Nucleosynthesis and Planck constraints

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Outline

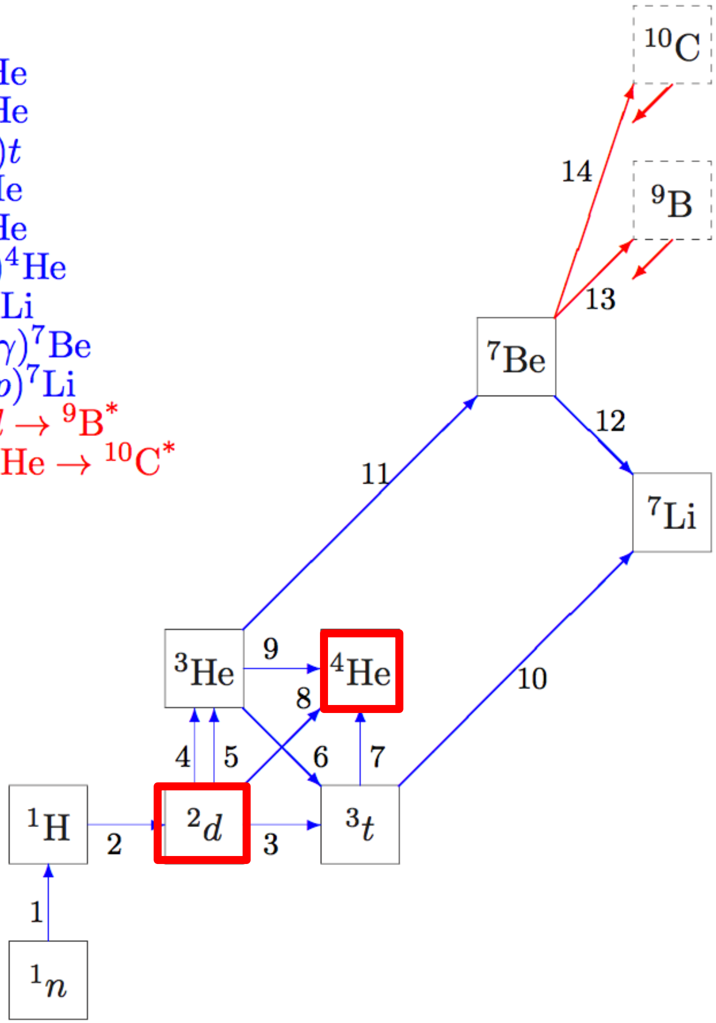
- Big Bang Nucleosynthesis as cosmological probe
  - Big Bang Nucleosynthesis
  - PArthENoPE
  - Astrophysical bounds
- Planck Data
- Results standard BBN (Y_P^{BBN} and y_{DP})
  - Bounds fixing the radiation density
  - Varying N_{eff}
- Planck direct measurement
  - Standard radiation density
  -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

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
- Errors coming from uncertainties on the neutron lifetime and the nuclear reaction rates
- From the PDG 2014 (Olive et al. 2014) the neutron lifetime is $\tau_n=(880.3 \pm 1.1)$ s
- Only ^4He, ^2H, ^3He, ^7Li nuclei produced
- This talk is focused on the ^4He 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: $n \to p\, e\, \nu$
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: $^7\mathrm{Be} + d \to {}^9\mathrm{B}^*$
14: $^7\mathrm{Be} + {}^3\mathrm{He} \to {}^{10}\mathrm{C}^*$



- 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
  - $Y_P^{BBN} = 0.2465 \pm 0.0097$ 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-α system at high redshift:
  - $y_{DP} = 2.53 \pm 0.04$ by Cooke and Pettini 2014
  - More conservative data collection by Iocco et al. 2009 $y_{DP} = 2.87 \pm 0.22$
- For Planck we used combination of Temperature and Polarization data including in some analysis also BAO observations
  - lowP: Pixel-based TQU likelihood l=2-29
  - Planck TT: Spectra-based temperature likelihood l=30-2508
  - Planck TT TE EE: Spectra-based temperature and polarization likelihood l=30-2508
- Bounds on ω_b model-dependent but very stable with model extensions to the minimal ΛCDM.
- Largest degradation with free N_{eff}

Planck 2014 results and comparison with 2013

- Let's start with the radiation density fixed to its standard value $N_{eff}=3.046$
- Planck 2013 (95%CL)

