The LUNA experiment

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

Carlo Broggini
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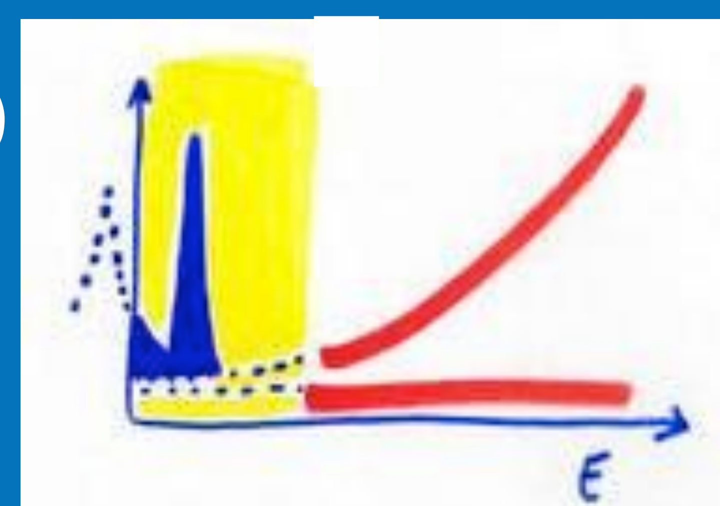
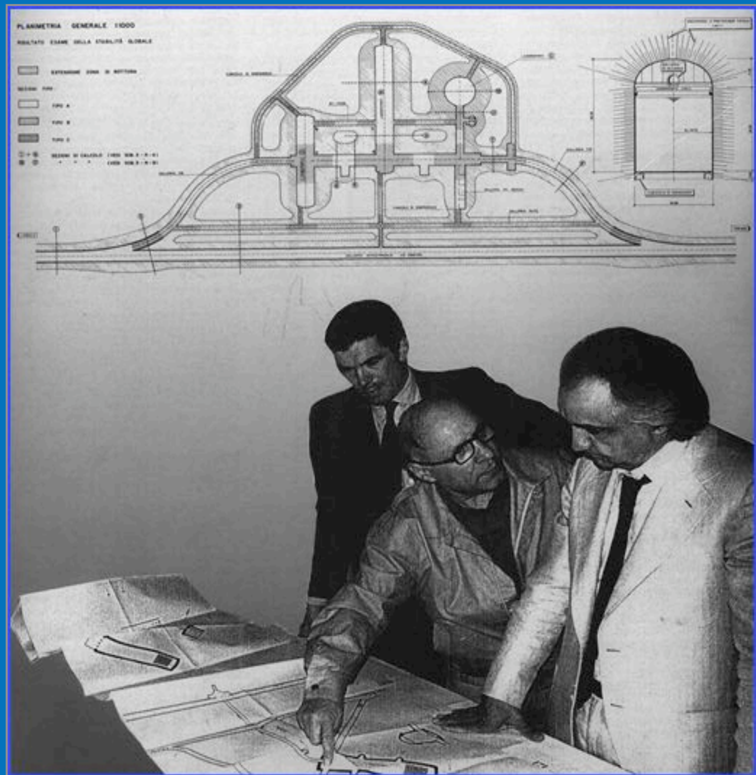
- Stellar Energy+Nucleosynthesis
- H Burning (past and present) + He and C Burning
- $\sigma(E_{star})$ with $E_{star} \ll E_{Coulomb}$

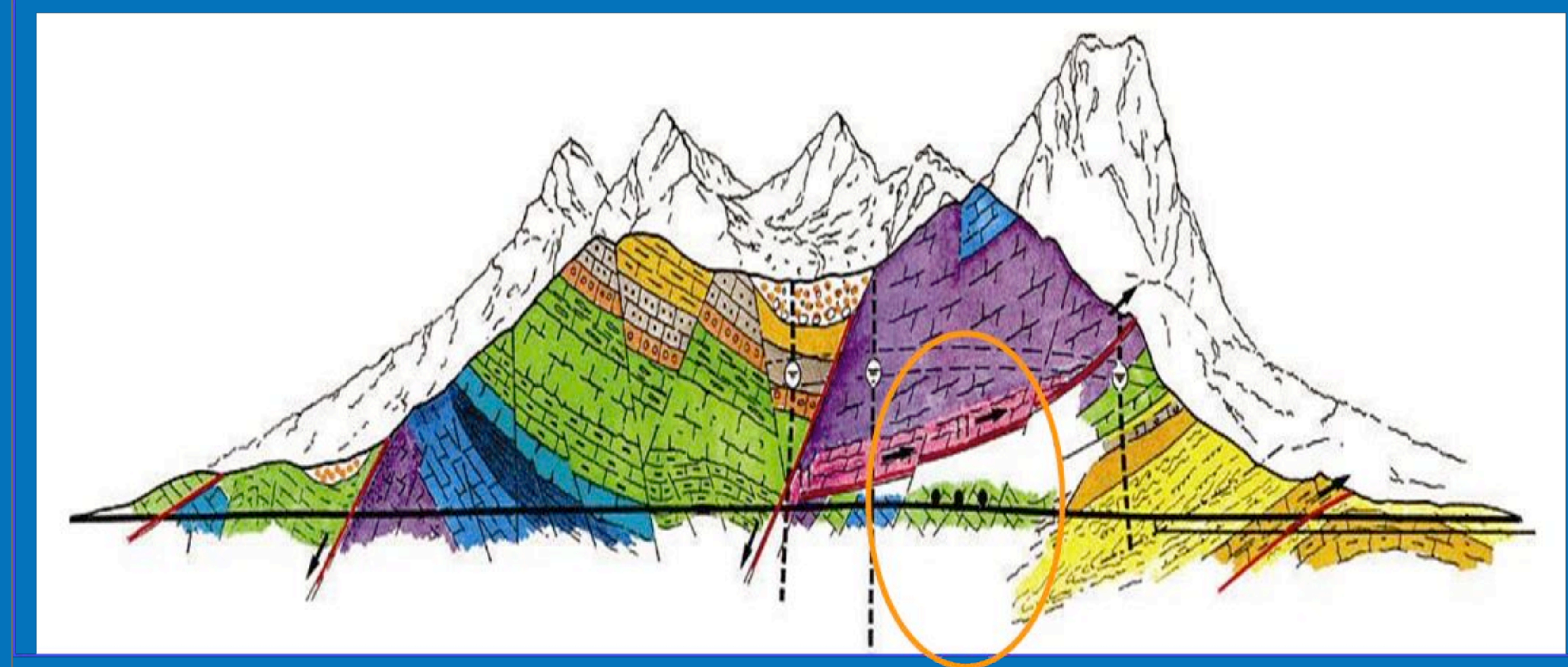
$$\sigma(E) = S(E)\, e^{-2\pi\eta}\, E^{-1}$$

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

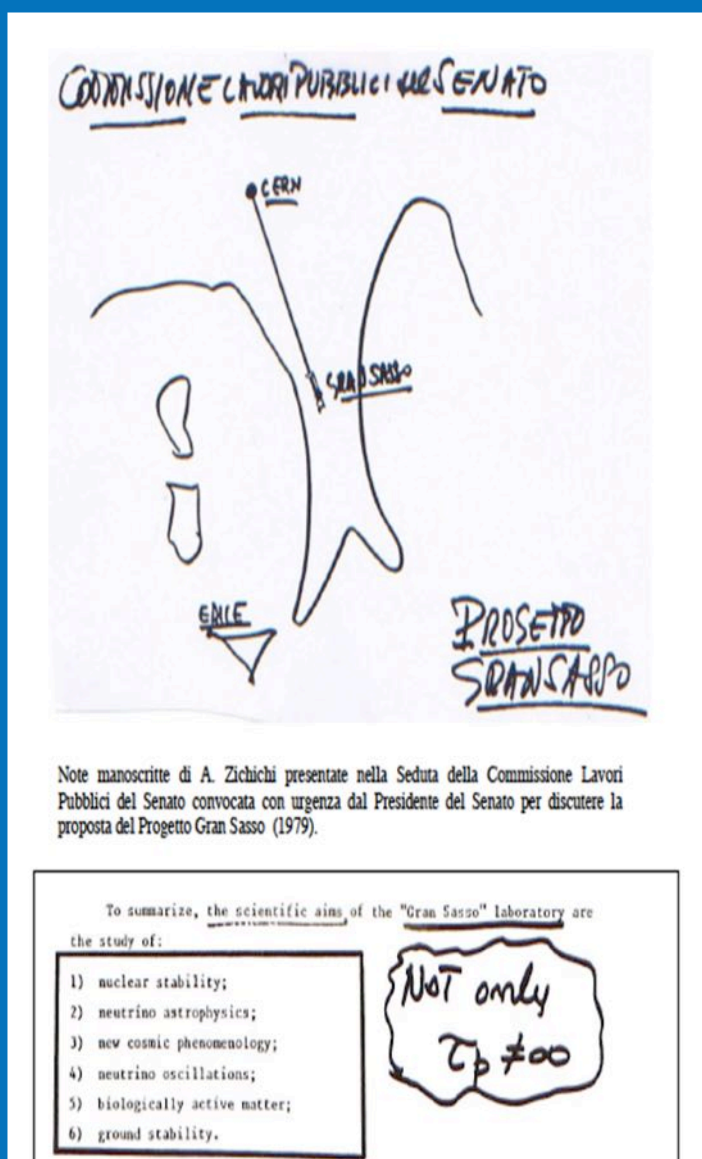
$$\text{Reaction Rate(star)} \div \int \Phi(E)\, \sigma(E)\, dE$$







1979 proposed by A. Zichichi , 1989 MACRO experiment ON



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.

