Anomalies in the ν sector: can cosmology help?

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How Cosmological Neutrinos enter the game

The Birth of cosmological ν's

T>> 1 MeV
Neutrinos in equilibrium

$$f_\nu(p,T)=f_{FD}(p,T)=\frac{1}{e^{p/T}+1} \qquad T_\nu = T_e = T_\gamma$$

Above ~MeV-scale temperatures, $e^\pm$ pairs can be created "Boltzmann unsuppressed". ν's are populated (& reach a thermal distribution) via reactions of the kind

$$\nu_a \nu_b \leftrightarrow \nu_a \nu_b$$
$$\nu_a \bar{\nu}_a \leftrightarrow \nu_b \bar{\nu}_b$$
$$\nu_a \bar{\nu}_a \leftrightarrow e^+ e^-$$
$$\nu_a e^- \leftrightarrow \nu_a e^-$$

They decouple from the plasma at T~O(1) MeV

Rate of weak processes

$$\Gamma_w \approx n\,\sigma\,c \approx g\,a^{-3}\,G_F^2 E^2 \approx g\,G_F^2 T^5$$

Hubble expansion rate

$$H \approx \sqrt{G_N \rho} \approx \sqrt{g\,G_N} T^2$$

$$\frac{\Gamma_w}{H} \approx \left(\frac{T}{\mathrm{MeV}}\right)^3$$

After this epoch (~O(1) s after Big Bang) ν's evolve only due to gravity

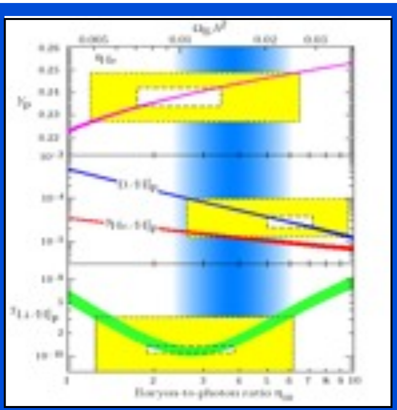
"Detection" of the CνB

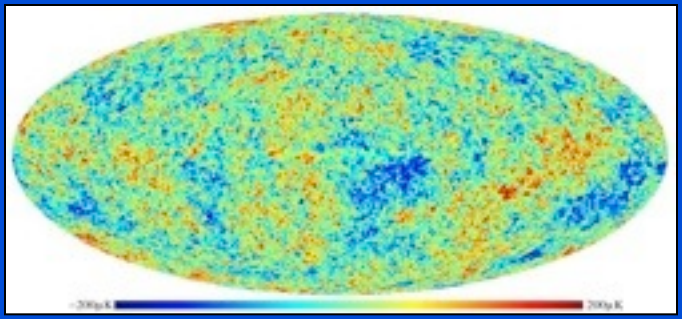
- Pseudo-thermal distribution: T_ν = 1.95 K
- Number density ($\nu + \bar{\nu}$): 112 cm^{-3}/flavour
- Mean kinetic energy: << meV

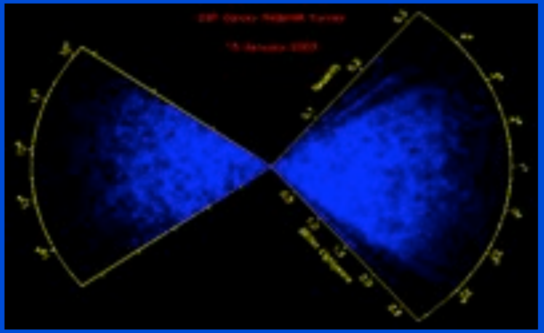
lower than 2.7 K of CMB due to later $e^+ e^- \rightarrow \gamma\gamma$ (heating of photons)

Direct searches hopeless?

Indirect searches: Cosmological observables







BBN	CMB	LSS
T ~ MeV	T ~ eV	
ν_e vs. $\nu_{\mu,\tau}$ N_{eff}	Gravity only (no flavor discr.)	N_{eff} & m_ν

Neutrinos & BBN: How do ν's enter the game?

Hubble Expansion Law

Gravity only, mostly integral quantity, extra relativistic species

$$H=\frac{\dot{a}}{a}=\left(\frac{8\pi G_N}{3}\right)^{1/2}(\rho_\gamma+\rho_e+\rho_b+\rho_\nu+\rho_X)^{1/2}$$

$$\rho_\nu+\rho_X \rightarrow \frac{7}{8}\frac{4^{1/3}}{11^{1/3}} N_{eff}\,\rho_\gamma$$

$N_{eff}=3$
(SM only & instantaneous decoupling)

Weak Rates: p↔n equilibrium

Very sensitive to weak interactions (only e-flavour matters), energy spectrum.

$$\nu_e + n \leftrightarrow e^- + p$$

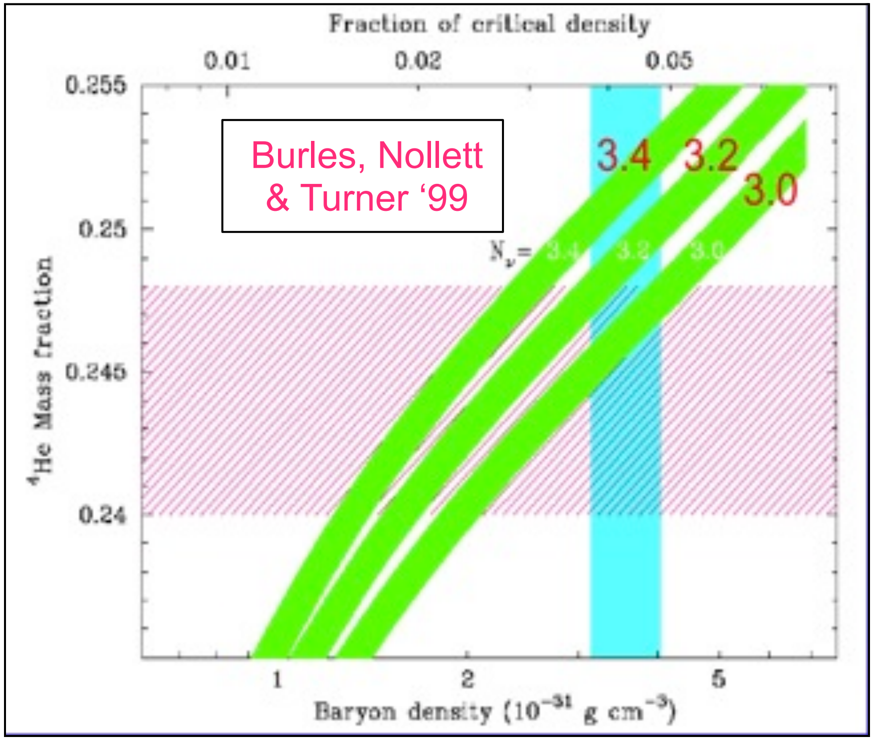
$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$\bar{\nu}_e + e^- + p \leftrightarrow n$$

Final n/p (& hence ^{4}He, where most neutrons are ultimately locked) depends on "when" $\Gamma_w=H$

For a review, see e.g. F. Iocco et al.
"Primordial Nucleosynthesis: from Precision Cosmology to fundamental physics"
Phys. Rept. 472, 1 (2009) [arXiv:0809.0631]

