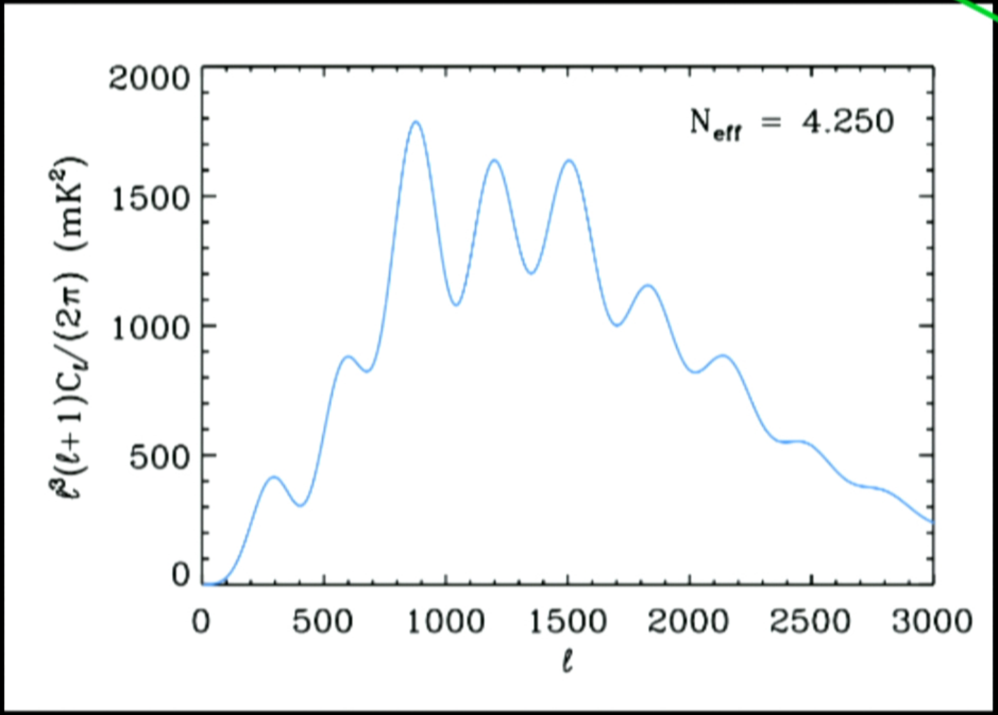
Title: Is there evidence for additional neutrino species from cosmology?

Date: Nov 12, 2013 11:00 AM

URL: http://pirsa.org/13110083

Abstract: It has been suggested that recent cosmological and flavor-oscillation data favor the existence of additional neutrino species beyond the three standard flavors. We apply Bayesian model selection to determine whether there is any evidence from current cosmological datasets for the standard cosmological model to be extended to include additional neutrino flavors. The datasets employed include cosmic microwave background temperature, polarization and lensing data, and measurements of the baryon acoustic oscillation scale and the Hubble constant. We also consider other additional neutrino physics, such as massive neutrinos, and possible degeneracies with other cosmological parameters.

Is there cosmological evidence for a fourth neutrino?



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

Stephen Feeney (IC)

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

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

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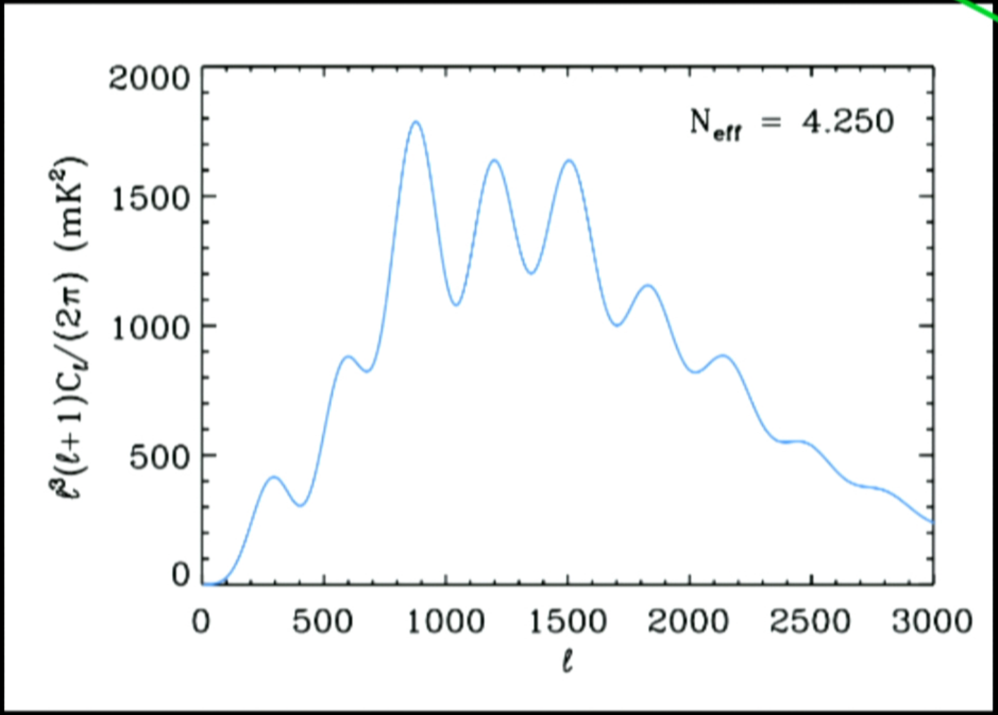

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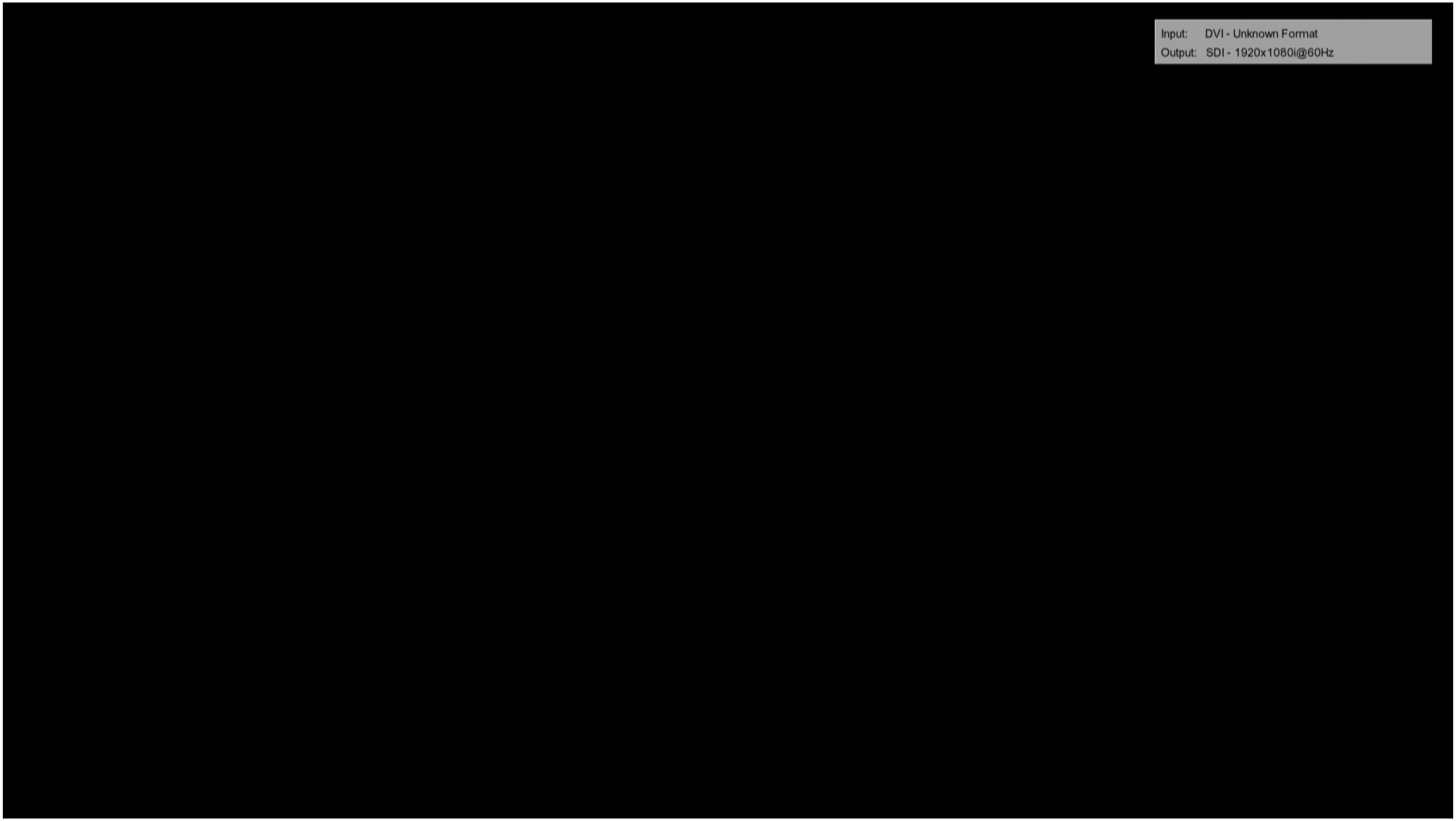
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Outline

