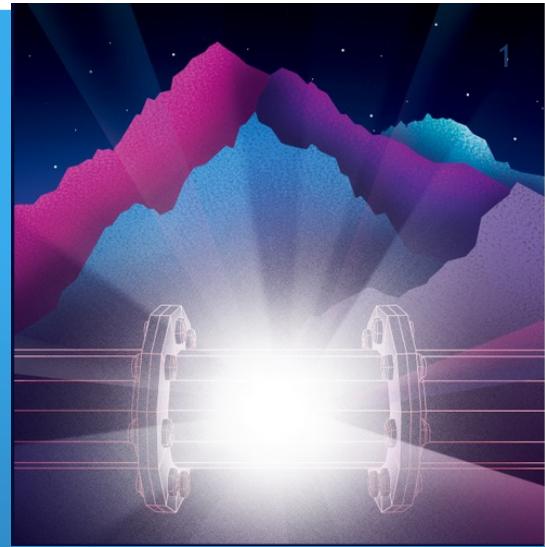


LUNA

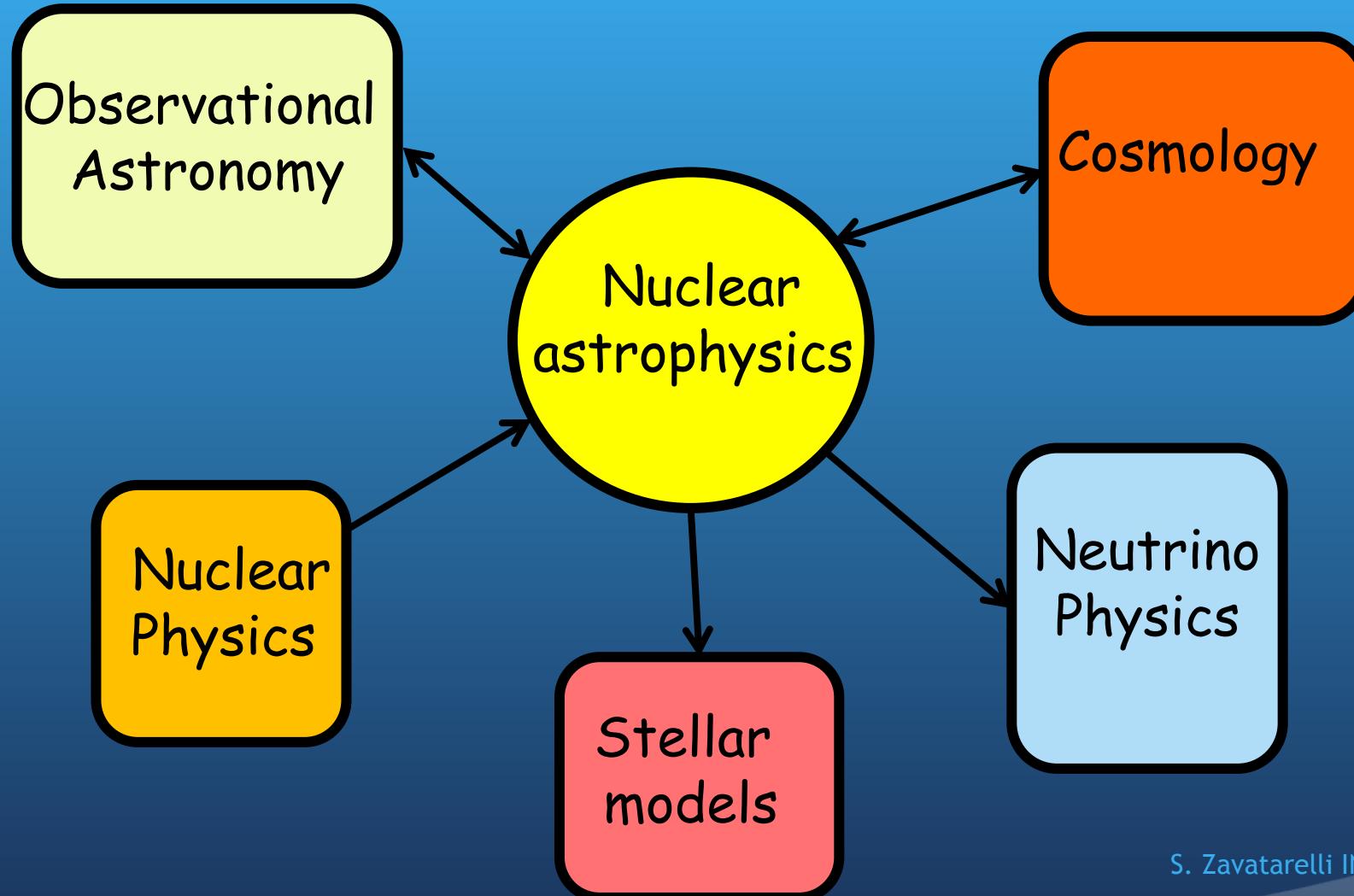


Nuclear astrophysics experiments deep underground at LUNA: recent results and next steps at the new 3.5MV facility

S. Zavatarelli
INFN - Genoa (Italy)
on behalf of the LUNA collaboration



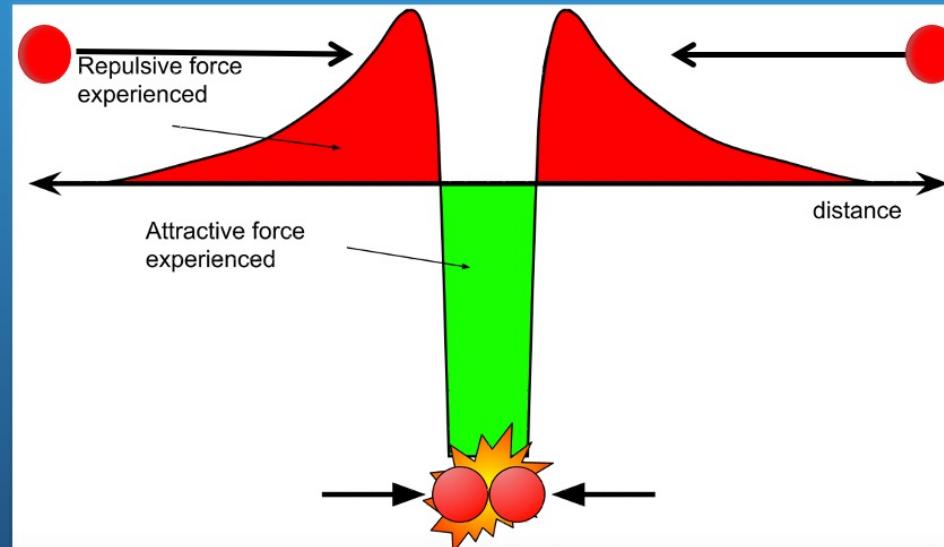
Nuclear astrophysics



Nuclear astrophysics is an extremely rich field, strongly correlated with many other research fields like neutrino physics, astronomy, stellar modeling and cosmology.

Nuclear reactions shape the star evolution but precise direct measurement at stellar energies... not an easy task!

Why?? Low cross sections...



Coulomb barrier

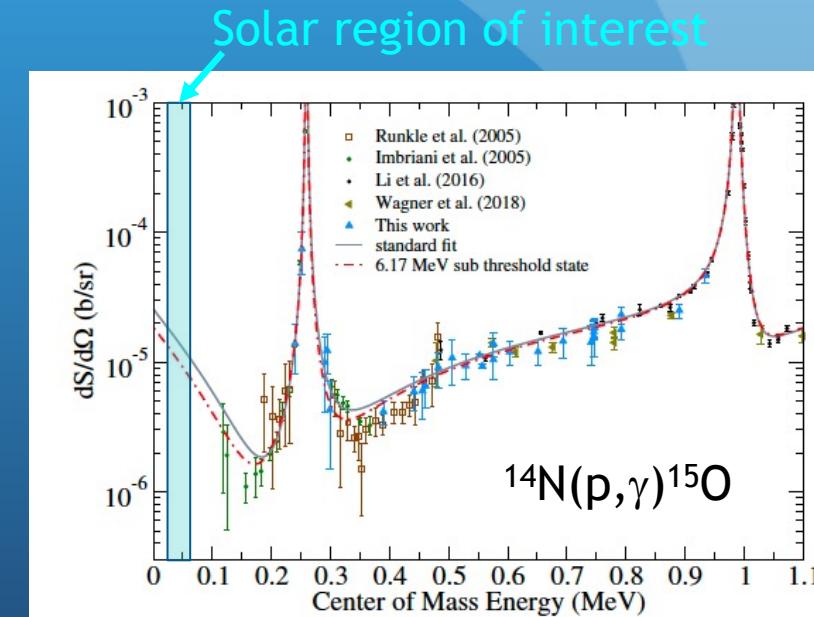
$$V_c = \frac{e^2}{4\pi\epsilon_0} \frac{Z_a Z_b}{R_a + R_b}$$

$$V_c \sim \text{MeV}$$

Typical thermal energies : 10-100 keV

The reaction can proceed only through the

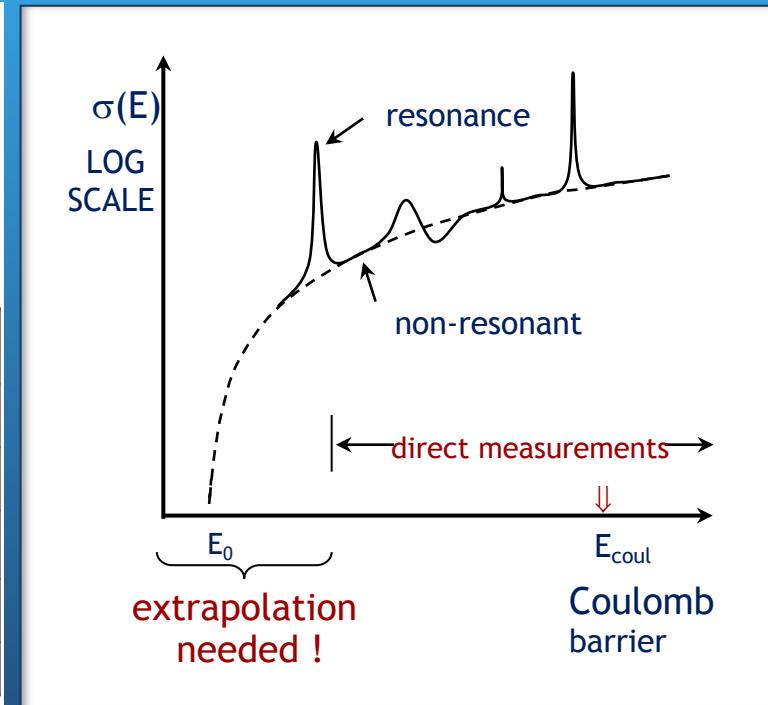
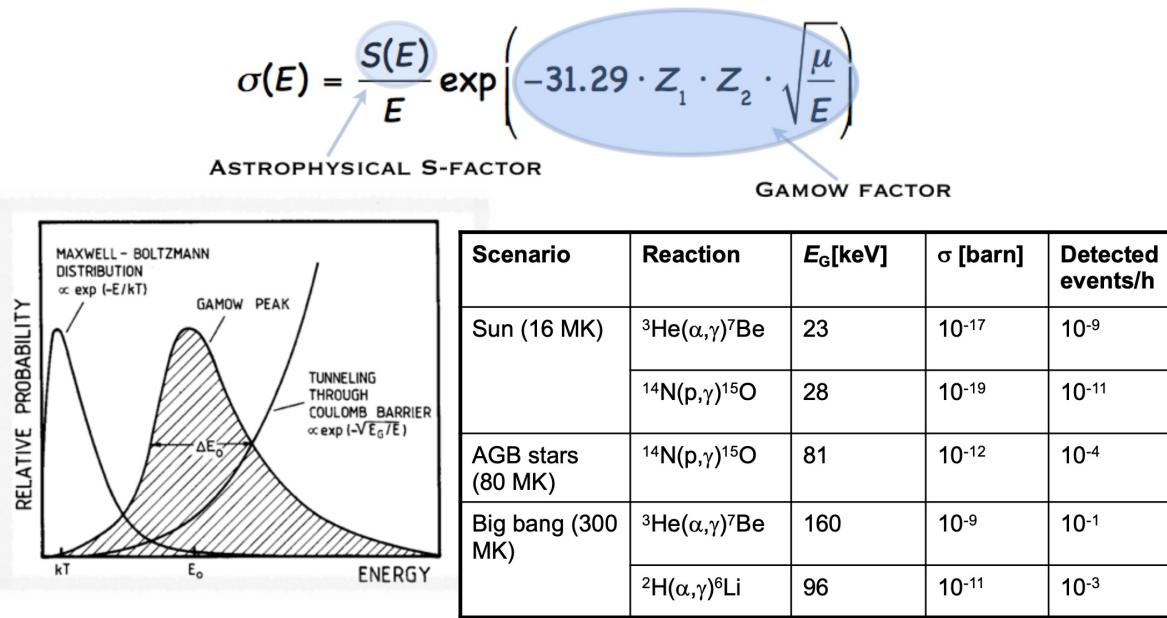
TUNNEL EFFECT



Charged particle induced reactions

Strong energy dependent cross sections..

