Study of the D(p,γ)^{3}H reaction at BBN energies with LUNA: implications in cosmology, particle physics and theoretical nuclear physics

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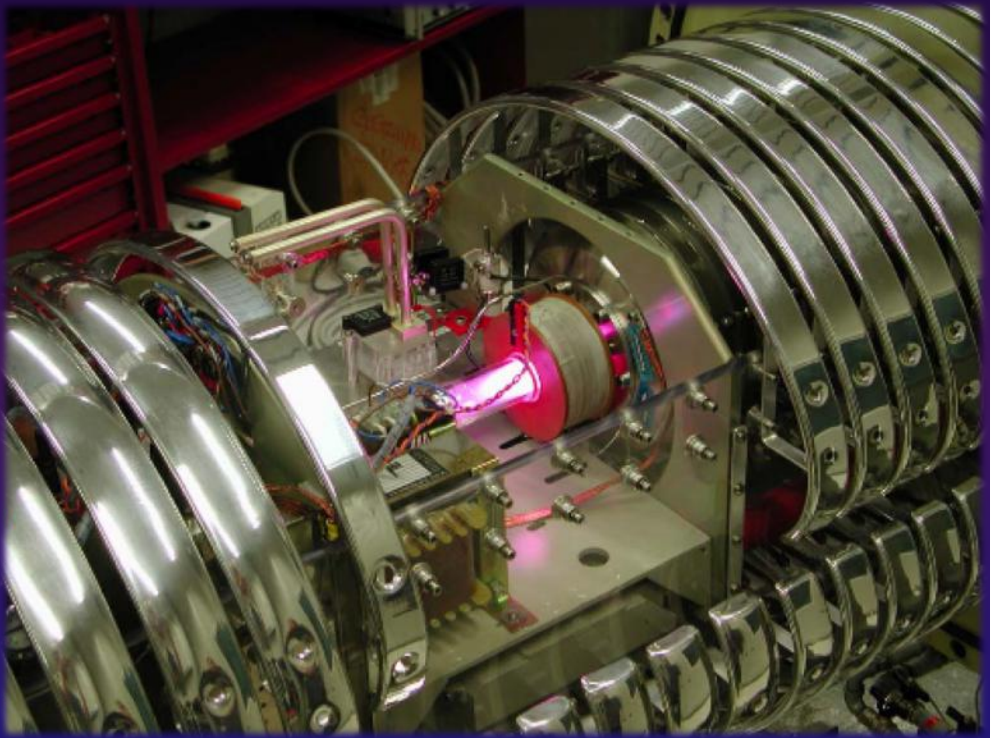
- Introduction
- The D(p,γ)^{3}He reaction at LUNA
- Experimental results
- dσ/dΩ Vs ab-initio calculations
- Baryon and radiation densities of Universe
- Conclusions

59th International Winter Meeting on Nuclear Physics
23-27 Jan 2023 Bormio, Italy

LUNA 400 kV at LNGS



$E_{beam} \approx 50 - 400$ keV

$I_{max} \approx 300\ \mu A$ protons, ^4He

Energy spread ≈ 70 eV

• $^{14}N(p,\gamma)^{15}O$	(Sun,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)
• $^{13}C(\alpha,n)^{16}O$	(s-process)
• $^{12,13}C(p,\gamma)^{13,14}N$	($^{12}C/^{13}C$ ratio)
• $^{22}Ne(\alpha,\gamma)^{23}Na$	(s-process)
• $^{2}H(p,\gamma)^{3}He$	(BBN)

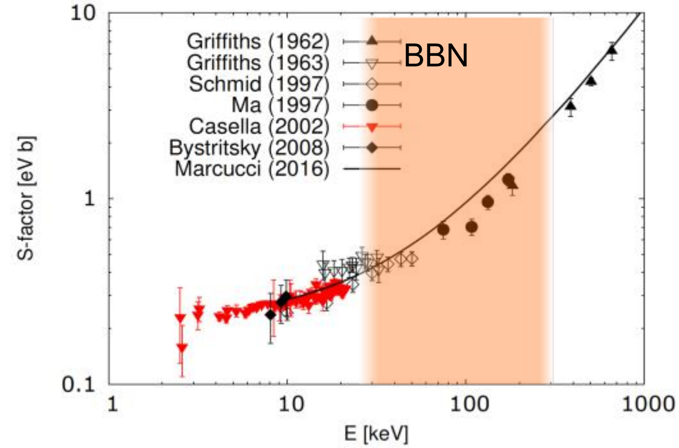
- Mixing parameters of solar neutrinos
- Temperature and metallicity of Sun
- Stellar evolution
- Universal chemical composition
- Age of Universe
- Cosmology
- Particle physics
- Theoretical Nuclear physics

Gran Sasso National Laboratories

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

D(p,γ)^{3}He reaction before LUNA400

- Large systematic error of measurements at BBN energies (~10%)
- Measurements NOT in agreement with "ab-initio" calculations at the 20% level.
- Deuterium abundance error mainly due to the D(p,γ)^{3}He reaction
- $\Delta(D/H)_{BBN} >> \Delta(D/H)_{obs}$



Reaction	$\Delta(D/H)_{BBN}/(D/H)_{BBN}$
$p(n,\gamma)D$	0.08%
$D(p,\gamma)^3He$	$\boxed{2.34\%}$
$D(d,n)^3He$	0.75%
$D(d,p)^3H$	0.49%

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

Measurement goal:

- Cross section measurement at $30<E_{cm}$[keV]<270 with ~ 3% accuracy
- Differential cross section measurement at $50<E_{cm}$[keV]<270

Physics:

- *Cosmology: measurement of Ω_b*
- *Neutrino physics: measurement of N_{eff}*
- *Nuclear physics: comparison of data with "ab initio" predictions*

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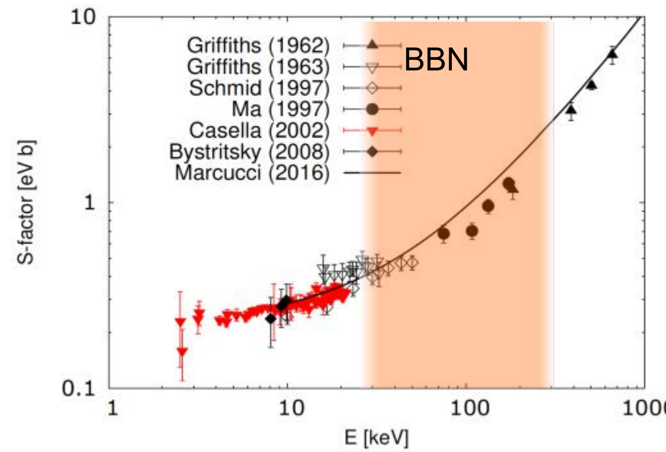

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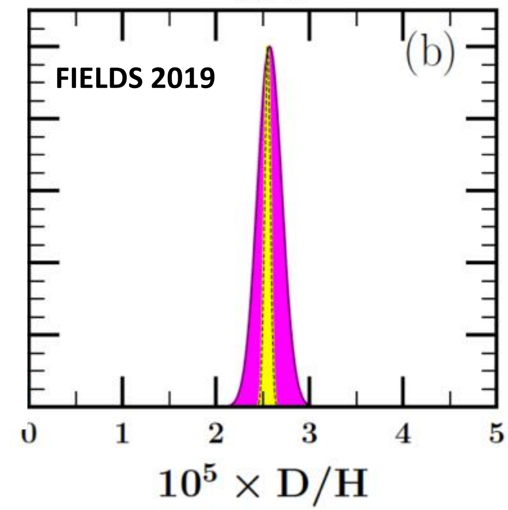

