BBN, Neutrinos and Nuclear Astrophysics
(Studying the Universe deep Underground)

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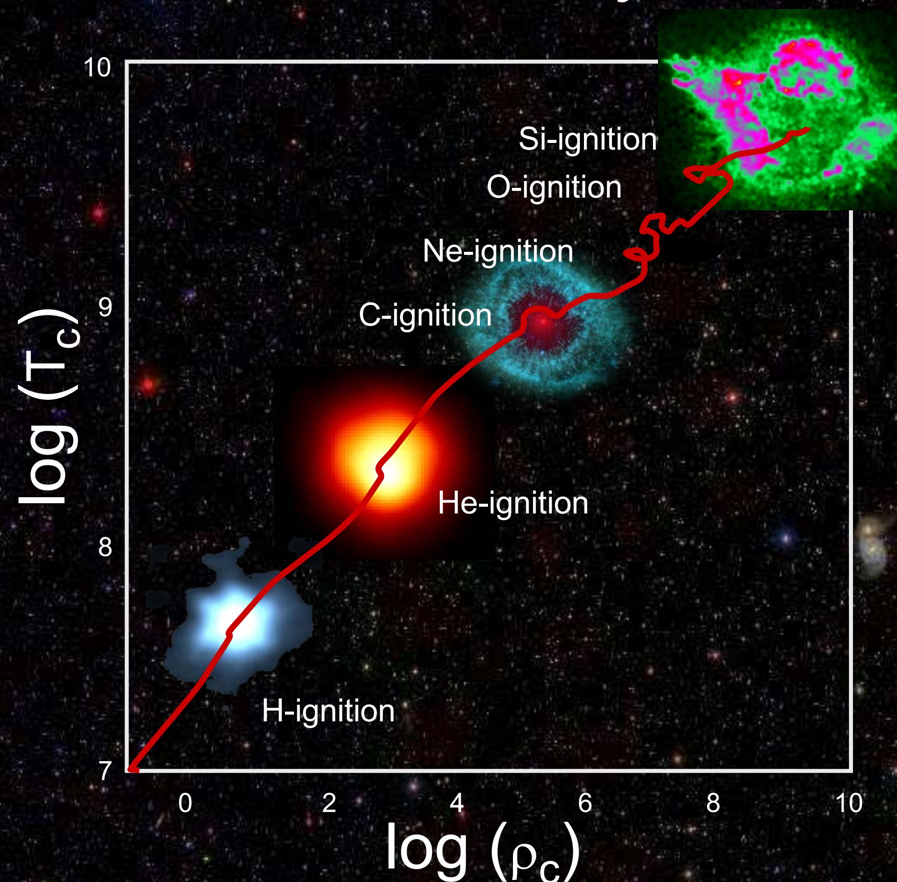
INFN Roma

Nuclear Astrophysics overview
LUNA experiment overview
Big Bang Nucleosynthesis overview
Big Bang Nucleosynthesis at LUNA
The $D(p,\gamma)^3He$ reaction at LUNA

Why Nuclear astrophysics?

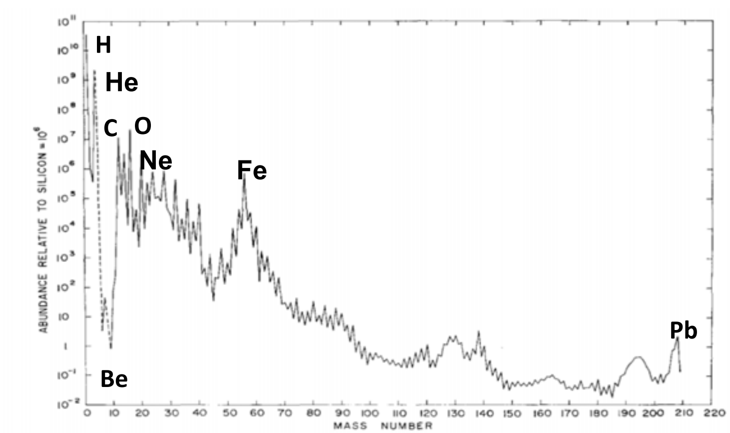


For a 15 M_{sun} star:

Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days

Nuclear reactions are responsible for the synthesis of the elements in the celestial bodies and BBN:
High precision data are required

- Understanding the Sun
- Stellar population
- Evolution and fate of stars
- Big Bang Nucleosynthesis
- Isotopic abundances in the cosmos
- Cosmology
- Particle Physics
- Theoretical nuclear physics

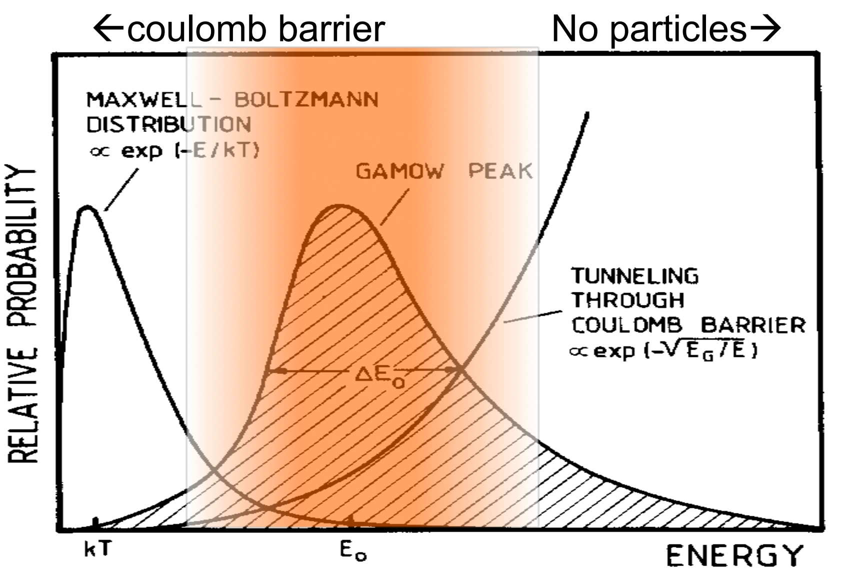


Why Underground Measurements?

Very low cross sections because of the Coulomb barrier

Underground accelerator to reduce the background induced by Cosmic Rays

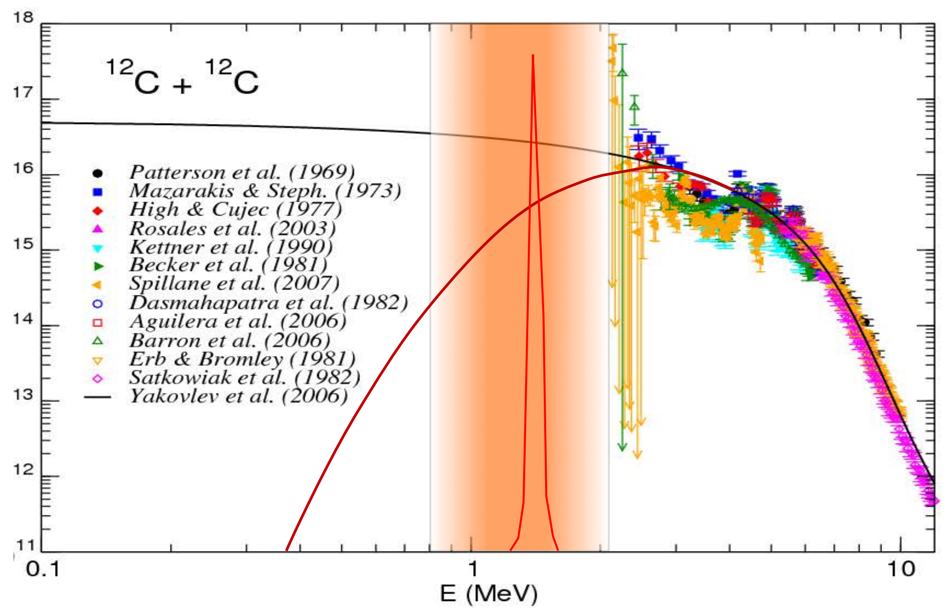
→Measurements at very low energies



Astrophysical Factor

Coulomb Barrier

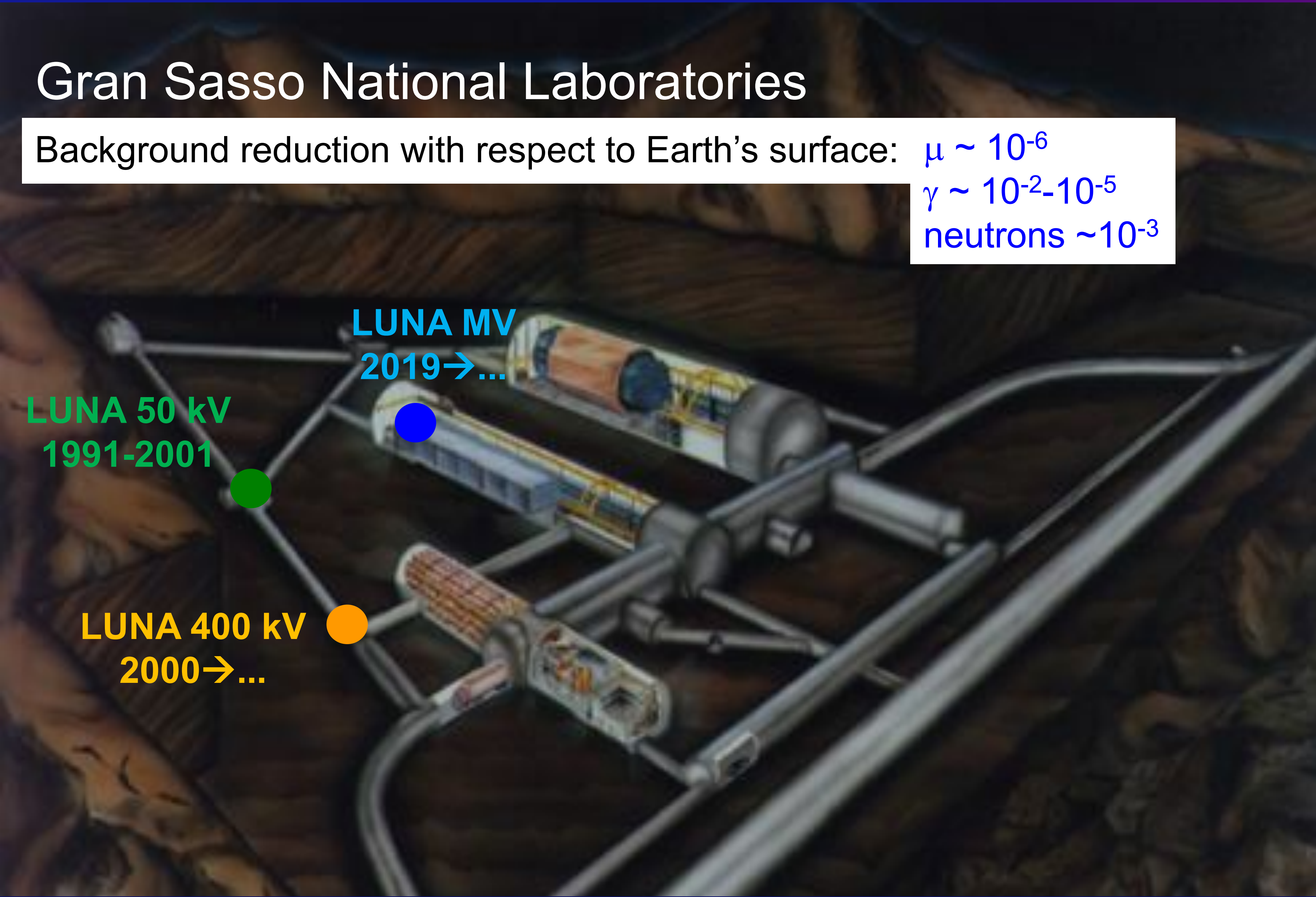
$$\sigma(E) = \frac{S(E)}{E} e^{-\sqrt{\frac{E_G}{E}}}$$



