Underground Nuclear Astrophysics and the Sun

PIC08- Perugia
Carlo Broggini, INFN-Padova

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

- Nuclear Burning in Stars
- $\sigma(E_{star})$

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

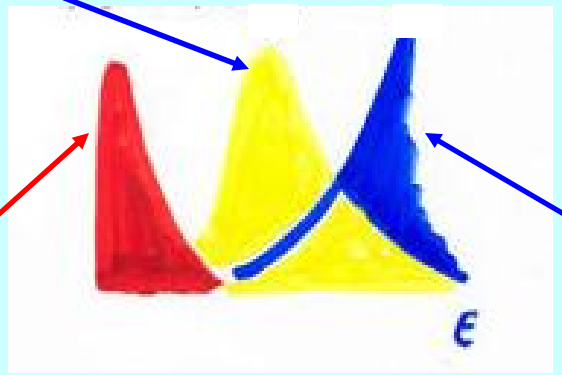
$$2\pi\eta = 31.29\, Z_1 Z_2 \sqrt{\mu/E}$$

$$\mu = m_1 m_2 / (m_1 + m_2)$$

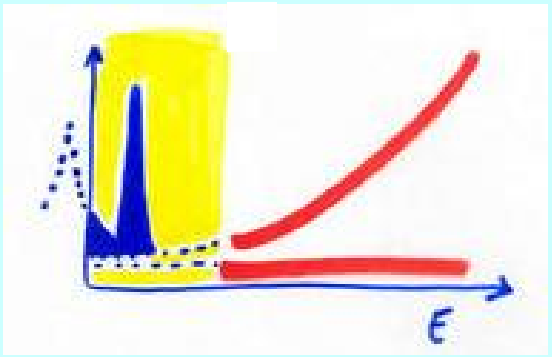
Reaction Rate(star) $\div \int \Phi(E)\, \sigma(E)\, dE$

