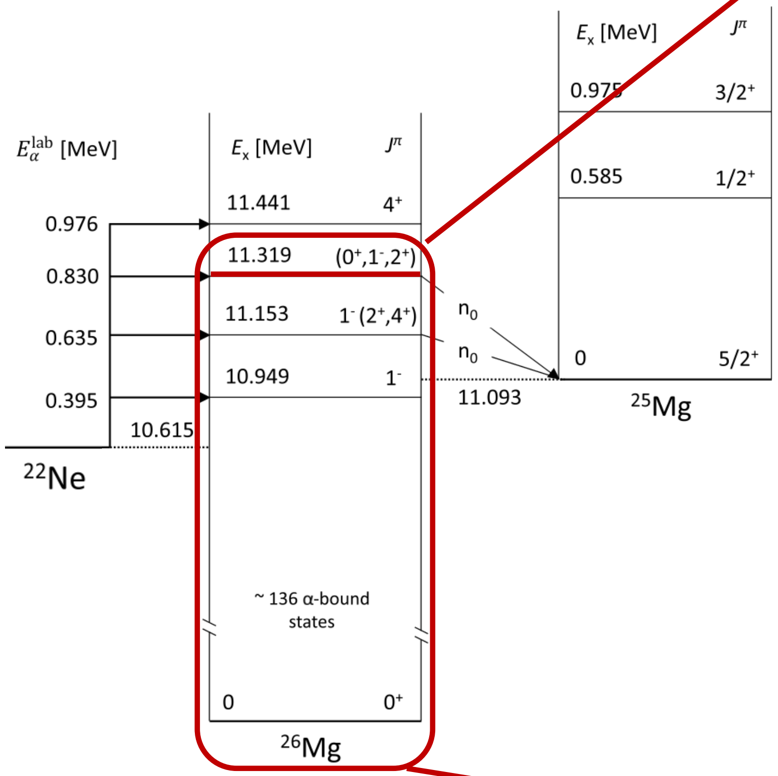
$E_R^{lab}(E_R^{cm})$ [keV]	E_X [MeV]	J^π	Γ_α [eV]	Γ_γ [eV]	$\omega\gamma_{(\alpha,\gamma)}$ [eV]	neutrons
123 (104)	10.719	1^-	2.5×10^{-36} [4]		$2.4^{+4.6}_{1.6} \times 10^{-35}$ [4]	no
396 (335)	10.950	1^-	6.7×10^{-14} [4] 3.00×10^{-14} [8, 9]		$2(1) \times 10^{-13}$ [4] $\leq 4.0 \times 10^{-11}$ [5] $\leq 1.5 \times 10^{-10}$ [5]	no
557 (471)	11.085	2^+	$\leq 8.4 \times 10^{-12}$ [4] 5.70×10^{-11} [6, 8, 9]	3	$\leq 4.2 \times 10^{-10}$ [4] 2.85×10^{-10} [7]	no
651 (551)	11.165	4^+ 2^+	$\leq 1.3 \times 10^{-11}$ [4] 1.00×10^{-7} [4] $< 1.3 \times 10^{-11}$ [9]		$\leq 1.5 \times 10^{-5}$ [3]	yes yes
830 (702)	11.320	1^-	5.00×10^{-5} [4] 2.70×10^{-5} [6] 1.30×10^{-5} [8] 3.00×10^{-5} [9]	0.4 – 1.0	$3.5(4) \times 10^{-5}$ [4] $(3.6 \pm 0.4) \times 10^{-5}$ [1] $(4.6 \pm 1.2) \times 10^{-5}$ [2] $(3.5 \pm 0.4) \times 10^{-5}$ [3]	yes

[1] Wolke et al. (1989) [2] Hunt et al. (2019) [3] Shahina et al. (2022) [4] Talwar et al. (2016) **[5] Piatti et al. (2020)**
[6] Adsley et al. (2018) [7] Adsley et al. (2020) [8] Jayatissa et al. (2020) [9] Ota et al. (2020).

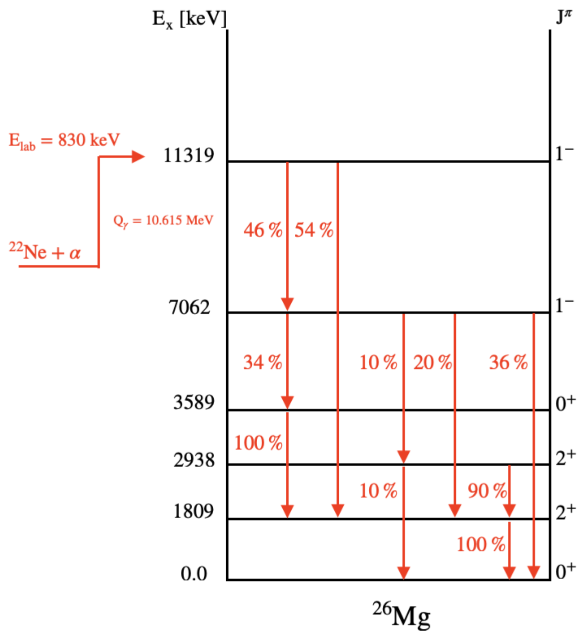


Credits: Giovanni Ciani

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

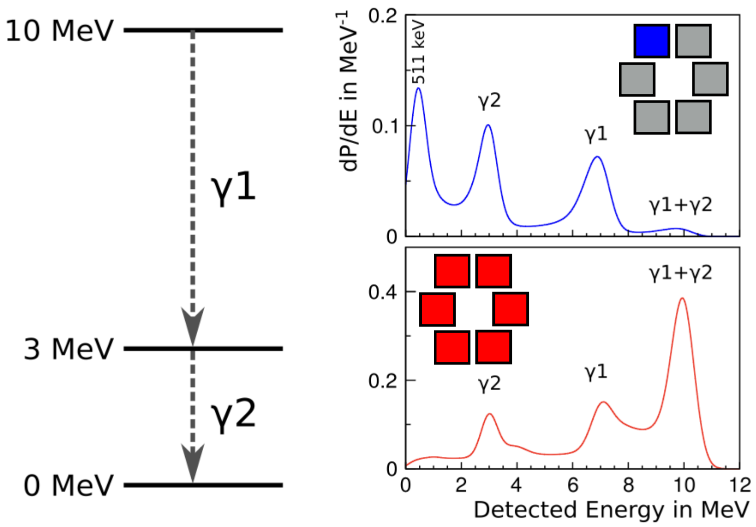


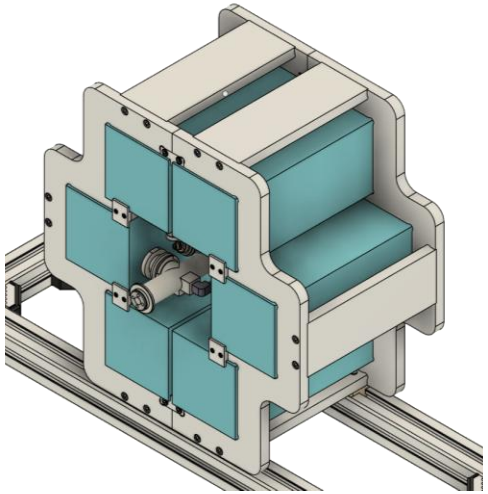
Best et al. (2025)



E_γ [keV]	B.R. [%]	Transition	Reference
1129	90	2938 → 1809	NNDC
1780	100	3589 → 1809	NNDC
1809	100	1809 → 0	NNDC
3473	34	7062 → 3589	NNDC
4258	46	R → 7062	Hunt et al. (2019)
7062	36	7062 → 0	NNDC
9511	54	R → 1809	Hunt et al. (2019)

Adapted from Boeltzig et al. (2018)



