NUCLEAR ASTROPHYSICS IN UNDERGROUND LABORATORIES: THE LUNA EXPERIMENT

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17th International Symposium on Nuclei in the Cosmos
Daejeon, Korea

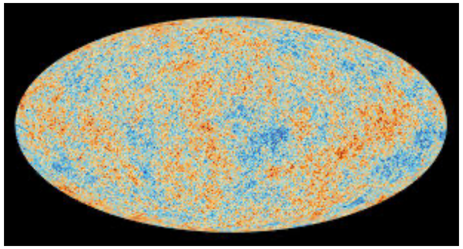
NUCLEAR ASTROPHYSICS: AN INTERDISCIPLINARY FIELD

Meteoritic grains

Observational astronomy

Cosmology

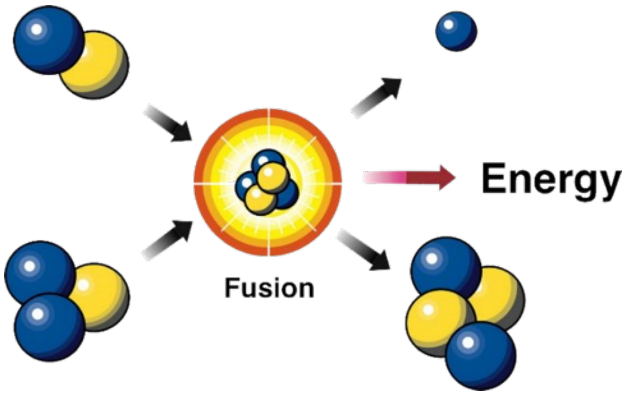
Nuclear astrophysics

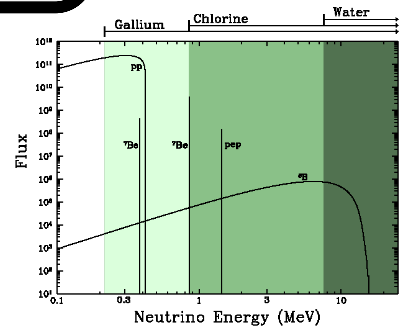


Nuclear physics

Neutrino physics

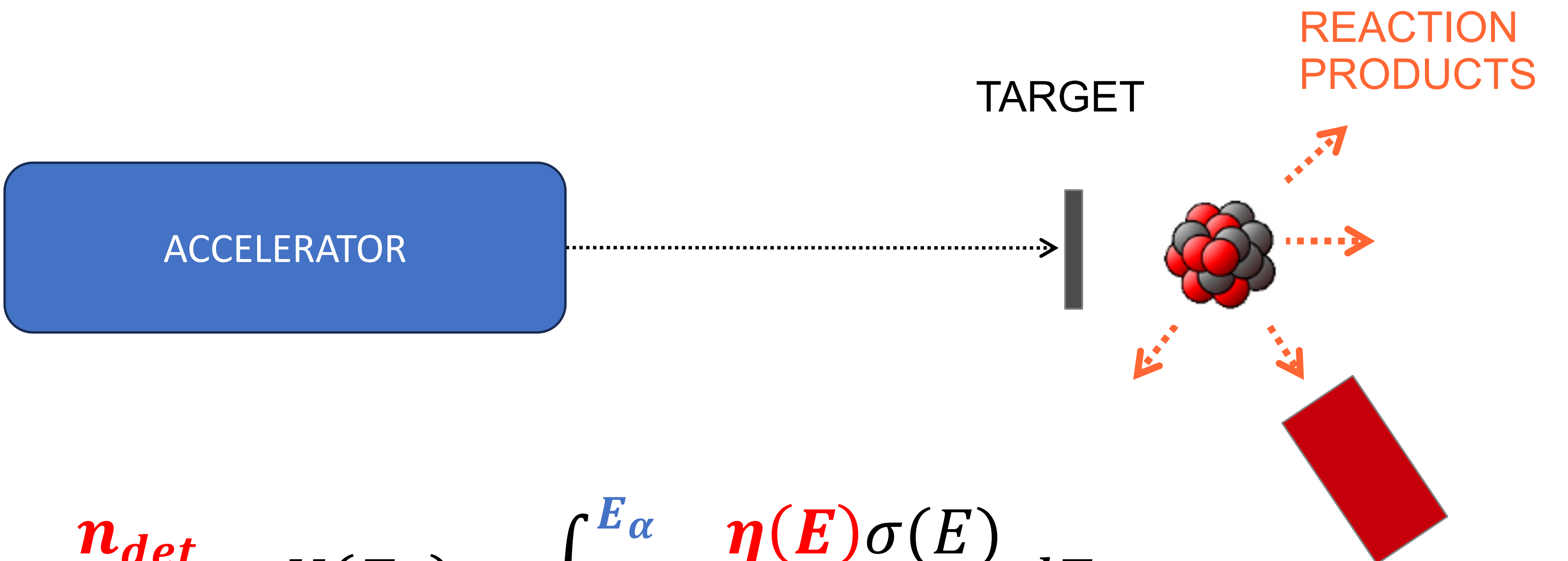
Stellar Models





REACTION RATE IN THE LABORATORY

$$\sigma = \frac{N_{reactions} \;/\; t}{N_{proj} \;/\; t \qquad N_{target} \;/\; A}$$



$$\frac{n_{det}}{I t} = Y(E_\alpha) = \int_{E_{\alpha-\Delta E}}^{E_\alpha} \frac{\eta(E)\sigma(E)}{\varepsilon(E)} dE$$

DETECTORS

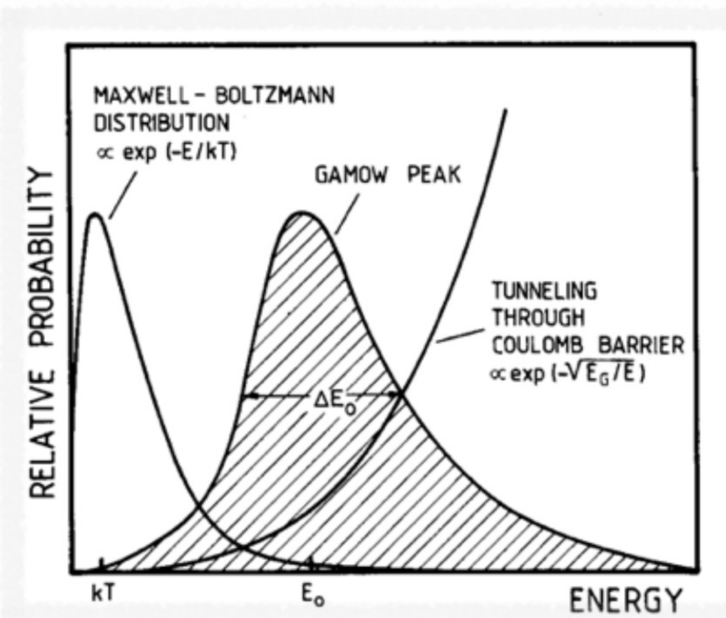
CHARGED PARTICLES INDUCED REACTIONS

in the Sun: $T = 1.5\cdot10^7$ K, KT = 1 keV << Ecoul (0.5-2MeV)

$$\sigma(E) = \frac{S(E)}{E}\exp\left(-31.29\cdot Z_1\cdot Z_2\cdot\sqrt{\frac{\mu}{E}}\right)$$

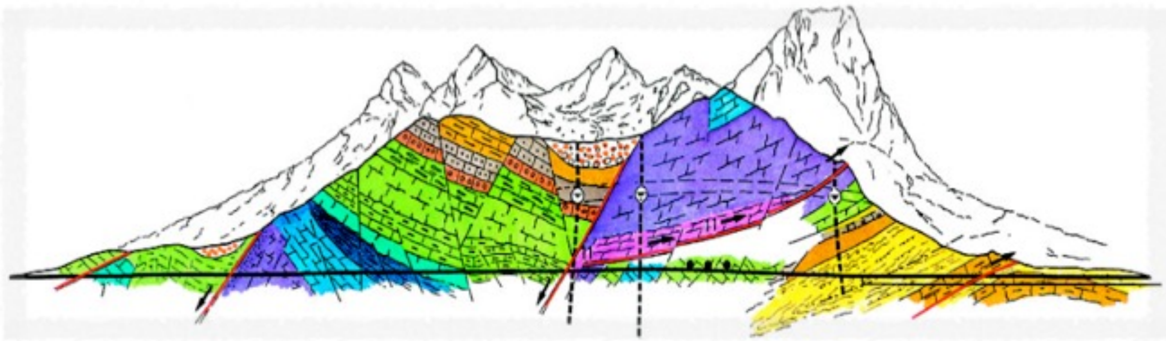
ASTROPHYSICAL S-FACTOR

GAMOW FACTOR



Scenario	Reaction	E_G[keV]	σ [barn]	Detected events/h
Sun (16 MK)	$^3He(\alpha,\gamma)^7Be$	23	10^{-17}	10^{-9}
	$^{14}N(p,\gamma)^{15}O$	28	10^{-19}	10^{-11}
AGB stars (80 MK)	$^{14}N(p,\gamma)^{15}O$	81	10^{-12}	10^{-4}
Big bang (300 MK)	$^3He(\alpha,\gamma)^7Be$	160	10^{-9}	10^{-1}
	$^2H(\alpha,\gamma)^6Li$	96	10^{-11}	10^{-3}

LABORATORI NAZIONALI DEL GRAN SASSO

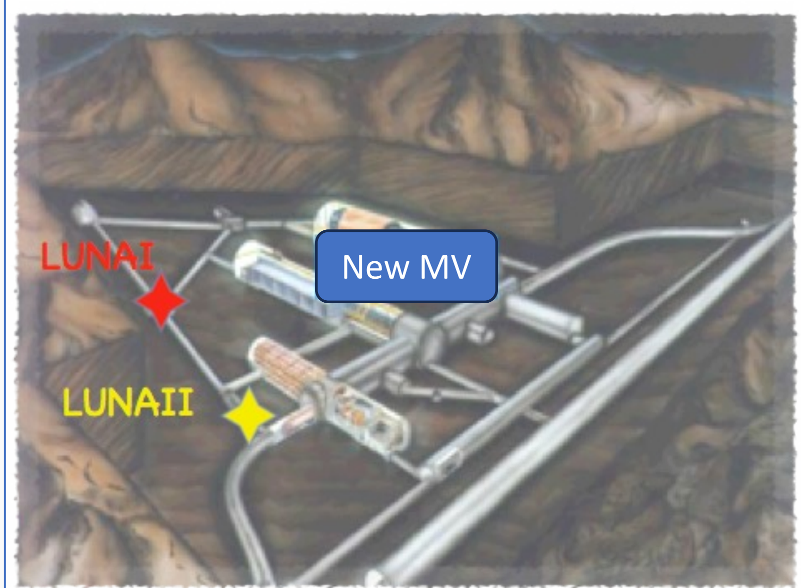


- 1400 m rock overburden (=3800 m.w.e.)
- Flux attenuation: n 10^{-3}
  μ 10^{-6}
- underground area 18000 m^2
- support facilities on the surface

https://www.lngs.infn.it/en

Currently 1100 scientists from 29 different Countries are taking part in the experimental activities of LNGS

LNGS research activities range from neutrino physics to dark matter search, to nuclear astrophysics, and also to earth physics, biology and fundamental physics



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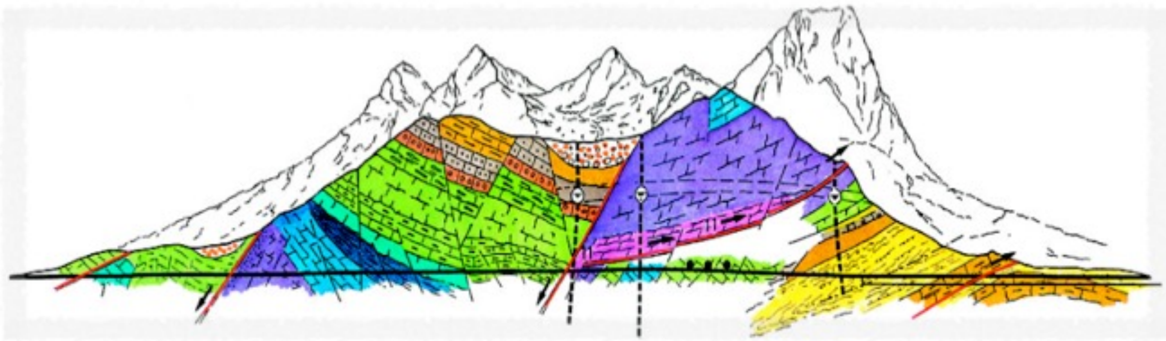

