# Cross section measurements of fusion reactions at astrophysical relevant energies: the LUNA experiment

A.Formicola, A.Compagnucci , G.F. Ciani
(on behalf of the LUNA collaboration)

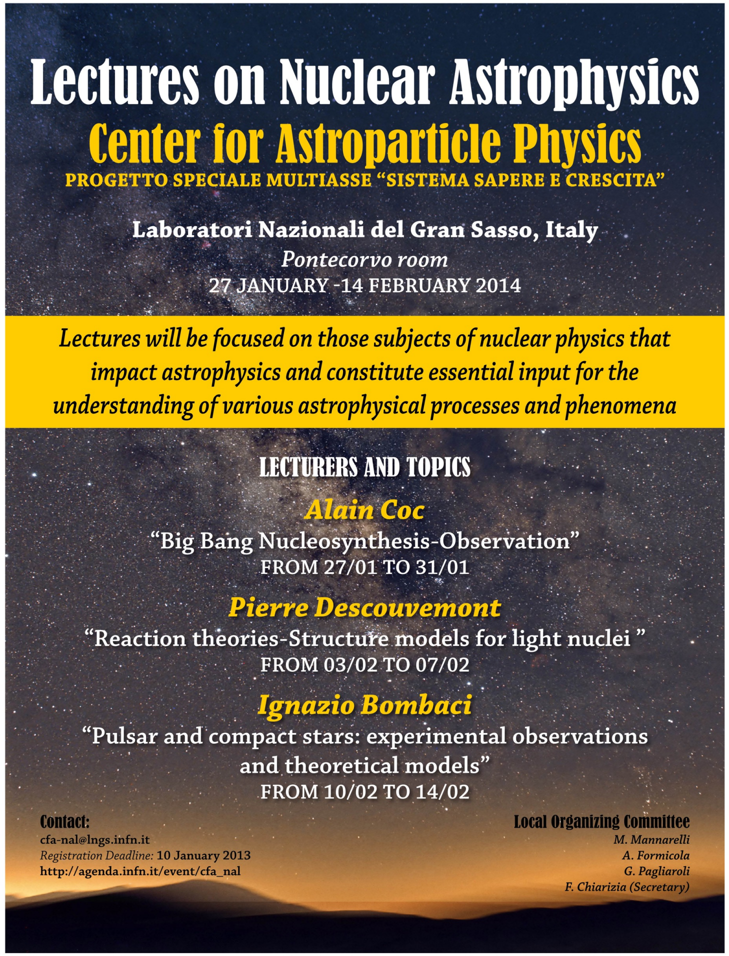
LUNA

**Exploring low-energy nuclear properties: latest advances on reaction mechanisms with light nuclei**

**Brussels June 1-2, 2023**

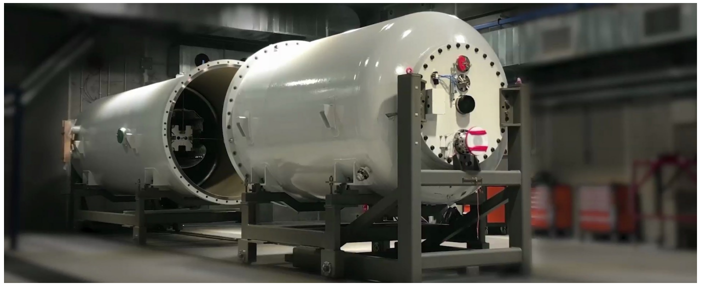
INFN
ROMA
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

NPA IV June 2009


Lectures on Nuclear Astrophysics
Center for Astroparticle Physics
PROGETTO SPECIALE MULTIASSE "SISTEMA SAPERE E CRESCITA"
Laboratori Nazionali del Gran Sasso, Italy
Pontecorvo room
27 JANUARY -14 FEBRUARY 2014
Lectures will be focused on those subjects of nuclear physics that impact astrophysics and constitute essential input for the understanding of various astrophysical processes and phenomena
LECTURERS AND TOPICS
Alain Coc
"Big Bang Nucleosynthesis-Observation"
FROM 27/01 TO 31/01
Pierre Descouvemont
"Reaction theories-Structure models for light nuclei "
FROM 03/02 TO 07/02
Ignazio Bombaci
"Pulsar and compact stars: experimental observations and theoretical models"
FROM 10/02 TO 14/02
Contact:
cfa-nal@lngs.infn.it
Registration Deadline: 10 January 2013
http://agenda.infn.it/event/cfa_nal
Local Organizing Committee
M. Mannarelli
A. Formicola
G. Pagliaroli
F. Chiarizia (Secretary)

# LUNA proposal at Bellotti Ion Beam Facility

- Energy range 0.3-3.5 MeV
- $H^+$,$He^+$,$^{12}C^+$,$^{12}C^{++}$
- High current, energy stability below $10^{-5}$, uninterrupted operation time >24h
- Scientific program:
  - $^{14}N(p,\gamma)^{15}O$
  - $^{12}C+^{12}C$, $^{22}Ne(\alpha,n)^{25}Mg$ , …$^{13}C(\alpha,n)^{16}O$ …

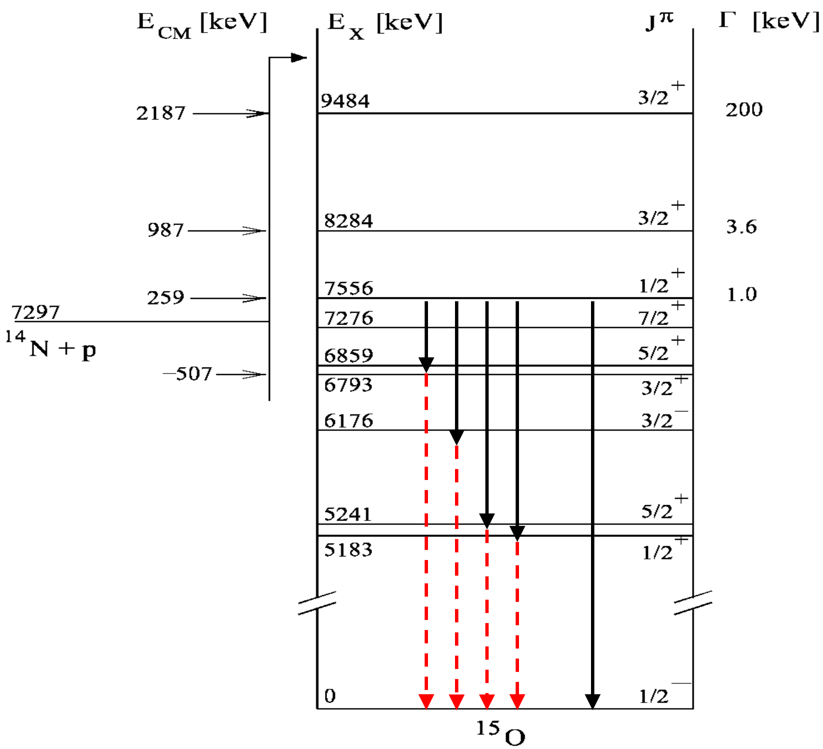


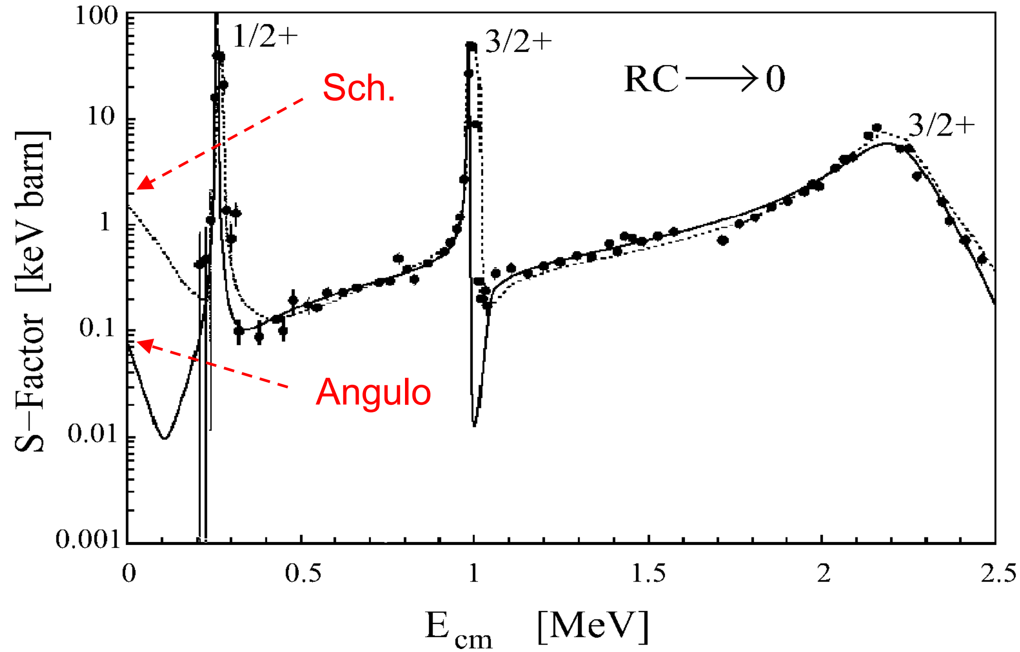

Sen, A. *et al.* (2019) '*Nuclear Instruments and Methods in Physics Research Section B:*, 450, pp. 390–395. doi:10.1016/j.nimb.2018.09.016.

| Ion specie | Beam Intensity (eμA) | |
|---|---|---|
| | TV range 0.3 MV–0.5 MV | TV range 0.5–3.5MV |
| $^{1}H^{+}$ | 500 | 1000 |
| $^{4}He^{+}$ | 300 | 500 |
| $^{12}C^{+}$ | 100 | 150 |
| $^{12}C^{+2}$ | 60 | 100 |

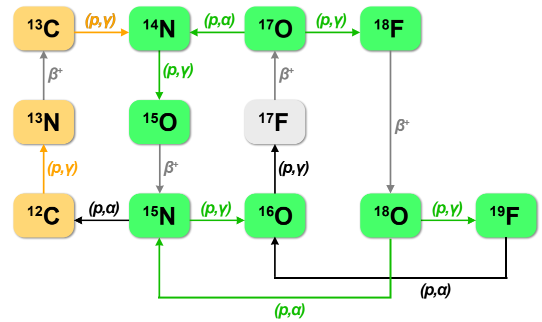
Beam intensity on target at different terminal voltage.

