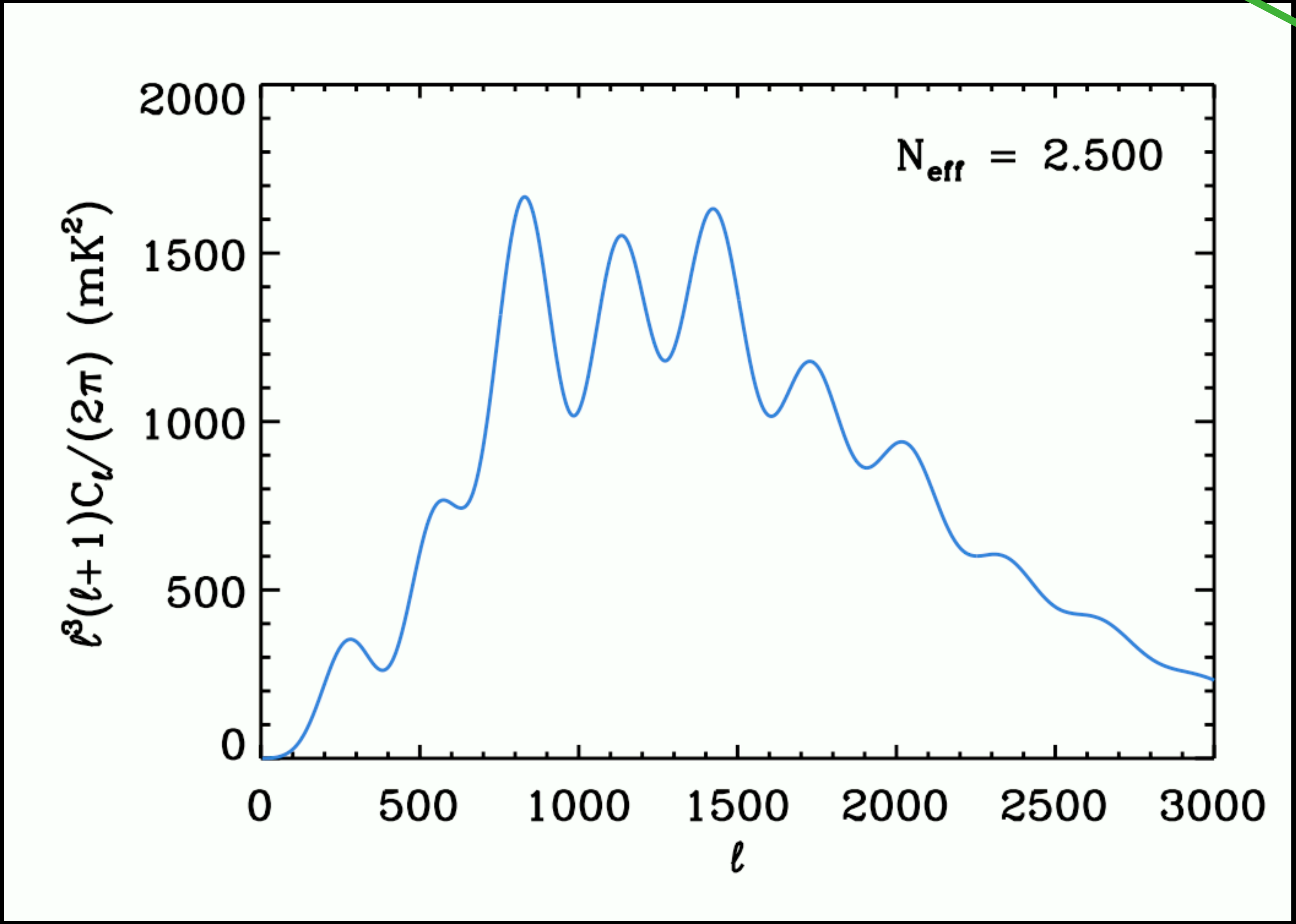
Is there cosmological evidence for a fourth neutrino?



or fifth?
or sixth?
or three-and-a-halfth?!

