Cosmology in Wonderland

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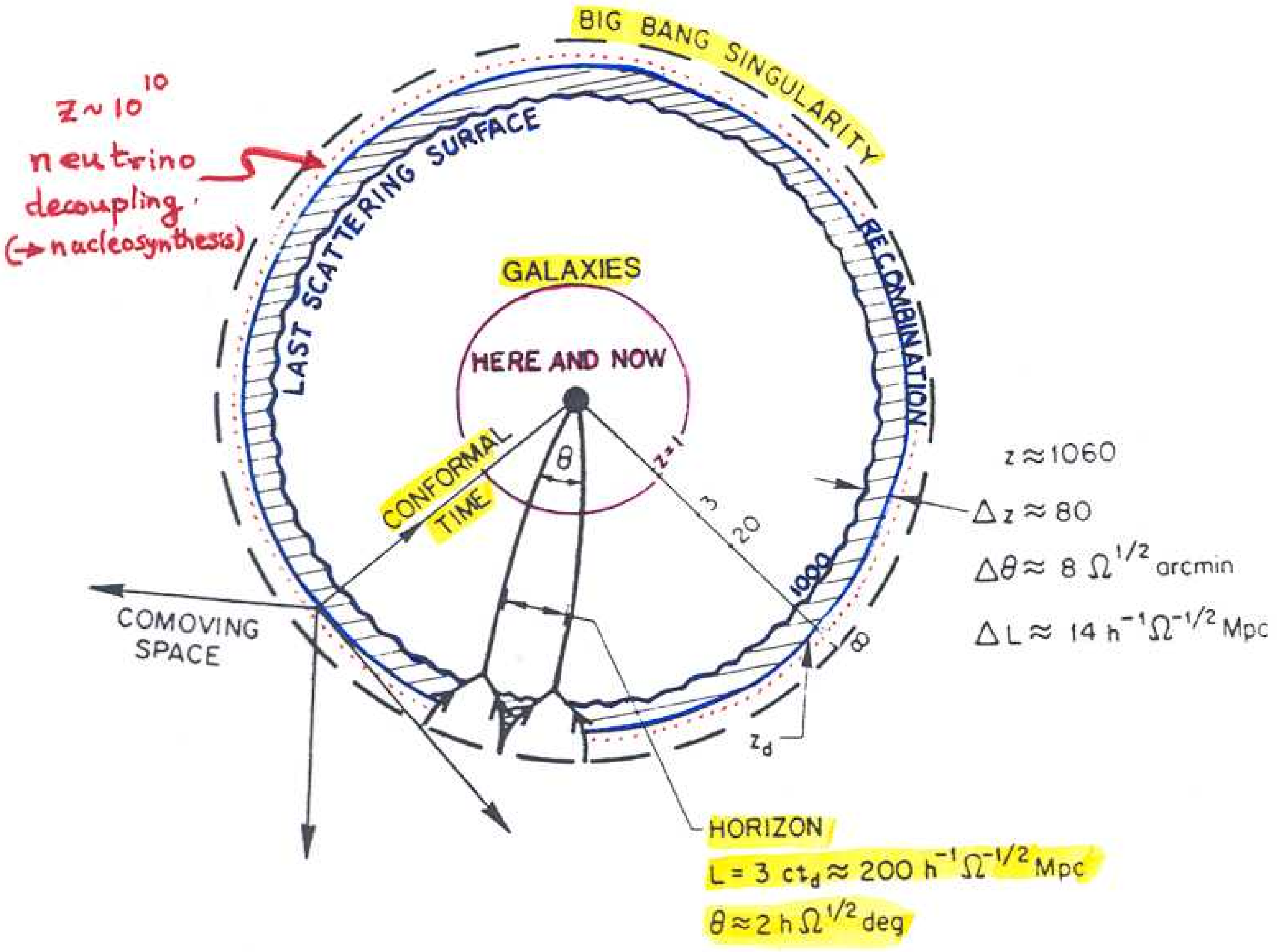
... cosmic microwave bkgd
... dark matter
... Vacuum energy
... scalar field inflation
... lepto/baryogenesis
... brane-world cosmology

... can we really believe what the universe seems to be telling us?

The standard cosmological model

... maximally symmetric (simply connected) space-time containing 'ideal fluids' (dust, radiation, vacuum energy ...)

$\omega \equiv p/\rho = \quad 0 \quad , \quad 1/3 \quad , \quad -1 \quad \ldots$



Conformal time : $d\tau \equiv \dfrac{dt}{a(t)}$, $1+z \equiv \dfrac{\lambda_0}{\lambda_{em}} = \dfrac{a(t_0)}{a(t_{em})}$

FRW metric : $ds^2 = -dt^2 + a^2(t)\left[\dfrac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$

Einstein equations : $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

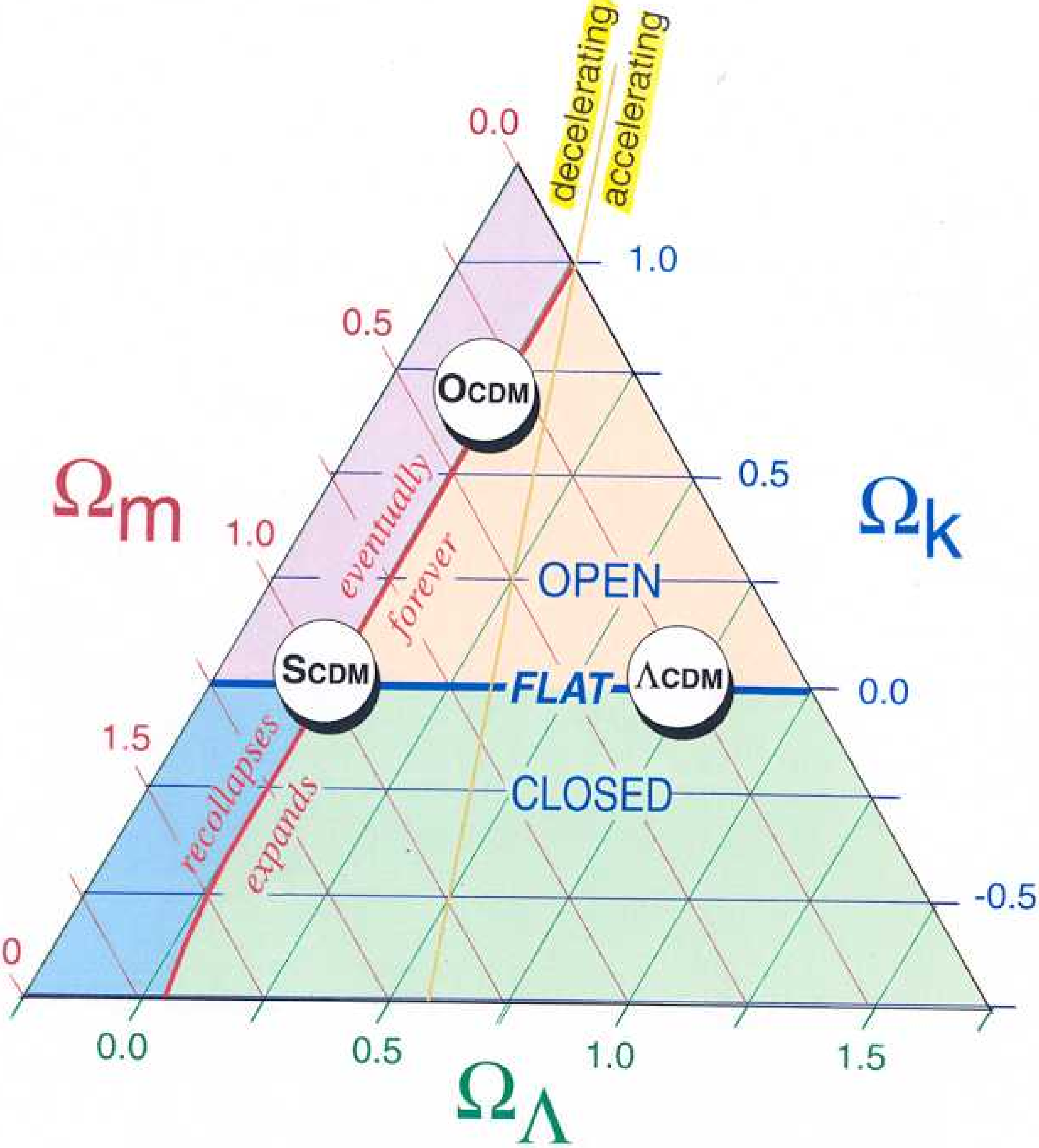
$$\Rightarrow \quad H^2 \equiv \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} = H_0^2\left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right]$$

$[\rho_c \equiv 3H^2/8\pi G]$; $\Omega_m \equiv \rho_m/\rho_c$; $\Omega_k \equiv k/a^2H^2$; $\Omega_\Lambda \equiv \Lambda/3H^2$

The Cosmic Triangle

Sum rule: $\Omega_m + \Omega_K + \Omega_\Lambda = 1$

$\Omega_m \sim \rho_m / \frac{3H_0^2}{8\pi G}$, $\Omega_K \sim -k/a_0^2 H_0^2$, $\Omega_\Lambda \sim \Lambda / 3H_0^2$



Bahcall et al. (astro-ph/9906463)

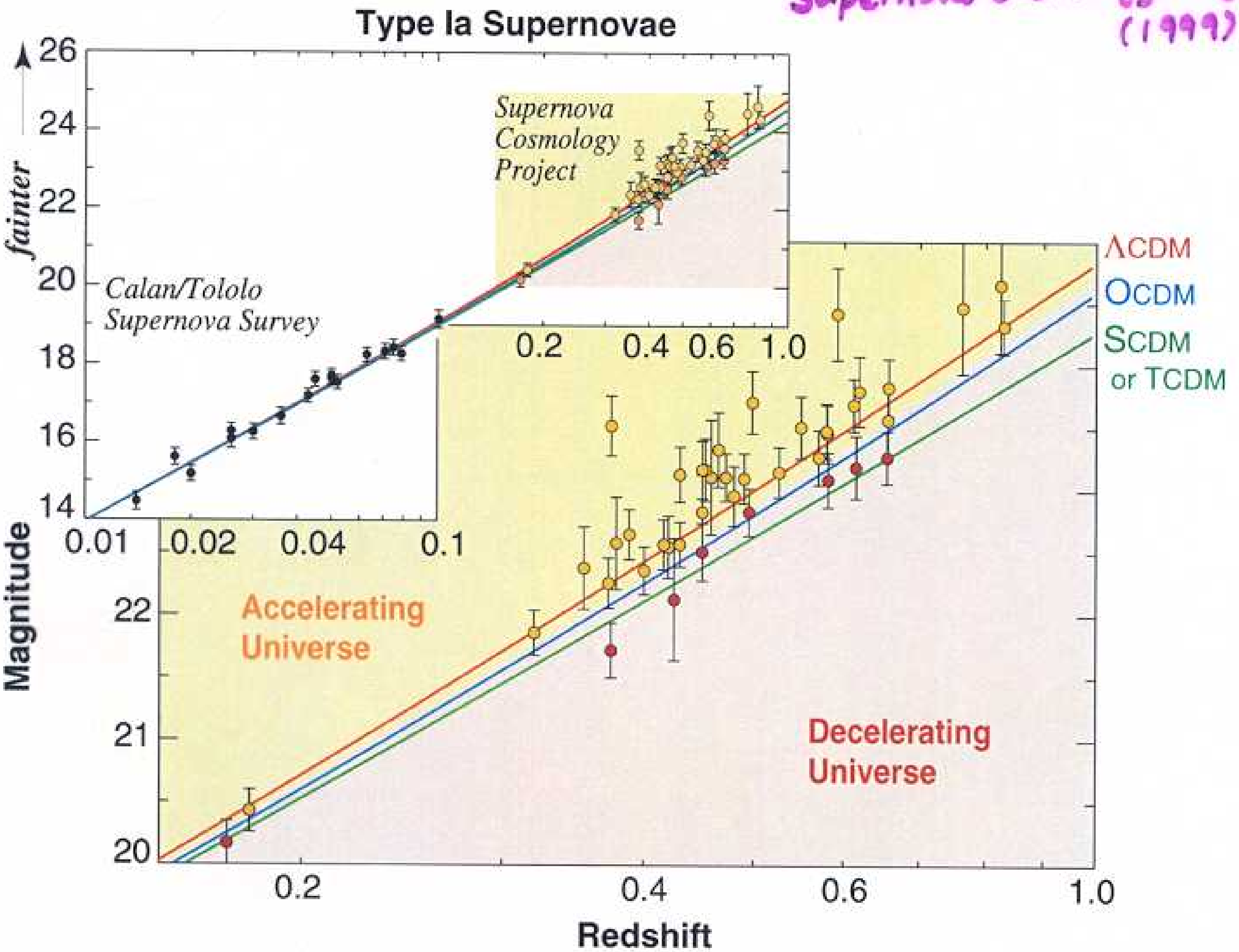
... distant SN Ia appear fainter than a "standard candle" in a freely coasting universe

$\Rightarrow$ accelerated expansion (@ 2σ) below redshift ~ 0.5

$$q_0 \equiv -\frac{\ddot{a}\,a}{\dot{a}^2} = \frac{\Omega_m}{2} - \Omega_\Lambda < 0$$

High-z Supernova Search Team (1998)

Supernova Cosmology Project (1999)



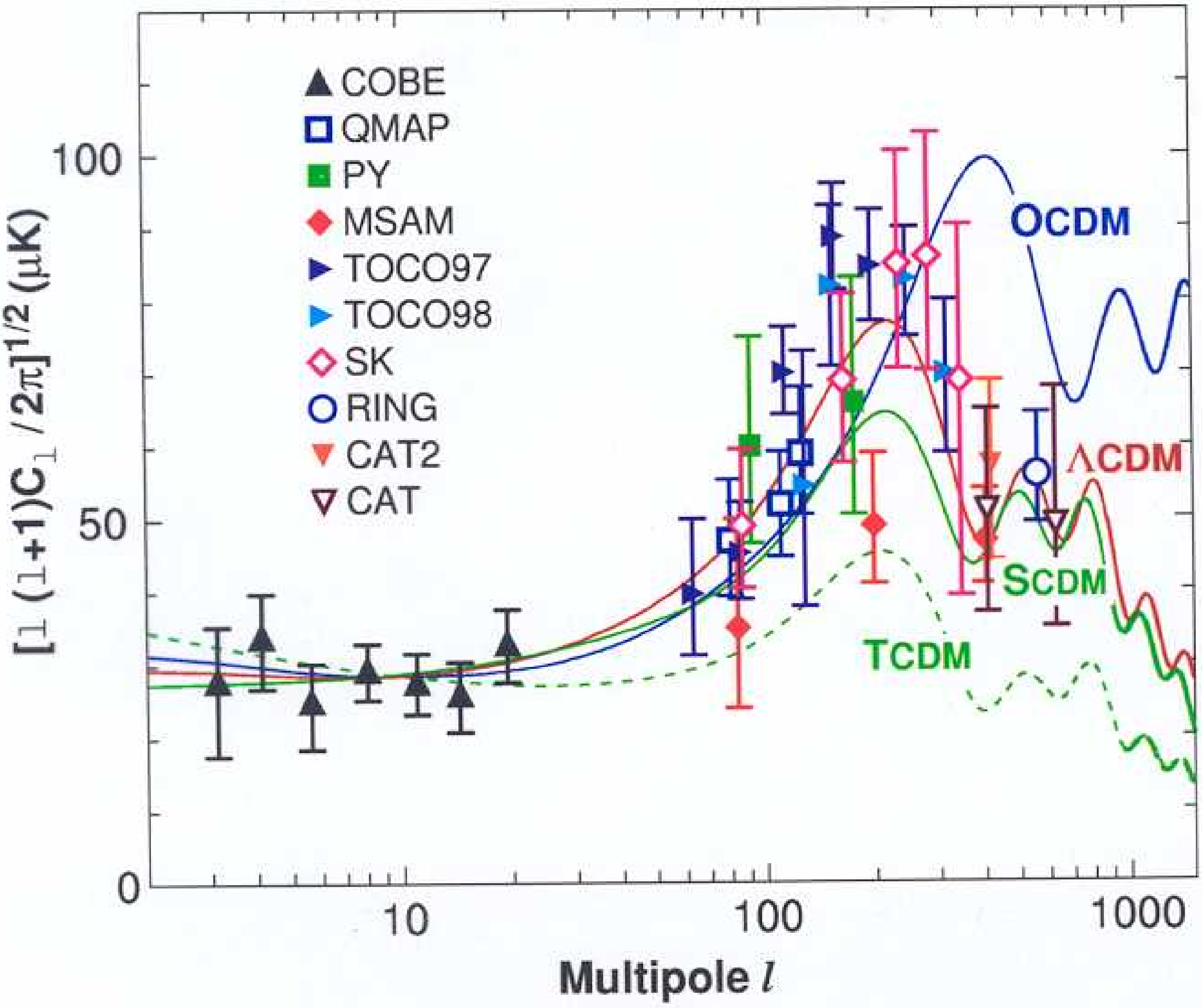
a (decelerating) Einstein-de Sitter universe ($\Omega_m = 1$) is rejected @ 8σ ... <u>if</u> SNIa are 'standard candles'

$$0.8\,\Omega_m - 0.6\,\Omega_\Lambda = -0.2 \pm 0.1$$

Bahcall et al (astro-ph/9906463)

... the position of the first peak ($\ell \simeq 200$) in the CMB angular power spectrum indicates a flat universe with