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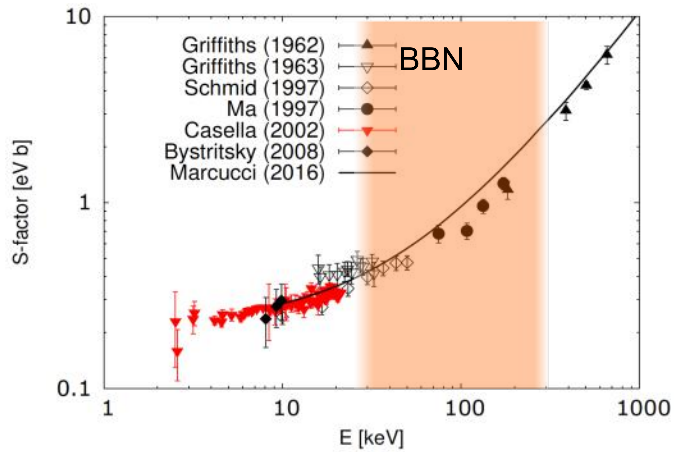

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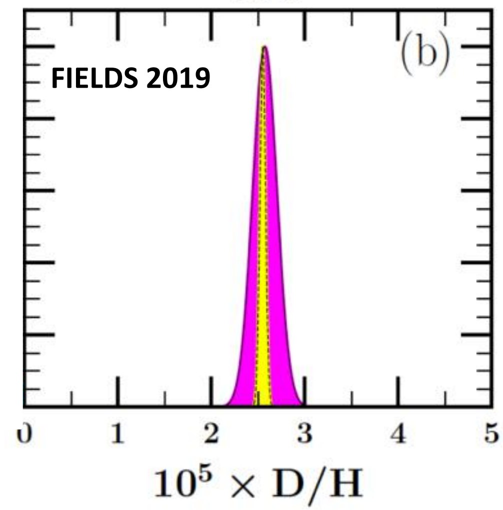

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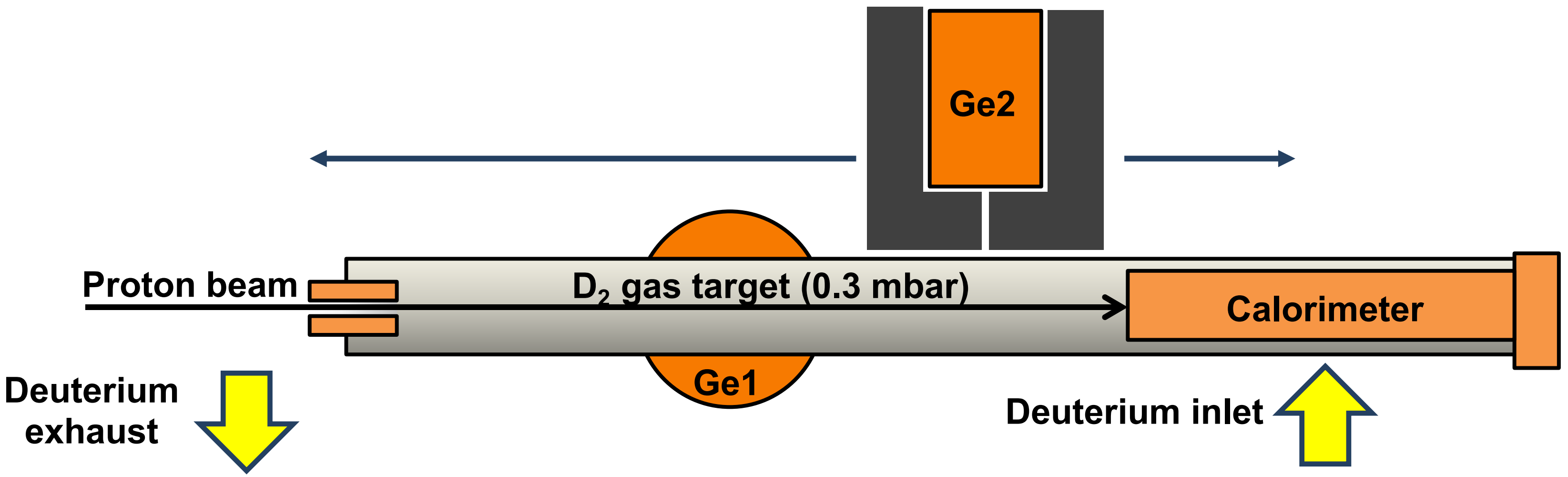
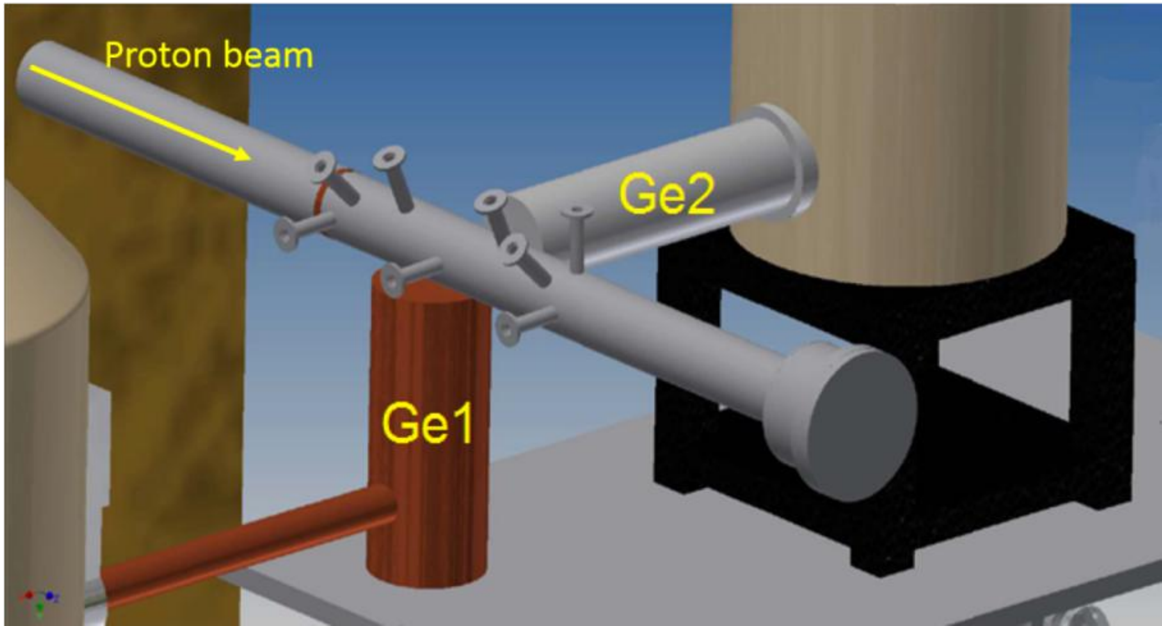
D(p,γ)^{3}He reaction: setup





Ge1: Detection of **D(p,γ)^{3}He** photons. Eγ~5.7 MeV
Ge2: Ancillary detector for calibrations and monitoring

Setup commissioning

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot I_{beam} \cdot \rho(z) \cdot \varepsilon(z)} W(\vartheta\,(z))\,dz$$

V. Mossa et al.:
Eur. Phys. J. A (2020) 56:144
https://doi.org/10.1140/epja/s10050-020-00149-1

Source	Method	$\Delta S/S$
Beam energy	Direct measurement	$\ll 1\%$
Energy loss	Low pressure	$\ll 1\%$
T and P profiles	Direct measurement	1.0%
Beam heating	Direct measurement	0.5%
Gas purity	Data sheet	$\ll 1\%$
Beam current	Calorimeter calibration	1.0%
Efficiency	Direct measurement	2.0%
Instrumental effects	Pulser method	$\ll 1\%$
Angular distribution	Peak shape analysis	0.5%
Total		2.6%

