Underground Study of Big Bang Nucleosynthesis in the Precision Era of Cosmology

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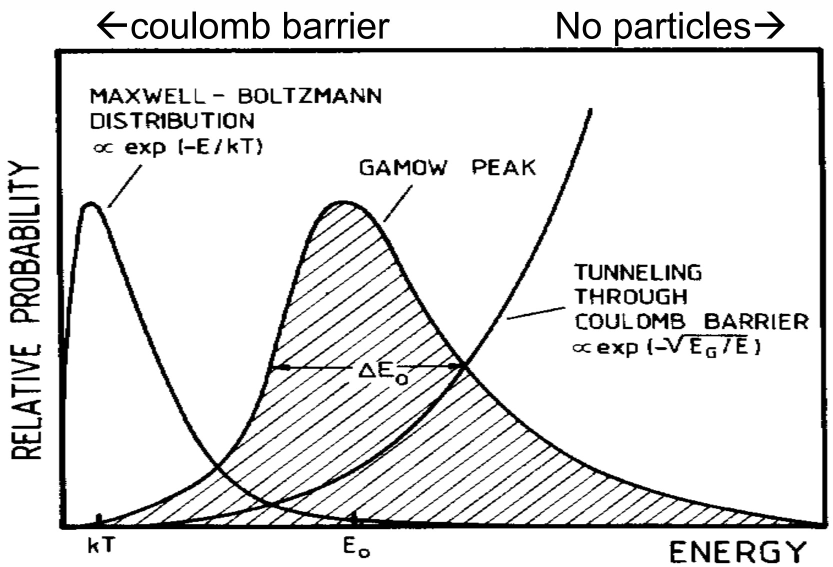
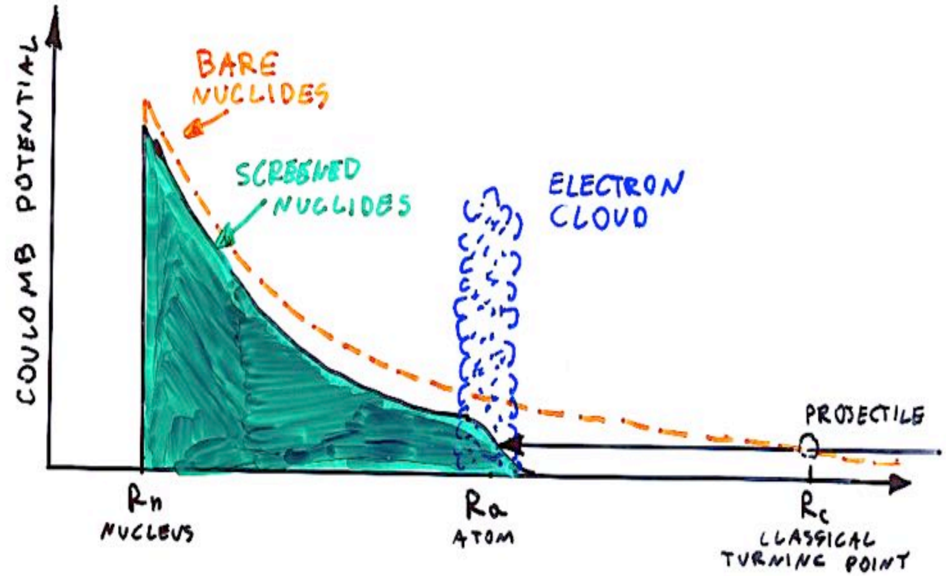
The LUNA experiment at LNGS
Big bang Nucleosynhesis
BBN at LUNA

$^{3}He(\alpha,\gamma)^{7}Be$ → ^{7}Li abundance
$d(\alpha,\gamma)^{6}Li$ → ^{6}Li abndance
$d(p,\gamma)^{3}He$ → D abundance

RICAP, june 22 2016

Why Underground measurements?

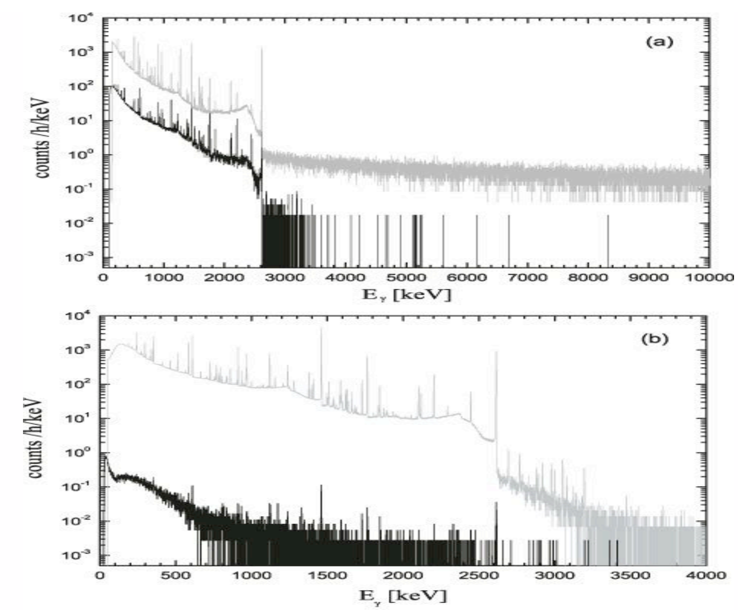




Astrophysical Factor

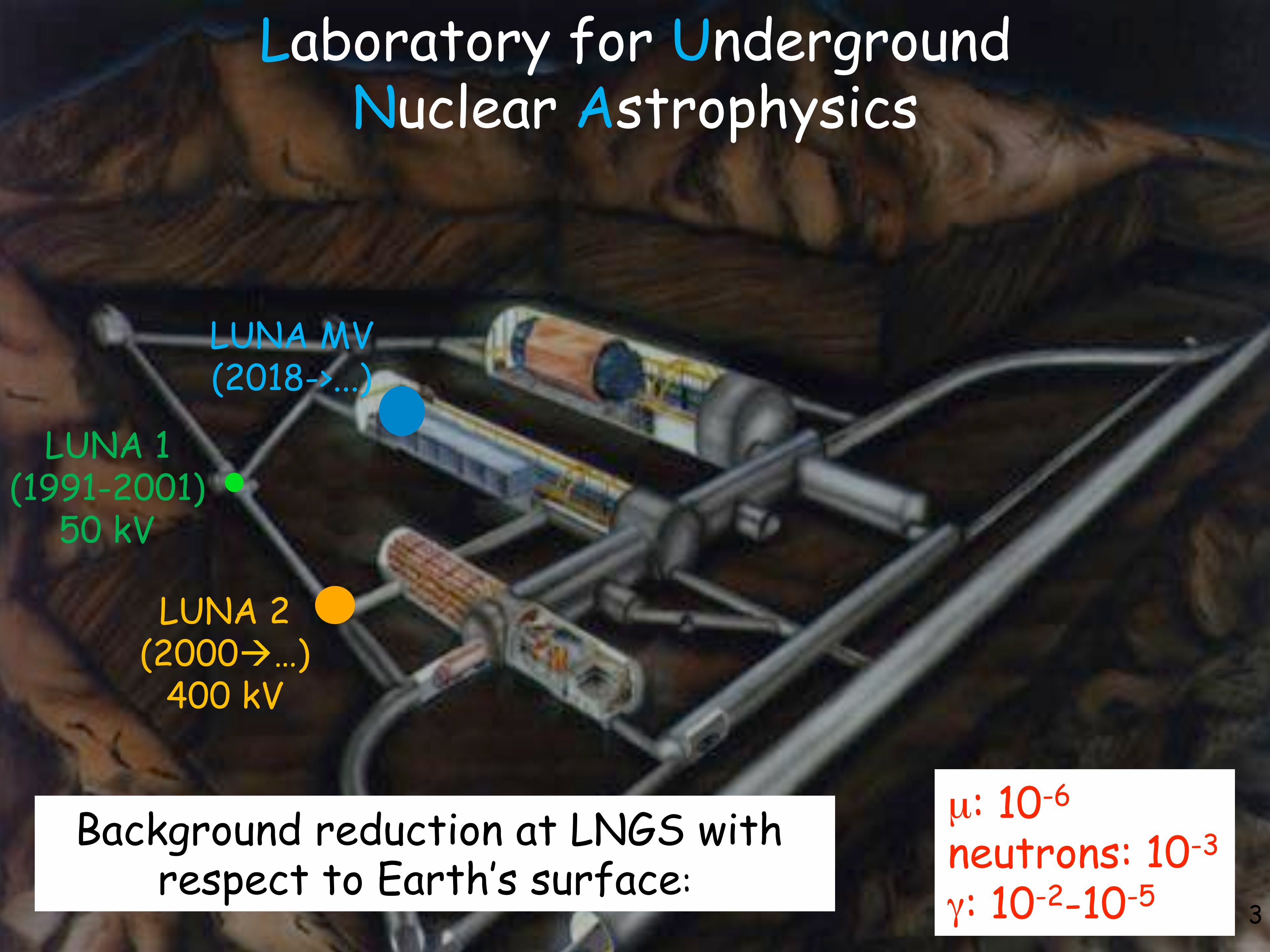
Coulomb Barrier

$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$



Very low cross sections because of the coulomb barrier
→UNDERGROUND ion accelerator to reduce the background induced by cosmic rays

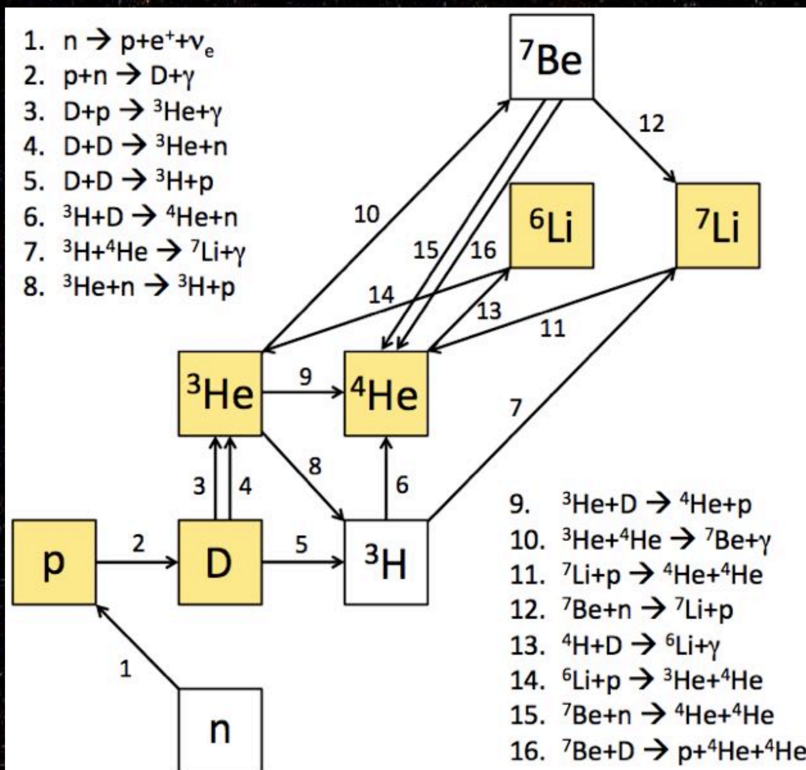
Laboratory for Underground Nuclear Astrophysics



Background reduction at LNGS with respect to Earth's surface:

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

Big Bang Nucleosynthesis



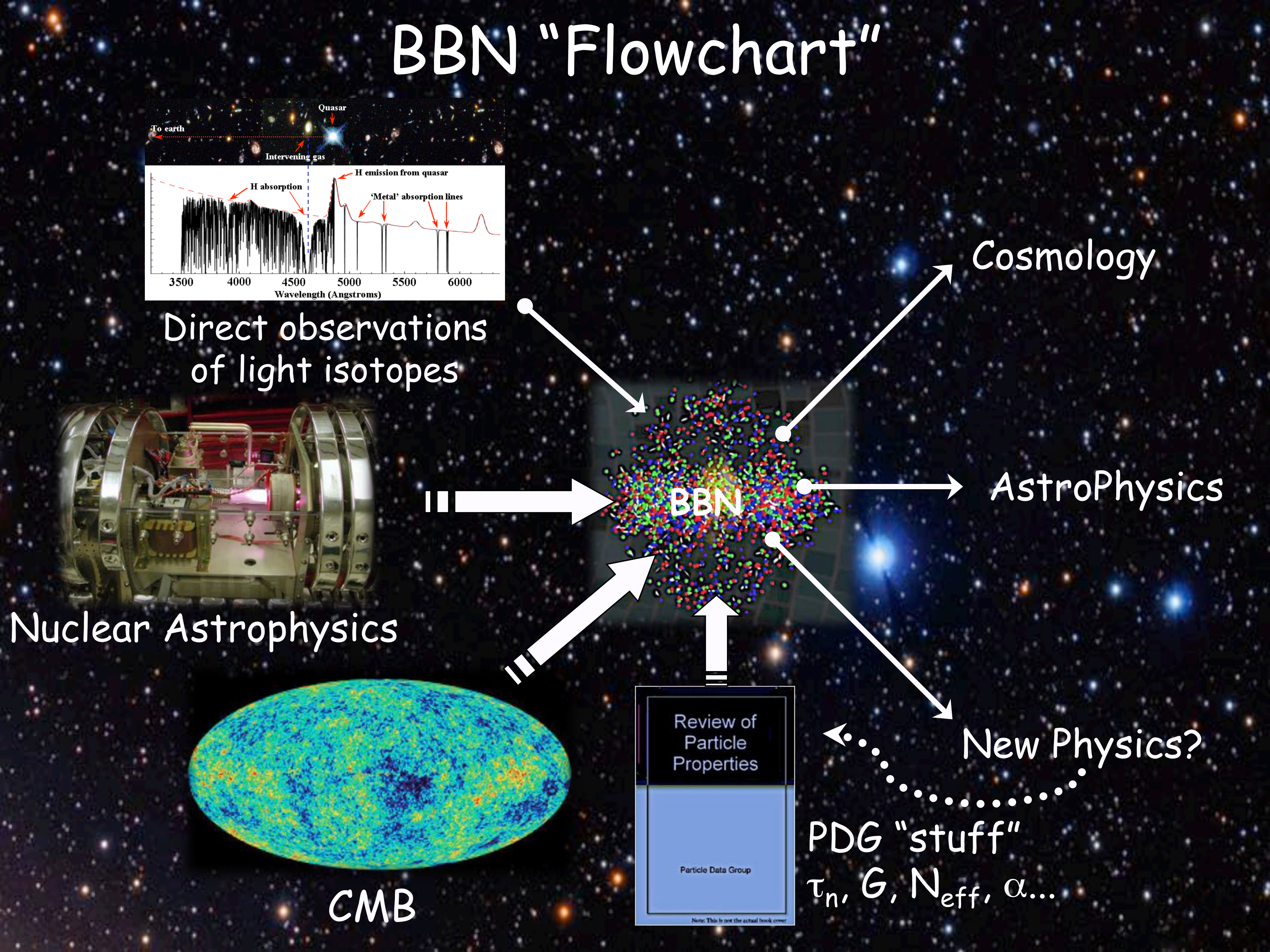
BBN is the result of the competition between the relevant nuclear processes and the expansion rate of the early universe:

$$H^2 = \frac{8\pi}{3} G\rho$$

$$\rho = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

Calculation of primordial abundances only depends on:
-Baryon density Ω_b
-Particle Physics (N_{eff}, α..)
-Nuclear Astrohysics, i.e. Cross sections of relevant processes at BBN energies

The comparison between calculated abundances and astrophysical observations represents a crucial check for the ΛCDM model and astrophysics.


BBN "Flowchart"
Quasar
To earth
Intervening gas
H emission from quasar
H absorption
'Metal' absorption lines
3500 4000 4500 5000 5500 6000
Wavelength (Angstroms)
Direct observations of light isotopes
Nuclear Astrophysics
CMB
BBN
Review of Particle Properties
Particle Data Group
Note: This is not the actual book cover
Cosmology
AstroPhysics
New Physics?
PDG "stuff"
τ_n, G, N_{eff}, α...

BBN predictions

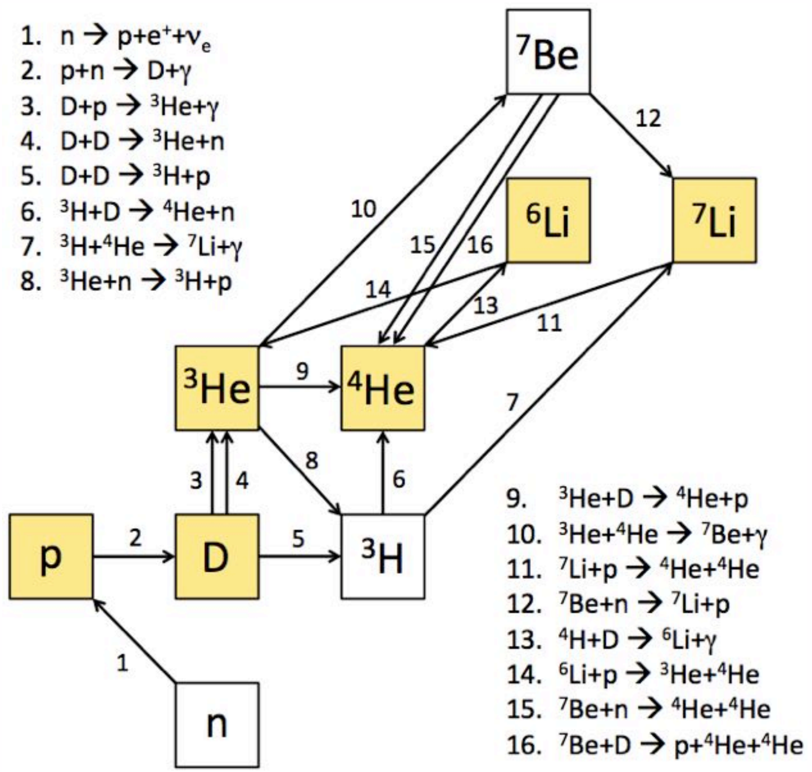
-The BBN begins with the formation of Deuterium.

-Nearly all the free neutrons end up bound in the most stable light element ^4He.

-Small abundance ^7Li and ^6Li have because of the absence of stable nuclei with mass number 5.

-Negligible amount of heavier elements because the lack of A=8 isotopes.

Accuracy mainly depends on nuclear cross section knowledge
→ Direct measurements at BBN energies.



BBN uncertainties:

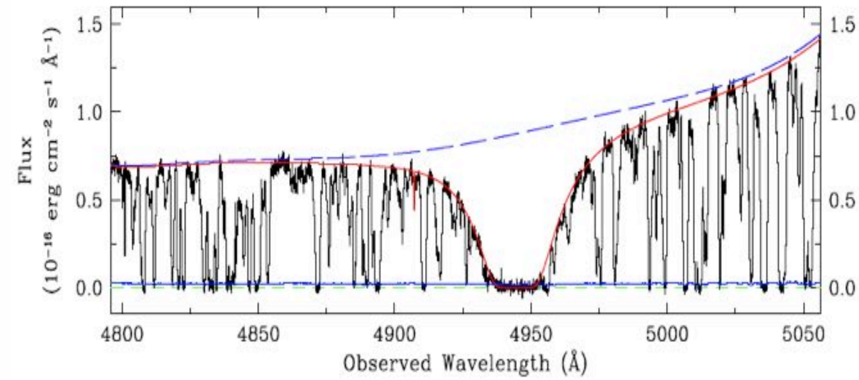
^4He:	Almost entirely due to $\Delta\tau_n$
D:	Mainly due to the $D(p,\gamma)^3He$ reaction
^3He:	Mainly due to the $^3He(d,p)^4He$ reaction
^6Li:	Mainly due $D(a,\gamma)^6Li$ reaction
^7Li:	..Many reactions of the BBN network

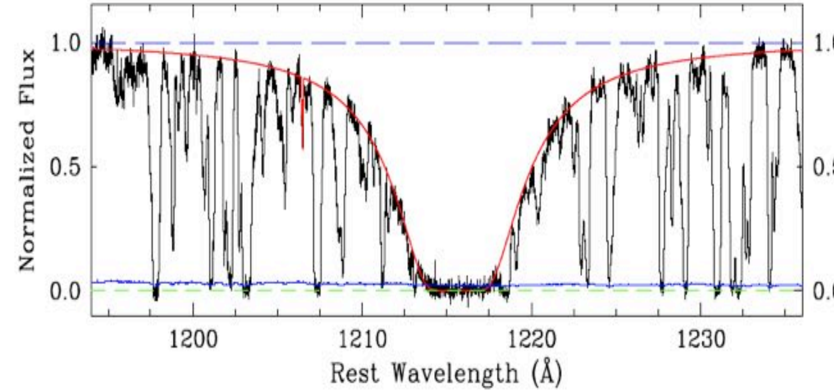
Astronomical observations

-Observation of metal-poor and faraway sites

-Extrapolate to zero metallicity:
Fe/H, O/H, Si/H → 0

-Systematics mainly due to post-primordial processes



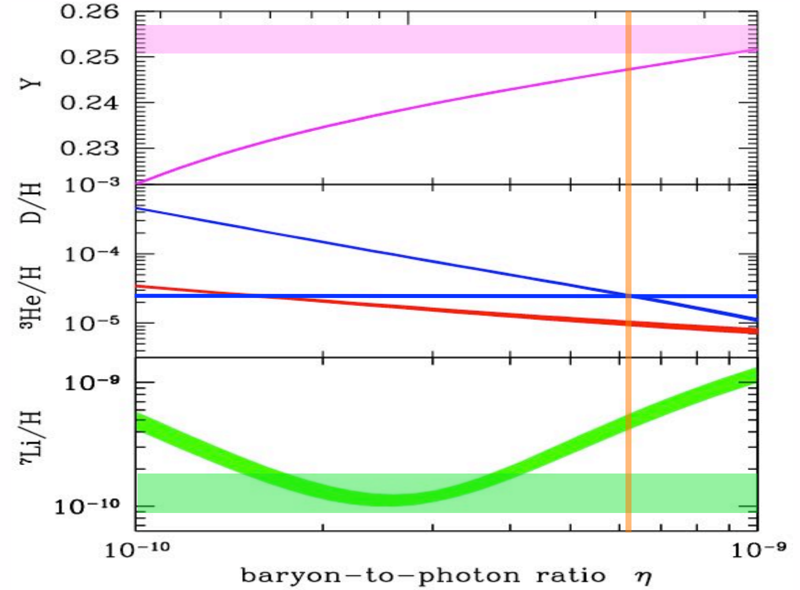


Observation errors:

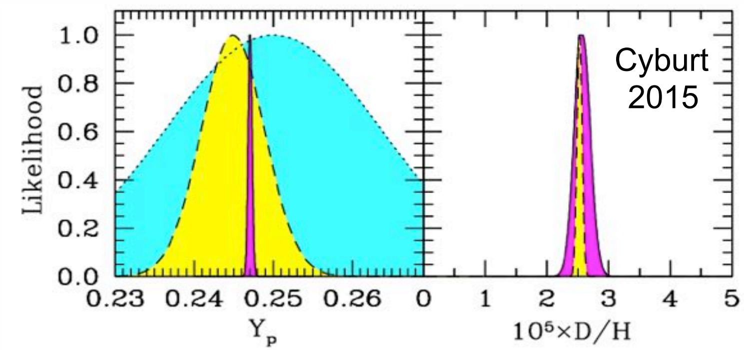
^{4}He: Observation in H_{II} regions, quite large systematics.
D: Observation of absorption lines in DLA systems. Accurate measurements.
^{3}He: Solar System, very large systematics, not a powerful probe for BBN.
^{7}Li: observation of metal poor stars absorption line (Spite plateau)
^{6}Li: observation of metal poor stars absorption lines (controversial)

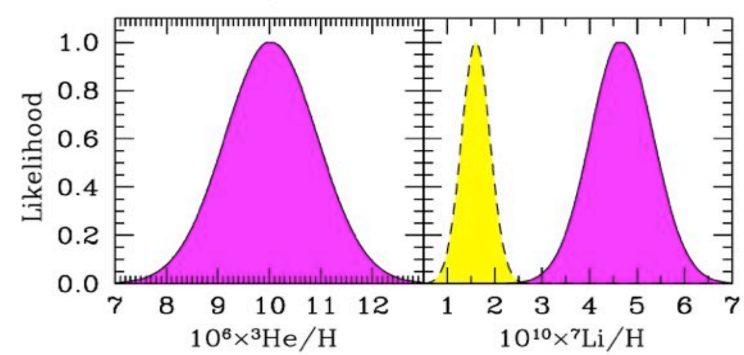
Theory Vs Observations

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.005)\times10^{-5}$	$(2.55\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$\lesssim 2.2\times10^{-5}$
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	$\lesssim 10^{-2}$



^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.
^{7}Li: Long standing "Lithium problem"
^{6}Li: "Second Lithium problem"?

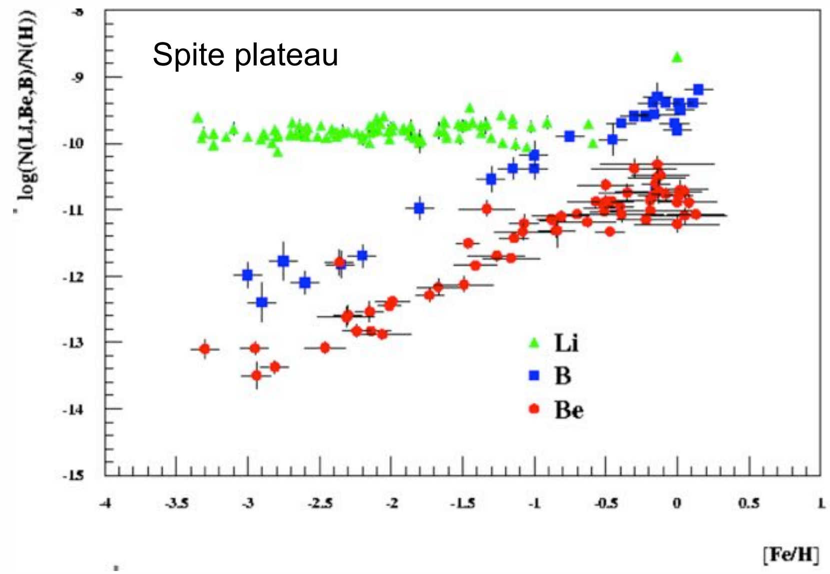




A coherent theory (Cosmology, Astrophysics, Particle physics, Gravitation…) must provide the matching between theory and observations for all the primordial light isotopes.

The Lithium problem(s)

- Observed ^{7}Li abundance is about 3 times lower than foreseen: Well established "Lithium problem".
- Debated claim of a huge abundance of ^{6}Li (Asplund2006).

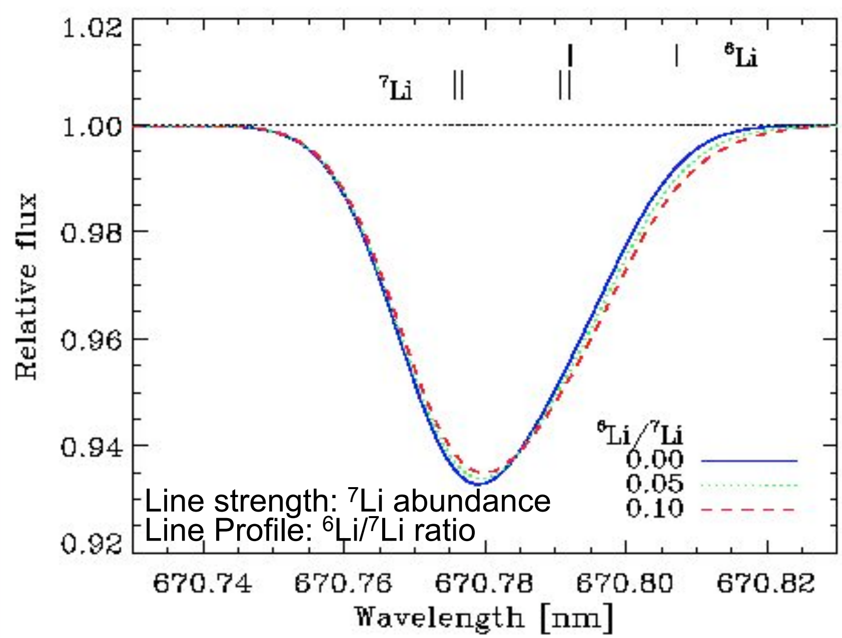


•Systematics in the measured ^{7}Li, ^{6}Li and abundances in the metal-poor stars of our Galaxy.

•Unknown processes before the birth of the galaxy

•New physics, e.g. sparticle annihilation/decay (Jedamzik2008), long lived negatively charged particles (Kusakabe2010)

•...Nuclear physics, i.e. the lack of knowledge of the relevant nuclear reactions.



$^3He(\alpha,\gamma)^7Be$ reaction @ LUNA 400

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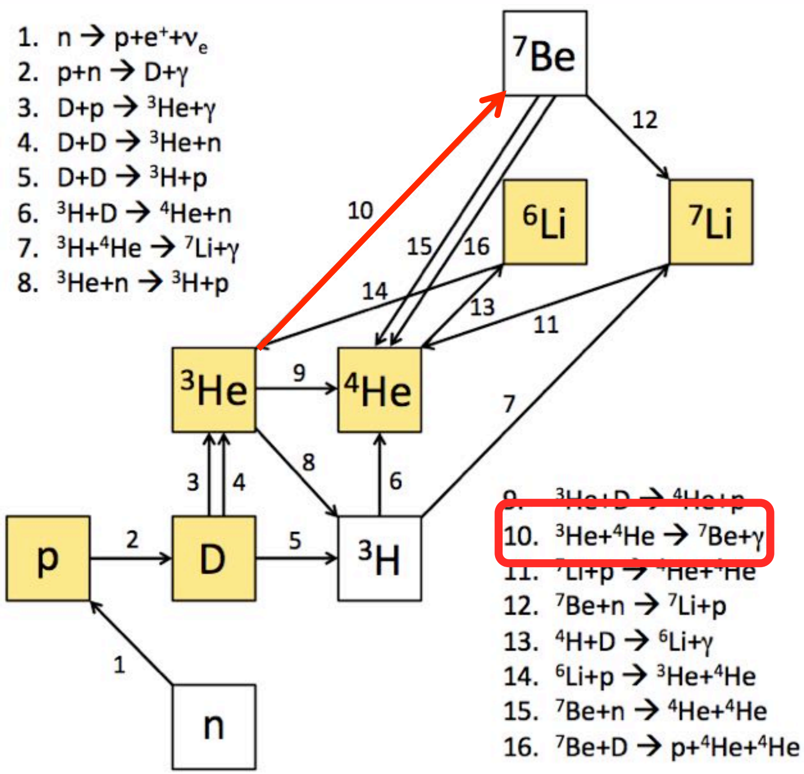
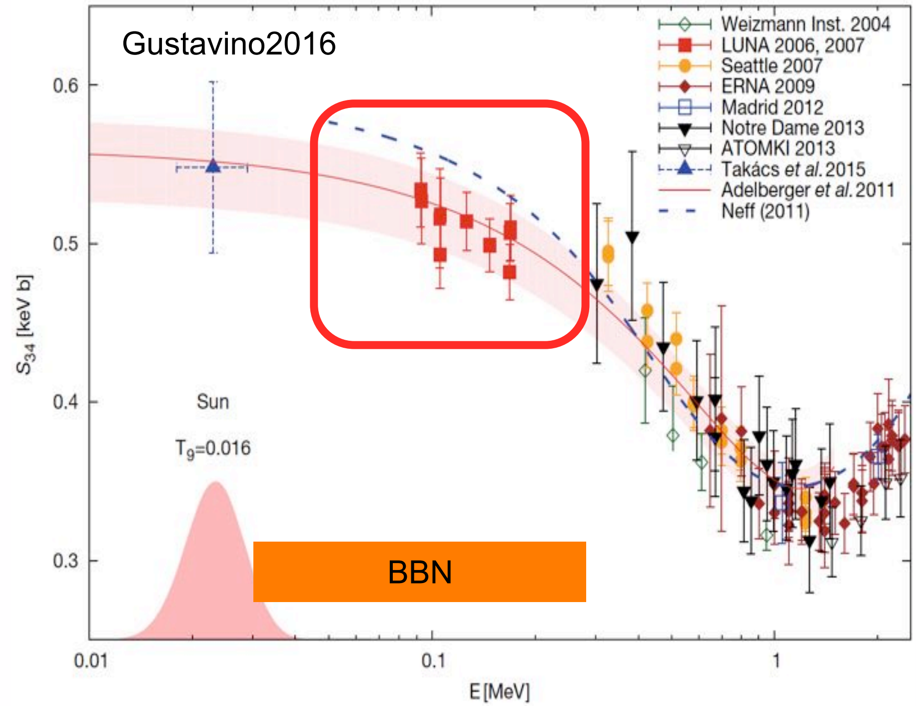
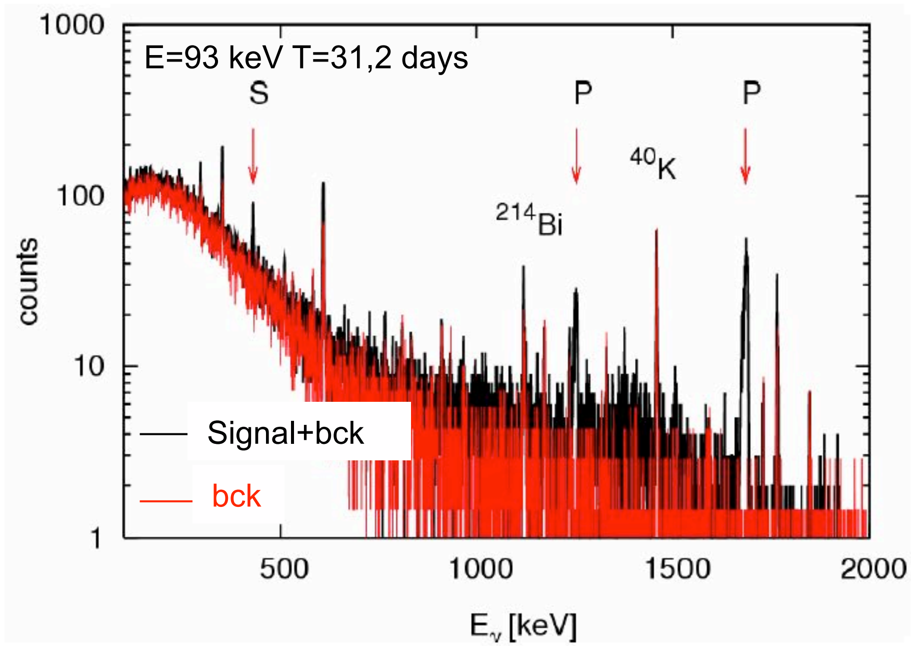


