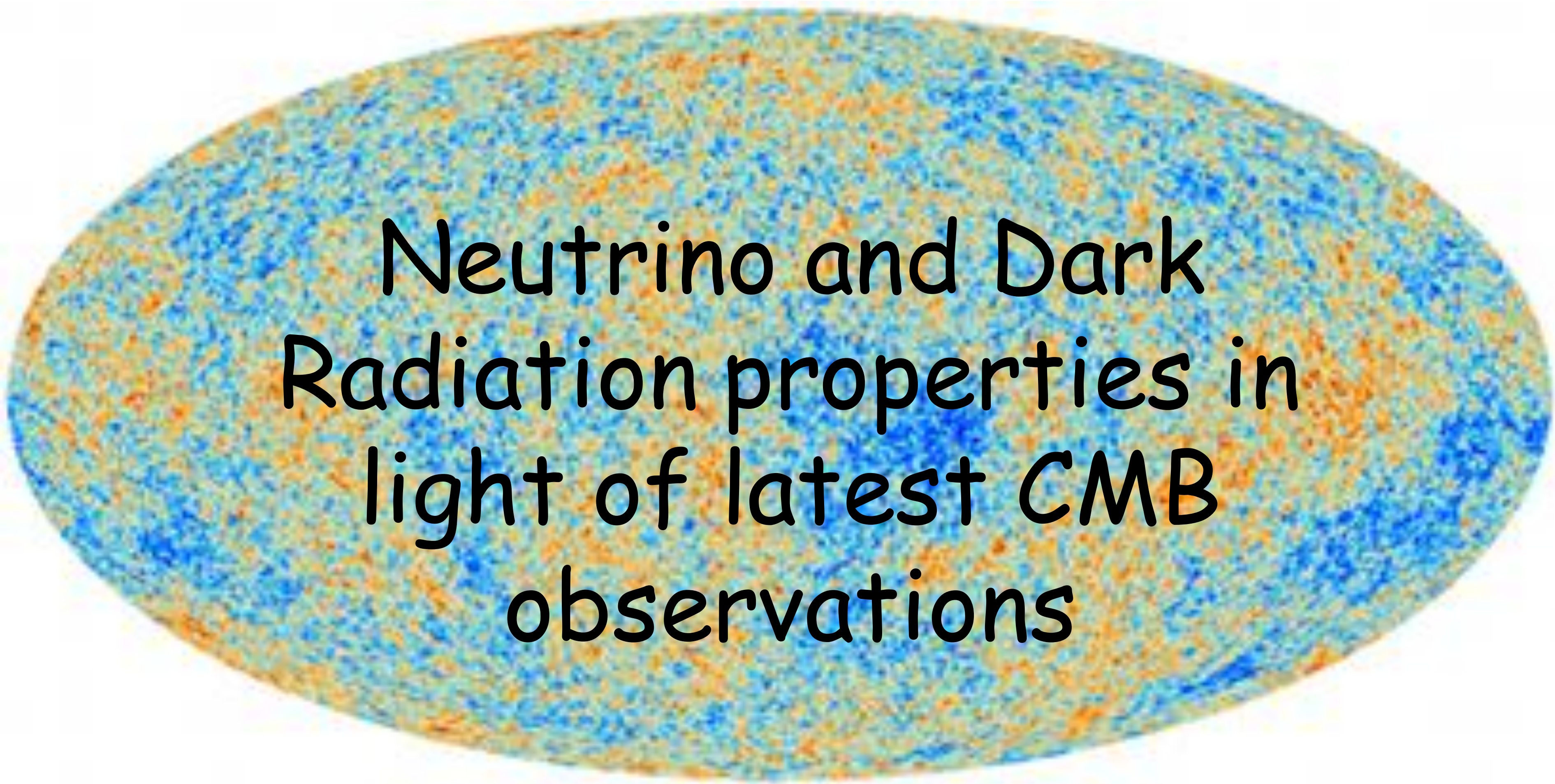


Neutrino and Dark Radiation properties in light of latest CMB observations

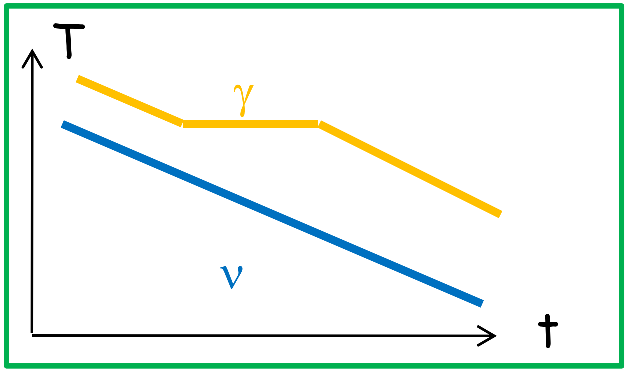
Maria Archidiacono, Elena Giusarma, Olga Mena and Alessandro Melchiorri
arXiv:1303.0134

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
- Conclusions

Before Planck!

Cosmic Neutrino Background



Weak interactions in the primordial plasma:

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

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

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

2me

If the decoupling was istantaneous, we get:

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

So nowaday $T_\nu = 1.95K$

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

Cosmological standard value $N_{eff} = 3.046$

(non-istantaneous decoupling)

