Determining neutrino properties from precision cosmology

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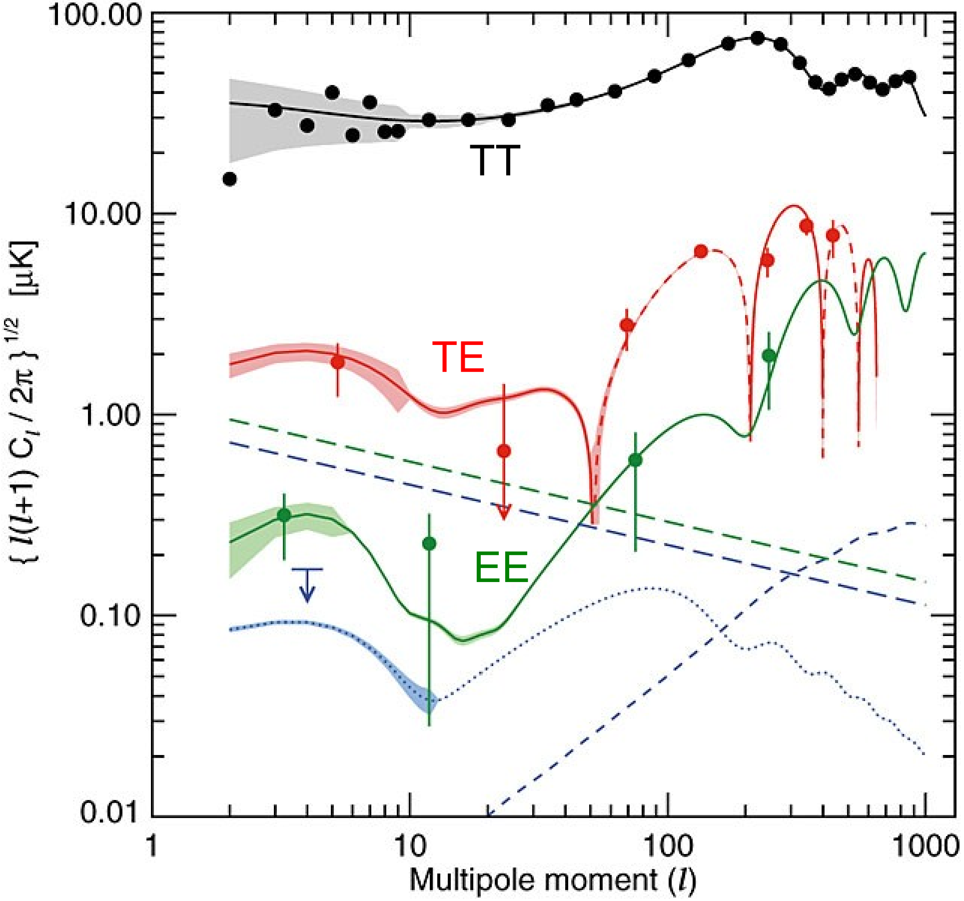
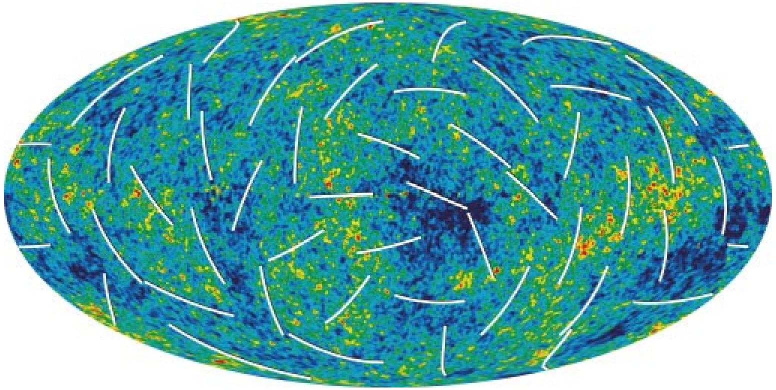
International workshop on double beta decay and neutrinos, Osaka,
November 14 – 17, 2011

Probe 1: Cosmic microwave background anisotropies...



NASA/WMAP science team

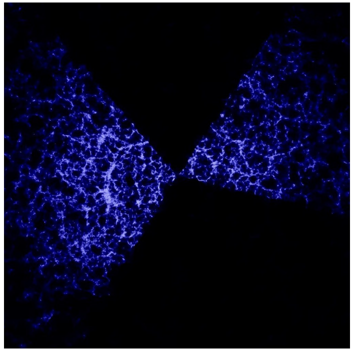


Many probes:

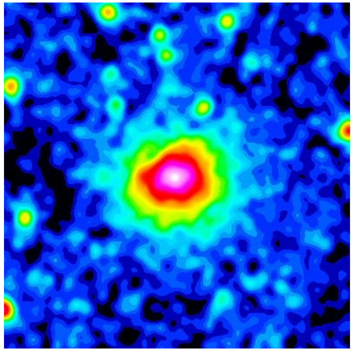
- > 0.5 deg: COBE, WMAP, Planck
- < 0.5 deg: DASI, CBI, ACBAR, Boomerang, VSA, QuaD, QUIET, BICEP, ACT, SPT, etc.

Probe 2: Large-scale structure (LSS) distribution...

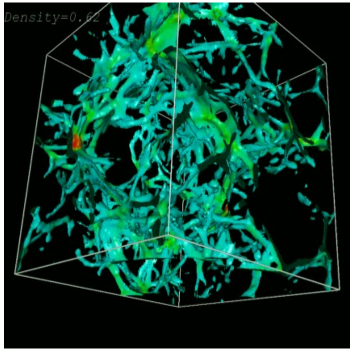
Galaxy clustering



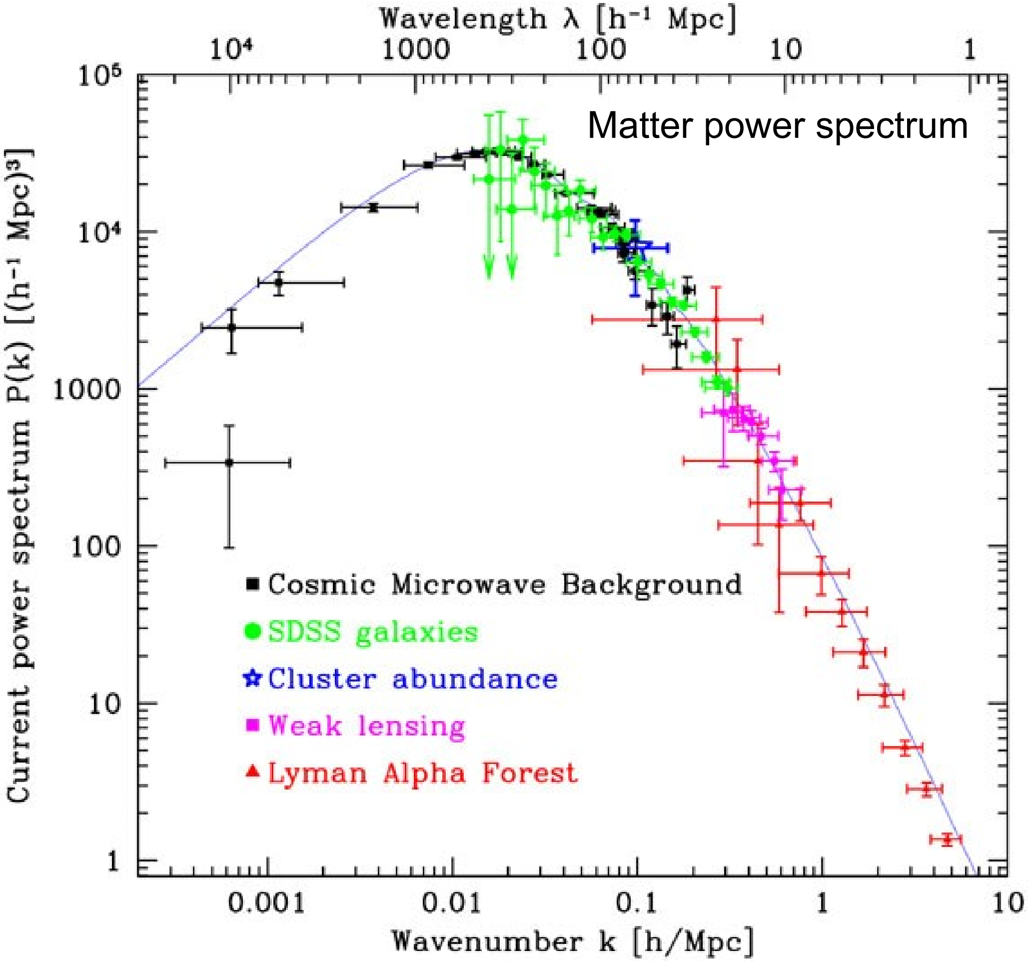
Cluster abundance



Gravitational lensing

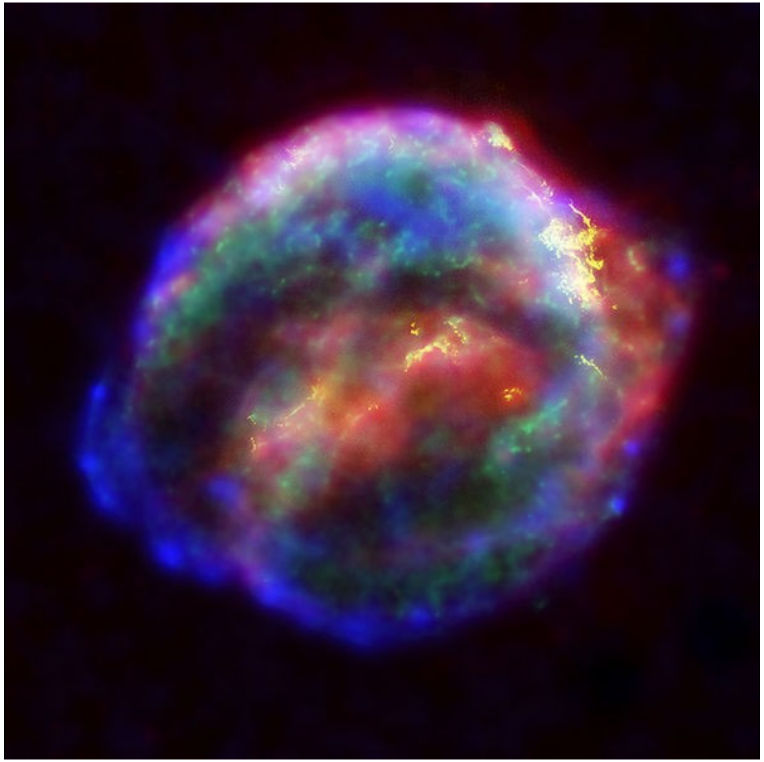


Intergalactic hydrogen clumps; Lyman-α



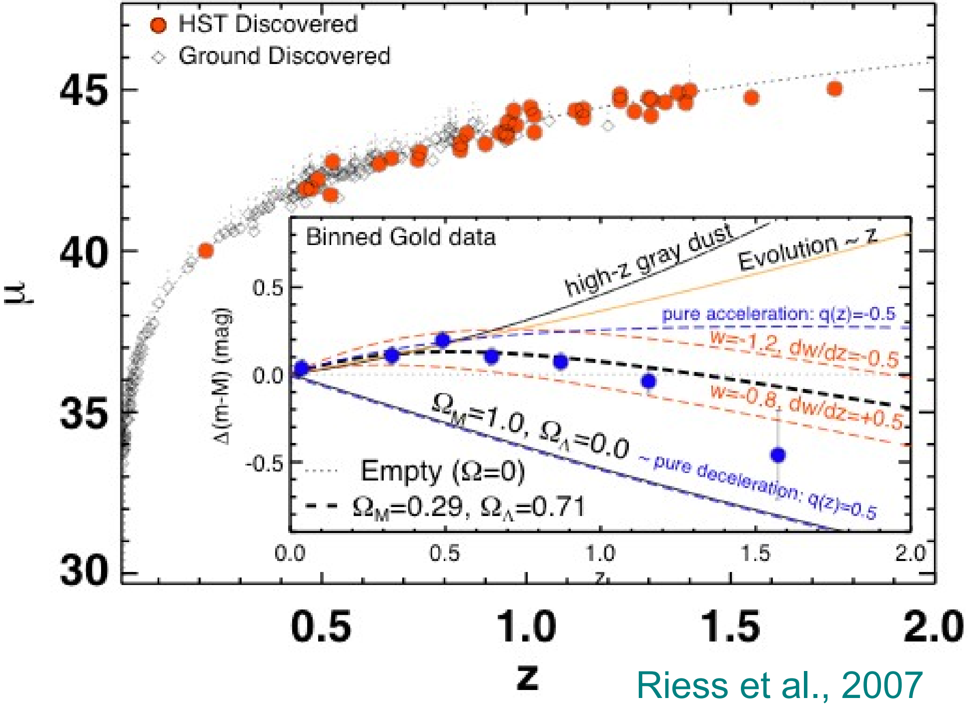
Tegmark et al., 2002

Probe 3: Standard candles (distance vs redshift)...



Type Ia supernova (SNIa).

- Objects of known luminosity.
- Hubble diagram of **SNIa** measures luminosity distance vs redshift.