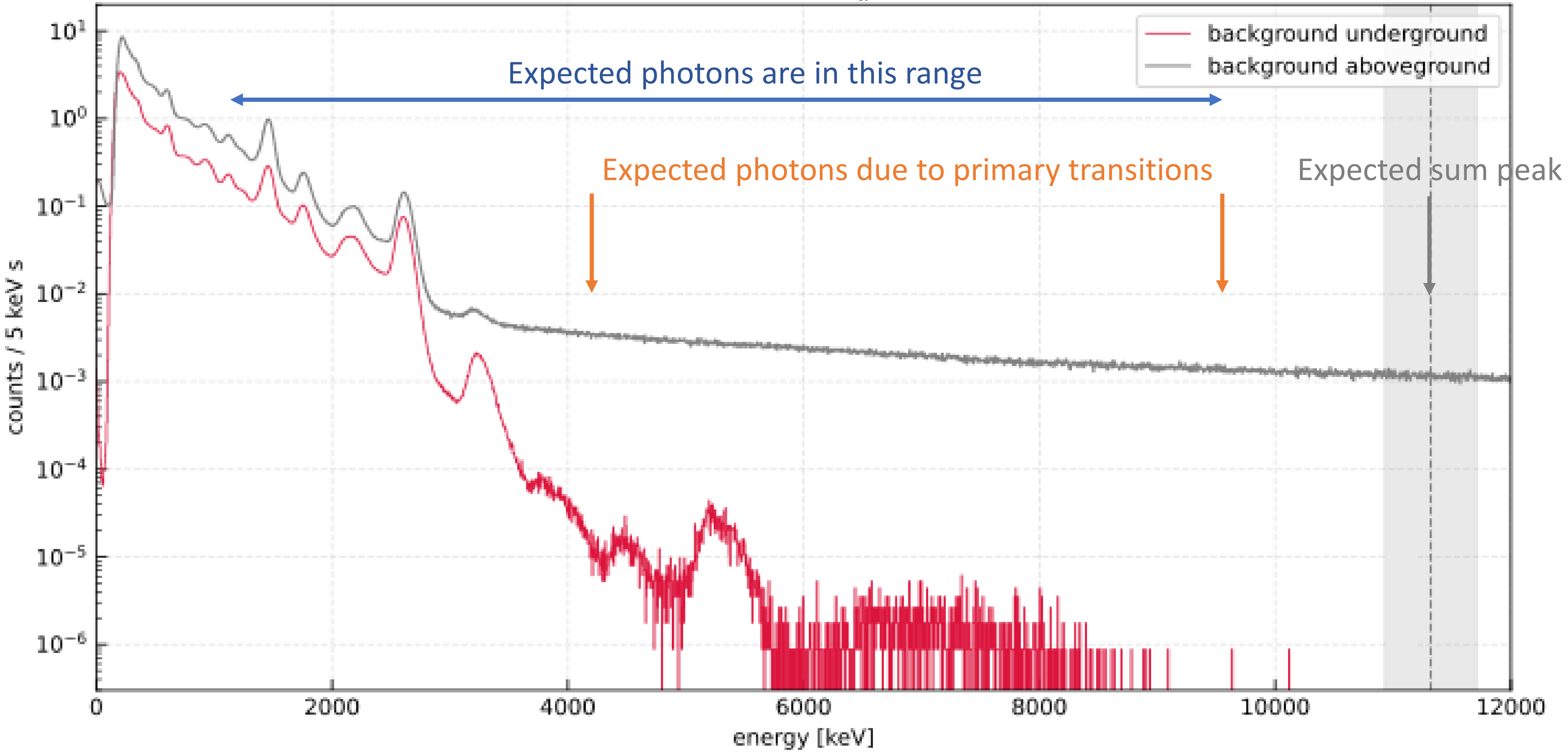


Credits: Marianna Vagnoni

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

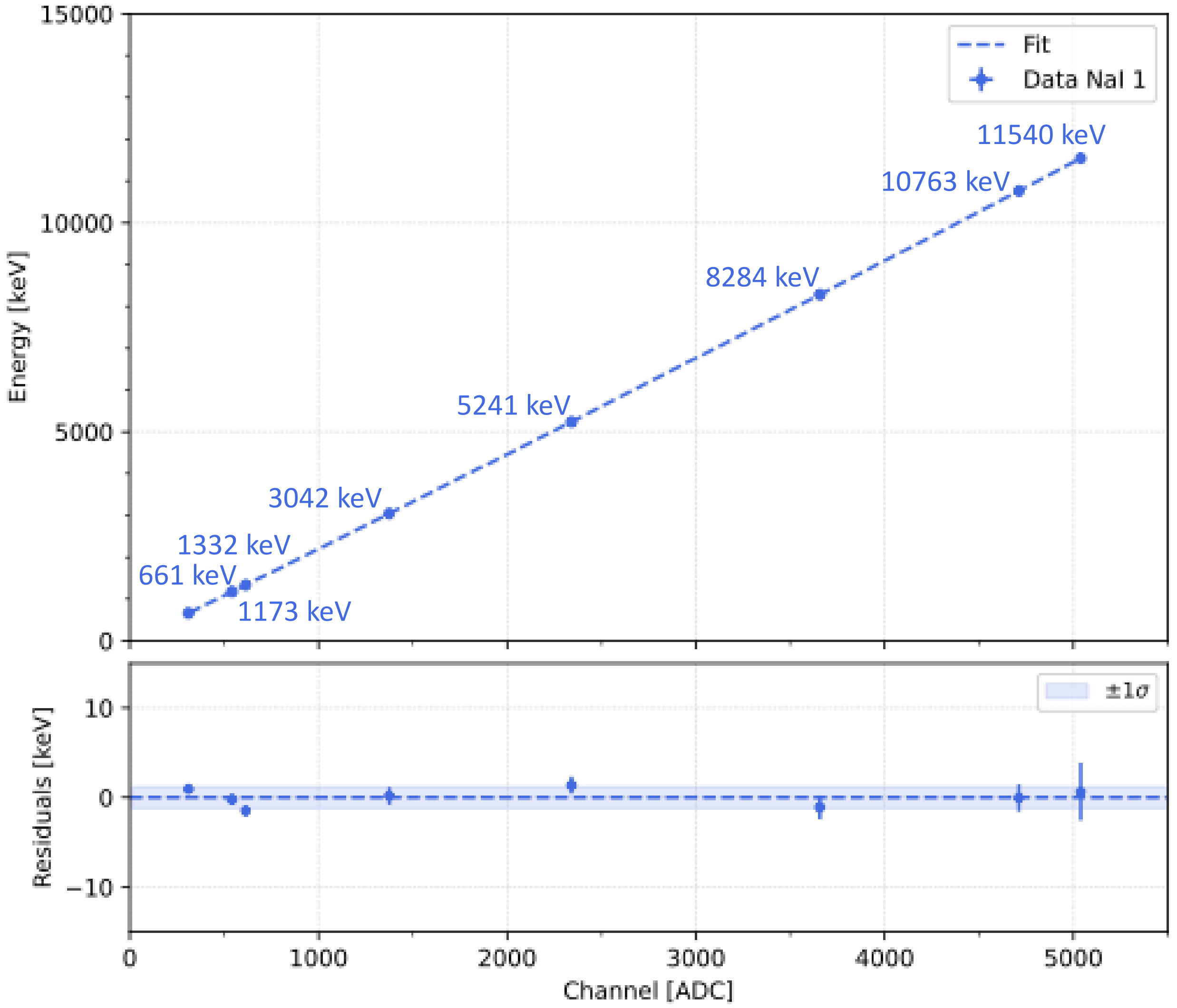
Credits: Marianna Vagnoni

Considering the resonance at E_α=830 keV…



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

Credits: Marianna Vagnoni



Each detector is calibrated using:

- 661 keV from ^{137}Cs
- 1173 keV and 1332 keV from ^{60}Co

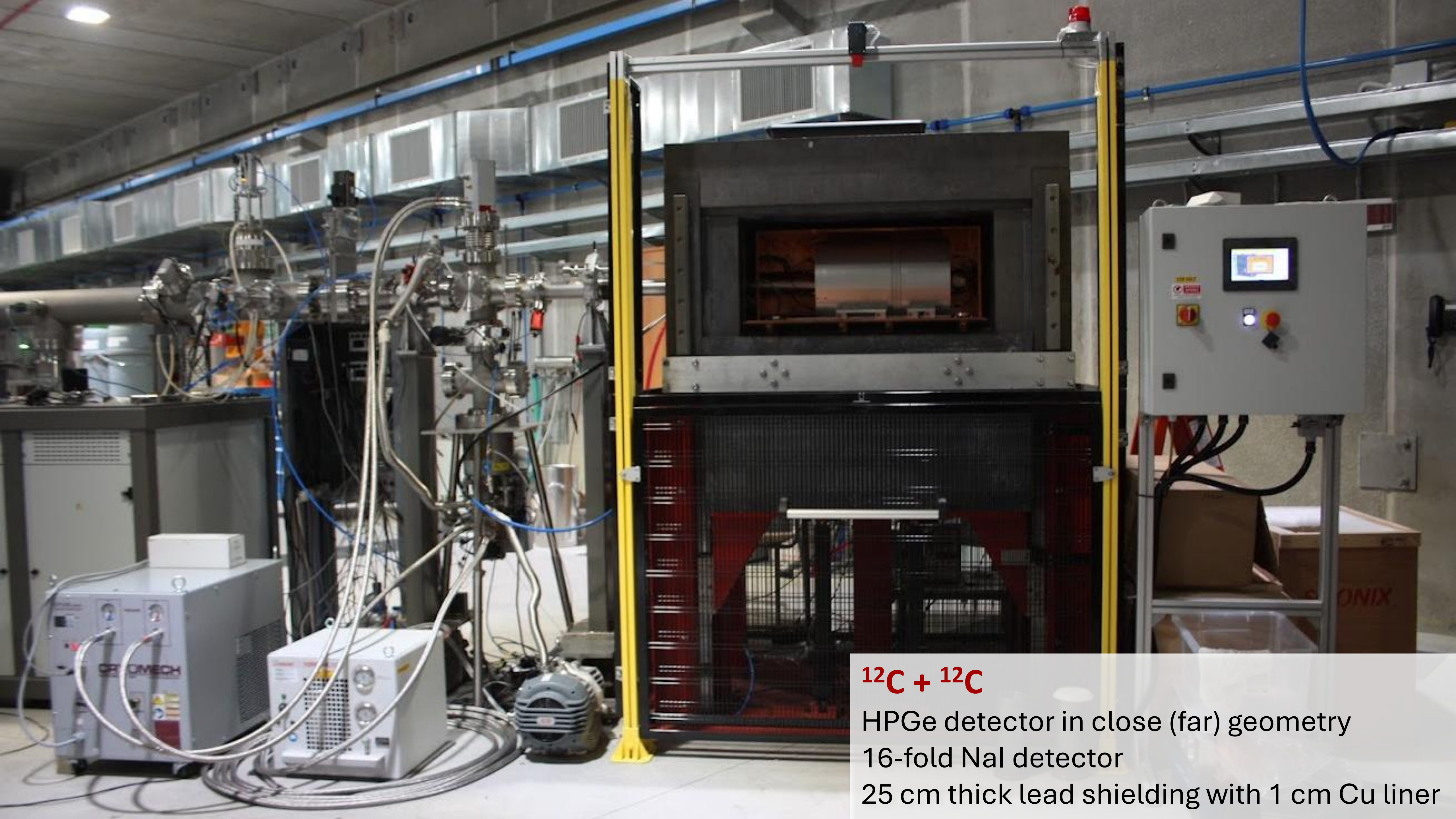
- 3042 keV, 5241 keV and 8284 keV from $^{14}N(p,\gamma)^{15}O$ at the plateau of 1058 keV resonance
- 10763 keV from $^{27}Al(p,\gamma)^{28}Si$ at the plateau of 992 keV resonance
- 11540 keV from $^{27}Al(p,\gamma)^{28}Si$ at the plateau of 1800 keV resonance

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

Giovanni Ciani and Marianna Vagnoni

- Setup for the measurement of the $^{22}Ne(\alpha,n)^{25}Mg$ now decommissioned
- setup for the $^{22}Ne(\alpha,\gamma)^{26}Mg$
  - mounted
  - commissioning ongoing

Measurements of the $^{22}Ne(\alpha,\gamma)^{26}Mg$ are going to start in mid-October



