

# Gauging the baryon density of the Universe from an improved rate of deuterium burning

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42 **Among the light elements produced during Big Bang Nucleosynthesis<sup>1,2</sup> (BBN), deuterium**  
43 **is an excellent indicator of cosmological parameters because its abundance is highly sensi-**  
44 **tive to the primordial baryon density and also depends on the number of neutrino species**  
45 **permeating the early Universe. While astronomical observations of primordial deuterium**  
46 **abundance have reached percent accuracy<sup>3</sup>, theoretical predictions<sup>4-6</sup> based on BBN are**  
47 **hampered by large uncertainties on the cross section of the deuterium burning  $D(p,\gamma)^3\text{He}$**   
48 **process. Here we show that our improved cross sections finally allow for BBN estimates of**  
49 **the baryon density at the 1.6% level, in excellent agreement with a recent analysis of the**  
50 **Cosmic Microwave Background<sup>7</sup>. Improved cross-section data were obtained by exploit-**  
51 **ing the negligible cosmic-ray background deep underground at the Laboratory for Under-**  
52 **ground Nuclear Astrophysics (LUNA) of the Laboratori Nazionali del Gran Sasso (Italy)<sup>8,9</sup>.**  
53 **We bombarded a high-purity deuterium gas target<sup>10</sup> with an intense proton beam from the**  
54 **LUNA 400 kV accelerator<sup>11</sup> and detected the  $\gamma$  rays from the nuclear reaction under study**  
55 **with a high-purity germanium detector. Our experimental results settle the most uncertain**  
56 **nuclear physics input to BBN calculations and substantially improve the reliability of using**  
57 **primordial abundances as probes of the physics of the early Universe.**

58 Light elements were produced in the first few minutes of the Universe through a sequence  
59 of nuclear reactions known as Big Bang Nucleosynthesis (BBN)<sup>1,2</sup>. The theoretical description of  
60 BBN is based on the standard cosmological model (hereafter the “ $\Lambda$ CDM model”<sup>2</sup>), which assumes  
61 a homogeneous and isotropic universe governed by general relativity and by the Standard Model of

62 particle physics. Under these assumptions, BBN predicts the abundances of primordial nuclides,  
63 mainly  $^2\text{H}$  (hereafter D),  $^3\text{He}$ ,  $^4\text{He}$ , and  $^7\text{Li}$ , as a function of one parameter only, the density of  
64 ordinary matter, or baryon density,  $\Omega_b h^2$  (see Fields *et al.*<sup>12</sup> for a recent review). Therefore, a  
65 comparison between the observed primordial abundances and those predicted by the BBN can be  
66 used to constrain this fundamental quantity. Yet an independent evaluation of  $\Omega_b h^2$  can also be  
67 obtained by measuring the anisotropies in the Cosmic Microwave Background (CMB), the relic  
68 electromagnetic radiation left over from the Big Bang.

69 It should be noted that  $\Omega_b h^2$  from the CMB reflects the baryon density of the Universe at  
70 the re-combination epoch, some 380,000 years after the Big Bang. However, according to the  
71  $\Lambda\text{CDM}$  model, the baryon density can only vary as a result of the expansion of the Universe and  
72 thus its present-day value inferred from either CMB and BBN should be the same. Therefore, the  
73 evaluation of  $\Omega_b h^2$  based on BBN alone is critical as it can either support the  $\Lambda\text{CDM}$  model or  
74 point to new physics between the BBN and CMB epochs<sup>2</sup>. We present a new evaluation of  $\Omega_b h^2$   
75 from BBN based on improved experimental nuclear physics inputs obtained at the Laboratory for  
76 Underground Nuclear Astrophysics (LUNA)<sup>8,9</sup> of the INFN Laboratori Nazionali del Gran Sasso  
77 (Italy).

78 Of the elements produced during the BBN, deuterium (D) is an excellent indicator of cosmo-  
79 logical parameters in the early Universe because its abundance is the most sensitive to the baryon  
80 density  $\Omega_b h^2$  and also depends on the radiation density, usually expressed in terms of the effec-  
81 tive number  $N_{\text{eff}}$  of neutrino species<sup>2</sup>. Since deuterium is almost exclusively produced during

82 BBN, and is only destroyed during stellar evolution, its primordial abundance can be obtained  
83 from astrophysical sites not affected by stellar evolution<sup>4</sup>. The best determination of the deu-  
84 terium abundance is presently obtained by analysing the light spectra of quasars crossing pristine  
85 gas clouds at high redshift. Recent astronomical observations<sup>3</sup> have reached excellent precision  
86 and provide a weighted mean value of the primordial deuterium abundance relative to hydrogen,  
87  $(D/H)_{\text{obs}} = (2.527 \pm 0.030) \times 10^{-5}$ , with a 1% uncertainty<sup>3</sup> (hereafter, quoted errors are at 68%  
88 confidence level unless stated otherwise). By contrast, theoretical predictions of D/H based on  
89 BBN,  $(D/H)_{\text{BBN}}$ , are less clear: Coc *et al.*<sup>5</sup> report a value in agreement with observations, but with  
90 a higher uncertainty, while Pitrou *et al.*<sup>4</sup> report a value in tension with observations, albeit with  
91 a similar precision. Improving such predictions requires an accurate knowledge of the nuclear  
92 reaction rates involved in the synthesis of deuterium: specifically, production via the well-known  
93  $p(n,\gamma)D$  process, and destruction via the  $D(d,n)^3\text{He}$ ,  $D(d,p)^3\text{H}$ , and  $D(p,\gamma)^3\text{He}$  reactions. Of these,  
94 the  $D(p,\gamma)^3\text{He}$  reaction<sup>4-6</sup> carries the largest uncertainties because of insufficient experimental data  
95 at relevant BBN energies. While the  $D(p,\gamma)^3\text{He}$  cross section, or equivalently its  $S$  factor (see  
96 Methods “ $D(p,\gamma)^3\text{He}$  cross-section measurements at LUNA”), is well known<sup>13</sup> at low energies,  
97  $E \simeq 3 - 20$  keV (energies are in the centre of mass system unless stated otherwise), higher energy  
98 data<sup>14-17</sup> are affected by systematic uncertainties of 9% or more. In addition, a recent *ab-initio*  
99 theoretical calculation<sup>18</sup> disagrees at the level of 20-30% with a widely used  $S$ -factor best fit<sup>19</sup> to  
100 selected data sets<sup>13-15,20</sup> and at the level of  $\sim 8\%$  with a fit by Iliadis *et al.*<sup>21</sup>. As a result, BBN  
101 predictions of primordial deuterium abundance remain unsatisfactory, which calls for improved  
102 measurements of the  $D(p,\gamma)^3\text{He}$  reaction cross-section over a wide energy range<sup>3-6,12</sup>.

