Constraints on the Dark Side of the Universe

Alessandro Melchiorri

Friedmann Cosmological Model works only if:

$$\Omega_\Lambda = 0.73 \pm 0.04$$

A model without cosmological constant is now ruled out at more than 18 sigma!

Why so small ? Why now ?

COSMOLOGICAL COSTANT vs "Something else"

$$\rho_\Lambda \equiv const$$

$$p_\Lambda = -\rho_\Lambda$$

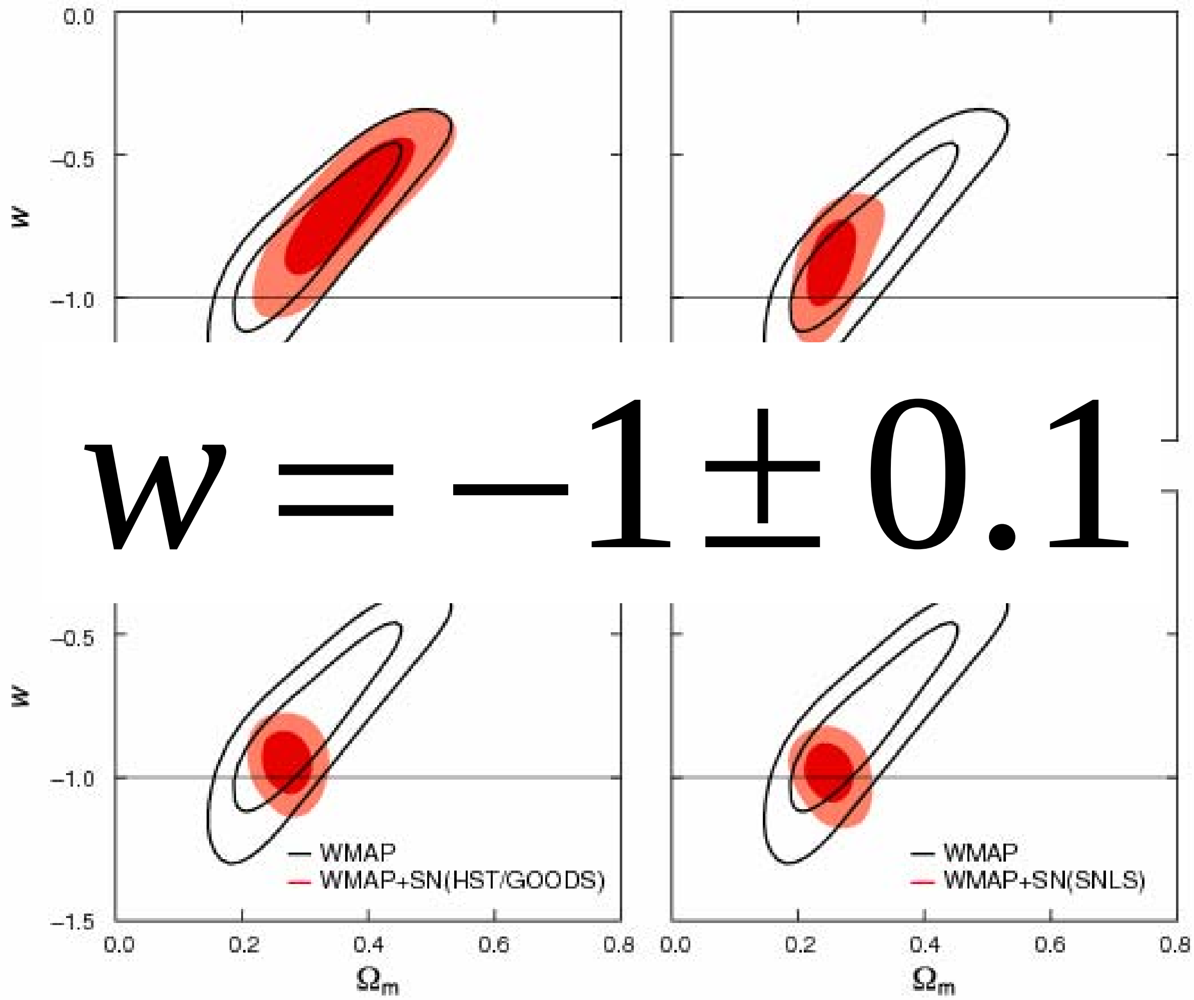
$$\delta\rho_\Lambda = 0$$

Vs.

$$\rho_X(z) \equiv \rho_X(0)\exp\left(3\int_0^z dz'\frac{1+w(z')}{1+z'}\right)$$

$$p_X = w(z)\rho_X$$

$$\delta\rho_X \neq 0$$



$$w = -1 \pm 0.1$$

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

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

HM 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

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

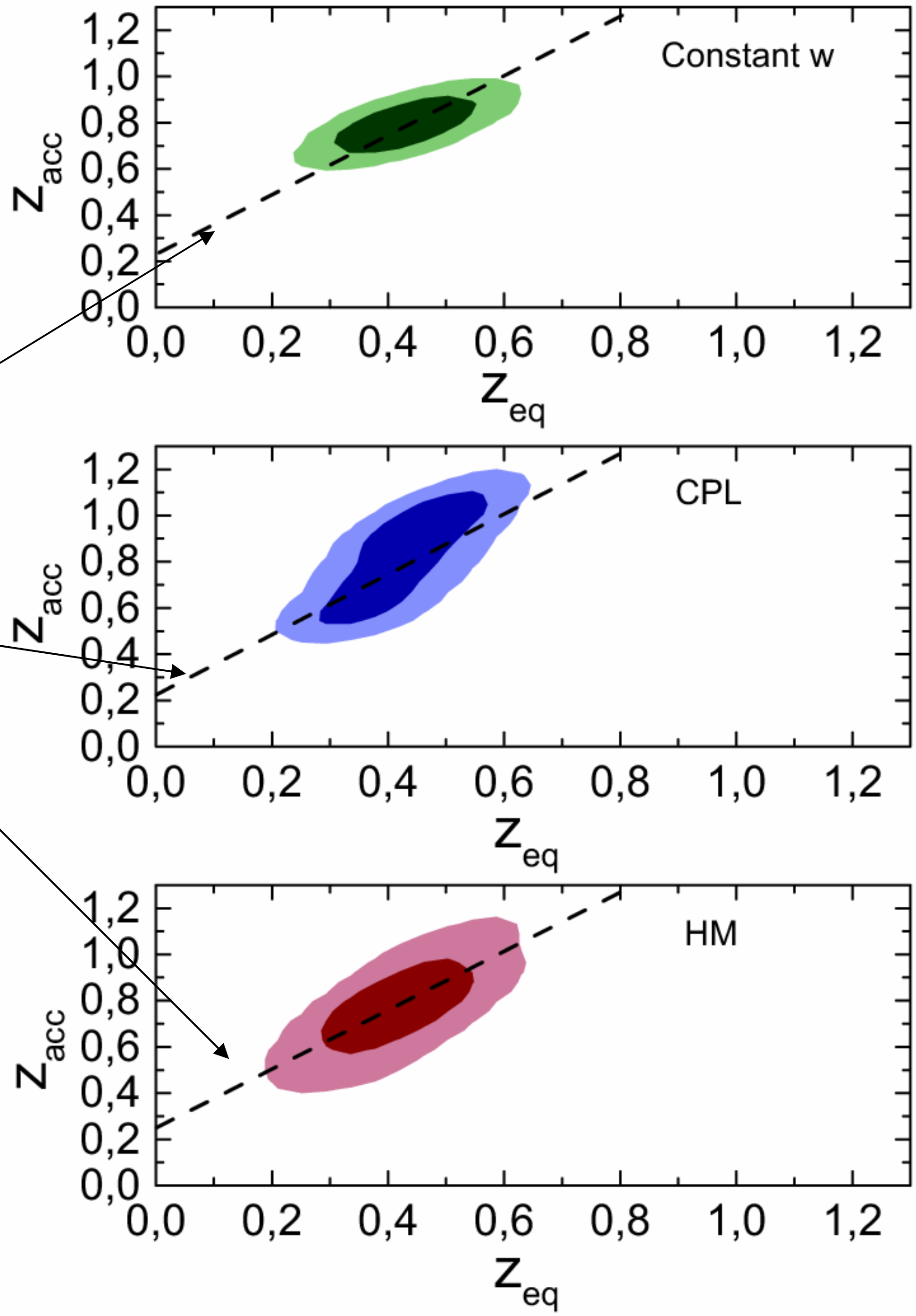
Redshift and Time of
onset of cosmic acceleration

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

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…



$$w(a) = w_0$$

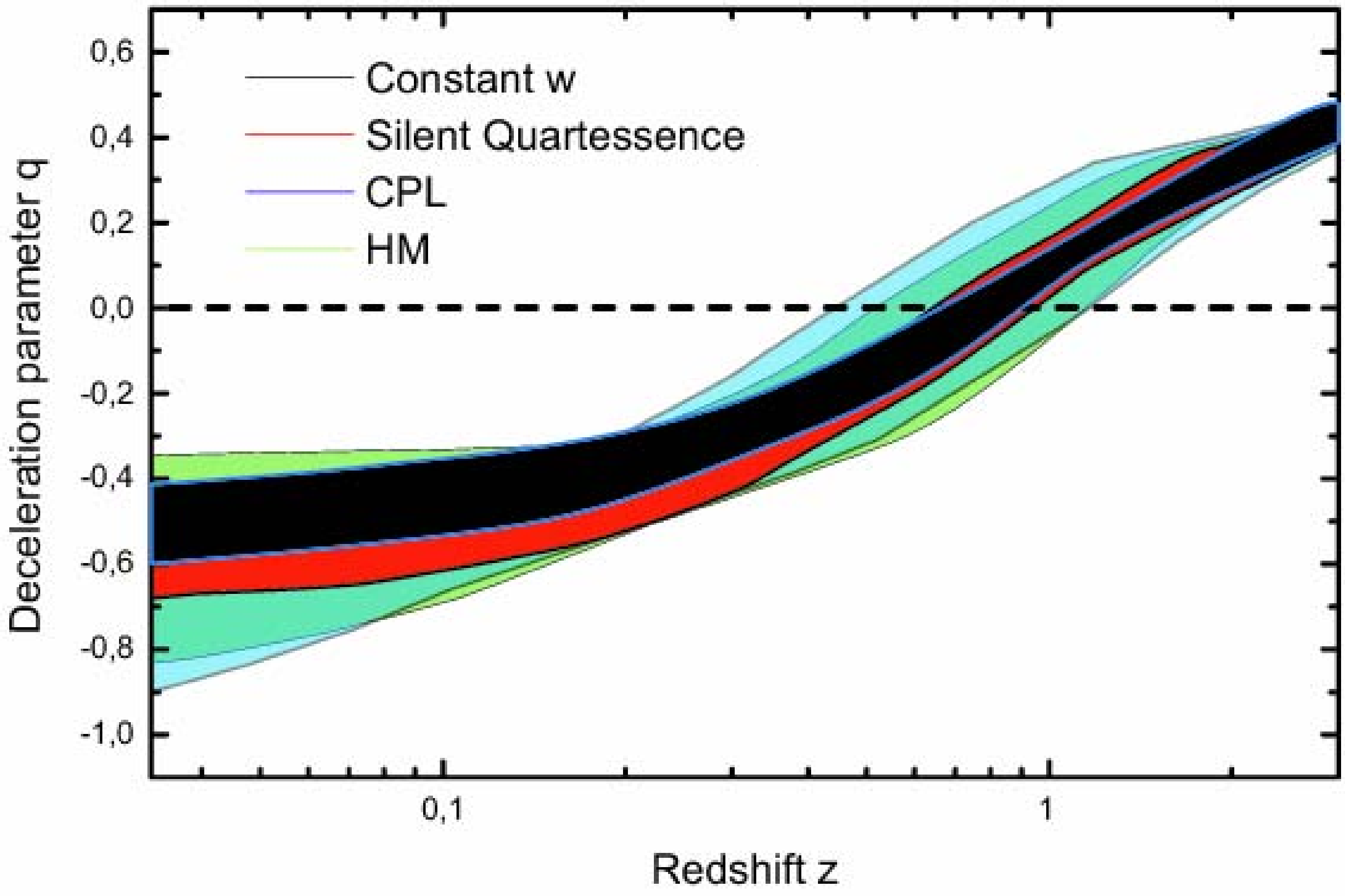
$$w(a) = w_0 + w_1(1 - a)$$

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

Cosmological
Constant

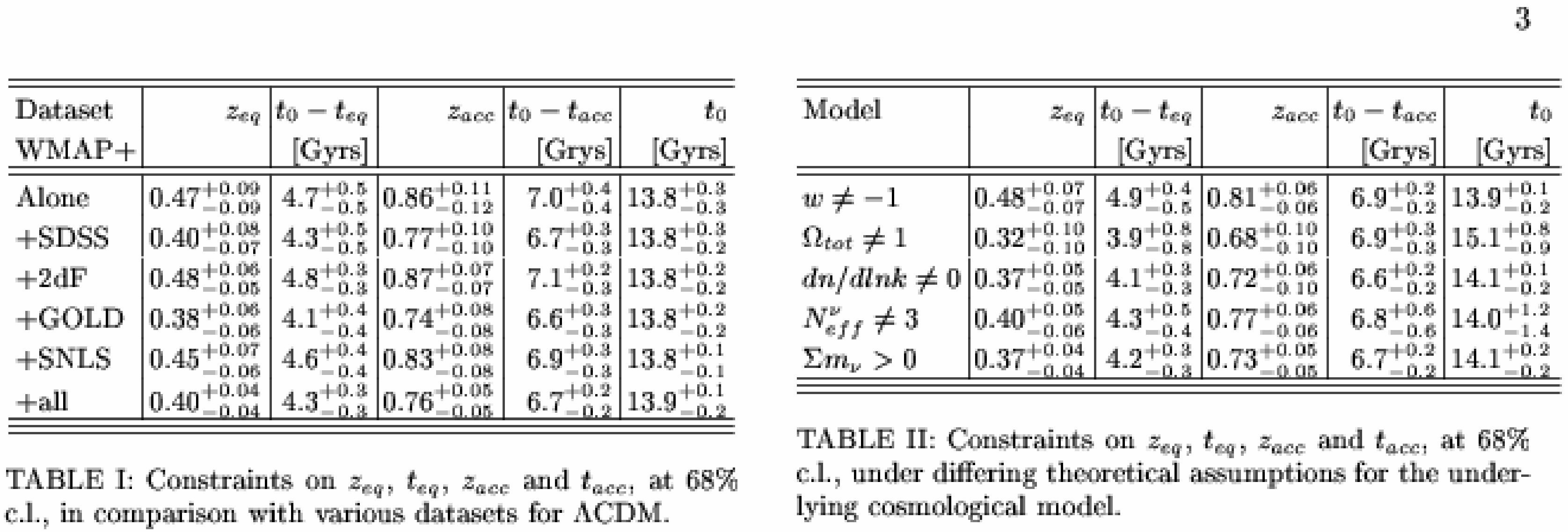
Melchiorri, Pagano, Pandolfi, PRD, 2007

When cosmological data are combined, the redshift of The onset of cosmic acceleration is consistent between the different parametrization of w.



Melchiorri, Pagano, Pandolfi, PRD, 2007

When did Cosmic acceleration start?



