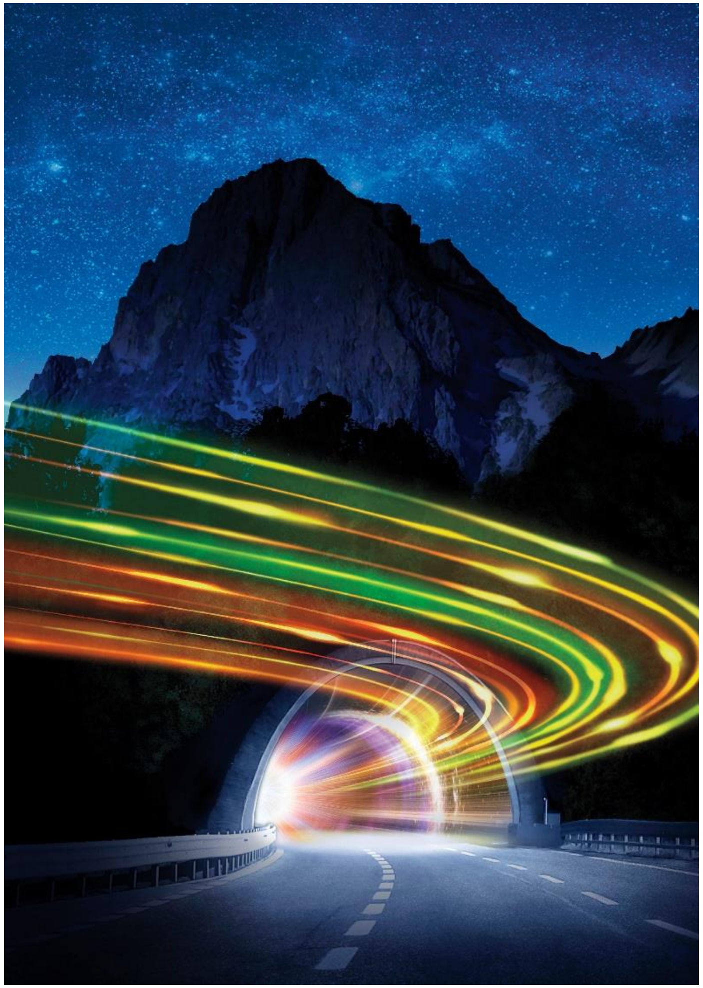
LUNA results on deuterium burning and cosmological implications



Francesca Cavanna

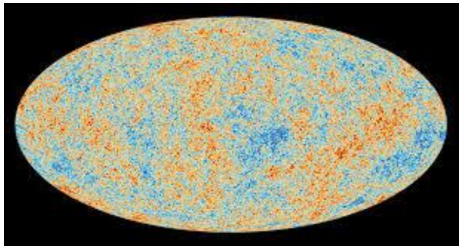
INFN Torino

Nuclear Astrophysics: an interdisciplinary field

Observational astronomy

Cosmology

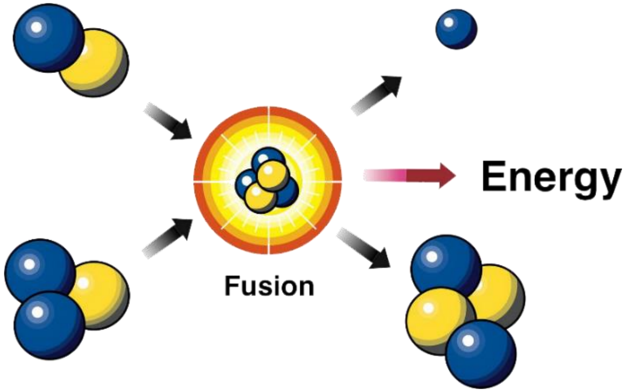
Nuclear astrophysics

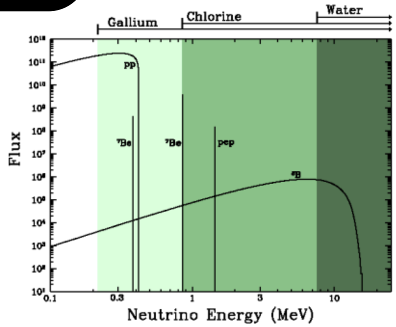


Nuclear physics

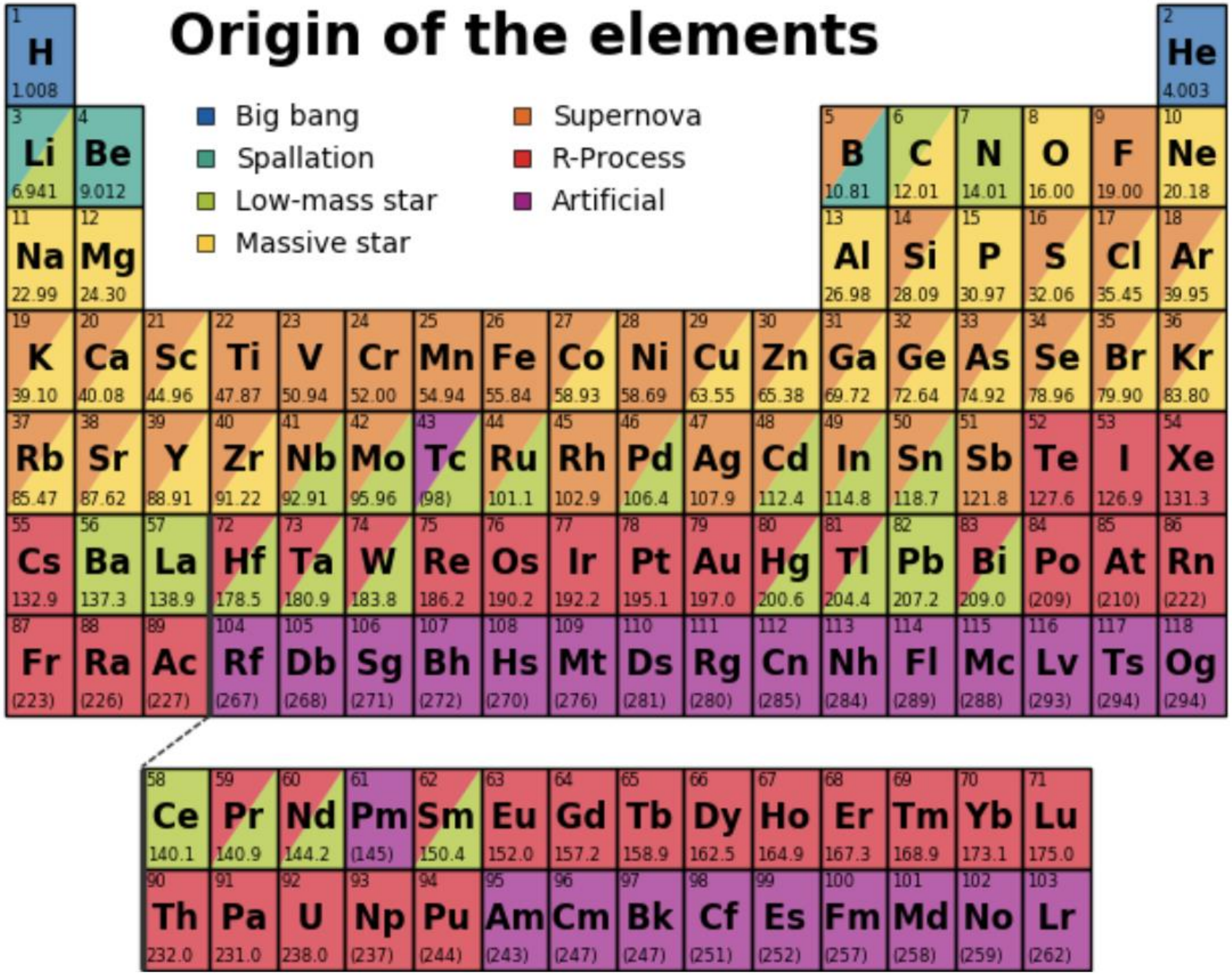
Neutrino physics

Stellar Models





The Origin of the Elements



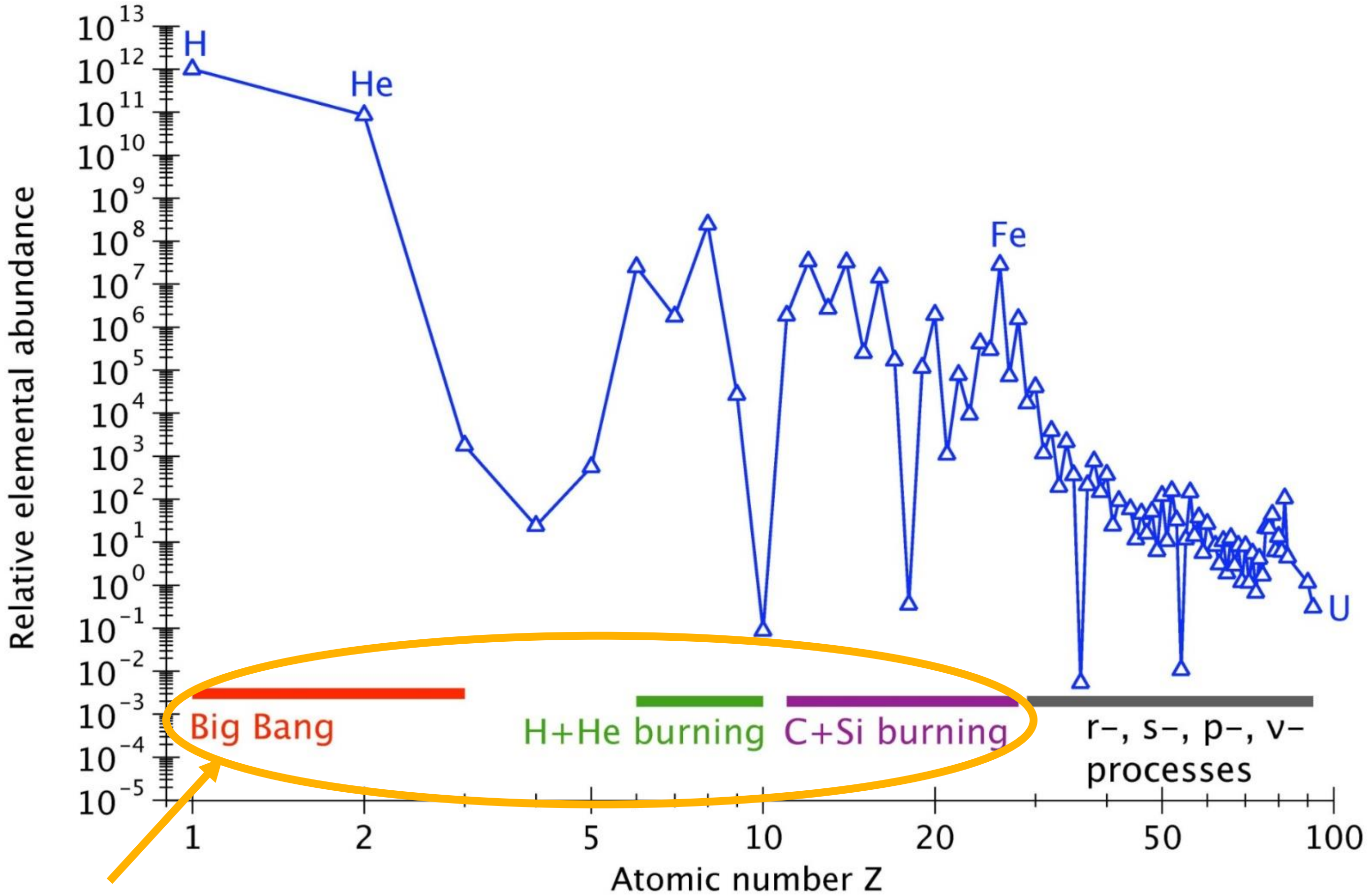
Origin of the elements

- 🟦 Big bang
- 🟩 Spallation
- 🟩 Low-mass star
- 🟨 Massive star
- 🟧 Supernova
- 🟥 R-Process
- 🟪 Artificial

1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.30											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.84	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.96	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (267)	105 Db (268)	106 Sg (271)	107 Bh (272)	108 Hs (270)	109 Mt (276)	110 Ds (281)	111 Rg (280)	112 Cn (285)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.1	71 Lu 175.0
90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