$^{12}C + ^{12}C$

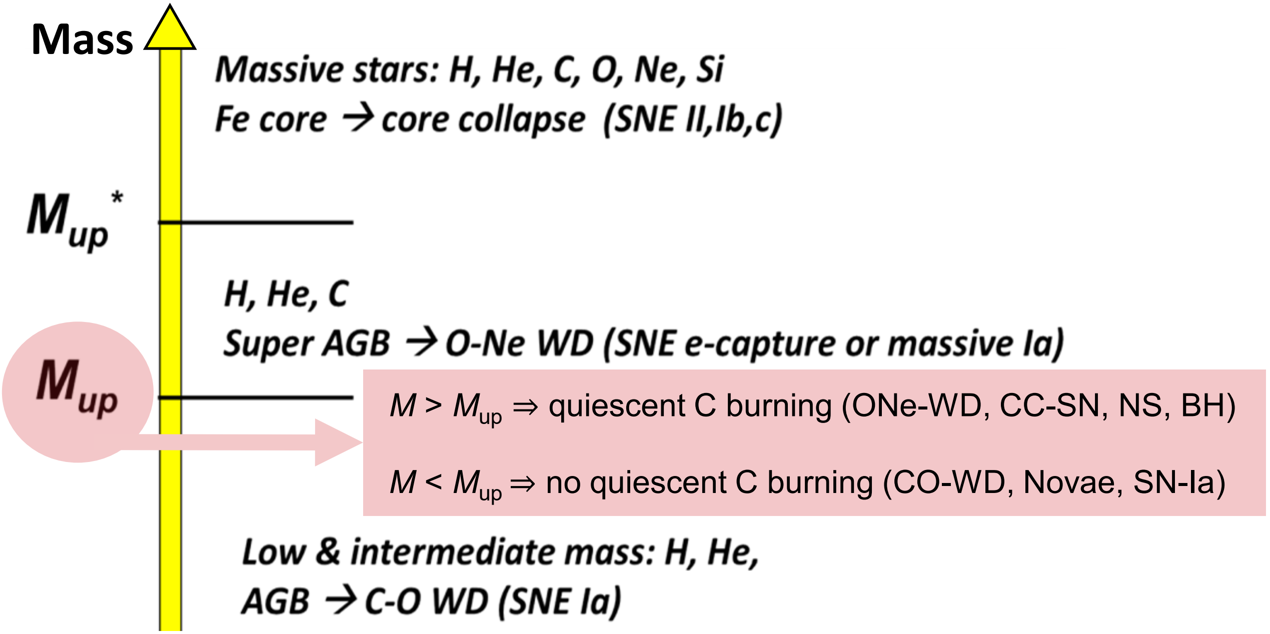
HPGe detector in close (far) geometry

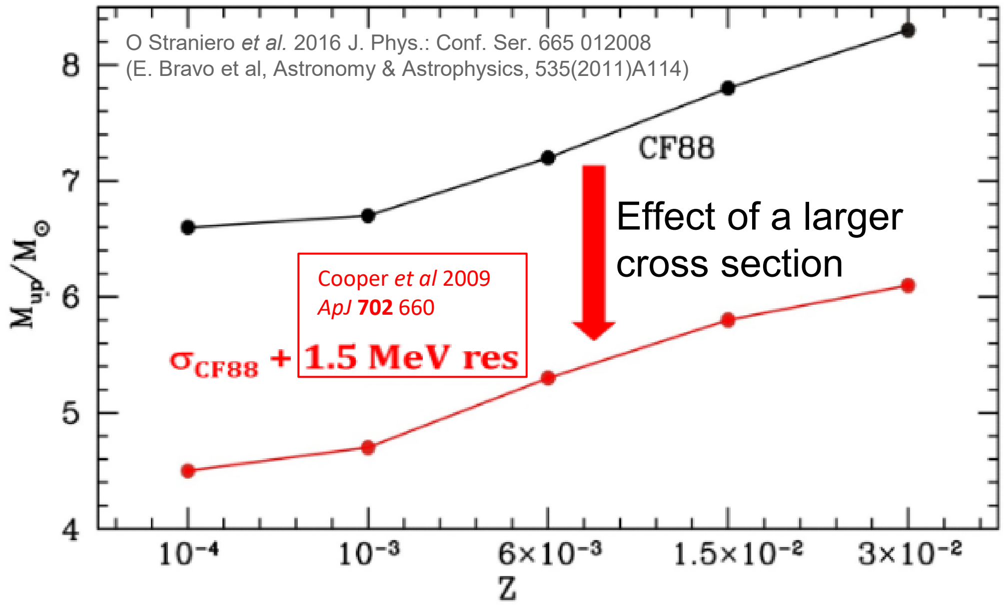
16-fold NaI detector

25 cm thick lead shielding with 1 cm Cu liner

$^{12}C + {}^{12}C$

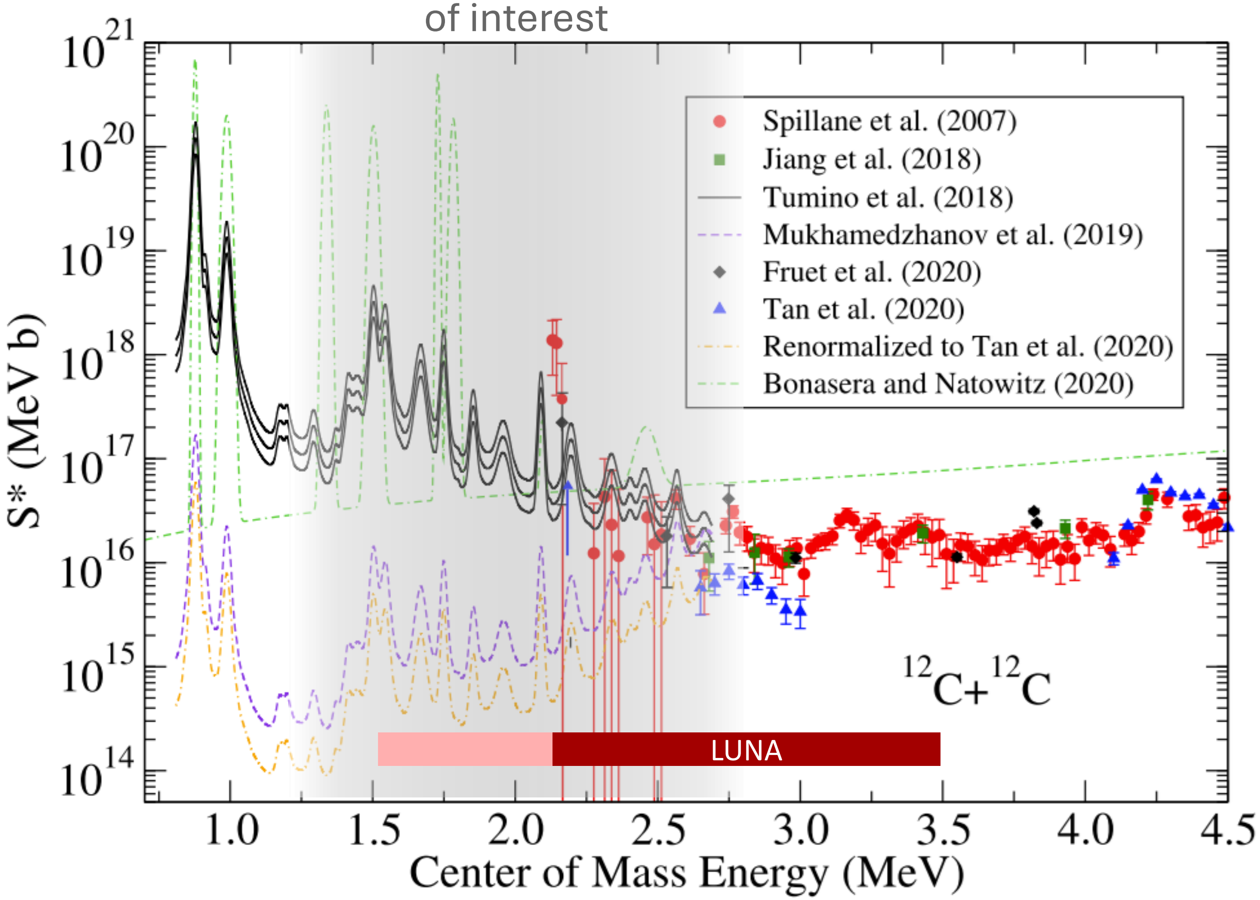
- its cross section **determines the ignition conditions of the carbon burning stage** of massive stars
- in an accreting WD it decides where and when the runaway starts, therefore the outcome of SN Ia
- it is related to the superburst recurrence time and outflows composition





$^{12}C + ^{12}C$

Energy range
of interest



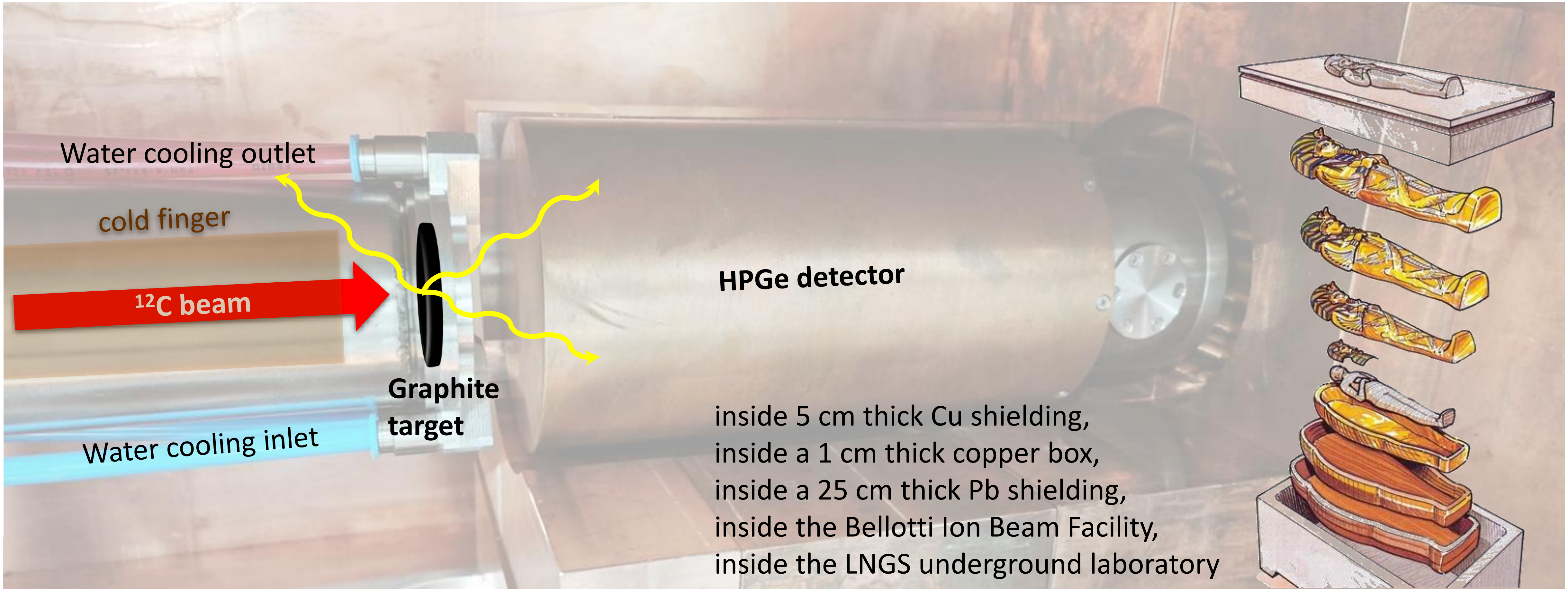
Several datasets and models

Direct measurements above 2.1 MeV (affected by large scattering, large uncertainties)