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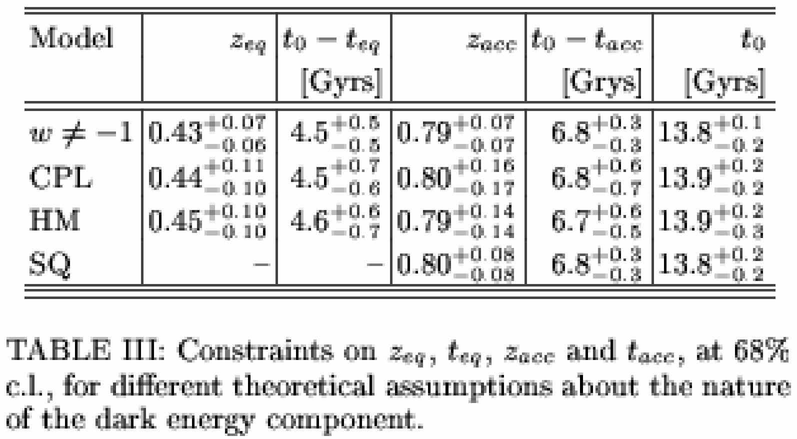
Dataset WMAP+	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
Alone	$0.47^{+0.09}_{-0.09}$	$4.7^{+0.5}_{-0.5}$	$0.86^{+0.11}_{-0.12}$	$7.0^{+0.4}_{-0.4}$	$13.8^{+0.3}_{-0.3}$
+SDSS	$0.40^{+0.08}_{-0.07}$	$4.3^{+0.5}_{-0.5}$	$0.77^{+0.10}_{-0.10}$	$6.7^{+0.3}_{-0.3}$	$13.8^{+0.3}_{-0.2}$
+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	–	–	$0.80^{+0.08}_{-0.08}$	$6.8^{+0.3}_{-0.3}$	$13.8^{+0.2}_{-0.2}$

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):

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

Evidence

Likelihood

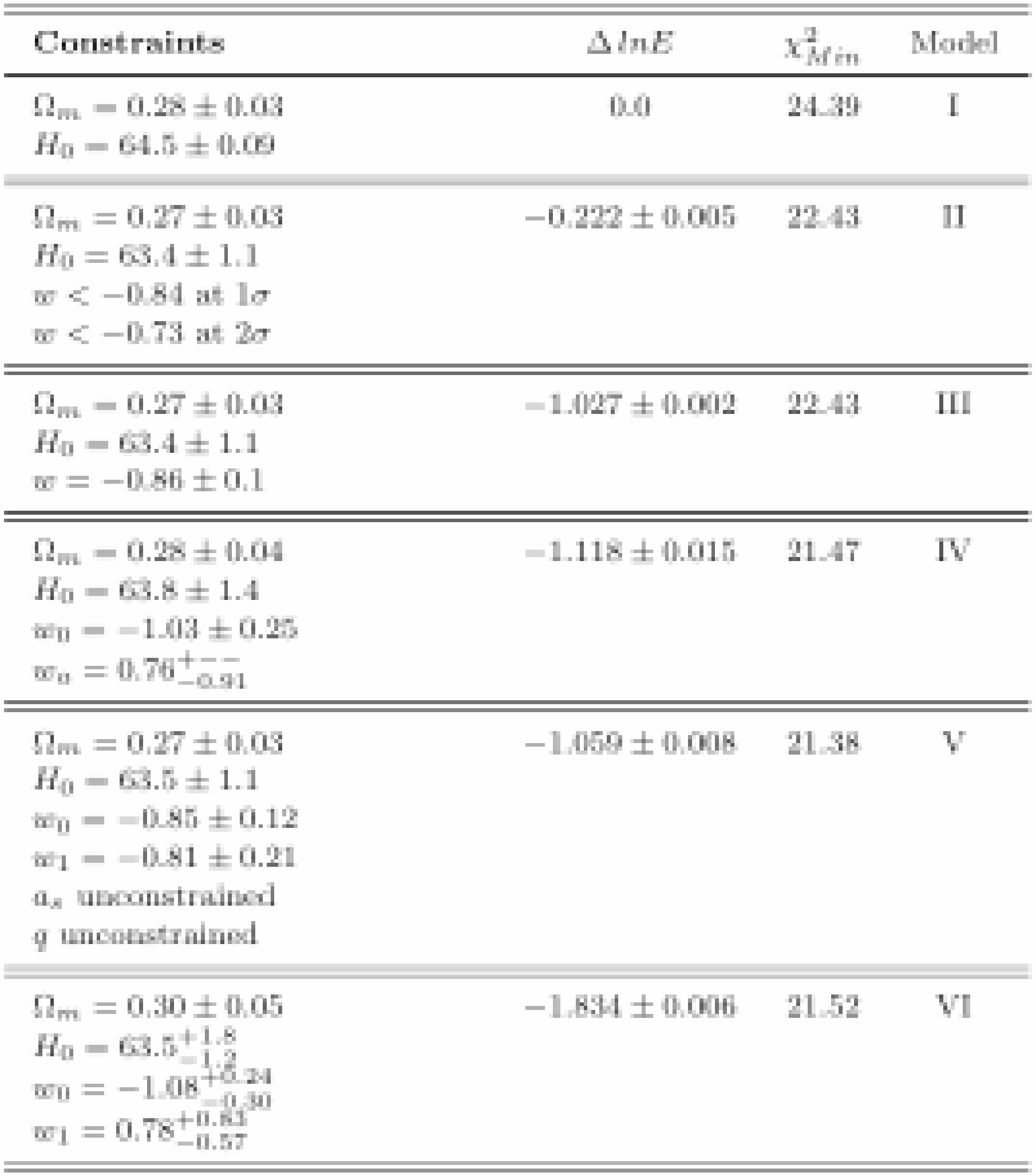
Prior

Jeffrey(1961):

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

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

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



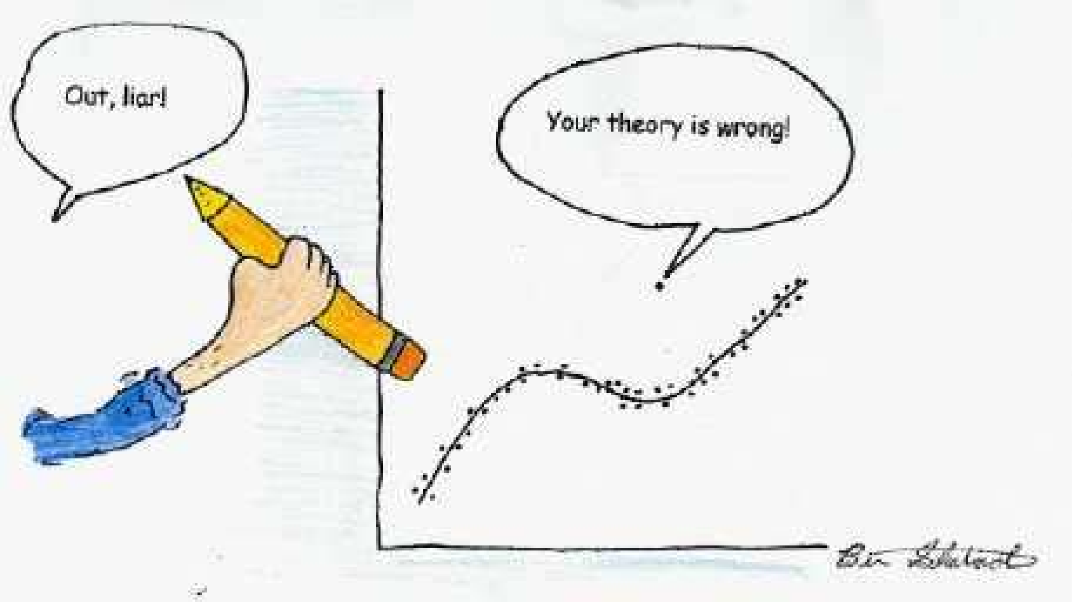
Constraints	ΔlnE	χ^2_{Min}	Model
$\Omega_m = 0.28 \pm 0.03$ $H_0 = 64.5 \pm 0.09$	0.0	24.39	I
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w < -0.84$ at 1σ $w < -0.73$ at 2σ	-0.222 ± 0.005	22.43	II
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w = -0.86 \pm 0.1$	-1.027 ± 0.002	22.43	III
$\Omega_m = 0.28 \pm 0.04$ $H_0 = 63.8 \pm 1.4$ $w_0 = -1.03 \pm 0.25$ $w_a = 0.76^{+--}_{-0.91}$	-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

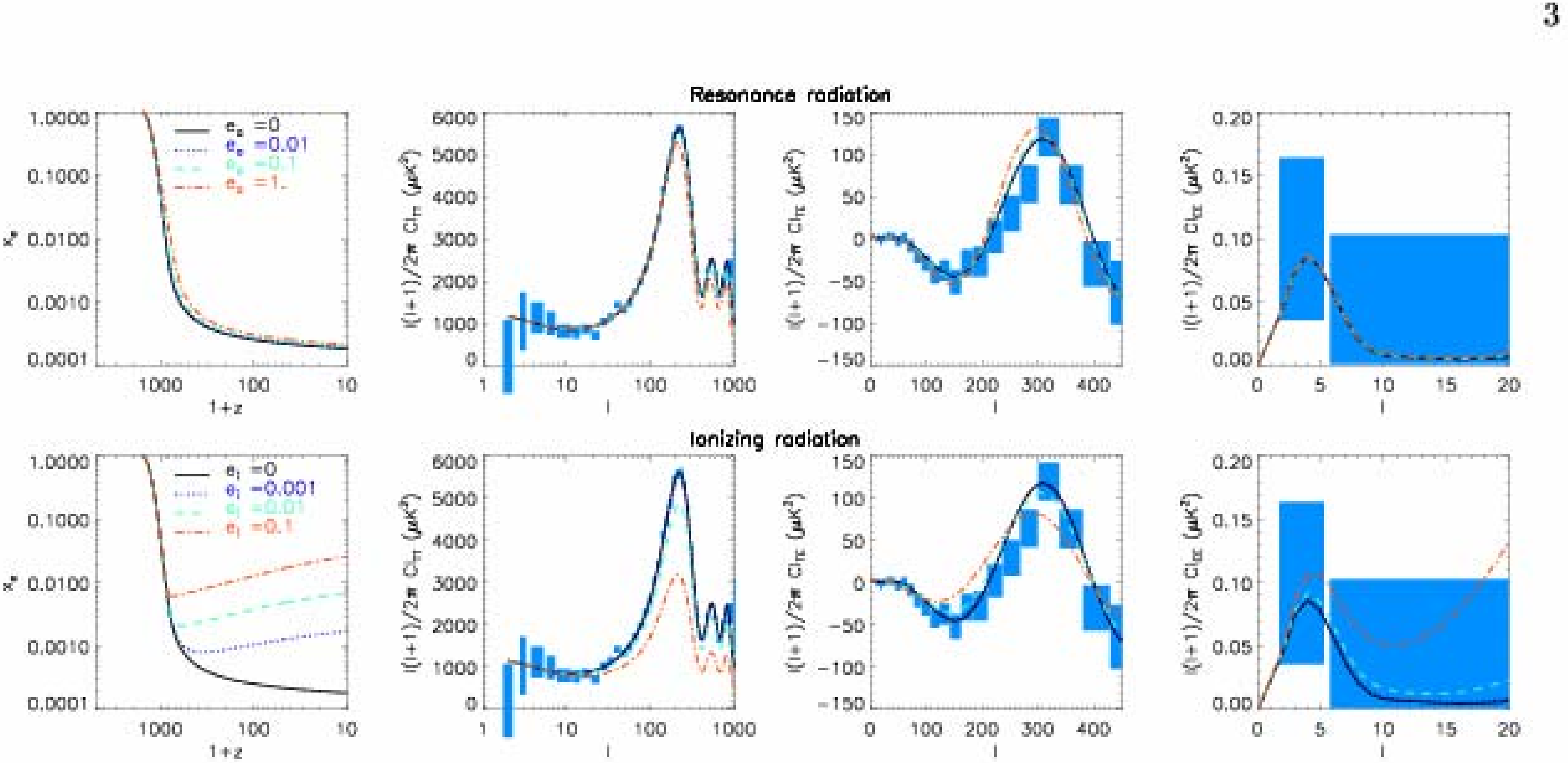
Wrong assumptions in the theoretical model ?



"It's somewhere between a nova and a supernova
... probably a pretty good nova."

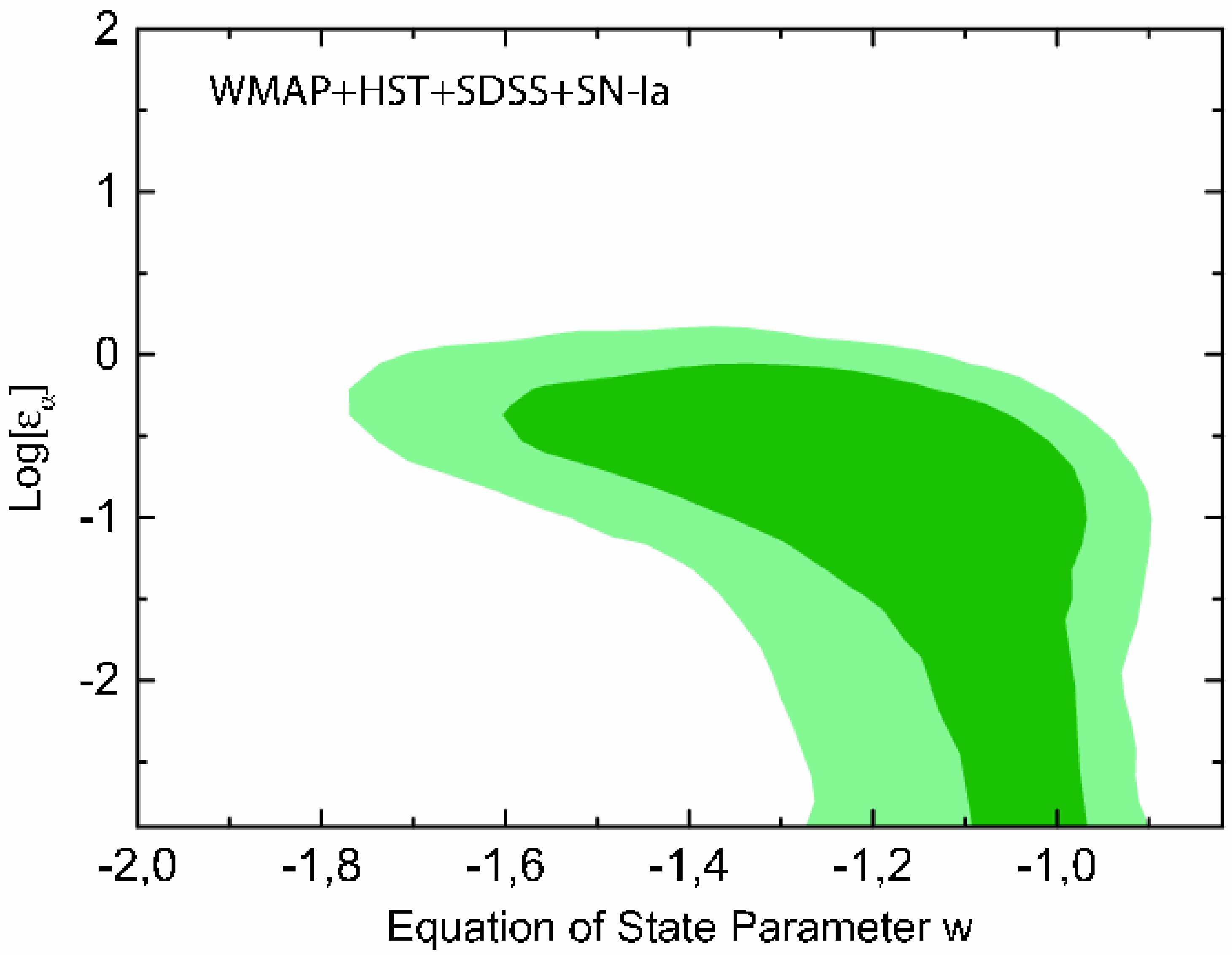
Delayed Recombination

If sources of Lya resonance radiation were present at z ~ 1000 (see Peebles et al., 2001) they would delay recombination, shifting the first CMB peak to larger angular scales, and producing a bias in the measure of w.



Bean, Melchiorri, Silk, Phys. Rev. D **75**, 063505 (2007)

Bean, Melchiorri, Silk, Phys. Rev. D., 2007



If resonant radiation is present, the true value of w could be less than -1. Delayed Recombination affects current aestimates on w.

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

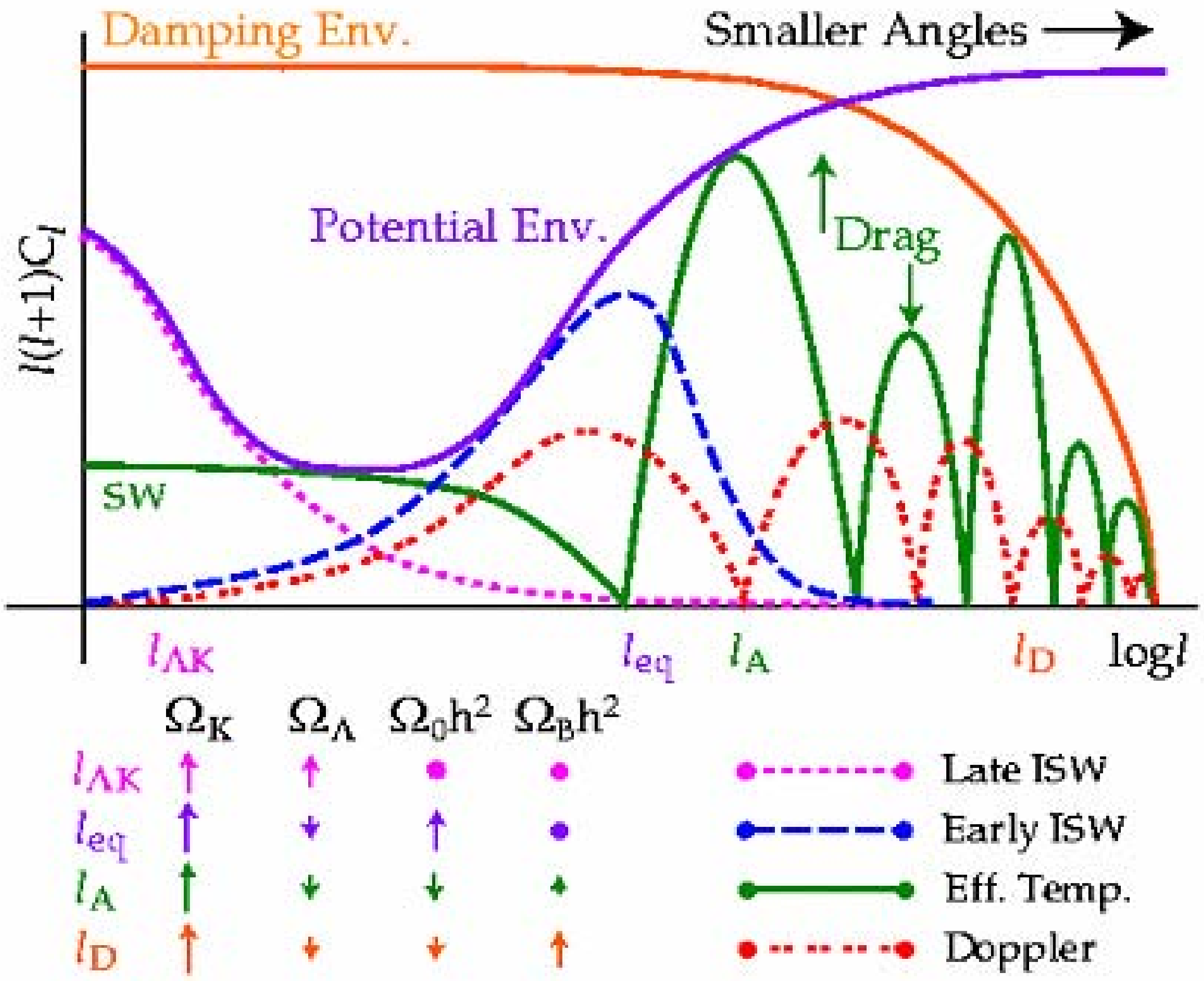
when does the linear potential change?

