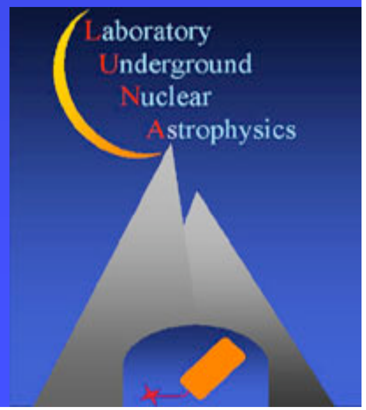
Laboratory Underground Nuclear Astrophysics

The Impact of LUNA Results on Astroparticle Physics

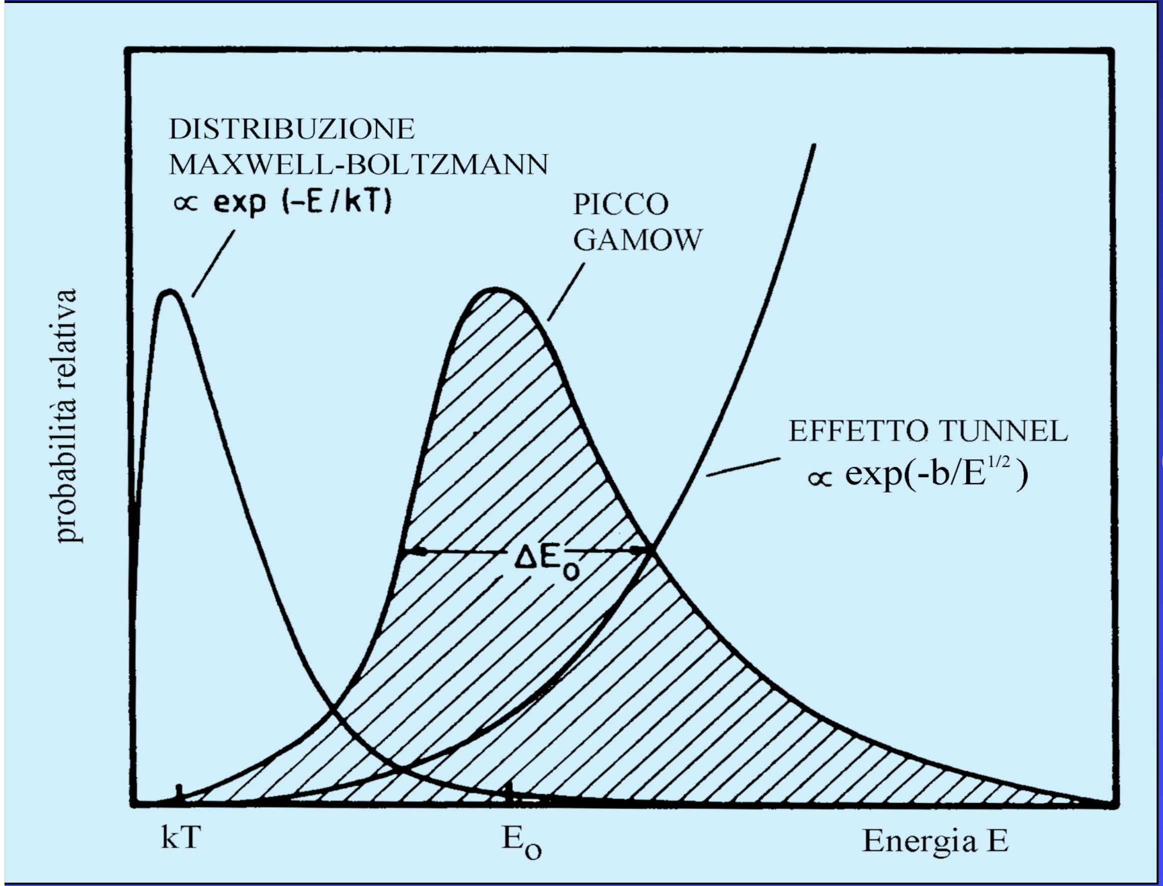
The LUNA experiment
- The hydrogen burning in the SUN
- The nucleosynthesis in the other stars
- The BBN
- Conclusions



Carlo Gustavino

For the LUNA collaboration

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

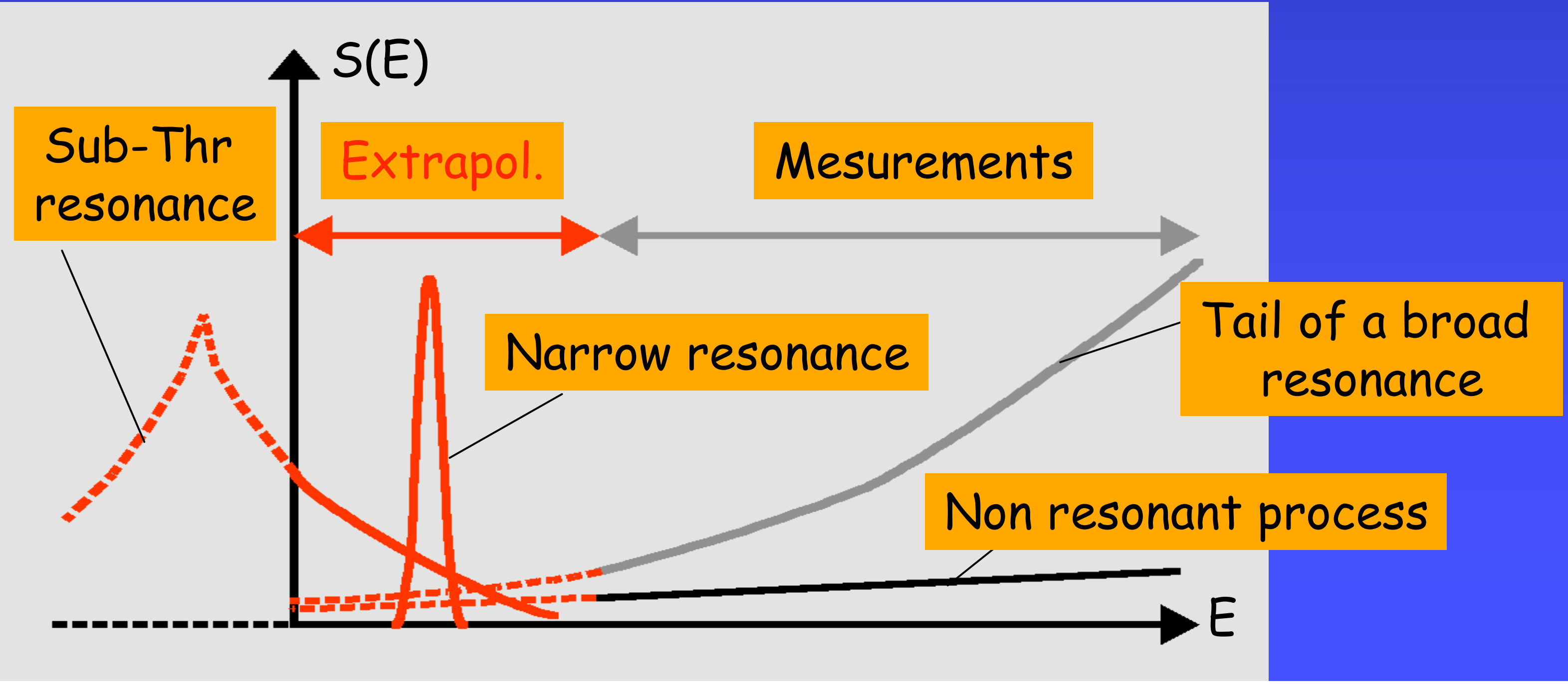
UG experiments to reduce the background due to cosmic ray

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

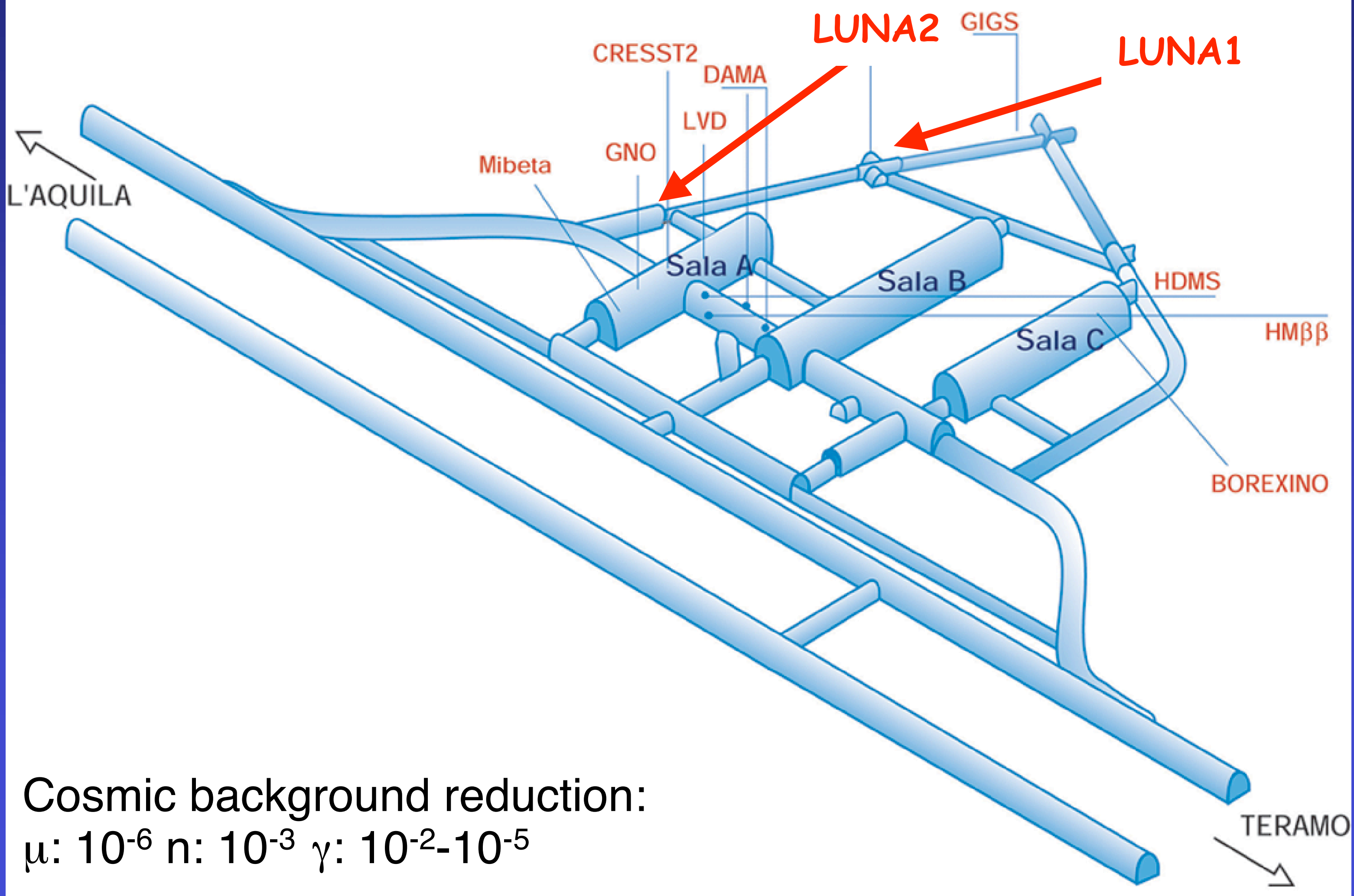
Why underground Measurements?

