

LUNA at Gran Sasso:

Nuclear reactions at the energy of the stars

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☀ Stellar Energy+Nucleosynthesis

☀ Hydrogen Burning

☀ $\sigma(E_{\text{star}})$ with $E_{\text{star}} \ll E_{\text{Coulomb}}$

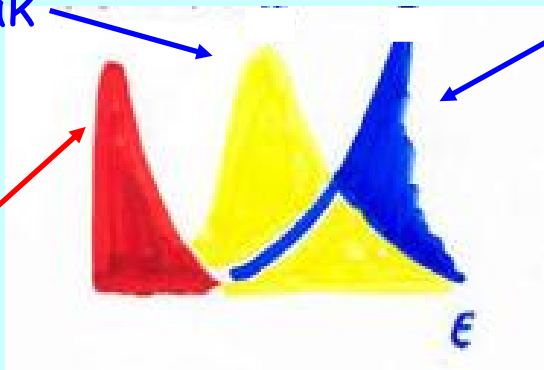
$$\sigma(E) = S(E) e^{-2\pi\eta} E^{-1}$$

$$2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\mu/E} \quad \mu = m_1 m_2 / (m_1 + m_2)$$

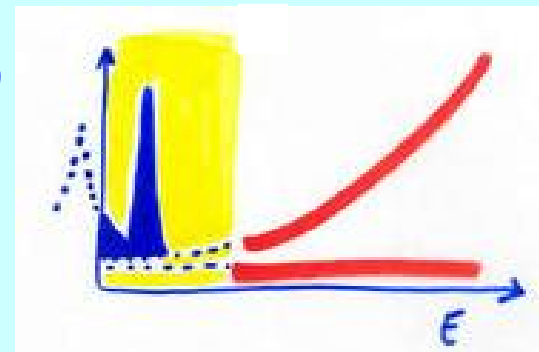
$$\text{Reaction Rate}(\text{star}) \div \int \Phi(E) \sigma(E) dE$$

Gamow Peak

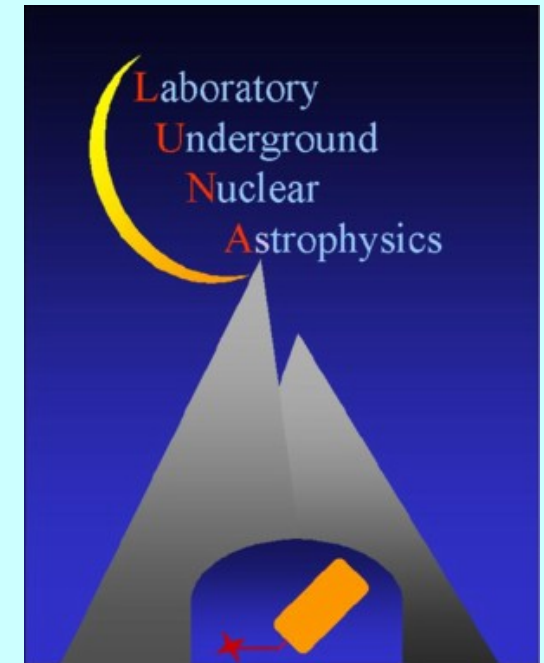
Maxwell
Boltzmann



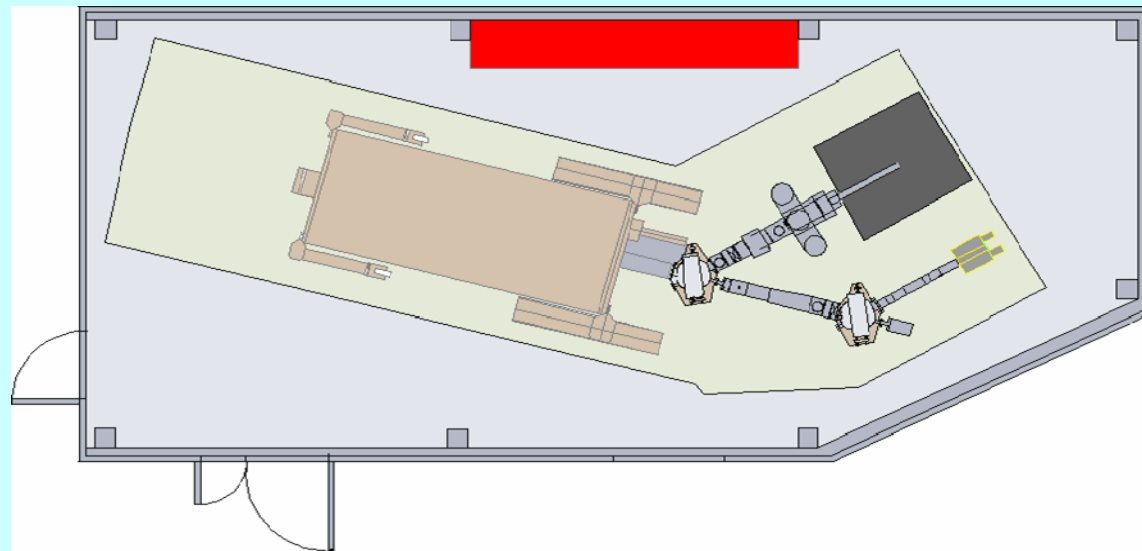
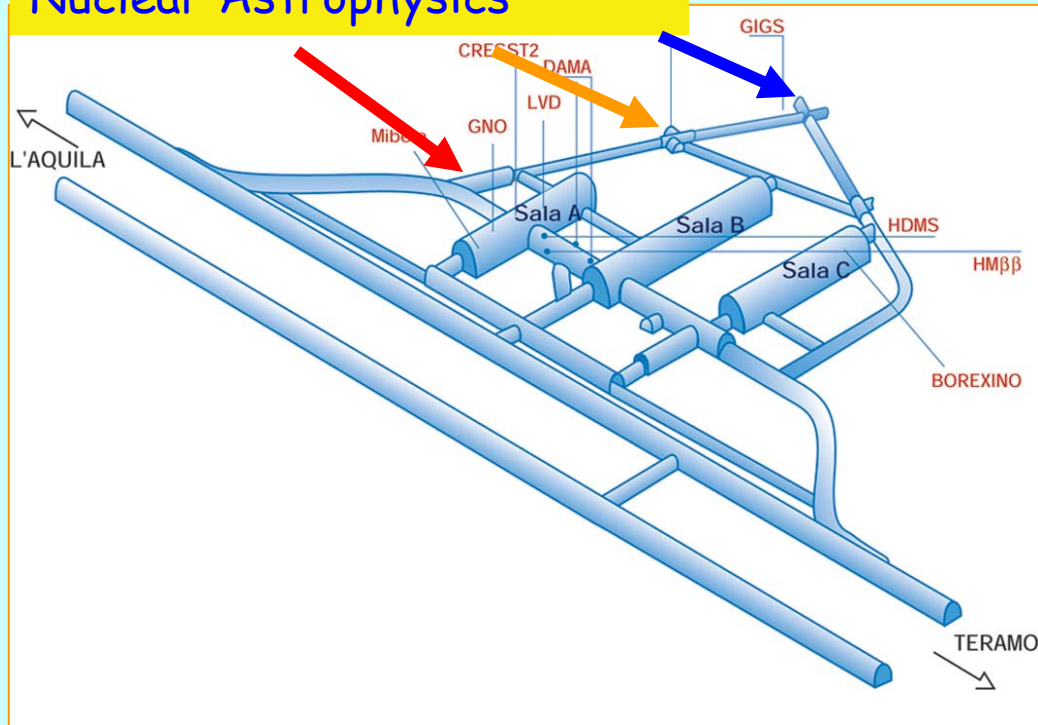
$S(E)$



