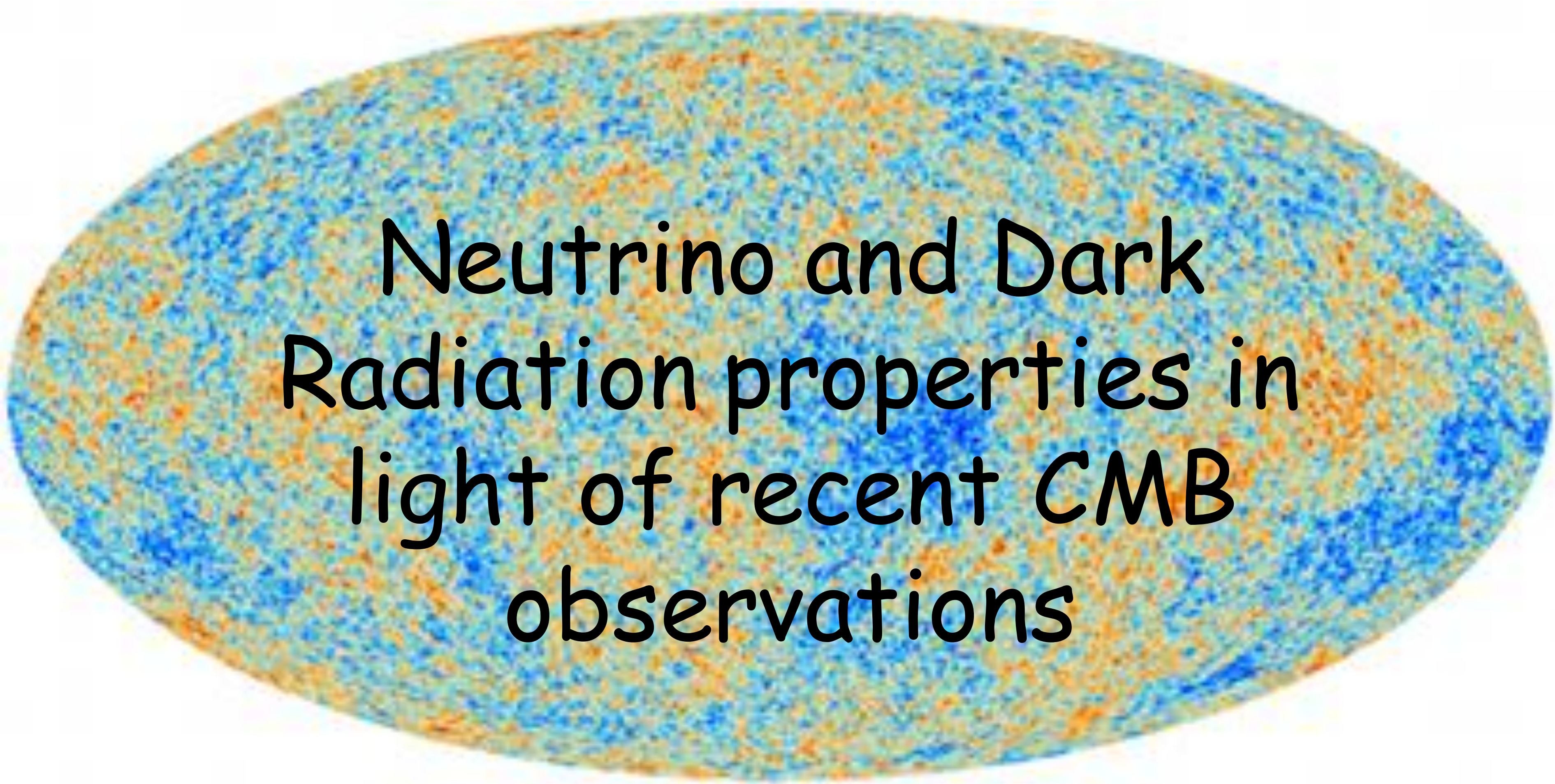
Neutrino and Dark Radiation properties in light of recent CMB observations



MA, Erminia Calabrese and Alessandro Melchiorri, PRD 84 (2011) 1230008
Smith, MA, Cooray, De Bernardis, Melchiorri, Smith, PRD 85 (2012) 123521
MA, Elena Giusarma, Olga Mena and Alessandro Melchiorri, arXiv:1303.0134 (2013)

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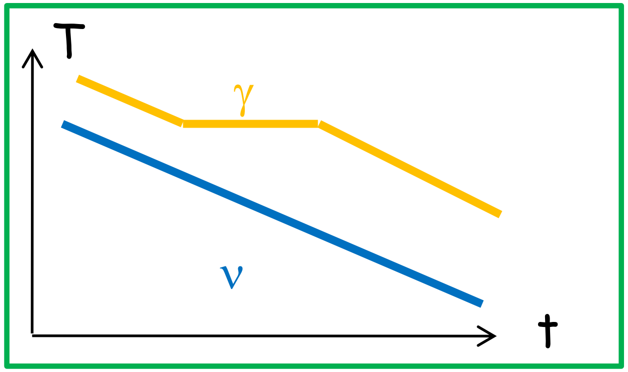
Astroparticle physics seminar @ DESY, Hamburg, 29 April 2013

Outline

- Cosmic Neutrino Background
- Massive Neutrinos and Dark Radiation effects on CMB and mpk
- State of art of the cosmological constraints on neutrino physics
- Adding external data sets and extending the cosmological scenarios
- Discrepancies and degeneracies
- Planck results
- Conclusions

Before Planck!

Cosmic Neutrino Background



Weak interactions in the primordial plasma:

$p + e^- \leftrightarrow n + \nu_e$ where $\Gamma = \langle \sigma_\nu n_\nu c \rangle$

When $\Gamma < H$ we have the neutrino decoupling

$$k_B T_{dec} = 1MeV$$

2me

If the decoupling was istantaneous, we get:

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

$e^+e^- \leftrightarrow \gamma\gamma$

So nowaday $T_\nu = 1.95K$

Cosmological standard value $N_{eff} = 3.046$

(non-istantaneous decoupling)

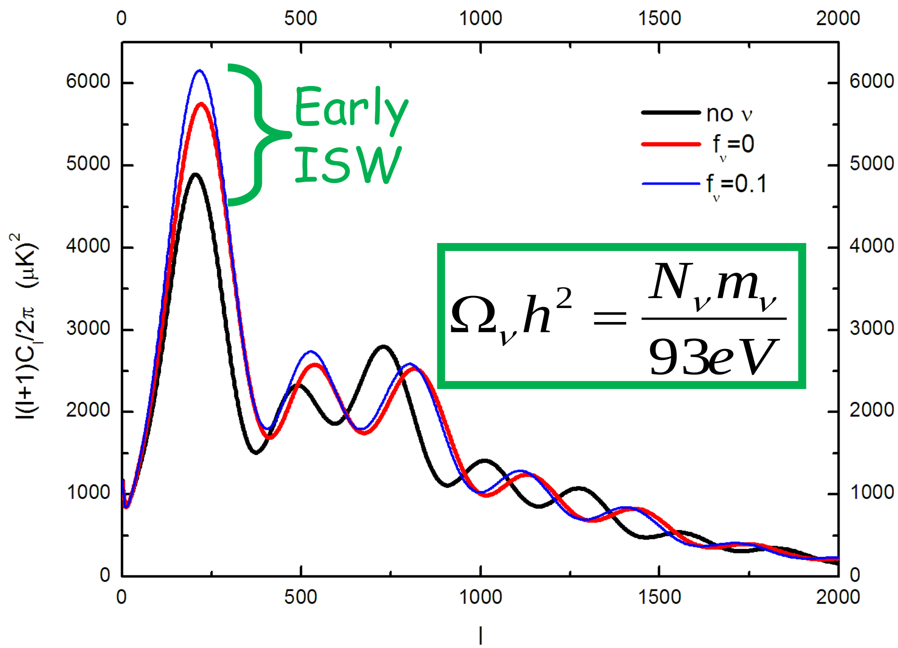
$e^+e^- \rightarrow \gamma\gamma$

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

Cosmological constraints

$$\begin{cases} \Omega_\nu h^2 = \dfrac{\Sigma_\nu m_\nu}{93eV} \\ N_{eff} = 3 + N_{\nu s} \end{cases}$$

Probing the Neutrino mass with cosmological data



WMAP-9 $\sum m_\nu < 1.3eV \ \ (95\%c.l.)$

Assuming 3 degenerate neutrinos

Hinshaw et al (2013)

