Is there cosmological evidence for a fourth neutrino?
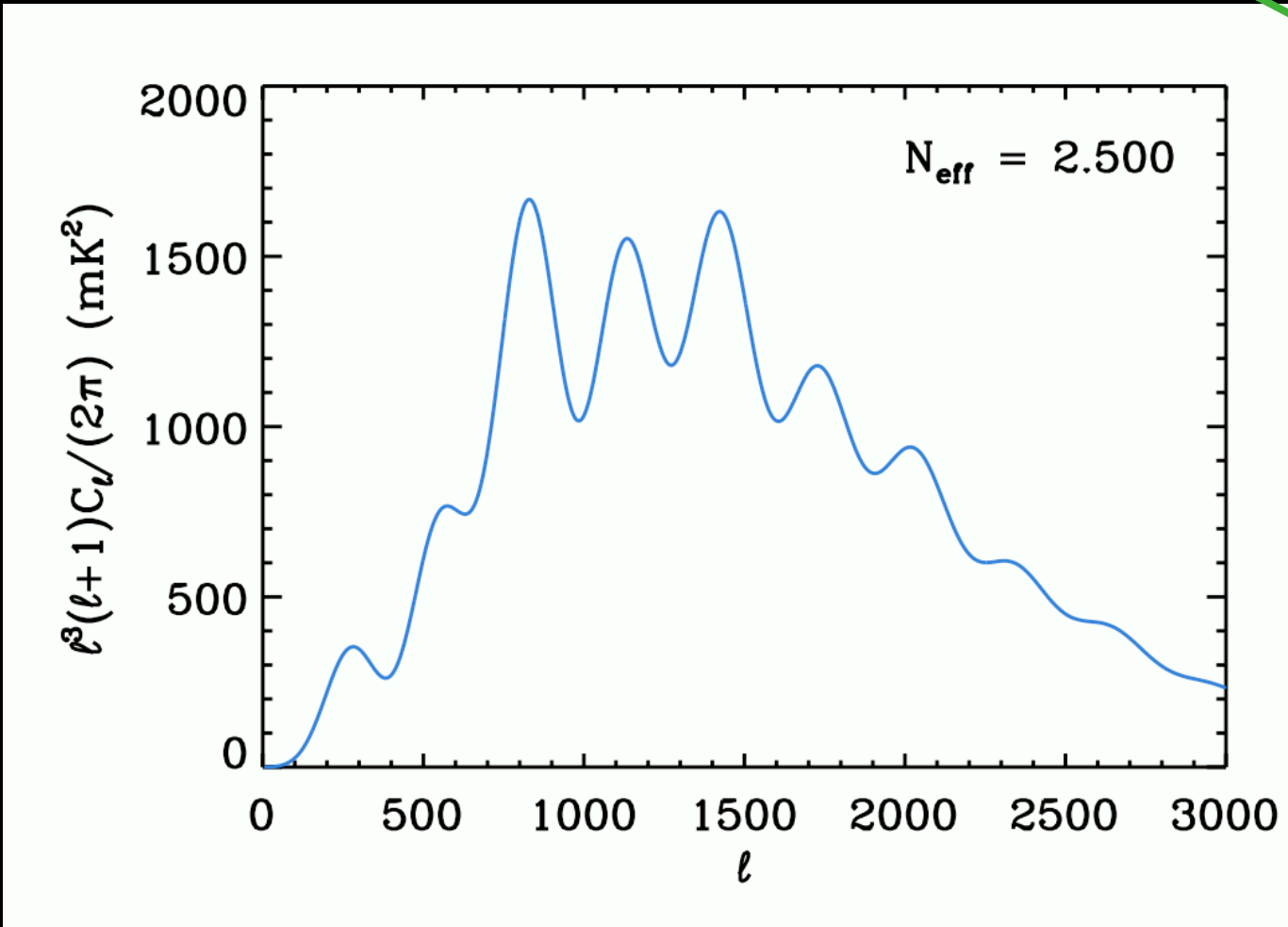