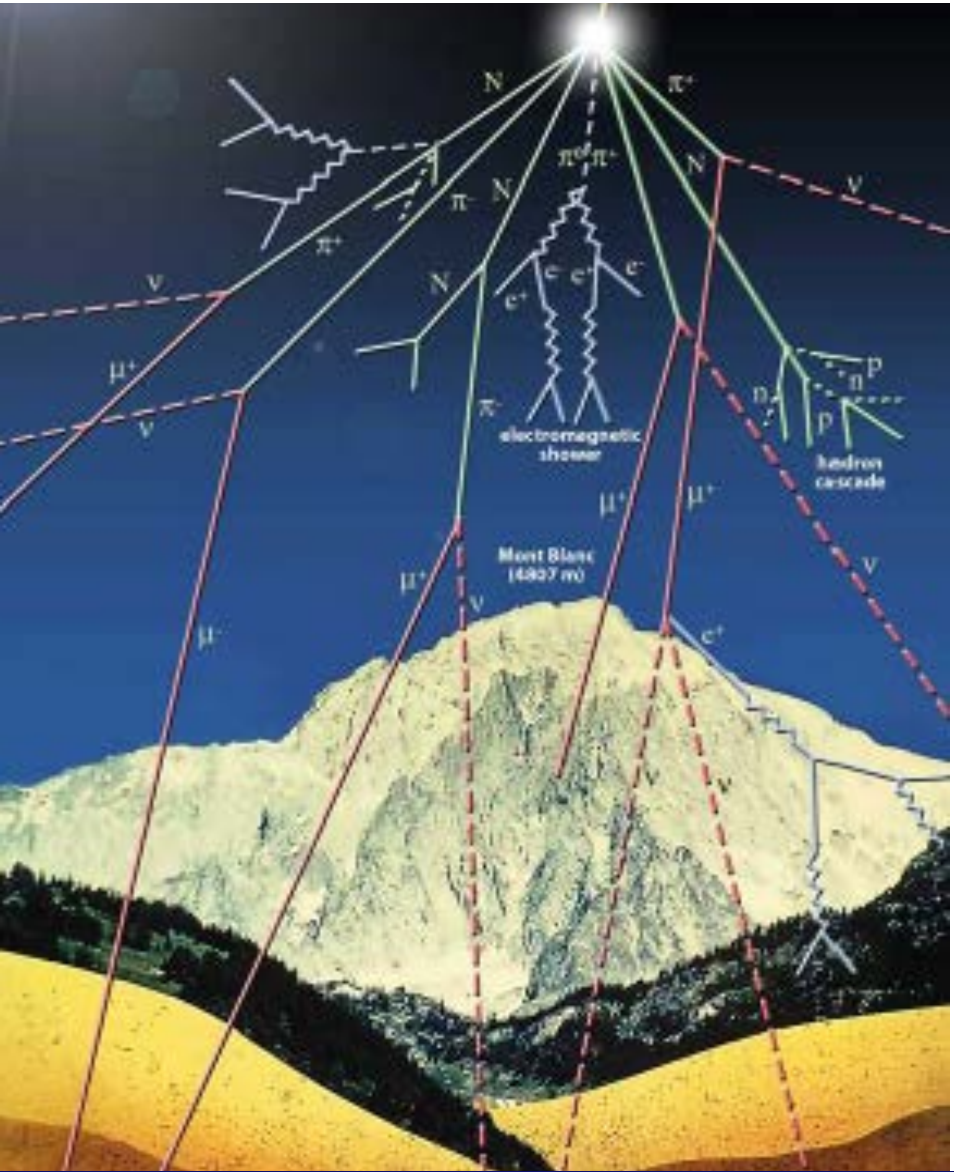
EXTRAPOLATION ← → DATA

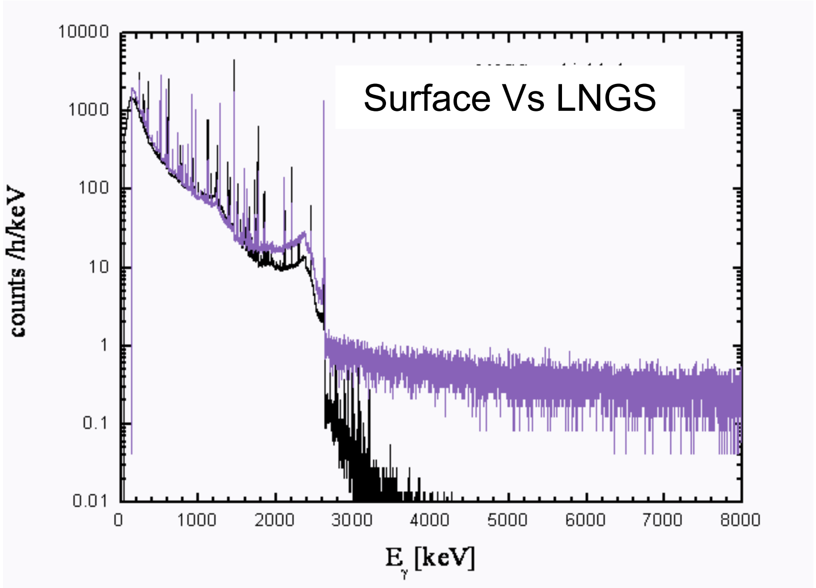
Gran Sasso National Laboratories

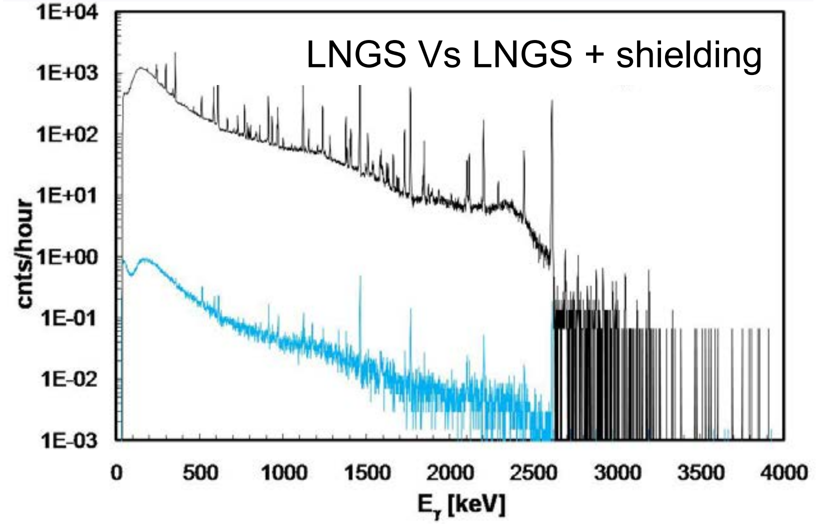
Background reduction with respect to Earth's surface:
$\mu \sim 10^{-6}$
$\gamma \sim 10^{-2}$-10^{-5}
neutrons $\sim 10^{-3}$



Background @ Gran Sasso



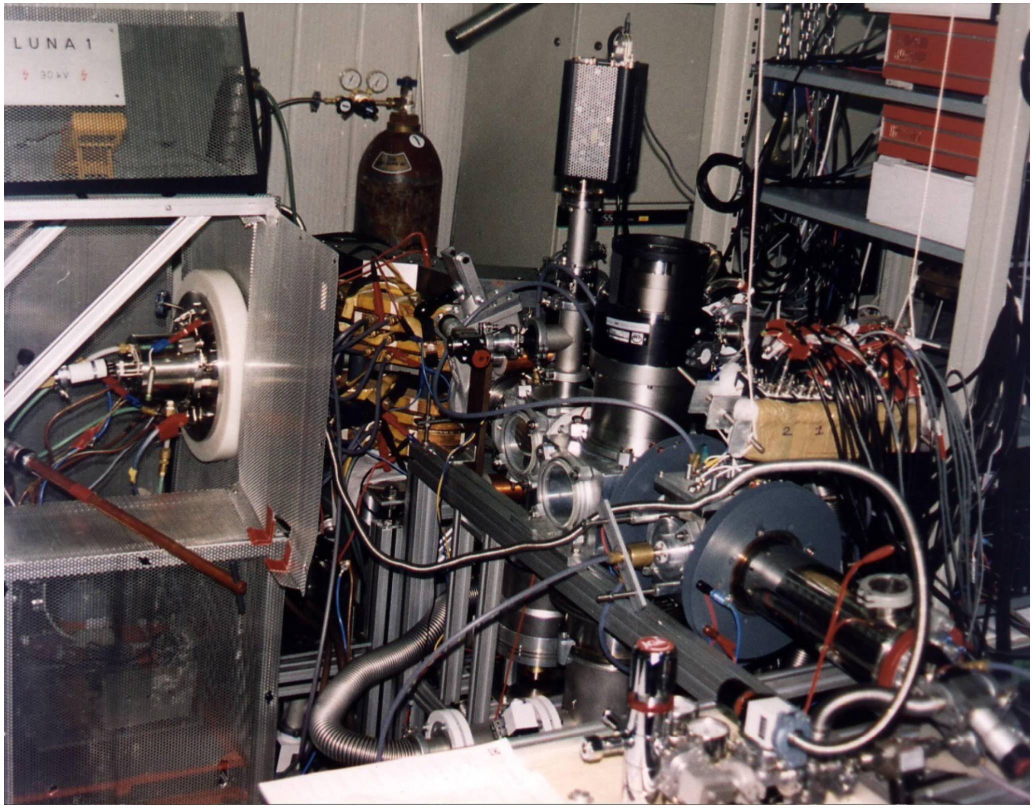




Passive shielding is more effective underground since the μ flux, that create secondary γs, is suppressed.

LUNA 50 kV

1991: Birth of underground Nuclear Astrophysics.
Thanks to E. Bellotti, C. Rolfs and G. Fiorentini

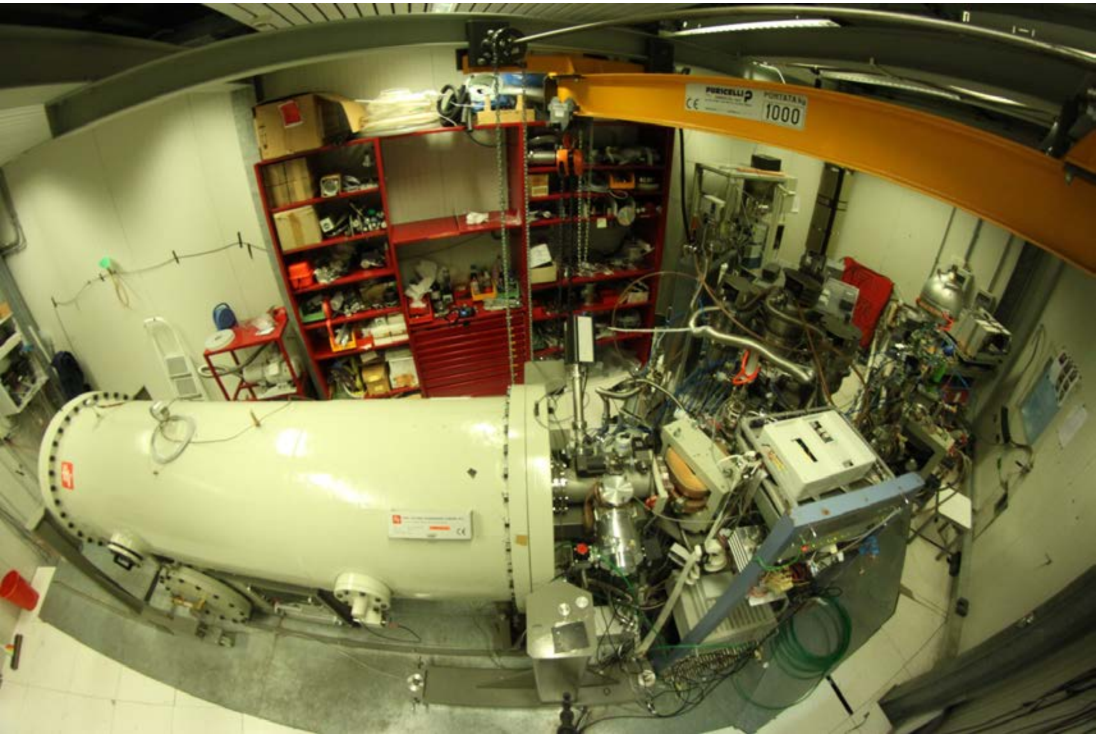


$^3He(^3He,2p)^4He$ (solar ν)
$^2H(p,\gamma)^3He$ (BBN)

$E_{beam} \approx 1 - 50$ keV
$I_{max} \approx 500\ \mu A$ protons, ^3He
Energy spread ≈ 20 eV

LUNA 400 kV

Still the word's only operating underground accelerator

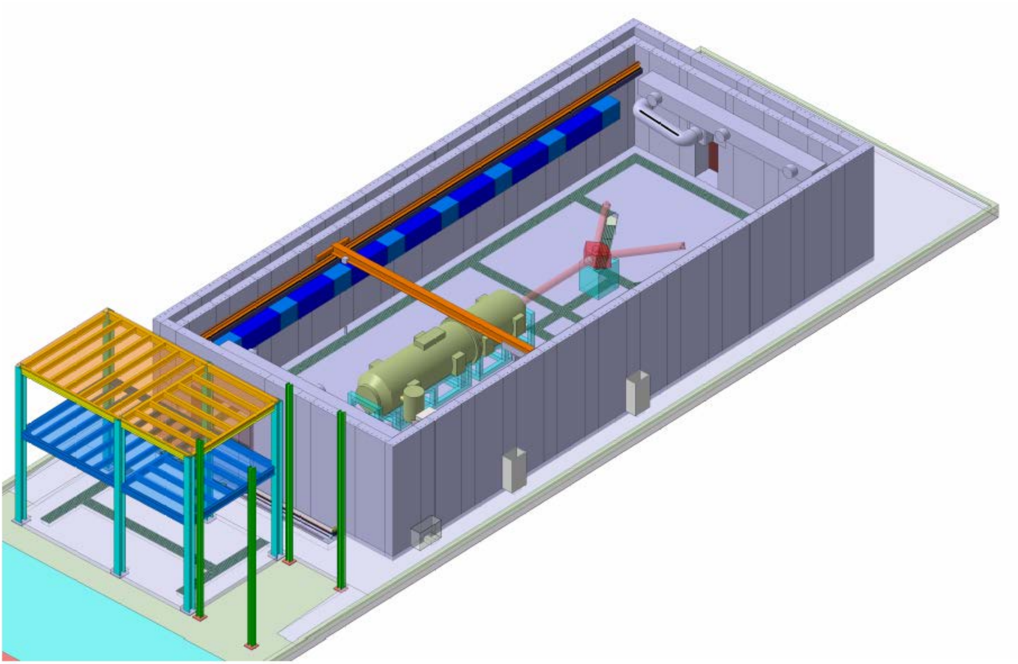


- $^{14}N(p,\gamma)^{15}O$ (CNO-I cycle)
- $^{3}He(^{4}He,\gamma)^{7}Be$ (Sun, BBN)
- $^{25}Mg(p,\gamma)^{26}Al$ (Mg-Al Cycle)
- $^{15}N(p,\gamma)^{16}O$ (CNO-II Cycle)
- $^{17}O(p,\gamma)^{18}F$ (CNO-III Cycle)
- $^{2}H(^{4}He,\gamma)^{6}Li$ (BBN)
- $^{22}Ne(p,\gamma)^{23}Na$ (Ne-Na Cycle)
- $^{2}H(p,\gamma)^{3}He$ (BBN)
- $^{13}C(\alpha,n)^{16}O$ (s-process)
- $^{12,13}C(p,\gamma)^{13,14}N$ ($^{12}C/^{13}C$ ratio)
- $^{22}Ne(\alpha,\gamma)^{23}Na$ (s-process)
-
-