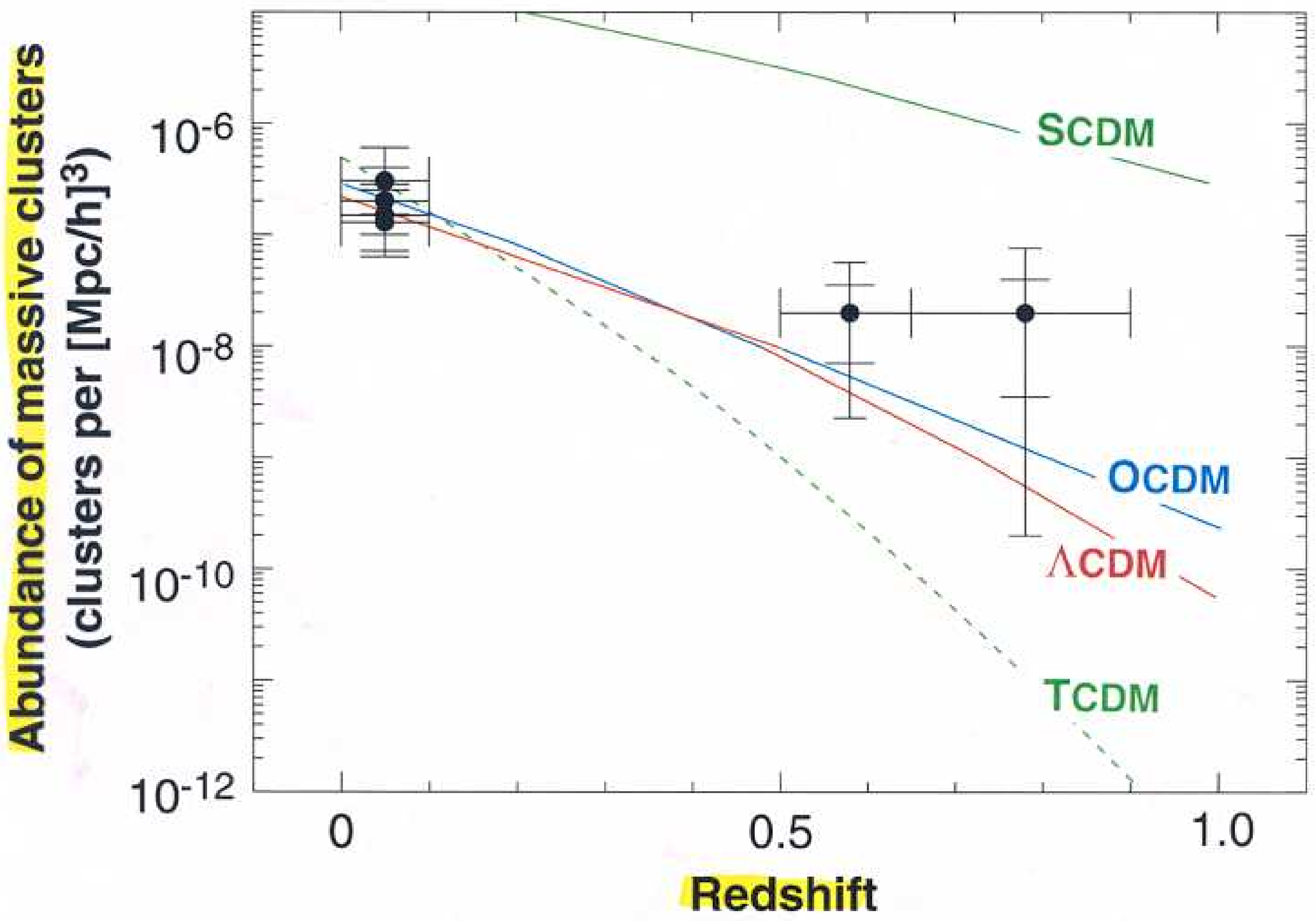
$$\Omega_K \simeq 0.00 \pm 0.3$$



... assuming the primordial fluctuations to be adiabatic

Bahcall et al (astro-ph/9906463)

... the observed slow evolution of the abundance of rich clusters of galaxies with redshift also argues for a low density universe, with $\Omega_m \sim 0.3 \pm 0.1$

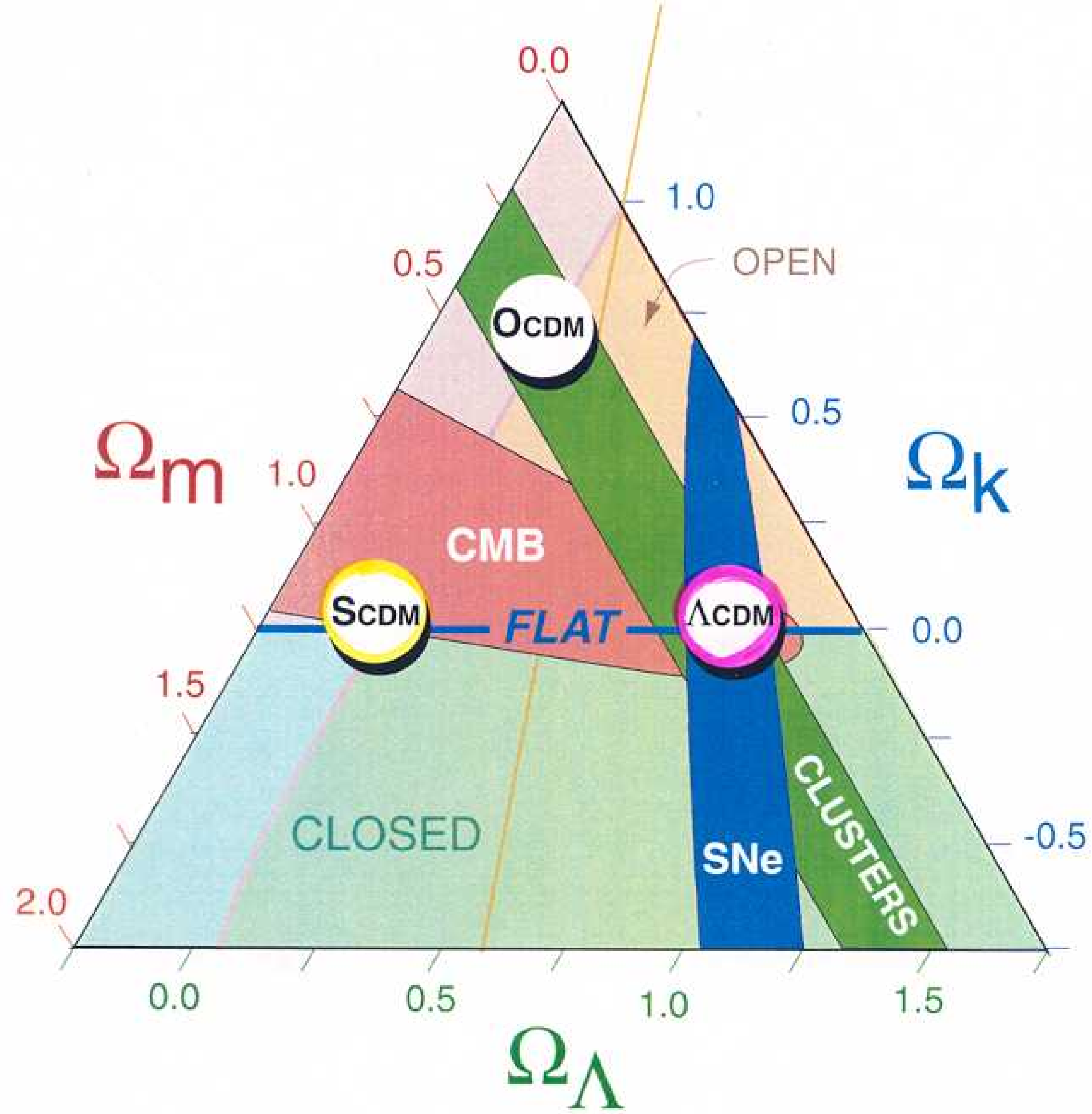


a high density ($\Omega_m \simeq 1$) universe is however allowed if the primordial spectrum of density fluctuations is, e.g., 'tilted' below a scale-invariant form

Bahcall et al.
(astro-ph/9906463)

... combining these observations indicates

$\Omega_m \sim 1/3$, $\Omega_\Lambda \sim 2/3$



"Discovery of the century"?

Bahcall et al
(astro-ph/9906463)

"What I say three times is true"

$\Omega_{\Lambda} \sim \Omega_{m} \sim \mathcal{O}(1) \Rightarrow$ energy density $\sim (10^{-3} \mathrm{eV})^4 \sim 10^{-120} M_P^4$

➡ if $\Omega_{\Lambda} = 0$ ... then must understand why different contributions to Λ cancel so accurately

➡ if $\Omega_{\Lambda} \simeq 10^{-120} M_P^4$ ... then must also understand why $\Omega_{\Lambda} \sim \Omega_{m}$ today

... models of 'quintessence' (evolving scalar field) which track the energy density of matter, address the second problem, not the first

- Vacuum energy is real (Casimir effect)

⊕

- Vacuum energy gravitates (otherwise construct perpetual motion machine!)

→ no solution to problem in field theory

Recent suggestions:

- Possible UV ↔ IR connection for FT in curved space-time
  'holographic principle'?

- 'self-tuning' of cosmological constant → 0 in "brane-world" constructions
  ... does not work!

- GR cannot be quantised (Hilbert space of finite dimension) unless embedded in a more complete theory

⋮

may be possible to understand why $\Lambda = 0$

... harder to understand $\Omega_\Lambda \sim \Omega_m$ today

Situation so bad that 'anthropic' arguments have begun to be invoked!

... justification from string theory "landscape"?!

Breakthrough Online
For an expanded version of this section, with references and links, see www.sciencemag.org/content/vol302/issue5653/#special

Breakthrough

#1 The Winner

Portraits of the earliest universe and the lacy pattern of galaxies in today's sky confirm that the universe is made up largely of mysterious dark energy and dark matter. They also give the universe a firm age and a precise speed of expansion.

Illuminating the Dark Universe

A lonely satellite spinning slowly through the void has captured the very essence of the universe. In February, the Wilkinson Microwave Anisotropy Probe (WMAP) produced an image of the infant cosmos, of all of creation when it was less than 400,000 years old. The brightly colored picture marks a turning point in the field of cosmology: Along with a handful of other observations revealed this year, it ends a decades-long argument about the nature of the universe and confirms that our cosmos is much, much stranger than we ever imagined.

Five years ago, *Science*'s cover sported the visage of Albert Einstein looking shocked by 1998's Breakthrough of the Year: the accelerating universe. Two teams of astronomers had seen the faint imprint of a ghostly force in the death rattles of dying stars. The apparent brightness of a certain type of supernova gave cosmologists a way to measure the expansion of the universe at different times in its history. The scientists were surprised to find that the universe was expanding ever faster, rather than decelerating, as general relativity—and common sense—had led astrophysicists to believe. This was the first sign of the mysterious "dark energy," an unknown force that counteracts the effects of gravity and flings galaxies away from each other.

Although the supernova data were compelling, many cosmologists hesitated to embrace the bizarre idea of dark energy. Teams of astronomers across the world rushed to test the existence of this irresistible force in independent ways. That quest ended this year. No longer are scientists trying to confirm the existence of dark energy; now they are trying to find out what it's made of, and what it tells us about the birth and evolution of the universe.

Lingering doubts about the existence of dark energy and the composition of the universe dissolved when the WMAP satellite took the most detailed picture ever of the cosmic microwave background (CMB). The CMB is the most ancient light in the universe, the radiation that streamed from the newborn universe when it was still a glowing ball of plasma. This faint microwave glow surrounds us like a distant wall of fire. The writing on the wall—tiny fluctuations in the temperature (and other properties) of the ancient light—reveals what the universe is made of.

Through a glass, darkly. Microwave data observed by the WMAP satellite (*upper left*), supernovae (*lower left*), and galaxy clusters (*above*) all reveal a universe dominated by dark energy.

Long before there were stars and galaxies, the universe was made of a hot, glowing plasma that roiled under the competing influences of gravity and light. The big bang had set the entire cosmos ringing like a bell, and pressure waves rattled through the plasma, compressing and expanding and compressing clouds of matter. Hot spots in the background radiation are the images of compressed, dense plasma in the cooling universe, and cold spots are the signature of rarefied regions of gas.

Just as the tone of a bell depends on its shape and the material it's made of, so does the "sound" of the early universe—the relative abundances and sizes of the hot and cold spots in the microwave background—depend on the composition of the universe and its shape. WMAP is the instrument that finally allowed scientists to hear the celestial music and figure out what sort of instrument our cosmos is.

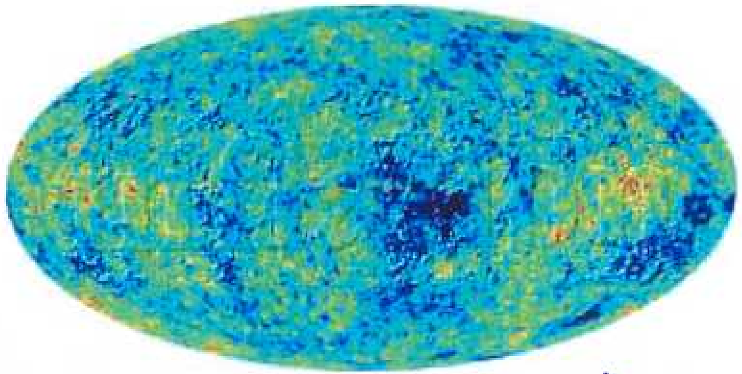
The answer was disturbing and comforting at the same time. The WMAP data confirmed the incredibly strange picture of the universe that other observations had been painting. The universe is only 4% ordinary matter, the stuff of stars and trees and people. Twenty-three percent is exotic matter: dark mass that astrophysicists believe is made up of an as-yet-undetected particle. And the remainder, 73%, is dark energy.

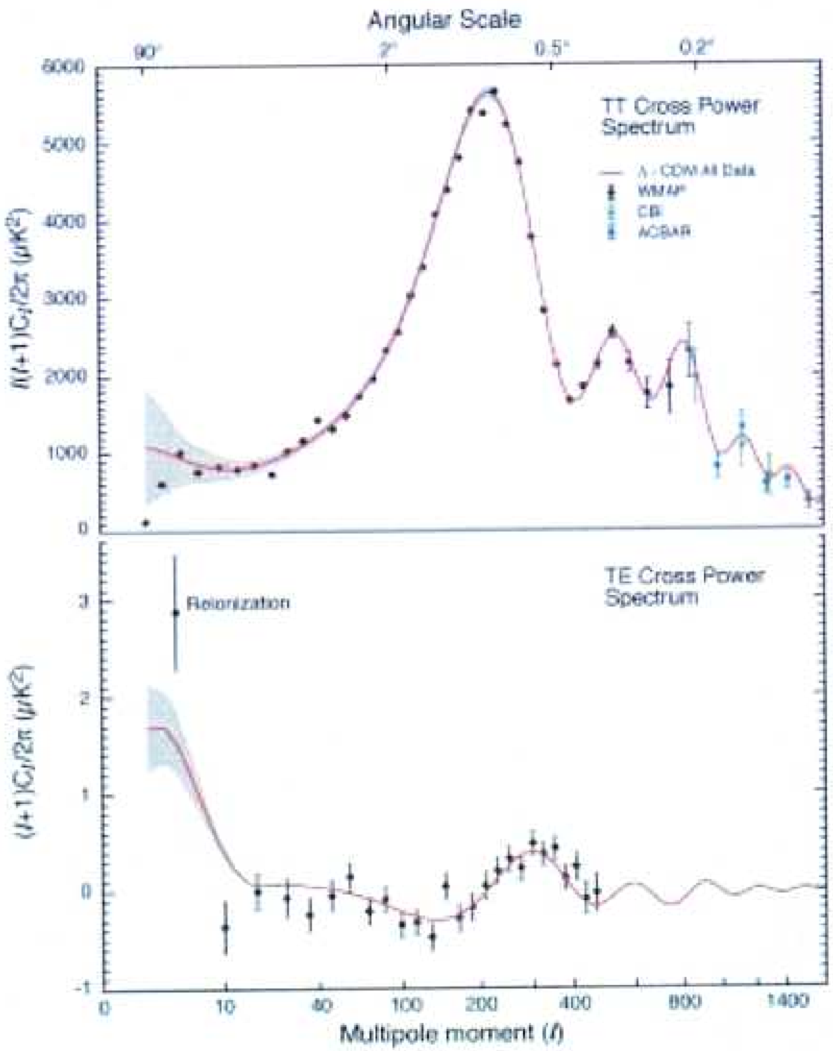
The tone of the cosmic bell also reveals the age of the cosmos and the rate at which it is expanding, and WMAP has nearly perfect pitch. A year ago, a cosmologist would likely have said that the universe is between 12 billion and 15 billion years old. Now the estimate is 13.7 billion years, plus or minus a few hundred thousand. Similar calculations based on WMAP data have also pinned down the rate of the universe's expansion—71 kilometers per second per megaparsec, plus or minus a few hundredths—and the universe's "shape": slate flat. All the arguments of the last few decades about the basic properties of the universe—its age, its expansion rate, its composition, its density—have been settled in one fell swoop.

As important as WMAP is, it is not this year's only contribution to cosmologists' understanding of the history of the universe. The Sloan Digital Sky Survey (SDSS) is mapping out a million galaxies. By analyz-

CREDITS: (CLOCKWISE FROM TOP) SDSS COLLABORATION; GSFC/NASA; NASA/WMAP SCIENCE TEAM

Wilkinson Microwave Anisotropy Probe February 2003





coherent oscillations

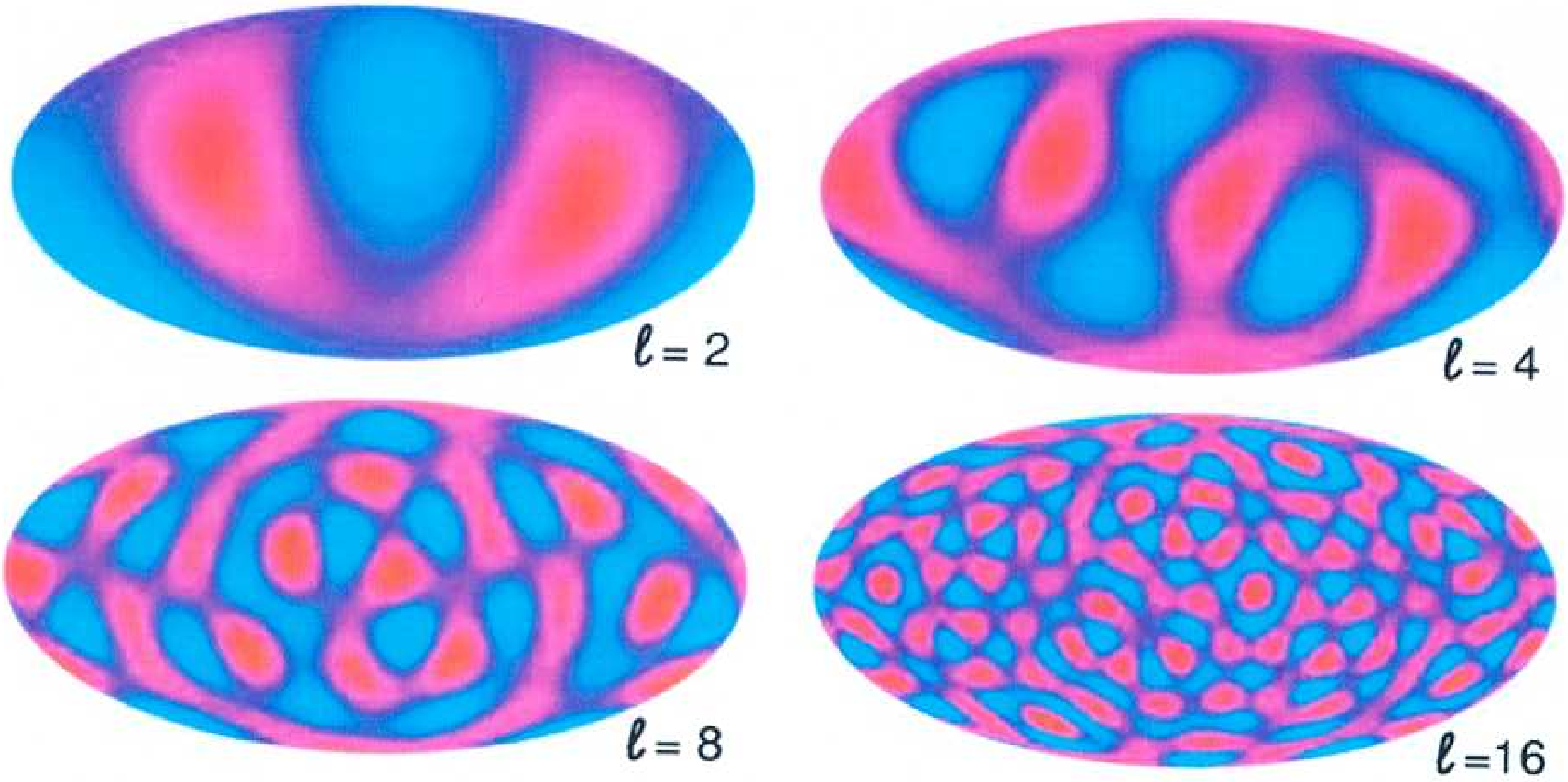
in photon-baryon plasma

from primordial density

perturbations

on super-horizon scales

Spherical Harmonic Decomposition



- $$T(\bar{x},\hat{n}) = T_0\left[1 + \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{+\ell} a_\ell^m(\bar{x})\, Y_\ell^m(\hat{n})\right]$$ … Angular Correlation Function