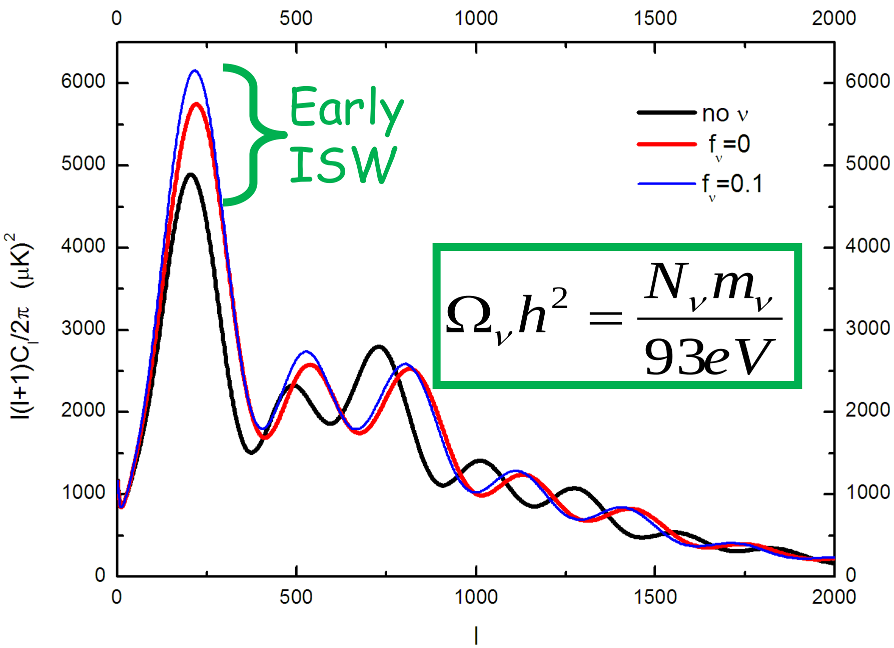
$$e^+ e^- \rightarrow \gamma\gamma$$

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

Cosmological constraints

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

Probing the Neutrino mass with cosmological data



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

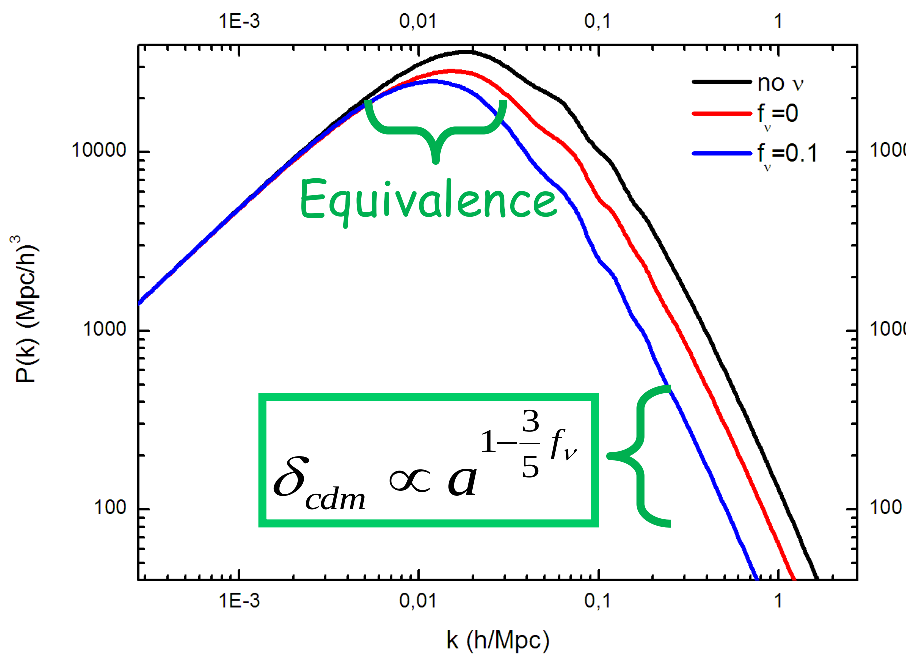
Assuming 3 degenerate neutrinos

Hinshaw et al (2013)

WMAP-7+SDSS+H0

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

Hannestad et al (2010)



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

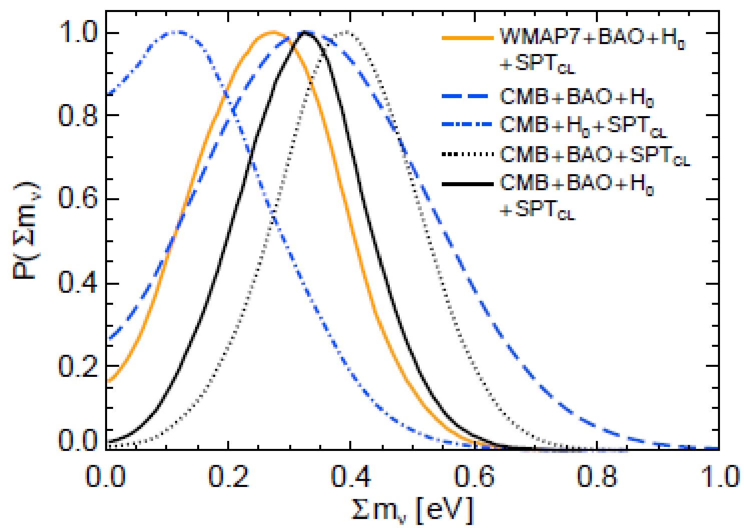
$$v_{th} \approx 150(1+z)\left(\frac{1eV}{m_\nu}\right)km/s$$

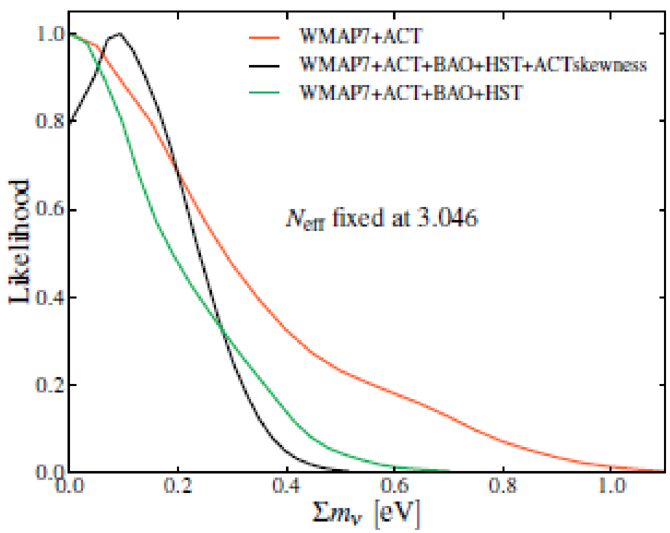
Pre-Planck state of art for Neutrino mass

SPT+WMAP7+H0+BAO+SPTcl:

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

Hou et al. 2012





ACT+WMAP7+H0+BAO:

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

Sievers et al. 2013

The number of effective 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 :

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

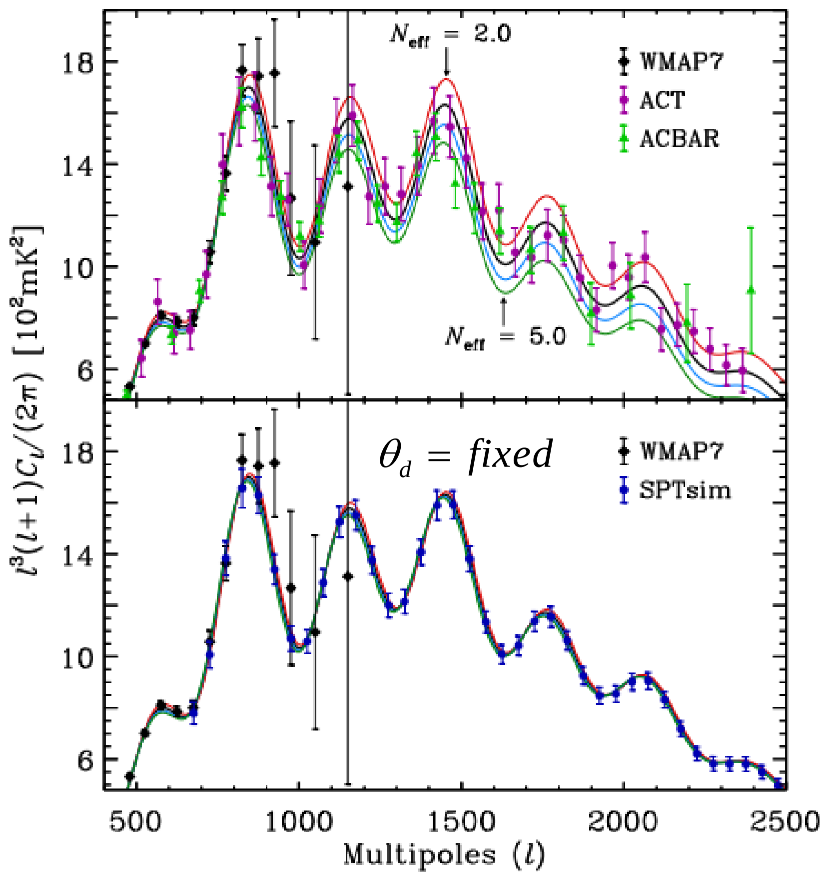
Probing the Neutrino number with CMB data

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)