103 The new measurement of the  $D(p,\gamma)^3\text{He}$  cross section discussed in this paper was performed  
 104 at the LUNA-400kV accelerator<sup>11</sup>, a world-leading facility to study nuclear reactions at the low-  
 105 est energies frontier of nuclear astrophysics. The million-fold reduction in cosmic-ray muons of  
 106 the deep-underground location<sup>8</sup> and a careful commissioning<sup>10</sup> of the experimental setup aimed  
 107 at minimising all sources of systematic errors have led to  $D(p,\gamma)^3\text{He}$  cross-section data of un-  
 108 precedented precision and with overall uncertainties below 3% over the measured energy region  
 109 ( $E = 32 - 263$  keV), relevant to BBN energies ( $E = 30 - 300$  keV, see Methods). As shown  
 110 in Figure 1, the new data represent a significant improvement compared to previous work<sup>14,15,17</sup>.  
 111 Our new  $S$ -factor best fit (red solid line) implies a destruction of deuterium that is faster com-  
 112 pared to the best fit<sup>19</sup> of previous experimental data (blue dashed curve), and slower compared to  
 113 predictions based on the *ab-initio* calculation<sup>18</sup> (black dotted curve).

114 To explore the impact of our  $D(p,\gamma)^3\text{He}$   $S$ -factor on the predicted primordial deuterium abun-  
 115 dance, we used the second release<sup>22</sup> of the numerical BBN code PArthENoPE. Under the assump-  
 116 tion of the  $\Lambda\text{CDM}$  model, with<sup>23,24</sup>  $N_{\text{eff}} = 3.045$ , we performed a Bayesian likelihood analysis  
 117 (see Methods) to derive  $\Omega_b h^2$  using the observed deuterium abundance,  $(D/H)_{\text{obs}}$ , and the the-  
 118 oretical behaviour of  $(D/H)_{\text{BBN}}$  (now including the new LUNA data). We obtain  $\Omega_b h^2(\text{BBN}) =$   
 119  $0.02233 \pm 0.00036$ . As shown in Figure 2, this value is a factor of 2 more precise than that obtained  
 120 using a previous  $S$  factor<sup>19</sup> and now in much better agreement with the  $\Omega_b h^2$  based on CMB data<sup>12</sup>  
 121 (see values in Table 1). The use of BBN deuterium alone as a baryometer has now approached a  
 122 precision comparable to that obtained from CMB analyses<sup>7,12</sup>. The fact that the present-day values  
 123 of  $\Omega_b h^2(\text{BBN})$  and  $\Omega_b h^2(\text{CMB})$  are fully consistent with each other (Table 1) offers evidence of

124 the validity of the  $\Lambda$ CDM model adopted here.

125 We note that if we use the baryon density provided by the PLANCK Collaboration<sup>7</sup>, we  
126 derive a theoretical prediction on deuterium abundance  $(D/H)_{\text{BBN}} = (2.52 \pm 0.03 \pm 0.06) \times 10^{-5}$ ,  
127 in excellent agreement with astronomical observations<sup>3</sup>  $(D/H)_{\text{obs}} = (2.527 \pm 0.030) \times 10^{-5}$ . The  
128 quoted errors on  $(D/H)_{\text{BBN}}$  stem from the propagation of uncertainties in the baryon density (first  
129 error) and the nuclear rates (second error).

130 To probe the existence of physics beyond the  $\Lambda$ CDM model, we performed likelihood analy-  
131 ses in which both  $\Omega_b h^2$  and  $N_{\text{eff}}$  were left as free parameters. Since the deuterium abundance alone  
132 cannot be used to constrain  $\Omega_b h^2$  and  $N_{\text{eff}}$  when they are both varied, we considered two cases  
133 with additional inputs. In one case, hereafter (D+CMB), we used the deuterium abundance, both  
134 observed  $(D/H)_{\text{obs}}$  and predicted  $(D/H)_{\text{BBN}}$ , combined with a Gaussian distribution of the CMB  
135 baryon density<sup>7</sup>, with mean value and uncertainty as obtained by PLANCK without constraining  
136  $N_{\text{eff}}$ ; in the second case, hereafter (D+ $Y_p$ ), we used observed and predicted values of both the deu-  
137 terium abundance and the  $^4\text{He}$  mass fraction<sup>25</sup>,  $Y_p$ , without constraining  $\Omega_b h^2$ . Results are shown  
138 in Figure 3 as contour plots in the plane  $N_{\text{eff}}$  vs.  $\Omega_b h^2$ . Numerical values at 68% confidence level  
139 are reported in Table 1. We note that, at the 99% confidence level, we obtain  $N_{\text{eff}} = 2.95^{+0.61}_{-0.57}$   
140 and  $N_{\text{eff}} = 2.86^{+0.75}_{-0.67}$  for the two (D+CMB) and (D+ $Y_p$ ) cases, respectively. Our largest values of  
141  $N_{\text{eff}}$  deviate by at most 20% from its standard value<sup>23,24</sup>  $N_{\text{eff}} = 3.045$ . This implies a maximum  
142 amount of “dark radiation”, due to particle species which are not foreseen by the standard model  
143 of particle physics, in agreement with PLANCK<sup>7</sup>.

144 Although the (D+CMB) and (D+ $Y_p$ ) cases discussed above lead to consistent outcomes,  
145 the (D+ $Y_p$ ) result depends on the value of  $Y_p$  used. In our analysis, we adopted the value of  
146 Aver *et al.*<sup>25</sup>, which is close to those of Peimbert *et al.*<sup>26</sup>, Valerdi *et al.*<sup>27</sup>, and the recommended  
147 value in Tanabashi *et al.*<sup>2</sup>. When the much higher  $Y_p$  value of Izotov *et al.*<sup>28</sup> is used, we obtain  
148  $N_{\text{eff}} = 3.60_{-0.43}^{+0.45}$  (99% confidence level).