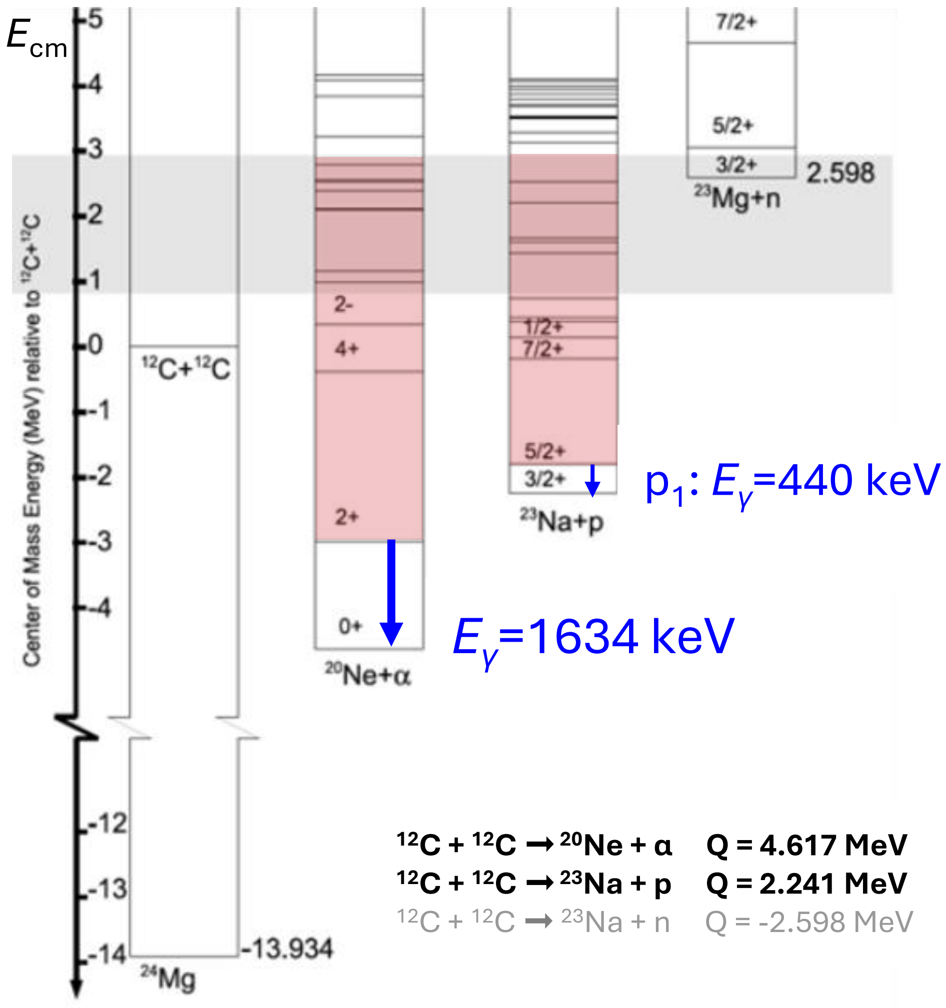
Indirect measurements below 2.1 MeV (but they need solid direct data to rely on)

Very large uncertainty below 2.5 MeV
(energy range of interest)

$^{12}C + ^{12}C$


Water cooling outlet
cold finger
12C beam
Graphite target
Water cooling inlet
HPGe detector
inside 5 cm thick Cu shielding,
inside a 1 cm thick copper box,
inside a 25 cm thick Pb shielding,
inside the Bellotti Ion Beam Facility,
inside the LNGS underground laboratory

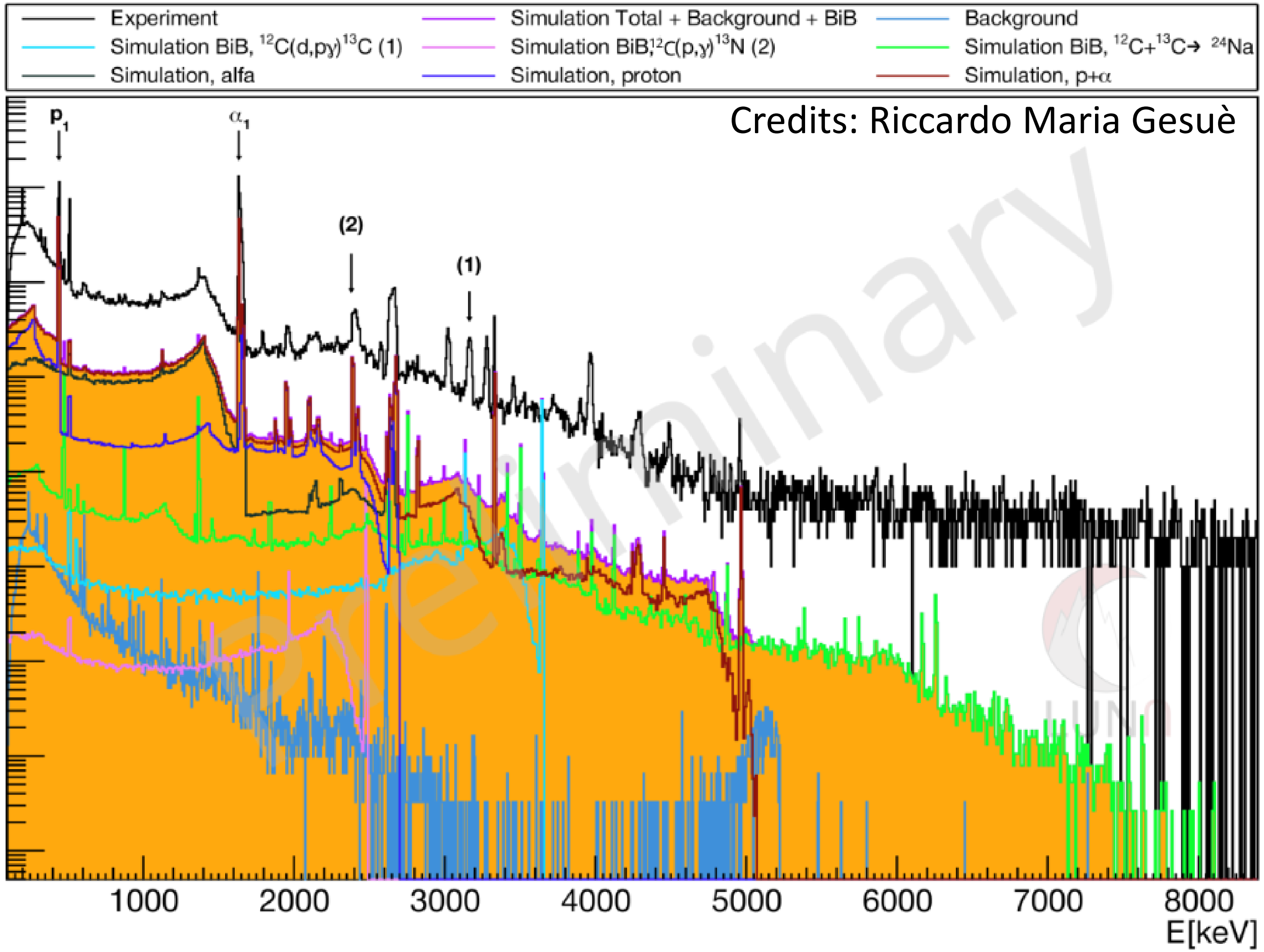
$^{12}C + ^{12}C$



$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ Q = 4.617 MeV

$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ Q = 2.241 MeV

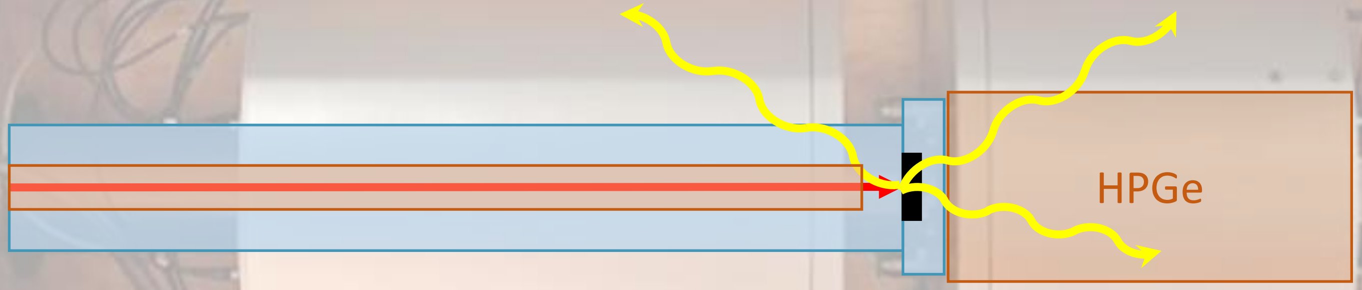
$^{12}C + ^{12}C \rightarrow ^{23}Na + n$ Q = -2.598 MeV