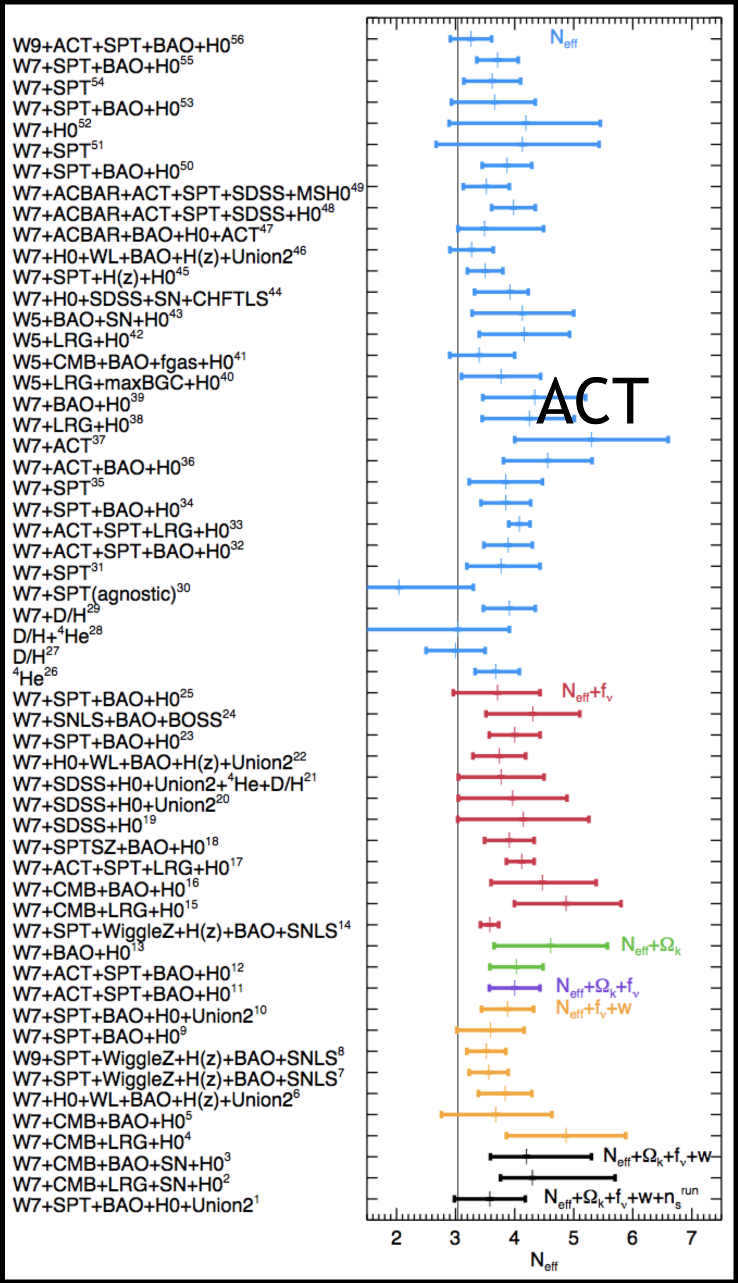
Stephen Feeney (UCL)

arXiv:1302.0014 (JCAP) and arxiv:1307.2904 (JCAP in press)

with H. Peiris (UCL), L. Verde (Barcelona & CERN) & D. Mortlock (IC)

Neutrinos beyond the Standard Model?

- Particle physics and cosmological data imply standard neutrino picture wrong
- Oscillations require neutrino mass
  - maybe extra sterile neutrino(s)?
- Cosmological tests hint at >3 species
- Concentrate on (effective) number of species (N_{eff}) for now



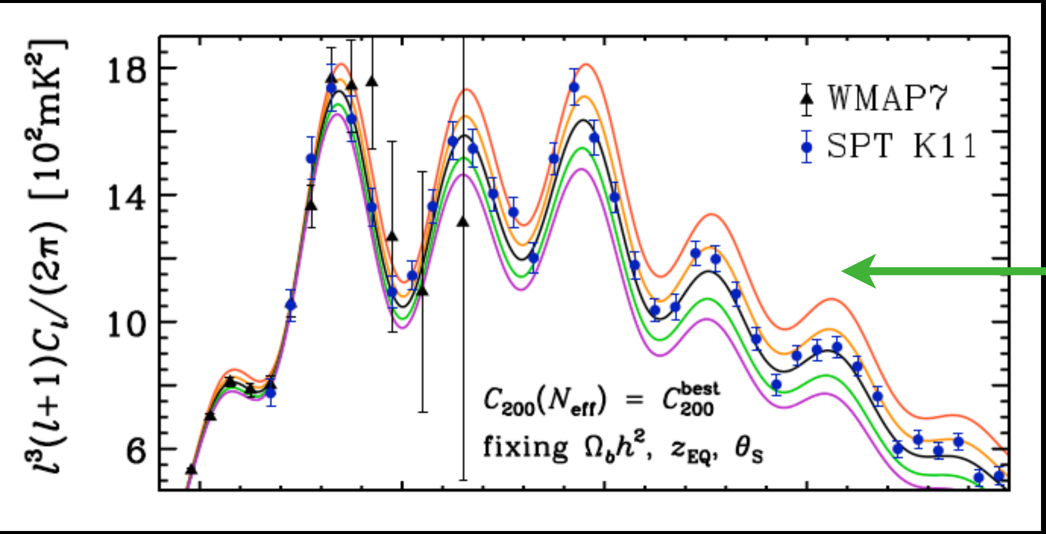
Riemer-Sørensen et al. [2013]

What do extra (light) neutrinos do?

