How many neutrino species are there?

Cosmological constraints on the radiation content of the Universe

Jan Hamann

based on work done in collaboration with:
S. Hannestad, J. Lesgourgues, G. Mangano, G. Raffelt,
C. Rampf, I. Tamborra and Y. Wong

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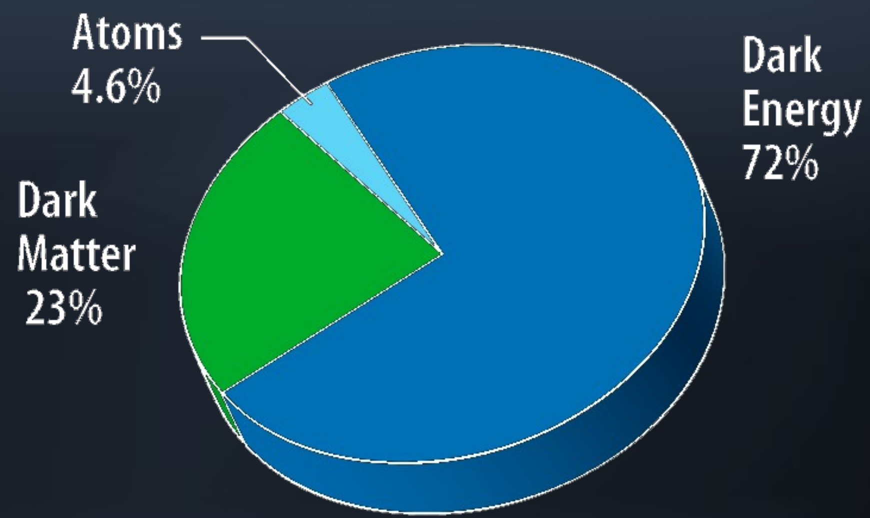
Stiftung/Foundation

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's propaganda pie



today (z = 0)

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's propaganda pie

Neutrinos 0.1 - 2%

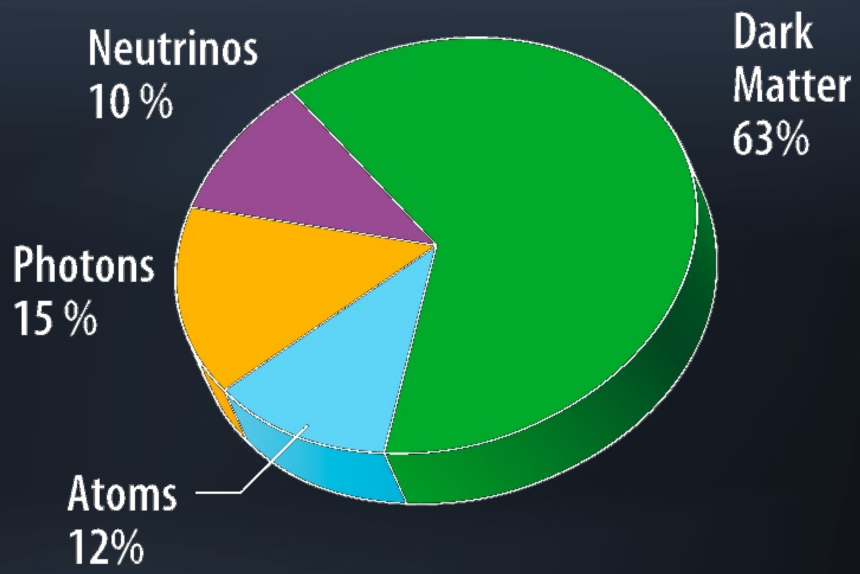
Photons 0.006%

today (z = 0)

What is the Universe made of?

Assuming the ΛCDM-model:

NASA's propaganda pie (2)



at decoupling (z = 1100)

Radiation content of the Universe

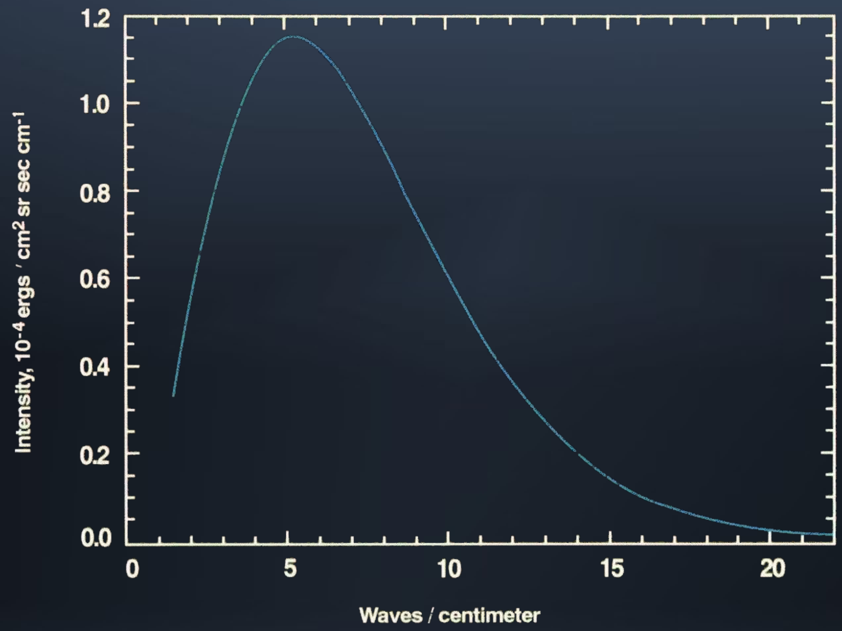
- Photons: CMB
- Neutrinos: CνB
- Other light particle species?

How can we find them?