Riess et al., 2007

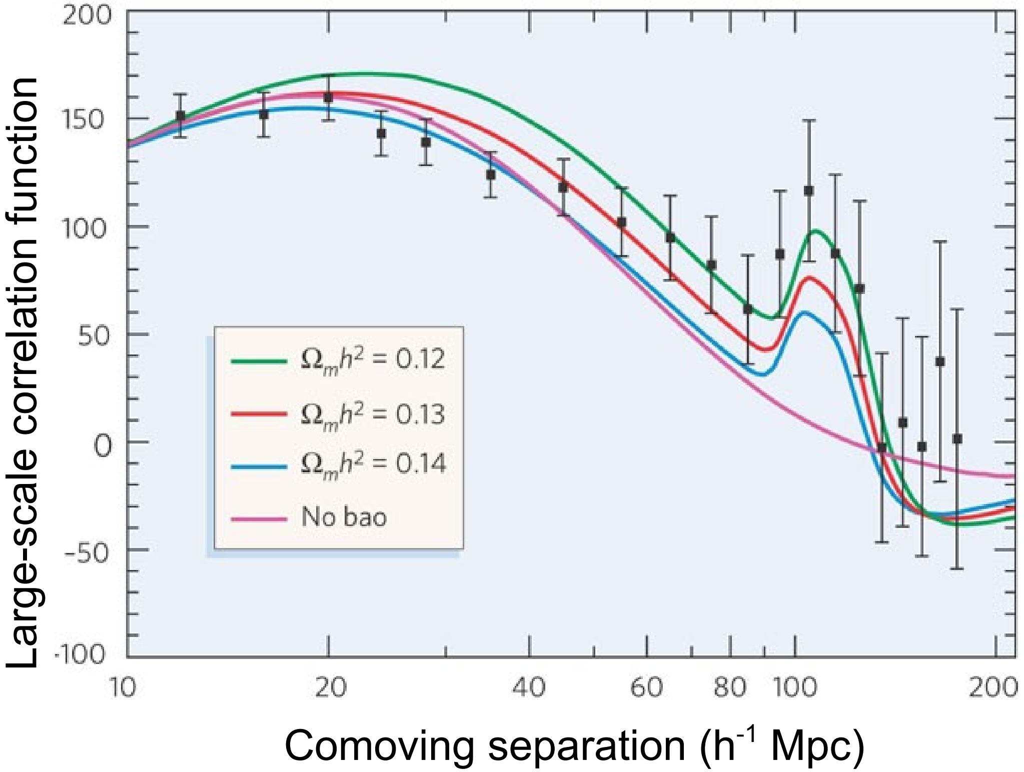
Probe 4: Standard rulers (distance vs redshift)...

- Objects of known physical size.

- BAO peak sourced by the same physics as CMB acoustic peaks

  → Position of peak in 2-point correlation of the matter distribution is known.

- Measures angular diameter distance vs redshift.

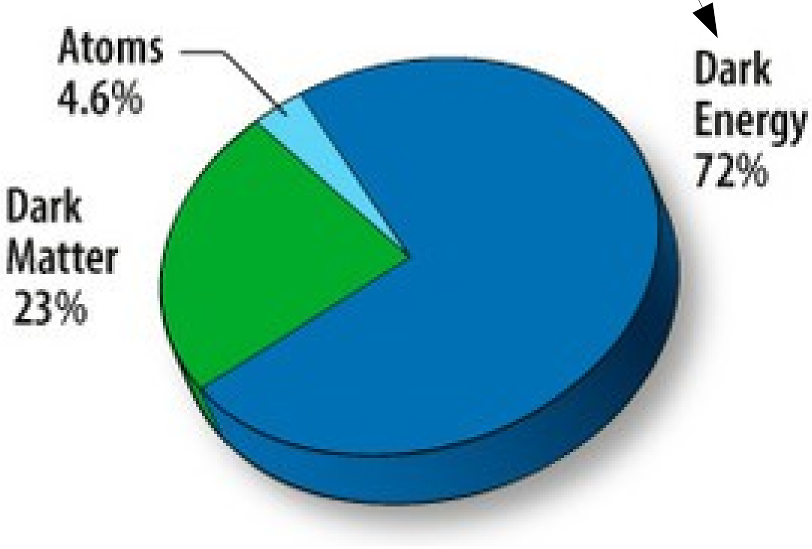


Baryon acoustic oscillation (BAO) peak
Measured by SDSS

Eisenstein et al., 2005

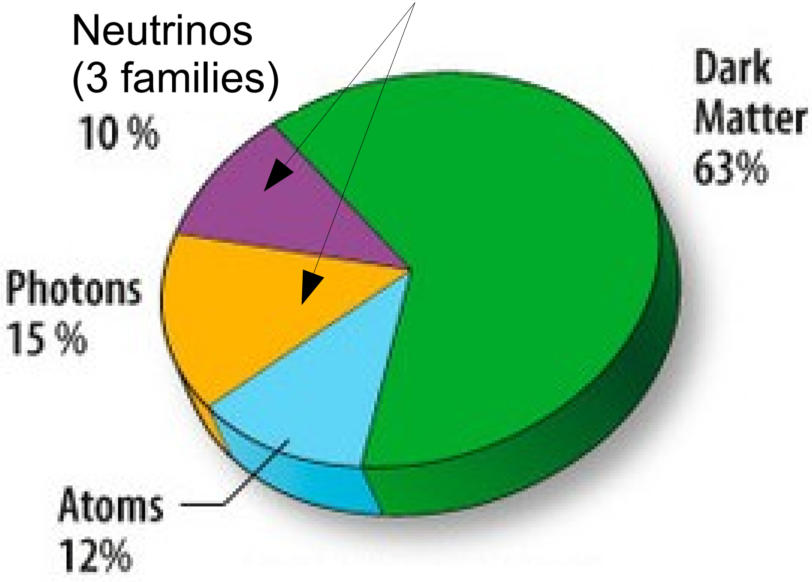
The concordance flat ΛCDM model...

- The simplest model consistent with **present observations**.



Cosmological constant

Composition today



Massless Neutrinos (3 families)

ν-to-γ energy density ratio fixed by SM physics

13.4 billion years ago
(at photon decoupling)

Plus flat spatial geometry+initial conditions from single-field inflation

Neutrino energy density (standard picture)...

- Neutrino decoupling at T ~ O(1) MeV. ← Fixed by weak interactions

- After e$^+$e$^-$ annihilation (T ~ 0.2 MeV):

Assuming instantaneous decoupling

  - **Temperature**: $$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$
  - **Number density** per flavour: $$n_\nu = \frac{6}{4}\frac{\zeta(3)}{\pi^2} T_\nu^3 = \frac{3}{11} n_\gamma$$
  - **Energy density** per flavour: $$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

Photon temperature, number density, & energy density

$$\frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$$

- If massive, then at T << m: $\rho_\nu = m_\nu n_\nu$ $\longrightarrow$ $$\Omega_{\nu,0} h^2 = \frac{m_\nu}{94\ \mathrm{eV}}$$

Hot dark matter (not within vanilla ΛCDM)

Plan...

- Constraining/measuring **neutrino masses** from cosmology.

- Hint of **sterile neutrinos** from the CMB?

Part 1:
Neutrino masses from cosmology

Neutrino dark matter...

$m_\nu > T_\nu \sim 10^{-4}$ eV

- If $m_\nu > 1$ meV, cosmological neutrinos are nonrelativistic today.

Total neutrino energy density

$$\Omega_{\nu,0} h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} \rightarrow$$

Neutrino dark matter

- Predictions based on laboratory limits:
  - **Neutrino oscillations**: $\min \sum m_\nu \sim 0.05 \text{ eV} \rightarrow \underline{\min \Omega_\nu \sim 0.1\,\%}$
  - **Tritium beta decay**: $\max \sum m_\nu \sim 7 \text{ eV} \rightarrow \underline{\max \Omega_\nu \sim 12\,\%}$

Neutrinos cannot make up all of the dark matter content in the universe

Neutrino hot dark matter...

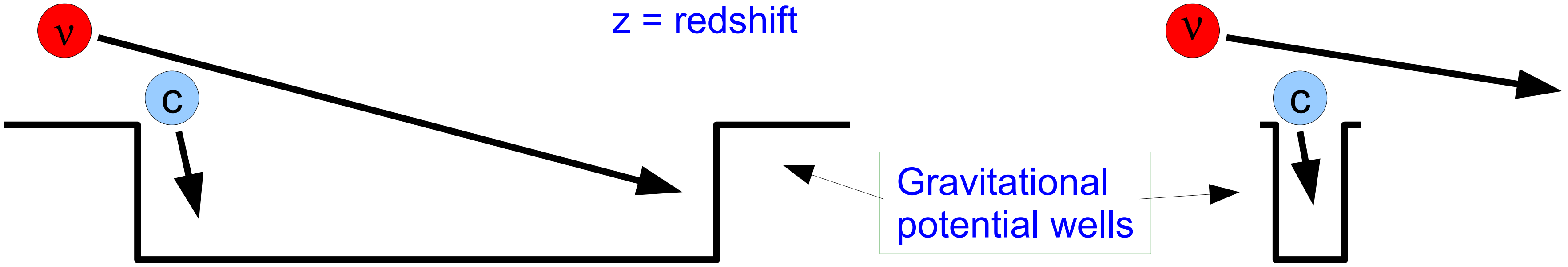
- Neutrino dark matter comes with significant “thermal” motion.

Thermal speed

$$c_\nu \simeq 81\,(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km\ s^{-1}}$$

→ Hinders clustering on small scales

z = redshift



Gravitational potential wells

- Free-streaming length scale & wavenumber:

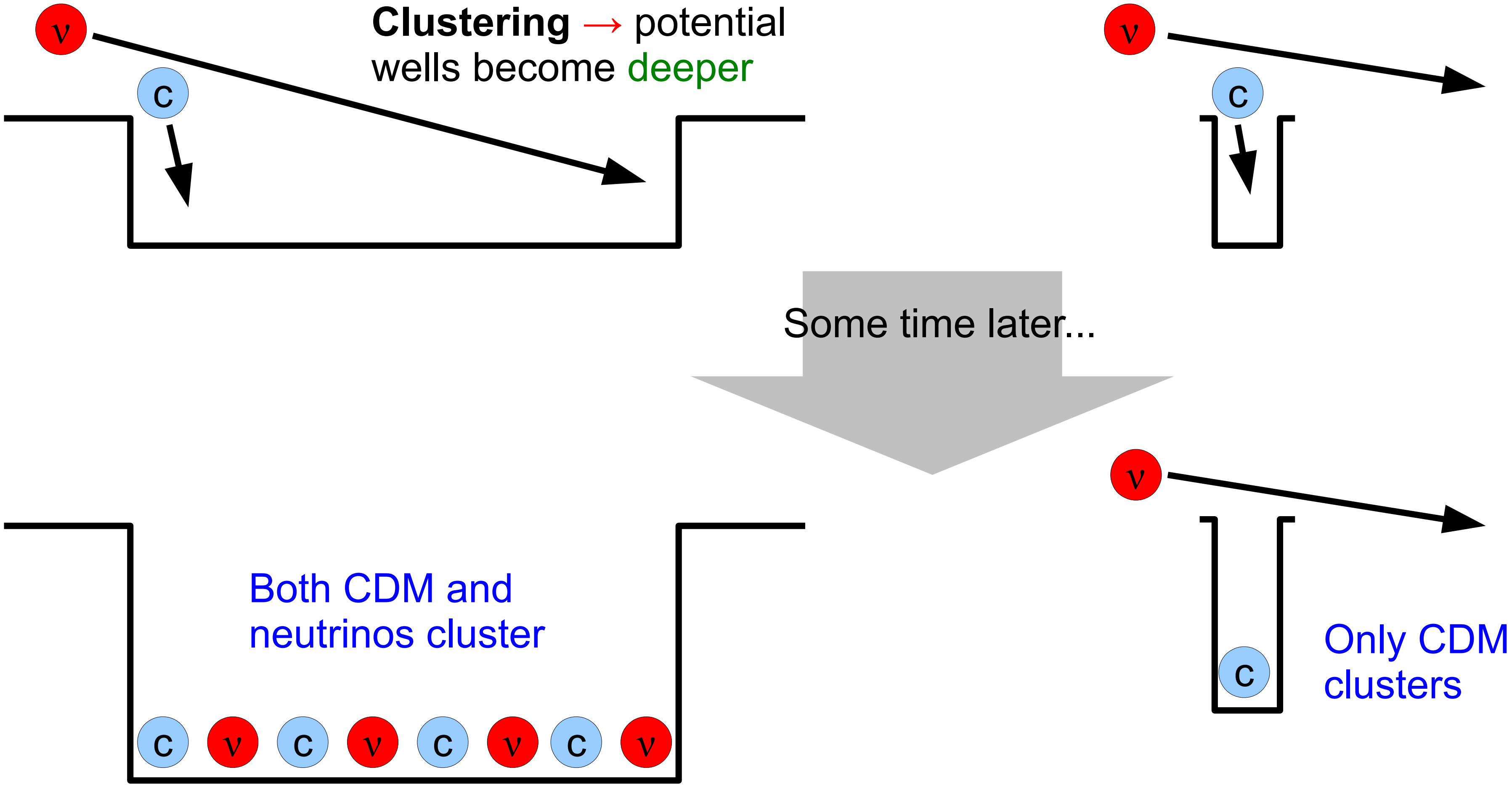
$$\lambda_{\mathrm{FS}} \equiv \sqrt{\frac{8\pi^2 c_\nu^2}{3\,\Omega_m H^2}} \simeq 4.2\sqrt{\frac{1+z}{\Omega_{m,0}}}\left(\frac{\mathrm{eV}}{m_\nu}\right)\ h^{-1}\ \mathrm{Mpc}$$

$$k_{\mathrm{FS}} \equiv \frac{2\pi}{\lambda_{\mathrm{FS}}}$$

$\lambda \gg \lambda_{\mathrm{FS}}$, $k \ll k_{\mathrm{FS}}$ Clustering

$\lambda \ll \lambda_{\mathrm{FS}}$, $k \gg k_{\mathrm{FS}}$ Non-clustering

- In turn, free-streaming (non-clustering) neutrinos slow down the growth of gravitational potential wells on **scales** $\lambda \ll \lambda_{FS}$ or **wavenumbers** $k \gg k_{FS}$.