- Extra radiation: boosted expansion rate

$$H^2 \simeq \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu) \quad \text{(rad. dom.)}$$

- Main effect: increasing N_{eff} increases Silk Damping scale (for fixed acoustic scale)



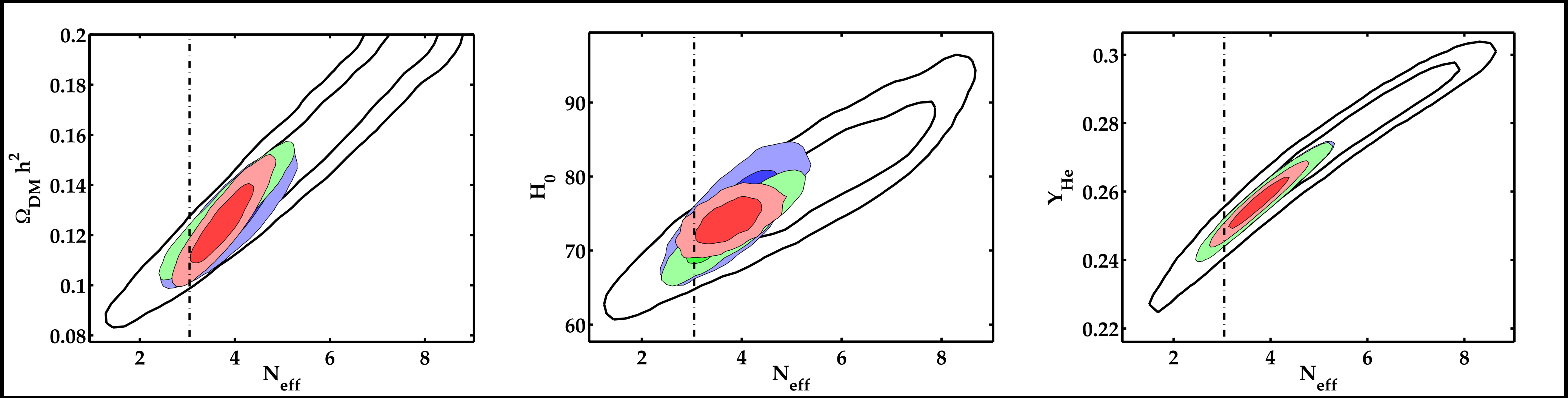
assuming $\Omega_b h^2$, θ_s & z_{eq} fixed

Hou et al. [2011]

- Constrain with high-l CMB, H_0 & $H(z)$; BAO and CMB lensing break degeneracies

Where could these hints come from?

- N_{eff} degenerate with dark matter & baryon densities, H_0, n_s, Y_{He}...



Feeney et al. [2013]

- Degeneracy is
  - cut at low N_{eff} (Bashinsky & Seljak [2004], Trotta & Melchiorri [2008])
  - but extends to high N_{eff}

- Mean of marginalized N_{eff} posterior $\therefore$ high!

Really need model selection

- Fundamental question: is Universe ΛCDM or ΛCDM+N_{eff}?
- Parameter constraints don't tell full story, hard to interpret when long degeneracies
- To answer question, need to compare model posteriors

$$\frac{\mathrm{Pr}(\Lambda\mathrm{CDM}|\mathbf{d})}{\mathrm{Pr}(\Lambda\mathrm{CDM}+N_{\mathrm{eff}}|\mathbf{d})} = \underbrace{\frac{\mathrm{Pr}(\Lambda\mathrm{CDM})}{\mathrm{Pr}(\Lambda\mathrm{CDM}+N_{\mathrm{eff}})}}_{\textit{prior probs}} \underbrace{\frac{\mathrm{Pr}(\mathbf{d}|\Lambda\mathrm{CDM})}{\mathrm{Pr}(\mathbf{d}|\Lambda\mathrm{CDM}+N_{\mathrm{eff}})}}_{\textit{evidence ratio}}$$

Calculating the evidence

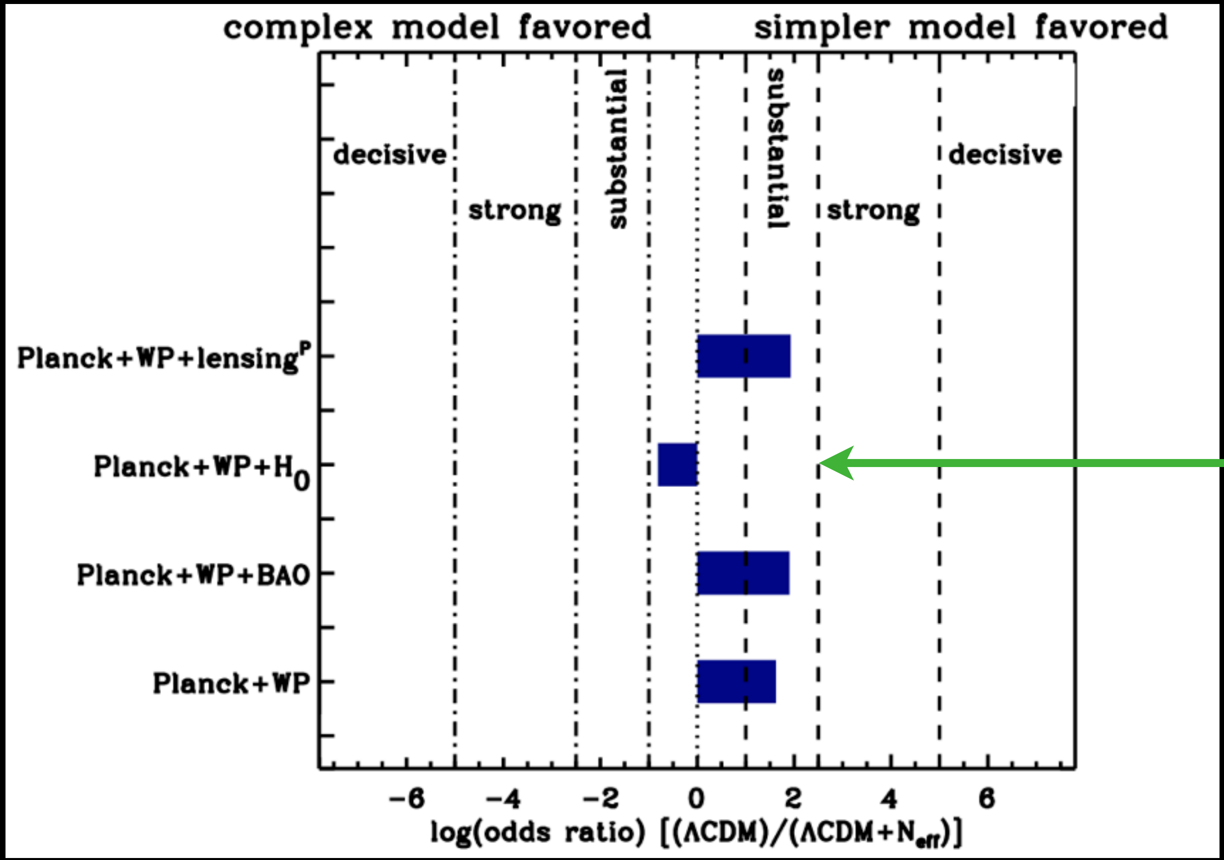
- If models nested — e.g. $\Lambda\mathrm{CDM} = (\Lambda\mathrm{CDM} + N_{\mathrm{eff}})|_{N_{\mathrm{eff}}=3.046}$ — then very simple!