- Directly: via (beyond) Standard Model interactions
- 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

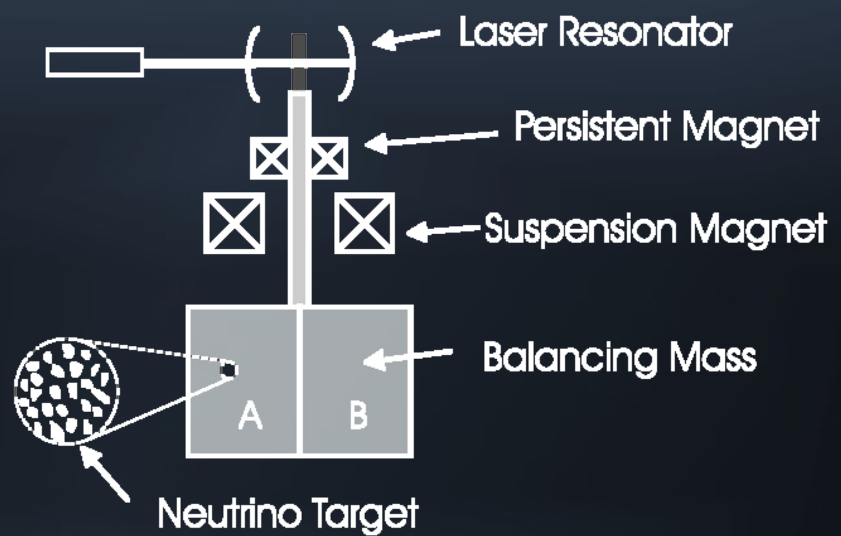
$$\longrightarrow \quad T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.95 \text{ K}$$

- extremely weakly interacting
- no direct detection to date

CνB direct detection: ideas (i)

Torsion balance: [Shvartsman (1982)]

Search for annual modulation

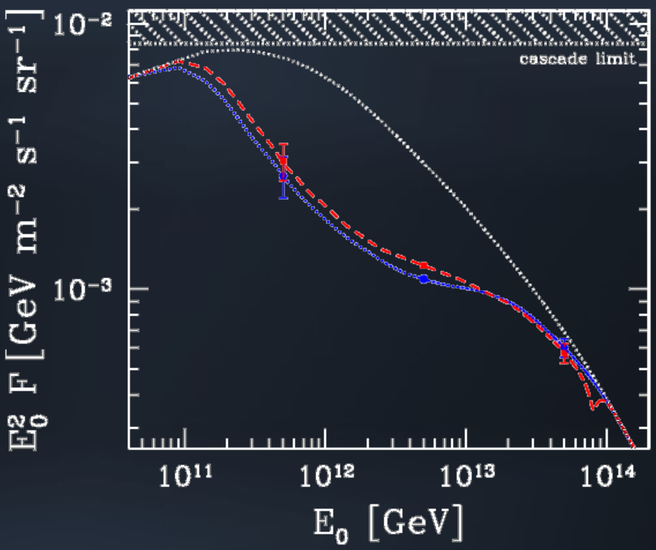


Current technology several orders of magnitude below required sensitivity

CνB direct detection: ideas (ii)

Absorption dips [Weiler (1984)]

- Search for absorption features due to resonant Z-production in spectra of ultra-high-energy neutrino sources

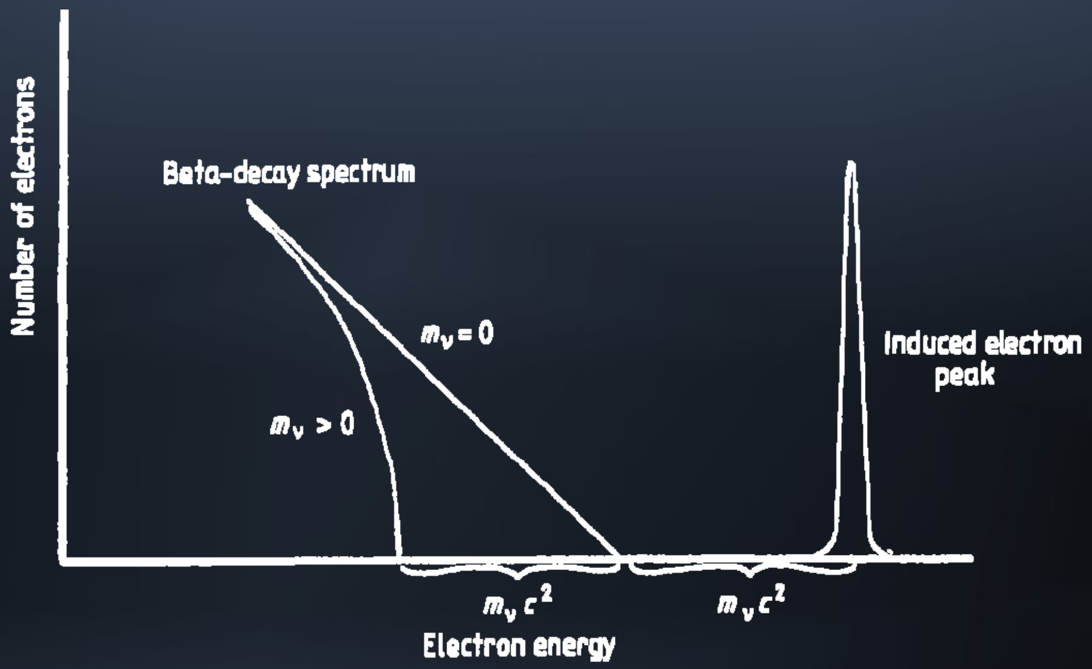


[Ringwald (2008)]

No sources of sufficiently high energy neutrinos

CνB direct detection (iii)

CνB-induced β-decay: [Weinberg (1962)]



KATRIN sensitivity is factor ~10^9 too low

[Kaboth, Formaggio, Monreal (2010)]

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

flavour oscillations ensure that
different mass/flavour eigenstates typically
share a common momentum distribution

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

Cosmic Neutrino Background

Neutrino energy density:

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

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

⟶ 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?