Planck+WP+HighL

□ω_b= 0.02207±0.00054
–Y_P^{BBN}=0.24725±0.00064
–y_{DP}=2.67±0.14

- Planck 2014 (95%CL)

Preliminary

Planck TT+lowP

□ω_b= 0.02222±0.00046
–Y_P^{BBN}=0.24665±0.00063
–y_{DP}=2.62±0.12

Planck TT TE EE+lowP

□ω_b= 0.02224±0.00030
–Y_P^{BBN}=0.24666±0.00061
–y_{DP}=2.616±0.098

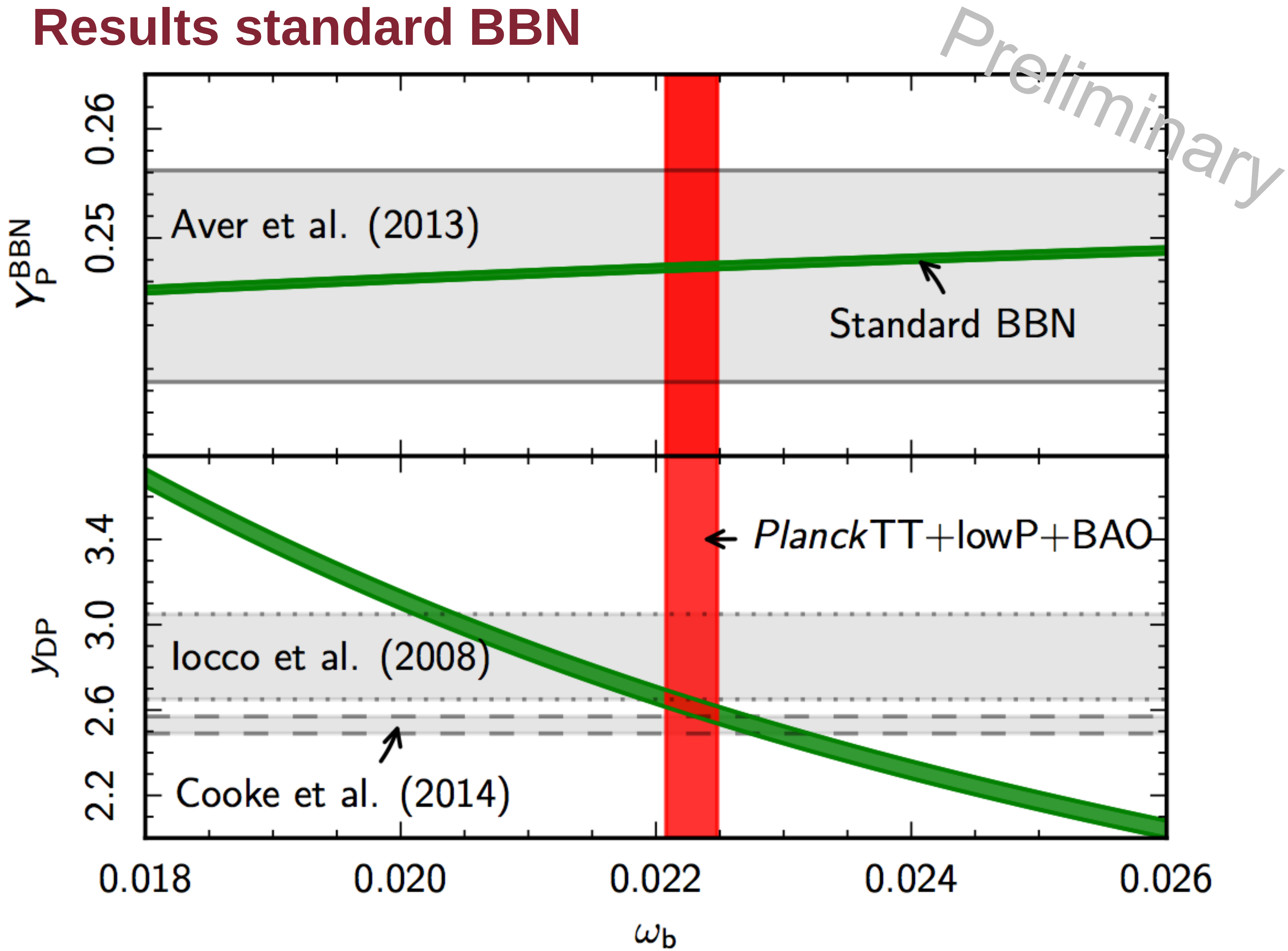
Planck TT+lowP+BAO

□ω_b= 0.02228±0.00039
–Y_P^{BBN}=0.24668±0.00063
–y_{DP}=2.61±0.11

- 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

For more details see poster by L.Salvati: **Planck constraints on Deuterium and comparison with direct observations**

