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Nuclear Astrophysics deep underground

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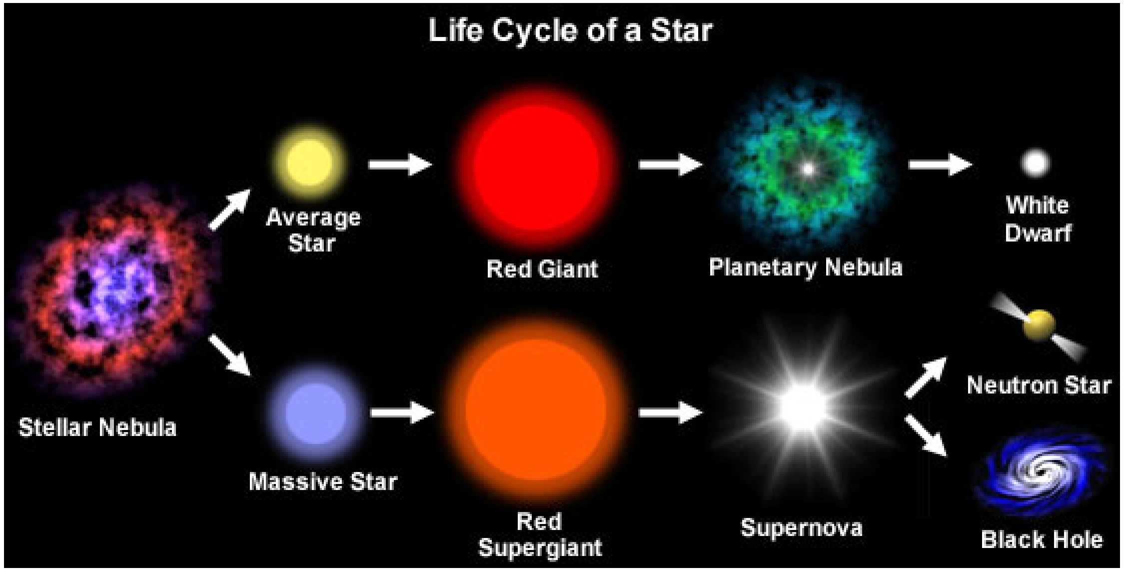
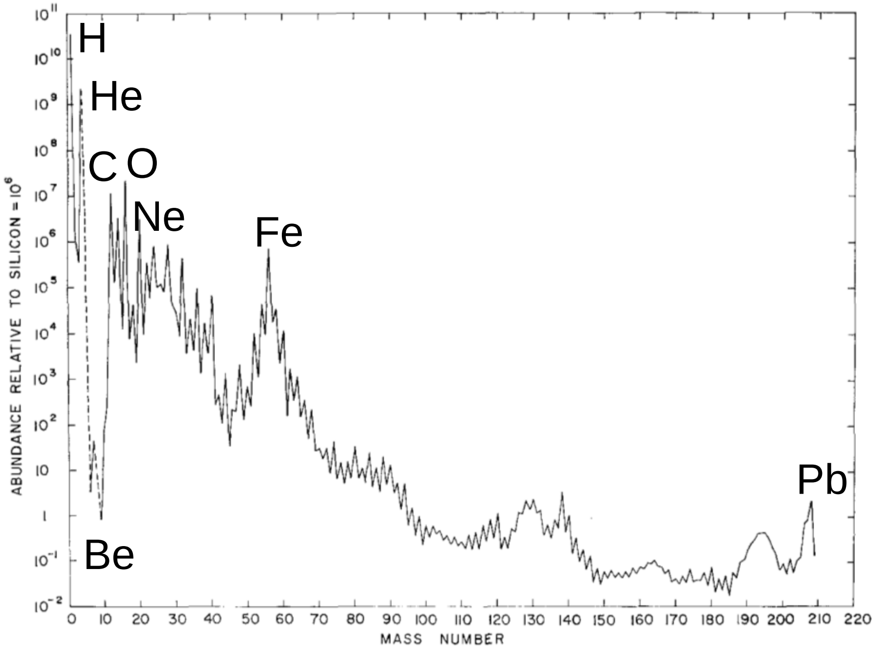
Why Nuclear Astrophysics?

- Stellar evolution strongly depends on nuclear reactions: **Nuclear fusion cross sections are key parameters in stellar modelling**

- Nuclear reactions are responsible for the synthesis of the elements in the cosmos: **High precision data are very often required**



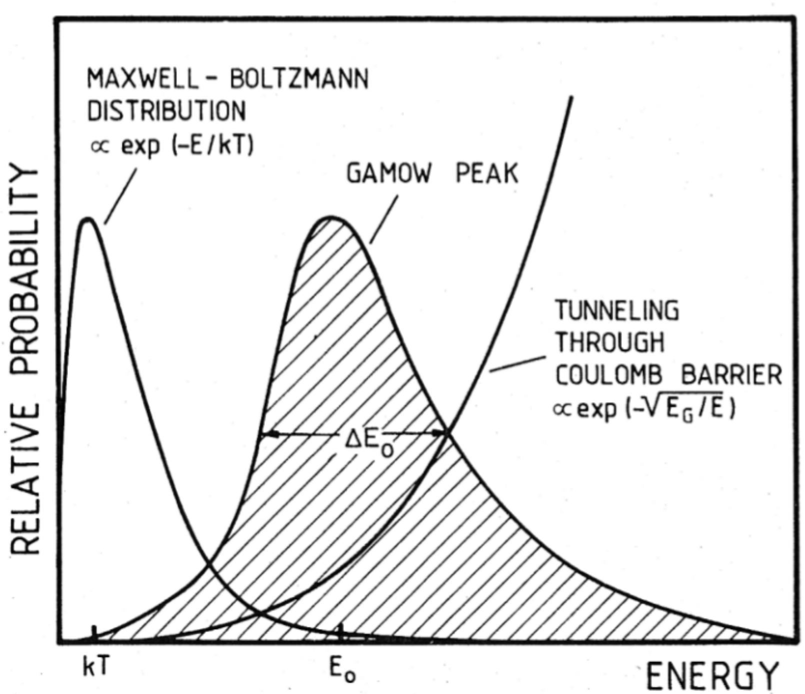


Charged-particle-induced reactions

$T_{sun} = 15$ MK $\rightarrow$ $E_{kin} \approx 1$ keV << E_{Coul} (0.5 - 2MeV)

$$\sigma(E) = \frac{1}{E} S(E) e^{-b/\sqrt{E}}$$

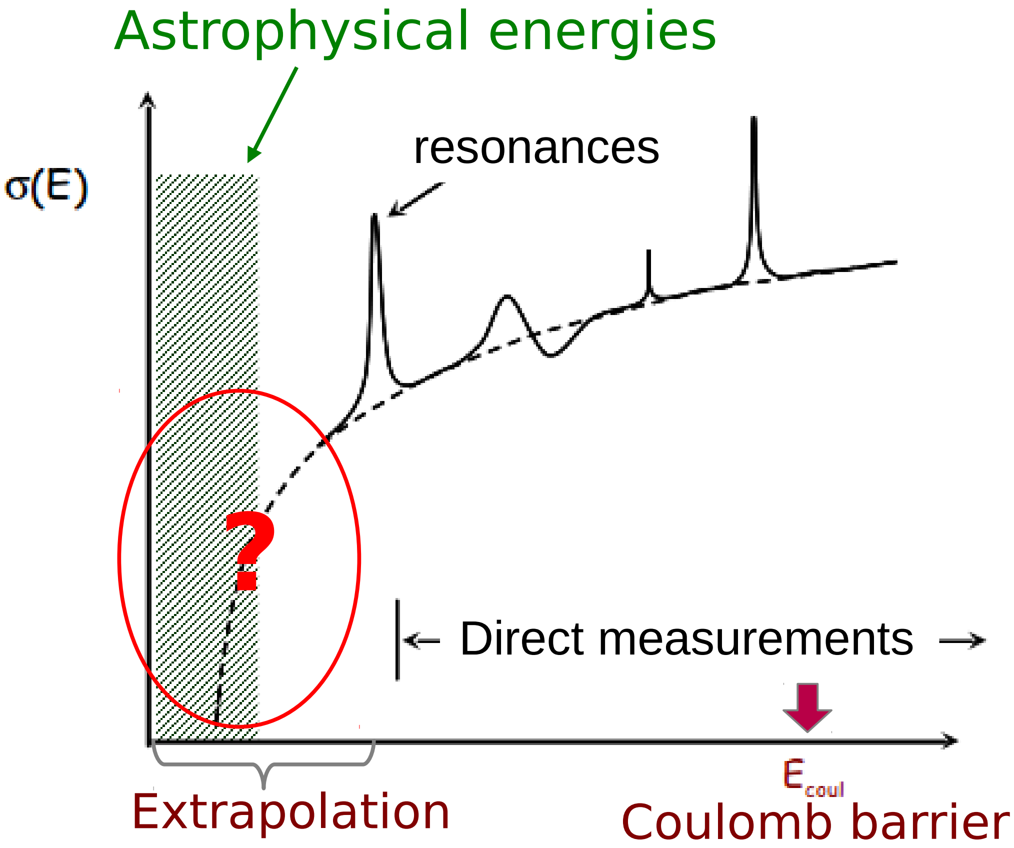
The nuclear fusion cross section decreases exponentially with the energy!



