Cosmological bounds on sterile neutrinos

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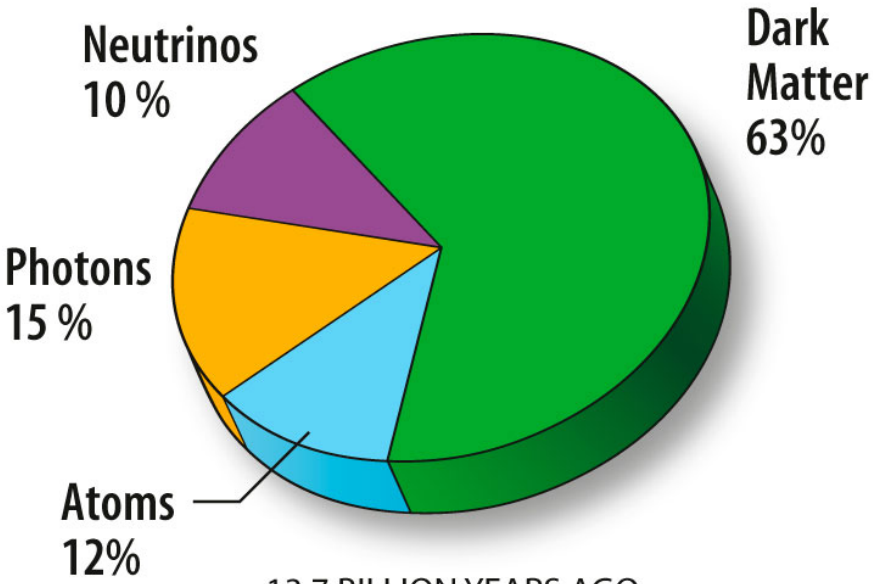
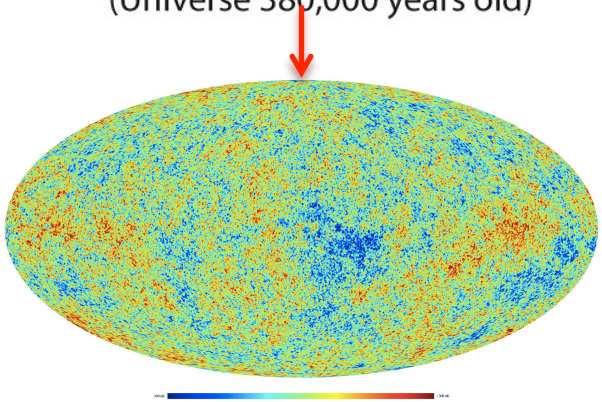
Outline

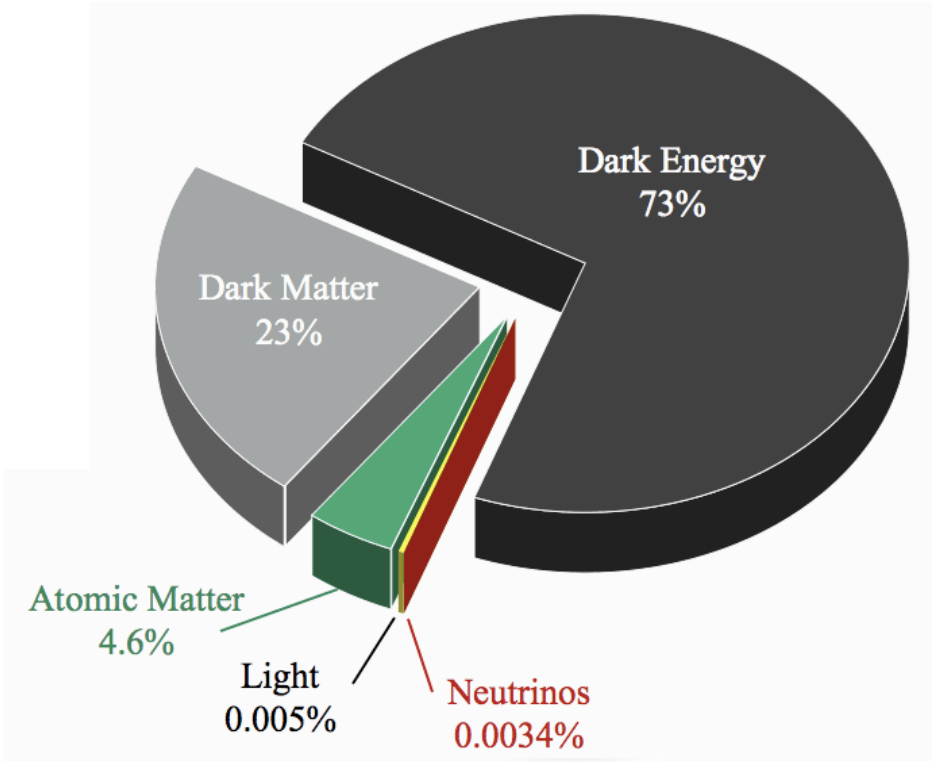
- The effective number of relativistic degrees of freedom and the case for dark radiation
- Constraints before and after Planck
- Cosmological effects on BBN and CMB
- Dark radiation models: sterile neutrinos
- Conclusions

Cosmic pie(s)



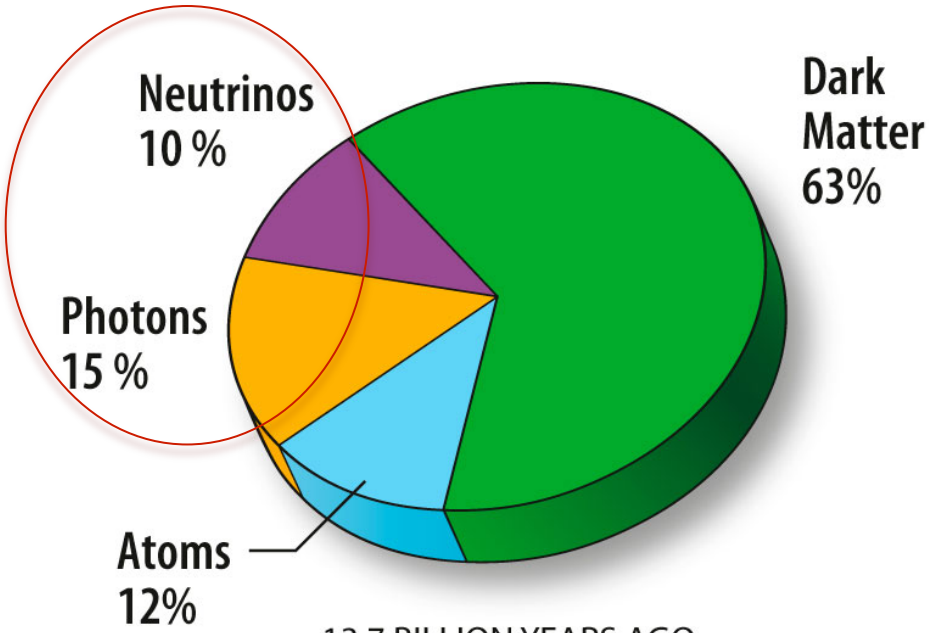
13.7 BILLION YEARS AGO
(Universe 380,000 years old)