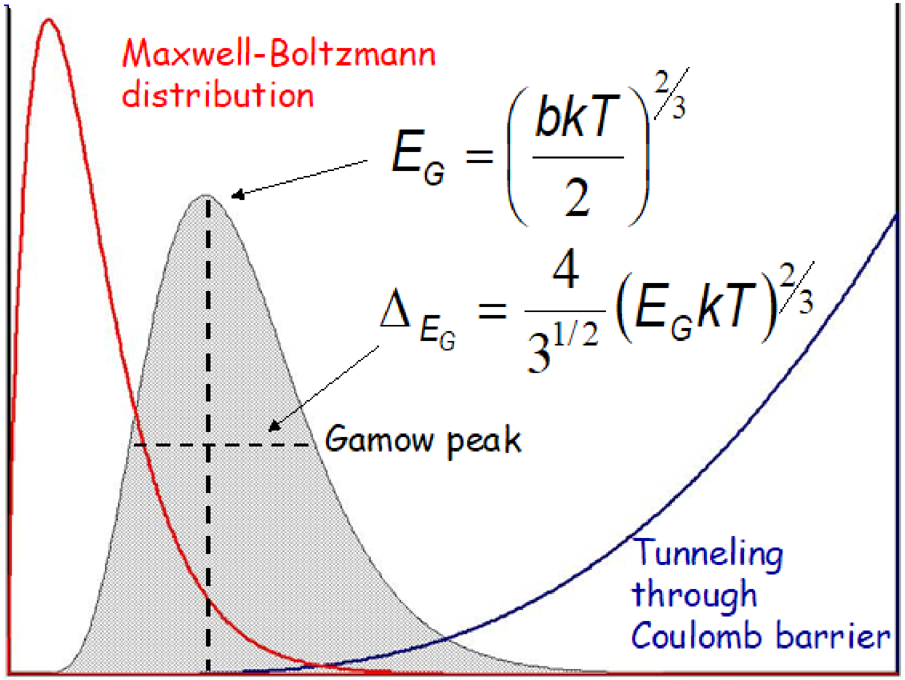
The Origin of the Elements



Charged-particle induced reactions

Challenges of nuclear astrophysics experiments

Relevant energy range



Low energies ⟹ small cross sections

Experimental Challenges of Direct Measurement

Counting Rate = N_p x N_t x cross section x detection efficiency

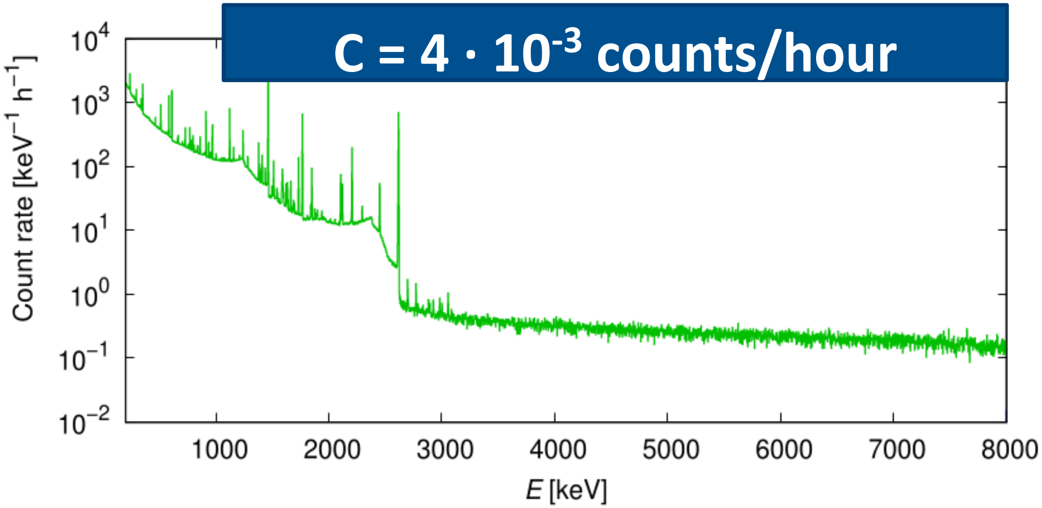
10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{18} atoms/cm^2 typical solid state targets

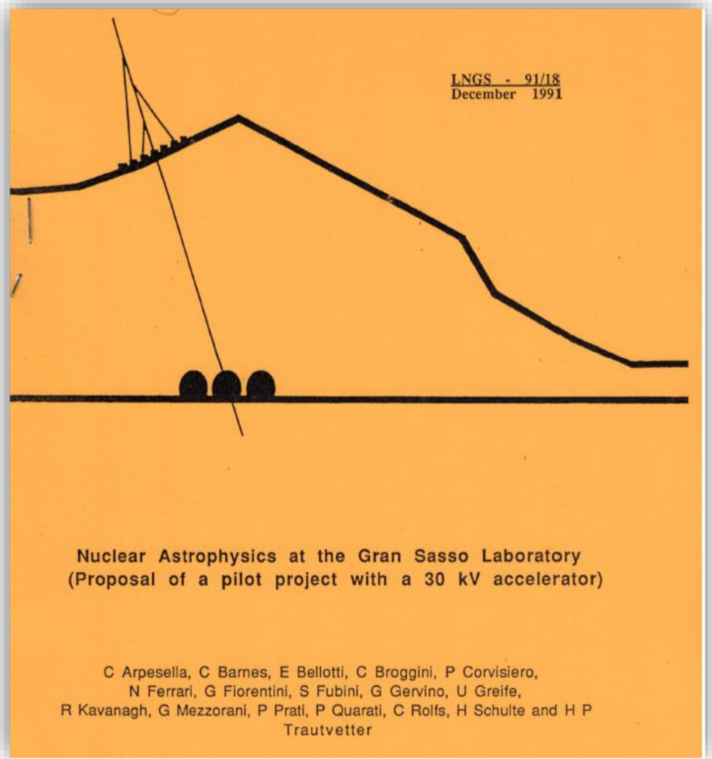
10^{-36} cm^2 (often even smaller)

~1-5% for gamma rays (HPGe detectors)

C = 4 · 10^{-3} counts/hour



How to improve the signal-to-noise ratio?



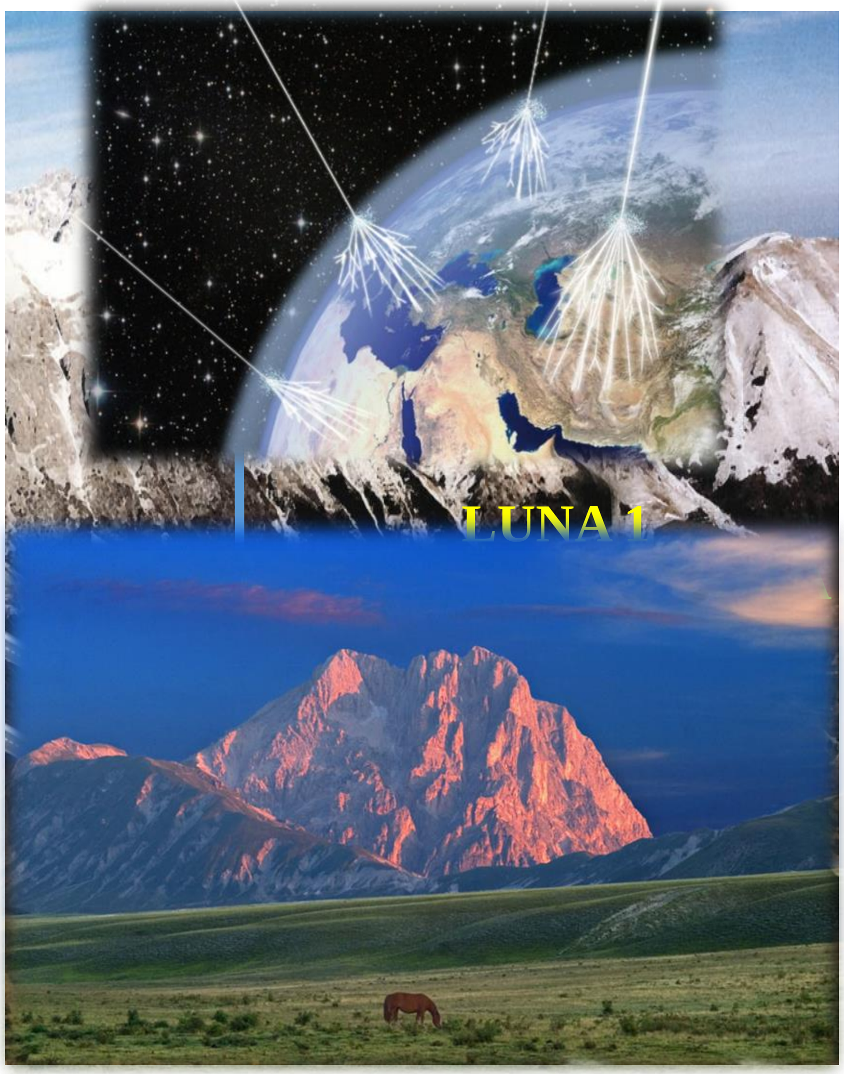
LNGS - 91/18
December 1991

Nuclear Astrophysics at the Gran Sasso Laboratory
(Proposal of a pilot project with a 30 kV accelerator)

C Arpesella, C Barnes, E Bellotti, C Broggini, P Corvisiero,
N Ferrari, G Fiorentini, S Fubini, G Gervino, U Greife,
R Kavanagh, G Mezzorani, P Prati, P Quarati, C Rolfs, H Schulte and H P Trautvetter

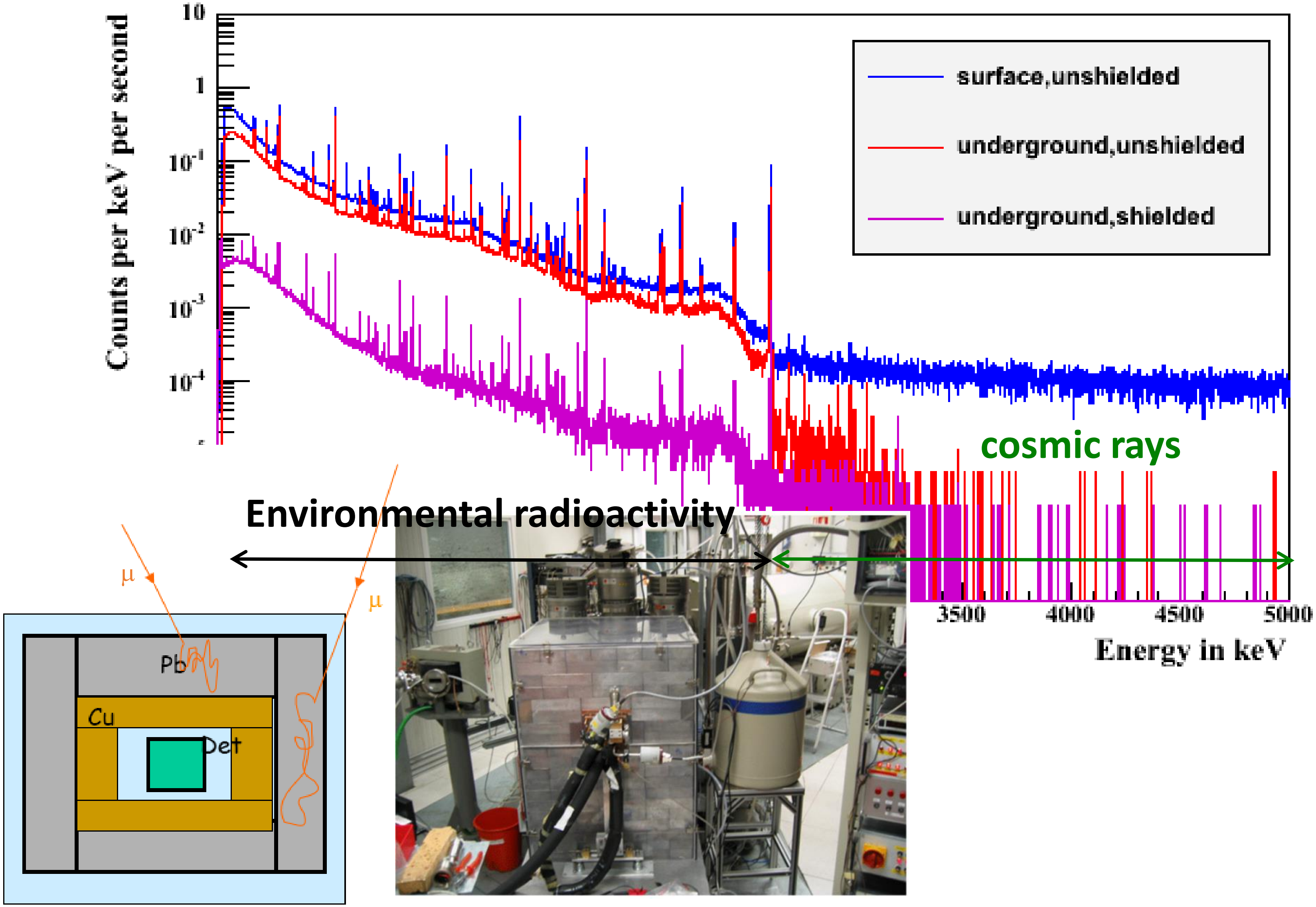
Laboratory for Underground Nuclear Astrophysics

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}



LNGS (1400 m rock shielding ≡ 4000 m w.e.)

