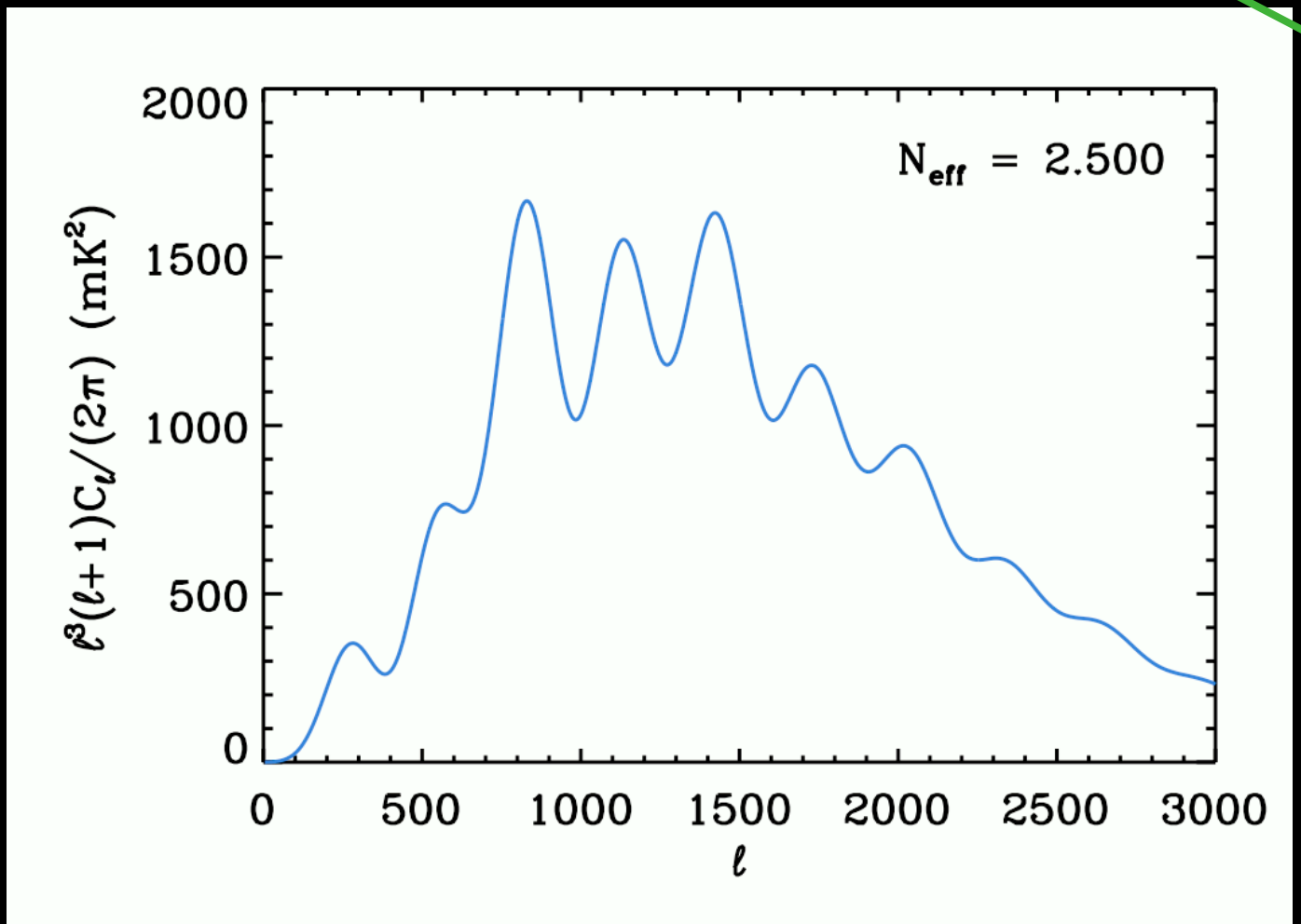
Is there cosmological evidence for a fourth neutrino?



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

Hiranya V. Peiris

University College London

Credits

Stephen Feeney

(UCL)

Licia Verde

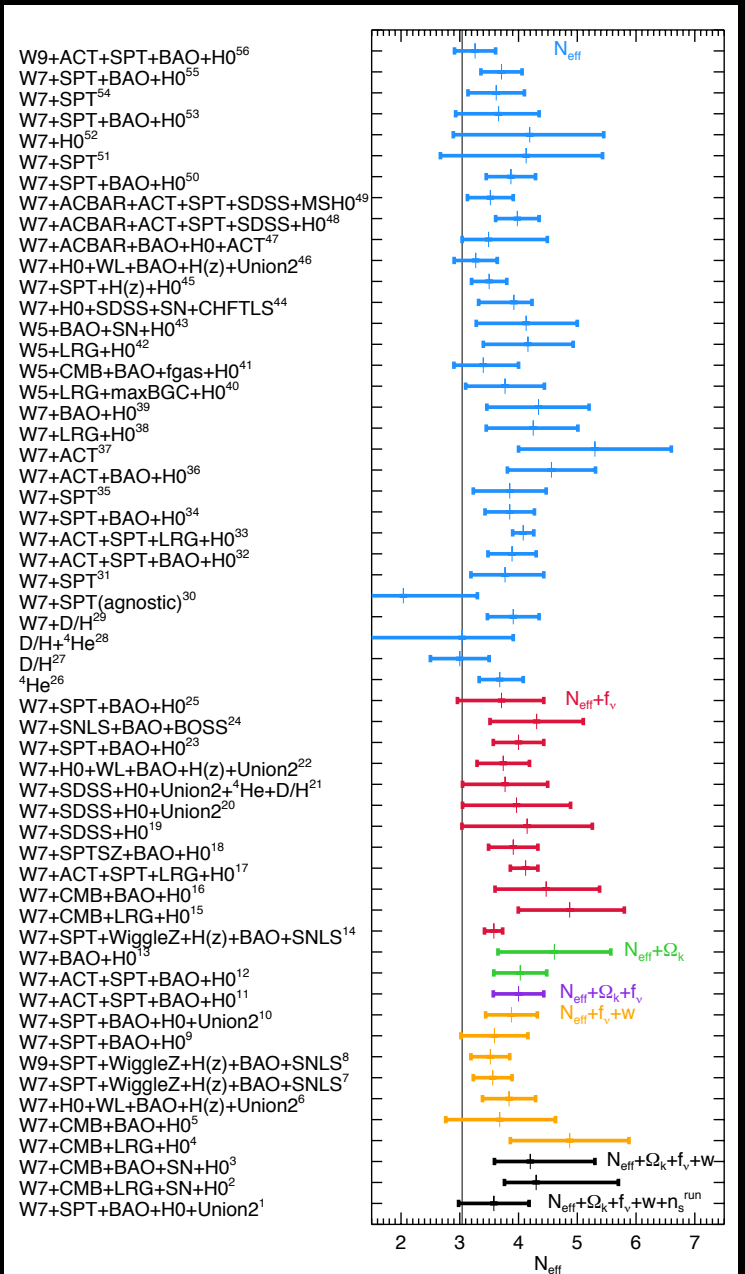
(Barcelona & CERN)

Feeney, Peiris and Verde (2013)

arXiv:1302.0014, JCAP accepted

Neutrinos beyond the Standard Model?

