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

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Abstract

Light elements were produced in the first few minutes of the Universe through a sequence of nuclear reactions known as Big Bang nucleosynthesis (BBN)[1,2]. Among the light elements produced during BBN[1,2], deuterium is an excellent indicator of cosmological parameters because its abundance is highly sensitive to the primordial baryon density and also depends on the number of neutrino species permeating the early Universe. Although astronomical observations of primordial deuterium abundance have reached percent accuracy[3], theoretical predictions[4–6] based on BBN are hampered by large uncertainties on the cross-section of the deuterium burning $D(p,\gamma)^3He$ reaction. Here we show that our improved cross-sections of this reaction lead to BBN estimates of the baryon density at the 1.6 percent level, in excellent agreement with a recent analysis of the cosmic microwave background[7]. Improved cross-section data were obtained by exploiting the negligible cosmic-ray background deep underground at the Laboratory for Underground Nuclear Astrophysics (LUNA) of the Laboratori Nazionali del Gran Sasso (Italy)[8,9]. We bombarded a high-purity deuterium gas target[10] with an intense proton beam from the LUNA 400-kilovolt accelerator[11] and detected the γ-rays from the nuclear reaction under study with a high-purity germanium detector. Our experimental results settle the most uncertain nuclear physics input to BBN calculations and substantially improve the reliability of using primordial abundances to probe the physics of the early Universe.

Primordial Nucleosynthesis

- Accurate determinations of the deuterium abundance can be obtained from the absorption strength in Lyman-α clouds along the line-of-sight to quasars at high redshift. [D/H] ≈ $(2.527\pm0.030)\times10^{-5}$.

$$p(n,\gamma)D$$

$$D(n,\gamma)^3H,\quad D(D,p)^3H$$

$$D(p,\gamma)^3He,\quad D(D,n)^3He,\quad ^3H(p,n)^3He,\quad ^3H(\ ,e\overline{\nu}_e)^3He$$

$$^3H(p,\gamma)^4He,\quad ^3H(D,n)^4He,\quad ^3He(n,\gamma)^4He,\quad ^3He(D,p)^4He,$$