*or fifth?
or sixth?
or three-
and-a-
halfth?!*
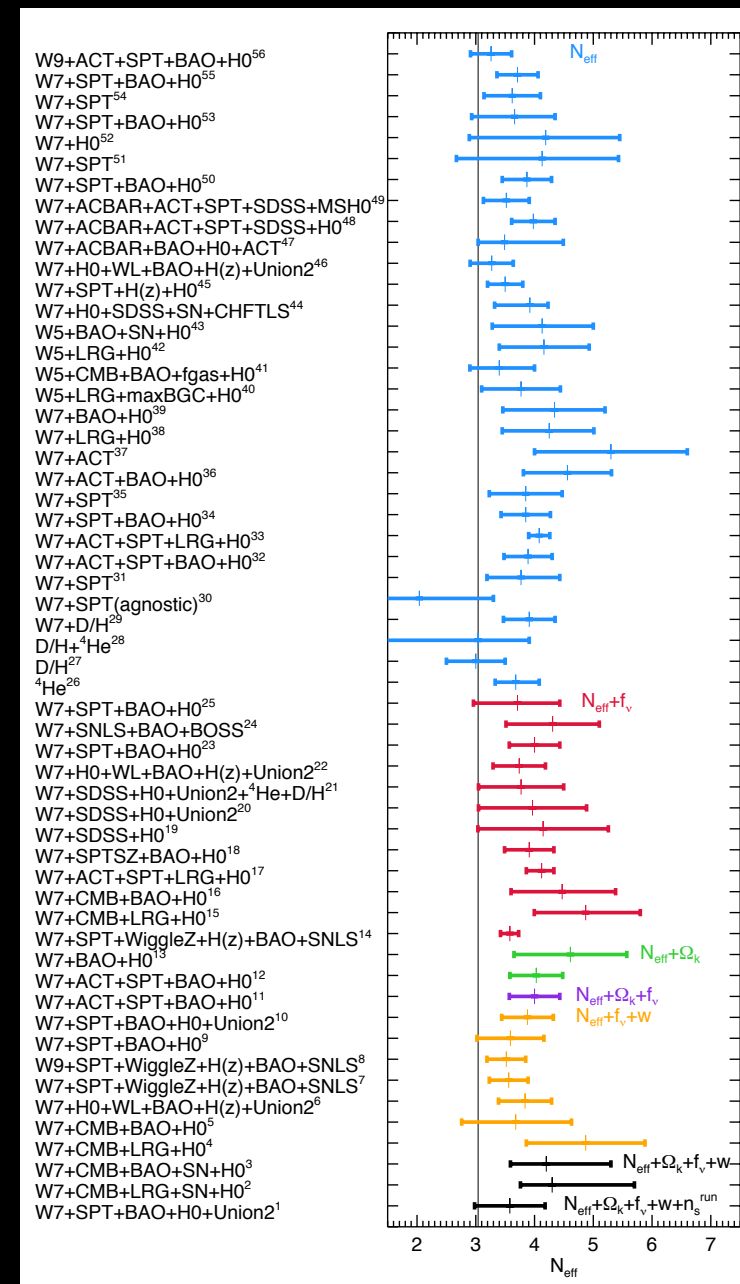
Stephen Feeney (UCL)

**with Hiranya Peiris (UCL) and Licia Verde (Barcelona & CERN)**

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}) for now

Riemer-Sørensen et al. [2013]

Where do these hints come from?

- N_{eff} degenerate with e.g. physical DM density, H_0
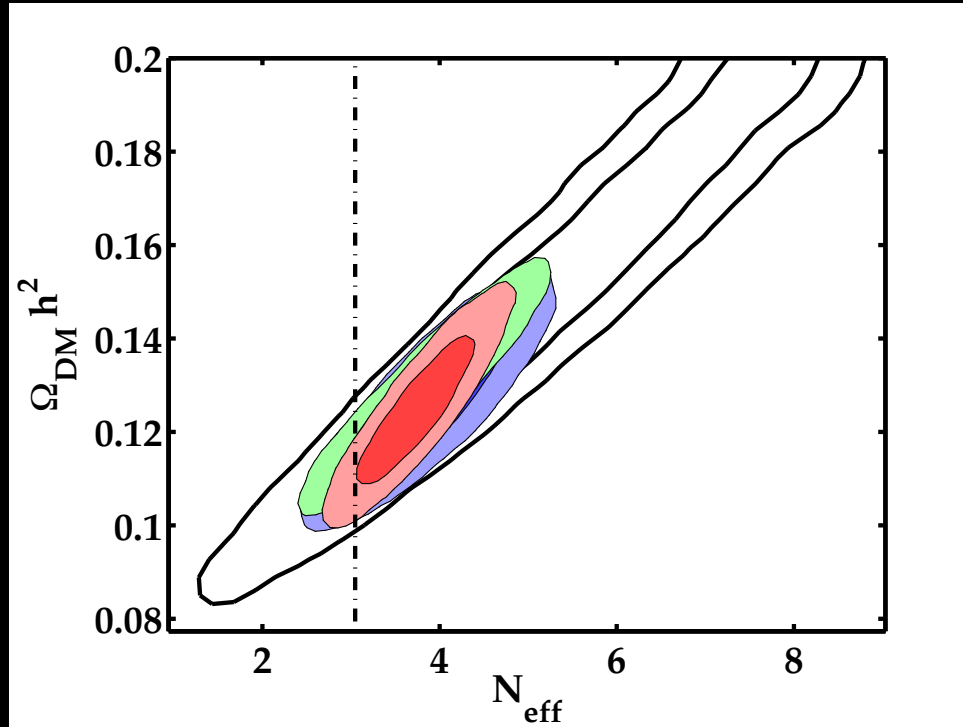
- Degeneracy is
  - cut at low N_{eff} (Bashinsky & Seljak [2004], Trotta & Melchiorri [2008])
  - but extends to high N_{eff}