- Data from particle physics and cosmology imply standard neutrino picture wrong
- Oscillations require neutrino mass
- Cosmological tests hint at >3 species
- Let's concentrate on (effective) number of species (N_{eff})
  - where do these hints come from?



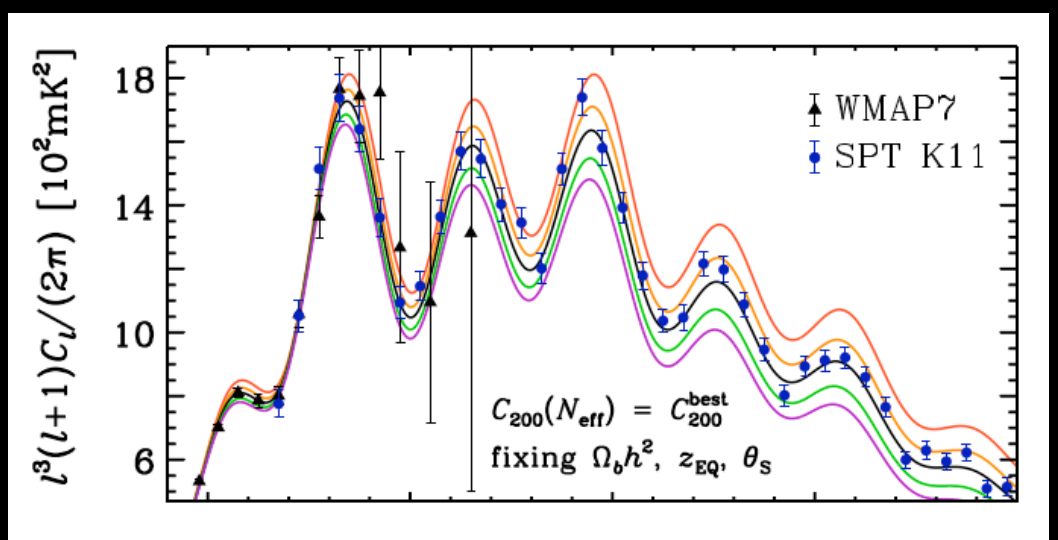
Riemer-Sørensen et al. [2013]

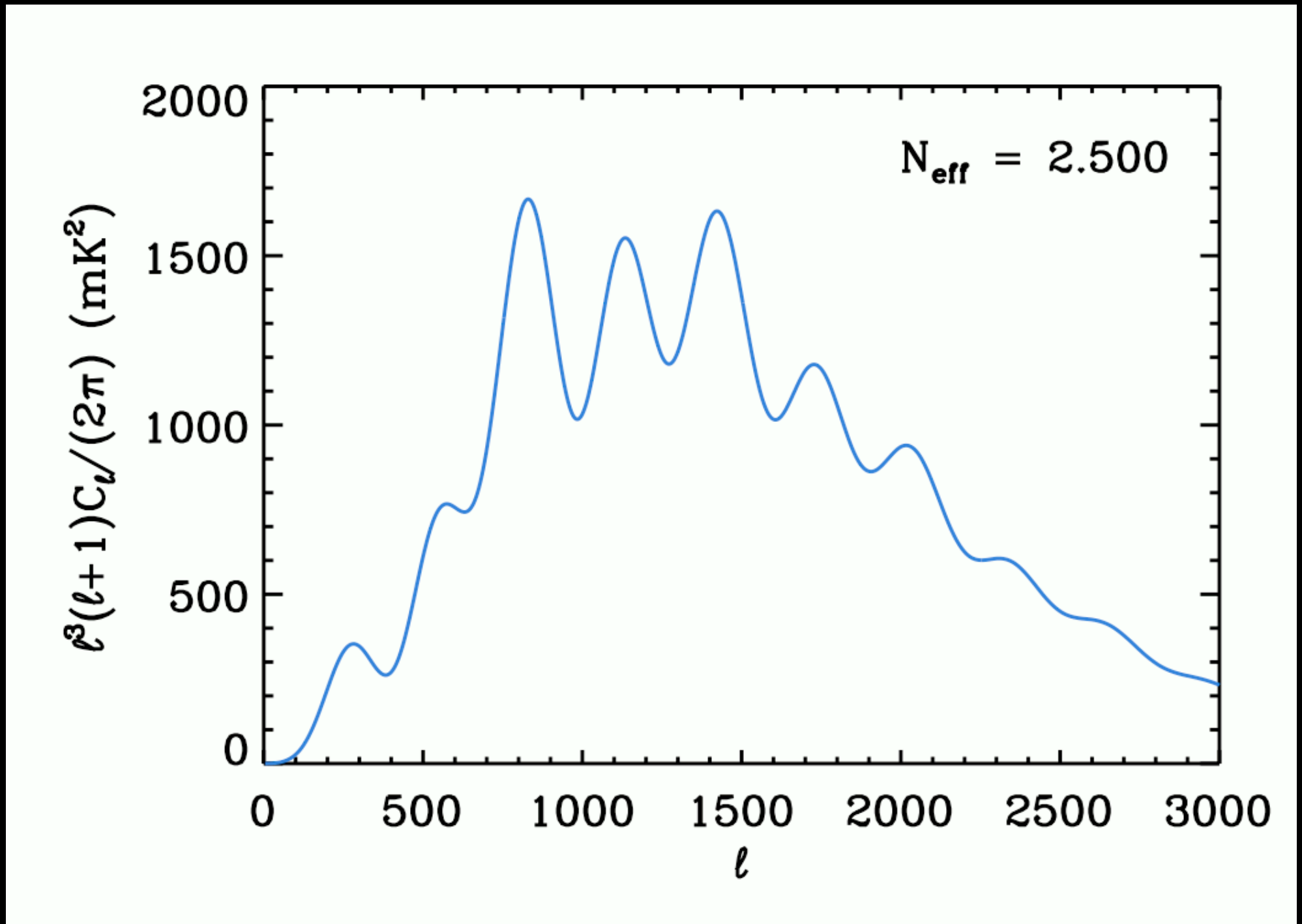
What do we measure in the CMB?