Estimating ^{4}He response to parameter changes



- High N_{eff} → High H → early freeze out (Γ_{pn}~H at high T) → high n/p → high Y_p

- $\nu_e > \bar{\nu}_e$ → $\nu_e\, n \to e^- p$ favored over $\bar{\nu}_e\, p \to e^+ n$ → low n/p at fr.out → low Y_p (chemical potential $\mu_{\nu e} > 0$)

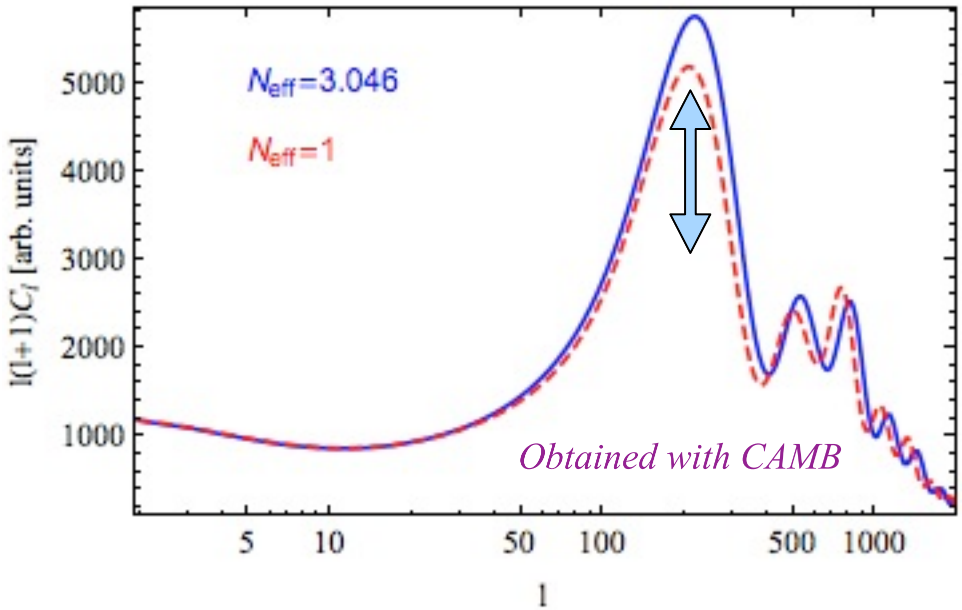
- ...

Neutrinos & CMB

For eV scale neutrinos, both m_ν and N_{eff} *mostly* affect the time of matter-radiation equality. All the rest fixed:

- Raising N_{eff} means more radiation, hence delayed equality.
- Lowering m_ν means that part of the total that we call now (dark) matter was behaving as ~radiation at CMB formation, hence delayed equality.

correlation expected!



for more details, see e.g.
J. Lesgourgues & S. Pastor
Phys.Rept. 429 (2006) 307-379

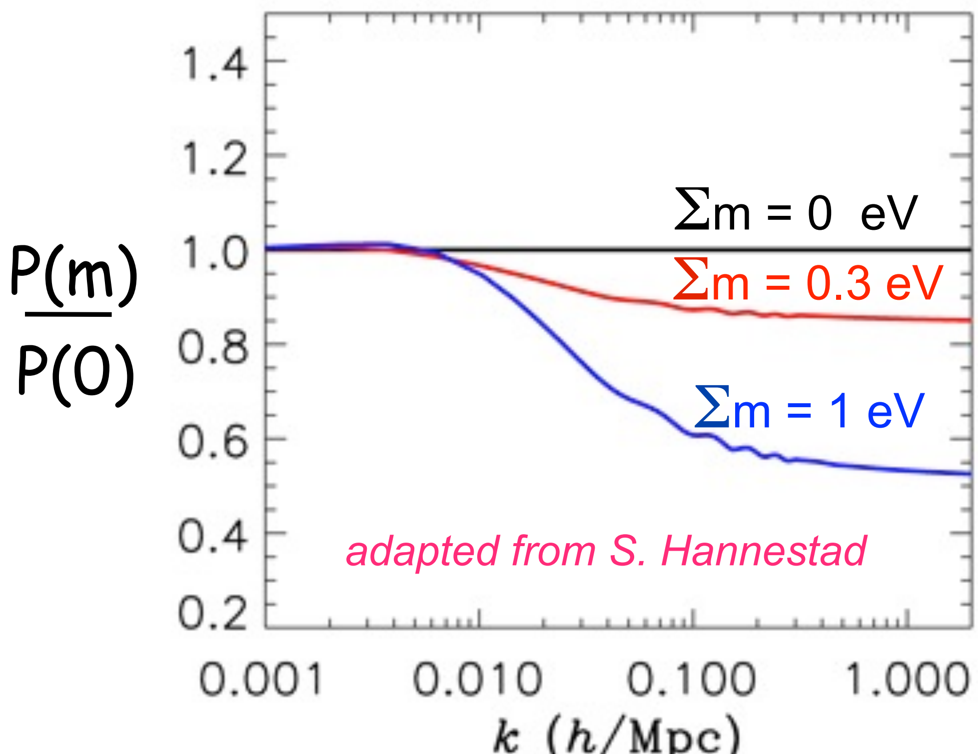
$$1+z_{\rm eq}=\frac{\Omega_m}{\Omega_r}\simeq\frac{\Omega_m}{\Omega_\gamma}\,\frac{1}{1+0.23\,N_{\rm eff}}$$

Suppression of power-spectrum due to m_ν

Unitl non-relativistic, ν's do not contribute to gravitational clustering below the free-streaming scale, but they do contribute to the homogeneous expansion. This "unbalance" introduces a peculiar spectral suppression. In linear theory one finds

$$\frac{\Delta P}{P} \approx -8 \frac{\Omega_\nu}{\Omega_m} \approx -0.8 \frac{\Sigma m_i}{1\ \mathrm{eV}} \frac{0.1}{\Omega_m h^2} \quad @\ k > k_{NR}$$

$$\approx 0.015\ (\Sigma m_{eV} \times \Omega_m h^2)^{1/2}\ \mathrm{Mpc}^{-1}$$



This is the key effect used to derive bounds on massive neutrinos from LSS

Adding sterile states...