Extrap. ← Meas. →



Laboratory for Underground Nuclear Astrophysics



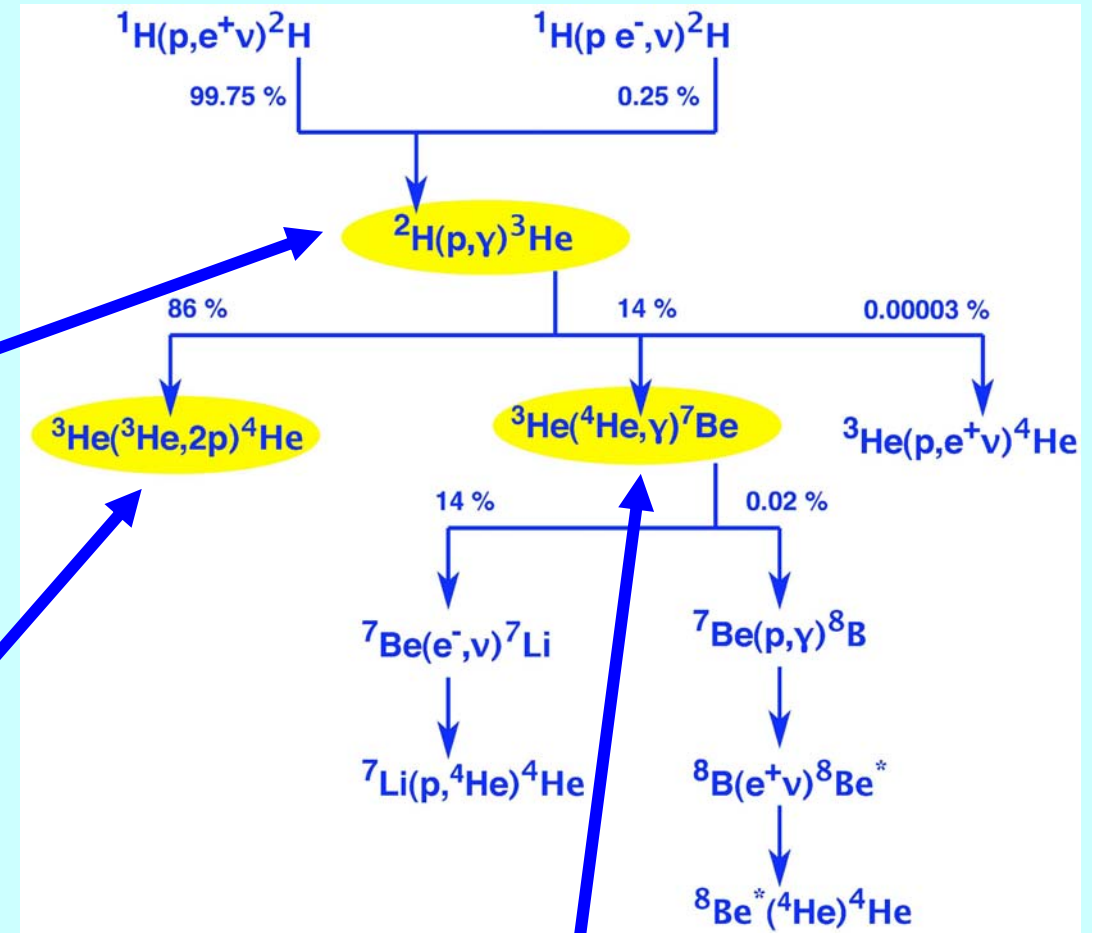
Beam: H, He
Voltage Range :50-400 kV
Output Current: ~1 mA
Absolute Energy error
±300 eV
Beam energy spread:
<100 eV
Long term stability (1 h) :
5 eV
Terminal Voltage ripple:
5 Vpp Ge detector

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

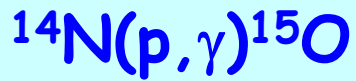
$6 \cdot 10^{11}$ kg/s of H \rightarrow He
+0.7% M_H \rightarrow E

H+ 2 H burning in proto-stars
@ 10^6 degrees

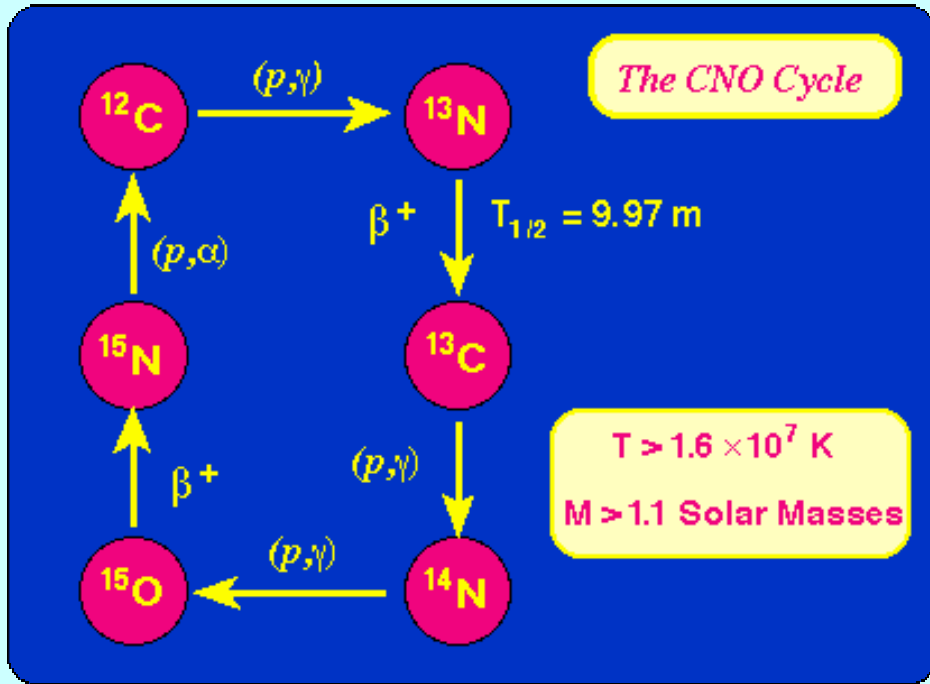
$\sigma_{\min} = 20$ fb (2 events/month)
No resonance at the Gamow peak
 \rightarrow Neutrino oscillations