TODAY

Cosmic pie(s)



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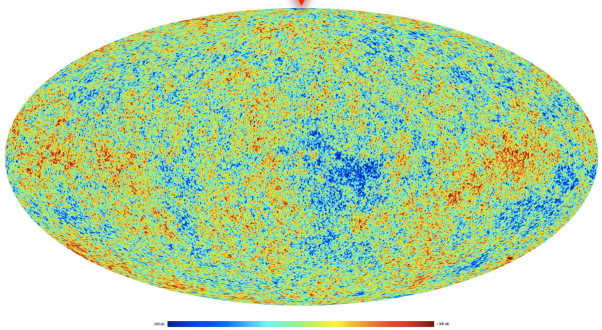
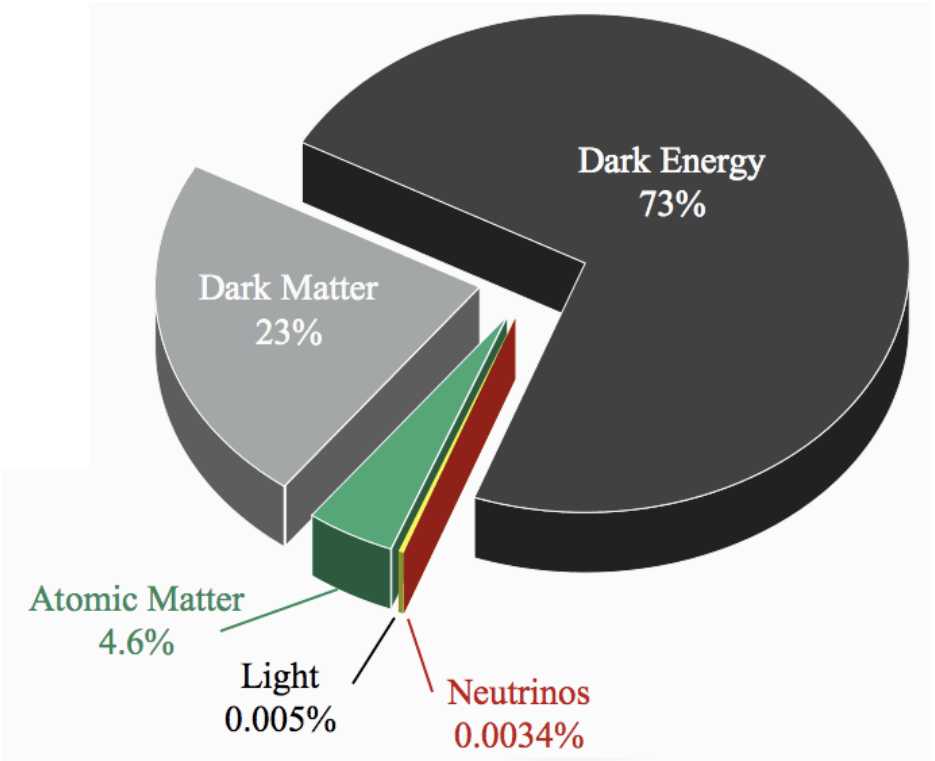




TODAY

The effective number of relativistic degrees of freedom

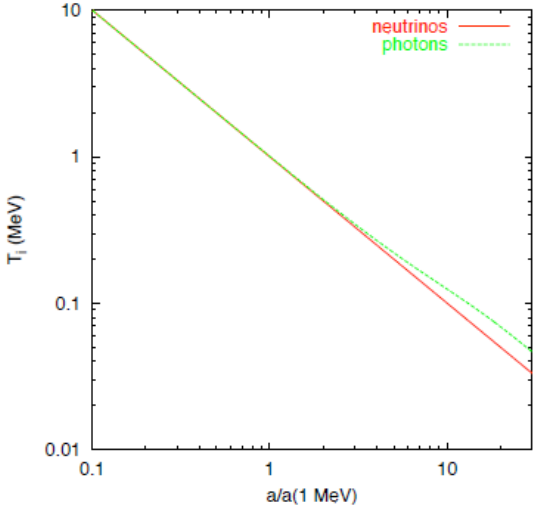
Radiation content of the Universe:

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

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

$$N_{eff}^s = 3.046$$ Mangano et al. (2005)

$$k_B T_{dec} \approx 1 MeV \rightarrow e^+ e^- \leftrightarrow \gamma\gamma \qquad T < T_{dec} \rightarrow$$



$$N_{eff} = N_{eff}^s + \Delta N_{eff}$$ ⇒ Dark radiation

Lesgourgues & Pastor (2012)

Effects on BBN

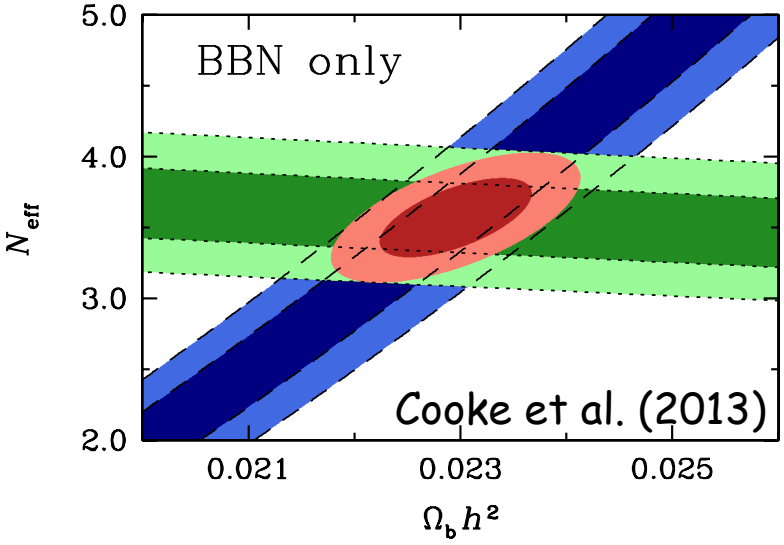
- Friedmann equation:

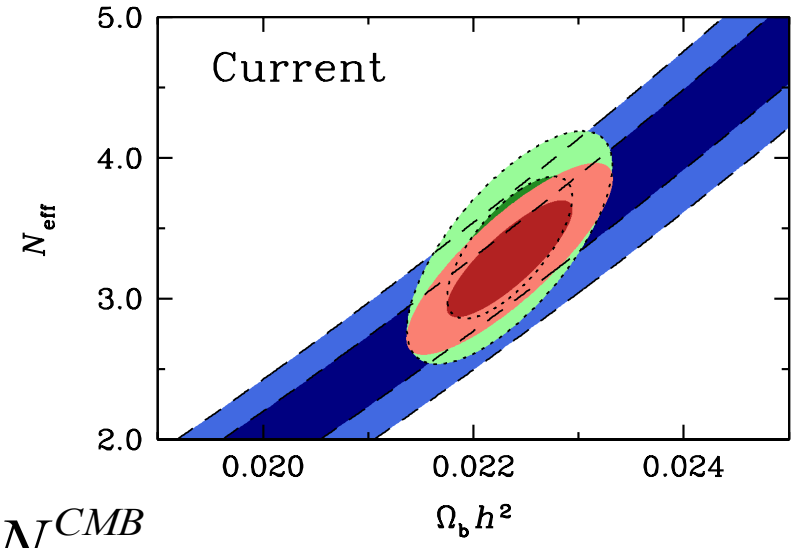
$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_M}{a^3} + \frac{\Omega_\gamma}{a^4} + \frac{\Omega_\nu}{a^4} + \Omega_\Lambda + \frac{\Omega_{DR}}{a^4}$$

increase of the expansion rate. Earlier freeze-out!

➡ higher primordial helium abundance

BBN bounds

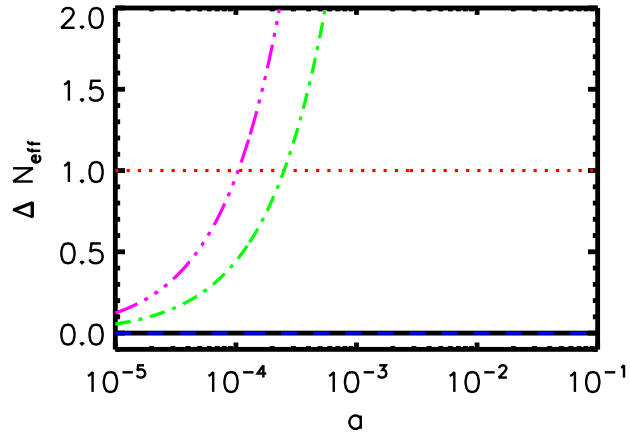




$$N_{eff}^{BBN} \neq N_{eff}^{CMB}$$

Bjaelde, Das, Moss (2012)
Gonzalez-Garcia, Niro, Salvado (2012)

Decay of massive particles between BBN (T~1MeV) and recombination (T~1eV)



Effects on CMB (1)

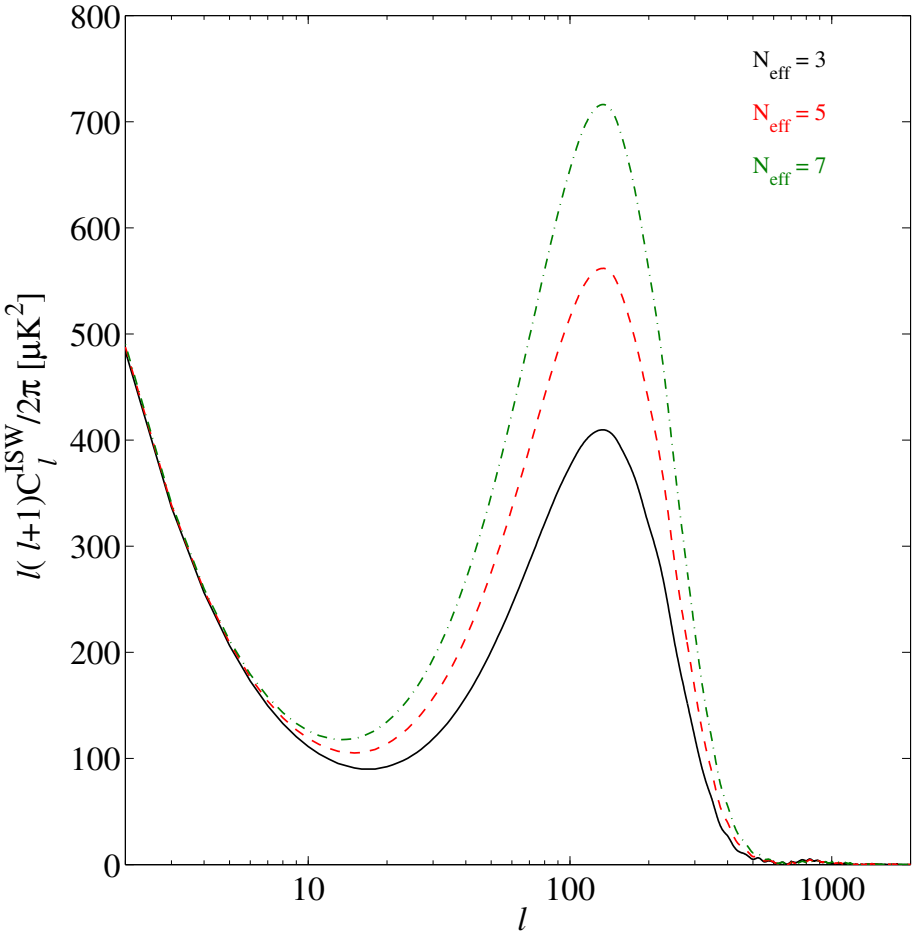
- Delay of the radiation-matter equivalence:

$$1 + z_{eq} = \frac{\Omega_m}{\Omega_r} \approx \frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1 + 0.2271 N_{eff}}$$

enhancement of the early ISW

➡ CMB first peak higher

Effects on CMB (1)



MA, Giusarma, Hannestad, Mena (2013)

Effects on CMB (2)

- Friedmann equation:

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

increase of the expansion rate at recombination
decrease of the size of the sound horizon