- Very low cross sections
- Danger in extrapolating

UnderGround Measurements



Gran Sasso National Laboratory (LNGS)



Cosmic background reduction:

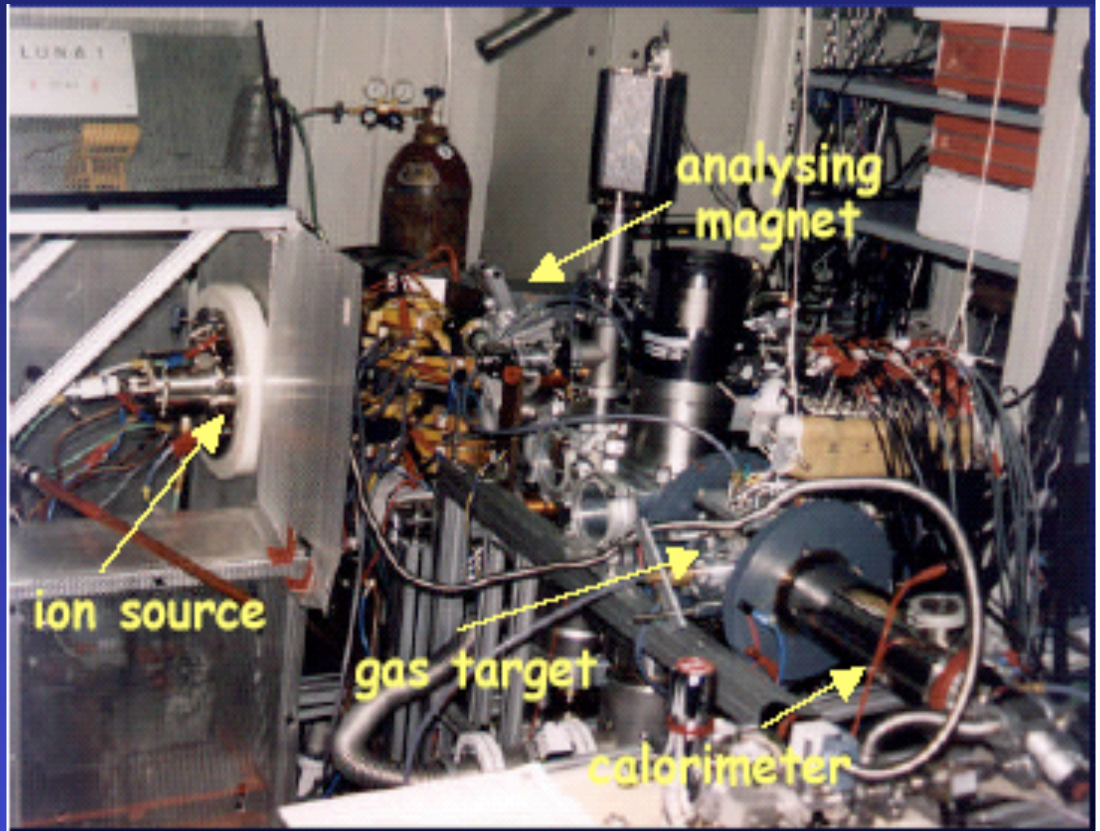
μ: 10^{-6} n: 10^{-3} γ: 10^{-2}-10^{-5}

The LUNA1 (50 kV) accelerator

$^3He(^3He,2p)^4He$

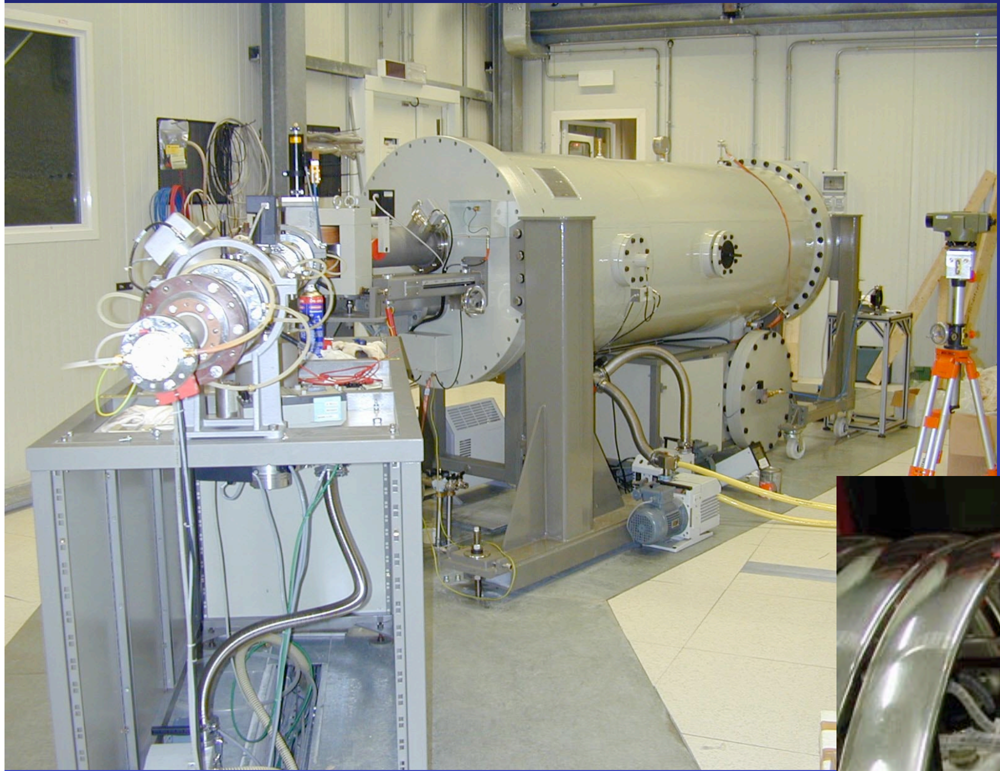
$P(D,\gamma)^3He$

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



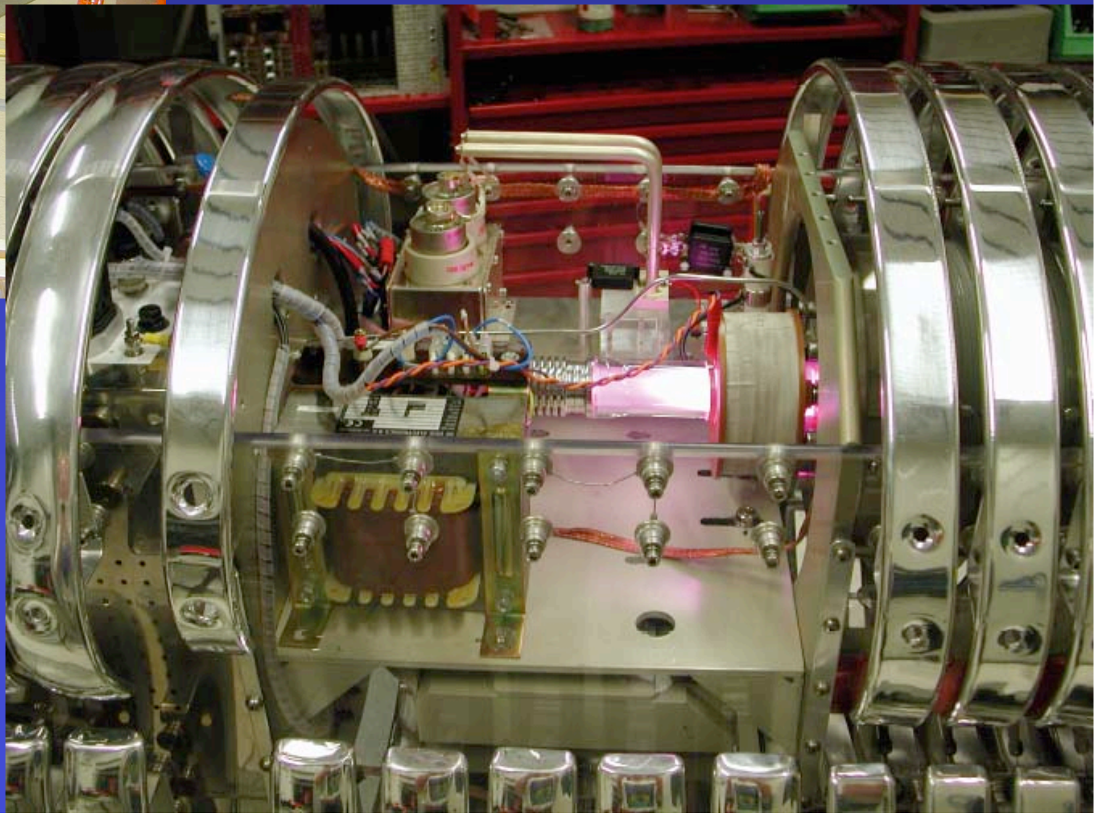
Voltage Range : 1 - 50 kV
Output Current: 1 mA
Beam energy spread: 20 eV
Long term stability (8 h): 10^{-4}
Terminal Voltage ripple: 5 10^{-5}

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.



