Neutrino masses in the universe

Yvonne Y. Y. Wong
RWTH Aachen

Neutrino town meeting, CERN
May 14 – 16, 2012

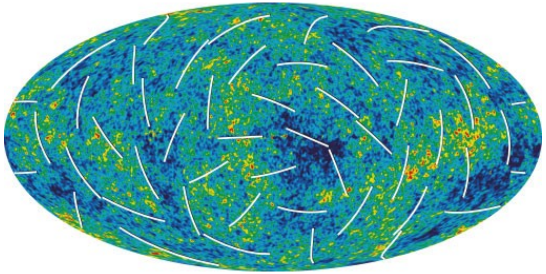
Evidence for sterile neutrinos from precision cosmology?

Yvonne Y. Y. Wong
RWTH Aachen

Neutrino town meeting, CERN
May 14 – 16, 2012

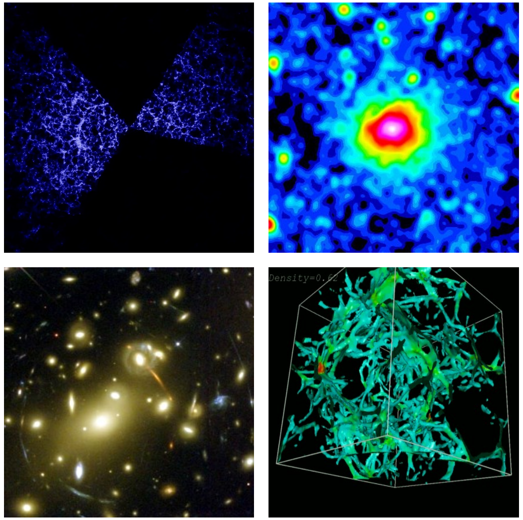
Precision cosmological probes...

Probes of inhomogeneities

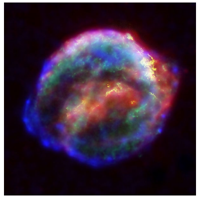


CMB temperature & polarisation anisotropies

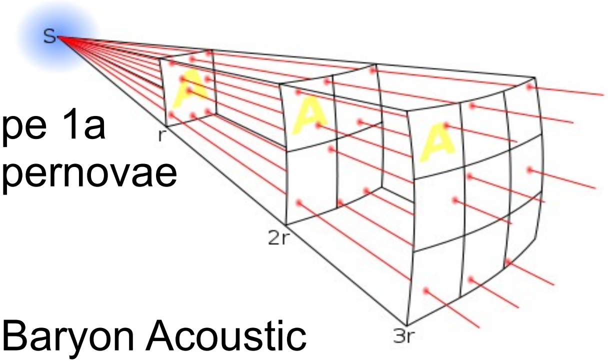
Large-scale matter distribution

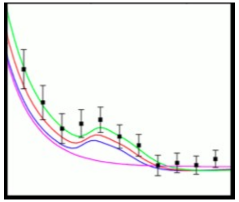


Distance vs redshift



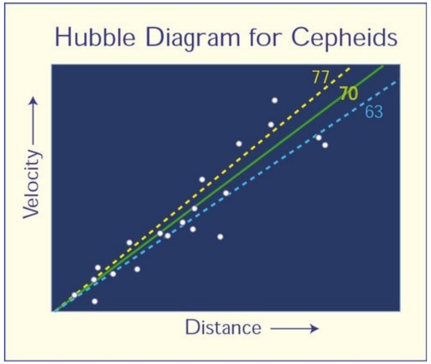
Type 1a supernovae





Baryon Acoustic Oscillation scale

Local Hubble expansion rate

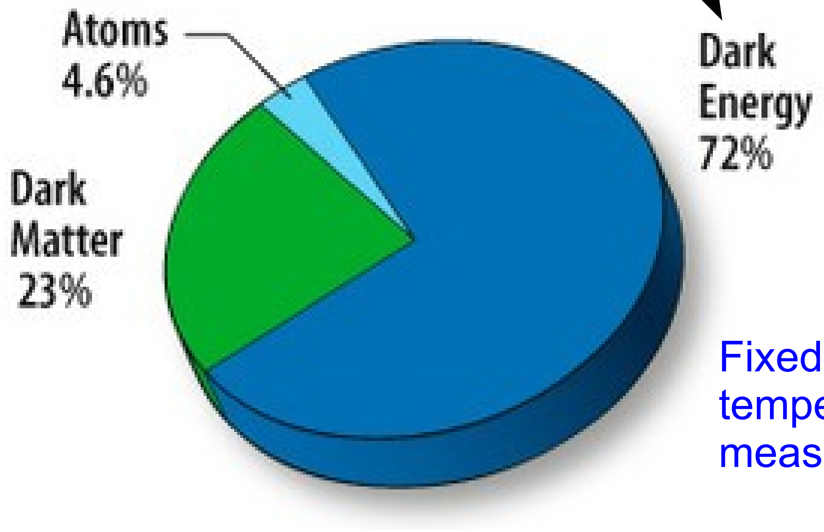


$$H_0 = 100\,h\ \mathrm{km/s/Mpc} = 73.8 \pm 2.4\ \mathrm{km/s/Mpc}$$

The concordance flat ΛCDM model...

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

Cosmological constant

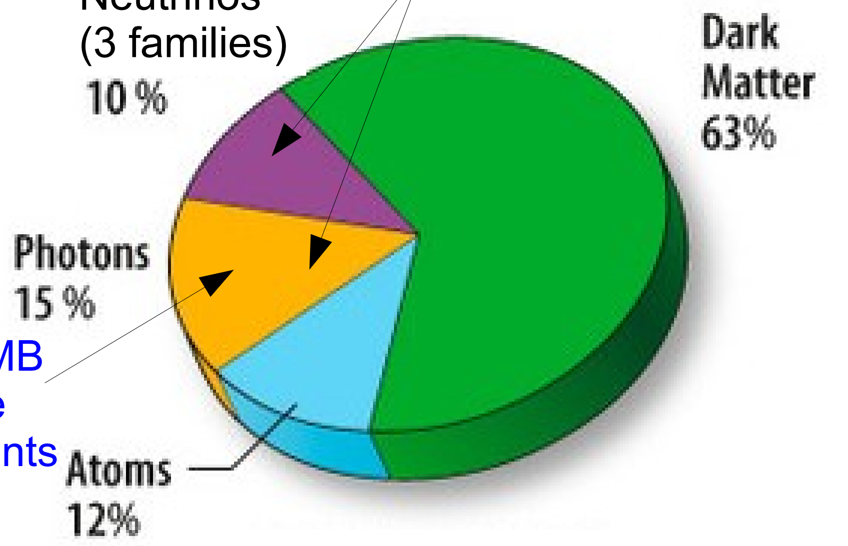


Composition today

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

Massless Neutrinos (3 families)

Fixed by CMB temperature measurements



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**:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

Photon temperature, number density, & energy density

  - **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:

$$\rho_\nu = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

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

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

Hot dark matter (not within vanilla ΛCDM)

Extending the “neutrino” sector...

- Any particle species whose production is associated with some thermal process and that decoupled while relativistic at relatively late times [T< O(100) MeV] will behave (more or less) like a neutrino as far as cosmological observations are concerned.

Neutrino temperature per definition

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

$$= \left(3.046 + \Delta N_{\text{eff}}\right)\rho_\nu^{(0)}$$

Three SM neutrinos

Other light stuff:
sterile neutrinos,
hidden photons,
etc.

Corrections due to non-instantaneous decoupling, finite temperature effects, and flavour oscillations

Plan...

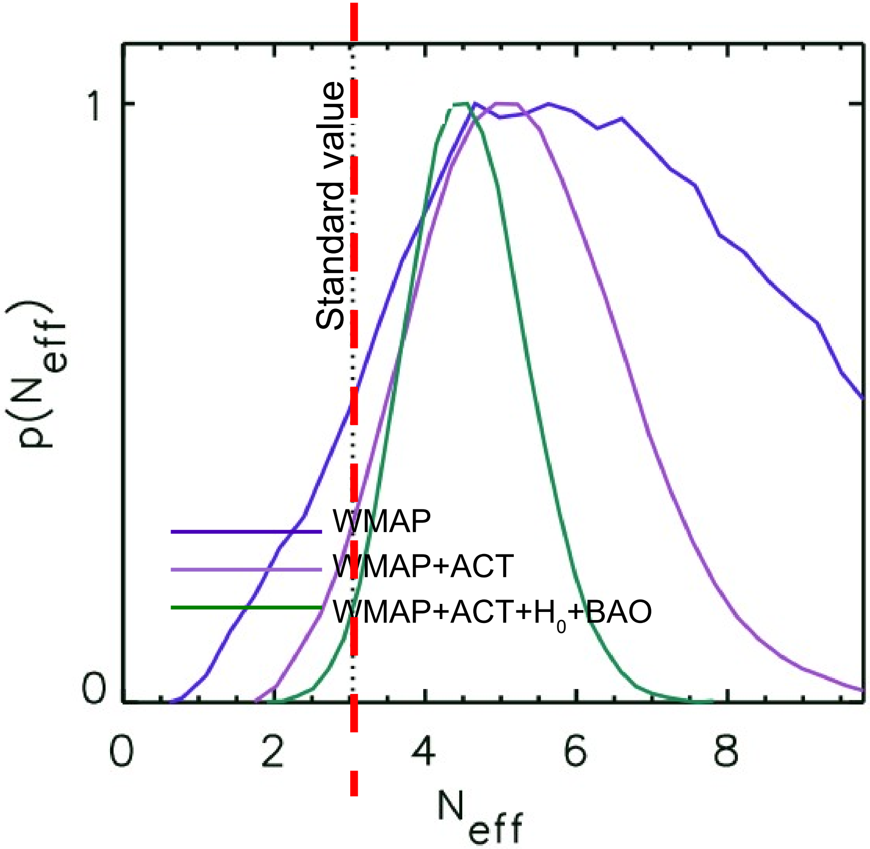
- Evidence of N_{eff}>3 from **CMB and large-scale structure** observations.
- Connection to the **short baseline sterile neutrino**.

