LUNA: from Sun to Novae and beyond

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Men in pits or wells sometimes see the stars….
Aristotle

- Stellar Energy+Nucleosynthesis
- Hydrogen Burning
- $\sigma(E_{star})$ with $E_{star} \ll E_{Coulomb}$

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

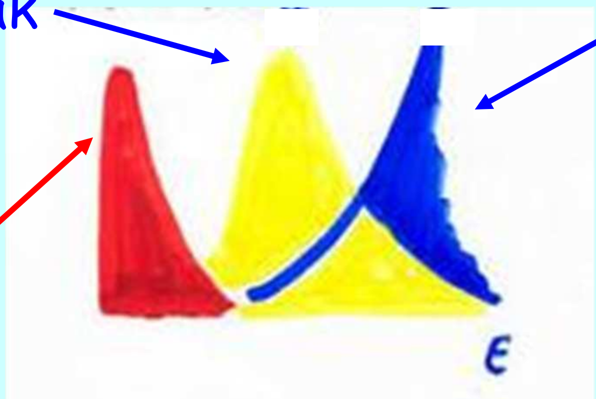
$$2\pi\eta = 31.29\, Z_1 Z_2 \sqrt{\mu/E} \qquad \mu = m_1 m_2 / (m_1+m_2),\ E \text{ in keV}$$

$$\text{Reaction Rate(star)} \div \int \Phi(E)\, \sigma(E)\, dE$$

Gamow Peak

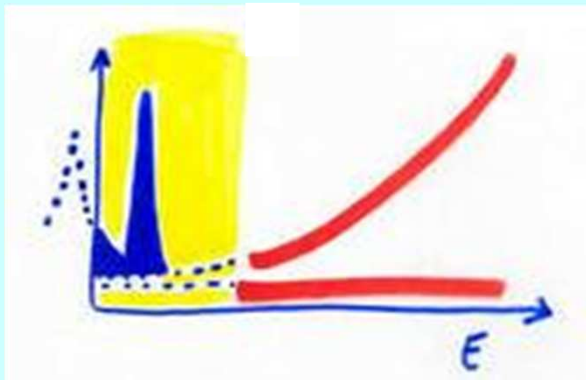
σ

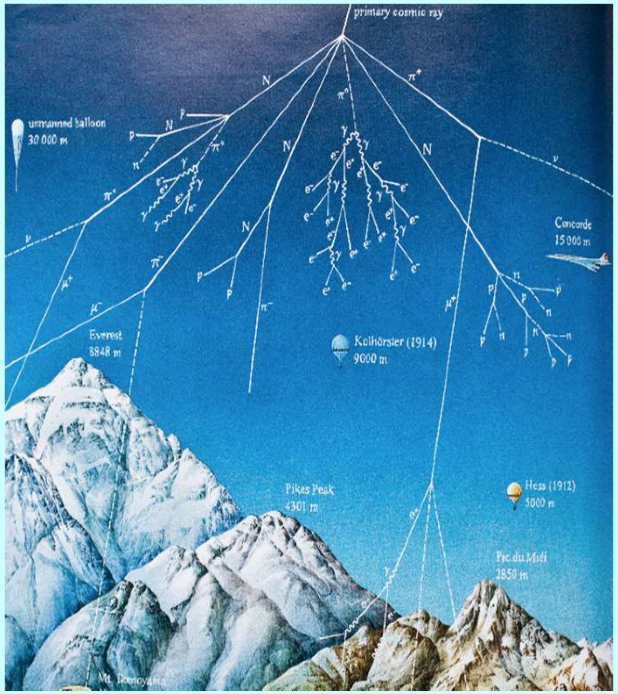
Maxwell Boltzmann



Extrap. ← Meas.→

S(E)