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

Poisson's equation

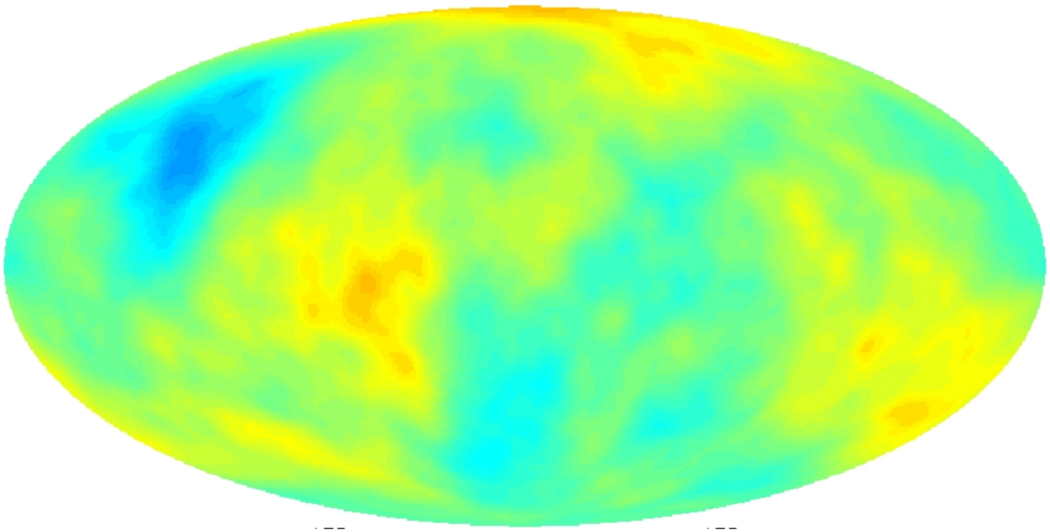
- constant during matter domination
- decays after curvature or dark energy come to dominate (z~1)

induces an additional, uncorrelated layer of large scale anisotropies

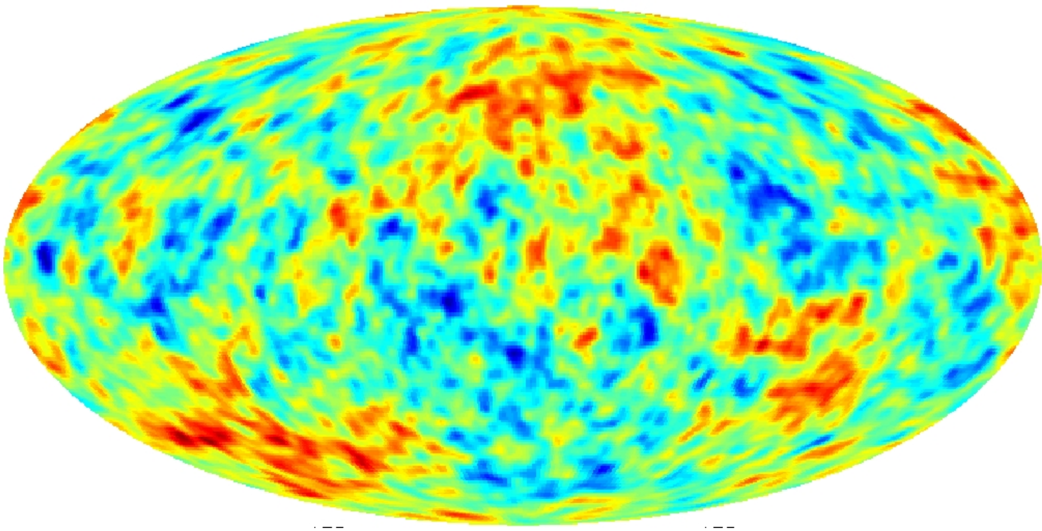


	Ω_K	Ω_Λ	$\Omega_0 h^2$	$\Omega_B h^2$
$l_{\Lambda K}$	↑	↑	●	●
l_{eq}	↑	↓	↑	●
l_A	↑	↓	↓	↑
l_D	↑	↓	↓	↑

two independent maps

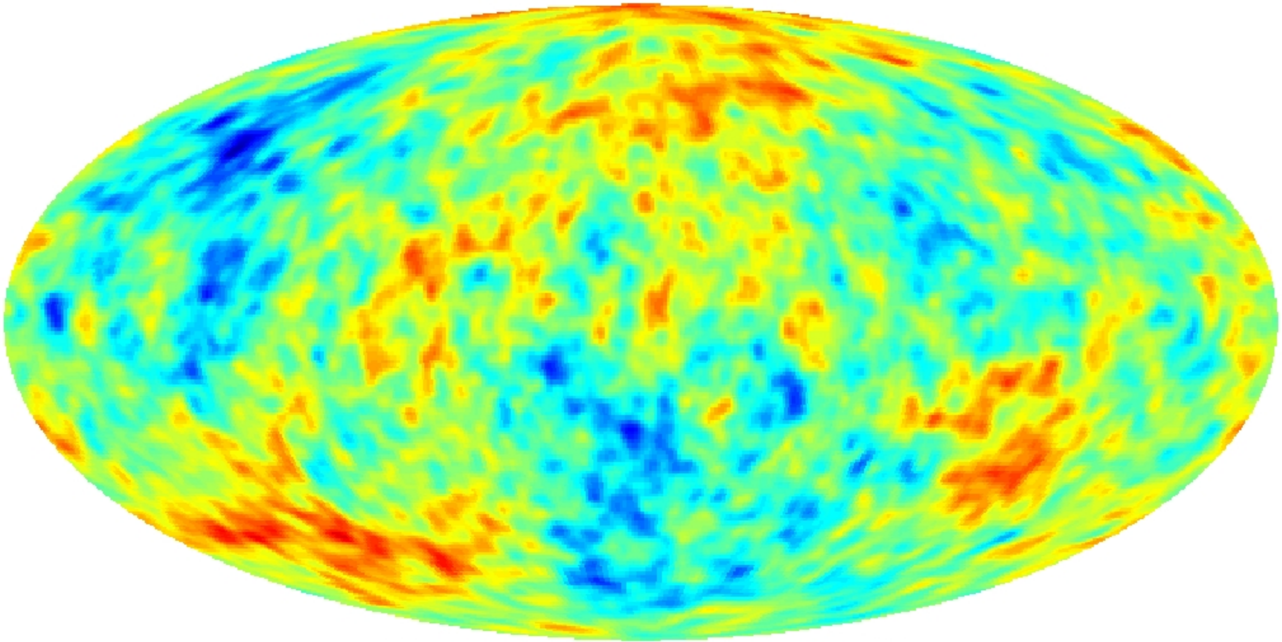


Integrated Sachs-Wolfe map
Mostly large angular features



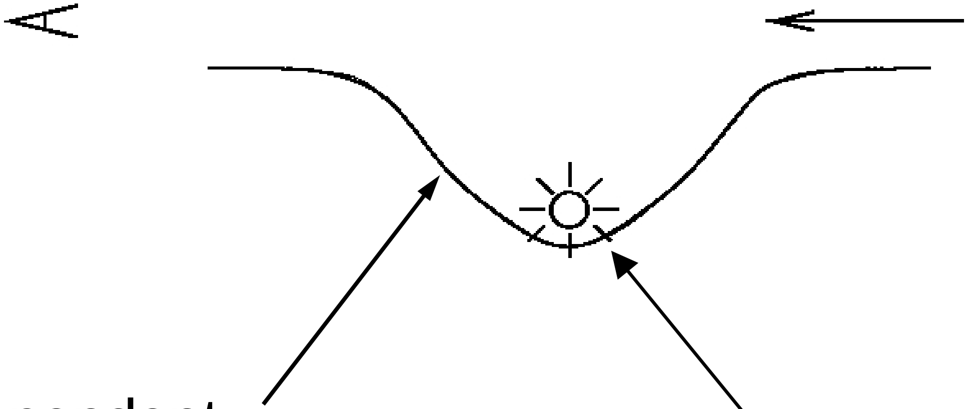
Early time map (z > 4)
Mostly from last scattering surface

Observed map is total of these, and has features of both (3 degree resolution)



compare with large scale structure

ISW fluctuations are correlated with the galaxy distribution!



observer

potential depth
changes as cmb
photons pass
through

time dependent
gravitational potential

density of galaxies traces
the potential depth

since the decay happens slowly, we need to see galaxies at high redshifts (z~1)

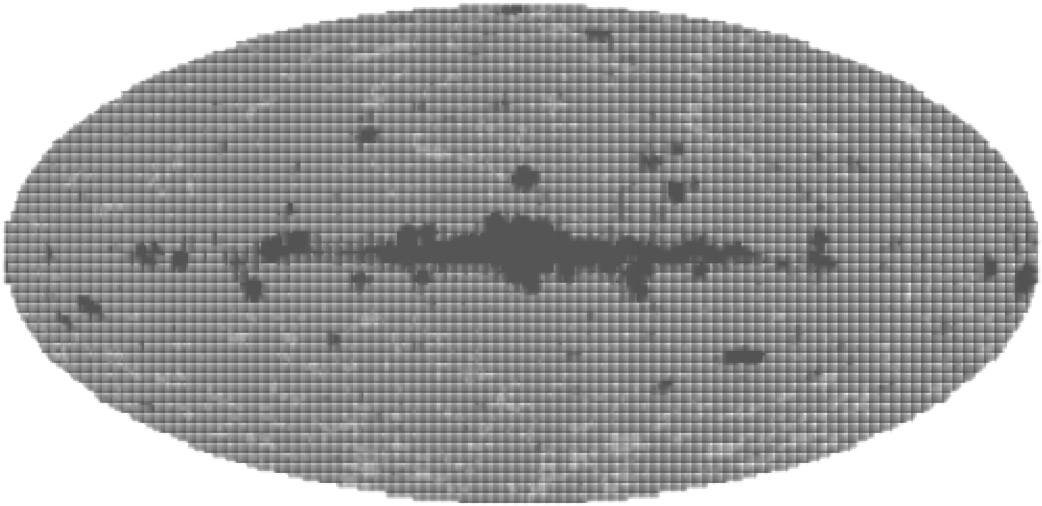
- ➢ active galaxies (quasars, radio, or hard x-ray sources)
- ➢ possibility of accidental correlations means full sky needed

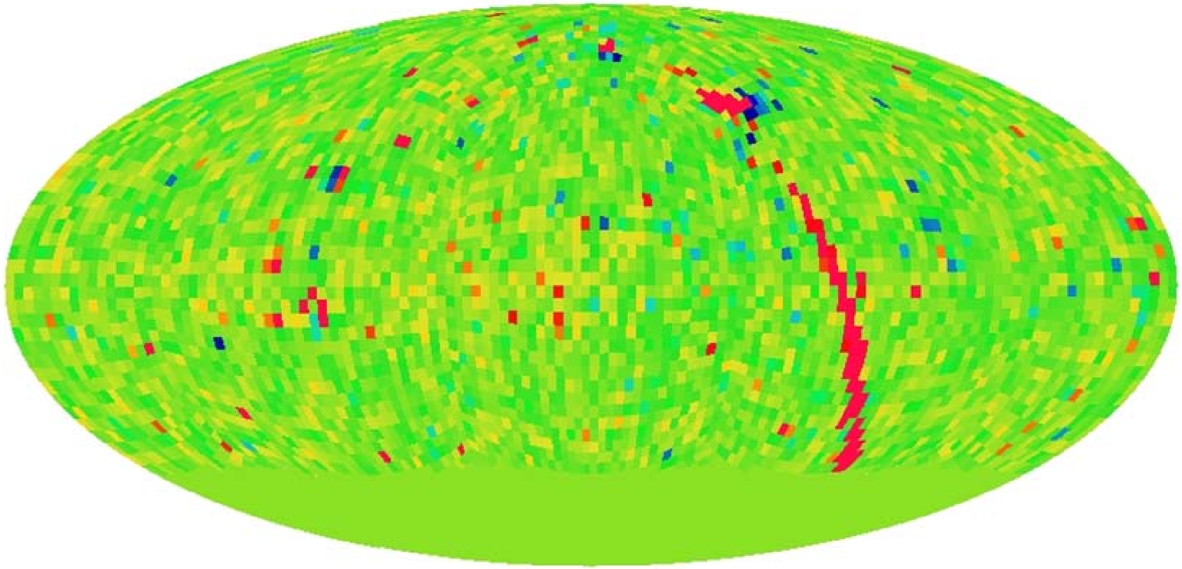
how do we trace the matter?

X-rays from active galaxies

HEAO-1 x-ray satellite

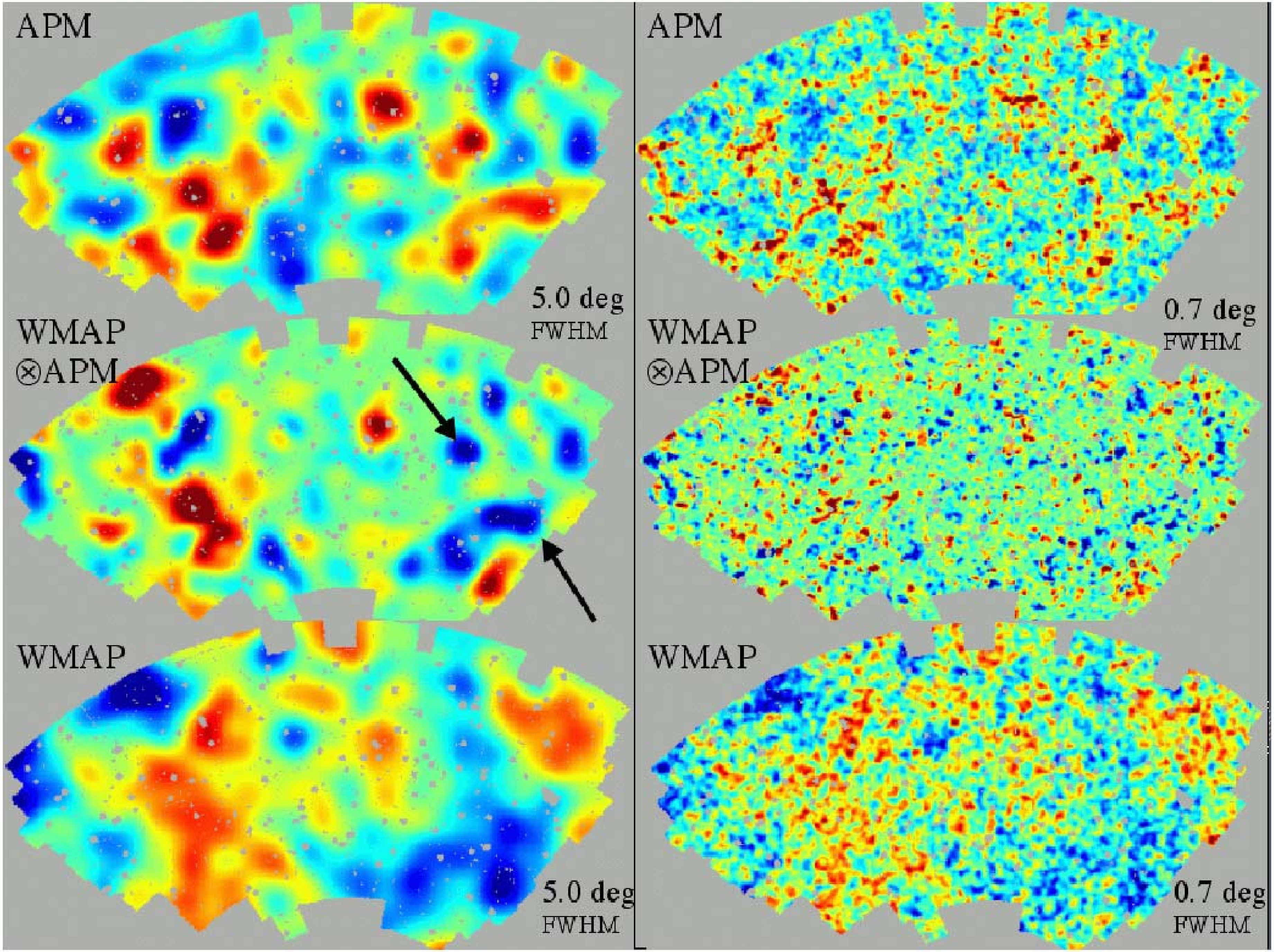
Galaxy and virtually all visible structures cleaned out





