Neutrinos & Cosmology

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25th Rencontres de Blois on
“Particle Physics and Cosmology”

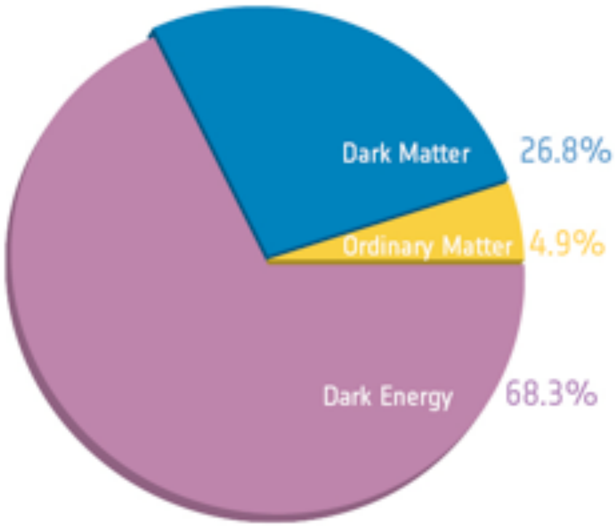
30/05/2013

In a nutshell: why neutrinos matter for cosmology?

- The energy budget of the Universe is dominated by "dark stuff."
- Neutrinos are the only "dark" component (cosmologically stable) present in the standard model
- We know that they are extremely light... "dark radiation"?
- The Lab tells us that, nonetheless, they are massive... "dark matter"?
- The Lab tells us that anomalies might be present in this sector... what would e.g. sterile neutrino imply for cosmology?

Why does it matter for neutrino physicists?

Just to tell one: Basically the only, numerous sample of non-relativistic neutrinos available!
Via gravitational effects, possible to infer something about their absolute mass scale!



Outline of the present talk

- Illustrate the basic physics through which ν states are populated in the early universe
- How they affect observables in BBN, CMB, LSS (“extra radiation” and “extra mass”)
- Adding sterile states... and some “theoretical caveats”.
- I will revisit the origin and fate (after Planck) of cosmological “anomalies” and critically examine the extent to which they can be considered to support current hints for sterile ν

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

$$\nu_a \nu_b \leftrightarrow \nu_a \nu_b$$

$$\nu_a \bar{\nu}_a \leftrightarrow \nu_b \bar{\nu}_b$$

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

$$\nu_a e^- \leftrightarrow \nu_a e^-$$

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$$\nu_a e^- \leftrightarrow \nu_a e^-$$

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

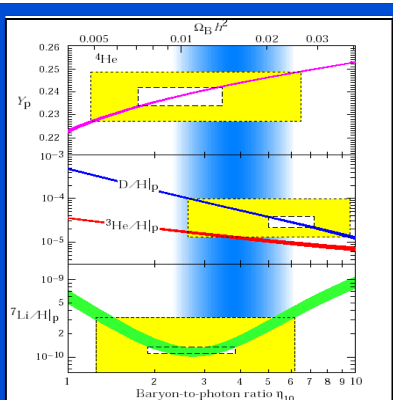
"Detection" of the CνB

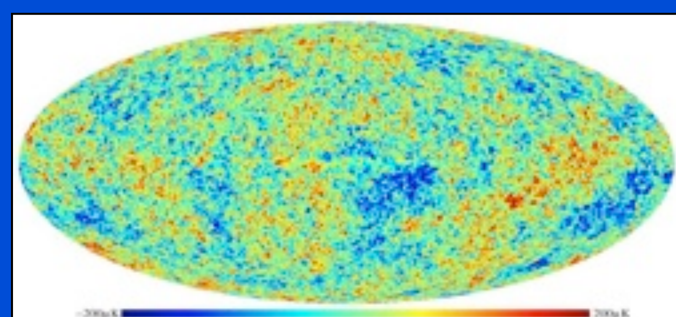
- Pseudo-thermal distribution: T_ν = 1.95 K
- Number density ($\nu + \bar{\nu}$): 112 cm^{-3}/flavour
- Mean kinetic energy: << meV

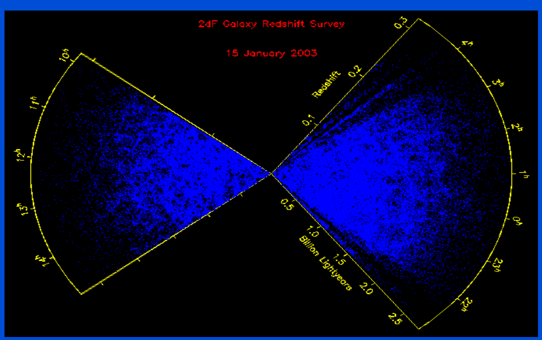
lower than 2.7 K of CMB due to later
$e^+ e^- \to \gamma\gamma$
(heating of photons)

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

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

Gravity only, mostly integral quantity, extra relativistic species

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

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

Weak Rates: p↔n equilibrium

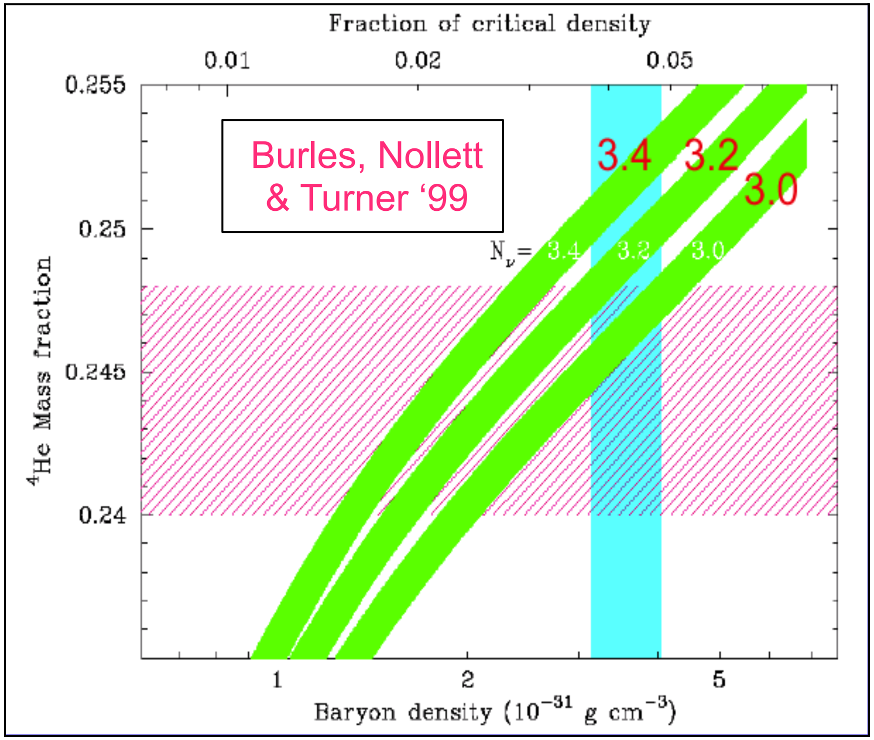
Very sensitive to weak interactions (only e-flavour matters), energy spectrum.

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

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



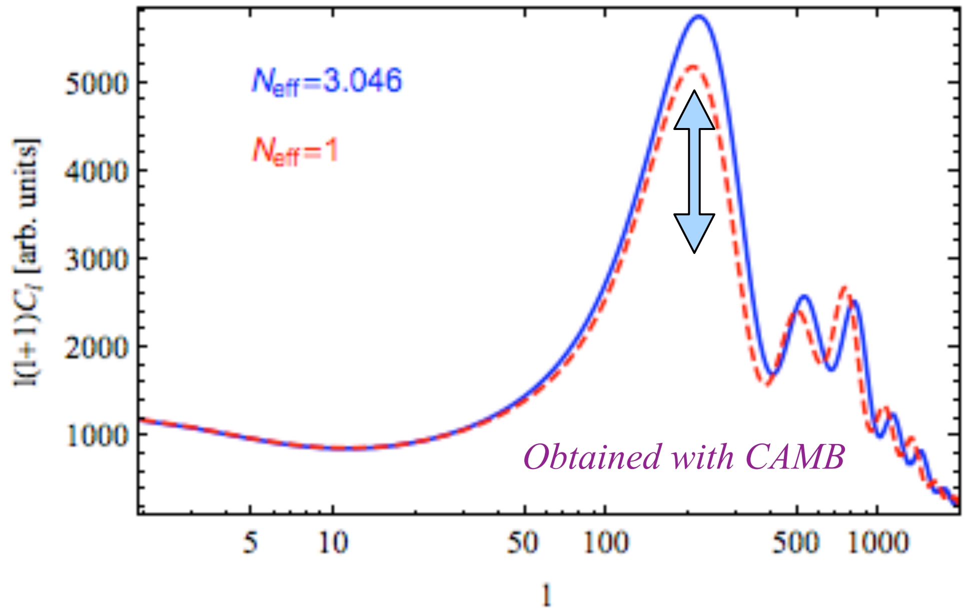
- High N_{eff} → High H → early freeze out ($\Gamma_{pn} \sim H$ at high T) → high n/p → high Y_p
- $\nu_e > \bar{\nu}_e \rightarrow \nu_e\, n \rightarrow e^- p$ favored over $\bar{\nu}_e\, p \rightarrow e^+ n$ → low n/p at fr.out → low Y_p (chemical potential $\mu_{\nu e} > 0$)
- ...

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!



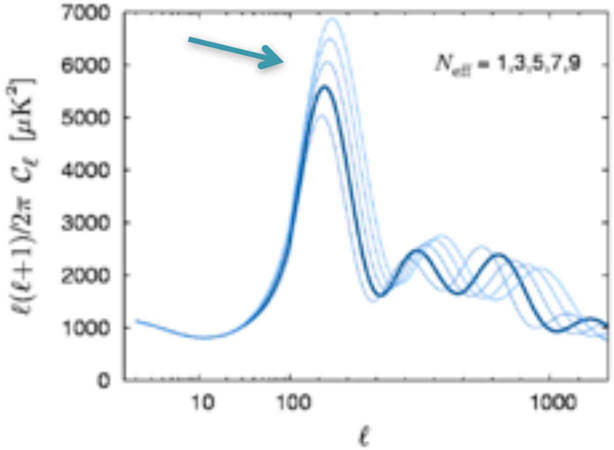
for more details, see e.g.
J. Lesgourgues & S. Pastor
Phys.Rept. 429 (2006) 307-379

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

Beware of degeneracies!