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

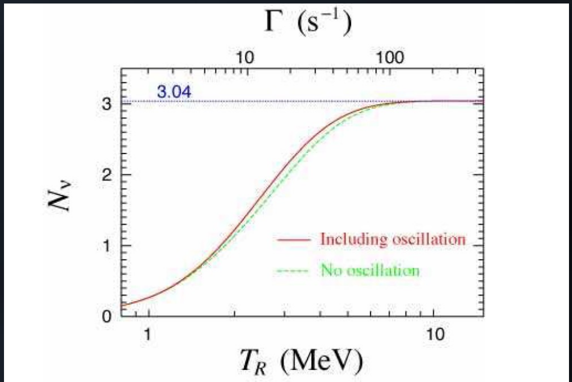
Putting it all together:

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

A few remarks on N_{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_{eff} ≤ 1 today)

- N_{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 rate ⟷ 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

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

$H \propto \sqrt{\rho_{\rm r}}$ ← $N_{\rm eff}$

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

BBN

Boltzmann equation

nuclear interaction rate ⟷ expansion rate

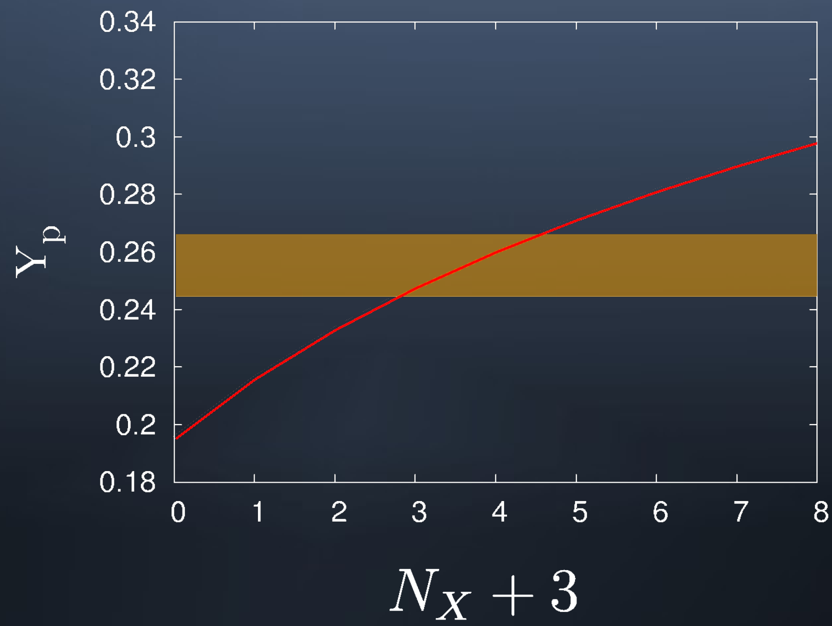
$\Gamma(\omega_{\rm b}, f_{\nu_{\rm e}})$ $H \propto \sqrt{\rho_{\rm r}}$ ← $N_{\rm eff}$

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

Helium abundance Y_p most sensitive to expansion rate

Other elements more sensitive to interaction rates

N_{eff} during BBN



Most serious uncertainty in theoretical prediction

Conflicting measurements of the free neutron lifetime:

- PDG average (2010): t = 885.7 ± 0.8 s
- Serebrov et al. (2005): t = 878.5 ± 0.9 s

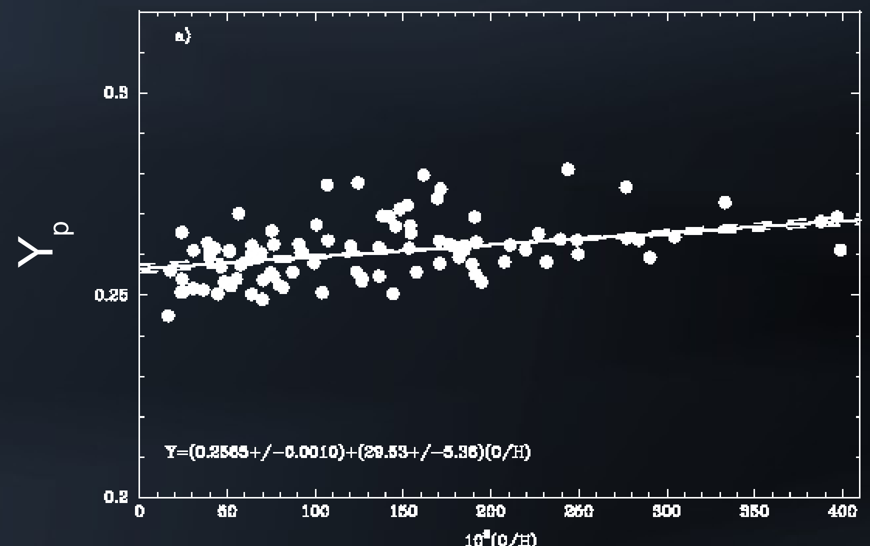
Measuring Y_p

Observe Hydrogen and Helium emission lines in H-II regions of metal-poor dwarf galaxies

Extrapolate to zero metallicity

Systematics

- Interstellar reddening
- Absorption lines in stellar continuum
- Radiative transfer
- Collisional corrections



[Izotov, Thuan (2010)]

N_{eff} from measurements of Y_p

Recent measurements:

Y_p = 0.2565 ± 0.001 (stat) ± 0.005 (syst) [Izotov, Thuan (2010)]

