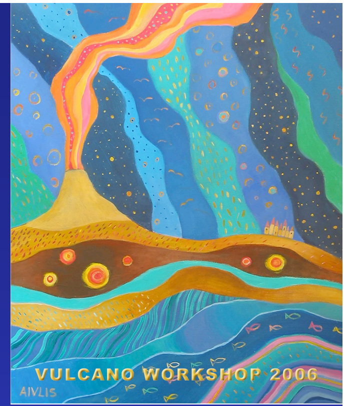
Laboratory Underground Nuclear Astrophysics



Measurements of nuclear cross sections of interest in BBN with the LUNA experiment

- BBN and the "Precision Cosmology" Epoch
- The LUNA experiment
- $P(D,\gamma)^3He$
- $^3He(D,p)^4He$

} 50 kV accelerator

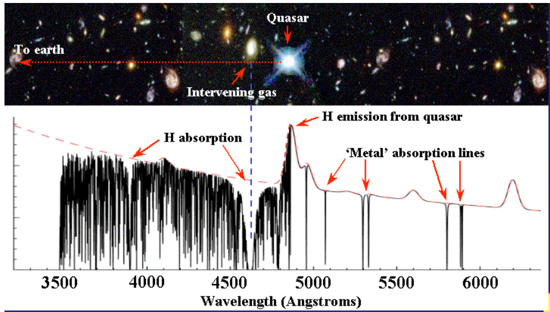
- $^3He(^4He,\gamma)^7Be$ In progress!!
- $D(^4He,\gamma)^6Li$

} 400 kV accelerator

- Conclusions

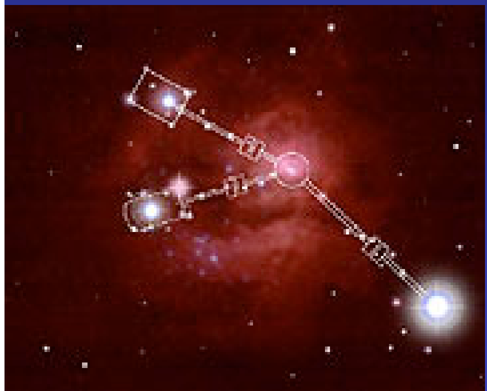
Carlo Gustavino
For the LUNA collaboration

BBN Flowchart



Primordial Elements Observations

Y_i Systematics!



σ(E) Data regression!

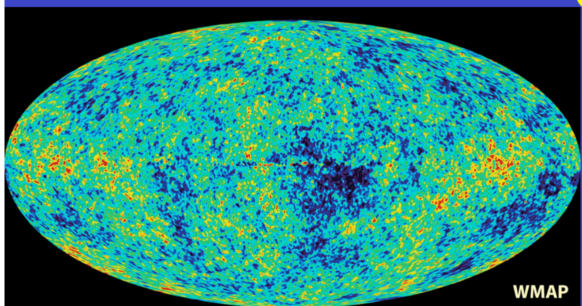
Nuclear Astrophysics

BBN

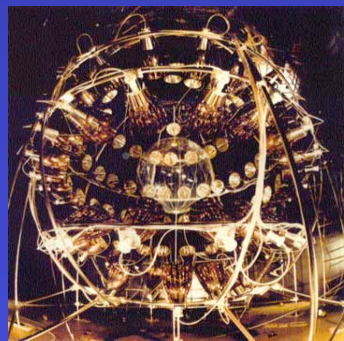
Cosmology

Astrophysics

New Physics?

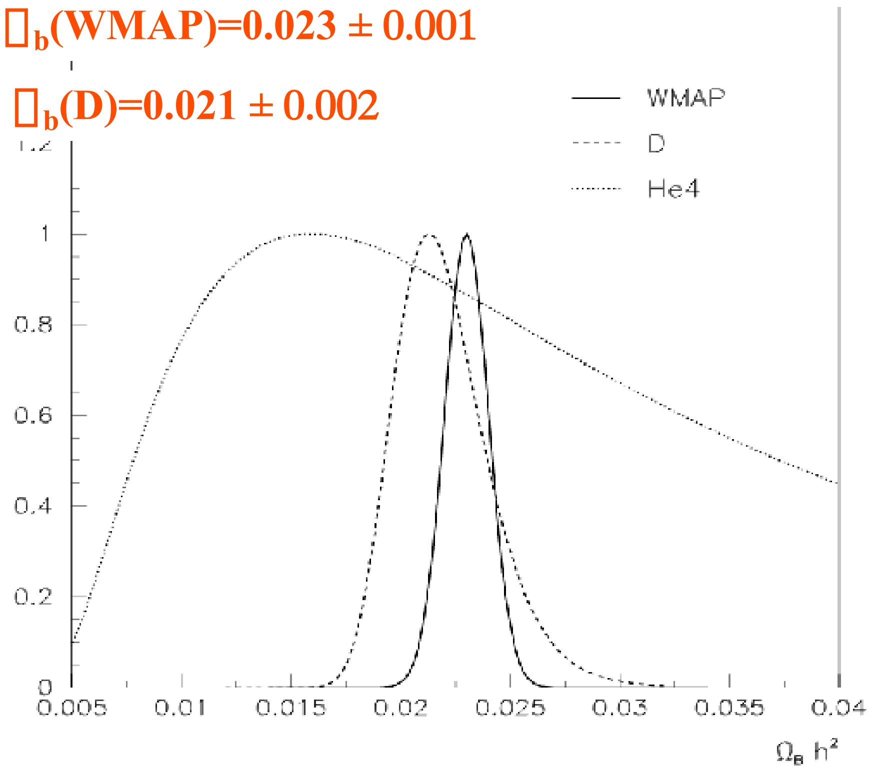


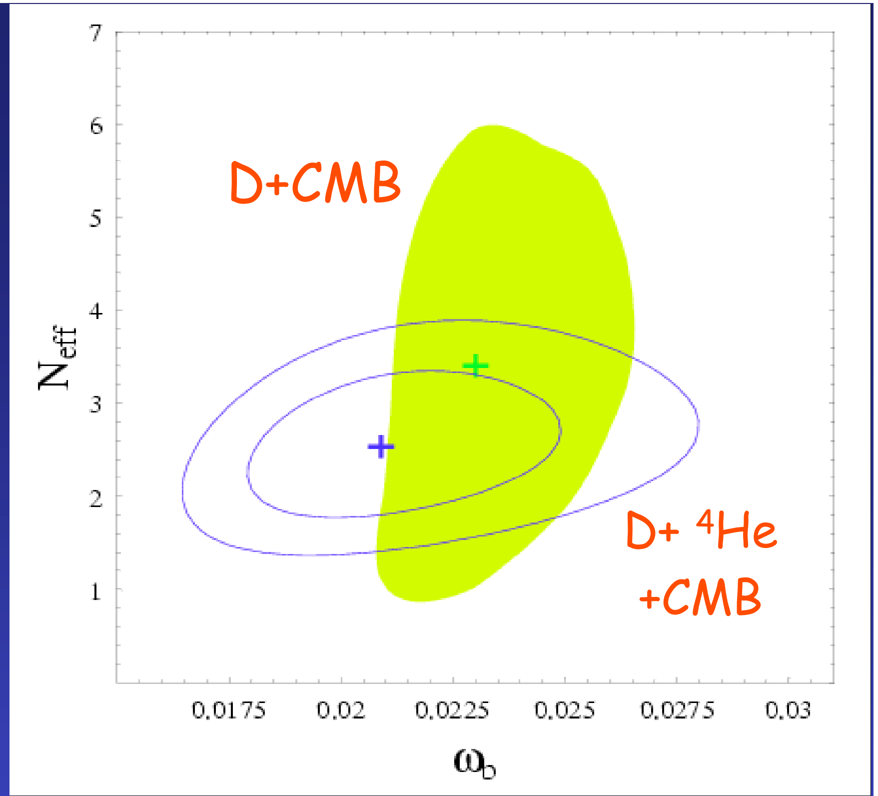
CMB Ω_b , $\Delta\Omega_b/\Omega_b$ <<1!!!



Particle Physics (τ_n, ν, ..)

P. D.Serpico et al. JCAP 0412 (2004) 010



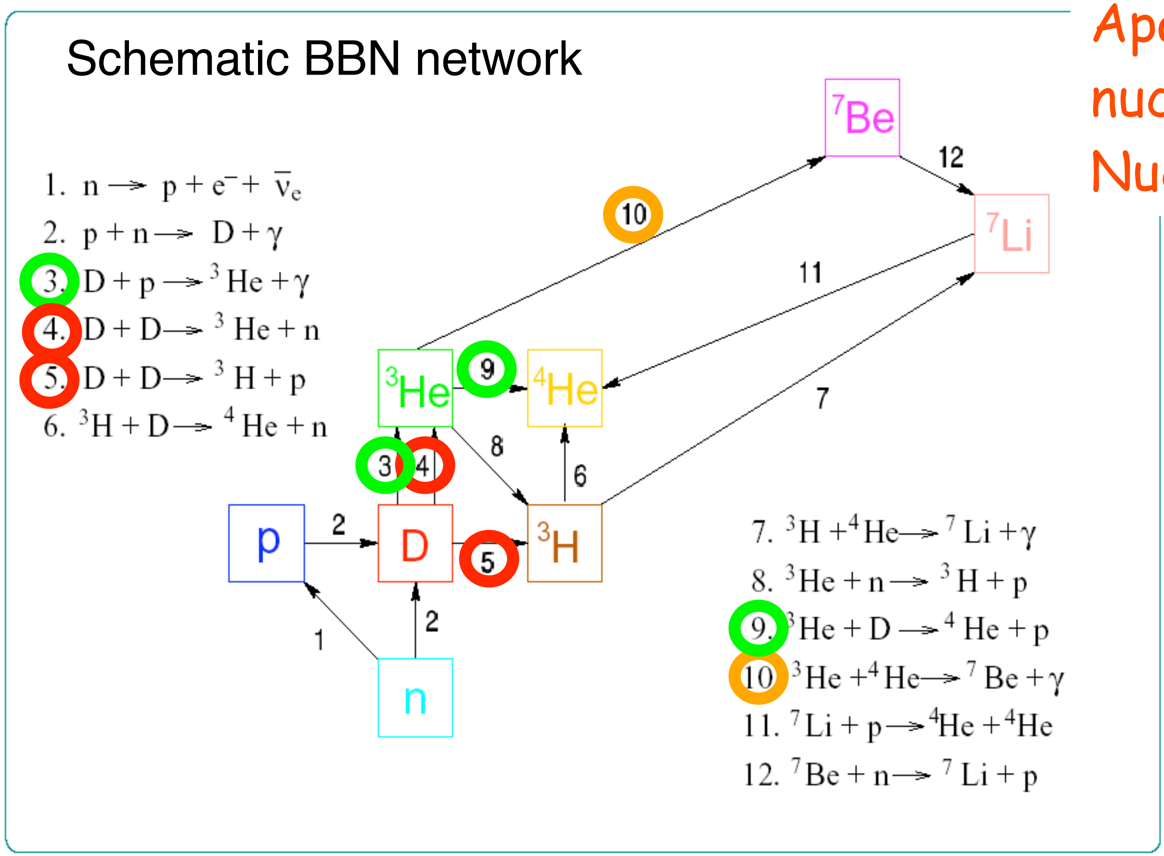


Agreement between two completely independent determinations of Ω_b !!!

