Cosmological constraints on the number of neutrino species

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Radiation content of the Universe

- **Microwave background**

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

- **Neutrino background**

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

standard model expectation:

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

[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

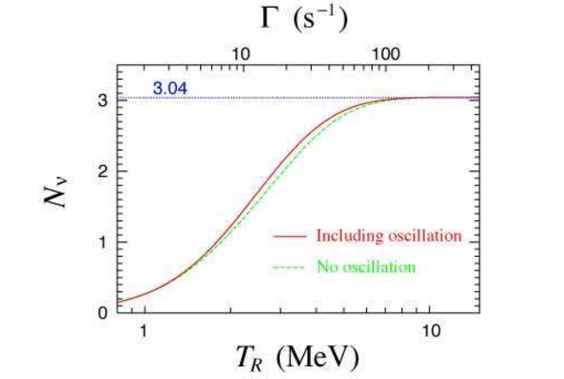
- **Putting it all together:**

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

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
- can be < 3.046, if neutrinos out of equilibrium; e.g., low reheating temperature:

  [Ichikawa, Kawasaki, Takahashi (2005)]



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

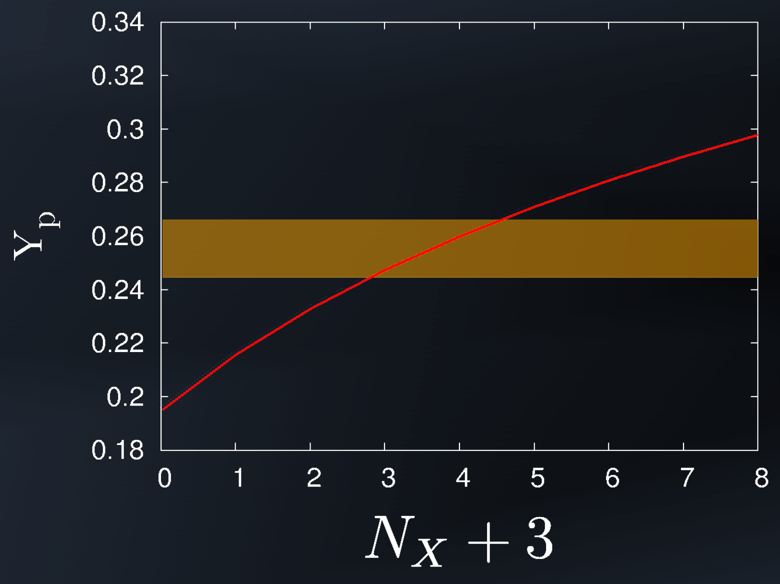
N_{eff} during BBN

- 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

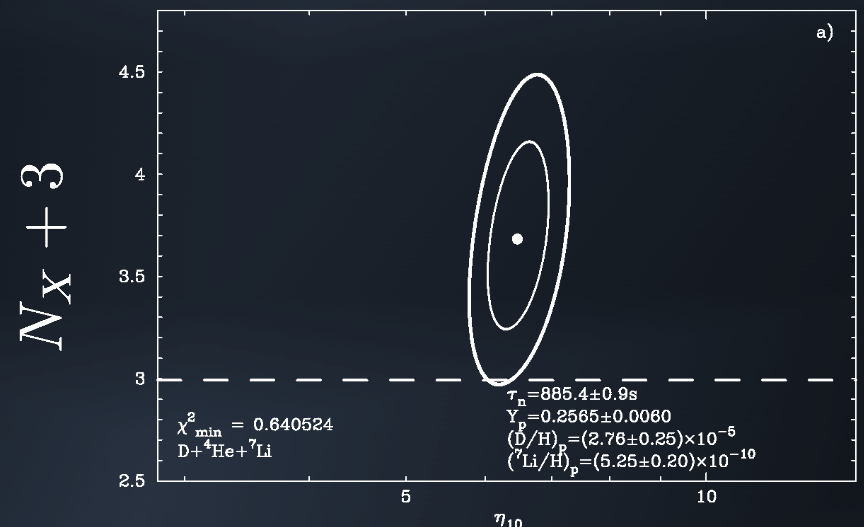
⟶ subject to systematics



$N_{\rm eff}$ 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)]

