Cosmological constraints on the neutron lifetime

28th Texas Symposium
on
Relativistic Astrophysics

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University of Rome, Sapienza

Introduction

Derive constraints on the **neutron lifetime**

- primordial abundances of light elements produced during Big Bang Nucleosynthesis
    - direct astrophysical observations
    - Cosmic Microwave Background anisotropies

Big Bang Nucleosynthesis

Big Bang Nucleosynthesis (BBN):
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Initial conditions $t \simeq 2\ \mathrm{s},\ \ E \sim 10^2\ \mathrm{keV}$

decoupling of neutrinos

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right] \rho_\gamma$$

Total energy density of radiation

neutron-to-proton ratio

$$\frac{n_{\mathrm{n}}}{n_{\mathrm{p}}} \simeq 0.2$$

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$$N_{\mathrm{eff,\ SM}} = 3.046$$

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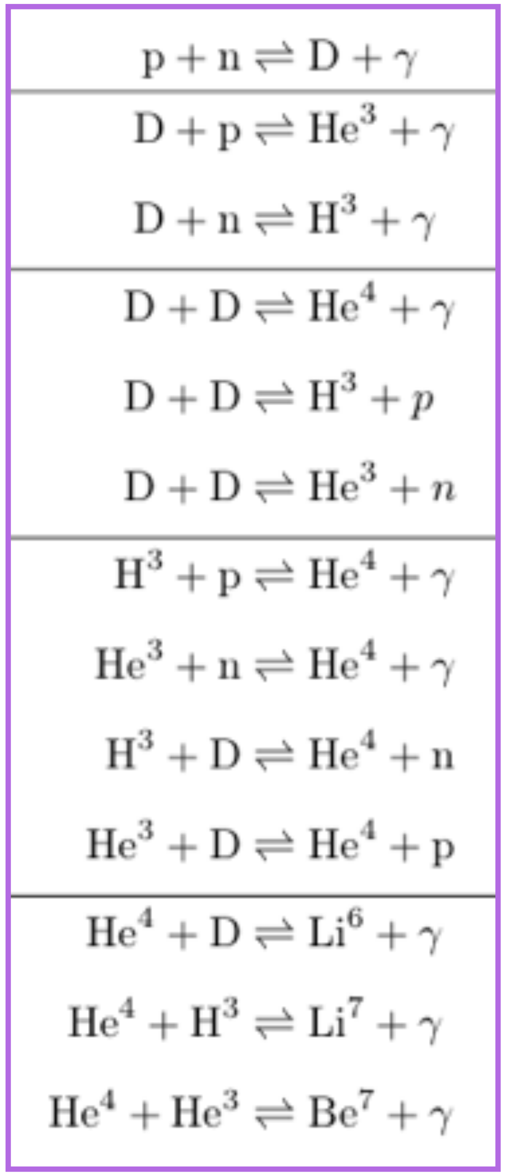
Final conditions $t \simeq 1000\ \mathrm{s},\ E < 30\ \mathrm{keV}$

- 75% H
- 25% He
- traces of other elements $\mathrm{D},\ \mathrm{He}^3,\ \mathrm{Li}^7,\ \mathrm{Be}^7$



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BBN: good check for Standard Model of Cosmology
Standard Model of Particle Physics

Cosmic Microwave Background

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radiation coming from Last Scattering Surface.

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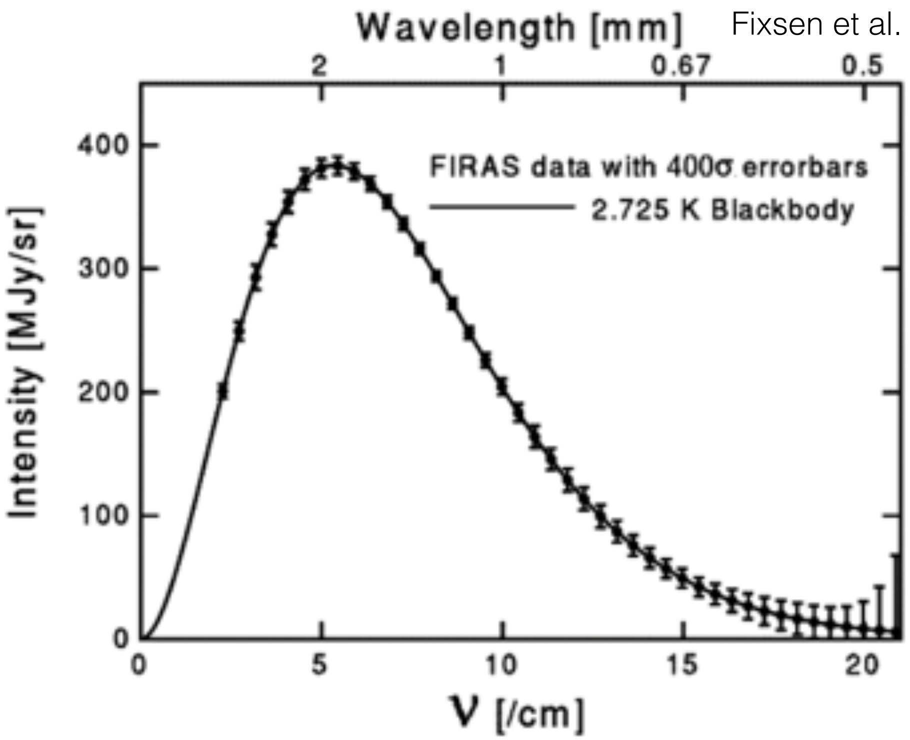

Fixsen et al. 1996 Apj 473 576.

$$\boxed{\langle T \rangle = 2.7255\ \mathrm{K}}$$

Planck 2013 results. XVI. 2014
A&A 571, A16

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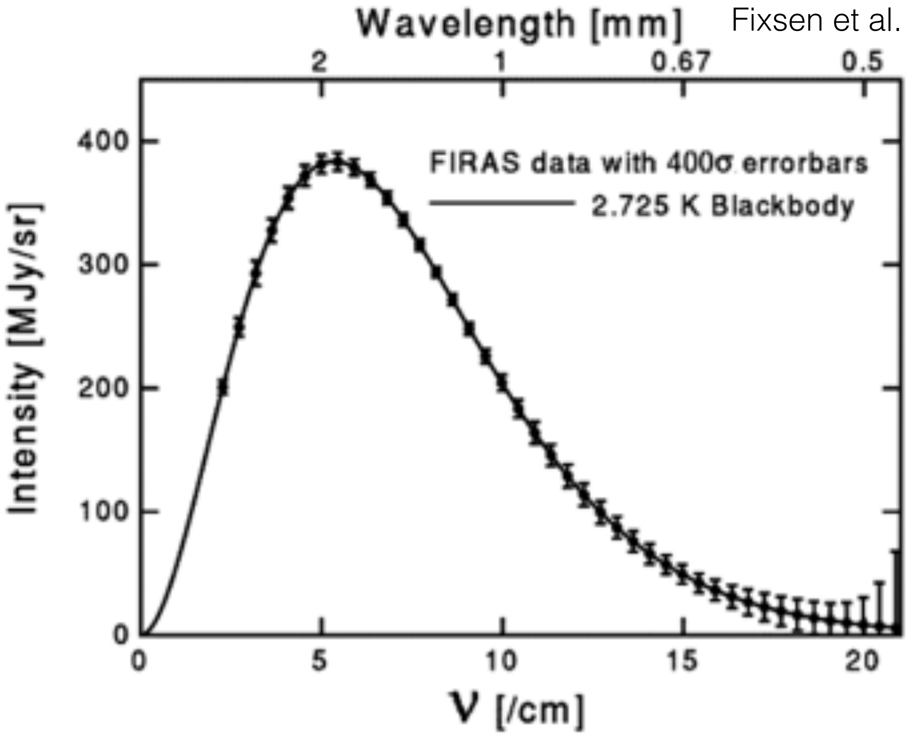


Fixsen et al. 1996 Apj 473 576.

$$\langle T \rangle = 2.7255\ \mathrm{K}$$

Planck 2013 results. XVI. 2014 A&A 571, A16

Temperature fluctuations

$$\sqrt{\left\langle \left(\frac{\Delta T}{T} \right)^2 \right\rangle} \sim 10^{-5}$$

Planck 2013 results. XVI. 2014 A&A 571, A16

Temperature anisotropies $\Delta T(\mathbf{n}) = \dfrac{T(\mathbf{n}) - \langle T \rangle}{\langle T \rangle}$

$$C(\theta) = \langle \Delta T(\mathbf{n}) \Delta T(\mathbf{n}') \rangle$$

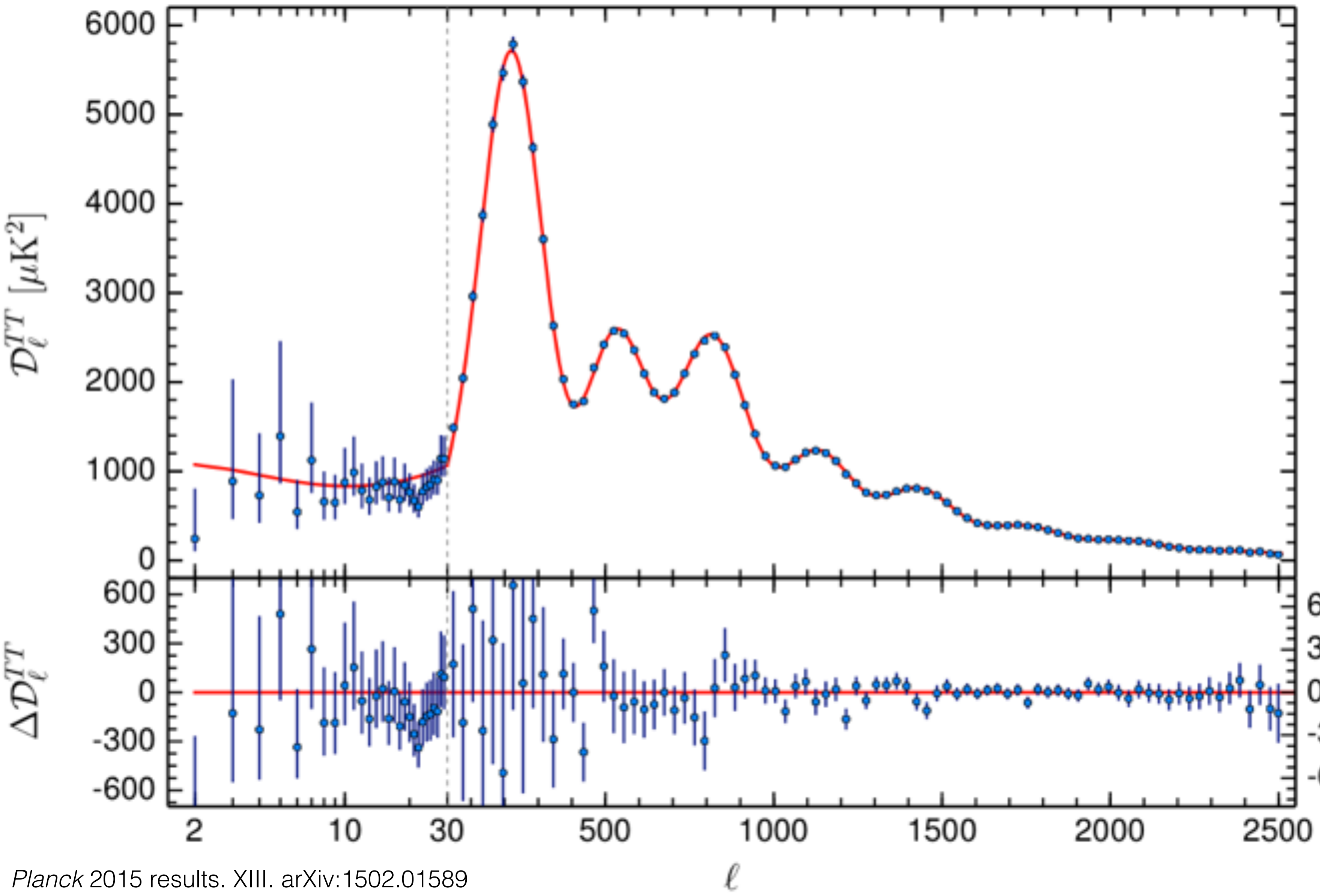
$$C(\theta) = \frac{1}{4\pi} \sum_{\ell=0}^{\infty} C_\ell (2\ell + 1) P_\ell(\cos\theta)$$

