Laboratory for Underground Nuclear Astrophysics

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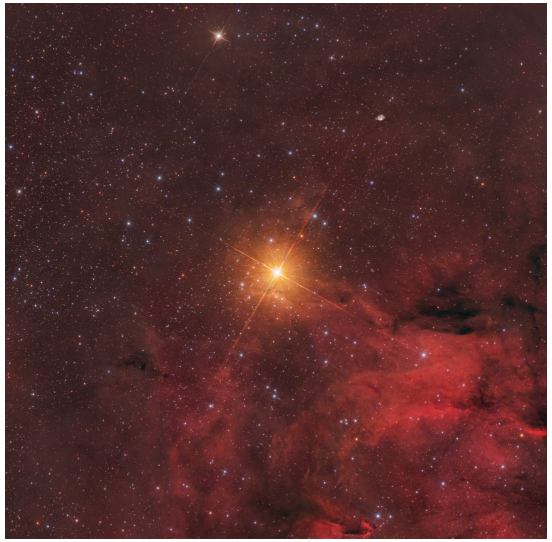
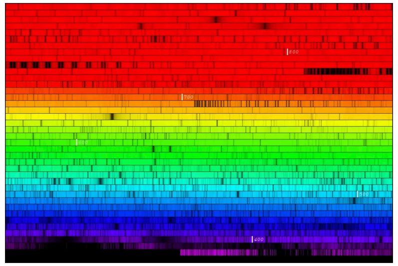
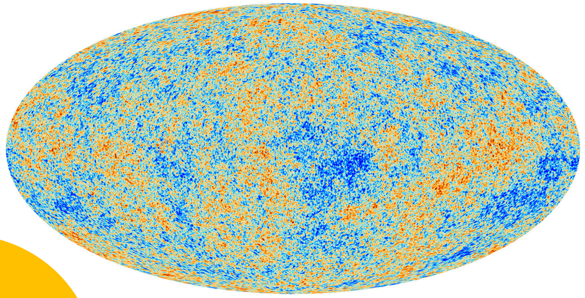


Astronomy

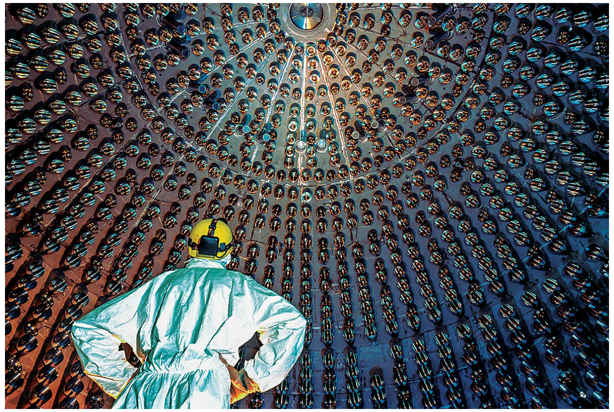




Stellar Models

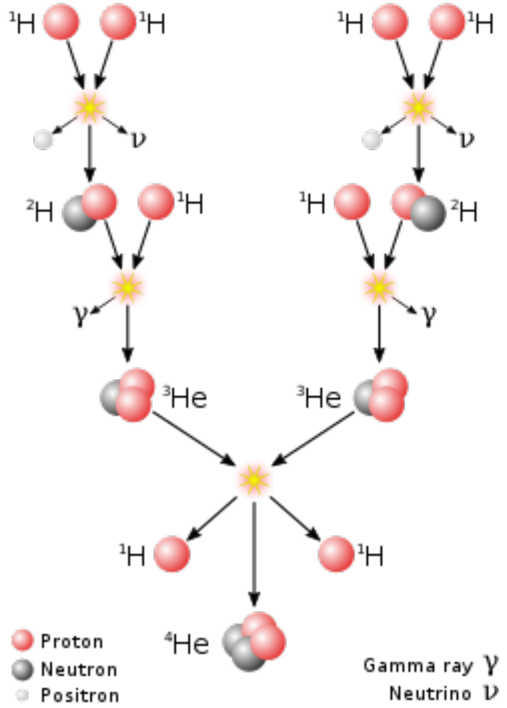
Cosmology

Nuclear Astrophysics



Neutrino Physics

Nuclear Physics



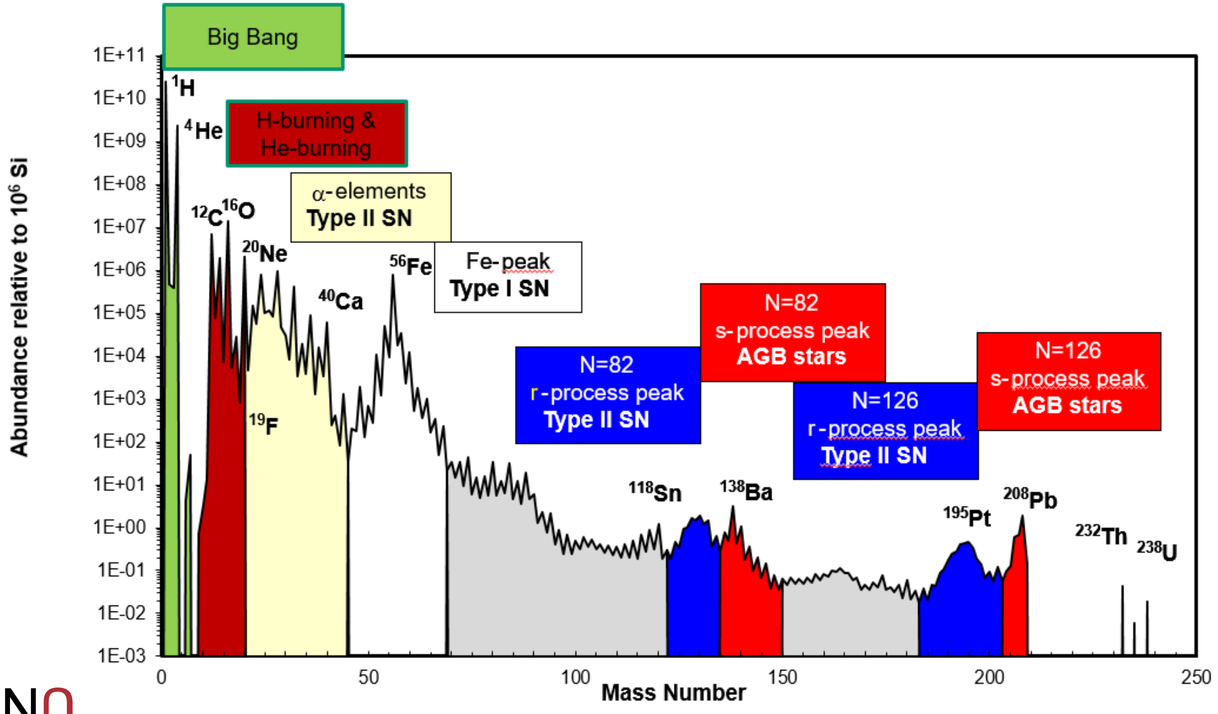
LUNA

Nuclear Astrophysics

Nuclear Astrophysics aims to understand how and where most of the elements are produced with the observed abundances.

Since the B2HF (1957) paper we know stars are responsible for the production of most of the elements in the universe.

Nuclear reactions, taking place during stellar evolution, are responsible for nucleosynthesis:



- Big Bang Nucleosynthesis main output: **H,^{4}He**, D, ^{3}He and ^{7}Li
- Charged particle induced reactions are responsible for the production of isotopes up to ^{56}Fe
- s-process
- r-process
- i-process(?)
- p-process
- Cosmic ray induced reactions output: Li, Be and B

Isotopes heavier than iron

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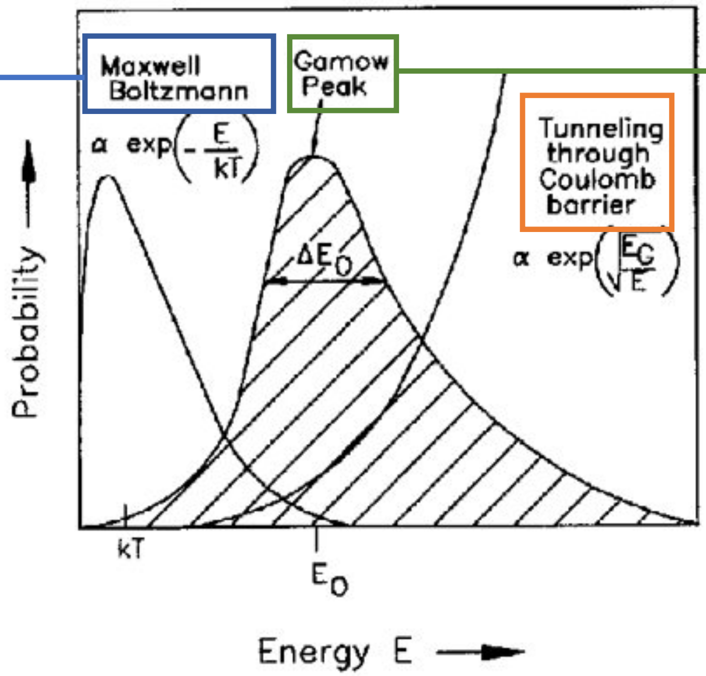
Are we done?

Absolutely not!

- More and more observational data are collected every day, sometimes confirming our understanding, sometimes highlighting a lack in our knowledge

- Precise observational data must be compared with precise predictions, which need very precise inputs, as the reaction **cross section inside the Gamow window**.

Ions energy distribution in stars



Pretty small window at low energies (depending on the scenarios few keV up to few MeV) at which charge particle induced reactions take place

cross section is small as pico- or femto-barn (1 barn = 10^{-24} cm^2)

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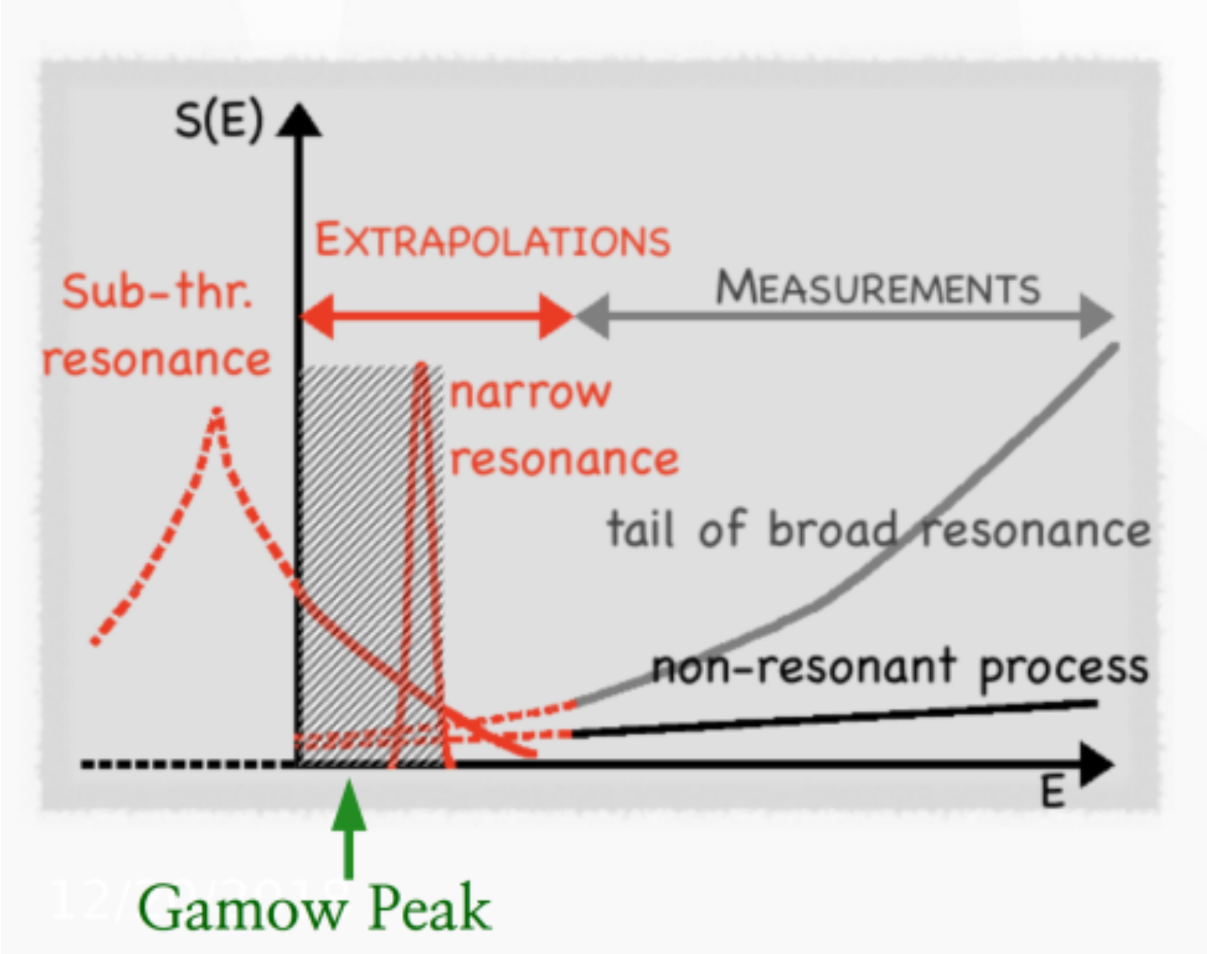
Are we done?