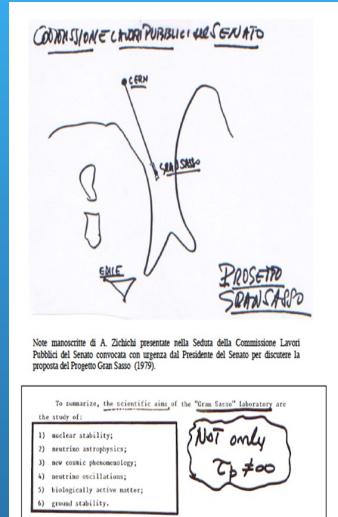
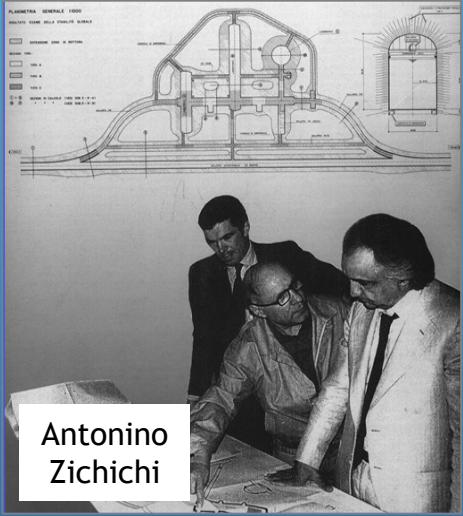
in the Sun: $T = 1.5 \cdot 10^7$ K, $kT = 1$ keV $\ll E_{\text{Coul}}$ (0.5-2MeV)



Direct measurements => Low background environment!!!

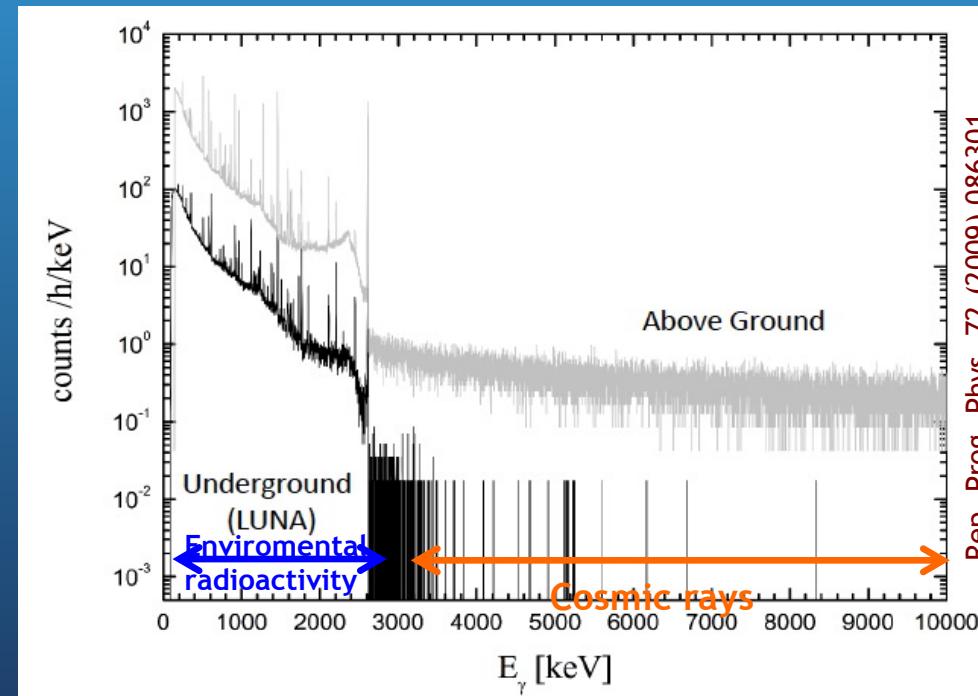
Laboratori Nazionali del Gran Sasso : an ideal location

space - Vienna



Radiation LNGS/surface

Muons	10^{-6}
Neutrons	10^{-3}
Gammas	$10^{-2}-10^{-5}$



Laboratory for Underground Nuclear Astrophysics



400 kV



Radio-frequency ion source

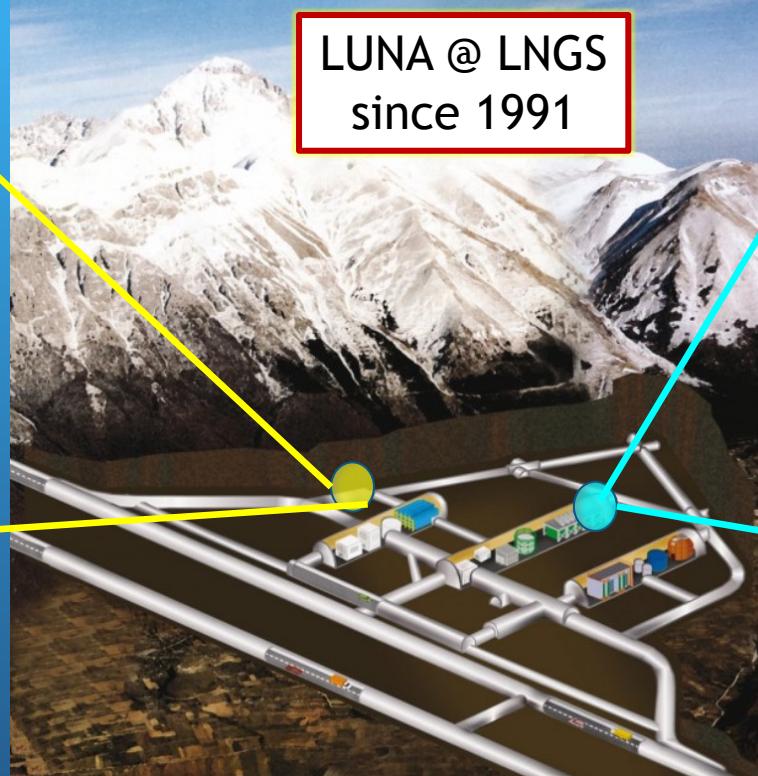
$E_{beam} \approx 50 - 400$ keV

Protons: $I_{max} \approx 500$ μA

4He : $I_{max} \approx 250$ μA

Energy spread ≈ 100 eV

Long term stability ≈ 5 eV/h



3.5 MV



- Inline Cockcroft Walton accelerator
- ECR ion source

TERMINAL VOLTAGE (TV): 0.2 - 3.5 MV

Energy reproducibility: 0.01% TV

Energy stability: 0.001% TV / h

Beam currents :

protons. : 500-1000 μA

4He : 500-1000 μA

$^{12}C^+, ^{12}C^{++}$: 150-100 μA

- Very stable, precise beam energy
- High beam currents

Laboratory for Underground Nuclear Astrophysics



400 kV



Radio-frequency ion source

$E_{beam} \approx 500$ keV

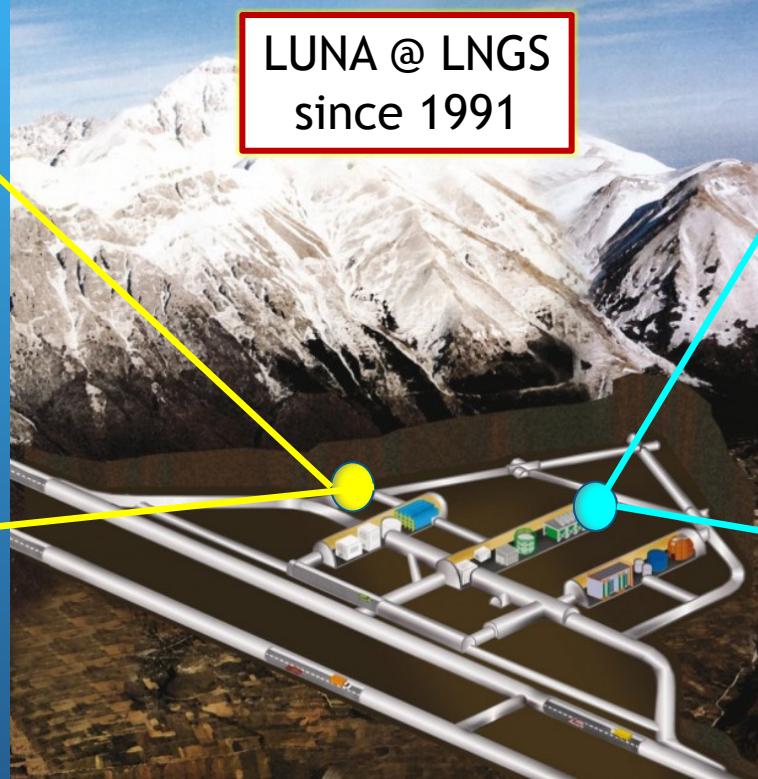
Proton current: 500 μ A

$I_{max} \approx 250 \mu$ A

Energy spread ≈ 100 eV

Long term stability ≈ 5 eV/h

LUNA @ LNGS
since 1991



MV



- Inline Cockcroft Walton
- ECR ion source

TERMINAL VOLTAGE: 0.2 - 3.5 MV

Energy spread: 0.01% TV

Error in energy: 0.001% TV / h

Beta-beams:

protons. : 500-1000 μ A

^{4}He : 500-1000 μ A

$^{12}\text{C}^+, ^{12}\text{C}^{++}$: 150-100 μ A

BBN and H burning

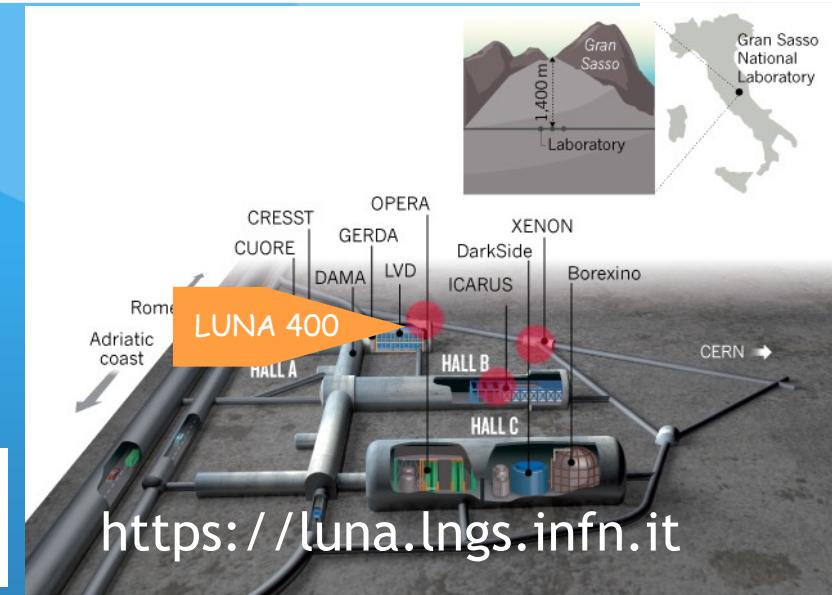
- Very stable, precise beam energy
- High beam currents

He and C burning

LUNA -400



2021-24 H Burning : hot CNO, NeNa, MgAl



Under publication:

- $^{12,13}\text{C}(\text{p},\gamma)^{13,14}\text{N}$
 $^{12}\text{C}/^{13}\text{C}$ abundance ratio
✓ paper accepted by PRL
- $^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$
Speed of Ne-Na cycle
✓ paper submitted to PRC

Data analysis and paper preparation:

$^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ and $^{16}\text{O}(\text{p},\gamma)^{17}\text{F}$

Abundance ratios of ^{18}O , ^{17}O , ^{16}O

Data taking:

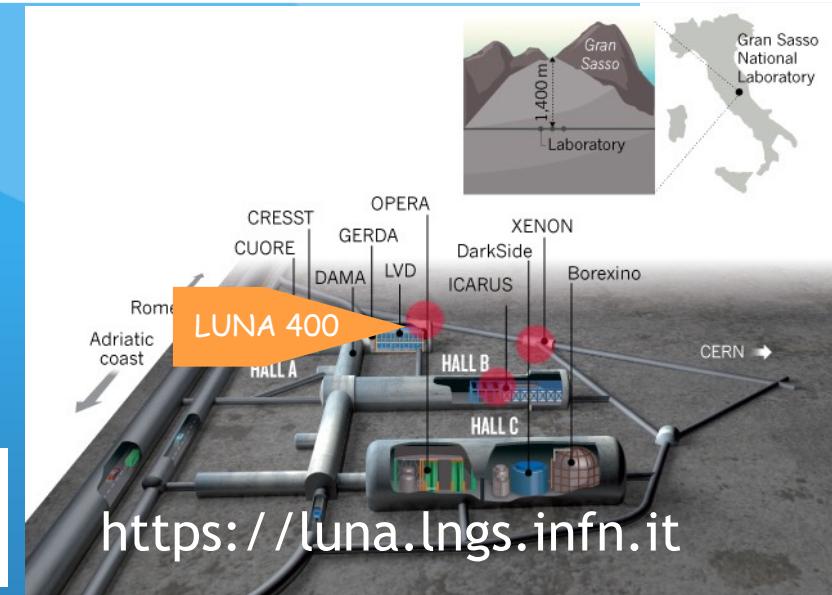
- $^{21}\text{Ne}(\text{p},\gamma)^{22}\text{Na}$
Ne, Na isotopes abundances
✓ data taking phase
- $^{23}\text{Na}(\text{p},\alpha)^{20}\text{Ne}$
O/Ne anticorrelation in globular clusters
✓ ready to start

ERC STG
ELDAR

LUNA -400



2021-24 H Burning : hot CNO, NeNa, MgAl



Under publication:

- $^{12,13}\text{C}(\text{p},\gamma)^{13,14}\text{N}$
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ERC STG
ELDAR

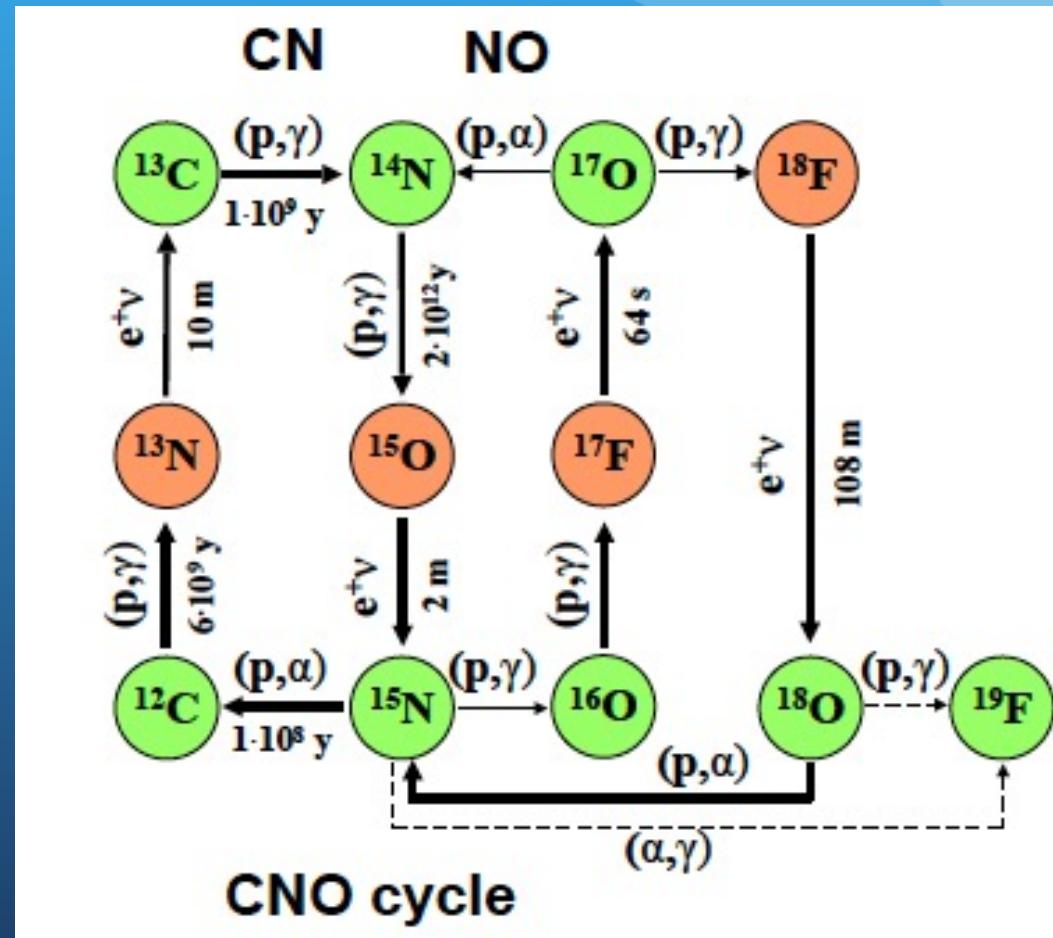
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$^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$ and $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$

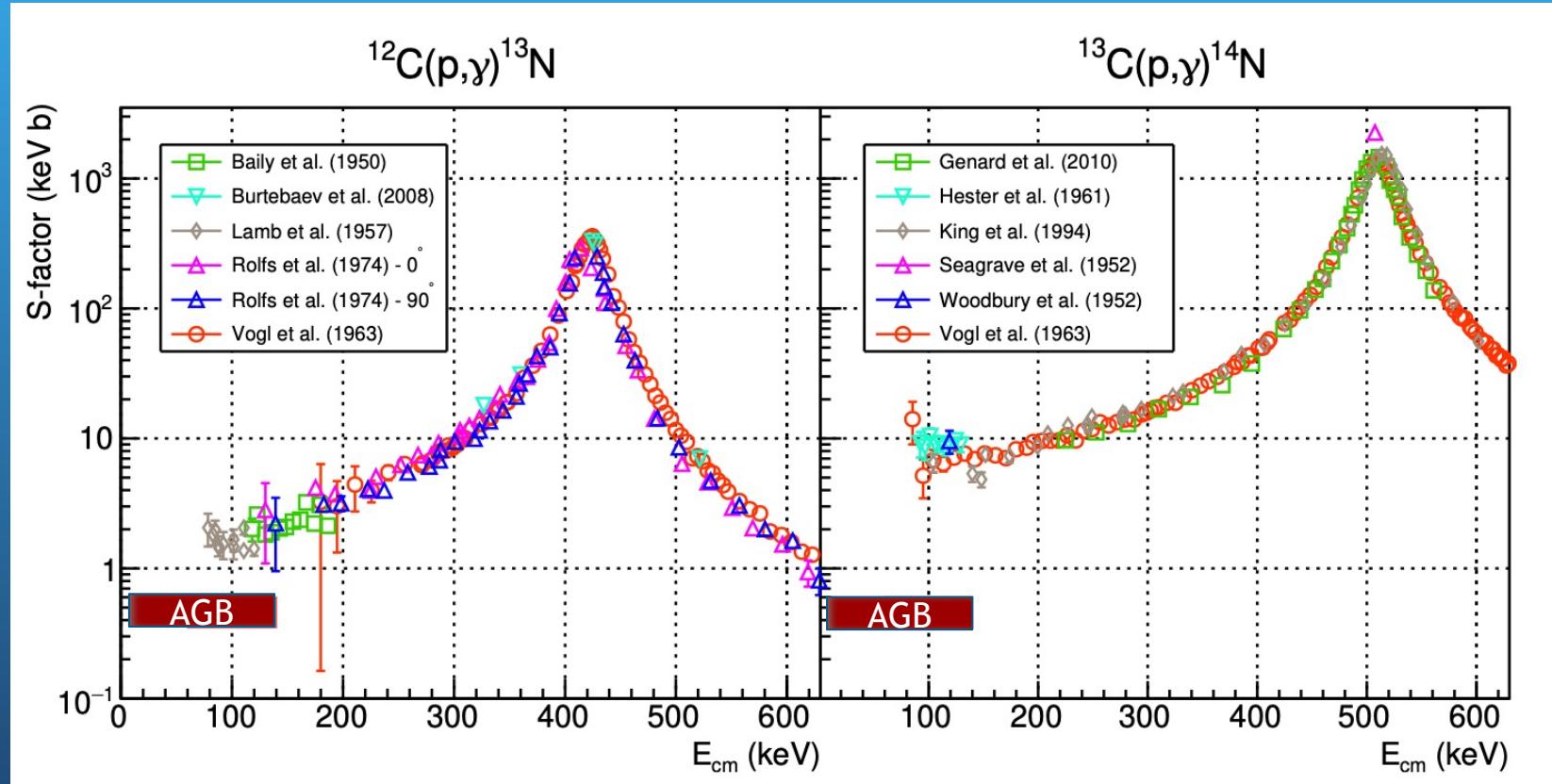
$^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$ and $^{13}\text{C}(\text{p},\gamma)^{13}\text{N}$: astrophysical scenarios

- $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$ and $^{13}\text{C}(\text{p},\gamma)^{13}\text{N}$ cross sections constrain the $^{12}\text{C}/^{13}\text{C}$ ratio in stellar environments
- $^{12}\text{C}/^{13}\text{C}$ can be measured directly and precisely from absorption lines in stellar spectra and SiC grains from meteorites => precise tests of stellar models
- Tracer of galactic chemical evolution and probe of mixing processes in Red Giants and AGB stars:
 - In the solar system $^{12}\text{C}/^{13}\text{C} = 89$, while in nearby molecular clouds ~ 68 => ^{13}C production in AGB stars from 4.6 Gyr ago ??
 - During RGB convective mixing ^{13}C pushes toward the surface=>the ratio should drop to 25 : some stars show 2-5 .. Extra-mixing??
 - $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$ is one of the main sources of the solar CNO neutrino flux, recently observed by Borexino through the β^+ decay of ^{13}N . The $^{12}\text{C}(\text{p}, \gamma)$ rate controls the onset of the cycle, before equilibrium, and radial profile of $^{13}\text{N}-\nu$ emission (present uncertainty 30%, needed 5%)



Status of the art

$^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}$: Q-value = 1.944 MeV, $^{13}\text{C}(\text{p}, \gamma)^{14}\text{N}$: Q-value= 7.551 MeV



$^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}$: at low energy data points scatter by 30%, bad agreement on resonance energy
 $^{13}\text{C}(\text{p}, \gamma)^{14}\text{N}$: strong data points scatter

Experimental approach: prompt γ yield + activation method

Targets : 4 mm thick ^{12}C disks and 8-15 keV thin targets of ^{12}C and 99% enriched ^{13}C powers evaporated on Ta backing

Two experimental campaigns:

- High energy resolution HPGe detector (at 0° and 55° for angular distribution studies)

$E_p = 80 - 400$ keV (step 10 keV)

