Dark radiation: the post-Planck status

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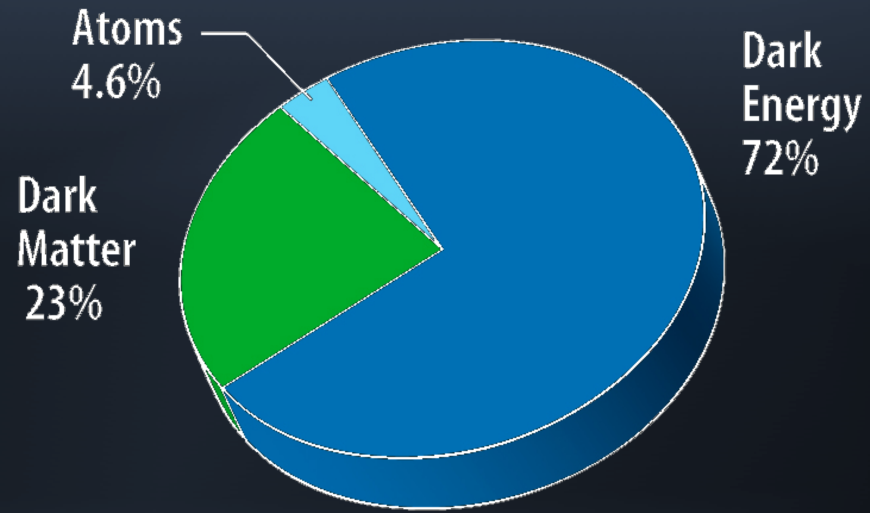
seminar @ LPSC Grenoble

24 May 2013

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's cosmic pie



today (z = 0)

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's cosmic pie

Neutrinos 0.1 - 2%

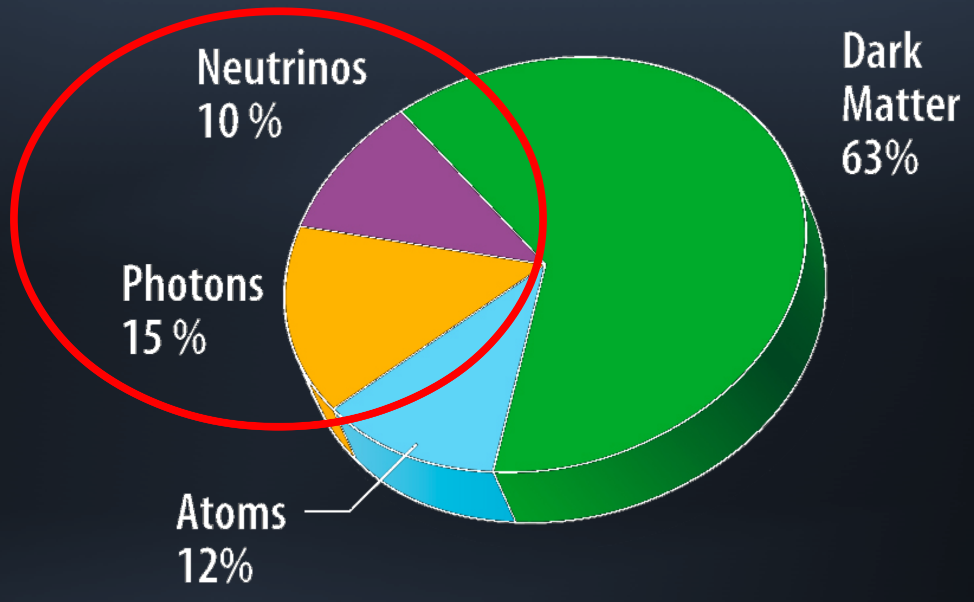
Photons 0.006%

today (z = 0)

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's cosmic pie (2)



at decoupling (z = 1100)

Radiation content of the Universe

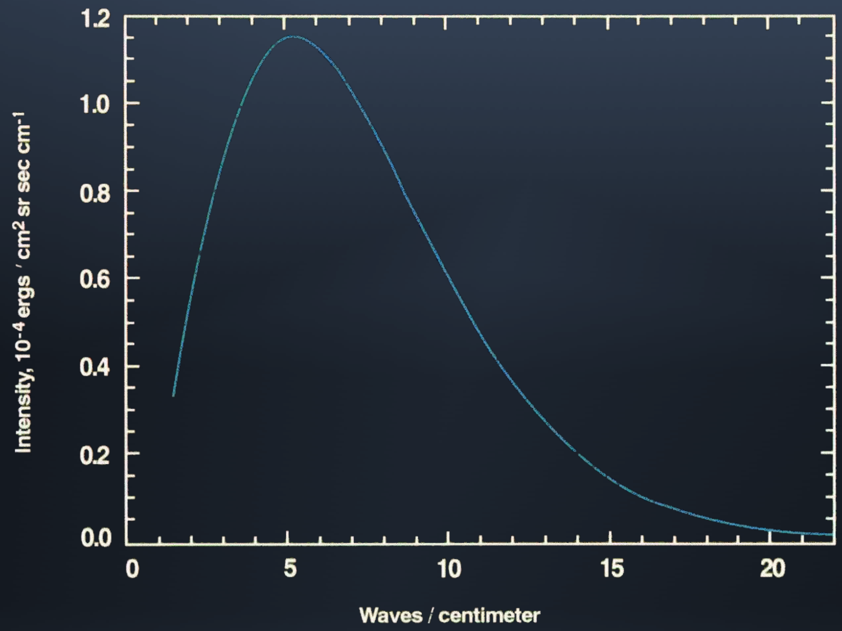
- Photons: CMB
- Neutrinos: CνB
- Other light particle species (*Dark Radiation*)?

How can we find them?

- Directly: via scattering
- Indirectly: via gravitational effects

Cosmic Microwave Background

Directly measured by COBE/FIRAS



[Mather et al. (1993)]

Blackbody spectrum with $T_\gamma = 2.72548 \pm 0.00057\ \mathrm{K}$

[Fixsen (2009)]

Cosmic Microwave Background

Also affects expansion rate through photon energy density:

$$\rho_\gamma = \frac{g_\gamma}{(2\pi)^3} \int \mathrm{d}^3q \, q \, f_{\mathrm{BE}}(q) = \frac{\pi^2}{15} T_\gamma^4$$

Cosmic Neutrino Background

Neutrinos decouple before e^+e^--annihilation

$$\longrightarrow \quad T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.95\ \mathrm{K}$$

- extremely low energy, O(meV)
- no direct detection to date (and likely not anytime soon)

Cosmic Neutrino Background

Neutrino energy density:

$$\rho_\nu^{\rm act} = 3 \cdot \frac{g_\nu}{(2\pi)^3} \int {\rm d}^3q \, q \, f_\nu(q) = N_{\rm eff}^{\rm act} \cdot \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

LEP: 2.984 ± 0.008

Large mixing ensures that
different mass/flavour eigenstates typically
share a common momentum distribution

[Dolgov et al. (2002), Wong (2002)]

Cosmic Neutrino Background

Neutrino energy density:

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For $f_\nu = f_{\rm FD}$, one would have $N_{\rm eff}^{\rm act} = 3$

- Small correction due to ν_es not being quite completely decoupled at e^+e^--annihilation + QED correction

→ Standard Model expectation:

$$N_{\rm eff}^{\rm act} = 3.046$$

[Mangano et al. (2005)]

Radiation content of the Universe

Other light stuff? (*Dark radiation*)

$$\rho_X = N_X \cdot \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

Radiation content of the Universe

Other light stuff? (*Dark radiation*)

$$\rho_X = N_X \cdot \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4$$

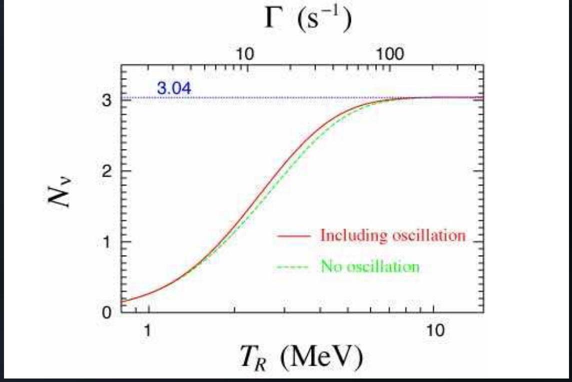
Putting it all together:

$$\begin{aligned} \rho_r &= \rho_\gamma + \rho_\nu^{\rm act} + \rho_X \\ &= \frac{\pi^2}{15} T_\gamma^4 \left[1 + \underbrace{(N_{\rm eff}^{\rm act} + N_X)}_{N_{\rm eff}} \cdot \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \right] \end{aligned}$$

A few remarks on $N_{\rm eff}$

- is not a constant, in general
  - increase through light decay products of massive particle
  - decrease when particles go non-relativistic
  - (in fact, technically $N_{\rm eff} \leq 1$ today)

- $N_{\rm eff}$ can be < 3.046 at early times if neutrinos out of equilibrium; e.g., low reheating temperature:



[Ichikawa, Kawasaki, Takahashi (2005)]

Determining N_{eff} from observation

Decoupling (T~1 eV)

- Cosmic Microwave Background anisotropies
- Large scale structure

Big Bang Nucleosynthesis (T~1 MeV)

- Primordial element abundances

Big Bang Nucleosynthesis

BBN

Boltzmann equation

nuclear interaction rates ⟷ expansion rate

T

$$n + \nu_e \rightleftharpoons p + e^-$$

neutrons and protons in equilibrium

~1 MeV

$$n \rightarrow p + e^- + \bar{\nu}_e$$

neutrons start decaying

~0.2 MeV

$$\longrightarrow \mathrm{D}, {}^4\mathrm{He}, \ldots$$

most surviving neutrons end up in ^{4}He

BBN

Boltzmann equation

nuclear interaction rate ⟷ expansion rate

$\Gamma(\omega_{\mathrm{b}}, f_{\nu_{\mathrm{e}}})$

$H \propto \sqrt{\rho_{\mathrm{r}}}$

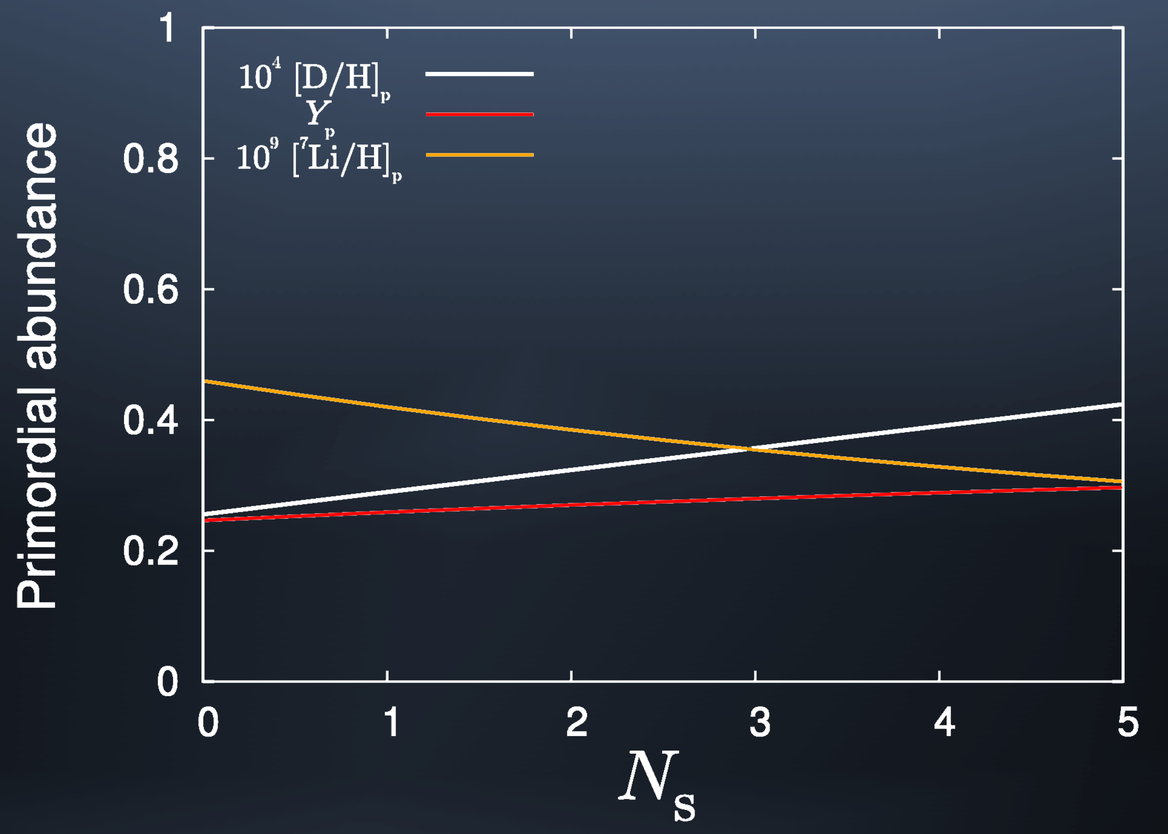
N_{eff}

primordial element abundances
as function of $(\omega_{\mathrm{b}}, f_{\nu_{\mathrm{e}}}, N_{\mathrm{eff}}, \ldots)$