- Given the low energy at play and thus **very low cross section, exponential decrease with energy,** either indirect or **direct measurement of a reaction rate are really hampered**

- For many reactions we have to rely on **extrapolation** of high energy data down to Gamow energies and below



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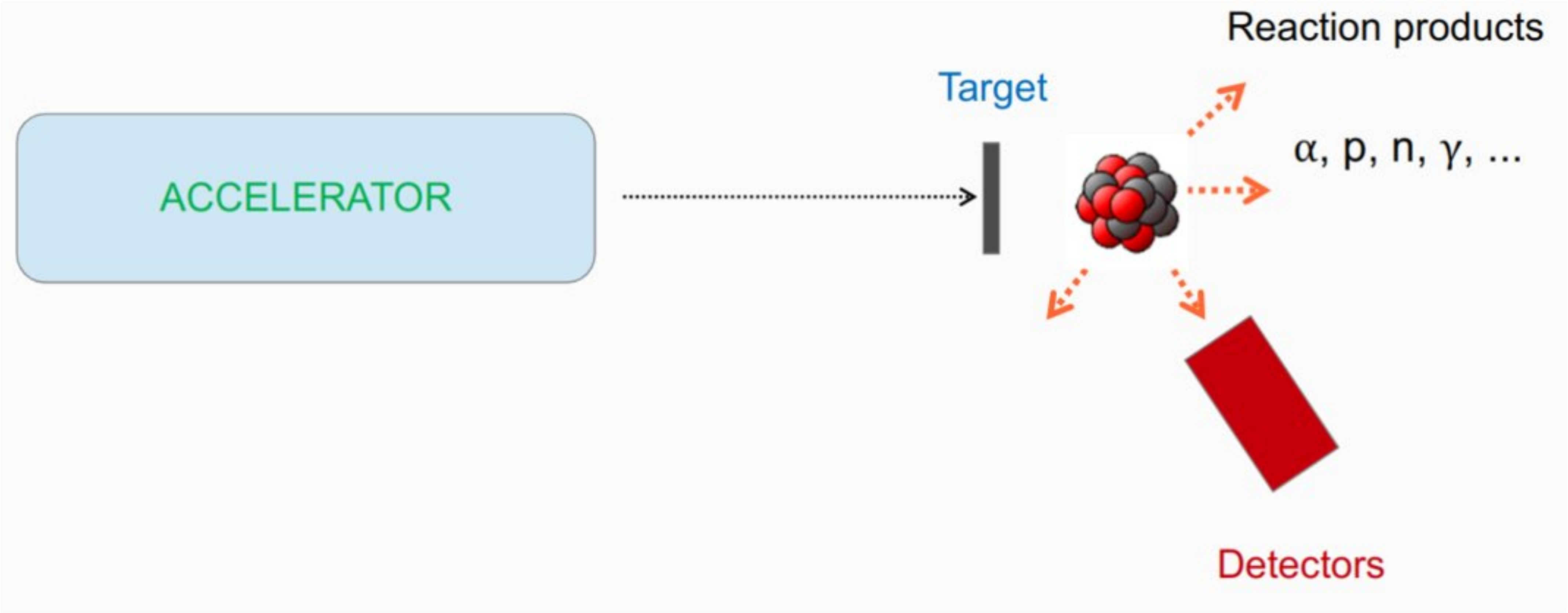
The hard life of the experimentalists



Observed Count Rate = N_b x N_t x σ(E) x efficiency(E)

The hard life of the experimentalists

Observed count rate = N_b **x** N_t **x** σ**(E) x efficiency(E)**

10^{12} pps (with typical beam current ~ μA q= 1+)

10^{18} atoms/cm^2 (solid target)

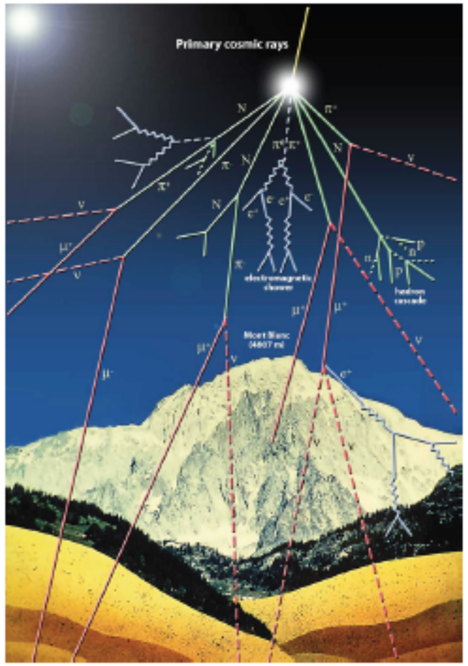
~ 10^{-12} barn (~ 10^{-36} cm^2) at energies of interest

from ≤ 1% up to 10% in case of HPGe detector(s)
up to ~60% with scintillators

= Observed Count Rate = 1-10 counts/day

Note:
Please consider the background: environmental radioactivity and cosmic ray induced background

= **S/N** ≤ 1



LUNA

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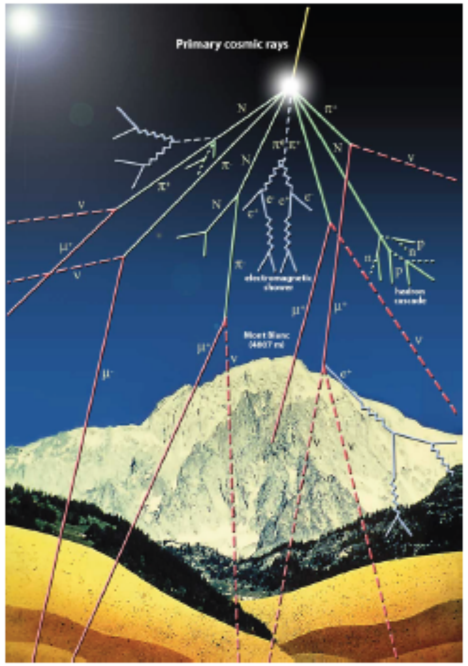

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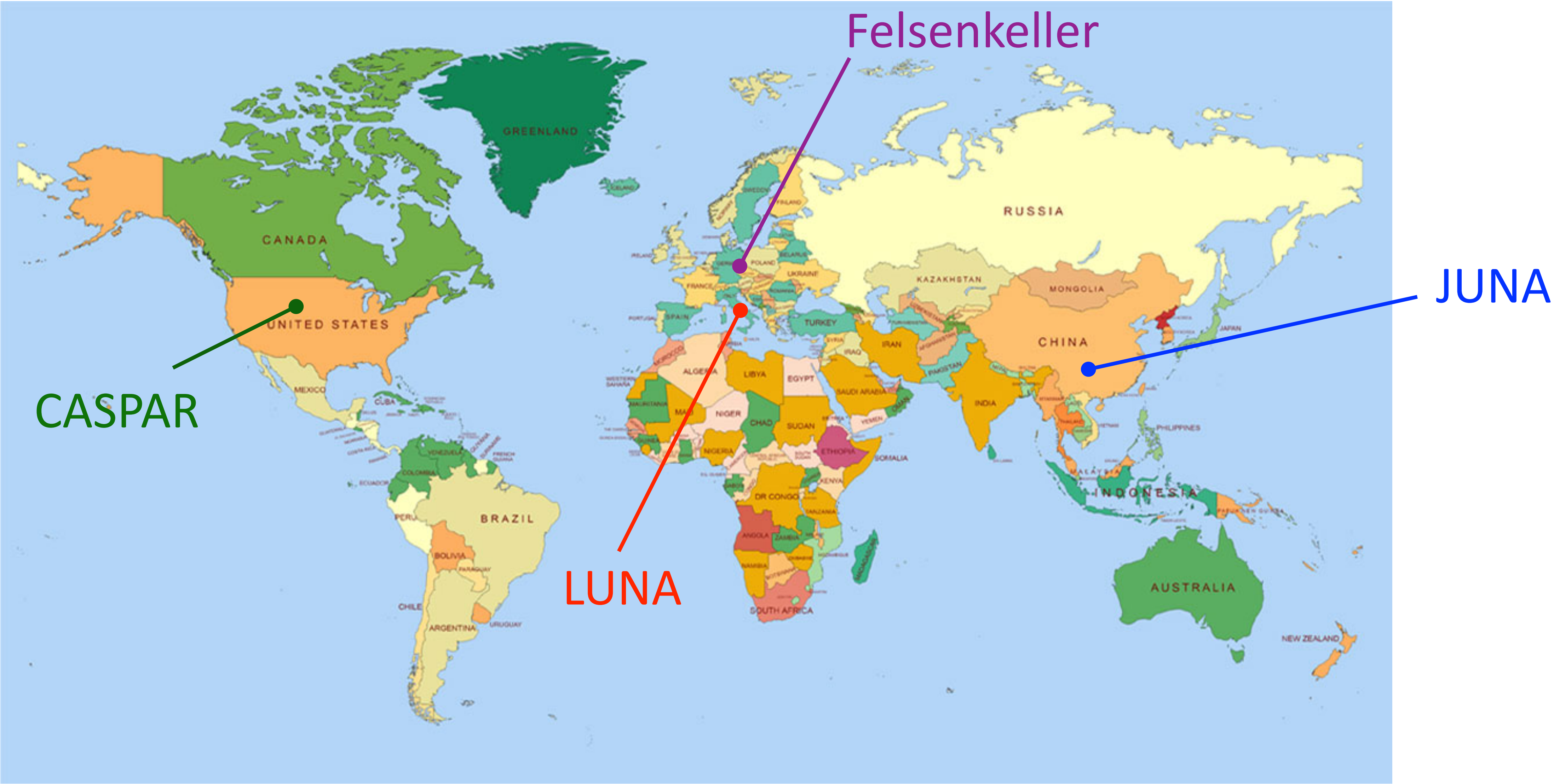
LUNA