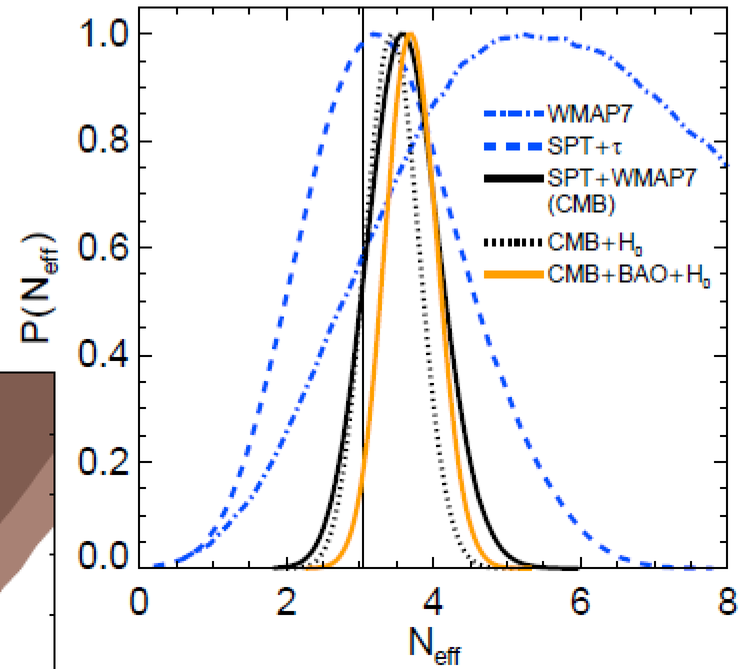
Moreover a larger neutrino number increases the early ISW as the neutrino mass .

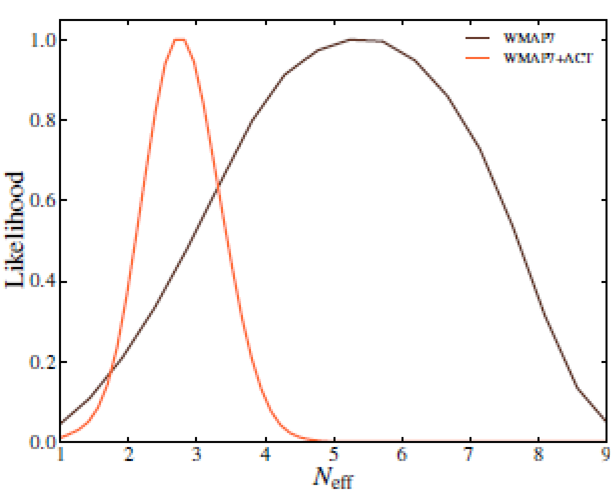
Pre-Planck state of art for Dark Radiation

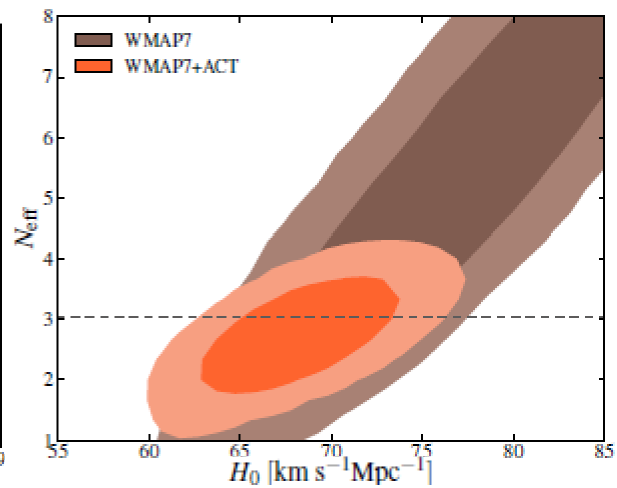
WMAP-7+SPT $N_{eff} = 3.62 \pm 0.48$

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

Hou et al. (2013)





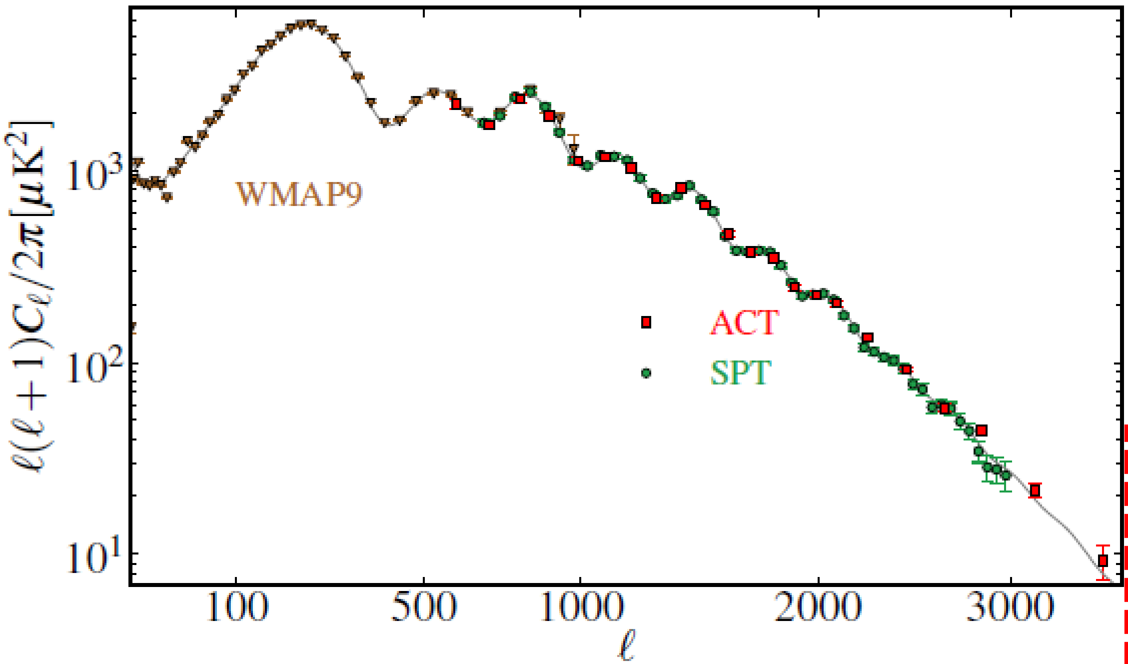


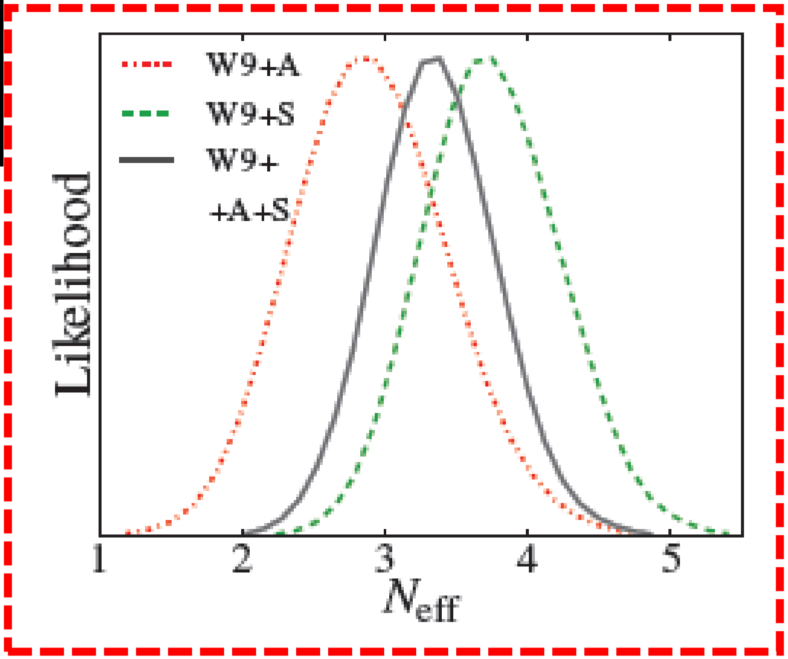
WMAP-7+ACT $N_{eff} = 2.78 \pm 0.55$

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)