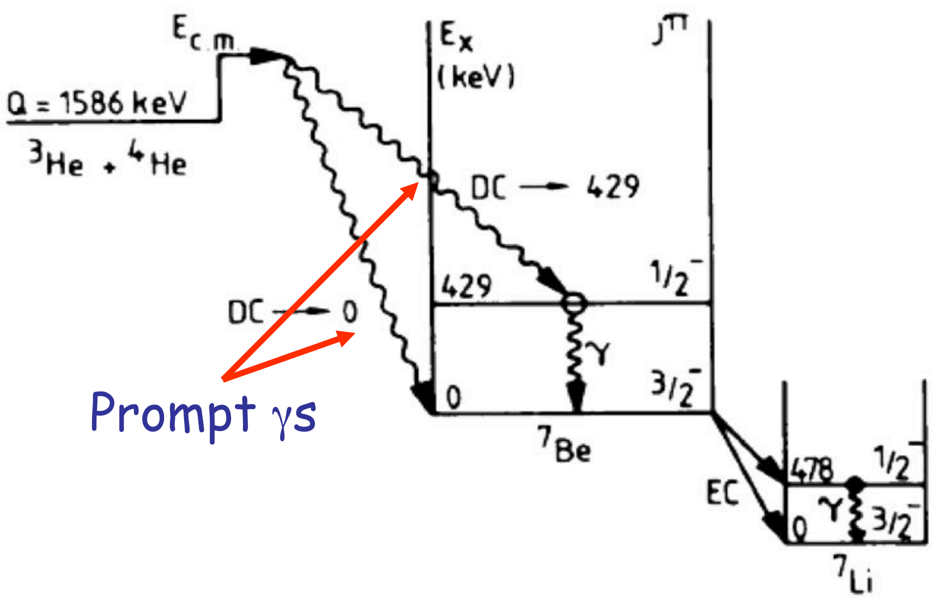


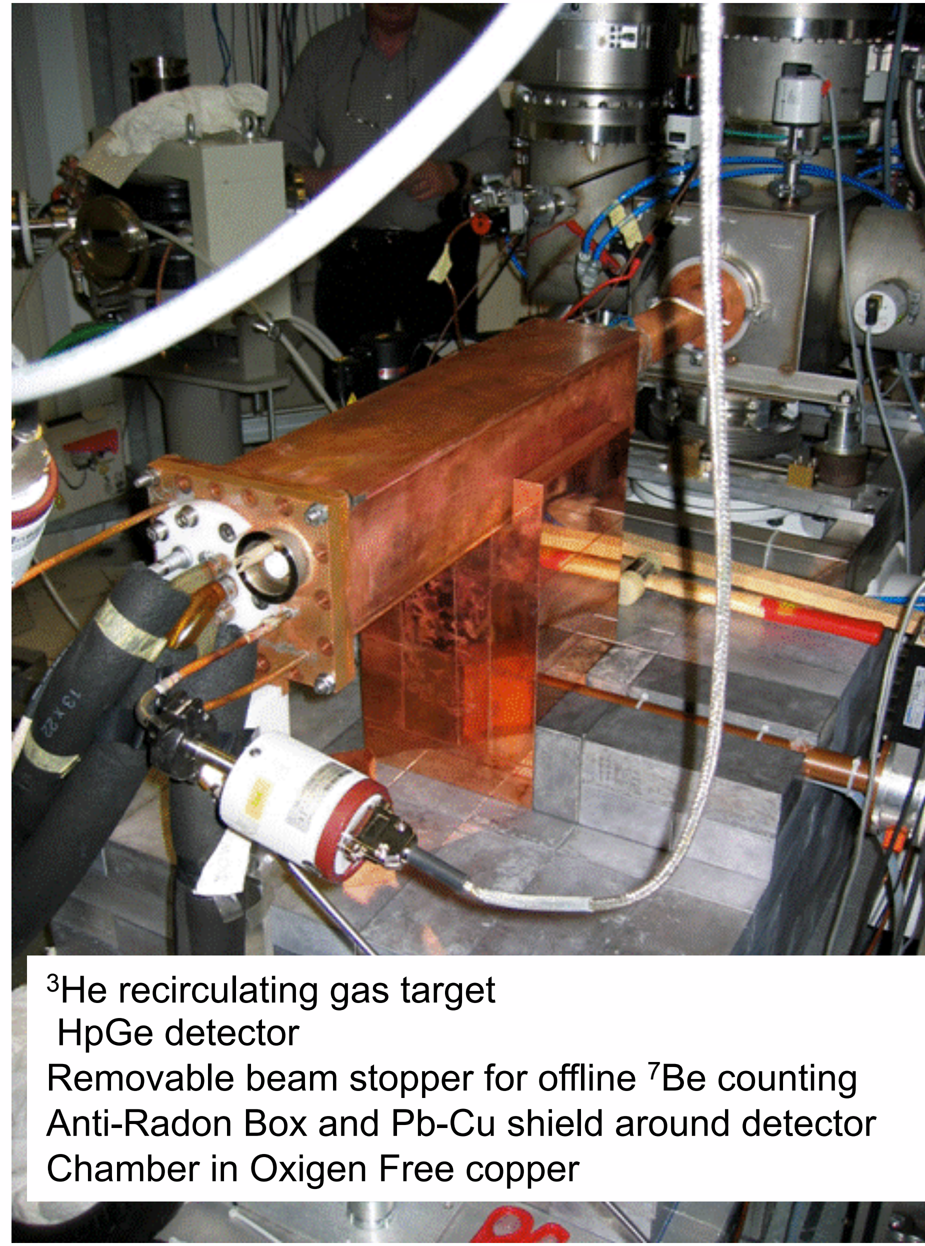
- LUNA data well inside the BBN energy region
- Low uncertainty (4%)
- Simultaneous measurement of prompt and delayed γs

→ Consolidation of "Lithium Problem"

$^3He(\alpha,\gamma)^7Be$ at LUNA: prompt γ's

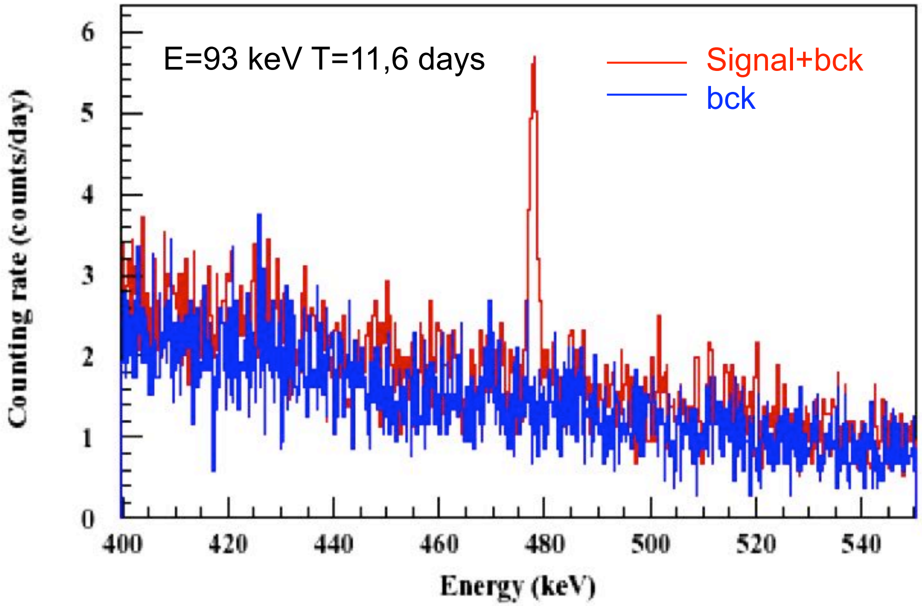


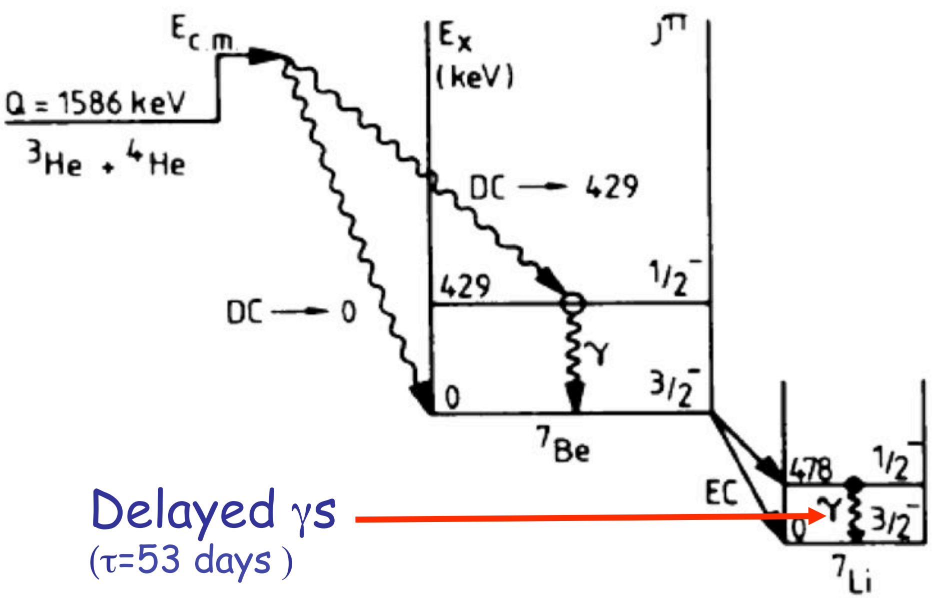




^3He recirculating gas target
HpGe detector
Removable beam stopper for offline ^7Be counting
Anti-Radon Box and Pb-Cu shield around detector
Chamber in Oxigen Free copper

$^3He(\alpha,\gamma)^7Be$ at LUNA: delayed γ's





Delayed γs
(τ=53 days)