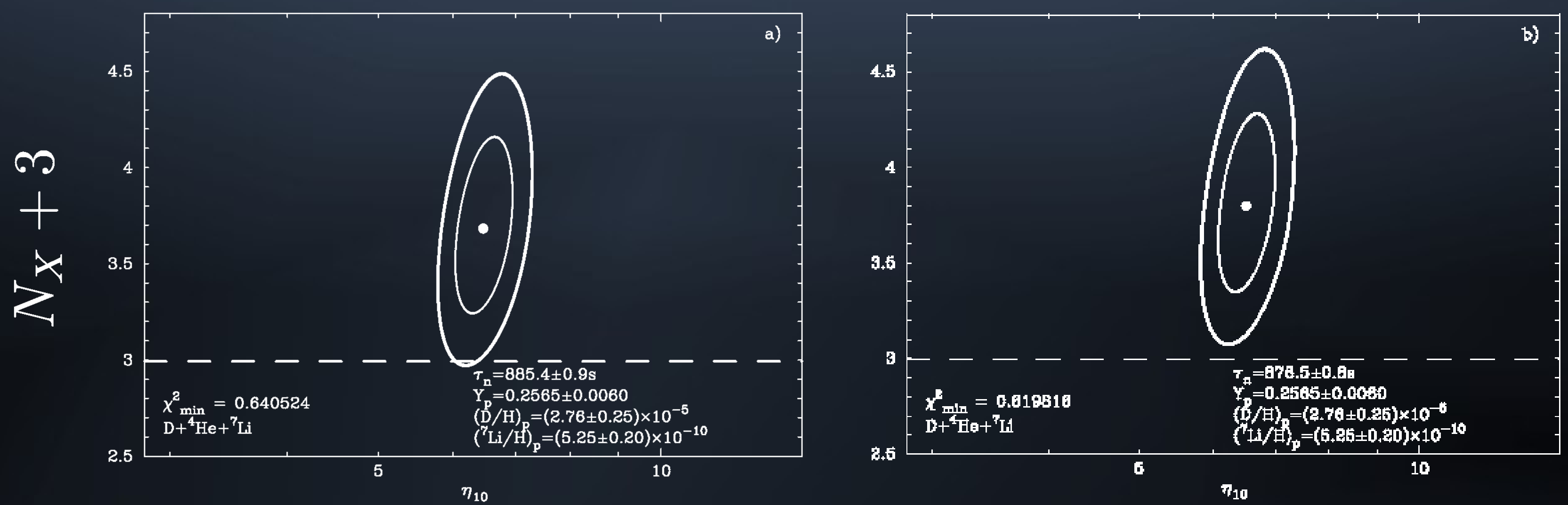
Y_p = 0.2561 ± 0.0108 [Aver, Olive, Skillman (2010)]

Combined with measurement of Deuterium abundance, and baryon-to-photon ratio from CMB:

$$N_X + 3 = 3.68^{+0.80}_{-0.70} \quad \left[N_X + 3 = 3.65^{+1.97}_{-1.57} \right] \quad \text{(95\% c.l.)}$$

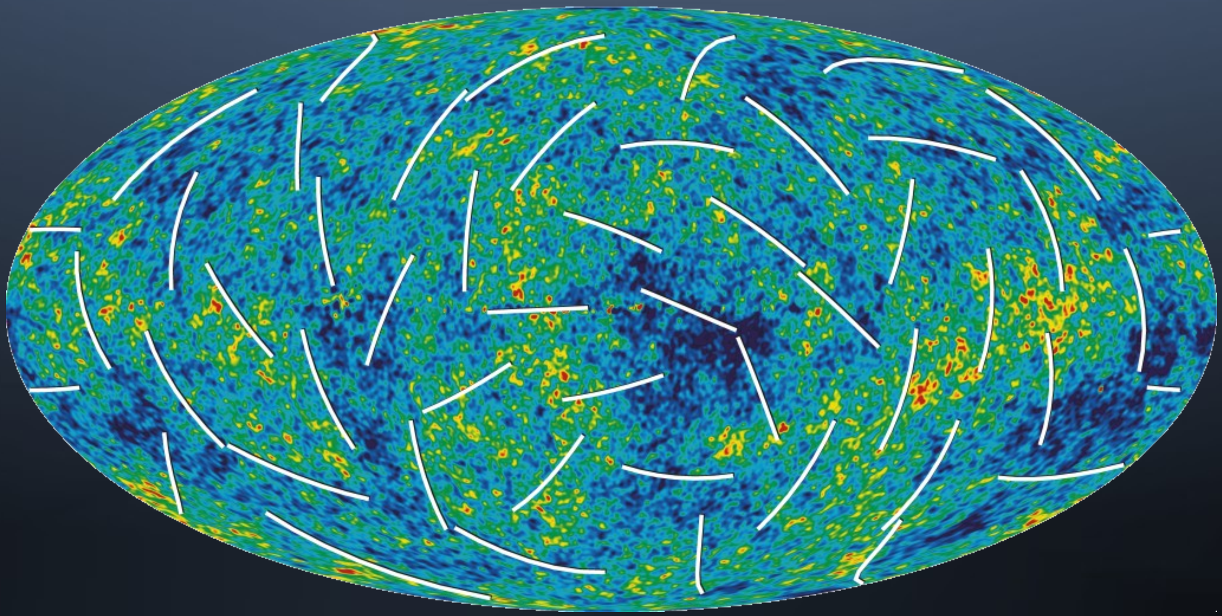
N_{eff} from measurements of Y_p

Effect of neutron lifetime:



[Izotov, Thuan (2010)]

