Dark Energy : 1984-2011

- 1984 : v_p, M/L, H_0
- 1990 : $P(k)$
- 1993 : M_b/M_{tot} in clusters
- 1995 : C_l
- 1998 : SNIa
- 2006 : BAO
- 2008 : $H(z)$
- + weak shear, redshift distortions, SZ
- Any dark energy ?

1984 : Peebles proclaims $\Lambda \neq 0$

ApJ 284 :439 (1984)

$0.1 < \Omega_M < 0.3$

- peculiar velocities toward mass concentrations $\Delta\rho$
  At edge of overdense region of radius R :
  $v_p \sim [G\Delta M/R^2]t_0 \sim [G\rho(\Delta\rho/\rho)R]t_0$ (Newton !)
  Assume "light traces mass" to measure $\Delta\rho/\rho$
- M/L(clusters)=M/L(universe)
- ages of stars$<$age of universe
  requires $\Omega_M < 1$ unless $H_0 <\sim 50$

Inflation and/or anti-coincidence $\Rightarrow \Omega_T \sim 1 \Rightarrow \Omega_\Lambda \sim 0.8$

Peebles understood it all :

"The problem....is that it does not seem plausible..... At the end of inflation.....

$$\frac{\rho_\Lambda}{\rho(T = 10^{14} GeV)} \sim 10^{-102}$$

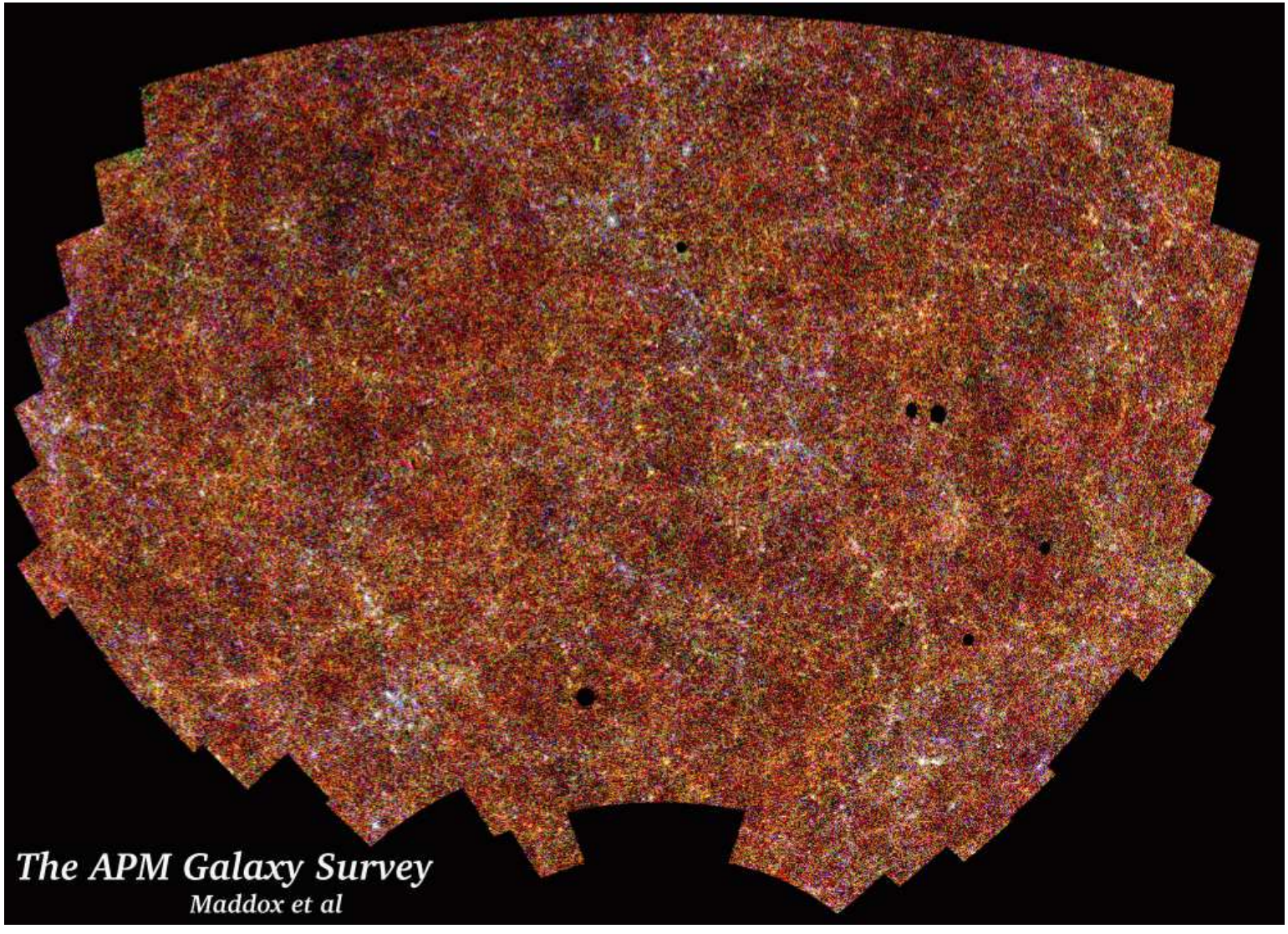
It would be an extraordinary conincidence if the expansion of the universe redshifted this to the wanted present value $\Omega_M^{-1} - 1 \sim 3 - 10$."