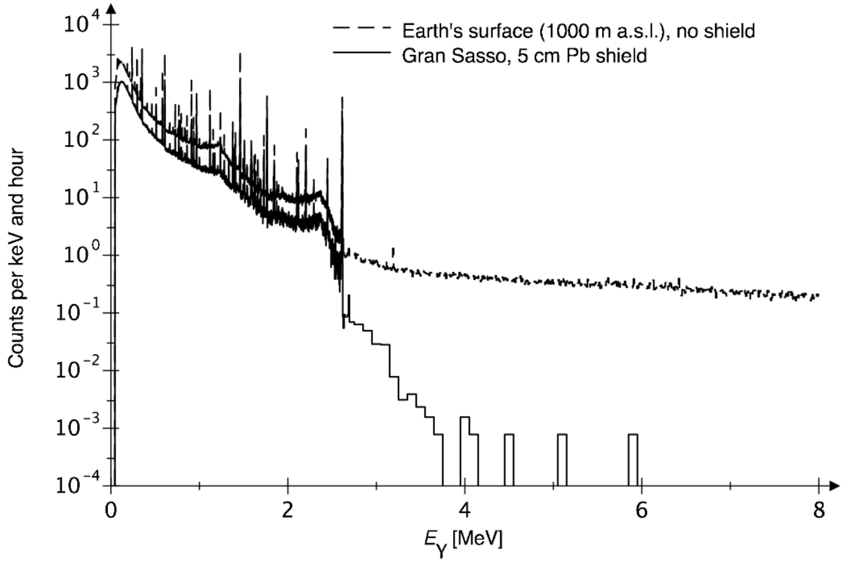
Let's go underground



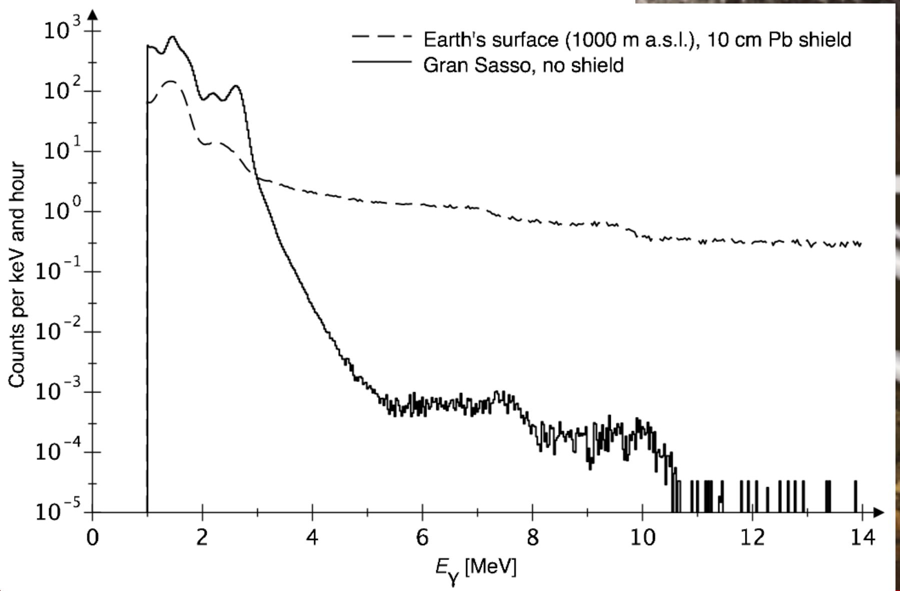
Let's go underground

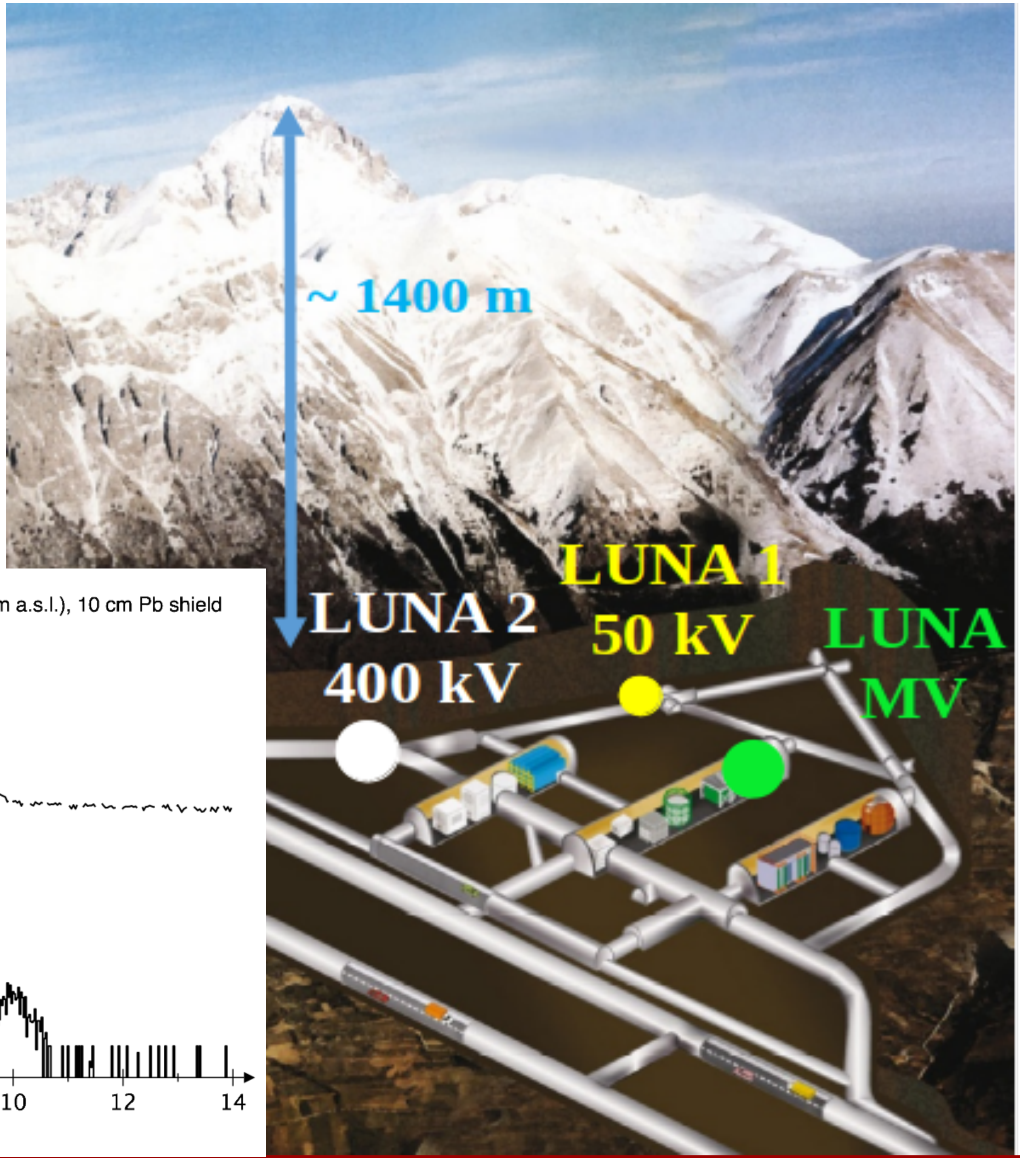
- LUNA is located at Laboratori Nazionali del Gran Sasso, Italy
- Shielded by 1400 m of rock (4000 m w.e.)
- Cosmic-ray induced background reduction:
  - Muon 10^{-6}
  - Neutron 10^{-3}

  -> γ-spectrum



Bemmerer D., EPJA 34,313 (2005)





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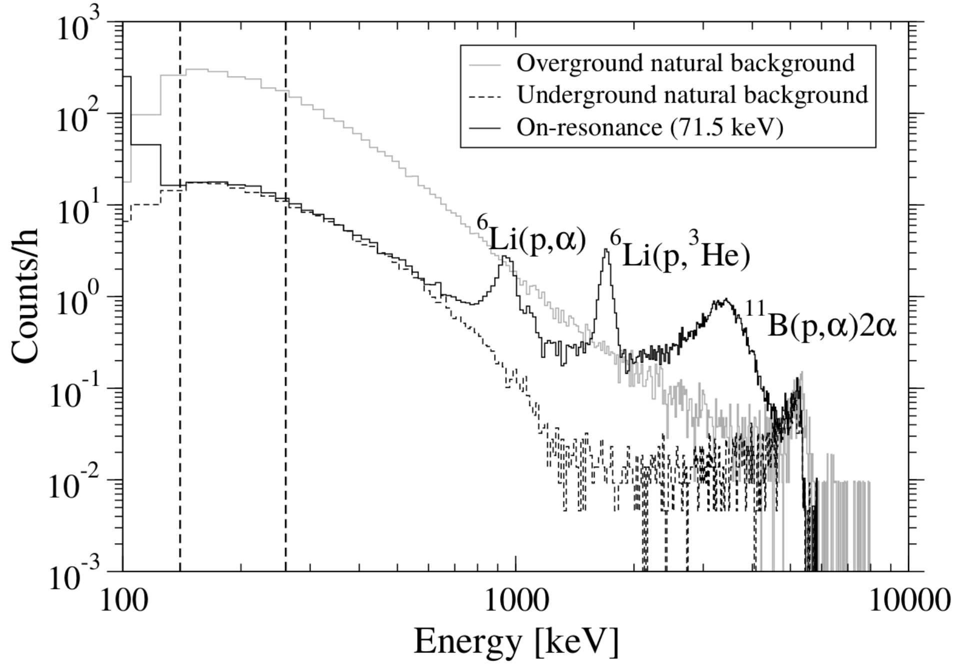
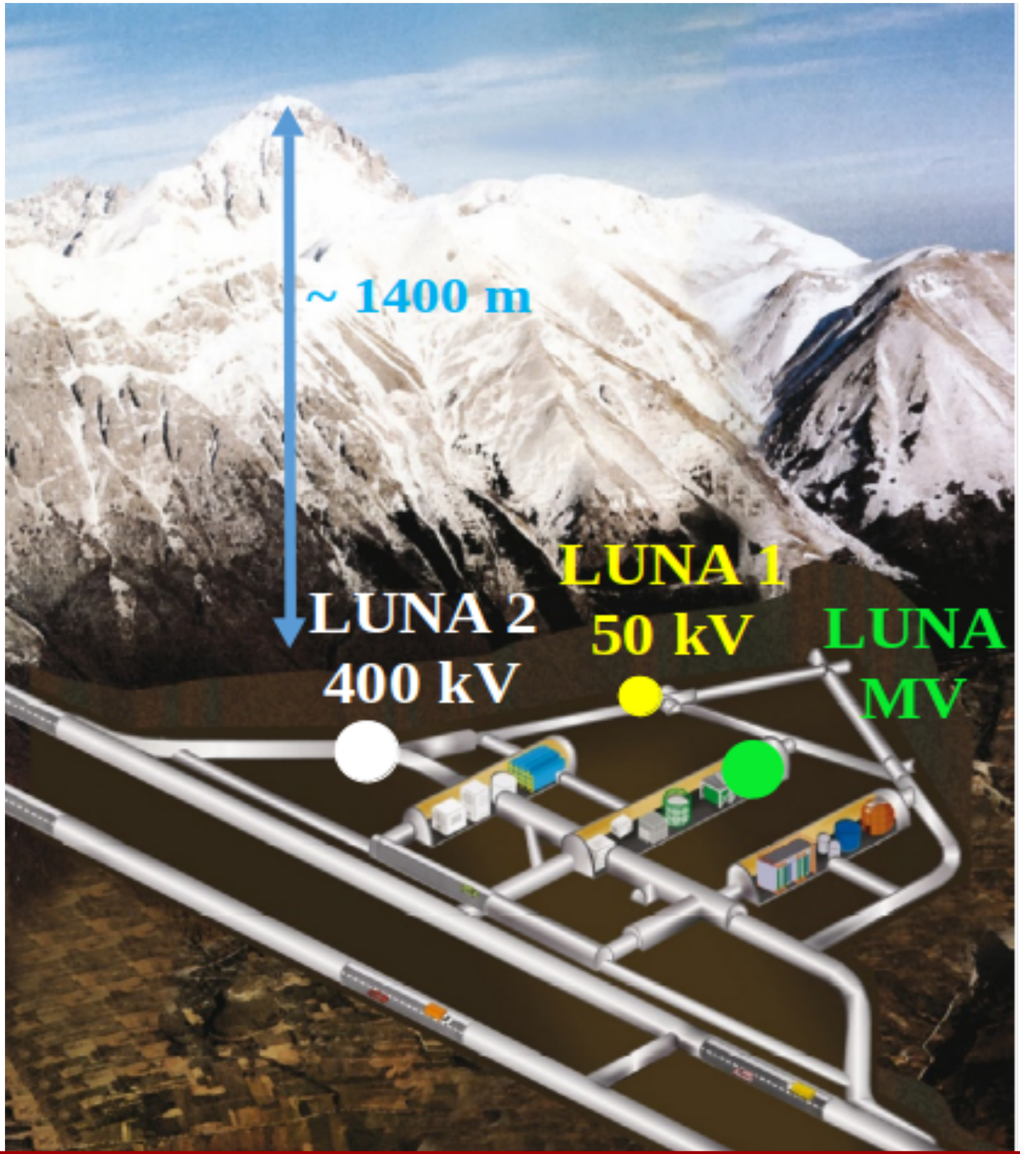
  - by factor 15 in particle spectrum

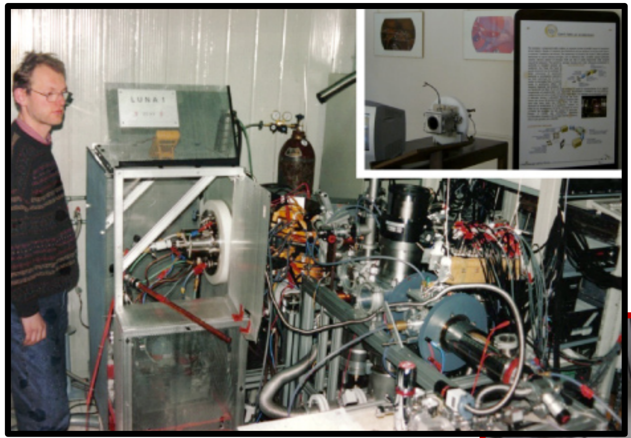


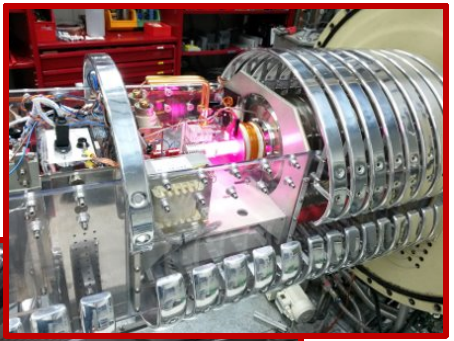
Bruno C., PRL 117, 142502 (2016)

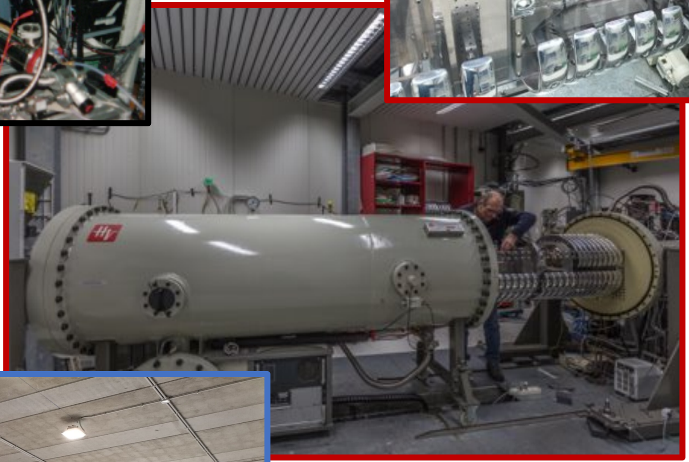


LUNAs

- 30 years long story -> 3 accelerators:
  - LUNA50kV(1991-2001)
    - Homemade machine [Greife U., NIMP A 350, 327 (1994)]
    - Intense H^+ and He^+ beam
  - LUNA400kV (2001-…)
    - HVEE machine
    - 1mA H^+ and 0.5mA He^+
    - High quality performance [A. Formicola et al., NIMP A 507, 609 (2003)]
    - 2 beamlines: gas target and solid target
  - 3.5 MV accelerator at the Bellotti Ion Beam facility (2023-…)
    - HVEE machine [A. Sen et al. NIMP B 450 (2019)]
    - 1mA H^+, 0.5mA He^+, 0.15 mA $^{12}C^+$, 0.08 mA $^{12}C^{++}$
    - Calibration and performance under study now
    - 2 beamlines







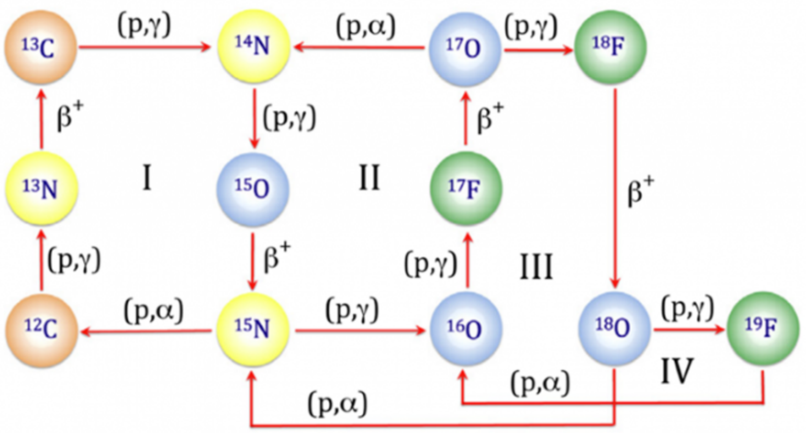
LUNA

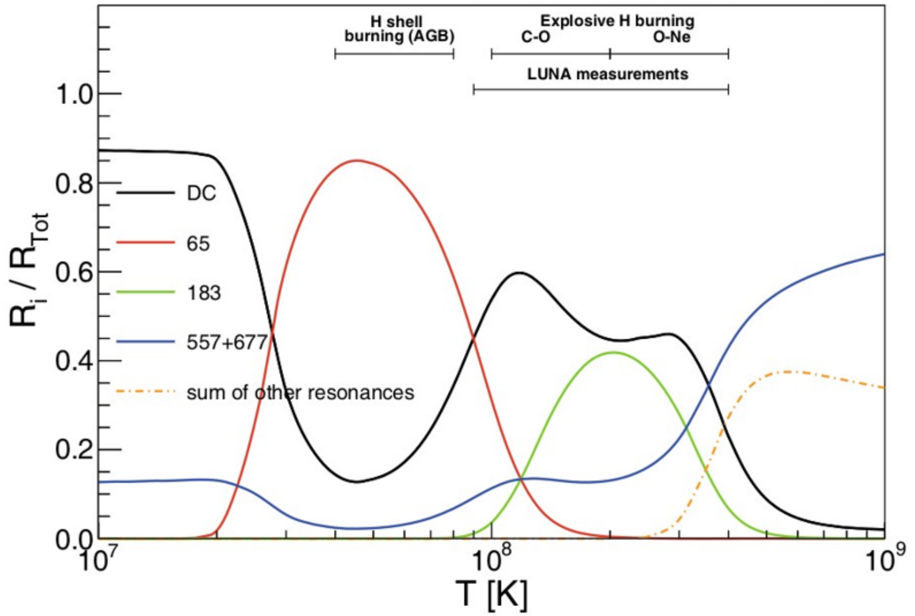
To make a long story short

Reaction	Accelerator	Astrophysical Motivation/Scenario
$D(\alpha,\gamma)^{6}Li$; $^{3}He(\alpha,\gamma)^{7}Be$; $D(p,\gamma)^{3}He$	LUNA400kV	Big Bang Nucleosynthesis (BBN), Lithium problem(s)
$^{3}He+^{3}He$; $D(p,\gamma)^{3}He$	LUNA50kV	pp-chain and Solar neutrinos
$^{6}Li(p,\gamma)^{7}Be$	LUNA400kV	Stars, cosmic-ray spallation and BBN; Resonance NOT confirmed
$^{12,13}C(p,\gamma)^{13,14}N$	LUNA400kV	CNO cycle kick off reactions; only few, poorly constrained data
$^{14,15}N(p,\gamma)^{15,16}O$	LUNA400kV	CNO cycle bottleneck;
$^{17,18}O(p,\alpha)^{14,15}N$	LUNA400kV	CNO cycle; crucial for oxygen isotopic abundance in AGB stars
$^{16,17,18}O(p,\gamma)^{17,18,19}F$	LUNA400kV	CNO cycle and CNO leak
$^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$	LUNA400kV	NeNa cycle; affecting abundances up to P
$^{23}Na(p,\gamma)^{24}Mg$	LUNA400kV	NeNa-MgAl cycle link
$^{25}Mg(p,\gamma)^{26}Al$	LUNA400kV	MgAl cycle; poorly constrained resonances dominate the rate
$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$	LUNA400kV	s-process crucial for isotopes heavier than iron

