(Some) New Constraints on The Dark Side

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CHARTA COSMOGRAPHICA, CVM VENTORVM PROPRIA NATVRA ET OPERATIONE.

Circius, Noordt noordtweſt. SEPTEN Septentrionalis, Noordt. TRIO Aquilo, Noordt noordt ooſt.

Argeſtis. Weſt noordtweſt.

OCCI Zephyrus DENS. Weſt,

Libs Weſt zuydtweſt.

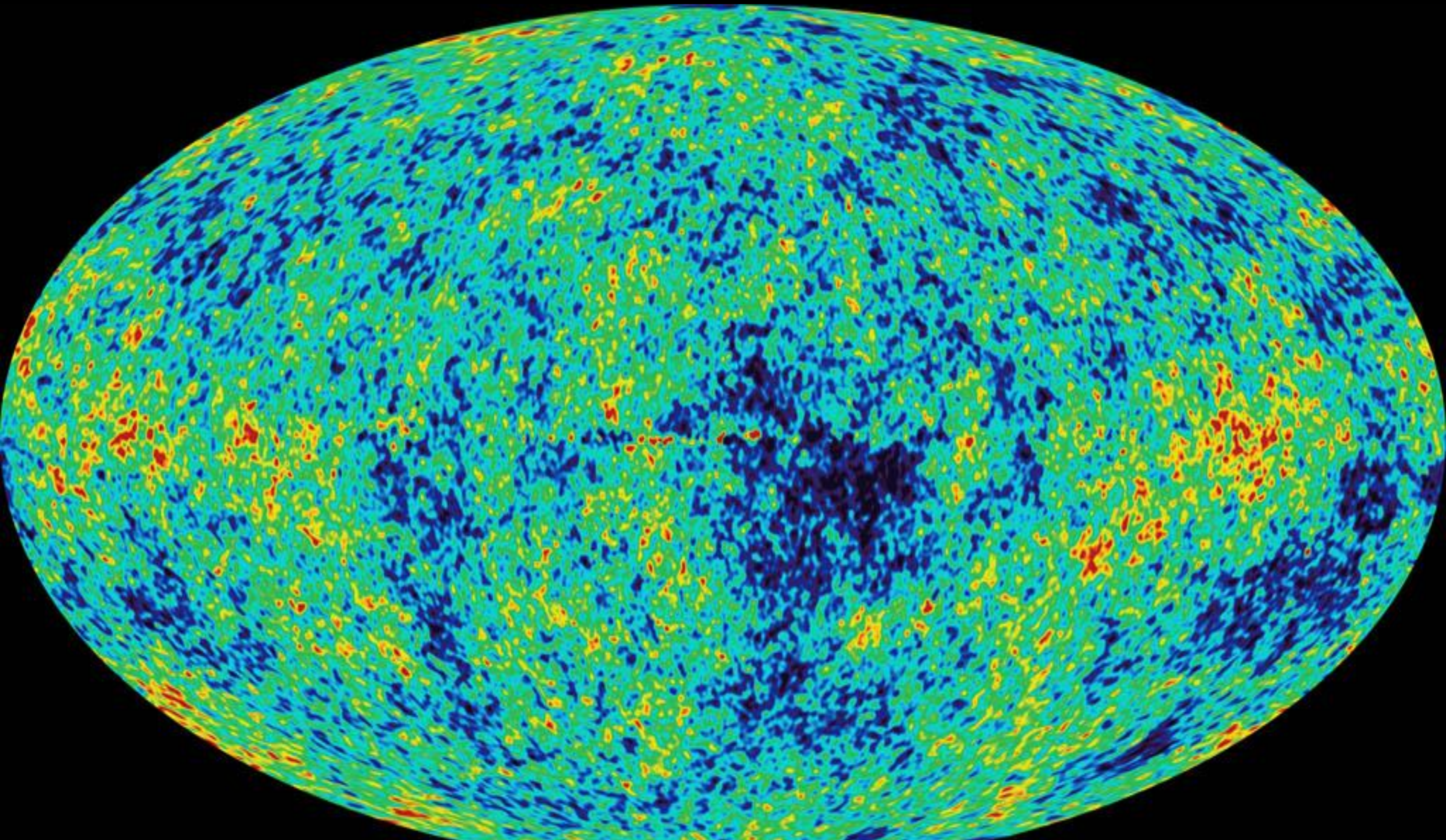
Helleſpontius Ooſt noordtooſt.

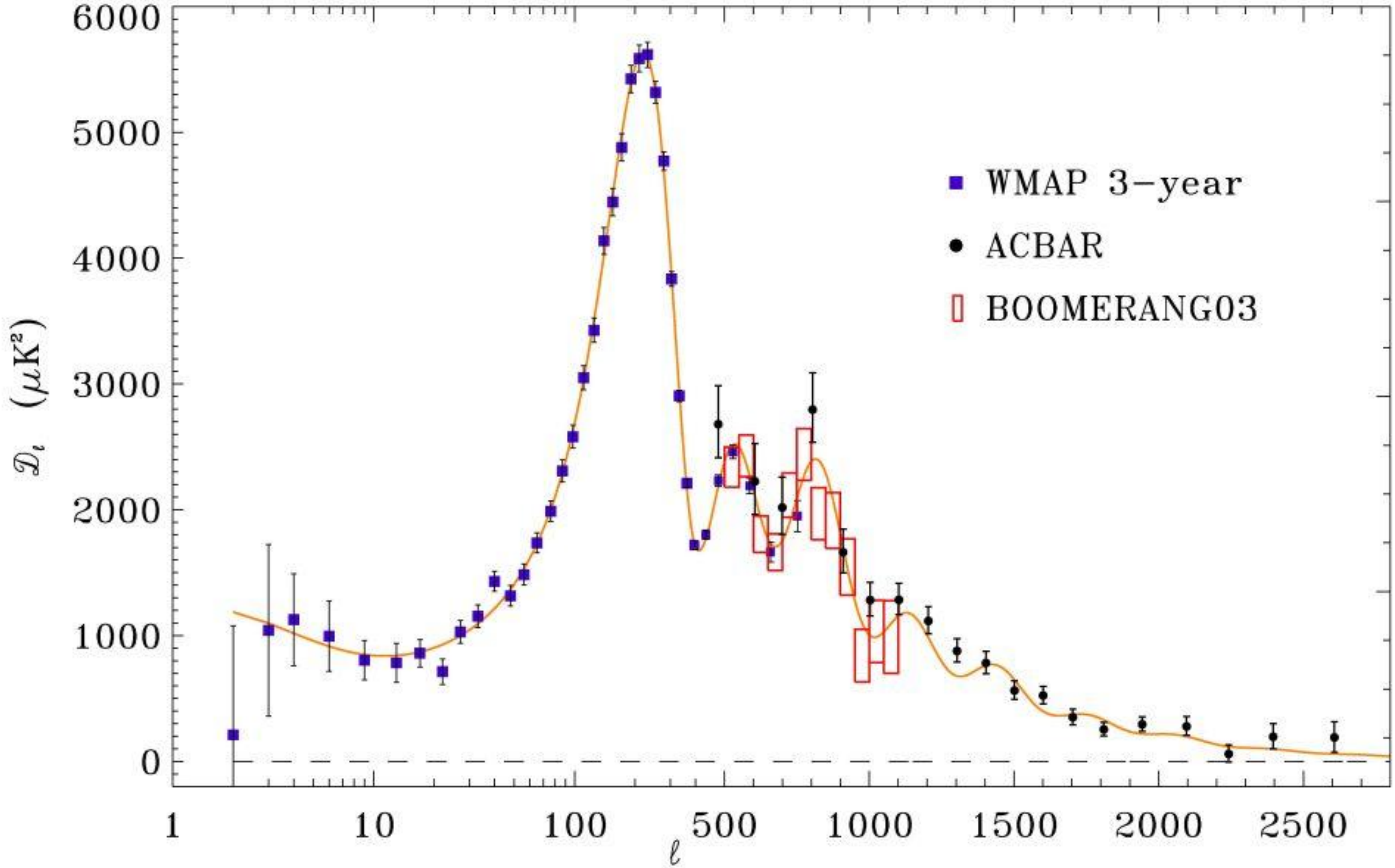
ORI Subſolanus ENS. Ooſt.

Vulturnus. Ooſt zuydtooſt.

Auſtroafricus. Zuydt zuydtweſt. MERI Auſter, Zuydt DIES. Euroaſter, Zuydt zuydtooſt. I

A.D. 1544

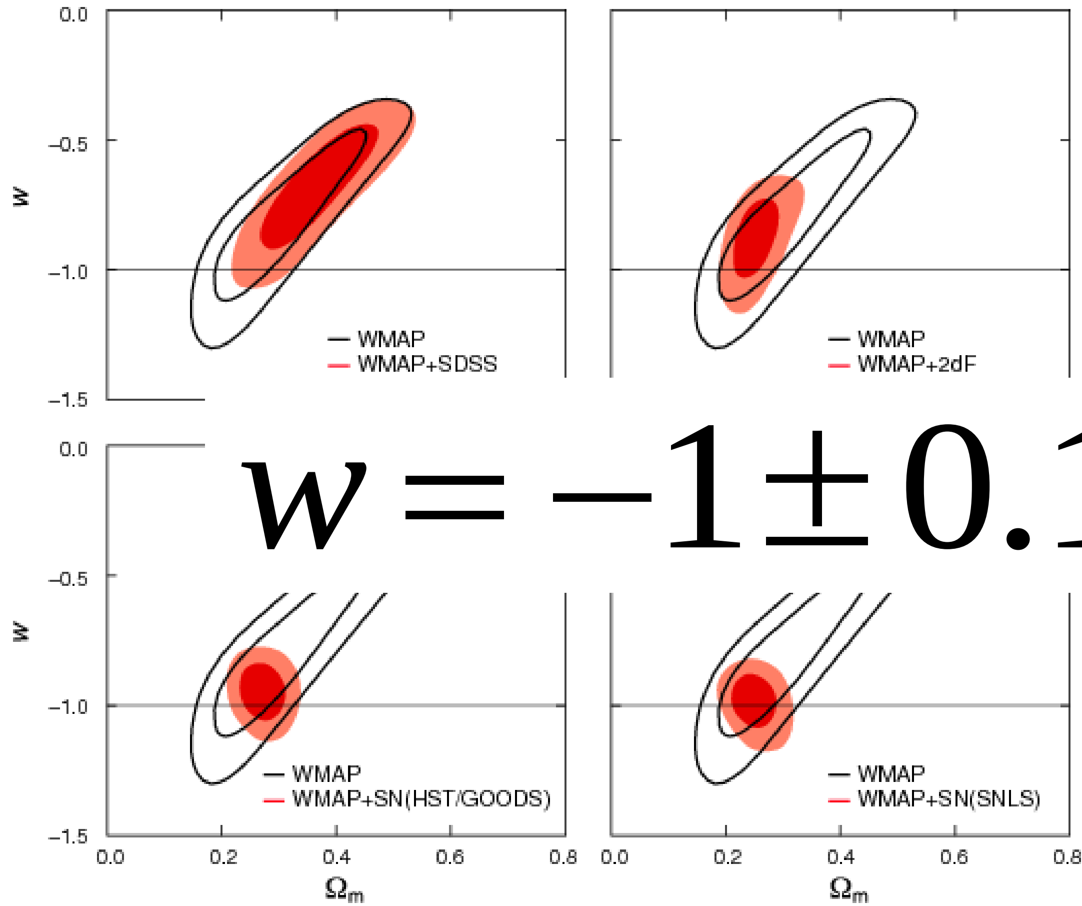




6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ (μK^2)
WMAP 3-year
ACBAR
BOOMERANG03
1
10
100
500
1000
1500
2000
2500
ℓ

Monsters in Modern Cosmology

- -Dark Energy
- -Inflation
- -Baryonic Matter
- -(Cold) Dark Matter
- -Neutrinos



$$w = -1 \pm 0.1$$

WMAP Cosmological Parameters, Spergel et al., 2007

Dark Energy Parametrizations (Just a Few...)

$$w(a) = w_0$$

Wanilla Parametrization

$$w(a) = w_0 + w_1(1-a)$$

CPL Parametrization

$$w(a) = w_0 w_1 \frac{a^q + a_s^q}{w_1 a^q + w_0 a_s^q}$$

Hannestad Mortsell Parametrization

$$w(a) = \frac{w_0}{-w_0 + (1+w_0)a^{-3(1+\alpha)}}$$

Unified Models: Chaplygin

When did Cosmic acceleration start?

In cosmology we can define two very important epochs:

Redshift and Time of
Matter-Dark energy equality

$$\Omega_X(z_{eq}) = \Omega_M(z_{eq})$$
$$t(z_{eq})$$

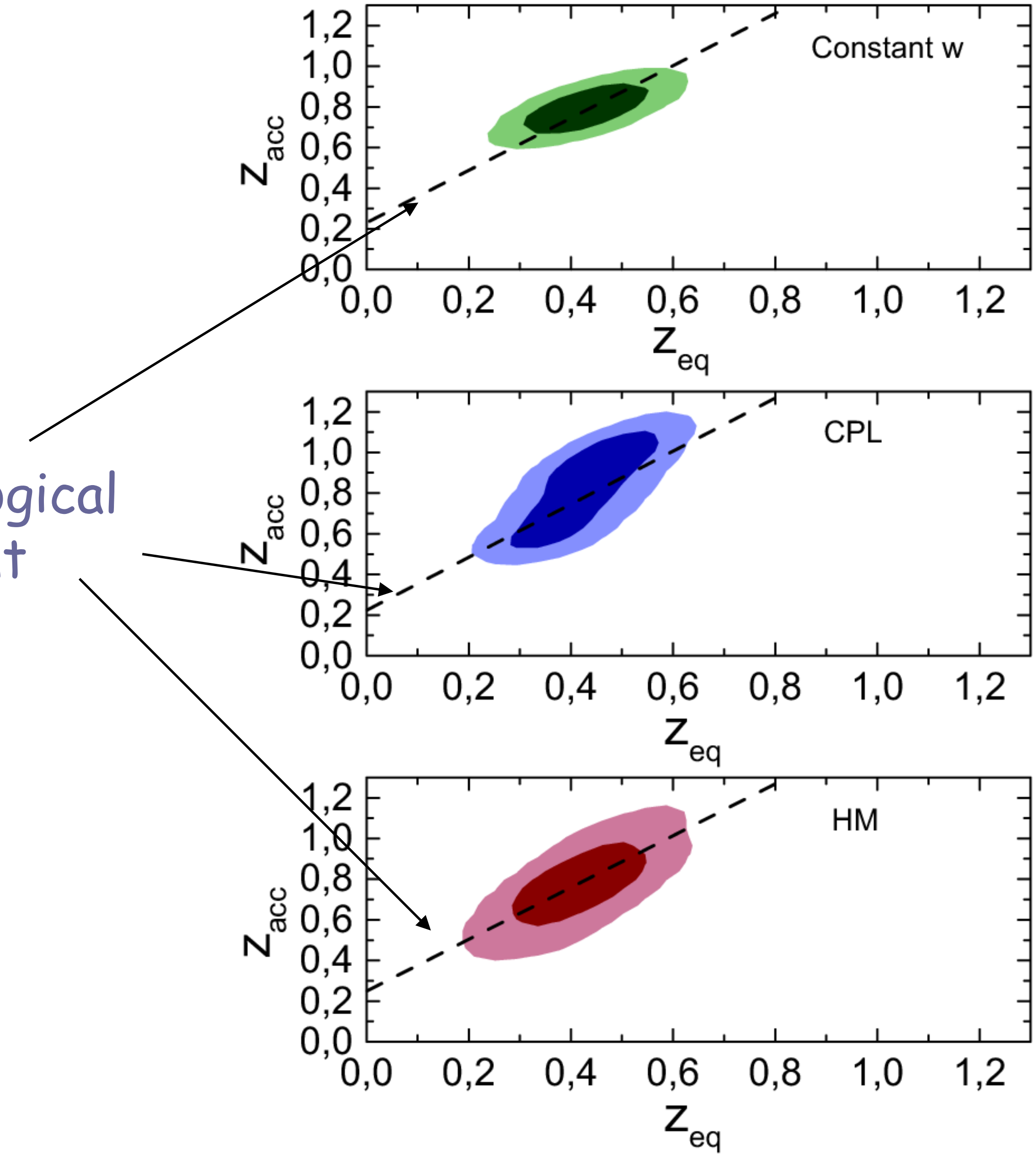
Redshift and Time of
onset of cosmic acceleration

$$q(z_{acc}) = -\frac{\ddot{a}}{aH^2}(z_{acc}) = 0$$
$$t(z_{acc})$$

Those two epochs can be different, for the case of a cosmological constant we have:

$$z_{acc} = 2^{1/3}(1+z_{eq}) - 1$$

But we may have a different relation for different dark Energy models...



Cosmological Constant

$$w(a) = w_0$$

$$w(a) = w_0 + w_1(1-a)$$

$$w(a) = w_0 w_1 \frac{a^q + a_s^q}{w_1 a^q + w_0 a_s^q}$$

Melchiorri, Pagano, Pandolfi, PRD, 2007

When did Cosmic acceleration start?

Dataset WMAP+	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
Alone	$0.47^{+0.09}_{-0.09}$	$4.7^{+0.5}_{-0.5}$	$0.86^{+0.11}_{-0.12}$	$7.0^{+0.4}_{-0.4}$	$13.8^{+0.3}_{-0.3}$
+SDSS	$0.40^{+0.08}_{-0.07}$	$4.3^{+0.5}_{-0.5}$	$0.77^{+0.10}_{-0.10}$	$6.7^{+0.3}_{-0.3}$	$13.8^{+0.3}_{-0.2}$
+2dF	$0.48^{+0.06}_{-0.05}$	$4.8^{+0.3}_{-0.3}$	$0.87^{+0.07}_{-0.07}$	$7.1^{+0.2}_{-0.3}$	$13.8^{+0.2}_{-0.2}$
+GOLD	$0.38^{+0.06}_{-0.06}$	$4.1^{+0.4}_{-0.4}$	$0.74^{+0.08}_{-0.08}$	$6.6^{+0.3}_{-0.3}$	$13.8^{+0.2}_{-0.2}$
+SNLS	$0.45^{+0.07}_{-0.06}$	$4.6^{+0.4}_{-0.4}$	$0.83^{+0.08}_{-0.08}$	$6.9^{+0.3}_{-0.3}$	$13.8^{+0.1}_{-0.1}$
+all	$0.40^{+0.04}_{-0.04}$	$4.3^{+0.3}_{-0.3}$	$0.76^{+0.05}_{-0.05}$	$6.7^{+0.2}_{-0.2}$	$13.9^{+0.1}_{-0.2}$

TABLE I: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., in comparison with various datasets for ΛCDM.

Model	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
$w \neq -1$	$0.48^{+0.07}_{-0.07}$	$4.9^{+0.4}_{-0.5}$	$0.81^{+0.06}_{-0.06}$	$6.9^{+0.2}_{-0.2}$	$13.9^{+0.1}_{-0.2}$
$\Omega_{tot} \neq 1$	$0.32^{+0.10}_{-0.10}$	$3.9^{+0.8}_{-0.8}$	$0.68^{+0.10}_{-0.10}$	$6.9^{+0.3}_{-0.3}$	$15.1^{+0.8}_{-0.9}$
$dn/d\ln k \neq 0$	$0.37^{+0.05}_{-0.05}$	$4.1^{+0.3}_{-0.3}$	$0.72^{+0.06}_{-0.10}$	$6.6^{+0.2}_{-0.2}$	$14.1^{+0.1}_{-0.2}$
$N^{\nu}_{eff} \neq 3$	$0.40^{+0.05}_{-0.06}$	$4.3^{+0.5}_{-0.4}$	$0.77^{+0.06}_{-0.06}$	$6.8^{+0.6}_{-0.6}$	$14.0^{+1.2}_{-1.4}$
$\Sigma m_{\nu} > 0$	$0.37^{+0.04}_{-0.04}$	$4.2^{+0.3}_{-0.3}$	$0.73^{+0.05}_{-0.05}$	$6.7^{+0.2}_{-0.2}$	$14.1^{+0.2}_{-0.2}$

TABLE II: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., under differing theoretical assumptions for the underlying cosmological model.

Model	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
$w \neq -1$	$0.43^{+0.07}_{-0.06}$	$4.5^{+0.5}_{-0.5}$	$0.79^{+0.07}_{-0.07}$	$6.8^{+0.3}_{-0.3}$	$13.8^{+0.1}_{-0.2}$
CPL	$0.44^{+0.11}_{-0.10}$	$4.5^{+0.7}_{-0.6}$	$0.80^{+0.16}_{-0.17}$	$6.8^{+0.6}_{-0.7}$	$13.9^{+0.2}_{-0.2}$
HM	$0.45^{+0.10}_{-0.10}$	$4.6^{+0.6}_{-0.7}$	$0.79^{+0.14}_{-0.14}$	$6.7^{+0.6}_{-0.5}$	$13.9^{+0.2}_{-0.3}$
SQ	–	–	$0.80^{+0.08}_{-0.08}$	$6.8^{+0.3}_{-0.2}$	$13.8^{+0.2}_{-0.2}$

TABLE III: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., for different theoretical assumptions about the nature of the dark energy component.

Results are reasonably consistent between datasets (tension between 2dF and SDSS) and DE parametrizations.
Age constraints change a lot if you include extra hot dark matter or Curvature.

