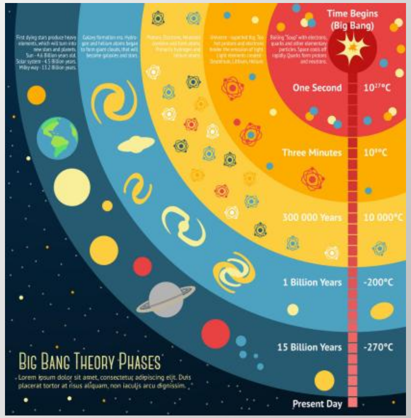
Status and perspectives of LUNA

Federico Ferraro

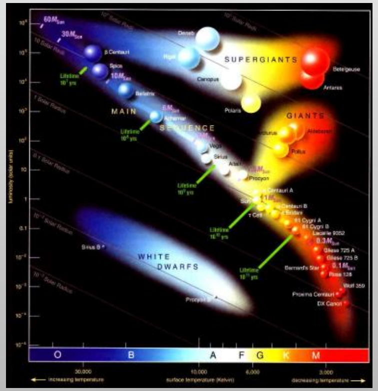
INFN – Laboratori Nazionali del Gran Sasso

HELIUM25 - 21-25 July 2025

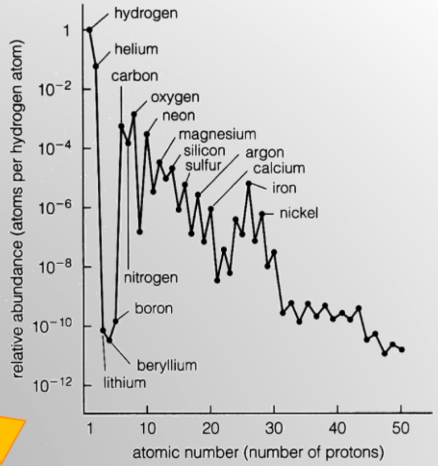
Evolution of early universe



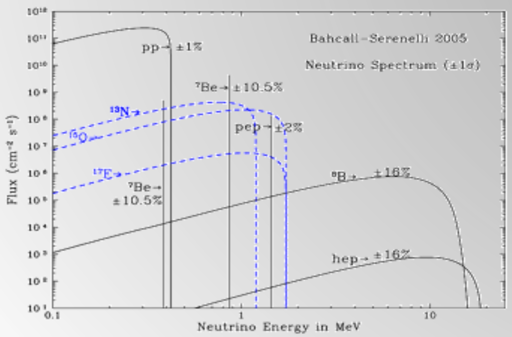
Stellar evolution



Nucleosynthesis

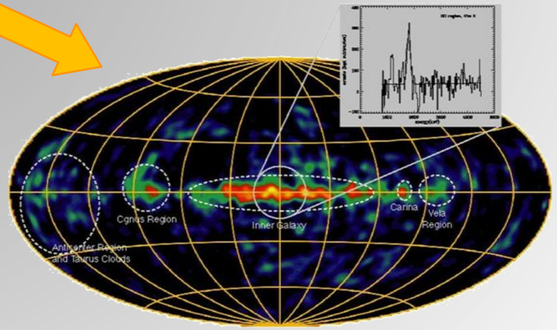


Nuclear cross sections



Solar neutrinos

Solar system



Astronomy

How do such nuclear reactions take place?

The energy of nuclei in a plasma follows a **Maxwell-Boltzmann distribution**

the **cross section** falls faster than exponentially as the energy decreases

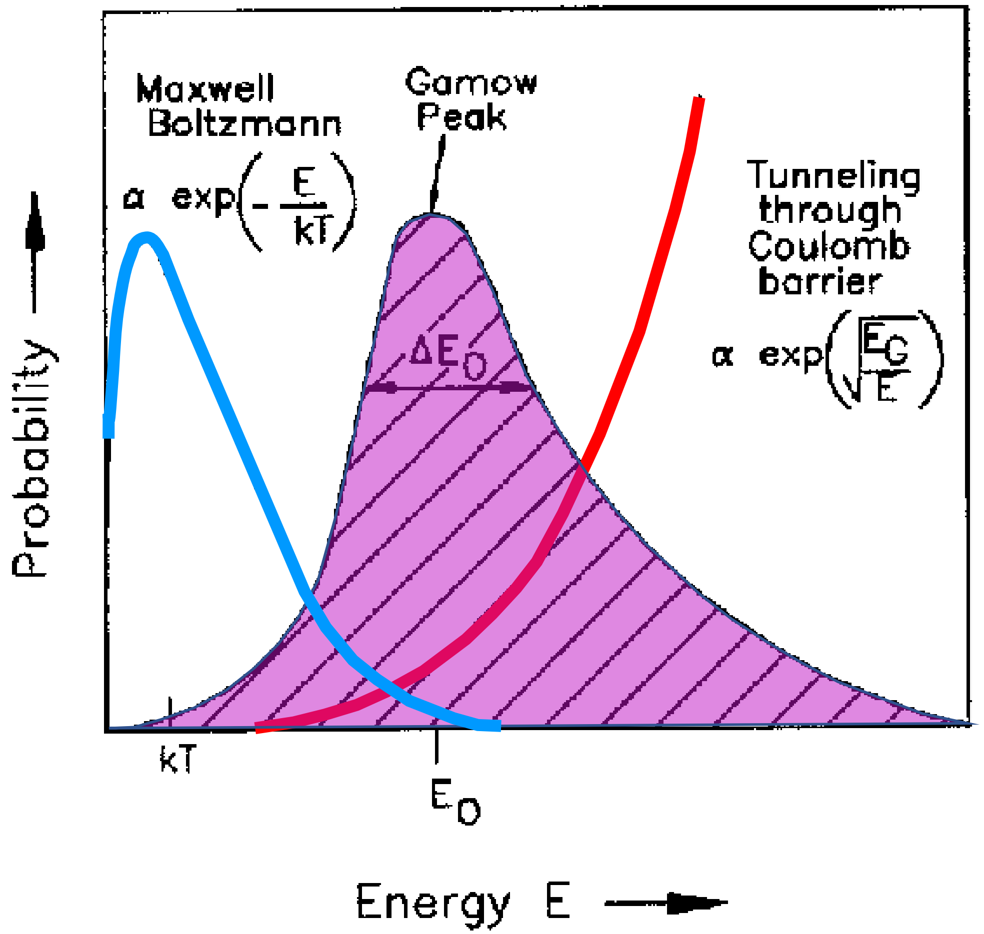
Consider a **reaction**

$$A + B \rightarrow C + D$$

The reaction rate is given by

$$\langle r \rangle = N_A N_B \int_0^{\infty} \phi(v)\, \sigma(v)\, v\, dv$$

The **Gamow peak** defines the relevant energy range for this reaction to occur



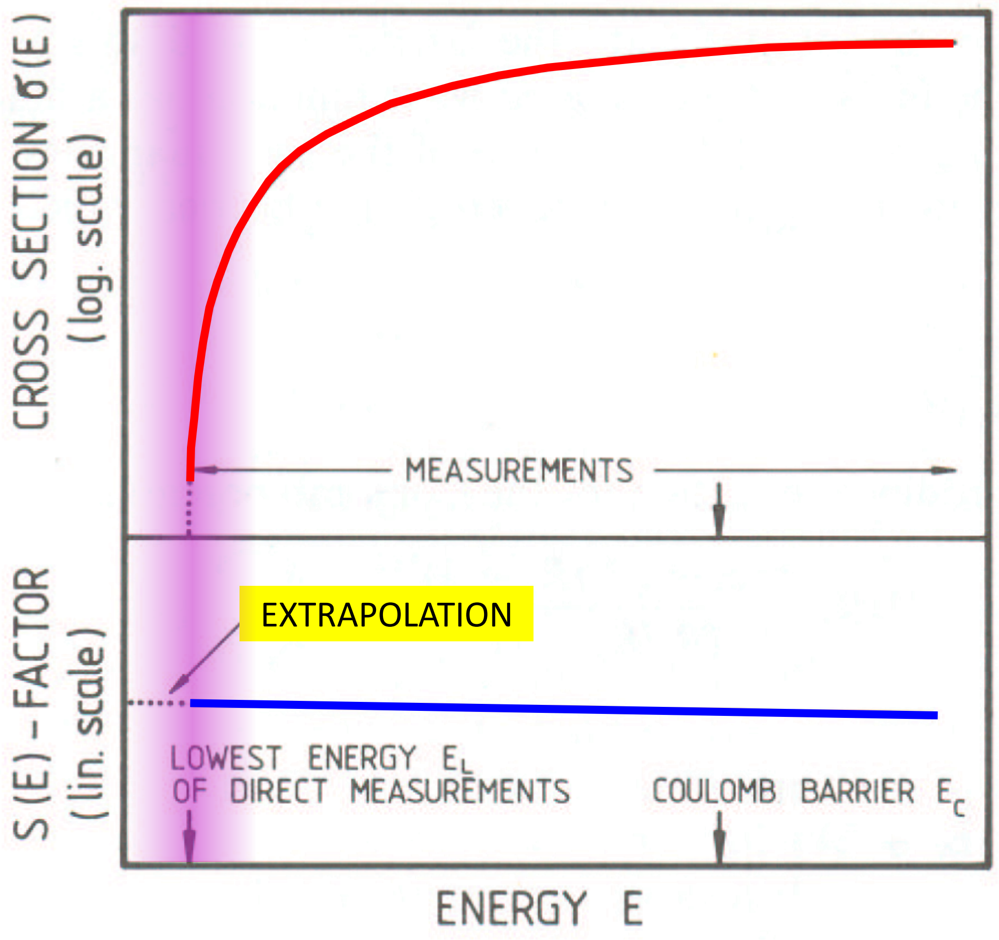
Challenges in Nuclear Astrophysics

Below a certain energy, the counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

Introducing the **astrophysical S-factor S(E)** and factorizing the **Coulomb interaction term** apart:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

it is possible to measure the cross section at high energy and extrapolate the astrophysical factor *S(E)* in the interesting energy range (Gamow window)



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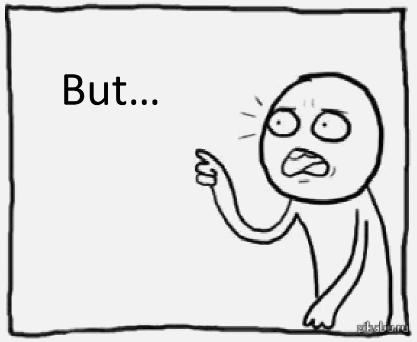
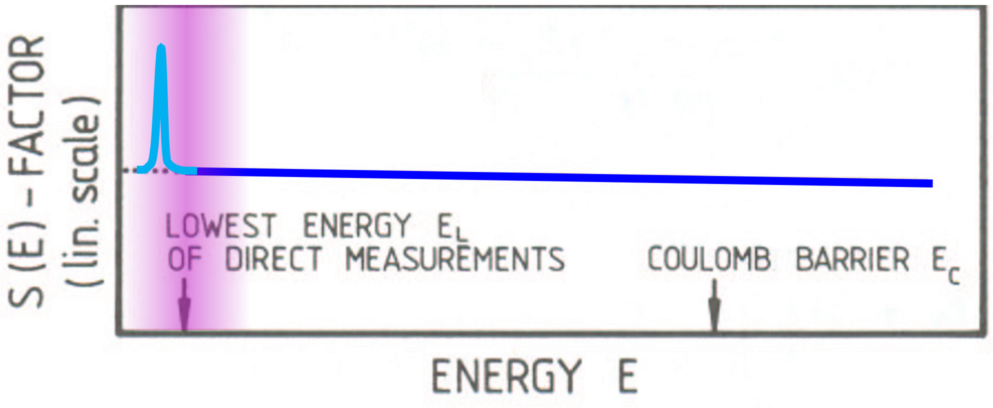


unexpected low-energy resonances may be present in the extrapolation region!



Challenges in Nuclear Astrophysics

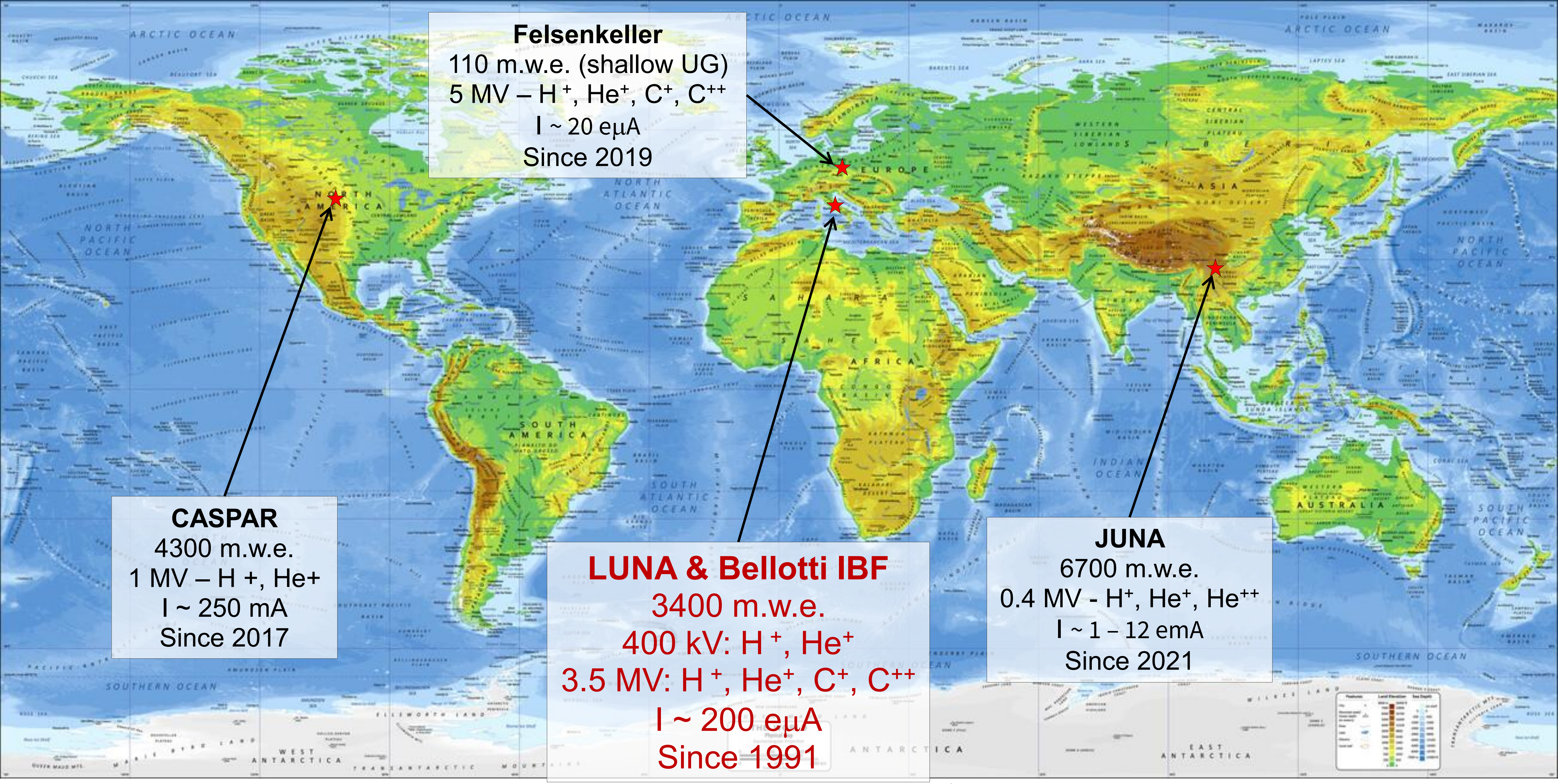
$$Counting\ rate = beam\ flux \times target\ nuclei\ areal\ density \times cross\ section \times detection\ efficiency$$

beam flux	10^{14} pps (100 μA 1^{+} beam)
target nuclei areal density	10^{19} atoms/cm^2 (often smaller)
cross section	10^{-36} cm^2 (often smaller)
detection efficiency	10^{-1} (often smaller)