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

Really need (Bayesian) model selection

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

- Parameter constraints insufficient, need

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

- 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)
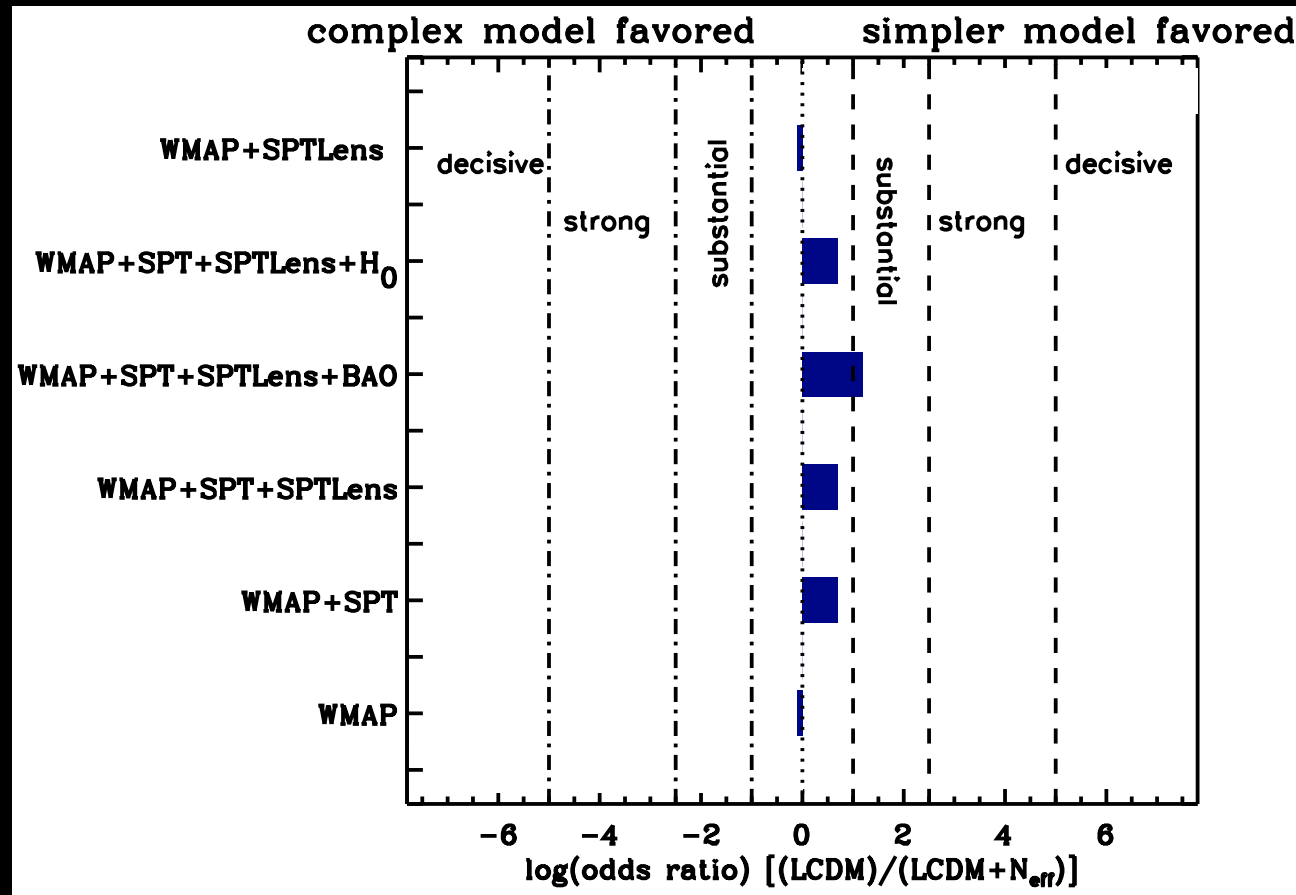
- No evidence for additional neutrinos!

