Cosmological constraints on Dark Radiation

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arxiv:1302.0014 (JCAP), arxiv: 1307.2904 (JCAP),
Leistedt et al. 2014 (to be submitted)

Outline

Focus on dark radiation interpreted as neutrino physics.

Focus on cosmological constraints only.

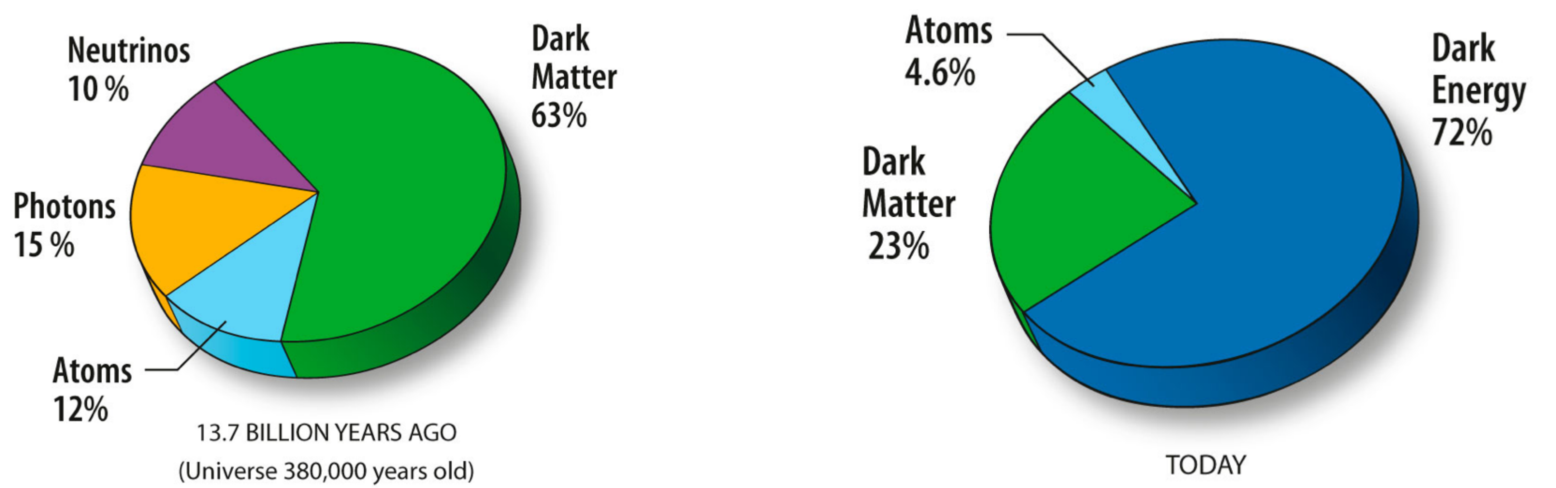
- neutrinos in cosmology
- extra neutrinos?
  .... *tension with local H0 measurement*
- massive sterile neutrinos?
  .... *tension with cluster constraints*

What is a neutrino? (in cosmology)

- Behaves like radiation at T~eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves as matter
- Small interactions (not perfect fluid)
- High velocity dispersion ("hot")

Image: LBNE/ Fermilab

Neutrinos in cosmology



- Neutrinos in equilibrium with primordial plasma through weak interaction. Decouple at ~1 MeV (2 sec, cf. CMB at 380,000 yrs)
  - *T ~ 1 eV at matter-radiation equality, T ~ 0.26 eV at recombination*
- Relativistic at decoupling ($m_\nu \ll T_\nu$) ➤ large velocity dispersions (1 eV ~ 100 km/s)
- 600 billion $\nu/cm^3/sec$ from the sun, 100 ν/cm^3 from the CνB

Image:WMAP/ NASA

Cosmic neutrino background

- Neutrinos almost decoupled by e+e- annihilation.
  some high-energy ν slightly reheated

- T_ν boost equivalent to increasing N_ν = 3 to $N_{\rm eff}$ = 3.046

$$\rho_\nu = N_{\rm eff}\frac{7\pi^2}{120}T_\nu^4$$

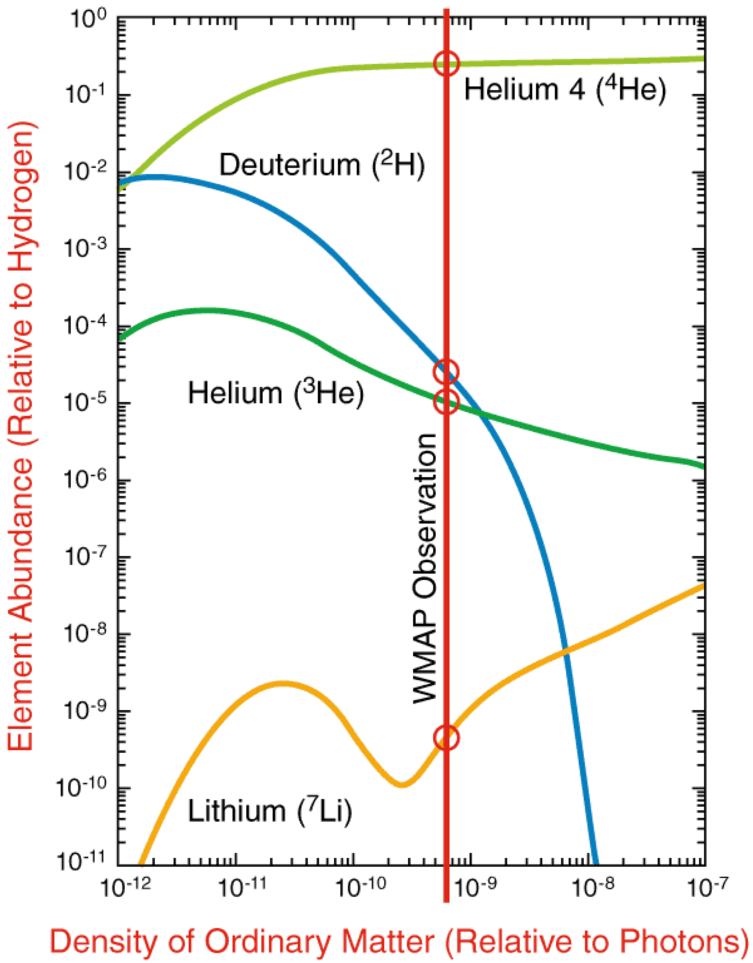
- Have a cosmic neutrino background today at temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.945\,{\rm K}$$

- For massive neutrinos, gives physical energy density

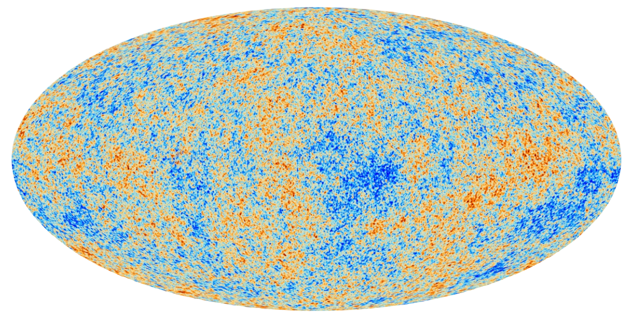
$$\Omega_\nu h^2 = \frac{\sum_i \alpha_i m_i}{94.07\,{\rm eV}}$$

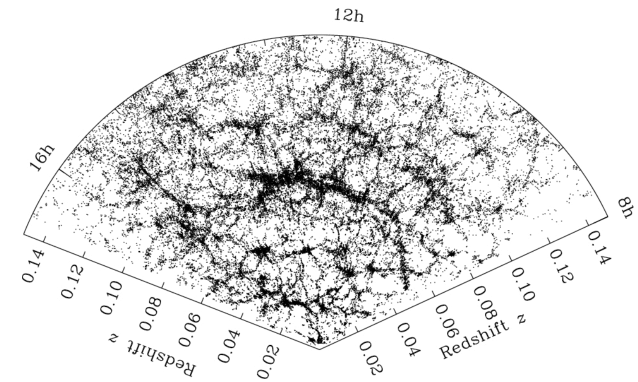
Neutrino observables in cosmology



BBN (T~MeV)

varying N$_{\rm eff}$ *changes neutron freezeout and hence* Y_{He} *&* Y_D





CMB + LSS (T<eV)

effects from both N$_{\rm eff}$ *and mass on both background and clustering*

Local measurements of H_0

N$_{\rm eff}$ *increases expansion rate at all redshifts*

Neutrinos beyond the Standard Model

- Standard Model: 3 flavours — ν_e, ν_μ and ν_τ — all massless.

- Particle physics experiments ➛ standard picture incomplete.
  solar, atmospheric and terrestrial ν change flavour

- Oscillations require neutrino mass
  - flavour eigenstates ≠ mass eigenstates
  - flavours can change as ν propagate

- What about number?

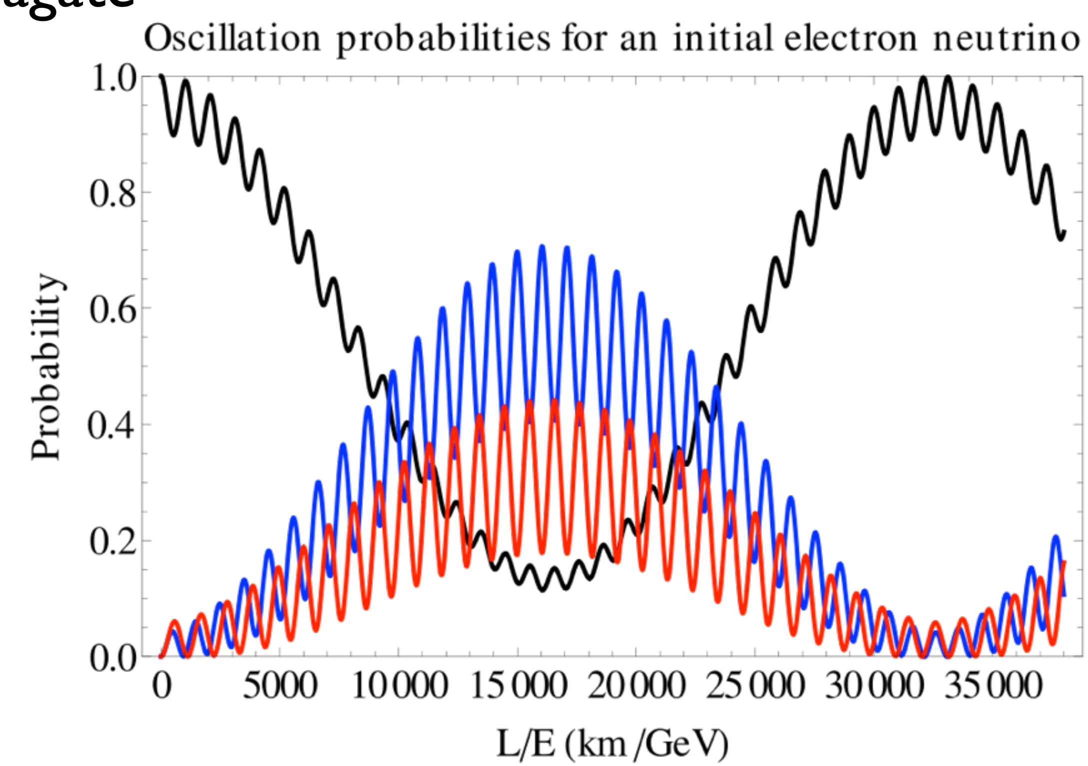


Image: Wikimedia Commons

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

- Measure CMB acoustic peak locations and heights

- Positions constrain angular scale of sound horizon, θ_s

- Relative heights ➛ redshift of matter/radiation equality, $1 + z_{eq}$ and baryon density, $\Omega_b h^2$

- Affected by:

-*propagation of sound waves*
-*Silk (diffusion) damping*

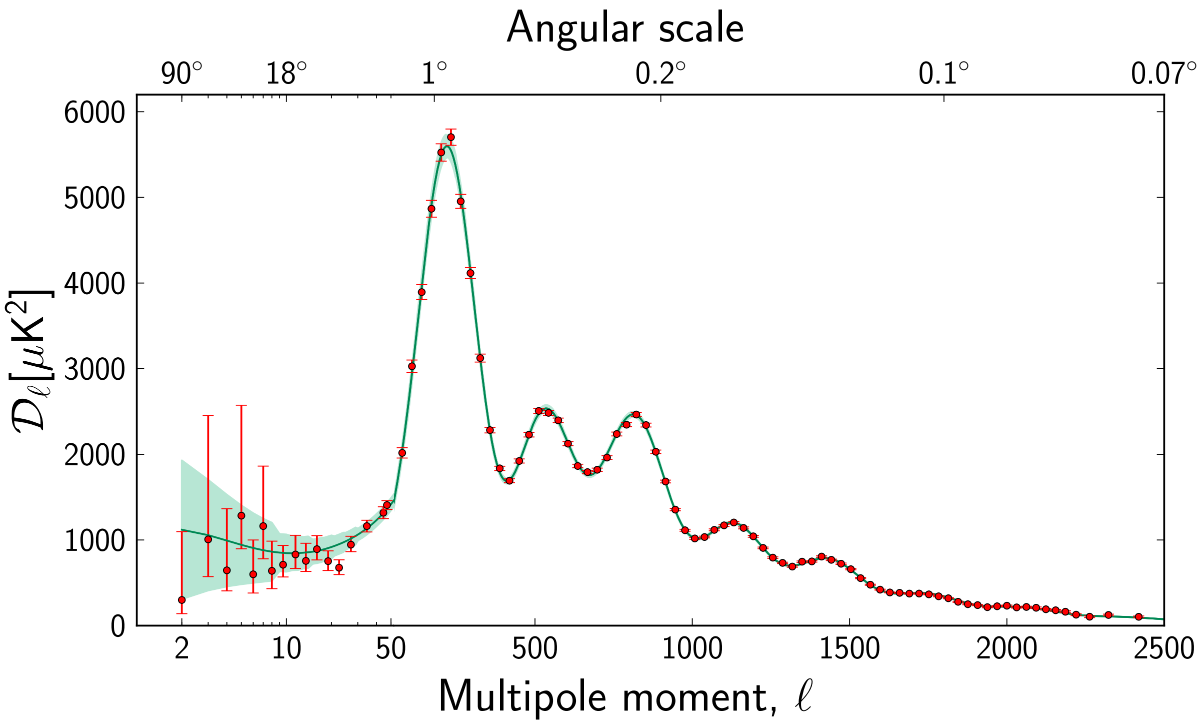


Image: ESA / Planck

How do massless neutrinos affect 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 θ_s, z_{eq}, $\Omega_b h^2$ fixed

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

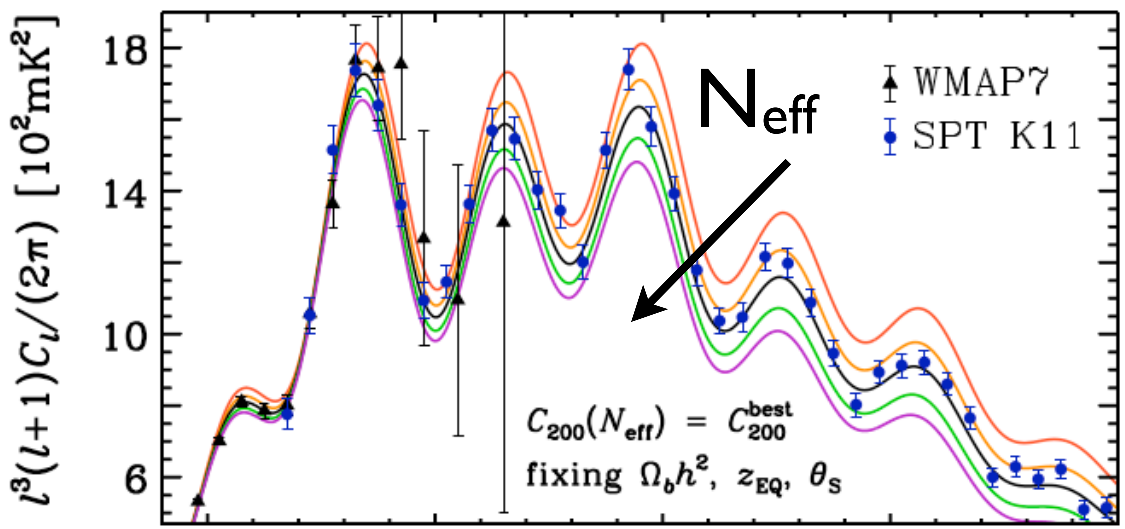
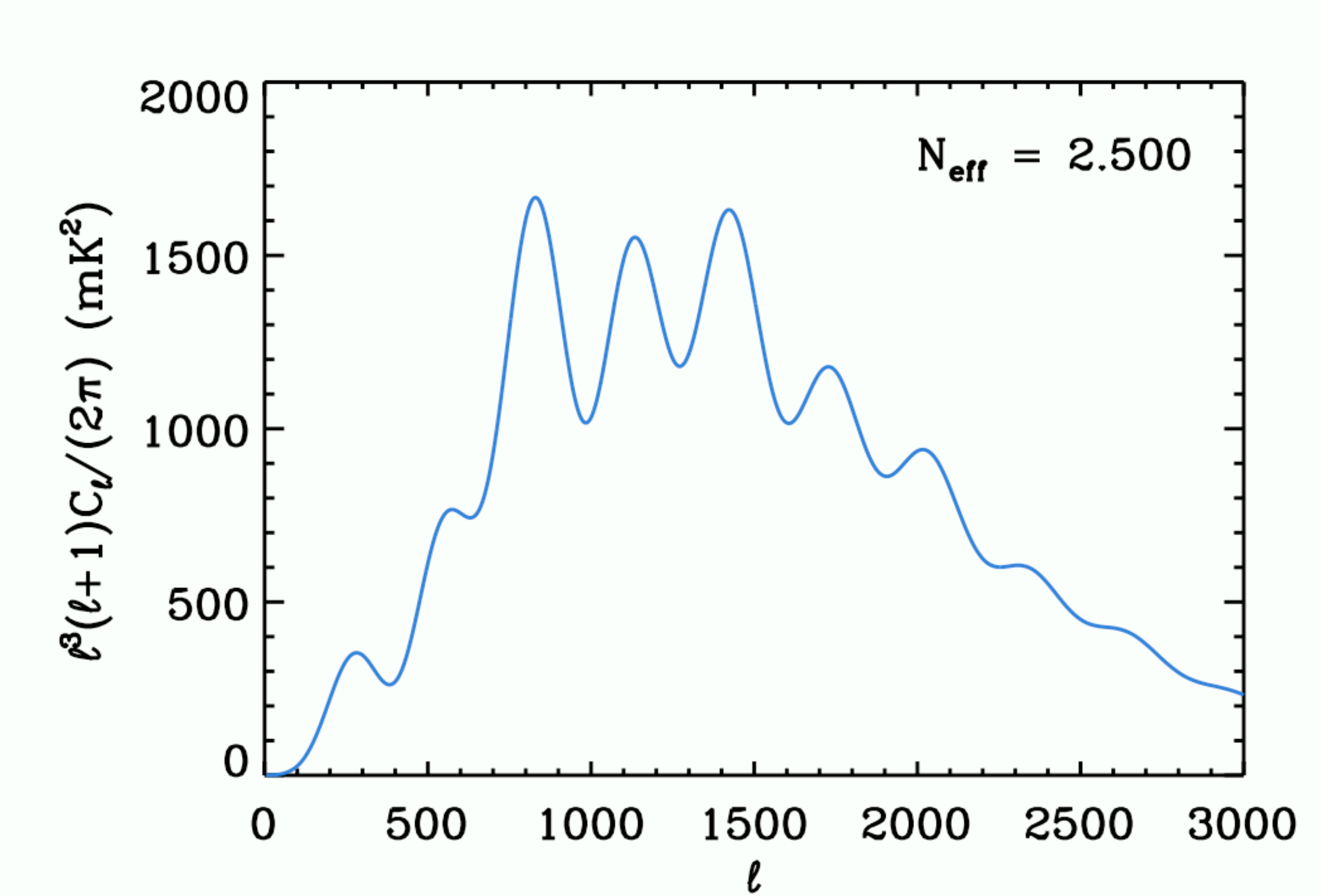


Image: Hou et al (2011)

How do massless neutrinos affect CMB?



Small phase shift too: neutrinos free-stream faster (at *c*) than sound speed of baryon-photon plasma ($c/\sqrt{3}$) [Bashinsky and Seljak 2002]

Animation: Stephen Feeney

Cosmological probes of N_{eff}

- **CMB damping tail**
  increasing N_{eff} damps small-scale power

- **H_0 & $H(z)$** both increase with N_{eff}

- **BBN**: 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

- **CMB lensing**
  better for neutrino mass

Extra neutrinos?

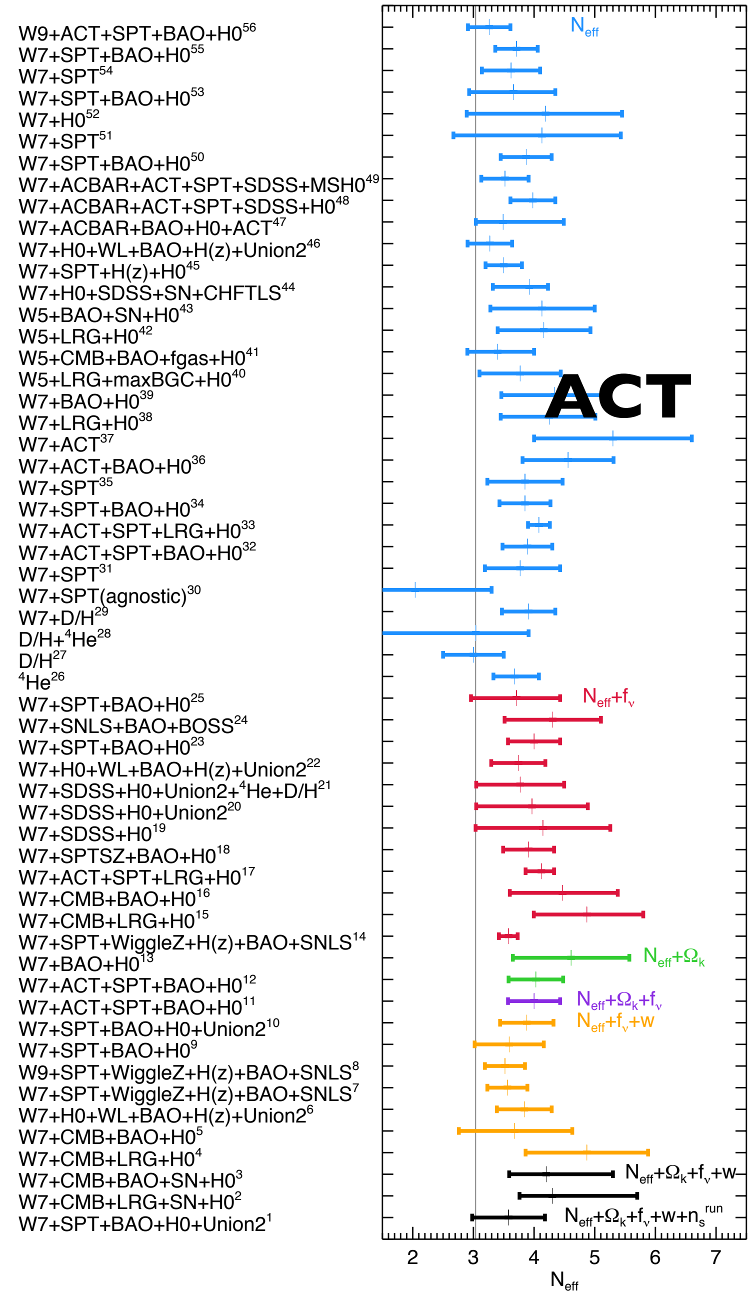
- Hint of sterile neutrino(s) from short-baseline oscillation experiments? (e.g. Gninenko [2011])
neutral leptons insensitive weak interactions, only interaction gravitational; LSND/MiniBooNE hints at 1-2 sterile neutrinos with ~eV masses