a few counts/day

fundamental to strongly suppress the background! → **UNDERGROUND LABORATORIES**

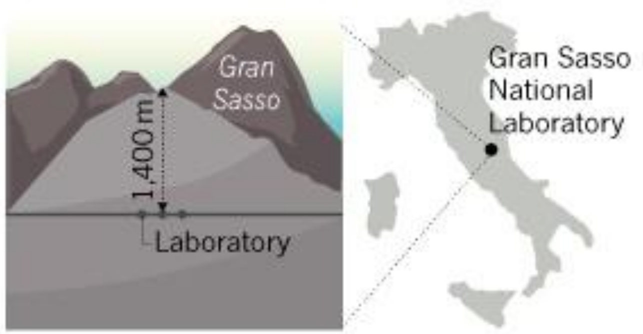
Beginning of PhD End of PhD

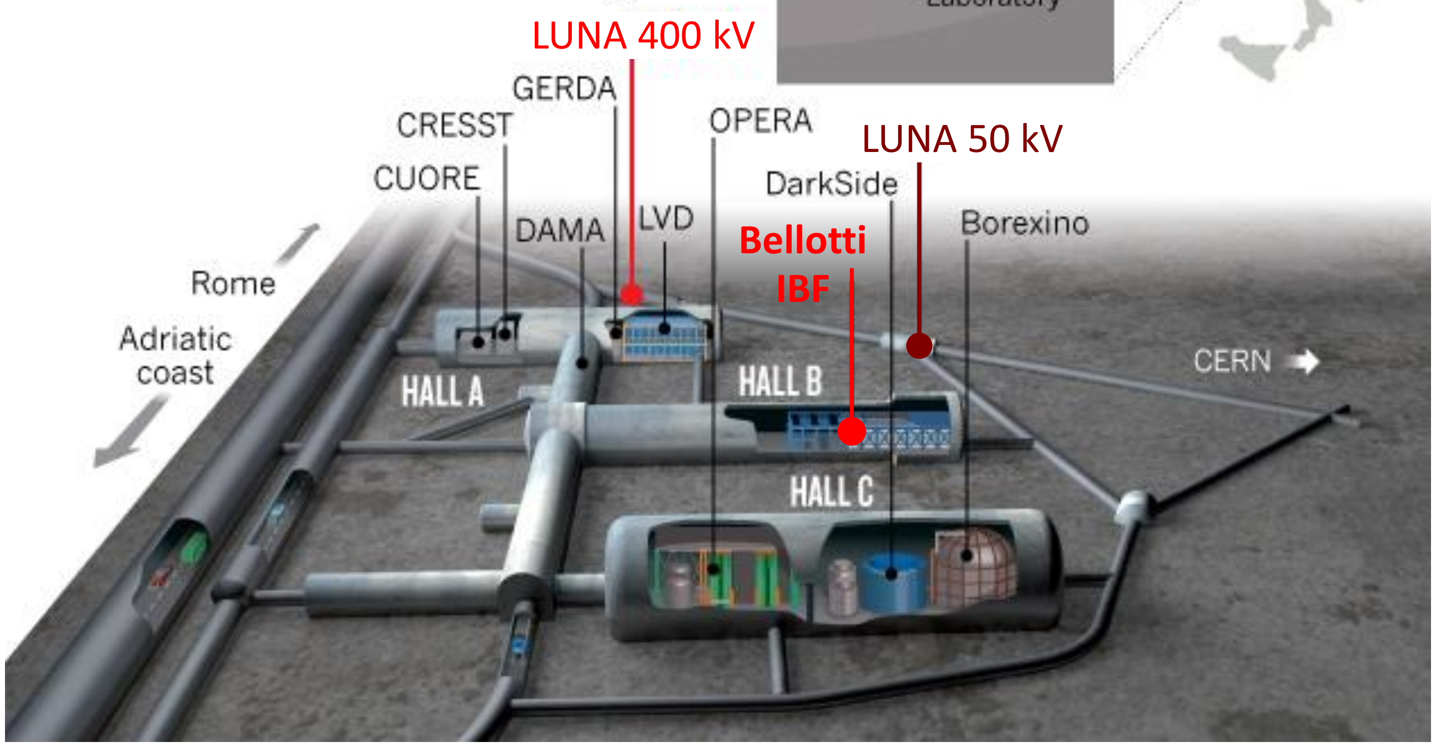


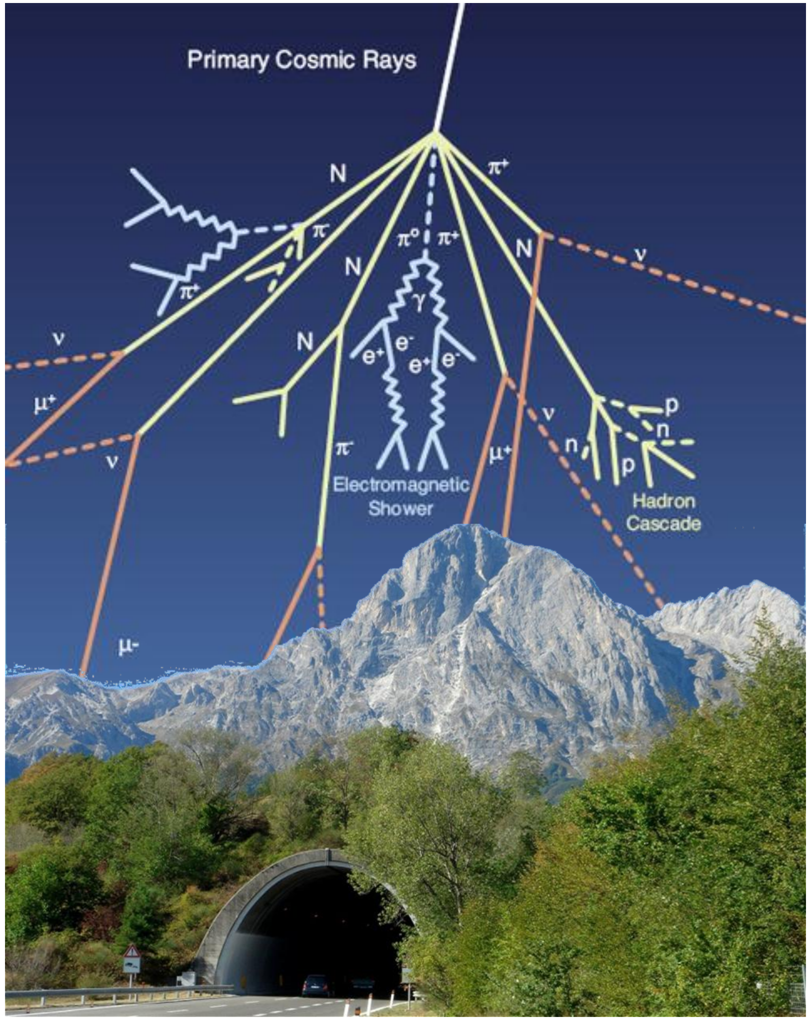
Underground Nuclear Astrophysics experiments/facilities worldwide

The Gran Sasso National Laboratory (LNGS)

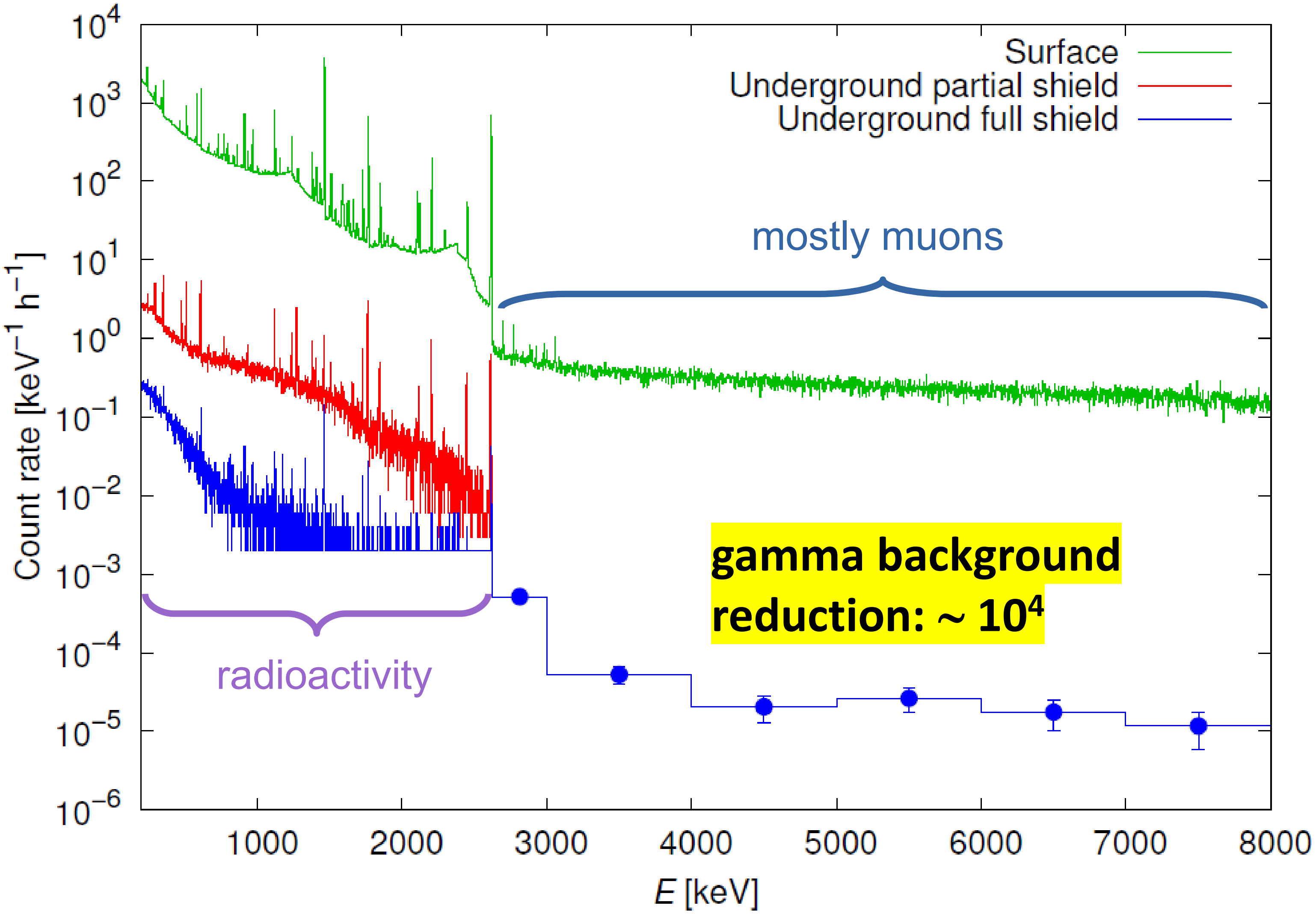
Min. overburden: 3400 mwe
muon flux reduction: $\sim 10^6$
neutron flux reduction: $\sim 10^3$