# $^{14}N(p,\gamma)^{15}O$ SAGA….36 years!




| Transition (MeV) | Schröder et al. (Nucl.Phys.A 1987) | Angulo et al. (Nucl.Phys.A 2001) |
|---|---|---|
| RC / 0 | 1.55 ± 0.34 | 0.08 ± 0.06 |
| RC / 6.18 | 0.14 ± 0.05 | 0.06 ± 0.02 |
| RC / 6.79 | 1.41 ± 0.02 | 1.63 ± 0.17 |
| S(0) [kev-b] | 3.20 ± 0.54 | 1.77 ± 0.20 |




# …Results for capture to gs $^{14}N(p,\gamma)^{15}O$

Available online at www.sciencedirect.com

SCIENCE DIRECT

Physics Letters B 591 (2004) 61–68

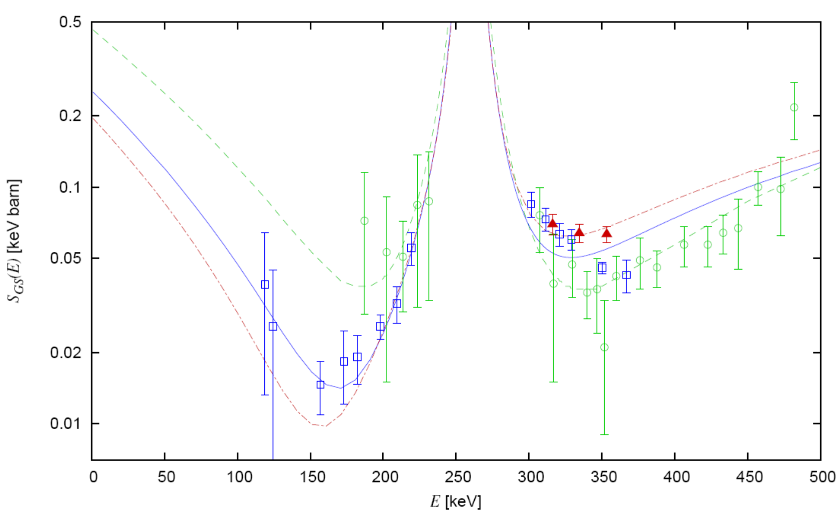
PHYSICS LETTERS B

www.elsevier.com/locate/physletb

## Astrophysical $S$-factor of $^{14}N(p,\gamma)^{15}O$ ☆

A. Formicola[a], G. Imbriani[b], H. Costantini[c], C. Angulo[d], D. Bemmerer[e], R. Bonetti[f], C. Broggini[g], P. Corvisiero[c], J. Cruz[h], P. Descouvemont[i], Z. Fülöp[j], G. Gervino[k], A. Guglielmetti[f], C. Gustavino[l], G. Gyürky[j], A.P. Jesus[h], M. Junker[l], A. Lemut[c], R. Menegazzo[g], P. Prati[c], V. Roca[m], C. Rolfs[a], M. Romano[m], C. Rossi Alvarez[g], F. Schümann[a], E. Somorjai[j], O. Straniero[b], F. Strieder[a], F. Terrasi[n], H.P. Trautvetter[a], A. Vomiero[o], S. Zavatarelli[c]

- LUNA (2004): 0.25±0.06 keV barn
- TUNL (2005): 0.49±0.08 keV barn
- LUNA (2008): 0.20±0.05 keV barn

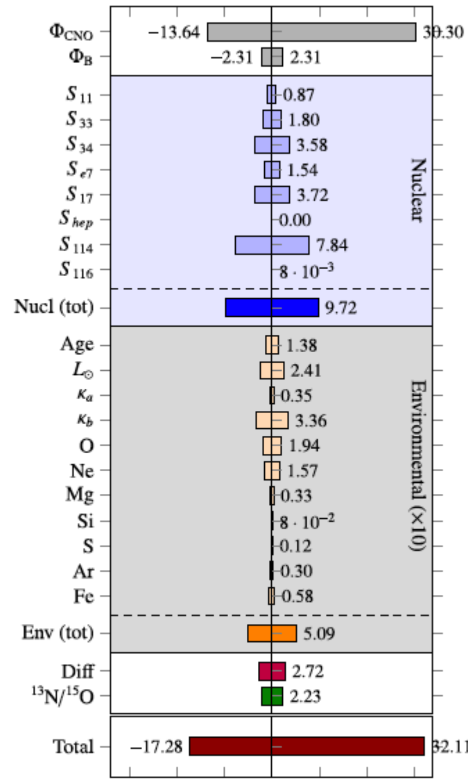



Adopted by Marta et al. PRC 2011

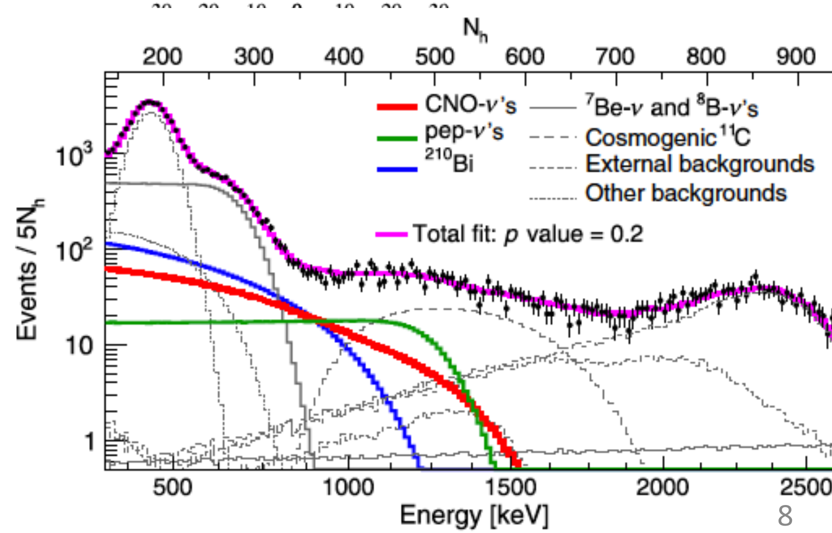
# Astrophysical motivation $^{14}N(p,\gamma)^{15}O$

- Solar CNO neutrino flux recently detected for the first time by Borexino (PRL 129, 252701 2022)→ 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.



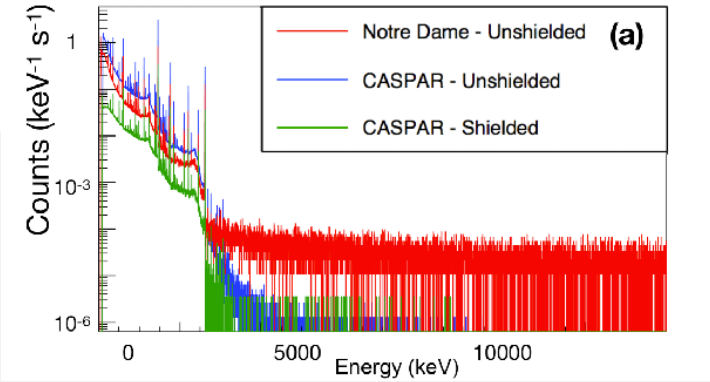


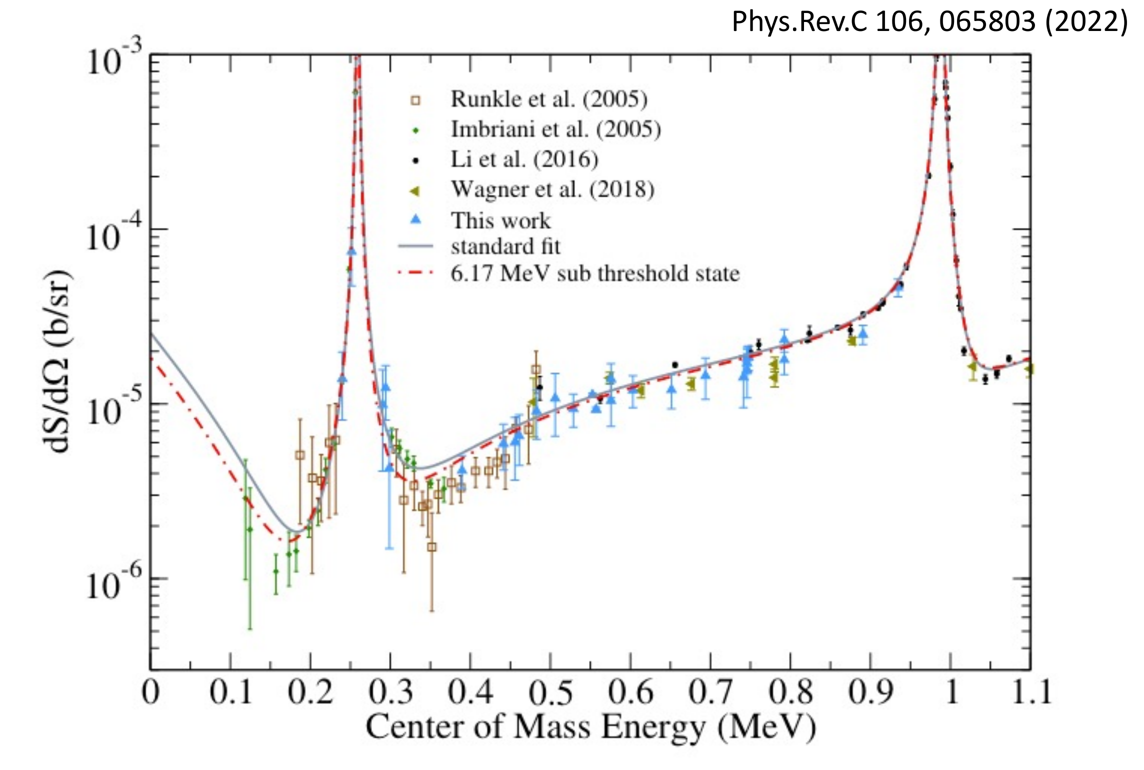


# Measurement at CASPAR

Frentz et al.Phys.Rev.C 106, 065803 (2022)

- **$E_p$ = 0.27 - 1.07 MeV**, 50-100 uA on target, 1 HPGe at 55°.
- Use of $^{14}N$ enriched ZrN sputtered targets.
- Only **6.79 MeV and g.s. transition** analyzed. Relative to $\omega\gamma_{278}$ = 12.6(3) meV of Daigle *et al.*
- R-Matrix analysis performed.
- Most data is plotted/treated as differential.