activation=prompt gamma
 σ at low energy with 4% error



$Q=7.3 \text{ MeV}$

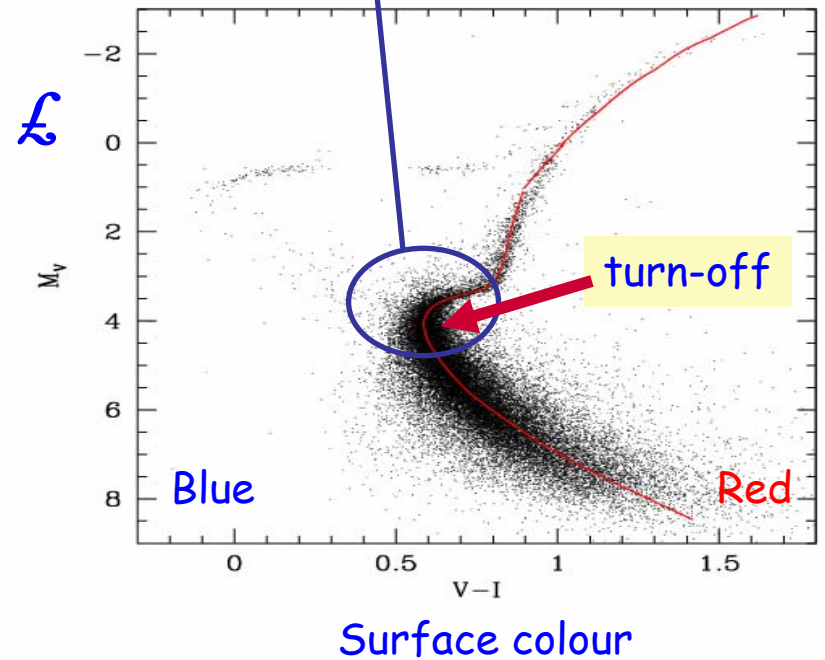
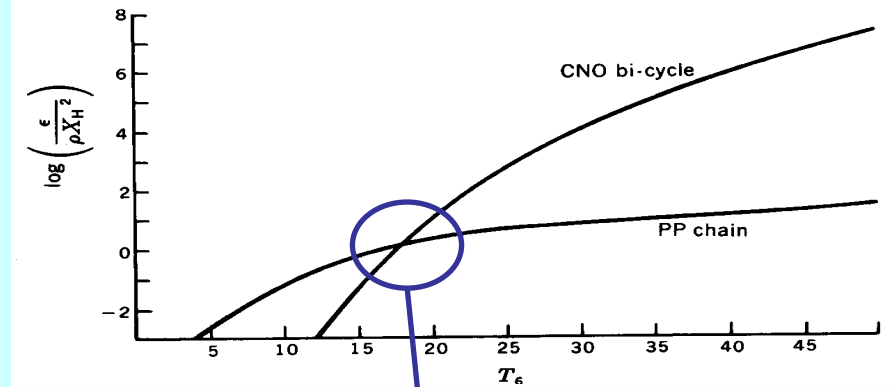


$V_{\text{cno}} \quad \Phi \sim S_{1,14}$

Globular Cluster Age

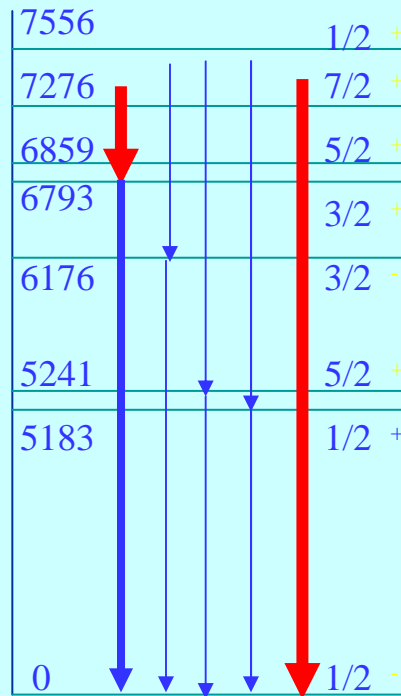
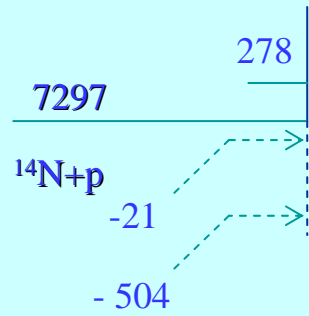
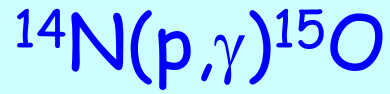
$S(0) = 3.5_{-1.6}^{+0.4} \text{ keV b (Ad98)}$

