Cosmological constraints on the number of neutrino species

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based on work in collaboration with:
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Setting the scene: hints for sterile neutrinos?

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

- LSND anomaly [Aguilar (2001)]
- MiniBooNE antineutrino results [Aguilar-Arevalo (2010)]
- Short-baseline reactor experiments (Bugey, ROVNO, Krasnoyarsk, ILL, Gösgen)
  - Recent re-evaluation of reactor fluxes

[Mention et al. (2011)]

Setting the scene: hints for sterile neutrinos?

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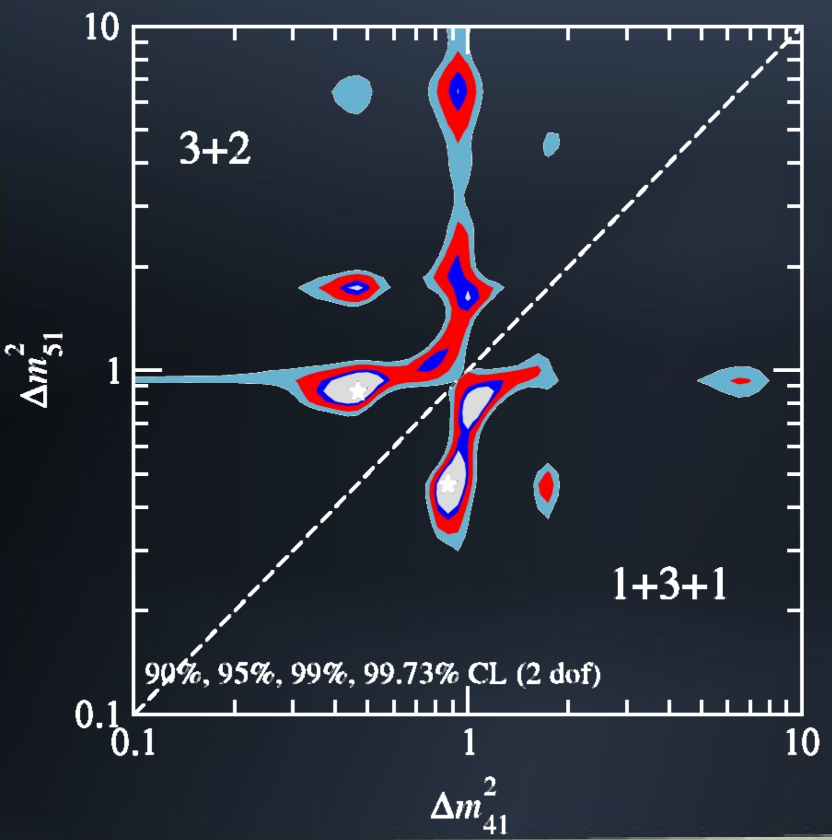
- MiniBooNE antineutrino results [Aguilar-Arevalo (2010)]
- Short-baseline reactor experiments (Bugey, ROVNO, Krasnoyarsk, ILL, Gösgen)
  - Recent re-evaluation of reactor fluxes [Mention et al. (2011)]

Can possibly resolved with oscillations into sterile neutrinos with $\Delta m^2 \sim eV^2$

Setting the scene: hints for sterile neutrinos?

- Results from reactor/global fit:



	Δm^2_{41} [eV^2]	$\|U_{e4}\|$	Δm^2_{51} [eV^2]	$\|U_{e5}\|$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

Table I: Best fit points for the 3+1 and 3+2 scenarios from reactor anti-neutrino data.

	Δm^2_{41}	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	Δm^2_{51}	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

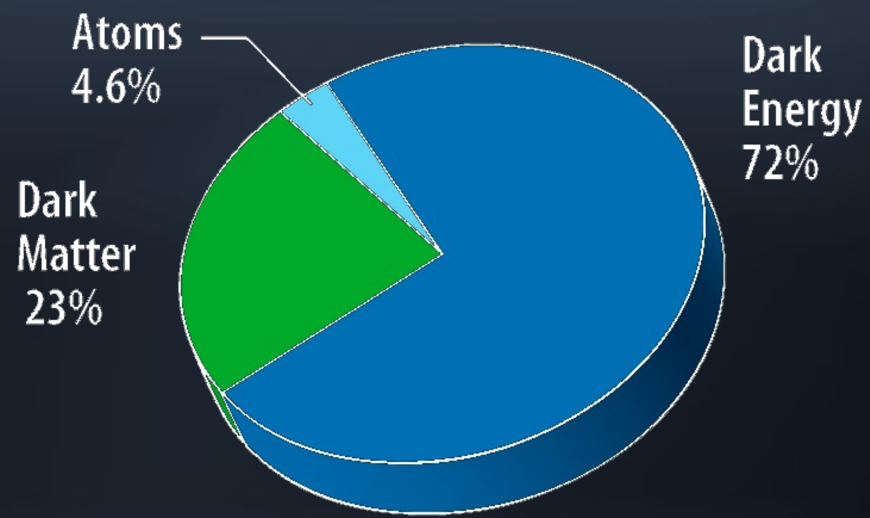
Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).

[Kopp, Maltoni, Schwetz (2011)]

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%

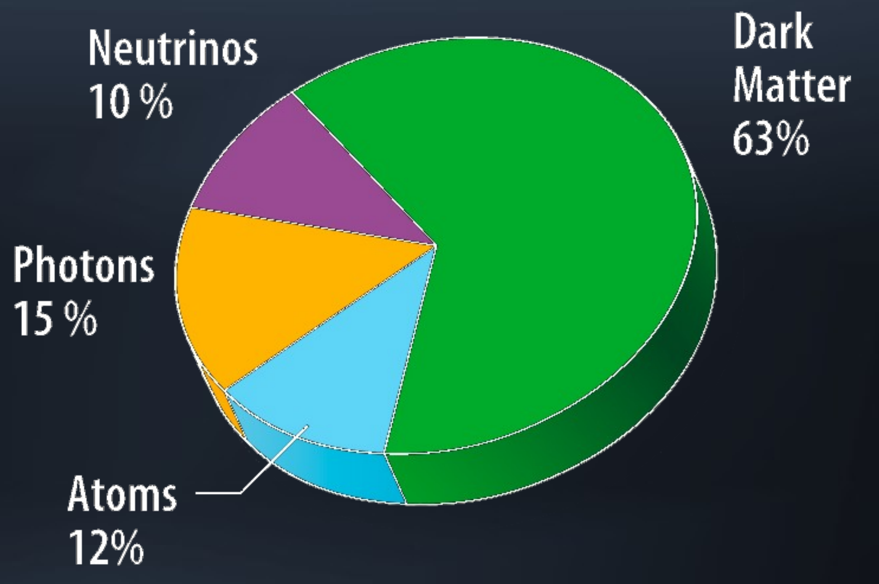
Photons 0.006%

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

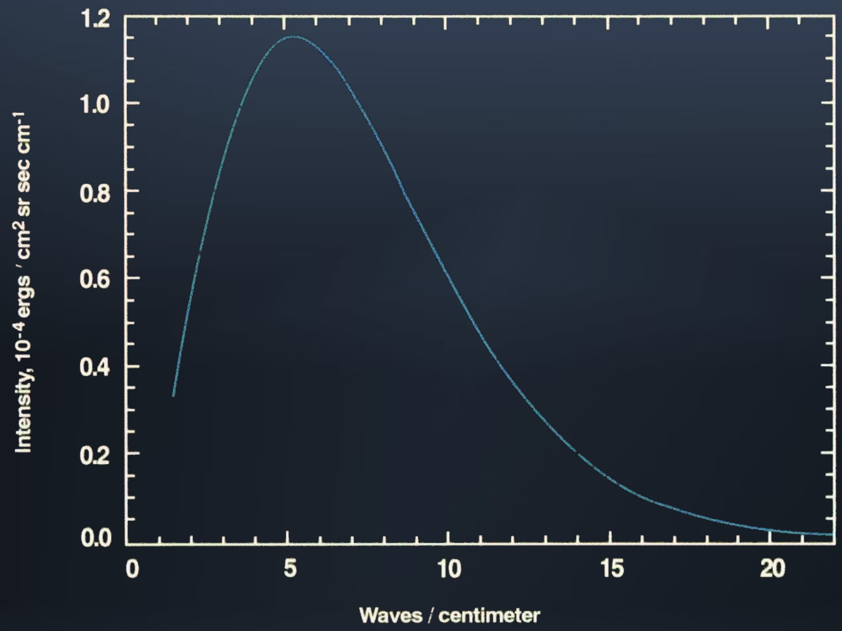
- Photons: CMB
- Neutrinos: CνB
- Other light particle species?

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 $T_\gamma = 2.725 \pm 0.001\ \mathrm{K}$

[Fixsen & Mather (2002)]

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
- no direct detection to date

Cosmic Neutrino Background

Neutrino energy density:

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

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:

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

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

$\longrightarrow$ Standard Model expectation:

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

[Mangano et al. (2005)]

Radiation content of the Universe

Other light stuff?