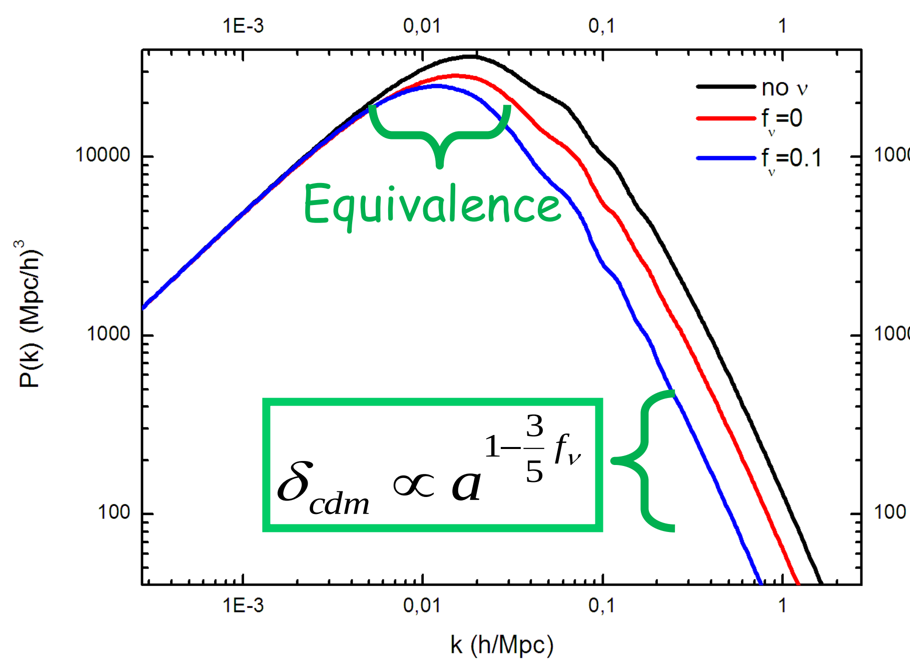
WMAP-7+SDSS+H0

$$\sum m_\nu < 0.44eV \ \ (95\%c.l.)$$

Hannestad et al (2010)

Free-streaming: $\lambda_{FS} = 2\pi\sqrt{\frac{2}{3}}\frac{v_{th}}{H}$

$$v_{th} \approx 150(1+z)\left(\frac{1eV}{m_\nu}\right)km/s$$

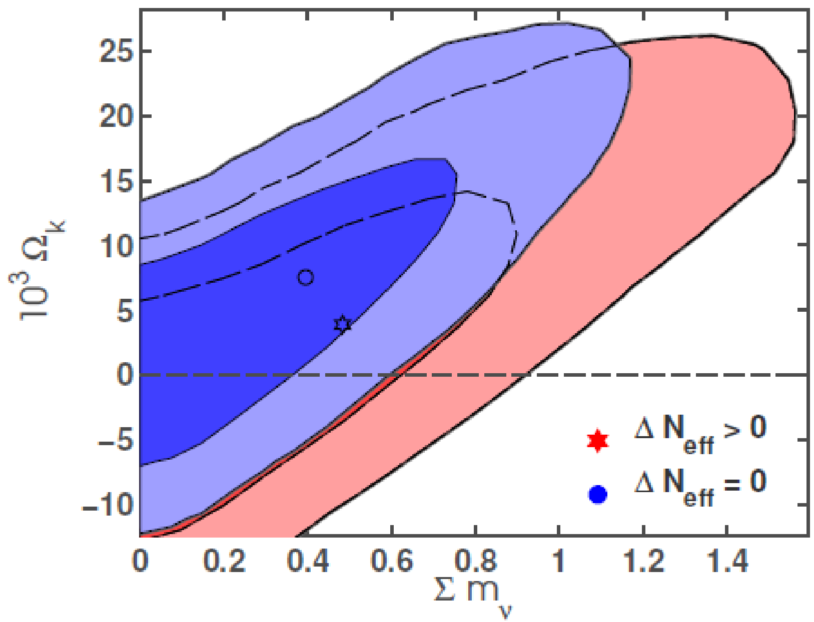


Model dependence: Curvature

WMAP-7 + ACT + SPT + BAO + H_0

Σm_ν	<0.45 eV (95%cl)	<0.95 eV (95%cl)
Ω_k 10^3	0	7.52±7.74

The degeneracy considerably increases the uncertainty in the sum of neutrino masses.



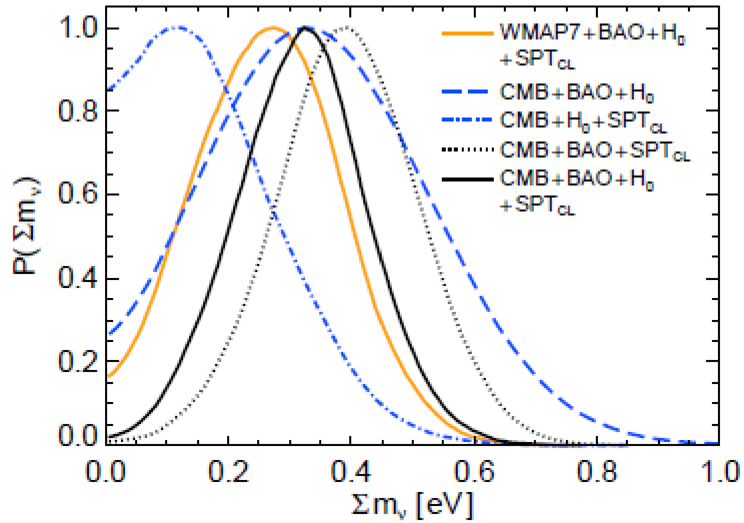
Smith, MA et al., PRD (2012)

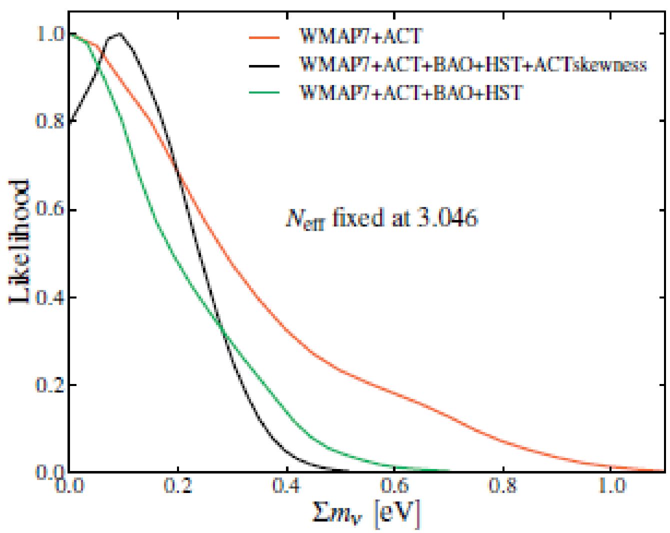
Pre-Planck state of art for Neutrino mass

SPT+WMAP7+H0+BAO+SPTcl:

$$\sum m_\nu = (0.32 \pm 0.11) eV$$

Hou et al. 2012





ACT+WMAP7+H0+BAO:

$$\sum m_\nu < 0.39 eV \;\; (95\% c.l.)$$

Sievers et al. 2013

The effective number of relativistic degrees of freedom

The total amount of relativistic degrees of freedom in the Universe is therefore parametrized in the following way:

$$\Omega_R h^2 = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\Omega_\gamma h^2$$

A value of $N_{eff} > 3.046$ is equivalent to the presence of a new «dark radiation» component :

$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_M}{a^3} + \frac{\Omega_\gamma}{a^4} + \frac{\Omega_\nu}{a^4} + \Omega_\Lambda + \frac{\Omega_{DR}}{a^4}$$

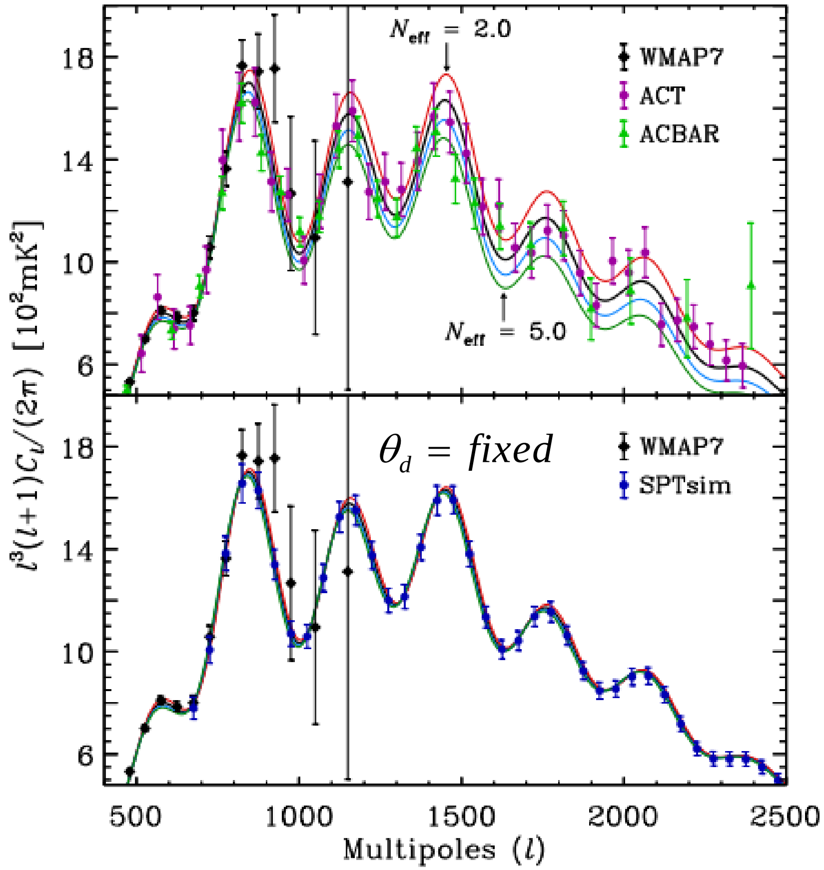
Probing the Neutrino number with CMB data