149 To conclude, we have measured the  $D(p,\gamma)^3\text{He}$  reaction cross section to an unprecedented  
150 precision of better than 3% by exploiting the million-fold reduction in cosmic-ray muons at LUNA.  
151 The new  $S$  factor has led to a remarkable improvement in the evaluation of the present-day baryon  
152 density,  $\Omega_b h^2$ , using standard Big Bang Nucleosynthesis alone. Our value is now in better agree-  
153 ment with the one derived from the analysis of the Cosmic Microwave Background anisotropies  
154 and provides further support to the standard cosmological model. When combined with additional  
155 inputs such as CMB baryon density or the primordial helium abundance, our data also provide a  
156 strong experimental foundation to constrain the amount of dark radiation.

157 **Methods**

158 **D(p, $\gamma$ )<sup>3</sup>He cross-section measurements at LUNA.** The cross section of the D(p, $\gamma$ )<sup>3</sup>He reaction  
 159 ( $Q = 5.493$  MeV) was measured in direct kinematics using a high intensity (100 – 300  $\mu$ A) proton  
 160 beam from the LUNA-400kV accelerator<sup>11</sup> over the full dynamic energy range  $E_p = 50 - 395$  keV,  
 161 corresponding to centre-of-mass energies  $E = 33 - 263$  keV. The beam was sent onto a windowless  
 162 and extended gas target containing high-purity (99.999%) deuterium maintained at a pressure of  
 163  $P = 0.3$  mbar by a system of three differential pumping stages. A copper calorimeter<sup>29</sup> at the end  
 164 of the gas target stopped the beam and allowed its intensity to be measured. Gamma rays from  
 165 the D(p, $\gamma$ )<sup>3</sup>He reaction were detected by a large high-purity germanium detector (HPGe) mounted  
 166 in close geometry under the target chamber and facing its centre. Full details of the experimental  
 167 setup and its commissioning have been described elsewhere<sup>10</sup>.

168 For an extended gas target of length  $L$ , the cross section of the D(p, $\gamma$ )<sup>3</sup>He reaction can be  
 169 expressed in terms of experimentally measurable quantities as:

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z) \epsilon(z, E_\gamma) W(z) dz} \quad (1)$$

170 where  $N_\gamma(E)$  is the net number of detected  $\gamma$  rays at a given interaction energy  $E$ ,  $N_p$  is the number  
 171 of incident protons,  $\rho(z)$  is the number density of target atoms as a function of interaction position  
 172  $z$  along the target,  $\epsilon(z, E_\gamma)$  is the  $\gamma$ -ray detection efficiency, and  $W(z)$  is a term accounting for the  
 173 angular distribution of the emitted  $\gamma$  rays.

174 Under experimental conditions at LUNA, the  $\gamma$  rays emitted by the D(p, $\gamma$ )<sup>3</sup>He reaction  
 175 ( $Q = 5.5$  MeV) have energies  $E_\gamma = 5.5 - 5.8$  MeV, *i.e.* far away from the energy of the com-

176 monly used radioactive sources. Thus, a measurement of the detection (photo-peak) efficiency was  
177 performed using different-energy  $\gamma$  rays emitted in cascade from the well-known resonant reac-  
178 tion  $^{14}\text{N}(p,\gamma_1\gamma_2)^{15}\text{O}$ . Efficiency corrections were validated by extensive Monte-Carlo simulations  
179 as described in detail in Mossa *et al.*<sup>10</sup>.

180 To reduce the uncertainty on the final cross-section, we performed dedicated measurements  
181 to minimise the systematic errors associated with each term of Eq. (1).

182 A typical  $\gamma$ -ray spectrum taken at a proton beam energy  $E_p = 50$  keV is shown in Extended  
183 Data Figure 1. We note that the  $\gamma$ -ray background at LUNA is 3-4 orders of magnitude lower than  
184 on the Earth's surface<sup>8</sup> in the region of interest ( $E_\gamma \simeq 5.5 - 5.8$  MeV) for the  $\text{D}(p,\gamma)^3\text{He}$  reaction.  
185 As a result, the counting statistical error could be kept below 1% at all beam energies. The main  
186 source of beam-induced background was due to the  $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$  reaction from the interaction  
187 of protons with fluorine contaminant usually present on collimators along the gas target and on  
188 the calorimeter<sup>10</sup> (beam dump). This beam-induced background ( $E_\gamma < 7$  MeV) was found to  
189 be negligible at beam energies  $E_p < 250$  keV. At higher energies, approaching the well-known  
190  $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$  resonance at  $E_p = 340$  keV, the beam-induced background was carefully accounted  
191 for in dedicated control runs in which (inert)  $^4\text{He}$  gas was used instead of deuterium. A sample  
192 spectrum taken at the highest beam energy studied ( $E_p = 395$  keV) is shown in Extended Data  
193 Figure 2.

194 The cross-section results obtained at LUNA for the  $\text{D}(p,\gamma)^3\text{He}$  reaction are shown in Figure 1  
195 (and summarised in Extended Data Table 1) in the form of the astrophysical  $S$  factor. This is

196 defined as<sup>30</sup>  $S(E) = E\sigma(E) \exp(2\pi\eta)$ , where  $E$  is the energy of interaction,  $\sigma(E)$  is the energy  
 197 dependent cross section, and  $\eta$  is the Sommerfeld parameter  $\eta(E) = Z_1 Z_2 \alpha (\mu c^2 / 2E)^{1/2}$  (where  
 198  $Z_1$  and  $Z_2$  are the atomic numbers of the interacting nuclei,  $\alpha$  is the fine structure constant,  $\mu$   
 199 is the reduced mass, and  $c$  is the speed of light). We achieved an overall systematic uncertainty  
 200 lower than 3%, with main contributions arising from uncertainties in beam current (1%), target  
 201 density profile (1.1%), and efficiency (2%), as described in Mossa *et al.*<sup>10</sup>. **We note that our new**  
 202 **experimental data are close to a previous fit<sup>21</sup> (not shown in Fig. 1) based on a Bayesian analysis**  
 203 **of previous selected experimental data sets.**

204 Our new  $S$  factor was used together with other data sets<sup>13–16,31–33</sup> to arrive at the best fit:

$$S(E) = 0.2121 + 5.973 \times 10^{-3} E + 5.449 \times 10^{-6} E^2 - 1.656 \times 10^{-9} E^3 \quad [\text{eV b}] \quad (2)$$

205 (with  $E$  in keV) shown in Fig. 1 (red solid line). The fit was performed over a broad energy range  
 206  $E_{\text{cm}} = 2 - 2000$  keV, following the approach of Serpico *et al.*<sup>34</sup>. At BBN energies, the fit is entirely  
 207 dominated by the new LUNA data **reported here**, thanks to their increased precision compared to  
 208 previous works. **We obtain a reduced  $\chi^2$  of 1.049.** The uncertainties on the fit (red band in Fig. 2)  
 209 are given by:

$$(\Delta S(E))^2 = 1.4 \times 10^{-5} + 2.97 \times 10^{-8} E^2 + 4.80 \times 10^{-13} E^4 + 1.12 \times 10^{-19} E^6 \quad [(\text{eV b})^2] \quad (3)$$

210 (with  $E$  in keV). The correlation among data points of the same data set was properly taken into  
 211 account<sup>34</sup> by introducing a single normalization factor for each data set, constrained by the so-  
 212 called penalty factor in the  $\chi^2$ .