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 2013 (95%CL)

Planck+WP+HighL

–$N_{eff} = 3.36 \pm 0.68$

+Aver et al. (2012) (Helium prior)

–$N_{eff} = 3.41 \pm 0.60$

+ Pettini & Cooke (2012) (Deuterium)

–$N_{eff} = 3.02 \pm 0.54$

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

- Planck 2014 (95%CL)

Planck TT+lowP (Massimiliano's and Julien's Talks)

–$N_{eff} = 3.13 \pm 0.64$

+ Aver et al. (2013)

–$N_{eff} = 3.11 \pm 0.57$

+ Cooke et al. (2014)

–$N_{eff} = 2.92 \pm 0.48$

Planck TT TE EE+lowP

–$N_{eff} = 2.98 \pm 0.40$

+ Aver et al. (2013)

–$N_{eff} = 2.98 \pm 0.36$

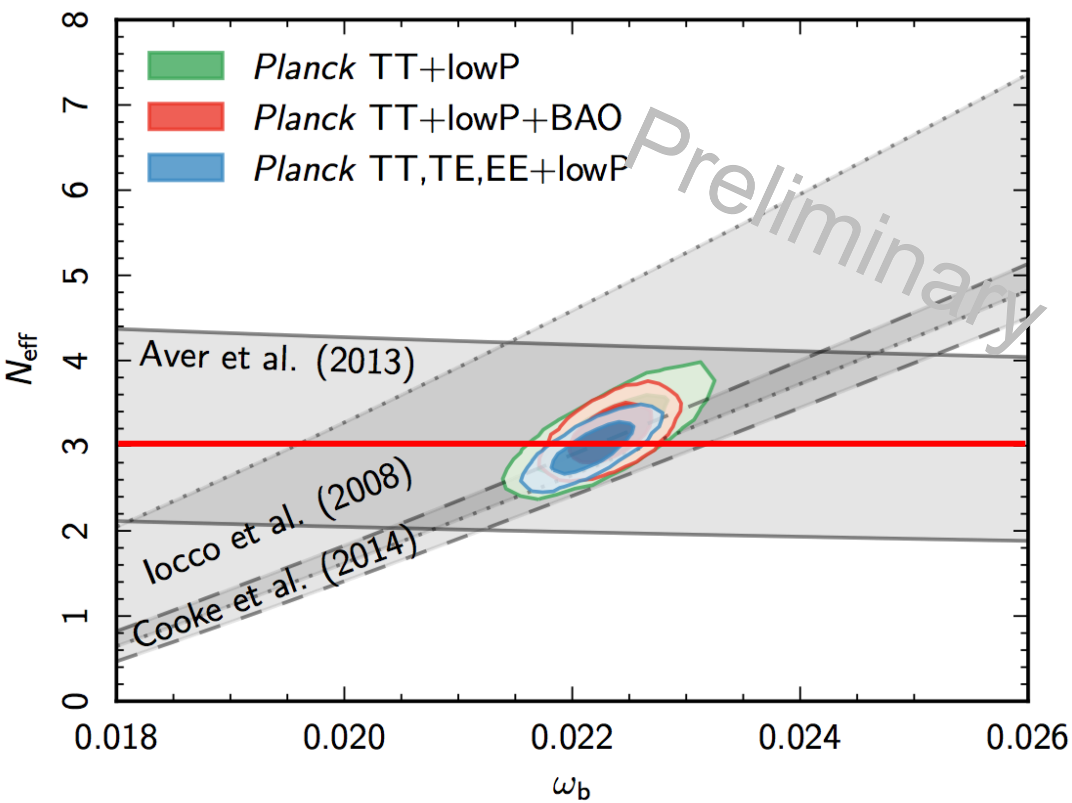
+ Cooke et al. (2014)