- Bonus slides: **Big bang nucleosynthesis**

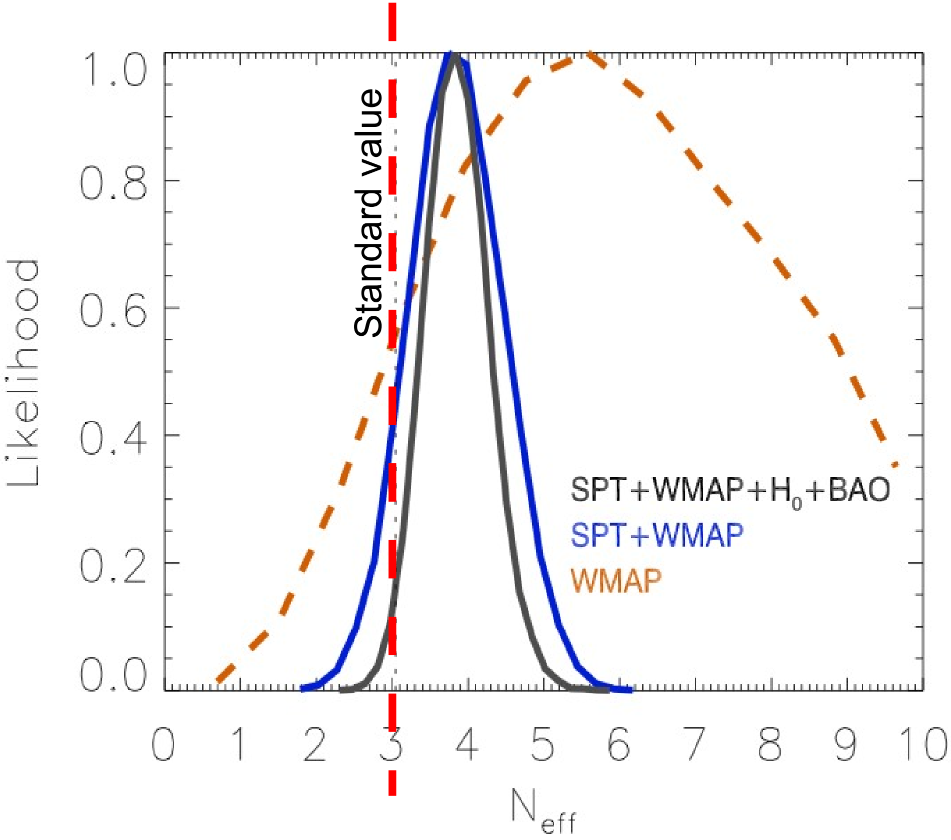
1. CMB+large-scale structure…

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

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



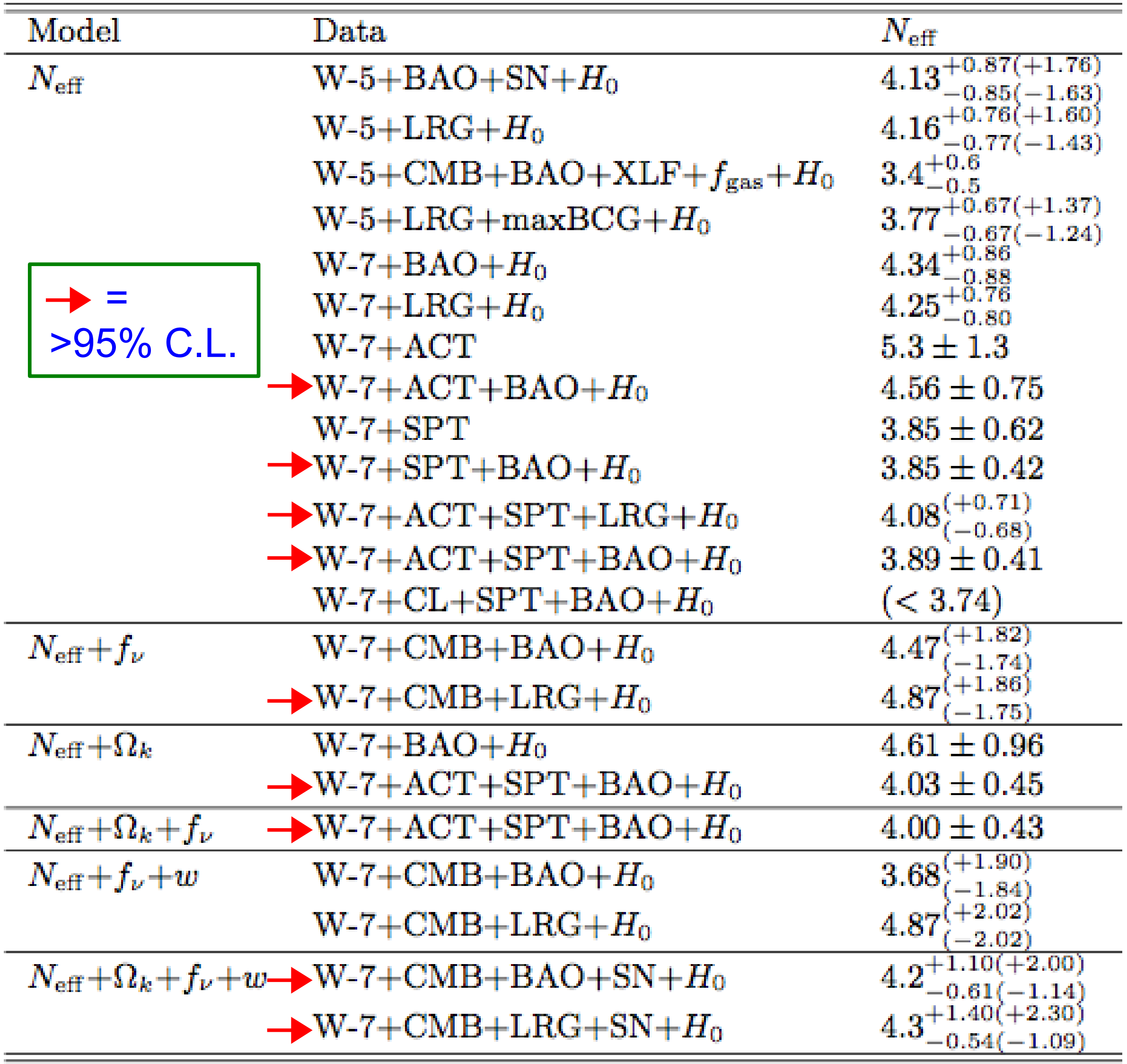
Dunkley et al. [Atacama Cosmology Telescope] 2010



Keisler et al. [South Pole Telescope] 2011

- N_{eff}>3 trend has been there since WMAP-5.
- Exact numbers depend on the cosmological model, and the combination of data.
- Many model+data combinations find N_{eff}>3 at 95% – 99% C.L.
- Central value N_{eff} ~ 4.

W-5=WMAP-5; W-7=WMAP-7



Model	Data	$N_{\rm eff}$
$N_{\rm eff}$	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	W-5+CMB+BAO+XLF+$f_{\rm gas}$+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	→ W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	→ W-7+SPT+BAO+H_0	3.85 ± 0.42
	→ W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	→ W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
	W-7+CL+SPT+BAO+H_0	(< 3.74)
$N_{\rm eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	→ W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{\rm eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	→ W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{\rm eff}+\Omega_k+f_\nu$	→ W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{\rm eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{\rm eff}+\Omega_k+f_\nu+w$	→ W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	→ W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

→ = >95% C.L.

Abazajian et al., “Light sterile neutrinos: a white paper”, 2012

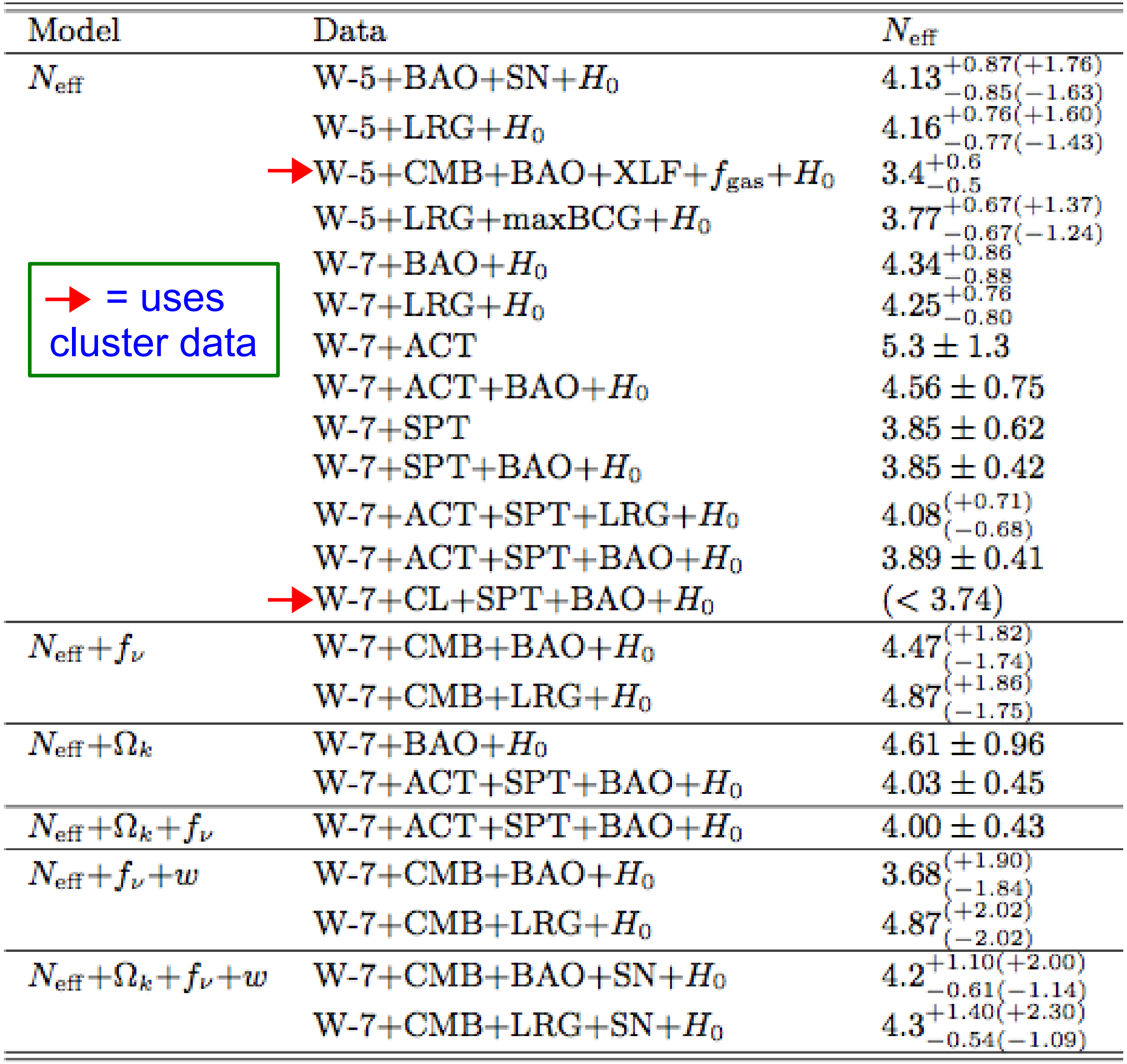
- **One exception**: cluster abundance from ROSAT All-sky Survey/Chandra X-ray observatory prefers a more “standard” value of N_{eff}.

$$N_{\text{eff}} < 3.74 \ (95\,\%\,\text{C.L.})$$

WMAP-7+Clusters+SPT+BA0+H_0 (N_{eff} restricted to ≥ 3)

Burenin & Vikhlinin 2012

W-5=WMAP-5; W-7=WMAP-7



→ = uses cluster data

Model	Data	$N_{\rm eff}$
$N_{\rm eff}$	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$
	→ W-5+CMB+BAO+XLF+$f_{\rm gas}$+H_0	$3.4^{+0.6}_{-0.5}$
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$
	W-7+ACT	5.3 ± 1.3
	W-7+ACT+BAO+H_0	4.56 ± 0.75
	W-7+SPT	3.85 ± 0.62
	W-7+SPT+BAO+H_0	3.85 ± 0.42
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41
	→ W-7+CL+SPT+BAO+H_0	(< 3.74)
$N_{\rm eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$
$N_{\rm eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45
$N_{\rm eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43
$N_{\rm eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$
$N_{\rm eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$

Abazajian et al., “Light sterile neutrinos: a white paper”, 2012

How does it work...