Data sets and models

- WMAP9 + SPT/ACT
- WMAP9 + SPT/ACT + HST
- WMAP9 + SPT/ACT + BAO
- WMAP9 + SPT/ACT + HST + BAO
- WMAP9 + SPT/ACT + SNLS3
- WMAP9 + SPT/ACT + SNLS3 + BAO

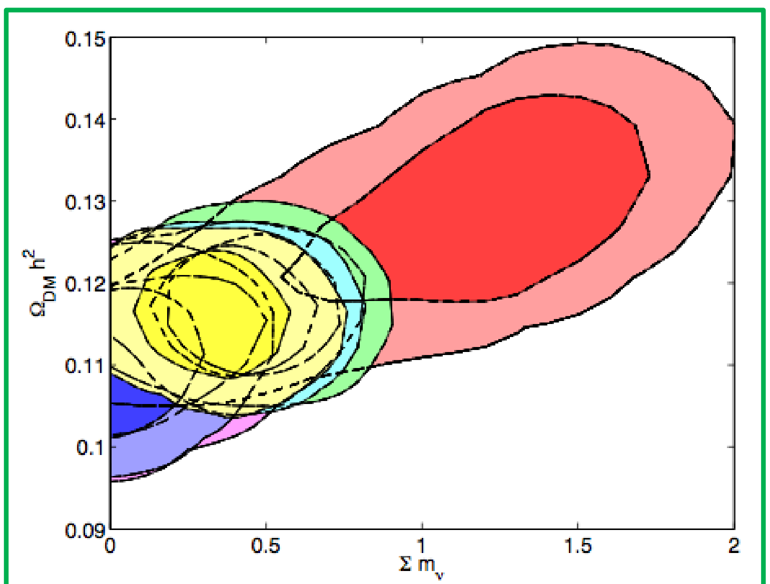
- ΛCDM + Σm_ν (N_{eff} = 3)
- ΛCDM + Σm_ν + N_{eff}
- ΛCDM + Σm_ν + w
- ΛCDM + Σm_ν + $dn_s/d\ln k$

- ΛCDM + N_{eff}
- ΛCDM + ΔN_{eff}
- ΛCDM + ΔN_{eff} + c^2_{eff} + c^2_{vis}
- ΛCDM + Σm_ν + ΔN_{eff} + c^2_{eff} + c^2_{vis}

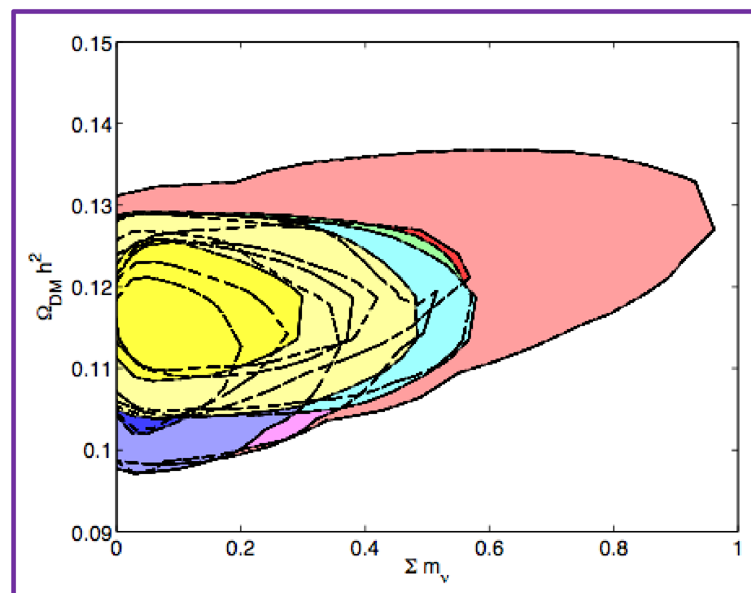
ΛCDM + Σm_ν

	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



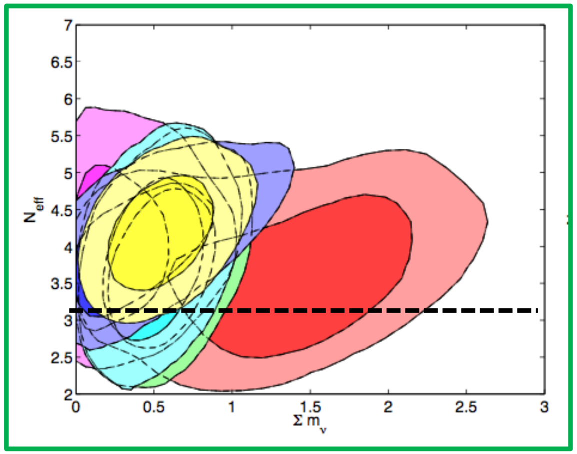
- CMB
- CMB+HST
- CMB+BAO
- CMB+BAO+HST
- CMB+SNLS
- CMB+SNLS+BAO