Sky temperature at position $\bar{x}$ in direction $\hat{n}$

→ the co-efficients $\{a_\ell^m\}$ are independent stochastic variables for random phase (Gaussian) initial conditions

$$\Rightarrow \langle a_\ell^m(\bar{x})\rangle = 0 \;,\quad \langle |a_\ell^m(\bar{x})|^2\rangle = C_\ell$$

… the average is over $\bar{x}$ ⇒ an ensemble average over all realizations of the LSS from a given position

(different observers see different $\{a_\ell^m\}$ ⇒ 'Cosmic variance')

- $$C(\alpha) \equiv \left\langle \frac{\Delta T}{T}(\hat{n}_1)\,\frac{\Delta T}{T}(\hat{n}_2)\right\rangle_{sky} = \frac{1}{4\pi}\sum_{\ell\geq 2} a_\ell^2 P_\ell(\cos\alpha)$$

$$a_\ell^2 = \sum_{m=-\ell}^{\ell} |a_\ell^m|^2 \;,\quad \alpha = \cos^{-1}(\hat{n}_1\cdot\hat{n}_2)$$

(Peebles '82)

χ^2 distribution with $(2\ell+1)$ degrees of freedom

$$\langle a_\ell^2\rangle = (2\ell+1)\,C_\ell$$ (Abbott & Wise '84)

→ for $P(k) = Ak^n$ spectrum of initial fluctuations:

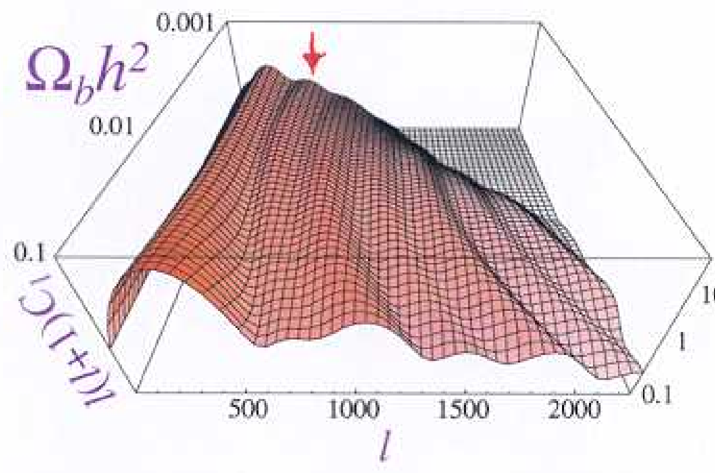
$$C_\ell = C_2\,\frac{\Gamma\left(\ell+\frac{n-1}{2}\right)\Gamma\left(\frac{9-n}{2}\right)}{\Gamma\left(\ell+\frac{5-n}{2}\right)\Gamma\left(\frac{3+n}{2}\right)} \;,\quad \text{for } n<3$$

… for spatially flat universe with $n=1$: $$C_\ell = \frac{A}{4\pi c^4}\,\frac{\Omega_m^{1.54} H_0^4}{\ell(\ell+1)}$$

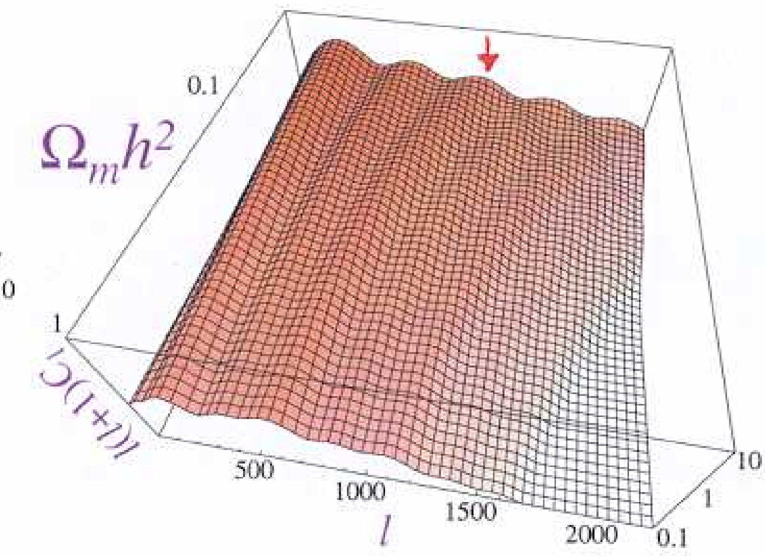
(Peebles '84)

Cosmological Parameters in the CMB

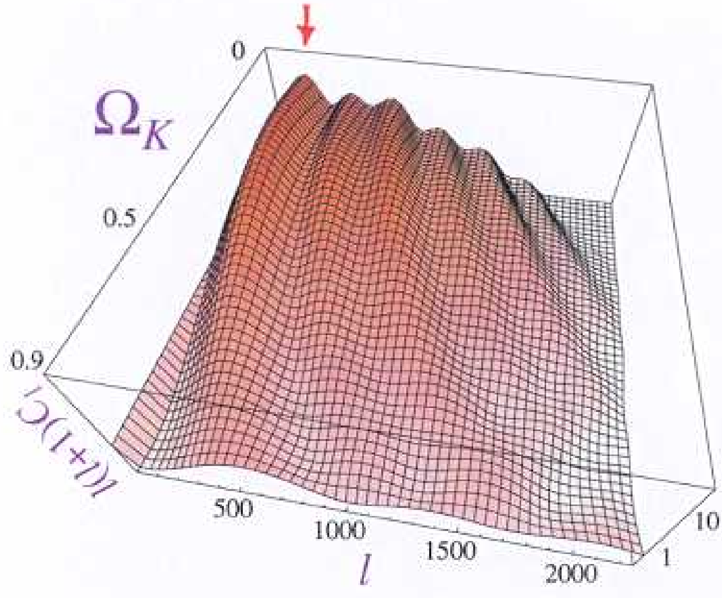
Baryon–Photon Ratio



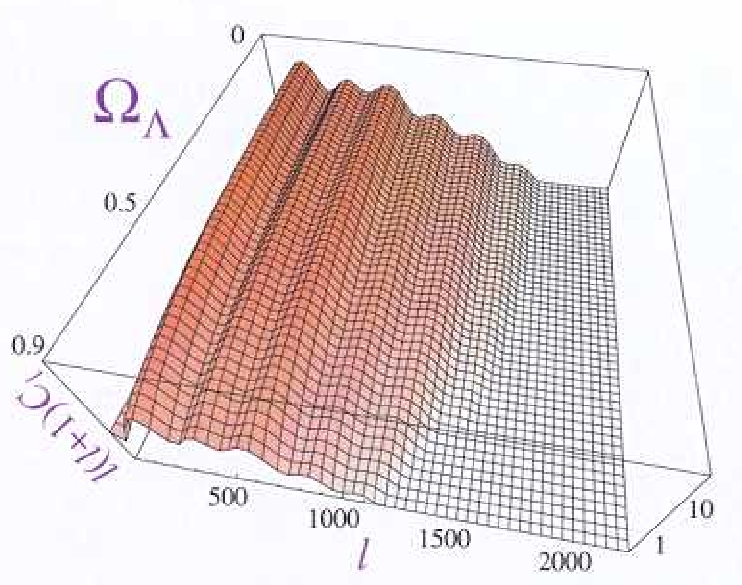
Matter–Radiation Ratio



Curvature



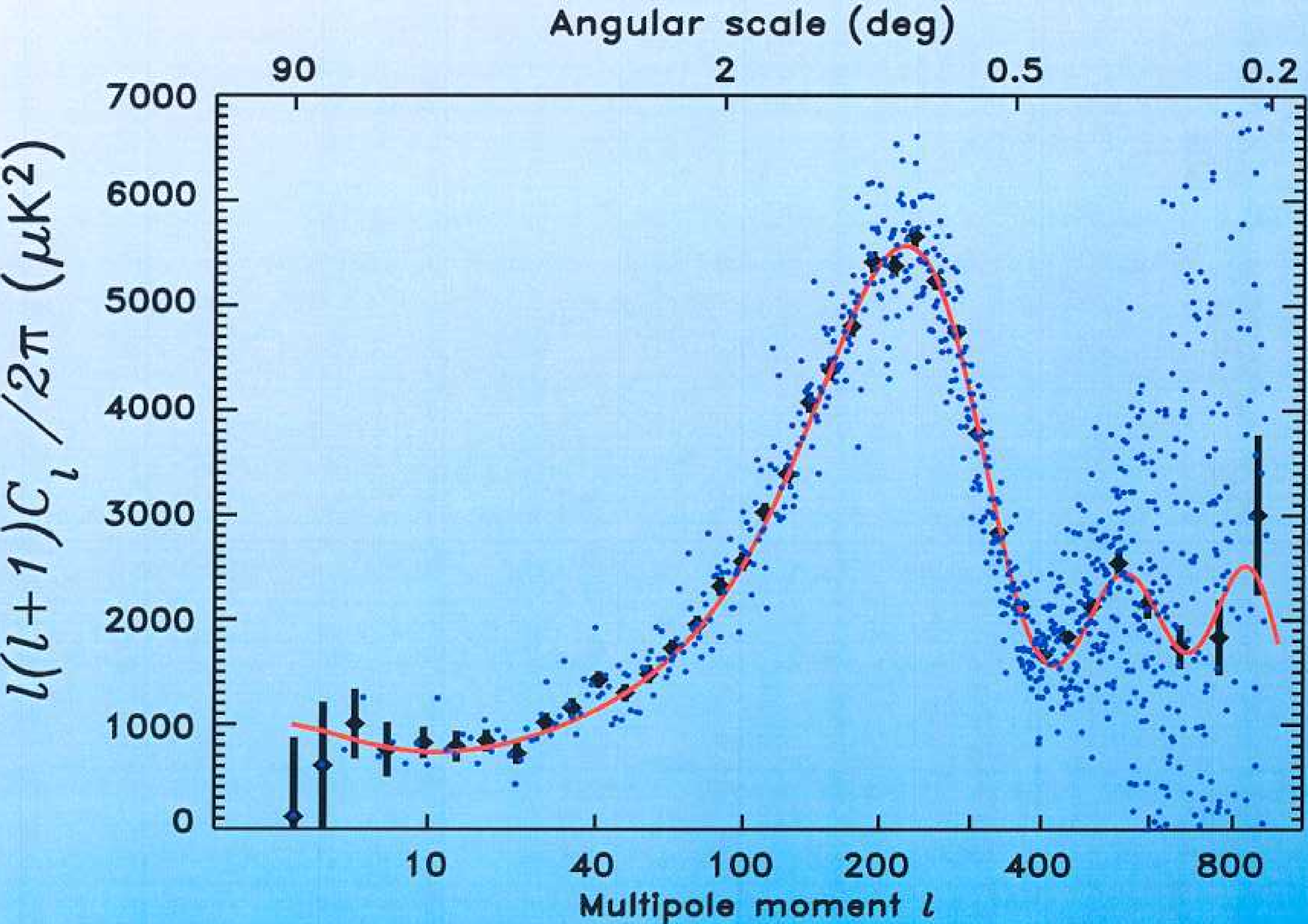
Cosmological Constant



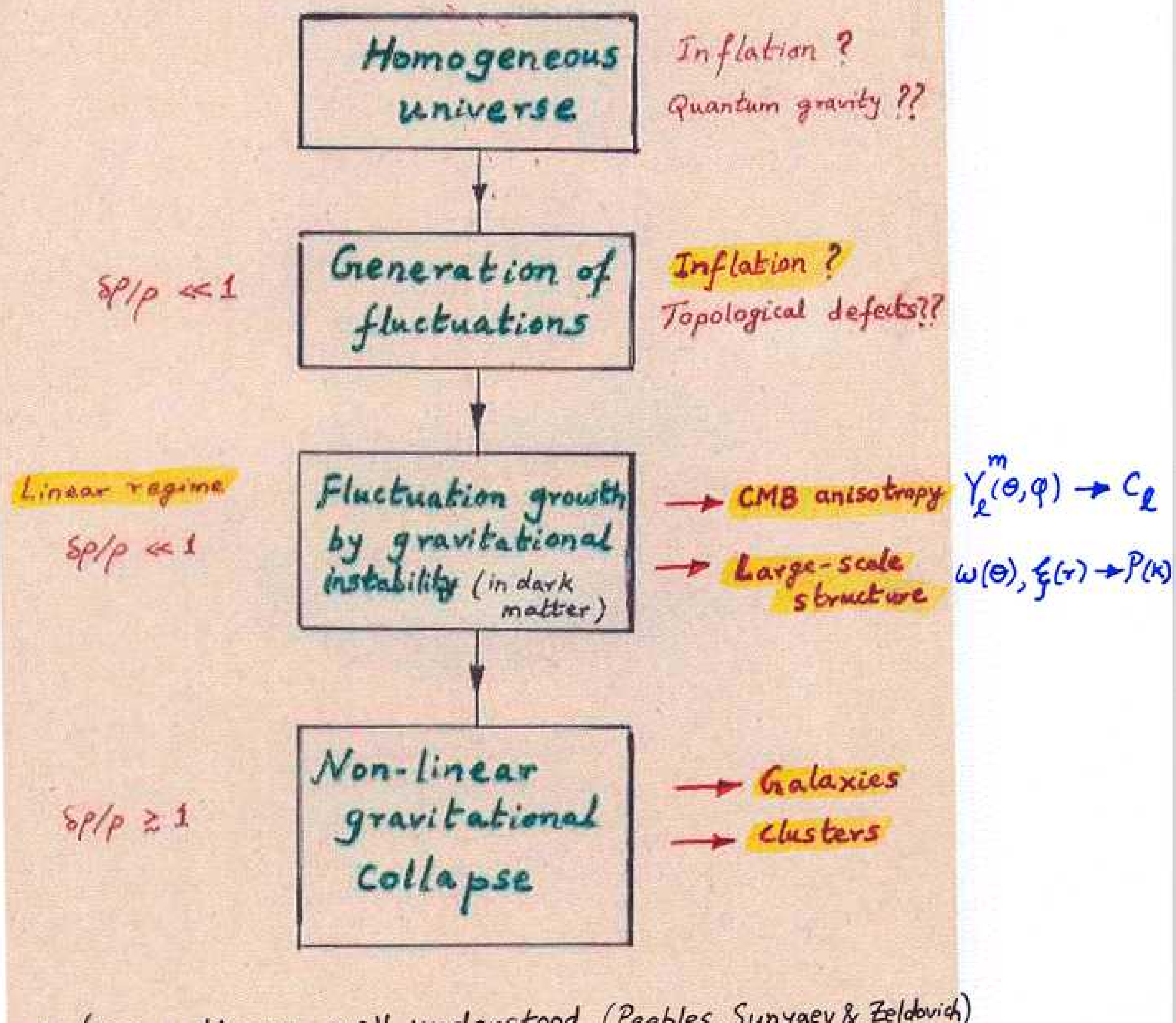
W.Hu 2/98

WMAP Angular Power Spectrum

Best-fit ΛCDM model (assumed flat) : $\Omega_m h^2 = 0.14 \pm 0.02$, $\Omega_B h^2 = 0.024 \pm 0.001$, $h = 0.72 \pm 0.05$
($\chi^2_{eff}/\nu = 973/893 \Rightarrow$ probability of 3%)



Formation of Structure in the Universe



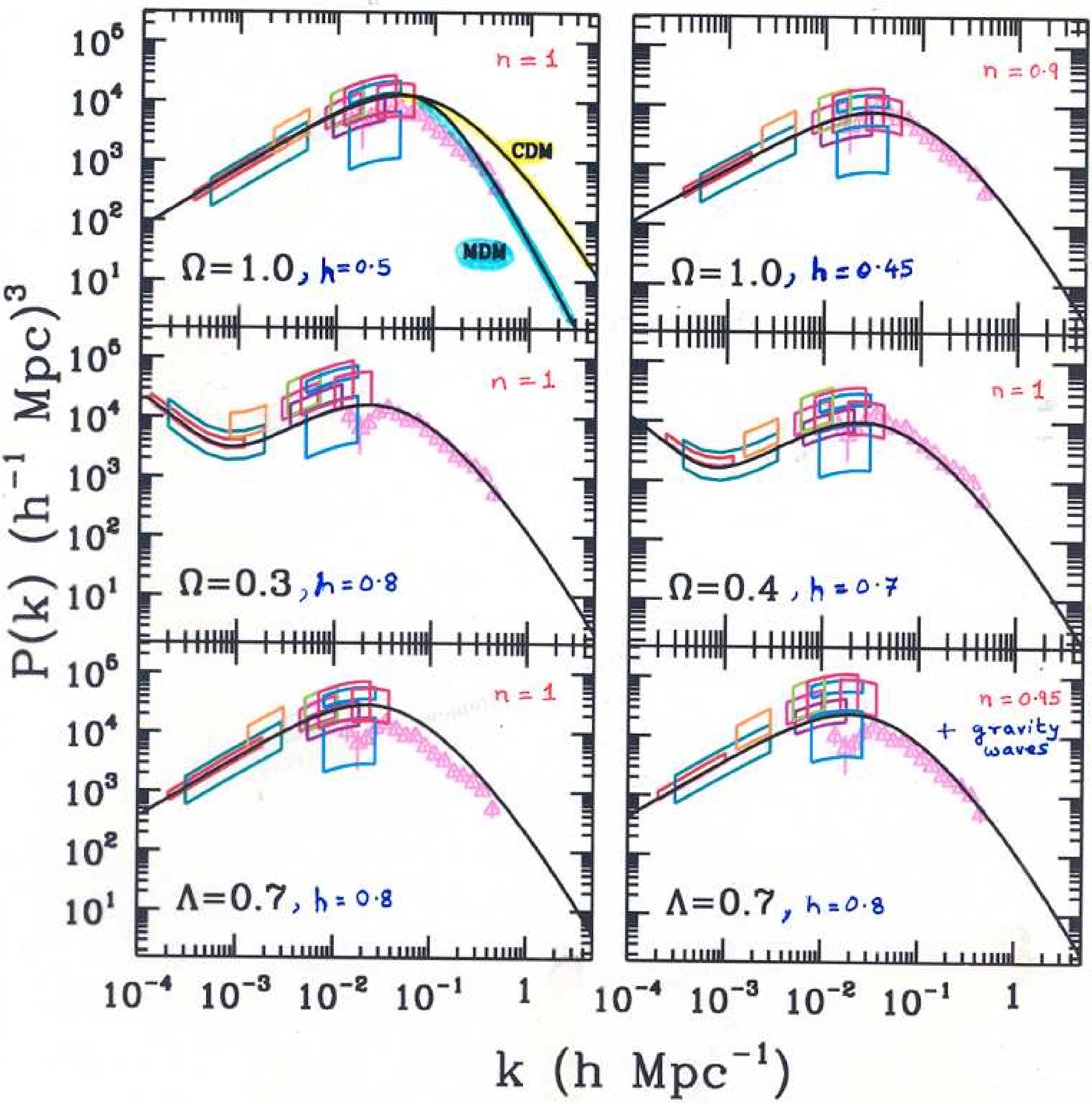
→ Linear theory well understood (Peebles, Yu 1970, Sunyaev & Zeldovich 1970)

→ Numerical codes (CMBFAST, CAMB ···) agree to <0·1%.

