Observational Bounds on the Cosmic Radiation Density

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Based on
arXiv:0705:0440, (to appear in JCAP)

in collaboration with
S. Hannestad, G. Raffelt and Y.Y.Y. Wong

What is the Universe made of?

Standard Model

- Photons (CMB)
- Baryonic matter
- Neutrinos (CνB)

Beyond Standard Model

- Cold Dark Matter
- Dark Energy
- other stuff?

Weakly interacting light particles $\longrightarrow$ radiation

- axion
- sterile neutrino
- light gravitino
- ...

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Cosmic Radiation Density

$$\rho_r = \frac{1}{15}\pi^2 T_\gamma^4 \left[1 + \frac{7}{8} N_{\rm eff} \left(T_\nu / T_\gamma\right)^4\right]$$

- $N_{\rm eff}$: Effective number of relativistic ("neutrino") dof
- Instant decoupling: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$
- Exact SM expectation: $N_{\rm eff} \simeq 3.04$ [Mangano et al.: 2001]

Probing $N_{\rm eff}$ at different epochs

BBN [$\mathcal{O}$(100 keV)]

Helium fraction

$2.10 \leq N_{\rm eff}^{\rm BBN} \leq 4.46$

[Cyburt et al.: 2004]

Matter-radiation eq. [$\mathcal{O}$(eV)]

CMB anisotropies

Large Scale Structure

Cosmic Radiation Density

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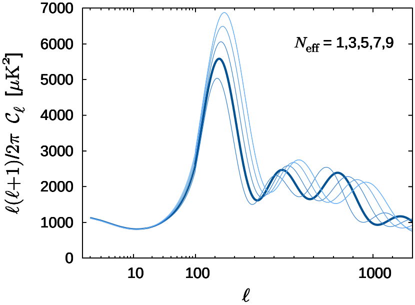
Effect on CMB Angular Power Spectrum

- N_{eff} affects time of matter-radiation equality, sound horizon at decoupling $\longrightarrow$ shifts CMB peaks



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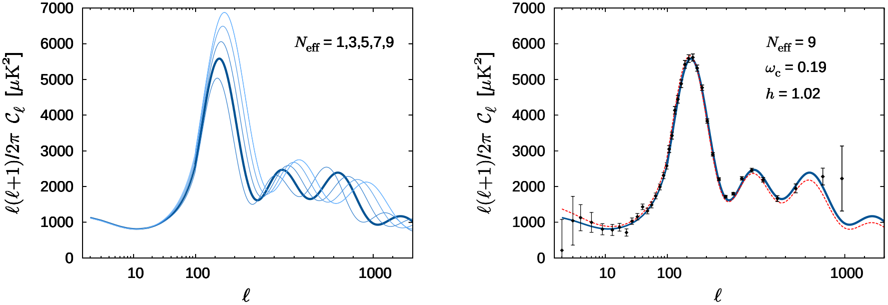


- Degeneracy between $N_{\rm eff}$ and (h, $\Omega_m h^2$, and normalisation)

Results of post-WMAP3 Analyses

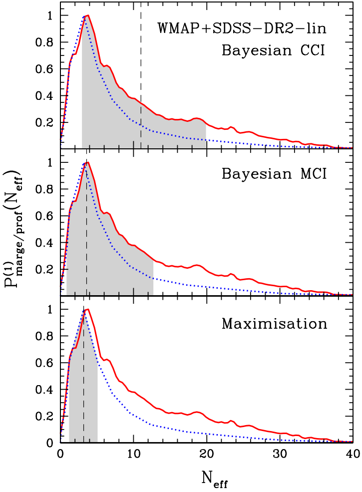
95% c.l. (“2σ”) intervals

- $3.6 \leq N_{\mathrm{eff}} \leq 7.4$ [Seljak, Slosar, McDonald: 2006]
- $3 \leq N_{\mathrm{eff}} \leq 7$ [Cirelli, Strumia: 2006]
- $0.9 \leq N_{\mathrm{eff}} \leq 8.2$ [Ichikawa, Kawasaki, Takahashi: 2006]
- $2.7 \leq N_{\mathrm{eff}} \leq 4.6$ [Hannestad, Raffelt: 2006]
- $3.1 \leq N_{\mathrm{eff}} \leq 6.2$ [Mangano, Melchiorri, Mena, Miele, Slosar: 2007]

New physics?!