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

➡ CMB acoustic peaks shifted towards higher multipoles

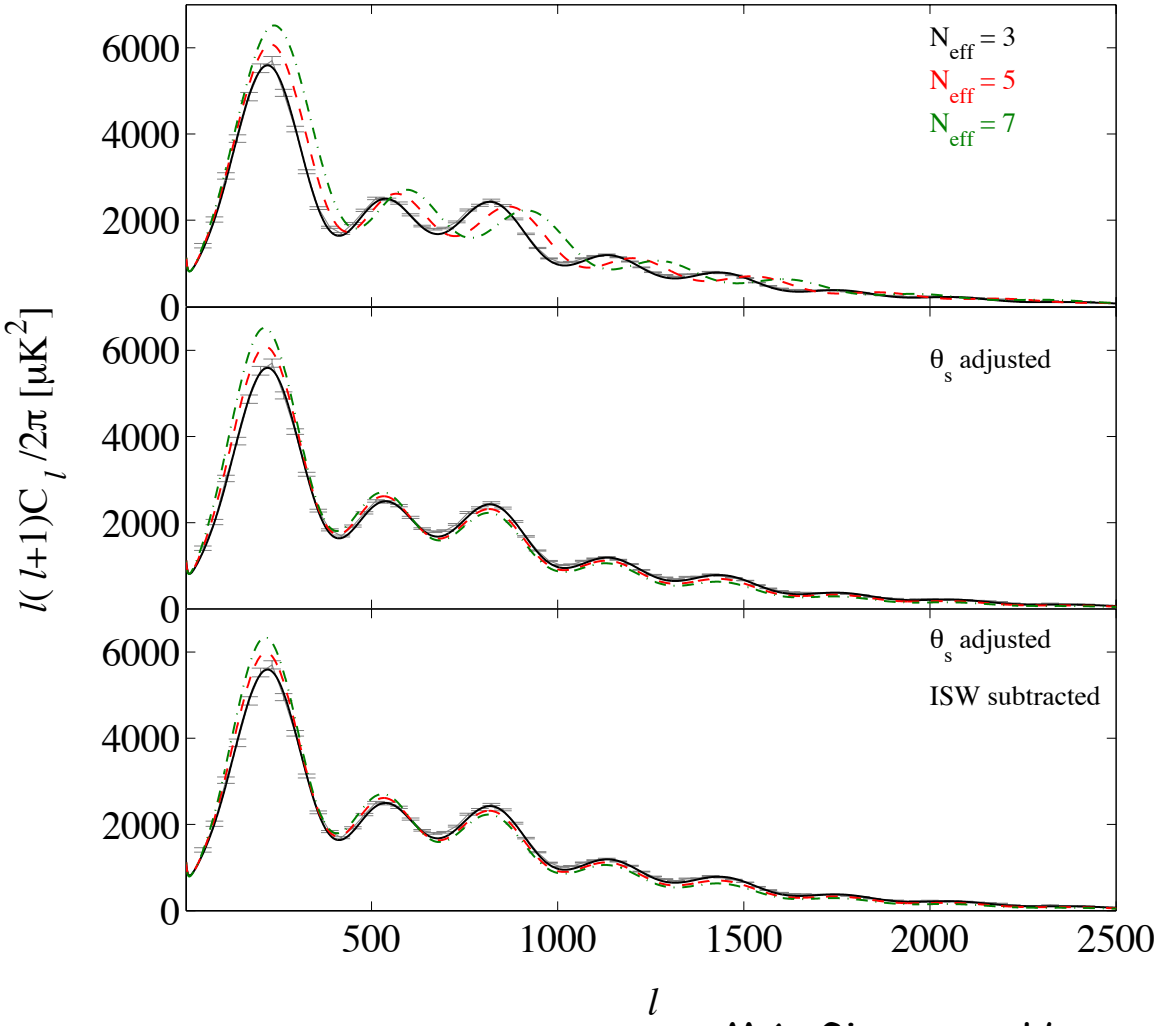
Effects on CMB (3)

- Increase of the Silk damping

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

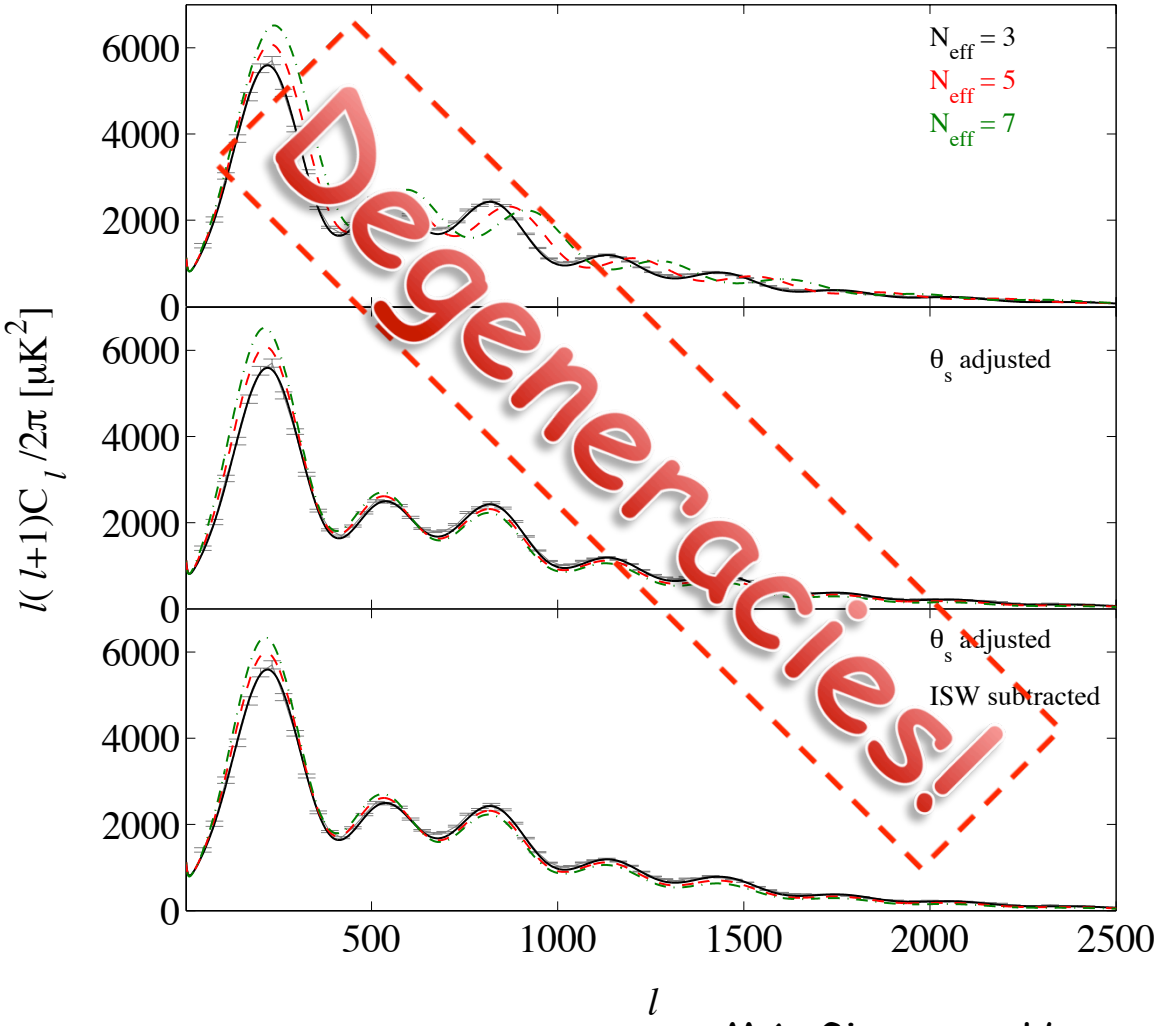
➡ smearing of the CMB acoustic peaks at high multipoles