- Measure CMB acoustic peak locations and heights
  - positions constrain angular scale of sound horizon, θ_s
  - relative heights constrain redshift of matter/radiation equality, $1 + z_{eq}$
- Cosmological parameters derived from these quantities
- Affected by two main physical processes
  - propagation of sound waves
  - Silk (diffusion) damping

How do massless neutrinos affect the CMB?

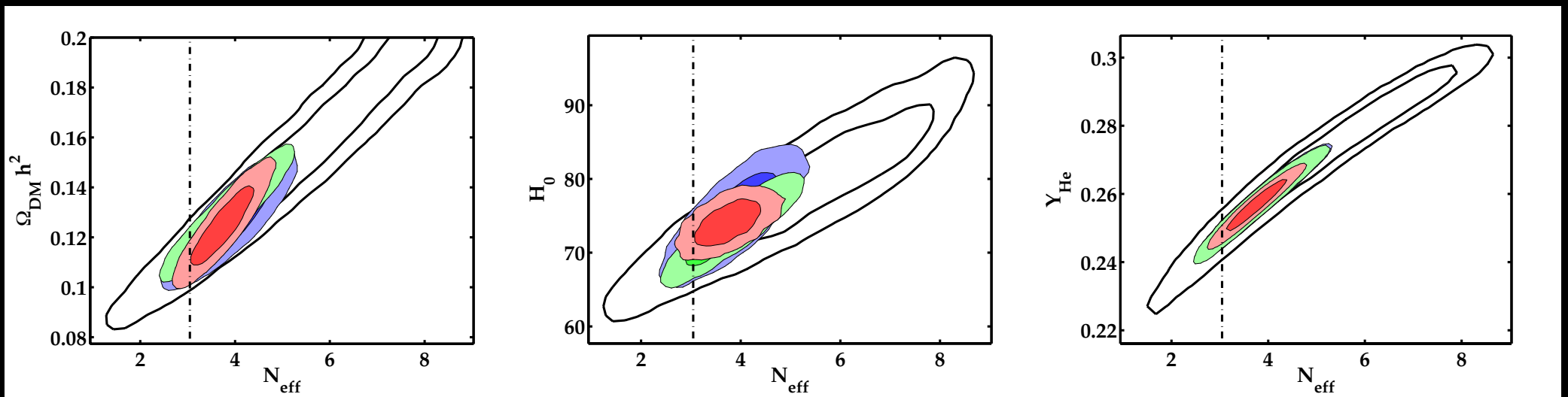
- Additional massless neutrinos means
  - extra radiation
  - boosted expansion rate: $H^2 \simeq \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu)$ (rad. dom.)
- Distance acoustic waves travel $\propto t \propto H^{-1}$
- Distance photons diffuse $\propto t^{1/2} \propto H^{-1/2}$ Hou et al. [2011]
- Main effect: increasing N_{eff} increases Silk Damping scale (for fixed θ_s)




N_{eff} = 2.500
$\ell^3(\ell+1)C_\ell/(2\pi)$ (mK^2)
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
ℓ

Degeneracies with other parameters

- N_{eff} degenerate with dark matter density, H_0, Y_{He}...



- Plots show WMAP (b&w) + SPT (blue) + BAO (green) or H_0 (red)

- Degeneracy reduced but not broken by extra data

So where do these hints come from?

- Degeneracy cut at low N_{eff} (Bashinsky & Seljak [2004], Trotta & Melchiorri [2008])...
  - need *some* neutrinos (damping and anisotropic stress) to explain peak heights and locations
- ... but extends to high N_{eff}
  - can tweak e.g. $\Omega_c h^2$, $\Omega_b h^2$, n_s to mimic effects
- Mean of marginalized N_{eff} posterior ∴ high!
  - easy to generate ~1σ "hints"

Really need (Bayesian) model selection

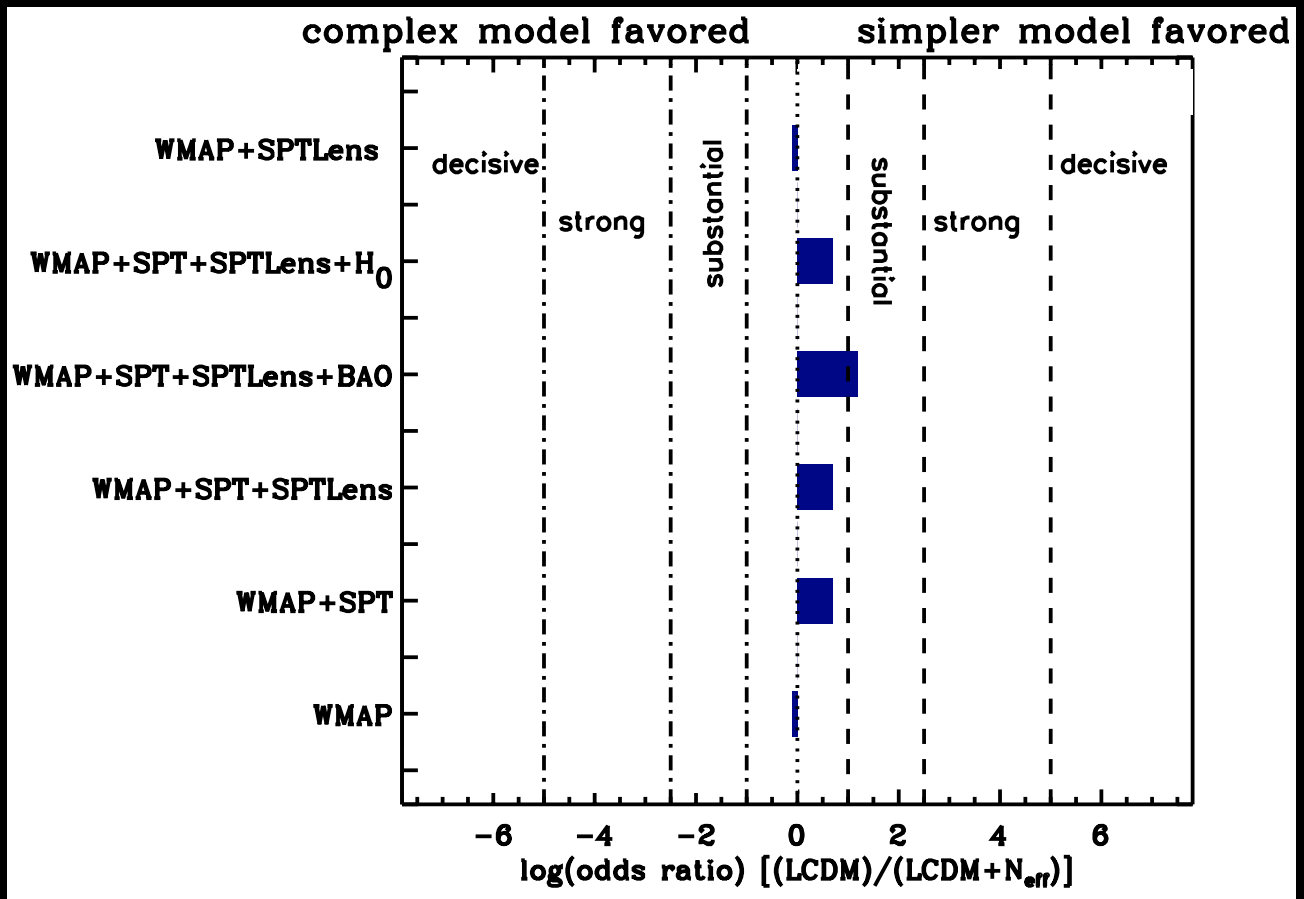
- Fundamental question: is Universe ΛCDM or ΛCDM+$N_{\rm eff}$?

