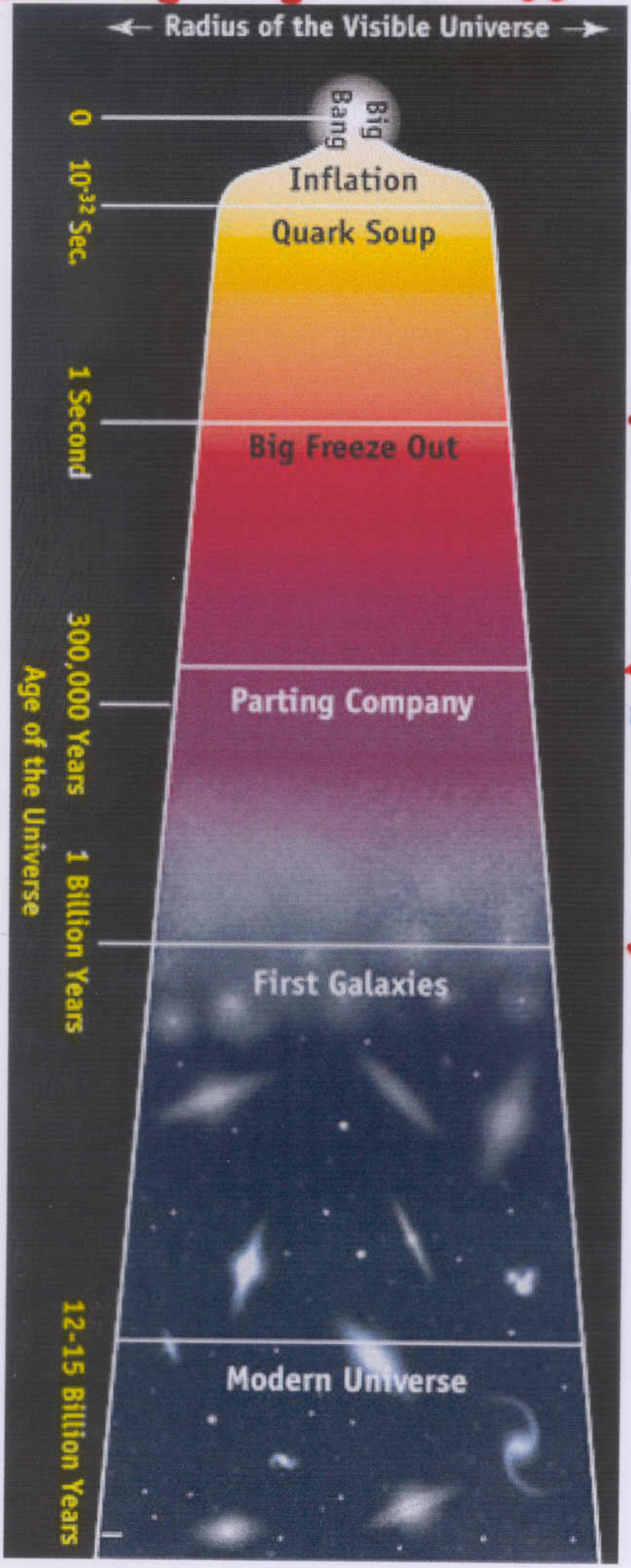
The Big Bang Cosmology



initial singularity?
homogeneity/isotropy?
phase transitions?
baryogenesis?
dark matter?
dark energy?

nucleosynthesis of light elements

decoupling of microwave background

formation of structure

The Standard Model (of cosmology ⊕ particle physics) is remarkably consistent with

- The Hubble expansion of galaxies
- The Cosmic Microwave background spectrum (and anisotropy)
- The inferred primordial abundances of D, ^{4}He, ^{7}Li
- The power spectrum of large-scale structure

when supplemented with these initial conditions:

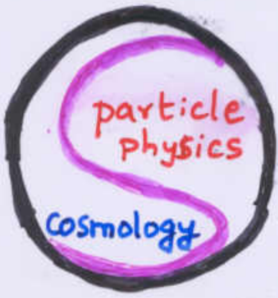
➡ a baryon asymmetry, $(n_B - n_{\bar{B}})/n_\gamma \sim 5\times10^{-10}$

➡ collisionless cold dark matter with $\Omega_m \gtrsim 0{\cdot}3$

➡ scale-invariant adiabatic density fluctuations (extending to super-horizon scales) with $\delta\rho/\rho \sim 10^{-5}$ in an otherwise homogeneous/isotropic universe

➡ a possible dark energy component with $\Omega_\Lambda \lesssim 0{\cdot}7$

→ this imposes interesting restrictive constraints on all extensions of the Standard Model (supersymmetry/supergravity, string/M-/brane-world theory) ... which must also yield the initial conditions



String theory ↔ Cosmology

… has not yet solved problems concerning

→ initial singularity
→ cosmological constant
→ homogeneity/isotropy
⋮

⋮

but created new problems for cosmology

→ dilaton stabilization
→ moduli domination
→ vacuum selection
⋮

in turn cosmology has struck back with the 'discovery' of

→ vacuum energy

"The existence of a future event horizon implies that the objects that string theory normally calculates, such as S-matrix elements, have no meaning …"

Cosmology in Wonderland

Subir Sarkar

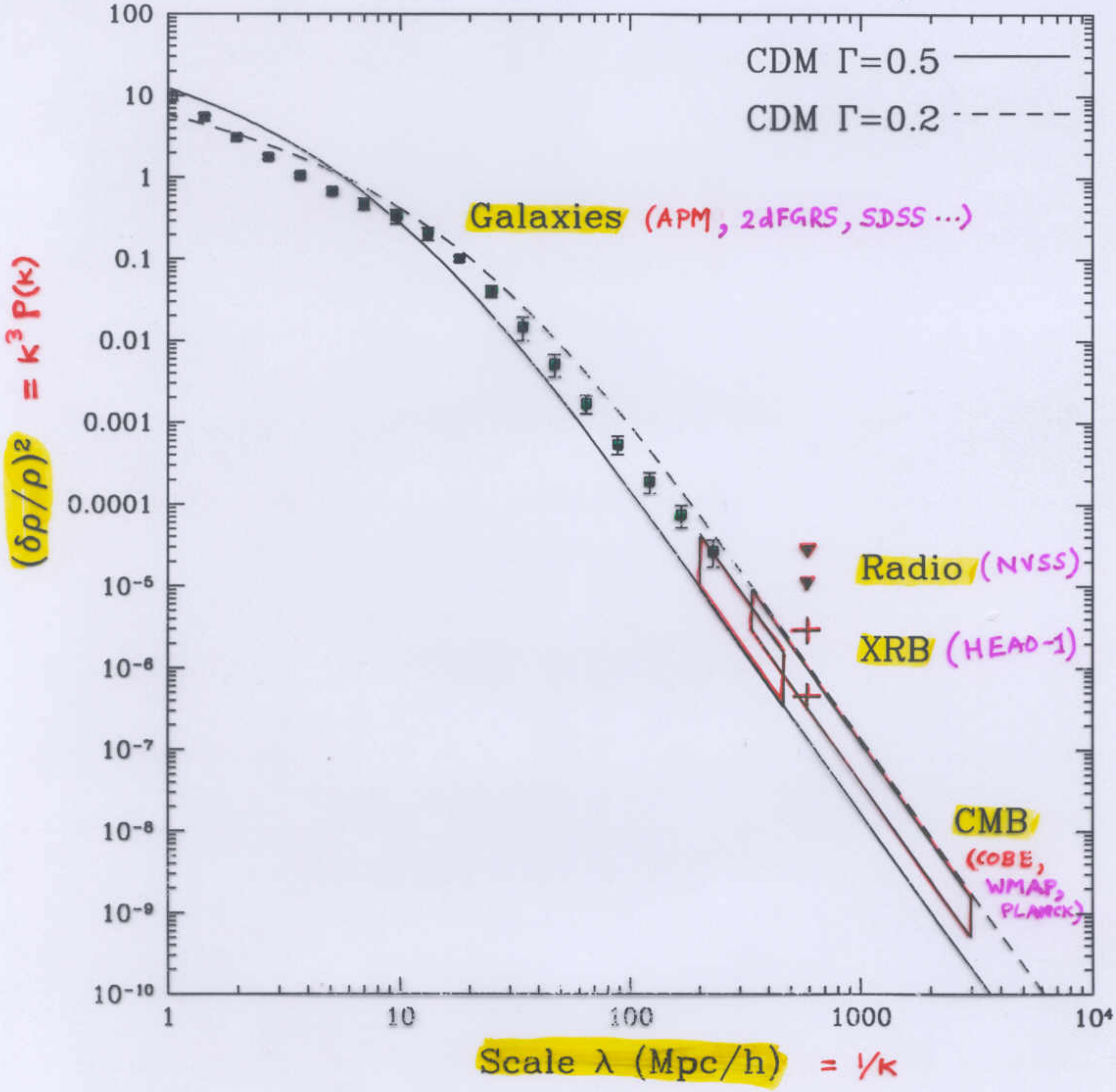
Oxford University

- ... 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 large-scale smoothness of the universe

... allows description using Friedman-Robertson-Walker models, evolving from a hot Big Bang (Lemaître)

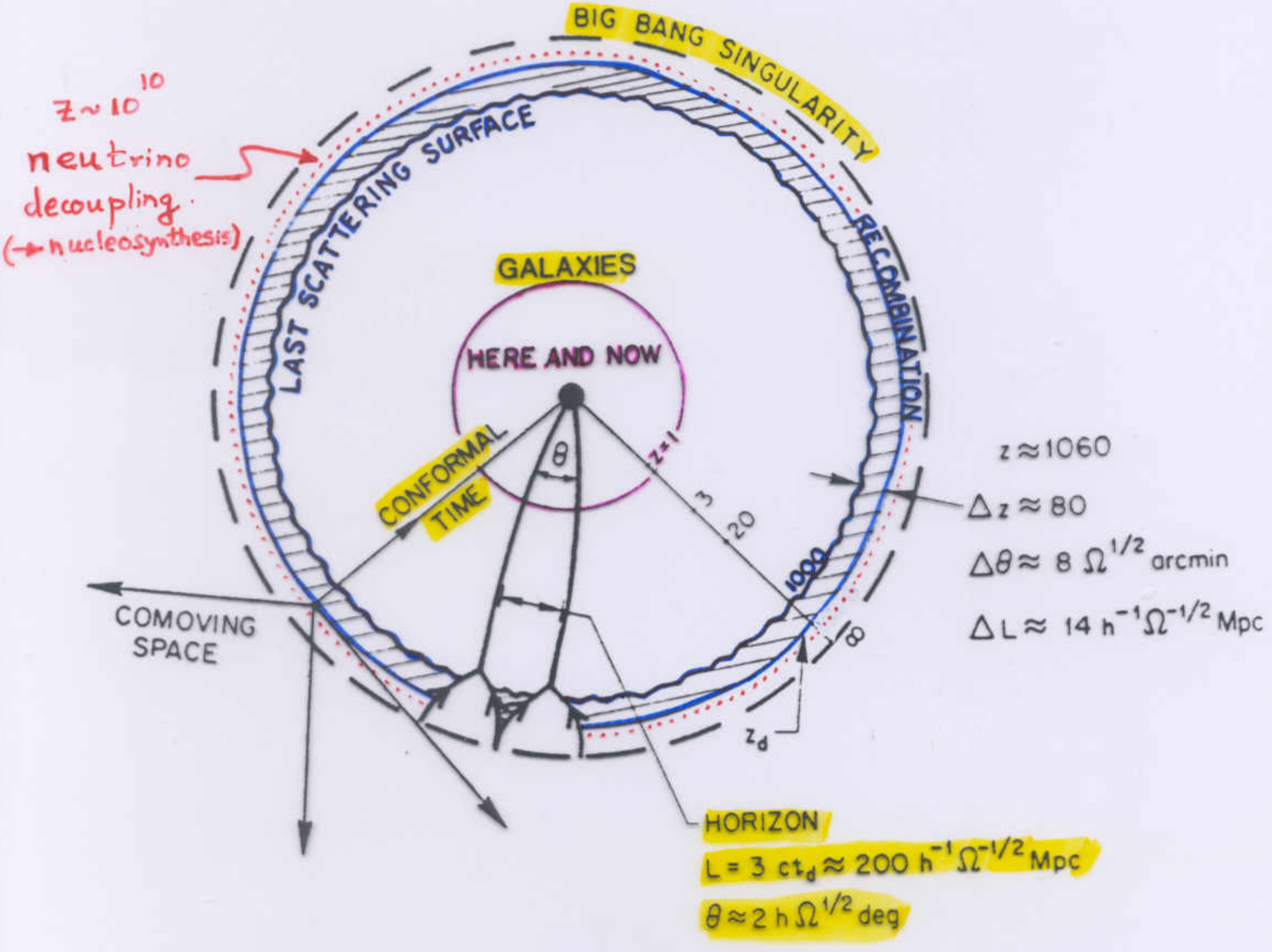


Remaining concerns : fractal structure of galaxy distribution , large-scale topology , ...

Wu, Lahav, Rees
(astro-ph/9804062)

The standard cosmological model

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



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

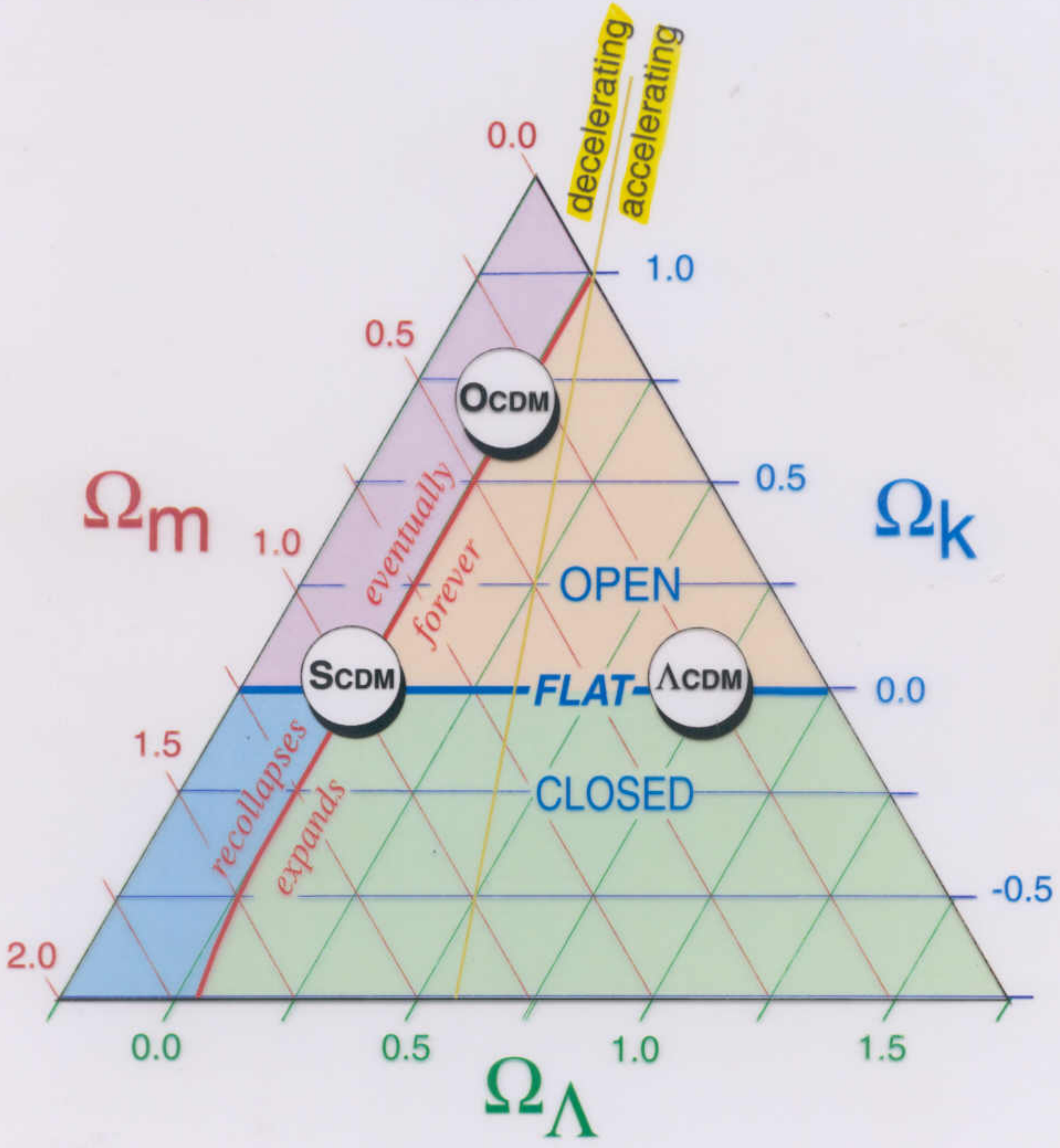
$$\Rightarrow \quad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} = H_0^2\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

The Cosmic Triangle

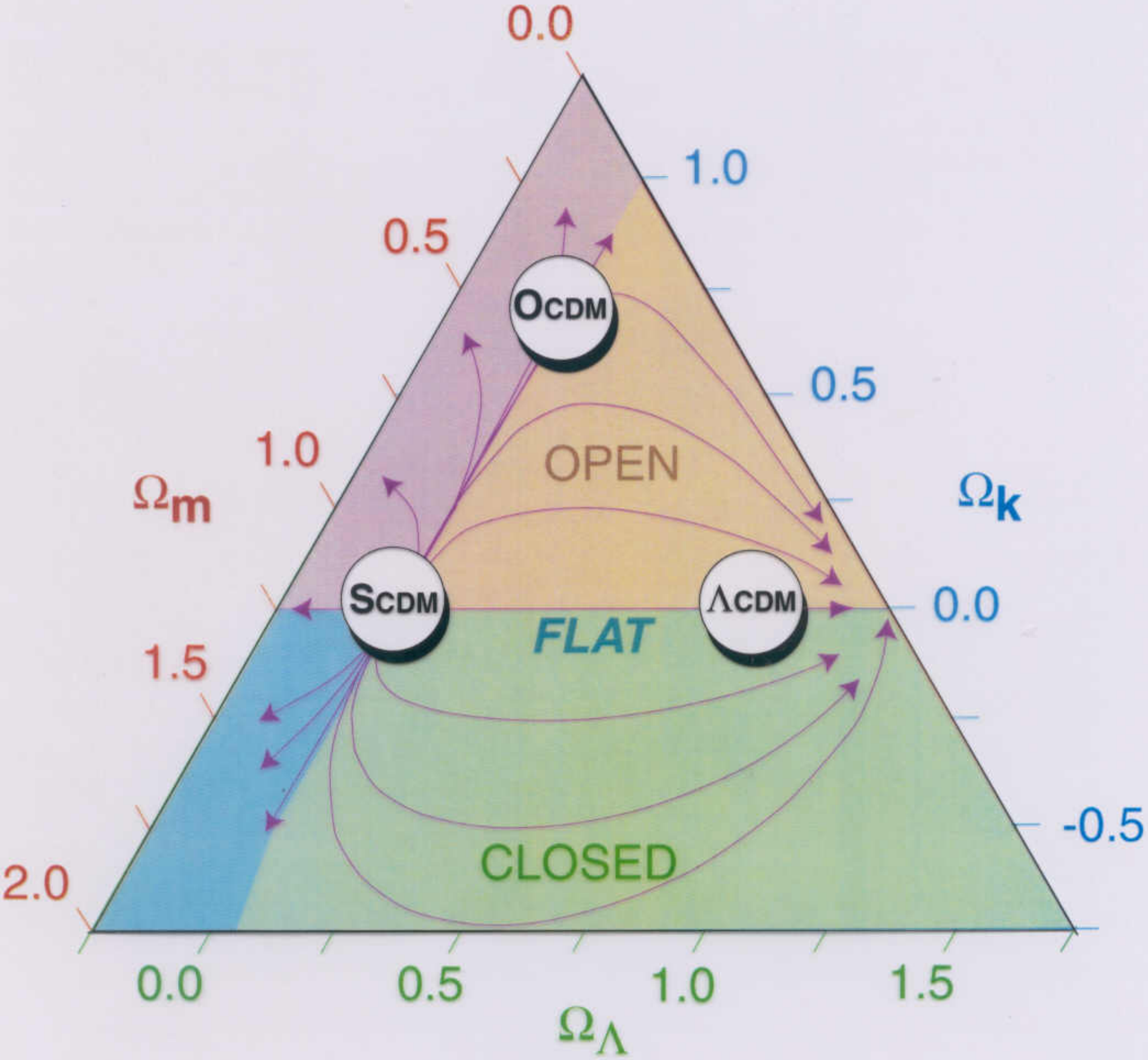
Sum rule: $\Omega_m + \Omega_K + \Omega_\Lambda = 1$

$\wr$ $\qquad$ $\wr$ $\qquad$ $\wr$

$\rho_m / \frac{3H_0^2}{8\pi G}$ $\qquad$ $-k/a_0^2 H_0^2$ $\qquad$ $\Lambda/3H_0^2$



Bahcall et al.
(astro-ph/9906463)



$\Omega_m = 1$ is an unstable critical point

$\Omega_\Lambda = 1$ is a stable critical point

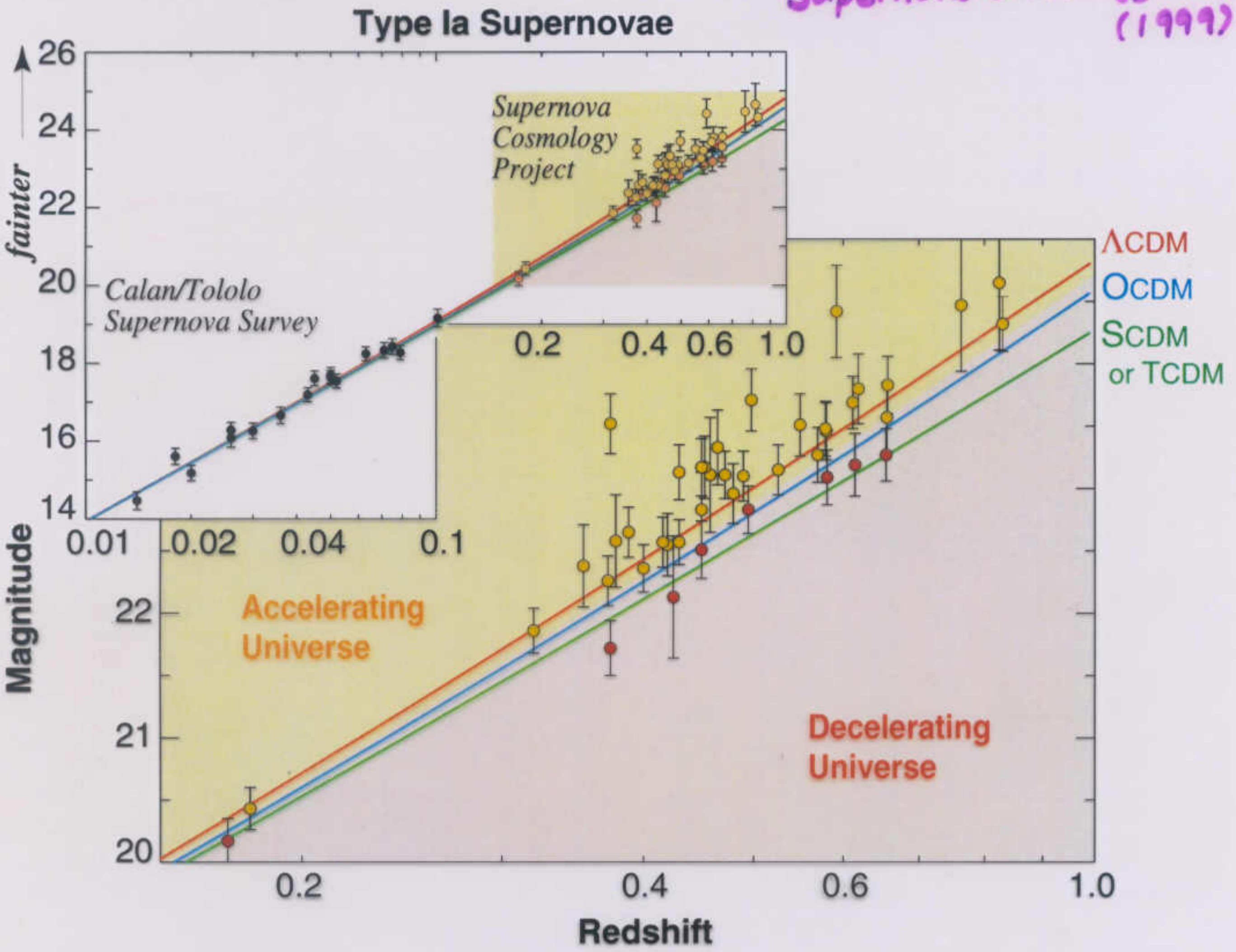
... distant SN Ia appear fainter than a "standard candle" in a freely coasting universe

$\Rightarrow$ 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 ... if SN Ia are 'standard candles'

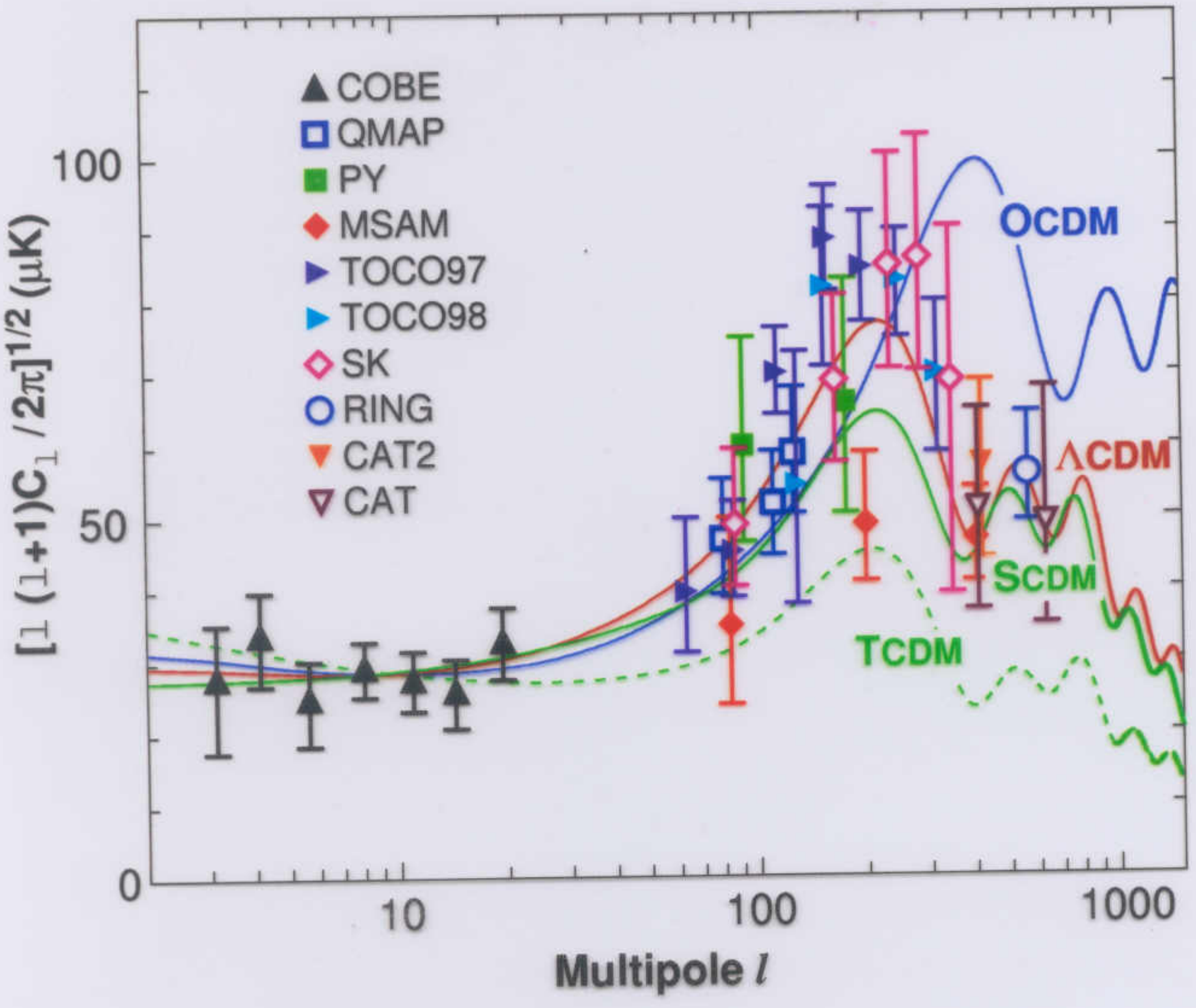
$$0.8\,\Omega_m - 0.6\,\Omega_\Lambda = -0.2 \pm 0.1$$