Gamow Peak

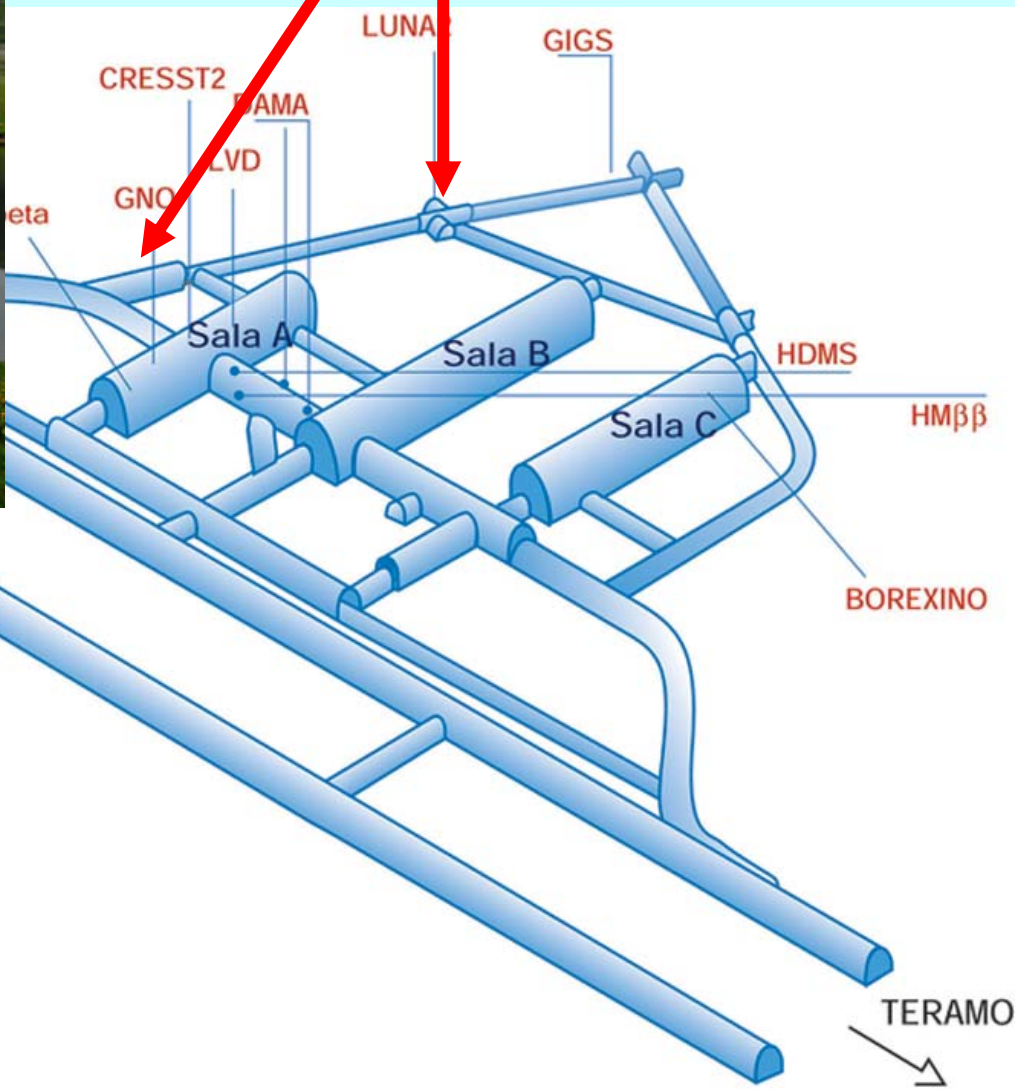
Maxwell Boltzmann



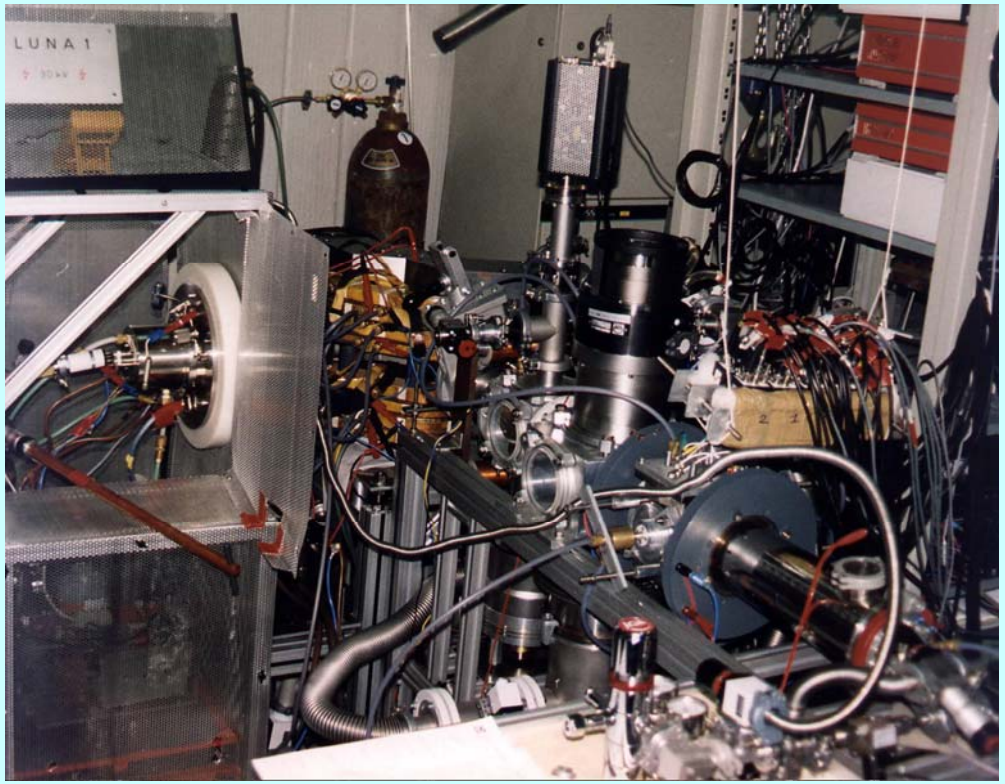
Extrap. ← Meas. →



Laboratory for Underground Nuclear Astrophysics

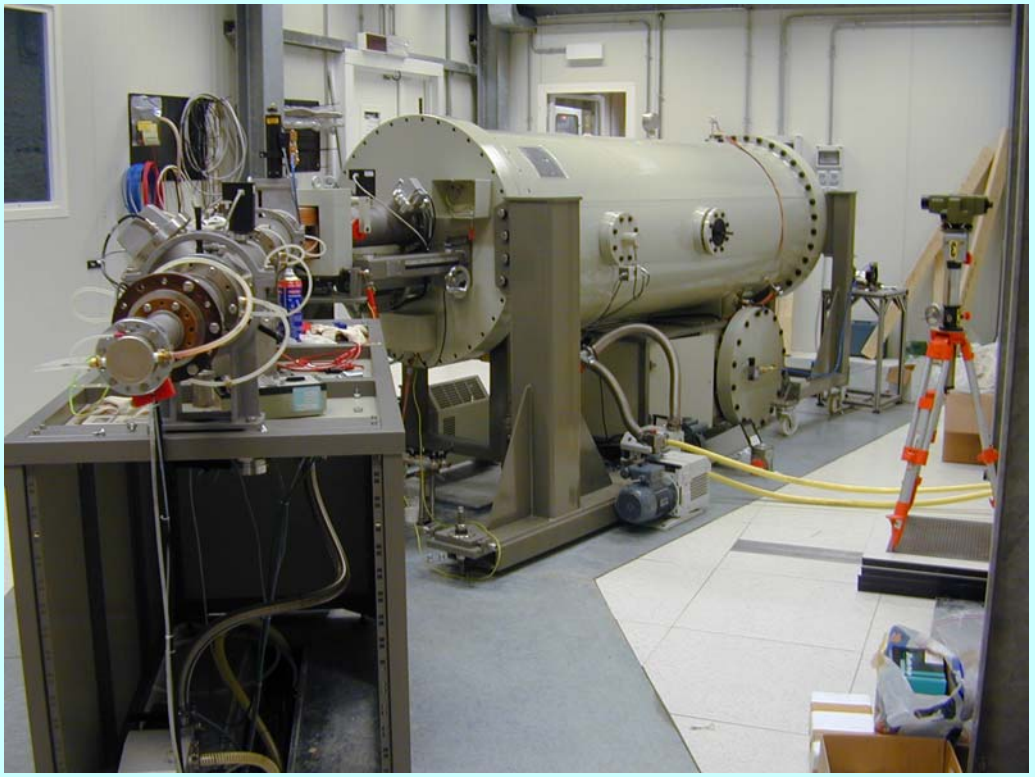


LUNA1 (50 kV)



Voltage Range :
1 - 50 kV
Output Current:
1 mA
Beam energy spread:
20 eV
Long term stability (8 h):
10^{-4}
Terminal Voltage ripple:
5 10^{-5}

LUNA2 (400 kV)



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

pp chain

$p + p \rightarrow d + e^+ + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84.7 %

13.8 %

$^3He + {}^3He \rightarrow \alpha + 2p$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