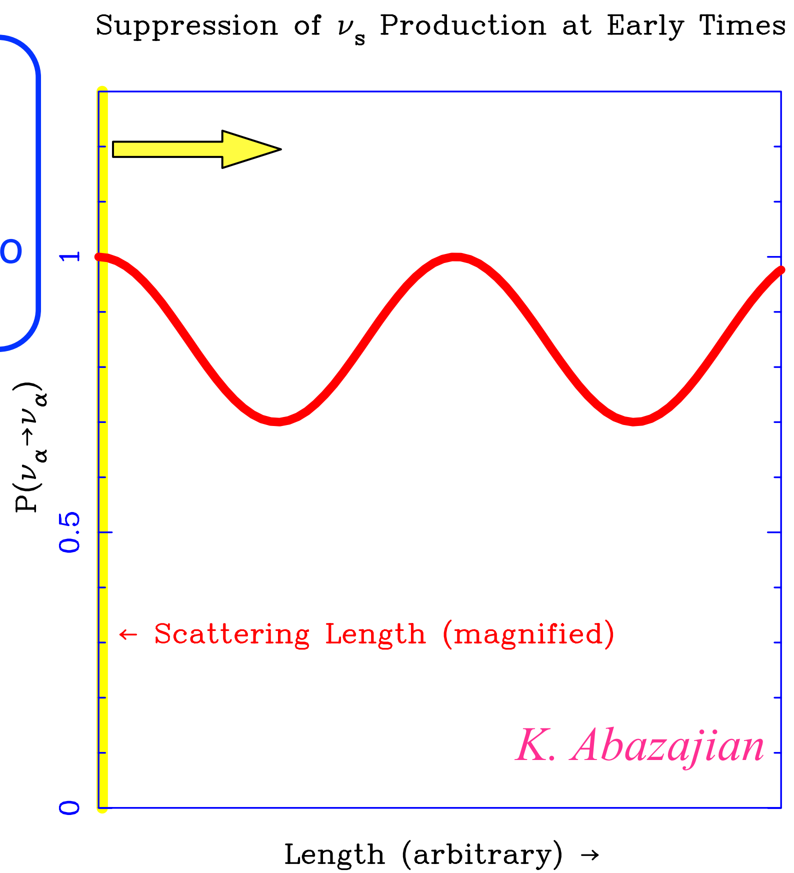
The Quantum Zeno effect (for production via osc.)

Each scattering of a ν acts as a "measurement" of its flavor state. At high temperatures (say, T≥100 MeV), λ_{scatt} is extremely short compared to λ_{osc}
Therefore, a population of active ν's won't have time to evolve into sterile ν's, but in small amounts.

$$\lambda_{\rm scatt} = [\sigma\, n]^{-1} \sim E^{-2} T^{-3} \propto T^{-5}$$

$$\lambda_{\rm osc} = \frac{4\pi E}{\Delta m^2} (\text{in vacuo}) \propto T$$

$$P_{\alpha\alpha}(\lambda_{\rm scatt}) = 1 - \sin^2(2\theta)\sin^2\left(\pi \frac{\lambda_{\rm scatt}}{\lambda_{\rm osc}}\right)$$



As the universe expands, cools & becomes less dense, λ_{scatt} ↗. Then, $P_{\alpha s}=(1-P_{\alpha\alpha})$ ↗

☞ The larger Δm^2, the faster ν's oscillate, the higher the conversion $P_{\alpha s}$

☞ Also, the larger θ^2, the larger $P_{\alpha s}$

Sterile neutrinos are born

❋ If oscillations are effective before decoupling: the additional species can be brought into equilibrium: $N_{eff}=4$

❋ If oscillations are effective after decoupling: $N_{eff}=3$ but the spectrum of active neutrinos is distorted (direct effect on n/p equilibrium!)

Matter effects are responsible for the hierarchy dependence (resonant vs. non-resonant case) See e.g. Kirilova '03, Dolgov & Villante, NPB 679 (2004)...

In 3+1 models, parameters are such that the fourth ν always thermalize: $N_{eff}\sim 4.05$
In 3+2 fits, "almost" true, $N_{eff}\sim 5$, although partial thermalization or some spectral *distortions* at BBN times are possible (see e.g. Melchiorri et al. JCAP 01 (2009) 036)

In the former models, one new state with ~1 eV is needed.
In the latter models, two states with about 1.5 eV total mass needed.

What does BBN say?

What do we know about ^{4}He?

Main problem

We cannot observe *primordial* abundances:
Stars have altered the primordial composition.
For ^{4}He, stars mostly burn H into He → $Y > Y_p$

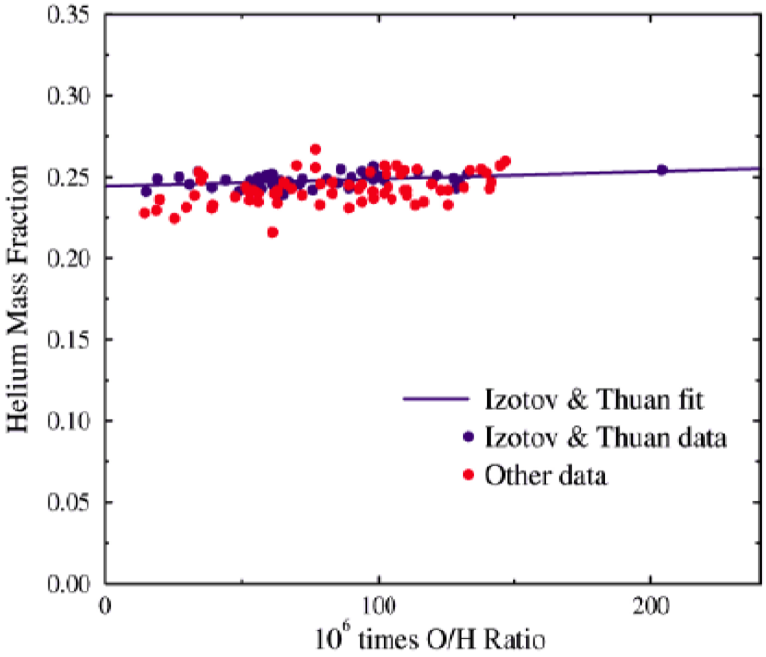
Observe systems with little chemical processing

HeII → HeI recombination lines in HII regions (about ~80 such regions known) of Blue Compact Dwarf Galaxies*

*small galaxies (~1/10 MW) containing large clusters of young, hot, massive stars. Among the least chemically evolved objects known.

Correct for chemical evolution

Extrapolate *linearly* to “zero metallicity” in Y_p vs O/H,N/H plots



A simpler strategy (bypass astrophysical ignorance)

Key Idea

We are not interested in primordial ^{4}He abundance.
We only care about an upper limit on N_{eff}.

Take the *observed* ^{4}He and just use the qualitative info $Y > Y_p$ to obtain an upper bound

No need to extrapolate or assume *linearity* in the extrapolation. No need to know Z-evolution as well or to worry about pre-galactic sources of ^{4}He (like popIII).

Using the data on 9 metal-poor object with high quality spectra of E. Aver, K.A. Olive, E.D. Skillman, arXiv:1012.2385.