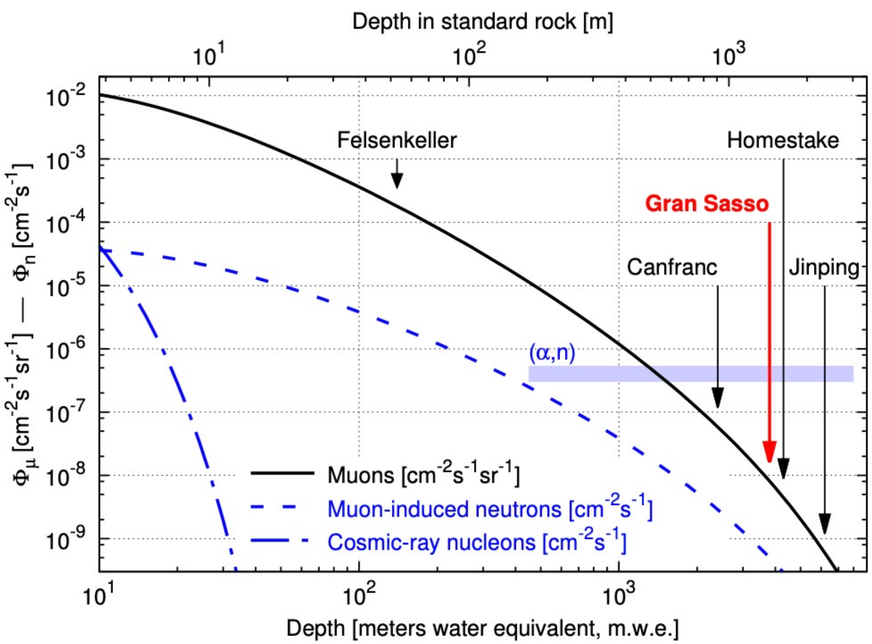

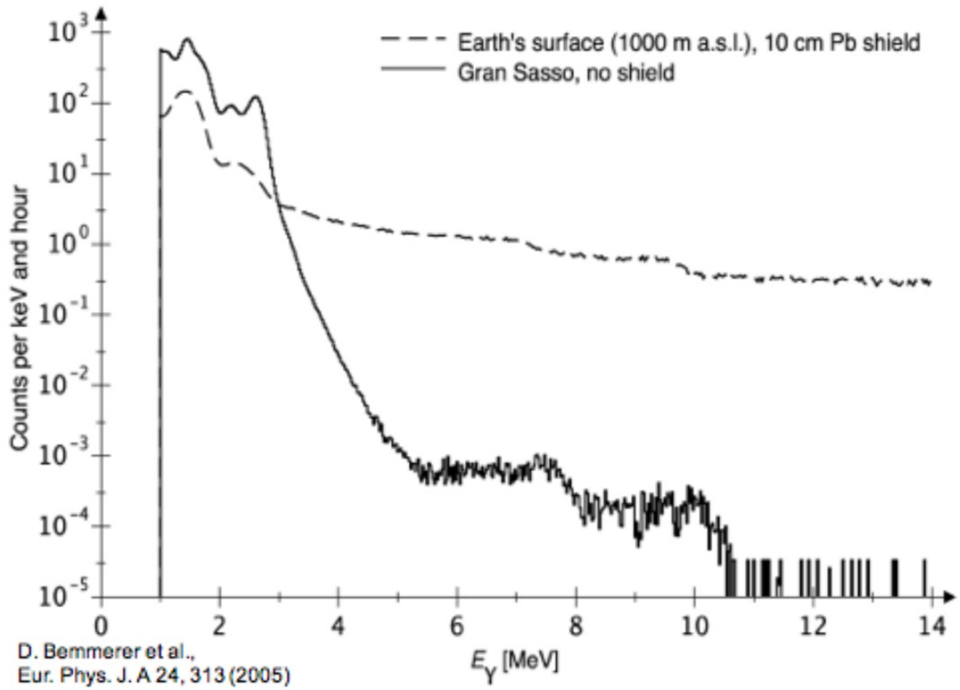

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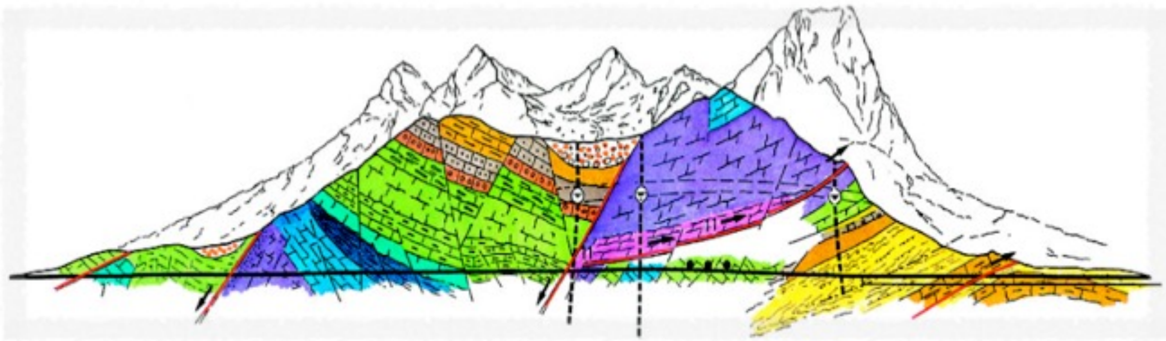