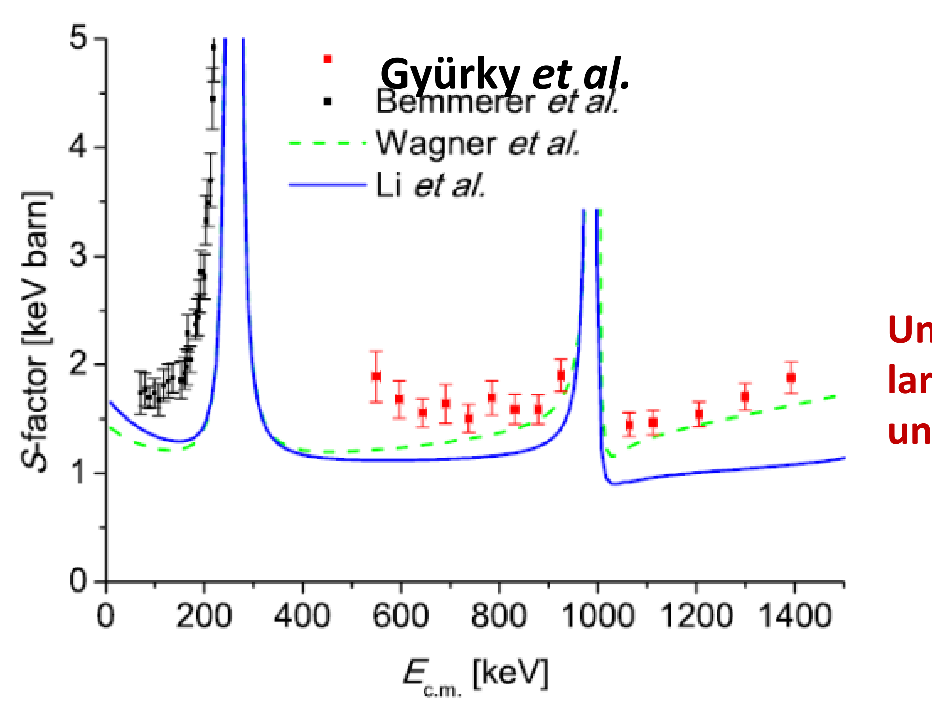


# Open Issues after Frentz. et al.

Transition to **ground state**

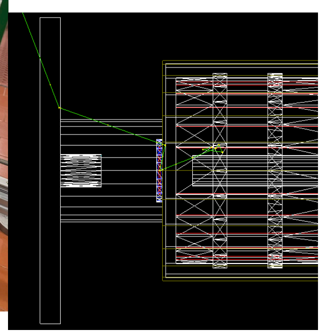
- Reccurrent issue in fitting the data below 500 keV with the higher energy data.
- Contribution of **6.17 MeV** state as a **subthreshold resonance** in the fit?
- Possible insight on a **missing state** as an additional source of interference.
- **No angular distribution data below 500 keV**.



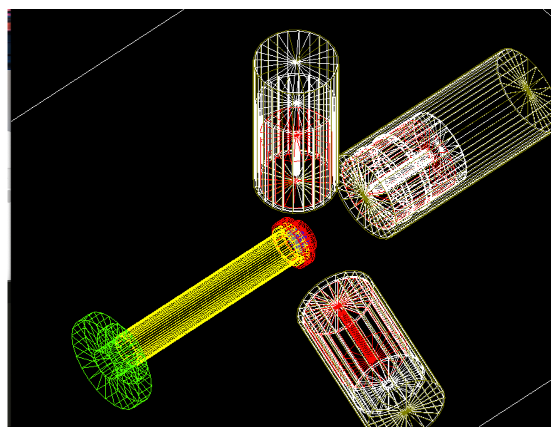

**Unacceptably large uncertainty**

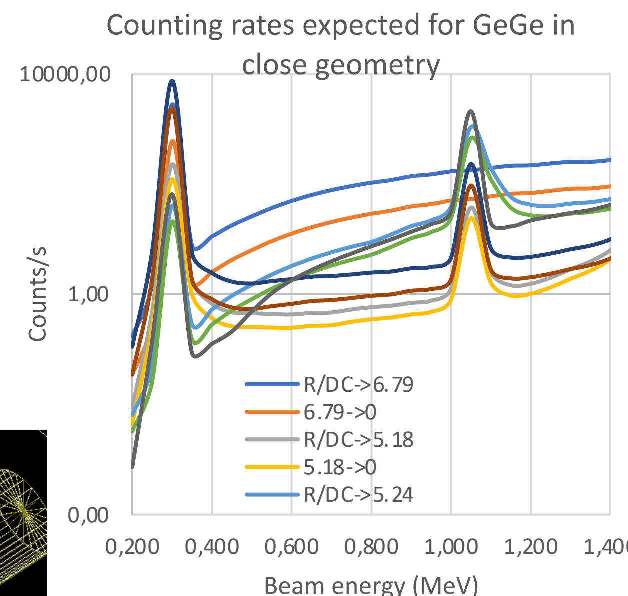
# $^{14}N(p,\gamma)^{15}O$ reaction measurement
## PhD project-A.Compagnucci

- Angular distribution + Excitation function in close geometry simulated with Geant4.
- 3 HPGe detectors with ~120% relative efficiency
- Detectors at 10 cm from target, angles covered: 0°,45°,90°,135°

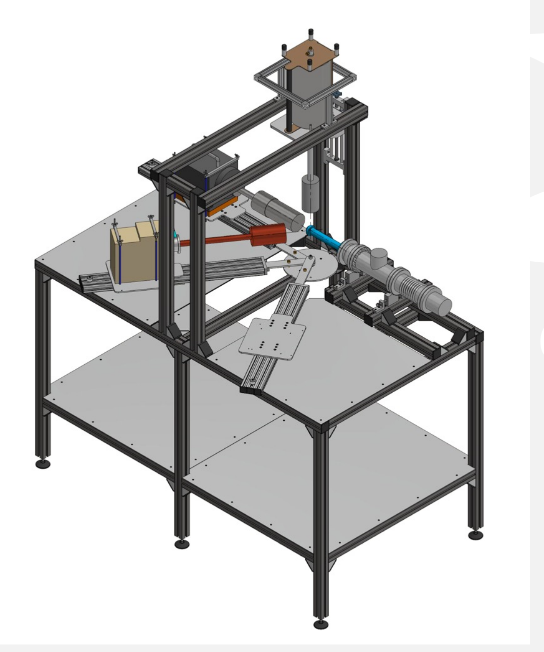


HPGe characterization with sources at STELLA (LNGS)