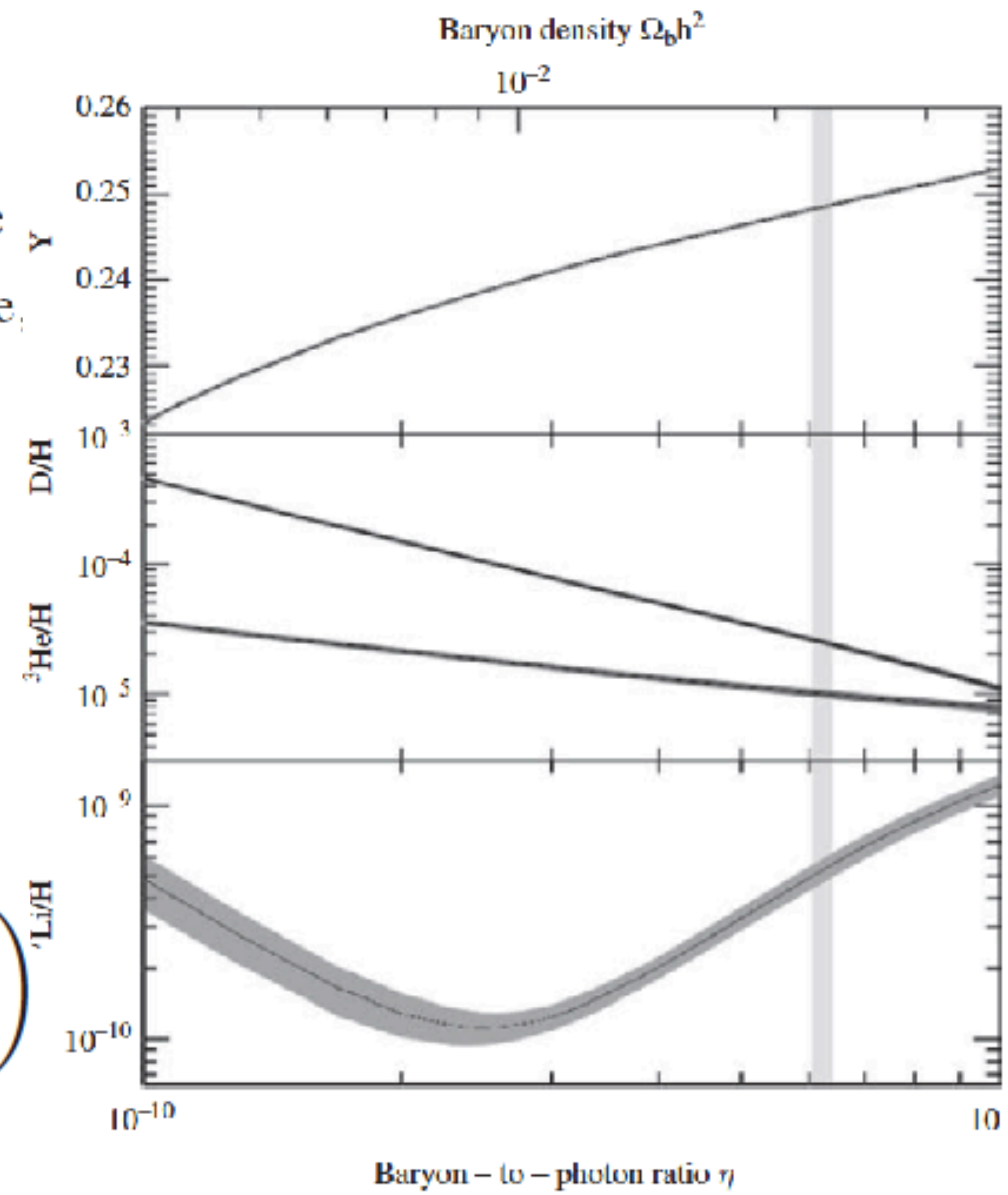
$$2\,^3He(\ ,2p)^4He,\quad ^7Li(p,\ )2\,^4He$$