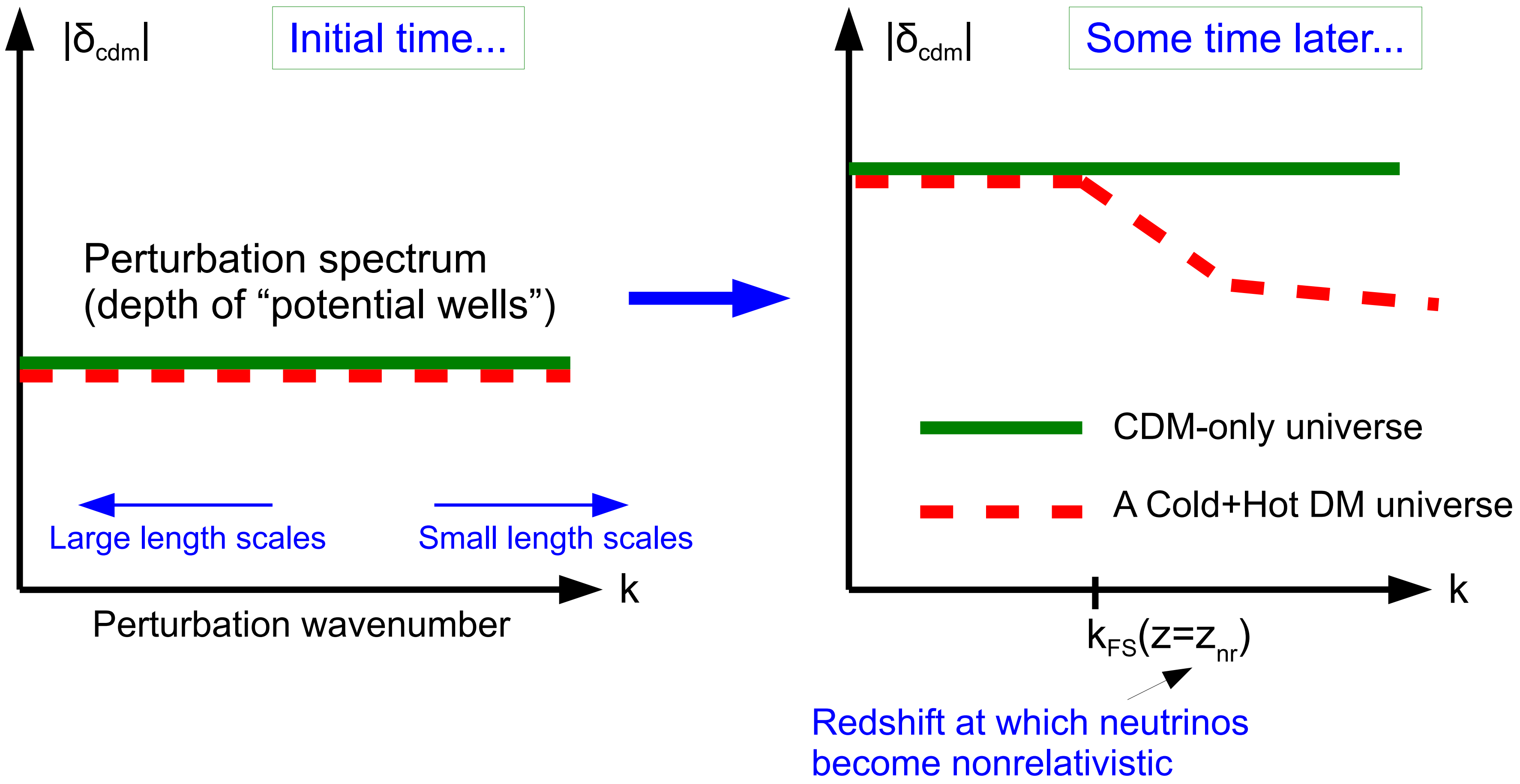


Clustering → potential wells become deeper

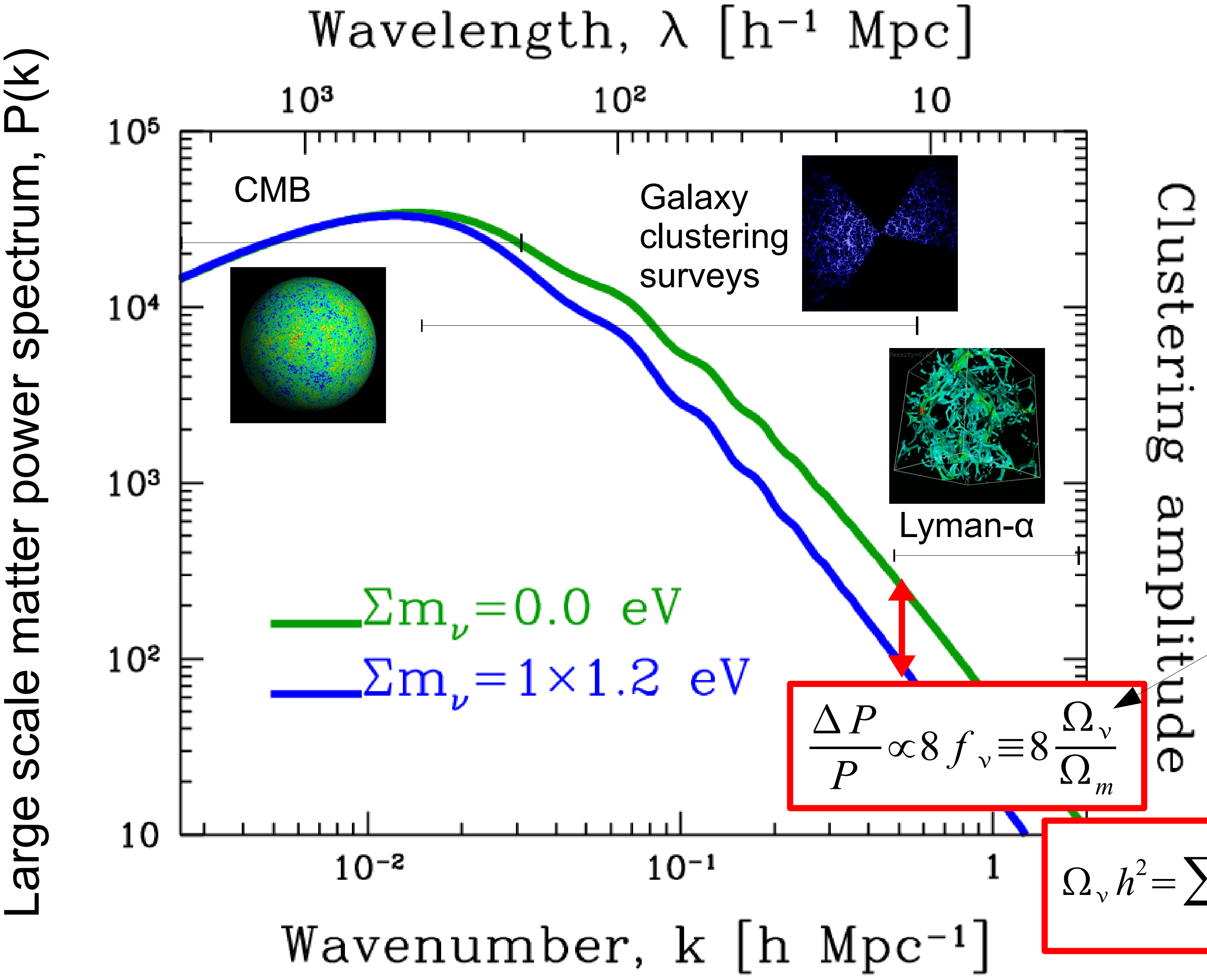
Some time later...

Both CDM and neutrinos cluster

Only CDM clusters



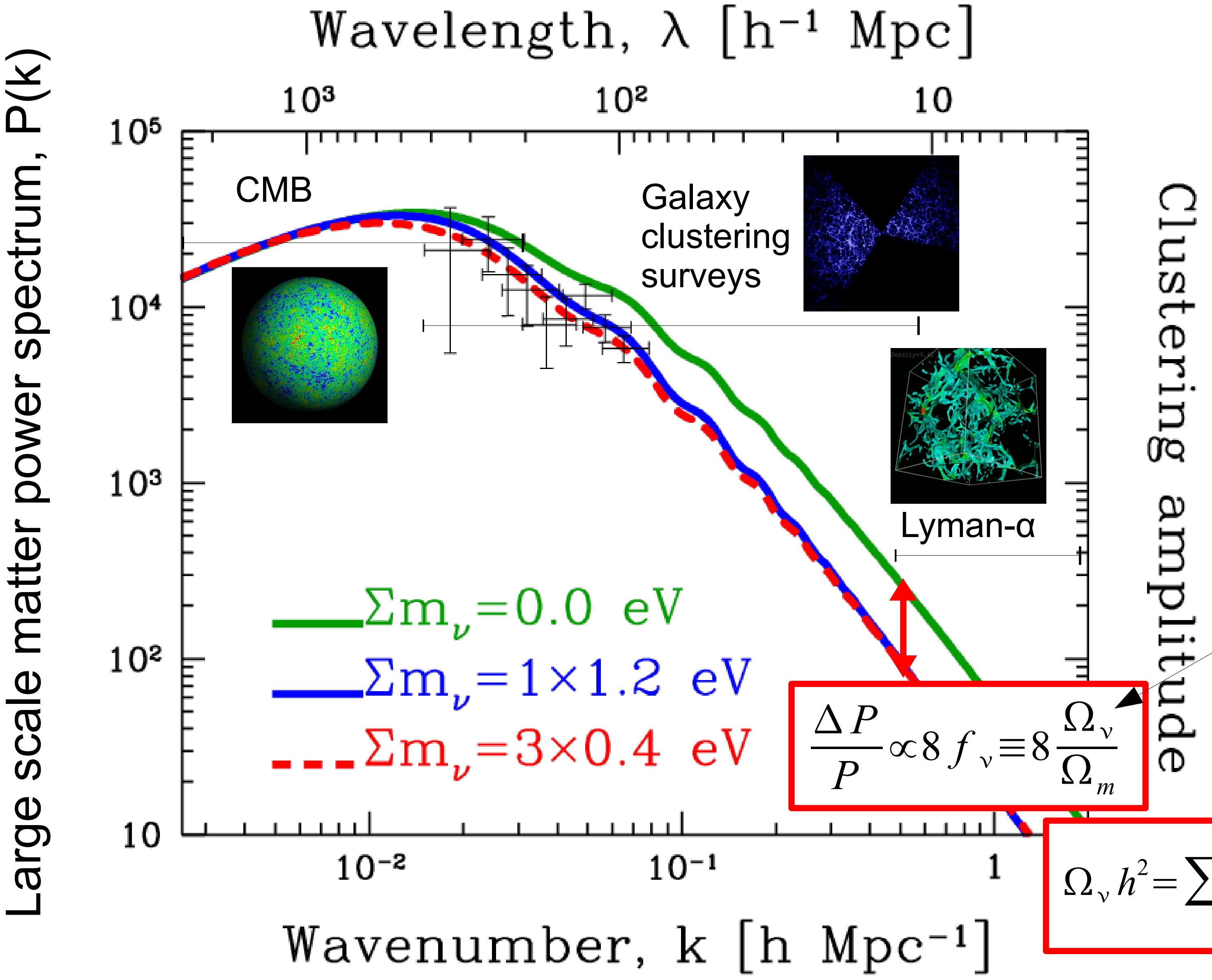
- The presence of **H**ot **D**ark **M**atter slows down the growth of **C**old **D**ark **M**atter perturbations at large wavenumbers k.



f_ν = Neutrino fraction

$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}$$



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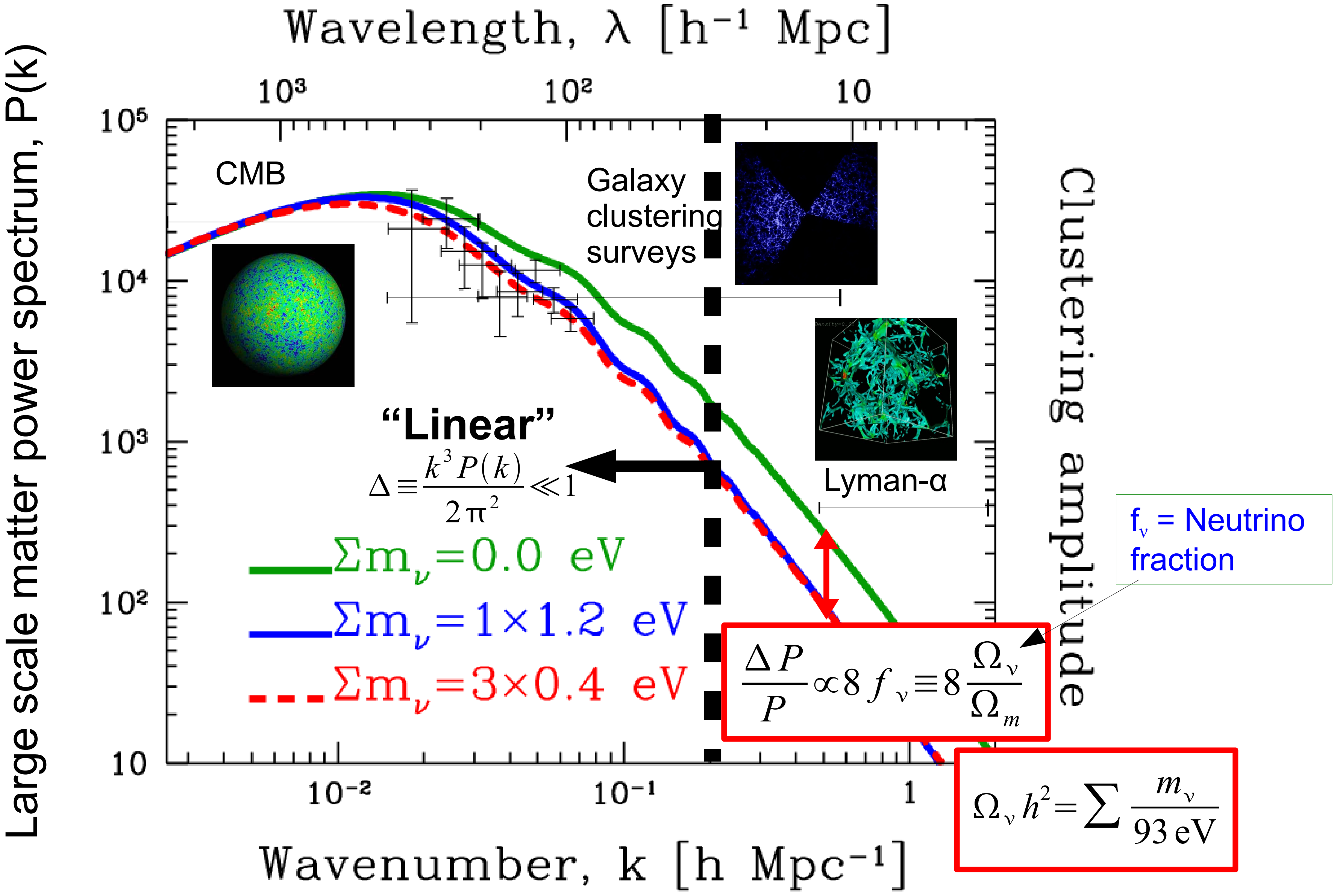