213 As the universe expands, BBN takes place over a temperature range of the nucleon-photon

214 plasma  $k_B T \sim 100 - 20$  keV, with  $k_B$  being the Boltzmann constant. To better assess the en-  
 215 ergy range where precise measurements of the  $D(p,\gamma)^3\text{He}$  cross section have the largest impact in  
 216 improving the accuracy of theoretical predictions of primordial deuterium abundance relative to  
 217 hydrogen,  $(D/H)_{\text{BBN}}$ , we used a *sensitivity function* (see for example Nollett *et al.*<sup>35</sup>), defined as  
 218 the ratio of the logarithmic derivatives of the  $D/H$  abundance and the corresponding  $S$  factor:

$$\zeta(E) = \frac{\delta \log(D/H)_{\text{BBN}}}{\delta \log S(E)} \quad (4)$$

219 Specifically, we varied the  $S$  factor in 10 keV energy bins, over a broad energy region of  
 220 10 – 500 keV, and calculated the corresponding thermal rate (obtained by convolution with the  
 221 Maxwell-Boltzmann distribution) bin by bin as a function of energy. The corresponding yield of  
 222 deuterium was obtained using the PARthENoPE code<sup>22</sup> (see also Methods “Bayesian Likelihood  
 223 Analysis”). The results are shown in Extended Data Figure 3. We note that the sensitivity curve  
 224 remains above 25% of the maximum variation in a range  $E = 20 - 240$  keV, with the deuterium  
 225 abundance being most sensitive to the  $D(p,\gamma)^3\text{He}$  cross section at  $E \simeq 80$  keV, i.e. in a region  
 226 where our precision underground measurements are essential. Our values of the  $D(p,\gamma)^3\text{He}$  thermal  
 227 rate and their uncertainties are provided in Extended Data Table 2.

228 **Bayesian Likelihood Analysis.** To study the effect of the new LUNA  $D(p,\gamma)^3\text{He}$   $S$  factor on  
 229 primordial deuterium produced during Big Bang Nucleosynthesis, we have computed the corre-  
 230 sponding thermal rate and updated it (Pisanti *et al.*, in preparation) in the second release of the  
 231 BBN code PARthENoPE<sup>22</sup>. The rates of the  $D(d,n)^3\text{He}$  and  $D(d,p)^3\text{H}$  have also been updated fol-  
 232 lowing the publication of new data sets<sup>36</sup>, although their inclusion has a negligible effect (Pisanti

233 *et al., in preparation*) on the uncertainty on the  $(D/H)_{\text{BBN}}$  value presented in this work. Starting  
 234 from conditions of nuclear statistical equilibrium, PARthENoPE solves a set of coupled ordinary  
 235 differential equations that follow the departure from chemical equilibrium of nuclear species and  
 236 determines their asymptotic abundances as a function of several input cosmological parameters  
 237 such as the baryon density  $\Omega_b h^2$ , the number of effective neutrino species  $N_{\text{eff}}$ , the value of the  
 238 cosmological constant, and neutrino chemical potentials (see, e.g. Pisanti *et al.*<sup>37</sup> for details).

239 The reduced uncertainty of the LUNA results affects the precision of BBN deuterium predic-  
 240 tion and can constrain the baryon density. In a first analysis we assume a standard BBN scenario  
 241 and fix the value of the relativistic degrees of freedom to photons and three active neutrino species  
 242 ( $N_\nu = 3$ ) corresponding to a contribution  $N_{\text{eff}} = 3.045$  in the energy density of neutrinos, conven-  
 243 tionally given<sup>6</sup> as  $\rho_\nu = \frac{7}{8}(\frac{4}{11})^{4/3}\rho_\gamma N_{\text{eff}}$  (with  $\rho_\gamma$  being the photon density). We use  $(D/H)_{\text{BBN}}$  as a  
 244 function of  $\Omega_b h^2$  and the deuterium abundance inferred from astronomical observations  $(D/H)_{\text{obs}}$ .  
 245 The likelihood function is:

$$\mathcal{L}_{D+3\nu}(\Omega_b h^2) = \exp \left[ -\frac{[(D/H)_{\text{BBN}}(\Omega_b h^2) - (D/H)_{\text{obs}}]^2}{2[\sigma_{\text{BBN}}^2(\Omega_b h^2) + \sigma_{\text{obs}}^2]} \right] \quad (5)$$

246 where  $\sigma_{\text{BBN}}$  is the propagated error on the deuterium yield due to the experimental uncertainties  
 247 on nuclear reactions, and  $\sigma_{\text{obs}}$  is the uncertainty on the astronomical observations.

248 We performed two other analyses in which both  $\Omega_b h^2$  and  $N_{\text{eff}}$  were free to vary and con-  
 249 strained the likelihood function  $\mathcal{L}_{\text{D}}(\Omega_b h^2, N_{\text{eff}})$  with other astrophysical inputs. In one case,  
 250 (D+CMB), we used the deuterium abundance (both predicted and observed) and **assumed a Gaus-**  
 251 **sian distribution on the baryon density,  $\mathcal{L}_{\text{CMB}}(\Omega_b h^2)$ , corresponding to the latest PLANCK value<sup>7</sup>**

252  $\Omega_b h^2(\text{CMB}) = 0.02224 \pm 0.00022$ , obtained without constraining  $N_{\text{eff}}$ . The likelihood function is