Changing the Neutrino effective number essentially changes the expansion rate H at recombination.
So it changes the size of the sound horizon at recombination:

$$r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s}{a^2}\frac{da}{H}$$

and the damping at recombination:

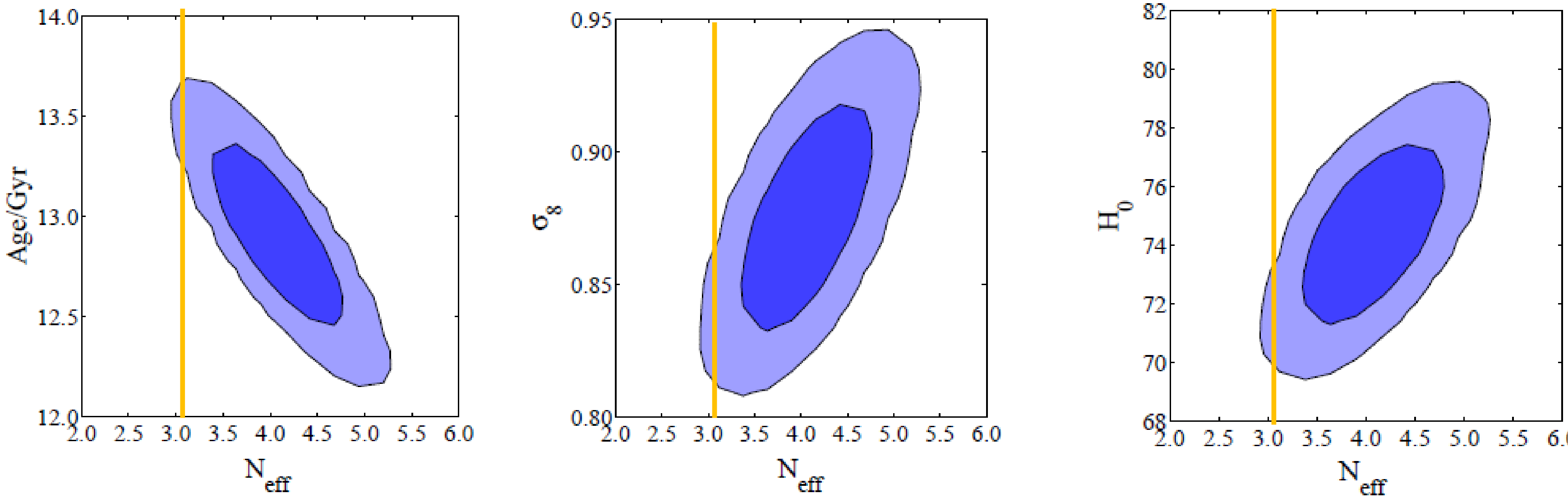
$$r_d^{\,2} = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H}\left[\frac{R^2 + \frac{6}{15}(1+R)}{6(1+R^2)}\right]$$



Hou et al (2011)

Moreover a larger neutrino number increases the early ISW as the neutrino mass .

Cosmological parameters degeneracies



Extra Dark Radiation
12.8 Gyrs

Clusters and Ly-alpha surveys
move to N_{eff} = 3

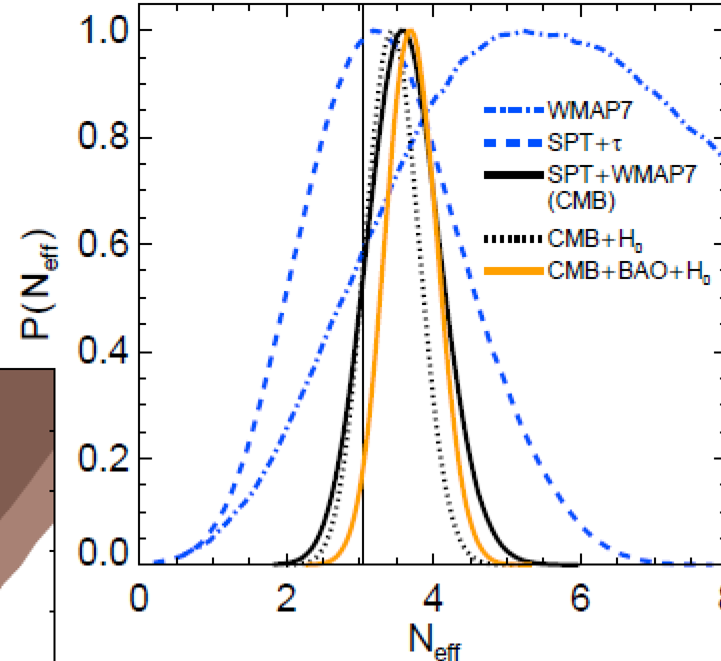
MA, Calabrese, Melchiorri, PRD (2011)

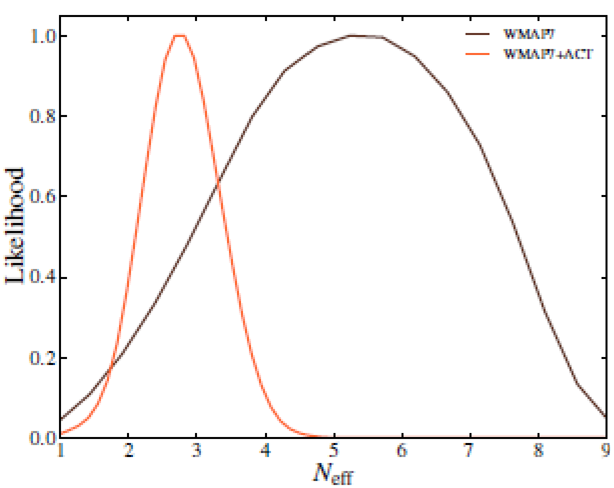
Pre-Planck state of art for Dark Radiation

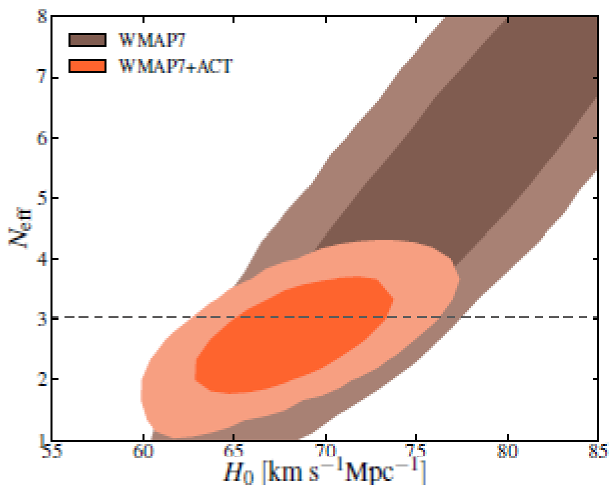
WMAP-7+SPT $N_{eff} = 3.62 \pm 0.48$

WMAP-7+SPT+BAO+H0 $N_{eff} = 3.71 \pm 0.35$

Hou et al. (2013)