"Linear"

$$\Delta \equiv \frac{k^3 P(k)}{2\pi^2} \ll 1$$

$$\boxed{\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}}$$

f_ν = Neutrino fraction

$$\boxed{\Omega_\nu h^2 = \sum \frac{m_\nu}{93\,\mathrm{eV}}}$$

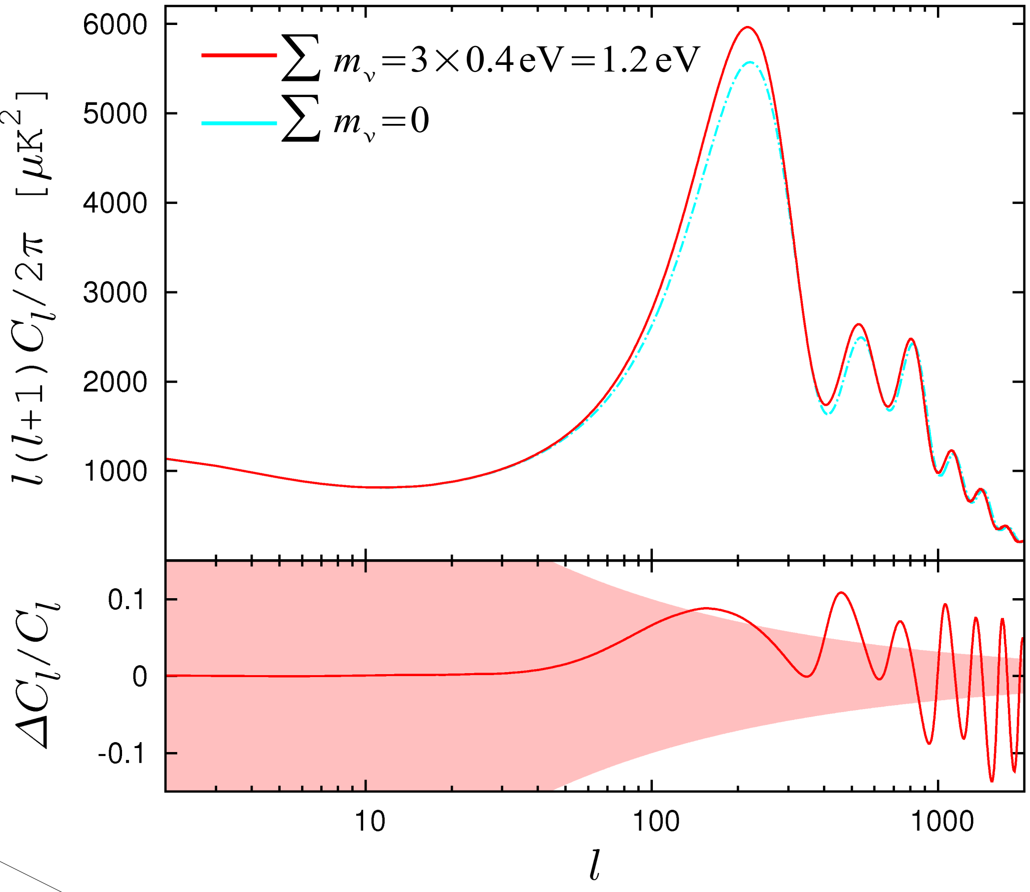
Neutrino effects on the CMB anisotropies...

- Present constraints come mainly via the early ISW effect:
  - γ decoupling: T ~ 0.26 eV.
  - Equality at T ~ 1 eV.

- A **O(0.1-1) eV** neutrino becomes nonrelativistic in the same time frame.

WMAP7 only (ΛCDM+m_ν):

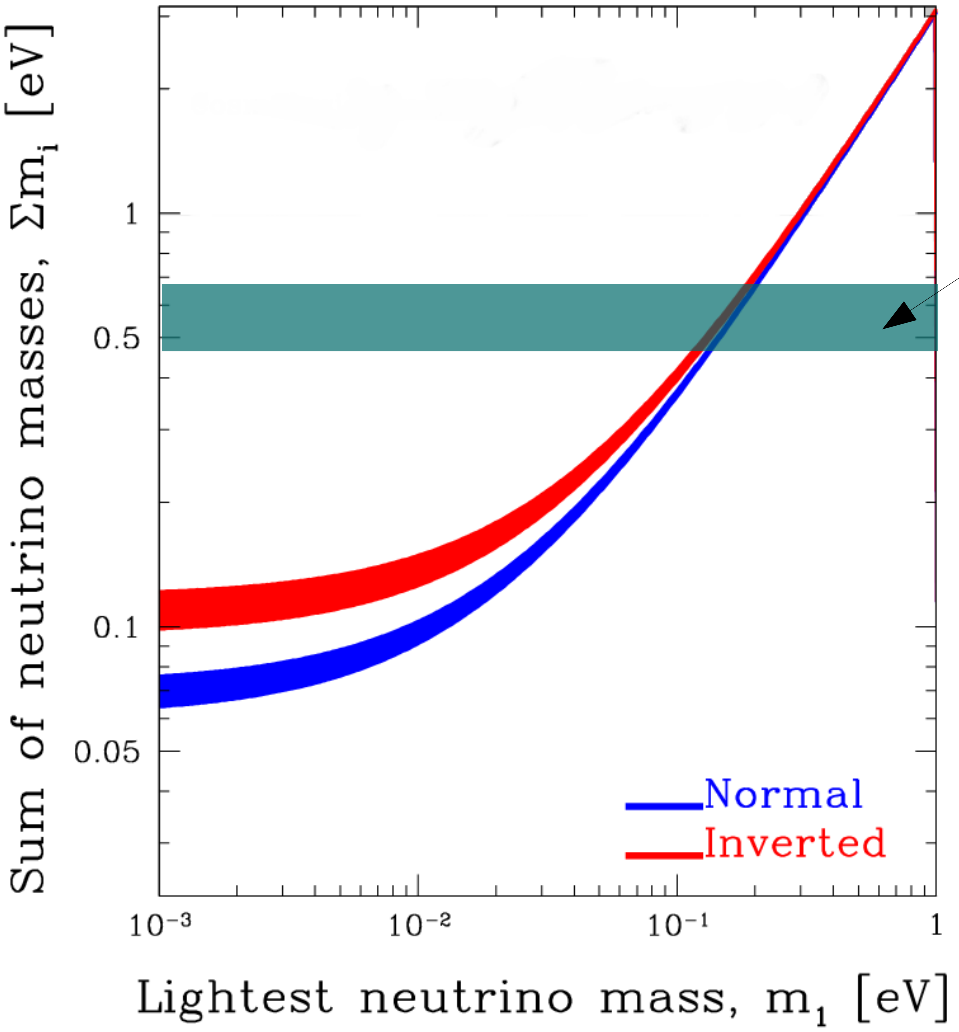
$$\sum m_\nu < 1.3\,\mathrm{eV}\,(95\,\%\,\mathrm{C.I.})$$



CMB = Minimal nonlinear physics

Komatsu et al. 2010, Hannestad et al. 2010

Present constraints...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

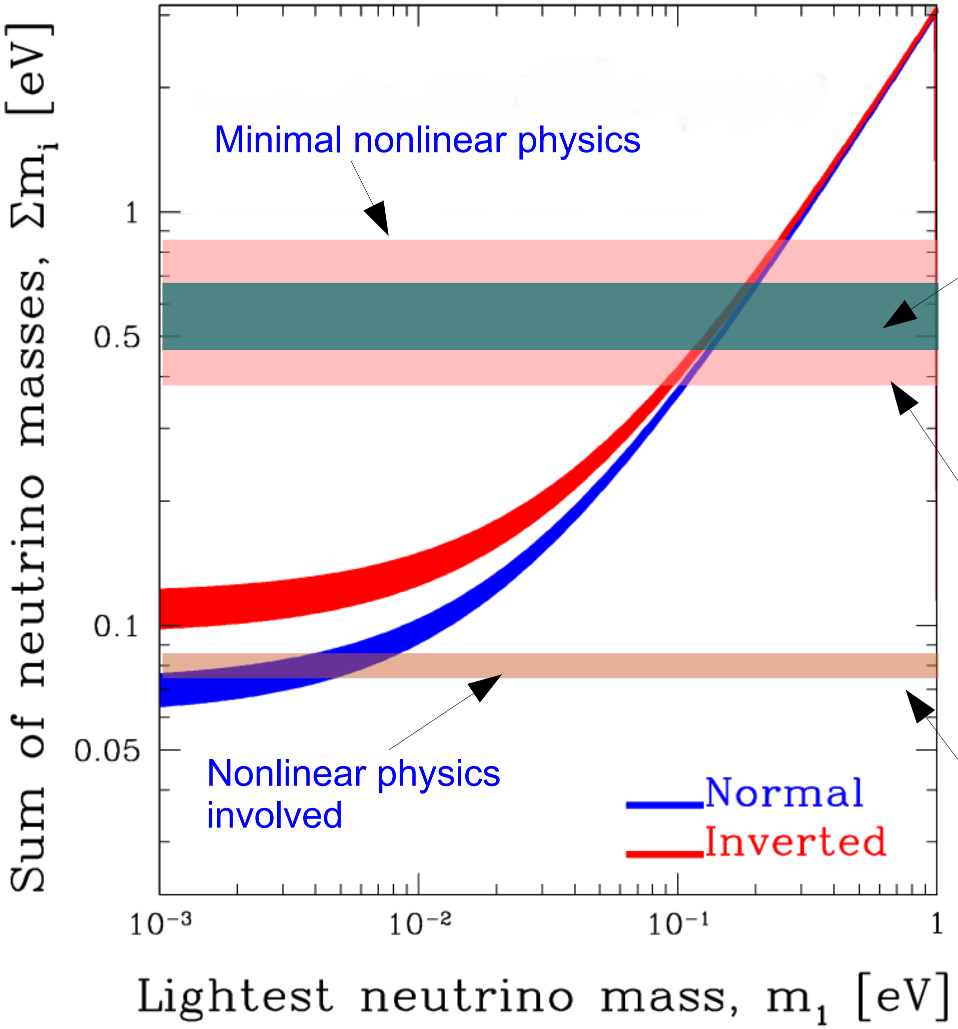
depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y^{3}W 2010
Gonzalez-Garcia et al. 2010, etc.

Includes uncertainties in

- Number of neutrinos
- Dark energy equation of state
- Inflation physics
  (tensors, running spectral index)
- Spatial curvature

Present constraints and future sensitivities...



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Planck alone (1 year) 2012–2013

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Perotto et al. 2006

Planck+Weak lensing (LSST) 2020+

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Hannestad, Tu & Y^3W 2006

Part II:
Hint of sterile neutrinos from the CMB?

Experimental anomalies & the sterile ν interpretation...

- Experiments at odds with the standard **3-neutrino interpretation** of global neutrino oscillation data:
  - LSND ($\bar{\nu}_e$ appearance)
  - MiniBooNE anti-neutrinos ($\bar{\nu}_e$ appearance)
  - Short baseline reactor experiments (re-evaluation of neutrino fluxes) ($\bar{\nu}_e$ disappearance)

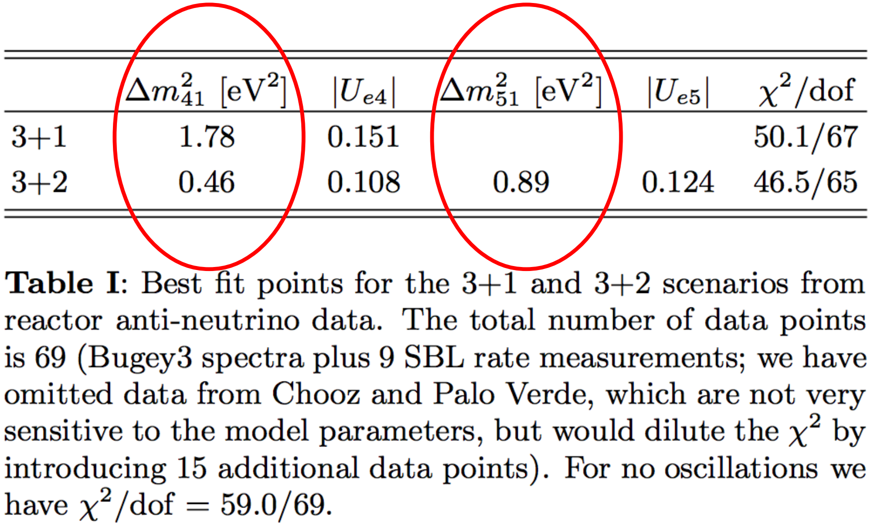
- If interpreted as oscillation signals → a 4th (or more) **sterile neutrino** with $\Delta m^2 \sim O(1\ \mathrm{eV}^2)$.

