

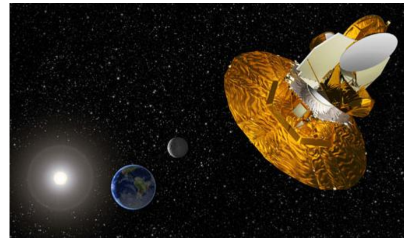


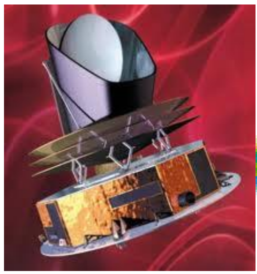
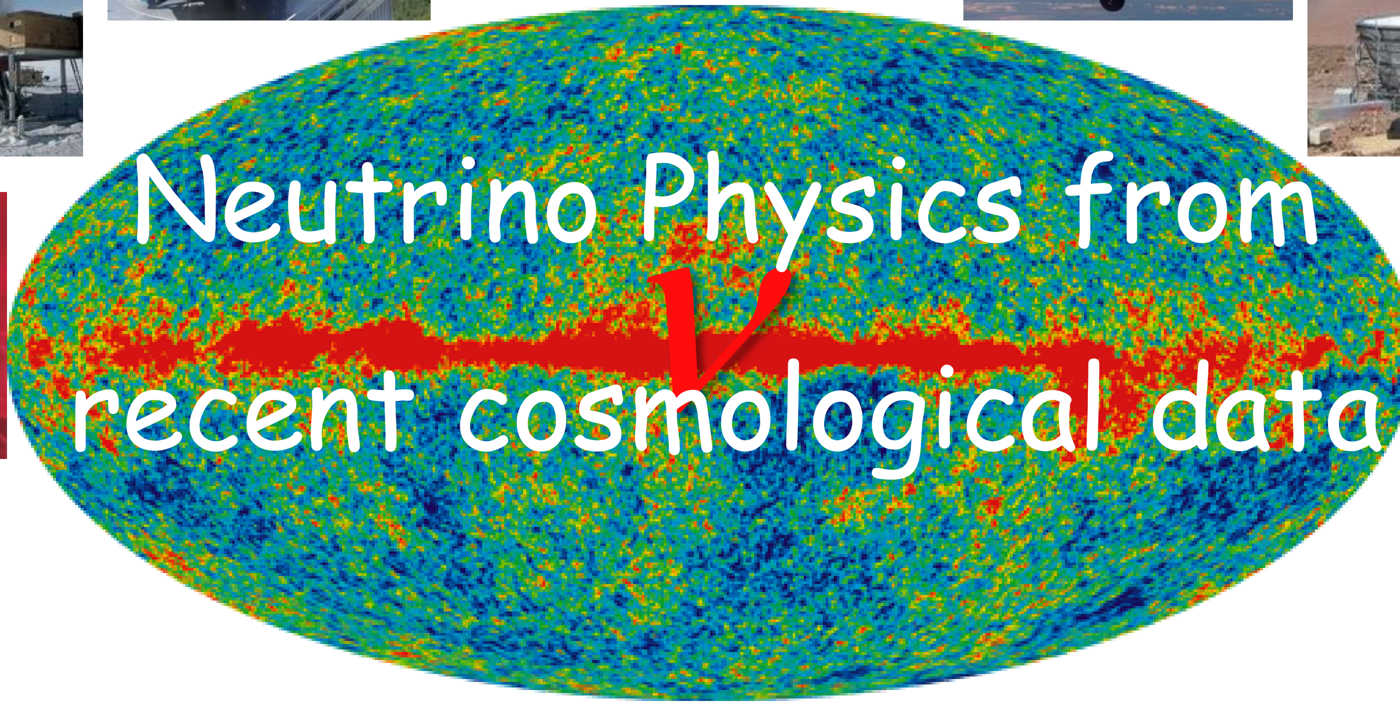

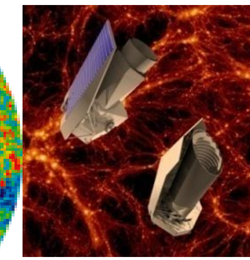

Neutrino Physics from recent cosmological data

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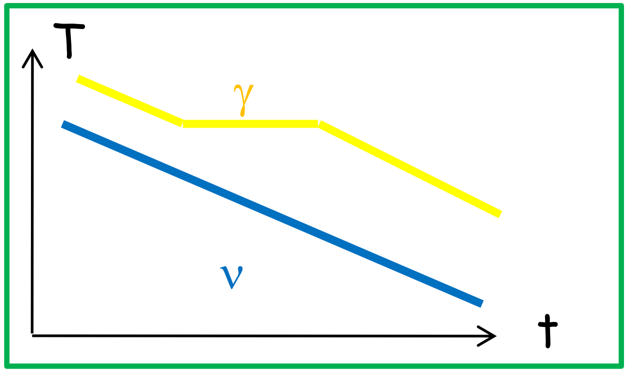
University of Rome "La Sapienza"

Invisibles pre-meeting, Madrid, 29-30 March

Outline

- Cosmic Neutrino Background: Neutrino Mass and Neutrino Number
- Neutrino Mass effects on cosmological observables
- Neutrino Masses and Reionization models
- Neutrino Number effects on CMB
- Is Extra Dark Radiation made of sterile neutrinos?
- Conclusions