Bahcall et al

(astro-ph/0002310)

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

$$\Omega_K \simeq 0{\cdot}00 \pm 0{\cdot}3$$

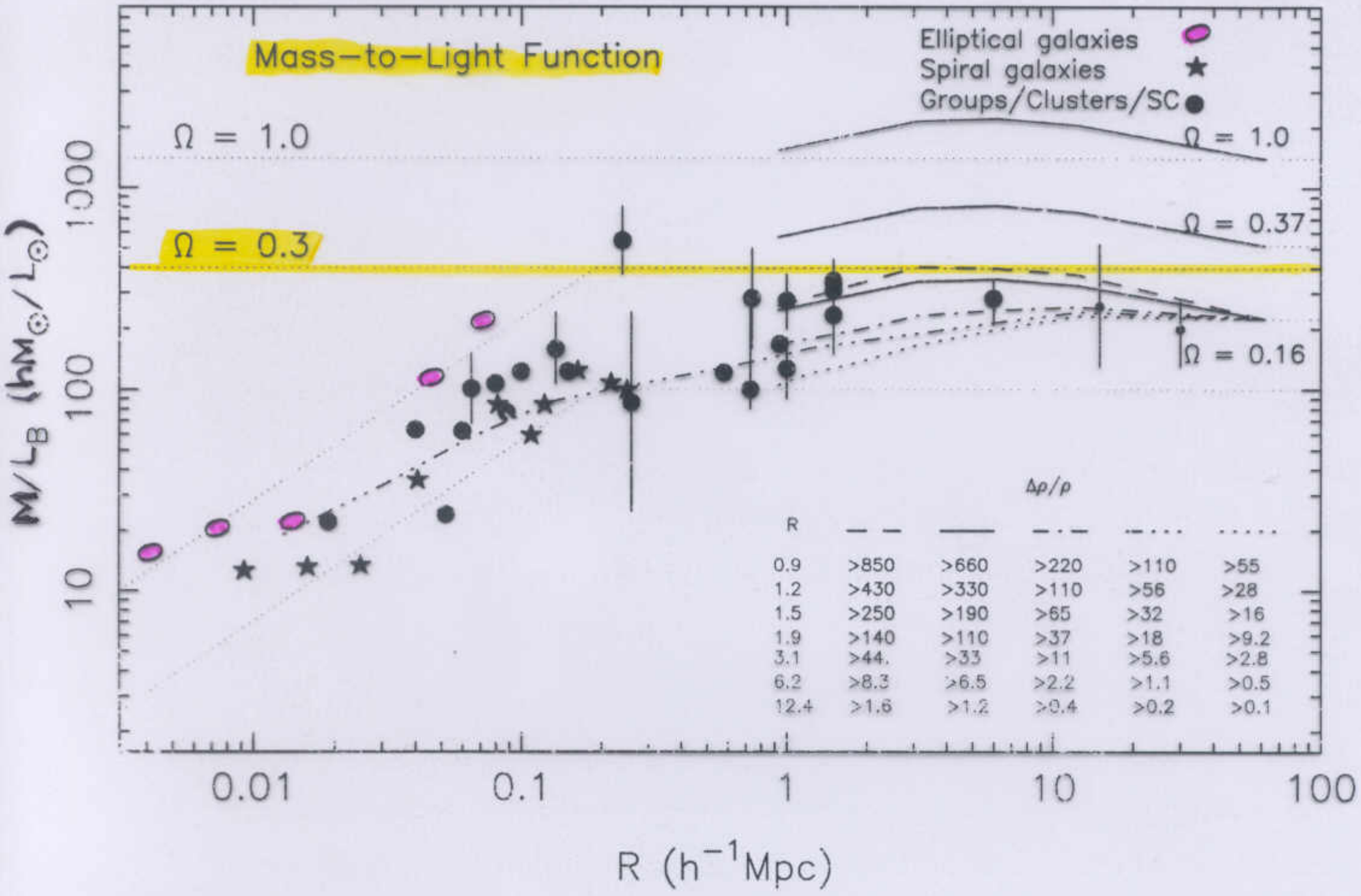


... assuming the primordial fluctuations to be adiabatic

Bahcall et al
(astro-ph/9906463)

But

... dynamical measurements of clustered matter indicate $\Omega_m \lesssim 0{\cdot}3$



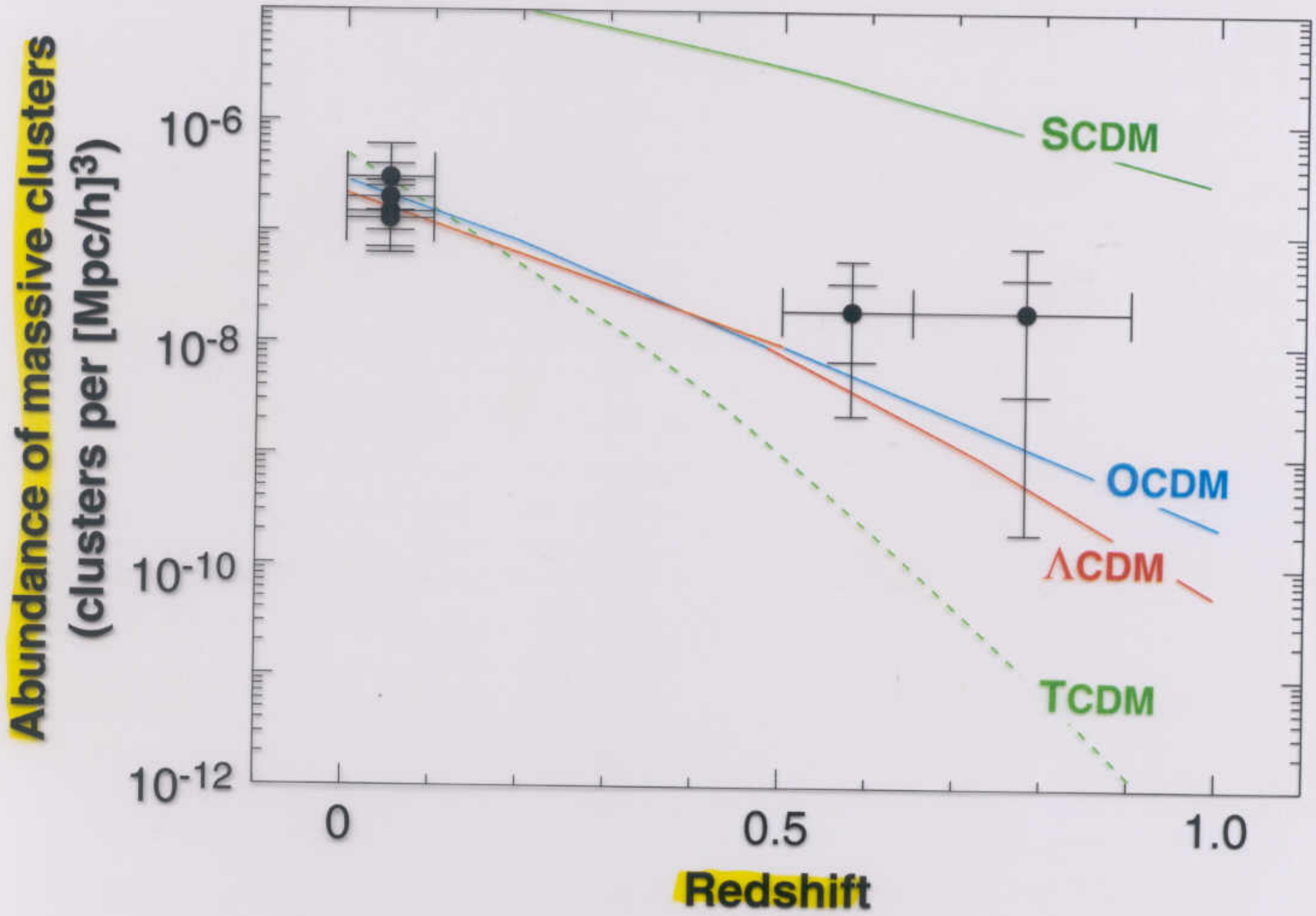
	Δρ/ρ				
R	— —	——	—·—	—···	·····
0.9	>850	>660	>220	>110	>55
1.2	>430	>330	>110	>56	>28
1.5	>250	>190	>65	>32	>16
1.9	>140	>110	>37	>18	>9.2
3.1	>44.	>33	>11	>5.6	>2.8
6.2	>8.3	>6.5	>2.2	>1.1	>0.5
12.4	>1.6	>1.2	>0.4	>0.2	>0.1

comparison with n-body simulations indicate

$$\Omega_m = 0{\cdot}16 \pm 0{\cdot}05$$

Bahcall et al
(astro-ph/0002310)

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

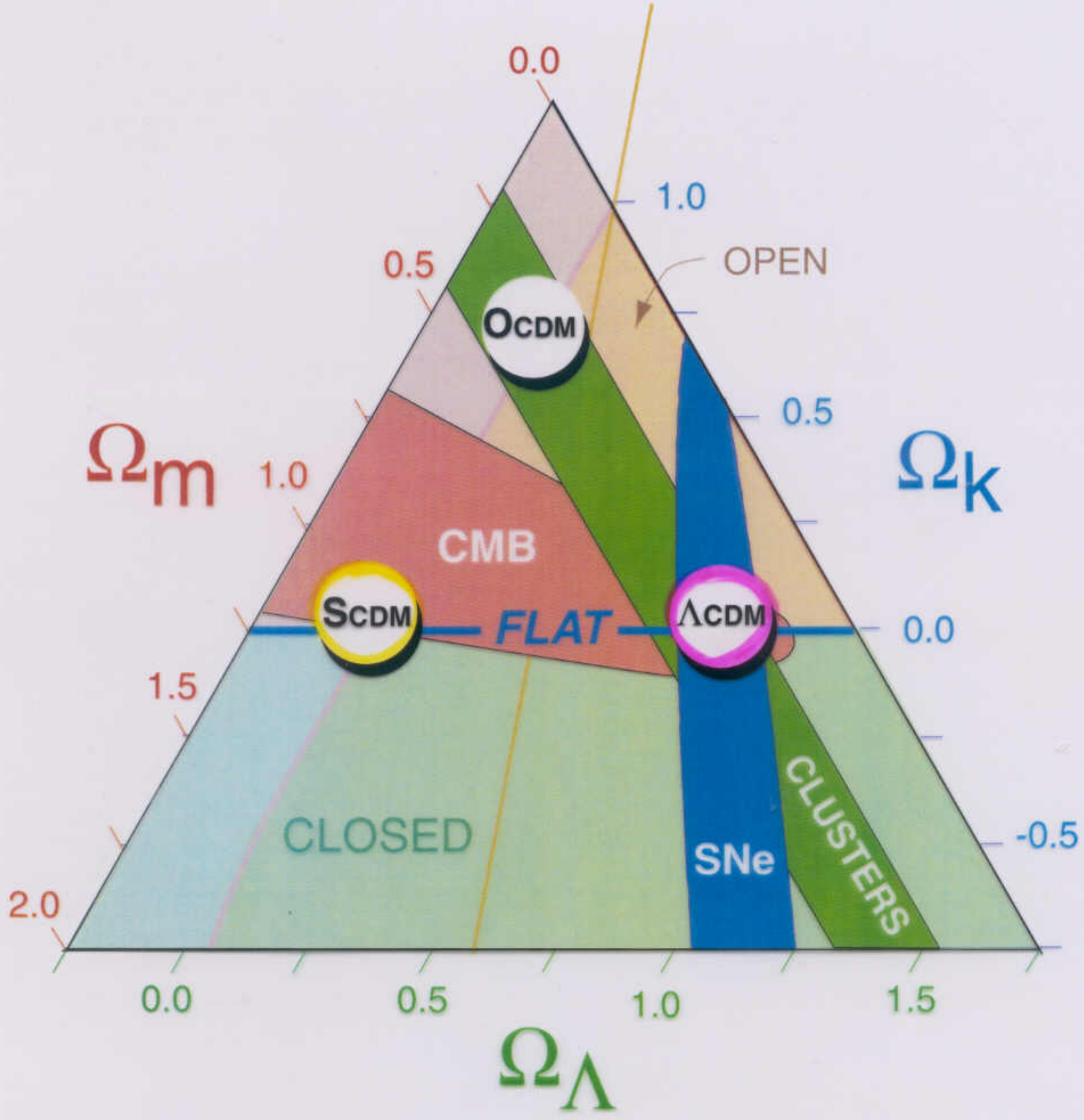


a high density ($\Omega_m \simeq 1$) universe is however allowed if the primordial spectrum of density fluctuations is, e.g., 'tilted' below a scale-invariant form

Bahcall et al.
(astro-ph/0002310)

... combining these observations indicates

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



"Discovery of the century"?

Bahcall et al
(astro-ph/0002310)

"What I say three times is true"

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

- 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)

$\oplus$

- 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
- 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

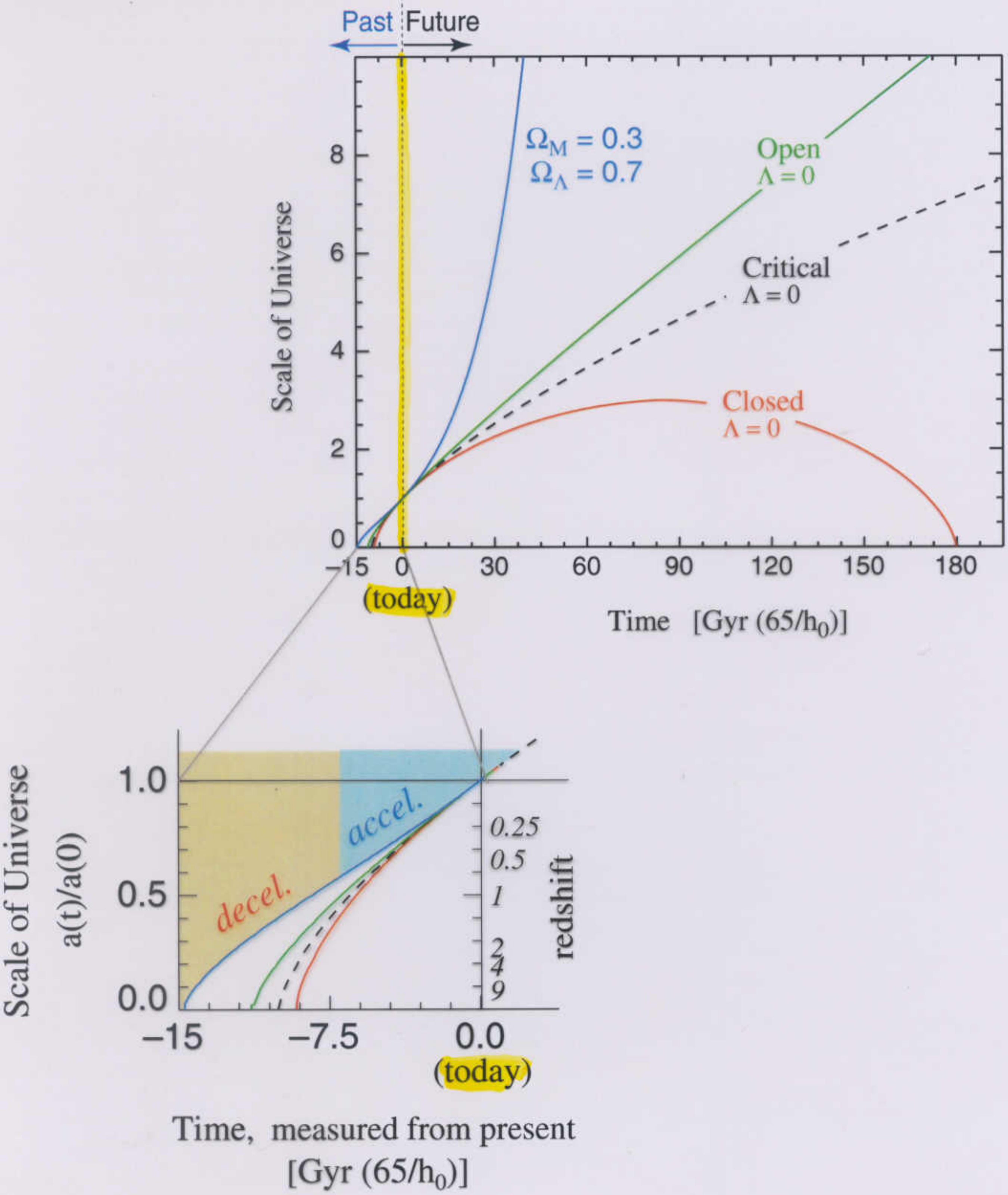
Situation so bad that 'anthropic' arguments have begun to be invoked!

When a physicist reads a paper by a typical astronomer, he finds an unfamiliar style in the treatment of uncertainties and errors. . . . The authors are apparently unwilling to state precisely the odds that their number is correct, although they have pointed out very carefully the many sources of error, and although it is quite clear that the error is a considerable fraction of the number. The evil is that often other cosmologists or astrophysicists take this number without regard to the possible error, treating it as an astronomical observation as accurate as the period of a planet. . . .

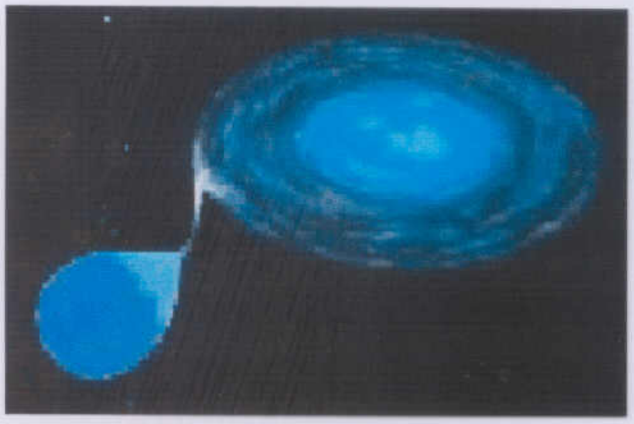
[Lectures on Gravitation, California Institute of Technology]

R. P. Feynman

Expansion History of the Universe



Type Ia Supernovae as Standardizable Candles



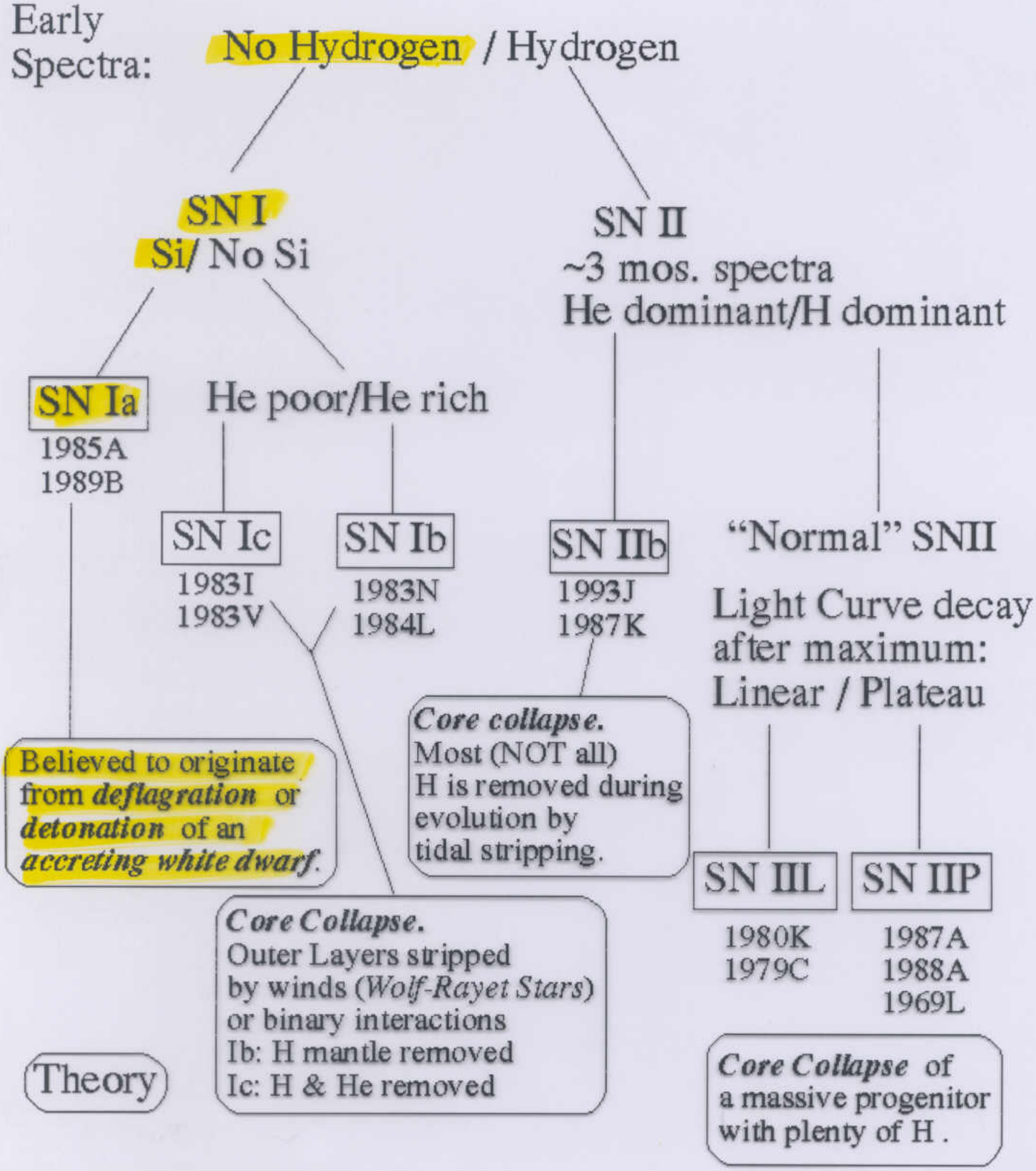
A white dwarf accretes mass until it surpasses the Chandrasekhar limit, and explodes into a SN Ia (or so we believe). → several other models

Peak luminosities are *almost* the same for all SNe Ia, although not quite. → scatter by ~50%

Phillips (1993) showed that there is a one-parameter family of SNe Ia, in which peak luminosity is monotonically related to decline rate of the light curve. (After Pskovskii 1977)

Brighter ⇔ slower decline
Dimmer ⇔ faster decline

Taxonomy of Supernovae



Early Spectra: No Hydrogen / Hydrogen

SN I
Si/ No Si

SN Ia
1985A
1989B

Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf***.

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

Core Collapse.
Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

SN II
~3 mos. spectra
He dominant/H dominant

SN IIb
1993J
1987K

Core collapse.
Most (NOT all) H is removed during evolution by tidal stripping.

"Normal" SNII

Light Curve decay after maximum:
Linear / Plateau

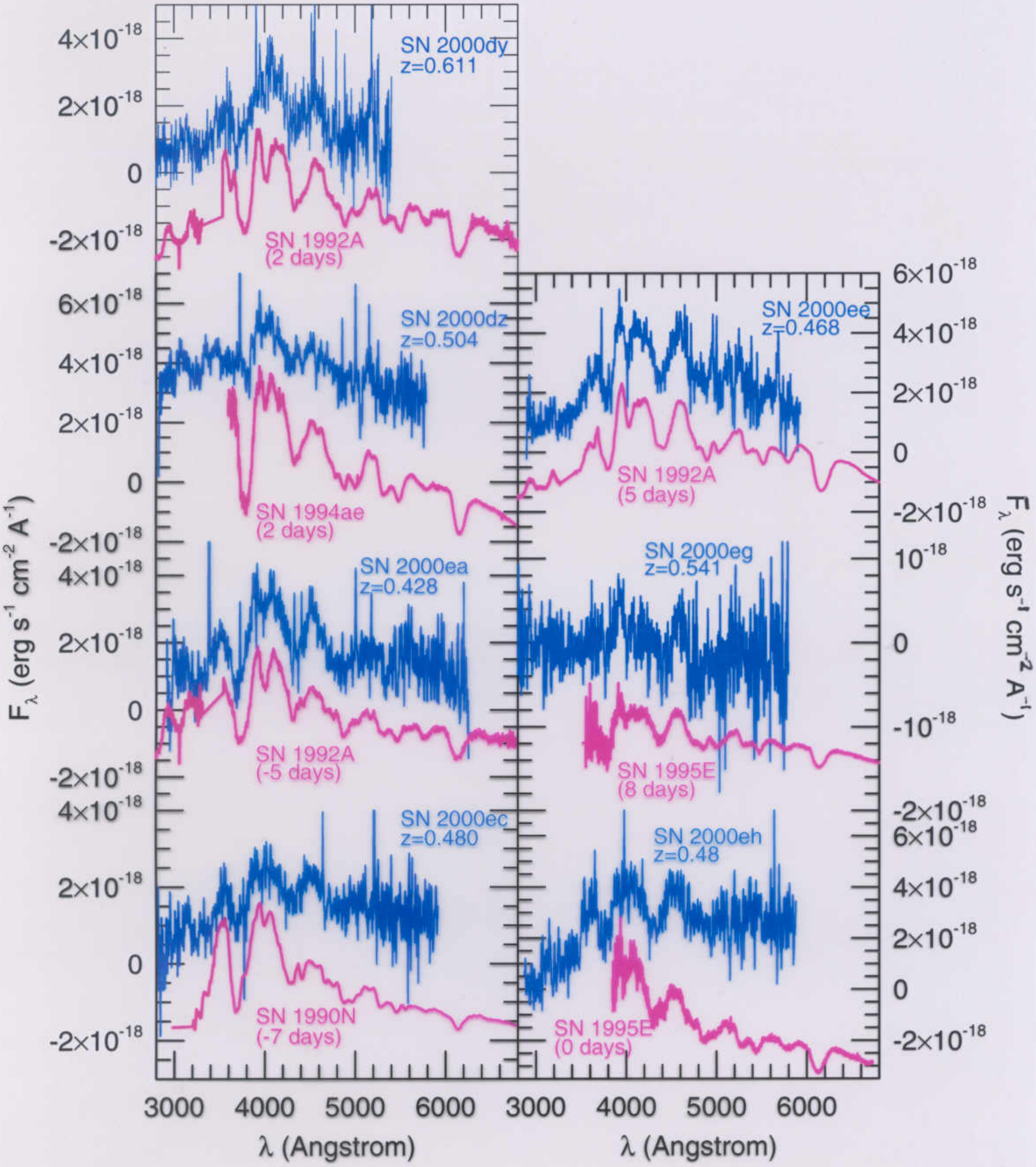
SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

Core Collapse of a massive progenitor with plenty of H .