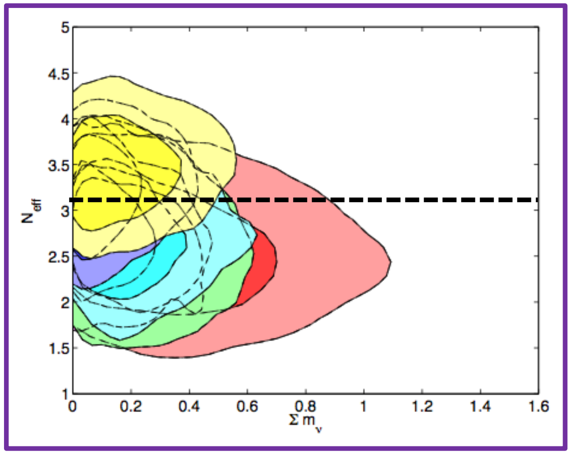


$\Lambda CDM + \Sigma m_\nu + N_{eff}$

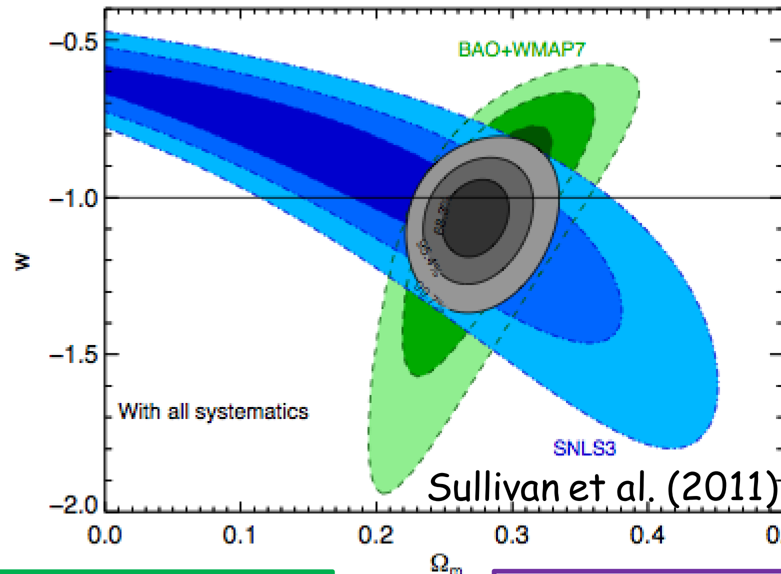
	W9+SPT	W9+SPT +HST	W9+SPT +BAO	W9+SPT +BAO +HST	W9+SPT +SNLS	W9+SPT +SNLS +BAO
Σm_ν (eV)	1.35±0.55	0.48±0.33	0.56±0.22	0.56±0.23	<0.91	0.50±0.21
N_{eff}	3.66±0.61	4.08±0.54	3.76±0.67	4.21±0.46	4.04±0.68	3.87±0.68

