Cosmology with Planck: Nucleosynthesis and neutron life-time constraints

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Outline

- Big Bang Nucleosynthesis as cosmological probe
  - Big Bang Nucleosynthesis
  - PArthENoPE
  - Astrophysical bounds
- Planck Data
- Results standard BBN (Y_P^{BBN} and y_{DP})
  - Bounds fixing the radiation density
  - Varying N_{eff}
- Planck direct measurement
  - Standard radiation density
- Neutron life-time estimation
- Conclusions

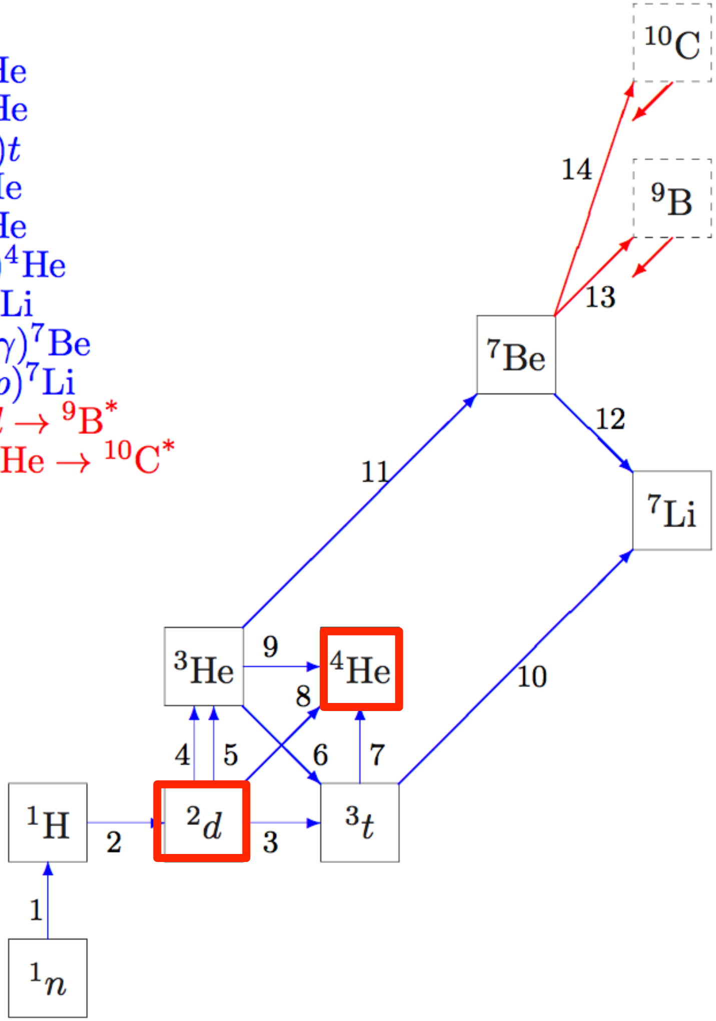
Based on:
Planck 2015 results. XIII. Cosmological parameters
Salvati, Pagano, Consiglio and Melchiorri, Cosmological constraints on the neutron lifetime, in preparation

Big Bang Nucleosynthesis

- BBN predicts the primordial abundance of light elements formed in the first minutes after the Big Bang
- Function of the baryon-to-photon density ratio η_b and the relativistic degrees of freedom parameterize as N_{eff}
- Fixing the photon temperature today (T_0=2.7255 K) η_b can be related to ω_b
- ^{4}He, ^{2}H, ^{3}He, ^{7}Li nuclei produced
- First part of this talk on the ^{4}He and Deuterium abundances expressed respectively as
  - $Y_P^{BBN} = 4n_{He}/n_b$
  - $y_{DP} = 10^5\ n_D/n_H$

Big Bang Nucleosynthesis

1: $n \rightarrow p\, e\, \nu$
2: $n(p,\gamma)d$
3: $d(d,p)t$
4: $d(p,\gamma)^3\mathrm{He}$
5: $d(d,n)^3\mathrm{He}$
6: $^3\mathrm{He}(n,p)t$
7: $t(d,n)^4\mathrm{He}$
8: $d(d,\gamma)^4\mathrm{He}$
9: $^3\mathrm{He}(d,p)^4\mathrm{He}$
10: $t(\alpha,\gamma)^7\mathrm{Li}$
11: $^4\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
12: $^7\mathrm{Be}(n,p)^7\mathrm{Li}$
13: $^7\mathrm{Be} + d \rightarrow {}^9\mathrm{B}^*$
14: $^7\mathrm{Be} + {}^3\mathrm{He} \rightarrow {}^{10}\mathrm{C}^*$



- BBN calculations based on **PArthENoPE** code (Pisanti et al.)
- Incorporates nuclear reaction rates, particle masses and fundamental constants
- Y_P^{BBN} and y_{DP} function of (ω_b , N_{eff})
- Theoretical uncertainties:
  - $\sigma(Y_P^{BBN})=0.0003$, **dominated by neutron lifetime**
  - $\sigma(y_{DP})=0.04$, based on uncertainties in nuclear rates (Serpico et al. 2004)
- Predictions can be confronted with direct measurements and also with CMB data $(\eta_b , N_{eff}$ and $Y_p)$