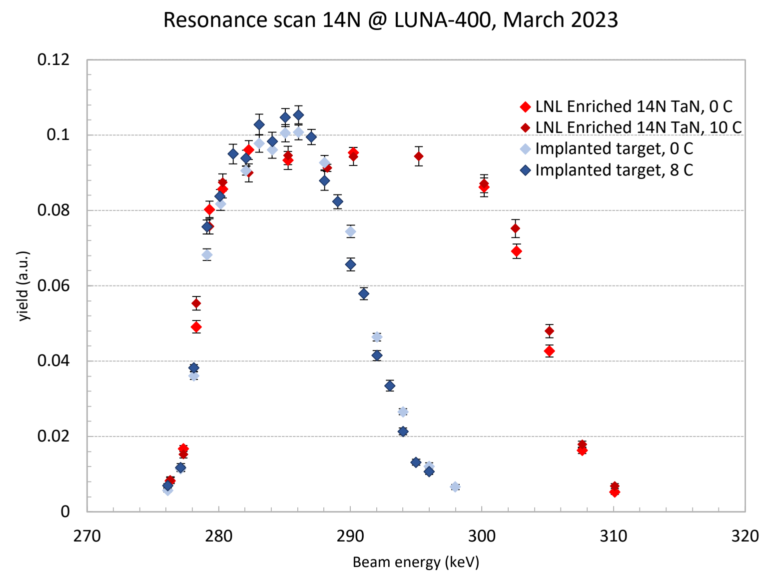


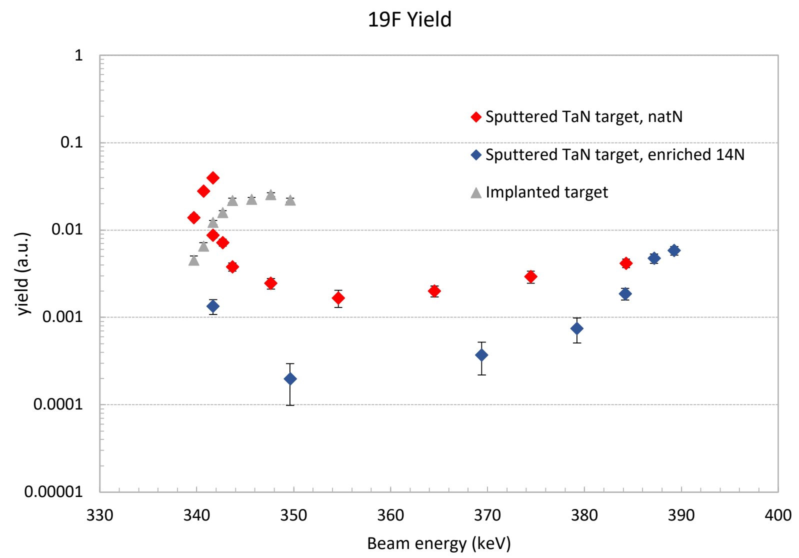
# An important science case

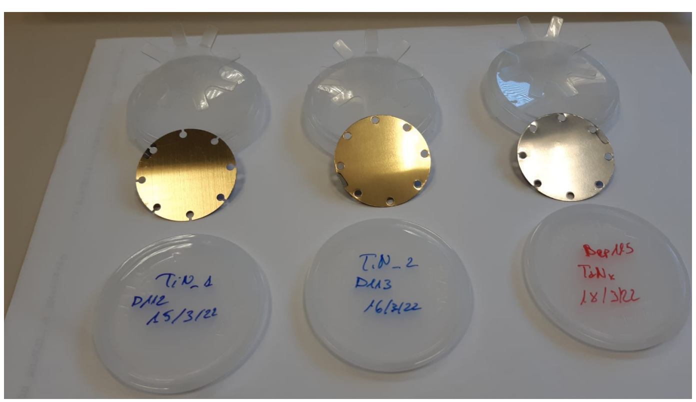


**The $^{14}N(p,\gamma)^{15}O$ cross section data taking ($E_p$=0.3-1.5 MeV) starts on 19 June 2023**

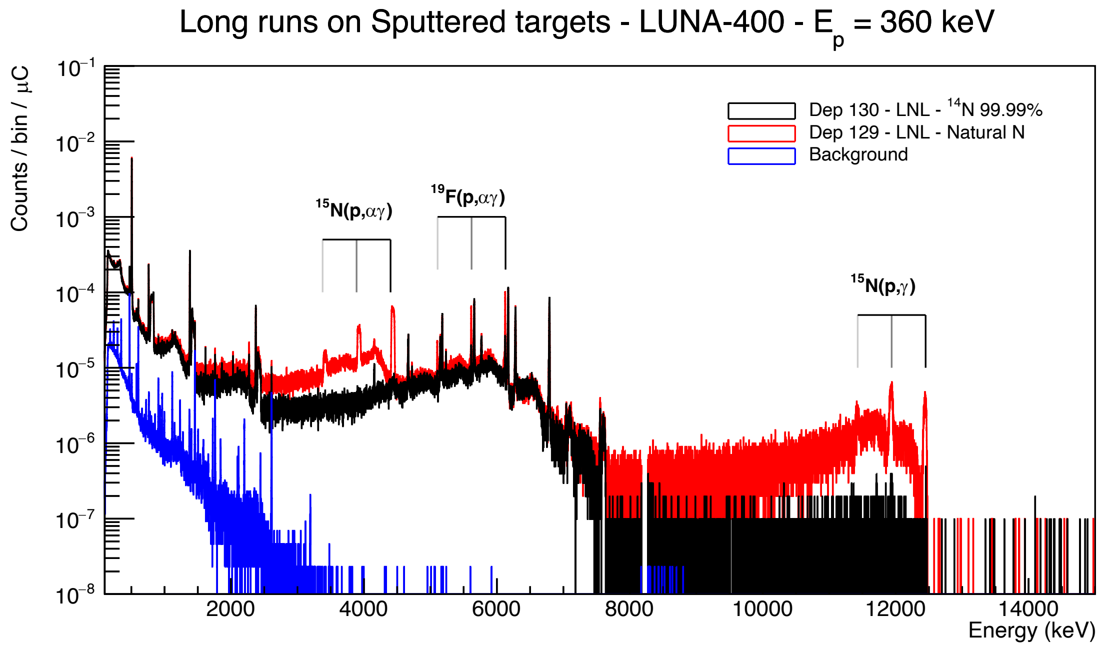
# Targets tested for stability and contaminants at LUNA-400



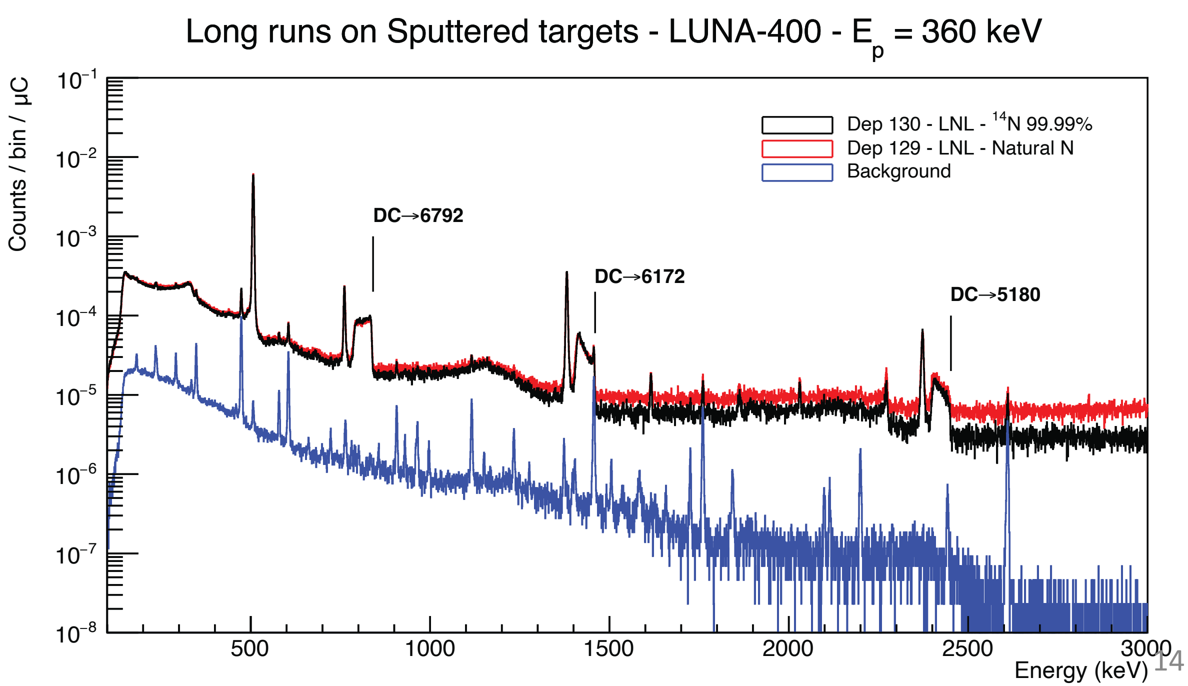




- Thin films on Ta backing produced using Reactive Magnetron Sputtering at LNL-INFN, with Matteo Compostrini and Valentino Rigato with enriched $^{14}$N gas, much lower Fluorine and $^{15}$N contamination.
- Implanted target produced at IST, Lisbon –( Under RADIATE Transnational Access) in collaboration with João Cruz

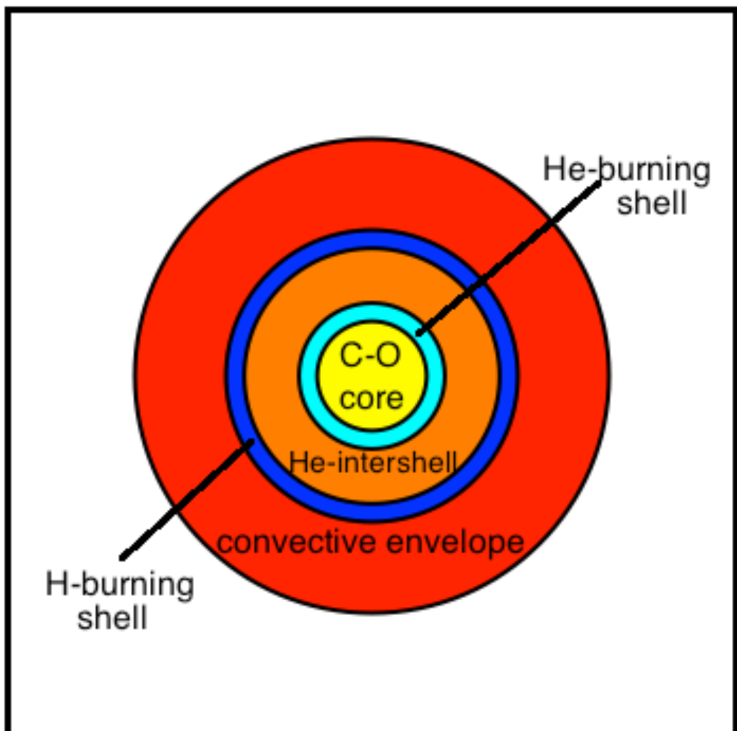


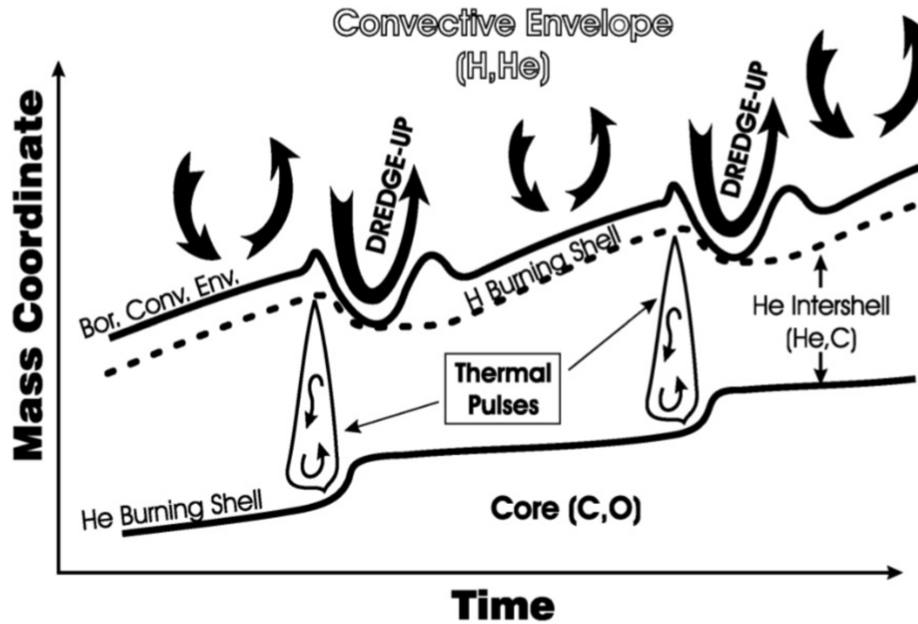

76 times less $^{15}N$ in the target produced with the enriched gas



# Astrophysical motivation
## $^{13}C(\alpha,n)^{16}O$ neutron source for s process

- $^{13}C(\alpha,n)^{16}O$ (Q=2.215 MeV) is the main neutron source feeding s-process in low (1-3 $M_{\odot}$) mass TP-AGB stars, responsible for nucleosynthesis of half of nuclides heavier than iron
- Average temperature $10^8$ K → Gamow window **140-250 keV**