Wonderful check of Standard Cosmological Model

X_D=best BBN “bariometer”

N_{eff} is much better bounded than with CMB alone



Apart for Helium, all the other nuclides are sensitive to the Nuclear reaction Network.

Several key reactions studied by LUNA

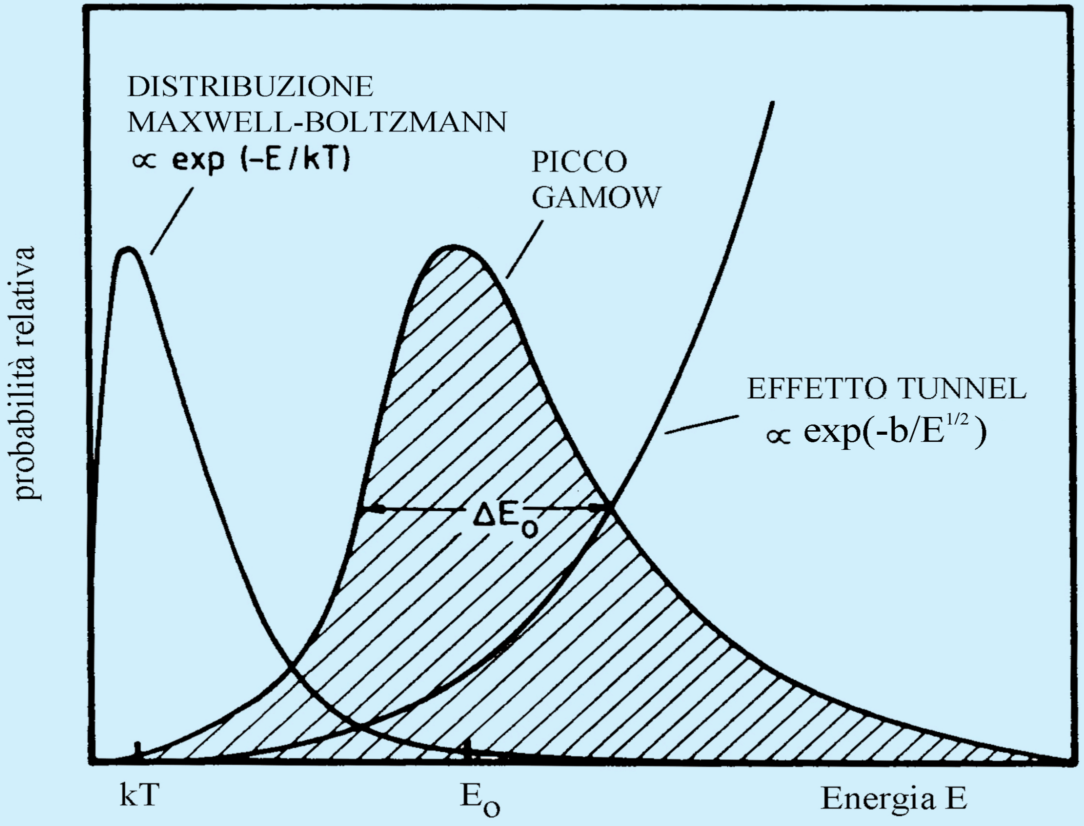
Past: $P(D,\gamma)^3He$ & $^3He(D,p)^4He$ — D,^{3}He abundance

Present: $^3He(^4He,\gamma)^7Be$ — ^{7}Li abundance

Next: $D(^4He,\gamma)^6Li$ — ^{6}Li abundance (not shown in the schematic)

Desirable: D+D reactions — D abundance (not underground)

Why underground Measurements?



Astrophysical Factor

Gamow Factor

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

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

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

- Very low cross sections because of the coulomb barrier

UG experiments to reduce the background due to cosmic ray

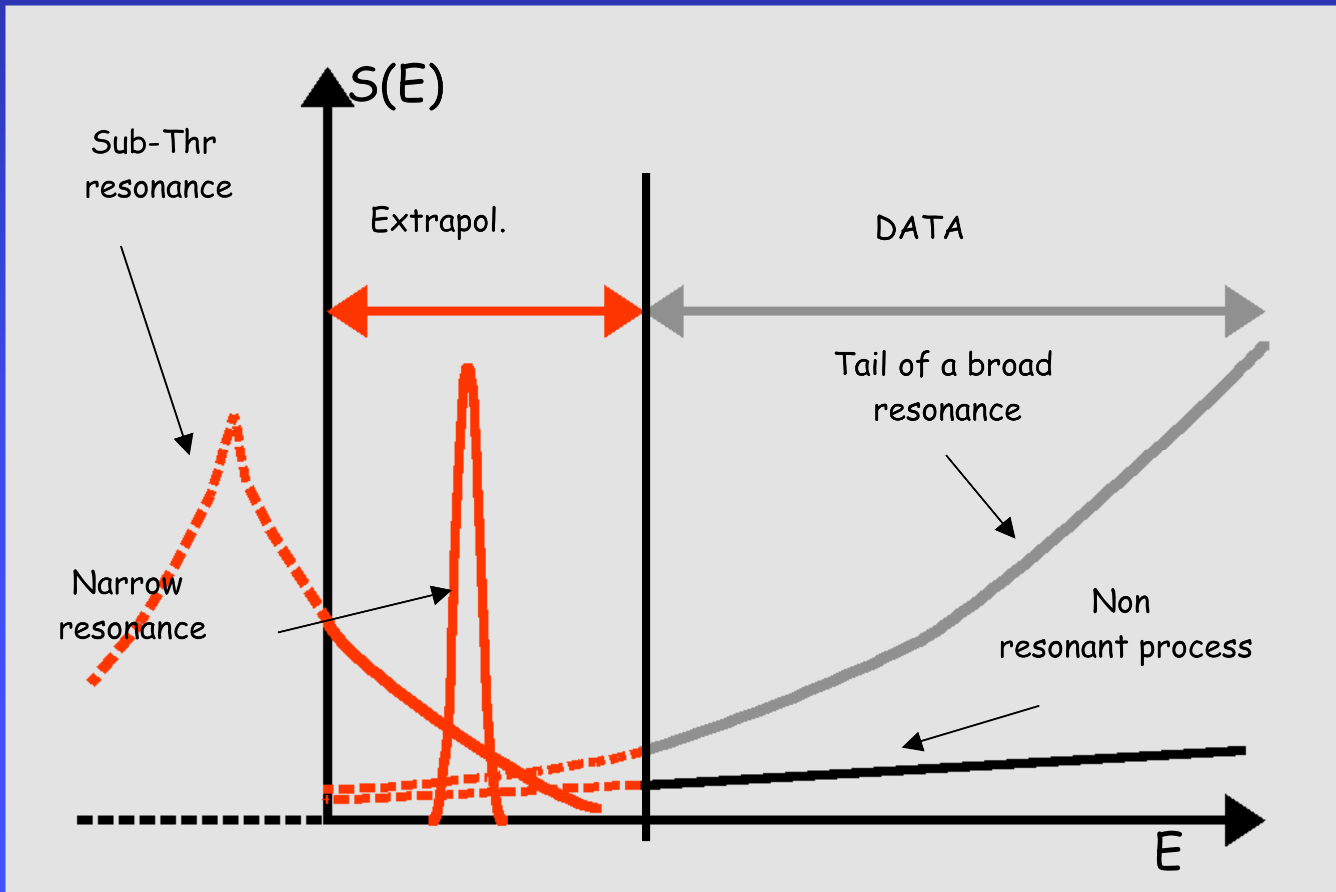
N.B. differently from stars, in BBN we don't have a fixed T (gamow peak), although there is a kinetic equilibrium

Why underground Measurements?

•Danger in extrapolating because of possible low energy nuclear resonances

•Direct measurement at low energies nedeed!

Solution: UnderGround Measurements, high beam current

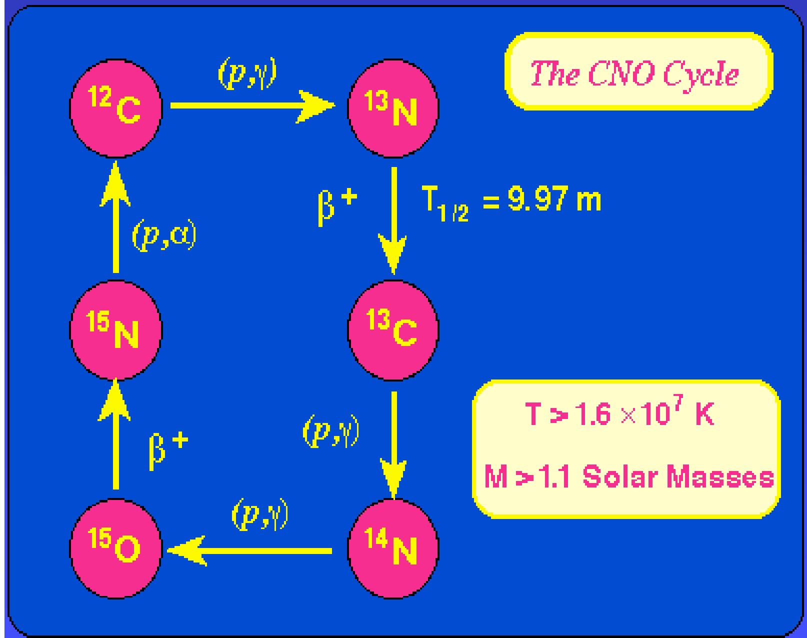


A good example: $^{14}N(p,\gamma)^{15}O$

$^{14}N(p,\gamma)^{15}O$ is the slowest CNO cycle therefore it regulates the CNO solar neutrino flux and plays an important role in estimating the age of Globular Clusters. The LUNA measurements ($E_{cm} \geq 71$ keV) show that this cross section is a factor 2 lower than the previous extrapolated values ($E_{cm} \geq 190$keV)