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

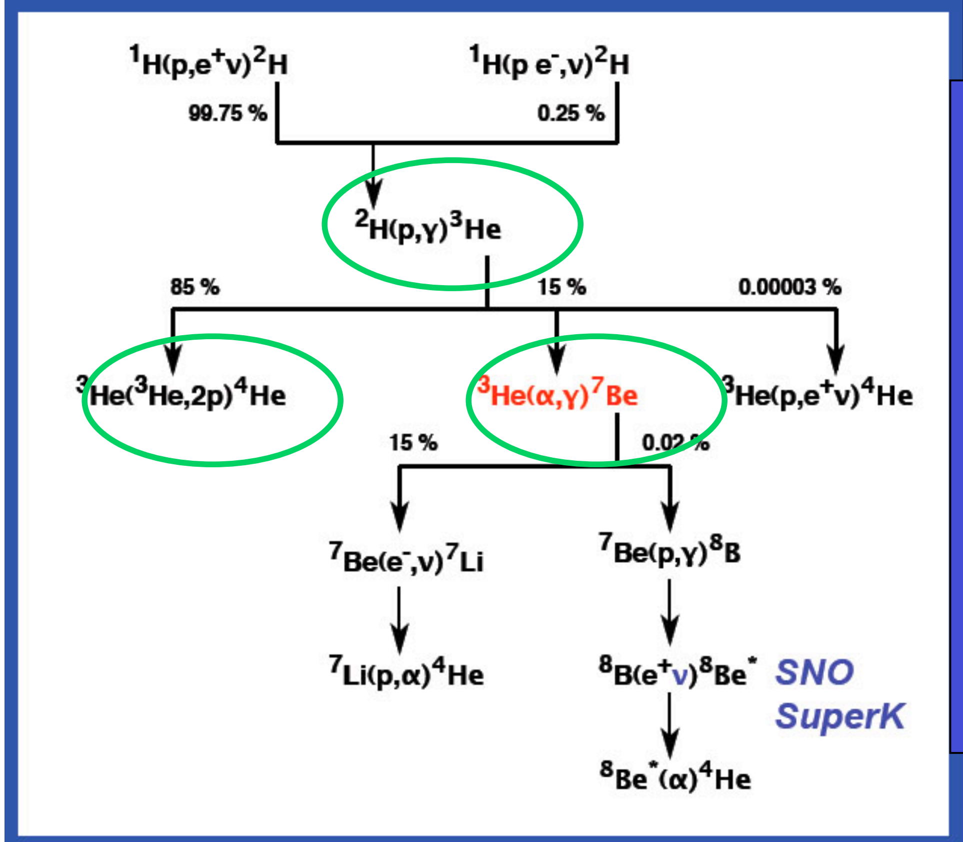
$^{3}He(^{4}He,\gamma)^{7}Be$

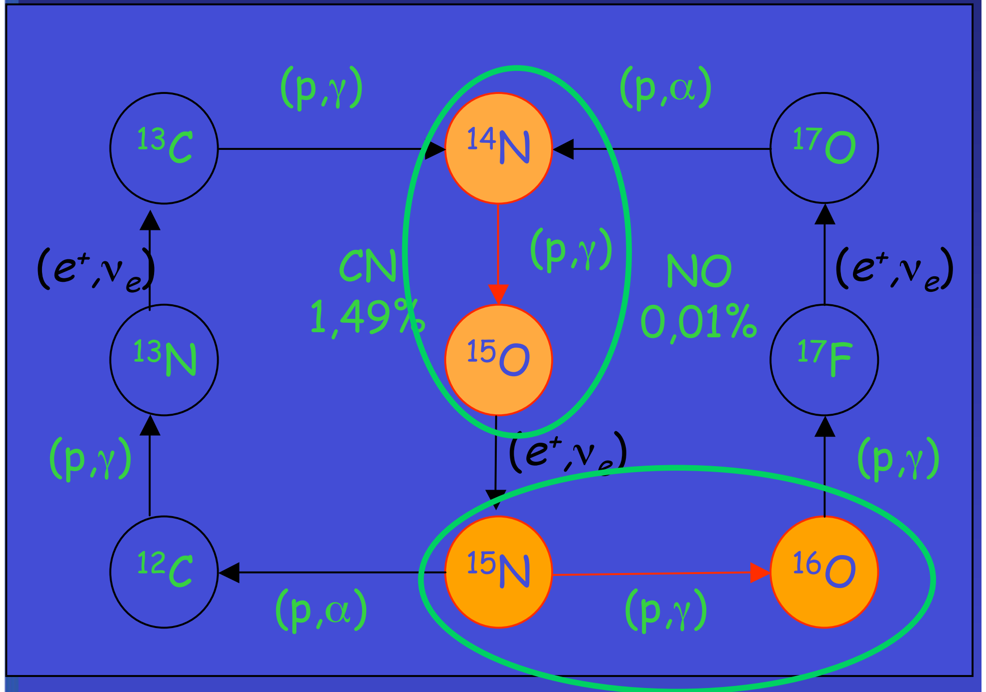
$^{25}Mg(p,\gamma)^{26}Al$

$^{15}N(p,\gamma)^{16}O$

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

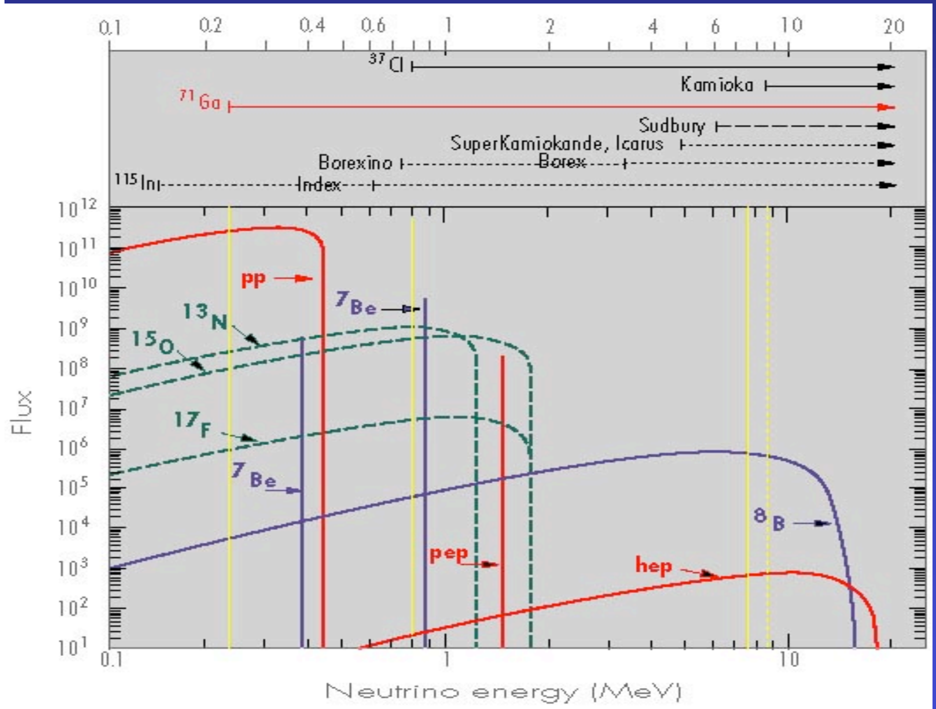
The Solar Hydrogen burning

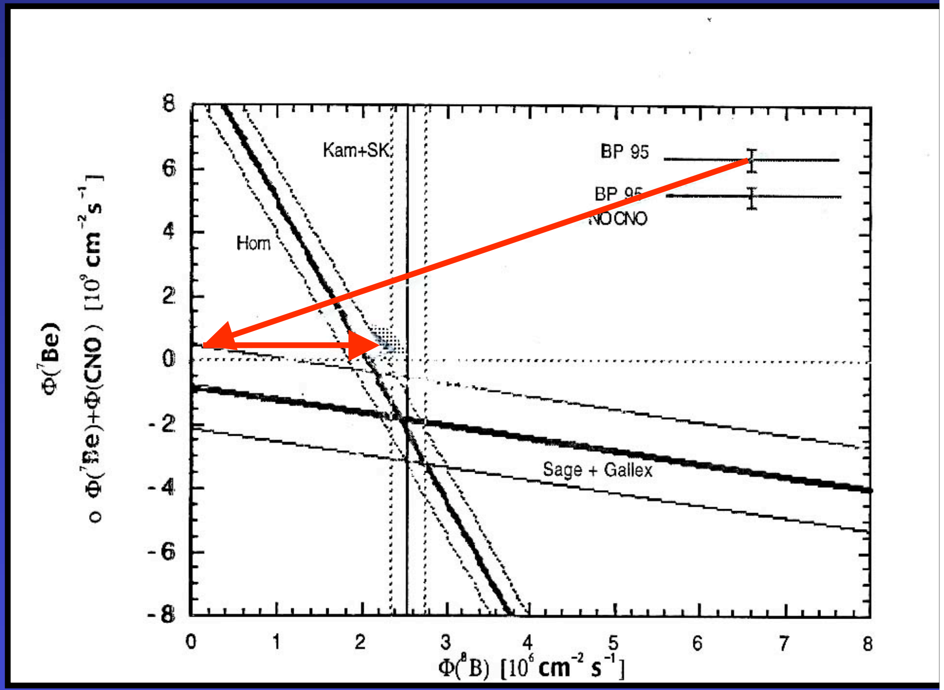




$^3He(^3He,2p)^4He$

Goal: Reject (or establish) a nuclear solution for the solar neutrino problem, by searching for a possible resonance inside the solar Gamow peak



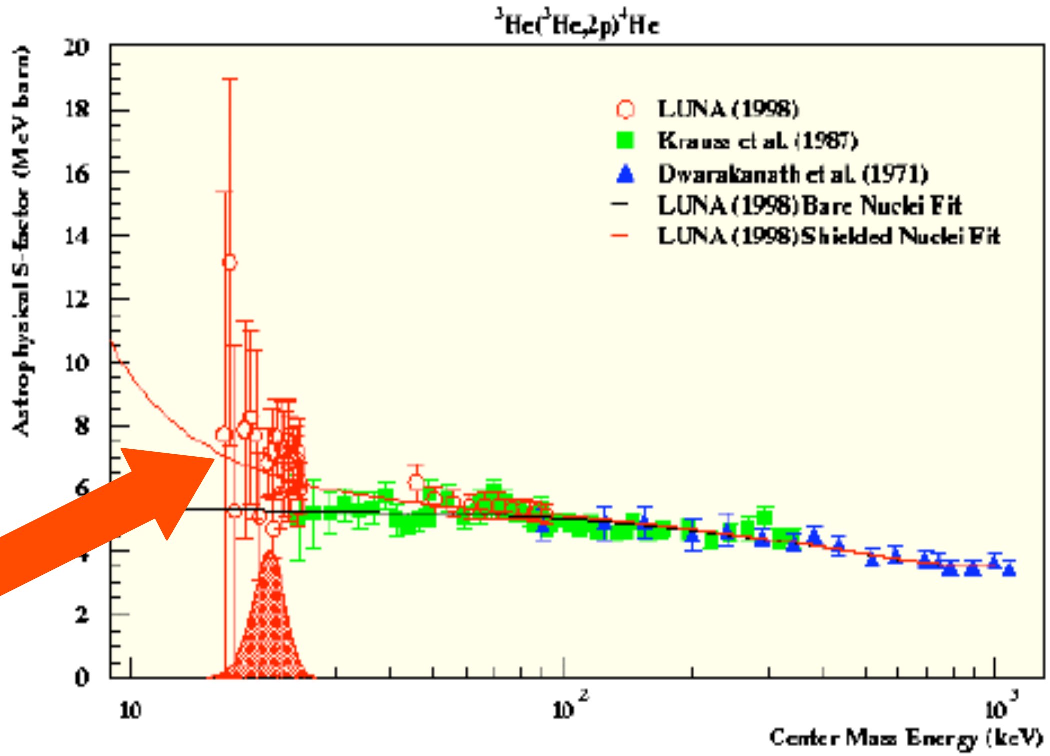


*PRL 82(1999) 5205

$S(0)=5.32\ (1\pm 6\%)$ MeVb

$\sigma_{min=}$ 0.02 pb

2 events/month !



J. Bachall: "Historical breakthrough"

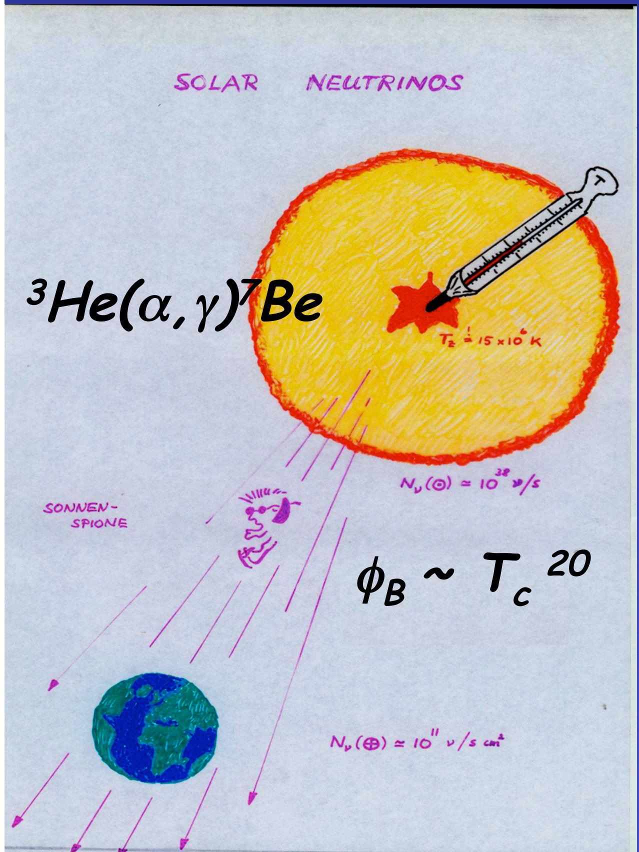
Dear Professors Corvisiero and Rolfs:

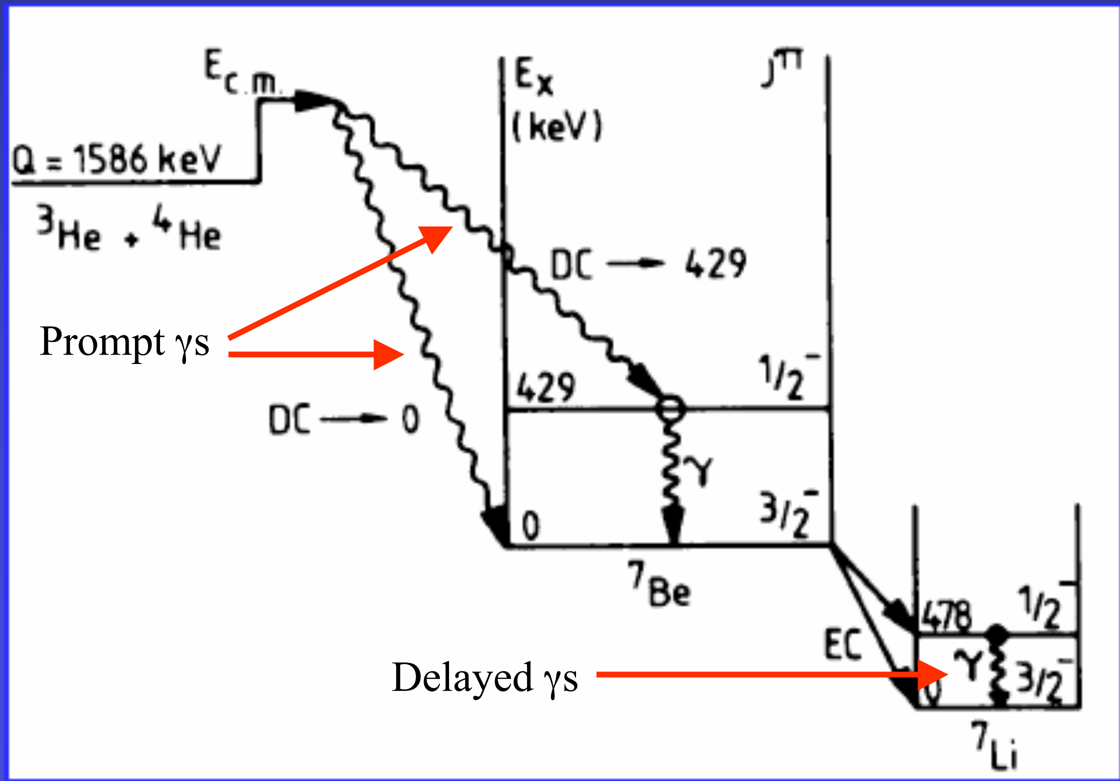
I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He - 3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