253 now expressed as:

$$\mathcal{L}_{\text{D+CMB}}(\Omega_b h^2, N_{\text{eff}}) = \mathcal{L}_{\text{CMB}}(\Omega_b h^2) \exp \left[ -\frac{[(\text{D}/\text{H})_{\text{BBN}}(\Omega_b h^2, N_{\text{eff}}) - (\text{D}/\text{H})_{\text{obs}}]^2}{2[\sigma_{\text{BBN}}^2(\Omega_b h^2, N_{\text{eff}}) + \sigma_{\text{obs}}^2]} \right] \quad (6)$$

254 In the other case,  $(\text{D}+Y_p)$ , we used BBN predictions and observed abundances of both deu-  
255 terium and  ${}^4\text{He}$  mass fraction ( $Y_p = 0.2449 \pm 0.0040$  from astronomical observations<sup>25</sup>) together  
256 with the most recent<sup>2</sup> neutron lifetime ( $\tau_n = 879.4 \pm 0.6$  s), which carries the largest uncertainty on  
257 the theoretical prediction of  ${}^4\text{He}$  primordial abundance. No prior distribution was assumed on the  
258 baryon density. In this case, the likelihood function is the product of two exponential functions:  
259 one for deuterium as that appearing in Eq. (6) and a similar one for  ${}^4\text{He}$ .

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346 Specifica TAsP.

347 **Author Contributions** The experiment at LUNA was proposed by CG and coordinated by FC and DT.  
348 PC, CG, SZ and VM planned the setup; SZ and PC developed the Monte Carlo simulations; SZ, FC, PC,  
349 CG, VM, KS and FF led the data analysis. Other authors contributed to the data taking over a period of 2  
350 years and to discussion and interpretation of the results obtained. MJ also has overall responsibility for the  
351 accelerator operations and the underground site. GM and OP performed all BBN calculations and Bayesian  
352 analyses. LEM, AK, MV performed *ab-initio* calculations. MA, FC, CG, GM and OP also wrote the paper.

353 **Competing interests** The authors declare no competing financial interests.

354 **Data availability** Experimental data taken at LUNA are proprietary to the Collaboration but can be made  
355 available from the corresponding authors upon reasonable request. Values of the thermonuclear reaction rate  
356 for smaller temperature steps can be obtained upon request to O.P.

357 **Code availability** The PARthENoPE code used for BBN calculations can be made available upon request  
358 to O.P.

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Table 1: **Mean values and 68% confidence-level ranges for the baryon density  $\Omega_b h^2$  (with relative uncertainties  $\delta$ ) and the effective number of neutrino species  $N_{\text{eff}}$ .** The first two lines show the results obtained from the likelihood analyses performed in this study, without and with the new  $D(p,\gamma)^3\text{He}$   $S$  factor obtained at LUNA and with  $N_{\text{eff}}$  fixed to its standard value<sup>23,24</sup> of 3.045. The third and fourth lines show results obtained, respectively, using CMB data alone<sup>12</sup> (CMB+ $3\nu$ ) and CMB data combined with the theoretical dependence of primordial  $^4\text{He}$  on baryon density<sup>7</sup> (PLANCK+ $3\nu$ ). The last two lines correspond to cases in which both  $\Omega_b h^2$  and  $N_{\text{eff}}$  are left as free parameters and the likelihood functions are constrained by either the deuterium abundance and a prior distribution on  $\Omega_b h^2$ , (D+CMB) case, or the observed and predicted abundances of both deuterium and helium, (D+ $Y_p$ ) case (in both cases the predicted deuterium abundance takes into account our new LUNA results; see Methods for details).

|                                | $\Omega_b h^2$           | $\delta$ [%] | $N_{\text{eff}}$       |
|--------------------------------|--------------------------|--------------|------------------------|
| D+ $3\nu$ (without LUNA data)  | $0.02271 \pm 0.00062$    | 2.73         | 3.045                  |
| D+ $3\nu$ (with new LUNA data) | $0.02233 \pm 0.00036$    | 1.61         | 3.045                  |
| CMB+ $3\nu$                    | $0.02230 \pm 0.00021^a)$ | 0.94         | 3.045                  |
| PLANCK+ $3\nu$                 | $0.02236 \pm 0.00015$    | 0.67         | 3.045                  |
| D+CMB                          | $0.02224 \pm 0.00022$    | 0.99         | $2.95 \pm 0.22$        |
| D+ $Y_p$                       | $0.0221 \pm 0.0006$      | 2.71         | $2.86^{+0.28}_{-0.27}$ |

<sup>a)</sup>Quoted in Fields *et al.*<sup>12</sup> as  $0.022298 \pm 0.000214$ .

Extended Data Table 1: **Astrophysical  $S$  factors for the  $D(p,\gamma)^3\text{He}$  reaction at the measured centre-of-mass energies.** Values of the astrophysical  $S$  factor as measured at LUNA over the full energy range explored. Statistical ( $\sigma_{\text{stat}}$ ) and systematic ( $\sigma_{\text{sys}}$ ) uncertainties at 68% confidence level are also reported. The statistical uncertainty is typically negligible except at the lowest energy point (3.6%), where it dominates over the systematic uncertainty (2.7%). Systematic uncertainties remain below 3% at all energies.

| $E$ [keV] | $S(E)$ [eV b] | $\sigma_{\text{stat}}$ [eV b] | $\sigma_{\text{sys}}$ [eV b] |
|-----------|---------------|-------------------------------|------------------------------|
| 32.4      | 0.386         | 0.014                         | 0.010                        |
| 66.7      | 0.627         | 0.009                         | 0.016                        |
| 99.5      | 0.850         | 0.008                         | 0.021                        |
| 115.9     | 0.966         | 0.009                         | 0.024                        |
| 132.9     | 1.133         | 0.004                         | 0.031                        |
| 149.3     | 1.223         | 0.006                         | 0.031                        |
| 166.1     | 1.375         | 0.004                         | 0.036                        |
| 182.7     | 1.475         | 0.006                         | 0.037                        |
| 199.5     | 1.648         | 0.003                         | 0.043                        |
| 222.8     | 1.791         | 0.006                         | 0.045                        |
| 232.9     | 1.866         | 0.012                         | 0.051                        |
| 252.9     | 2.073         | 0.012                         | 0.052                        |
| 262.9     | 2.156         | 0.020                         | 0.054                        |

Extended Data Table 2: **Thermonuclear reaction rate for the  $D(p,\gamma)^3\text{He}$  reaction.** Values of the thermonuclear reaction rate  $R$  obtained from our best fit  $S$  factor of the  $D(p,\gamma)^3\text{He}$  reaction as a function of temperature in GK. Low- and high-rates are quoted at the  $1\sigma$  level.