# Pioneering works

ORIGIN OF ANOMALOUS ABUNDANCES OF THE ELEMENTS IN GIANT STARS

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Iowa State College, Ames, Iowa

*Received July 9, 1954; revised September 14, 1954*

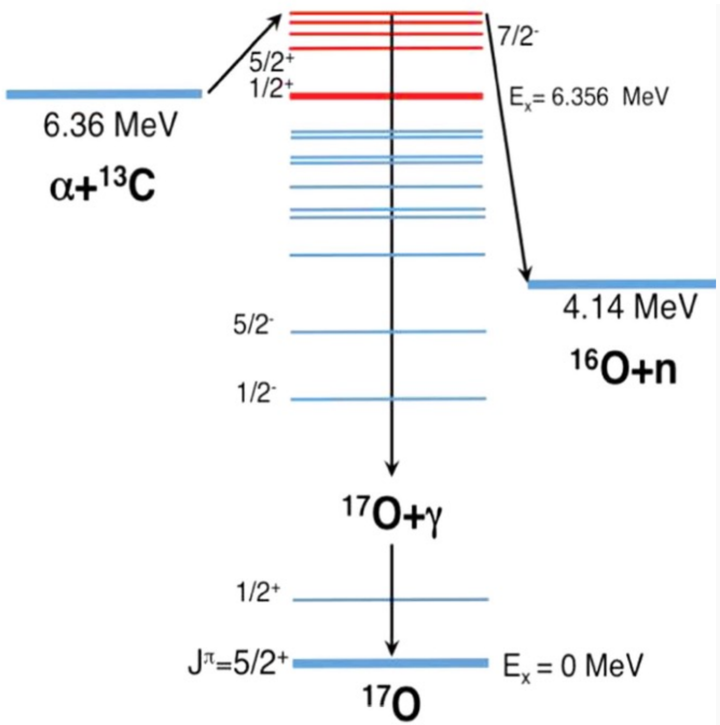
ABSTRACT

Following the exhaustion of hydrogen in the cores of certain massive stars, it appears that the cores contract and the envelopes expand, the stars becoming red giants. When the central temperature and density have increased sufficiently, thermonuclear reactions involving the helium in the core can take place with the nuclei which have taken part in the carbon cycle. The rate of the $C^{13}(\alpha, n)O^{16}$ reaction is calculated; it is found to produce neutrons rapidly at a temperature of $10^8$ ° K and a density of $5 \times 10^4$ gm/cm$^3$. These neutrons are slowed down until they reach thermal equilibrium with their surroundings (neutron energies of about 10 kev) and are then captured by the surrounding nuclei in proportion to their cosmic abundances and neutron-capture cross-sections. The latter quantities are estimated for neutron energies of 10 kev as a function of the mass number of the capturing nucleus. The heavier nuclei each appear to capture many neutrons (about 35 neutrons at mass number 100). Nuclei with closed shells of 50, 82, and 126 neutrons have much smaller cross-sections and become concentrated by the neutron-capture processes. With the assumption of a moderate amount of mixing between core and envelope of the star, it is thus found that the distinctive features of S-type and *Ba* II–type spectra can be explained. The further evolution of the star should then lead to the production of excess carbon by the Salpeter reactions, and the spectrum should gradually turn into that of type R or N.

The first stellar neutron source was proposed by Greenstein (Gr54) and by Cameron (Ca54, Ca55), namely the *exothermic* reaction:

$$C^{13}(\alpha,n)O^{16}+2.20 \text{ Mev.}$$

# Importance of the threshold state



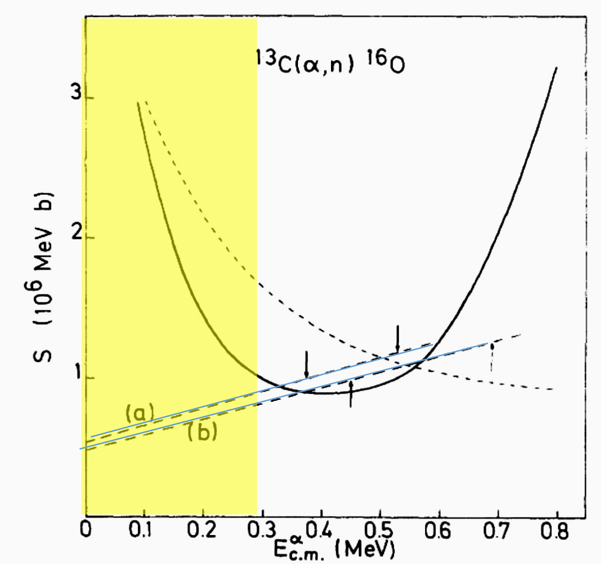
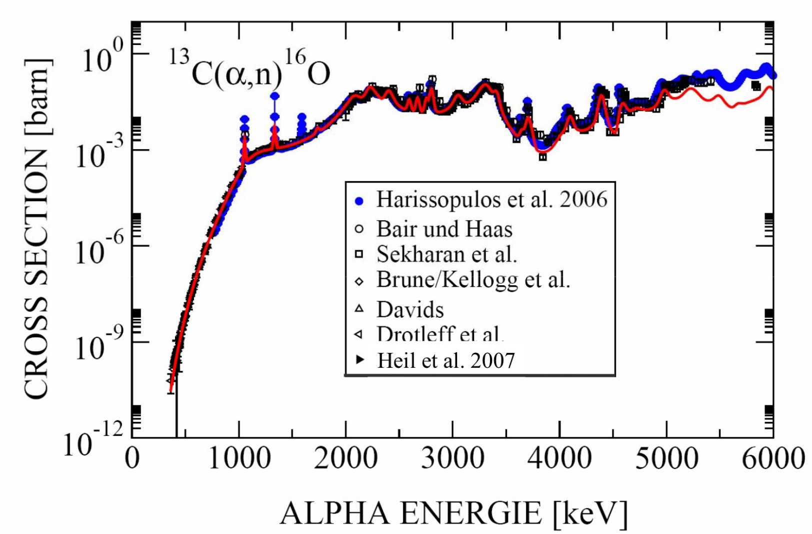




FIG. 6. $^{13}$C(α,n)$^{16}$O *S* factor. The dotted line represents the GCM result; the full line is obtained with the Breit-Wigner parametrization (see text); the dashed lines are the experimental data taken from Ref. 3 (a) and Ref. 4 (b). The arrows indicate the energy range where the experiments are carried out.

P. Descouvemont PRC(1987)

This case of a near-threshold cluster resonance in the $^{13}$C(α, n) $^{16}$O reaction is an example of the impact of cluster configurations in nuclear astrophysics

# State of the art $^{13}C(\alpha,n)^{16}O$



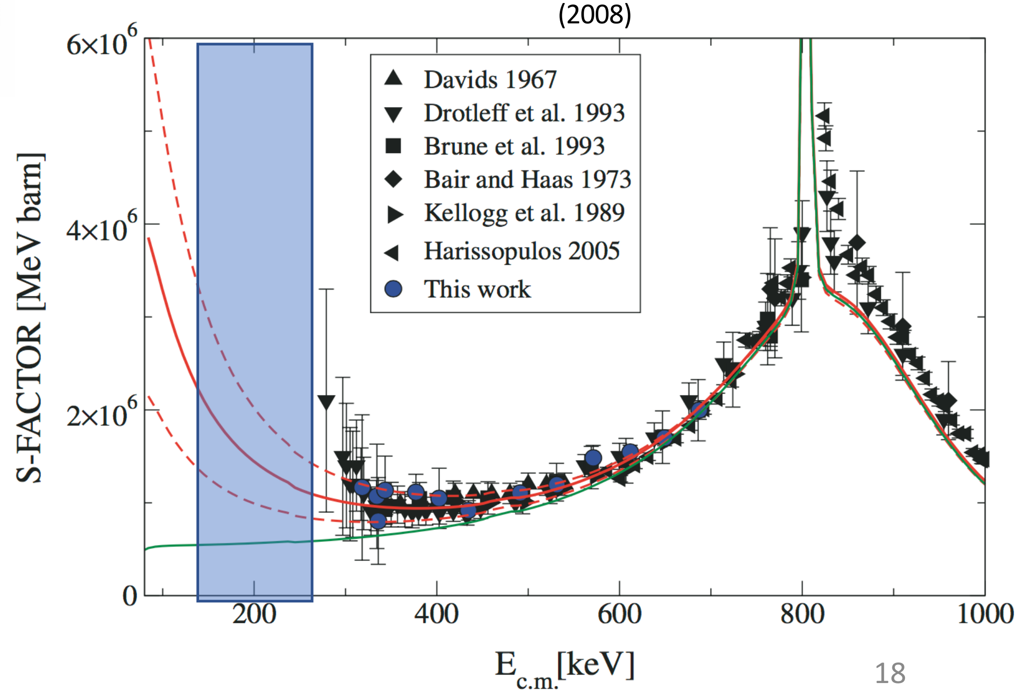

**DIRECT MEASUREMENTS**

Lowest point at $E_{cm}$ = 280 keV by Drotleff et al.

Most recent meas + R Matrix at low energies: Heil (2008)

High systematic uncertainty from target control (degradation, C build up)

Figure from Heil et al,PRC 78, 025803 (2008)




**LUNA GOAL**

A direct meauserement of the $^{13}C(\alpha,n)^{16}O$ (230-330keV) approaching the Gamow window with a 20% uncertainty.