Angular correlation function

Angular power spectrum

Cosmic Microwave Background

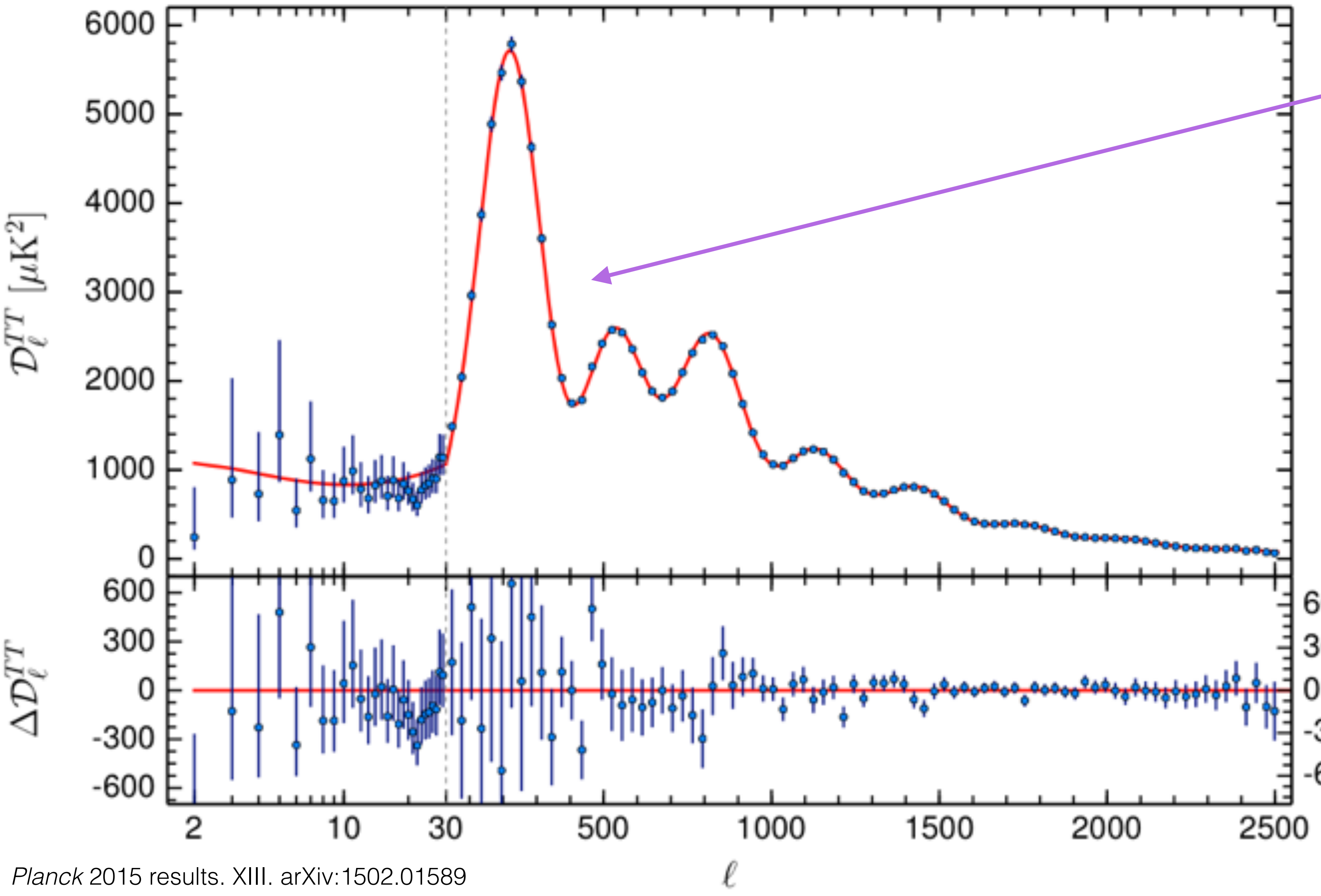
Planck TT spectrum



Planck 2015 results. XIII. arXiv:1502.01589

Cosmic Microwave Background

Planck TT spectrum



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<u>Acoustic peaks:</u>

froze-in of photon-baryonic fluid oscillations.

increase of $\omega_b = \Omega_b h^2$

$\downarrow$

higher amplitude of odd peaks

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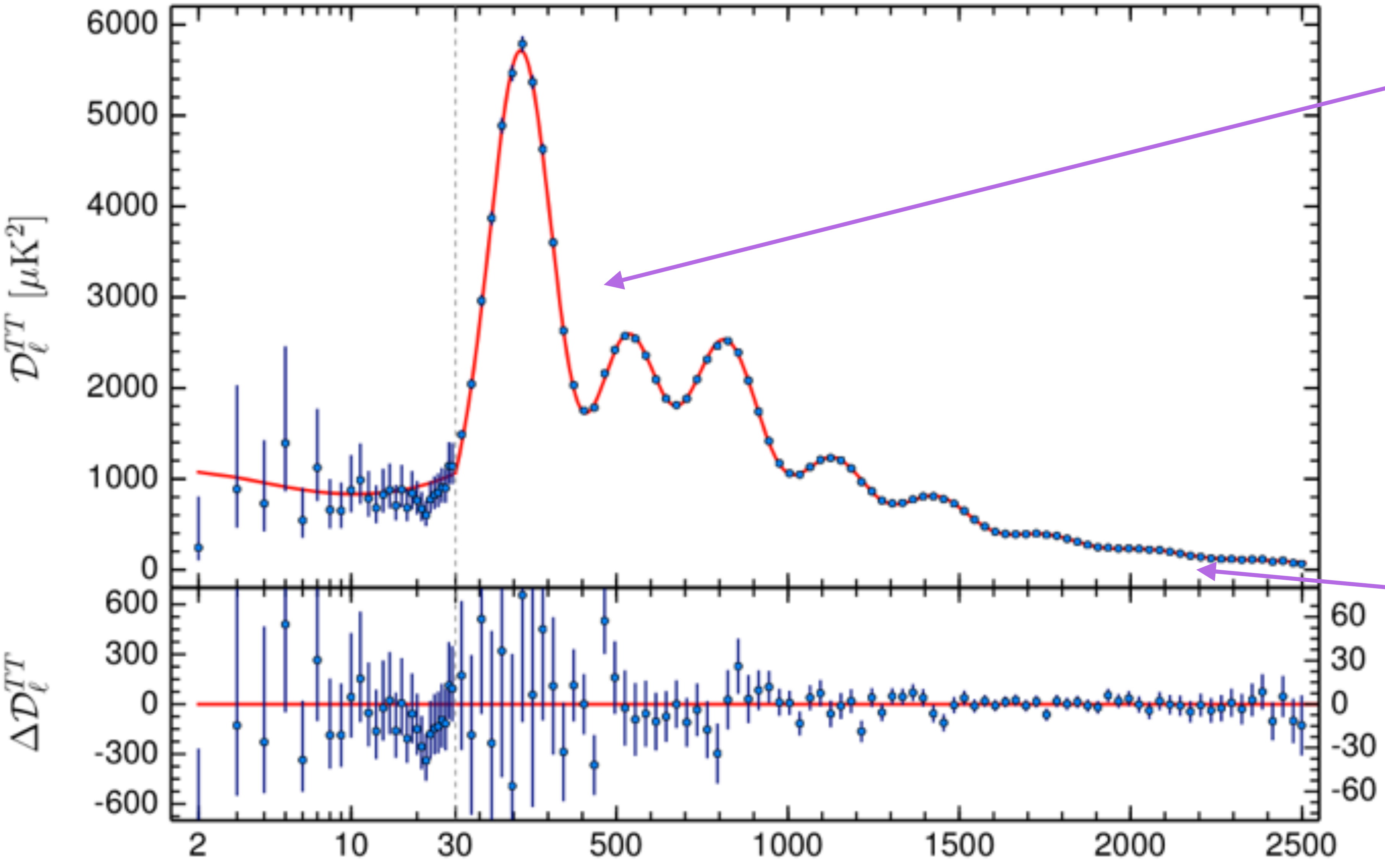

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<u>Damping tail</u> :

related to the thickness of LSS. Damping of anisotropies on scales smaller than this thickness.

Cosmic Microwave Background

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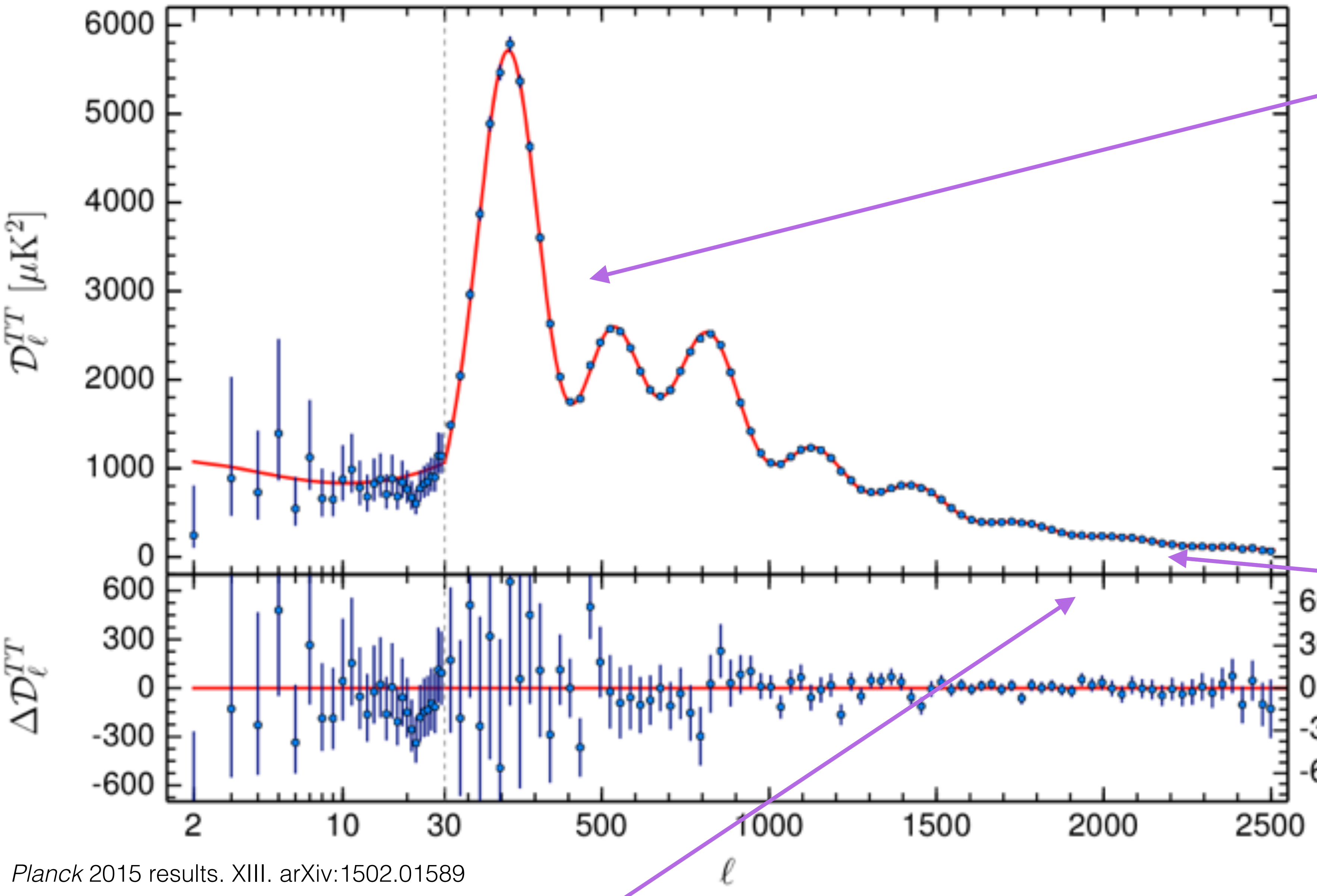

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Damping tail :

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Helium recombination :

it affects free electrons fraction.

