How many neutrino species are there?

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Radiation content of the Universe

- **Microwave background**

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

- **Neutrino background**

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

standard model expectation:

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

[Mangano et al. (2005)]

- **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

- **Putting it all together:**

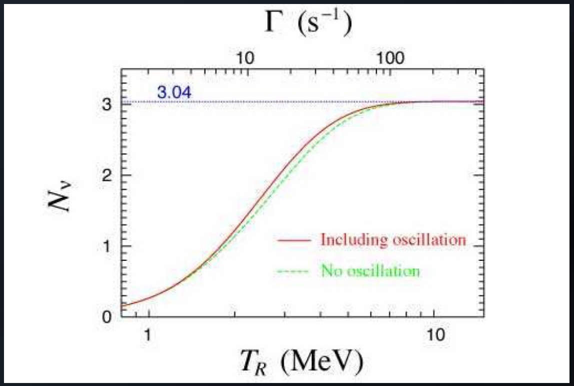
$$\begin{aligned}\rho_r &= \rho_\gamma + \rho_\nu^{\text{act}} + \rho_X \\ &= \frac{\pi^2}{15} T_\gamma^4 \left[1 + \underbrace{\left(N_{\text{eff}}^{\text{act}} + N_X\right)}_{N_{\text{eff}}} \cdot \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} T_\gamma^4 \right]\end{aligned}$$

A few remarks on N_{eff}

- is not a constant, in general
  - increase through light decay products of massive particle
  - decrease when particles go non-relativistic

- Could in principle be < 3.046,
  if neutrinos out of equilibrium;
  e.g., O(MeV) reheat temperature:

[Ichikawa, Kawasaki, Takahashi (2005)]



A few remarks on N_{eff}

- Cosmology can probe N_{eff}
  - at BBN
  - at decoupling

- Cosmology typically only feels the gravitational effects of extra light particles
  $\rightarrow$ identification requires input from laboratory experiments

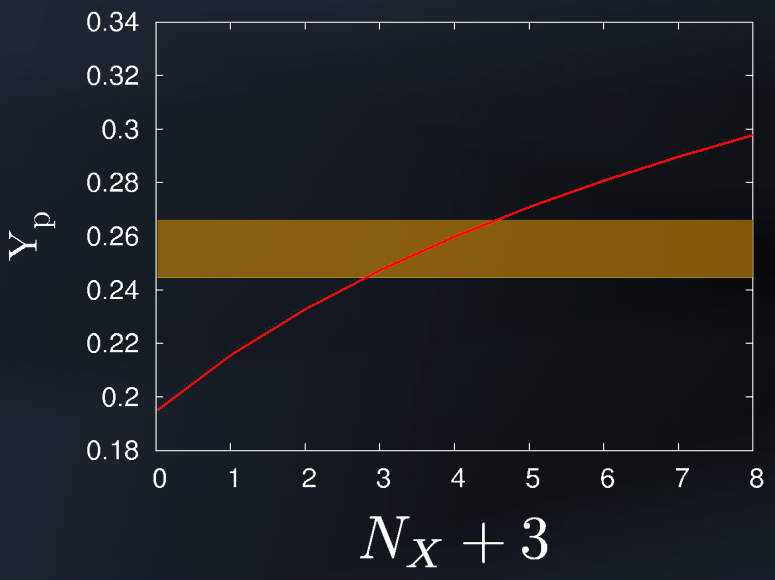
$N_{\rm eff}$ during BBN

- BBN element abundances depend on:
  - nuclear interaction rates ⟵ $f_\nu(q)$
  - expansion rate ⟵ $f_\nu(q)$ ρ_X

N_{eff} during BBN

- BBN element abundances depend on:
  - nuclear interaction rates ⟵ $f_\nu(q)$
  - expansion rate ⟵ $f_\nu(q)$ ρ_X
- Most sensitive probe: ^{4}He abundance Y_p
- Y_p measured in metal-poor H-II regions