... akin to a scattering experiment

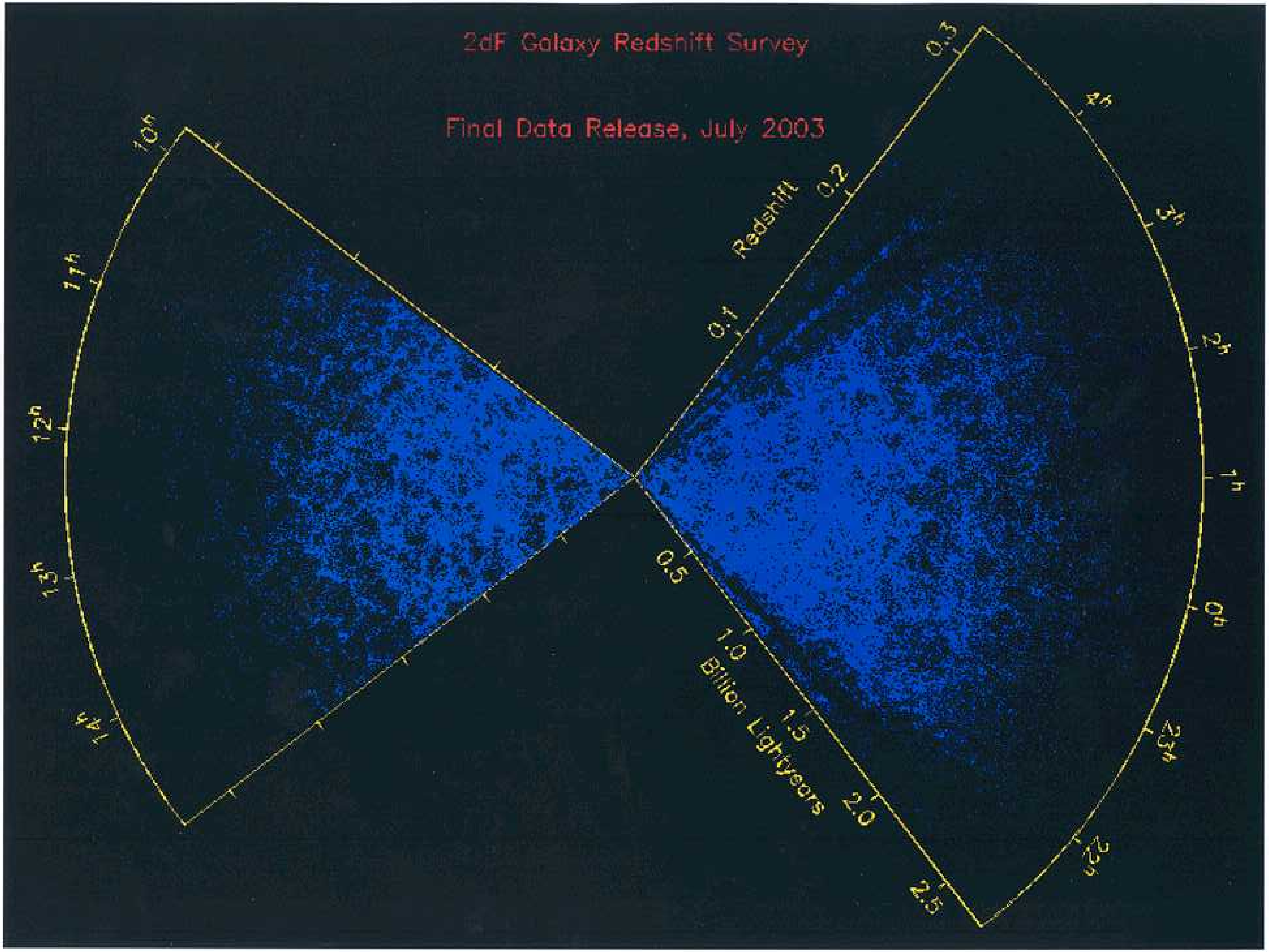
→ trying to infer properties of target and detector, with assumed beam!

The matter power spectrum for modified CDM models



... can fit data with ΛCDM or MDM or TCDM ...

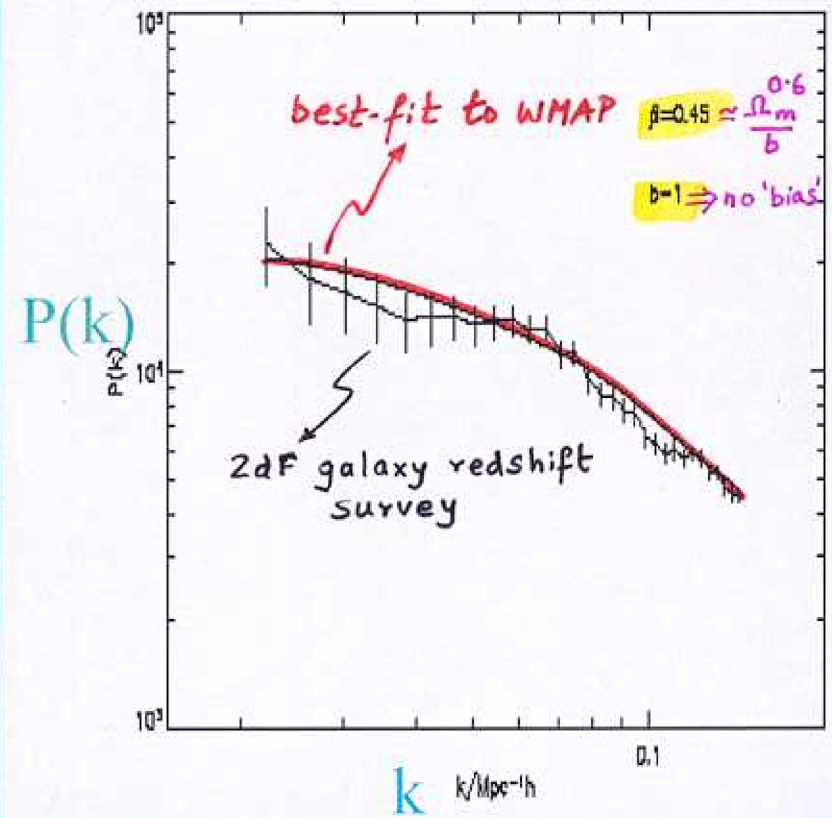
Scott, Silk, White
(astro-ph/9505015)


2dF Galaxy Redshift Survey
Final Data Release, July 2003
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h

Spergel, CAPP 2003

Consistent Cosmological Model

- Consistent with BBN estimate of baryon density
- HST measurements of expansion rate
- Stellar evolution estimates of stellar ages
- Estimates of density fluctuations
  - Gravitational lensing
  - Clusters
  - Large scale structure
  - Lyman α forest



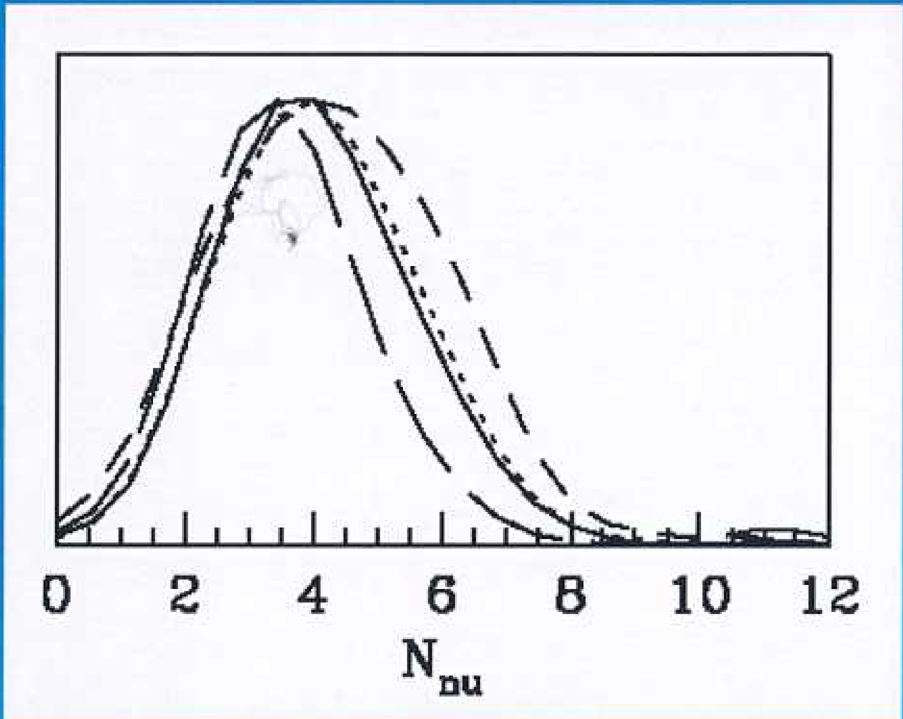
2dfGRS

CMB + External Data

- Supernova: $D_A(z)$
- Large Scale Structure
  - Shape of transfer function sensitive to $\Omega_m h$ and $\Omega_b h$
  - Three point function → bias → σ_8
  - Clustering & Velocity Field → $\sigma_8 \Omega^{0.6}$
- Lyman α forest
  - Sensitive to n, $\Omega_m h$ and $\Omega_b h$

Spergel, CAPP 2003

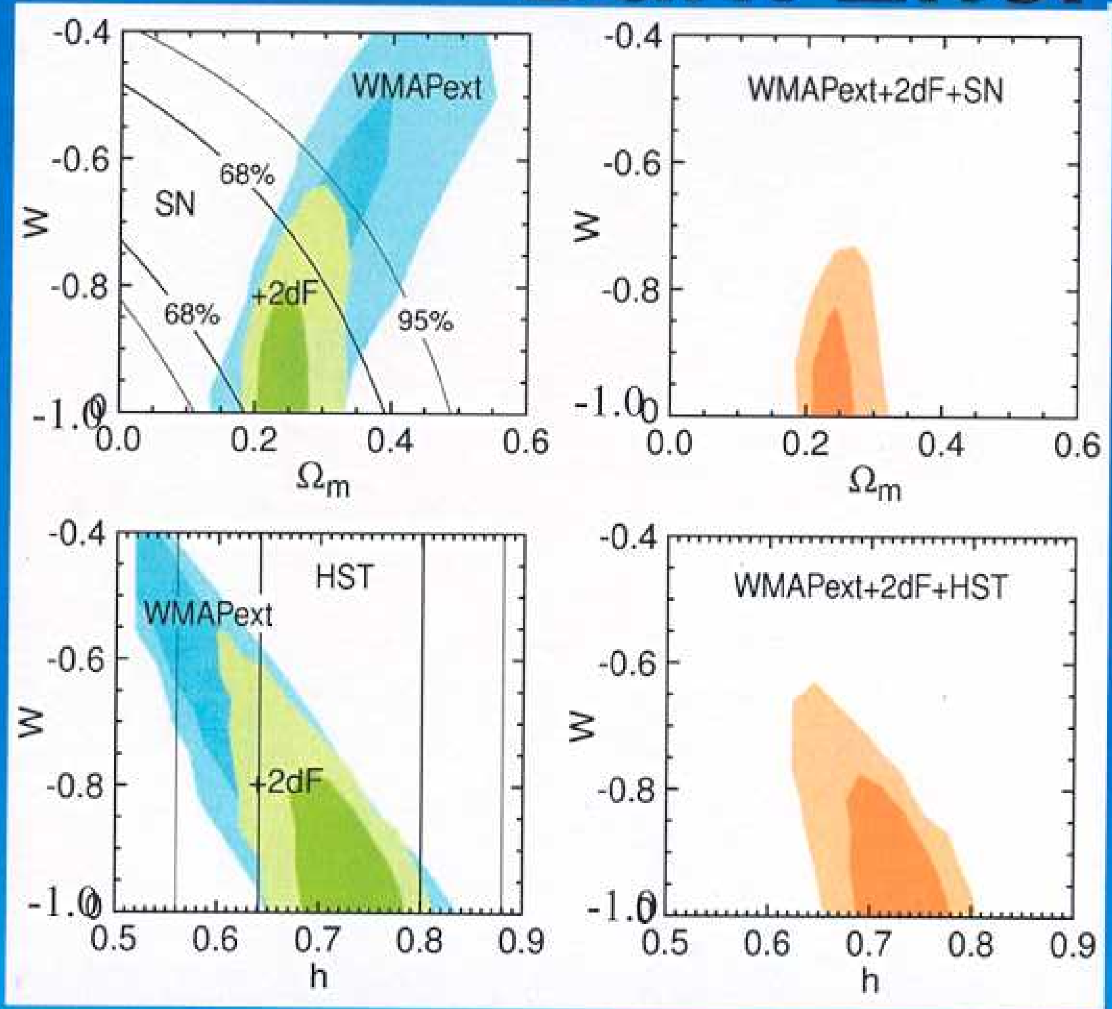
Constraining Composition of Universe



- Varying energy density in relativistic species alters evolution of CMB fluctuations: $1.6 < N_\nu < 8$ (Hannested 2003; Pierpaoli 2003)
- Growth of structure constrains neutrino mass $m_\nu < 0.23$ eV
- Dark matter must be non-baryonic
- Evidence for Dark Energy independent of Supernovae
- Rules out "standard CDM"

Spergel, CAPP 2003

Beyond the Standard Model: Dark Energy



CMB data consistent with other data sets if w is near -1

(dark energy is a cosmological constant)

Standard Cosmological Model

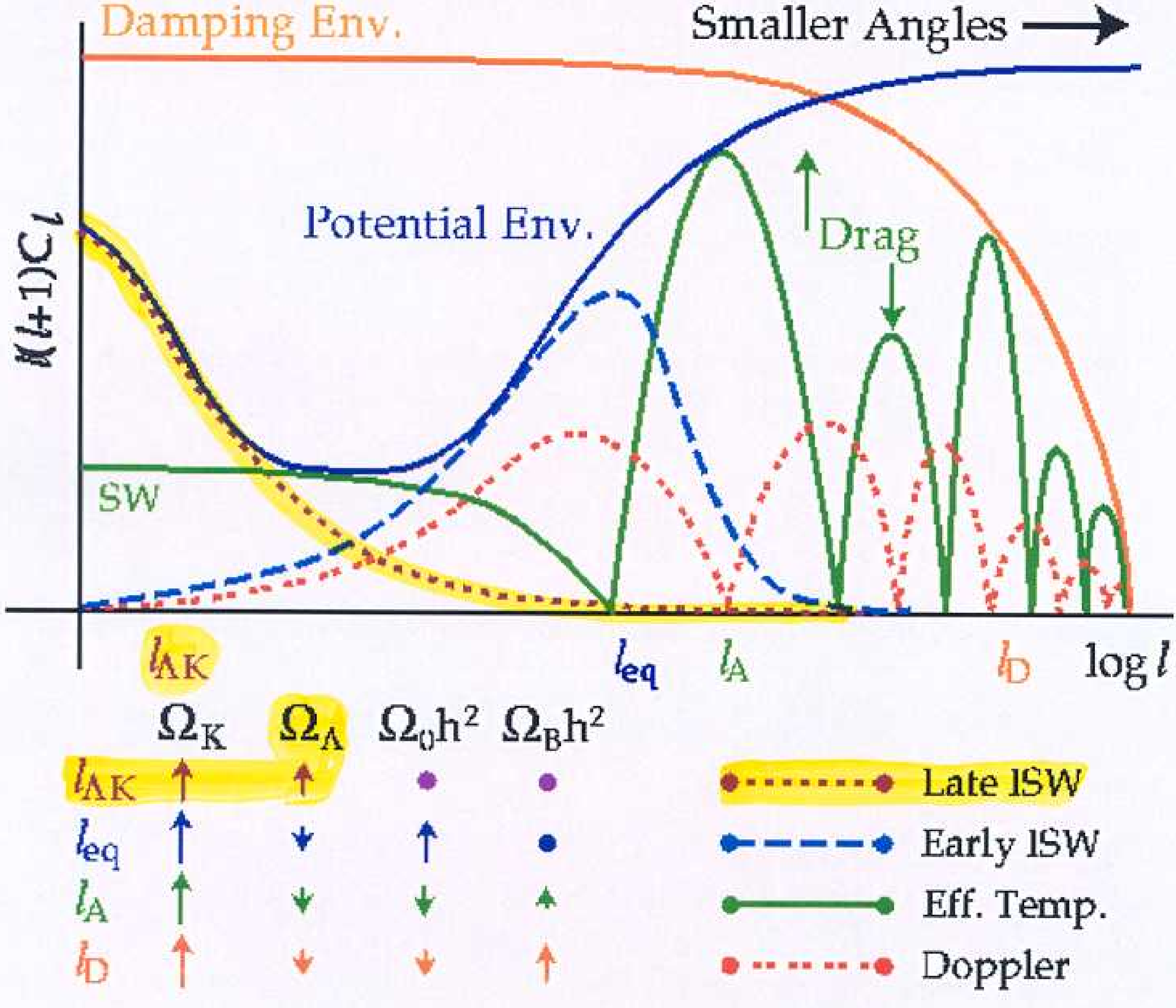
- General Relativity + Uniform Universe ⇨ Big Bang
  - Density of universe determines its fate + shape
- Universe is flat (total density = critical density)
  - Atoms 4%
  - Dark Matter 23%
  - Dark Energy (cosmological constant?) 72%
- Universe has tiny ripples
  - Adiabatic, scale invariant, Gaussian Fluctuations
  - Harrison-Zeldovich-Peebles
  - Inflationary models

When the universe becomes dominated by Λ, gravitational potential wells decay ...