- Effects can be seen on the damping tail: increase of the diffusion damping.

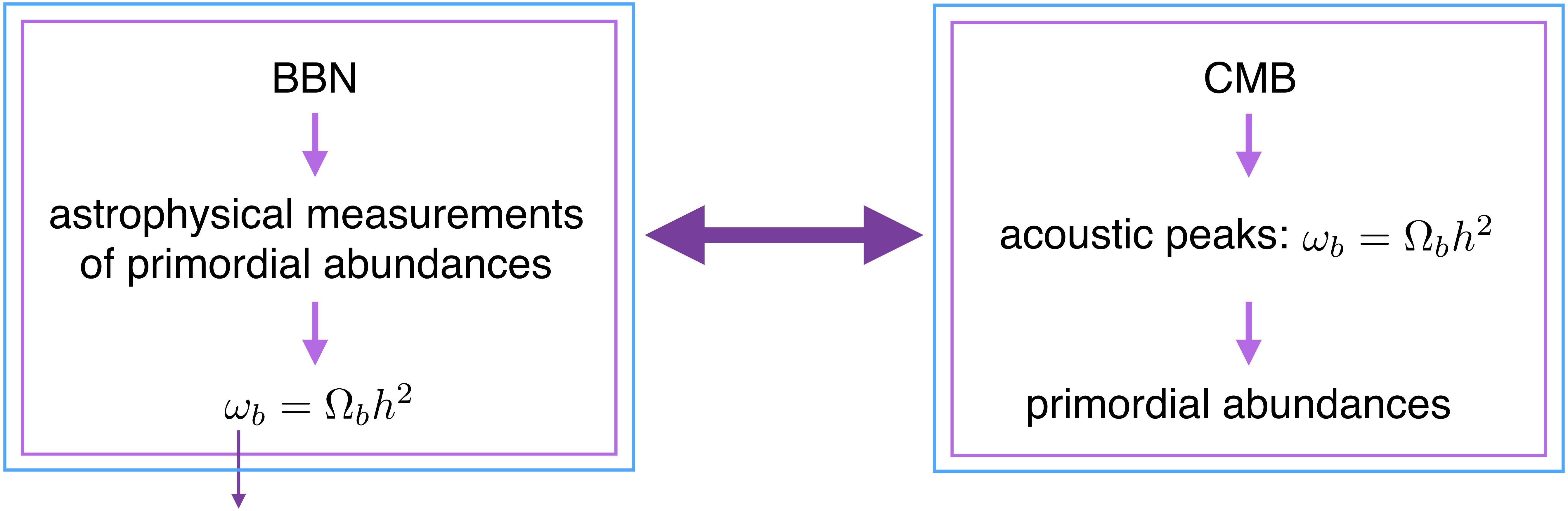
increase of Y_p

↓

higher suppression at high ℓ

$$Y_\mathrm{p}^\mathrm{BBN} = \frac{4n_\mathrm{He}}{n_\mathrm{b}}$$

BBN and CMB



BBN

astrophysical measurements of primordial abundances

$\omega_b = \Omega_b h^2$

CMB

acoustic peaks: $\omega_b = \Omega_b h^2$

primordial abundances

$$\eta_{10} = 10^{10} \frac{n_{\mathrm{b}}}{n_\gamma} = 273.78 \left(\frac{T_{\mathrm{CMB}}}{2.7255\,\mathrm{K}} \right)^{-3} \Omega_b h^2$$

Ishida et al., Phys. Rev. D 90 (2014) 8, 083519

BBN and CMB

Primordial abundances from CMB

PArthENoPE code →

Pisanti et al., Comput. Phys. Commun. 178 (2008) 956

- beginning: nuclear statistical equilibrium conditions
- set of coupled differential equations
- departure from chemical equilibrium of nuclear species
- asymptotic abundances as functions of cosmological parameters

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Standard BBN

$$Y(\underbrace{\omega_b,\, N_{\rm eff}}_{\text{from cosmology}},\, \underbrace{\tau_n,\, \xi}_{\text{from particle/nuclear physics}})$$

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Standard BBN

$$Y(\omega_b,\, N_{\rm eff},\, \tau_n,\, \xi)$$

from cosmology ← $\omega_b,\, N_{\rm eff}$

$\tau_n,\, \xi$ → from particle/nuclear physics

$$\left\{ \begin{array}{l} N_{\rm eff} = 3.046 \quad \text{(LCDM)} \\ \tau_n = (880.3 \pm 1.1)\ [\mathrm{s}] \\ |\xi| = |\frac{\mu_\nu}{T_\nu}| \ll 1 \end{array} \right. \longrightarrow Y(\omega_b)$$

K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, 38, 090001 (2014)

BBN and CMB

Results from Planck 2015

Planck 2015 results. XIII. arXiv:1502.01589

95% c.l., PlanckTTTEEE+lowP

TTTEEE: spectrum-based temperature-polarization likelihood (including cross-correlation) $\ell = 30 \div 2500$

lowP: temperature-polarization likelihood (including cross-correlation) $\ell = 2 \div 29$

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$Y_\mathrm{P}^\mathrm{BBN} = 0.24667^{+(0.00014)0.00062}_{-(0.00014)0.00062}$ → $\sigma(Y_\mathrm{P}^\mathrm{BBN}) = 0.0003$ → due to propagation of the error on neutron lifetime

$y_\mathrm{DP} = 2.614^{+(0.057)0.13}_{-(0.060)0.13}$ → $\sigma(y_\mathrm{DP}) = 0.06$ → due to the error on the reaction rate of $\mathrm{d(p,\gamma)^3He}$

Adelberger et al., Rev. Mod. Phys. 83 (2011) 195

agreement with direct astrophysical observations of primordial abundances

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agreement with direct astrophysical observations of primordial abundances

N_eff → in agreement with the standard value within $1\,\sigma$

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Constraints on neutron lifetime

main uncertainties are due to particle-nuclear physics → main uncertainty on Helium-4 is due to the one on neutron lifetime τ_n .

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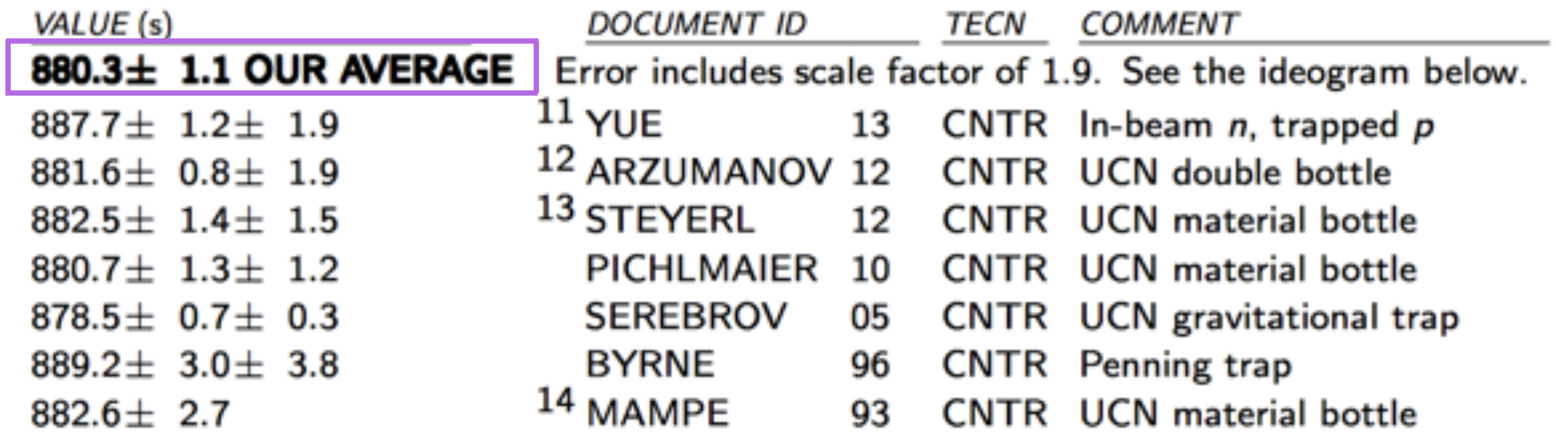
Current estimate

State of the art from particle physics experiments (Particle Data Group)



VALUE (s)		DOCUMENT ID		TECN	COMMENT
880.3± 1.1 OUR AVERAGE		Error includes scale factor of 1.9. See the ideogram below.			
887.7± 1.2± 1.9	[11]	YUE	13	CNTR	In-beam *n*, trapped *p*
881.6± 0.8± 1.9	[12]	ARZUMANOV	12	CNTR	UCN double bottle
882.5± 1.4± 1.5	[13]	STEYERL	12	CNTR	UCN material bottle
880.7± 1.3± 1.2		PICHLMAIER	10	CNTR	UCN material bottle
878.5± 0.7± 0.3		SEREBROV	05	CNTR	UCN gravitational trap
889.2± 3.0± 3.8		BYRNE	96	CNTR	Penning trap
882.6± 2.7	[14]	MAMPE	93	CNTR	UCN material bottle

credits: http://pdg.lbl.gov

→ standard weighted least-squares procedure

beam method

$$\tau_n^{\text{beam}} = (888.0 \pm 2.1)\,\text{s}$$

bottle method

$$\tau_n^{\text{bottle}} = (879.6 \pm 0.8)\,\text{s}$$

$3.8\,\sigma$ discrepancy

Pignol, arXiv:1503.03317

F.~E.~Wietfeldt et al., Rev. Mod. Phys. 83, 1173 F.~E.~Wietfeldt, arXiv:1411.3687