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

Goal: After the discovery of neutrino oscillation, the solar neutrino are back to study the Solar interior.
Three objectives for the LUNA measurement:

- Lowest energy ever reached (90 keV)
- Lowest uncertainty (4%)
- Simultaneous measurement of prompt and delayed γs (systematic discrepancy od previous measurements)

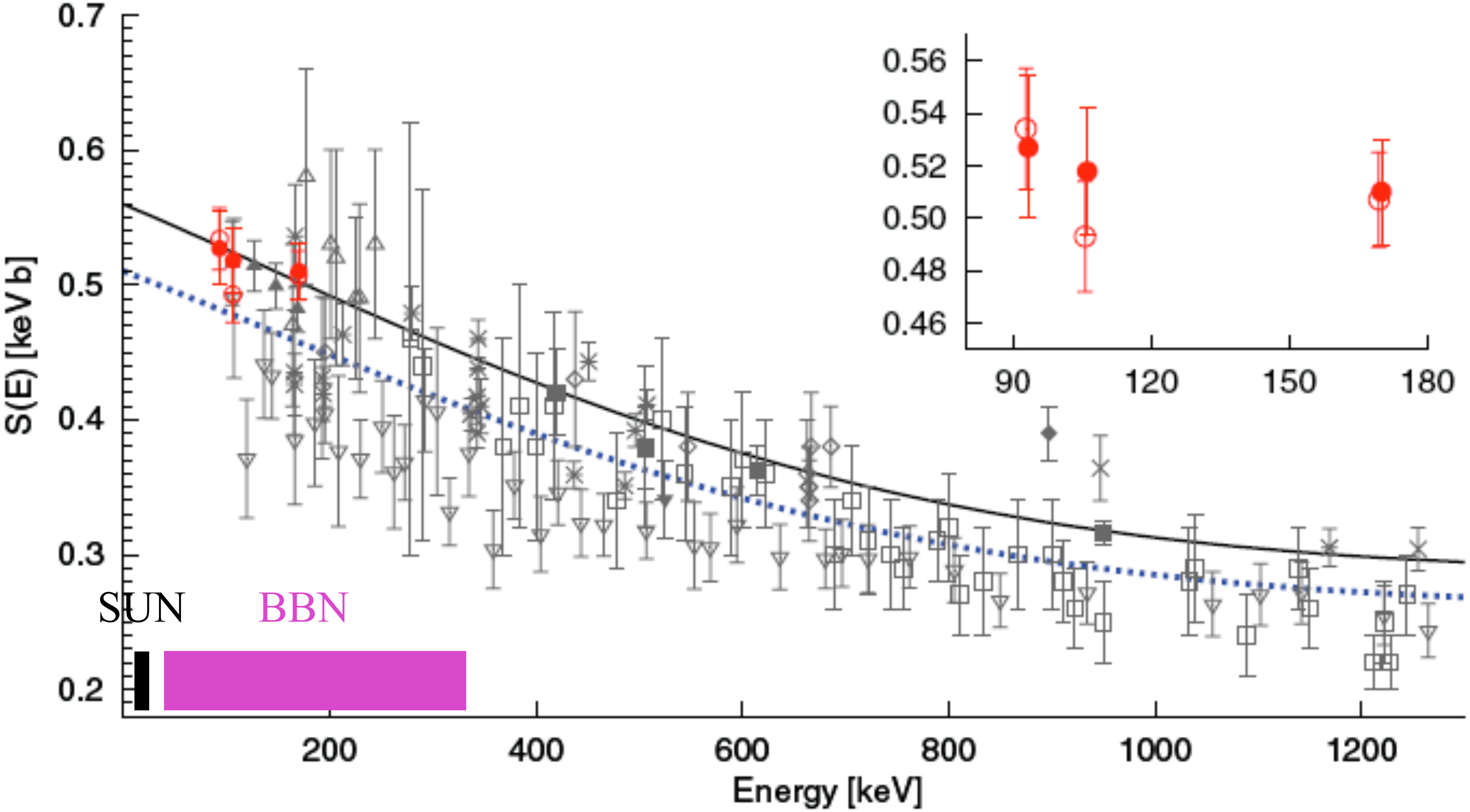




$^{3}He(^{4}He,\gamma)^{4}He$

The uncertainty on the predicted ^{8}B neutrino flux due to S_{34} is now reduced from 7.5% to 2.4% and the total uncertainty, including astrophysical parameters, goes from 12% to 10% [37]. Similarly, the uncertainty on ^{7}Be predicted flux goes from 9.4% to 5.5%, being the contribution of S_{34} error reduced from 8% to 2.5% [37].

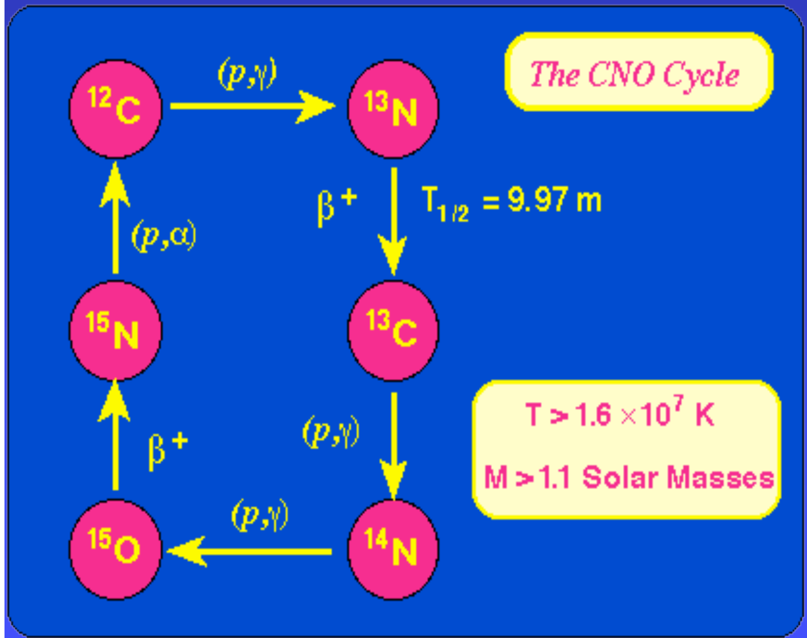
F.Confortola et al., PRC 75,065803(2007)



The CNO cycle bottleneck: $^{14}N(p,\gamma)^{15}O$

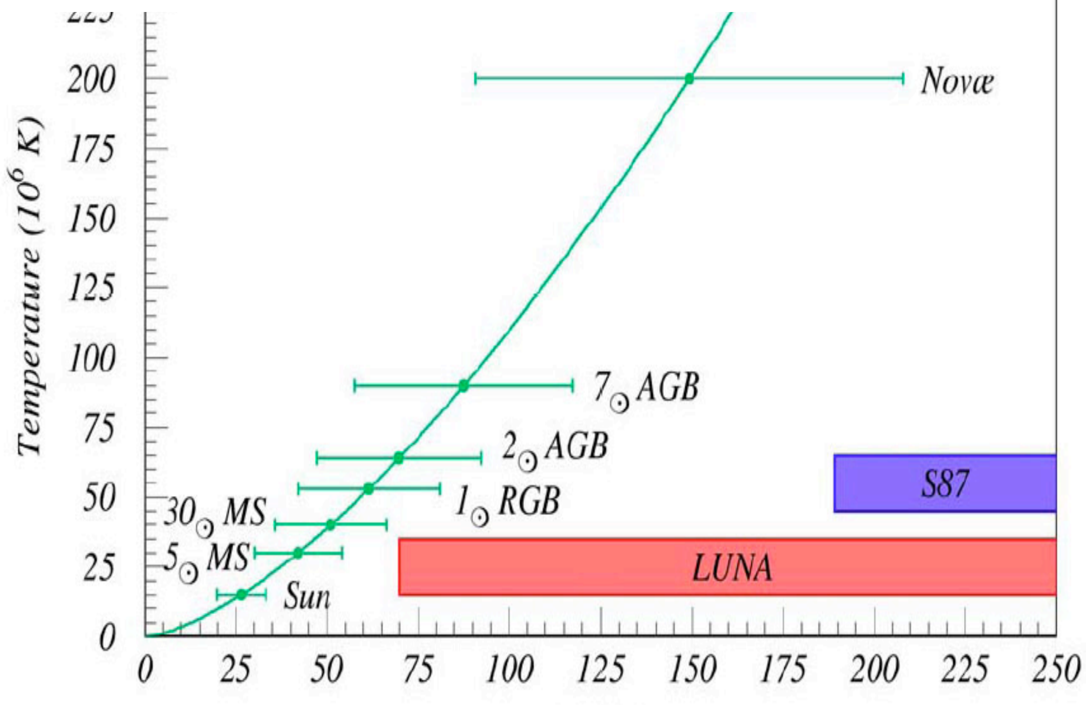
$^{14}N(p,\gamma)^{15}O$ is the slowest CNO cycle therefore it regulates the CNO solar neutrino flux and plays an important role in estimating the age of Globular Clusters. The LUNA measurements ($E_{cm} \geq 71$ keV) show that this cross section is a factor 2 lower than the previous extrapolated values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

GC age estimation increases of 0.7 Gyr
CNO neutrino flux decreases of a factor ≈ 2

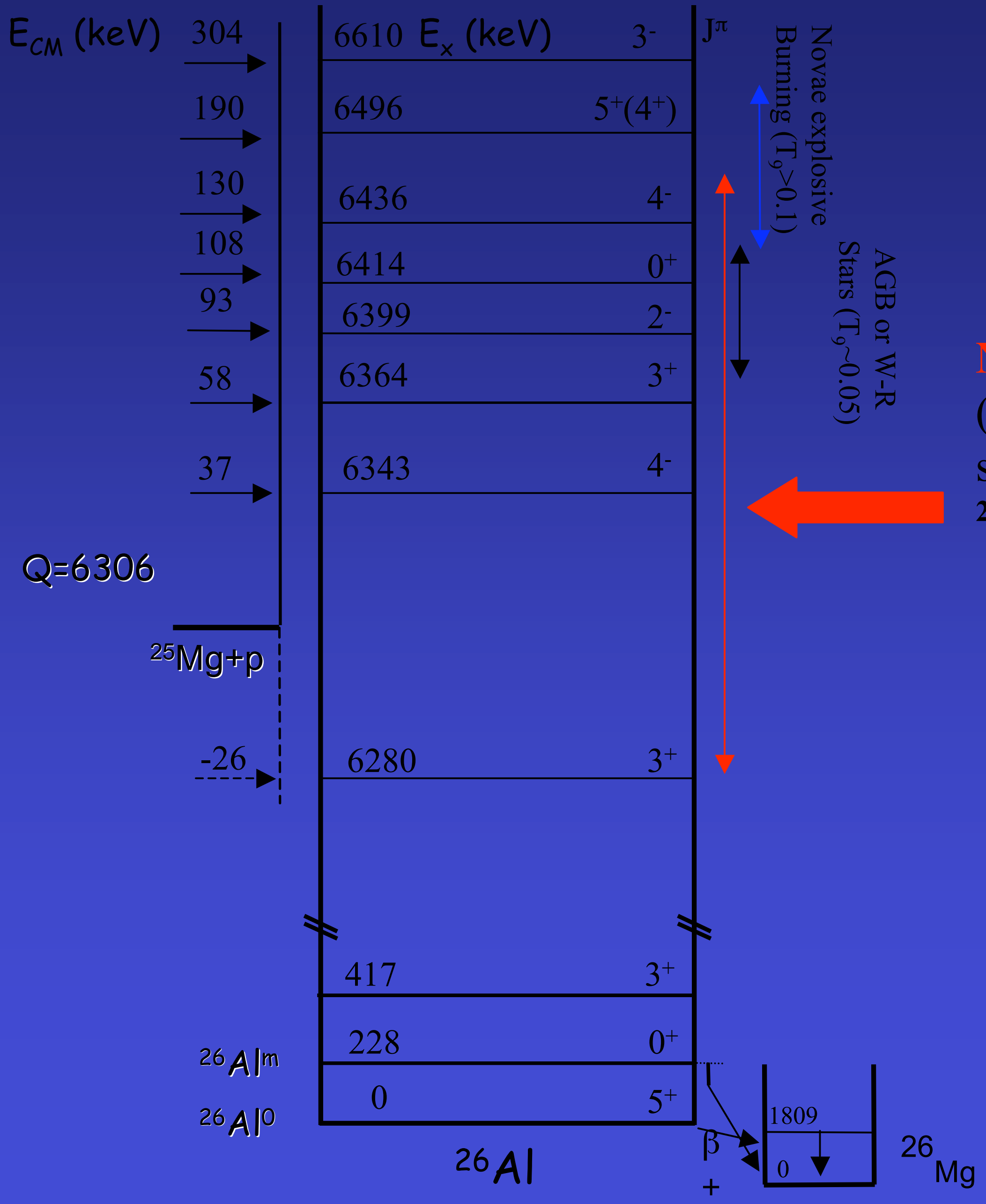


$S_0 = 1.7 \pm 0.1 \pm 0.2$ keV b

A.Formicola et al., Phys. Lett. B 591 (2004) 61
A. Lemut et al., Phys. Lett. B 634, 483 (2006)