1400 m of dolomite rock, $CaMg(CO_3)_2$, (~3800 m w.e.)
Surf.: 17 800 m^2, Vol.: 180 000 m^3, Ventilation: 1 vol / 3.5 hours (Rn in air 20-80 Bq m^{-3})

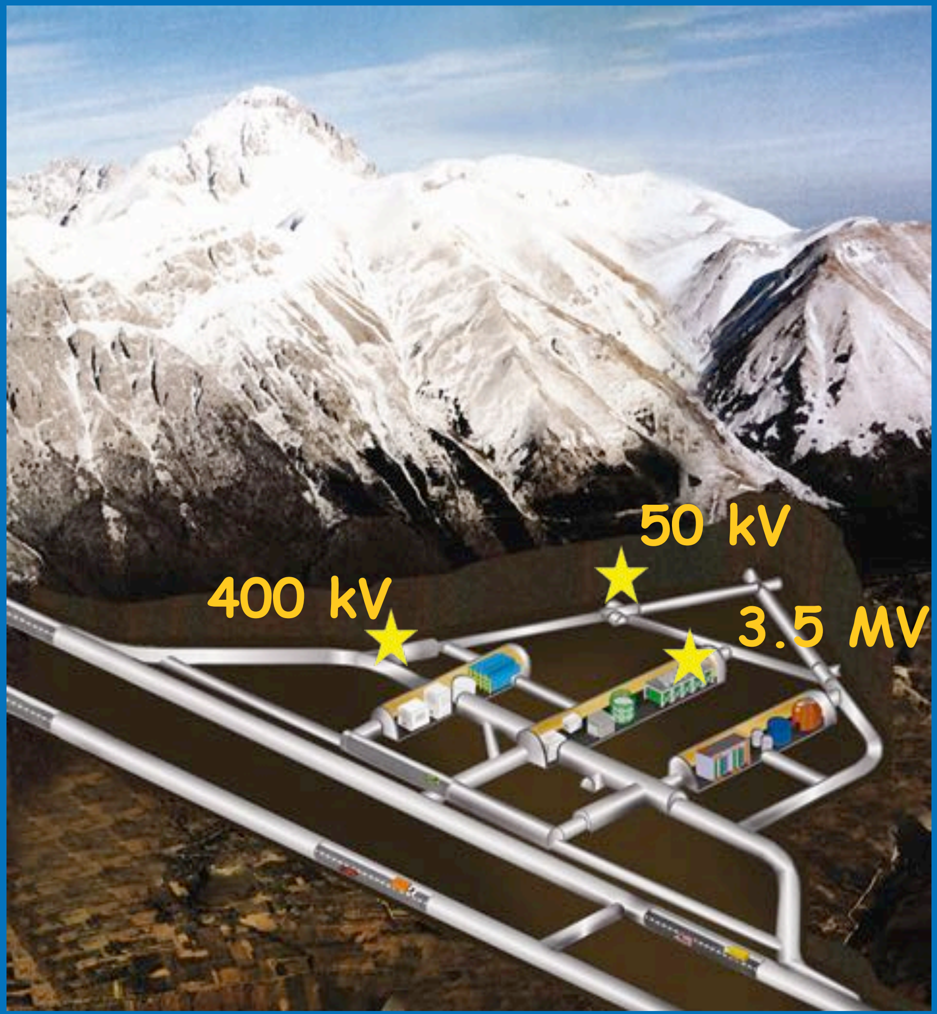
Muon flux: 1.1 $m^{-2}h^{-1}$, 6 orders of magnitude reduction

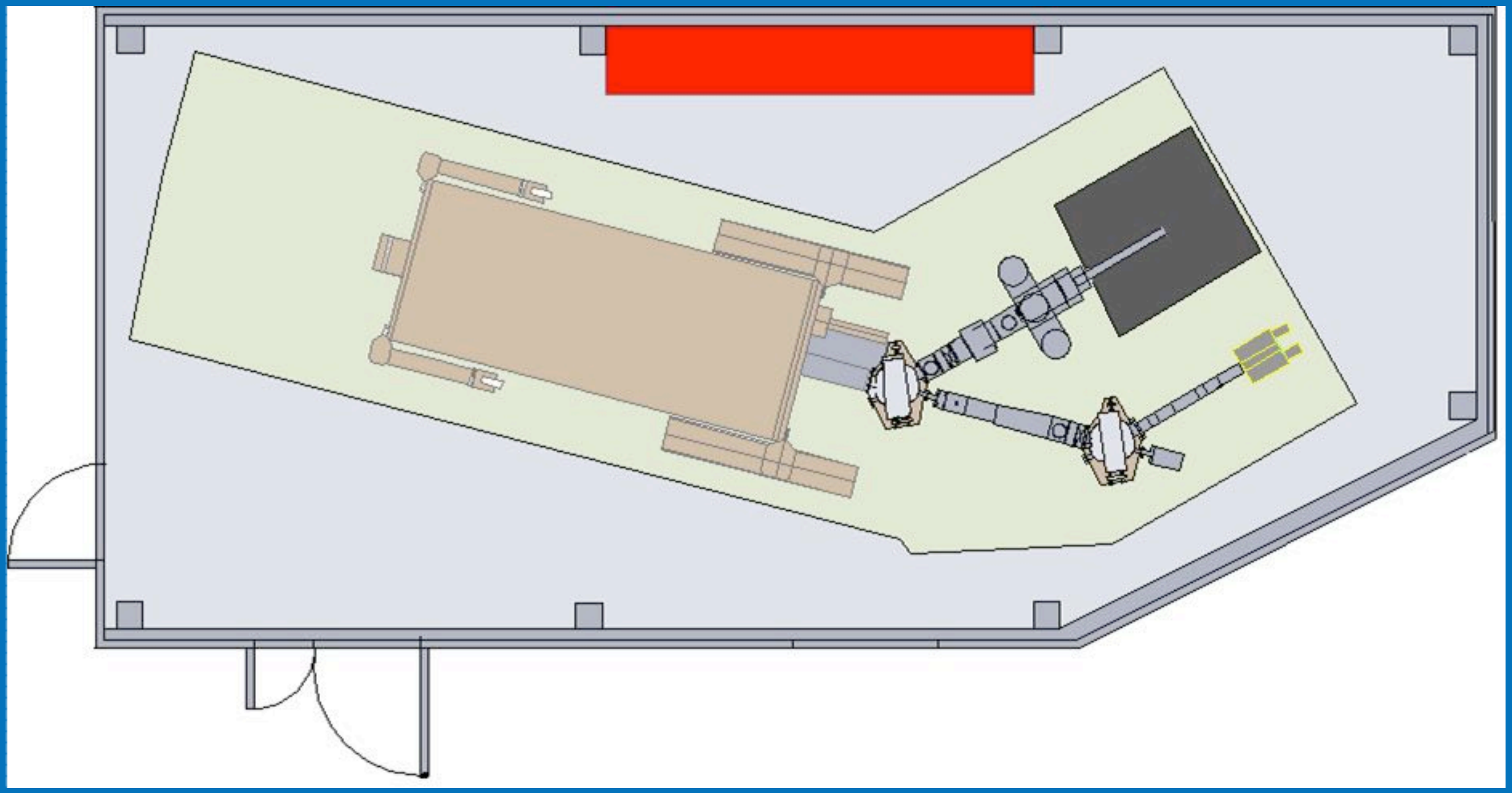
Neutron flux, mainly from (α,n): 2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV), 0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV), 3 orders of magnitude reduction

Gamma rays: only 1 order of magnitude reduction, but with thick shield about 5 orders of magnitude in the region of natural radioactivity and 4-5 orders above 3.2 MeV without any shield

Alpha particles: factor ~15 below 3 MeV (shielded Si detector)

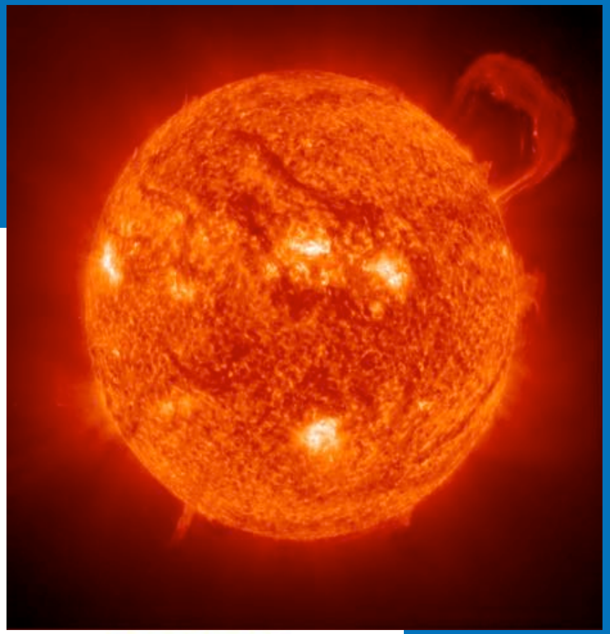
Laboratory for Underground Nuclear Astrophysics: LUNA