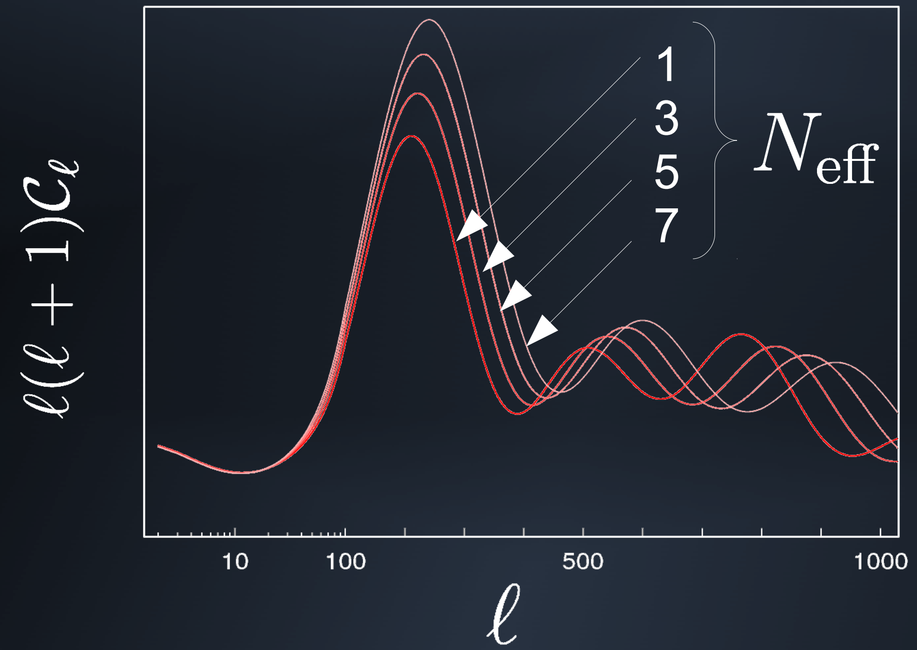
→ $N_X + 3 = 3.68^{+0.80}_{-0.70}$ $\left[N_X + 3 = 3.65^{+1.97}_{-1.57} \right]$ (2σ)