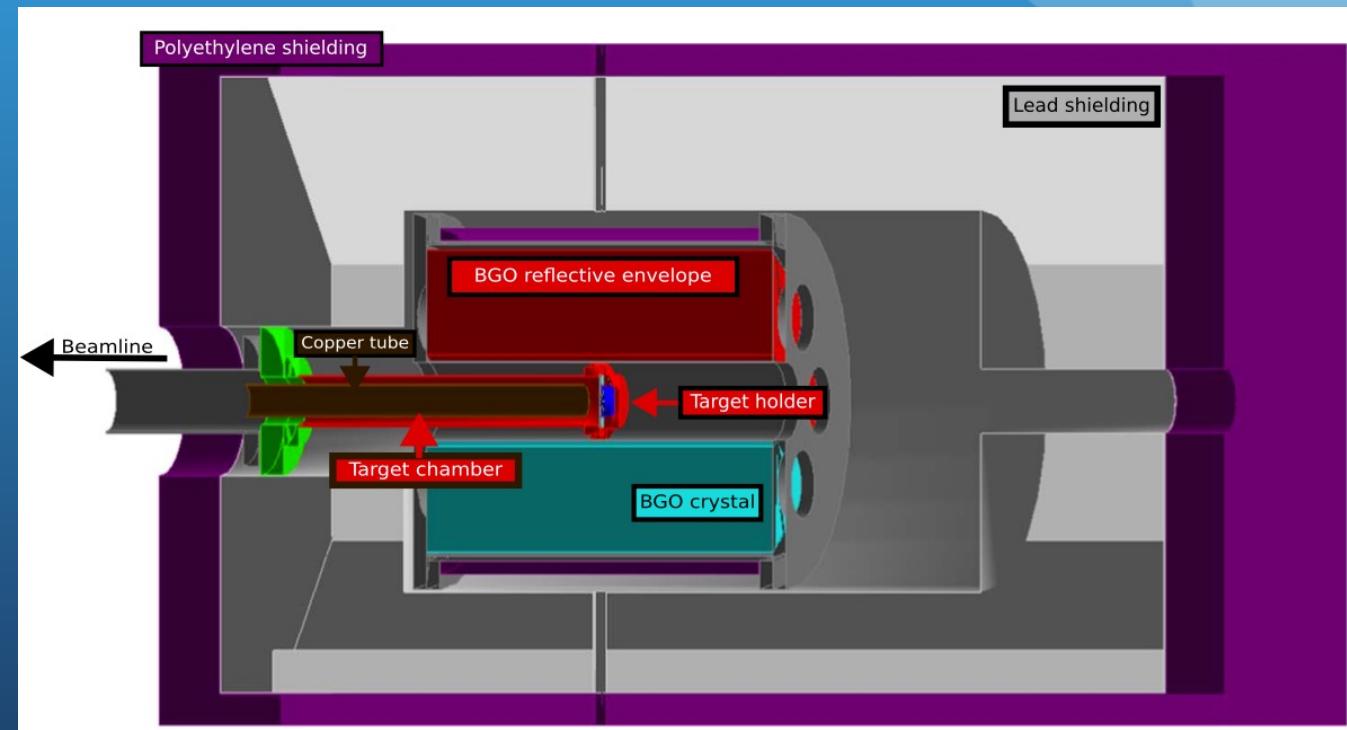
Cross section from fit of primary Gamma Peak Shape

- 4π -BGO detector (6 sectors in phi)

$E_p = 65 - 400$ keV (step 10 keV)

$^{13}\text{C}(p,\gamma)^{14}\text{N}$: Sum Peak Method ($\eta = 37\%$)

$^{12}\text{C}(p,\gamma)^{13}\text{N}$: Activation Method, studied the 511 keV γ coincidence for $^{13}\text{N}-\beta^+$ decay ($T_{1/2} = 10$ min., $\eta = 22\%$)

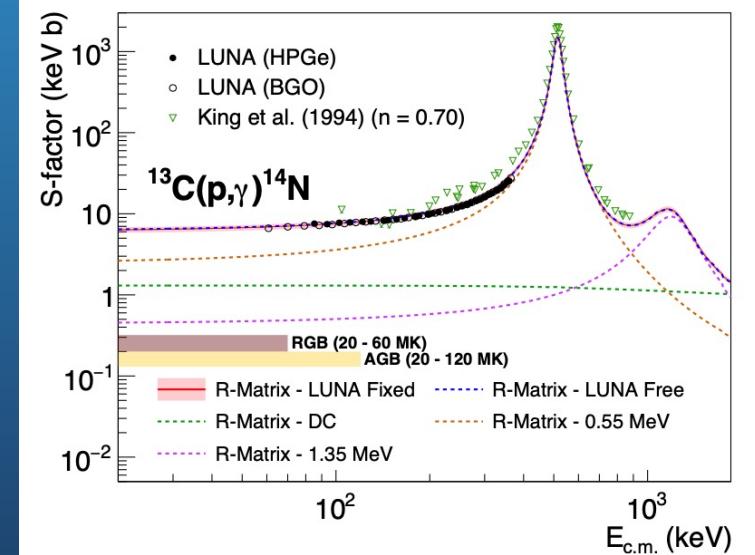
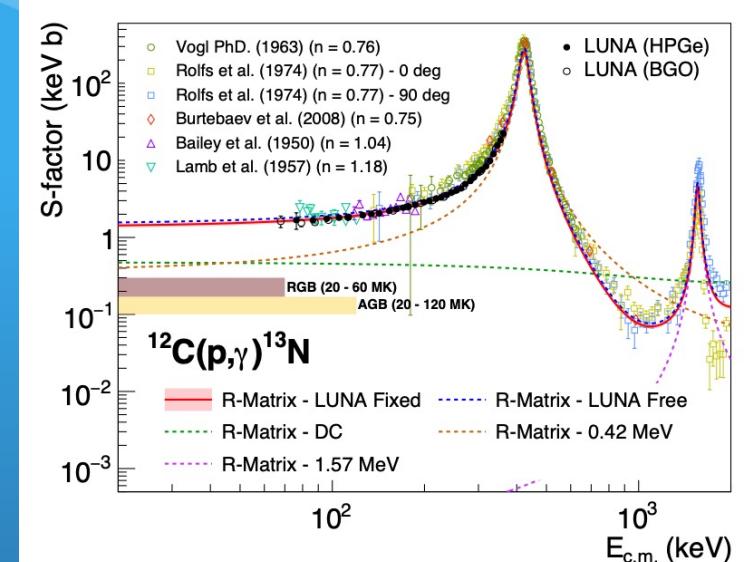


Astrophysical S-factor

LUNA: Highest precision measurement down to 65 – 70 keV in laboratory frame i.e., within the Gamow energy region of interest for AGB and, for the first time, RGB stars.

Results obtained with different experimental techniques: stat. error 1 % (>10 % below 90 keV); Syst.: 7 – 8 %.

- $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$: ~ 25% lower than literature, $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$: ~ 35% lower than literature.
- R-matrix fit to available S-factor data : the red with fixed LUNA data (black symbols) and normalized literature data (coefficients n in the legend), the blue with free normalization also for the LUNA data. Uncertainties are statistical only.

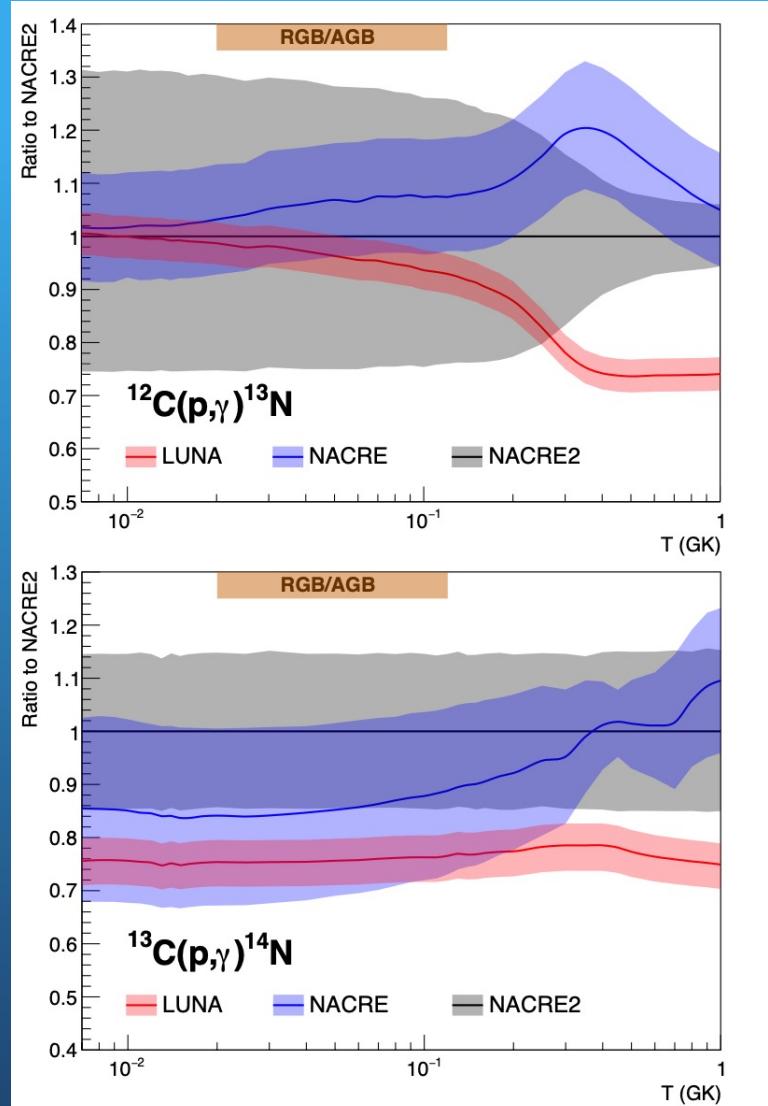


Reaction rate

- computer the reaction rate respect to NACRE and NACRE2.
- The brown bar represents the temperature range of interest for RGB and AGB stars.
- Strong reduction of the uncertainty!
- Paper on astrophysical consequences in preparation
- Our revised reaction rates result in a reduced C isotopic ratio at relevant temperature for mixing effects in giant stars.

Paper accepted on PRL

NACRE : Nucl. Phys. A 656, 3 (1999)
 NACRE2: Nucl. Phys. A 918, 61 (2013)



$^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$

$^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$ and the NeNa cycle

The $^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$ ($Q = 2431.6 \text{ keV}$) reaction is the first and slowest reaction of the NeNa cycle

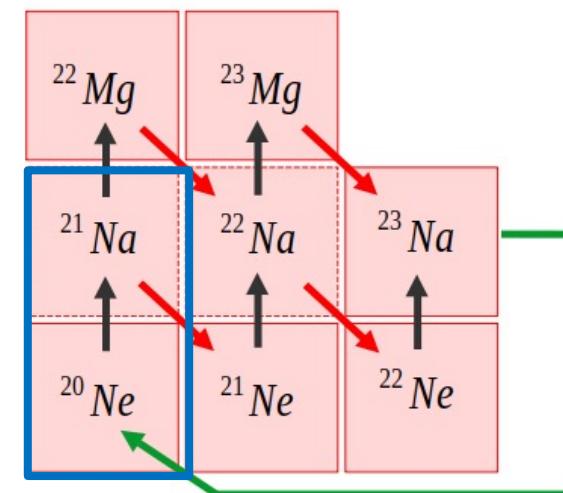
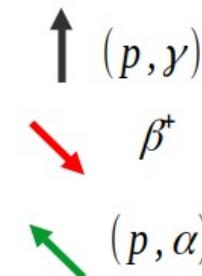
The $^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$ impacts the production of neon and sodium isotopes!

Key Astrophysical sites:

- RGB stars (Red Giant Branch)
- AGB stars (Asymptotic Giant Branch)
- O-Ne Novae
- Massive stars