Decay of 7Be implanted on the beam stopper.
$^7Be \rightarrow ^7Li + \gamma$

D(α,γ)^{6}Li reaction @ LUNA 400

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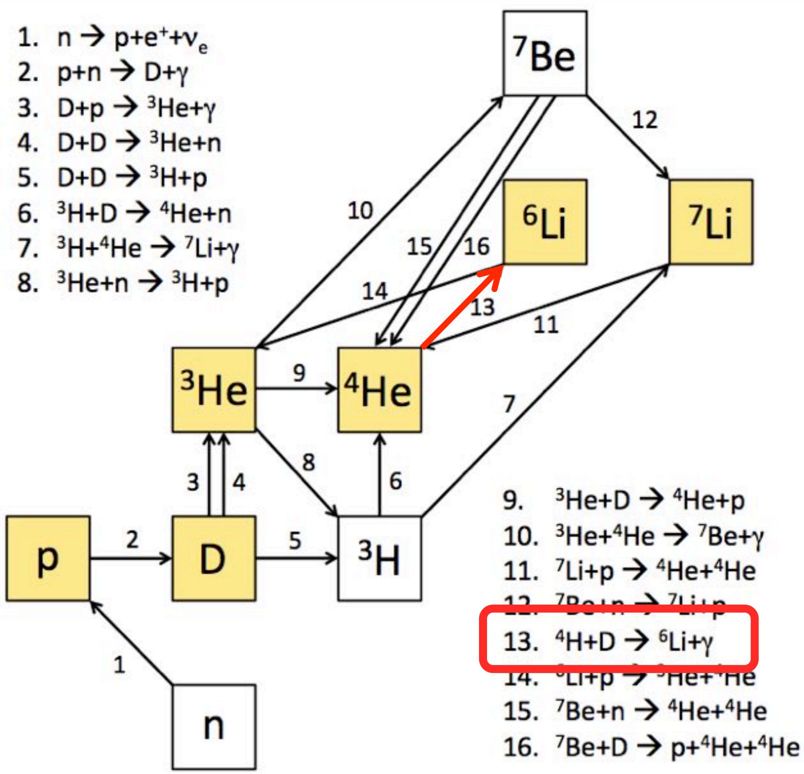
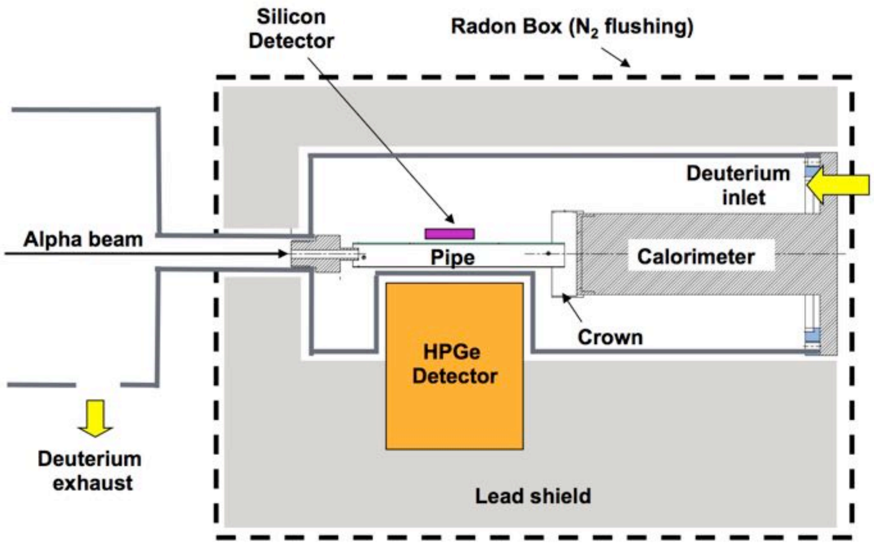


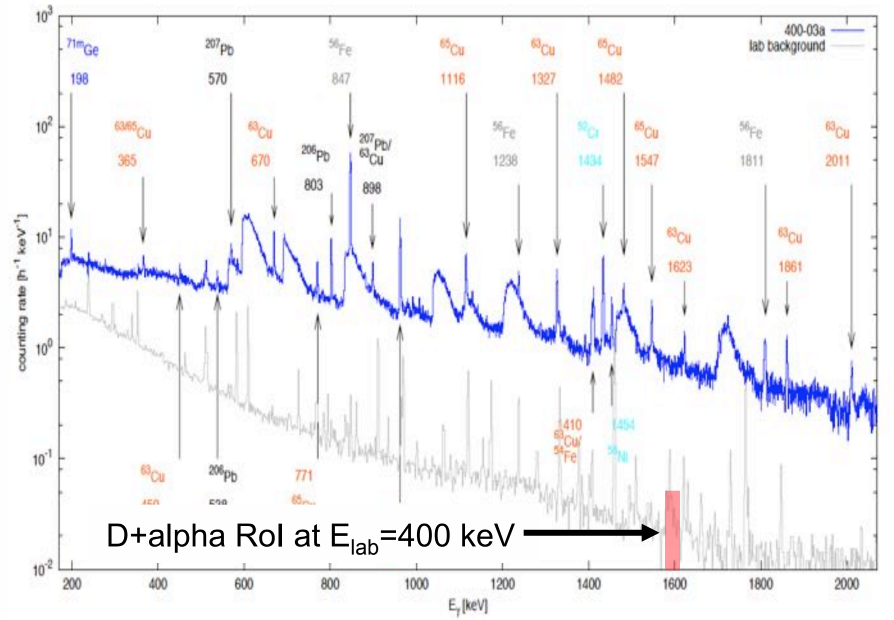
-First measurement in the BBN energy window

-LUNA data exclude a nuclear solution for the ^{6}Li problem...

D(α,γ)^{6}Li reaction @ LUNA 400

Main problem: beam induced background

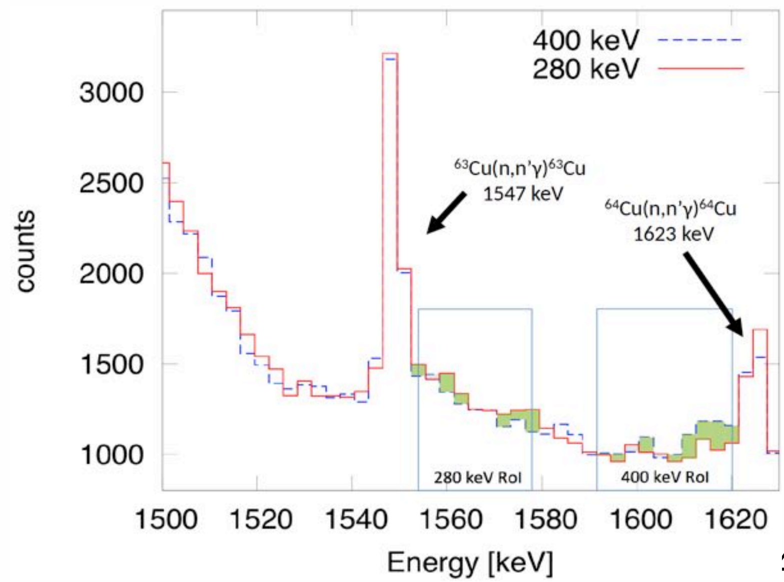




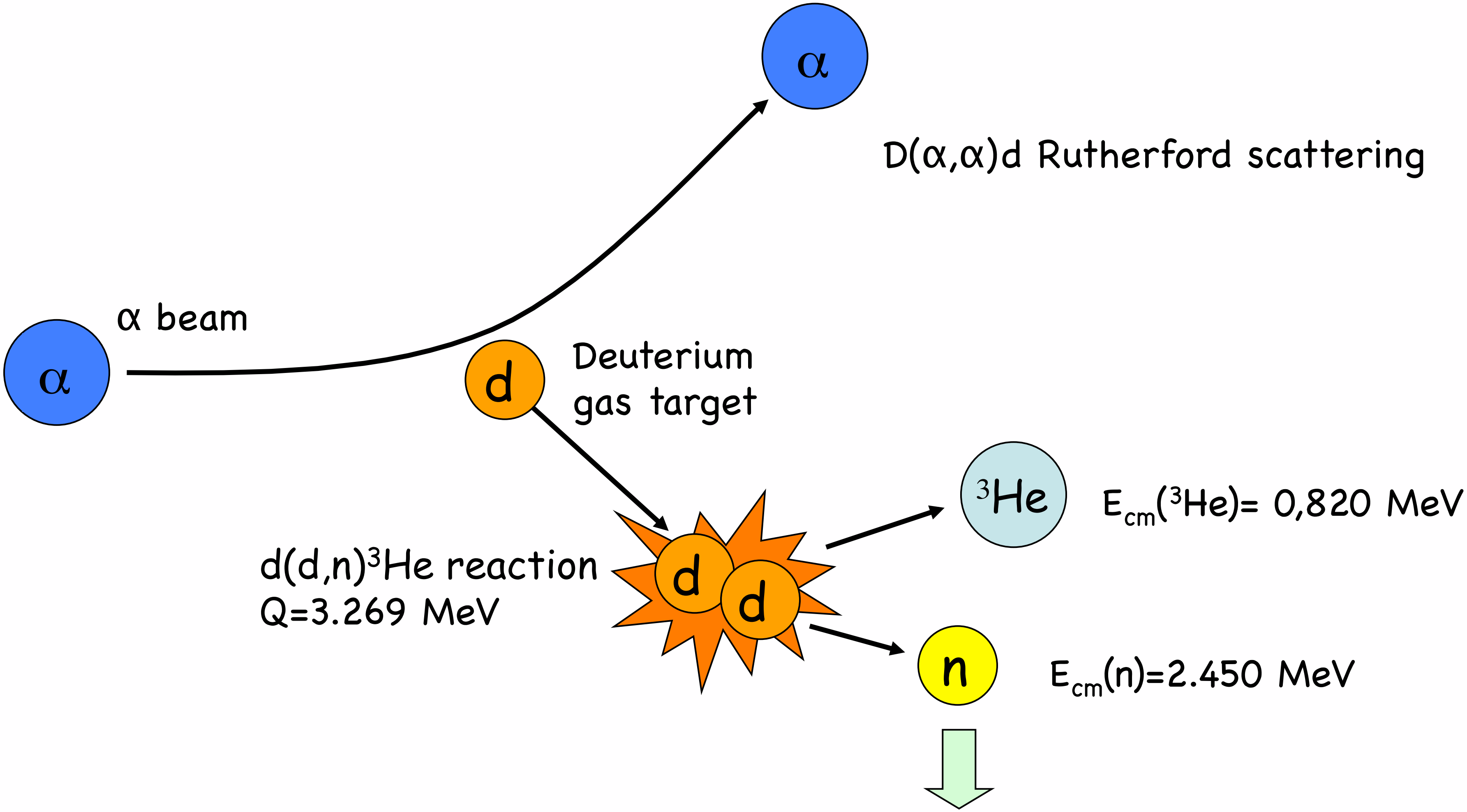
Method:

1. Measurement with E_α=400 keV on D_2 target. Signal is expected in a well defined RoI (1587-1625 keV).
2. Same as 1., but with E_α =280 keV. The Background is essentially the same as before, while the gammas from the D(α,γ)^{6}Li reaction are expected at 1550-1580 keV.