Effects on CMB



MA, Giusarma, Hannestad, Mena (2013)

Effects on CMB



MA, Giusarma, Hannestad, Mena (2013)

The case for dark radiation

Pre-Planck constraints

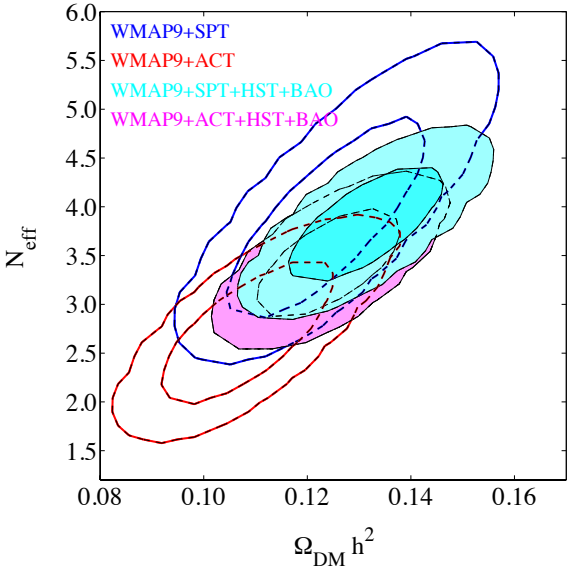
WMAP-9+SPT $N_{eff} = 3.93 \pm 0.68$

WMAP-9+ACT $N_{eff} = 2.74 \pm 0.47$

WMAP-9+SPT+BAO+H0 $N_{eff} = 3.83 \pm 0.41$

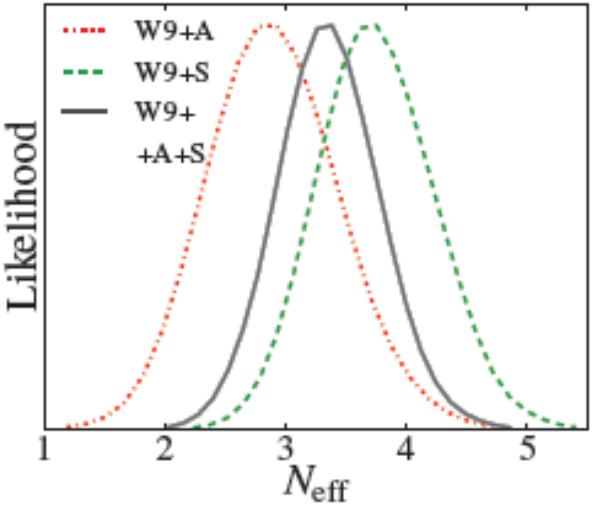
WMAP-9+ACT+BAO+H0 $N_{eff} = 3.43 \pm 0.36$

MA, Giusarma, Melchiorri, Mena, PRD (2013)



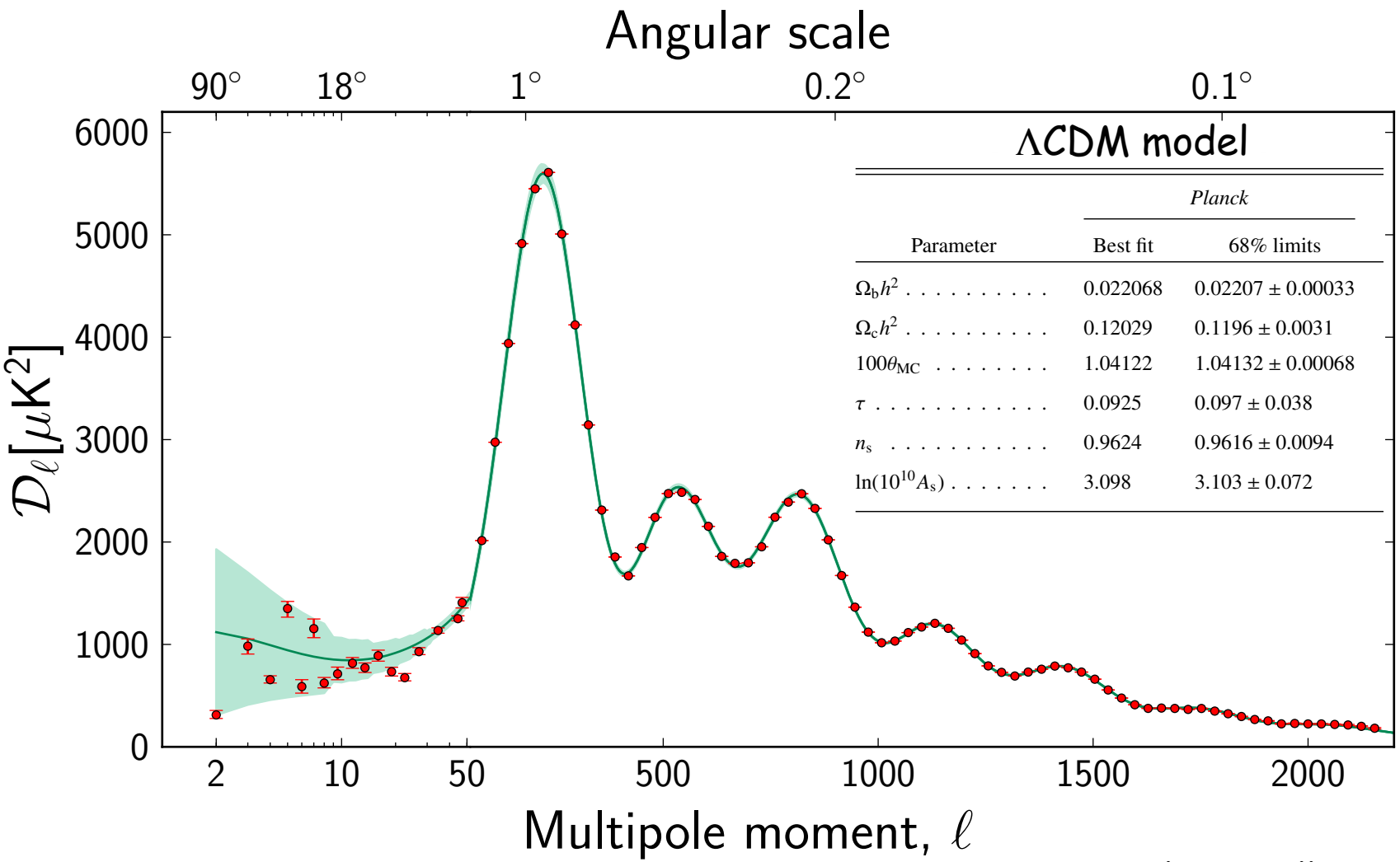
WMAP-9+SPT+ACT $N_{eff} = 3.37 \pm 0.42$