–$N_{eff} = 2.87 \pm 0.35$

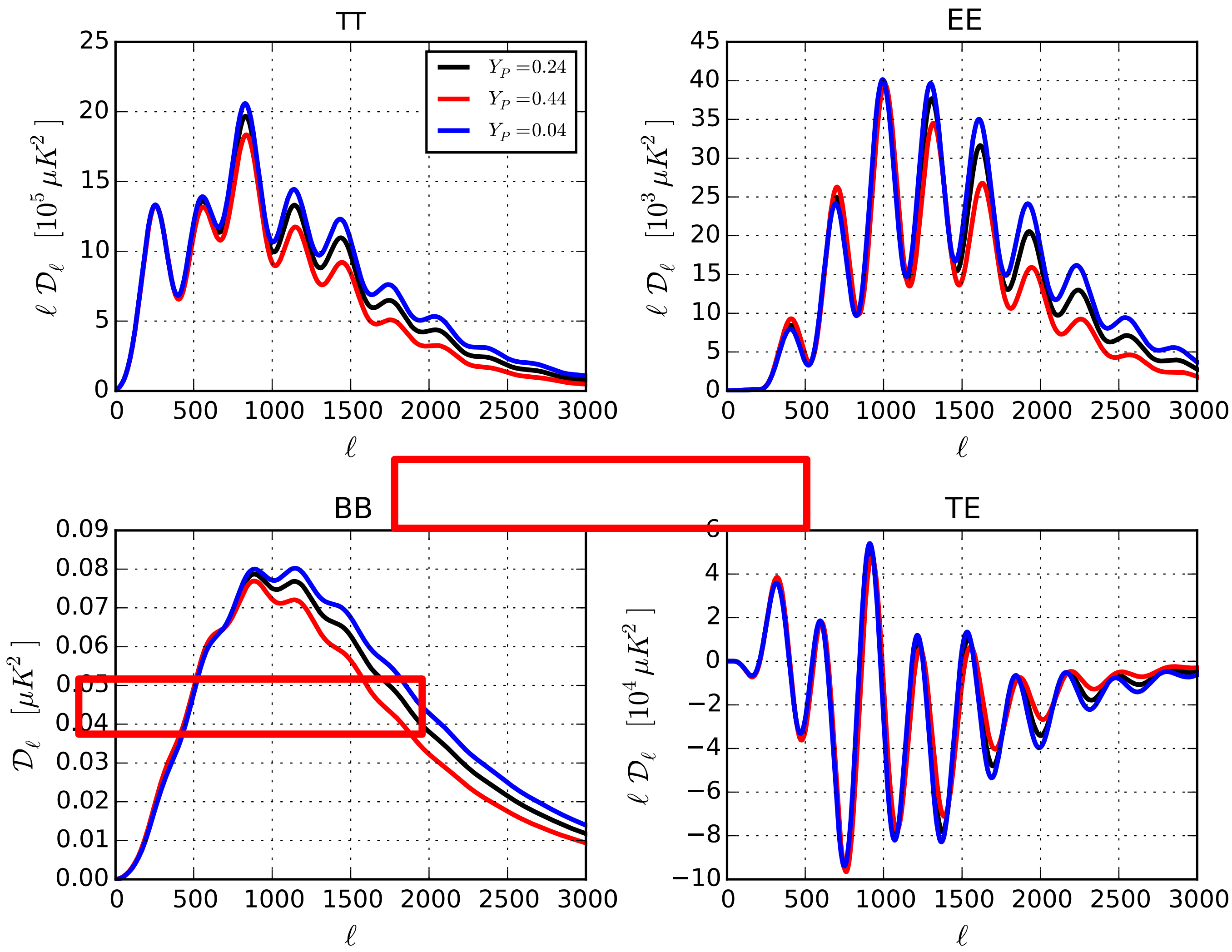
Preliminary

Results standard BBN

- The region singled out by CMB observations lays at the intersection between all Helium and Deuterium 68% CL preferred regions, confirming **great agreement between CMB and BBN**
- The size of the allowed region does not increase significantly when other parameters are allowed to vary at the same time
- We checked that this conclusion applies to models with free neutrino masses, tensor fluctuations or running of the primordial spectrum tilt