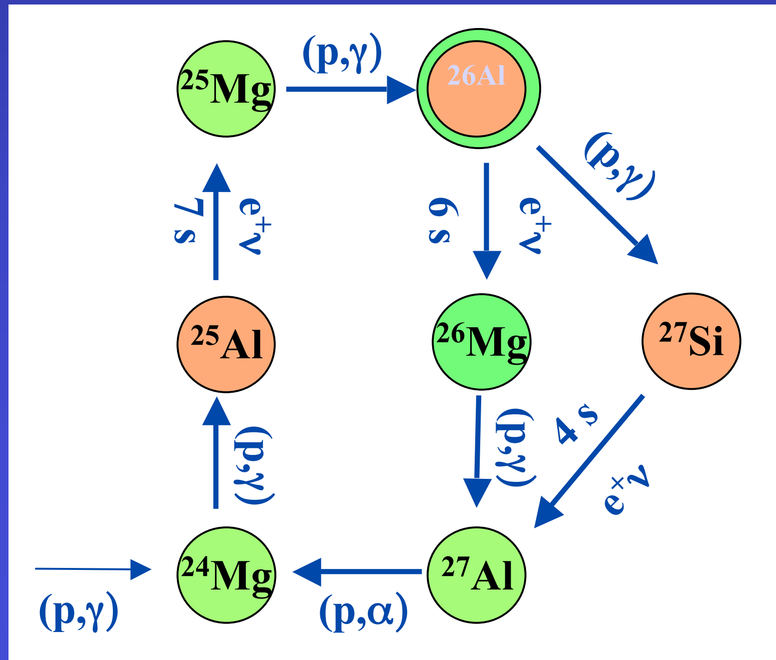
Other (p,γ) reaction of astrophysical interest



$^{25}Mg(p,\gamma)^{26}Al$

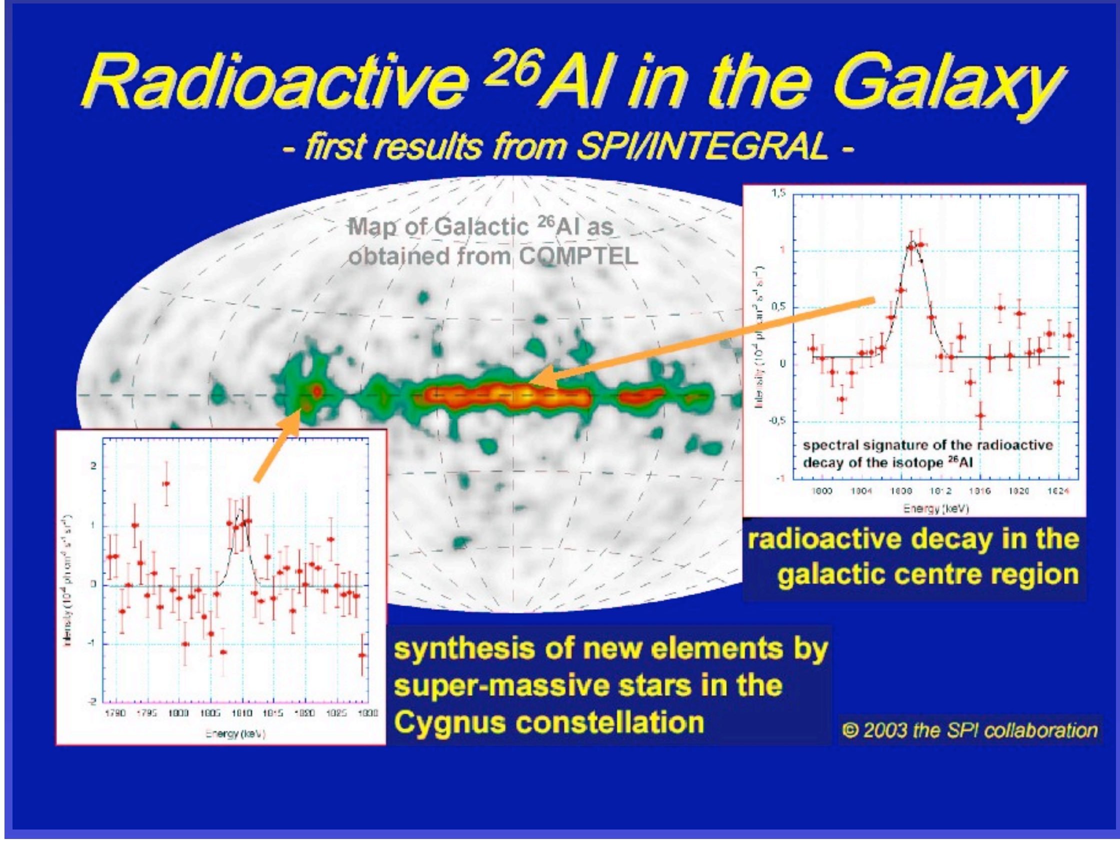
No direct strength resonance data

(level structure derived from the singe particle transfer reaction: **$^{25}Mg(^{3}He,\gamma)^{26}Al$**)



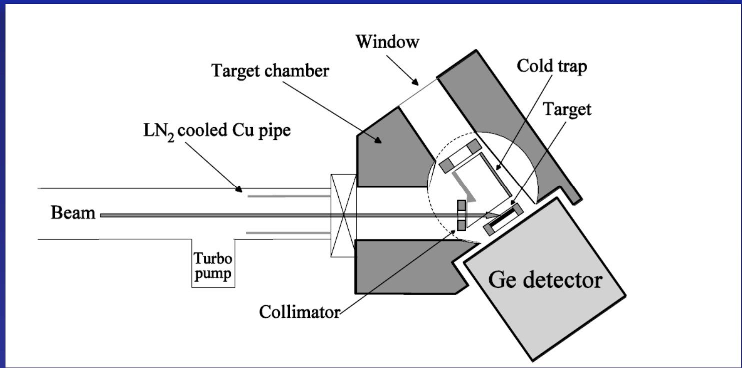
Motivations – γ astronomy

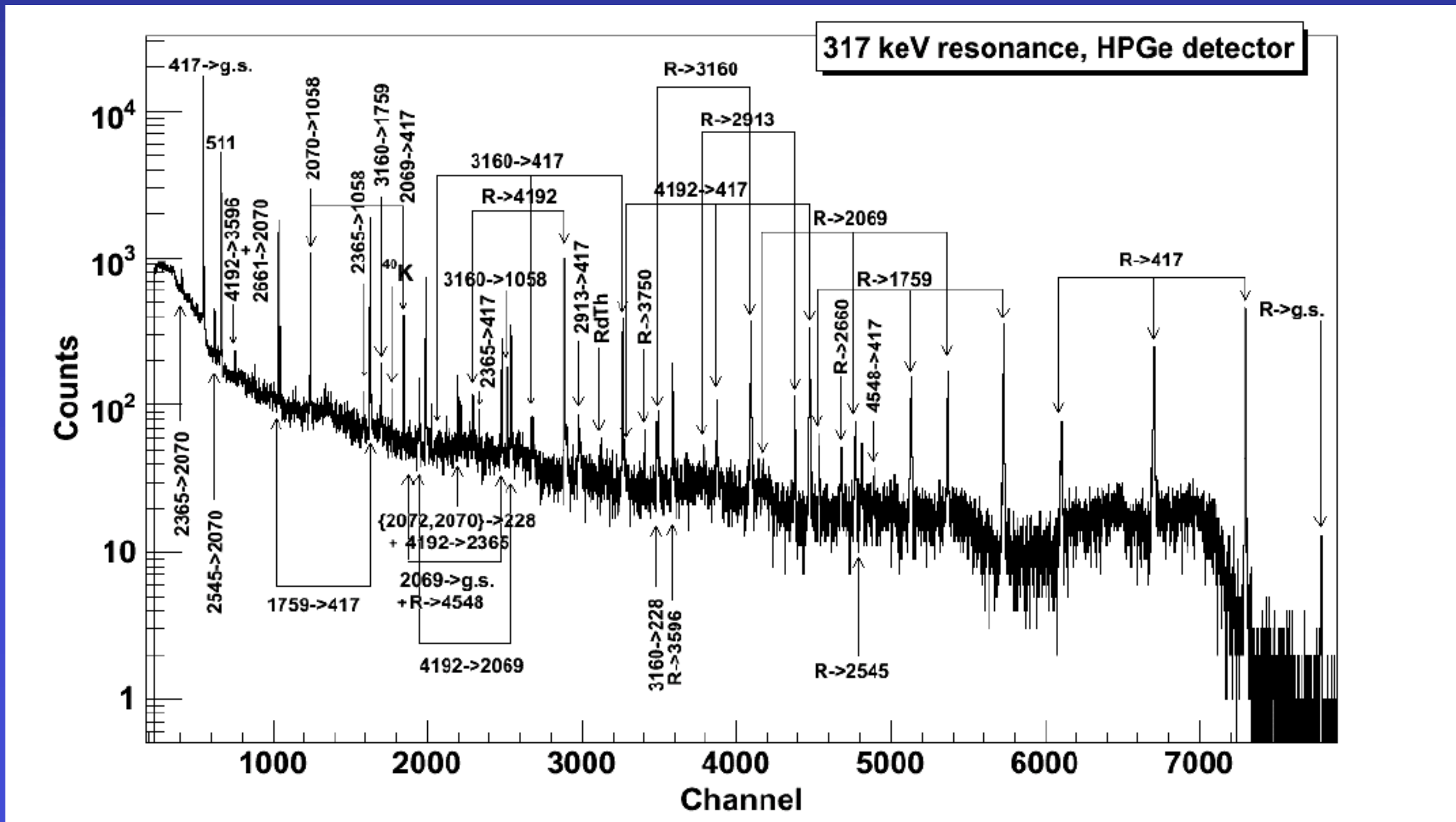
- Astronomical interest of 1809 keV ^{26}Mg γ line;
- $T_{1/2} = 7.2\ 10^{5}$ y