13.78 %

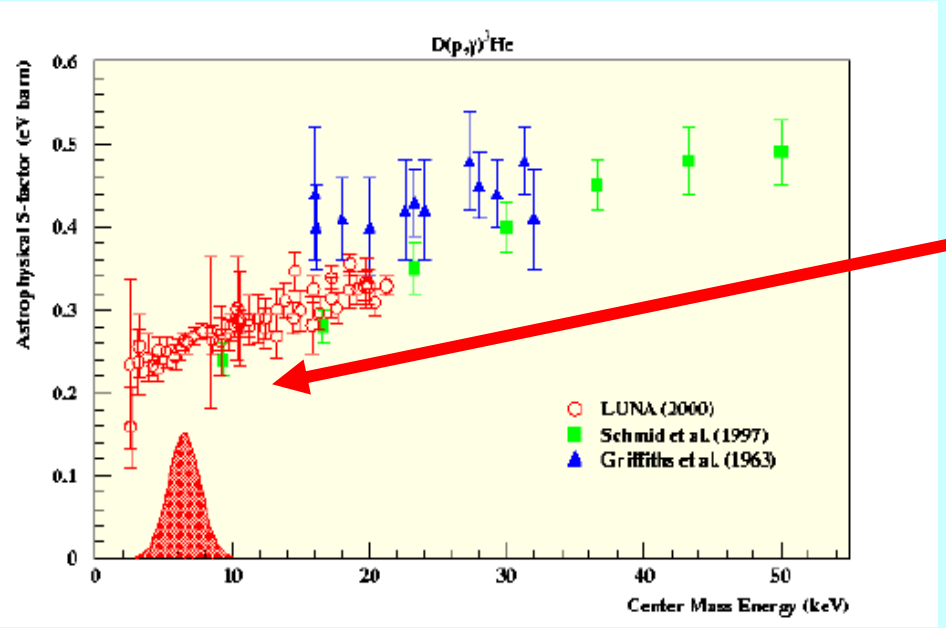
0.02%

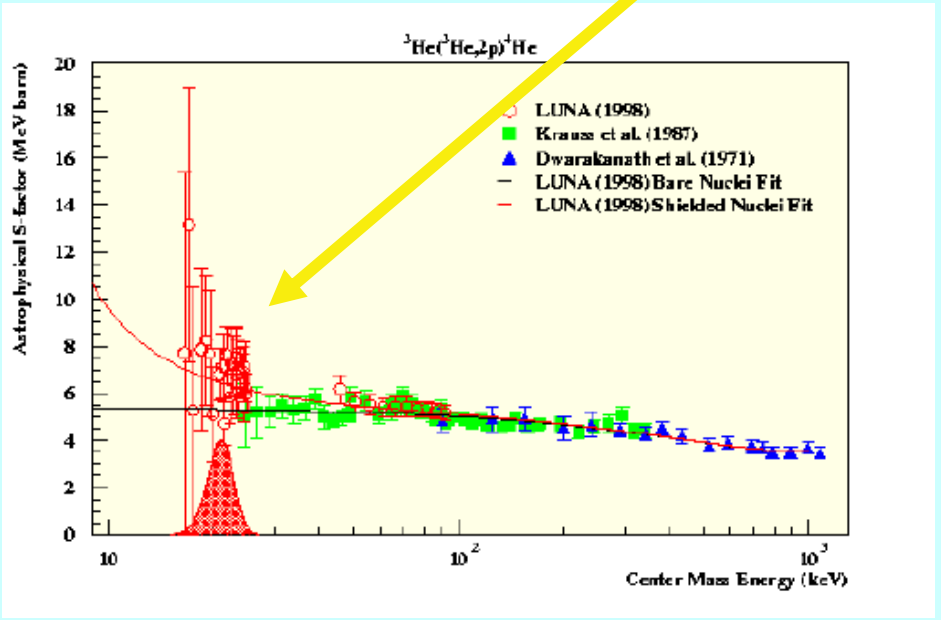
$^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