    – 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

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

  - prior-"independent"

  - not rigorous model selection, but informative

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

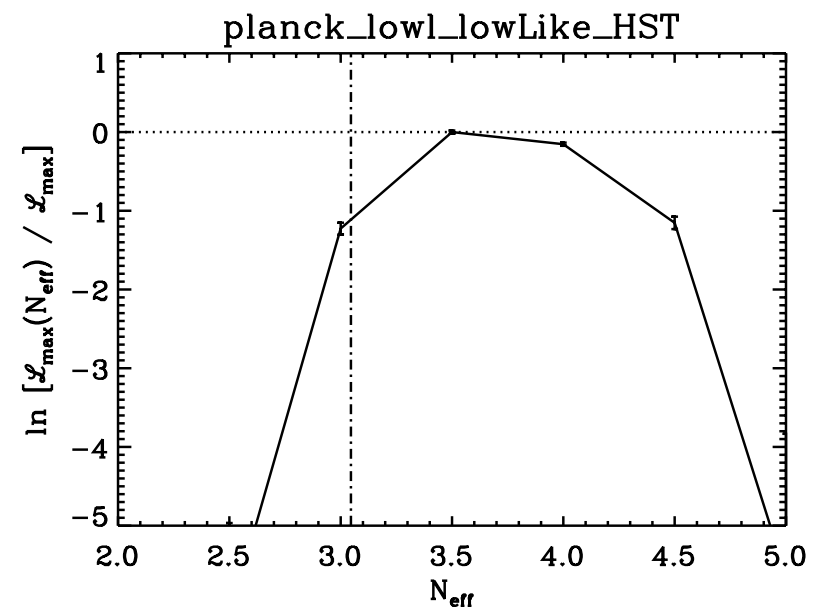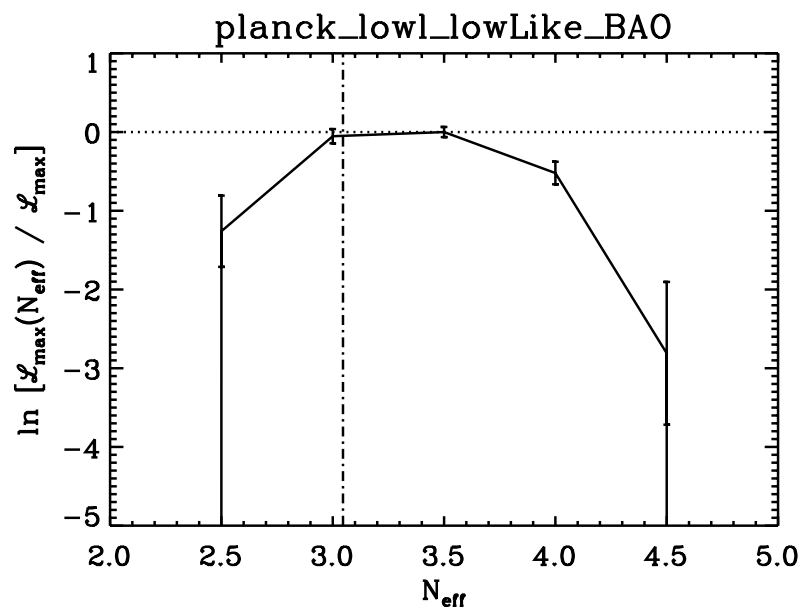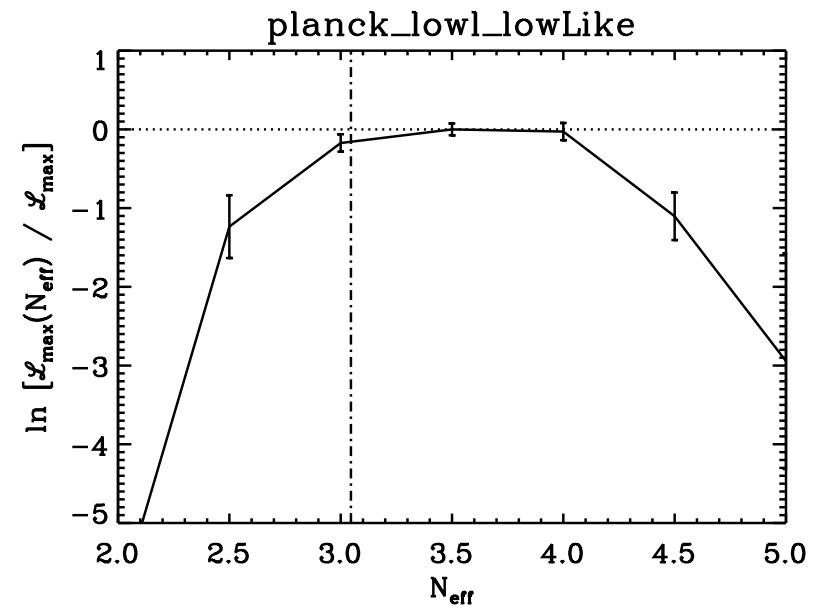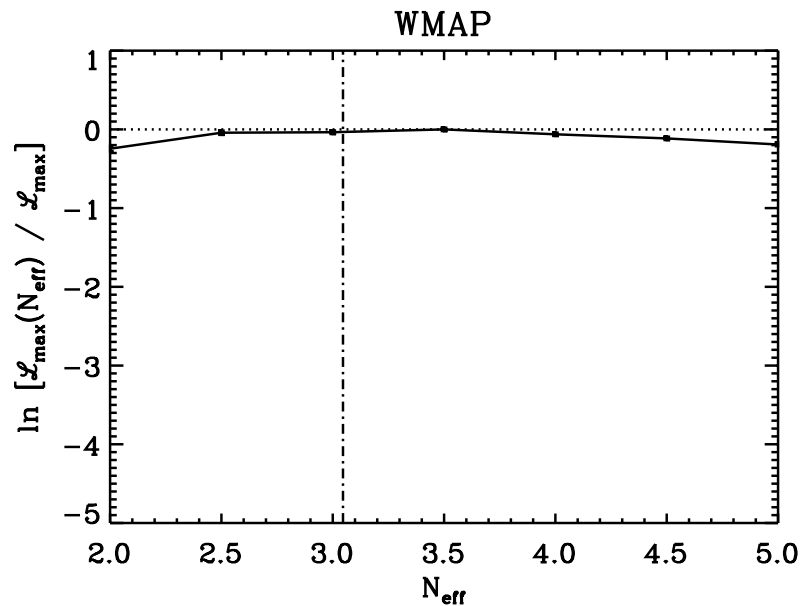# Profile likelihood ratios (pre-Planck)
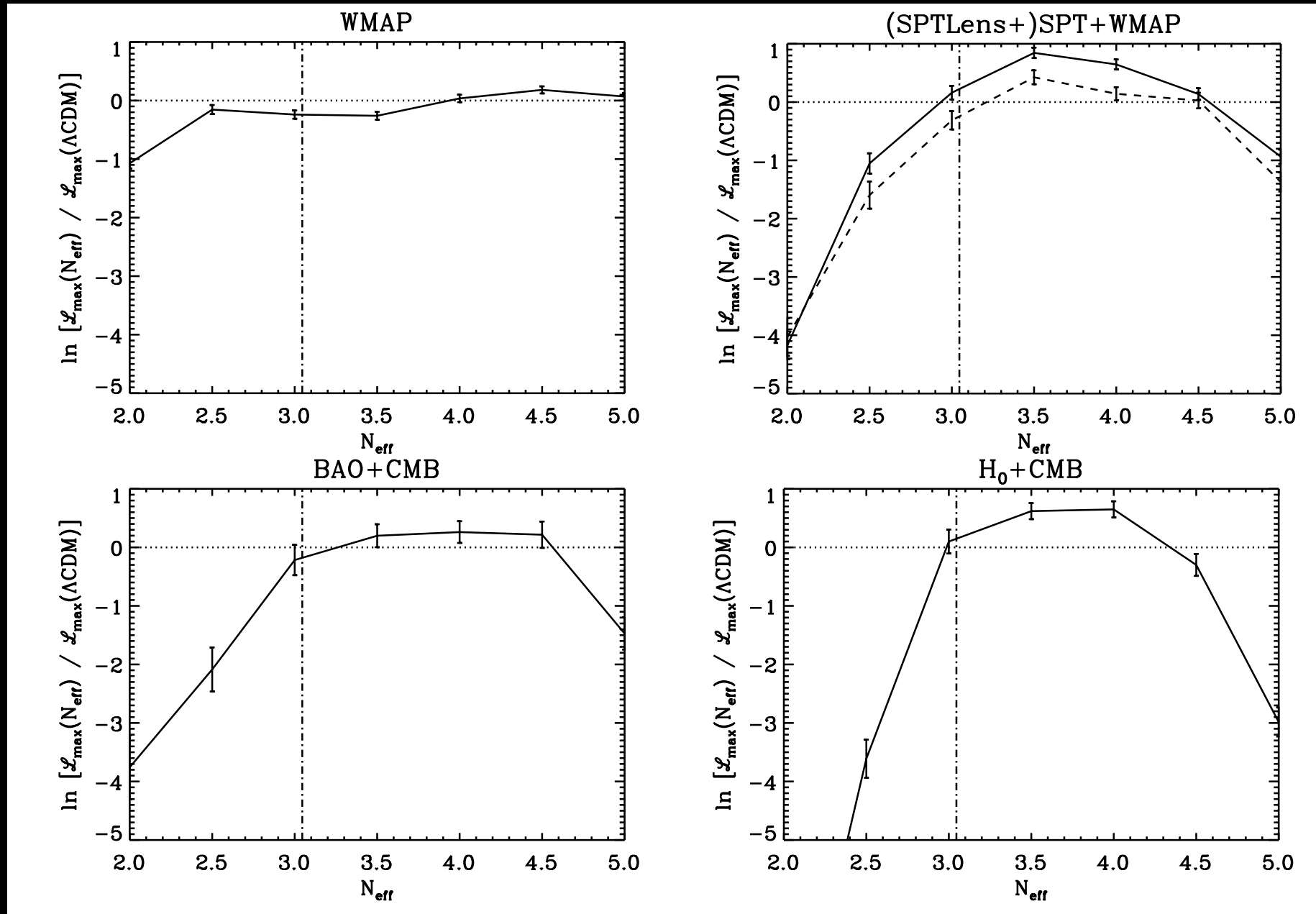
- No *preference* for additional neutrinos