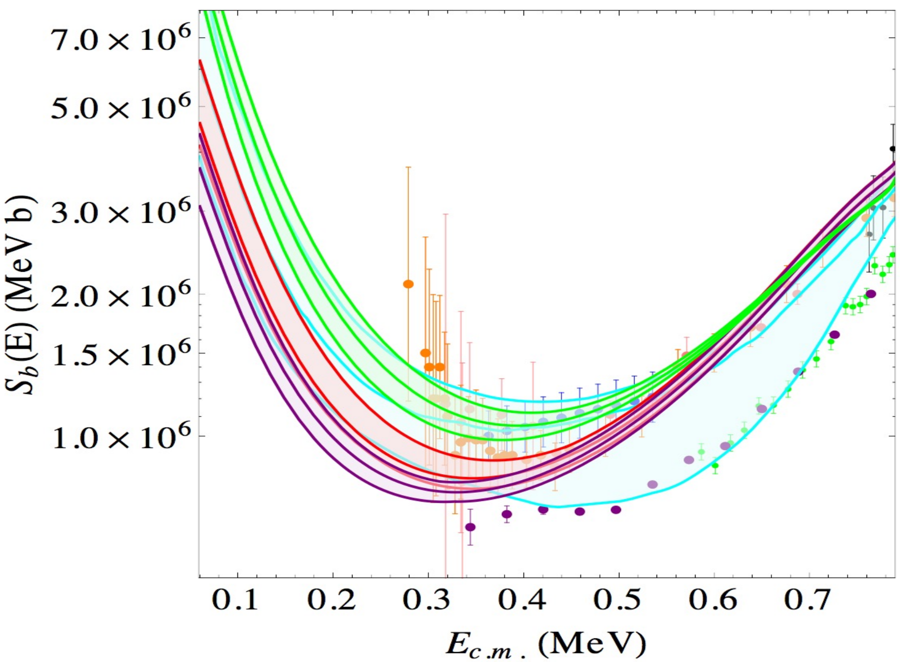
# State of the art $^{13}C(\alpha,n)^{16}O$ indirect measurements

Trippella (red band) et al.(2017) and La Cognata (green band) et al. (2013) with the THM

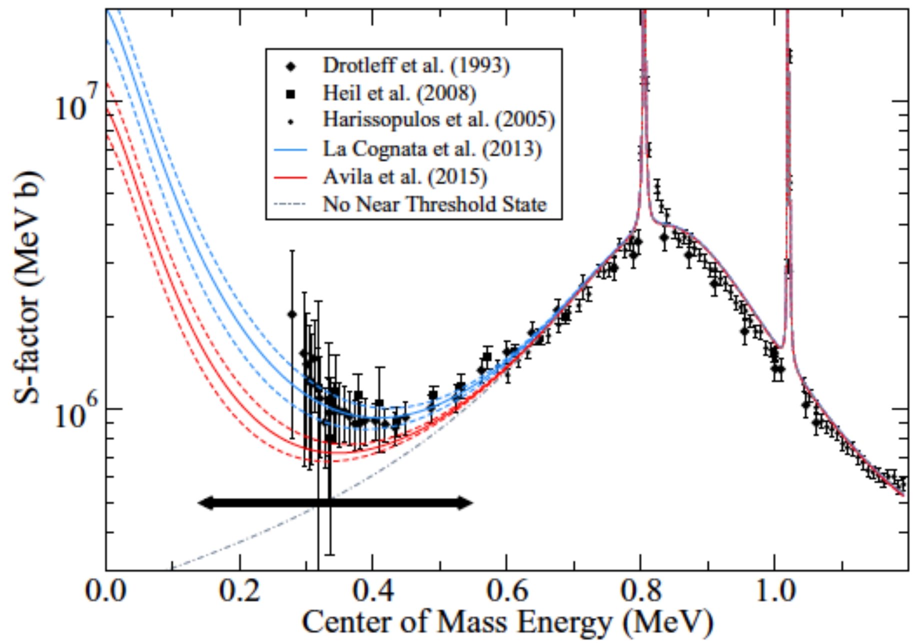
ANC: Avila (violet band) et al (2015)

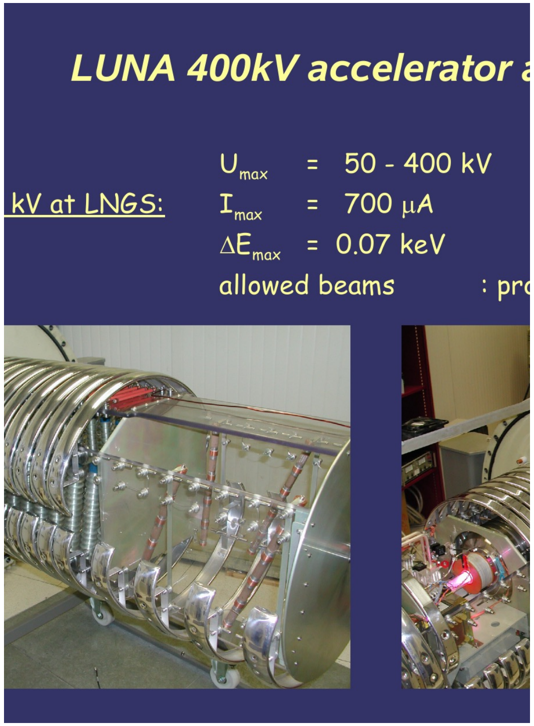
Cyan band is NACRE II compilation

Trippella O. & La Cognata M., ApJ, 837, 41 (2017)




R.J Deboer PRC 101 837, 045802 (2020)

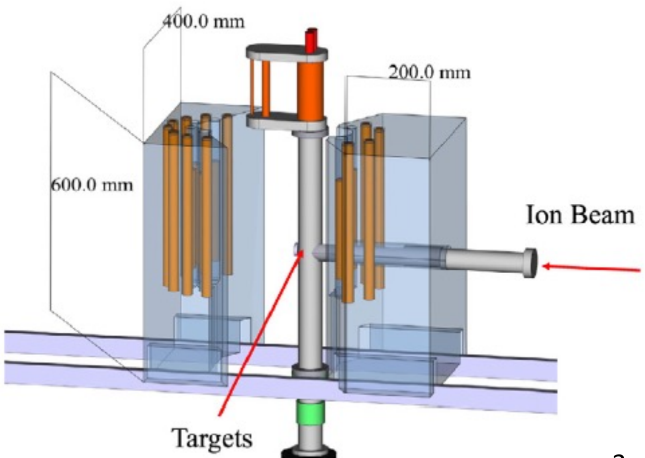


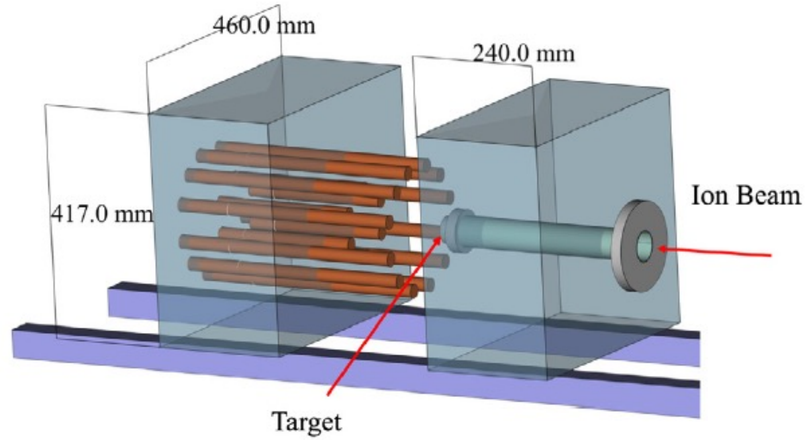



# LUNA 400kV accelerator

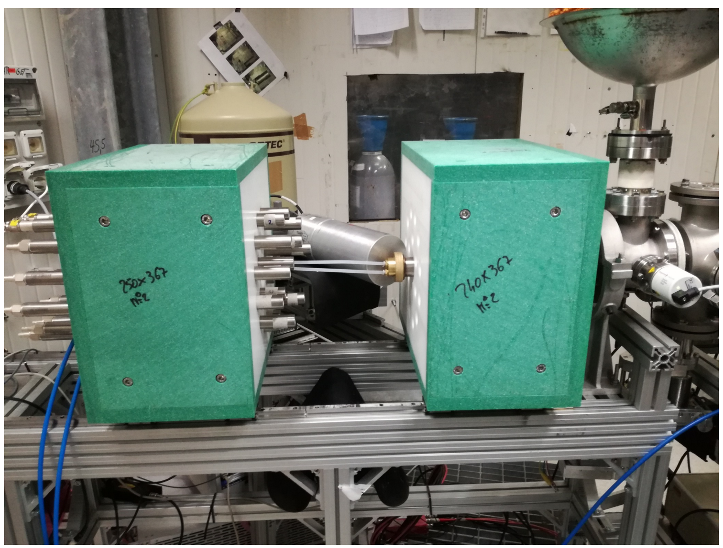
- $U_{terminal}$ = 50 – 400kV
- $I_{max}$ = 220mA (on target)
- Allowed beams: $H^+$, $^4He$, ($^3He$)