| $T$ [GK] | $R$ [ $\text{cm}^3\text{mol}^{-1}\text{s}^{-1}$ ] | $R_{\text{low}}$ [ $\text{cm}^3\text{mol}^{-1}\text{s}^{-1}$ ] | $R_{\text{high}}$ [ $\text{cm}^3\text{mol}^{-1}\text{s}^{-1}$ ] |
|----------|---|--|---|
| 0.001    | $1.37 \times 10^{-11}$                            | $1.35 \times 10^{-11}$   | $1.39 \times 10^{-11}$  |
| 0.005    | $2.57 \times 10^{-5}$                             | $2.53 \times 10^{-5}$  | $2.62 \times 10^{-5}$   |
| 0.01     | $1.53 \times 10^{-3}$                             | $1.51 \times 10^{-3}$  | $1.56 \times 10^{-3}$   |
| 0.05     | $9.08 \times 10^{-1}$                             | $8.94 \times 10^{-1}$  | $9.22 \times 10^{-1}$   |
| 0.10     | $5.74 \times 10^0$                                | $5.65 \times 10^0$   | $5.84 \times 10^0$  |
| 0.50     | $1.29 \times 10^2$                                | $1.26 \times 10^2$   | $1.32 \times 10^2$  |
| 1.0      | $3.63 \times 10^2$                                | $3.52 \times 10^2$   | $3.74 \times 10^2$  |
| 1.5      | $6.32 \times 10^2$                                | $6.09 \times 10^2$   | $6.56 \times 10^2$  |
| 2.0      | $9.20 \times 10^2$                                | $8.79 \times 10^2$   | $9.62 \times 10^2$  |
| 3.0      | $1.52 \times 10^3$                                | $1.43 \times 10^3$   | $1.61 \times 10^3$  |
| 4.0      | $2.11 \times 10^3$                                | $1.95 \times 10^3$   | $2.28 \times 10^3$  |
| 5.0      | $2.67 \times 10^3$                                | $2.40 \times 10^3$   | $2.93 \times 10^3$  |
| 6.0      | $3.16 \times 10^3$                                | $2.76 \times 10^3$   | $3.55 \times 10^3$  |
| 7.0      | $3.56 \times 10^3$                                | $3.00 \times 10^3$   | $4.12 \times 10^3$  |
| 8.0      | $3.85 \times 10^3$                                | $3.09 \times 10^3$   | $4.61 \times 10^3$  |
| 9.0      | $4.01 \times 10^3$                                | $3.02 \times 10^3$   | $5.01 \times 10^3$  |
| 10.0     | $4.02 \times 10^3$                                | $2.75 \times 10^3$   | $5.30 \times 10^3$  |

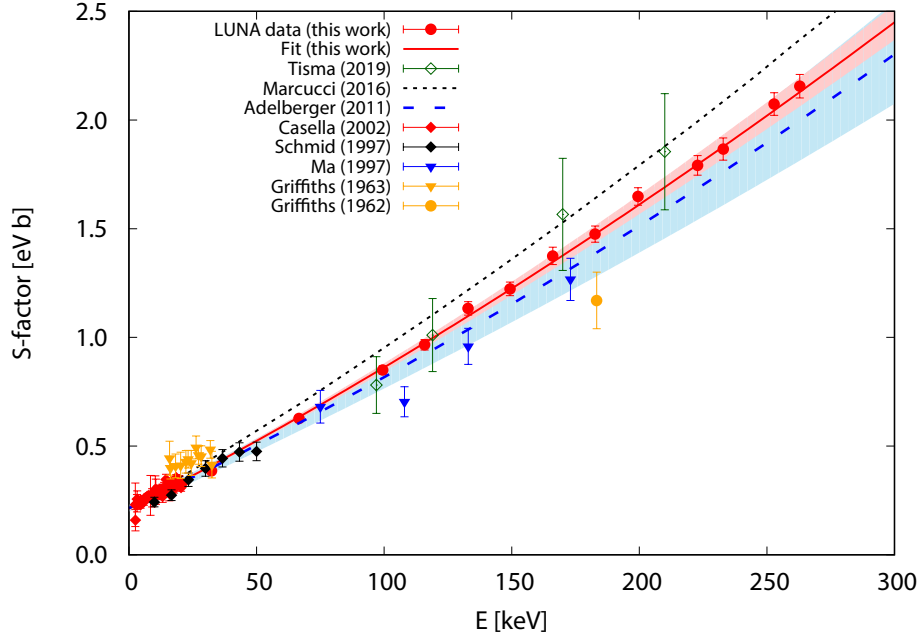


Figure 1:  **$S$  factor of the  $D(p,\gamma)^3\text{He}$  reaction.** At BBN energies ( $E_{\text{cm}} \simeq 30 - 300$  keV), the new LUNA results (filled red circles) indicate a faster deuterium destruction compared to a best fit<sup>19</sup> (blue dashed line) of previous experimental data, but a slower destruction compared to theoretical calculations<sup>18</sup> (black dotted line). At BBN energies, the best fit (red solid line, Eq. 2) obtained in this work is entirely dominated by the LUNA data. The fit includes all experimental data<sup>13–16,31–33</sup> (note that those by Warren *et al.*<sup>32</sup> and Geller *et al.*<sup>33</sup> lie outside the energy range shown here). Bands represent the 68% confidence level.