- Cosmological tests hint at >3 species

- Focus on (effective) number N_{eff}

- Many analyses indicate $N_{eff} > 3.046$ at 1-2 σ

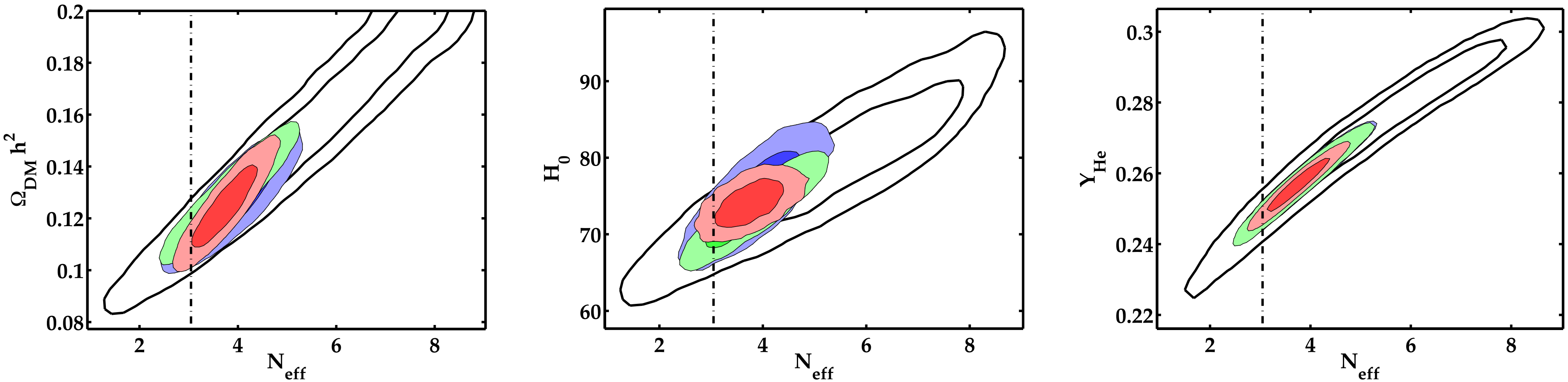
    - *ACT (Dunkley et al. [2010]) "weirdest"*
    - *not independent, of course!*



Riemer-Sørensen et al. (2013)

Degeneracies

- 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

Feeney, HVP, Verde (2013)

Degeneracies

- Degeneracy cut at low N_{eff}

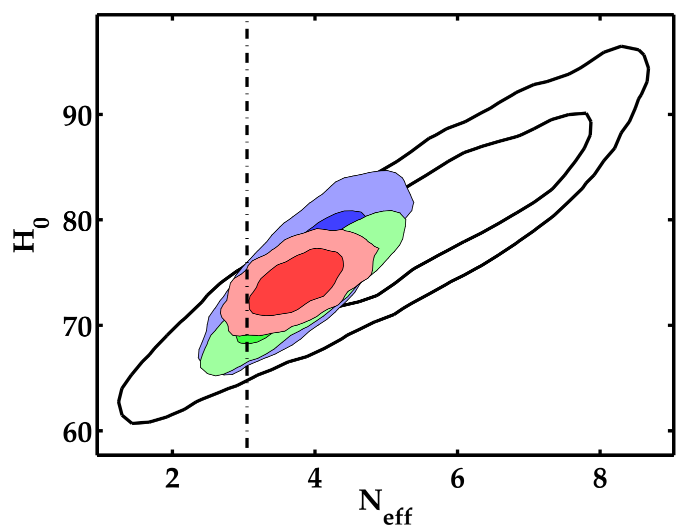
  neutrino perturbations: Bashinsky & Seljak [2004], Trotta & Melchiorri [2008]...

- 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 $\therefore$ high!

- Easy to generate ~1σ "hints"; adopted value of H_0 matters!



Feeney, HVP, Verde (2013)

Reminder:
parameter estimation vs model comparison

posterior: probability of the model given the data

probability of the data given the model

prior probability

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{\int P(D|\theta)P(\theta)d\theta}$$

Evidence: normalizing factor

Evidence: model-averaged likelihood

Bayes' theorem: competing models succeed or fail based on their predictivity, not their simplicity

Statistical framework: model selection

- Fundamental question: is Universe **ΛCDM** or **ΛCDM+N$_{\text{eff}}$**?

- Parameter posteriors insufficient:

-only tells us most likely parameter value in single model
-hard to interpret cf. long degeneracies

- Need to calculate model posteriors

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

↑ *prior probability* ↑ *evidence ratio*

Bayesian model selection

- Must calculate model-averaged likelihood, aka Evidence

$$\Pr(\mathrm{d}|M) = \int d\theta \, \Pr(\theta|M)\Pr(\mathrm{d}|\theta, M)$$

- If models nested can use Savage-Dickey Density Ratio (SDDR)

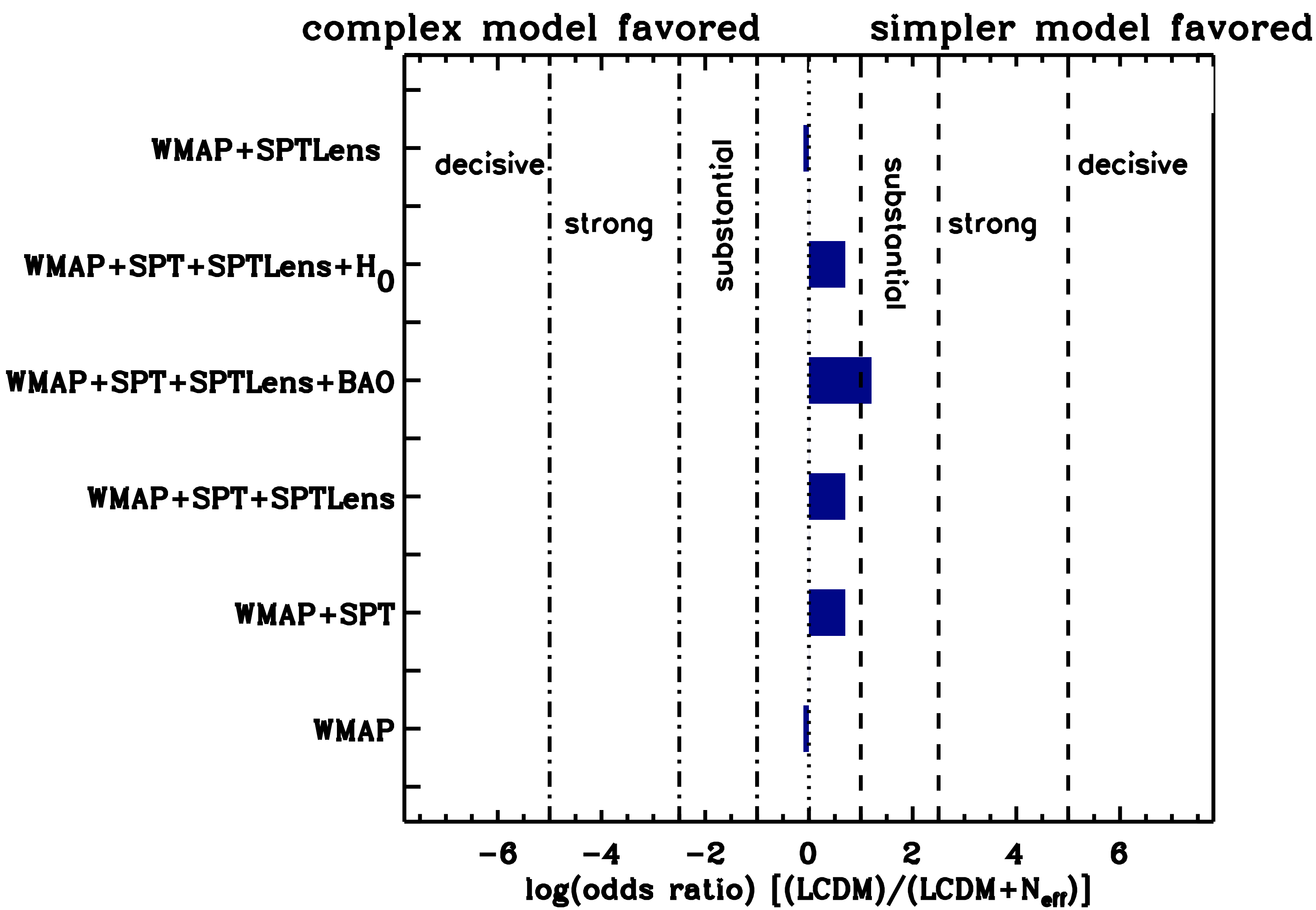
Dickey (1971), see also Trotta (2007), Verde, Feeney, Mortlock, HVP (2013)

- Just need ratio of posterior and prior at nested parameter value, e.g., $\Lambda\mathrm{CDM} = (\Lambda\mathrm{CDM} + N_{\mathrm{eff}})|_{N_{\mathrm{eff}}=3.046}$ so can do:

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

- Can compute from MCMC.

Evidence (pre-Planck)



No evidence for additional neutrinos! odds 3:1 in favour of ΛCDM.

Feeney, HVP, Verde (2013)

What if we lack physical priors?

- Are hints present in likelihood?

- Use profile likelihood ratio (PLR, Wilks [1938])
  ratio of conditional to unconditional maximum likelihoods