N_{eff} from CMB data

- Matter-radiation equality

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



larger N_{eff}

↓

later equality

↓

enhanced early ISW effect,

shifted sound horizon

$N_{\rm eff}$ from CMB data

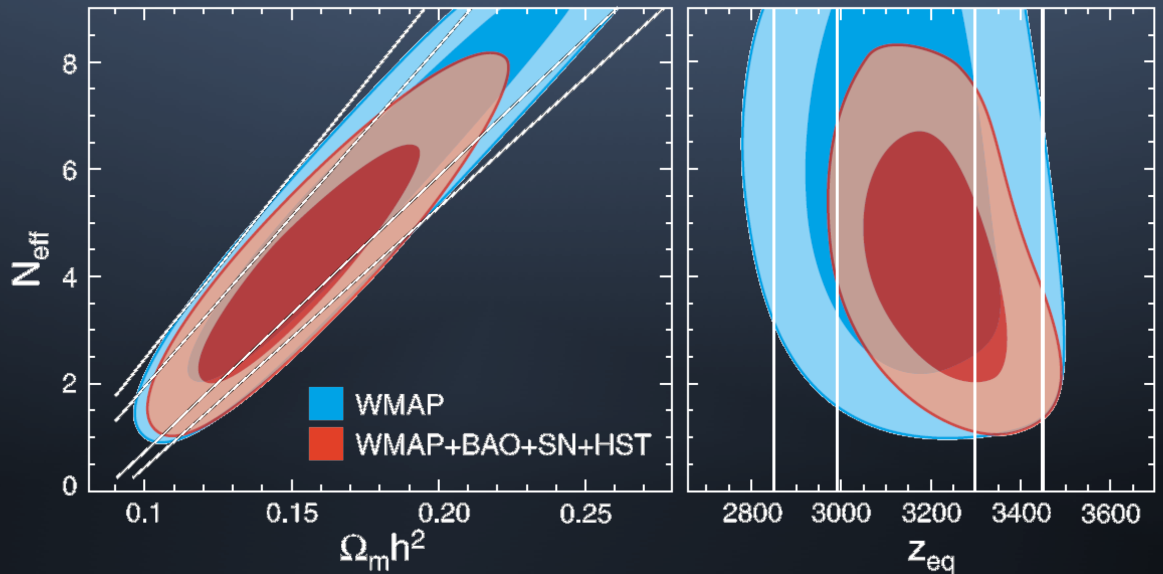
- Matter-radiation equality

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

$\longrightarrow$ serious degeneracy with matter density!

- Anisotropic stress
  - present for neutrinos or other non-interacting particles, but not for photons
  - can help break degeneracy with matter density

N_{eff} from CMB+LSS+...

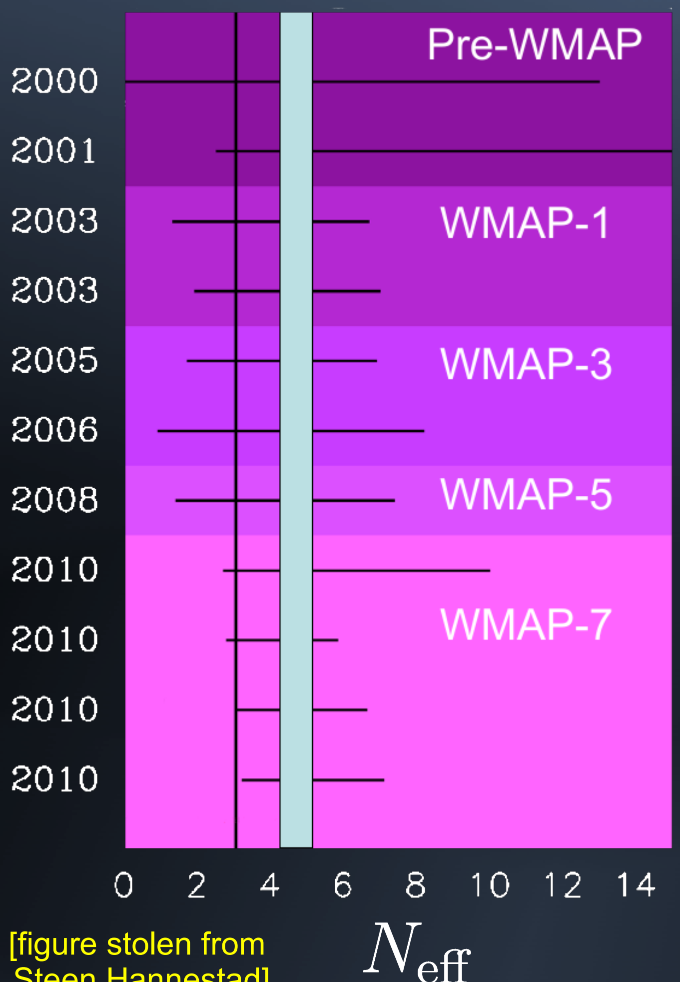


- lower limit from CMB alone (⟶ anisotropic stress)
- upper limit by combining with other data sets sensitive to matter density

[Komatsu et al. (2008)]

CMB+X bounds on N_{eff}

95%-credible intervals



[figure stolen from Steen Hannestad]