GC age estimation increases of 0.7-1 Gyr

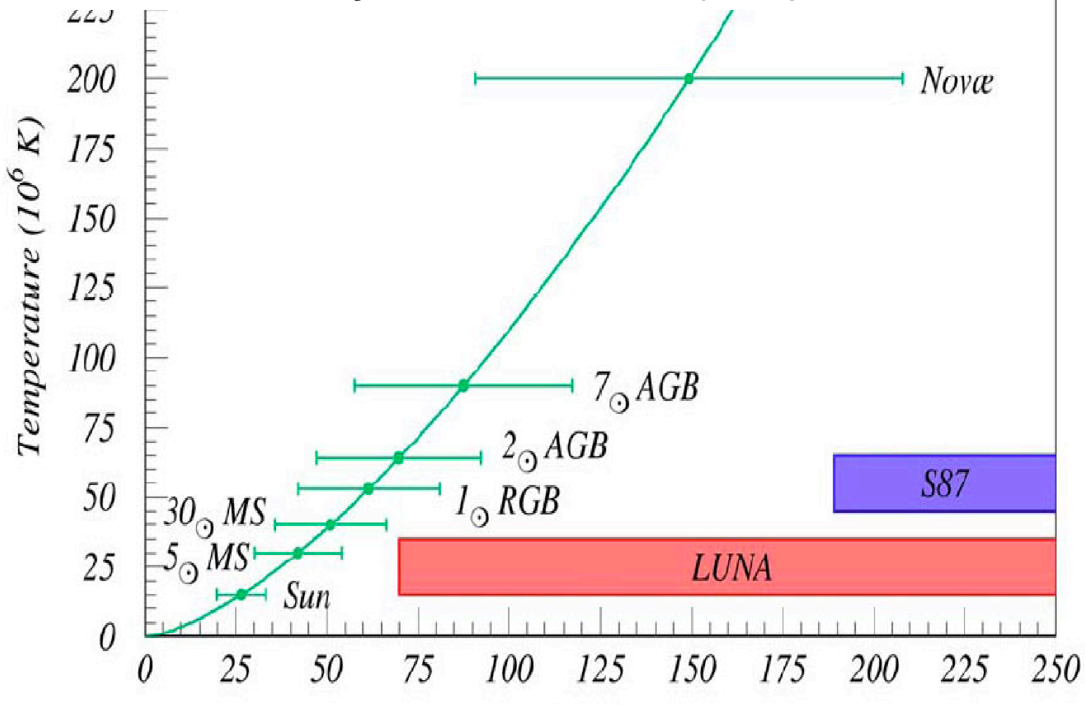
CNO neutrino flux decreases of a factor ≈ 2



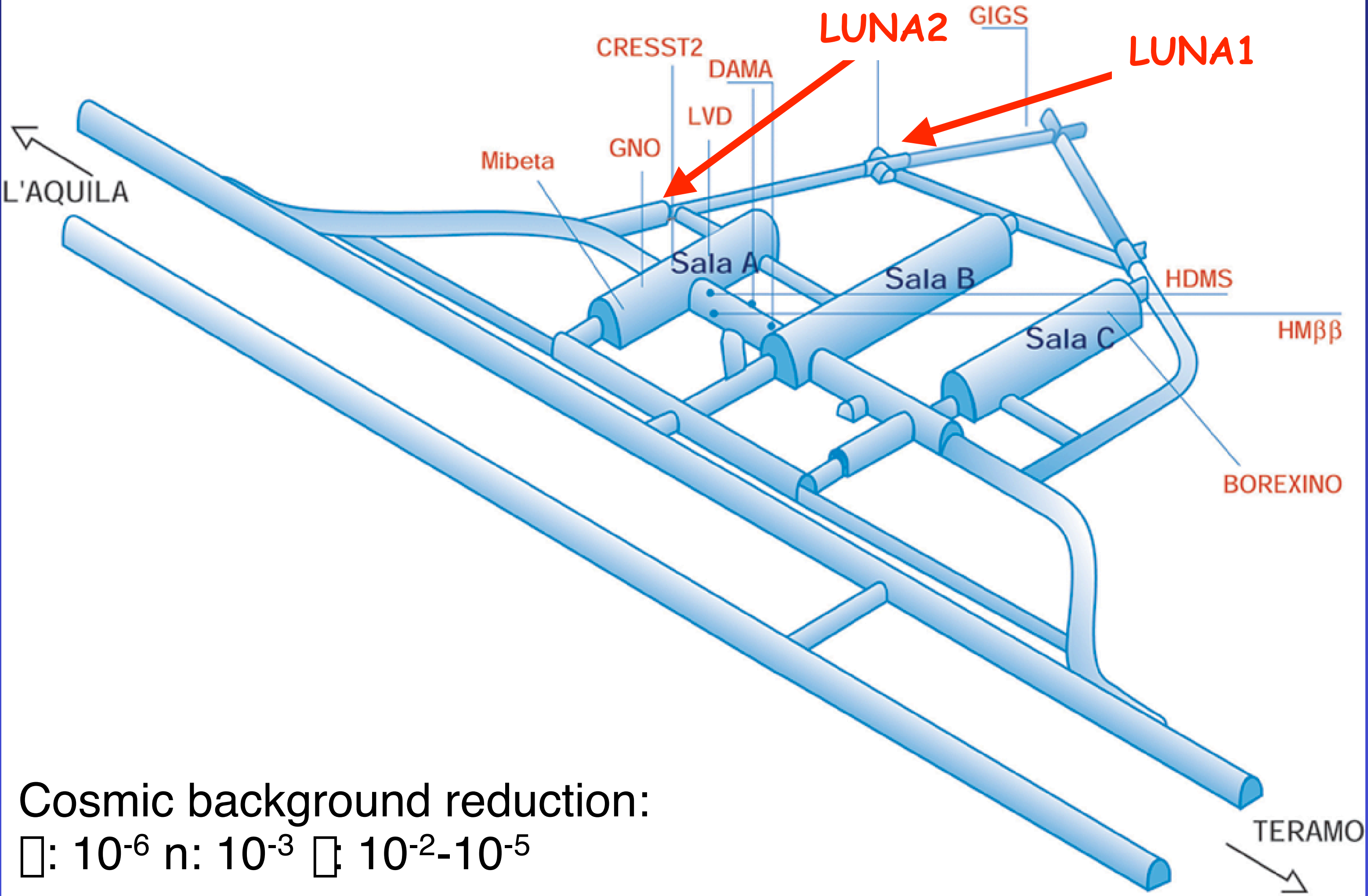
$S_0 = 1.7 \pm 0.1 \pm 0.2$ keV b

A.Formicola et al., Phys. Lett. B 591 (2004) 61

A. Lemut et al., Phys. Lett. B 634, 483 (2006)



Gran Sasso National Laboratory (LNGS)



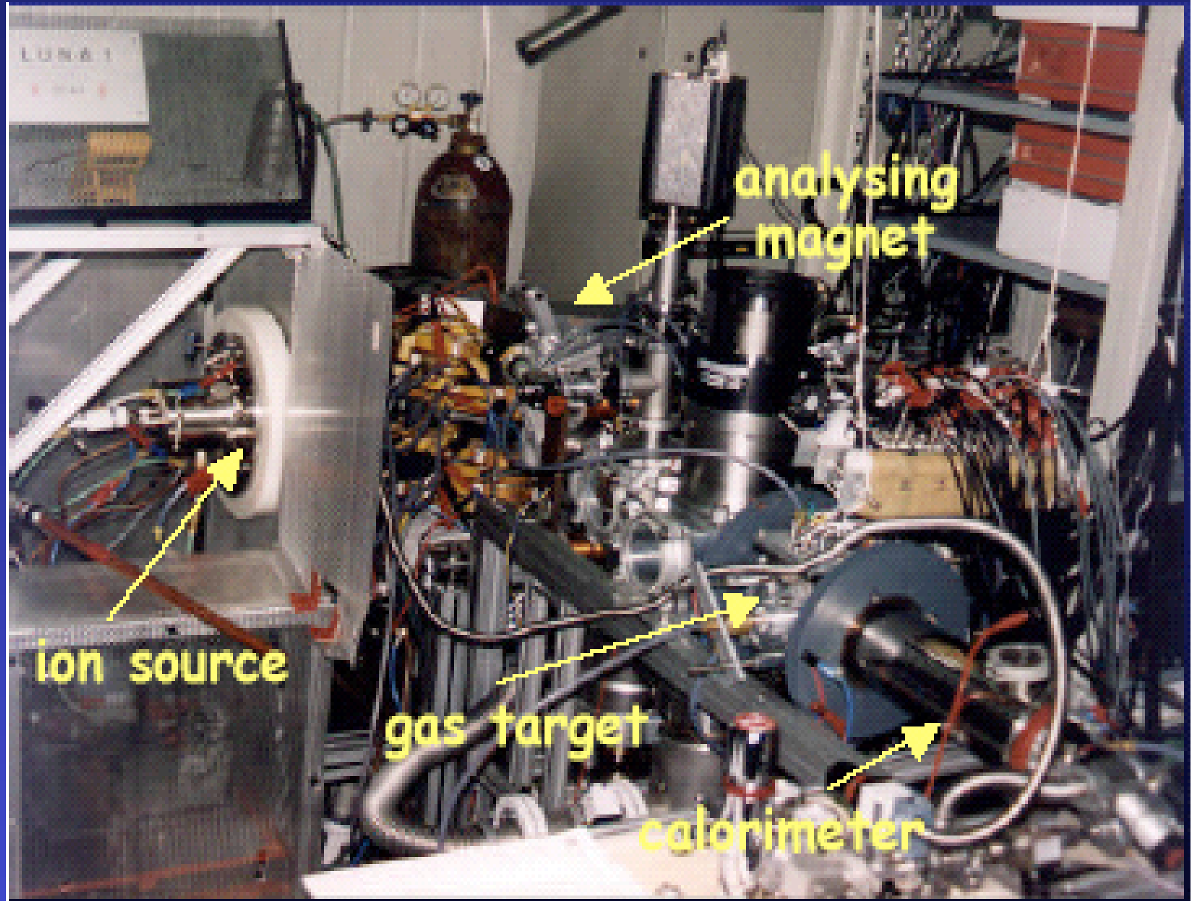
Cosmic background reduction:

□: 10^{-6} n: 10^{-3} □: 10^{-2}-10^{-5}

The LUNA1 (50 kV) accelerator

$P(D,\gamma)^3He$

$D(^3He,p)^4He$



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}

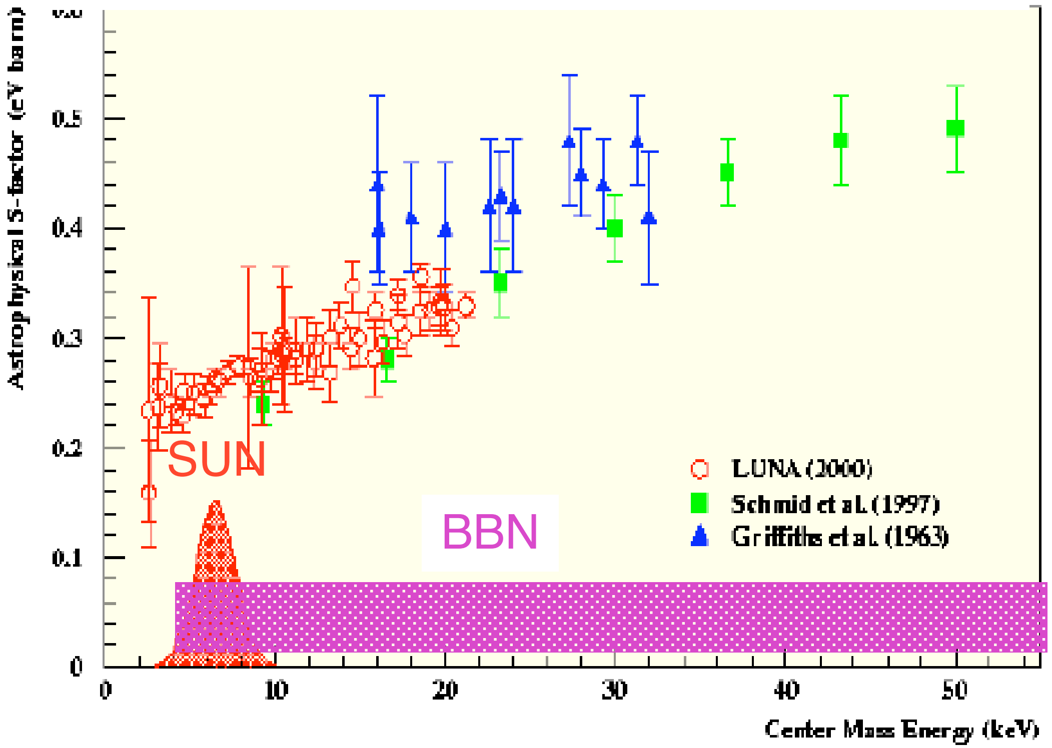
$D(p,\gamma)^3He$ Q = 5.5 MeV

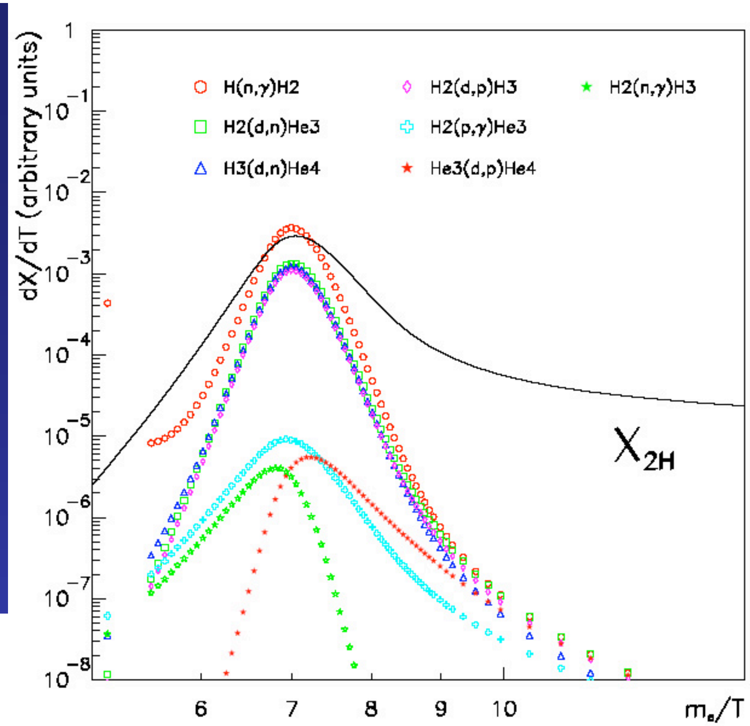
S(0)=0.216± 0.006 eVbarn

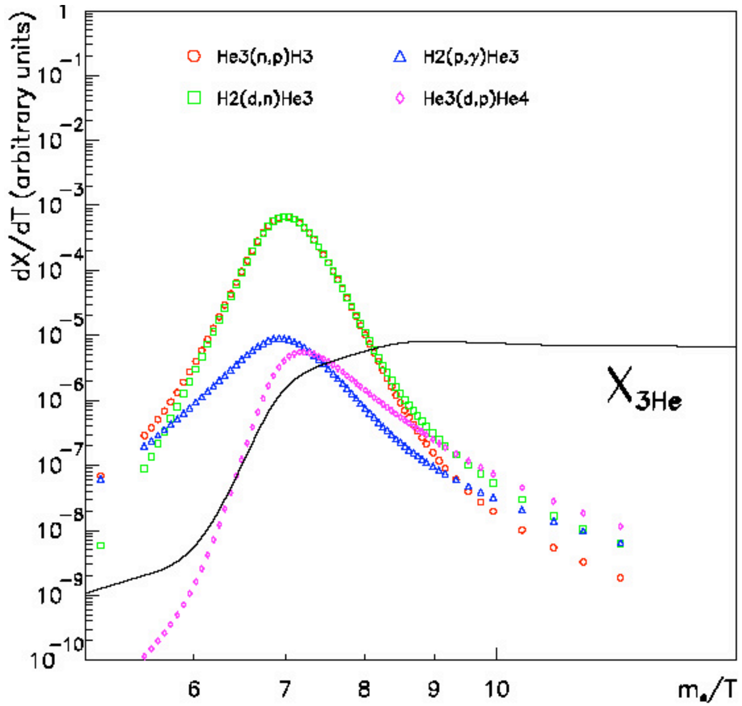
One of the main responsible of D and ^3He synthesis

LUNA data crucial to reduce X_D error budget (~factor 2)