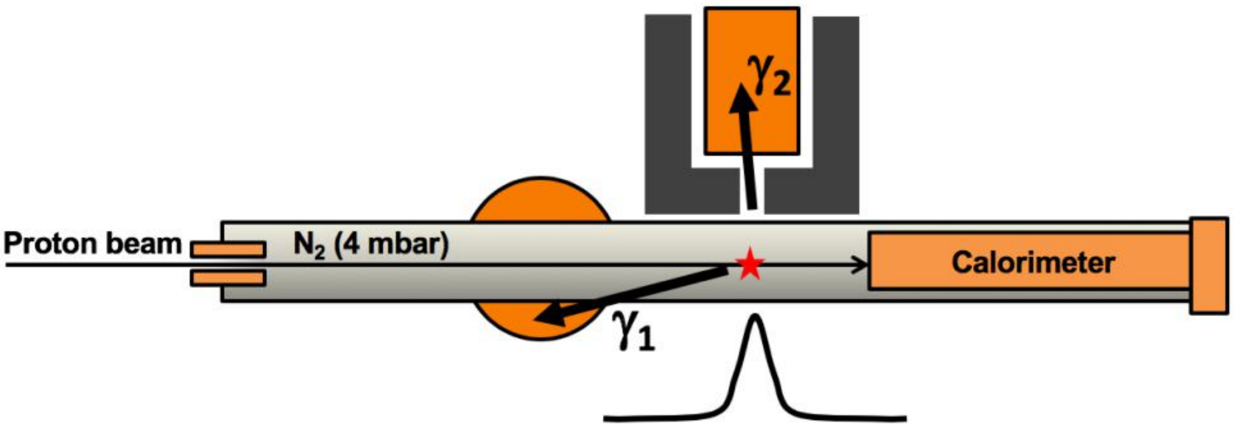
Moreover:

- Beam induced background →Dedicated measurements
- Energy loss→Ziegler formulae/direct measurements
- Detailed simulation to correct second order effects
-

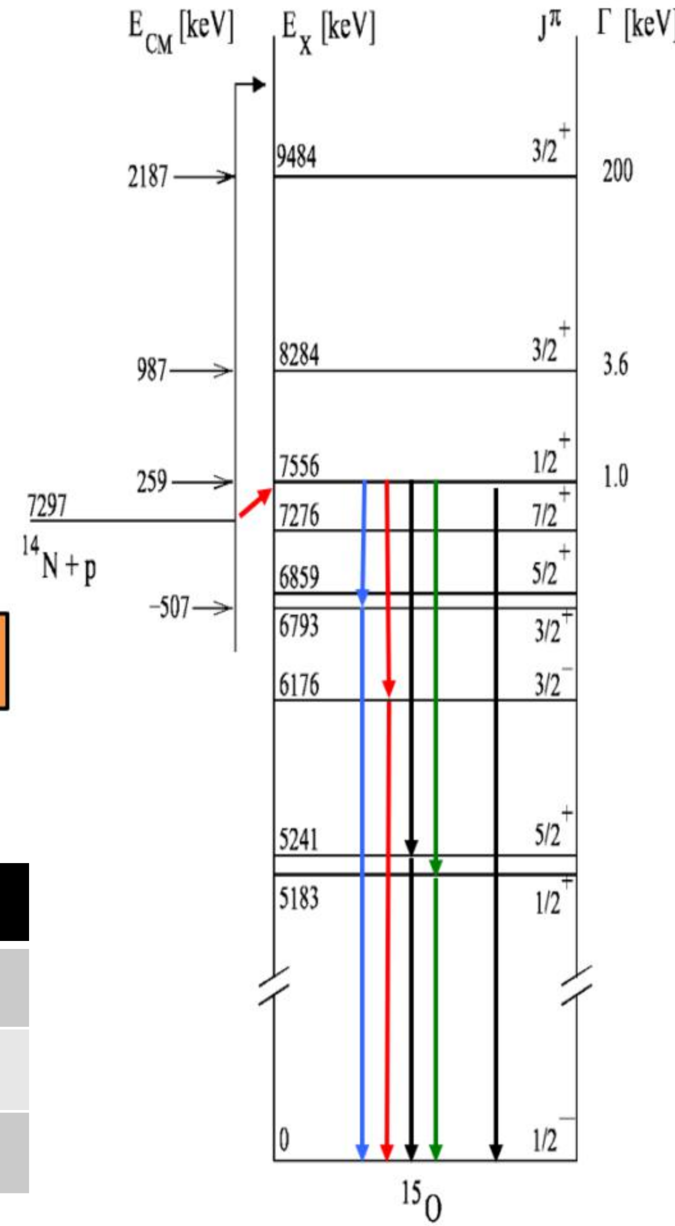
Setup commissioning

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot I_{beam} \cdot \rho(z) \cdot \boxed{\varepsilon(z)}} W(\vartheta\,(z))\,dz$$

The gamma efficiency along the target is measured exploiting gamma coincidence of the **^{14}N(p,2γ)^{15}O** reaction at **E_R=259 keV**