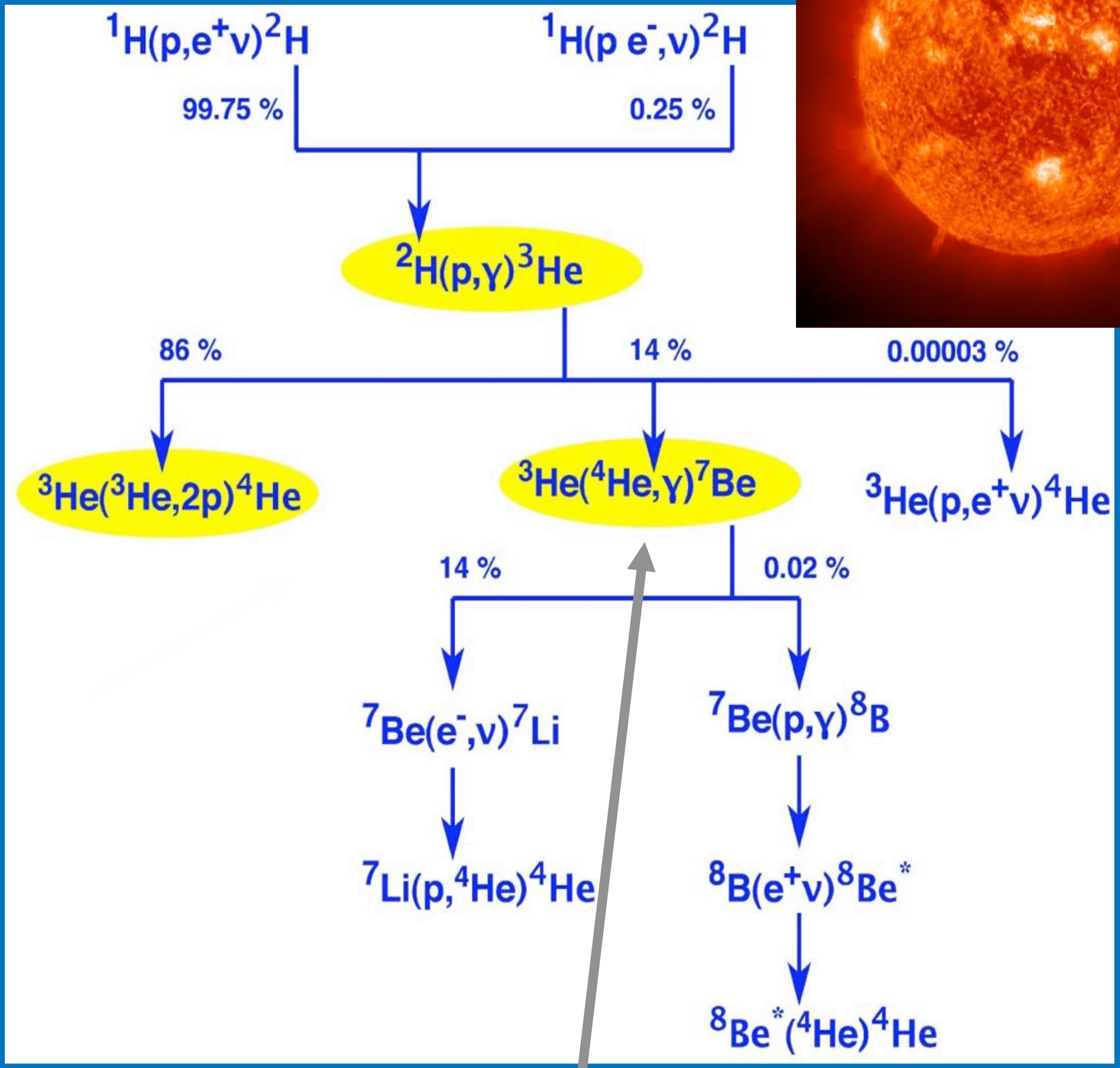
Beam: H,He
Voltage Range :50-400 kV
Output Current: ~1 mA
Absolute Energy error
±300 eV
Beam energy spread:
<100 eV
Long term stability (1 h) :
5 eV
Terminal Voltage ripple:
5 Vpp Ge detector