$$T \cong 0.05-1 \text{ GK}$$

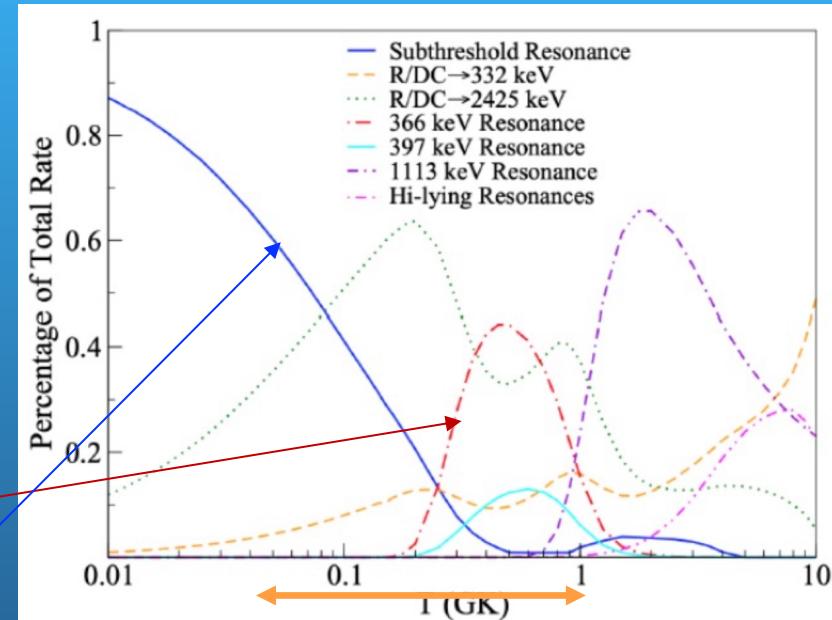
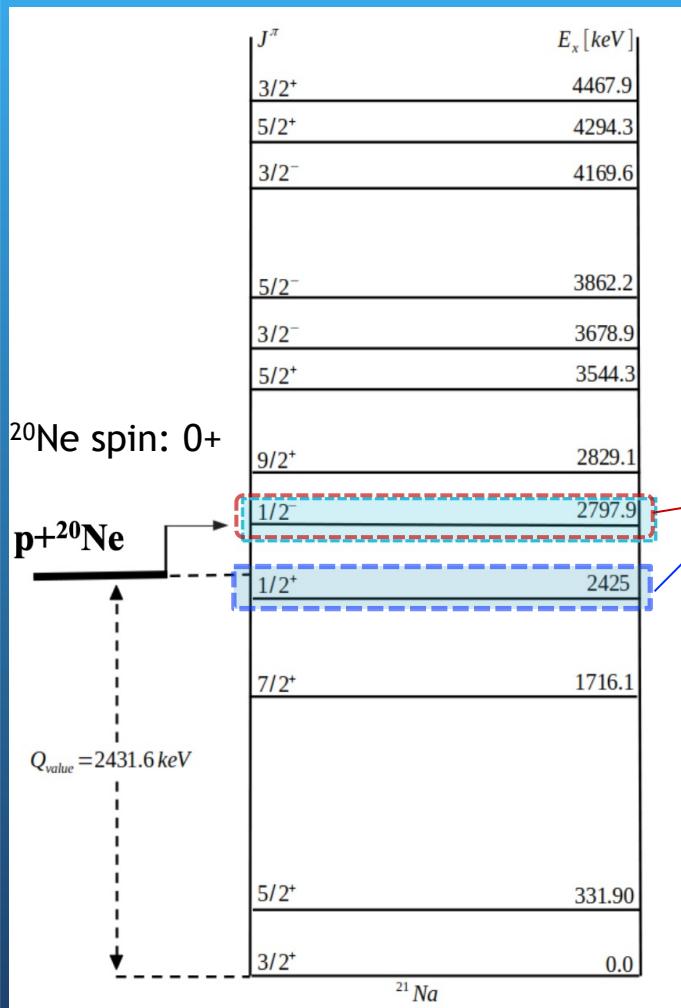
A better understanding of this cycle can help solving the puzzle of the Na-O anticorrelation in Globular Clusters



NeNa cycle

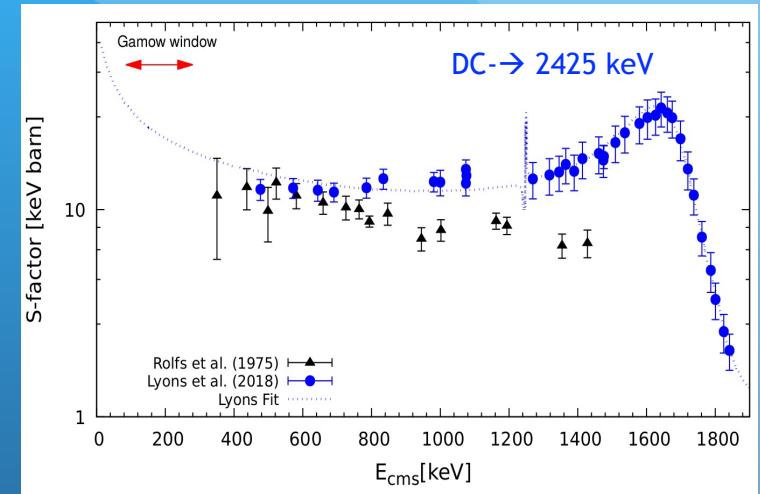
Through the $^{23}\text{Na}(\text{p},\gamma)^{24}\text{Mg}$ reaction, it links to MgAl cycle influencing also Mg and Al isotopes production

The $^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$ reaction ($Q=2431.6 \text{ keV}$)



S.Lyons et al PHYSICAL REVIEW C 97, 0655802 (2018)

- Relevant contributions between 0.1 and 1 GK: the direct capture (DC), the subthreshold resonance at $E_R = -7 \text{ keV}$ and the $E_R = 366 \text{ keV}$ resonance



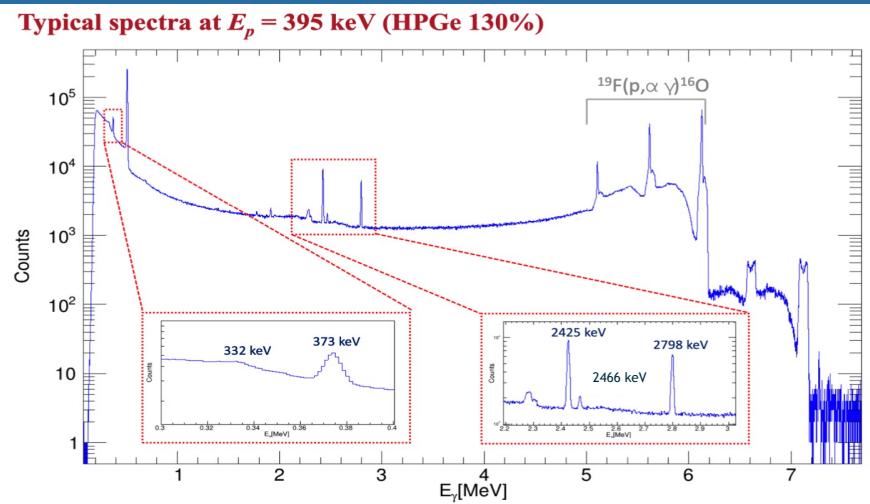
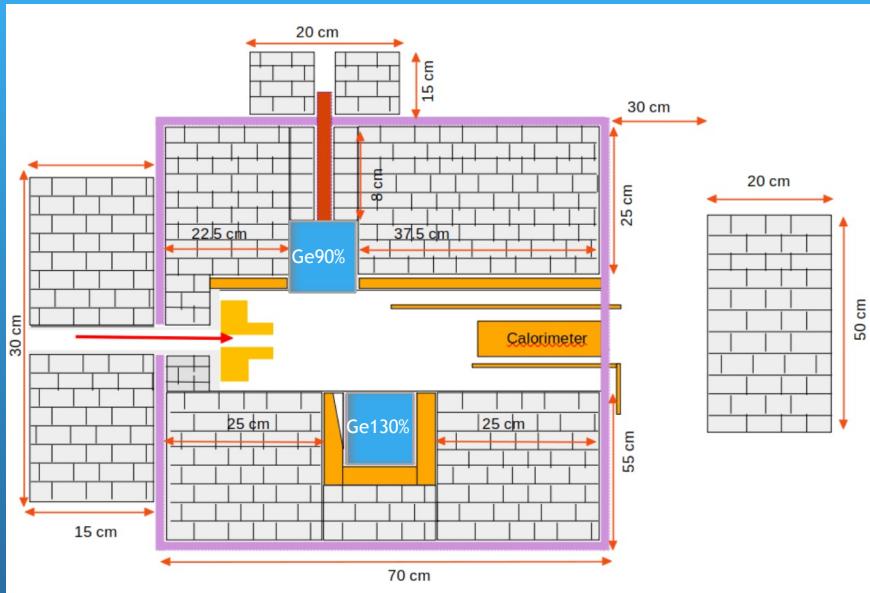
Status of the art:

- Only a few measurements available
- No low energy data

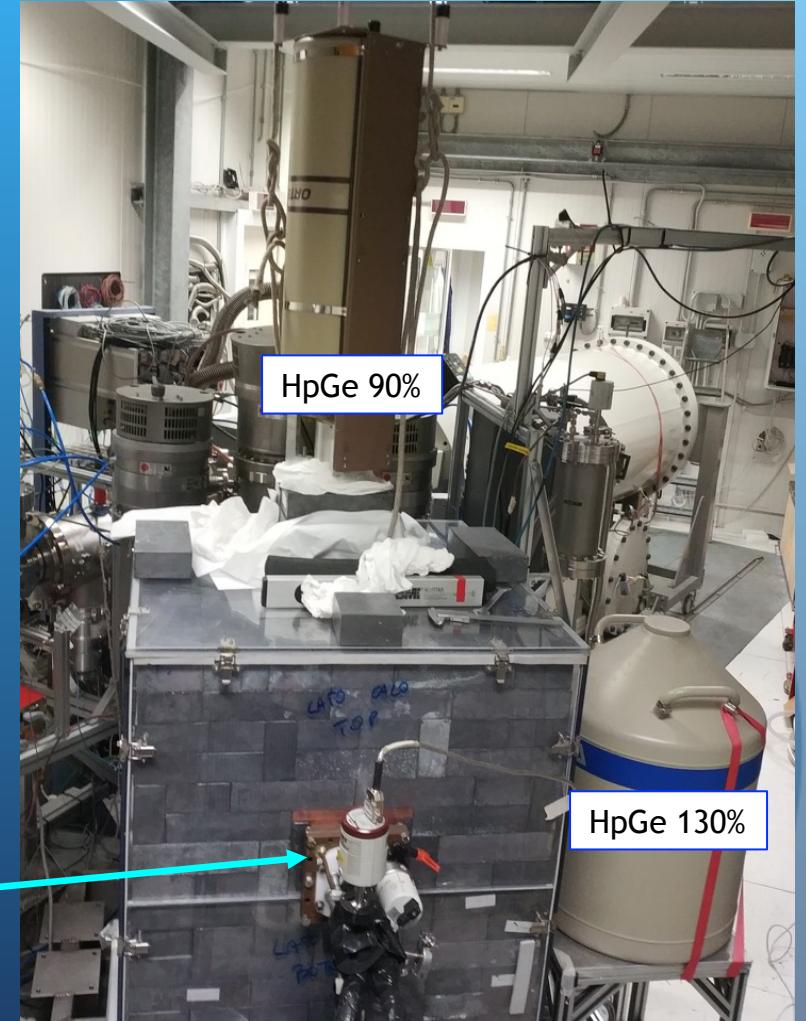
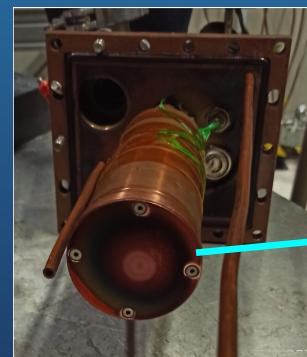
LUNA GOALS

- ❖ Study of the $E_{\text{cm}} = 366 \text{ keV}$ resonance
 - $\omega\gamma = 0.11 \pm 0.02 \text{ meV}$ (Rolfs et al. 1975)
 - $\omega\gamma = 0.0722 \pm 0.0068 \text{ meV}$ (Cooper 2019, Ph.D thesis)
- ❖ Direct capture below 400 keV

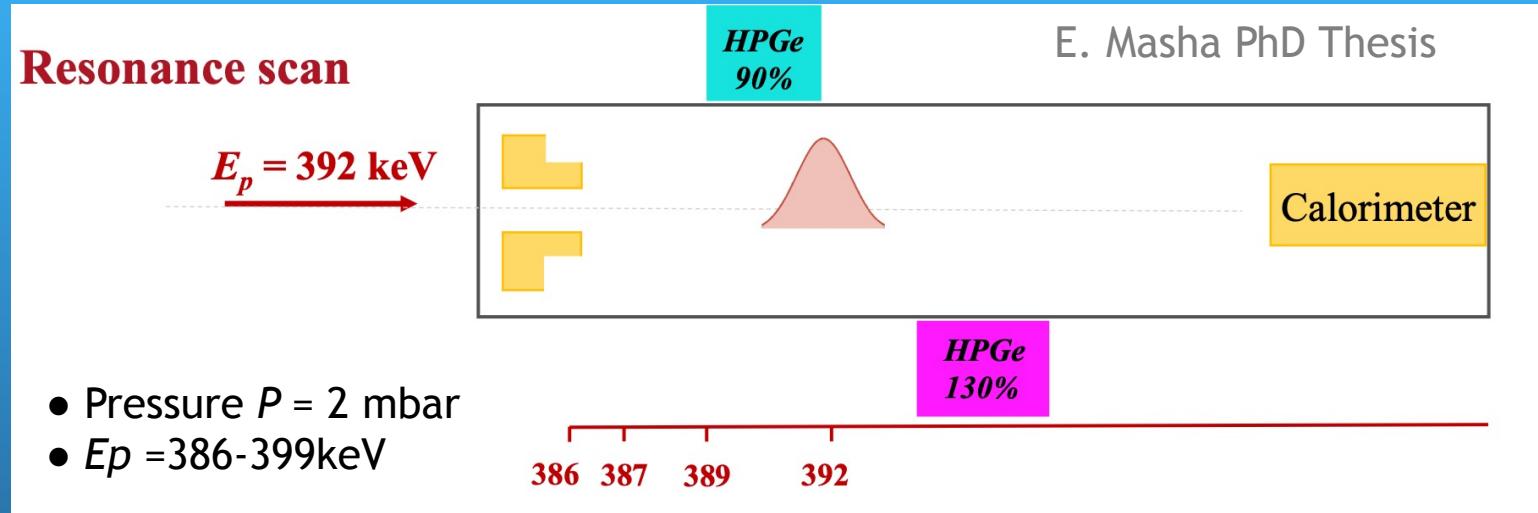
Experimental setup



- ◆ $260 \text{ keV} < E_p < 400 \text{ keV}$
- ◆ Natural Ne windowless gas target (90.3% ^{20}Ne)
 $P = 2 \text{ mbar}$
- ◆ HPGe detectors:
 - Relative efficiency 130%
 - Relative efficiency 90%
- ◆ Lead + copper shielding
- ◆ Anti-Radon box