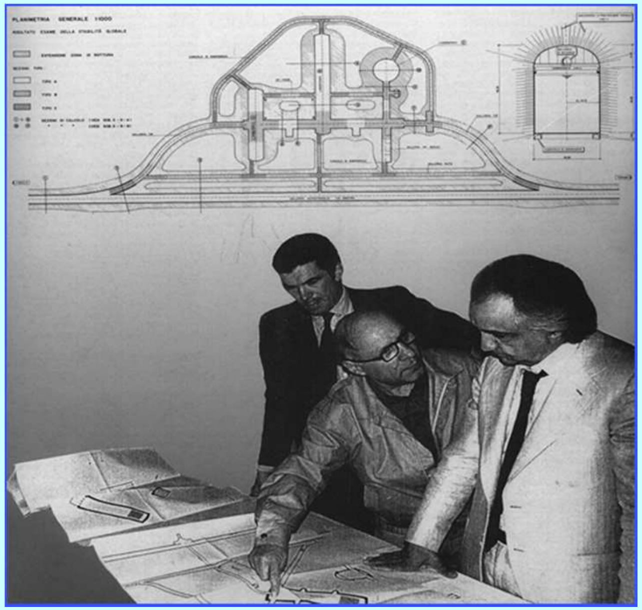


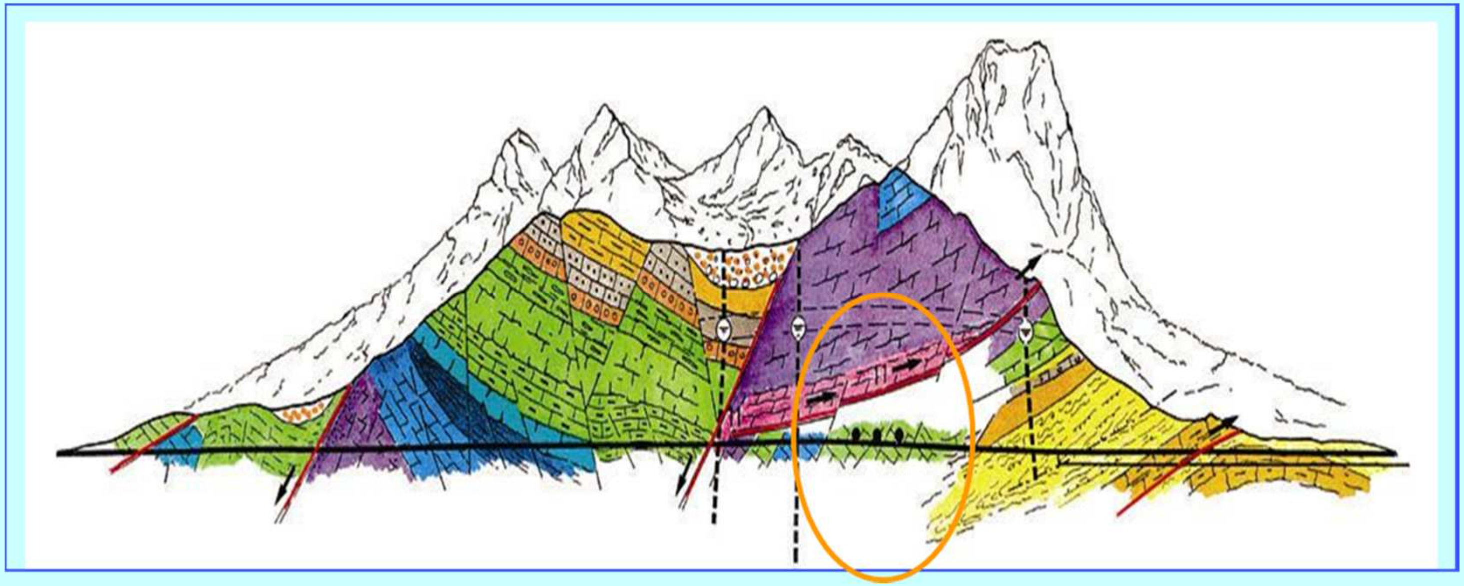


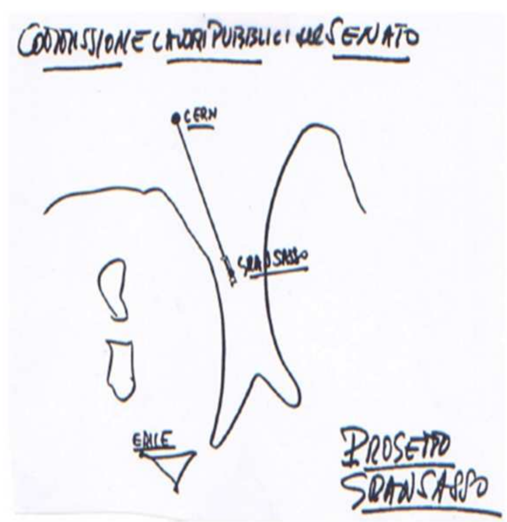
Background due to cosmic rays:
- Electromagnetic component
- Hadrons
- Muons: ionization, spallation, radioactive nuclei, neutrons
- Mu-stop: radioactive nuclei
- Gamma rays

1979 proposal by A. Zichichi

1989 first underground experiment running







Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

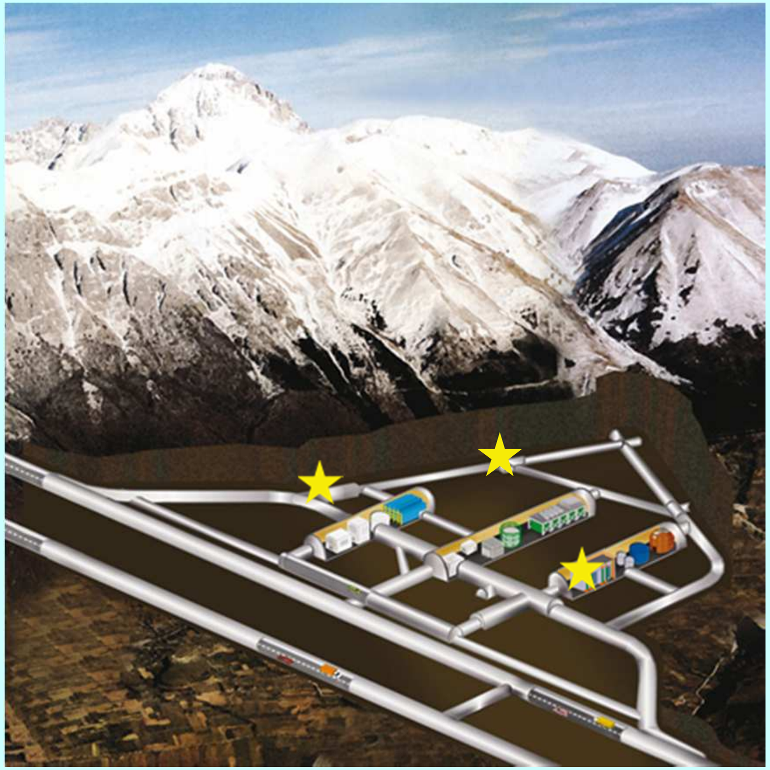
1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

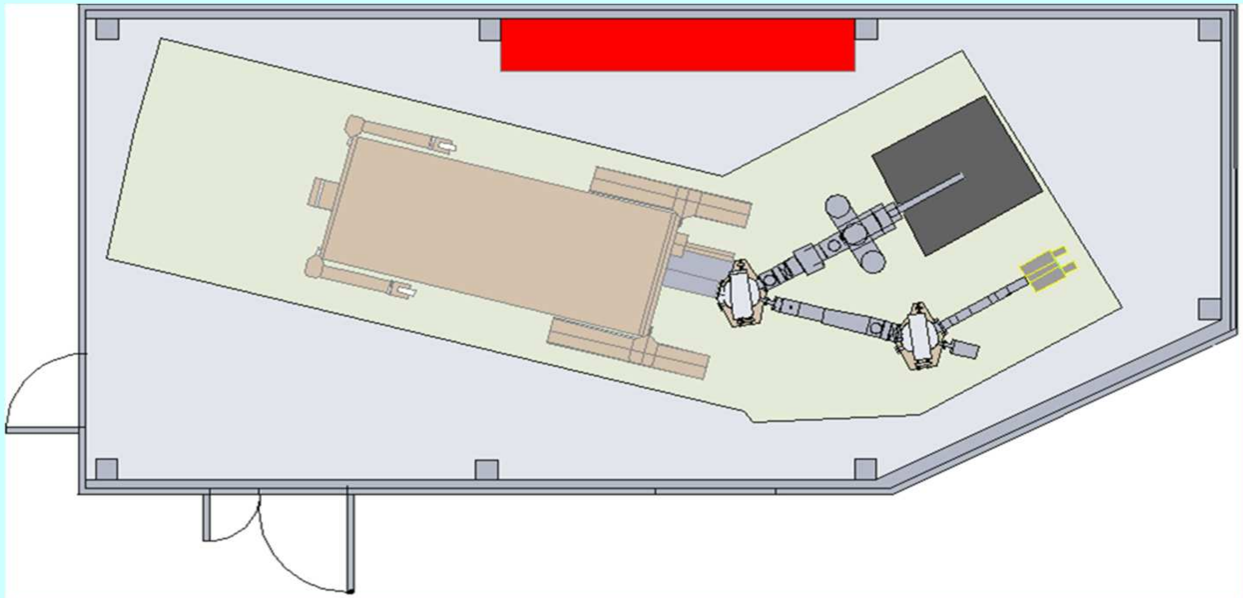
NOT only $\tau_p \neq \infty$

Surface: 17 800 m^2, Volume: 180 000 m^3, Ventilation: 1 vol / 3 hours
Muon flux: 3.0 10^{-8} cm^{-2}s^{-1}

Neutron flux, mainly from (α,n) : 2.92 10^{-6} cm^{-2}s^{-1} (0-1 keV), 0.86 10^{-6} cm^{-2}s^{-1} (> 1 keV)
Rn in air: 20-80 Bq m^{-3}