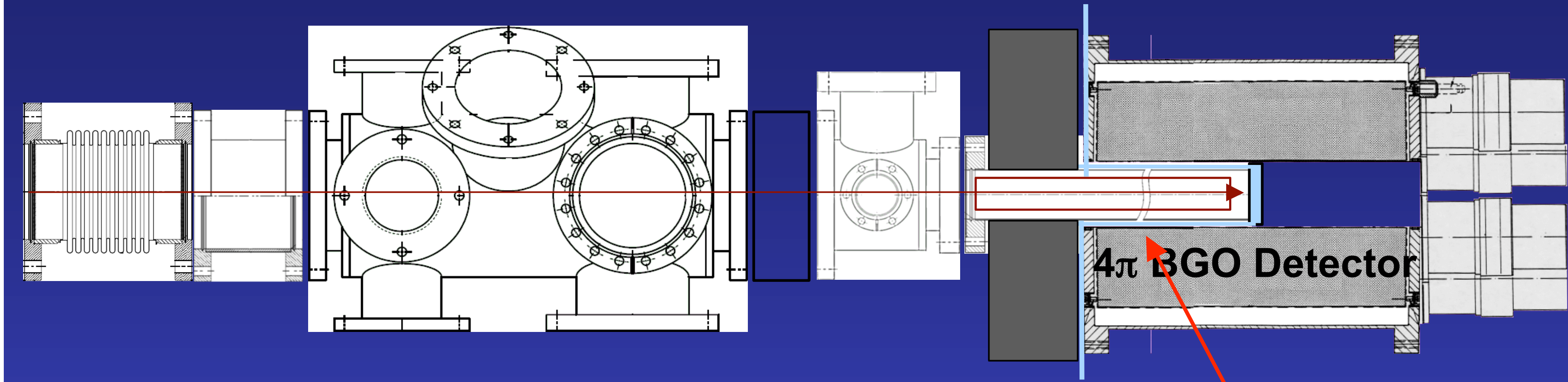
^{26}Mg excess in meteorites

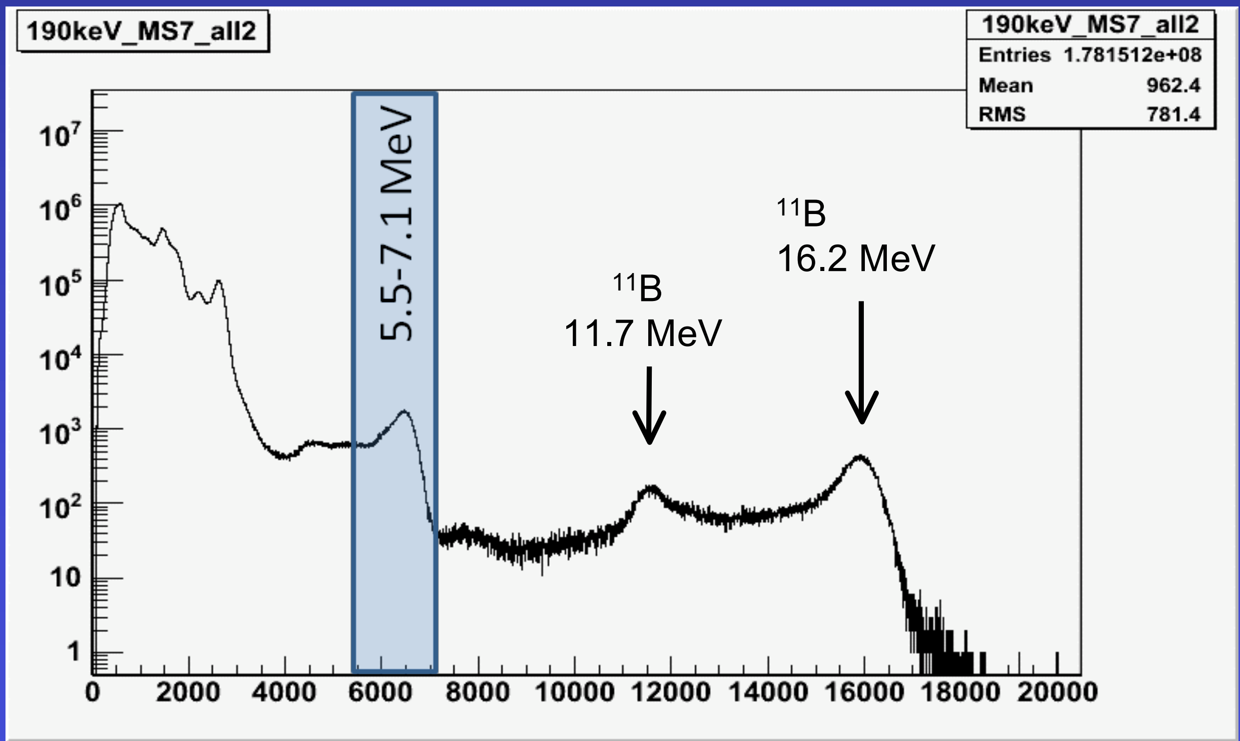
High resolution set-up





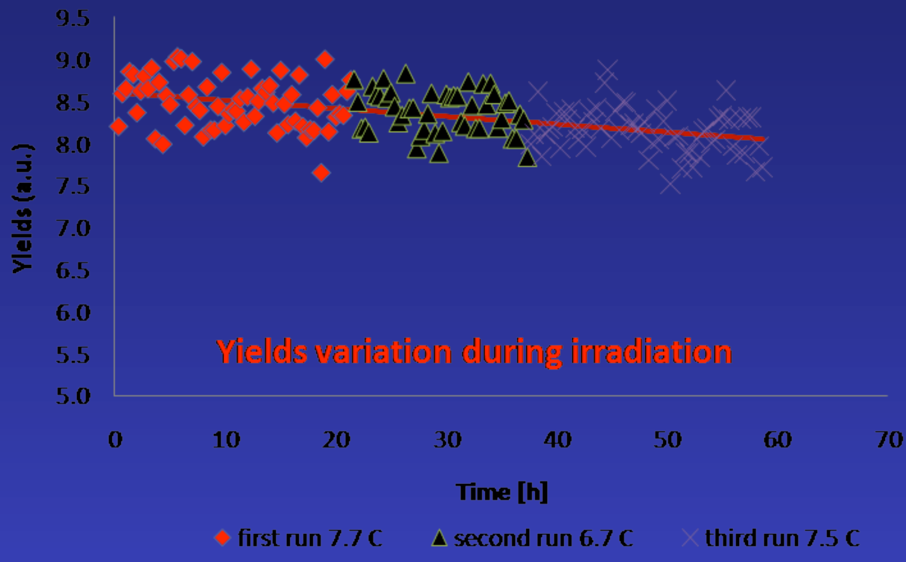
High efficiency set-up





The AMS measurement

CIRCE lab. Caserta, Italy



Results of the $^{26}Al/^{27}Al$ measurement

Sample	Total time (s)	Experimental ratio(a.u)	Error (%)
S1	11270	9.06e-12	0.8
S2	11270	8.90e-12	0.9
BLK_1	11270	3.5e-14	37
V1	11270	1.51e-11	0.6
M11	11270	8.78e-12	0.7

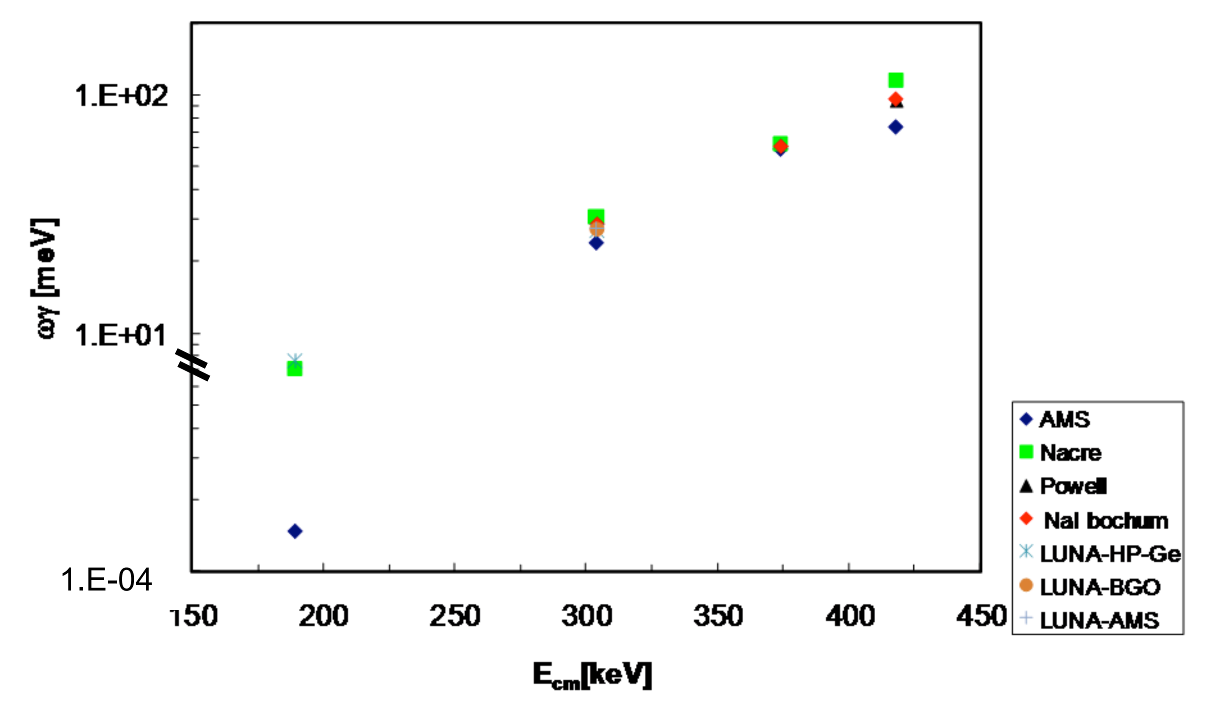
$\omega\gamma$ results ($\omega\gamma_{gs}/\omega\gamma$=88.5 %)

	Iliadis (γ-meas.)	**Arazi (AMS)**	**PD070701_7 (AMS-meas)**
$\omega\gamma_{gs}$ (meV)	**25+/-4**	**2.1+/-0.2**	**23.9+/-0.4**
$\omega\gamma$ tot(meV)	**29+/-4**	**2.4+/-0.2**	**27.5+/-0.4**

Preliminary Results

E_R [keV]	ωγ [meV] Nacre	ωγ [meV] AMS Arazi	ωγ [meV] Powell	ωγ [meV] NaI Bochum	ωγ [meV] HPGe LUNA	ωγ [meV] BGO LUNA	ωγ [meV] AMS LUNA
190	(7.1 ± 1.0)10-4	$(1.5 \pm 0.3)10^{-4}$			**$(7.7 \pm 0.5)10^{-4}$**		
304	31 ± 2	21 ± 2		29 ± 2	**27.0 ± 0.4**	**27.4 ± 0.4**	**27.5 ± 0.5**
374	62 ± 4	60 ± 6		61 ± 5			
418	116 ± 6	74 ± 2	94.2 ± 6.5	97 ± 8			
745	136 ± 8			139 ± 12			

PRELIMINARY

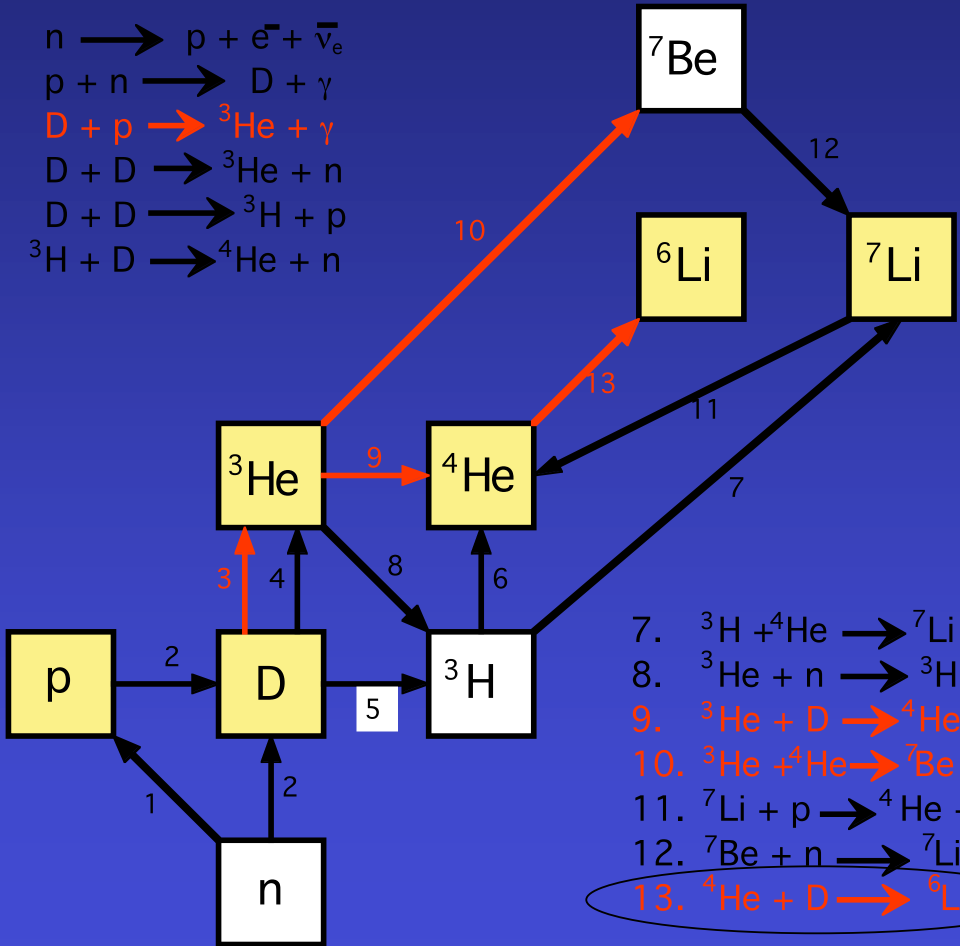


BBN reactions

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

Schematic BBN network

1. $n \longrightarrow p + e^- + \bar{\nu}_e$
2. $p + n \longrightarrow D + \gamma$
3. $D + p \longrightarrow {}^3He + \gamma$
4. $D + D \longrightarrow {}^3He + n$
5. $D + D \longrightarrow {}^3H + p$
6. ${}^3H + D \longrightarrow {}^4He + n$