- Just need ratio of posterior and prior at nested parameter value (Dickey [1971], see also Trotta [2007])

$$\frac{\Pr(\mathbf{d}|\Lambda\mathrm{CDM})}{\Pr(\mathbf{d}|\Lambda\mathrm{CDM}+N_{\mathrm{eff}})} = \left.\frac{\Pr(N_{\mathrm{eff}}|\mathbf{d},\Lambda\mathrm{CDM}+N_{\mathrm{eff}})}{\Pr(N_{\mathrm{eff}}|\Lambda\mathrm{CDM}+N_{\mathrm{eff}})}\right|_{N_{\mathrm{eff}}=3.046}$$

- Can use publicly released *Planck* chains: thanks *Planck*!
  - provided posterior is well-sampled at nested value!

Planck evidence ratios



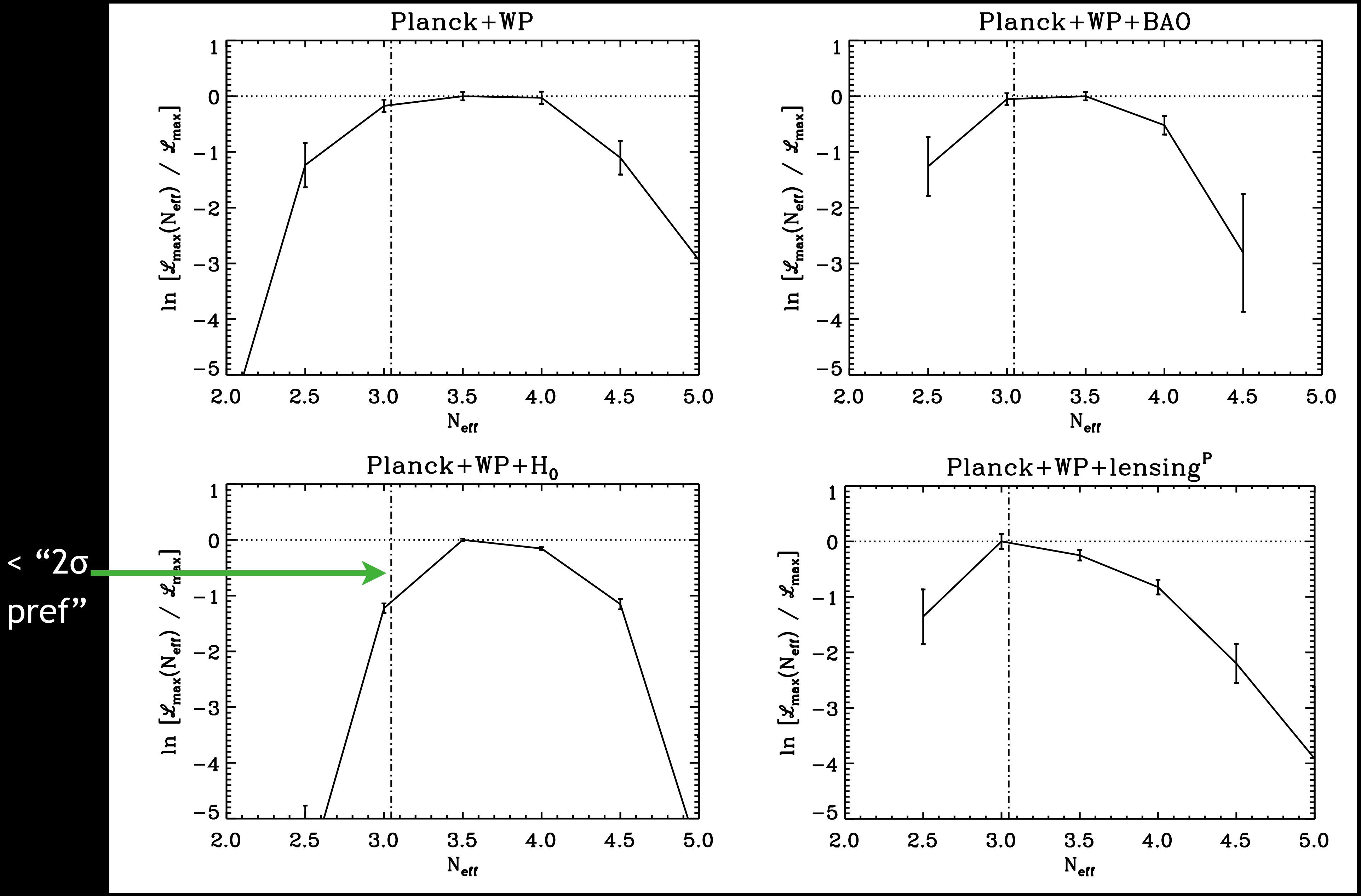
datasets in tension!