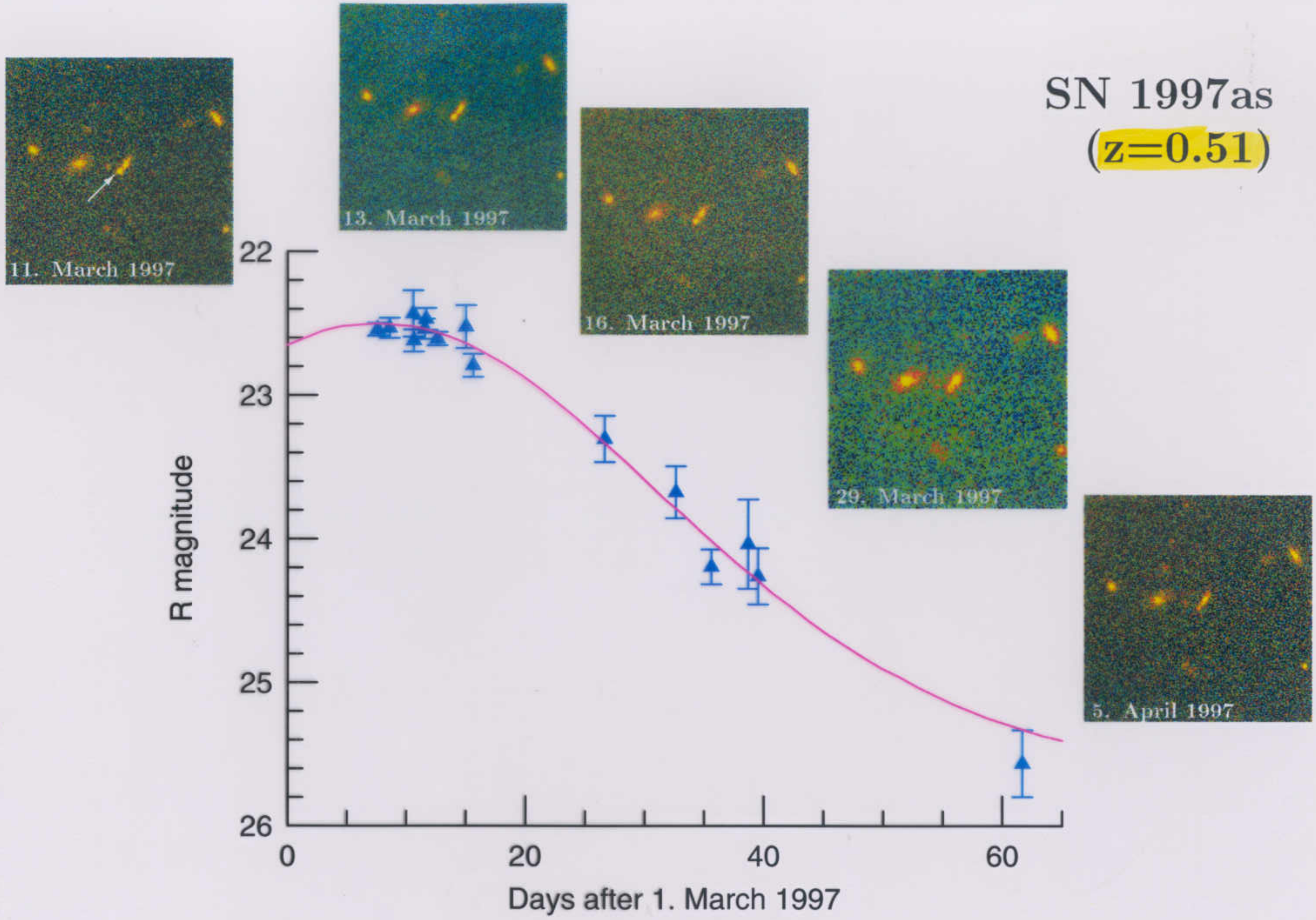
Theory

Distant SNIa have spectra (near peak) similar to nearby ones ...



(Leibundgut 2001)

SN 1997as
(z=0.51)



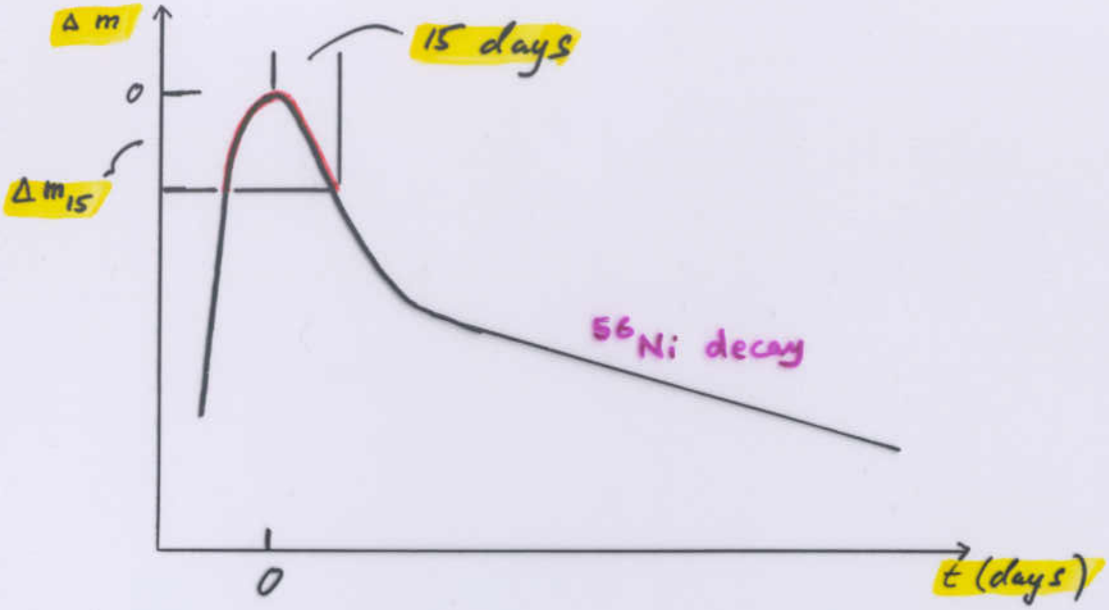
$$m - M = 5 \log\left(\frac{D_L}{Mpc}\right) + 25$$

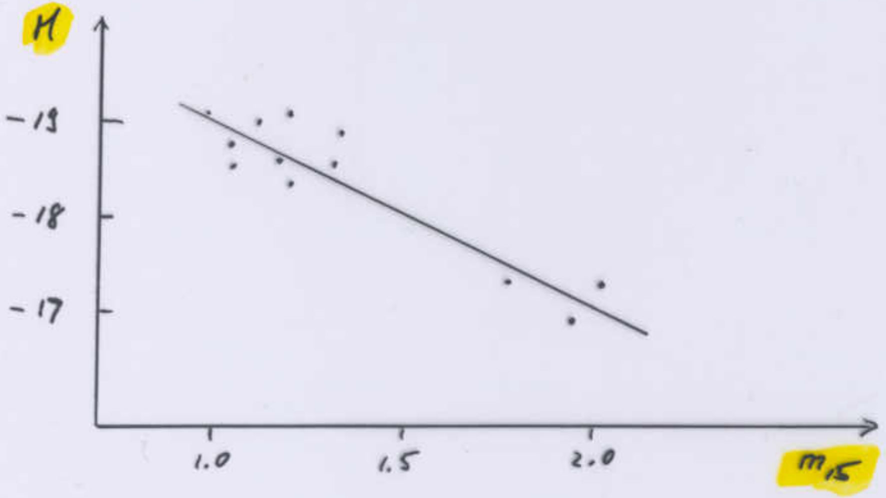
apparent magnitude

absolute magnitude

(Leibundgut 2001)

Mark Phillips

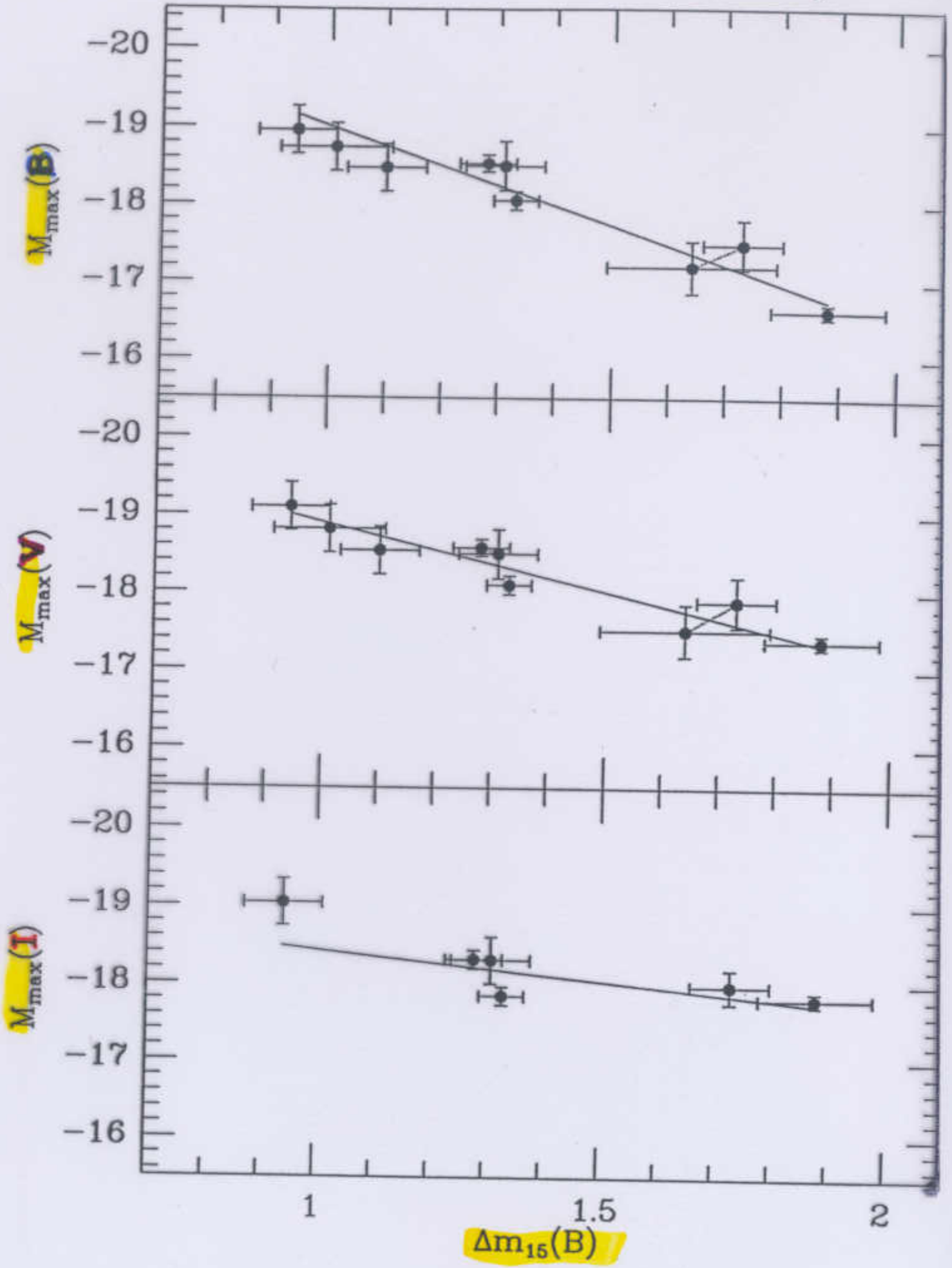




Light curves are non-uniform!

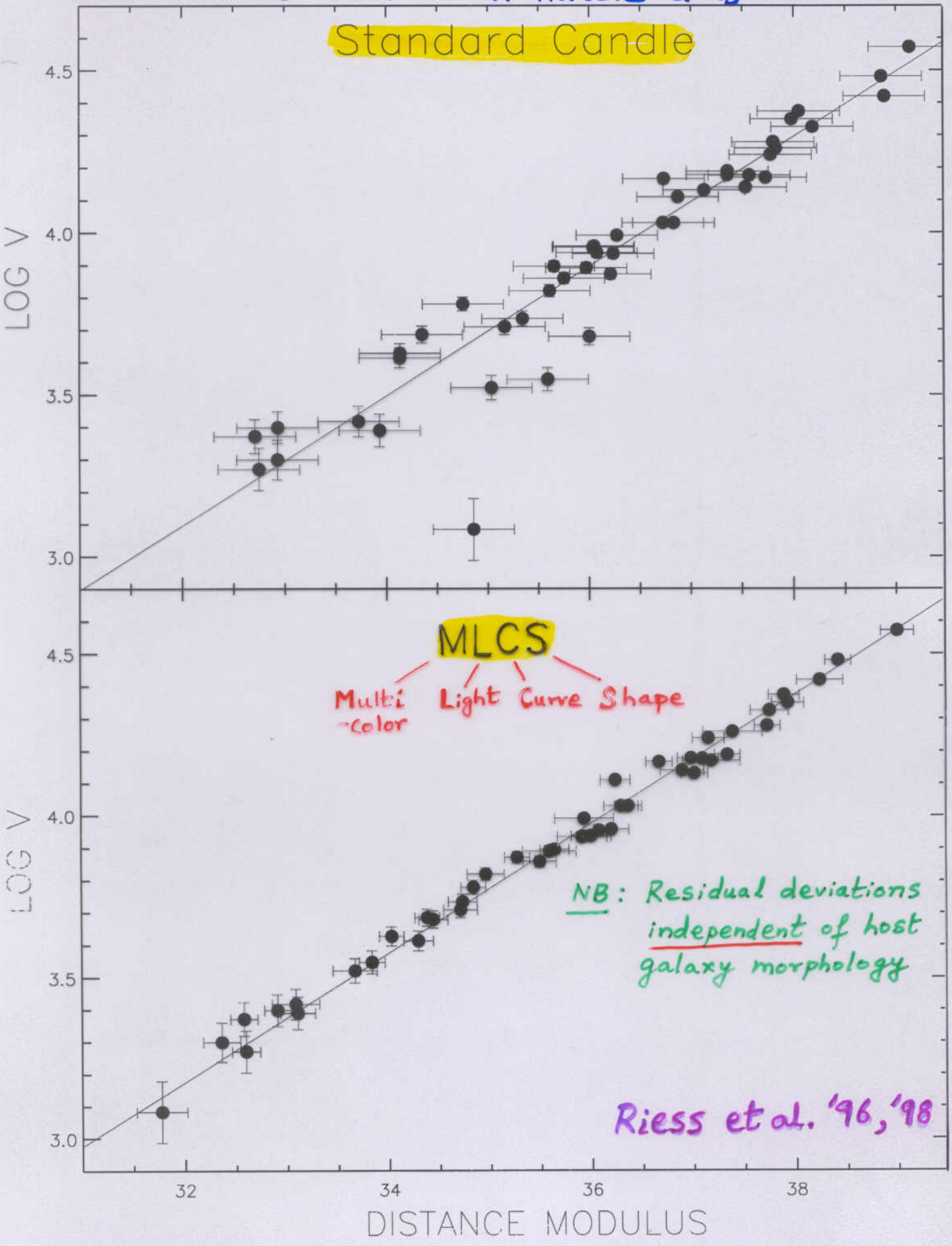
Multi-color Light Curve Shape method

Phillips 1993



Intrinsically brighter SN Ia decline more slowly

→ use observed light curve to calibrate M (hence D_L) and reduce scatter in Hubble diagram



Standard Candle

MLCS

Multi-color Light Curve Shape

NB: Residual deviations independent of host galaxy morphology

Riess et al. '96, '98

... alternatively, fit to template light-curve:

$$I(t)/I_{max} = \underbrace{f_R}_{\text{R-band}} \left[(t-t_{max})/\underbrace{s}_{\text{`Stretch-factor'}}(1+z)\right] + \underbrace{b}_{\text{baseline}}$$

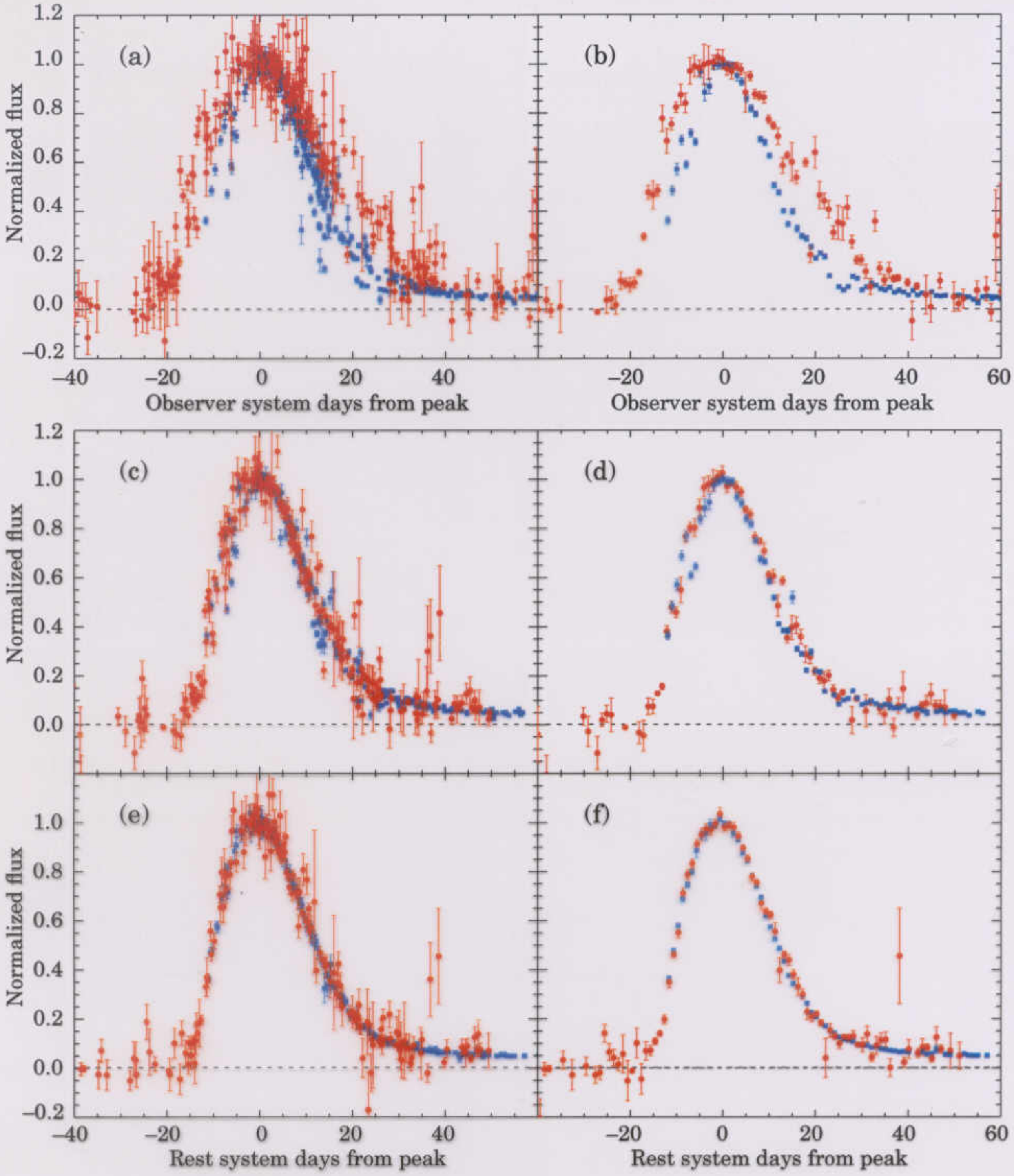
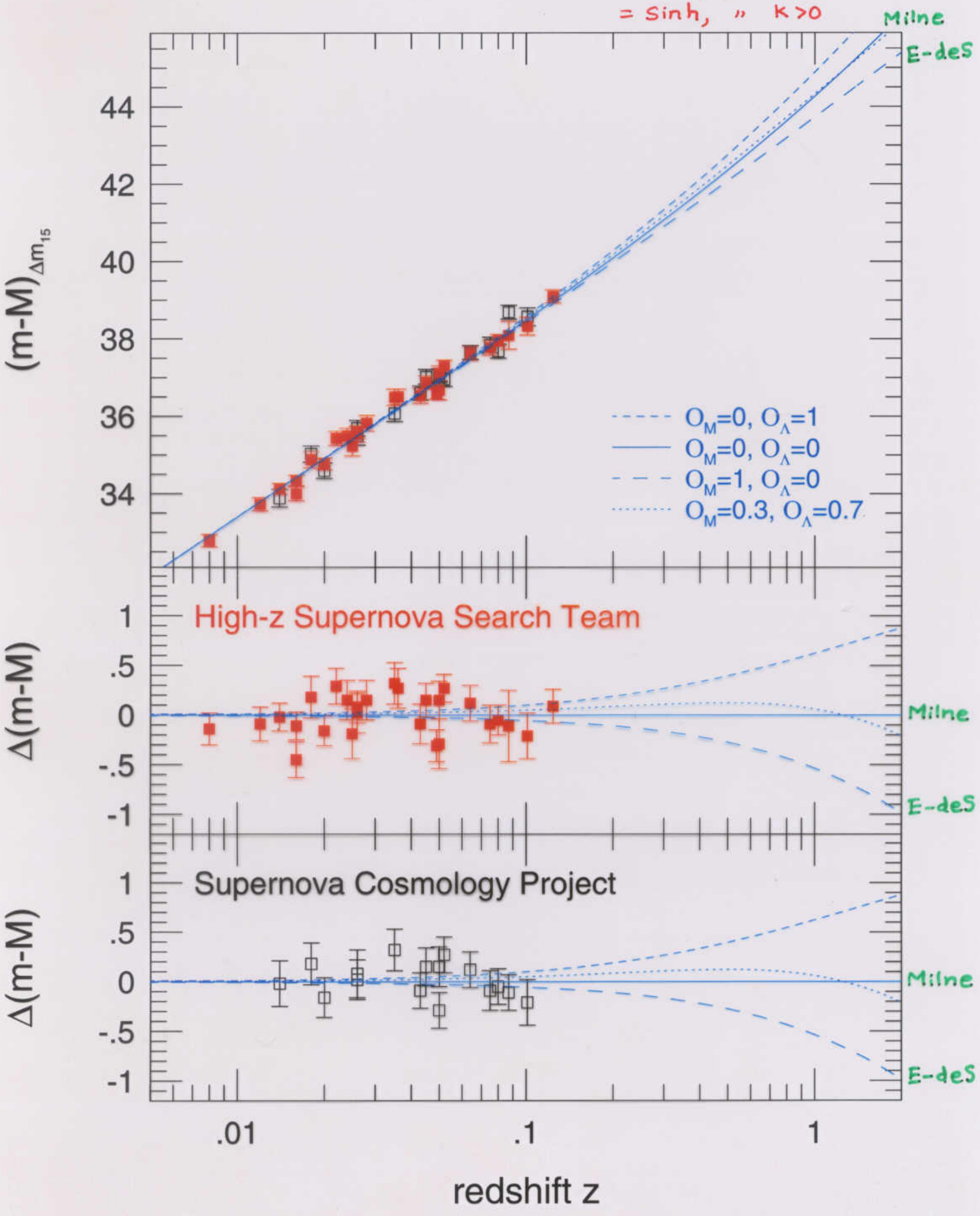


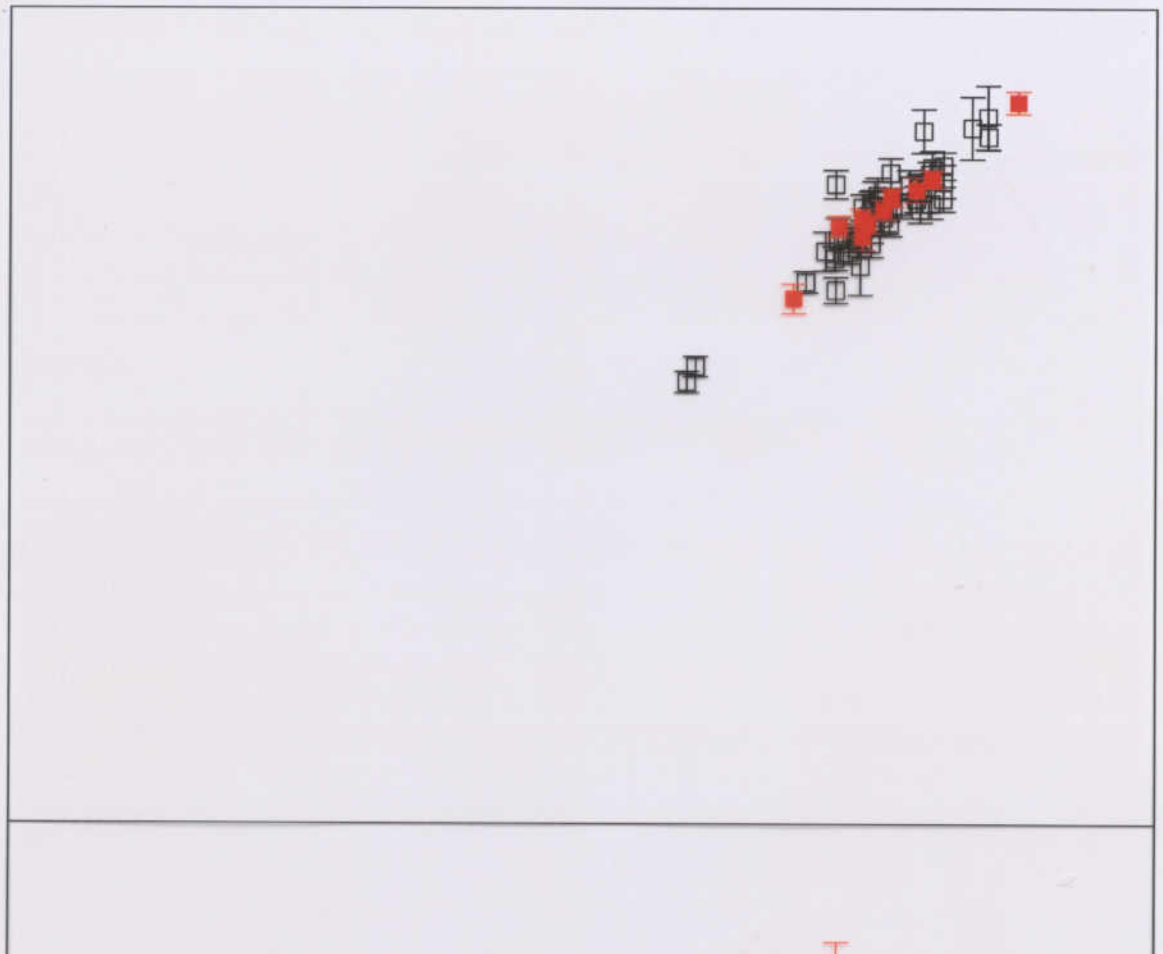
Fig. 1.— (a) The photometry points for the 35 SCP (full red circles) and 18 Calán/Tololo SNe (blue squares), fitted to Parab-18 with the maximum flux normalized to unity and the time of maximum adjusted to zero in the observer system. (b) shows the same data as in (a) averaged over one-day intervals and over each set of SNe. (c) and (d) show the same data, transformed to the rest system. In (e) and (f) the time axis for each photometry point is additionally divided by the corresponding stretch factor *s*.