→ Late Integrated Sachs-Wolfe effect

... boosts CMB anisotropy on large scales

$$C_\ell^{ISW} = \frac{2}{\pi}\int k^2 dk \left| \int 2\dot{\Phi}(k,\tau_0-\tau)\, j_\ell(k(\tau_0-\tau))\, d\tau \right|^2$$



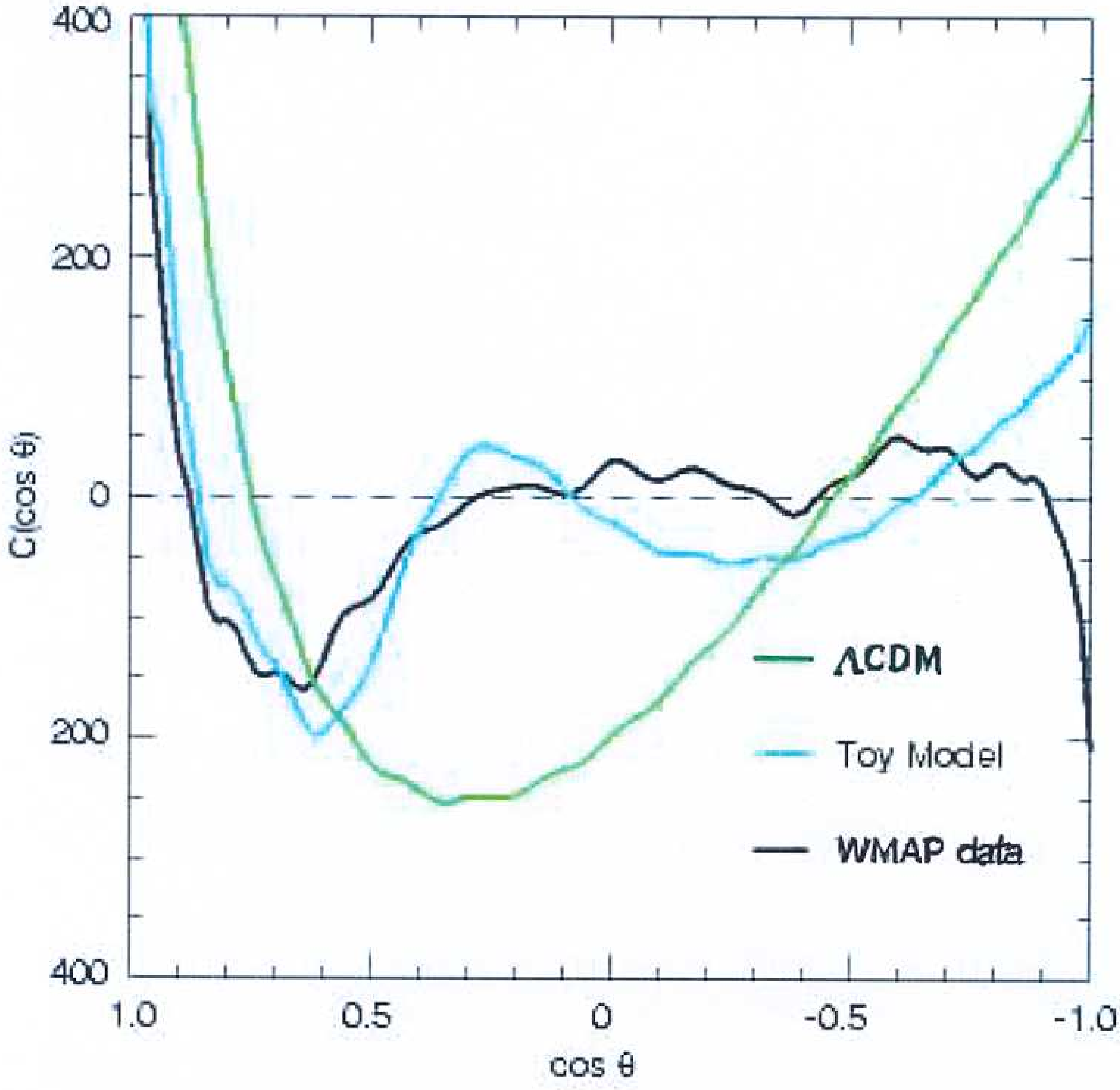
This is the most direct probe of Λ using the CMB ... should also induce correlations between the CMB and large-scale structure

The late ISW effect due to Λ should boost the CMB anisotropy on large scales

... the WMAP data show instead a decrease in the power (Spergel et al, astro-ph/0302209)

→ cannot be accounted for by cosmic variance, foreground removal etc ...

$\Omega_\Lambda \simeq 0.7$ is unlikely @ $> 2\sigma$



Searches for the expected Λ-induced correlations between the CMB and tracers of large-scale structure are inconclusive so far ... (< 3σ significance)

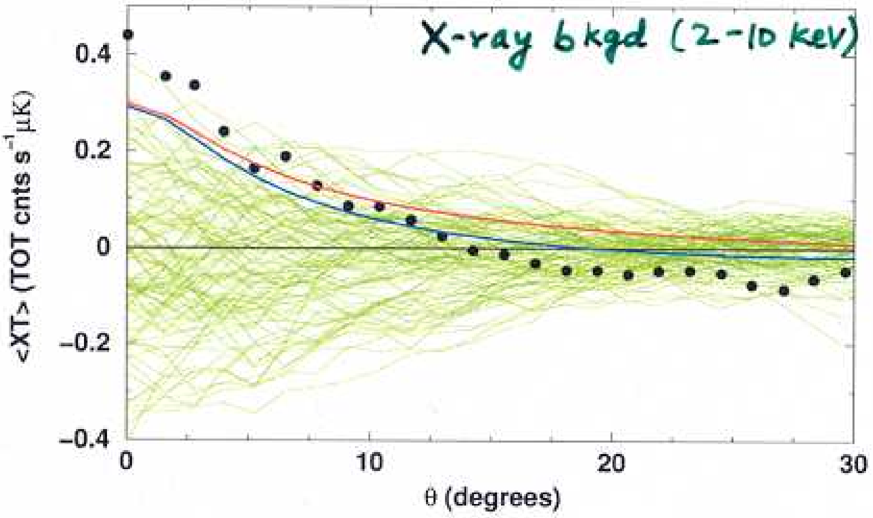


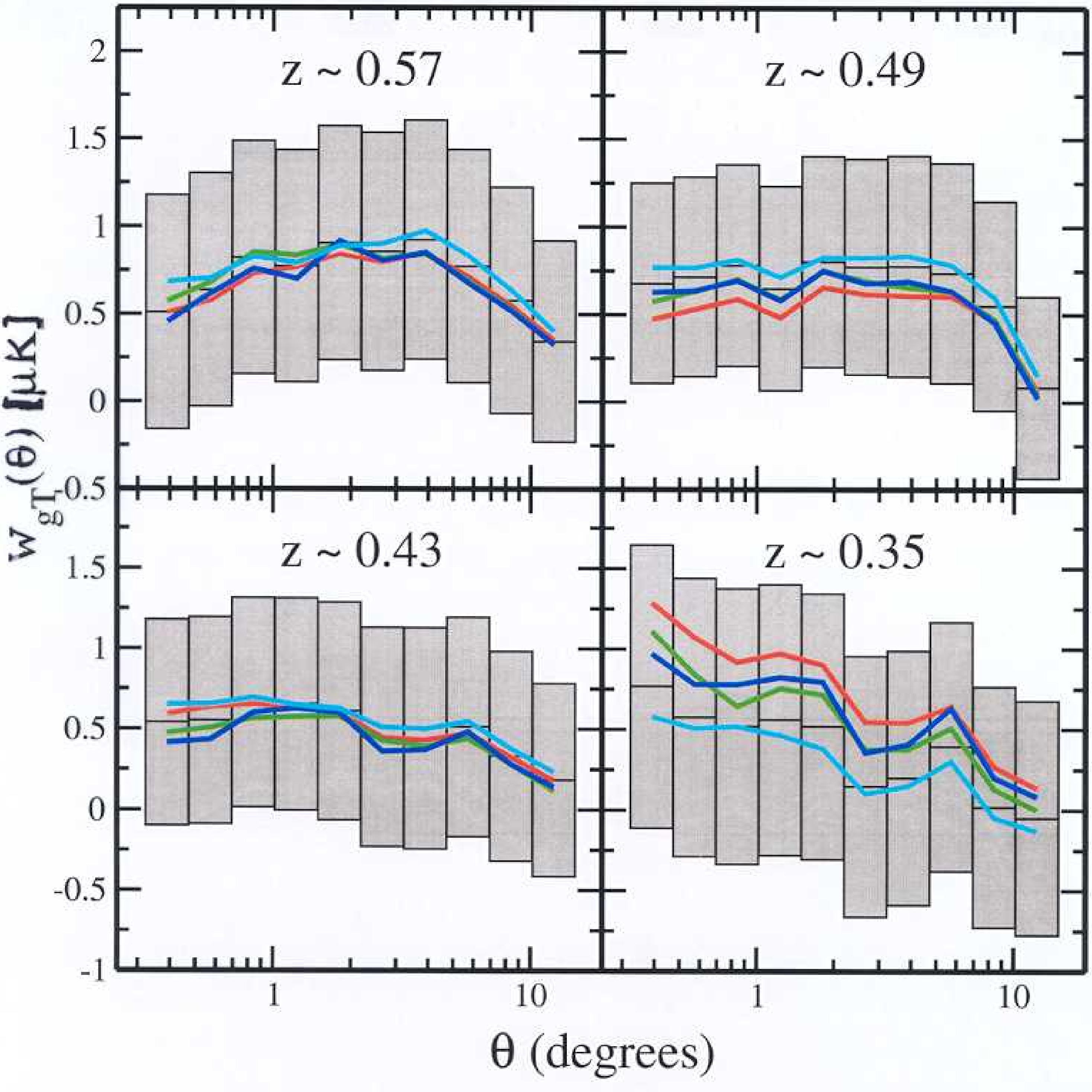
Figure 1: **The X-ray intensity measured by HEAO-A1 is correlated with the microwave sky measured by WMAP at a higher level than would be expected by chance correlations.** Here we plot the cross correlation between the X-ray intensity fluctuations and the CMB temperature fluctuations along with the theoretical predictions for the ISW effect in a cosmological constant ($\Omega_\Lambda = 0.72$), the best fit WMAP model for scale invariant fluctuations. To give an idea of the level of accidental correlations, the green curves show the result of correlating the X-ray map with 100 independent Monte Carlo realized CMB maps with the same power spectrum as the WMAP data. The variance increases at smaller angular separations, where there are fewer pairs of pixels contributing to the correlation and one can see that the signals in neighboring bins are highly correlated for a given realization. Due to the shape of the expected correlation, the signal to noise is greatest at smaller angular separations. For $\theta = 0°$, $1.3°$, and $2.6°$, the Monte Carlo trials exceed the amplitude of the actual X-ray/CMB correlation only 0.3%, 0.8%, and 0.3% of the time respectively. These correspond to 2.4 to 2.8 σ. At larger angular separations, the observed correlations appear to fall faster than predicted by theory. The blue line shows the theoretical predictions if the quadrupole and octupole modes are suppressed as suggested by the measured WMAP temperature spectrum. While it seems to fit the data better, the larger angular separations have very low signal to noise.

Boughn & Crittenden (astro-ph/0305001)

... earlier searches for correlations with COBE had provided an upper bound: $\Omega_\Lambda < 0.5$

Physical evidence for dark energy

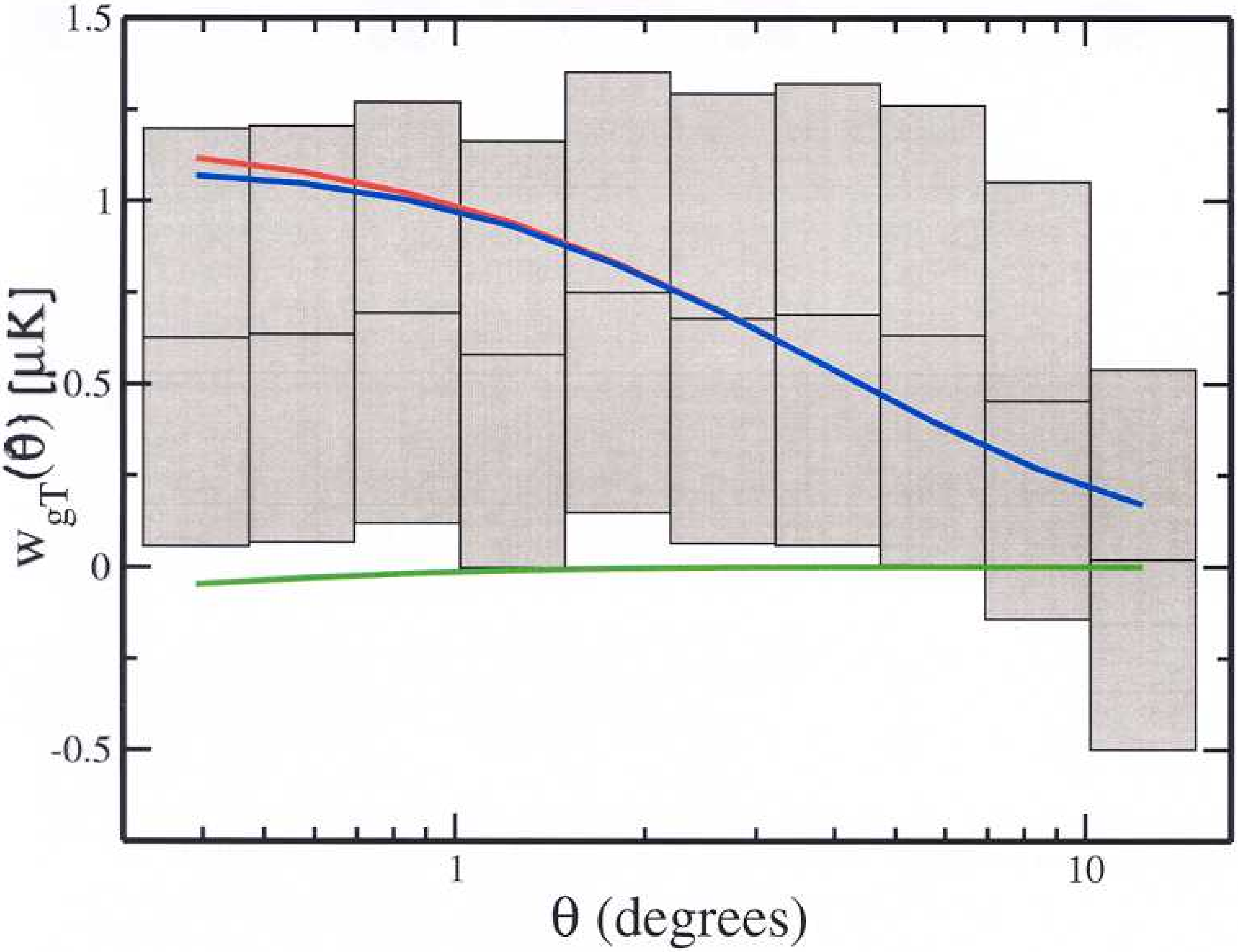
(Scranton et al, astro-ph/0307335)



Correlations between WMAP and SDSS galaxies are achromatic only for high z samples

... significance of detection is ~ 1·8 σ (90% c.l.)

Cross-correlation of WMAP (W channel) with SDSS (z ~ 0.49 subsample)



Expected ISW effect (for $\Omega_\Lambda \sim 0.7$) is preferred to the null hypothesis at the 99% c.l. (using jackknife errors)

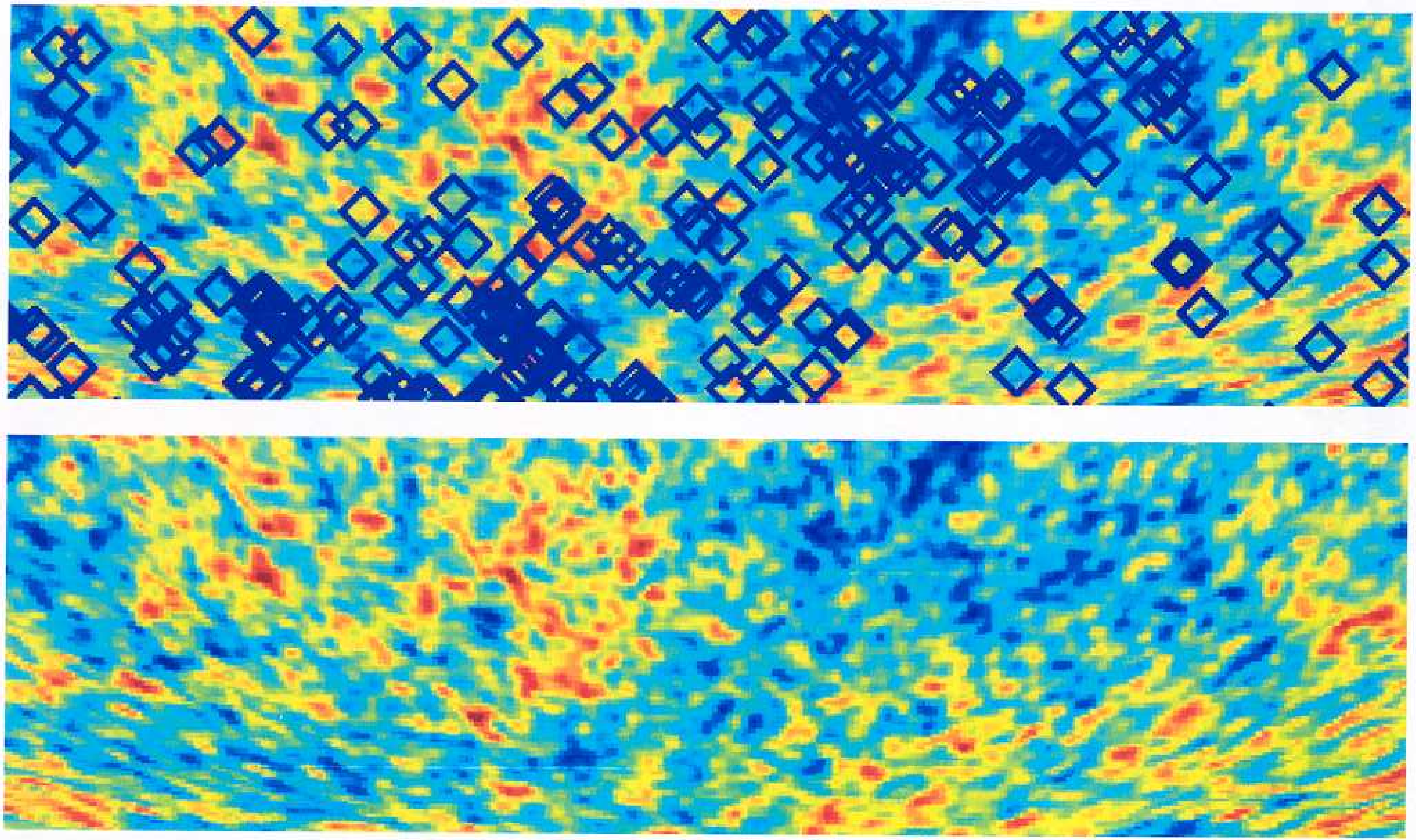
... not yet even 3σ evidence

→ will require all-sky survey with 10 million galaxies ($0 < z < 1$) to obtain 5σ detection

Ashfordi (astro-ph/0401166)

Galaxy clusters (ACO, APM, 2MASS) anti-correlated with **CMB** temperature (WMAP)

→ evidence for Sunyaev-Zeldovich effect (extending upto $\sim 1^\circ$ around clusters)



... more distant ($z \gtrsim 0.2$) clusters may have contaminated the first acoustic peak!