$$^4He(^3H,\gamma)^7Li,\quad ^4He(^3He,\gamma)^7Be,\quad ^7Be(e,\nu_e)^7Li.$$

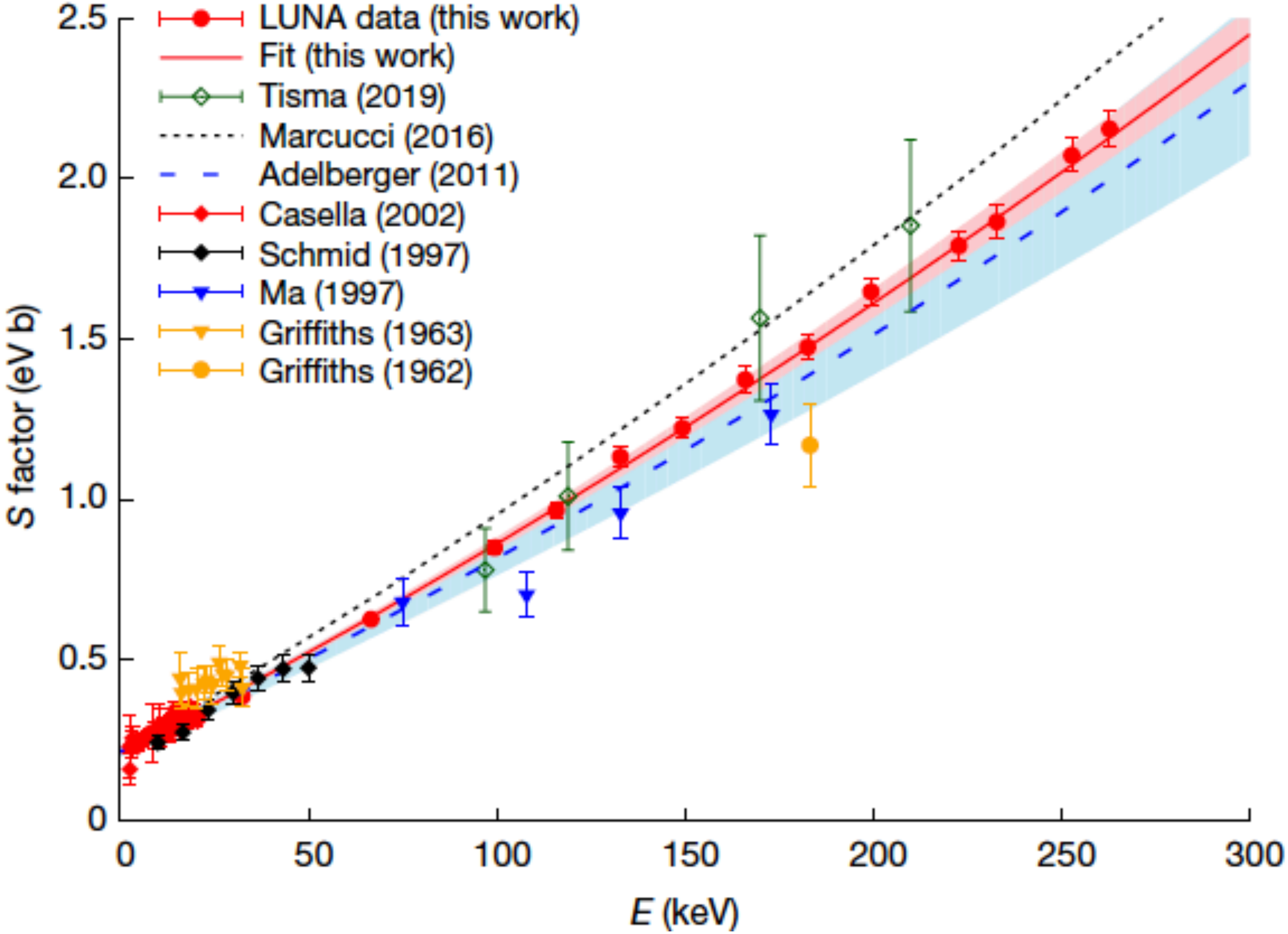
$$\Gamma = (4.55\times10^{-20}\,\mathrm{cm^3\,s^{-1}})n_p$$

$$\approx 2.9\times10^4 X_p\Omega_{b,0}h^2\left(\frac{T}{10^{10}\,\mathrm{K}}\right)^3\ \mathrm{s^{-1}}$$

$$X_D \approx 16.4\eta X_n X_p \eta \left(\frac{m_N}{T}\right)^{-3/2}\exp\left(\frac{2.22\,\mathrm{MeV}}{T}\right)$$