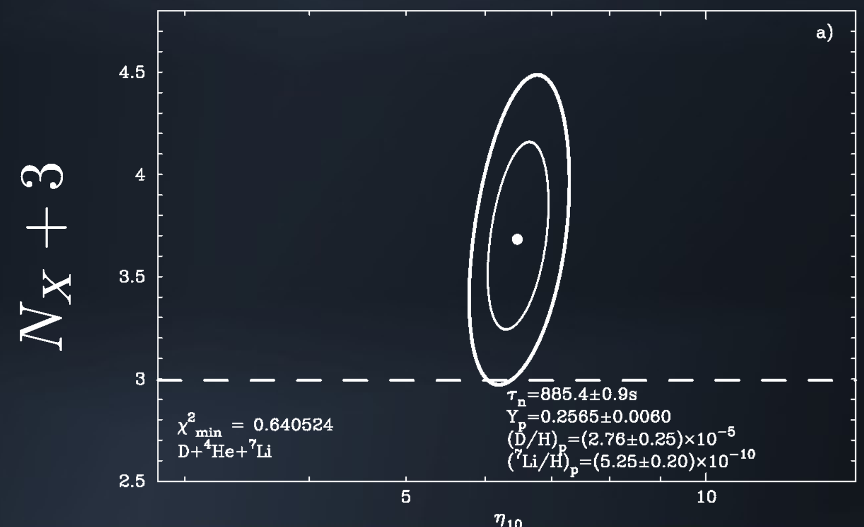
⟶ subject to systematics



N_{eff} from measurements of Y_p

- Recent measurements:
  - Y_p = 0.2561 ± 0.0108 [Aver, Olive, Skillman (2010)]
  - Y_p = 0.2565 ± 0.001 (stat) ± 0.005 (syst) [Izotov, Thuan (2010)]

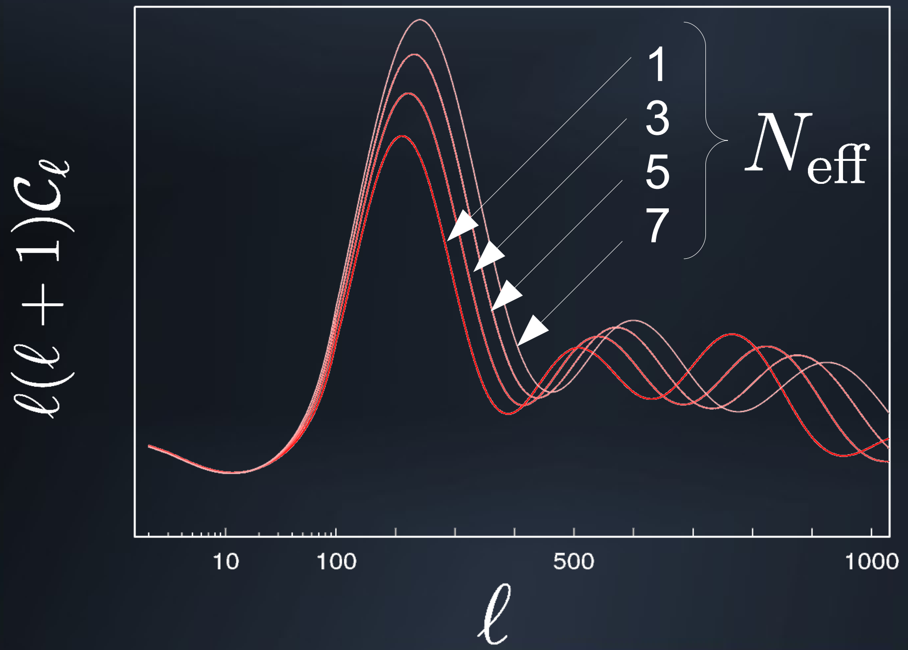
$$\longrightarrow \quad N_X + 3 = 3.68^{+0.80}_{-0.70} \quad \left[N_X + 3 = 3.65^{+1.97}_{-1.57} \right] \quad (2\sigma)$$