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

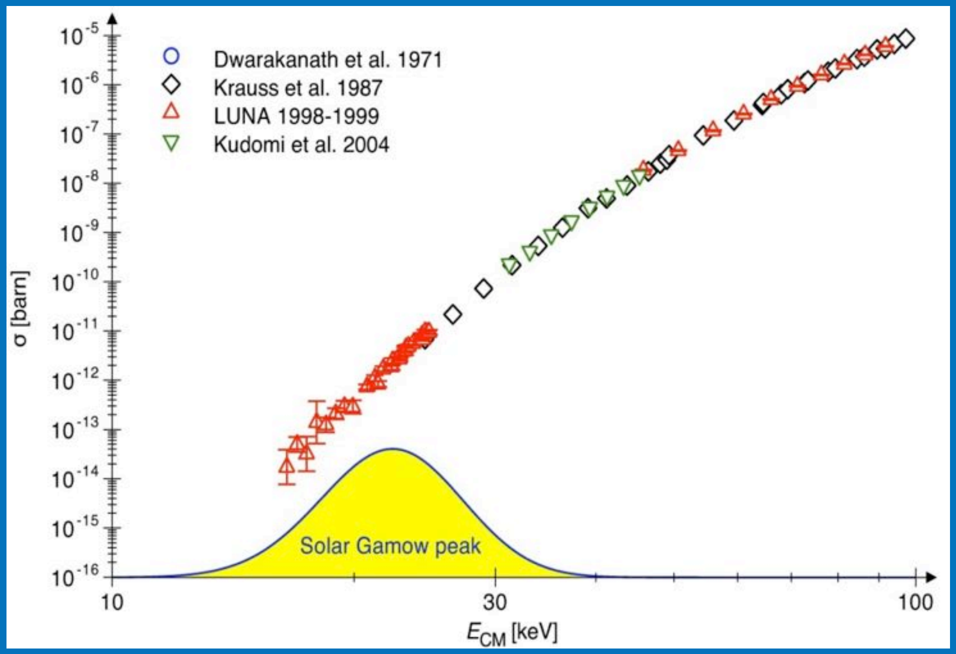


$6*10^{11}$ kg/s H $\longrightarrow$ He
+0.7% M_H $\longrightarrow$ E

$4H \rightarrow He + 2e^+ + 2\nu_e + 26.7$ MeV



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

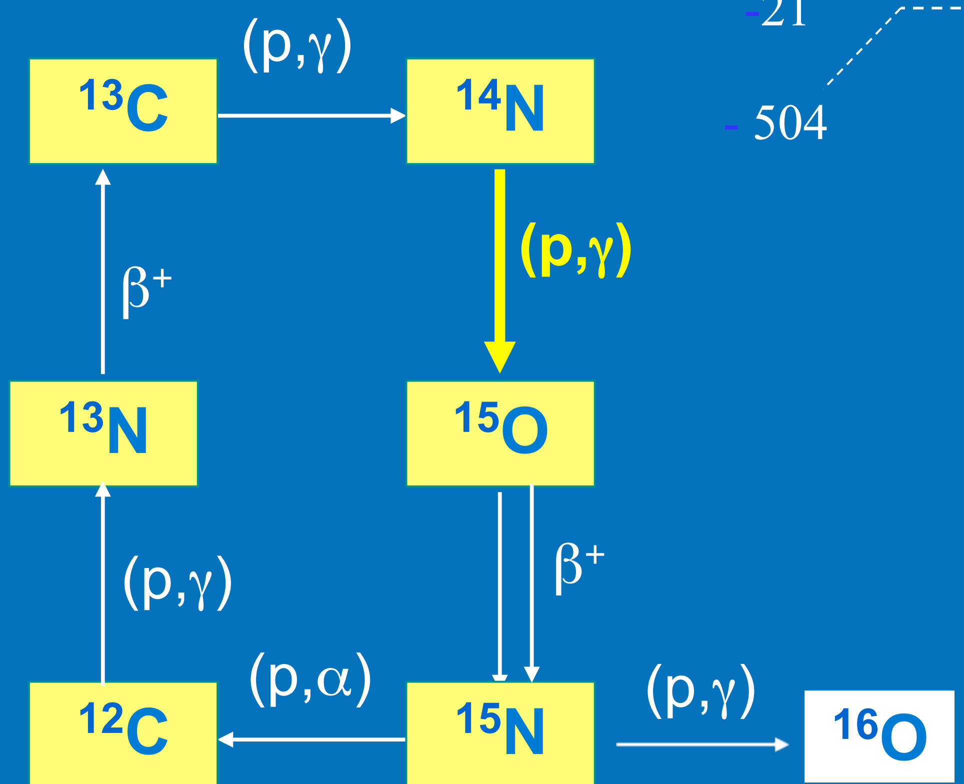


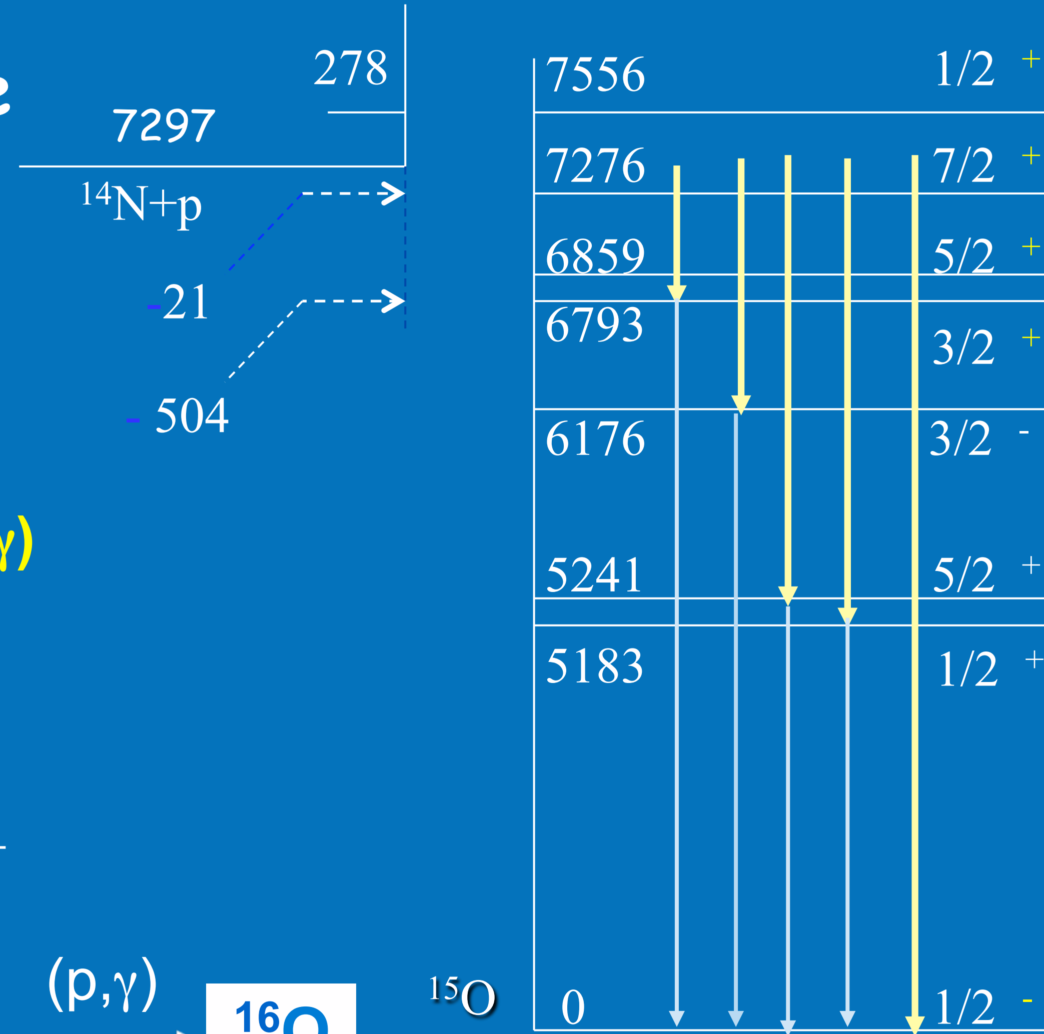
No ghost resonance @ solar Gamow peak

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

The CNO Cycle

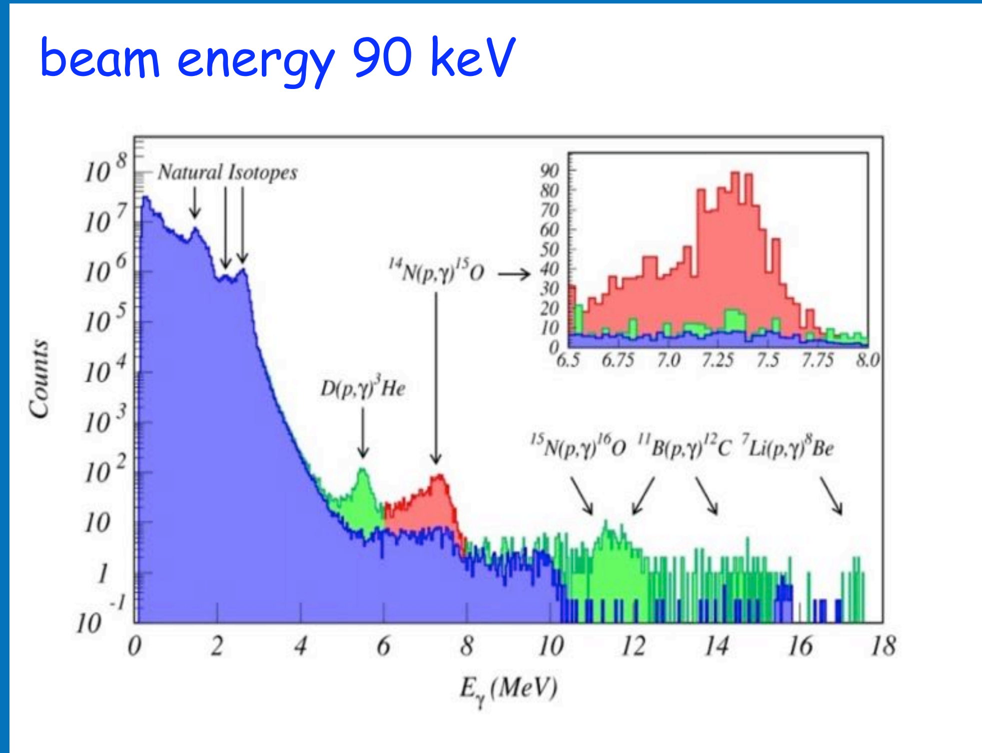
$^{14}N(p,\gamma)^{15}O$

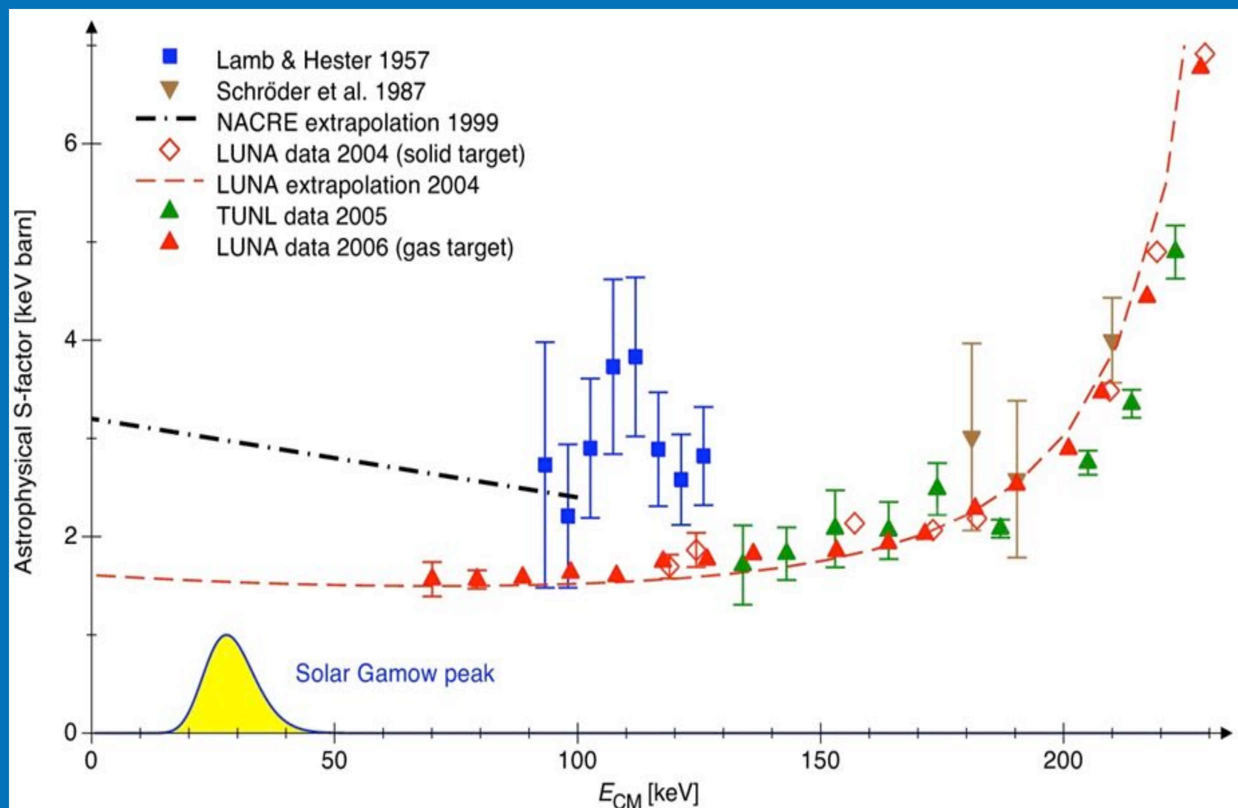