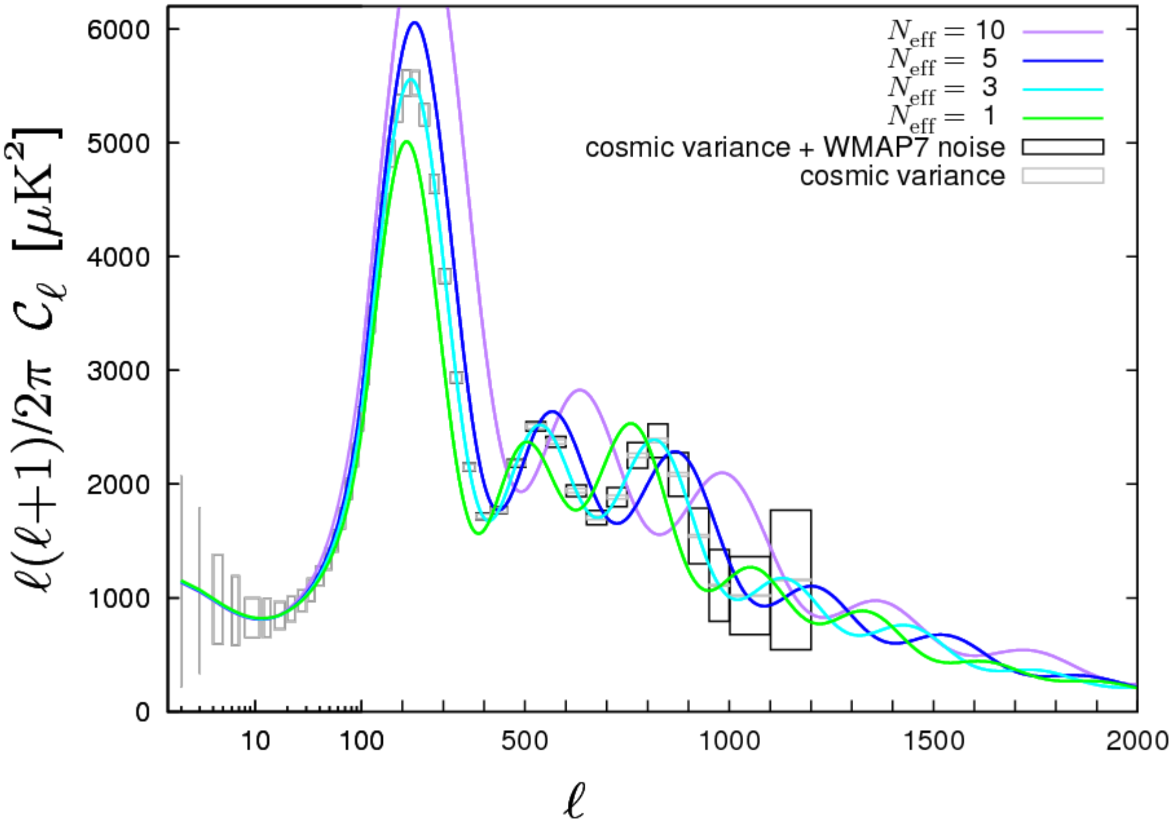
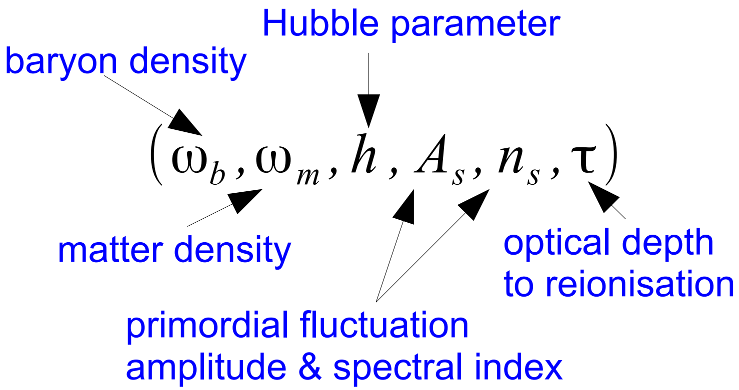


Figure courtesy of J. Hamann

- N_{eff} looks easy to detect..
- But we also use the same data to measure at least 6 other cosmological parameters:



Hubble parameter

baryon density

$$(\omega_b, \omega_m, h, A_s, n_s, \tau)$$

matter density

optical depth
to reionisation

primordial fluctuation
amplitude & spectral index

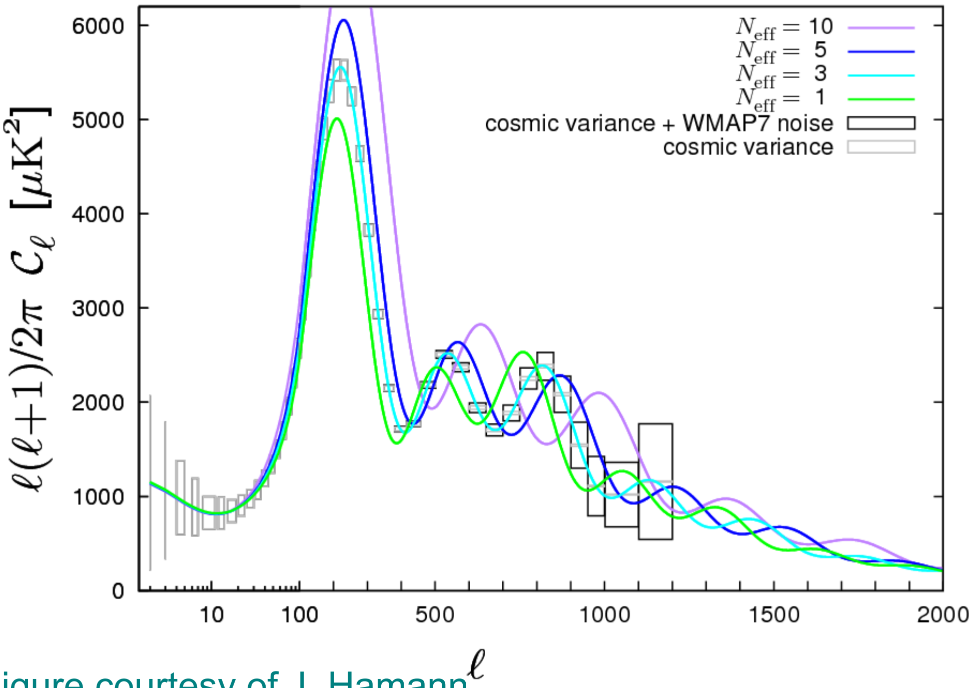
- Plenty of parameter degeneracies!

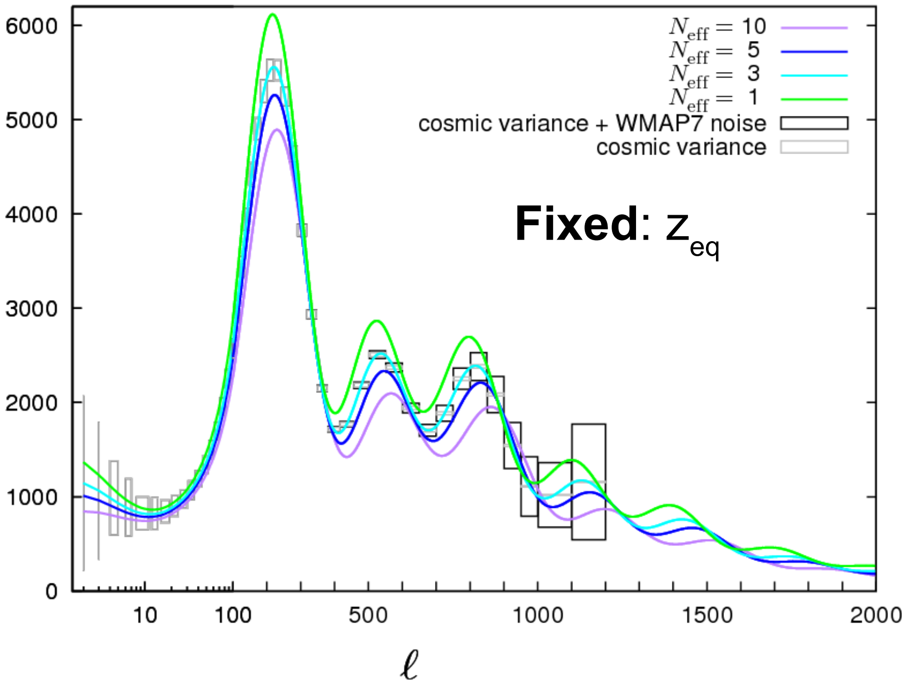
What the CMB really probes: equality redshift...

- Ratio of 3rd and 1st peaks sensitive to the redshift of matter-radiation equality via the early ISW effect.

Exact degeneracy between the physical matter density ω_m and N_{eff}.

$$1+z_{\rm eq}=\frac{\omega_m}{\omega_r}\simeq\frac{\omega_m}{\omega_\gamma}\,\frac{1}{1+0.2271\,N_{\rm eff}}$$





Fixed: z_{eq}

Figure courtesy of J. Hamann

What the CMB really probes: sound horizon...

Exact degeneracy between ω_m and the Hubble parameter h.

- Peak positions depend on:

$$\theta_s = \frac{r_s}{D_A}$$

Sound horizon at decoupling

Angular distance to the last scattering surface

Flat ΛCDM

$$\theta_s \propto \frac{\left(\omega_m h^{-2}\right)^{-1/2}}{\int_{a_*}^{1} \frac{da}{\sqrt{\omega_m h^{-2} a^{-3} + \left(1-\omega_m h^{-2}\right)}}}$$