- Parameter constraints insufficient, need

$$\frac{\Pr(\Lambda\mathrm{CDM}|\mathbf{d})}{\Pr(\Lambda\mathrm{CDM}+N_{\rm eff}|\mathbf{d})} = \frac{\Pr(\Lambda\mathrm{CDM})}{\Pr(\Lambda\mathrm{CDM}+N_{\rm eff})}\frac{\Pr(\mathbf{d}|\Lambda\mathrm{CDM})}{\Pr(\mathbf{d}|\Lambda\mathrm{CDM}+N_{\rm eff})}$$

- Calculate evidence (model-averaged likelihood)
  - i.e. $\Pr(\mathbf{d}|M) = \int \mathrm{d}\theta \Pr(\boldsymbol{\theta}|M)\Pr(\mathbf{d}|\boldsymbol{\theta},M)$
  - nested sampling (Skilling [2004])
  - Savage-Dickey Density Ratio (Dickey [1971])

Evidence (pre-Planck)



- No evidence for additional neutrinos!
  - odds 3:1 in favour of ΛCDM
- But do we (or do *you*) trust our priors?

What if we don't trust our priors?

- Check: are hints present in likelihood?

- Use profile likelihood ratio

  - ratio of conditional to unconditional maximum likelihoods

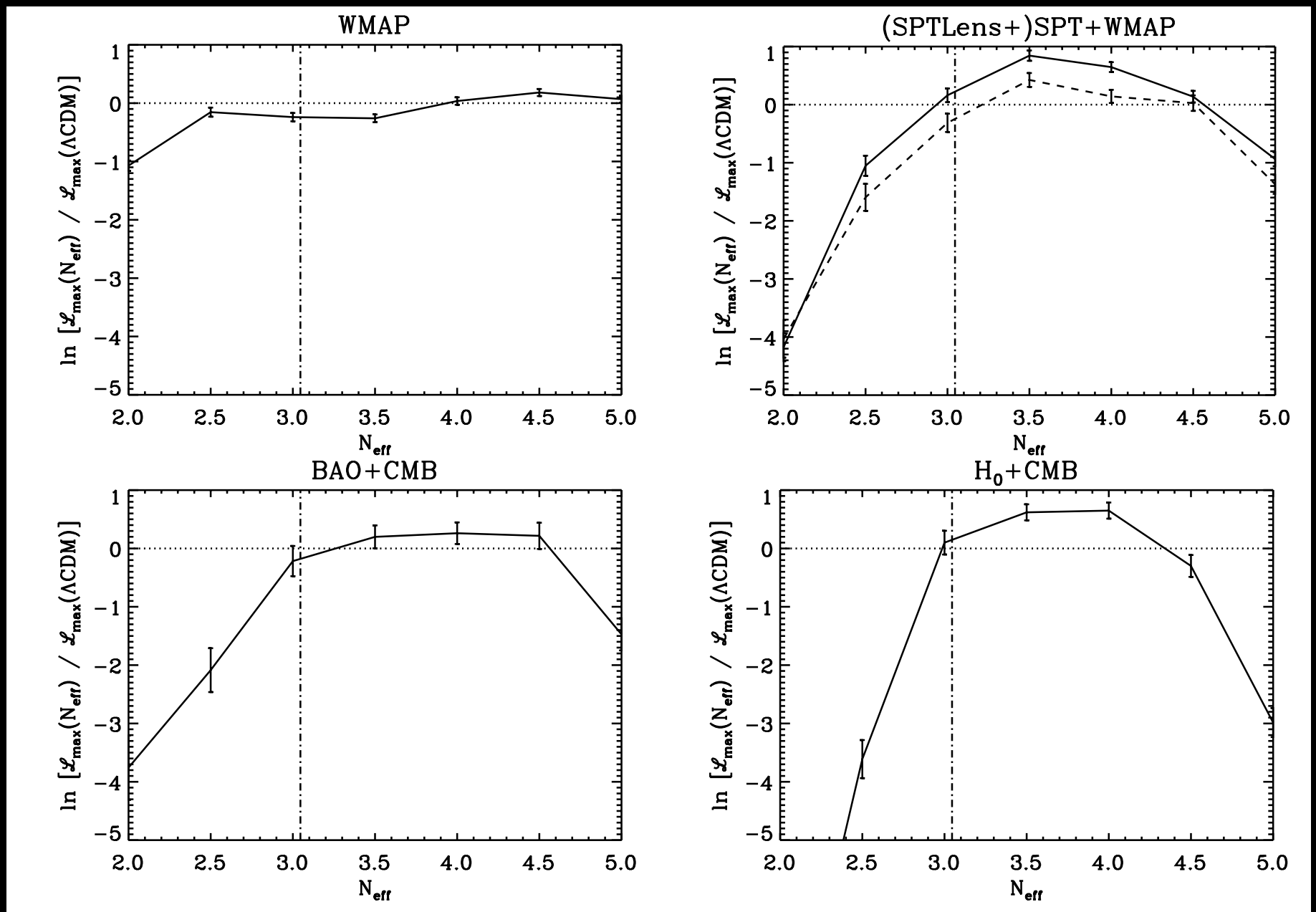
  - PLR $(N^*_{\rm eff}) = \dfrac{\max[\Pr(\mathbf{d}|\boldsymbol{\theta}_{\Lambda\rm CDM}, N_{\rm eff} = N^*_{\rm eff})]}{\max[\Pr(\mathbf{d}|\boldsymbol{\theta}_{\Lambda\rm CDM}, N_{\rm eff})]}$