Input: DVI - 1920x1080p@59.78Hz
Output: SDI - 1920x1080i@60Hz

- Neutrino background
  - Standard Model neutrinos
  - Motivation for extensions
- Additional neutrinos
  - Effects on cosmology
  - Model selection, not parameter estimation
  - Data and results
- Massive neutrinos (and other extensions)
  - Effects on cosmology
  - Results

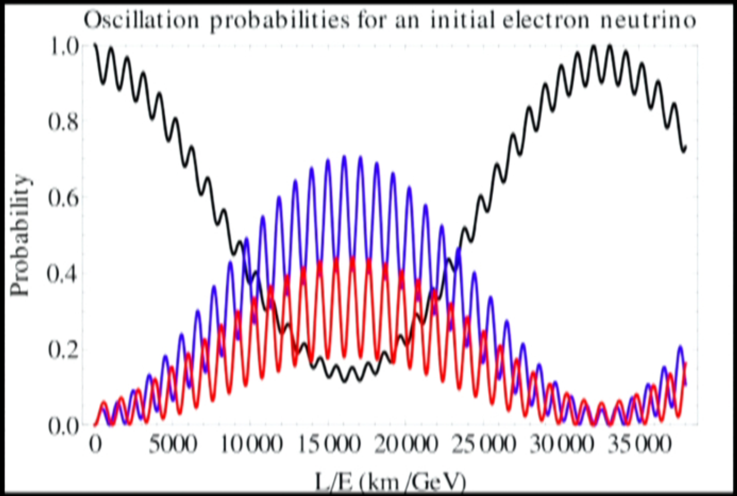
Cosmological Neutrinos

- Standard Model + Big Bang predicts neutrino background
- 3 flavours — ν_e, ν_μ and ν_τ — all massless
- Weakly interacting: decouple at T ~ 1MeV
- *Almost* decoupled before e^--e^+ annihilation: $T_\nu < T_{CMB}$
  - some high-energy ν slightly reheated
- T_ν boost equivalent to increasing $N_\nu = 3$ to $N_{eff} = 3.046$

$$\rho_\nu = N_{\rm eff} \frac{7\pi^2}{120} T_\nu^4 \qquad\qquad T_\nu = \left(\frac{4}{11}\right)^{1/3} T_{\rm CMB}$$

Neutrinos beyond the Standard Model

- Particle physics experiments imply standard neutrino picture wrong
  - solar, atmospheric and terrestrial ν observed to change flavour
- Oscillations require neutrino mass
  - flavour eigenstates ≠ mass eigenstates
  - flavours can change as ν propagate



Wikipedia Commons

- If we've got massless bit wrong, what about number?

Neutrinos *further* beyond the Standard Model?

- Hint of sterile neutrino(s) from short-baseline oscillation experiments? (e.g. Gninenko [2011])

- Cosmological tests hint at >3 species
  - many analyses indicate N_{eff} > 3.046 at 1-2 σ
  - ACT (Dunkley et al. [2010]) “weirdest”
  - not independent, of course!

- Let’s concentrate on (effective) number of species (N_{eff})
  - what could cause hints?
  - how does cosmology constrain N_{eff}?

Riemer-Sørensen et al. [2013]

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What do we measure in the (low-l) CMB?

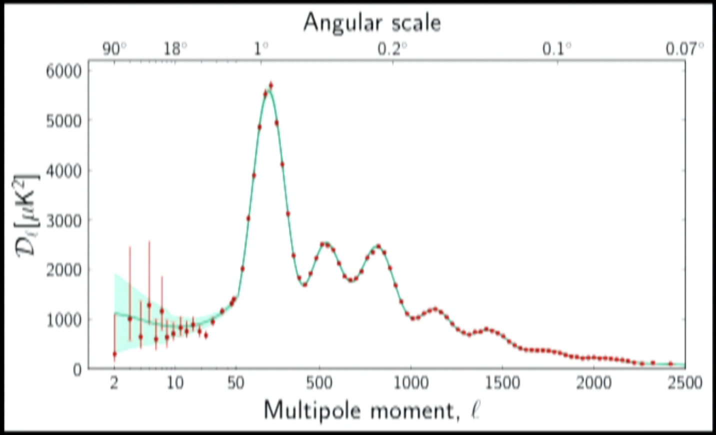
- Measure CMB acoustic peak locations and heights

following Hou et al. [2011]

  - positions constrain angular scale of sound horizon, θ_s
  - relative heights constrain redshift of matter/radiation equality, $1 + z_{eq}$ and baryon density, $\Omega_b h^2$

- Cosmological parameters derived from these quantities

- Affected by two main physical processes
  - propagation of sound waves
  - Silk (diffusion) damping



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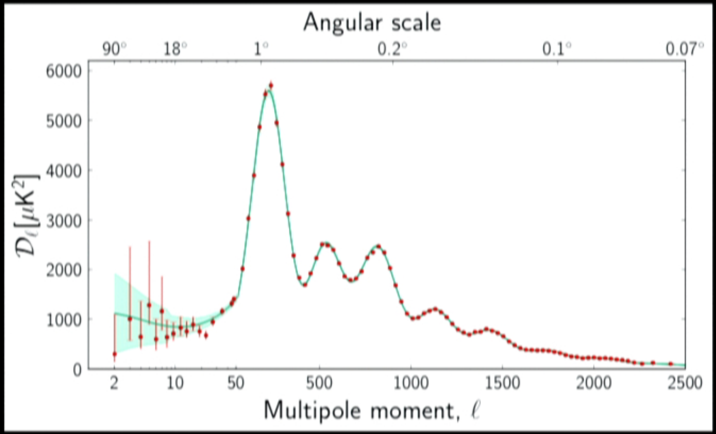