1) "High" energy: solid target + HpGe

2) Low energy: gas target + BGO



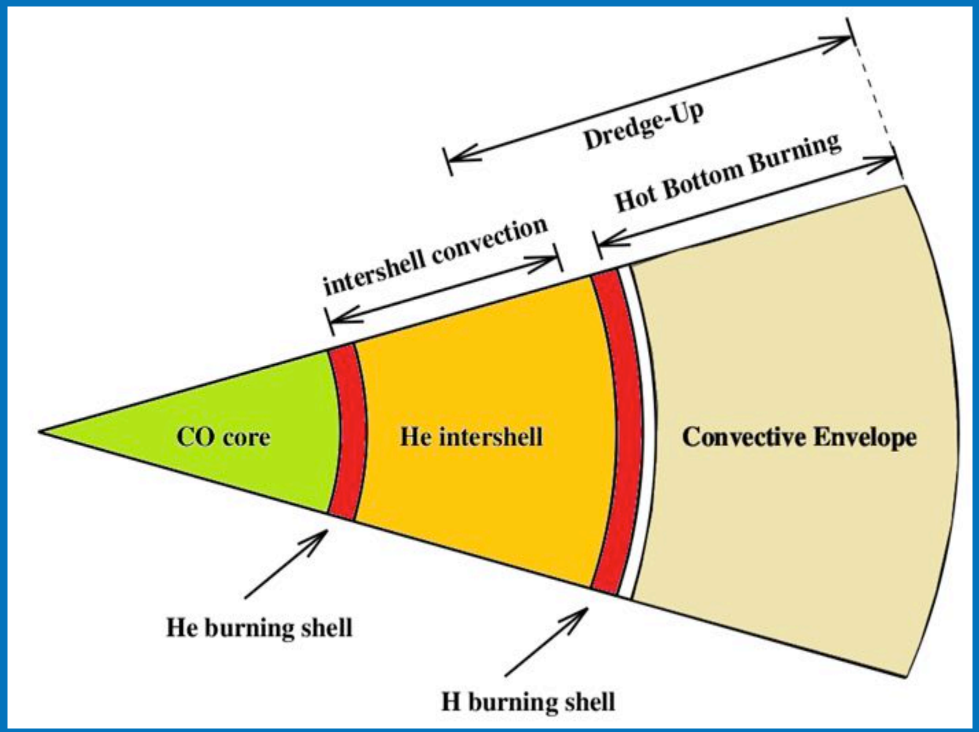


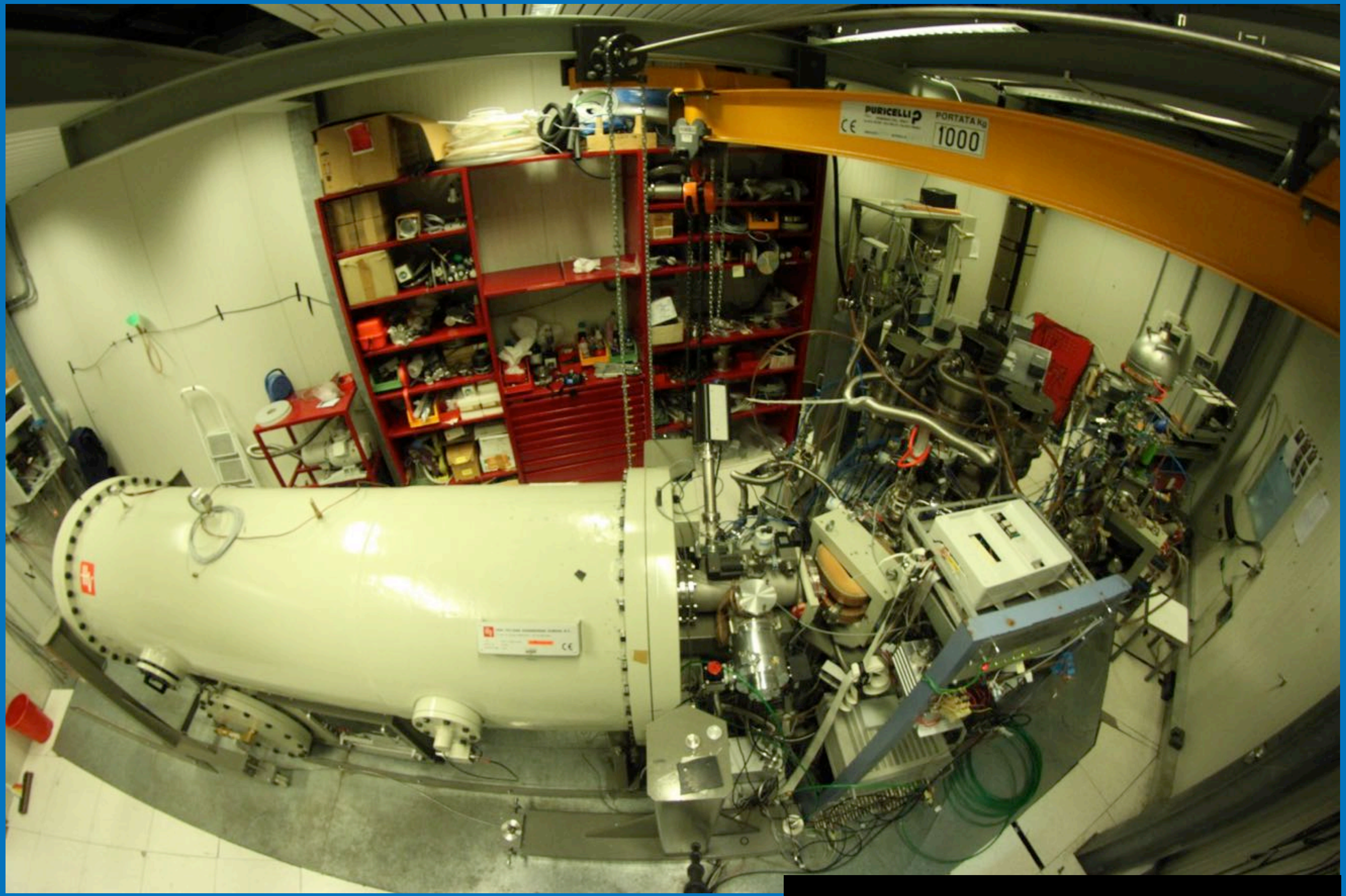
$S_t(0)$=1.57±0.13 keV b
as reported by indirect measurements
(Mukhamedzhanov et al. 2003)

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

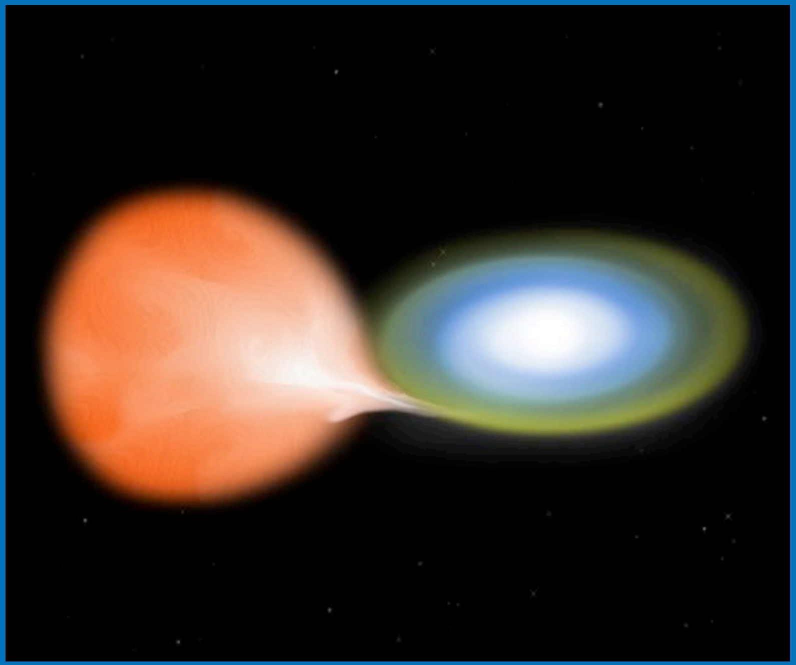
$\nu_{cno} = F(S_{1,14}, Z_{core})$
probe of the metallicity Z of the Sun core

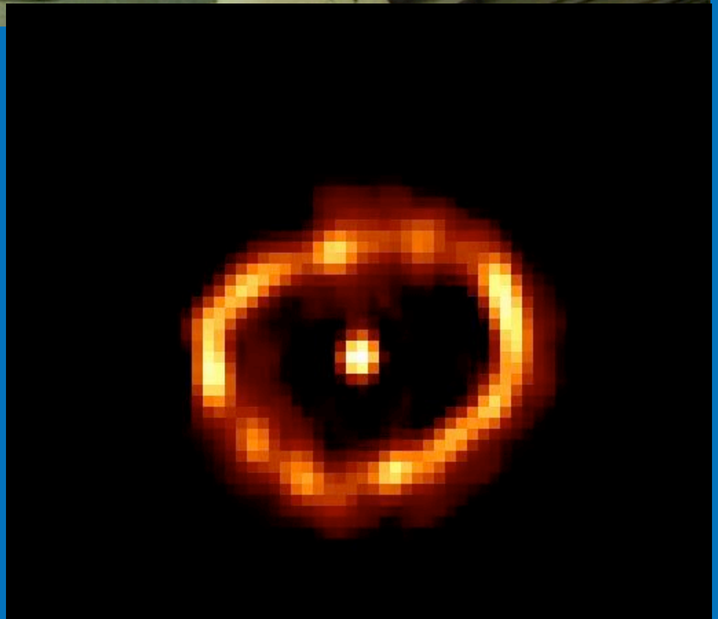
LUNA beyond the Sun: isotope production in the hydrogen burning shell of AGB stars (~30-100 T_6), Nova nucleosynthesis (~100-400 T_6) and BBN