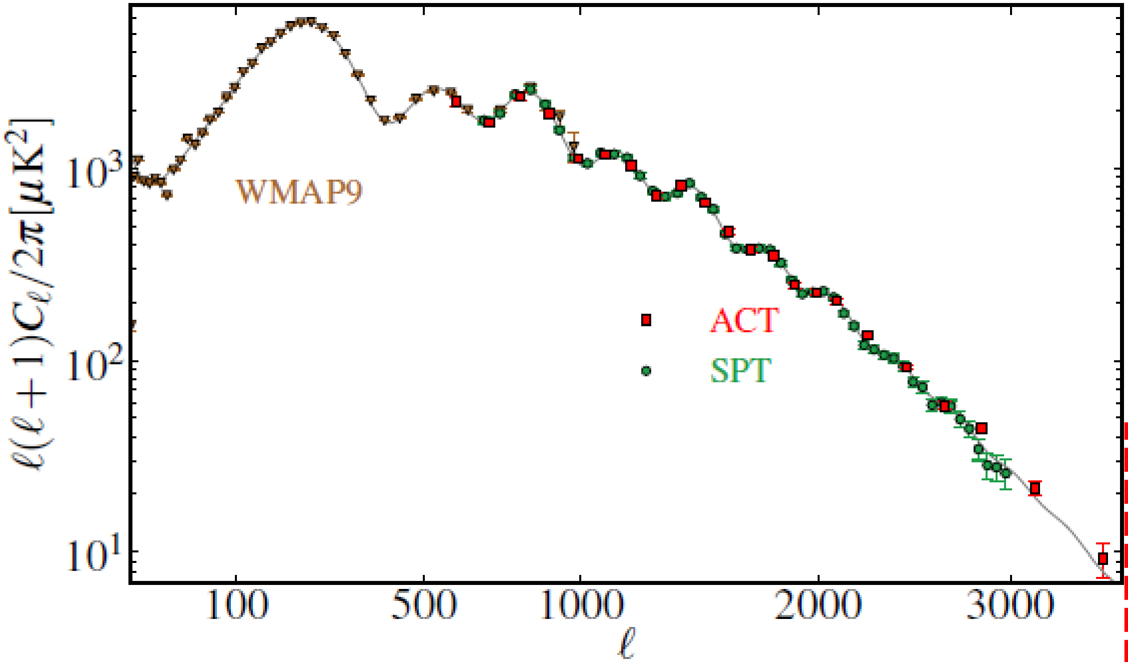


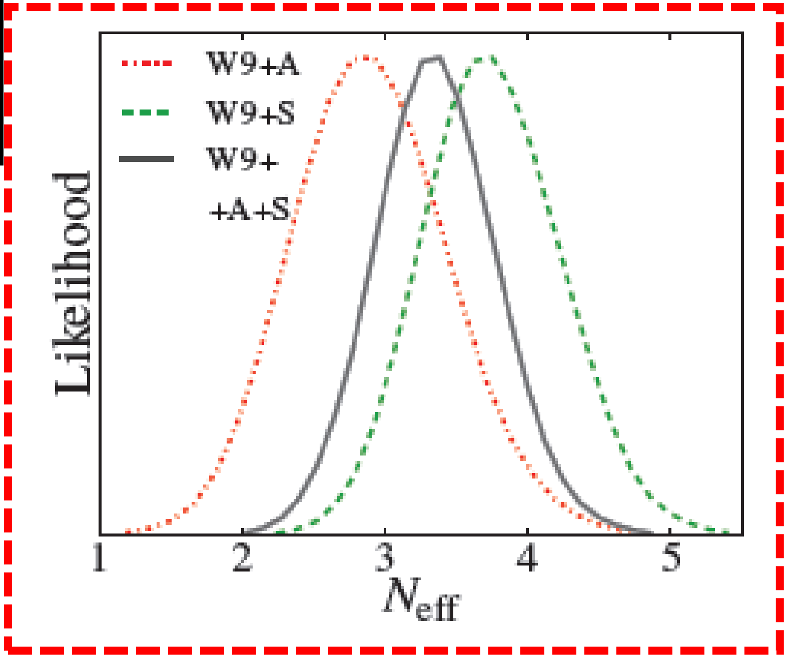
WMAP-7+ACT $N_{eff} = 2.78 \pm 0.55$

WMAP-7+ACT+BAO+H0 $N_{eff} = 3.51 \pm 0.39$

Sievers et al. (2013)

Pre-Planck state of art for Dark Radiation





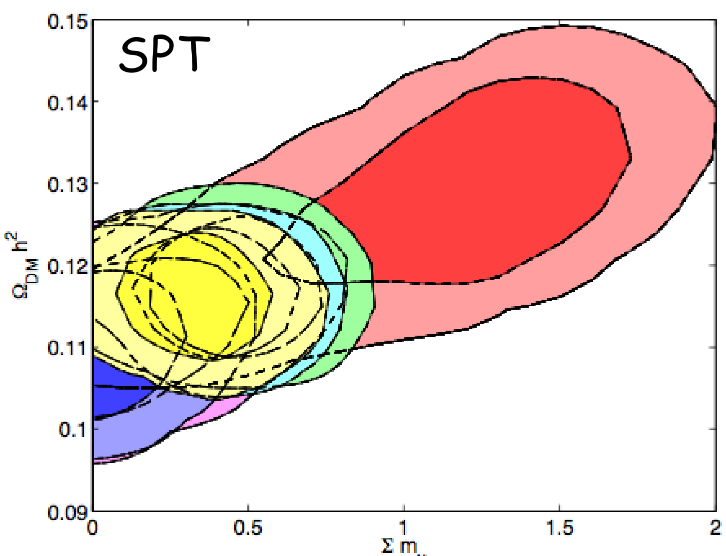
WMAP-9+SPT+ACT $N_{eff} = 3.37 \pm 0.42$

Calabrese et al. (2013)

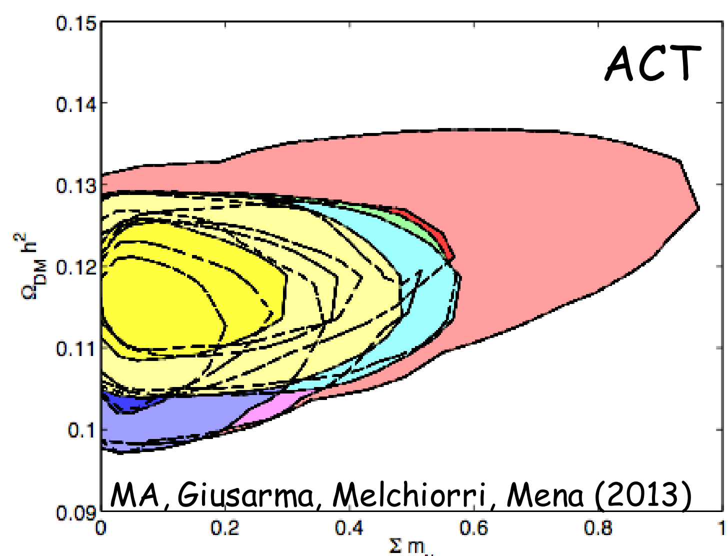
ΛCDM + 3 massive neutrinos

	W9+SPT	W9+SPT +HST	W9+SPT +BAO	W9+SPT +BAO +HST	W9+SPT +SNLS	W9+SPT +SNLS +BAO
Σm_ν (eV)	1.14±0.41	<0.50	0.46±0.18	0.33±0.17	<0.80	0.40±0.18

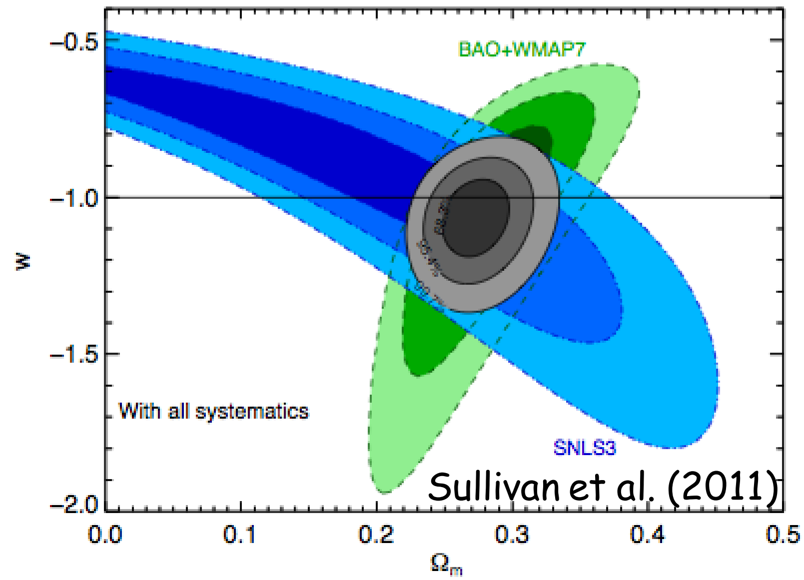
	W9+ACT	W9+ACT +HST	W9+ACT +BAO	W9+ACT +BAO +HST	W9+ACT +SNLS	W9+ACT +SNLS +BAO
Σm_ν (eV)	<0.89	<0.34	<0.53	<0.44	<0.49	<0.54