$^{12}C + ^{12}C$

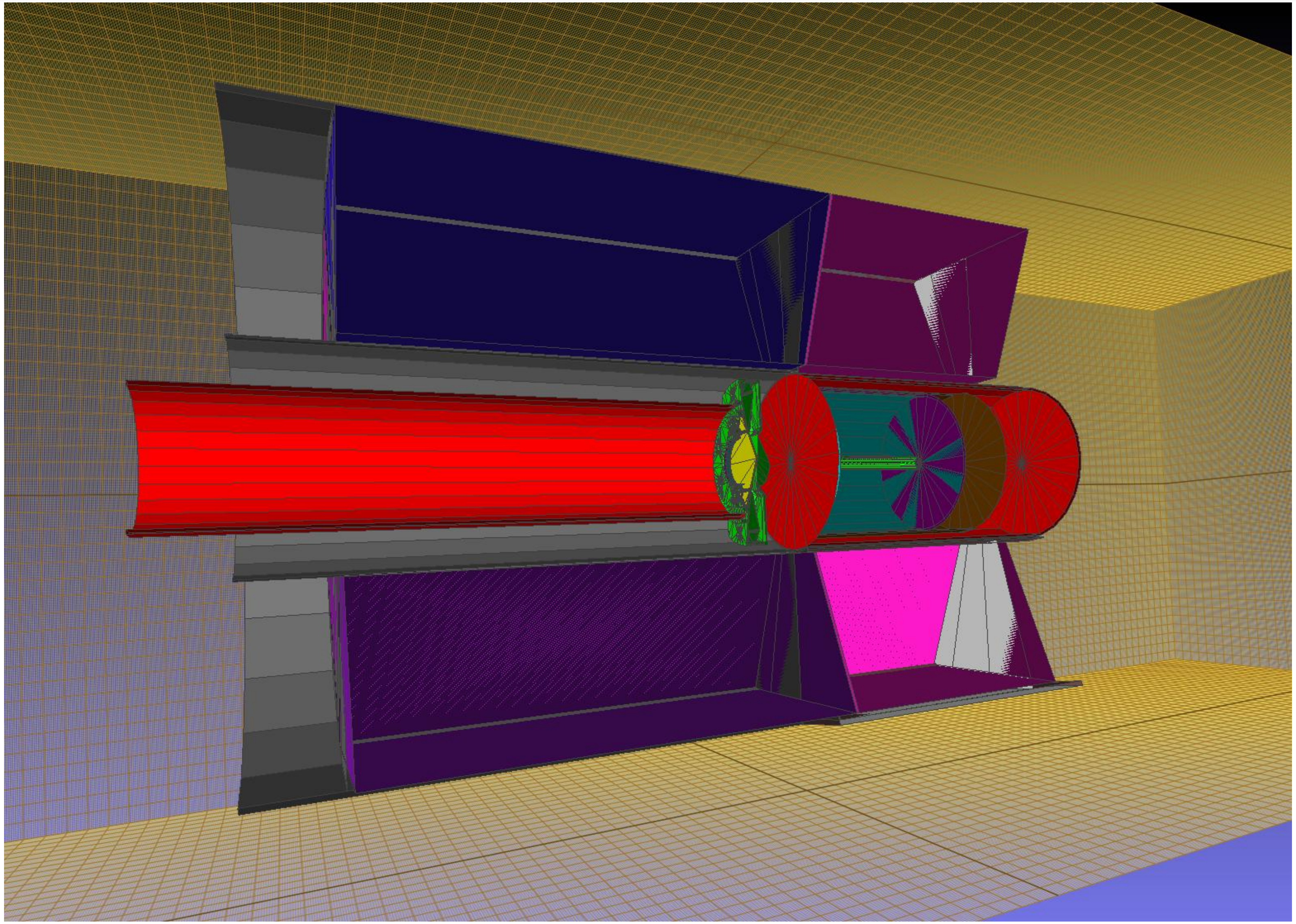
Two 8-fold annular NaI detectors will be used

- as anti-Compton veto
- as segmented high-efficiency spectrometer



~~inside 5 cm thick Cu shielding,~~
inside a 10 cm thick NaI detector,
inside a 1 cm thick copper box,
inside a 25 cm thick Pb shielding,
inside the Bellotti Ion Beam Facility,
inside the LNGS underground laboratory

$^{12}C + ^{12}C$

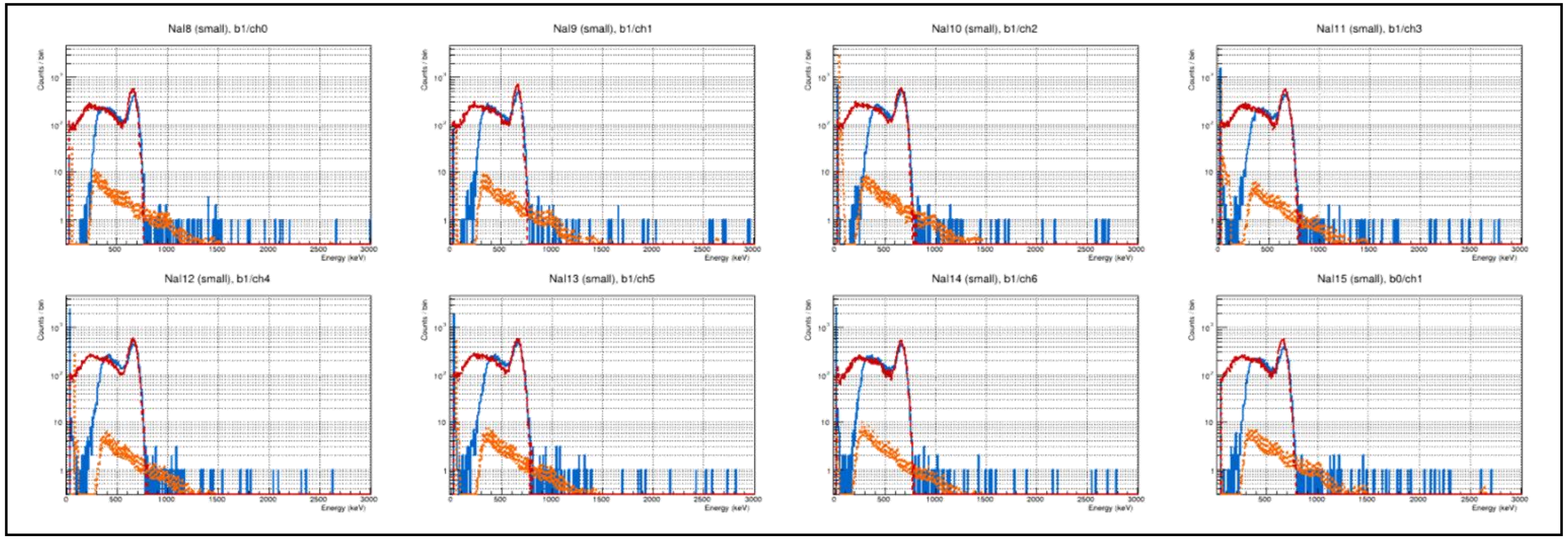


Credits: Giovanni Saturno

Geant4-based SimLUNA code

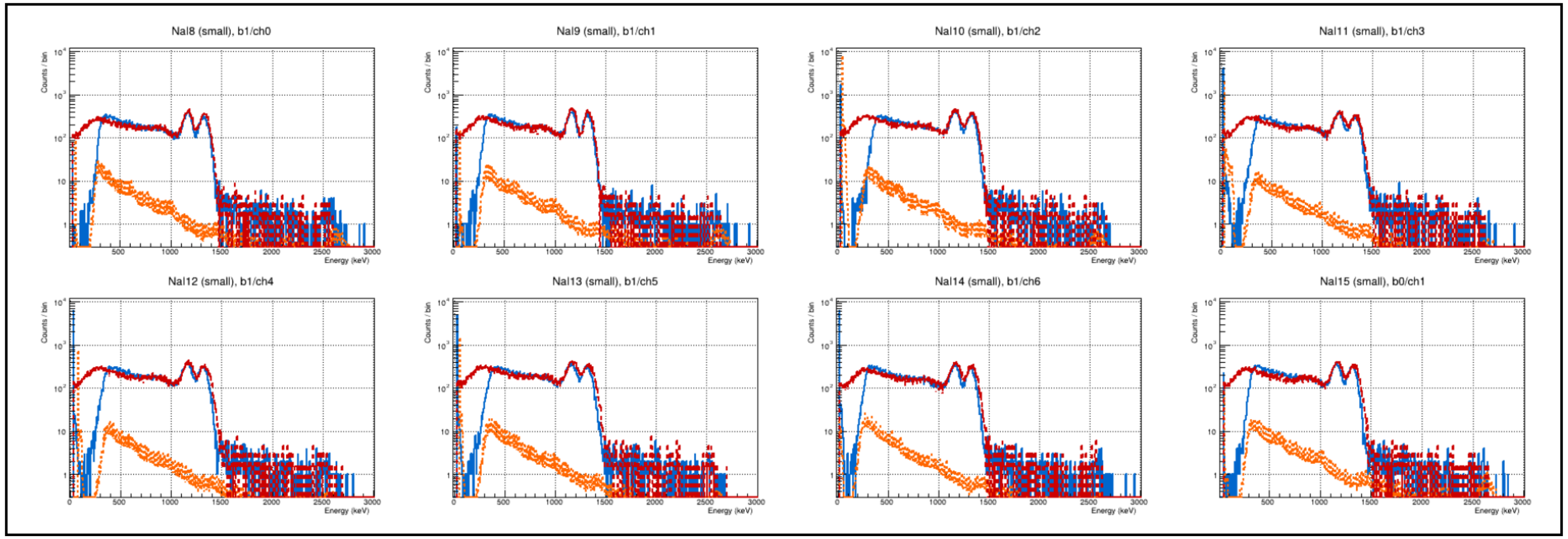
$^{12}C + ^{12}C$

Credits: Giovanni Saturno



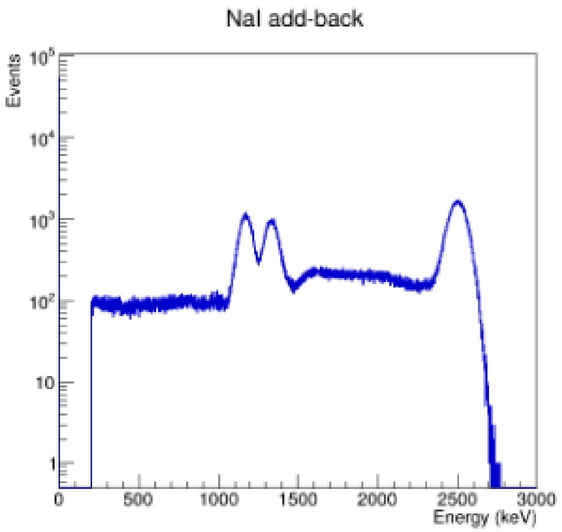
Small annulus
^{137}Cs source
“close” geometry