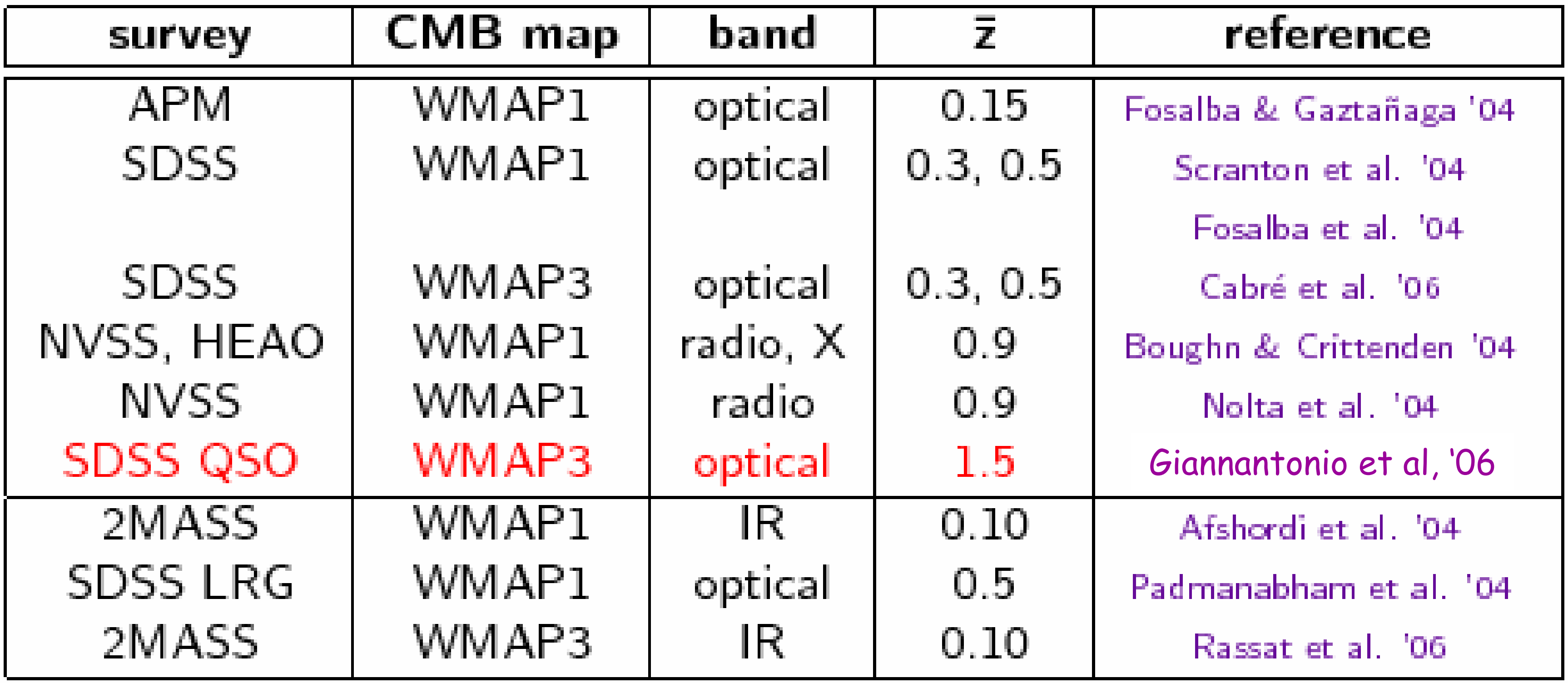
Radio galaxies

NRAO VLA Sky Survey (NVSS)

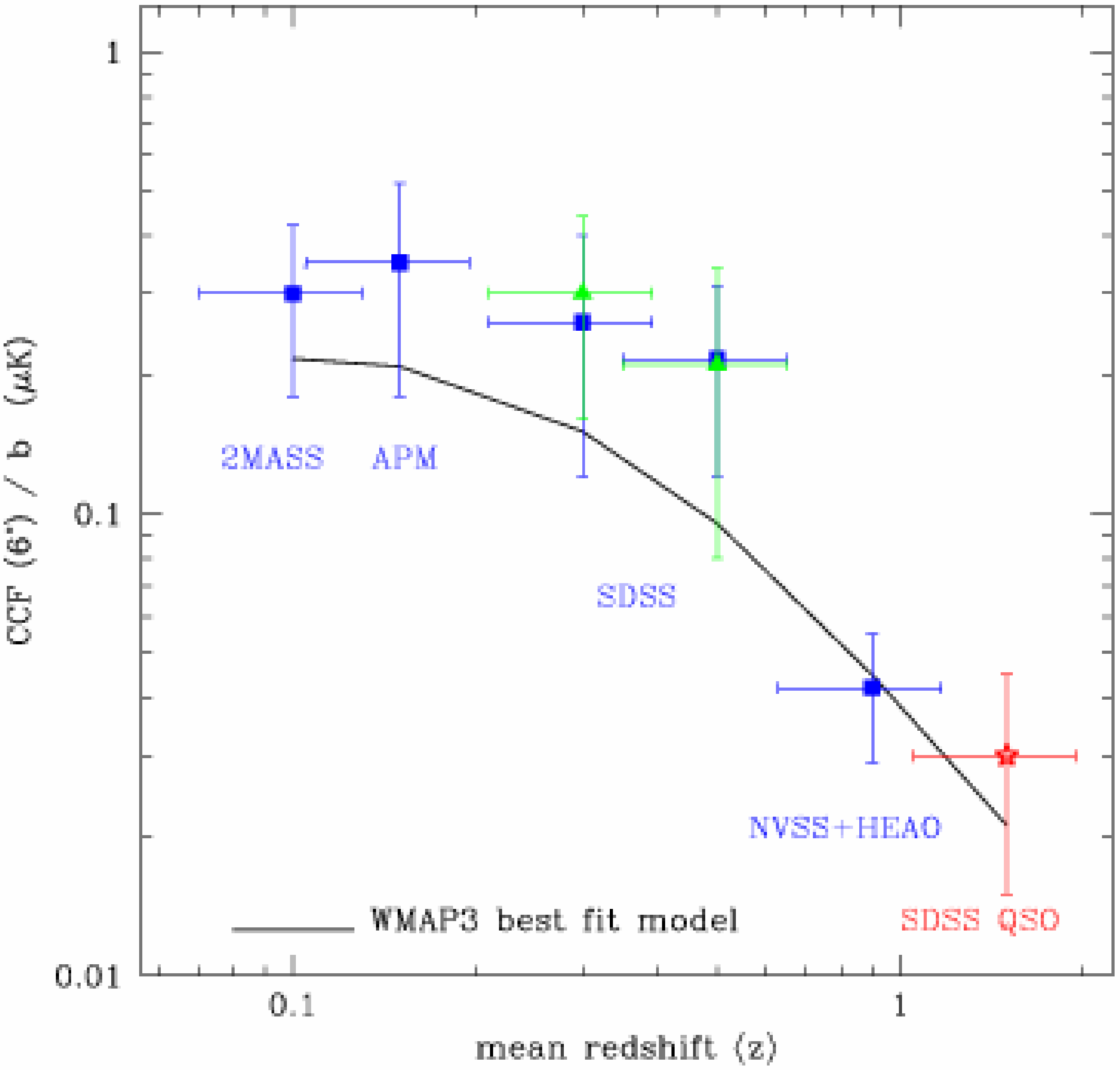


Fosalba, Gaztanaga 2004

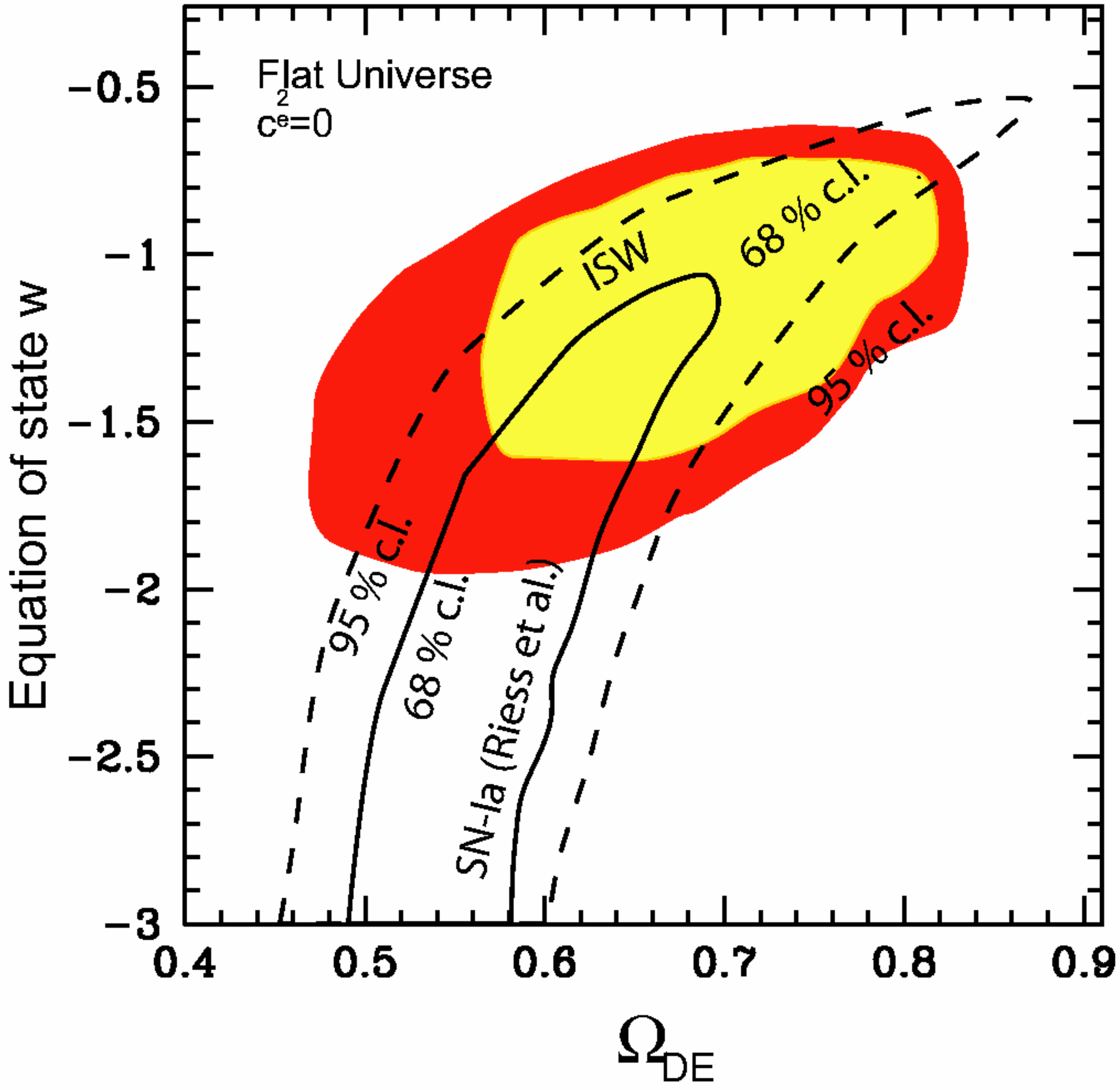
Current Observational status



survey	CMB map	band	$\bar{z}$	reference
APM	WMAP1	optical	0.15	Fosalba & Gaztañaga '04
SDSS	WMAP1	optical	0.3, 0.5	Scranton et al. '04
				Fosalba et al. '04
SDSS	WMAP3	optical	0.3, 0.5	Cabré et al. '06
NVSS, HEAO	WMAP1	radio, X	0.9	Boughn & Crittenden '04
NVSS	WMAP1	radio	0.9	Nolta et al. '04
SDSS QSO	WMAP3	optical	1.5	Giannantonio et al, '06
2MASS	WMAP1	IR	0.10	Afshordi et al. '04
SDSS LRG	WMAP1	optical	0.5	Padmanabham et al. '04
2MASS	WMAP3	IR	0.10	Rassat et al. '06


1
0.1
0.01
0.1
1
CCF (6') / b (μK)
mean redshift (z)
2MASS
APM
SDSS
NVSS+HEAO
SDSS QSO
WMAP3 best fit model

Corasaniti, Giannantonio, AM, Phys.Rev. D71 (2005) 123521



A Test for departure from Einstein General Relativity with Cosmological Constant

Caldwell, Cooray, AM, Phys. Rev. D **76**, 023507 (2007)

Consider the FRW perturbed metric in conformal gauge:

$$ds^2 = a^2(t)[-(1+2\psi)d\tau^2 + (1-2\phi)d\vec{x}^2]$$

For standard LCDM (no radiation) we have:

$$\psi = \phi$$

Newtonian Potential:
Strenght of gravity

Longitudinal Potential:
Amount of curvature produced
per unit rest mass

Modification to General Relativity may lead to a different relation:

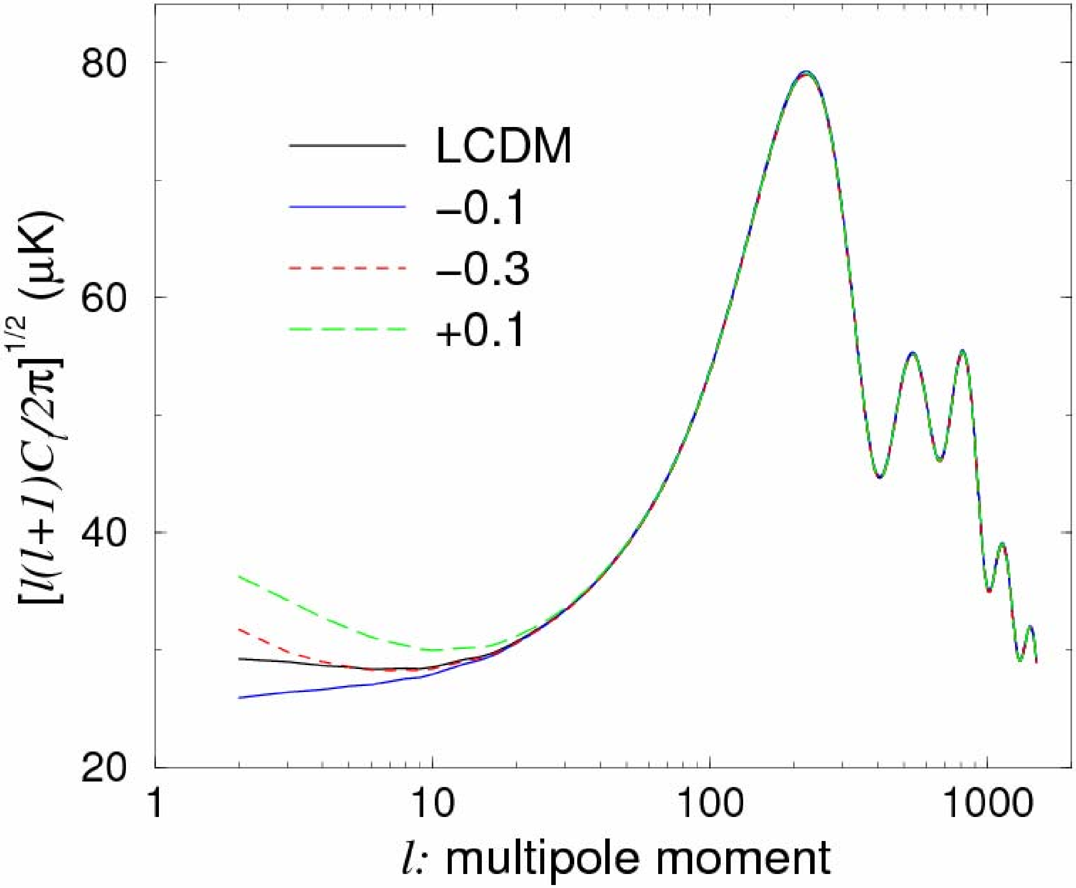
$$\psi = (1+\varpi)\phi$$

Degeneracy with anisotropic stresses from relativistic fluids:

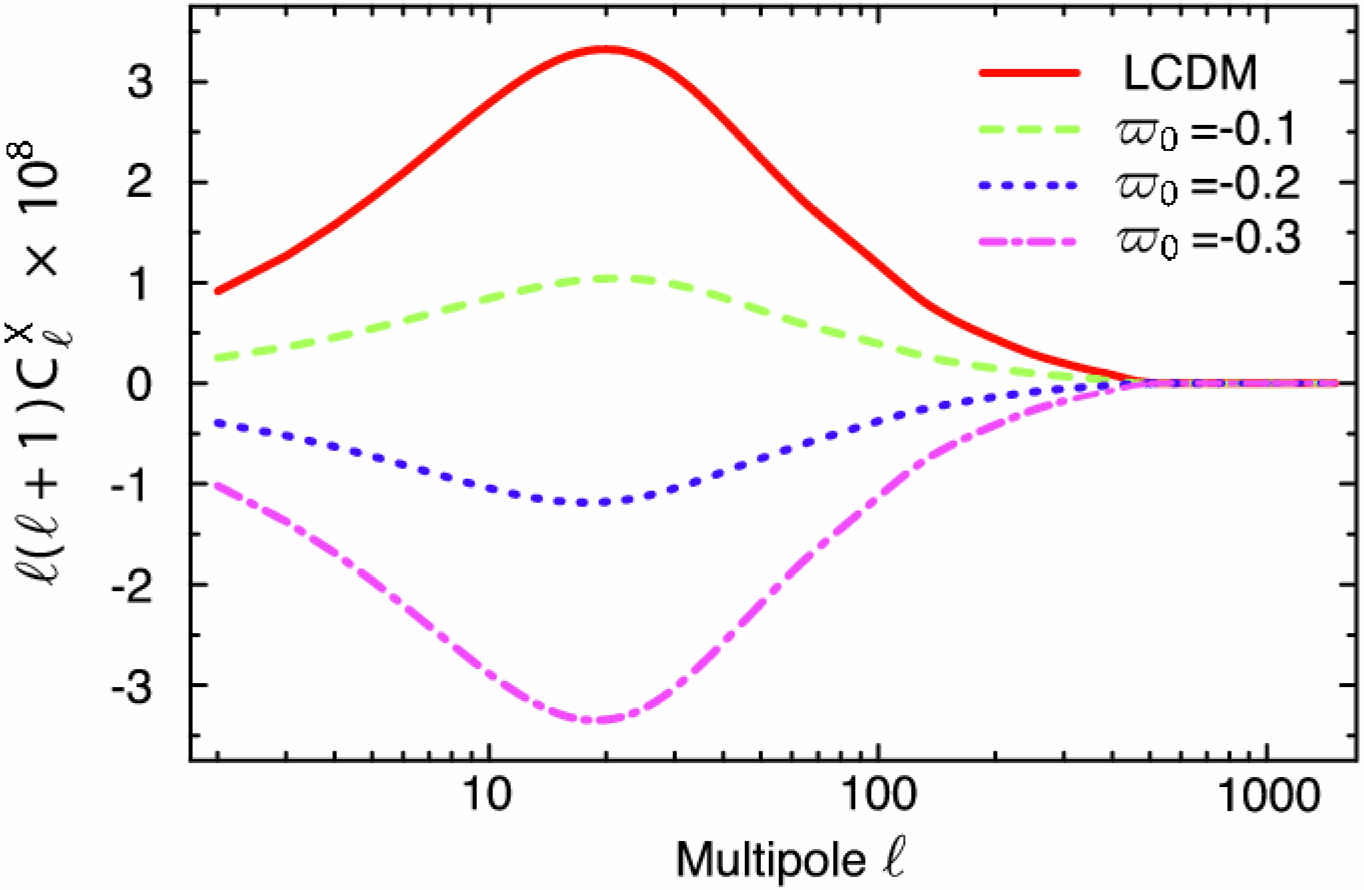
$$k^2(\phi-\psi) = 12\pi G a^2 \sigma_{\gamma,\nu} - k^2 \varpi \phi$$

Let's assume: $\varpi = \varpi_0 \frac{\rho_{DE}}{\rho_M}$

Caldwell, Cooray, AM, Phys. Rev. D **76**, 023507 (2007)



But we get more information from ISW-Galaxy cross correlation: Correlation could be negative !



$$\frac{\delta T}{T}_{ISW} = \int d\chi((2+\varpi)\phi)_{,\tau}$$

From ISW data we get (at 95%c.l.):

$$-0.2 < \varpi < 0.1$$

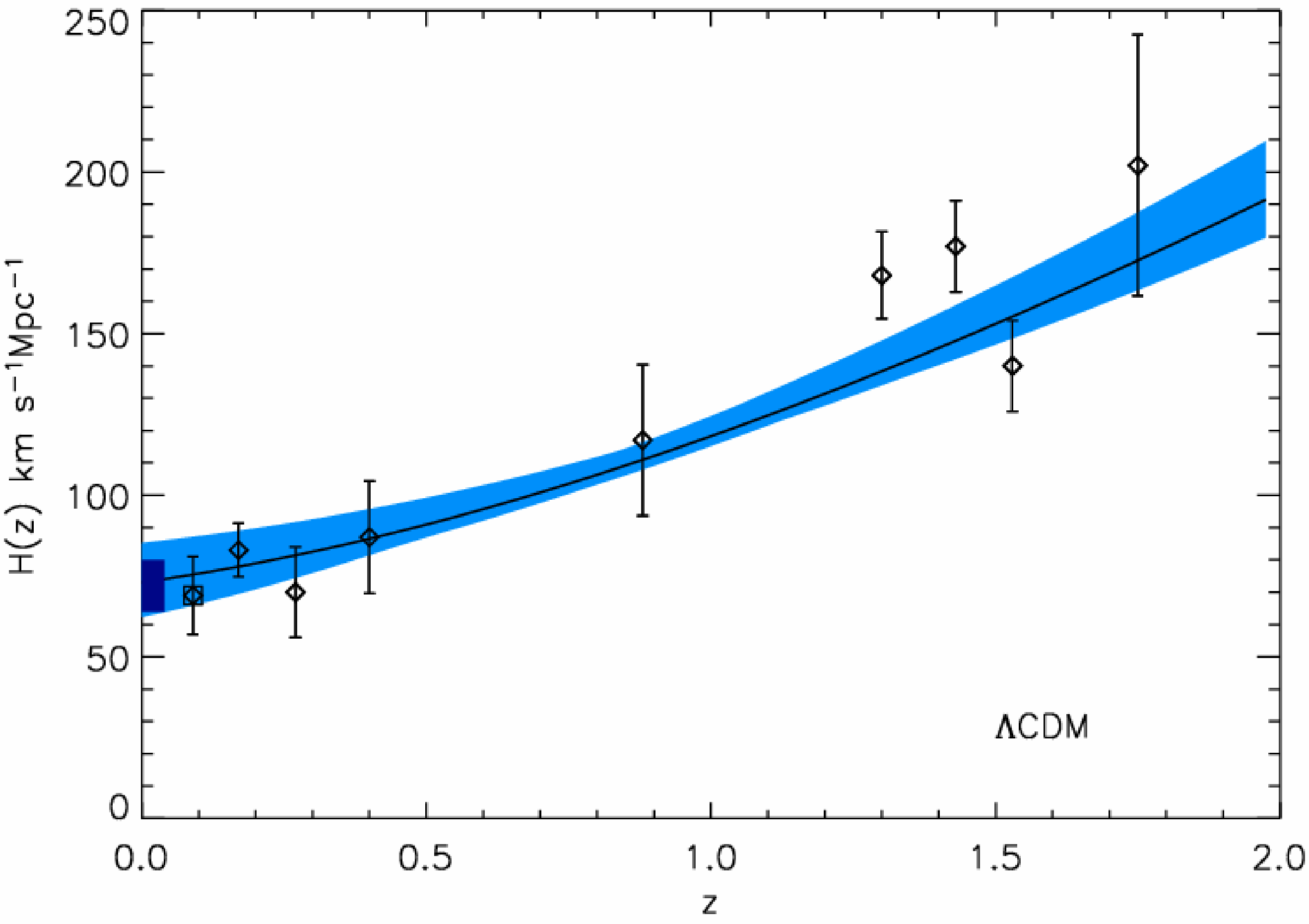
Caldwell, Cooray, AM, Phys. Rev. D **76**, 023507 (2007):

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)



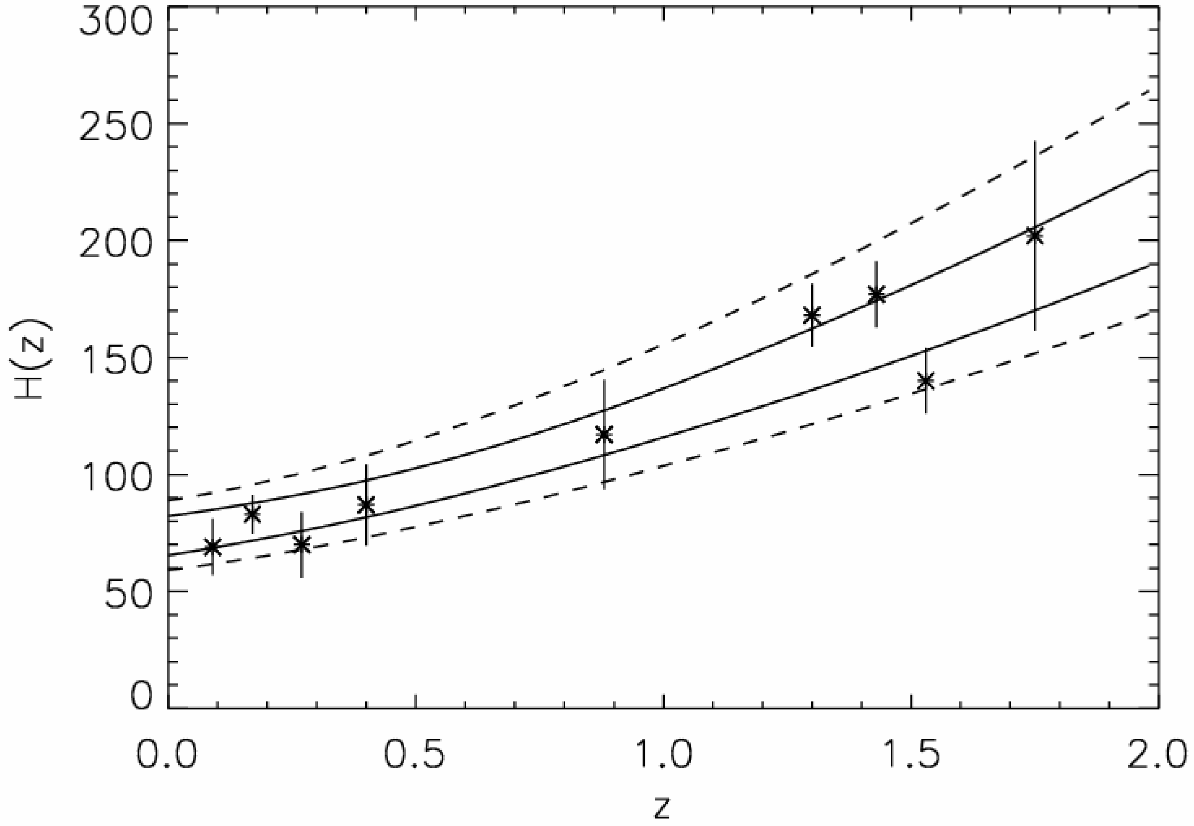
Direct
and "model
independent"
age aestimates
have much
larger
error bars !
Not so good
for constraining
DE

Spergel et al., 2007

Age of the Universe

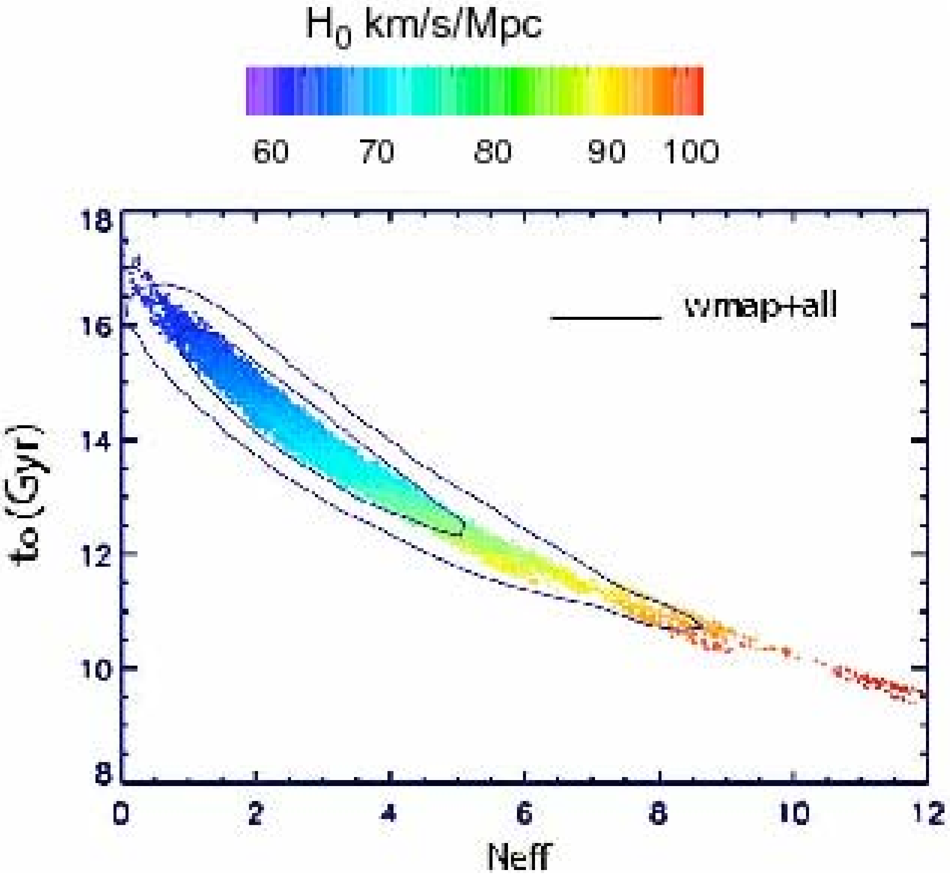
…however the WMAP constrain is model dependent.
Key parameter: energy density in relativistic particles.

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



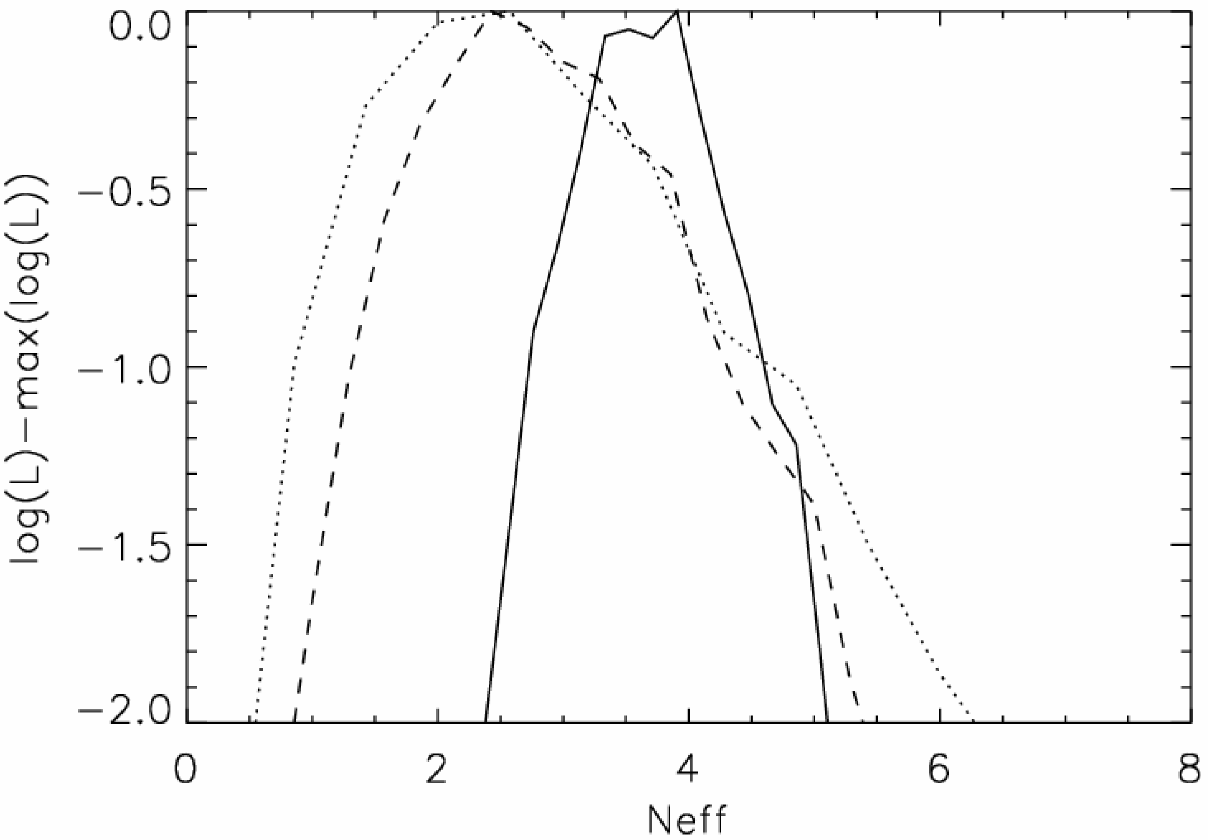
Error bars
on age
a factor 10
larger when
Extra
Relativistic
particles are
Included.