Astrophysical bounds and Planck data

- Several observation data on primordial abundances
- From spectroscopic observations in metal-poor H_{II} regions
  - Y_P^{BBN} =0.2465±0.0097 by **Aver et al. 2013**
  - Dominated by systematics
- Proto-Solar helium abundance more conservative upper bound
  - Y_P^{BBN} <0.295 at 95% c.l. by Serenelli & Basu 2010
- Deuterium absorption line systems in quasar spectra, very metal-poor Lyman-a system at high redshift:
  - y_{DP}= 2.53±0.04 by **Cooke and Pettini 2014**
  - More conservative data collection by **Iocco et al. 2009** y_{DP}= 2.87±0.22
- For Planck we used combination of Temperature and Polarization data including in some analysis also BAO observations
  - lowP: Pixel-based TQU likelihood at large scales
  - Planck TT: Spectra-based temperature likelihood at small scales
  - Planck TT TE EE: Spectra-based temperature and polarization likelihood at small scales
- Bounds on ω_b model-dependent but very stable with model extensions to the minimal LCDM.

Planck 2015 results

- Let’s start with the radiation density fixed to its standard value $N_{eff}=3.046$

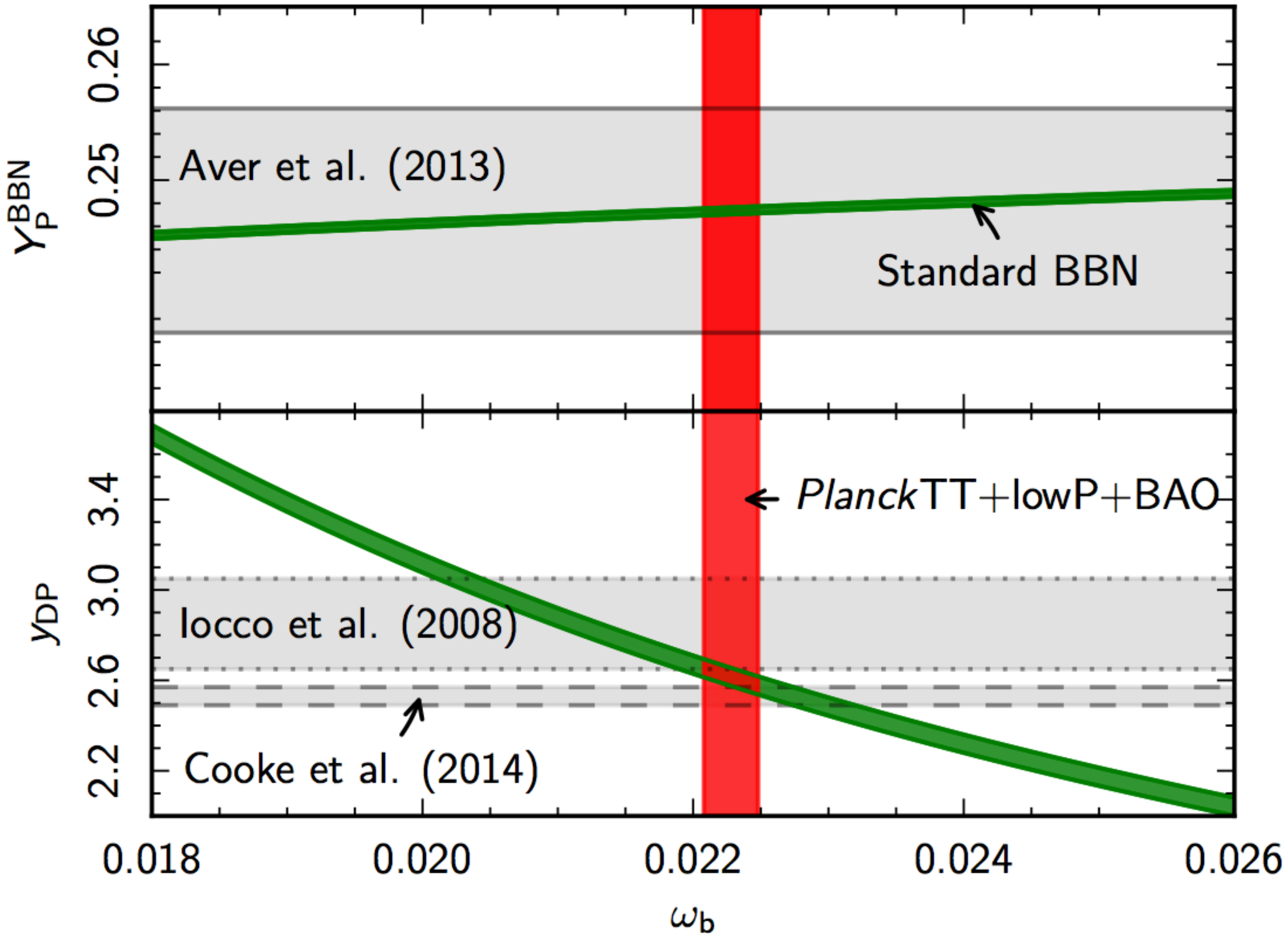
- Planck 2015 (95%CL)

  Planck TT TE EE+lowP

  - $\omega_b = 0.02225 \pm 0.00031$
  - $Y_P^{BBN} = 0.24667 \pm (0.0014)\ 0.00062$
  - $y_{DP} = 2.614 \pm (0.058)\ 0.13$
  - Error bars in parentheses reflect only the uncertainty on ω_b.
  - The second set includes the theoretical uncertainty on the BBN predictions.