Myers et al. (astro-ph/0306180)

Fitting cosmological models to data

Do we know how many parameters we need?

cf.

Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model

(effective field theory valid upto $E < \Lambda$)

super-renormalisable

$\phi^2 \Lambda^2$, Λ^4

↓

solve by (softly) broken supersymmetry

(another $\mathcal{O}(100)$ parameters)

→ huge 'cosmological constant' when coupled to gravity

... no solution known!

(how many parameters will it have?)

renormalisable

(19 parameters)

non-renormalisable

neutrino mass

proton decay

FCNC

⋮

Moral: The "simplest" cosmological models may not be adequate to describe the real universe

Astronomers have traditionally assumed a Harrison-Zeldovich spectrum for the primordial density perturbation : $P(k) \propto k^n$, $n = 1$

... but inflation models generically predict departures from scale-invariance, e.g. in single-field models:

$$\delta_H^2(k) \propto \frac{P(k)}{k} \propto \left.\frac{V^3(\phi)}{V'^2}\right|_{k=H} \Rightarrow n(k) = 1 + \frac{2V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

→ since $V(\phi)$ steepens towards the end of inflation there will be a scale-dependent spectral tilt

e.g. in simplest F-term N=1 SUGRA model,

$$V = V_0 - \alpha\phi^3 + \cdots \Rightarrow n \simeq 1 - \frac{4}{N_*} \simeq 0{\cdot}9 \text{ for } N_* \sim 50$$

where $N_* \simeq 50 + \ln\left(\frac{k^{-1}}{3000\,h^{-1}\,\mathrm{Mpc}}\right)$ subject to limits on T_{reheat} etc

In multi-field models, can have sudden changes in e.g. mass of inflaton field due to other flat directions undergoing symmetry-breaking phase transitions

→ will generate spectral features ('steps', 'bumps'...)

The density perturbation need not be scale-free!

An alternative to the ΛCDM model

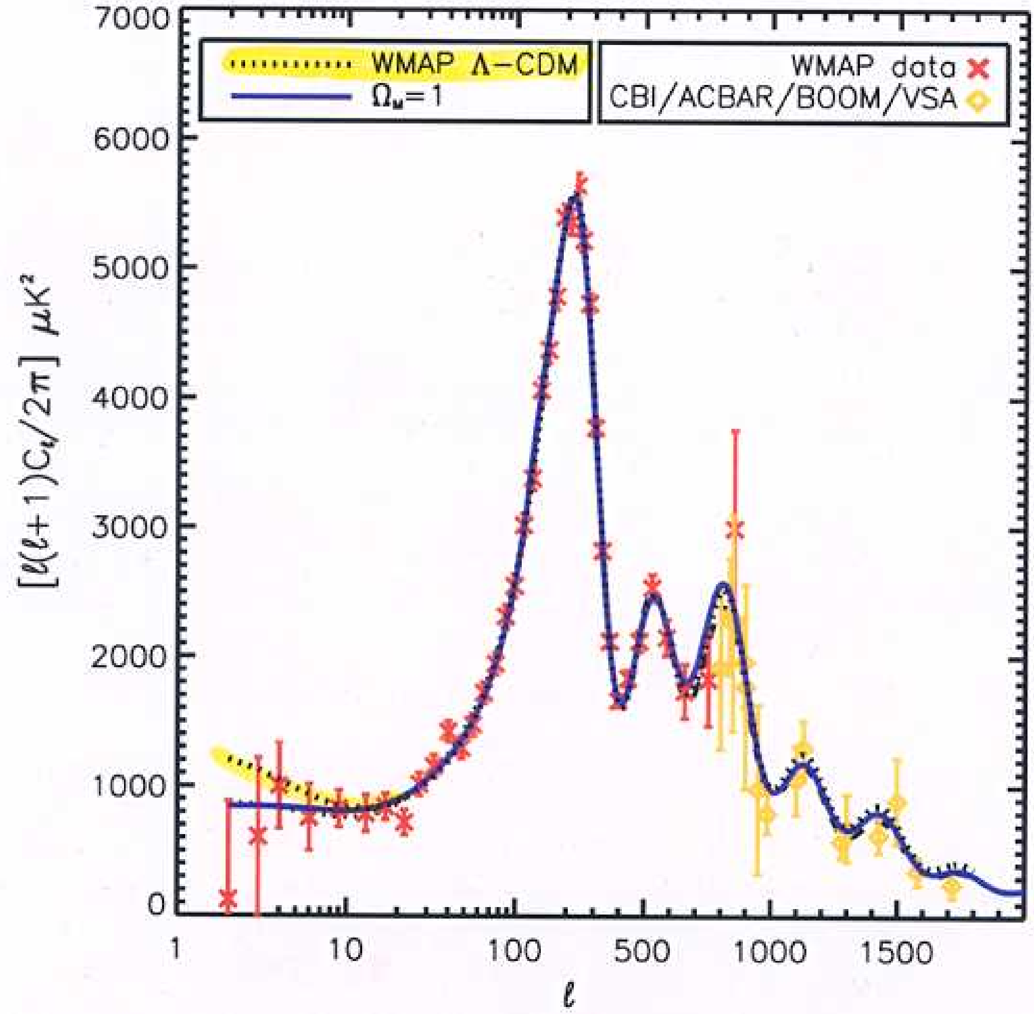
WMAP 'concordance' model: $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, $h = 0.72$, $n = 0.99$

Our E-deS model: $\Omega_\Lambda = 0$, $\Omega_m = 1$, $h = 0.46$

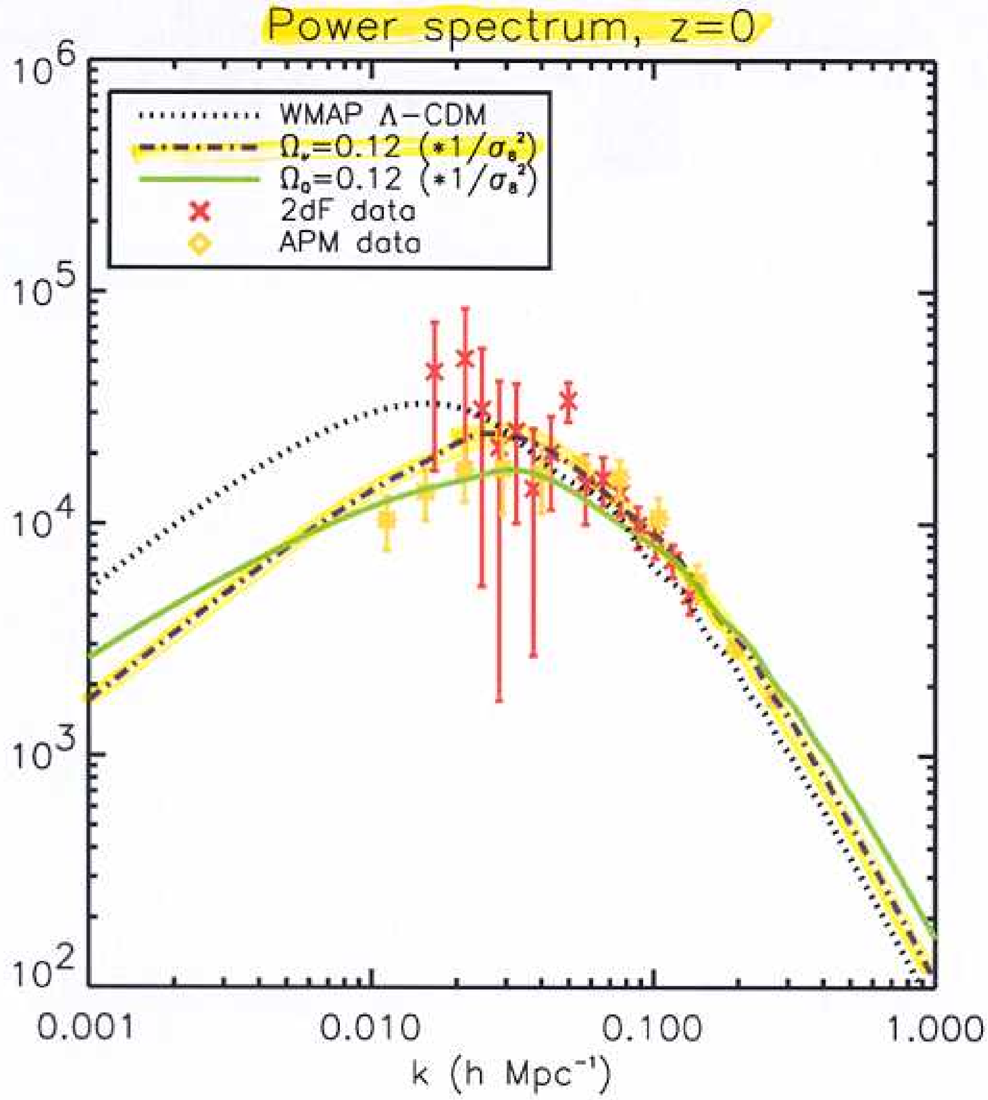
$n \simeq 1$, for $k < k_1 = 0.01$ Mpc^{-1}

$\simeq 0.8$, for $k > k_1$

... fits even better!



Blanchard, Douspis, Rowan-Robinson, S.S.
(astro-ph/0304237)



→ on smaller scales, clustering of matter would be excessive ... unless damped by e.g. a hot (neutrino) dark matter component

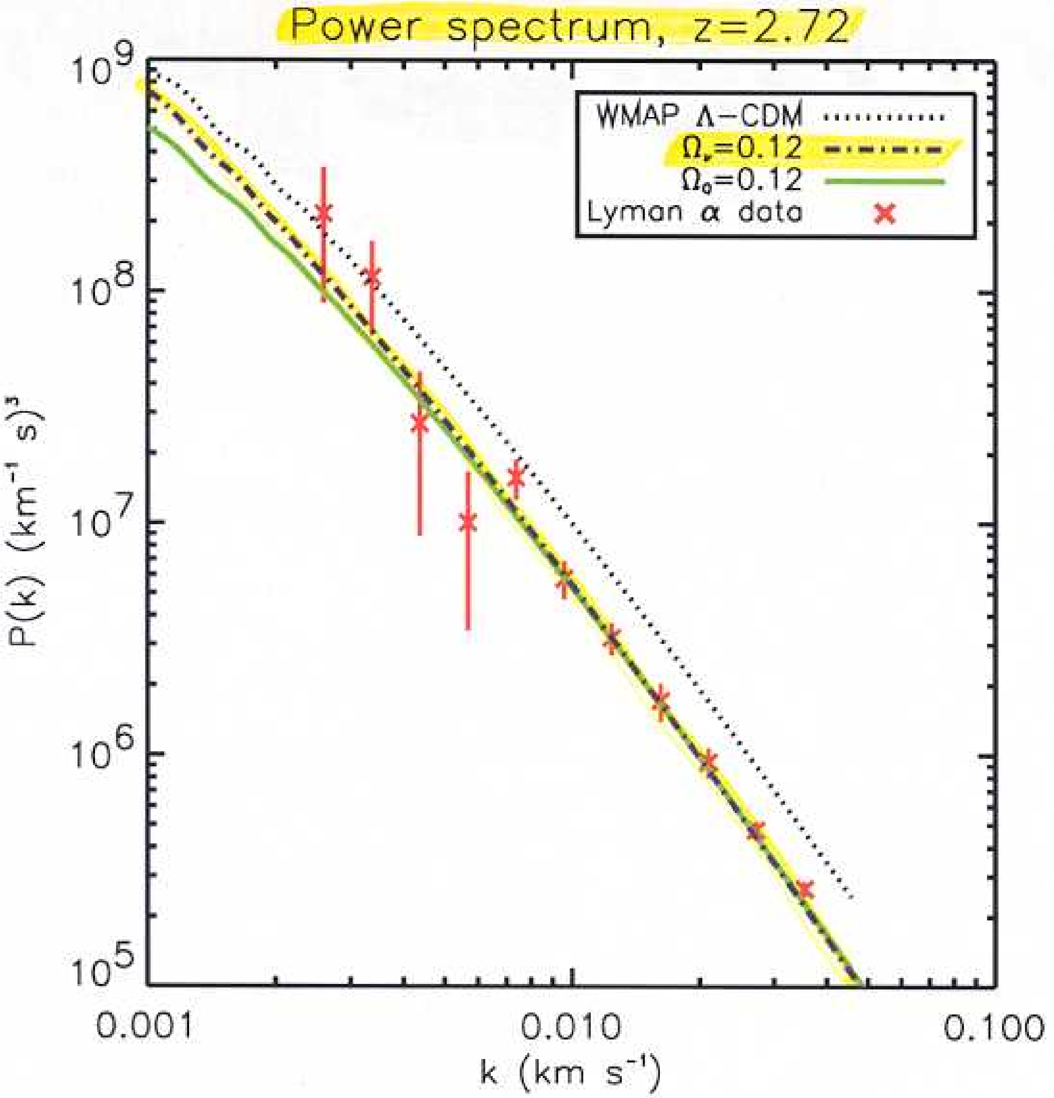
Obtain good fit to large-scale structure data with 3 quasi-degenerate neutrinos of mass ~0.8 eV

$\Rightarrow \Omega_\nu = 0.12$ (NB: Well above WMAP 'bound'!)

and $\Omega_B h^2 = 0.021$ (in agreement with BBN value)

$\Rightarrow$ baryon fraction in clusters of ~11% (acceptable)

and $\sigma_8 = 0.64$ (consistent with weak lensing determination)



... with a bias factor $b \simeq 1/\sigma_8$, can also fit power spectrum of Lyman-alpha forest (if amplitude is reduced by ~1σ calibration uncertainty)
⇒ 20%.

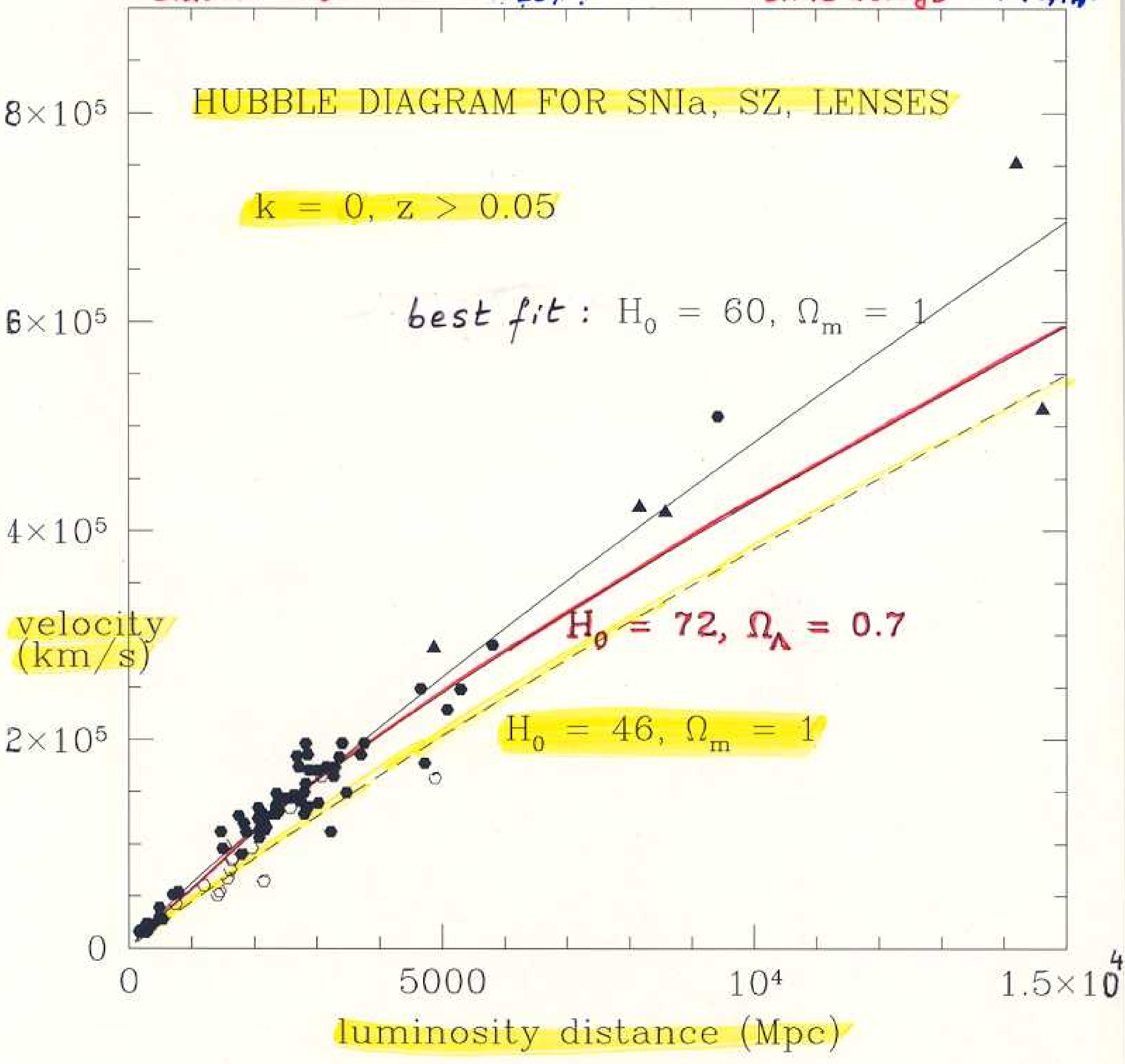
→ in these fits, the optical depth to last scattering is $\tau \simeq 0{\cdot}1$ ... easier to accomodate with our understanding of star formation in CDM cosmogony ...