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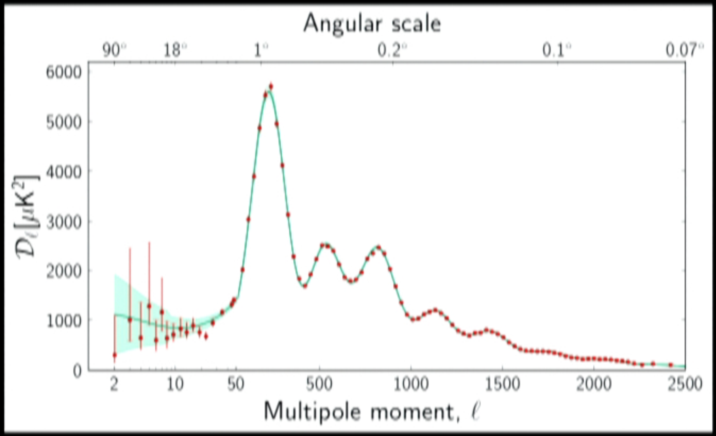


Planck I [2013]

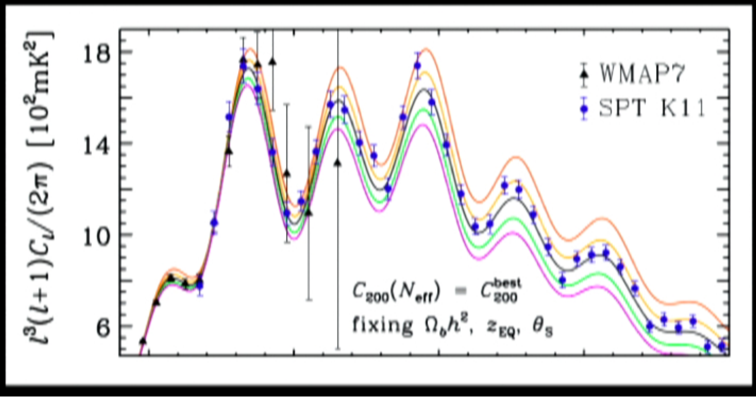
How do massless neutrinos affect the CMB?

- 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 $\propto t^{1/2} \propto H^{-1/2}$

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

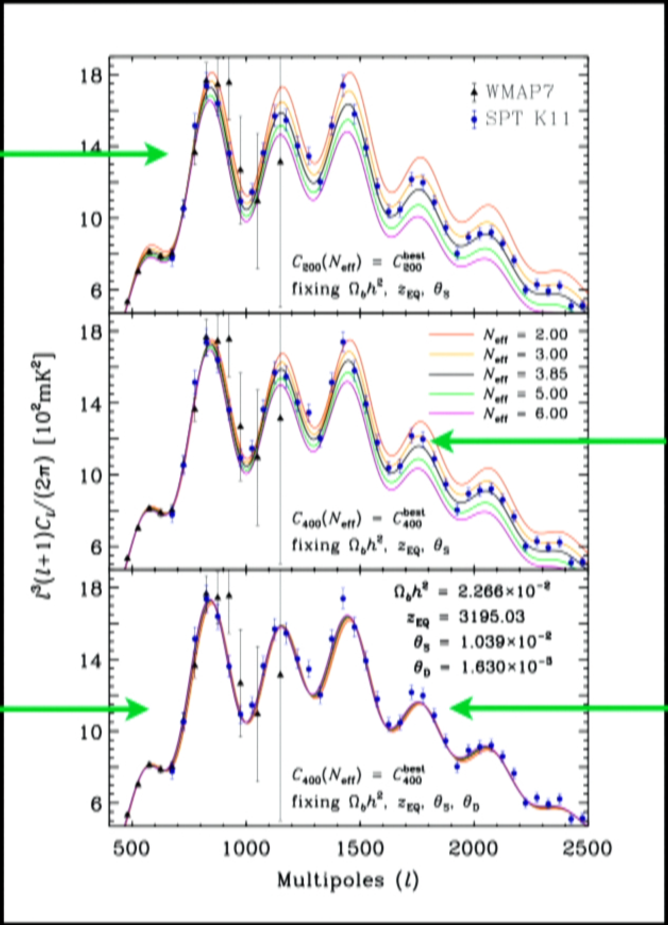
- Main effect: increasing N_{eff} increases Silk Damping scale (for fixed θ_s)

Hou et al. [2011]



How massless neutrinos affect the CMB

Fix z_{eq}, θ_s and $\Omega_b h^2$, vary N_{eff}



Normalize at l = 400: not early ISW

Now fix θ_d too: hardly any difference!

Note tiny phase shift though! (Bashinsky & Seljak [2002])

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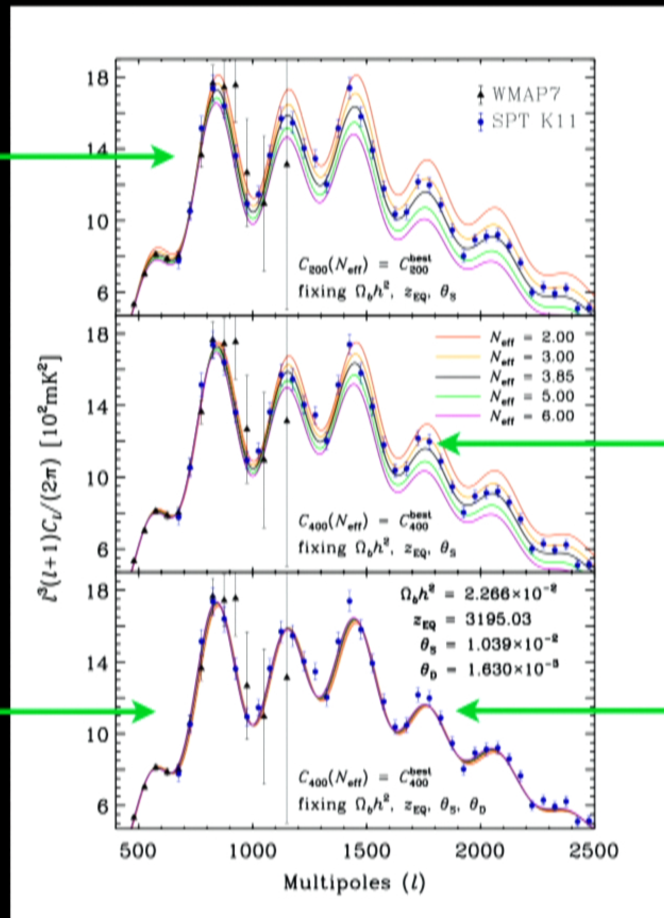

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Hou et al. [2011]

Which cosmological probes are useful?

- High-l CMB (obviously)
  - increasing N_{eff} damps small-scale power
- H_0 & H_z both increase with N_{eff}
- Measurements of light-element abundances
  - varying N_{eff} changes neutron freezeout and hence Y_{He} & Y_D
- BAO not directly helpful with N_{eff} (Hou et al. [2011])
  - can help constrain other params though
- CMB lensing (though better for neutrino mass)

What else could $N_{eff} \neq 3.046$ be?