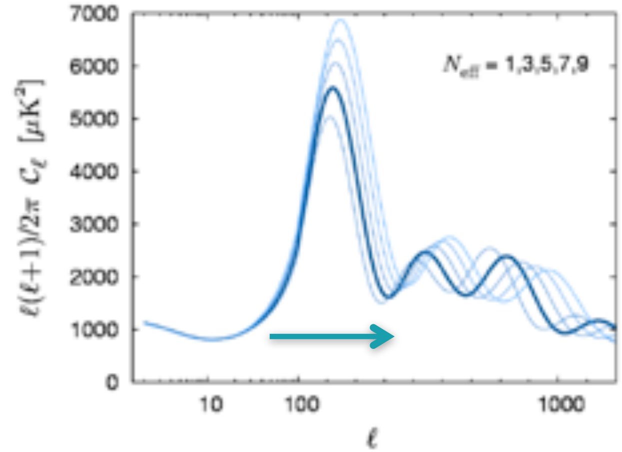
Matter-radiation equality

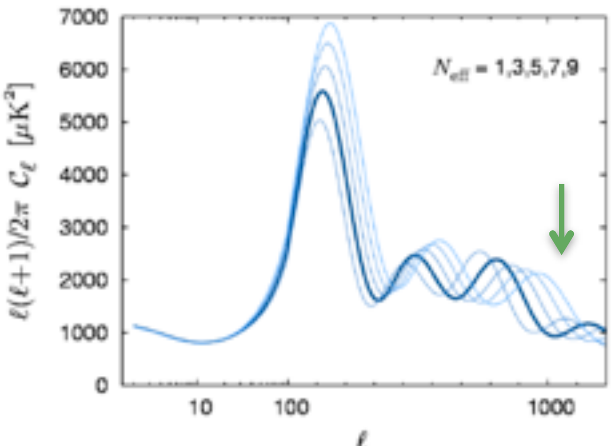
degenerate with Ω_m



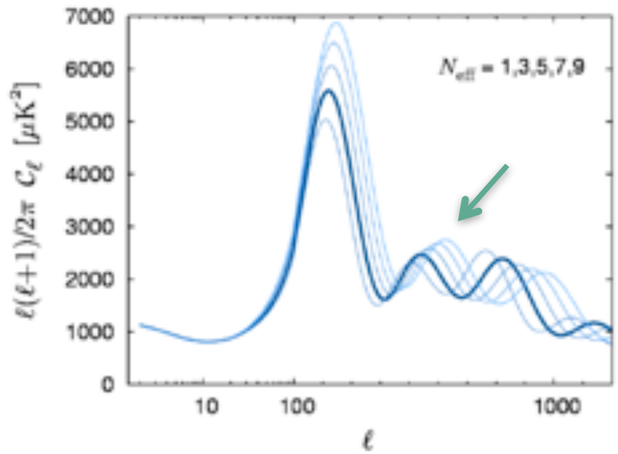
Sound horizon/angular positions of the peaks

degenerate with Ω_m and h





Damping tail
degenerate with Y_p



Anisotropic stress

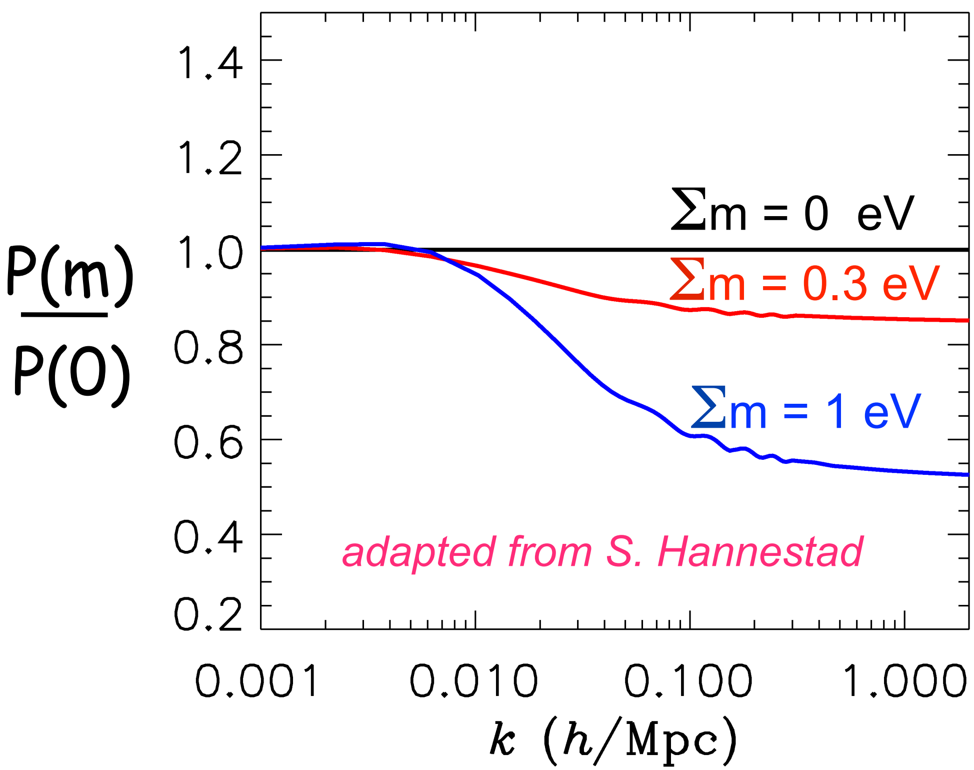
(partially) degenerate with A_s and n_s

adapted from Y. Wong

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

$$\frac{\Delta P}{P} \approx -8 \frac{\Omega_\nu}{\Omega_m} \approx -0.8 \frac{\Sigma m_i}{1\ \mathrm{eV}} \frac{0.1}{\Omega_m h^2} \qquad @\ k > k_{NR} \approx 0.015\ (\Sigma m_{eV} \times \Omega_m h^2)^{1/2}\ \mathrm{Mpc}^{-1}$$



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

Adding sterile states...

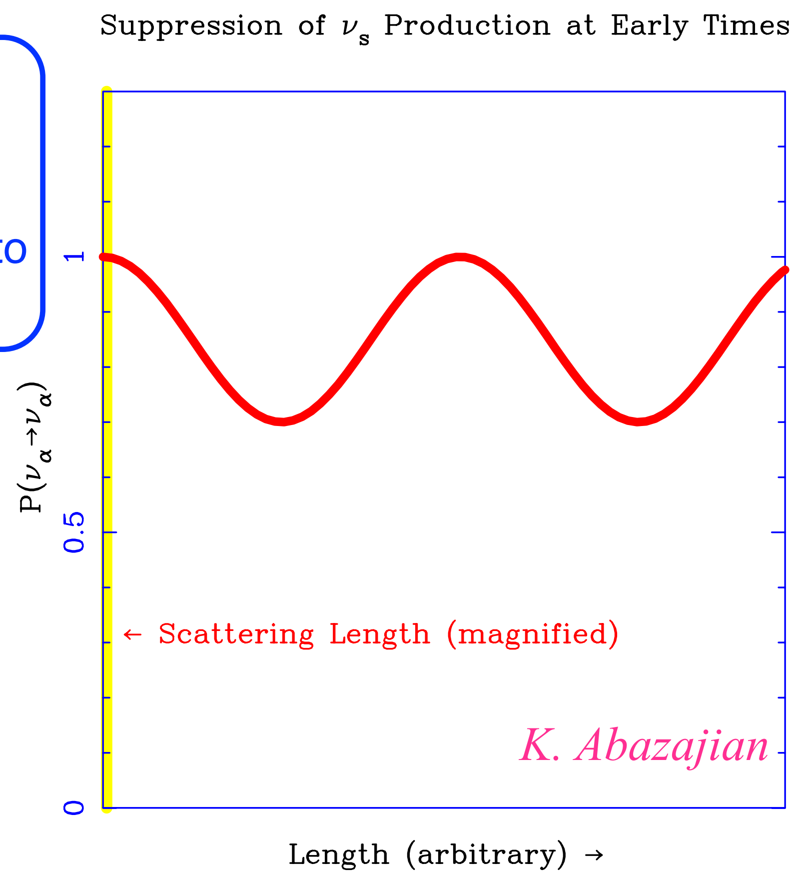
The Quantum Zeno effect (for production via osc.)

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

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

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

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



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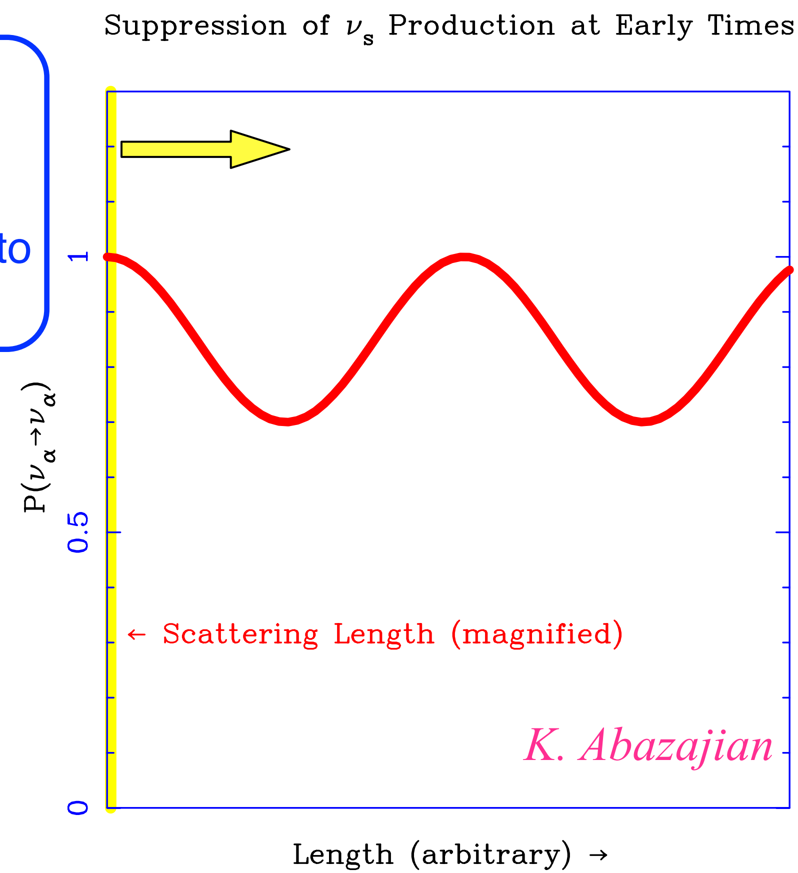

As the universe expands, cools & becomes less dense, λ_{scatt} ↗. Then, $P_{\alpha s}=(1-P_{\alpha\alpha})$ ↗

☞ 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 fits to anomalies, parameters such that the 4th ν always thermalize: $N_{eff}\sim4.05$
In 3+2 fits, "almost" true, $N_{eff}\sim5$, although partial thermalization or some spectral *distortions* at BBN times are possible (see e.g. Melchiorri et al. JCAP 01 (2009) 036)

Roughly speaking, 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.