AGB R Sculptoris – ALMA





Nova Cigni - Hubble

Isotopic abundances: how and where

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

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

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

$^{2}H(a,g)^{6}Li$ Q=1.47 MeV

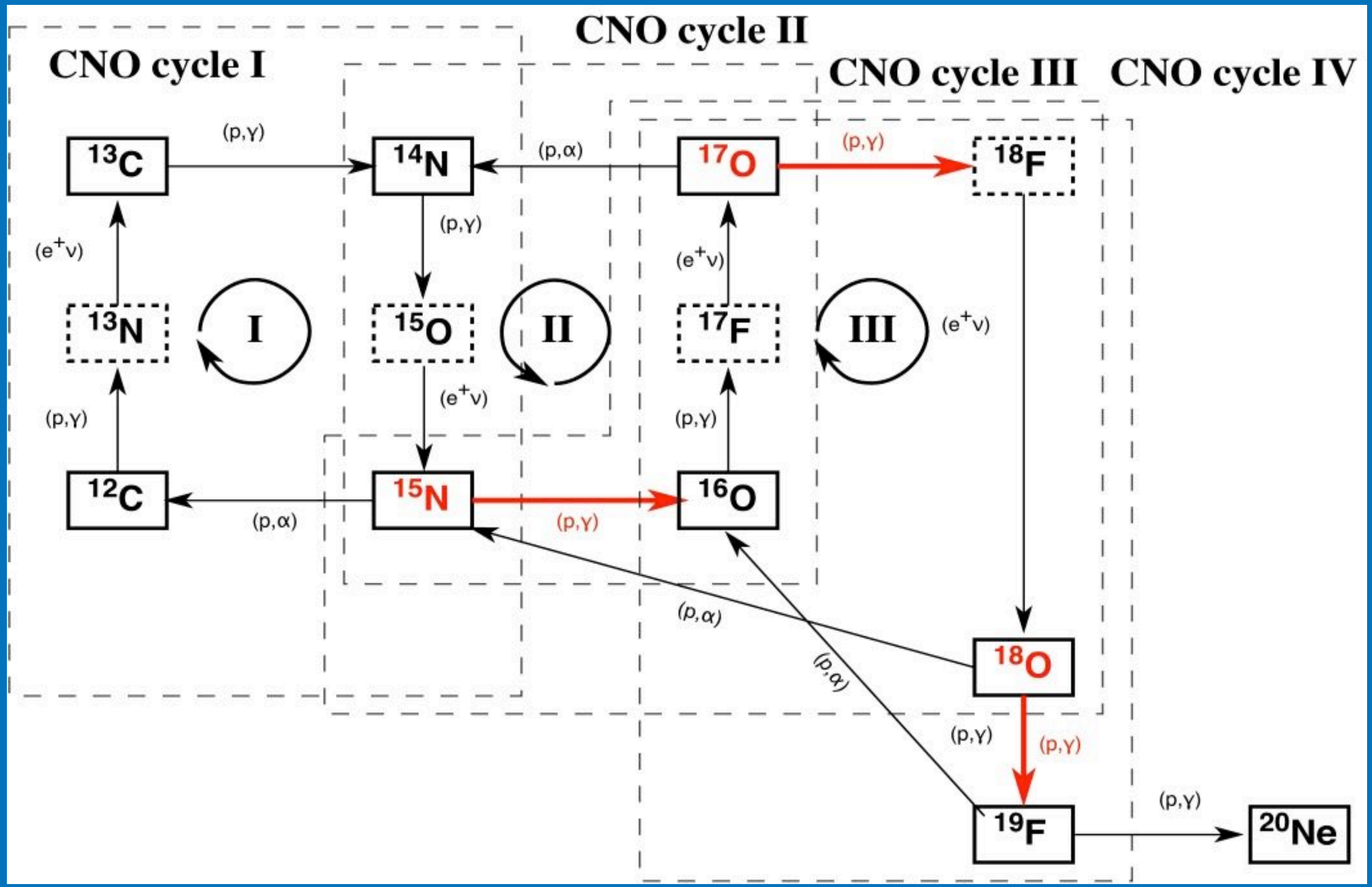
$^{17}O(p,\alpha)^{14}N$ Q=1.2 MeV

$^{22}Ne(p,g)^{23}Na$ Q=8.8 MeV

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

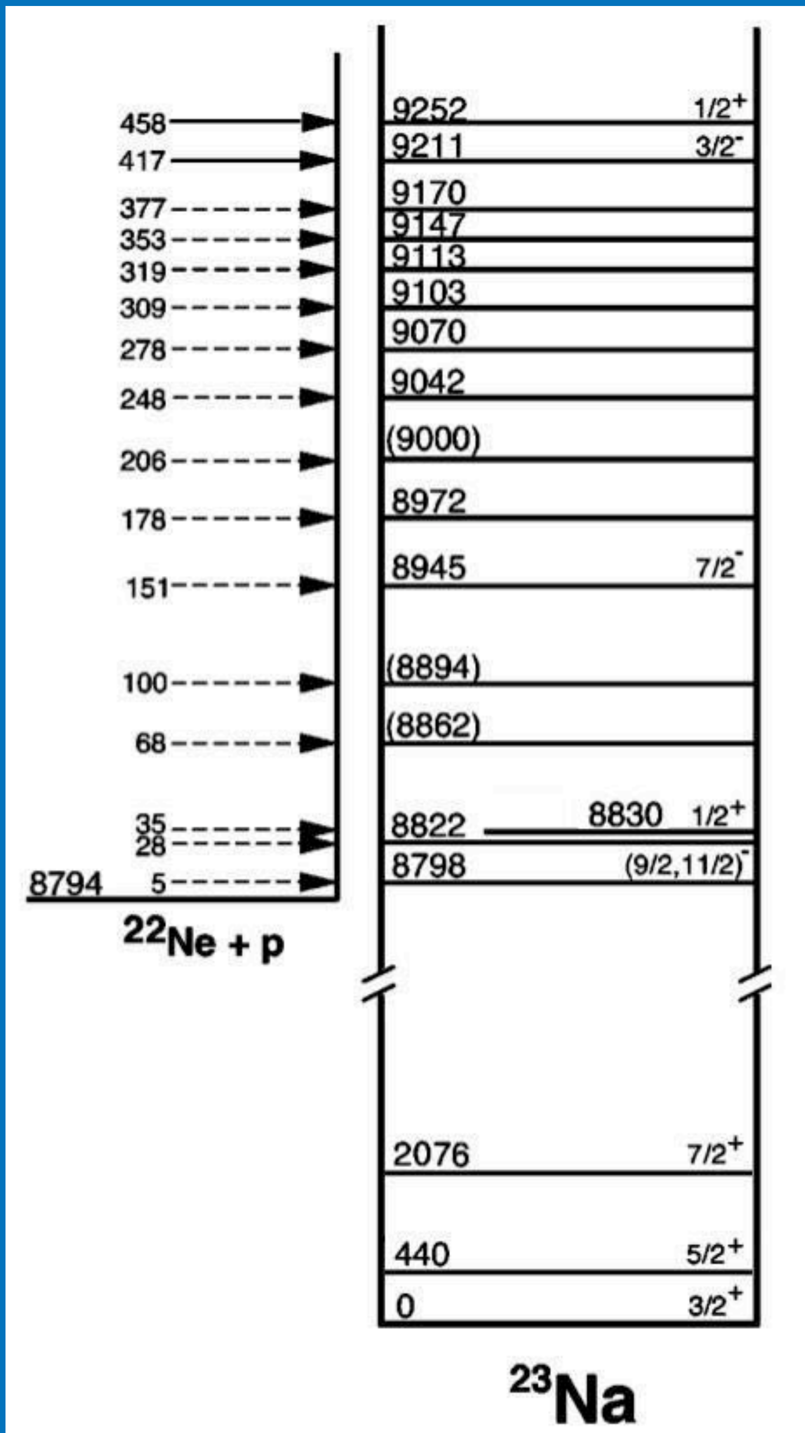
$^{18}O(p,g)^{19}F$ Q=8.0 MeV

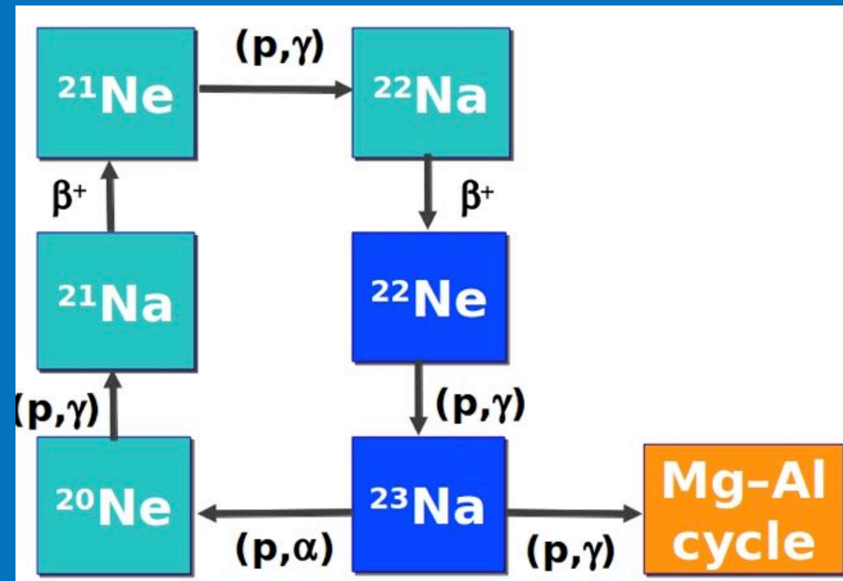
$^{18}O(p,\alpha)^{15}N$ Q=4.0 MeV



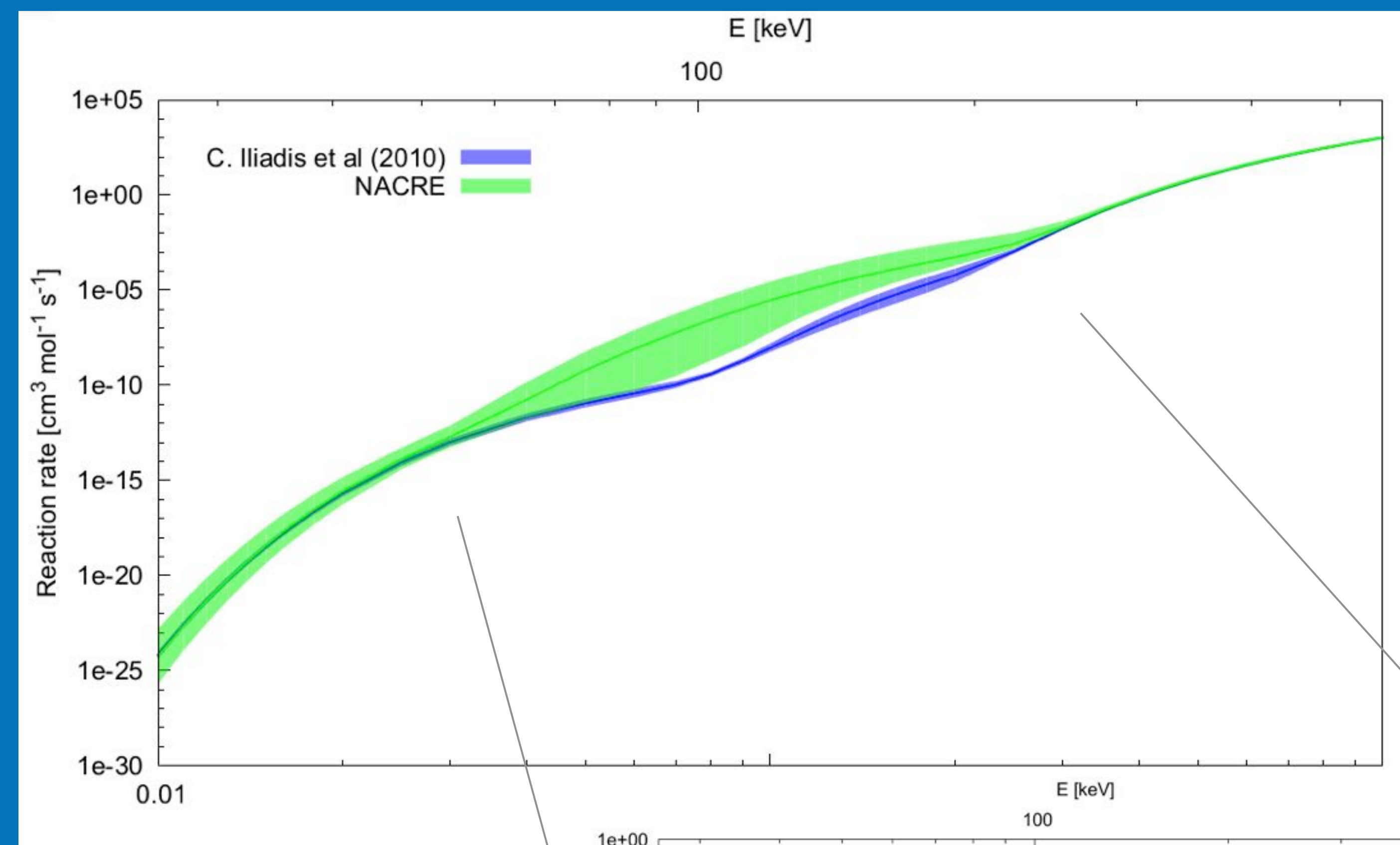
- First measurement of the 92 keV resonance in $^{25}Mg(p, \mathbf{g})^{26}Al$, $\omega\gamma=(2.9\pm0.6)\times 10^{-10}$eV Sky Map @ 1.8 MeV)
- Uncertainty on ^{16}O, ^{17}O, ^{18}O and ^{19}F at Nova temperature less than 10% (from 40-50%)
- First measurement of $^{2}H(a,\mathbf{g})^{6}Li$ at the BBN energies: $^{6}Li/^{7}Li =(1.5\pm0.3)*10^{-5}$, no nuclear solution to the primordial ^{6}Li problem