The **Gamow peak** is the energy window in which non resonant reactions take place in stellar environment

Charged-particle-induced reactions

At astrophysical energies, nuclear fusion cross sections can be very low (pbarn – nbarn) → **environmental background dominates over signal**

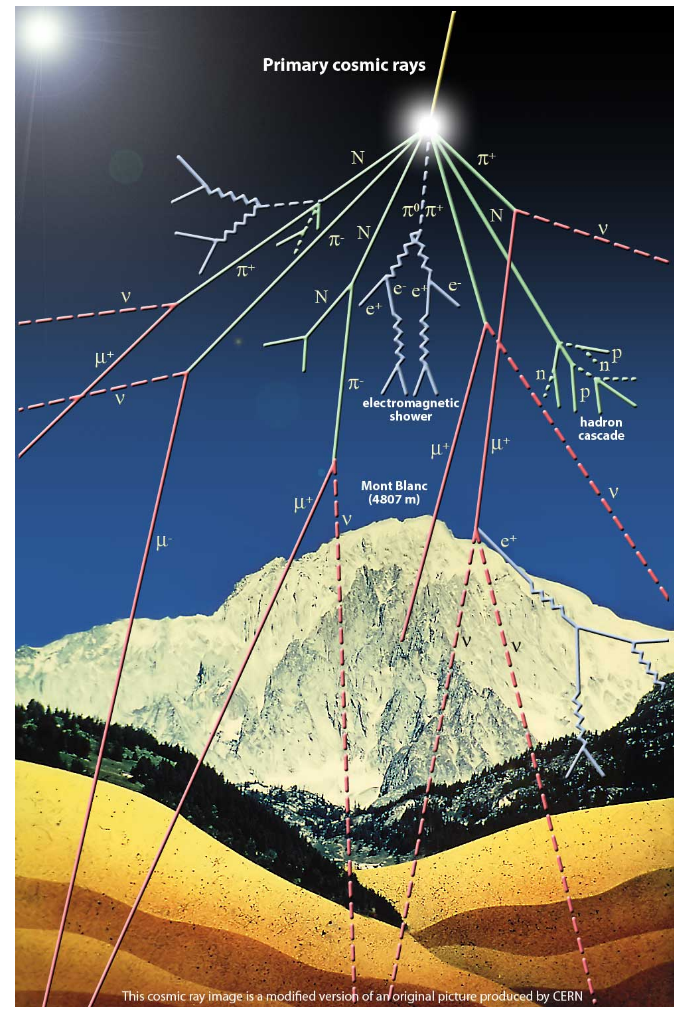


Gran Sasso National Laboratories

Main sources of background in a gamma ray spectrum:

- **Environmental radioactivity**:
  ^{238}U and ^{232}Th chains and ^{40}K

- **Cosmic rays:**
  mainly muons at sea level



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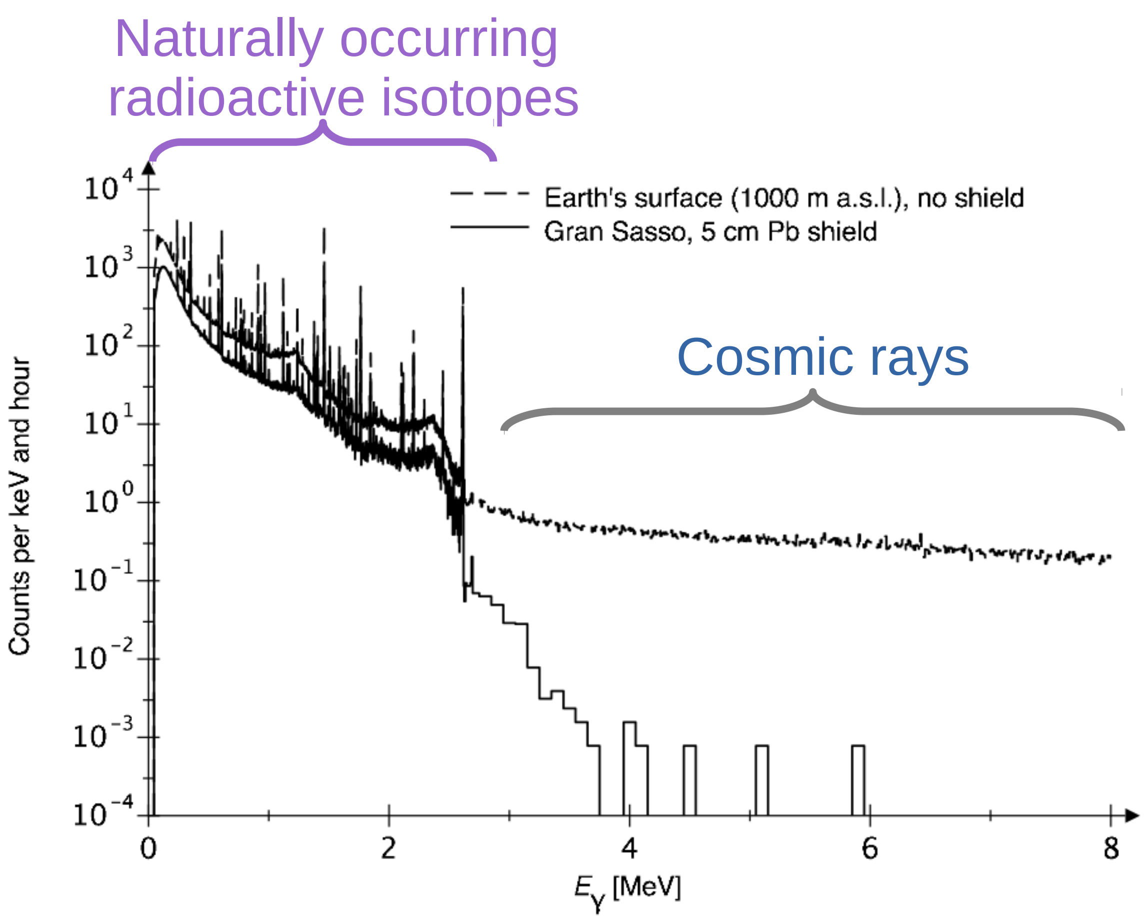
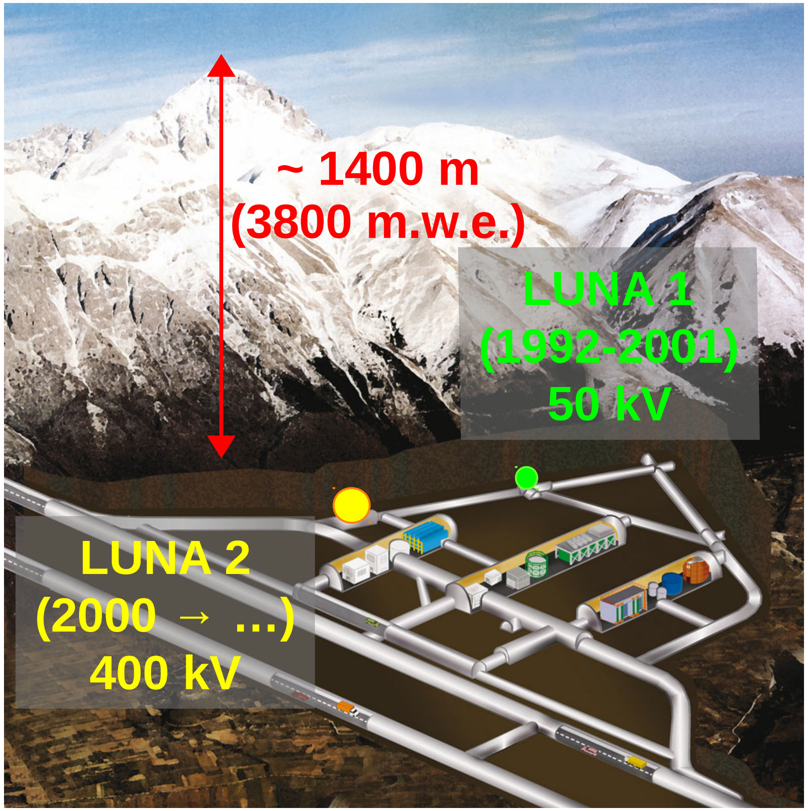
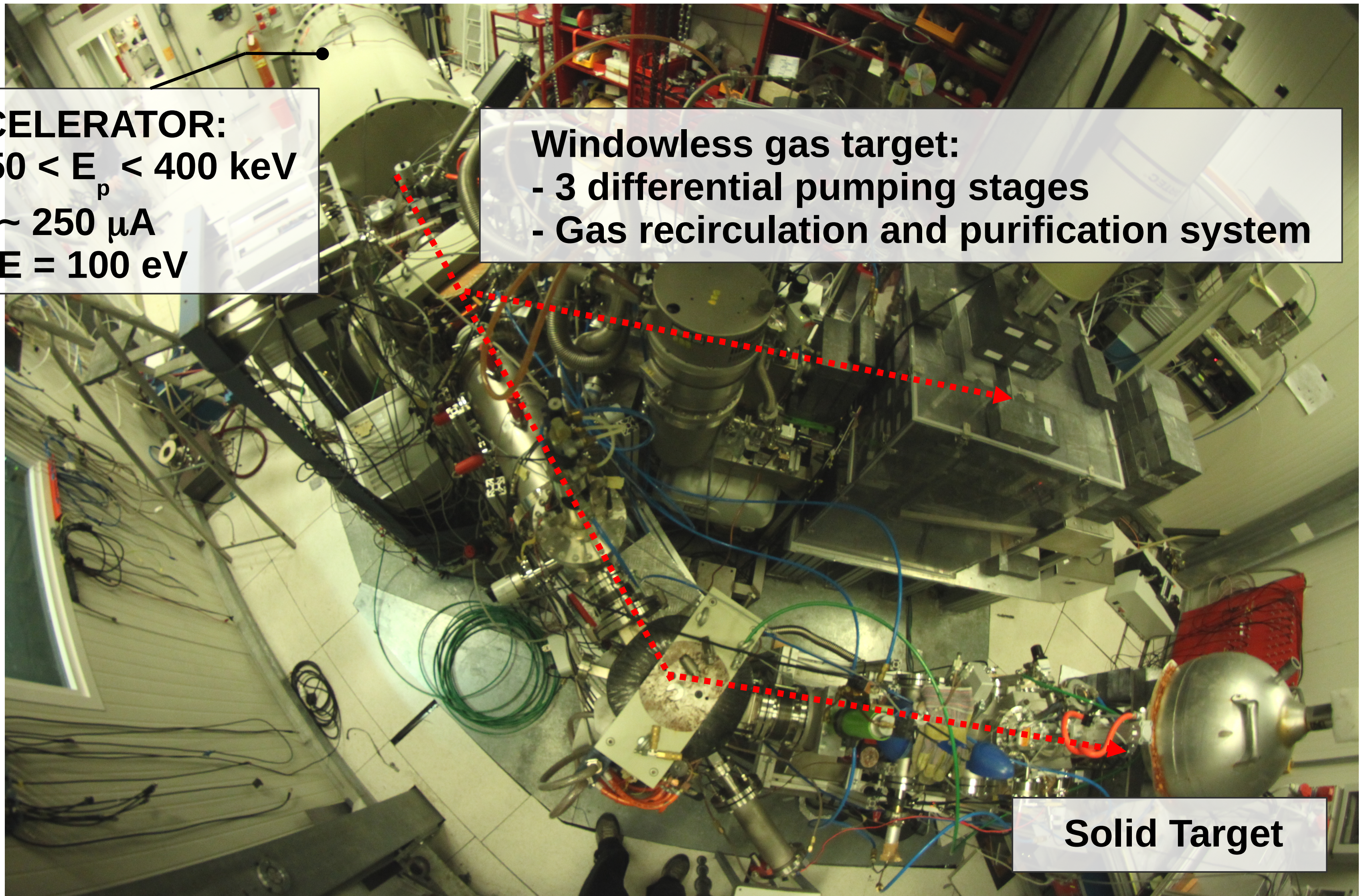