Model-independent bounds on Helium fraction



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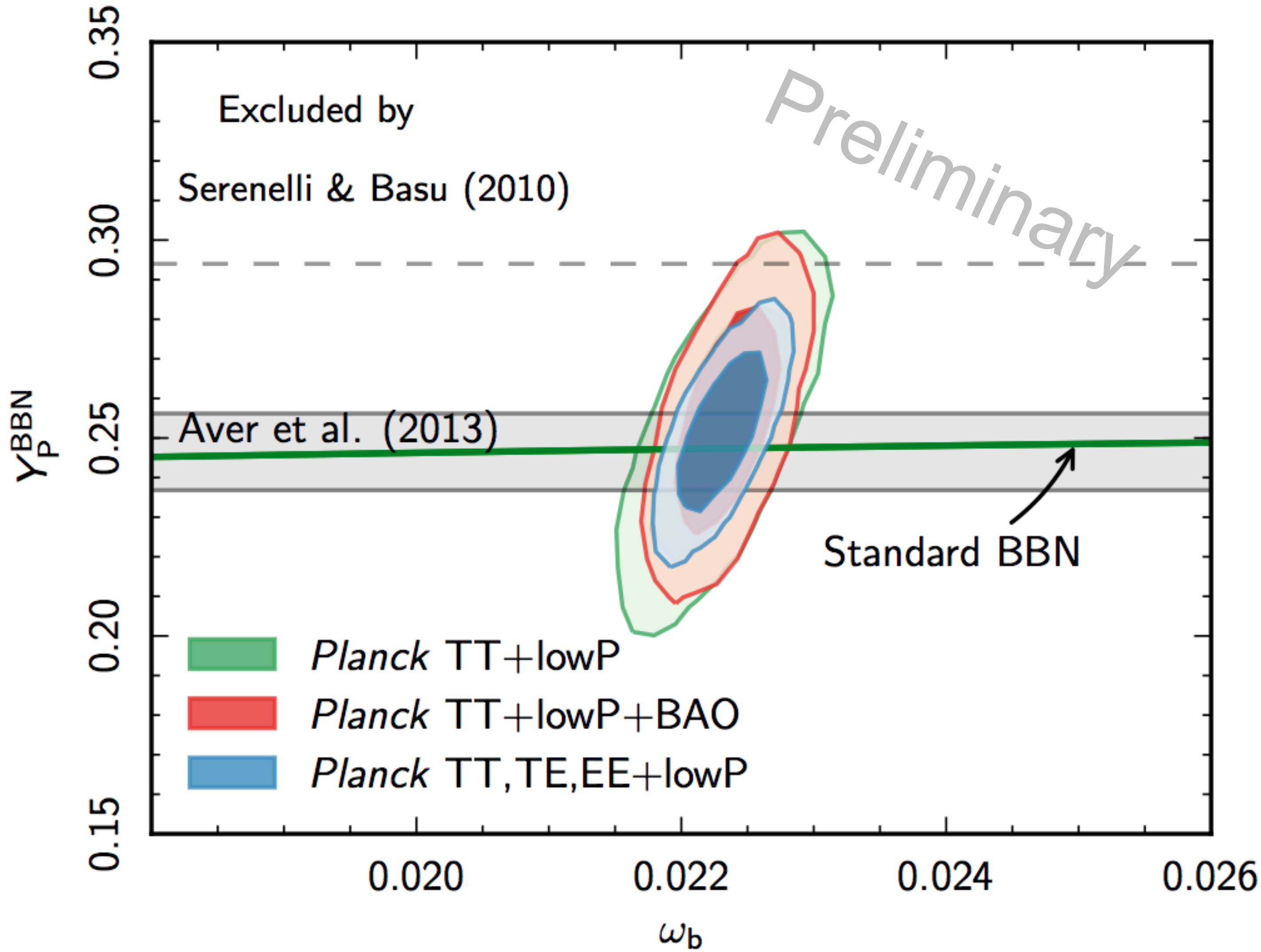
Model-independent bounds on Y_P – N_{eff}=3.046