$N_{\rm eff}$ from CMB data

- 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 $N_{\rm eff}$

$\downarrow$

later equality

$\downarrow$

enhanced early ISW effect,

shifted sound horizon

N_{eff} from CMB data

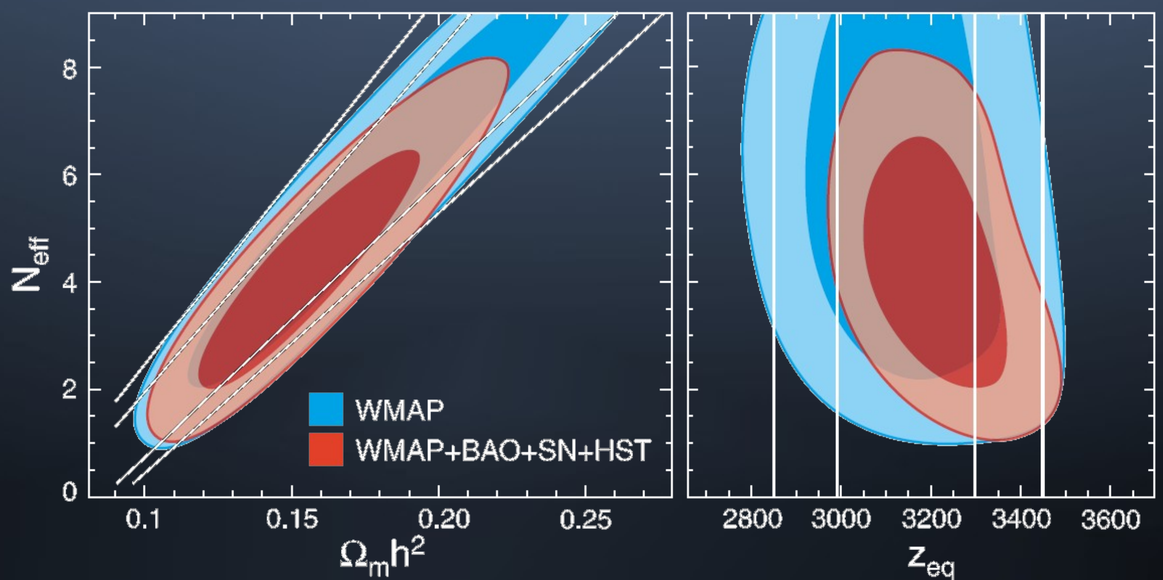
- Matter-radiation equality

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

$\longrightarrow$ serious degeneracy with matter density!

- Can mitigate/break this degeneracy:
  - Anisotropic stress
    $\rightarrow$ damping of acoustic oscillations
  - Increased Silk damping
    $\rightarrow$ higher expansion rate at decoupling [Hou et al. (2011)]
  - Combine with other probes of matter density

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

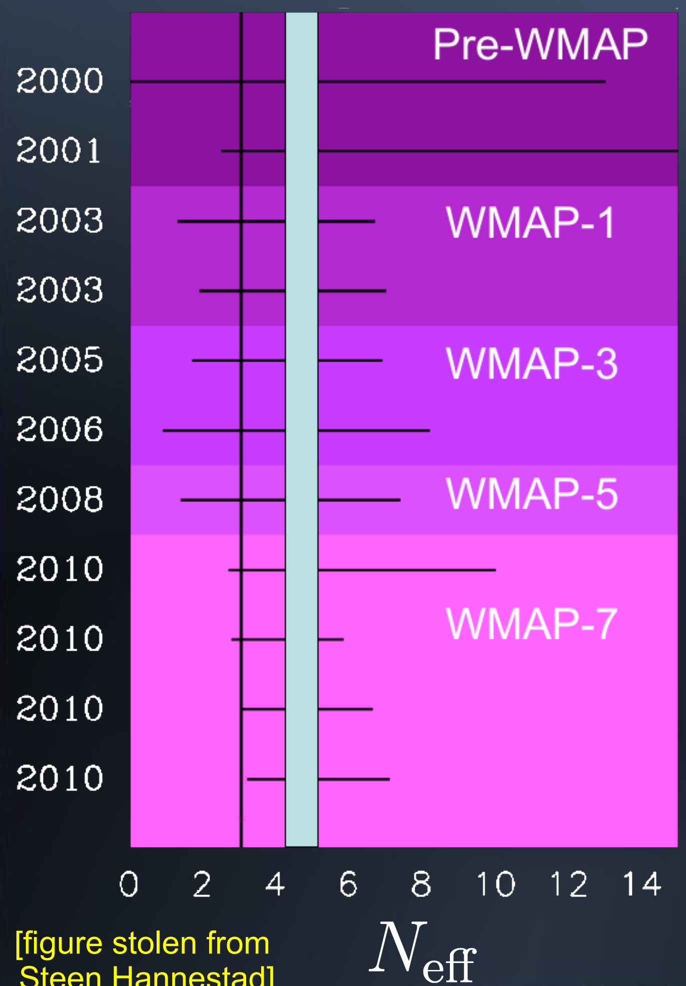


- lower limit from CMB alone (⟶ anisotropic stress)
- upper limit by combining with other data sets sensitive to matter density