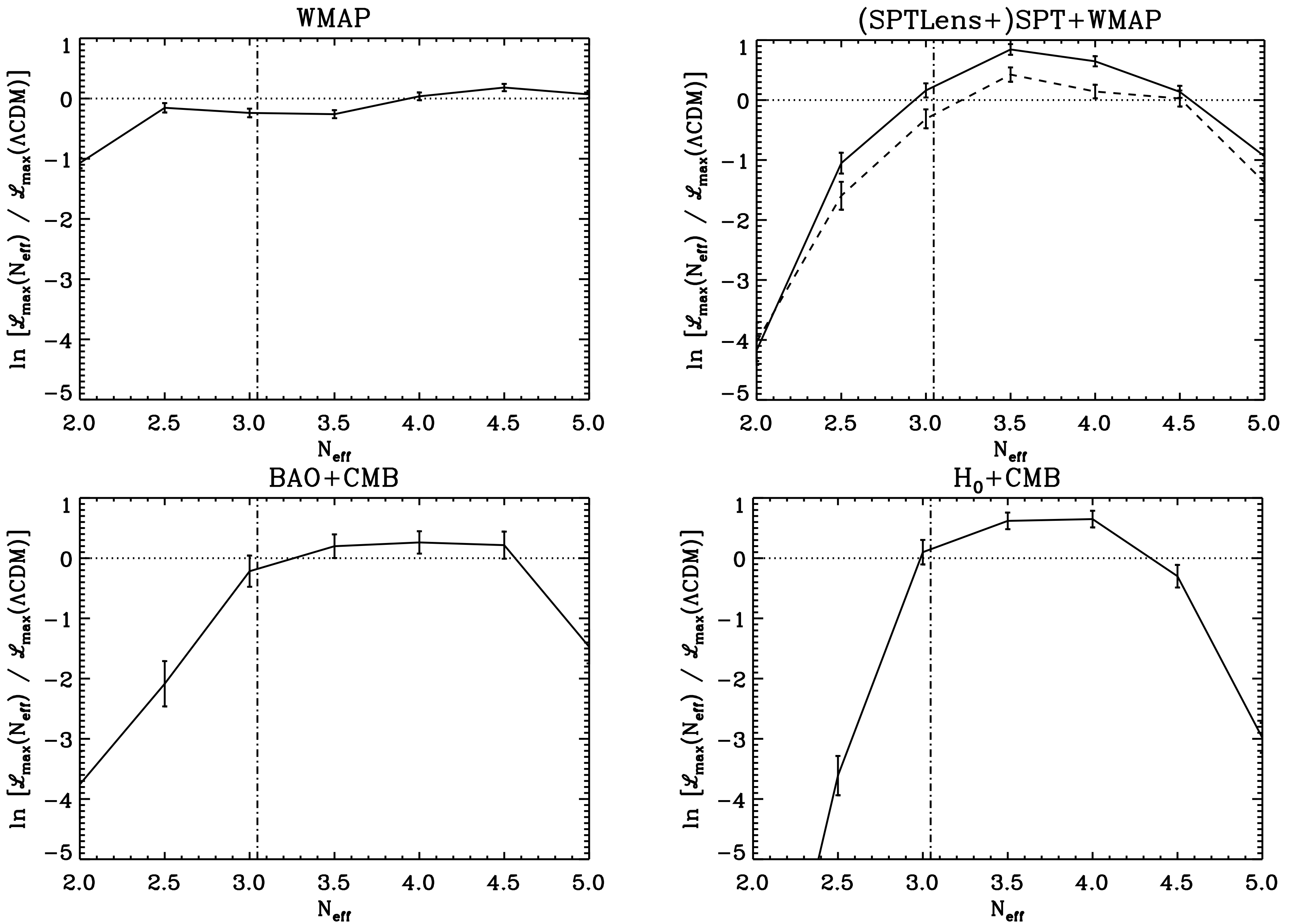
$$\mathrm{PLR}(N_{\mathrm{eff}}^{*}) = \frac{\max\left[\Pr(\mathrm{d}|\theta_{\Lambda\mathrm{CDM}}, N_{\mathrm{eff}} = N_{\mathrm{eff}}^{*})\right]}{\max\left[\Pr(\mathrm{d}|\theta_{\Lambda\mathrm{CDM}}, N_{\mathrm{eff}})\right]}$$

- Prior-“independent”

- Max likelihood ≃ upper bound on evidence for “just-so” model
  Verde, Feeney, Mortlock, HVP (2013)

- If PLR peak away from $N_{\mathrm{eff}} = 3.046$: evidence for deviation

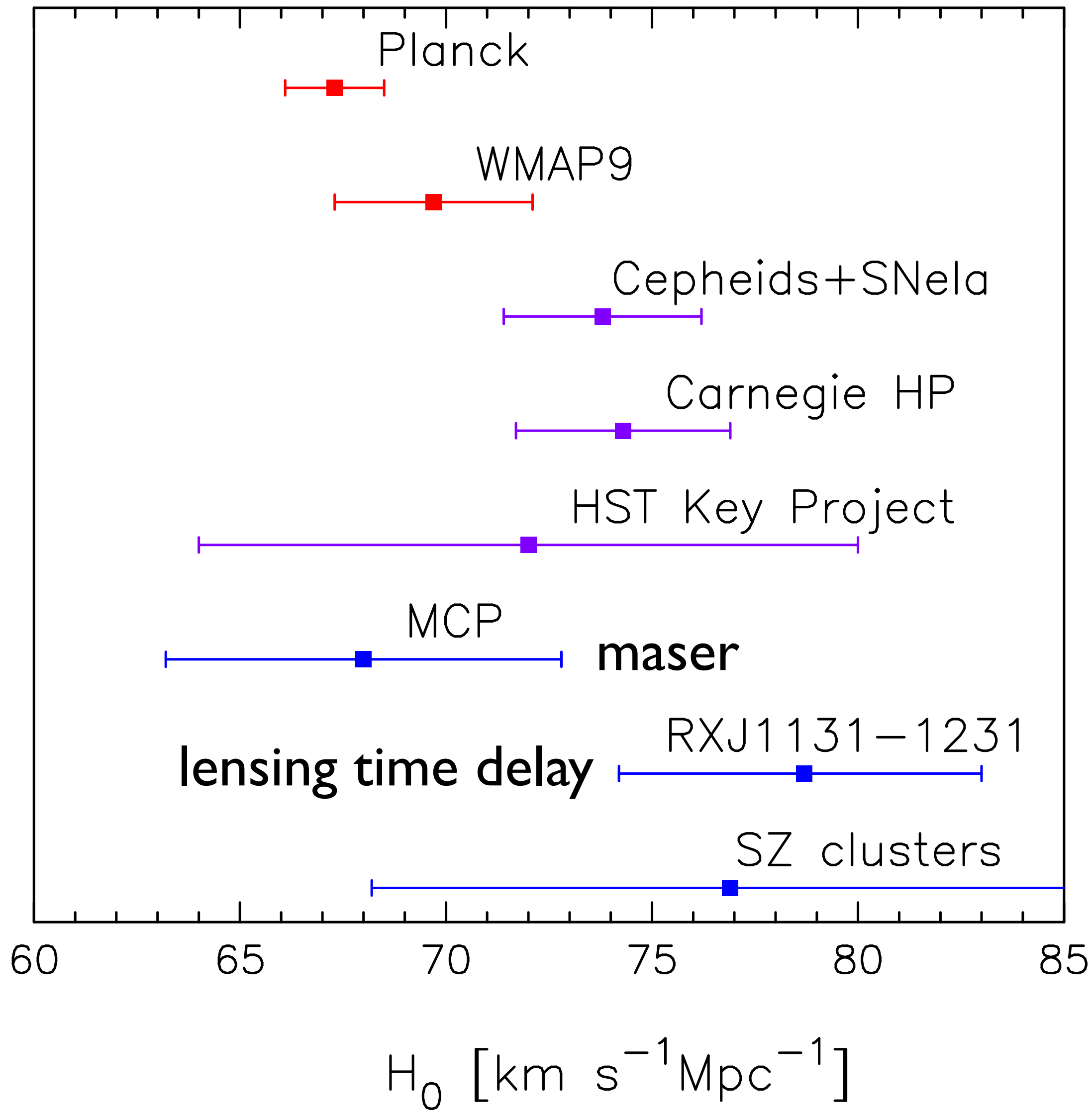
Profile likelihoods (pre-Planck)



No preference for additional neutrinos!

Feeney, HVP, Verde (2013)

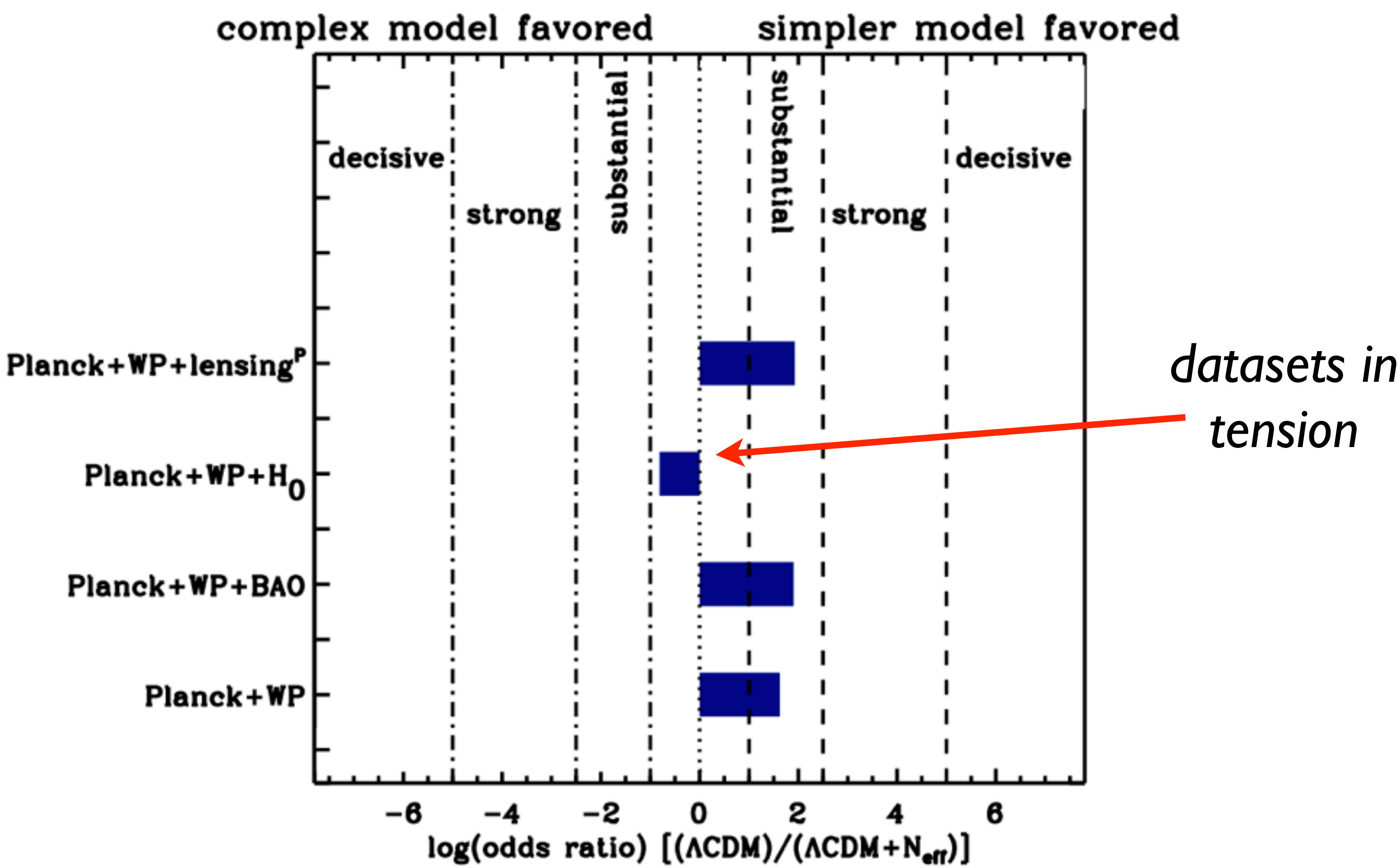
Planck + tension with local H_0



- Posterior for N_{eff} peaks high. Revived interest in resolving tension via N_{eff} *[e.g., Di Valentino, Melchiorri, Mena 2013]*

Figure: Planck XVI (2013)