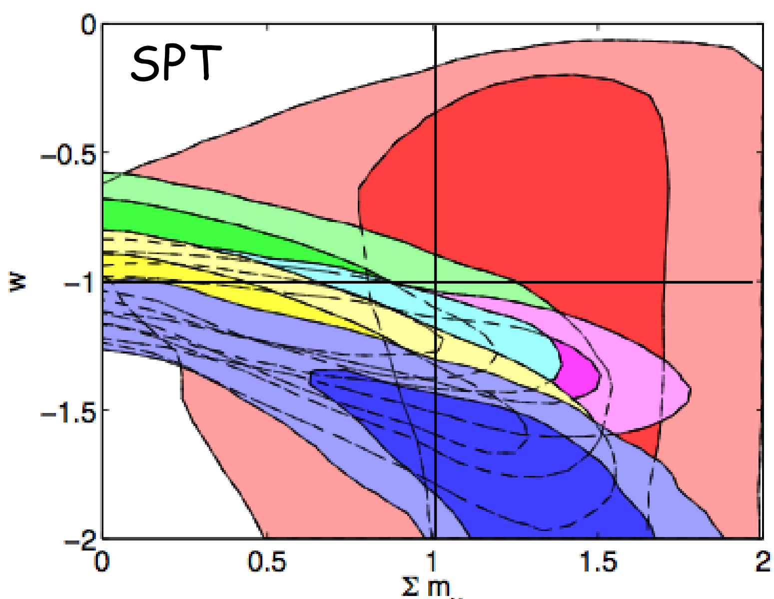


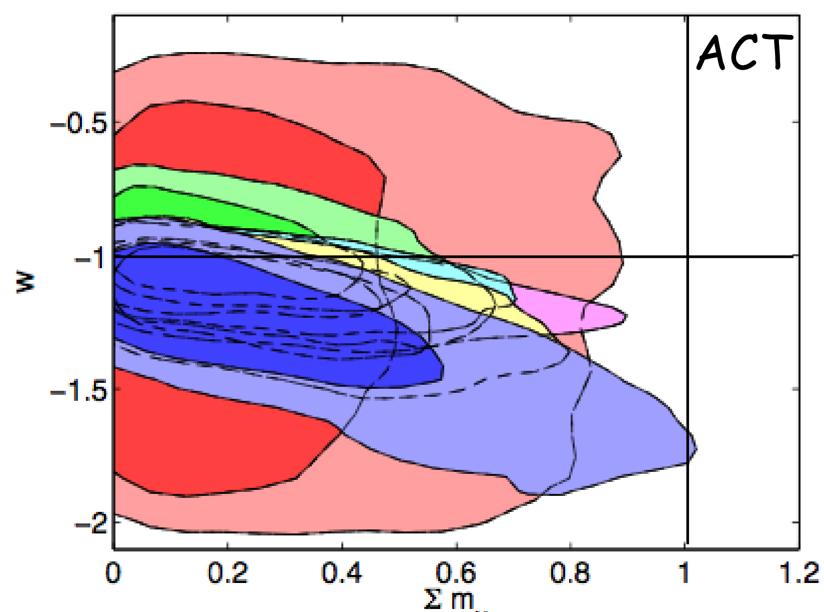
- CMB
- CMB+HST
- CMB+BAO
- CMB+BAO+HST
- CMB+SNLS
- CMB+SNLS+BAO



ΛCDM + 3 massive neutrinos + w



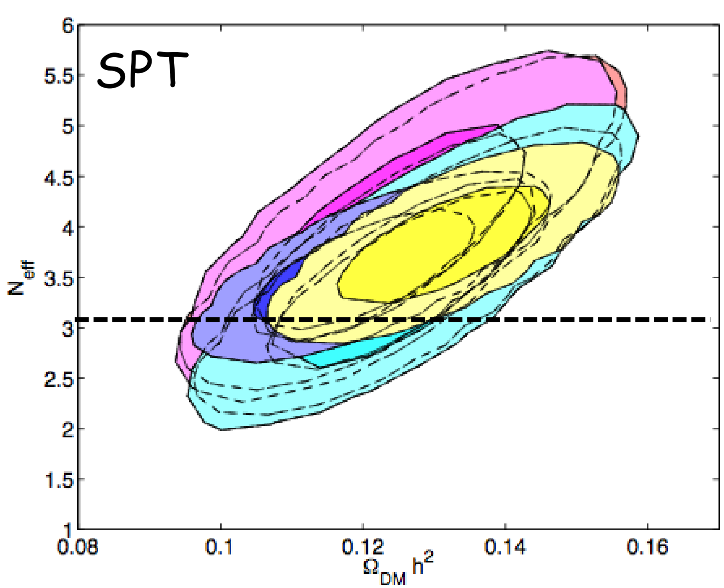


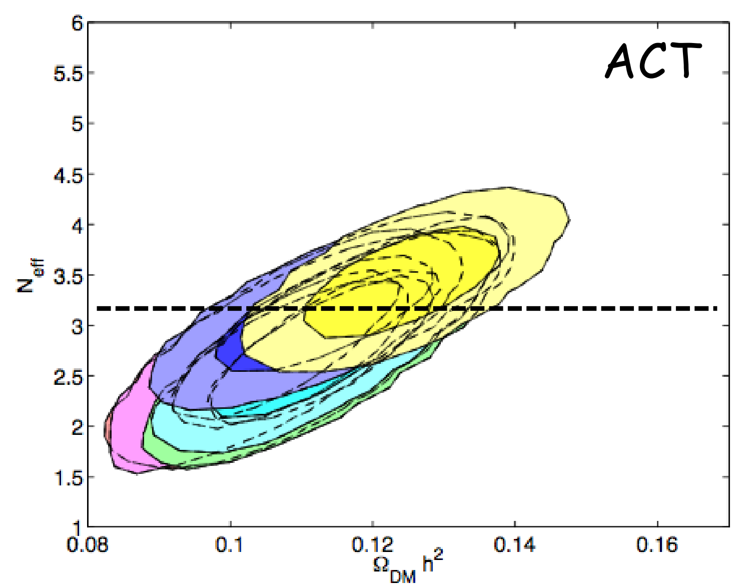


$\Lambda CDM + N_{eff}$

	W9+SPT	W9+SPT +HST	W9+SPT +BAO	W9+SPT +BAO +HST	W9+SPT +SNLS	W9+SPT +SNLS +BAO
N_{eff}	3.93±0.68	3.59±0.39	3.50±0.59	3.83±0.41	4.93±0.69	3.55±0.63

	W9+ACT	W9+ACT +HST	W9+ACT +BAO	W9+ACT +BAO +HST	W9+ACT +SNLS	W9+ACT +SNLS +BAO
N_{eff}	2.74±0.47	3.12±0.38	2.77±0.49	3.43±0.36	2.77±0.49	2.83±0.47

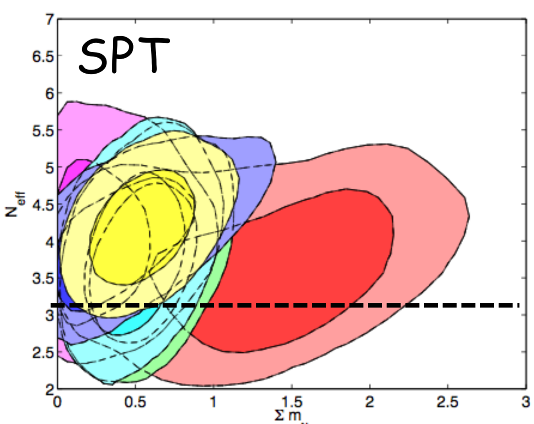


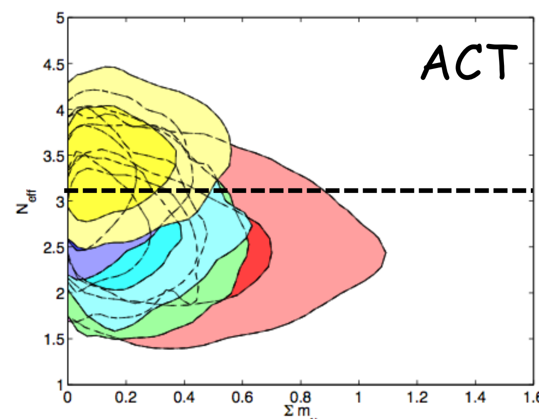


ΛCDM + massive N_{eff}

	W9+SPT	W9+SPT +HST	W9+SPT +BAO	W9+SPT +BAO +HST	W9+SPT +SNLS	W9+SPT +SNLS +BAO
Σm_ν (eV)	1.35±0.55	0.48±0.33	0.56±0.22	0.56±0.23	<0.91	0.50±0.21
N_{eff}	3.66±0.61	4.08±0.54	3.76±0.67	4.21±0.46	4.04±0.68	3.87±0.68

	W9+ACT	W9+ACT +HST	W9+ACT +BAO	W9+ACT +BAO +HST	W9+ACT +SNLS	W9+ACT +SNLS +BAO
Σm_ν (eV)	<0.89	<0.34	<0.53	<0.44	<0.49	<0.54
N_{eff}	2.64±0.51	3.20±0.38	2.63±0.48	3.44±0.37	2.75±0.44	2.78±0.46





What Dark Radiation is made of? Sterile Neutrinos?