C.Casella et al., Nucl. Phys. A706(2002)203



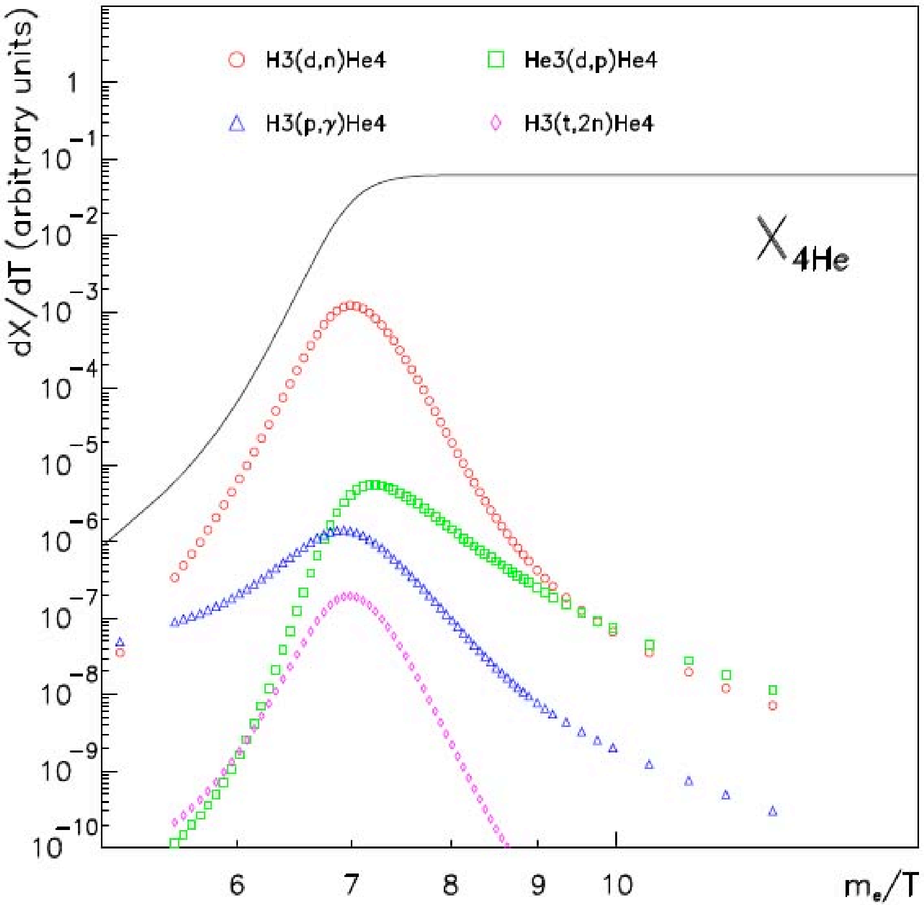


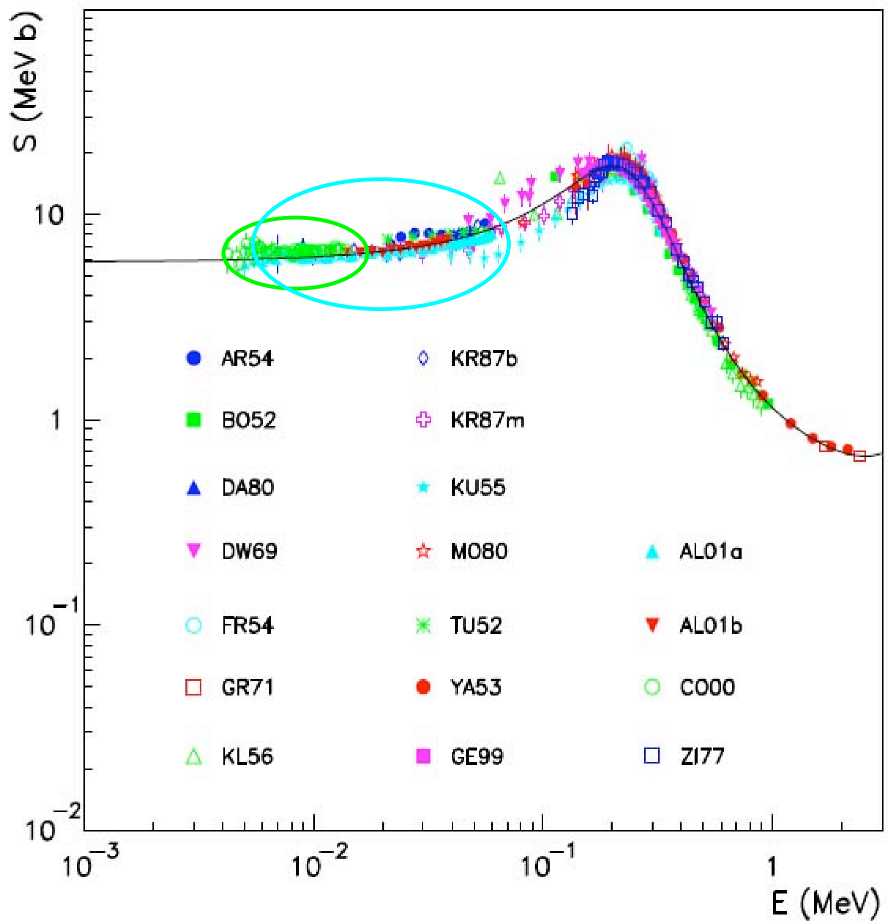


$D(^3He,p)^4He$ Q = 18.4 MeV S(0)=6.7 MeVbarn

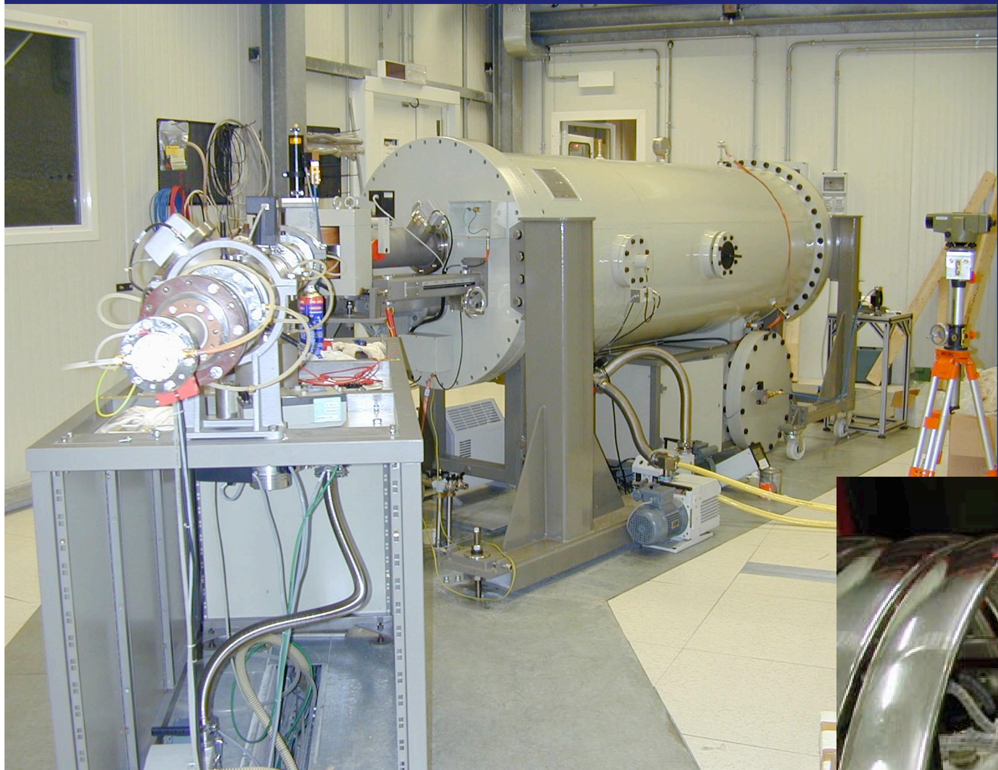
^4He synthesis. Also important for electron screening and stopping power study

H. Costantini et al., Phys. Lett. B482(2000)43
M.Aliotta et al., Nuclear Physics A690(2001)790





The LUNA2 (400 kV) accelerator



Voltage Range: 50-400 kV

Output Current: 1 mA (@ 400 kV)

Absolute Energy error: ±300 eV

Beam energy spread: <100 eV

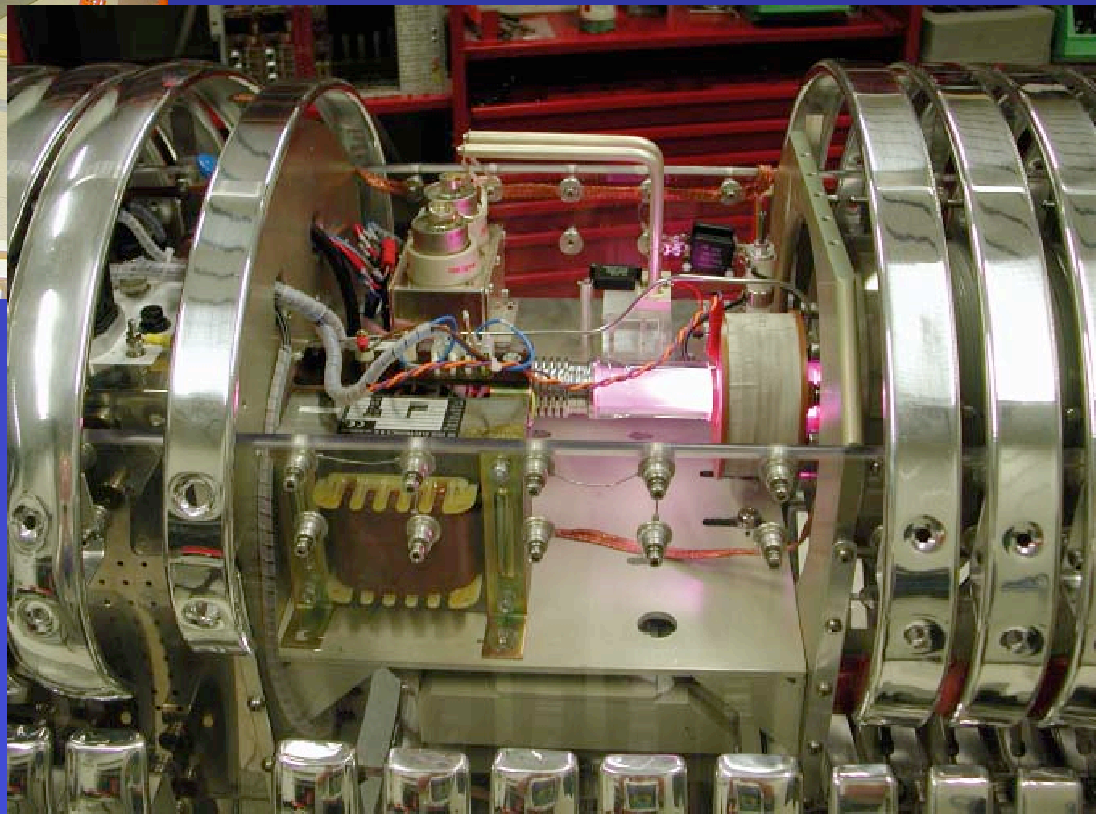
Long term stability (1 h) : 5 eV

Terminal Voltage ripple: 5 Vpp

A. Formicola et al., NIMA 527 (2004) 471.

^{3}He(^{4}He,γ)^{7}Be

D(^{4}He,γ)^{6}Li



$^{3}He(^{4}He,\gamma)^{7}Be$ The ^{7}Li puzzle

The primordial production of ^{7}Li depends directly on the $^{3}He(^{4}He,\gamma)^{7}Be$ rate. The ^{7}Li abundance predicted by BBN models based on the WMAP baryon density is not compatible with "Spite plateau" data for metal-poor population II stars.

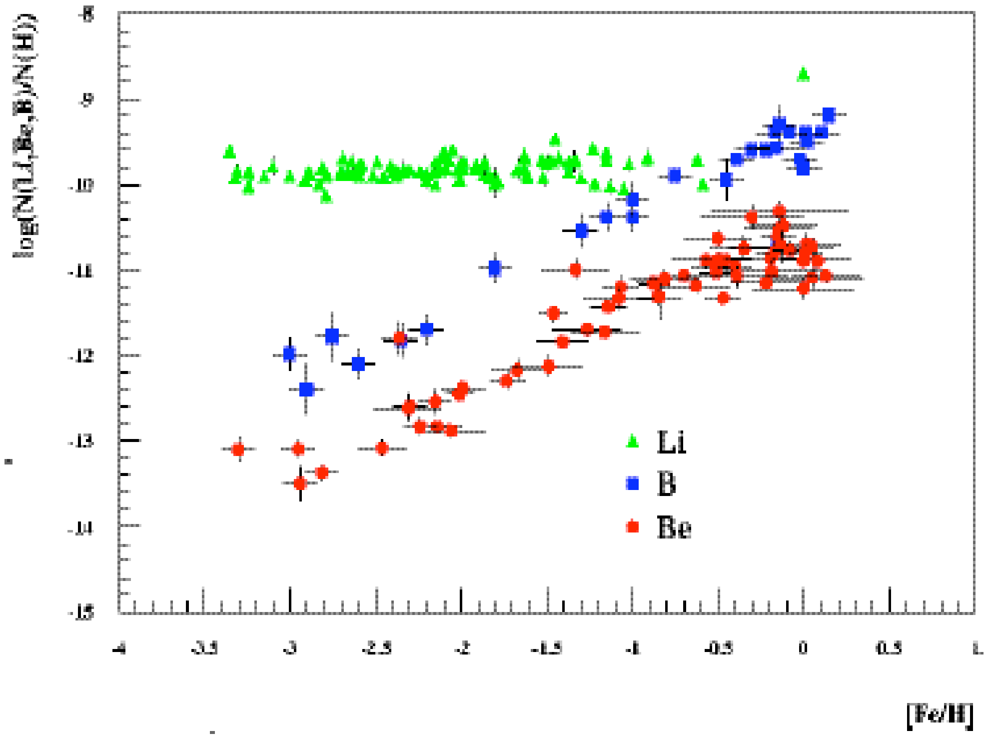
Systematics in Astrophysics?

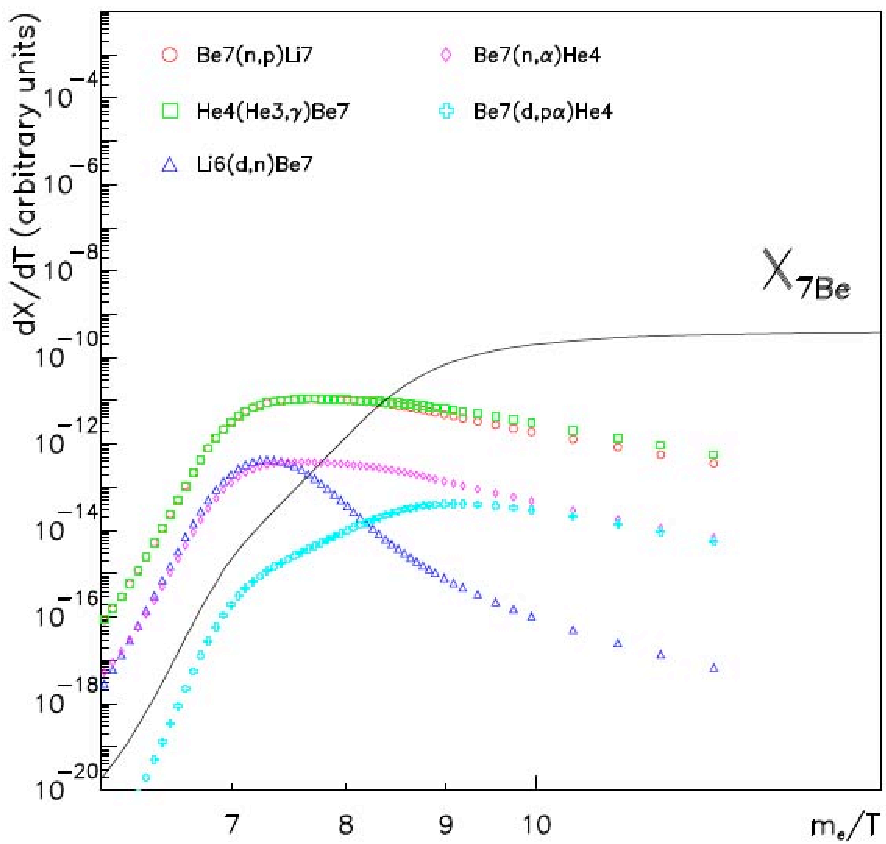
Models?