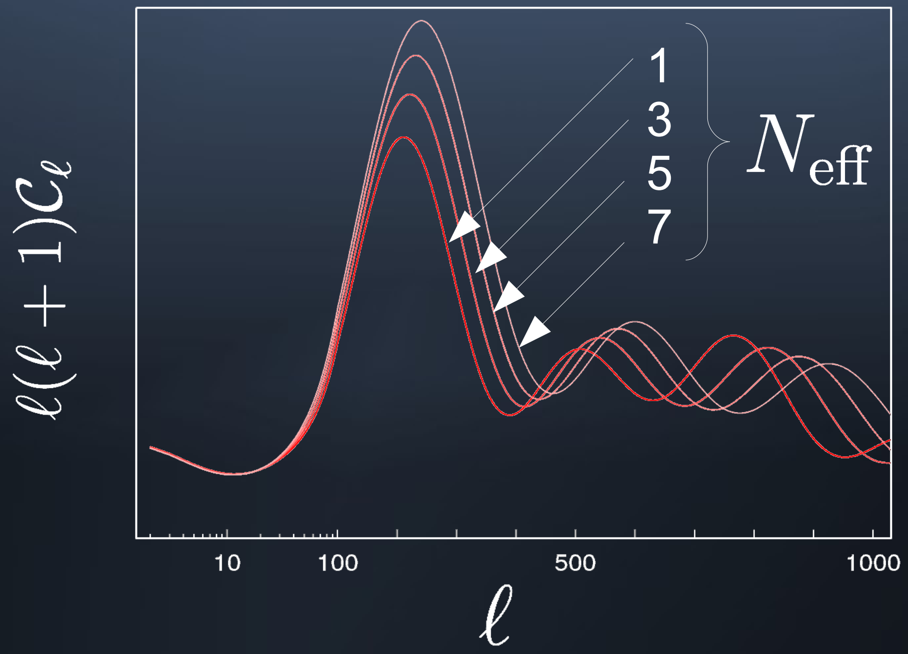
N_{eff} and the CMB



Presence of extra radiation affects

- Background (growth of the scale factor)
- Evolution of perturbations

$N_{\rm eff}$ and the CMB



- Looks like a clear-cut signature
- However: parameter degeneracies!

Impact on background

Matter-radiation equality

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

- only sensitive to particles being relativistic
- effect is virtually equivalent to changing matter density
- affects perturbations indirectly:

larger $N_{\rm eff}$ ⟶ later equality

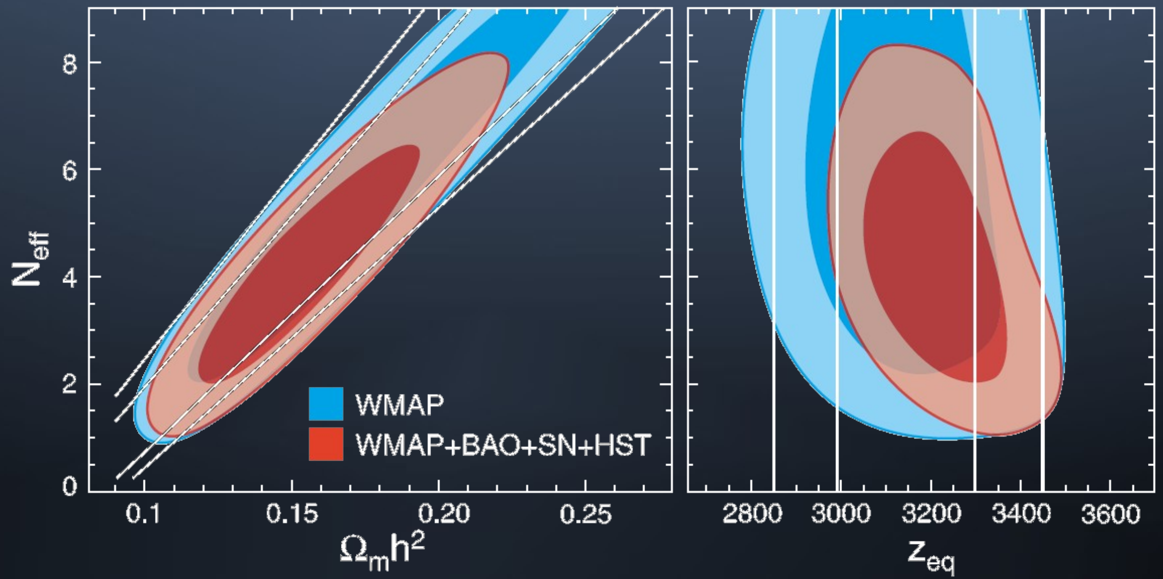
⟶ enhanced early integrated Sachs-Wolfe effect

⟶ shifted sound horizon

Impact on perturbation eqns

- Free-streaming particle fluids contribute to anisotropic stress (traceless spatial part of stress-energy tensor)
- Photons are stress-free before decoupling, neutrinos (or other decoupled relativistic species) are not
- Leads to damping of fluctuations on small scales
- Can to a certain extent be mimicked by other parameters (e.g., spectral index)