F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, 2007


H$_0$ km/s/Mpc
60
70
80
90
100
wmap+all
18
16
14
12
10
8
to (Gyr)
0
2
4
6
8
10
12
Neff

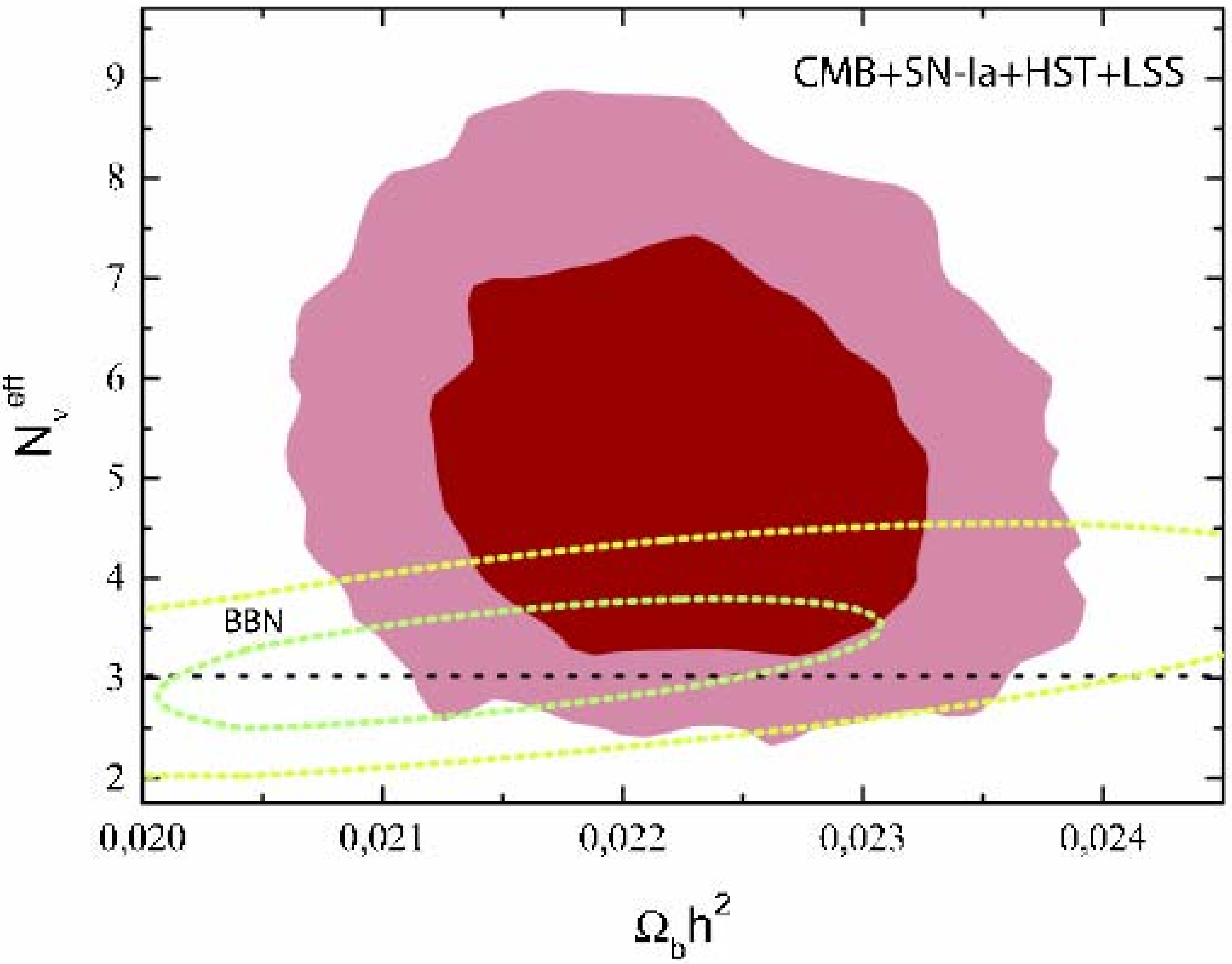
Independent age aestimates are important.
Using Simon, Verde, Jimenez aestimates plus WMAPall we get:

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

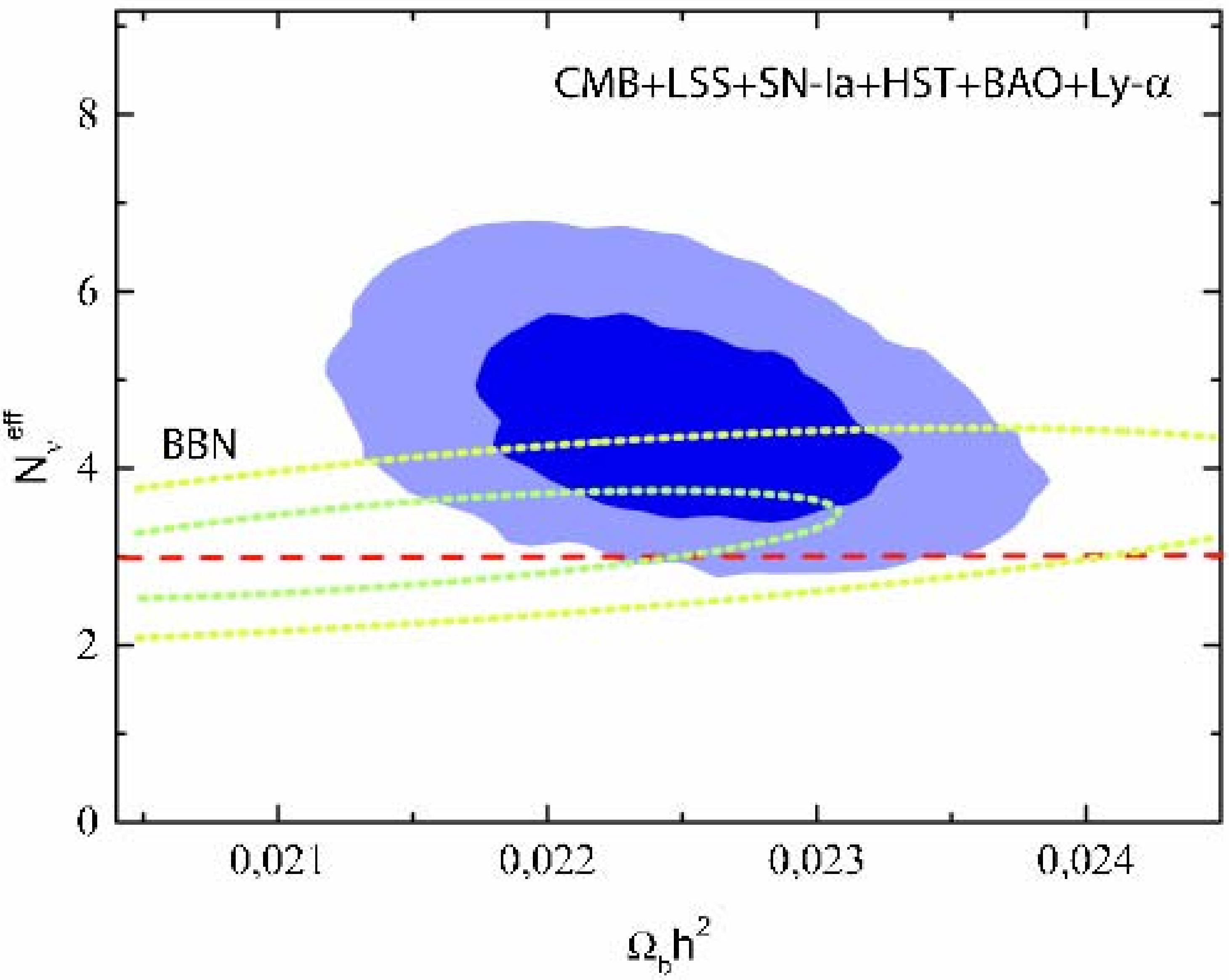


F. De Bernardis, A. Melchiorri, L. Verde, R. Jimenez, 2007

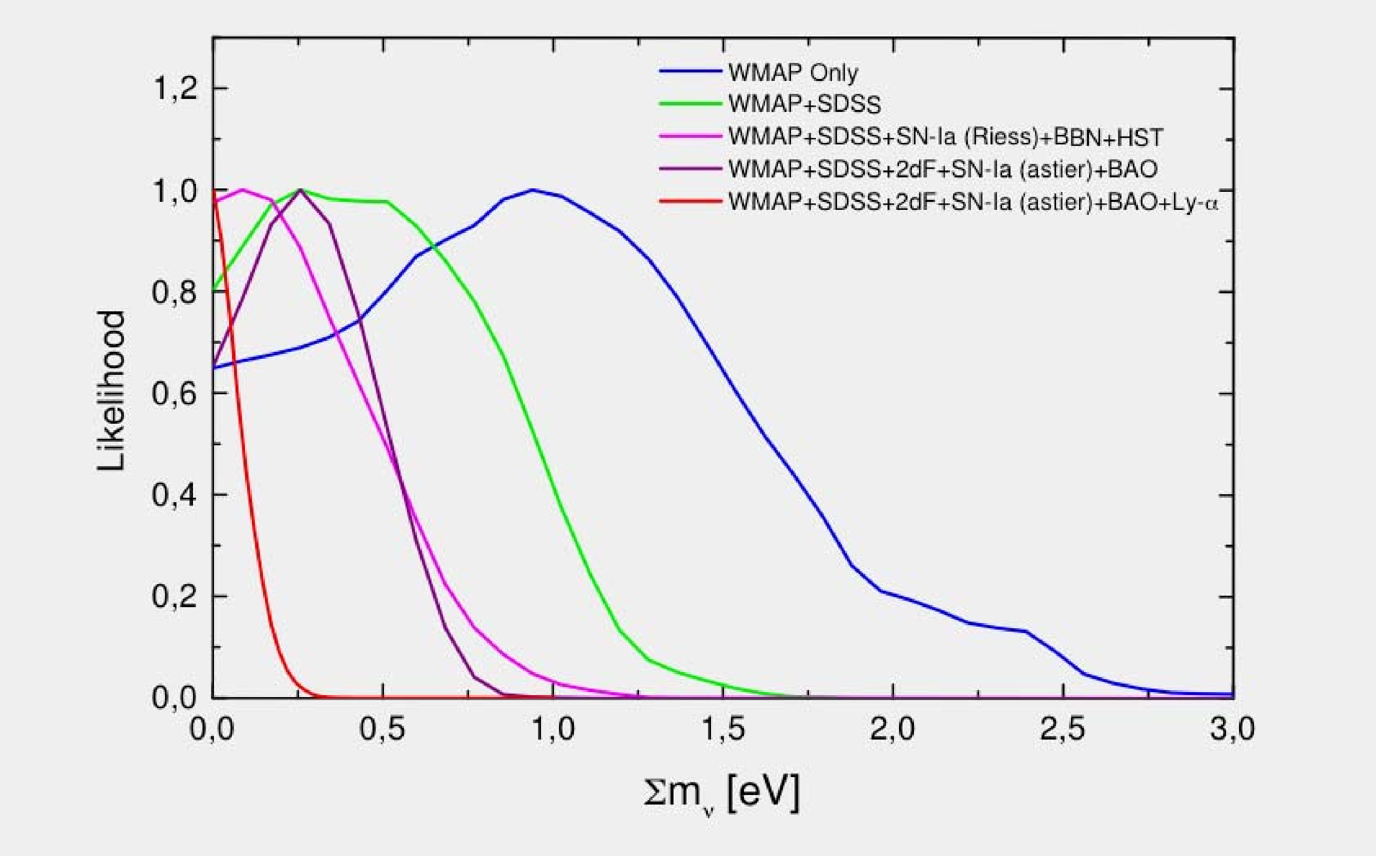
Indication for N>3 from Cosmology ?



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



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

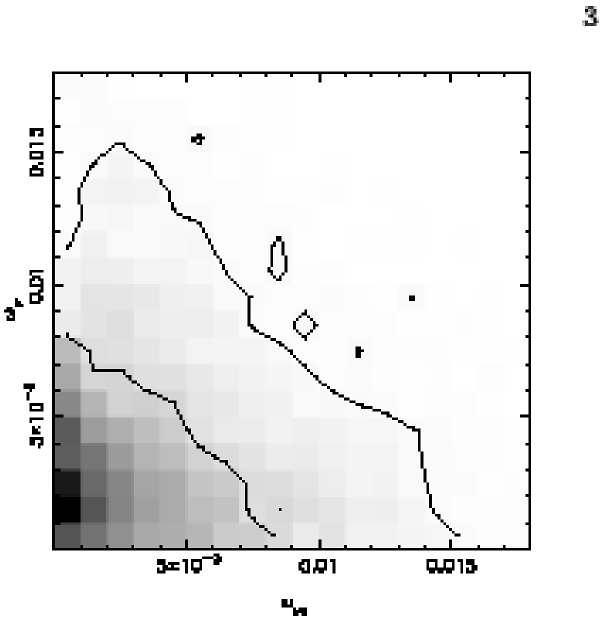


Bounds on Σ for increasingly rich data sets (assuming 3 Active Neutrino model):

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

Fogli, Lisi, Marrone, Melchiorri, Palazzo, Serra,Slosar, Silk., Phys. Rev. D 75, 053001 (2007)

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

What about a thermal axion component ?

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

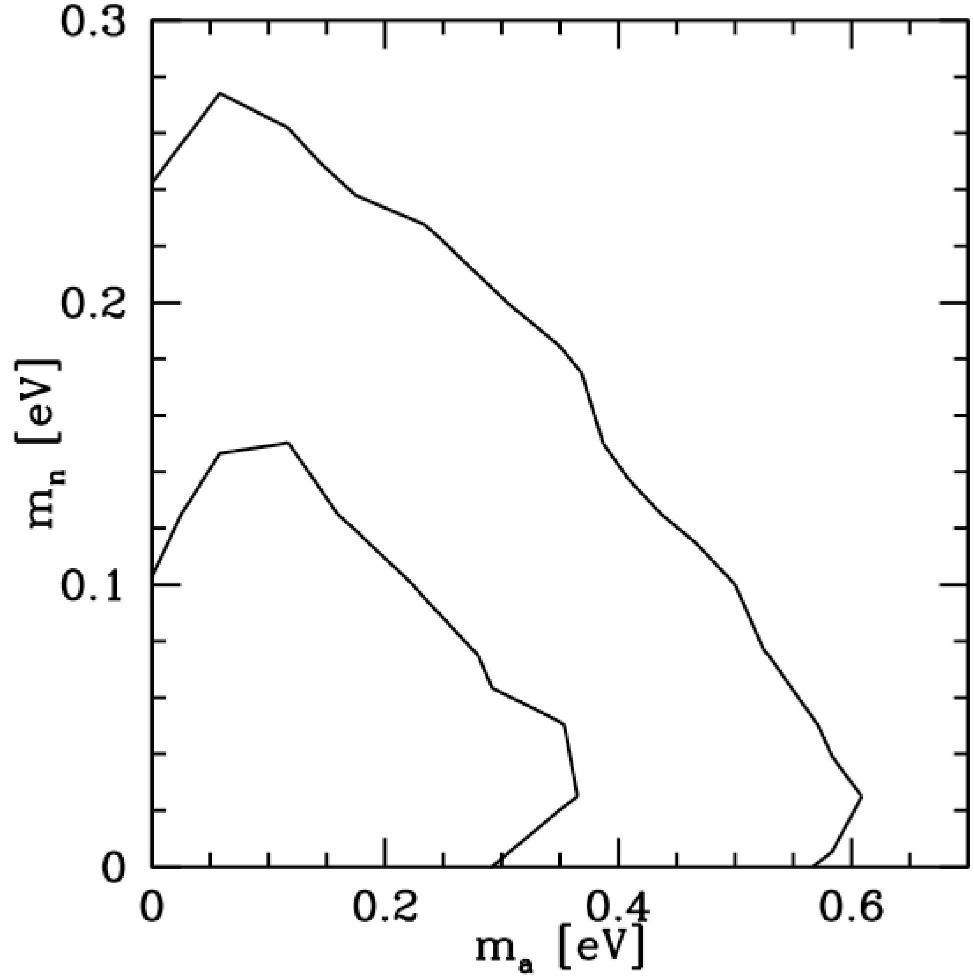
$$\Omega_a h^2 = \frac{m_a}{131 eV}\left(\frac{10}{g_{*S}(T_D)}\right)$$

$$m_a < 0.42 eV \text{ at 95\% c.l.}$$

(all cosmological data)

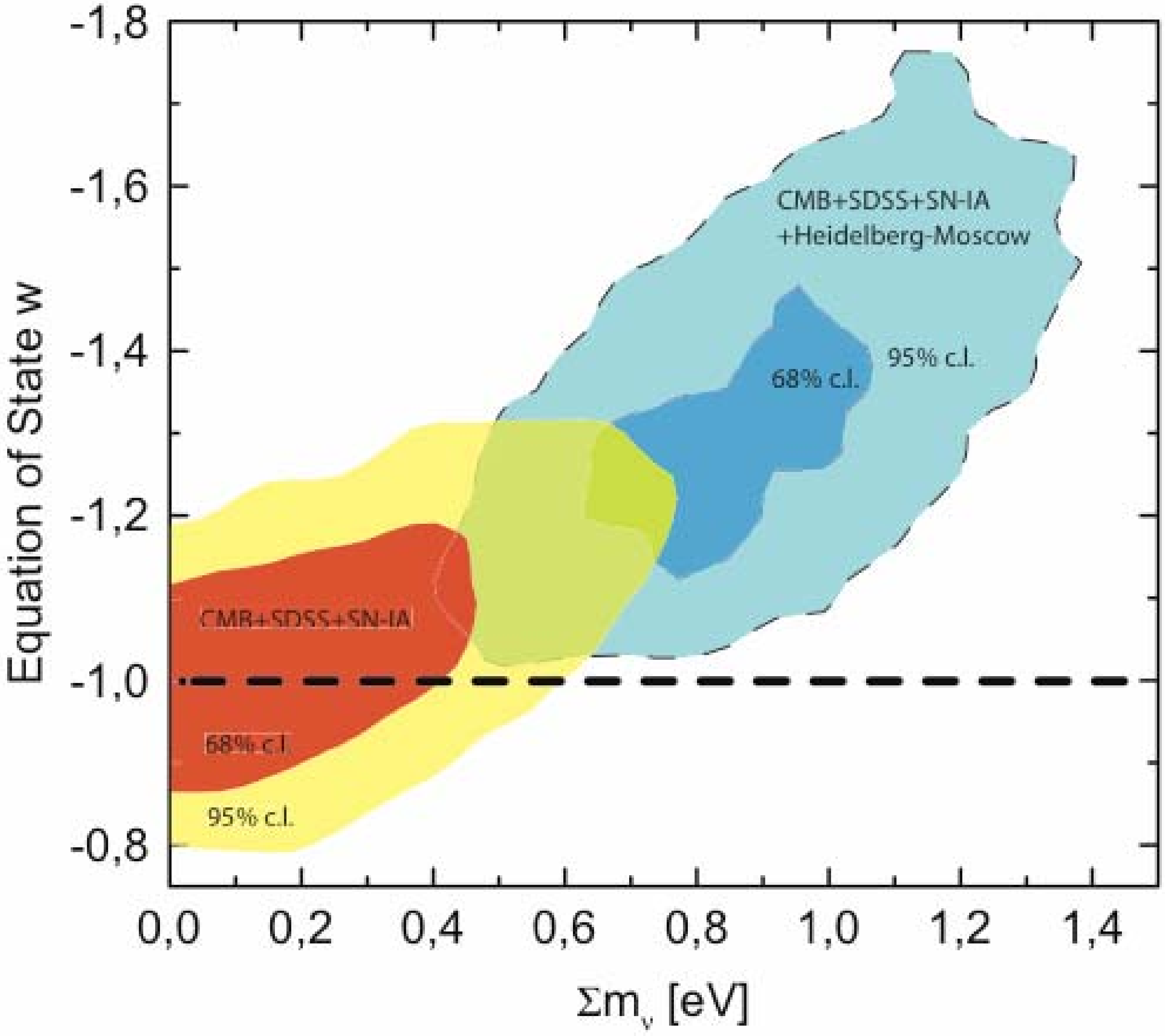
$$m_a < 0.38 eV \text{ at 95\% c.l.}$$

(all cosmological data
Plus H.I. for neutrino masses)