- No evidence for additional neutrinos (in these datasets)!
  - odds ~6:1 in favour of ΛCDM
- But do we (or do *you*) trust our priors (uniform in range $0.05 \leq N_{eff} \leq 10$)?

Are hints present in *likelihood*?

- Use profile likelihood ratio (Wilks [1938])
  - ratio of conditional to unconditional maximum likelihoods
  - PLR $(N_{\rm eff}^*) = \dfrac{\max[\Pr(\mathbf{d}|\boldsymbol{\theta}_{\Lambda{\rm CDM}}, N_{\rm eff} = N_{\rm eff}^*)]}{\max[\Pr(\mathbf{d}|\boldsymbol{\theta}_{\Lambda{\rm CDM}}, N_{\rm eff})]}$
  - prior-“independent”
- Max likelihood ≃ upper bound on evidence for “just-so” model
- PLR peak away from Neff = 3.046: evidence for deviation

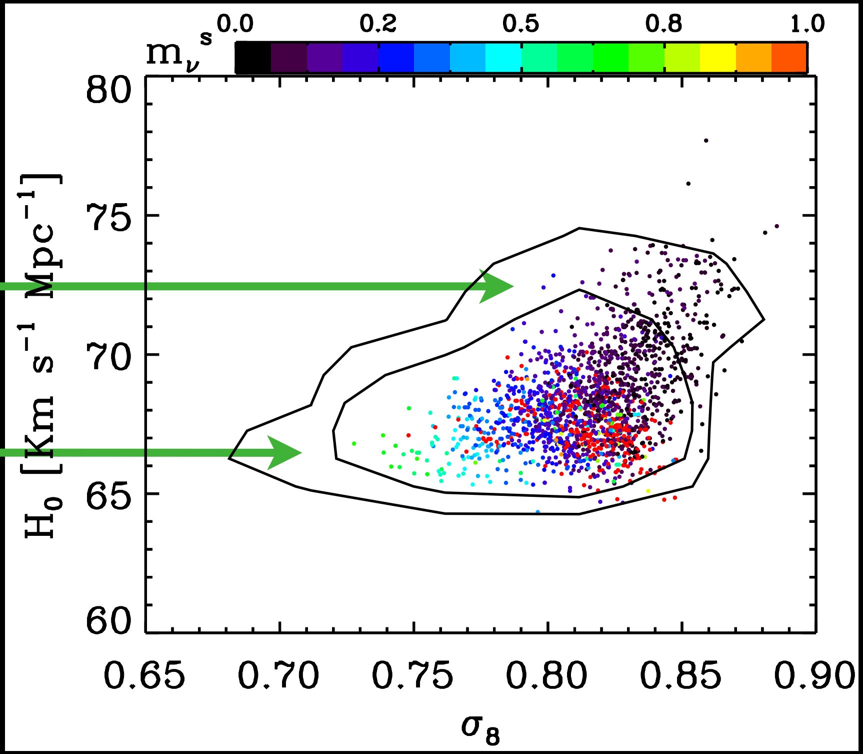
Planck profile likelihood ratios



- No *preference* for additional neutrinos

Conclusions & recent contradictions?

- This work: no evidence / preference for additional neutrino species (Feeney et al. [2013], Verde et al. [2013])
- Recent papers prefer (~3σ) one extra sterile, massive neutrino (Wyman et al. [2013], Hamann & Hasenkamp [2013], Battye & Moss [2013])
- Datasets used in tension with *Planck* & each other
  - HST H_0 high: wants high σ_8, low m_ν
  - clusters σ_8 low: wants low H_0, high m_ν
- No new concordance!



What data do we use?