[Komatsu et al. (2008)]

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

95%-credible intervals



[figure stolen from Steen Hannestad]

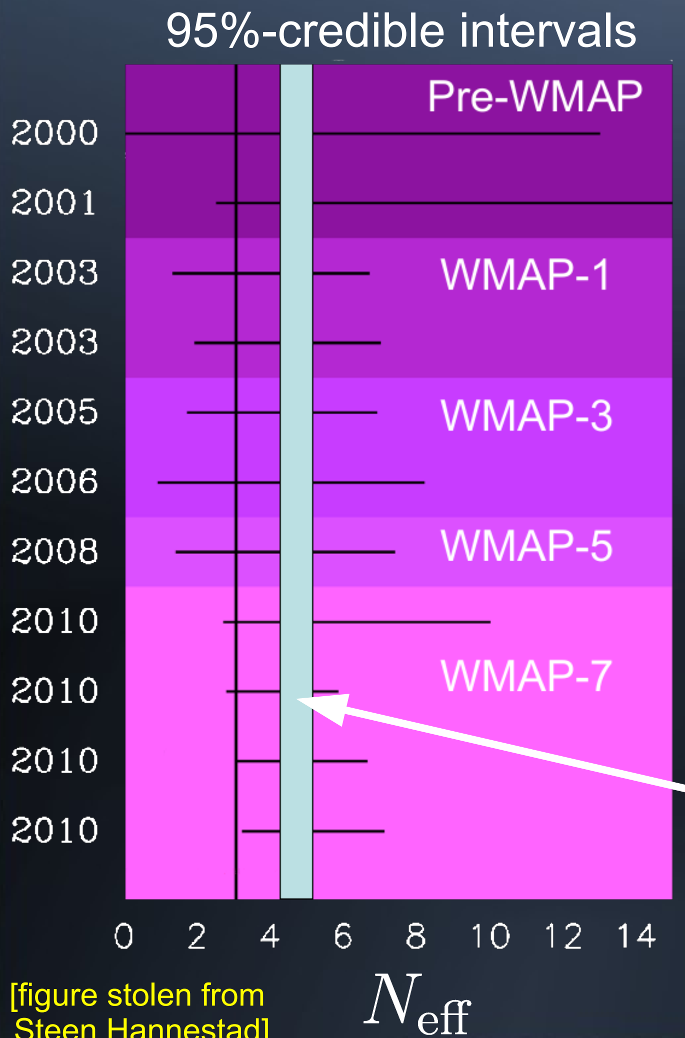
- Precise numbers depend on cosmological model and data sets used
- Recent analysis: $N_{\rm eff} = 4.47^{+1.82}_{-1.74}$