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

Radiation content of the Universe

Other light stuff?

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

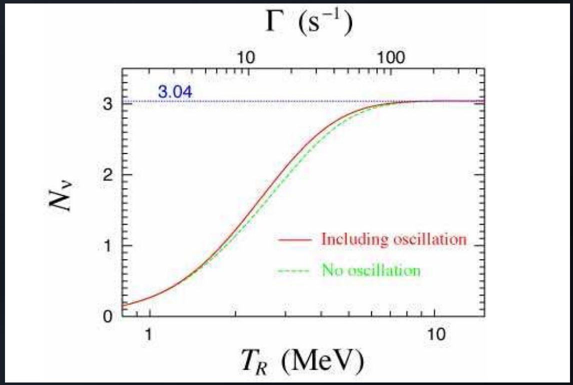
Putting it all together:

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

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

Big Bang Nucleosynthesis

- Primordial element abundances

Decoupling

- Cosmic Microwave Background anisotropies
- Large scale structure

BBN

Boltzmann equation

nuclear interaction rates $\longleftrightarrow$ 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 $\longleftrightarrow$ expansion rate

$\Gamma(\omega_\mathrm{b}, f_{\nu_\mathrm{e}})$ $\qquad$ $H \propto \sqrt{\rho_\mathrm{r}}$

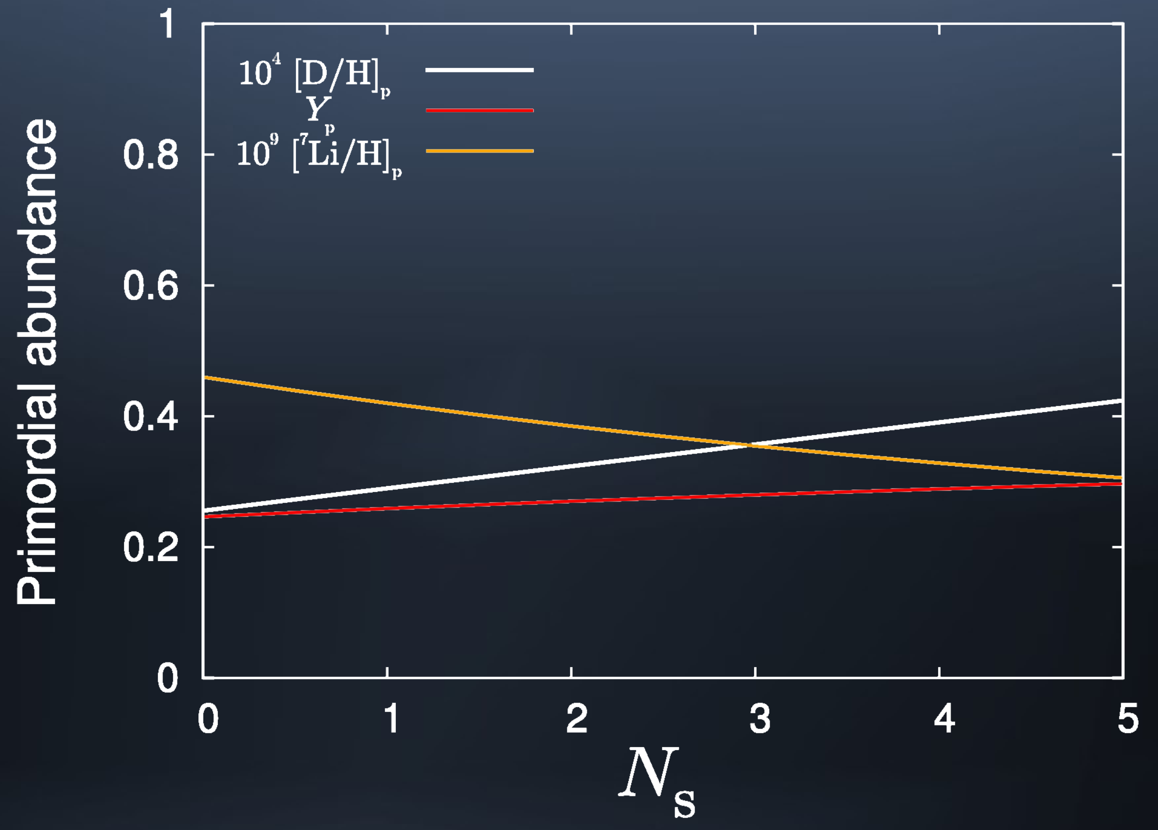
N_eff

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

BBN

- Assume standard BBN with 3 active neutrinos and N_s additional effective "sterile neutrino" species

BBN



Measure primordial abundances → infer N_s

BBN

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

Measure primordial abundances → infer N_{eff}

Primordial abundances: Deuterium

- Measure absorption of quasar light in low-metallicity hydrogen clouds at high z
- Relatively "clean" probe
- Deuterium abundance not subject to strong evolution with redshift
- From seven measured objects:

$$\log\,[\mathrm{D}/\mathrm{H}]_{\mathrm{p}} = -4.55 \pm 0.03$$

[Pettini et al. (2008)]

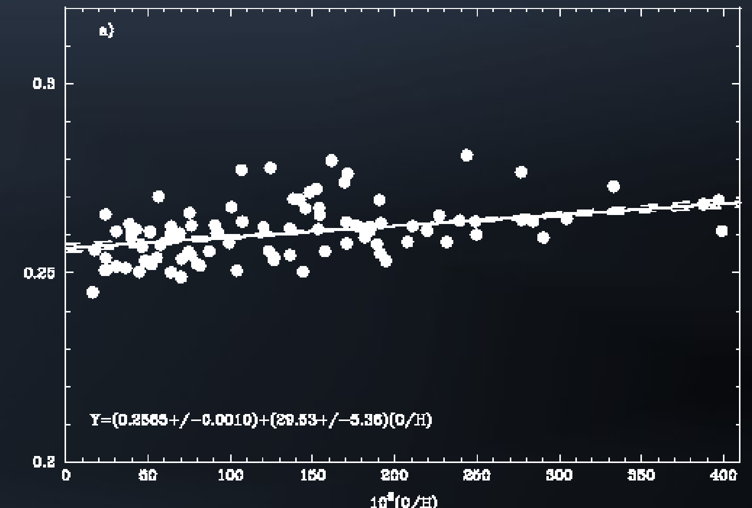
Primordial abundances: Helium

- 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 → dY/dZ > 0

Y



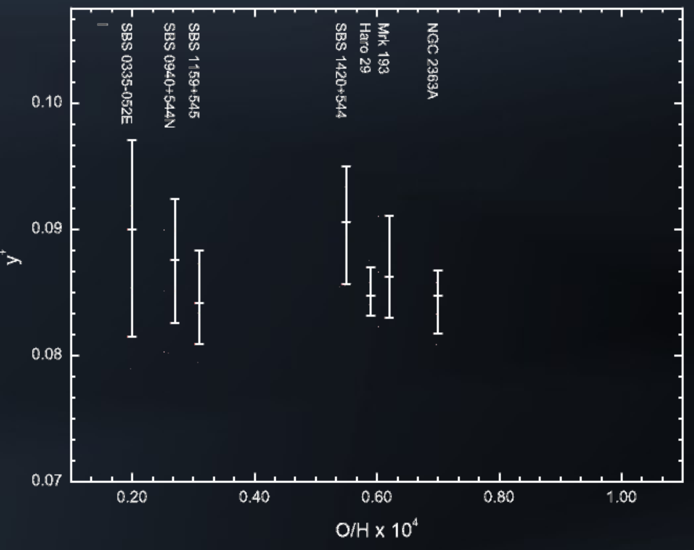
Metallicity Z

[Izotov, Thuan (2010)]

Primordial abundances: Helium

- Reliable treatment of systematics for seven "high-quality" systems
- Linear regression to zero metallicity, limited to positive slopes

$$Y_{\mathrm{p}} = 0.2573^{+0.0033}_{-0.0088}$$



[Aver, Olive, Skillman (2010)]