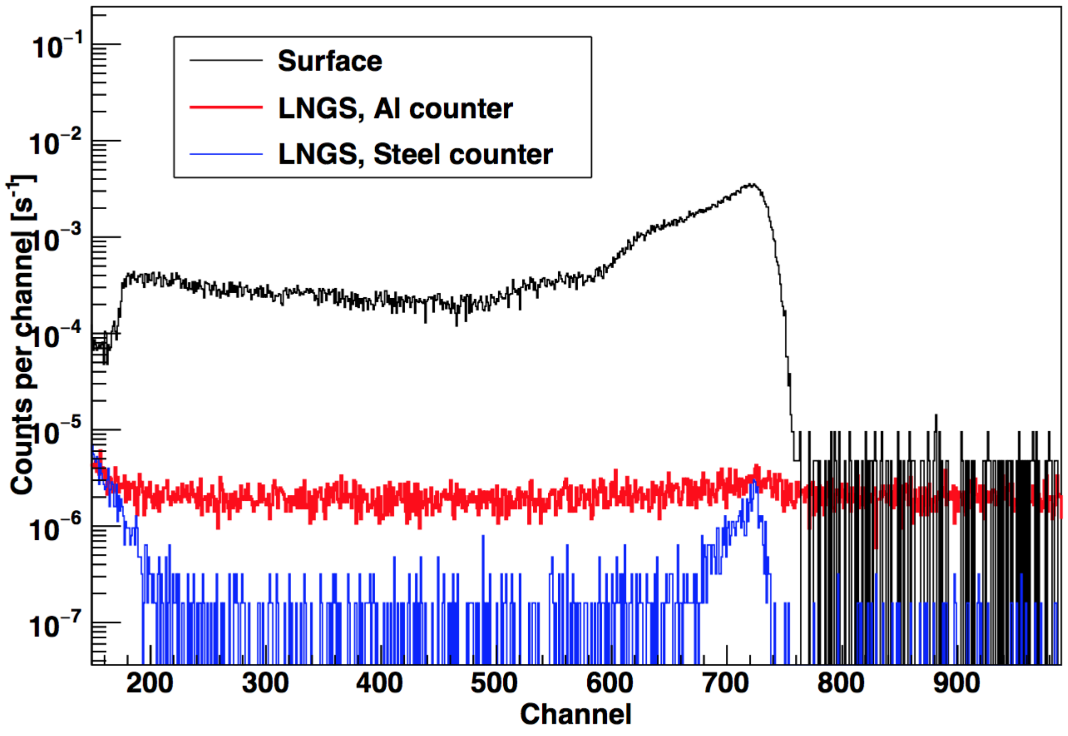


Gamma background reduction @ LNGS

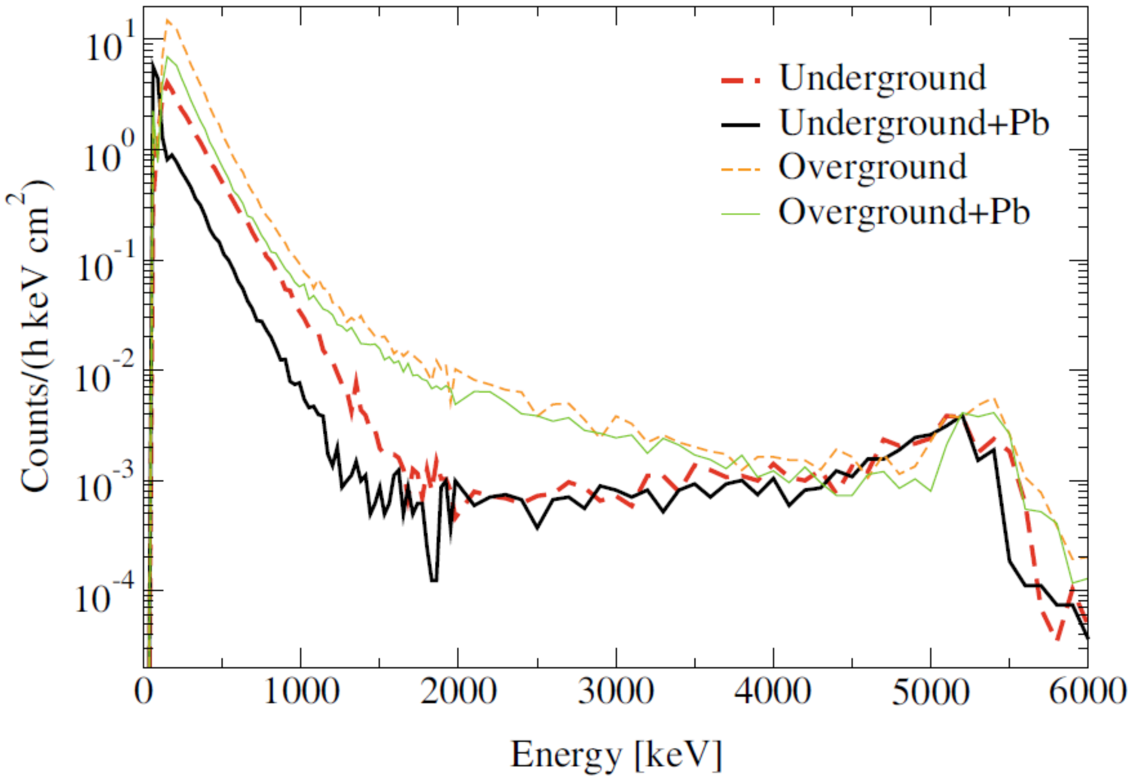


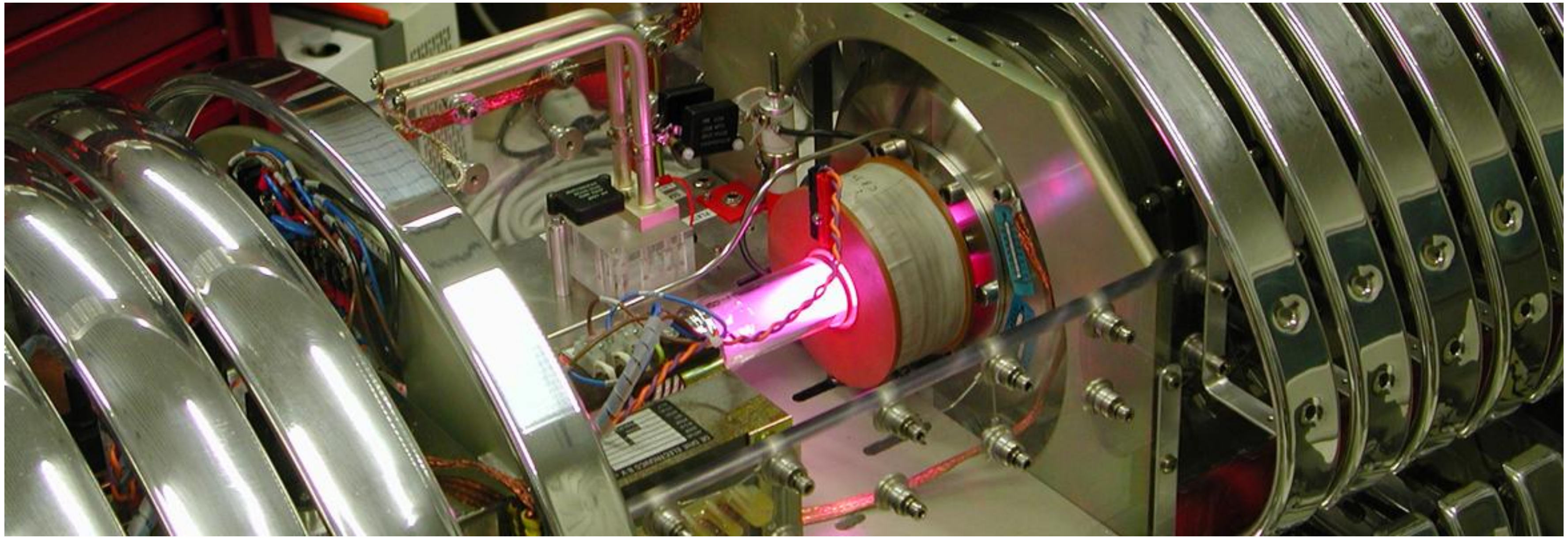
Reduction of particle background @ LNGS

Neutrons



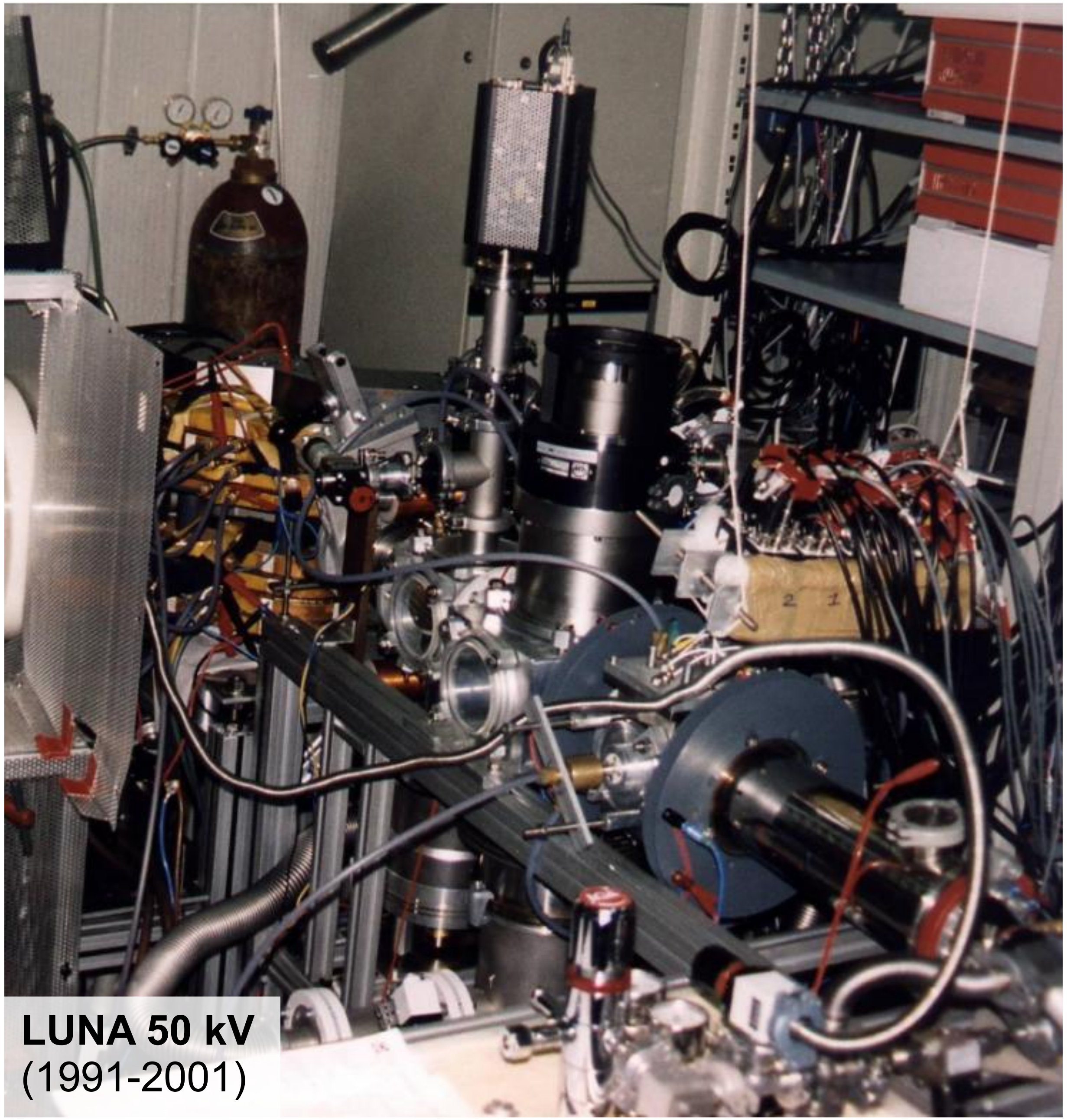
Charged particles



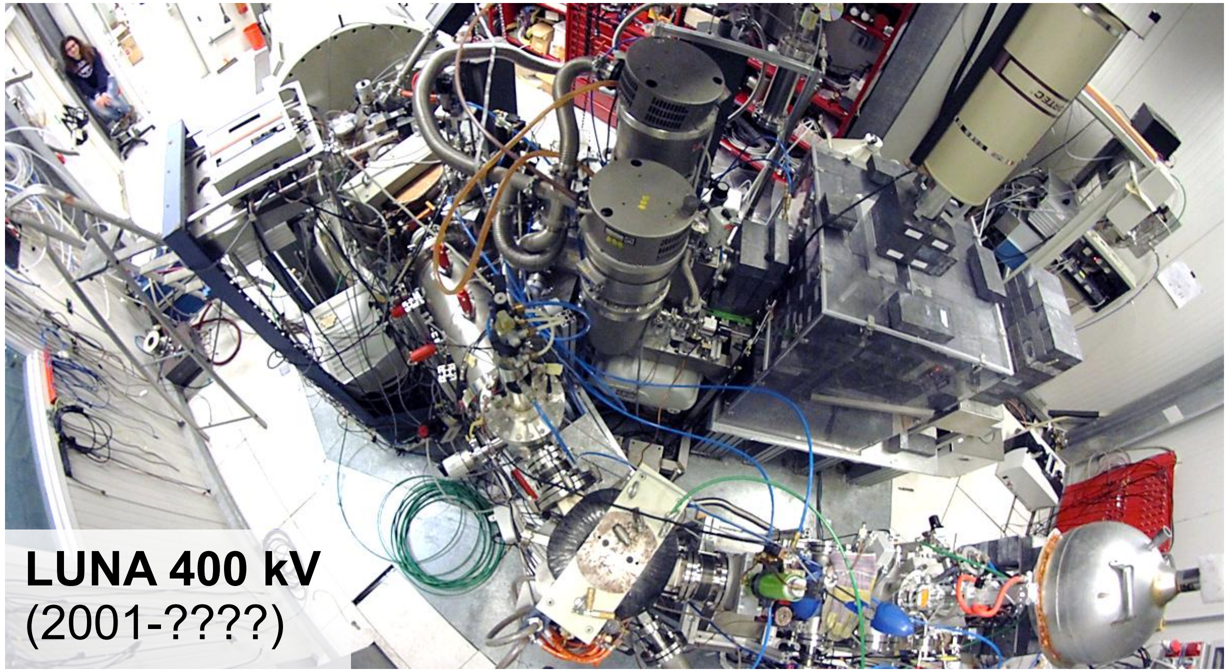


It has been the only deep underground accelerator for nuclear astrophysics for 26 years

Its results include
- solar physics (solar neutrinos)
- cosmological model (Ω_b, N_{eff} in Λ-CDM)
- big bang nucleosynthesis (BBN)
- stellar nucleosynthesis (H, He and C burning, s-process)



LUNA 50 kV
(1991-2001)

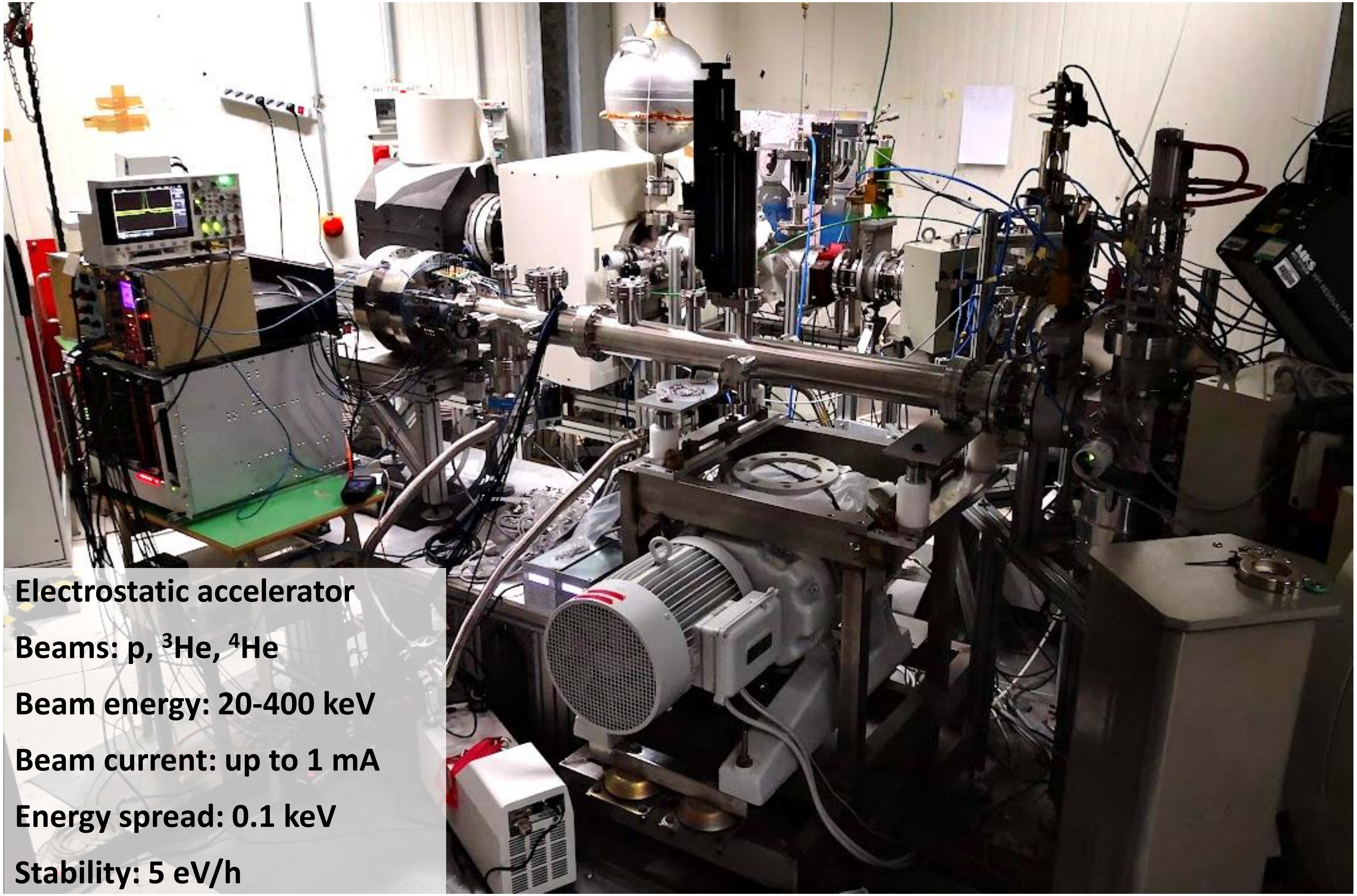


LUNA 400 kV
(2001-????)

LUNA-MV @ Bellotti IBF
(2023-????)

LUNA
Laboratory for Underground Nuclear Astrophysics

LUNA 400 kV
(2001-????)



Electrostatic accelerator

Beams: p, ^{3}He, ^{4}He

Beam energy: 20-400 keV

Beam current: up to 1 mA

Energy spread: 0.1 keV

Stability: 5 eV/h

Present measurements @ LUNA 400 kV

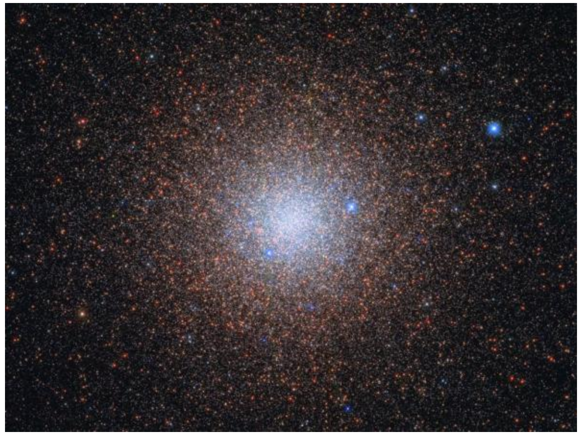
$^{14}N(p,\gamma)^{15}O$	**SoCIAL** SOlar Composition Investigated At Luna	Data taking concluded
$^{23}Na(p,\alpha)^{20}Ne$	**ELDAR** Elements in the Lives and Deaths of stARs	Data taking ongoing
$^{11}B+\alpha$	**NUCLEAR** Nuclear Clustering Effects in Astrophysical reactions	Data taking just started
$^{19}F(p,\gamma)^{20}Ne$		Data taking ongoing
$^{24}Mg(p,\gamma)^{25}Al$		Preliminary tests concluded

^{23}Na(p,a)^{20}Ne

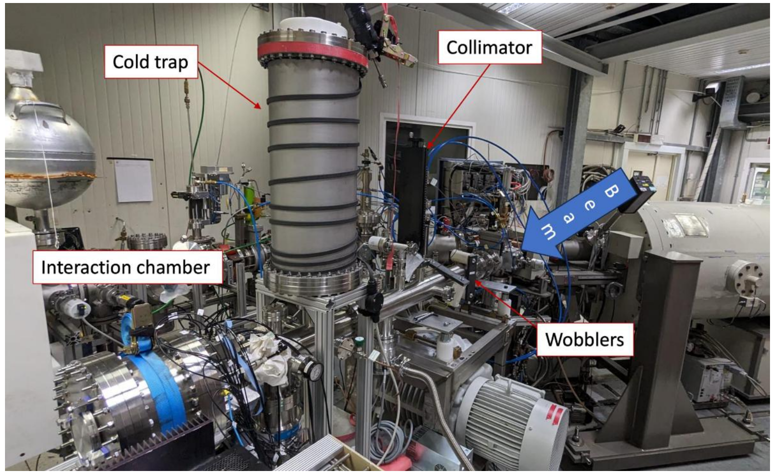
Part of NeNa and MgAl cycles at $T \sim 50$ MK

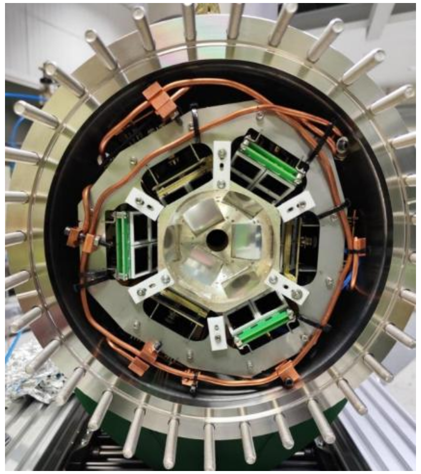
Possible cause of O/Na **anti-correlation** (models of GCs predict **correlation** instead**!**)

Uncertainty dominated by weak resonances (E_p=144 keV)



“This discrepancy would be much alleviated if the cross section of the sodium-destroying reaction ^{23}Na(p,α)^{20}Ne were actually a factor of a few lower than currently estimated” [Renzini et al 2015]