- **The theoretical error dominates the total error on Y_P**
- On Y_P^{BBN} the Planck prediction is in agreement with Aver et al. measurements
- For y_{DP} the **Planck measurement lays in between Cooke et al. and Iocco et al. results**

Results standard BBN



Joint CMB+BBN predictions on N_{eff}

- Relaxing the assumption on N_{eff}
- But stick to the hypothesis that electronic neutrinos have a standard distribution, with a negligible chemical potential
- Assuming standard BBN we can identify the region of N_{eff} - ω_b parameter space that is compatible with direct measurement of the primordial Helium and Deuterium abundances
- Planck 2015 (95%CL)

  Planck TT TE EE+lowP
  - N_{eff}= 2.99±0.40

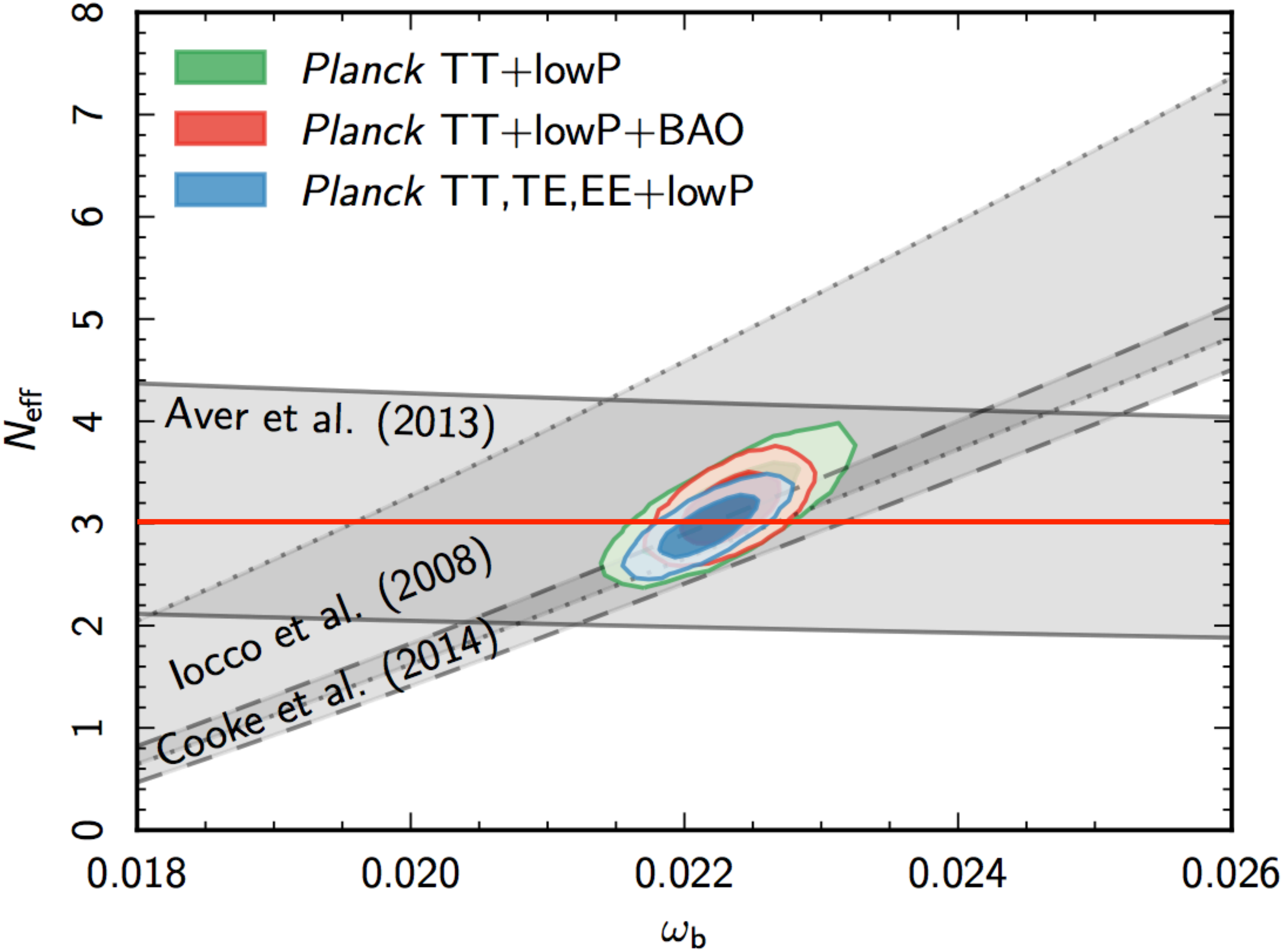
  \+ Aver et al. (2013)
  - N_{eff}= 2.99±0.39