  - prior-"independent"

  - not rigorous model selection, but informative

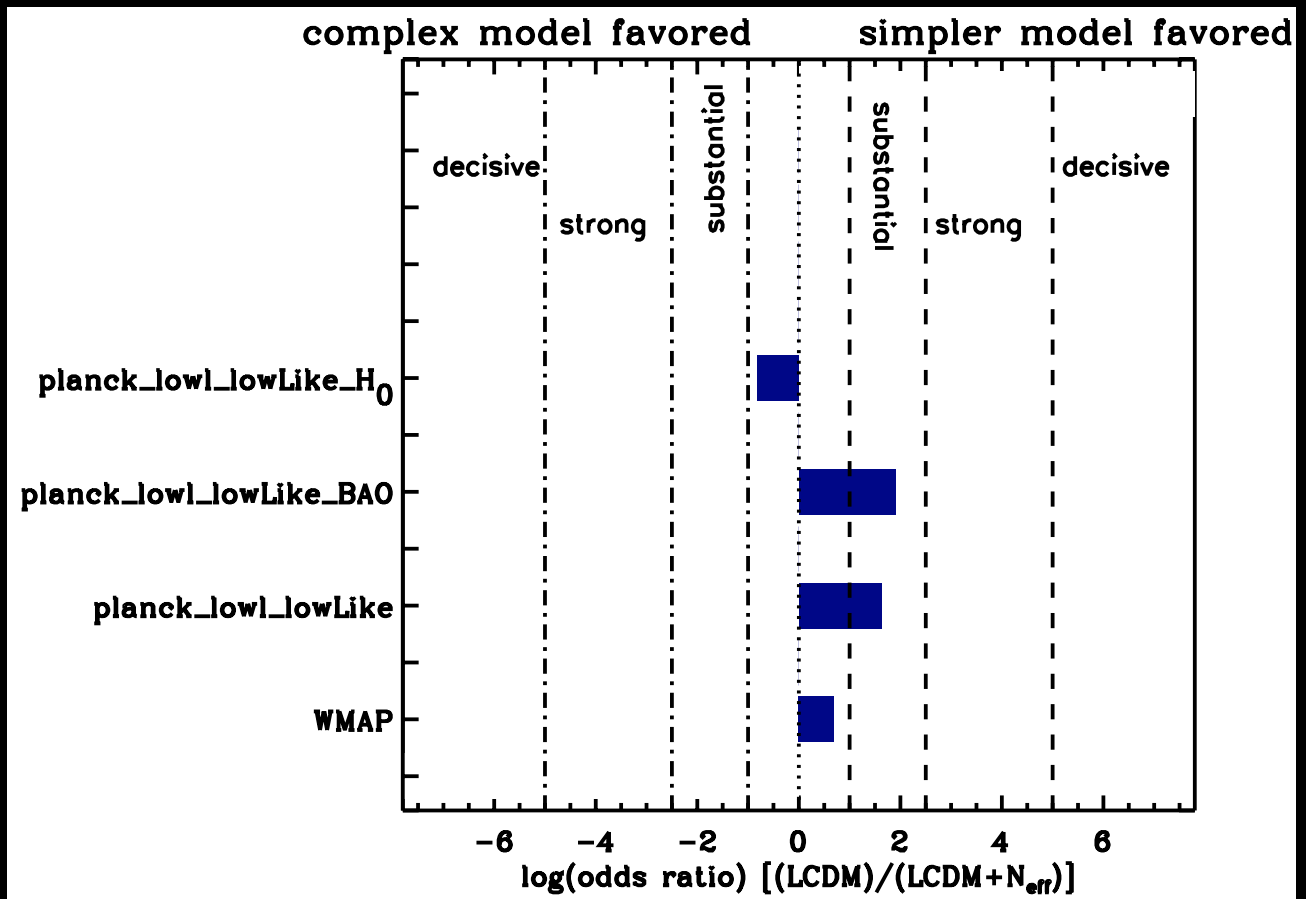
- PLR($N_{\rm eff} \neq 3.046$) > $n^2/2$ indicates n-sigma "evidence"

Profile likelihood ratios (pre-Planck)