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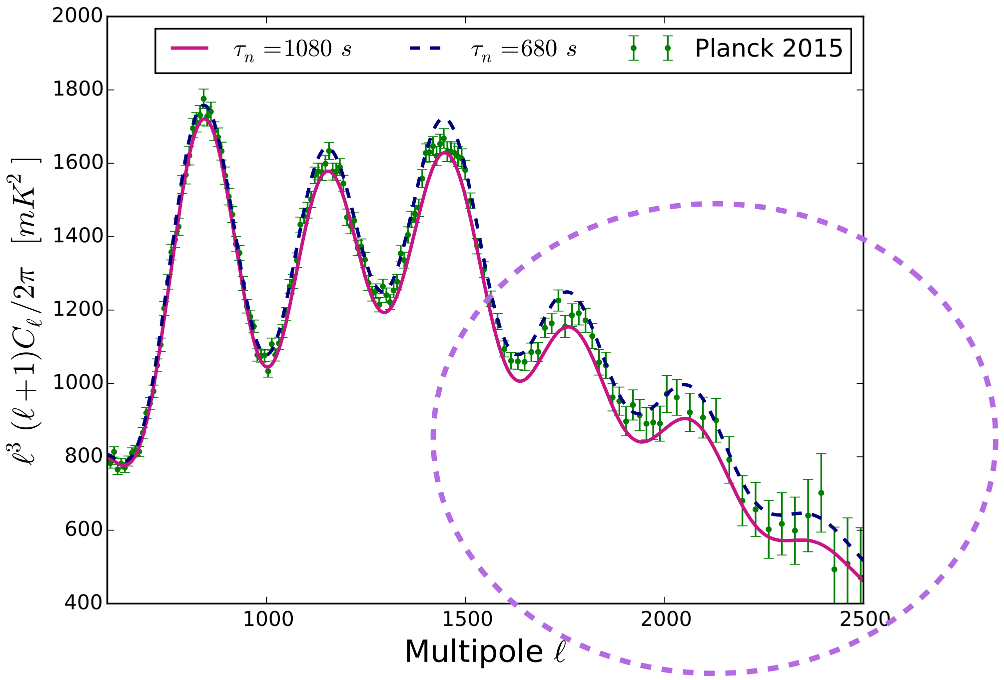
$$\times\,[p(n,\gamma)d]^{0.005}\,[d(d,n)^3\mathrm{He}]^{0.006}\,[d(d,p)t]^{0.005}$$

$$\frac{\mathrm{D}}{\mathrm{H}} \propto \tau_n^{0.41},\quad \frac{^3\mathrm{He}}{\mathrm{H}} \propto \tau_n^{0.15},\quad \frac{^7\mathrm{Li}}{\mathrm{H}} \propto \tau_n^{0.43}$$

Cyburt et al., arXiv:1505.01076



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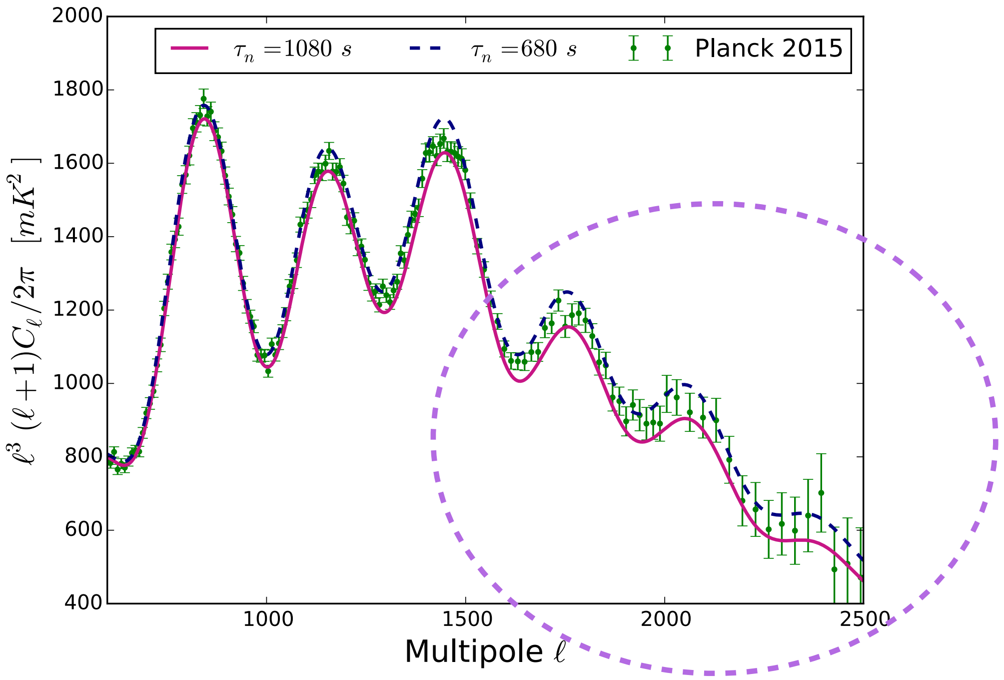


$$Y_p^{\mathrm{BBN}}(\omega_b, \Delta N_{\mathrm{eff}}, \tau_n) = \left(\frac{\tau_n}{880.3}\right)^{0.728} \cdot \Big[0.2311 + 0.9502\cdot\omega_b - 11.27\cdot\omega_b^2 +$$
$$+\Delta N_{\mathrm{eff}}\cdot(0.01356 + 0.008581\cdot\omega_b - 0.1810\cdot\omega_b^2) +$$
$$+\Delta N_{\mathrm{eff}}^2\cdot(-0.0009795 - 0.001370\cdot\omega_b + 0.01746\cdot\omega_b^2)\Big]$$

PArthENoPE BBN code

Pisanti et al., Comput. Phys. Commun. 178 (2008) 956

$$\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$$

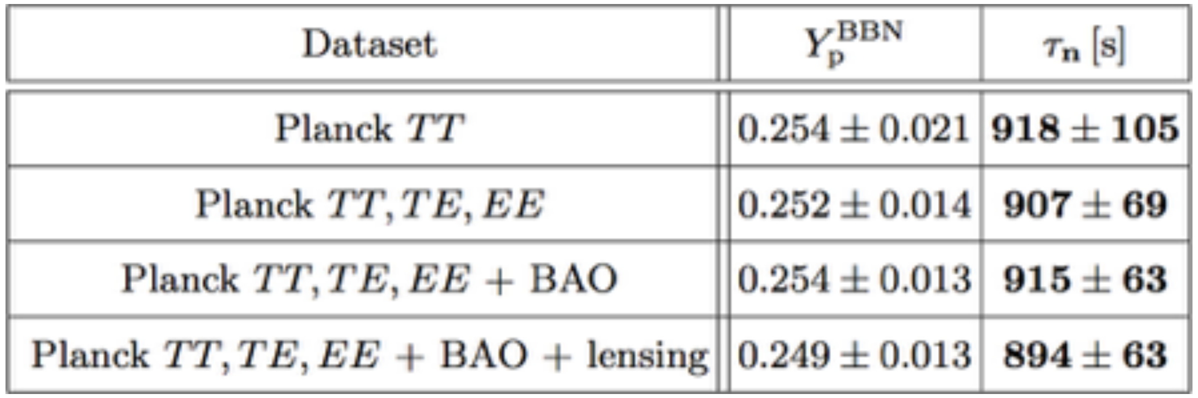
Constraints on neutron lifetime

For the analysis:

- Monte Carlo Markov Chain (MCMC) package cosmomc (publicly available).
- Each step in MCMC:
  - evaluate $Y_{\rm p}$ using a fitting formula from PArthENoPE BBN code,
  - evaluate neutron life-time.

Planck and current cosmological data

ΛCDM model + τ_n



Dataset	$Y_{\rm p}^{\rm BBN}$	$\tau_{\rm n}$ [s]
Planck TT	0.254 ± 0.021	$\mathbf{918 \pm 105}$
Planck TT, TE, EE	0.252 ± 0.014	$\mathbf{907 \pm 69}$
Planck TT, TE, EE + BAO	0.254 ± 0.013	$\mathbf{915 \pm 63}$
Planck TT, TE, EE + BAO + lensing	0.249 ± 0.013	$\mathbf{894 \pm 63}$

(68% c.l.)

Constraints on neutron lifetime

Salvati, Pagano, Consiglio, Melchiorri, arXiv:1507.07243

CMB observations + direct astrophysical observations

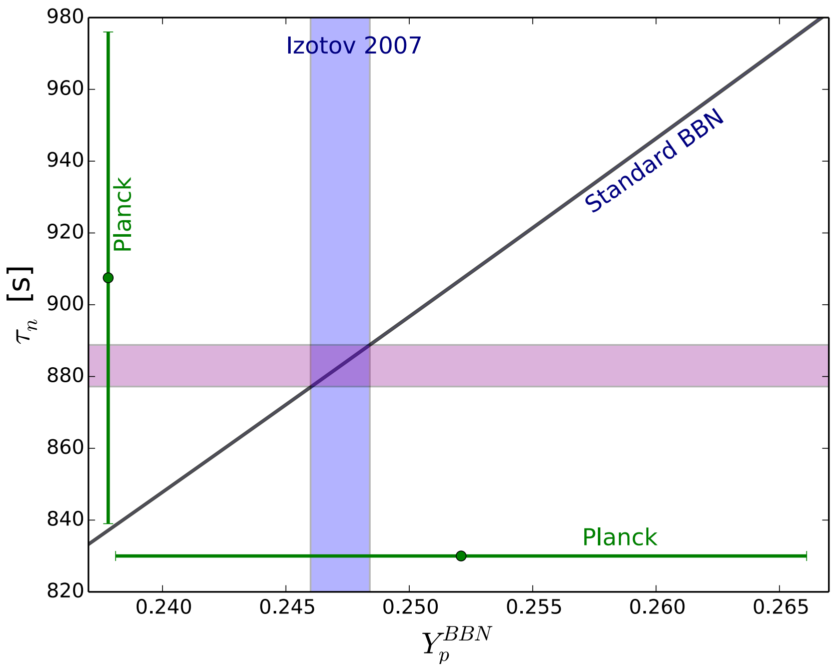
Dataset	$Y_{\rm p}^{\rm data}$	$Y_{\rm p}^{\rm BBN}$	$\tau_{\rm n}$ [s]
Olive et al. (2004)	0.249 ± 0.009	0.2498 ± 0.0076	$\mathbf{896 \pm 37}$
Izotov et al. (2007)	0.2472 ± 0.0012	0.2472 ± 0.0012	$\mathbf{883.0 \pm 5.8}$
Peimbert et al. (2007)	0.2477 ± 0.0029	0.2478 ± 0.0029	$\mathbf{886 \pm 14}$
Aver et al. (2015)	0.2449 ± 0.0040	0.2455 ± 0.0038	$\mathbf{875 \pm 19}$
Izotov et al. (2013)	0.254 ± 0.003	0.2539 ± 0.0029	$\mathbf{916 \pm 15}$
Izotov et al. (2014)	0.2551 ± 0.0022	0.2550 ± 0.0022	$\mathbf{921 \pm 11}$
Mucciarelli et al. (2014-1)	0.241 ± 0.004	0.2419 ± 0.0038	$\mathbf{857 \pm 19}$
Mucciarelli et al. (2014-2)	0.2521 ± 0.003	0.2521 ± 0.0029	$\mathbf{907 \pm 14}$