AM, Luca Pagano, Stefania Pandolfi arXiv:0706.131
Phys. Rev. D **76**, 041301 (2007)

Bayesian Model Selection

Current cosmological data are in agreement with more complicated Dark energy parametrizations, but do we need more parameters ?
More complicated models should give better fits to the data.
In model selection we have to pay the larger number of parameters (see e.g. Mukherjee et al., 2006):

$$E = P(\vec{D} \mid H) = \int P(\vec{D} \mid \vec{\theta}, H) P(\vec{\theta}, H)$$

Evidence

Likelihood

Prior

Jeffrey(1961):

$$1 < \Delta \ln(E) < 2.5 \quad \text{Substantial}$$

$$2.5 < \Delta \ln(E) < 5 \quad \text{Strong}$$

$$5 < \Delta \ln(E) \quad \text{Decisive}$$

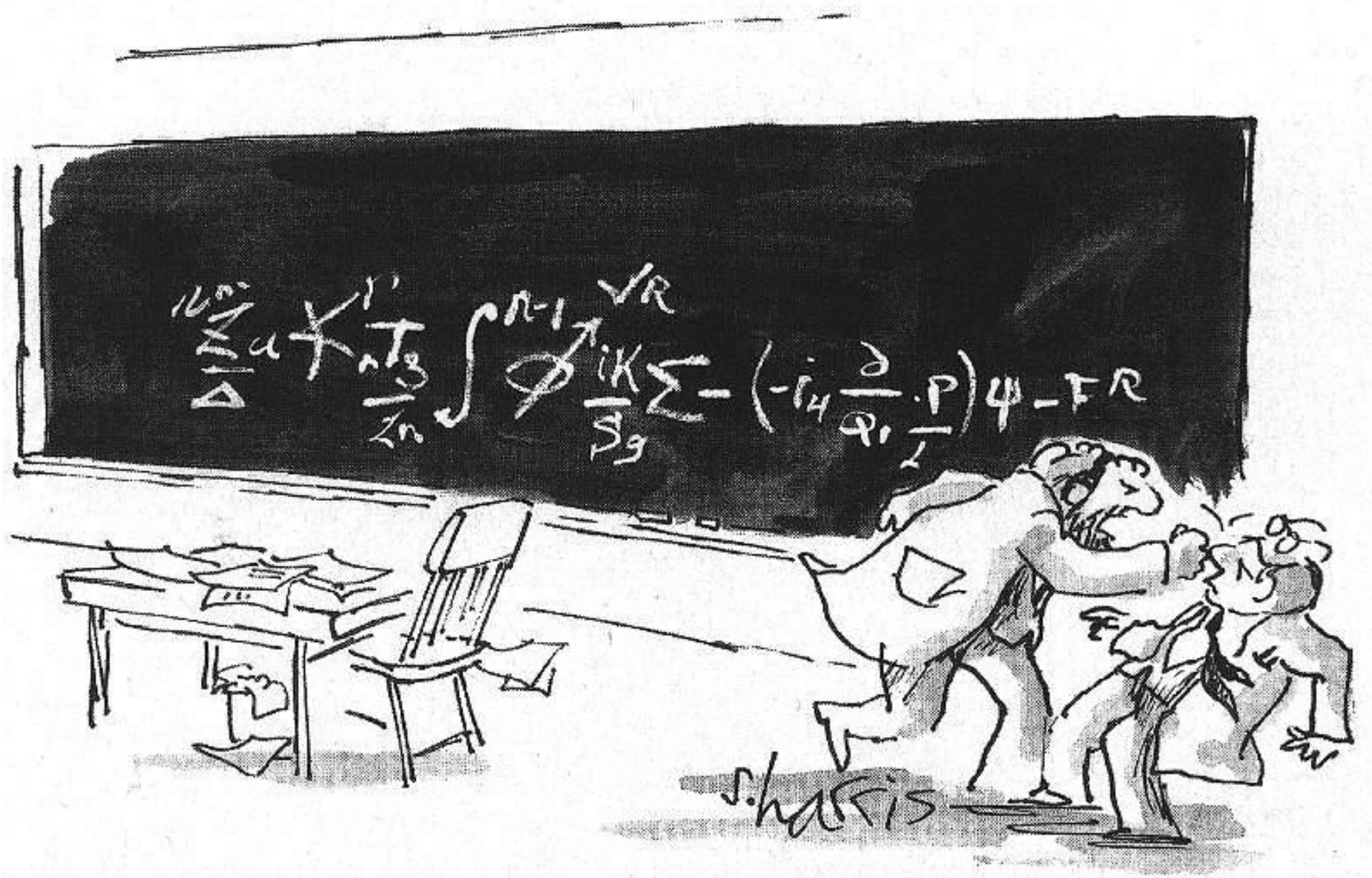
Constraints	$\Delta \ln E$	χ^2_{Min}	Model
$\Omega_m = 0.28 \pm 0.03$ $H_0 = 64.5 \pm 0.09$	0.0	24.39	I
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w < -0.84$ at 1σ $w < -0.73$ at 2σ	-0.222 ± 0.005	22.43	II
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w = -0.86 \pm 0.1$	-1.027 ± 0.002	22.43	III
$\Omega_m = 0.28 \pm 0.04$ $H_0 = 63.8 \pm 1.4$ $w_0 = -1.03 \pm 0.25$ $w_a = 0.76^{+--}_{-0.91}$	-1.118 ± 0.015	21.47	IV
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.5 \pm 1.1$ $w_0 = -0.85 \pm 0.12$ $w_1 = -0.81 \pm 0.21$ a_s unconstrained q unconstrained	-1.059 ± 0.008	21.38	V
$\Omega_m = 0.30 \pm 0.05$ $H_0 = 63.5^{+1.8}_{-1.2}$ $w_0 = -1.08^{+0.24}_{-0.30}$ $w_1 = 0.78^{+0.83}_{-0.57}$	-1.834 ± 0.006	21.52	VI

More Parameters

Current data:
"Substantial"
Evidence
for a cosmologica
constant…

P. Serra, A. Heavens,
A. Melchiorri
Astro-ph/0701338
MNRAS, 379, 1,169
2007

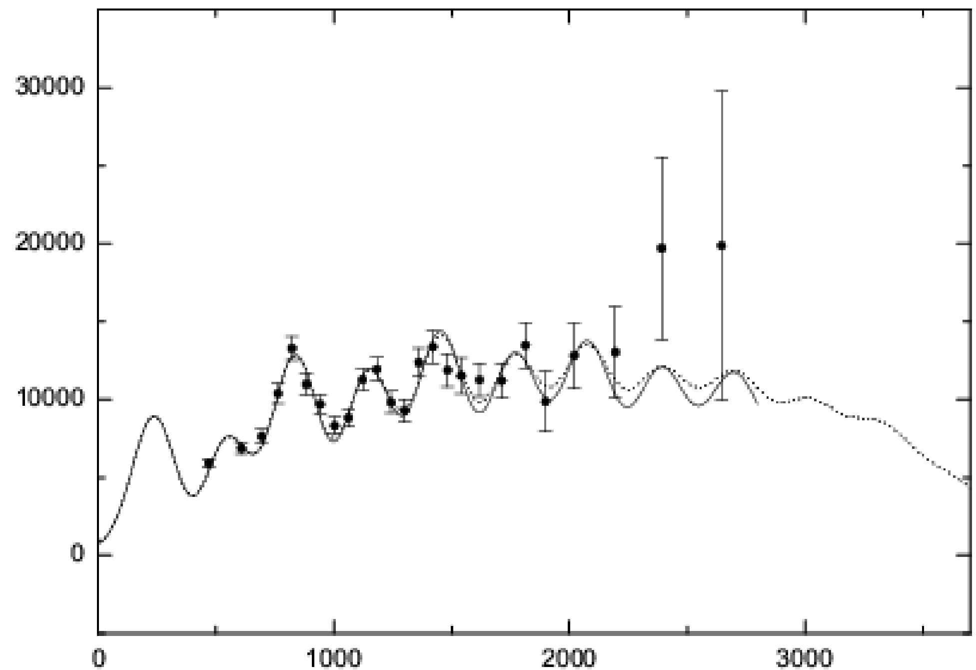
A direct proof for modified gravity ?



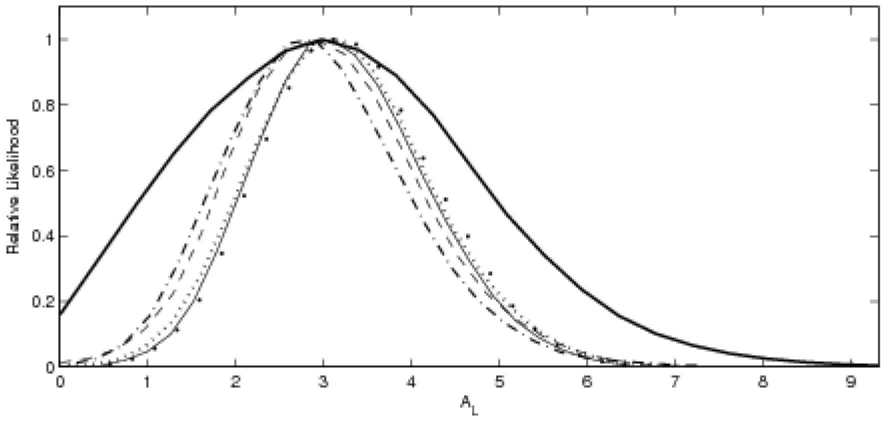
"YOU WANT PROOF? I'LL GIVE YOU PROOF!"

Too much lensing in the CMB ?

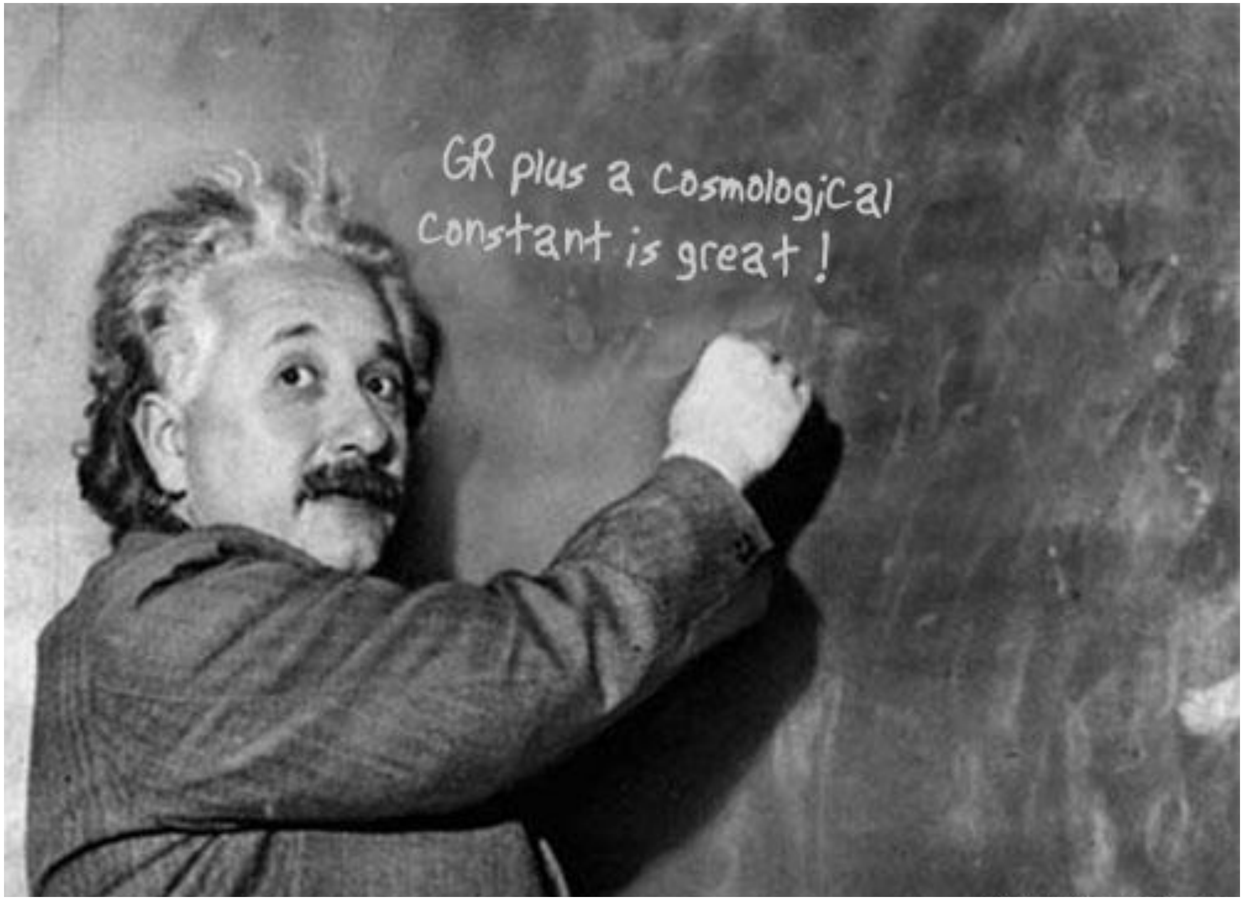
Weak Lensing is related to the growth and amplitude of CDM Perturbations.
ACBAR data seems to Suggest 3 times more Lensing than expected.



Systematics ?
Modified Gravity ?
LCDM excluded at 2.5σ



Calabrese, Slosar, Melchiorri, Smoot, Zahn, arXiv:0803.2309


GR plus a cosmological
constant is great!

Monsters in Modern Cosmology

-Dark Energy

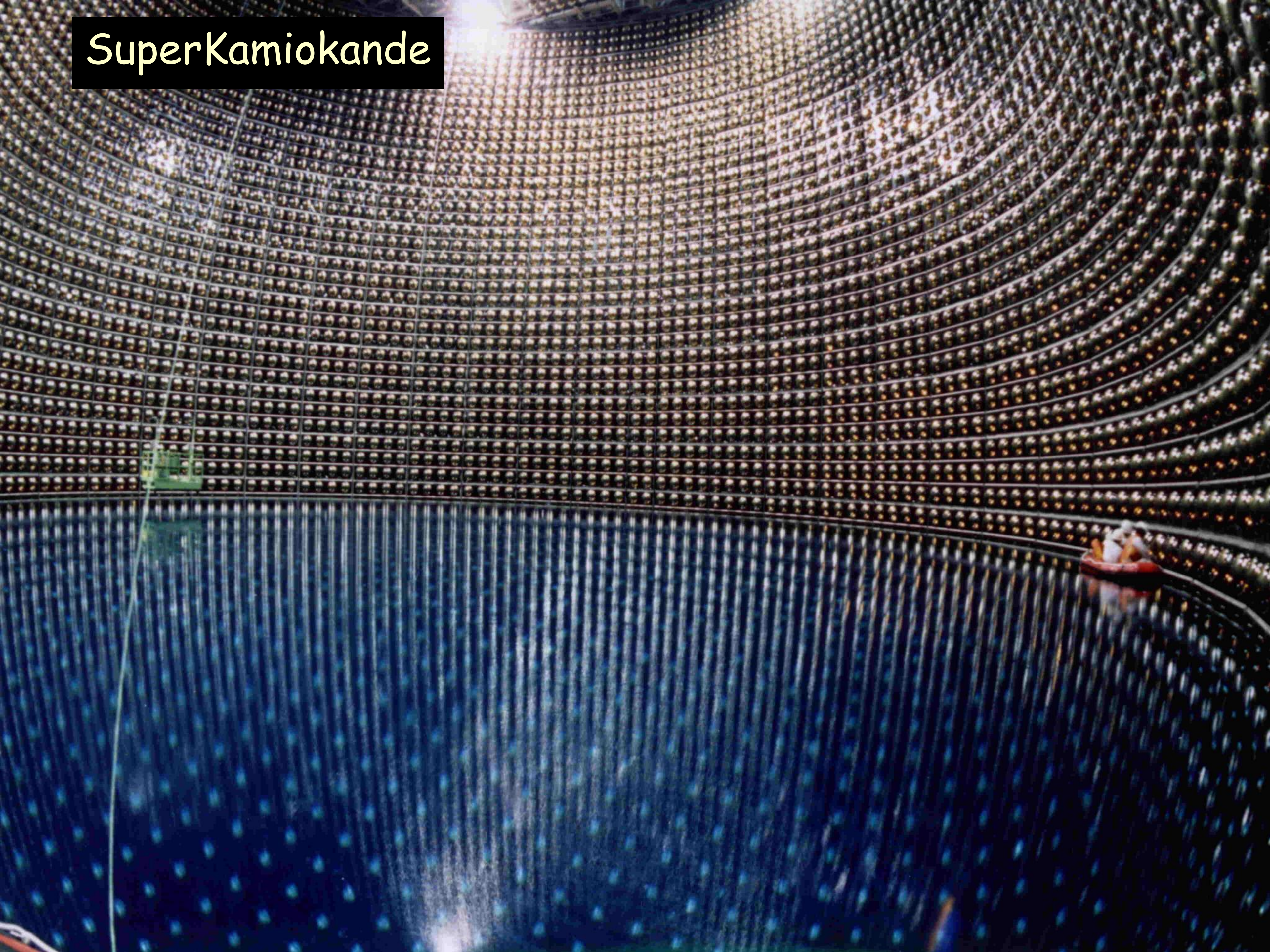
-Inflation

-Baryonic Matter

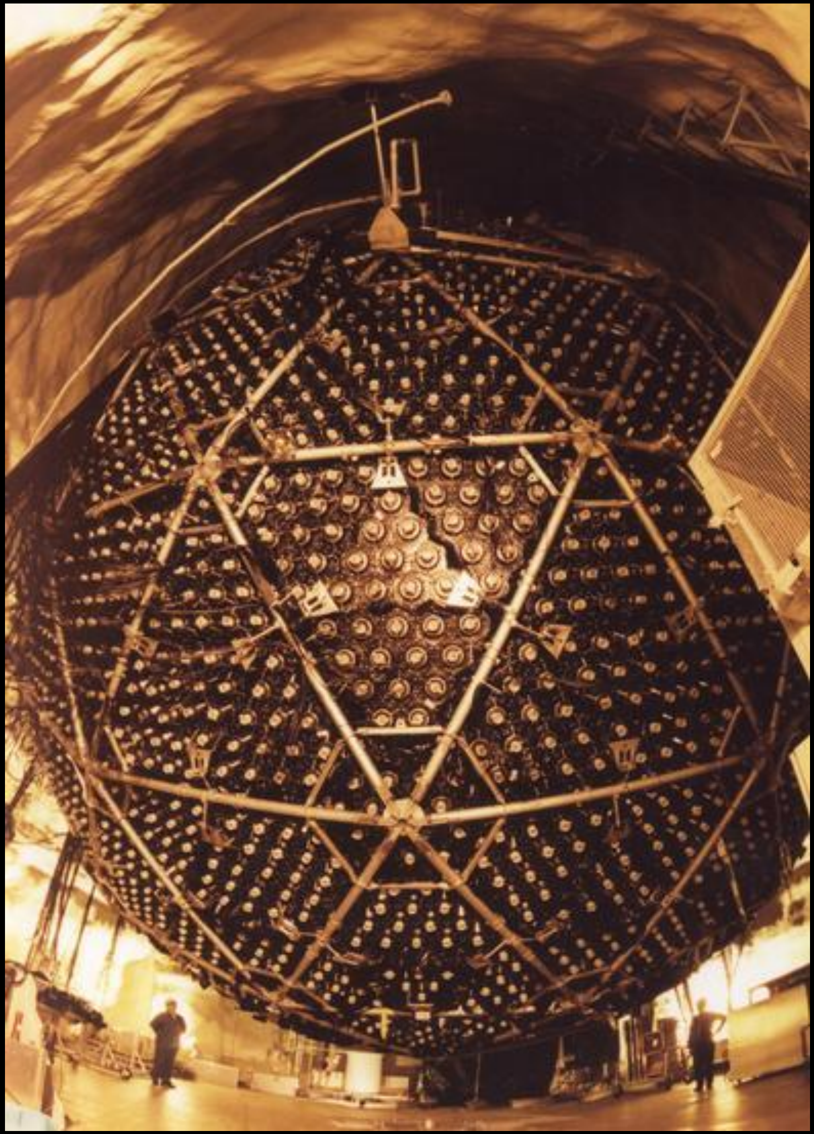
-(Cold) Dark Matter

-Neutrinos

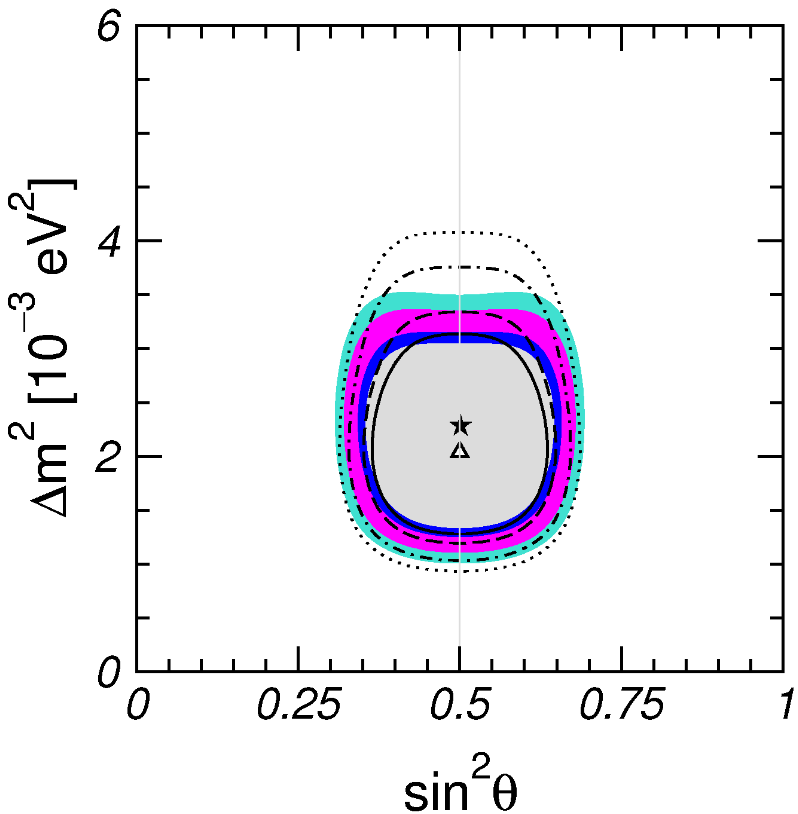
SuperKamiokande



SNO

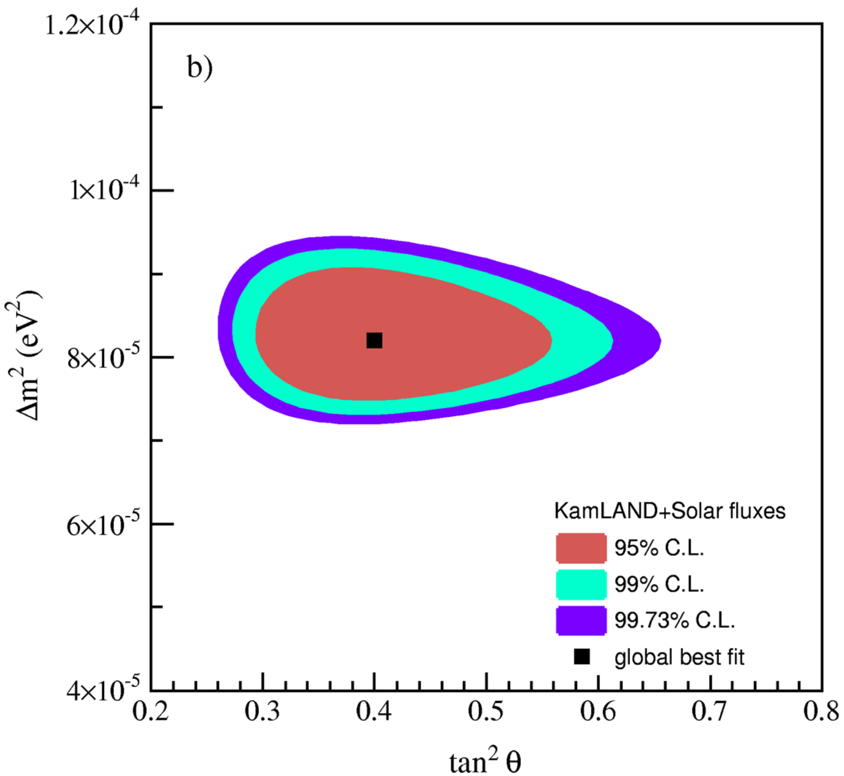


STATUS OF 2-3 MIXING (ATMOSPHERIC + K2K)