7. ${}^3H + {}^4He \longrightarrow {}^7Li + \gamma$
8. ${}^3He + n \longrightarrow {}^3H + p$
9. ${}^3He + D \longrightarrow {}^4He + p$
10. ${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$
11. ${}^7Li + p \longrightarrow {}^4He + {}^4He$
12. ${}^7Be + n \longrightarrow {}^7Li + p$
13. ${}^4He + D \longrightarrow {}^6Li + \gamma$

Already done:

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

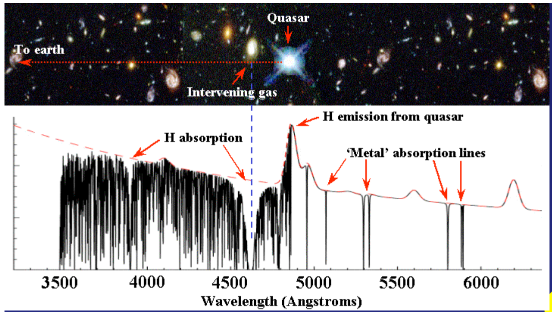
${}^3He(D,p){}^4He$

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

D, ${}^3He$, ${}^7Li$ abundance

Next: $D({}^4He,\gamma){}^6Li$ ${}^6Li$ abundance

BBN Flowchart



Primordial Elements Observations

Y_i Systematics!

Nuclear Astrophysics

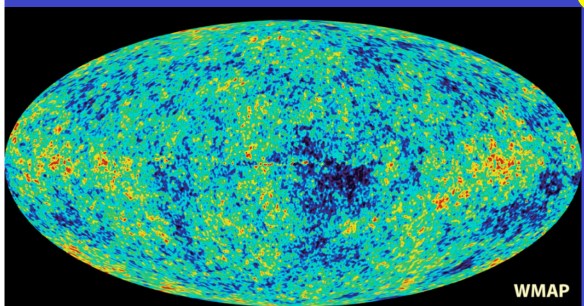
σ(E) Data regression!

BBN

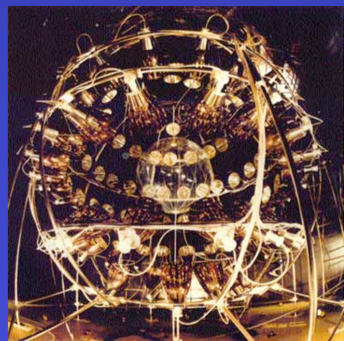
Cosmology

Astrophysics

New Physics?



CMB ω_b , $\delta\omega_b/\omega_b$ <<1!!!



Particle Physics (τ_n, ν, α..)

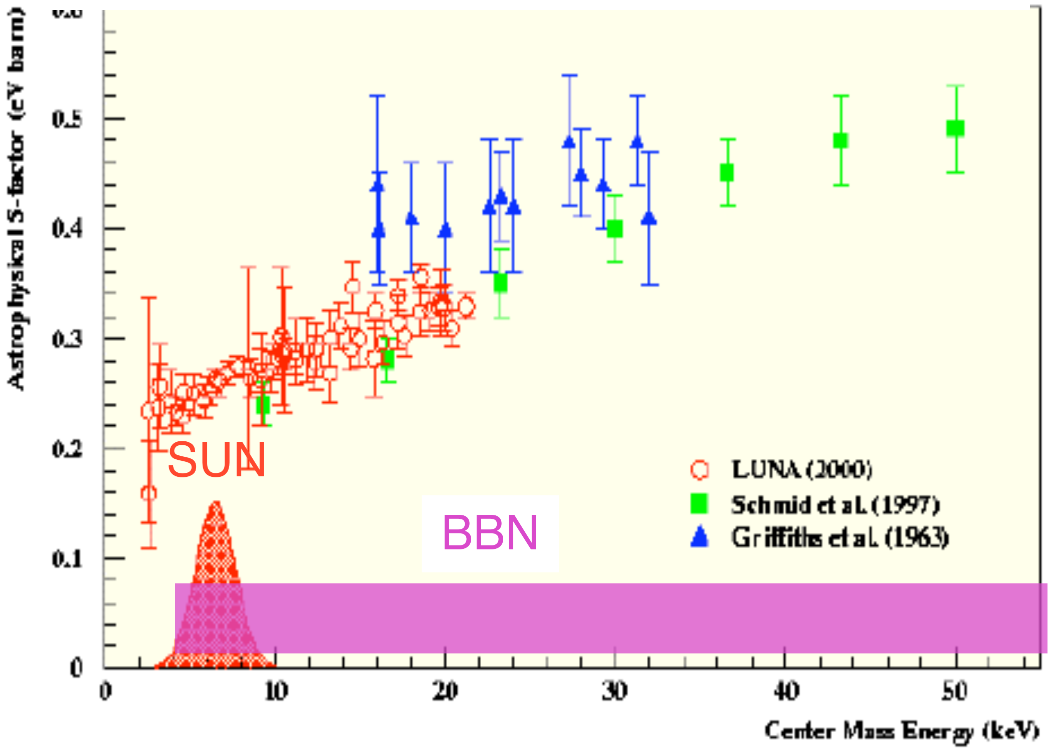
P. D.Serpico et al. JCAP 0412 (2004) 010

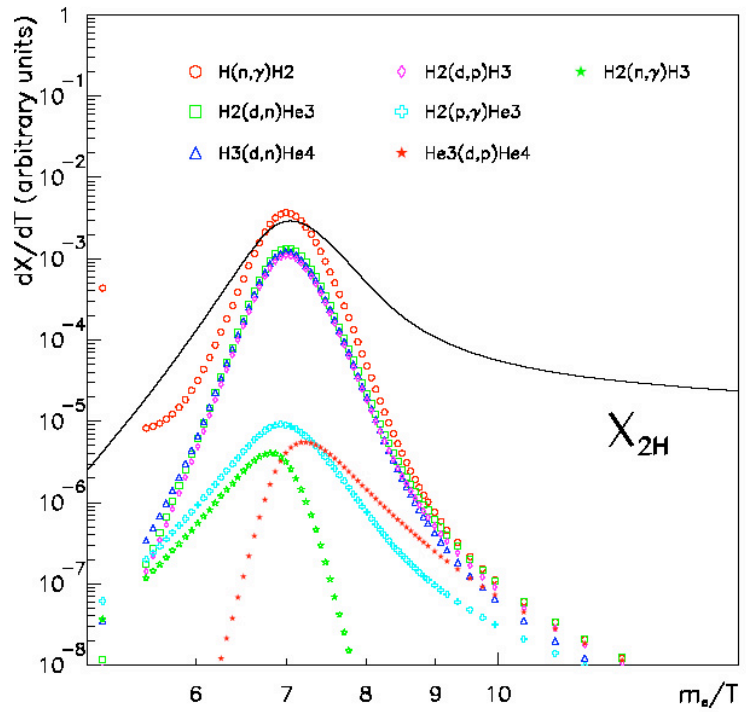
$D(p,\gamma)^3He$ Q = 5.5 MeV

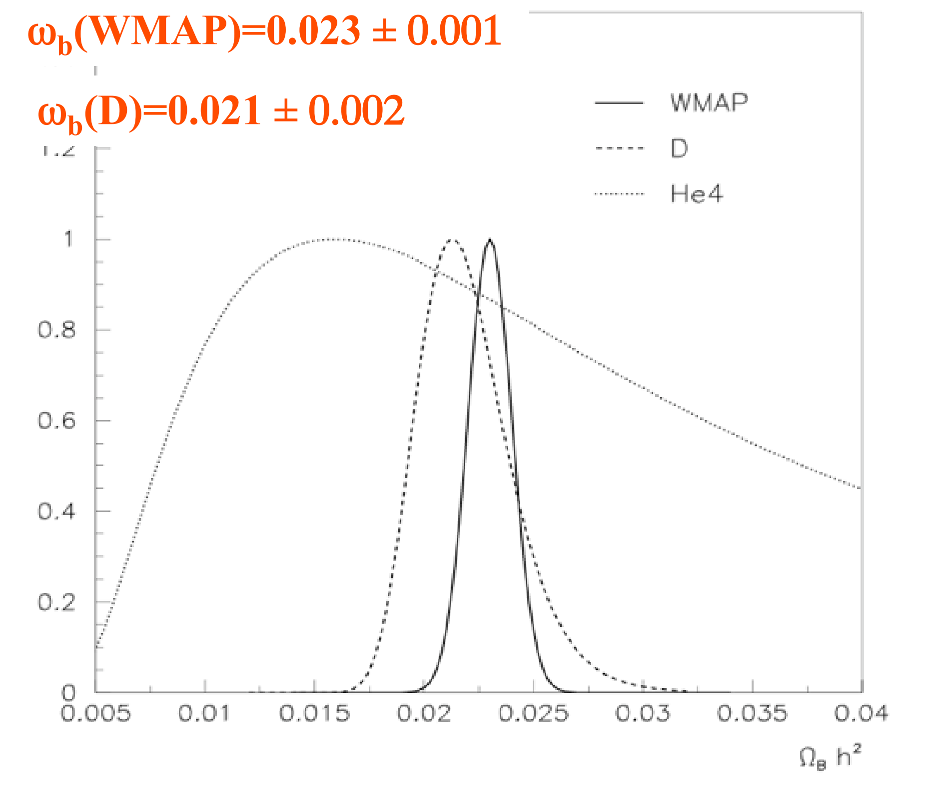
S(0)=0.216± 0.006 eVbarn

One of the main responsible of D and ^3He synthesis
LUNA data crucial to reduce X_D error budget (~factor 3!)
Also important for Proto-stars burning

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







Agreement between two completely independent determinations of ω_b !!!

Wonderful check of Standard Cosmological Model

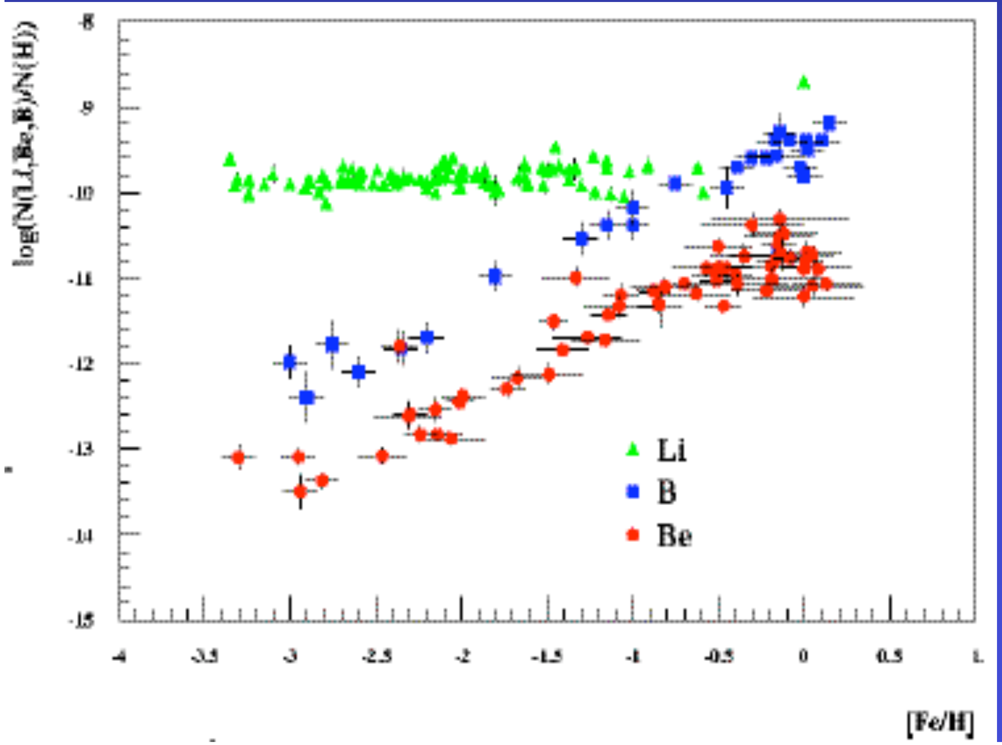
X_D=best BBN "bariometer"

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

The primordial production of ^7Li depends directly on the $^3He(^4He,\gamma)^7Be$ rate. The ^7Li 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?