$^7Be + p \rightarrow {}^8B + \gamma$

$^7Li + p \rightarrow \alpha + \alpha$

$^8B \rightarrow 2\alpha + e^+ + \nu_e$

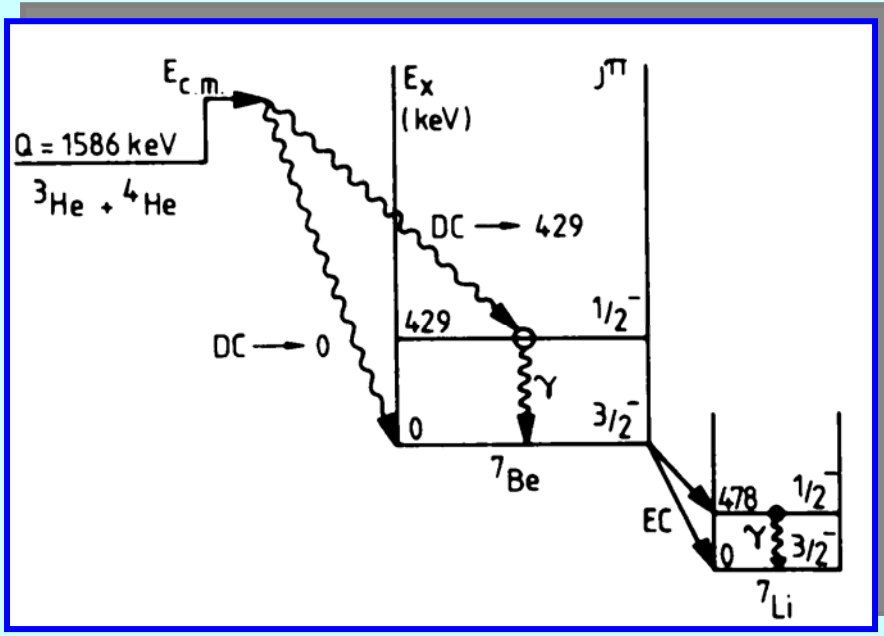




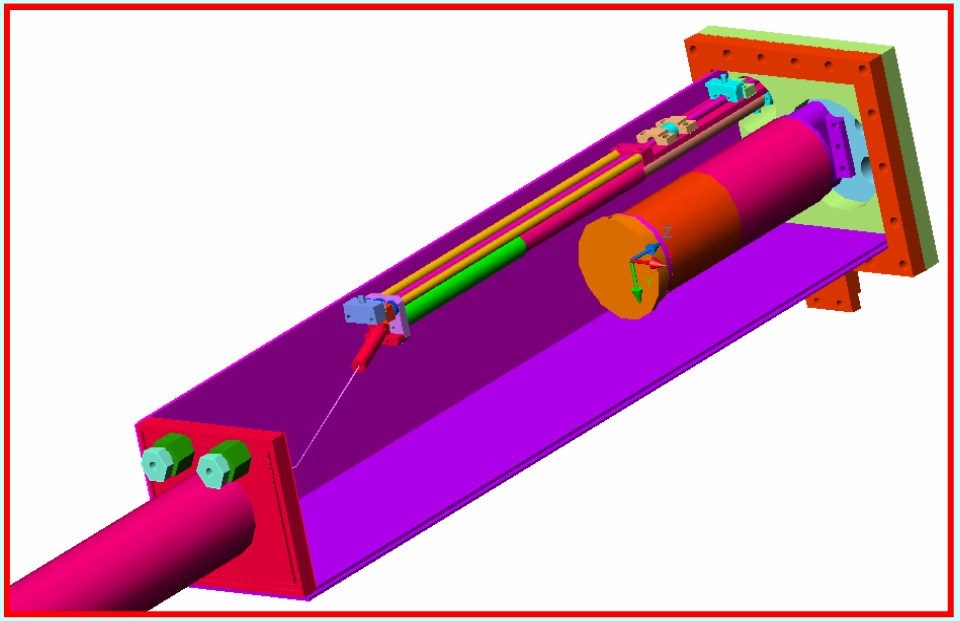
$^3He(\alpha,\gamma)^7Be$

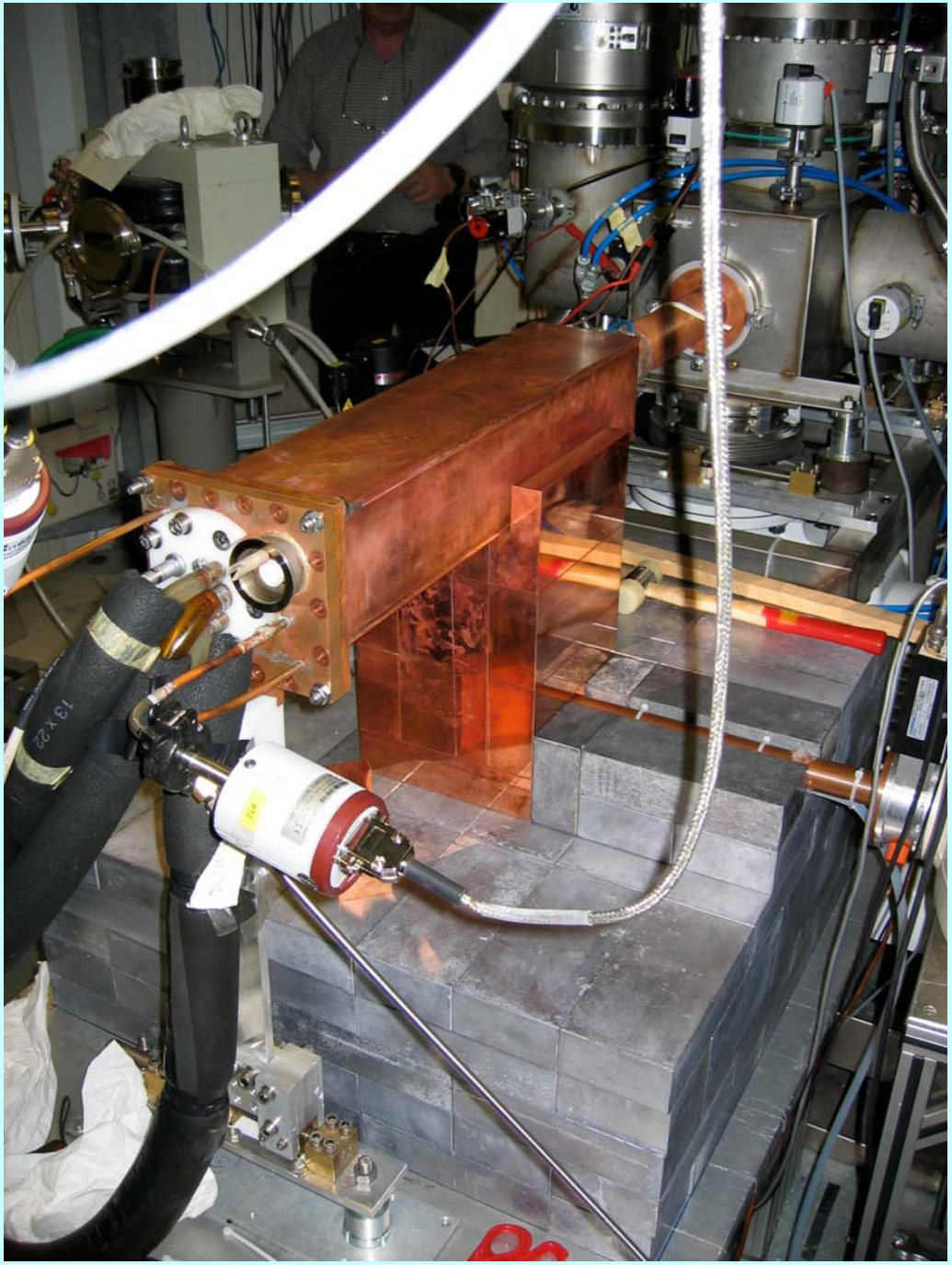
Q=1.6 MeV

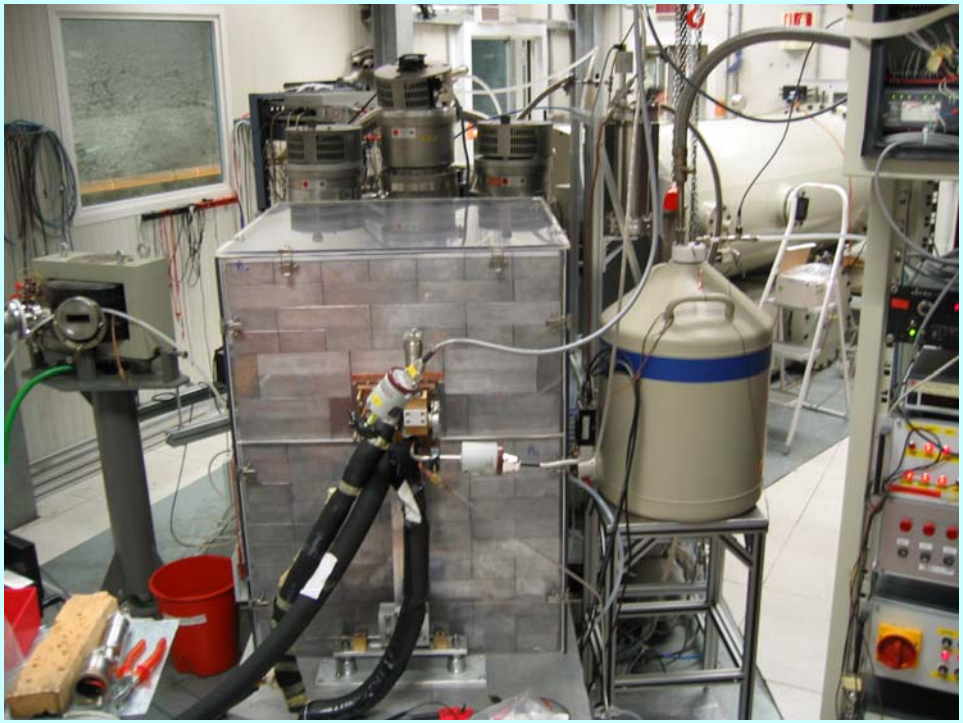
- Solar Neutrinos: ^7Be, ^8B
- BBN ^7Li

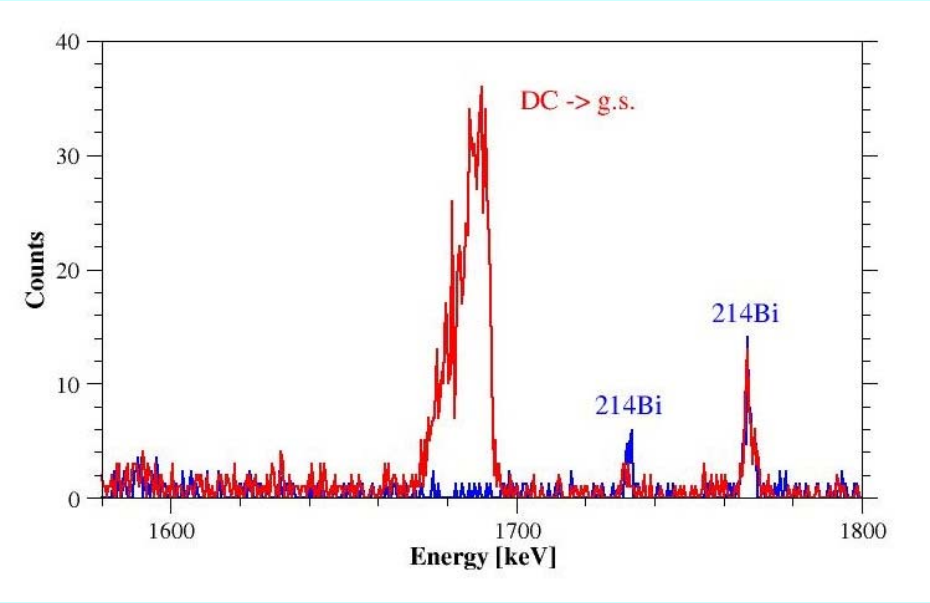


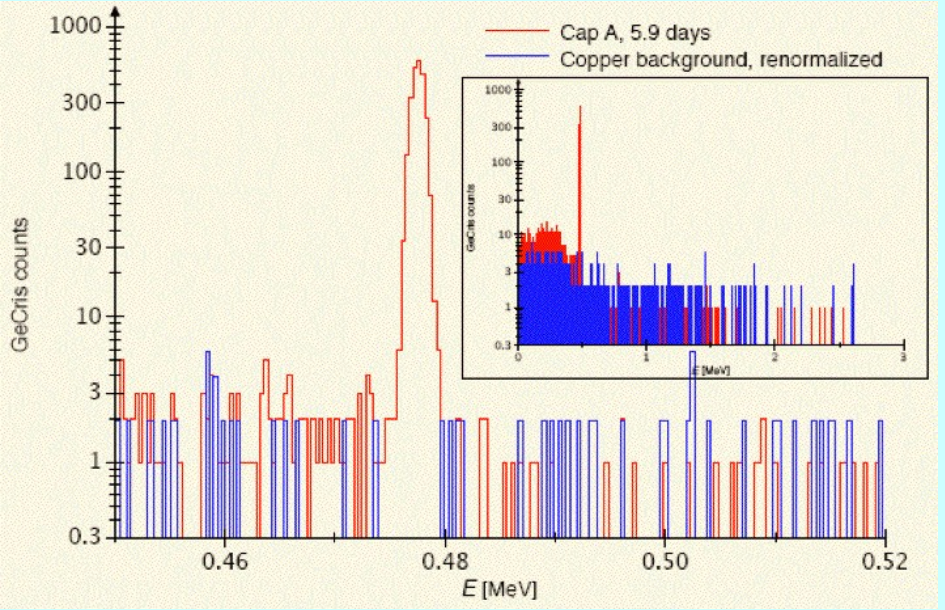
- Cross section from **prompt gamma** down to 90 keV (CM energy) using ^4He beam on ^3He target