$S(0) = 3.2_{-0.8}^{+0.8} \text{ keV b (An99)}$



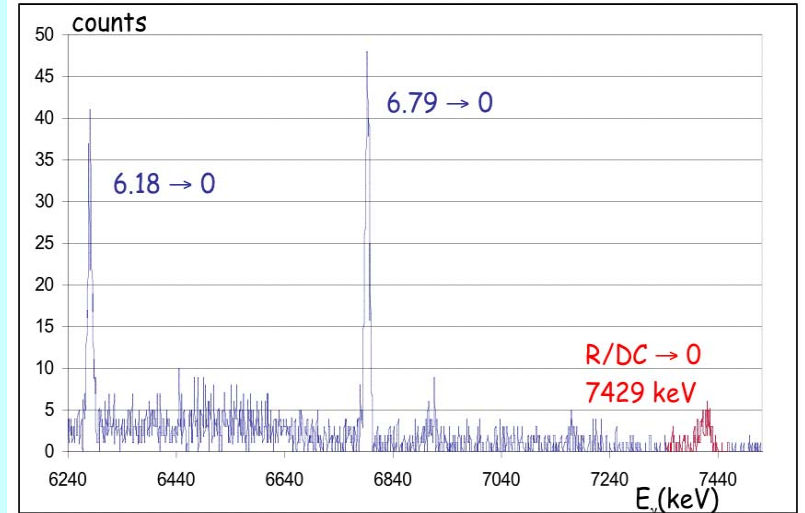
$\text{Age}_{\text{Cluster}} = F(\log L_{\text{turn-off}})$

$\log L_{\text{to}} = F(S_{1,14})$



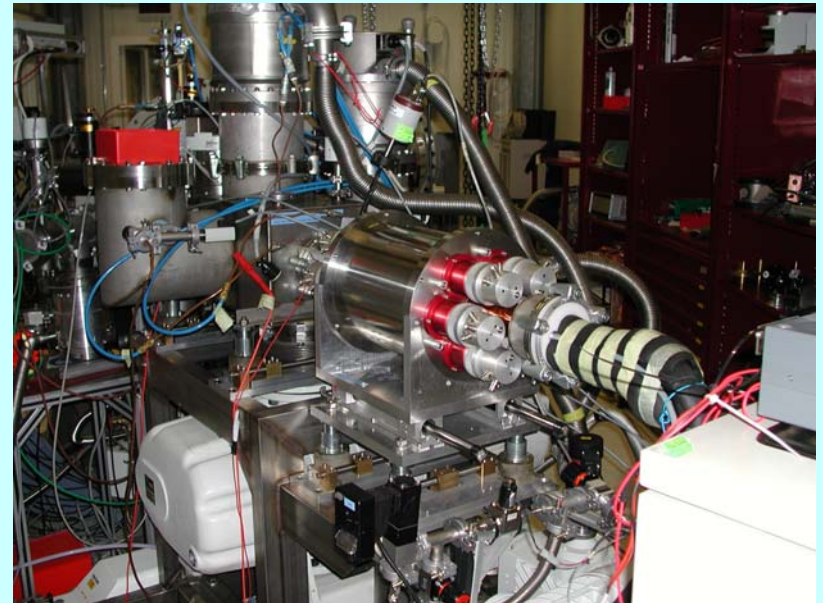
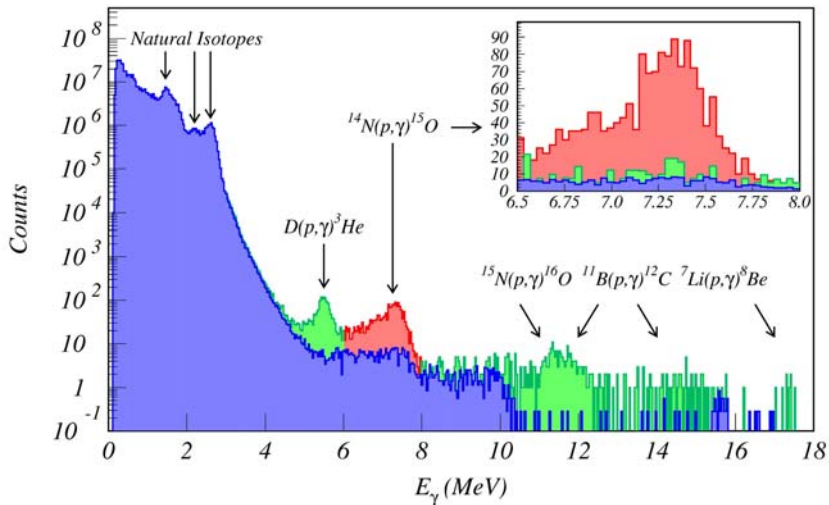
"High" energy: solid target + HpGe

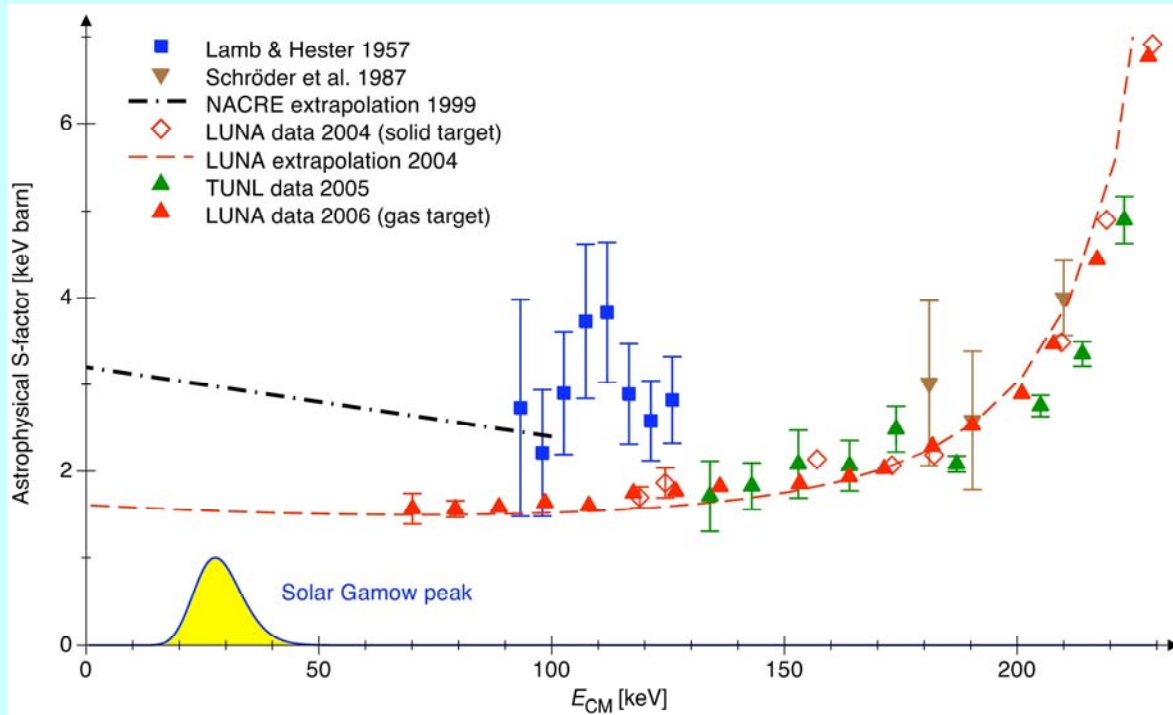
gamma spectrum of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ at 140 keV beam energy