Measurement of the $^{17}O(p,\gamma)^{18}F$ 65 keV resonance

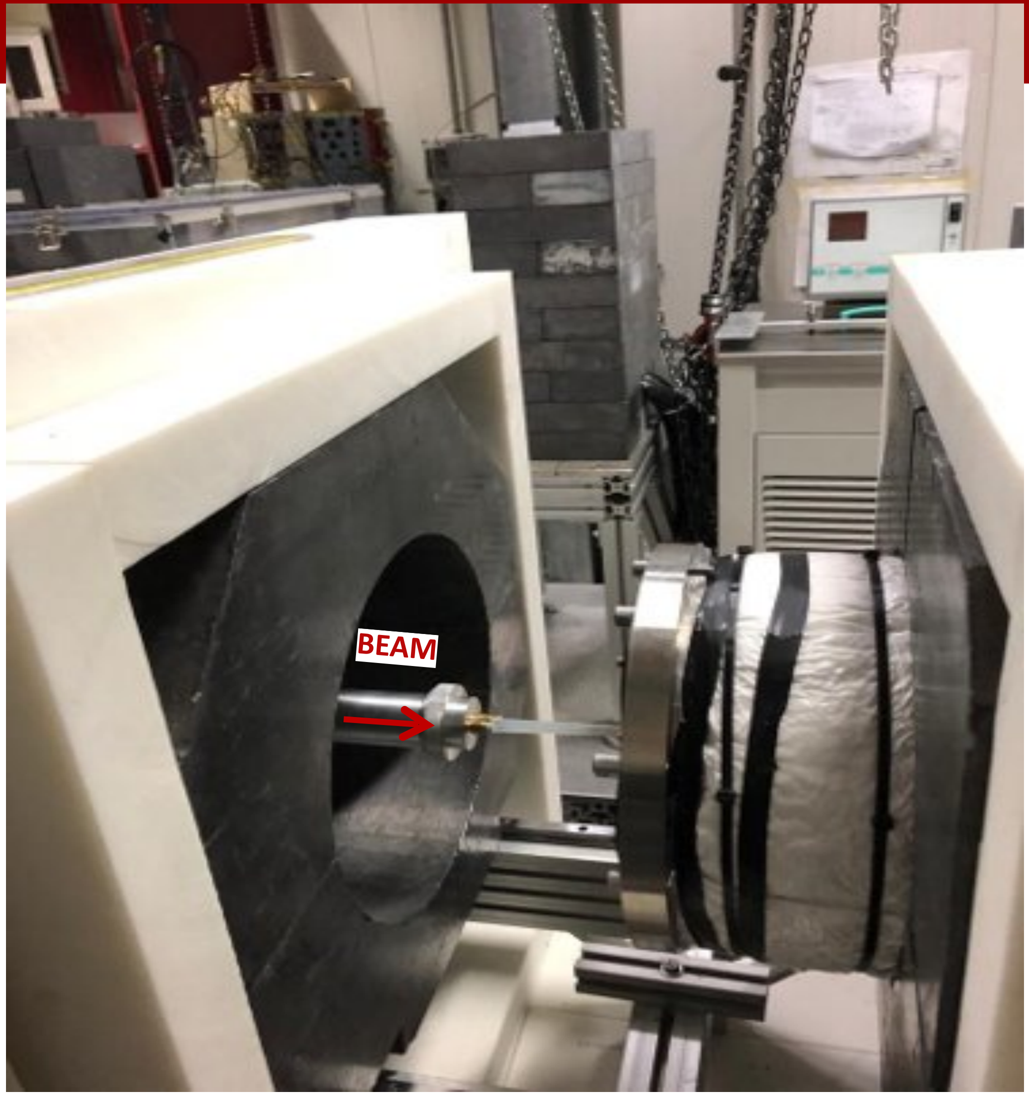
- $^{17}O(p,\gamma)^{18}F$ reaction (Q = 5607 keV) kicks off the CNOIII cycle.
- Impact on the observed oxygen isotopic ratio to trace R/AGB nucleosynthesis and mixing process as well as GCE; and presolar grains origin
- For 30 < T < 100 MK (35 < E_G < 140 keV) the resonance E_{cm}=65 keV (E_x = 5672 keV) dominates the reaction rate
- Only indirect measurement reported in literature: tension between results for Γ_p
- **ωγ = (1.6 ± 0.3) × 10^{-11} eV** [M.Q. Buckner et al. PRC (2015)] : cr_{exp}= 0.08 reactions/h !!!!!





Fractional contributions to the reaction rate of the $^{17}O(p,\gamma)^{18}F$ as a function of the temperature.

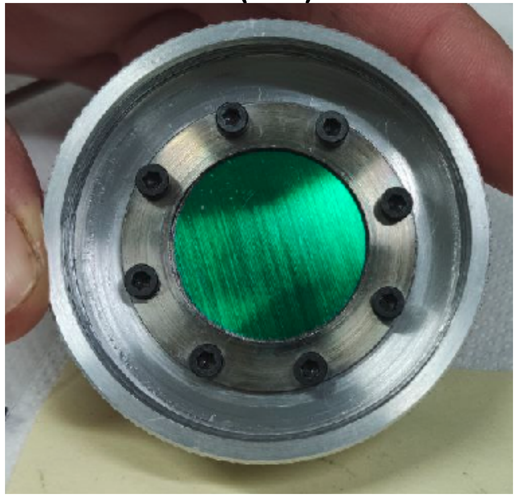
To the limit

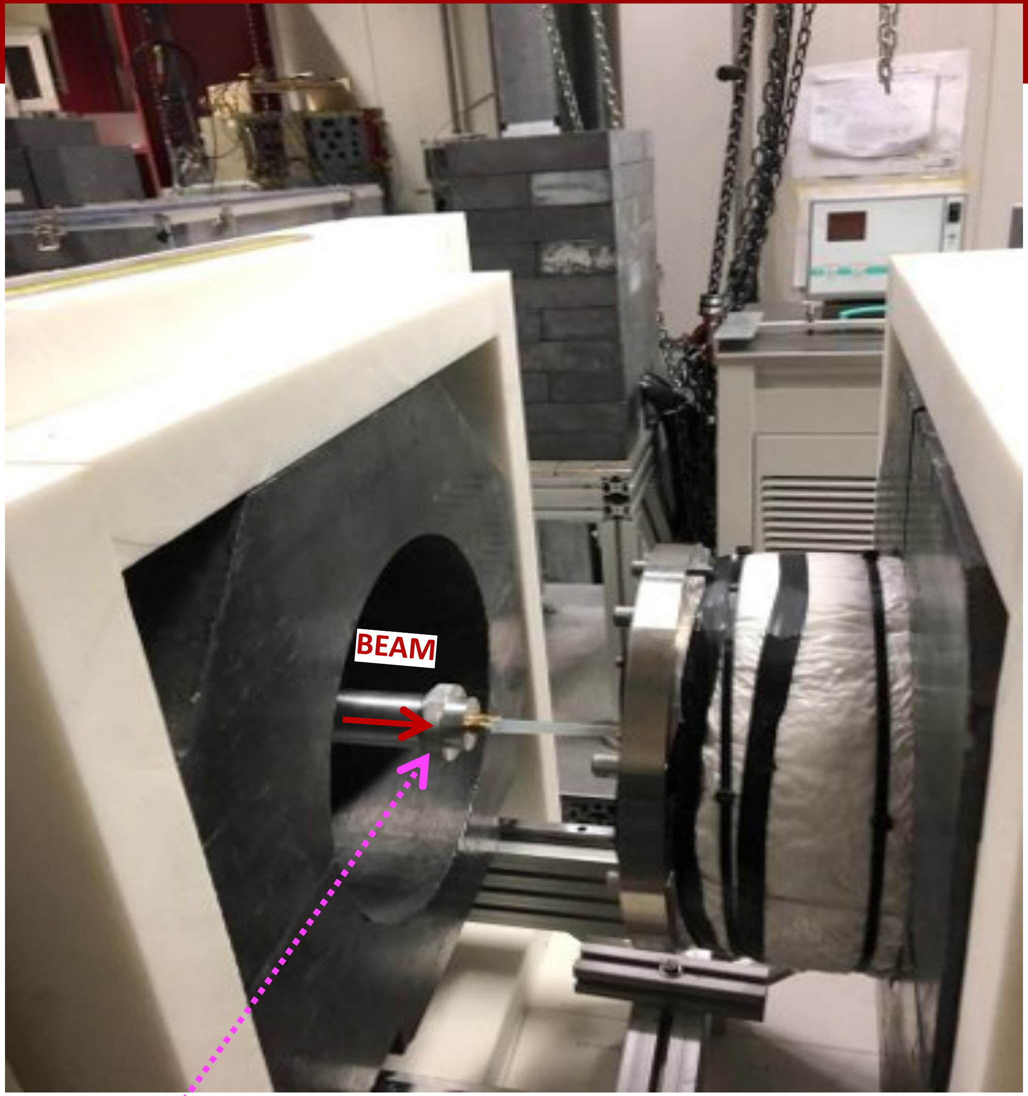


This part can move back and forth

To the limit

Ta_2O_5 target made by anodic oxidation with ^{17}O (90%) enriched water





Al CHAMBER AND TARGET HOLDER

This part can move back and forth

To the limit

4Π BGO DETECTOR
6 independent crystals
TAS mode possible: coincident events in different channels are summed up OFFLINE to produce the addback spectrum

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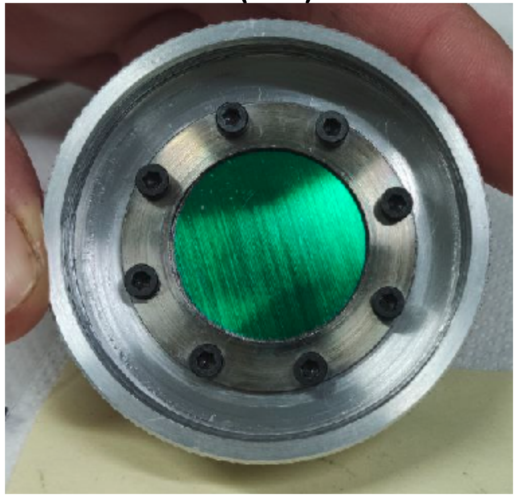