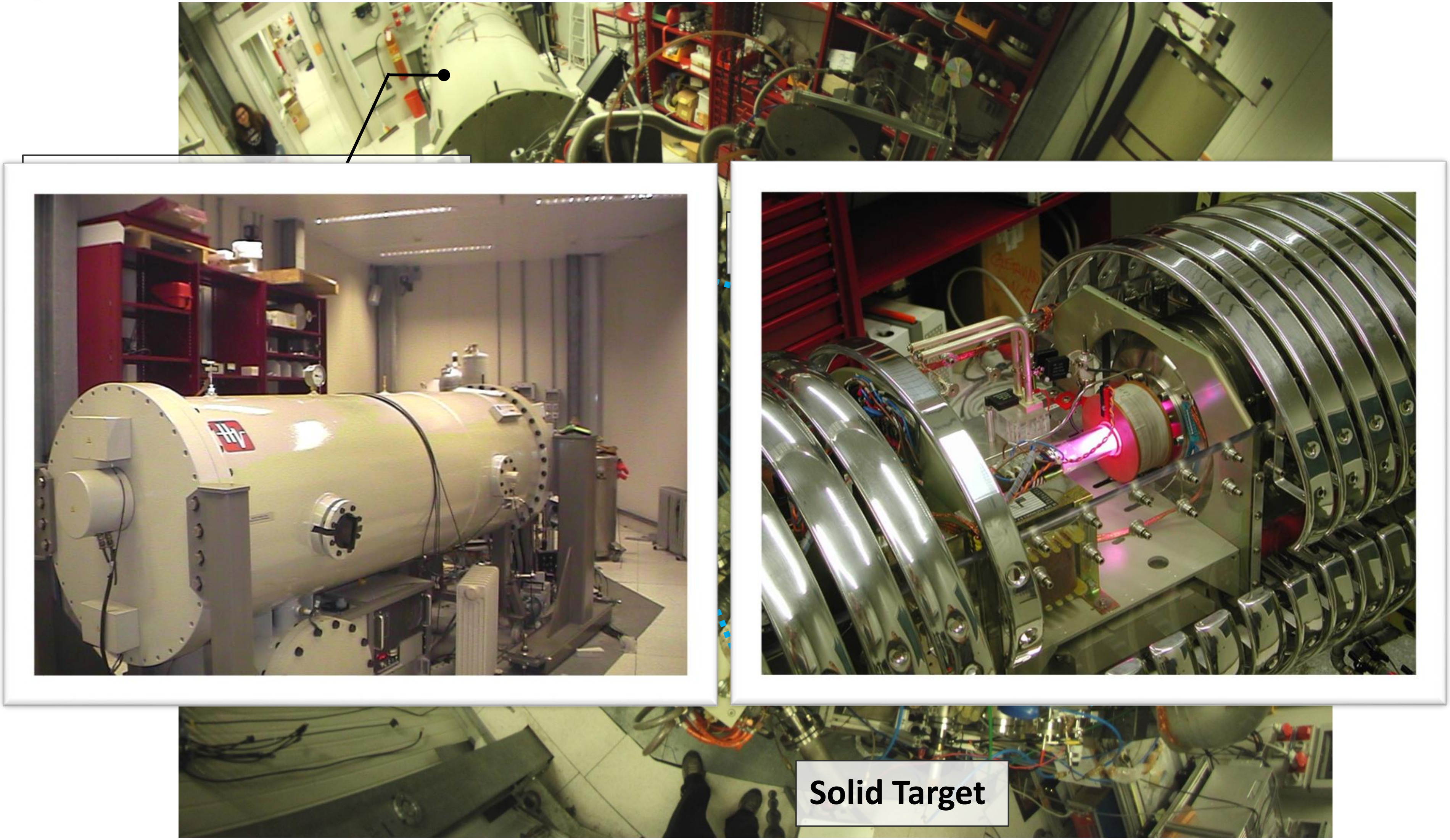
Gamma background reduction at LNGS



cosmic rays

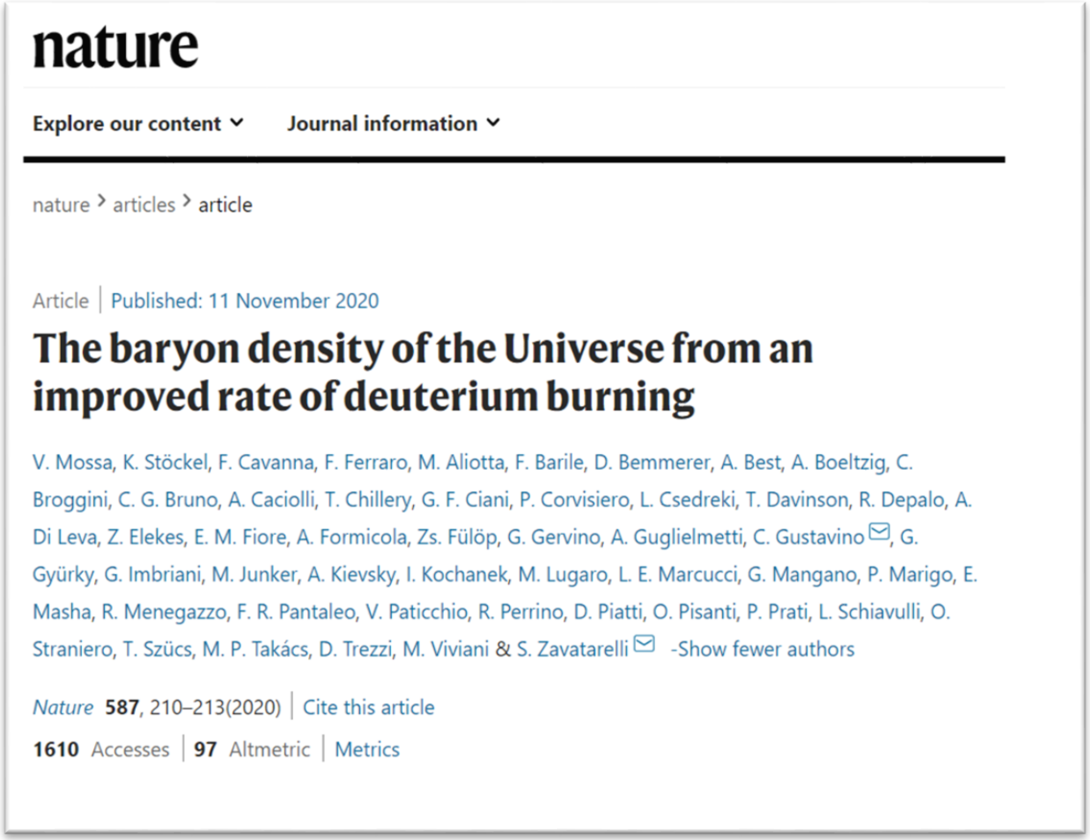
Environmental radioactivity

LUNA experimental setup



Recent achievement

A new paper is out!



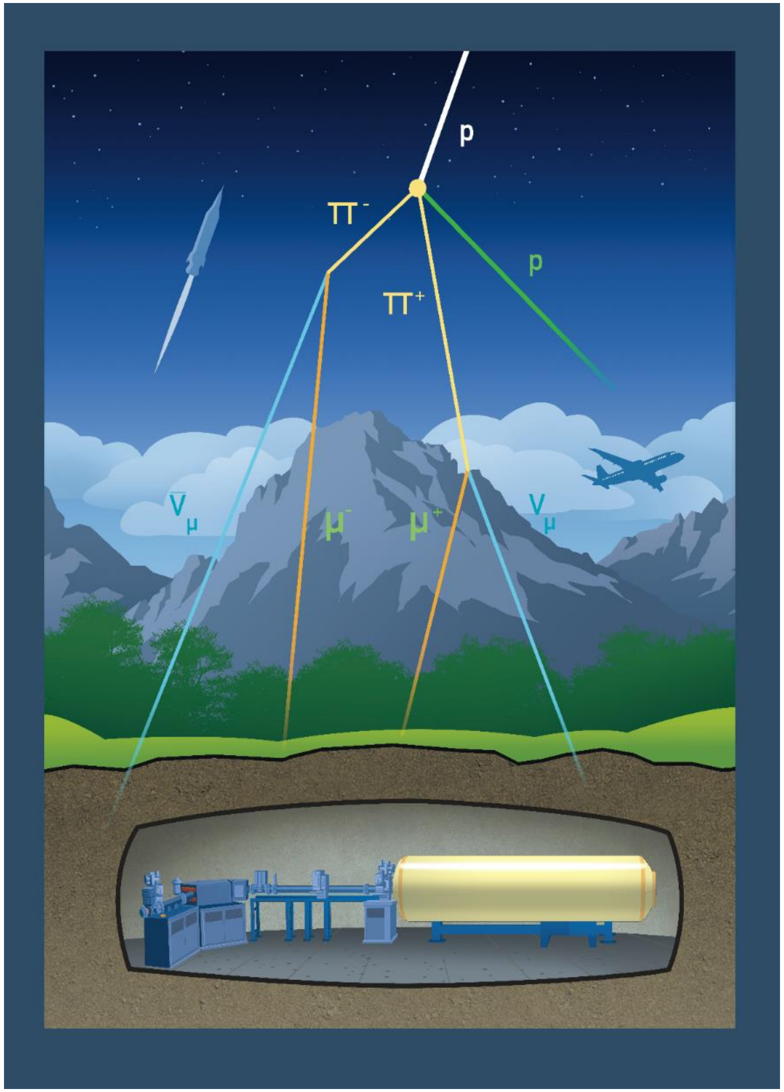
Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

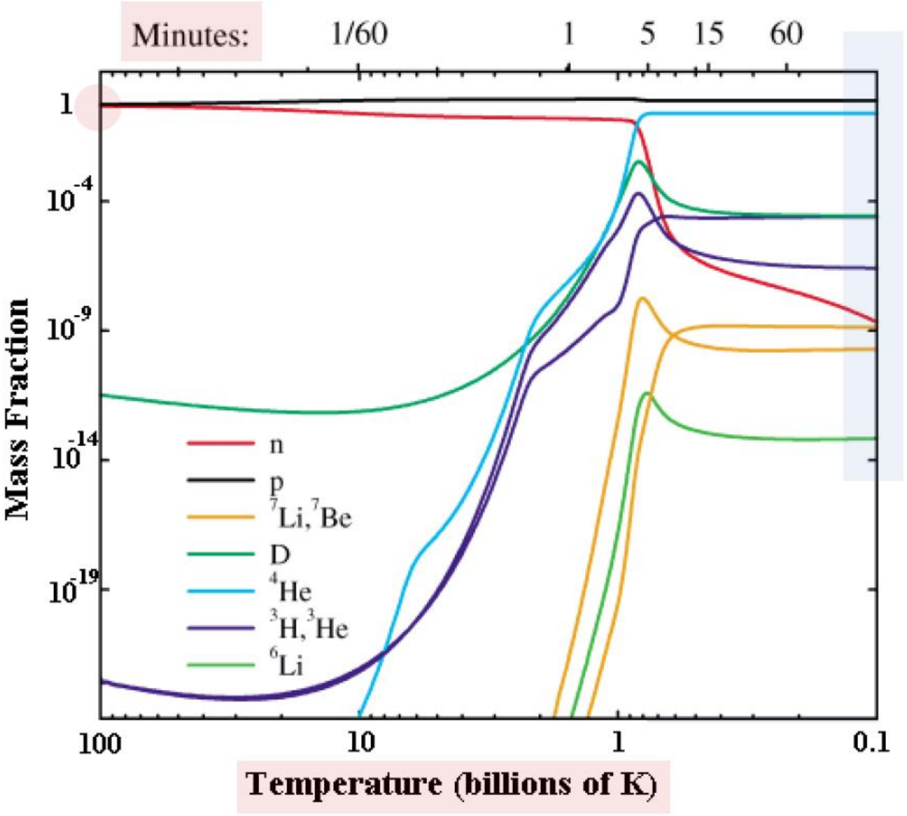
V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli -Show fewer authors

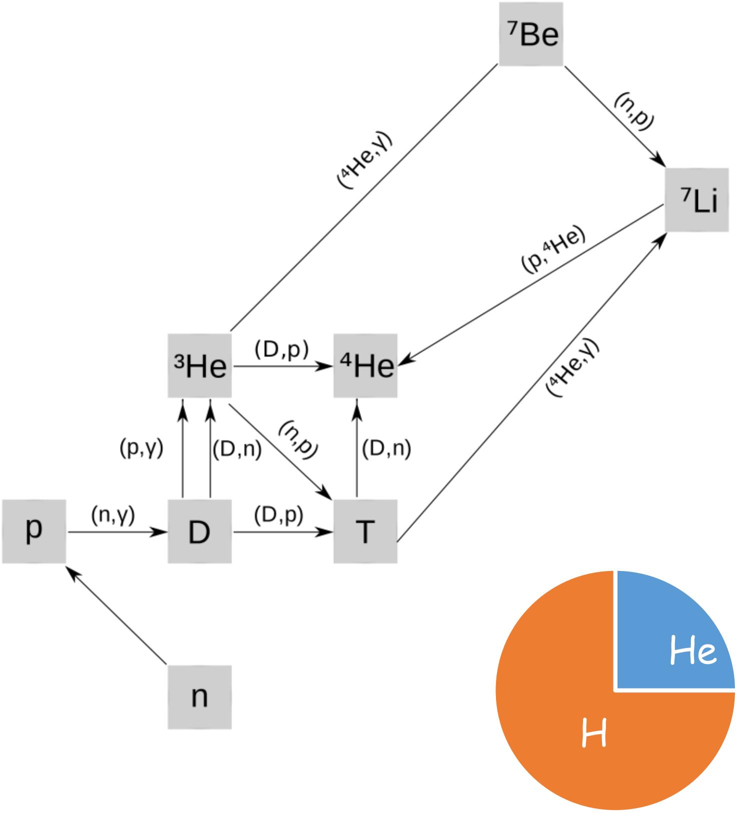
Nature **587**, 210–213(2020) | Cite this article

1610 Accesses | **97** Altmetric | Metrics



Big Bang Nucleosynthesis





- ✓ BBN occurs 3 minutes after Big Bang
- ✓ After BBN we have mainly H and ^{4}He plus small amounts of D, ^{3}He, ^{6}Li and ^{7}Li

The primordial deuterium abundance

✓ The primordial deuterium abudance [D/H] can be obtained by:

- Observed abundance

Direct astronomical observations

$[D/H]_{OBS} = (2.527 \pm 0.030) \times 10^{-5}$

Cooke et al, APJ 855 (2018) 102

1% accuracy

- Predicted abundance (BBN theory):

From BBN theory, knowing the cosmological parameters and the cross sections of the processes responsible for D creation and destruction $[D/H]_{BBN}$

Depending on the adopted cross sections ➡

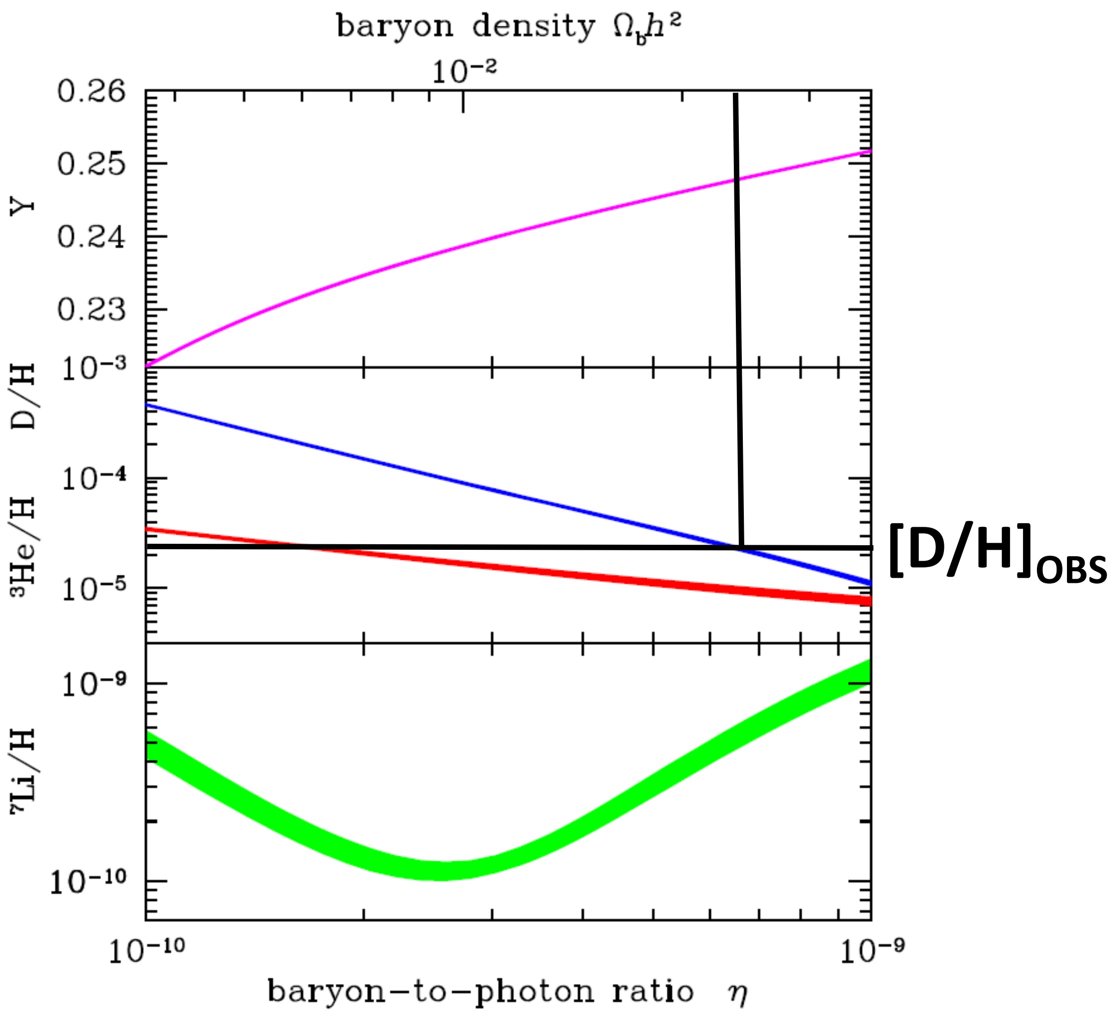
$[D/H]_{BBN} = (2.587 \pm 0.055) \times 10^{-5}$