Exotic models:

- gravitational waves
- axions
- decay of non-relativistic matter
- Early Dark Energy

Massless neutrinos equations of perturbations:

$$\dot{\delta}_\nu = \frac{\dot{a}}{a}\left(1 - 3c_{eff}^2\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - k\left(q_\nu + \frac{2}{3k}\dot{h}\right),$$

$$\dot{q}_\nu = kc_{eff}^2\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu - \frac{2}{3}k\pi_\nu,$$

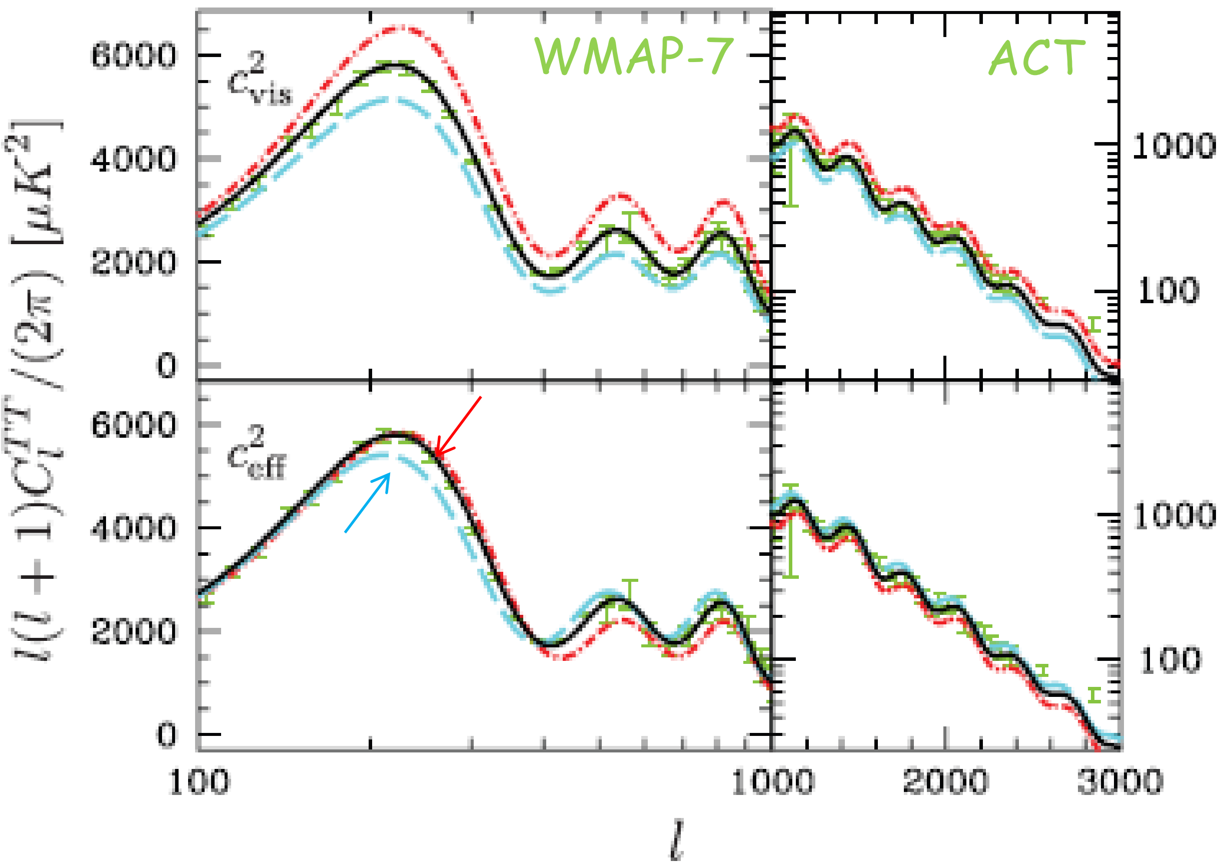
$$\dot{\pi}_\nu = 3c_{vis}^2\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right) - \frac{3}{5}kF_{\nu,3},$$

$$\frac{2l+1}{k}\dot{F}_{\nu,l} - lF_{\nu,l-1} = -(l+1)F_{\nu,l+1}, \quad l \geq 3.$$

c_{eff}^2 The effective sound speed

c_{vis}^2 The viscosity parameter

Effective sound speed and viscosity speed



$c^2_{eff} = c^2_{vis} = 1/3$

$c^2_{eff} = 1/3,\ c^2_{vis} = 0$

$c^2_{eff} = 1/3,\ c^2_{vis} = 1$

$c^2_{eff} = 0.2,\ c^2_{vis} = 1/3$

$c^2_{eff} = 0.7,\ c^2_{vis} = 1/3$

If Dark Radiation is made of free-streaming particles,

$$c^2_{eff} = c^2_{vis} = 1/3$$

Hu (1998), Smith et al. (2012)

ΛCDM + ΔN_{eff} + c^2_{eff} + c^2_{vis}

+ 3 massive (0.3 eV) neutrinos with standard perturbations' parameters

W9+SPT $\Delta N_{eff} = 1.31 \pm 0.60$

W9+SPT+HST $\Delta N_{eff} = 0.92 \pm 0.39$

W9+ACT $\Delta N_{eff} = 0.38 \pm 0.32$

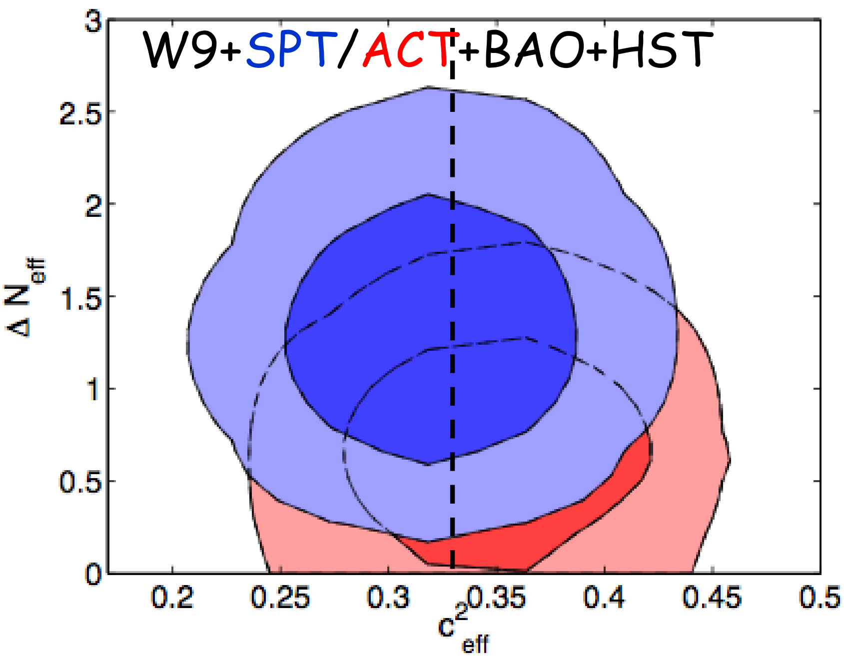
W9+ACT+HST $\Delta N_{eff} = 0.62 \pm 0.41$