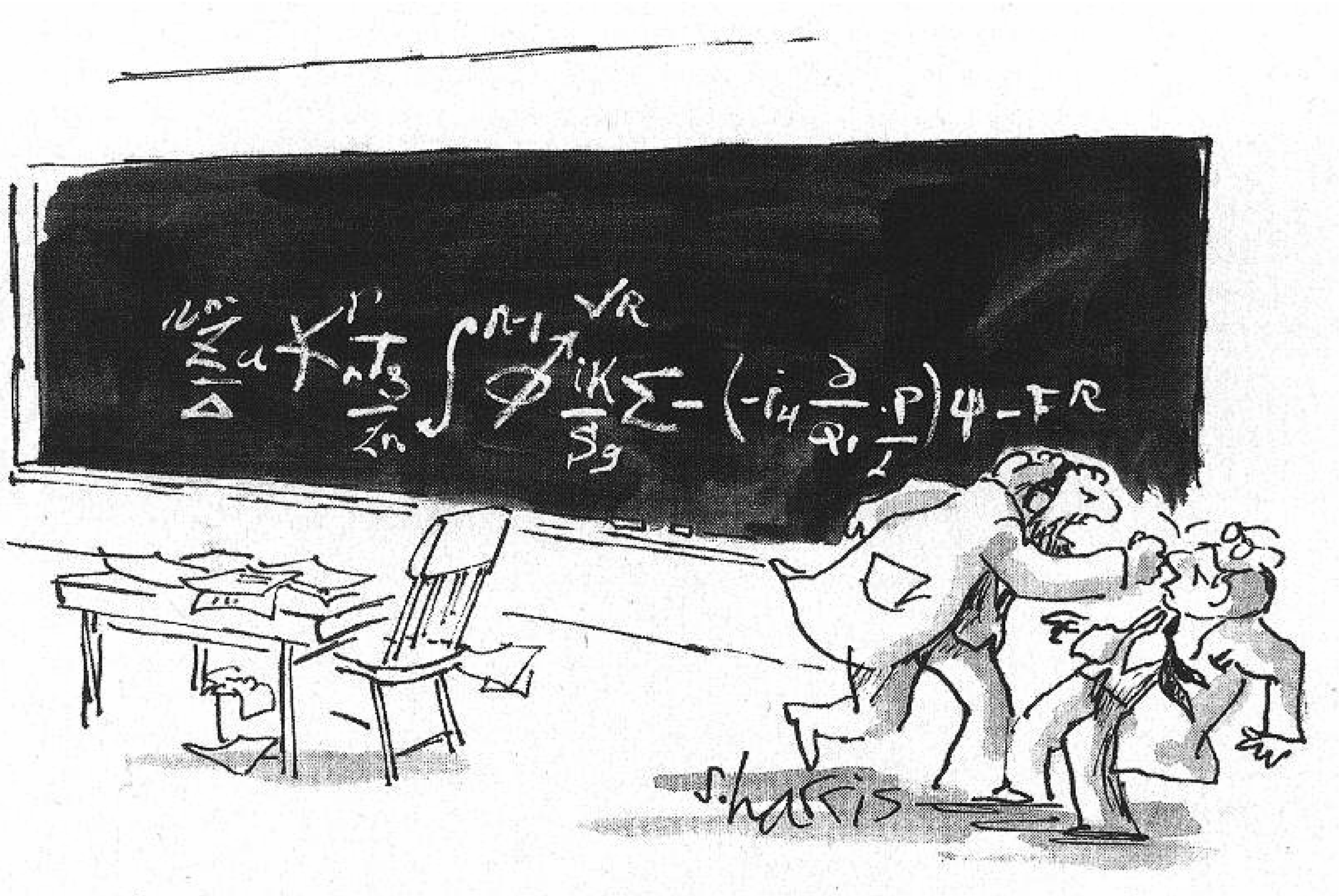
Melchiorri, Mena, Slosar

PRD 2007, In press.
arXiv:0705.2695



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

A direct proof for dark energy ?



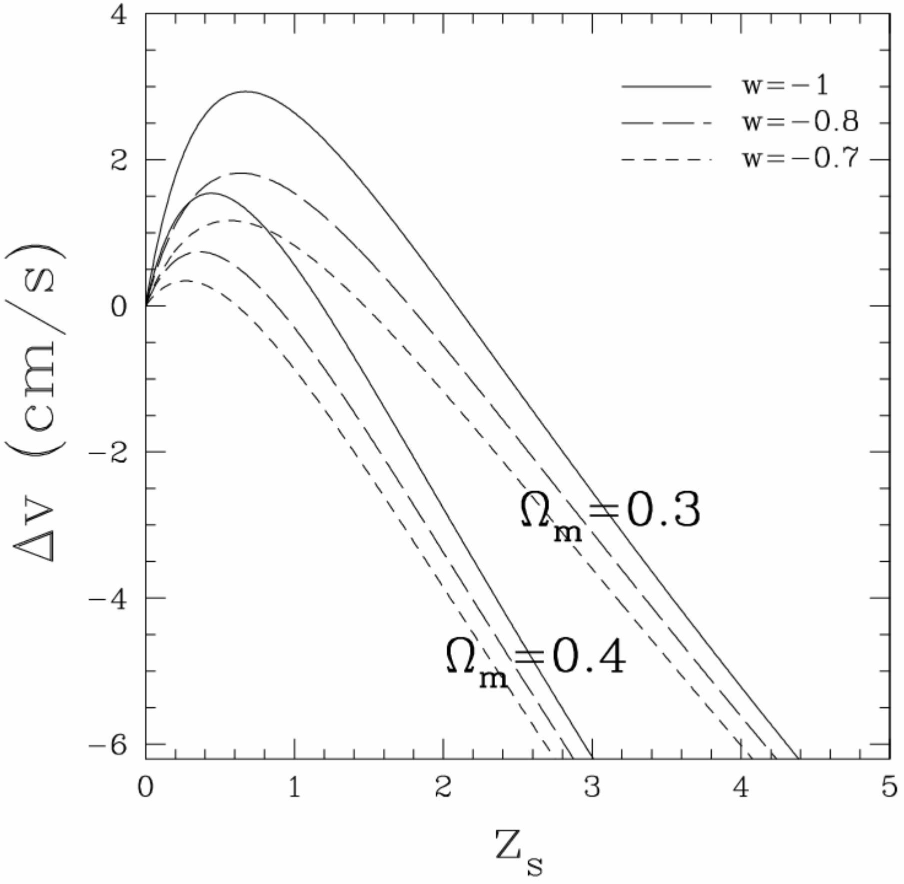
"YOU WANT PROOF? I'LL GIVE YOU PROOF!"

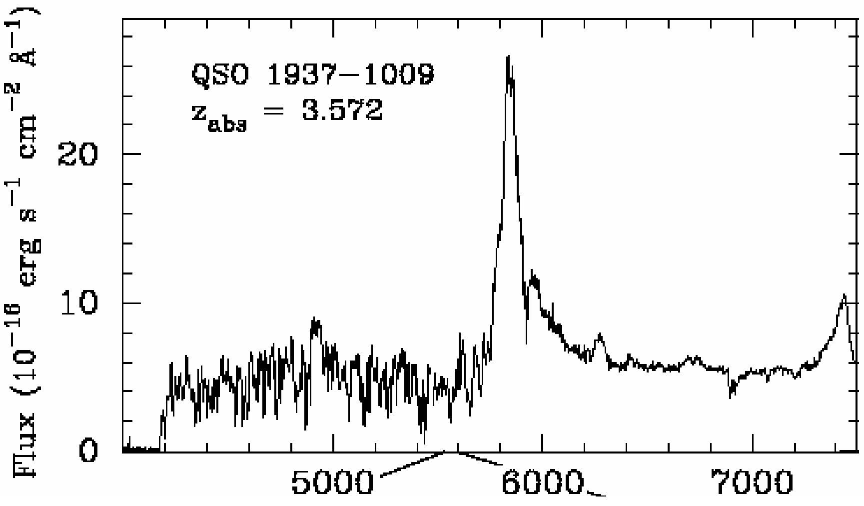
Can we constrain H(z) directly ?

Investigated by Sandage 1961, Loeb proposed the use of Lyman-alpha in 1998 (see Corasaniti, Huterer,AM, Phys. Rev. D **75**, 062001 (2007))

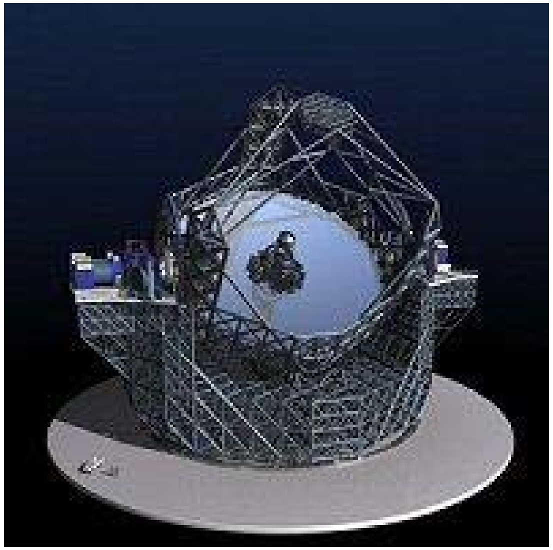
$$\frac{\Delta v}{c} = H_0 \Delta t_0 \left[1 - \frac{E(z_s)}{1+z_s} \right]$$

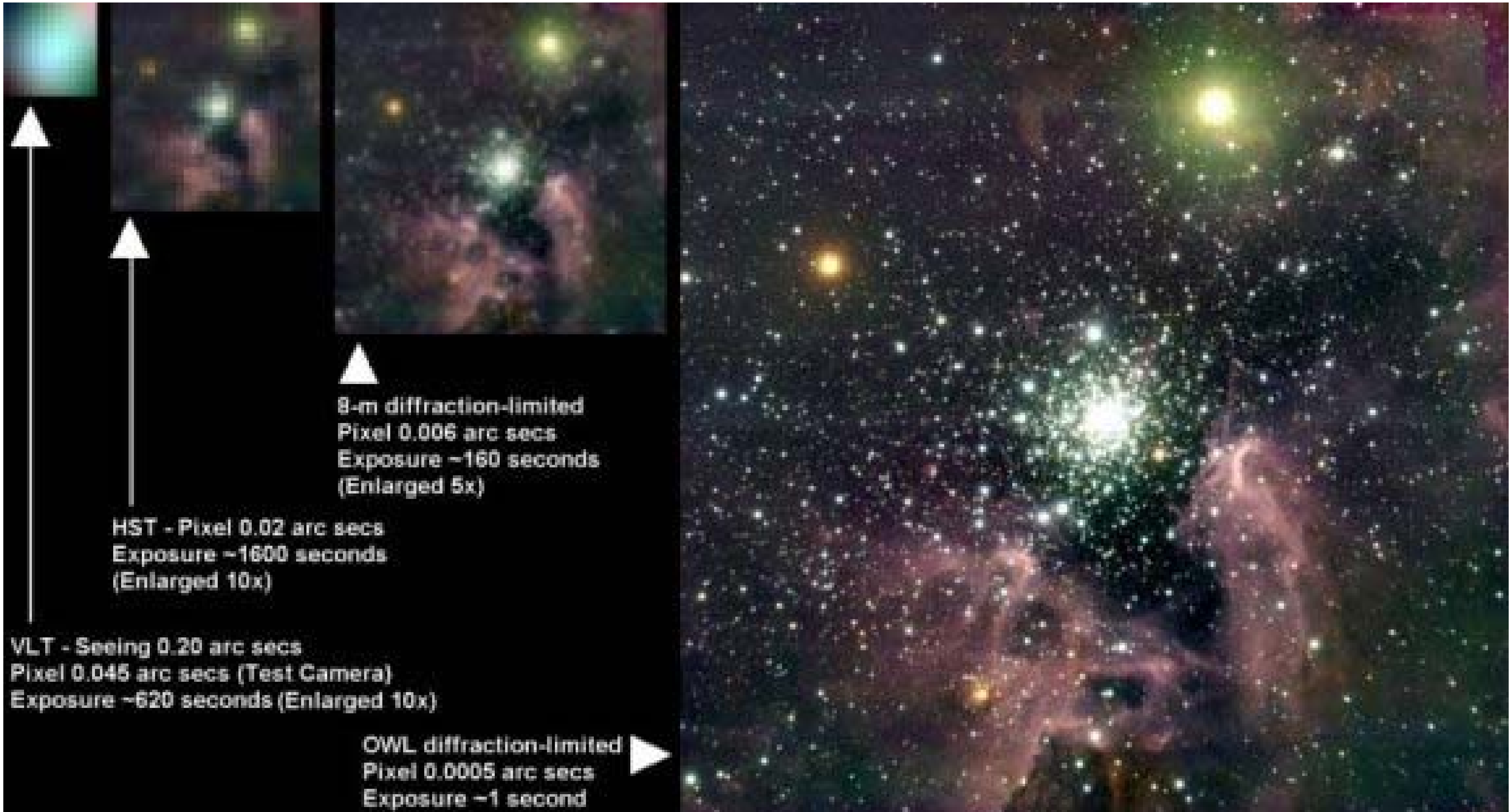
$$E(z) = \left[\Omega_M (1+z)^3 + \Omega_X (1+z)^{3(1+w)} + \Omega_K (1+z)^2 \right]^{1/2}$$





ELT: Extreme Large Telescope
42m telescope (in 10 years time)
+ CODEX Spectrograph (see Pasquini et al., 2005)





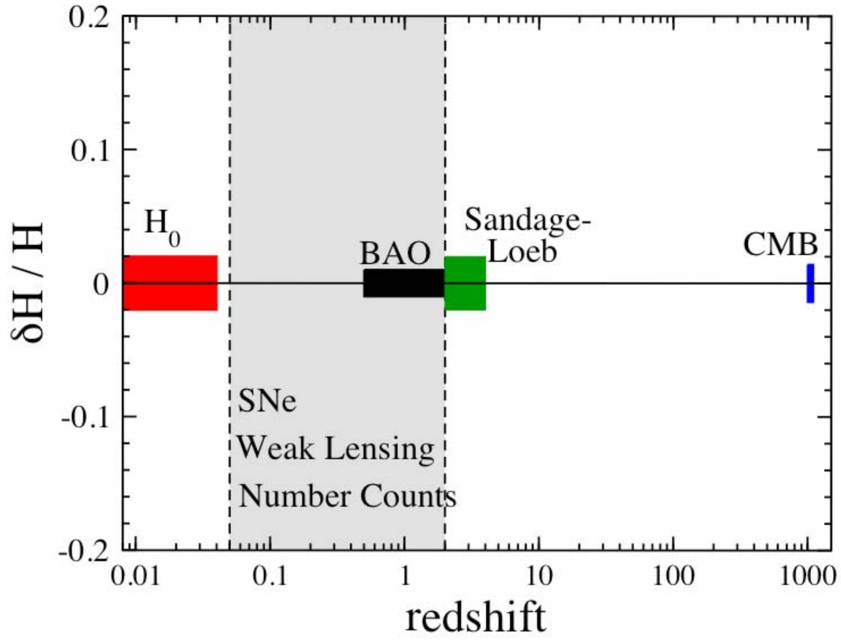
8-m diffraction-limited
Pixel 0.006 arc secs
Exposure ~160 seconds
(Enlarged 5x)