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

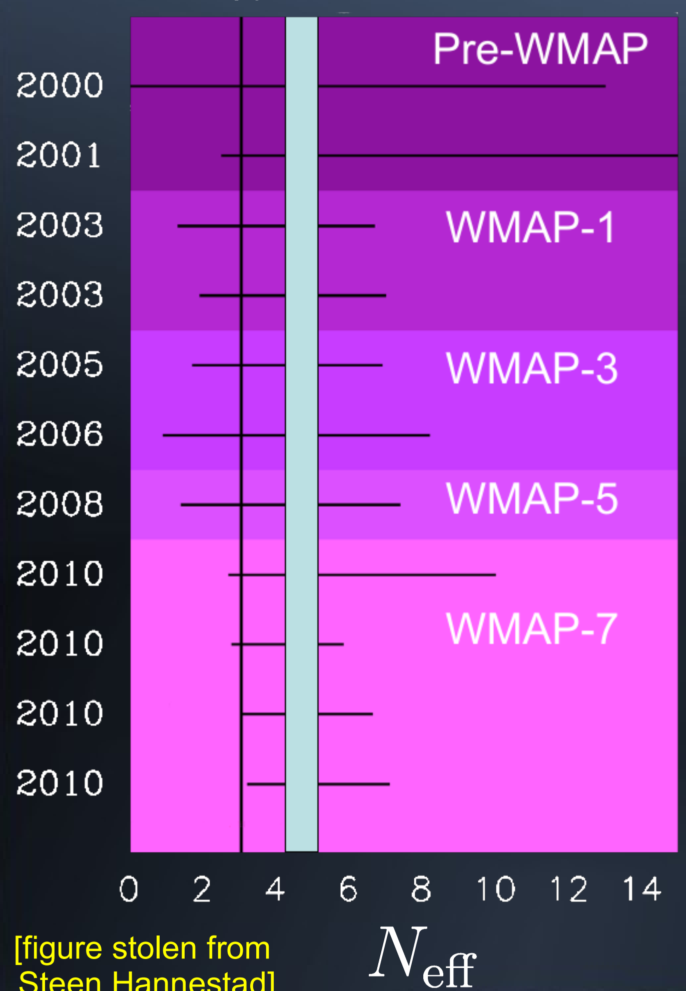


- lower limit from CMB alone (→ anisotropic stress)
- meaningful upper limit requires combination with other data sets sensitive to matter density

[WMAP: Komatsu et al. (2008)]

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

95%-credible intervals



[figure stolen from Steen Hannestad]

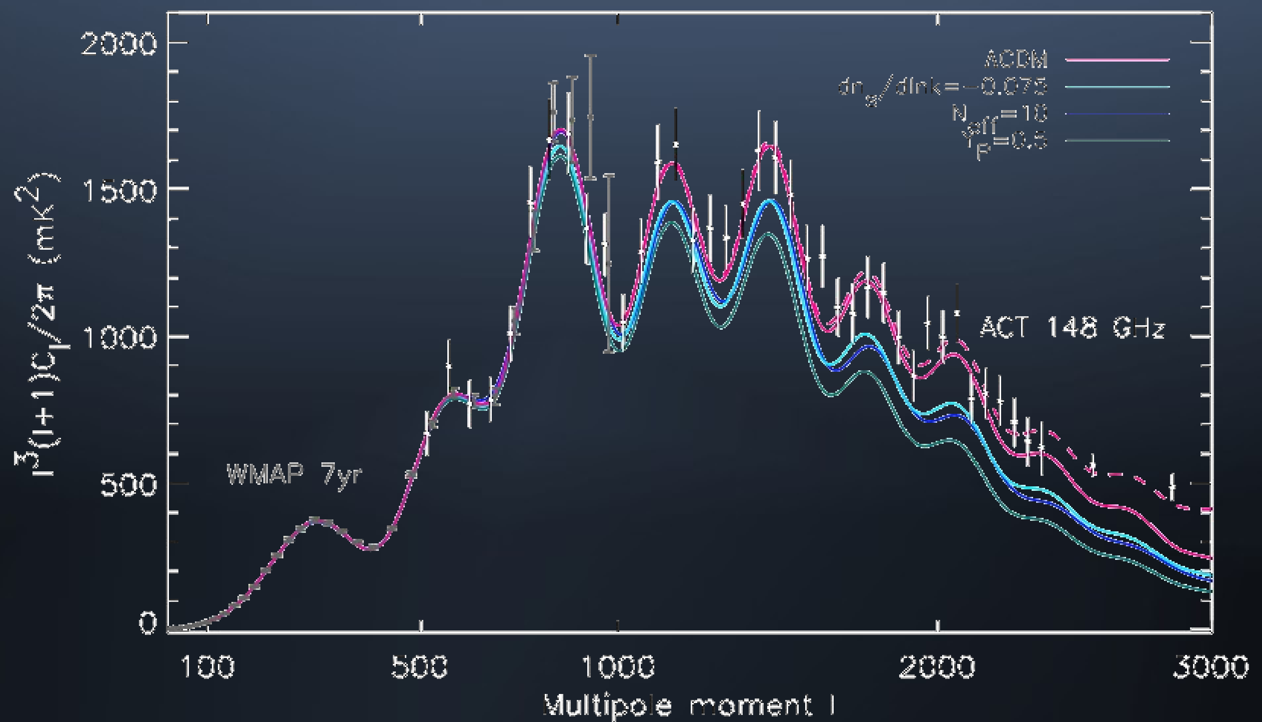
- Precise numbers depend on cosmological model and data sets used
- Recent analysis: $N_{\rm eff} = 4.47^{+1.82}_{-1.74}$

CMB + SDSS-DR7-BAO + HST

ΛCDM + neutrino mass + $N_{\rm eff}$

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

CMB bounds on N_{eff}



[ACT: Dunkley et al. (2010)]