  \+ Cooke et al. (2014)
  - N_{eff}= 2.91±0.37

$$\chi^2(\omega_\mathrm{b}, N_\mathrm{eff}) \equiv \frac{[y(\omega_\mathrm{b}, N_\mathrm{eff}) - y_\mathrm{obs}]^2}{\sigma^2_\mathrm{obs} + \sigma^2_\mathrm{theory}}$$

- No improvement adding Helium abundance
- **D+Planck(T+P) best estimate of N_{eff}**

Results standard BBN

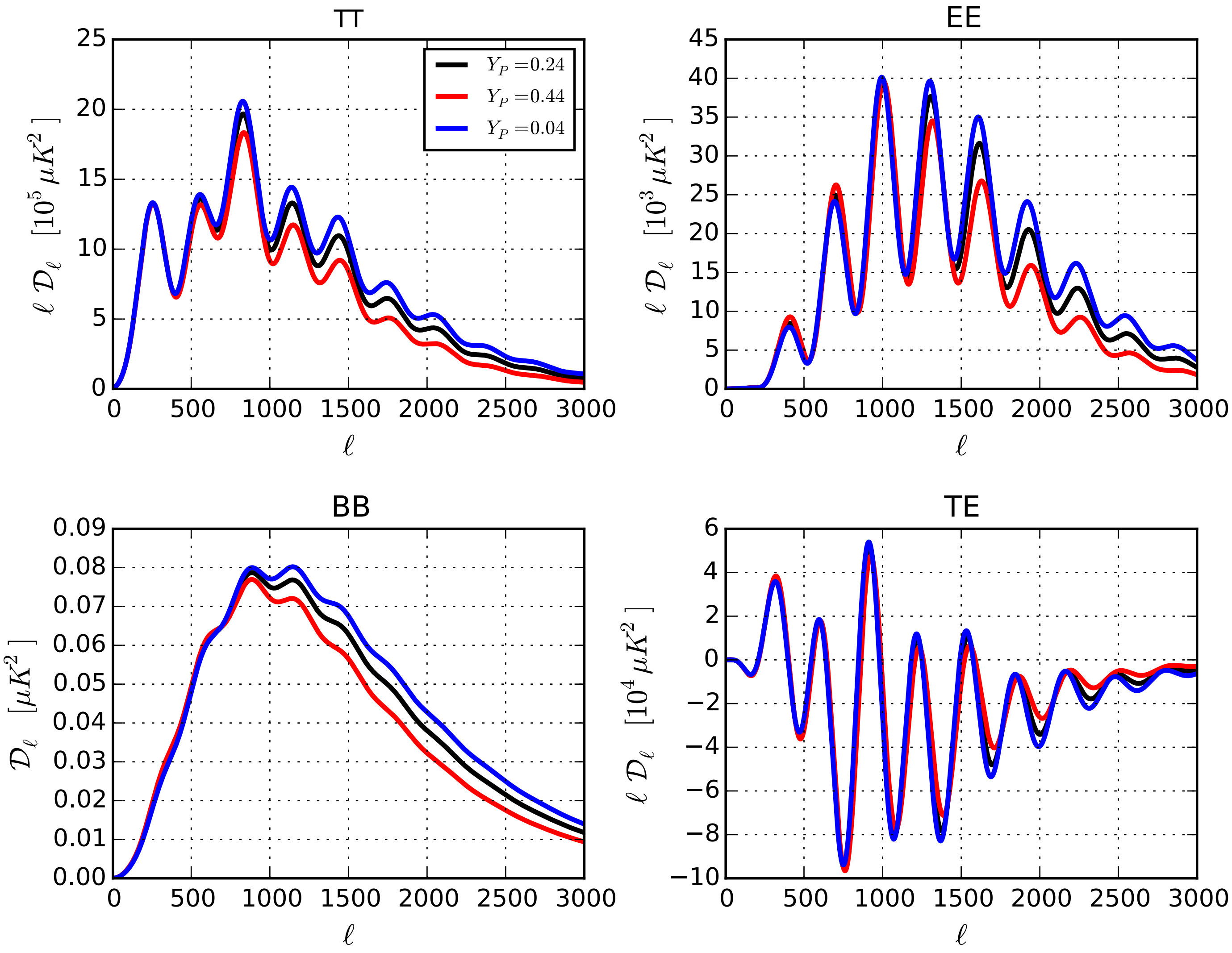


Model-independent bounds on Helium fraction from Planck

- Instead of inferring the primordial helium abundance from BBN codes
- We can measure it directly with *Planck*, using the sensitivity of the redshift of last scattering and of the diffusion damping scale to Y_P
- The primordial Helium mass fraction is a free parameter in recombination and Boltzmann codes
- Converting this number in density fraction we can compare the CMB predictions with astrophysical constrains
- Fixing $N_{eff}=3.046$