New physics?

New measurements to fix nuclear physics input parameters…

Leading processes: $^{3}He(^{4}He,\gamma)^{7}Be$ $^{7}Be(n,\alpha)^{4}He$





$^3He(^4He,\gamma)^7Be$

We get:

$10^{10}(^7Li\ /H)_{th} = 4.8 \pm 0.4 \pm 0.4$ →

Due to $\square\square_b=0.001$

Due to nuclear uncertainties

rate	$\delta\sigma_{Li}^2/\ \sigma_{Li}^2(\%)$
$^7Be(n,^4He)^4He$	40.9
$^4He(^3He,\gamma)^7Be$	25.1
$^7Be(d,p)^4He^4He$	16.2
$^3He(d,p)^4He$	8.6
$^2H(p,\gamma)^3He$	4
others	5.2

P. D.Serpico et al. JCAP 0412 (2004) 010

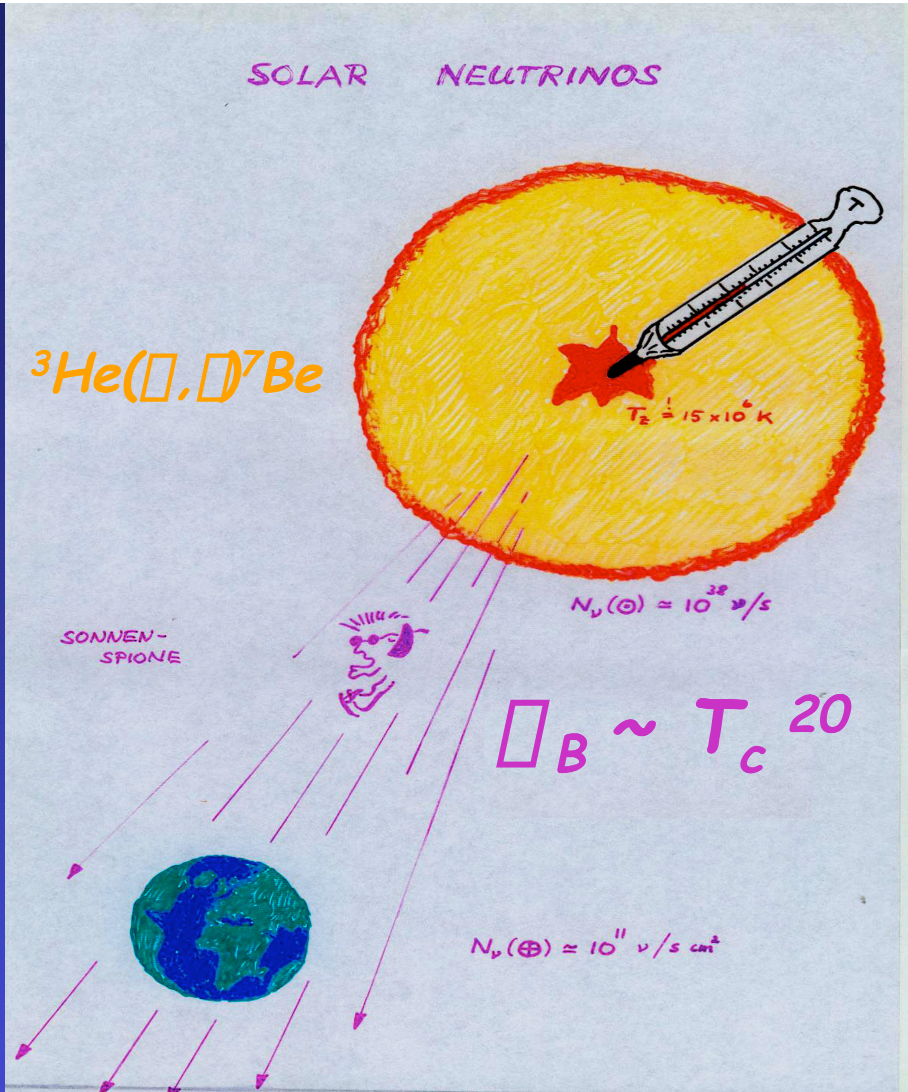
While the "Spite plateau" and other measurements suggest:

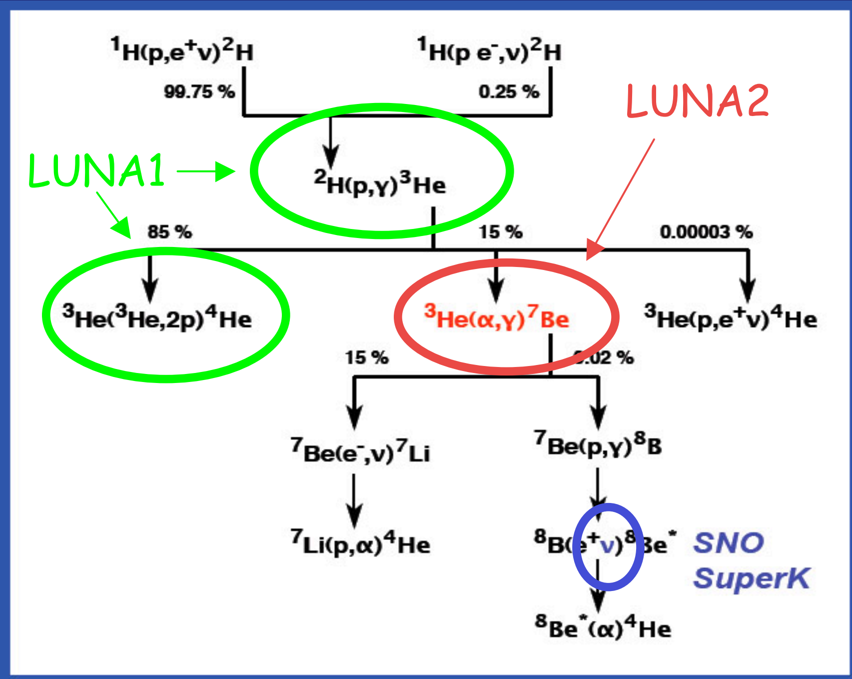
$$1 < 10^{10}(^7Li\ /H)_{exp} < 2$$

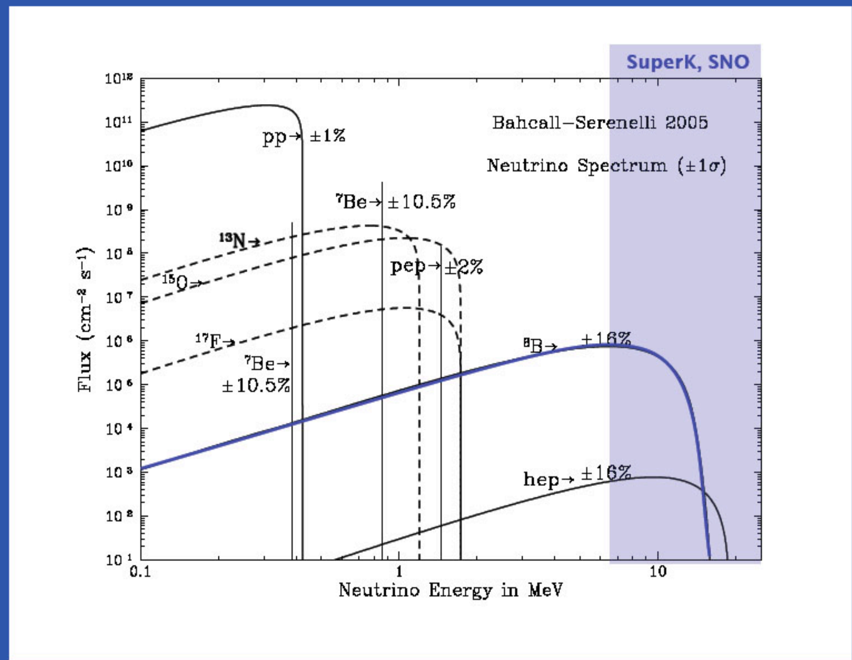
Still an open problem: the most puzzling for Standard BBN

New clues on Astrophysics?

A window on non-standard Physics in the Early Universe?

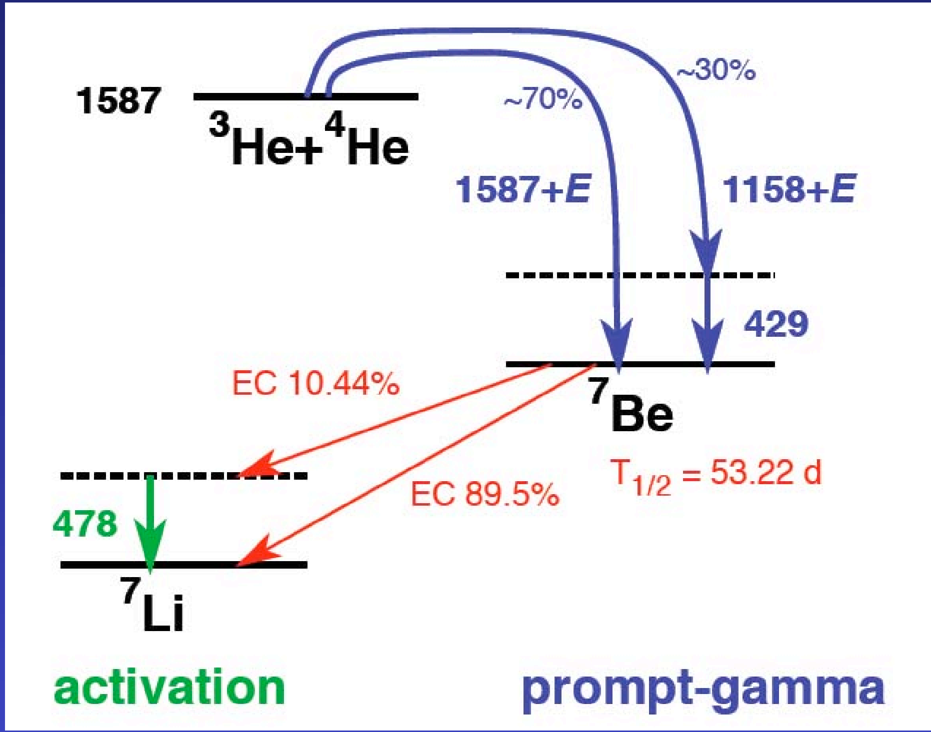






Boron ν's are wonderful probes of solar interior. They provide an independent measurement of T with respect to helioseismology, at the level of ~0.3%. $^3He(\alpha,\gamma)^7Be$ and $^7Be(p,\gamma)^8B$ are the main source of uncertainty in the determination of the ^8B ν's.