	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

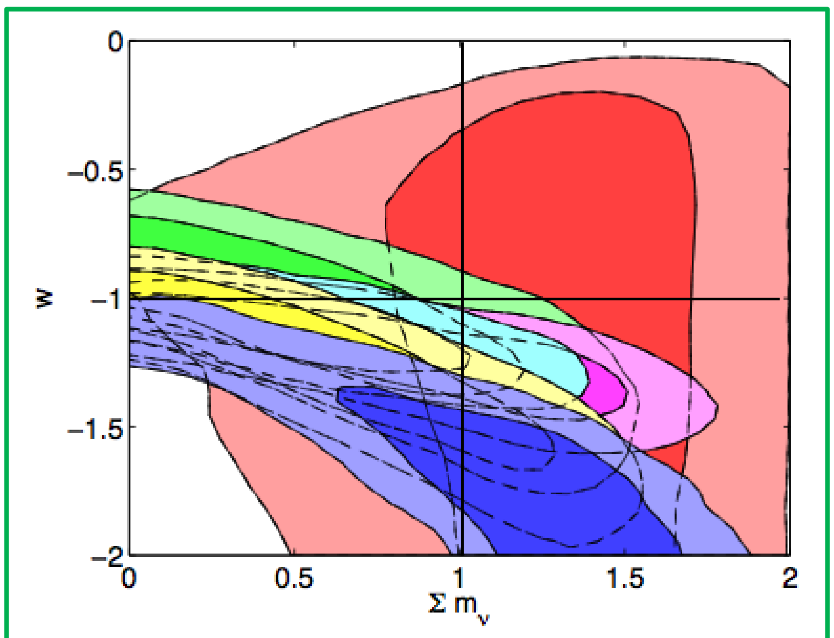




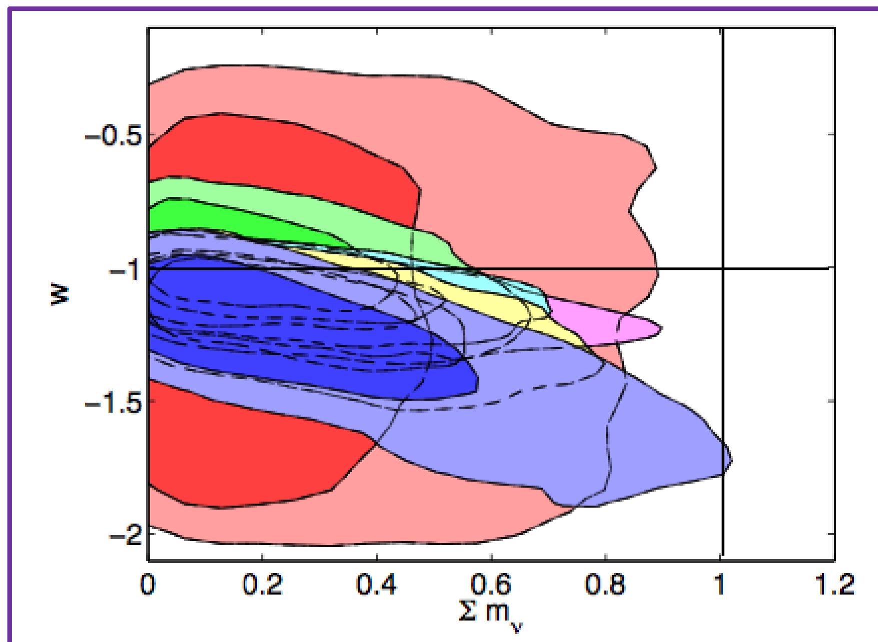
ΛCDM + Σm_ν + w



SPT



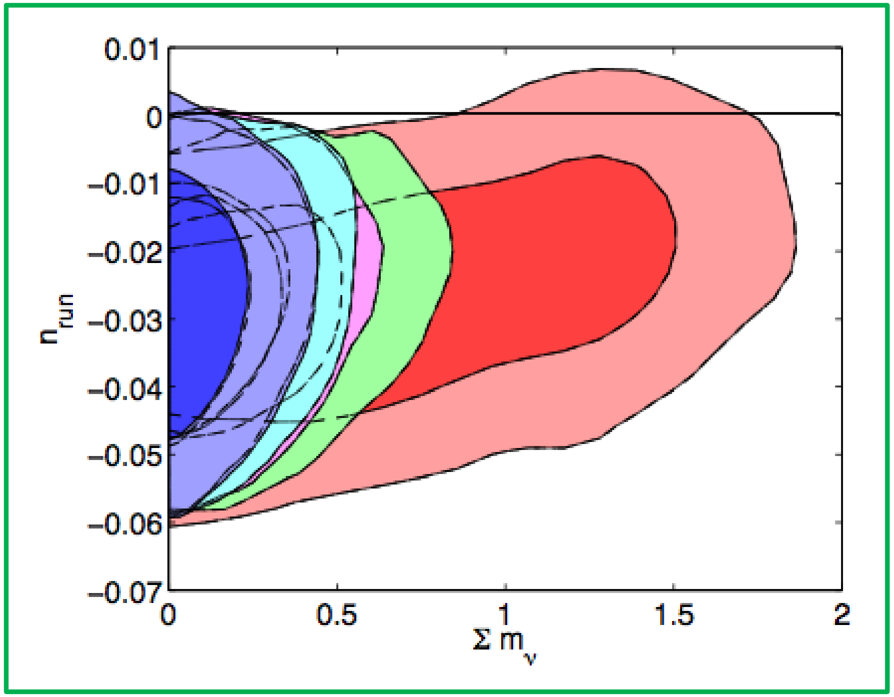
ACT



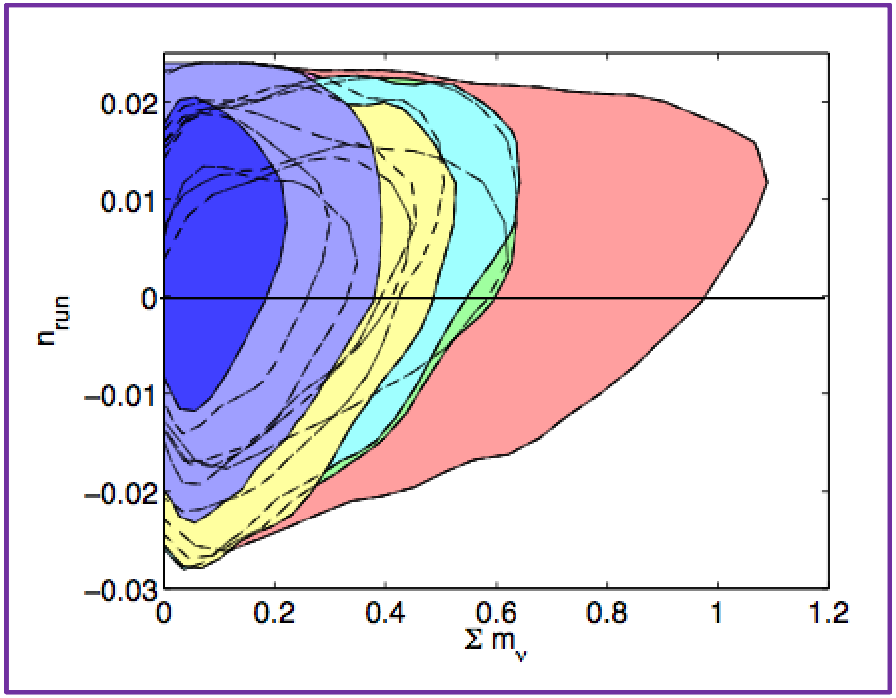
ΛCDM + Σm_ν + $dn_s/d\ln k$

$$P(k) \equiv A_S k^{n(k)} \propto \left(\frac{k}{k_0}\right)^{n_S + \ln(k/k_0)(dn/d\ln k)+\ldots} \qquad (k_0 = 0.002 Mpc^{-1})$$

SPT



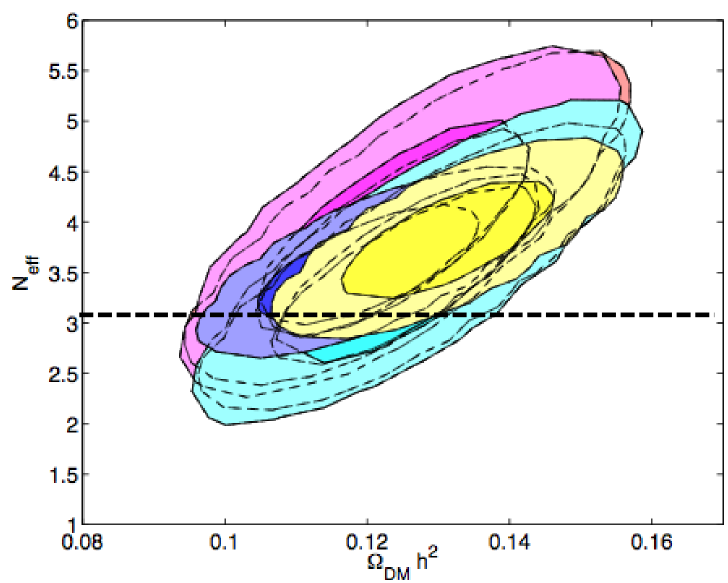
ACT



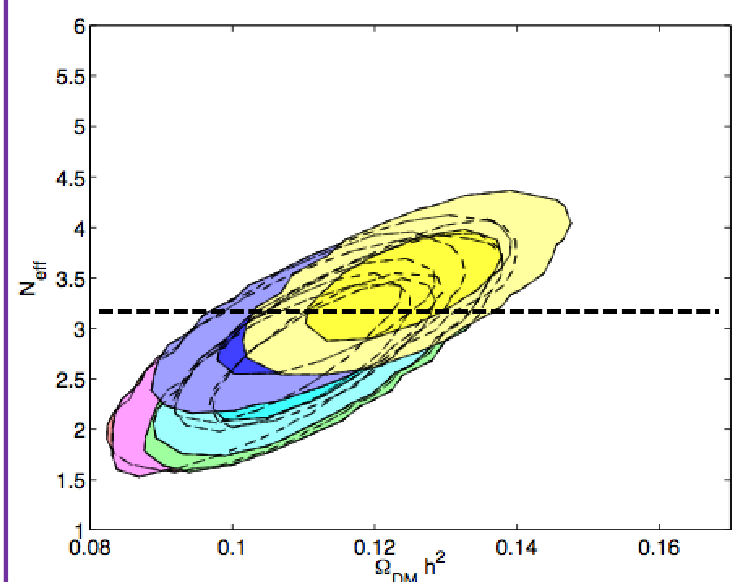
ΛCDM + N_{eff}

	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



The situation is similar in ΛCDM + ΔN_{eff}



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:

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

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

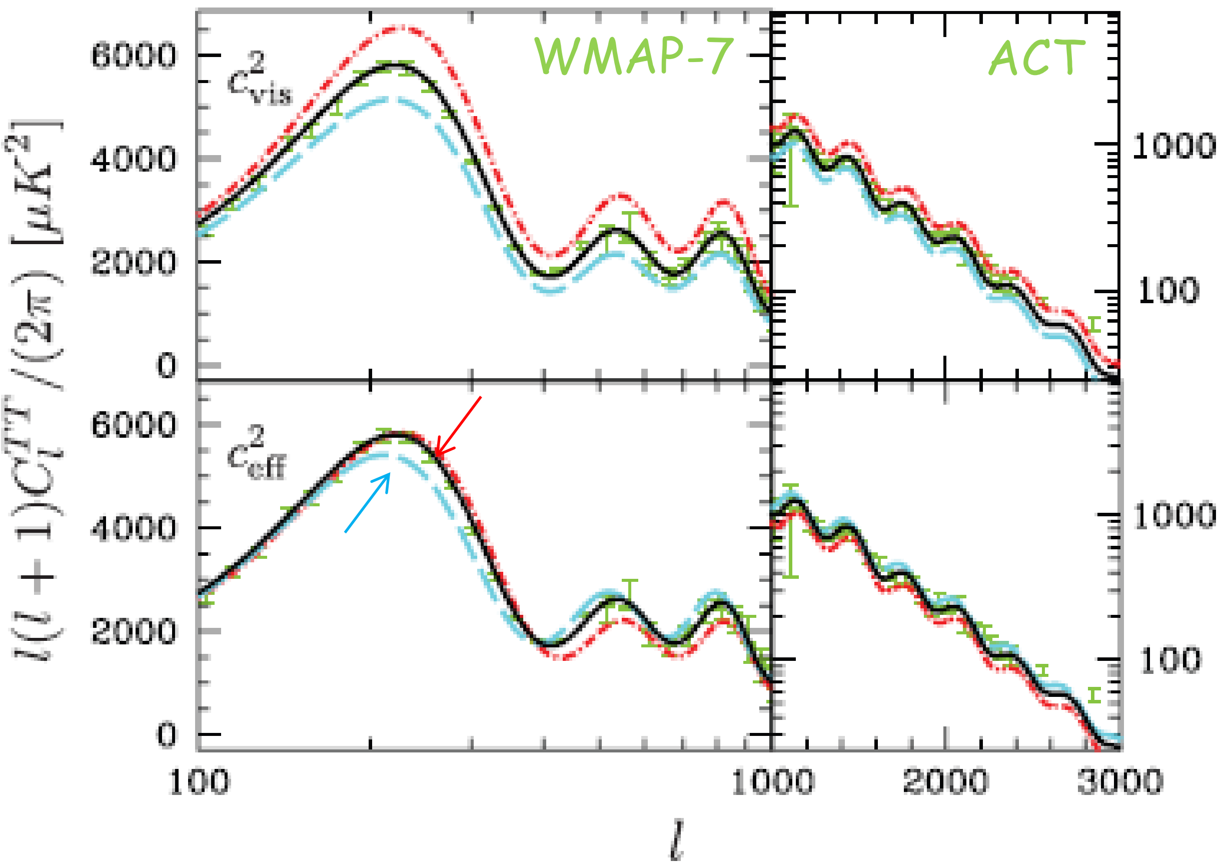
$$\dot{\pi}_\nu = \underline{3c_{vis}^2}\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right) - \frac{3}{5}kF_{\nu,3},$$