Laboratory for Underground Nuclear Astrophysics: LUNA

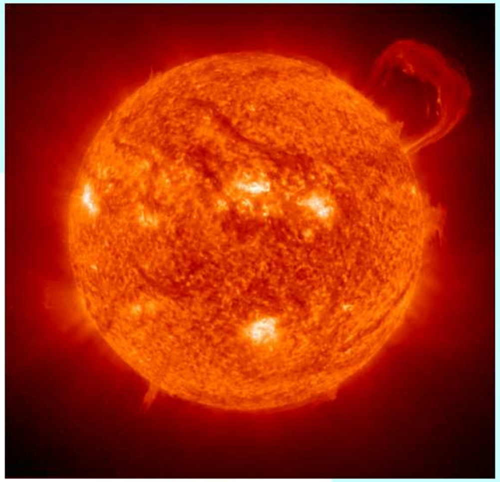


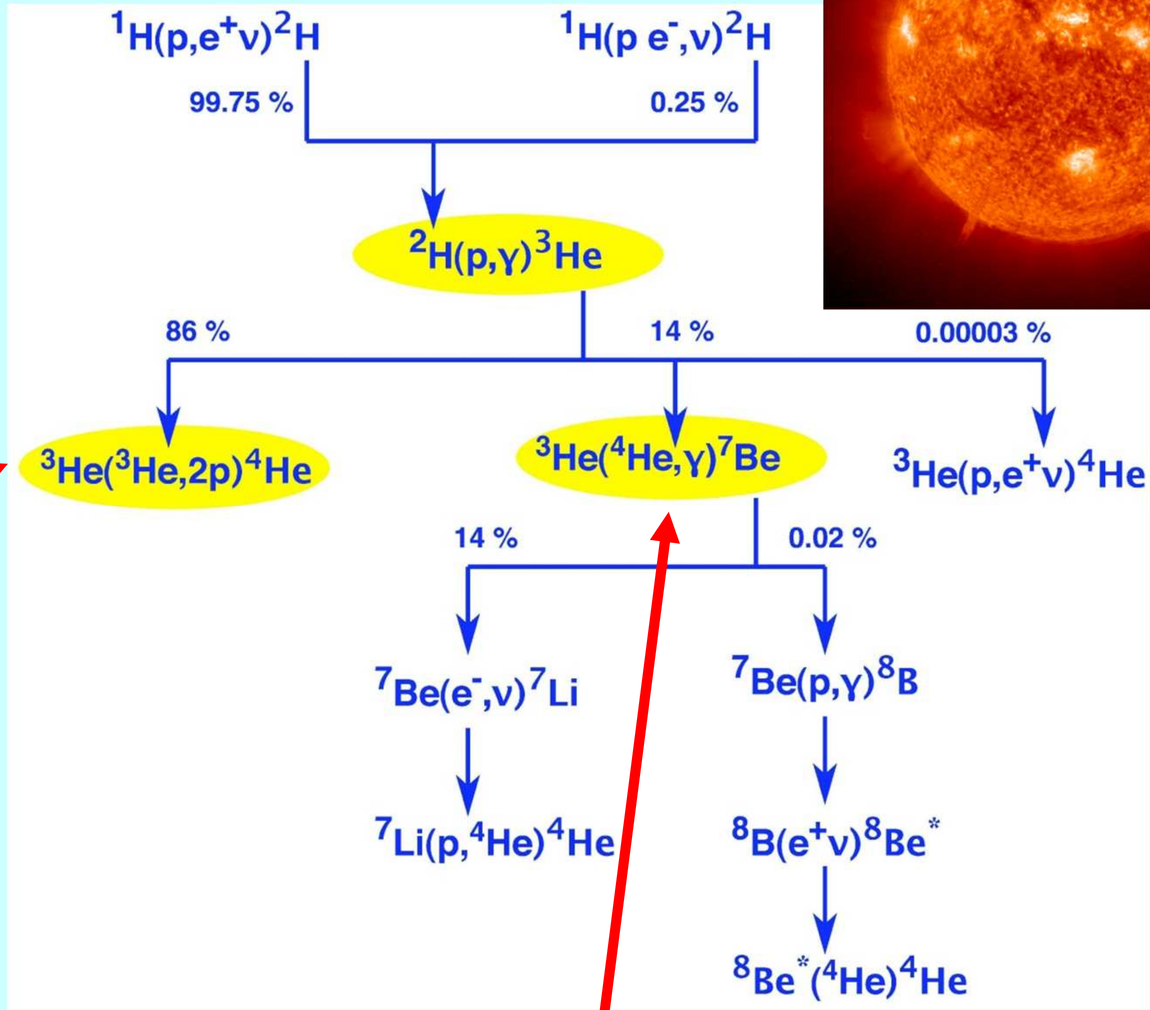


Beam: H,He
Voltage Range :50-400 kV
Output Current: ~1 mA
Absolute Energy error
±300 eV
Beam energy spread:
<100 eV
Long term stability (1 h) :
5 eV
Terminal Voltage ripple:
5 Vpp Ge detector

Hydrogen burning in the Sun @$15*10^6$ degrees:

$6*10^{11}$ kg/s H ⟶ He
+0.7% M_H ⟶ E

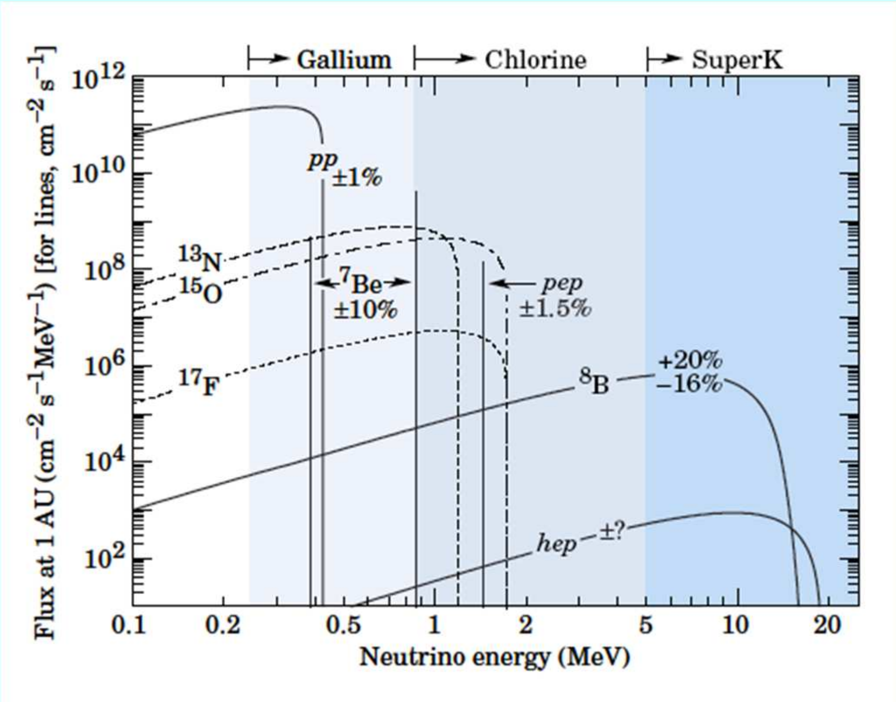




^{3}He burning in the p-p chain

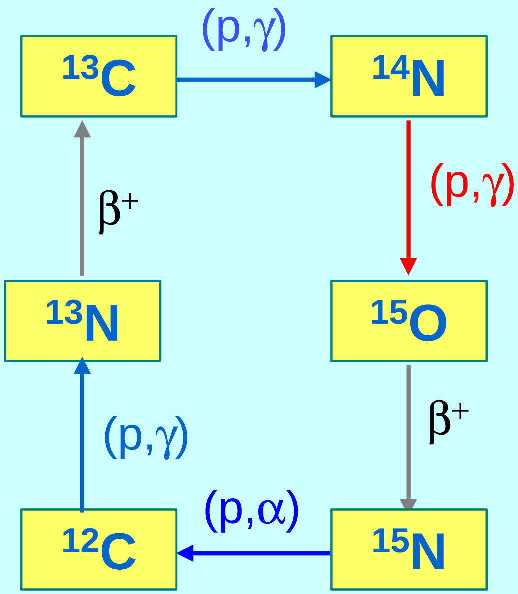
no resonance
@ solar Gamow peak

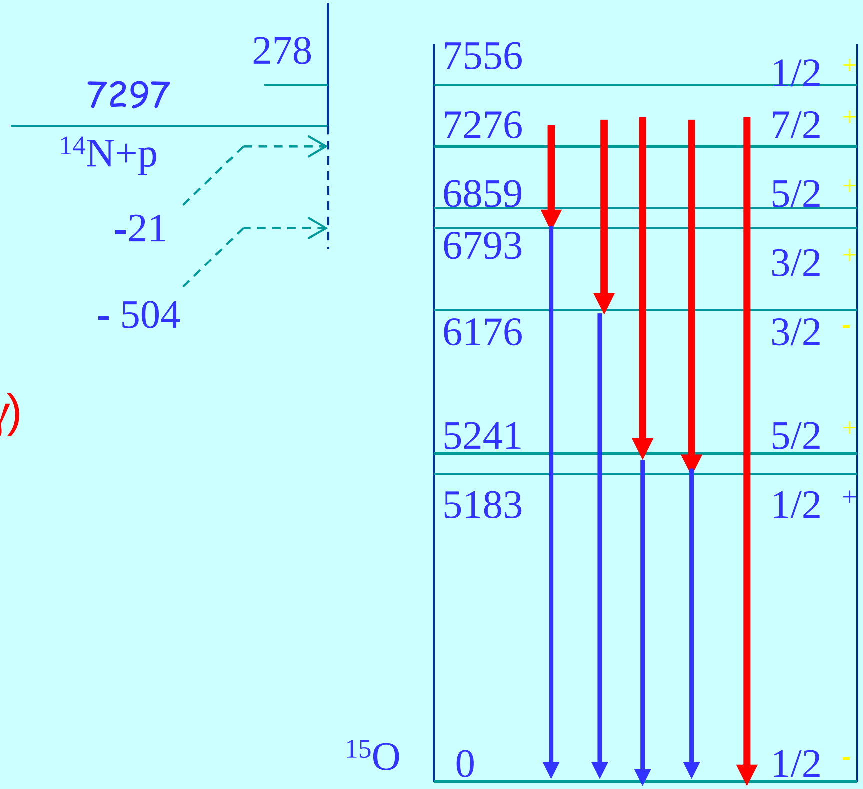
activation=prompt gamma
no monopole contribution to σ
σ at low energy with 4% error



The CNO Cycle

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

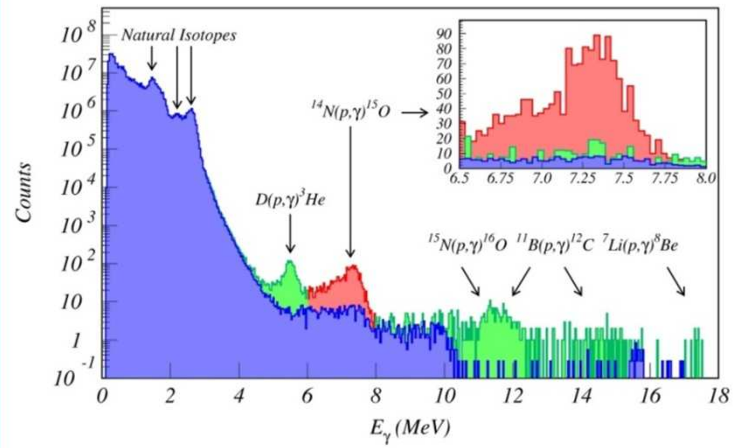




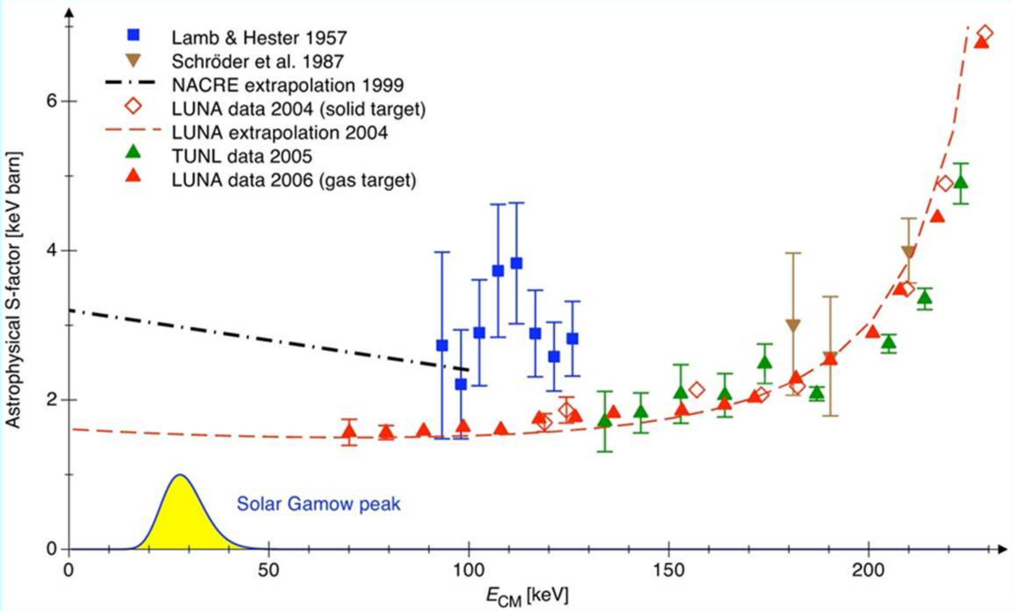
1) "High" energy: solid target + HpGe

2) Low energy: gas target + BGO

beam energy 90 keV



$S_{1}(0)$=1.57±0.13 keV b
as reported by indirect measurements
(Mukhamedzhanov et al. 2003)