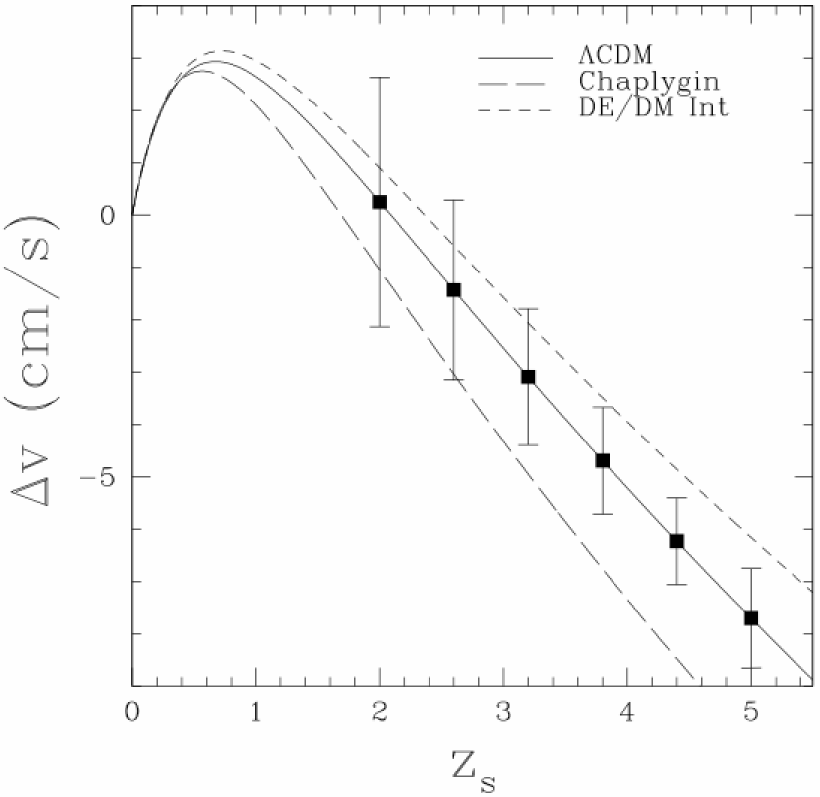
HST - Pixel 0.02 arc secs
Exposure ~1600 seconds
(Enlarged 10x)

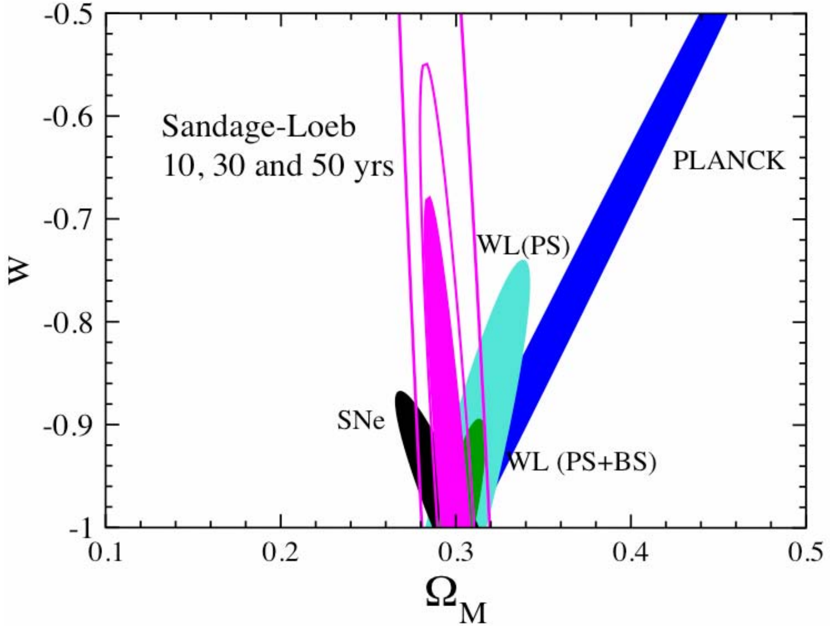
VLT - Seeing 0.20 arc secs
Pixel 0.045 arc secs (Test Camera)
Exposure ~620 seconds (Enlarged 10x)

OWL diffraction-limited
Pixel 0.0005 arc secs
Exposure ~1 second

Can we constrain H(z) directly ?



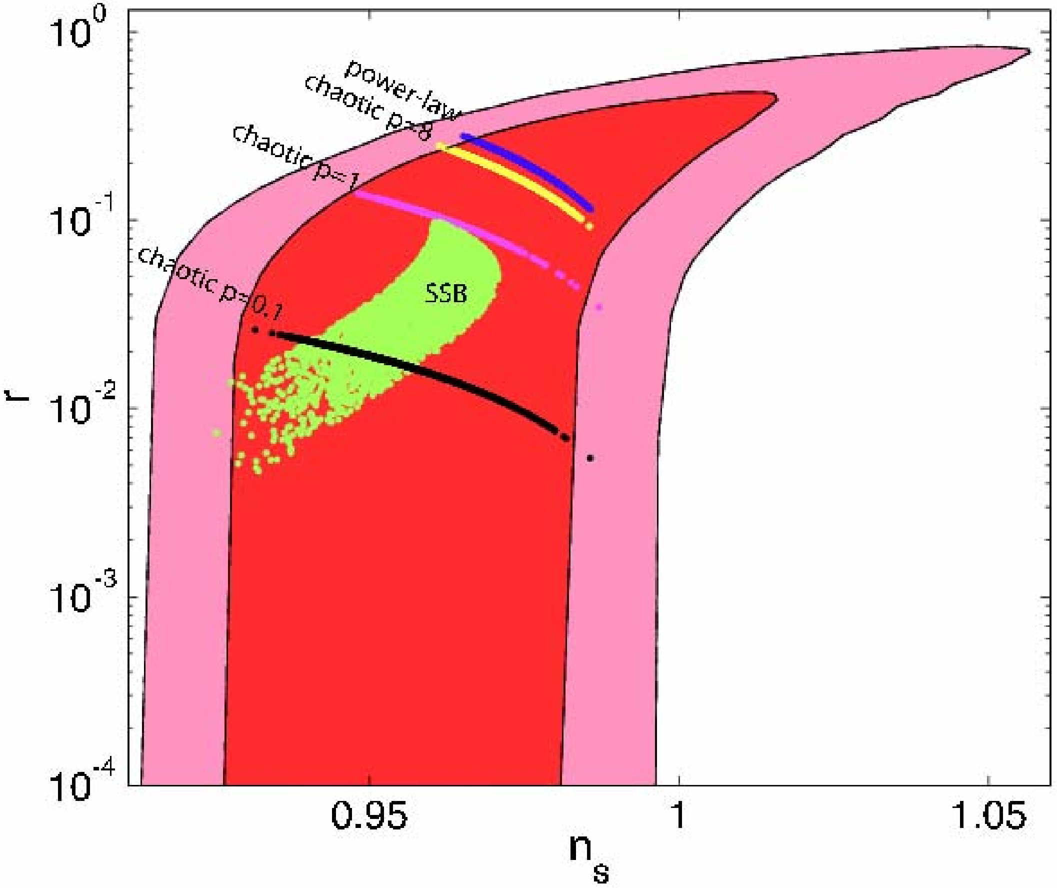




SL test is definitly for “patient”
Cosmologists !
Not competitive with WL and SN-Ia
For constant w.
It may shed light on non-standard
Models as DE/DM Interaction

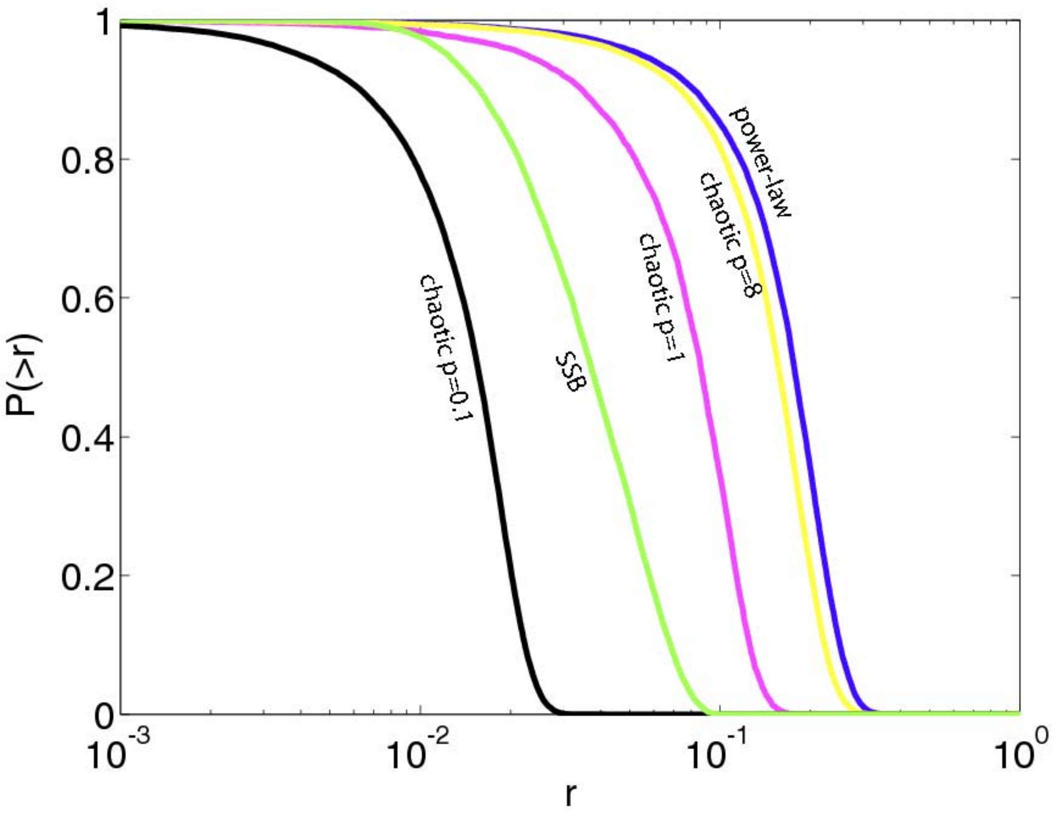
Prospects for future detection of Gravity waves

Pagano, Cooray, Melchiorri, Kamionkowsky, arXiv:0707.2560



If we assume some particular inflationary model (see de Vega's Talk 2 days ago) as strong prior, WMAP provides already a (very indirect) indication for r>0.

Pagano, Cooray, Melchiorri, Kamionkowsky, arXiv:0707.2560



If we are sensible to r=.001 we can measure most of those models. Can future experiments do this ?

Pagano, Cooray, Melchiorri, Kamionkowsky, arXiv:0707.2560

Model	WMAP8yr	Planck 6ch	BPol	Epic
Power-law	0.45/0	1/0.98	1/1	1/1
Chaotic p=1	0/0	0.99/0.67	1/1	1/1
Chaotic p=8	0.30/0	1/0.97	1/1	1/1
Chaotic p=0.1	0/0	0.60/0	1/1	1/1
SSB (Ne = 47 – 62)	0/0	0.78/0.09	1/1	1/1

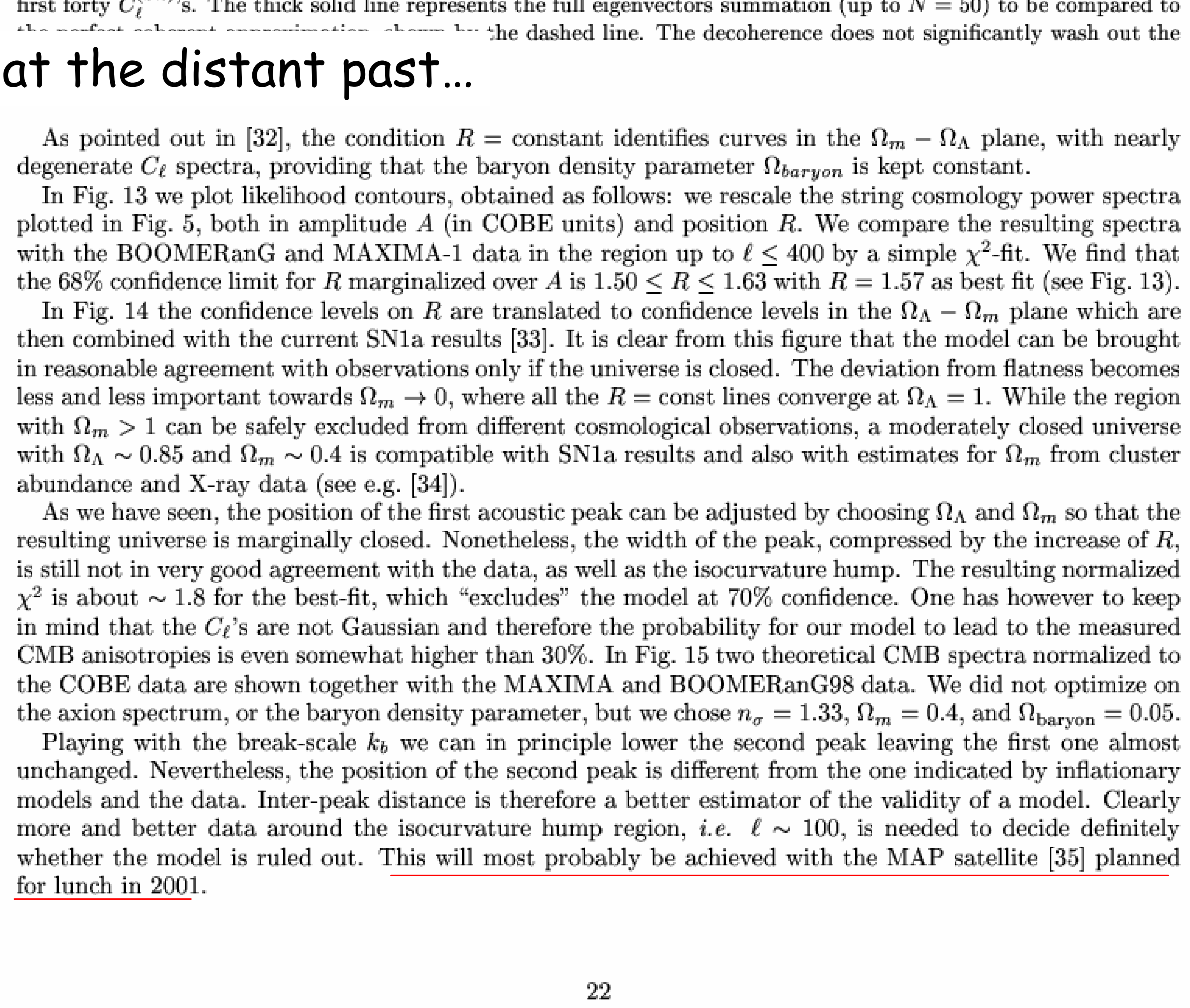
Percentage of models in agreement with the WMAP observations and with an IGW background detectable at 2 and 5 confidence levels by the experimental configurations listed in Table II.

Pagano, Cooray, Melchiorri, Kamionkowsky, arXiv:0707.2560

Less optimistic view for Planck…

Model	4ch	100GHzch	allchT+C
Power Law	1/0.97	0.99/0.30	0.81/0.02
Chaotic p=1	0.99/0.61	0.92/0	0.25/0
Chaotic p=8	1/0.96	0.99/0.16	0.81/0
Chaotic p=0.1	0.50/0	0/0	0/0
SSB (Ne = 62–47)	0.77/0.07	0.36/0	0/0

Looking at the distant past…



first forty C_ℓ's. The thick solid line represents the full eigenvectors summation (up to $N = 50$) to be compared to the perfect coherent approximation shown by the dashed line. The decoherence does not significantly wash out the

As pointed out in [32], the condition $R =$ constant identifies curves in the $\Omega_m - \Omega_\Lambda$ plane, with nearly degenerate C_ℓ spectra, providing that the baryon density parameter Ω_{baryon} is kept constant.

In Fig. 13 we plot likelihood contours, obtained as follows: we rescale the string cosmology power spectra plotted in Fig. 5, both in amplitude A (in COBE units) and position R. We compare the resulting spectra with the BOOMERanG and MAXIMA-1 data in the region up to $\ell \leq 400$ by a simple χ^2-fit. We find that the 68% confidence limit for R marginalized over A is $1.50 \leq R \leq 1.63$ with $R = 1.57$ as best fit (see Fig. 13).

In Fig. 14 the confidence levels on R are translated to confidence levels in the $\Omega_\Lambda - \Omega_m$ plane which are then combined with the current SN1a results [33]. It is clear from this figure that the model can be brought in reasonable agreement with observations only if the universe is closed. The deviation from flatness becomes less and less important towards $\Omega_m \to 0$, where all the $R =$ const lines converge at $\Omega_\Lambda = 1$. While the region with $\Omega_m > 1$ can be safely excluded from different cosmological observations, a moderately closed universe with $\Omega_\Lambda \sim 0.85$ and $\Omega_m \sim 0.4$ is compatible with SN1a results and also with estimates for Ω_m from cluster abundance and X-ray data (see e.g. [34]).

As we have seen, the position of the first acoustic peak can be adjusted by choosing Ω_Λ and Ω_m so that the resulting universe is marginally closed. Nonetheless, the width of the peak, compressed by the increase of R, is still not in very good agreement with the data, as well as the isocurvature hump. The resulting normalized χ^2 is about ~ 1.8 for the best-fit, which "excludes" the model at 70% confidence. One has however to keep in mind that the C_ℓ's are not Gaussian and therefore the probability for our model to lead to the measured CMB anisotropies is even somewhat higher than 30%. In Fig. 15 two theoretical CMB spectra normalized to the COBE data are shown together with the MAXIMA and BOOMERanG98 data. We did not optimize on the axion spectrum, or the baryon density parameter, but we chose $n_\sigma = 1.33$, $\Omega_m = 0.4$, and $\Omega_{\text{baryon}} = 0.05$.

Playing with the break-scale k_b we can in principle lower the second peak leaving the first one almost unchanged. Nevertheless, the position of the second peak is different from the one indicated by inflationary models and the data. Inter-peak distance is therefore a better estimator of the validity of a model. Clearly more and better data around the isocurvature hump region, *i.e.* $\ell \sim 100$, is needed to decide definitely whether the model is ruled out. This will most probably be achieved with the MAP satellite [35] planned for lunch in 2001.

Vernizzi, Melchiorri, Phys.Rev. D63 (2001) 063501