Sterile = does not violate
LEP bound on Z decay width

Experimental anomalies & the sterile ν interpretation...

- **Best-fits** parameters: Kopp, Maltoni & Schwetz 2011

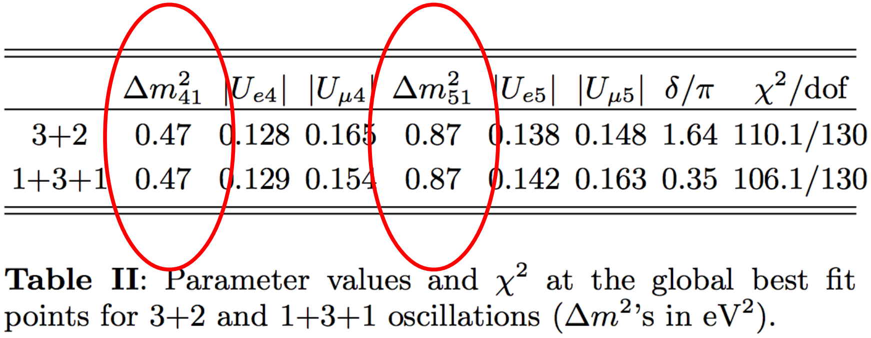
Reactor experiments only



	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

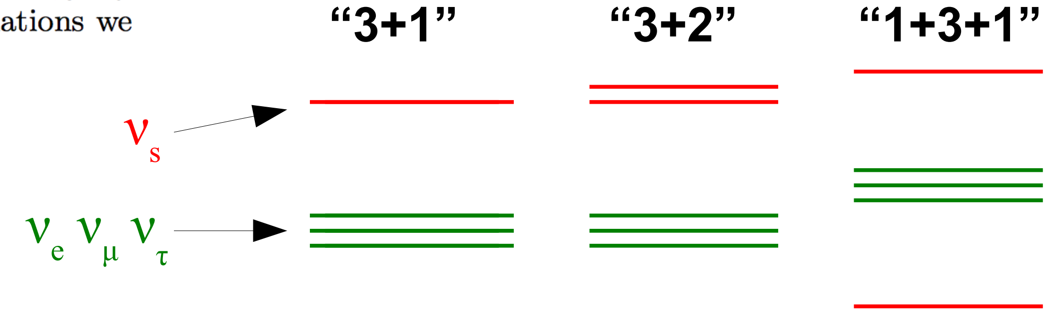
Table I: Best fit points for the 3+1 and 3+2 scenarios from reactor anti-neutrino data. The total number of data points is 69 (Bugey3 spectra plus 9 SBL rate measurements; we have omitted data from Chooz and Palo Verde, which are not very sensitive to the model parameters, but would dilute the χ^2 by introducing 15 additional data points). For no oscillations we have $\chi^2/\text{dof} = 59.0/69$.

Global short baseline
(including LSND+MiniBooNE)



	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).



Impact of light (eV mass) sterile ν on cosmology...

- Preferred Δm^2 and mixing → thermalisation of sterile neutrino state prior to neutrino decoupling.

→ Excess relativistic energy density.

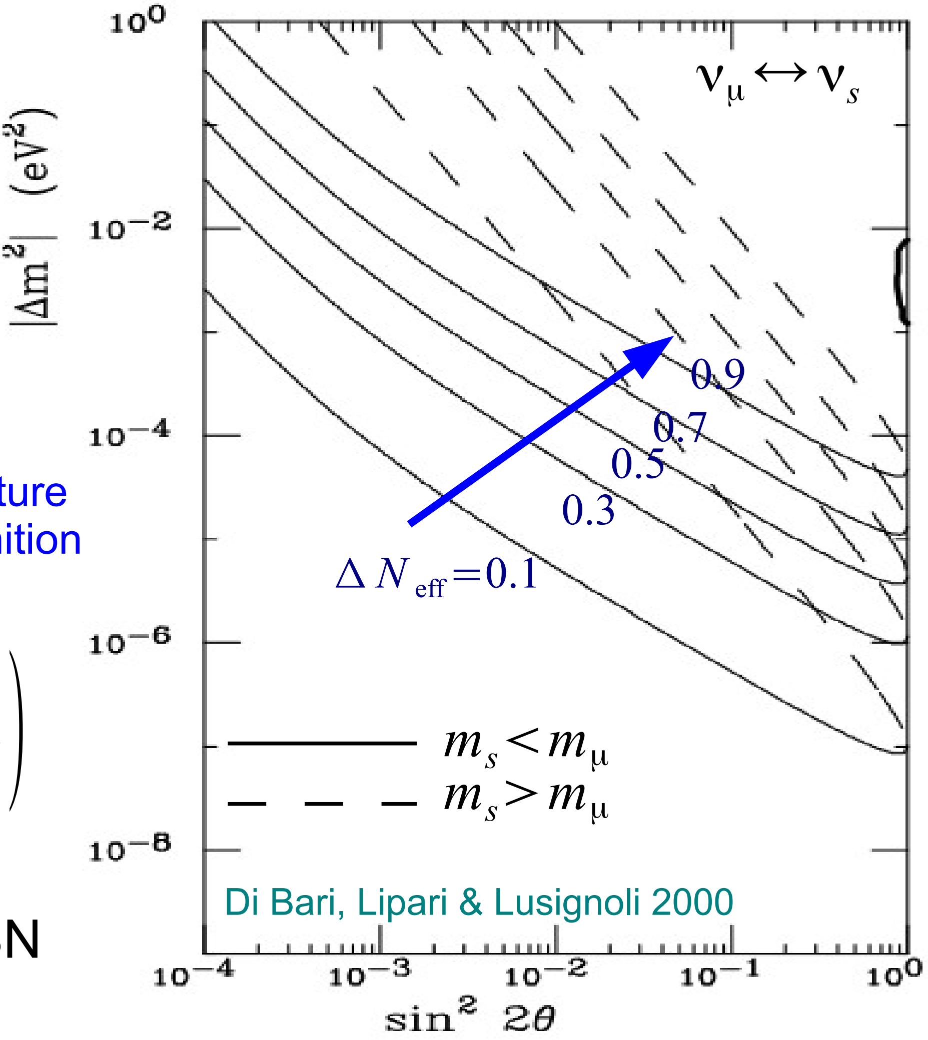
$$\rho_\nu + \rho_X = N_{\mathrm{eff}}\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$

$$= (3.046 + \Delta N_{\mathrm{eff}})\left(\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right)$$

Neutrino temperature per definition

Observables

→ CMB, large-scale structure, BBN



Di Bari, Lipari & Lusignoli 2000

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Neutrino temperature per definition

Observables

→ CMB, large-scale structure, BBN

- If the sterile neutrino is sufficiently massive → **hot dark matter**.

$$\Omega_s h^2 = \frac{m_s}{94\,\mathrm{eV}}$$

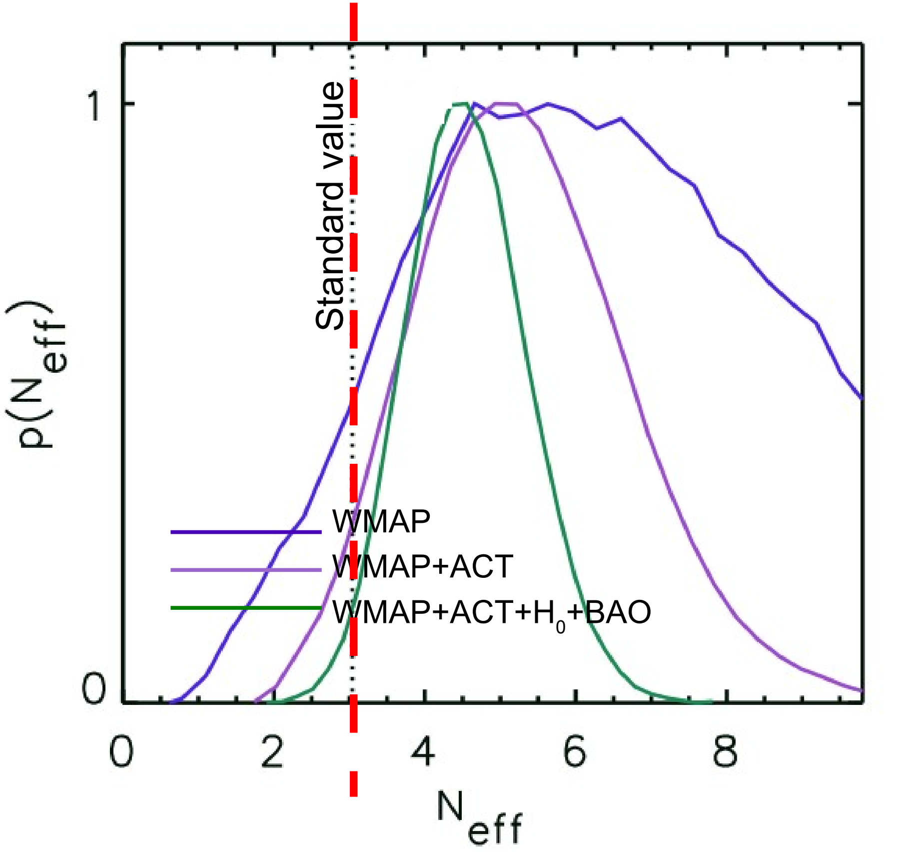
↓

CMB, large-scale structure

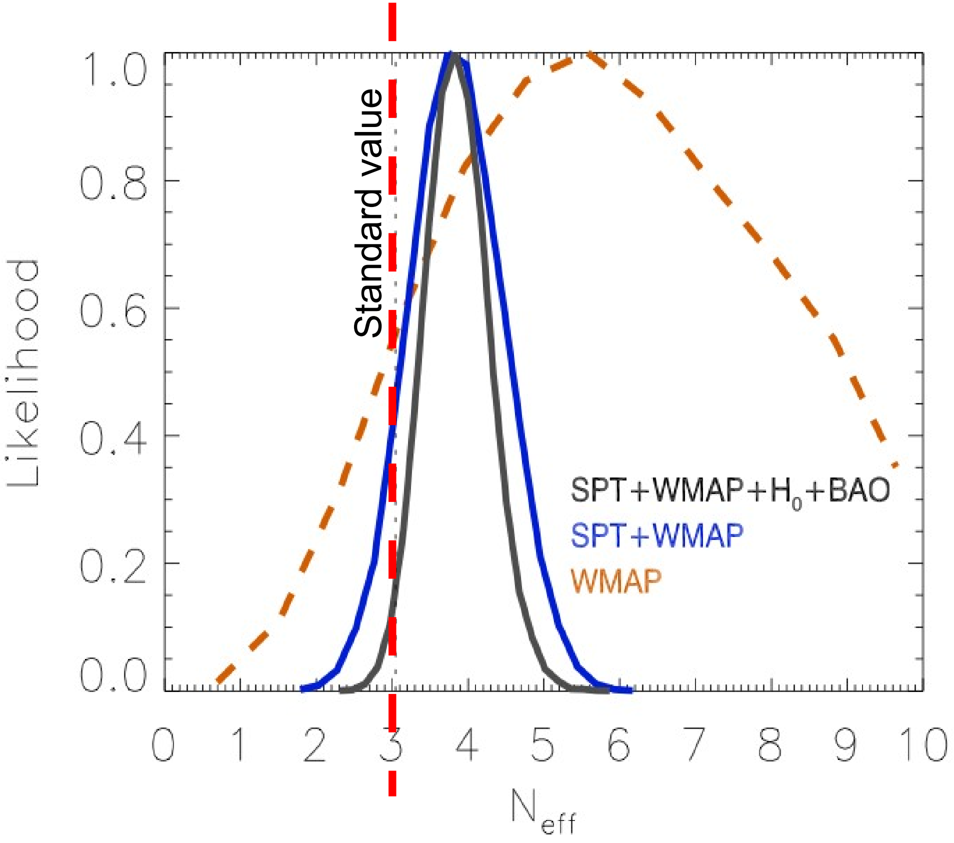
2a. CMB+LSS

Evidence for $N_{eff} > 3$ from CMB+LSS...

- Recent CMB+LSS data appear to prefer $N_{eff} > 3$!



Dunkley et al. [Atacama Cosmology Telescope] 2010



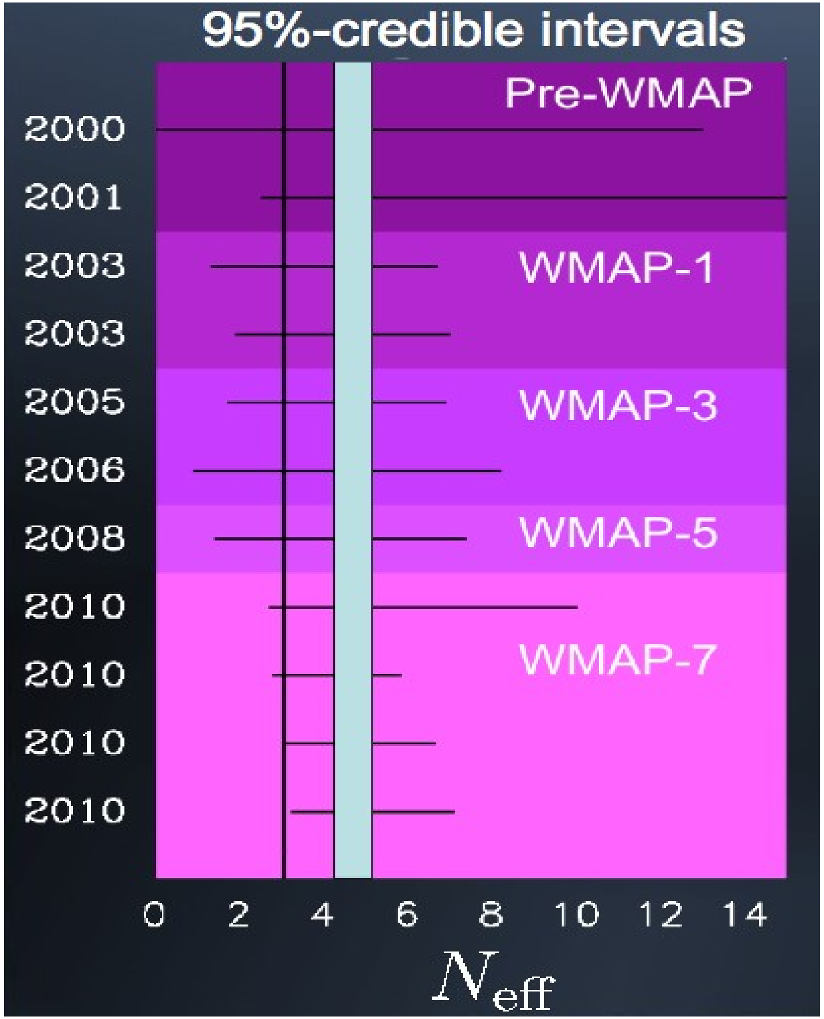
Keisler et al. [South Pole Telescope] 2011

Evidence for N_{eff} > 3 from CMB+LSS...