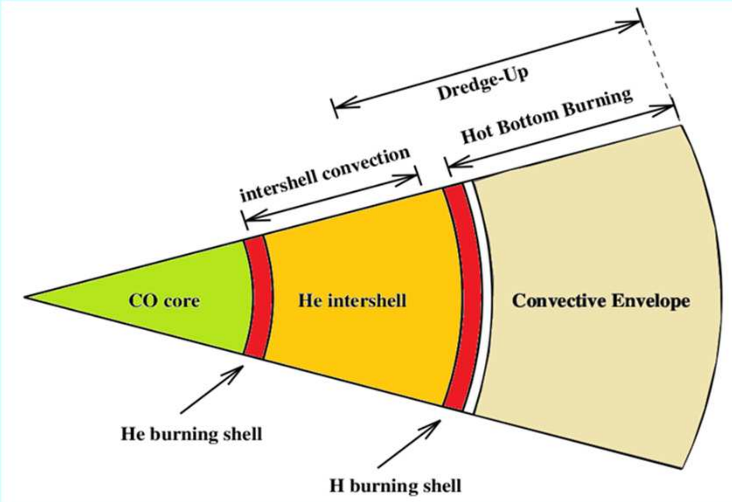


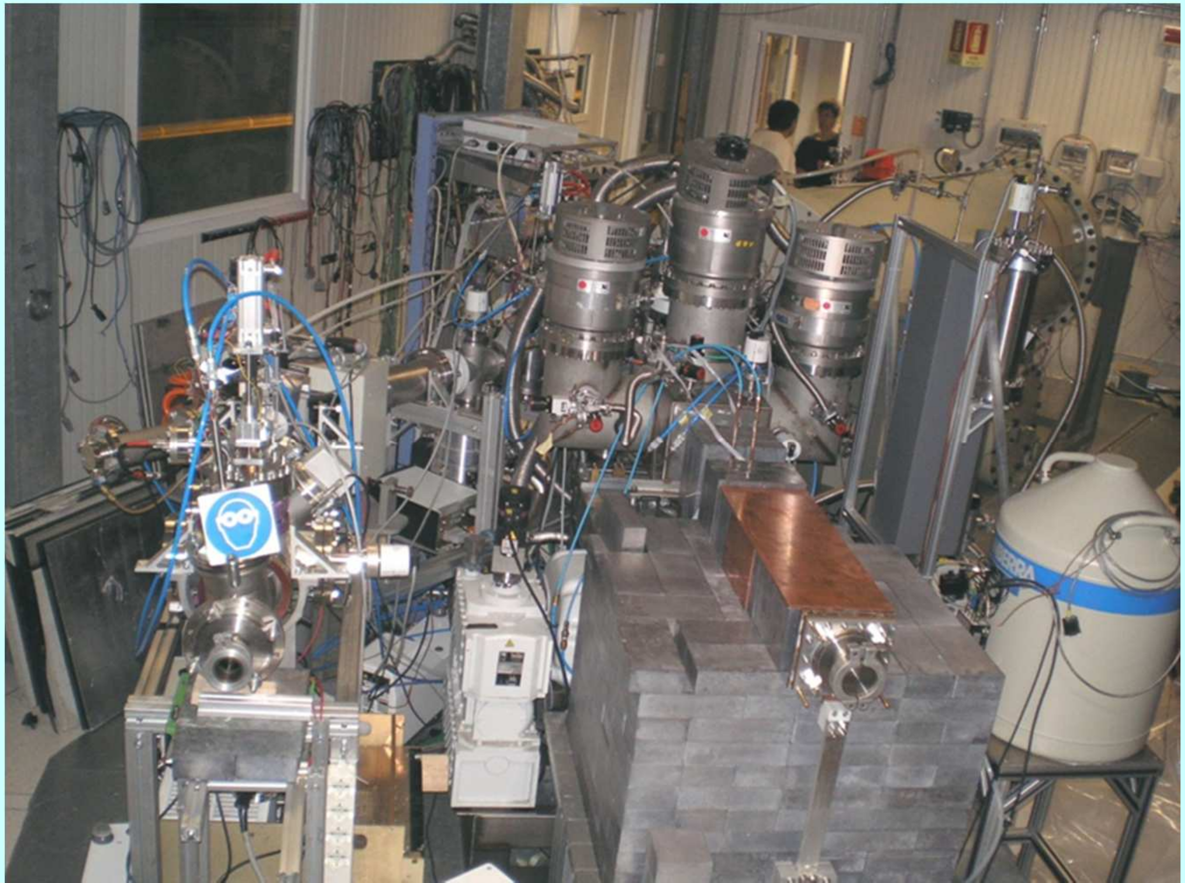
* $\frac{1}{2}\nu_{cno}$ from the Sun
* Globular Cluster age +1Gy
* more C at the surface of AGB

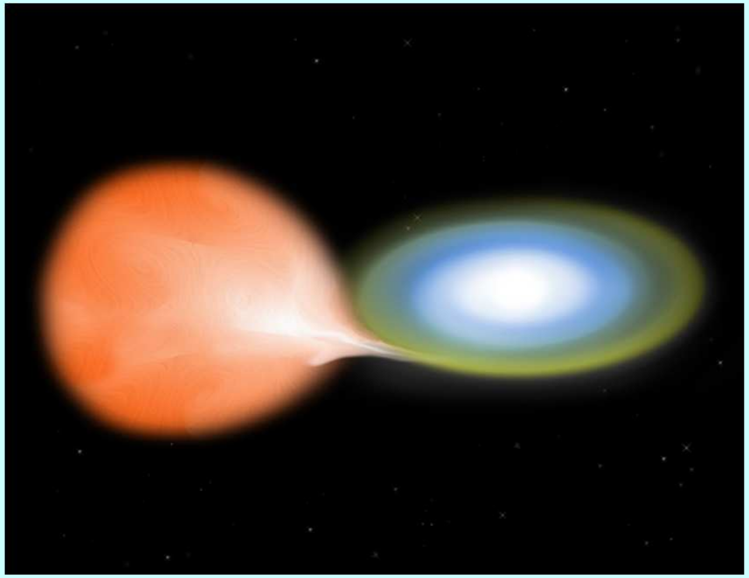
$$\nu_{cno} = F(S_{1,14}, Z_{core})$$

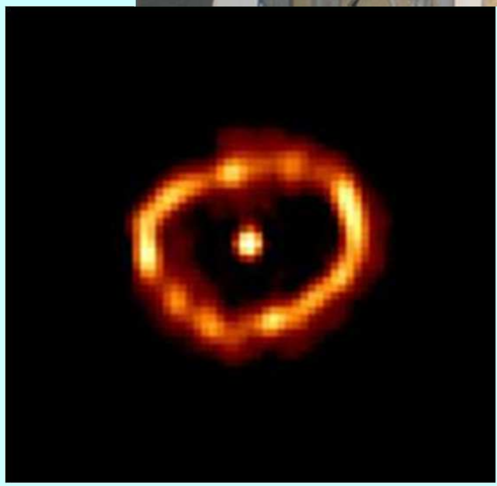
probe of the metallicity Z of the Sun core

LUNA beyond the Sun: isotope production in the hydrogen burning shell of AGB stars (~30-100 T_6), Nova nucleosynthesis (~100-400 T_6) and BBN