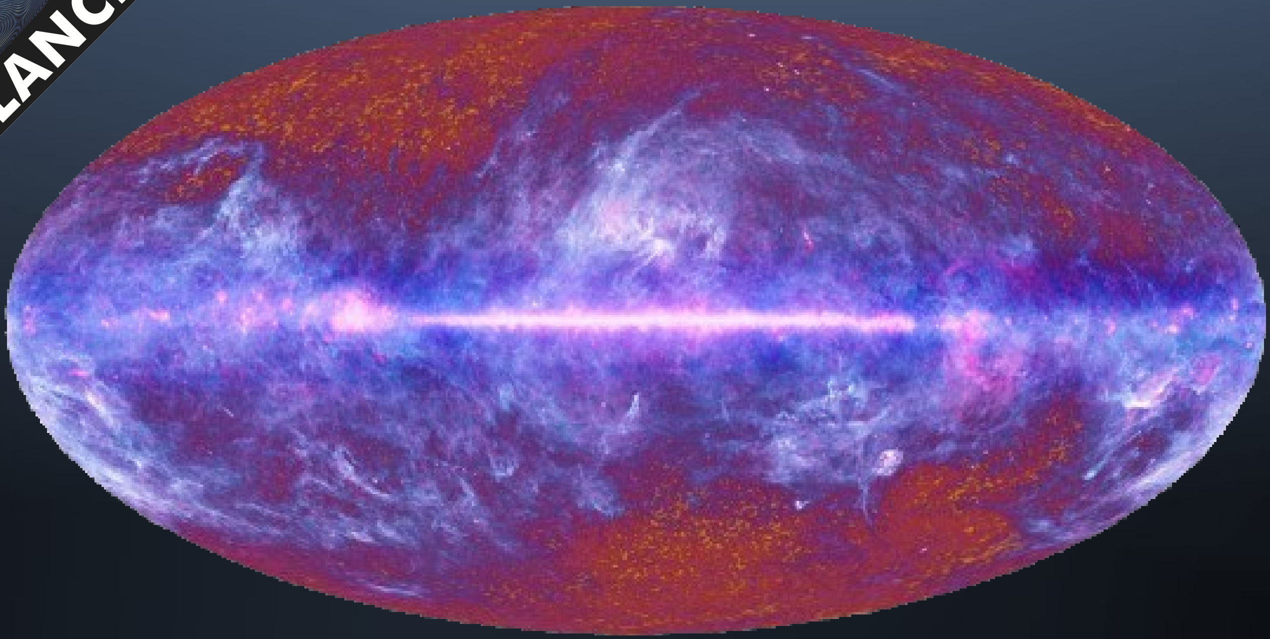
- Disentangling N_{eff} from other effects requires good resolution of 4$^{\text{th}}$ and 5$^{\text{th}}$ acoustic peaks

PLANCK

- Launched 9th May 2009
- In orbit around Lagrange point L_2
- Measures CMB in 9 frequency channels 30-857 GHz
- ~ 5 arcmin resolution
  → 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

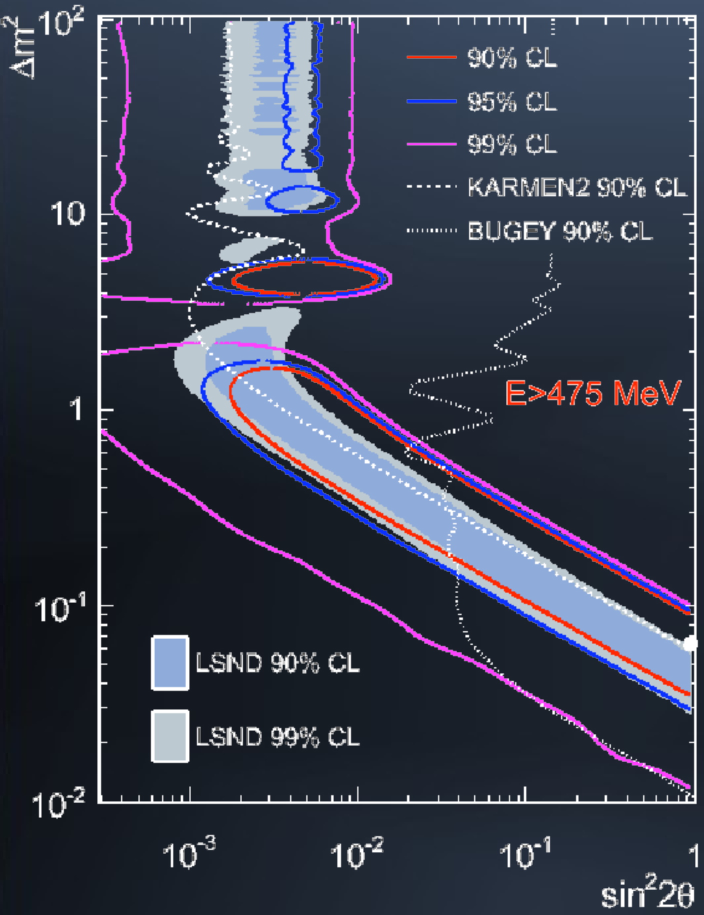


- Last week: PLANCK early papers (mostly concerning instrument performance and foreground physics)
- Cosmology papers: late 2012

What if we took these signals seriously?

- BBN: extra radiation
- CMB+LSS: extra radiation with anisotropic stress
- However, these data will not allow us to further identify the source of this effect
- Need additional input from laboratory experiments

Other hints: sterile neutrinos?



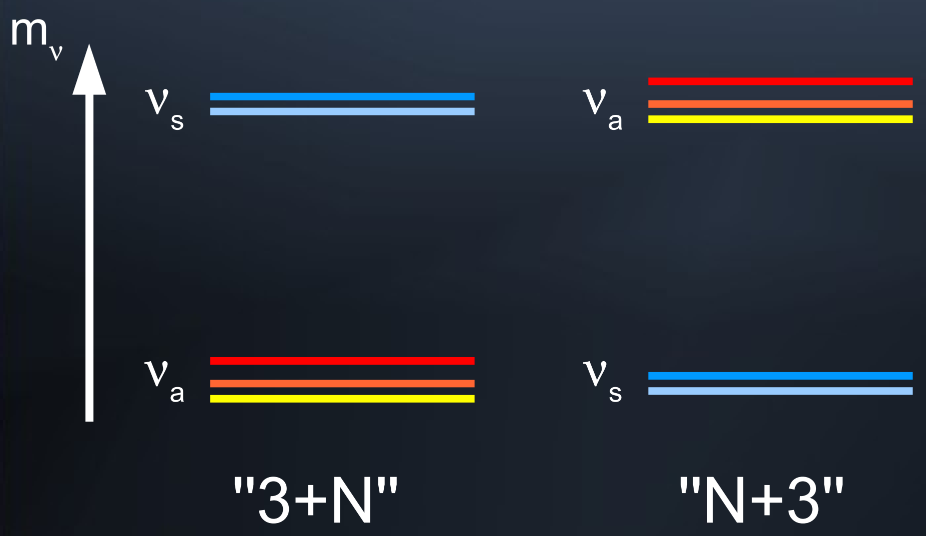
[van de Water, talk @ Neutrino 2010]