24 Si PIN diodes + 3 MSPADs (4 ch each):15% coverage

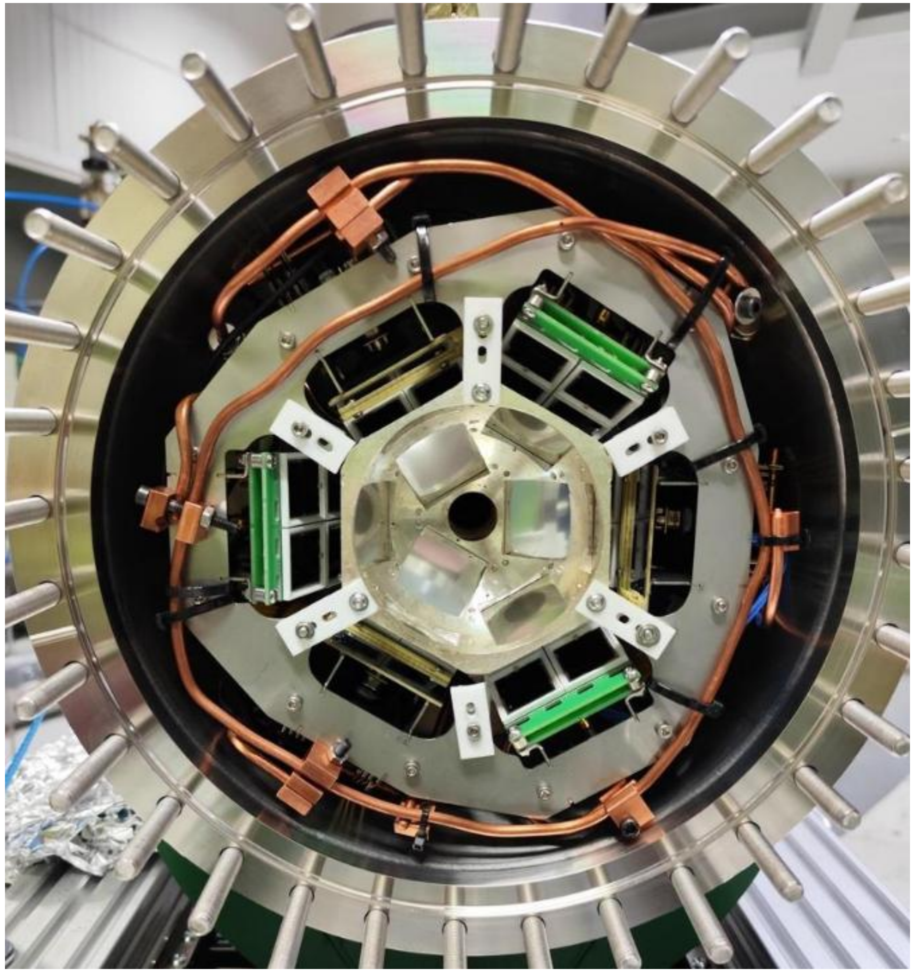
Electronic noise due to antenna-like effect: solved

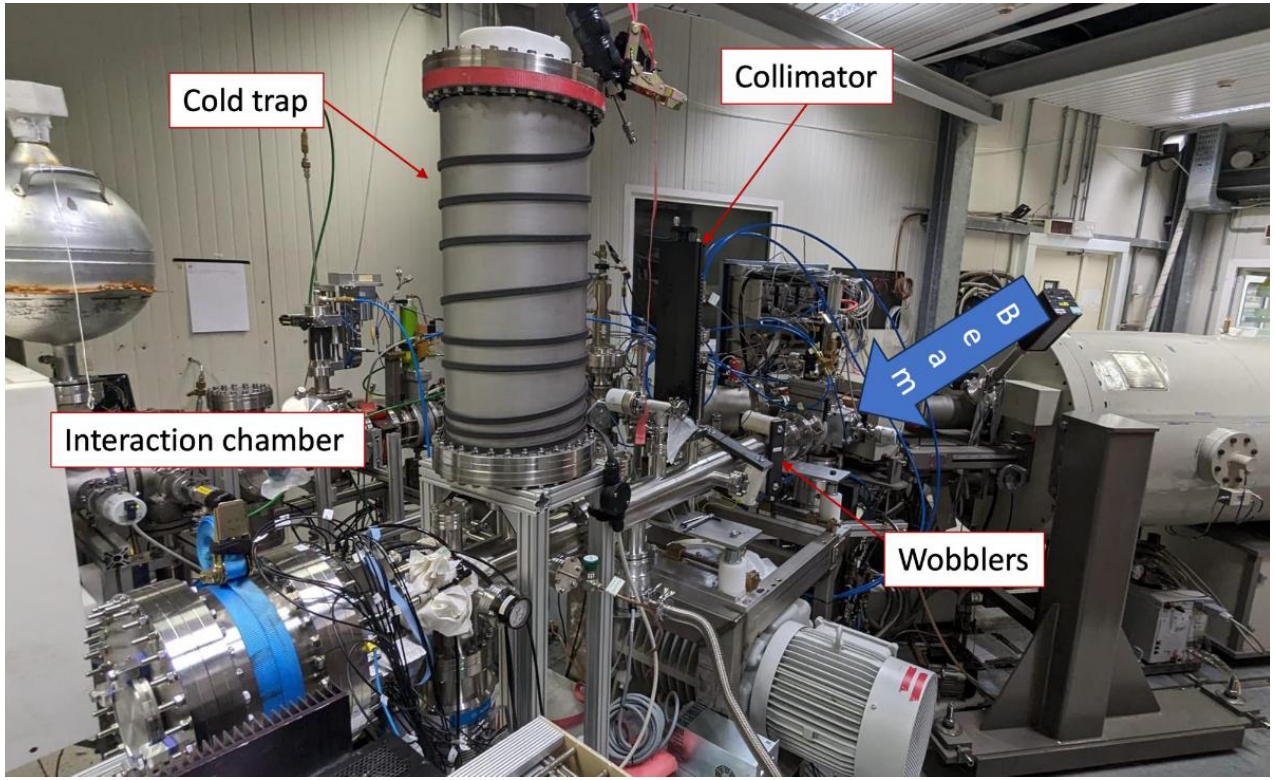
BIB due to ^{6}Li(p,α)^{3}He and ^{11}B(p,α)^{8}Be: mitigated

Target degradation: monitored via E_p= 286 keV resonance

Very interesting results: STAY TUNED!

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





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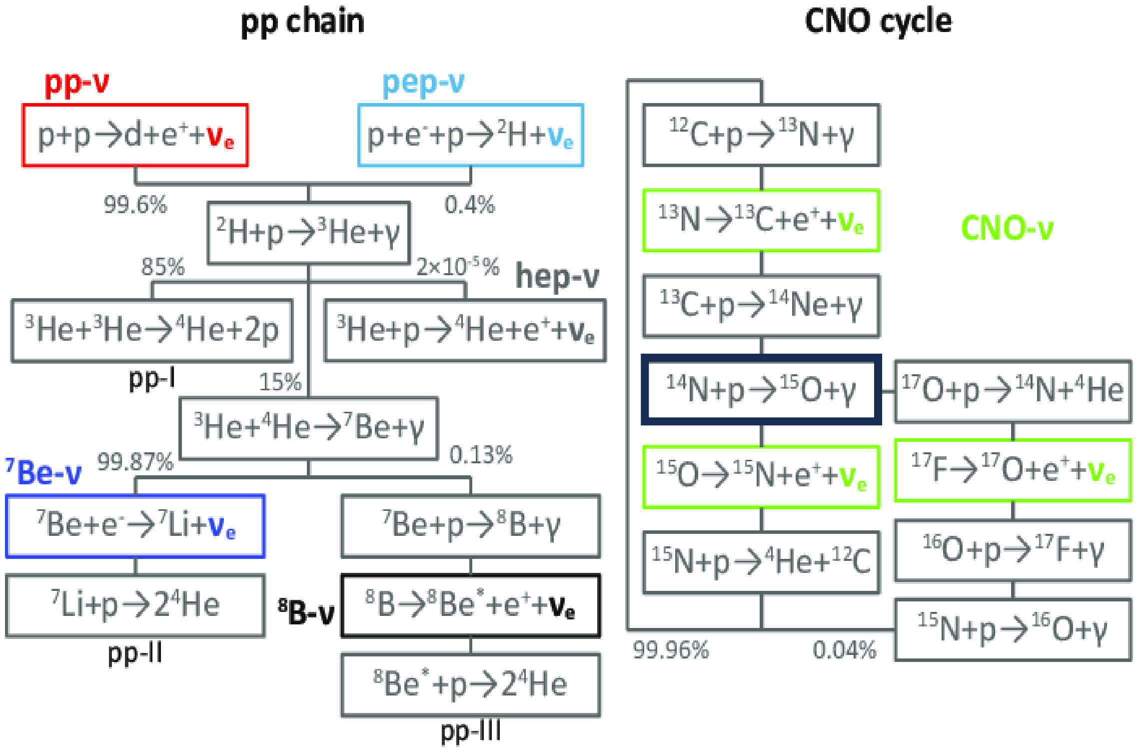
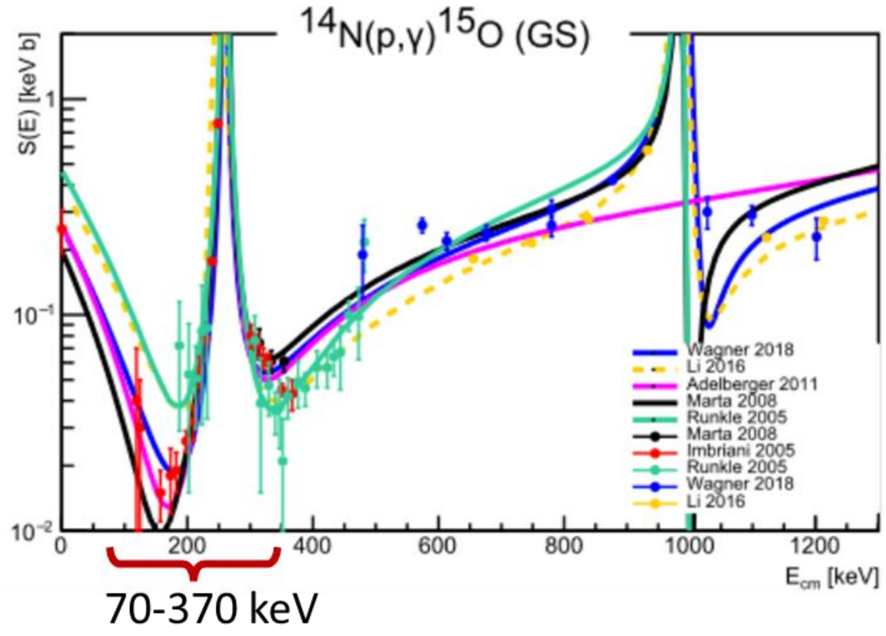
$^{14}N(p,\gamma)^{15}O$: bottleneck of CNO cycle



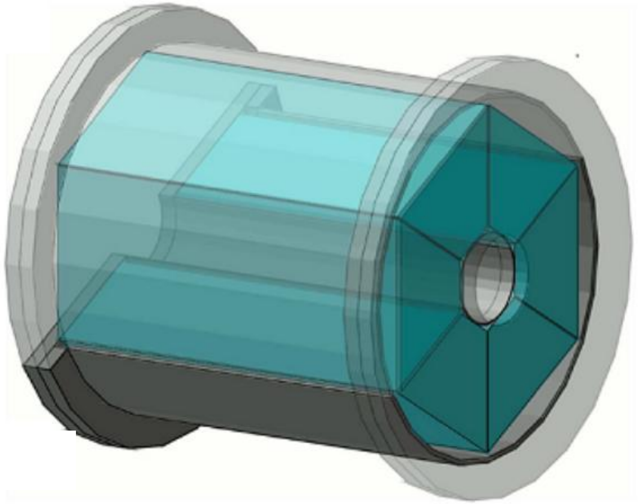


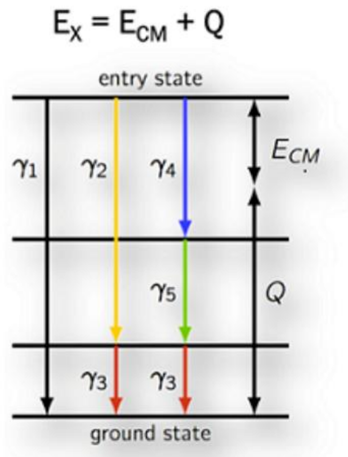
Goals:

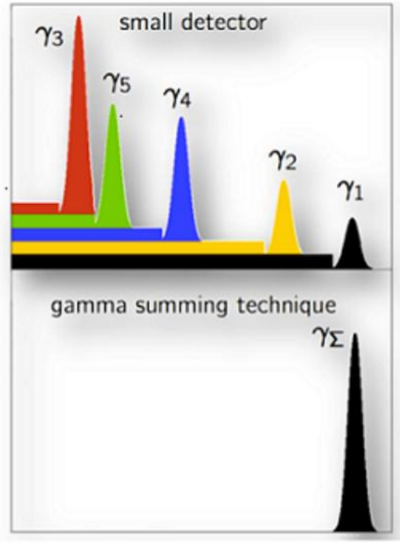
- below 100 keV → total cross section
- 100-370 keV → contribution of each excited state

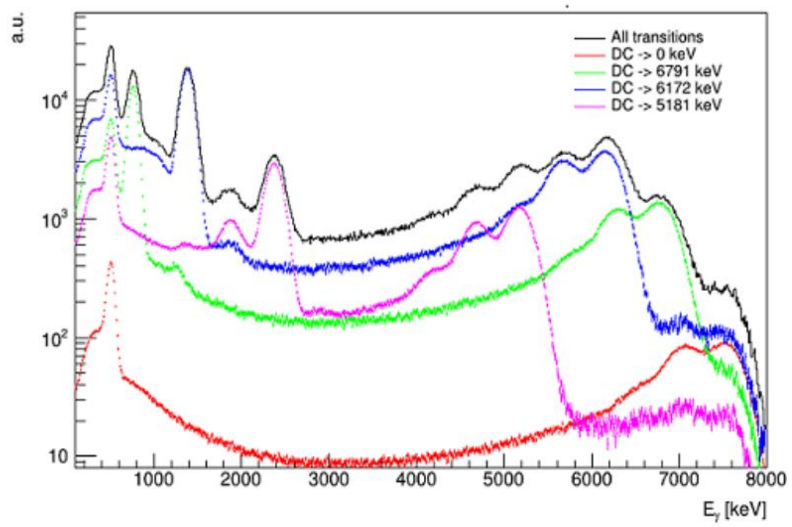
using a segmented, high-efficiency detector

$^{14}N(p,\gamma)^{15}O$: bottleneck of CNO cycle









It is possible to see both the sum peak and the contribution from each gamma emitted in the de-excitation of ^{15}O

Better determination of the cross section, branching ratios and summing effects (**coming soon!**)

$^{10}B+\alpha$

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https://doi.org/10.1140/epja/s10050-020-00339-x

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Nuclear clusters as the first stepping stones for the chemical evolution of the universe

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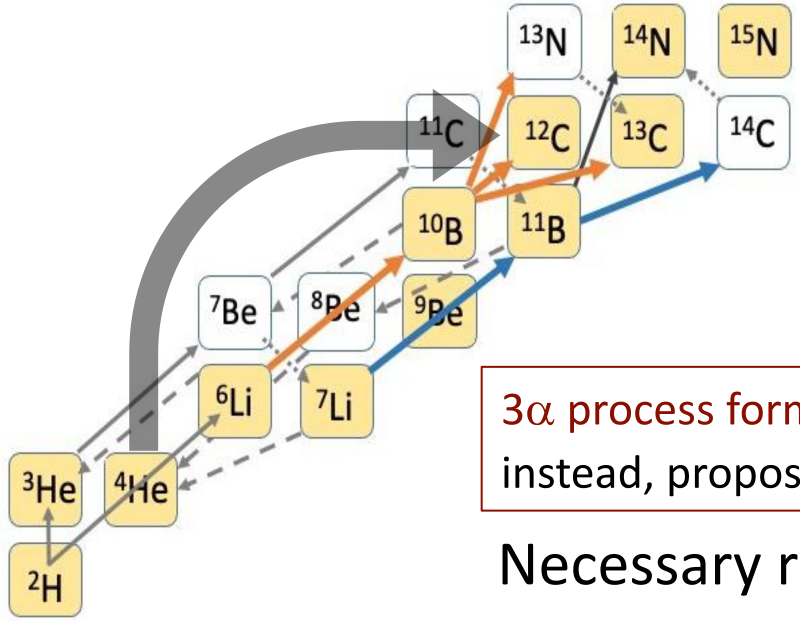
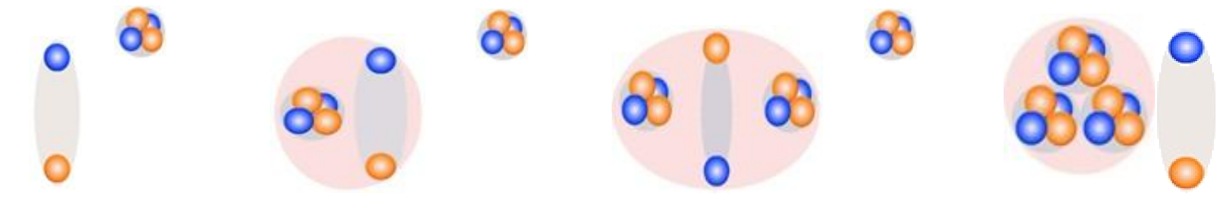
[2] Department of Physics & Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada



nuclear clustering may greatly
enhance fusion probabilities
at low (i.e. astrophysical) energies

proposed reactions involve strong cluster configurations

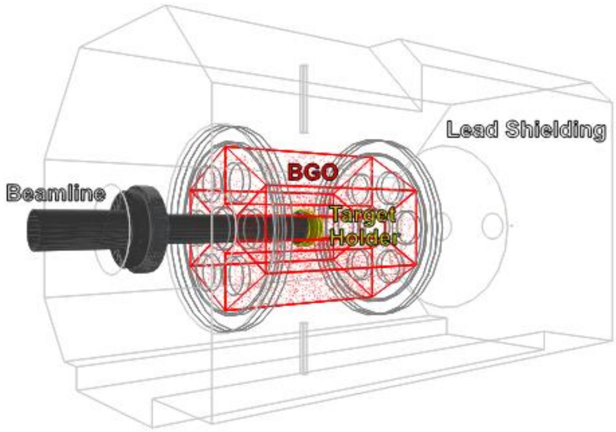
$d + \alpha \rightarrow {}^{6}Li + \alpha \rightarrow {}^{10}B + \alpha \rightarrow {}^{14}N$