- Extensions to neutrino sector
  - neutrino decoupling more complex than modelled
  - one or more sterile neutrino(s) (Hamann et al. [2010])
- "Dark radiation"
  - early dark energy (Calabrese et al. [2011])
  - grav. waves from e.g. cosmic strings (Lizarraga et al. [2012])
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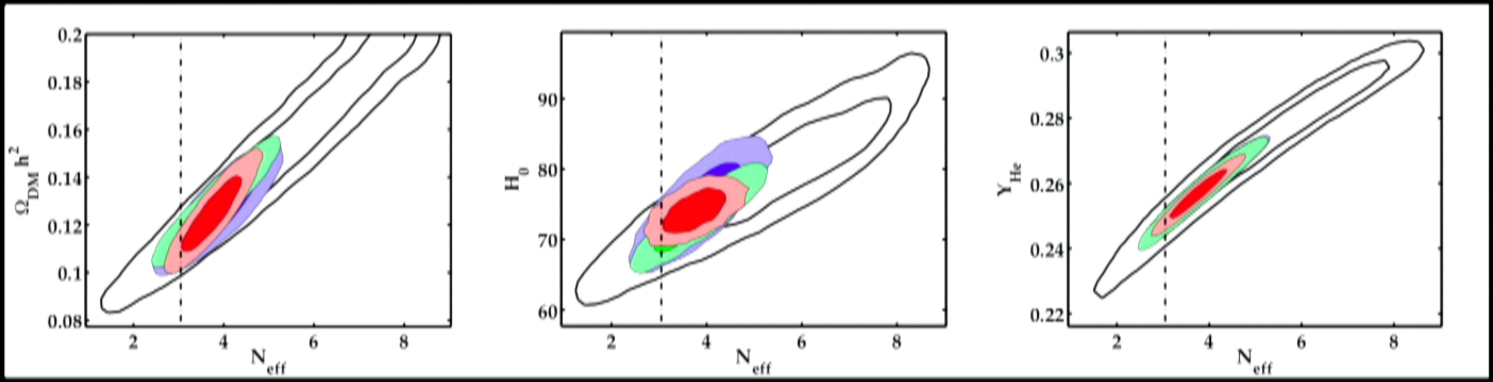
But wait: Here be Degeneracies!

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



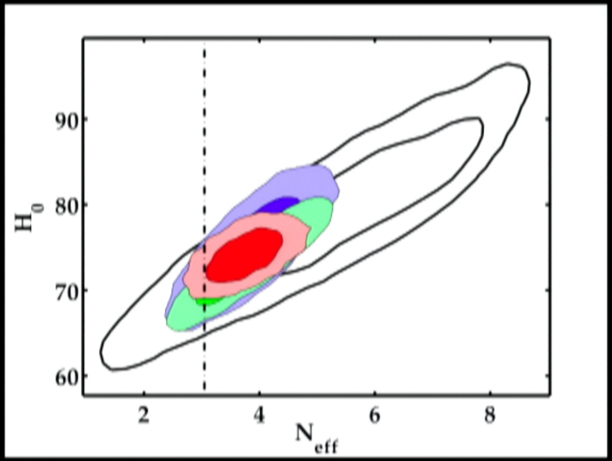
Feeney et al. [2013]

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

- Degeneracy reduced but not broken by extra data

So where else could 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 counterbalance N_{eff}
- Mean of marginalized N_{eff} posterior ∴ high!
  - easy to generate ~1σ "hints"

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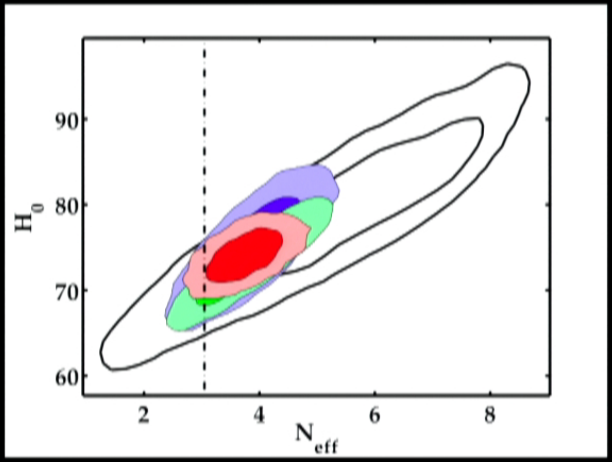

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Statistical Framework

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

- Parameter constraints insufficient
  - only tells us most likely parameter value in single model
  - hard to interpret when long degeneracies

- To answer question, need to compare model posteriors

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

prior probs — *evidence ratio*

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prior probs *evidence ratio*

Input: DVI - 1920x1080p@59.78Hz
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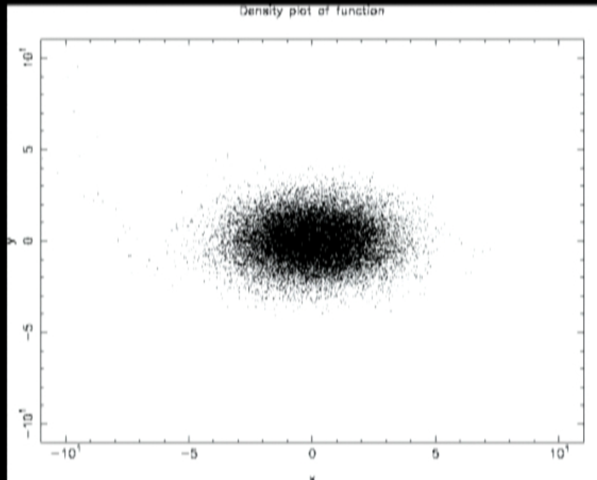
Bayesian model selection

- Must calculate model-averaged likelihood, aka Bayesian Evidence
  - i.e. $$\Pr(\mathbf{d}|M) = \int \mathrm{d}\theta \, \Pr(\boldsymbol{\theta}|M) \, \Pr(\mathbf{d}|\boldsymbol{\theta}, M)$$
- To calculate likelihood, need likelihood function(s) and data
- Two methods to calculate evidence
  - nested sampling (Skilling [2004])
  - Savage-Dickey Density Ratio (Dickey [1971])

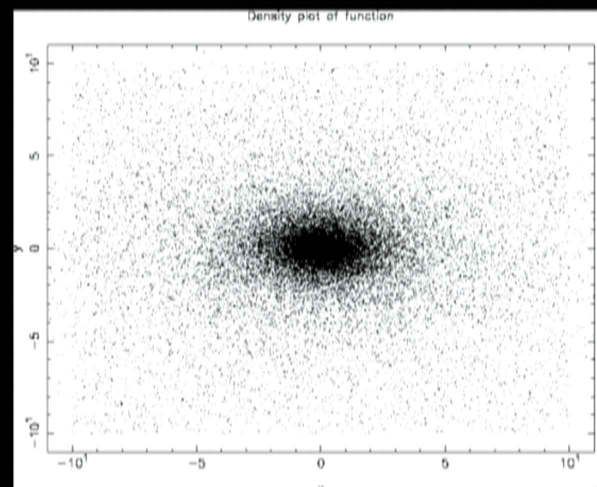
Evidence calculation 1: nested sampling



van Haasteren [2011]

- MCMC doesn't calculate Evidence by default
  - tuned to sample from posterior near peak
  - must wait a long time to explore tails

- Nested sampling designed to calculate Evidence
  - sample from prior within nested regions of constant likelihood
  - outputs parameter constraints too



van Haasteren [2011]

Evidence calculation 2: Savage-Dickey Density Ratio

- 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!

What data do we use (post-Planck)?