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

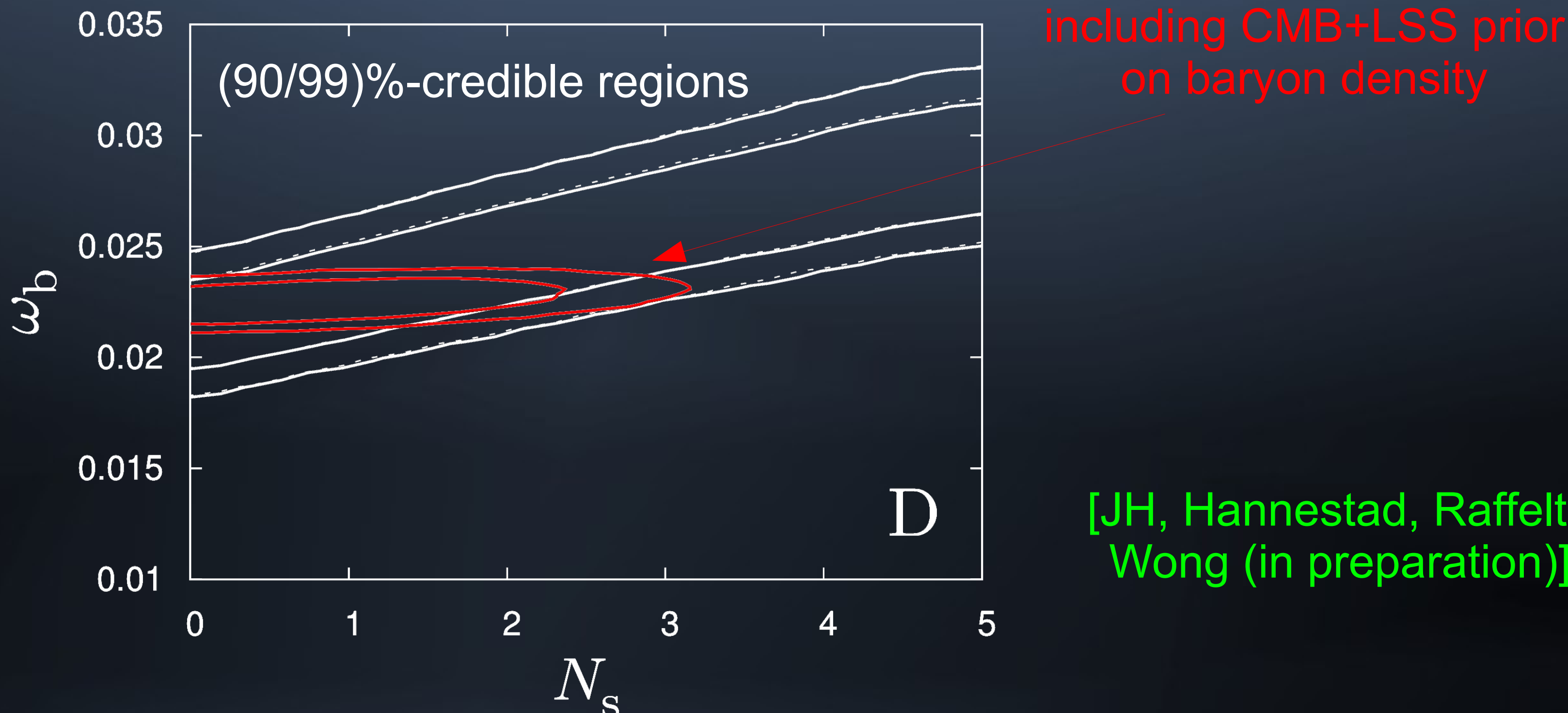
    → folded into likelihood function
  - Free neutron lifetime

    negligible for Deuterium, 0.6% for Helium

Free neutron lifetime

- No universally agreed upon value:
  - $\tau_{\mathrm{n}}^{\mathrm{PDG}} = 885.7 \pm 0.8\ \mathrm{s}$ [Particle Data Group (2010)]
  - $\tau_{\mathrm{n}}^{\mathrm{S}} = 878.5 \pm 0.8\ \mathrm{s}$ [Serebrov et al. (2005)]
  - $\tau_{\mathrm{n}}^{\mathrm{P}} = 880.7 \pm 1.8\ \mathrm{s}$ [Pichlmaier et al. (2010)]
- Averaging would not be reasonable
- Re-analysis of older measurements claims bias of roughly +6 s [Serebrov, Fomin (2010)]
- We consider the two extremal values until the matter is settled

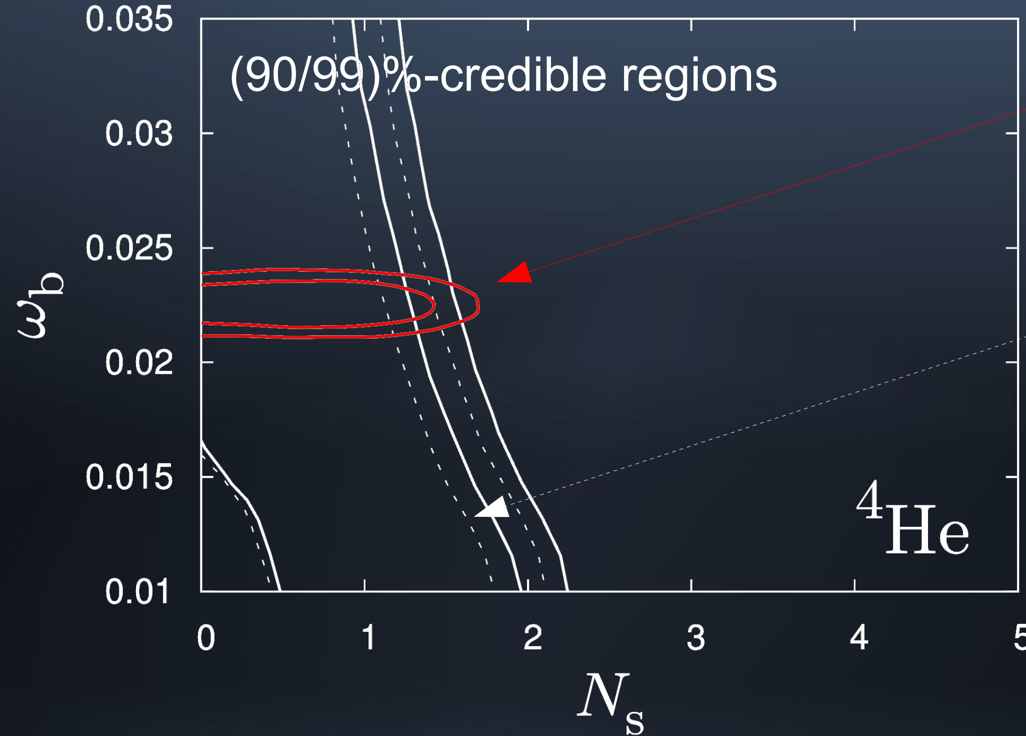
BBN constraints: Deuterium only



[JH, Hannestad, Raffelt, Wong (in preparation)]

- N_s unconstrained from Deuterium alone
- Combination with baryon density prior gives upper limit

BBN constraints:
Helium only



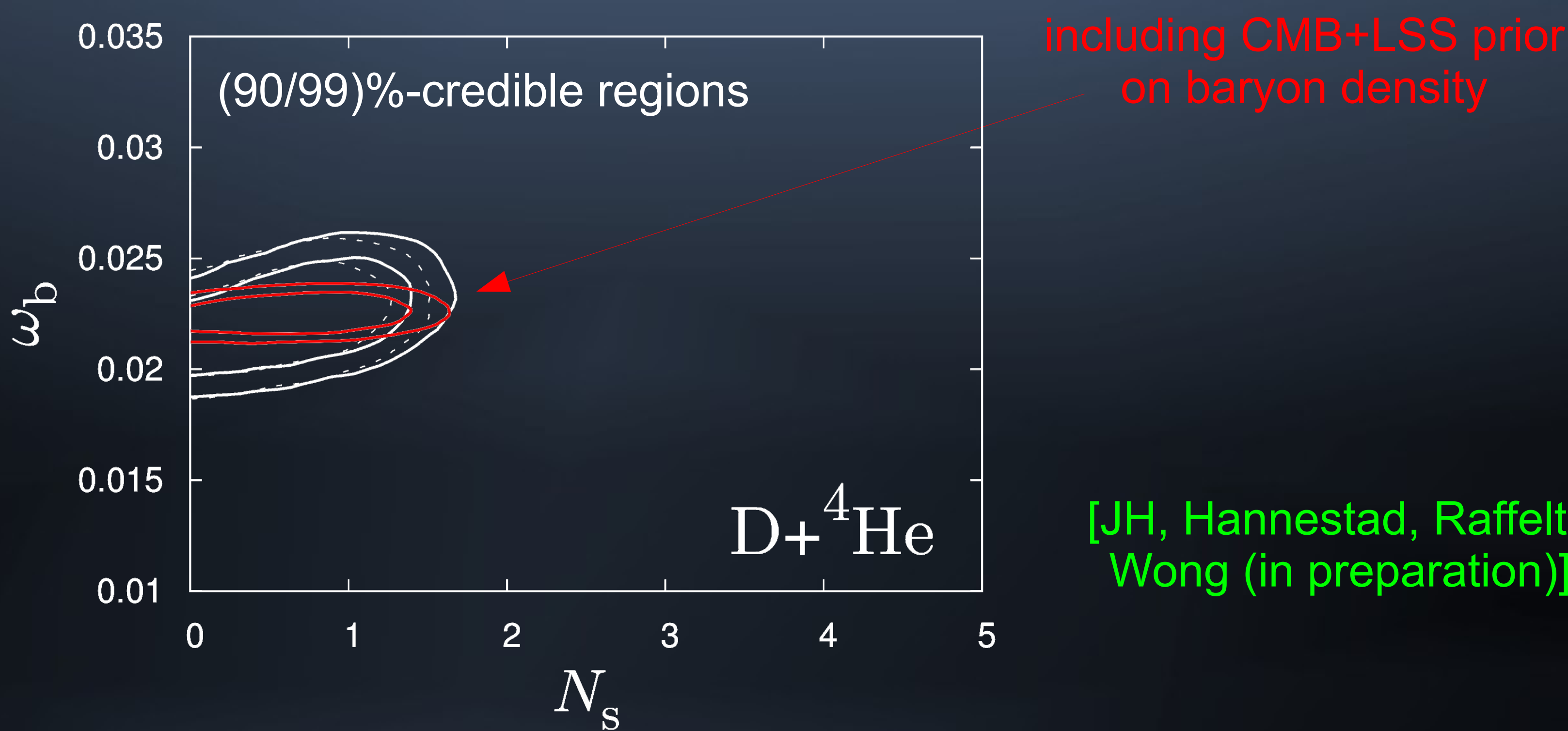
including CMB+LSS prior on baryon density

effect of going to higher neutron lifetime
→ higher predicted Y_p
→ tighter bound on N_S