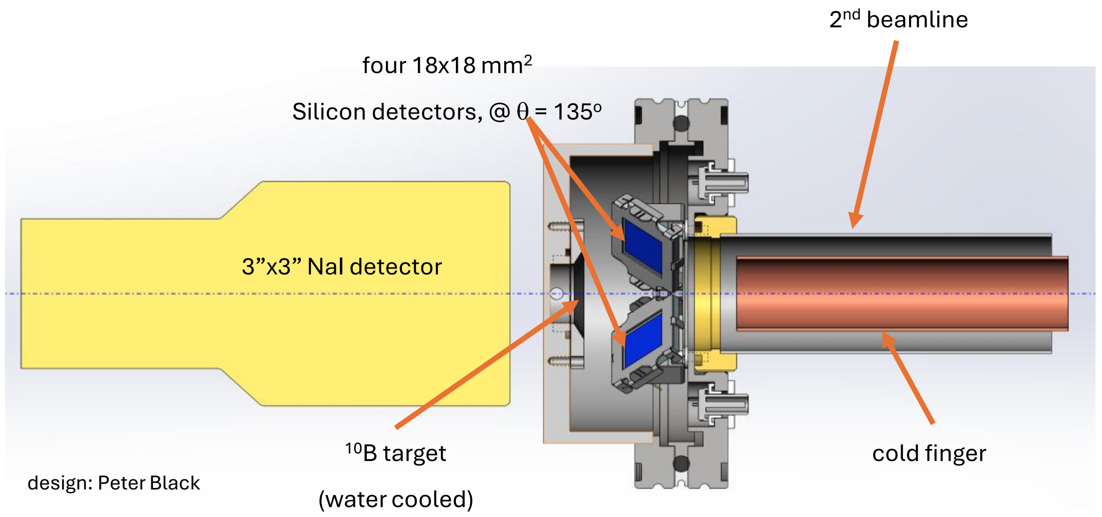


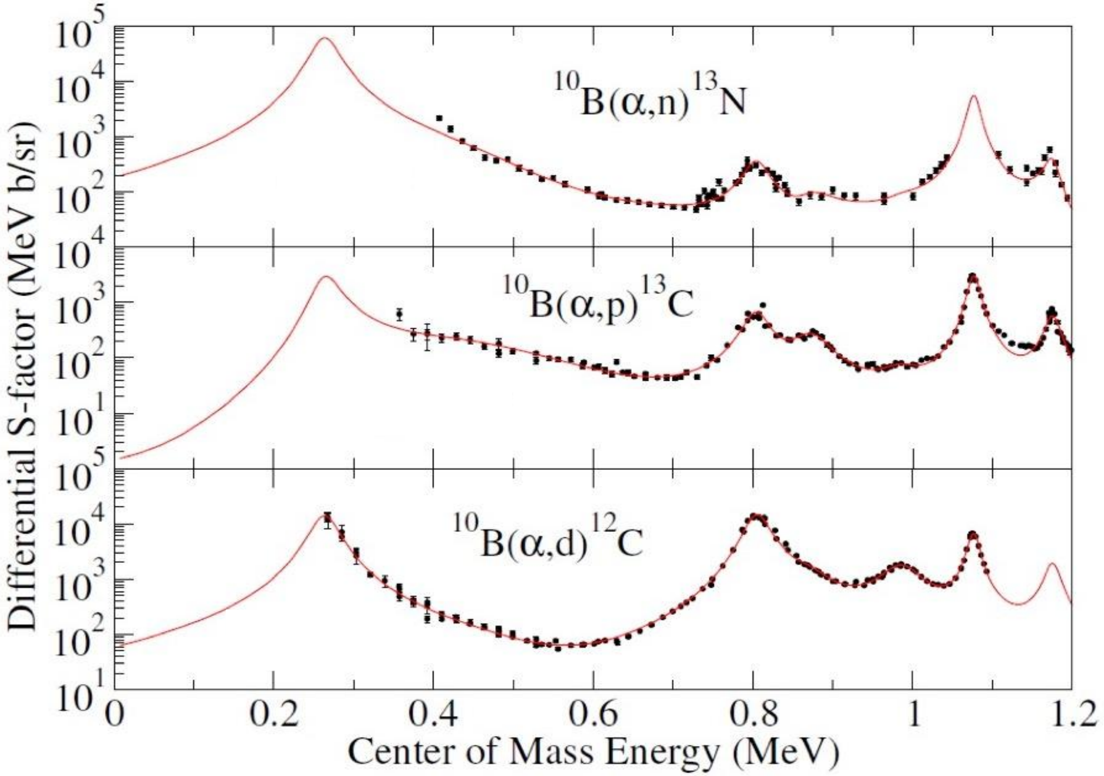
3α process forms C but completely by-passes Li
instead, proposed reaction sequences would also alter Li abundances → solution to CLiP?

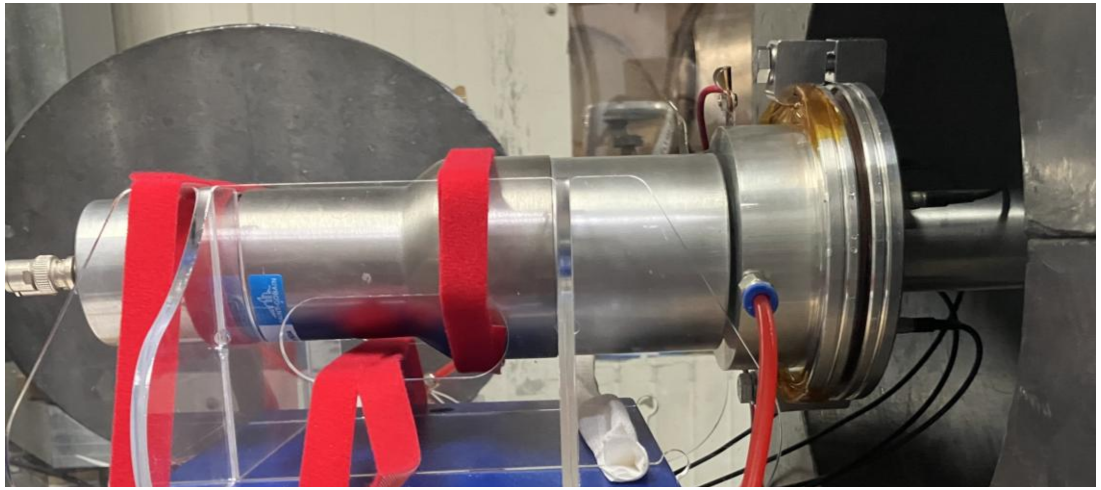
Necessary requirement: strong enhancement of (α,γ) reaction rates

$^{10}B+\alpha$









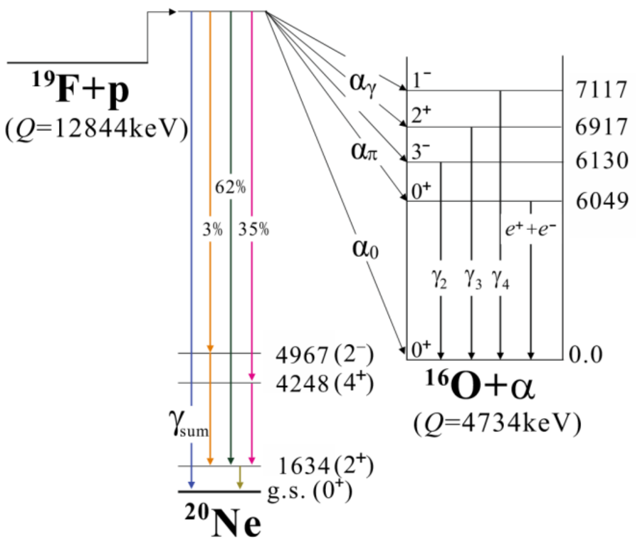
Single Si efficiency: 2.1 % (with 2 MeV alphas)

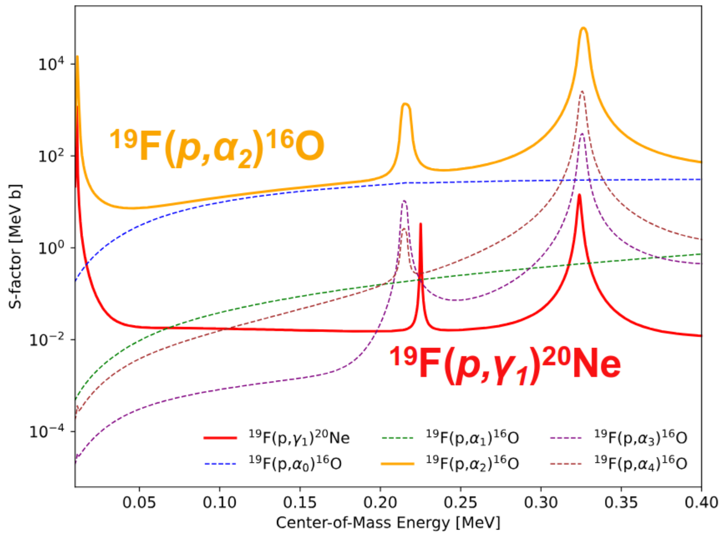
Total Si efficiency: 8.6 %

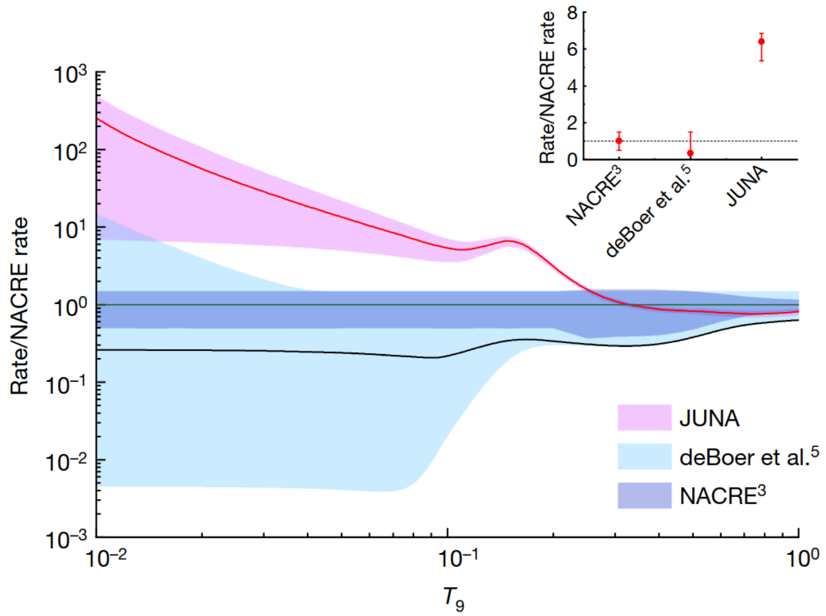
NaI FEP efficiency: 5.1 % @ 1 MeV

NaI Total Efficiency : 14.6 % @ 1 MeV

$^{19}F(p,\gamma)^{20}Ne$

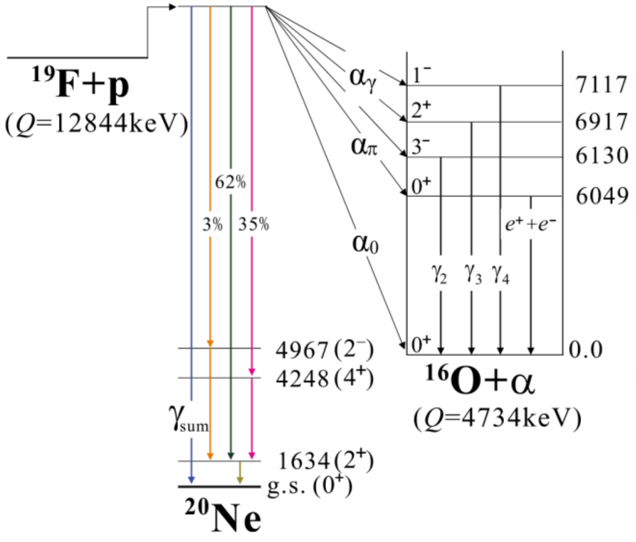


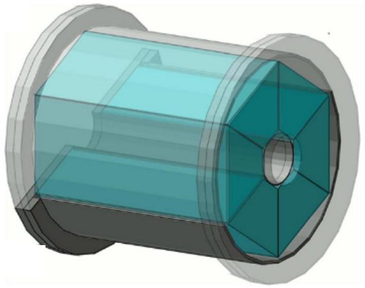




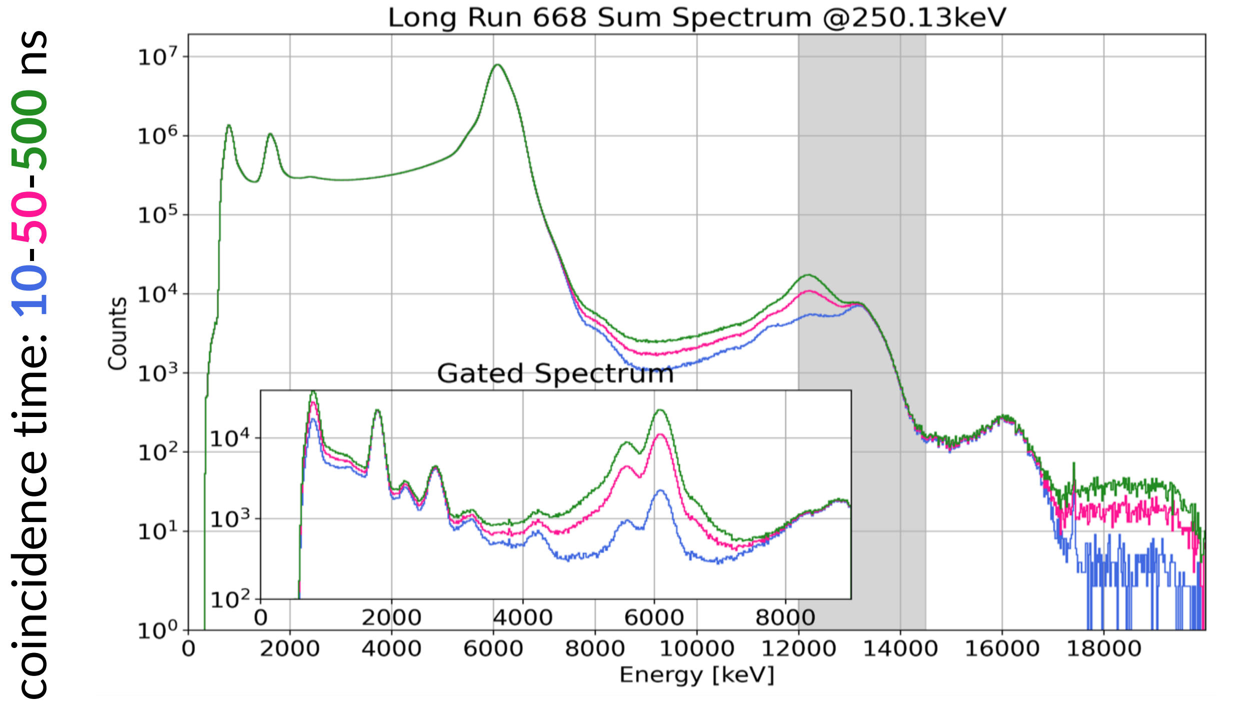
- Link between CNO and NeNa cycles
- Hot CNO breakout may play a key role in explaining the observed Ca abundance in metal-poor stars
- $^{19}F(p,\gamma)^{20}Ne$ and $^{19}F(p,\alpha\gamma)^{16}O$ ratio defines the elements production of first stars
- Zheng et al. (2022) found the Elab = 240 keV resonance, drastically enhancing the reaction rate
- No other literature data are available < 300 keV!