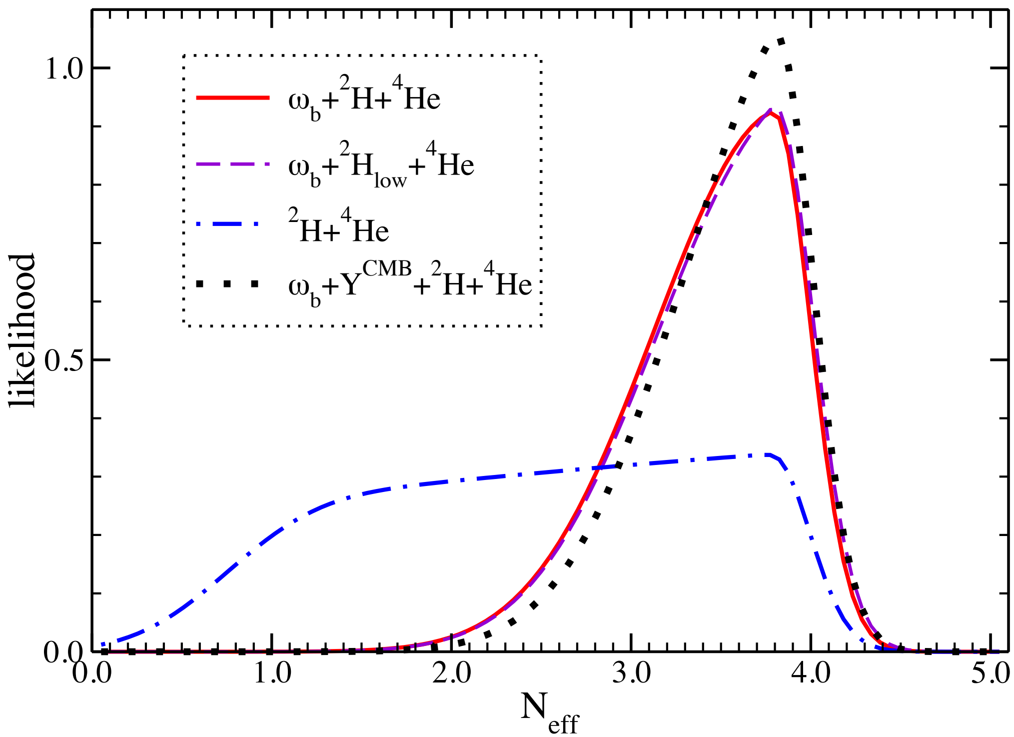
$$\langle Y_0 \rangle \pm \sigma_0 = 0.2581 \pm 0.0025 \ (68\% \text{ C.L.})$$

$$\ell(Y_p) \propto \Theta\big(\langle Y_0 \rangle - Y_p\big) + \Theta\big(Y_p - \langle Y_0 \rangle\big) \exp\left[-\frac{(Y_p - \langle Y_0 \rangle)^2}{2\sigma_0^2}\right].$$

G. Mangano & PS, PLB 701 (2011) 296

Results

- ✓ BBN alone (He+D) has no preference for extra dof [blue c.]
- ✓ Adding the CMB prior on ω_b , the preference for larger N_{eff} is not significant (~ 1σ) [red curve]
- ✓ The result doesn't change if observed D used only as lower limit to primordial value [purple curve]
- ✓ Minor change if Y_p info from CMB is used [black curve]



Datasets	N_{eff}^{max}	N_{eff}^{min}	$L(N_{eff} \leqslant N_{eff}^{SM})$
$\omega_b + {}^2H + {}^4He$	4.05	2.56	0.20
$\omega_b + {}^2H_{low} + {}^4He$	4.08	2.57	0.19
${}^2H + {}^4He$	3.91	0.80	0.67
$\omega_b + Y_p^{CMB} + {}^2H + {}^4He$	4.08	2.71	0.15

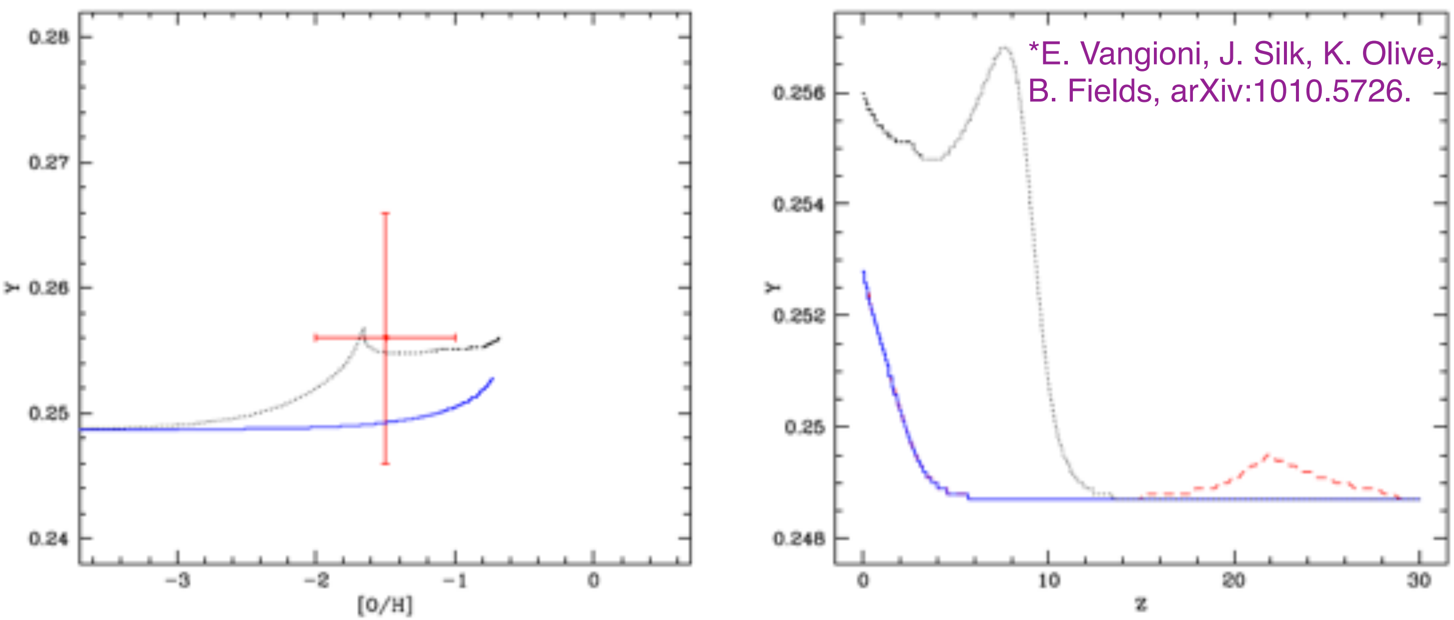
G. Mangano & PS, PLB 701 (2011) 296

Conclusions from BBN

- ✓ BBN imposes a conservative upper limit to the extra dof of about $\Delta N_{eff} \leq 1$

- ✓ Even in a conservative analysis, there is only a slight preference (~1 σ) for $\Delta N_{eff} \geq 0$