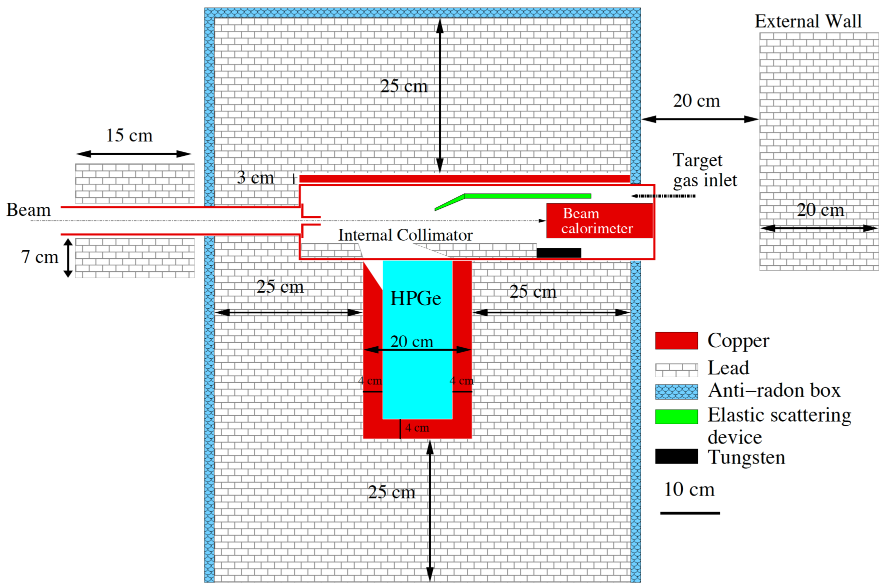

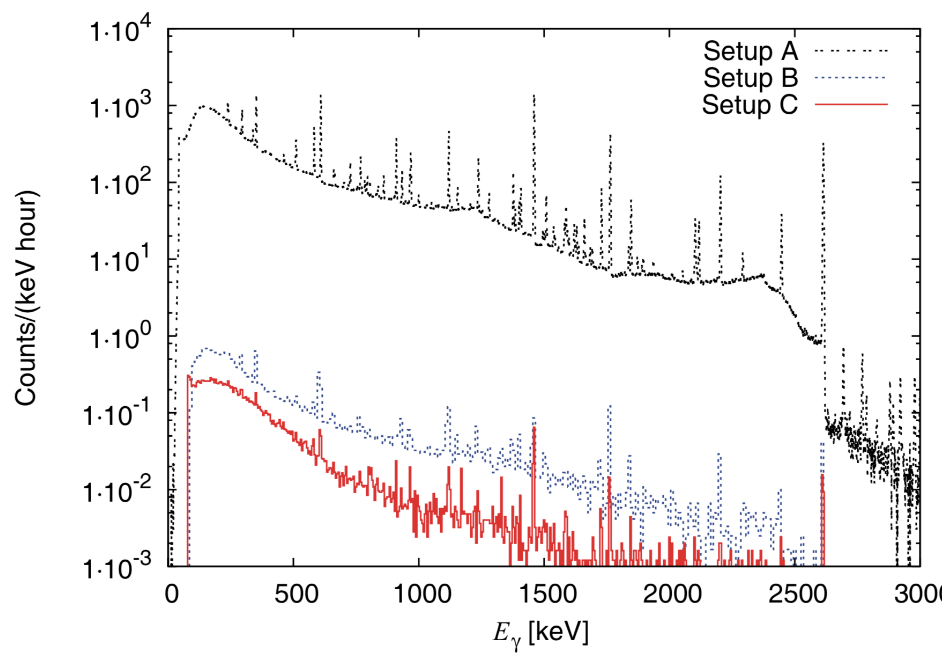

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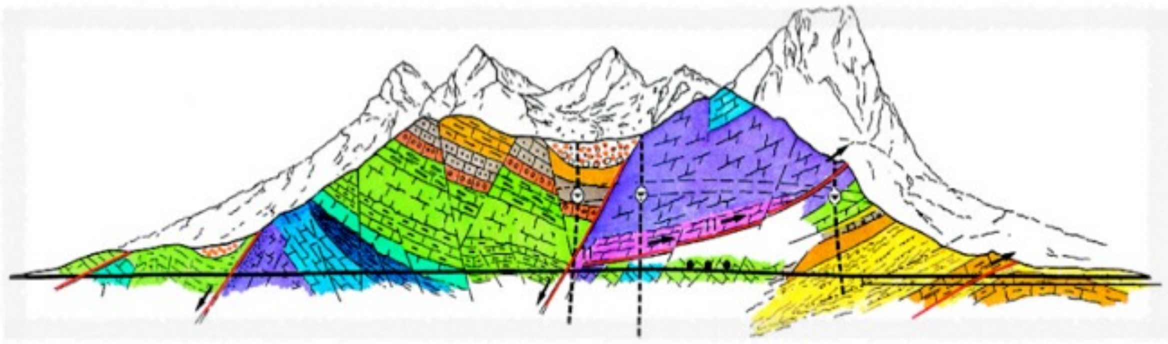
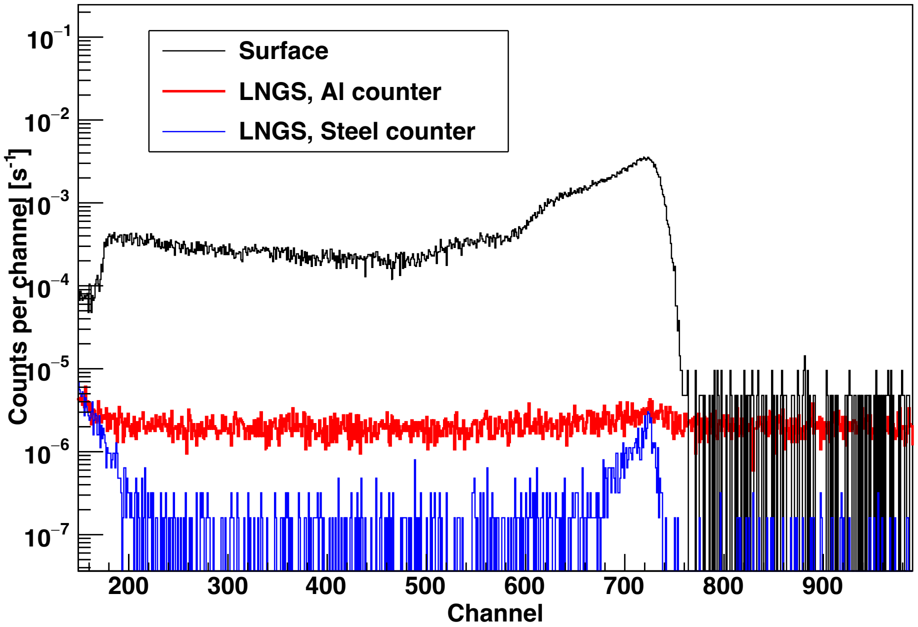
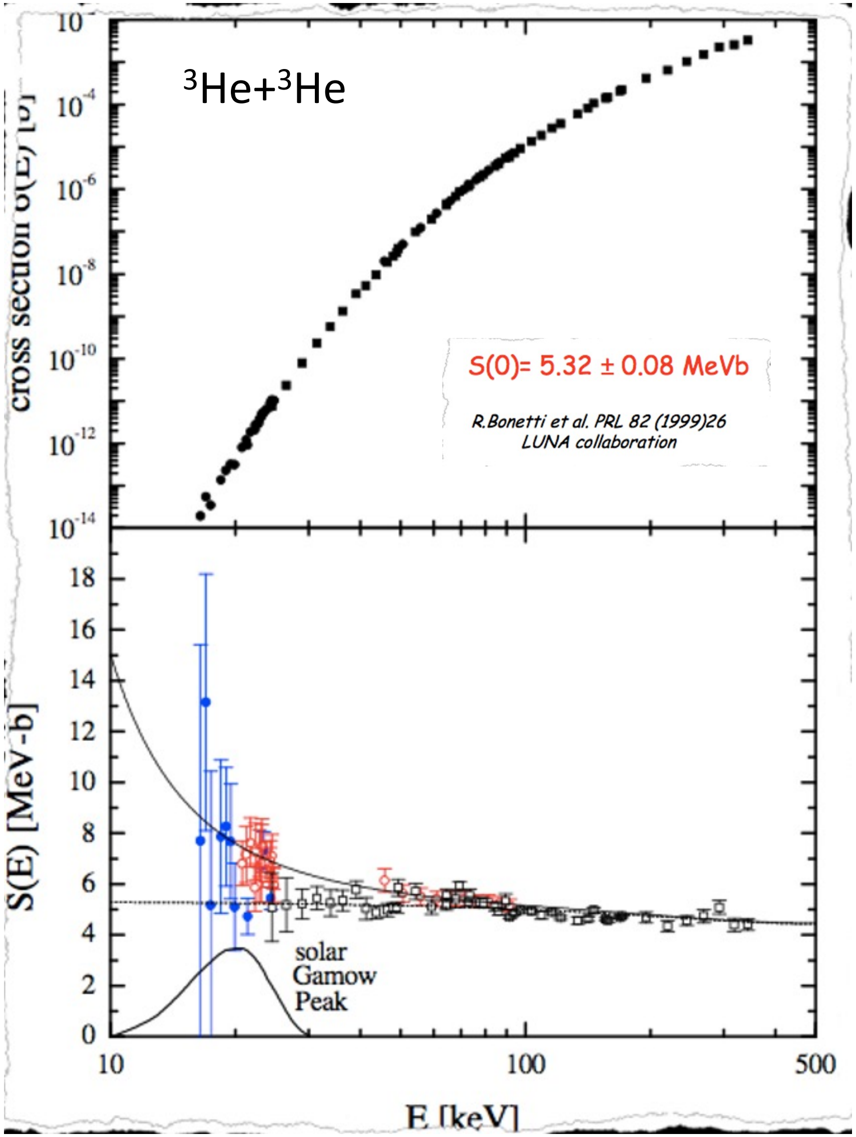


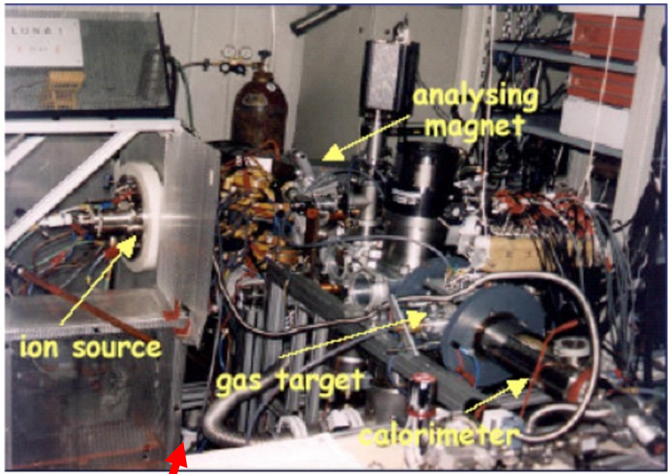


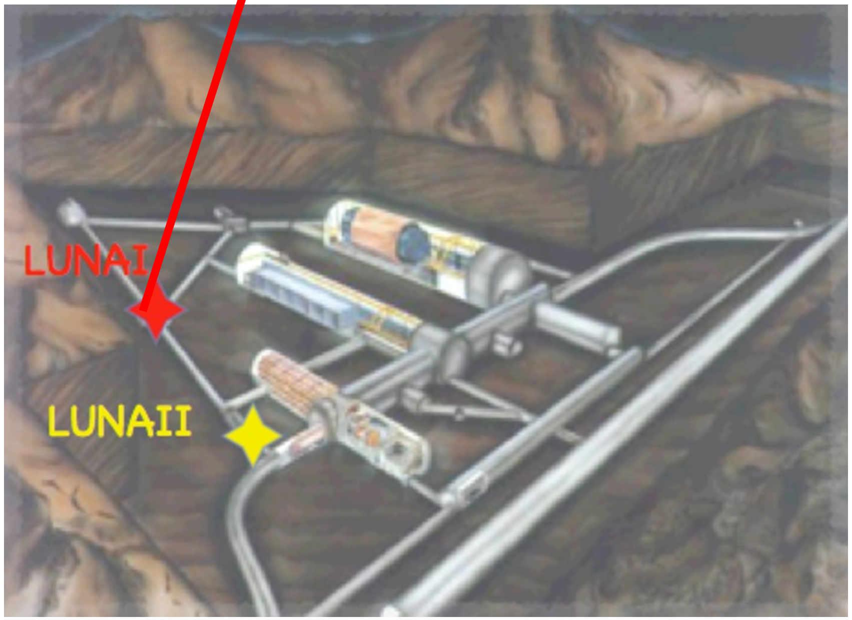
Being underground a reduction on neutron detector background is visible and can be improved by selecting properly the setup material

See Andreas Best talk

LUNA: MORE THAN 30 YEARS OF UNDERGROUND NUCLEAR ASTROPHYSICS







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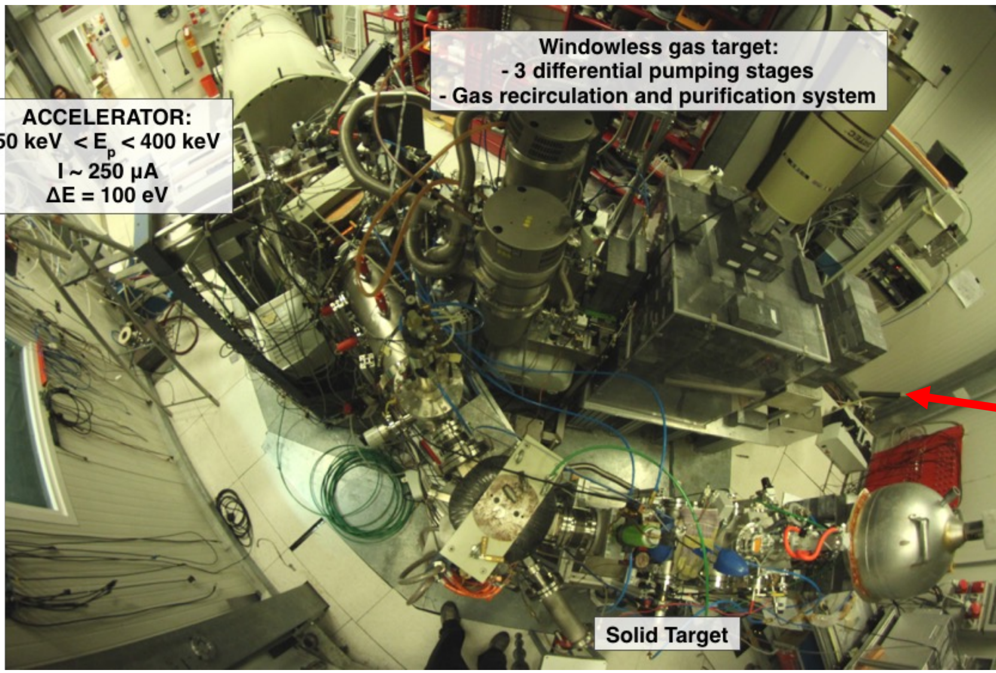
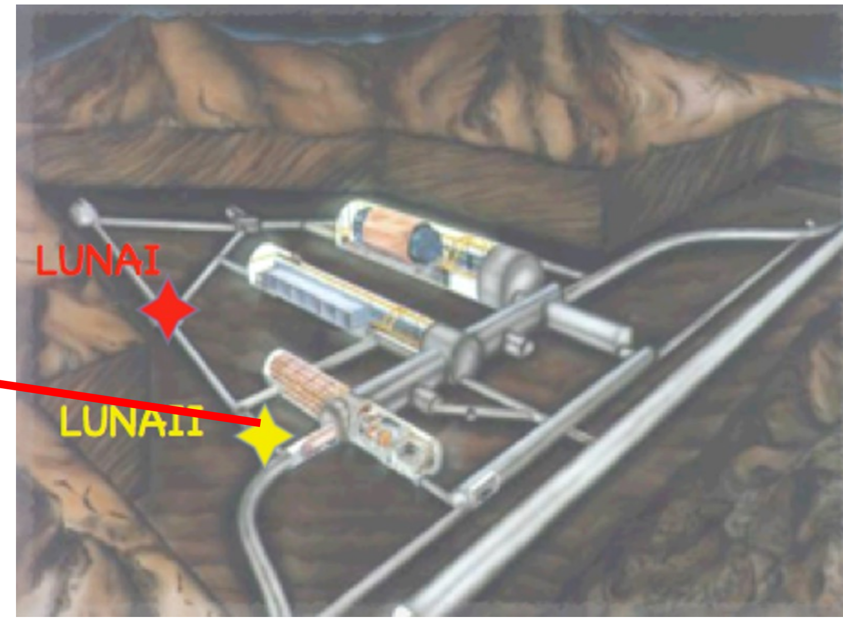




LUNA: MORE THAN 30 YEARS OF UNDERGROUND NUCLEAR ASTROPHYSICS

LUNA

- **solar fusion reactions**

  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$

- **electron screening and stopping power**

  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$

  Axel Boeltzig's talk

- **CNO, Ne-Na and Mg-Al cycles**

  $^{14}N(p,\gamma)^{15}O$ $^{15}N(p,\gamma)^{16}O$ $^{22}Ne(p,\gamma)^{23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$
  $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$ **$^{12}C(p,\gamma)^{13}N$** **$^{13}C(p,\gamma)^{14}N$**
  $^{21}Ne(p,\gamma)^{22}Na$ **$^{20}Ne(p,\gamma)^{21}Na$** **$^{23}Na(p,\alpha)^{20}Ne$**