"Also, the wanted present value of Λ defines a characteristic energy :

$$[\rho_\Lambda (\hbar c)^3]^{1/4} \sim 3meV$$

which does not seem to be a "natural" quantity".

1990 APM galaxy correlatons



1990 : APM $\Rightarrow$ $\Omega_\Lambda \sim 0.7$

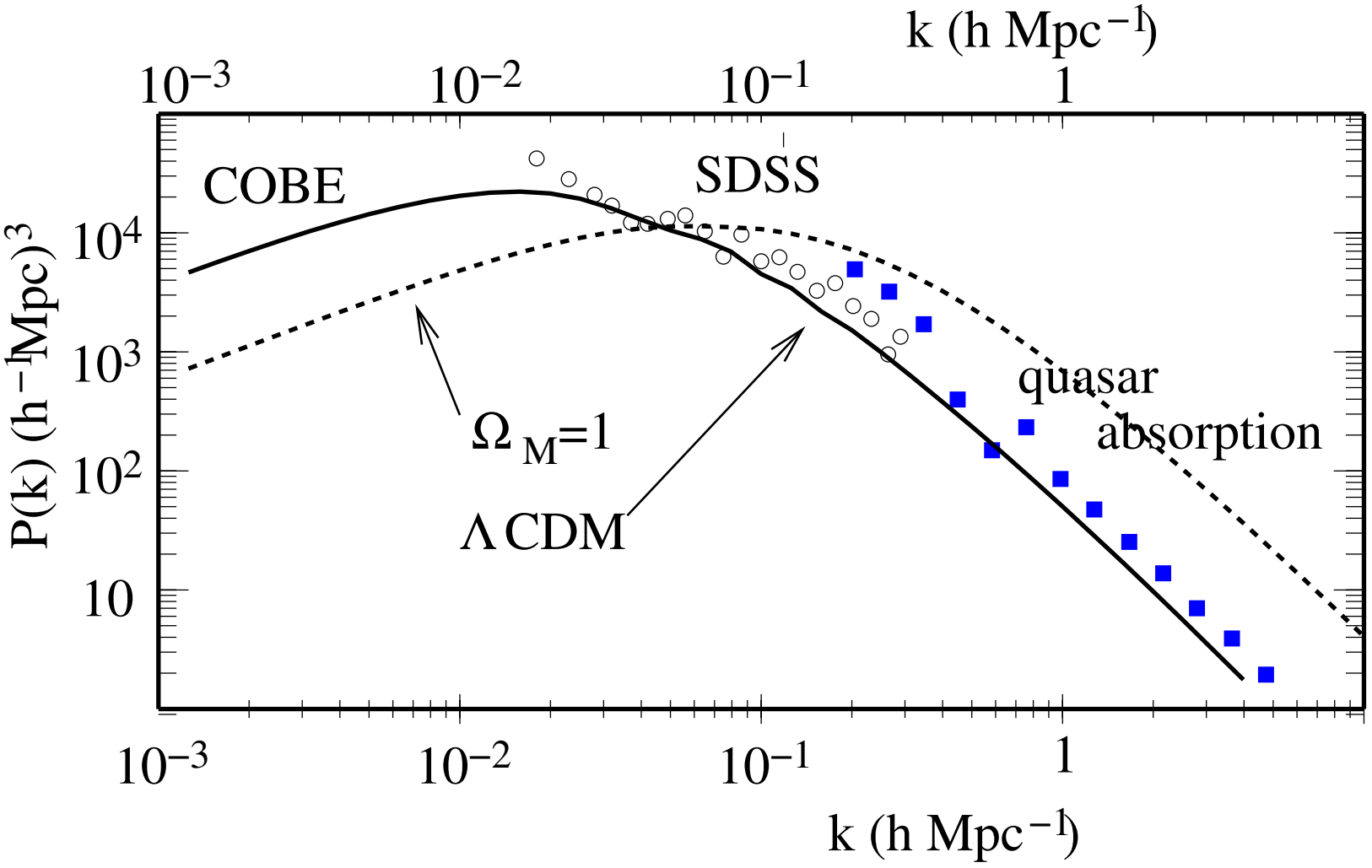
"In particular, our results imply more large-scale clustering (of galaxies) than predicted by popular ($\Omega_M = 1$) versions of the Cold Dark Matter cosmogony"