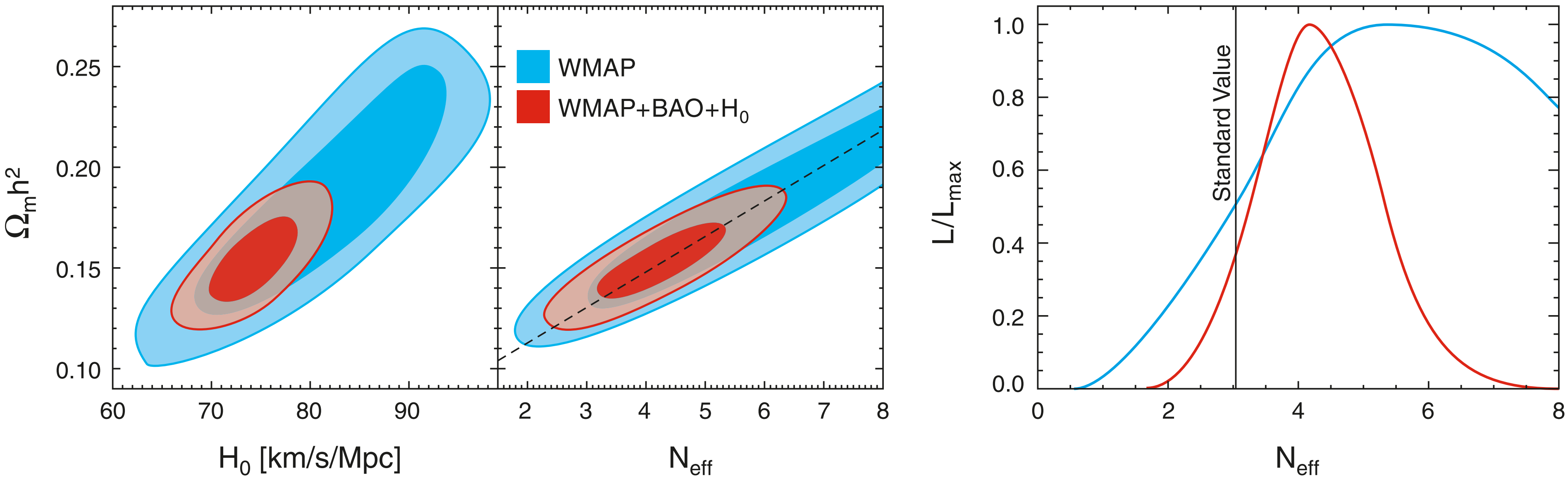
- ✓ Accounting for "astrophysical pollution" (including popII regression and popIII contribution) the upper limit could be converted into a plausible value of Y_p corresponding to $\Delta N_{eff} \approx 0.5$ below what observed* (almost centered on expectation). This is of course model-dependent, but suggest that there might be no anomaly at all in BBN...



*See also R. Salvaterra, A. Ferrara, Mon. Not. Roy. Astron. Soc. 340 (2003) L17, astro-ph/0302285.

What does CMB say?

Till WMAP-7



WMAP [7-year], arXiv:1001.4538

- ✓ Preference for Neff>3.05 not significant (~1 σ)
- ✓ If combined with other data (BAO, Hubble), slightly increased (still less than 2 σ)

☞ judge yourself the extent to which one can speak of "hints"...

☞ lower limits depends on the anisotropic stress (due to free streaming nature of ν's, which damps oscillations at l>200)

Adding small scale data (CMB damping tail)

✦ Adjust:
- Matter-radiation equality
- Baryon density
- Sound horizon

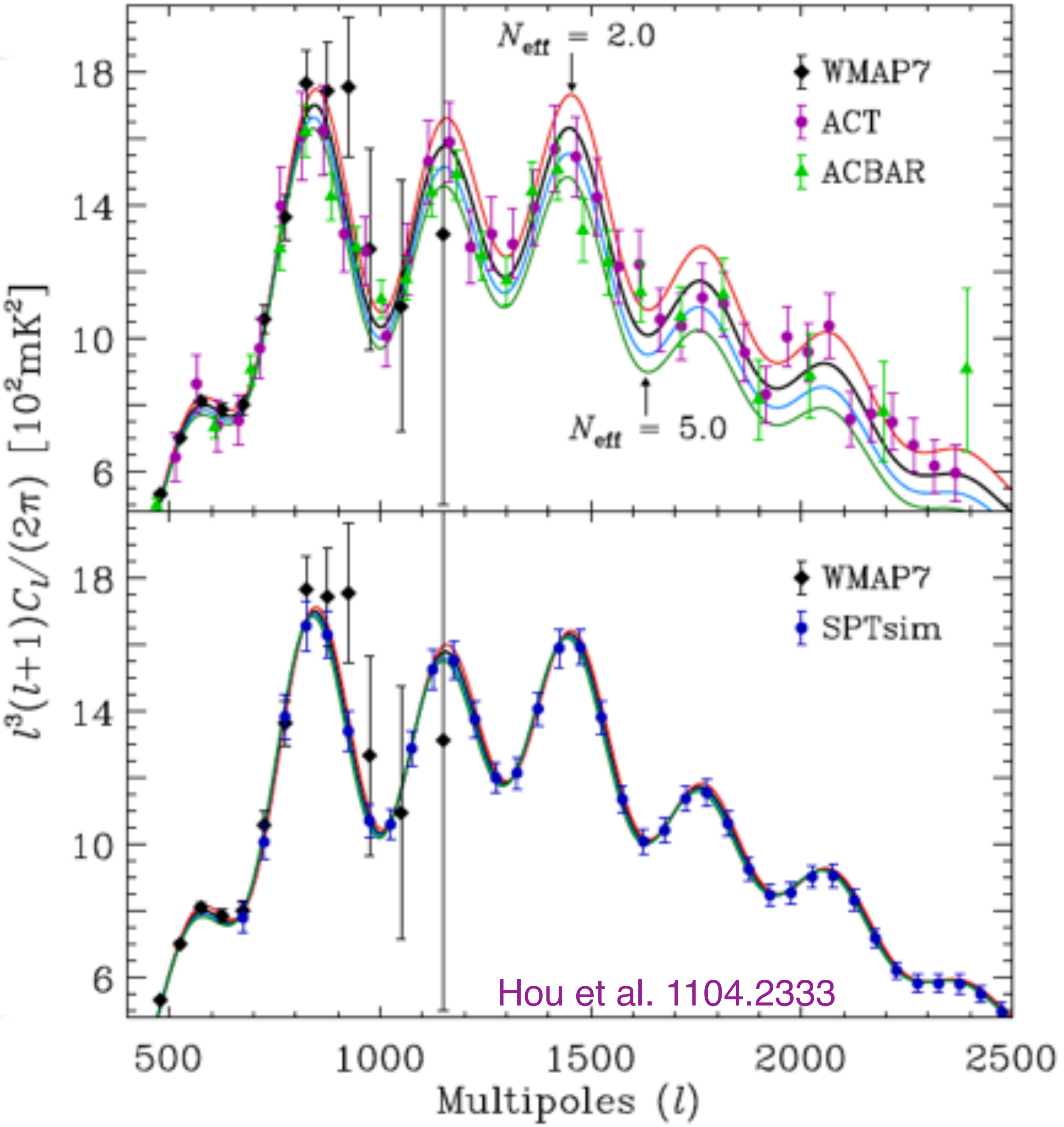
to agree with WMAP-7
(1st peak, invisible in the plot...)