BBN

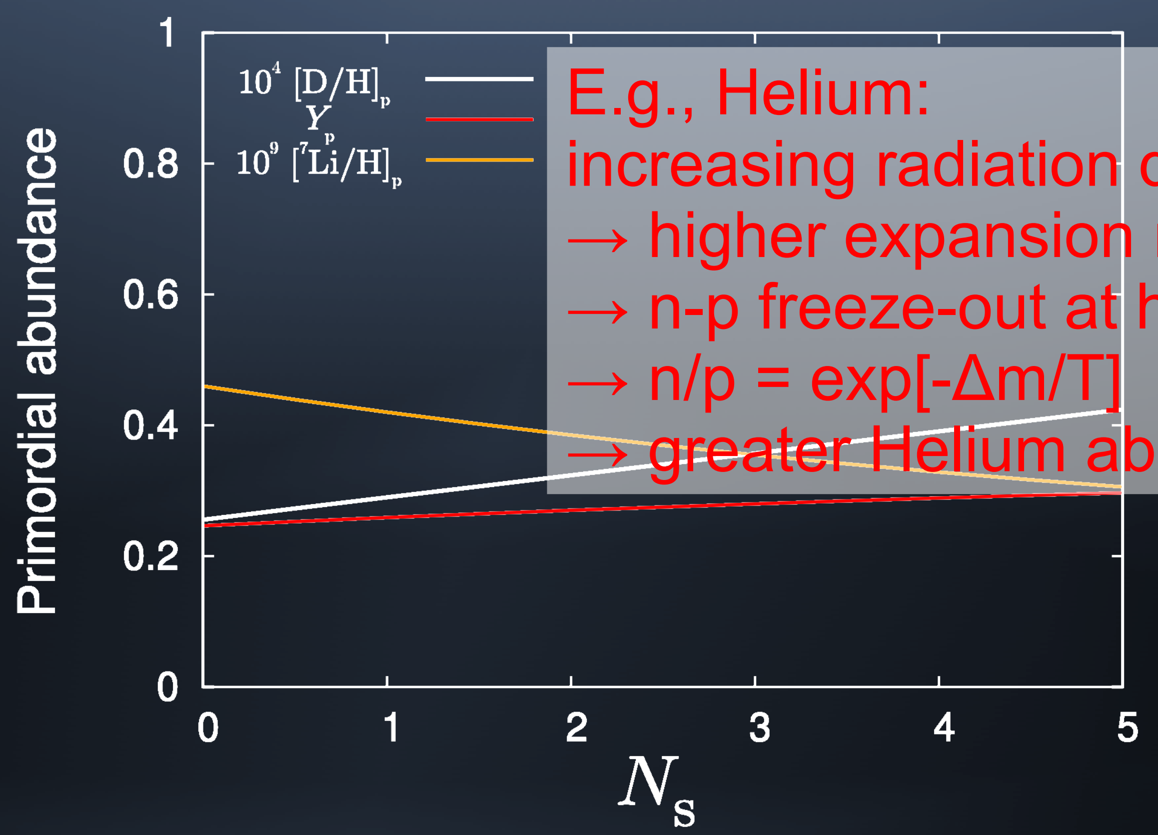
- Assume standard BBN with standard active neutrino sector $\rightarrow$ $N_{eff} > 3.046$
  (would have to make assumptions about momentum distribution of electron neutrinos otherwise, since they participate in nuclear reactions)
- Define $N_s \equiv N_{eff} - 3.046$

BBN



Measure primordial abundances → infer N_s

BBN



E.g., Helium:
increasing radiation density
→ higher expansion rate
→ n-p freeze-out at higher T
→ n/p = exp[-Δm/T]
→ greater Helium abundance

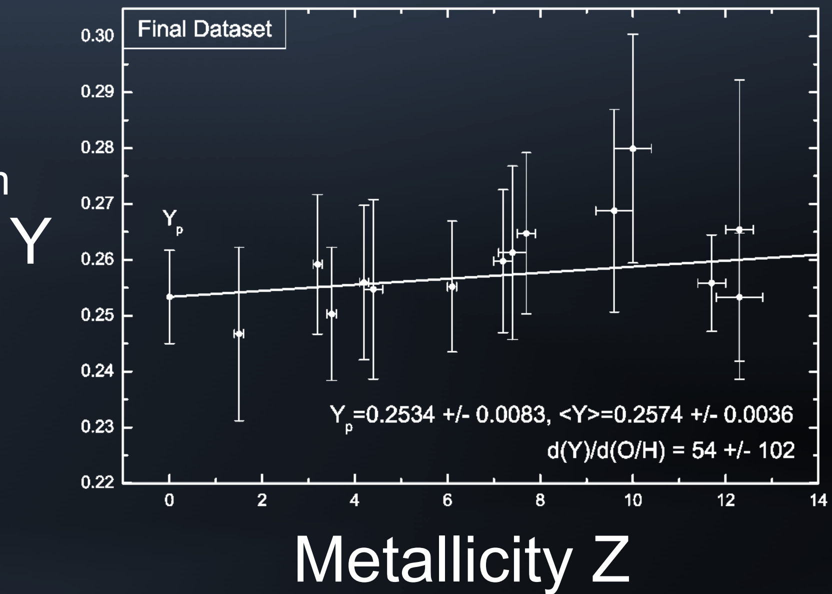
Measure primordial abundances → infer N_s

Primordial abundances: Deuterium

- Measure absorption of quasar light in low-metallicity hydrogen clouds at high z
- Relatively "clean" probe, in principle
- Deuterium abundance not subject to strong evolution with redshift
- However, objects are rare:
  - Pettini et al. (2008): seven systems
  - Pettini & Cooke (2012): *one(!)* system

Primordial abundances: Helium-4

- Observe Hydrogen and Helium emission lines in H-II regions of metal-poor dwarf galaxies
- Astrophysical systematics
  - Interstellar reddening
  - Absorption lines in stellar continuum
  - Radiative transfer
  - Collisional corrections
- Helium production by Pop III stars $\rightarrow$ $dY/dZ > 0$
- Extrapolate to $Z = 0$



Systematics-dominated!

[Aver, Olive, Skillman (2012)]

Calculating theoretical abundances

- Solve Boltzmann equations numerically (e.g., ParthENoPE)

[Pisanti et al. (2008)]

- Theoretical uncertainties:
  - Nuclear rates

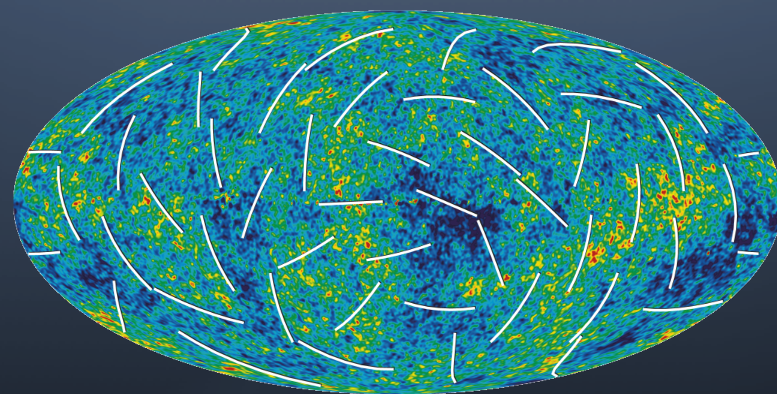
    negligible for Helium, 1.8% for Deuterium
  - Free neutron lifetime

    negligible for Deuterium, 0.6% for Helium

Decoupling

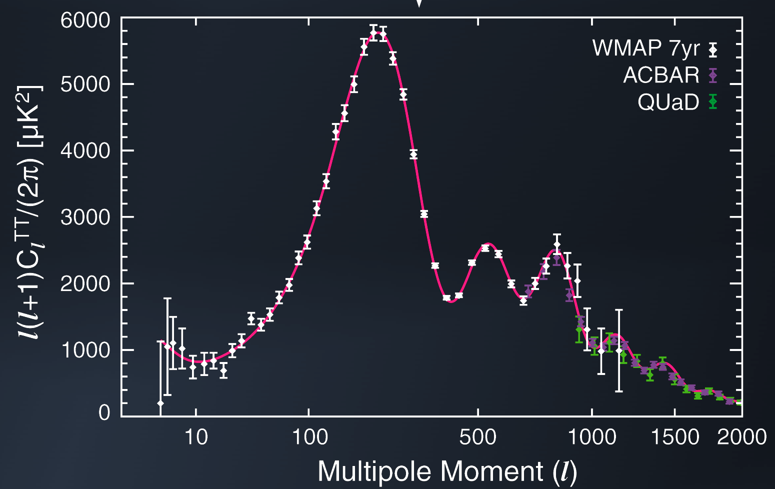
N_{eff} and the CMB

CMB map



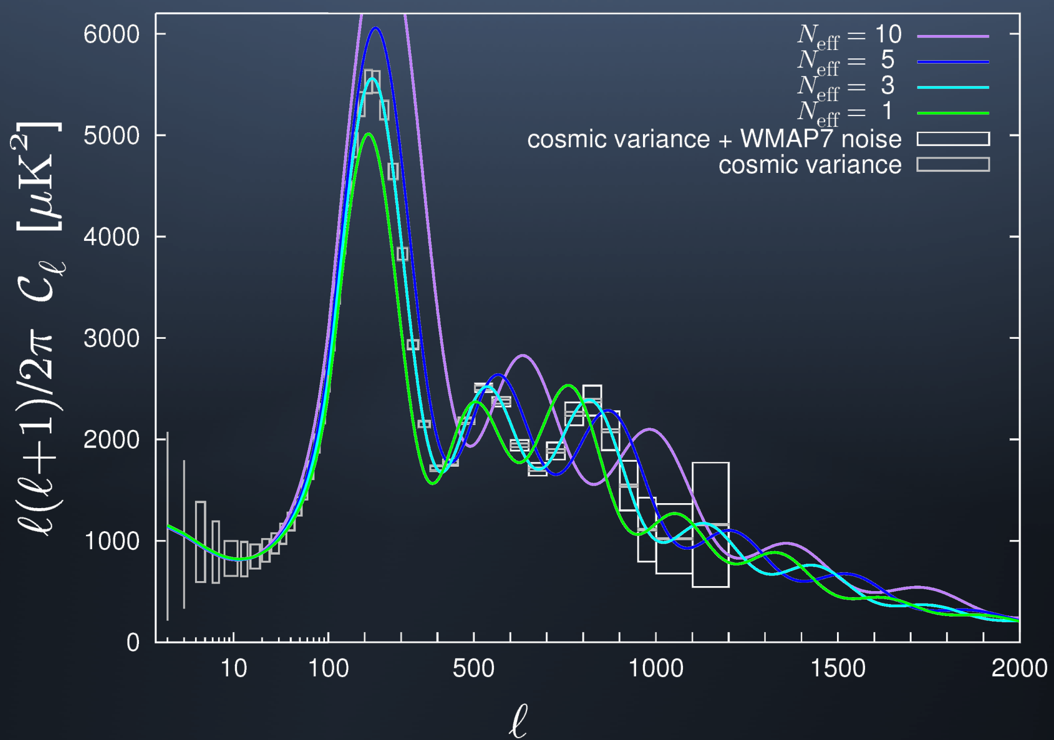
expand in spherical harmonics

CMB angular power spectrum



[e.g., WMAP (2010)]

N_{eff} and the CMB



- Angular power spectrum is a function of O(10) cosmological parameters (e.g., ω_b, ω_{dm}, ω_v, Ω_{de}, N_{eff},...)