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



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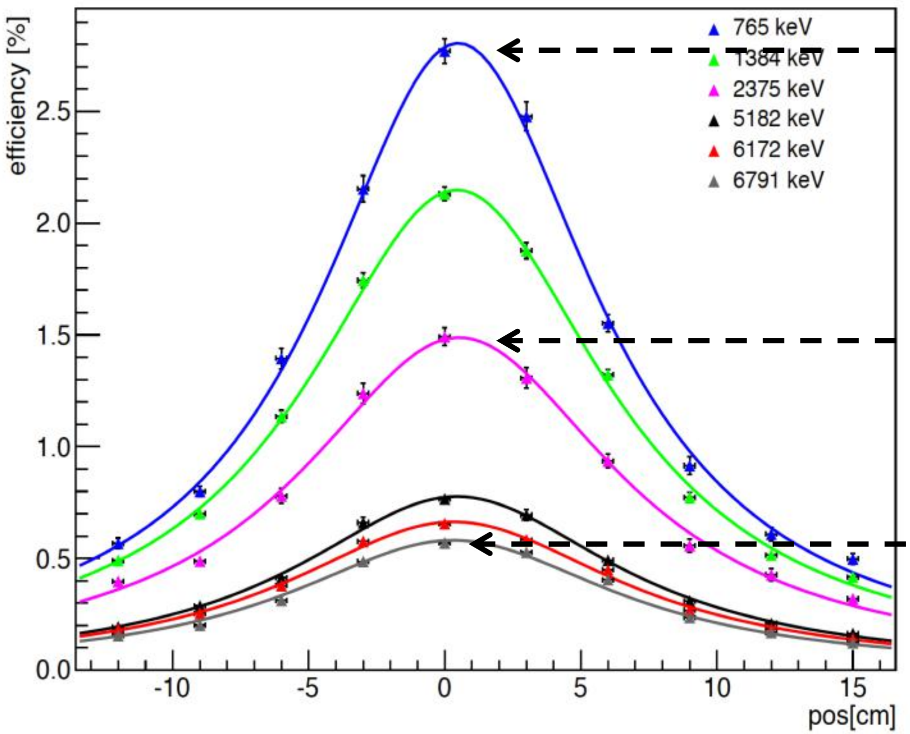
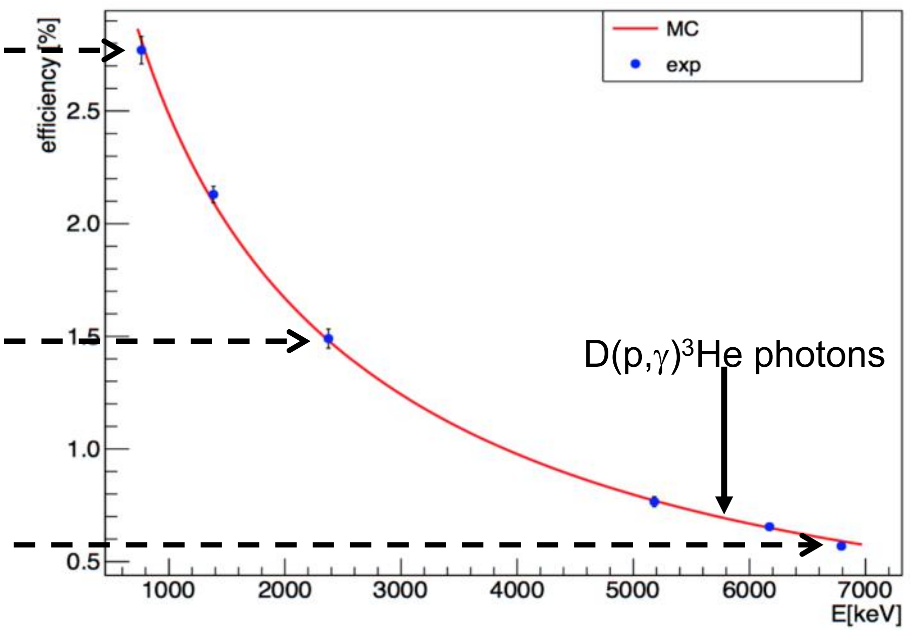
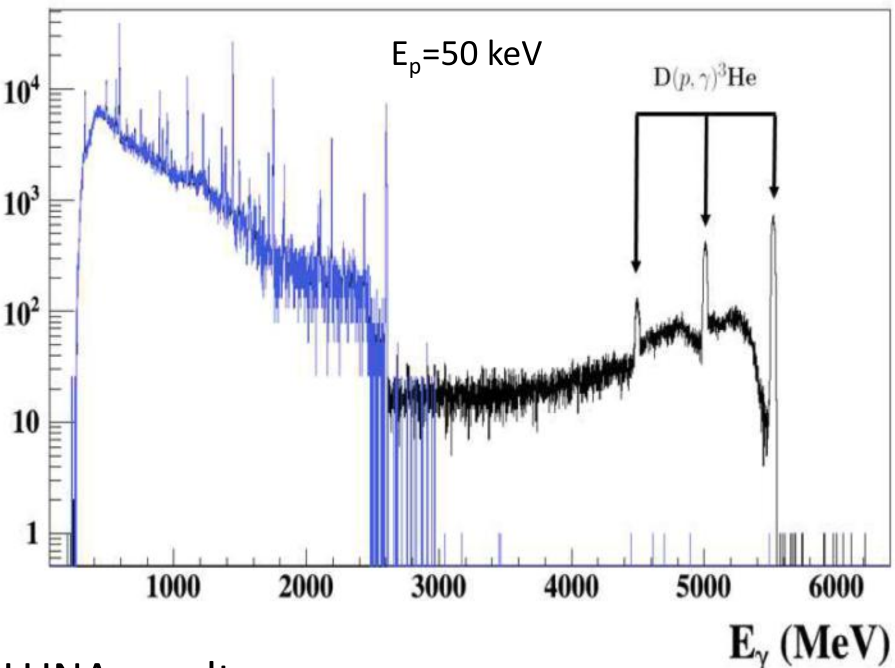
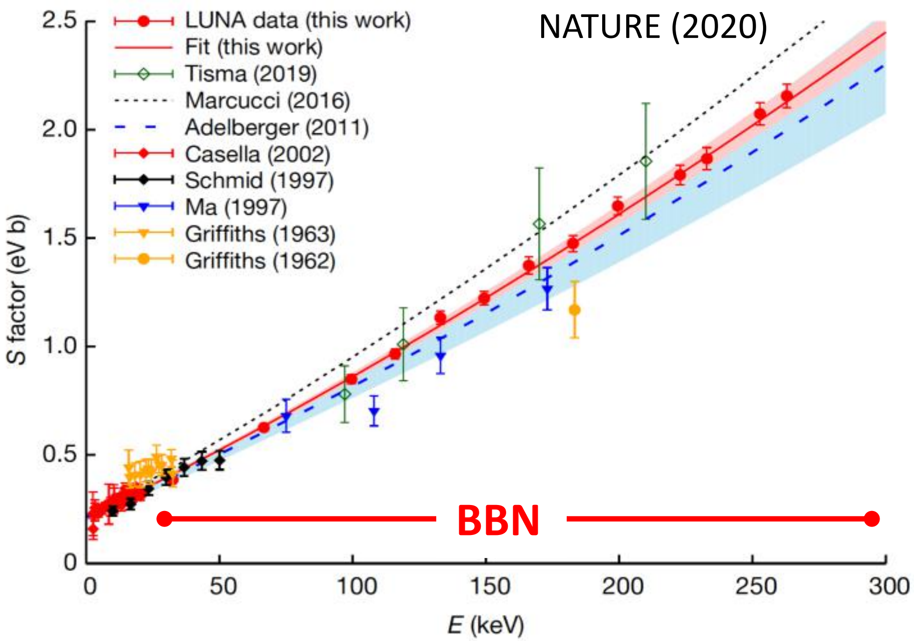




D(p,γ)^{3}He Total cross section

$$\sigma(E) = \int_0^L \frac{N_\gamma \cdot e}{t \cdot I_{beam} \cdot \rho(z) \cdot \varepsilon(z)} W(\vartheta\,(z))\,dz$$