- **Explosive hydrogen burning in novae and AGB stars**

  $^{16}O(p,\gamma)^{17}F$ **$^{17}O(p,\gamma)^{18}F$** $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$

  poster by R.M. Gesuè

- **Big Bang nucleosynthesis**

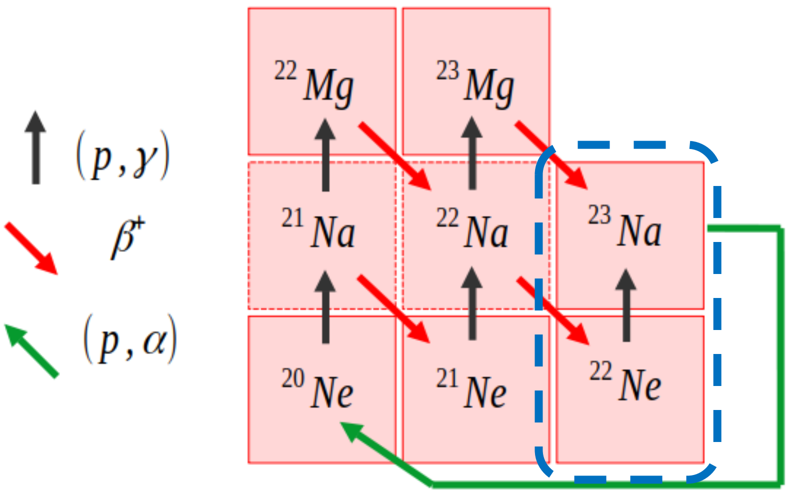
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$ $^{6}Li(p,\alpha)^{3}He$

- **neutron capture nucleosynthesis**

  $^{13}C(\alpha,n)^{16}O$

Future scientific programs will be presented

THE NeNa CYCLE



Key Astrophysical sites:

RGB stars (Red Giant Branch)

AGB stars (Asymptotic Giant Branch)

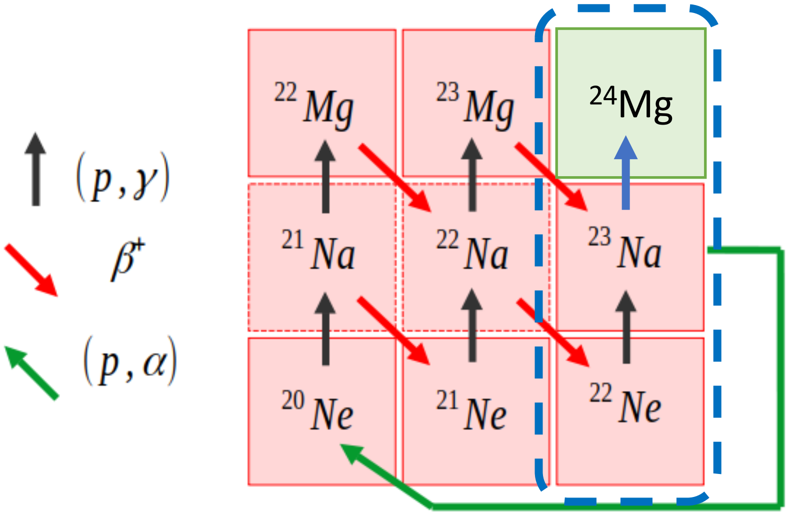
Novae

Massive stars

^{22}Ne(p,γ)^{23}Na studied in two different experiments

- Three resonances measured directly and
- Direct capture cross section below 400 keV observed for the first time

THE NeNa CYCLE



Key Astrophysical sites:

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Novae

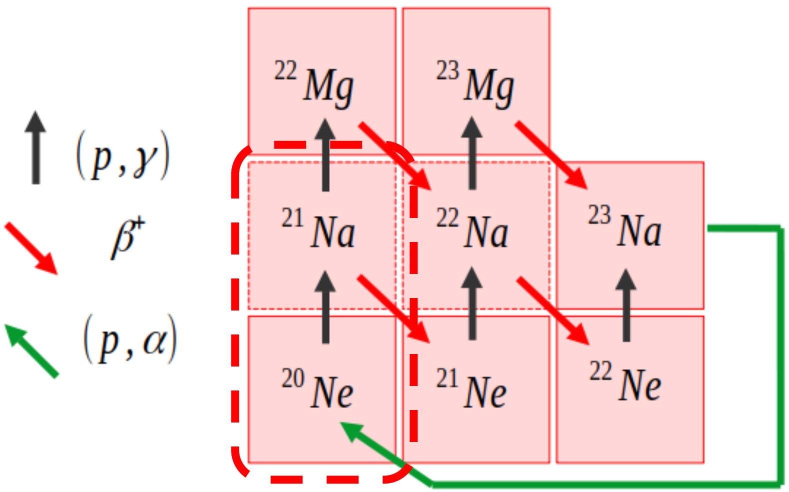
Massive stars

^{22}Ne(p,γ)^{23}Na studied in two different experiments
- Three resonances measured directly and
- Direct capture cross section below 400 keV observed for the first time

^{23}Na(p,γ)^{24}Mg → three resonances measured with improved precision wrt literature

Cavanna et al., PRL115(2015)252501
Ferraro et al., PRL121(2018)172701
Boeltzig et al., PLB 705(2019)122
Slemer et al., MNRAS465(2017)4817

THE NeNa CYCLE



NeNa cycle

Key Astrophysical sites:

RGB stars (Red Giant Branch)

AGB stars (Asymptotic Giant Branch)

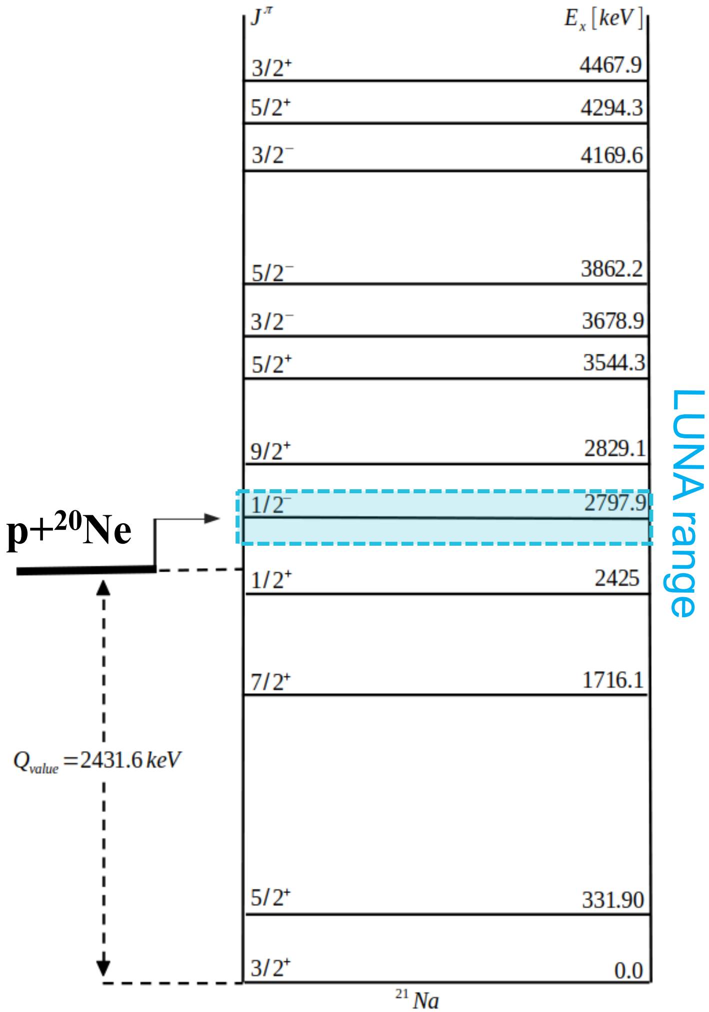
Novae

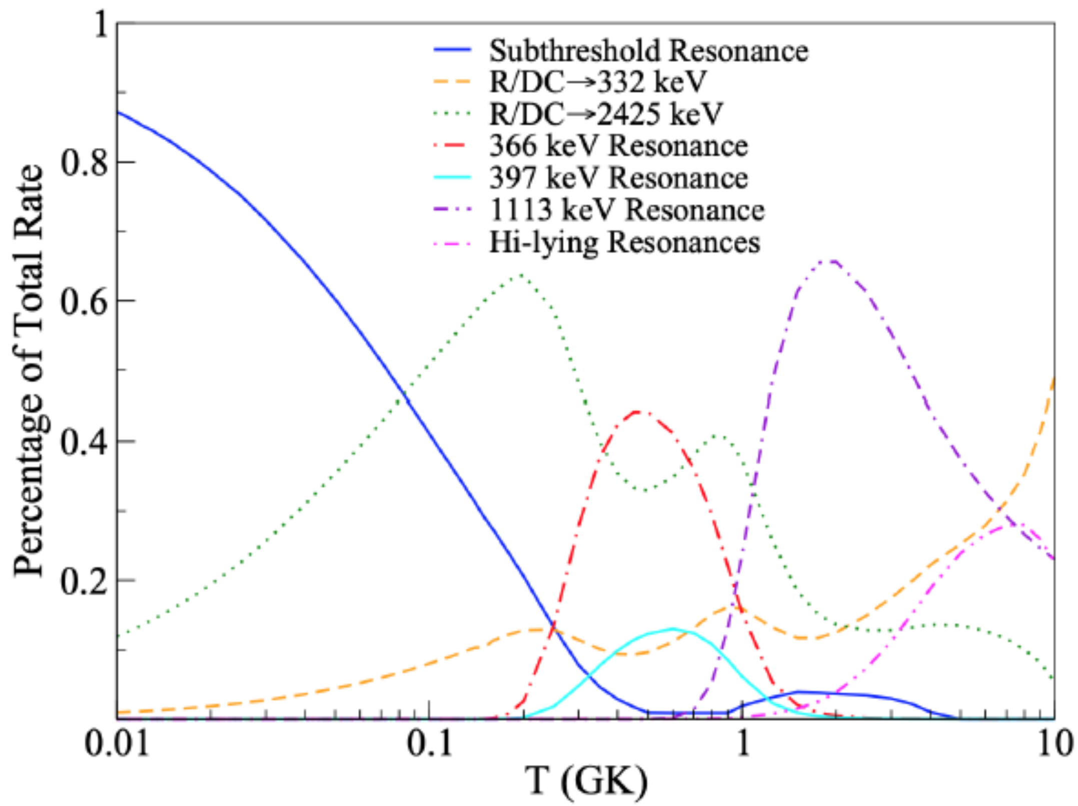
Massive stars

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

The **^{20}Ne(p,γ)^{21}Na** impacts the production of neon isotopes!