Cosmic ray flux attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

The Laboratory for Underground Nuclear Astrophysics



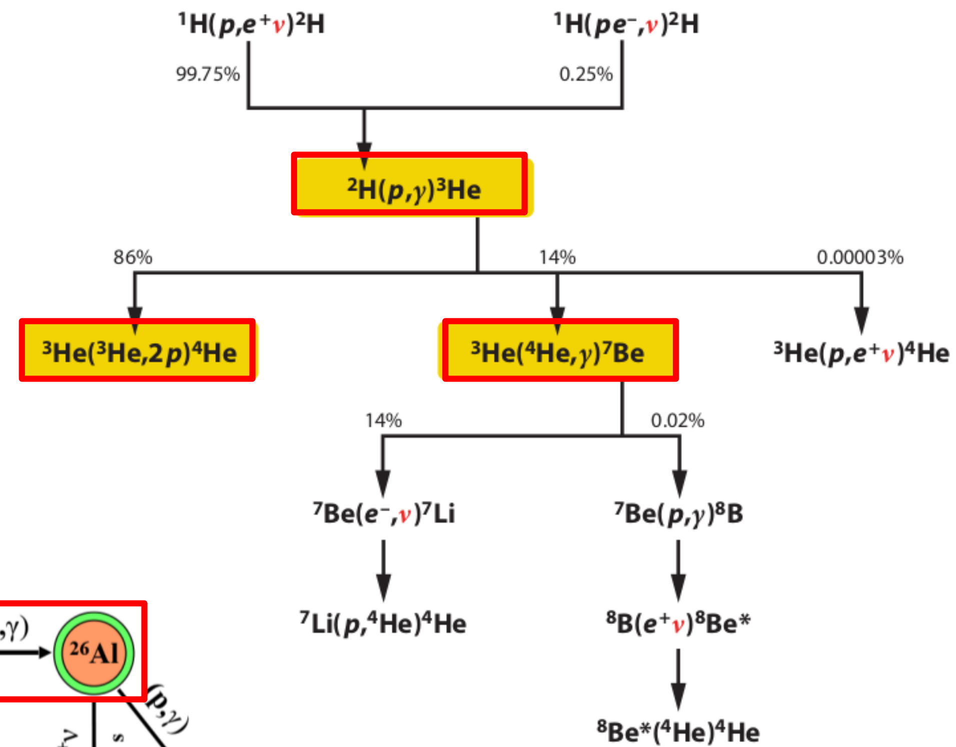
ACCELERATOR:
→ $50 < E_p < 400$ keV
→ I ~ 250 μA
→ ΔE = 100 eV

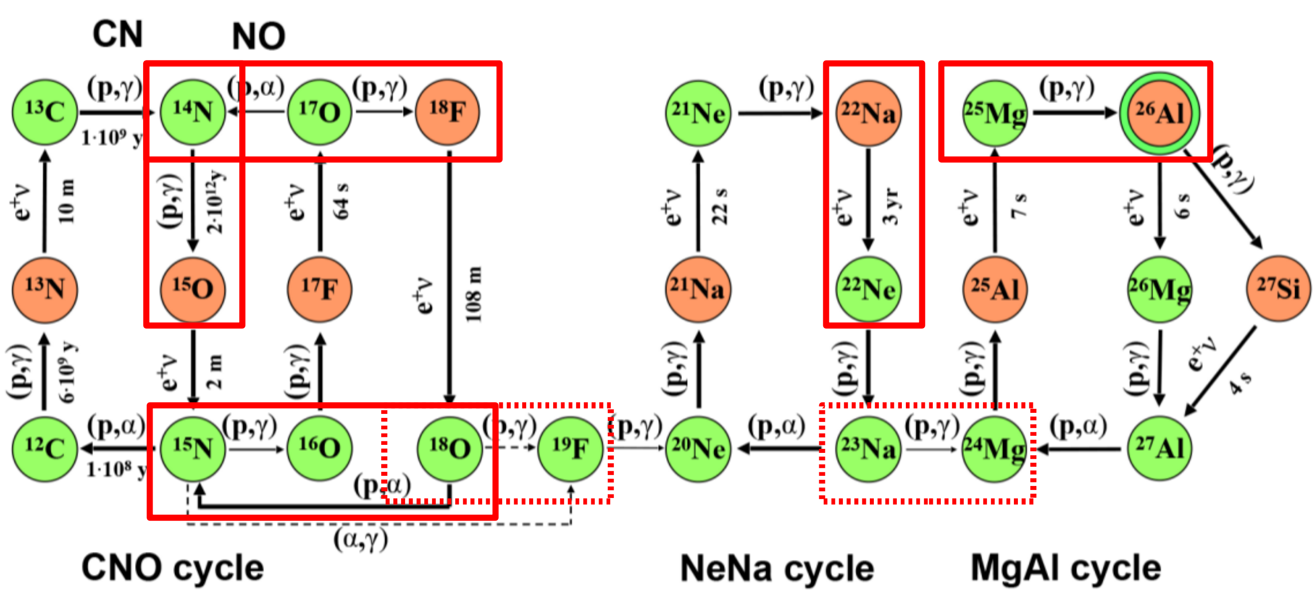
Windowless gas target:
- 3 differential pumping stages
- Gas recirculation and purification system

Solid Target

Reactions studied since 1992

Hydrogen burning at typical energies of main sequence stars and red giant stars

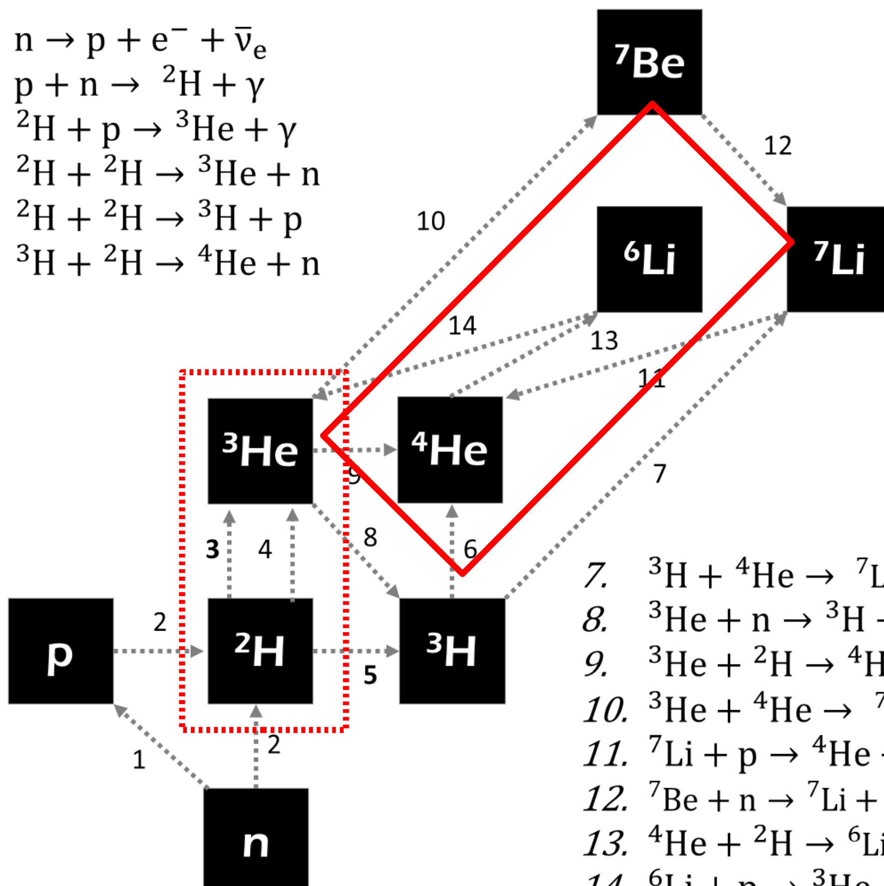




Reactions studied since 1992

Big Bang nucleosynthesis

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow {}^2H + \gamma$
3. ${}^2H + p \rightarrow {}^3He + \gamma$
4. ${}^2H + {}^2H \rightarrow {}^3He + n$
5. ${}^2H + {}^2H \rightarrow {}^3H + p$
6. ${}^3H + {}^2H \rightarrow {}^4He + n$