Or just systematics?

Construction of Credible Intervals



Bayesian

"What are the most likely values?"

Posterior $\longrightarrow$ marginalisation

- Central interval $\leftrightarrow$ median
- Minimal interval $\leftrightarrow$ mode

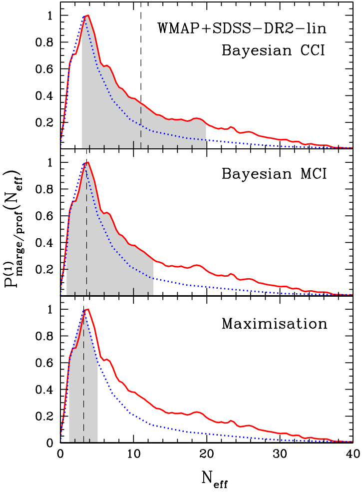
Non-Bayesian

"Which values fit the data well?"

Likelihood $\longrightarrow$ maximisation

- $\Delta\chi^2 = N^2$ determines "$N\sigma$"-interval

Construction of Credible Intervals



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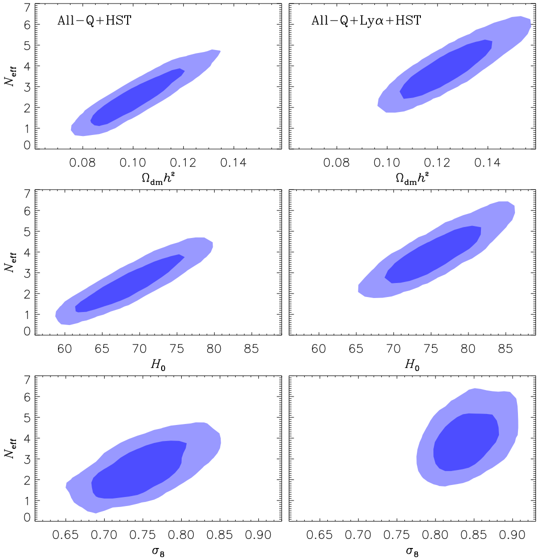
Degeneracies and Ly-α

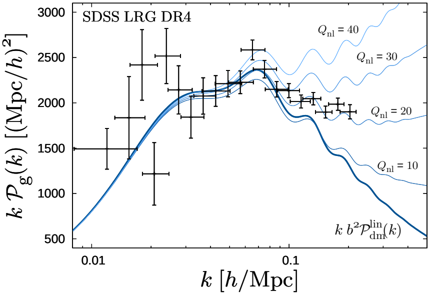


- Ly-α data prefers high values of normalisation

  [McDonald et al.: 2006]

- Bias towards larger values of $N_{\rm eff}$ (and $\Omega_c h^2$, h)

Galaxy Power Spectrum and Non-linearities



- Nonlinear effects at scales $k \gtrsim 0.1$ h/Mpc
- Conservative approach: fit only large scale data
- More speculative:

$$\mathcal{P}_{\rm g}(k) = b^2 \frac{1 + Q_{\rm nl}\, k^2}{1 + A_g\, k} \mathcal{P}^{\rm lin}_{\rm dm}(k)$$

[Cole et al.: 2005]

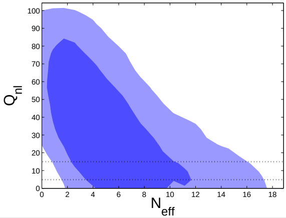
Corrections to the Linear Power Spectrum

$$\mathcal{P}_{\rm g}(k) = b^2 \, \frac{1 + Q_{\rm nl}\, k^2}{1 + A_g\, k} \, \mathcal{P}^{\rm lin}_{\rm dm}(k)$$

- Fitted to (vanilla!) simulations
- May not apply to all surveys (problematic with SDSS main)

[Cole, Sanchez: 2007]

- Introduce new degeneracy (between $Q_{\rm nl}$ and $N_{\rm eff}$)
  $\longrightarrow$ bias for non-flat priors on $Q_{\rm nl}$