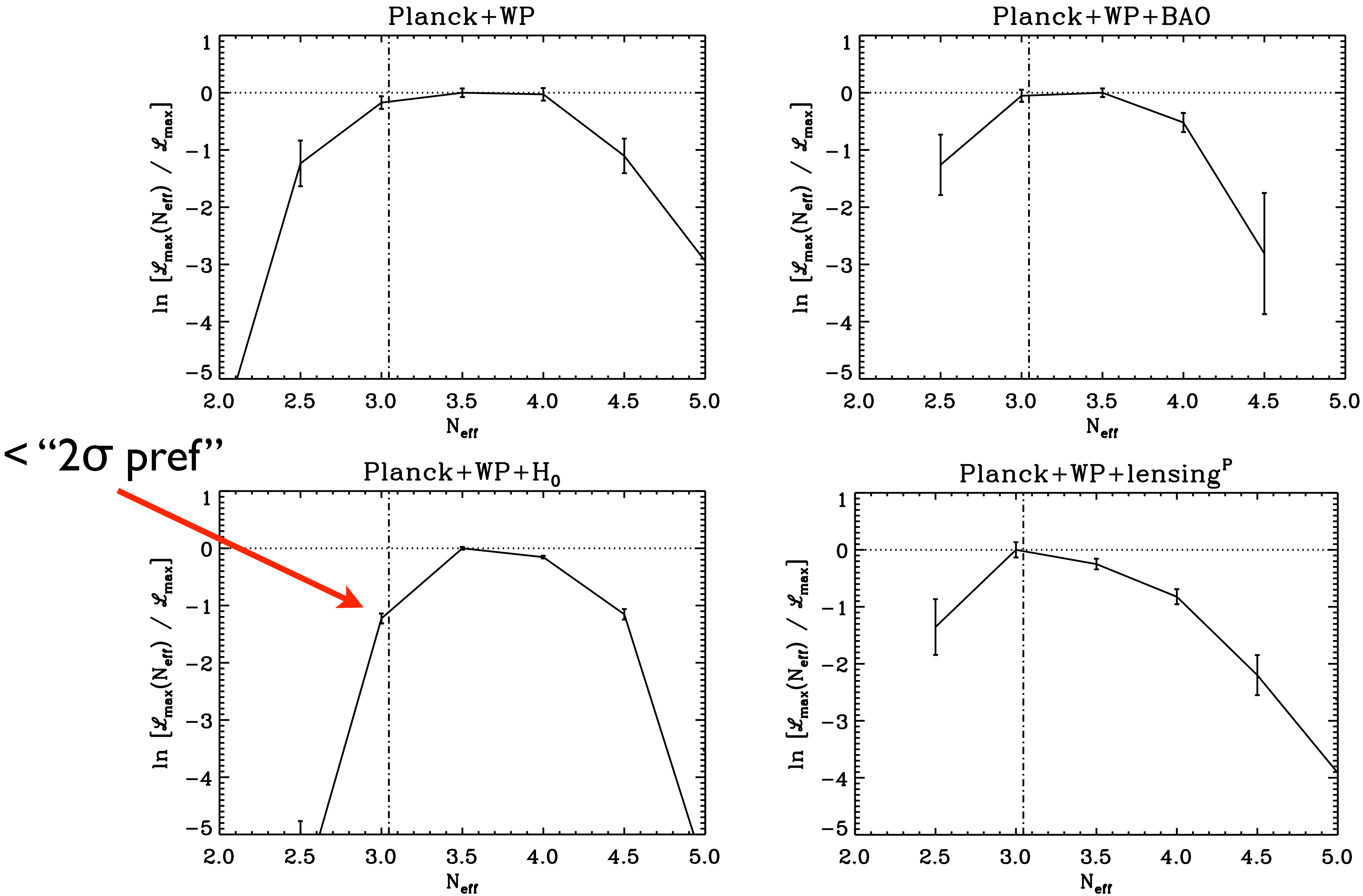
Evidence (post-Planck)



No evidence for additional neutrinos! increased odds 6:1 in favour of ΛCDM.

Verde, Feeney, Mortlock, HVP (2013)

Profile likelihoods (post-Planck)



No preference for additional neutrinos! Cannot distinguish N_{eff} ~3 and 4.

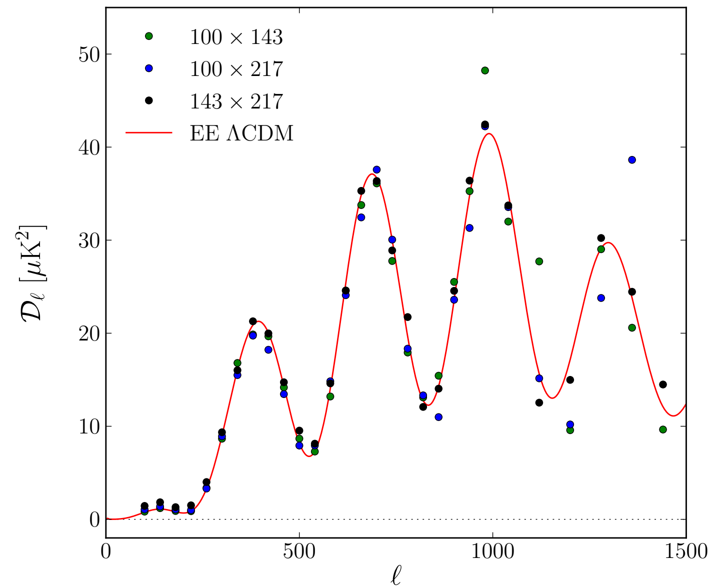
Verde, Feeney, Mortlock, HVP (2013)

What could end the debate?

- Planck polarisation

  -polarisation peaks more prominent (Bashinsky & Seljak 2004)

  -pin down phase shift: must be neutrinos ($\Delta N_{eff} \sim 0.18$)



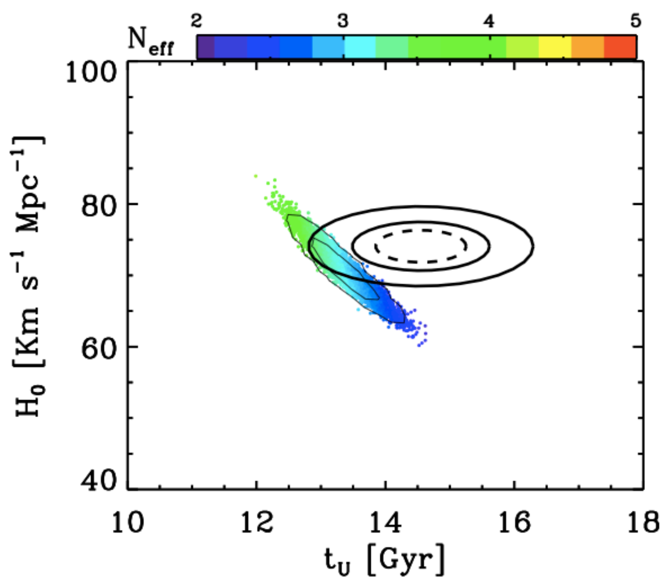
Planck XV (2013)

- Precise local measurements of H_0 & age of Universe

  -see Verde, Jimenez & Feeney (2013)

  -ages of low-metallicity stars (Bond et al. 2013)

  -investigation of systematics in H_0



Verde, Protopapas & Jimenez (2013)

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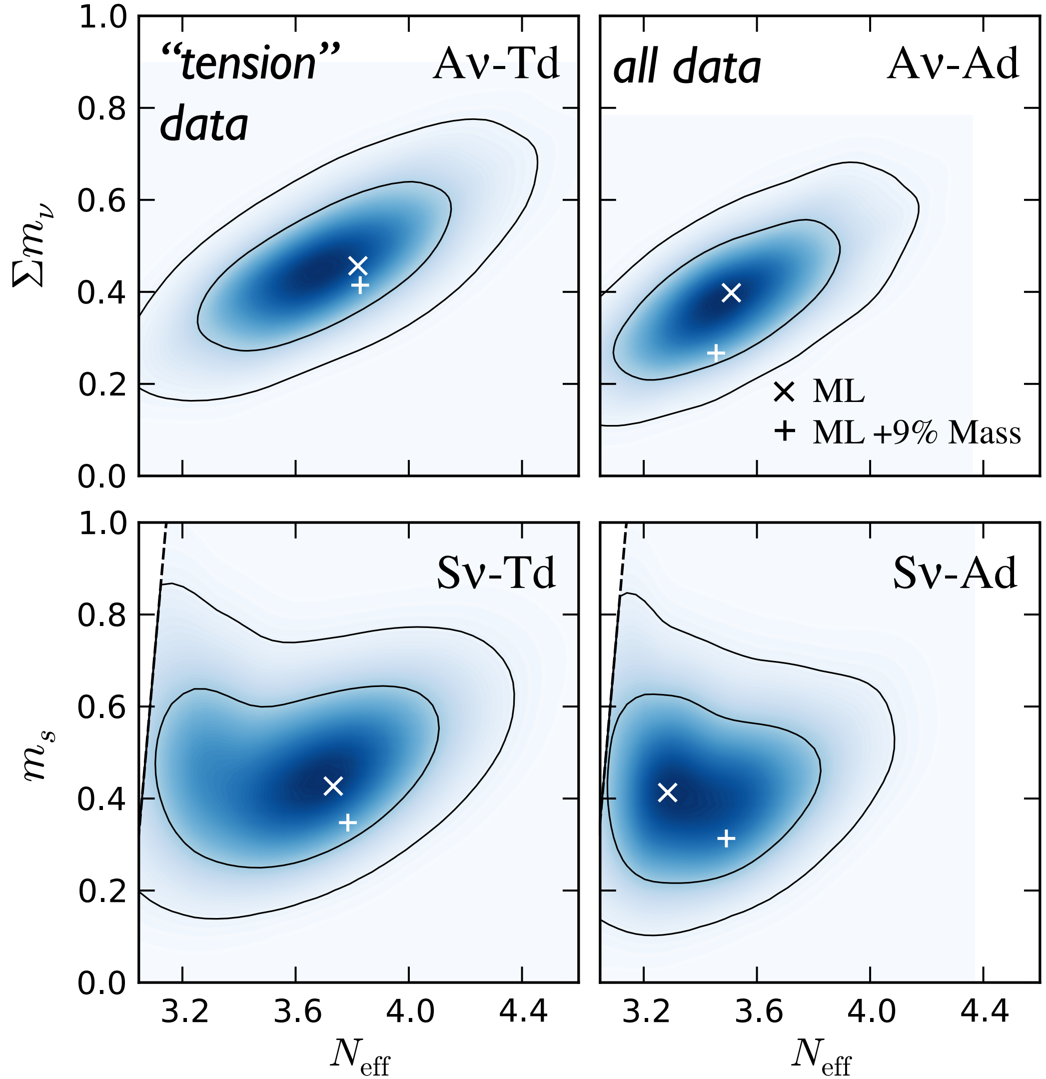
  neutral leptons insensitive weak interactions, only interaction gravitational;
  LSND/MiniBooNE hints at 1-2 sterile neutrinos with ~eV masses

  .... tension with cluster constraints

Massive sterile neutrinos?!

Recent papers prefer (~3σ) one extra sterile, massive neutrino

Wyman et al. (PRL, 2013), Hamann & Hasenkamp (JCAP, 2013), Battye & Moss (PRL, 2013)



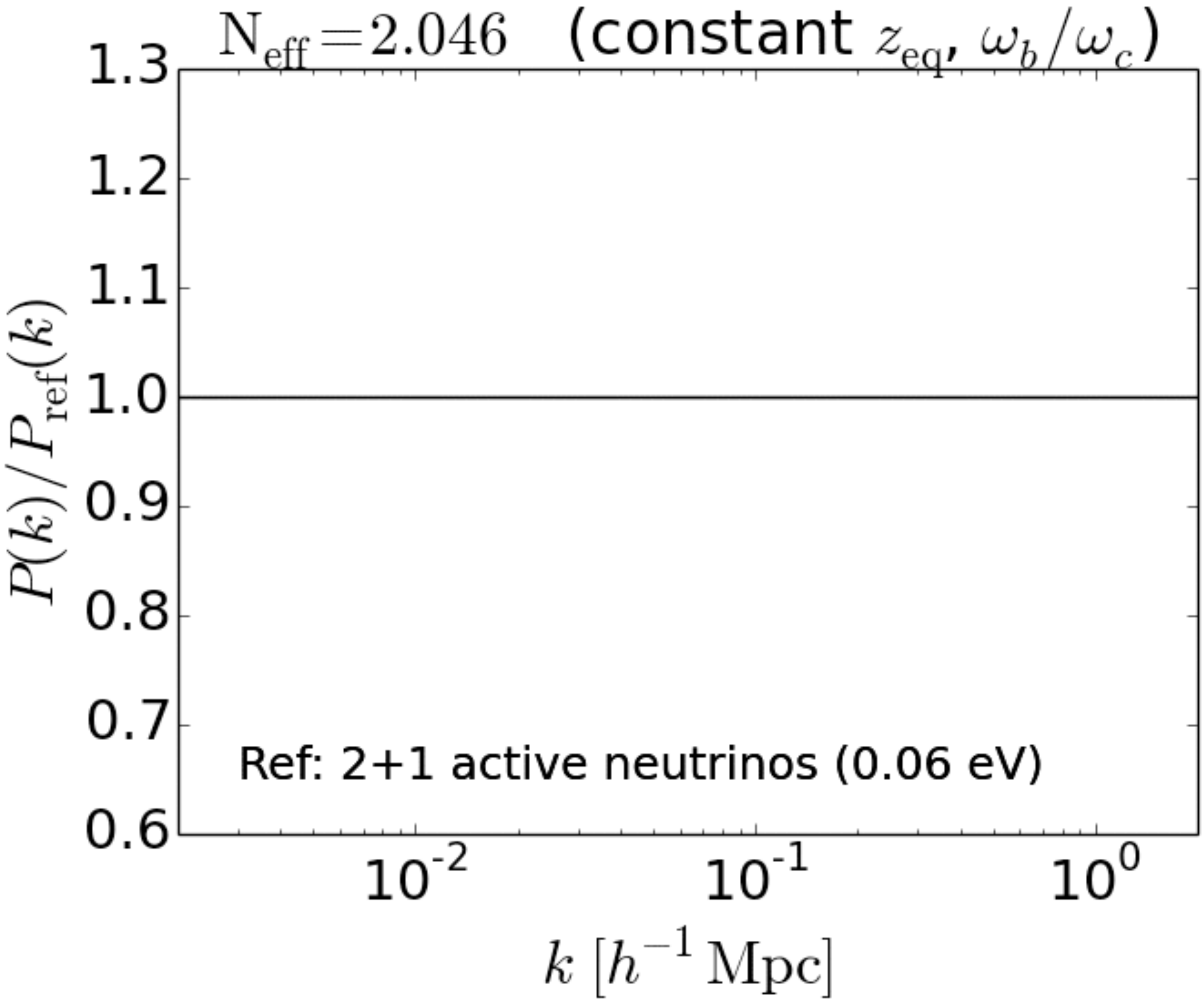
Datasets used (clusters, H_0, cosmic shear) in tension with *Planck*+BAO in ΛCDM.