Maddox, Efstathiou, Sutherland and Loveday
MNRAS (1990) 242, 43

"It is argued here that the success of the cosmological cold dark matter (CDM) model can be retained and the new observations of very large scale cosmological structures can be accommodated in a spatially flat cosmology in which as much as 80 percent of the critical density is provided by a positive cosmological constant."

Maddox, Efstathiou and Sutherland
Nature (1990) 348, 705

1991 COBE, 2007 SDSS : $P(k)$



$\Rightarrow \Omega_M \neq 1$ unless primordial spectrum not scale invariant (TCDM)

1990 : Kolb & Turner

"The Early Universe" Chapter 9, Section 7 :

The Ω Problem

Solution : "A smooth component of mass density"

- $(\Omega_\Lambda, \Omega_M) \sim (0.8, 0.2)$ (ΛCDM)
  "a very good match to the observed universe"
- $\Omega_R \sim 0.8$: Relativistic particles from recent decays
- Uniform distribution of faint galaxies.
  $\rightarrow$ biased formation of bright galaxies

$\Rightarrow$Importance of "Hubble diagrams" $m(z)$, $\theta(z)$, $n(z)$

1986 : $n_{gal}(z) \Rightarrow \Omega_M = 1$?

Edwin D. Loh, Phys.Rev.Lett. 57 (1986)

"Theoretical studies of luminosity evolution should be made to see whether the tests of evolution that have already been performed are adequate."

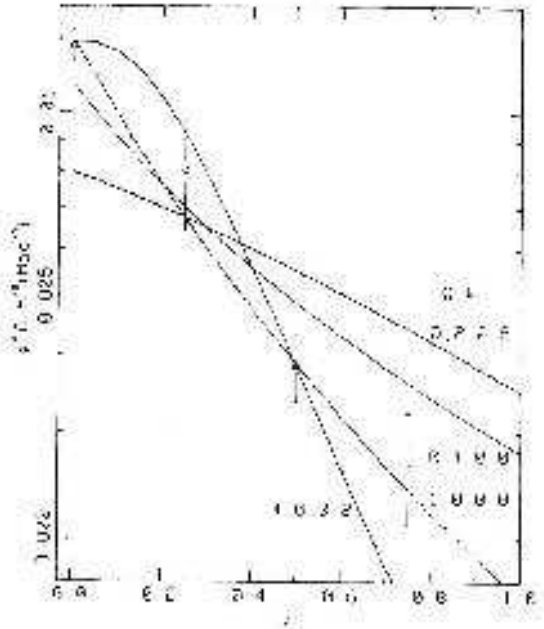


FIG. 1. The normalized number density ϕ^*A vs red shift z. The data (Ref. 1 except at $z=3$ which is from Ref. 6) are displayed with 1σ error bars. The curves show several several cosmological models labeled with (Ω,λ) with ϕ^* adjusted for minimum χ^2. The model (0.2,0.8), which differs from the Einstein–de Sitter model (1.0,0.0) only in the variable $\Omega=\lambda$.

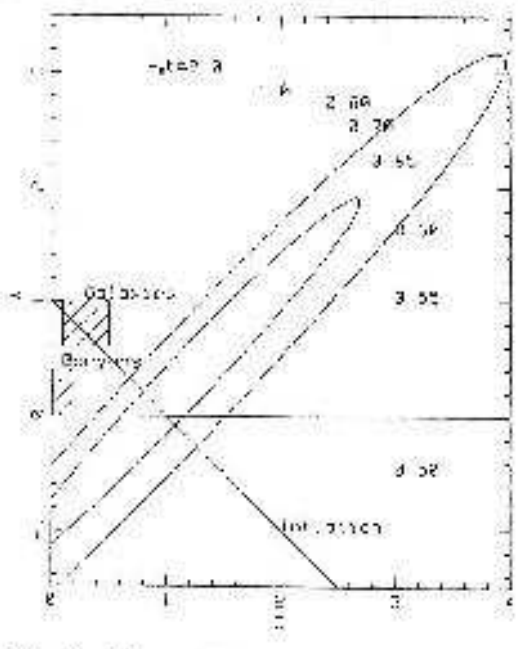


FIG. 2. The 95%- and 67%-confidence regions in the Ω-λ plane. Other measurements (at the 95%-confidence level) of the mass density are shown as hatched regions: $0.03 < \Omega_{baryon} < 0.2$ from Ref. 12 and $0.1 < \Omega_{gal} < 0.5$ from Ref. 9. The prediction of the inflationary theory is shown as the diagonal line. Loci (dotted lines) of models with equal H_0 are