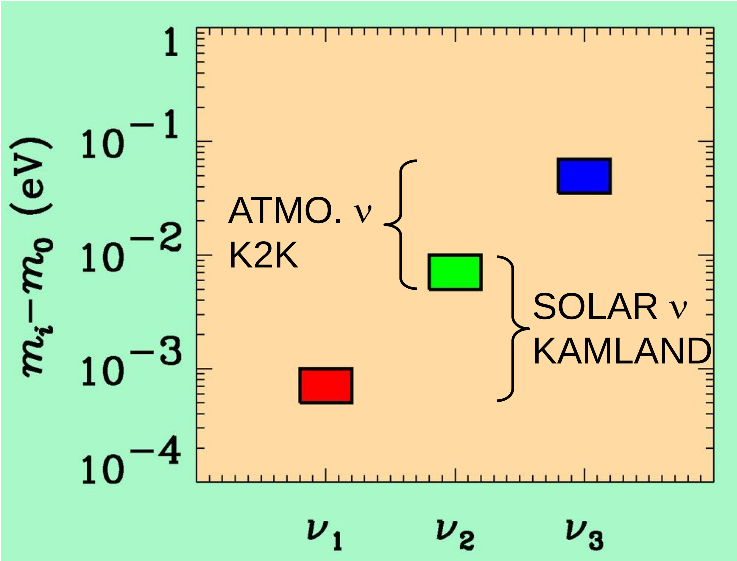
Maltoni et al. hep-ph/0405172

STATUS OF 1-2 MIXING (SOLAR + KAMLAND)



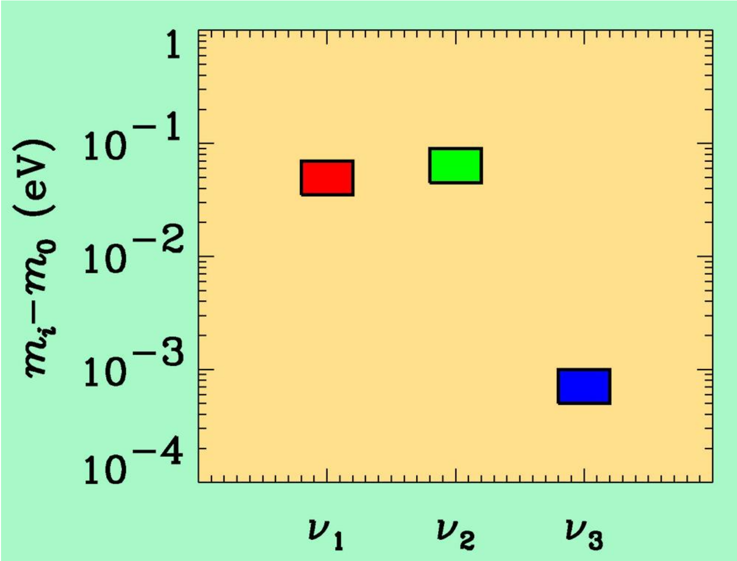
Araki et al. hep-ex/0406035

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy

$$m_3 > m_2 > m_1$$



Inverted hierarchy

$$m_2 > m_1 > m_3$$

Moreover neutrino masses can also be degenerate

$$m_1, m_2, m_3 >> \delta m_{\text{atmospheric}}$$

Laboratory bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

Tritium beta decay:

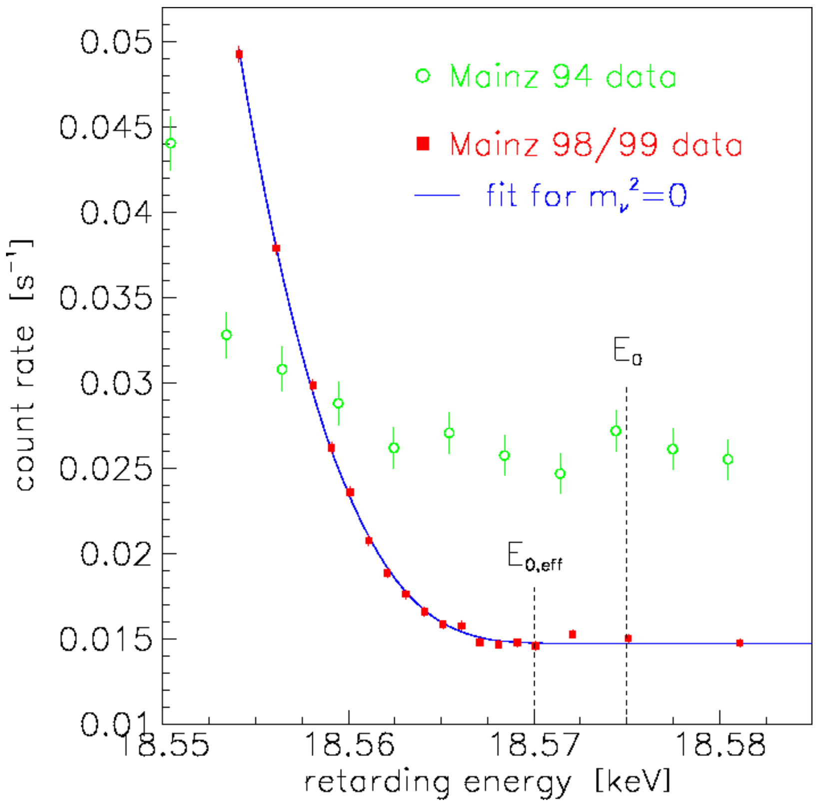
$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2}$$

$$m_\beta^2 = -1.2 \pm 3.0 \quad eV^2 \text{ (Mainz)}$$

$$m_\beta^2 = -2.3 \pm 3.2 \quad eV^2 \text{ (Troitsk)}$$

$$m_\beta < 1.8 \quad eV \qquad (2\sigma)$$

Best fit gives a negative mass !!!



Bounds on neutrino mass

Experiments sensitive to absolute neutrino mass scale :

Neutrinoless double beta decay (only if neutrino are majorana particles!):

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

Neutrinoless doule beta decay processes have been searched in many experiments with different isotopes, yielding negative results. Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a $0\nu2\beta$ signal from the ^{76}Ge isotope. If the claimed signal is entirely due to a light Majorana neutrino masses then we have the constraint:

$$0.17 \quad eV < m_{\beta\beta} < 2.0 \quad eV \quad (3\sigma)$$

Cosmological Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1 MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945 K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

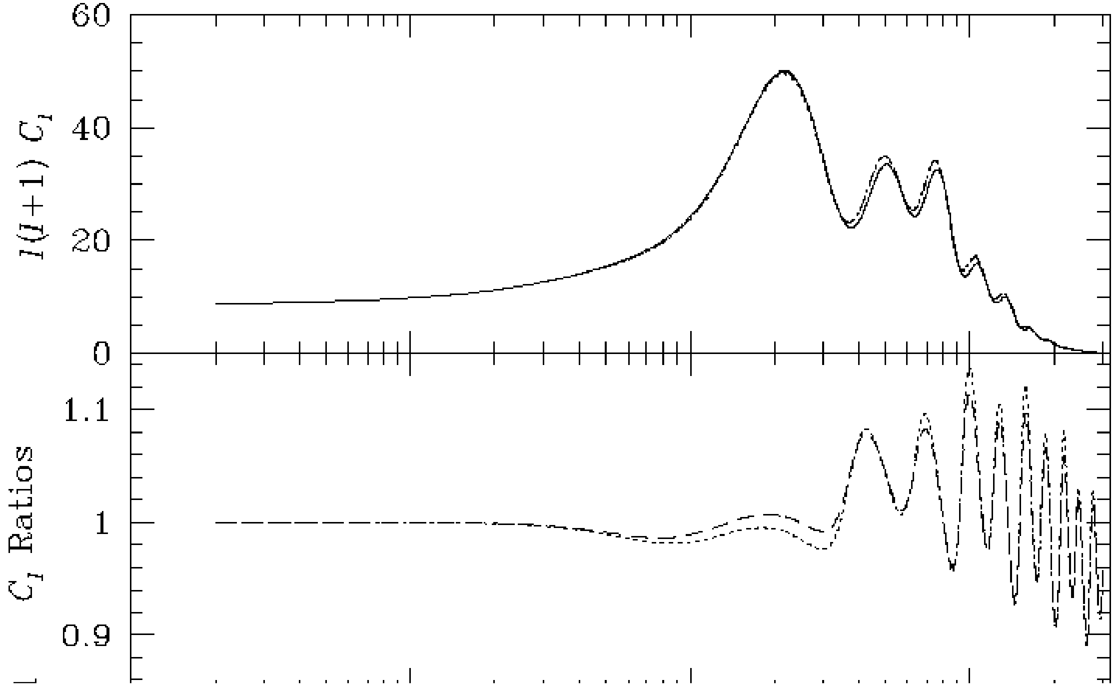
With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

$$\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \approx \frac{1}{h^2}\frac{m_k}{92.5 eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum_k m_k}{92.5 eV}$$

CMB anisotropies



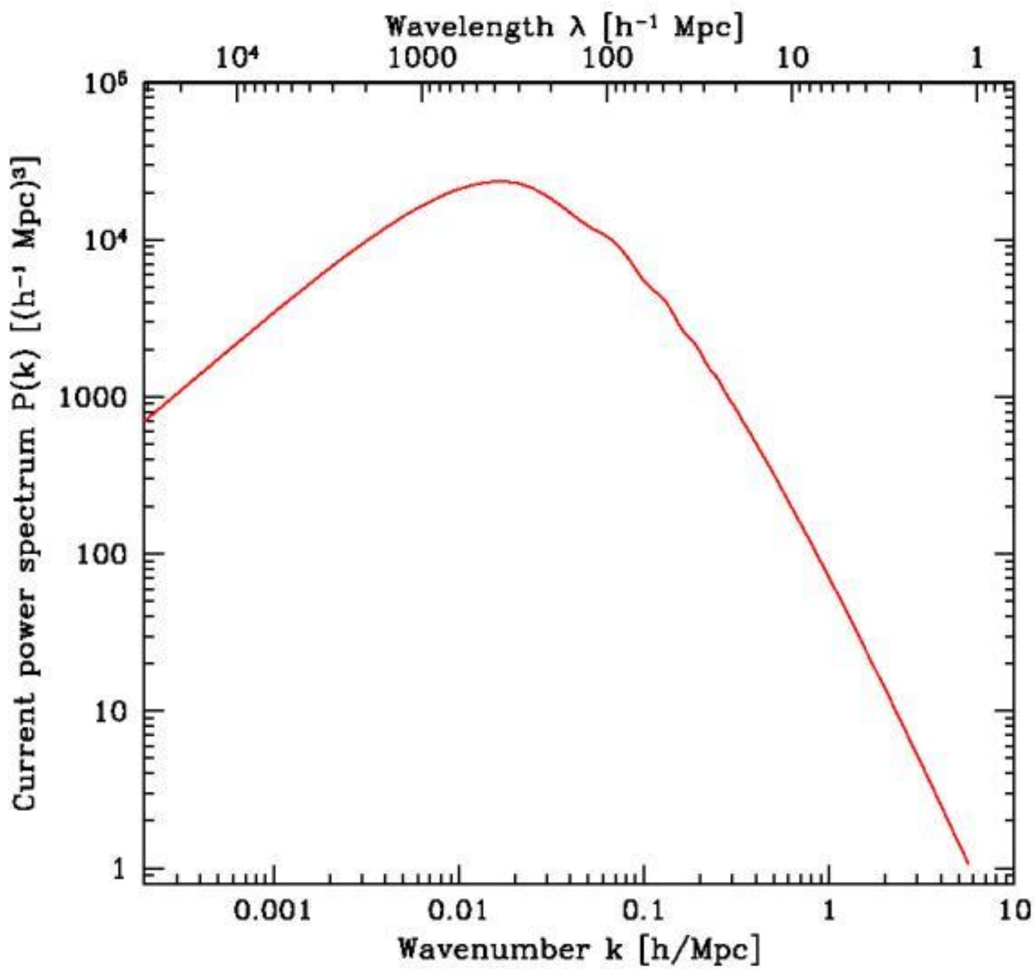
CMB Anisotropies are weakly affected by massive neutrinos. However they constrain very well the matter density and other parameters and, when combined with LSS data can break several degeneracies.

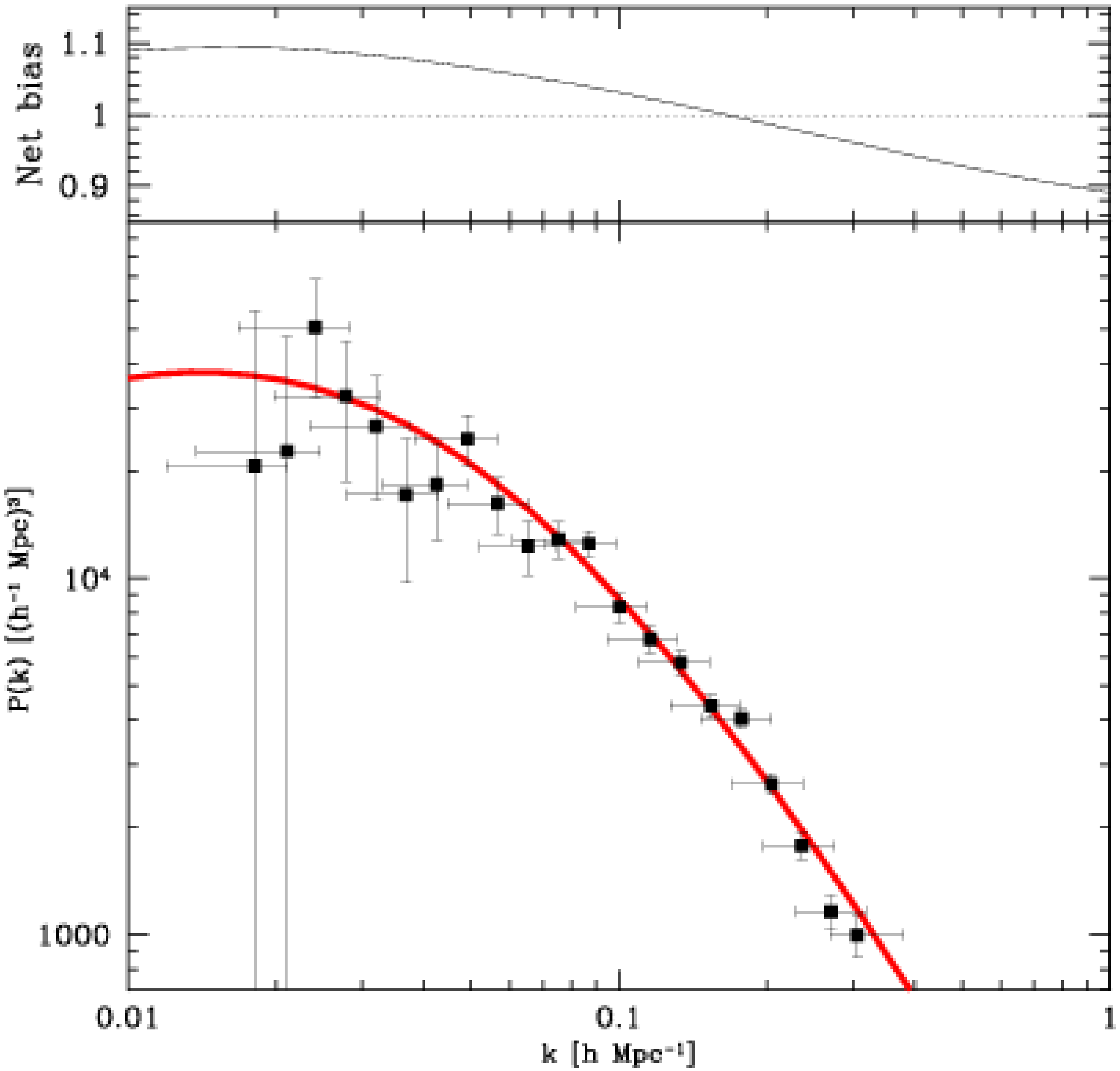
Galaxy Clustering: Theory

$$\xi(\vec{r},t) = \langle \delta(\vec{x},t)\,\delta(\vec{x}+\vec{r},t) \rangle$$

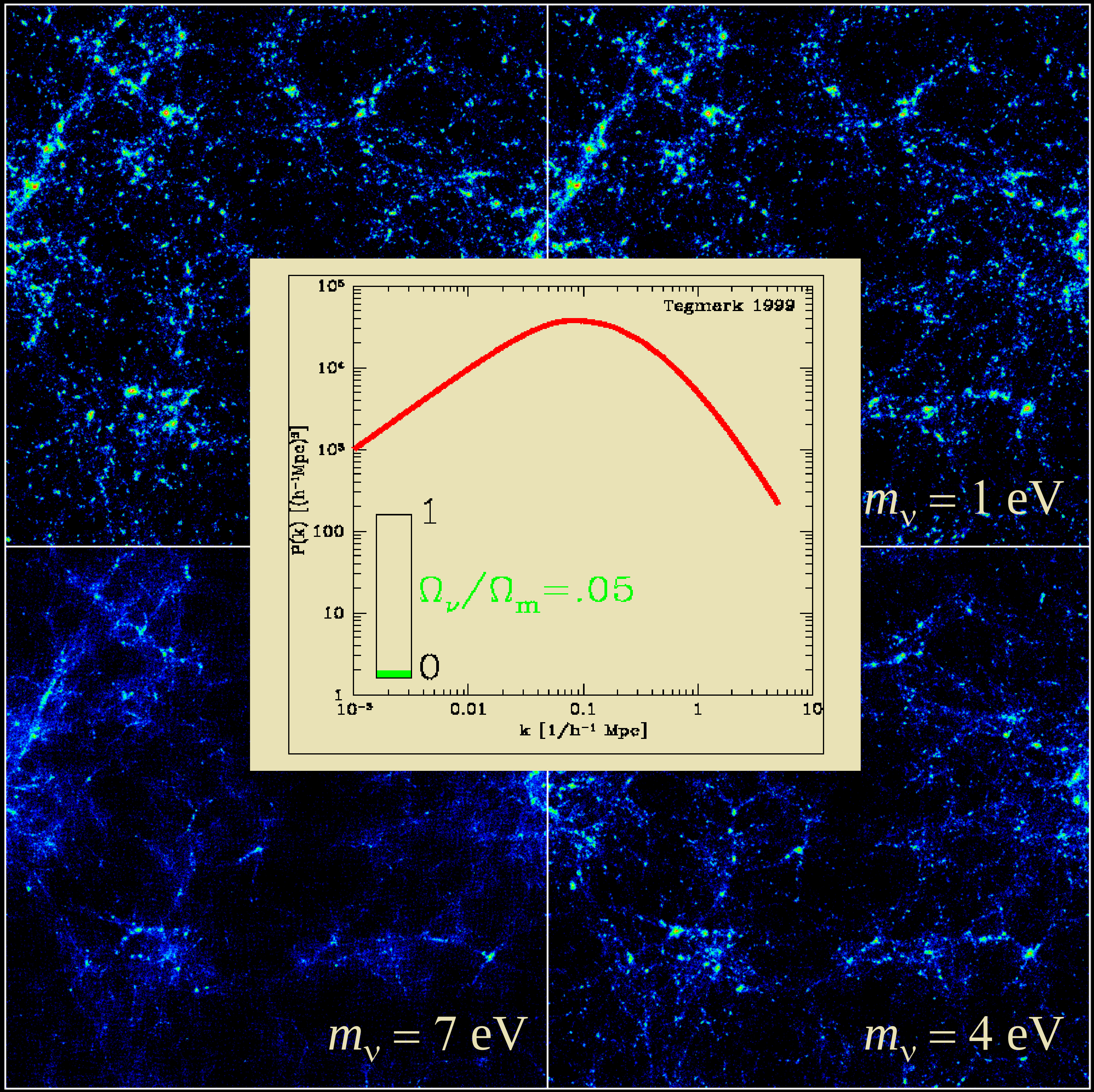
$$P(k,t) = \int d^3r\, \xi(\vec{r},t)\, e^{i\vec{k}\cdot\vec{r}}$$

$$\xi_{galaxies}(\vec{r},t) = b^2 \xi(\vec{r},t)$$





Tegmark et al. 2003



Tegmark 1999
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]
$\Omega_\nu/\Omega_m=.05$
1
0
$m_\nu = 1$ eV
$m_\nu = 7$ eV
$m_\nu = 4$ eV