✦ Higher N_{eff} increases Silk damping **at fixed z_{eq}** (For an explanation see Hou et al. 1104.2333)

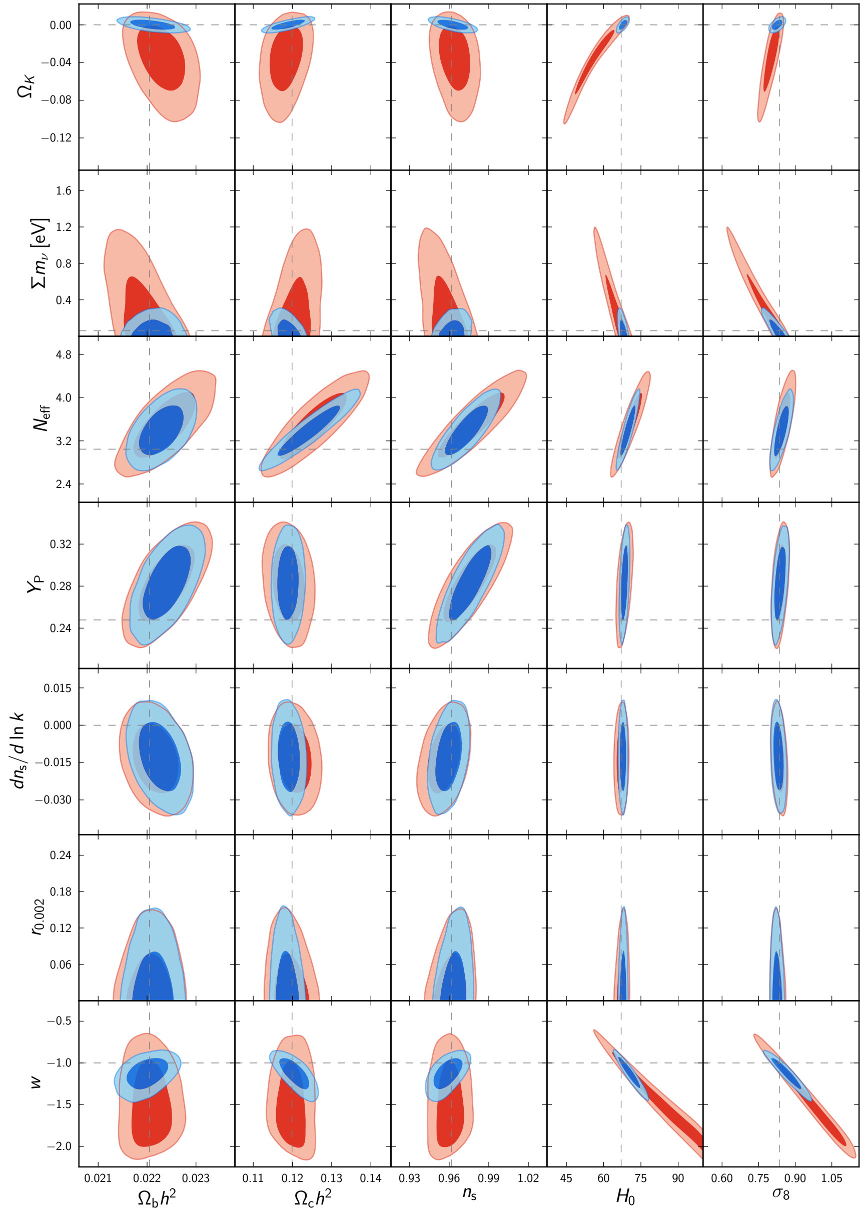
✦ Different N_{eff} visible in the damping tail (probed by ACT, ACBAR... soon Planck!)

✦ It's this tail that brings significance to about 2.4 σ

✦ Some degeneracy with the Y_p (Keep in mind when combining with BBN...)

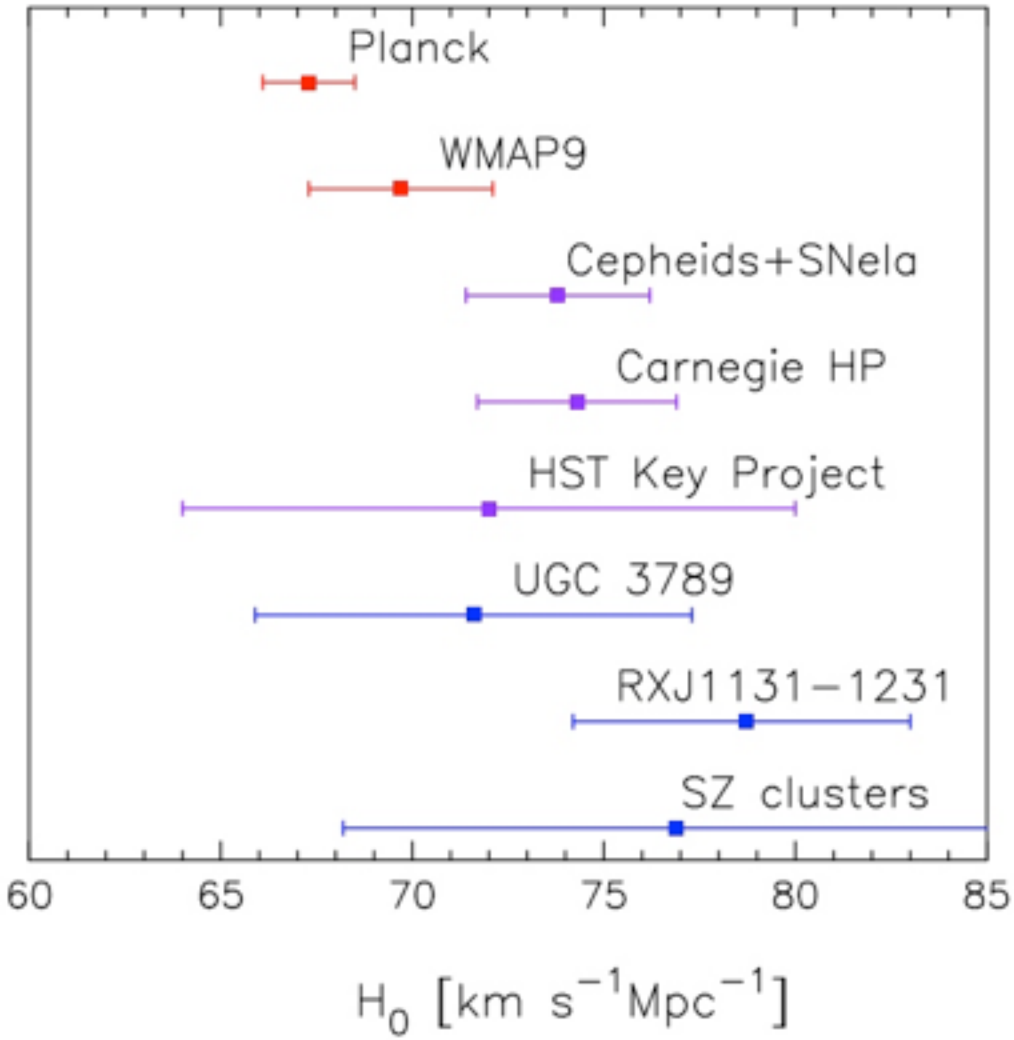


Hubble reloaded



.21. 68% and 95% confidence regions on one-parameter extensions of the base ΛCDM model for *Planck*+WP (red) and *ıck*+WP+BAO (blue). Horizontal dashed lines correspond to the fixed base model parameter value, and vertical dashed lines *v* the mean posterior value in the base model for *Planck*+WP.