Calabrese et al. (2013)



Planck

"A simple but challenging Universe"

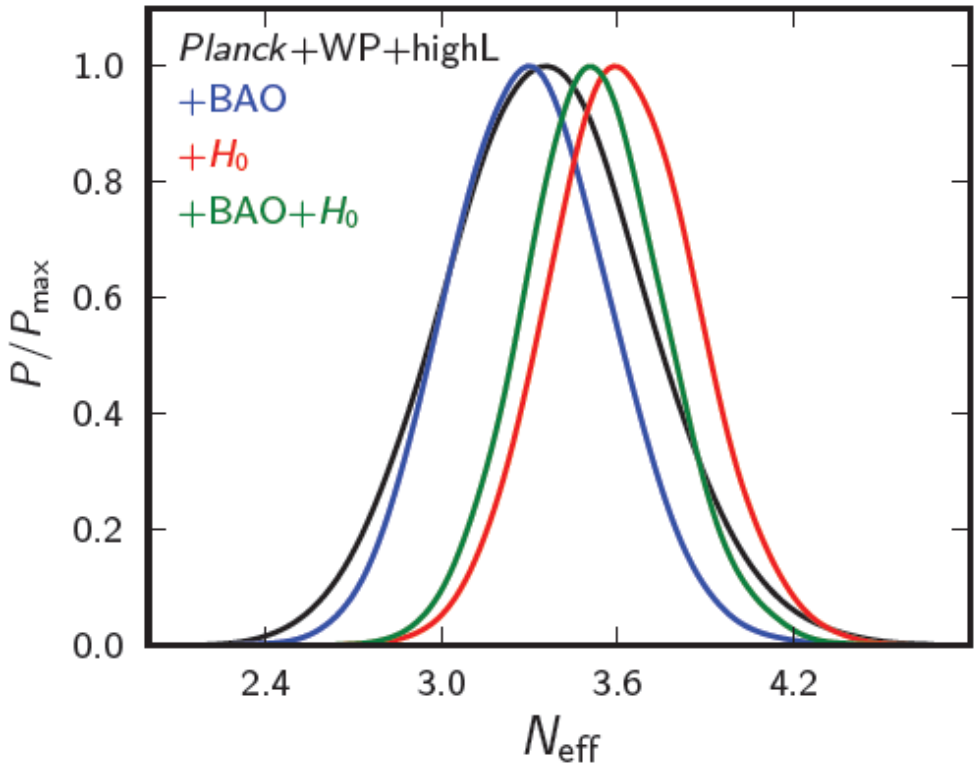


ΛCDM model

Parameter	*Planck* Best fit	*Planck* 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

Planck Collaboration

Planck constraints



Planck+WMAP9polarization +highl(SPT+ACT)

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

Planck+WMAP9polarization +highl(SPT+ACT)+H0

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

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

Planck Collaboration

$$H_0 = 73.8 \pm 2.4 \ km/s/Mpc$$

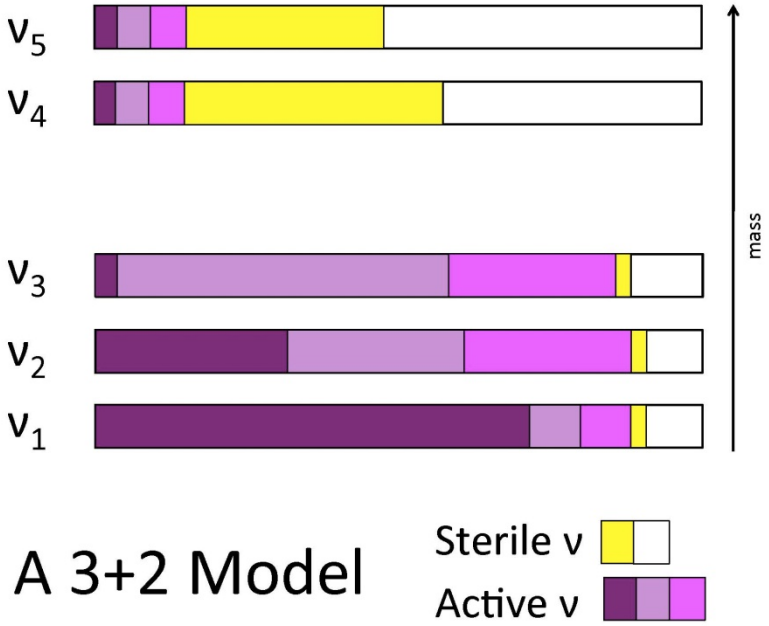
H0, Riess et al

What DR is made of?

- Sterile neutrinos
  (MA, Giusarma, Hannestad, Mena, arXiv:1307.0637)
- Axions (MA, Hannestad, Mirizzi, Raffelt, Wong, arXiv:1307.0615)
- Decay of massive particles (Gonzalez-Garcia, Niro, Salvado, 2012)
- Early dark energy (Calabrese et al., 2011)
- ...

Sterile neutrinos: oscillation experiments

LSND, MiniBooNE, …



A 3+2 Model

Conrad et al. (2012)