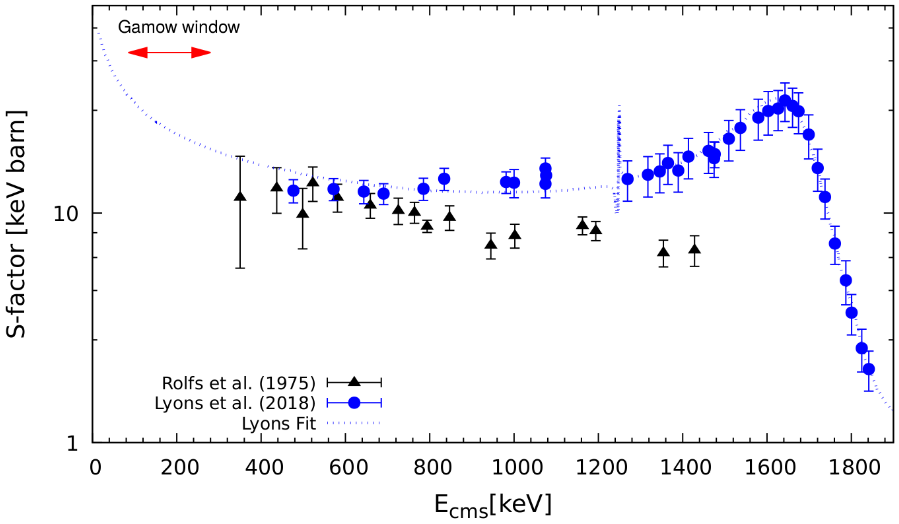
THE $^{20}Ne(p,\gamma)^{21}Na$ REACTION





$$< \sigma v >_{aX} = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty \exp\left(-\frac{E}{kT}\right)\sigma(E)EdE$$

STATE OF THE ART



Only a few measurements available

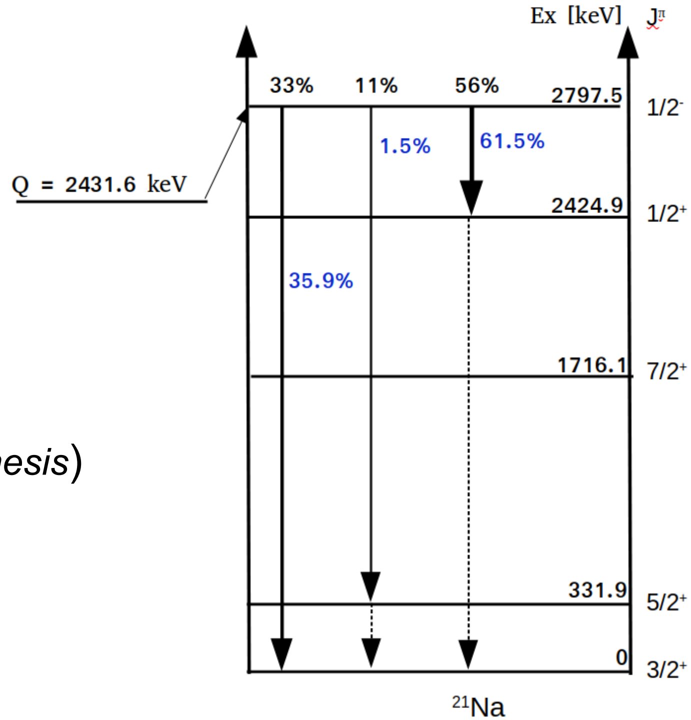
No low energy data

LUNA GOALS:

❖ Study of the E_{cm} = 366 keV resonance

$\omega\gamma_{Rolfs}$ = 0.11 ± 0.02 meV *(Rolfs et al. 1975)*

$\omega\gamma_{Cooper}$ = 0.0722 ± 0.0068 meV (*Cooper 2019, Ph.D thesis*)



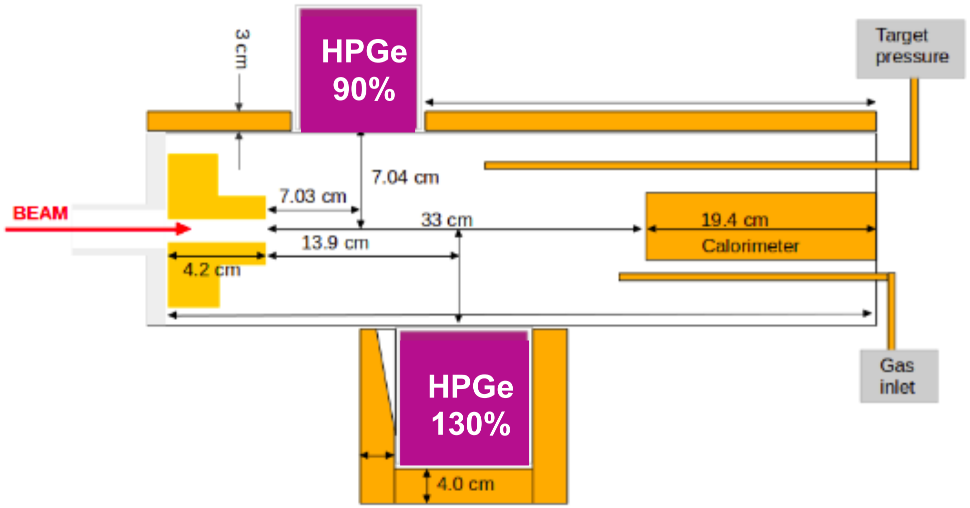
❖ Direct capture below 400 keV

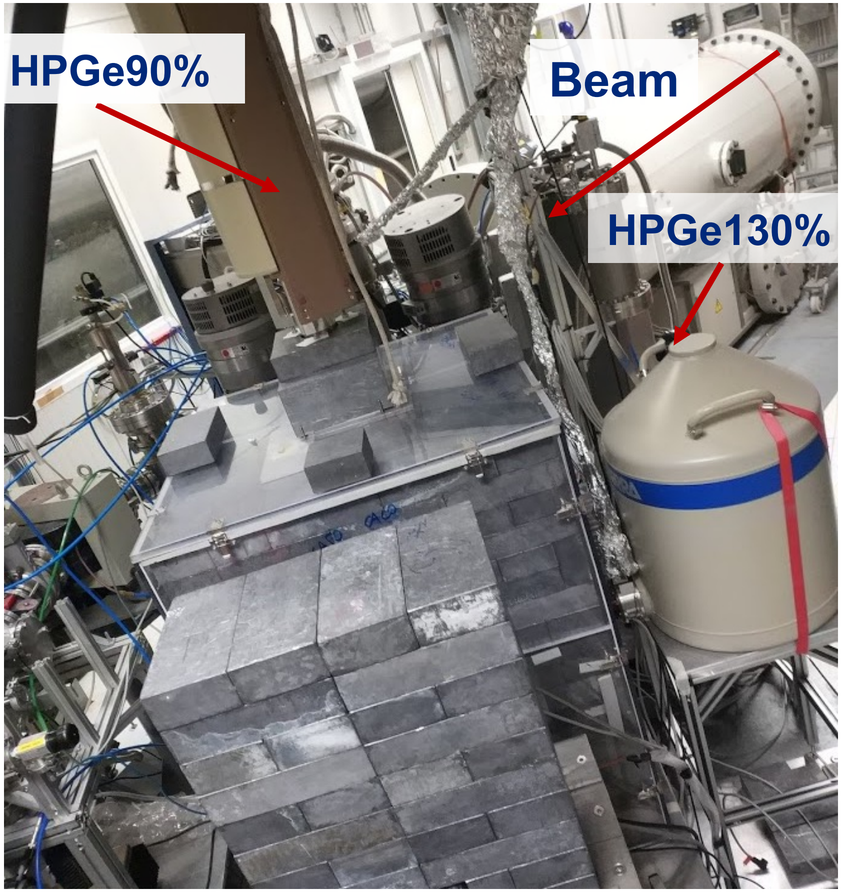
THE EXPERIMENT AT LUNA

- 260 keV < E_p< 400 keV
- Natural Ne gas target (90.3% ^{20}Ne) P = 2 mbar
- HPGe detecors:

  Relative efficiency 130%(GePD)
  Relative efficiency 90% (GeDD)

- Lead shielding
- Radon box





Two different phases:
- Resonance measurement
- Direct capture

AND RESULTS: RESONANCE AND BRANCHING RATIOS

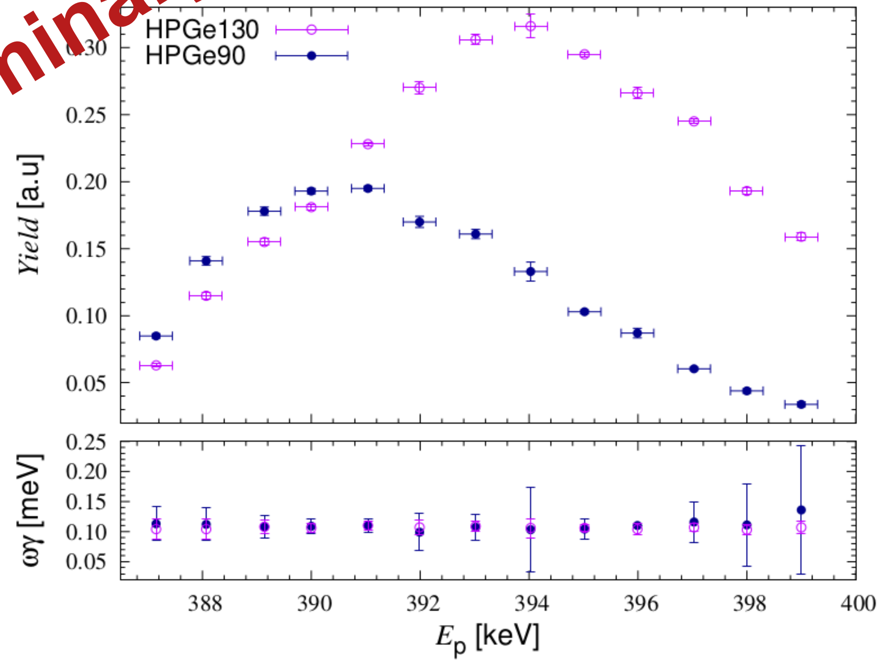
$$Br_i = \frac{1}{\sum_j (N_j/\eta(E_j))} \cdot \frac{N_i}{\eta(E_i)}$$

Transition [keV]	Rolfs et at. (1975) [%]	LUNA [%]
2425 →0	56±4	57.4±3.4
2798 →332	11±4	4.0±0.2
2798 →0	33±4	38.5±2.2