$E_{beam} \approx 50 – 400$ keV
$I_{max} \approx 300\ \mu A$ protons, ^{4}He
Energy spread ≈ 70 eV

Next: LUNA MV

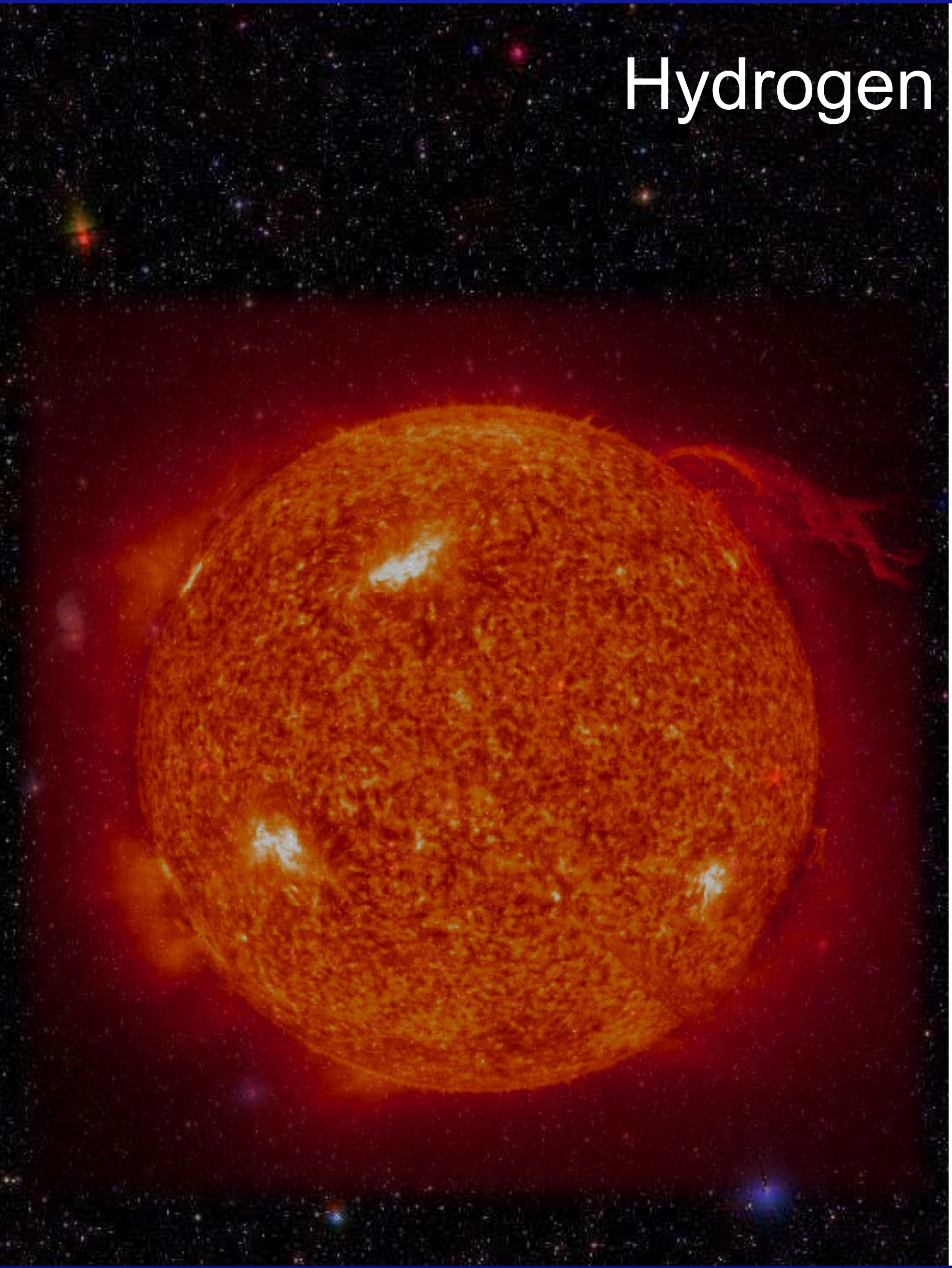
Funded by the Italian Research Ministry as a “premium project”.
First run scheduled in june 2019.



Starting program:

$^{14}N(p,\gamma)^{15}O$	(CNO I Cycle)
$^{12}C+^{12}C$	(Carbon burning)
$^{13}C(\alpha,n)^{16}O$	(s-process)
$^{22}Ne(\alpha,n)^{25}Mg$	(s-process)

Terminal Voltage ≈ 0.2 – 3.5 MV
$I_{max} \approx$ 100-1000 μA protons, ^{4}He, $^{12}C^{+}$, $^{12}C^{++}$



Hydrogen Burning

Many rections regulating the Hydrogen burning in stars have been studied by LUNA:

- pp-chain,
- CNO cycles
- Ne-Na cycle
- Mg-Al cicle

..With outstanding results related to:

-Mixing parameters of solar neutrinos
-Stellar evolution
-Age of Universe
-Isotopic abundances.
-Temperature and metallicity of Sun
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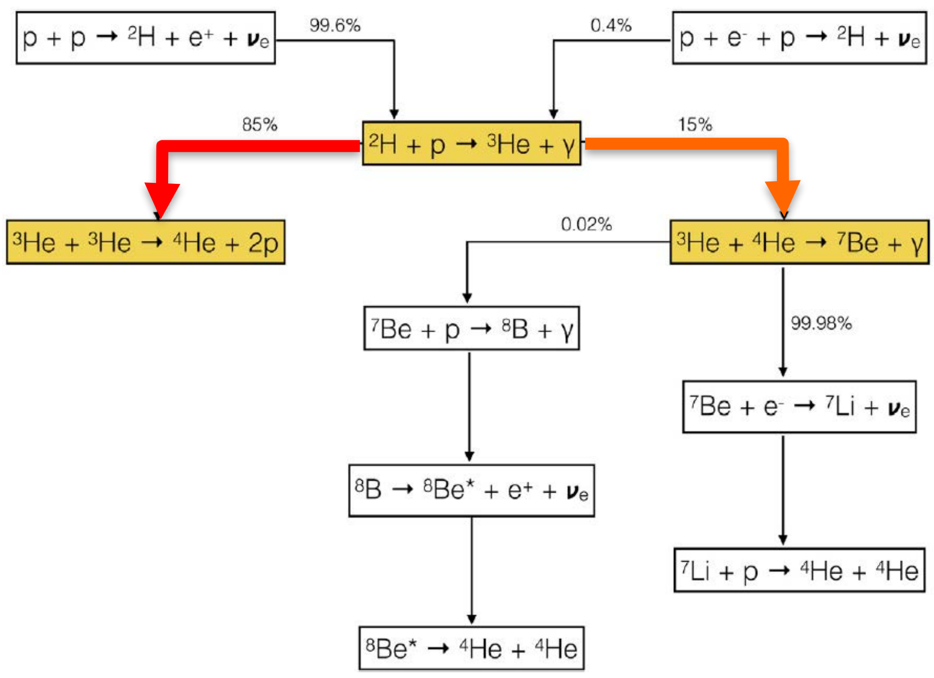
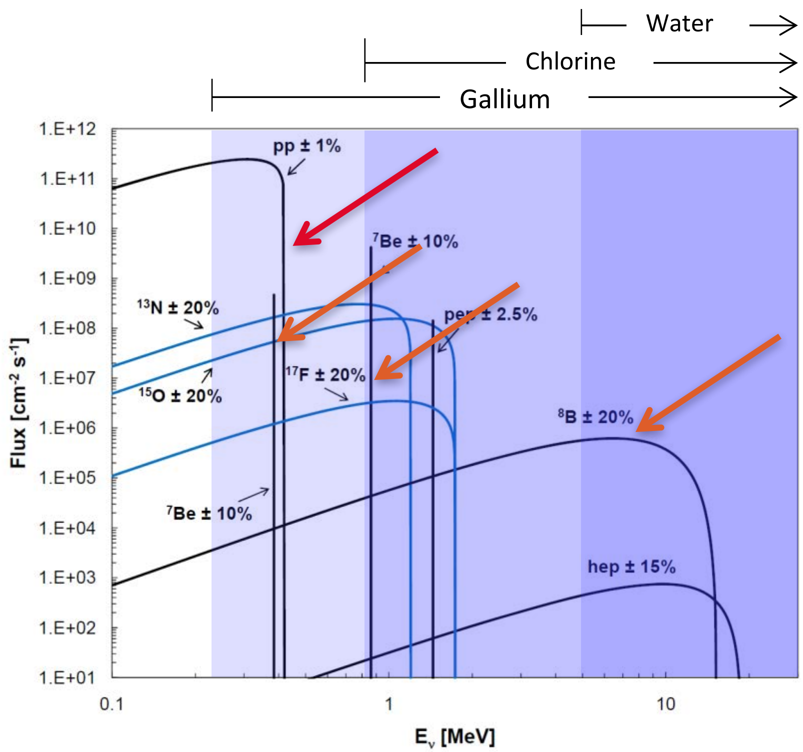
Solar Neutrinos

In the Sun, 98% of neutrinos are produced by the p-p chain.

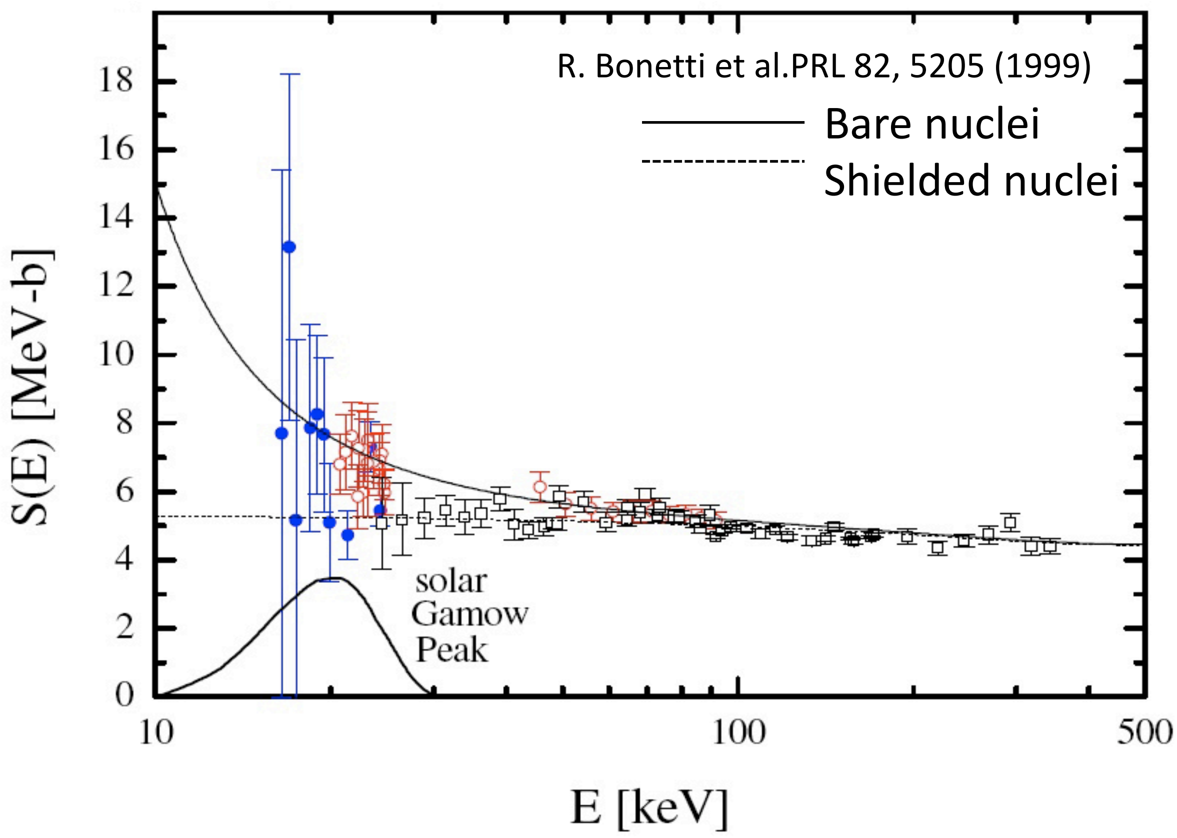


p-p chain



Following the Fowler idea, a natural way to explain the observed neutrino deficit was the existence of a narrow resonance inside the ^{3}He+^{3}He solar gamow peak