CMB + SDSS-DR7-BAO + HST

ΛCDM + neutrino mass + $N_{\rm eff}$

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

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



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  CMB + SDSS-DR7-BAO + HST

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

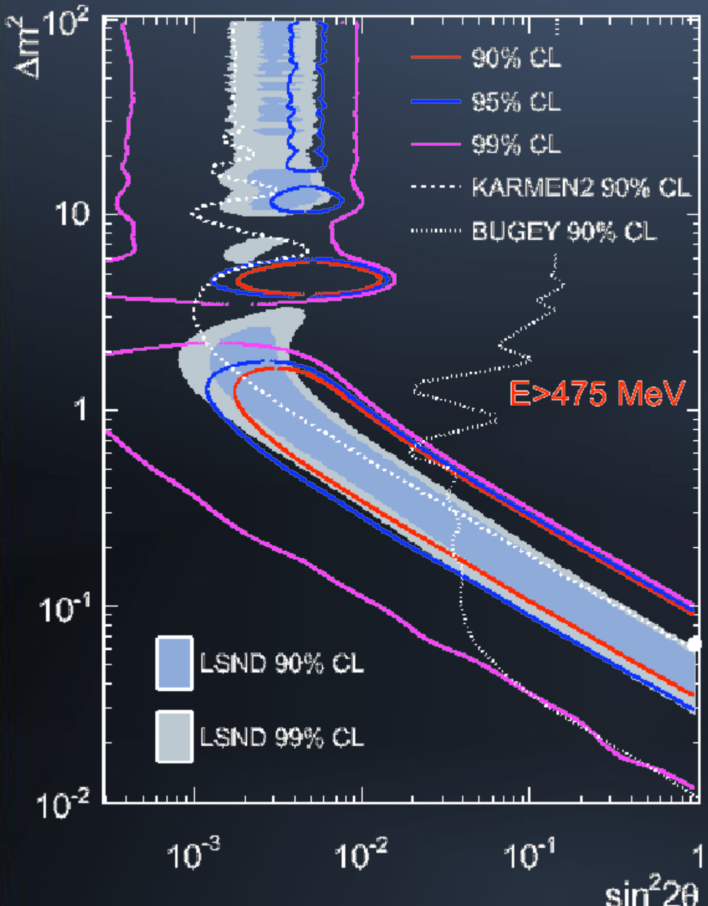
Planck will probe CMB damping tail

$\rightarrow$ expected sensitivity

$\sigma_{N_{\rm eff}} \approx 0.2$

[JH, Lesgourgues, Mangano (2007)]

Sterile neutrinos?



[van de Water, talk @ Neutrino 2010]

- LSND & MiniBooNE observe the appearance of fewer anti-electron neutrinos than expected
- These anomalies may be resolved with CP-violating sterile neutrino oscillations in a "3+2" model

[Karagiorgi, talk @ Neutrino 2010]

Sterile neutrinos?

- Recent re-evaluation of reactor neutrino fluxes

  [Mention et al. (2011)]

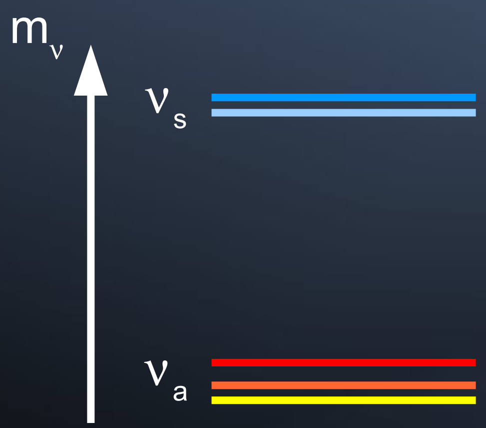
  $\rightarrow$ reactor disappearance experiments also support this scenario:

	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

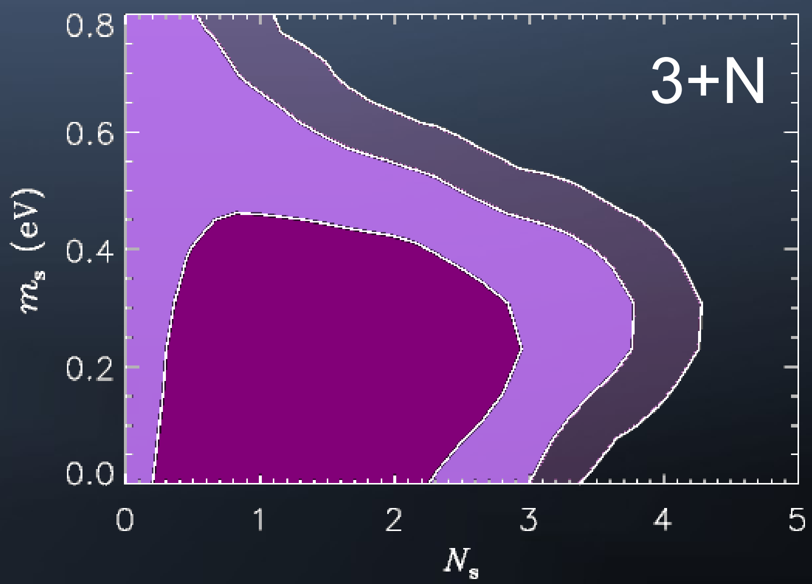
Table I: Best fit points for the 3+1 and 3+2 scenarios from reactor anti-neutrino data. The total number of data points is 69 (Bugey3 spectra plus 9 SBL rate measurements; we have omitted data from Chooz and Palo Verde, which are not very sensitive to the model parameters, but would dilute the χ^2 by introducing 15 additional data points). For no oscillations we have $\chi^2/\mathrm{dof} = 59.0/69$.