[JH, Hannestad, Raffelt, Wong (in preparation)]

- Helium is a much better probe of N_S

BBN constraints: Deuterium + Helium

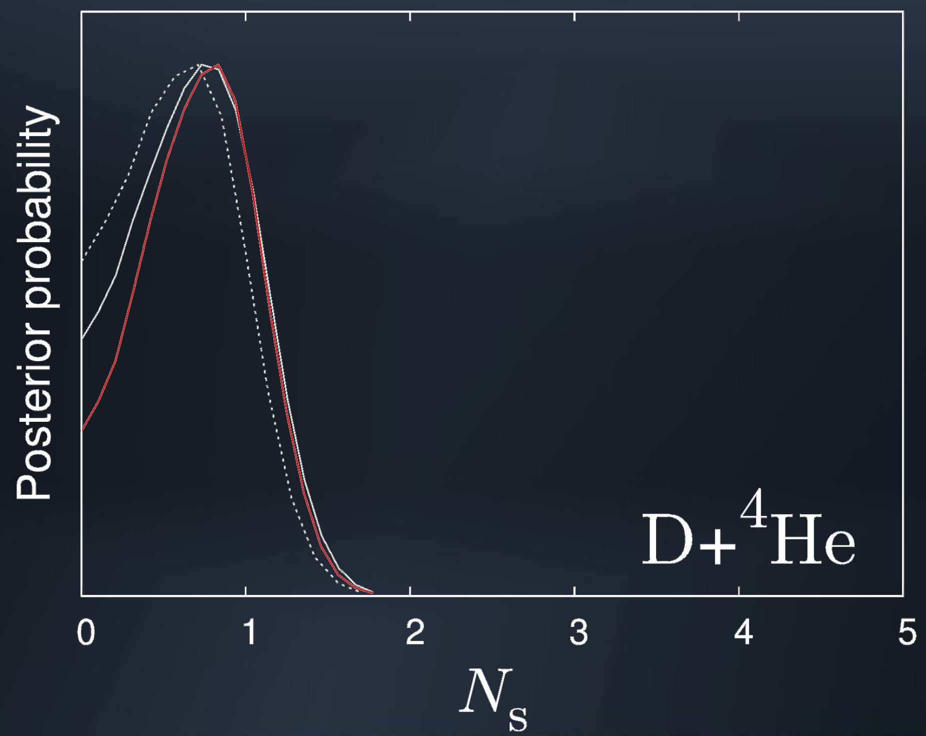


[JH, Hannestad, Raffelt, Wong (in preparation)]

- N_s < 1.26 (1.24) @95% credibility
- Best-fit at N_s = 0.86

BBN and sterile neutrinos

- 3+1 scenario slightly preferred over 3+0
- 3+2 ruled out at high significance ...



[JH, Hannestad, Raffelt, Wong (in preparation)]

BBN and sterile neutrinos

- 3+1 scenario slightly preferred over 3+0
- 3+2 ruled out at high significance ...
  … unless:
  - Incomplete thermalisation

    → effective N_s is smaller than 2
  - Non-standard BBN?

Degenerate BBN

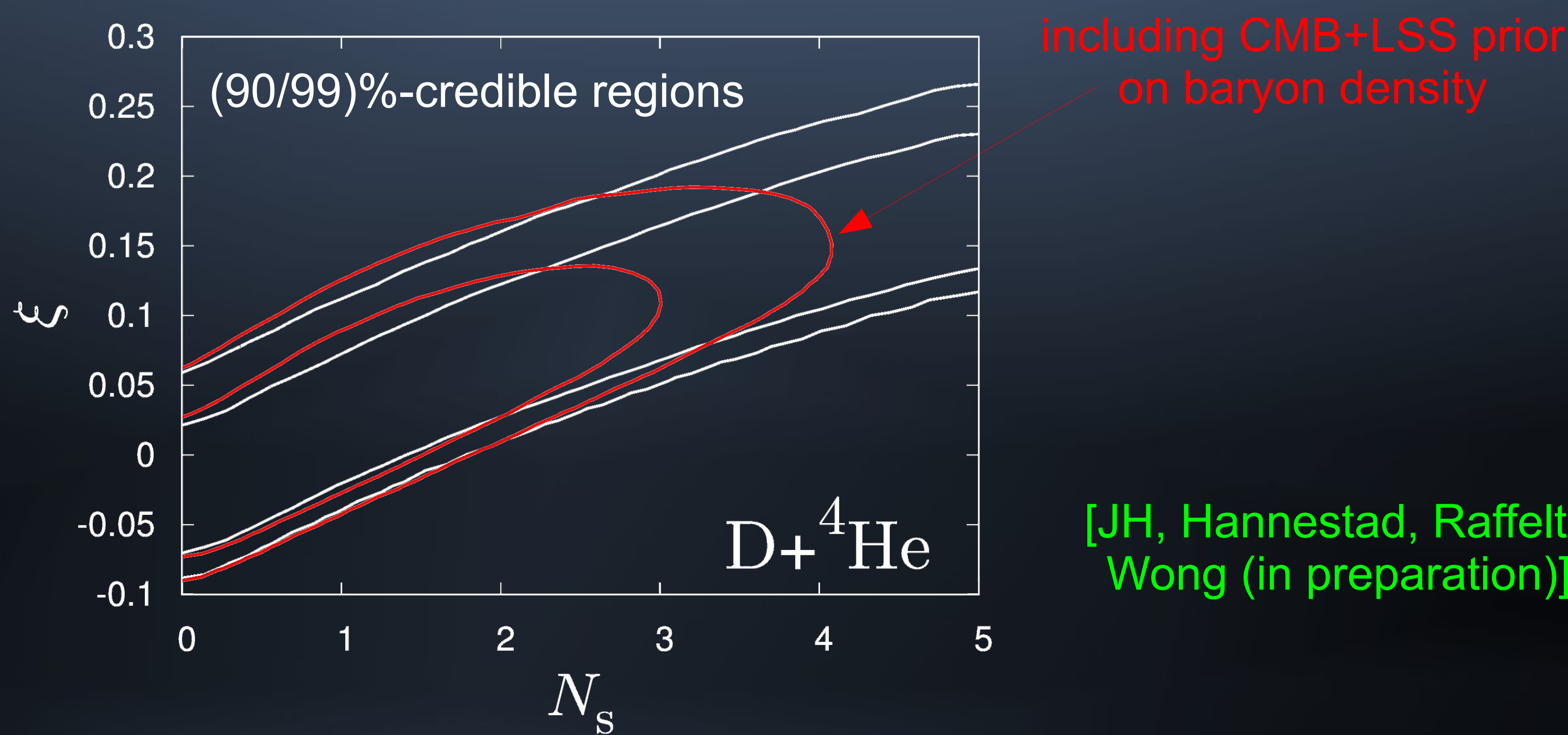
- Allow for a neutrino chemical potential ξ
- Assume all active species share the same ξ
- Two effects:
  - Additional radiation energy density

$$\Delta N_{\mathrm{eff}} = \frac{45}{7}\left[2\left(\xi/\pi\right)^2 + \left(\xi/\pi\right)^4\right]$$

  - Change in initial equilibrium n/p ratio

$$n/p = \exp\left(-\frac{\Delta m}{T} - \xi\right)$$

BBN constraints: Degenerate BBN

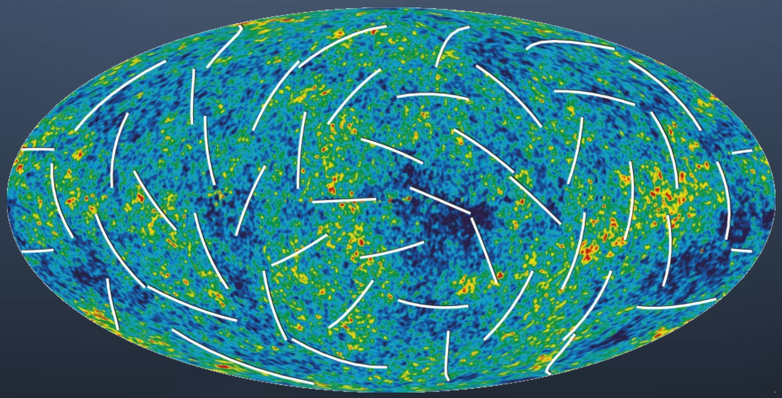


[JH, Hannestad, Raffelt, Wong (in preparation)]

- ξ of order 0.1 could save 3+2 (and even 3+3!)