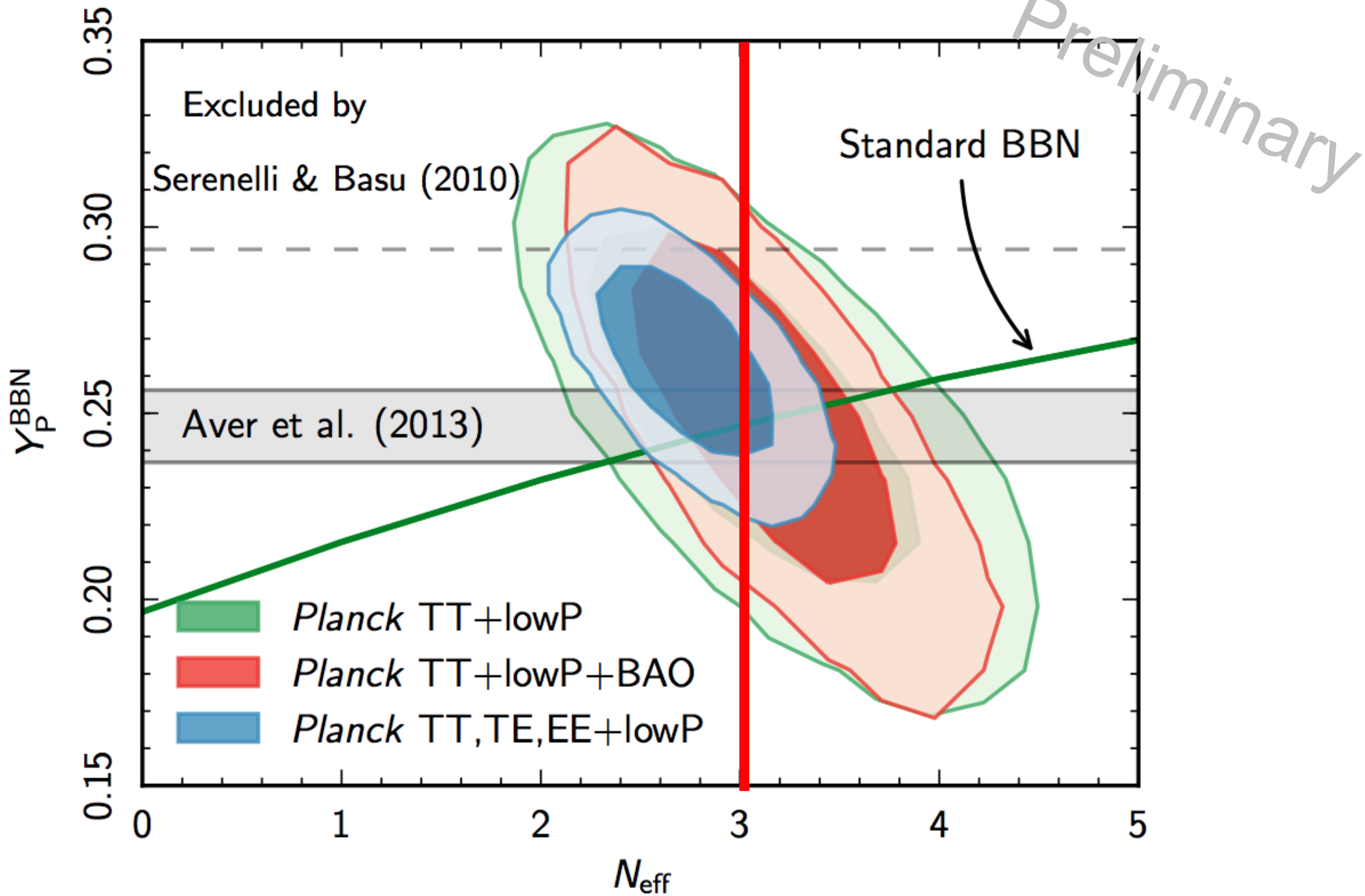


Model-independent bounds on Helium fraction from Planck

- There is a well-known parameter degeneracy between Y_P and the radiation density
- Marginalizing over N_{eff}
- Planck 2013 Y_P^{BBN}=0.254+0.82-0.66
- Planck 2014:
  - Y_P^{BBN}=0.248+0.060-0.066 95%CL (Planck TT + lowP)
  - Y_P^{BBN}=0.248+0.058-0.065 95%CL (Planck TT + lowP + BAO)
  - Y_P^{BBN}=0.262+0.033-0.035 95%CL (Planck TT,TE,EE + lowP)
- The impact of polarisation data is important, and helps to reduce the degeneracy
- Well compatible with N_{eff}=3.046
- Relaxing priors on the Helium fraction does not offer the possibility to accommodate one extra thermalised species.

Preliminary

Model-independent bounds on Y_P – varying N_{eff}



Conclusions

- Planck 2014 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 Helium estimation, dominated by the neutron lifetime uncertainty
  - 30% improvement on primordial deuterium
  - Compatible with Iocco et al. and Cooke et al. measurements, there is no significant tension between CMB and primordial element results
  - N_{eff}=3.046 perfectly consistent
  - Astrophysical priors almost ineffective
- Helium directly from Planck data:
  - 40% improvement fixing the radiation density to its standard value
  - Almost at the same level of the direct measurements Aver et al.
  - 50% improvement Marginalizing over N_{eff}
  - Compatible with standard radiation content

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