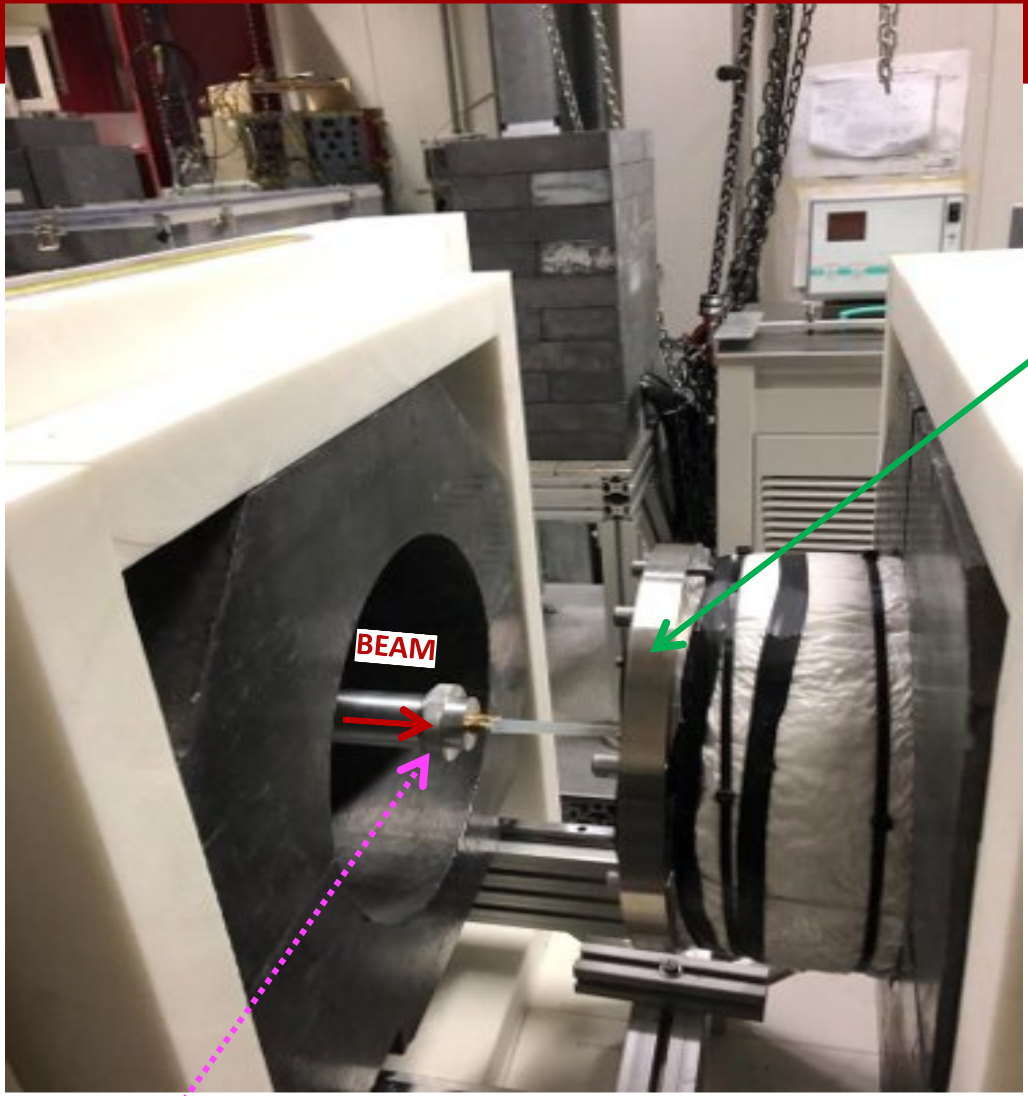

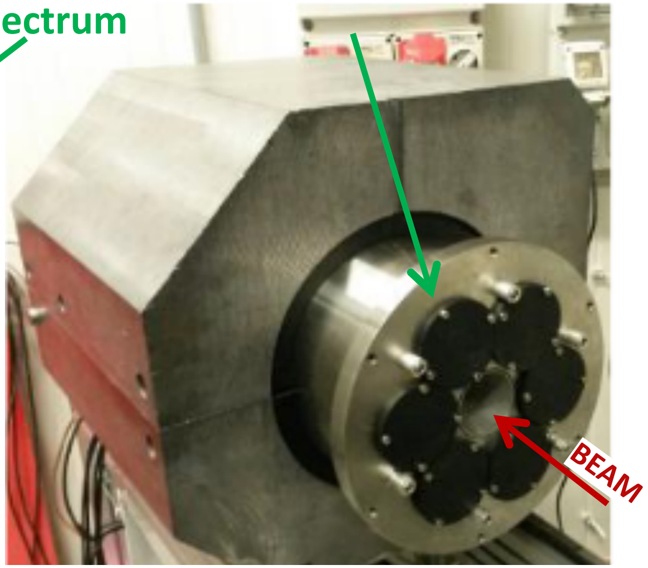

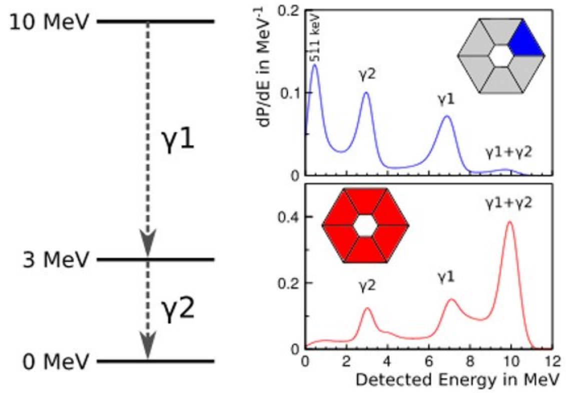

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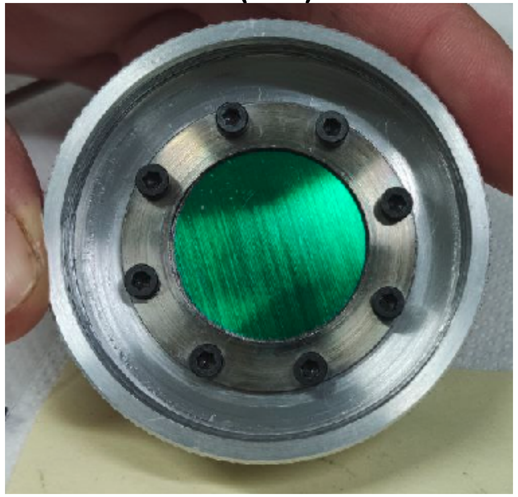

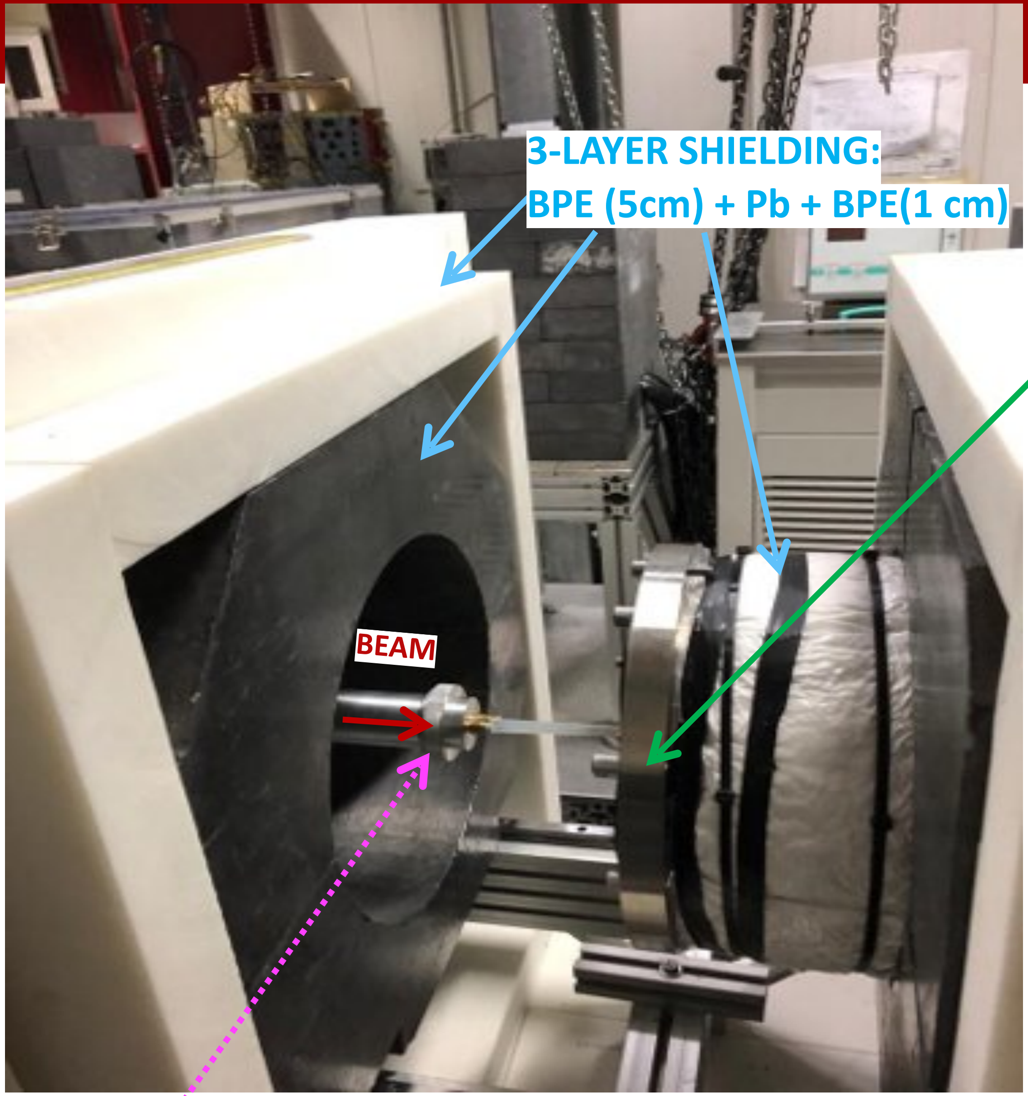

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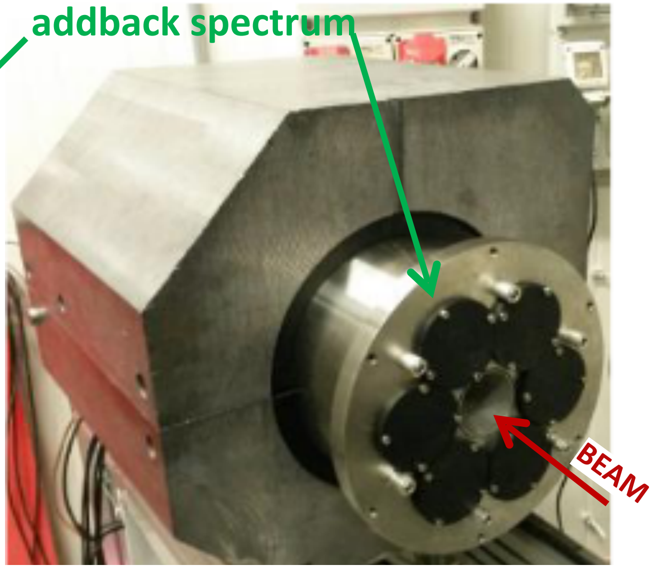
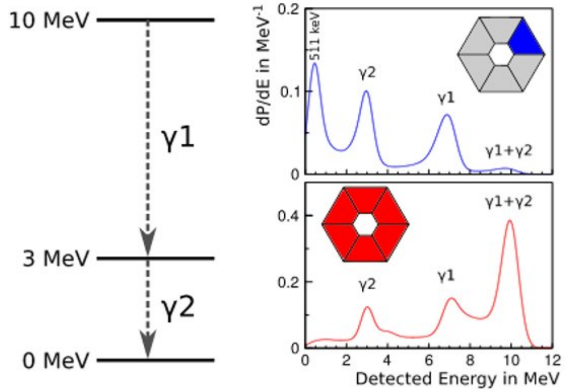
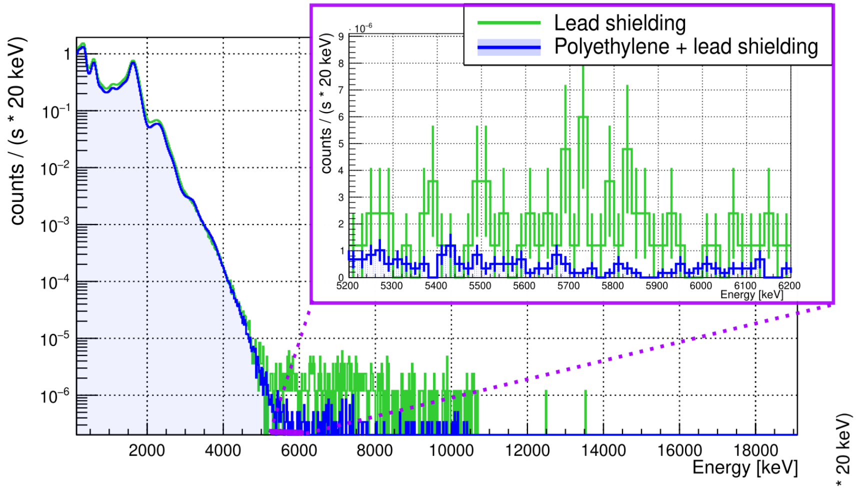
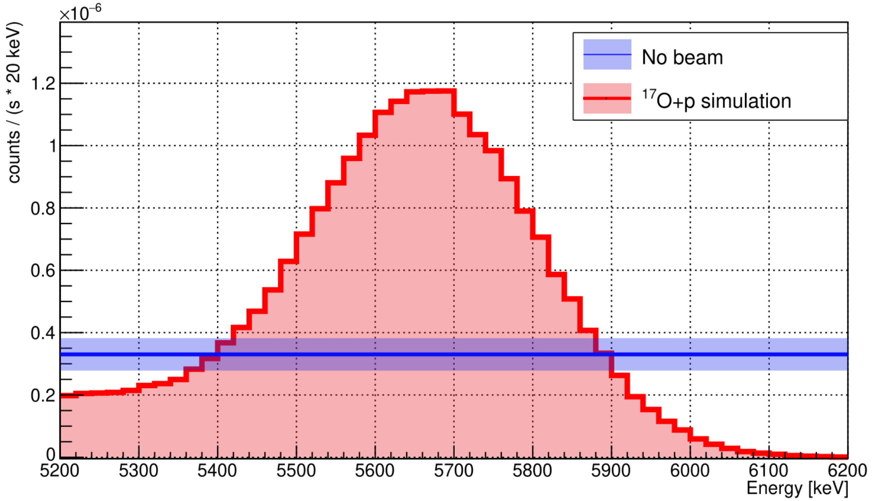


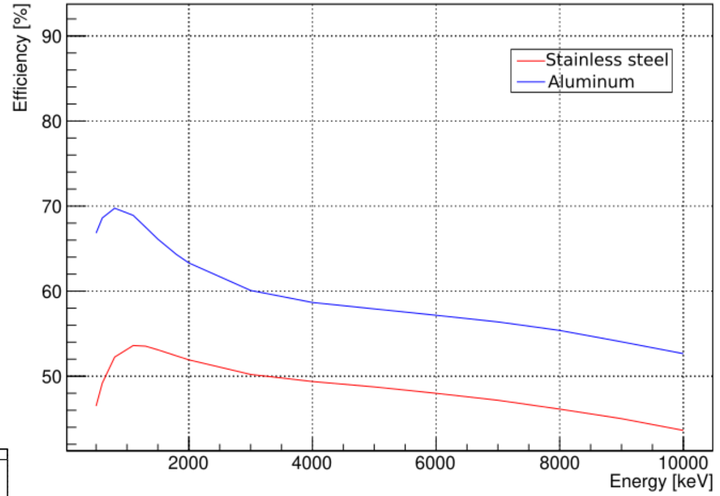


We made it!