$$0.1\ eV^2 < \Delta m^2 < 10\ eV^2$$

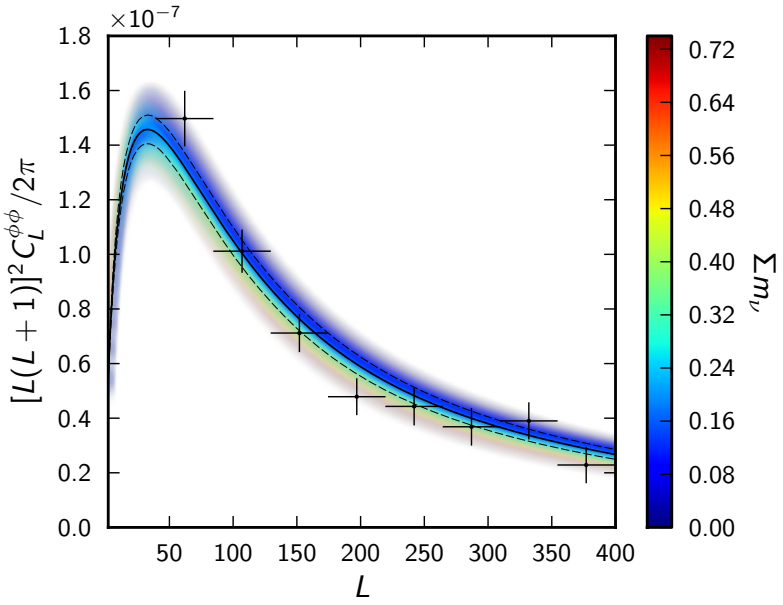
~ see talk by Carlo Giunti

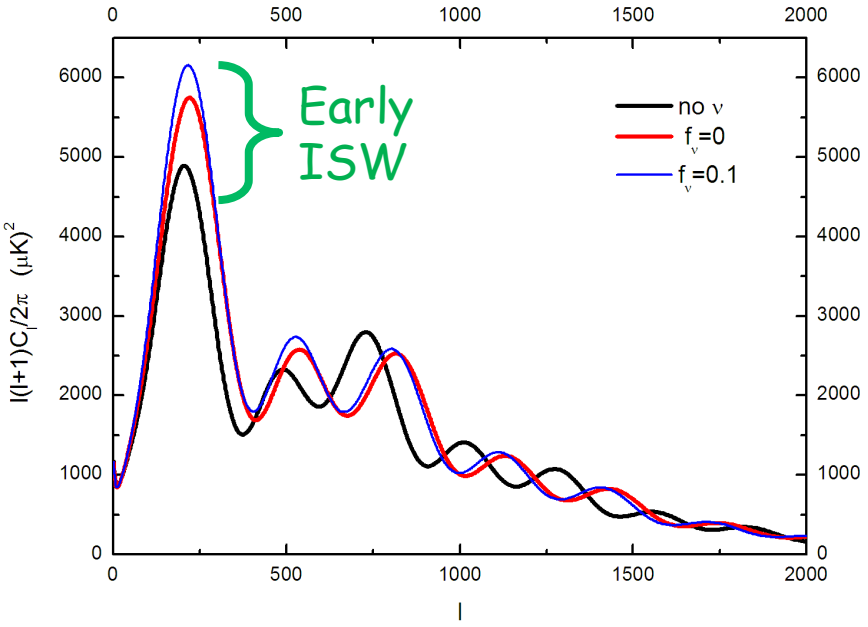
Neutrino mass effects on CMB

~ see talk by Yvonne Y. Y. Wong

$$\Omega_\nu h^2 = \frac{N_\nu m_\nu}{94eV}$$

caveat



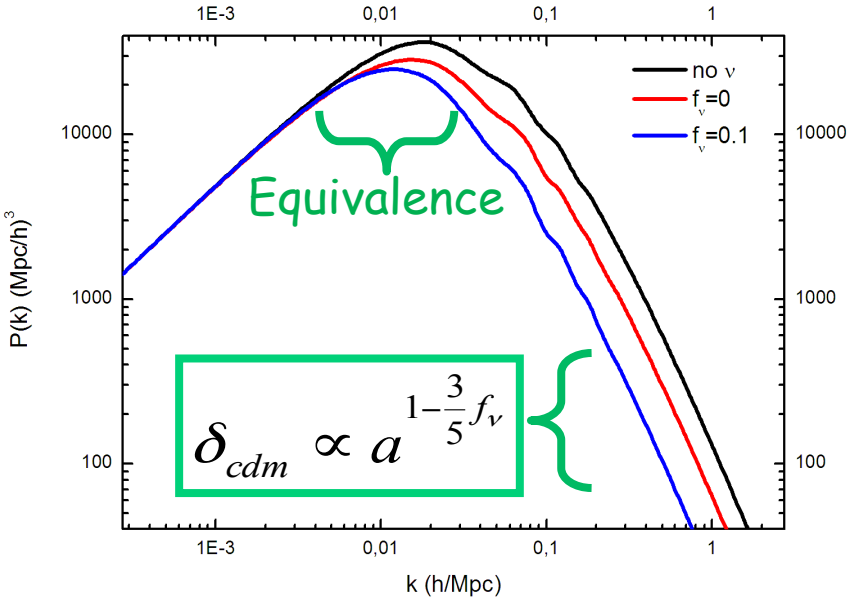


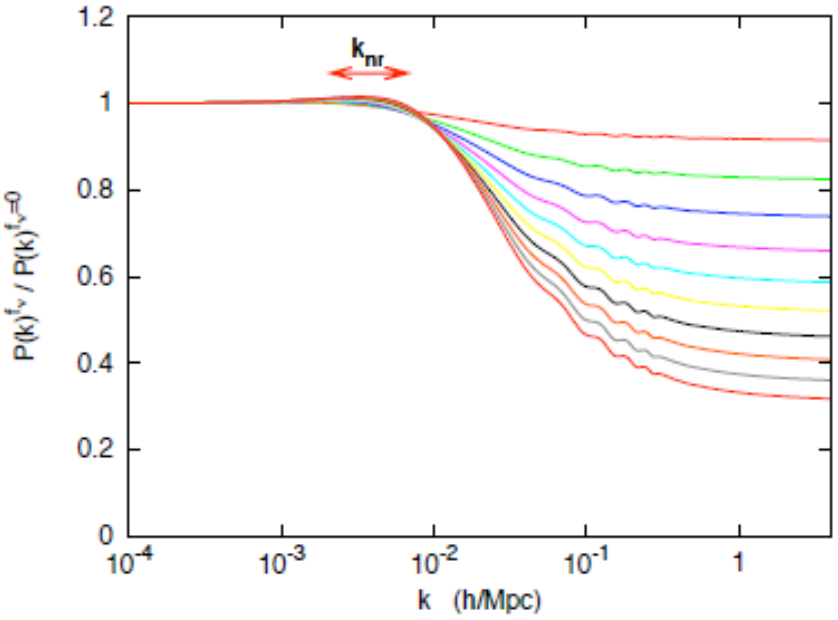
Free-streaming:
Suppression of lensing potential
(now with Planck!)