Goldhaber et al
(astro-ph/0104382)

luminosity distance: $d_L \equiv \sqrt{\frac{L}{4\pi F}} = \frac{c}{H_0} \frac{(1+z)}{\sqrt{k}} \, \mathrm{Sinn}\left[\sqrt{k}\int_0^z \left\{k(1+z')^2+\Omega_m(1+z')^3+\Omega_\Lambda\right\}^{-1/2} dz'\right]$

= sin, for k<0
= sinh, " k>0

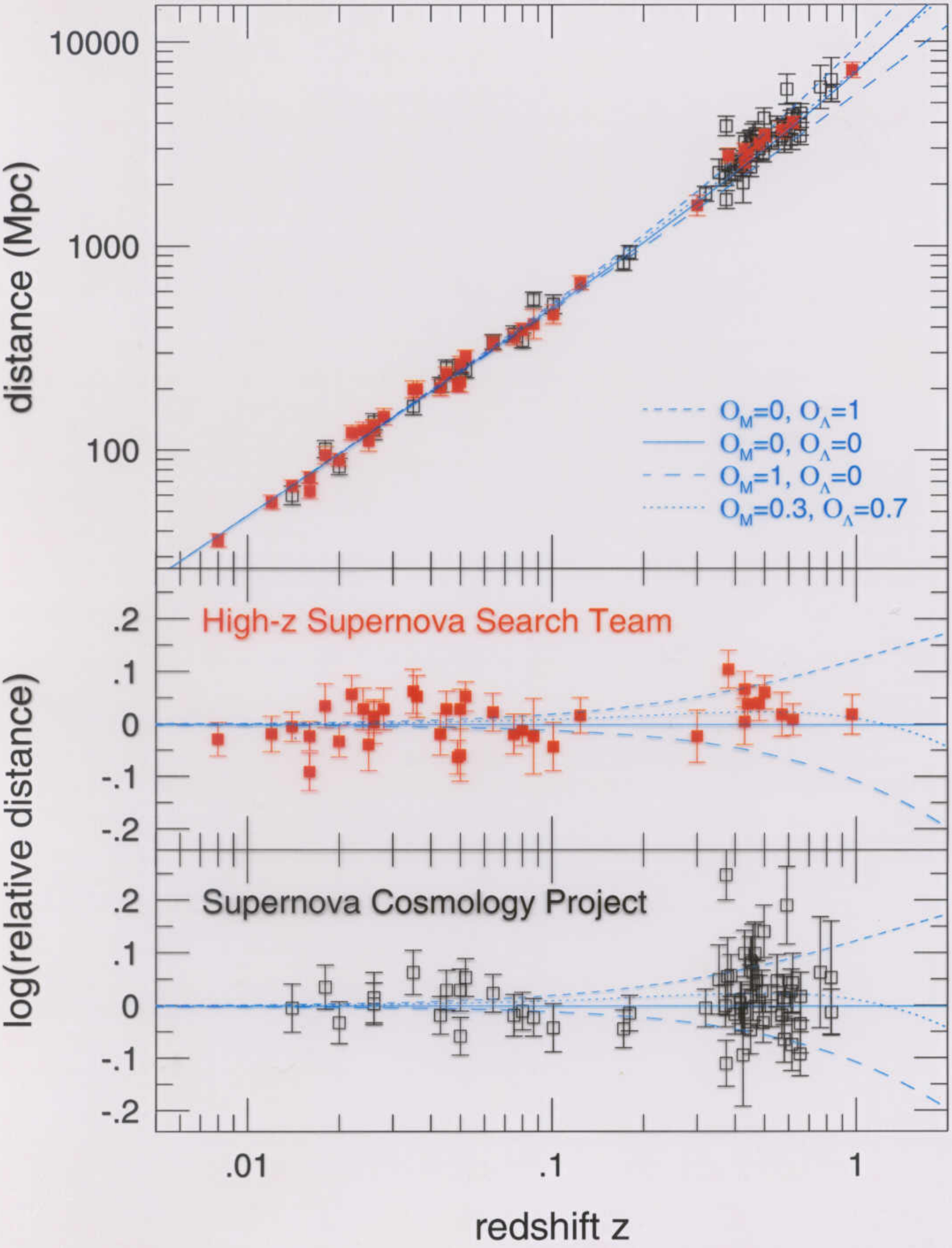




... at $z \sim 0.5$, SNIa are 0.20 ± 0.06 mag fainter than in an empty (coasting) universe (using Δm_{15} correction)

0.14 ± 0.06 (MLCS)

0.06 ± 0.04 (SCP)



Leibundgut, ARAA '01

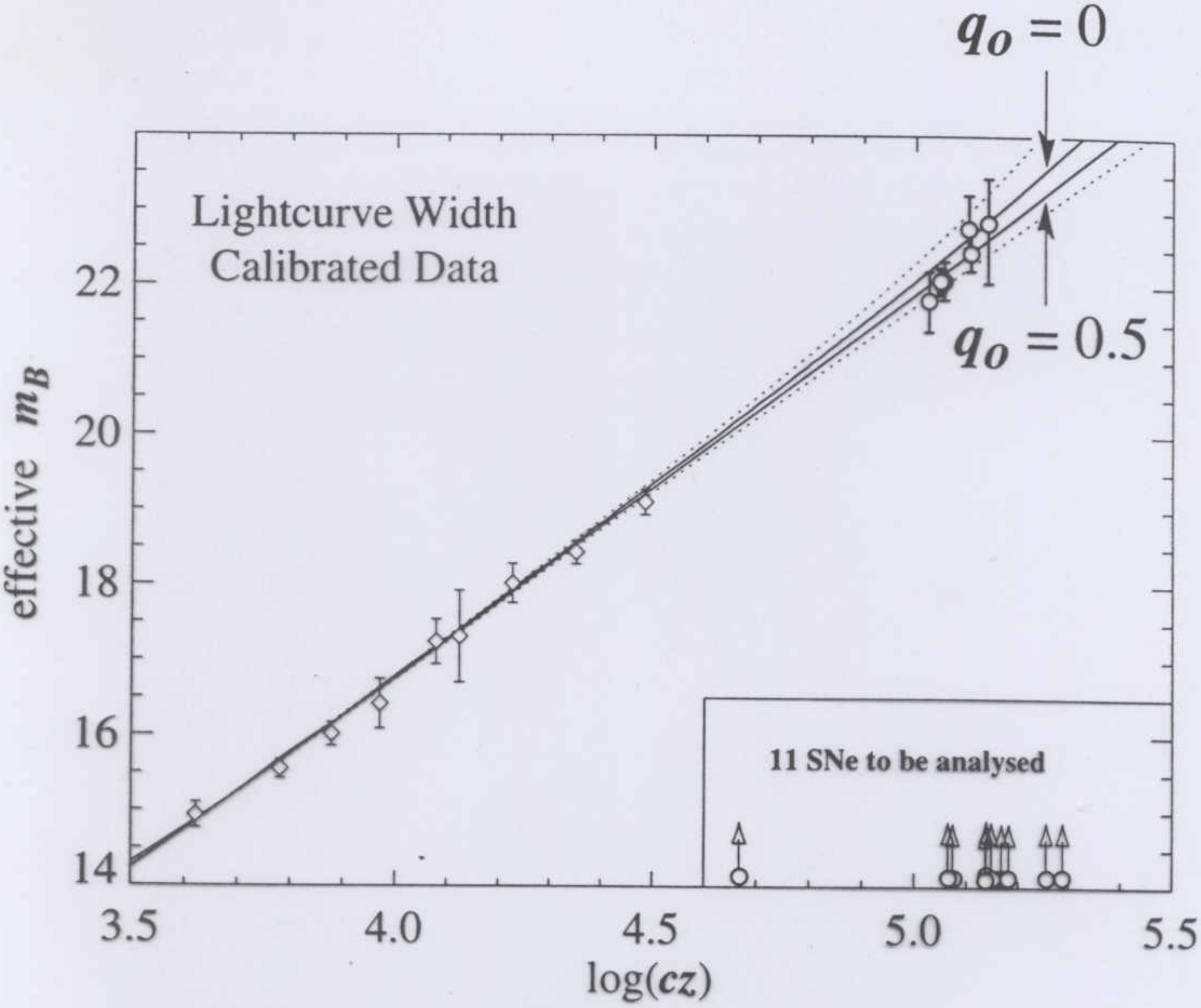
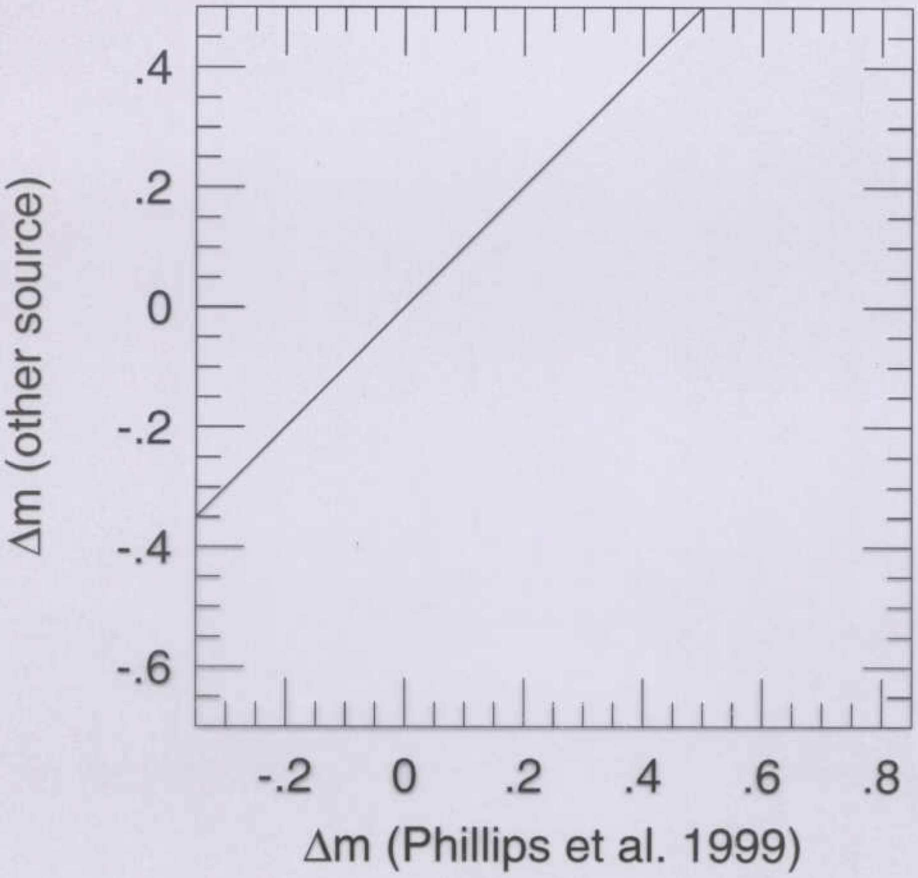
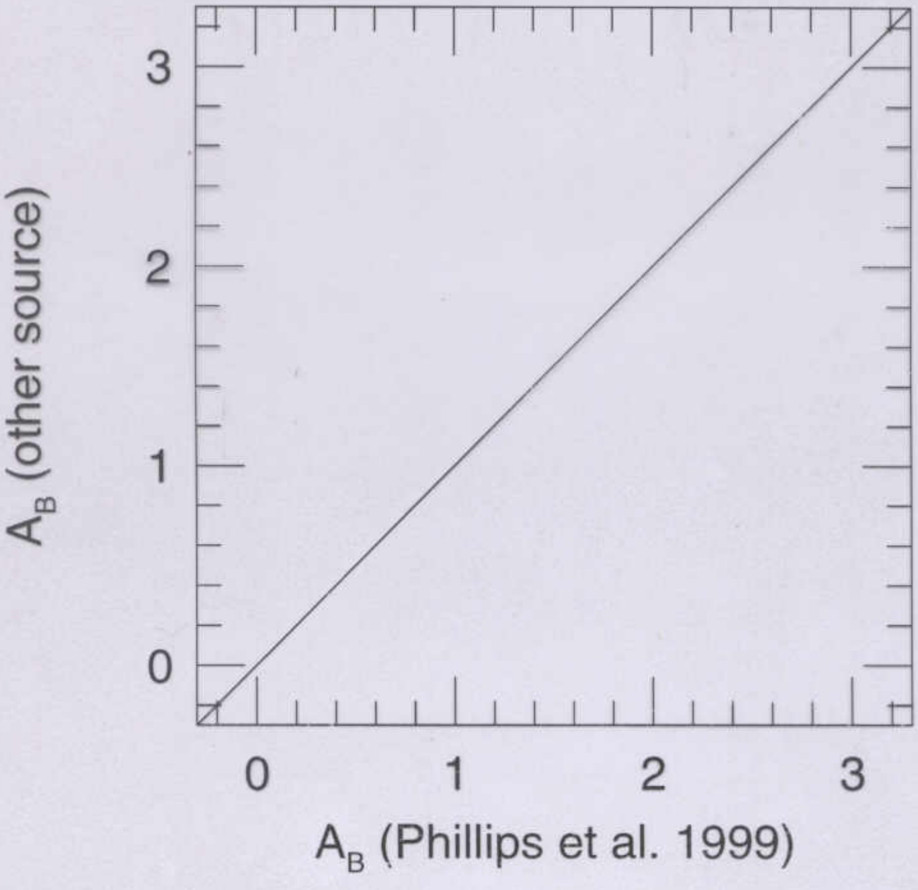


Figure 1. The type Ia supernova Hubble diagram, from Perlmutter et al. 1996. The apparent magnitude at maximum light has been corrected for light-curve shape. The deceleration parameter appears to be positive, and the upper dotted line ($q_0 = -1$) is clearly excluded. This places models with a dominant cosmological constant in some difficulty.

... but earlier, the indication had been that the universe is decelerating as expected

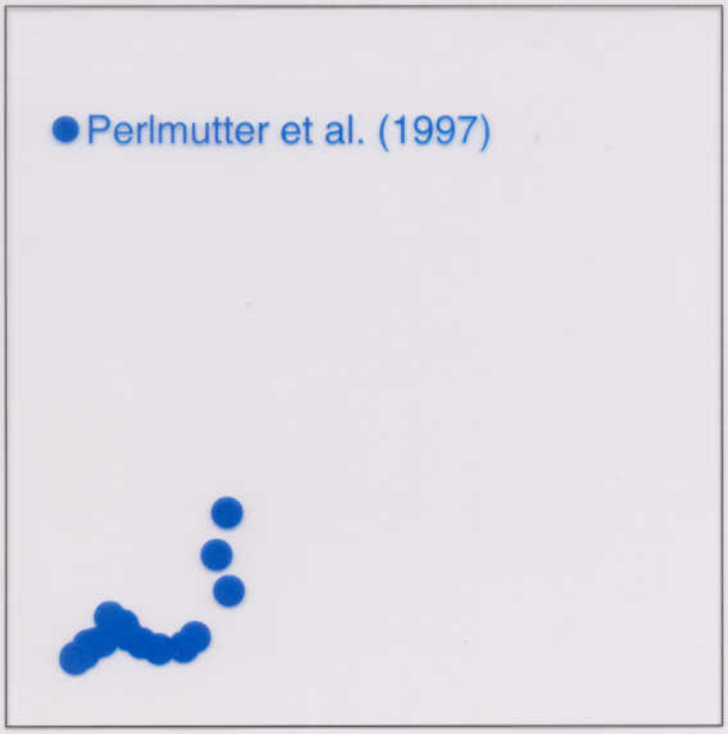
Different methods used to calibrate peak luminosity (using its linear correlation with decline rate) do not agree with each other ...

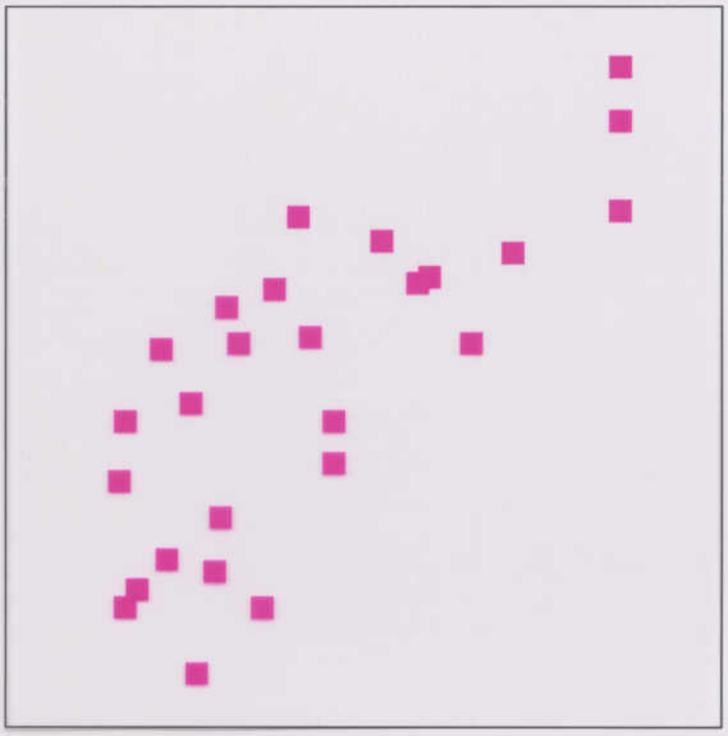




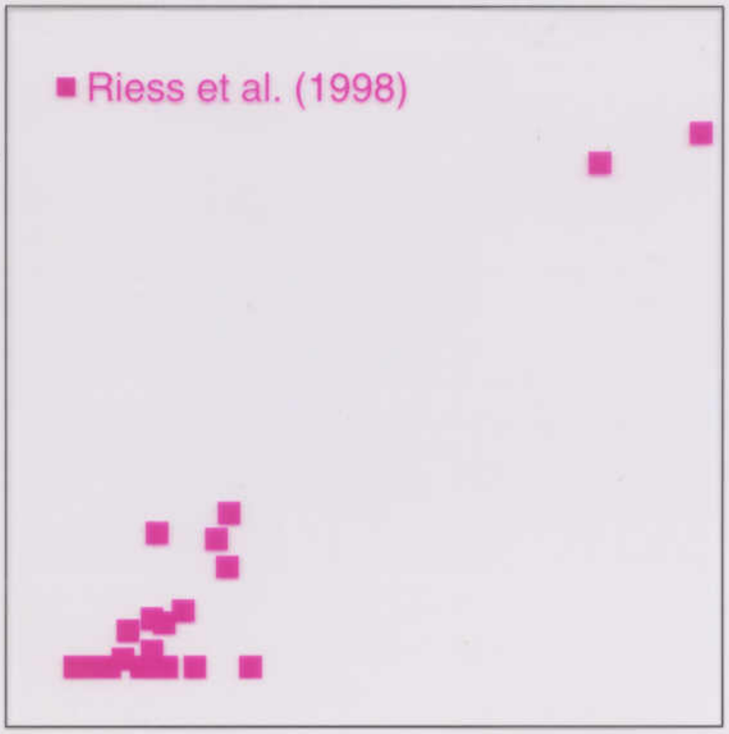
... inferred absorption (by dust) also different

Slope = 0·29 ± 0·04
Zero-point offset
−0·03 ± 0·01 mag





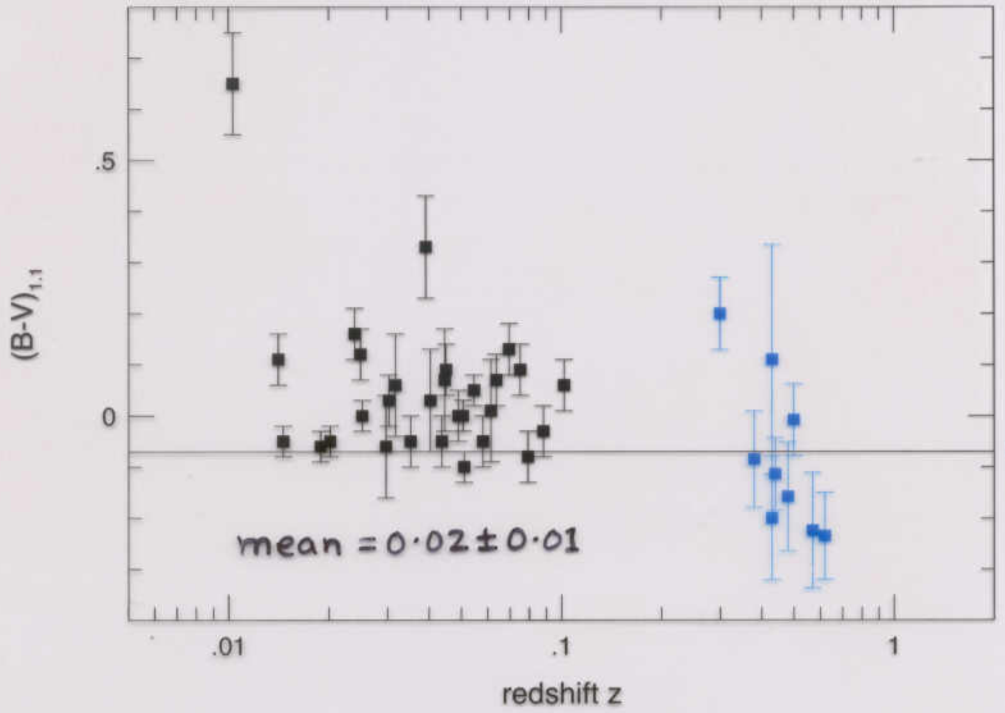
Slope= 0·77±0·13
also zero-point
offset 0·25±0·04



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



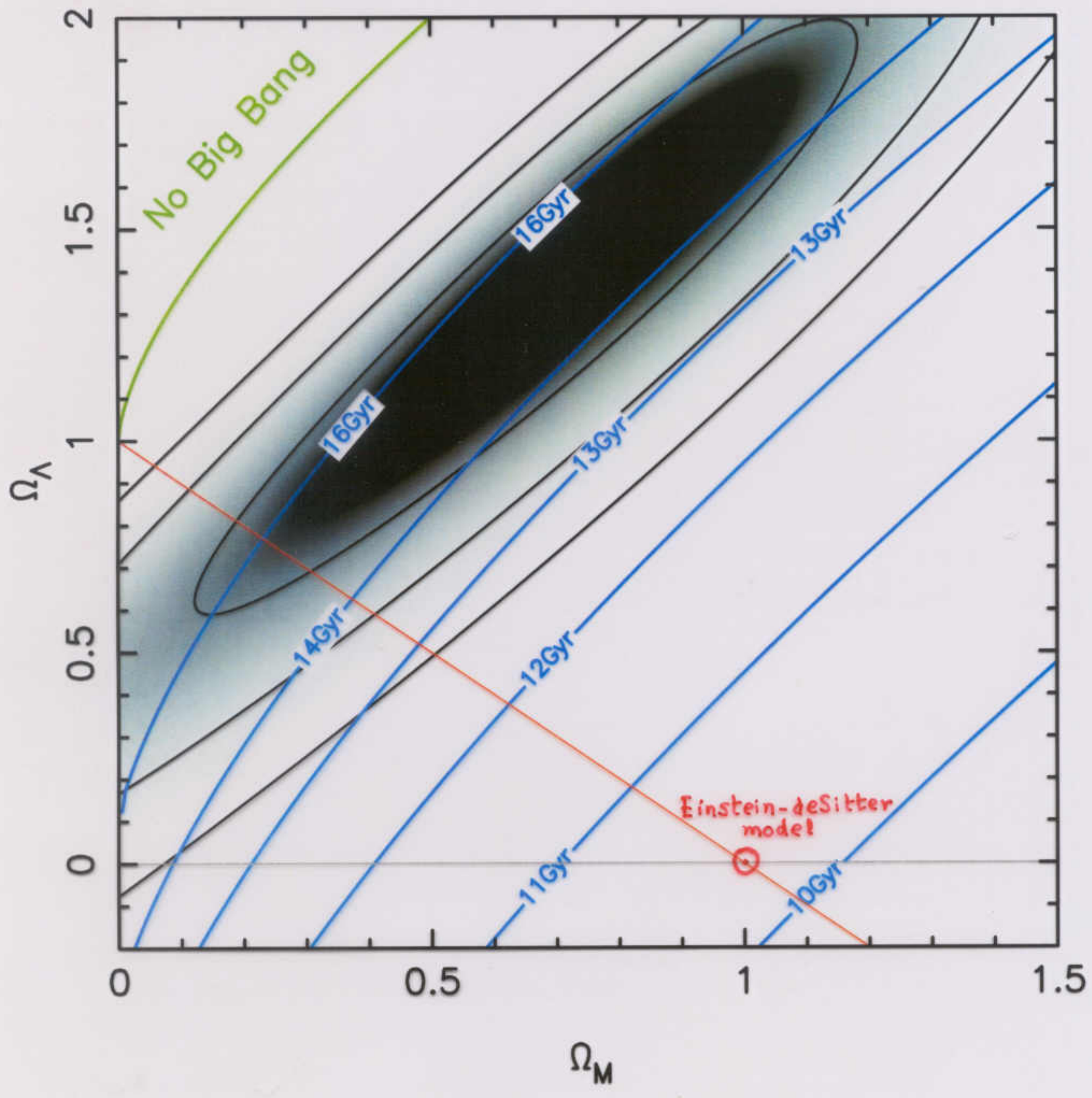
mean = 0·02±0·01

−0·06±0·03

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).

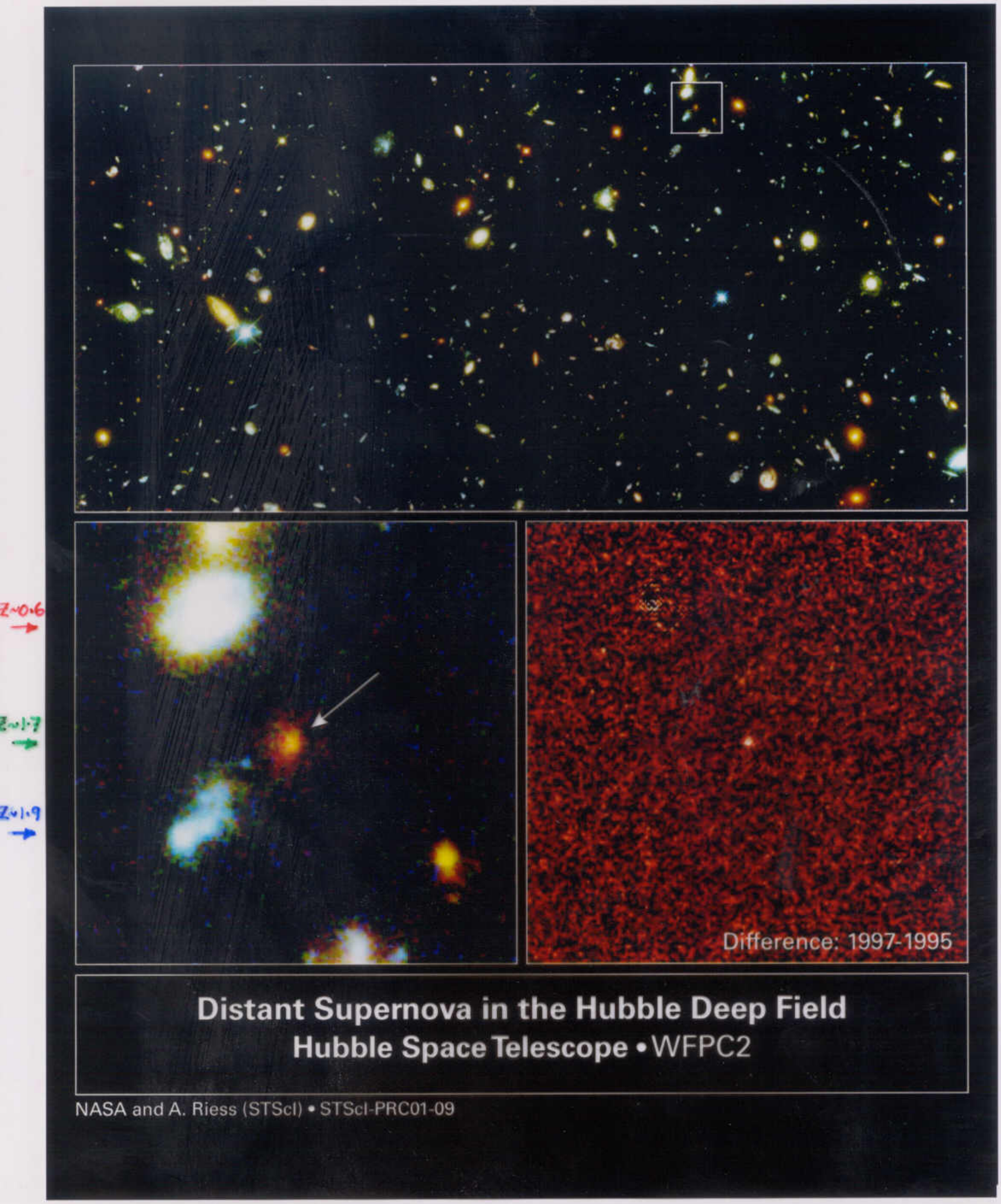
(Leibundgut, ARAA 2001)

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!)



(Leibundgut, ARAA '01)

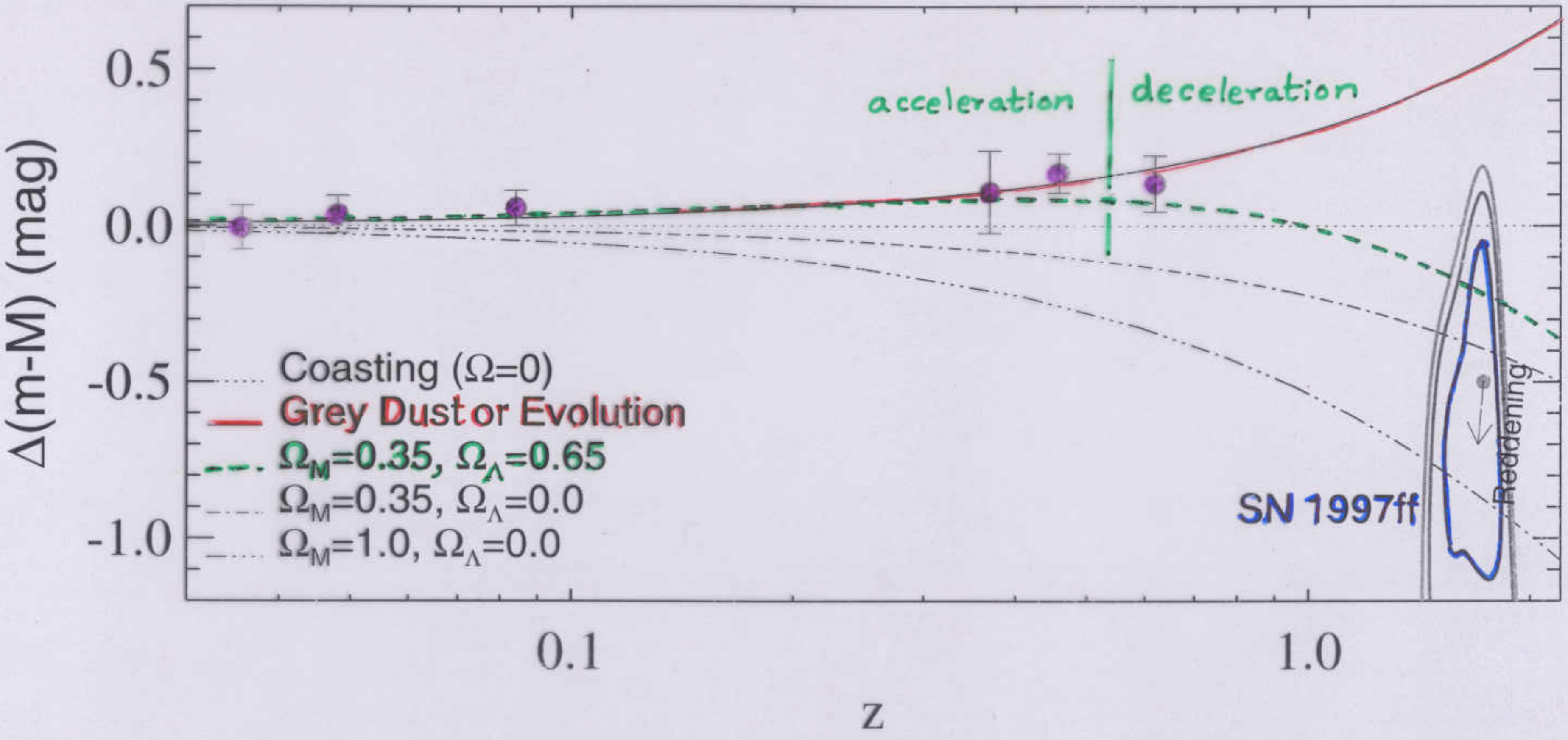
Discovery of SN 1997ff at $z \sim 1.7$ – the 'smoking gun' for Λ?