- Activation via off-line **radioactive decay** measurements of the ^7Be atoms collected in the beam catcher
- All with a final error < 5 %



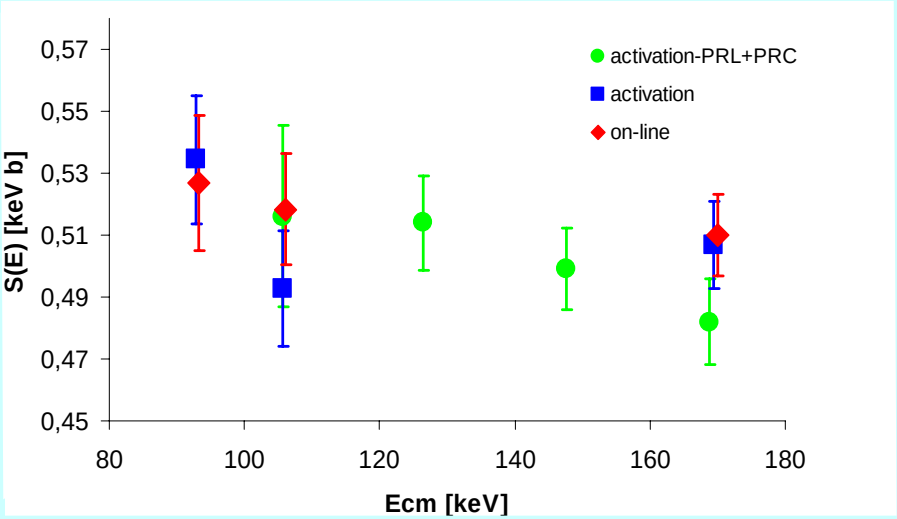


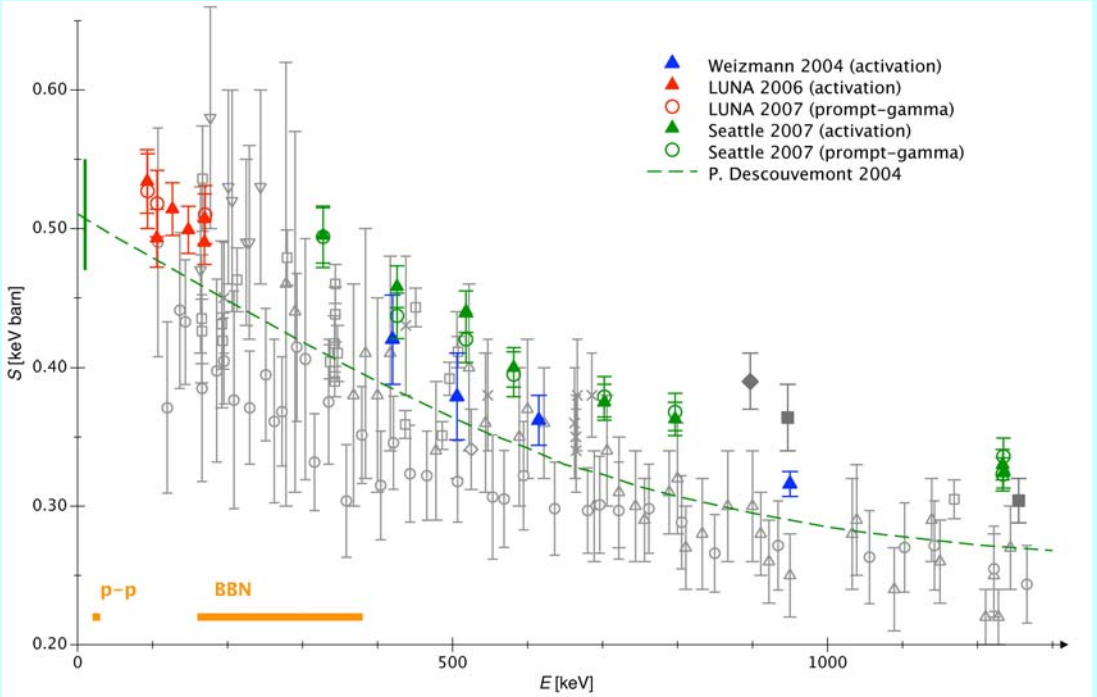



DC -> g.s.
214Bi
214Bi
Counts
Energy [keV]


Cap A, 5.9 days
Copper background, renormalized
GeCris counts
E [MeV]

ΔS = -1.4 ± 4.2 %


activation-PRL+PRC
activation
on-line
S(E) [keV b]
Ecm [keV]


Weizmann 2004 (activation)
LUNA 2006 (activation)
LUNA 2007 (prompt-gamma)
Seattle 2007 (activation)
Seattle 2007 (prompt-gamma)
P. Descouvemont 2004
S [keV barn]
p-p
BBN
E [keV]