$N_{\rm eff}$ and the CMB

- Physical impact of changing $N_{\rm eff}$
  - Matter-radiation equality
  - Sound horizon
  - Anisotropic stress
  - Damping tail

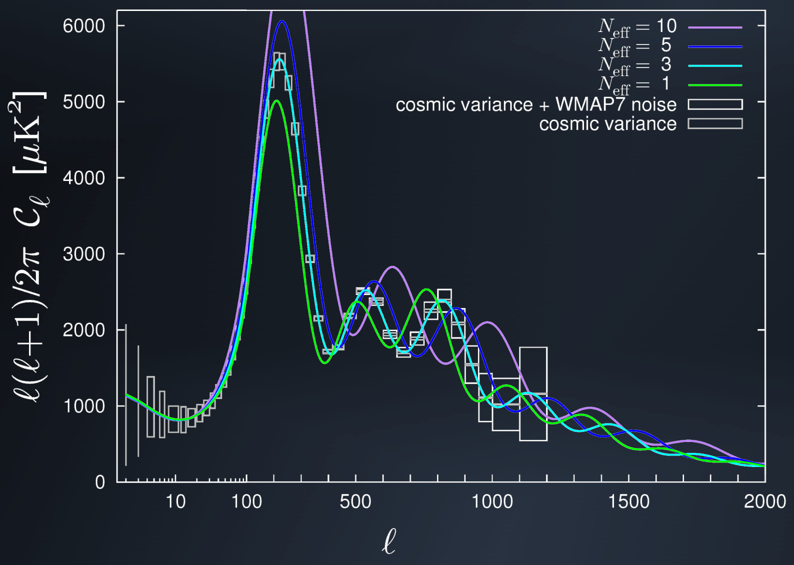
[Seljak & Bashinsky (2003), Hou et al. (2010,2012), Lesgourgues et al. (2013)]

- All of these effects can to some extent be mimicked by adjusting other parameters

Matter-radiation equality

$$1 + z_{\rm eq} = \frac{\Omega_{\rm m}}{\Omega_{\rm r}} \simeq \frac{\Omega_{\rm m} h^2}{\Omega_\gamma h^2} \frac{1}{1 + 0.2271 N_{\rm eff}}$$

- Larger $N_{\rm eff}$ $\rightarrow$ later equality $\rightarrow$ enhanced early integrated Sachs-Wolfe-effect $\rightarrow$ first/higher peak ratio larger



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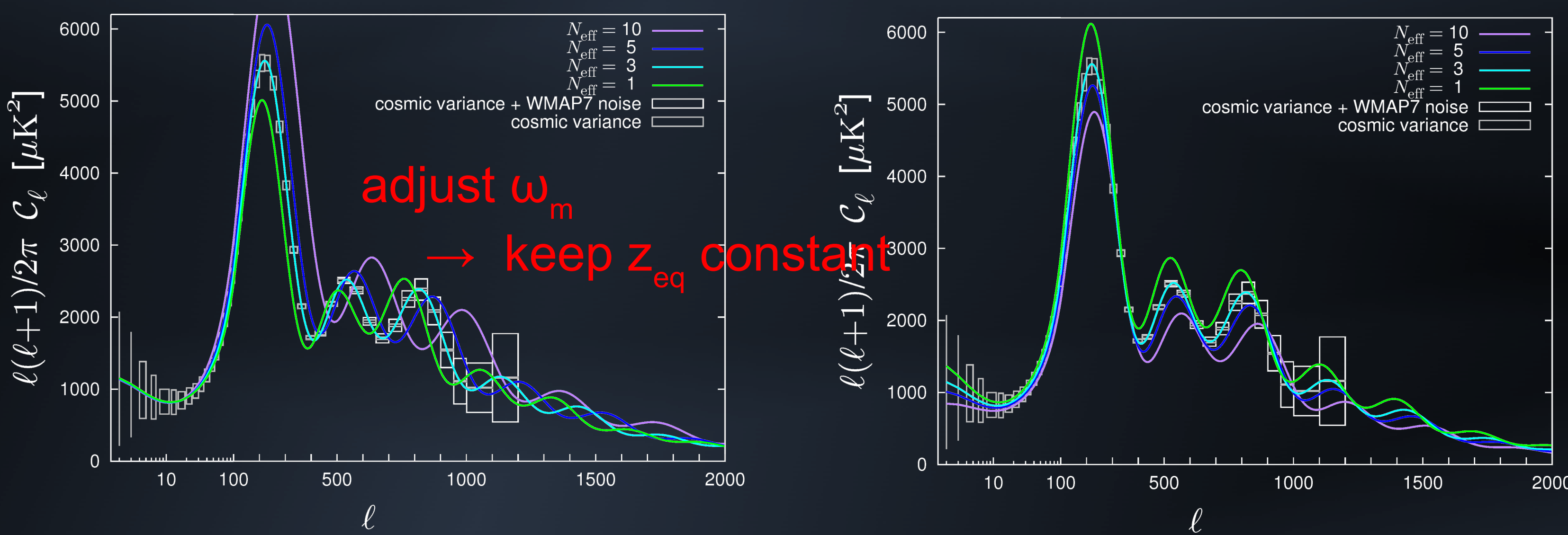


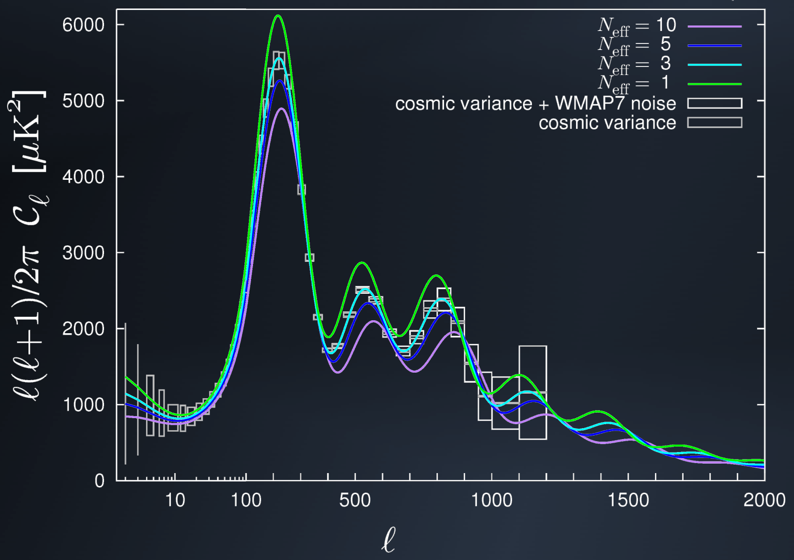
Sound horizon

- θ_s = Sound horizon/distance to last scattering surface
  → determines positions of acoustic peaks

$$\theta_s \propto \frac{\Omega_m^{-1/2}}{\int_{a_*}^{1} \frac{da}{a^2\sqrt{\Omega_m a^{-3} + (1-\Omega_m)}}}$$

$$\Omega_m = \omega_m / h^2$$

[Abazajian et al. (2012)]



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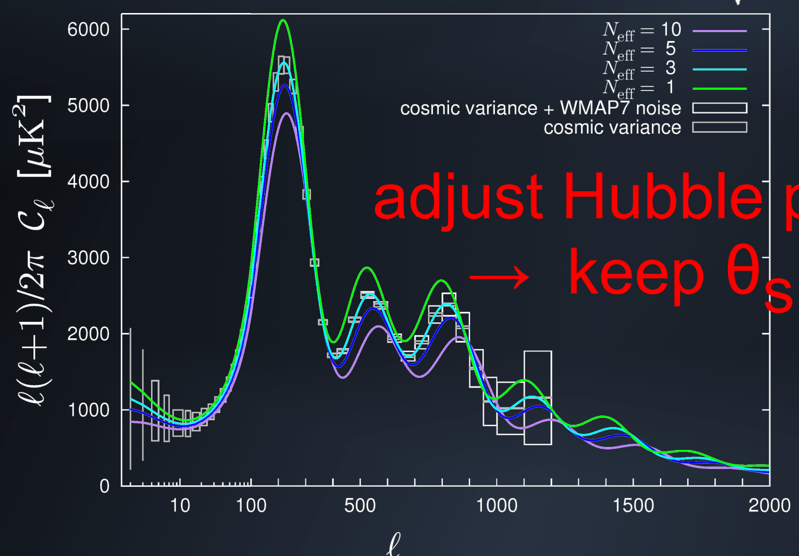
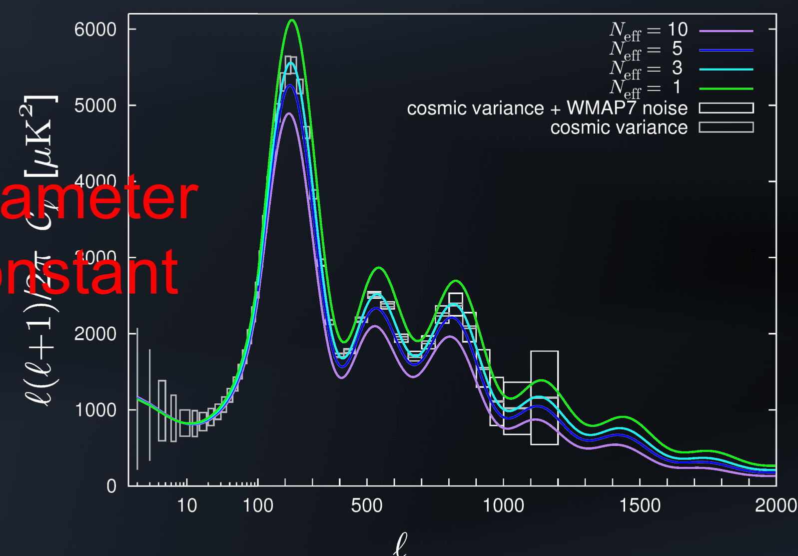
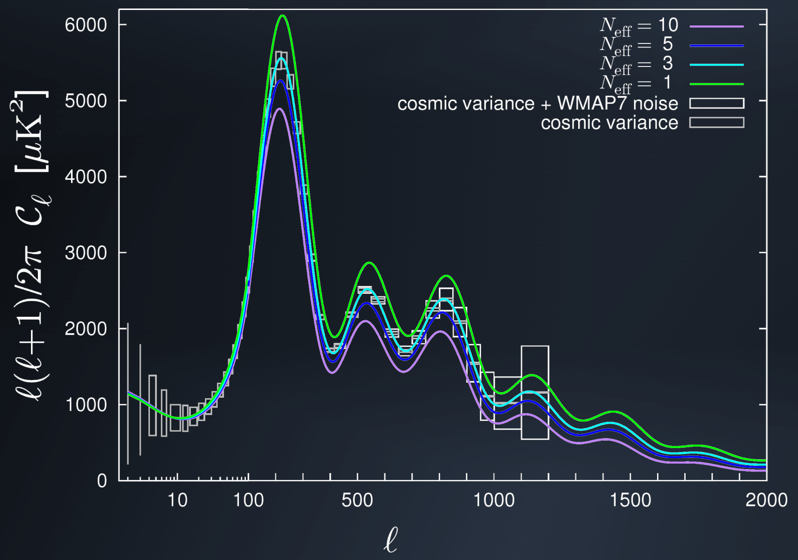




adjust Hubble parameter
→ keep θ_s constant

Anisotropic stress

- Neutrinos are decoupled → free streaming → anisotropic stress
- Dampens fluctuations during radiation domination
- Suppression of power at multipoles > 200