Low energy: gas target + BGO

beam energy 90 keV





$$S_{\dagger}(0) = 1.57 \pm 0.13 \text{ keV b}$$

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

Solar composition problem:
 $Z/X \sim 0.024 \longrightarrow \sim 0.018$
SSM predictions disagree with Helioseismology results

$V_{\text{cno}} = f(Z, S_{14})$, $\sim 30\%$ decrease from high to low metallicity

From a measurement of V_{cno} from the Sun

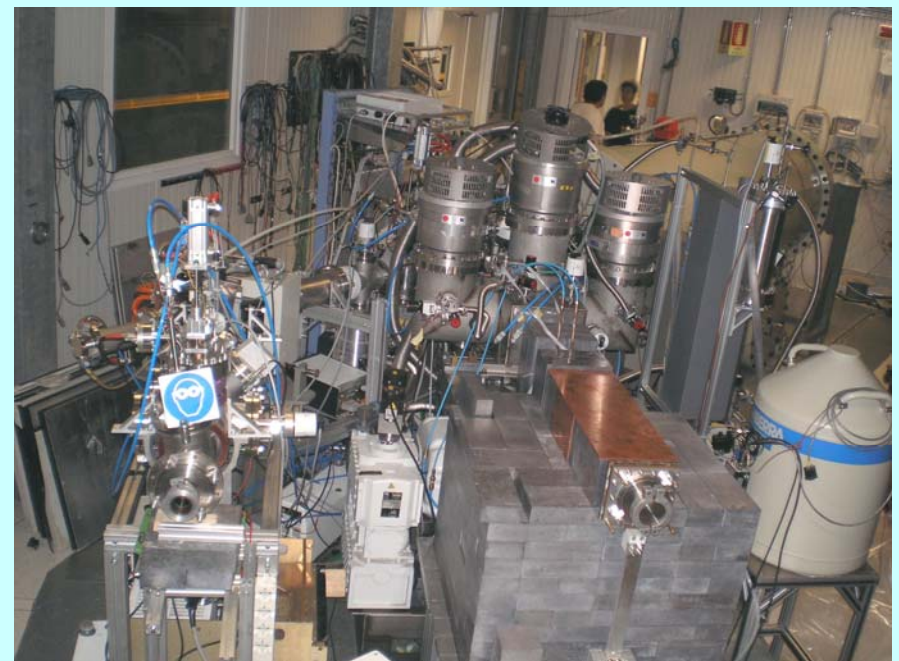
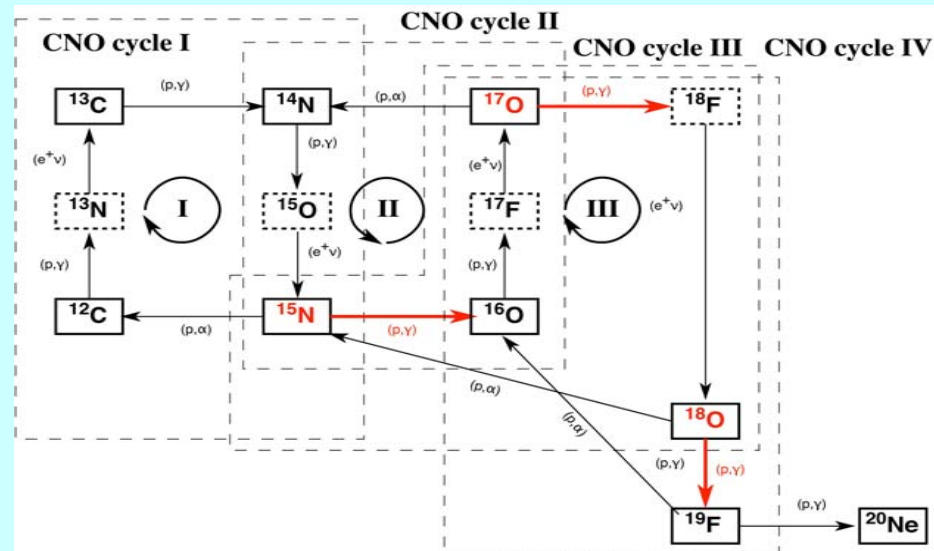


**Metallicity of the Sun core (C+N)
 Photosphere and core metallicity equal?**

LUNA beyond the Sun: isotope production in the hydrogen burning shell of AGB stars ($\sim 30\text{-}100 T_6$), Nova nucleosynthesis ($\sim 100\text{-}500 T_6$) and BBN