Fixed z_{eq}, ω_b

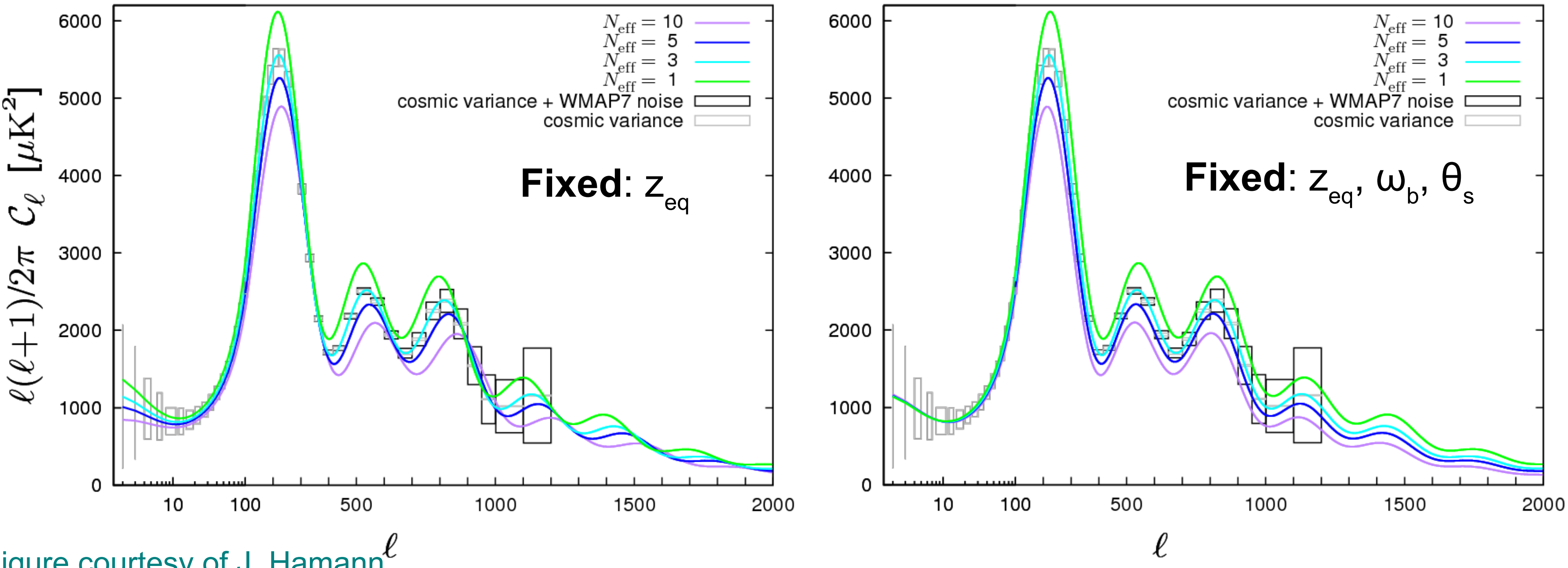
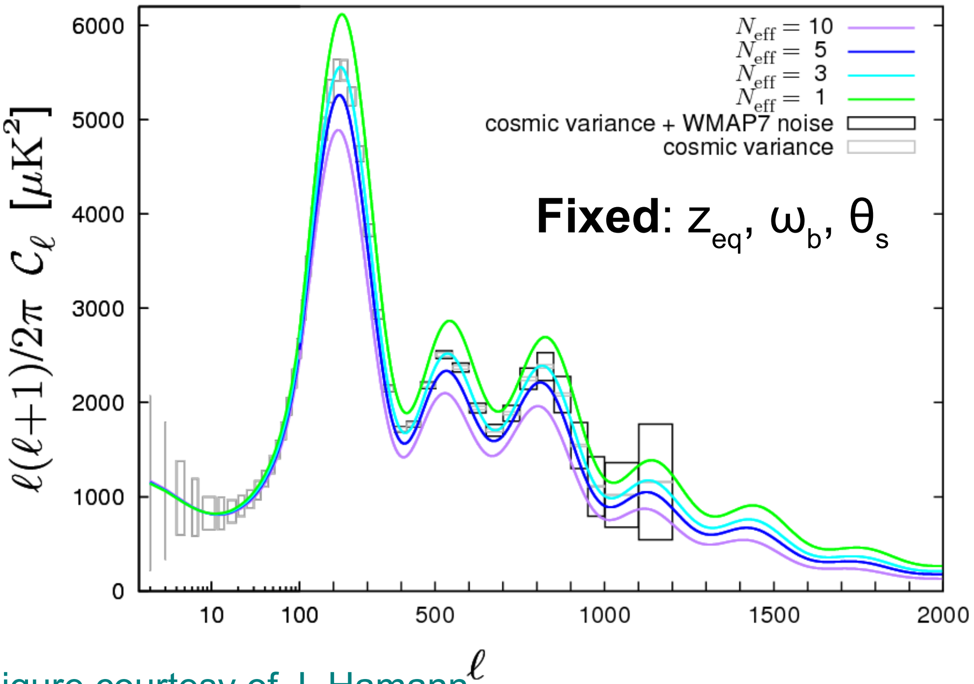


Figure courtesy of J. Hamann

What the CMB really probes: anisotropic stress...

- Apparent (i.e., not physical) partial degeneracies with primordial fluctuation amplitude A_s and spectral index n_s.

- However, free-streaming particles have **anisotropic stress**.
- First real signature of N_{eff} in the 3rd peak!



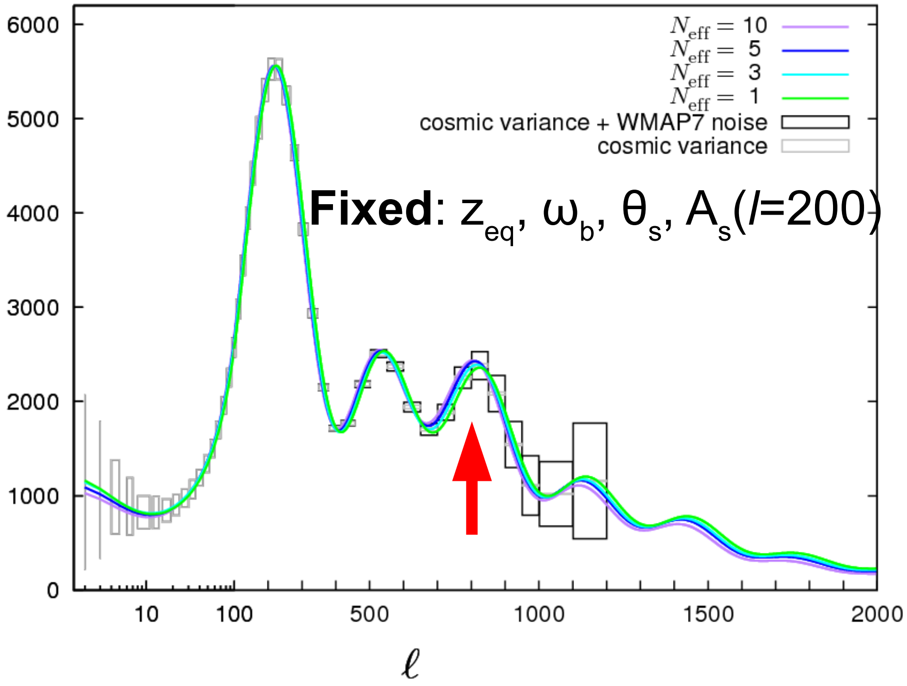
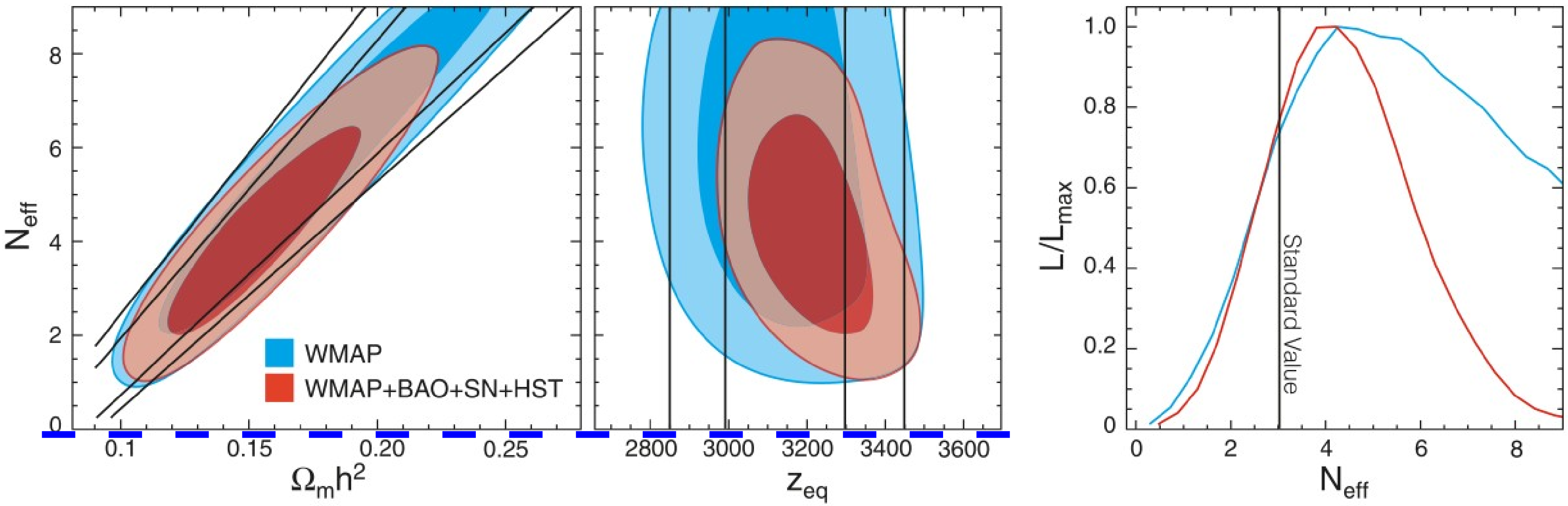


Figure courtesy of J. Hamann

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

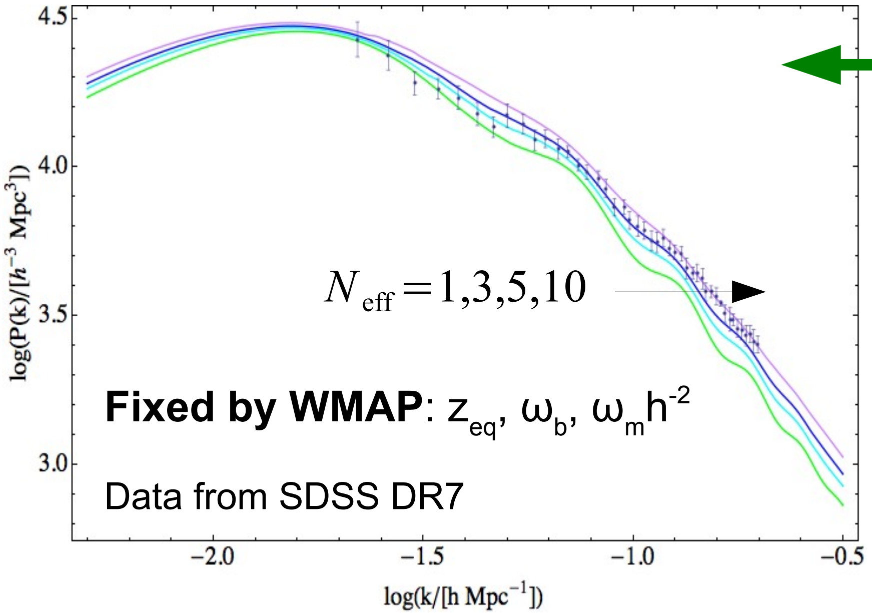


Komatsu et al. [WMAP5] 2008

- **Upper limit** requires combination of WMAP with other observations to break the remaining N_{eff}–ω_m–h parameter degeneracies.
  - Pinning down either ω_m or h will do!

from local ($z<0.1$) expansion rate measurements

Breaking the remaining parameter degeneracies...