$Y_P^{BBN}=0.250\pm0.041$	95%CL	(Planck TT + lowP)
$Y_P^{BBN}=0.254\pm0.036$	95%CL	(Planck TT + lowP + BAO)
$Y_P^{BBN}=0.252\pm0.027$	95%CL	(Planck TT,TE,EE + lowP)

- In the *Planck* TT,TE,EE + lowP case, the helium fraction determined with a standard deviation of 0.013
  - 30% larger than in the data compilation of Aver et al.(2013)


TT
EE
BB
TE
$Y_P = 0.24$
$Y_P = 0.44$
$Y_P = 0.04$
$\ell\,\mathcal{D}_\ell\ \ [10^5\,\mu K^2]$
$\ell\,\mathcal{D}_\ell\ \ [10^3\,\mu K^2]$
$\mathcal{D}_\ell\ \ [\mu K^2]$
$\ell\,\mathcal{D}_\ell\ \ [10^4\,\mu K^2]$
ℓ
0
500
1000
1500
2000
2500
3000
25
20
15
10
5
45
40
35
30
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
6
4
2
−2
−4
−6
−8
−10

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- The primordial Helium mass fraction is a free parameter in recombination and Boltzmann codes
- Converting this number in density fraction we can compare the CMB predictions with astrophysical constrains
- Planck 2013 result: $\boxed{Y_P^{BBN}=0.266 \pm 0.042}$ @ 95%CL (Planck+WP+highL).
- Fixing $N_{eff}=3.046$
  - $Y_P^{BBN}=0.250\pm0.041$ 95%CL (Planck TT + lowP)
  - $Y_P^{BBN}=0.254\pm0.036$ 95%CL (Planck TT + lowP + BAO)
  - $\boxed{Y_P^{BBN}=0.252\pm0.027}$ 95%CL (Planck TT,TE,EE + lowP)
- In the *Planck* TT,TE,EE + lowP case, the helium fraction determined with a standard deviation of 0.013
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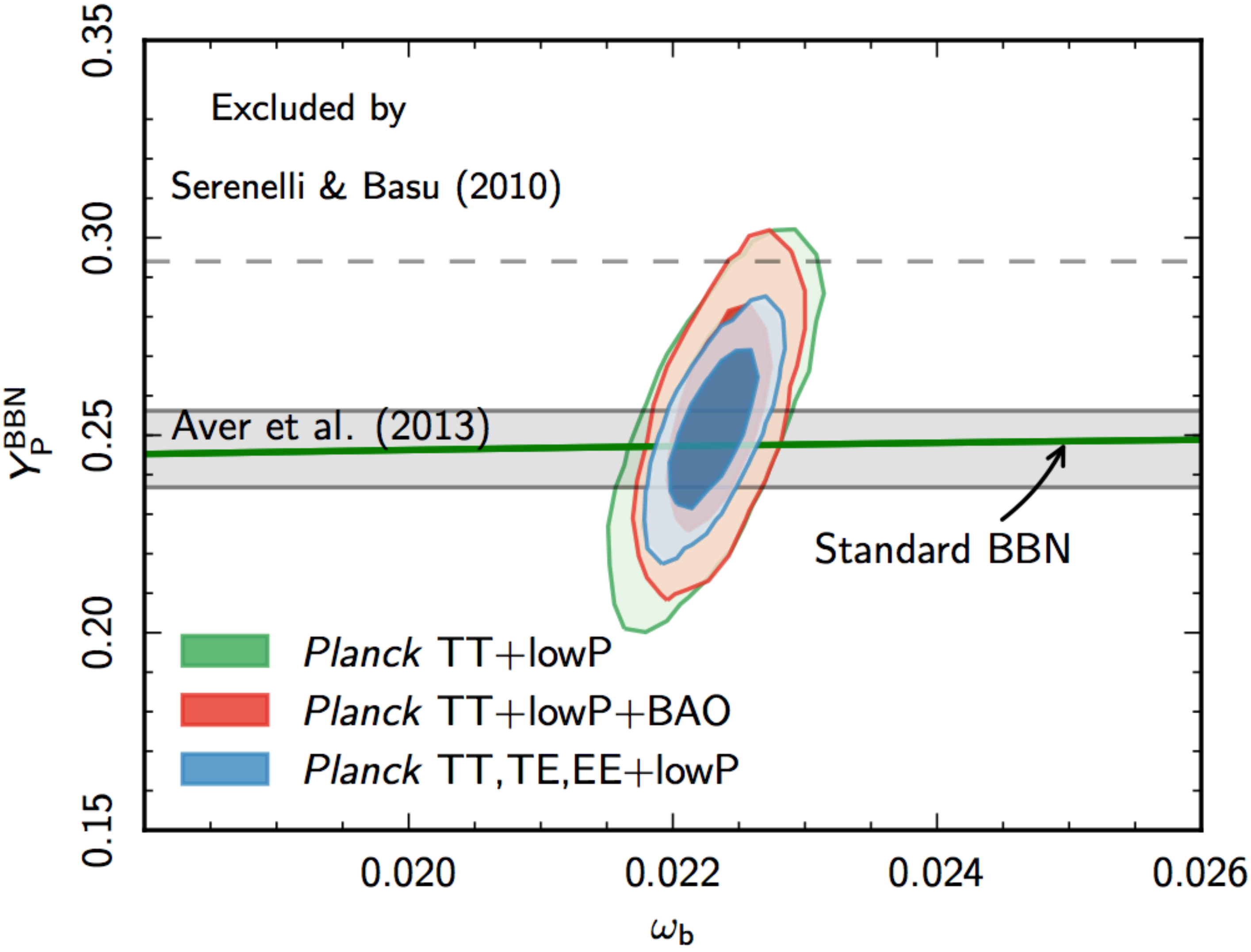
Model-independent bounds on Y_P – N_{eff}=3.046