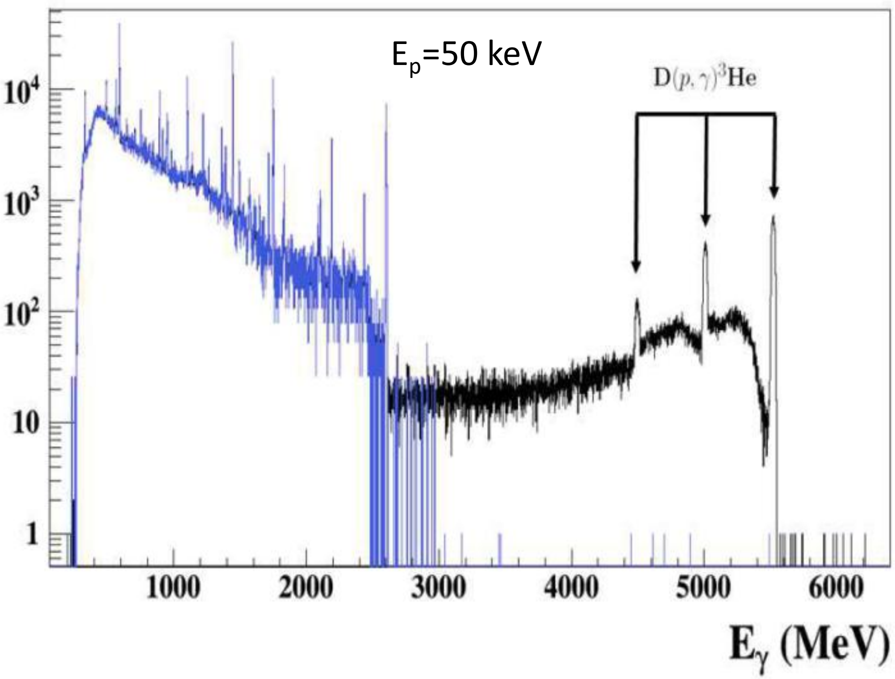


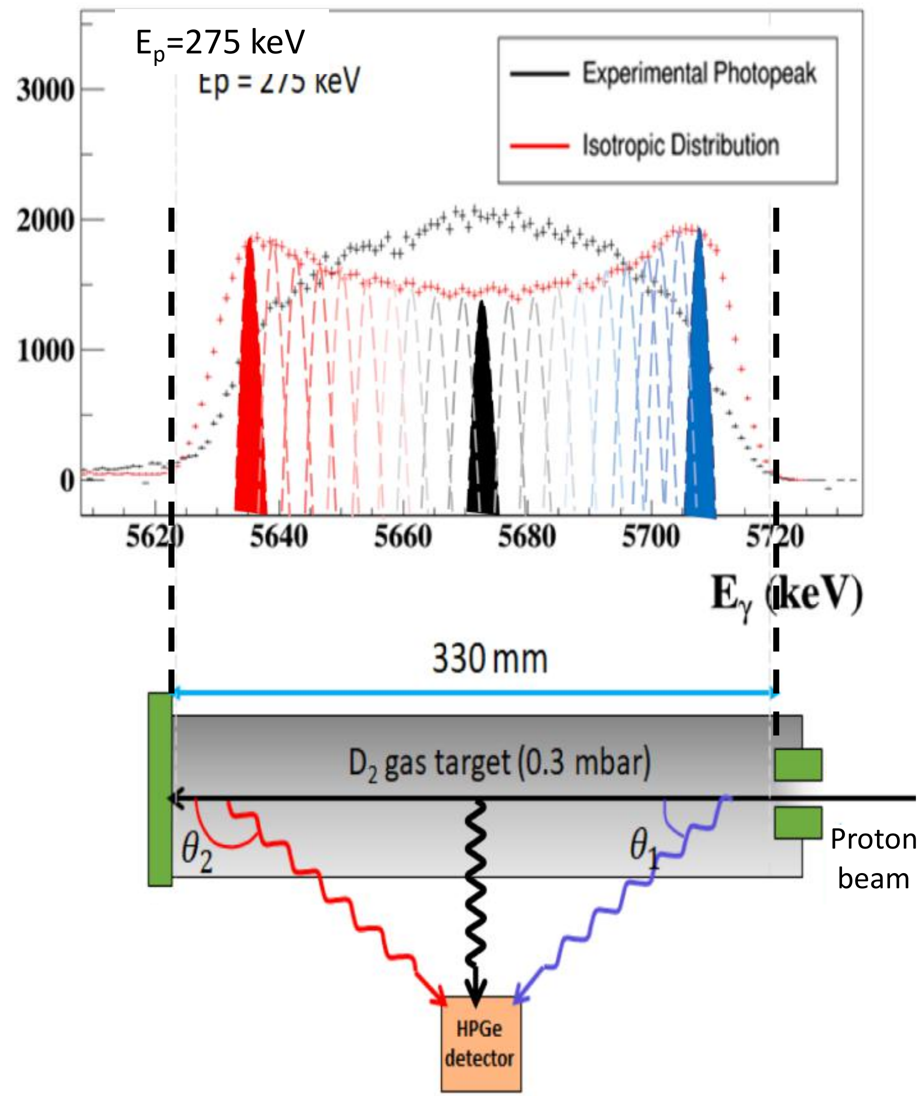
LUNA result:

- Improved accuracy with respect to previous data
- Higher cross section with respect to previous experimental data
- Lower cross section with respect to theoretical calculations

D(p,γ)³He differential cross section

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



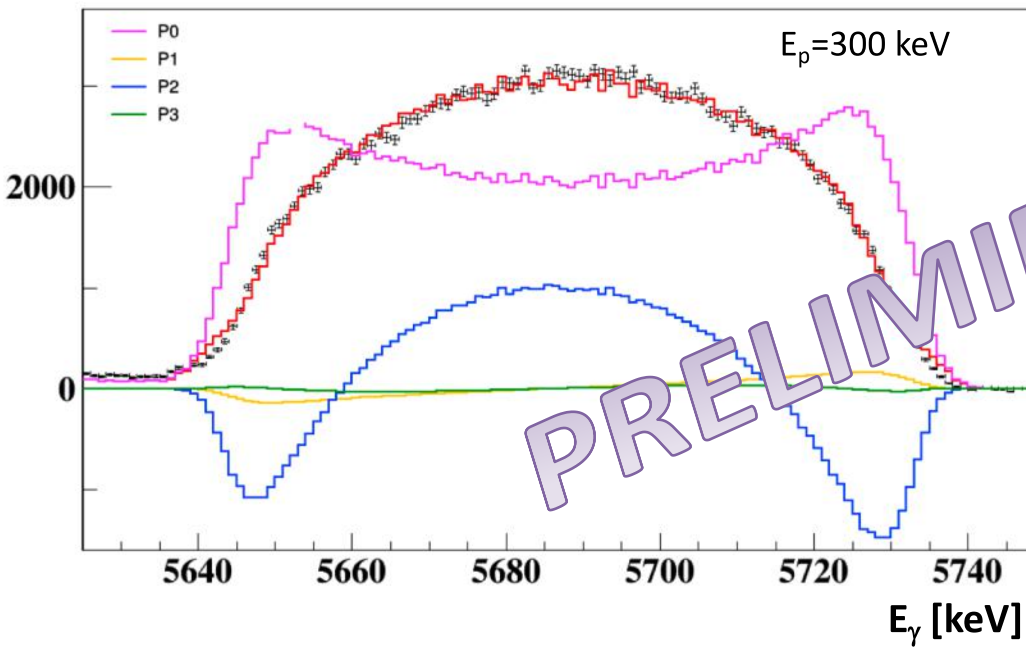


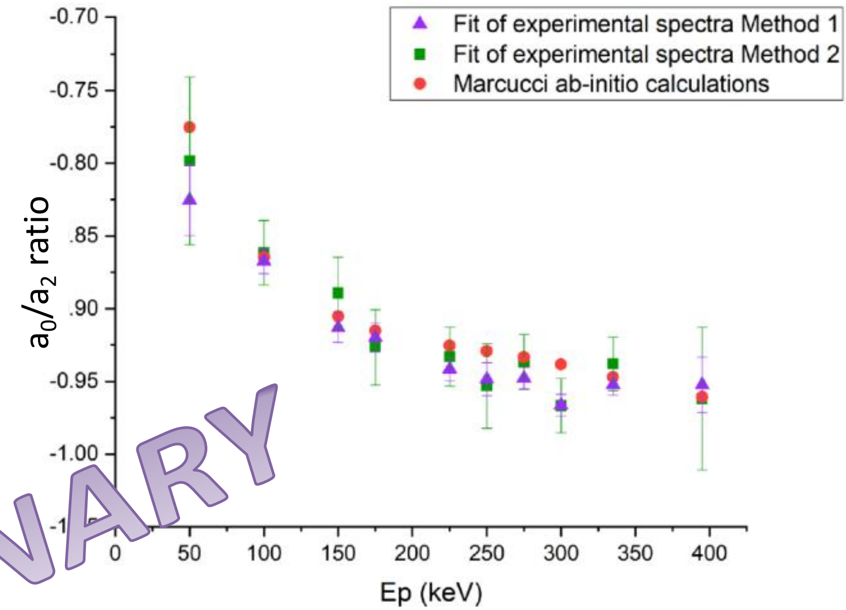
The use of extended target leads to a doppler broadening of the full detection peak