$^{19}F(p,\gamma)^{20}Ne$





- $^{19}F(p,\alpha\gamma)^{16}O$ creates a huge pile-up background
- Beam-induced background from contaminants like $^{11}B(p,\gamma)^{12}C$



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$^{24}Mg(p,\gamma)^{25}Al$

- part of the **MgAl cycle** →
- sets the abundance of Mg and Al isotopes
  - in Globular Cluster stars (among the oldest star in the Universe)
  - in stardust grains formed around Asymptotic Giant Branch stars
- activates during H burning for temperatures 30 MK < T < 60 MK

Straniero et al. 2013 APJ 763

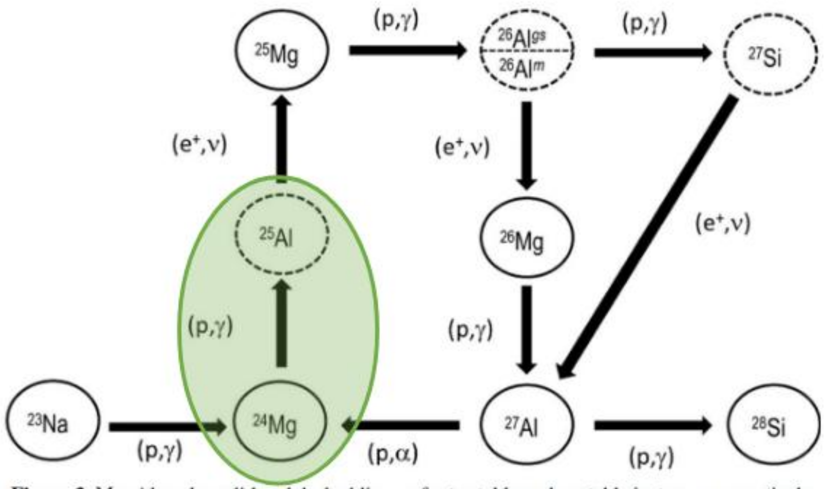
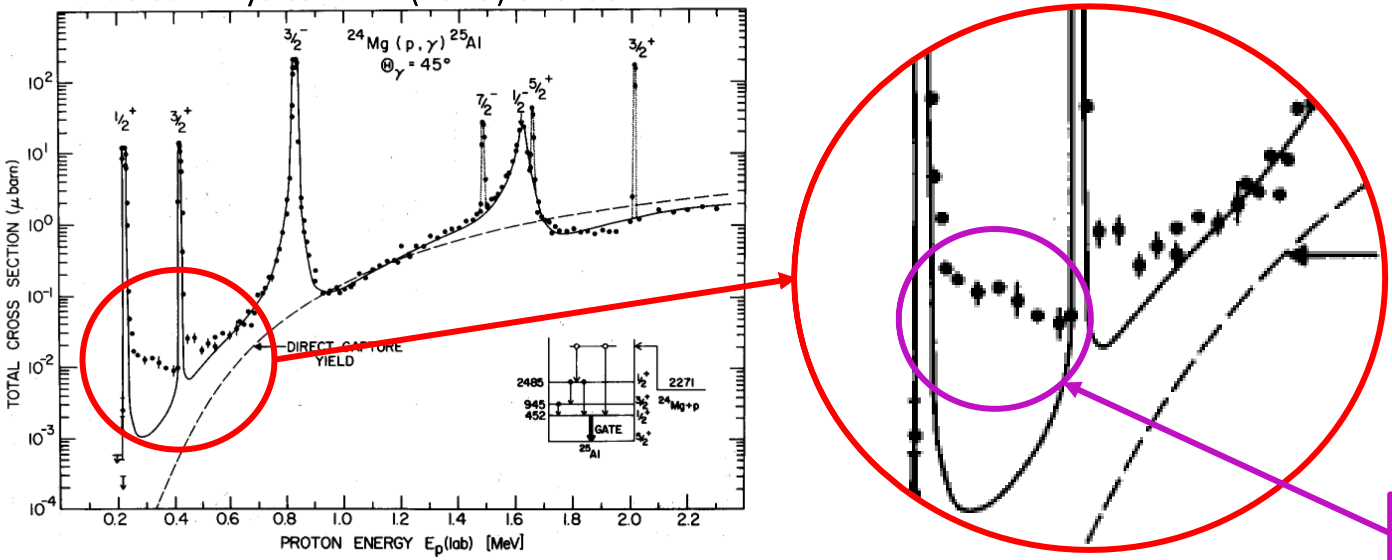


Figure 3. Mg–Al cycle: solid and dashed lines refer to stable and unstable isotopes, respectively.

Nuclear Physics A242 (1975) 519-532

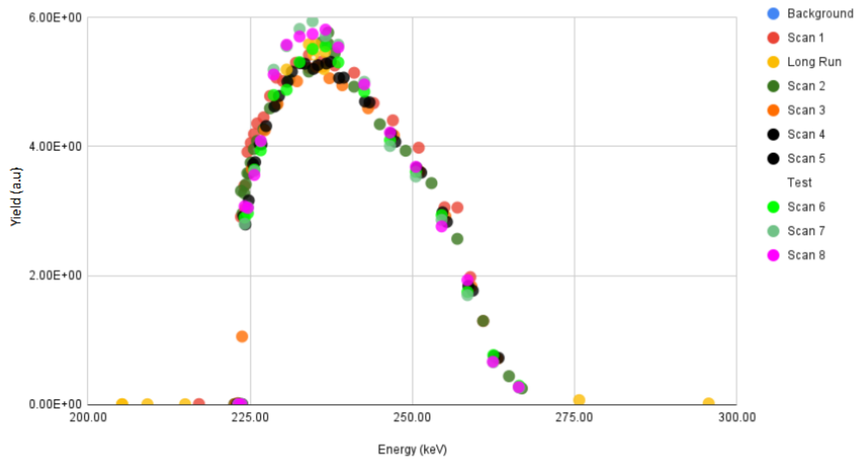


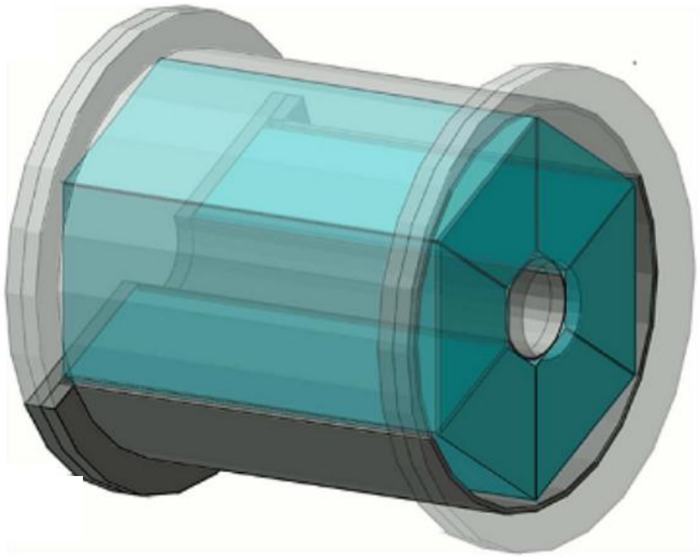
E_p=200-400 keV

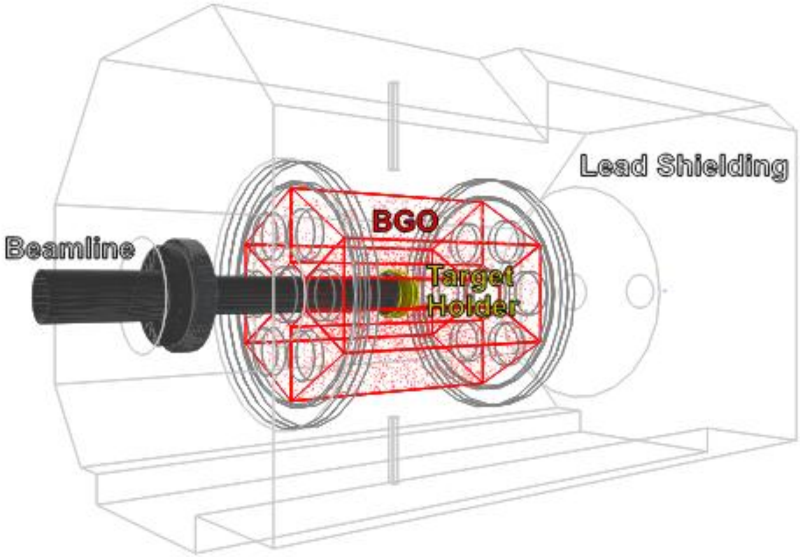
- compound nucleus structure well understood
- resonant captures quite understood and reproduced by models
- DC mechanism not well reproduced by models at the lower energies -> possible experimental misinterpretations

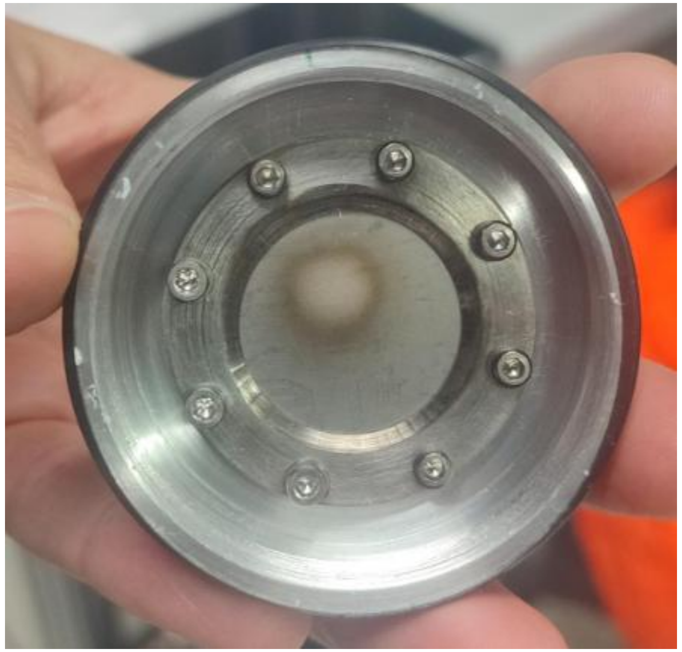
$^{24}Mg(p,\gamma)^{25}Al$

- At E_p=200-400 keV the cross section is about 1-10 nb
- High efficiency is needed -> 4π BGO detector
- Low background is required -> enriched target









The Bellotti Ion Beam Facility at LNGS

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

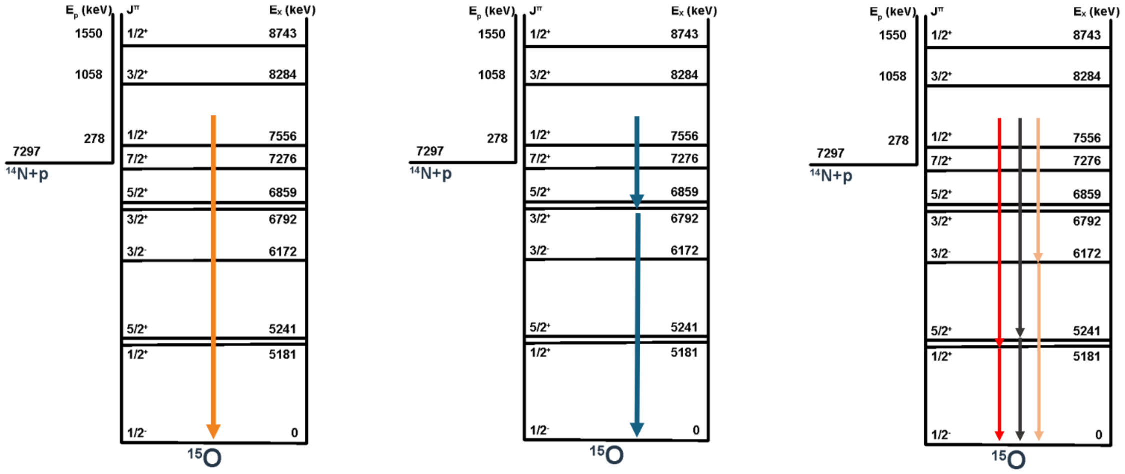
* Many thanks to the Accelerator Service of INFN-LNGS for operating this facility at their best!

LUNA @ Bellotti **IBF** (2023-2025-????)

Measurements approved by the Program Advisory Committee:

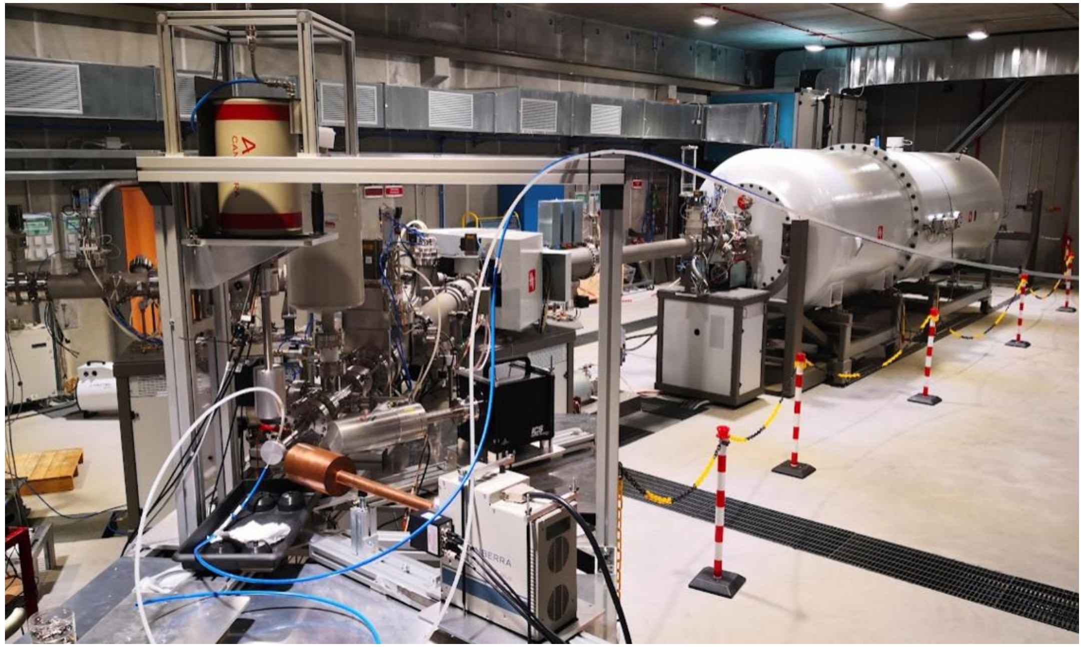
$^{14}N(p,\gamma)^{15}O$	perfect as **commissioning measurement** - interesting science case - well known targets - well known resonance at low E	Data taking concluded
$^{22}Ne(\alpha,n)^{25}Mg$	erc — SHADES Scintillator-He3 Array for Deep-underground Experiments on the S-process	Data taking ongoing
$^{22}Ne(\alpha,\gamma)^{26}Mg$	MUR (Ministero dell'Università e della Ricerca) — EASγ	Preparation ongoing
$^{12}C+^{12}C$	MUR (Ministero dell'Università e della Ricerca) — CaBS Carbon Burning in Stars	Data taking ongoing

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



- Transition to the 6.79 MeV excited state of ^{15}O is the most important contribution to the total cross section
- very difficult to reconcile all the measurements in a consistent picture
- Solar Fusion III: S114(0) = 1.68 ± 0.14 keV b, increased uncertainty since SFII recommendation.
- Chen et al. : Ep = 110 - 260 keV, all transition reported, S114(0) = 1.92 ± 0.08 keV b, Chen et al. (2024)

- Direct measurement over a wide-energy range
  - angular distribution
  - weaker transitions
- Pilot LUNA project at the Bellotti IBF
  - accelerator acceptance tests
  - energy calibration

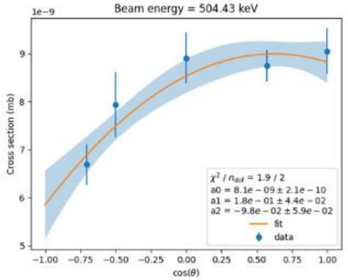


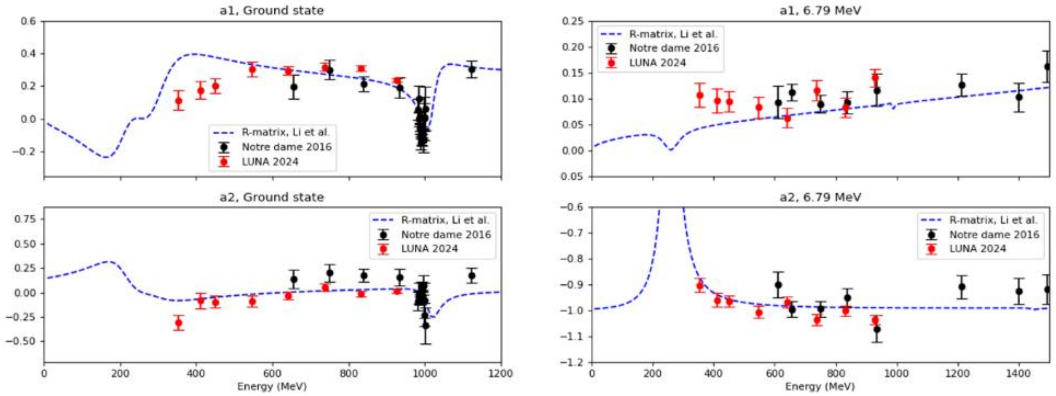
$^{14}N(p,\gamma)^{15}O$

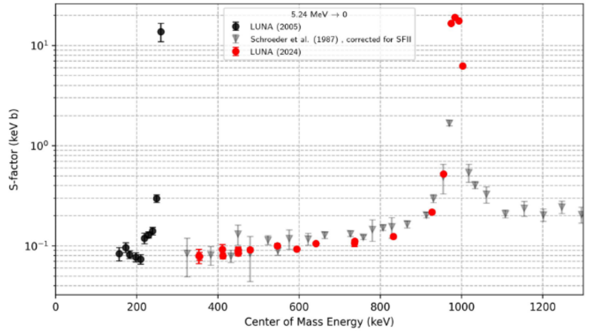
- Cross section measured in the energy range 0.25 - 1.3 MeV
- Angular distributions measured for the two most important transition R/DC→ 6.79 MeV and G.S. down to 400 keV
- We measured most of the weaker transitions, many of them not observed by previous authors
- Multi-channel R-matrix analysis started.