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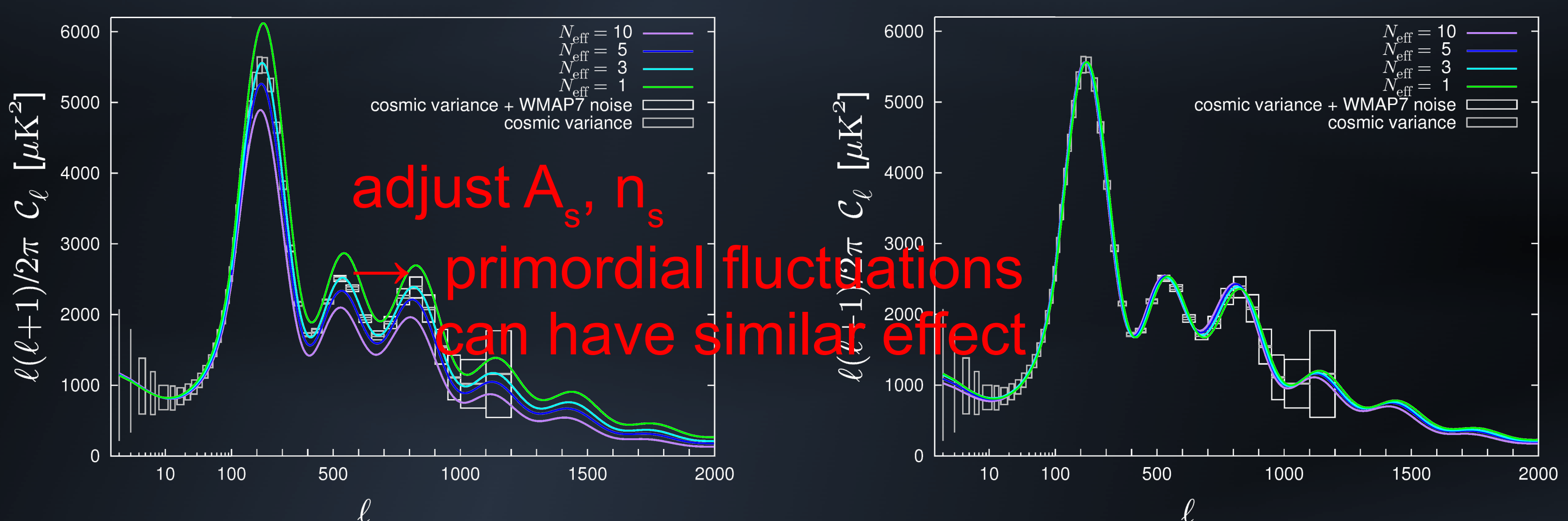
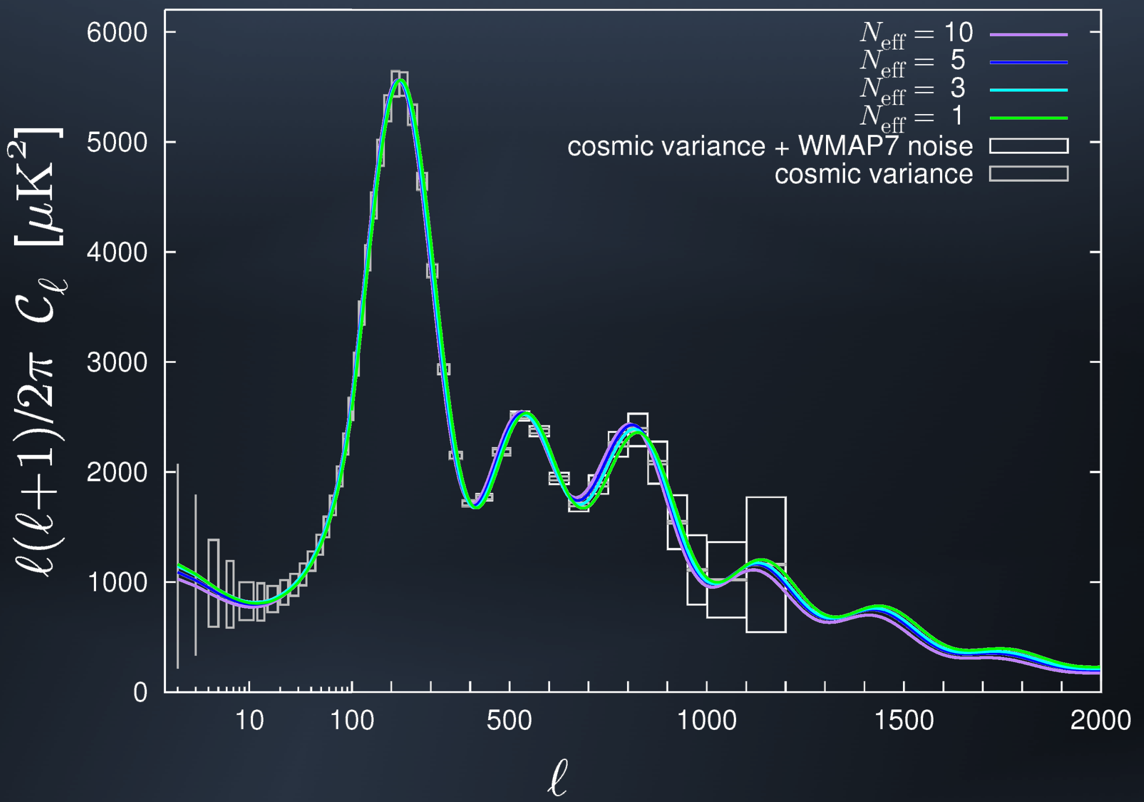


adjust A_s, n_s

→ primordial fluctuations can have similar effect

Damping tail

- Last scattering surface has finite thickness
  → exponential damping of fluctuations below damping scale

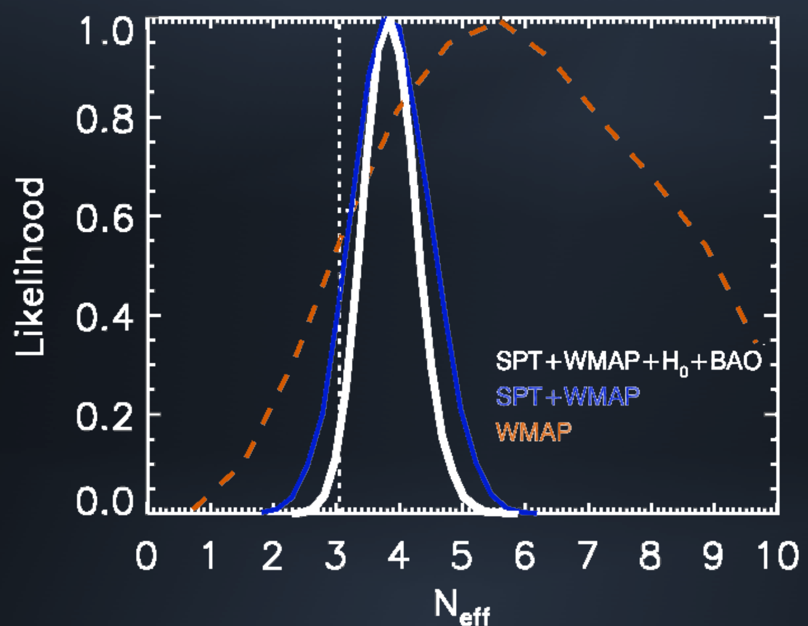


Observational constraints: massless dark radiation

N_{eff} from CMB: pre-2013 status

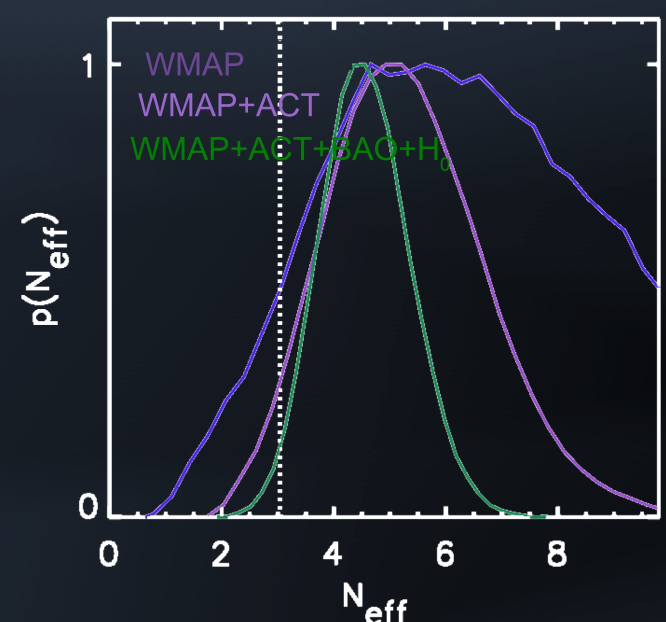
- Interesting hints for N_{eff} > 3.046 (at ~2σ) from 7-year WMAP data combined with data from... [WMAP7 (2010)]

South Pole Telescope



[Keisler et al. (2011)]

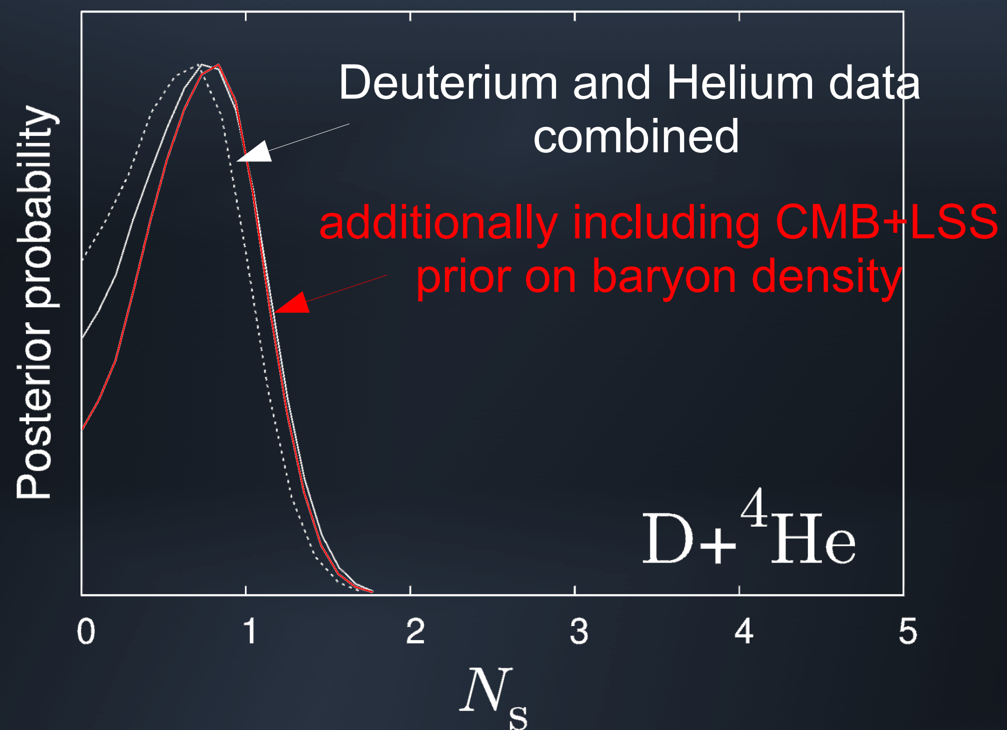
Atacama Cosmology Telescope



[Dunkley et al. (2010)]

BBN: pre-2012 status

- Using Deuterium data from Pettini et al. (2008) and Helium data from Aver et al. (2010):