Blanchard et al (astro-ph/0304237)

$H_0 = 46$ km/s/Mpc is inconsistent with the Hubble key Project value (72±8 km/s/Mpc)

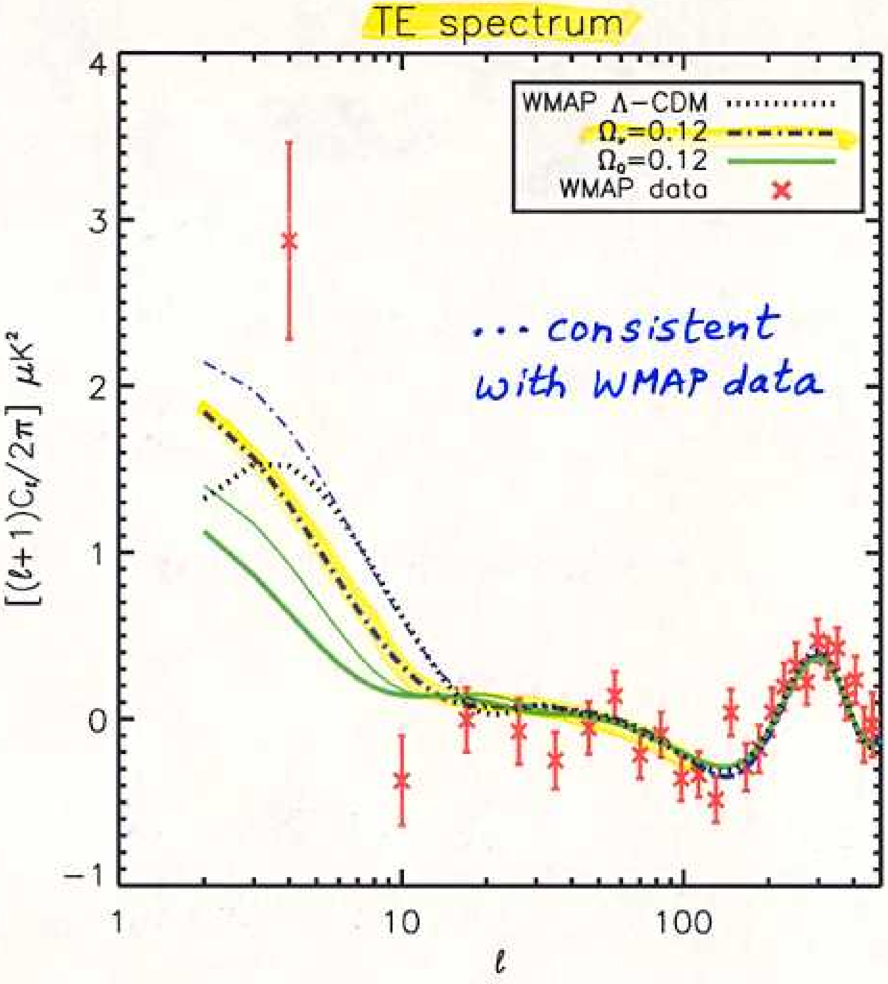
... but not with direct (and deeper) methods:

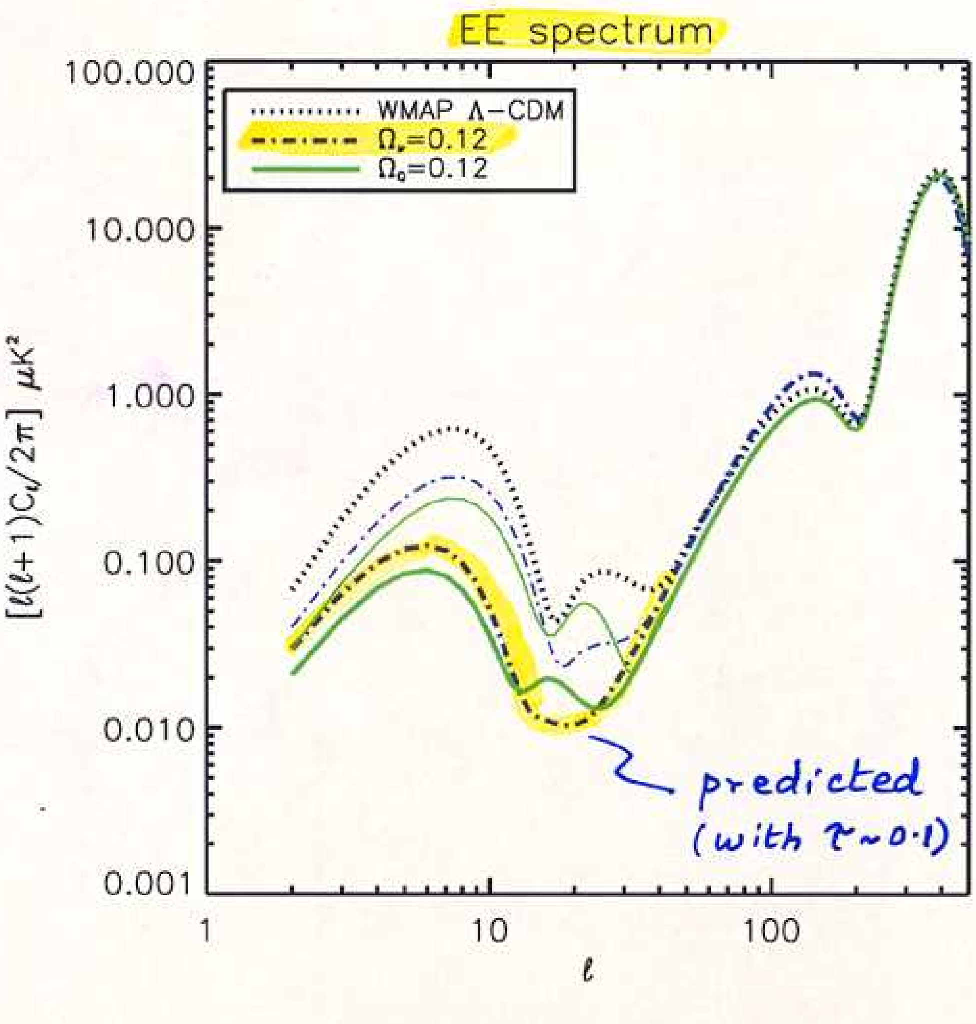
Sunyaev-Zeldovich cluster distances (54±4 km/s/Mpc, −20%?), gravitational lens time delays (48±3±? km/s/Mpc)



→ need further work on the distance scale (e.g. metallicity effects on Cepheid calibration ...)

Blanchard et al. (astro-ph/0304237)


TE spectrum
WMAP Λ−CDM
Ω=0.12
Ω₀=0.12
WMAP data
... consistent with WMAP data
[ℓ(ℓ+1)Cℓ/2π] μK²
4
3
2
1
0
−1
1
10
100
ℓ


EE spectrum
WMAP Λ−CDM
Ω=0.12
Ω₀=0.12
predicted (with τ~0·1)
[ℓ(ℓ+1)Cℓ/2π] μK²
100.000
10.000
1.000
0.100
0.010
0.001
1
10
100
ℓ

 (astro-ph/0311081)

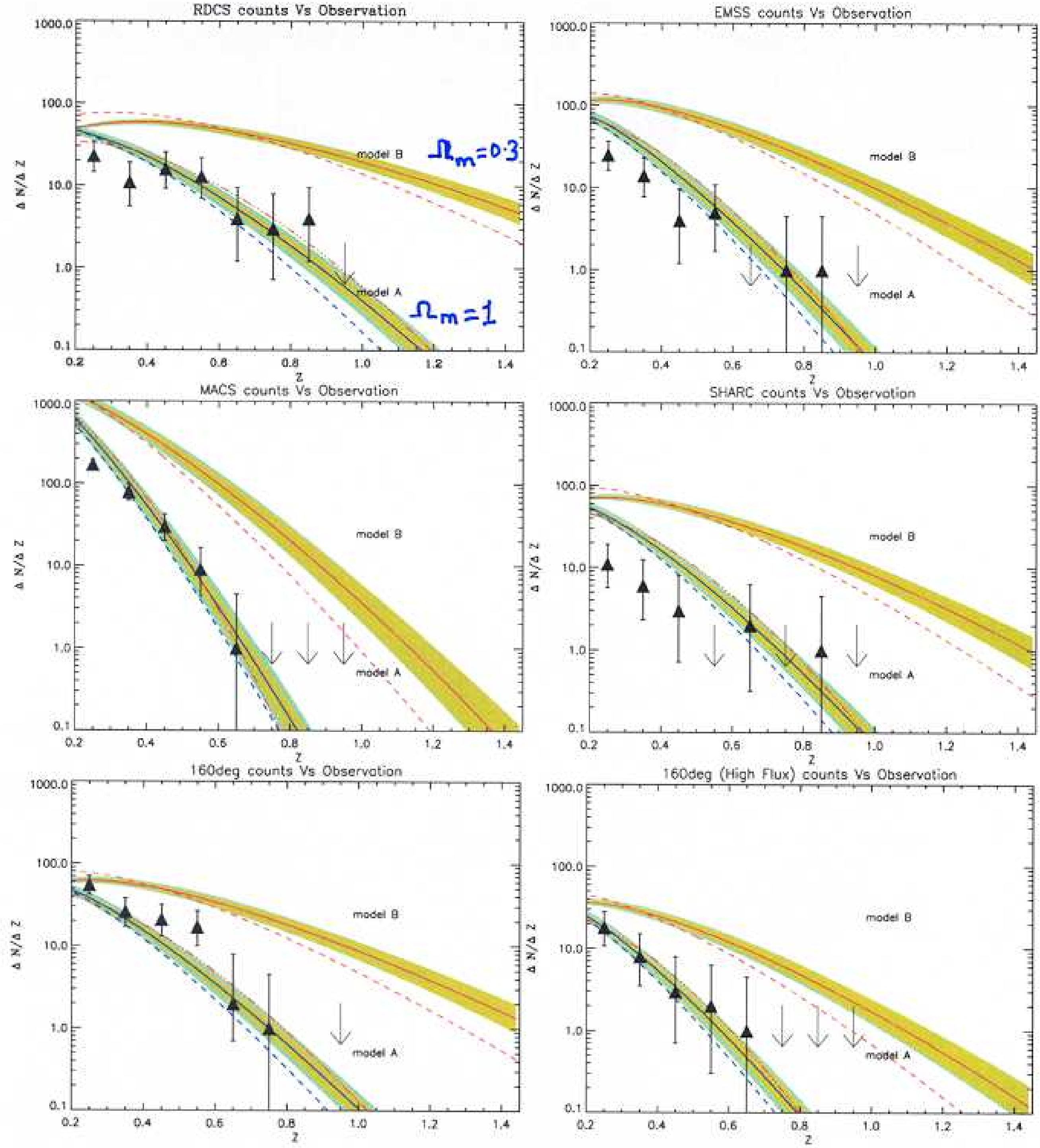


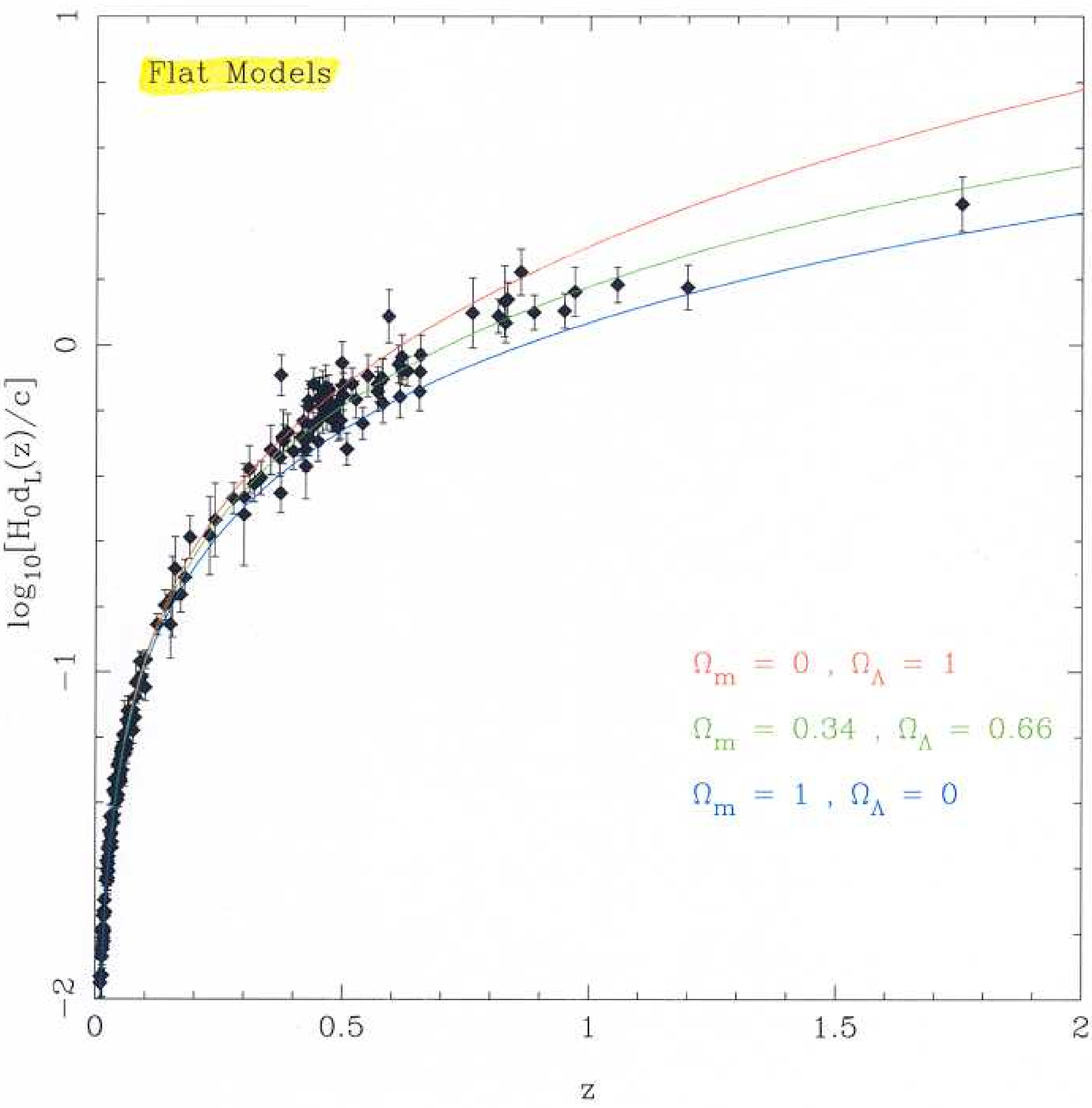
Fig. 2. Theoretical number counts in bins of redshift ($\Delta z = 0.1$) for the different surveys: RDCS, EMSS, SHARC, MACS and 160deg^2. Observed numbers are triangles with 95% confidence interval on the density assuming poissonian statistics (arrows are 95% upper limits). For the 160deg^2 survey we have also examined the counts for the brightest part (160deg^2(high flux) corresponding to fluxes $f_x > 2 \times 10^{-13}$ erg/s/cm^2), in order to show that the excess seen at $z \sim 0.5$ is not due to luminous clusters. The upper (red) curves are the predictions in the concordance model (model B). The lower (blue) curves are for model A (see table 1.). Different $M - T$ are figured: the dashed lines correspond to $T_{15} = 6.5$keV (M98 $M - T$) while the continuous lines are for $T_{15} = 4.$keV, corresponding to virial mass nearly twice larger, close to BN98 normalization. The dark grey (green) area is the uncertainty range from our estimates on the uncertainty in the evolution of the $L - T$ relation while the light grey area is the uncertainty on number counts due to the dispersion on σ_8. The 3-dotted-dashed lines show the predicted counts in the concordance model using $M - T$ relation from Eq. 6 violating the standard scaling with redshift.

Evolution of cluster abundance with redshift indicates a high density universe!

"The indication of $\Omega_\Lambda \neq 0$ from the SNe Ia Hubble diagram is very interesting and important, but on its own the conclusion is susceptible to small systematic effects ..."

Fukugita & Hogan
(Particle Data Group '00)

what has happened since then?