$$W(\theta) = a_0(1 + \sum_{i=1}^{n} a_i Q_i P_i(\cos\theta))$$

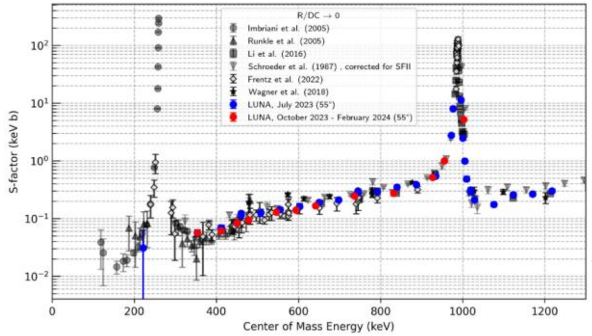
Example fit



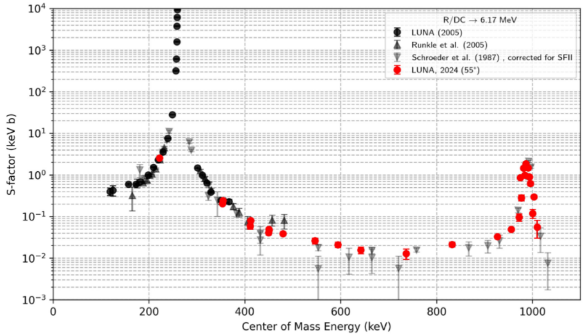




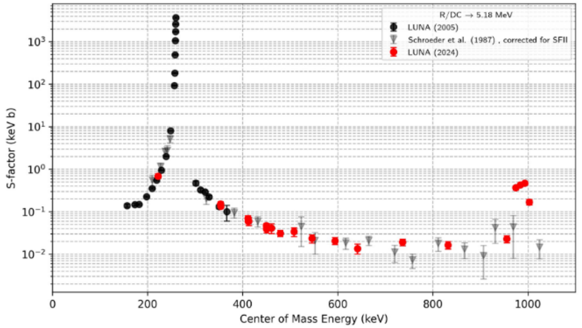
R/DC → GS



R/DC → 6.17 MeV



R/DC → 5.24 MeV



R/DC → 5.18 MeV

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

~ half the elements between Fe and Y (56≲A≲90) are produced via the weak s-process in massive stars ($M > 8M_\odot$)

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

$^{22}Ne(\alpha,n)^{25}Mg$: need for data!

R matrix courtesy of R. J. deBoer, University of Notre Dame/JINA

Cross section is highly uncertain: practically no direct data in Gamow window!

Capabilities on surface labs exhausted (20 years since last direct measurement)

Current lowest rate: 2 reactions/minute

One resonance close to Gamow peak

upper limits spanning ≈ 300 keV

Many states can contribute to the cross section

$^{22}Ne(\alpha,n)^{25}Mg$: experimental setup @ Bellotti IBF

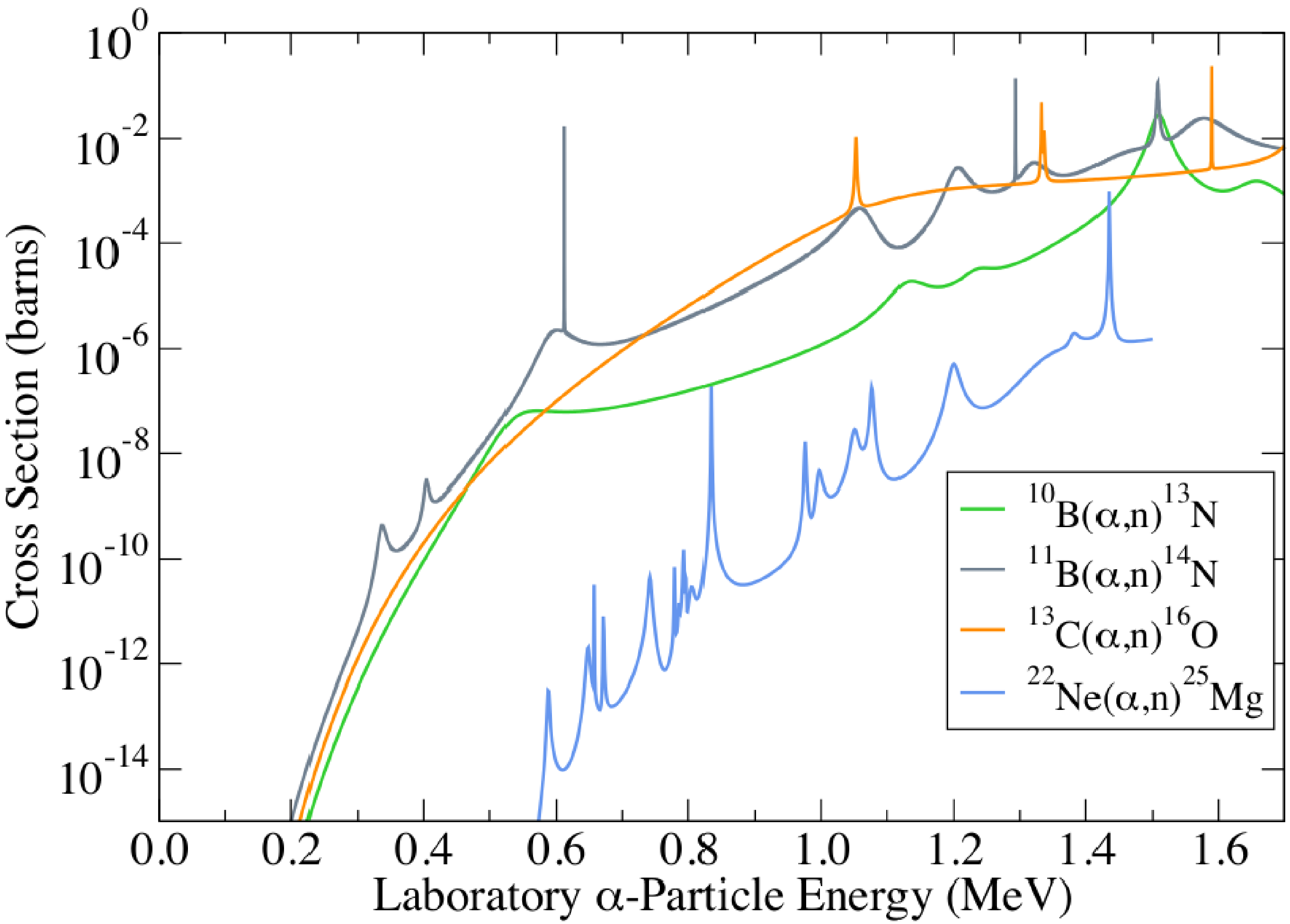
LUNA-MV accelerator
of the new IBF of LNGS

Windowless, differential
pumping gas target with
RBS beam current reading
high purity
high stability

3He + LS neutron detector

- high neutron detection intrinsic efficiency
- large solid angle coverage

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

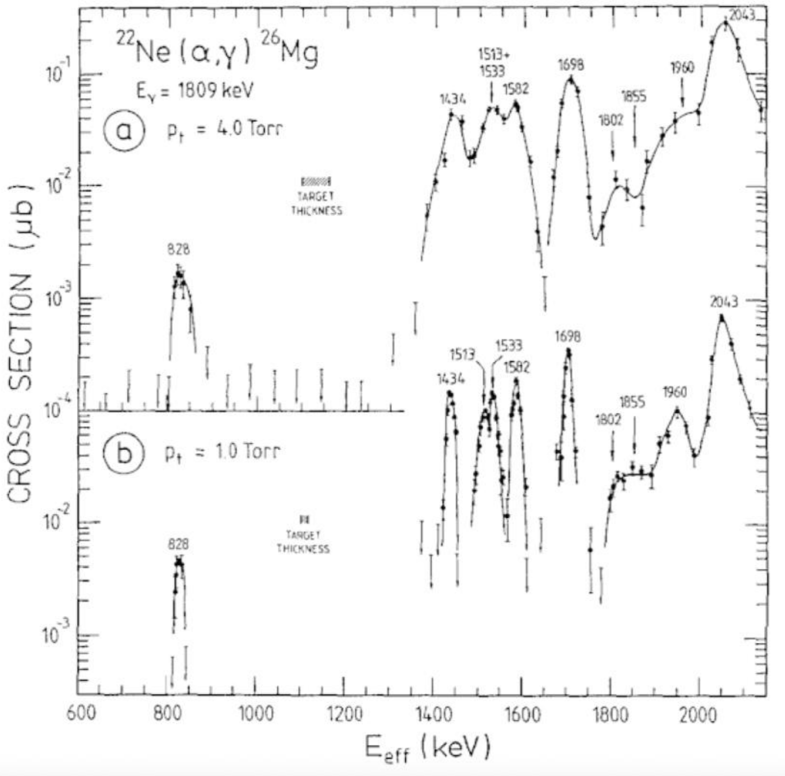


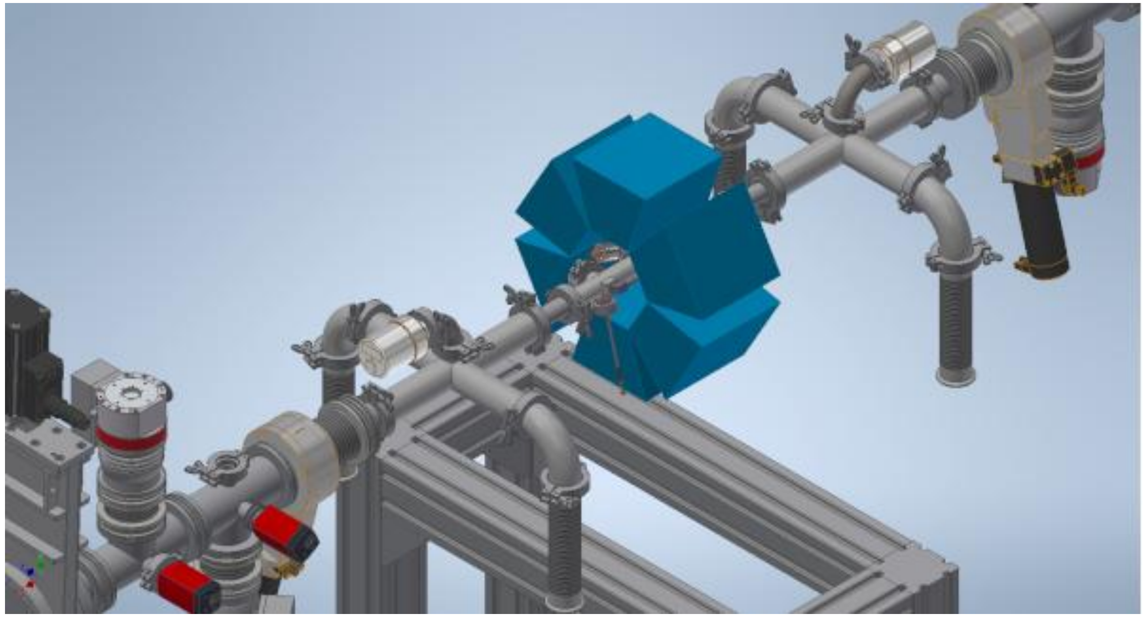
Q-values:

- **$^{22}Ne(\alpha,n)^{25}Mg$** = - 478 keV
- **$^{10}B(\alpha,n)^{13}N$** = 1059 keV
- $^{11}B(\alpha,n)^{14}N$ = 158 keV
- $^{13}C(\alpha,n)^{16}O$ = 2216 keV

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

The $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction, active throughout He-burning due to its positive Q-value, competes with the $^{22}Ne(\alpha,n)^{25}Mg$ neutron source and reduces available ^{22}Ne.

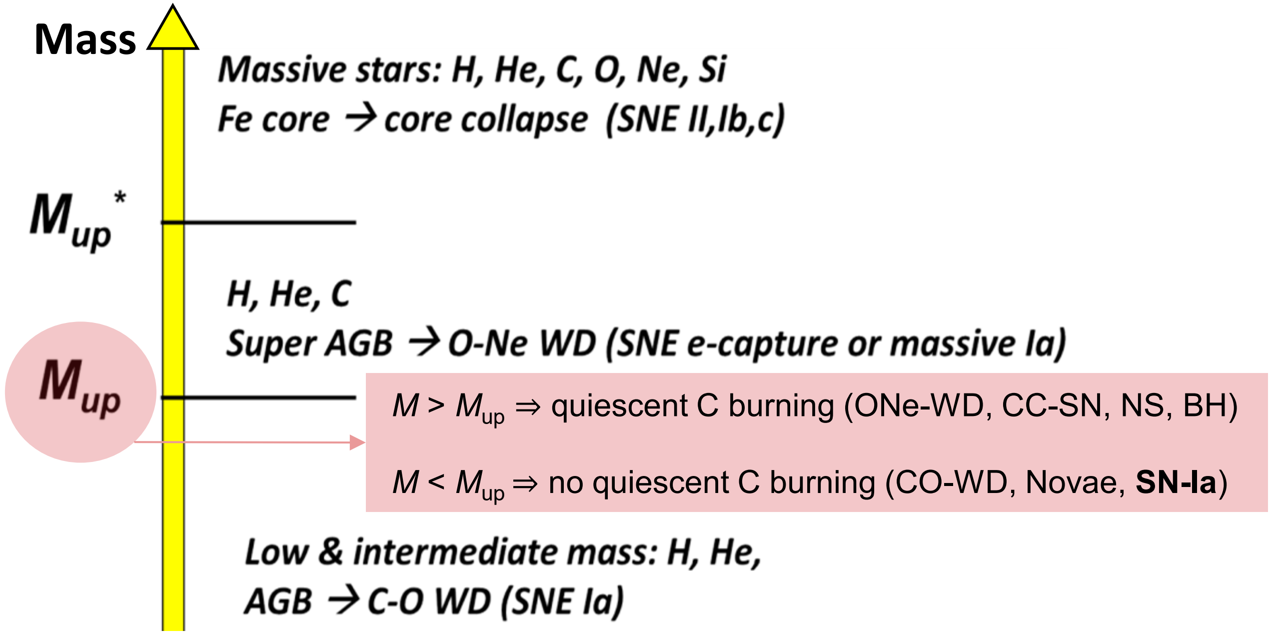


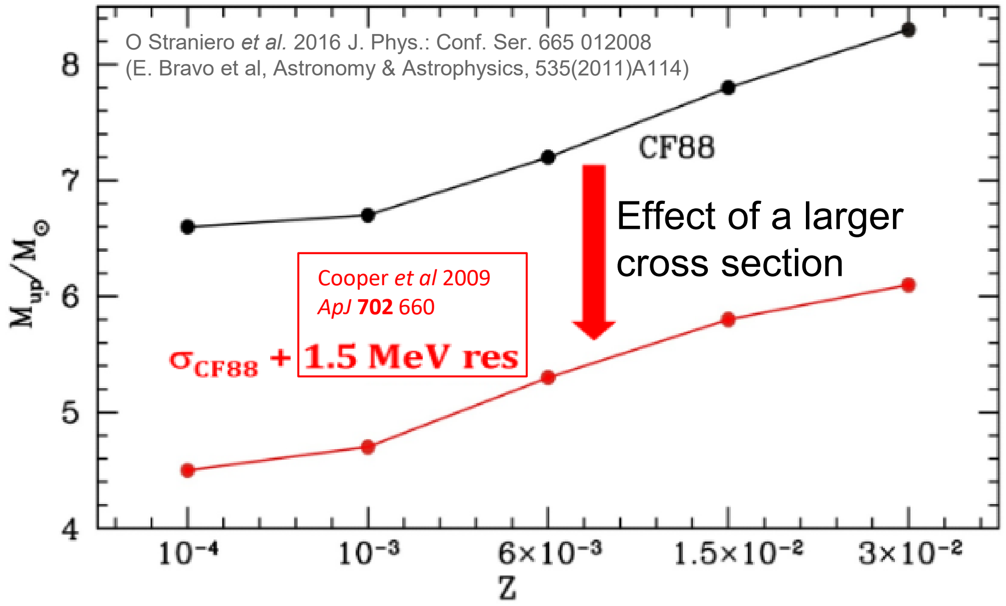


- Gas target very similar to the one used for the measurement of the $^{22}Ne(\alpha,n)^{25}Mg$ reaction
- Array of NaI detectors

$^{12}C+^{12}C$: motivation

- **Quiescent C-burning** in massive stars
- Ignition of **type Ia supernovae**
- **superburst** ignition (triggered by $^{12}C+^{12}C$ fusion)
- **revival of H- and He-burning** (induced by p and α produced because of $^{12}C+^{12}C$)





$^{12}C+^{12}C$: need for data!