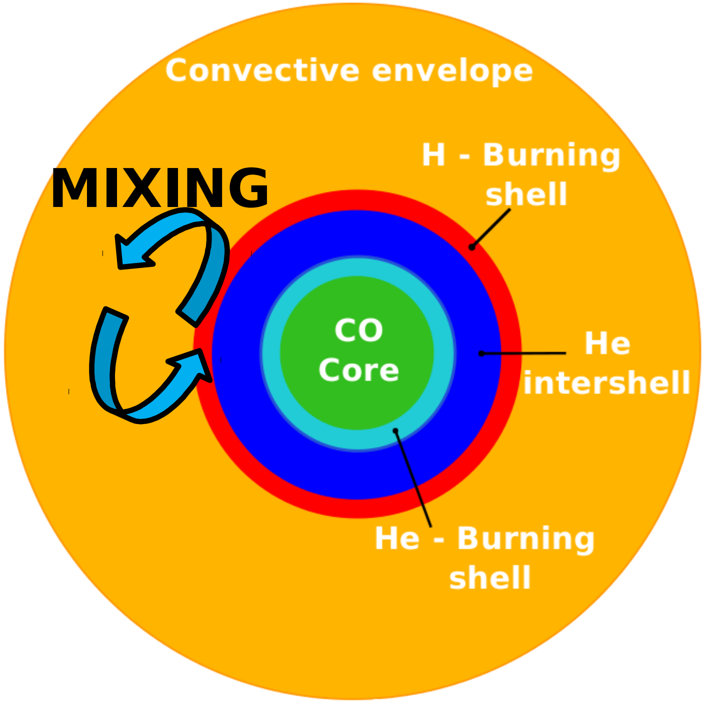
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + {}^2H \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$
13. ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14. ${}^6Li + p \rightarrow {}^3He + {}^4He$

Recently published from LUNA: $^{17}O(p,\alpha)^{14}N$

In AGB stars (T=0.03-0.1 GK) CNO cycle takes place in H burning shell

CNO signature is observed in outer layers

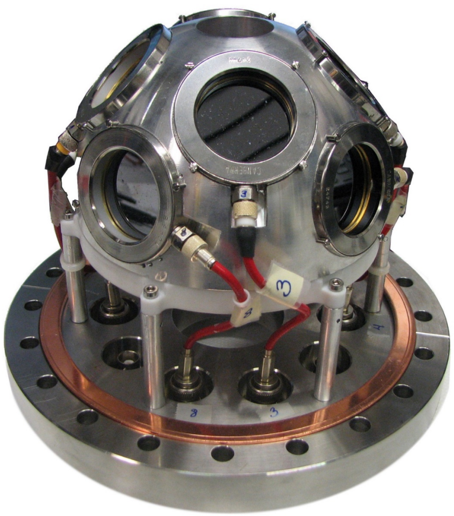
^{17}O and ^{18}O are tracers of CNO nucleosynthesis at high temperatures

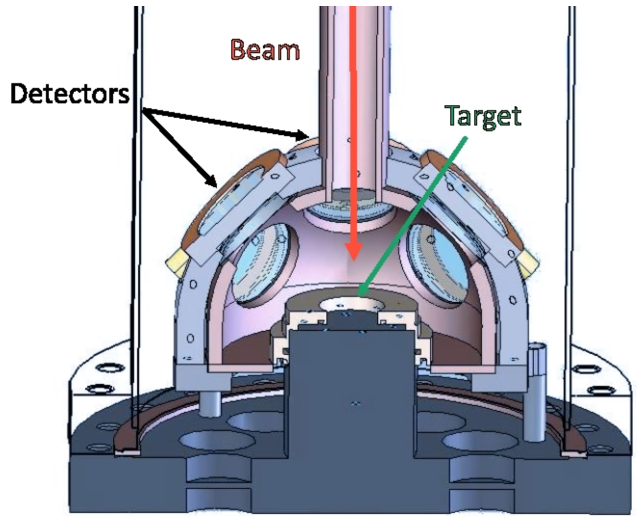


Information on mixing processes can be derived if the cross sections of all reactions involved are well known

Recently published from LUNA: $^{17}O(p,\alpha)^{14}N$

Two narrow resonances at **70** and **193 keV** dominate the $^{17}O(p,\alpha)^{14}N$ reaction rate at astrophysical temperatures, both were re-measured at LUNA





- ^{17}O target enriched at 95%
- Array of 8 silicon detector
- Mylar + Al foils to stop backscattered beam

The new LUNA rate is almost a factor of 2 higher than the rate previously adopted, compatible with the hypothesis of oxygen enriched pre-solar grains in group II produced by massive AGB stars

Bruno et al., EPJ A 51, 94 (2015)
Bruno et al., PRL 117, 142502 (2016)
Lugaro et al., Nature Astronomy 1, 0027 (2017)

Recently published from LUNA: $^{22}Ne(p,\gamma)^{23}Na$ – HPGe Phase

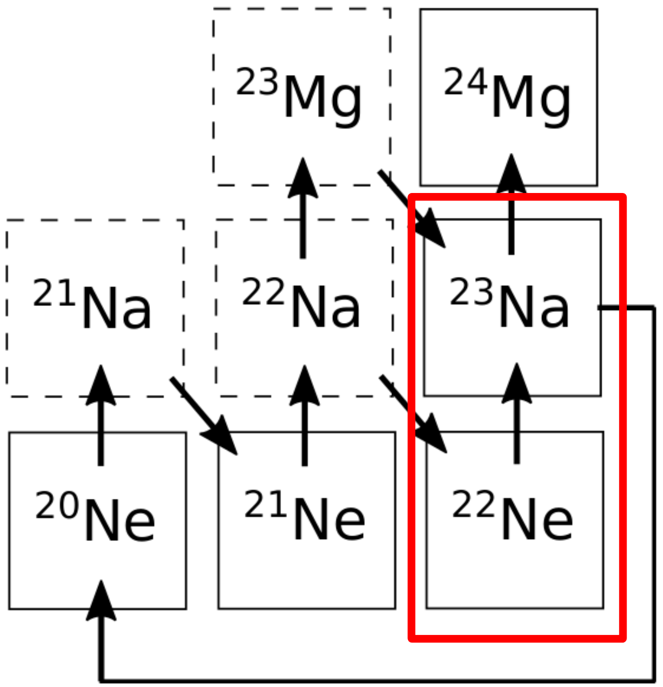
The Neon - Sodium cycle strongly influences the abundance of Ne, Na, Mg and Al in:

Hydrostatic H burning:

- Core H burning in massive stars
- Shell H burning in Red Giant Branch and Asymptotic Giant Branch stars (Na-O anticorrelation problem)

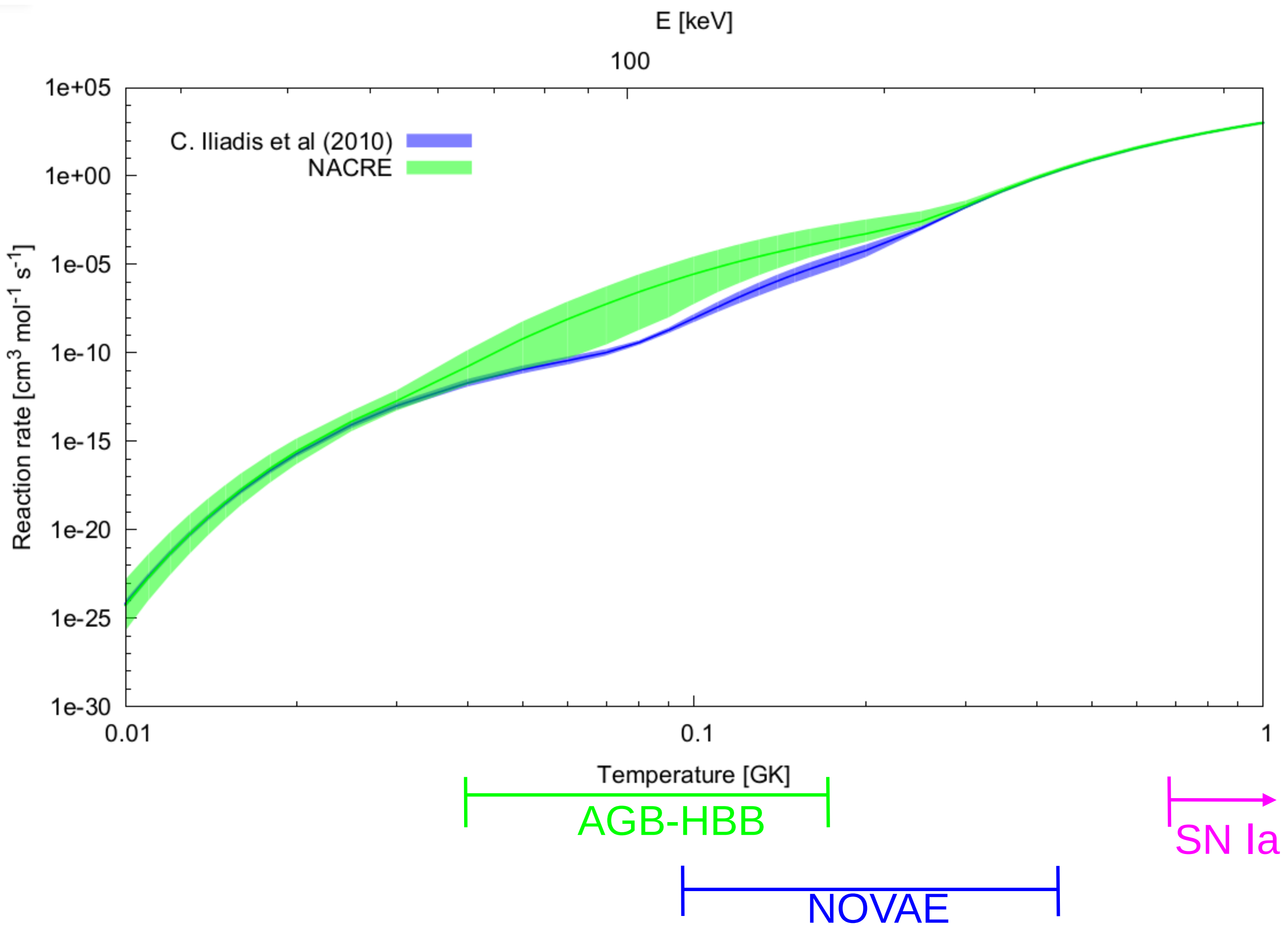
Explosive H burning:

- Classical novae
- Type Ia supernovae



$^{22}Ne(p,\gamma)^{23}Na$ is the most uncertain reaction in the NeNa cycle

Recently published from LUNA: $^{22}Ne(p,\gamma)^{23}Na$ – HPGe Phase



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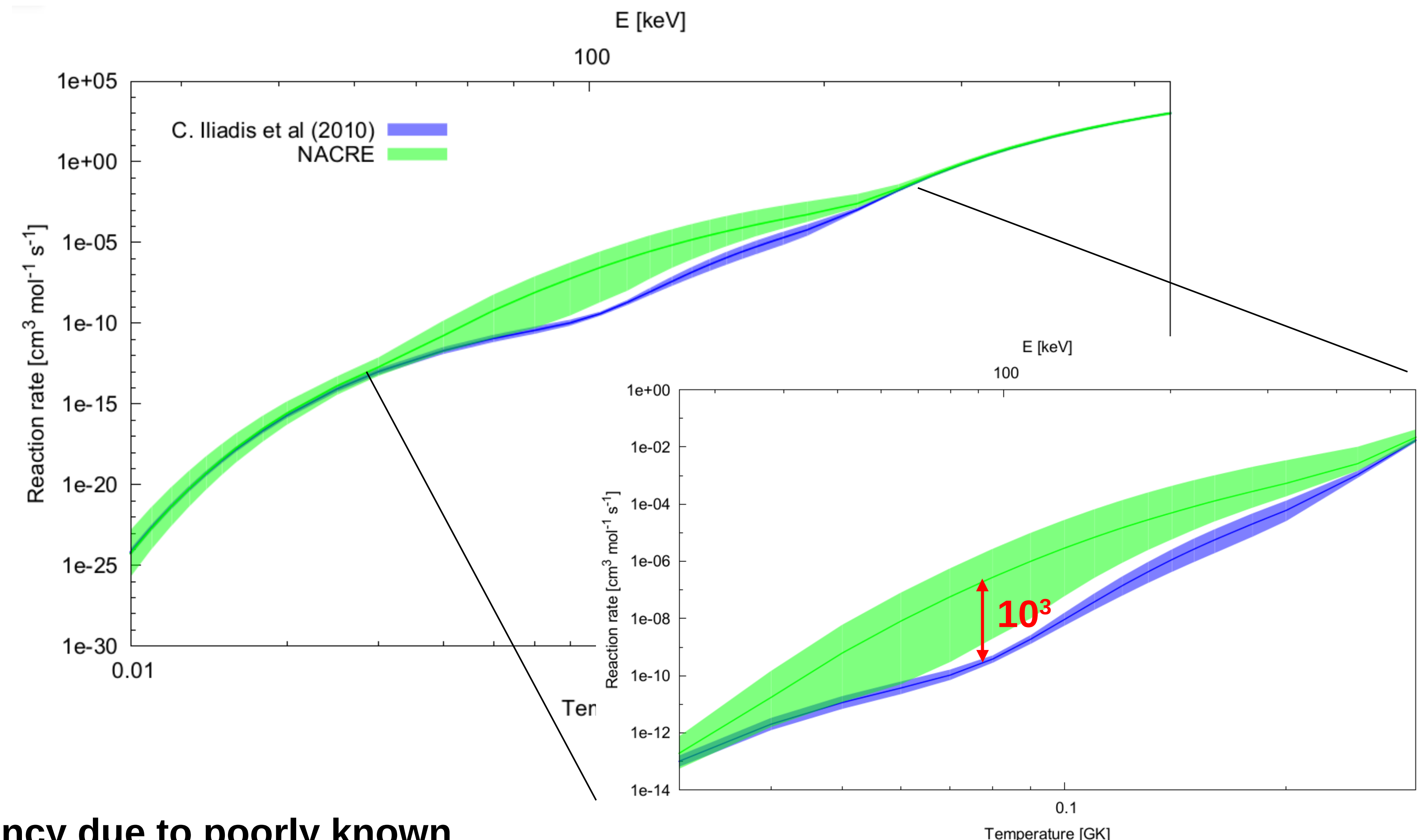
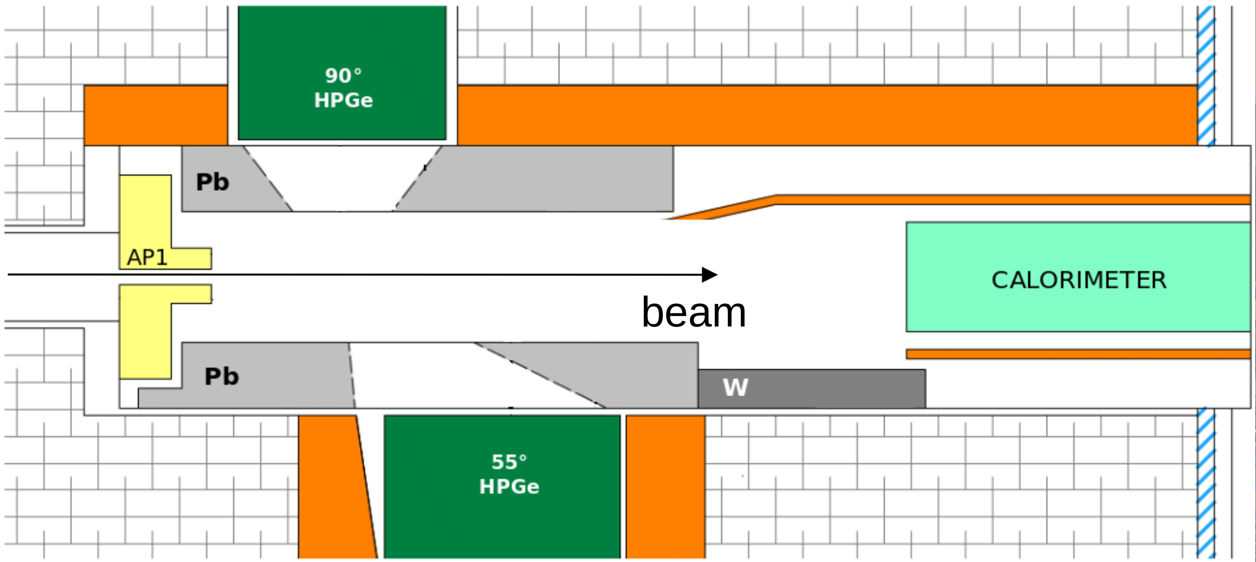


Discrepancy due to poorly known resonances at energies below 400 keV

Recently concluded experiments: $^{22}Ne(p,\gamma)^{23}Na$ – HPGe phase



- Windowless gas target with recirculation system
  ^{22}Ne gas enriched at 99.9%
- 2 HPGe γ ray detectors collimated at 55° and 90°
- Pb + Cu shielding (~ 30 cm)

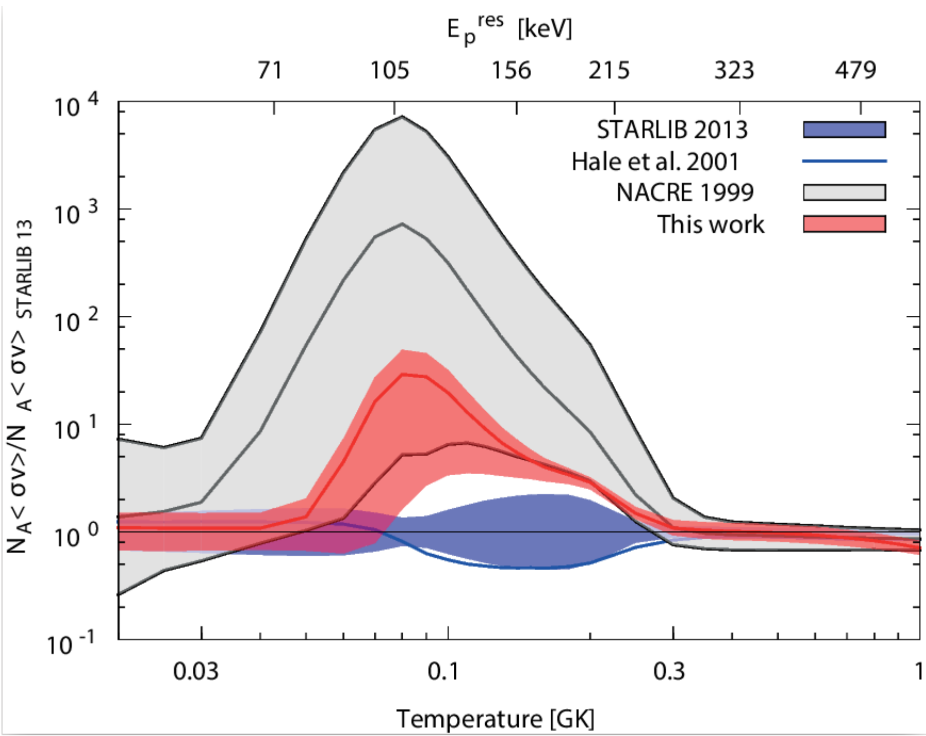
F. Cavanna et al EPJ A 50, 179 (2014)