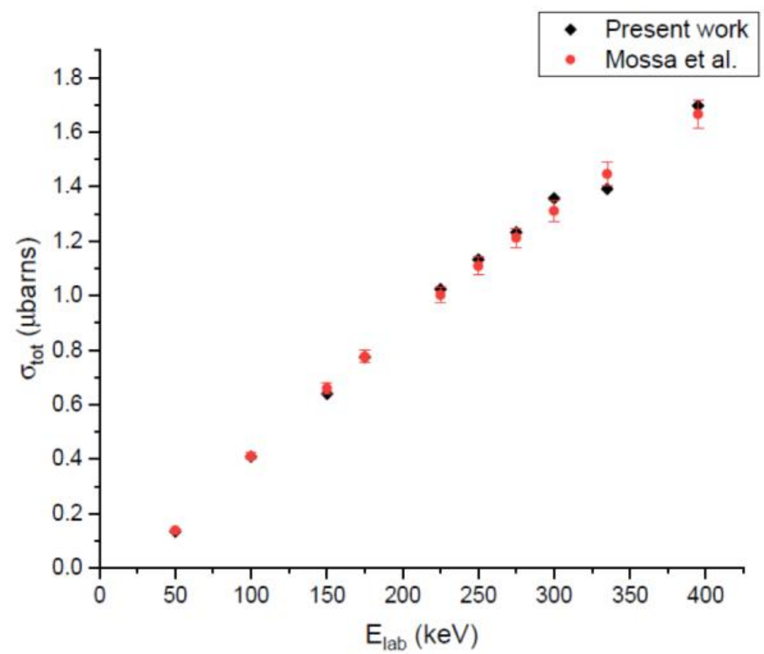
Peak Shape Analysis (PSA) provides the angular distribution of emitted photons

Peak shape analysis

$$F(E_\gamma) \propto \sum_{l=0}^{3} a_l P_l^*(E_\gamma)$$

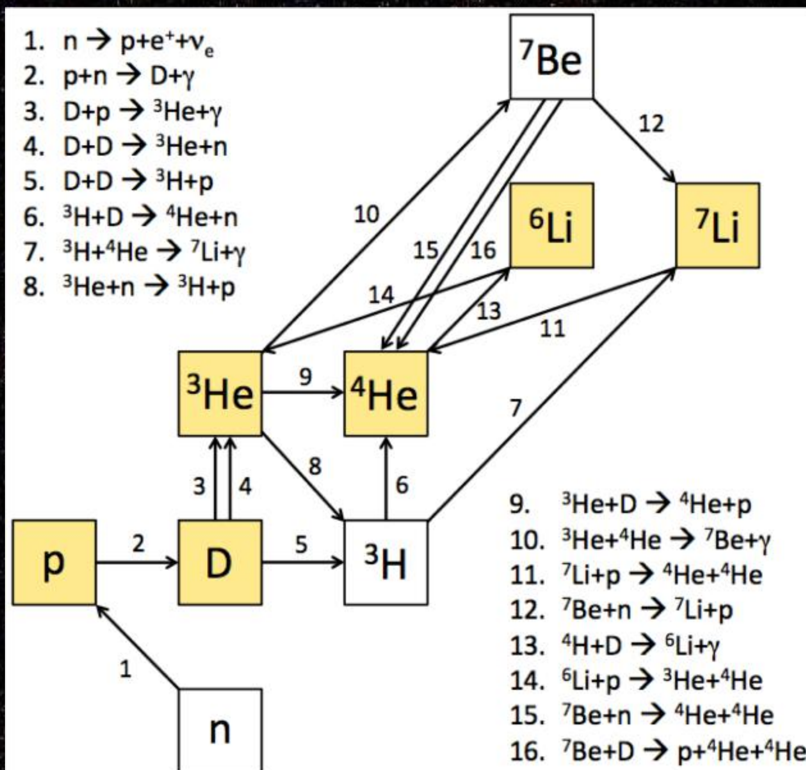






- Good agreement of the angular distribution of photons with ab-initio predictions
- Total cross section with PSA method fully consistent with the previous analysis

Deuterium abundance Vs Big Bang Nucleosynthesis



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

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

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

Deuterium 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

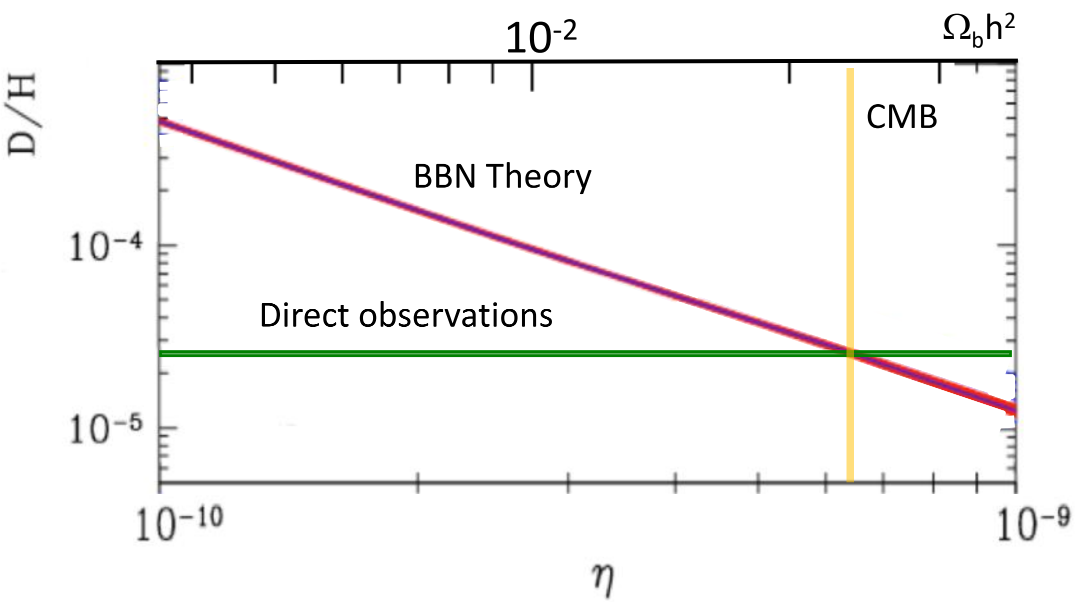
Comparison of calculations and observations leads to:
-Determination of the baryon density $(\Omega_b h^2)_{BBN}$
-Constrain on "dark radiation" (axions, sterile ν,..)

Baryon density

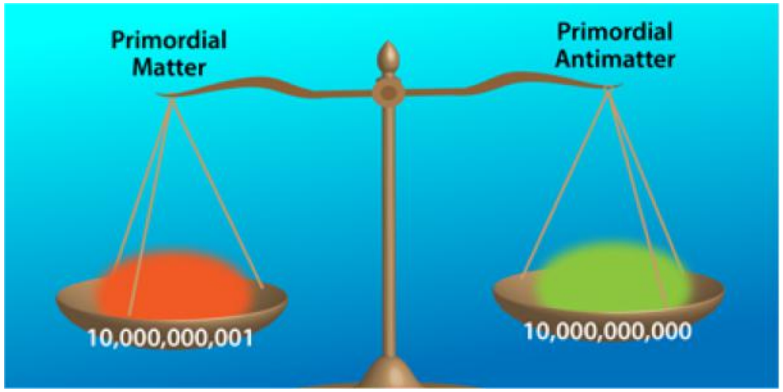
-the baryon density $\Omega_b h^2$ (i.e. the baryon-to-photon ratio η) is a fundamental cosmological free parameter. Its value is directly related to the matter-antimatter asymmetry of Universe.