Cosmological constraints on neutron lifetime

- Main uncertainty on helium abundance is due to the one on the neutron life-time τ_n
- From Particle Data Group:
  - Combining 5 most recent measurements with “bottle method”:

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

Pignol, arXiv:1503.03317.

  - Combining 2 most recent measurements with “beam method”.

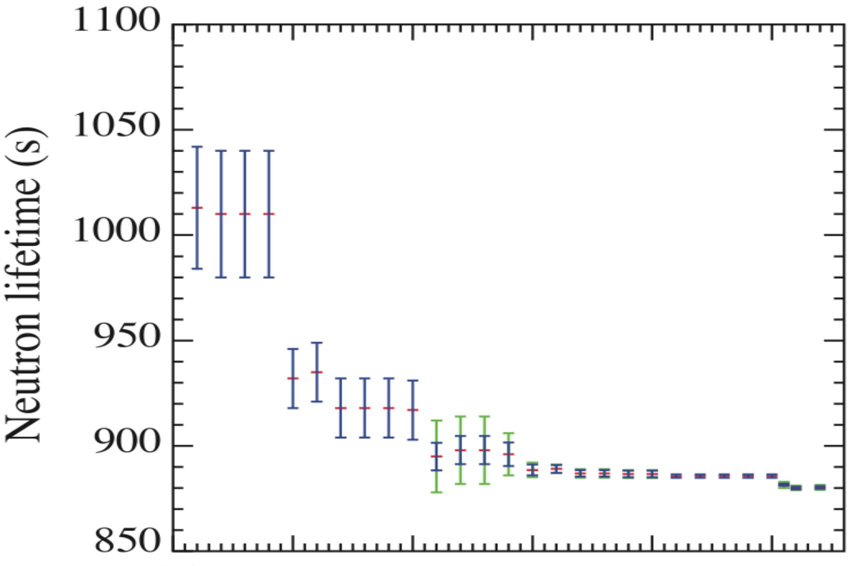
$$\tau_n^{\text{beam}} = (888.0 \pm 2.1)\ [\text{s}]$$

- Weighted average quoted by the PDG

$$\tau_n^{\text{PDG}} = (880.3 \pm 1.1)\ [\text{s}]$$

- Dominated by systematic errors

Olive et al., (PDG), Chin. Phys. C, 38, 090001 (2014).

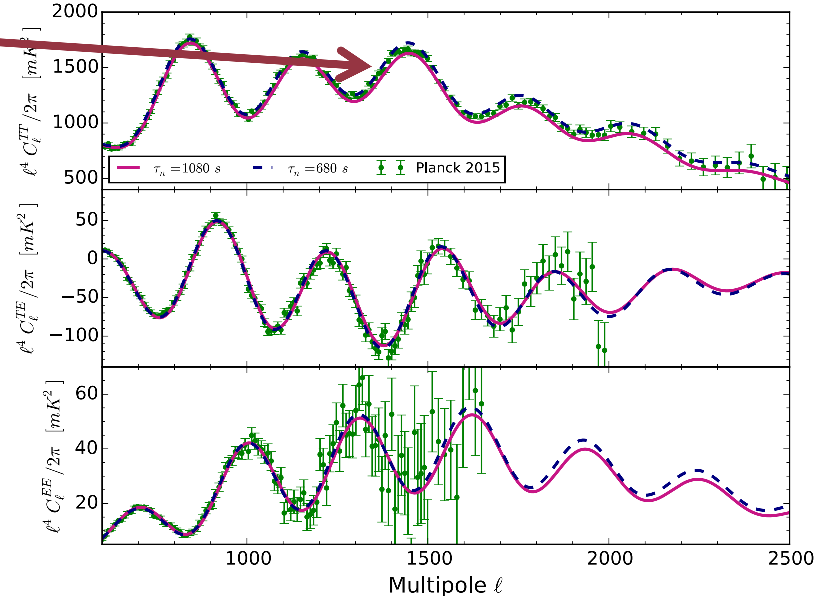


Cosmological constraints on neutron lifetime

Salvati, Pagano, Consiglio and Melchiorri, Cosmological constraints on the neutron lifetime, in preparation

- Assuming Standard BBN
- CMB: $\omega_b,\ Y_{\rm p}$ + BBN: $Y_{\rm p}(\omega_b,\ N_{\rm eff},\ \tau_n)$ ➔ constraints on τ_n