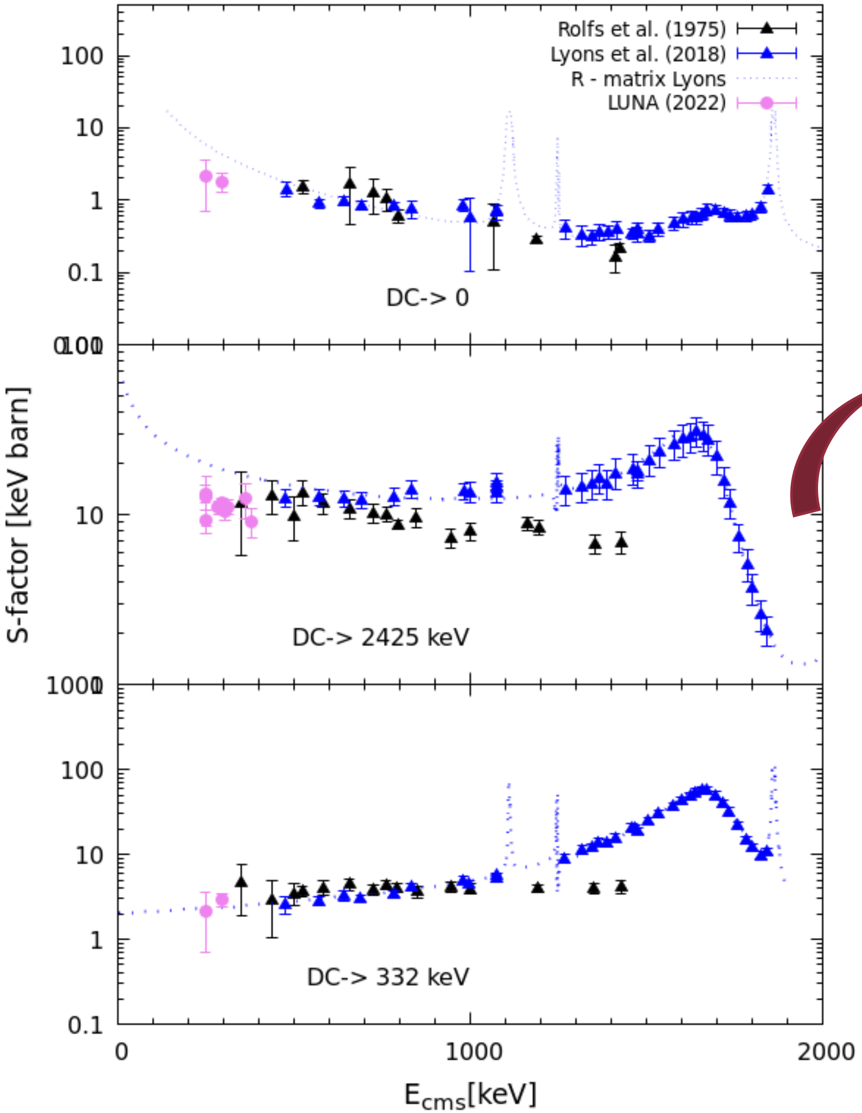
Preliminary

Resonance strength

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

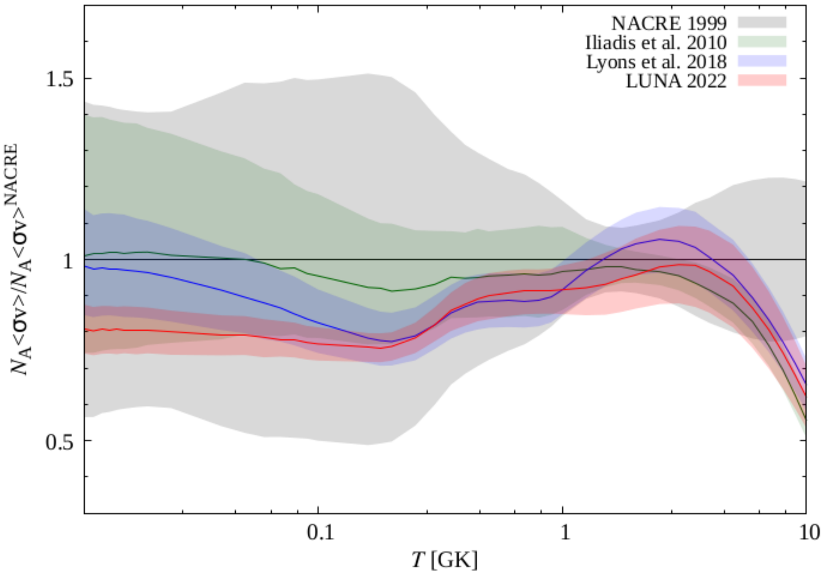


THE S-FACTOR



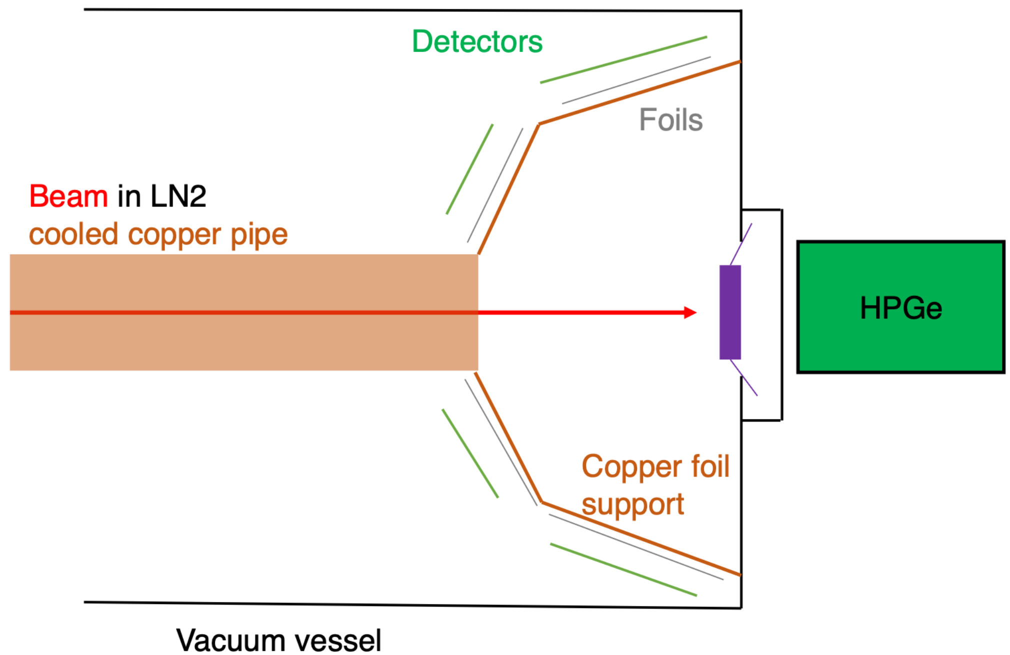
Direct capture studied in the energy range : E_p = 260 keV – 400 keV

Preliminary



$^{23}Na(p,\alpha)^{20}Ne$

E_r [keV]	J^π	$\omega\gamma$ [eV]
37	0^+	$< 3.3 \times 10^{-20}$
138	? (l_p=0)	$< 1.6 \times 10^{-6}$
	? (l_p=1)	$< 7.5 \times 10^{-8}$
	? (l_p=2)	$< 2.8 \times 10^{-9}$
	? (l_p=3)	$< 5.4 \times 10^{-11}$
167	$(6,7,8)^+$	? (negligible)
170	1^-	$(23 \pm 5) \times 10^{-3}$



- ✓ Targets produced with evaporation and reactive sputtering
- ✓ New beamline to be mounted in Q4 2023
- ✓ data taking starting within the end of 2023

Supported by the ELDAR EU Starting Grant (PI Carlo Bruno)

A MV MACHINE TO EXPLORE HE AND C BURNINGS

H, He, C+, C++ beams with high intensity

3.5 MV terminal voltage

Commissioning summer 2022

Final authorizations end of 2022

First scientific beam planned in June 2023

responsible of accelerator service: M. Junker

Age of Globular Clusters and AGB nucleosynthesis: $^{14}N(p,\gamma)^{15}O$

Main neutron sources: $^{22}Ne(\alpha,n)^{25}Mg$

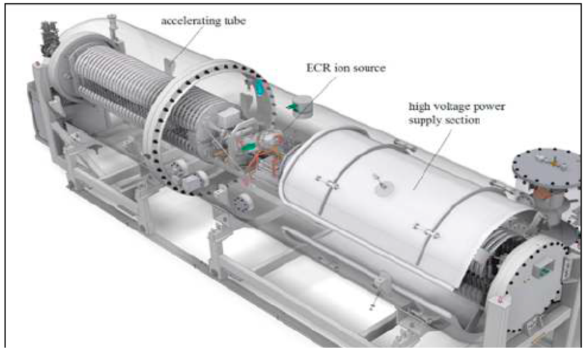
Advaced burnings: $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$

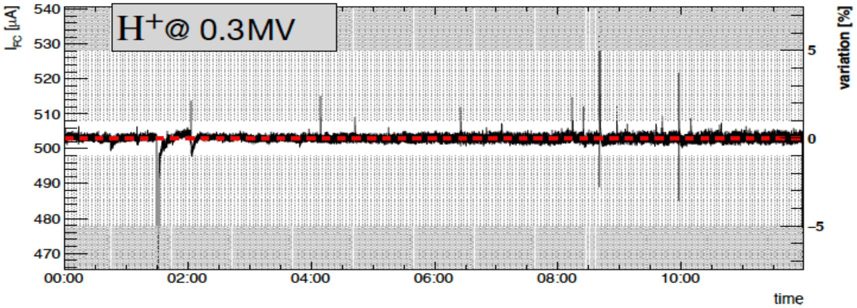
Talk by Andreas Best

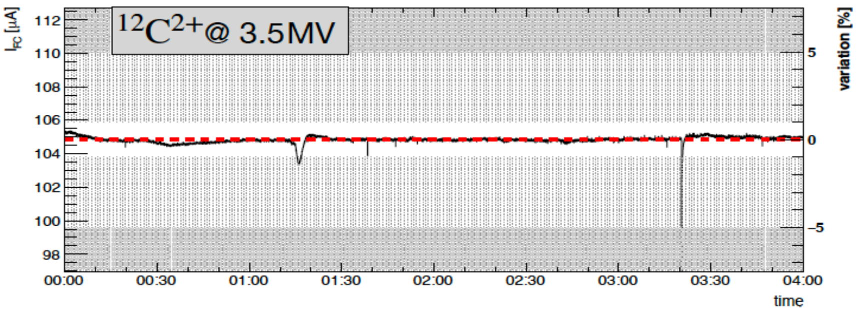
European Research Council
Established by the European Commission

A MV MACHINE TO EXPLORE HE AND C BURNINGS

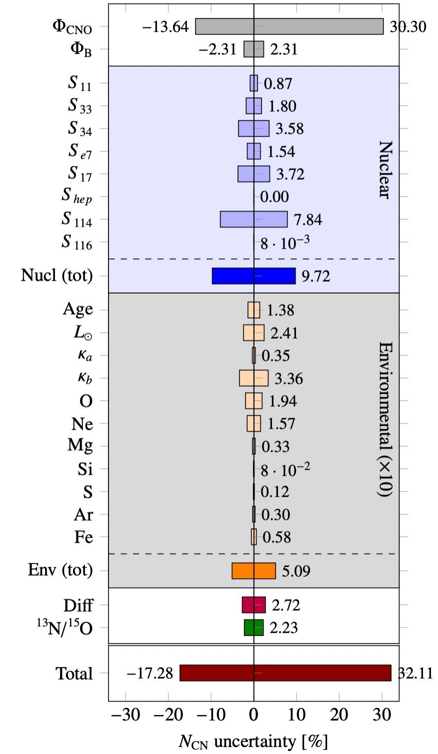
Beam intensity on target at different terminal voltage		
Ion specie	Terminal Voltage	
	0.3 MV – 0.5 MV	0.5 MV - 3.5 MV
$^{1}H^{+}$	500 μA	1000 μA
$^{4}He^{+}$	300 μA	500 μA
$^{12}C^{+}$	100 μA	150 μA
$^{12}C^{+2}$	60 μA	100 μA
Number of beam lines		2
Terminal Voltage range		0.3 – 3.5 MV





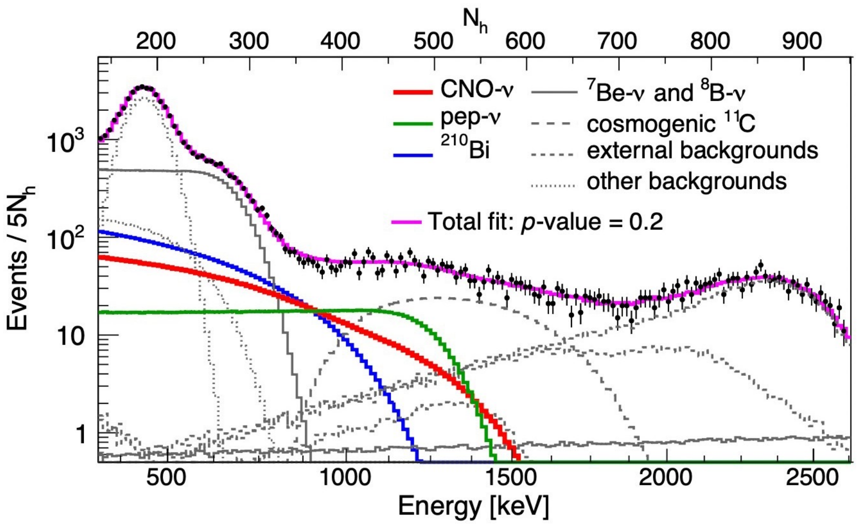


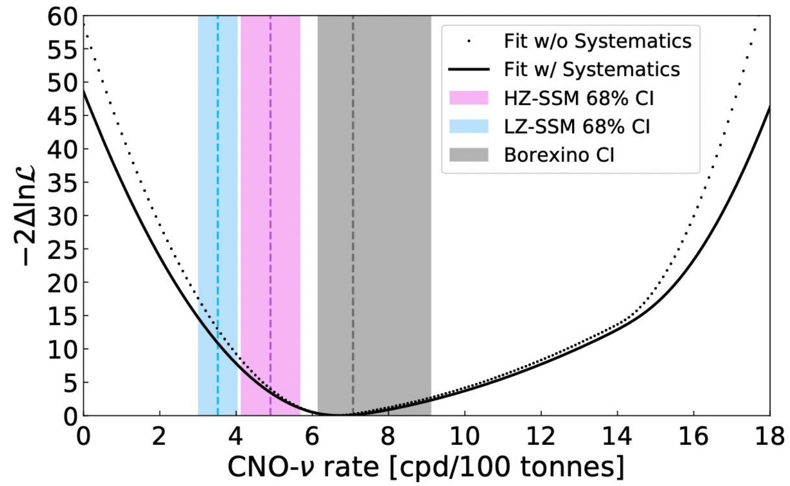
Sen, A., NIM B https://doi.org/10.1016/j.nimb.2018.09.016