Our results

	Bayesian CCI $\langle N_{\rm eff}\rangle^{68\%\uparrow,\ 95\%\uparrow}_{68\%\downarrow,\ 95\%\downarrow}$		Bayesian MCI $\hat{N}^{(1)}_{\rm eff}\,{}^{68\%\uparrow,\ 95\%\uparrow}_{68\%\downarrow,\ 95\%\downarrow}$		Maximisation $\hat{N}_{\rm eff}\,{}^{1\sigma\uparrow,\ 2\sigma\uparrow}_{1\sigma\downarrow,\ 2\sigma\downarrow}$	
Data	$0.2 \le h \le 2.0$	$0.4 \le h \le 1.0$	$0.2 \le h \le 2.0$	$0.4 \le h \le 1.0$	$0.2 \le h \le 2.0$	$0.4 \le h \le 1.0$
WMAP	$22^{37,\ 46}_{7.3,\ 2.6}$	$5.8^{8.8,\ 11}_{3.0,\ 1.5}$	$6.8^{32,\ 45}_{2.8,\ 1.5}$	$4.2^{7.9,\ 11}_{2.2,\ 1.2}$	$3.9^{6.1,\ 27}_{1.5,\ 0.6}$	$3.9^{6.1,\ 12}_{1.5,\ 0.6}$
+SDSS-DR2-Q	$14^{26,\ 37}_{3.6,\ 1.2}$	$4.8^{7.7,\ 10}_{2.1,\ 1.0}$	$3.6^{18,\ 34}_{0.6,\ 0.0}$	$3.7^{6.4,\ 9.7}_{1.1,\ 0.7}$	$2.6^{5.6,\ 14}_{1.0,\ 0.3}$	$2.3^{5.6,\ 11}_{1.0,\ 0.6}$
+SDSS-DR2-lin	$11^{20,\ 32}_{3.0,\ 1.2}$	$4.9^{8.0,\ 10}_{2.0,\ 0.7}$	$3.6^{13,\ 28}_{0.7,\ 0.3}$	$4.3^{6.5,\ 9.9}_{0.9,\ 0.5}$	$3.2^{5.1,\ 12}_{1.2,\ 0.2}$	$3.2^{5.1,\ 11}_{1.3,\ 0.2}$
+2dF-Q	$3.2^{5.2,\ 8.4}_{1.1,\ 0.3}$	$2.6^{4.3,\ 5.7}_{1.1,\ 0.4}$	$1.6^{4.2,\ 7.5}_{0.4,\ 0.0}$	$1.4^{3.9,\ 5.5}_{0.7,\ 0.0}$	$1.5^{2.4,\ 5.3}_{0.6,\ -}$	$1.5^{2.4,\ 5.0}_{0.6,\ -}$
+2dF-lin	$4.6^{7.1,\ 10}_{2.2,\ 1.1}$	$4.4^{6.8,\ 9.6}_{2.1,\ 1.1}$	$2.9^{5.8,\ 9.5}_{1.3,\ 0.6}$	$3.2^{5.7,\ 9.4}_{1.4,\ 0.7}$	$2.6^{4.5,\ 7.9}_{1.2,\ 0.6}$	$2.6^{4.5,\ 7.9}_{1.2,\ 0.6}$
+SDSS-LRG-Q	$3.5^{5.1,\ 7.4}_{2.0,\ 1.1}$	$3.5^{5.1,\ 7.4}_{2.0,\ 1.1}$	$2.6^{4.5,\ 6.9}_{1.5,\ 0.8}$	$2.5^{4.5,\ 6.9}_{1.5,\ 0.8}$	$2.7^{4.1,\ 6.3}_{1.5,\ 0.8}$	$2.7^{4.1,\ 6.3}_{1.5,\ 0.8}$
+SDSS-LRG-lin	$4.0^{5.8,\ 9.4}_{2.1,\ 1.2}$	$3.5^{5.0,\ 6.6}_{2.1,\ 1.3}$	$2.6^{4.9,\ 8.4}_{1.5,\ 0.7}$	$2.8^{4.6,\ 6.3}_{1.8,\ 1.1}$	$2.7^{4.3,\ 6.2}_{1.8,\ 0.8}$	$2.7^{4.0,\ 6.2}_{1.8,\ 1.2}$
+BAO	$3.5^{5.0,\ 6.8}_{2.1,\ 1.1}$	$3.5^{5.0,\ 6.8}_{2.1,\ 1.1}$	$2.8^{4.7,\ 6.4}_{1.8,\ 0.8}$	$2.8^{4.7,\ 6.4}_{1.8,\ 0.8}$	$2.1^{4.7,\ 6.6}_{1.4,\ 0.9}$	$2.1^{4.7,\ 6.6}_{1.4,\ 0.9}$
+SNIa	$20^{34,\ 44}_{6.4,\ 2.3}$	$5.9^{9.1,\ 11}_{2.8,\ 0.9}$	$4.3^{28,\ 42}_{2.8,\ 0.4}$	$4.1^{8.7,\ 11}_{2.4,\ 0.9}$	$3.6^{6.3,\ 24}_{1.4,\ 0.3}$	$3.6^{6.3,\ 12}_{1.6,\ 0.3}$