$N_{\text{eff}} = 1,3,5,10$

Fixed by WMAP: z_{eq}, ω_b, $\omega_m h^{-2}$

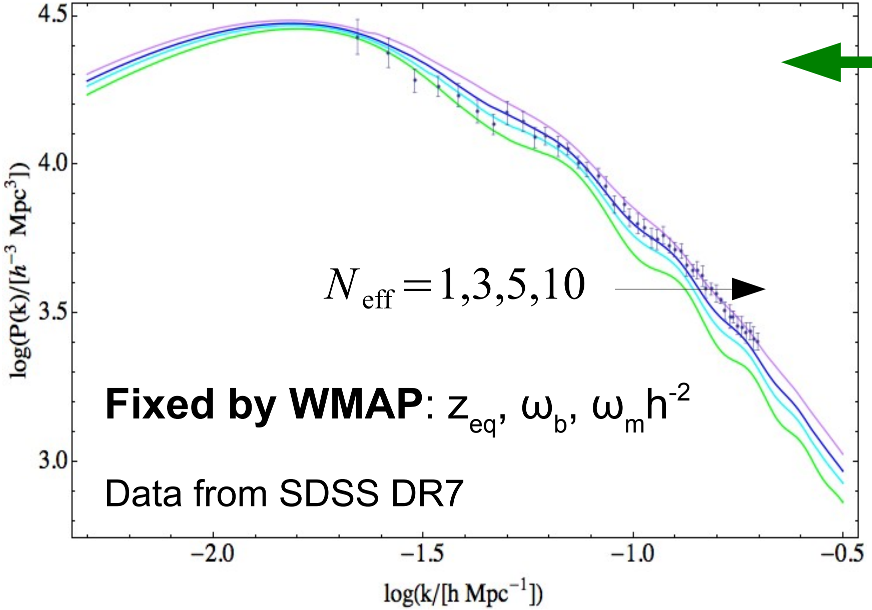
Data from SDSS DR7

Large-scale matter power spectrum
(probes baryon fraction)

$$f_b \equiv \frac{\omega_b}{\omega_m}$$

ω_b fixed by CMB

Breaking the remaining parameter degeneracies...



$N_{\rm eff} = 1,3,5,10$

Fixed by WMAP: z_{eq}, ω_b, $\omega_m h^{-2}$

Data from SDSS DR7

Large-scale matter power spectrum
(probes baryon fraction)

$$f_b \equiv \frac{\omega_b}{\omega_m}$$

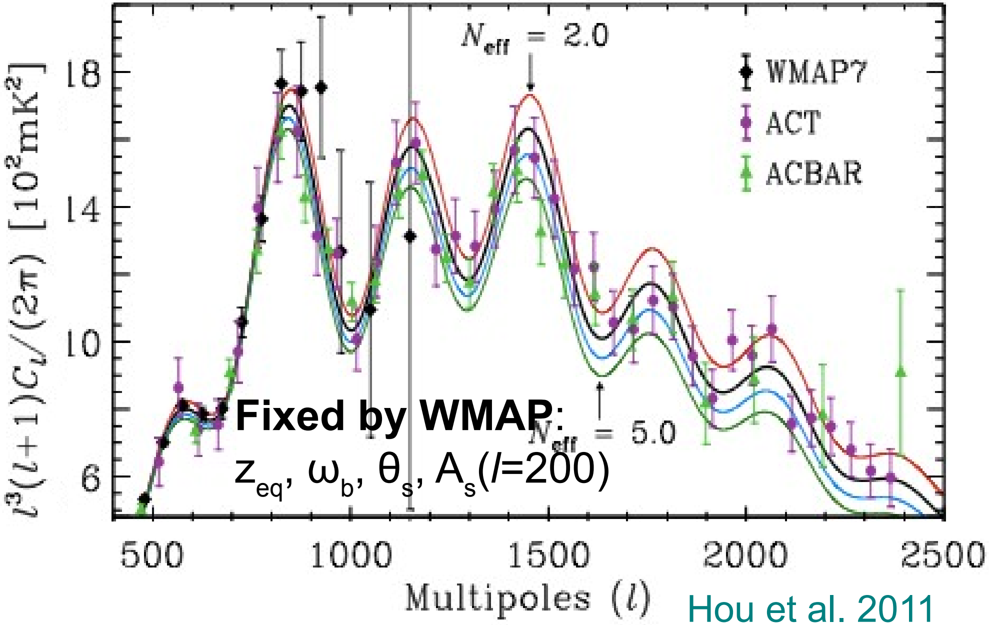
ω_b fixed by CMB

CMB damping tail
(probes photon diffusion scale)

ACT since 2010
SPT since 2011

$$\frac{\theta_d}{\theta_s} = \frac{r_d}{r_s} \propto \omega_m^{1/4}$$

Fixed by WMAP



Fixed by WMAP:
z_{eq}, ω_b, θ_s, $A_s(l=200)$

Hou et al. 2011

2. Connection to the short baseline sterile neutrino...

Experimental anomalies & the sterile ν interpretation...

- **Best-fits** parameters: e.g., Kopp, Maltoni & Schwetz 2011; Giunti & Laveder 2011

Reactor experiments only

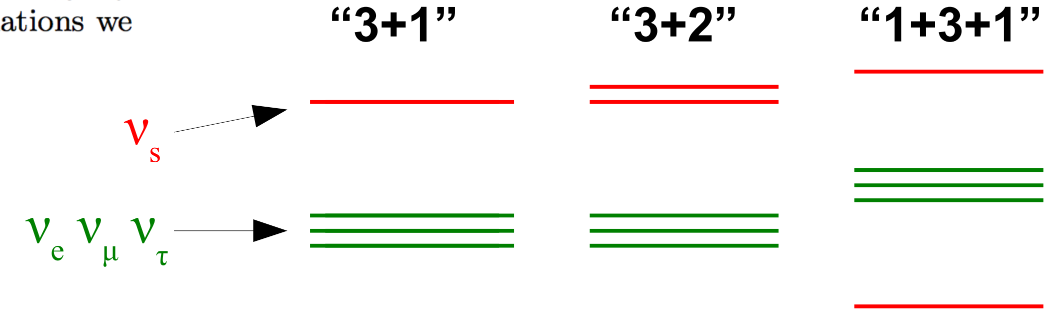
	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

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).

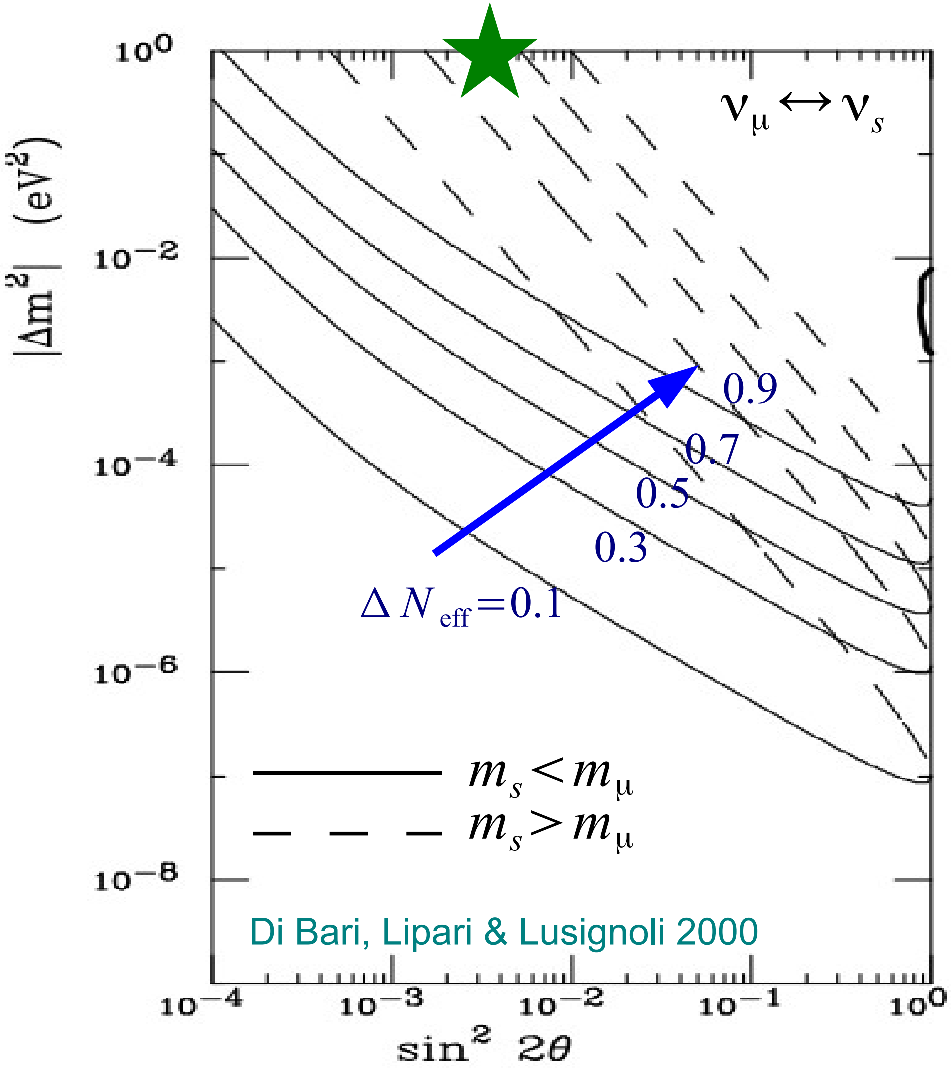


Light sterile neutrinos and N_{eff}...

- SBL-preferred Δm^2 and mixing favour the **production and thermalisation** of sterile neutrinos in the early universe via $\nu_\alpha \leftrightarrow \nu_s$ oscillations + ν_α scattering.

→ Can easily produce an excess relativistic energy density of $\Delta N_{eff} \sim 1$.

→ Sterile states have the same temperature as the SM neutrinos.



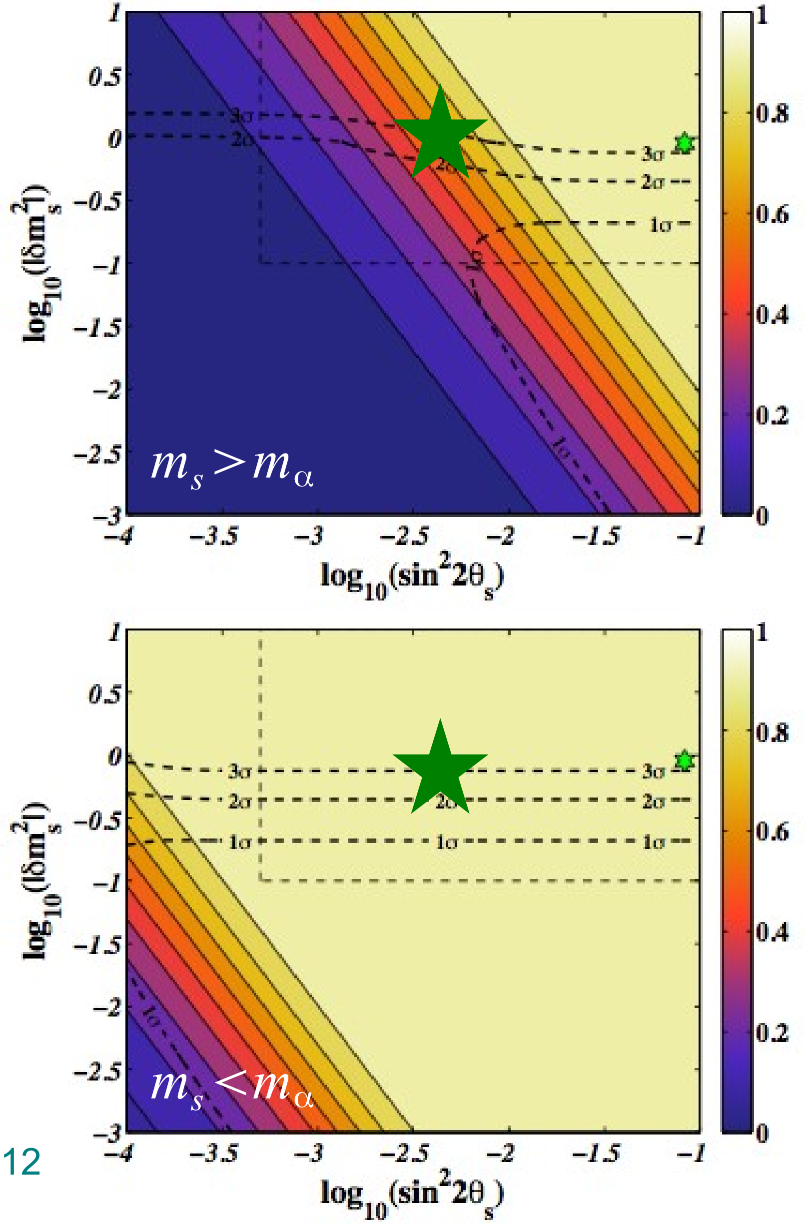
Di Bari, Lipari & Lusignoli 2000

Light sterile neutrinos and N_{eff}...