- 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])
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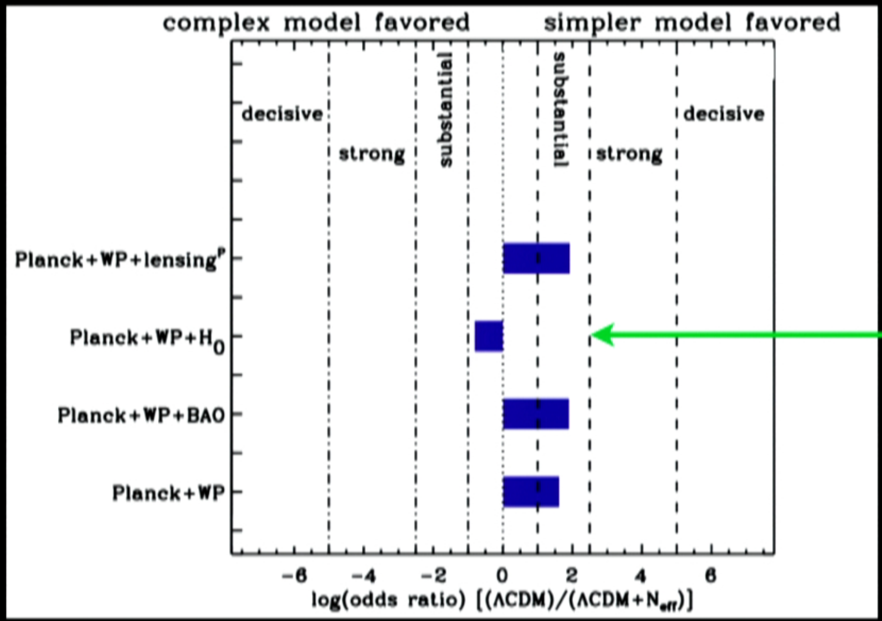
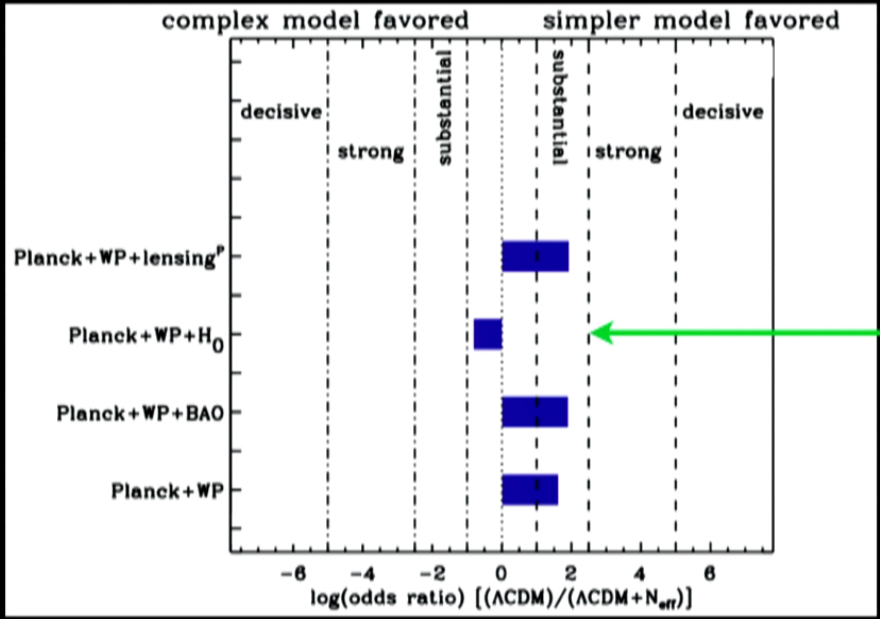
Planck evidence ratios



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 $0.05 \le N_{eff} \le 10$)?

Planck evidence ratios



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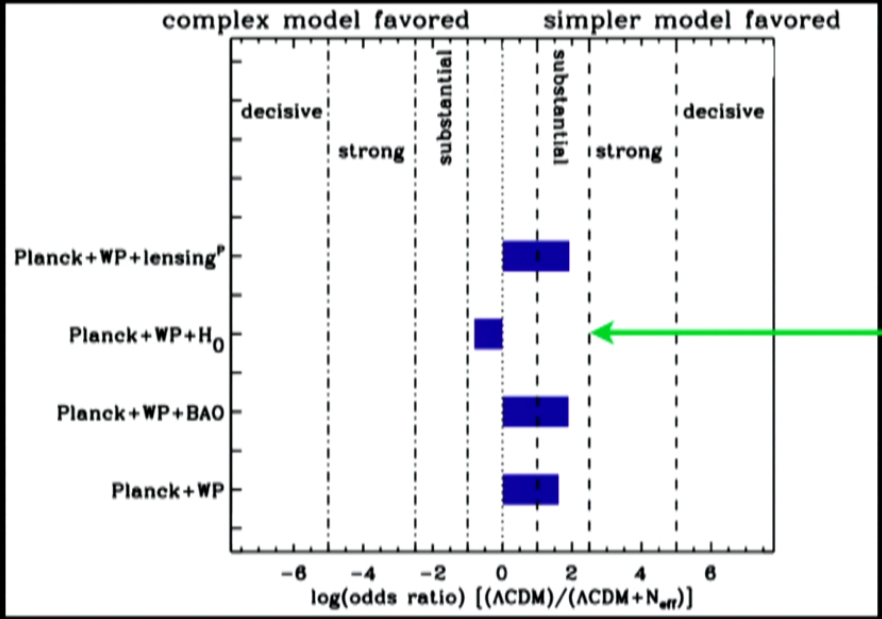

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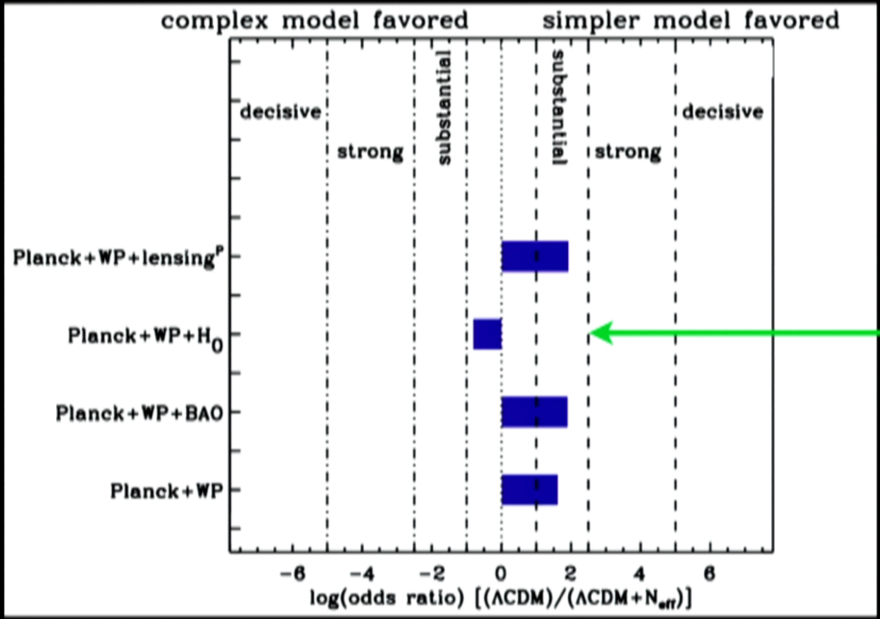