$^{3}He(^{4}He,\gamma)^{7}Be$ Q = 1.6 MeV



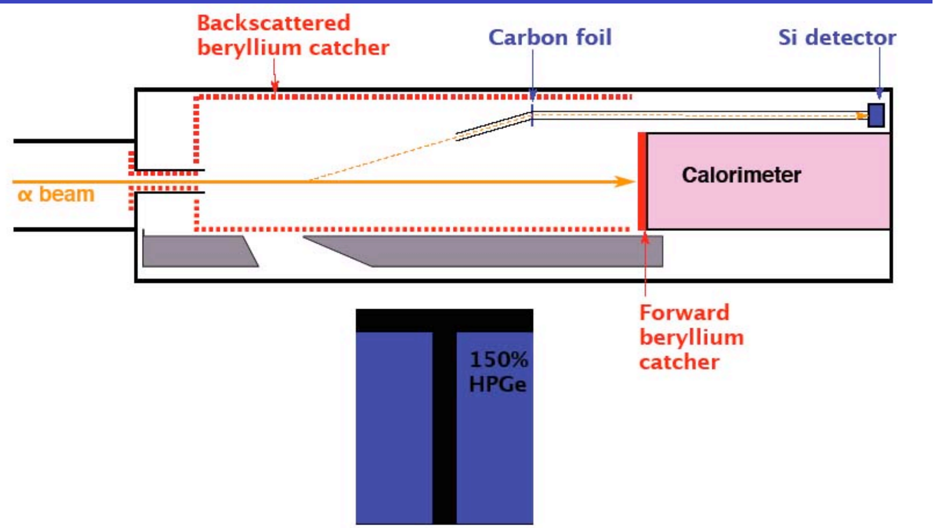
Experiment goals:

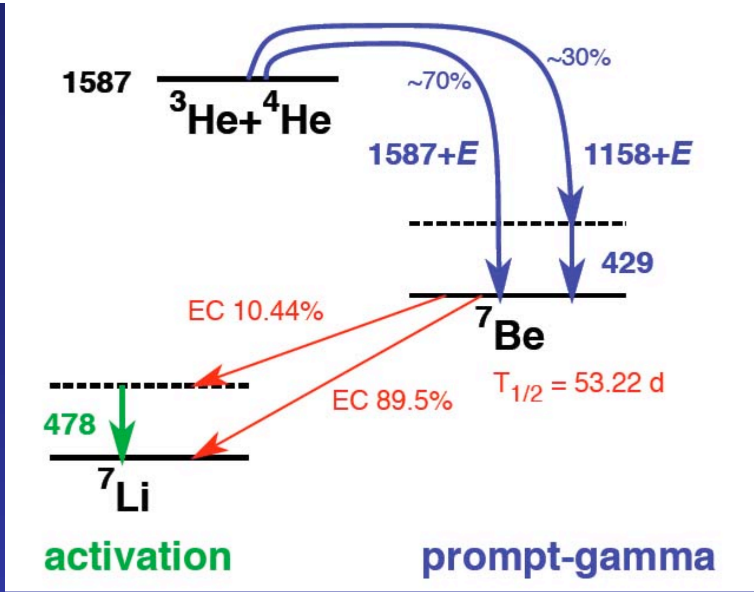
- Cross section of direct reaction down to E_{cm}= **50-60** keV.
- Reaction yield around E_{cm}= **100-150** keV via off-line ^{7}Be radioactive decay collected in the beam catcher
- Final error < 3 % !

N.B. $S(0)_{\gamma\text{-prompt}}$ = 0.507±0.016 keV barn
$S(0)_{\gamma\text{-decay}}$ = 0.572±0.026 keV barn

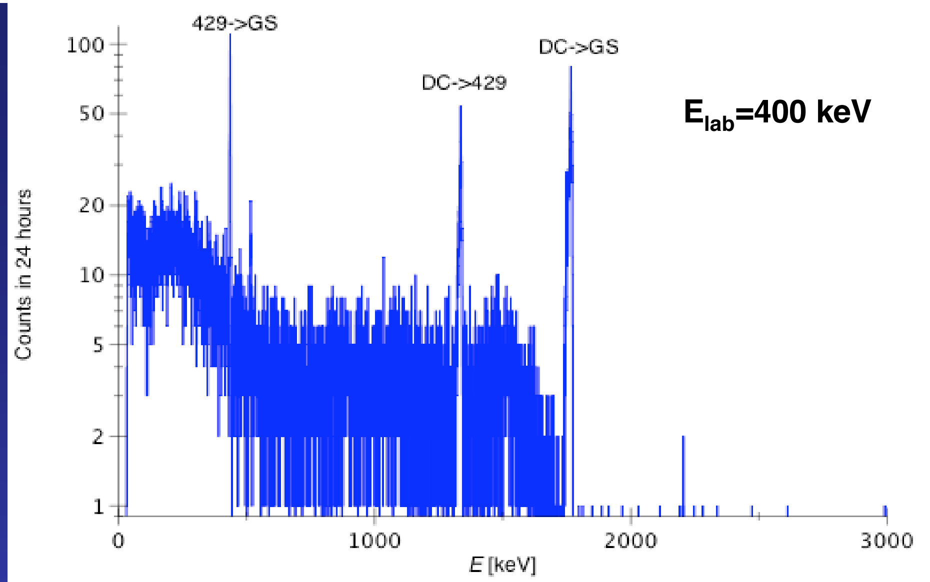
Experimental tecnique:

- ^{4}He beam (low D_2^+ contamination), ^{3}He gas target, HPGe detector (prompt γs)
- High purity Copper beam catcher, HPGe detector (^{7}Be decay γs)
- Calorimetric measurement of beam intensity