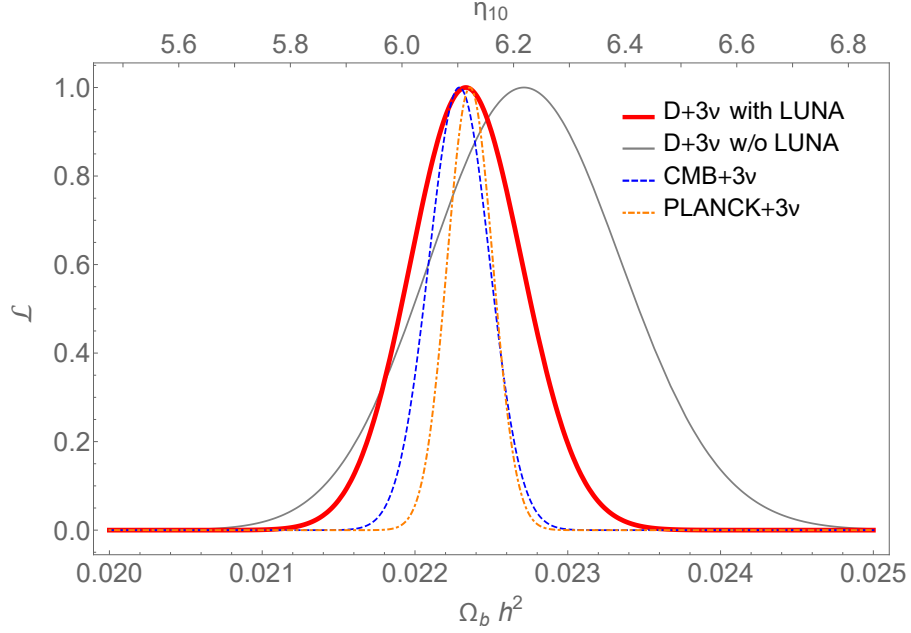


Figure 2: **Likelihood distribution of the baryon density (lower  $x$ -axis) and baryon-to-photon ratio ( $\eta_{10}$ , upper  $x$ -axis).** The red curve (D+3 $\nu$  with LUNA) shows the distribution of the baryon density obtained using the new LUNA  $S$  factor for the predicted deuterium abundance  $(D/H)_{\text{BBN}}$ . Note the factor of 2 reduction in the uncertainty, as compared to the distribution based on previous  $S$  factor<sup>19</sup> (grey curve, D+3 $\nu$  w/o LUNA). Our new determination of  $\Omega_b h^2$  is now in much better agreement with the value obtained from CMB data alone<sup>12</sup> (blue dashed curve, CMB+3 $\nu$ ) and with the best determination of baryon density obtained by PLANCK<sup>7</sup> from CMB data combined with additional observational inputs and with the theoretical dependence of primordial  ${}^4\text{He}$  on baryon density (orange dot-dashed curve, PLANCK+3 $\nu$ ).

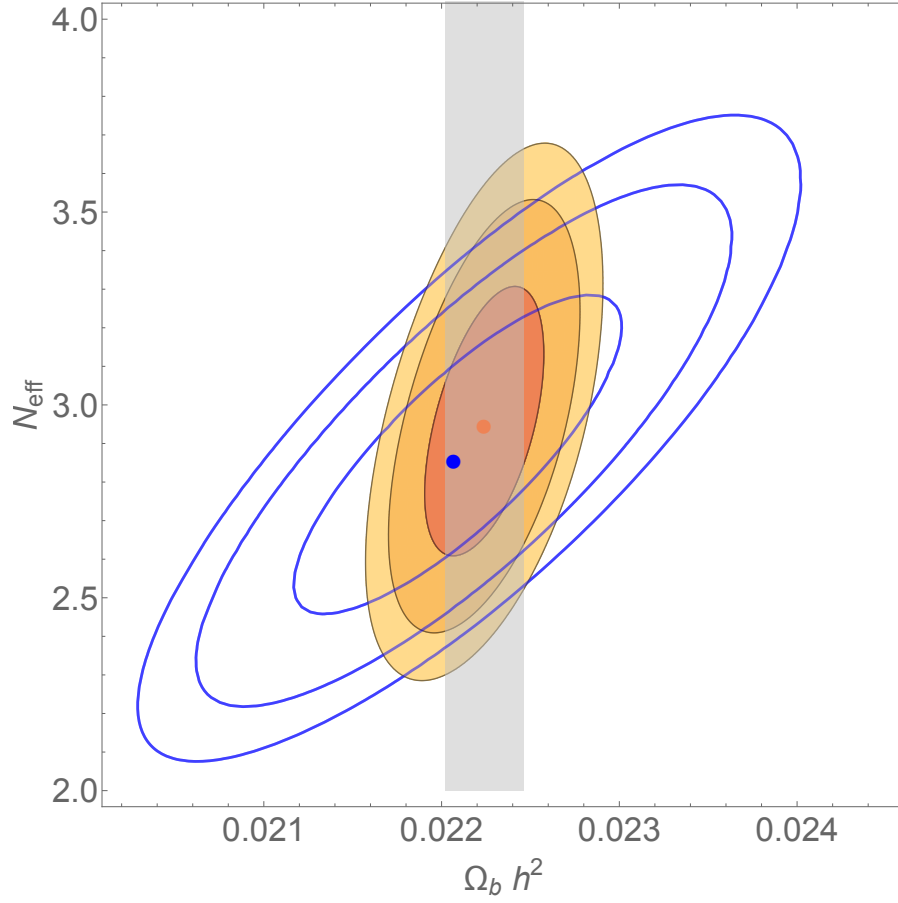
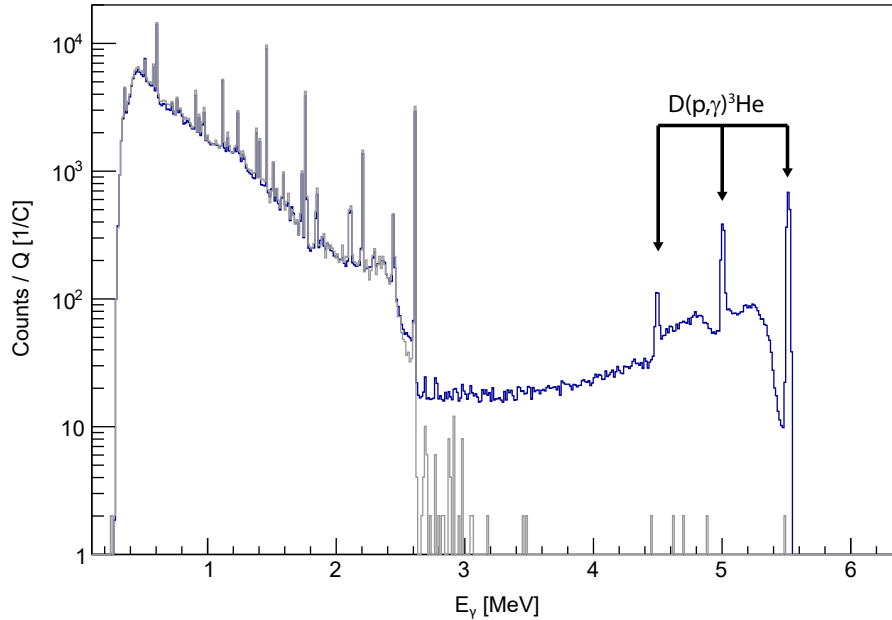
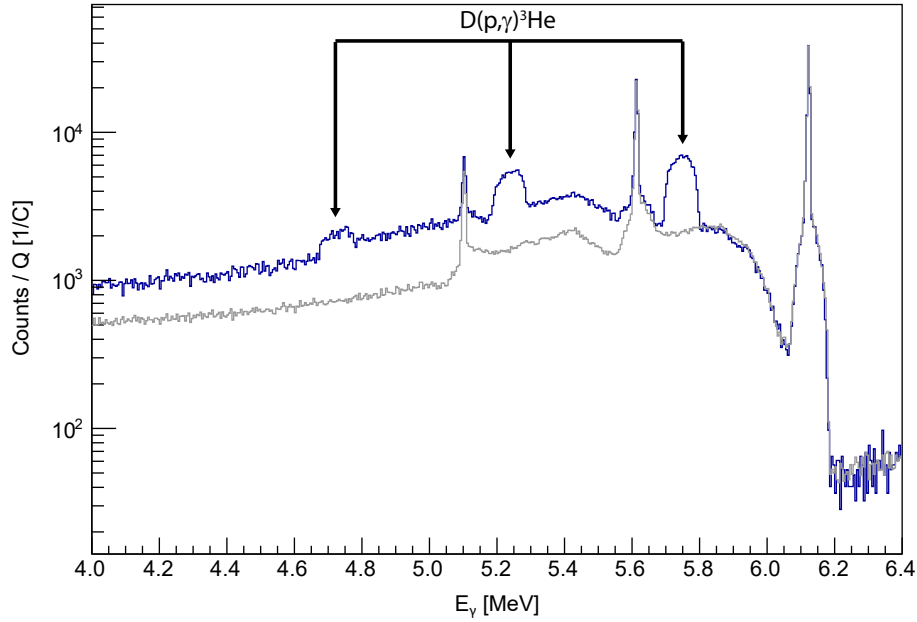