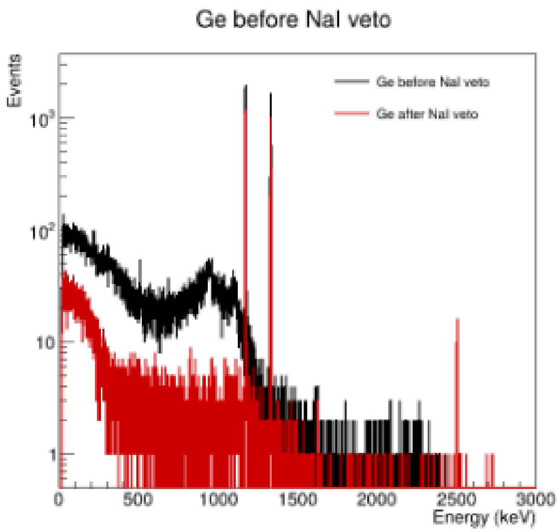
Fine tuning of the simulation ongoing

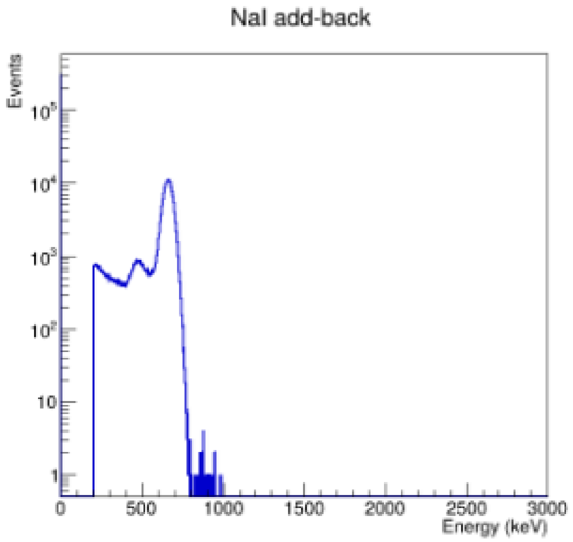


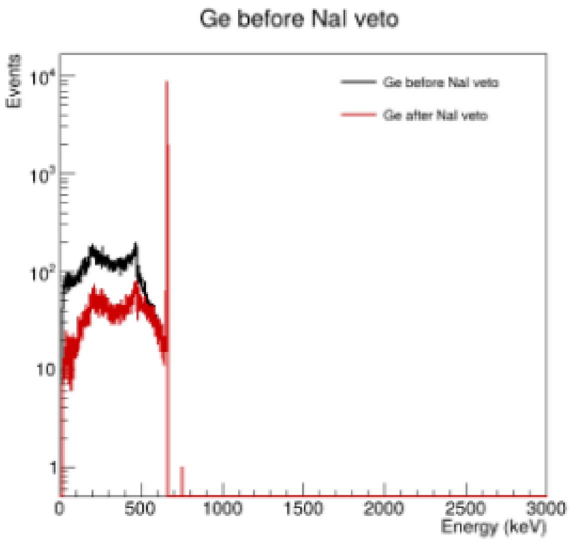
Small annulus
^{60}Co source
“far” geometry

$^{12}C + ^{12}C$







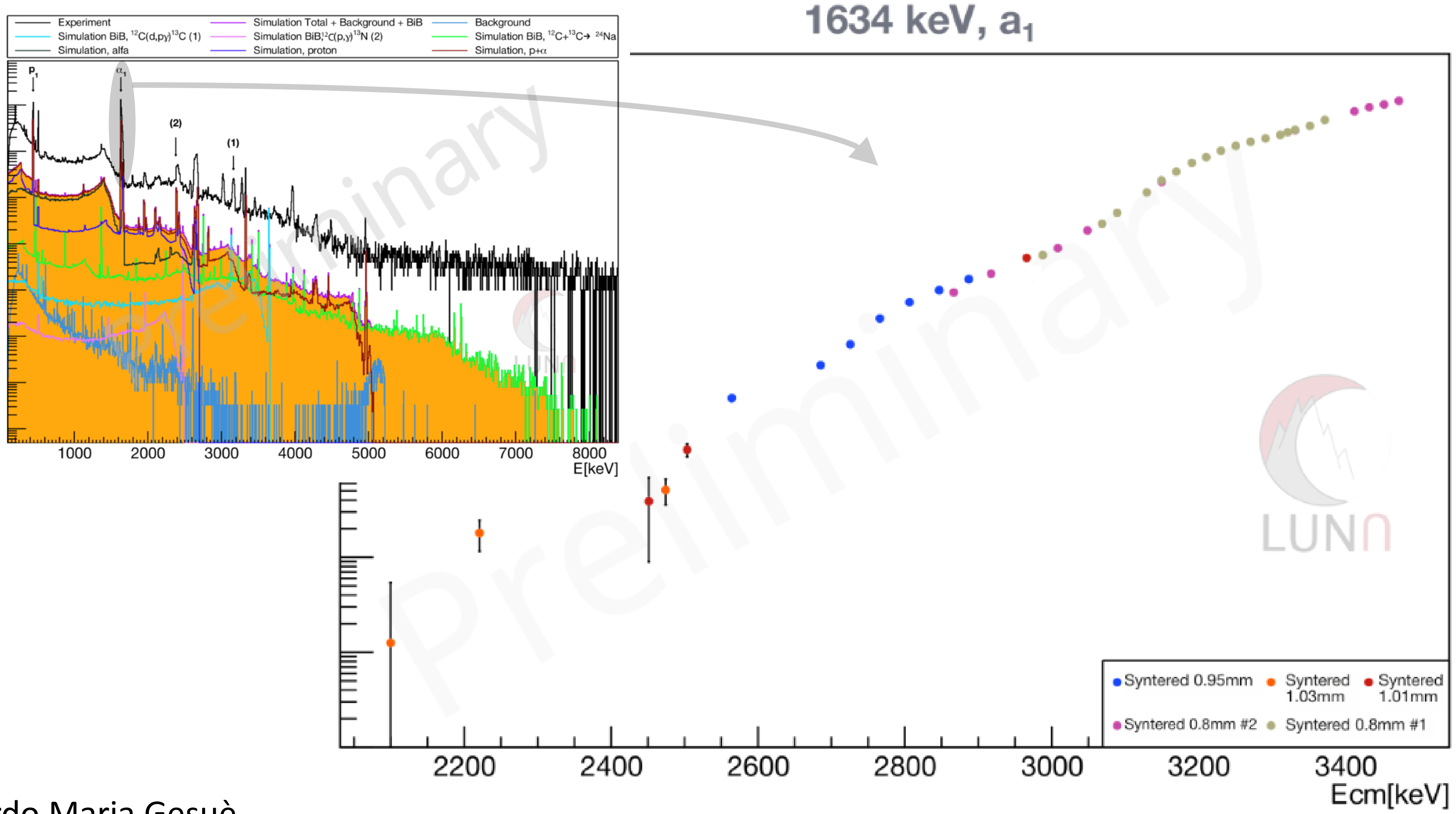


NaI veto-tag probability : 66.1 %
Ge events accepted after veto: 28.2 %
Photopeak retention: 60.9 %
Compton rejection: 76.2 %

NaI veto-tag probability (any hit): 76.0 %
Ge events accepted after veto: 59.8 %
Photopeak retention: 99.6 %
Compton rejection: 59.5 %