→D(α,γ)^{6}Li Signal is obtained by subtracting the two spectra



Beam Induced Background



(n,n′γ) reaction on the surrounding materials (lead, steel, copper and germanium)
γ-ray background in the RoI for the D(α,γ)^{6}Li DC transition (~1.6 MeV)

$D(p,\gamma)^3He$ reaction @ LUNA 50

Isotope	BBN Theory	Observations
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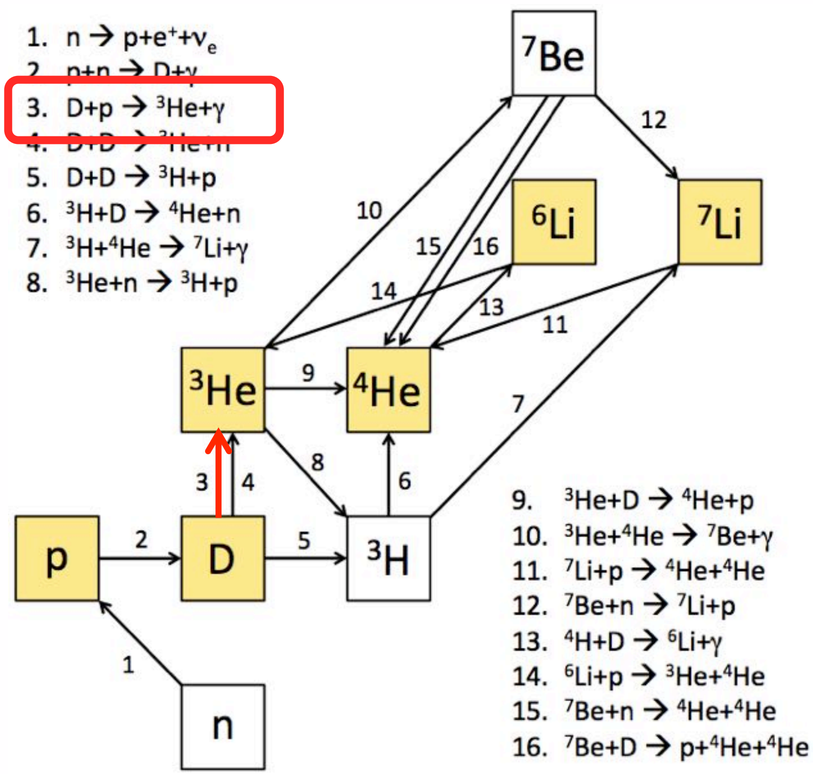
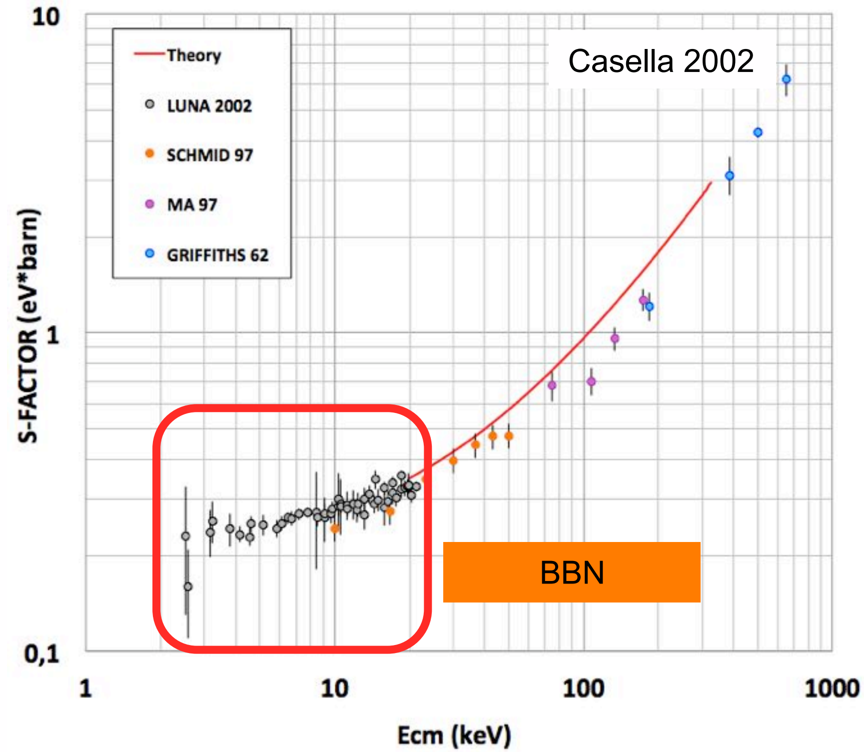


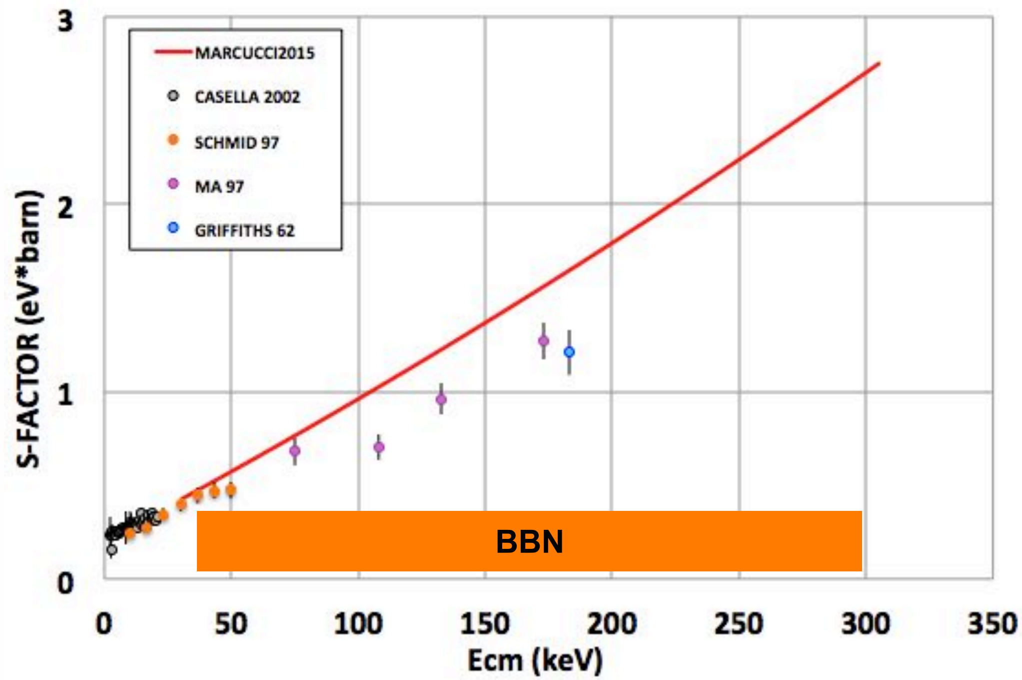


Reduction of $(D/H)_{BBN}$ error of a factor 3

D(p,γ)^{3}He reaction @ LUNA 400

Reaction	Rate Symbol	$\sigma_{^2H/H} \cdot 10^5$
$p(n,\gamma)^2H$	R_1	±0.002
$d(p,\gamma)^3He$	R_2	±0.062
$d(d,n)^3He$	R_3	±0.020
$d(d,p)^3H$	R_4	±0.013

(Di Valentino et al. 2014)



-The error of computed deuterium abundance $(D/H)_{BBN}$ is mainly due to the D(p,γ)^{3}He reaction

-"Ab-Initio" calculations (1% error) not in agreement with measurements (9% error)

Measurement goal:

-Cross section measurement at $30<E_{cm}<260$ with 3% accuracy

-Differential cross section measurement at $100<E_{cm}<260$

Physics:

-*Cosmology: measurement of Ω_b.*

-*Neutrino physics: measurement of N_{eff}.*

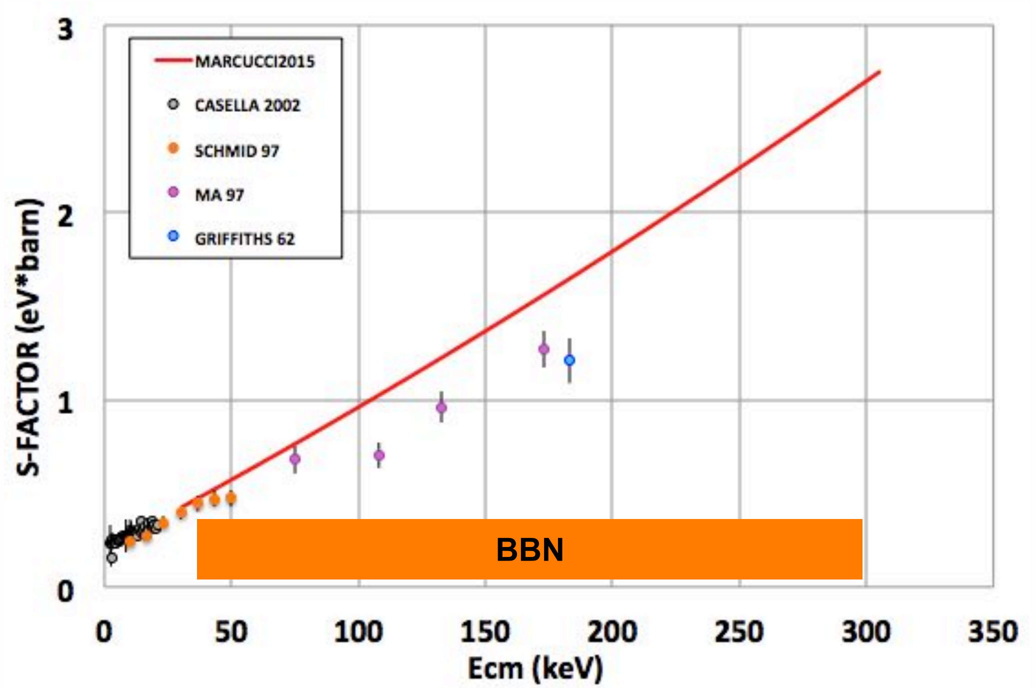
-*Nuclear physics: comparison of data with "ab initio" predictions.*

data taking and analysis in progress

$D(p,\gamma)^3He$: Baryon density

The best estimation of Baryon density Ω_b is based on recent CMB data:

$100\Omega_{b,0}h^2(\text{CMB})=2.22\pm0.02$ (PLANCK2015)



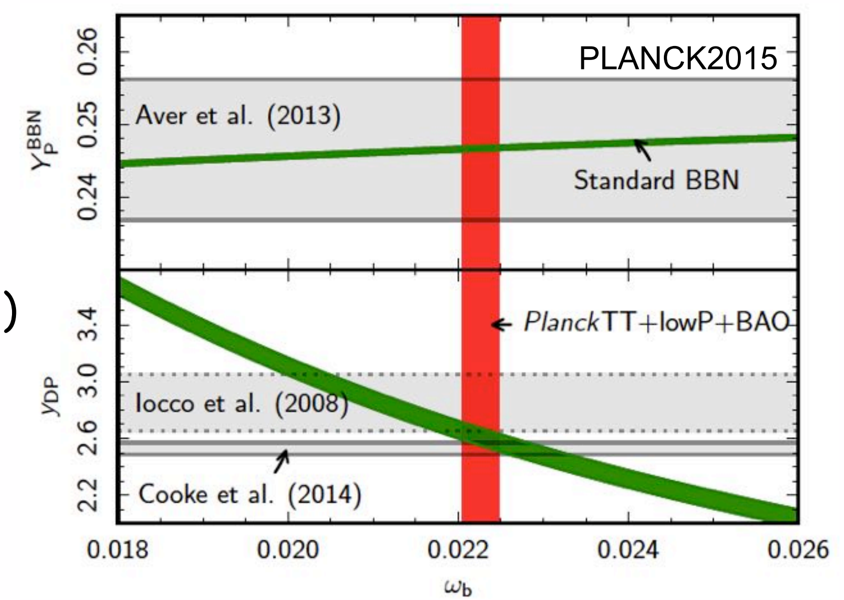
BBN provides an indipendent estimate, comparing observed and computed deuterium abundance:

Dpγ data fit

$100\Omega_{b,0}h^2(\text{BBN})=2.20\pm0.04\pm0.02$ (Cooke&Pettini 2013)
$100\Omega_{b,0}h^2(\text{BBN})=2.16\pm0.01\pm0.02$