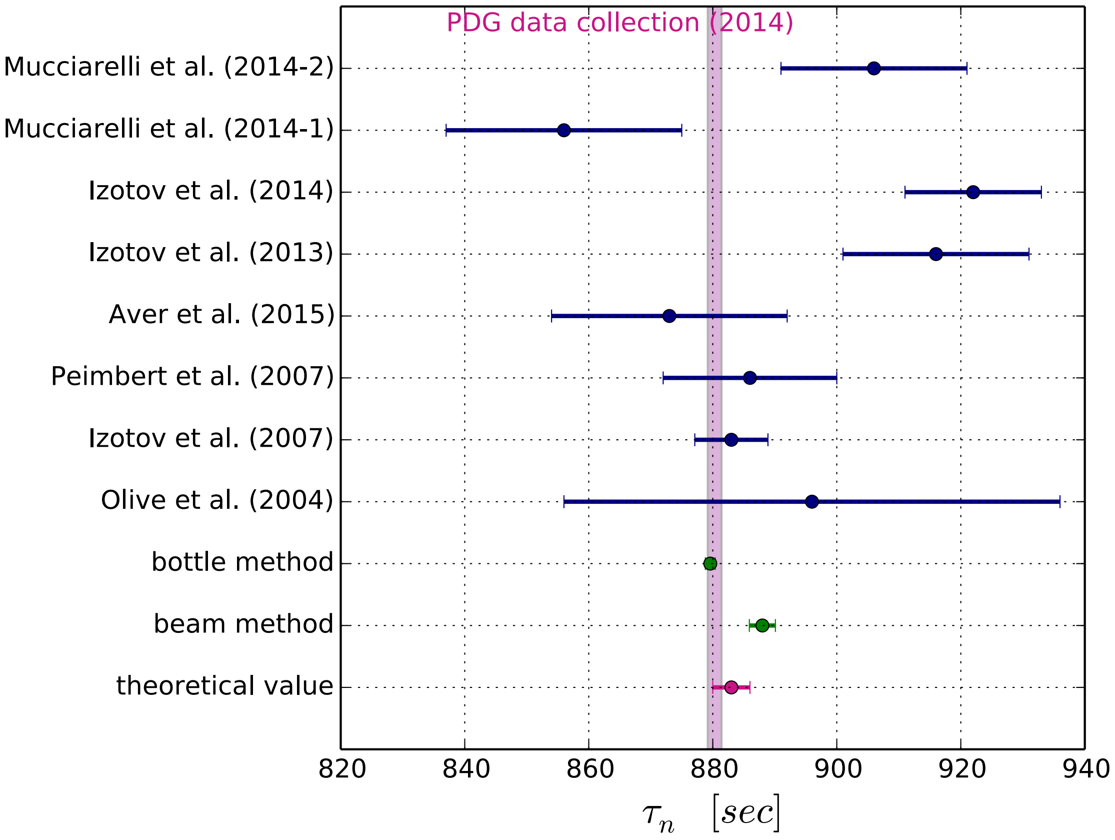
(68% c.l.)

experimental prior

recovered He mass fraction

CMB + He measurements: tighter constraints on τ_n.





Constraints on neutron lifetime

Salvati, Pagano, Consiglio, Melchiorri, arXiv:1507.07243

Extensions to Standard Model

Varying the extra relativist degrees of freedom → N_{eff}

(68% c.l.)

$$N_{\text{eff}} = 2.95 \pm 0.24$$

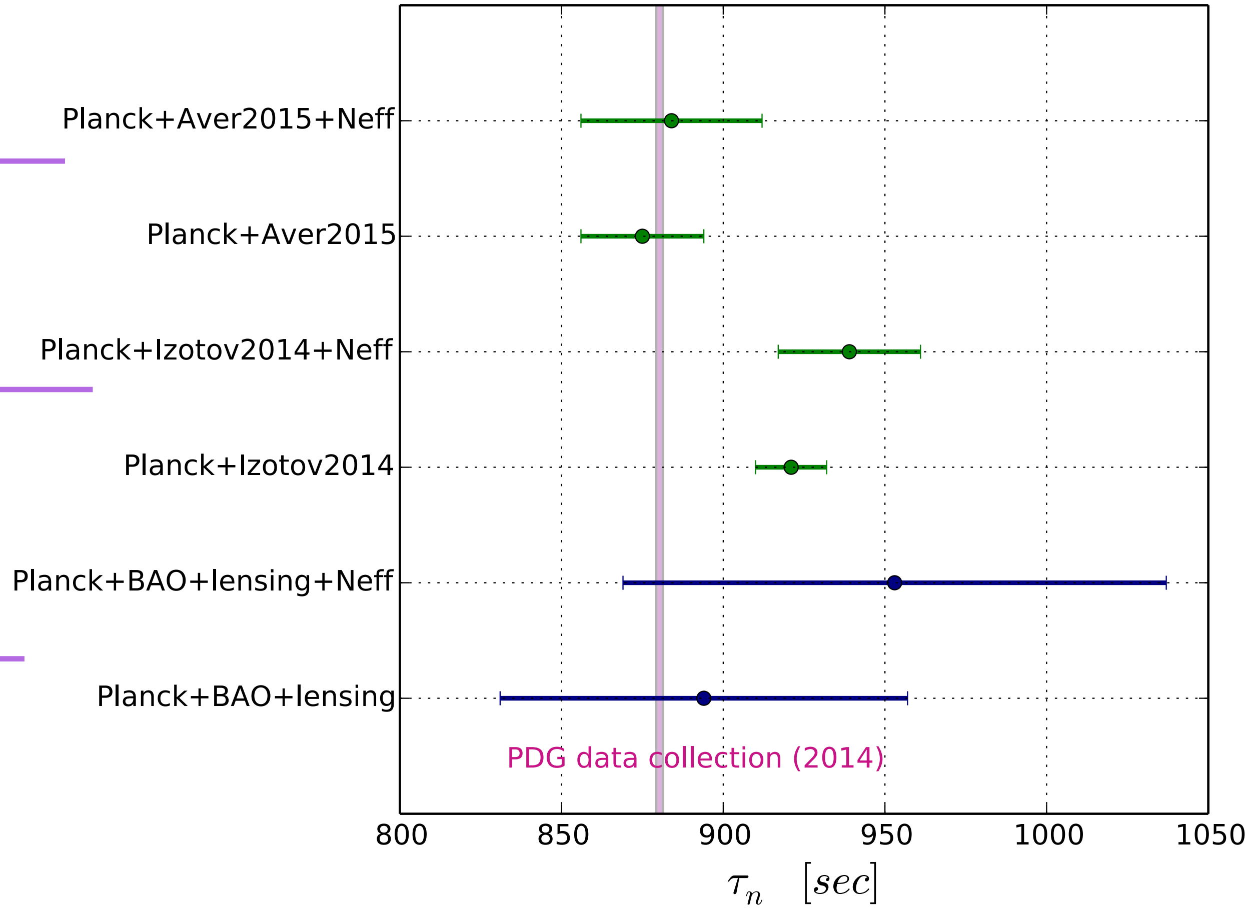
$$\frac{N_{\text{eff,SM}} - N_{\text{eff,var}}}{\sigma_{N_{\text{eff,var}}}} = 0.4$$

$$N_{\text{eff}} = 2.83 \pm 0.23$$

$$\frac{N_{\text{eff,SM}} - N_{\text{eff,var}}}{\sigma_{N_{\text{eff,var}}}} = 0.94$$

$$N_{\text{eff}} = 2.83 \pm 0.25$$

$$\frac{N_{\text{eff,SM}} - N_{\text{eff,var}}}{\sigma_{N_{\text{eff,var}}}} = 0.86$$



Constraints on neutron lifetime

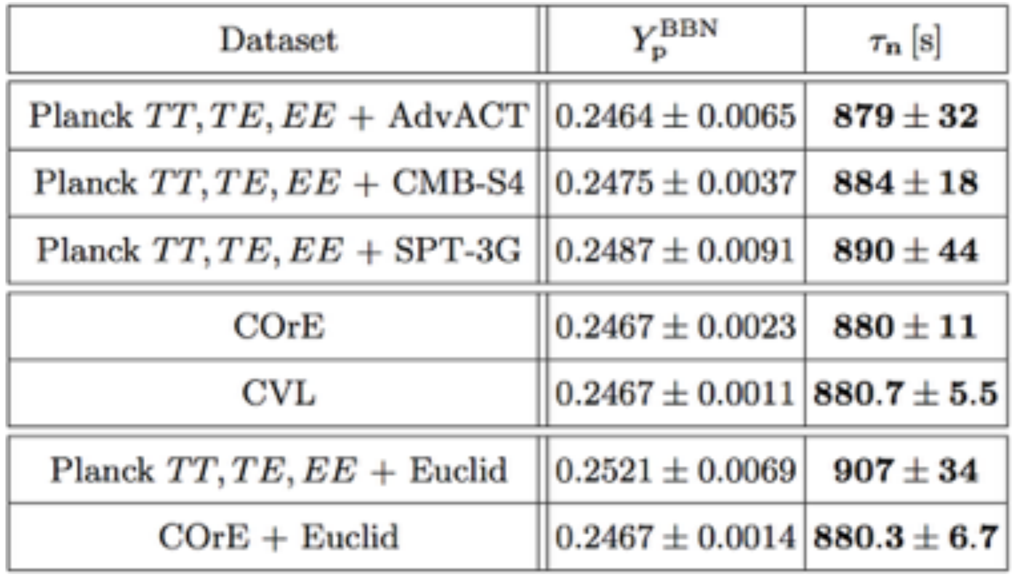
Salvati, Pagano, Consiglio, Melchiorri, arXiv:1507.07243

Future cosmological constraints

CMB - τ_n :
small-scale region
of power spectrum

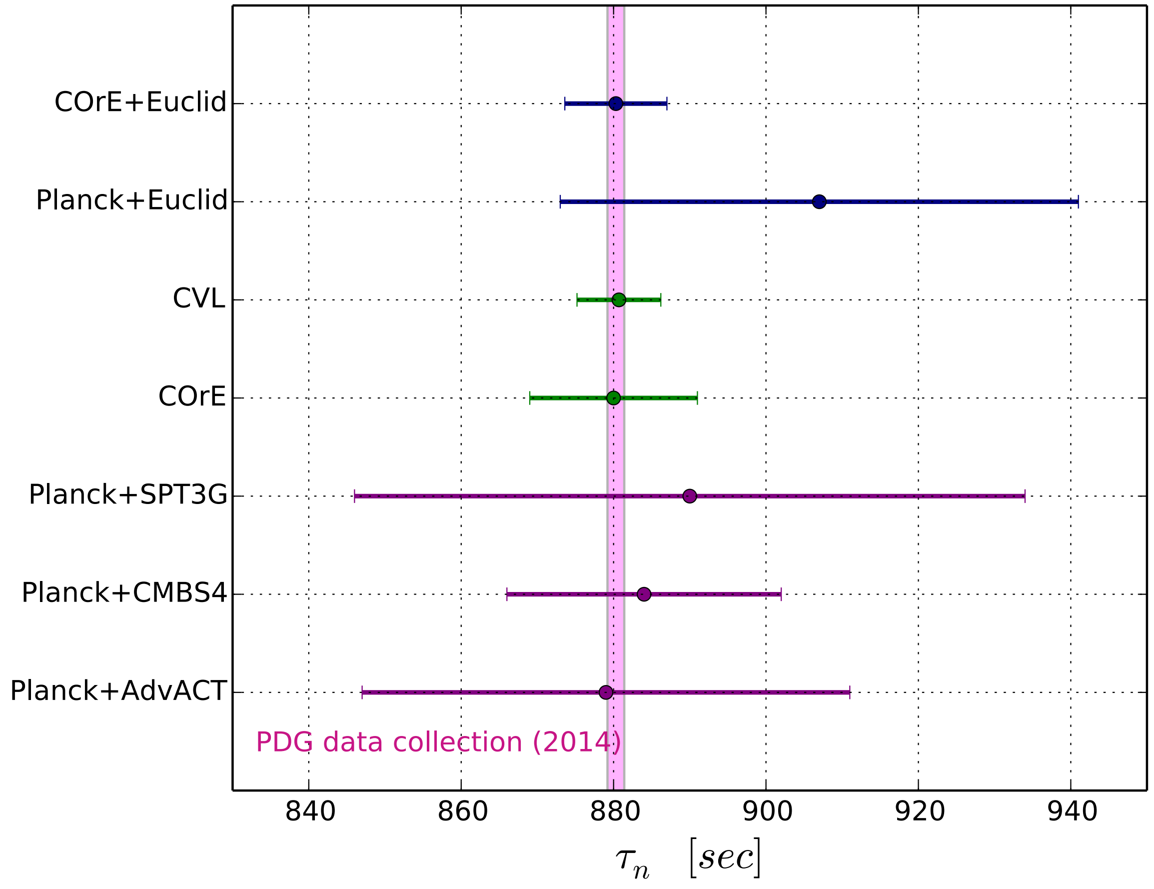
→

next generation CMB
missions in high - ℓ
regime



Dataset	Y_p^{BBN}	τ_n [s]
Planck TT, TE, EE + AdvACT	0.2464 ± 0.0065	$\mathbf{879 \pm 32}$
Planck TT, TE, EE + CMB-S4	0.2475 ± 0.0037	$\mathbf{884 \pm 18}$
Planck TT, TE, EE + SPT-3G	0.2487 ± 0.0091	$\mathbf{890 \pm 44}$
COrE	0.2467 ± 0.0023	$\mathbf{880 \pm 11}$
CVL	0.2467 ± 0.0011	$\mathbf{880.7 \pm 5.5}$
Planck TT, TE, EE + Euclid	0.2521 ± 0.0069	$\mathbf{907 \pm 34}$
COrE + Euclid	0.2467 ± 0.0014	$\mathbf{880.3 \pm 6.7}$

(68% c.l.)