- 3 layer shielding: BPE + Pb + BPE -> reduction of the background by a factor ~5
- Al chamber and target holder -> ~20% increase in efficiency w.r.t. previous brass and stainless steel setup







[Skowronski J., J Phys. G 50, 045201 (2023)]

The Beam Induced Background Nightmare

- BIB is due to contaminants in the oxide layer or in the backing that react with the beam
- The scariest contaminants are those that populates the ROI, mimicking the signal of interest, and have much higher cross section than the reaction of interest
- Ta is known for its H and D storage properties
- p+D reaction has a Q = 5493.5 keV (only ~ 100 keV lower than the $^{17}O(p,\gamma)^{18}F$ reaction) and a cross section higher by many orders of magnitudes
- With BGO poor resolution the ROI for $^{17}O(p,\gamma)^{18}F$ reaction is 5200-6200 keV

No way to distinguish/resolve the p+D and the $^{17}O(p,\gamma)^{18}F$ *sum* peak

Never give up and be smart!

Ok looking at the sum peak we cannot tell a difference between our signal and BIB signal but is there any difference?

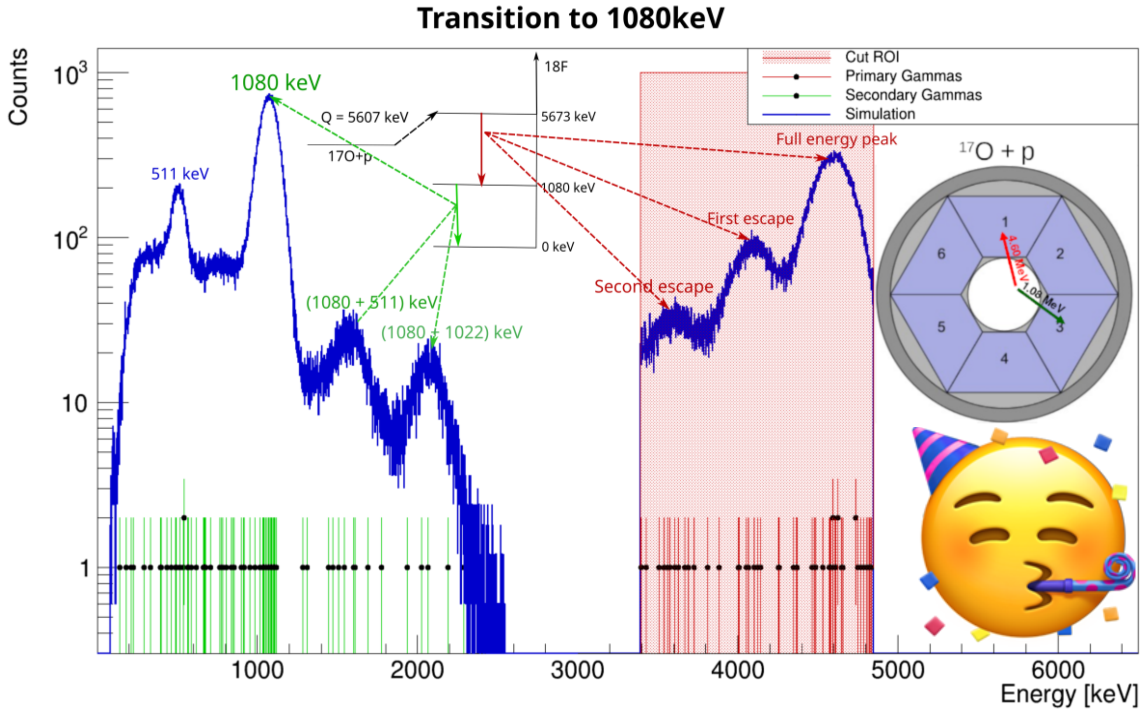
Sure, check NNDC (https://www.nndc.bnl.gov/):

E(level) (keV)	E(γ) (keV)	I(γ)	Final Levels	
5672.57 *32*	2539	28.5 *20*	3133.87	1-
	2611	4.0 *4*	3061.84	2+
	3572	0.4 *2*	2100.61	2-
	3972	0.8 *3*	1700.81	1+
	4592	52 *3*	1080.54	0-
	4631	8.1 *7*	1041.55	0+
	5673	6.2 *4*	0.0	1+

...while the p+D give rise to single γ-rays of Eγ ~ 5560 keV

This is a not trivial difference

- As well as you can construct the sum peak you can also de-construct it
- Gating in the ROI and looking at which γ-rays contributed to the sum peak
- You consider only coincident γ-rays corresponding to the $^{17}O(p,\gamma)^{18}F$ cascade



Coming soon!

Two proposals submitted for:

LUNA400kV

- $^{14}N(p,\gamma)^{15}O$
- $^{23}Na(p,\alpha)^{20}Ne$
- $^{27}Al(p,\alpha)^{24}Mg$
- $^{19}F(p,\alpha_{0,1,2,3,4})^{16}O$
- $^{19}F(p,\gamma)^{20}Ne$
- $^{24}Mg(p,\gamma)^{25}Al$
- …

3.5MV accelerator at BIBF:

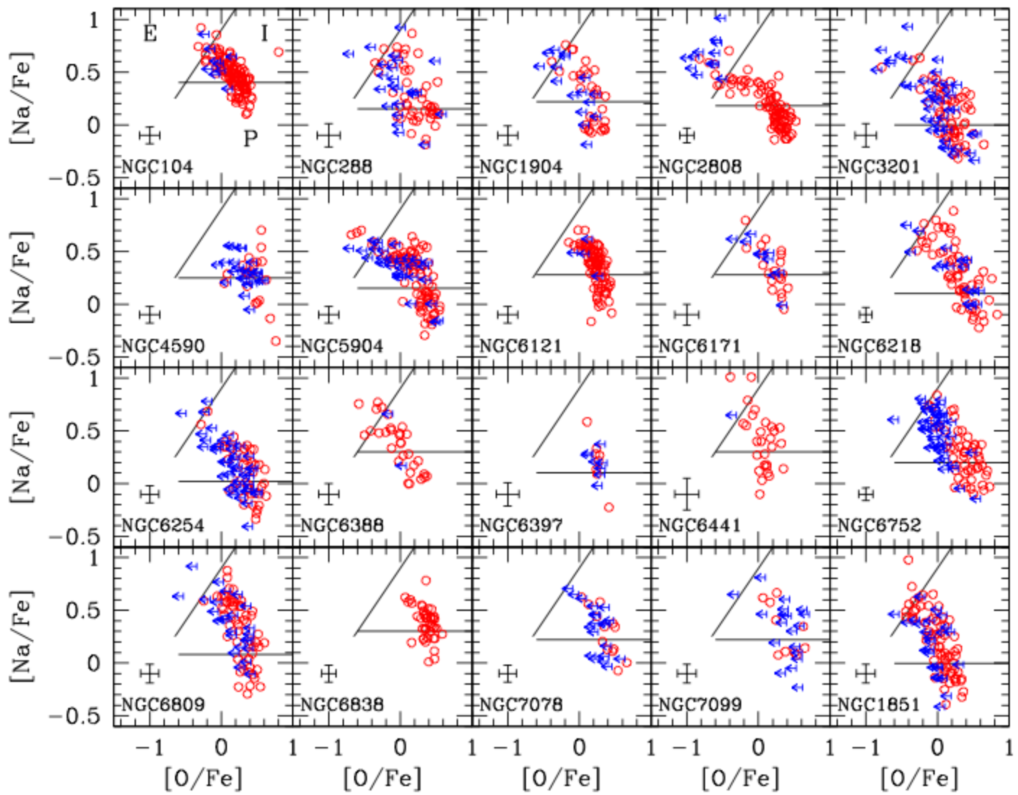
- $^{14}N(p,\gamma)^{15}O$
- $^{22}Ne(\alpha,n)^{25,26}Mg$
- $^{12}C+^{12}C$
- …

$^{23}Na(p,\alpha)^{20}Ne$ – Why?

- The measurement of $^{23}Na(p,\alpha)^{20}Ne$ is one of the last piece of information to understand the Globular Cluster Anomalies

- Main sources of uncertainty are poorly constrained resonances, which fall inside the energy of interest (corresponding to T = 0.05-0.1 GK typical of HBB in AGB stars)

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^-	$(23 \pm 5) \times 10^{-3}$

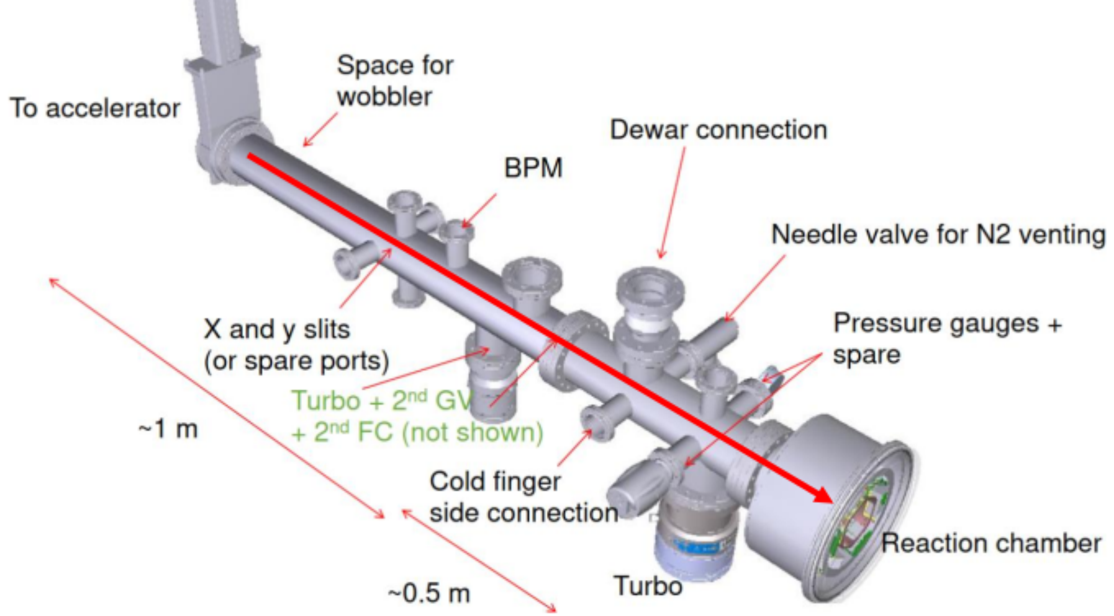


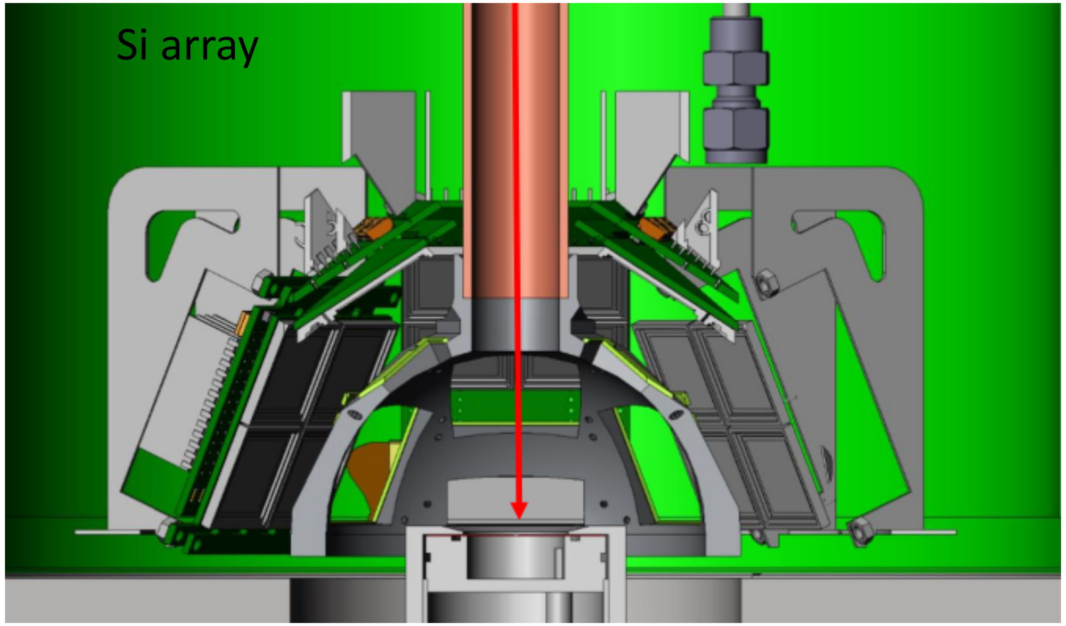
E. Carretta et. al., A&A, 516 (2010)

LUNA

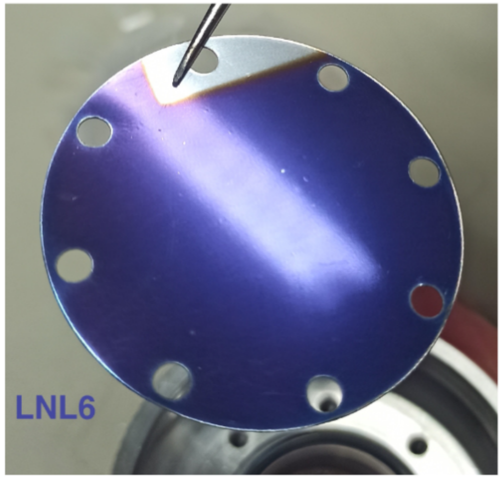
^{23}Na(p,α)^{20}Ne – How?