Distant Supernova in the Hubble Deep Field
Hubble Space Telescope • WFPC2

NASA and A. Riess (STScI) • STScI-PRC01-09

... rules out (continued) luminosity evolution as explanation for faintness of SNIa at $z \lesssim 1$ (wrt coasting universe) because it is <u>brighter</u> (as expected for Λ-model at $z \gtrsim 1$)



however gravitational lensing by foreground galaxies would have brightened SN1997ff by ~0.4-1 mag ! (Lewis & Ibata, astro-ph/0104254)

... so not definite evidence for deceleration (Moertsell et al, astro-ph/0105355)

" 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)

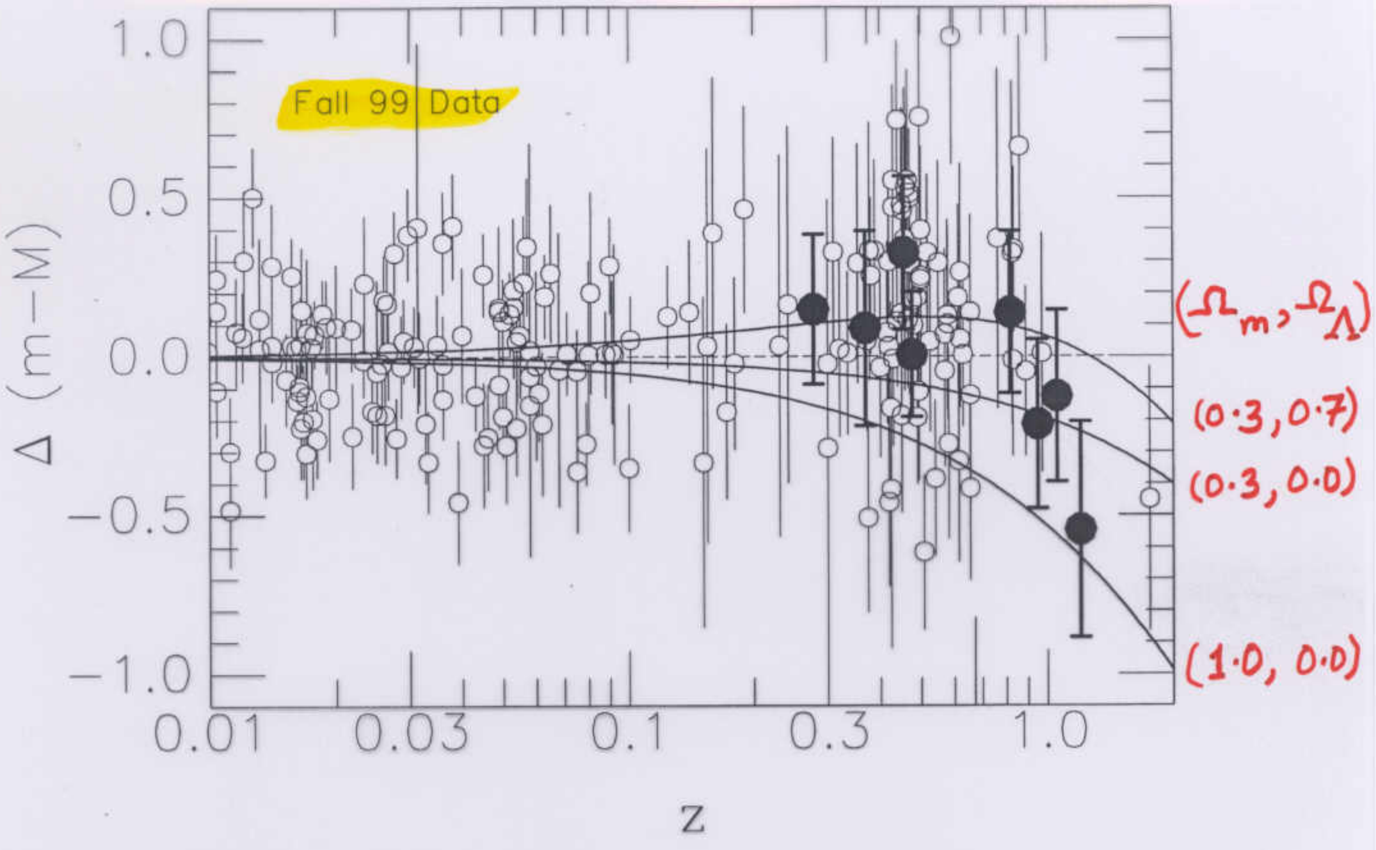


Fig. 8.— The Fall 1999 and other data points are shown in a residual Hubble diagram with respect to an empty universe. From top to bottom the curves show $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$, (0.3,0.0), and (1.0,0.0), respectively, and the Fall 1999 points are highlighted.

209 SNIa (Tonry et al, astro-ph/0305008)

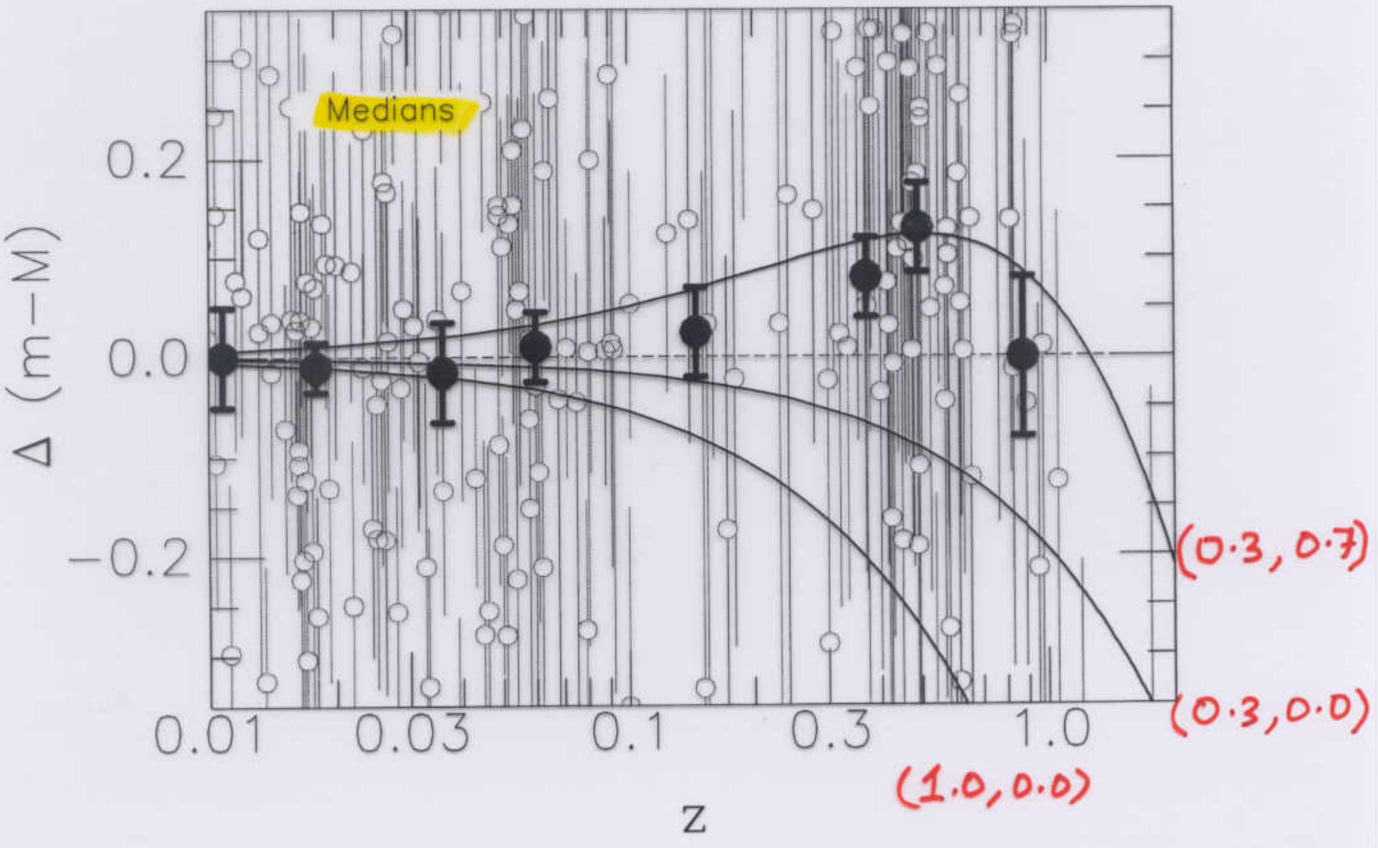


Fig. 9.— The Fall 1999 and other data points are shown in a residual Hubble diagram with respect to an empty universe. In this plot the highlighted points correspond to median values in eight redshift bins. From top to bottom the curves show $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$, (0.3,0.0), and (1.0,0.0), respectively.

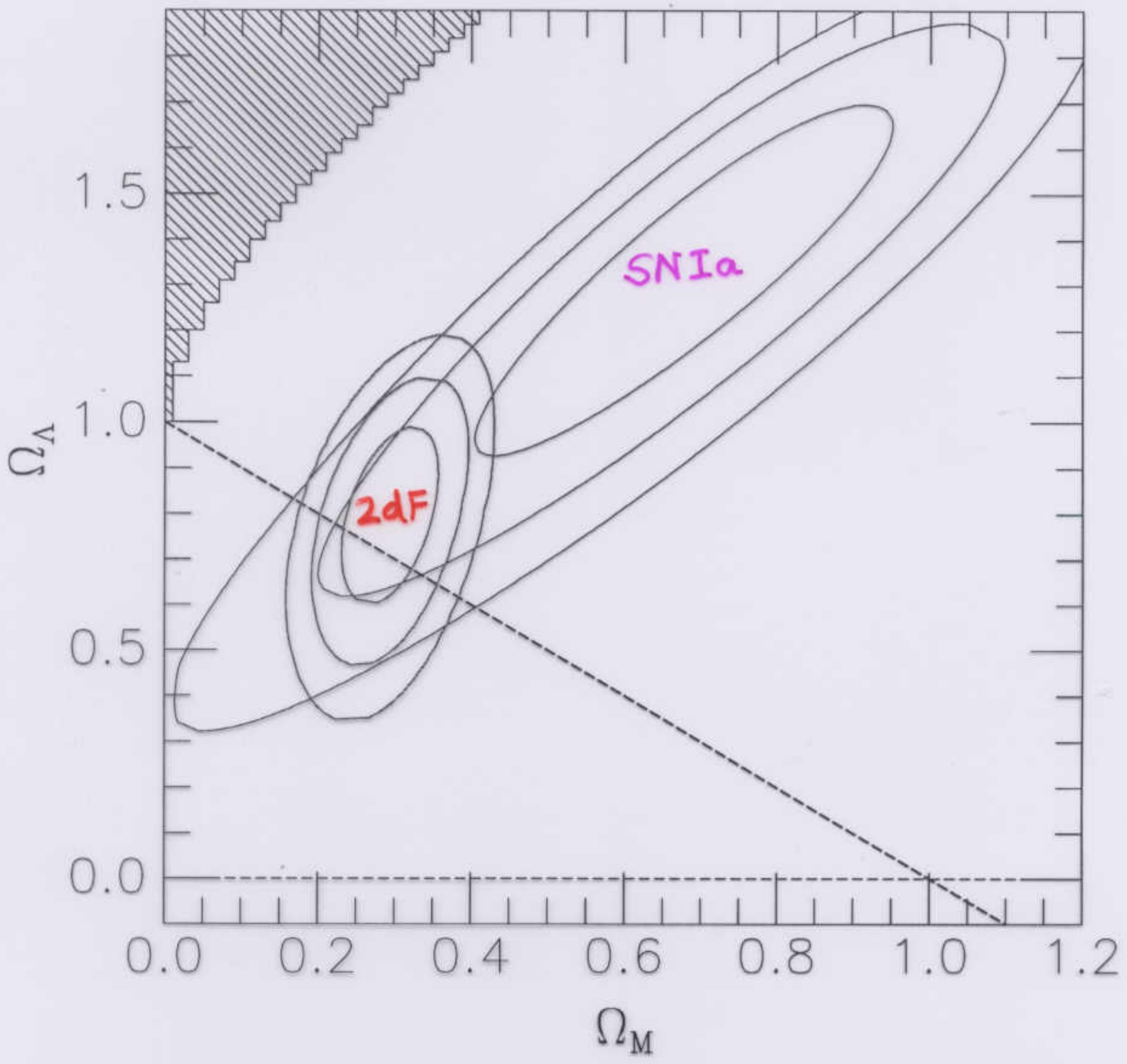
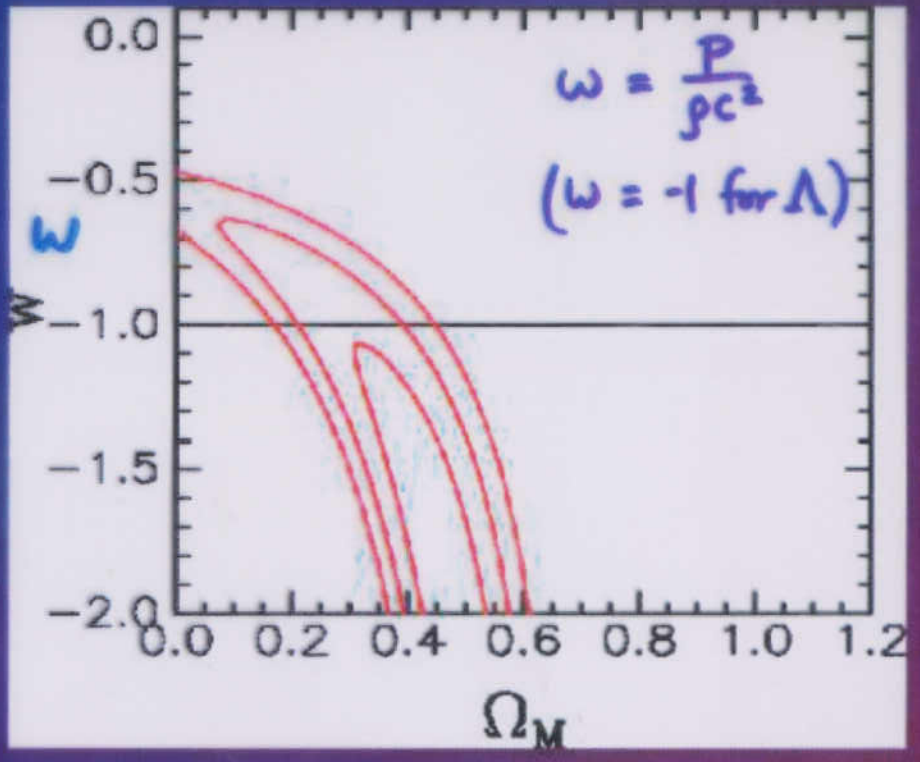


Fig. 12.— Probability contours for Ω_Λ versus Ω_M are shown at 1σ, 2σ, and 3σ with $w = -1$. We also give 1σ, 2σ, and 3σ contours when we adopt a prior of $\Omega_M h = 0.20 \pm 0.03$ from the 2dF survey (Percival et al. 2001). These constraints use the full sample of 172 SN Ia with $z > 0.01$ and $A_V < 0.5$ mag.

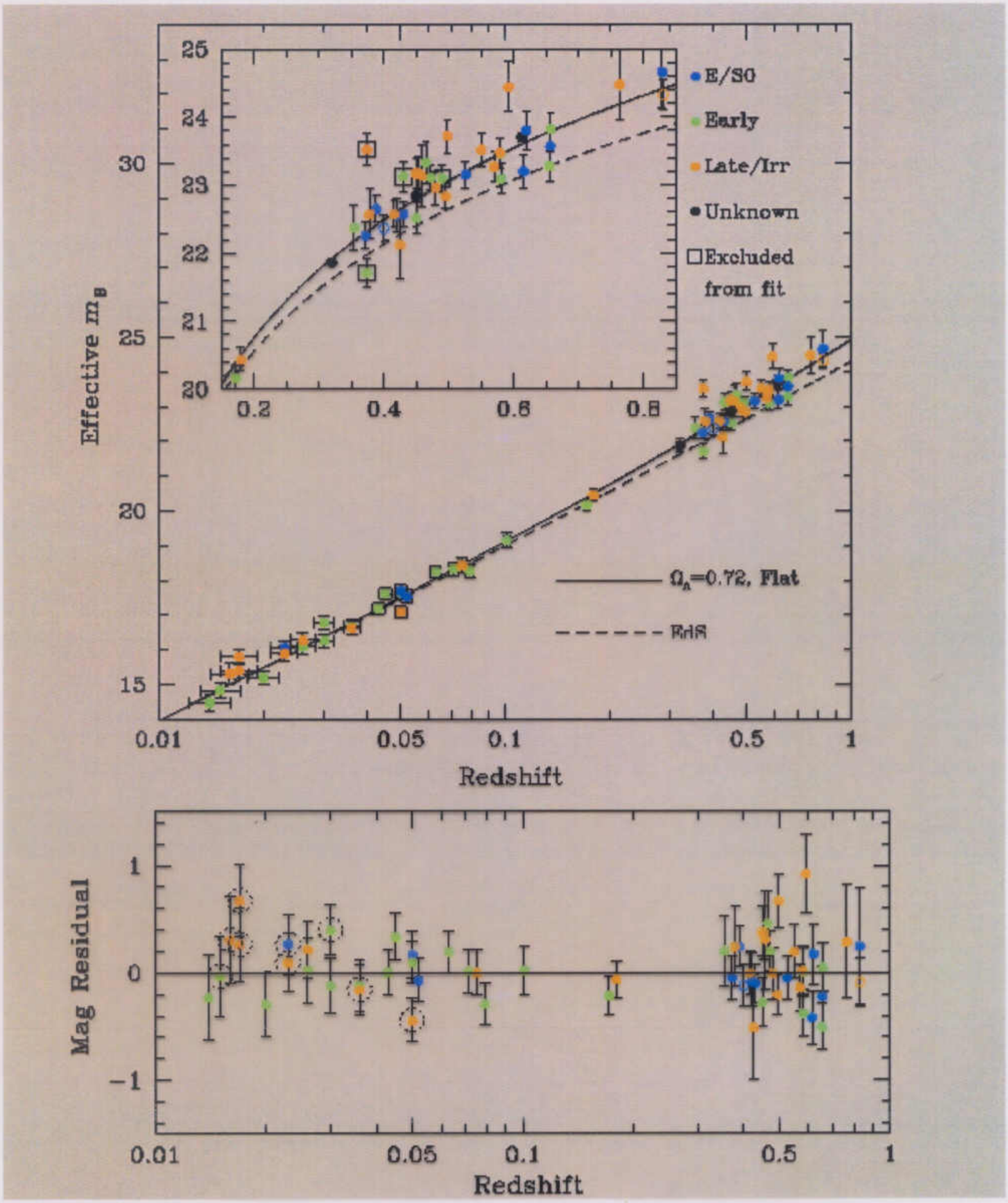
Tonry et al
(astro-ph/0305008)

SN1a constraints

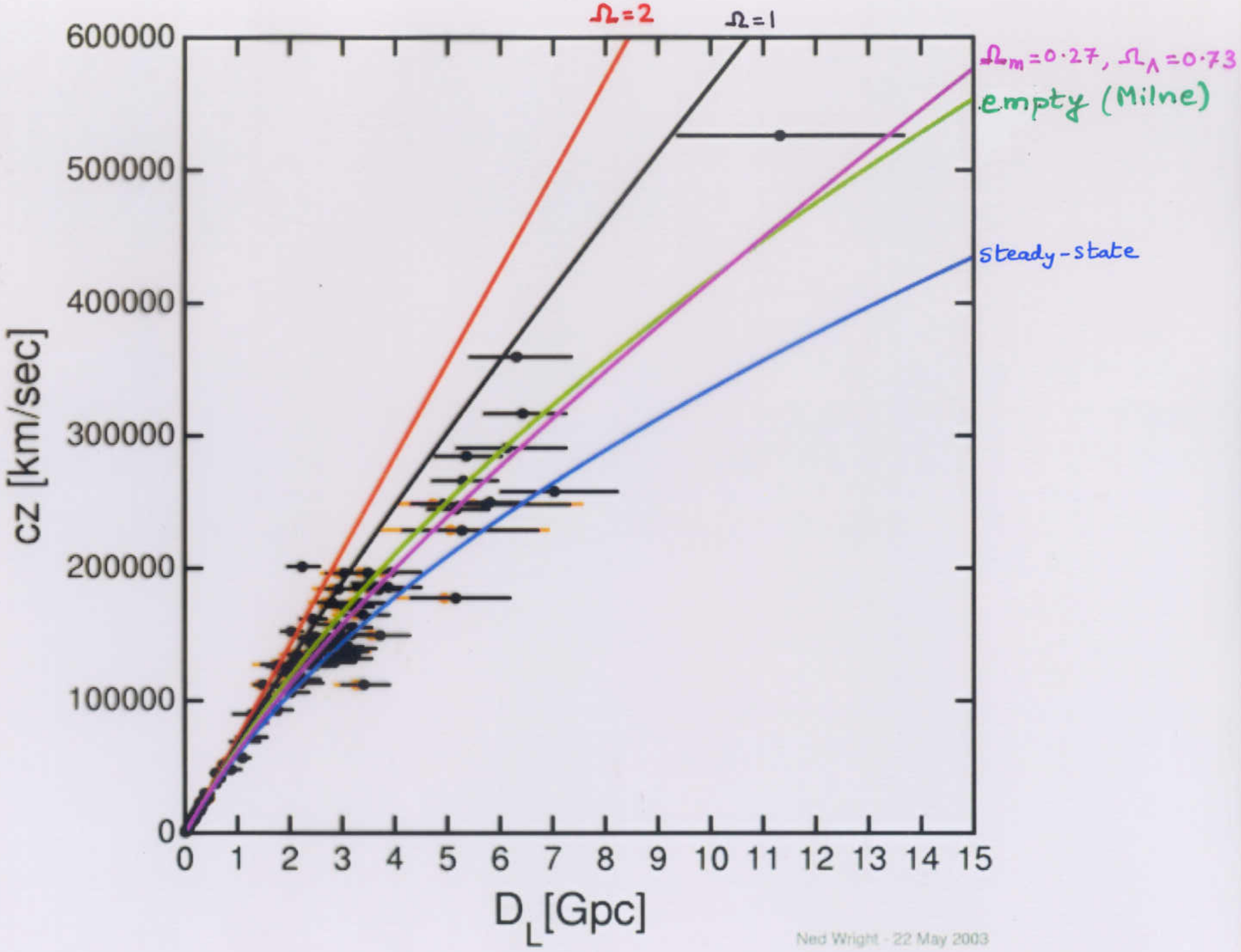


Best fit $\Rightarrow$ $\omega \simeq -2$ "phantom energy"!

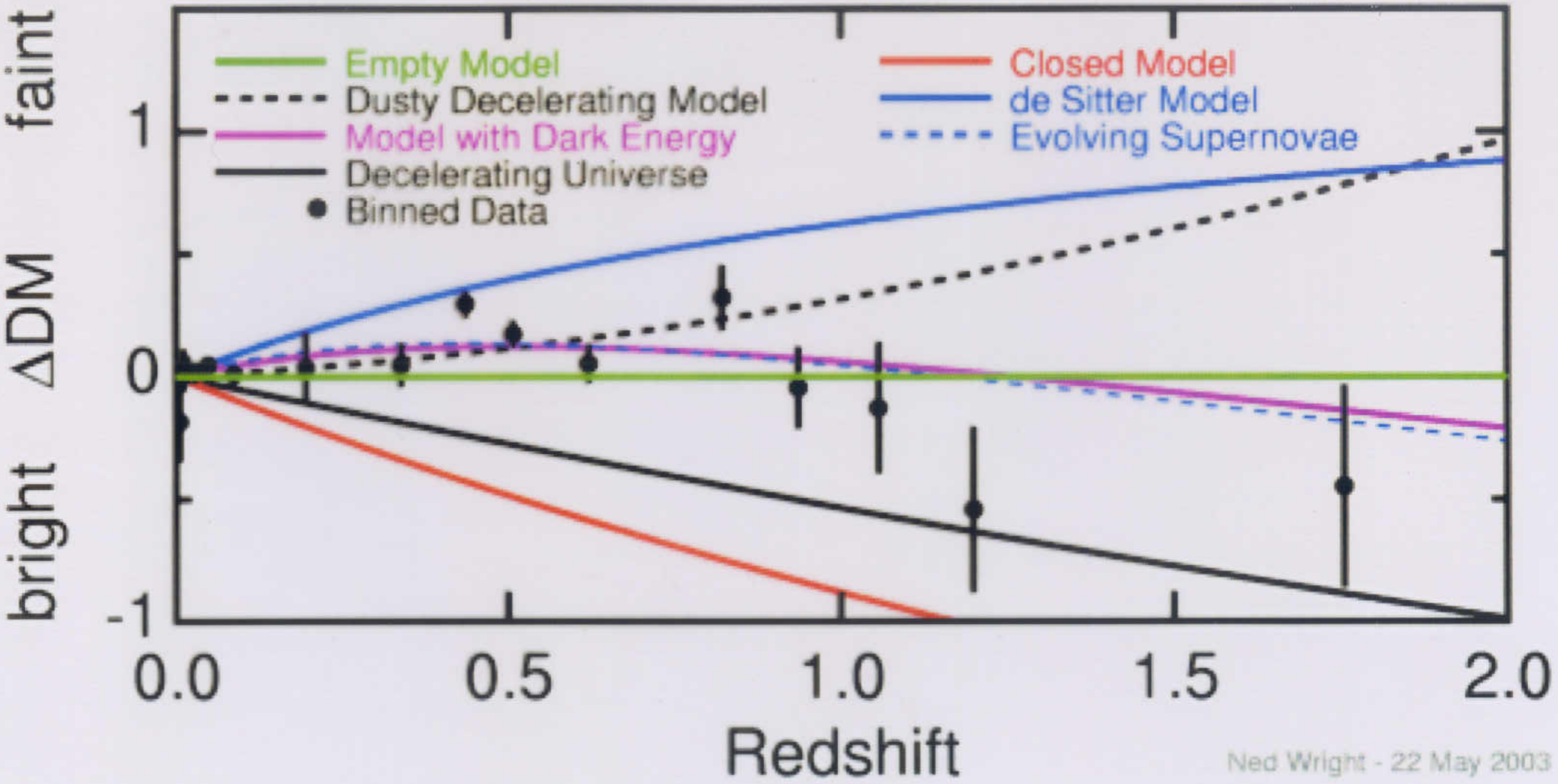
... violates weak energy condition



The Supernova Cosmology Project
(astro-ph/0211444)

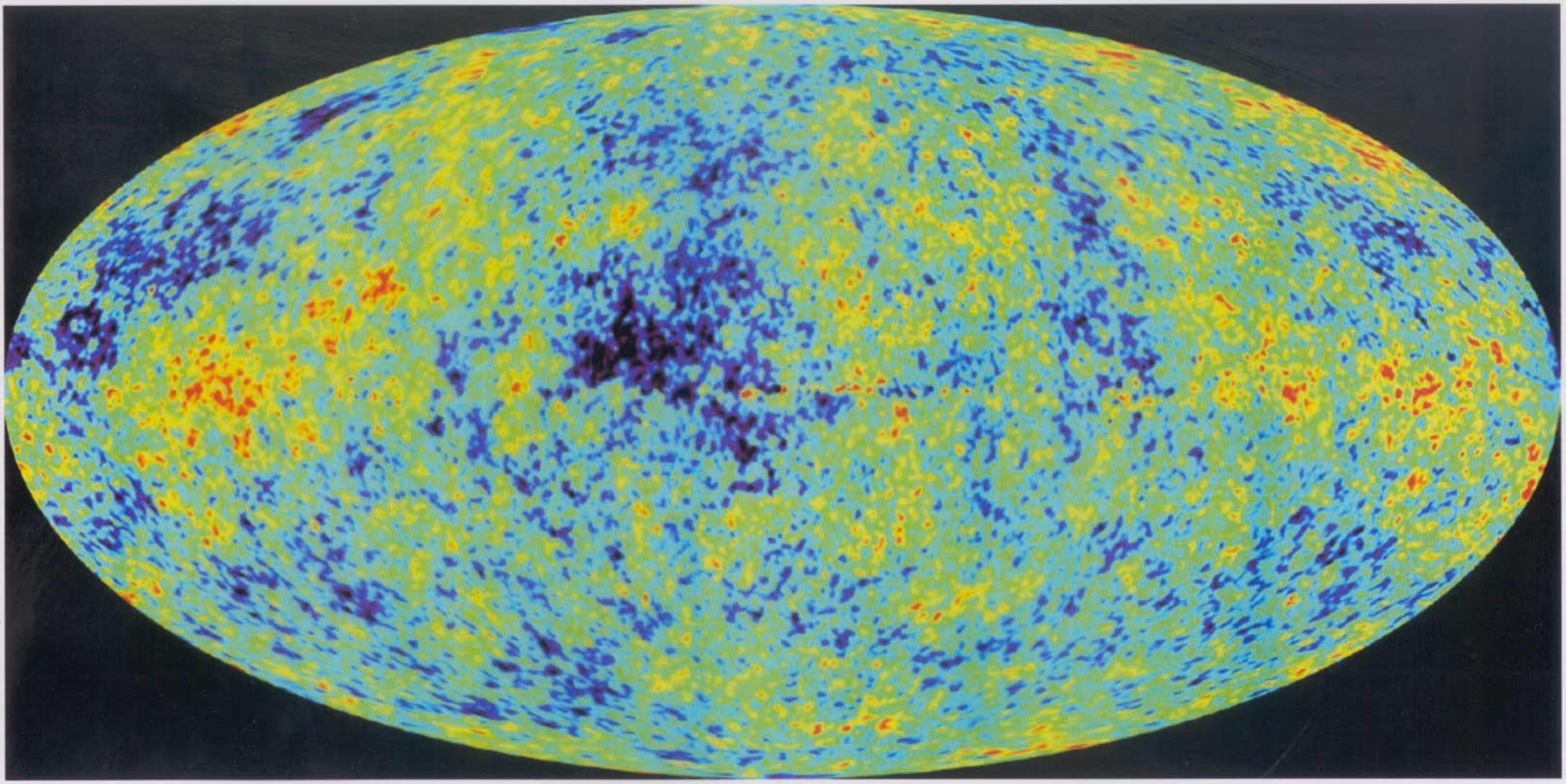


Ned Wright - 22 May 2003



Ned Wright - 22 May 2003

Wilkinson Microwave Anisotropy Probe , 1^{st} yr data release



Bennett et al
(astro-ph/0302208)

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

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

… 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')

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

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

(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 $n=1$: $C_\ell = \dfrac{A}{4\pi c^4}\,\dfrac{\Omega_0^{1.54}H_0^4}{\ell(\ell+1)}$

(Peebles '84)

Why study CMB anisotropies?