- SBL-preferred Δm^2 and mixing favour the **production and thermalisation** of sterile neutrinos in the early universe via $\nu_\alpha \leftrightarrow \nu_s$ oscillations + ν_α scattering.

→ Can easily produce an excess relativistic energy density of $\Delta N_{eff} \sim 1$.

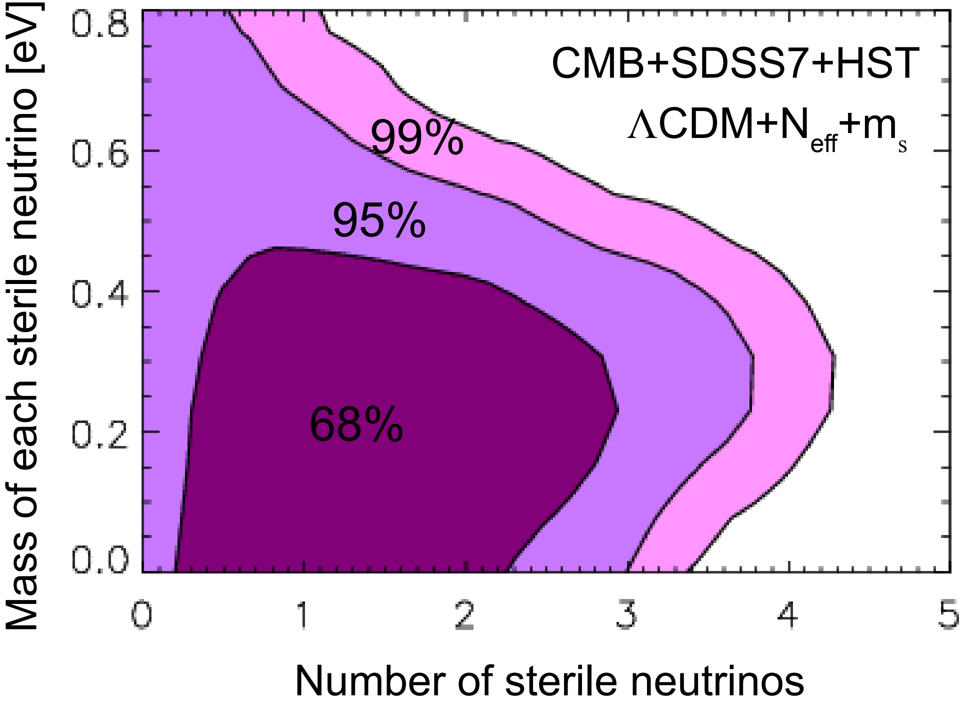
→ Sterile states have the same temperature as the SM neutrinos.



Hannestad, Tamborra & Tram 2012

Can the short baseline sterile neutrino explain $N_{eff} > 3$?

- **Short answer**: Not so easy.
- **Reason**: eV mass neutrinos violate CMB+LSS hot dark matter bounds.



- 3+1 thermalised sterile:

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

Lab best-fit: $m_s \sim 1$ eV

- 3+2 thermalised sterile:

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

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

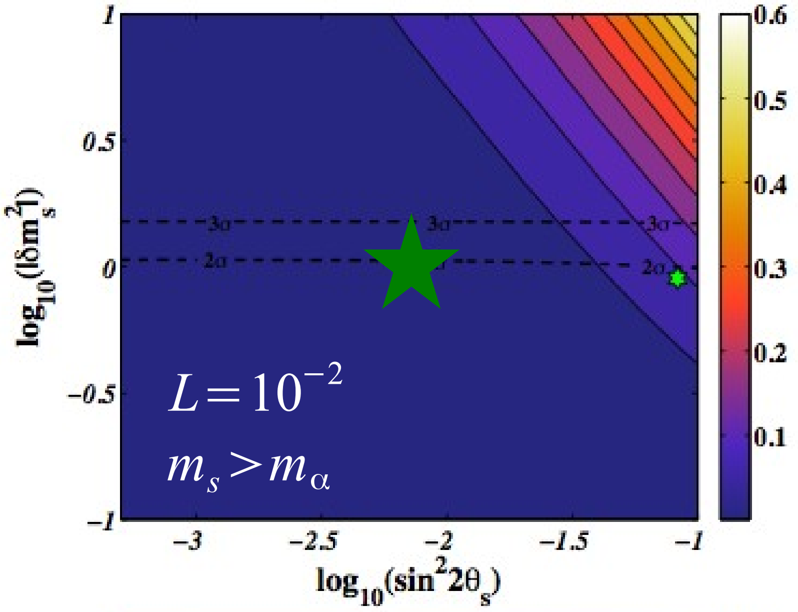
Hamann, Hannestad, Raffelt, Tamborra & Y^3W 2010

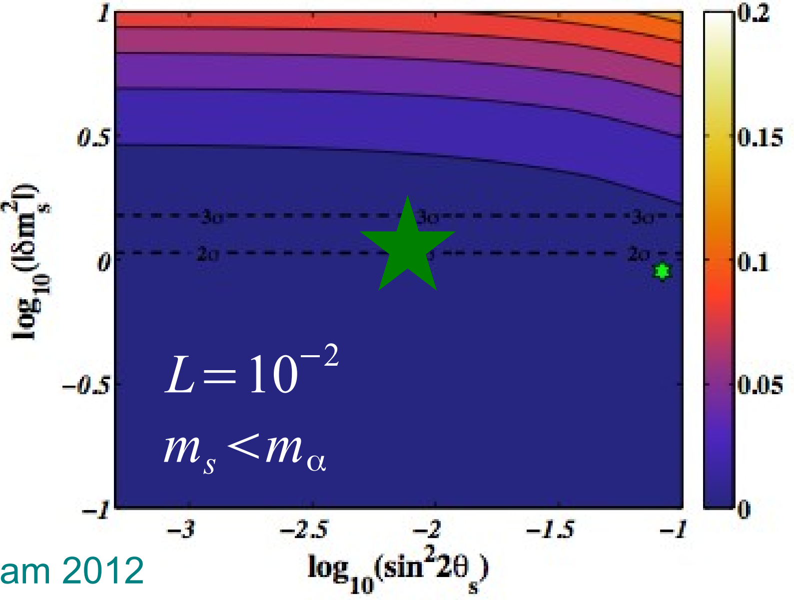
Is there a way out? Plan A...

- Suppress sterile neutrino thermalisation using, e.g., a large lepton asymmetry (L >> B ~ 10^{-10}).

  Foot & Volkas 1995

  - Generating a large lepton asymmetry requires new physics.
  - If complete suppression, then $N_{eff} > 3$ must be explained by some other physics (sub-eV thermal axions, hidden photons, etc.?)





Hannestad, Tamborra & Tram 2012

Grin, Smith, and Kamionkowski, Axion constrains in non-standard thermal histories, arXiv:0711.1352 [astro-ph]; **Kawasaki, Nakayama ,and Senami**, Cosmological implications of supersymmetric axion models, arXiv:0711.3083 [hep-ph]; **Feng, Tu and Yu**, Thermal Relics in Hidden Sectors, arXiv:0808.2318 [hep-ph]; **Nelson and Walsh**, Chameleon vector bosons, arXiv:0802.0762 [hep-ph]; **Ackermann, Buckley, Carroll, and Kamionkowski**, Dark Matter and Dark Radiation, arXiv:0810.5126 [hep-ph]; **Mahato**, Torsion, Dirac Field, Dark Matter and Dark Radiation, gr-qc/0603134; **Jäckel, Redondo, and Ringwald**, Signatures of a hidden cosmic microwave background, arXiv:0804.4157 [astro-ph]; **Hasenkamp,** Dark radiation from the axino solution of the gravitino problem, arXiv:1107.4319 [hep-ph]; **Kobayashi, Takahashi, Takahashi, and Yamaguchi**, Dark Radiation from Modulated Reheating, arXiv:1111.1336 [astro-ph.CO]; **Feng, Rentala and Surujon**, WIMPless Dark Matter from an AMSB Hidden Sector with No New Mass Parameters, arXiv:1111.4479 [hep-ph]; **Hooper, Queiroz, and Gnedin,** Non-Thermal Dark Matter Mimicking An Additional Neutrino Species In The Early Universe, arXiv:1111.6599 [astro-ph.CO]; **Menestrina and Scherrer**, Dark Radiation from Particle Decays during Big Bang Nucleosynthesis, arXiv:1111.0605 [astro-ph.CO]; Aslanbeigi, **Robbers, Foster, Kohri, and Afshordi**, Phenomenology of Gravitational Aether as a solution to the Old Cosmological Constant Problem, arXiv:1106.3955 [astro-ph.CO]; **Chen and Lin**, Cosmon as the Modulon: Non-Gaussianity from Dark Enegry, arXiv:1104.0982 [hep-ph]; **Das and Weiner**, Late Forming Dark Matter in Theories of Neutrino Dark Energy, astro-ph/0611353; **Nakayama, Takahashi, and Yanagida**, A theory of extra radiation in the Universe, arXiv:1010.5693 [hep-ph;] **Fischler and Meyers**, Dark Radiation Emerging After Big Bang Nucleosynthesis?, arXiv:1011.3501 [astro-ph.CO]; **Dreiner, Hanussek, Kim, and Sarkar**, Gravitino cosmology with a very light neutralino, arXiv:1111.5715 [hep-ph]; **Foot**, Mirror dark matter cosmology – predictions for Neff[CMB] and Neff[BBN], arXiv:1111.6366 [astro-ph.CO]; **Jeong and Takahashi**, Light Higgsino from Axion Dark Radiation, arXiv:1201.4816 [hep-ph]; **Kaplan, Krnjaic, Rehermann, and Wells**, Dark Atoms: Asymmetry and Direct Detection, arXiv:1105.2073 [hep-ph]; **Cicoli**, Large extra dimensions and light hidden photons from anisotropic string vacua, arXiv:1111.0790 [hep-th];

Is there a way out? Plan B...

- Failing to suppress ν_s thermalisation, exploit parameter degeneracies in the CMB+LSS to **engineer a good fit**.
- No room for play within the ΛCDM model, but extensions of ΛCDM can help to relax the hot dark matter constraint on m_s:
  - Non-standard dark energy equation of state.
  - Modified gravity.
  - Non-flat spatial geometry.
  - Even more massless degrees of freedom.
  - …

Elgarøy & Kristiansen 2011; Hamann, Hannestad, Raffelt & Y^3W 2011
Giusarma et al. 2012; Motohashi, Starobinsky & Yokoyama 2012

Is there a way out? Plan B...