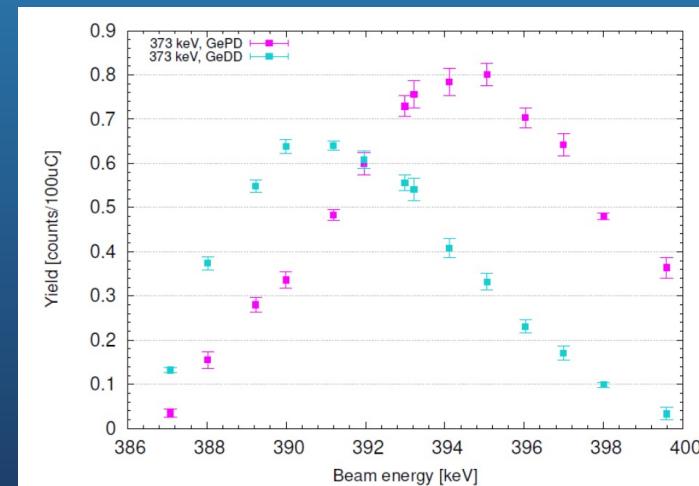


366 keV Resonance study



RESONANCE SCAN
 Varying the beam energy, the resonance is populated at different positions along the target chamber, where the detectors have different efficiencies.

Detector	η (center)
HPGe90%	0.2%
HPGe130%	0.4%



$$E_{R,lab} = E_p - Z \frac{dE}{dz}$$

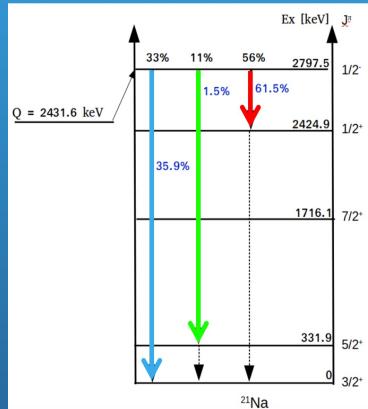
E_p at the maximum yield
 Position of the maximum of the detection efficiency
 Energy loss

↓
Resonance energy

Rolfs et al. (1975) [keV]	LUNA (2023) [keV]
384 ± 5	386.0 ± 0.5

Branching ratios and resonance strength

Branching ratios from the high statistic runs at the maximum detection efficiency:



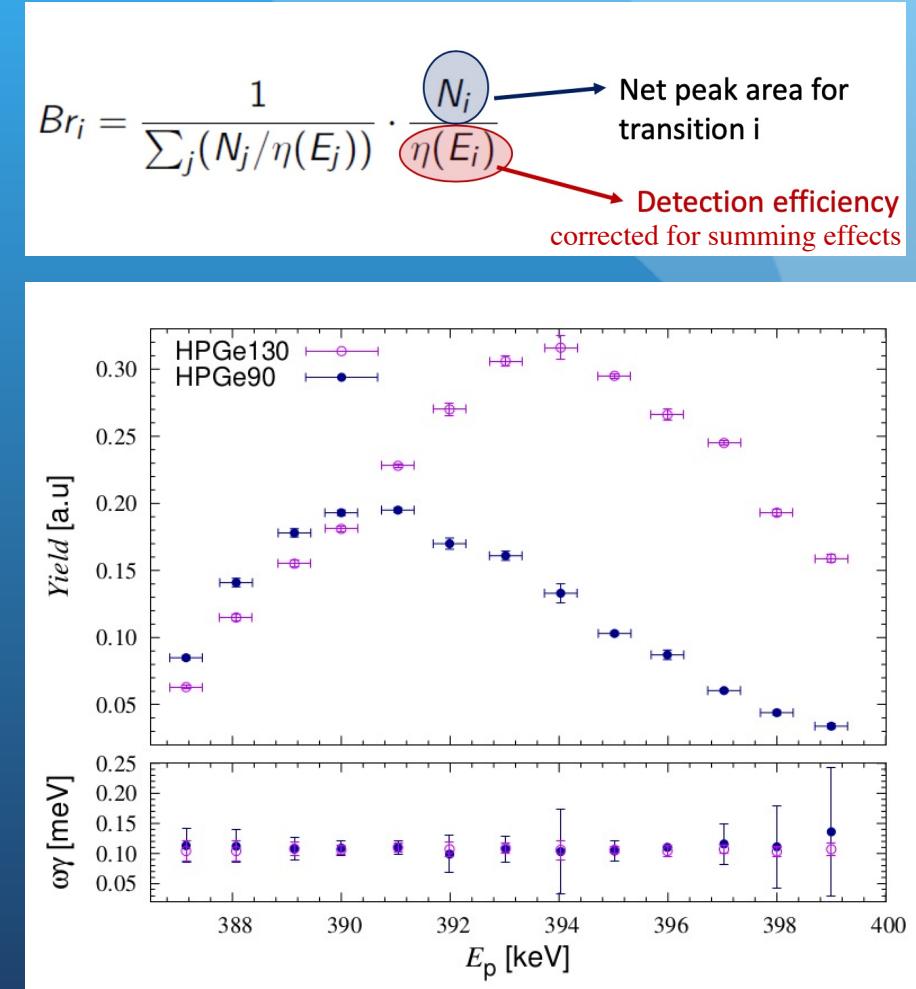
	Measured γ [keV]	Rolfs et al '75 %	LUNA %
R->2425 keV	2425 -> 0	56 ± 4	57 ± 2
R-> 332 keV	2798 -> 332	11 ± 4	4.0 ± 0.2
R->0 keV	2798 -> 0	$33. \pm 4$	39 ± 2

Preliminary

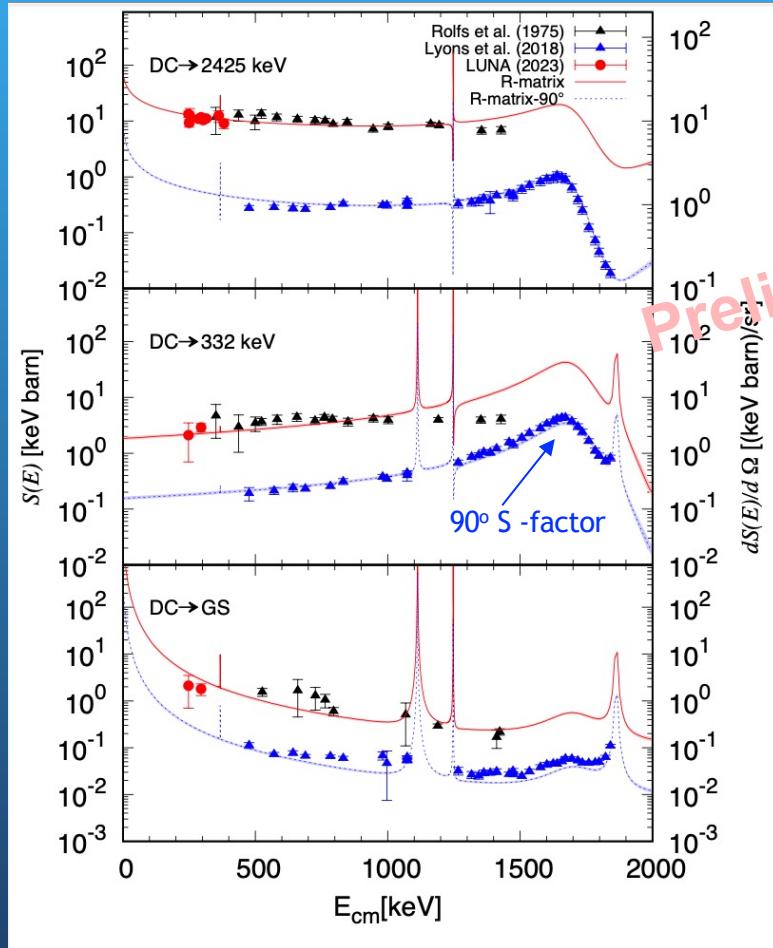
Resonance strength

LUNA [meV]	Rolfs et al. (1975) [meV]
$0.110 \pm 0.002_{\text{stat}} \pm 0.005_{\text{sys}}$	0.11 ± 0.02

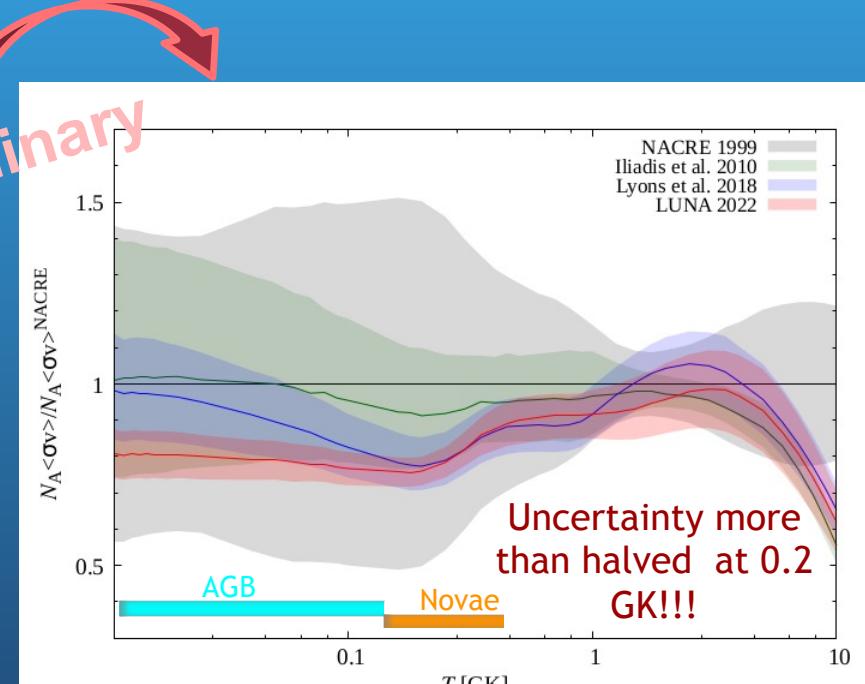
20 -> 6 % precision!



The non resonant S-factor



Direct capture studied in the energy range : $E_p = 260 \text{ keV} - 400 \text{ keV}$



$$\langle \sigma v \rangle_{aX} = \left(\frac{8}{\pi \mu} \right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty \exp\left(-\frac{E}{kT}\right) \sigma(E) E dE$$

paper submitted
to PRC

Some astrophysical consequences:

- For a $5M_\odot$, low metallicity TP-AGB star: ^{21}Ne abundance reduced by 26% respect to NACRE
- In O-Ne novae of $1.25M_\odot$ accreting material at $2 \times 10^{-10} M_\odot/\text{year}$ the production of Ne, Na, and Al isotopes is reduced by 5-40% , in particular 20% reduction in the produced ^{22}Na .

The future at LUNA-400

REACTIONS ALREADY ON THE GROUND, SEVERAL OTHER REACTIONS MAY BE MEASURED...

The 400 kV accelerator will be moved in the hall B, on the MV facility roof

Data taking or close to start:

- $^{21}\text{Ne}(\text{p},\gamma)^{22}\text{Na}$
Ne, Na isotopes abundances
✓ data taking phase
- $^{23}\text{Na}(\text{p},\alpha)^{20}\text{Ne}$
O/Ne anticorrelation in globular clusters
followed by:
- $^{27}\text{Al}(\text{p},\alpha)^{24}\text{Mg}$

ERC STG
ELDAR

Among others..