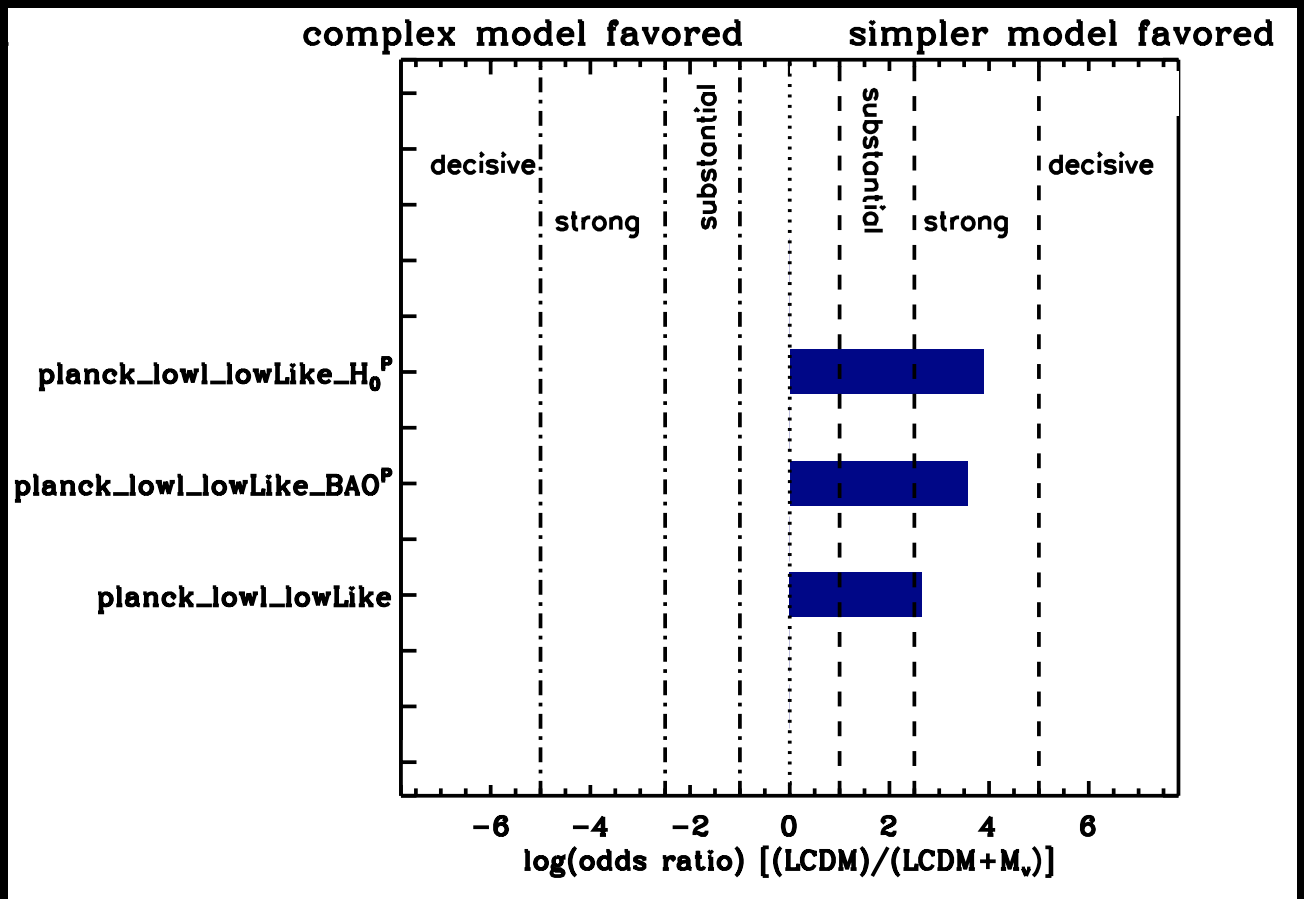
- No *preference* for additional neutrinos