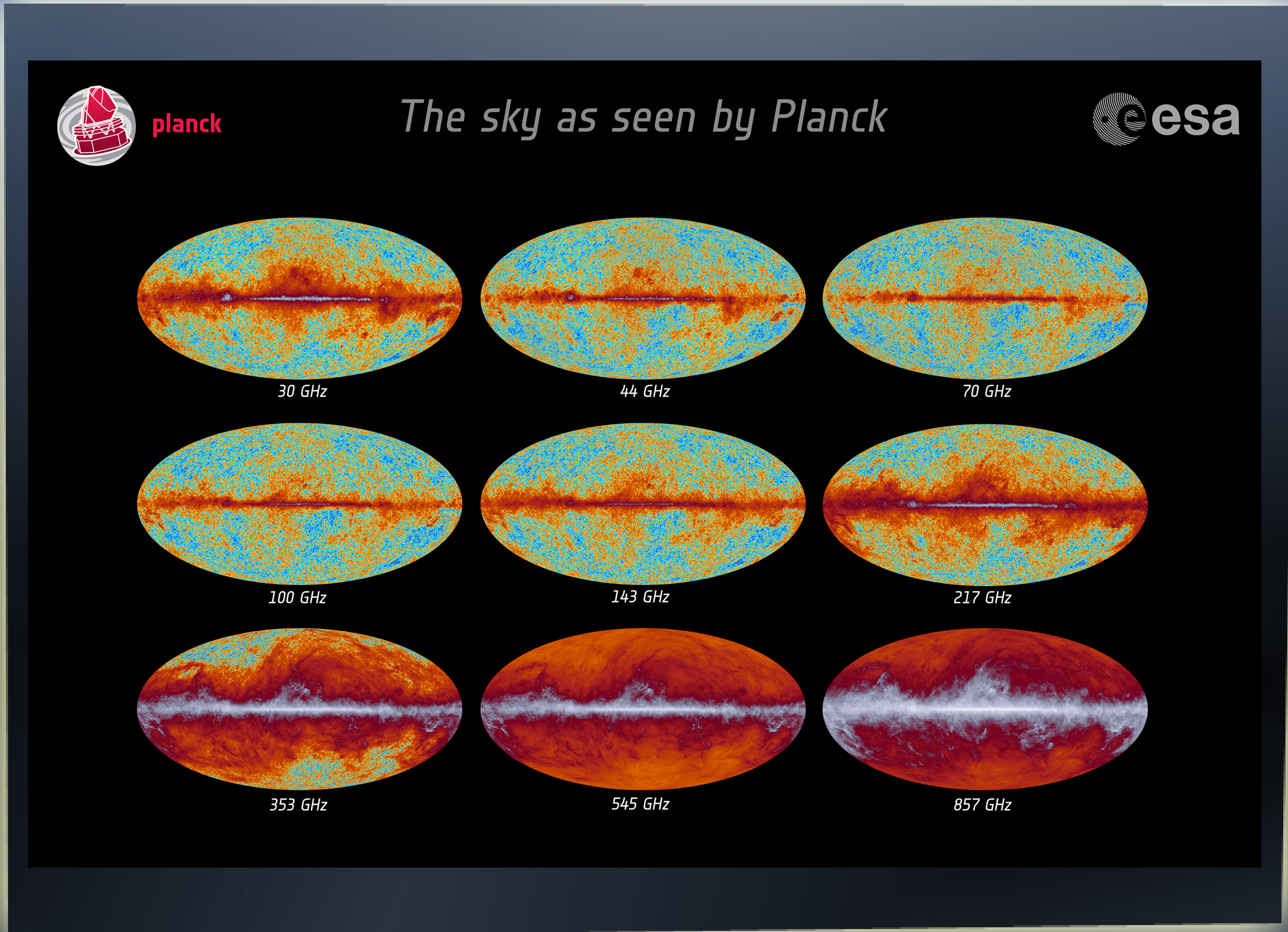


[JH, Hannestad, Raffelt, Wong (2011)]

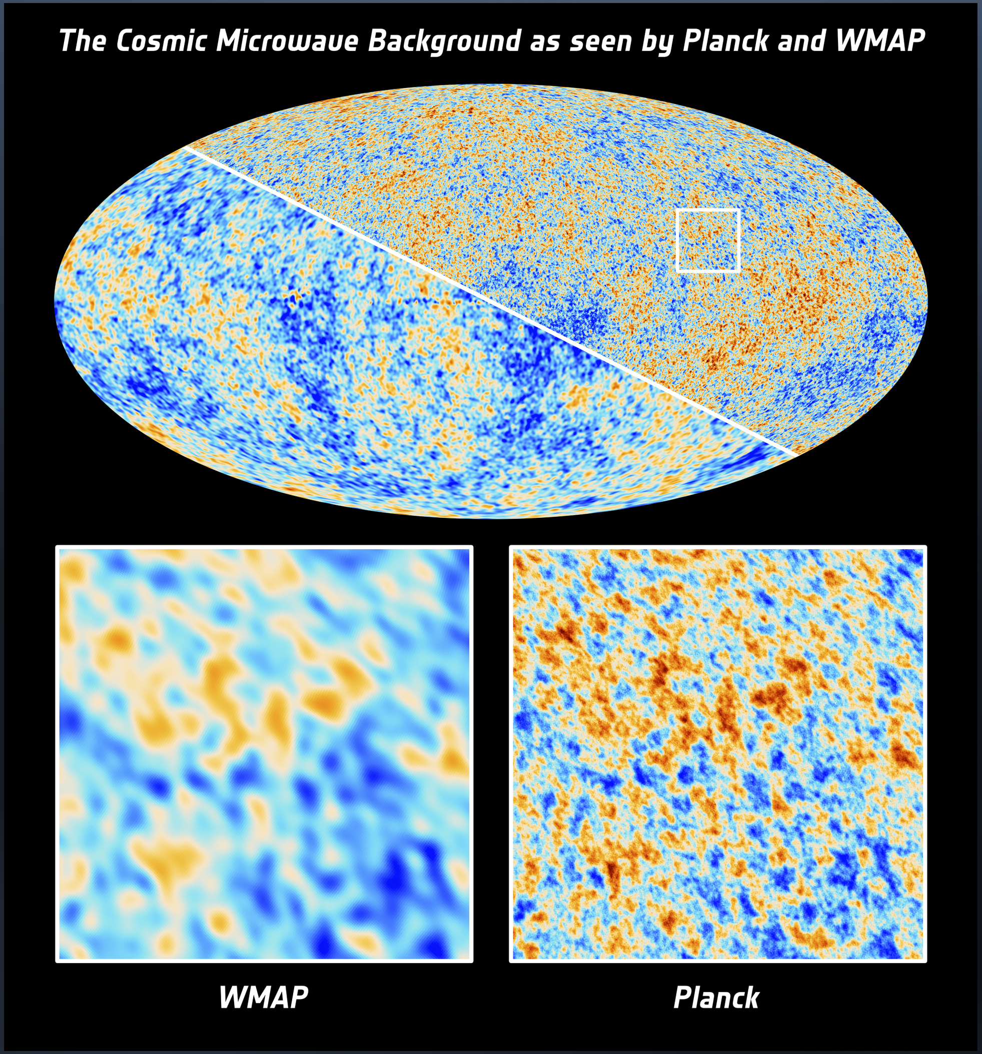
Planck

- Launched 9th May 2009
- Full-sky microwave survey in 9 freq channels (30-857 GHz)
- First set of cosmology papers released last month

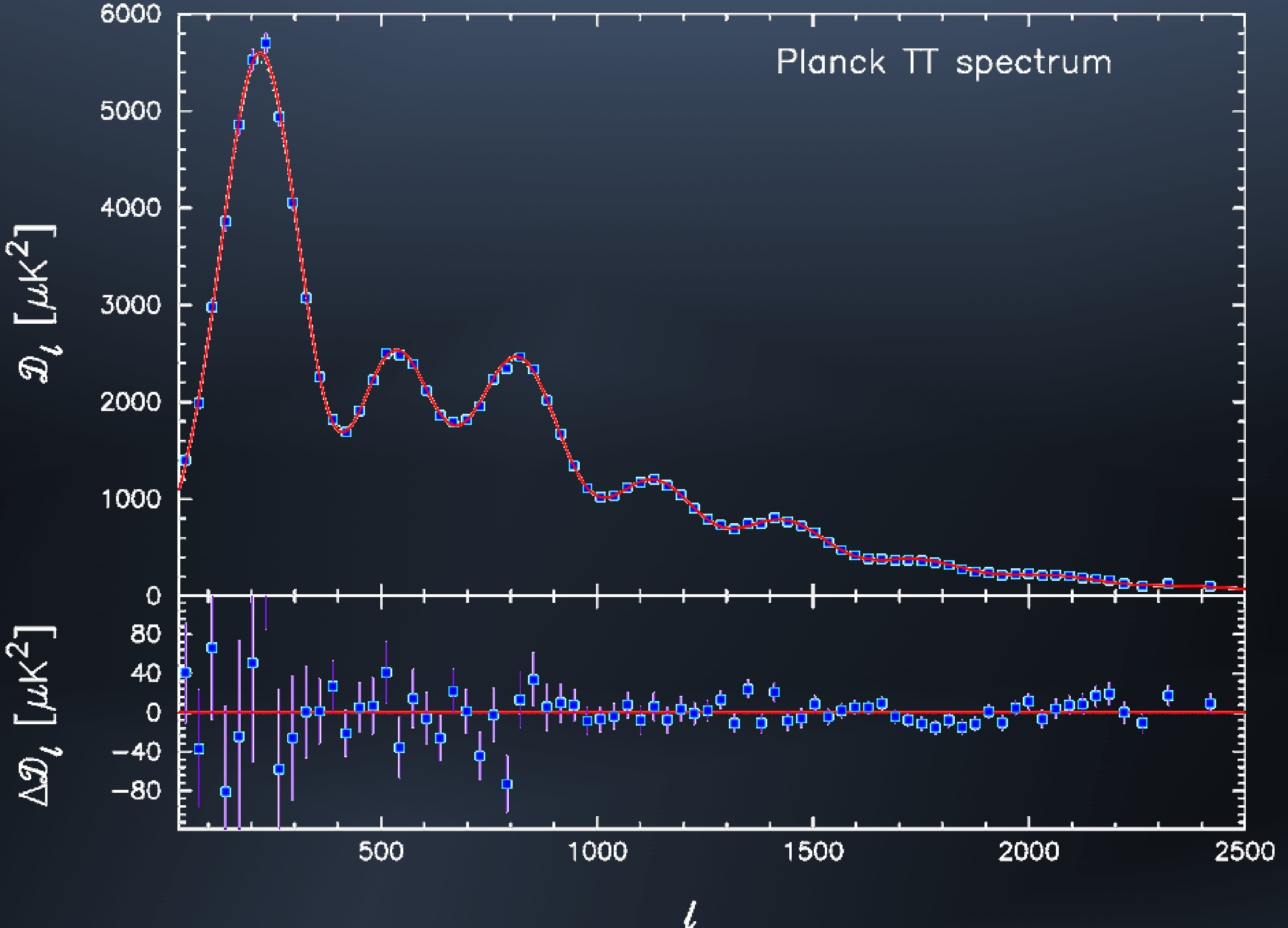
[Planck collaboration (2013)]


planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

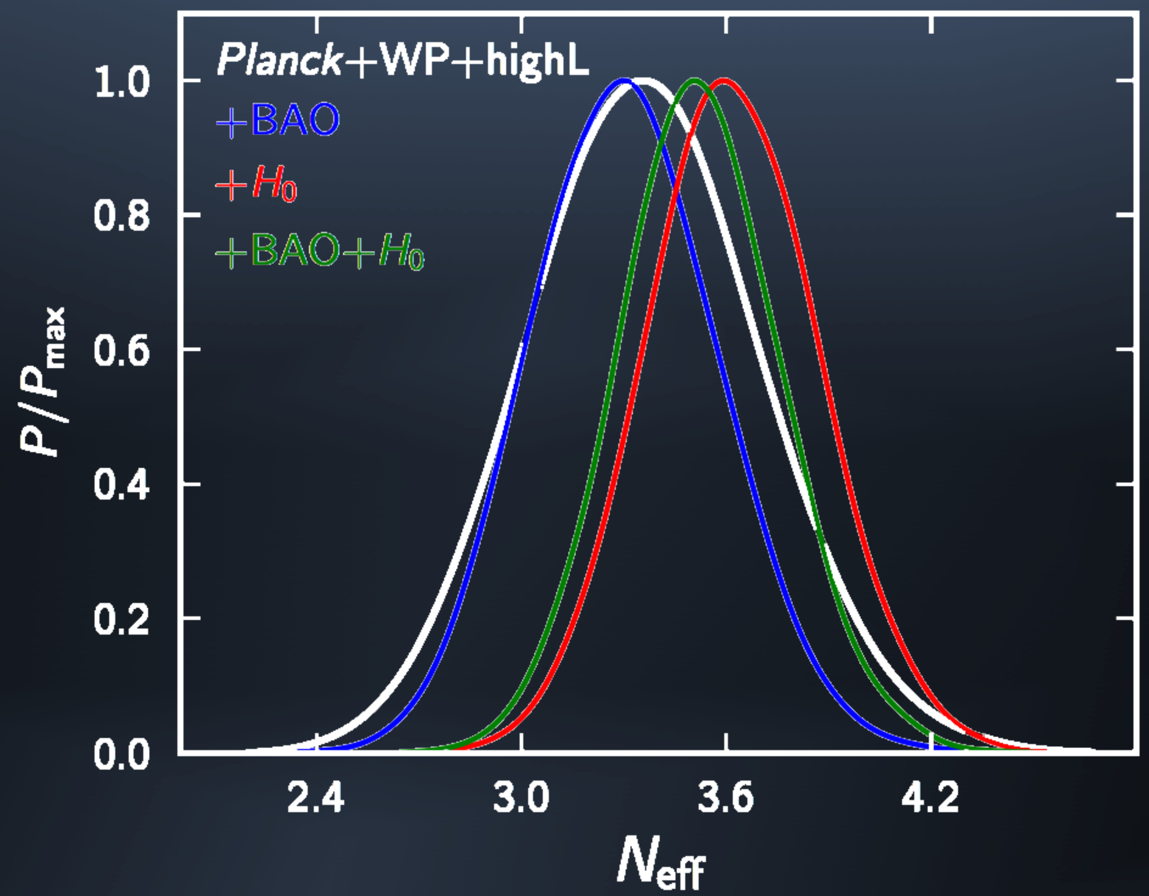
Planck vs. WMAP



Planck temperature angular power spectrum



Planck constraints on $N_{\rm eff}$



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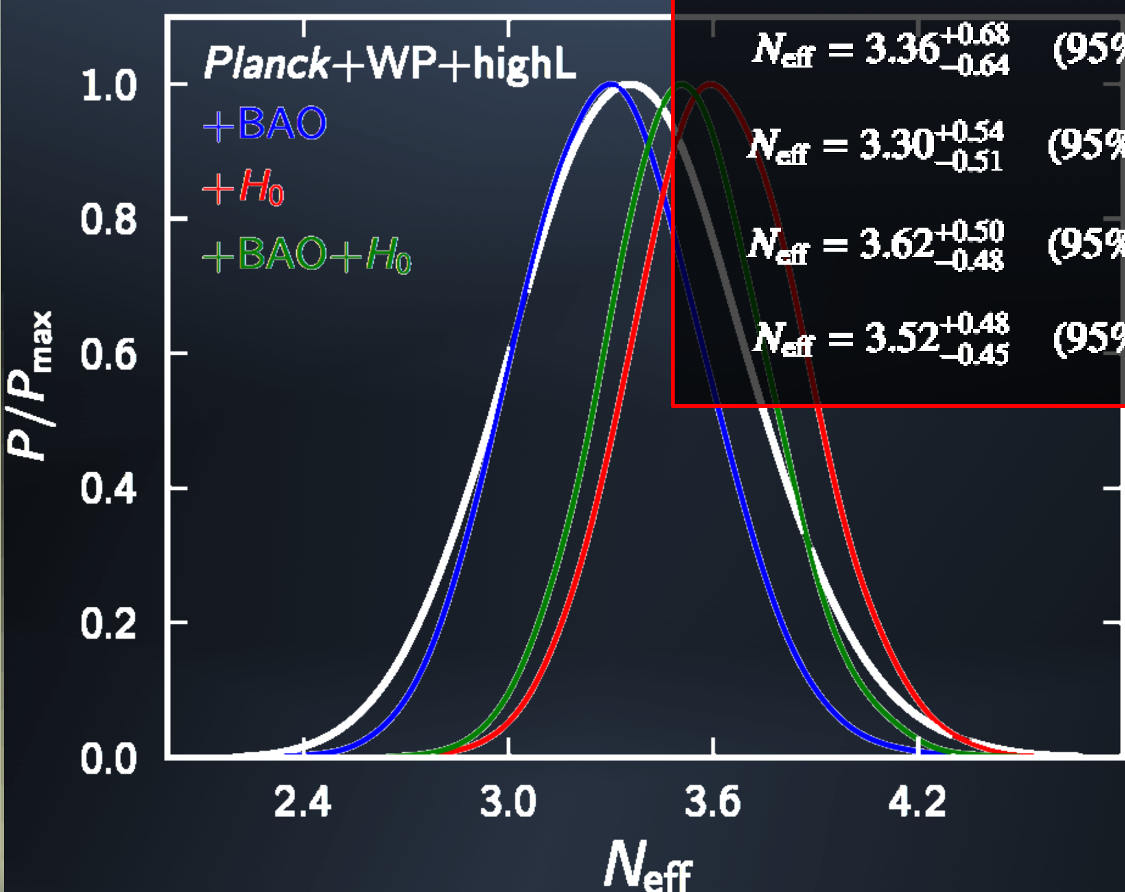

$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ (95%; *Planck*+WP+highL).

$N_{\rm eff} = 3.30^{+0.54}_{-0.51}$ (95%; *Planck*+WP+highL+BAO).

$N_{\rm eff} = 3.62^{+0.50}_{-0.48}$ (95%; *Planck*+WP+highL+H_0).

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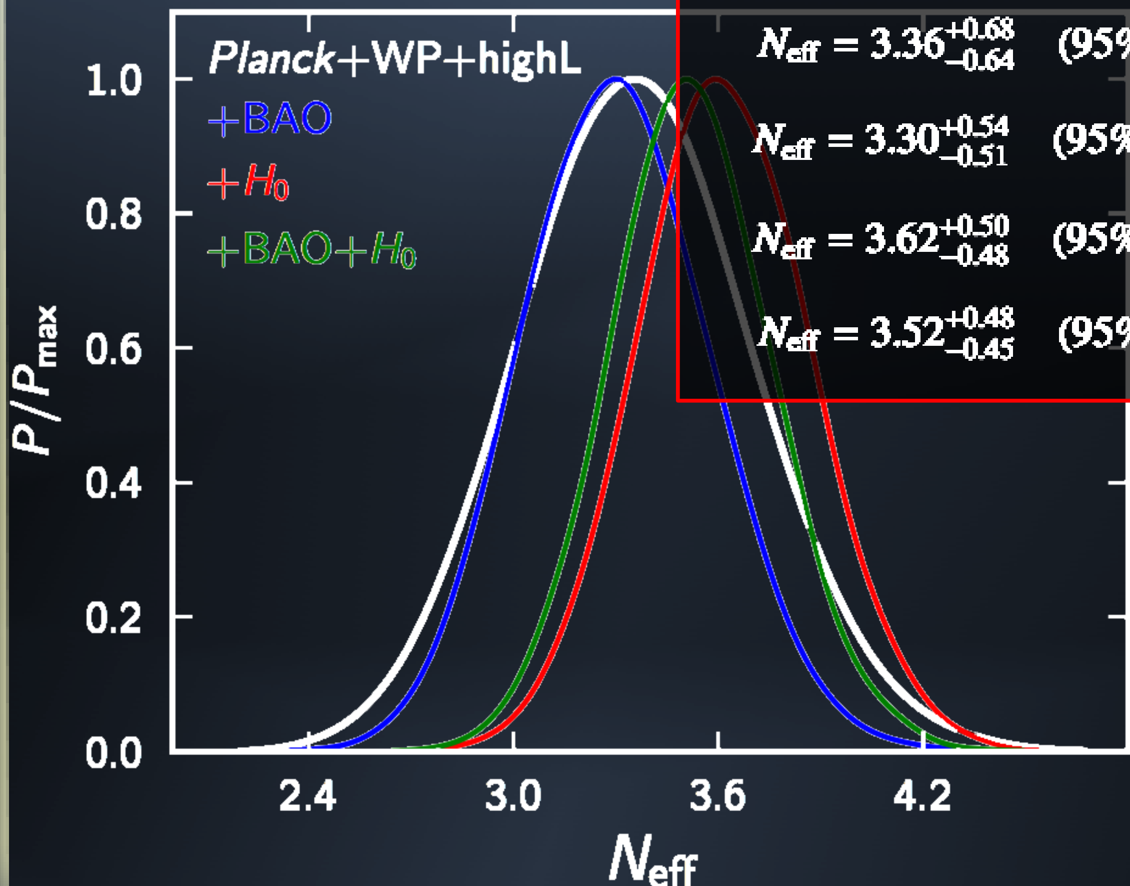

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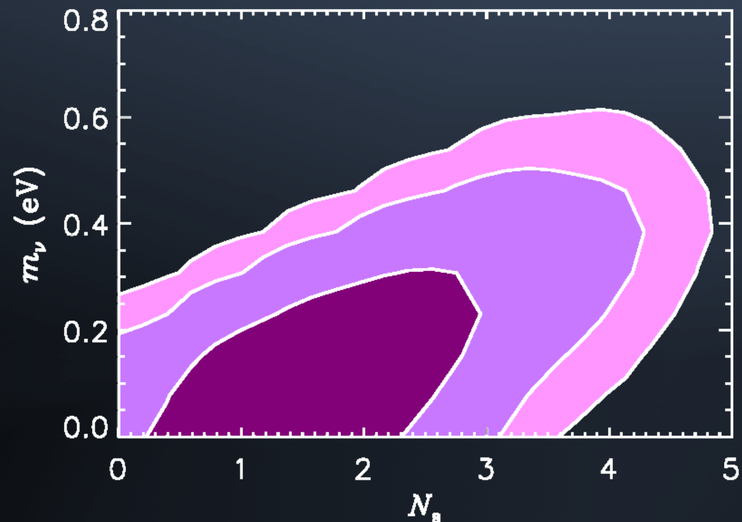
HST-measurement of Hubble parameter prefers larger values, but mild/moderate tension with CMB/BAO data

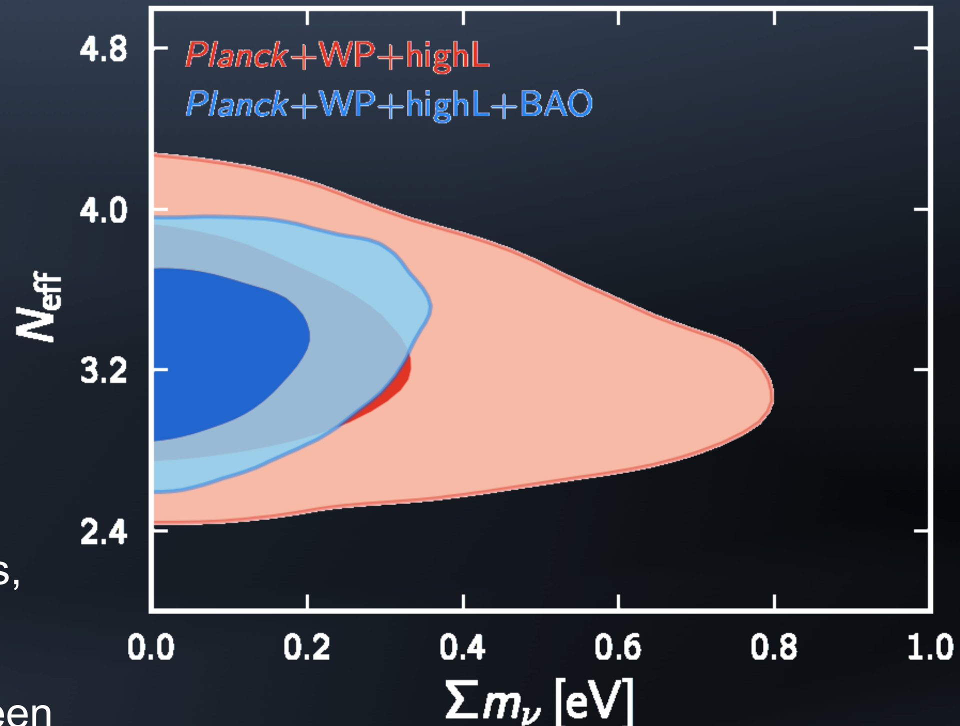
→ systematics in H_0?