Cosmic Neutrinos



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

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

→ 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

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

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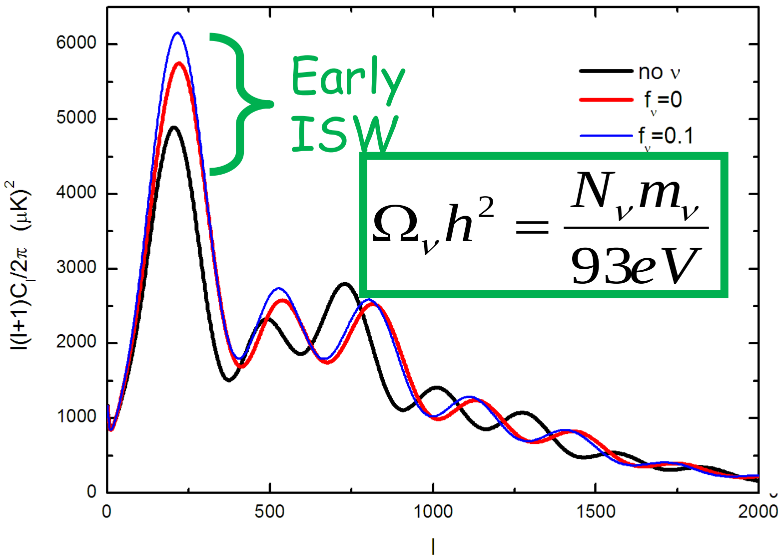
Probing the Neutrino mass with cosmological data



WMAP-7 $\sum m_\nu < 1.3eV$ (95% cl)

Assuming 3 degenerate neutrinos

Komatsu et al (2010)

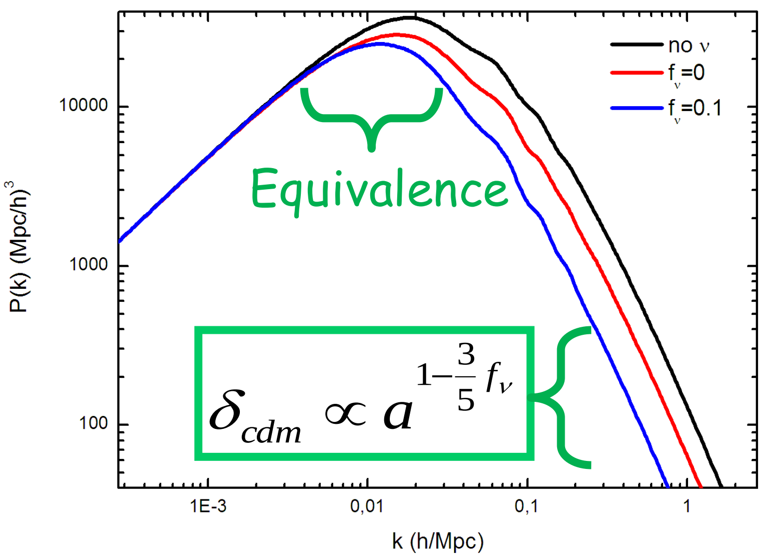
WMAP-7+H0+SDSS DR7

$\sum m_\nu < 0.44eV$ (95% cl)

Hannestad et al (2010)

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

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



But, are these limits stable?!

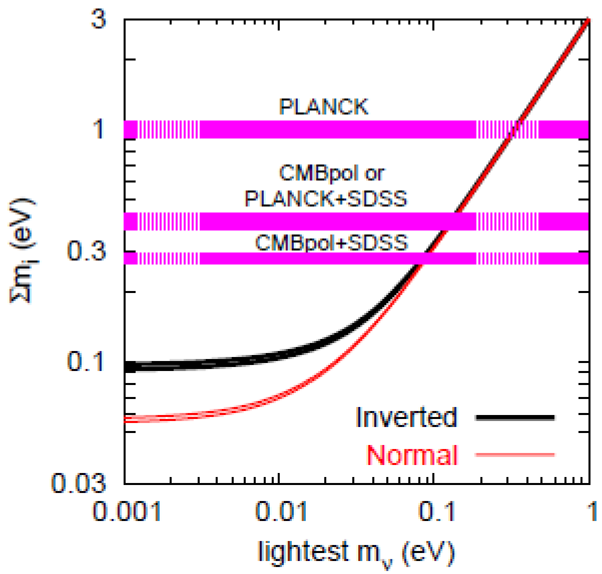
Current constraints

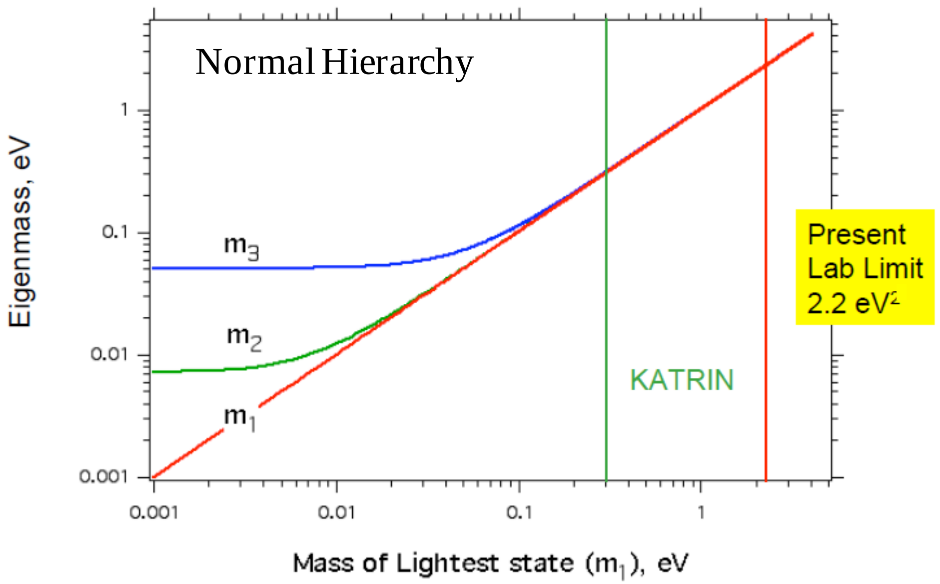
CMB + mpk (status) $\sum m_\nu < 0.44 eV$ model dependent!