HST H_0 high: wants high σ_8, low m_ν

Clusters σ_8 low: wants low H_0, high m_ν

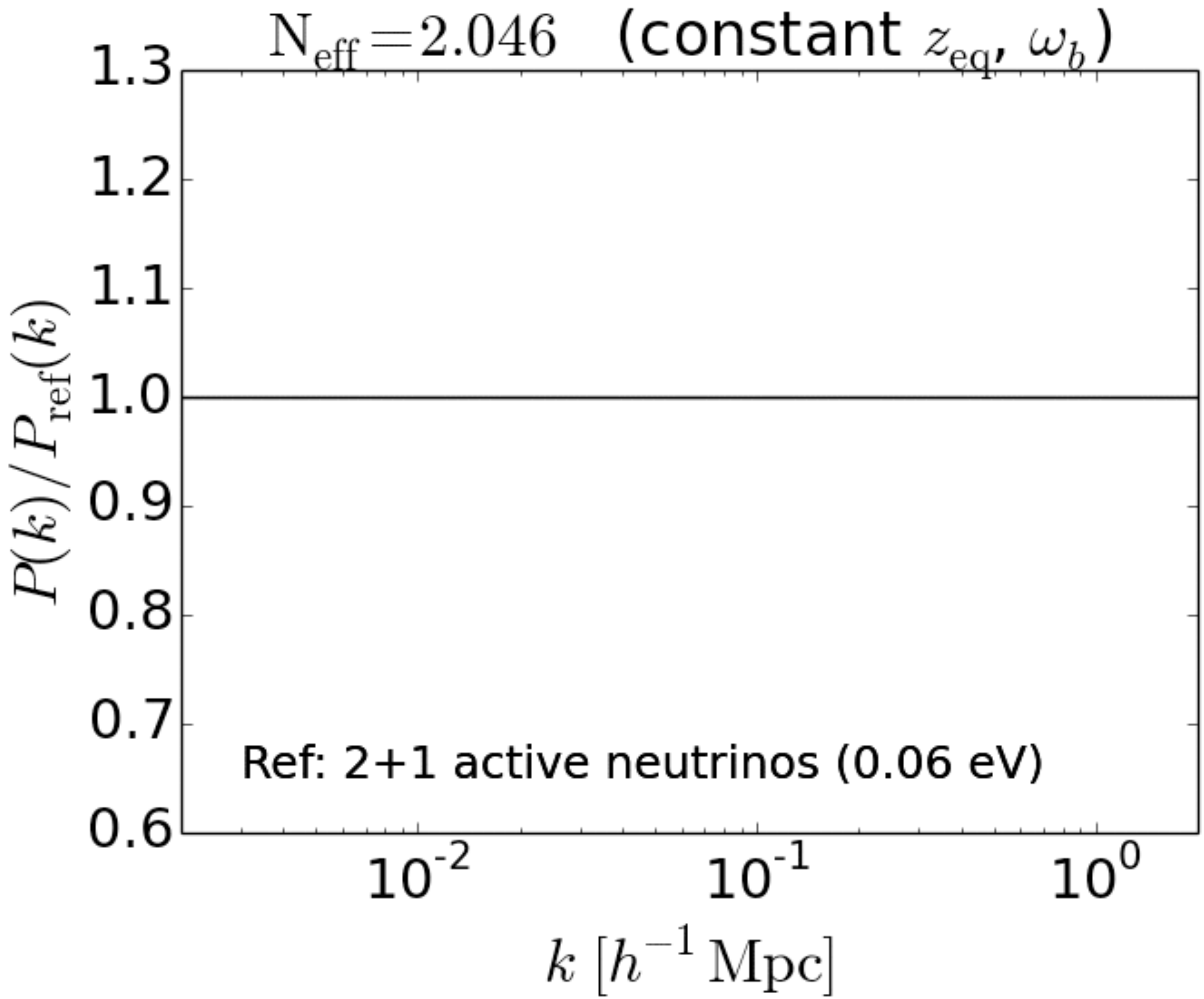
Figure: Wyman et al (2013)

Impact of N_{eff} on matter P(k)



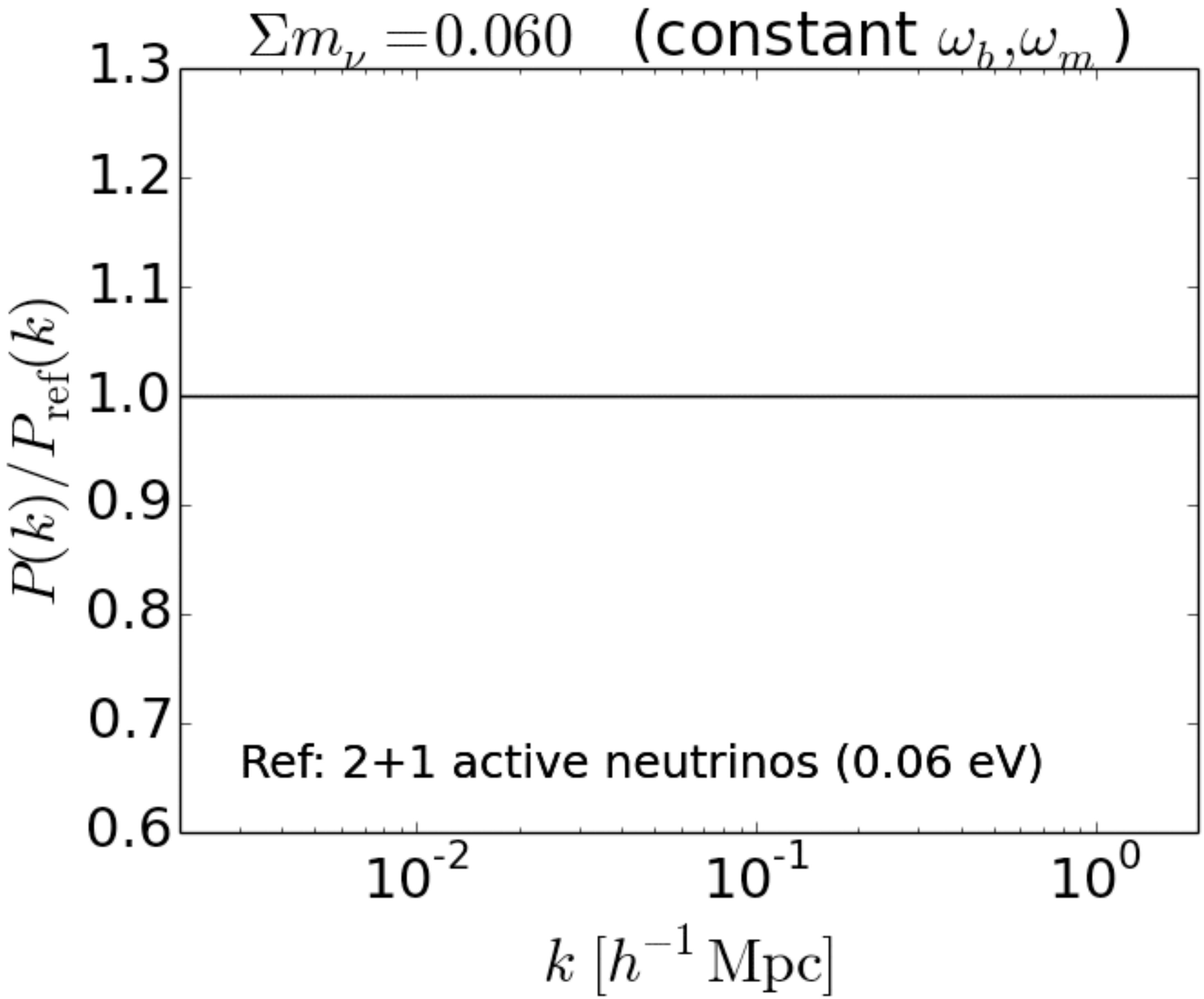
Animation: Boris Leistedt

Impact of N_{eff} on matter P(k)



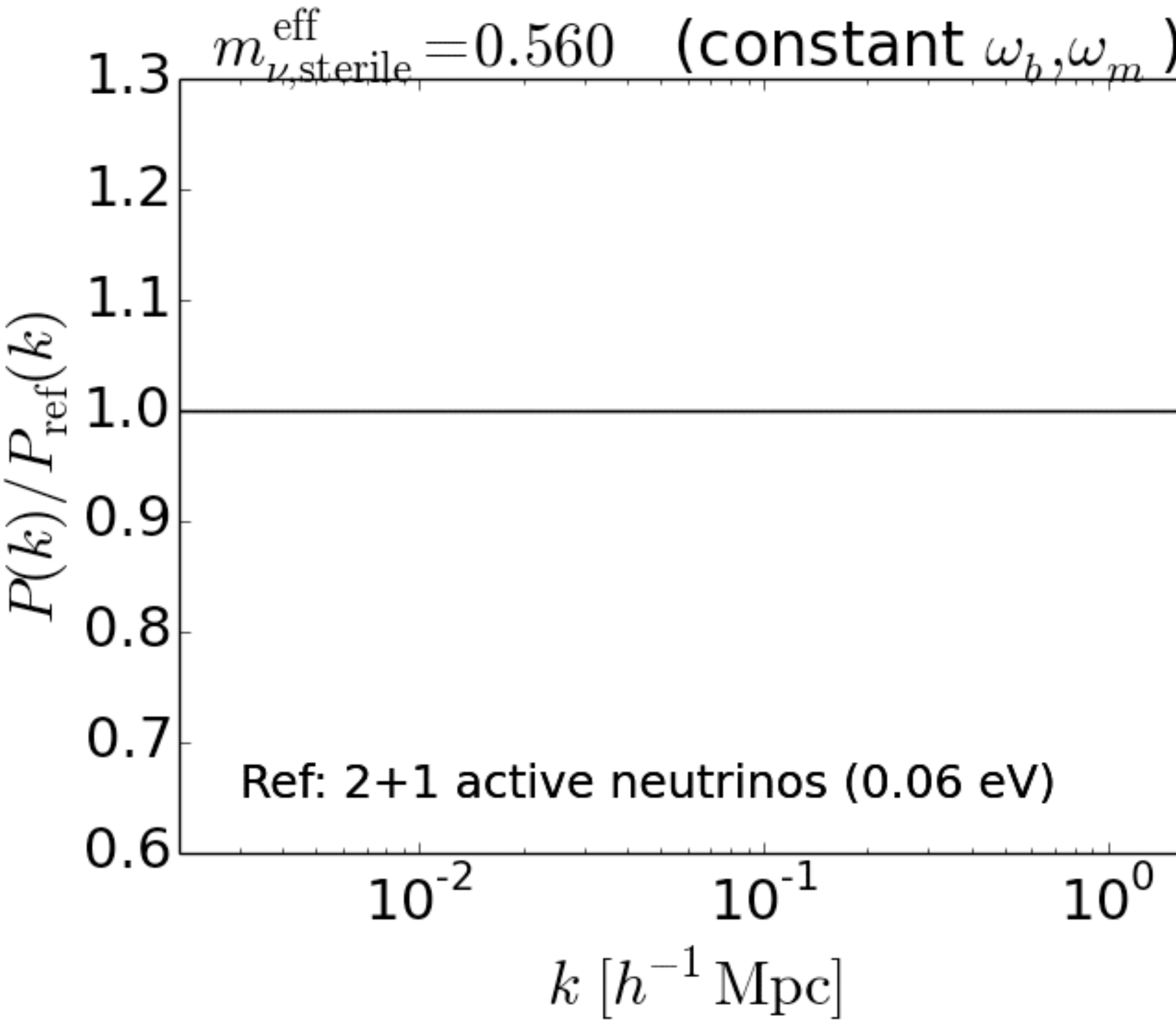
Animation: Boris Leistedt

Impact of massive neutrino on matter P(k)