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

CMB + SDSS-DR7-BAO + HST

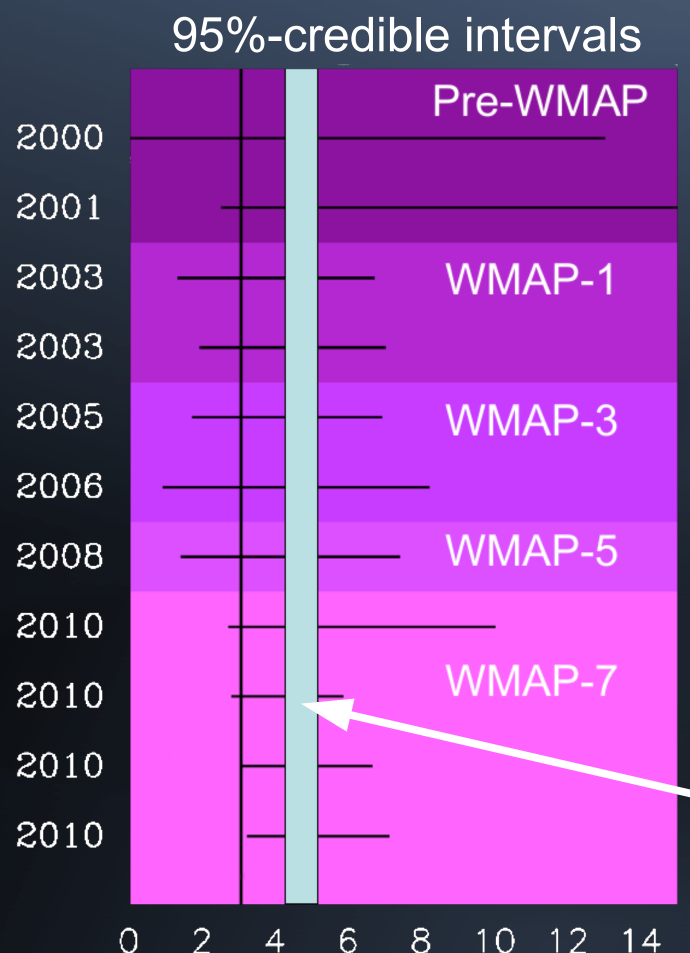
ΛCDM + neutrino mass + N_{eff}

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

today: arXiv:1009.0866
including ACT small scale CMB data

$N_{\mathrm{eff}} = 4.56 \pm 1.5$ (95%)

CMB+X bounds on N_{eff}



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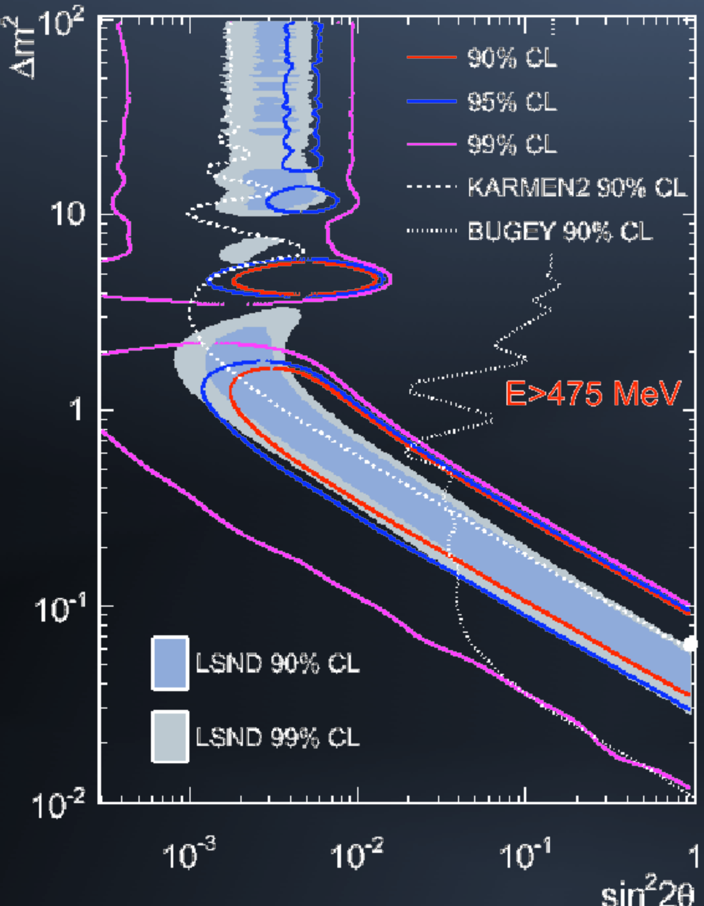
  [JH, Hannestad, Lesgourgues, Rampf, Wong (2010)]

PLANCK expected sensitivity

$\sigma_{N_{eff}} \approx 0.15$

[JH, Lesgourgues, Mangano (2007)]

Other hints: sterile neutrinos?