Recombination ($z \simeq 1000$) makes Universe transparent.

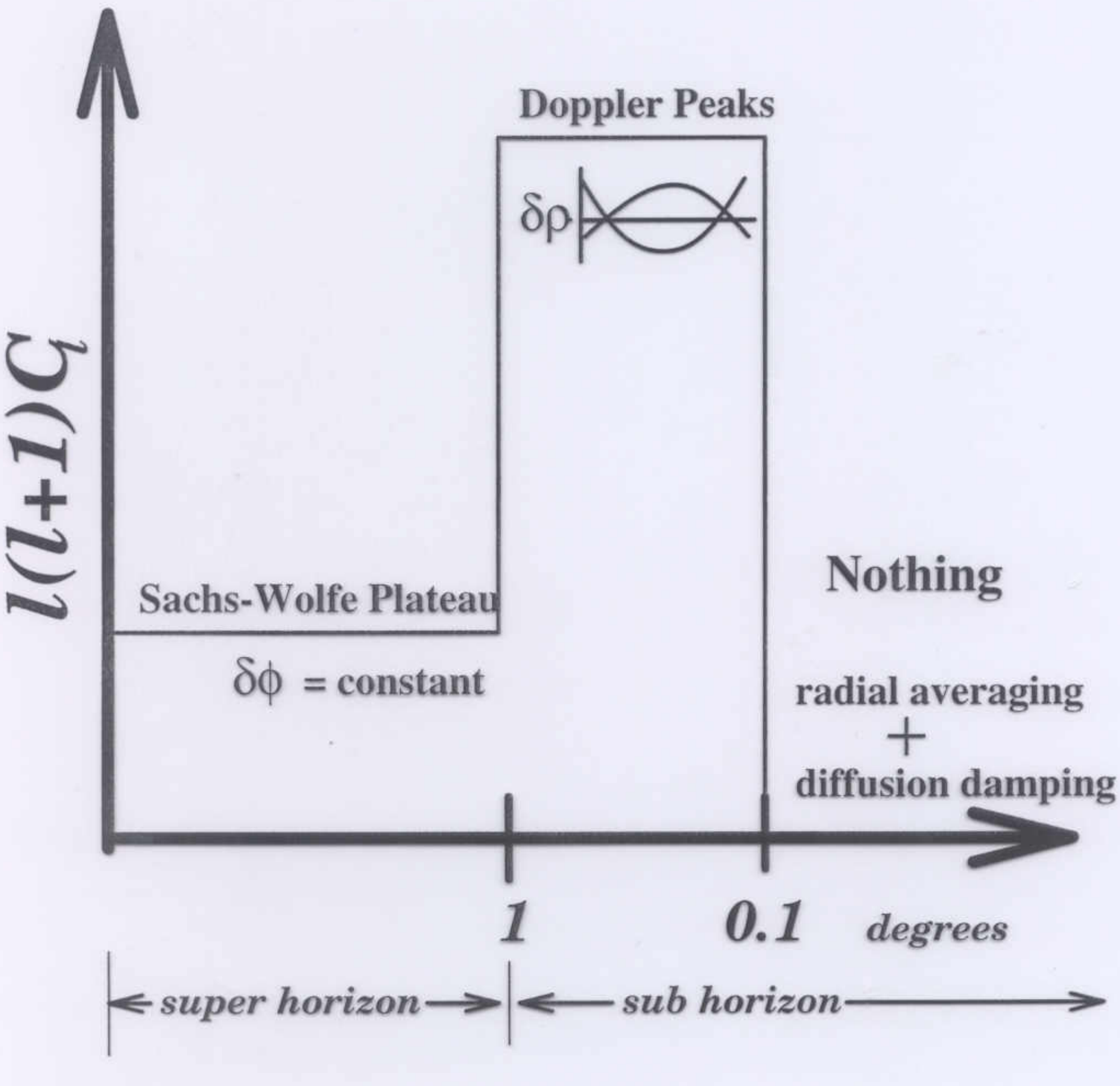
Primordial fluctuations (on sub-horizon scales) filtered through non-contentious physical processes and become observable.

In principle accurately constrain $\Omega_K, \Omega_\Lambda, \Omega_0 h^2, \Omega_{\mathrm{B}} h^2$.

(Notation: $\Omega_K + \Omega_\Lambda + \Omega_0 = 1$, $\Omega_x\, h^2$ is a density.)

BUT

1) Primordial fluctuations highly model-dependent.
2) Foreground subtraction problematic


Doppler Peaks
δρ
l(l+1)C
Sachs-Wolfe Plateau
δφ = constant
Nothing
radial averaging
+
diffusion damping
1
0.1
degrees
super horizon
sub horizon

Acoustic Waves

Photons compressed by potential, but resist compression ⇒ oscillations. Phase frozen at recombination.

Depend on sound horizon s_*.

$\Delta T/T \sim \cos(nks_*)$ adiabatic, inflation only

$\Delta T/T \sim \sin(nks_*)$ isocurvature, others

Produces evenly spaced peaks in spectrum (first peak at l_A).

Projection: observed l_A sensitive $(\Omega_K, \Omega_\Lambda)$. ($\Omega_0 h^2$ enters both projection and s_* to nearly cancel.)

Smoothed by orientation wrt los.

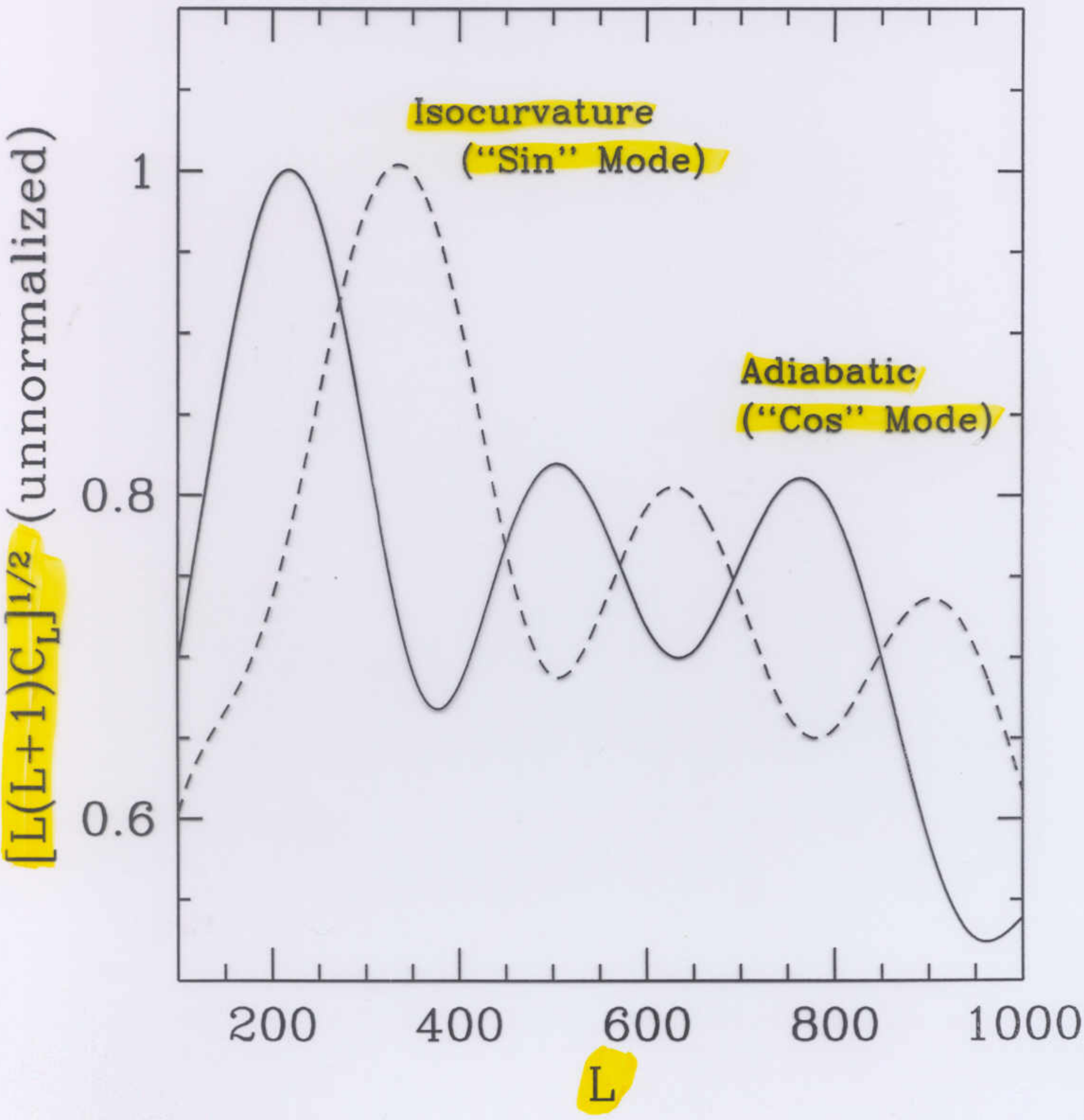
Also Doppler shifts, $\pi/2$ out of phase; only los part effective, so smaller.

Baryon drag (depends on $\Omega_\mathrm{B} h^2$): increases gravitational compression, enhances odd peaks suppresses even peaks.

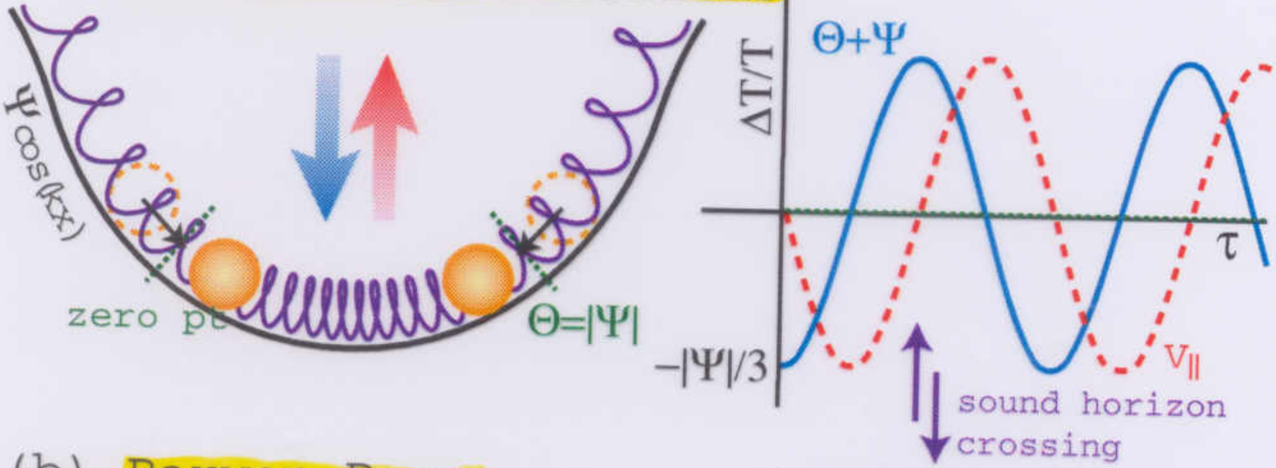
Photons diffuse while Compton scattering, mix hot and cold regions. Diffusion damping (scale l_D) increases with $\Omega_\mathrm{B} h^2$.

Angular power spectrum of CMB

... sensitive to nature of initial perturbations
(adiabatic vs isocurvature , gaussianity?)



(a) Acoustic Oscillations



(b) Baryon Drag

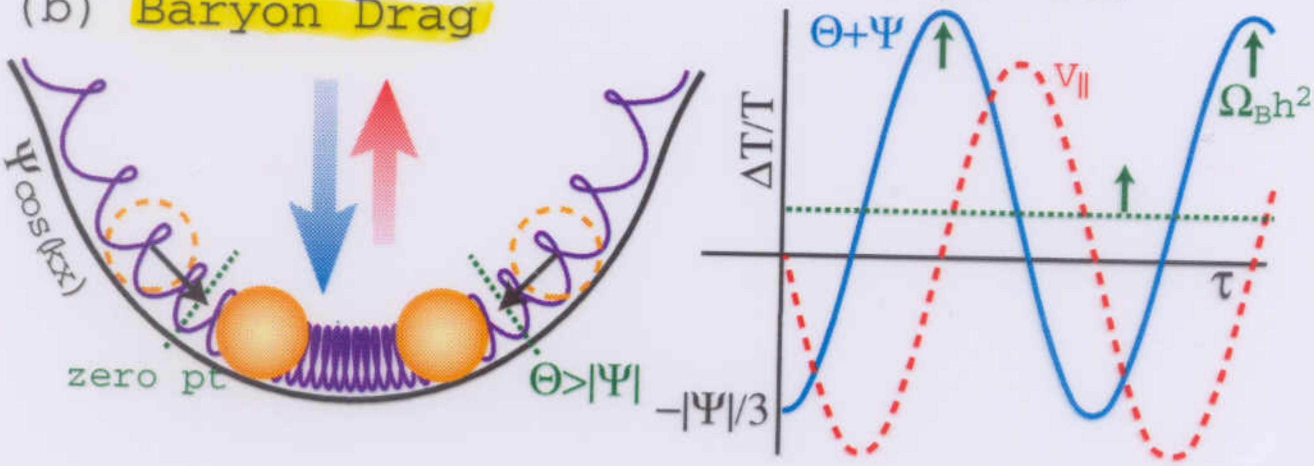


FIG. 2. (a) Acoustic oscillations. Photon pressure resists gravitational compression of the fluid setting up acoustic oscillations (left panel, real space). Springs and balls schematically represent fluid pressure and effective mass respectively. Gravity displaces the zero point to $|\Psi|$ (blue arrow) with $\Psi/3$ oscillations (right panel, time). The displacement is cancelled by the redshift (red arrow) a photon experiences climbing out of the well. The $V_\parallel$ Doppler effect is shifted by $\pi/2$ in phase. (b) Baryon drag decreases the sound horizon and increases the gravitating mass, causing more infall and a net zero point displacement, even after redshift (unequal red and blue arrows). Temperature crests (compression) are enhanced over troughs (rarefaction) and Doppler contributions.

Hu, Sugiyama, Silk
(astro-ph/9604166)

Integrated Sachs-Wolfe (ISW) effect

Effect of photon passing through changing potential wells (double special relativistic effect).

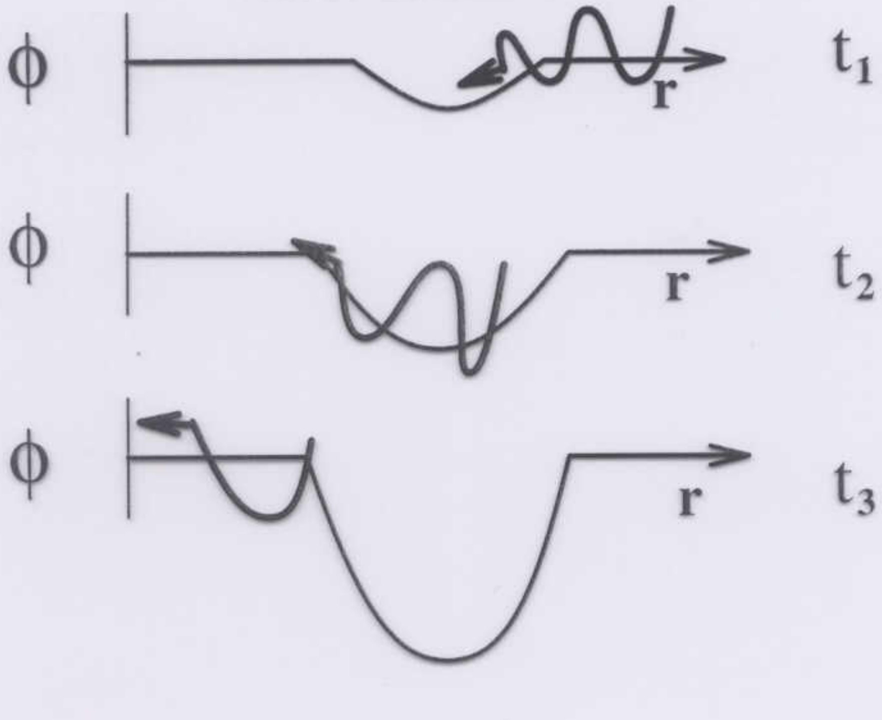
Rees-Sciama effect: SW with nonlinear potential perturbations.

Late ISW effect: Universe dominated by K or Λ has rapid expansion; potential decays independent of l. But SW cancellation within horizon ($l > l_{\Lambda K}$).

Early ISW effect: Recombined but still radiation dominated stage, potential decays at current s_*; boosts $l > l_{\rm eq}$.

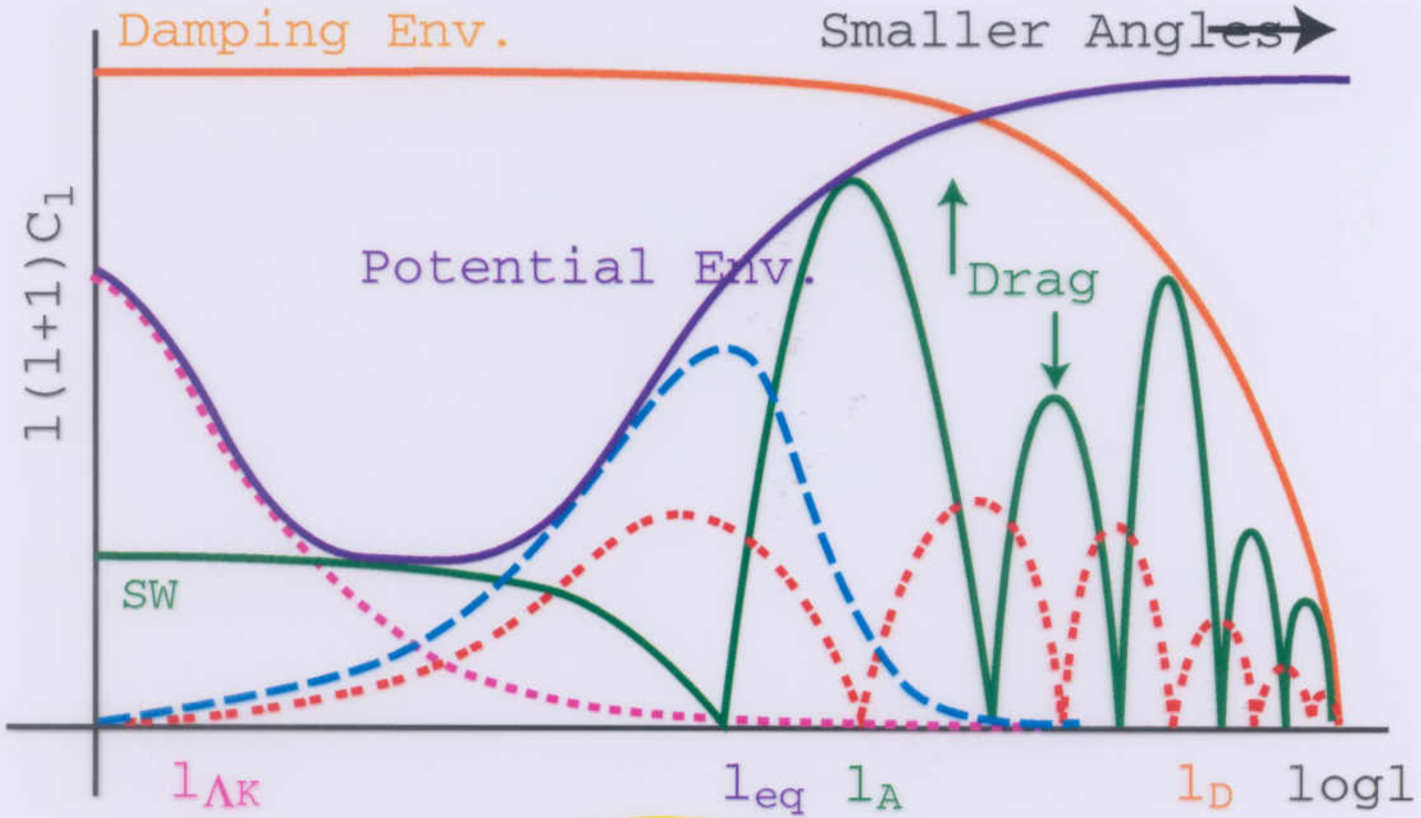
$$\text{ISW:} \quad \int_{t_{dec}}^{t_o} \dot{\phi}\,(r,t)\,dt$$

Rees-Sciama Effect



The physics of CMB anisotropies

... acoustic oscillations of $\overset{\text{coupled}}{\llcorner}$ baryon-photon fluids



	Ω_K	Ω_Λ	Ω_0h^2	Ω_Bh^2
$l_{\Lambda K}$	↑	↑	●	●
l_{eq}	↑	↓	↑	●
l_A	↑	↓	↓	↑
l_D	↑	↓	↓	↑

●········● Late ISW

●– – – –● Early ISW

●———● Eff. Temp.

●- - - -● Doppler

→ baryon drag ($\propto \Omega_B h^2$): increases grav. compression – enhances odd peaks / suppresses even peaks

(Hu, Sugiyama & Silk
astro-ph/9604166)

Things to measure

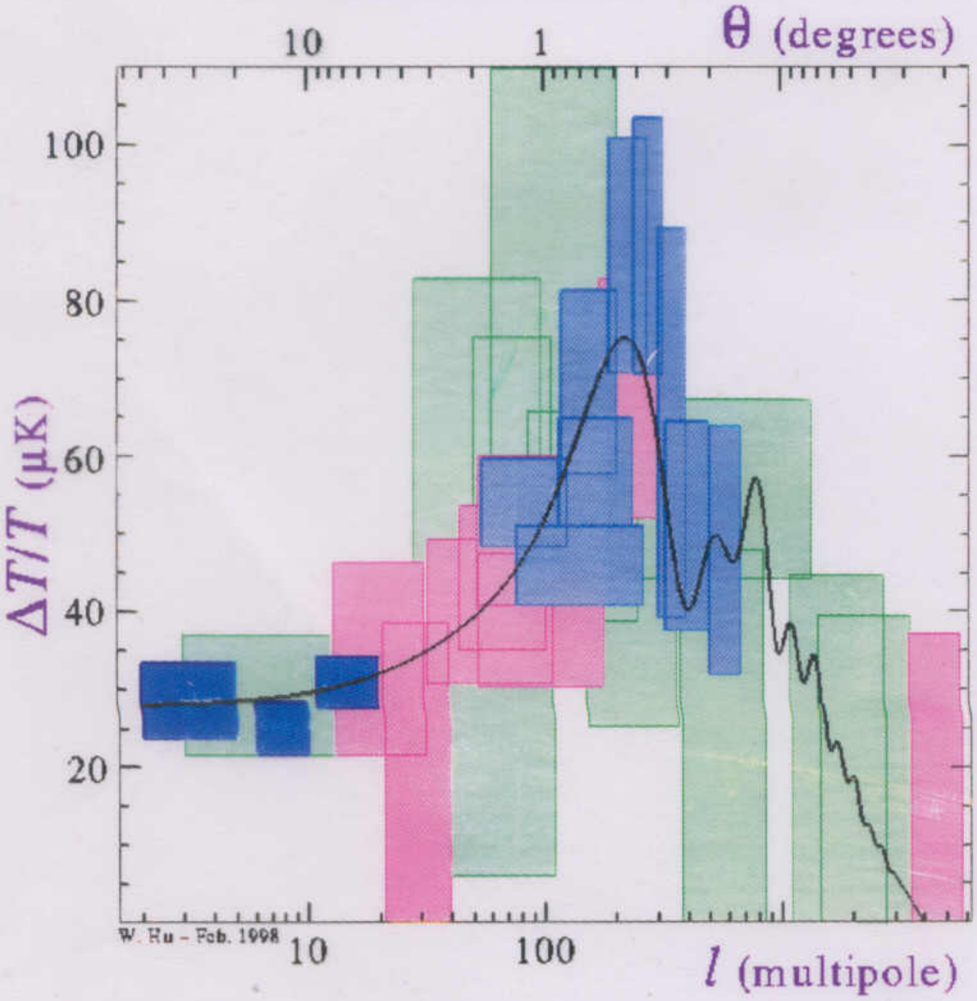
l_{A} clean measure of Ω_K. (Degenerate with Ω_Λ, but not if $\boldsymbol{l}_{\Lambda K}$ constrained.)