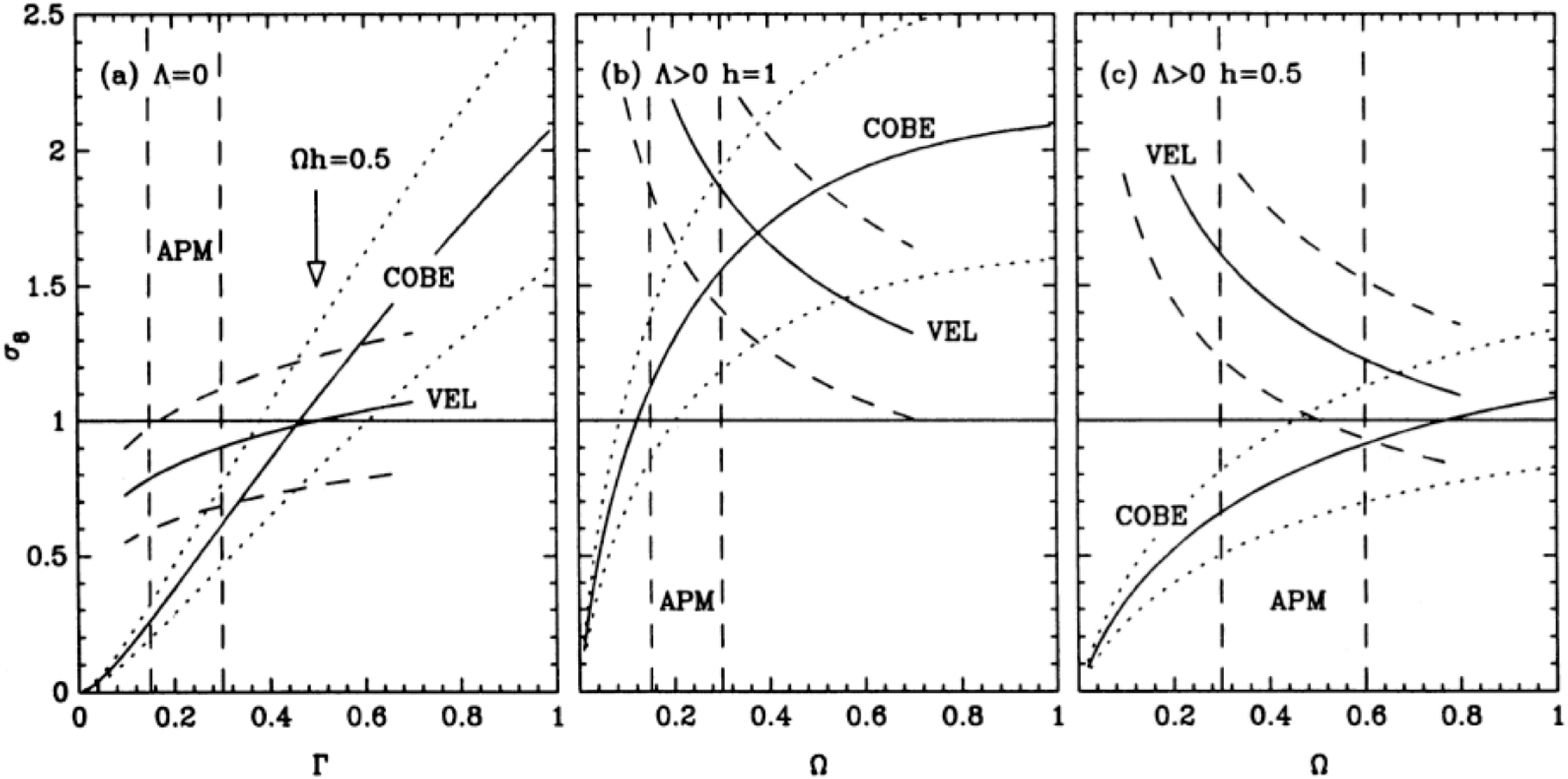
Animation: Boris Leistedt

Impact of massive sterile neutrino



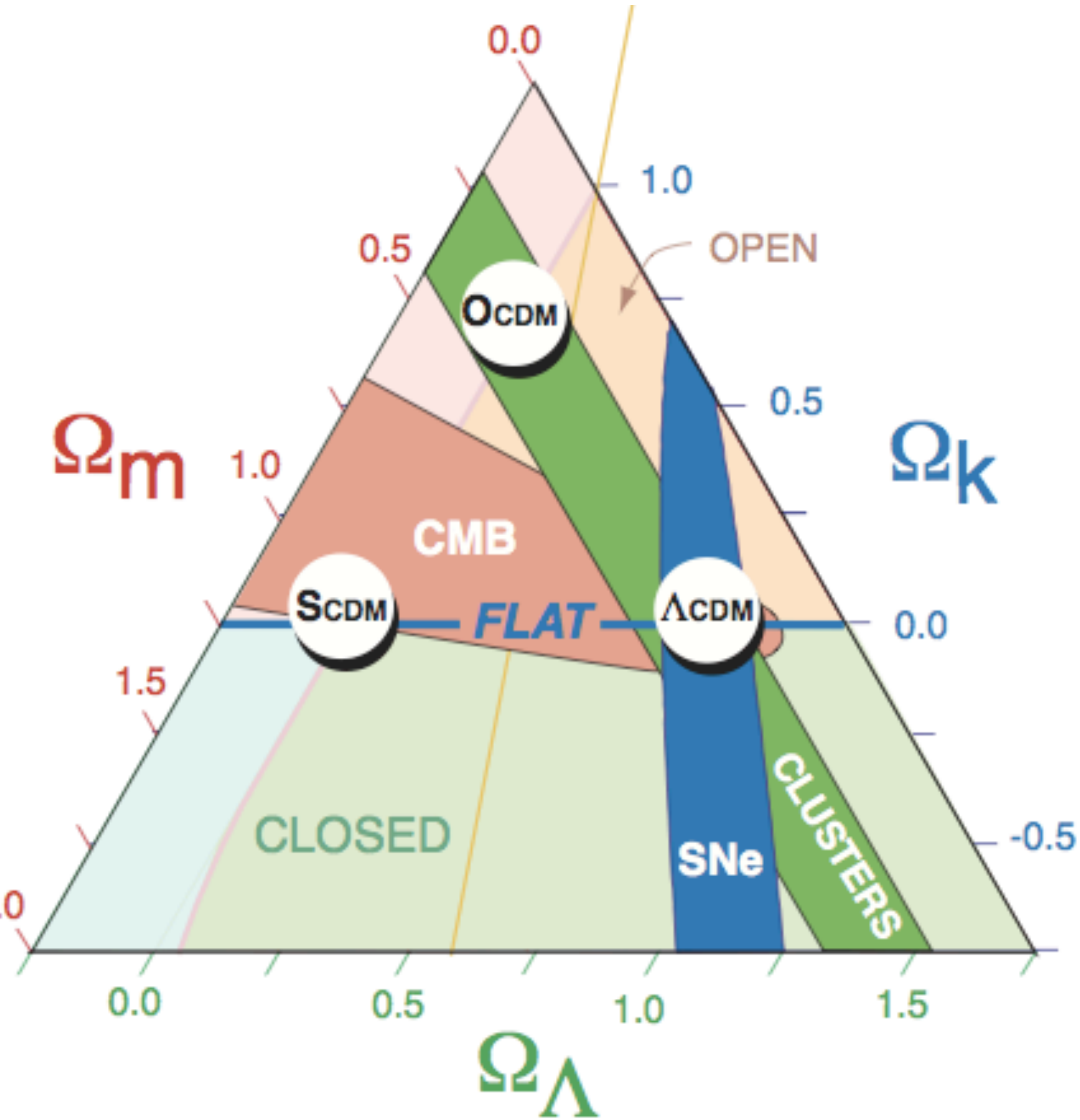
Animation: Boris Leistedt

Adding parameters for concordance



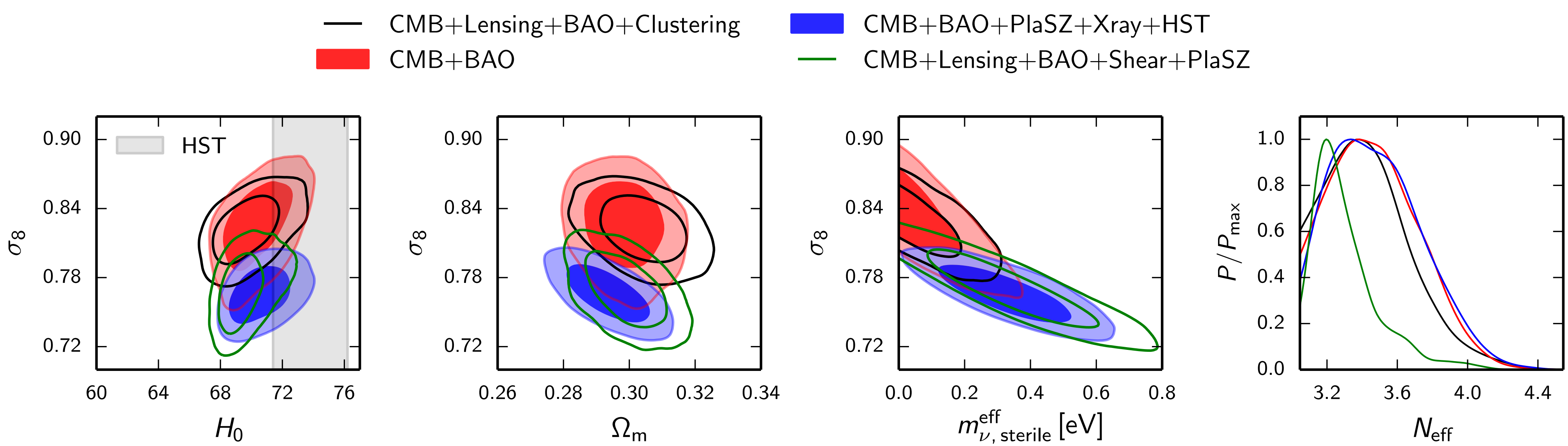
Efstathiou, Bond, White (1992)

Adding parameters for concordance



Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

A new cosmic concordance?