Planck evidence ratios
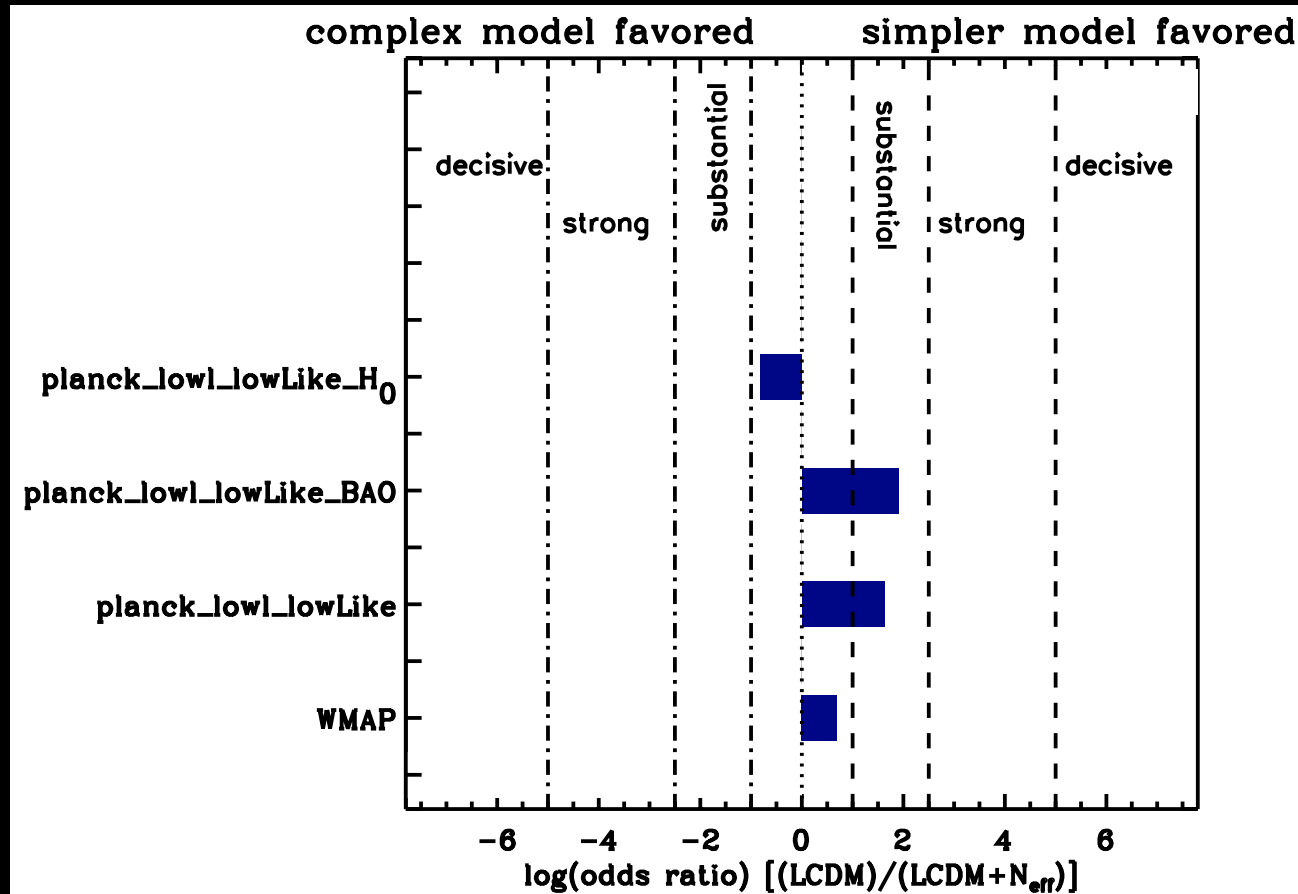
- No evidence for additional neutrinos!