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

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 $\Delta N_{eff} = 1.31 \pm 0.60$

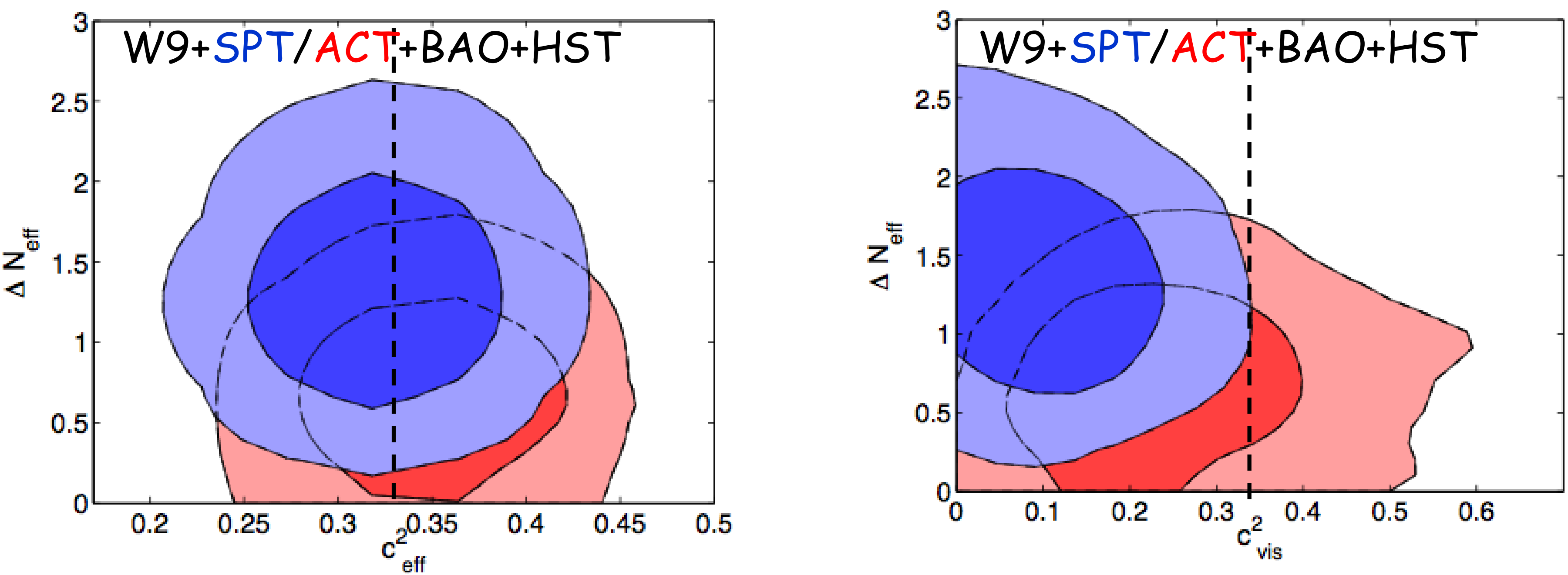
W9+SPT+HST $\Delta N_{eff} = 0.92 \pm 0.39$