Varying the sum of standard neutrino masses

[JH et al. (2010)]

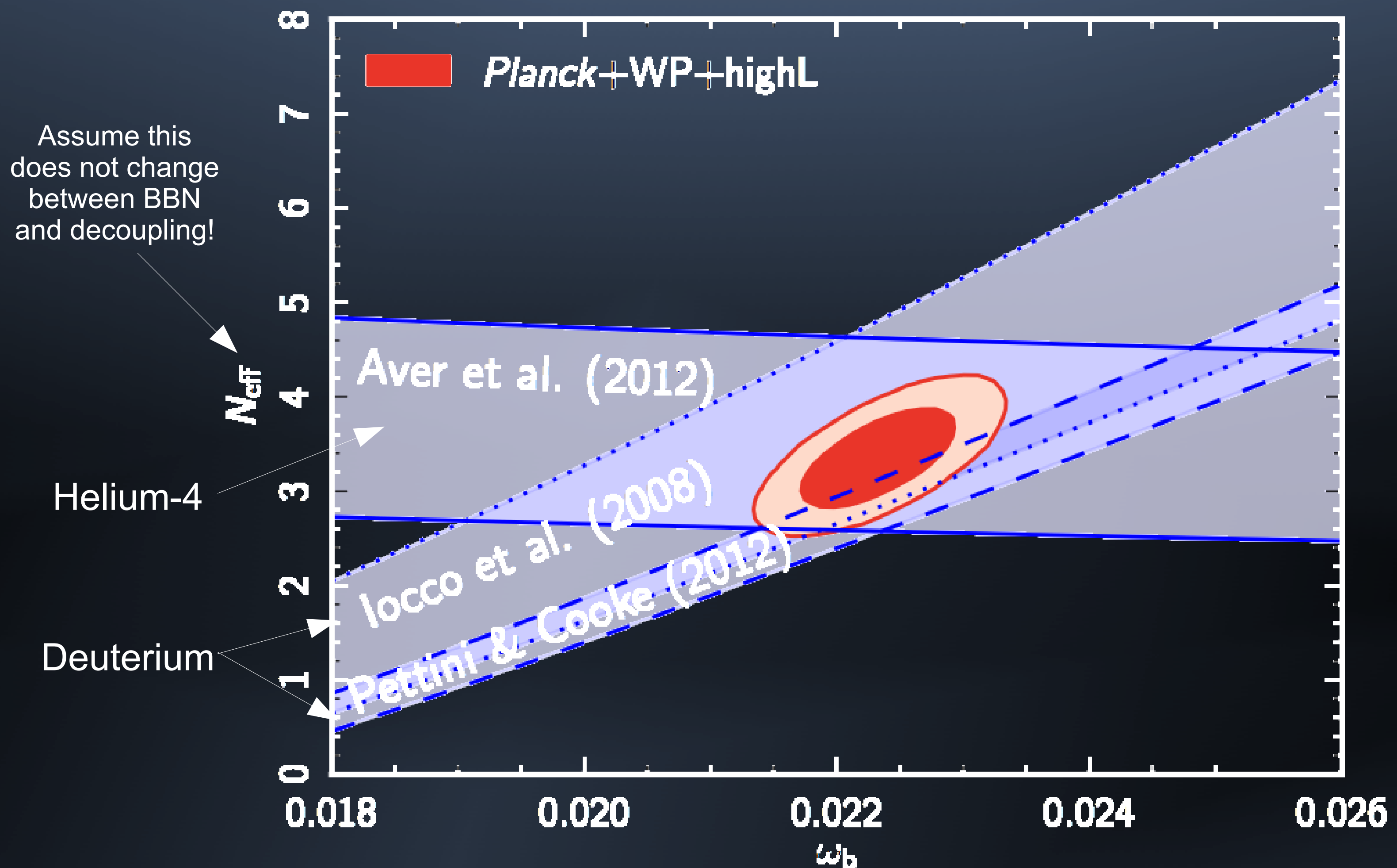


[Planck (2013)]



- 3 standard neutrinos with equal mass, $N_s \equiv N_{eff} - 3.046$ massless species
- Planck data break degeneracy between sum of neutrino masses and extra radiation degrees of freedom

BBN vs. CMB constraints



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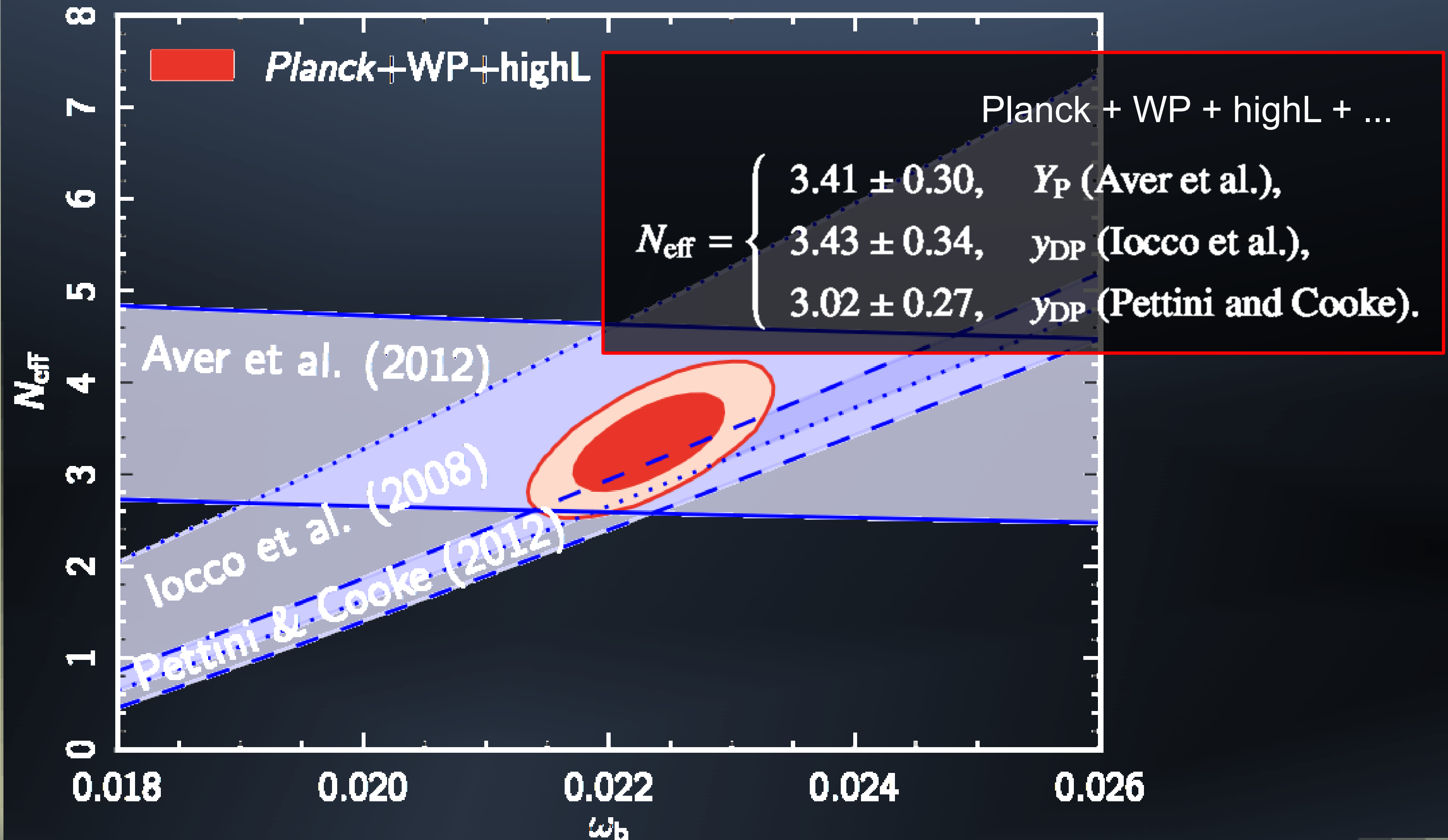


What if the dark radiation consists of massive (~eV) particles?

Motivation: neutrino oscillation data

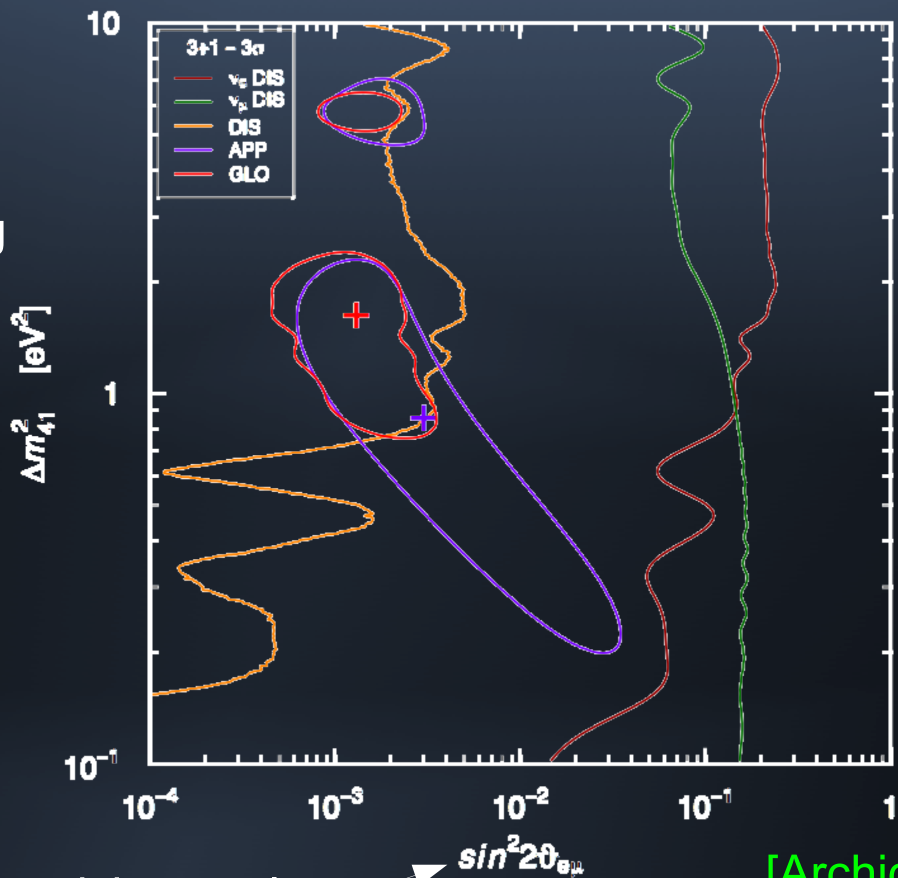
Observations at odds with standard 3-neutrino interpretation of global oscillation data

- $\nu_\mu \rightarrow \nu_e$ appearance (e.g., LSND anomaly) [Aguilar (2001)]
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance (e.g., MiniBooNE anomaly) [Aguilar-Arevalo et al. (2012)]
- ν_e and $\bar{\nu}_e$ disappearance
  - Short-baseline reactor experiments [Mention et al. (2011)]
  - Gallium experiments [Giunti & Laveder (2010)]