2 pages Explanation

A classic result is that if all the matter contributing to the Cosmic density is able to cluster, the fluctuations grow as the Cosmic scale factor:

$$\delta \approx a$$

If only a fraction Ω_* can cluster then the equation is generalized to

$$\delta \approx a^p \qquad p \approx \Omega_*^{3/5}$$

In the radiation dominated era p=0 and so we don't have clustering.
In the recent Λ-dominated epoch again, p=0. Fluctuations grow only in the matter dominated epoch with a net growth of

$$\left(\frac{a_{\Lambda D}}{a_{MD}}\right)^p \approx 4700^p$$

Massive non relativistic neutrinos are unable to cluster on small scales because of their high velocities. Between matter domination and dark energy domination they constitute a roughly constant fraction of the matter density:

$$f_\nu = 1 - \Omega_\nu$$

Since the neutrino number density is determined by standard model neutrino Freezeout, the fraction is a function of the sum of the 3 neutrino masses:

$$f_\nu \approx \frac{M_\nu}{\Omega_* h^2 \times 92.5 eV}$$

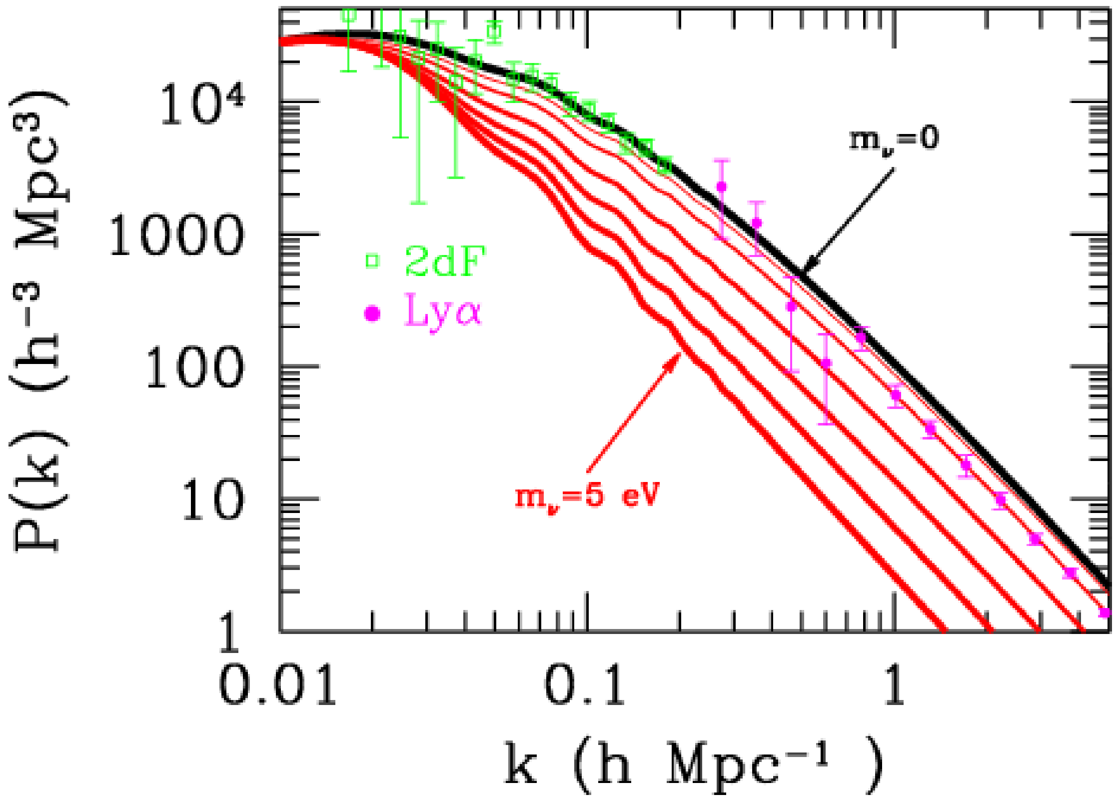
The net fluctuation growth factor is therefore given by:

$$\left(\frac{a_{\Lambda D}}{a_{MD}}\right)^p \approx 4700^p \approx 4700^{(1-f_\nu)^{3/5}} \approx 4700 e^{-4 f_\nu}$$

The power spectrum is the variance of fluctuations in Fourier space, so Massive neutrinos suppress it by a factor:

$$P(k, f_\nu) \cong e^{-8 f_\nu} P(k, 0)$$

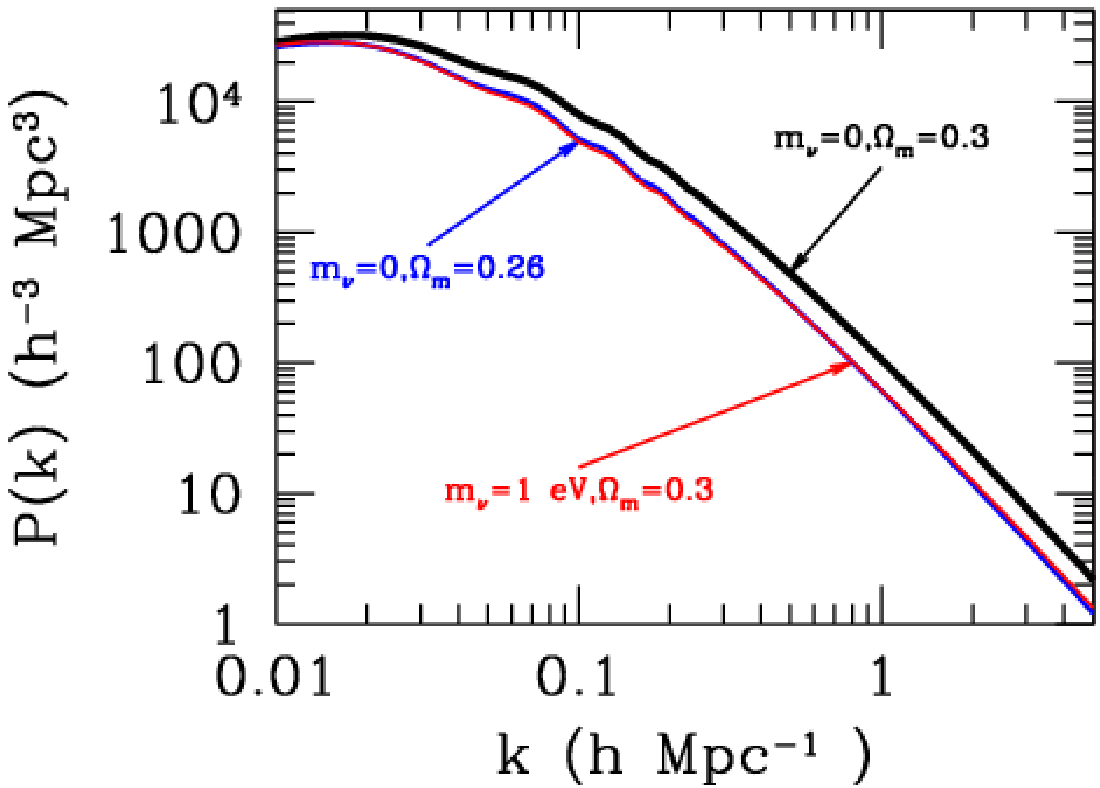
The lenght scale below which Neutrino clustering is suppressed is called the neutrino free-streaming scale and roughly corresponds to the distance neutrinos have time to travel while the universe expands by a factor of two. Neutrinos will clearly not cluster in an overdense clump so small that its escape velocity is much smaller than typical neutrino velocity.
On scales much larger than the free streaming scale, on the other hand, Neutrinos cluster just as cold dark matter.
This explains the effects on the power spectrum.

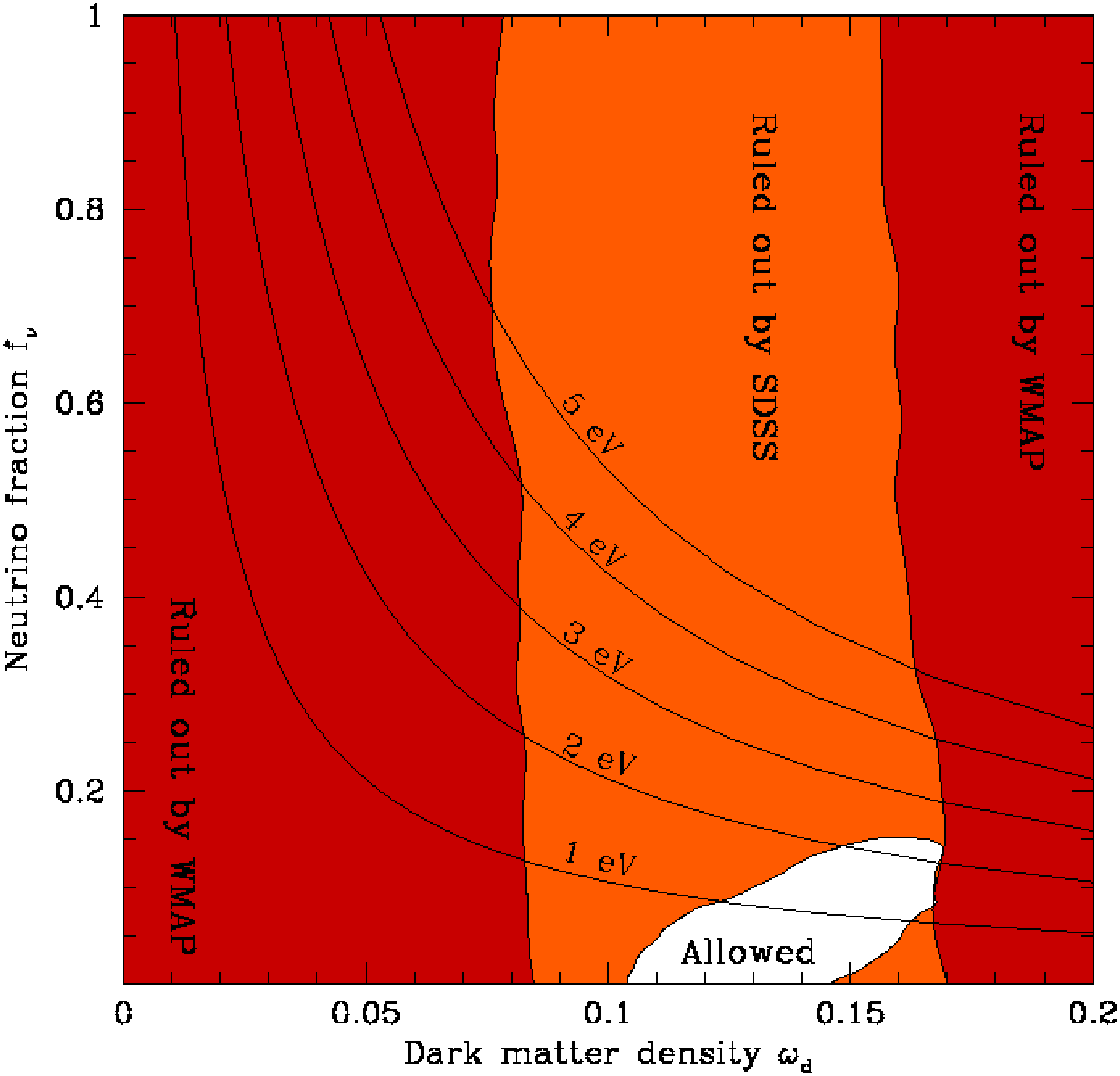


...but we have degeneracies...

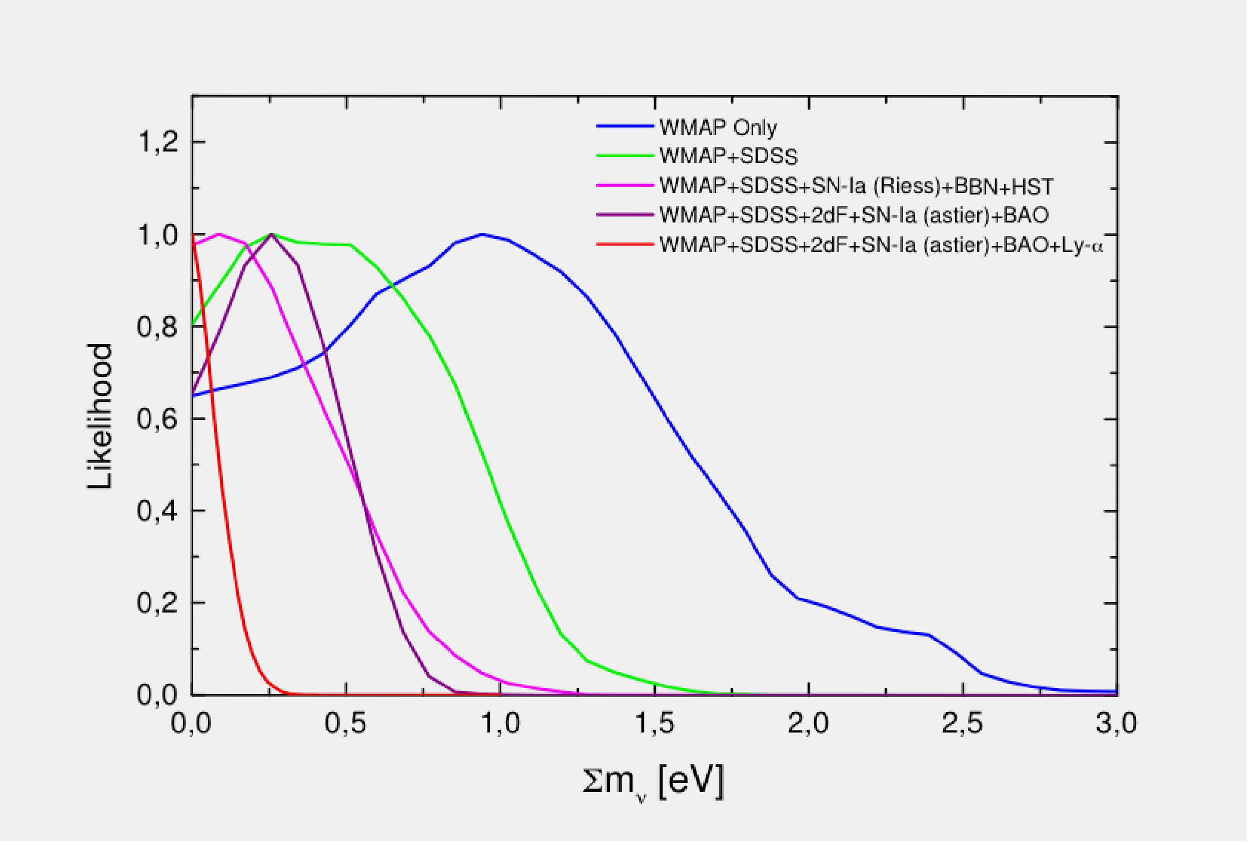
- Lowering the matter density suppresses the power spectrum

- This is virtually degenerate with non-zero neutrino mass





Ruled out by WMAP
Ruled out by SDSS
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
Allowed
Neutrino fraction f_ν
Dark matter density ω_d
0
0.05
0.1
0.15
0.2
0.2
0.4
0.6
0.8
1



Bounds on Σ for increasingly rich data sets (assuming 3 Active Neutrino model):

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

LEPTONS

Neutrino Properties

SUM OF THE NEUTRINO MASSES, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.17–2.3		[54] FOGLI	07	COSM	
< 0.66		[55] SPERGEL	07	COSM	
< 0.63–2.2		[56] ZUNCKEL	07	COSM	
< 0.24	95	[57] CIRELLI	06	COSM	
< 0.62	95	[58] HANNESTAD	06	COSM	
< 0.52	95	[59] KRISTIANSEN	06	COSM	
< 1.2		[60] SANCHEZ	06	COSM	
< 0.17	95	[57] SELJAK	06	COSM	
< 2.0	95	[61] ICHIKAWA	05	COSM	
< 0.75		[62] BARGER	04	COSM	
< 1.0		[63] CROTTY	04	COSM	
< 0.7		[64] SPERGEL	03	COSM	WMAP
< 0.9		[65] LEWIS	02	COSM	
< 4.2		[66] WANG	02	COSM	CMB
< 2.7		[67] FUKUGITA	00	COSM	
< 5.5		[68] CROFT	99	ASTR	Ly α power spec
<180		SZALAY	74	COSM	
<132		COWSIK	72	COSM	
<280		MARX	72	COSM	
<400		GERSHTEIN	66	COSM	

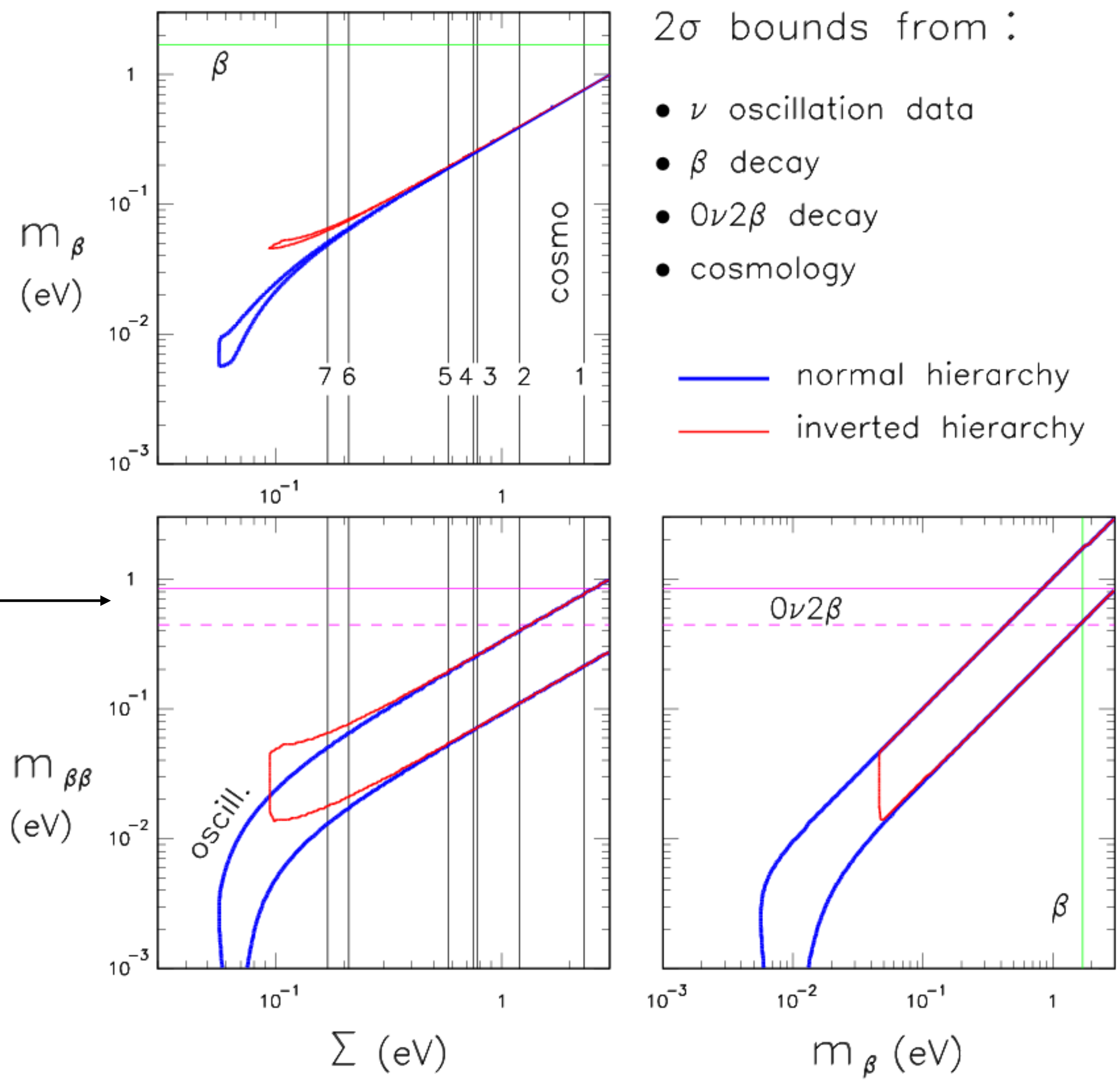
[54] Constrains the total mass of neutrinos from neutrino oscillation experiments and cosmological data. The most conservative limit uses only WMAP three-year data, while the most stringent limit includes CMB, large-scale structure, supernova, and Lyman-alpha data.

[55] Constrains the total mass of neutrinos from three-year WMAP data combined with other CMB, large-scale structure and supernova data.