Neutrino mass effects on mpk

~ see talk by Yvonne Y. Y. Wong

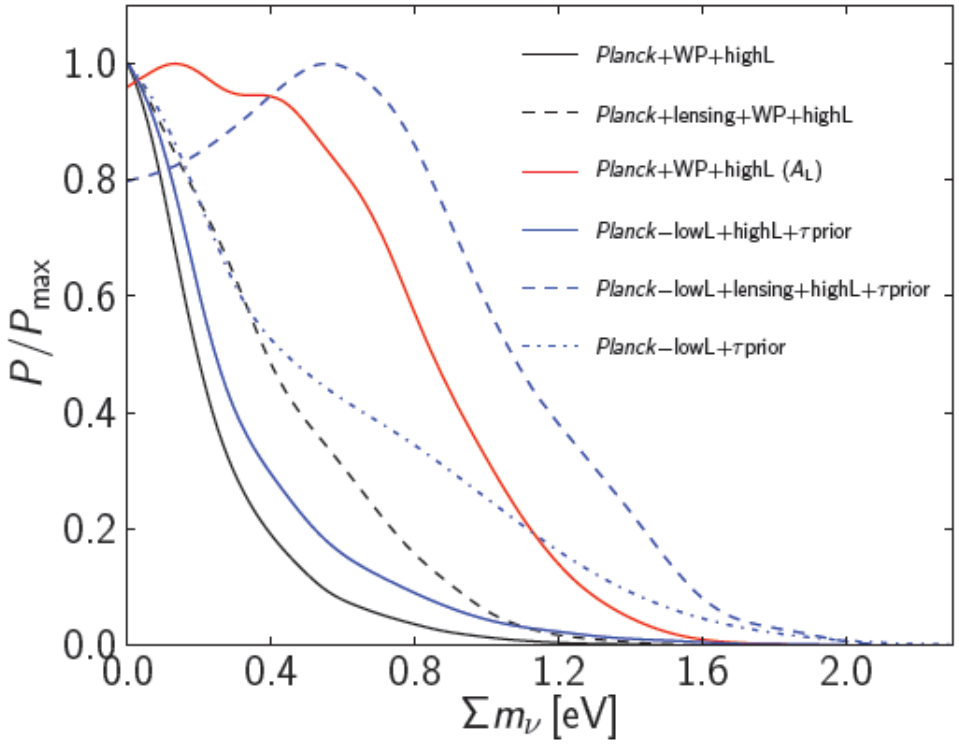
Free-streaming:
Effects on matter power spectrum:
Suppression on scales smaller than the scale of the horizon at the non-relativistic transition.





Lesgourgues & Pastor (2012)

Planck constraints



Planck+WMAP9polarization +highl(SPT+ACT)

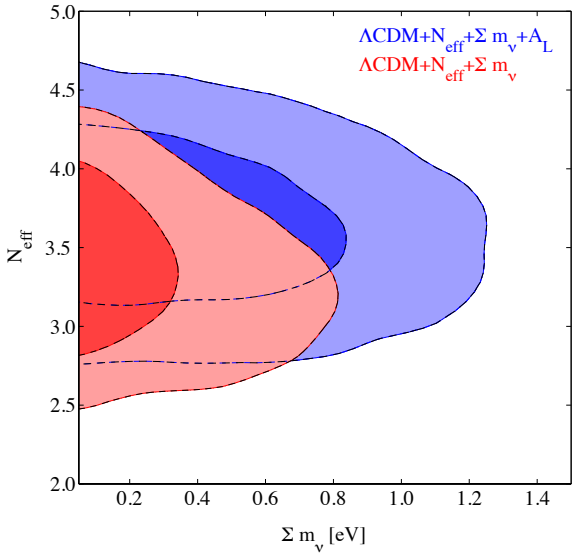
$$\sum m_\nu < 0.66eV \ \ (95\% c.l.)$$

Planck Collaboration

Sterile neutrinos in cosmology: Impact of lensing

	Planck+WP +highL	Planck+WP +highL
N_{eff}	3.38±0.36	3.65±0.38
Σm_ν (eV)	<0.64	<1.03
A_L	1	1.36±0.14

1σ errors and 95% upper bounds

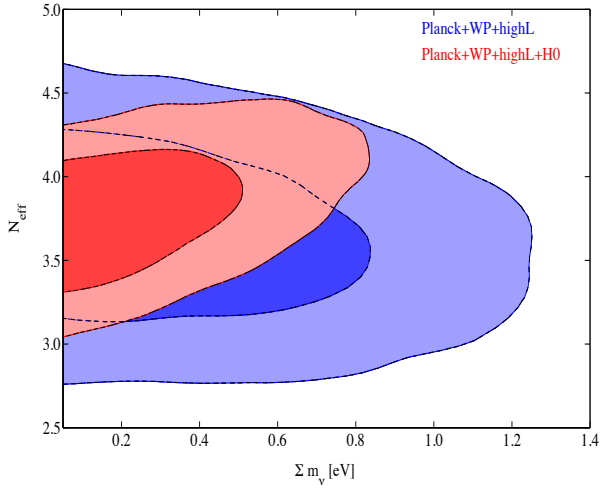


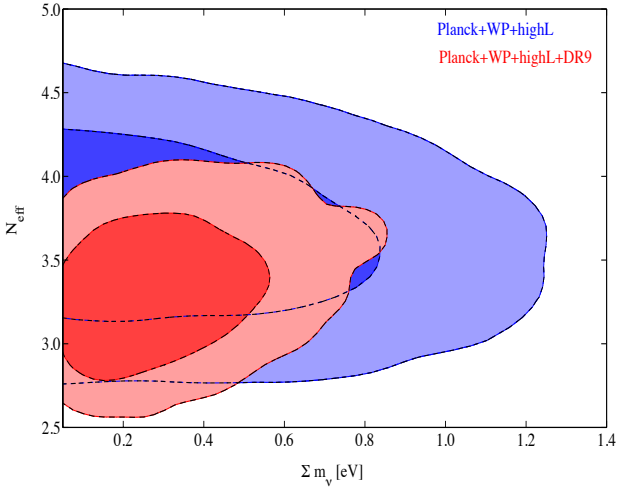
MA, Giusarma, Hannestad, Mena (2013)

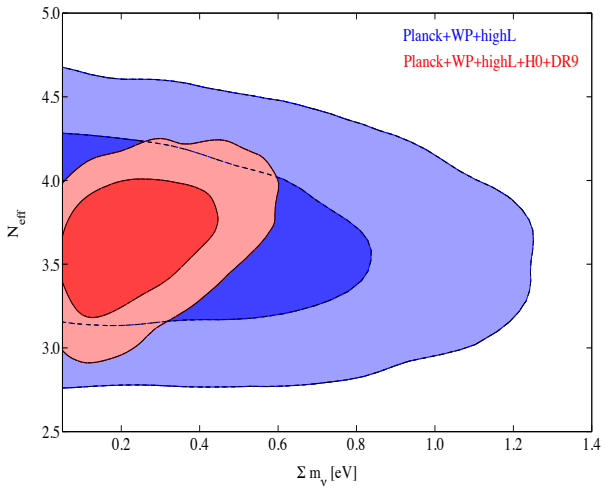
Sterile Neutrinos: results

	Planck+WP +highL	Planck+WP +highL +H0	Planck+WP +highL +CMASS9	Planck+WP +highL +H0 +CMASS9
N_{eff}	3.65±0.38	3.81±0.28	3.33±0.31	3.65±0.26
Σm_ν (eV)	<1.03	<0.66	<0.66	<0.51
A_L	1.36±0.14	1.36±0.14	1.10±0.08	1.10±0.07

1σ errors and 95% upper bounds







MA, Giusarma, Hannestad, Mena (2013)

Conclusions

- Connection between cosmology and particle physics
- We need to be conservative
  different models/data sets ➔ different results

✓ ΛCDM + N_{eff} ➔ Planck vs H_0

✓ ΛCDM + N_{eff} + Σm_ν + A_l ➔ sterile neutrinos
Planck+WP+highl+H_0
2.7σ preference

Thank you!