Nova Cigni 1992

$^{15}N(p,\gamma)^{16}O$ Q=12.13 MeV

$^{25}Mg(p,\gamma)^{26}Al$ Q=6.3 MeV

$^{17}O(p,\gamma)^{18}F$ Q=5.6 MeV

$^{2}H(\alpha,\gamma)^{6}Li$ Q=1.47 MeV, **BBN**

$^{17}O(p,\alpha)^{14}N$ Q=1.2 MeV

$^{18}O(p,\gamma)^{19}F$ Q=8.0 MeV

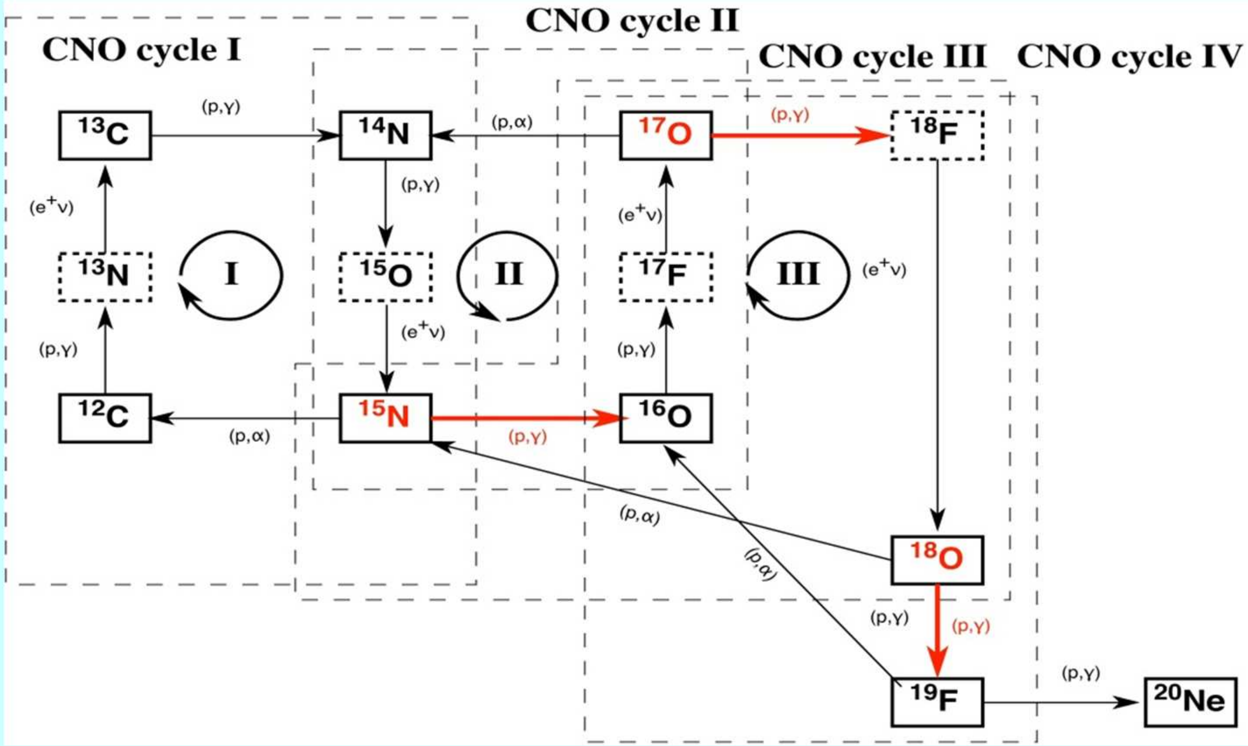
$^{22}Ne(p,\gamma)^{23}Na$ Q=8.8 MeV R. Depalo talk

$^{18}O(p,\alpha)^{15}N$ Q=4.0 MeV

$^{23}Na(p,\gamma)^{24}Mg$ Q=11.7 MeV

. . . .

Isotopic abundances: how and where



Production of $^{26}Al^{gs}$ in H-burning regions is less efficient than previously obtained

Uncertainty on ^{16}O, ^{17}O, ^{18}O, ^{18}F and ^{19}F at Nova temperature less than 10% (from 40-50%)

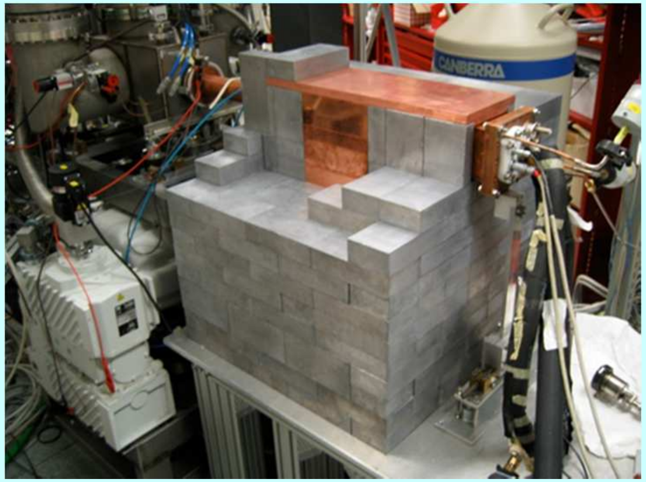
Big Bang Nucleosynthesis

$D(\alpha,\gamma)^6Li$ Q=1.47 MeV

The ^6Li problem: in some very old stars $^6Li/^7Li$ measured (from the asymmetry of the ^7Li absorption line) ~$5*10^{-2}$, BBN predicted ~10^{-5}

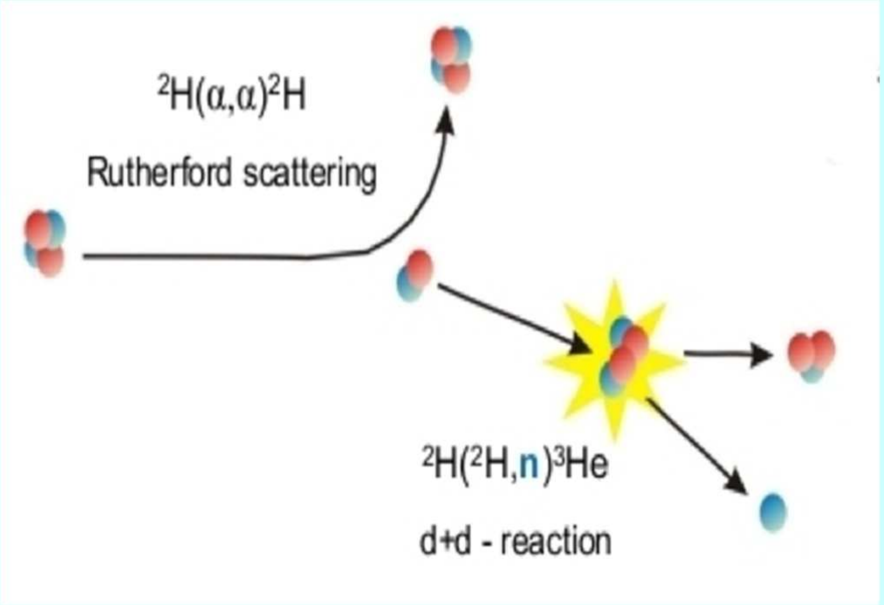
^6Li source: $D(\alpha,\gamma)^6Li$, measured only down to 711 keV (BBN production below 400 keV)

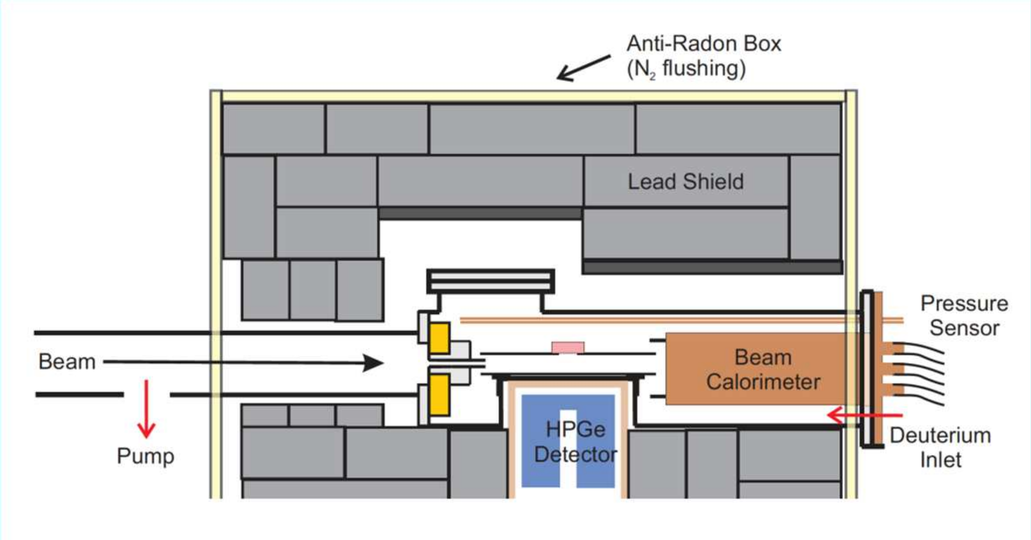
Possible nuclear explanation of the ^6Li problem?