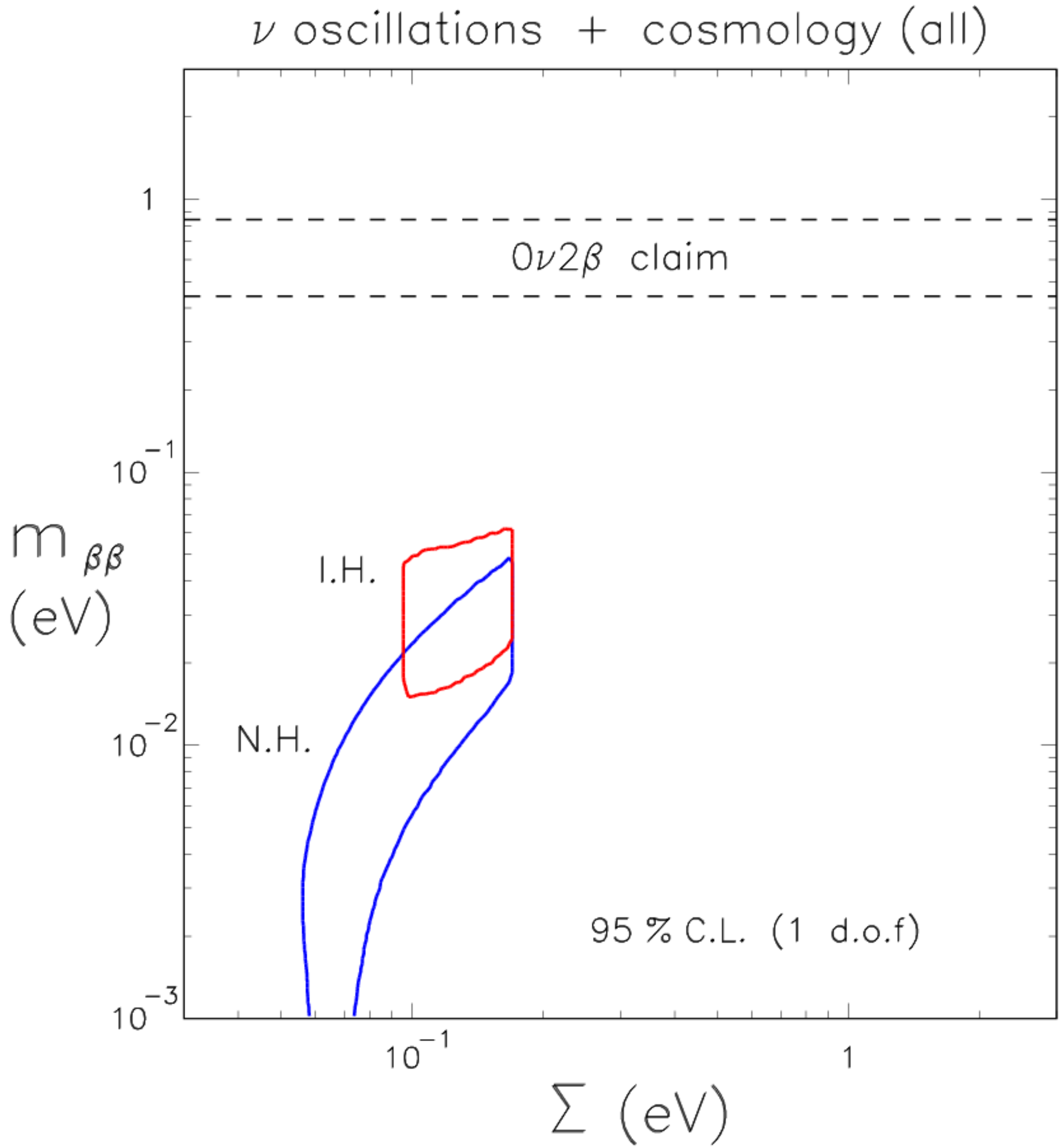
[56] Constrains the total mass of neutrinos from the CMB and the large scale structure data.

Particle Data Group, 2008

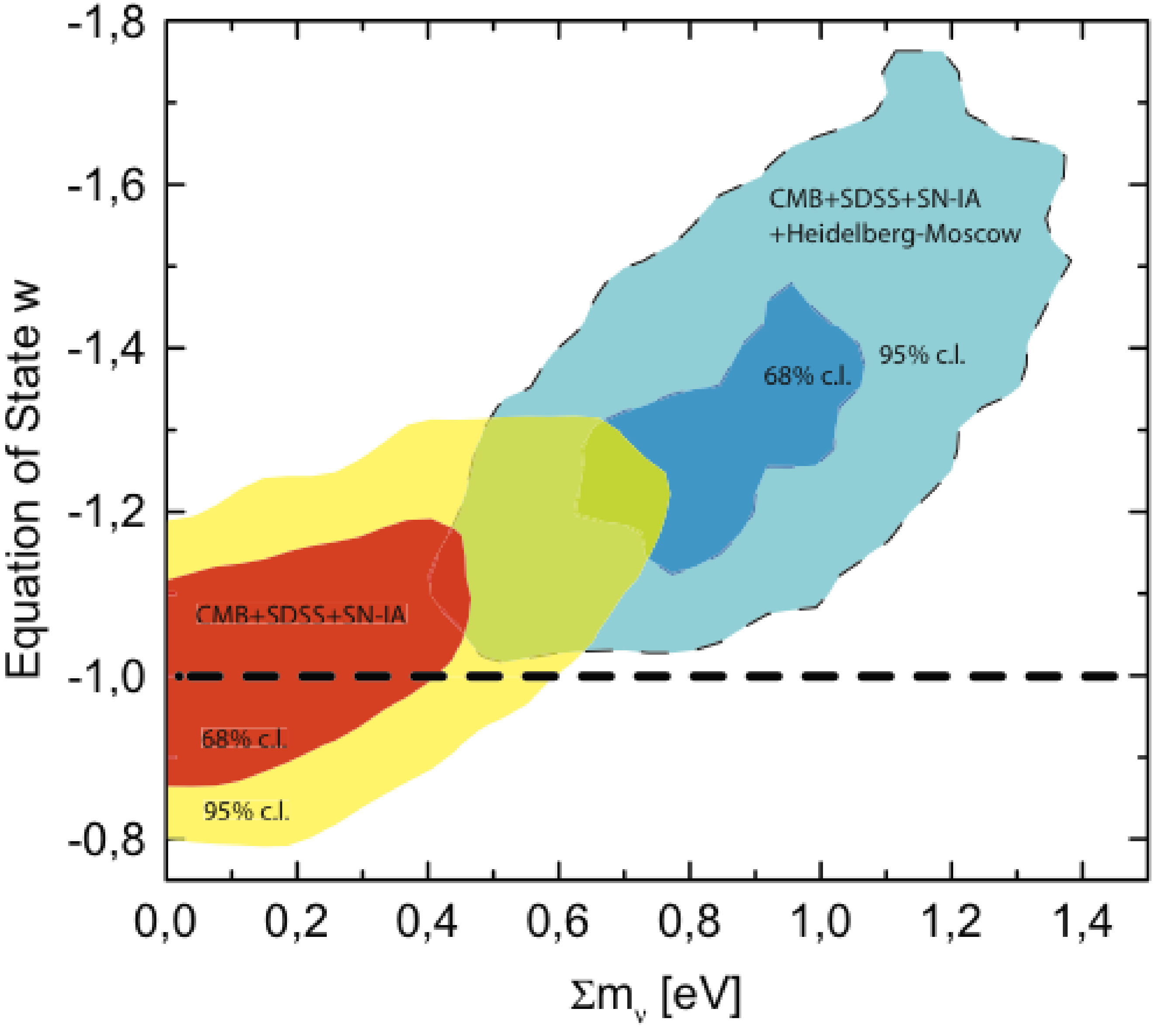
Klapdor's claim



Fogli et al., Phys. Rev. D 75, 053001 (2007)



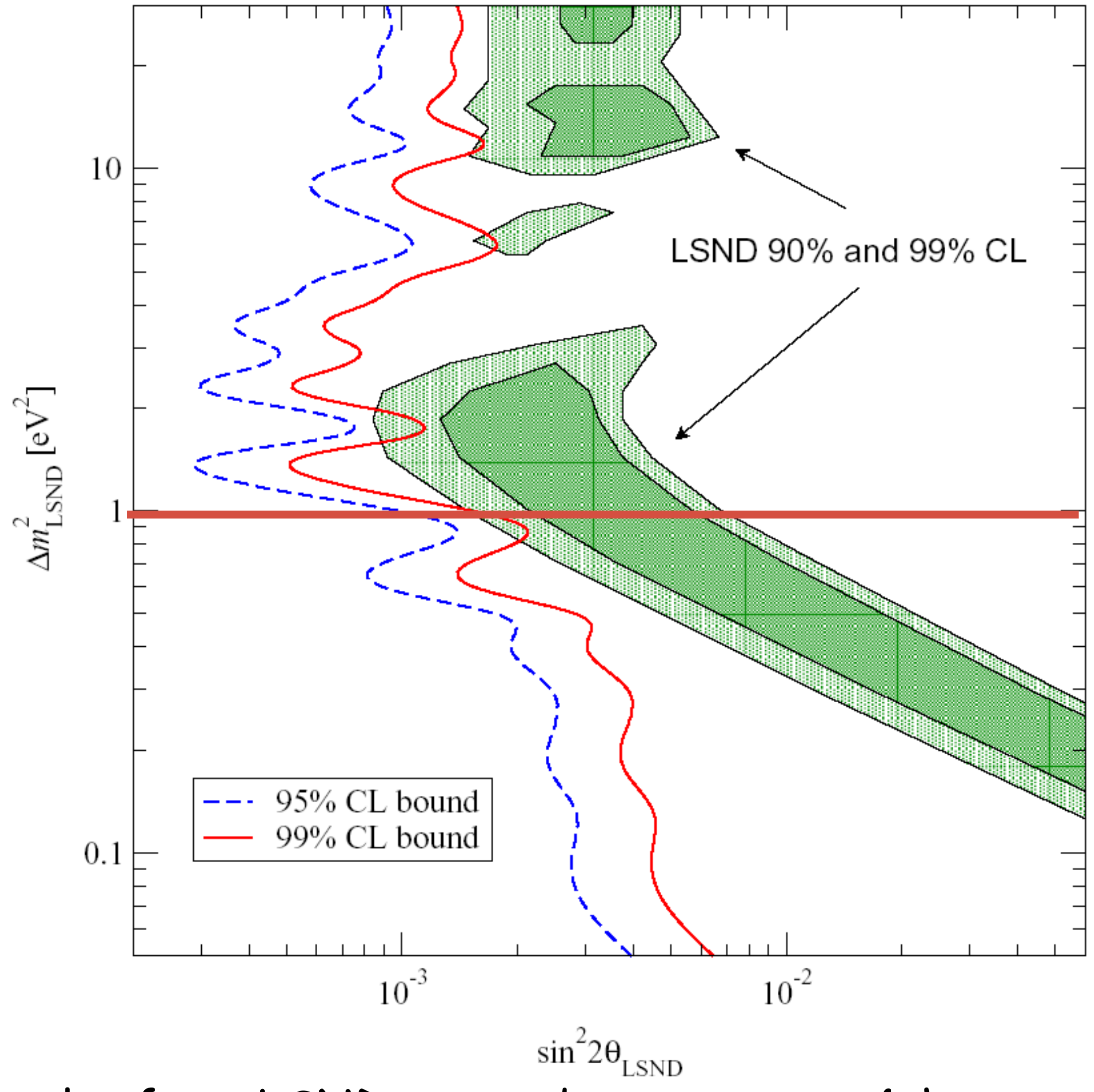
Fogli et al., Phys. Rev. D 75, 053001 (2007)



Axel De La Macorra, **Alessandro Melchiorri**, **Paolo Serra**, **Rachel Bean**
Astroparticle Physics 27 (2007) 406-410

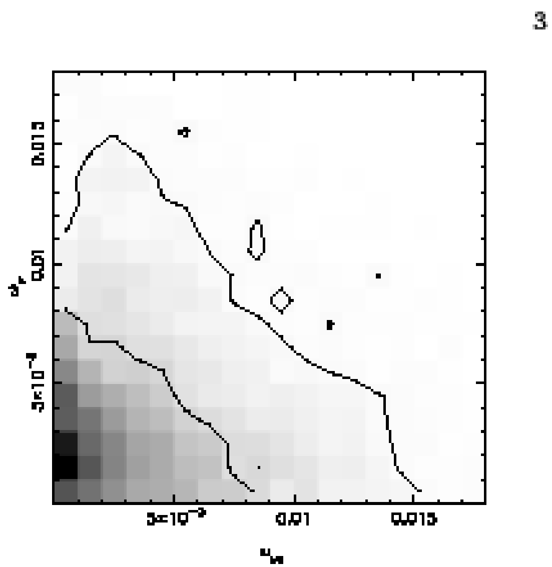
What about N=3+1 (massive) ?

$N_\nu = 4???$



Controversial results from LSND seemed to suggest a 4th sterile neutrino (not favoured by oscillation experiments.
NO ALLOWED REGIONS EXIST FOR LOW Δm^2.
(Pierce & Murayama, hep-ph/0302131; Giunti hep-ph/0302173)

What about a fourth massive sterile neutrino ?



CMB+2df+
Sloan+Ly-α

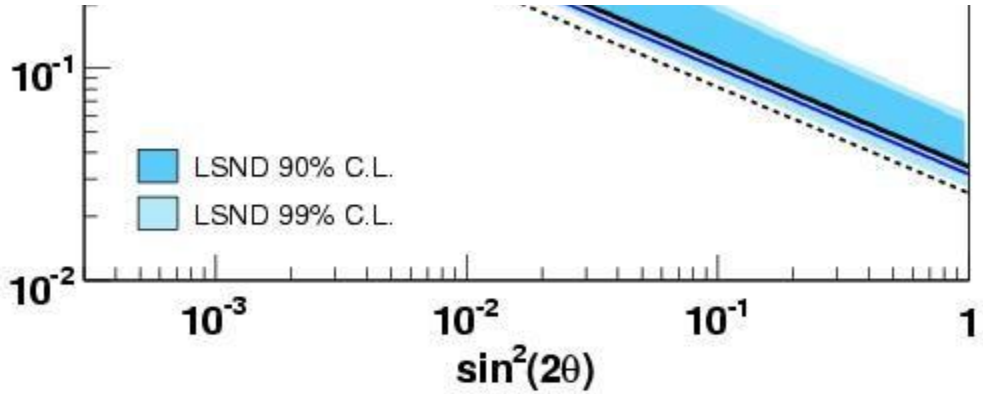
$$\omega_s = 0.0106 \frac{m_s}{eV}$$

$$\omega_\nu = 0.0106 \frac{3m_\nu}{eV}$$

m_s<0.23 eV at 95% c.l.

Dodelson, Melchiorri, Slosar, Phys.Rev.Lett. 97 (2006) 04301

April 2007
MINIBOONE RULES OUT LSND:
WE "KNEW" IT !!!



Miniboone results, April 2007 "excludes" LSND

Butts on the line

"The implications were staggering," says Scott Dodelson at Fermilab. "Cosmologically, we decided (Dodelson, Melchiorri, Slosar, 2006) there should not be a sterile neutrino, so to some extent, our butts were on the line."

New Scientist, April 2007

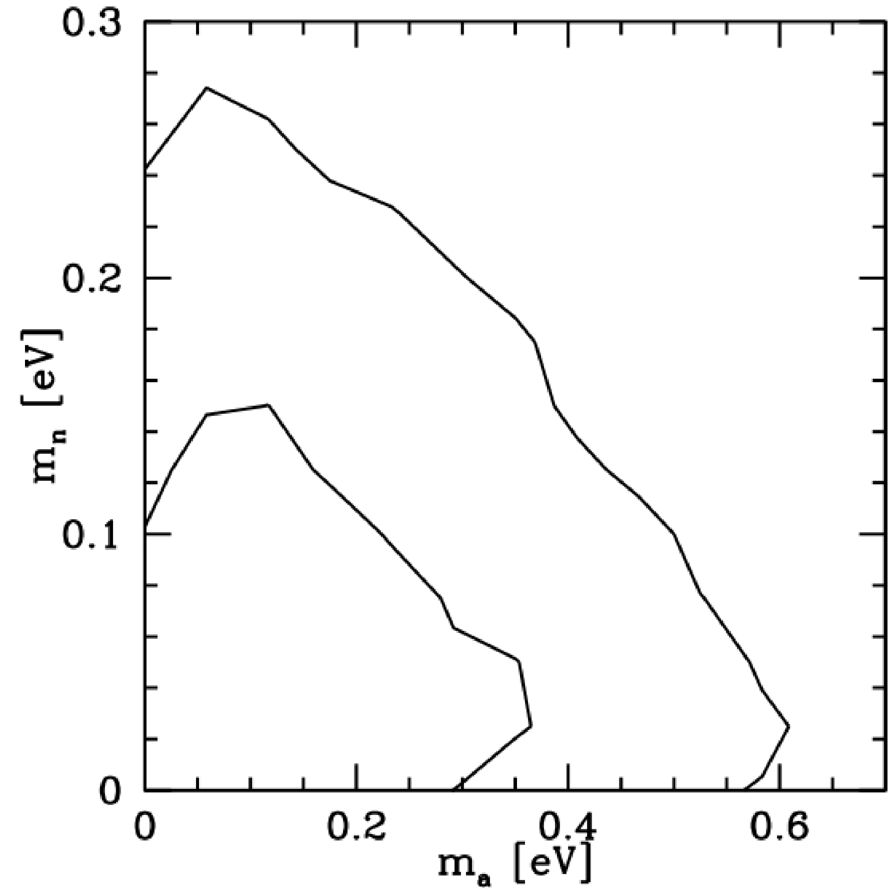
What about a thermal axion component ?

Relic thermal axion could play the role of a Hot dark matter Component.

$$\Omega_a h^2 = \frac{m_a}{131eV}\left(\frac{10}{g_{*S}(T_D)}\right)$$

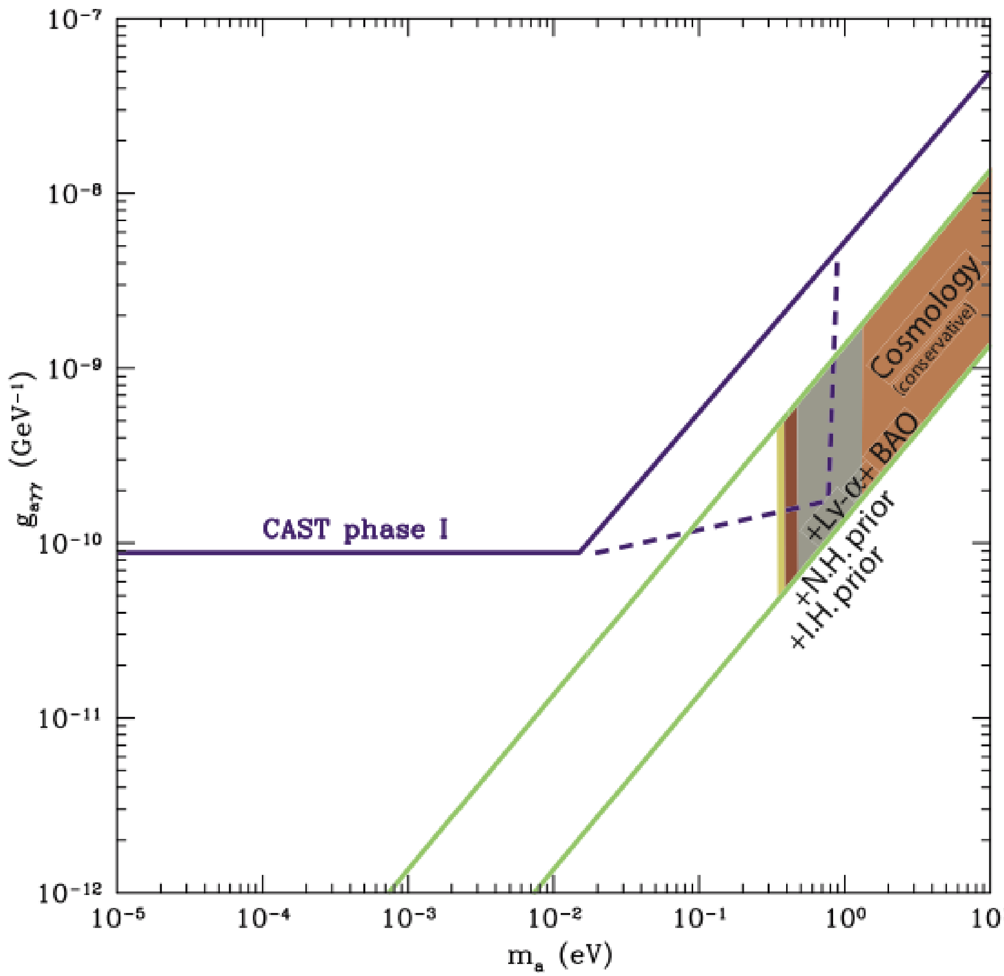
$m_a < 0.42eV$ at 95% c.l.
(all cosmological data)

$m_a < 0.38eV$ at 95% c.l.
(all cosmological data Plus H.I. for neutrino masses)



Melchiorri, Mena, Slosar
Phys. Rev. D 76, 041303(R) (2007)

CAST
CERN Axion Solar Telescope



Melchiorri, Mena, Slosar
Phys. Rev. D 76, 041303(R) (2007)

Do we have neutrinos in cosmology ?

Interesting possibilities for N_ν different from 3:

Presence of EXTRA RELATIVISTIC RELICS like sterile n's (thermalized or not), axion, light gravitinos, majoron, extra-D...