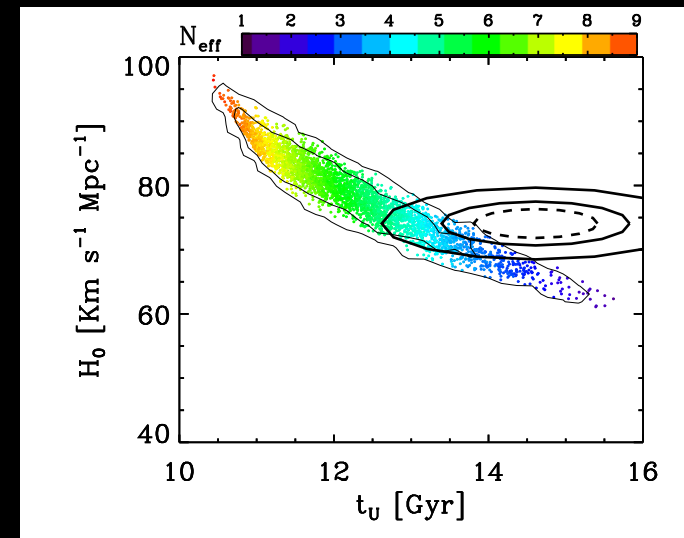 - odds ~6:1 in favour of ΛCDM

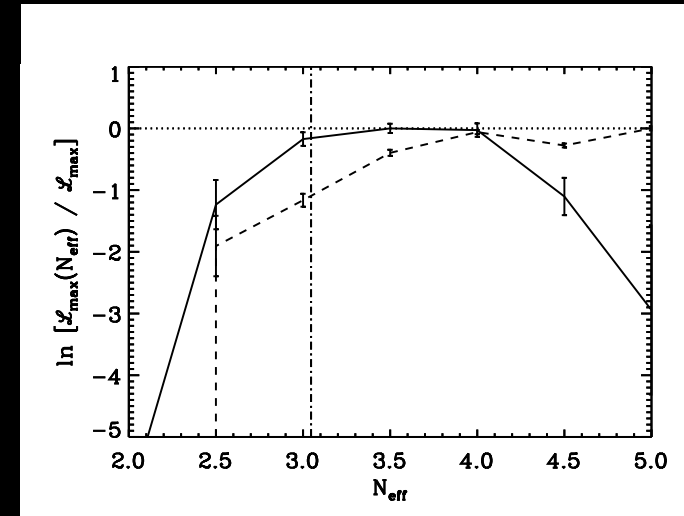# Planck profile likelihood ratios

- Even with discrepant HST data, not even 2 sigma
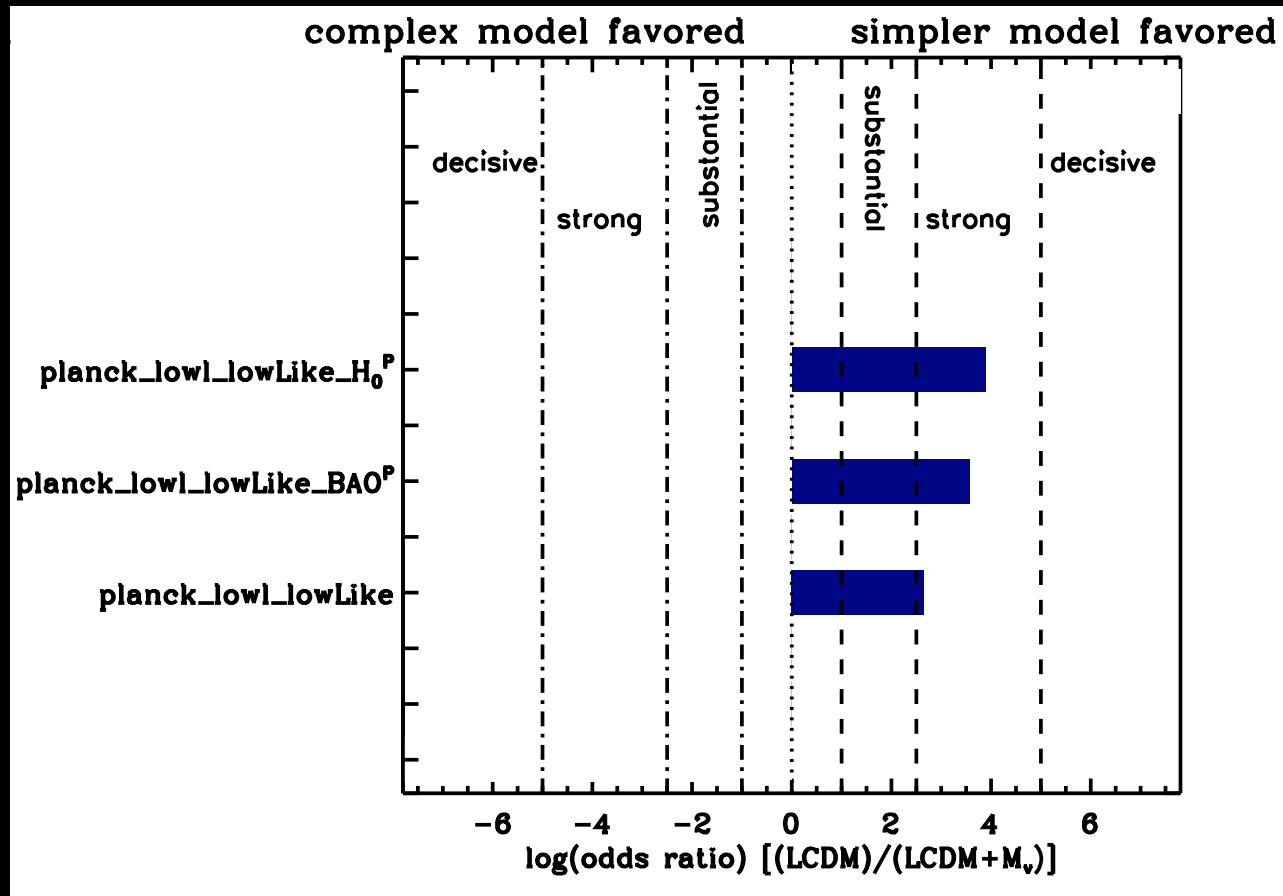
Where do we go from here?