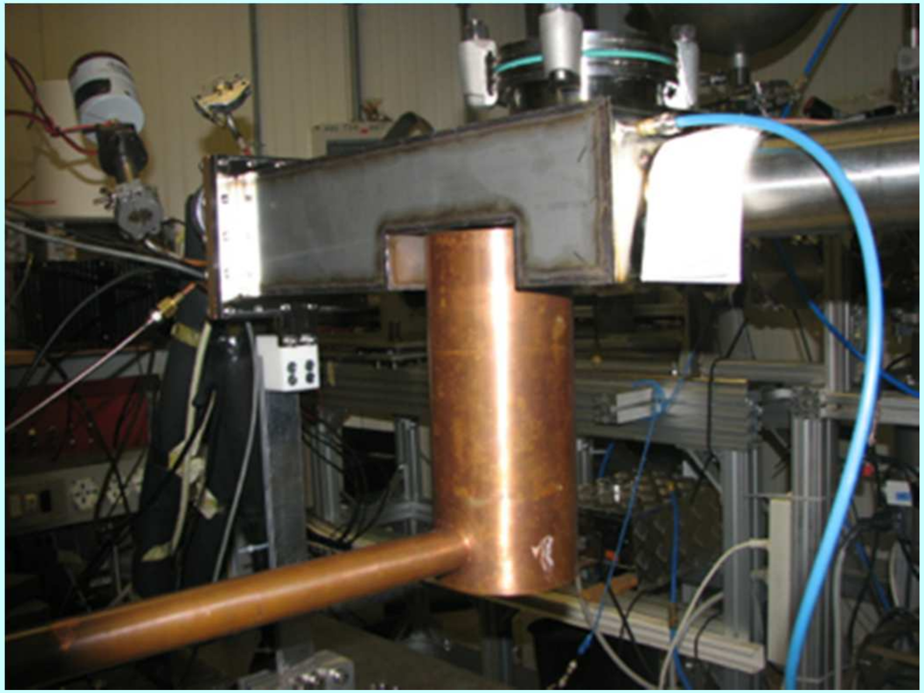


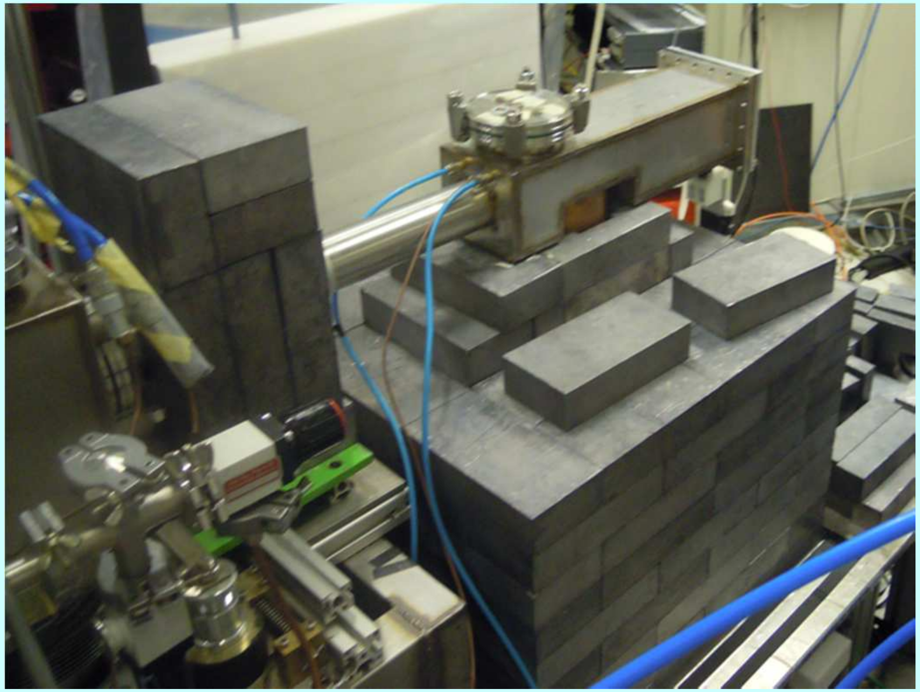
~$^3He(\alpha,\gamma)^7Be$ set-up (similar Q-value) but…

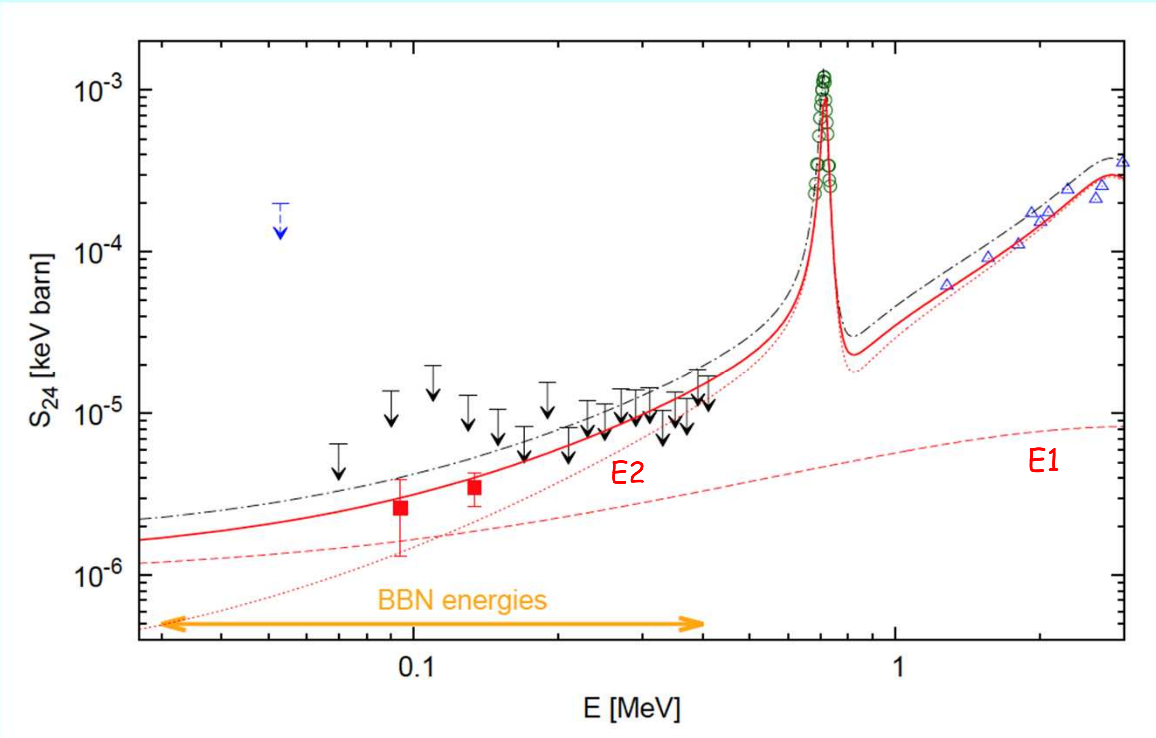
important γ background due to (n,n' γ) on Ge, Cu, Fe…..