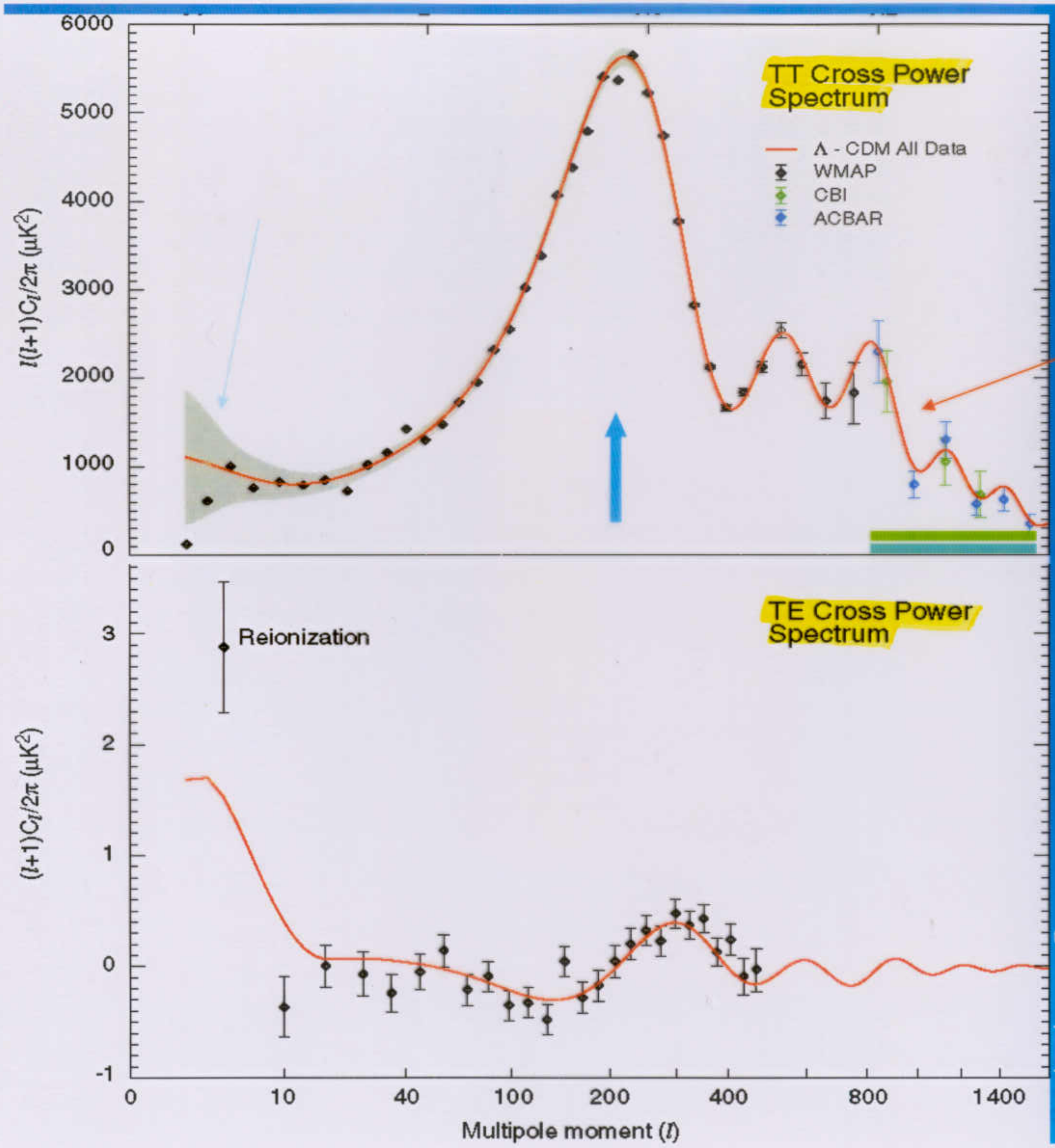
$l_{\mathrm{eq}}/l_{\mathrm{A}}$ independent of Ω_Λ, Ω_K, weakly on $\Omega_{\mathrm{B}}h^2$; isolates $\Omega_0 h^2$.

$l_{\mathrm{A}}/l_{\mathrm{D}}$ independent of Ω_Λ, Ω_K, weakly on $\Omega_0 h^2$; isolates $\Omega_{\mathrm{B}}h^2$.

Together possibly h.

Current CMB Quilt





Temperature

85% of sky

Best fit model

$n=0.99$

$\sigma_8 = 0.9$

$\Omega_b h^2 = 0.024$

$\Omega_x h^2 = 0.126$

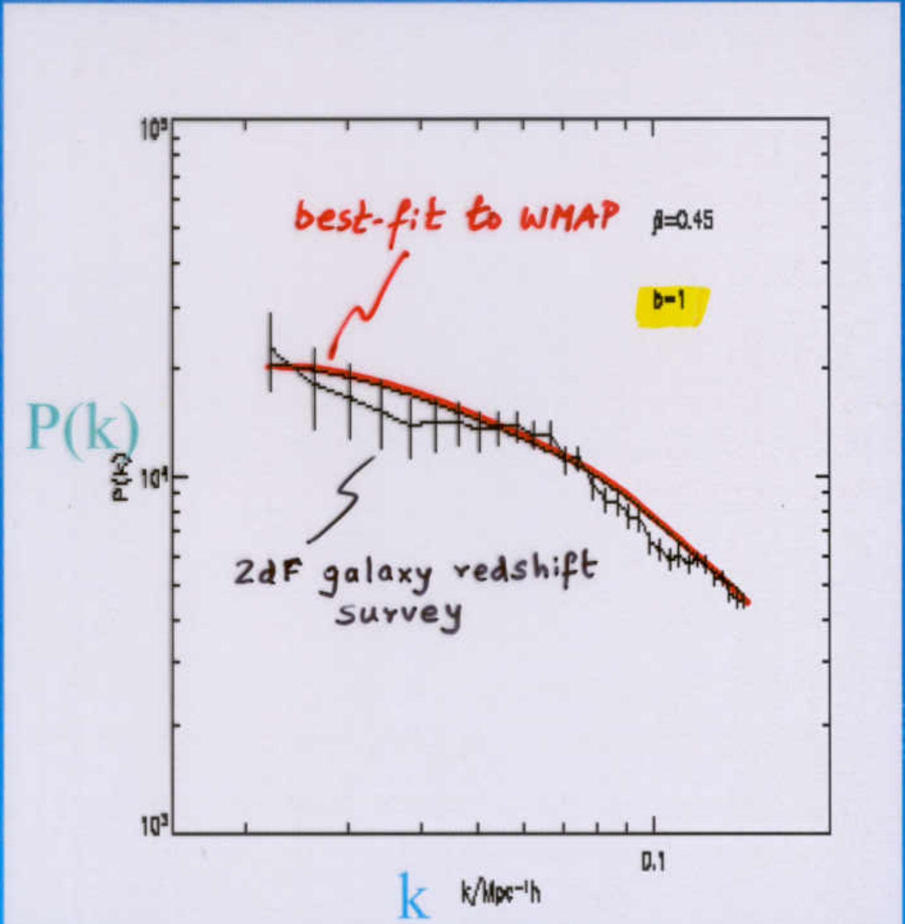
$H_0 = 72$

$\tau = 0.17$

Temperature-polarization

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

LCDM Best Fit Parametrs

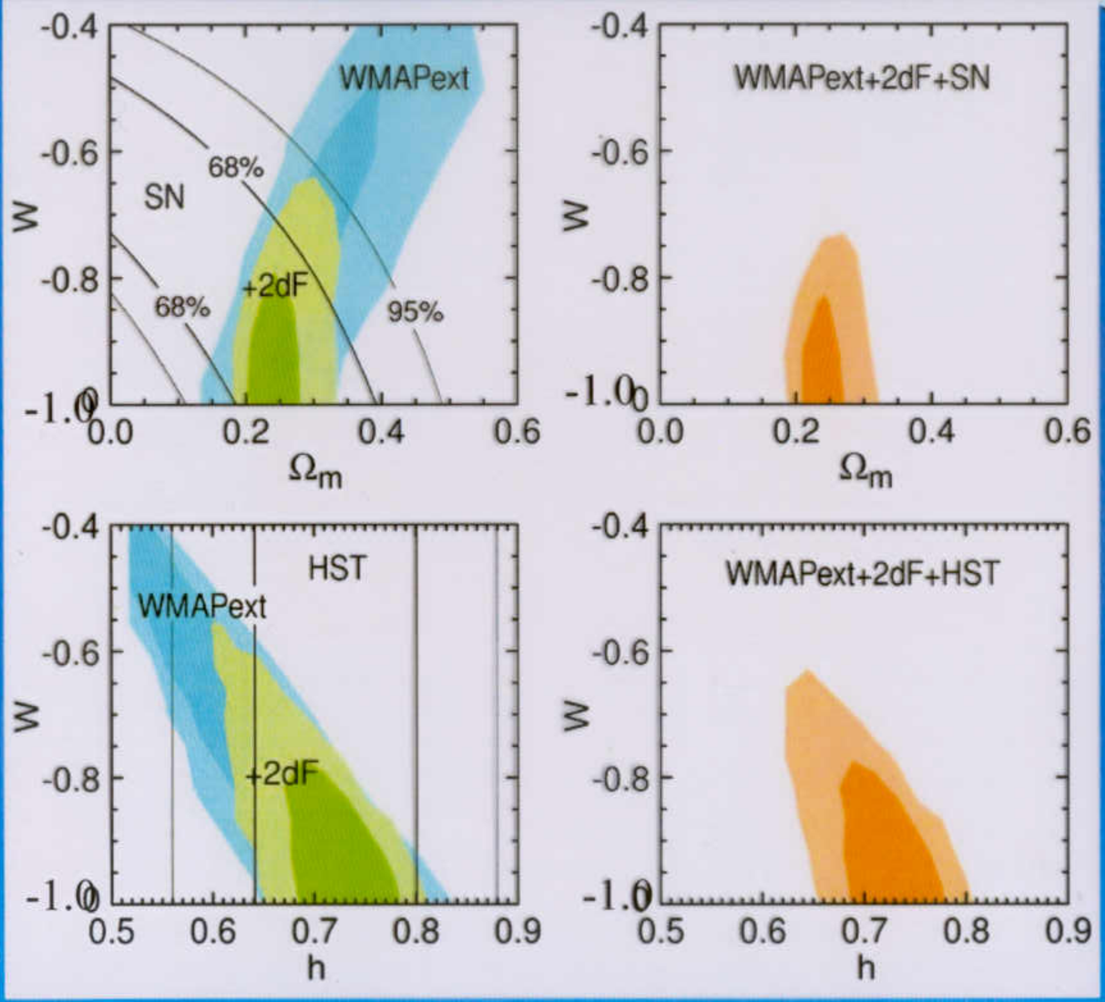
Table 7. Best Fit Parameters: Power Law Λ CDM

	WMAP	WMAPext[16]a	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	$0.75^{+0.08}_{-0.07}$
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
τ	$0.166^{+0.076}_{-0.071}$	$0.143^{+0.071}_{-0.062}$	$0.148^{+0.073}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
h	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.03	0.72 ± 0.03
$\Omega_m h^2$	0.14 ± 0.02	0.13 ± 0.01	0.134 ± 0.006	0.133 ± 0.006
$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0226 ± 0.0008
χ^2_{eff}/ν	1431/1342	1440/1352	1468/1381	... [b]

[a] *WMAP* +CBI+ACBAR

[b] Since the Lyman α data points are correlated, we do not quote an effective χ^2 for the combined likelihood including Lyman α data (see Verde et al. (2003)).

Beyond the Standard Model: Dark Energy



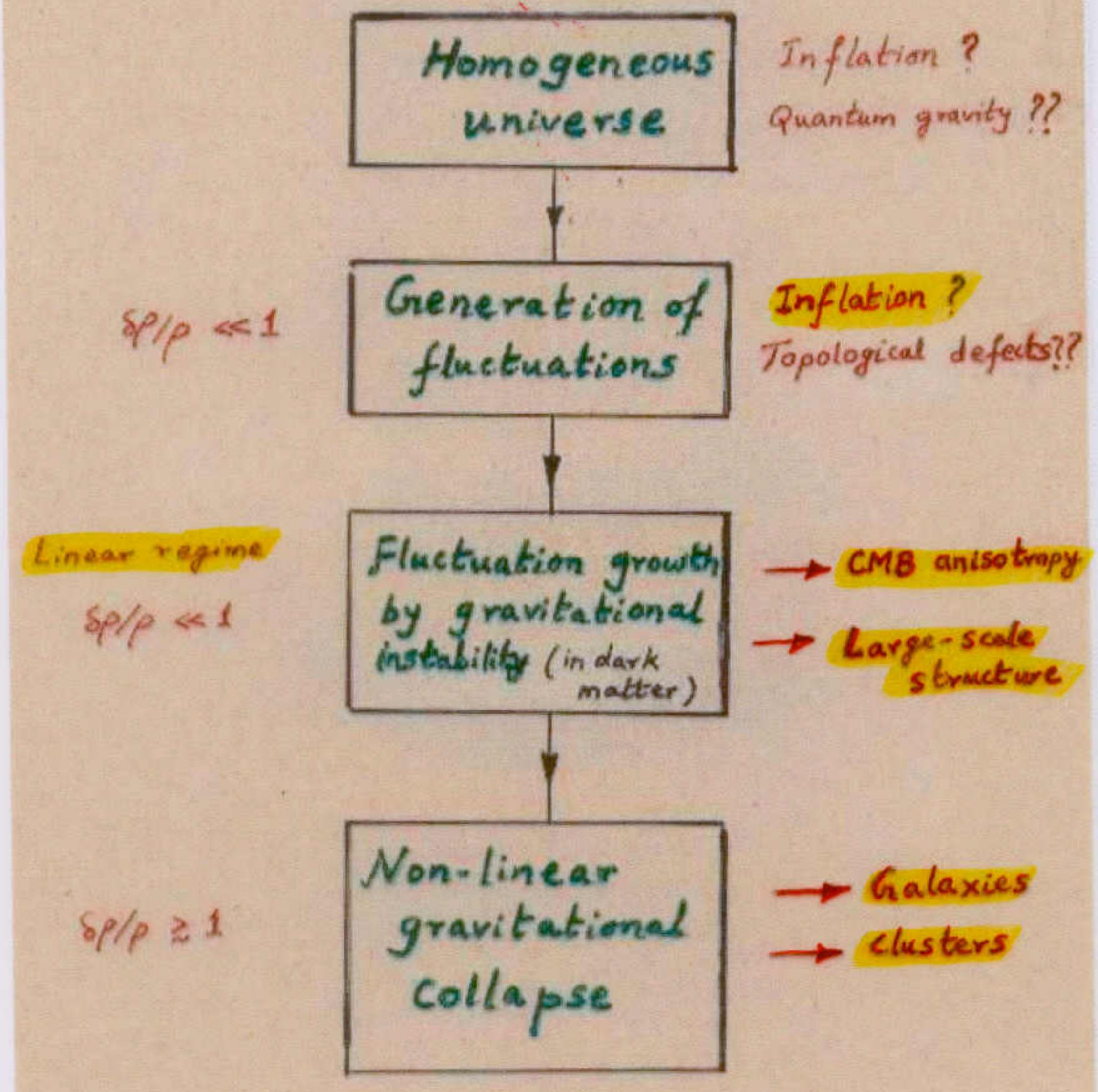
CMB data consistent with other data sets if w is near -1

(dark energy is a cosmological constant)

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 $\Omega_b h$

Formation of Structure in the Universe



Homogeneous universe

Inflation ?

Quantum gravity ??

$\delta\rho/\rho \ll 1$

Generation of fluctuations

Inflation ?

Topological defects??

Linear regime

$\delta\rho/\rho \ll 1$

Fluctuation growth by gravitational instability (in dark matter)

→ CMB anisotropy

→ Large-scale structure

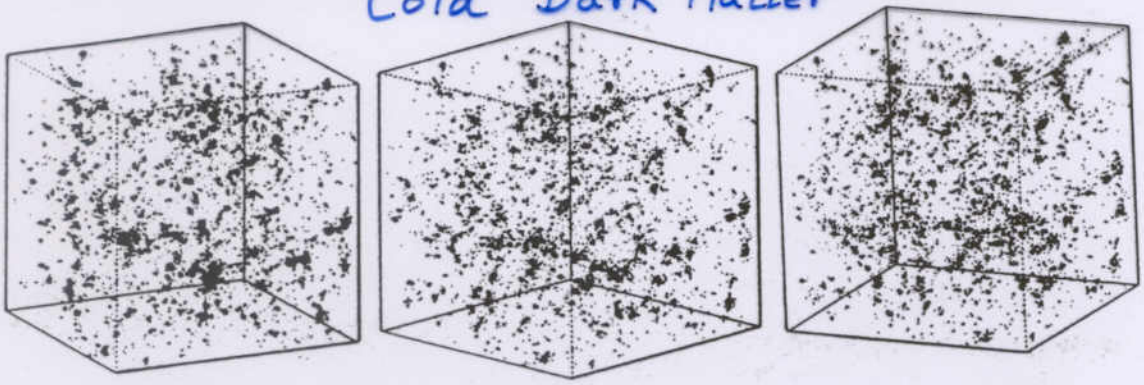
$\delta\rho/\rho \gtrsim 1$

Non-linear gravitational collapse

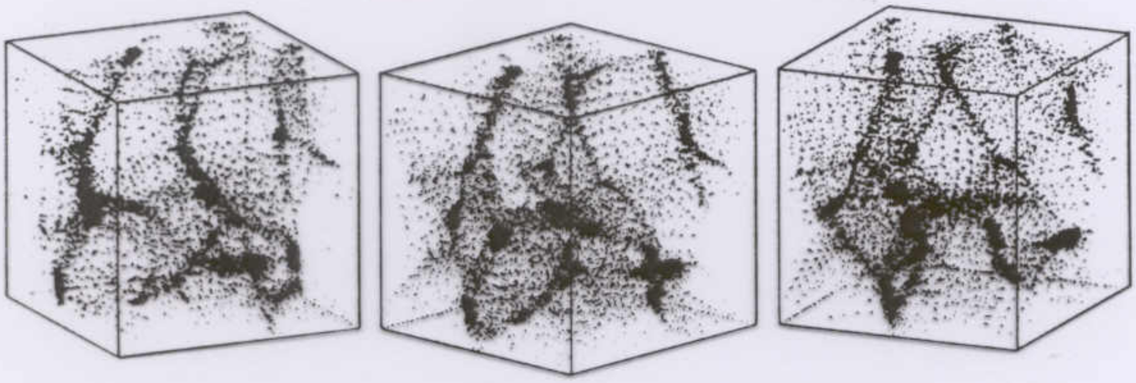
→ Galaxies

→ Clusters

Cold Dark Matter



Hot Dark Matter



Computer simulations of structure formation in the cold dark-matter (top) and hot dark-matter (bottom) scenarios (assuming random overdensities act as the seeds). Galaxies form first and cluster later in cold dark-matter models; with hot dark matter, by contrast, clustering occurs first at large scales, followed later by fragmentation and galaxy formation.

$$\frac{\delta\rho}{\rho}(\tilde{x},t) = \frac{1}{(2\pi)^3}\int d^3k\; \delta_{\tilde{k}}(t)\, e^{-i\tilde{k}\cdot\tilde{x}} \quad ; \quad \langle \delta_{\tilde{l}}\, \delta_{\tilde{m}} \rangle = \langle |\delta_k|^2 \rangle (2\pi)^3 \delta^{(3)}(\tilde{l}-\tilde{m})$$

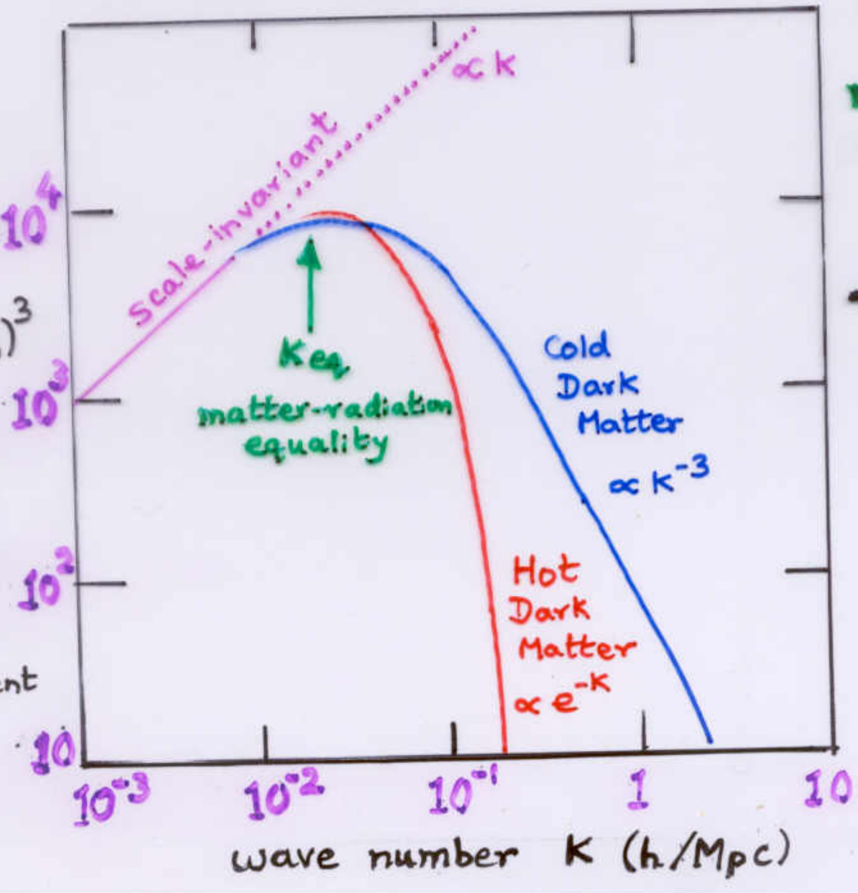
Plane-wave expansion

$$\equiv$$

$$P(k) = Ak^n$$

$n=1$ ⇒ Scale-invariant Harrison-Zeldovich Spectrum

→ "expected" from inflation



Power

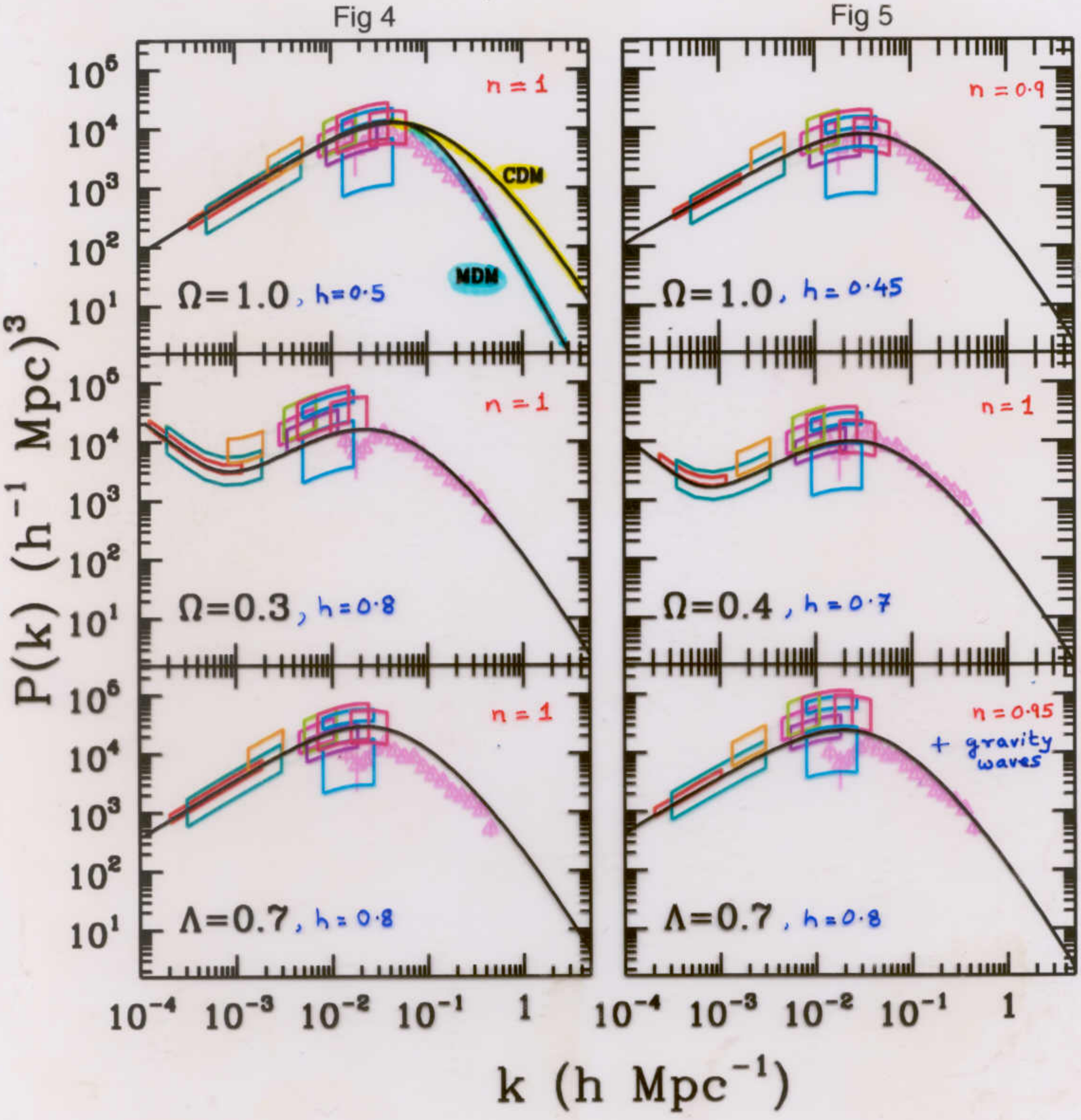
$\mathcal{P}(k)$ $(\text{Mpc}/h)^3$

$= Ak^n \otimes T^2(k)$

"transfer fn."

... dependent on (dark) matter content

The matter power spectrum for modified CDM models



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

Studies of structure formation usually assume a Harrison-Zeldovich spectrum for the primordial density perturbation $P(k) \propto k^n$, $n=1$

... but inflationary models generically predict (logarithmic) departures from scale-invariance

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

$$\Rightarrow n(k) = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

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

$$\delta_H^2 \propto \left[51 + \ln\left(\frac{k^{-1}}{3000h^{-1}\,\mathrm{Mpc}}\right)\right]^\alpha$$

e.g. $\alpha = 4$ for $V \propto \phi^3 \Rightarrow n \simeq 0{\cdot}9$

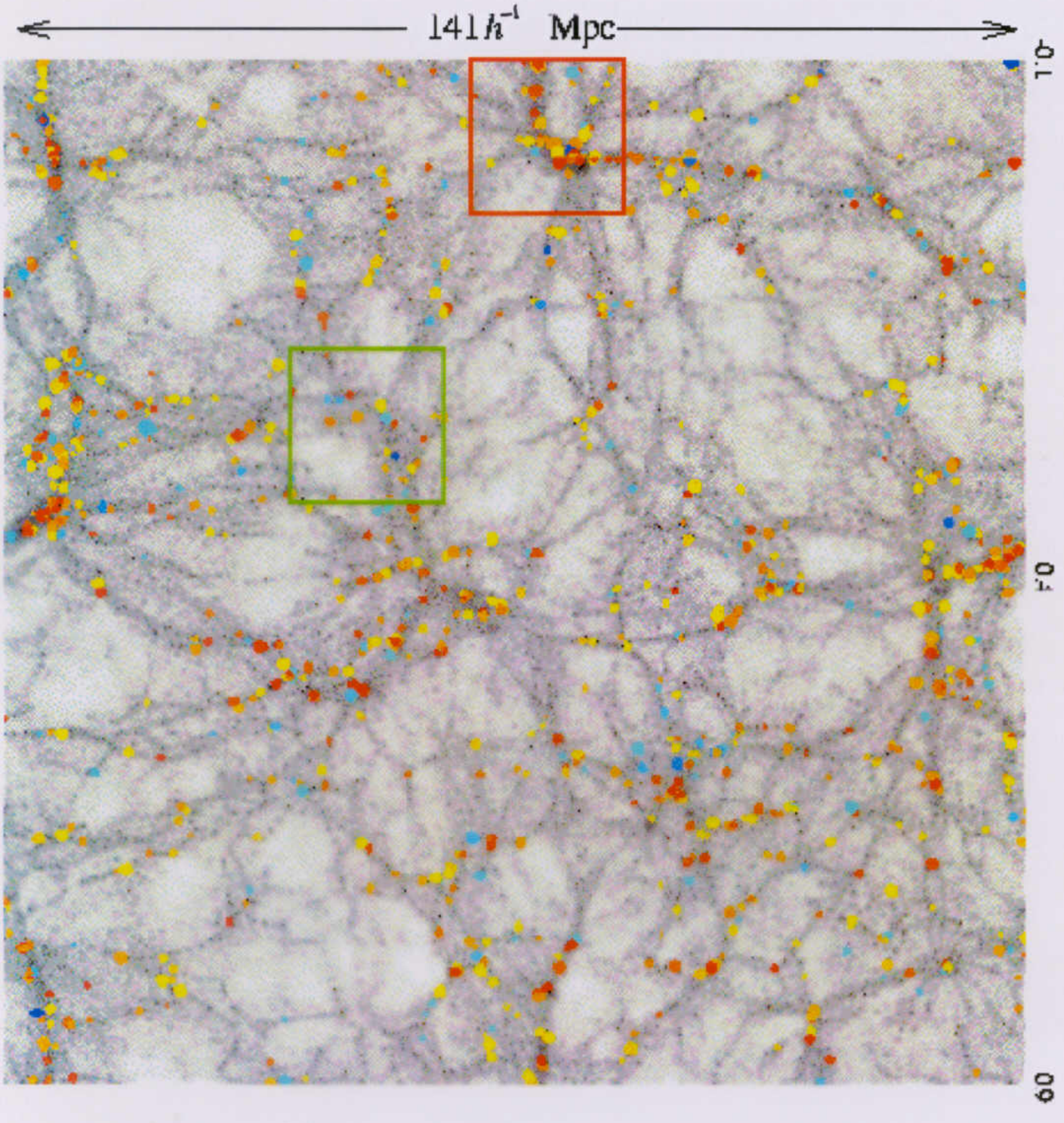
Adams, Ross & Sarkar
(hep-ph/9608336)

... however the spectrum can be very close to scale-invariant for an exponential potential ('power-law' inflation) or in 'hybrid' inflation (where the dynamics of a second field ends inflation)

But in multi-field models, can even generate features in the spectrum — 'bumps', 'steps' ...