- No evidence / preference [delete as appropriate] for additional neutrino species (MBν?)

- Continuing the search:
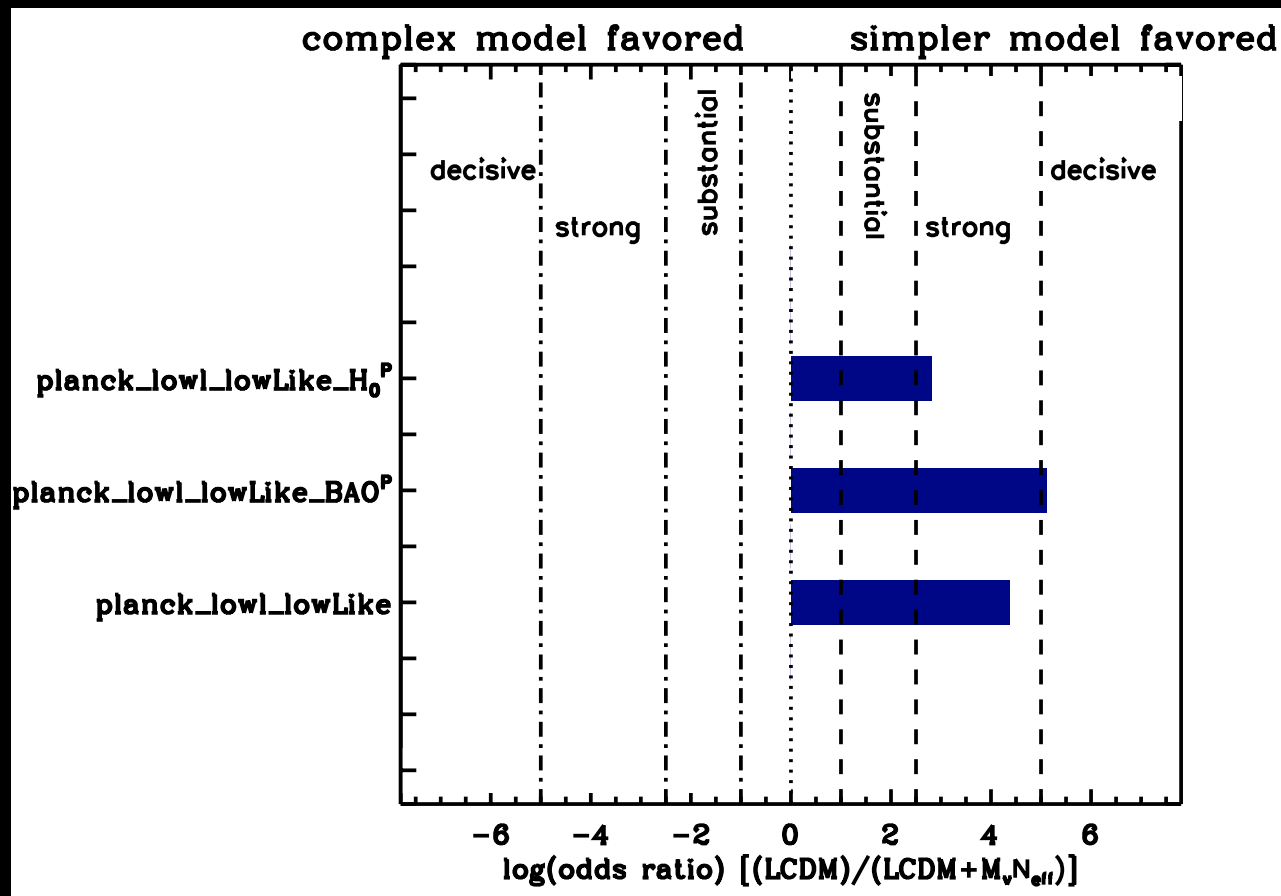
    - Planck polarisation

    - Local measurements of H_0 and age of the Universe

        - see Verde, Jimenez & SF (arXiv: 1303.5341)

    - CMB lensing

Neutrino mass

Neutrino mass *and* number of species

Number of species assuming one sterile