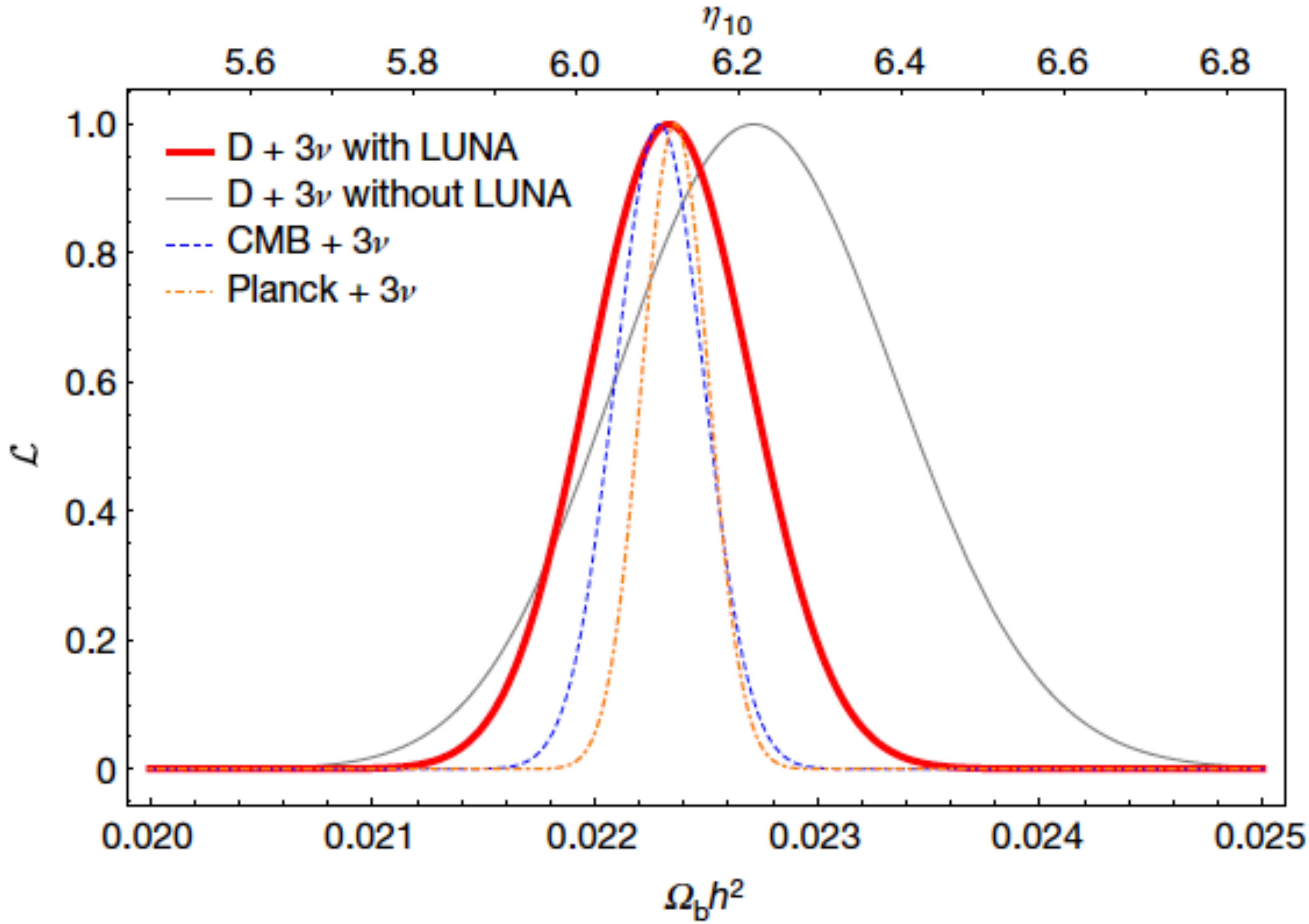


Experiment



LUNA data (this work)
Fit (this work)
Tisma (2019)
Marcucci (2016)
Adelberger (2011)
Casella (2002)
Schmid (1997)
Ma (1997)
Griffiths (1963)
Griffiths (1962)
S factor (eV b)
0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
250
300
E (keV)

Results



η_{10}
5.6
5.8
6.0
6.2
6.4
6.6
6.8
1.0
0.8
0.6
0.4
0.2
0
$\mathcal{L}$
D + 3ν with LUNA
D + 3ν without LUNA
CMB + 3ν
Planck + 3ν
0.020
0.021
0.022
0.023
0.024
0.025
$\Omega_b h^2$

Results

Table 1 | Mean values and 68% confidence level ranges for $\Omega_b h^2$ (with relative uncertainties δ) and N_{eff}

	$\Omega_b h^2$	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	$2.86^{+0.28}_{-0.27}$

Results