Credits: Giovanni Saturno

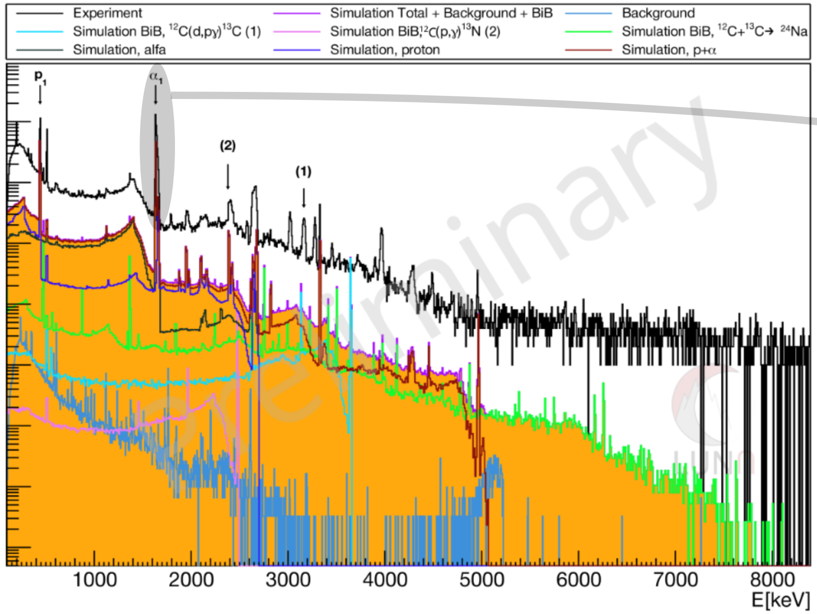
$^{12}C + ^{12}C$



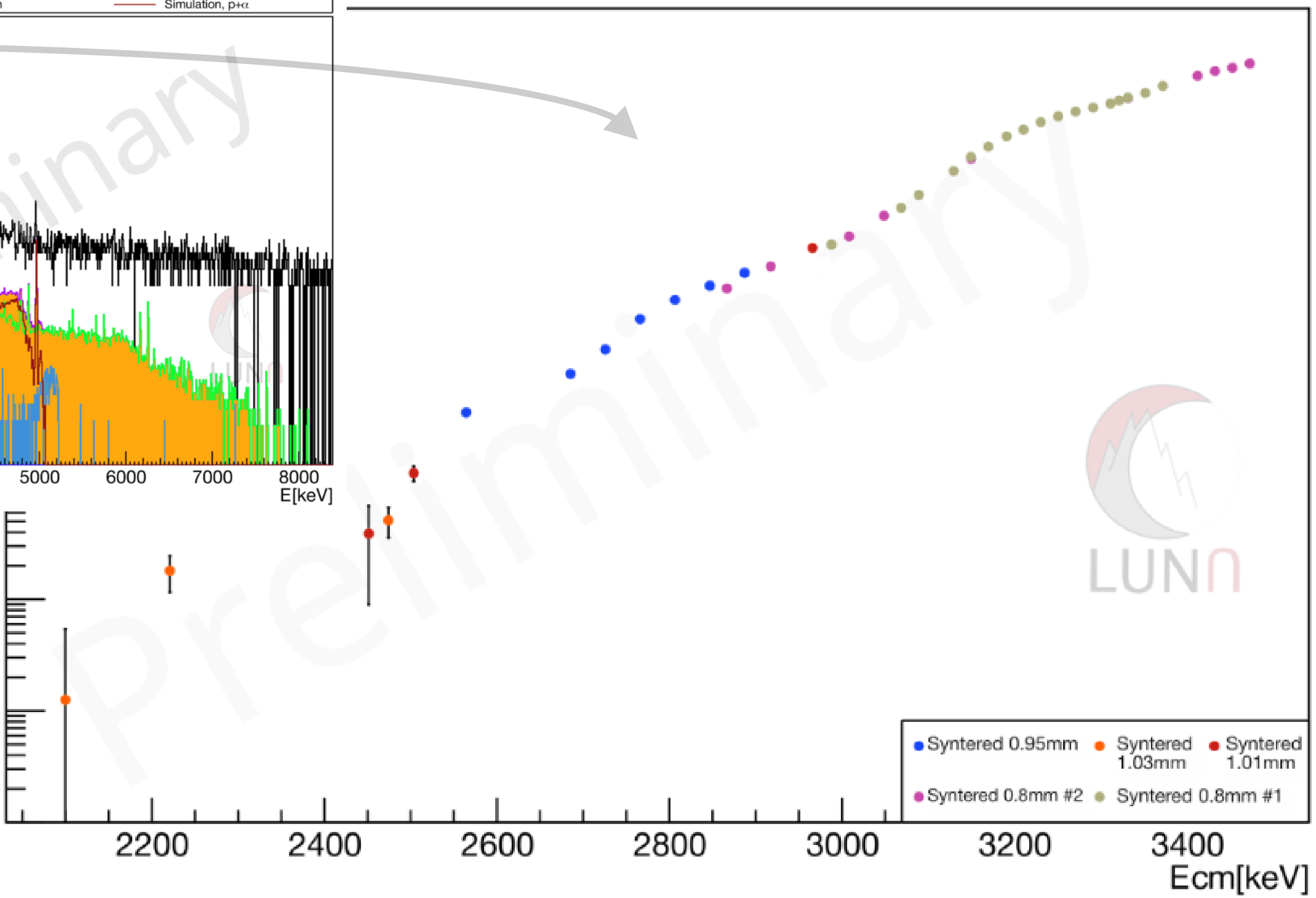
Credits: Riccardo Maria Gesuè

$^{12}C + ^{12}C$

More details in the talk by Dipali Basak



$1634\ keV,\ a_1$

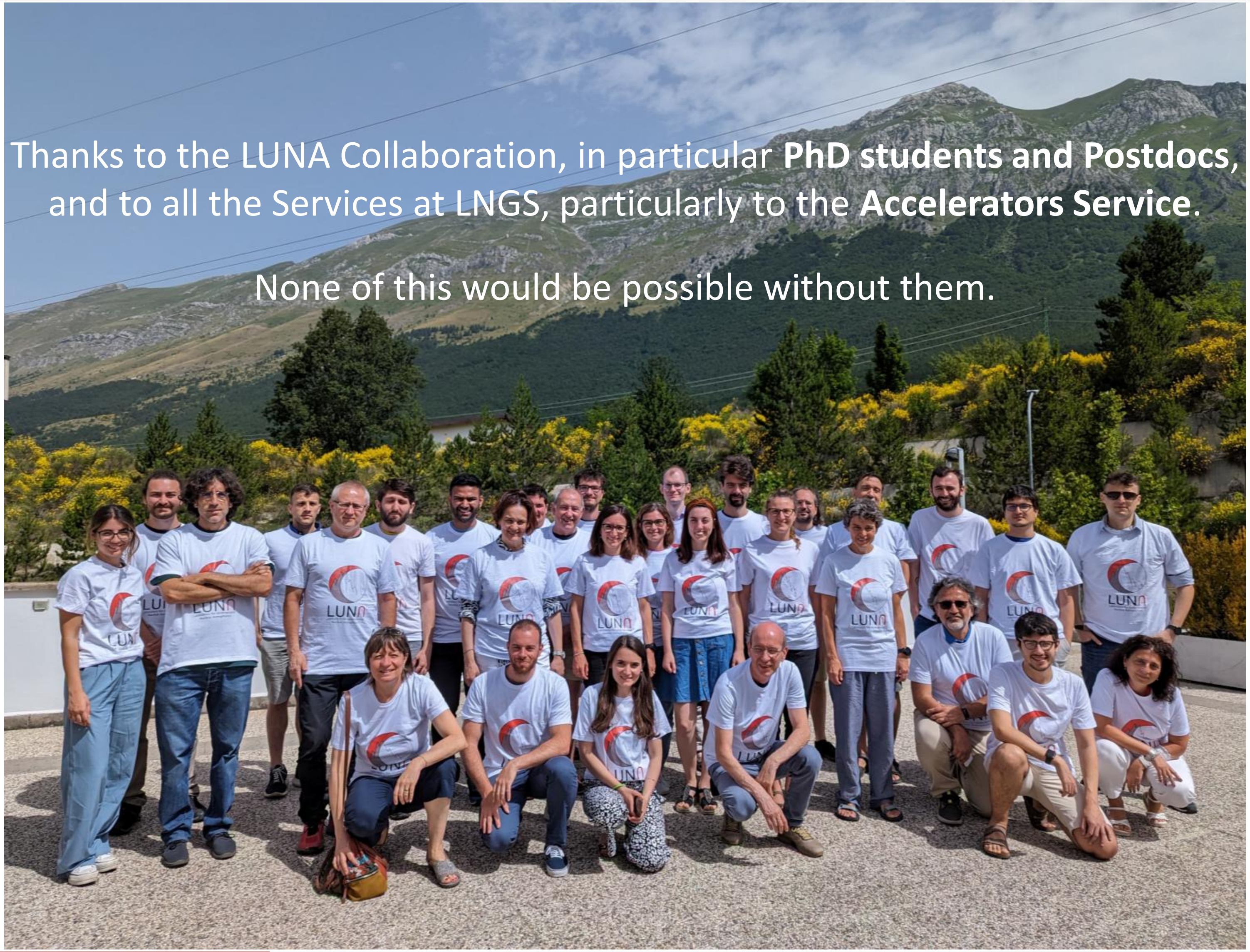


Next beamtime starting Tuesday next week!

STAY TUNED!

Credits: Riccardo Maria Gesuè

Acknowledgements time!



Thanks to the LUNA Collaboration, in particular **PhD students and Postdocs**, and to all the Services at LNGS, particularly to the **Accelerators Service**.

None of this would be possible without them.

Thank you!

Backup

An interesting paper

THE ASTROPHYSICAL JOURNAL, 981:84 (9pp), 2025 March 1 https://doi.org/10.3847/1538-4357/adb41f

Neutrino luminosity overcomes photon luminosity at the onset of C-burning!

