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 ($Y_{PB}^{BBN}$ and $\gamma_{DP}$)
  – 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 $\eta_b$ and the relativistic degrees of freedom parameterize as $N_{\text{eff}}$
- Fixing the photon temperature today ($T_0=2.7255$ K) $\eta_b$ can be related to $\omega_b$
- $^4\text{He}$, $^2\text{H}$, $^3\text{He}$, $^7\text{Li}$ nuclei produced
- First part of this talk on the $^4\text{He}$ and Deuterium abundances expressed respectively as
  - $Y^\text{BBN}_p=4n_{\text{He}}/n_b$
  - $y_{DP}=10^5 n_D/n_H$
Big Bang Nucleosynthesis

- 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 $(\omega_b, N_{eff})$
- 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\textsubscript{II} regions
  - \(Y_{P}^{BBN}=0.2465\pm0.0097\) 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:
  - \(y_{DP}=2.53\pm0.04\) by Cooke and Pettini 2014
  - More conservative data collection by Iocco et al. 2009 \(y_{DP}=2.87\pm0.22\)
- 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 \(\omega_b\) 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 $N_{\text{eff}} = 3.046$

• Planck 2015 (95%CL)
  
  
  Planck TT TE EE+lowP
  
  - $\omega_b = 0.02225 \pm 0.00031$
  - $Y_{P,\text{BBN}} = 0.24667 \pm (0.0014) 0.00062$
  - $y_{DP} = 2.614 \pm (0.058) 0.13$

  Error bars in parentheses reflect only the uncertainty on $\omega_b$.
  
  - The second set includes the theoretical uncertainty on the BBN predictions.

• The theoretical error dominates the total error on $Y_P$

• On $Y_{P,\text{BBN}}$ 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

\[
\begin{align*}
Y_{\text{BBN}}^P & \quad 0.25, 0.26 \\
Y_{\text{DP}} & \quad 2.2, 2.6, 3.0, 3.4 \\
\omega_b & \quad 0.018, 0.020, 0.022, 0.024, 0.026 \\
\end{align*}
\]

- Standard BBN
- Aver et al. (2013)
- Planck TT + low P + BAO
- locco et al. (2008)
- Cooke et al. (2014)
Joint CMB+BBN predictions on $N_{\text{eff}}$

- Relaxing the assumption on $N_{\text{eff}}$
- 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 $N_{\text{eff}}$ - $\omega_b$ parameter space that is compatible with direct measurement of the primordial Helium and Deuterium abundances
- Planck 2015 (95%CL)
  \[
  \chi^2(\omega_b, N_{\text{eff}}) = \frac{[y(\omega_b, N_{\text{eff}}) - y_{\text{obs}}]^2}{\sigma^2_{\text{obs}} + \sigma^2_{\text{theory}}}
  \]
  - $N_{\text{eff}} = 2.99 \pm 0.40$
  - Aver et al. (2013)
  - $N_{\text{eff}} = 2.99 \pm 0.39$
  - Cooke et al. (2014)
  - $N_{\text{eff}} = 2.91 \pm 0.37$

- No improvement adding Helium abundance
- D+Planck(T+P) best estimate of $N_{\text{eff}}$
Results standard BBN

Nucleosynthesis and neutron life-time constraints 09/07/2015
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 $N_{\text{eff}}=3.046$
  - $Y_P^{BBN}=0.250\pm0.041$ 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)
Model-independent bounds on Helium fraction from Planck

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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: $Y_P^{BBN} = 0.266 \pm 0.042$ @ 95%CL (Planck+WP+highL).
- Fixing $N_{\text{eff}}=3.046$
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Model-independent bounds on $Y_P - N_{\text{eff}} = 3.046$
Cosmological constraints on neutron lifetime

- Main uncertainty on helium abundance is due to the one on the neutron life-time $\tau_n$
- From Particle Data Group:
  - Combining 5 most recent measurements with “bottle method”:
    \[
    \tau_n^{\text{bottle}} = (879.6 \pm 0.8) \text{ [s]}
    \]
  - 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


Nucleosynthesis and neutron life-time constraints
Cosmological constraints on neutron lifetime

- Assuming Standard BBN
- CMB: $\omega_b, Y_p$ + BBN: $Y_p(\omega_b, N_{\text{eff}}, \tau_n)$ \Rightarrow constraints on $\tau_n$
- Affects the damping tail
- We fit for $\Lambda$CDM + $\tau_n$

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

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### Planck and current cosmological data:

<table>
<thead>
<tr>
<th>Dataset</th>
<th>$Y_{p}^{BBN}$</th>
<th>$\tau_n$ [s]</th>
</tr>
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<tbody>
<tr>
<td>Planck $TT$</td>
<td>$0.254 \pm 0.021$</td>
<td>$918 \pm 105$</td>
</tr>
<tr>
<td>Planck $TT, TE, EE$</td>
<td>$0.252 \pm 0.014$</td>
<td>$907 \pm 69$</td>
</tr>
<tr>
<td>Planck $TT, TE, EE + BAO$</td>
<td>$0.254 \pm 0.013$</td>
<td>$915 \pm 63$</td>
</tr>
<tr>
<td>Planck $TT, TE, EE + BAO +$</td>
<td>$0.249 \pm 0.013$</td>
<td>$894 \pm 63$</td>
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### Future cosmological constraints:

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<tr>
<td>Planck $TT, TE, EE + AdvACT$</td>
<td>$0.2464 \pm 0.0065$</td>
<td>$879 \pm 32$</td>
</tr>
<tr>
<td>Planck $TT, TE, EE + CMB-S4$</td>
<td>$0.2475 \pm 0.0037$</td>
<td>$884 \pm 18$</td>
</tr>
<tr>
<td>Planck $TT, TE, EE + SPT-3G$</td>
<td>$0.2487 \pm 0.0091$</td>
<td>$890 \pm 44$</td>
</tr>
<tr>
<td>COre</td>
<td>$0.2467 \pm 0.0023$</td>
<td>$880 \pm 11$</td>
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<td>CVL</td>
<td>$0.2467 \pm 0.0011$</td>
<td>$880.7 \pm 5.5$</td>
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<td>Planck $TT, TE, EE + Euclid$</td>
<td>$0.2521 \pm 0.0069$</td>
<td>$907 \pm 34$</td>
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<td>$0.2467 \pm 0.0014$</td>
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Cosmic Variance Limited: most accurate precision reached from CMB experiments.
**Cosmological constraints on neutron lifetime**

- 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

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Conclusions

- Planck 2015 BBN results consistent with the 2013 results
- Errorbars on $\omega_b$ 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 $N_{\text{eff}}$ 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