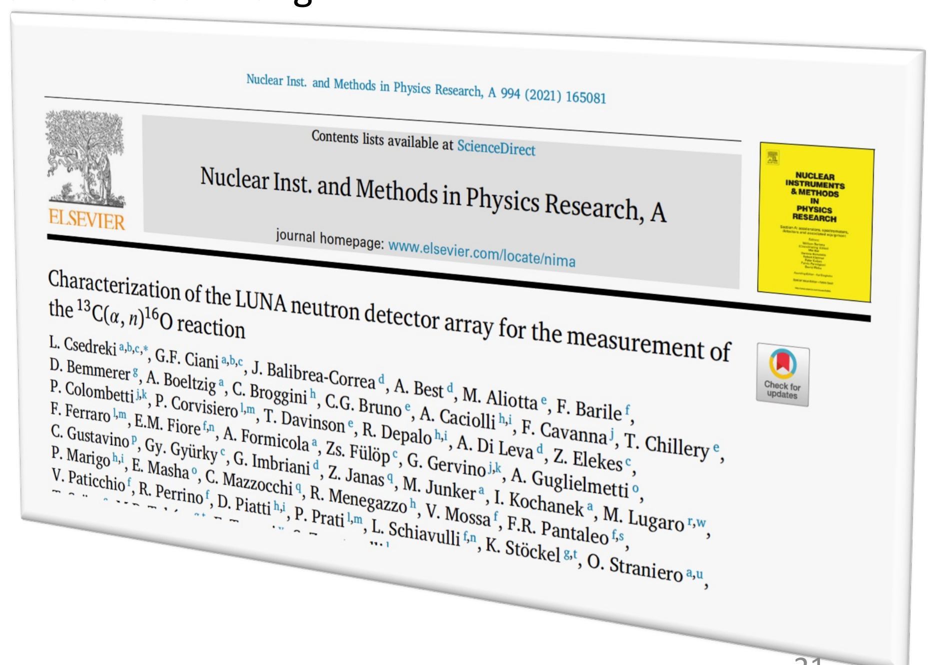
# Experimental setup of the $^{13}C(\alpha,n)^{16}O$ reaction




12 $^{3}$He steel counters 40 cm long .
6 $^{3}$He steel counters 25 cm long




Nuclear Inst. and Methods in Physics Research, A 994 (2021) 165081

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Characterization of the LUNA neutron detector array for the measurement of the $^{13}C(\alpha, n)^{16}O$ reaction

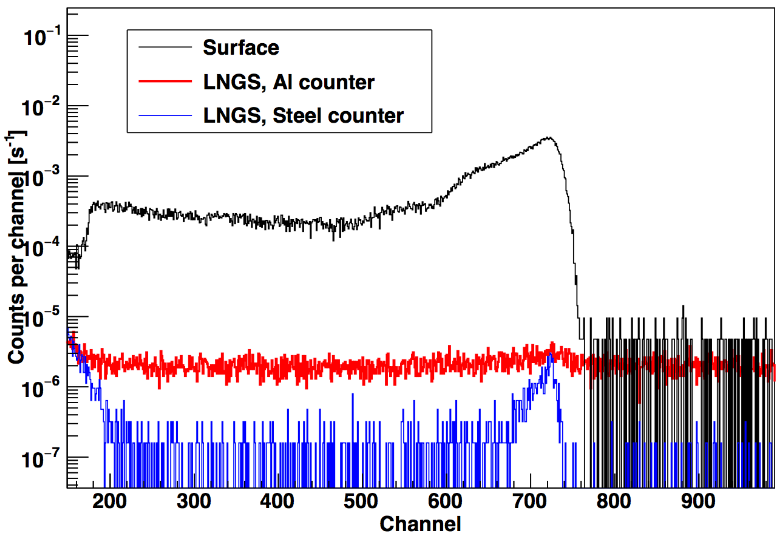
L. Csedreki[a,b,c,*], G.F. Ciani[a,b,c], J. Balibrea-Correa[d], A. Best[d], M. Aliotta[e], F. Barile[f], D. Bemmerer[g], A. Boeltzig[a], C. Broggini[h], C.G. Bruno[e], A. Caciolli[h,i], F. Cavanna[j], T. Chillery[e], P. Colombetti[j,k], P. Corvisiero[l,m], T. Davinson[e], R. Depalo[h,i], A. Di Leva[d], Z. Elekes[c], F. Ferraro[l,m], E.M. Fiore[f,n], A. Formicola[a], Zs. Fülöp[c], G. Gervino[j,k], A. Guglielmetti[o], C. Gustavino[p], Gy. Gyürky[c], G. Imbriani[d], Z. Janas[q], M. Junker[a], I. Kochanek[a], M. Lugaro[r,w], P. Marigo[h,i], E. Masha[o], C. Mazzocchi[q], R. Menegazzo[h], V. Mossa[f], F.R. Pantaleo[f,s], V. Paticchio[f], R. Perrino[f], D. Piatti[h,i], P. Prati[l,m], L. Schiavulli[f,n], K. Stöckel[g,t], O. Straniero[a,u],

# Background reduction

**ENVIRONMENTAL**: neutron flux reduction of a factor 1000 **in Underground Laboratory**

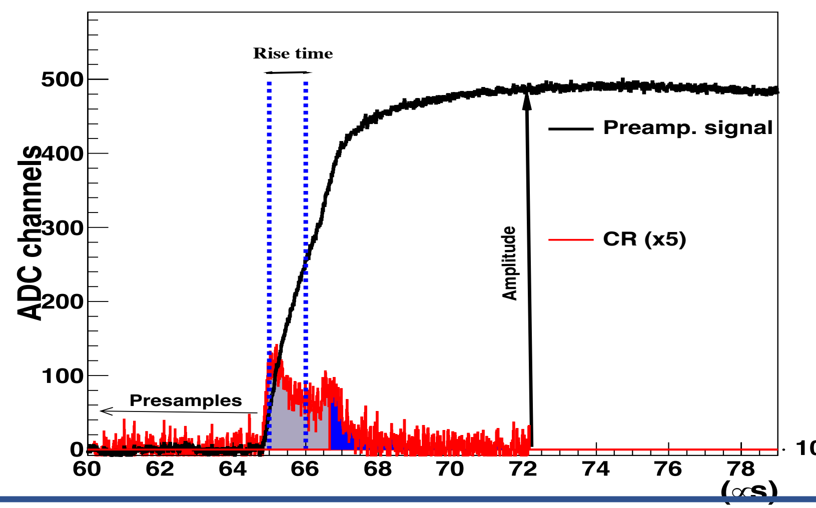
**INTRINSIC:** $\alpha$ particles source of intrinsic background from U and Th impurities in the counters' case

**10 atm** pressurised $^3He$ counters with a stainless steel case with low intrinsic background
Background (n+$\alpha$): (2.93+-0.09) counts/h in the ROI




**POST Processing PULSE SHAPE DISCRIMINATION***
**(rejects 90% alpha and 10% neutrons)**
Background rate (ROI) for the entire $^3He$ setup:
~ (1.05+-0.06) counts/hour

*J. Balibrea-Correa et al., NIM A 906,103-109, (2018)



## Neutron detection efficiency

## $^{13}C(\alpha,n)^{16}O \rightarrow E_n$=2.2-2.6 MeV emission

- Geant4 simulations validated by experimental measurements

**$^{51}V(p,n)^{51}Cr$**

- 5 MV Van dee Graaff at Atomki, Hungary
- $^{51}Cr$ decay via electron capture
  ($T_{1/2}$=27.7 days and emission of $E\gamma$=320 keV)
- $E_{p,lab}$=1.7, 2.0, 2.3 MeV
  ($E_n$=0.13, 0.42, 0.71 MeV)

**Calibrated AmBe source**

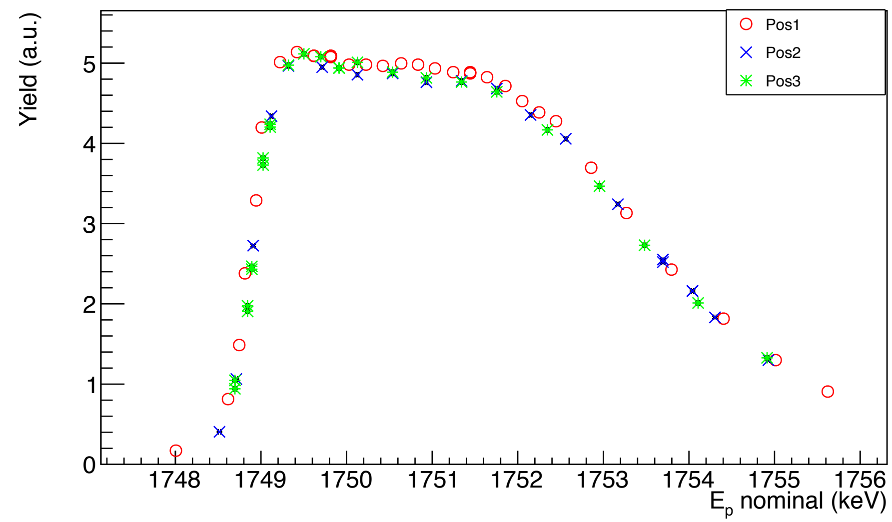
- $E_n$=0-12 MeV ; weighted $E_n$~ 4.0 MeV

Efficiency interpolated (red diamond) in the ROI: $(38 \pm 3)\%$

L. Csedreki et al. NIM A 994 (2021)

## Target Characterization

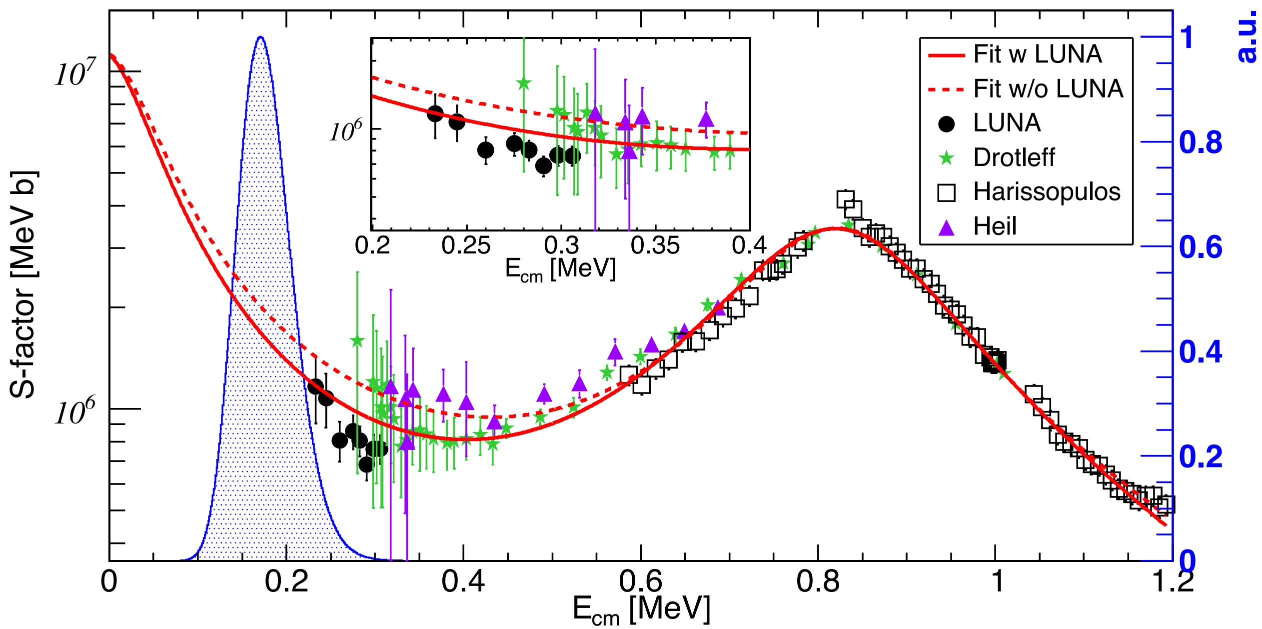
### $^{13}C(p,\gamma)^{14}N$




Thickness at $E_{lab}$ = 1747.6 keV ($\Gamma_R$ = 122 eV)
<I> 500 nA- 5 MV ATOMKI Tandetron