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



-First measurement below the Gamow peak
-2 events/month @ E_{cm}=16,5 keV→s(16,5 keV)=20±10 fb
-No evidence for a narrow resonance → SSM validation
-LUNA measurement "triggered" the second generation of solar neutrino experiment (Borexino, Kamland, SNO), focused on the measurement of v's mixing parameters

Hydrogen burning cycles

Sun: ~15 MK
Massive Stars: ~ 100 MK
AGB:~30-100 MK
Novae~100-400 MK
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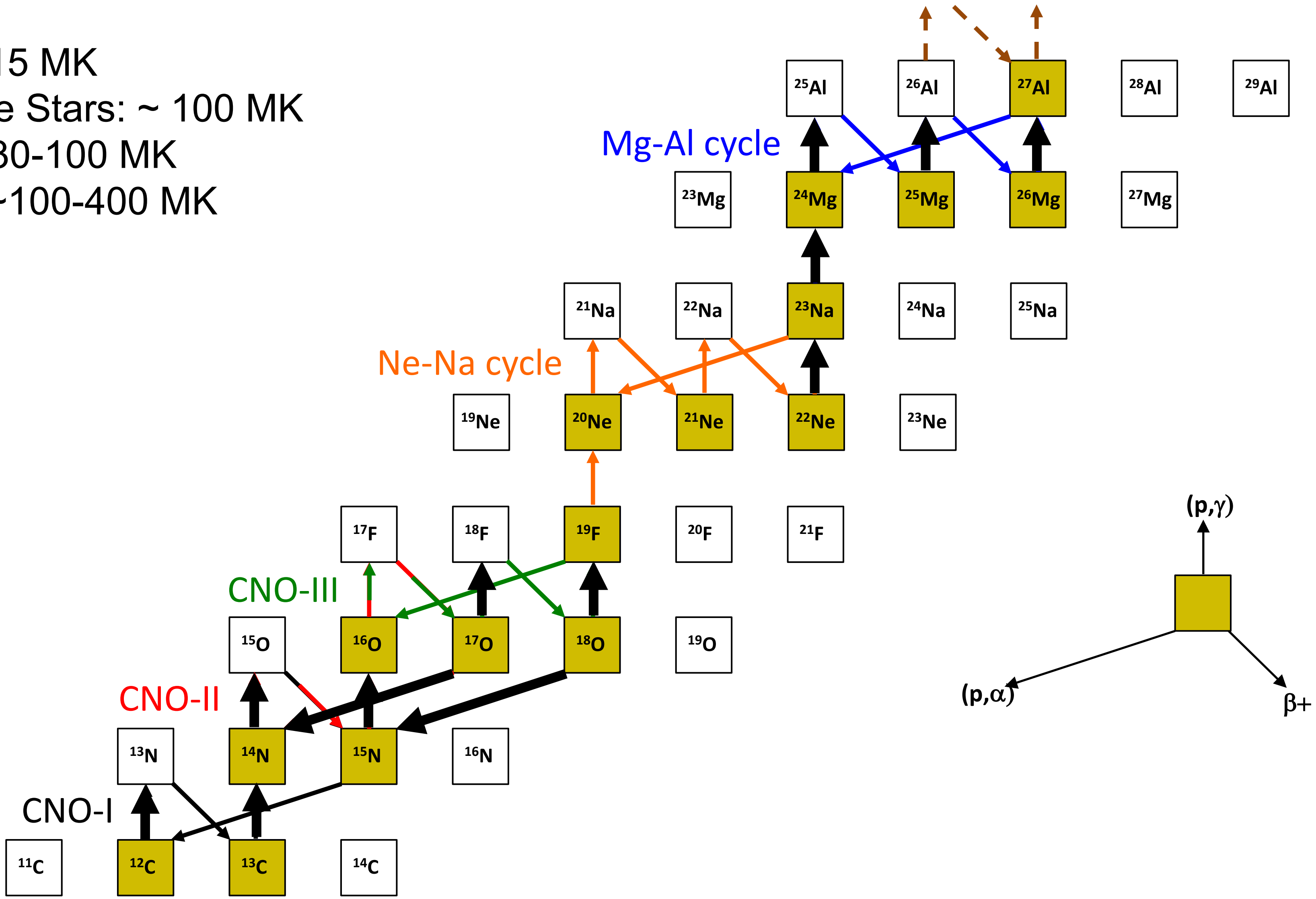
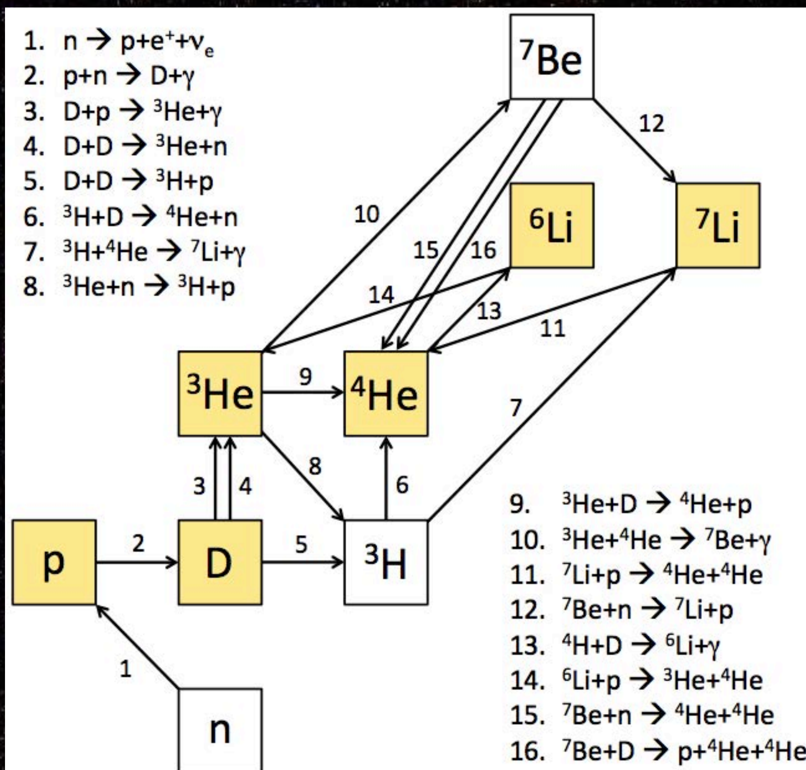


Big Bang Nucleosynthesis

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



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

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

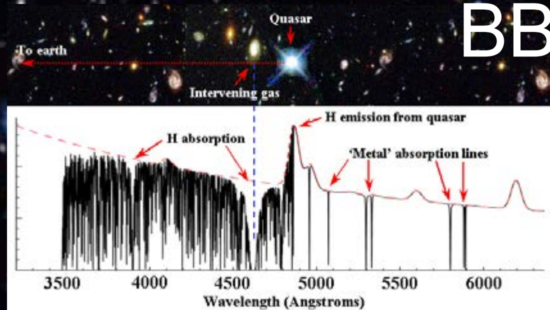
Calculation of primordial abundances only depends on:

-Baryon density Ω_b

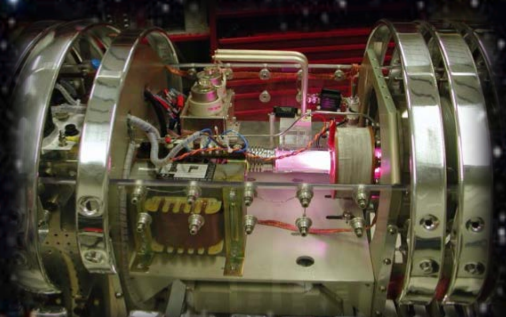
-Particle Physics (N_{eff}, α..)

-Nuclear Astrohysics, i.e. Cross sections of relevant processes at BBN energies

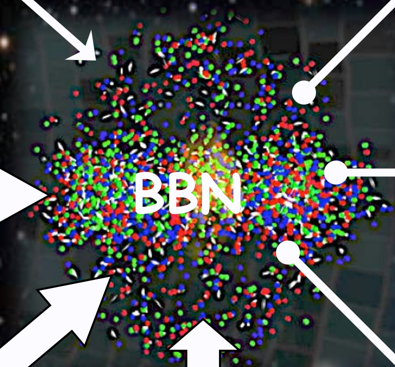
BBN "Flowchart"

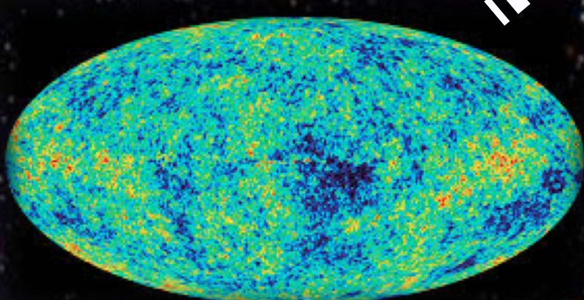


Direct observations of light isotopes

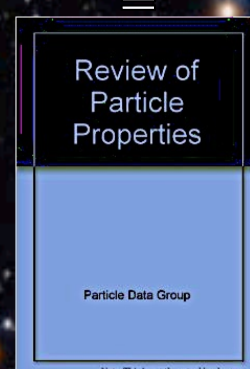


Nuclear Astrophysics





CMB



PDG "stuff"

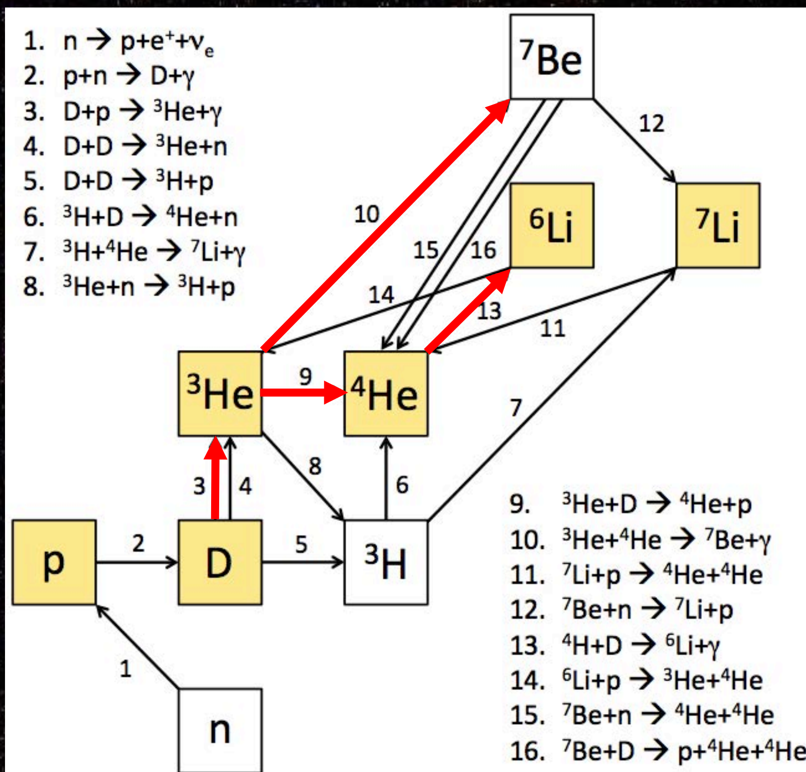
τ_n, G, N_{eff}, α...

Cosmology

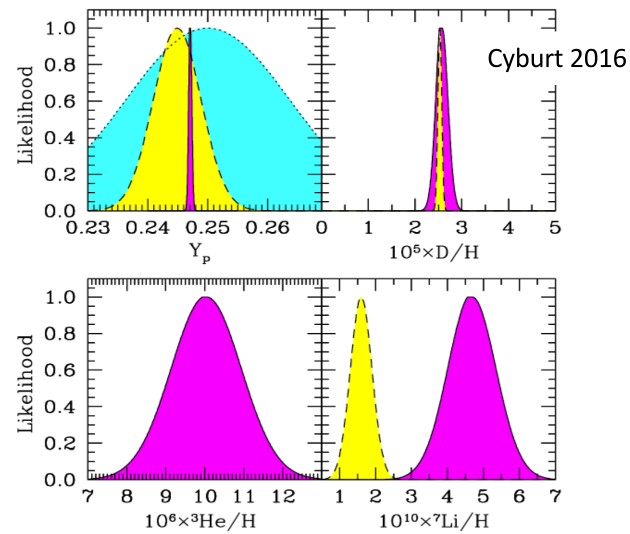
AstroPhysics

New Physics?