Constraints on neutron lifetime

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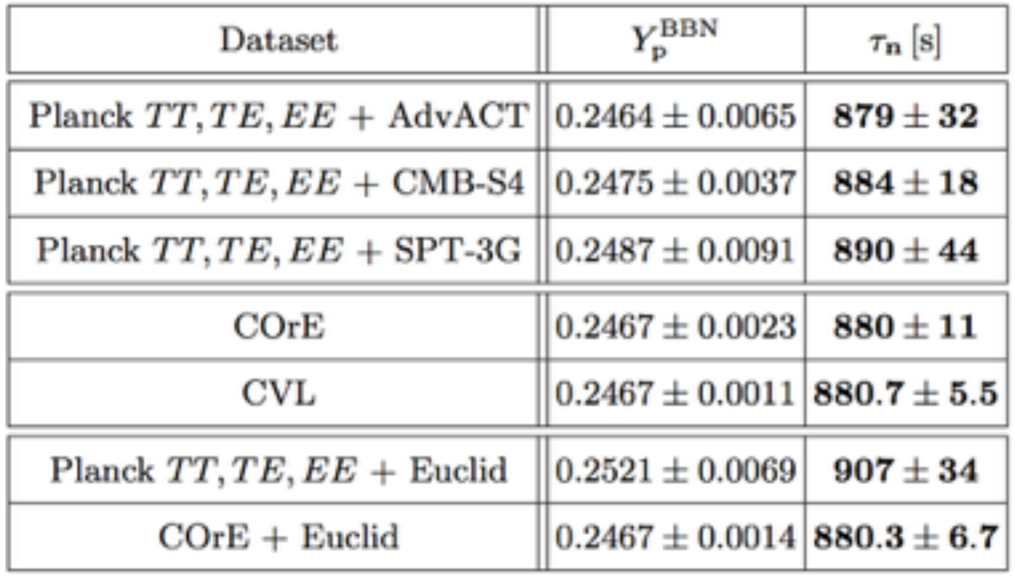

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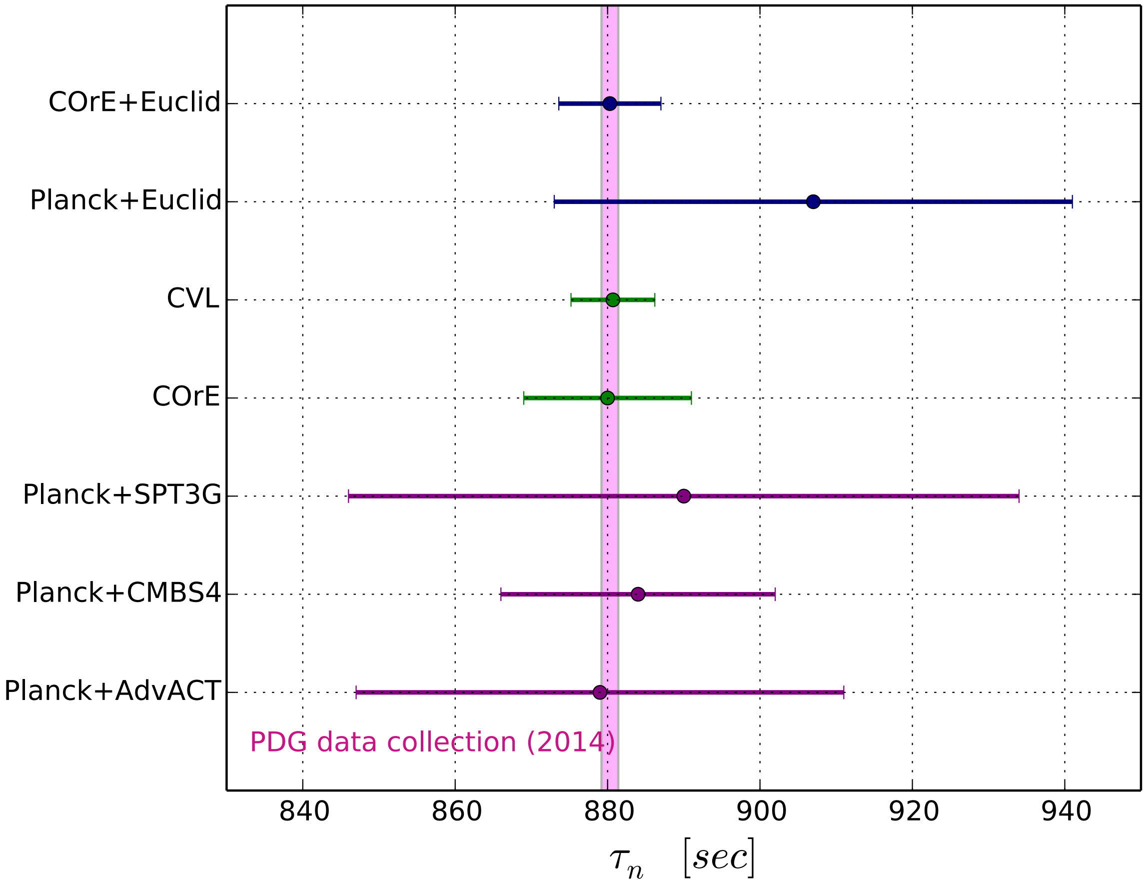


Future astrophysical observations

To reach PDG accuracy $\Longrightarrow$ $\sigma(Y_{\rm p}) = 0.0002$ → better control of systematics.

Conclusions

Constrain neutron lifetime with cosmology and astrophysics

current cosmological data

$\sigma_{\tau_n} \simeq 60\,\mathrm{s}$

→

current cosmological and astrophysical data

$\sigma_{\tau_n} \simeq 15\,\mathrm{s}$

→

future cosmological data

$\sigma_{\tau_n} \simeq 7\,\mathrm{s}$

→

future cosmological and astrophysical data

$\sigma_{\tau_n} \sim \ \mathrm{s}$

beam-bottle discrepancy: 8.4 s
$3.8\,\sigma$

Model-dependent analysis ↔ Independent estimation

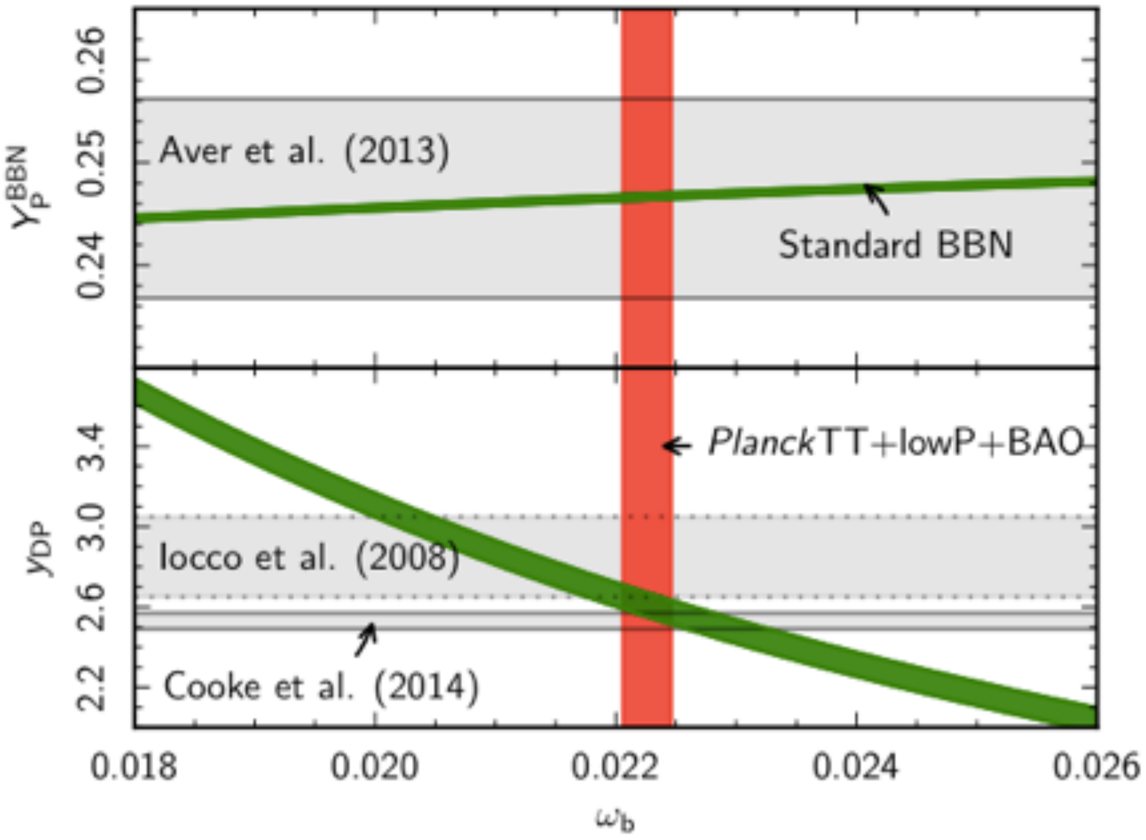
Thank you for your attention

BBN and CMB

Results from Planck 2015

Planck 2015 results. XIII. arXiv:1502.01589

$N_{\rm eff} = 3.046 \qquad \Lambda{\rm CDM} \implies \omega_b$



Astrophysical observations

Aver et al. (2013) (95% c.l.)

$Y_P^{BBN} = 0.2465 \pm 0.019$

Cooke et al. (2014) (95% c.l.)

$y_{DP} = 2.53 \pm 0.08$

Iocco et al. (2009) (95% c.l.)