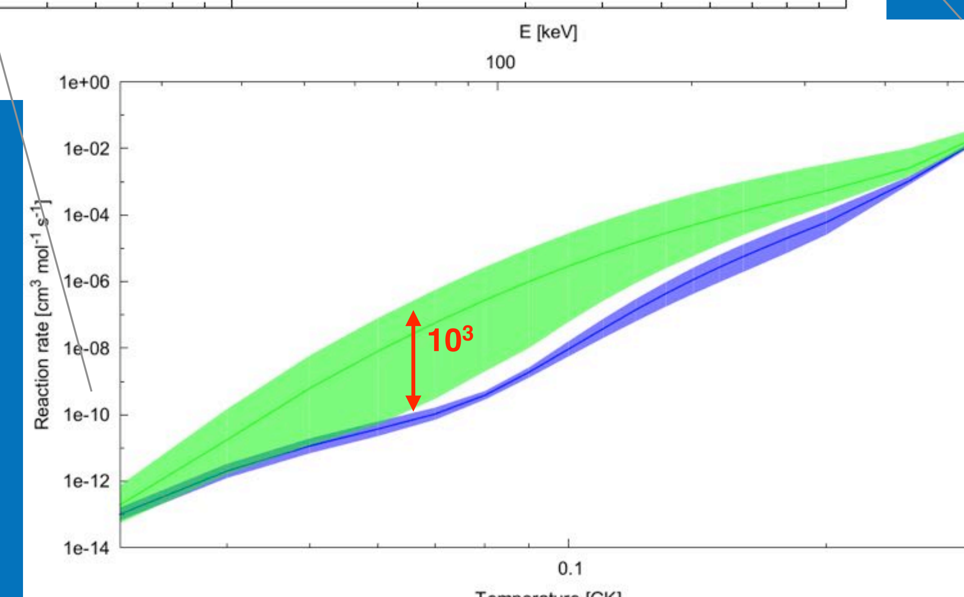
The Ne-Na Cycle



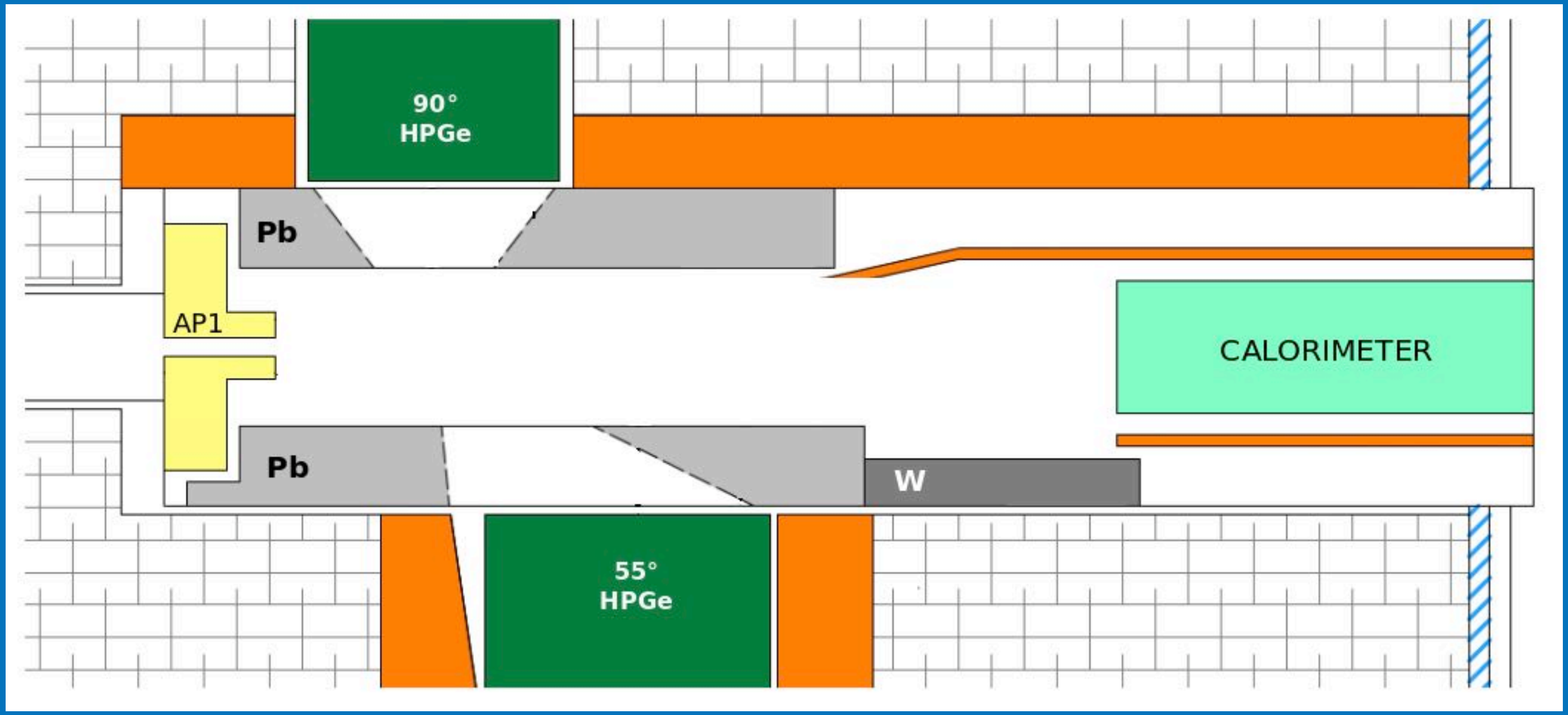


^{22}Ne(p,g)^{23}Na Q=8.8 MeV





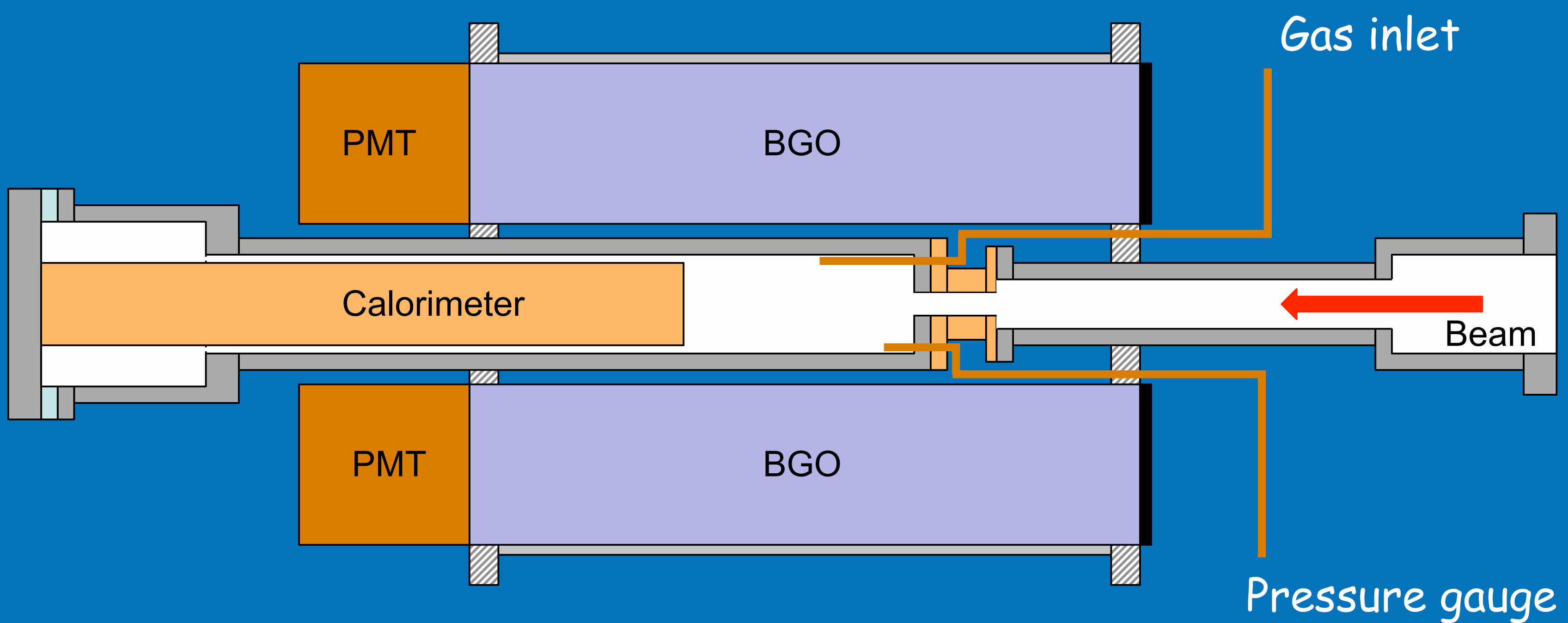
Only upper limits (~μeV) on the strength of the resonances below 400 keV (factor 1000 on the reaction rate) ➡
Ne, Na, Mg and Al yield in AGB and Novae (up to a factor 100)

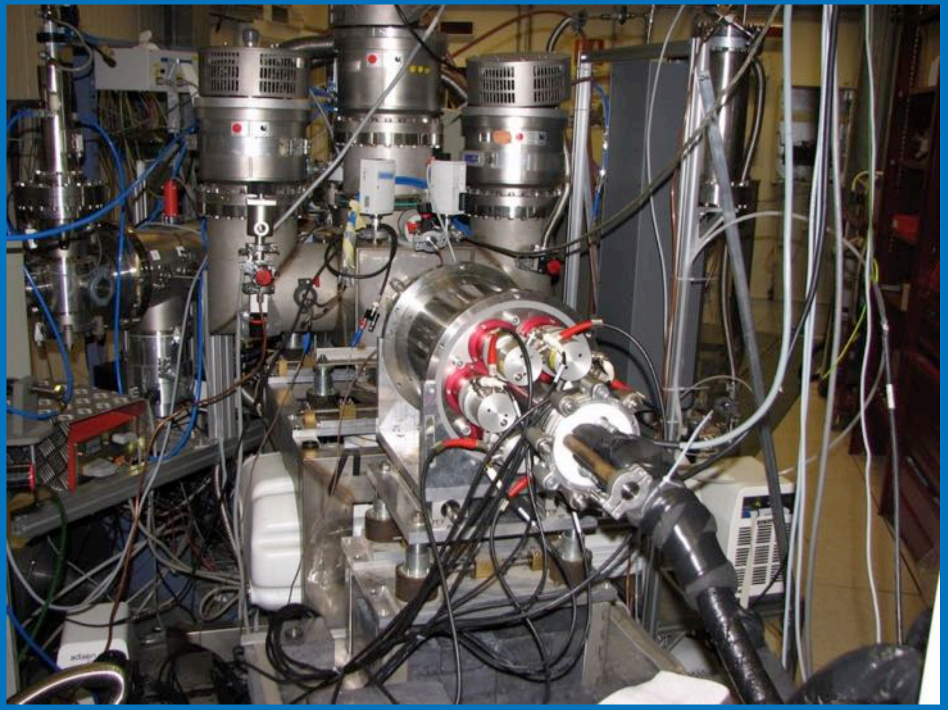


Windowless gas target with recirculation ^{22}Ne enriched at 99.9%, effective target length: 8 cm
2 HPGe detectors at 55° (130%) and 90° (88%)
Cu+Pb (~ 30 cm) + anti-Radon shielding