- Failing to suppress ν_s thermalisation, exploit parameter degeneracies in the CMB+LSS to **engineer a good fit**.
- No room for play within the ΛCDM model, but extensions of ΛCDM can help to relax the hot dark matter constraint on m_s:
  - Non-standard dark energy equation of state.
  - Modified gravity.
  - Non-flat spatial geometry.
  - Even more massless degrees of freedom.
  - …

1 x 1 eV sterile neutrino can be reasonably accommodated.

1 x 2eV or 2 x 1 eV is still problematic...

Elgarøy & Kristiansen 2011; Hamann, Hannestad, Raffelt & Y^3W 2011
Giusarma et al. 2012; Motohashi, Starobinsky & Yokoyama 2012

Is there a way out? Plan B...

Modified gravity scenario to explain accelerated expansion in lieu of dark energy

- **An example**: accommodating 1eV sterile neutrinos with f(R) gravity:

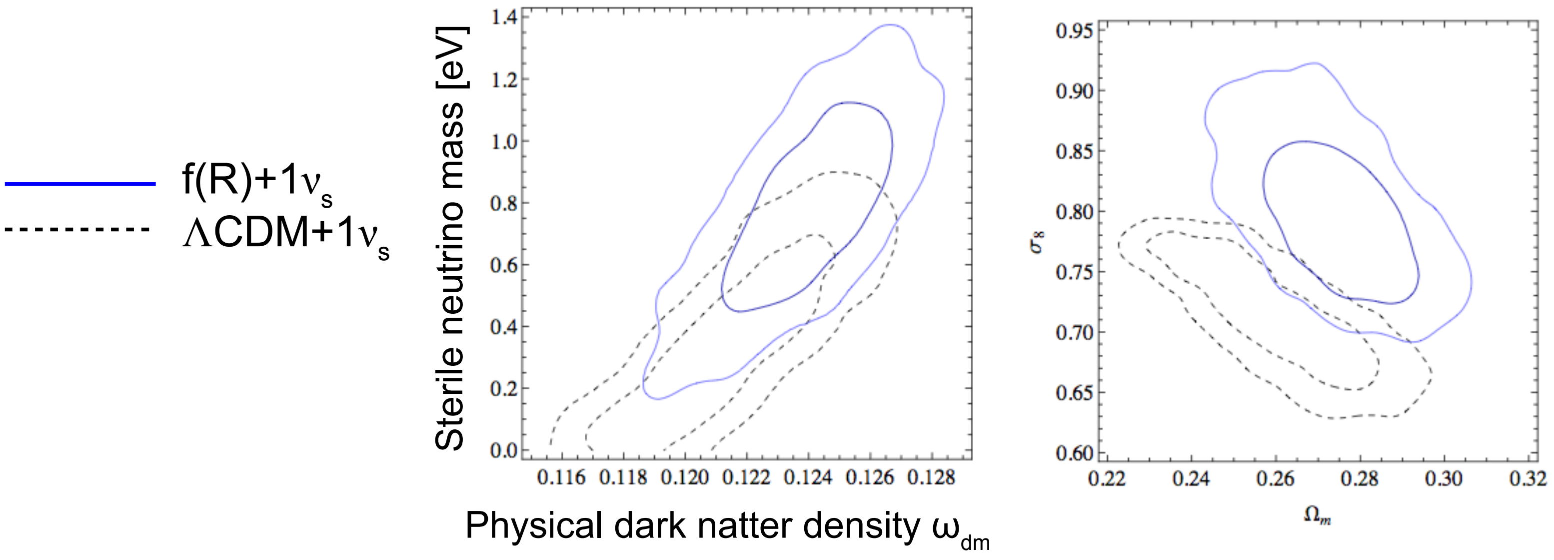
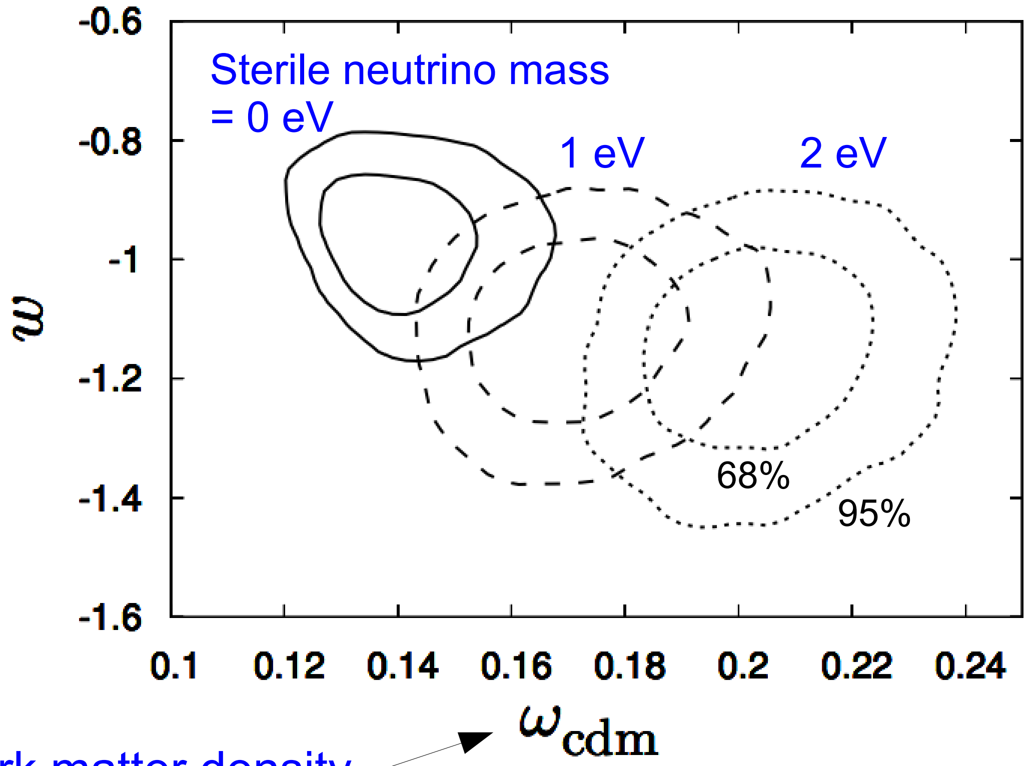


FIG. 1: 1 and 2σ contours of the sterile neutrino mass (left) and σ_8 (right) for the cases with three massless and one massive neutrinos in the ΛCDM model (dashed black) and $f(R)$ gravity (solid blue). $\chi^2_{\rm eff} = 3774.1$ and 3767.0, respectively.

Motohashi, Starobinsky & Yokoyama 2012

Necessary side effects...

- Exploiting parameter degeneracies also implies that other (unrelated) cosmological parameter values will change.



Dark energy equation of state parameter

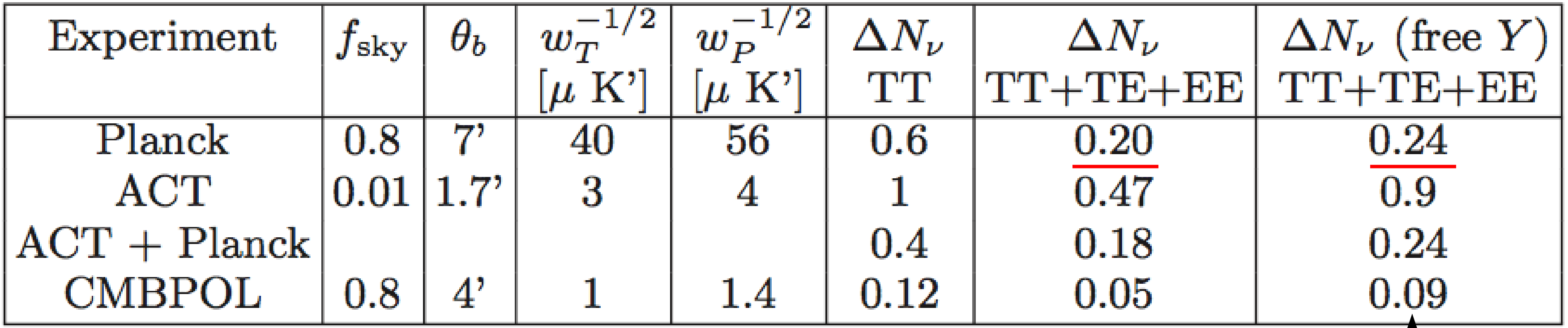
Cold dark matter density

Hamann, Hannestad, Raffelt & Y^3W 2011

Planck and N_{eff}...

- If N_{eff} is as large as 4, it will be settled almost immediately by Planck (launched May 14, 2009; public data release early 2013).

68% sensitivities

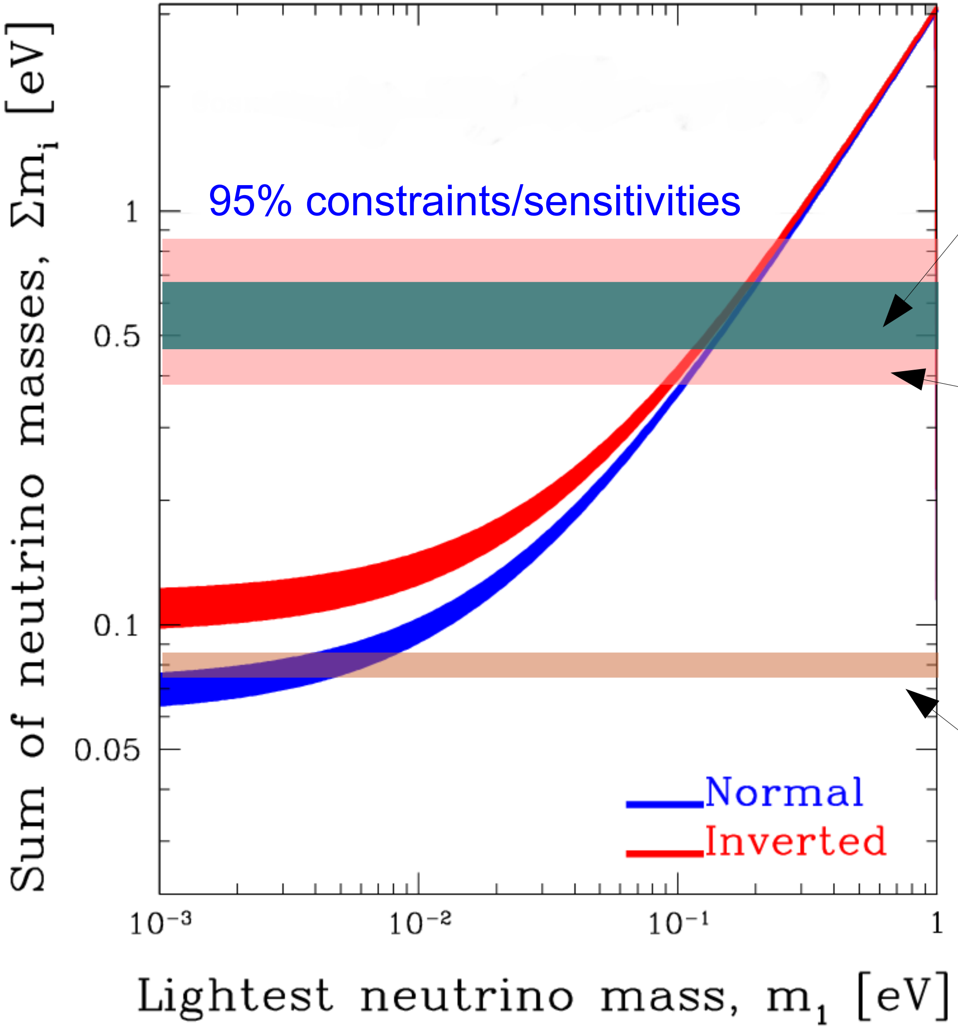


Experiment	$f_{\rm sky}$	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Bashinsky & Seljak 2004

Helium fraction
as a free parameter

Planck and neutrino mass...