Why things may become involved...

When active neutrinos depart from thermal distributions and sterile population are significant, large non-linearities are present among many modes!

Density Matrices

Need to describe of the evolution in time of the flavor content (and p-distribution) of a neutrino system propagating in a medium.

As long as true "many body effects" (higher-order, multi-field correlations) are negligible and the medium is close to homogeneity, density matrices provide an efficient tool

$$\psi(x) = \int \mathrm{d}\mathbf{p}[a(\mathbf{p})u_{\mathbf{p}} + b^\dagger(-\mathbf{p})v_{-\mathbf{p}}]\, e^{i\,\mathbf{p}\cdot\mathbf{x}}$$

$$\langle a_j^\dagger(\mathbf{p})a_i(\mathbf{p}')\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\rho_{ij}(\mathbf{p})$$

$$\langle b_i^\dagger(\mathbf{p})b_j(\mathbf{p}')\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\bar{\rho}_{ij}(\mathbf{p})$$

(Inverted i↔j to transform the same under Unitary-rotation in flav. space)

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EOM: Liouville eq. $i\partial_t\rho=[H,\rho] + C[\rho]$ (for each neutrino mode)

Occupation numbers

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

"Entanglement"

EOM for ν evolution in the Early Universe

Vacuum mixing

Refractive term due to e⁻-e⁺ energy density (Not e⁻-e⁺ difference, less important!)

Self-refraction

on total active ν's E-density

on total active ν's # density difference

Collisions

$$i\frac{d\varrho}{dx} = +\frac{x^2}{2m^2\,y\,\overline{H}}\left[\mathsf{M}^2,\varrho\right] + \frac{\sqrt{2}G_F\,m^2}{x^2\,\overline{H}}\left[\left(-\frac{8\,y\,m^2}{3\,x^2\,m_W^2}\mathsf{E}_\ell - \frac{8\,y\,m^2}{3\,x^2\,m_Z^2}\mathsf{E}_\nu + \mathsf{N}_\nu\right),\varrho\right] + \frac{x\,\widehat{C}[\varrho]}{m\,\overline{H}}\,,$$

Eqs. rewritten in terms of (to factor out expansion)

$$x \equiv m\,a \qquad y \equiv p\,a \qquad z \equiv T_\gamma\,a$$

(rescaled) Hubble parameter ~ x-independent

$$\overline{H} \equiv \frac{x^2}{m}H$$

Asymmetric self-refraction term

$$\mathsf{N}_\nu = \frac{1}{2\pi^2}\int dy\,y^2\left\{\mathsf{G}_s(\varrho(x,y)-\bar{\varrho}(x,y))\mathsf{G}_s + \mathsf{G}_s\mathrm{Tr}\left[(\varrho(x,y)-\bar{\varrho}(x,y))\mathsf{G}_s\right]\right\}$$

Symmetric self-refraction term

$$\mathsf{E}_\nu = \frac{1}{2\pi^2}\int dy\,y^3\,\mathsf{G}_s(\varrho(x,y)+\bar{\varrho}(x,y))\mathsf{G}_s$$

What does BBN say?

What do we know about ^4He?

Main problem

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

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Observe systems with little chemical processing

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

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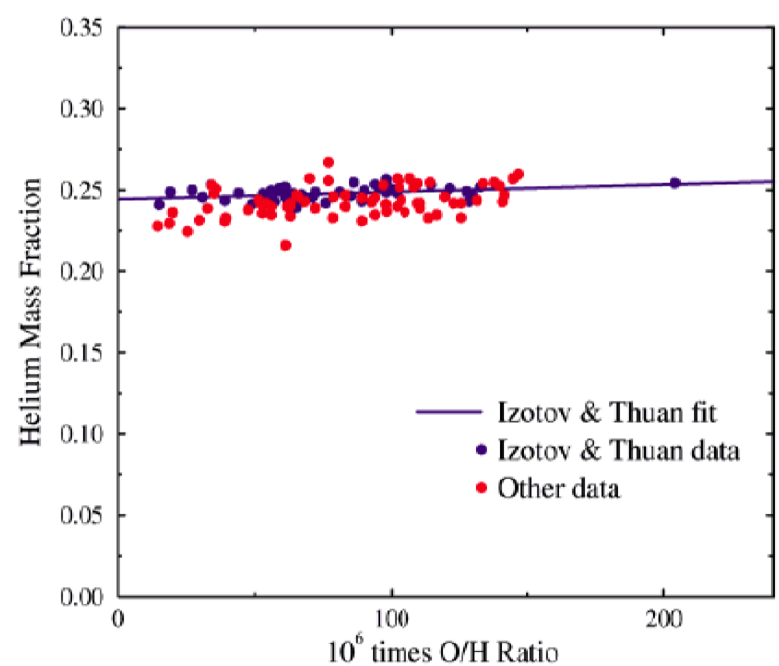
Correct for chemical evolution

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.

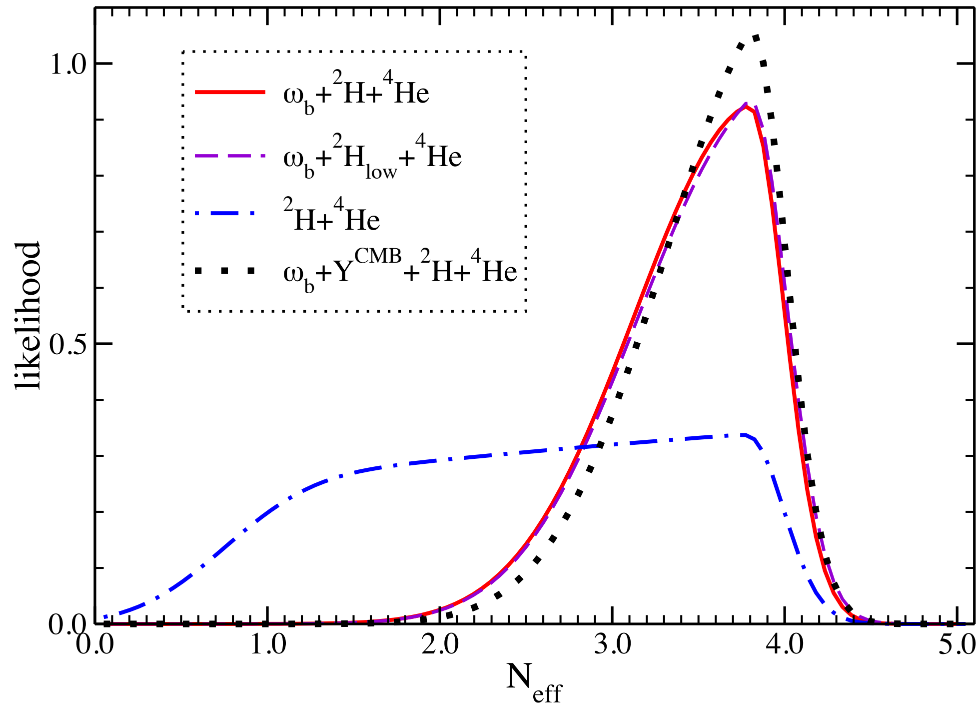
$$\langle Y_0 \rangle \pm \sigma_0 = 0.2581 \pm 0.0025 \ (68\%\ \text{C.L.})$$

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

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

Results: $\Delta N_{eff} \leq 1$

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

Alternative: avoid Y_p, take ω_b from CMB & "clean" determination of D/H (Nollet, Holder '11)

N_{eff} =3.0±0.5 Pettini & Cooke, MNRAS (1205.3785) but relies on single system...

What does CMB say?

Pre-PLANCK

"Precision cosmological data since the WMAP 5-year data release have consistently shown a mild preference for an excess of relativistic energy density."

Hint of *dark radiation?*

Caveat I. Analyses are **not-independent** (WMAP is always in common, H_0 often in common)

Caveat II. It's ~ 2 σ...

Caveat III. Requires combining many datasets (errors in quadrature)... chance that systematic errors eventually dominate grows!

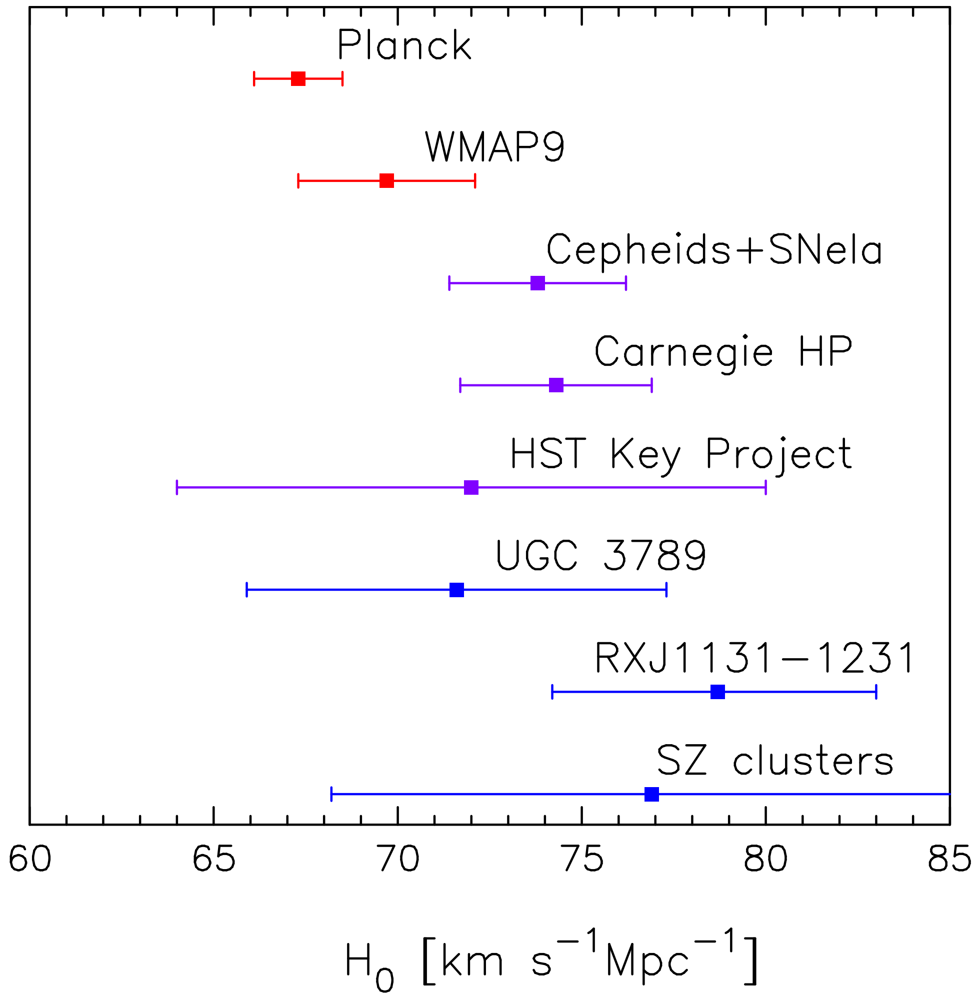
Caveat IV. Effect of Priors...