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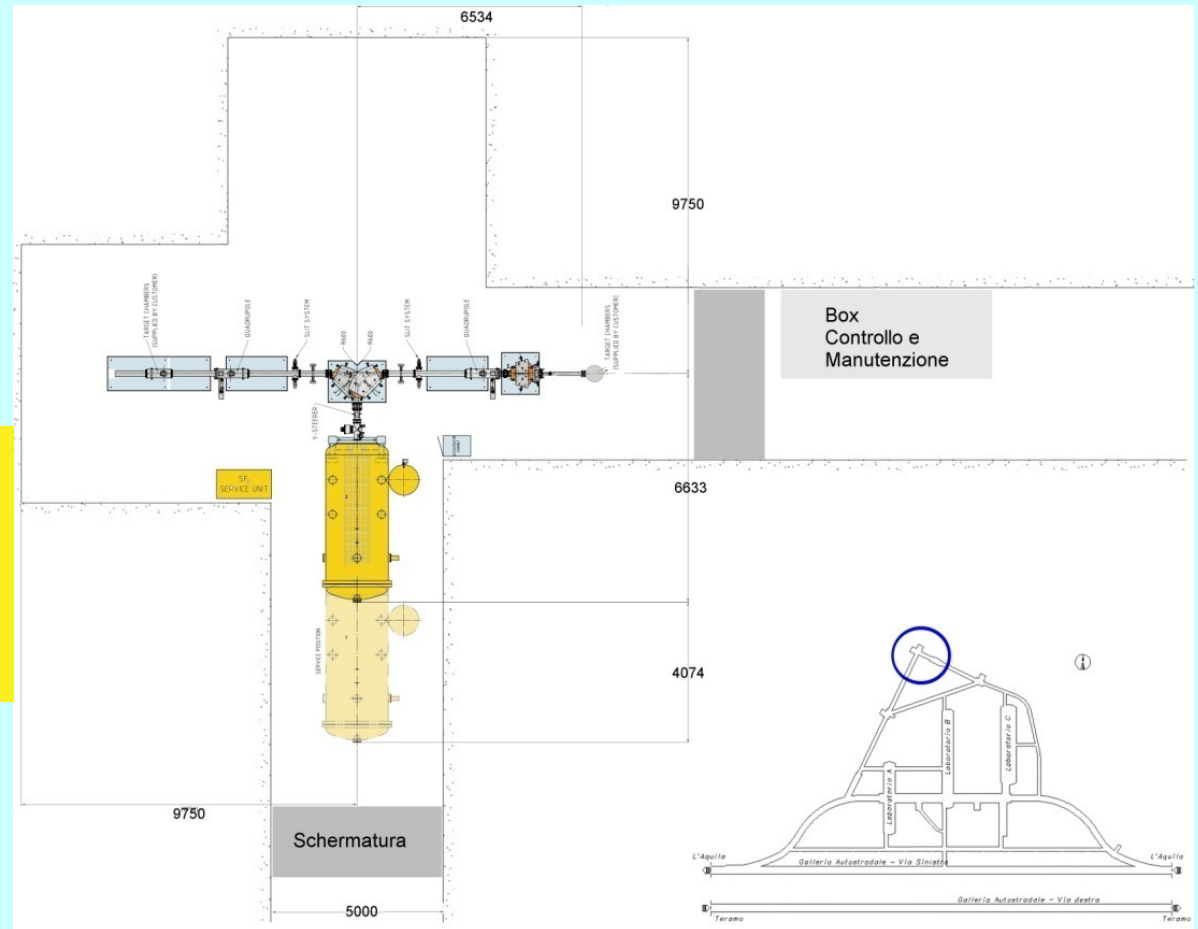
LUNA beyond the Hydrogen burning: 3.5 MV accelerator mainly devoted to Helium-Burning (in stars: $\sim 100\text{-}400 T_6$)

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

$^{13}\text{C}(\alpha, n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ the stellar sources of the neutrons responsible for the S-process

(α, γ) on ^{14}N , ^{15}N , ^{18}O

June 2012: accelerator+site preparation financed by the Italian Ministry of University and Research with 2.8 ME



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

☀ ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$: ${}^7\text{Be} \approx$ prompt γ
Cross section measured with 4% error

☀ ${}^{14}\text{N}(p,\gamma){}^{15}\text{O}$: σ down to 70 keV

V_{cno} reduced by ~ 2 with 8% error \rightarrow Sun core metallicity
Globular cluster age increased by 0.7-1 Gy
More carbon at the surface of AGB stars

☀ ${}^{15}\text{N}(p,\gamma){}^{16}\text{O}$: σ down to 70 keV, reduced by ~ 2

${}^{25}\text{Mg}(p,\gamma){}^{26}\text{Al}$: first measurement of the 92 keV
resonance, strength $\omega\gamma = (2.9 \pm 0.6) \times 10^{-10}$ eV

☀ Future: Hydrogen and Helium burning (3.5 MV accelerator)

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${}^3\text{He} ({}^3\text{He}, 2p) {}^4\text{He}$

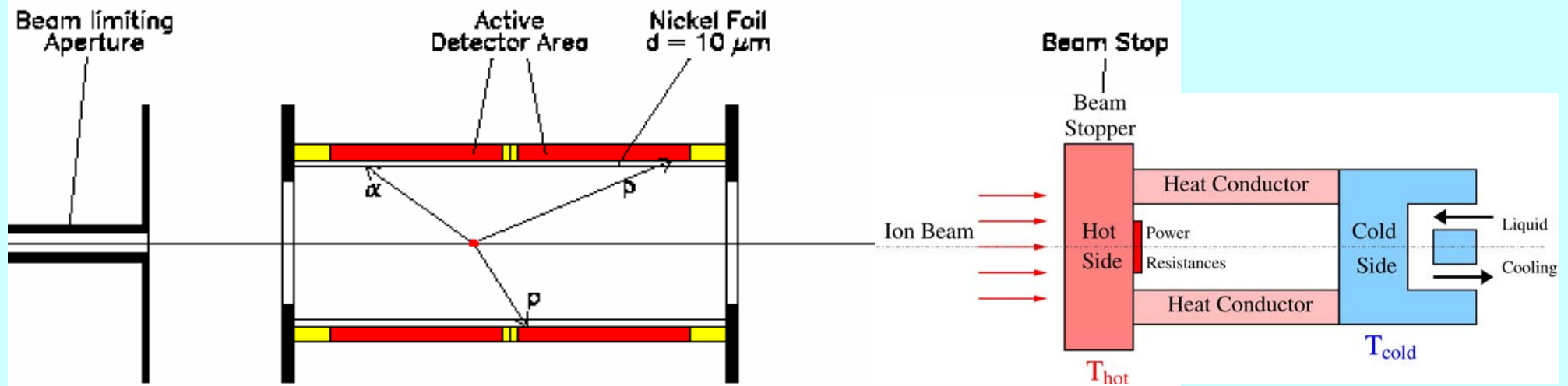
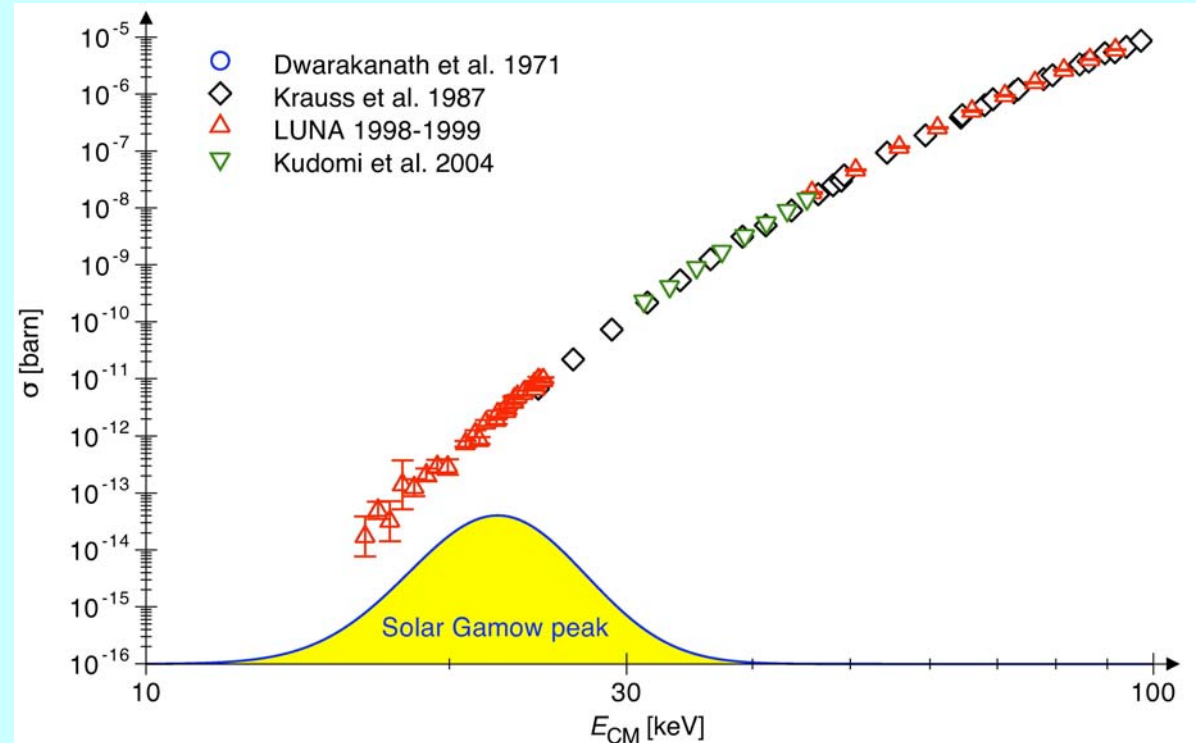
$$Q = 12.86 \text{ MeV}$$