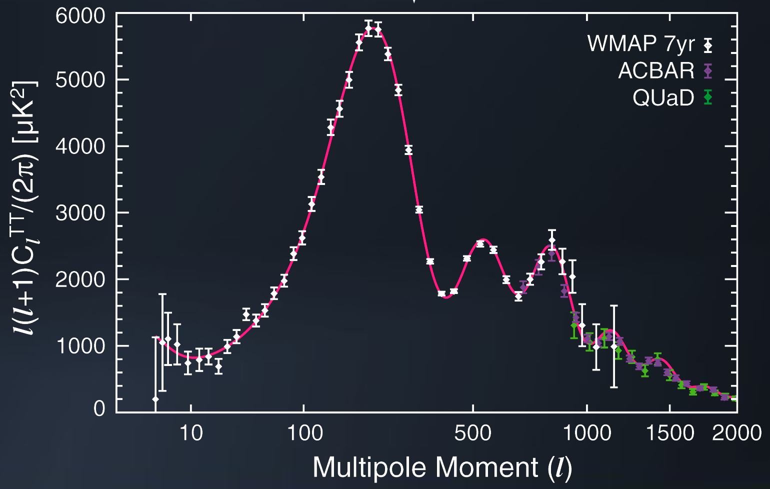
$N_{\rm eff}$ and the CMB

CMB map



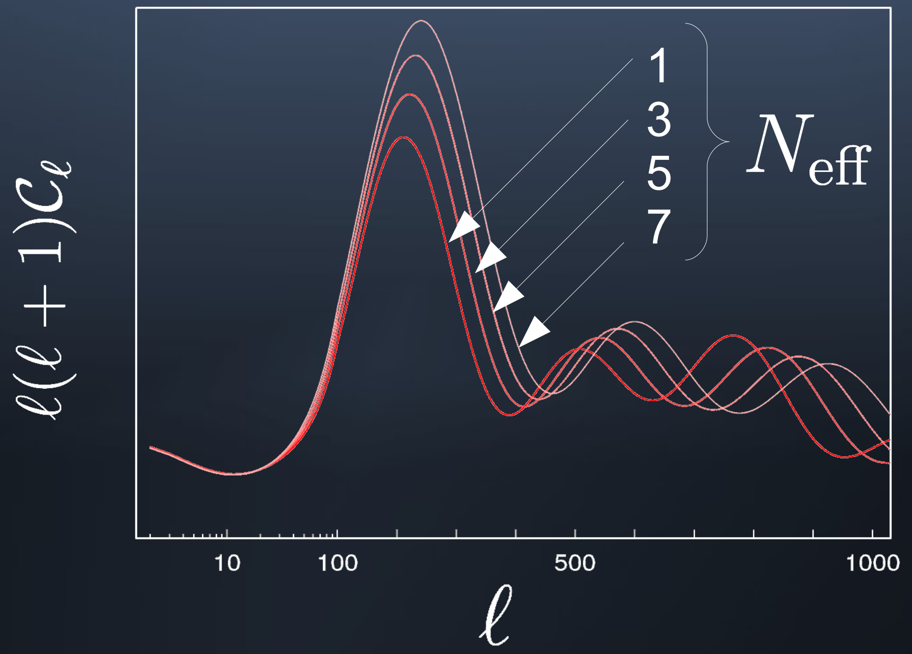
expand in spherical harmonics

CMB angular power spectrum



[WMAP (2010)]

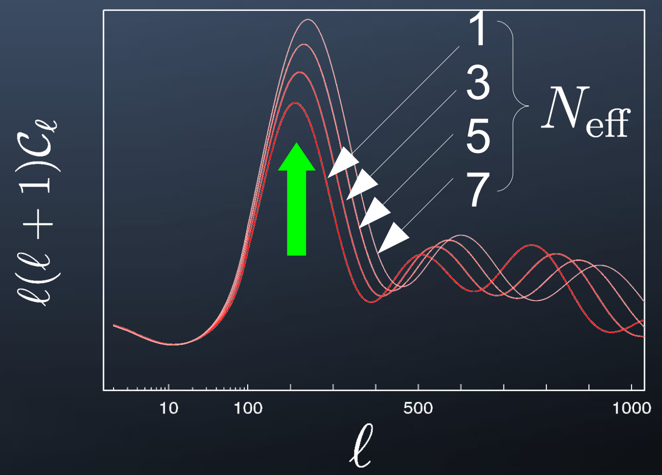
N_{eff} and the CMB



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

N_{eff} and the CMB

- Matter-radiation equality
- Sound horizon
- Anisotropic stress
- Damping tail

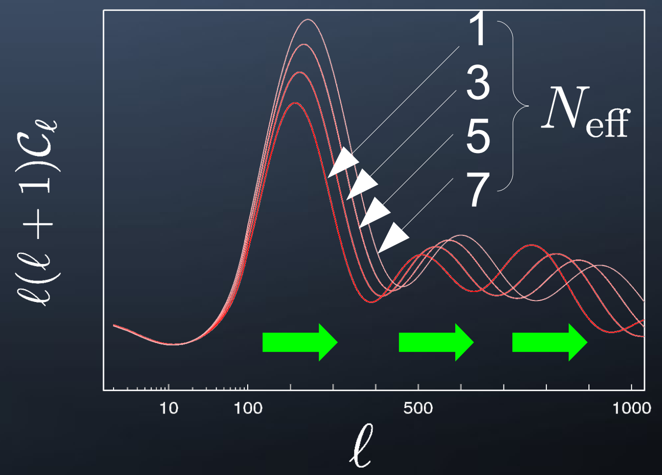


$$1 + z_{\mathrm{eq}} = \frac{\Omega_{\mathrm{m}}}{\Omega_{\mathrm{r}}} \simeq \frac{\Omega_{\mathrm{m}} h^2}{\Omega_\gamma h^2} \frac{1}{1 + 0.2271 N_{\mathrm{eff}}}$$

- Completely degenerate with matter density
- Larger N_{eff} $\rightarrow$ later equality $\rightarrow$ enhanced early integrated Sachs-Wolfe-effect $\rightarrow$ higher first peak

$N_{\rm eff}$ and the CMB

- Matter-radiation equality
- Sound horizon
- Anisotropic stress
- Damping tail

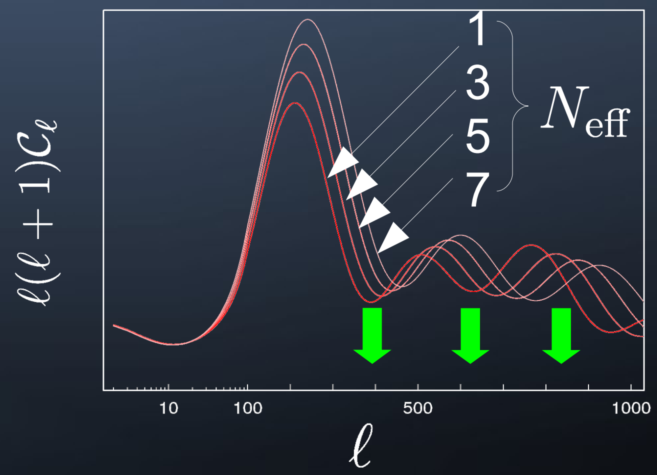


- Function of radiation, baryon and matter densities
- θ_s = Sound horizon/distance to last scattering surface determines positions of acoustic peaks

also depends on dark energy density

N_{eff} and the CMB

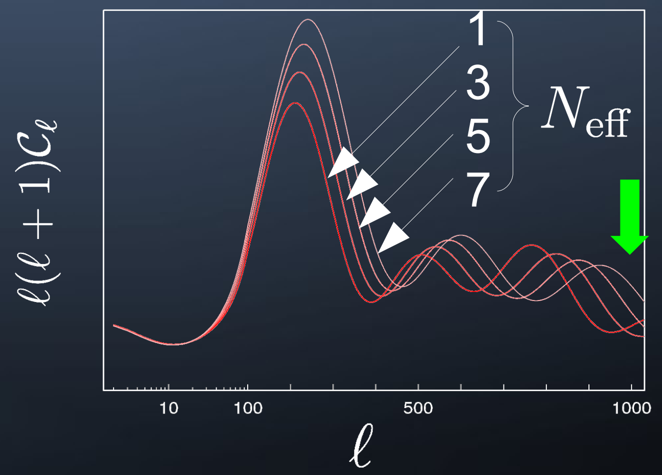
- Matter-radiation equality
- Sound horizon
- Anisotropic stress
- Damping tail