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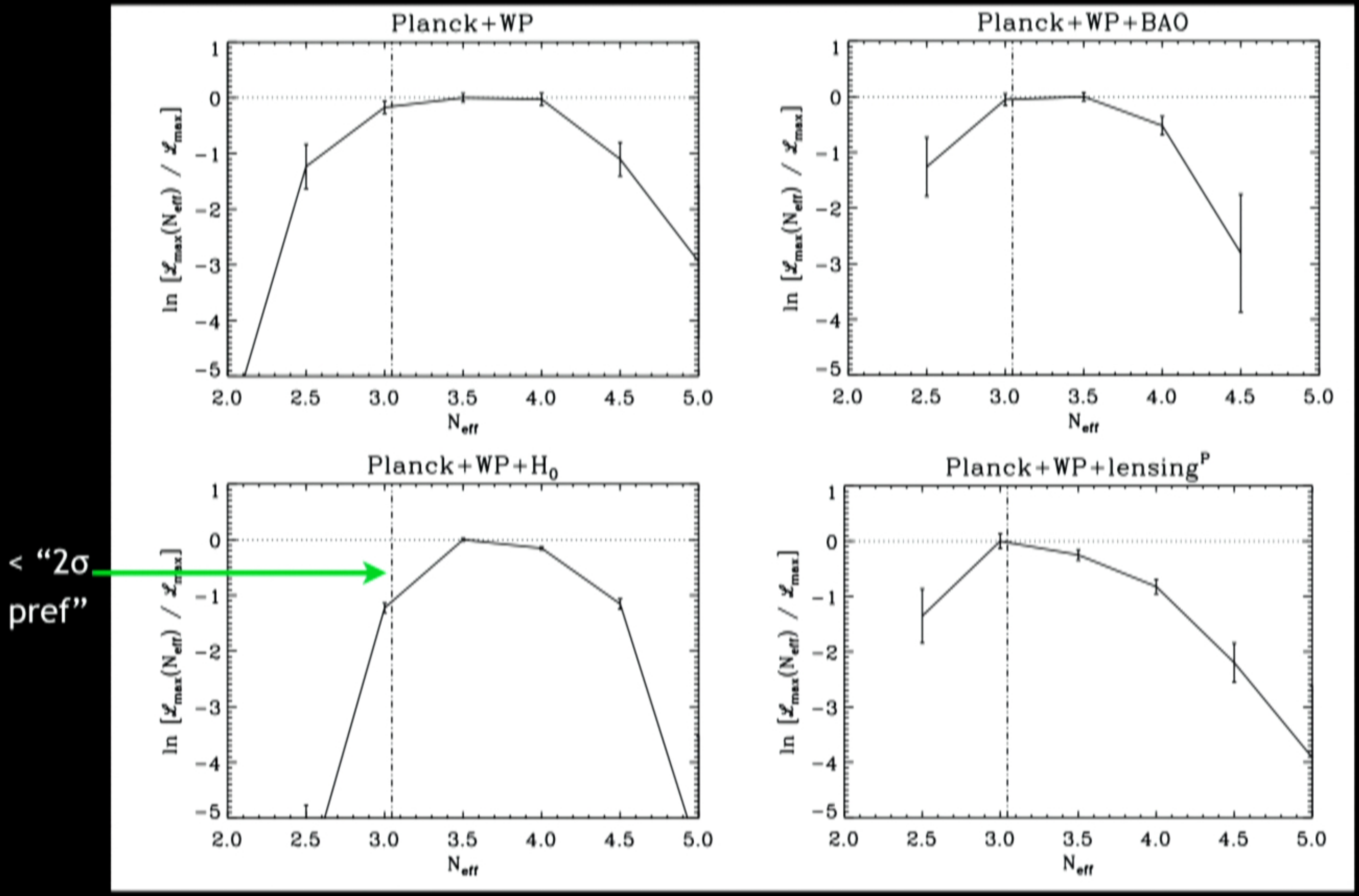
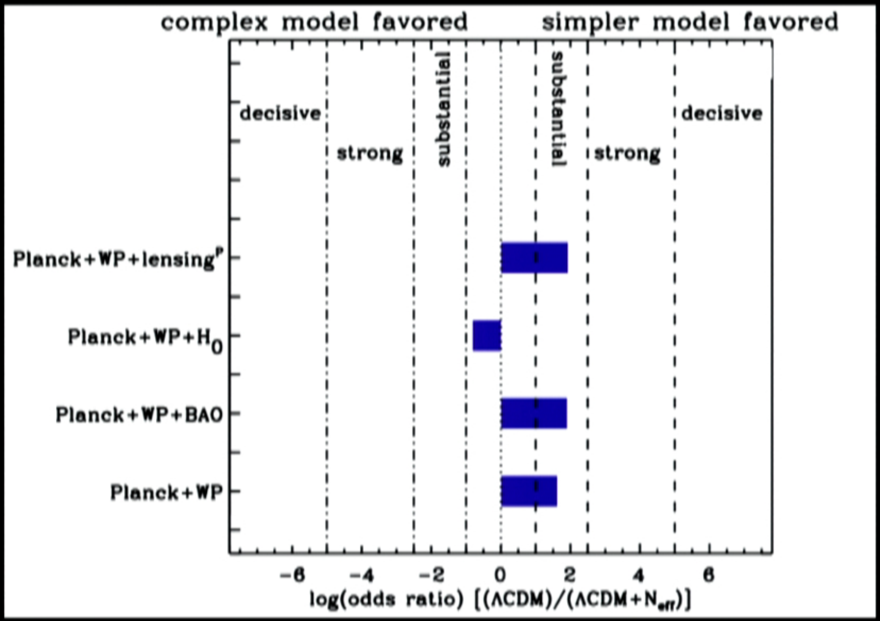
Planck profile likelihood ratios



- No *preference* for additional neutrinos

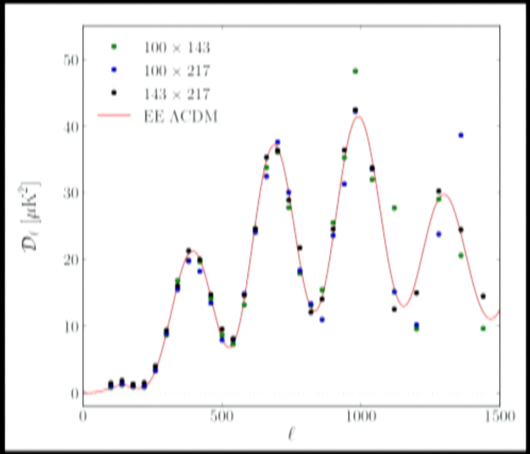
N_{eff} Conclusion

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



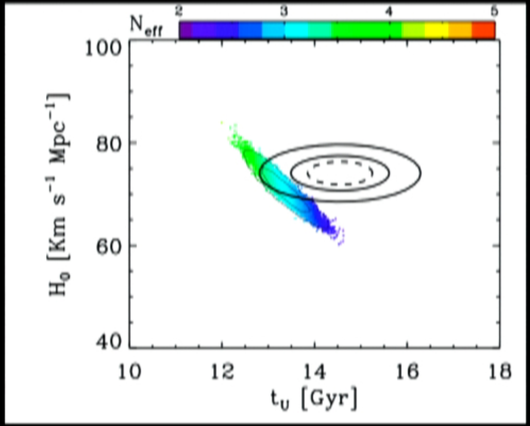
What could end the debate?

- Planck polarisation
  - polarisation peaks more prominent (Bashinsky & Seljak [2004])
  - pin down phase shift: must be neutrinos (ΔN_{eff} ~ 0.18)



Planck XV [2013]

- Precise local measurements of H_0 and age of the Universe
  - see Verde, Jimenez & Feeney (arXiv: 1303.5341, Phys. Dark Universe)
  - ages of low-metallicity stars (Bond et al. [2013])
  - investigation of systematics in H_0



Verde, Protopapas & Jimenez [2013]

Massive neutrinos

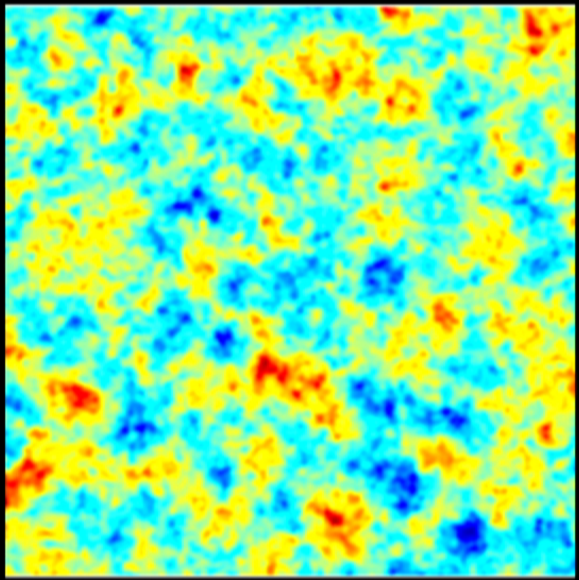
- Two mass differences measured: at least two ν are massive
  - $\Delta m_{21}^2 = 8.0 \times 10^{-5}\ eV^2$; $\Delta m_{31}^2 = 2.4 \times 10^{-3}\ eV^2$
  - one neutrino (at least) therefore > 0.050 eV
- If masses < 1eV, ultra-relativistic at decoupling, relativistic at recombination
  - neutrinos = radiation for CMB purposes
- Eventually become non-relativistic
  - hot/warm dark matter
  - damp structure formation on scales < free-streaming length

What does cosmology tell us?