Ciani et al, Eur. Phys. J. A(2020) 56:75

# S(E) factor towards the Gamow window




Three reaction rates evaluated

- NO LUNA (about +2σ)
- LUNA
- LOW LUNA (about -2σ)

- Data taking in 4 campaigns of 3 months each in about 2 years (more than 100 targets used)
- Statistical uncertainty lower than 10% for the whole dataset ($E_{cm}$ 230-305 keV)
- Lowest energy data ever achieved and at the Gamow window edge of low mass AGB.
- Reaction rate uncertainty reduced to about 10%

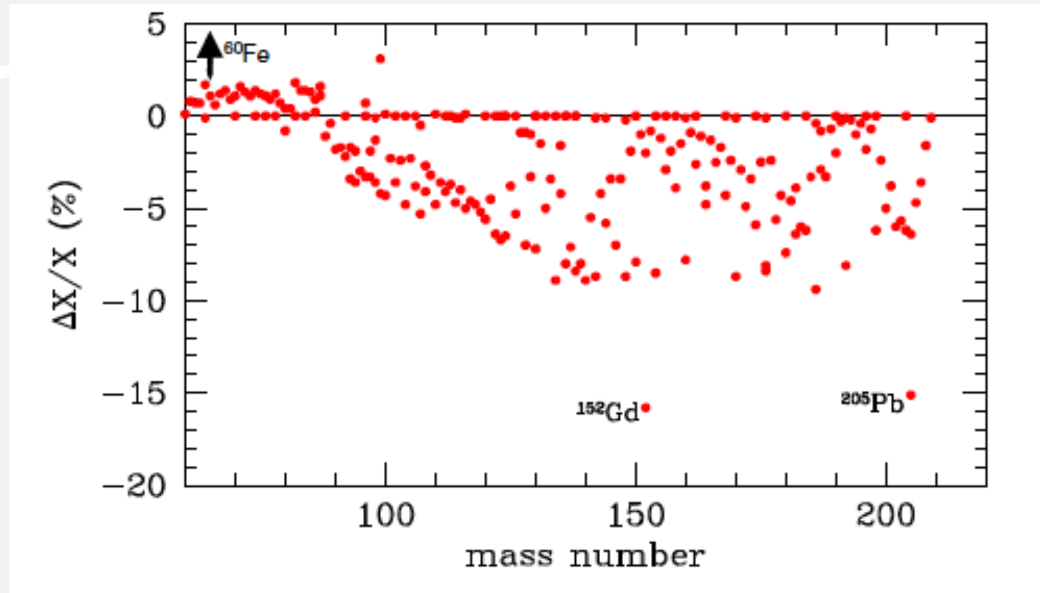
# From S(E)-Factor to reaction rate

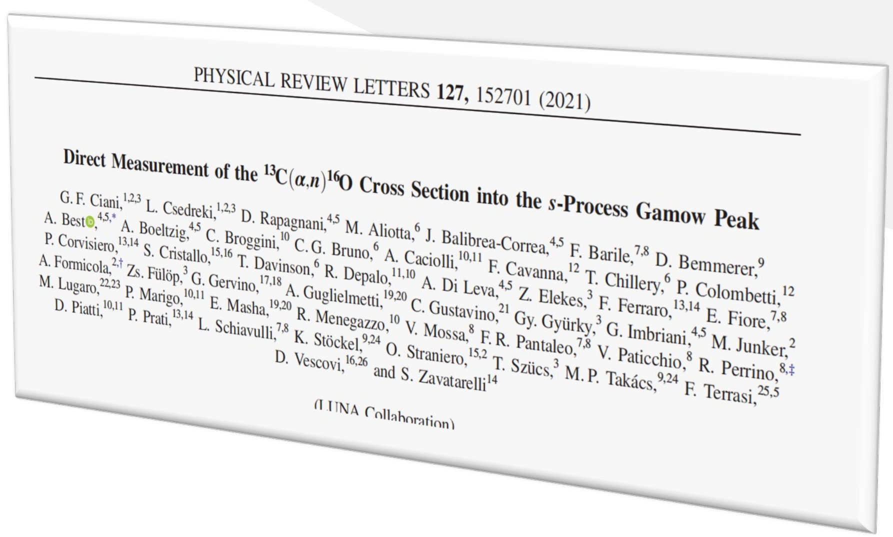
M=2M$_\odot$

metallicity Z= 0.02 and Y= Y= 0.27

Calculated percentage variation of heavy isotopes in LOW LUNA swith respect to NO LUNA data

**The new low-energy cross-sectional measurements imply sizeable variations of the $^{60}$Fe, 152Gd, and $^{205}$Pb yields.**



PHYSICAL REVIEW LETTERS **127**, 152701 (2021)

**Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the *s*-Process Gamow Peak**

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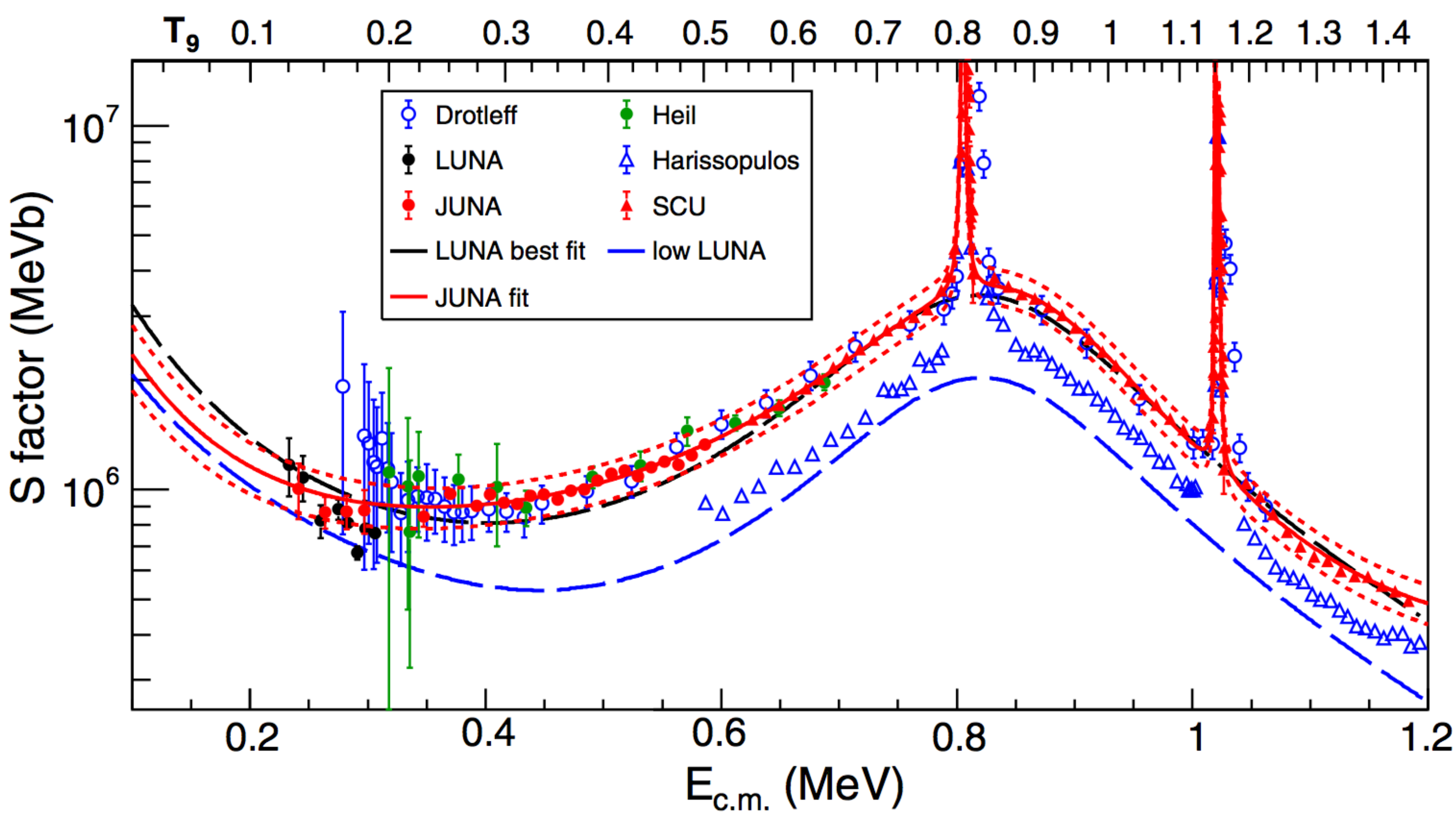
(LUNA Collaboration)

# $^{13}C(\alpha,n)^{16}O$ reaction JUNA collaboration




Adopted from Gao B. et al, PRL 129, 132701 (2022)

# Deep Underground Laboratories World-wide


Image courtesy of Susana Cebrián

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