- σ of $^3He(\alpha,\gamma)^7Be$ down to 93 keV

  $^7Be \approx$ prompt γ

- $S_{34}(0) = 0.560 \pm 0.017$ keV barn

  $\Delta\Phi(\nu_B)$ reduced from 12% to 10%

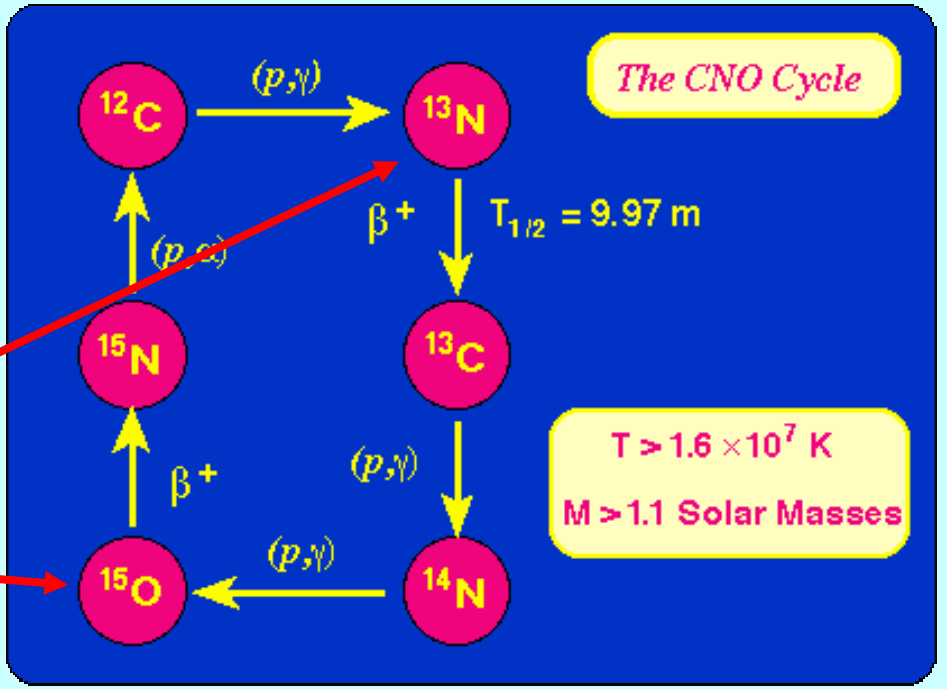
  $\Delta\Phi(\nu_{Be})$ reduced from 9.4% to 5.5%

  (C. Pena Garay)

  → Borexino-Kamland

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

Q=7.3 MeV



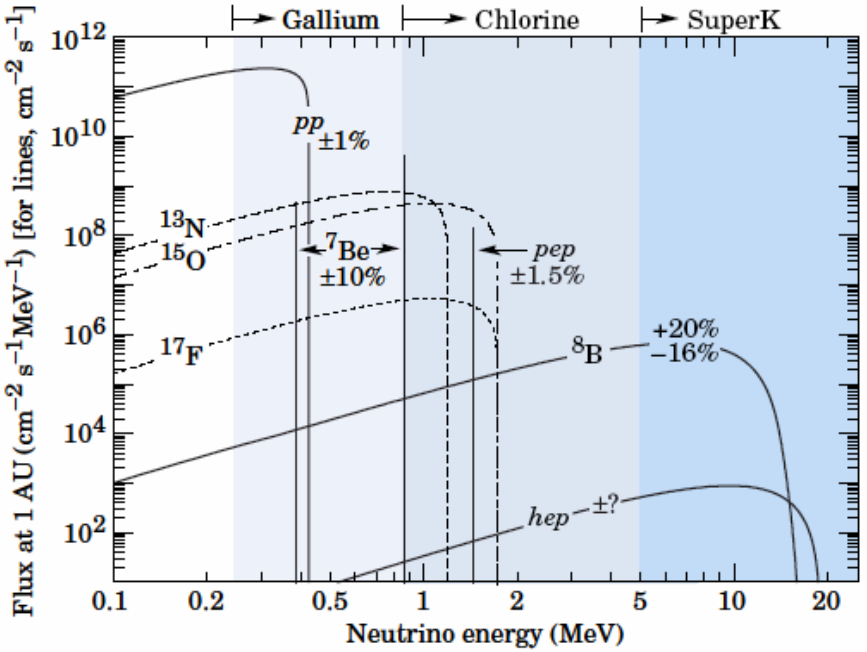
ν E<1.2 MeV

ν E<1.7 MeV

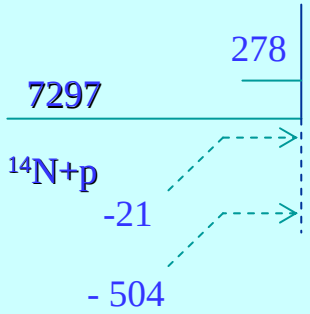
- ν_{cno} $\Phi_{cno} \sim S_{1,14}$
- Globular Cluster Age

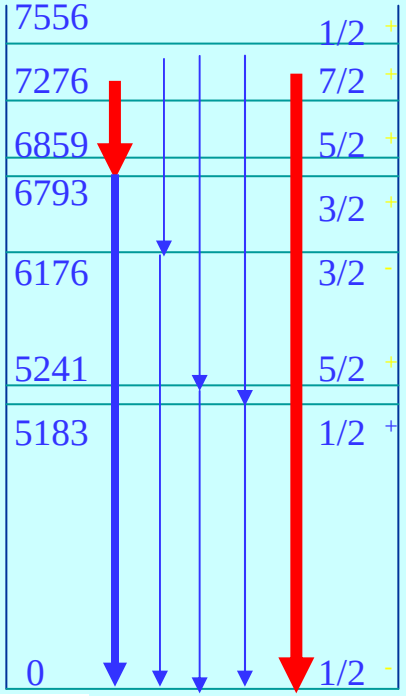
$S(0)=3.5_{-1.6}^{+0.4}$ keV b (Ad98)

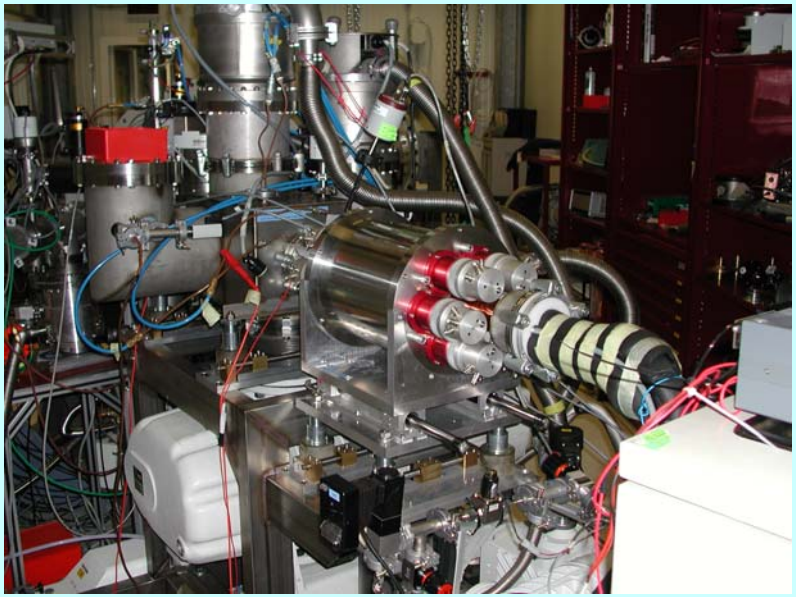
$S(0)=3.2_{-0.8}^{+0.8}$ keV b (An99)