Caveat V. Comparing different cosmological models: do we really need adding one parameter wrt ΛCMD? (Bayesian evidence...)

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[346]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[346]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[349]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[346]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[338]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[338]
	W-7+ACT	5.3 ± 1.3	[343]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[343]
	W-7+SPT	3.85 ± 0.62	[344]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[344]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[350]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[351]
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[352]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[352]
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[351]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[352]
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[351]
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[352]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[352]
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[353]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[353]

Tab 3, white paper 1204.5379 on light sterile neutrinos

Planck found... Hubble$_0$ recession (to smaller value)



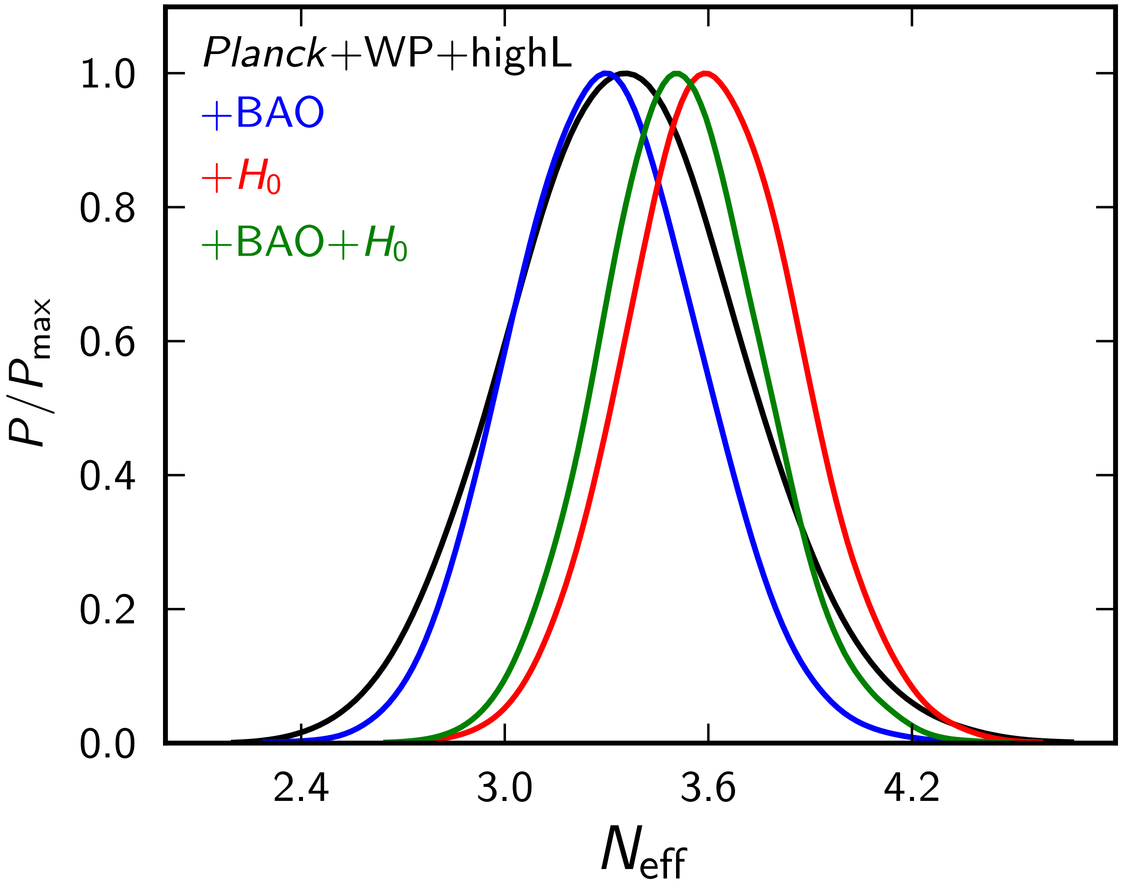
Planck XVI, 1303.5076

*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**]***

Not surprisingly...

*Using BAO and CMB data, we find **Neff= 3.30±0.27***

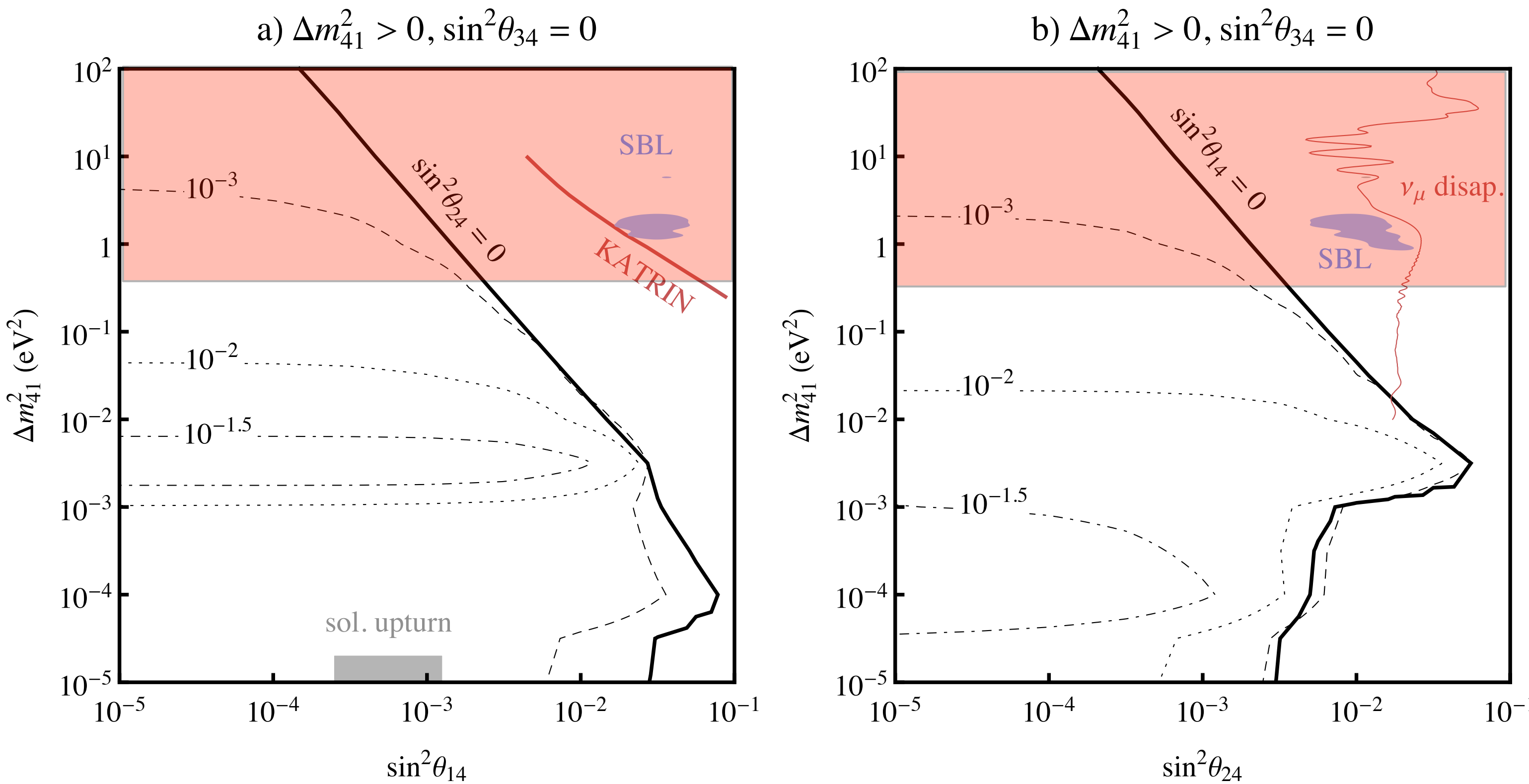
(WP: WMAP low-l polarization)
(highL: ACT, SPT, ground based)



Our results are in excellent agreement with BBN and the standard value of N_{eff}

In the relativistic limit at CMB epoch...

Just by imposing the above-mentioned 95% CL constraint on N_{eff}, the limit to the # of relativistic species excludes everything to the right of the curves...



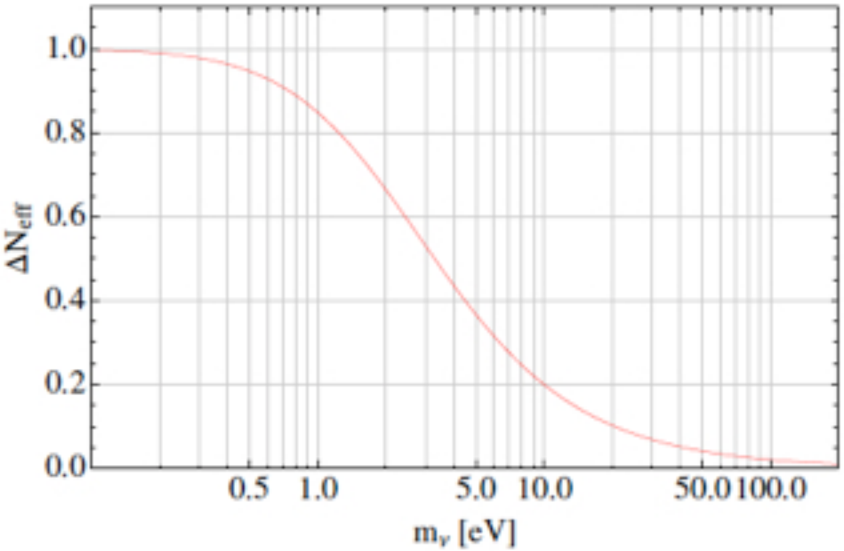
Other non vanishing mixing angles enlarge region where **ΔN_{eff}>0.8** is achieved.
Note: in the high-mass limit for the sterile, non-relativistic approximation breaks down, but mass constraints become important...