Many datasets (often inconsistent)

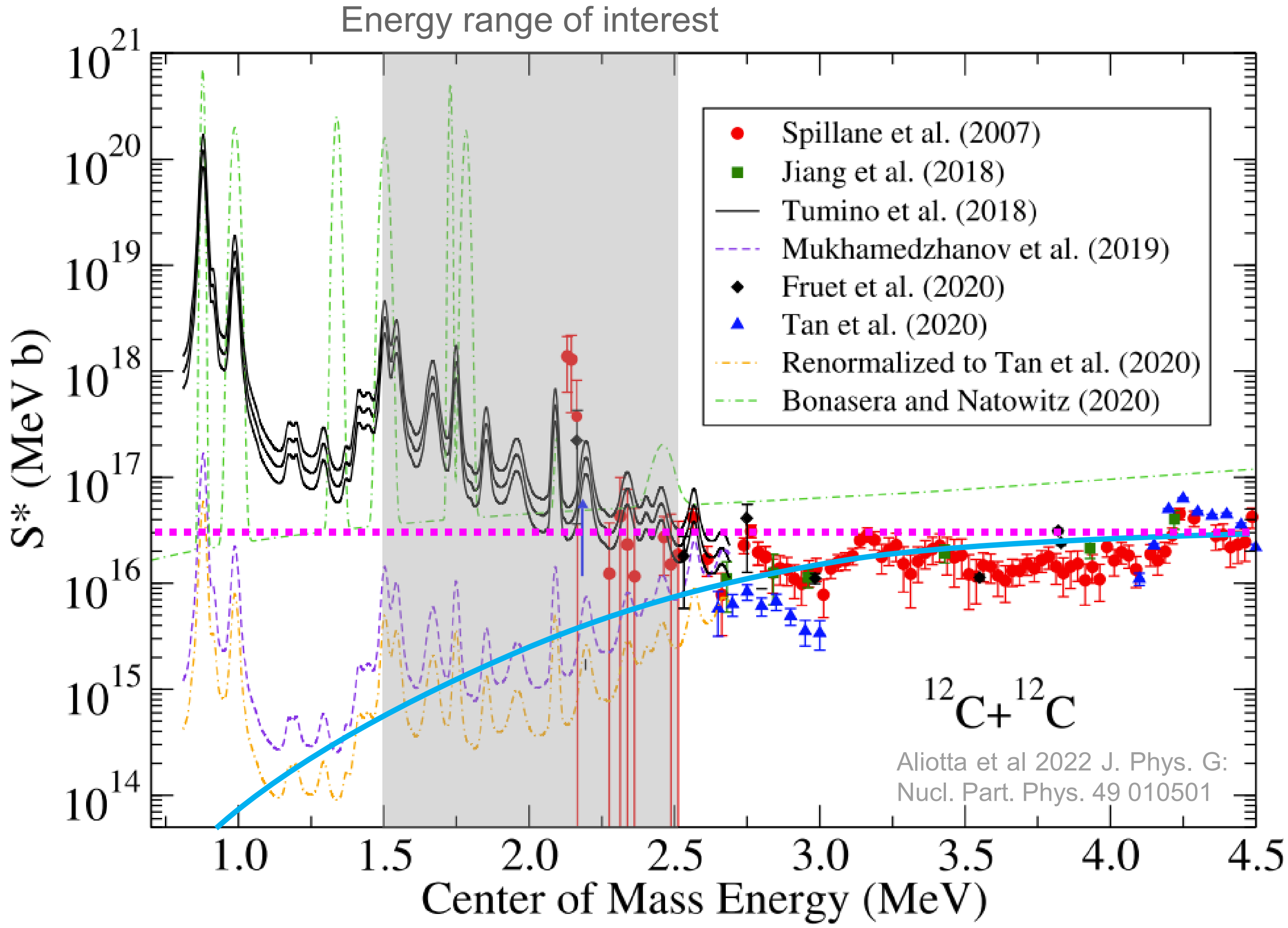
- Direct and indirect measurements
- Particle, photon or particle+photon detection

A few models to interpret the data

- **Tumino** states that Coulomb interactions are negligible and uses PWBA
- **Mukhamedzhanov** states that Coulomb interactions are non-negligible and uses DWBA
- **Bonasera and Natowitz** extended the Neck Model to sub barrier energies within the Feynman Path Integral Method framework
- **Hindrance** model lower than **CF88** at low *E*

Different normalizations

- **Mukhamedzhanov** (renormalized to Tan)



$^{12}C+^{12}C$: experimental method

To measure the cross section it is possible to count emitted charged particles (not the topic of this presentation)

but

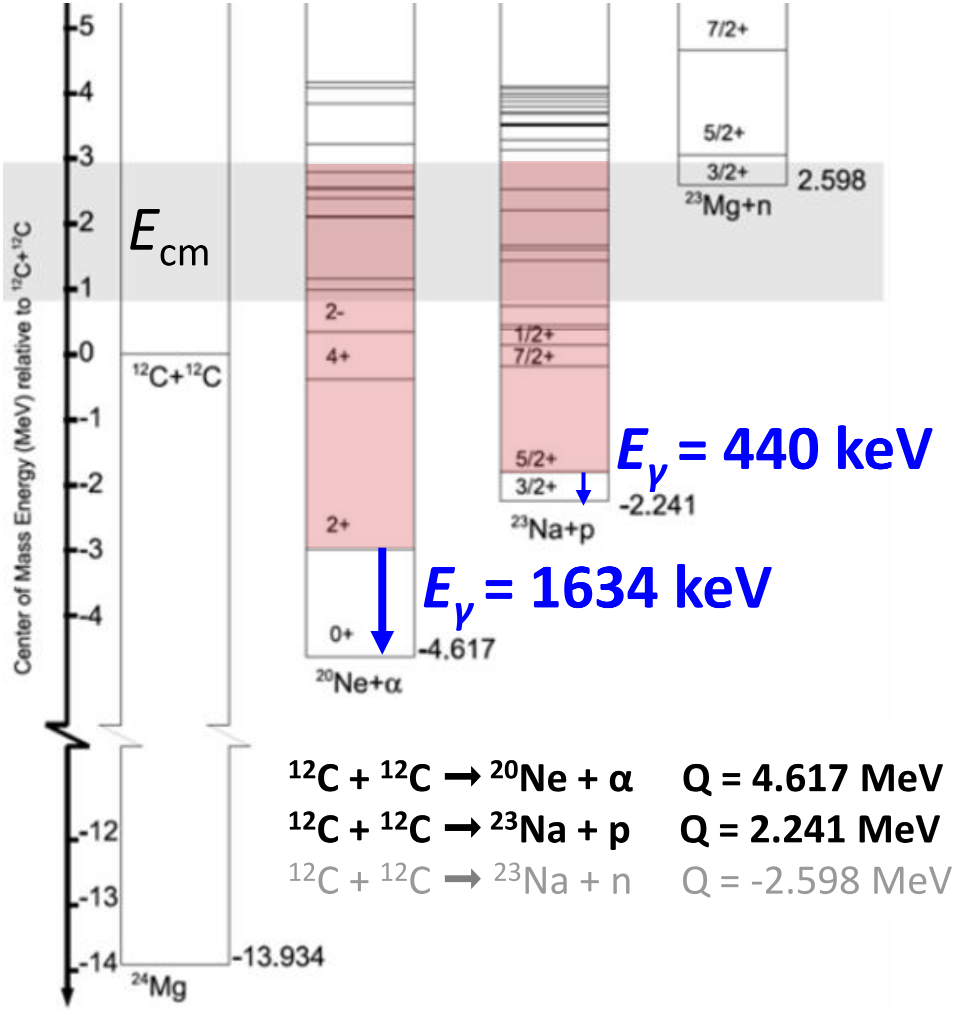
~½ of the reactions leave the final nucleus in an excited state

so

it is possible to count photons emitted (isotropically) in the **de-excitation of the final nucleus**

very often involves the **transition from the 1st excited state to the GS**

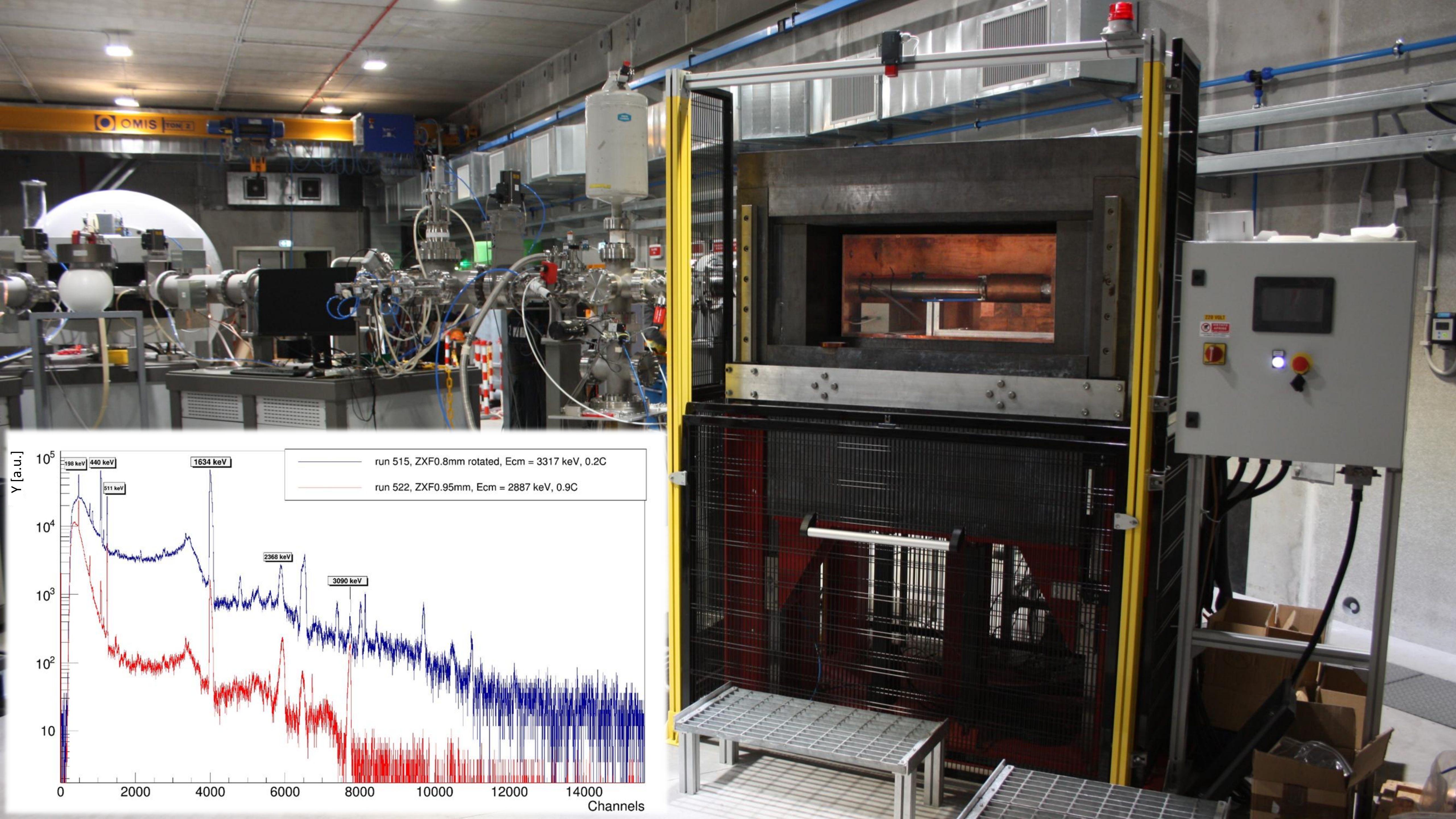
We are able to detect other transitions too



$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ 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


OMIS
TON 2
Y [a.u.]
10^5
10^4
10^3
10^2
10
198 keV
440 keV
511 keV
1634 keV
2368 keV
3090 keV
run 515, ZXF0.8mm rotated, Ecm = 3317 keV, 0.2C
run 522, ZXF0.95mm, Ecm = 2887 keV, 0.9C
0
2000
4000
6000
8000
10000
12000
14000
Channels

LUNA – mid-term plan (read “perspectives”)

*dated end of October 2024

Table 1 List of the reactions described in previous sections that can be studied at LNGS, along with the machine required the measurement

Reaction	Machine	Upgrade	Phase
D (p, γ) ^{3}He	3.5 MV	None	C
D (α, γ) ^{6}Li	3.5 MV	None	C
^{3}He(^{4} He, γ)^{7}Be	3.5 MV	Targets	C
^{14}N (p, γ) ^{15}O	400 kV	Detectors	B
^{14}N (p, γ) ^{15}O	3.5 MV	None	A
^{23}Na (p, α) ^{20}Ne	400 kV	Detectors	A
^{27}Al (p, α) ^{24}Mg	400 kV	Detectors	A
^{30}Si (p, γ) ^{31}P	400 kV	Detectors	C
^{19}F (p, $\alpha_{0,1}$) ^{16}O	400 kV	Detectors	B
^{19}F (p, $\alpha_{2,3,4}$) ^{16}O	400 kV	Detectors	B
^{19}F (p, γ) ^{20}Ne	400 kV	Detectors	B
^{6}Li (α, γ) ^{10}B	400 kV	Targets	C
^{7}Li (α, γ) ^{11}B	400 kV	Targets	C
^{10}B (α, d) ^{12}C	400 kV	Detectors	C
^{10}B (α, p) ^{13}C	400 kV	Detectors	C
^{10}B (α, n) ^{13}N	400 kV	Detectors	C
^{11}B (α, n) ^{14}N	400 kV	Detectors	C
^{18}O (α, γ) ^{22}Ne	3.5 MV	Detectors	B
^{17}O (α, γ) ^{21}Ne	3.5 MV	Detectors	B
^{15}N (α, γ) ^{19}F	3.5 MV	Detectors	B
^{14}N (α, γ) ^{18}F	3.5 MV	Detectors	B
^{12}C (α, γ) ^{16}O	3.5 MV	Target and detectors	C
^{22}Ne (α, n) ^{25}Mg	3.5 MV	Gas target	A
^{22}Ne (α, γ) ^{26}Mg	3.5 MV	Gas target	B
^{13}C (α, n) ^{16}O	3.5 MV	None	A
^{12}C + ^{12}C	3.5 MV	Target and detectors	A (gamma)
^{12}C + ^{12}C	3.5 MV	Target and detectors	C (particles)

The necessary upgrades to the experimental setup and time schedule are indicated: phase A corresponds to the next 2–3 years, phase B to 3–5 years, and phase C to 5–7 years

Anticipated because of the possible relocation of the 400 kV accelerator

LUNA – mid-term plan (read “perspectives”)

	Phase A	Phase B	Phase C	
LNGS 400 kV	$^{23}Na(p,\alpha)^{20}Ne$, $^{27}Al(p,\alpha)^{24}Mg$	$^{14}N(p,\gamma)^{15}O$, $^{19}F(p,\alpha)^{16}O$, $^{19}F(p,\gamma)^{16}O$	$^{30}Si(p,\gamma)^{31}P$	H burning
LNGS 400 kV			$^{6}Li(\alpha,\gamma)^{10}B$, $^{7}Li(\alpha,\gamma)^{11}B$, $^{10}B(\alpha,d)^{12}C$, $^{10}B(\alpha,p)^{13}C$, $^{10}B(\alpha,n)^{13}N$, $^{11}B(\alpha,n)^{14}N$	He burning
LNGS 3.5MV			$D(p,\gamma)^{3}He$, $D(\alpha,\gamma)^{6}Li$, $^{3}He(\alpha,\gamma)^{7}Be$	BBN
LNGS 3.5MV	$^{14}N(p,\gamma)^{15}O$			H burning
LNGS 3.5MV		$^{14}N(\alpha,\gamma)^{18}F$, $^{15}N(\alpha,\gamma)^{19}F$, $^{16}O(\alpha,\gamma)^{20}Ne$, $^{17}O(\alpha,\gamma)^{21}Ne$, $^{18}O(\alpha,\gamma)^{22}Ne$	$^{12}C(\alpha,\gamma)^{16}O$	He burning
LNGS 3.5MV	$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$	$^{22}Ne(\alpha,\gamma)^{26}Mg$		neutron sources
LNGS 3.5MV	$^{12}C+^{12}C$ (γ detection)		$^{12}C+^{12}C$ (particle detection)	C burning

Thank you for your attention!

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