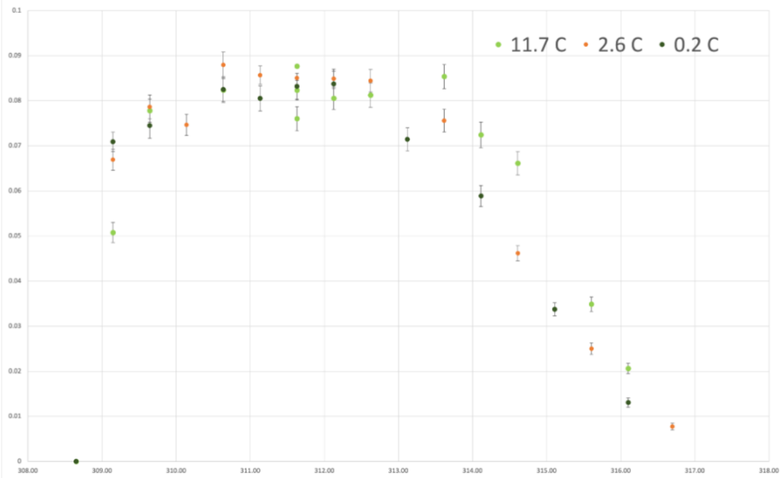
Brand new beam line at LUNA400kV





New dedicated target, made by sputtering technique, already tested and showed a good profile





$^{12}C+^{12}C$ – Why?

- First burning phase involving heavy ions
- C ignition is possible ONLY for stars with $M>M_{up}$
- How much is M_{up}? We do not know!
- A star fate is fully determined by $^{12}C+^{12}C$ reaction rate
- Gamow window = 1.5-2 MeV
- Few direct data available and with large uncertainty
- Recent indirect measurement found many resonances below 2.5 MeV resulting in a net increase of the reaction rate!
- Need for direct measurements

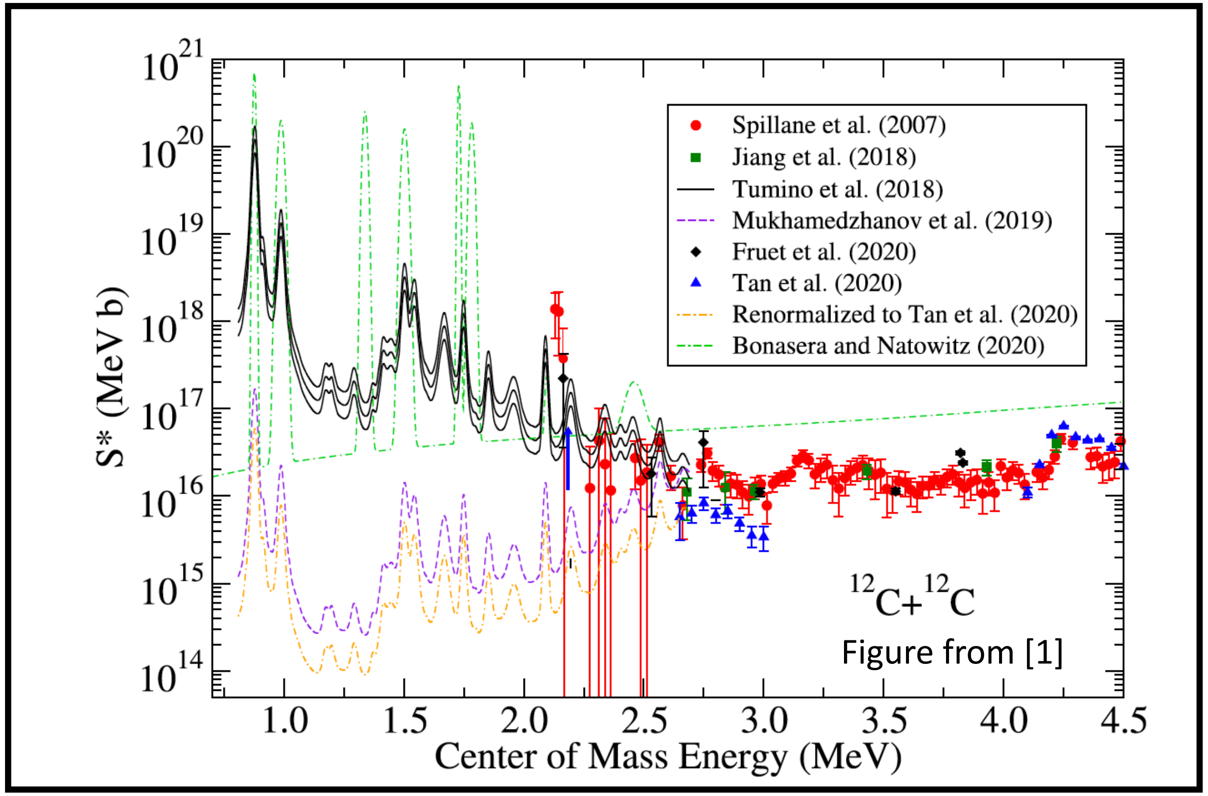
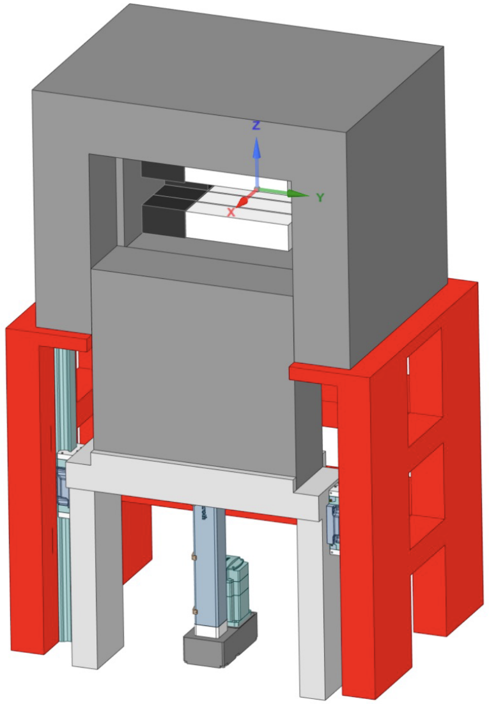


Figure from [1]

$^{12}C+^{12}C$ – How?

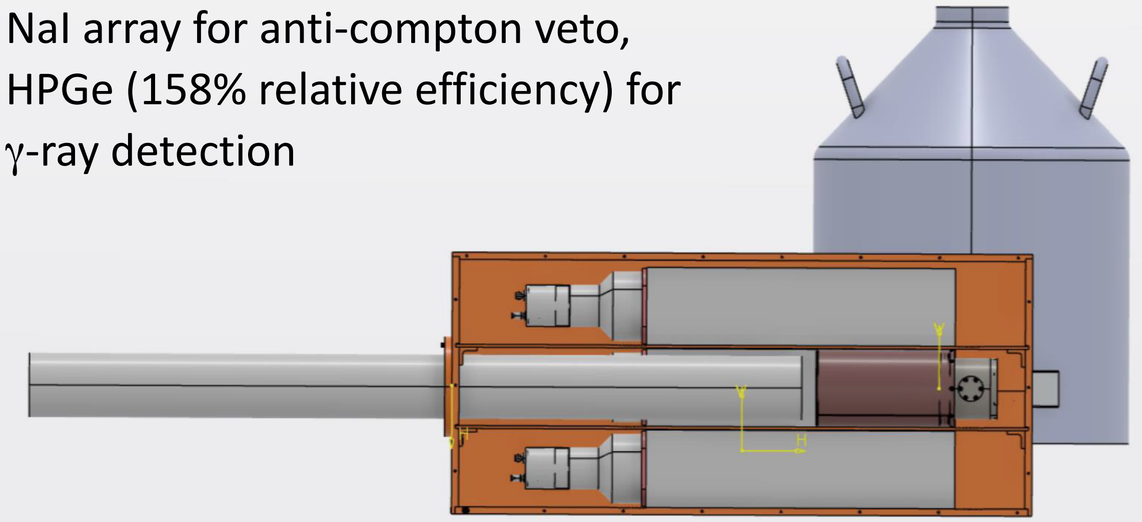
$$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha\ (+\gamma)\ (Q = 4.62\ MeV)$$
$$\rightarrow {}^{23}Na + p\ (+\gamma)\ (Q = 2.24\ MeV)$$

Main exit channels
(experiments are performed detecting charged particles and/or gamma rays)



Full Pb+Cu shield setup

NaI array for anti-compton veto, HPGe (158% relative efficiency) for γ-ray detection



Tests on different type of target plans ongoing at Felsenkeller lab.

LUNA

LUNA Collaboration

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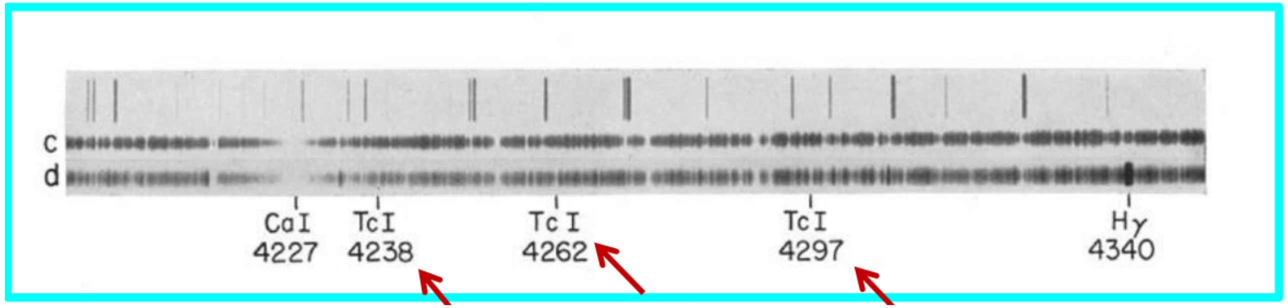
"The amazing thing is that every atom in your body came from a star that exploded. And, the atoms in your left hand probably came from a different star than your right hand. It really is the most poetic thing I know about physics: You are all stardust."

L.M.Krauss

Thank you for your attention

Backup

1952: the first evidence



Tc absorption line in red giant R Andromeda

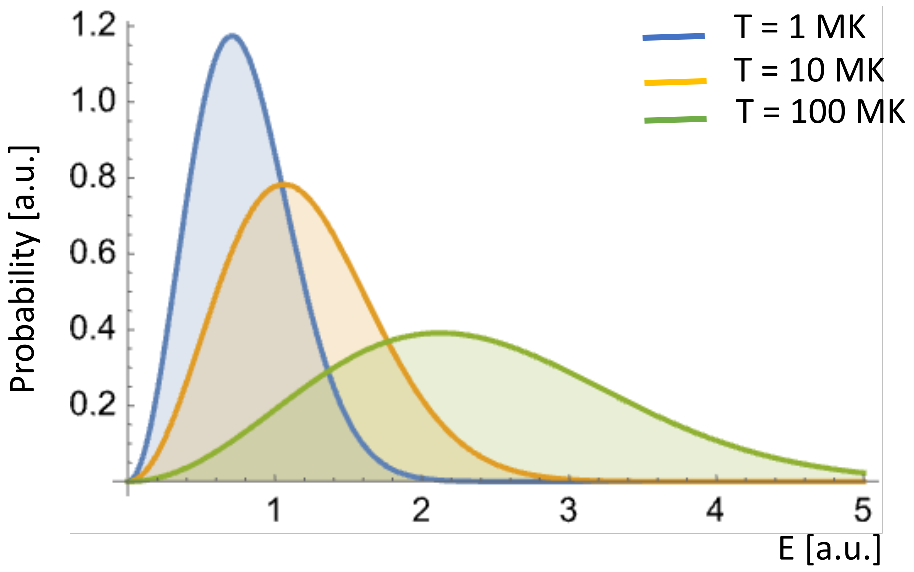
Ident.	Wave Length
ABSORPTION	
ZrO	4471, 4620, 4638
TiO	4584, 4626, 4761, 4955
Ba II	4554, 4934
Low-temp.:	
Al I	3944, 3961
K I	4044, 4047
Ca I	4226
Cr I	4254, 4274, 4289
Sr I	4607
Tc I	4031, 4238, 4262, 4297

Merrill P., ApJ 116, 21 (1952)

^{99}Tc is a radioisotope with $T_{1/2}$= 2.1E+05 y << 10^9 years corresponding to the star age

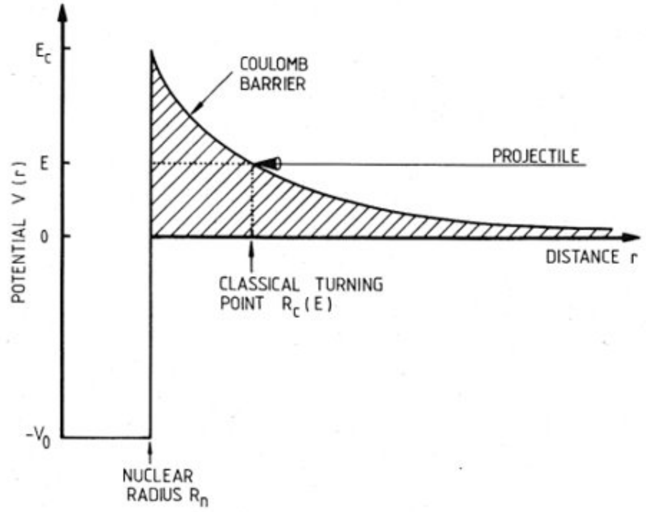
Honestly sir, you are a foul!