Recently concluded experiments: $^{22}Ne(p,\gamma)^{23}Na$ – HPGe phase

- 3 resonances (156.2, 189.5, 259.7 keV) observed for the first time:
  → new gamma decay modes and branching ratios

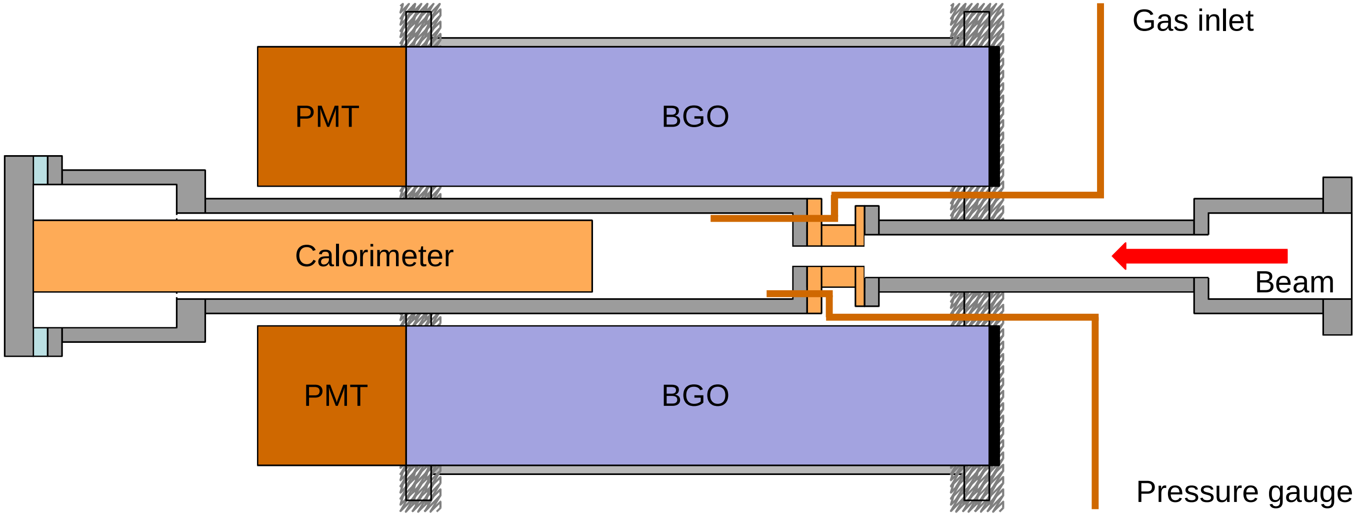
  → Energies of observed resonances measured with 0.7 keV uncertainty

- New upper limits on 71, 105 and 215 keV resonances: 2 orders of magnitude (or more) lower compared to the previous direct measurement



F. Cavanna et al. PRL 115, 252501 (2015)
R. Depalo et al. PRC 94, 055804 (2016)

Recently concluded experiments: $^{22}Ne(p,\gamma)^{23}Na$ – BGO phase



Goal of the BGO phase: reduce further the upper limits on resonances at 71 and 105 keV, direct capture

Resonances at 156.2, 189.5 and 259.7 keV also re-measured for consistency check

LUNA 400 kV program 2016 - 2019

$^{2}H(p,\gamma)^{3}He$ → ^{2}H abunadnce in BBN

$^{6}Li(p,\gamma)^{7}Be$ → BBN & Li depletion in early stages of star evolution

$^{22}Ne(\alpha,\gamma)^{26}Mg$ → competes with $^{22}Ne(\alpha,n)^{25}Mg$ neutron source

$^{13}C(\alpha,n)^{16}O$ → neutron source for s-process

$^{12}C(p,\gamma)^{13}N$ and **$^{13}C(p,\gamma)^{14}N$** → relative abundance of $^{12}C/^{13}C$ in the deepest layers of H-rich envelopes of any star

Ongoing experiments: $^{2}H(p,\gamma)^{3}He$

PRIMORDIAL ABUNDANCE OF ^{2}H:

- <u>Direct measurements</u>: observation of absorption lines in DLA system

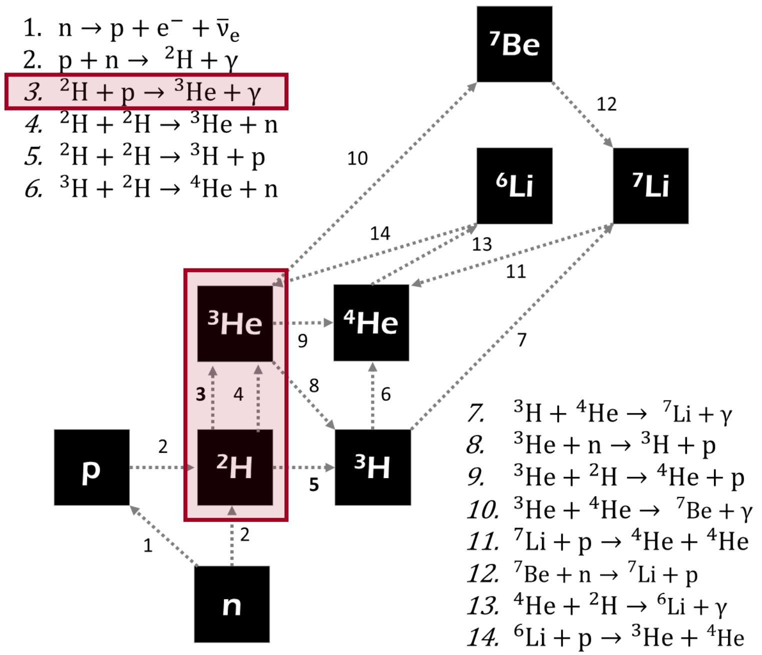
$$\left[\frac{D}{H}\right]_{OBS} = (2.547 \pm 0.033) \cdot 10^{-5}$$

*R. Cooke at al., ApJ. 830 (2016)

- <u>BBN theory</u>: from the cosmological parameters and the cross sections of the processes involved in ^{2}H creation and destruction

$$\left[\frac{D}{H}\right]_{BBN} = (2.65 \pm 0.07) \cdot 10^{-5}$$

*E. Di Valentino et al., Phys. Rev. D 90 (2014)



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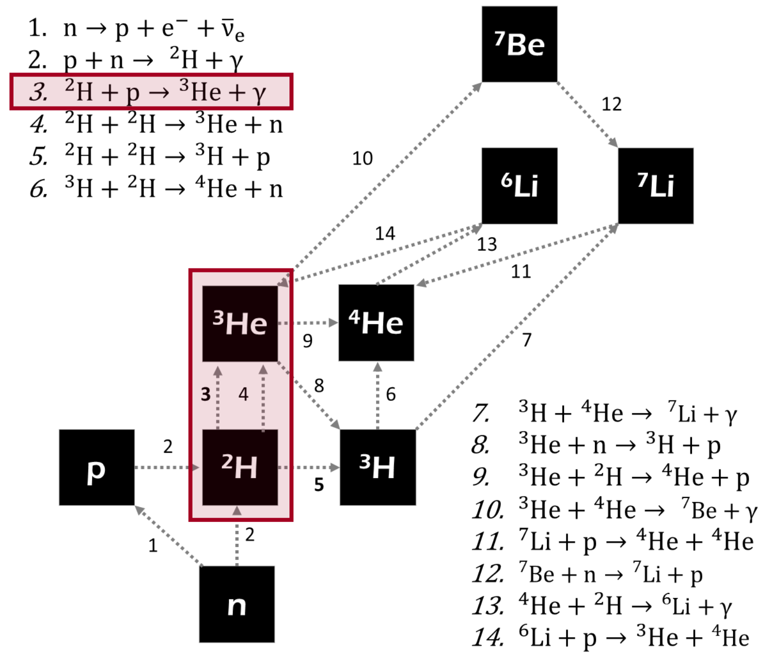


Error mainly due to the $^{2}H(p,\gamma)^{3}He$ reaction!

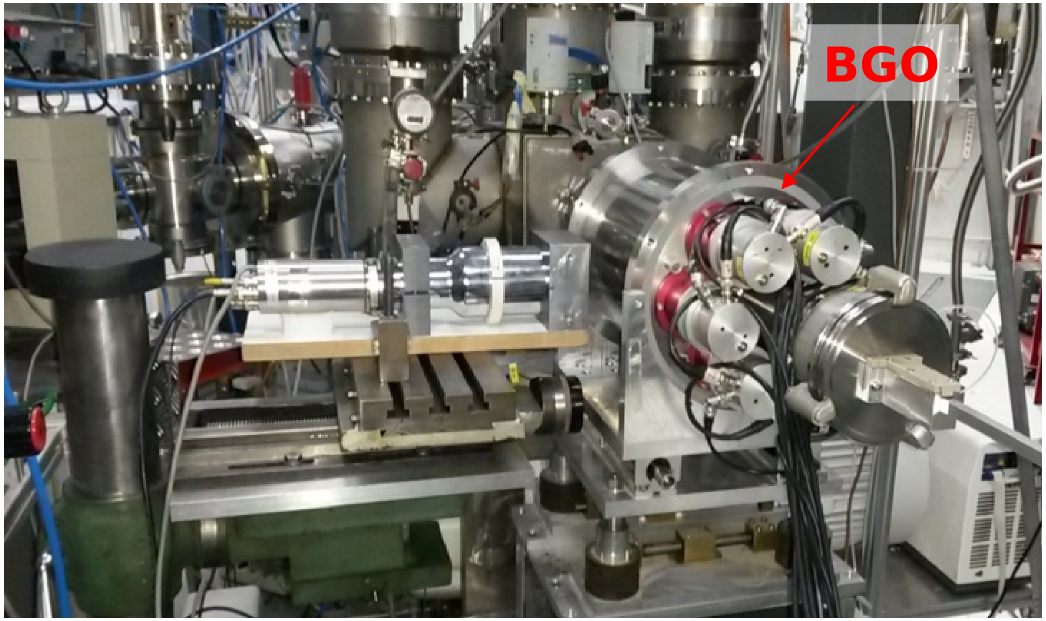
Reaction	$\sigma_{^2H/H} \times 10^5$
$p(n,\gamma)^2H$	± 0.002
$d(p,\gamma)^3He$	± 0.062
$d(d,n)^3He$	± 0.020
$d(d,p)^3H$	± 0.013