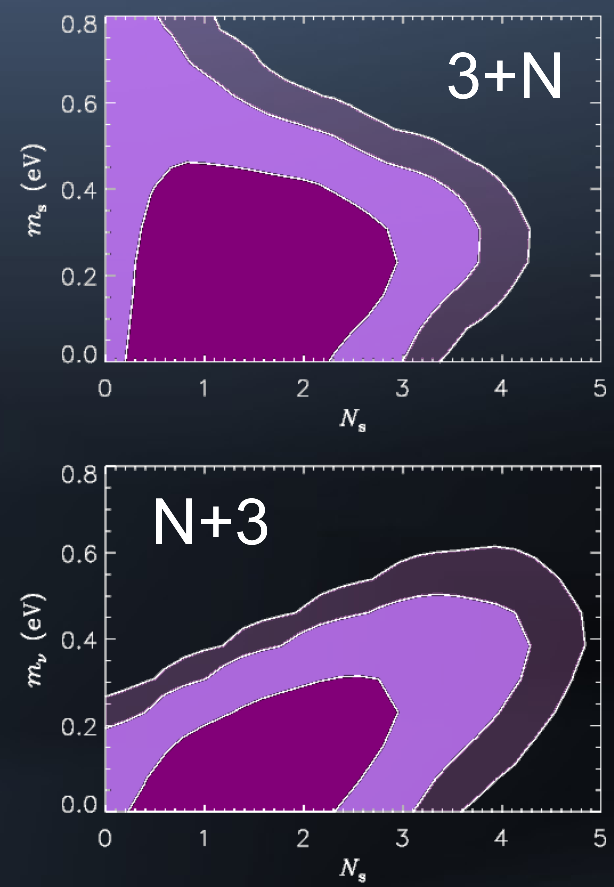
- LSND & MiniBooNE anomalies may be resolved with sterile neutrinos
  - "3+1"
  - "3+2"
  - "3+1" with non-standard interactions

[e.g., Akhmedov, Schwetz (2010)]

Sterile neutrino scenario

Two qualitatively different mass hierarchies:

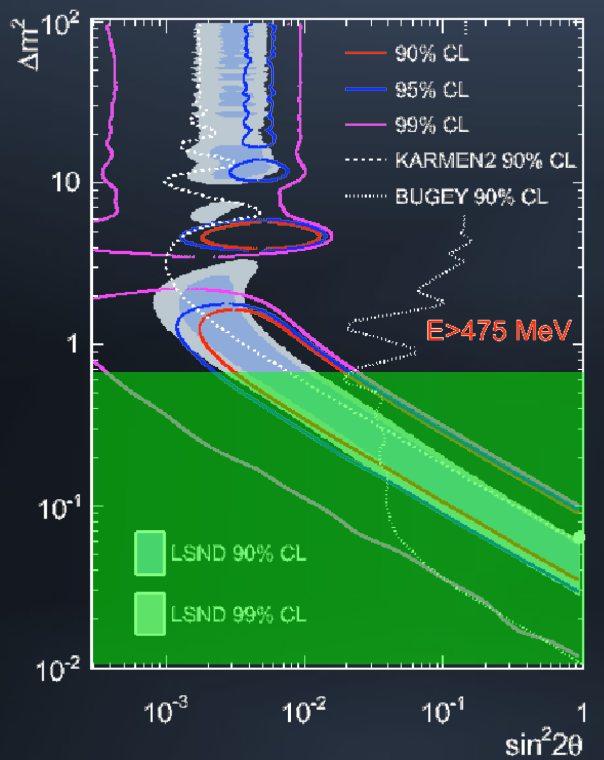


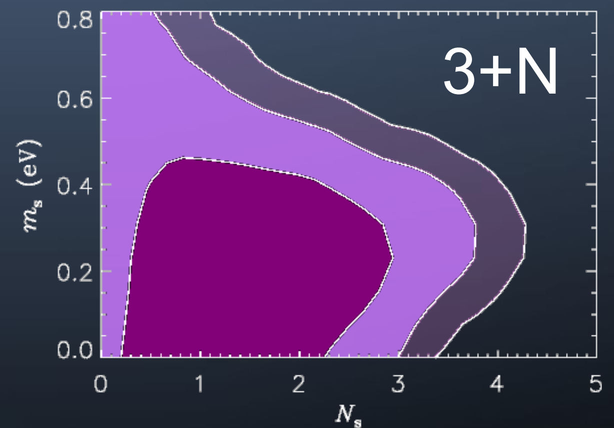


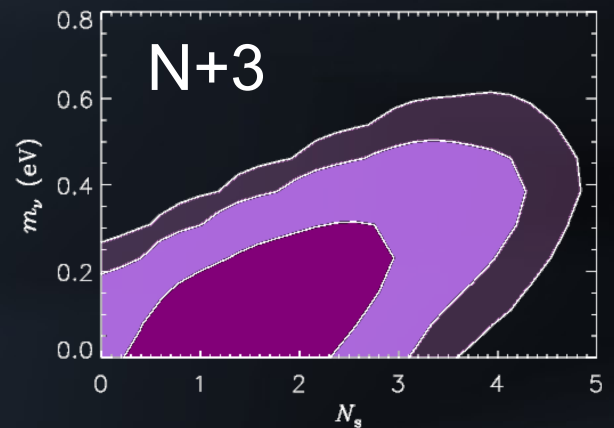
[JH, Hannestad, Raffelt, Tamborra, Wong (2010)]

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
- Data even show a slight preference for extra radiation
- Two (perhaps even three) thermalised sterile neutrino species compatible with cosmological data
- Planck will settle the issue!