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



BBN summary (1)

Reaction	before LUNA	after LUNA
$D(p,\gamma)^3He$	13.2% (Cyburt '01)	3% (Serpico '04)
$^3He(^4He,\gamma)^7Be$	8% (20%)	4%

Future perspectives

$D(^4He,\gamma)^6Li$ 10% (presently error is of 1 or 2 order of magnitude)

Impact on BBN

Present status (including LUNA

but not $^3He(^4He, \gamma)^7Be$)

$X_{^2H}/X_H \quad (10^{-5})$	2.44	± 0.04
$X_{^3He}/X_H \quad (10^{-5})$	1.01	± 0.03
$X_{^6Li}/X_H \quad (10^{-14})$	1.1	± 1.7
$X_{^7Li}/X_H \quad (10^{-10})$	4.9	± 0.4

rate	$\delta\sigma^2_{^2H^2H}/\sigma^2_{^2H^2H}(\%)$
$dp\gamma$	49
ddn	37
ddp	14

rate	$\delta\sigma^2_{^3He^3He}/\sigma^2_{^3He^3He}(\%)$
$he3dp$	80.7
$dp\gamma$	16.8
ddp	1.3
ddn	1.2

rate	$\delta\sigma^2_{^7Li^7Li}/\sigma^2_{^7Li^7Li}(\%)$
$be7n\alpha$	40.9
$he4he3\gamma$	25.1
$be7dp\alpha$	16.2
$he3dp$	8.6
$dp\gamma$	4.0
$be7np$	2.7
ddn	1.8
$others$	0.7

BBN study LUNA improvements: (basically due to $D(p, \gamma)^3He$)

- Error on D decreased by a factor 3 (now is fine, error is presently dominated by uncertainty on baryon density)
- Error on ^3He decreased by a factor 2
- Error on ^7Li decreased by a factor 1.3
- ^4He only sensitive to weak rates…

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

^7Li error almost the same, central value may shift by few percent. Main problems is the apparent discrepancy between observations and theory (a factor 2-3) perhaps due to systematics in measurments (7Li in Spite plateau is not primordial)

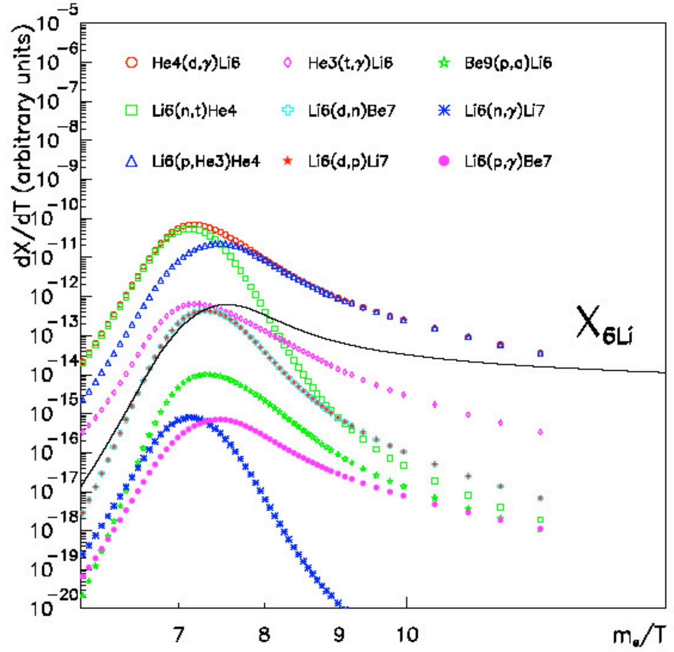
Future:

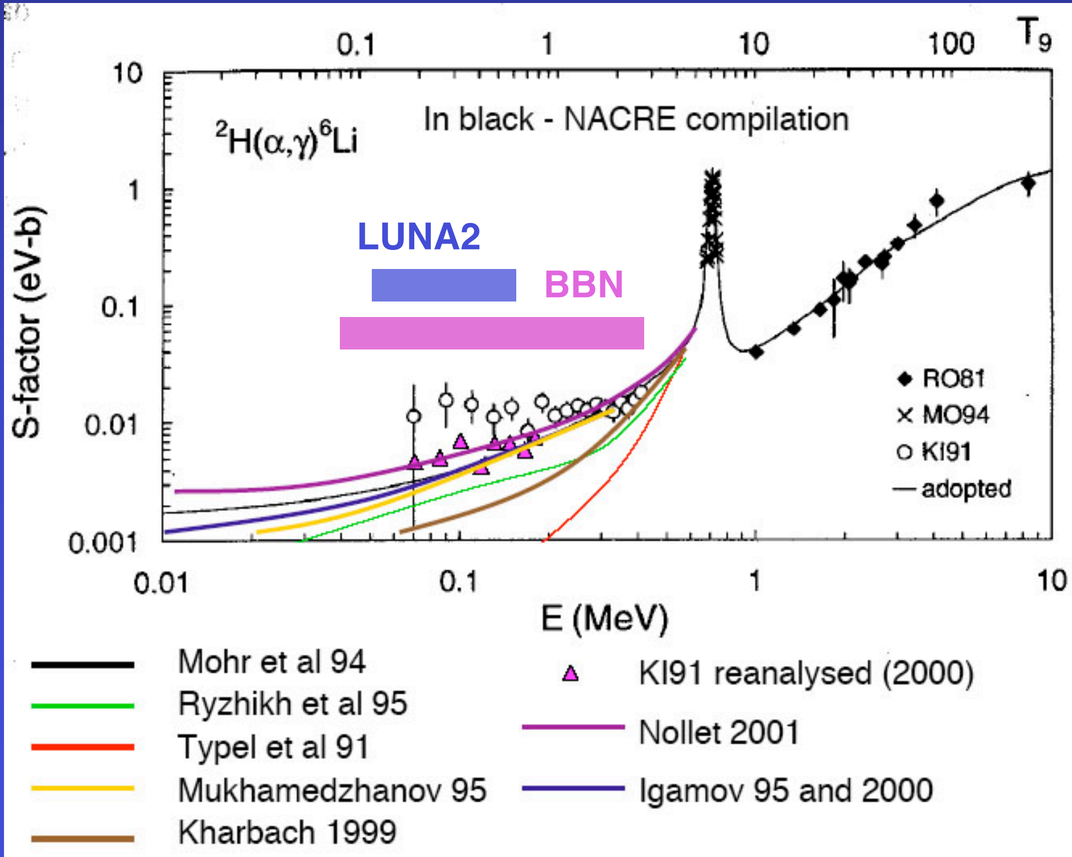
Crucial: $D(^4He, \gamma)^6Li$ theoretical uncertainty on ^6Li would decrease by at least one order of magnitude (presently is 100%)

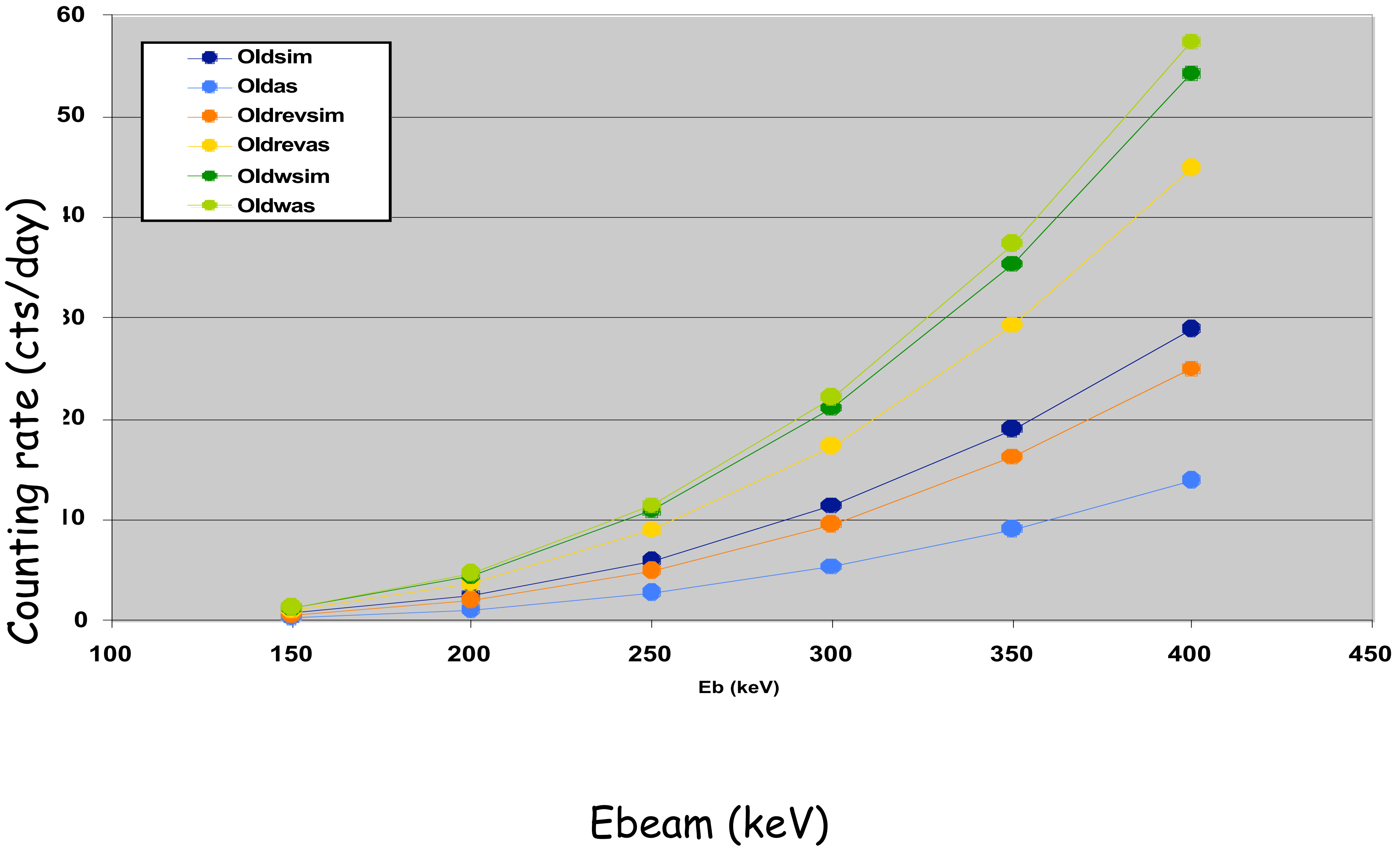
$D(^4He,\gamma)^6Li$ Q = 1.5 MeV

Main reaction for ^6Li production

- No direct measurements for E_{cm}<650 keV !
- Theoretical calculations of S-factor differs for more than one order of magnitude







Oldsim
Oldas
Oldrevsim
Oldrevas
Oldwsim
Oldwas
Counting rate (cts/day)
0
10
20
30
40
50
60
100
150
200
250
300
350
400
450
Eb (keV)
Ebeam (keV)

Conclusion

A new importan measurement has been done by the LUNA colaboration: $^{3}He(^{4}He,\gamma)^{7}Be$

It is very important for the solar study with neutrino experiments and for BBN nucleosynthesis.

$^{25}Mg(p,\gamma)^{26}Al$ and $^{15}N(p,\gamma)^{16}O$ are in progress

FUTURE:

$D(\alpha,\gamma)^{6}Li$ is under study

LOI for a 4 MeV accelerator underground $^{12}C(\alpha,\gamma)^{16}O$