A.M. Mukhamedzhanov et al., 2011

F. Hammache et al., 2010

LUNA results, 2014, PRL 113, 042501

J. Kiener et al., 2010

F.E. Cecil et al., 1996

R.G.H. Robertson et al., 1981

P. Mohr et al., 1994

BBN predictions with LUNA results:
$^{6}Li/^{7}Li = (1.5 \pm 0.3) * 10^{-5}$, no nuclear solution

What Next: 3.5 MV accelerator mainly devoted to Helium-Burning (in stars: ~100 T_6, ~10^5 gr/cm^3)

$^{12}C(\alpha,\gamma)^{16}O$ the most important reaction of nuclear astrophysics: production of the elements heavier than A=16, star evolution from He burning to the explosive phase (core collapse and thermonuclear SN) and ratio C/O

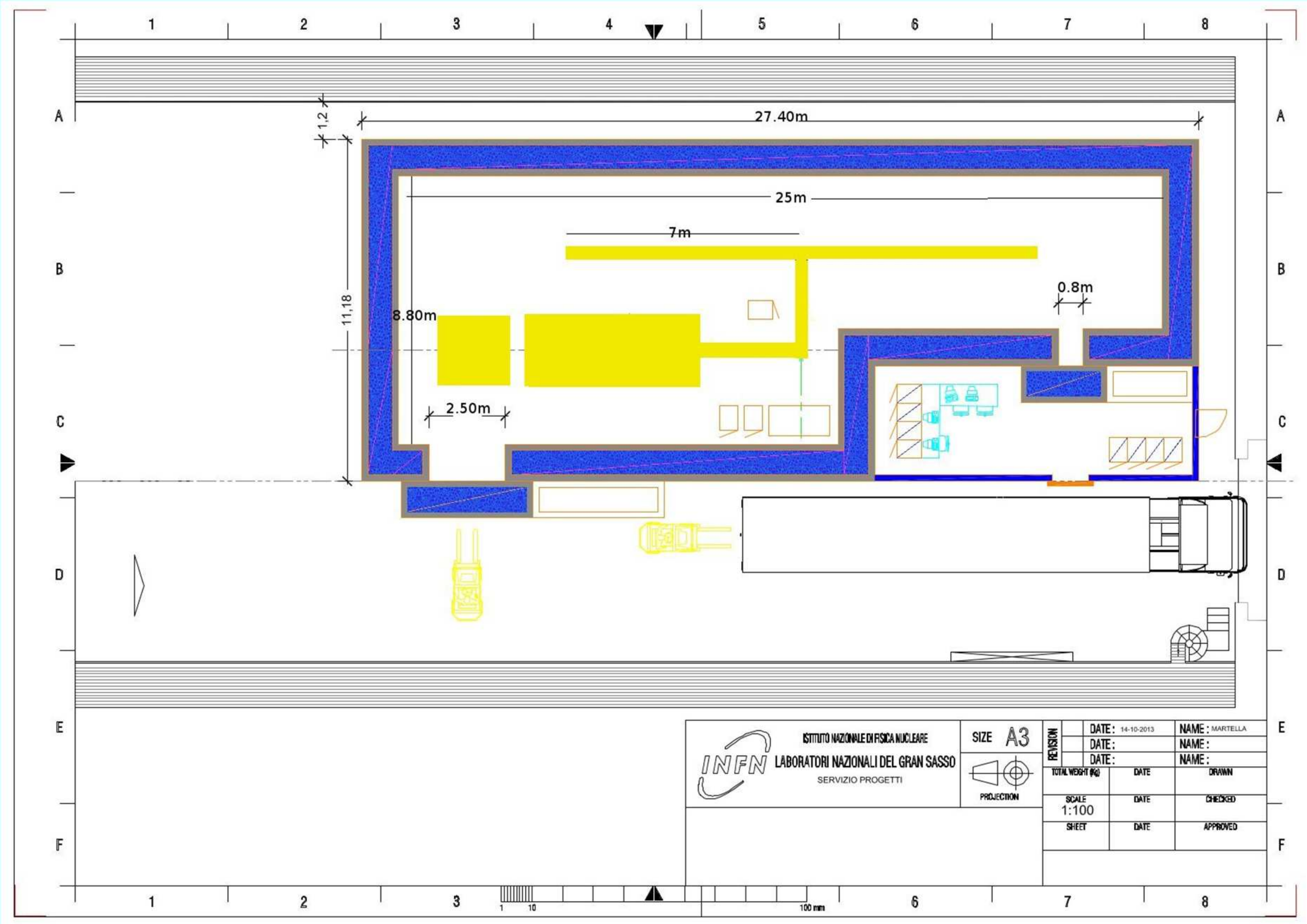
Sources of the neutrons responsible for the S-process: 50% of the elements beyond Iron

$^{13}C(\alpha,n)^{16}O$: isotopes with A≥90 during AGB phase of low mass stars

$^{22}Ne(\alpha,n)^{25}Mg$: isotopes with A<90 during He and C burning in massive stars

(α,γ) on ^{3}He, ^{14}N, ^{15}N, ^{18}O……

LUNA-MV accelerator financed by MIUR, to be installed in Hall C of LNGS (Opera space), very preliminary design



- $^3He(^3He,2p)^4He$: σ down to 16 keV
  no resonance within the solar Gamow Peak
- $^3He(\alpha,\gamma)^7Be$: $^7Be \approx$ prompt γ , cross section measured with 4% error
- $^{14}N(p,\gamma)^{15}O$: σ down to 70 keV

  ν_{cno} reduced by ~ 2 with 8% error → Sun core metallicity
  Globular cluster age increased by 0.7-1 Gy
  More carbon at the surface of AGB stars
- $^{15}N(p,\gamma)^{16}O$: σ down to 70 keV, reduced by ~ 2
- $^{25}Mg(p,\gamma)^{26}Al$: first measurement of the 92 keV resonance,
  strength $\omega\gamma=(2.9\pm0.6)\times 10^{-10}$ eV
- $^{17}O(p,\gamma)^{18}F$: rate uncertainty @ Novae temperature reduced to 5%
  → uncertainty on ^{18}O, ^{18}F and ^{19}F less than 10% (from 40-50%)
- $D(\alpha,\gamma)^6Li$: no nuclear solution to the ^6Li problem
- Future: Hydrogen and **Helium** burning (3.5 MV accelerator)

LUNA Collaboration

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