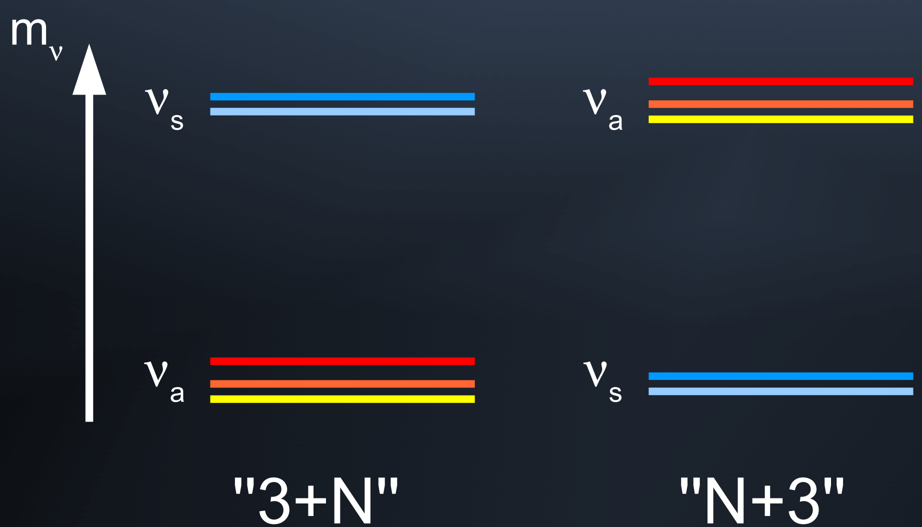
[van de Water, talk @ Neutrino 2010]

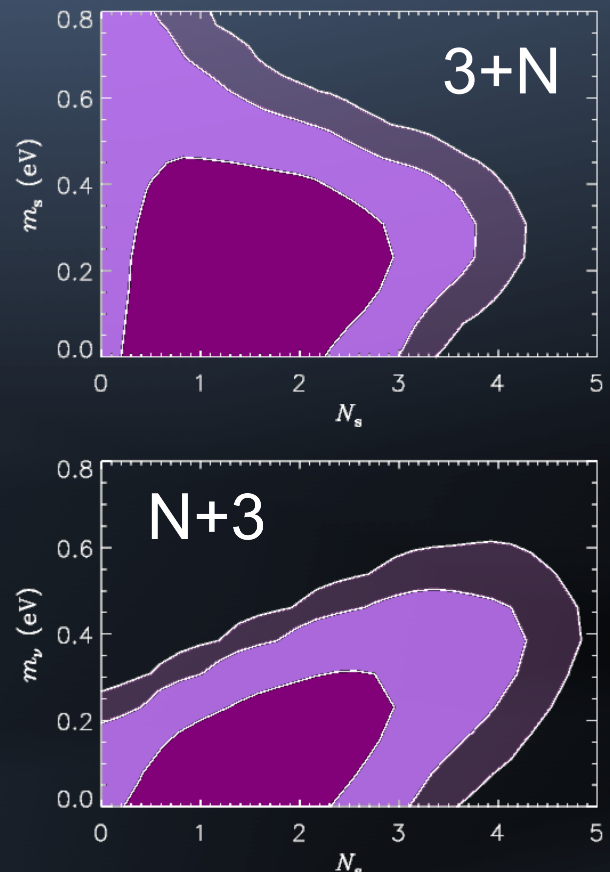
- LSND & MiniBooNE anomalies may be resolved with CP-violating sterile neutrino oscillations in a "3+2" model (however: disfavoured by disappearance experiments)