$$E_p^{\text{max}} = 10.7 \text{ MeV}$$

Suppression of ${}^7\text{Be}$ and ${}^8\text{B}$
 ν_e due to a resonance?

Rate: 2 events/month

$$\sigma_{\text{min}} = 0.02 \text{ pb}$$

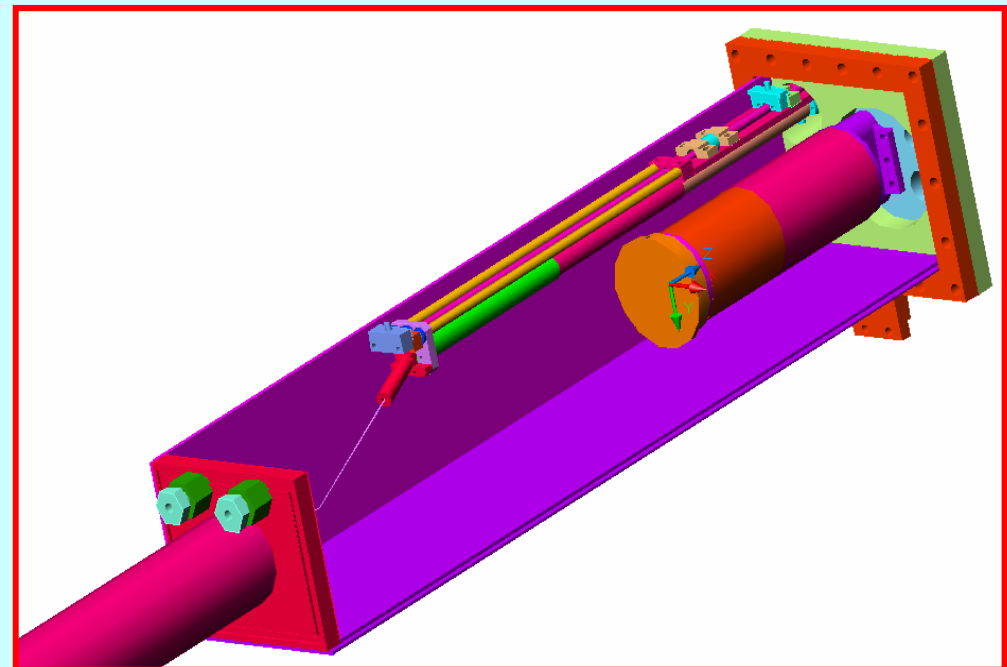
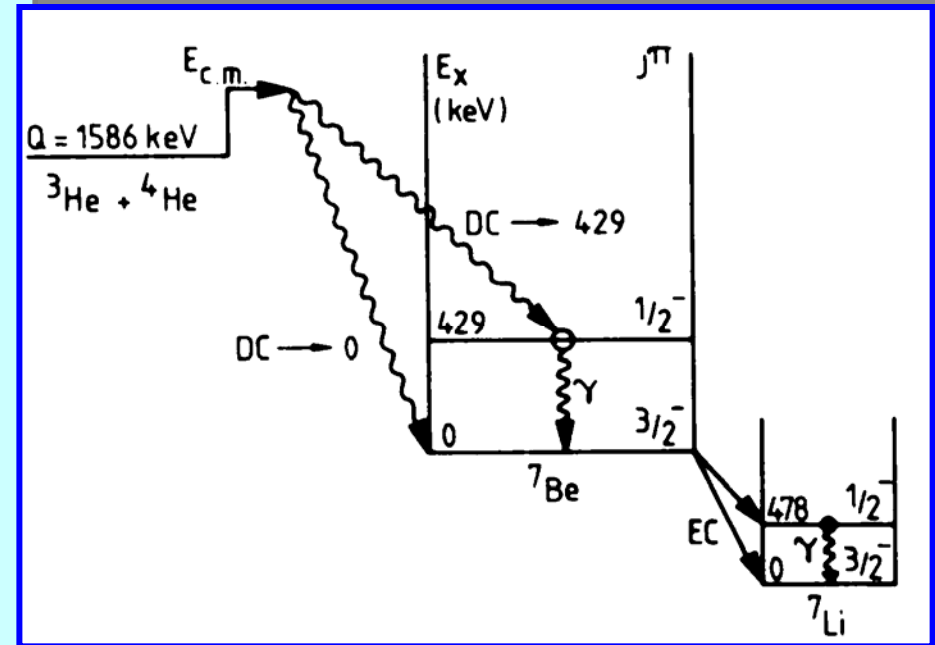
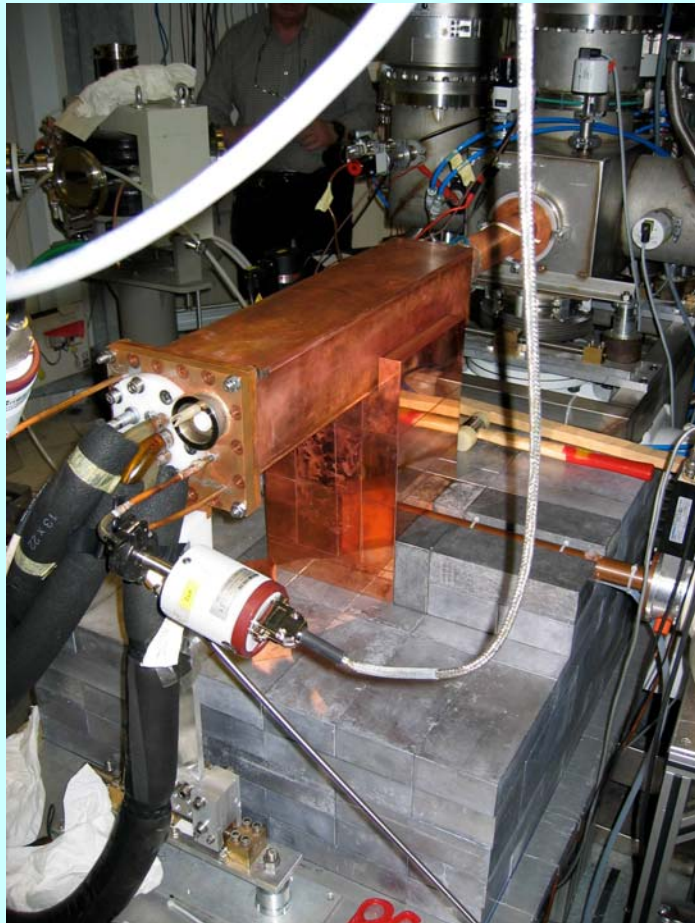