- Affects the damping tail
- We fit for ΛCDM + τ_n



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

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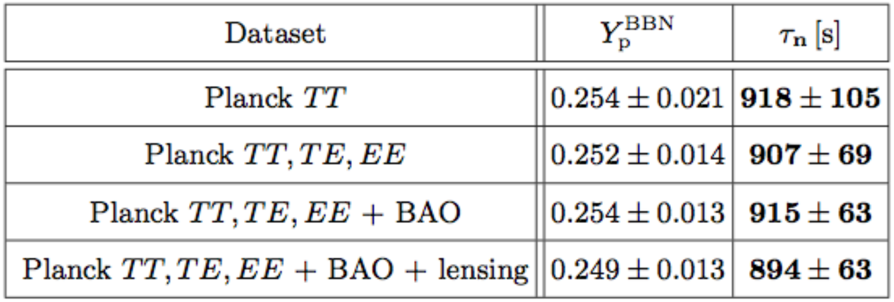
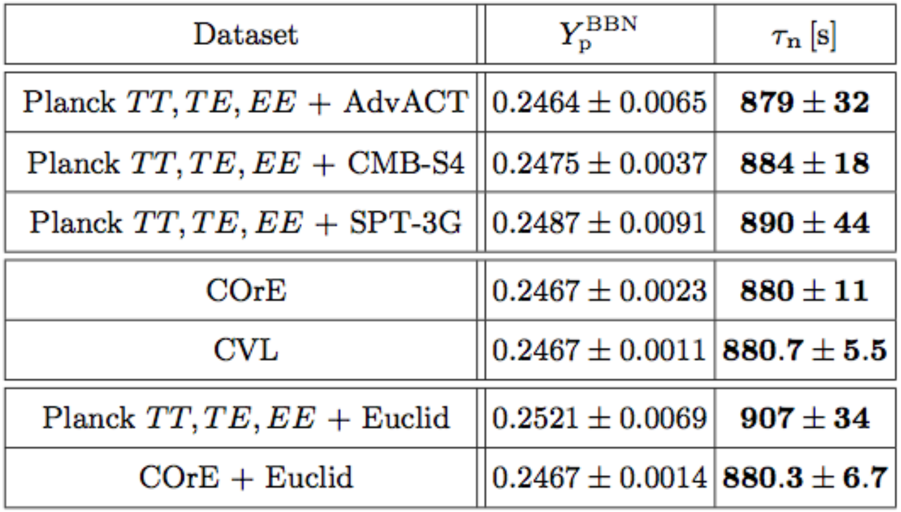
- Planck and current cosmological data:



Dataset	$Y_p^{\rm BBN}$	τ_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	$\mathbf{894 \pm 63}$

- Future cosmological constraints:



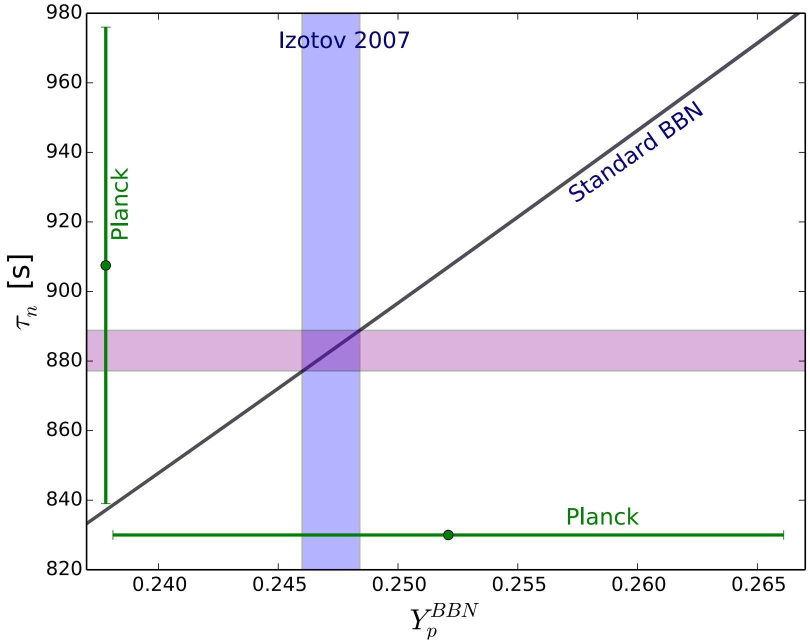
Dataset	$Y_p^{\rm BBN}$	τ_n [s]
Planck TT, TE, EE + AdvACT	0.2464 ± 0.0065	$\mathbf{879 \pm 32}$
Planck TT, TE, EE + CMB-S4	0.2475 ± 0.0037	$\mathbf{884 \pm 18}$
Planck TT, TE, EE + SPT-3G	0.2487 ± 0.0091	$\mathbf{890 \pm 44}$
COrE	0.2467 ± 0.0023	$\mathbf{880 \pm 11}$
CVL	0.2467 ± 0.0011	$\mathbf{880.7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

Cosmic Variance Limited: most accurate precision reached from CMB experiments.