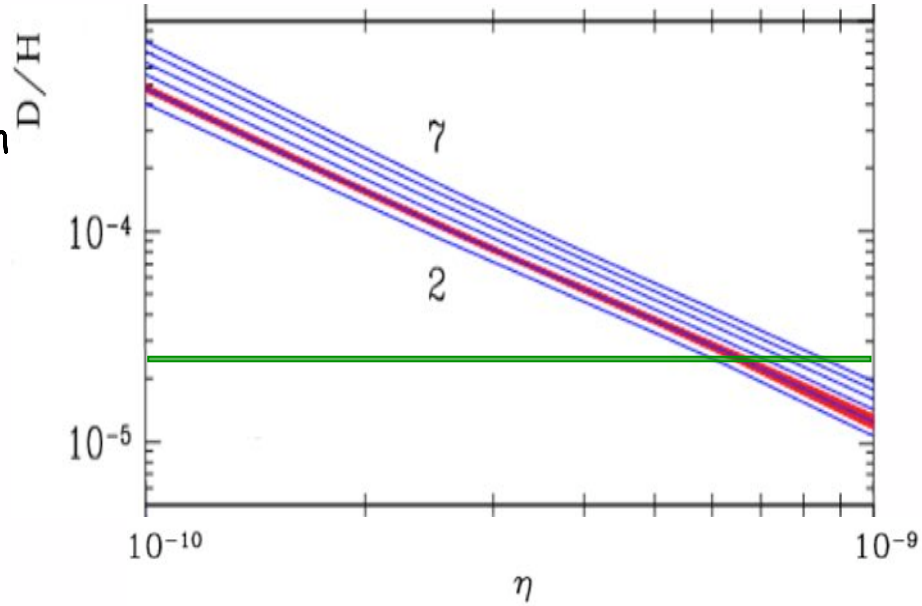
D/H observations

Dpγ "ab-initio"

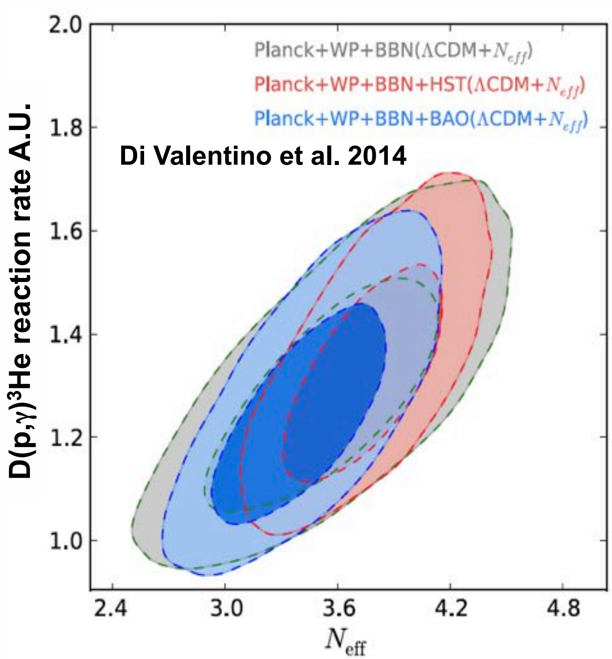


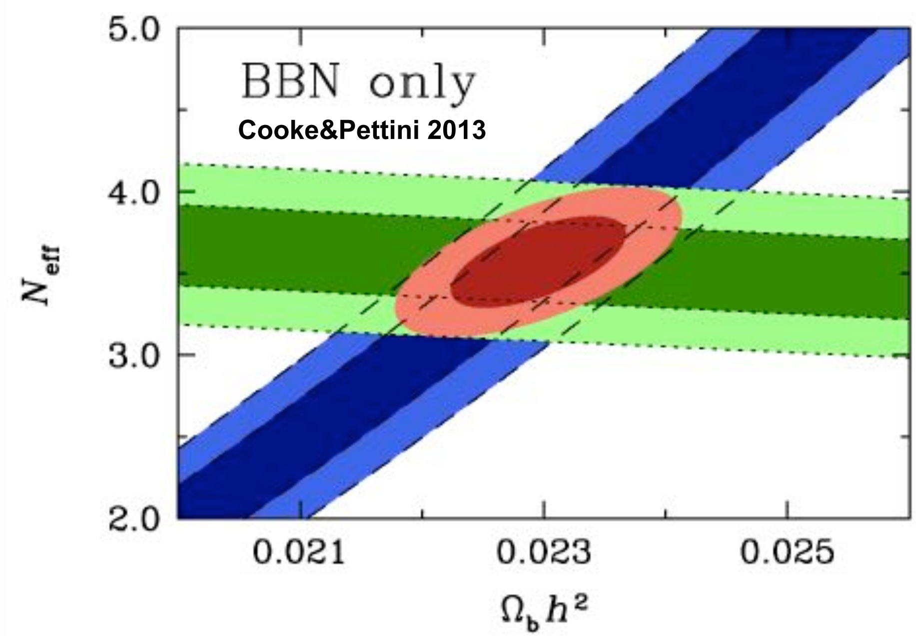
$D(p,\gamma)^3He$: N_{eff}

Deuterium adundance depends on the density of relativistic particles, (photons and 3 neutrinos in SM). Therefore it is a tool to constrain "dark radiation". Assuming literature data for the $D(p,\gamma)^3He$ reation:

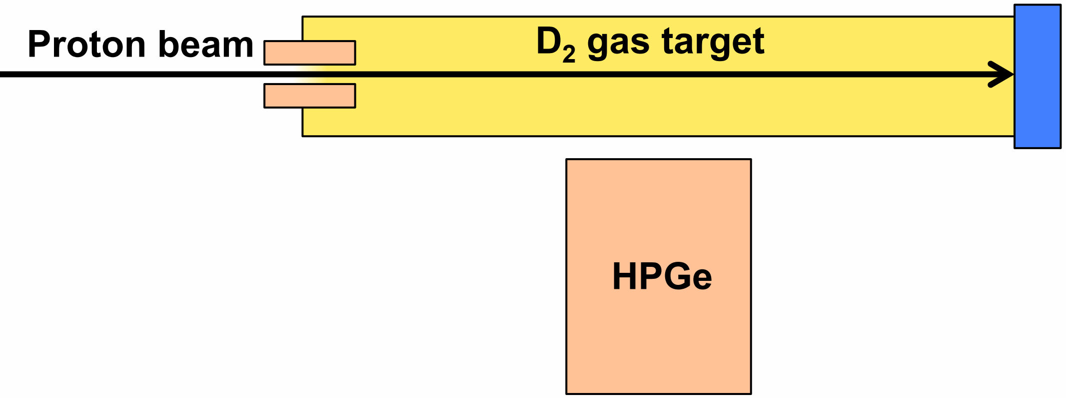


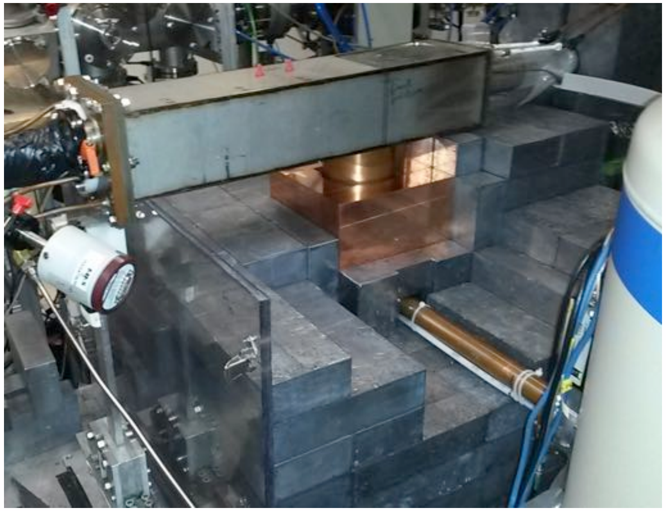
N_{eff} (BBN) = 3.57±0.18 (Cooke&Pettini 2013)
N_{eff} (CMB) = 3.36±0.34 (PLANCK 2013)
N_{eff} (SM) = 3.046