- Free streaming particles → anisotropic stress
- Dampens fluctuations during radiation domination
- Suppression of power at multipoles > 200

$N_{\rm eff}$ and the CMB

- Matter-radiation equality
- Sound horizon
- Anisotropic stress
- Damping tail



- Last scattering surface has finite thickness
  → exponential damping of fluctuations below damping scale
- For fixed peak positions, increasing $N_{\rm eff}$ enhances damping

$N_{\rm eff}$ and the CMB

- Damping tail can help break degeneracies with other parameters

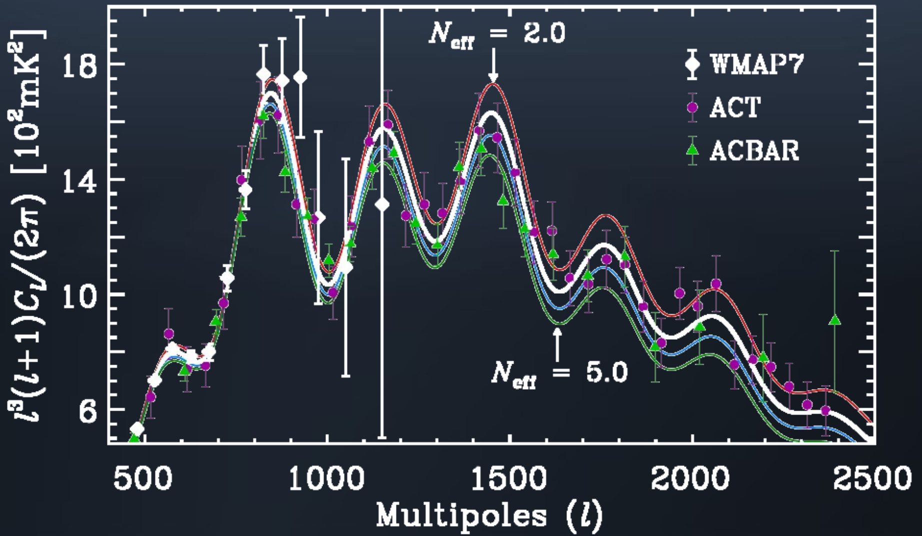
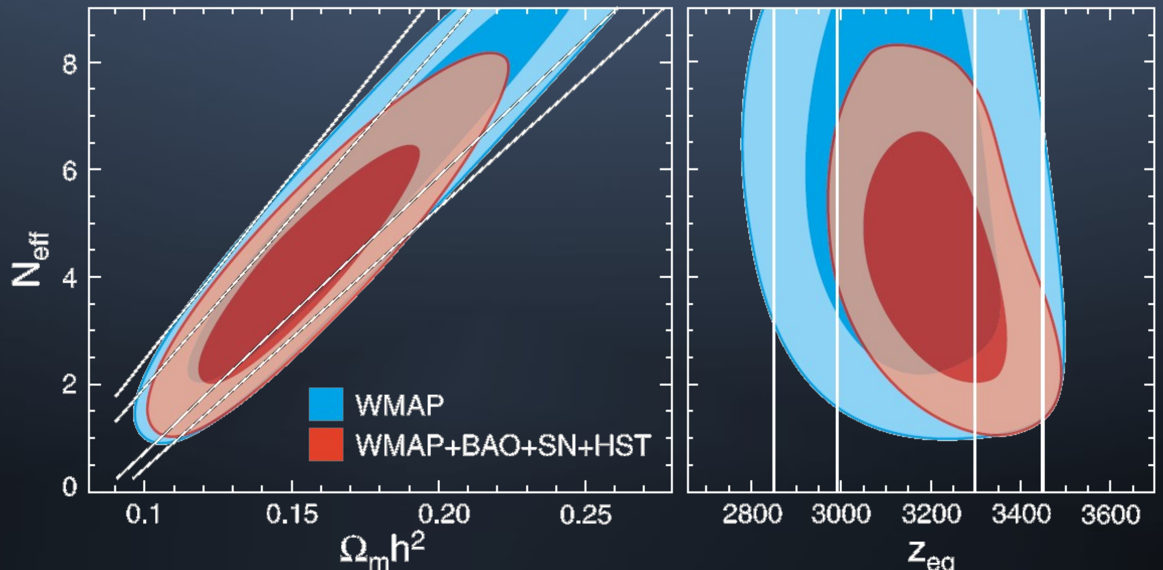


FIG. 1. *Top panel: WMAP*, ACBAR and ACT power spectrum measurements, and theoretical power spectra normalized at $\ell = 200$ for $N_{\rm eff}$ varying from 2 to 5 with ρ_b, θ_s, and $z_{\rm EQ}$ held fixed.

[Millea et al. (2011)]

$N_{\rm eff}$ from WMAP+LSS+...



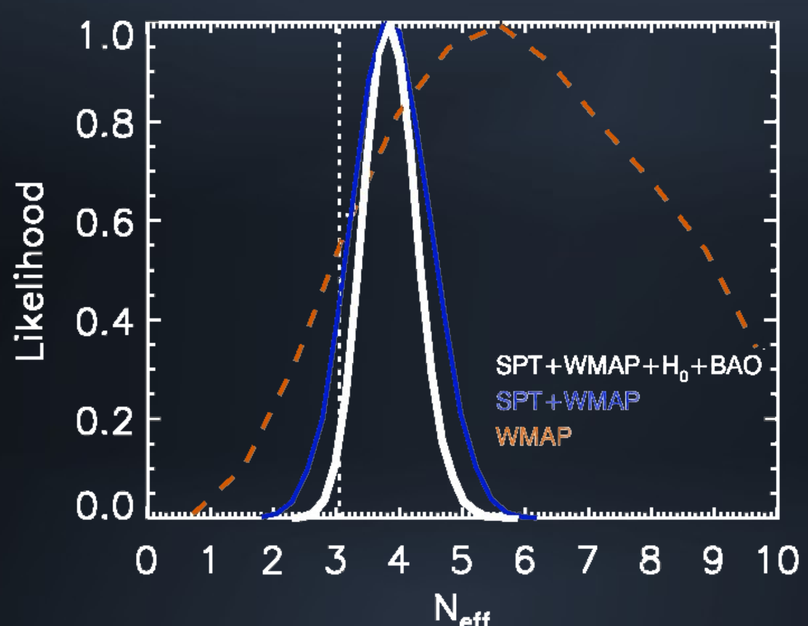
- lower limit from WMAP alone (→ anisotropic stress)
- meaningful upper limit requires combination with other data sets sensitive to matter density and expansion rate ...

[WMAP: Komatsu et al. (2008)]

N_{eff} from CMB alone

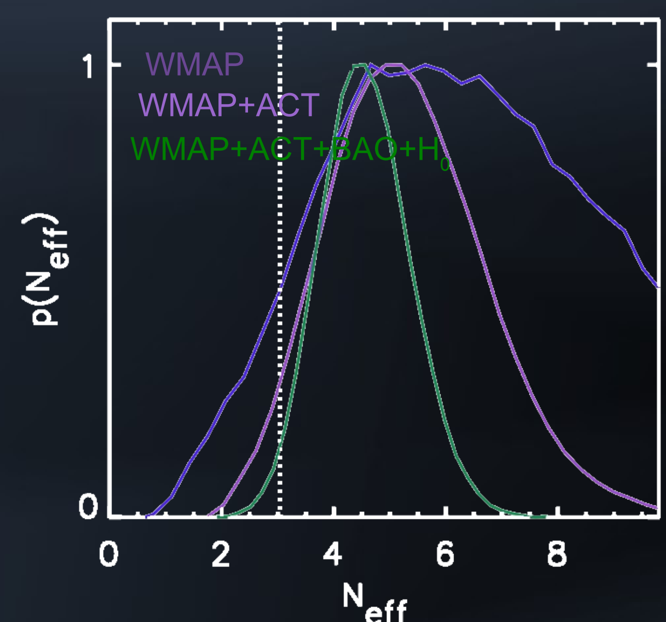
- … or measurement of the damping tail of the CMB angular power spectrum