$[D/H]_{BBN} = (2.439 \pm 0.052) \times 10^{-5}$

Planck, A&A 641 (2018) A6

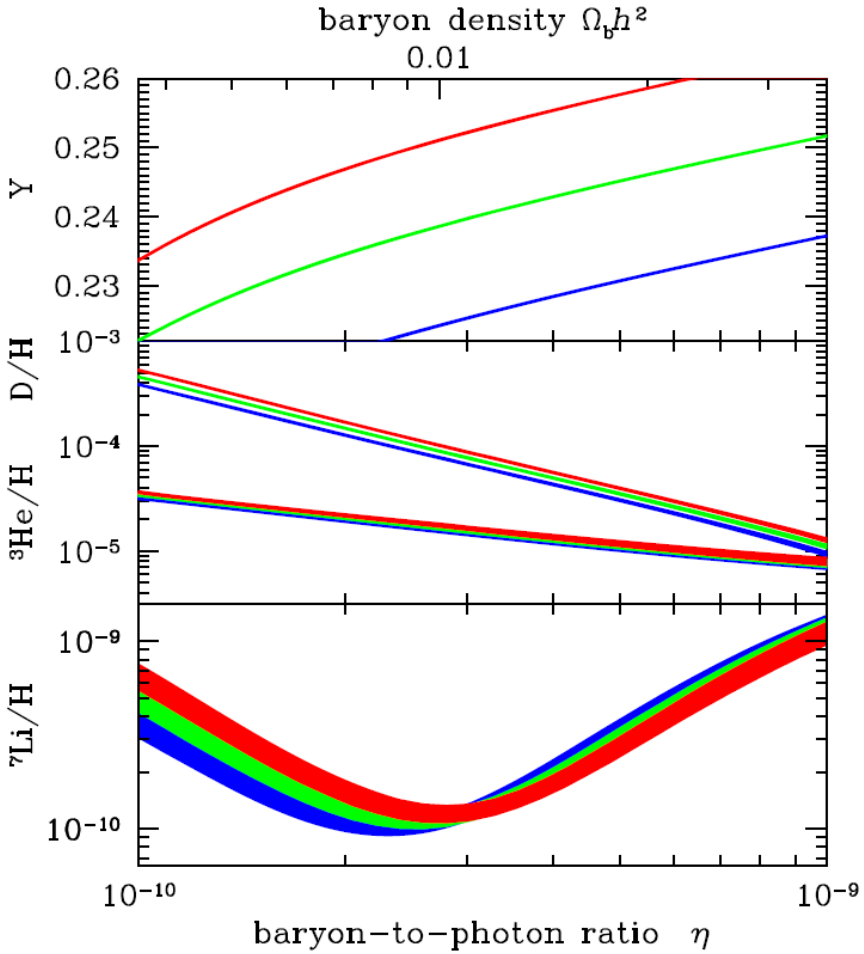
✓ By comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$ → the universal barion density Ω_B and/or N_{eff} can be derived

The primordial deuterium abundance



The primordial deuterium abundance is sensitive to the baryon density of the Universe

The primordial deuterium abundance



The primordial deuterium abundance is also sensitive to the number of neutrino species, N_{eff}= 2, 3 and 4

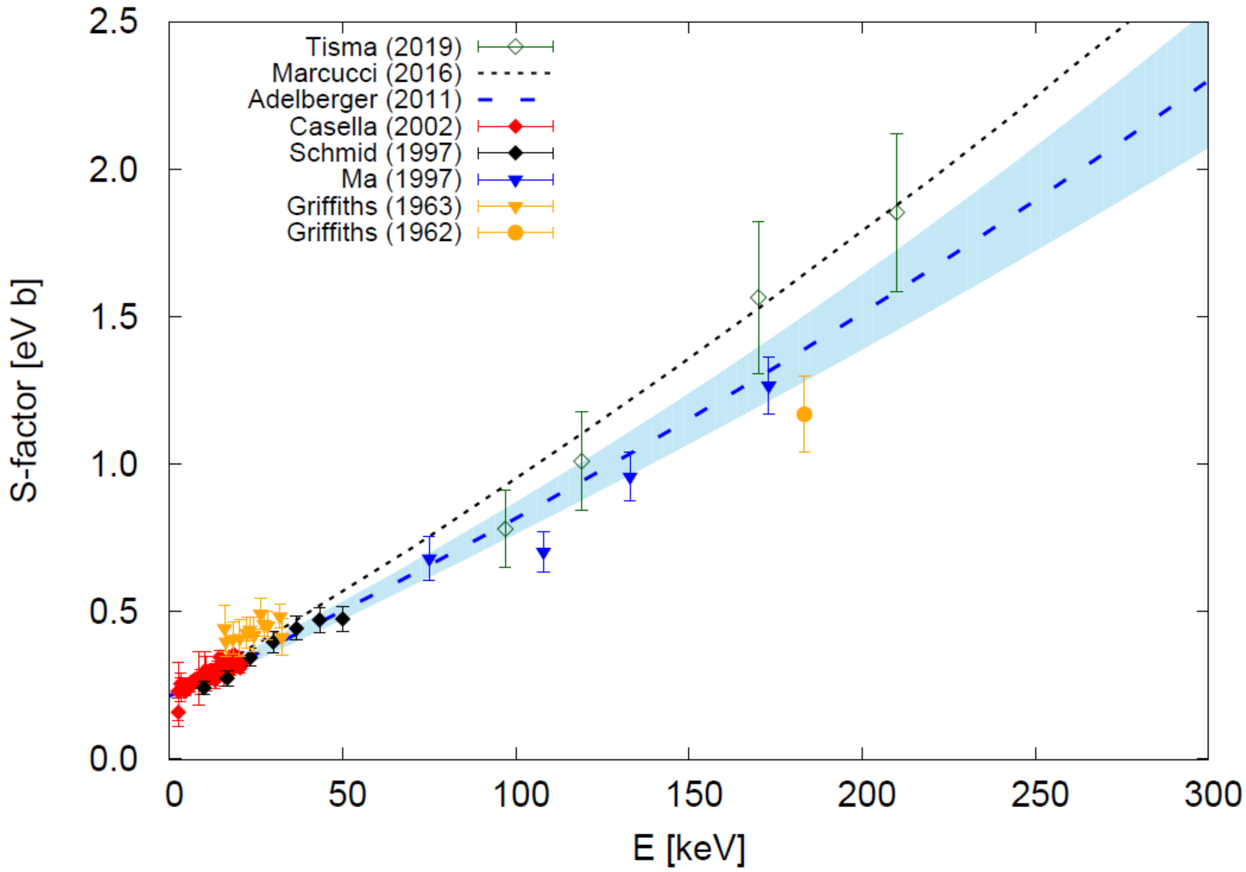
$D(p,\gamma)^3He$: State of the art

- ✓ The uncertainty on $[D/H]_{BBN}$ is related to the knowledge of the reactions involved in the deuterium production and distruction

Reaction	**σ_D 10^5**
$p(n,\gamma)D$	0.002
$D(p,\gamma)^3He$	0.062
$D(d,n)^3He$	0.020
$D(d,p)^3H$	0.013

- ✓ The uncertainty on $[D/H]_{BBN}$ is dominated by the uncertainty on the $D(p,\gamma)^3He$ S-factor

D(p,γ)^{3}He: State of the art



- ✓ Experimental data: two datasets currently available in the BBN energy range with a systematic error of 9-15%
- ✓ Ab initio calculations disagree with experimental data

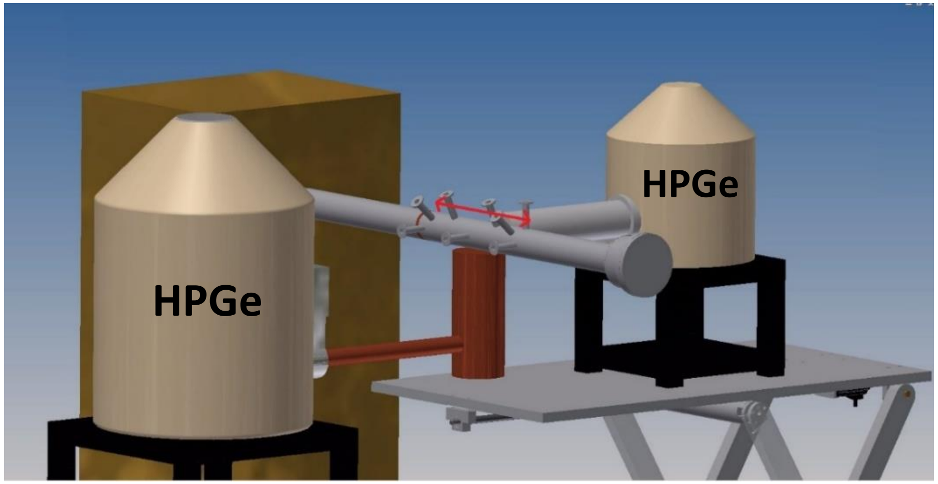
D(p,γ)^{3}He: experimental setup

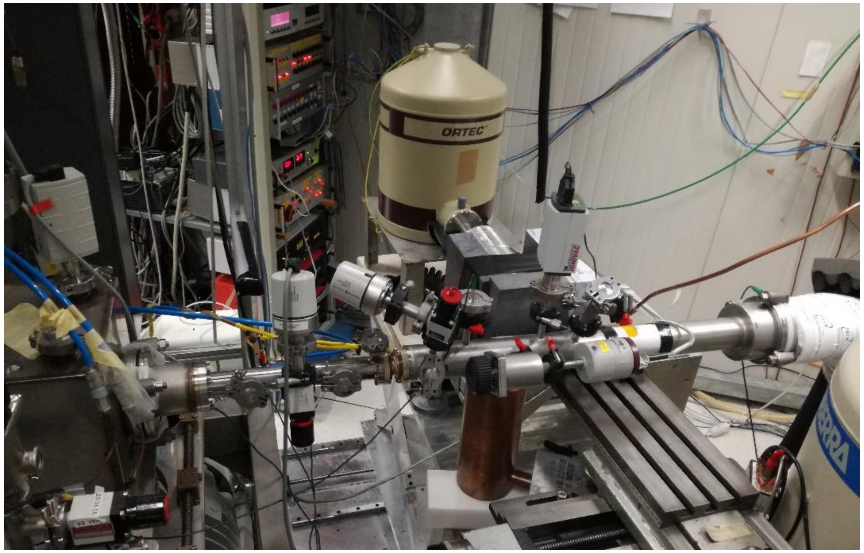
Measurement goal:

- ✓ Cross section measurement with ~3% accuracy
- ✓ E_{cm}= 30-300 keV

Experimental setup:

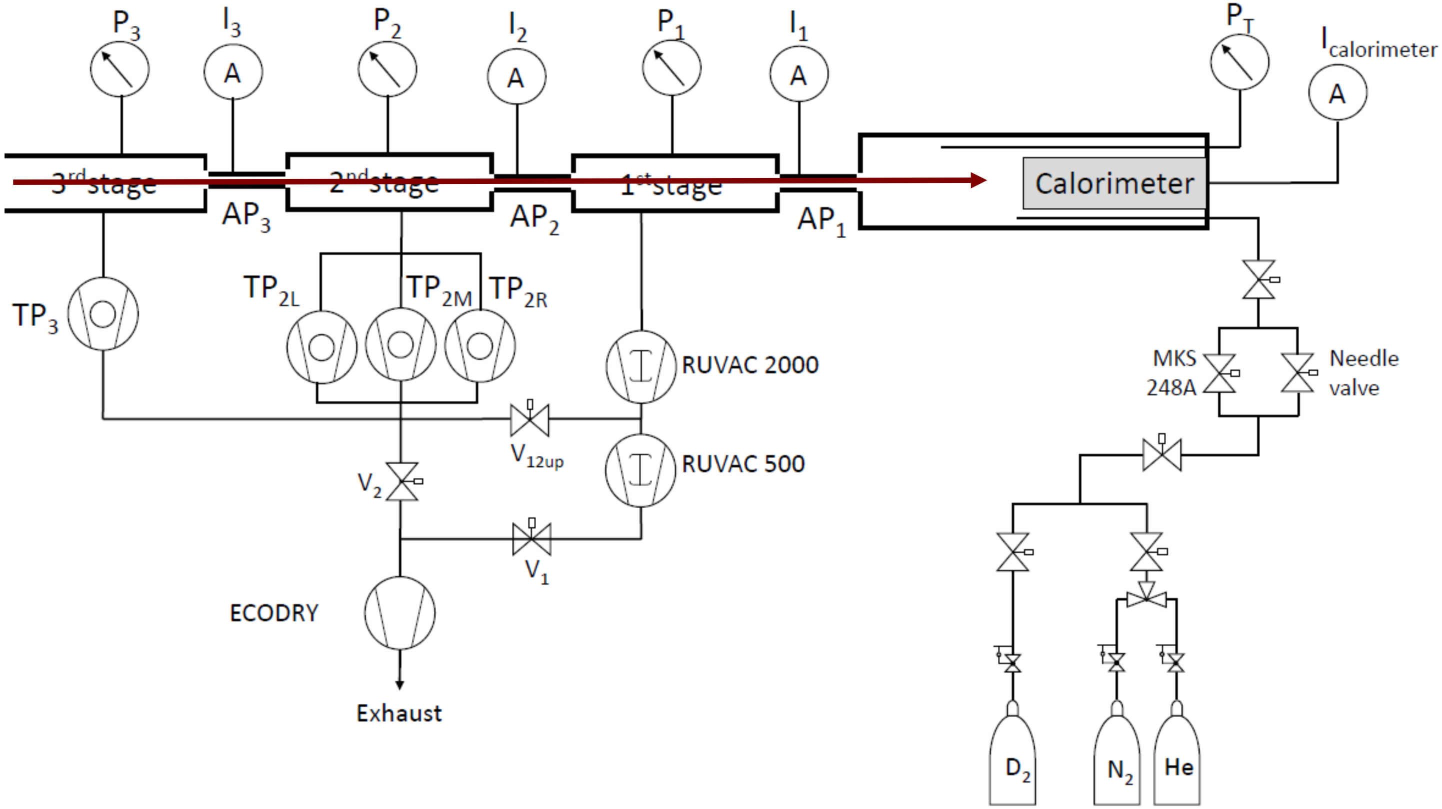
- ✓ Proton beam
- ✓ D_2 windowless gas target (P=0.3 mbar)
- ✓ HPGe detectors for γ-rays