Theory Vs observations



Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
$^3He/H$	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
$^7Li/H$	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
$^6Li/^7Li$	$(1.5\pm0.3)\times10^{-5}$	$<\sim10^{-2}$



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

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

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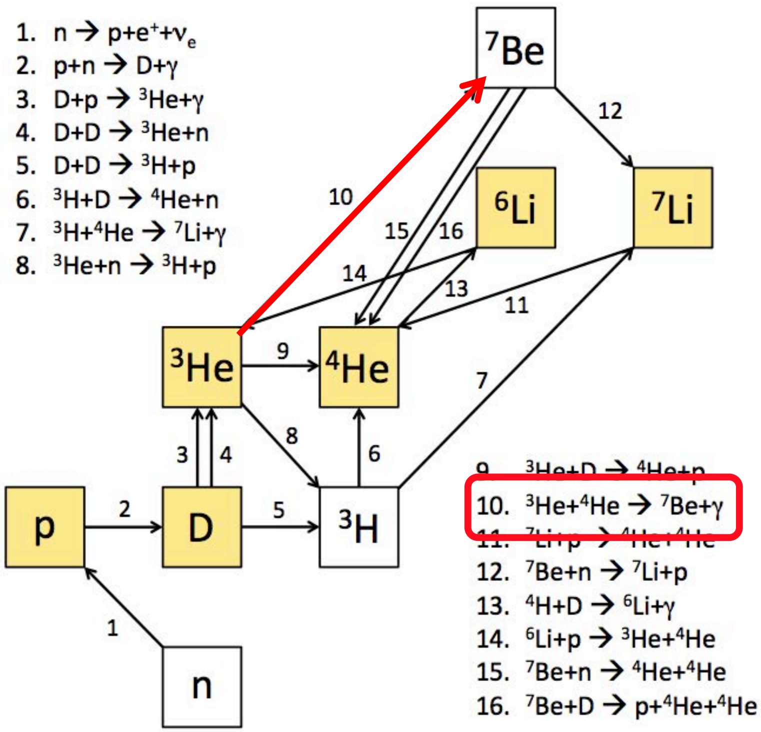
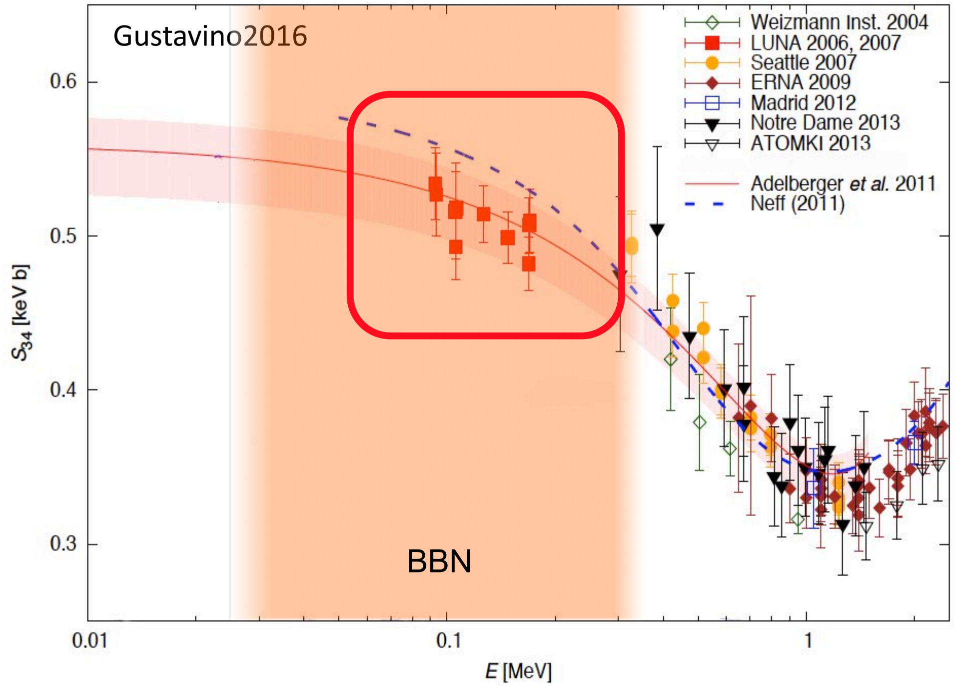


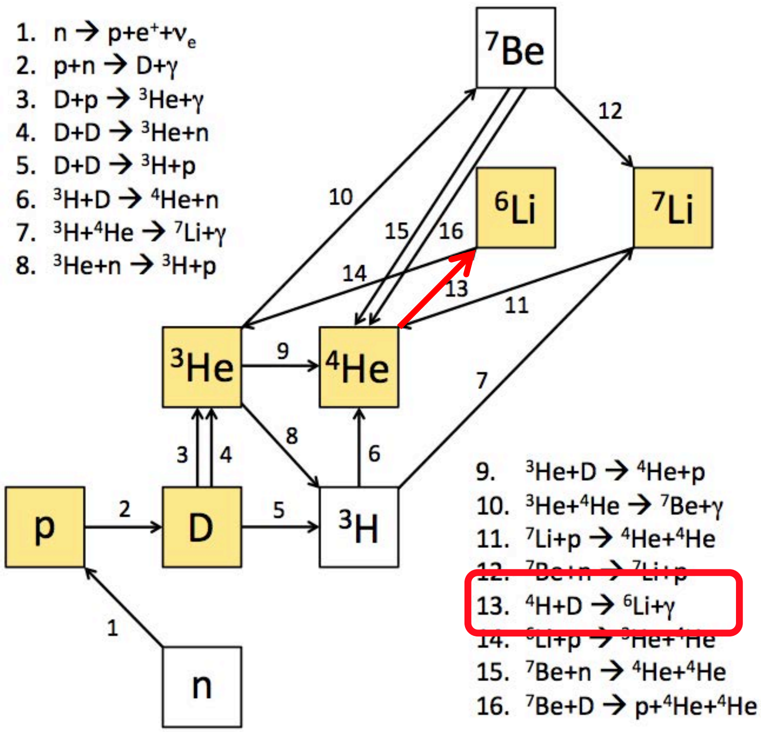


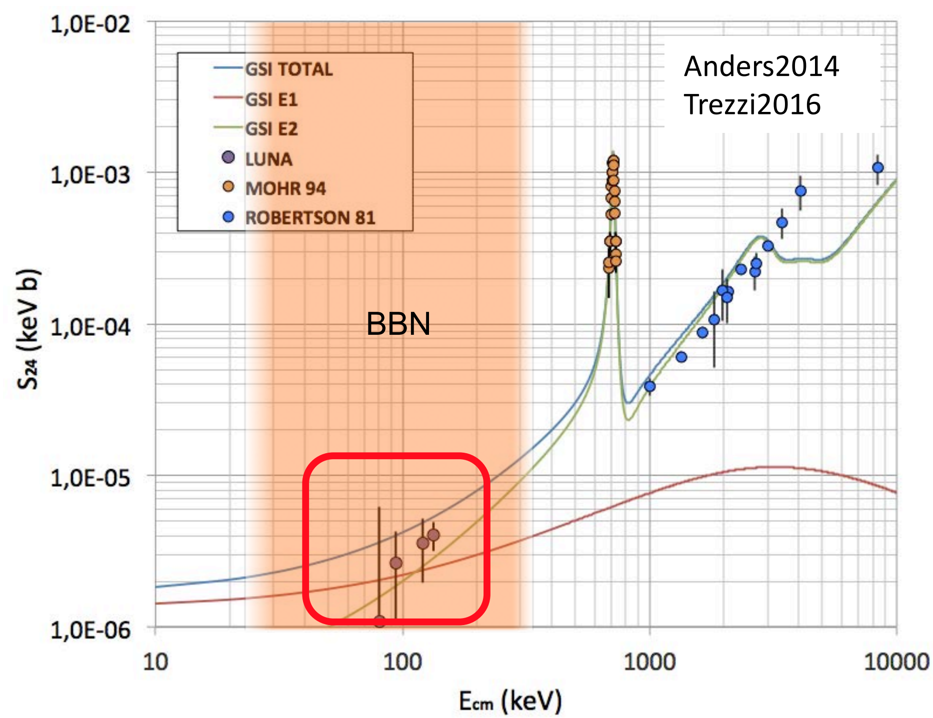
- LUNA data well inside the BBN energy region
- Low uncertainty (4%)
- Simultaneous measurement of prompt and delayed γs

→ Consolidation of "Lithium Problem"

D(α,γ)^{6}Li reaction

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
^{3}He/H	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
^{7}Li/H	$(4.68\pm0.67)\times10^{-10}$	$(1.23^{+0.68}_{-0.32})\times10^{-10}$
^{6}Li/^{7}Li	$(1.5\pm0.3)\times10^{-5}$	<~10^{-2}





First direct measurement in the BBN energy region

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

D(p,γ)^{3}He reaction

Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
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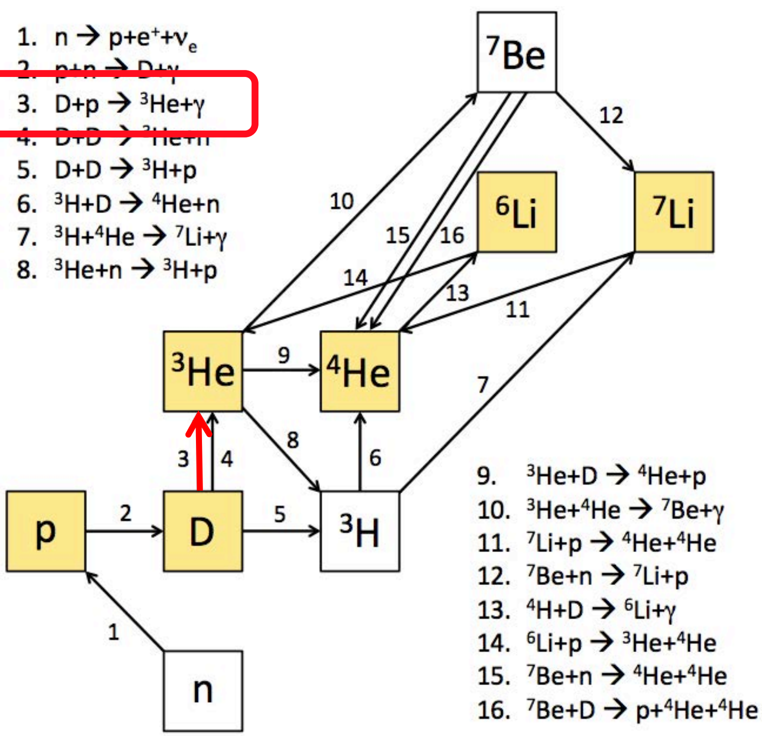
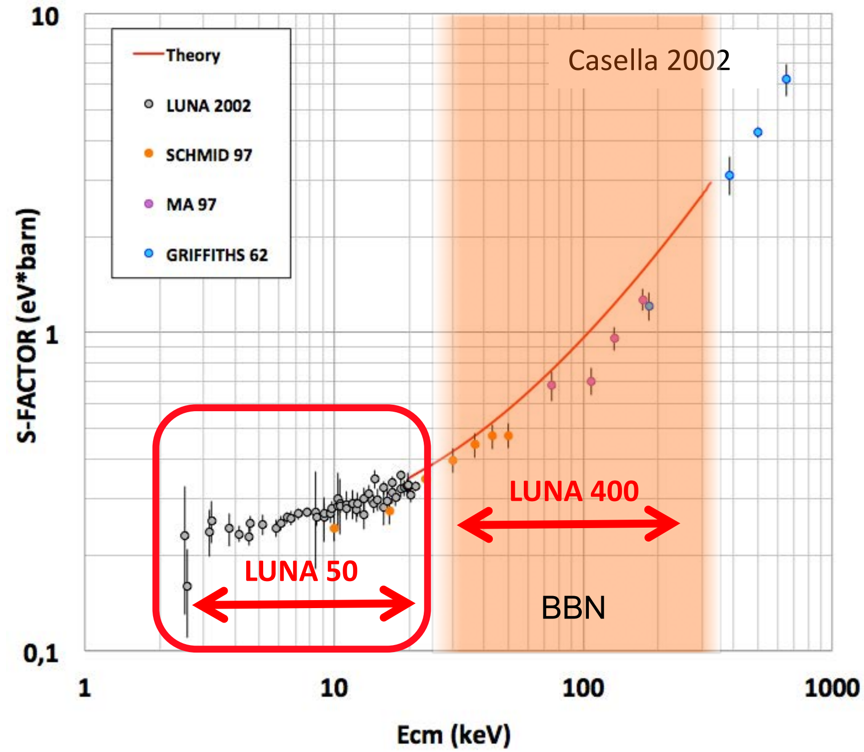




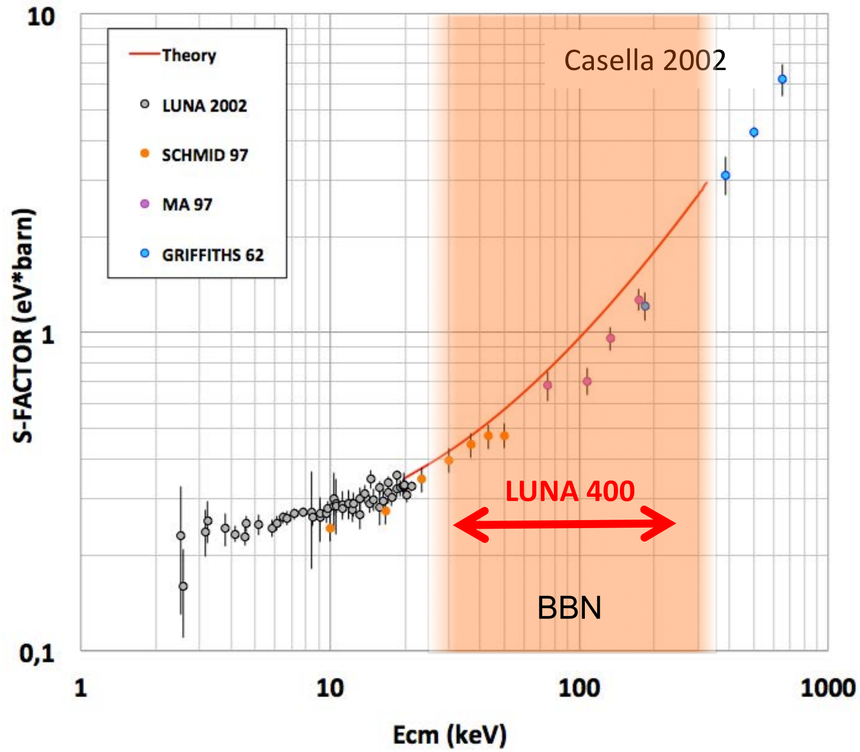
Reduction of $(D/H)_{BBN}$ error of a factor 3 with LUNA 50 kV

D(p,γ)³He reaction @ LUNA400

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

(Di Valentino, C.G. et al. 2014)

-The error budget of computed abundance of deuterium is mainly due to the D(p,γ)³He reaction
-measurements (9% error) NOT in agreement with recent "Ab-Initio" calculations.