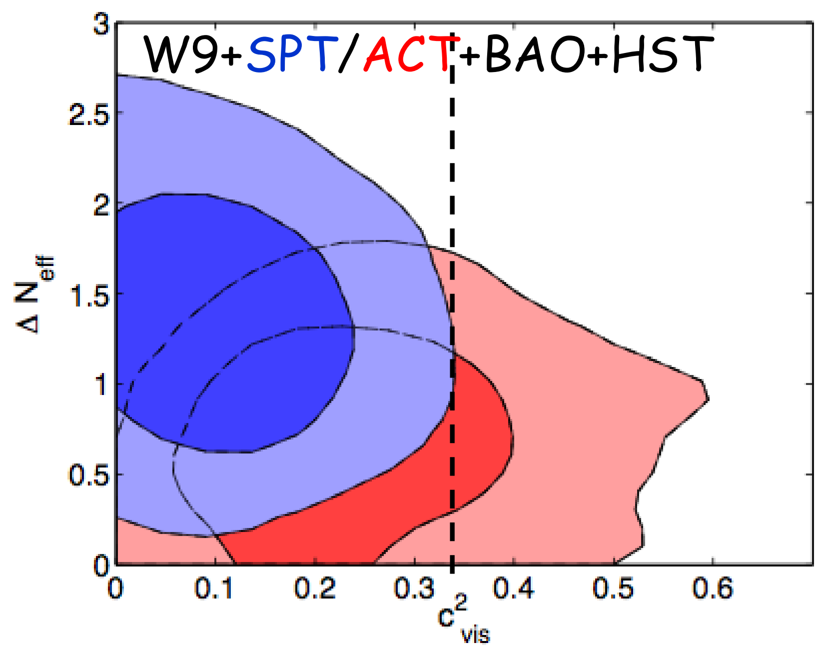
W9+SPT+BAO+HST

$c^2_{vis} = 0.15 \pm 0.07$

W9+ACT+BAO+HST

$c^2_{vis} = 0.25 \pm 0.13$





$\Lambda CDM + \Sigma m_\nu + \Delta N_{eff} + c^2_{eff} + c^2_{vis}$

W9+SPT+BAO+HST

$$\Delta N_{eff} = 1.35 \pm 0.50$$

W9+ACT+BAO+HST

$$\Delta N_{eff} = 0.74 \pm 0.40$$

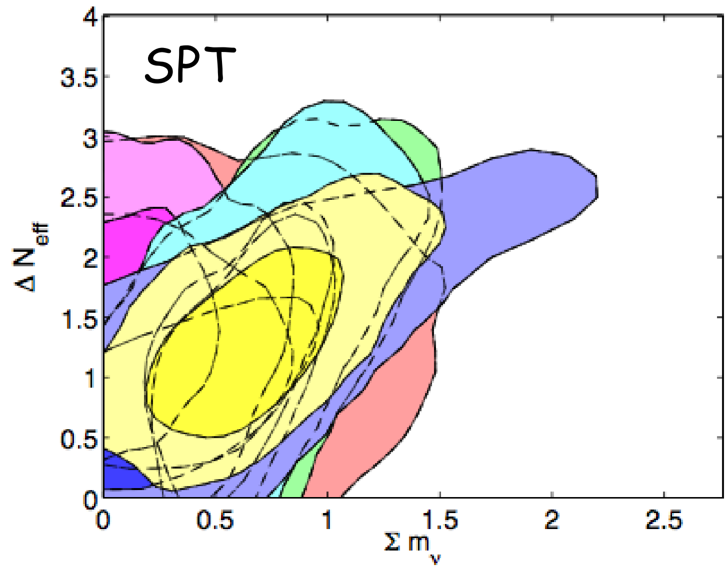
W9+SPT+BAO+HST

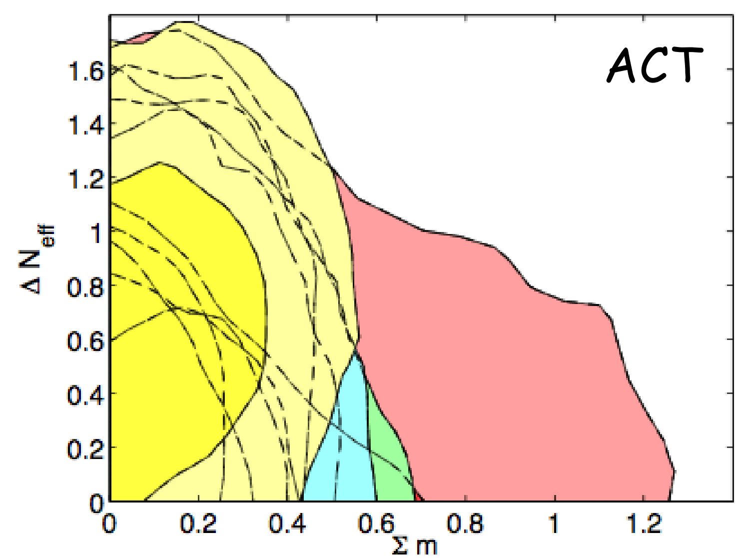
$$c^2_{vis} = 0.13 \pm 0.07$$

W9+ACT+BAO+HST

$$c^2_{vis} = 0.25 \pm 0.11$$

The evidence for neutrino mass still remains if SPT is combined with BAO

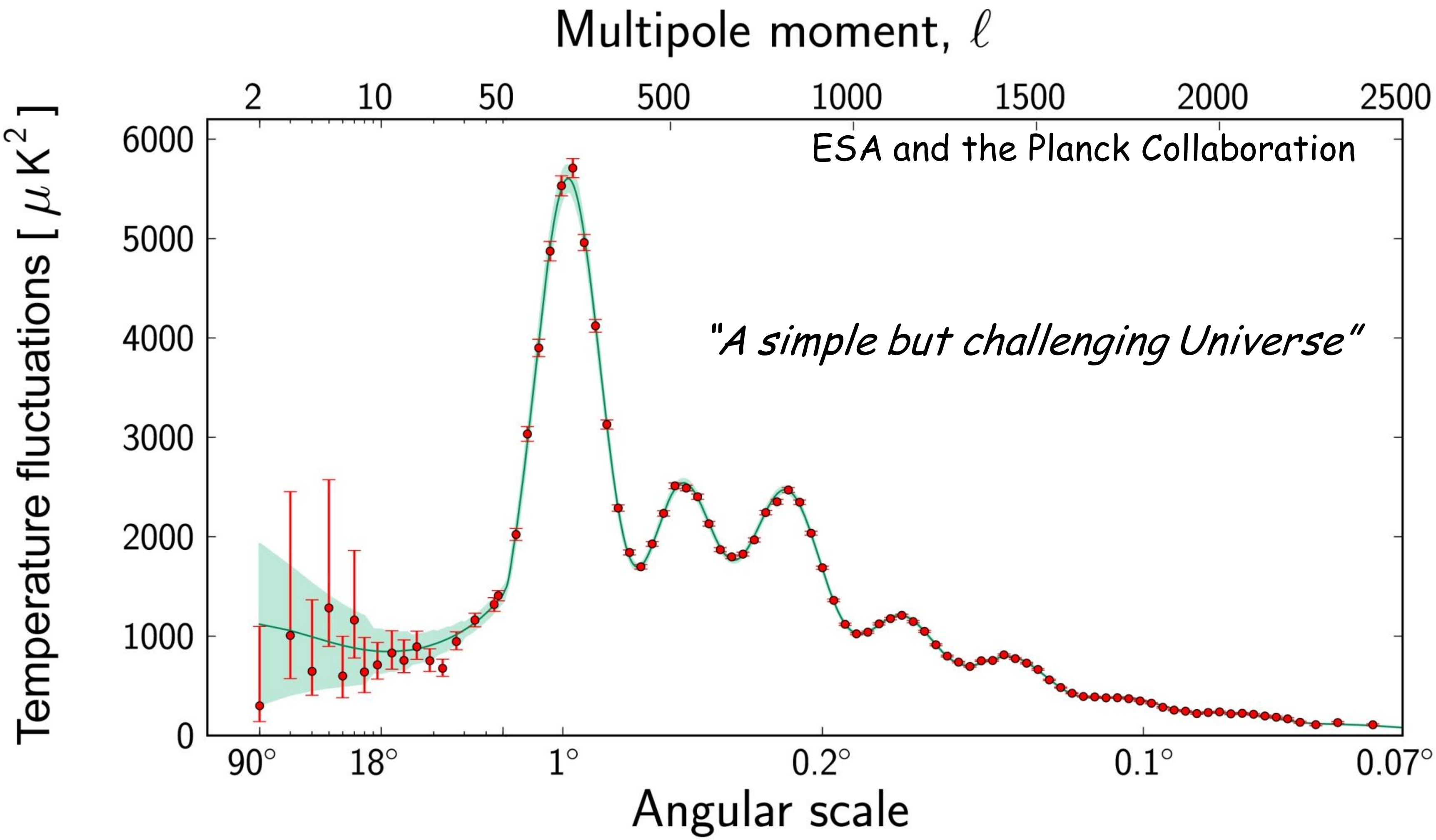




To sum up …

	W9+SPT	W9+SPT+ external data	W9+ACT	W9+ACT+ external data
Standard Model Neutrino Mass	Detection	Detection (BAO, BAO+HST, BAO+SN)	No detection	No detection
Extended Model Neutrino Mass	No detection	No detection w:detect. with SN	No detection	No detection
Standard Model Dark Radiation	Evidence	Evidence	No evidence	Evidence only with BAO+HST
Extended Model Dark Radiation	Evidence Non-standard c^2_{vis}	Evidence Non-standard c^2_{vis}	No evidence	Evidence only with BAO+HST