A. Mirizzi et al. arXiv:1303.5368

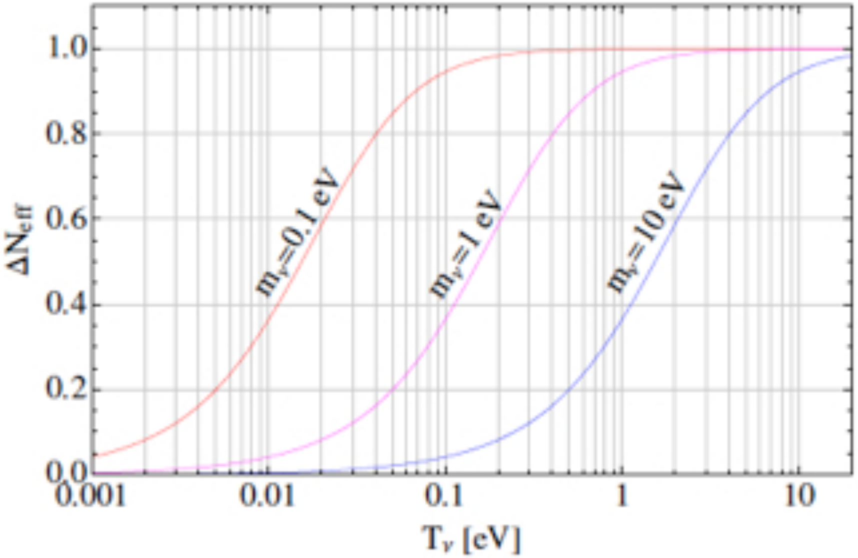
Transition to non-relativistic

Jacques, Krauss, Lunardini arXiv:1301.3119

At matter-radiation equality, as function of *m*



For 3 values of *m,* as function of T



Mass bounds (including Large Scale Structures)

Before Planck...

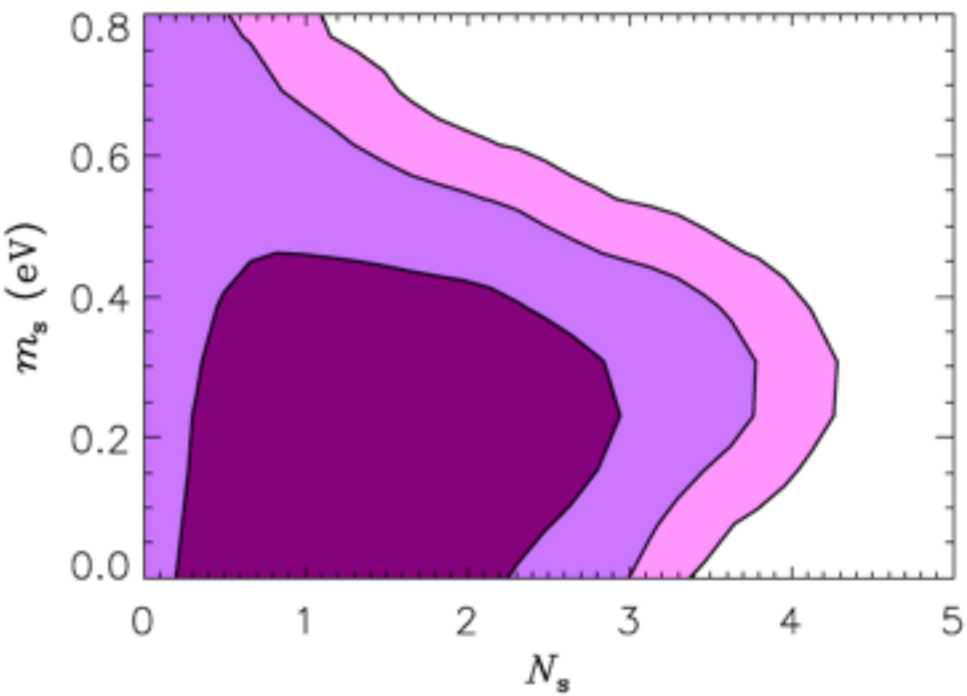
Let us take seriously the ~2 sigma preference for extra radiation.

Was it consistent with a "sterile ν interpretation" in the "anomalies-preferred" parameter space?

Actually NOT!
Why? Because they were already 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)



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

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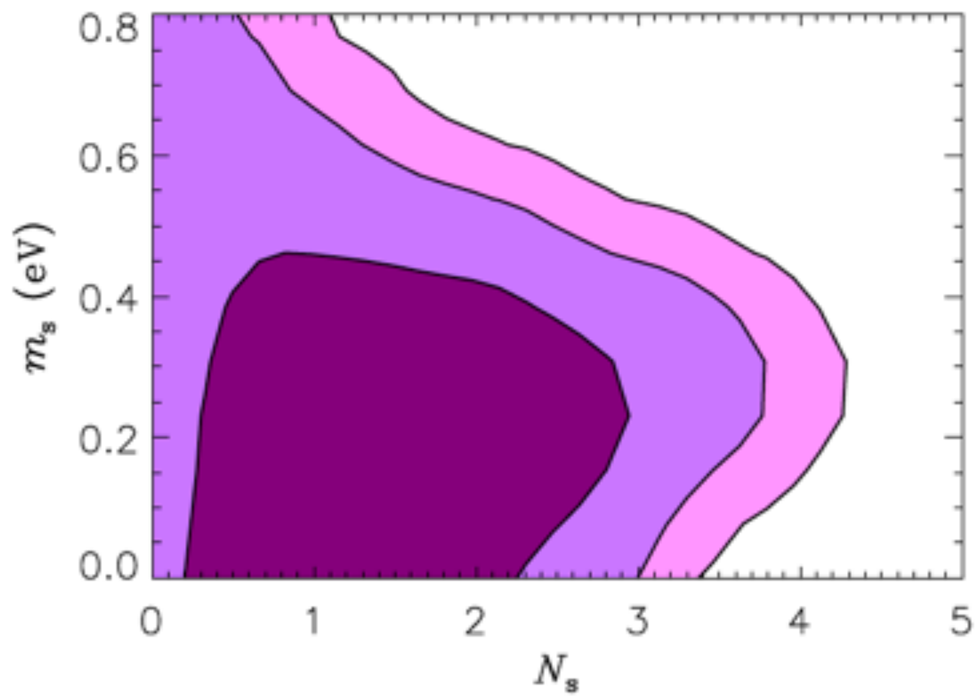
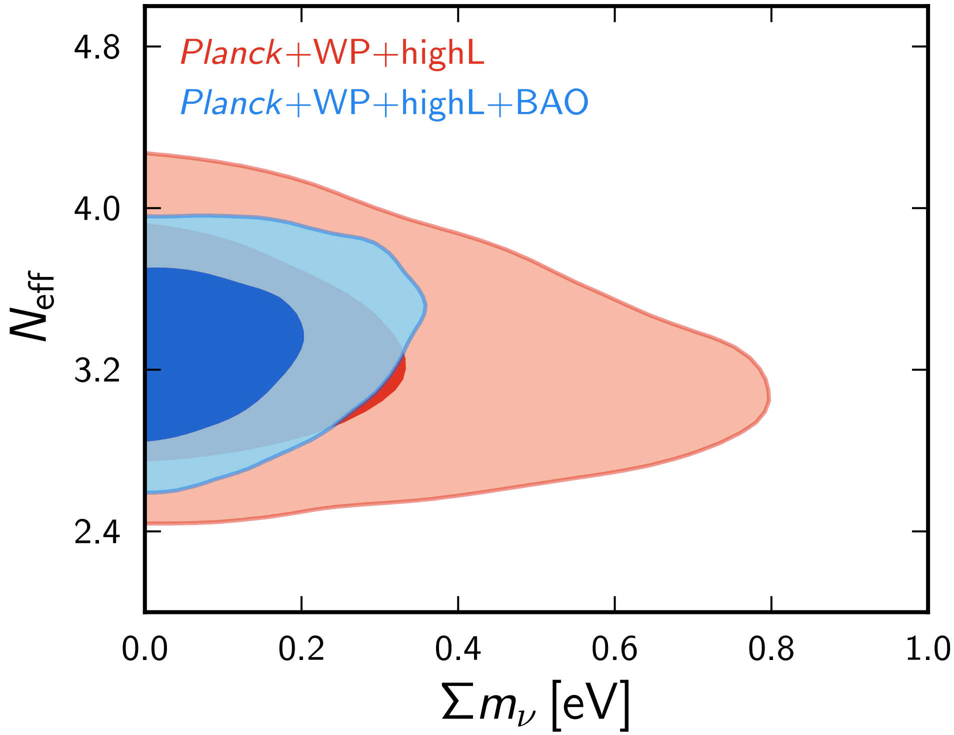
From a pure statistical point of view, adding eV scale massive neutrinos (1 or 2 states) was more disfavoured by cosmology than the weak preference for ΔN_{eff}>0