- Planck CMB temperature power spectrum (Planck XV [2013])
- WMAP CMB polarization power spectra (Bennett et al. [2012])
- BAO: 6dF (Beutler et al. [2011]) + SDSS reconstruction (Padmanabhan et al. [2012]) + BOSS (Anderson et al. [2013])
- H_0 (Riess et al. [2011])
- Planck CMB lensing (Planck XVII [2013])
- Evidence ratios from SDDR applied to Planck chains (Planck XVI [2013])

Massive neutrinos

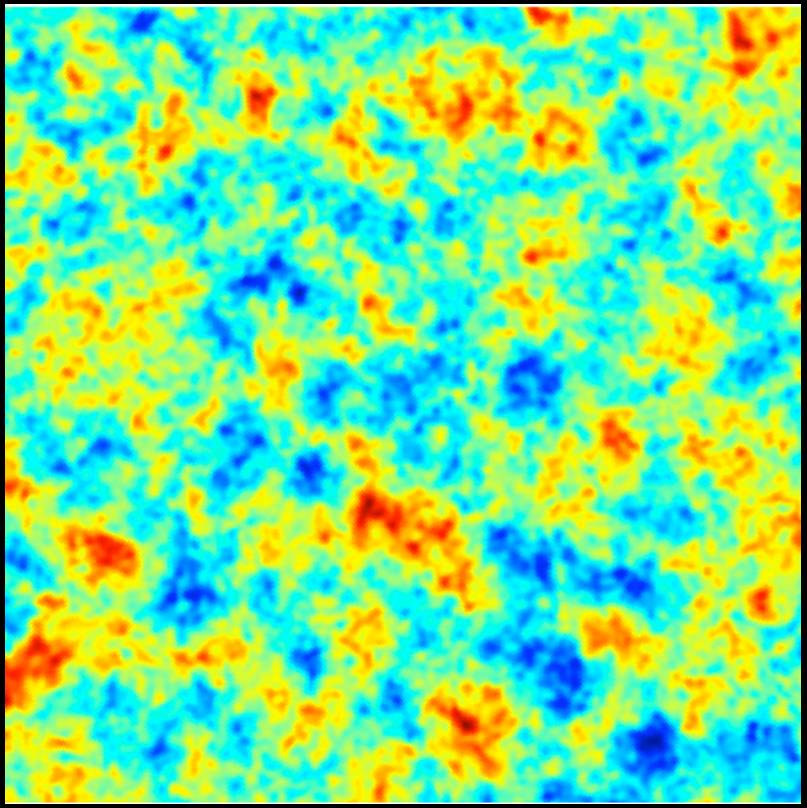
- Two mass differences measured: at least two ν are massive
- If masses < 1eV, ultra-relativistic when they decouple, and relativistic during recombination
  - therefore basically = radiation for CMB purposes
- Eventually become non-relativistic
  - hot/warm dark matter
  - damp structure formation on scales < free-streaming length
  - larger effect, if can measure

What does cosmology tell us?

- Sum of neutrino masses, M_ν
  - or more accurately, neutrino energy density:

$$\Omega_\nu h^2 = \frac{\sum_{i=1}^{N_\nu} m_{\nu,i}}{94\mathrm{eV}}$$

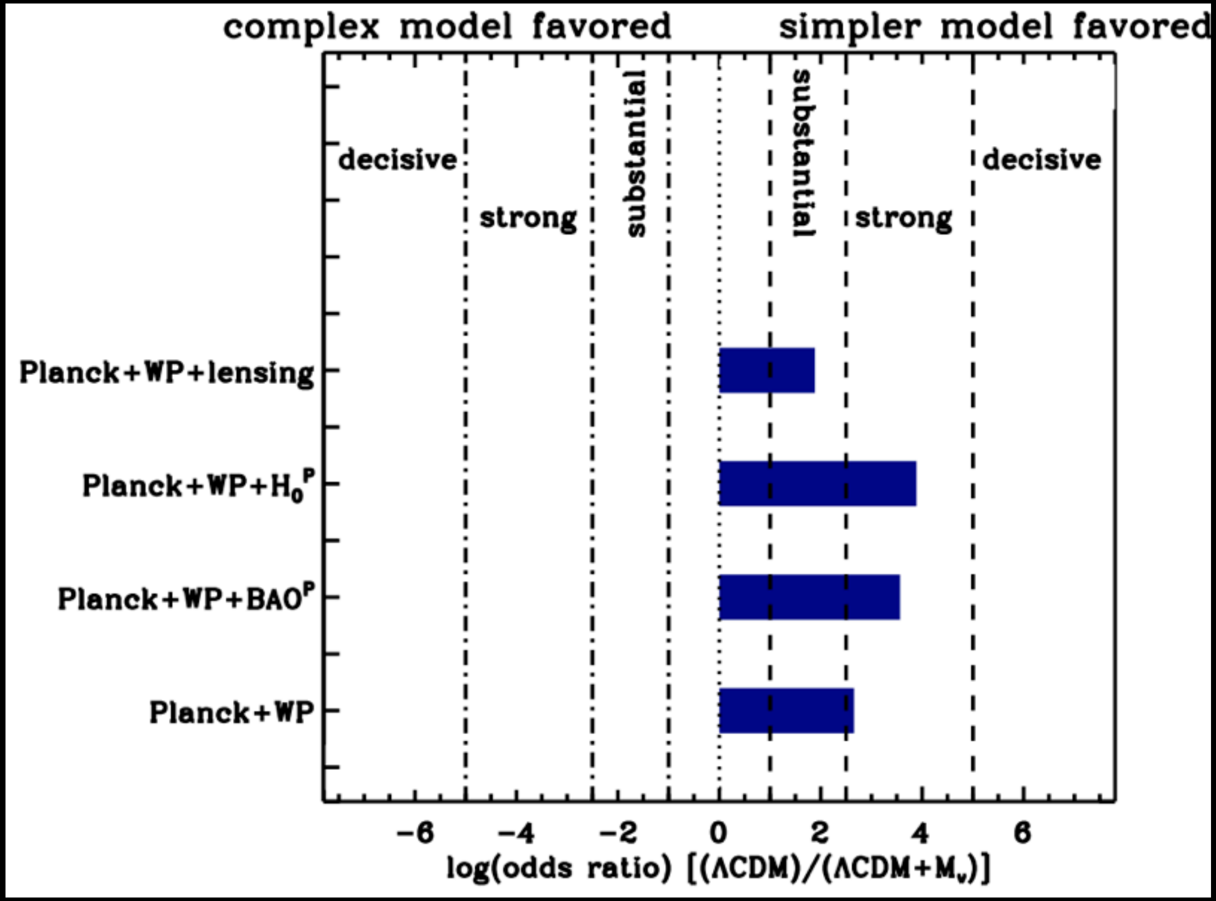
- Post-CMB effect largest, so need
  - late-time observables on small scales
  - high-l CMB