Measurement goal:

-Cross section measurement at $30<E_{cm}(keV)<260$ 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.

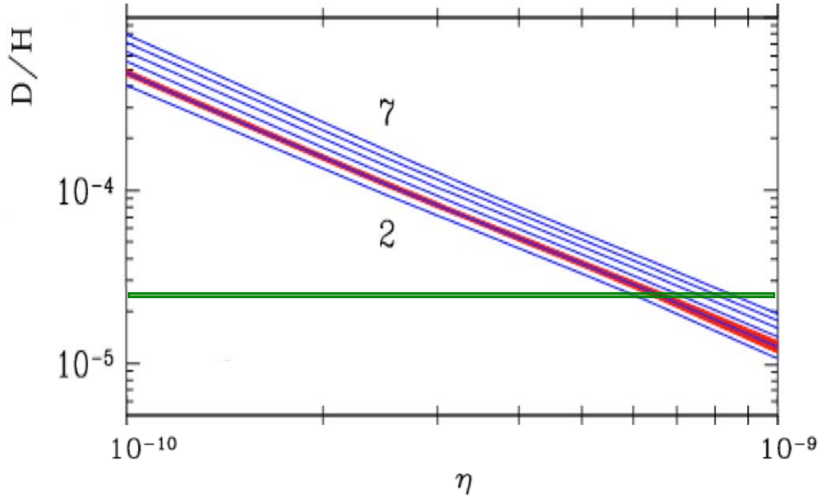
$D(p,\gamma)^3He$ reaction: Ω_b and N_{eff}

-BBN provides a precise estimate of Baryon density Ω_b , through the comparison of $(D/H)_{BBN}$ and $(D/H)_{obs}$:

Dpγ data fit

$100\Omega_{b,0}h^2(BBN)=2.20\pm0.04\pm0.02$ (Cooke2013)
$100\Omega_{b,0}h^2(BBN)=2.16\pm0.01\pm0.02$ (Cooke2016)

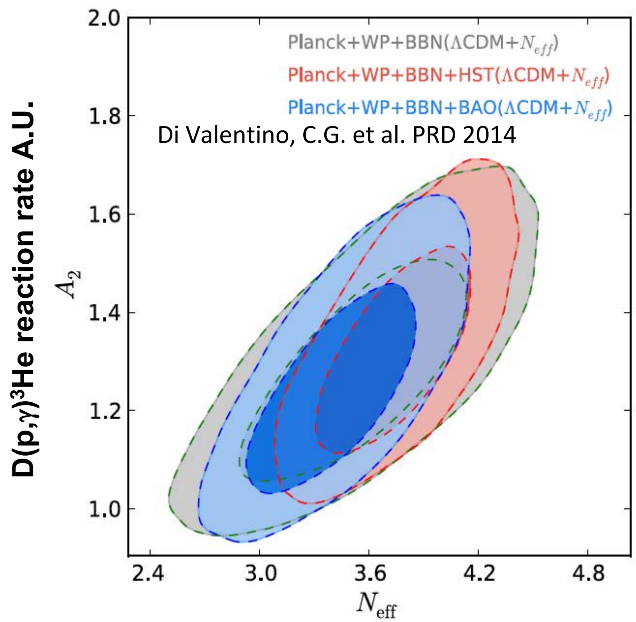
Dpγ "ab-initio"
D/H observations



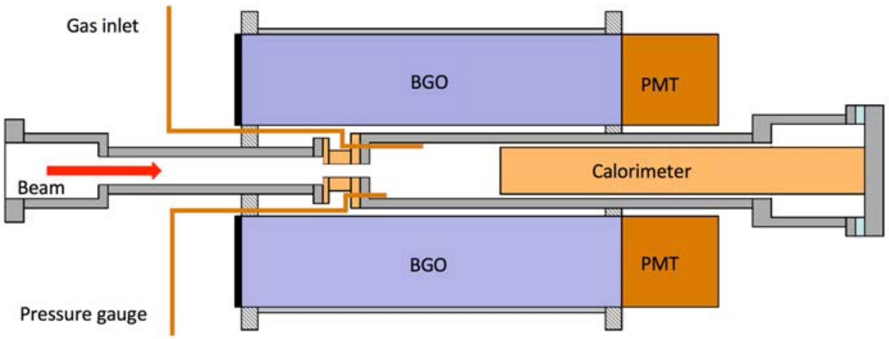
From CMB data:
$100\Omega_{b,0}h^2(CMB)=2.22\pm0.02$ (PLANCK2015)

-Deuterium abundance also 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 $D(p,g)^3He$ reaction:

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

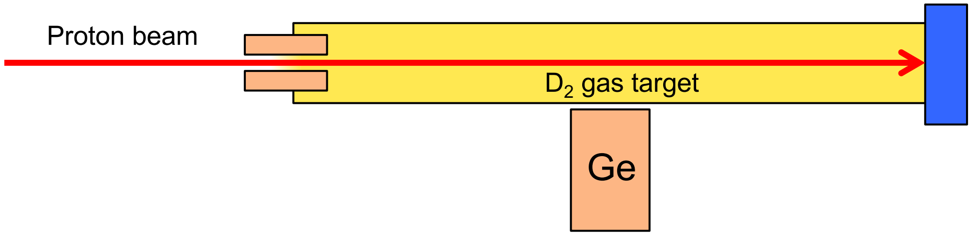


D(p,γ)^{3}He reaction: setup



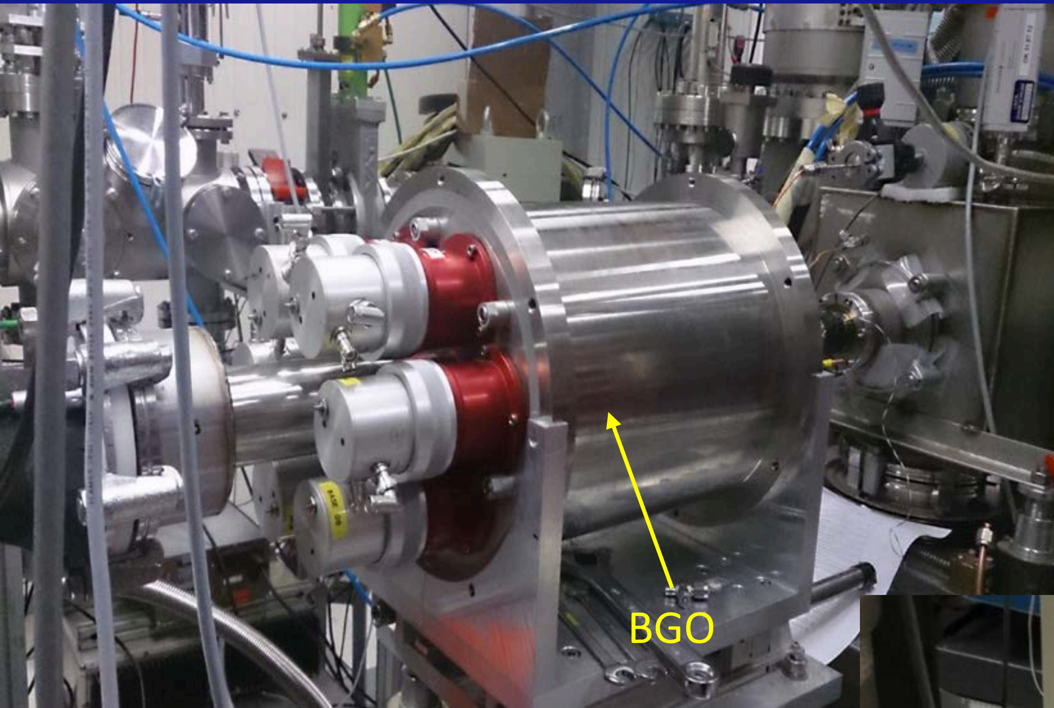
High efficiency (~60%, ~4π acceptance)

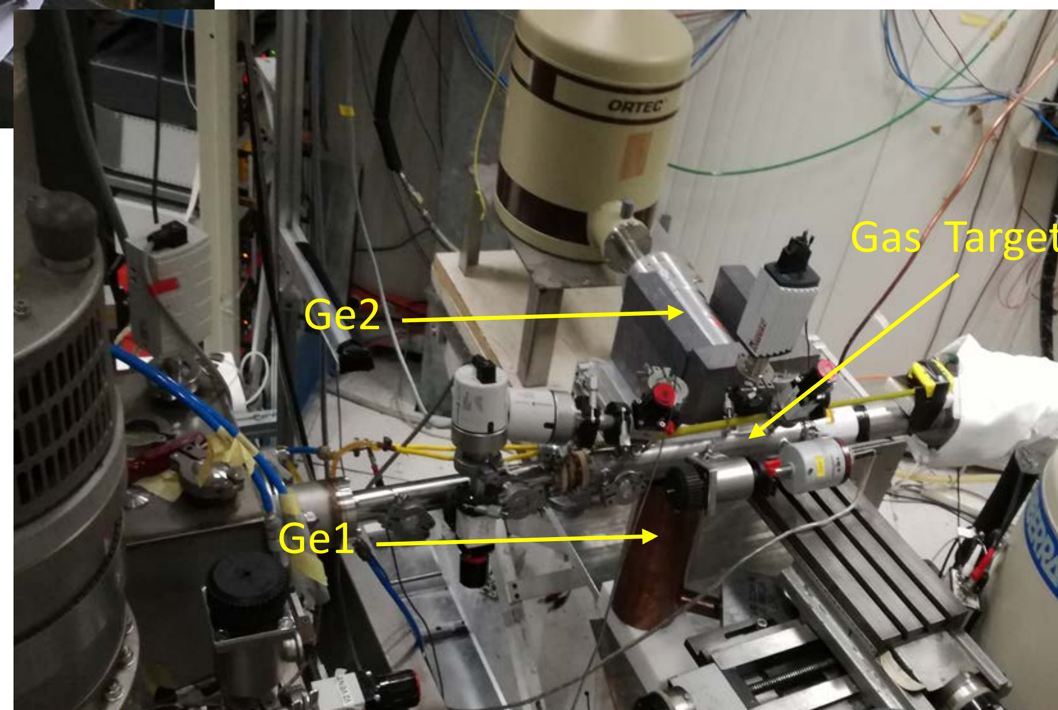
BGO detector



High energy resolution (~10 keV @ 6 MeV)

Ge(Li) detector


BGO

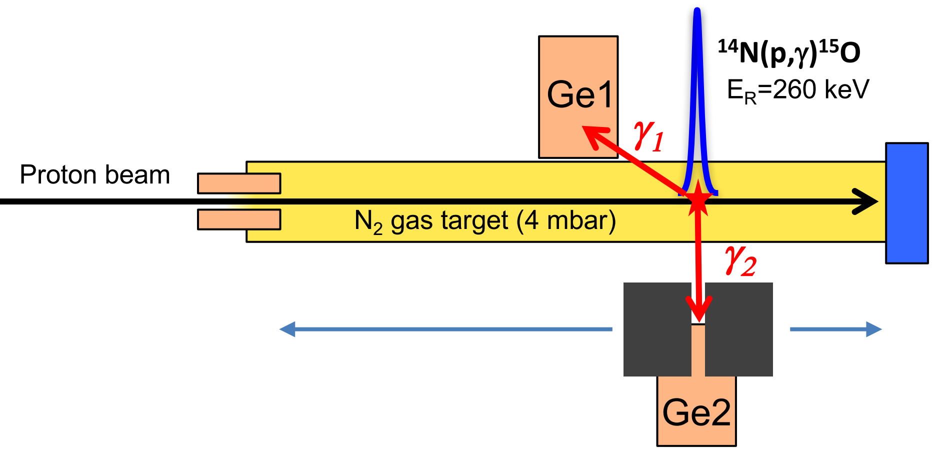

ORTEC
Gas Target
Ge2
Ge1

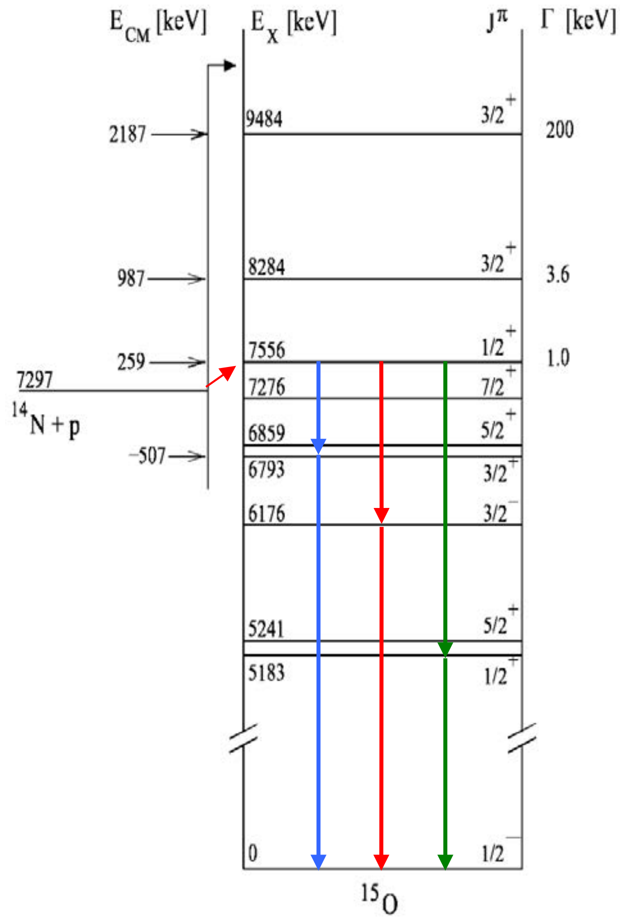
Systematics: efficiency

HPGe Source	Method
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,\gamma)^{15}O$ reaction
ANGULAR DISTRIBUTION	Pulse Shape Analysis
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement
BEAM CURRENT	Calibration with Faraday Cup