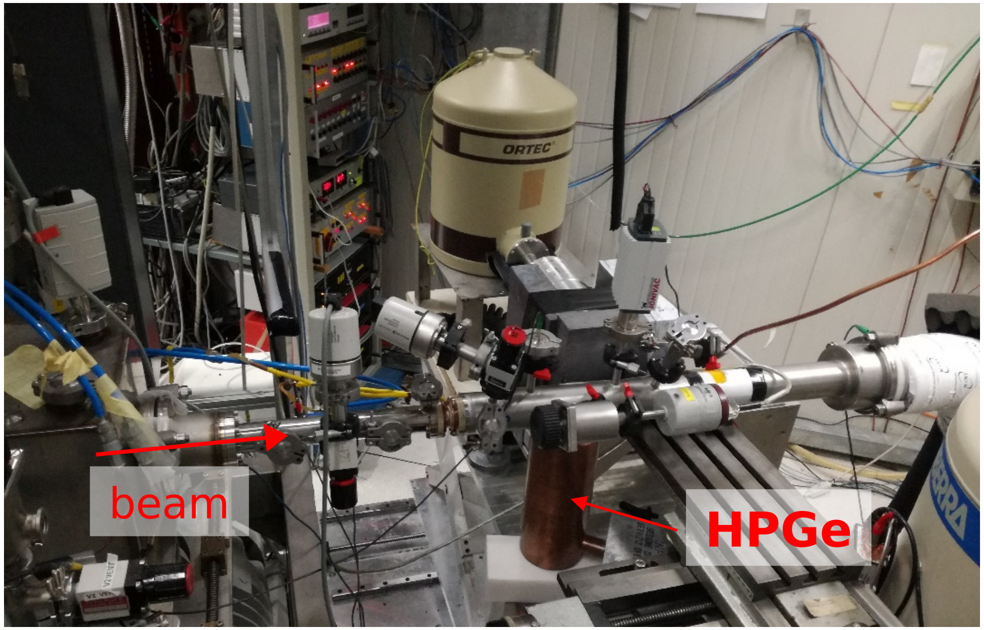
*E. Di Valentino et al., Phys. Rev. D 90 (2014) 023543

Ongoing experiments: $^{2}H(p,\gamma)^{3}He$

The reaction is being studied in two phases with different setups in order to lower the final systematics uncertainties (final goal 3%):

- **BGO** detector setup with high efficiency, to extend data down to very low energy E_p = 70keV
- **HPGe** detector setup with extended gas target to study the angular distribution with peak shape analysis

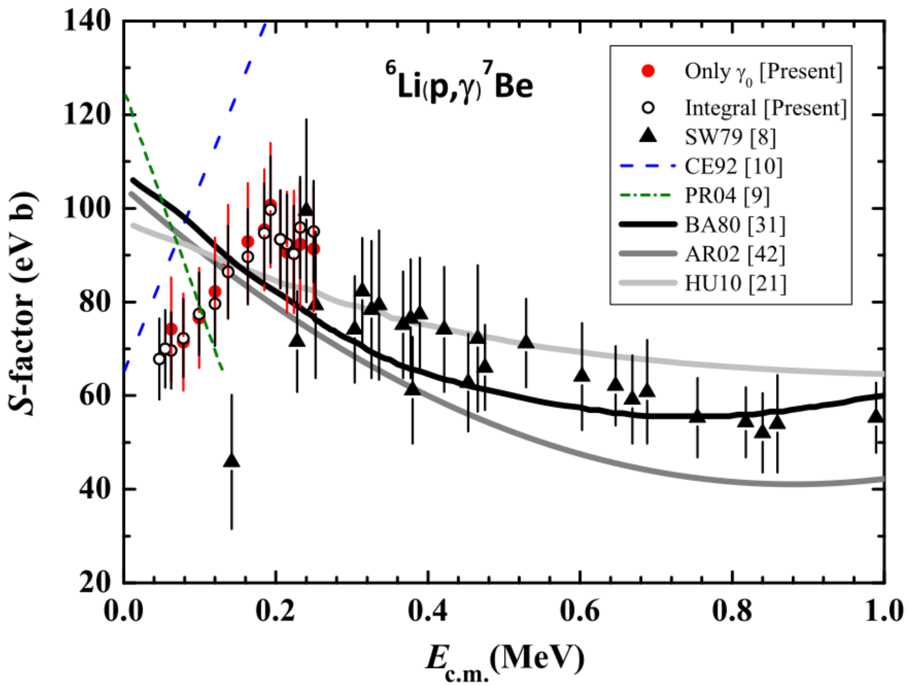




Ongoing experiments: ^{6}Li(p,γ)^{7}Be

The ^{6}Li(p,γ)^{7}Be reaction is involved in Big Bang Nucleosynthesis as well as in lithium depletion in the early stages of stellar evolution.

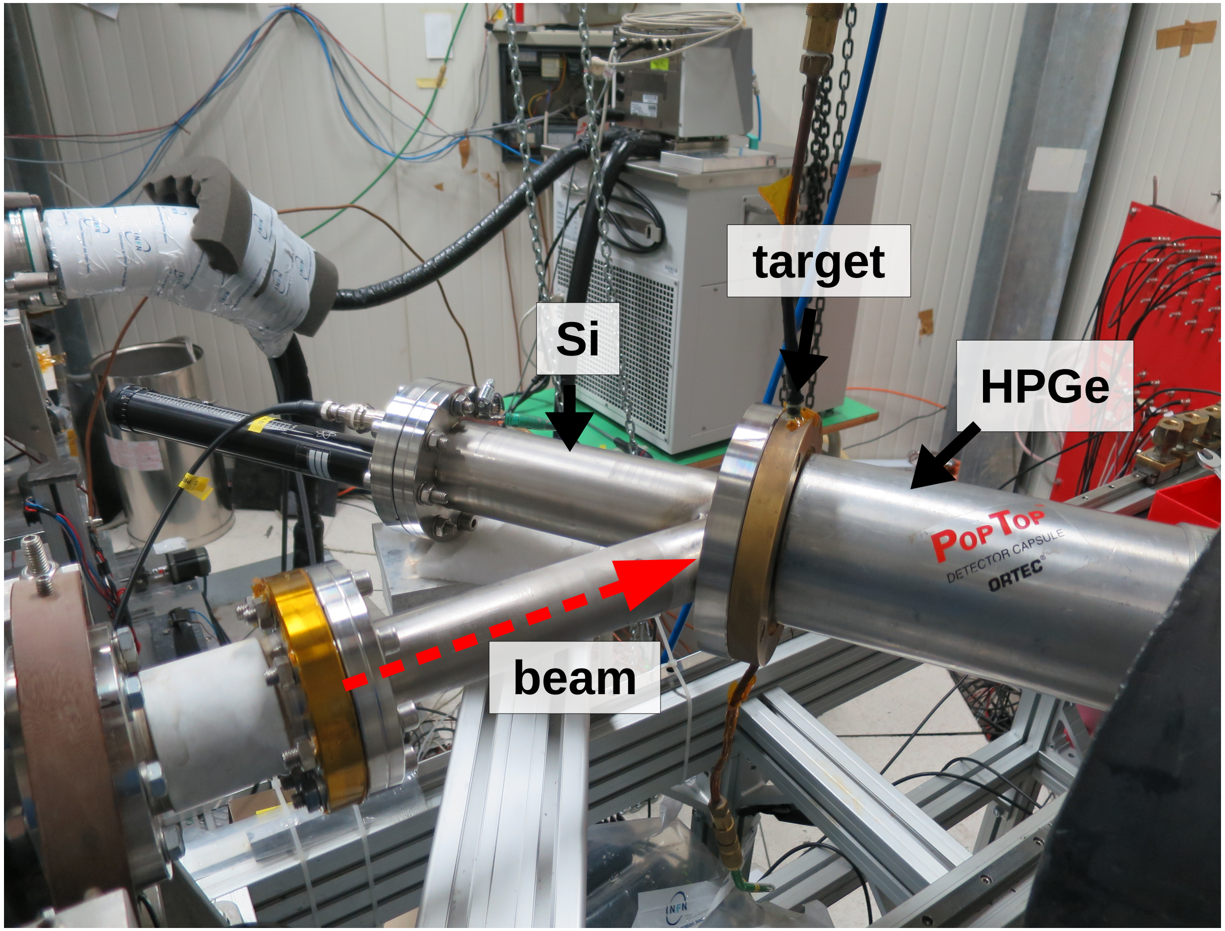
A resonance-like structure in the ^{6}Li(p,γ)^{7}Be cross section at center of mass energy of 195 keV was discovered in a recent experiment [J. J. He et al. Phys. Lett. B 725, 287 (2013)].