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

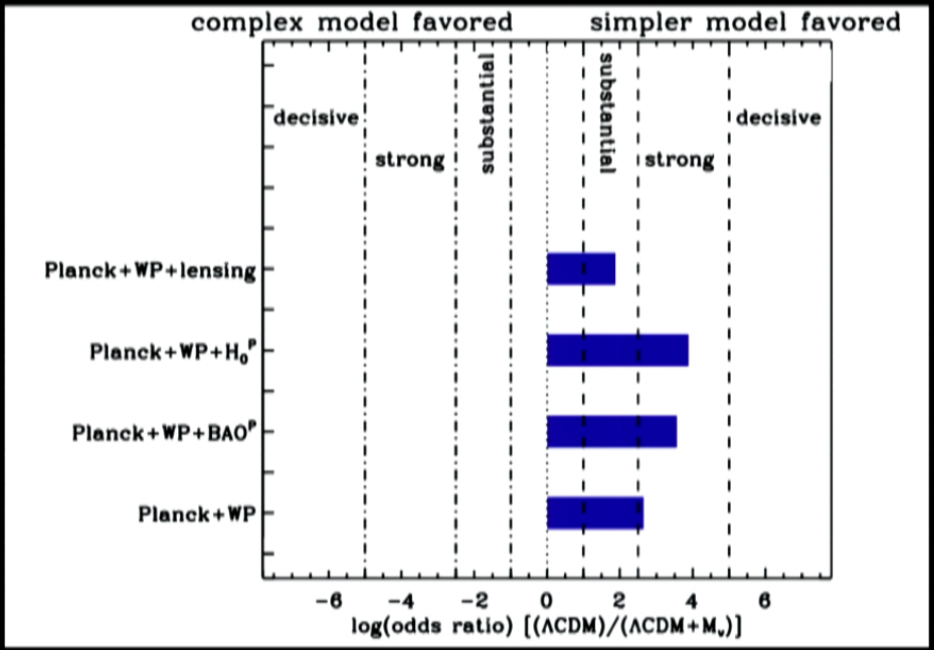
$$\Omega_\nu h^2 = \frac{\sum_{i=1}^{N_\nu} m_{\nu,i}}{94\mathrm{eV}}$$

- 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 $0 \leq M_\nu \leq 5$ eV (degenerate)



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

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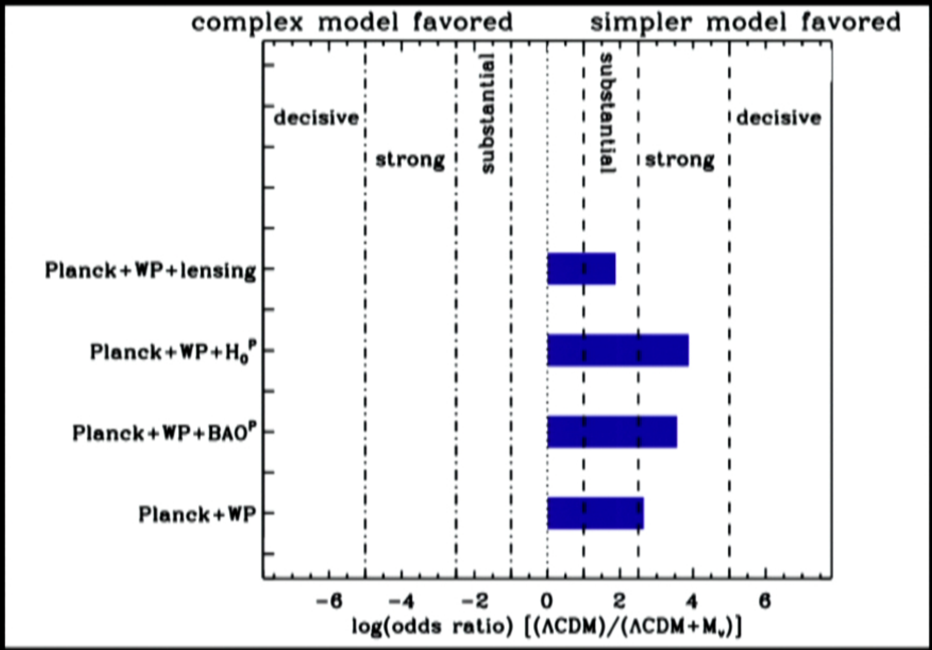

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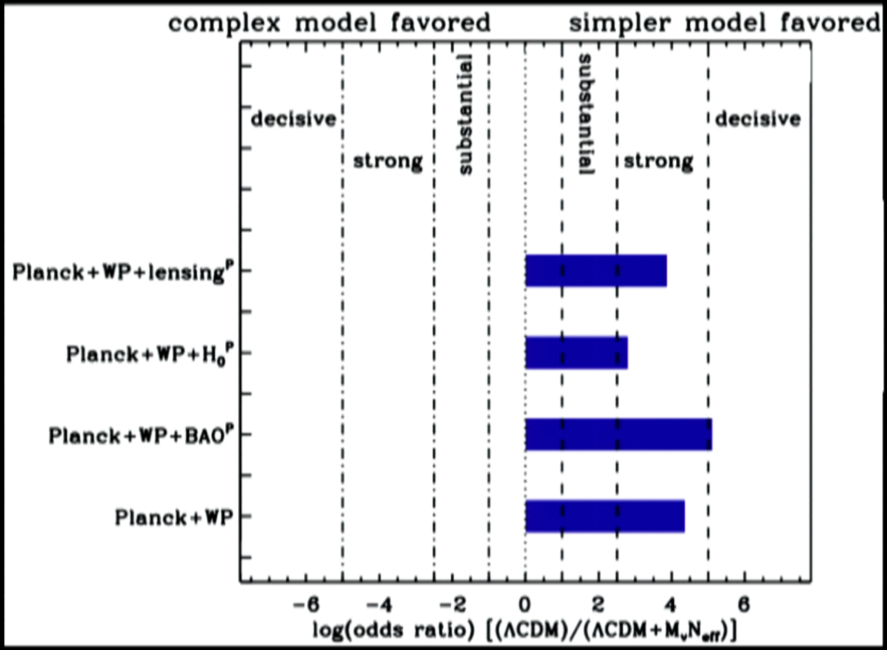
Extra neutrinos *and* neutrino mass