Calibration exploiting the reaction:

$^{14}N+p \rightarrow {}^{15}O+\gamma_1+\gamma_2$





Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1

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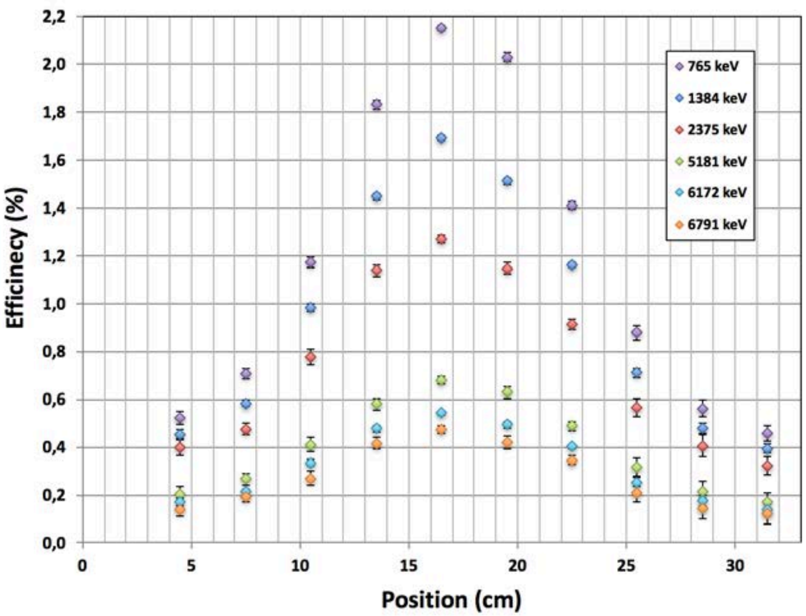

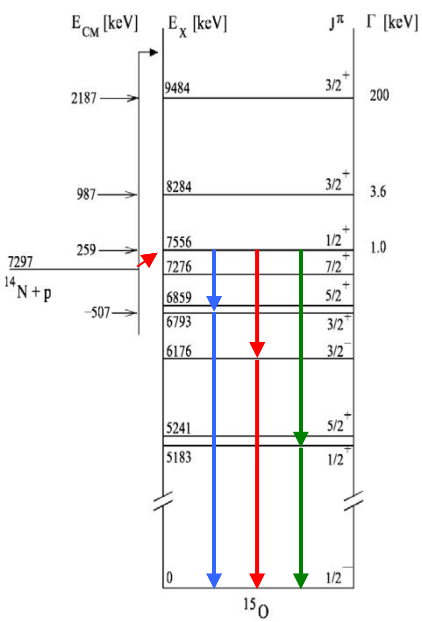

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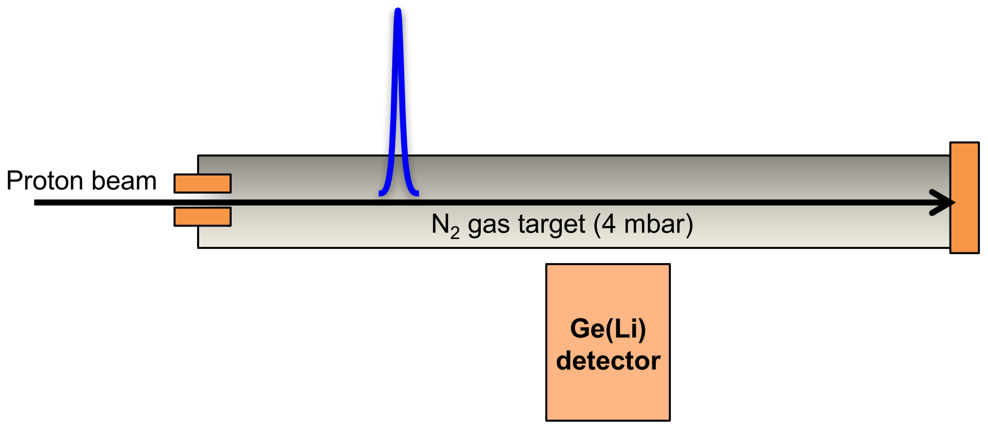

Systematics: efficiency

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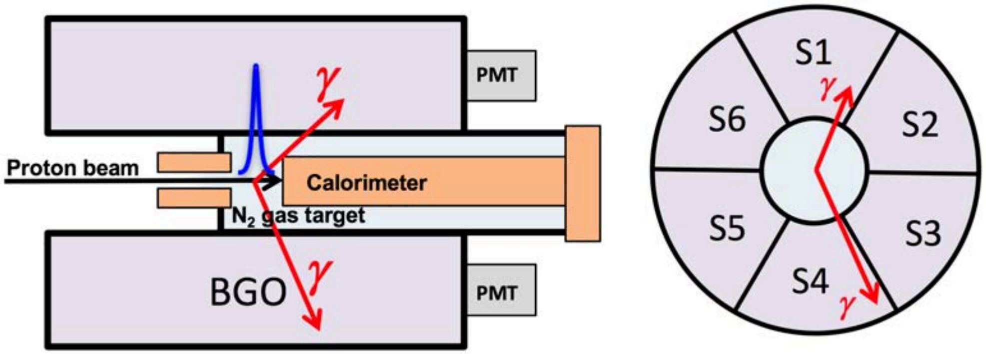
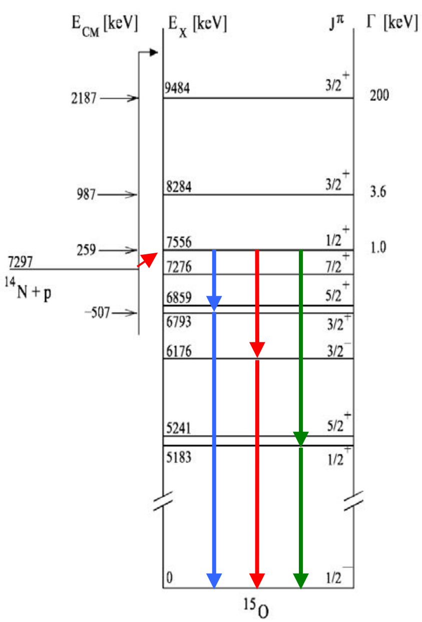
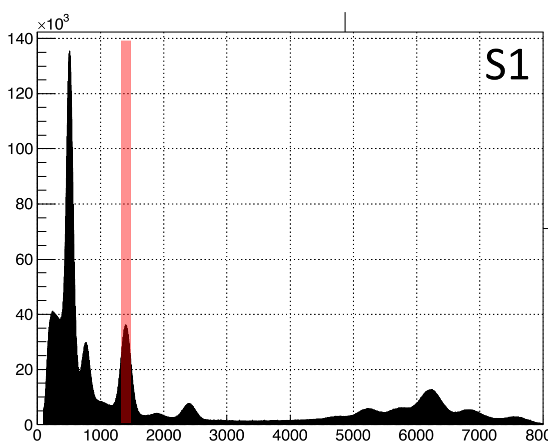
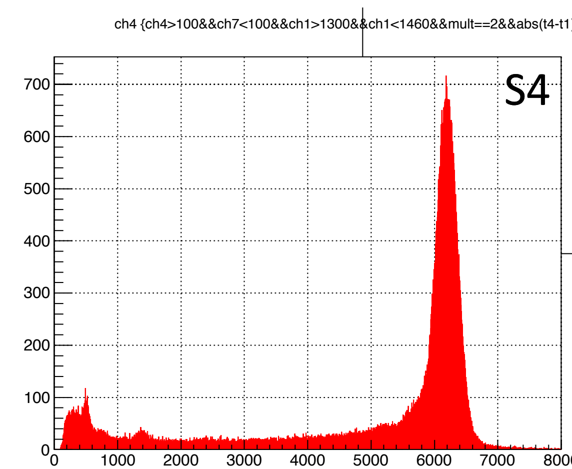




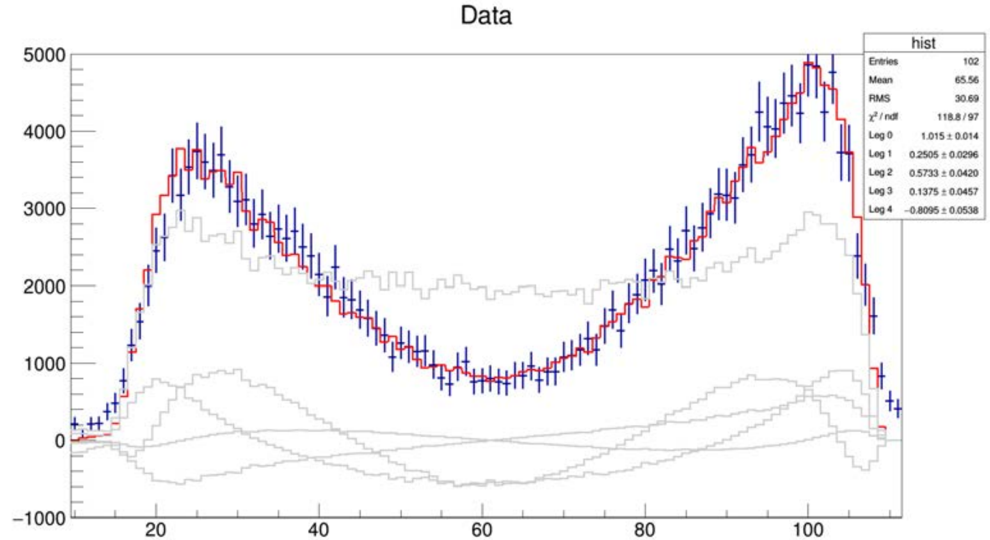
Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1





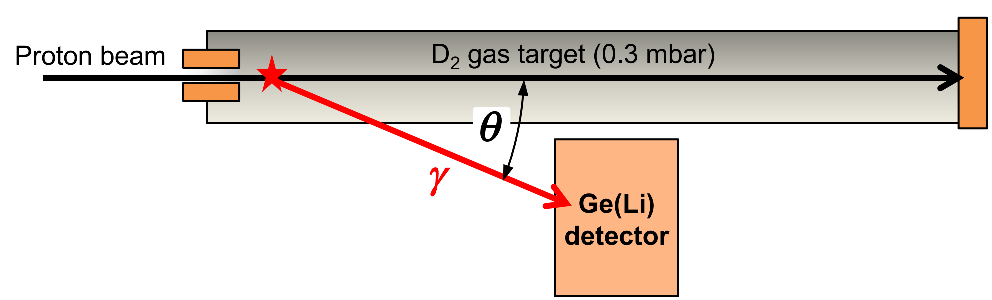
Systematics: angular distribution

HPGe Source	Method
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,g)^{15}O$ reaction
ANGULAR DISTRIBUTION	Pulse Shape Analysis
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement
BEAM CURRENT	Calibration with Faraday Cup