W9+SPT+BAO+HST
$c^2_{vis} = 0.15 \pm 0.07$

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

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

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+SPT+BAO+HST

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

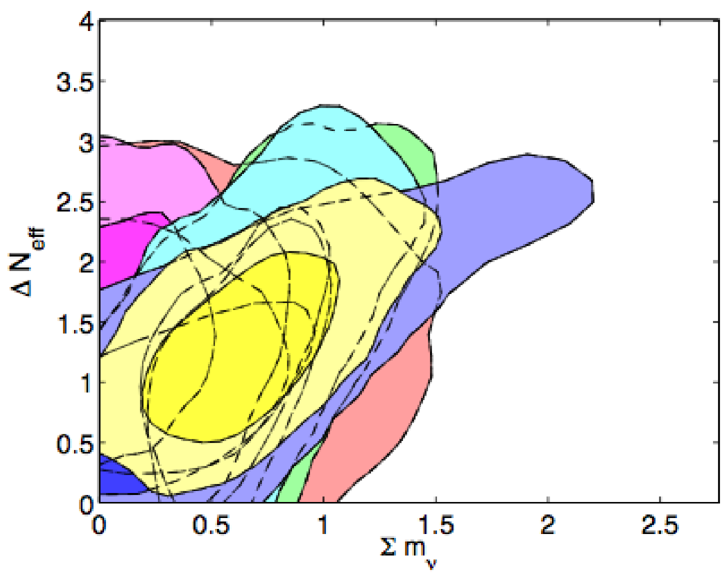
W9+ACT+BAO+HST

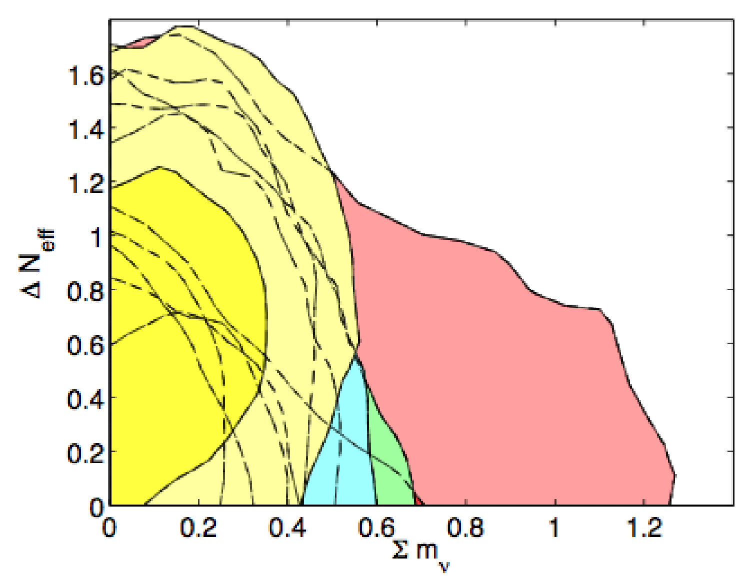
$\Delta N_{eff} = 0.74 \pm 0.40$

W9+ACT+BAO+HST

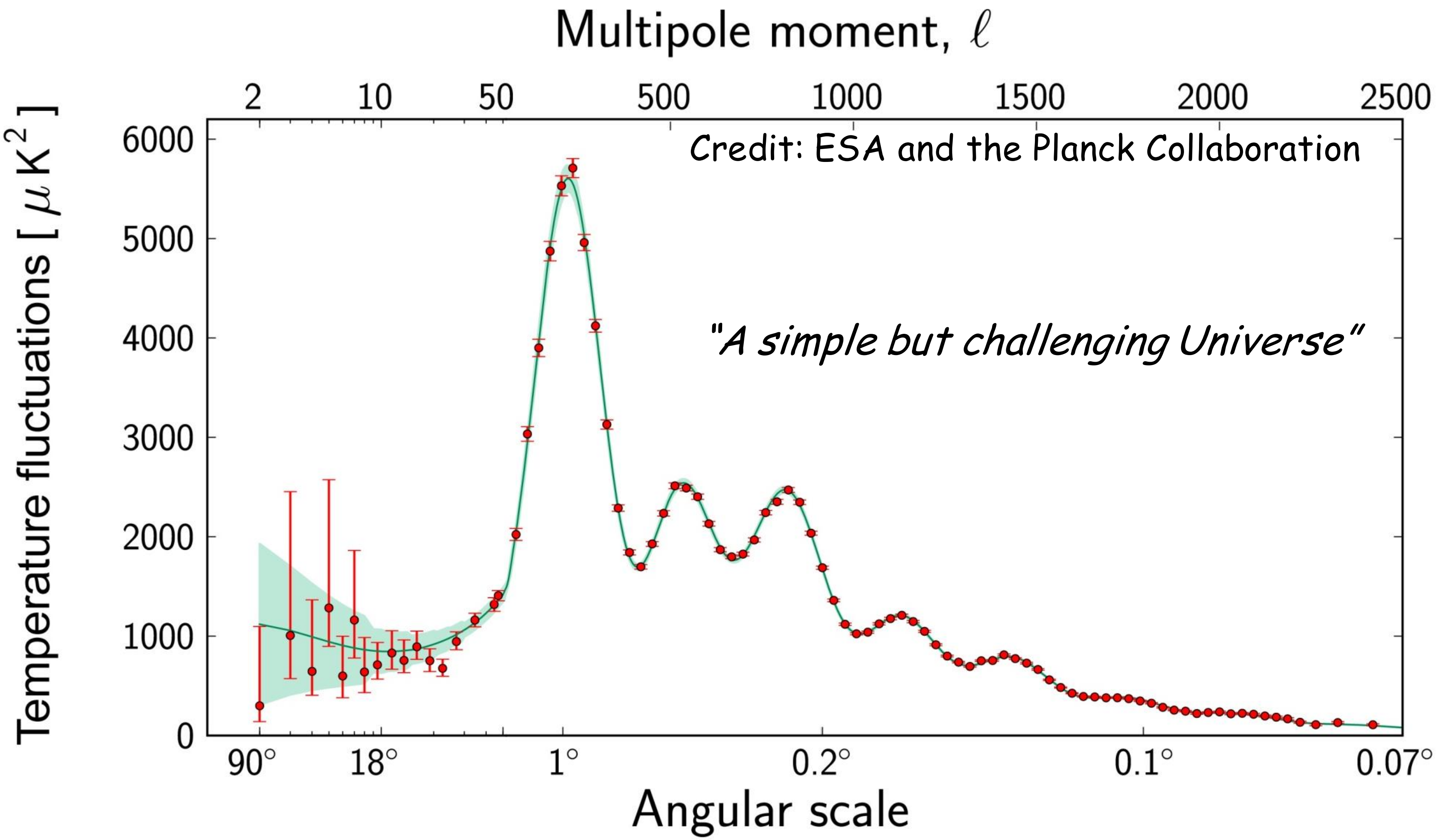
$c^2_{vis} = 0.25 \pm 0.11$

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





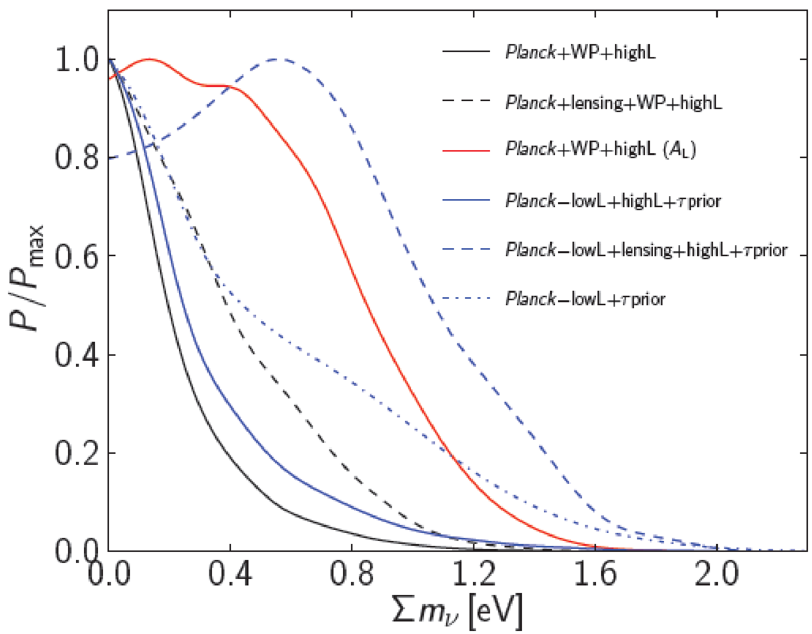
Planck

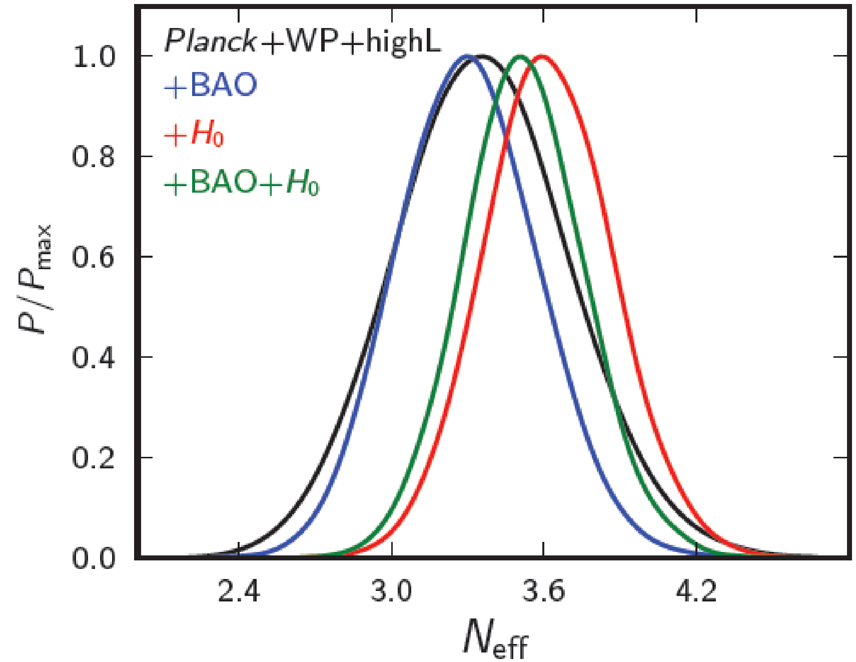


$$H_0 = (67.3 \pm 1.2) Km/s/Mpc \ (68\% c.l.)$$

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

Planck and neutrinos





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)

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

Planck+WMAP9polarization
+highl(SPT+ACT)

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

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

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

Credit: ESA and the Planck Collaboration

Conclusions

	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