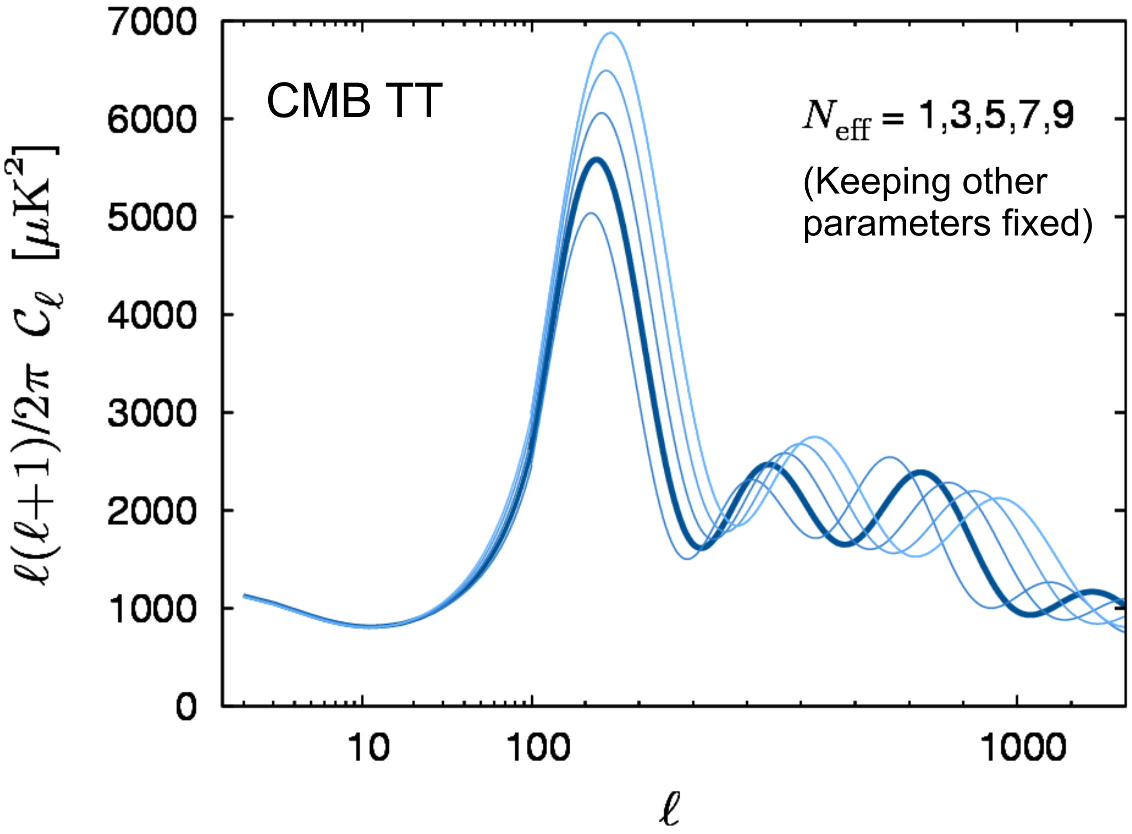
- Trend since WMAP-1.
- Exact numbers depend on the cosmological model and the combination of data used.
- Simplest model (vanilla ΛCDM+N_{eff}):
  - **Evidence for N_{eff} > 3 @ 98.4%** (WMAP7+ACT+ACBAR+H_0+BAO).

Hou, Keisler, Knox, et al. 2011

Adapted from S. Hannestad



How it works...

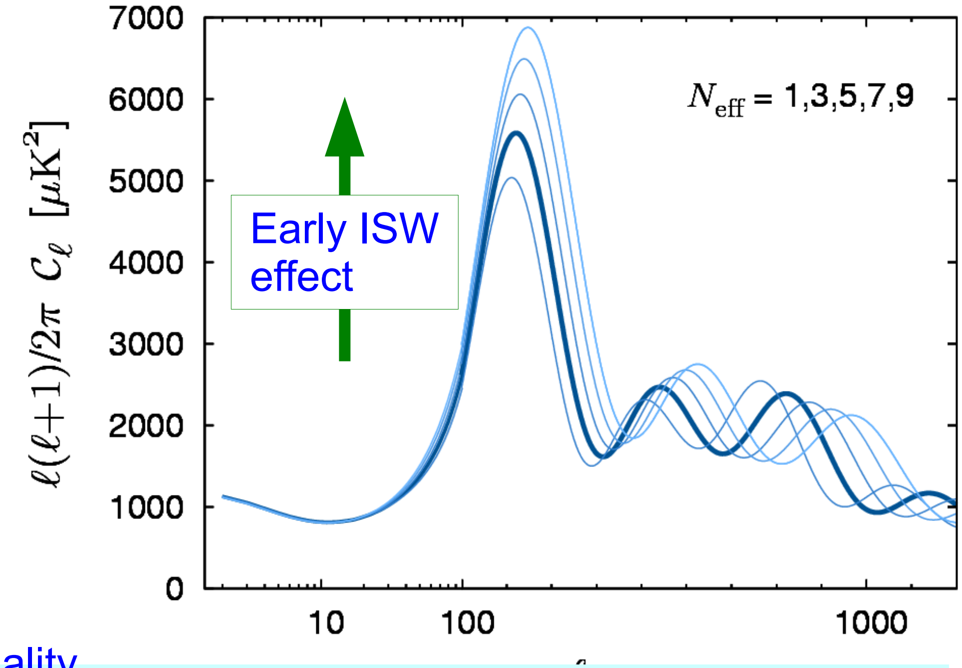


- Looks easy... but we also use the same data to measure at least 6 other cosmological parameters: $\left(\Omega_b h^2, \Omega_m h^2, h, n_s, A_s, \tau\right)$

How it works: parameter degeneracies...

$N_{\rm eff}$ effects on the CMB...

- Matter-radiation equality (first peak height relative to plateau)
- Sound horizon/angular positions of peaks
- Anisotropic stress
- Damping tail



Early ISW effect

Degeneracies...

- Matter density

Redshift of equality

$$1+z_{\rm eq}=\frac{\Omega_m}{\Omega_r}\approx\frac{\boxed{\Omega_m h^2}}{\Omega_\gamma h^2}\,\frac{1}{1+0.2271\,\boxed{N_{\rm eff}}}$$

How it works: parameter degeneracies...

N_{eff} effects on the CMB...

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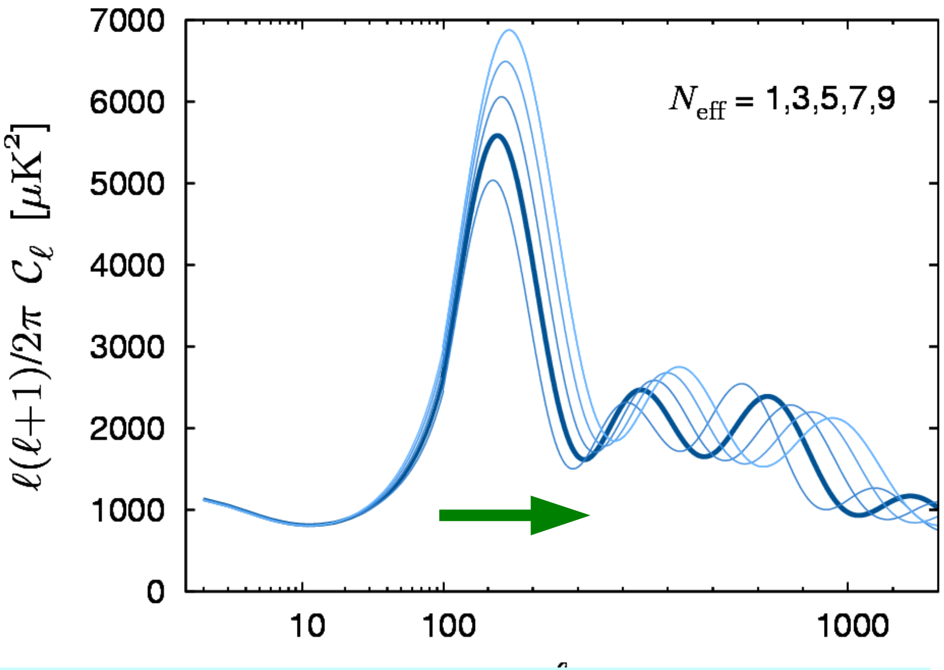


Degeneracies...

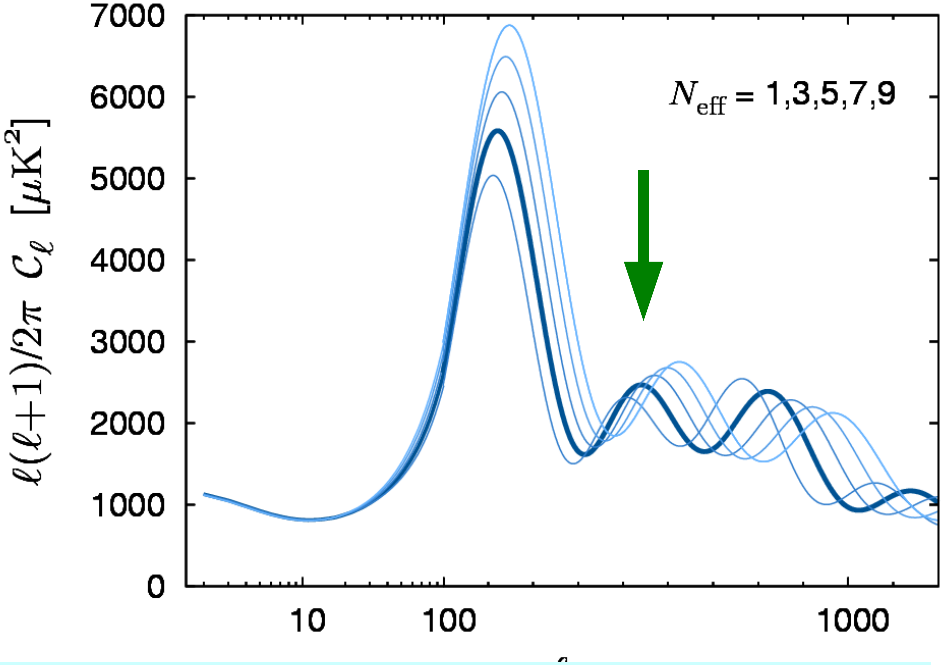
- z_{eq} affects the sound horizon: degenerate with baryon and DM densities.
- Angular positions depend on distance to LSS and hence on DE density.

How it works: parameter degeneracies...

N_{eff} effects on the CMB...

- Matter-radiation equality (first peak height relative to plateau)
- Sound horizon/angular positions of peaks
- Anisotropic stress
- Damping tail

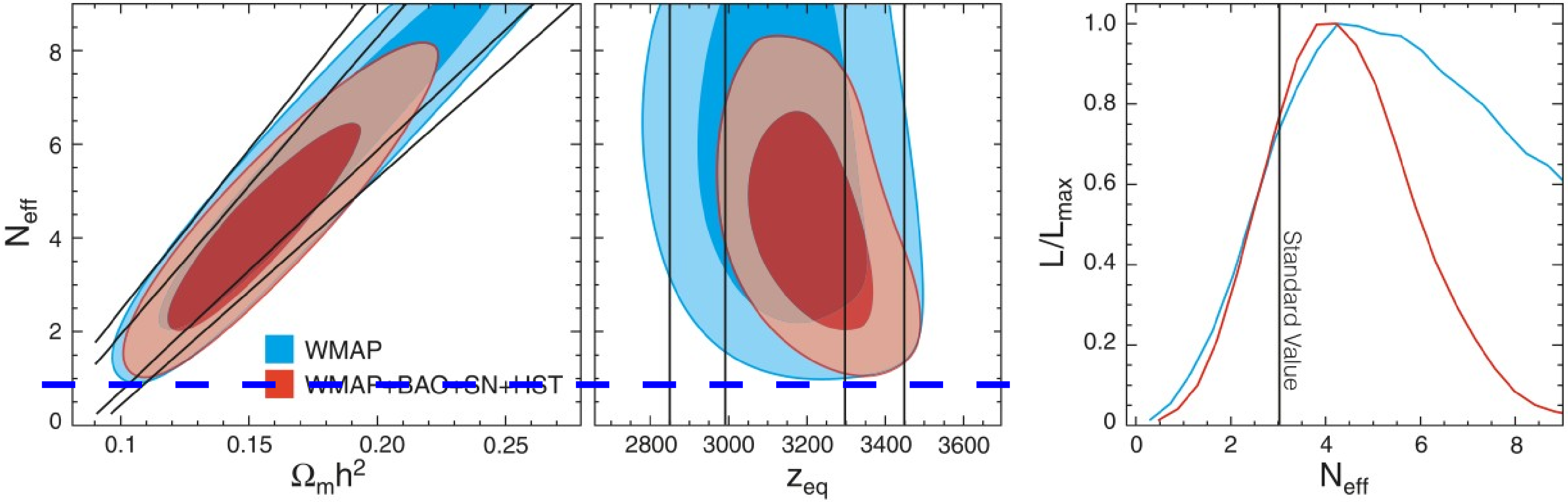
Free-streaming particles



Degeneracies...