Potential: Planck + Euclid $\sum m_\nu < 0.037 eV$

β-decay $m_\nu < 2.2 eV$ model independent

Potential: KATRIN $m_\nu < 0.2 eV$





Model dependence

Gonzalez Garcia, Maltoni & Salvado (2011)

Spatial flatness: $\sum m_\nu < 0.61 eV$

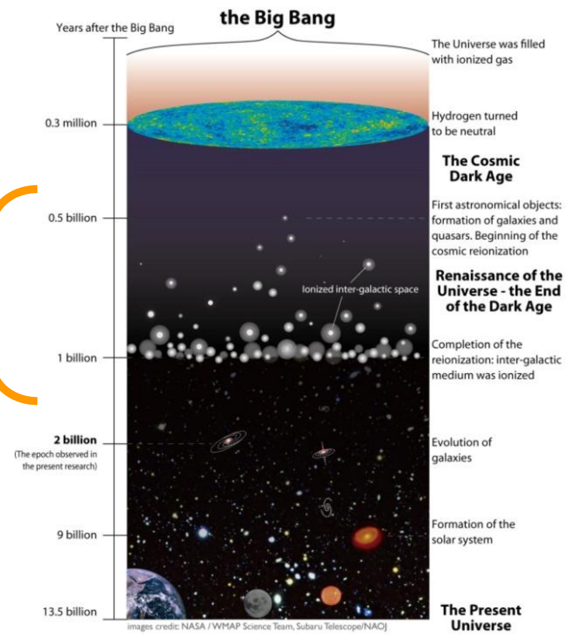
$\Omega_K \neq 0$: $\sum m_\nu < 1.5 eV$

Reionization:

Quasar

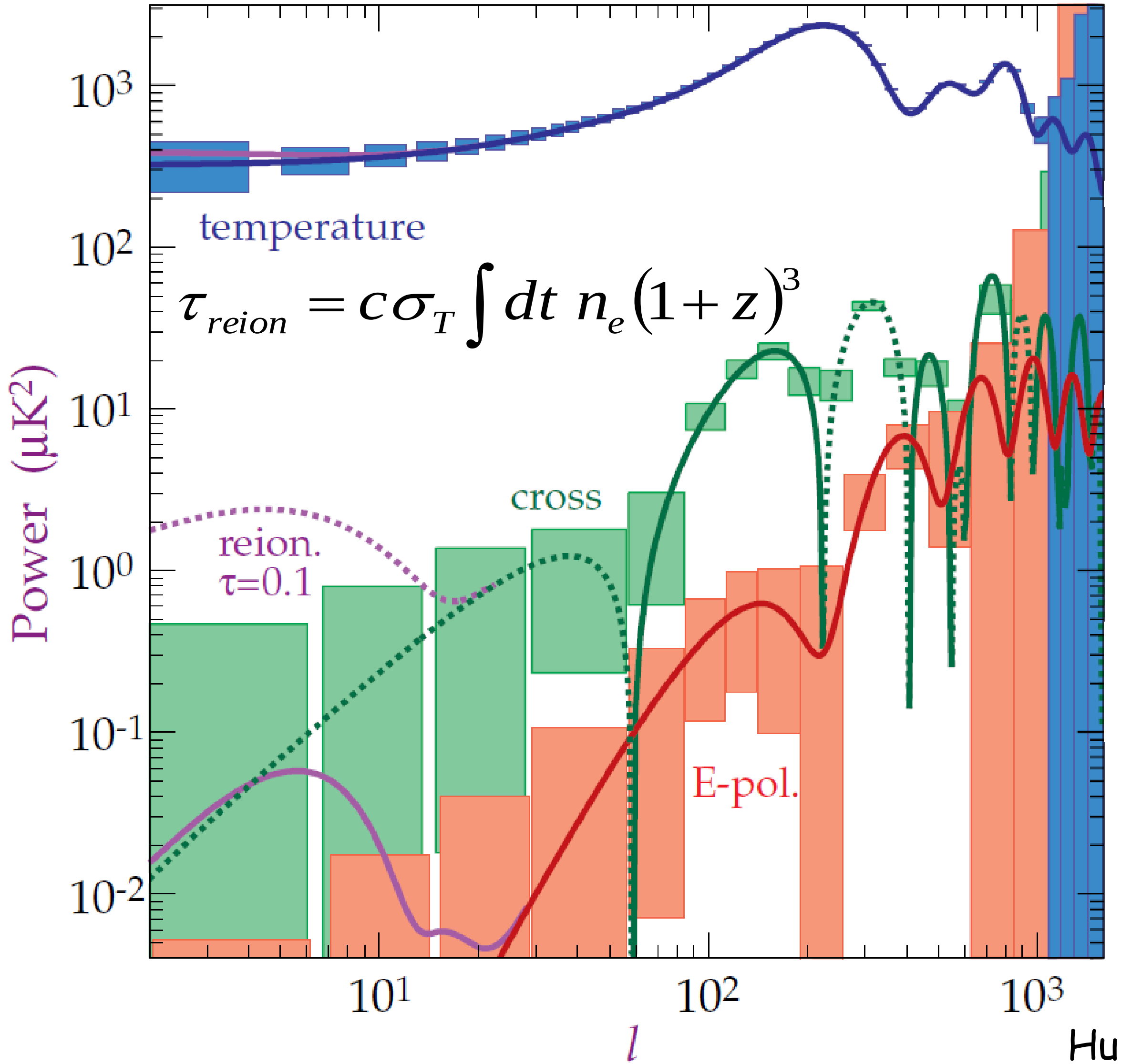
Reionization
20>z>6

Gunn-Peterson
effect



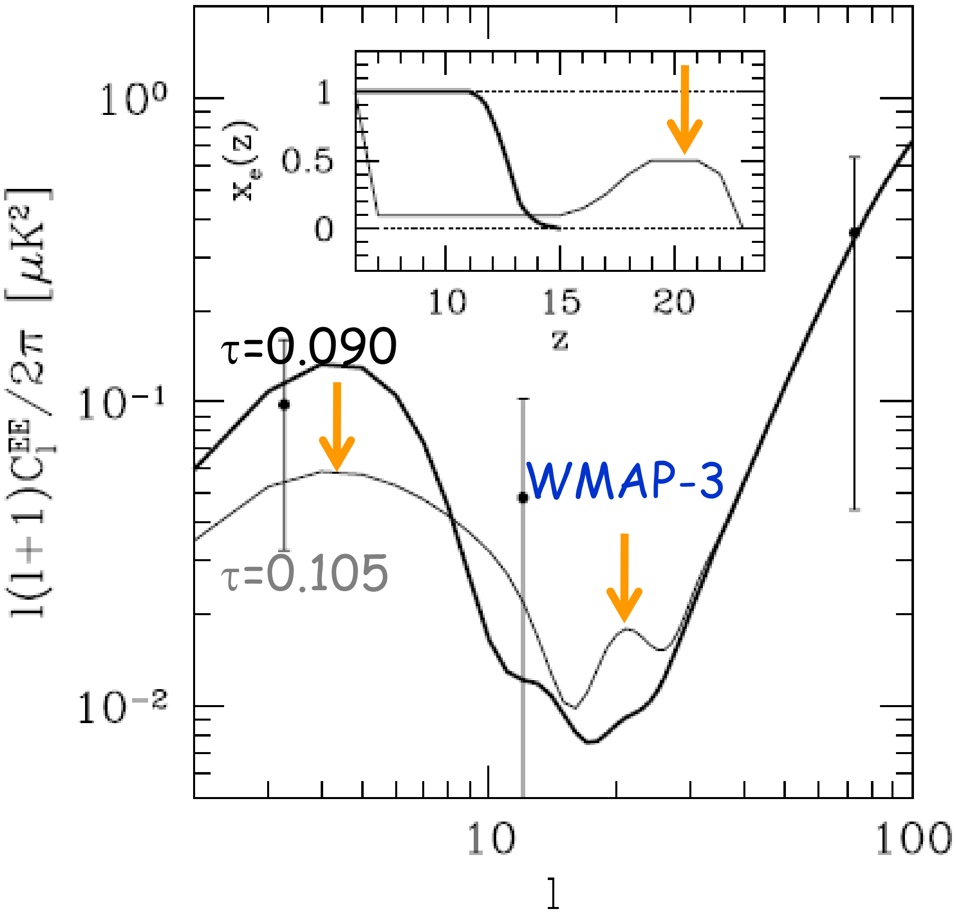
Ionized Universe
Neutral Universe
Dark Age
Reionized Universe

Reionization effects on CMB



Hu & White (1997)

Reionization models



Sudden reionization

Double peak reionization

Mortonson & Hu (2008)

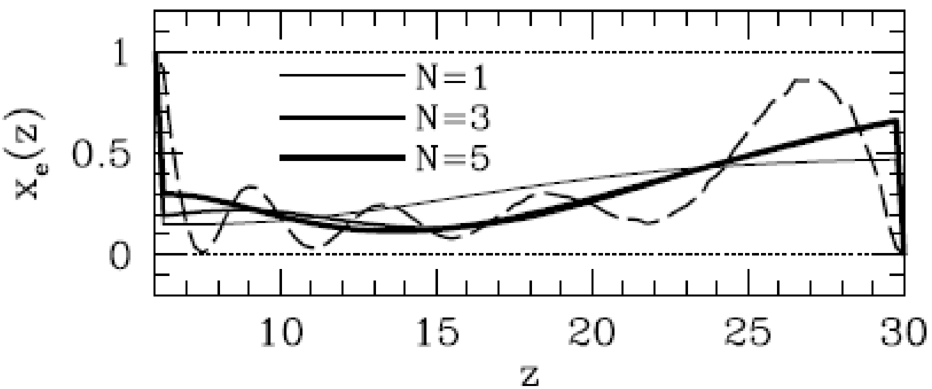
- There is no direct correspondence between z and l
- Moreover we don't know the behaviour of x_e between z=20 and z=6

Principal components

PCs: Fisher matrix eigenfunctions

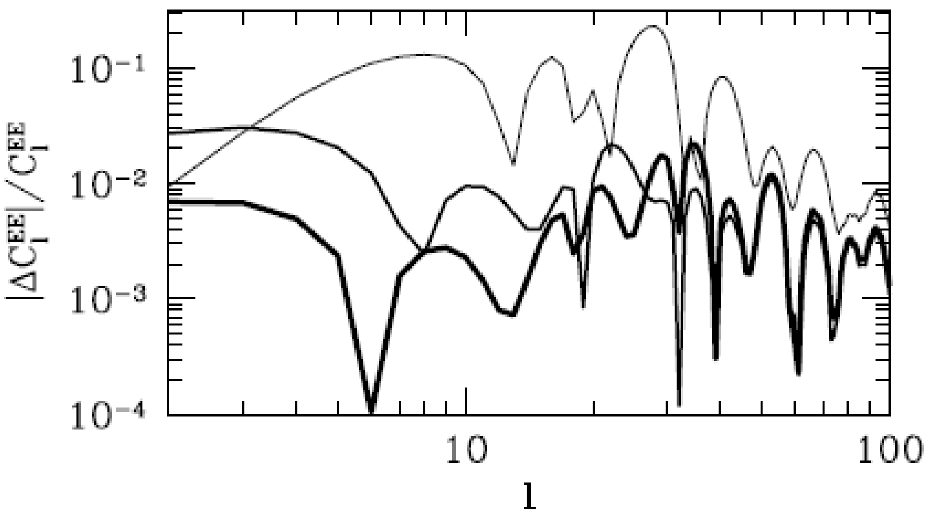
The first 3-5 modes provide all the informations about reionization that are relevant in the E mode polarization spectrum at large scales.