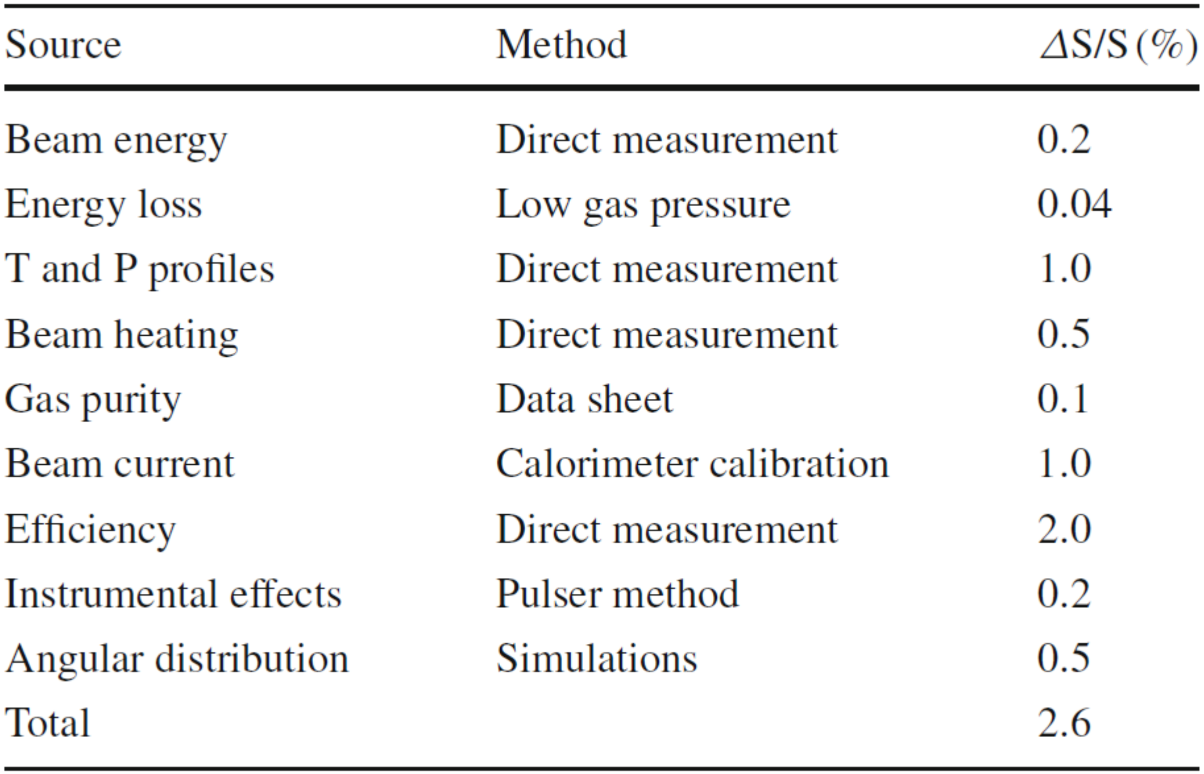
D(p,γ)^{3}He: experimental setup

- ✓ Windowless gas target setup



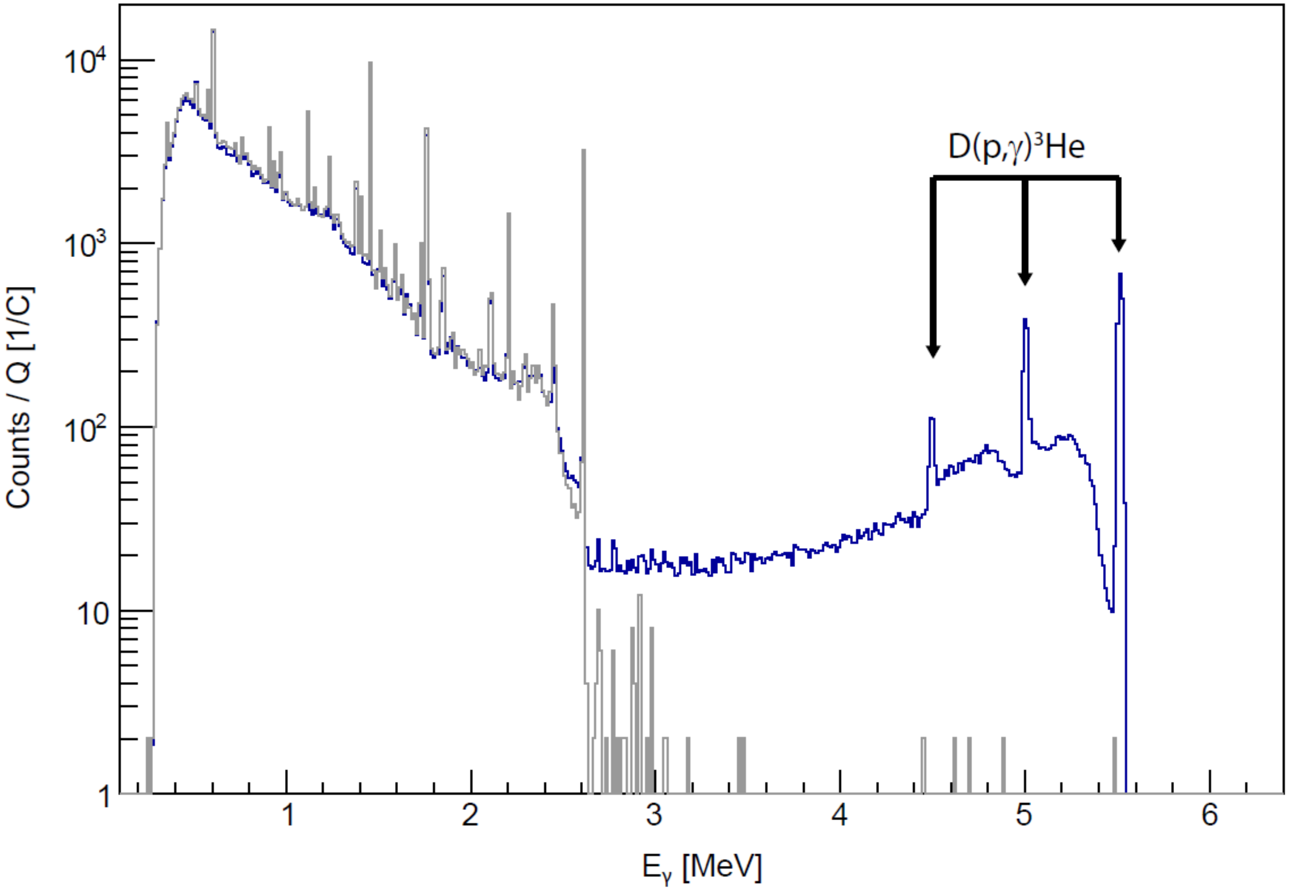
$D(p,\gamma)^3He$: study of systematic uncertainties

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z, E_\gamma)W(z)dz}$$



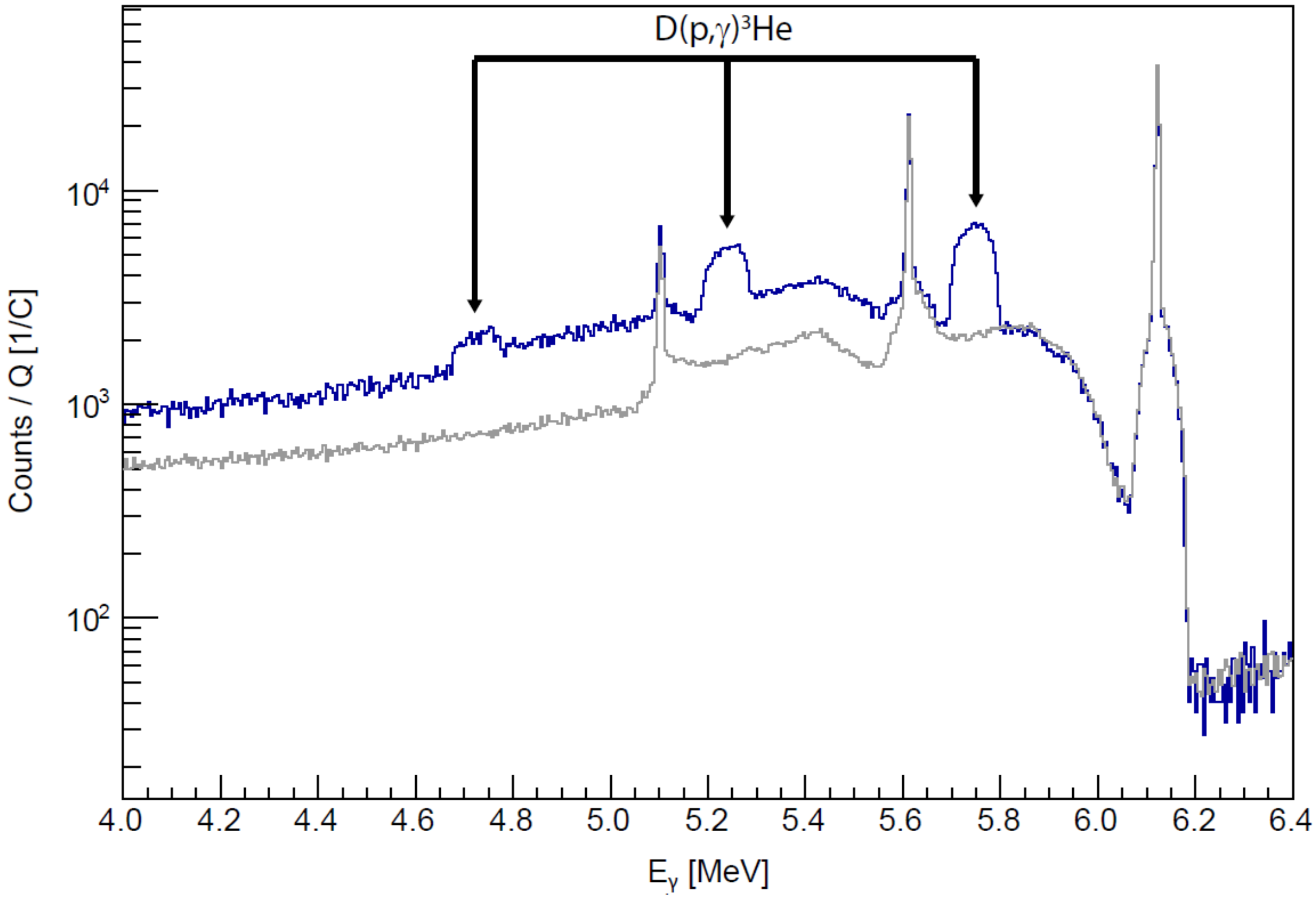
Source	Method	ΔS/S (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