Current constraints

Band = model complexity

Planck alone (1 year) 2013
(+ current LSS probes → not much
improvement) Perotto et al. 2006

Not quite good enough to rule in or rule out 1 eV sterile neutrinos definitively...

Planck+Euclid weak lensing 2020+

Hannestad, Tu & Y^3W 2006

Summary...

- Current precision cosmological data show a preference for extra relativistic degrees of freedom (beyond 3 neutrinos).

- Sterile neutrino interpretation of short baseline neutrino anomalies does not quite fit into the simplest picture though...

    - 3+2: **Too many** for BBN

    - 3+1, 3+2: **Too heavy** for CMB/LSS

- Non-trivial extensions to ΛCDM can reasonably accommodate 1 x 1 eV fully thermalised sterile neutrino species.

- **Planck with tell** (at least part of the story).

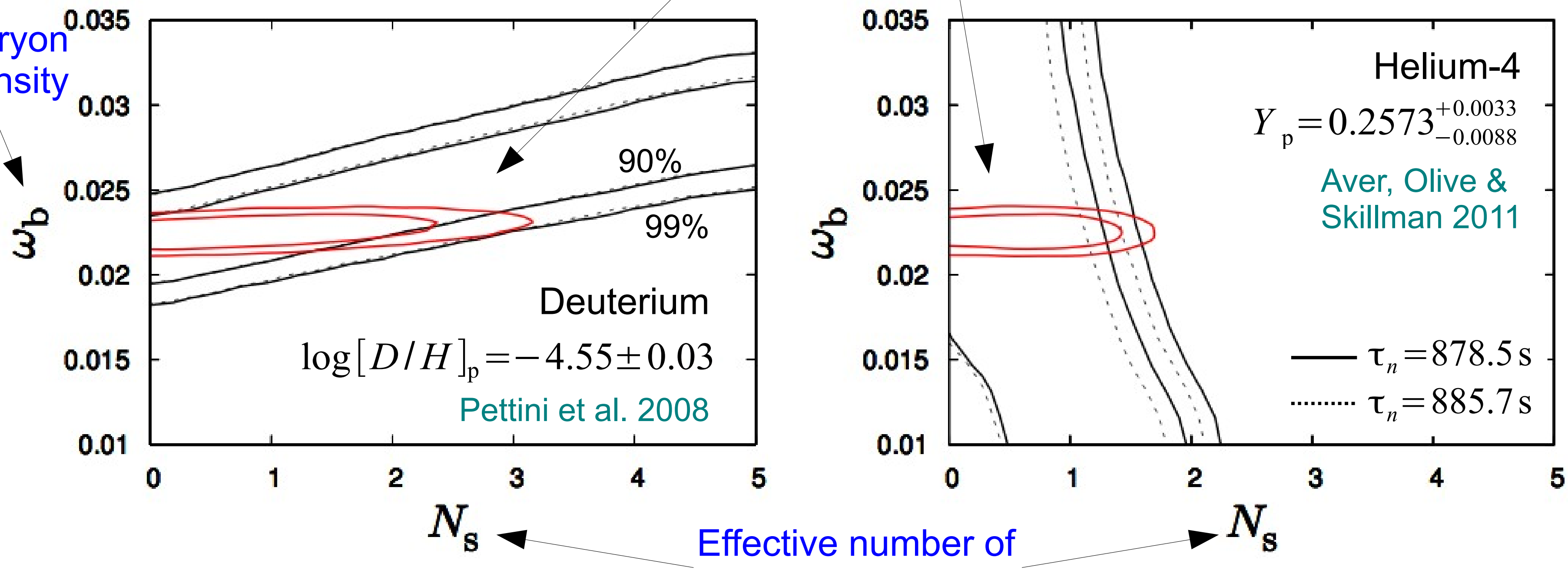
3. Extra slides: BBN

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

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

Using CMB prior on ω_b

Baryon density



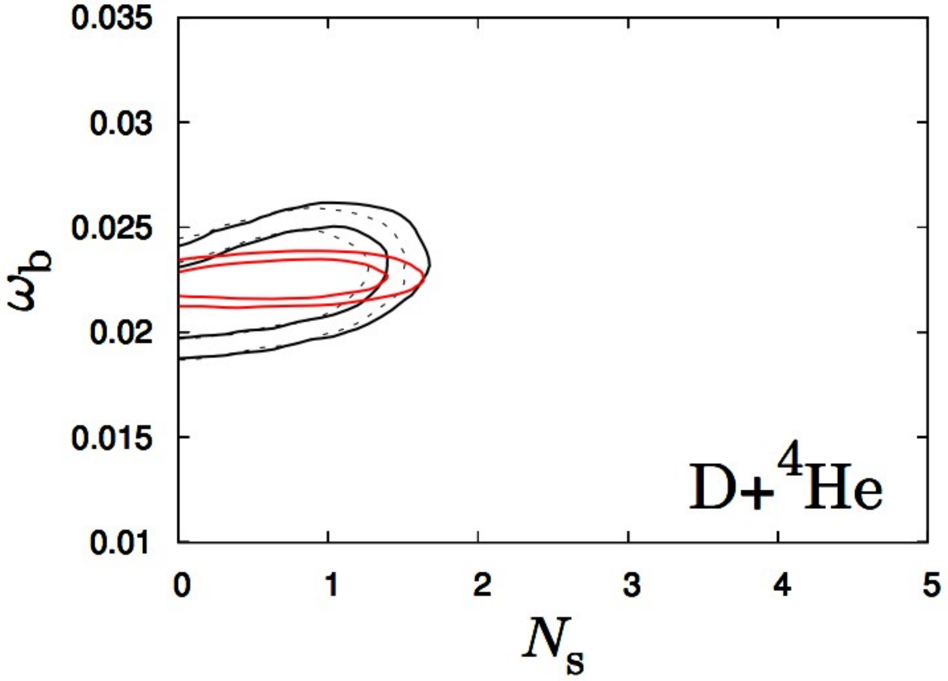
Effective number of sterile neutrinos

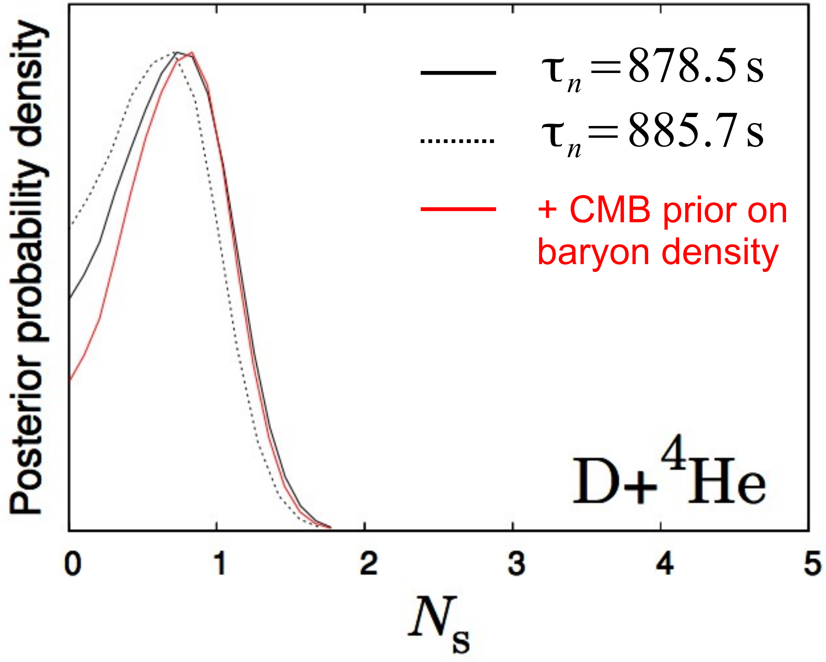
$N_{\text{eff}} = 3.046 + N_s$

Hamann, Hannestad, Raffelt & Y^3W 2011

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

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





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

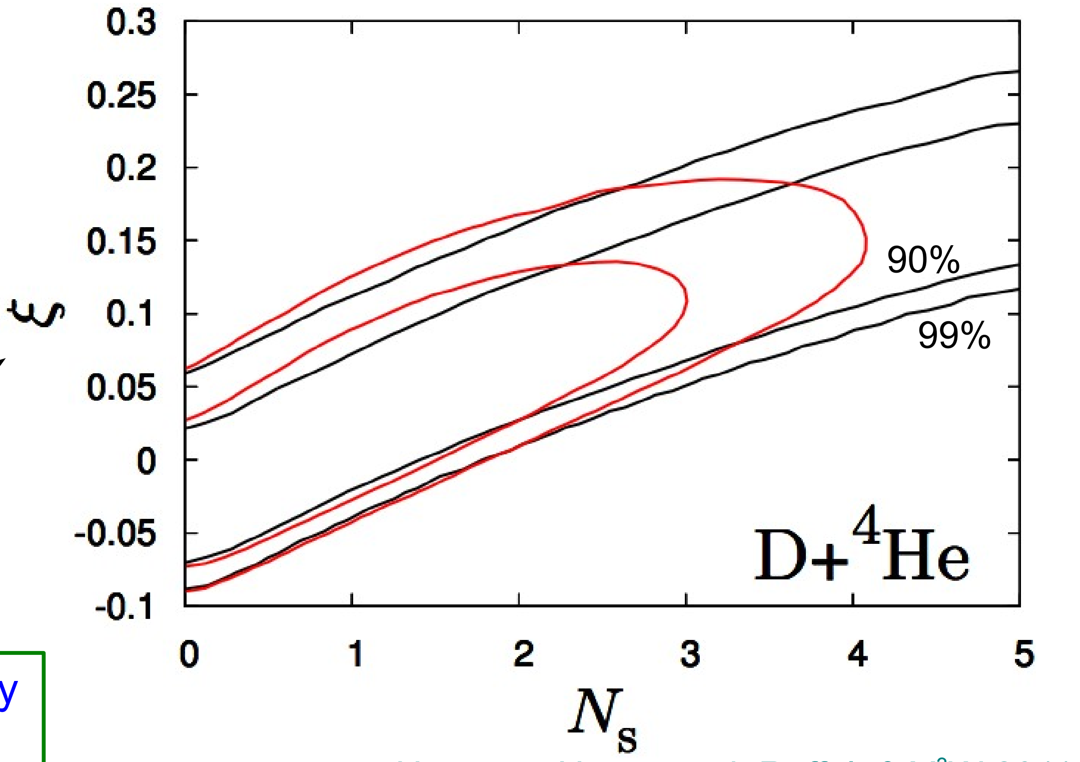
Quick fix: degenerate BBN...

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

Lepton asymmetry

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

Neutrino chemical potential



Hamann, Hannestad, Raffelt & Y^3W 2011

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