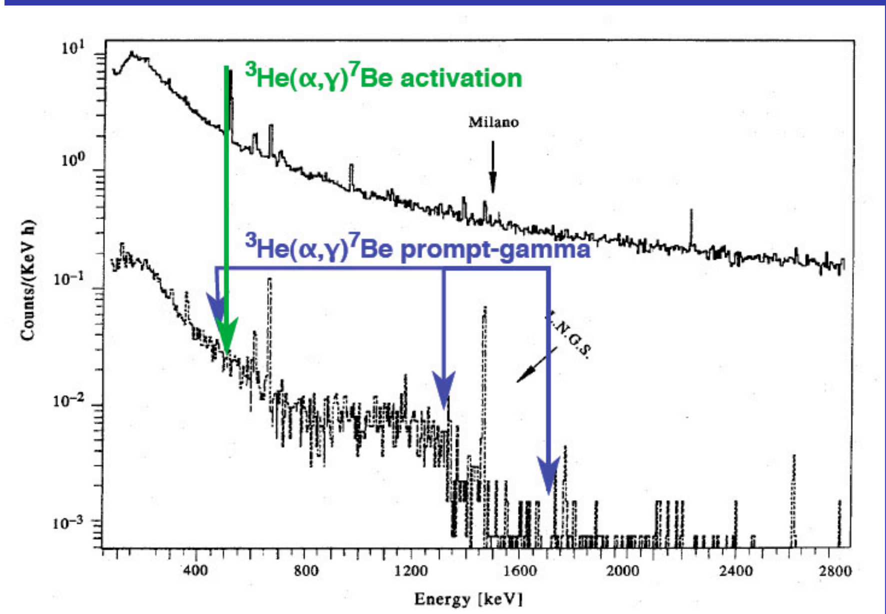




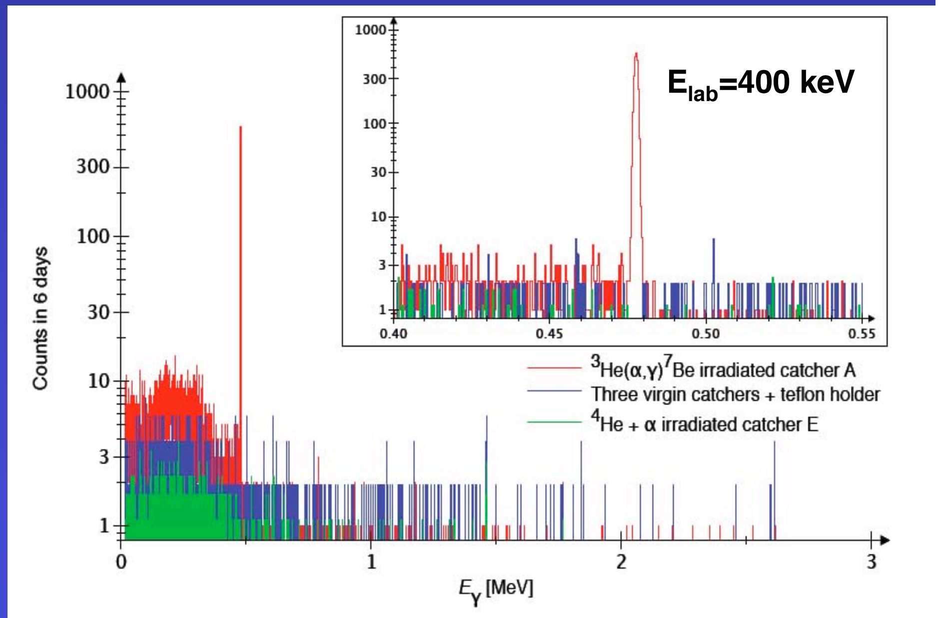
Schematic



Prompt □



Background



Activation □

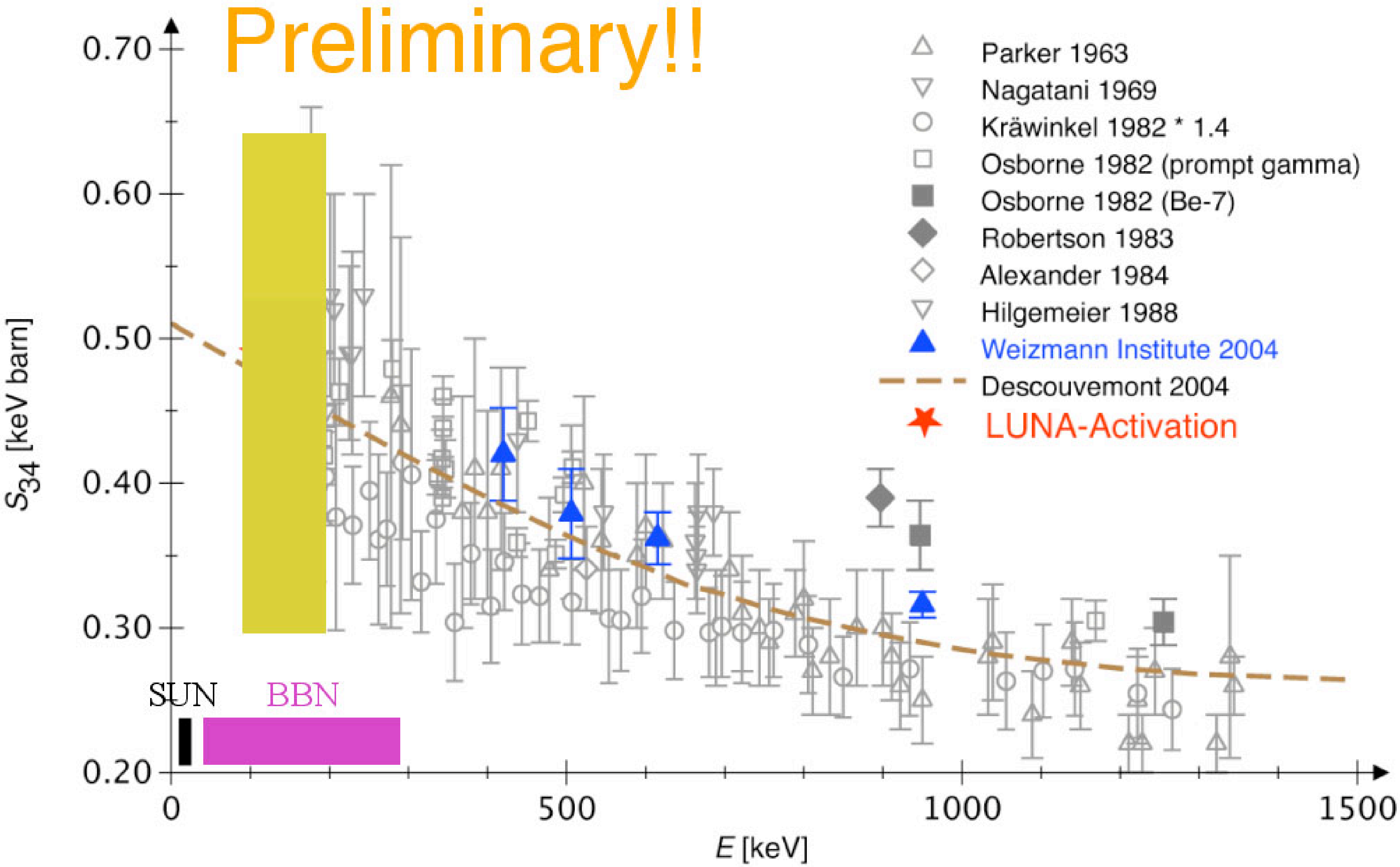
$^{3}He(^{4}He,\gamma)^{7}Be$

Systematics

	Determination	Uncert.
Beam current	Calibrated calorimeter	<1%
Target thickness	Pressure profile measurements (z,r), gas purity on line measurement (Si- detector)	0.6%
Beam heating	Measured	<0.4%
Detector efficiency	Measured	1.8%
Parasitic ^{7}Be production	Measured upper limit ($^{4}He+^{4}He$)	0.04%
Backscattering loss	Measured and simulated	0.7%
Sputtering loss	Upper limit from Monte Carlo Simulation	0.02%
Gamma-recoil effect	Measured, simulated	0.5%

Total systematic uncertainty: <2.3%

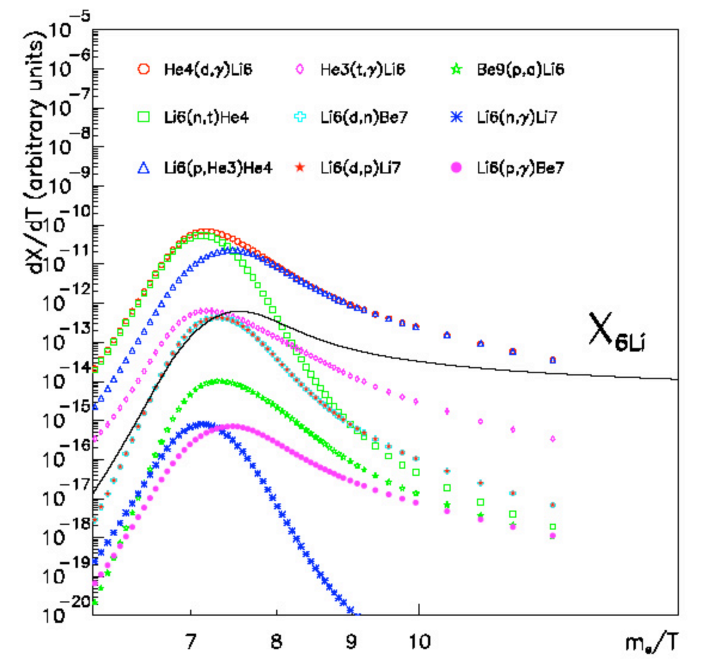
$^{3}He(^{4}He,\gamma)^{7}Be$ LUNA Activation preliminary results

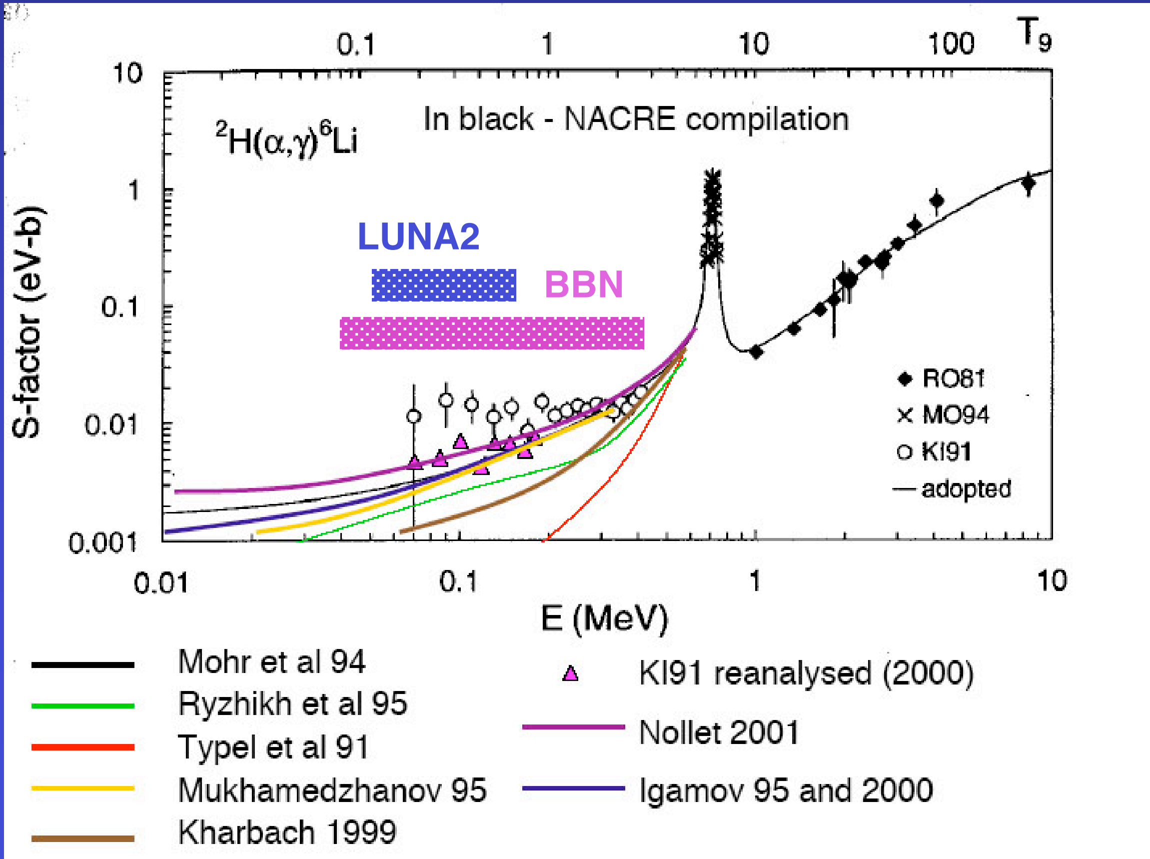


D(^{4}He,□)^{6}Li Q = 1.5 MeV

Main reaction for ^{6}Li production

- No direct measurements for E_{cm}<100 keV
- Theoretical calculations of S-factor differs for more than one order of magnitude





$D(^4He,\gamma)^6Li$

Very low cross section

"Identical" experimental set up respect to the one of the running $^3He(^4He,\gamma)^7Li$ but the gas target (D_2 instead of ^3He)

$\sigma(711\ keV_{CM}) = 140$ nb $\Rightarrow$ $3x10^5$ photons/h*

$\sigma(100\ keV_{CM}) = 37$ pb $\Rightarrow$ 74 photons/h*

$\sigma(50\ keV_{CM}) = 2.2$ pb $\Rightarrow$ 4 photons/h*

*assuming 100 μA alphas bombarding 10^{18} nuclides/cm^2

Conclusion

LUNA has shown that is possible to measure nuclear reactions at $\sigma(E_{star})$:

$^{3}He\ (^{3}He,2p)^{4}He$	ν from the sun
$^{14}N(p,\gamma)^{15}O$	ν_{CNO} and GC age
$^{3}He(\alpha,\gamma)^{7}Be$	The Sun

The LUNA program foresees also precision measurements of BBN key reactions:

- Scenario: BB, ν-decoupling, BBN
- Theory: Standard Physics+WMAP+Nuclear Physics
- Observations: D, ^{4}He, ^{3}He, ^{6}Li, ^{7}Li…
- Hints: Cosmology, Astrophysics, New Physics

Past: $D(p,\gamma)^{3}He$ $^{3}He(D,p)^{4}He$	D,^{3}He abundance
Present: $^{3}He(^{4}He,\gamma)^{7}Be$	^{7}Li abundance
Future (Underground): $^{4}He(D,\gamma)^{6}Li$	^{6}Li producer
Desirable (Surface): *$D(D,p)^{3}H$, $D(D,n)^{3}He$*	*D, ^{3}He,…abundance*