[Karagiorgi, talk @ Neutrino 2010]

Sterile neutrino scenario

- Two qualitatively different mass hierarchies:

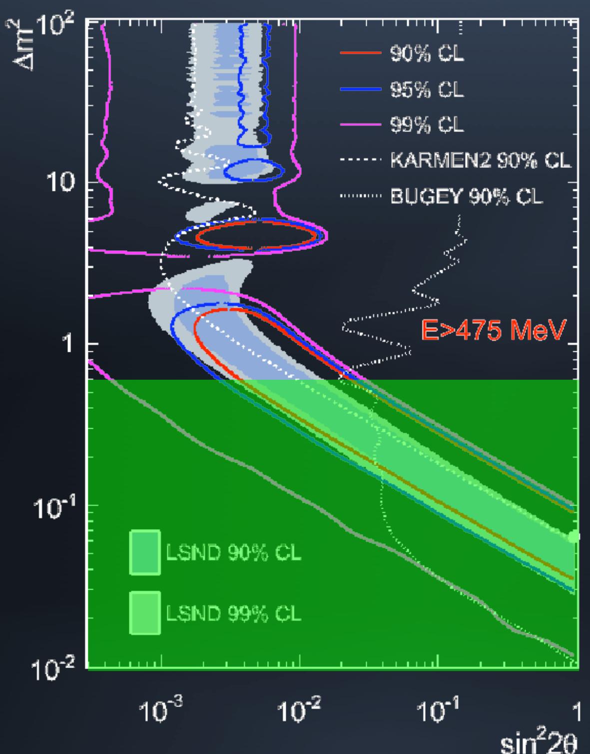


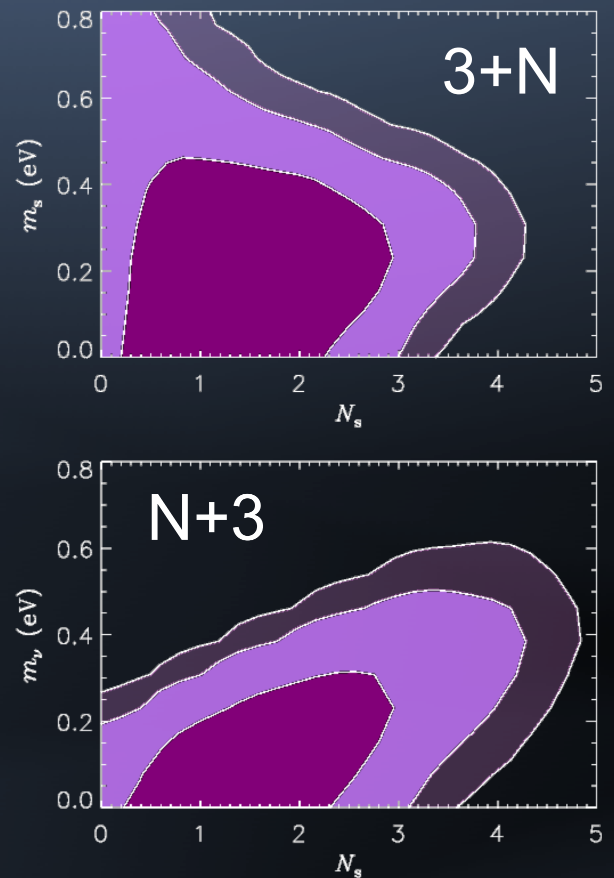


[JH, Hannestad, Raffelt, Tamborra, Wong (2010)]

Sterile neutrino scenario

- 3+2: $m_s < 0.45$ eV (@ 95% c.l.)





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

Conclusions

- Cosmological observations are a powerful probe of the Universe's radiation content
- Compelling indirect evidence for the existence of a cosmic neutrino background, from both BBN and CMB+LSS data
- Two sterile neutrino species still compatible with cosmological data
- Planck will settle the issue!