- Anisotropic stress; damps oscillations at l > 200.
- Partially degenerate with primordial fluctuation amplitude.

- Measurement of the anisotropic stress (since WMAP-5) gives lower limit on N_{eff} from CMB alone (without supplementary large-scale structure data).



Komatsu et al. [WMAP5] 2008

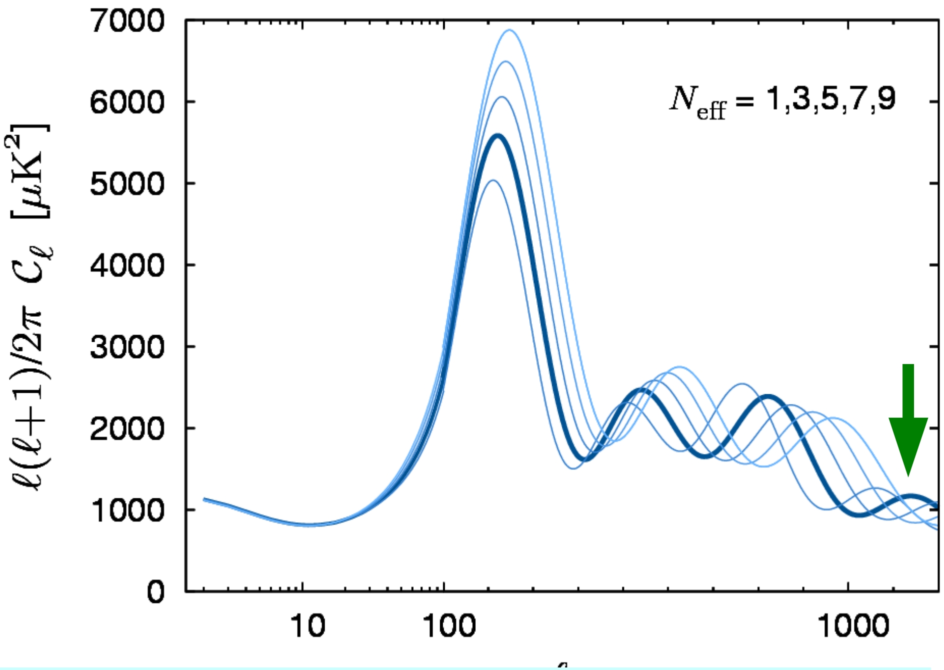
- **Upper limit** (pre 2010) requires combination with other observations (LSS, HST, SN) sensitive to the matter density and the expansion rate...

OR...

How it works: parameter degeneracies...

N_{eff} effects on the CMB...

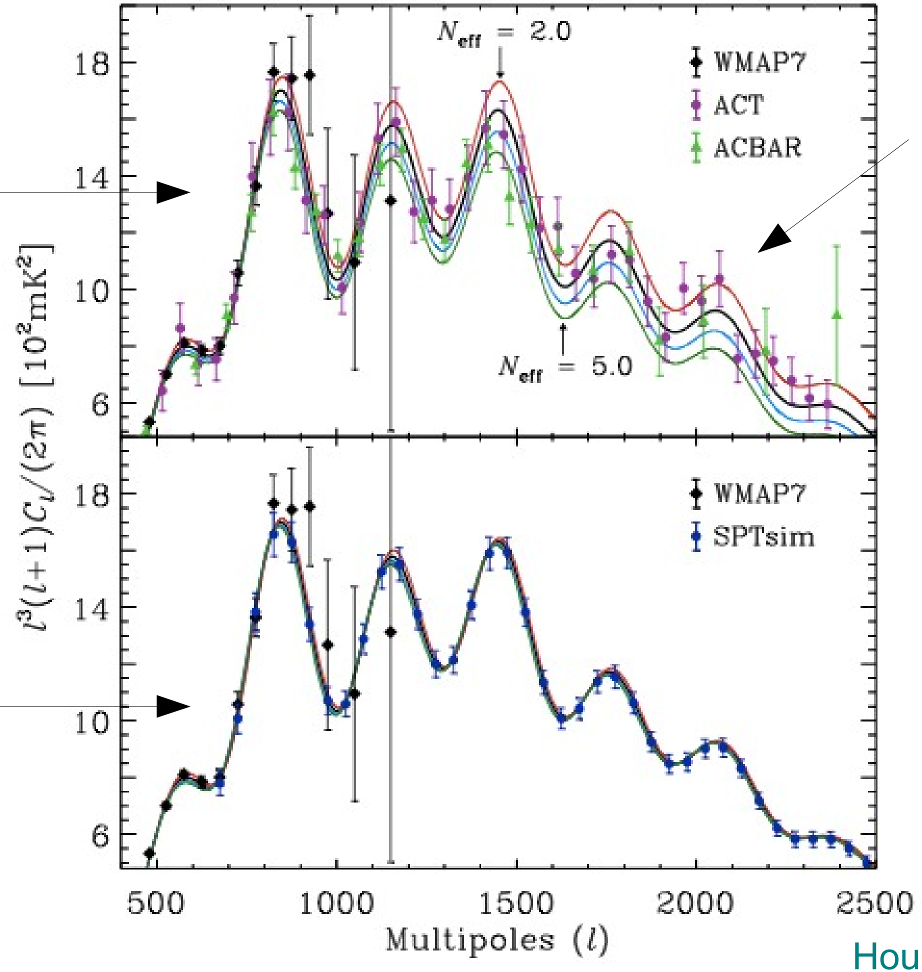
- Matter-radiation equality (first peak height relative to plateau)
- Sound horizon/angular positions of peaks
- Anisotropic stress
- Damping tail



Degeneracies...

- N_{eff} → higher expansion rate → more Silk damping.
- Some degeneracy with the Helium fraction.

- N_{eff} and the CMB damping tail:



- Matter-radiation equality
- Baryon density
- Sound horizon

fixed to agree with WMAP

Different N_{eff} visible in the damping tail (probed by ACT & SPT and Planck)

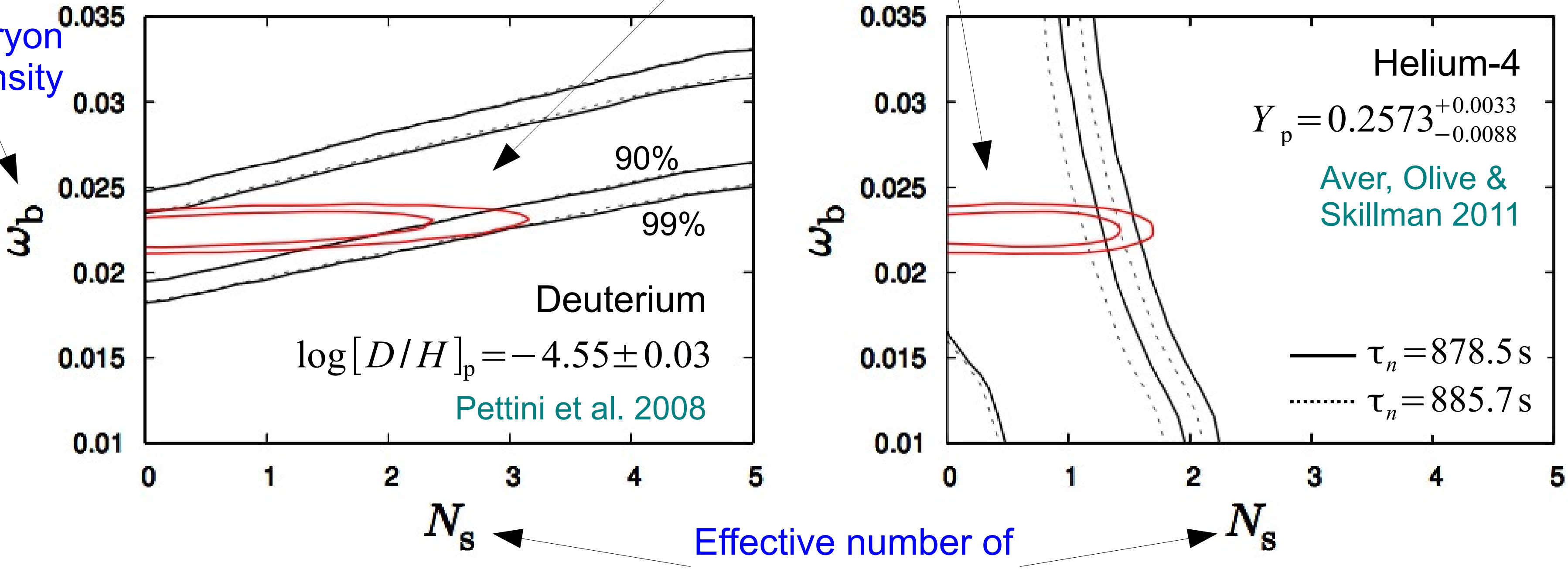
Degeneracy with the helium fraction is not exact
→ Can be resolved with Planck

Hou, Keisler, Knox et al. 2011

2b. BBN

Evidence for $N_{eff} > 3$ from BBN...

- Light element abundances are sensitive to excess relativistic energy density.



Baryon density

Using CMB prior on ω_b

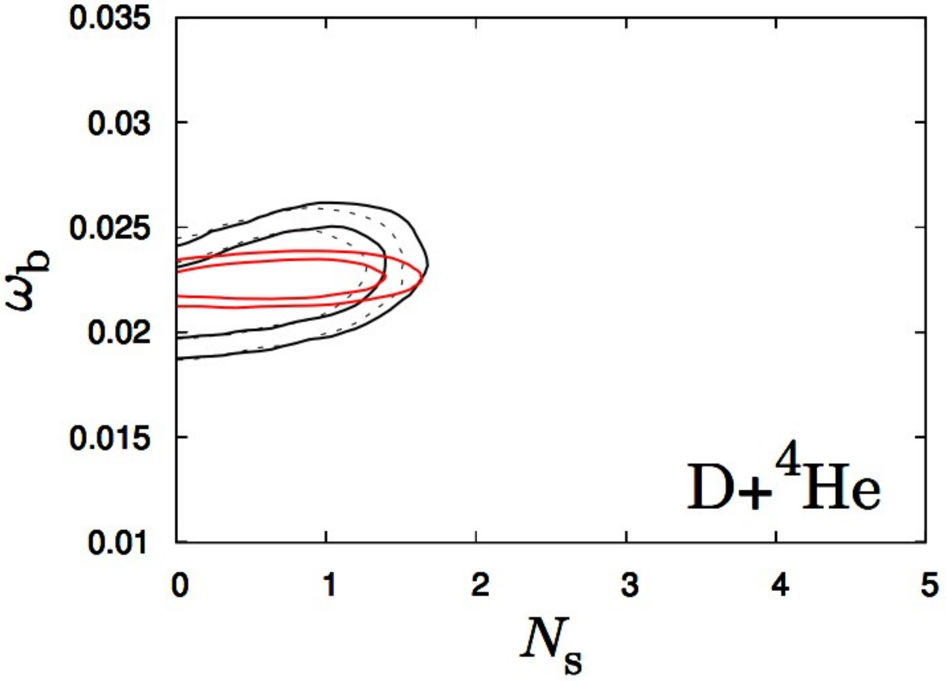
Effective number of sterile neutrinos

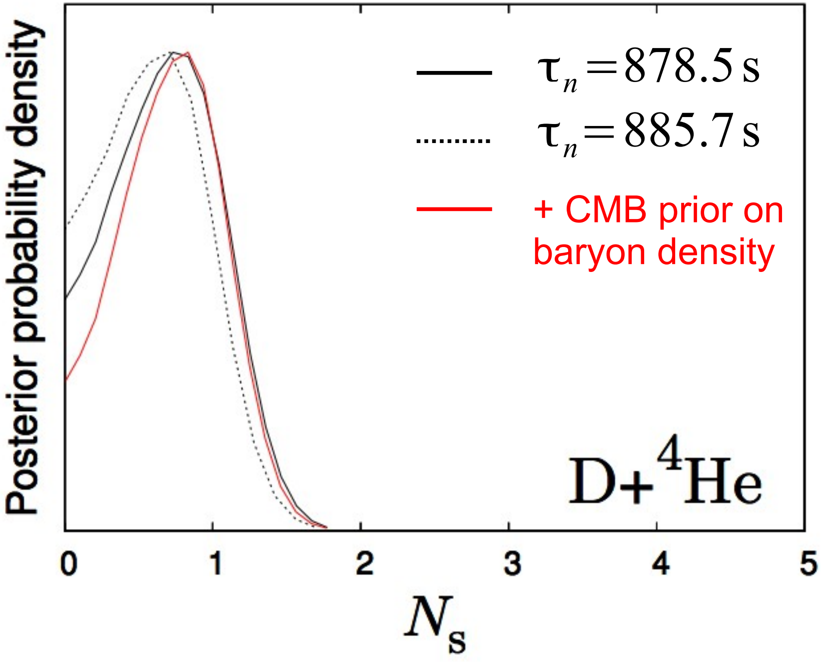
$N_{eff} = 3.046 + N_s$

Hamann, Hannestad, Raffelt & Y^{3}W 2011

Evidence for $N_{\text{eff}} > 3$ from BBN...

- Mild preference for $N_{\text{eff}} > 3$ (or $N_s > 0$) from Deuterium+Helium-4.
- But $N_s = 2$ is strongly disfavoured.