South Pole Telescope



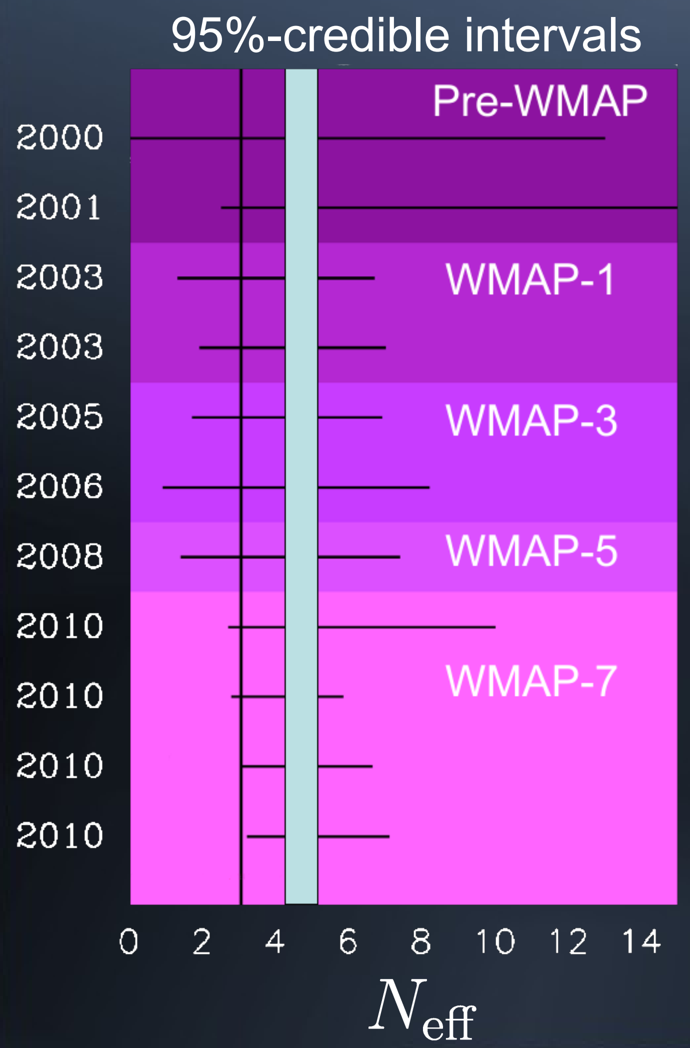
[Keisler et al. (2011)]

Atacama Cosmology Telescope



[Dunkley et al. (2010)]

CMB+X bounds on $N_{\rm eff}$



- Precise numbers depend on cosmological model and data sets used
- Recent analysis: $N_{\rm eff} = 4.47^{+1.82}_{-1.74}$

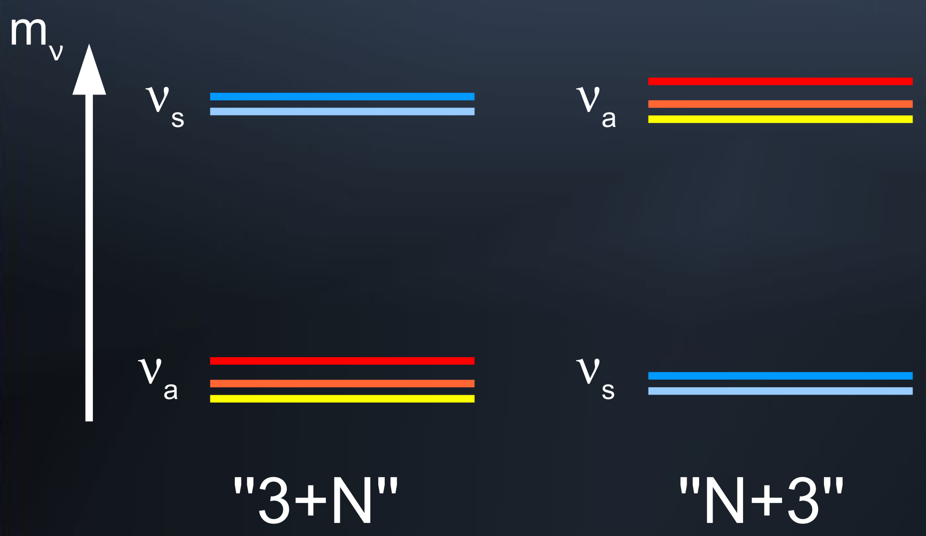
  CMB + SDSS-DR7-BAO + HST

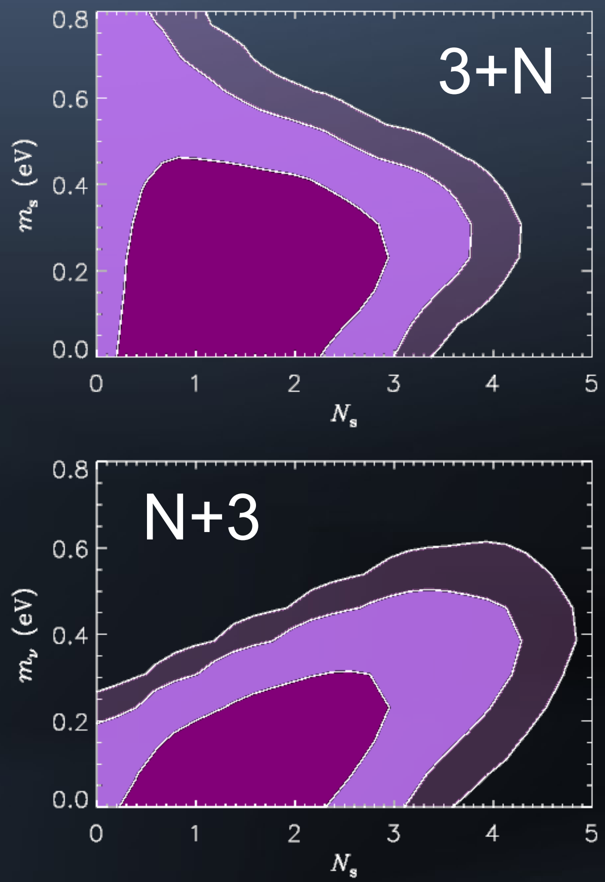
  ΛCDM + neutrino mass + $N_{\rm eff}$

  [JH, Hannestad, Lesgourgues, Rampf, Wong (2010)]

Sterile neutrino scenario

Two qualitatively different
mass hierarchies:

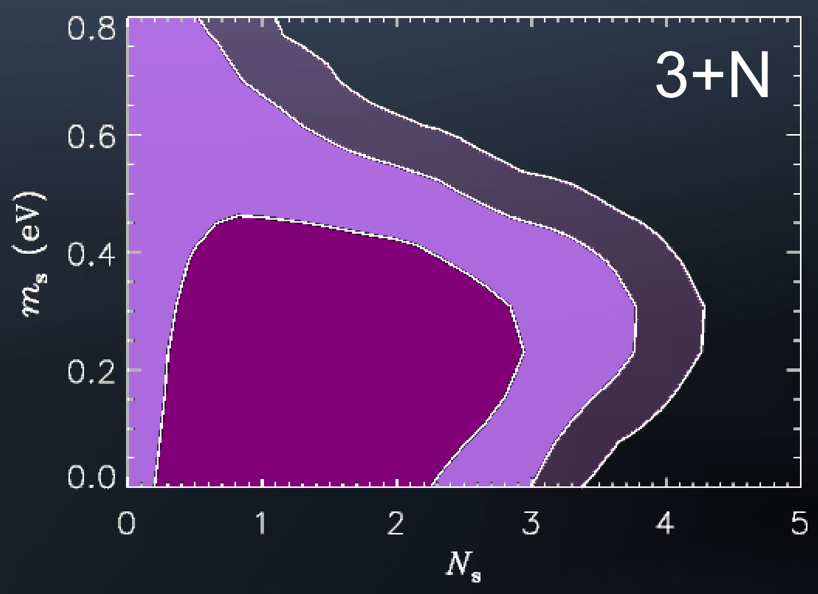




[JH, Hannestad, Raffelt, Tamborra, Wong (2010)]

Sterile neutrino scenario

- 3+1, 3+2, 3+3 are fine ...
  … *as long as the steriles are light enough!*
- Unfortunately, 1 eV appears to be somewhat too heavy
- Reminder: we assumed minimal extension of cosmological standard model (ΛCDM+N_{eff}+m_ν)



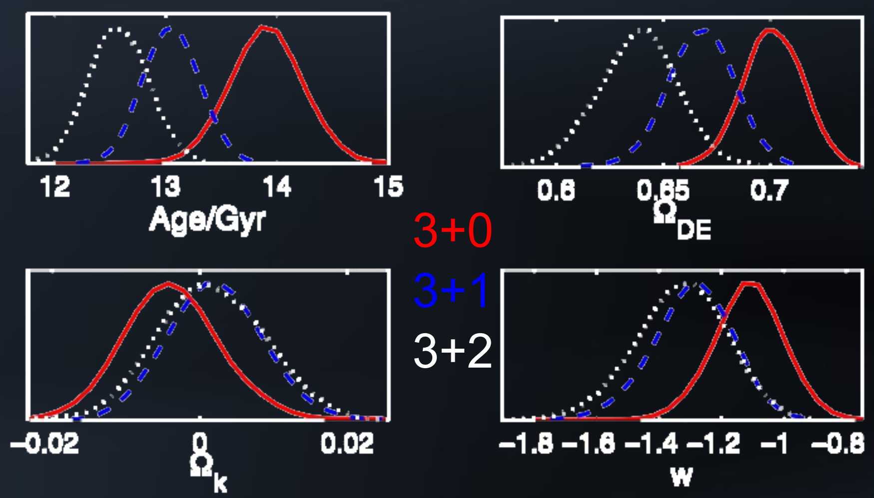
[JH, Hannestad, Raffelt, Tamborra, Wong (2010)]

Impact on cosmological model

- Assume laboratory hints for steriles are real, fix masses to best-fit values in 3+1/3+2
- Extend model and allow curvature parameter Ω_k and dark energy equation of state parameter w to vary
- $\rightarrow$ w < -1 at more than 95% c.l.