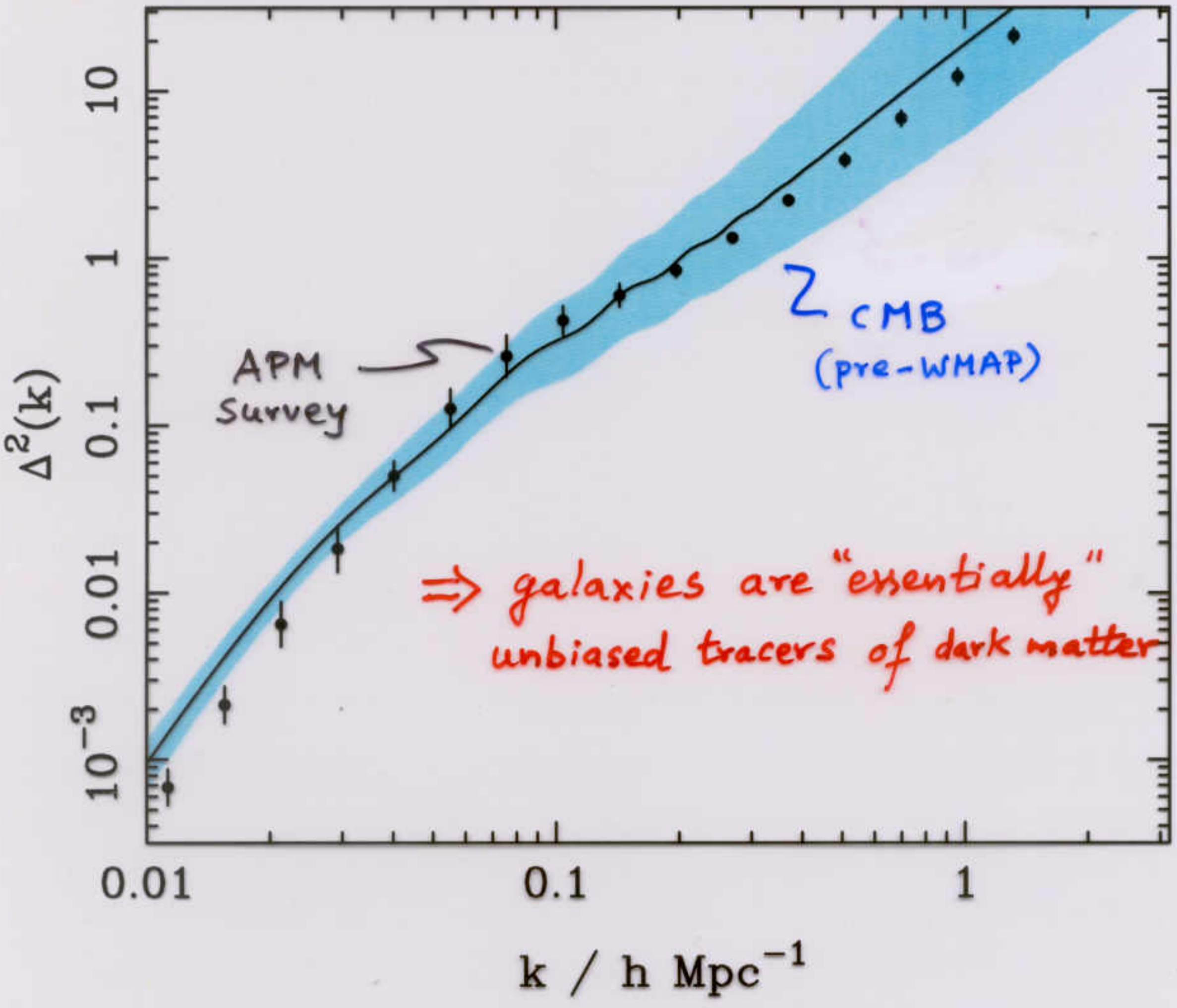
Adams, Ross, Sarkar
(hep-ph/9704286)

Do galaxies trace the dark matter?



VIRGO Collaboration
AP^{3}M simulation

Mass fluctuations from CMB vs galaxy clustering



⇒ galaxies are "essentially" unbiased tracers of dark matter

Peacock et al
(astro-ph/0105450)

Galaxy Clustering varies with Galaxy Type

How are each of them related to the underlying Mass distribution?

Bias depends upon Galaxy Color & Luminosity

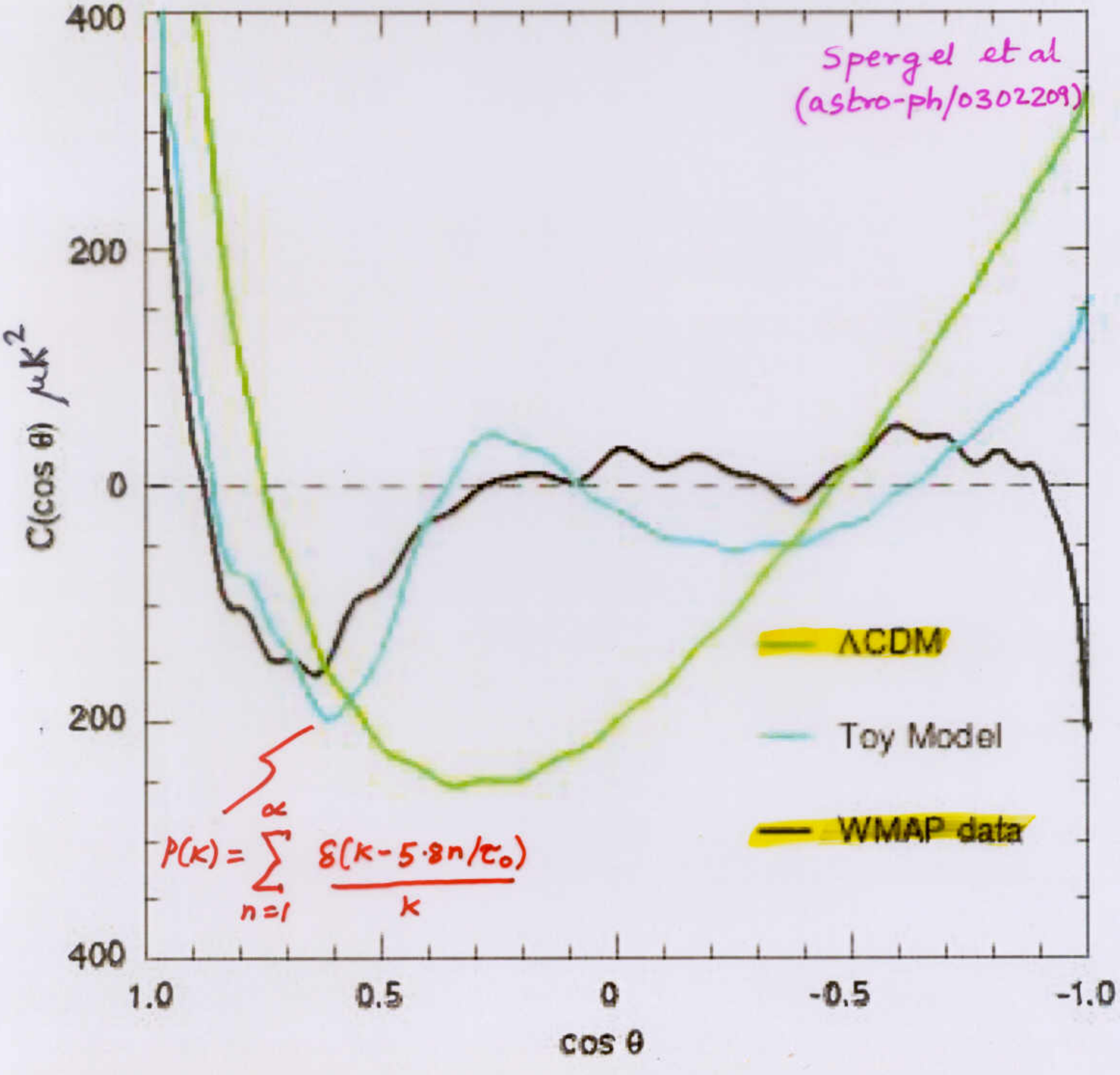
Caveat for inference of Cosmological Parameters from LSS

Frieman, CAPP 2003

expected temperature correlations
at large angles due to Λ (late ISW effect)
not seen by WMAP (and COBE)

$\Rightarrow$ 'best-fit' ΛCDM model unlikely @ ~1% level
(even after accounting for "cosmic variance")

is this indication of an infrared cutoff in
the primordial fluctuations on the scale of H_0^{-1}?



$$P(k) = \sum_{n=1}^{\infty} \frac{\delta(k-5\cdot 8n/\tau_0)}{k}$$

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

$\phi^2 \Lambda^2 \; , \; \Lambda^4$

↓

Solve by (softly) broken supersymmetry

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

renormalisable

(19 parameters)

non-renormalisable

neutrino mass

proton decay

FCNC

⋮

huge 'cosmological constant' when coupled to gravity

... no solution known!

(how many parameters will it have?)

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

An alternative to the ΛCDM model

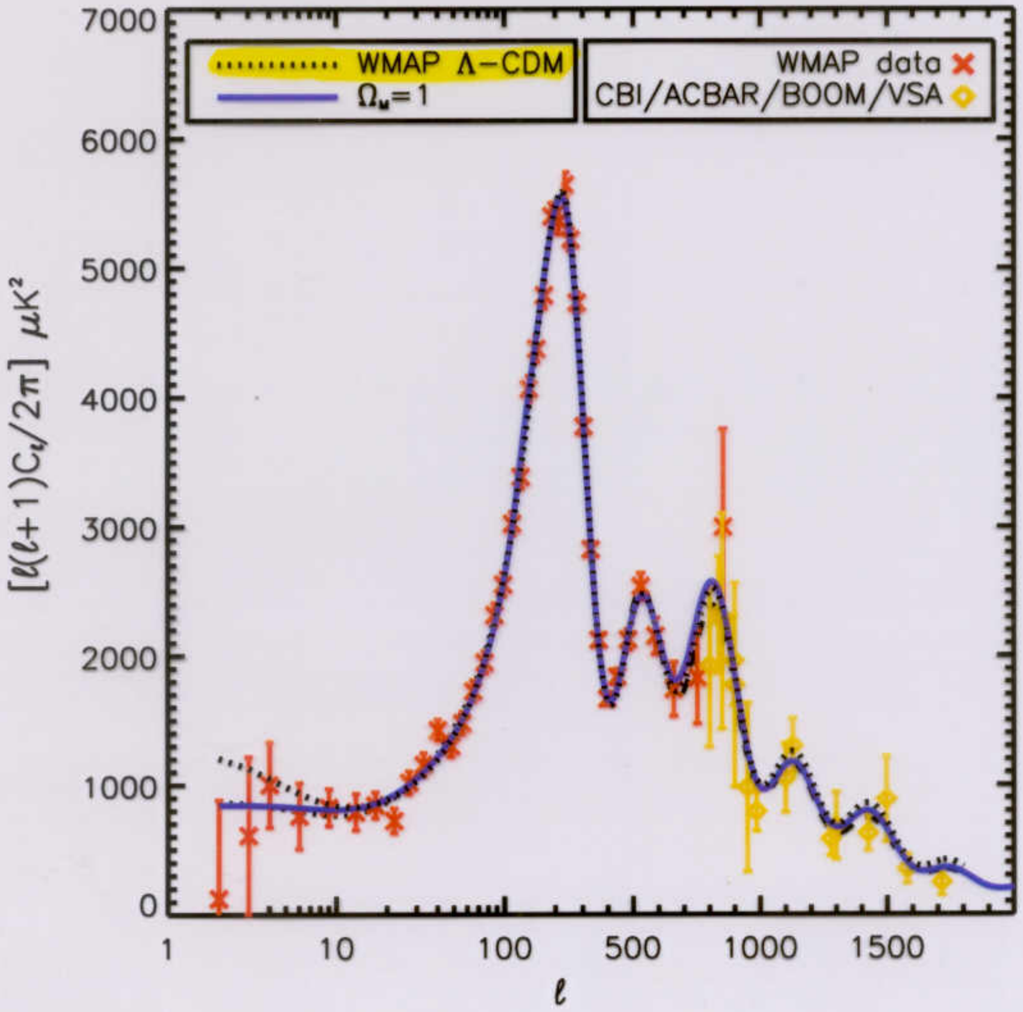
WMAP 'concordance' model: $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, $h = 0.72$, $n = 0.99$

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

$n = 1.02$, for $k < k_1 = 0.0096\ \mathrm{Mpc}^{-1}$

$= 0.81$, for $k > k_1$

... fits even better!

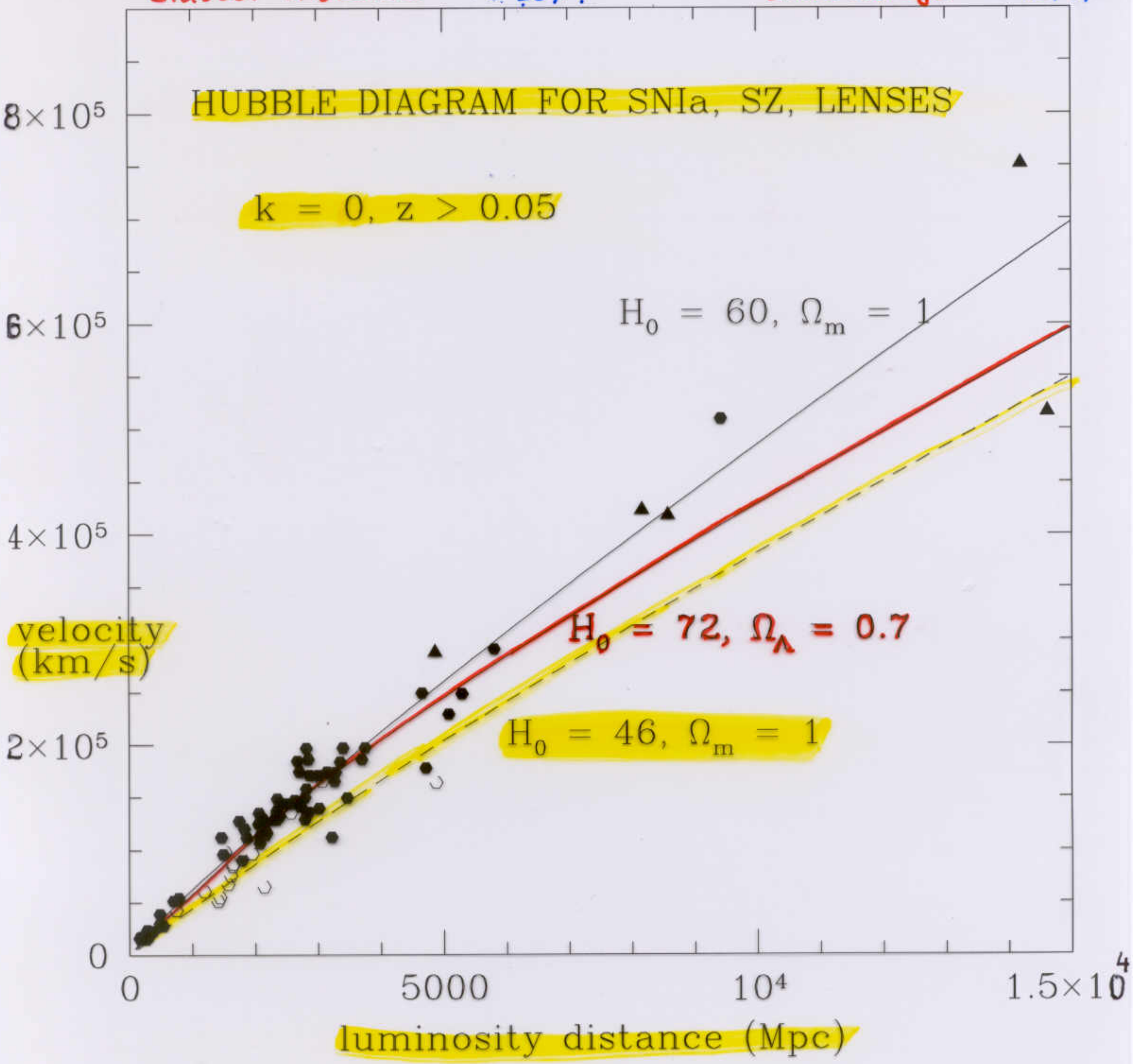


Blanchard, Douspis, Rowan-Robinson, S.S.
(astro-ph/0304237)

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

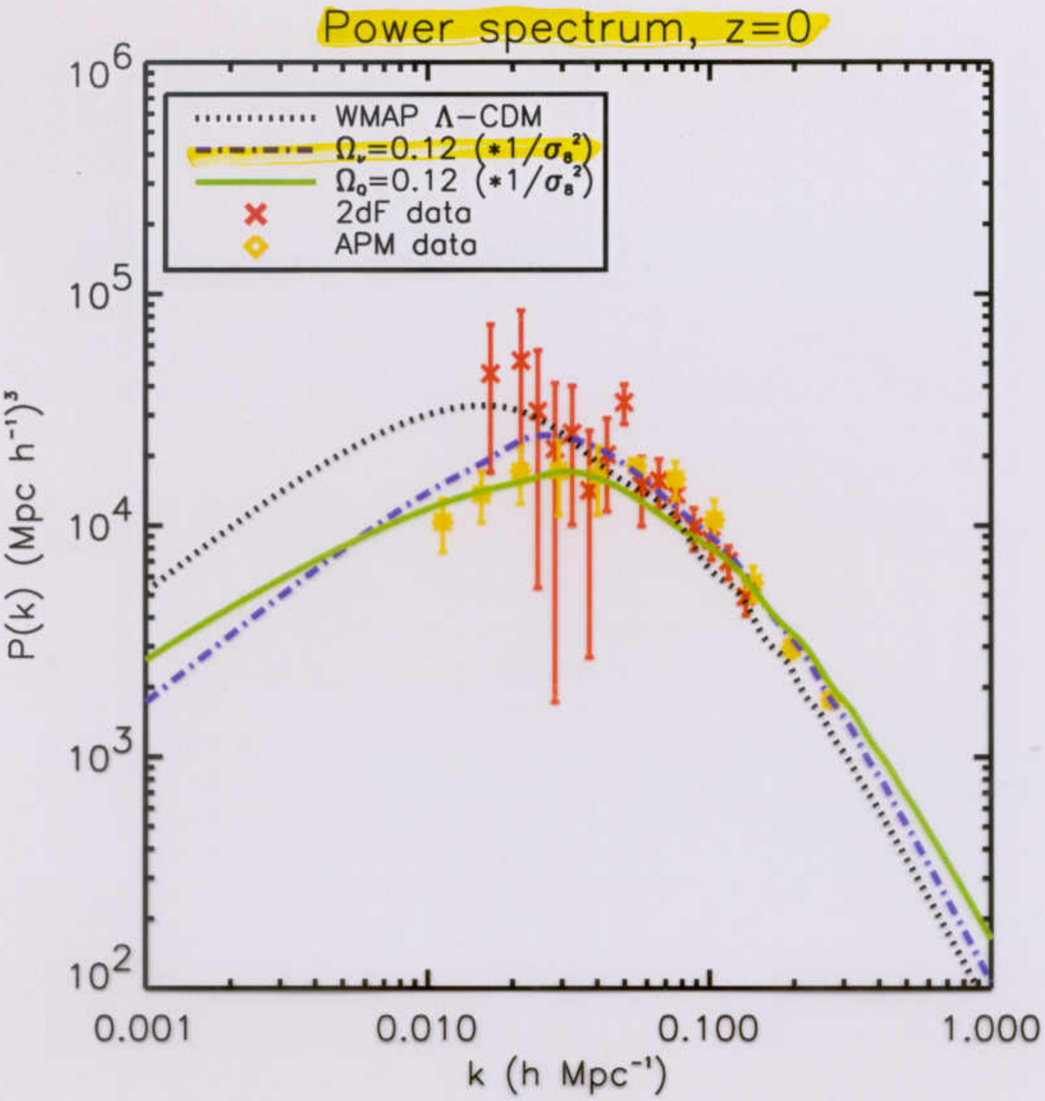
... but not with direct (and deeper) methods:

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)


Power spectrum, z=0

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

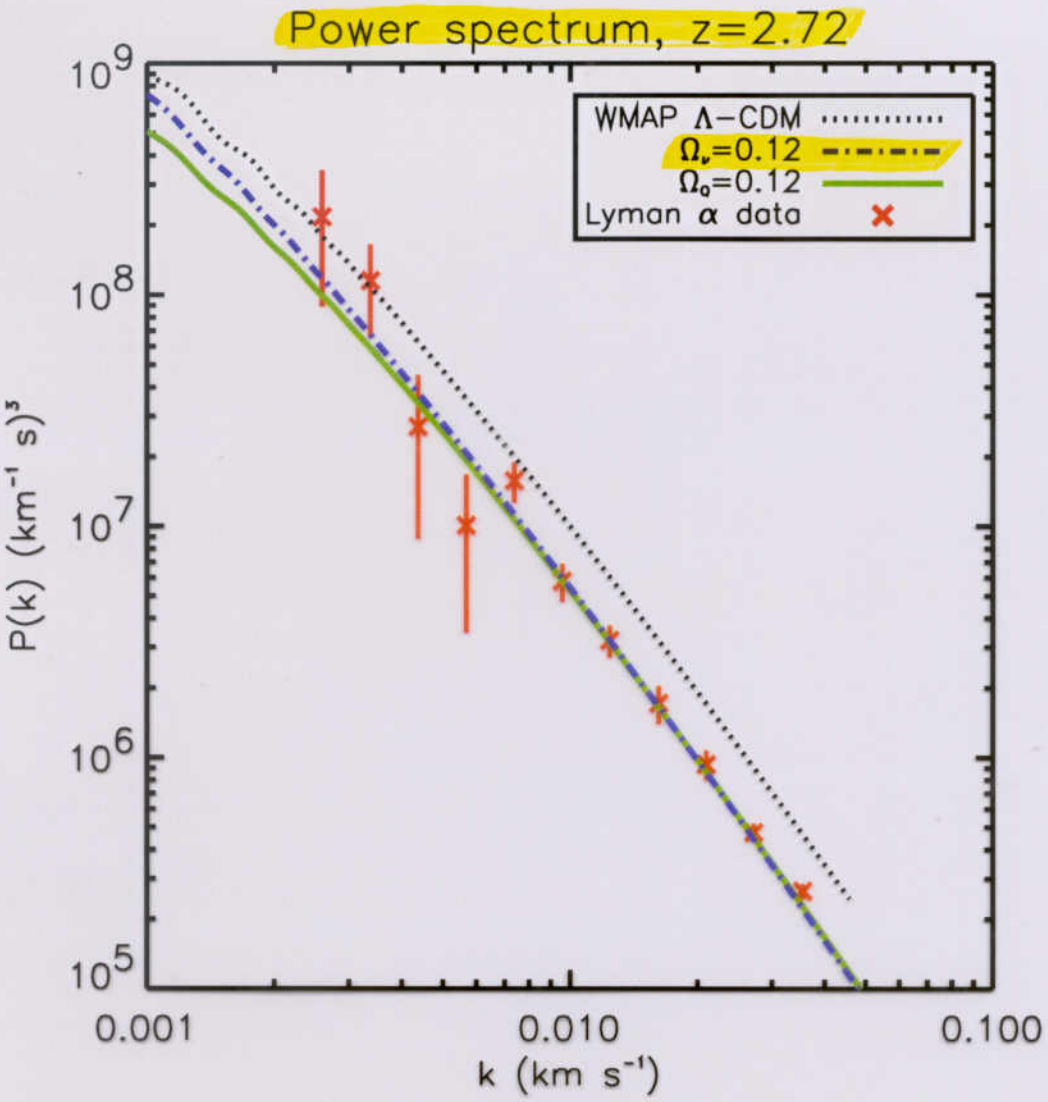
Obtain good fit to large-scale structure data with 3 quasi-degenerate neutrinos of mass ~0·8 eV

⇒ $\Omega_\nu = 0\cdot12$ (NB: Well above WMAP 'bound'!)

and $\Omega_B h^2 = 0\cdot021$ (in agreement with BBN value)

⇒ baryon fraction in clusters of ~15% (acceptable?)

and $\sigma_8 = 0\cdot64$ (consistent with weak lensing determination)

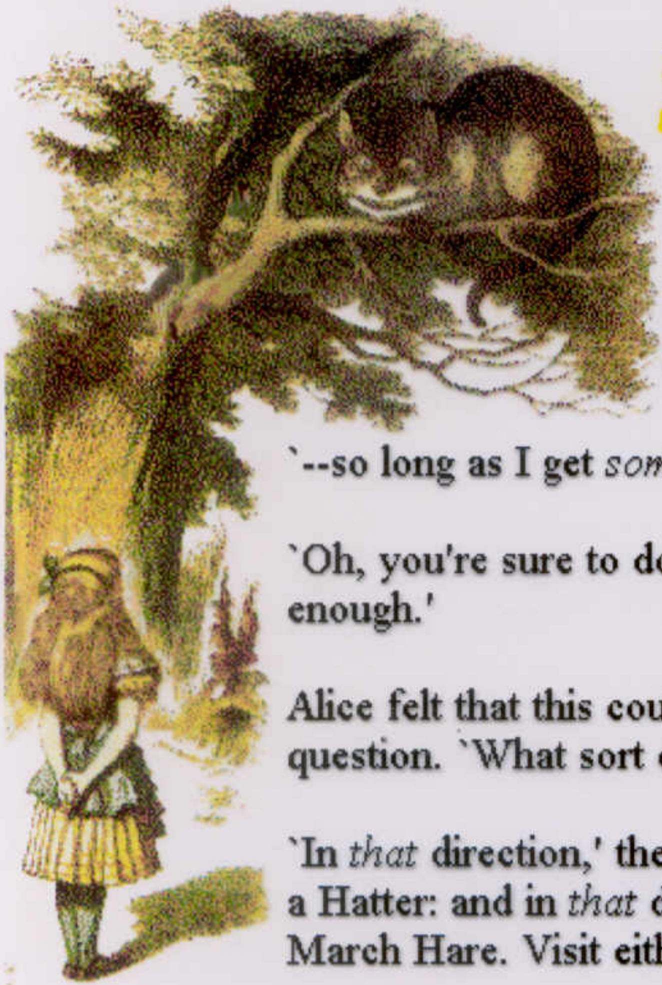


... with a bias factor $b \simeq 1/\sigma_8$, can also fit power spectrum of Lyman-alpha forest (if amplitude is reduced by ~1σ calibration uncertainty) $\Rightarrow$ 20%.

→ 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)

... 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