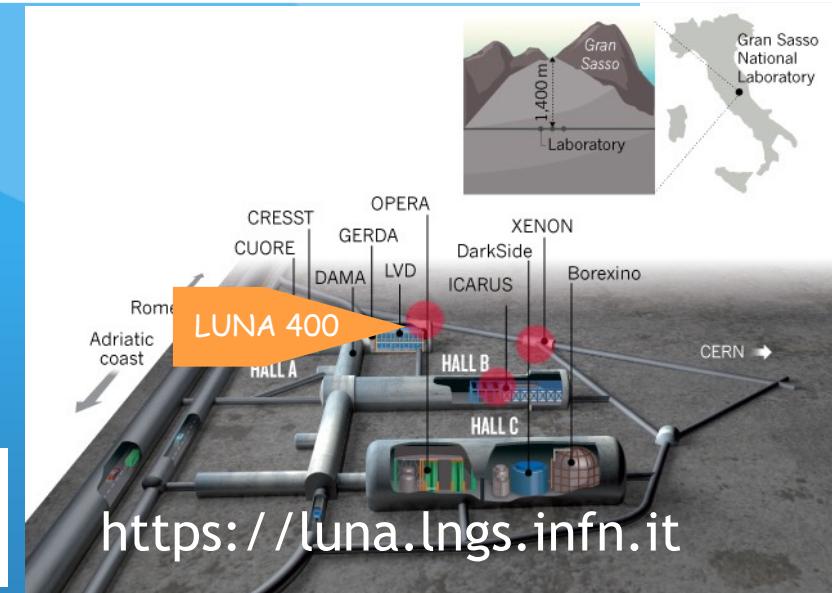
	motivation
$^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$	Solar Neutrino and core and shell H-burning
$^{19}\text{F}(\text{p},\gamma)^{20}\text{Ne}$ $^{19}\text{F}(\text{p},\alpha)^{16}\text{O}$	NeNa cycle in AGB
$^{24}\text{Mg}(\text{p},\gamma)^{25}\text{Al}$	Mg-Al cycle in AGB
$^{10}\text{B}(\alpha,\text{p or d})$	First generation stars
$^{6,7}\text{Li}(\alpha,\gamma)^{10,11}\text{B}$	First generation stars

MIUR PRIN
Social

LUNA -400



2021-24 H Burning : hot CNO, NeNa, MgAl



Under publication:

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- $^{23}\text{Na}(\text{p},\alpha)^{20}\text{Ne}$
O/Ne anticorrelation in globular clusters
✓ ready to start

ERC STG
ELDAR

A MV machine to explore He and C burning

- 3.5 MV terminal voltage
- H, He, C+, C++ beams with high intensity

- Commissioning summer 2022
- Final authorizations end of 2022
- Scientific data acquisition started in June 2023



- **Age of Globular Clusters and C production in AGB:**

$^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ setup ready on first beam line:
PAC assigned 9 weeks of beam in 2023 starting from 06 2023

- **Neutron sources:**

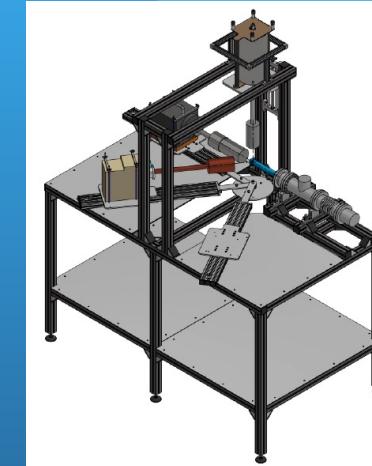
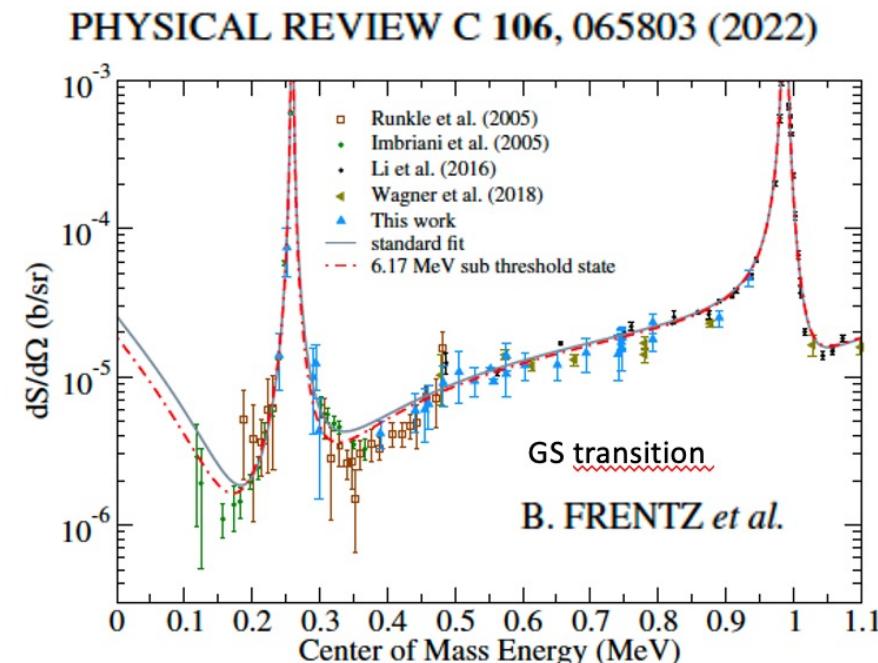
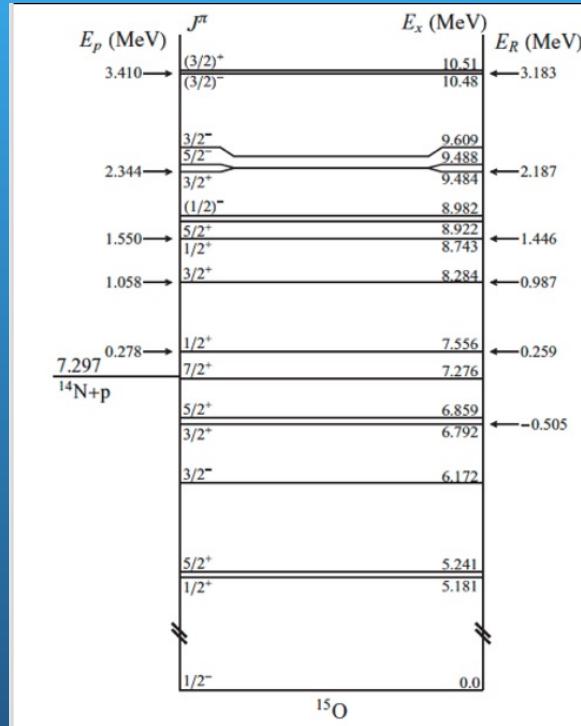
$^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$ setup mouting 07 2023:
PAC assigned 3 weeks of beam in fall 2023 for a beam test

- **He and advanced burning:**

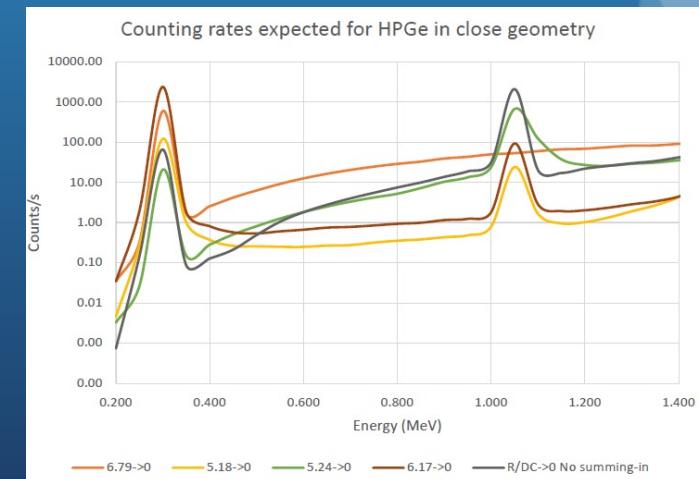
$^{12}\text{C}+\text{He}$ setup ready to be mounted beginning of 2024:
scientific presentation to PAC october 2023

$^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$: an open issue

Reason of interest: speed of CNO cycle, Age of Globular Clusters, solar ν

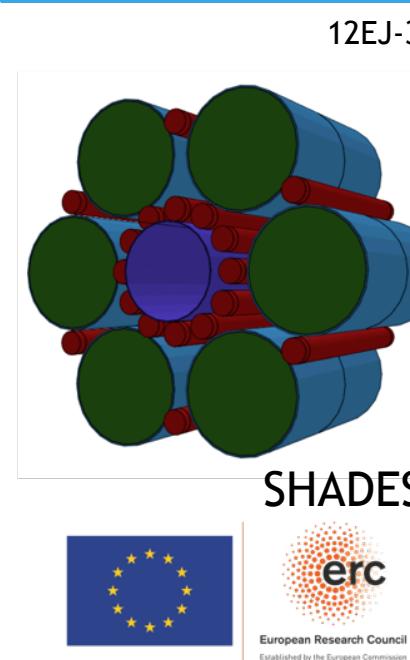
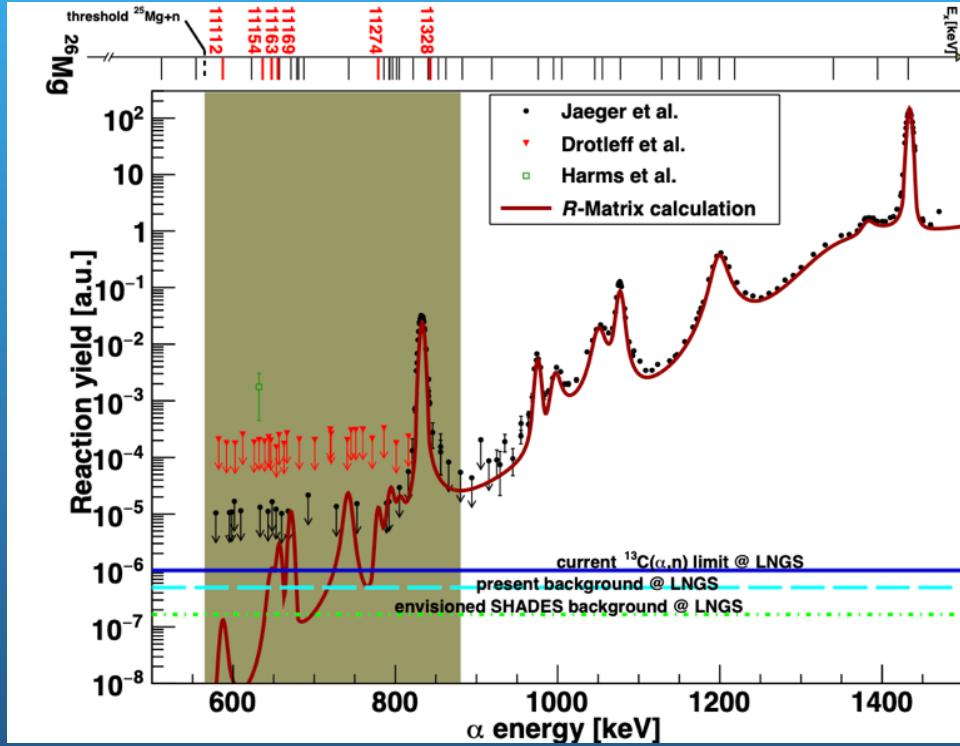


3 HPGe detectors
for angular
distribution
measurement.



There is the need to cover the energy window between about 1.5 MeV down to 250 keV using the same detection setup, possibly to extend the study -> 50 keV @ LUNA-400

$^{22}\text{Ne}(\alpha, \text{n})^{25}\text{Mg}$: neutron source for weak s-process