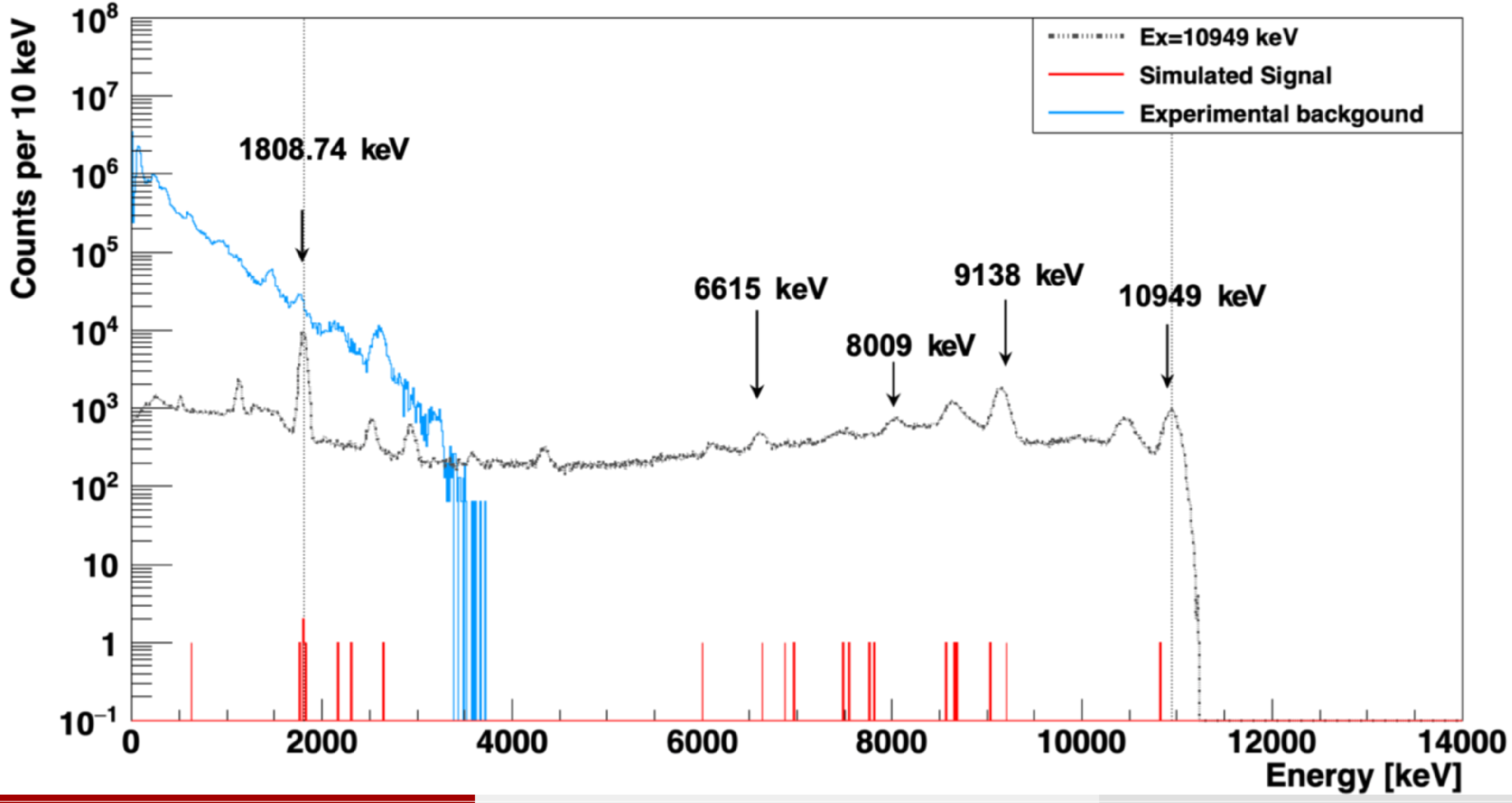
Neutrinos from Carbon-burning Red Supergiants and Their Detectability

Gwangeon Seong[1], Kyujin Kwak[1], Dongsu Ryu[1,2], and Bok-Kyun Shin[1,3]
[1] Department of Physics, College of Natural Sciences, UNIST, Ulsan 44919, Republic of Korea; kkwak@unist.ac.kr, dsryu@unist.ac.kr
[2] Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
[3] Pohang Accelerator Laboratory, Pohang-si, Gyeongsangbuk-do 37673, Republic of Korea
Received 2024 December 10; revised 2025 February 6; accepted 2025 February 7; published 2025 February 28

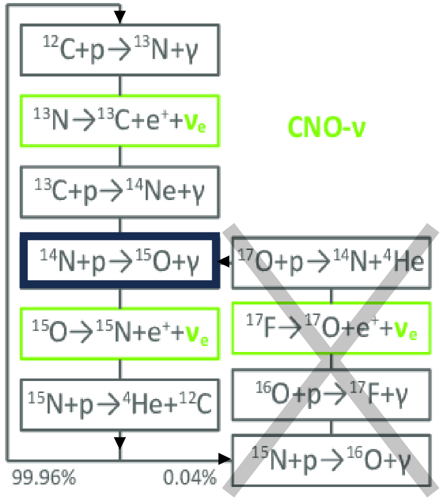
- ~ 1000 Red SuperGiants (RSGs) in the Milky Way, many of them expected to be in the C-burning phase (10 within 1 kpc)
- For a nearby 30 $M_\odot$ carbon-burning RSG located ~ 200 pc away: ~ 10^5 $cm^{-2}s^{-1}$ neutrinos reaching Earth, with a spectrum peaking at ~ 0.6 MeV
- **Is it possible to detect these neutrinos in underground facilities, particularly in hybrid detectors equipped with water-based liquid scintillator and ultra-fast photodetector (to separate Cherenkov and scintillation light)?**
- In detectors with a volume comparable to Super-Kamiokande: **up to ~ 50 neutrino events per year** with directional information (~ 10^3 times smaller rate than CNO neutrinos, ~ 10^6 times smaller than estimated background)
- although detecting neutrinos from carbon-burning RSGs **seems difficult** with currently available detector technologies, it could become feasible in the future (exploiting directionality and new detection techniques)

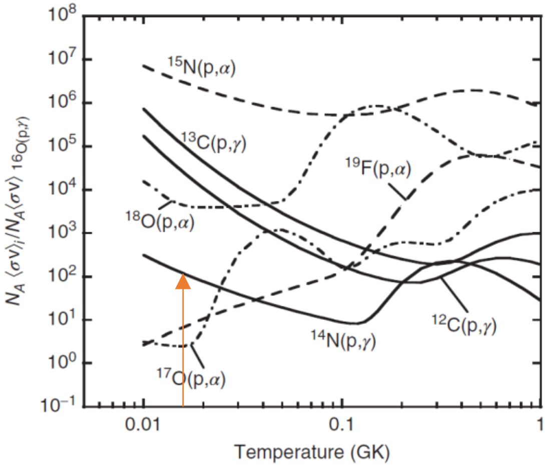
$^{22}Ne(\alpha,\gamma)^{26}Mg$

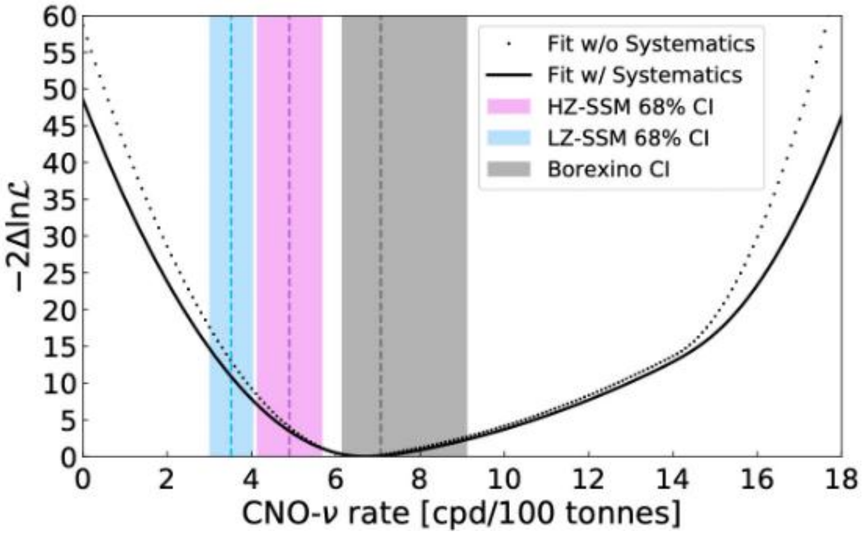
Credits: Thomas Chillery



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

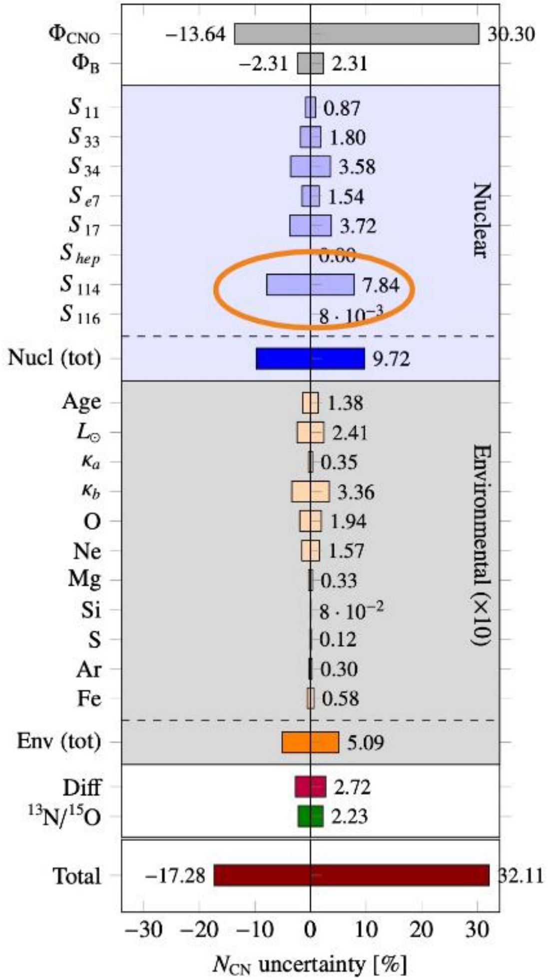






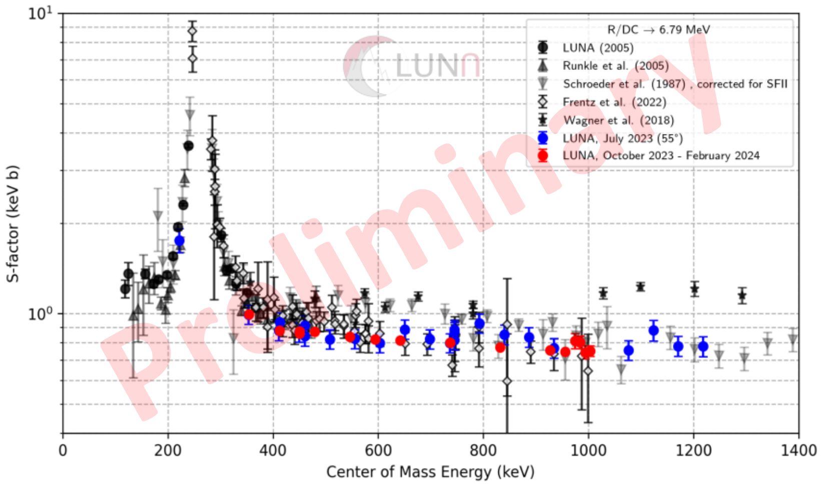
Borexino disfavors LZ-SSM more than HZ-SSM, but large uncertainties remain

The biggest nuclear contribution to the uncertainty budget comes from the $^{14}N(p,\gamma)^{15}O$ cross section



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

Credits: Alessandro Compagnucci



This measurement was part of the calibration of the 3.5 MV accelerator

new measurements are consistent with previous LUNA data and extend them to higher energy

the analysis on the angular dependence is ongoing