- Resonances studied with a few neV strength sensitivity and 700 eV uncertainty on the energy
- 156.2, 189.5 and 259.7 keV resonances measured for the first time. Increase by a factor 10-30 of the reaction rate for T in the range 0.08-0.3 GK
- New upper limits on 71, 105 and 215 keV
- Yield measured at 291, 320 and 334 keV compatible with Direct Capture

High efficiency phase: Windowless gas target + BGO detector to study the low resonances @ 71 and 105 keV (~0.05 neV strength sensitivity) + Direct Capture





A bridge towards LUNA-MV:

$^{13}C(\alpha,n)^{16}O$ – neutron source (LUNA-MV)

$^{12}C(p,g)^{13}N$ and $^{13}C(p,g)^{14}N$ – $^{12}C/^{13}C$ in the deepest layers of H-rich envelopes of any star

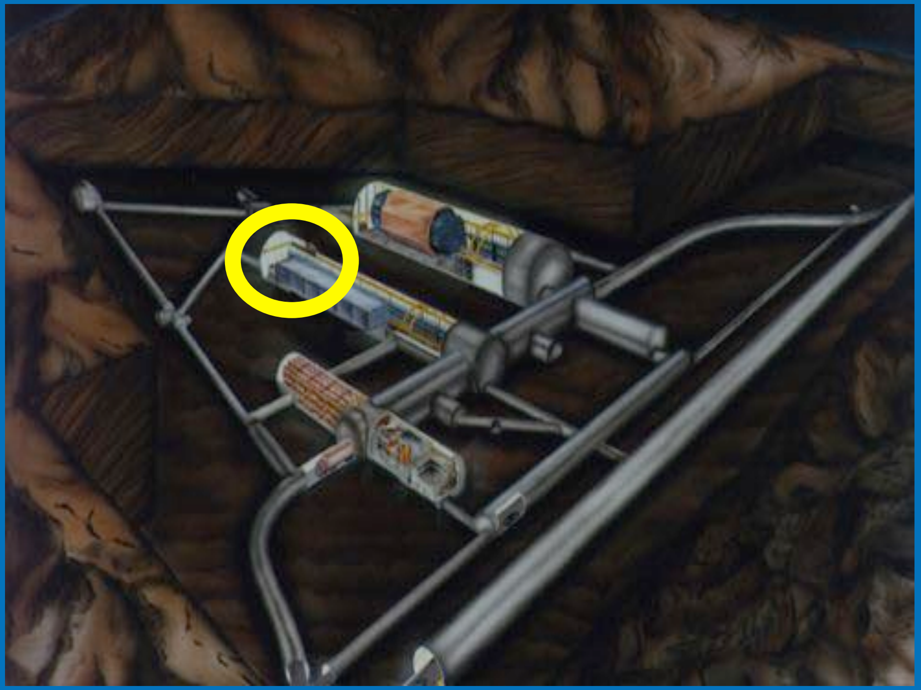
$^{2}H(p,g)^{3}He$ – ^{2}H production in BBN

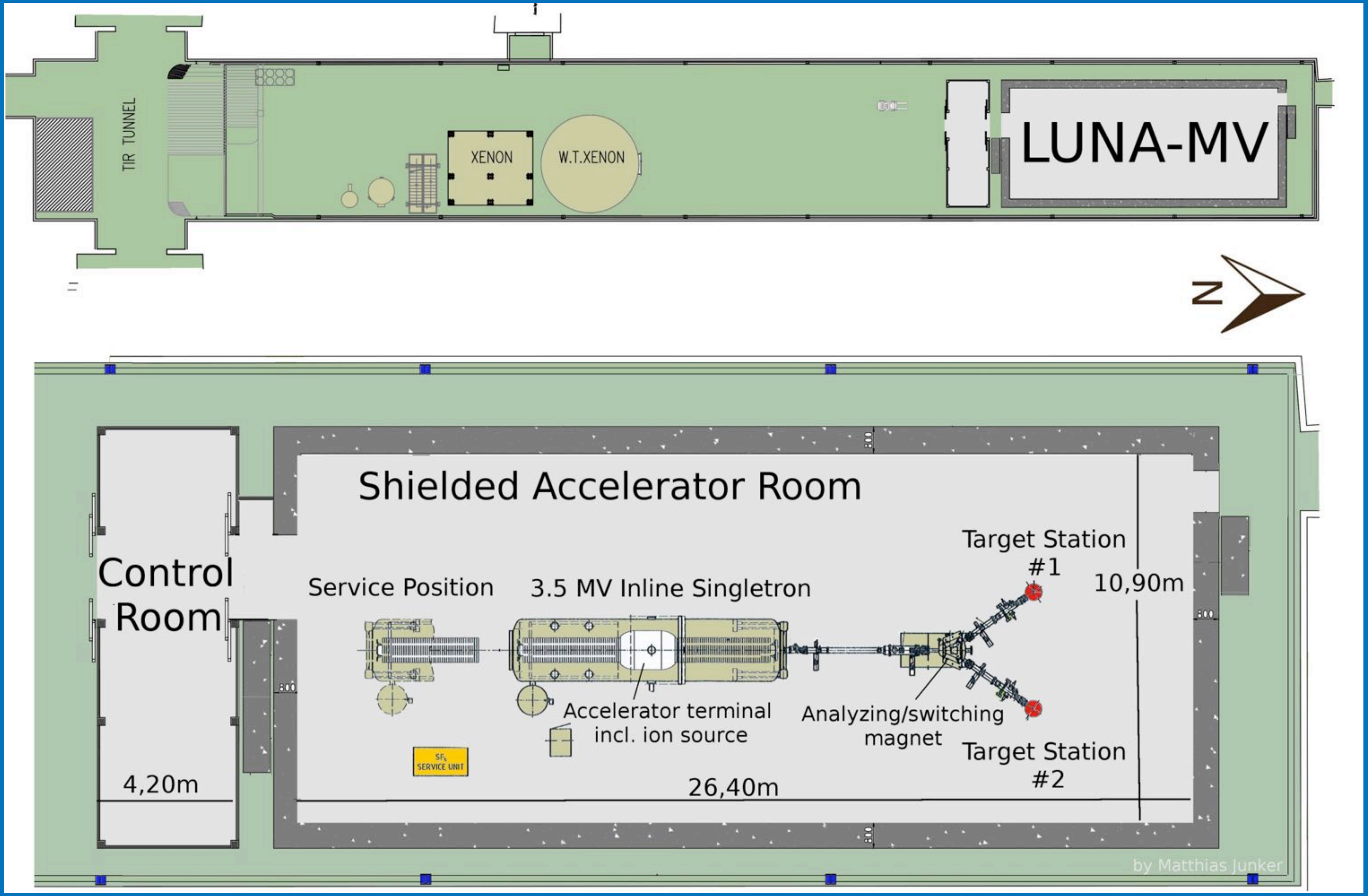
$^{22}Ne(\alpha,g)^{26}Mg$ – competes with $^{22}Ne(a,n)^{25}Mg$ neutron source (LUNA-MV)

$^{6}Li(p,g)^{7}Be$ – low energy resonance?

A new accelerator, LUNA-MV, will be installed at the north side of Hall B at LNGS (ICARUS space) during the first months of 2018.

New shielded accelerator room (80 cm concrete walls and ceiling) to suppress the produced neutrons





In the worst case scenario Φ_n^{mean} is a factor 20 lower than laboratory Φ_n with a similar spectrum

Inline Cockcroft Walton accelerator, terminal voltage: 0.3-3.5 MV
High current H^+ (1 mA), $^4He^+$, $^{12}C^+$ e $^{12}C^{++}$ (100 eμA) beams in the energy range: 0.3 MeV-3.5 (7) MeV,.Energy stability 10^{-5} *TV or 20 V over 1 h

Scientific program > 10 years mainly devoted to:

Helium-Burning (in stars: ~100 T_6, ~10^5 gr/cm^3)

$^{12}C(\alpha,g)^{16}O$ one of the most important reactions 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

Carbon-Burning (~500 T_6, ~$3\cdot10^6$ gr/cm^3)

$^{12}C(^{12}C,\alpha)^{20}Ne$, $^{12}C(^{12}C,p)^{23}Na$ determine the lower stellar mass bound for the Carbon ignition

+ (α,g) on ^3He, ^{14}N, ^{15}N, ^{18}O......

- $^{3}He(^{3}He,2p)^{4}He$: σ down to 16 keV
  no resonance within the solar Gamow Peak

- $^{3}He(\alpha,g)^{7}Be$: ^{7}Be ≈ prompt g cross section measured with 4% error

- $^{14}N(p,g)^{15}O$: 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

- $^{25}Mg(p,g)^{26}Al$: measurement of the 92 keV resonance, $\omega\gamma=(2.9\pm0.6)\times 10^{-10}$ eV

- Uncertainty on ^{16}O, ^{17}O, ^{18}O and ^{19}F from Novae less than 10%

- $^{2}H(\alpha,g)^{6}Li$: no nuclear solution to the ^{6}Li problem

- Future: Helium and Carbon burning with the new 3.5 MV accelerator

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