NB: This is not true for the whole reionization process.



Mortonson & Hu (2008)

The default case is with 10 PCs



Results

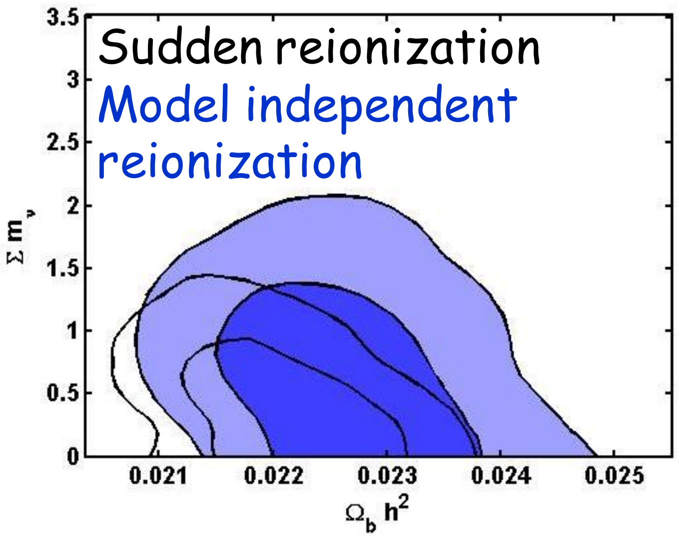
How do the constraints on the cosmological parameters (in particular on the neutrino mass) change, if, instead of using a sudden reionization model, we analyze the process of reionization through the Principal Components, making it independent from the model?

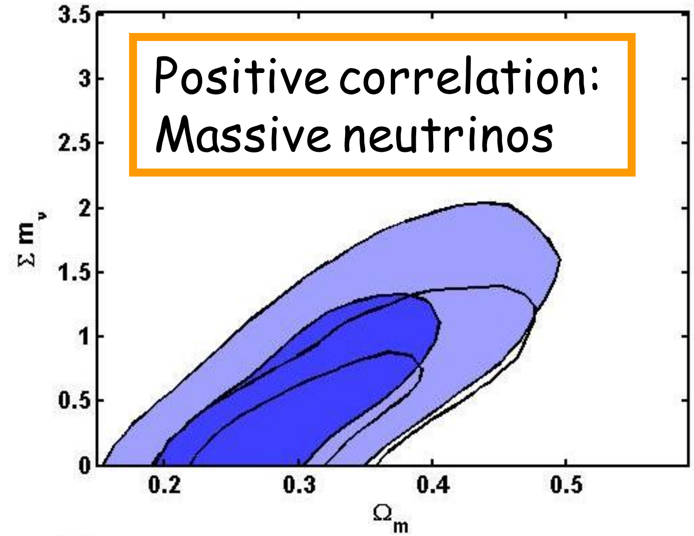
CosmoMC modifiyed to account for a model independent reionization with the first 5 PCs.

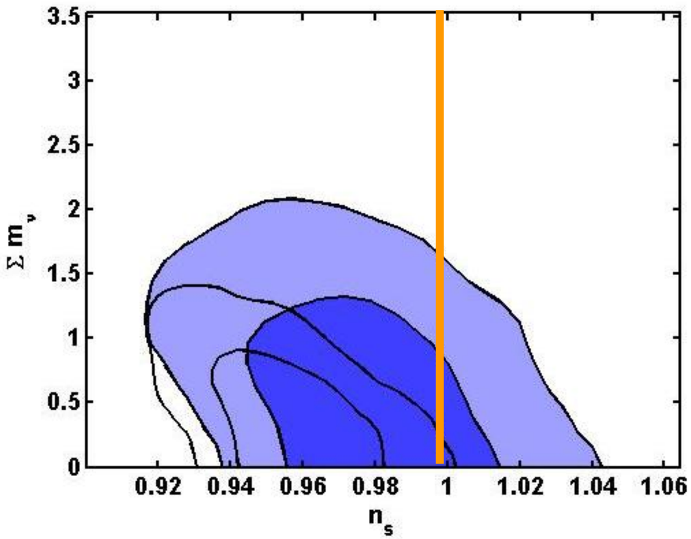
Parameters	WMAP7 (Sudden reionization)	WMAP7 (model independent reionization)
$\Omega_b h^2$	0.0221±0.0012	0.0226±0.0015
$\Omega_c h^2$	0.117±0.013	0.115±0.017
Ω_Λ	0.674±0.134	0.675±0.148
n_s	0.955±0.033	0.975±0.045
H_0	65.7±8.2	66.0±10.2
Σm_ν	<1.15eV(95%)	<1.66eV(95%)

Archidiacono et al., PRD (2010)

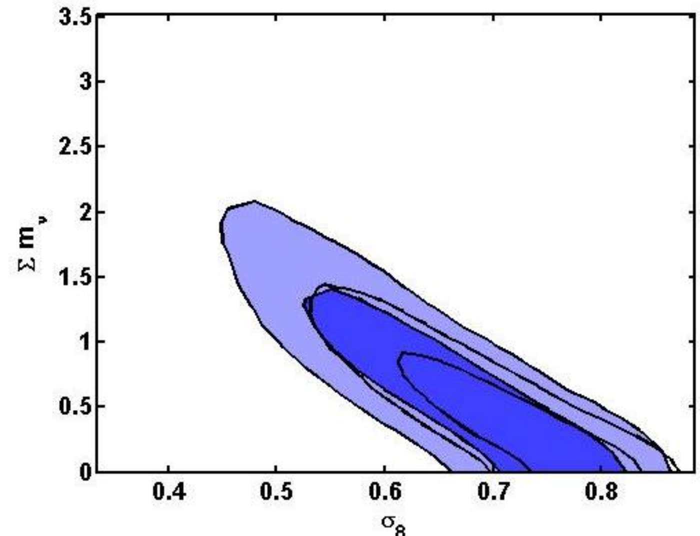
Results







The model independent reionization agrees with the Harrison Zel'dovich primordial spectrum within 1σ