Figure 3: **Likelihood contours (at 68%, 95% and 99% confidence level) on the  $N_{\text{eff}}$  vs.  $\Omega_b h^2$  plane.** Orange filled contours are obtained for the D+CMB case using the observed deuterium abundance<sup>3</sup>  $(D/H)_{\text{obs}}$  and the adopted PLANCK distribution on baryon density<sup>7</sup> (grey vertical band at the 68% confidence level). Blue contours correspond to the D+ $Y_p$  case, as obtained from a likelihood analysis with observed abundances of deuterium<sup>3</sup> and  $^4\text{He}$  mass fraction<sup>25</sup>,  $Y_p$ , and the corresponding BBN theoretical predictions (see Methods for details). Central values for each case are indicated by dots.

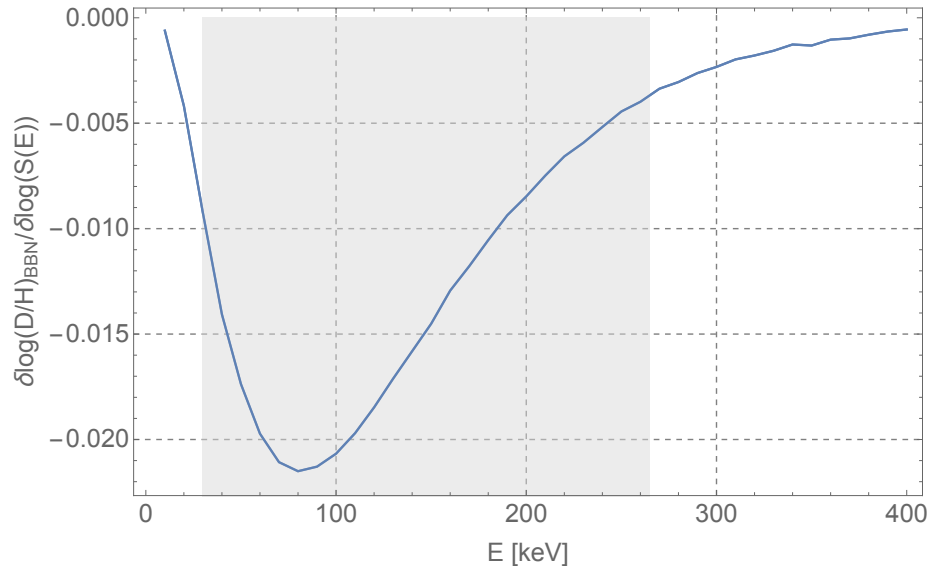


Extended Data Figure 1: **Typical  $\gamma$ -ray spectrum obtained underground with the HPGe detector at proton beam energy  $E_p = 50$  keV.** Typical  $\gamma$ -ray spectrum (blue) obtained with the deuterium gas target at  $P = 0.3$  mbar, clearly showing the full-energy, single- and double-escape peaks from the  $D(p,\gamma)^3\text{He}$  reaction. The continuum is mainly due to Compton scattering events in which photons deposit only part of their energy in the detector. In grey is the beam-induced background spectrum acquired in the control run under the same experimental conditions but with an inert  $^4\text{He}$  gas target. Both spectra are normalised to the integrated beam current. The region of interest ( $E_\gamma \sim 4.5 - 5.8$  MeV) is essentially background free thanks to the million-fold shielding<sup>8</sup> from cosmic-ray muons obtained at the LUNA underground laboratory.



Extended Data Figure 2: **Typical  $\gamma$ -ray spectrum taken at proton beam energy  $E_p = 395$  keV.**

In blue,  $\gamma$ -ray spectrum obtained with the deuterium gas target at  $P = 0.3$  mbar (the peaks from the  $D(p,\gamma)^3\text{He}$  reaction are broadened by the Doppler effect at this higher beam energy). In grey, beam-induced background spectrum (acquired with an inert  $^4\text{He}$  gas target) due to the  $^{19}\text{F}$  contaminant (see text). Its contribution was subtracted leading to net counts on the full energy peak with a statistical uncertainty of 0.9%. Both spectra are normalised to the integrated beam current.



Extended Data Figure 3: **Sensitivity of the primordial deuterium abundance to the  $D(p,\gamma)^3\text{He}$  reaction cross section as a function of centre-of-mass energy.** The greatest sensitivity is obtained around  $E = 80$  keV, where underground measurements are especially effective. The grey area represents the energy region explored at LUNA (see Methods for details).