→ possibly resolved by oscillations into extra, sterile states

3+1 scenario and oscillation data

mass splitting



mixing angle

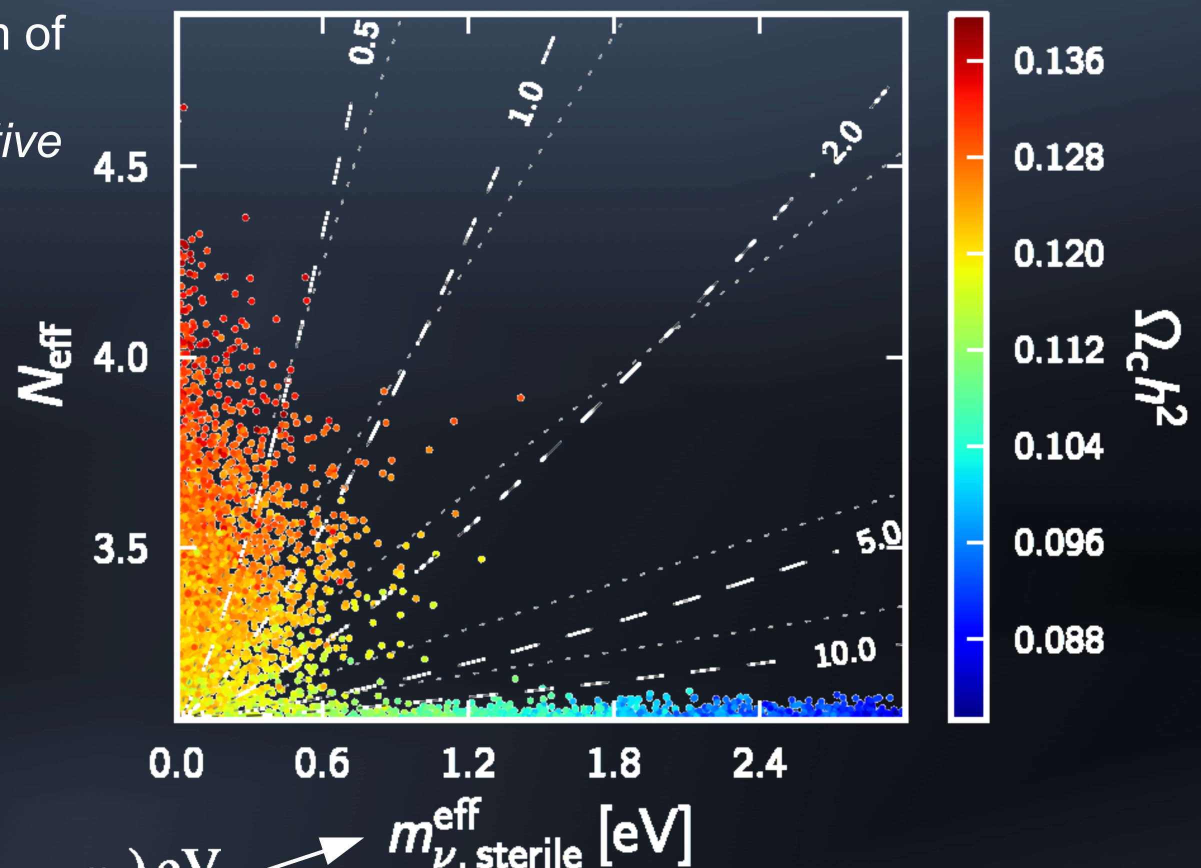
[Archidiacono et al. (2013)]

Planck constraints on massive light particles

Assume minimal sum of masses for standard neutrinos, vary *effective* sterile neutrino mass

Effective mass equal to physical mass, if

- Steriles fully thermalised, and
- $T_{sterile} = T_\nu$

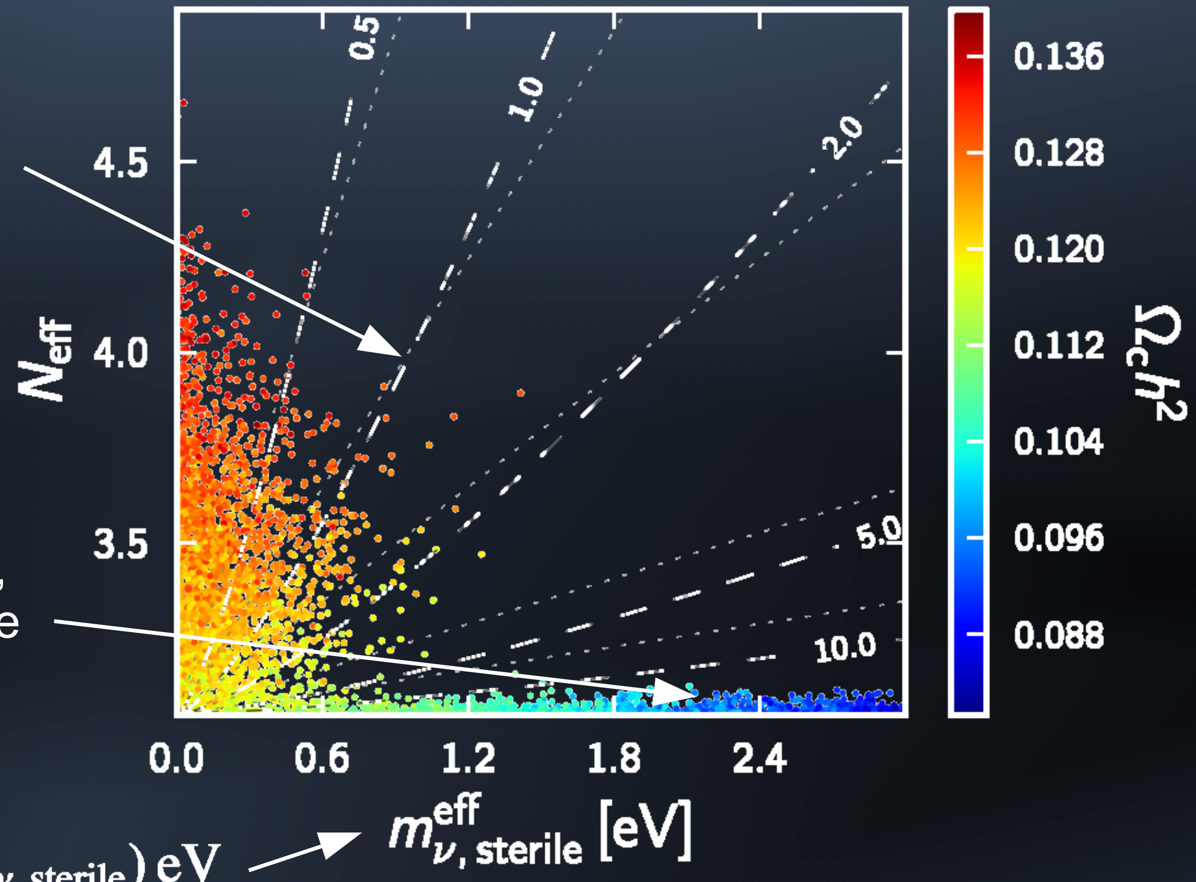


$$m^{eff}_{\nu,\,sterile} \equiv (94.1\,\omega_{\nu,\,sterile})\,\mathrm{eV}$$

Planck constraints on massive light particles

Fully thermalised sterile with eV-mass and temperature T_ν not compatible with Planck data

mass unconstrained, as long as abundance is low enough



$m^{eff}_{\nu,\,sterile} \equiv (94.1\omega_{\nu,\,sterile})\,eV$

Can the (m~eV) sterile neutrino scenario be saved?

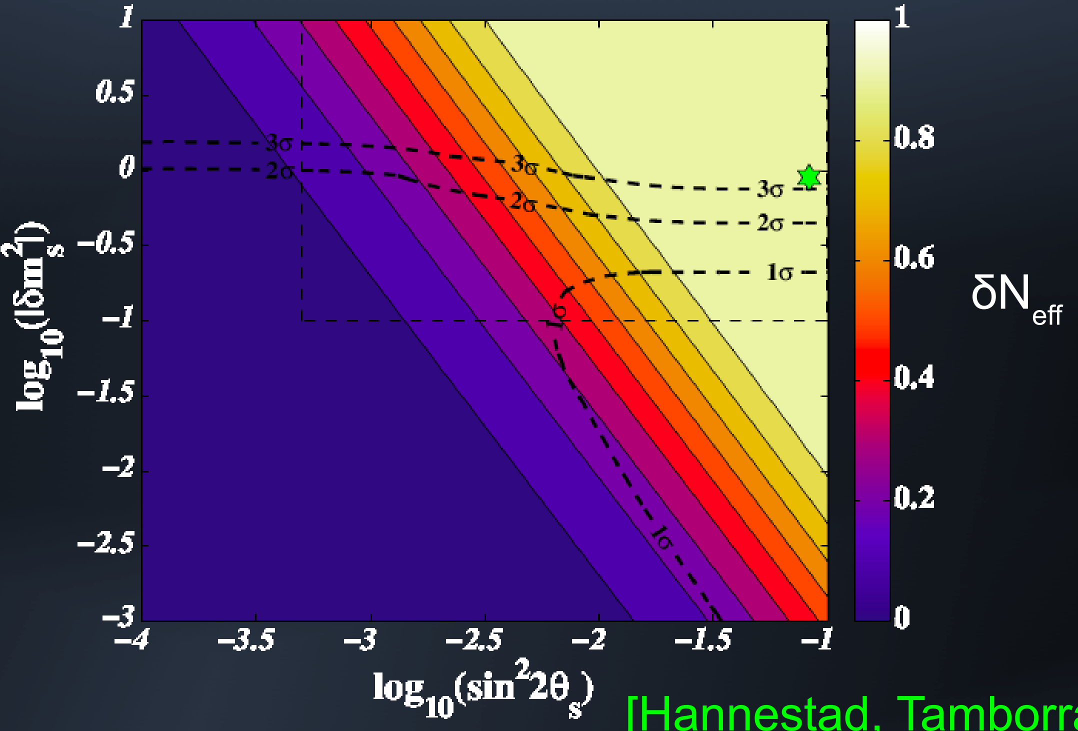
Sterile neutrino production

- Start with active neutrinos in thermal equilibrium, no steriles
- Sterile states will be populated through oscillations
- Solve quantum kinetic equations until neutrinos decouple

[Hannestad, Tamborra, Tram (2012)]

Sterile neutrino production

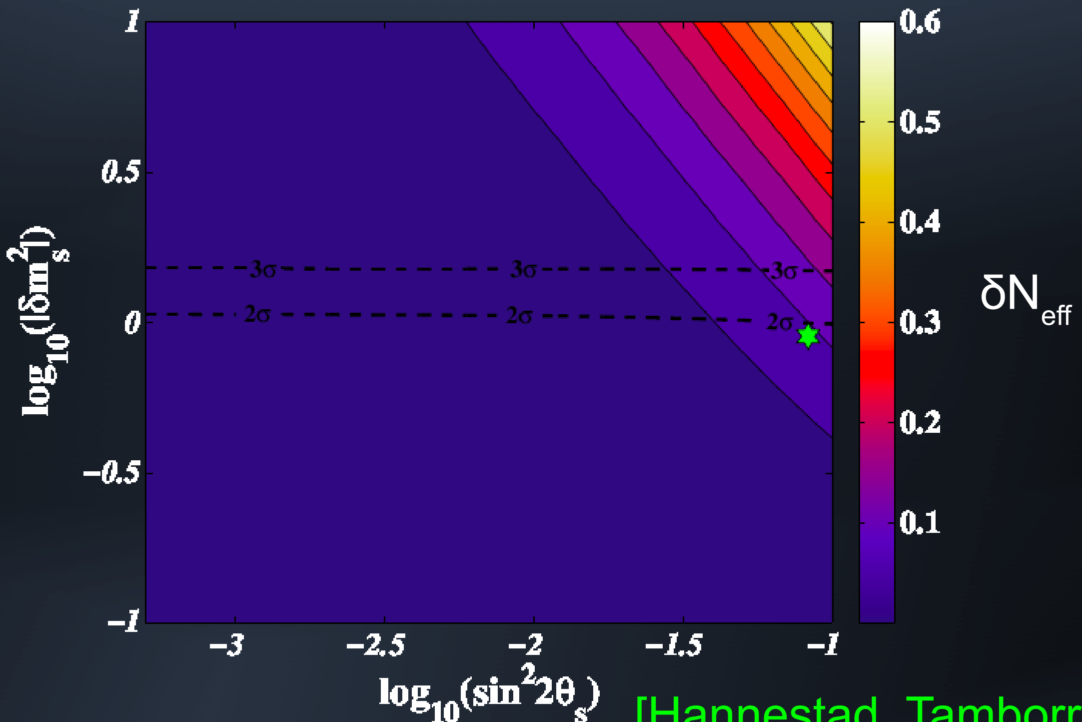
- For 1+1 model:
  Complete thermalisation if mixing/mass splitting as required by oscillation experiments



[Hannestad, Tamborra, Tram (2012)]

Sterile neutrino production

- Presence of large-ish initial lepton asymmetry could suppress production of steriles (e.g., for L=0.01):



[Hannestad, Tamborra, Tram (2012)]

Conclusions

- Post-Planck data are compatible with no extra radiation, though (depending on the exact combination of data sets) up to one additional effective massless species is still allowed
- Fully thermalised sterile neutrinos of mass O(1 eV) are ruled out
- Sterile scenario could be saved by suppressing their production, e.g., with a large lepton asymmetry
- Future large-volume galaxy surveys (LSST, EUCLID) can potentially reach $\sigma_{N_{\rm eff}} \approx 0.05$