Hubble reloaded



Using BAO and CMB data, we find ***Neff= 3.30±0.27*** *effective number of relativistic degrees of freedom, and an* ***upper limit of 0.23 eV for the sum of neutrino masses.***

Planck XVI, 2013

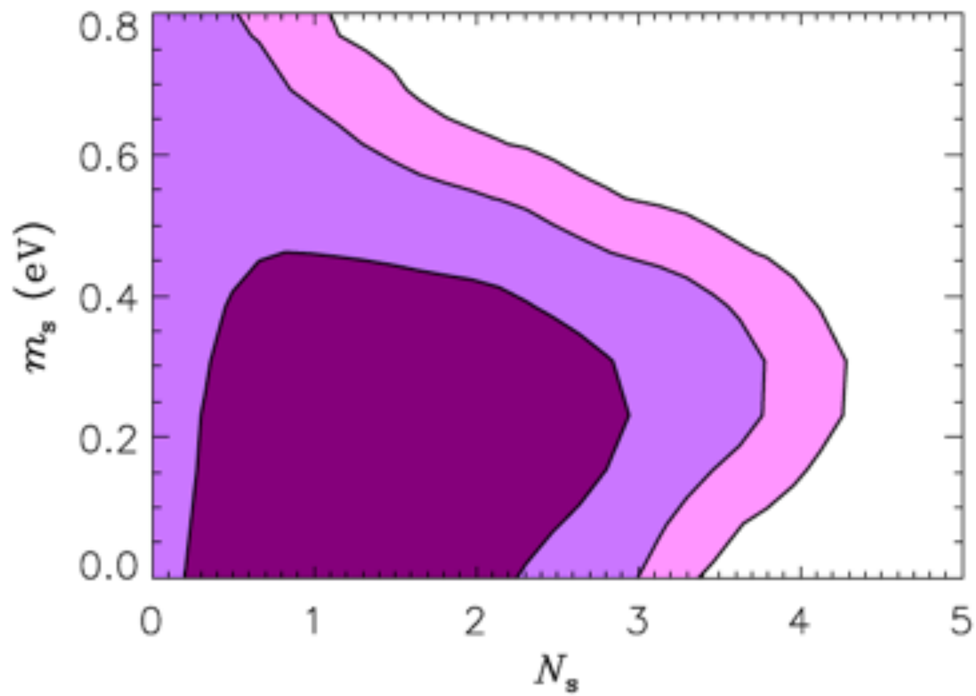
Large Scale Structures

Are sterile ν's fitting Lab anom. the cause of $N_{eff}>3$?

Most likely NOT!
Why? Because they are inconsistent with CMB+LSS mass bounds!

✦ In 3+1 models (fully thermalized)
$m_4<0.48$ eV (95% CL)
(vs. about 1 eV expected from Lab)

✦ In 3+2 models (fully thermalized)
$m_4+m_5<0.9$ eV
(vs about 1.5 expected from Lab)



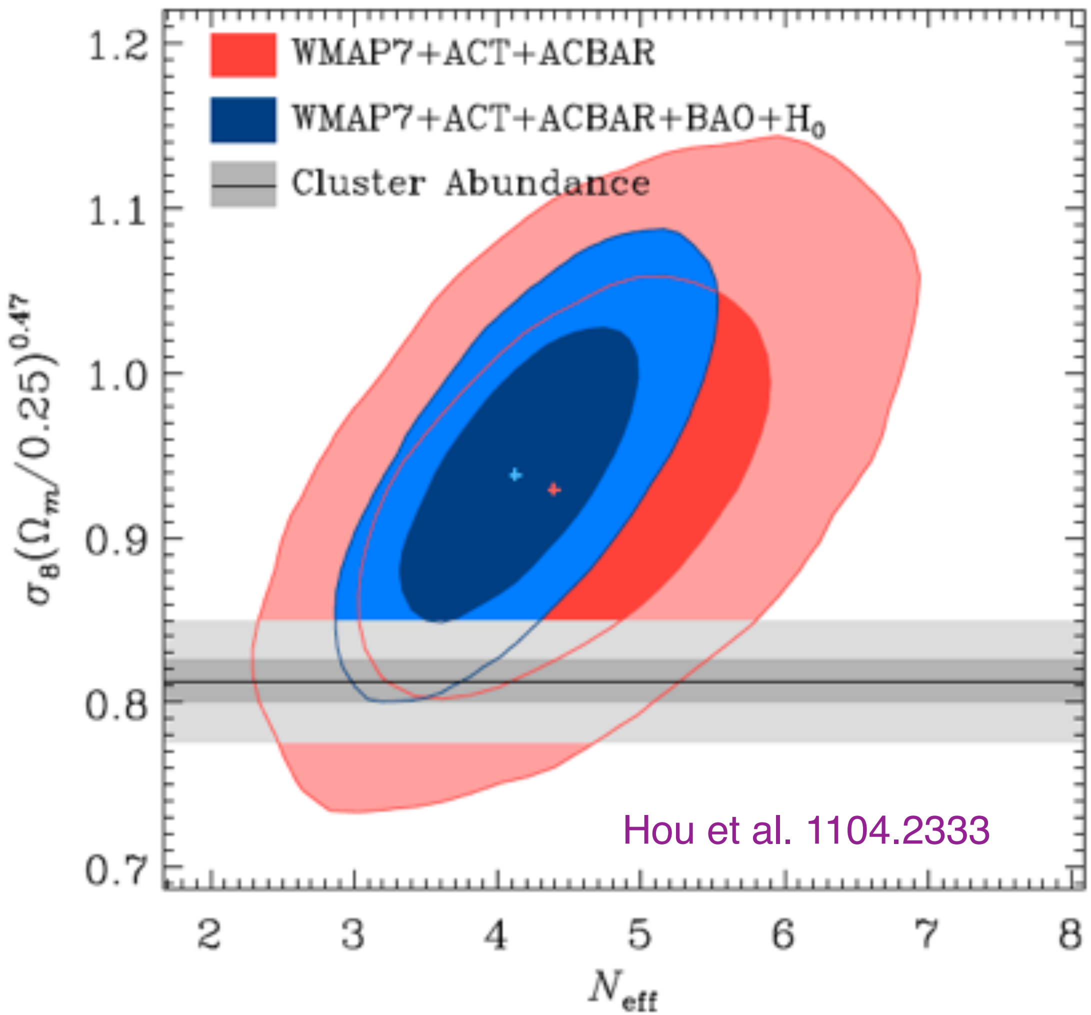
From a pure statistical point of view, adding eV scale massive neutrinos (1 or 2 states) is more disfavoured by cosmology than the weak preference for $\Delta N_{eff}>0$

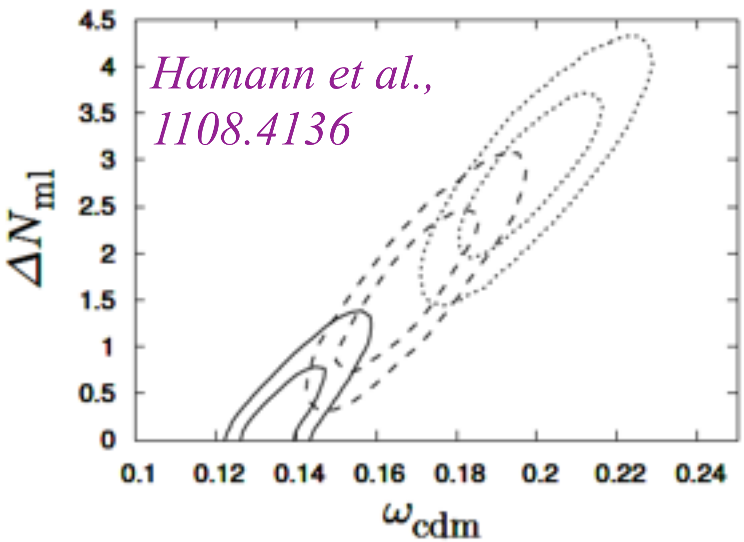
J. Hamann et al., PRL 105, 181301 (2010)

Not the only problem: Clusters!