Archidiacono et al., PRD (2010)

The number of effective relativistic degrees of freedom

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

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 :

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

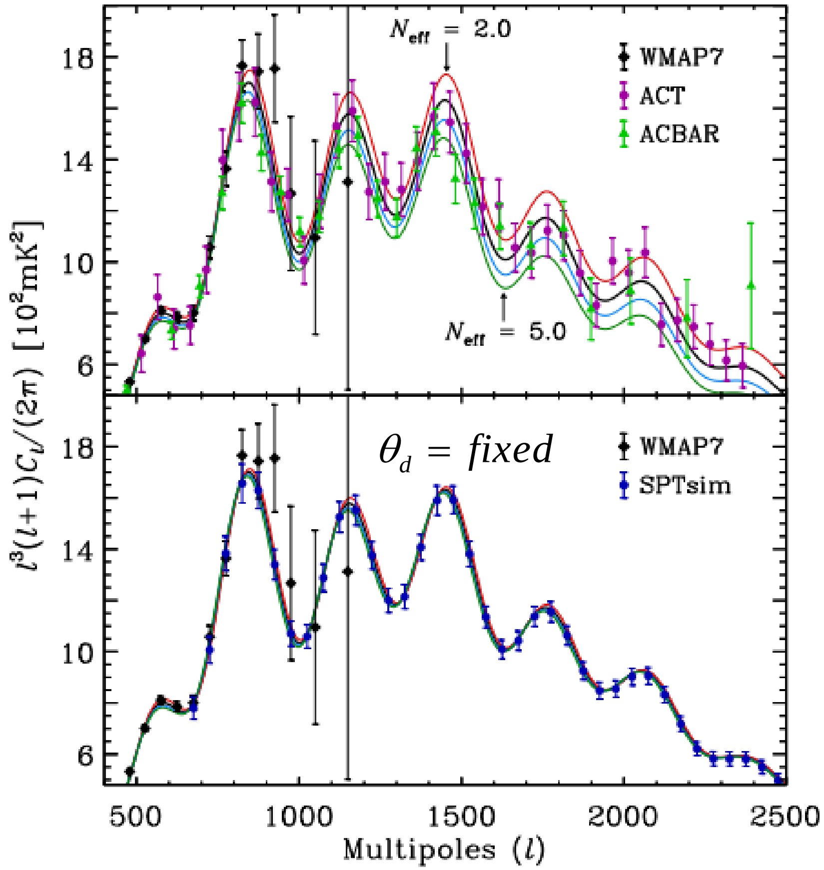
Probing the Neutrino number with CMB data

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

$$r_s = \int_0^{t_*} c_s \; dt / a \; = \int_0^{a_*} \frac{c_s}{a^2} \frac{da}{H}; \qquad \theta_s = \frac{r_s}{D_A}$$

and the damping scale at recombination:

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



Hou et al (2011)

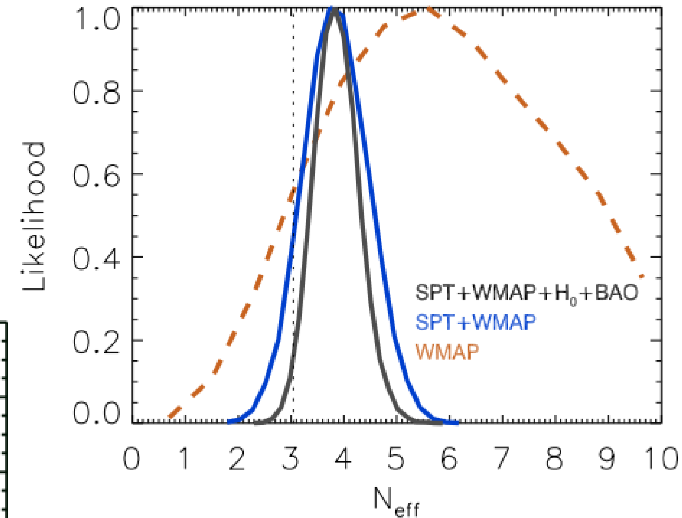
Moreover a larger neutrino number increases the early ISW as the neutrino mass .

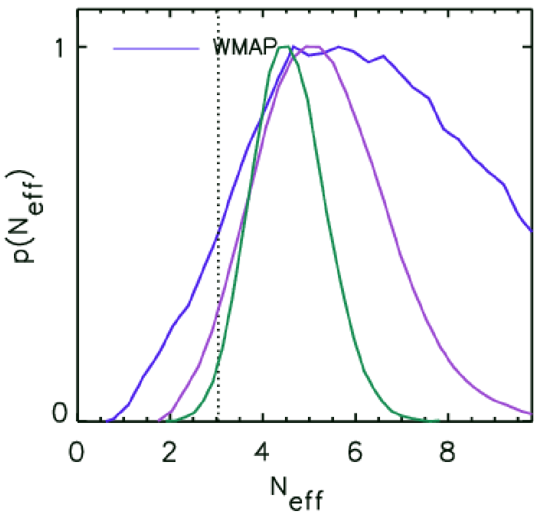
Hints for a Dark Radiation

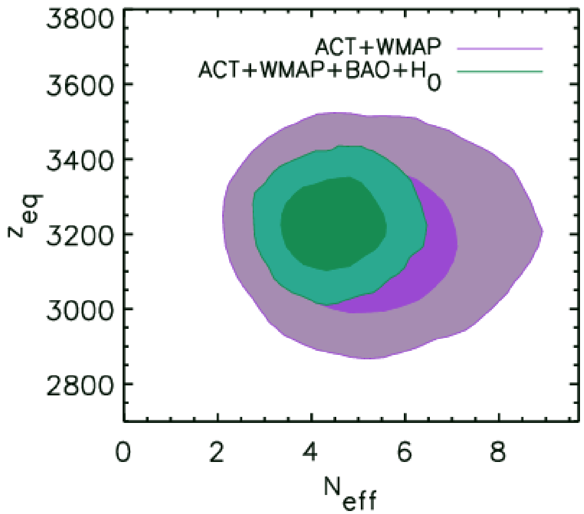
WMAP-7+SPT $N_{eff} = 3.85 \pm 0.62$

WMAP-7+SPT+BAO+H0 $N_{eff} = 3.86 \pm 0.42$

Keisler et al. (2011)