-$\Omega_b h^2$(BBN) is derived by comparing $(D/H)_{obs}$ with $(D/H)_{BBN}$.

-$\Omega_b h^2$(CMB) is also inferred from the global analysis of CMB anisotropies.



$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$



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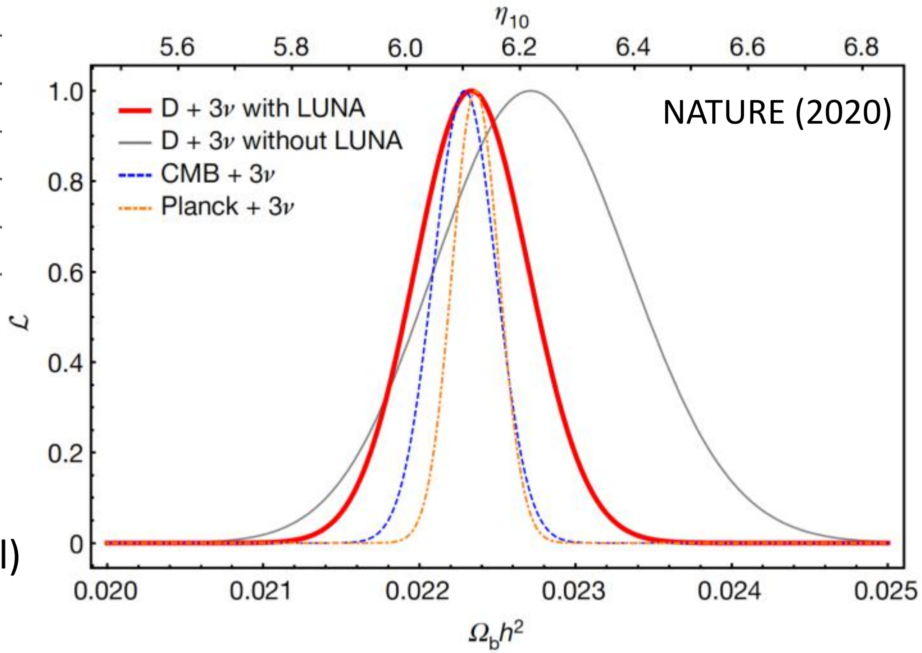
	$\Omega_b h^2$	δ (%)	N_{eff}
D + 3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D + 3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB + 3ν	0.02230 ± 0.00021[a]	0.94	3.045
Planck + 3ν	0.02236 ± 0.00015	0.67	3.045



Assuming ΛCDM:

$100\Omega_b h^2$(BBN)=2.271 ± 0.062 (w/o new LUNA data)

$100\Omega_b h^2$(BBN)=2.233 ± 0.036 (with new LUNA data)

$100\Omega_b h^2$(CMB)=2.230 ± 0.021 (w/o BBN assumptions)

- Comparable Ω_b(BBN) - Ω_b(CMB) accuracy (~1% level)
- Good greement between Ω_b(BBN) and Ω_b(CMB)

N.B.

$\Omega_b h^2$(BBN) reflects the Universe as it was in the first minutes of Cosmic time.

$\Omega_b h^2$(CMB) is derived when the Universe was some 380.000 years old.

Radiation density

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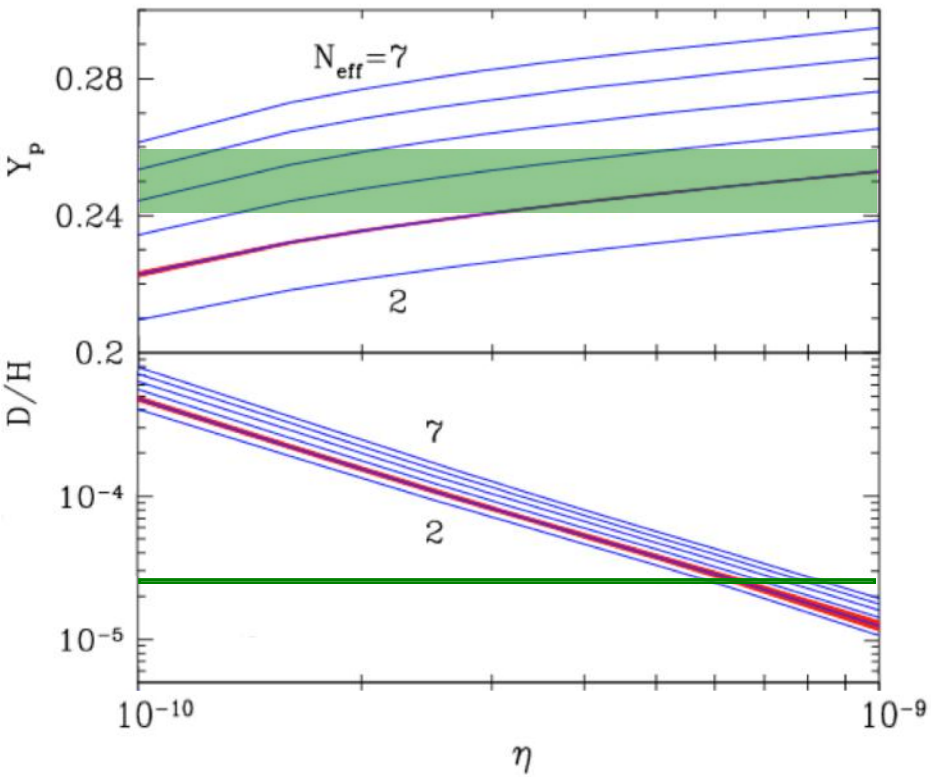

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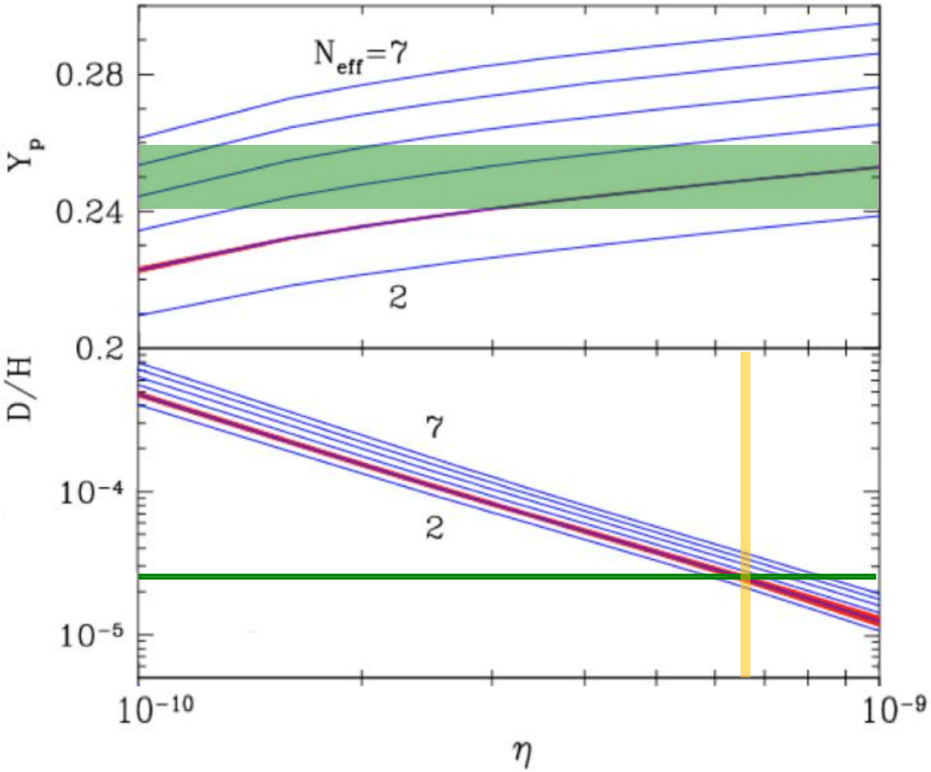