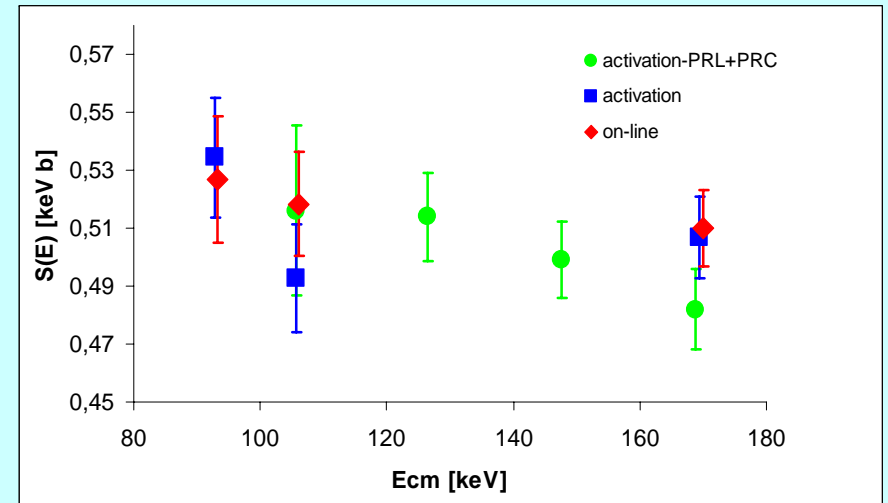
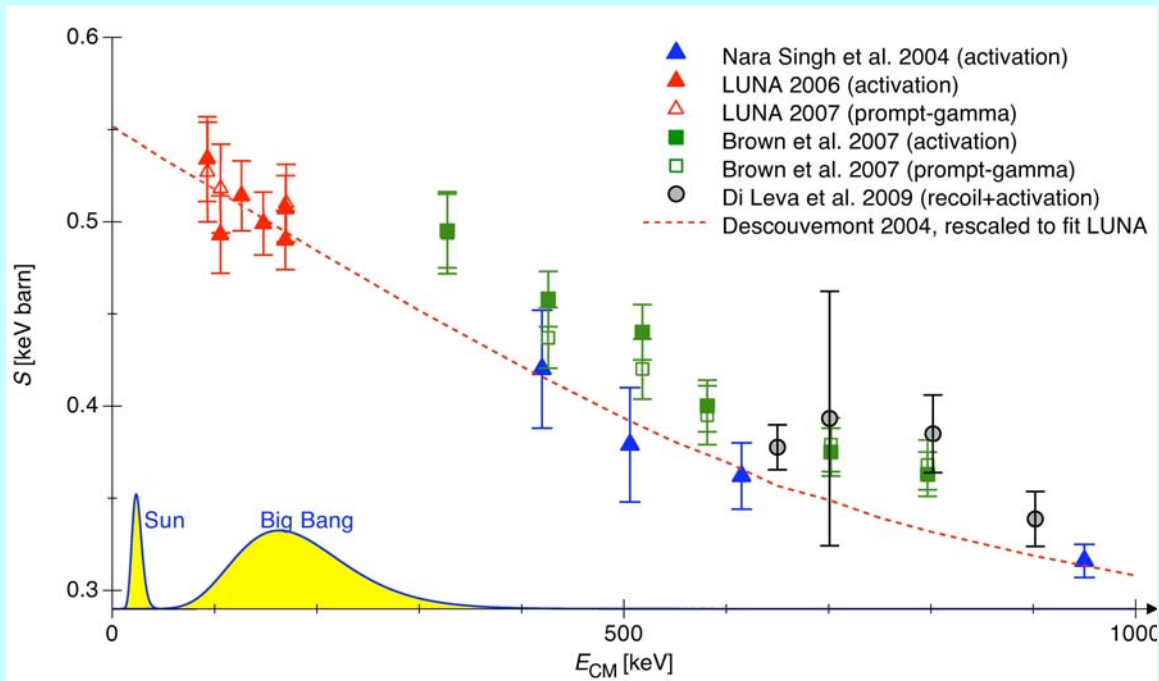
${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ $Q=1.6 \text{ MeV}$

☀ Solar Neutrinos: ${}^7\text{Be}$, ${}^8\text{B}$

$\Phi \sim S_{34}$

☀ BBN ${}^7\text{Li}$





☀ σ down to 93 keV

${}^7\text{Be} \approx \text{prompt } \gamma$

☀ $S_{34}(0) = 0.567 \pm 0.018 \text{ keV barn}$