Non-Standard NEUTRINO DECOUPLING

- standard model (non-instantaneous) :
  - e^-e^+ annihilation heats ν's
  - finite T° QED corrections $N_\nu = 3.0395$
- exotic models (out of thermal equilibrium)
  - $N_\nu \neq 3.04$ e.g. low-scale (MeV) reheating

Non-Standard Big Bang Nucleosynthesis

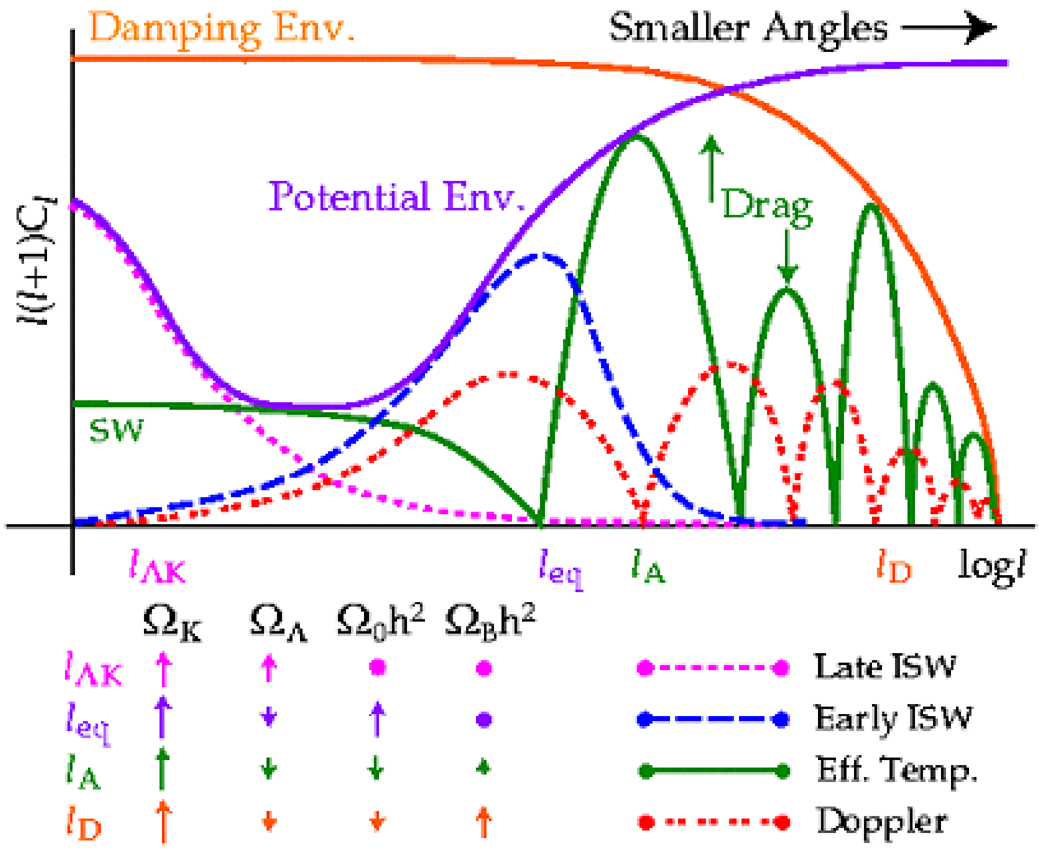
sBBN : 2 free parameters $\{\Omega_b h^2, N_n\}$

- $\Omega_b h^2 = 0.022 \pm 0.004$ (2σ)
- $N_\nu = 2.5 \pm 1.1$ (2σ)

test $\nu - \nu$ asymmetry, i.e. neutrino chemical potential

$$\Delta N_\nu = \frac{15}{7}\left[2\left(\frac{\xi_\nu}{\pi}\right)^2 + \left(\frac{\xi_\nu}{\pi}\right)^4\right]$$

neutrino light component: effects on the CMB



Hu, Sugiyama, Silk, Nature 1997, astro-ph/9604166

Integrated Sachs-Wolfe effect

while most cmb anisotropies arise on the last scattering surface, some may be induced by passing through a time varying gravitational potential:

$$\frac{\delta T}{T} = -2\int d\tau\, \dot{\Phi}(\tau)$$

linear regime – integrated Sachs-Wolfe (ISW)

non-linear regime – Rees-Sciama effect

when does the linear potential change?

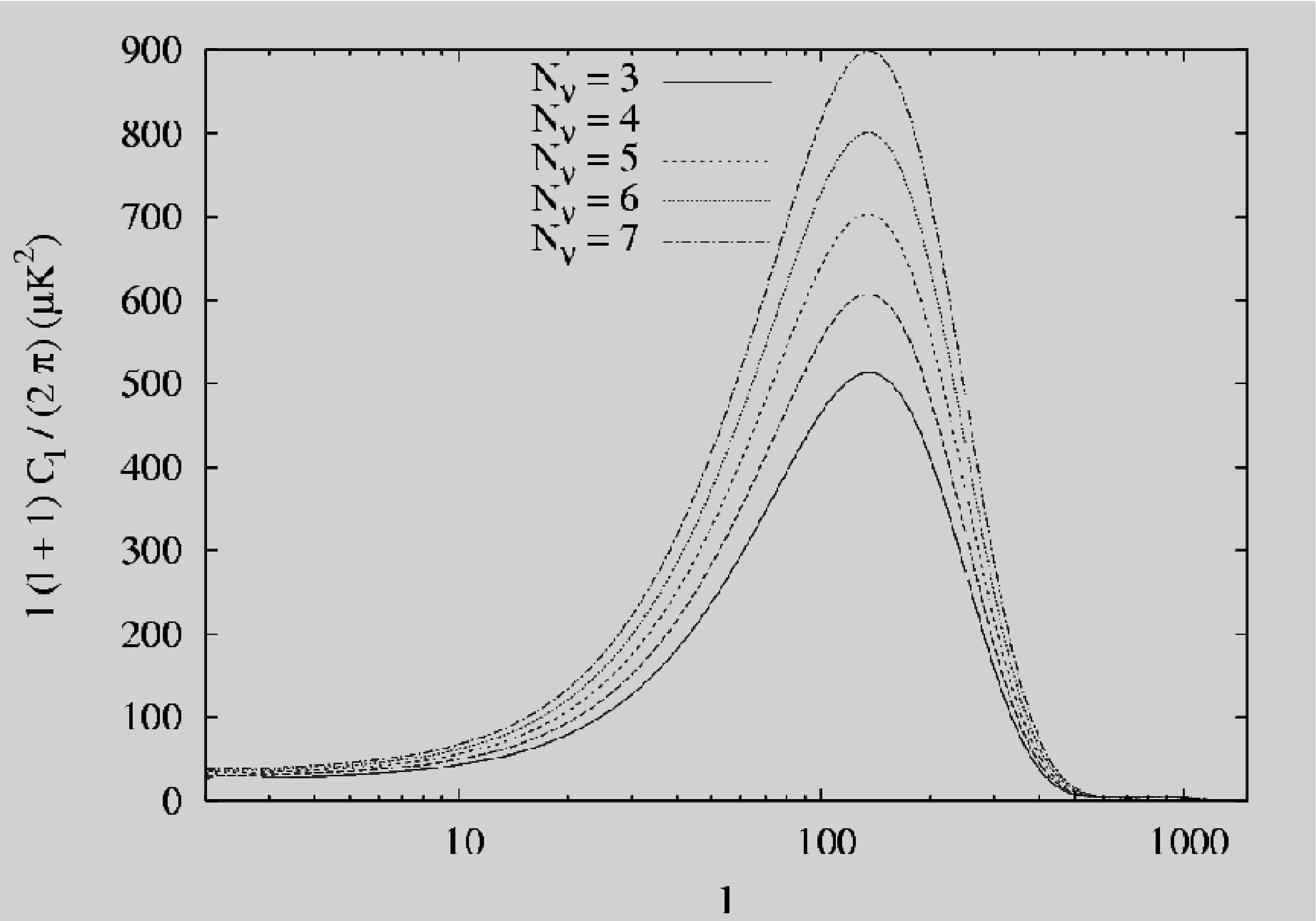
$$\nabla^2 \Phi = 4\pi G a^2 \bar{\rho}\, \delta$$

Poisson's equation

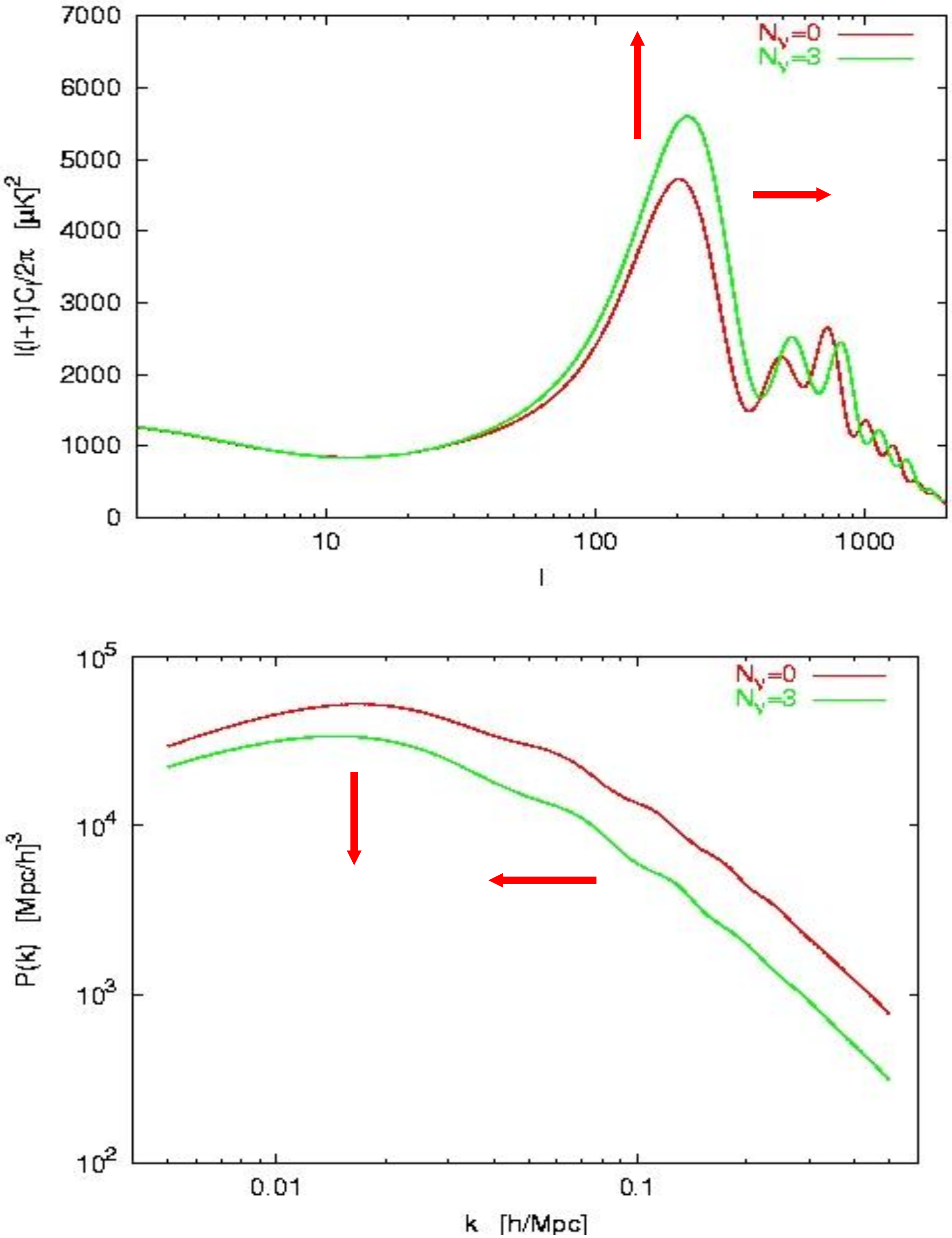
- changes during radiation domination
- decays after curvature or dark energy come to dominate (z~1)

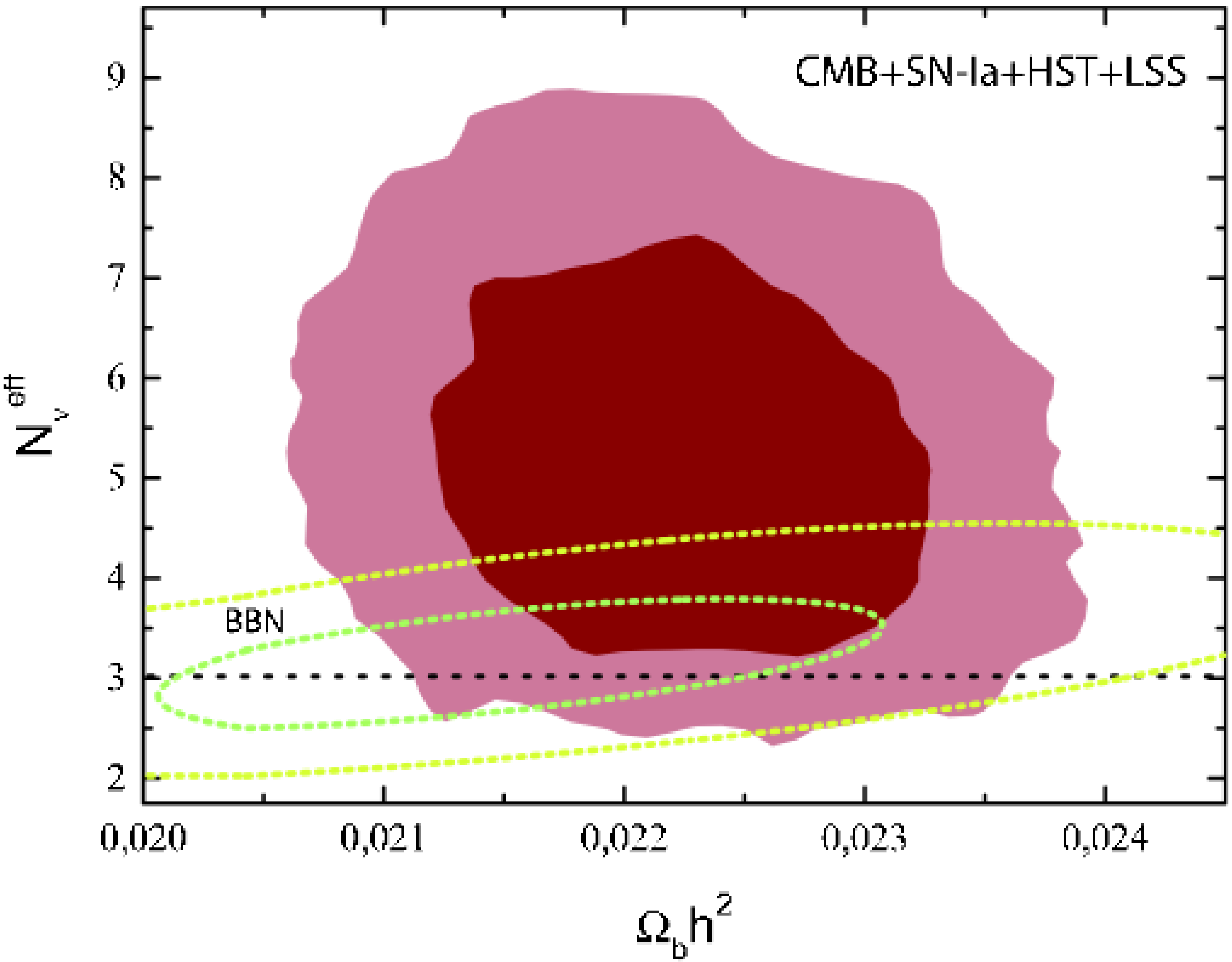
Effect of Neutrinos in the CMB: ISW

Changing the number of neutrinos (assuming them as massless) shifts the epoch of equivalence, affecting the ISW:

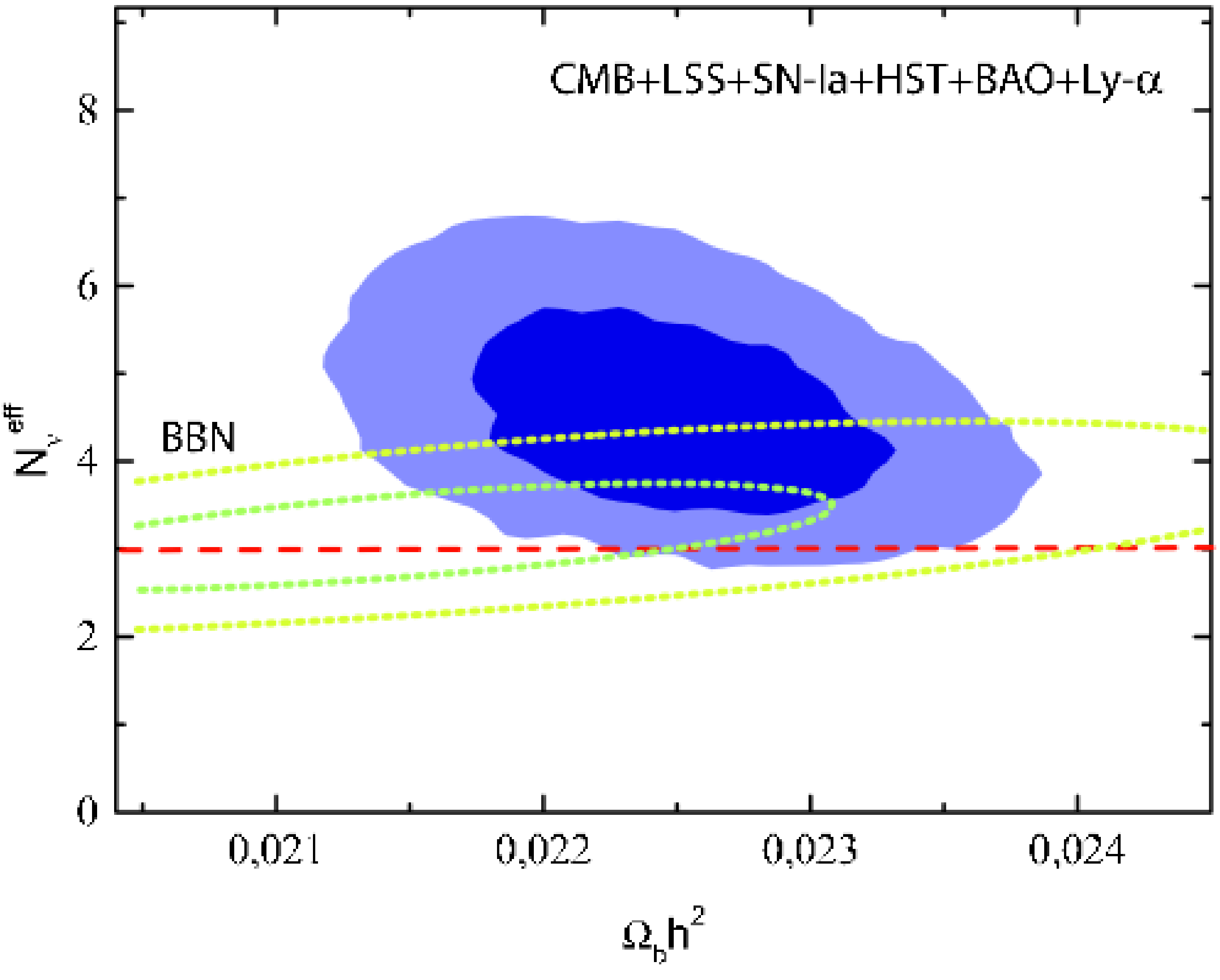


Increasing the Neutrino Massless number postpone the equivalence (while keeping constant the time of decoupling).
This produces a shift in the CMB power spectra since changes the sound horizon at decoupling. The height of the first peak is also increased thanks to the Early Integrated Sachs-Wolfe. The LSS matter power spectrum is also shifted since the size of the horizon at equivalence is now larger.
There is less growth of perturbations in the MD regime.





Mangano, Melchiorri, Mena, Miele, Slosar JCAP03(2007)006



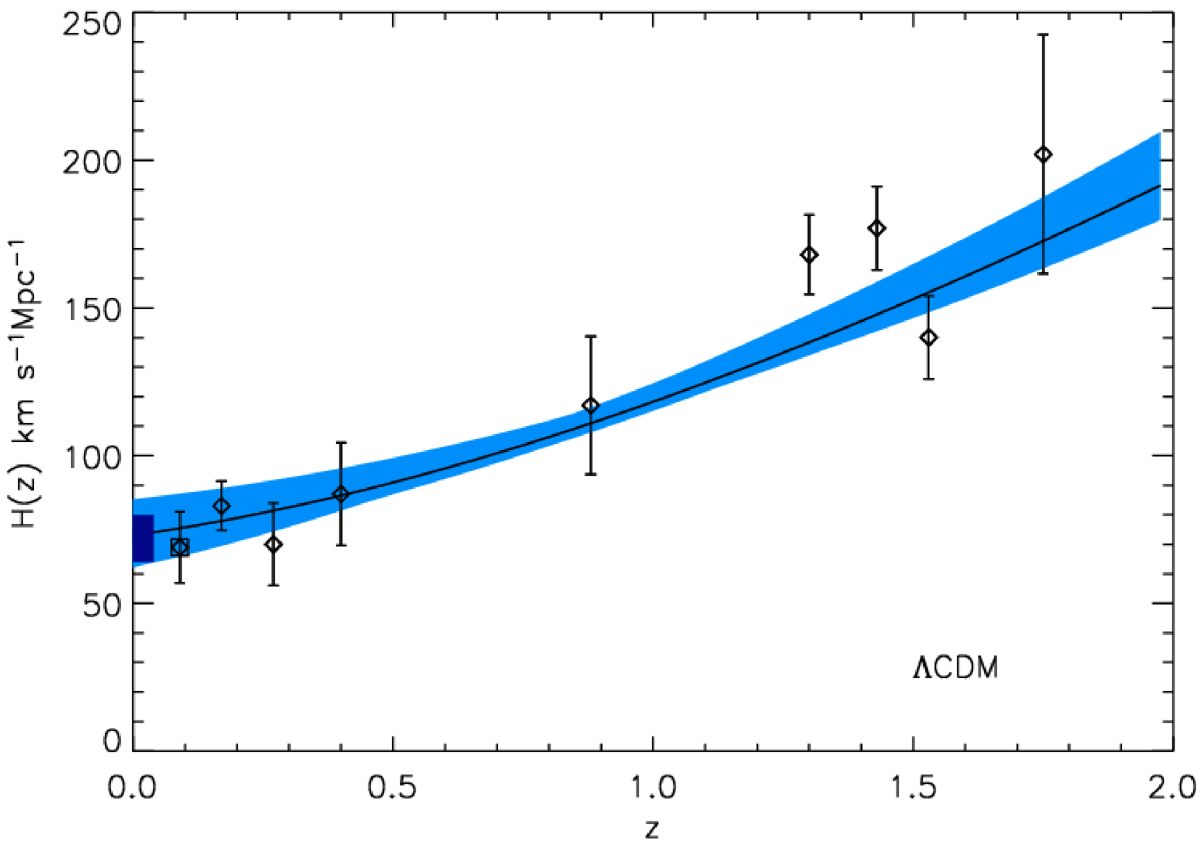
Mangano, Melchiorri, Mena, Miele, Slosar JCAP03(2007)006