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



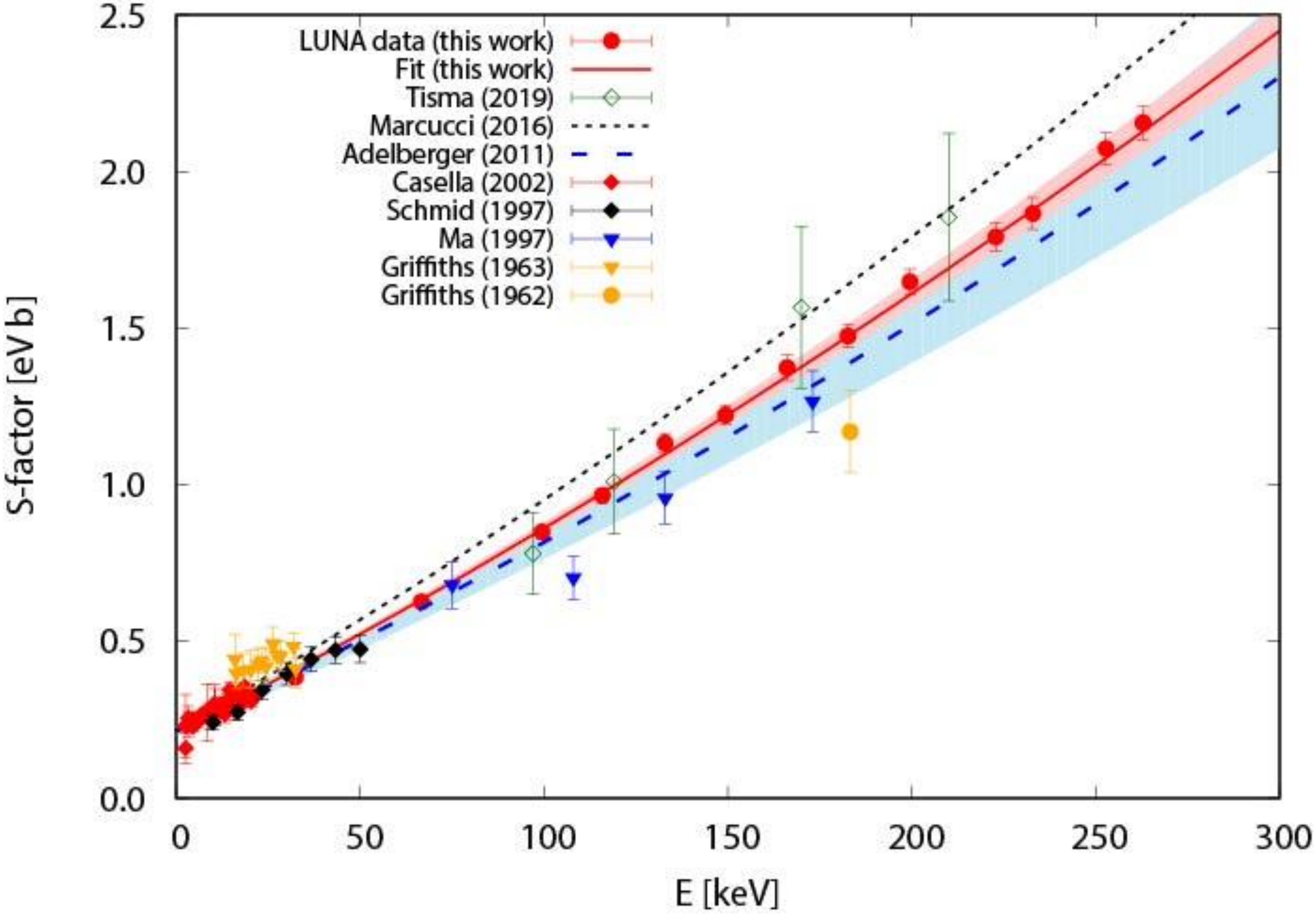
- ✓ Spectrum obtained @ E_p = 50 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 50 keV with ^4He gas target (P=0.4 mbar)

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



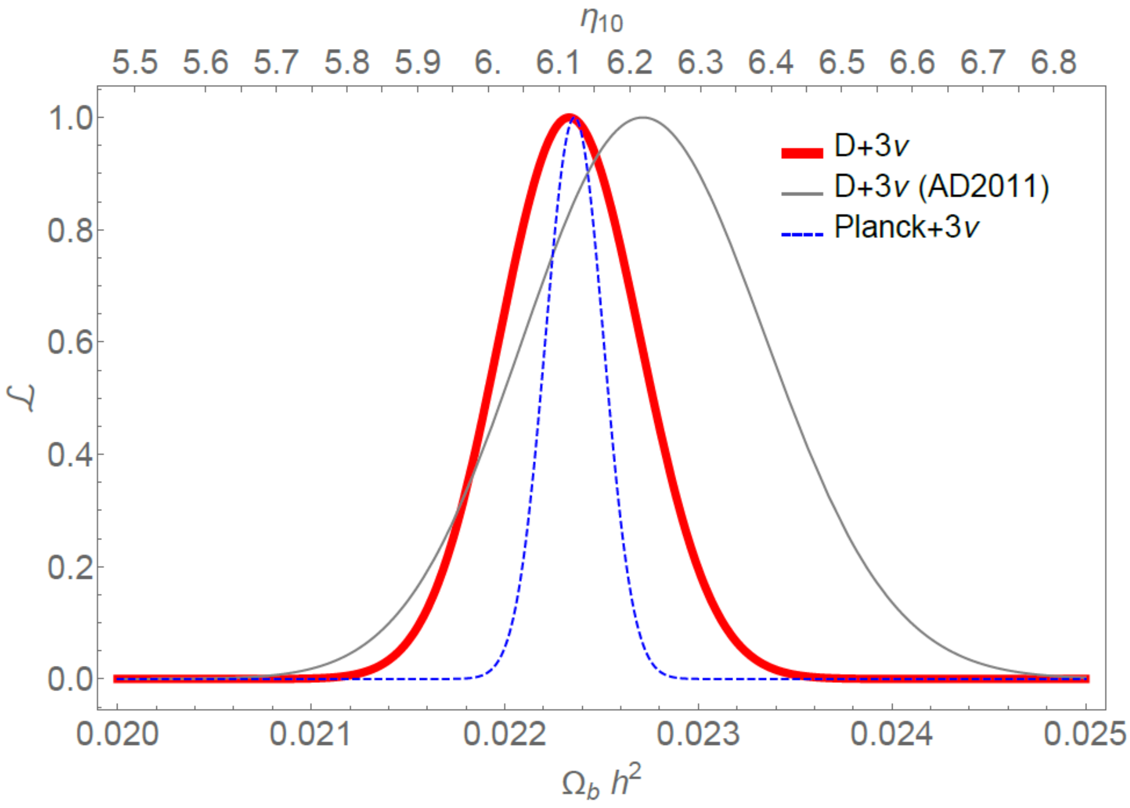
- ✓ Spectrum obtained @ E_p = 395 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 395 keV with ^4He gas target (P=0.3 mbar)

D(p,γ)^{3}He: S-factor results



The baryon density of the Universe

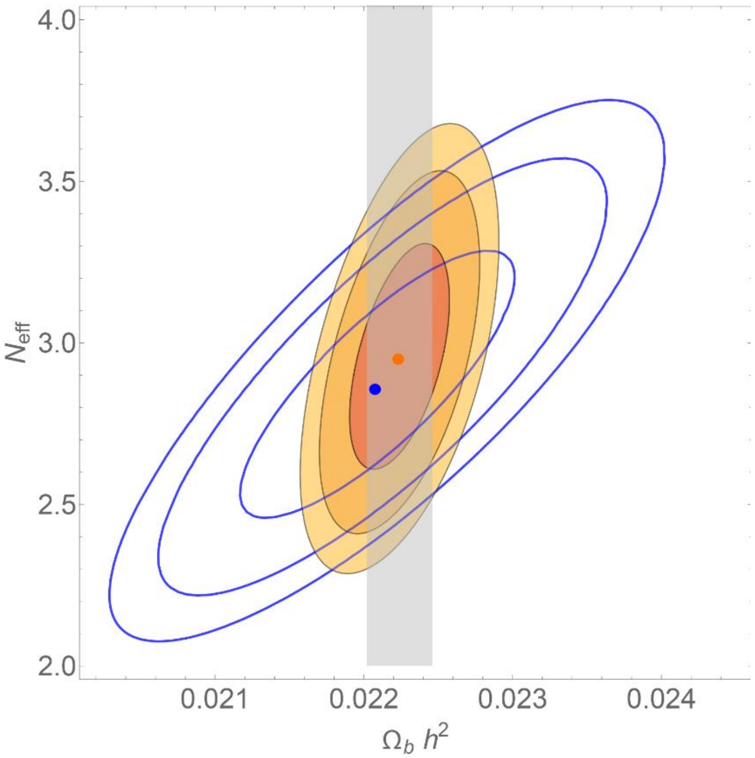
- ✓ Baryon density obtained with PARTHENOPE code by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- ✓ $N_{eff} = 3.045$, fixed
- ✓ Comparison with Planck results



Analysis performed by Ofelia Pisanti and Gianpiero Mangano

Evidence of new physics?

- ✓ Likelihood analysis in wich both $\Omega_b h^2$ and N_{eff} were left as free parameters
  - ❖ D+CMB case with $(D/H)_{obs}$ and $(D/H)_{BBN}$, combined with the CMB baryon density from Planck
  - ❖ D+Y_p case with observed and predicted values of both the deuterium abundance and the ^{4}He mass fraction, Y_p



$$N_{eff} = 2.95^{+0.61}_{-0.57}$$

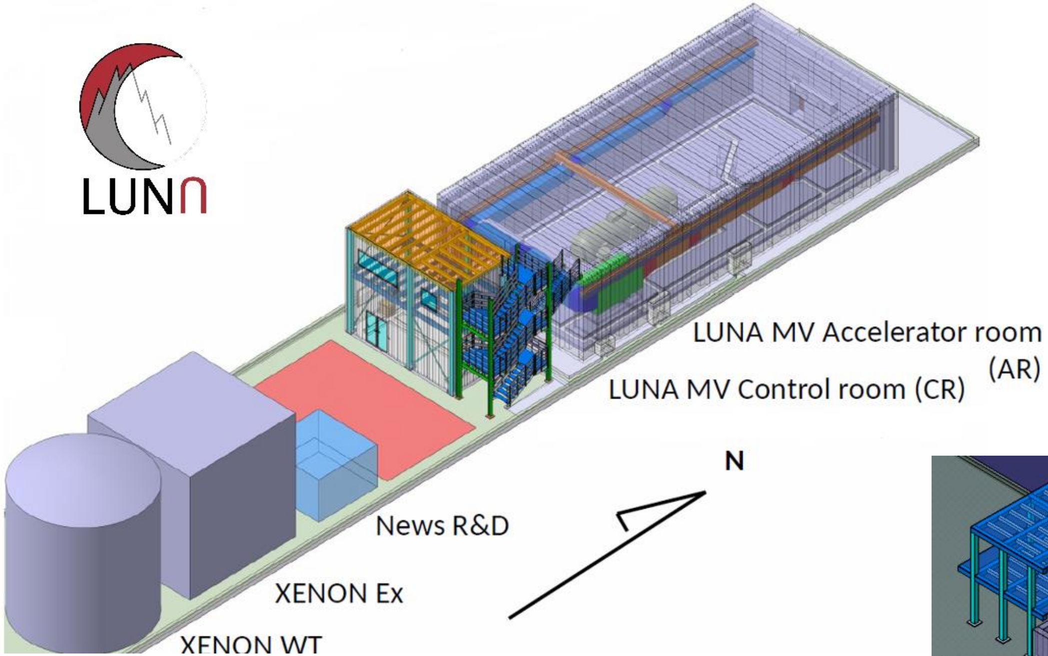
$$N_{eff} = 2.86^{+0.75}_{-0.67}$$

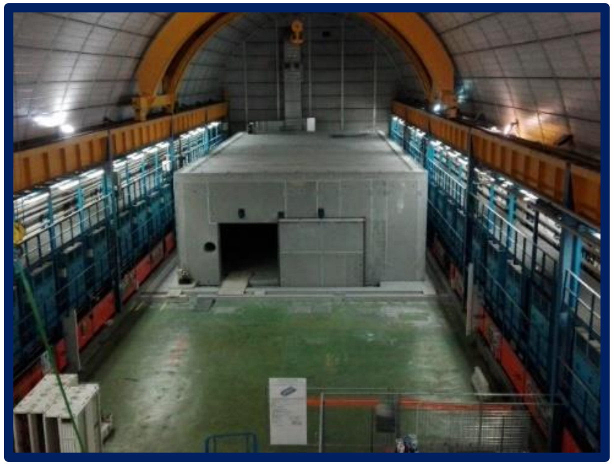
Our largest value of N_{eff} deviates by at most 20% from N_{eff} = 3.045

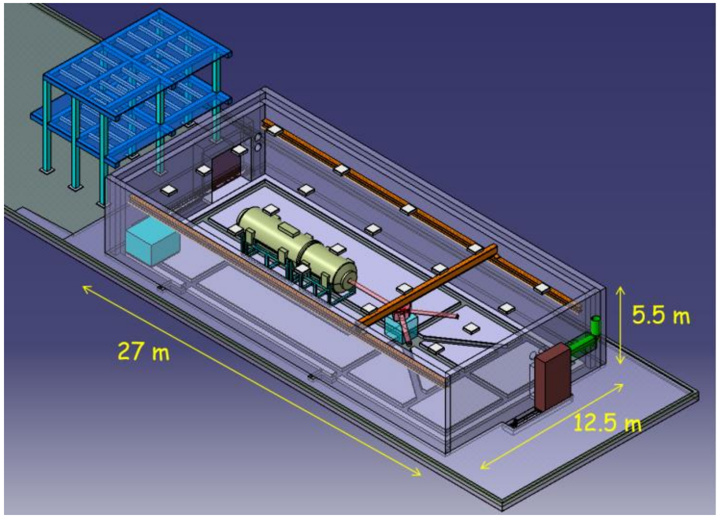
The future

LUNA MV: A 3.5 MV accelerator

LUNA







H $^{1}H^{+}$ (TV: 0.3 – 3.5 MV): 500-1000 µA

He $^{4}He^{+}$ (TV: 0.3 – 3.5 MV): 300-500 µA

C $^{12}C^{+}$ (TV: 0.3 – 3.5 MV): 150 µA

$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 µA

LUNA MV: scientific program (first five years)

- ✓ $^{14}N(p,\gamma)^{15}O$ reaction: commisioning measurement
  - ❖ Already studied at LUNA
  - ❖ High scientific interest: Solar Standard Model prediction for the solar composition → a measurement in a wide energy range is needed
- ✓ Neutron sources for the weak and main s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
  - ❖ $^{13}C(\alpha,n)^{16}O$: for a better extrapolation at low energies a measurement in a wide energy range is needed
  - ❖ $^{22}Ne(\alpha,n)^{25}Mg$: in the energy region of interest $570\ \text{keV} < E_\alpha < 800\ \text{keV}$ no direct experimental data are available
- ✓ $^{12}C + {}^{12}C$: of crucial importance for C burning. It influences the chemical composition of the Universe