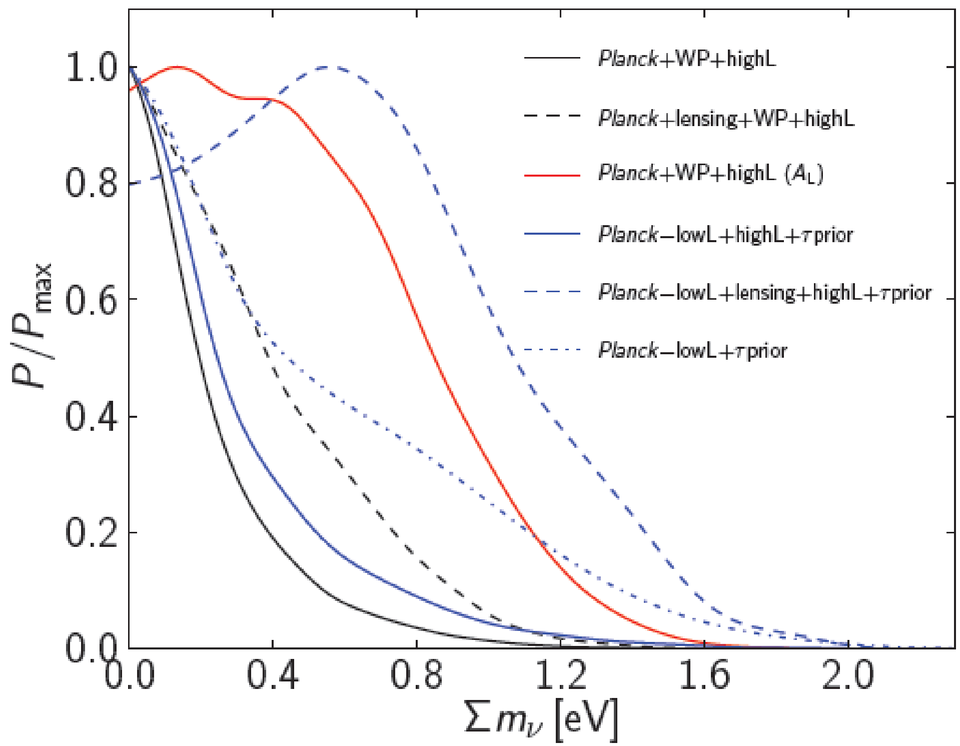
Planck



$$H_0 = (67.3 \pm 1.2)\ km/s/Mpc\ (68\% c.l.)$$

$$H_0 = 73.8 \pm 2.4\ km/s/Mpc$$ HST, Riess et al (2011)

Planck and Neutrino mass



Planck+WMAP9polarization +highl(SPT+ACT)

ΛCDM + Σm_ν + A_{lens}

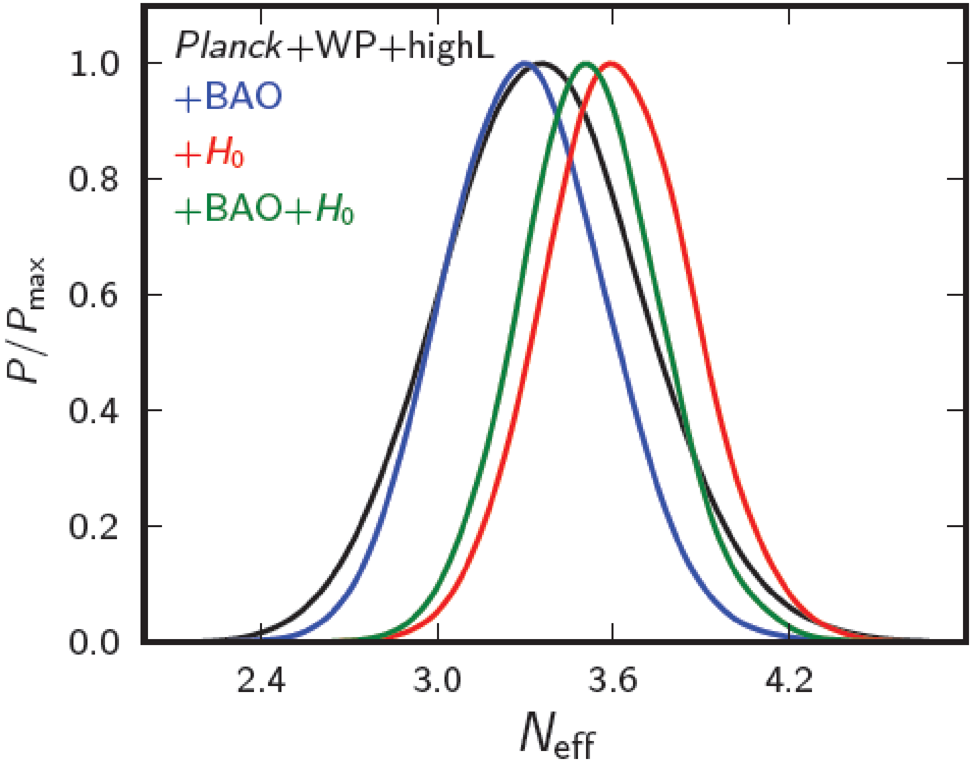
$$\sum m_\nu < 0.66 eV \ \ (95\% c.l.)$$

ΛCDM + Σm_ν (A_{lens} = 1)

$$\sum m_\nu < 1.08 eV \ \ (95\% c.l.)$$

ESA and the Planck Collaboration

Planck and Dark Radiation



Planck+WMAP9polarization
+highl(SPT+ACT)

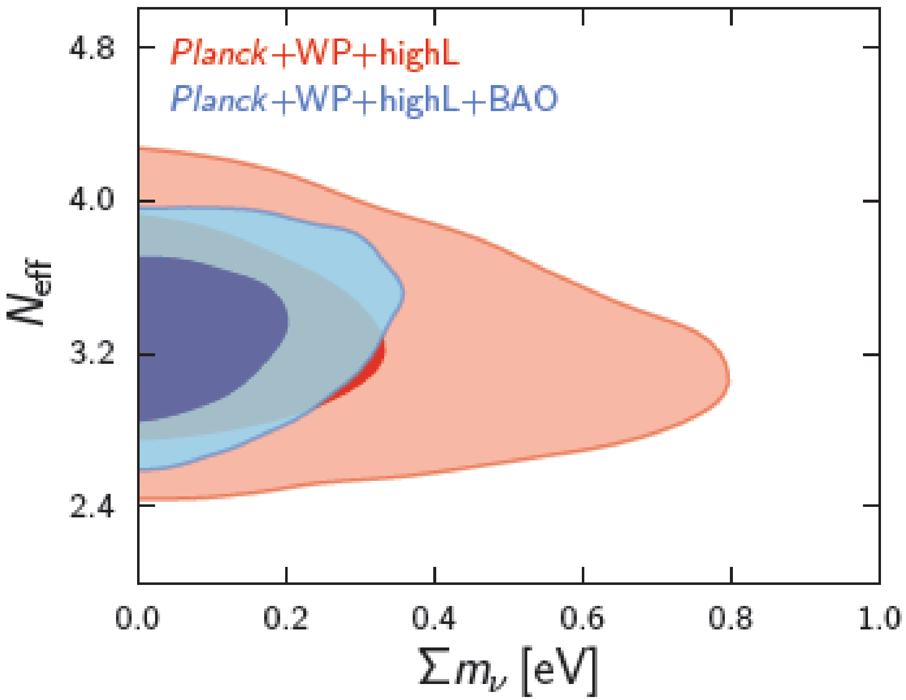
$$N_{eff} = 3.36^{+0.68}_{-0.64} \ (95\% c.l.)$$

Planck+WMAP9polarization
+highl(SPT+ACT)+HST

$$N_{eff} = 3.62^{+0.50}_{-0.48} \ (95\% c.l.)$$

ESA and the Planck Collaboration

Planck and Sterile Neutrinos



Planck+WMAP9polarization
+highl(SPT+ACT)

$$\begin{cases} N_{eff} = 3.29^{+0.67}_{-0.64} \ (95\% c.l.) \\ \sum m_\nu < 0.60 eV \ (95\% c.l.) \end{cases}$$

Planck+WMAP9polarization
+highl(SPT+ACT)+ BAO

$$\begin{cases} N_{eff} = 3.32^{+0.54}_{-0.52} \ (95\% c.l.) \\ \sum m_\nu < 0.28 eV \ (95\% c.l.) \end{cases}$$

ESA and the Planck Collaboration

Conclusions

• Detection of a non zero neutrino mass by SPT, tight upper bound on the absolute neutrino mass scale with Planck combined with high-l;

• Evidence for extra dark radiation with SPT, standard N_{eff} with ACT, evidence for extra dark radiation with Planck only if combined with HST.

• The extra dark radiation seen by SPT can be related to exotic models ($c_{vis}^2 < 0.33$ @95%cl)

• Massive sterile neutrinos of Short BaseLine Oscillation experiments are not excluded, but a partial thermalisation must be invoked.