$y_{DP} = 2.87 \pm 0.44$

“systematics” errors

$\sigma(y_{DP}) = 0.06$

$\sigma(Y_P^{BBN}) = 0.0003$

<u>Planck TTTEEE + lowP</u> (95% c.l.)

$$\omega_b = 0.02225^{+0.00032}_{-0.00030} \qquad Y_P^{BBN} = 0.24667^{+(0.00014)0.00062}_{-(0.00014)0.00062} \qquad y_{DP} = 2.614^{+(0.057)0.13}_{-(0.060)0.13}$$

statistical errors

TTTEEE: spectrum-based temperature-polarization likelihood (including cross-correlation) $\ell = 30 \div 2500$

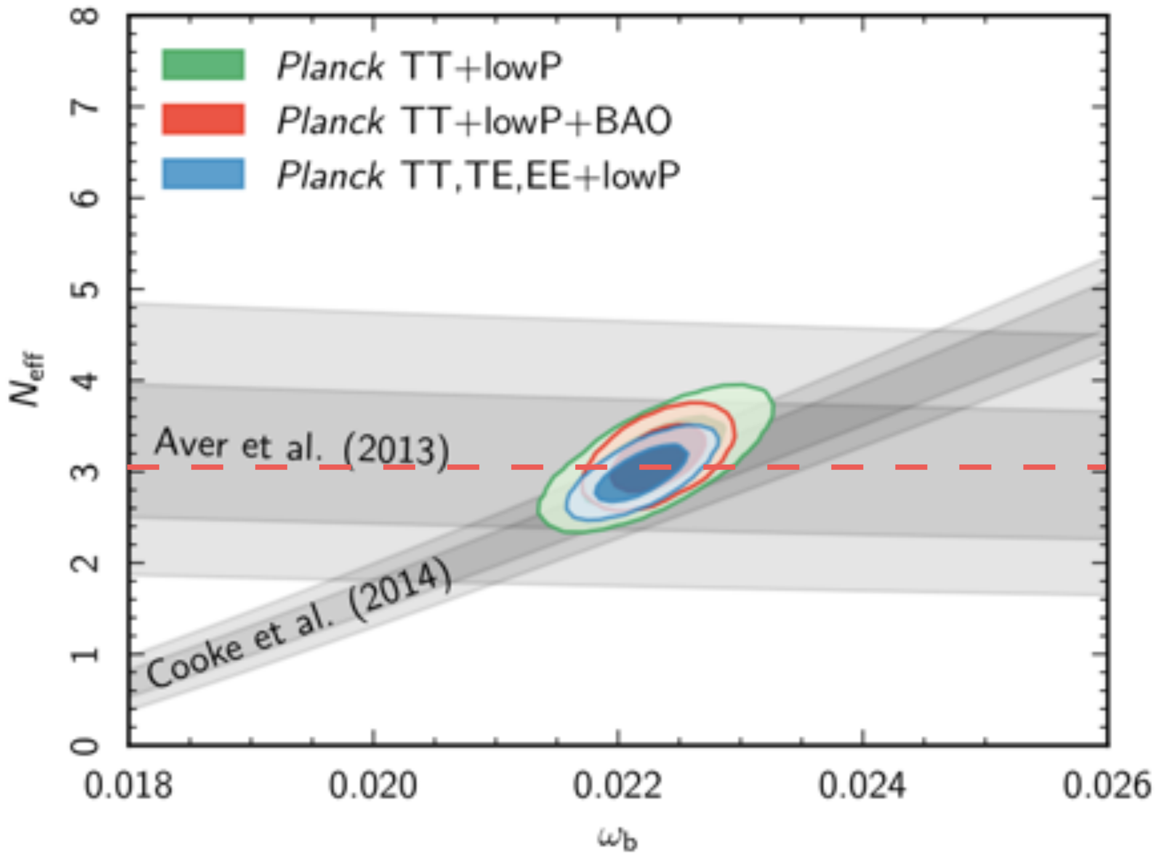
lowP: temperature-polarization likelihood (including cross-correlation) $\ell = 2 \div 29$

BBN and CMB

Results from Planck 2015

Planck 2015 results. XIII. arXiv:1502.01589

Relaxing $N_{\rm eff}$



He + Planck TTTEEE + lowP (95% c.l.)

$$\boxed{N_{\rm eff} = 2.99^{+0.39}_{-0.39}}$$

D + Planck TTTEEE + lowP (95% c.l.)

$$\boxed{N_{\rm eff} = 2.91^{+0.37}_{-0.37}}$$

TTTEEE: spectrum-based temperature-polarization likelihood (including cross-correlation) $\ell = 30 \div 2500$

lowP: temperature-polarization likelihood (including cross-correlation) $\ell = 2 \div 29$

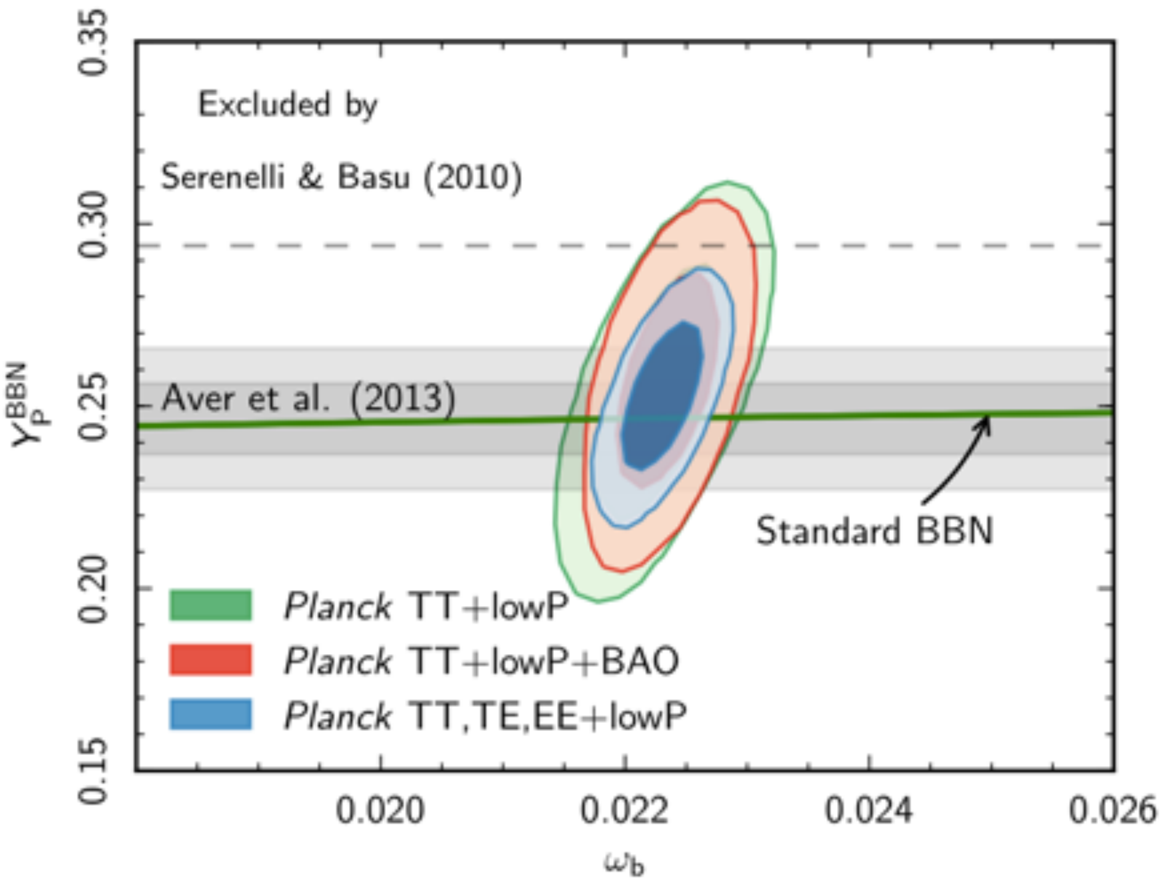
BBN and CMB

Results from Planck 2015

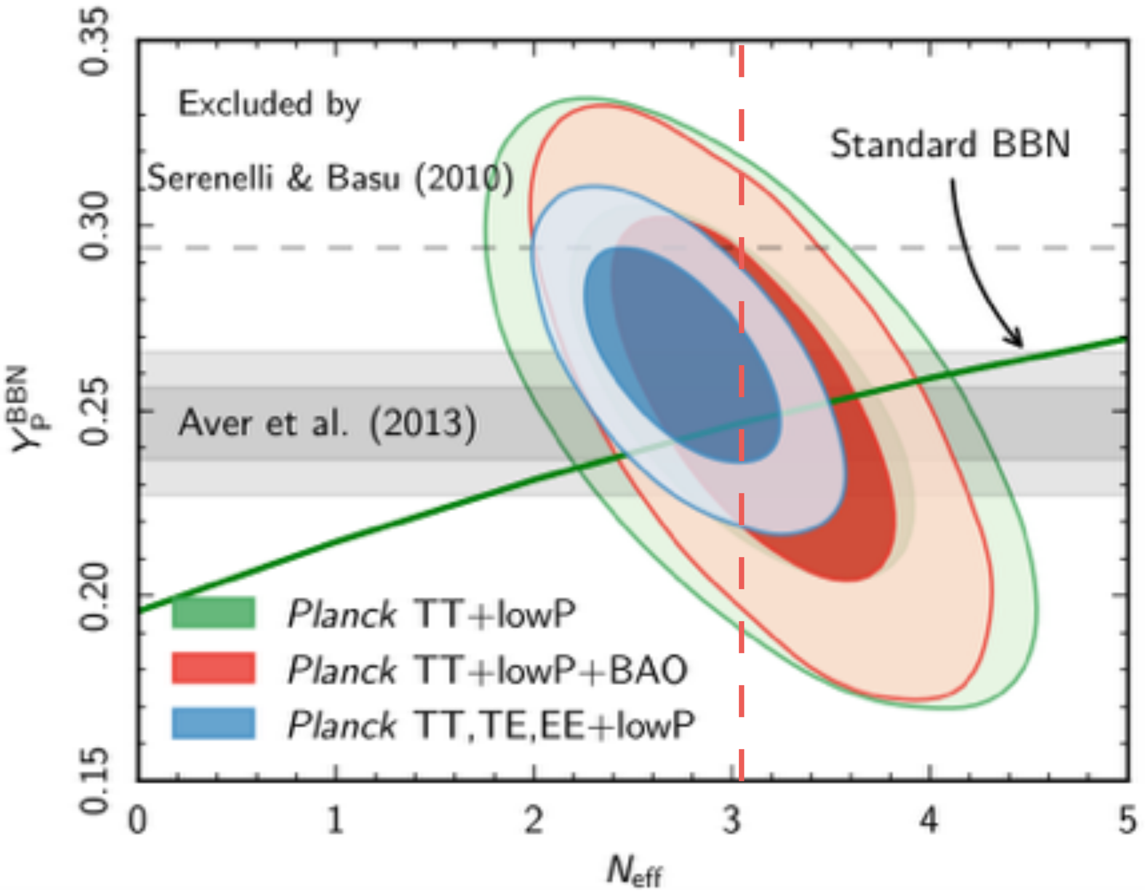
Planck 2015 results. XIII. arXiv:1502.01589

Measuring Y_p directly from CMB.