- CMB lensing is great!
- We know ν have mass: do data?

Evidence: sum of neutrino masses

- Prior uniform in range $0 \le M_\nu \le 5$ eV



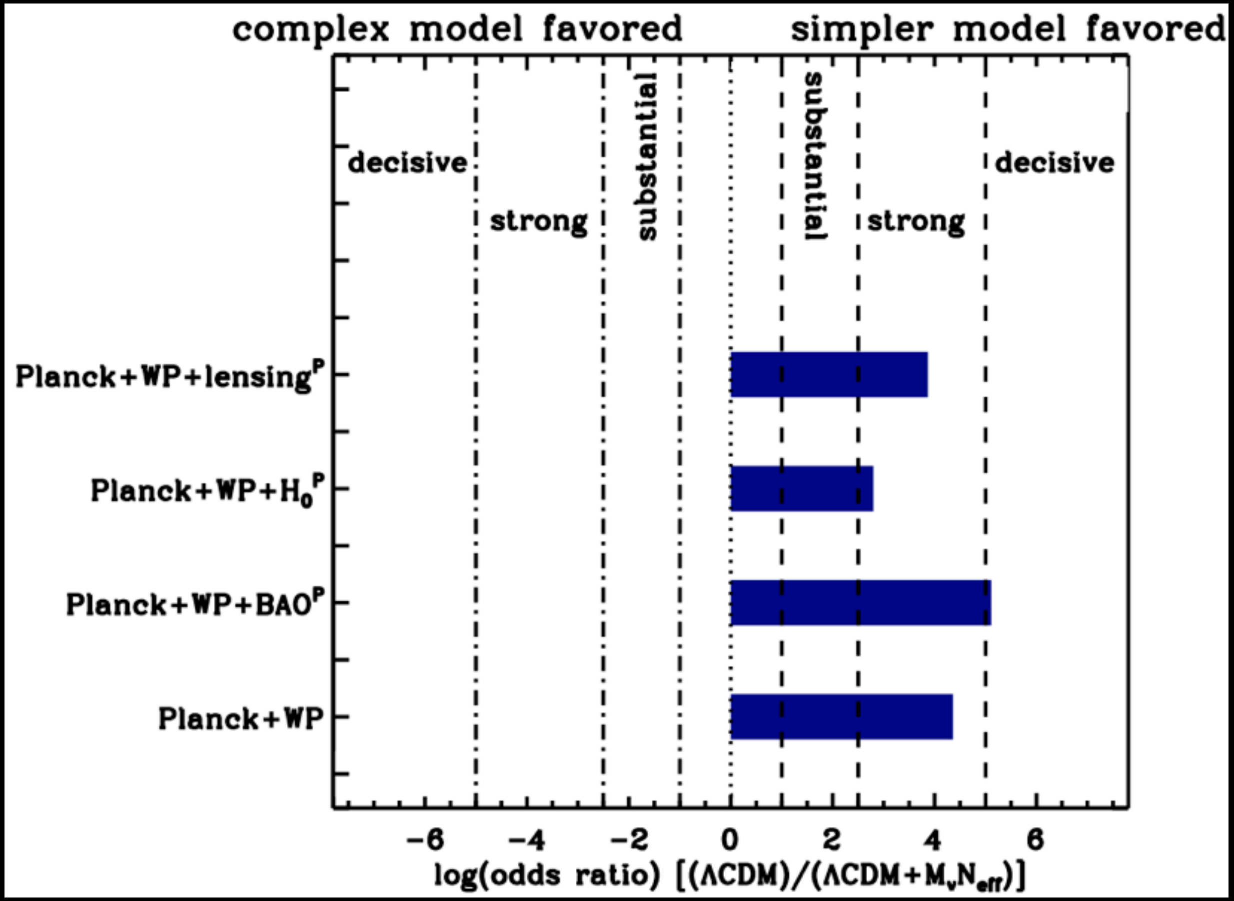
- Do we need to include M_ν in cosmological analyses? No!