+HST	$3.9^{5.7,\ 8.3}_{2.1,\ 1.2}$	$4.0^{5.7,\ 7.5}_{2.4,\ 1.4}$	$3.3^{5.1,\ 7.7}_{1.6,\ 0.8}$	$3.6^{5.3,\ 7.0}_{2.1,\ 1.0}$	$2.9^{4.6,\ 7.6}_{1.6,\ 0.4}$	$2.9^{4.5,\ 6.4}_{1.6,\ 0.9}$
+Lyα	$7.6^{10,\ 13}_{5.2,\ 3.6}$	$6.9^{9.0,\ 11}_{4.9,\ 3.5}$	$6.8^{9.3,\ 12}_{4.6,\ 3.3}$	$6.4^{8.8,\ 11}_{4.6,\ 3.2}$	$6.6^{8.0,\ 12}_{4.9,\ 3.3}$	$6.6^{7.7,\ 10}_{5.3,\ 3.3}$
All-lin	—	$2.9^{4.0,\ 5.3}_{1.8,\ 1.1}$	—	$2.6^{3.7,\ 5.1}_{1.5,\ 0.9}$	—	$2.7^{3.3,\ 5.0}_{1.5,\ 0.8}$
All-lin+HST	—	$2.8^{3.7,\ 4.9}_{1.9,\ 1.3}$	—	$2.6^{3.6,\ 4.8}_{1.8,\ 1.1}$	—	$2.7^{3.2,\ 4.5}_{2.0,\ 1.1}$
All-Q	—	$2.3^{3.2,\ 4.4}_{1.4,\ 0.7}$	—	$2.0^{3.1,\ 4.1}_{1.2,\ 0.5}$	—	$2.0^{2.4,\ 4.0}_{1.3,\ 0.6}$
All-Q+HST	—	$2.5^{3.5,\ 4.3}_{1.6,\ 1.0}$	—	$2.4^{3.3,\ 4.3}_{1.6,\ 0.9}$	—	$2.2^{2.7,\ 3.8}_{1.6,\ 0.9}$
All-Q+Lyα	—	$4.4^{5.5,\ 6.9}_{3.3,\ 2.4}$	—	$4.4^{5.4,\ 6.6}_{3.2,\ 2.3}$	—	$4.2^{4.7,\ 6.4}_{3.4,\ 2.4}$
All-Q+Lyα+HST	—	$3.9^{4.8,\ 5.9}_{3.0,\ 2.3}$	—	$3.8^{4.7,\ 5.8}_{2.9,\ 2.2}$	—	$4.0^{4.3,\ 5.6}_{3.1,\ 2.3}$

[JH, Hannestad, Raffelt, Wong: 2007]

Our results

- WMAP3 alone with wide prior on h: $N_{\text{eff}} < 45$
- Adding reasonable prior $0.4 \leq h \leq 1$, or LSS data tightens constraints considerably
- More constraining data $\longrightarrow$ less difference between different interval constructions (gaussianity)

Summary

Vanilla+N_{eff}

- Conservative (linear data only):

$$1.1 \leq N_{\text{eff}} \leq 4.8, \quad \text{best fit: } 2.6$$

- Aggressive (all data):

$$2.2 \leq N_{\text{eff}} \leq 5.8, \quad \text{best fit: } 3.8$$

Extended models

- N_{eff} massive species $+\alpha_S+w$:

$$1.2 \leq N_{\text{eff}} \leq 6.4, \quad \text{best fit: } 2.6$$

- 3 massive neutrinos, $(N_{\text{eff}} - 3)$ massless species:

$$0 \leq N_{\text{eff}} - 3 \leq 3.7, \quad \text{best fit: } 0.2$$

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Conclusions

- No evidence for additional relativistic degrees of freedom
- Systematic effects can bias parameter estimation
- Need better understanding of scale-dependent bias
- You should use the minimal credible interval!