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

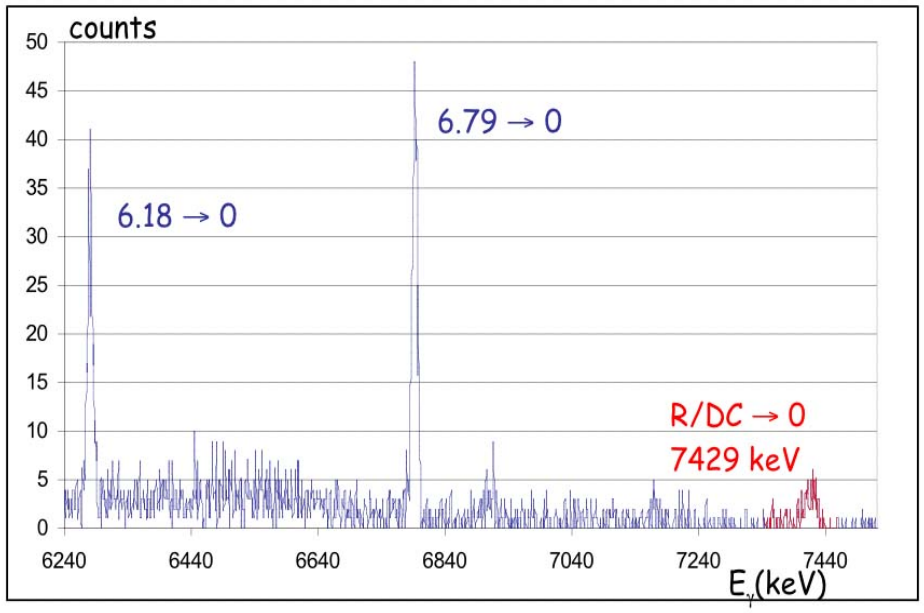






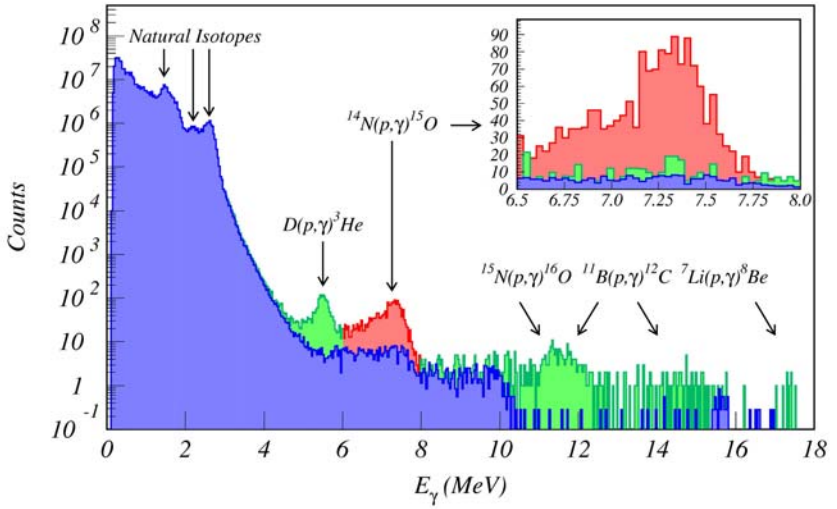
"High" energy: solid target + HpGe

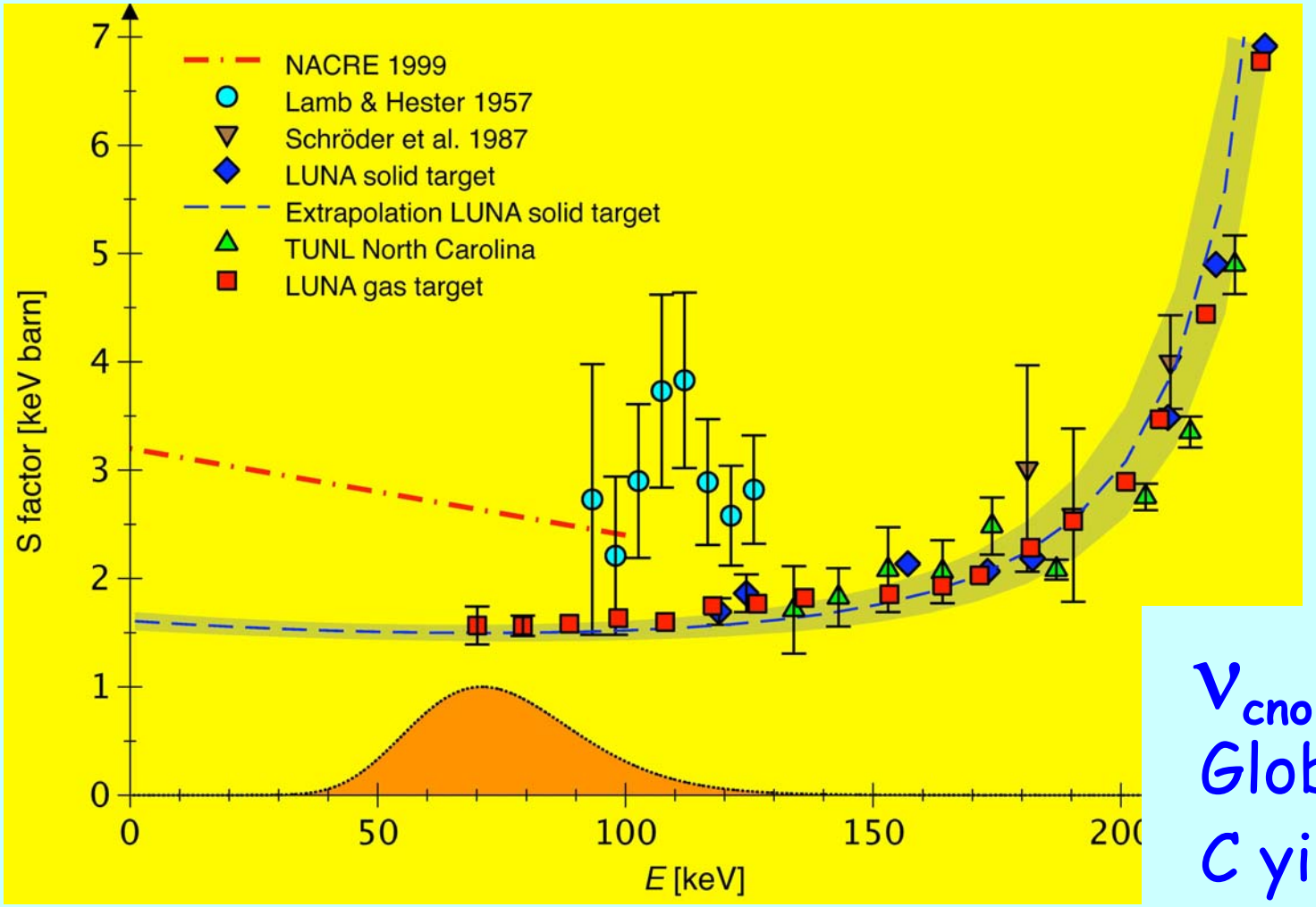
Low energy: gas target + BGO



gamma spectrum of $^{14}N(p,\gamma)^{15}O$ at Ep=140 keV

beam energy 90 keV



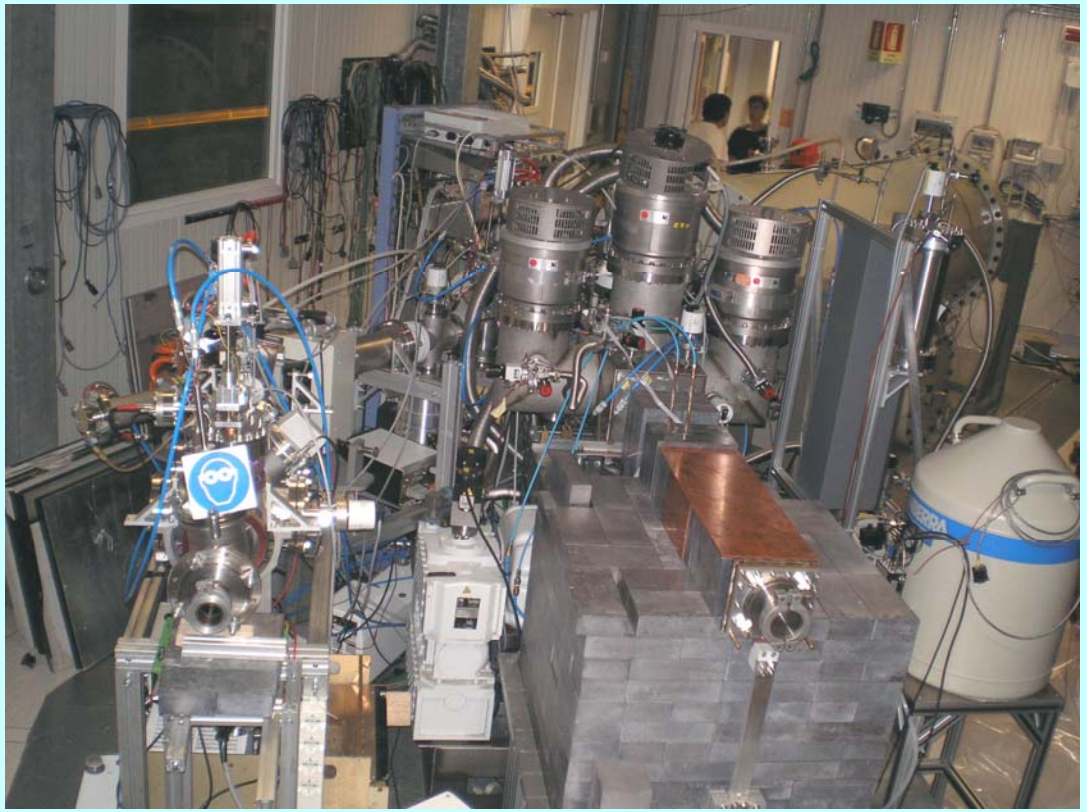


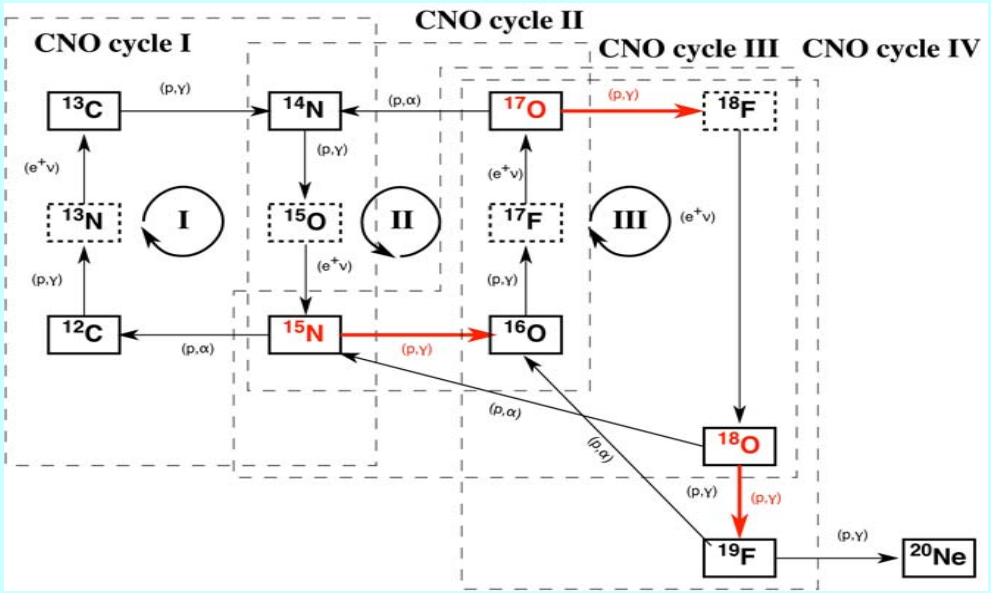
ν_{cno} from the Sun
Globular cluster age
C yield in AGB stars

$S_t(0)=1.61\pm0.18$ keV b

'clover' study of the capture to the ground state: error on $S_t(0)$= ±0.13

ν_{cno} from the Sun ⟶ solar core metallicity





Rich program of Nuclear Astrophysics:

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

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

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

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

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

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

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

. . . . . .

New underground accelerators:
Gran Sasso, DUSEL, Boulby mine, Canfranc, Romania…

$^{12}C(\alpha,\gamma)^{16}O$

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

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

(α,γ) on ^{14}N, ^{15}N, ^{18}O……

- **LUNA** has shown that it is possible to measure

  $\sigma(E_{star})$: **^{3}He (^{3}He,2p)^{4}He, ^{2}H(p,γ)^{3}He**

- **^{3}He (^{3}He,2p)^{4}He:** σ down to 16 keV

  no resonance within the solar Gamow Peak

- **^{3}He(α,γ)^{7}Be:** **^{7}Be** ≈ prompt γ

  $\Delta\Phi(\nu_{Be})$ reduced from 9.4% to 5.5%

- **^{14}N(p,γ)^{15}O:** σ down to 70 keV (T=60 T_6)

  ν_{cno} reduced by ~ 2 with 8% error → **core metallicity**

  Globular cluster age increased by 0.7-1 Gy

  Higher C yield in AGB stars