- Alt: data not precise enough to tell us about masses

Extra neutrinos *and* neutrino mass

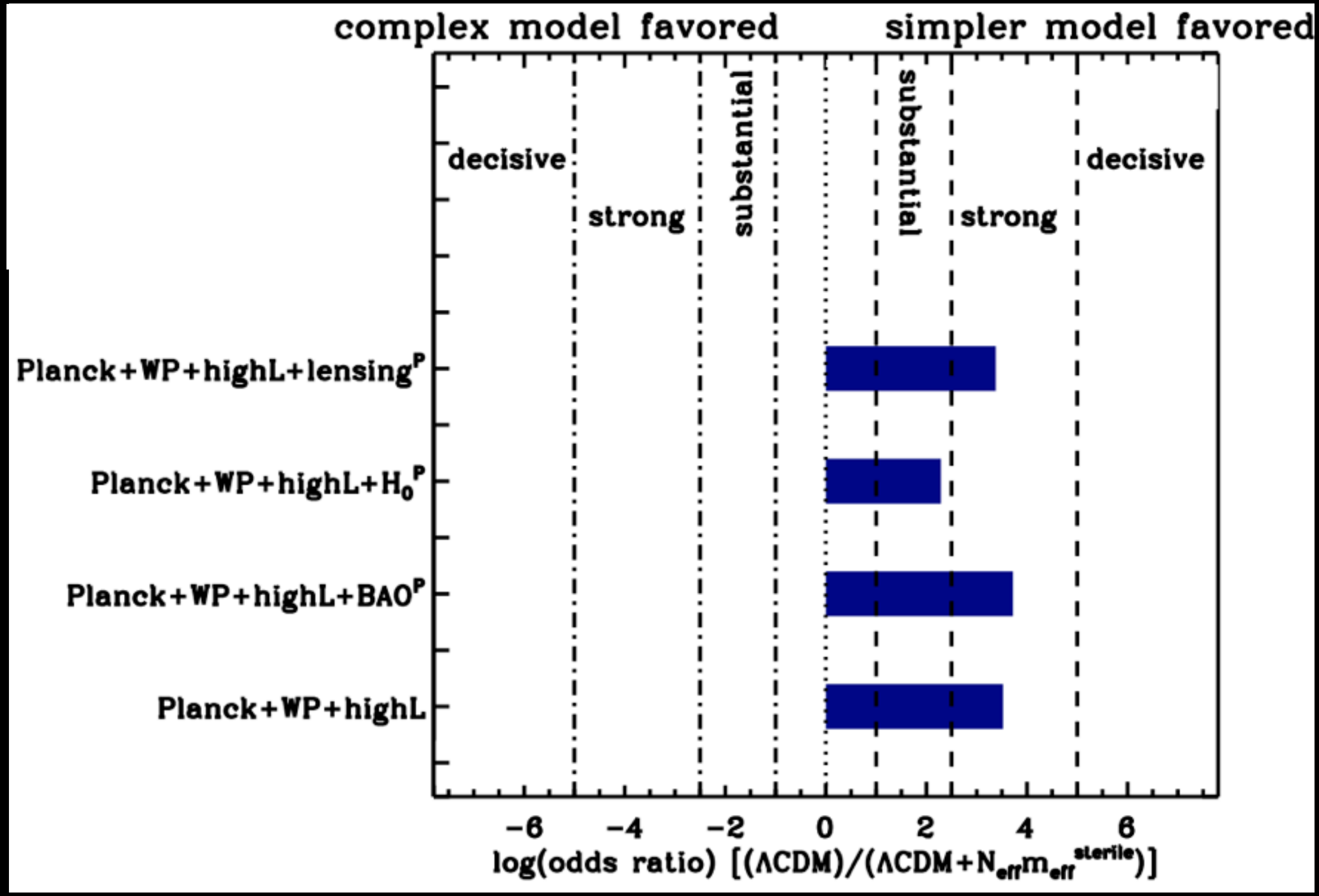
- Planck tested two models:
  - three massive ν and N_{eff}-3.046 extra massless ν
  - one massive & two massless active ν and one sterile massive ν
- Models test whether
  - there are extra light relics as well as massive ν
  - the particle physics hints of a sterile ν are supported
- Priors
  - $0 \leq M_\nu \leq 5$ eV and $0.05 \leq N_{eff} \leq 10$
  - $0 \leq m_{eff,\ sterile} \leq 3$ eV and $0.05 \leq N_{eff} \leq 10$ (fix temp & mass of sterile ν)

Evidence: neutrino mass *and* number, active



- Strong evidence in favour of standard cosmology

Evidence: three plus one sterile



- Strong evidence in favour of standard cosmology