Age of the Universe

CMB data are able to tightly constrain the age of the Universe (see e.g. Ferreras, AM, Silk, 2002). For WMAP+all and LCDM:

$$t_0 = 9.8 H_0^{-1} \int_0^1 \frac{a\,da}{\sqrt{\Omega_m a + \Omega_\Lambda a^4 + \Omega_r}} = 13.84 \pm 0.23 \ \text{Gyrs} \longrightarrow 13.83 \pm 0.3 \ \text{Gyrs}$$

(if w is included)



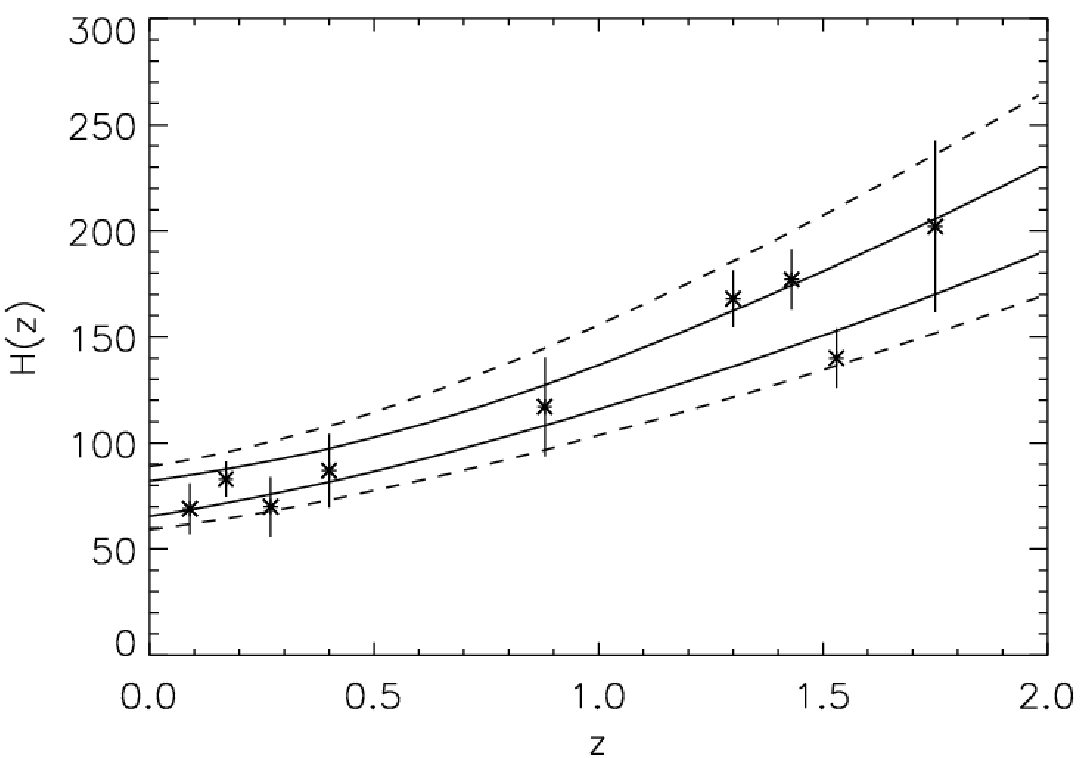
Direct and "model independent" age aestimates have much larger error bars ! Not so good for constraining DE

Spergel et al., 2007

Age of the Universe

…however the WMAP constrain is model dependent.
Key parameter: energy density in relativistic particles.

$$\omega_{rel} = \omega_\gamma + N_\nu^{eff}\,\omega_\nu \longrightarrow t_0 = 13.8^{+2.3}_{-3.2}\ \text{Gyrs}$$

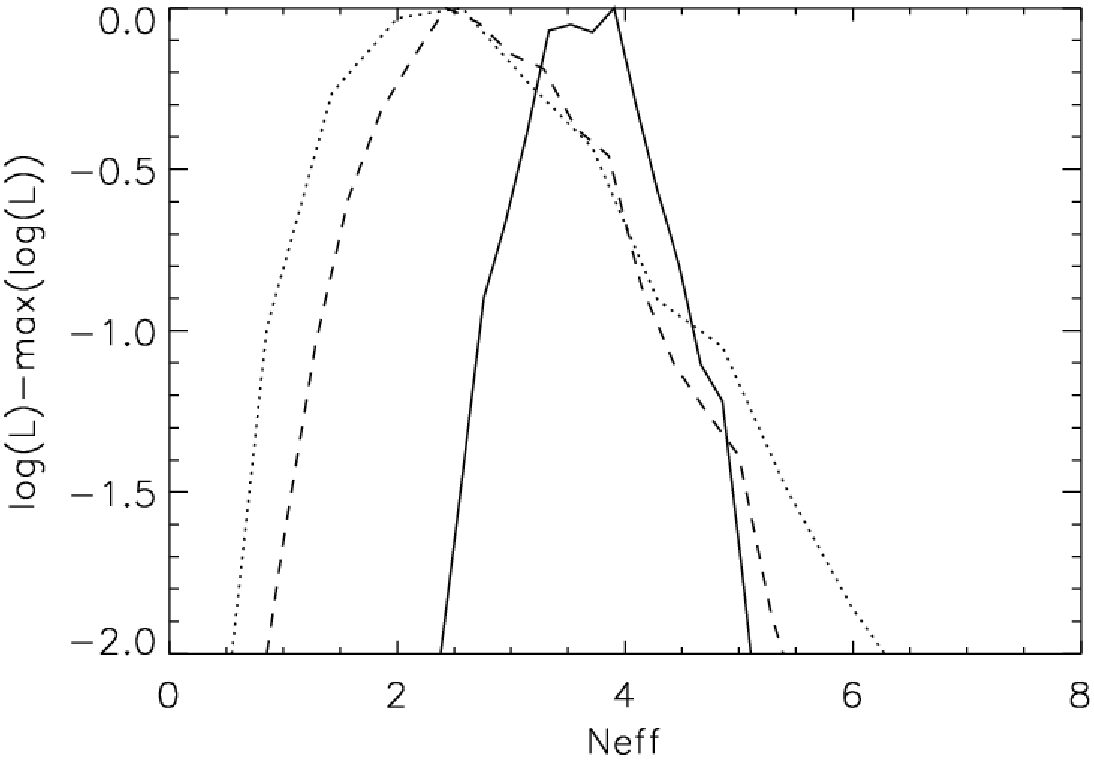


Error bars on age a factor 10 larger when Extra Relativistic particles are Included.

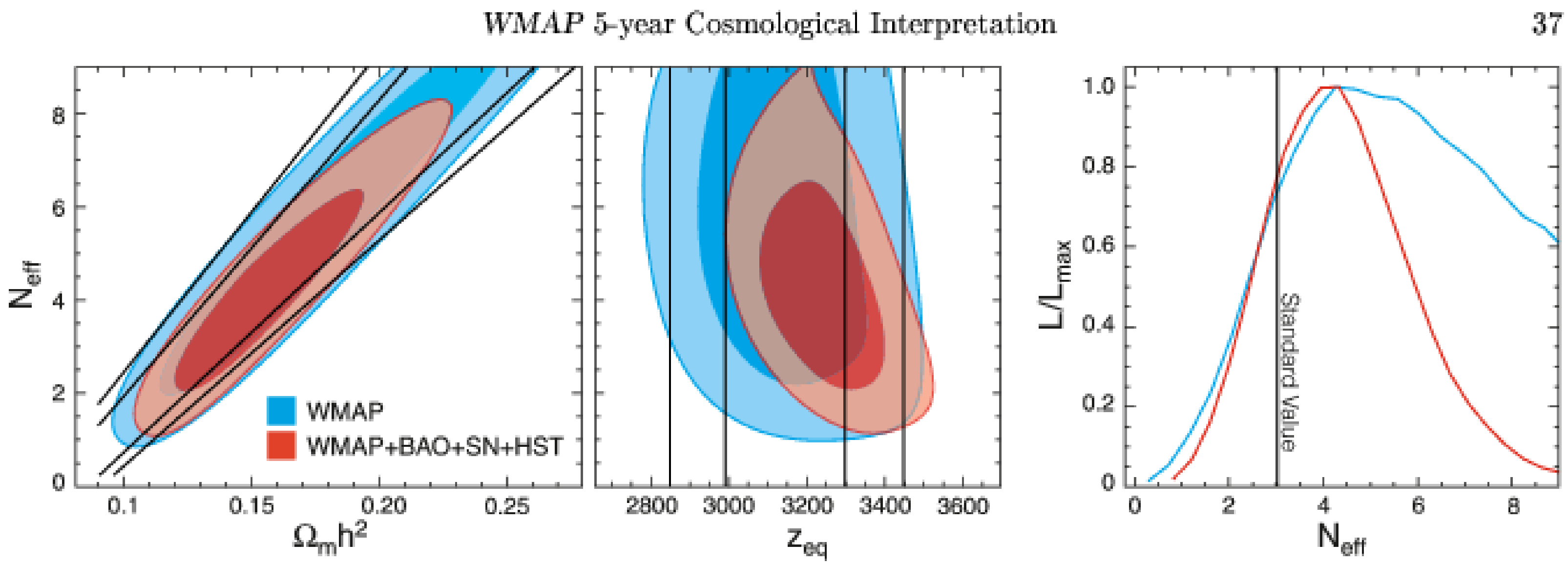
F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020

Independent age aestimates are important.
Using Simon, Verde, Jimenez aestimates plus WMAP we get:

$$N_\nu^{eff} = 3.7 \pm 1.1$$



F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, JCAP 03(2008)020



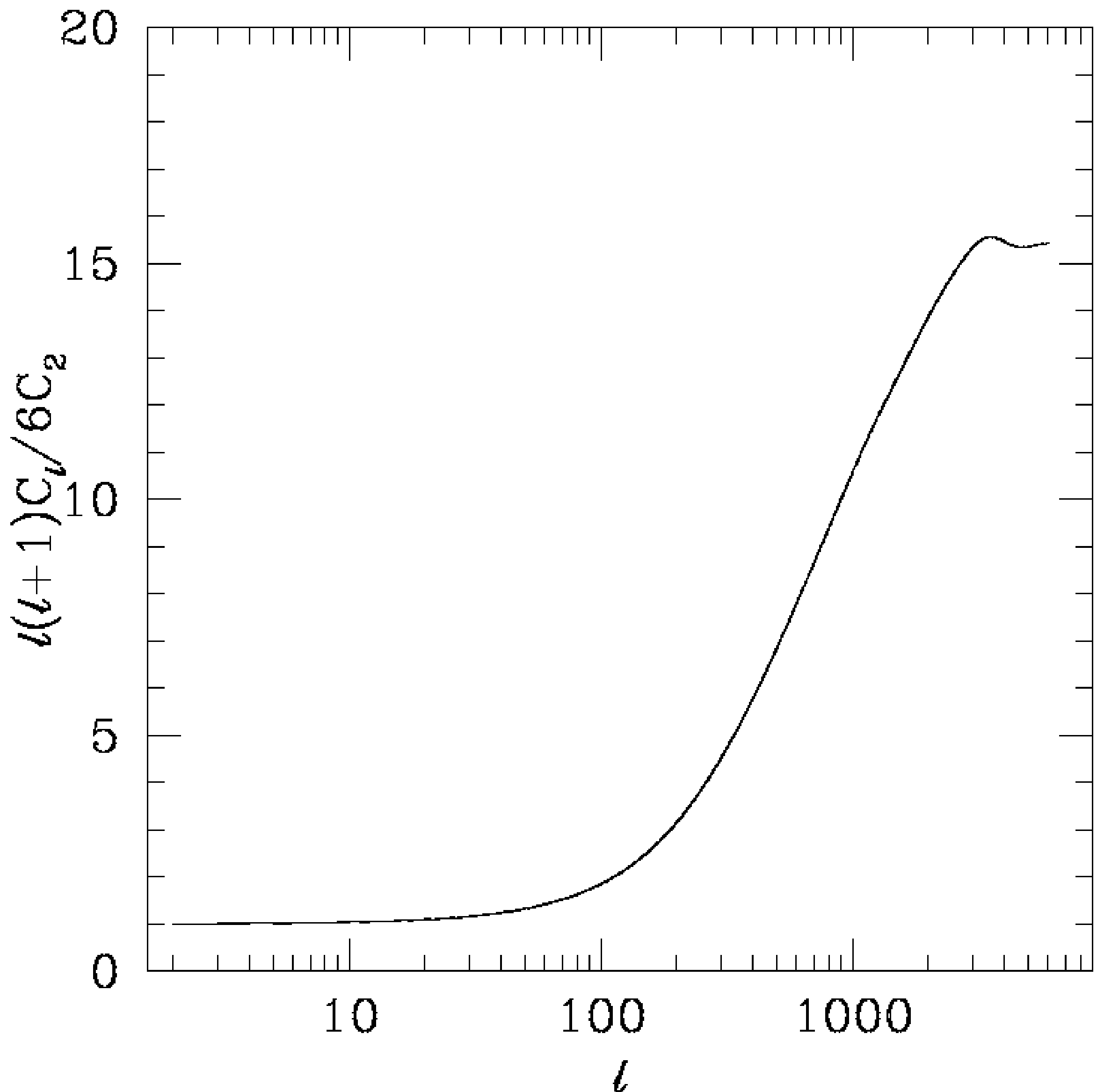
Latest results from WMAP5 N>0 at 95 % c.l. from CMB DATA alone (Komatsu et al., 2008).

Massless neutrinos, like photons, have anisotropies which follow a Liouville differential equation:

$$\frac{\partial \iota}{\partial t} + \frac{\gamma_i}{a}\frac{\partial \iota}{\partial x^i} - 2\dot{h}_{jk}\gamma_j\gamma_k = 0$$

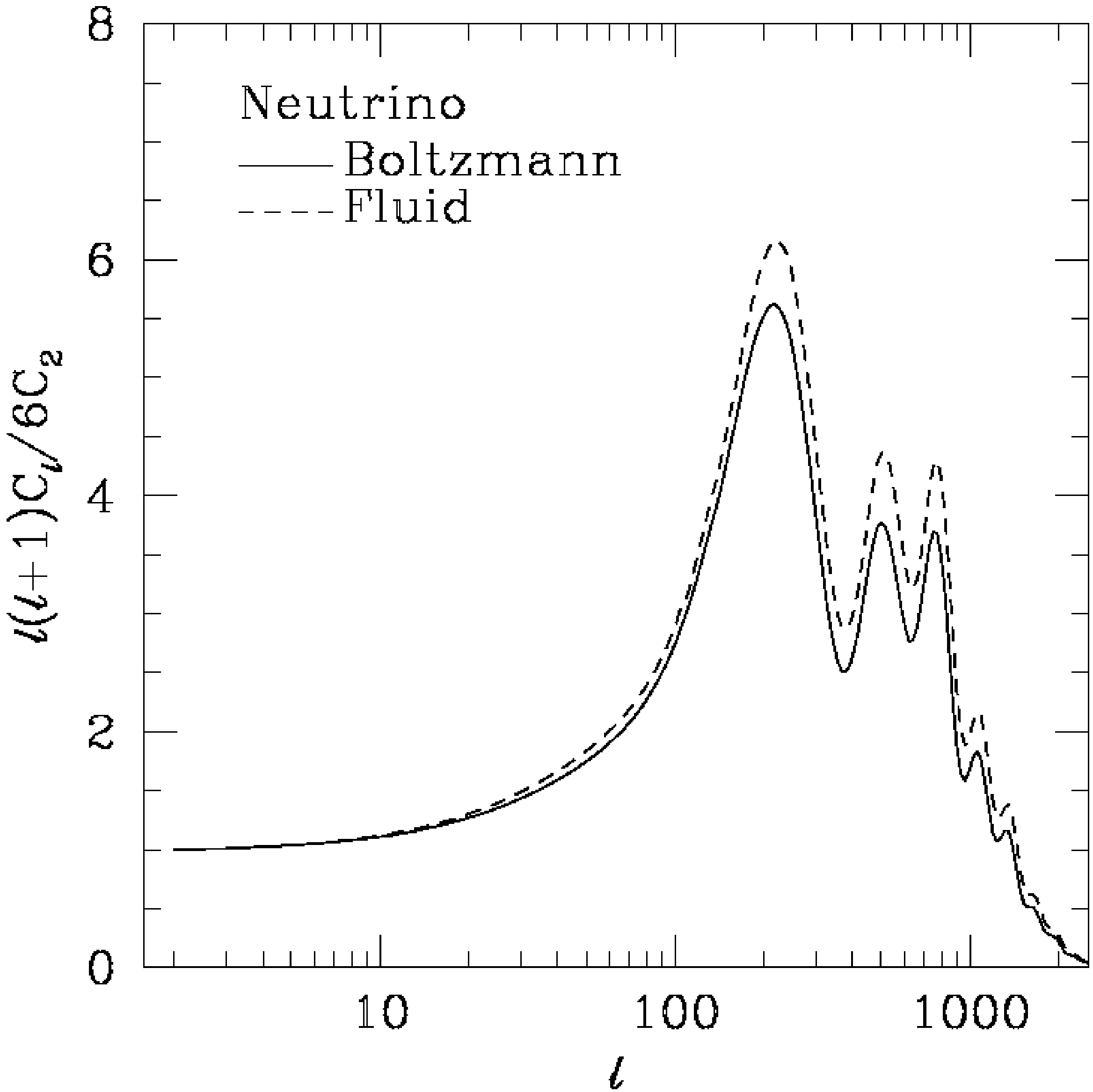
As in the case of photons, these anisotropies can be computed integrating a hierarchy of differential equations.

Can we see them ?

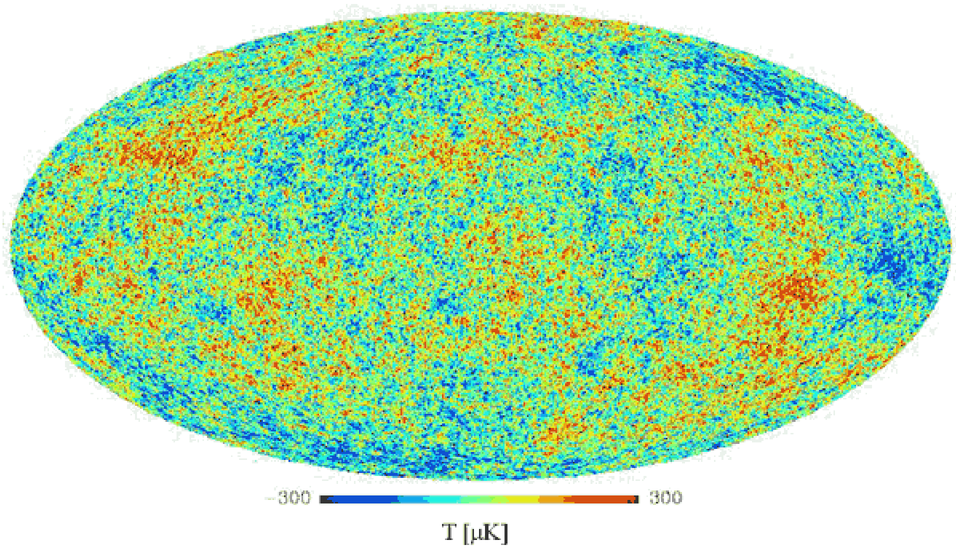


Hu et al., astro-ph/9505043

Not directly!
But we can see the effects on the CMB angular spectrum !
CMB photons see the NB anisotropies through gravity.