Cosmological constraints on neutron lifetime

Salvati, Pagano, Consiglio and Melchiorri, Cosmological constraints on the neutron lifetime, in preparation

- CMB measurements + direct astrophysical bounds on Y_p
- For the analysis:
  - select **eight primordial He measurements** (latest ten years)
  - combine these with Planck data: **gaussian likelihood on the input Helium abundance**



Dataset	$Y_p^{\rm data}$	$Y_p^{\rm BBN}$	τ_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	$\mathbf{907 \pm 14}$
M12-I14	0.2519 ± 0.0016	0.2519 ± 0.0016	$\mathbf{905.7 \pm 7.8}$
M12-P	0.2479 ± 0.0018	0.2479 ± 0.0018	$\mathbf{886.7 \pm 8.8}$

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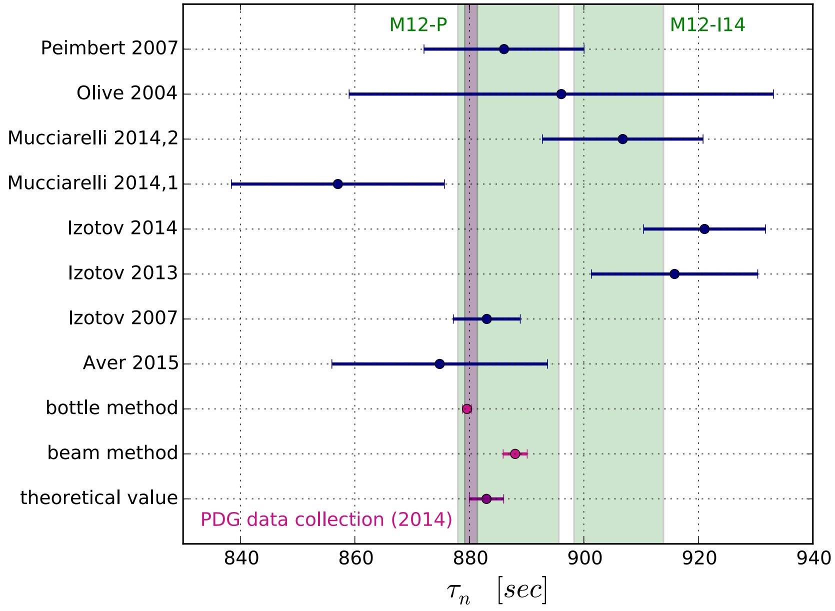

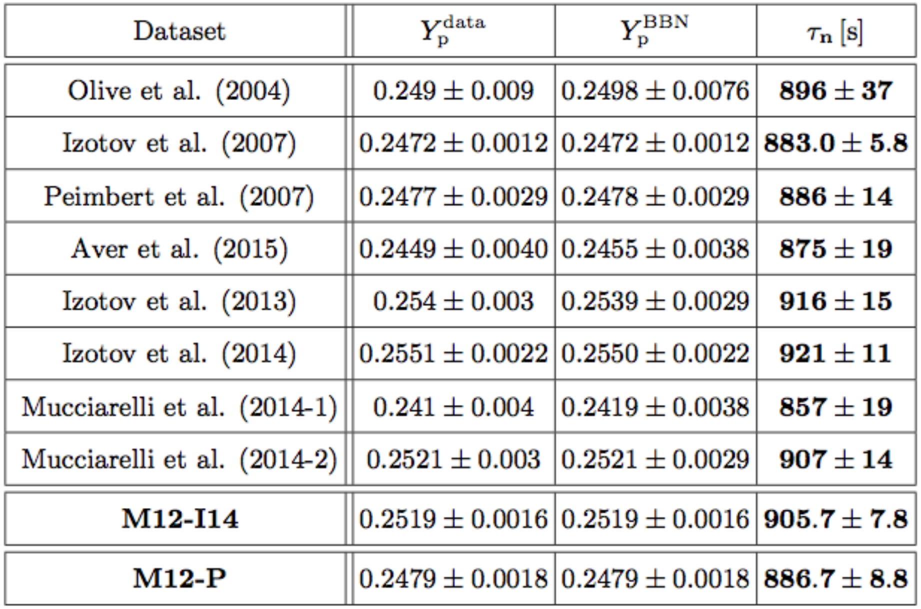

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Conclusions

- Planck 2015 BBN results consistent with the 2013 results
- Errorbars on ω_b halved thanks to high-ell polarization measurements
- Assuming Standard BBN:
  - No improvement on the He estimation, dominated by the neutron lifetime uncertainty
  - 30% improvement on primordial deuterium
  - Compatible with Iocco et al. and Cooke et al. measurements,
  - Standard N_{eff} perfectly consistent
  - Astrophysical priors almost ineffective, modest improvement
- Helium directly from Planck data:
  - Almost at the same level of the direct measurements
- Neutron life-time estimation
  - 60 sec error from current data CMB data, 6 sec reachable with future data
  - Imposing astrophysical priors few seconds error already reached
  - To reach PDG precision better precision on direct measurements needed