[Kopp, Maltoni, Schwetz (2011)]

Sterile neutrino scenario



"3+N"



Mass hierarchy:
3 massless + N massive neutrino species

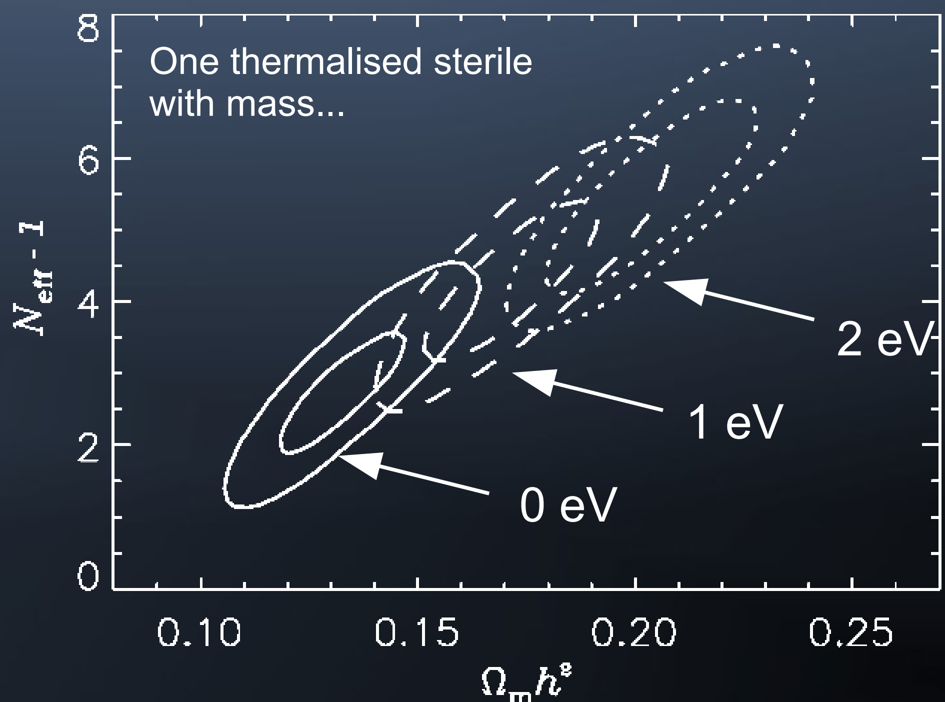
Sterile neutrinos with O(eV) masses are somewhat problematic in standard cosmology...

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

Cosmology with eV-sterile neutrinos

- Allow additional massless species
  → much higher matter density

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



- Allow dynamical dark energy
  → for 2 massive steriles: strong preference for w < -1

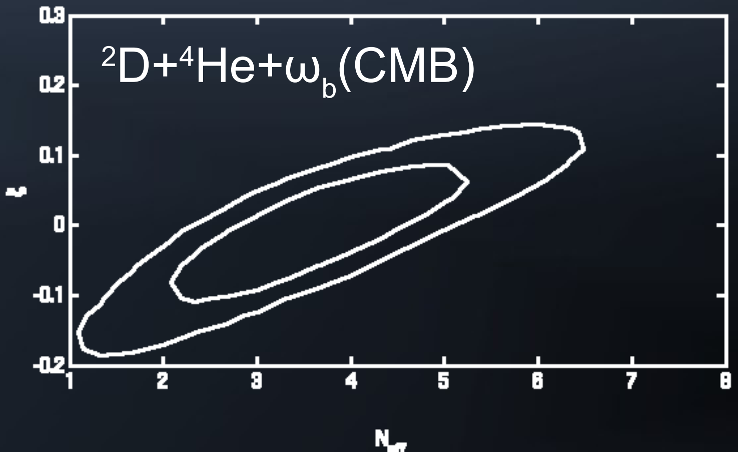
[Kristiansen & Elgarøy (2011)]

BBN with extra neutrinos

- Too many neutrino species in tension with BBN

$$N_X + 3 = 3.68^{+0.80}_{-0.70}$$

- Can be remedied by
  - a lepton asymmetry with a neutrino chemical potential ξ



  - or a decay of heavy particles into sterile neutrinos between BBN and decoupling

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

Conclusions

- Cosmological data show slight preference for non-standard radiation component
- Sterile neutrinos are possible candidate
- Neutrino experiments hint at O(eV) sterile neutrinos
- If they exist, may require additional modifications to our cosmological picture
- Planck will settle the issue!