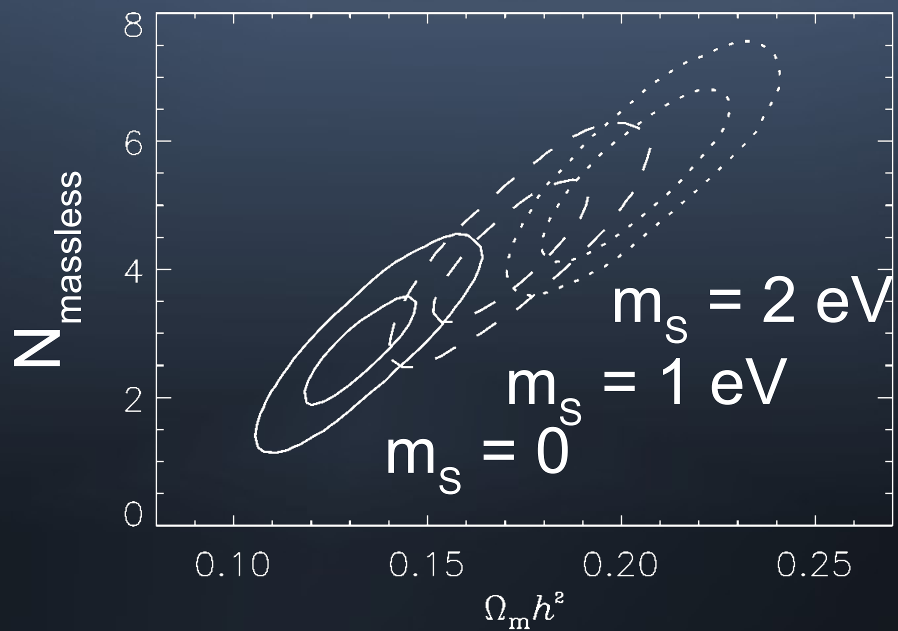
	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

Table I: Best fit points for the 3+1 and 3+2 scenarios from reactor anti-neutrino data.



[Kristiansen, Elgarøy (2011)]

Impact on cosmological model

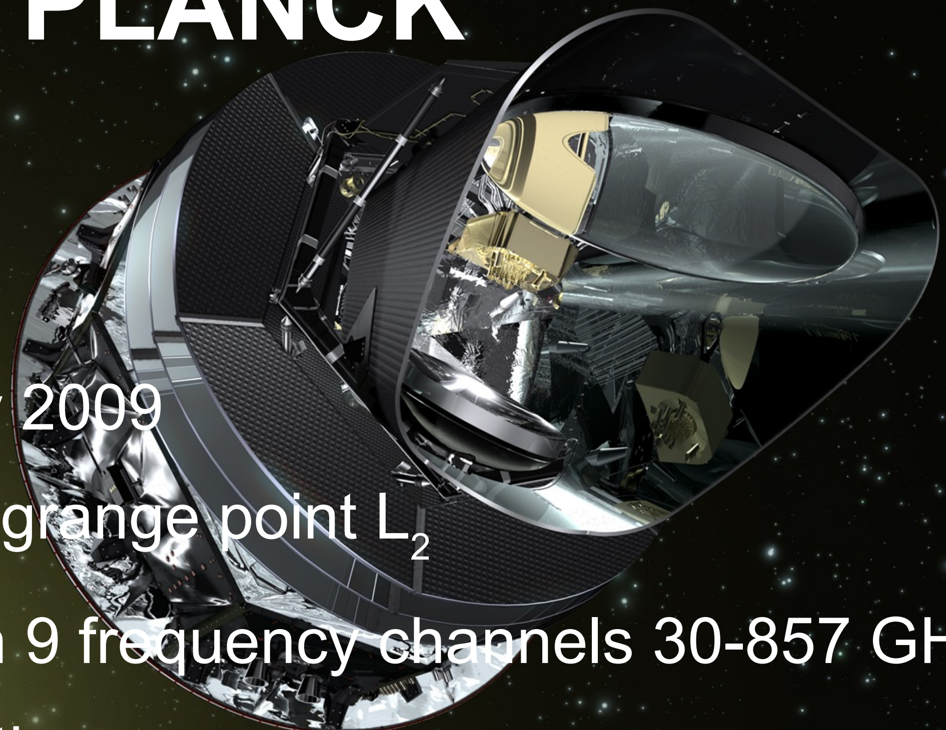


CMB+BAO +HST+H_0

- E.g., 1 massive + N massless species
- For eV-mass steriles: prefer additional massless species and high matter density

[JH, Hannestad, Raffelt, Wong (in preparation)]

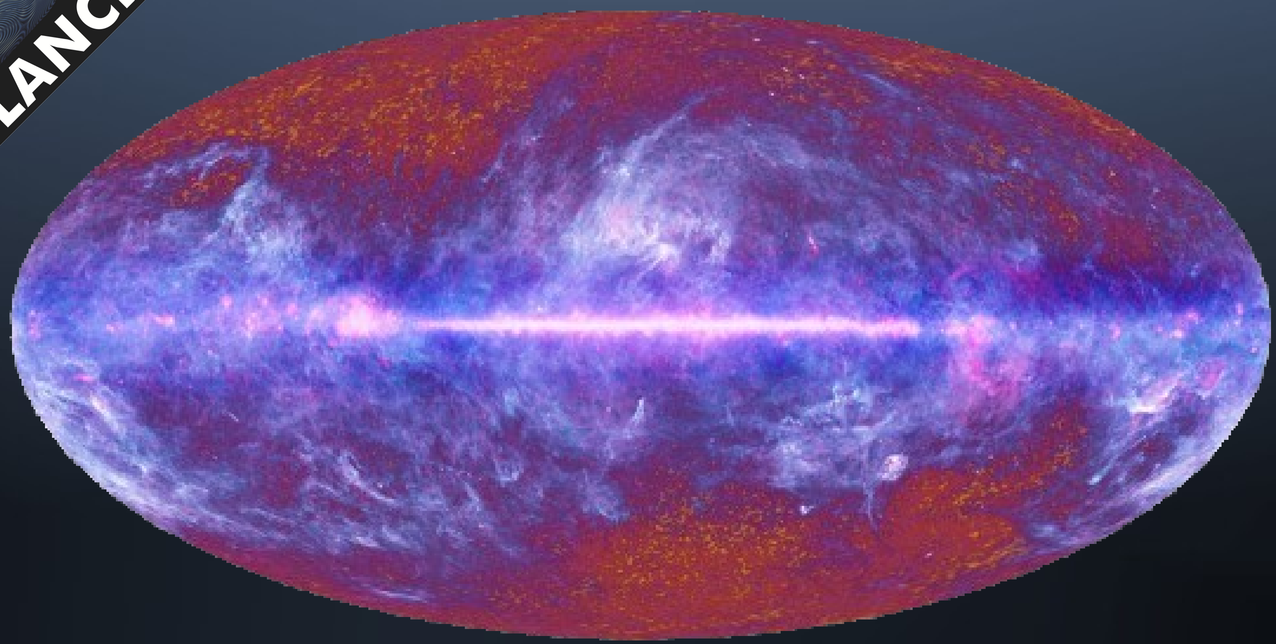
PLANCK



- Launched 9th May 2009
- In orbit around Lagrange point L_2
- Measures CMB in 9 frequency channels 30-857 GHz
- ~ 5 arcmin resolution
  $\longrightarrow$ limited by cosmic variance up to multipoles of ~2000
- Expected sensitivity to $N_{\rm eff}$: $\sigma_{N_{\rm eff}} \approx 0.2$

[JH, Lesgourgues, Mangano (2007)]

PLANCK



- January: PLANCK early papers (mostly concerning instrument performance and foreground physics)
- Cosmology papers: early 2013

Conclusions

- Cosmological data show slight preference for additional relativistic degrees of freedom, such as sterile neutrinos
- 3+2 sterile neutrino interpretation of LSDN/MiniBooNE/ reactor data is problematic if implemented in naïve minimal cosmological model (too many for BBN, too heavy for CMB+LSS)
- Incomplete thermalisation or an extension of the cosmological model are required for compatibility
- Exciting results from PLANCK soon!