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

After Planck

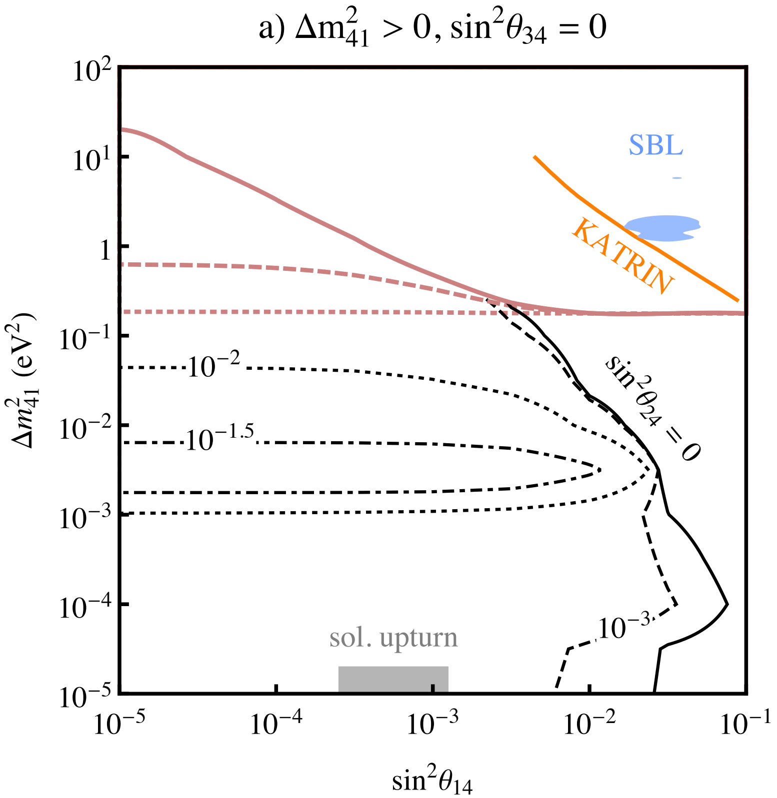
Using BAO and CMB data, we find an ***upper limit of 0.23 eV for the sum of neutrino masses. [****Planck XVI, 2013****]***

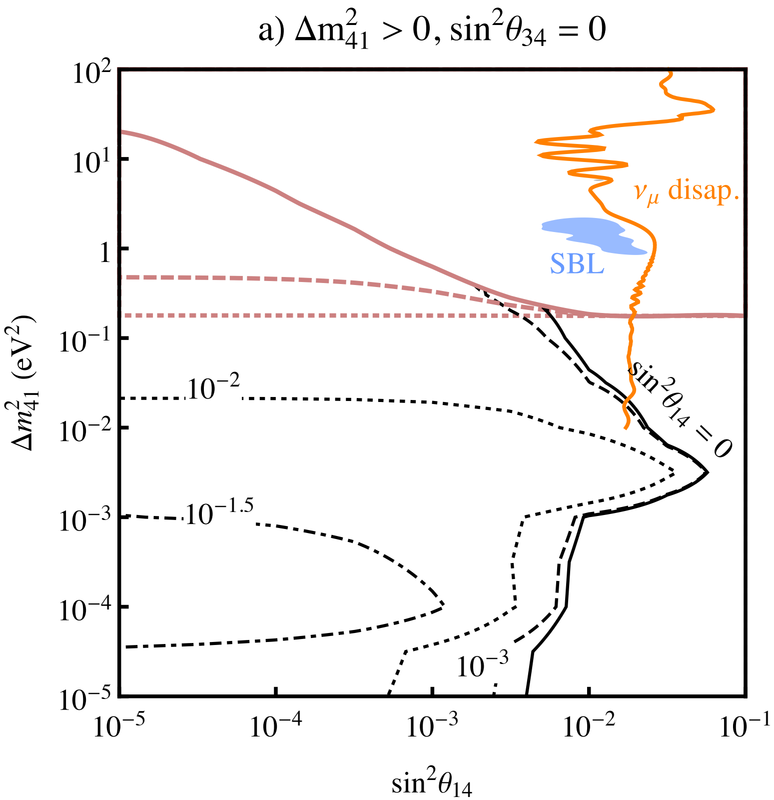


here extra ν's are massless, active ones massive

Although the "self-consistent" bounds where it is the sterile (and in general non-thermally distributed) neutrino to be massive remain to be published, the obtained improvement suggests that the previous "exclusion" argument holds stronger!

Preliminary results...





Courtesy A. Mirizzi et al.

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 preferred (at ~2 σ value) a larger N_{eff} were ***CMB in combination with others***

But:

LSS already excluded mass values needed to fit lab data

After-Planck

✓ the former anomaly seems to be significantly gone

✓ Mass constraints are tighter

In Summary

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But:

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After-Planck

✓ the former anomaly seems to be significantly gone

✓ Mass constraints are tighter

➡ Cosmology **does not** support sterile neutrino interpretations of Lab data. Rather, similarly to disappearance experiments, **it disfavors** them

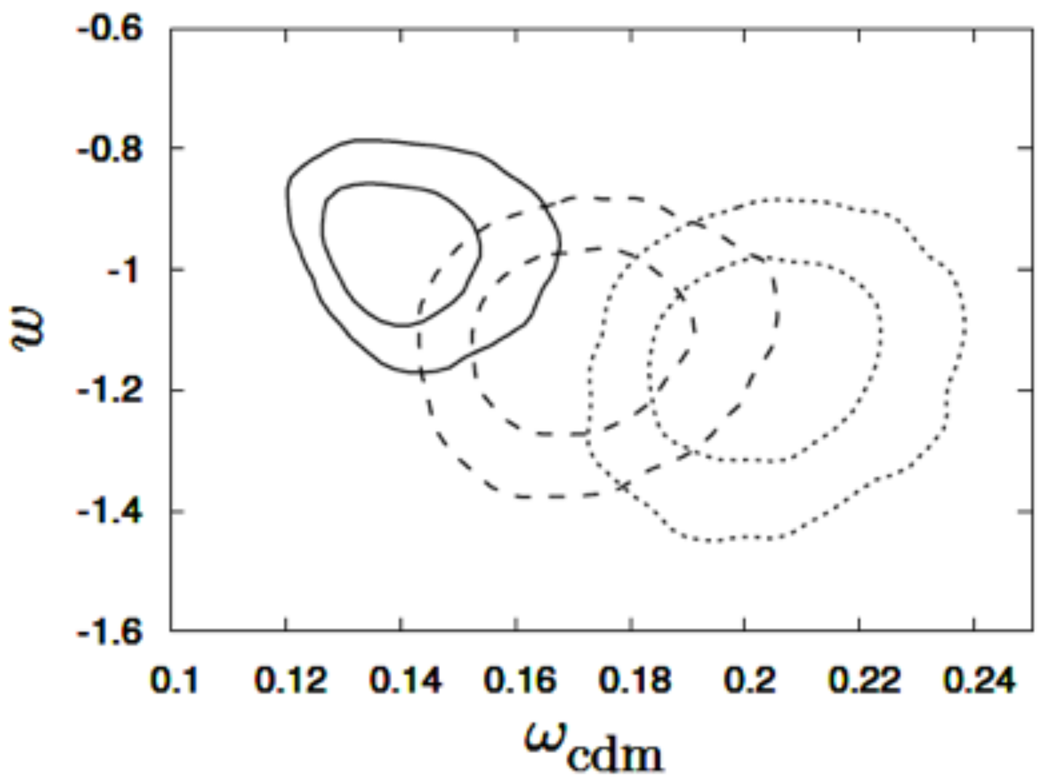
➡ Feel free not to trust Cosmology, but **please do not interpret "anomalies" in Neff (if any) as evidence for eV-scale sterile neutrinos**

What if Lab confirms eV-scale steriles?

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



Would be exciting... but unclear if/how well it works!

Neutrino asymmetries as way out?

Introducing $L_{\nu_\alpha} = \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} \simeq 0.7\xi_\alpha$

Suppresses thermalization of sterile ν's

(Effective ν_a-ν_s mixing reduced by large "matter" term $\propto L$)

Caveat: L can also generate MSW-like resonant flavor conversions among active and sterile neutrinos enhancing their production

A lot of work has been done in this direction, a non-exhaustive list:

Enqvist et al., 1990, 1991,1992; Foot, Thomson & Volkas, 1995;Bell, Volkas & Wong, 1998; Dolgov, Hansen, Pastor & Semikoz, 1999;Di Bari & Foot, 2000; Di Bari, Lipari and lusignoli , 2000;Kirilova & Chizhov, 2000; Di Bari, Foot, Volkas & Wong, 2001; Dolvgov & Villante, 2003; Abazajian, Bell, Fuller, Wong, 2005; Kishimoto, Fuller, Smith, 2006; Chu & Cirelli, 2006; Abazajian & Agrawal, 2008;

In a simplified scenario, ***$L \sim 10^{-4}$ was found to be enough in order to have a significant reduction of the sterile neutrino abundance***
(and hardly associated to any other signature) ***e.g. Chu & Cirelli, 2006***

Not so simple...

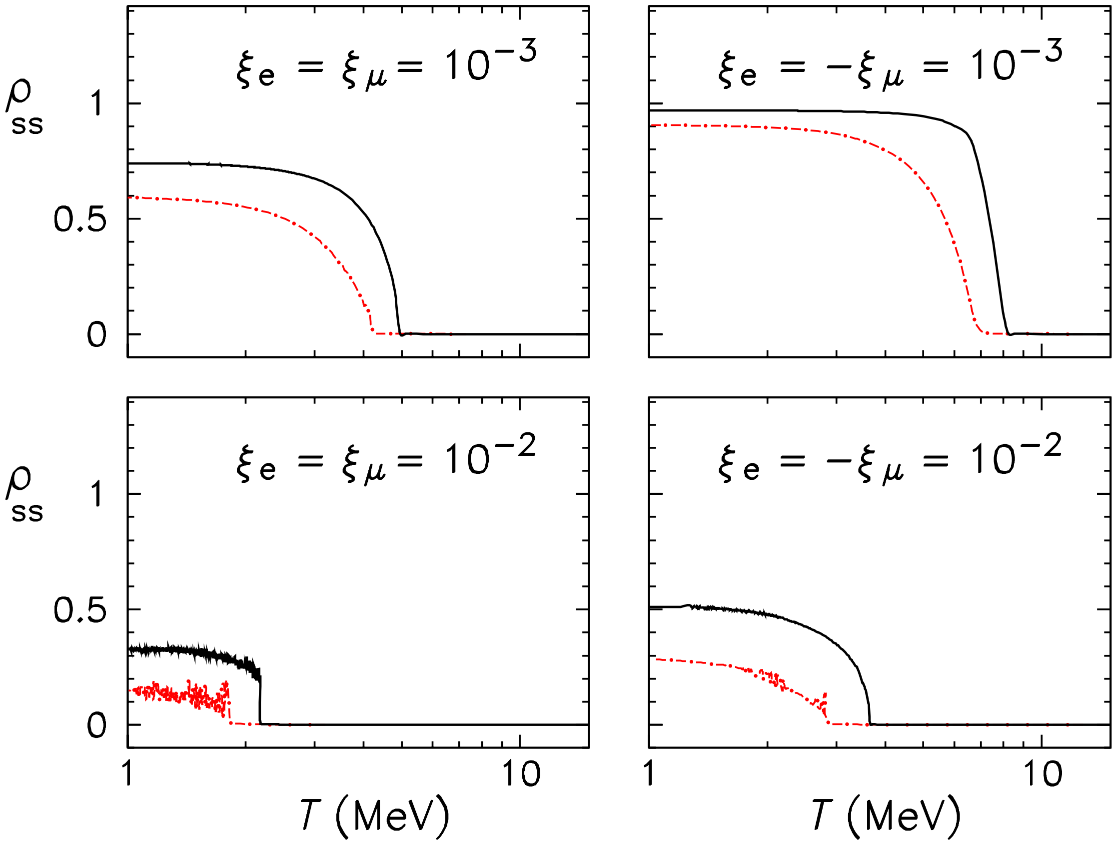
In *1206.1046, 1302.1200* we relaxed
many of the previous approximations, accounting for:

- ✓ 3+1, 2+1
- ✓ dynamic asymmetries
- ✓ realistic account of the ν-ν coupling (non-linearities)
- ✓ Explored several scenarios and effects:
  - different and opposite asymmetries
  - CP violation
- ✓ Finally, relaxing the averaged momentum

(full calculation, but for a specific choice of parameters)

We found that virtually any improvement wrt simplified treatments lead
to a less and less effective inhibition of the population

Results



- ✓ the asymmetry will quickly change sign (populating resonantly both neutrinos and antineutrinos)
- ✓ the asymmetry needed to significantly suppress thermalization is higher (~0.01!)
- ✓ For such high values ➙ populated *after decoupling* ➙ significant spectral distortions ➙ "Large" effects on Y_p, altered Y_p-N_{eff} relation (also for CMB analysis)

Generating large asymmetries theoretically difficult & hard to account for properly: Not an "easy way out"!

Final message

★ Cosmology is becoming a precision tool for neutrino physics:
N_{eff} matches SM predictions with 1 sigma (~10% error),
neutrino mass detection may be near!

★ There is a strong tension/exclusion with lab “anomalies”,
if interpreted as due to eV scale sterile states...

★ ... an eventual confirmation from the Lab would shake up not only particle physics standard model, but also the “standard cosmological model”, so I wish those looking for it all the best!

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Thank you for attention!

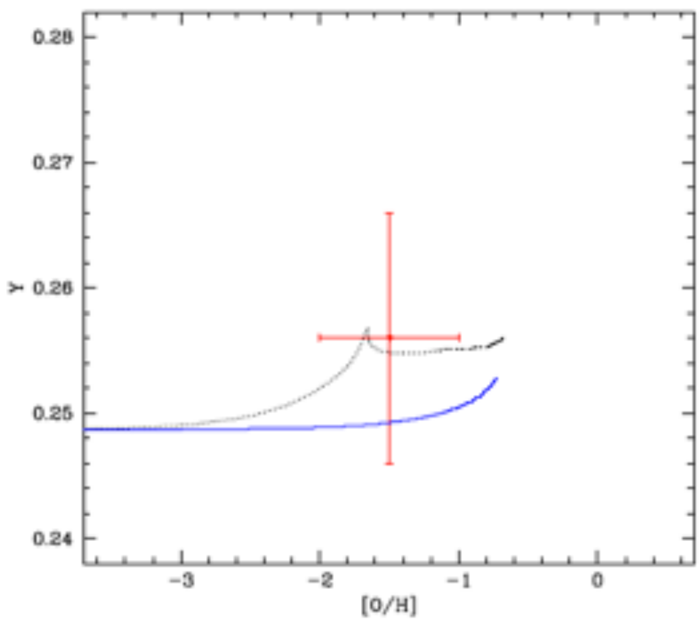
Extra Slides

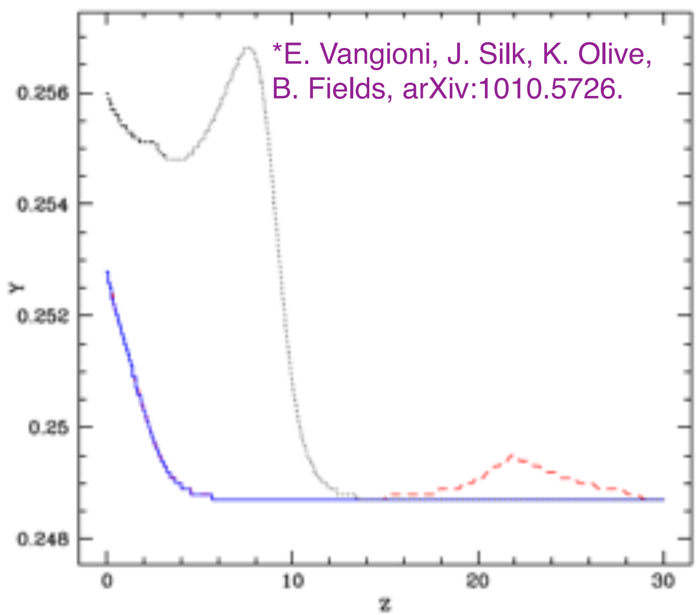
Conclusions from BBN

✓ 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...

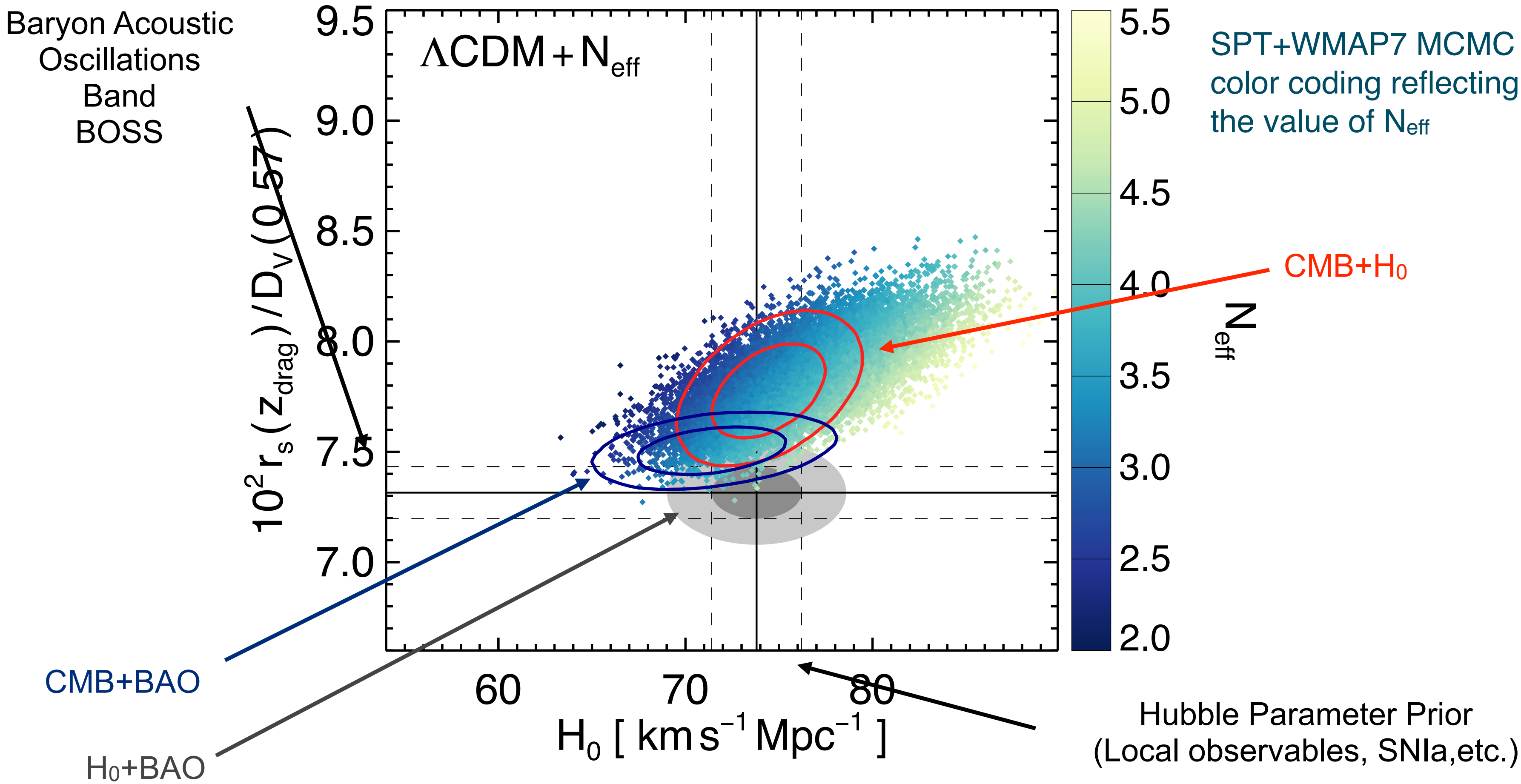




*E. Vangioni, J. Silk, K. Olive, B. Fields, arXiv:1010.5726.