- 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

Evidence: neutrino mass *and* number, active

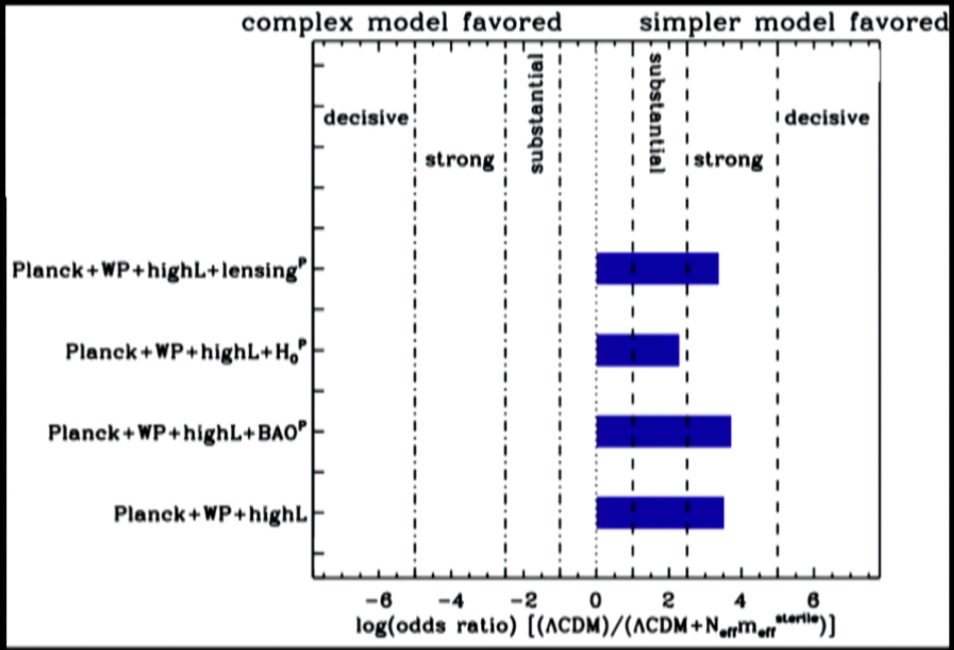
- Uniform priors: $0 \leq M_\nu \leq 5$ eV and $0.05 \leq N_{eff} \leq 10$



- Strong evidence in favour of standard cosmology

Evidence: three plus one sterile

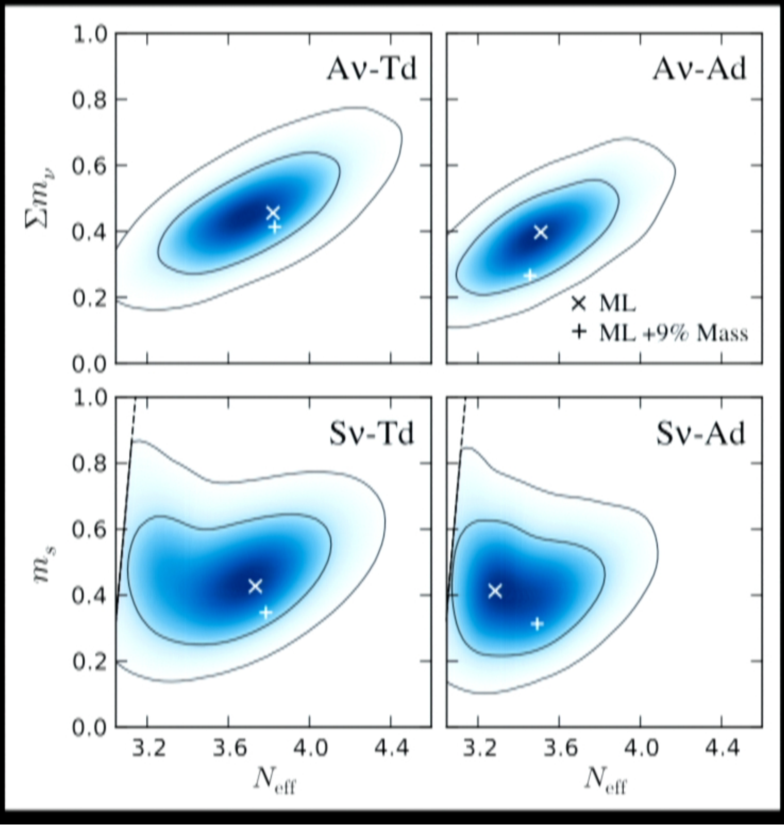
- Uniform priors: $0 \leq m_{eff,\,sterile} \leq 3$ eV and $0.05 \leq N_{eff} \leq 10$
  - fix temp & mass of sterile ν



- Again, strong evidence in favour of standard cosmology

Recent contradictions?

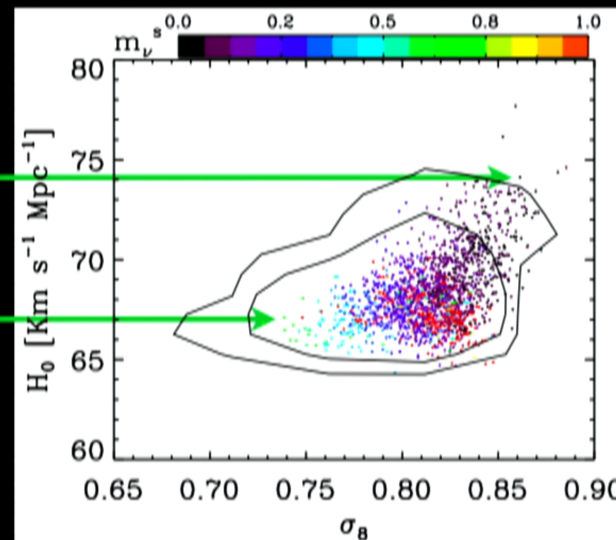
- Recent papers prefer (~3σ) one extra sterile, massive neutrino (Wyman et al. [2013], Hamann & Hasenkamp [2013], Battye & Moss [2013])



Wyman et al. [2013]

Concordance or contradiction?

- Datasets used (clusters, H_0, lensing) in tension with Planck and each other
  - HST H_0 high: wants high σ_8, low m_ν
  - clusters σ_8 low: wants low H_0, high m_ν

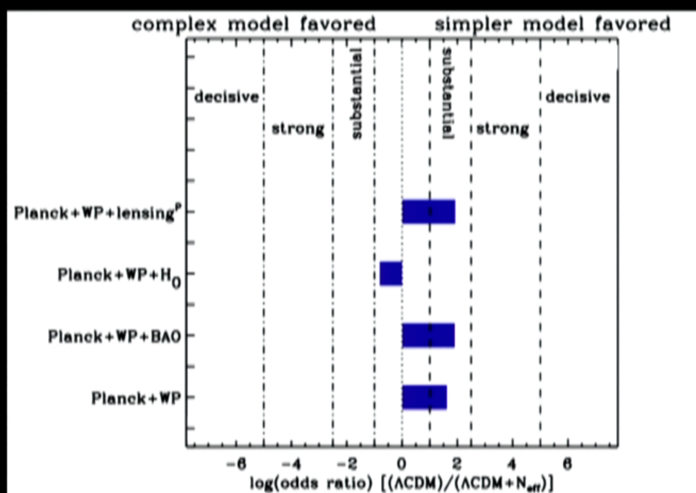


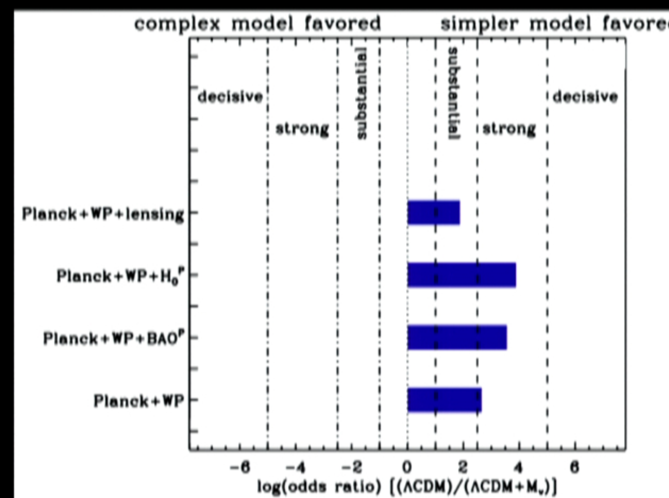
- No new concordance…
- New physics or systematics?
  - in clusters? in H_0? in *gasp* Planck?

Conclusions

- No evidence / preference [delete as appropriate] for additional neutrino species

- Neutrino mass measurement beyond cosmology for now





- Future is very interesting!