12EJ-309 +18 ^3He counters



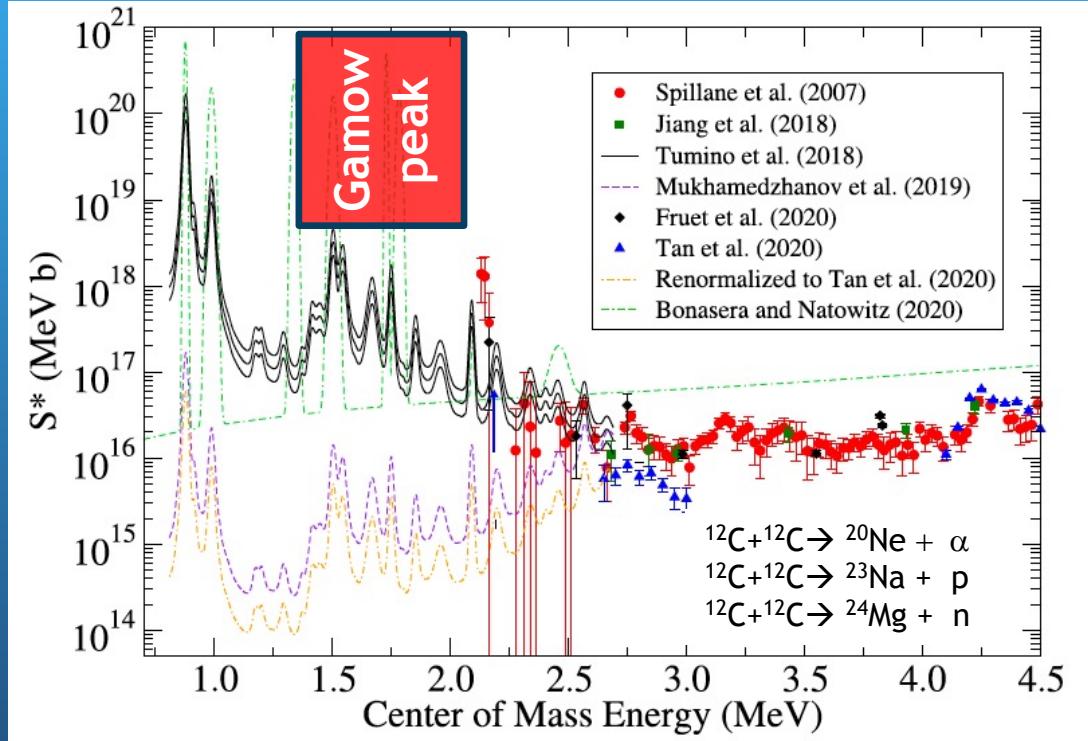
Gas target system



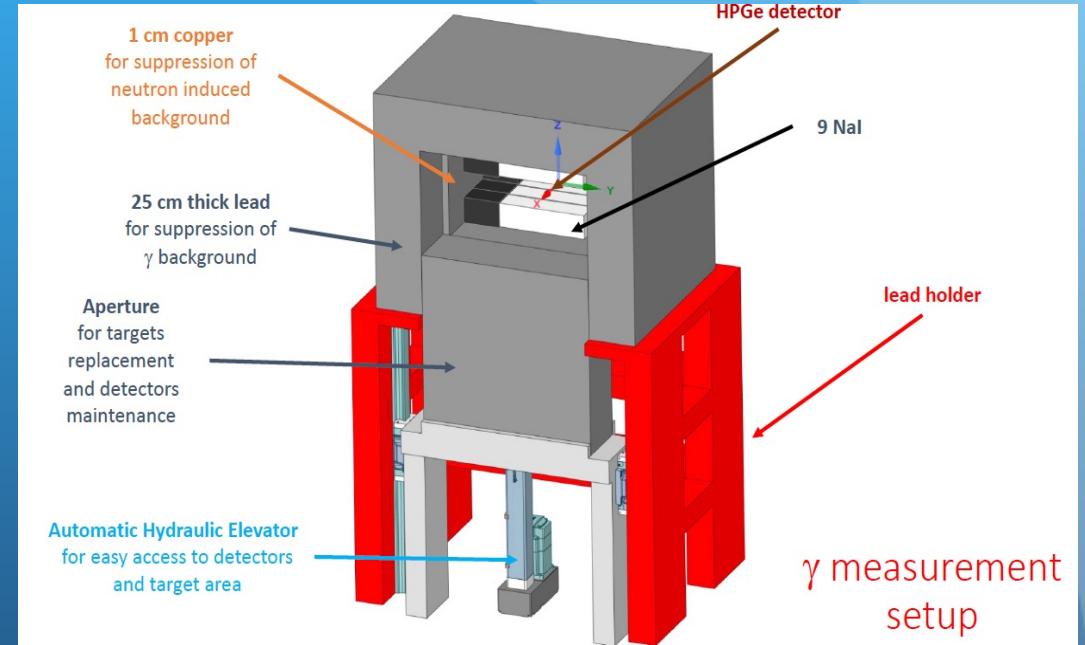
- Many states can contribute to the cross section in the Gamow region
- Background on surface too high, no progress since ~20 years.
- Novel high-efficiency, energy sensitive detector array (^3He +liquid scintillator).

$^{12}\text{C} + ^{12}\text{C}$

Reason of interest: Carbon burning determines the final destiny of massive stars and of low mass stars in close binary systems.



- Direct measurements above 2.1 MeV (large scattering, large uncertainties)
- Only indirect measurements below 2.1 MeV (problems with normalization and other discrepancies)
- Very large uncertainty below 2.5 MeV



- 25 cm thick lead shielding, under production;
- A 150% HPGe + 16 Nal detector as further active shielding/anti-Compton;
- Work ongoing on targets characterization in collaboration with Legnaro Laboratory

Conclusions

- ✓ Recently the $^{20}\text{Ne}(\text{p},\gamma)^{21}\text{Na}$, $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$ and $^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction has been studied by LUNA
- ✓ New results constrain the low energy extrapolations and have a direct impact on RGB, AGB and Nova explosion scenarios;
- ✓ New experimental campaigns are planned during 2023 and 2024 to improve our knowledge on the NeNa cycle and therefore on the Globular Cluster anomaly, and on hot CNO and MgAl cycles;
- ✓ Scientific data taking has started in June at the MV accelerator;
- ✓ **New exciting physics is expected at the LUNA400 and MV facilities in LNGS in the future years !**



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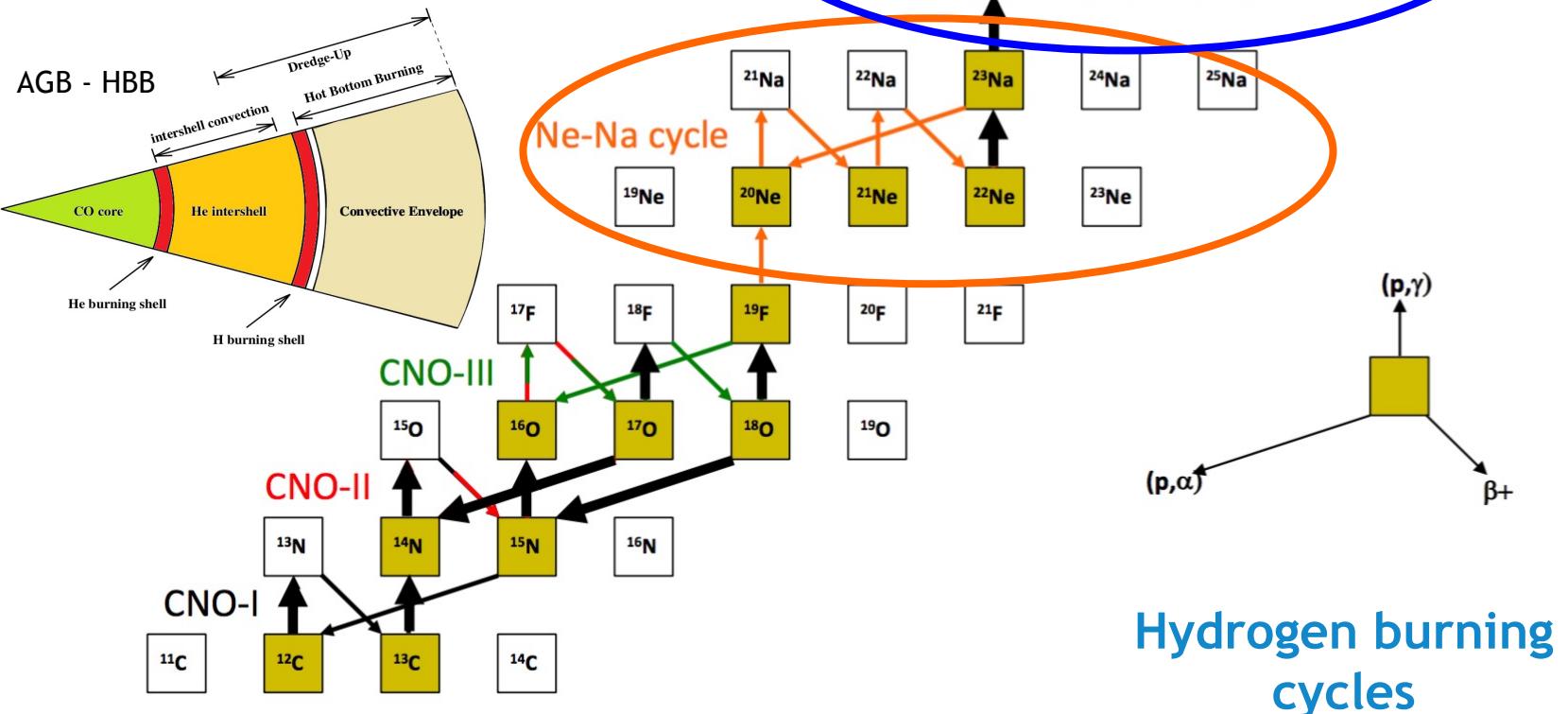
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Backup



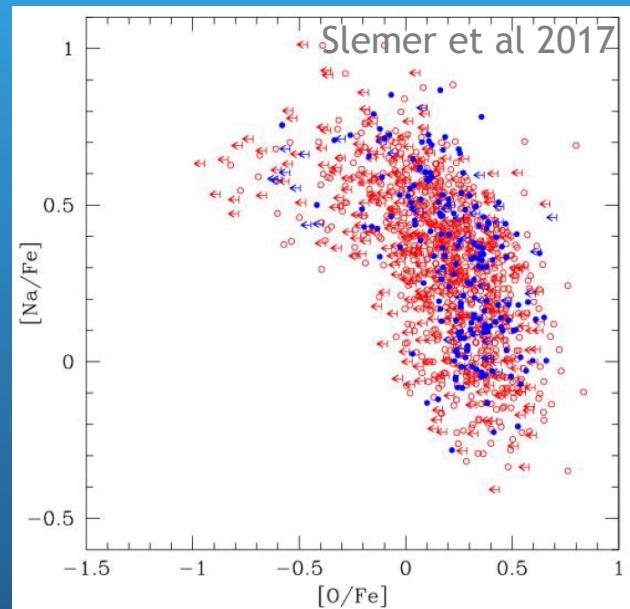
Neon-Sodium cycle

Sun: ~15 MK
Massive Stars: ~ 100 MK
AGB:~30-100 MK
Novae~100-400 MK

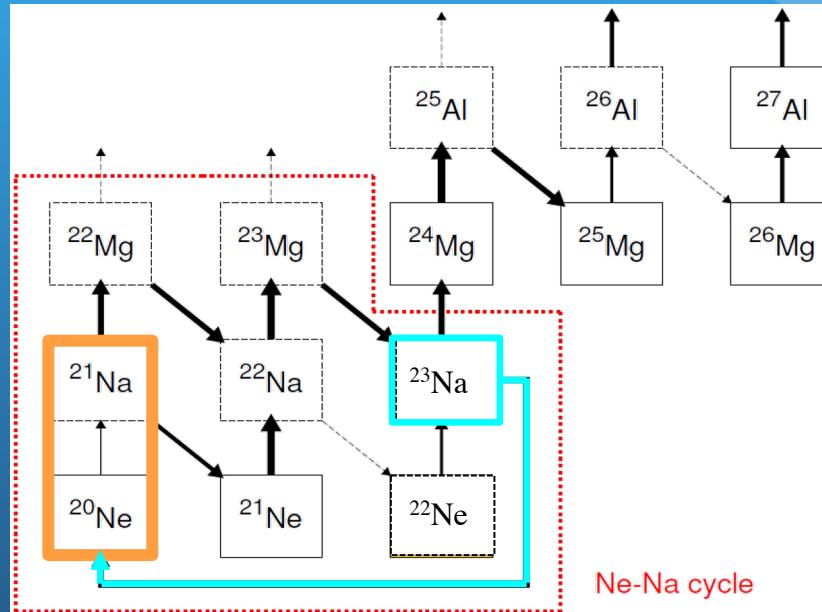


NeNa cycle : astrophysical scenarios

Issue: peculiar chemical patterns measured in stars belonging to the most ancient objects of our galaxy, the Globular Clusters (GC)



Na/O anti-correlation in GC



First-generation massive AGB stars, burning H through the NeNa cycle indicated as possible explanation of the observed anti-correlations in O-Na exhibited by the stars of Galactic globular clusters. Very important to measure: $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ and $^{23}\text{Na}(p,a)^{20}\text{Ne}$