WMAP-7+ACT $N_{eff} = 5.3 \pm 1.3$

WMAP-7+ACT+BAO+H0 $N_{eff} = 4.8 \pm 0.8$

Dunkley et al. (2010)

What Dark Radiation is made of?

Exotic models:

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

If N_{eff} is not close to an integer, it could be not made of neutrinos!

Massless neutrinos equations of perturbations:

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

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

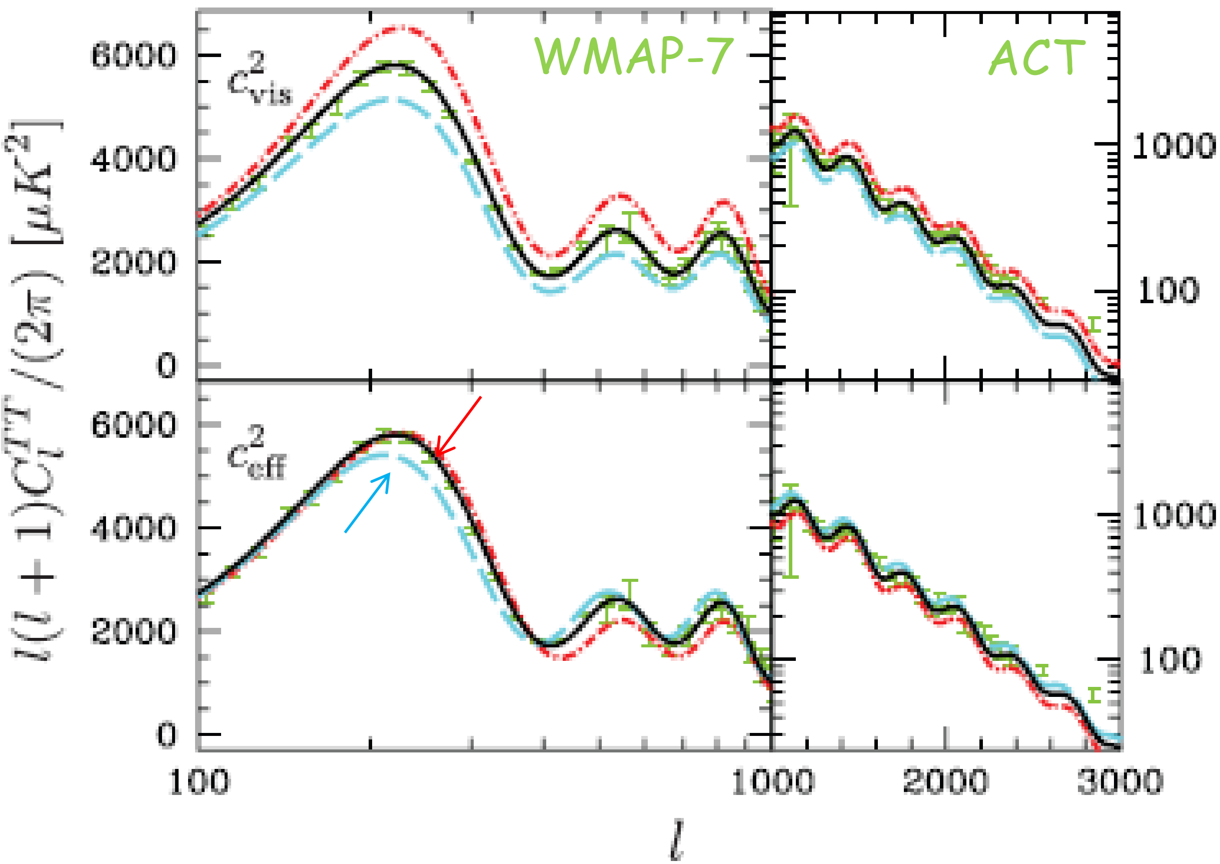
$$\dot{\pi}_\nu = 3c_{vis}^2\left(\frac{2}{5}q_\nu + \frac{8}{15}\sigma\right) - \frac{3}{5}kF_{\nu,3},$$

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

c_{eff}^2 The effective sound speed

c_{vis}^2 The viscosity speed

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)