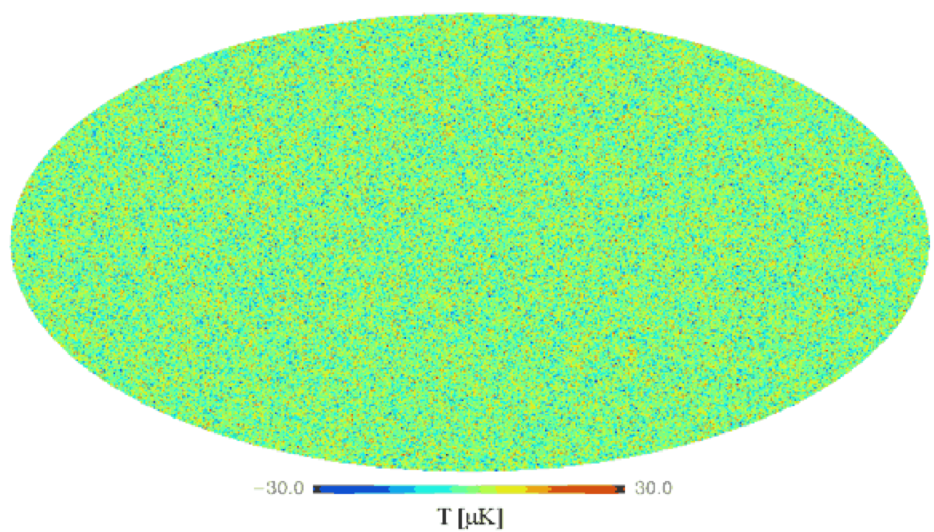


Standard Model



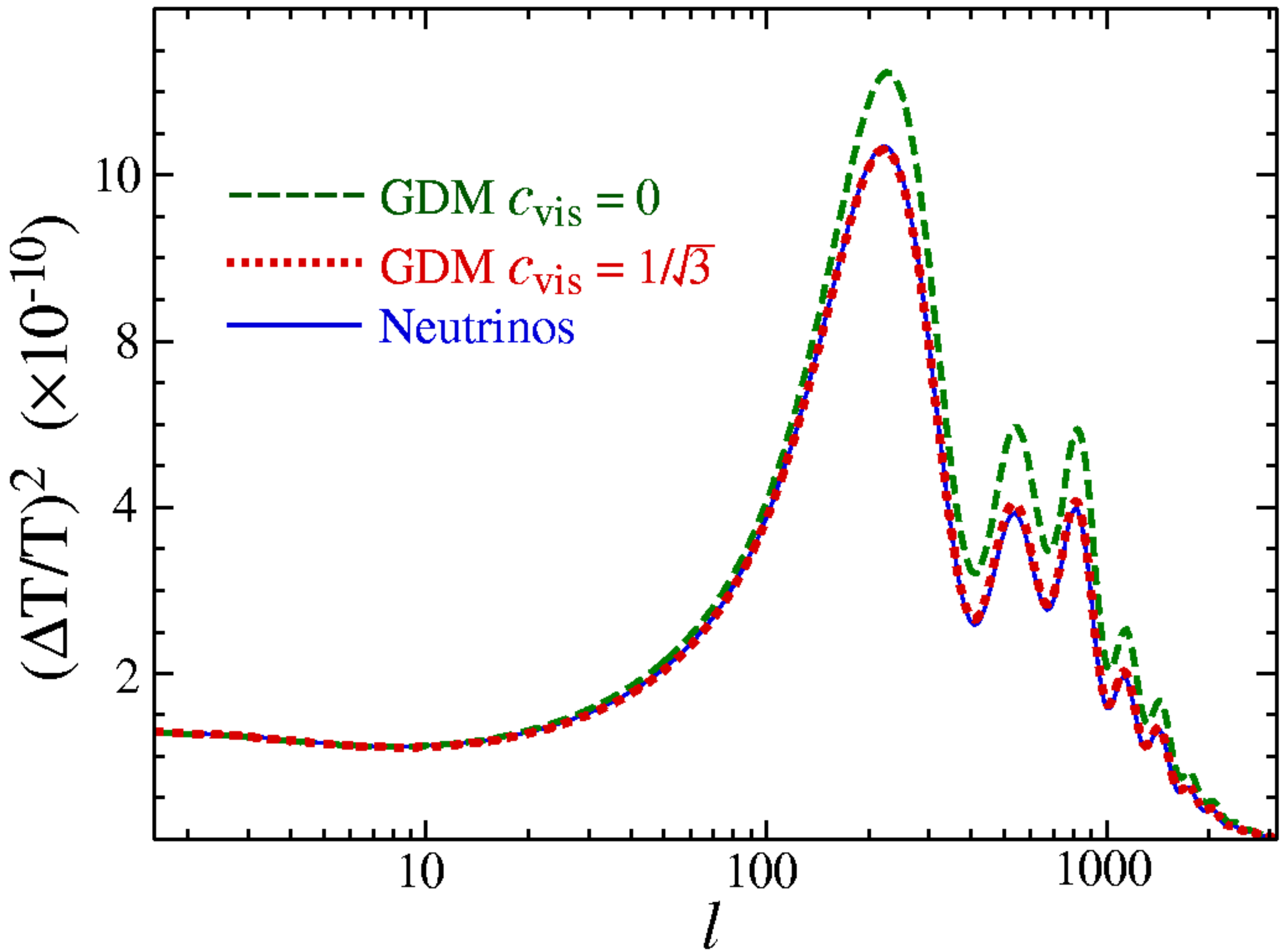
Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

Contribution from neutrino ripples



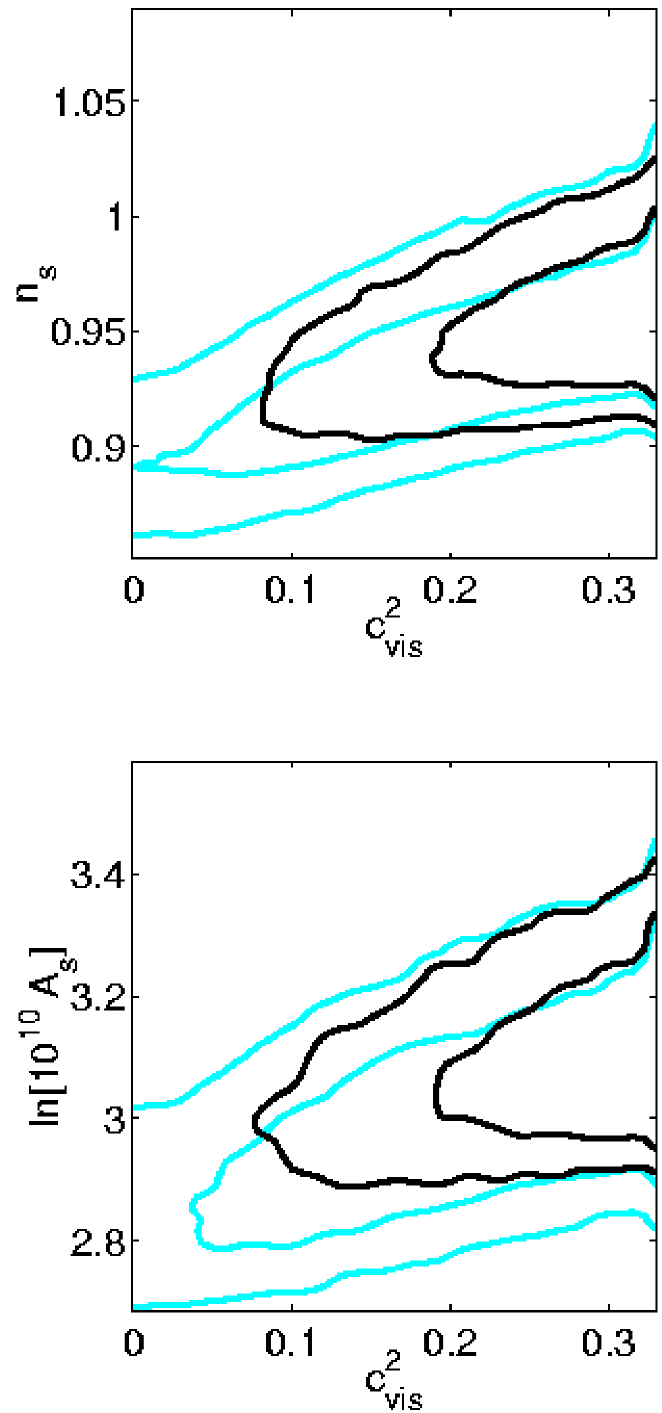
The net effect on the Microwave Background of the presence of neutrino ripples, interpreted as the signature of the existence of neutrino fluctuations as predicted in the Standard Model.

The Neutrino anisotropies can be parameterized through the “speed viscosity” c_{vis}. which controls the relationship between velocity/metric shear and anisotropic stress in the NB.

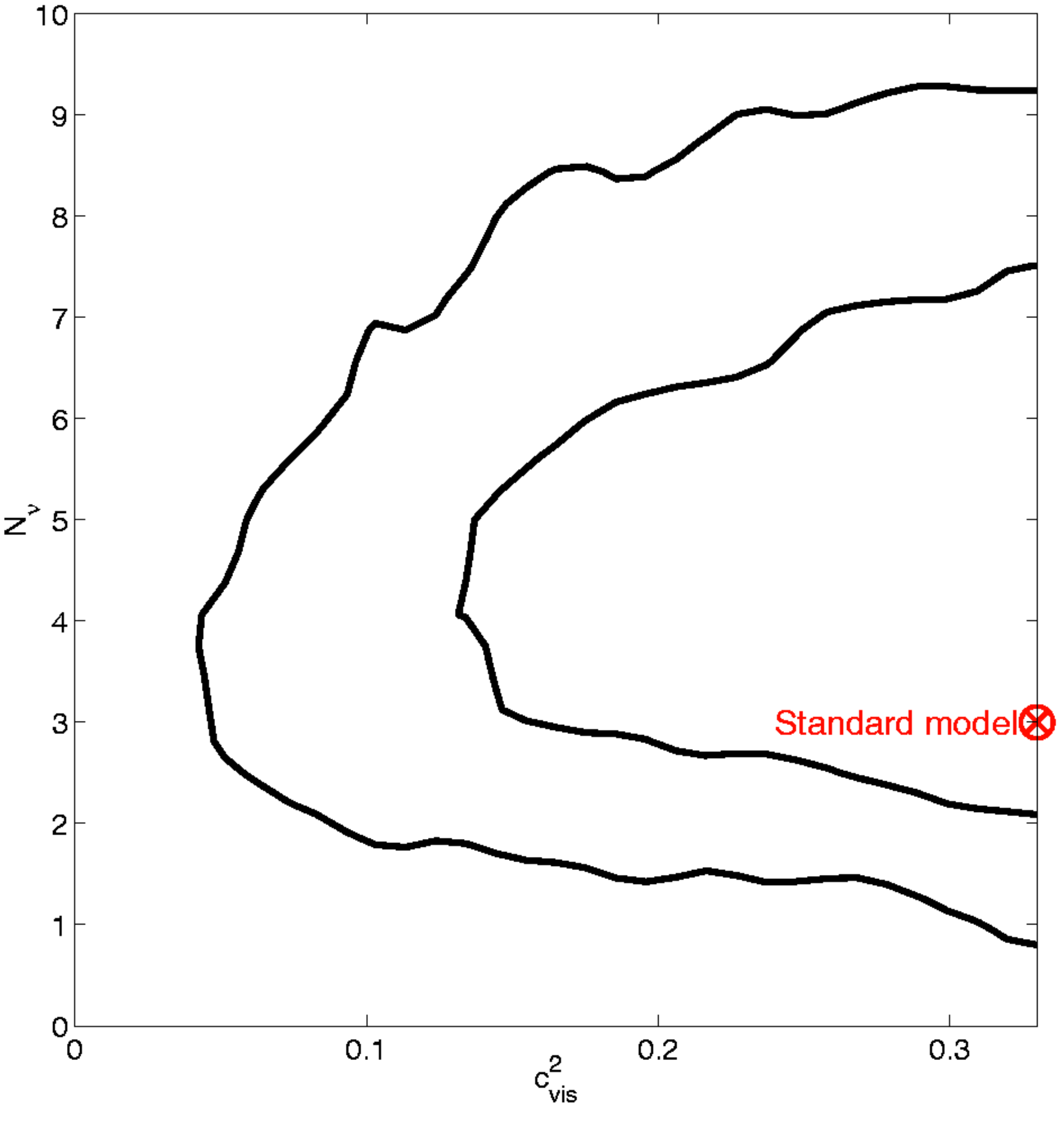


Hu, Eisenstein, Tegmark and White, 1999

Current CMB+SLOAN data provide evidence at 2.4 σ for anisotropies in the Neutrino Background.
Standard Model o.k.
R. Trotta, AM
Phys Rev Lett.
95 011305 (2005)



CMB+SDSS+
HST



R. Trotta and AM, astro-ph/0412066, PRL2005

Komatsu et al. 2008 WMAP5 paper

(68% and 95% CL), showing a strong degeneracy between $\Omega_m h^2$ and $N_{\rm eff}$. This degeneracy line is given by the equality redshift, $1+z_{\rm eq} = \Omega_m/\Omega_r = (4.050\times 10^4)\Omega_m h^2/(1+0.2271 N_{\rm eff})$. The thick solid lines show the 68% and 95% limits calculated from the WMAP-only limit on $z_{\rm eq}$: $z_{\rm eq} = 3141^{+154}_{-157}$ (68% CL). The 95% CL contours do not follow the lines below $N_{\rm eff}\sim 1.5$ but close there, which shows a strong evidence for the cosmic neutrino background from its effects on the CMB power spectrum via the neutrino anisotropic stress. The BAO and SN provide an independent constraint on $\Omega_m h^2$, which helps reduce the degeneracy between $N_{\rm eff}$ and $\Omega_m h^2$. (*Middle*) When we transform the horizontal axis of the left panel to $z_{\rm eq}$, we observe no degeneracy. The vertical solid lines show the one-dimensional marginalized 68% and 95% distribution calculated from the WMAP-only limit on $z_{\rm eq}$: $z_{\rm eq} = 3141^{+154}_{-157}$ (68% CL). Therefore, the left panel is simply a rotation of this panel using a relation between $z_{\rm eq}$, $\Omega_m h^2$, and $N_{\rm eff}$. (*Right*) One-dimensional marginalized distribution of $N_{\rm eff}$ from WMAP-only and WMAP+BAO+SN+HST. Note that a gradual decline of the likelihood toward $N_{\rm eff}\gtrsim 6$ for the WMAP-only constraint should not be trusted, as it is affected by the hard prior, $N_{\rm eff}<10$. The WMAP+BAO+SN+HST constraint is robust. This figure shows that the lower limit on $N_{\rm eff}$ is coming solely from the *WMAP* data. The 68% interval from WMAP+BAO+SN+HST, $N_{\rm eff} = 4.4\pm 1.5$, is consistent with the standard value, 3.04, which is shown by the vertical line.

The distance information from BAO and SN provides us with an independent constraint on $\Omega_m h^2$, which helps to reduce the degeneracy between $z_{\rm eq}$ and $\Omega_m h^2$.

The anisotropic stress of neutrinos also leaves distinct signatures in the CMB power spectrum, which is not degenerate with $\Omega_m h^2$ (Hu et al. 1995; Bashinsky & Seljak 2004). Trotta & Melchiorri (2005) (see also Melchiorri & Serra 2006) have reported on evidence for the neutrino anisotropic stress at slightly more than 95% CL. They have parametrized the anisotropic stress by the viscosity parameter, $c^2_{\rm vis}$ (Hu 1998), and found $c^2_{\rm vis} > 0.12$ (95% CL). However, they had to combine the *WMAP* 1-year data with the SDSS data to see the evidence for non-zero $c^2_{\rm vis}$.

In Dunkley et al. (2008) we report on the lower limit to $N_{\rm eff}$ solely from the *WMAP* 5-year data. In this paper we shall combine the *WMAP* data with the distance information from BAO and SN as well as Hubble's constant from HST to find the best-fitting value of $N_{\rm eff}$.

6.2.3. *Results*

Figure 18 shows our constraint on $N_{\rm eff}$. The contours in the left panel lie on the expected linear correlation between $\Omega_m h^2$ and $N_{\rm eff}$ given by

$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right), \quad (84)$$

which follows from equation (83). (Here, $\Omega_m h^2 = 0.1308$ and $z_{\rm eq} = 3138$ are the maximum likelihood values from the simplest ΛCDM model.) The width of the degeneracy line is given by the accuracy of our determination of $z_{\rm eq}$, which is given by $z_{\rm eq} = 3141^{+154}_{-157}$ (WMAP-only) for this model. Note that the mean value of $z_{\rm eq}$ for the simplest ΛCDM model with $N_{\rm eff} = 3.04$ is $z_{\rm eq} = 3176^{+151}_{-150}$, which is close. This confirms that $z_{\rm eq}$ is one of the fundamental observables, and $N_{\rm eff}$ is merely a secondary parameter that can be derived from $z_{\rm eq}$. The middle panel of Fig. 18 shows this clearly: $z_{\rm eq}$ is determined independently of $N_{\rm eff}$. For each value of $N_{\rm eff}$ along a constant $z_{\rm eq}$ line, there is a corresponding $\Omega_m h^2$ that gives the same value of $z_{\rm eq}$ along the line.

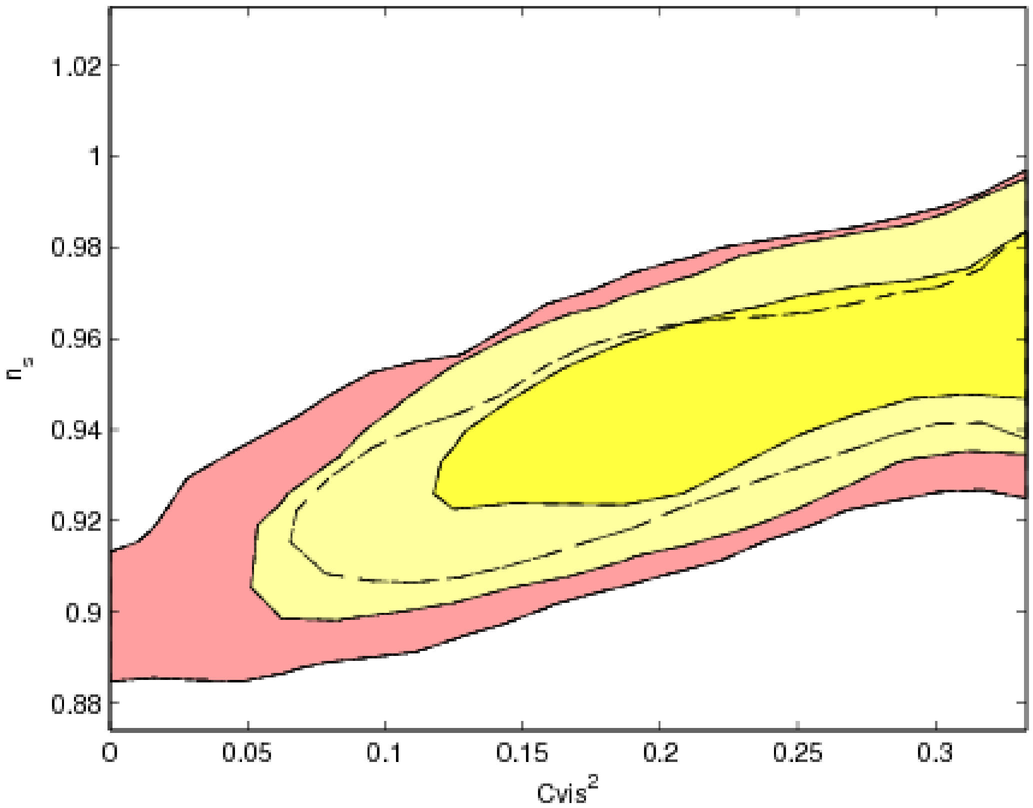
However, the contours do not extend all the way down to $N_{\rm eff} = 0$, although equation (84) predicts that $N_{\rm eff}$ should go to zero when $\Omega_m h^2$ is sufficiently small. This indicates that we are seeing the effect of the neutrino anisotropic stress at a high significance. While we need to repeat the analysis of Trotta & Melchiorri (2005) in order to prove that our finding of $N_{\rm eff} > 0$ comes from the neutrino anisotropic stress, we believe that there is a strong evidence that we see non-zero $N_{\rm eff}$ via the effect of neutrino anisotropic stress, rather than via $z_{\rm eq}$.

While the *WMAP* data alone can give a lower limit on $N_{\rm eff}$ (Dunkley et al. 2008), they cannot give an upper limit owing to the strong degeneracy with $\Omega_m h^2$. Therefore, we use the BAO, SN, and HST data to break the degeneracy. We find $N_{\rm eff} = 4.4\pm 1.5$ (68%) from WMAP+BAO+SN+HST, which is fully consistent with the standard value, 3.04 (see the right panel of Fig. 18).

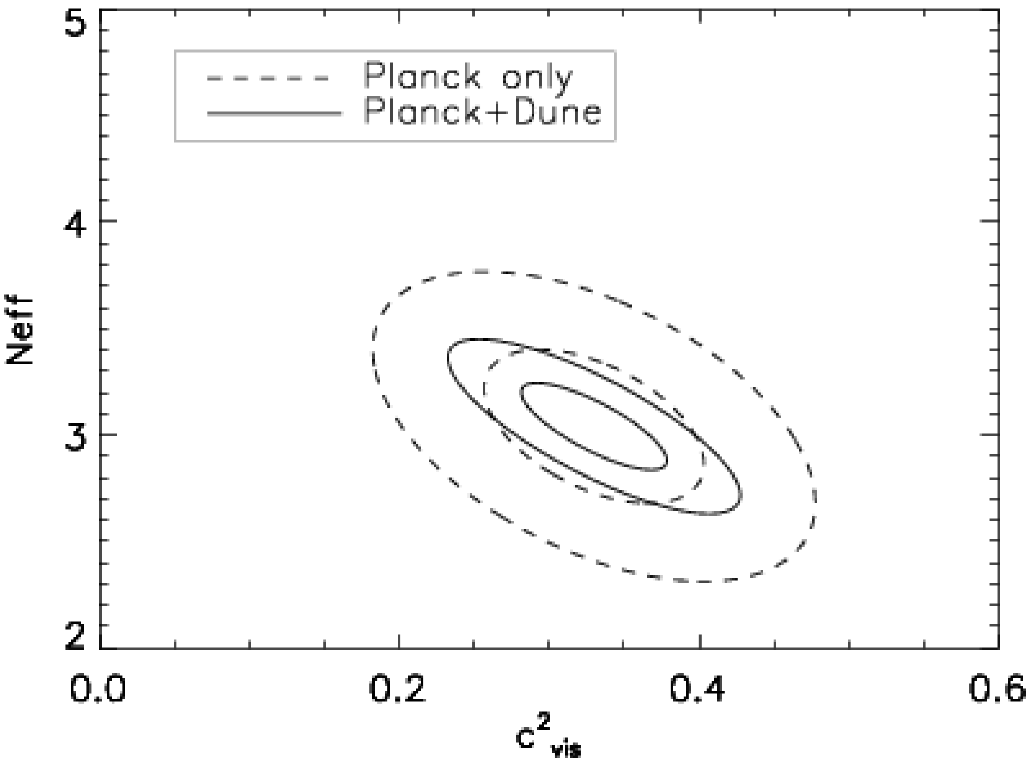
7. CONCLUSION

With 5 years of integration, the *WMAP* temperature and polarization data have improved significantly. An improved determination of the third acoustic peak has enabled us to reduce the uncertainty in the amplitude of matter fluctuation, parametrized by σ_8, by a factor of 1.4 from the *WMAP* 3-year result. The E-mode polarization is now detected at 5 standard deviations (c.f., 3.0 standard deviations for the 3-year data; Page et al. 2007), which rules out an instantaneous reionization at $z_{\rm reion} = 6$ at the 3.5σ level. Overall, the *WMAP* 5-year data continue to support the simplest, 6-parameter

De Bernardis, Pagano et al., in preparation.



What about the future ?



De Bernardis, Pagano et al., in preparation.

Conclusions

- Current CMB and LSS data are in very good agreement with the standard scenario. Limits on N_ν are still weak, Sensitivity comparable to BBN is possible in the very near future. If Lyman-alpha are included there is "some" suggestion that N>3.

- Cosmological constraints on neutrino mass are rapidly improving. If one includes Ly-alpha then $\Sigma<0.17$ eV. Tension with the $0\nu\beta\beta$ results.Fourth sterile massive neutrino if thermal is constrained to be $m_s<0.25$eV. Cosmology not compatible with LSND and $0\nu\beta\beta$(Klapdor). Compatible with latest MINIBOONE :-)

- Correlations with other possible HDM components (axions).

- All those results can be tested in the very near future by Laboratory experiments.