Conclusions

The LUNA result settles the most uncertain nuclear physics input to BBN calculations and substantially improve the reliability of using primordial abundances as probes of the physics of the early Universe

le Scienze

edizione italiana di Scientific American

COMPUTER SCIENCE ASTROFISICA FARMACI COVID-19 MEMORIA EVOLUZIONE ALIMENTAZIONE

Kia Service: 100% Ricambi Originali SCOPRI DI PIÙ › KIA

18 novembre 2020

Studiata in dettaglio una reazione nucleare avvenuta poco dopo il big bang

di Thomas Lewton/Quanta Magazine

The LUNA collaboration

- A. Boeltzig, A. Compagnucci*, M. Junker| INFN LNGS/ *GSSI, L'AQUILA, Italy
- D. Bemmerer, K. Stoeckel| HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski | Università di Padova and INFN Padova, Italy
- A. Formicola, C. Gustavino | INFN Roma1, Italy
- L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyurky, T. Szucs | MTA-ATOMKI Debrecen, Hungary
- M. Lugaro | Konkoly Observatory, Hungarian Academy of Sciences, Budapest, Hungary
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
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- A. Best, G.F. Ciani, A. Di Leva, G. Imbriani, D.Rapagnani| Università di Napoli and INFN Napoli, Italy
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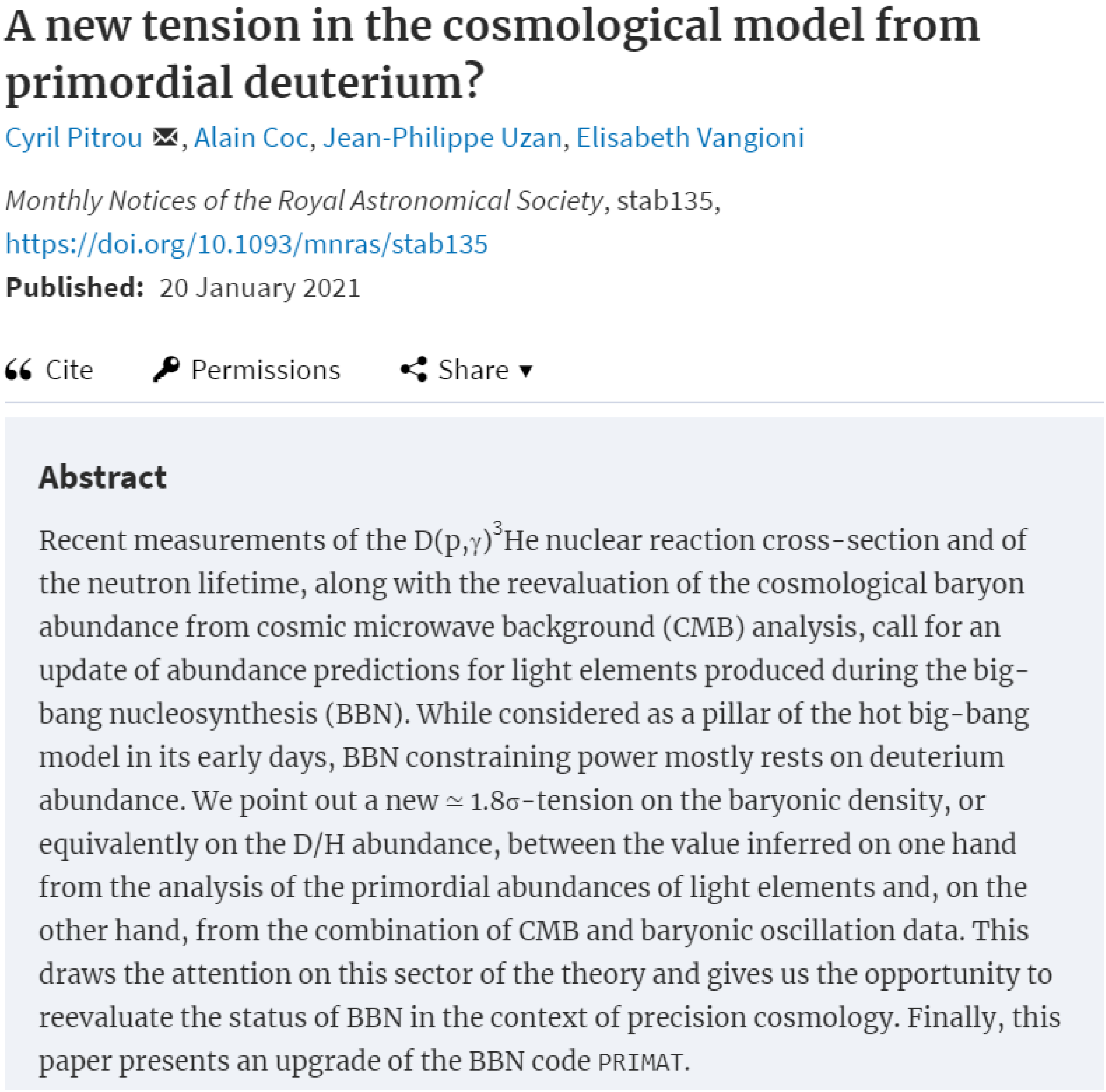
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh, United Kingdom
- F. Barile, V. Mossa, V. Paticchio, R. Perrino*, L. Schiavulli| Università di Bari and INFN Bari/*Lecce, Italy

Extra slides



A new tension in the cosmological model from primordial deuterium?

Cyril Pitrou ✉, Alain Coc, Jean-Philippe Uzan, Elisabeth Vangioni

Monthly Notices of the Royal Astronomical Society, stab135,
https://doi.org/10.1093/mnras/stab135
Published: 20 January 2021

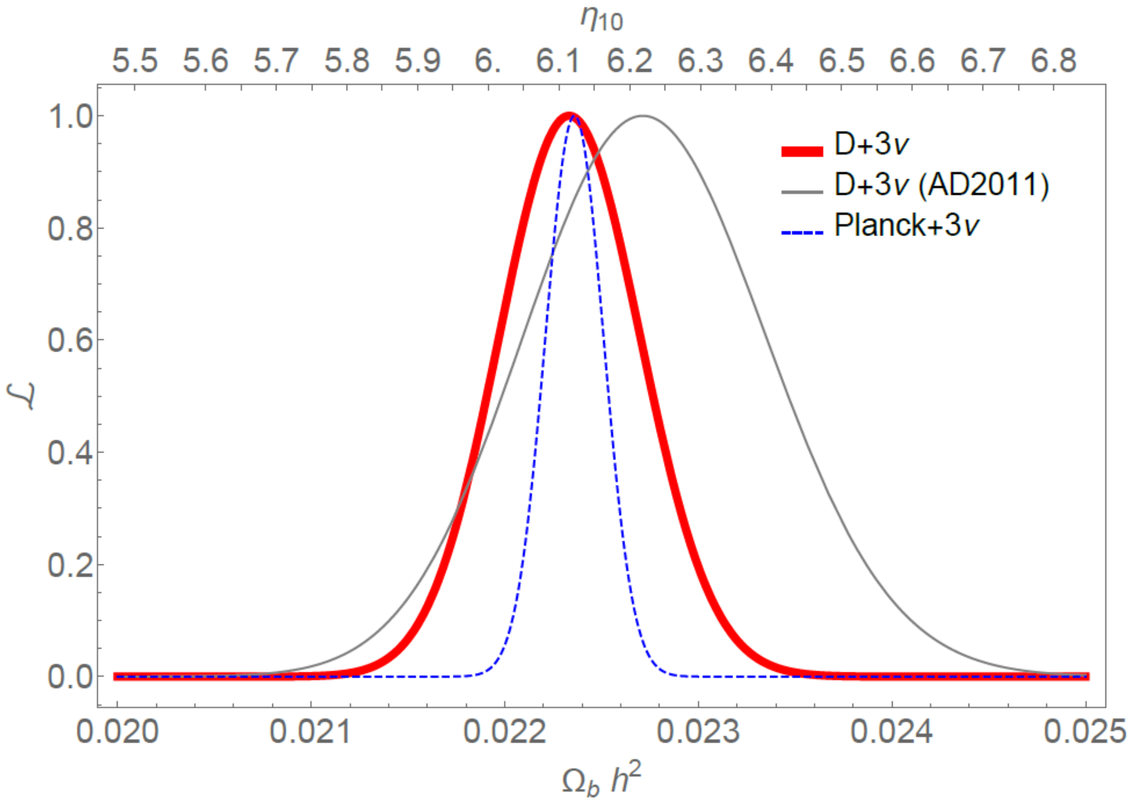
Abstract

Recent measurements of the D(p,γ)^{3}He nuclear reaction cross-section and of the neutron lifetime, along with the reevaluation of the cosmological baryon abundance from cosmic microwave background (CMB) analysis, call for an update of abundance predictions for light elements produced during the big-bang nucleosynthesis (BBN). While considered as a pillar of the hot big-bang model in its early days, BBN constraining power mostly rests on deuterium abundance. We point out a new $\simeq 1.8\sigma$-tension on the baryonic density, or equivalently on the D/H abundance, between the value inferred on one hand from the analysis of the primordial abundances of light elements and, on the other hand, from the combination of CMB and baryonic oscillation data. This draws the attention on this sector of the theory and gives us the opportunity to reevaluate the status of BBN in the context of precision cosmology. Finally, this paper presents an upgrade of the BBN code `PRIMAT`.

The baryon density of the Universe

- ✓ Baryon density obtained by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- ✓ $N_{eff} = 3.045$, fixed
- ✓ Comparison with Planck results

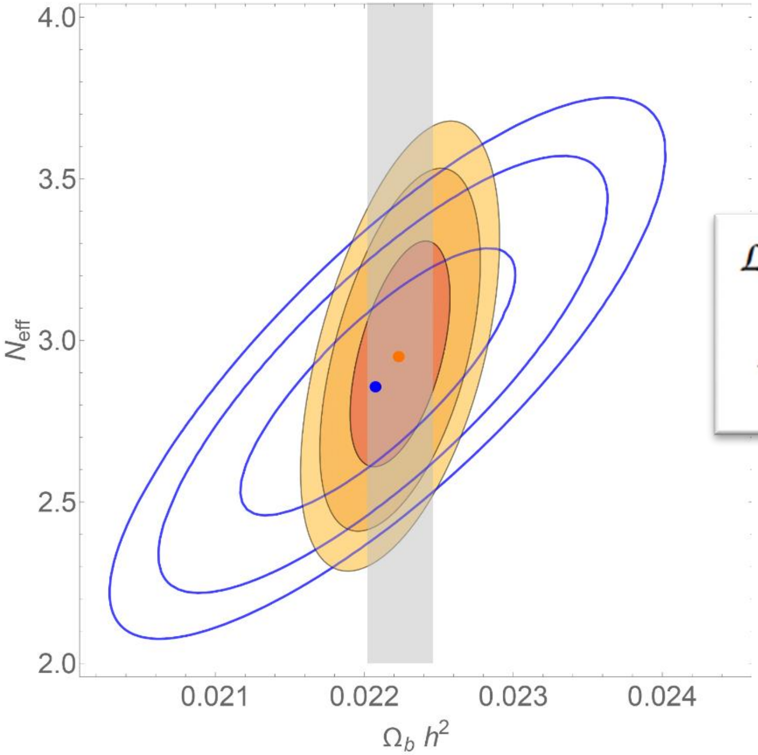
$$\mathcal{L}_{D+3\nu}(\Omega_b h^2) = \exp\left[-\frac{[(D/H)_{BBN}(\Omega_b h^2) - (D/H)_{obs}]^2}{2[\sigma^2_{BBN}(\Omega_b h^2) + \sigma^2_{obs}]} \right]$$

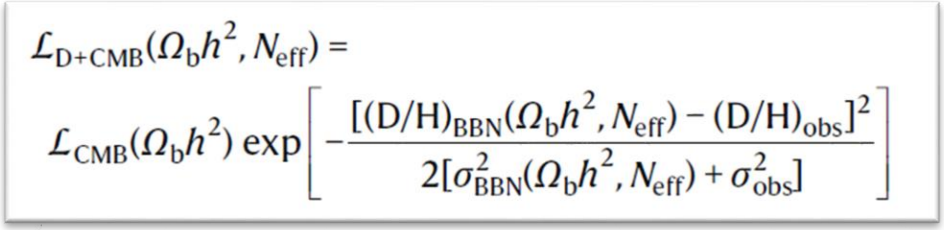


Analysis performed by Ofelia Pisanti and Gianpiero Mangano

Evidence of new physics?

- ✓ Likelihood analysis in wich both $\Omega_b h^2$ and N_{eff} were left as free parameters
  - ❖ D+CMB case with $(D/H)_{obs}$ and $(D/H)_{BBN}$, combined with the CMB baryon density from Planck
  - ❖ D+Y_p case with observed and predicted values of both the deuterium abundance and the ^{4}He mass fraction, Y_p





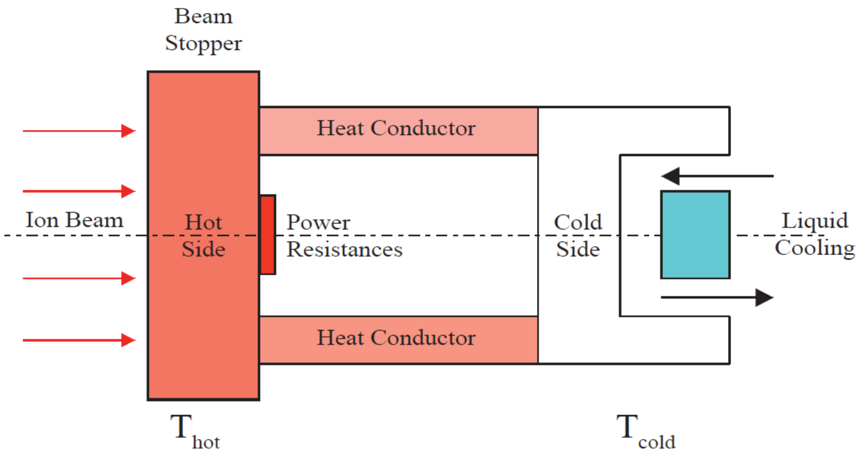
$$\mathcal{L}_{\mathrm{D+CMB}}(\Omega_b h^2, N_{\mathrm{eff}}) = \mathcal{L}_{\mathrm{CMB}}(\Omega_b h^2)\exp\left[-\frac{[(\mathrm{D/H})_{\mathrm{BBN}}(\Omega_b h^2, N_{\mathrm{eff}}) - (\mathrm{D/H})_{\mathrm{obs}}]^2}{2[\sigma^2_{\mathrm{BBN}}(\Omega_b h^2, N_{\mathrm{eff}}) + \sigma^2_{\mathrm{obs}}]}\right]$$