RECENT BOREXINO RESULTS

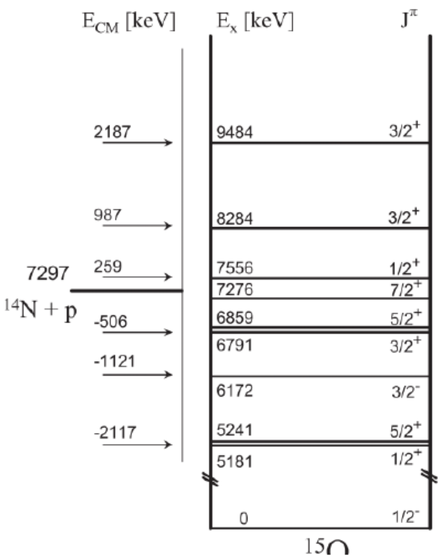
- Solar CNO neutrino flux recently detected for the first time by Borexino (2020). → Solar metallicity probe.
- The result of Borexino disfavours "low metallicity" SSM prediction, but large uncertainties still remains. After CNO Flux itself, biggest contribution to the uncertainty budget from $^{14}N(p,\gamma)^{15}O$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

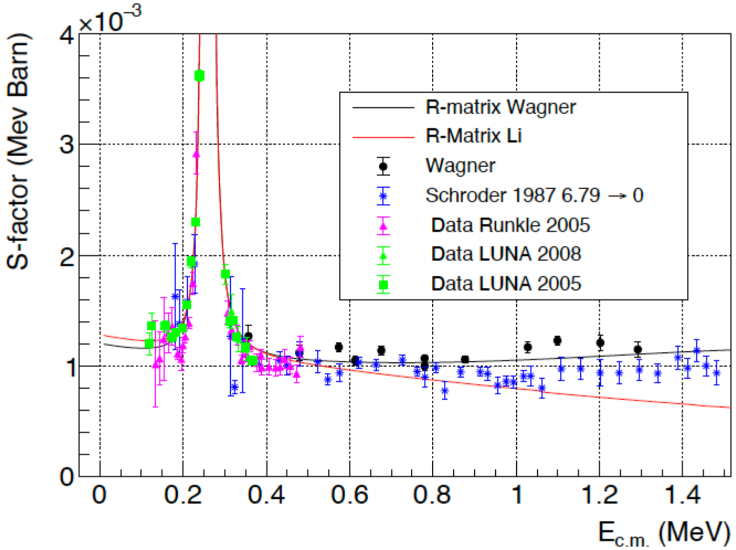


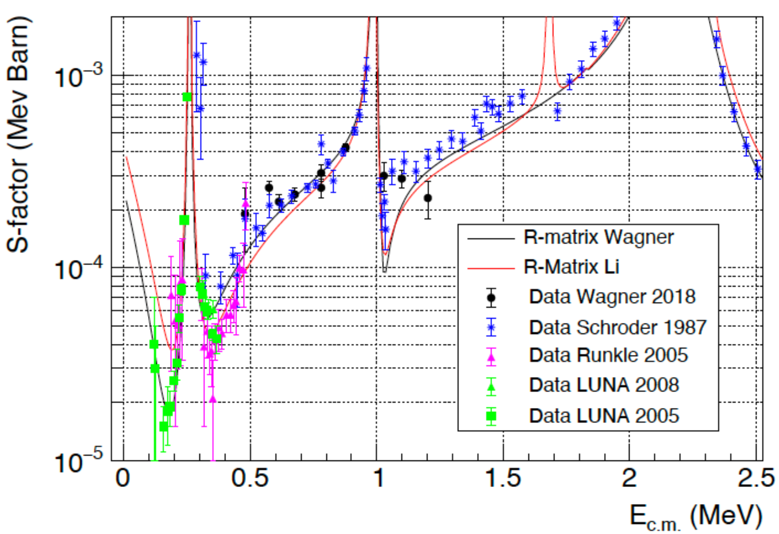


UNCERTAINTIES IN THE S-FACTOR DETERMINATION

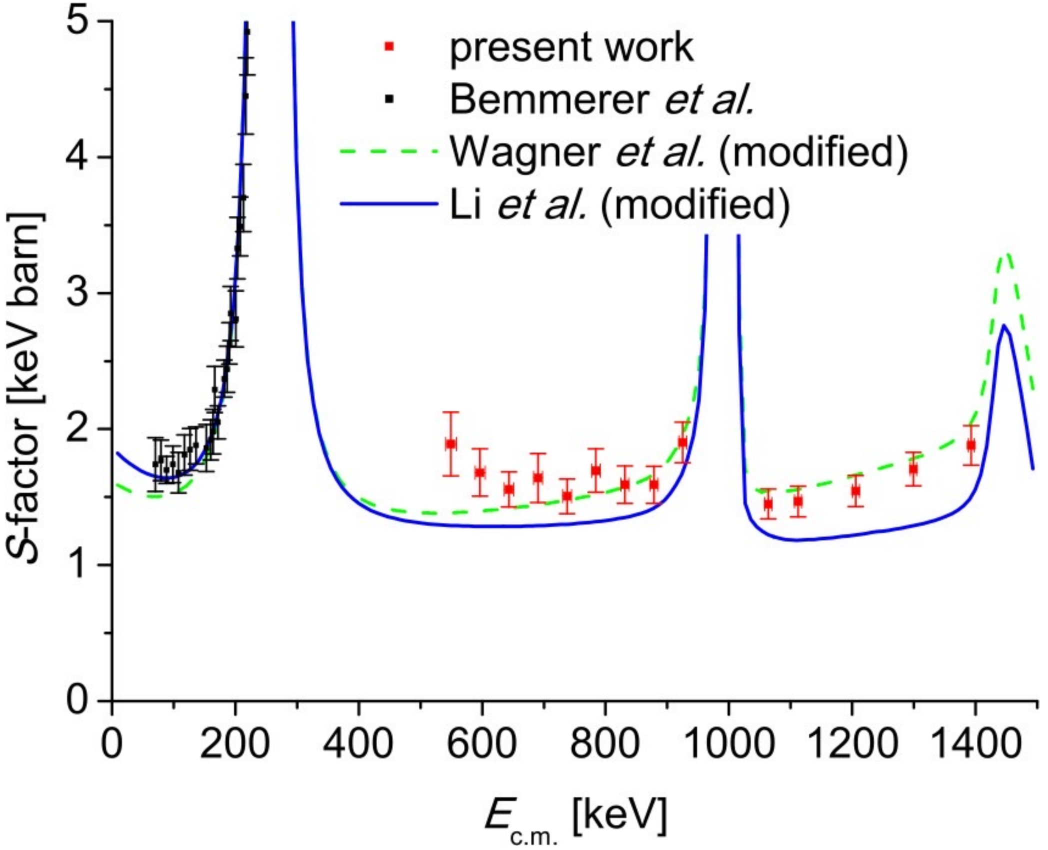
- Most important transitions contributing to the total capture: 6.79 MeV excited state, g.s of ^{15}O
- Secondary transitions: 6.17, 5.24, 7.28, 6.86, 5.18 MeV
- R-matrix analysis fails to provide a consistent view of both high and low energy data, why?







RECENT ACTIVATION EXPERIMENT



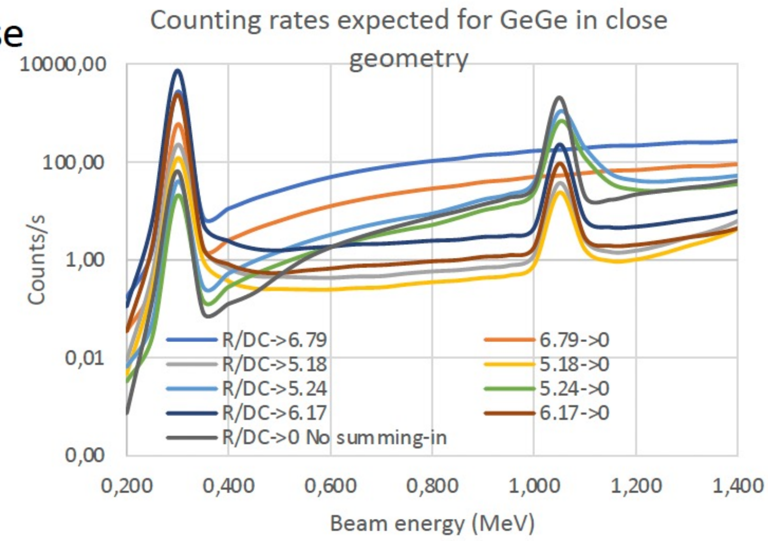
"…reasonable agreement is found **only if the weak transitions – not measured in those works – are included**. This indicates that further experiments are needed in this energy range – and in general in an energy range as wide as possible from the lowest measurable energies to the several MeV range – including all the relevant transitions." Gyurky et al., 2022

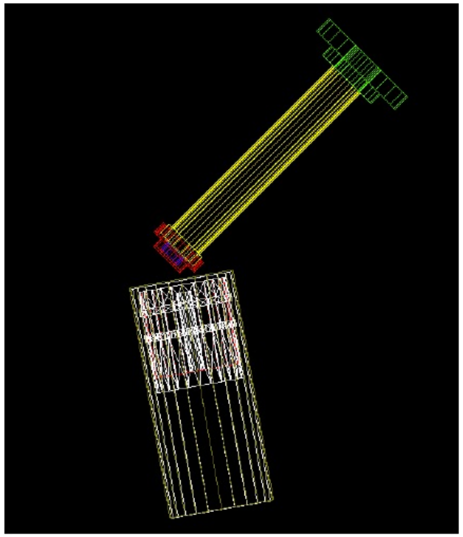
THE GOAL OF LUNA EXPERIMENT

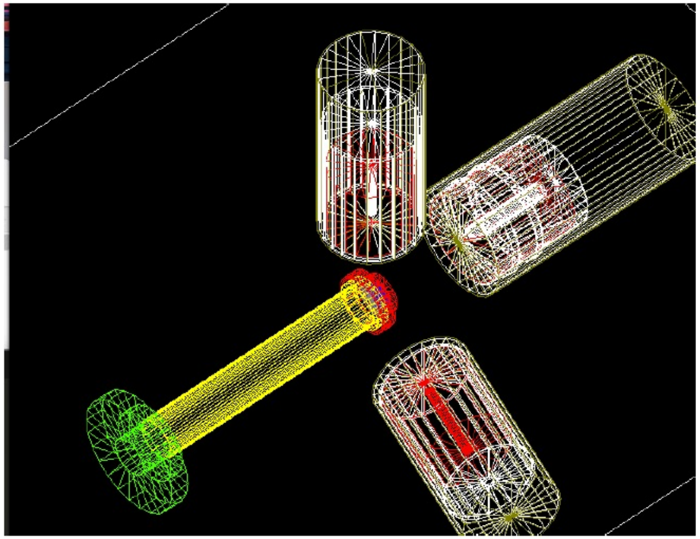
Angular distribution setup + Excitation function in close geometry simulated with Geant4.

3 HPGe detectors with ~120% relative efficiency

Detectors at 10 cm from target, angles covered: 0°,45°,90°,135°...







Beam time (h) to 3%, down to 250 keV, primary trans.