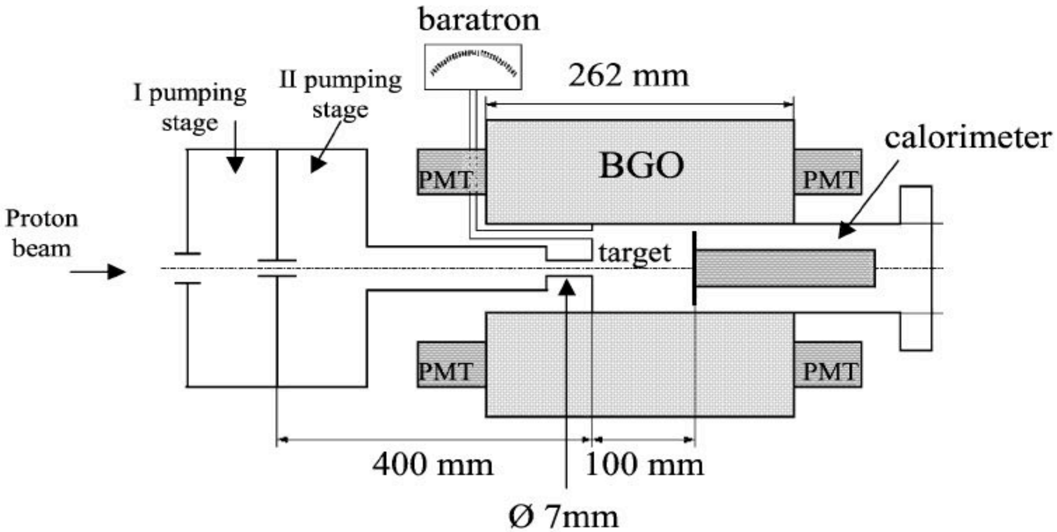


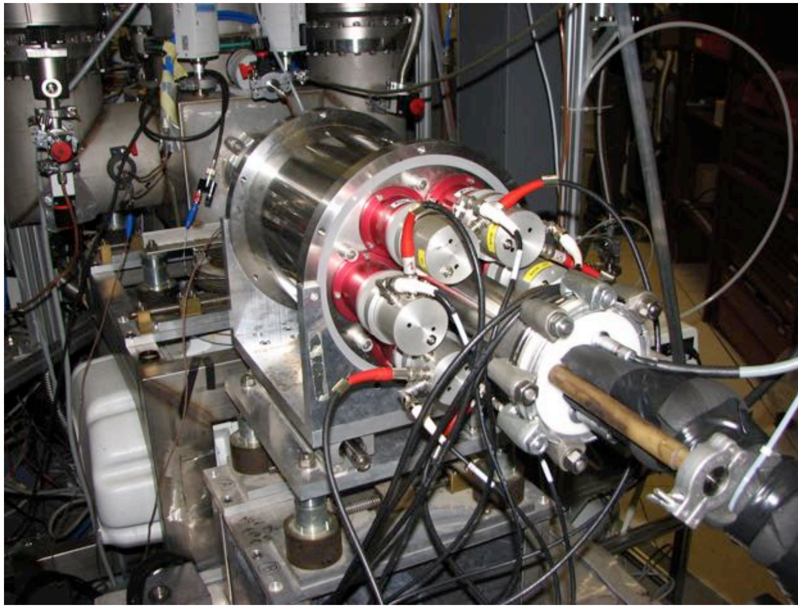
Experimental setup





Ge(Li) detector: **Angular distribution of emitted photons**



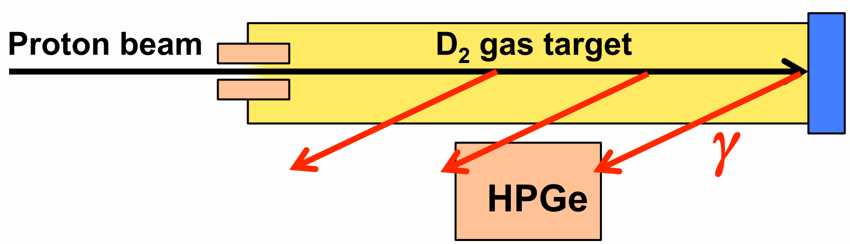


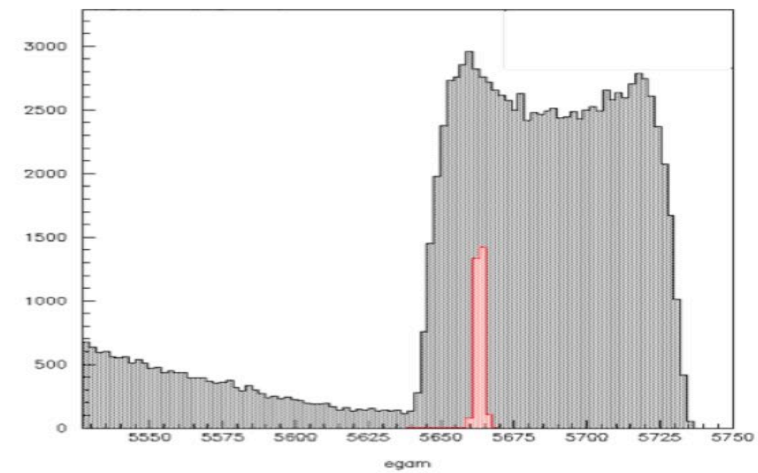
4π BGO detector: **Total cross section Vs Energy**

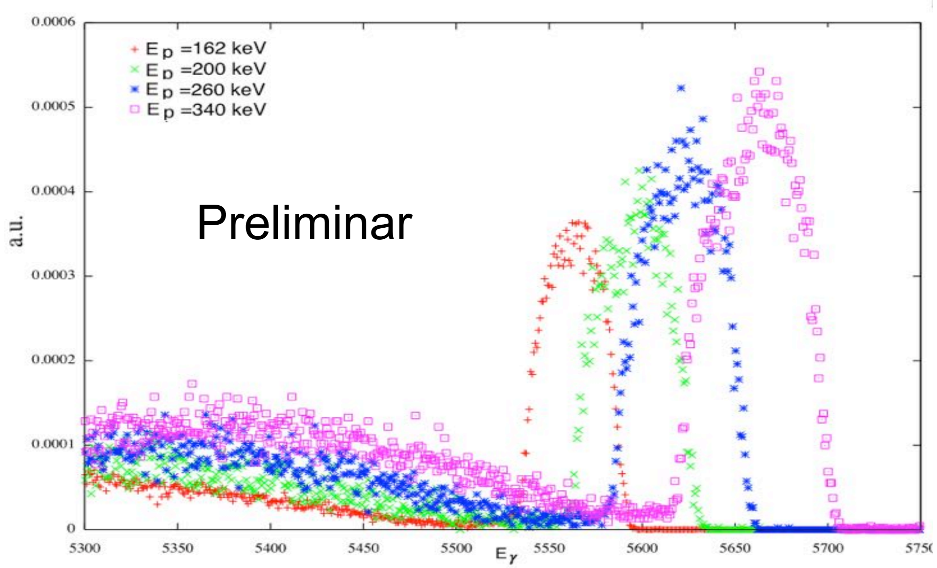
HPGe Preliminary results

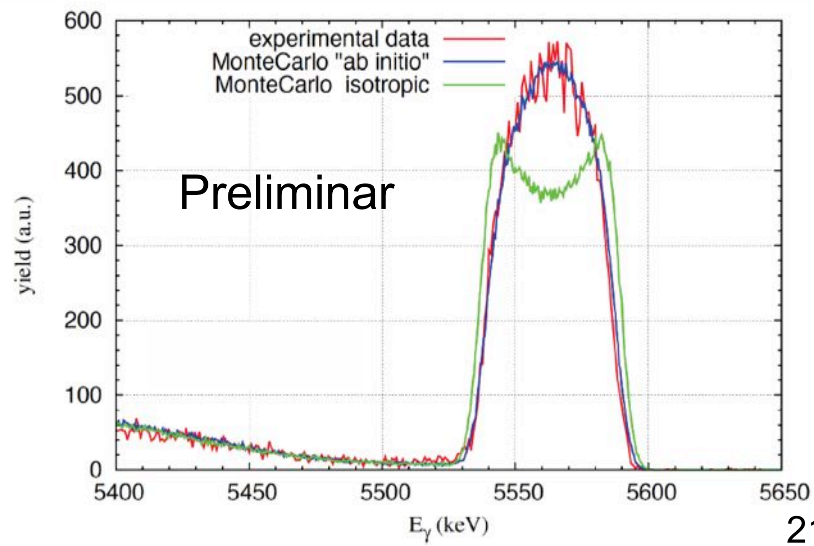
The high resolution of Germanium detector allows to measure the angular distribution of photons emitted by the $d(p,\gamma)^3He$ reaction exploiting the doppler effect:

$$E_\gamma = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p m_d}{2(E_p + m_d^2 - p_p \cos(\theta_{cm}))}$$

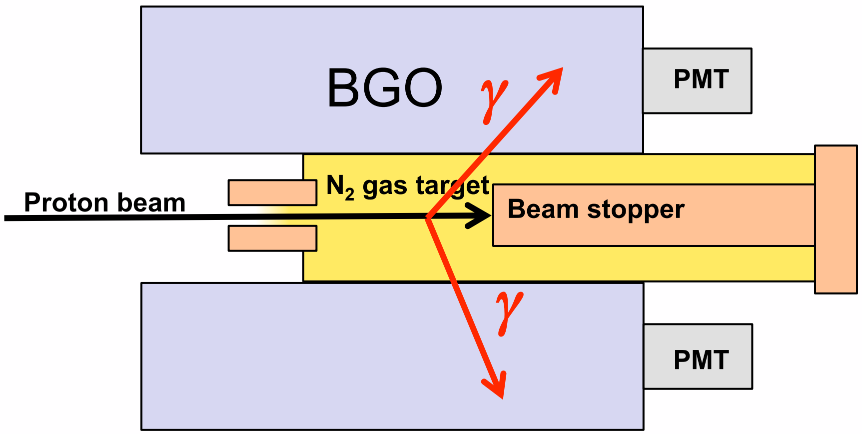


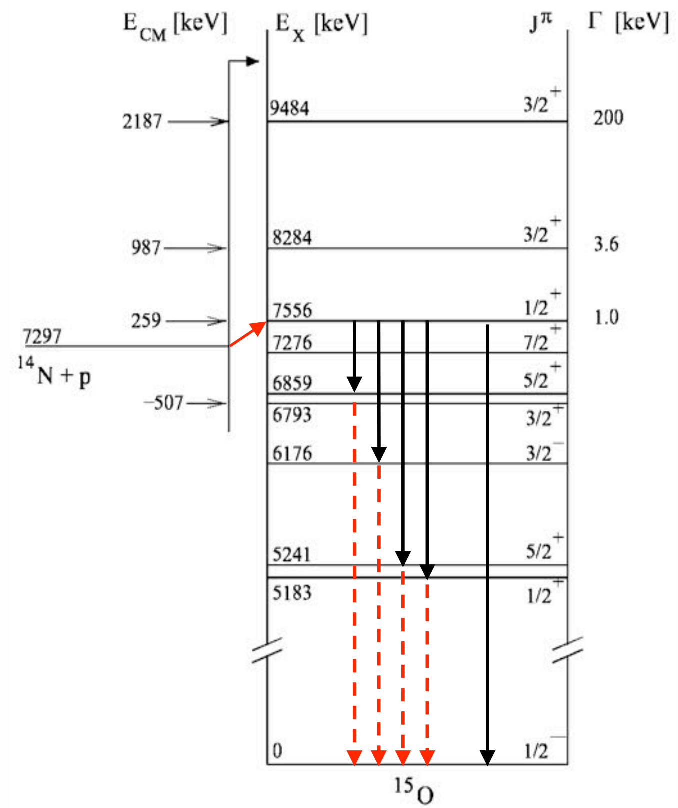


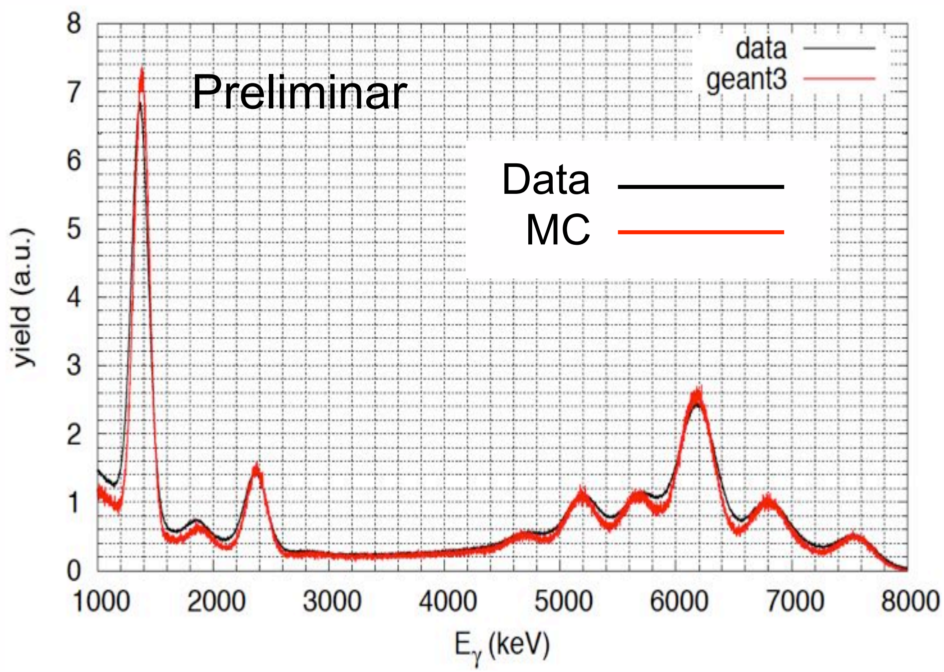




BGO Preliminary results







Eγ (keV)	Branching (%)
5181+2375 (14N)	17.1±0.2 (1.2%)
5241+2315	0.6±0.3 (50%)
6172+1384	57.8±0.3 (0.5%)
6791+765	22.9±0.3 (1.3%)
7556+0	1.6±0.1 (6.2%)

Conclusions

There have been tremendous improvements in recent years in the determination of cosmological parameters from astrophysical measurements. In particular:

-The cosmic density of baryons Ω_b is now known to percent level thanks to the PLANCK mission.

-The primordial abundance of deuterium has been deduced from observations of pristine gas at high redshifts with similar accuracy.

These measurements offer the means to test sensitively cosmology and particle physics. Of particular importance are:

-The comparison of Ω_b(CMB) and Ω_b (BBN).

-The precise estimate of effective number of neutrino families N_{eff}.

The most important obstacle to improve present constraints is the poorly known S-factor of the $d(p,\gamma)^3He$ reaction at BBN energies.

...But a precision study of $d(p,\gamma)^3He$ reaction at BBN energies is in progress at LUNA.

Data taking with dedicated setup: sept 2016 < T < may 2017

STAY TUNED!

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