Fit to recent data for 194 SNIa (Tonry et al '03, Barris et al '03) assuming 'standard candle':

$\Omega_m = 0.34 \pm 0.05$

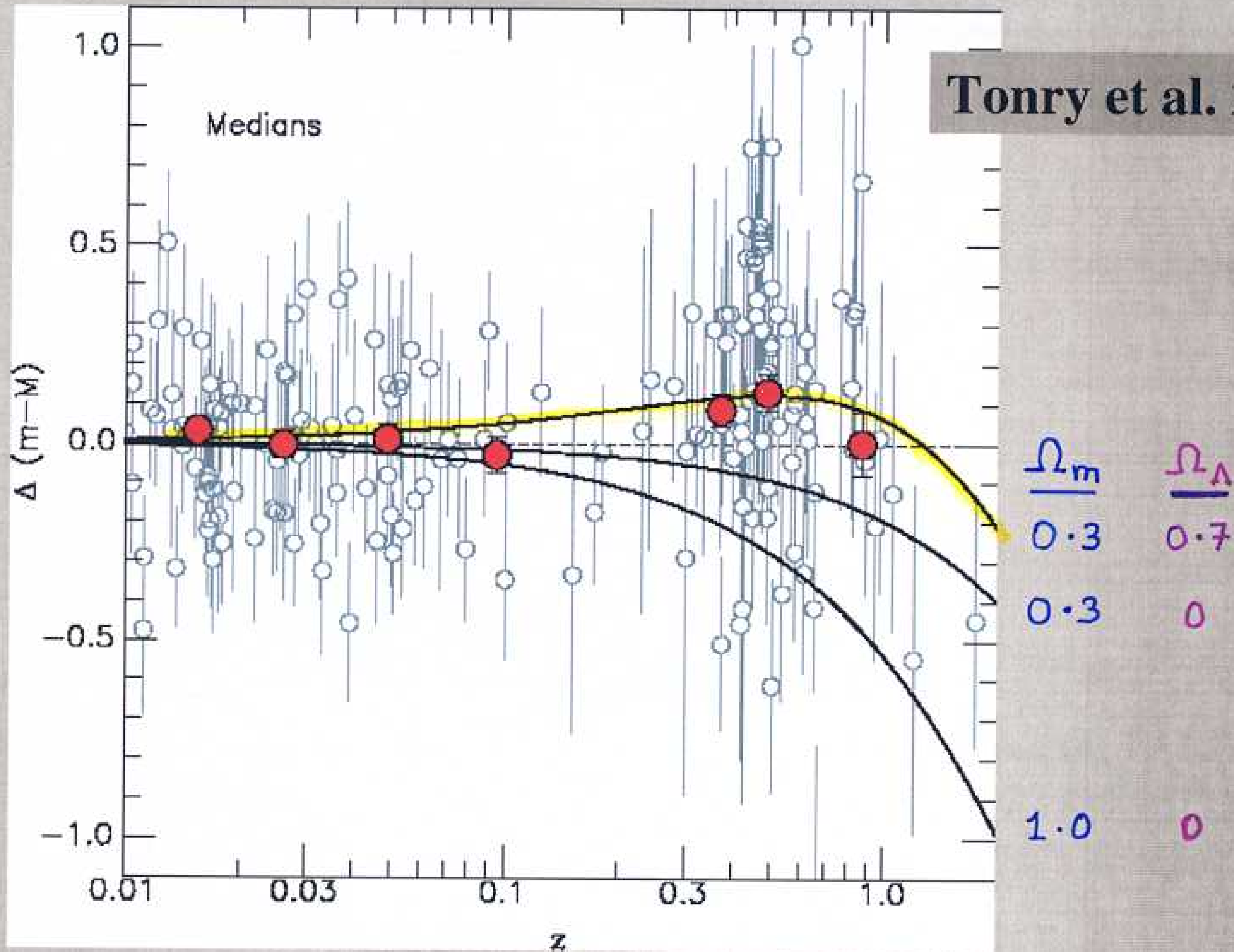
(for $\Omega_m + \Omega_\Lambda = 1$)

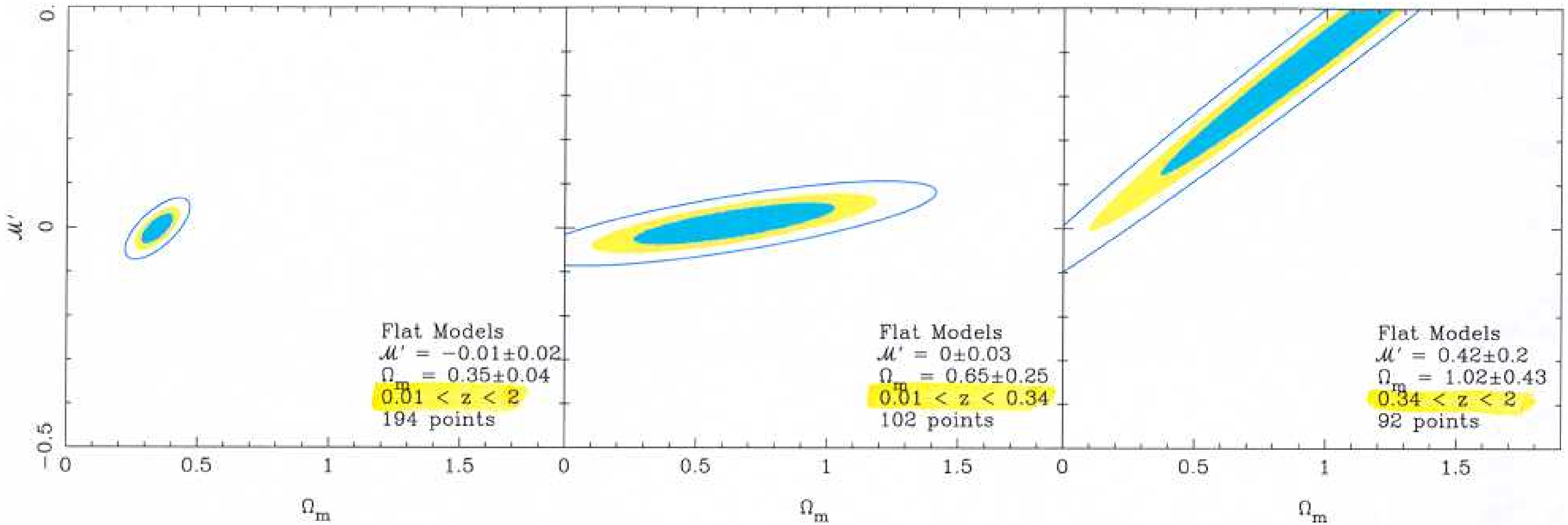
→ the accelerating phase should begin at $z \lesssim 0.34$

Roy Choudhury & Padmanabhan (astro-ph/0311622)

209 SN Ia and medians

Tonry et al. 2003



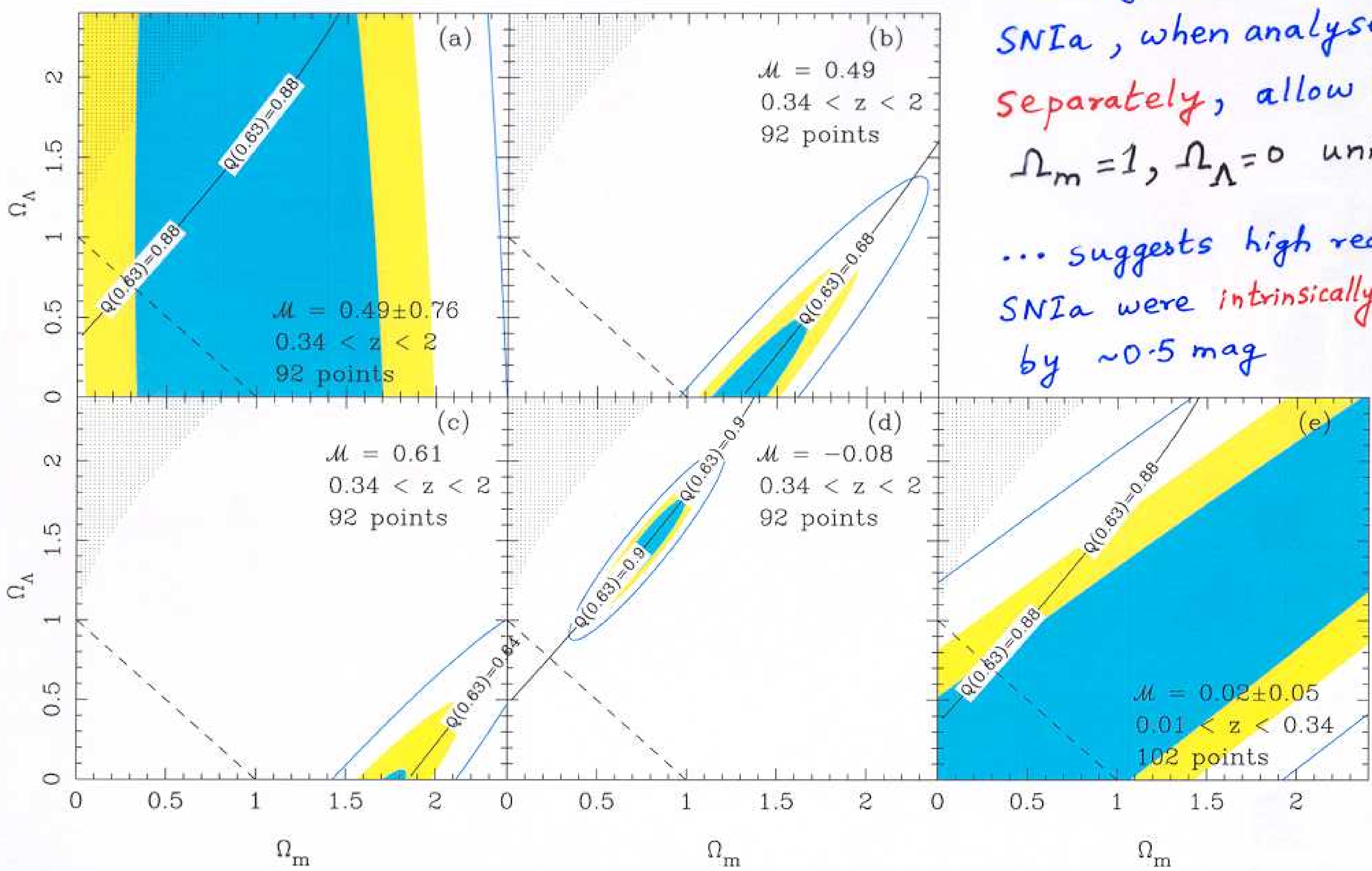


But when the low redshift (102 SNIa @ $z < 0.34$) data is analysed separately, the best-fit is : $\Omega_m = 0.65 \pm 0.25$

The best-fit to the high redshift sample (92 SNIa @ $0.34 < z < 2$) is: $\Omega_m = 1.02 \pm 0.43$ with absolute luminosity dimmer by ~ 0.5 mag

→ need ~200 SNIa at intermediate redshifts to check this (Leibundgut)

Roychoudhury & Padmanabhan (astro-ph/0311622)



The high and low redshift SNIa, when analysed separately, allow a $\Omega_m = 1$, $\Omega_\Lambda = 0$ universe

... suggests high redshift SNIa were intrinsically dimmer by ~0.5 mag

Roychoudhury & Padmanabhan (astro-ph/0311622)

Are SNIa at high redshift intrinsically fainter?

... there is no 'Standard model' for the explosion mechanism (Hillebrandt & Niemeyer, ARAA '00) and little is known about the progenitors observationally

→ some evidence that distant SNIa are bluer ... if this is intrinsic, then derived distances too small

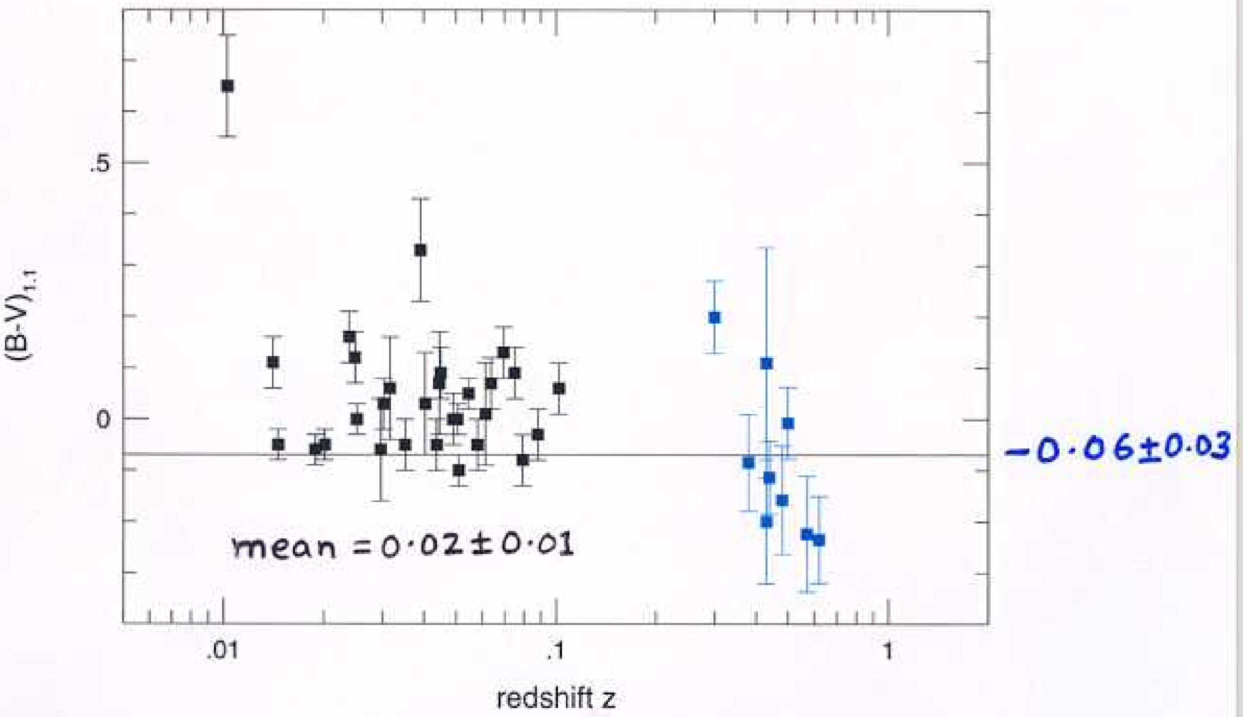
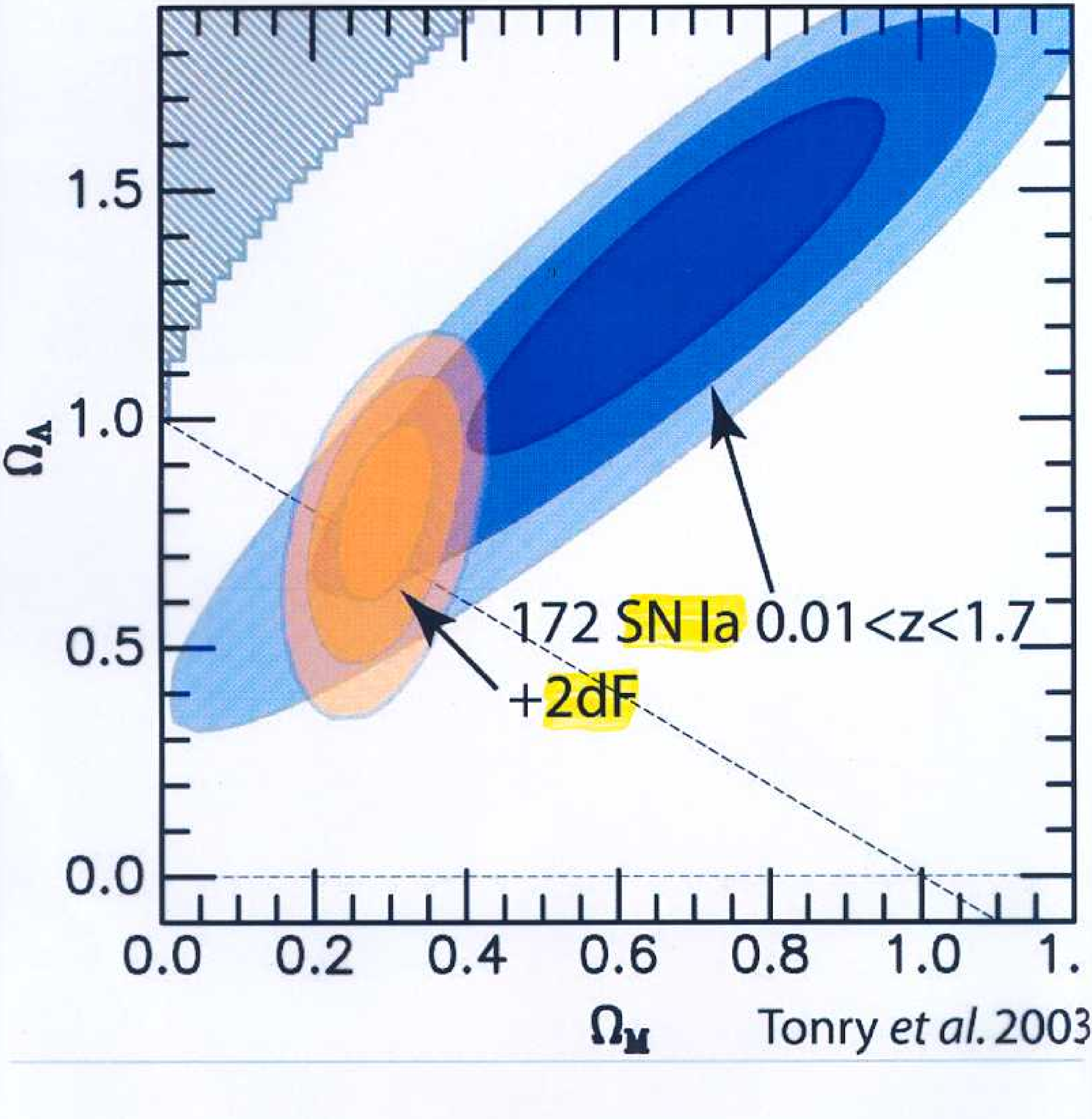


Figure 2: The observed colors of SNe Ia as a function of redshift. The data are from Phillips et al. (1999) for the low-redshift and Riess et al. (1998) for the high-z sample. The line shows the intrinsic color as defined for the nearby SNe Ia in Phillips et al. (1999).

(Leibundgut, ARAA 2001)

distant SNIa will then deviate from correlation between light curve shape and colour seen for nearby SNIa (in high-z SN search but not in SCP!)

... presently there is a ~2σ discrepancy between interpretations of large-scale structure and the SNIa Hubble diagram ...



Nevertheless, it remains conceivable that we have dramatically misinterpreted the data, and the apparent agreement of an $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ cosmology with a variety of observations is masking the true situation. For example, the supernova observations rely on the nature of Type Ia supernovae as "standardizable candles," an empirical fact about low-redshift supernovae which could somehow fail at high redshifts (although numerous consistency checks have confirmed basic similarities between SNe at all redshifts). Given the many other observations, this failure would not be enough to invalidate our belief in an accelerating universe; however, we could further imagine that these other methods are conspiring to point to the wrong conclusion. This point of view has been taken by Blanchard et al. (2003), who argue that a flat matter-dominated ($\Omega_M = 1$) universe remains consistent with the data. To maintain this idea, it is necessary to discard the supernova results, to imagine that the Hubble constant is approximately 46 km/sec/Mpc (in contrast to the Key Project determination of 70 ± 7 km/sec/Mpc, Freedman et al. 2001), to interpret data on clusters and large-scale structure in a way consistent with $\Omega_M = 1$, to relax the conventional assumption that the power spectrum of density fluctuations can be modeled as a single power law, and to introduce some source beyond ordinary cold dark matter (such as massive neutrinos) to suppress power on small scales. To most workers in the field this conspiracy of effects seems (even) more unlikely than an accelerating universe.

Carroll
(astro-ph/0310342)

... so where do we go from here?

'That depends a good deal on where you want to get to,' said the Cat.

'I don't much care where--' said Alice.

'Then it doesn't matter which way you go,' said the Cat.

'--so long as I get *somewhere*,' Alice added as an explanation.

'Oh, you're sure to do that,' said the Cat, 'if you only walk long enough.'

Alice felt that this could not be denied, so she tried another question. 'What sort of people live about here?'

'In *that* direction,' the Cat said, waving its right paw round, 'lives a Hatter: and in *that* direction,' waving the other paw, 'lives a March Hare. Visit either you like: they're both mad.'

"Cosmologists are often wrong, but never in doubt"
(Landau)

... we may be "not even wrong" (Pauli)
but we are not without doubt!
⋮
exciting times ahead