Transition	0 deg	90 deg
6.79	6.2	0.7
5.18	27.1	25.0
g.s (+ summing-in)	37.6	33. 6

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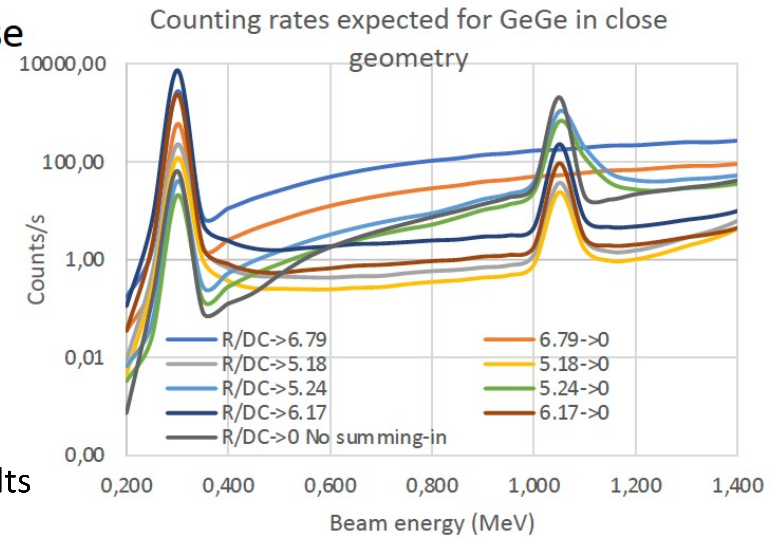
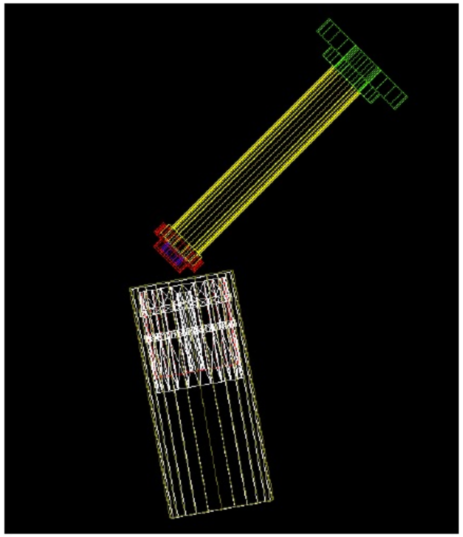
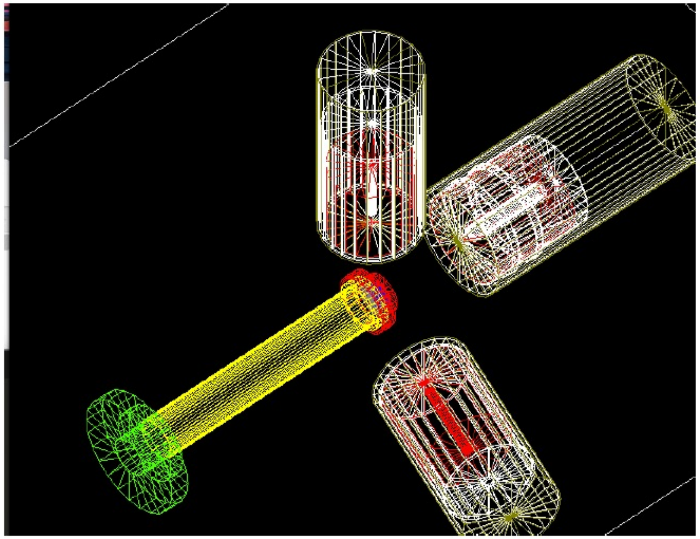
See A. Compagnucci's poster for more details and preliminary results







Beam time (h) to 3%, down to 250 keV, primary trans.

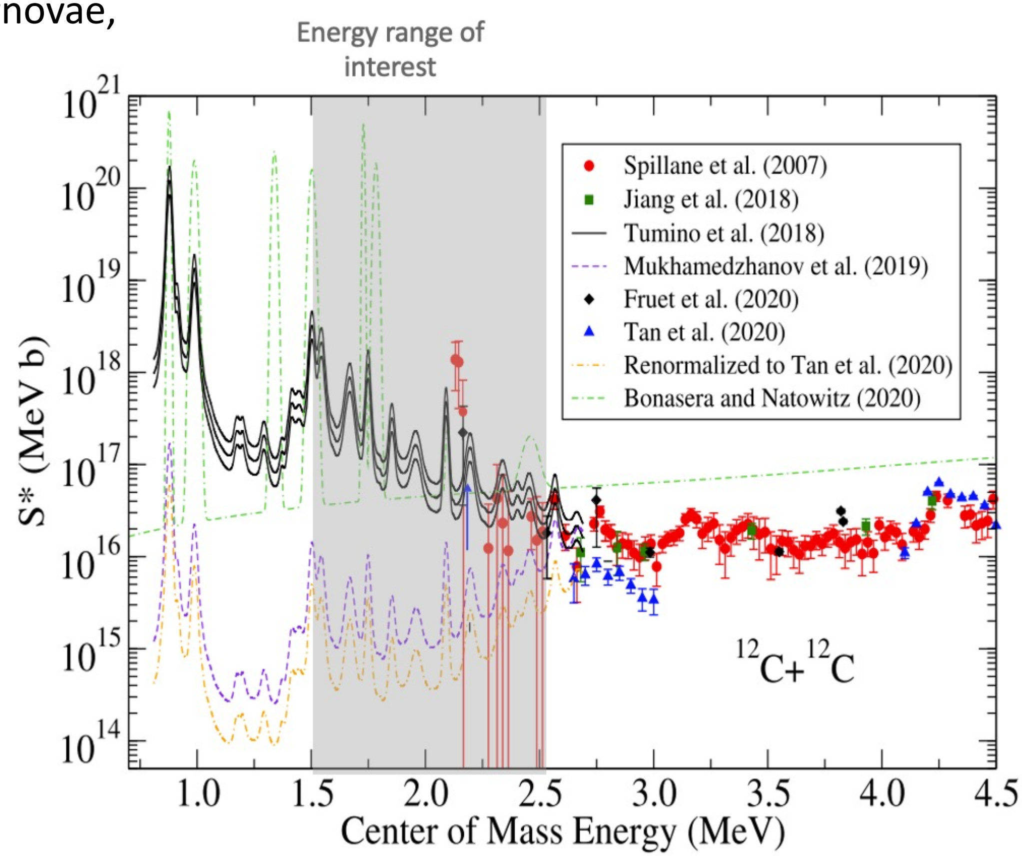
Transition	0 deg	90 deg
6.79	6.2	0.7
5.18	27.1	25.0
g.s (+ summing-in)	37.6	33. 6

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

$M_{up,}$ is a fundamental parameter:
$M < M_{up}$ 12C+12C cannot be ignited-> white dwarfs, nova, type Ia supernovae
$M > M_{up}$ 12C+12C ignited -> core-collapse supernovae, neutron stars, stellar mass black holes

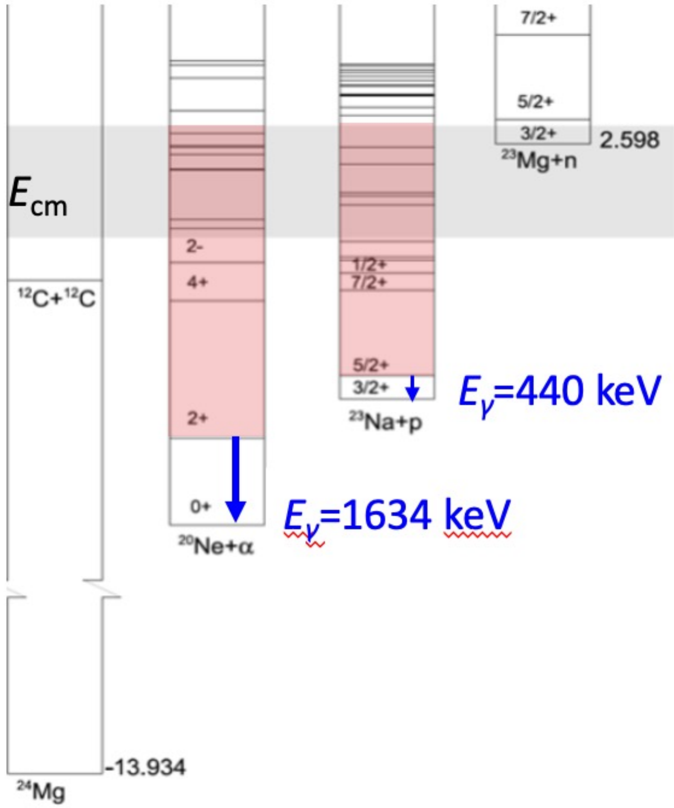
$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ Q = 4.617 MeV
$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ Q = 2.241 MeV
$^{12}C + ^{12}C \rightarrow ^{23}Mg + n$ Q = -2.598 MeV

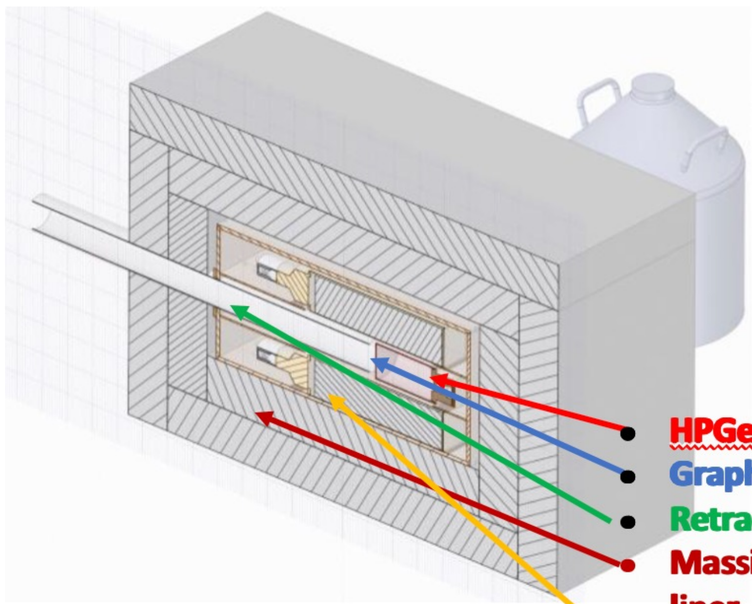
M_{up} strongly dependent on the 12C+12C rate at temperature between 0.5 and 1 GK



γ-DETECTION EXPERIMENT

~50% of the reactions leave the final nucleus in an excited state. The first method to study the two channels will be the detection of photons emitted (isotropically) in the de-excitation of the final nucleus





CONCLUSIONS

In the last 30 years of experiments LUNA studied many reactions of hydrogen burning and BBN nucleosynthesis

A new MV accelerator is now installed at LNGS and with this machine we could be able to explore He, C burning and neutron emitter for the s-process

To explore this new exciting physics cases, we need young researchers, and many positions are opened (in Padua, Naples, LNGS, Torino ….)

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Thank You!

https://luna.lngs.infn.it

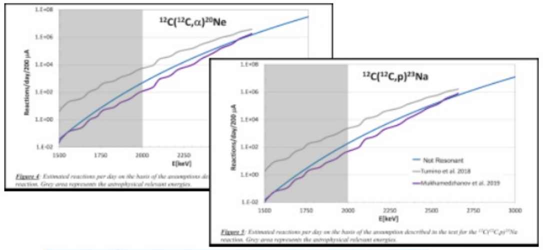
LUNA 400 kV LoI future activities

	motivation	target	detectors
$^{14}N(p,\gamma)^{15}O$	Solar Neutrino and core and shell H-burning	Solid target	BGO or more segmented High efficiency detector
$^{19}F(p,\gamma)^{20}Ne$	NeNa cycle in AGB	Solid target	BGO or more segmented High efficiency detector
$^{24}Mg(p,\gamma)^{25}Al$	Mg-Al cycle in AGB	Solid target	HpGe
$^{10}B(\alpha$,p or d or n)	First generation stars	Solid target	Particles and n detectors
$^{6,7}Li(\alpha,\gamma)^{10,11}B$	First generation stars	Solid target	New source for the accelerator

EXPECTED SENSITIVITY

Minimum daily reaction rate to reach 50% statistical uncertainty, considering detection efficiency, beam current (200 pμA) and data taking time (60 days). Units: reactions/day

	$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ E_γ=1634 keV	$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ E_γ=440 keV
HPGe	5	13
HPGe + Sum of Scintillators	3	11



		1500 keV	1750 keV	2000 keV
α_1 (1640 keV)	Tumino 2018	3.5	350	5500
	No Resonant	0.038	7.5	525
	Mukhamedzhanov 2019	0.025	3.5	125
p_1 (440 keV)	Tumino 2018	1.5	150	2500
	No Resonant	0.02	3	200
	Mukhamedzhanov 2019	0.01	1.5	50