Measurement of the ^{6}Li(p,γ)^{7}Be cross section recently performed at LUNA

Ongoing experiments: $^{6}Li(p,\gamma)^{7}Be$

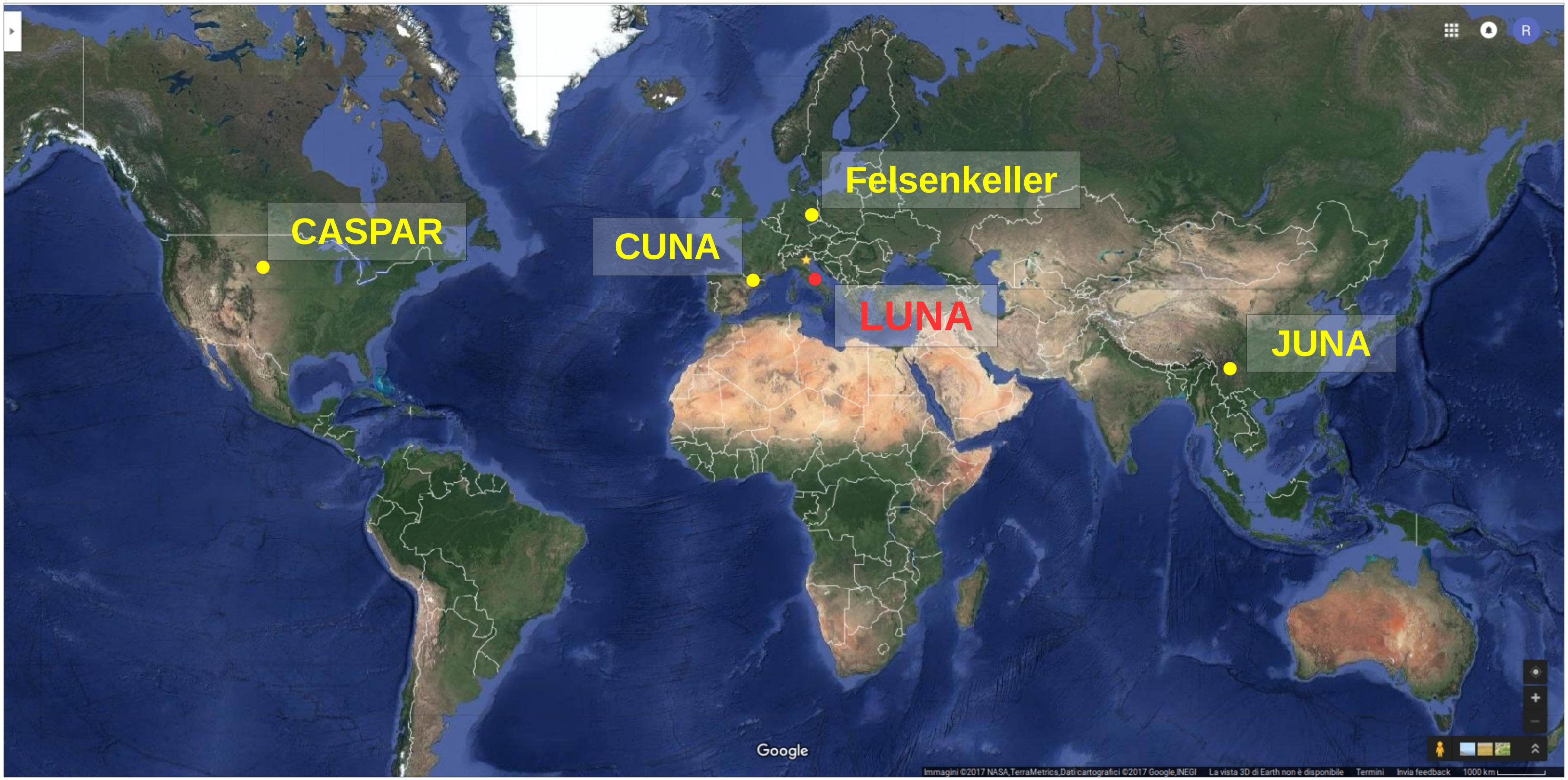
- Ep = 60 – 340 keV
- Evaporated ^{6}Li solid targets (95% isotop. enrichment): $^{6}Li_2O$, $^{6}Li_2WO_4$, $^{6}LiCl$
- 1 HPGe in close geometry
- 1 Si detector for $^{6}Li(p,^{4}He)^{3}He$



Underground laboratories worldwide

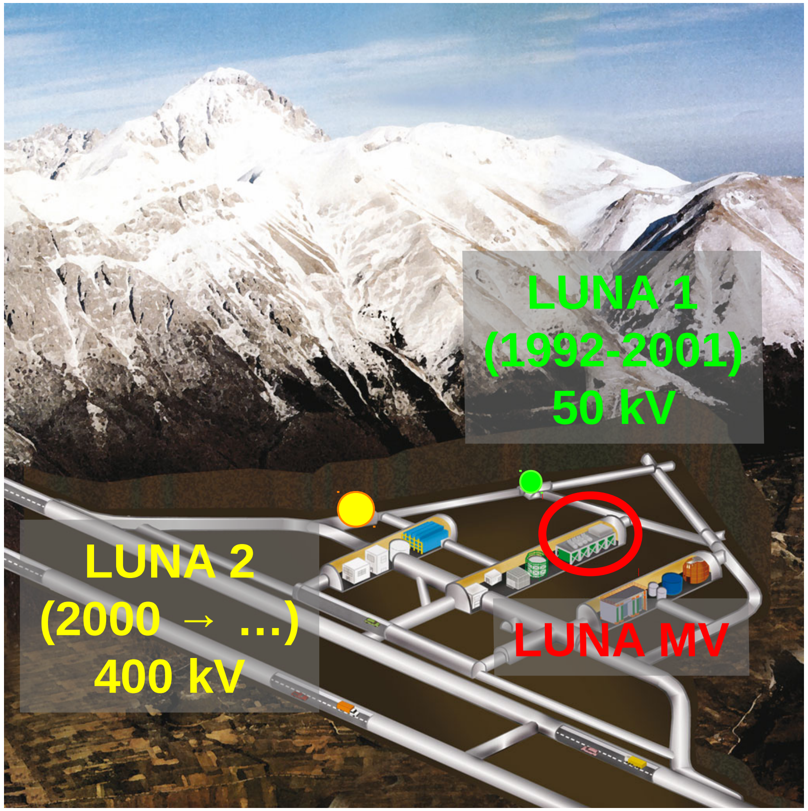
Many reactions cannot be studied with a 400 kV accelerator alone (stellar Helium and Carbon burning, neutron sources for astrophysical s-processes etc):

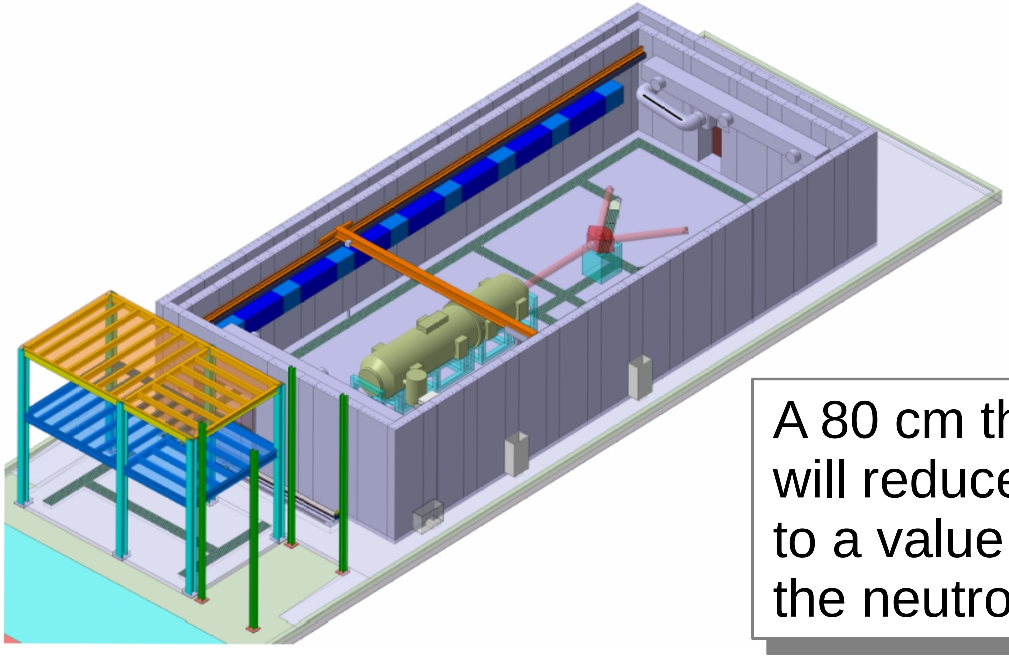
New, higher energy underground accelerators are needed!



The LUNA-MV project

- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE:** 0.2 – 3.5 MV
- **Precision of terminal voltage reading:** 350 V
- **Beam energy reproducibility:** 0.01% TV
- **Beam energy stability:** 0.001% TV / h
- **Beam current stability:** < 5% / h





A 80 cm thick concrete shielding is foreseen. This will reduce the neutron flux just outside the shielding to a value about one order of magnitude lower than the neutron flux at LNGS, $\Phi = 3 \cdot 10^{-6}$ n/(cm^2 s)

LUNA-MV scientific program (2019 - 2023)

In 2016 a scientific proposal has been presented to the LNGS Scientific Committee (SC) containing key reactions (mainly He and C burning and neutron sources for the s-process) to be studied in the first years of the LUNA-MV machine:

$^{14}N(p,\gamma)^{15}O$ at high energies (also used as commissioning measurement)

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

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

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

Many other reactions are extremely important for He and C burning and will be included in the future program of the LUNA-MV

LUNA-MV status and schedule

Action	Date
Beginning of the clearing works in Hall B	February 2017
Beginning of the construction works in Hall B	December 2017
Beginning of the construction of the plants in the LUNA-MV building	March 2018
Completion of the new LUNA-MV building and plants	September 2018
LUNA-MV accelerator delivering at LNGS	December 2018
Conclusion of the commissioning phase	May 2019
Beginning First Experiment	June 2019

Thank you!

The LUNA Collaboration

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