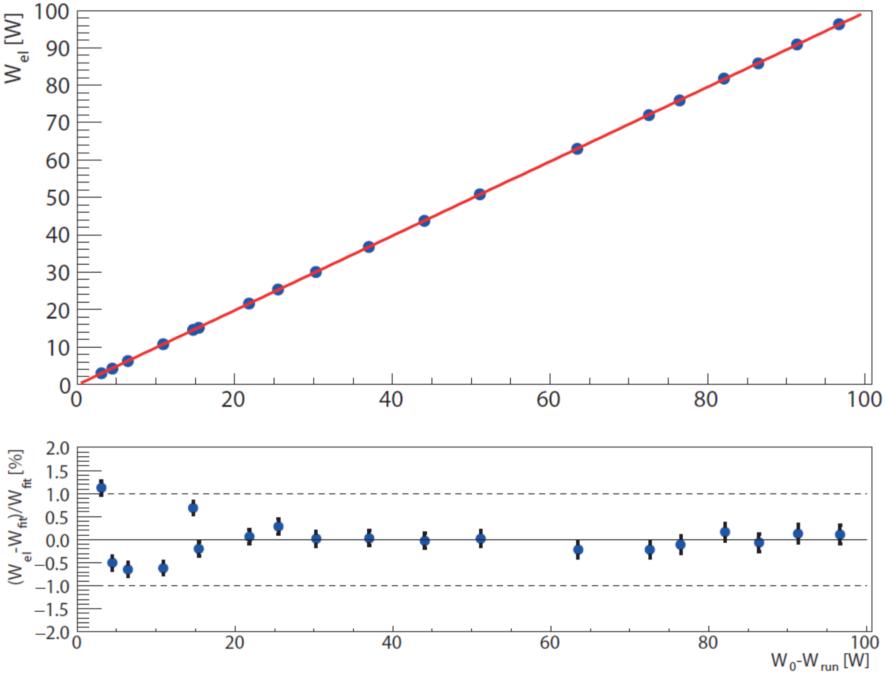
$$N_{eff} = 2.95^{+0.61}_{-0.57}$$

$$N_{eff} = 2.86^{+0.75}_{-0.67}$$

$D(p,\gamma)^3He$: systematic uncertainties

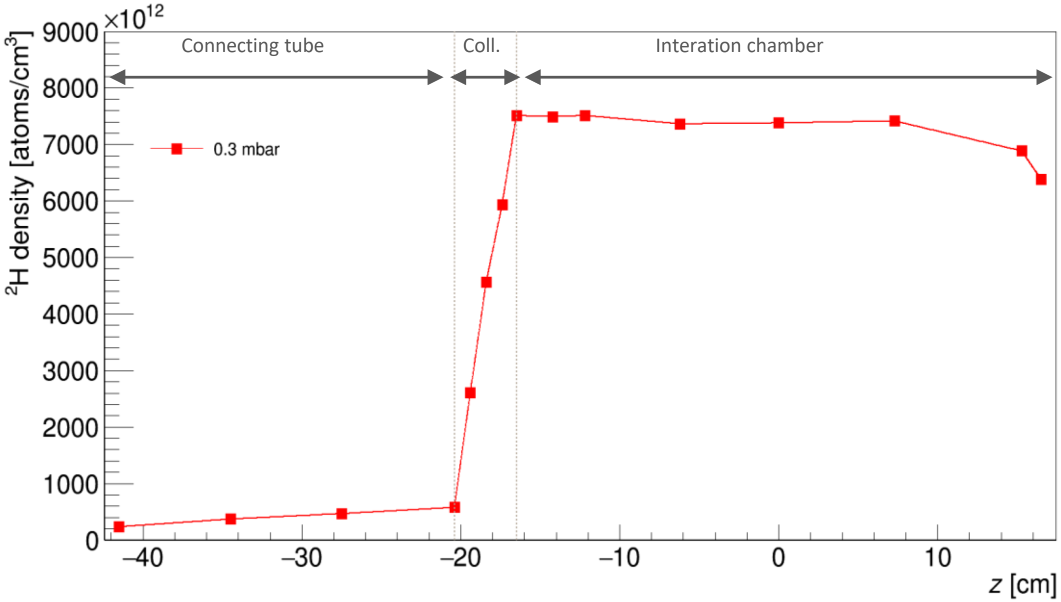
- ✓ Goal: 3% accuracy on the $D(p,\gamma)^3He$ cross section (Q= 5.5 MeV)
- ✓ $\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$





D(p,γ)^{3}He: systematic uncertainties

- ✓ Goal: 3% accuracy on the D(p,γ)^{3}He cross section (Q= 5.5 MeV)
- ✓ $\sigma(E) = \dfrac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$

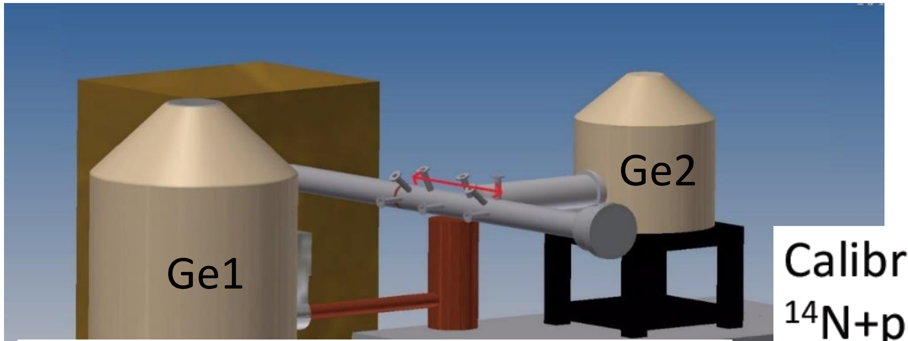


D(p,γ)^{3}He: systematic uncertainties

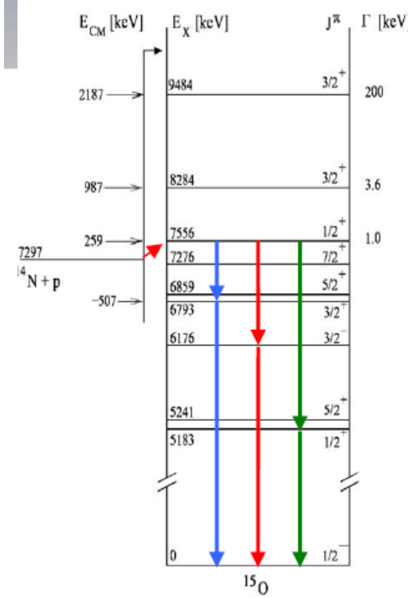
$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$$

E_γ= 5.5-5.8 MeV → efficiency calibration:

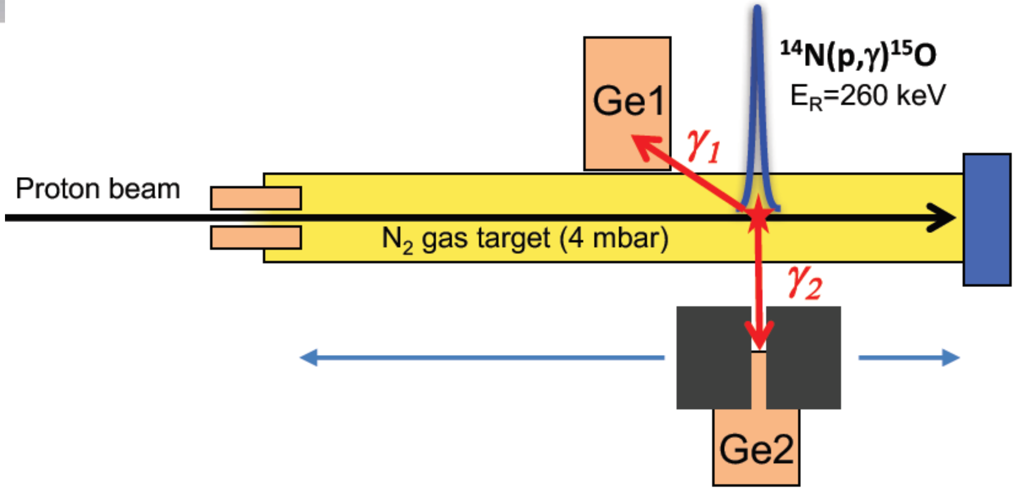
- ✓ radioactive sources
- ✓ E_R = 260 keV resonance of ^{14}N(p,γ)^{15}O



Calibration exploiting the reaction:
$^{14}N+p \rightarrow ^{15}O+\gamma_1+\gamma_2$

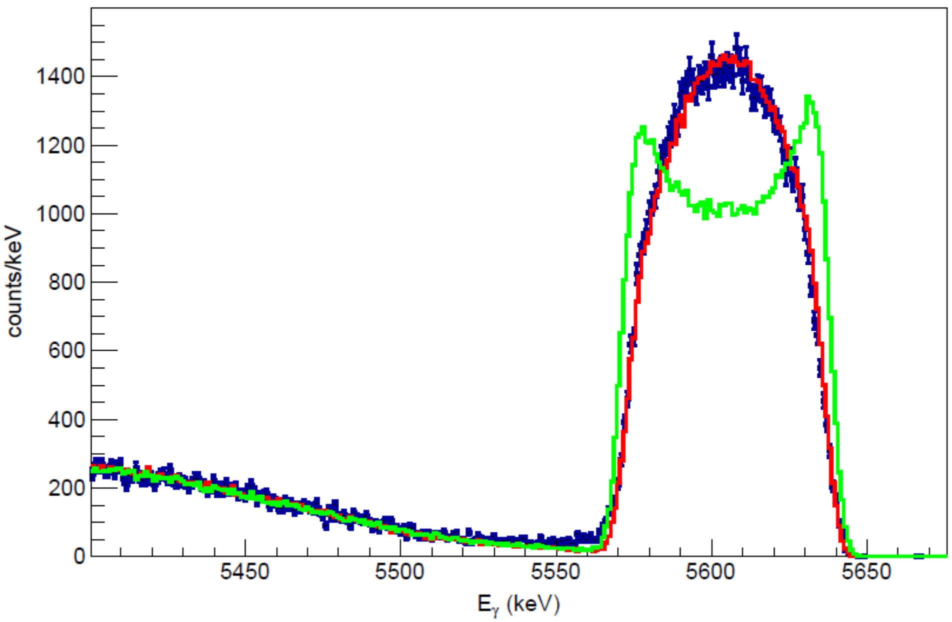


Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1



D(p,γ)^{3}He: systematic uncertainties

- ✓ Goal: 3% accuracy on the D(p,γ)^{3}He cross section (Q= 5.5 MeV)
- ✓ $\sigma(E) = \dfrac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$



$$E_\gamma = \frac{m_\mathrm{p}^2 + m_\mathrm{D}^2 - m_\mathrm{He}^2 + 2(E_\mathrm{p} + m_\mathrm{p})m_\mathrm{D}}{2(E_\mathrm{p} + m_\mathrm{p} + m_\mathrm{D} - p_\mathrm{p}\cos\theta_\mathrm{lab})}$$

Primordial deuterium abundance

- ✓ Deuterium abundance:

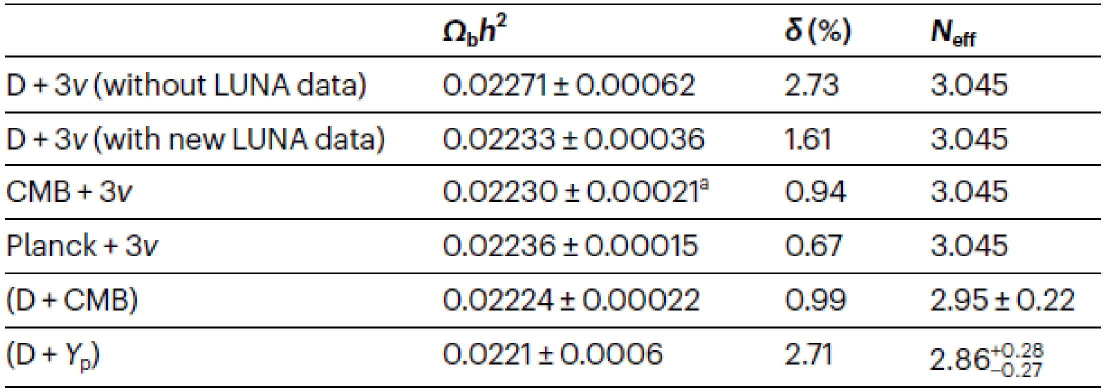
$$\frac{D}{\mathrm{H}} = 2.51 \times 10^{-5}\, R_{pn\gamma}^{-0.20}\, R_{dp\gamma}^{-0.31}\, R_{ddn}^{-0.51}\, R_{ddp}^{-0.42} \left(\frac{\omega_b}{0.02242}\right)^{-1.61} \left(\frac{\tau_n}{879.4\,\mathrm{s}}\right)^{0.43} \left(1 + \frac{\Delta N_{\mathrm{eff}}}{3.045}\right)^{0.41}$$

- ✓ Chi2:

$$\chi^2(a_l, \omega_k) = \sum_{i_k} \frac{(S_{th}(E_{i_k}, a_l) - \omega_k\, S_{i_k})^2}{\omega_k^2\, \sigma_{i_k}^2} + \sum_k \frac{(\omega_k - 1)^2}{\epsilon_k^2} \equiv \chi^2_{stat} + \chi^2_{norm}$$

$$\rho \approx \rho_{\mathrm{rad}} = \frac{\pi^2}{30}\left(2 + \frac{7}{2} + \frac{7}{4} N_\nu\right) T^4$$

Baryon density of the Universe



	$\Omega_b h^2$	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
(D + CMB)	0.02224 ± 0.00022	0.99	2.95 ± 0.22
(D + Y_p)	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$

$$D/H_{BBN} = (2.52 \pm 0.03 \pm 0.06)\ 10^{-5}$$

Before and after LUNA measurement

	$\sigma_{\mathrm{D}}^{(i)} \cdot 10^5$	$\delta\sigma_i^2/\sigma_{\mathrm{tot}}^2$ (%)	$(\sigma_{\mathrm{D}}^{(i)})_{\mathrm{old}} \cdot 10^5$	$(\delta\sigma_i^2/\sigma_{\mathrm{tot}}^2)_{\mathrm{old}}$ (%)
$R_{pn\gamma}$	0.002	0.3	0.002	0.1
$R_{dp\gamma}$	0.027	58.5	0.062	87.0
R_{ddn}	0.018	26.9	0.020	9.1
R_{ddp}	0.013	14.2	0.013	3.8

Cosmological parameters and D/H abundance