Results

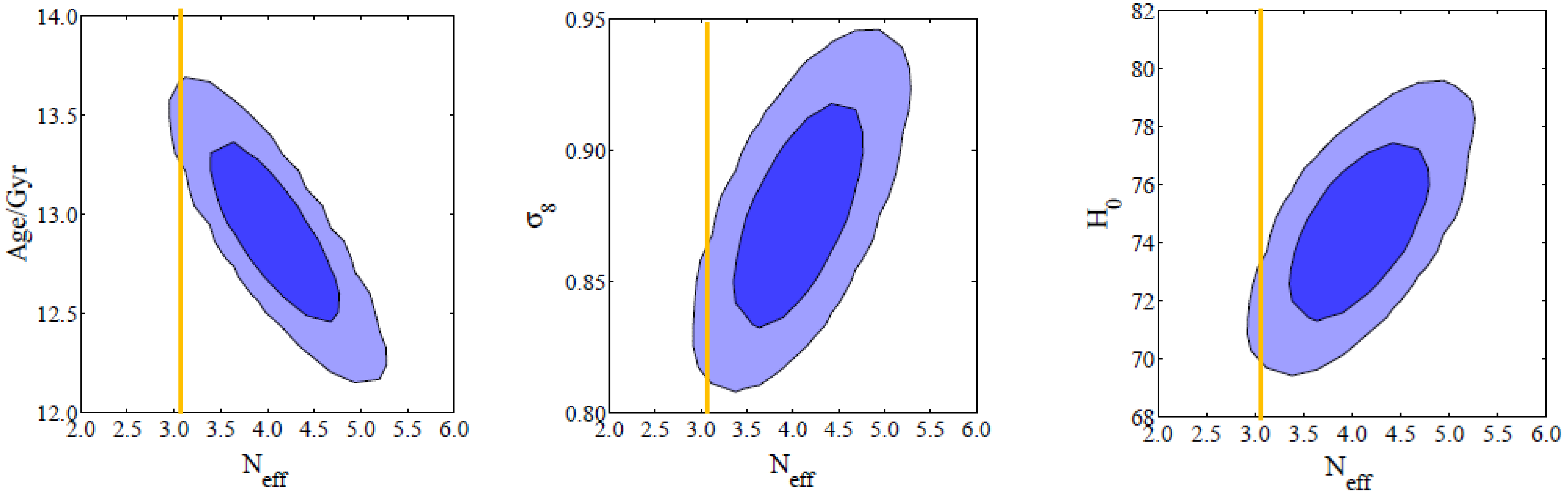
	$N_{eff}, c^2_{eff}, c^2_{vis}$	N_{eff}
N_{eff}	4.08±0.71	3.89±0.70
c^2_{eff}	0.312±0.026	1/3
c^2_{vis}	0.29±0.21	1/3

c^2_{eff} and c^2_{vis} consistent with 1/3

2σ evidence for $N_{eff} > 3.046$

Archidiacono, Calabrese, Melchiorri, PRD (2011)

Cosmological parameters degeneracies



Extra Dark Radiation
12.8 Gyrs

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

Archidiacono, Calabrese, Melchiorri, PRD (2011)

Results

	$N_{\nu s}$, c^2_{eff}, c^2_{vis}	$N_{\nu s}$, c_{vis}	$N_{\nu s}$, c^2_{eff}, c^2_{vis}, Σm_ν
$N_{\nu s}$	1.10±0.79	1.46±0.76	1.12±0.86
c^2_{eff}	0.24±0.13	1/3	0.24±0.13
c^2_{vis}	<0.91 (95%cl)	<0.74 (95%cl)	<0.92 (95%cl)
Σm_ν	—	—	<0.79 eV (95%cl)

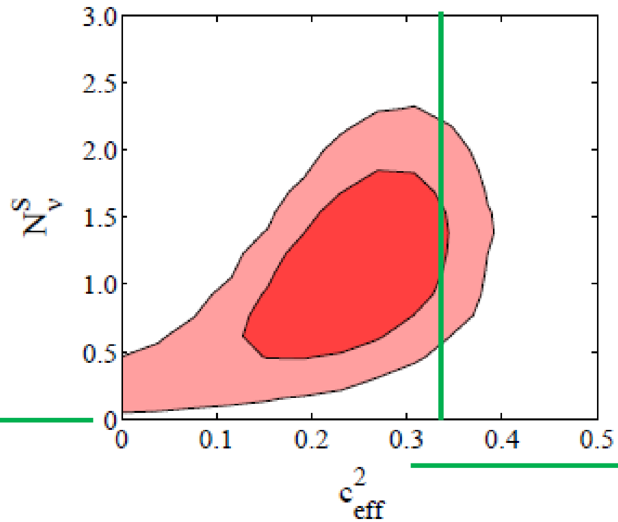
$N_{\nu s}$ detection at 2σ

c^2_{eff} and c^2_{vis} consistent with 1/3 within 1σ

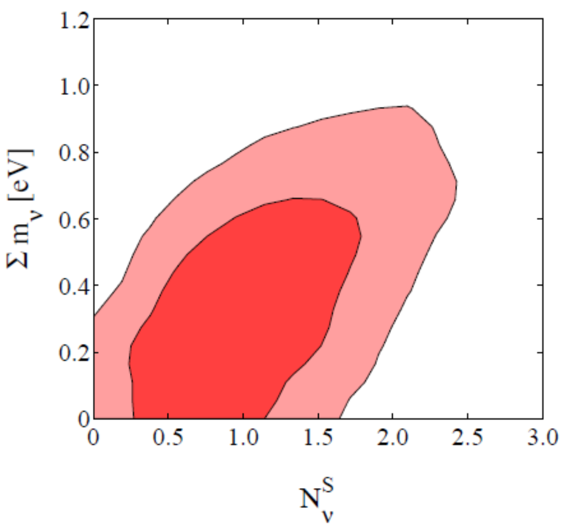
Archidiacono, Calabrese, Melchiorri, PRD (2011)

Neutrino parameters degeneracies

$N_{\nu s}$ detection at 2σ



c^2_{eff} consistent with 1/3 within 1σ



Degeneracy between the sum of the masses of the active neutrinos and the number of sterile neutrinos

Archidiacono, Calabrese, Melchiorri, PRD (2011)

Conclusions

• Neutrino Masses

We investigated the influence of the theoretical assumptions about reionization on the cosmological neutrino mass bounds. We saw that the cosmological constraints on the neutrino masses are weakened if we parametrize the reionization process through the Principal Components, making it independent from the model.

• Neutrino Number

We found a 2σ evidence for Dark Radiation.

Moreover, the values we get for the effective sound speed and viscosity speed are consistent with the value of 1/3 that a free-streaming relativistic component should have.

So sterile neutrinos are a good candidate for extra Dark Radiation.

Thank you!