Planck evidence ratios

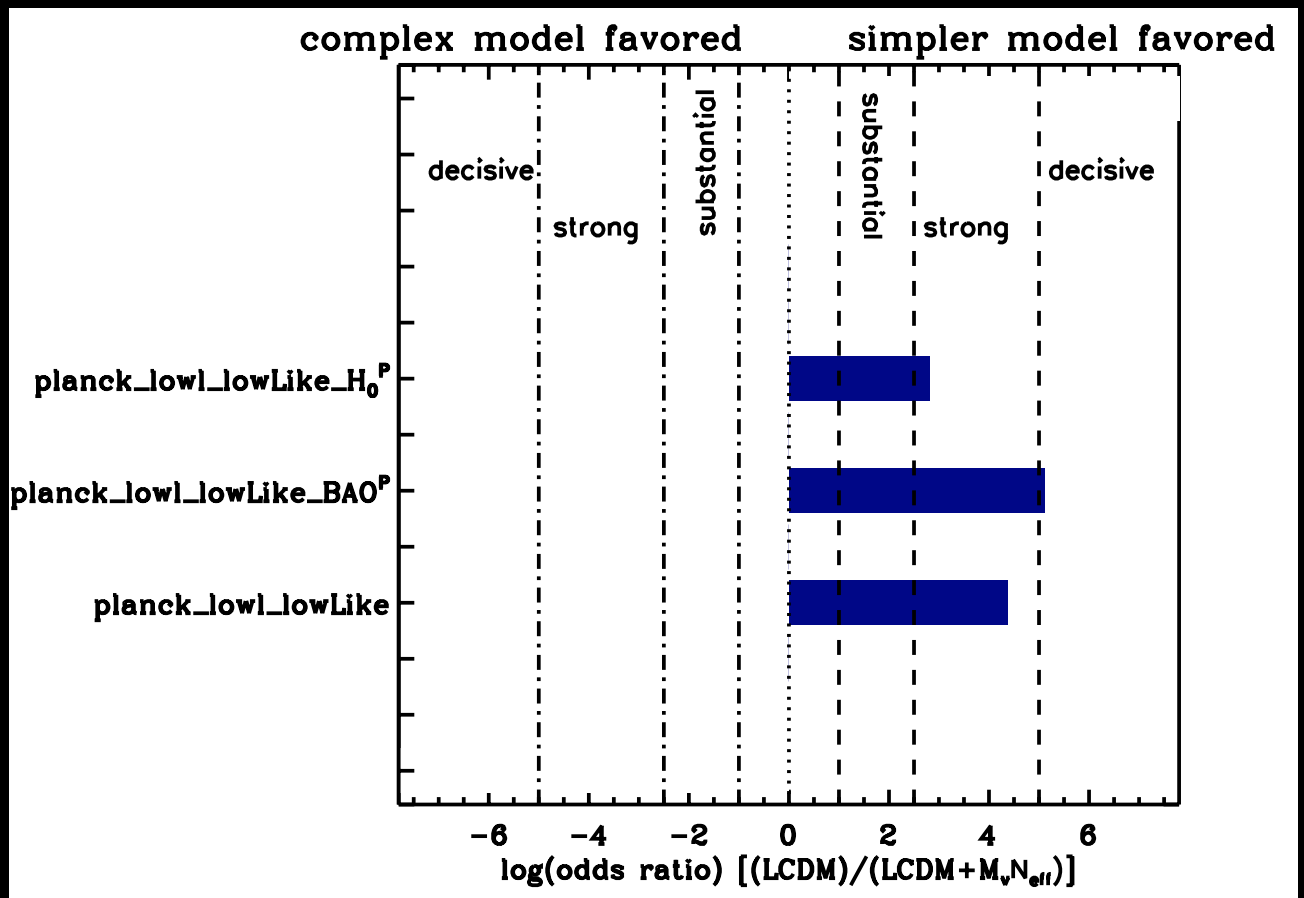


- No evidence for additional neutrinos!
  - odds ~6:1 in favour of ΛCDM

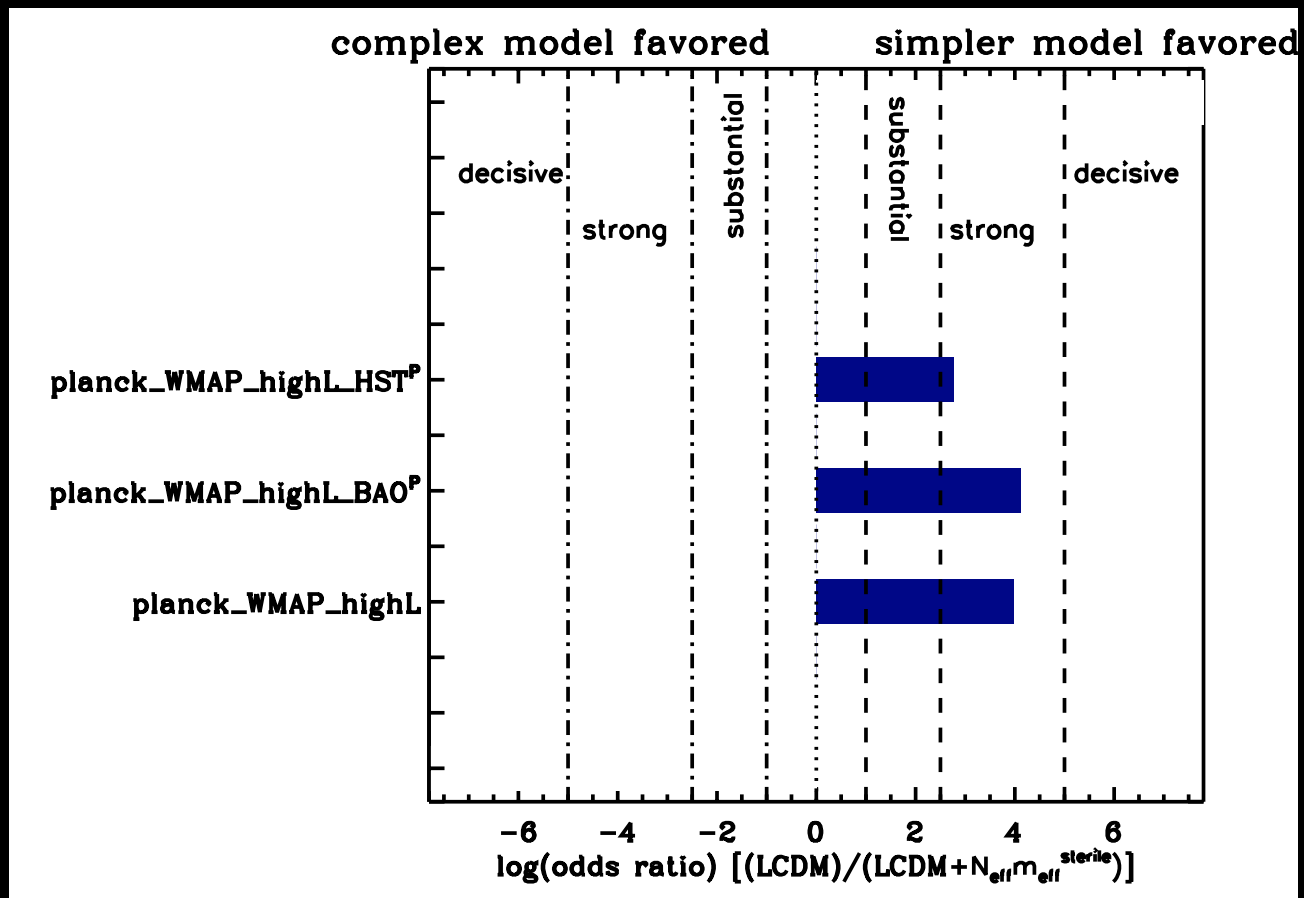
Neutrino mass



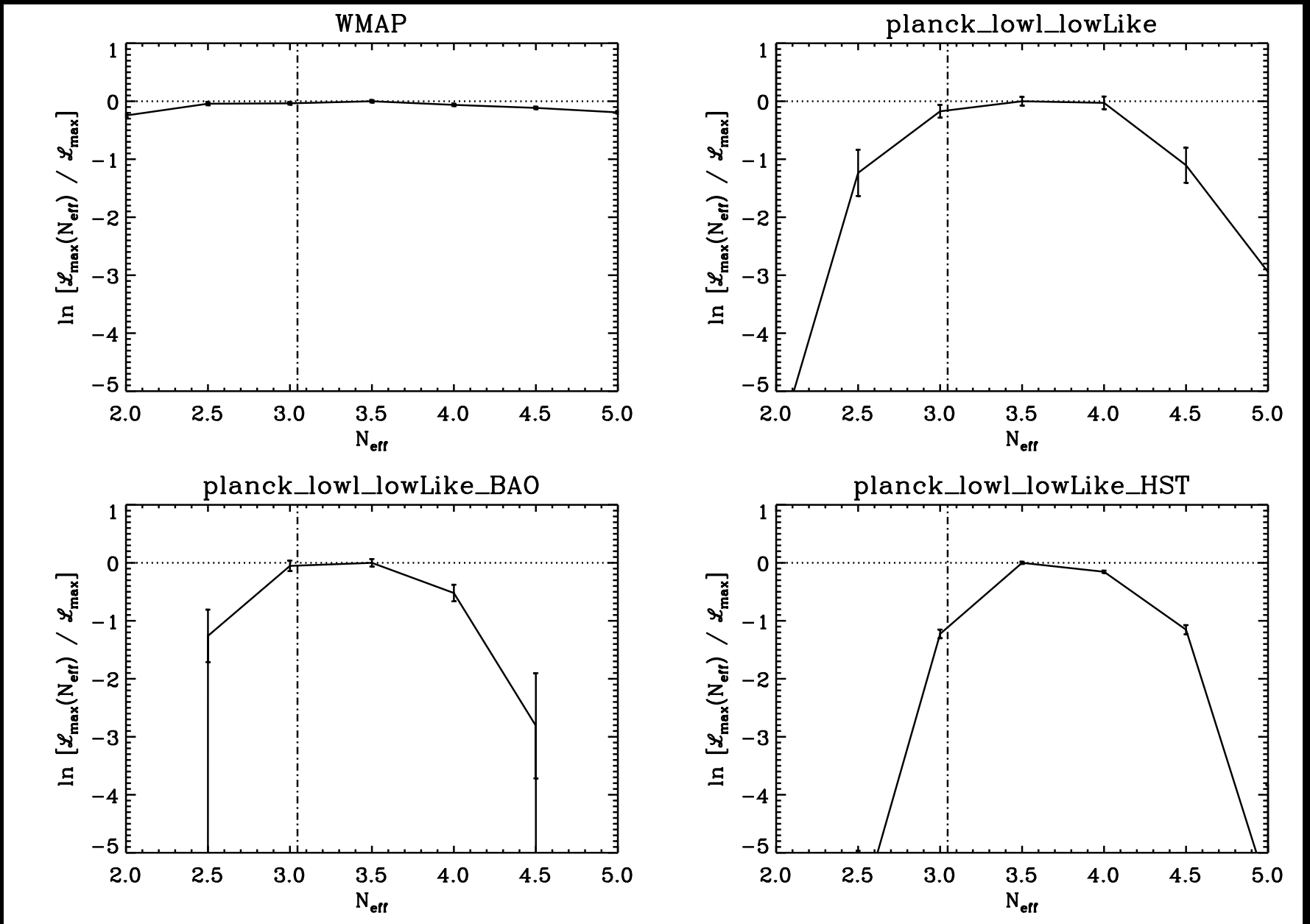
Neutrino mass *and* number of species



Number of species assuming one sterile



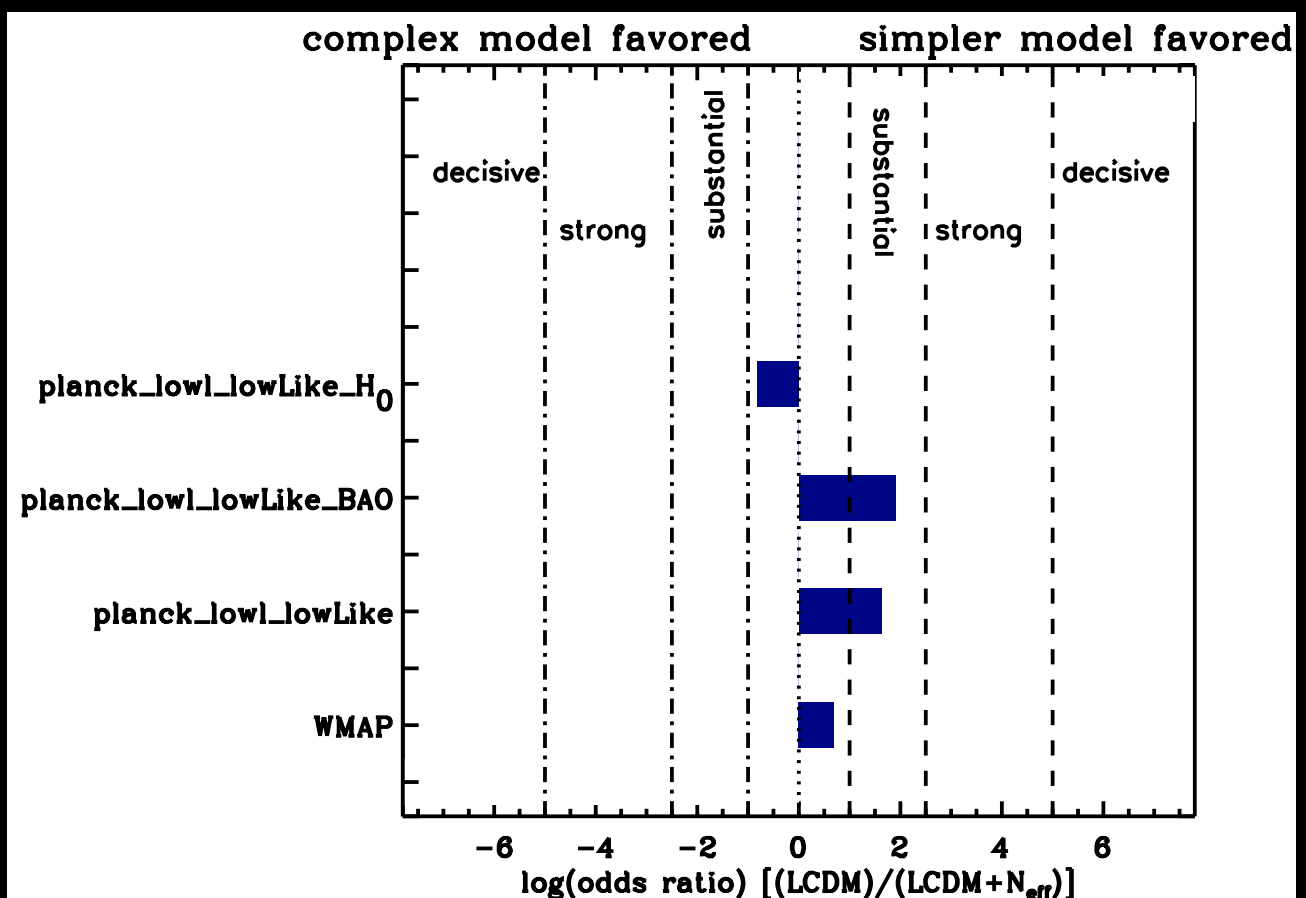
Planck profile likelihood ratios



- Even with discrepant HST data, not even 2 sigma

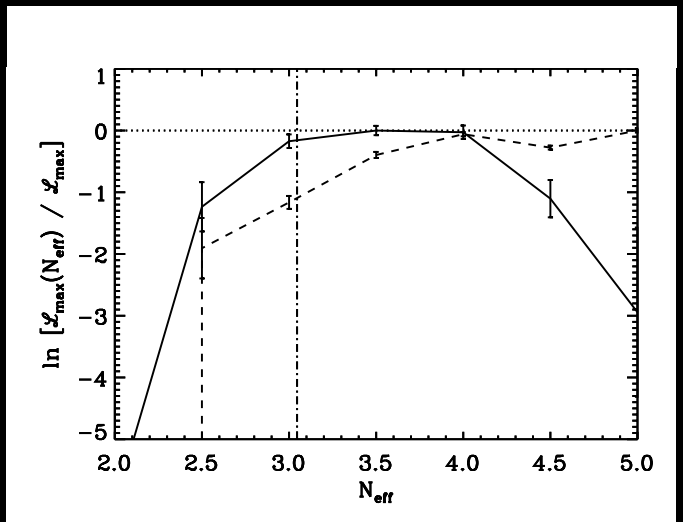
Conclusion

- No evidence / preference [delete as appropriate] for additional neutrino species (MBν?)
  - typical odds 6:1 in favour of LCDM & Standard Model



What could end the debate?

- Planck polarisation
  - polarisation peaks sharper
  - pin down phase shift (ΔN_{eff} ~ 0.18)



- CMB lensing helps break degeneracies (and measure mass!)
- Precise local measurements of H_0 and age of the Universe
  - see Verde, Jimenez & Feeney (arXiv: 1303.5341)