$N_\mathrm{eff} = 3.046$



Relaxing N_eff



Planck TTTEEE + lowP (95% c.l.)

$$\boxed{Y_\mathrm{P}^\mathrm{BBN} = 0.251^{+0.026}_{-0.027}}$$

Planck TTTEEE + lowP (95% c.l.)

$$\boxed{Y_\mathrm{P}^\mathrm{BBN} = 0.263^{+0.034}_{-0.037}}$$

TTTEEE: spectrum-based temperature-polarization likelihood (including cross-correlation) $\ell = 30 \div 2500$

lowP: temperature-polarization likelihood (including cross-correlation) $\ell = 2 \div 29$

Particle Data Group

To average data: standard weighted least-squares method

- increasing errors with a “scale factor”. PDG. Chinese Physics C Vol. 38, No. 9 (2014) 090001

$$\bar{x} \pm \delta\bar{x} = \frac{\sum_i w_i \, x_i}{\sum_i w_i} \pm \left(\sum_i w_i\right)^{-1/2}$$

$$w_i = 1/(\delta x_i)^2$$

assuming uncorrelated measures

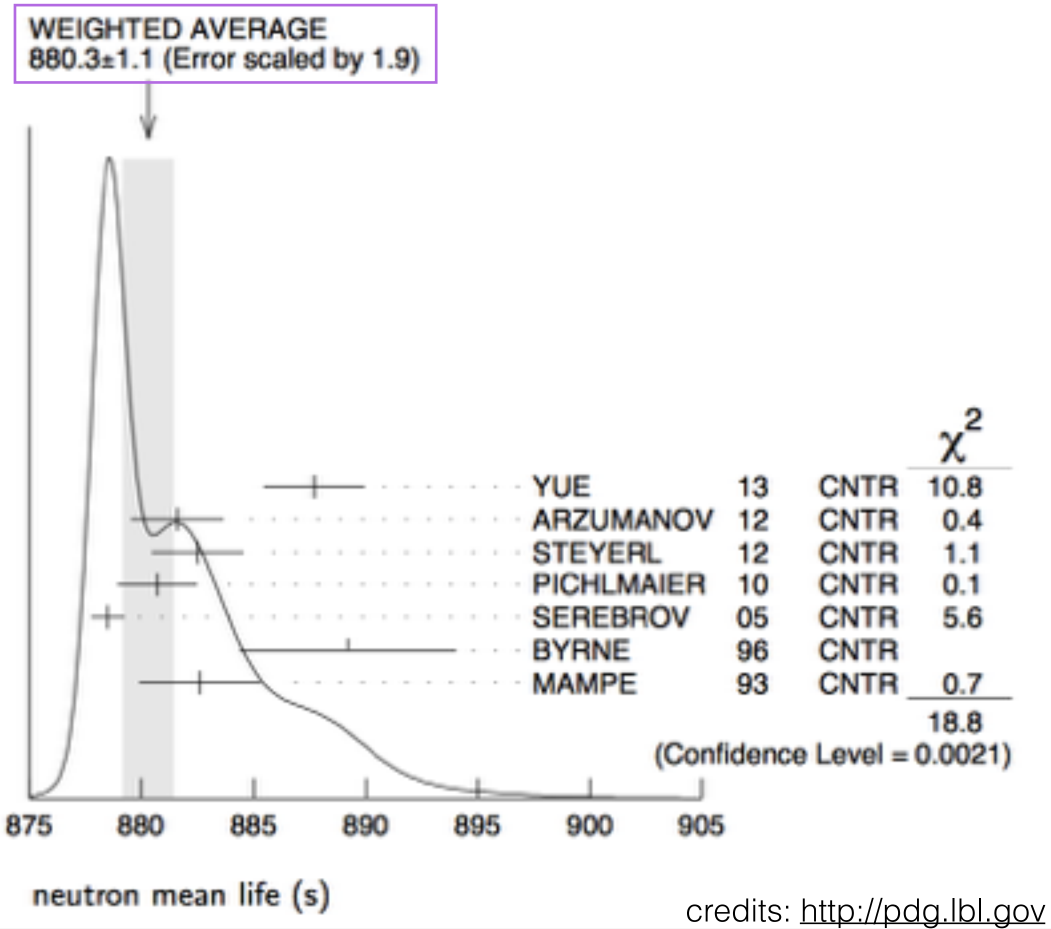
$$\chi^2 = \sum_i w_i (\bar{x} - x_i)^2$$

if $\dfrac{\chi^2}{N-1} > 1$

$$S = \sqrt{\frac{\chi^2}{N-1}}$$

scale factor

$$\delta\bar{x}_{\text{fin}} = S \cdot \delta\bar{x}$$



			χ^2
YUE	13	CNTR	10.8
ARZUMANOV	12	CNTR	0.4
STEYERL	12	CNTR	1.1
PICHLMAIER	10	CNTR	0.1
SEREBROV	05	CNTR	5.6
BYRNE	96	CNTR	
MAMPE	93	CNTR	0.7
			18.8

(Confidence Level = 0.0021)

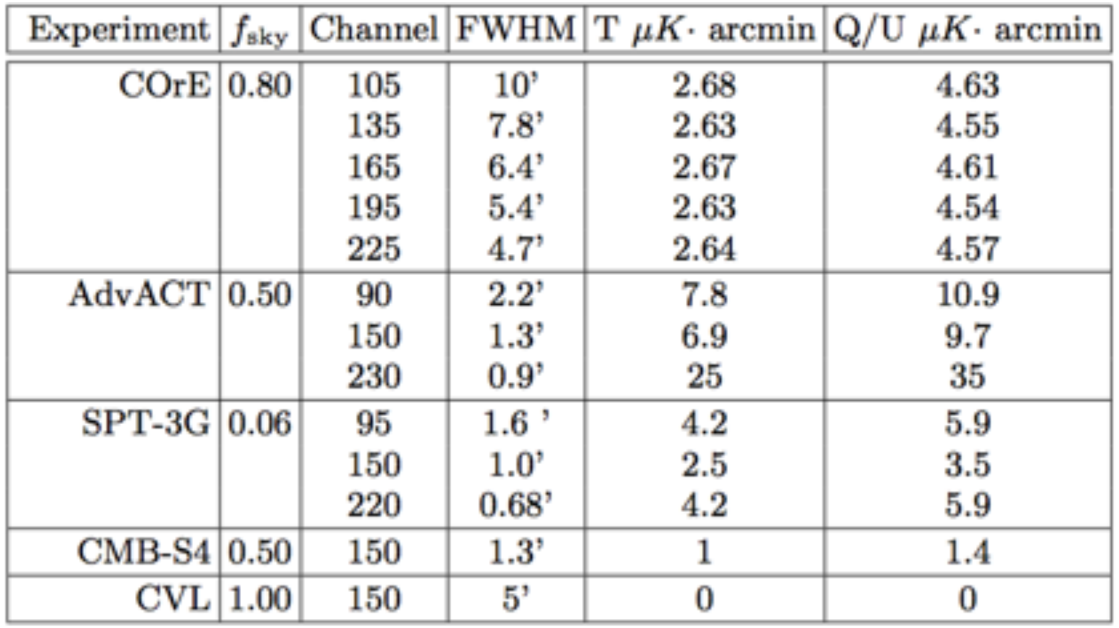
credits: http://pdg.lbl.gov

Forecasts

Produce a CMB dataset (experimental dataset):

- Planck 2015 best-fit as fiducial model
- uncertainties due to foreground removal smaller than statistical errors
- negligible beam uncertainties
- white noise.

Lewis, Phys. Rev. D 71 (2005) 083008



Experiment	$f_{\rm sky}$	Channel	FWHM	T $\mu K\cdot$ arcmin	Q/U $\mu K\cdot$ arcmin
COrE	0.80	105	10'	2.68	4.63
		135	7.8'	2.63	4.55
		165	6.4'	2.67	4.61
		195	5.4'	2.63	4.54
		225	4.7'	2.64	4.57
AdvACT	0.50	90	2.2'	7.8	10.9
		150	1.3'	6.9	9.7
		230	0.9'	25	35
SPT-3G	0.06	95	1.6 '	4.2	5.9
		150	1.0'	2.5	3.5
		220	0.68'	4.2	5.9
CMB-S4	0.50	150	1.3'	1	1.4
CVL	1.00	150	5'	0	0

Euclid mission:

- experimental specification in Martinelli et al., Phys. Rev. D 83 (2011) 023012
- Fisher matrix formalism.

BBN and CMB

How to improve estimate of primordial abundances:

- main uncertainties are due to particle-nuclear physics.

Deuterium

$$y_{\rm DP} = 2.620^{+(0.083)0.15}_{-(0.085)0.15}$$

Planck 2015 results. XIII. arXiv:1502.01589

SMALL TENSION

$$y_{\rm DP,C} = 2.53 \pm 0.04$$

Cooke et al. arXiv:1308.3240

uncertainty on the rate of the reaction $d(p,\gamma)\mathrm{He}^3$

$$S(E)^{\rm exp} < S(E)^{\rm th} \quad \text{of about} \quad 5 \div 10\%$$

$$30\,\mathrm{keV} < E_{\rm BBN} < 300\,\mathrm{keV}$$

PArthENoPE code

$$\boxed{R_2(T) = A_2 R_2^{exp}(T)}$$

Di Valentino et al., Phys. Rev. D 90 (2014) 2, 023543

Considering Deuterium observations

$$A_2 = 1.106 \pm 0.071$$

Planck 2015 results. XIII. arXiv:1502.01589

Higher reaction rate:

- more deuterium is destroyed
- better agreement between Planck and direct astrophysical measurements.

present CMB data: provide information on nuclear physics

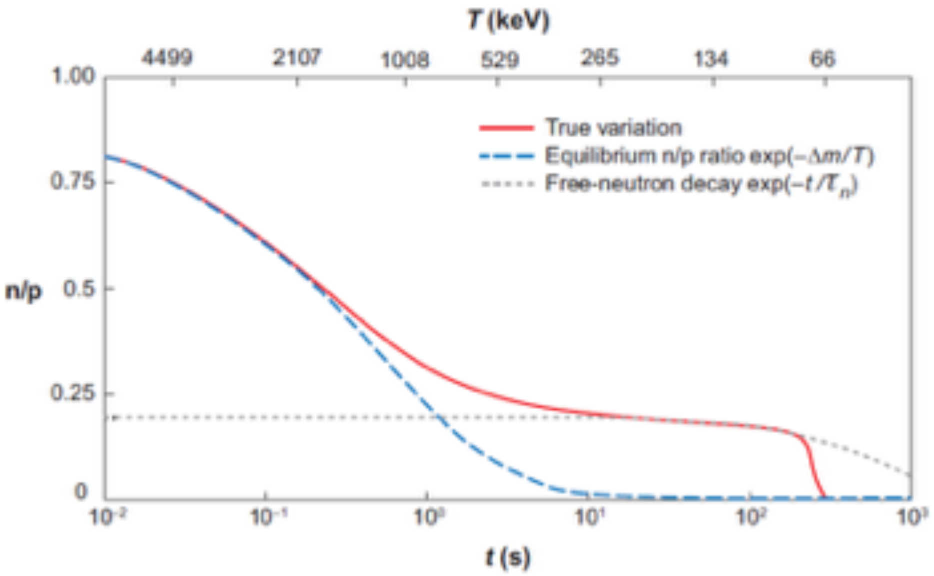
Big Bang Nucleosynthesis

Big Bang Nucleosynthesis (BBN):
formation of light nuclei in the first minutes after the Big Bang.

Before BBN:

- neutrinos decoupling
  $2.0\ \mathrm{MeV} < E < 3.5\ \mathrm{MeV}$
  - $e^{\pm}$ annihilation, photons reheating
- departure from equilibrium for $\frac{n_\mathrm{n}}{n_\mathrm{p}}$.

$$\frac{n_\mathrm{n}}{n_\mathrm{p}} = \exp\left(-\frac{(m_\mathrm{n}-m_\mathrm{p})c^2}{KT}\right)$$



Steigmann, Annu. Rev. Nucl. Part. Sci. 2007.57:463-491

$$\rho_{\nu,\mathrm{ID}} = 3 \cdot \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

neutrinos energy density,
Instantaneous Decoupling

$$\rho_\nu \equiv \frac{N_\mathrm{eff}}{3}\rho_{\nu,\mathrm{ID}}$$

neutrinos energy density,
Non Instantaneous Decoupling

→ Relativistic degrees of freedom

$$N_\mathrm{eff} = 3.046$$

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\mathrm{eff}\right]\rho_\gamma$$

Total energy density of radiation

Lesgourgues et al., New J. Phys.16 (2014) 065002