Hamann, Hannestad, Raffelt & Y^{3}W 2011

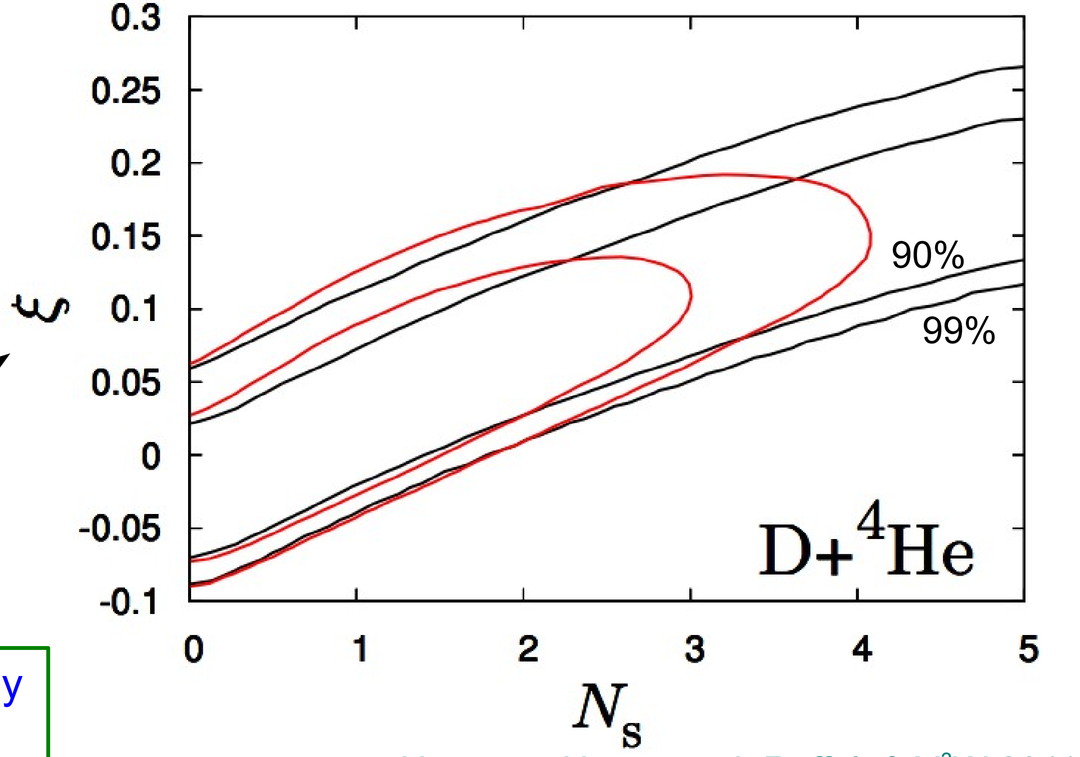
Quick fix: degenerate BBN...

- Introduce a neutrino chemical potential (= O(0.1) lepton asymmetry).
- Then even $N_s = 3$ is allowed by BBN.

Lepton asymmetry

$$L \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\frac{T_\nu}{T_\gamma}\right)^3 \left(\pi^2 \xi + \xi^3\right)$$

Neutrino chemical potential



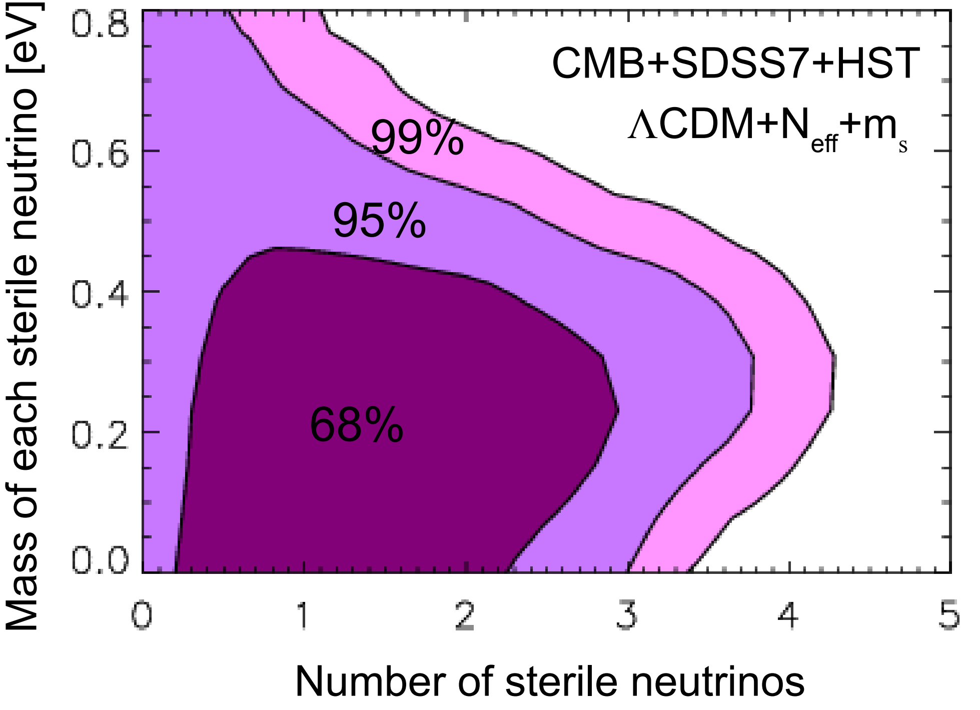
Hamann, Hannestad, Raffelt & Y^3W 2011

Question: How to simultaneously get L = O(0.1) and B = O(10^{-10})?

2c. Implications for the LSND/MiniBooNE/reactor ν_s

Can the reactor/MiniBooNE sterile ν explain $N_{eff} > 3$?

- **Short answer**: Not so easy.
- **Reason**: eV mass sterile neutrinos violate CMB+LSS ν mass bounds.



Hamann, Hannestad, Raffelt, Tamborra & Y^{3}W 2010

- 3+1 thermalised sterile:

$$m_s < 0.48 \text{ eV} \quad (95\% \, C.I.)$$

Lab best-fit: $m_s \sim 1 \text{ eV}$

- 3+2 thermalised sterile:

$$m_{s1} + m_{s2} < 0.9 \text{ eV} \quad (95\% \, C.I.)$$

Lab best-fit: $m_{s1} \sim 0.7 \text{ eV}, \; m_{s2} \sim 0.9 \text{ eV}$

Is there a way out?

- **Plan A**: Suppress sterile neutrino thermalisation (e.g., using a large lepton asymmetry).
  - $N_{eff} > 3$ explained by some other physics (sub-eV thermal axions, hidden photons, etc.?)

Is there a way out?

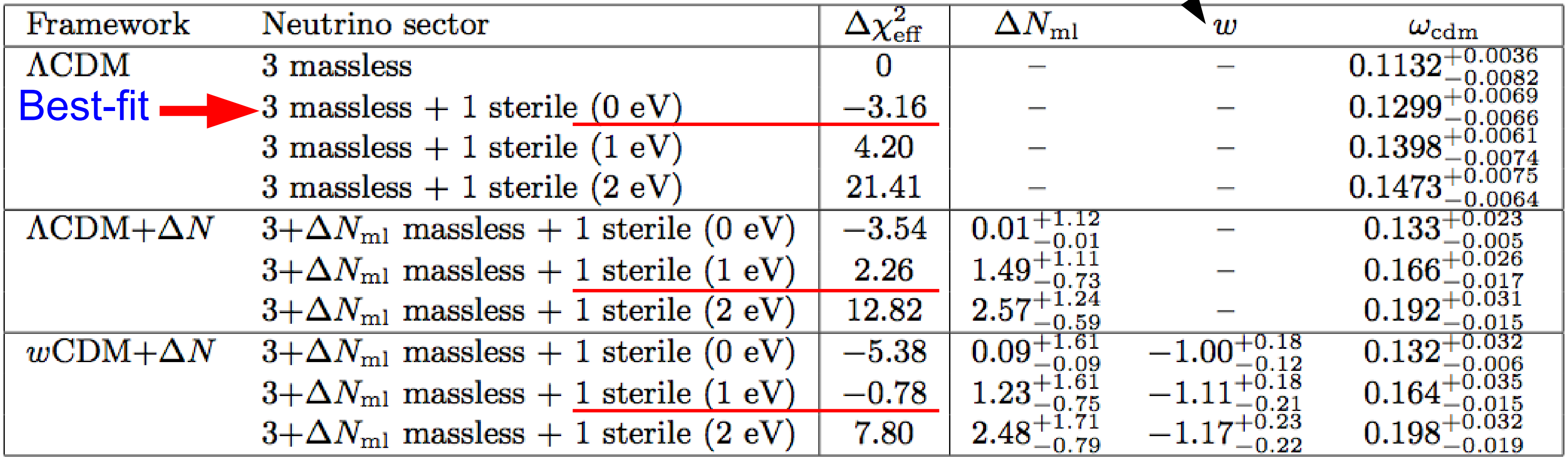
- **Plan A**: Suppress sterile neutrino thermalisation (e.g., using a large lepton asymmetry).
  - $N_{\mathrm{eff}} > 3$ explained by some other physics (sub-eV thermal axions, hidden photons, etc.?)
- **Plan B**: Failing to suppress ν_s thermalisation, exploit parameter degeneracies in the CMB+LSS to engineer a good fit.
  - Some known degeneracies:
    - Neutrino mass ↑ – Extra massless degrees of freedom ↑
    - Neutrino mass ↑ – Dark energy EoS parameter w ↓

Either way new physics is required...

Even more thermalised massless species

Non-standard dark energy equation of state

Best-fit



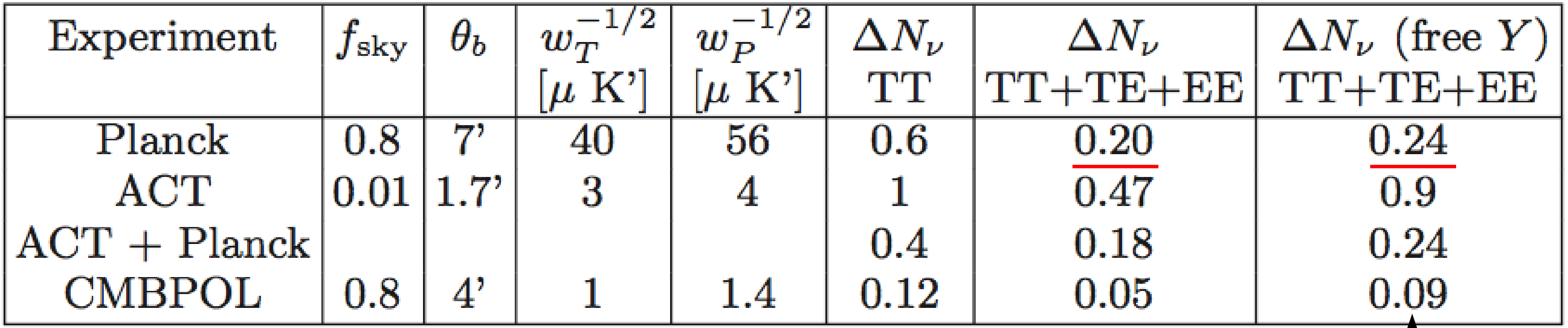
Framework	Neutrino sector	$\Delta\chi^2_{\rm eff}$	$\Delta N_{\rm ml}$	w	$\omega_{\rm cdm}$
ΛCDM	3 massless	0	–	–	$0.1132^{+0.0036}_{-0.0082}$
	3 massless + 1 sterile (0 eV)	-3.16	–	–	$0.1299^{+0.0069}_{-0.0066}$
	3 massless + 1 sterile (1 eV)	4.20	–	–	$0.1398^{+0.0061}_{-0.0074}$
	3 massless + 1 sterile (2 eV)	21.41	–	–	$0.1473^{+0.0075}_{-0.0064}$
ΛCDM+ΔN	$3+\Delta N_{\rm ml}$ massless + 1 sterile (0 eV)	-3.54	$0.01^{+1.12}_{-0.01}$	–	$0.133^{+0.023}_{-0.005}$
	$3+\Delta N_{\rm ml}$ massless + 1 sterile (1 eV)	2.26	$1.49^{+1.11}_{-0.73}$	–	$0.166^{+0.026}_{-0.017}$
	$3+\Delta N_{\rm ml}$ massless + 1 sterile (2 eV)	12.82	$2.57^{+1.24}_{-0.59}$	–	$0.192^{+0.031}_{-0.015}$
wCDM+ΔN	$3+\Delta N_{\rm ml}$ massless + 1 sterile (0 eV)	-5.38	$0.09^{+1.61}_{-0.09}$	$-1.00^{+0.18}_{-0.12}$	$0.132^{+0.032}_{-0.006}$
	$3+\Delta N_{\rm ml}$ massless + 1 sterile (1 eV)	-0.78	$1.23^{+1.61}_{-0.75}$	$-1.11^{+0.18}_{-0.21}$	$0.164^{+0.035}_{-0.015}$
	$3+\Delta N_{\rm ml}$ massless + 1 sterile (2 eV)	7.80	$2.48^{+1.71}_{-0.79}$	$-1.17^{+0.23}_{-0.22}$	$0.198^{+0.032}_{-0.019}$

- CMB+LSS can reasonably accommodate 1 x 1 eV sterile neutrinos if we modify the dark energy sector and put in extra massless d.o.f.
- 1 x 2 eV is still problematic...

Hamann, Hannestad, Raffelt & Y^3W 2011
also Elgarøy & Kristiansen 2011

Planck and N_{eff}...

- The question of whether $N_{eff} \sim 4$ will be settled almost immediately by Planck (launched May 14, 2009; public data early 2013).



Experiment	$f_{\rm sky}$	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Bashinsky & Seljak 2004

Helium fraction
as a free parameter

Summary...

- Precision cosmology constrains sum of neutrino masses to < 1 eV.
  - Will do even better in the future.

- Current precision cosmological data show a preference for extra relativistic degrees of freedom (beyond 3 neutrinos).
  - Sterile neutrino interpretation of reactor/MiniBooNE/LSND anomalies does not quite fit into the simplest picture...
    - 3+2: **Too many** for BBN
    - 3+1, 3+2: **Too heavy** for CMB/LSS
  - Non-trivial extensions to ΛCDM can alleviate the tension somewhat.
  - **Planck with tell**!