Ions energy distribution in stars is a Maxwell-Boltzman (~ exp(-E/kT):



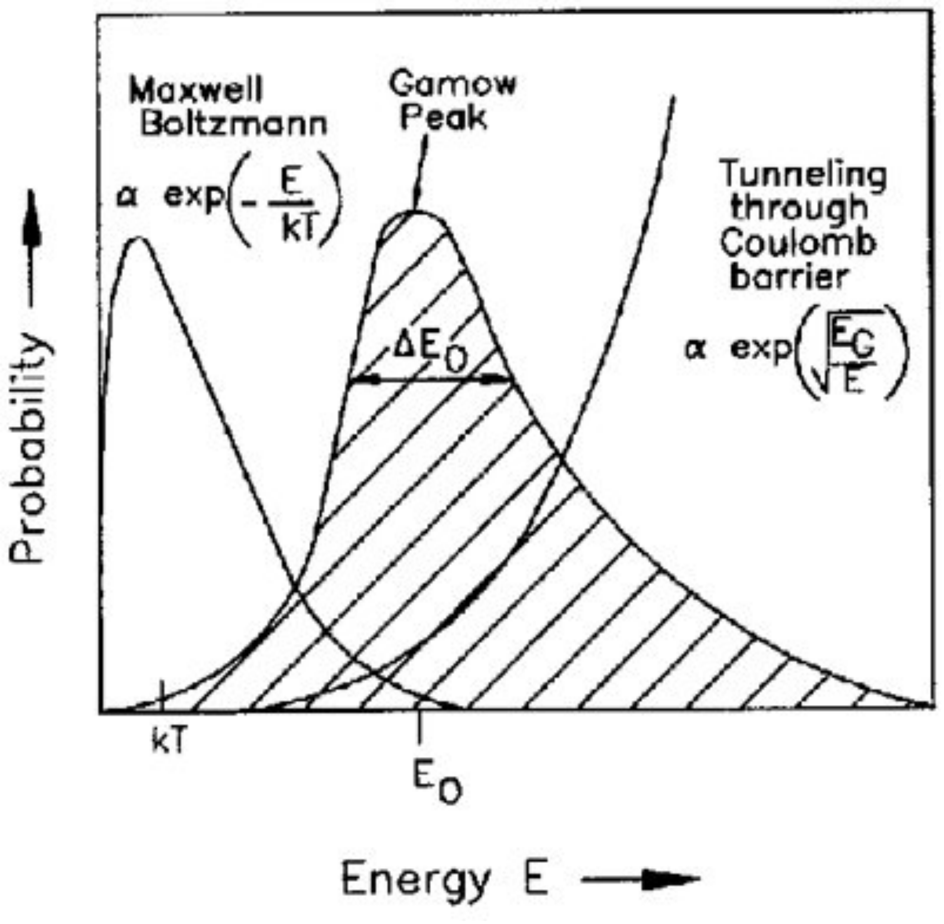
Particles most frequently have energy around E ~kT:
In the Sun E ~ 100 eV, in more advanced stars ~ few keV to few MeV

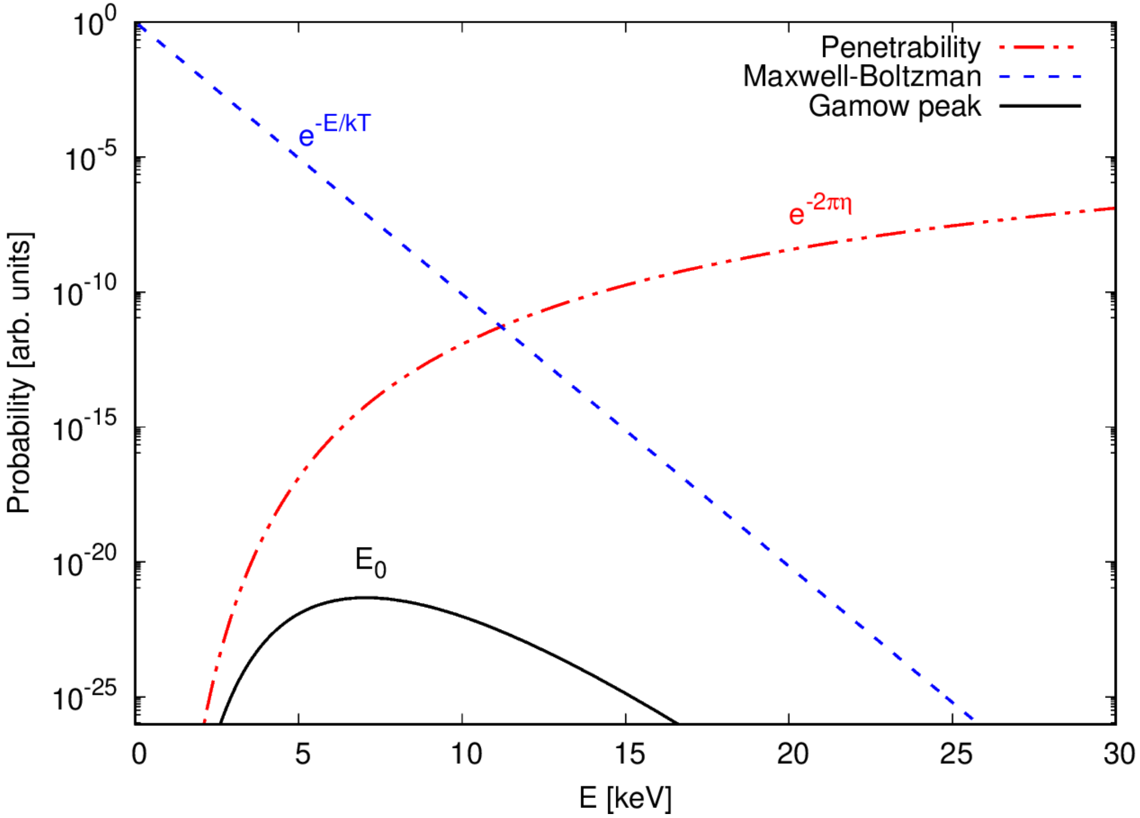
Most of the ions have energy well below the coulomb barrier (= the repulsion between charge particle)



Ops, sorry sir you were right!

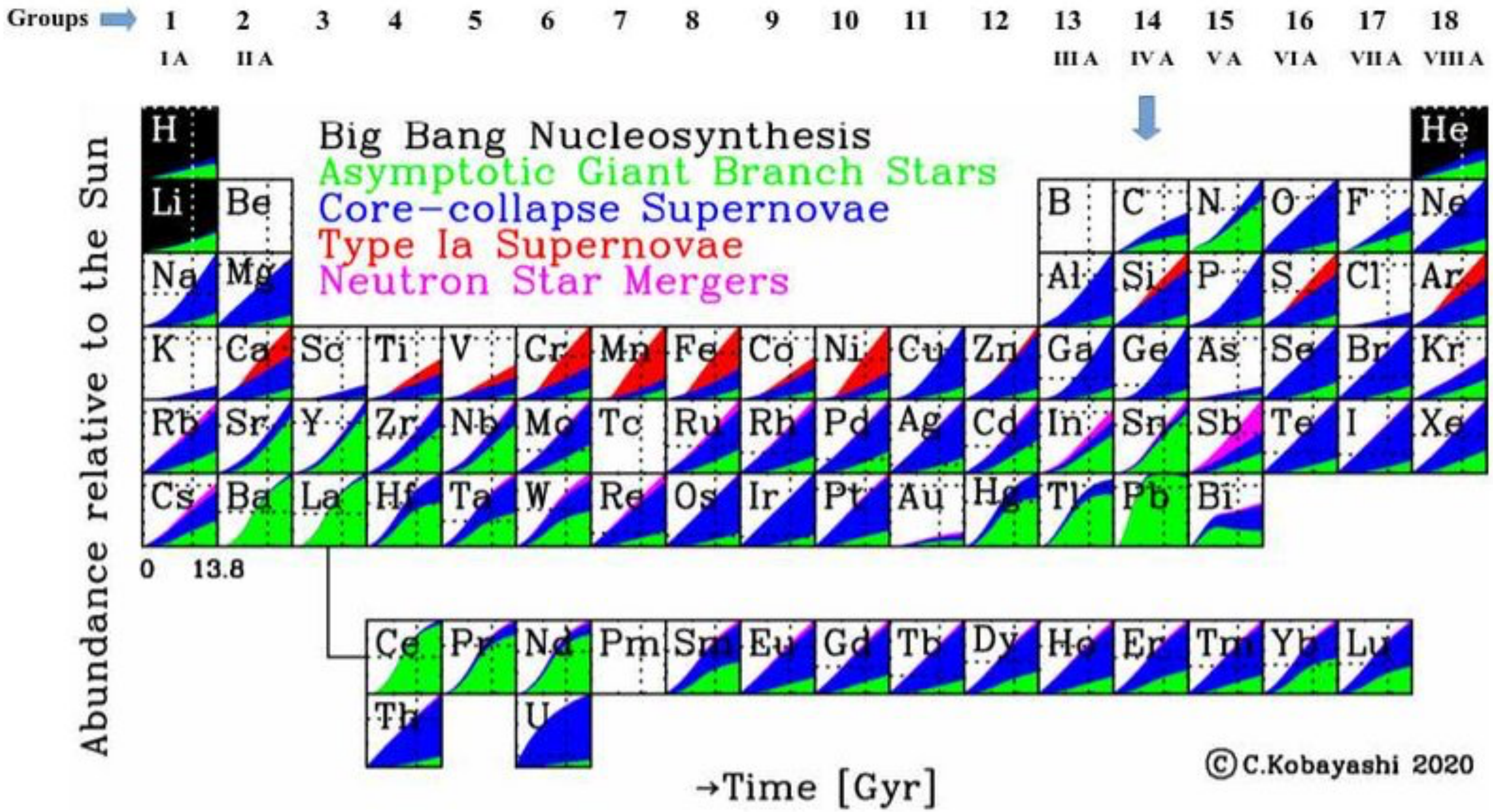
Gamow's work on quantum tunneling effect which pointed to a non-negligible probability, inside a pretty small window, that charge particle induced reactions take place inside stellar core





Gamow peak for $^{6}Li(p,\gamma)^{7}Be$ reaction at T = 5 MK

Where we are now?



What can we do?

- Can we have thicker and thicker target?

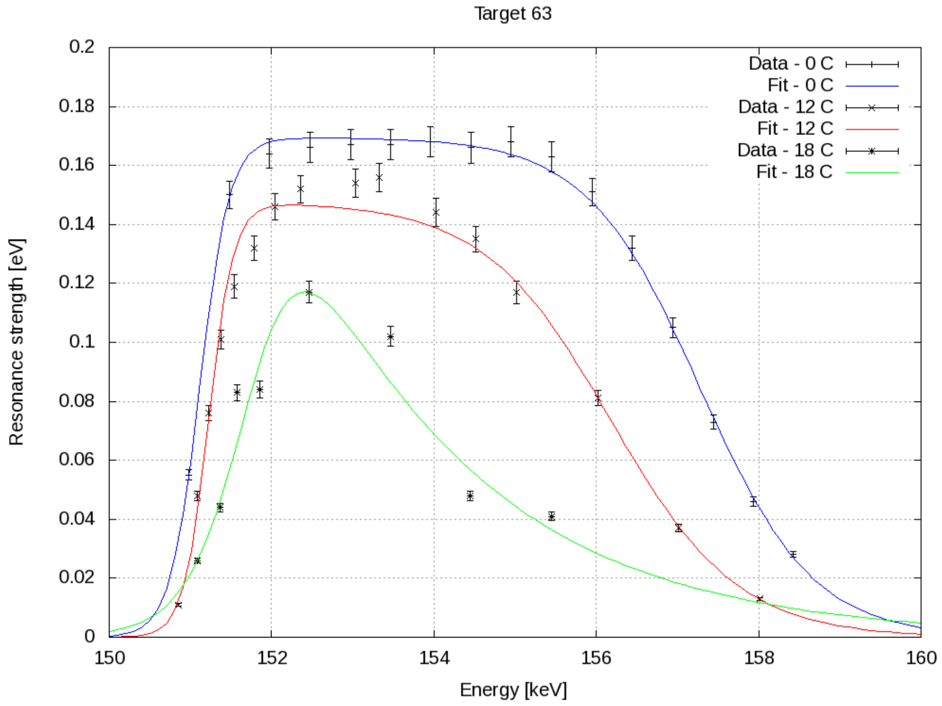
Not really.
The beam is losing energy while passing through the target then reactions take place at different beam energies and so we cannot recover which events correspond to a particular energy!
No gain

- Could we have higher and higher intensity beams?

Not really because of the risk of target degradation!

- Detector as big as we want?

Not really. If you need high resolution you will go for an HPGe and crystal size are still limited. With scintillators you have more options but intrinsic background and bad resolution can limit you!



LUNA

Some notes on recent successful campaigns

$\sigma(E)$ measured at 3% precision level
-> BBN $\Omega_b h^2$ estimate at 1.6% level
See Mossa V., Nature 587, 210 (2020)

Reaction	Accelerator	Astrophysical Motivation/Scenario
$D(\alpha,\gamma)^6Li$; $^3He(\alpha,\gamma)^7Be$, $D(p,\gamma)^3He$	LUNA400kV	Big Bang Nucleosynthesis (BBN), Lithium problem(s)
$^3He+^3He$; $D(p,\gamma)^3He$	LUNA50kV	pp-chain and Solar neutrinos
$^6Li(p,\gamma)^7Be$	LUNA400kV	Stars, cosmic-ray spallation and BBN; Resonance NOT confirmed
$^{12,13}C(p,\gamma)^{13,14}N$	LUNA400kV	CNO cycle kick off reactions; only few, poorly constrained data
$^{14,15}N(p,\gamma)^{15,16}O$	LUNA400kV	CNO cycle bottleneck;
$^{17,18}O(p,\alpha)^{14,15}N$	LUNA400kV	CNO cycle; crucial for oxygen isotopic abundance in AGB stars
$^{16,17,18}O(p,\gamma)^{17,18,19}F$	LUNA400kV	CNO cycle and CNO leak
$^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$	LUNA400kV	NeNa cycle; affecting abundances up to P
$^{23}Na(p,\gamma)^{24}Mg$	LUNA400kV	NeNa-MgAl cycle link
$^{25}Mg(p,\gamma)^{26}Al$	LUNA400kV	MgAl cycle; poorly constrained resonances dominate the rate
$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$	LUNA400kV	s-process crucial for isotopes heavier than iron

First direct measurement of the 65 keV resonance
->Rate increased by a factor ~2
-> a group of presolar grains linked to its progenitors
See Bruno C., PRL 117, 142502 (2016)

LUNA

Some notes on recent successful campaigns

$\sigma(E)$ down to 60 keV, lowest energy to date. Offset of 25 and 30% w.r.t. literature -> improved $^{12}C/^{13}C$ ratio
See Skowronski J., PRL 131, 162701 (2023)

$\sigma(E)$ measured very close to s-process Gamow peak
See Ciani G.F., PRL 127, 152701 (2021)

Reaction	Accelerator	Astrophysical Motivation/Scenario
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$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$	LUN...	...cial for isotopes heavier than iron

3 resonances observed for the first time.
DC component down to lowest energy to date
Improve knowledge of Na-O anti correlation in GC
See Ferraro.F., PRL 121, 172701 (2018)