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

Pre-PLANCK



Hou et al., arXiv:1212.6267

In Short: Pre-Planck CMB data alone by itself inconclusive on N_{eff} (but for a firm detection of $N_{eff}>0$)
It's only the combination with small-scale CMB data, H_0 & BAO that gives ~2 σ preference for $N_{eff}>3$

Alternative explanation of role of CMB damping tail

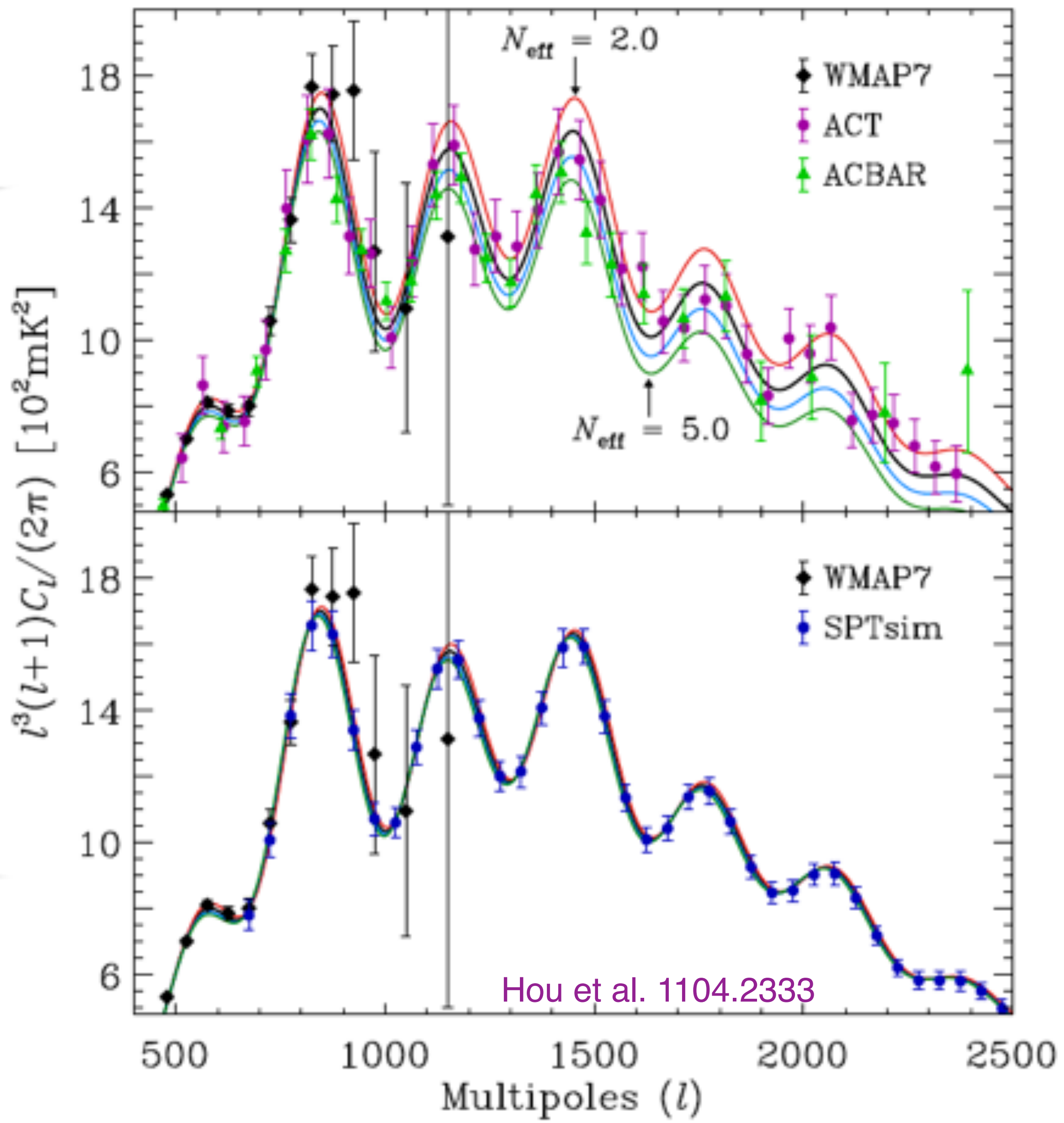
✦ Adjust:
- Matter-radiation equality
- Baryon density
- Sound horizon

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

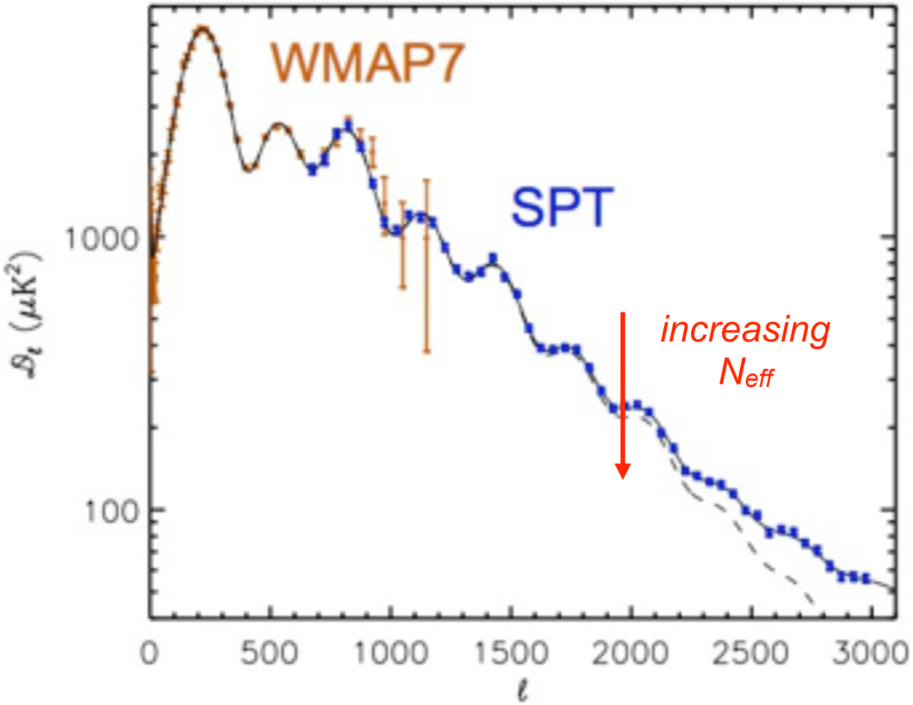
✦ **Higher N_{eff} increases Silk damping at fixed z_{eq}** (For an explanation see Hou et al. 1104.2333)

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

✦ It's this tail that made significance higher

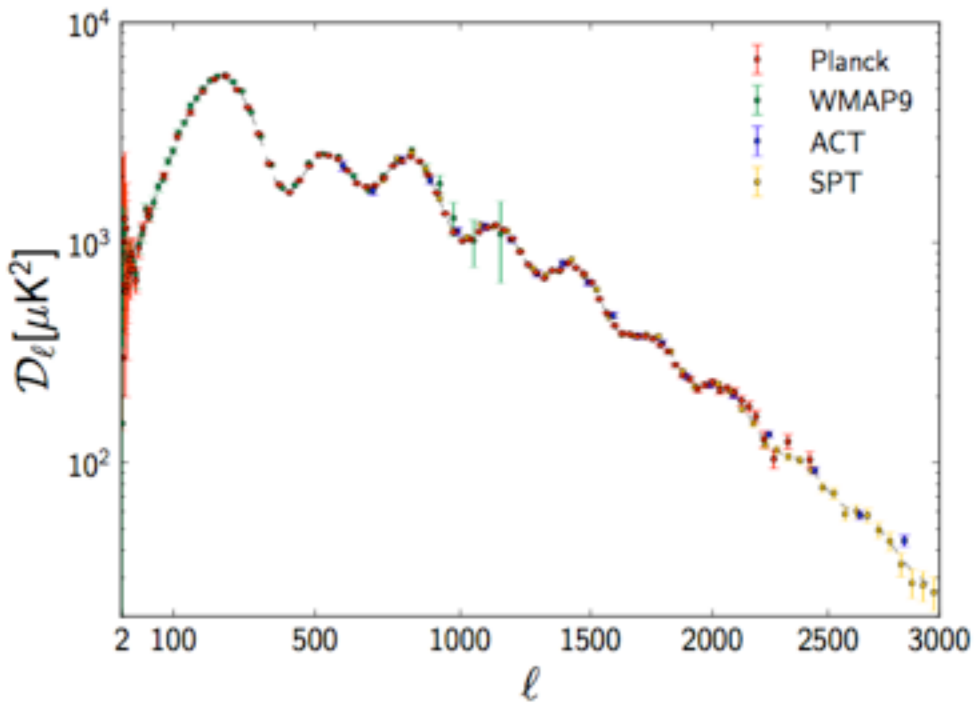


Pre-Planck: challenging calibration of high-l

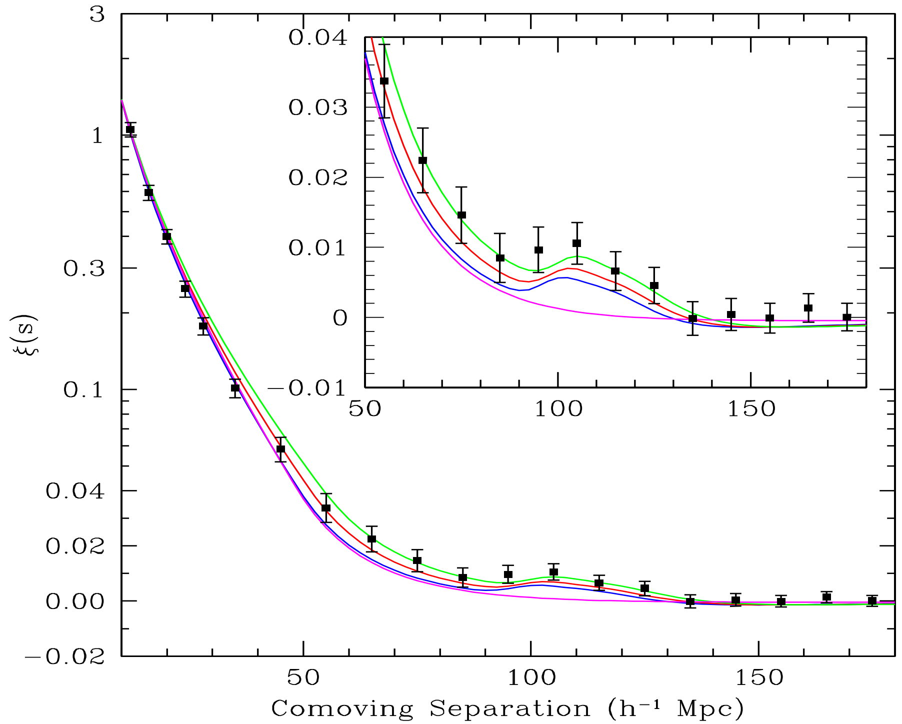


To combine with WMAP, SPT/ACT had to "anchor" at their largest scale (smallest scale for WMAP), with edges of angular range more prone to systematic errors...

Example where gained **resolution in a single instrument** does matter!



what's the BAO



B. A. Bassett and R. Hlozek, arXiv:0910.5224

Fig. 1.1. The Baryon Acoustic Peak (BAP) in the correlation function – the BAP is visible in the clustering of the SDSS LRG galaxy sample, and is sensitive to the matter density (shown are models with $\Omega_m h^2 = 0.12$ **(top)**, 0.13 **(second)** and 0.14 **(third)**, all with $\Omega_b h^2 = 0.024$). The bottom line without a BAP is the correlation function in the pure CDM model, with $\Omega_b = 0$. From Eisenstein *et al.*, 2005 (52).

Preferred scale in clustering of galaxies, reflecting the acoustic peak of the CMB...
hence can be used as "standard ruler" → one can make cosmology with it!