CMB power spectrum is sensitive to $1+z_{eq}$, "fixed" by data. If we use the tail to fix the radiation content, the constraint on $1+z_{eq}$ becomes a constraint on Ω_m.

The best fit assuming additional neutrino species implies a tension with Ω_m inferred by clusters!





$$1 + z_{eq} = \frac{\Omega_m}{\Omega_r} \simeq \frac{\Omega_m}{\Omega_\gamma} \frac{1}{1+0.23\, N_{eff}}$$

In Summary

BBN is barely consistent with N_{eff}~4, but does not prefer significantly $\Delta N_{eff} \geq 0$

The only data that somehow prefer (at ~2 σ value) a larger N_{eff}
are CMB ones, in particular including small scales (damping tail)

But:

this fit/combination of parameters is in tension with cluster determination of Ω_m,
especially for 2 extra species.

LSS excludes the mass values needed to fit lab data (well above the 99% C.L.!)

While there might be some "anomaly" in cosmology,
Cosmology **does not** support sterile neutrino interpretations of Lab data.

Rather, similarly to disappearance experiments, **it disfavors** them
(at a C.L. larger than the so-called intriguing anomalies)

Feel free not to trust Cosmology, but in no case one should quote just the first line of the above statement

So, what is the cosmological N_{eff} anomaly?

Could it be an artifact of priors?

A. X. Gonzalez-Morales, R. Poltis, B. D. Sherwin and L.Verde,
"Are priors responsible for cosmology favoring additional neutrino species?," arXiv:1106.5052.

We have presented a way to make the cosmological analysis as prior-independent as possible; we borrowed from the frequentist approach the so-called generalized likelihood ratio to report confidence intervals. We have considered a suite of cosmological data sets and data sets combinations and found that prior-independent confidence intervals for $\Delta N_{eff} \geq 0$ do not show any evidence of additional effective neutrino species.

J. Hamann,
"Evidence for extra radiation? Profile likelihood versus Bayesian posterior," arXiv:1110.4271

found that 2/3 σ lower evidence is found indeed when using "frequentist approach" and WMAP+ACT data, but this effect reduces to ≤1/3 σ when Hubble constant data is added, so likely does not explain most of it (<u>though the presence of an additional statistical bias introduced, e.g., by the modelling of foregrounds, remains a possibility</u>)

(and don't forget that we talk here of 2 sigmish effects!)

Alternative interpretations?

➡ E.g. could equally be interpreted as 3 neutrinos, but with anomalous sound speed or viscosity T. Smith, S. Das and O. Zahn, 1105.3246

➡The result becomes insignificant (~1.5 σ) if one admits a larger parameter space, e.g. allowing to vary:

- spectral running in P(k)
- Y_p
- rest-frame sound speed or viscosity parameters

$N_{\rm eff}$	$c^2_{\rm vis}$	$c^2_{\rm eff}$	α	Y_p
$4.0^{+0.17+0.58}_{-0.18-0.57}$	$1/3$	$1/3$		
$3.77^{+0.18+0.68}_{-0.19-0.65}$	$0.33^{+0.04+0.21}_{-0.06-0.15}$	$0.31 \pm 0.015^{+0.029}_{-0.030}$		
3	$0.44^{+0.056+0.27}_{-0.085-0.21}$	$0.30 \pm 0.013^{+0.027}_{-0.026}$		
3.53±0.21±0.72	1/3	1/3	-0.020±.013±.026	
$3.64_{-.24}^{+.21}{}_{-.79}^{+.86}$	1/3	1/3		0.257±.051±0.1

Tristan L. Smith, Sudeep Das and Oliver Zahn, 1105.3246

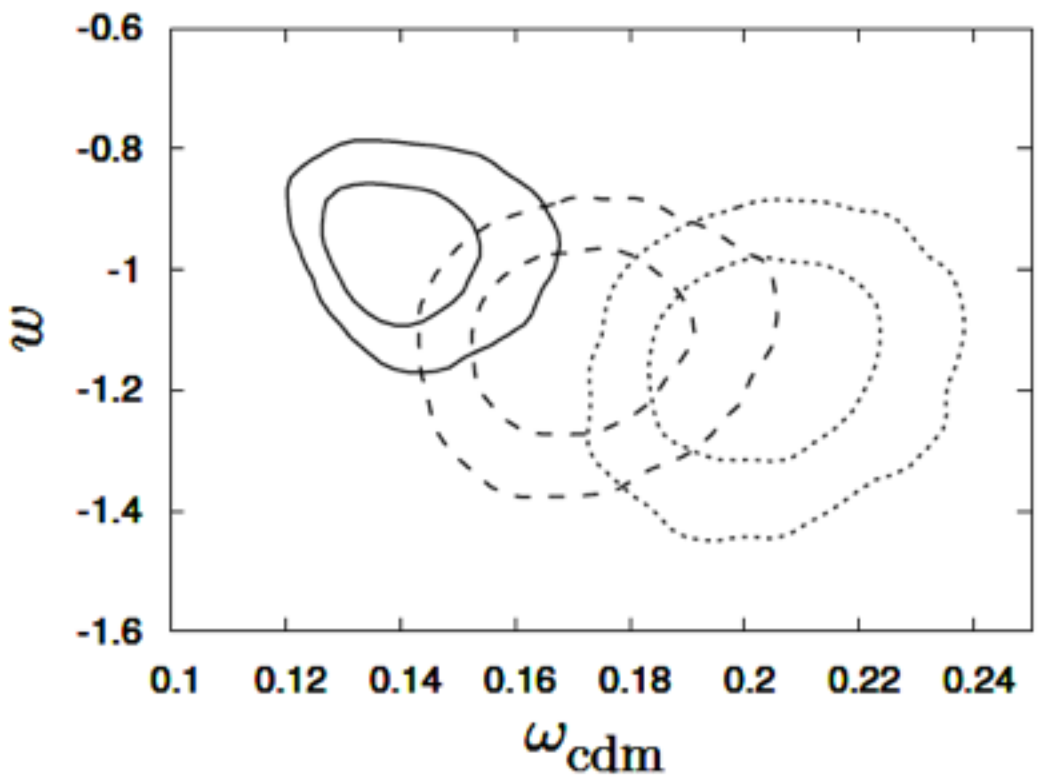
Don't forget that N_{eff} might having nothing to do with ν's !

What if Lab confirms eV-scale steriles?

One would need to go to contrived (exciting?!) cosmologies

- ✓ Introduce chemical potentials of O(0.1) to get around BBN (how to generate them?)
- ✓ modify dark energy sector (eg. wCDM) plus add additional non-massive radiation
- ✓ Explain why cluster determination of DM does not seem to fit (any idea?)

see e.g. Hamann et al., 1108.4136



But neither the Lab evidence nor the cosmo “appeal” seem strong enough...