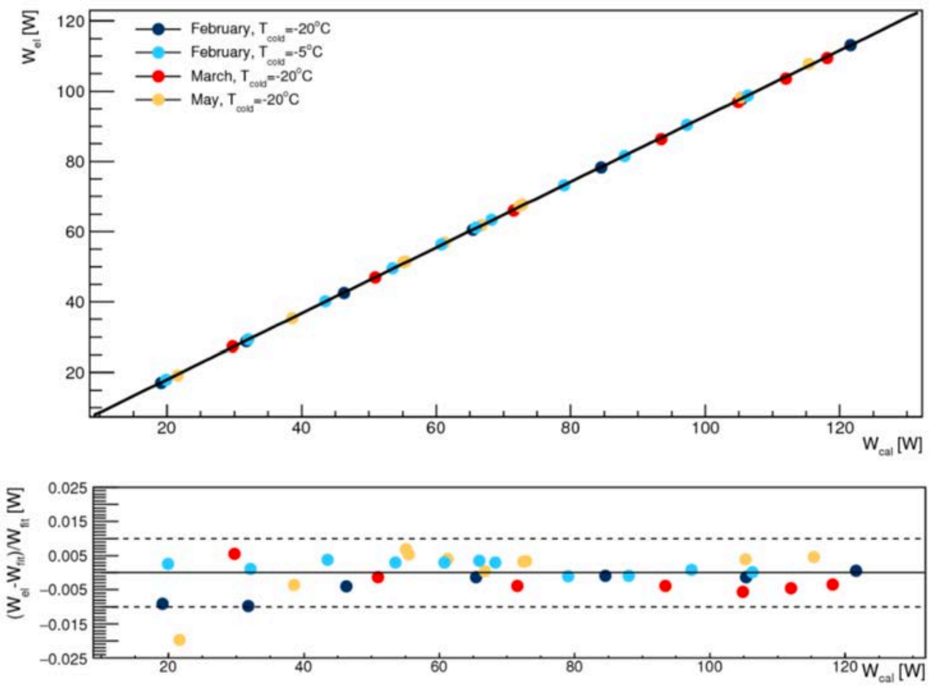
$$E_\gamma = \frac{m_p^2 + m_d^2 - m_{He}^2 + 2E_p m_d}{2(E_p + m_d^2 - p_p cos(\theta_{cm}))}$$

E_{beam} (keV)	$E\gamma_{min}$ (keV)	$E\gamma_{max}$ (keV)	ROI (keV)
200	5583	5660	77,4
300	5640	5736	95,9
400	5699	5811	112,1



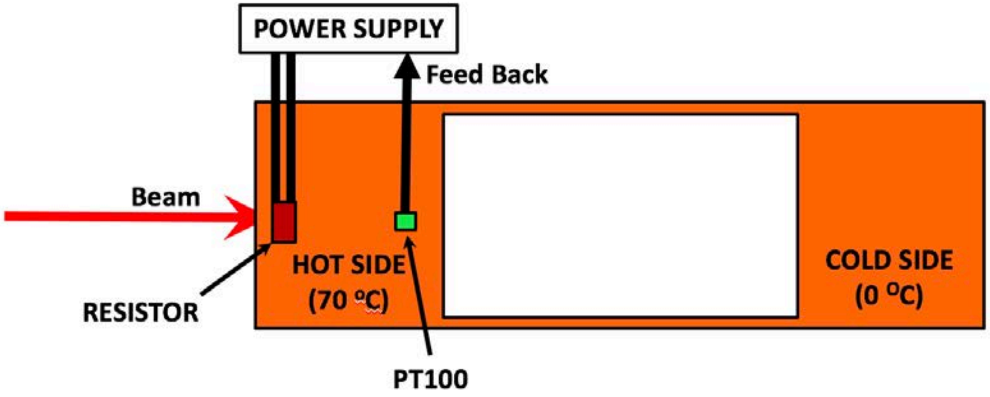
Systematics: beam intensity

HPGe Source	Method
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,g)^{15}O$ reaction
ANGULAR DISTRIBUTION	Pulse Shape Analysis
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement



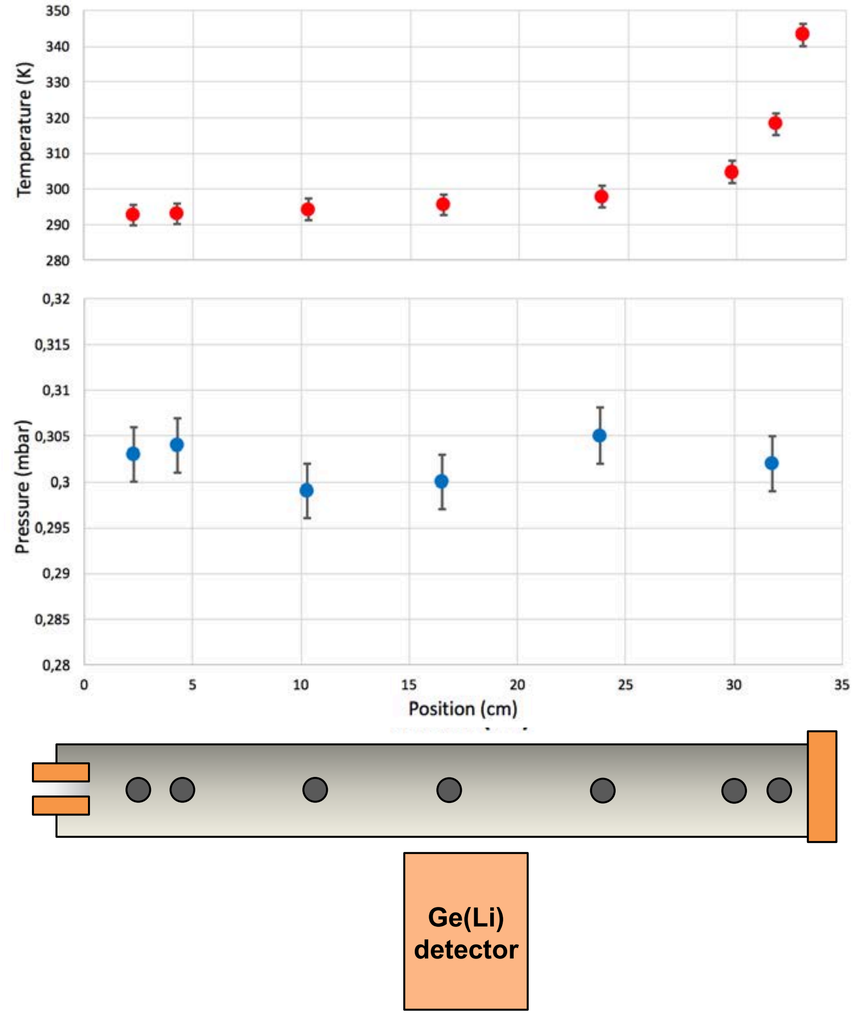
Constant temperature gradient calorimeter

$$I_{beam} = \frac{W_0 - W_{beam}}{E_p/e}$$



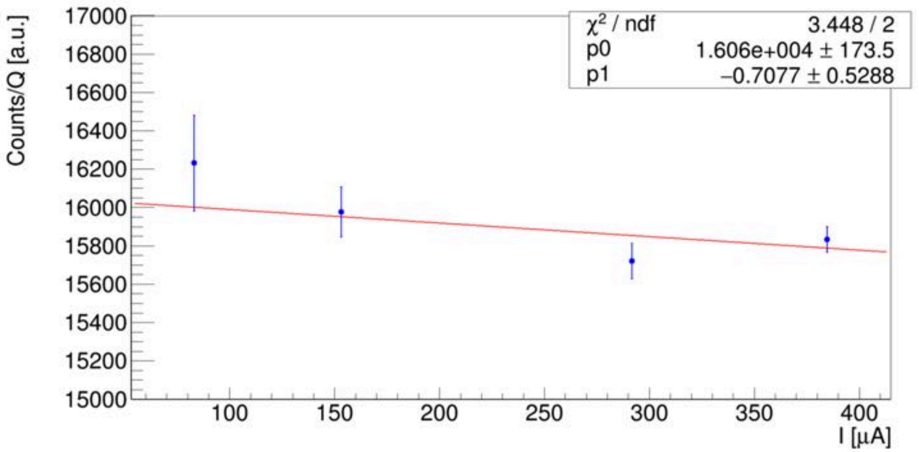
Systematics: Target density

HPGe Source	Method
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,g)^{15}O$ reaction
ANGULAR DISTRIBUTION	Pulse Shape Analysis
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement



Systematics: Target density

HPGe Source	Method
DETECTOR EFFICIENCY	Calibration with $^{14}N(p,g)^{15}O$ reaction
ANGULAR DISTRIBUTION	Pulse Shape Analysis
BEAM CURRENT	Calibration with Faraday cup
TEMPERATURE PROFILE	Direct Measurement
PRESSURE PROFILE	Direct Measurement
BEAM HEATING	Rate Vs Current measurement

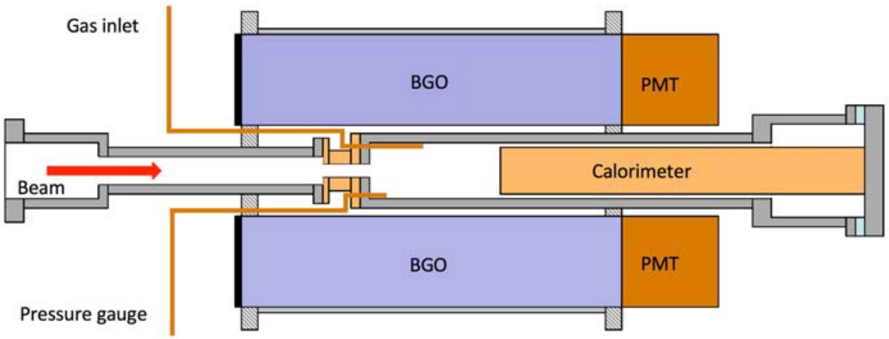


Measurement of the D(p,γ)^{3}He reaction Yield Vs beam current

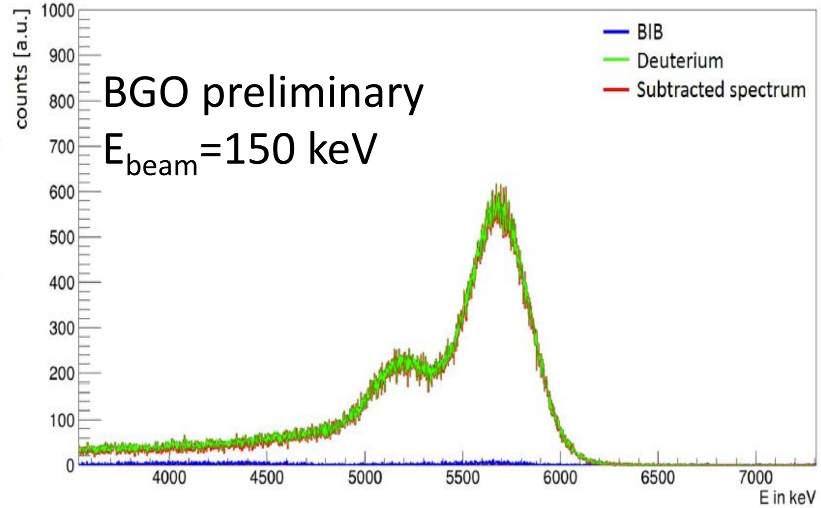
Moreover:

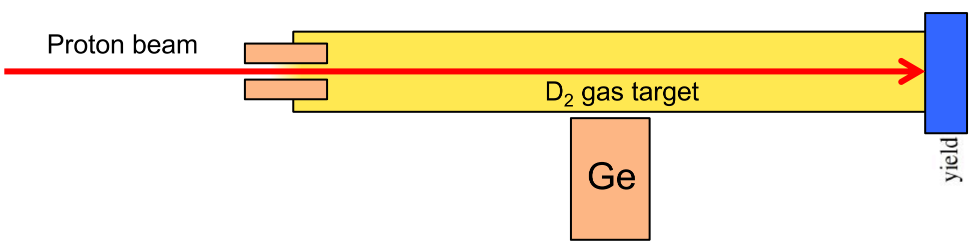
- Beam induced background→Dedicated measurements in vacuum or inert gas target
- Instrumental effects (Dead time, pile-up, etc)→Pulser method
- Energy loss→Ziegler formulae/direct measurements
- Detailed simulation to correct second order effects
-
-

Preliminary results

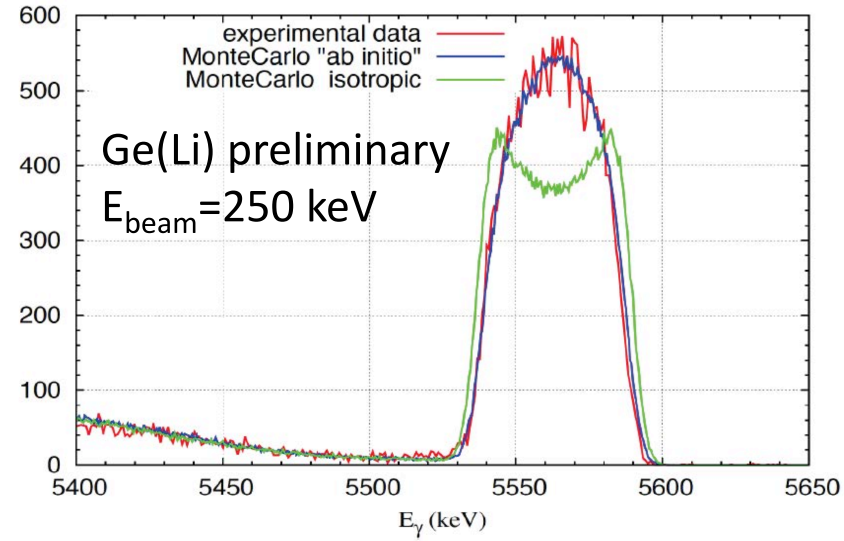


BGO detector





Ge(Li) detector



Conclusions

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

-Cosmic baryon density Ω_b is now known at percent level thanks to the PLANCK mission.

-Primordial abundance of Deuterium is now known at percent level from observations of pristine gas.

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 the determination of these quantities is the poorly known S-factor of the D(p,γ)^{3}He reaction at BBN energies.

Within this scenario, the LUNA measurement is of crucial importance.

Data analysis is in progress, results will come soon.

Thanks for the attention!

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