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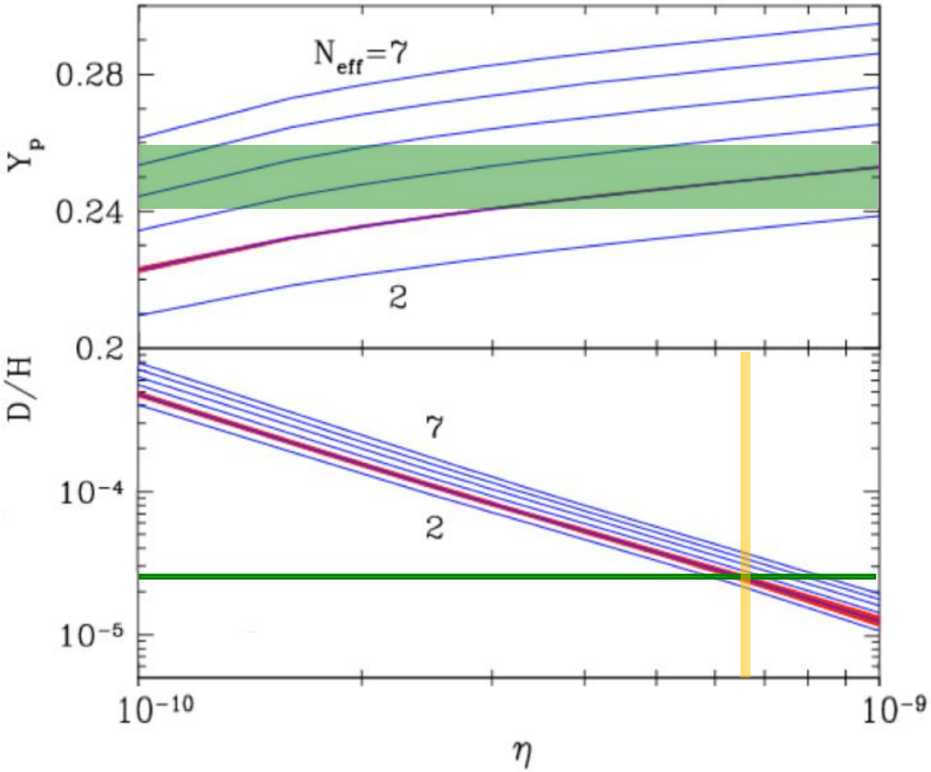
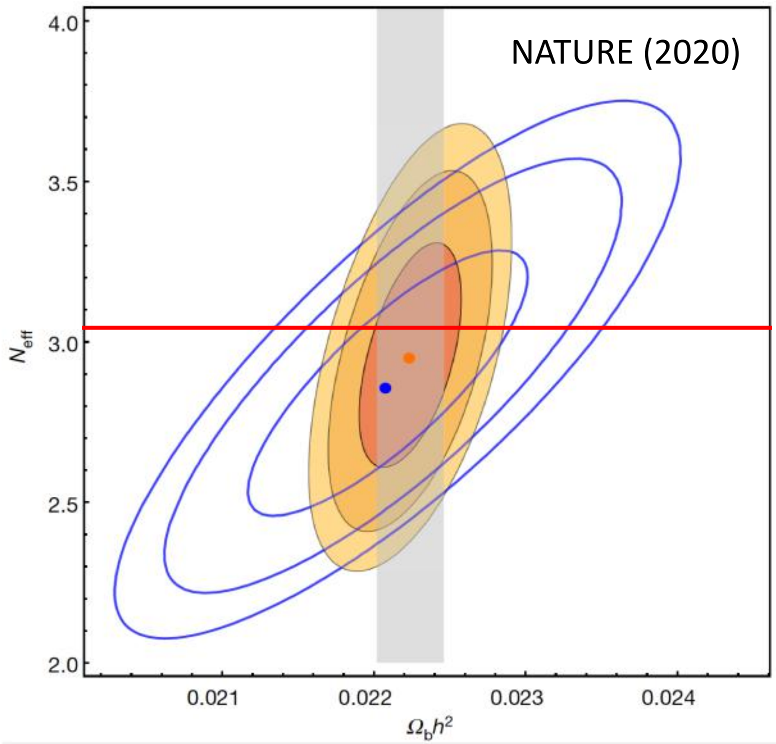
1) Combining observed and predicted D/H with the observed and predicted Y_p →**N_{eff}=2.87±0.28**
2) Combining observed and predicted D/H with Ω_b(CMB) →**N_{eff}=2.95±0.22**



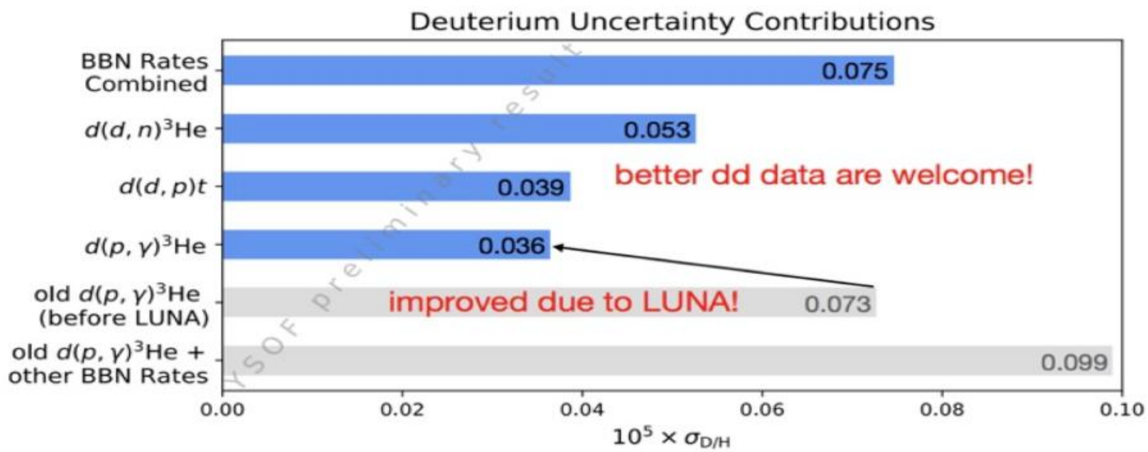


→LUNA data are consistent with the existence of only **3 neutrino families**. **No evidence of a sizeable amount of "dark radiation"** (e.g. sterile neutrinos, hot axions).

Summary and outlook

-The theoretical $(D/H)_{BBN}$ abundance has been improved by the D(p,γ)^{3}He study at LUNA
-Ω_b(BBN) is now derived with a precision of 1.6% percent, in excellent agreement with Ω_b(CMB)
-Room for a sizeabe amount of extra relativistic particles is further reduced ($\Delta N_{eff}/N_{eff}$~7%)

Looking forward:
OBSERVATIONS: More accurate determination of the primordial **^{4}He abundance**, with 4th generation of CMB experiments and/or with improved **^{4}He** direct observations → **N_{eff}**
NUCLEAR PHYSICS: New precision **d(d,n)^{3}He** and **d(d,p)t** data → **Ω_b(BBN)**



Plot from
Yeh, Shelton, Olive, & Fields

Thank you!