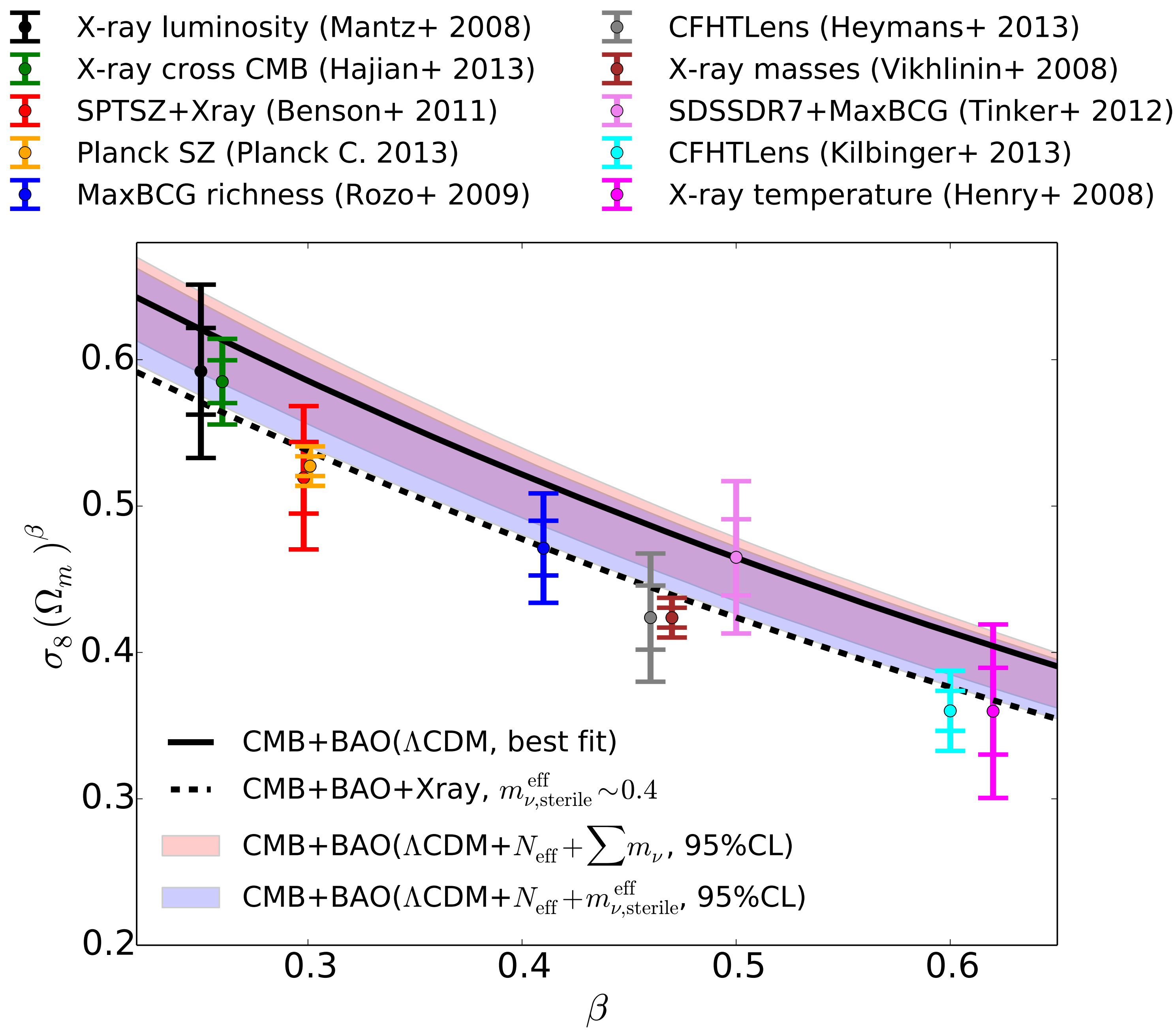
- Non-zero sterile neutrino mass only favoured due to:

-tension between CMB and clusters (Planck SZ, X-ray) in σ_8–Ω_m plane

-degeneracy between σ_8 & neutrino mass.

Leistedt, HVP, Verde (to be submitted)

A new cosmic concordance?



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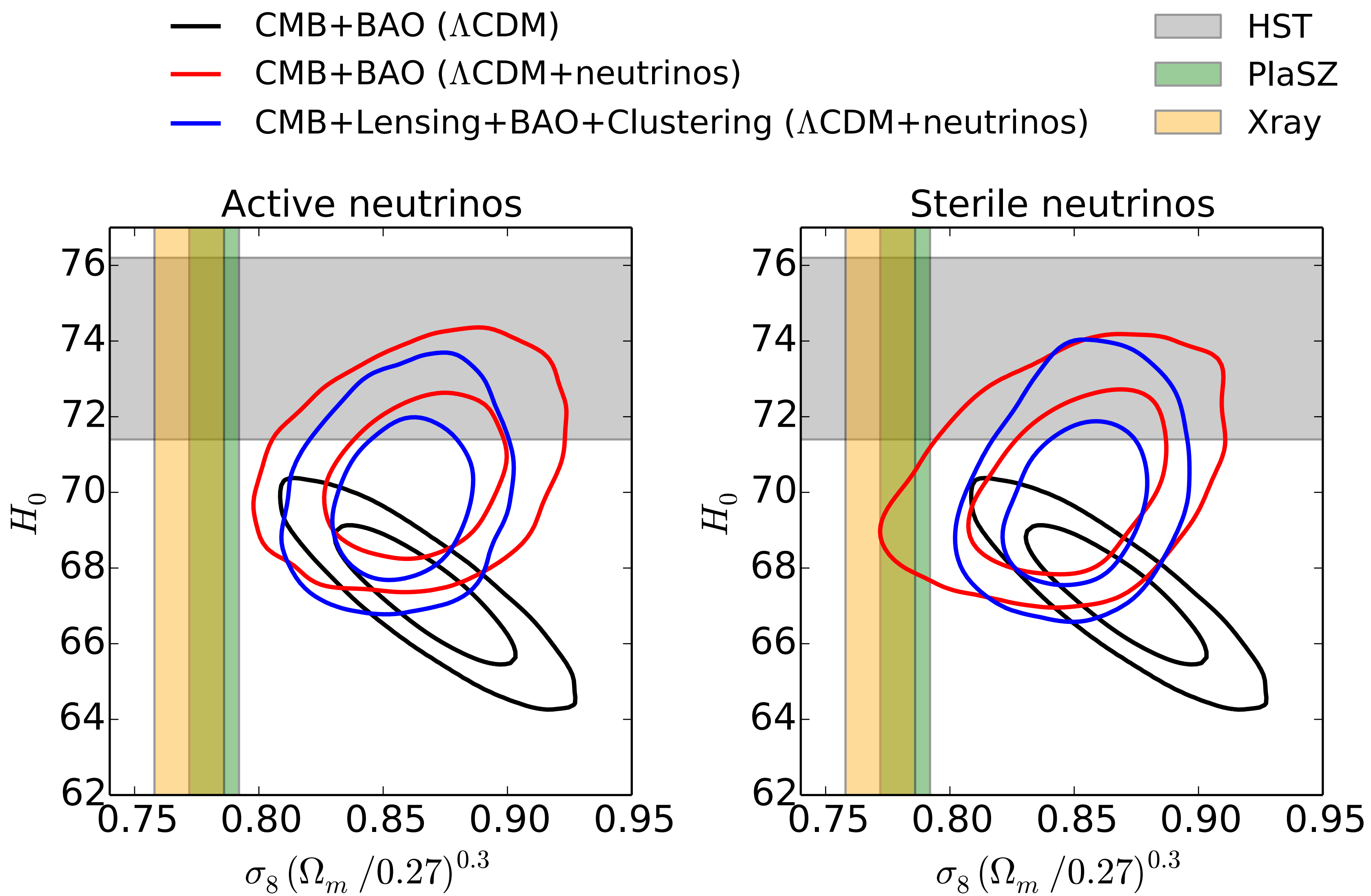


Bayesian Evidence does not support massive sterile neutrino model even when combining conflicted datasets

Leistedt, HVP, Verde (to be submitted)

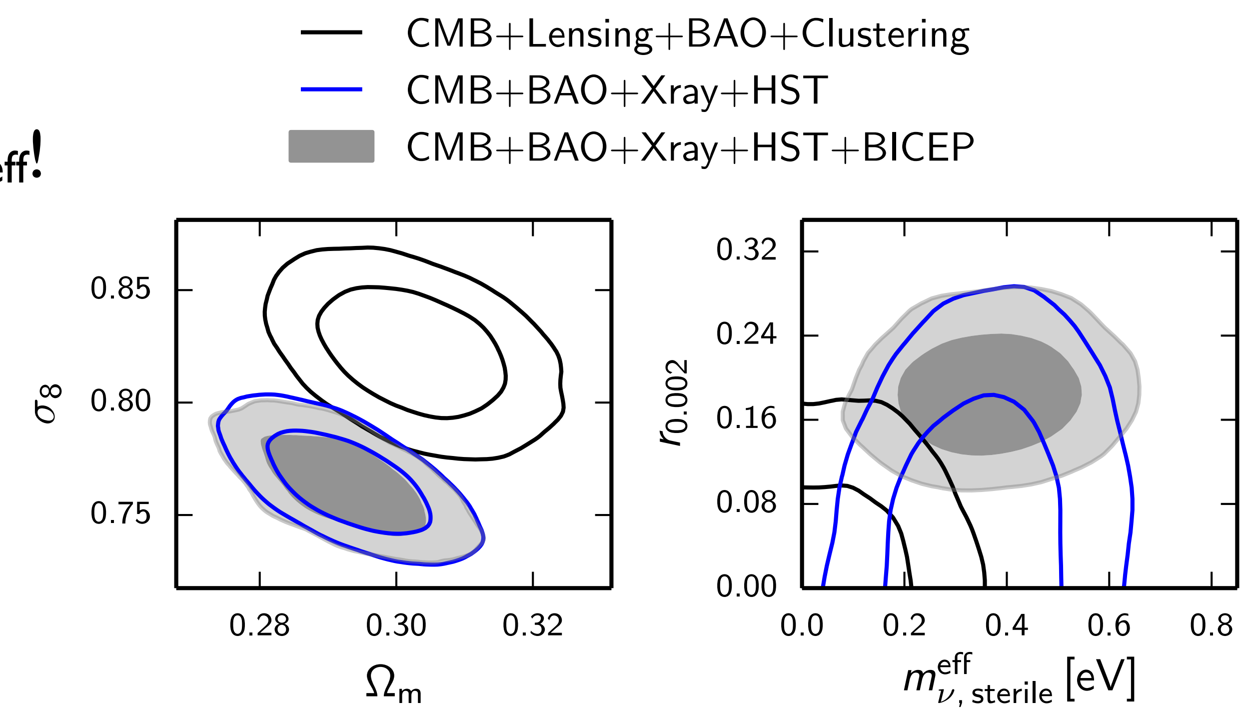
A new cosmic concordance?

Planck: r<0.11 (95% CL); BICEP2: r~0.2

- "Neutrinos help reconcile Planck measurements with both Early and Local Universe" *[Dvorkin, Wyman, Rudd, Hu 2014]*
Evidence for massive sterile neutrinos increased by BICEP2?

- Conclusion premature; datasets remain in tension
Leistedt, HVP, Verde (undergoing Planck EB review)

BUT! If r~0.2, B-mode spectrum can constrain $N_{\rm eff}$!
Zhao, Zhang, Xia (2009)



Conclusions

- **Tensions** between CMB+BAO++ and [local measurements of H0 | SZ, X-ray cluster measurements] not resolved by new concordance model based on massive sterile neutrinos.

- Current data cannot distinguish between $\mathbf{N_{eff}}$ ~ 3 and 4.

- Robust data combinations give tight limits <0.3 for sum of (active| sterile) **neutrino masses**.

- **Future** is in combined probes; systematics are key.