1993 : v_p : Last stand for $\Omega_M = 1$

Ω and the initial fluctuations from velocity and density fields Nusser and Dekel, ApJ 405(1993)

$\Omega_M < 0.3$ ruled out a 4-6σ !

"The fact that the simplest choices of $\Omega = 1$, Gaussian initial fluctuations and IRAS galaxies tracing mass are all consistent with one another under gravitational instability is a remarkable result in favor the the standard model

1993 : baryon fraction in clusters

"Challenge to cosmological orthodoxy"
White, Navarro, Evard, Frenk, Nature 366 (1993)

Nucleosynthesis $\Rightarrow \Omega_b h^2 = 0.0125 \pm 0025$

Clusters : $M_b/M_{tot} > 0.05 h^{-3/2} + 0.009 \quad \sim 0.1$
Rosat data

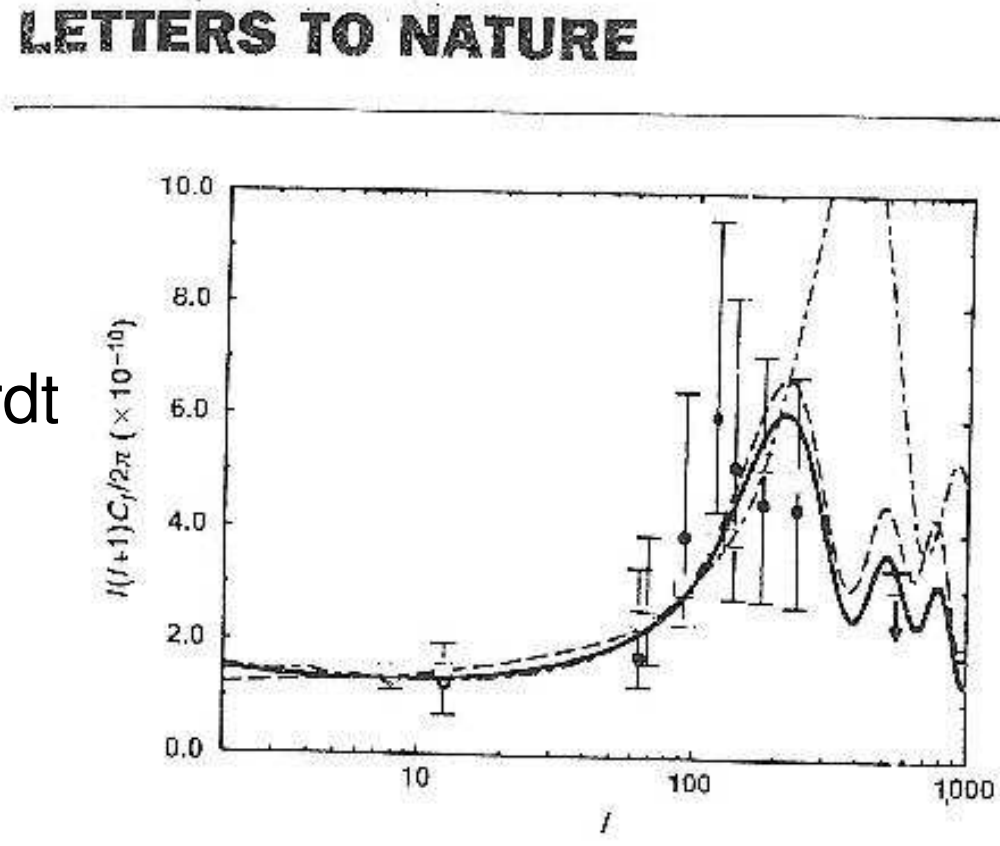
Clusters are representative of the universe
Simulations of baryon/darkmatter infall

$$\Rightarrow \Omega_M = \Omega_b \frac{M_{tot}}{M_b} = \frac{0.16 h^{-1/2}}{1 + 0.16 h^{3/2}} \sim 0.12$$

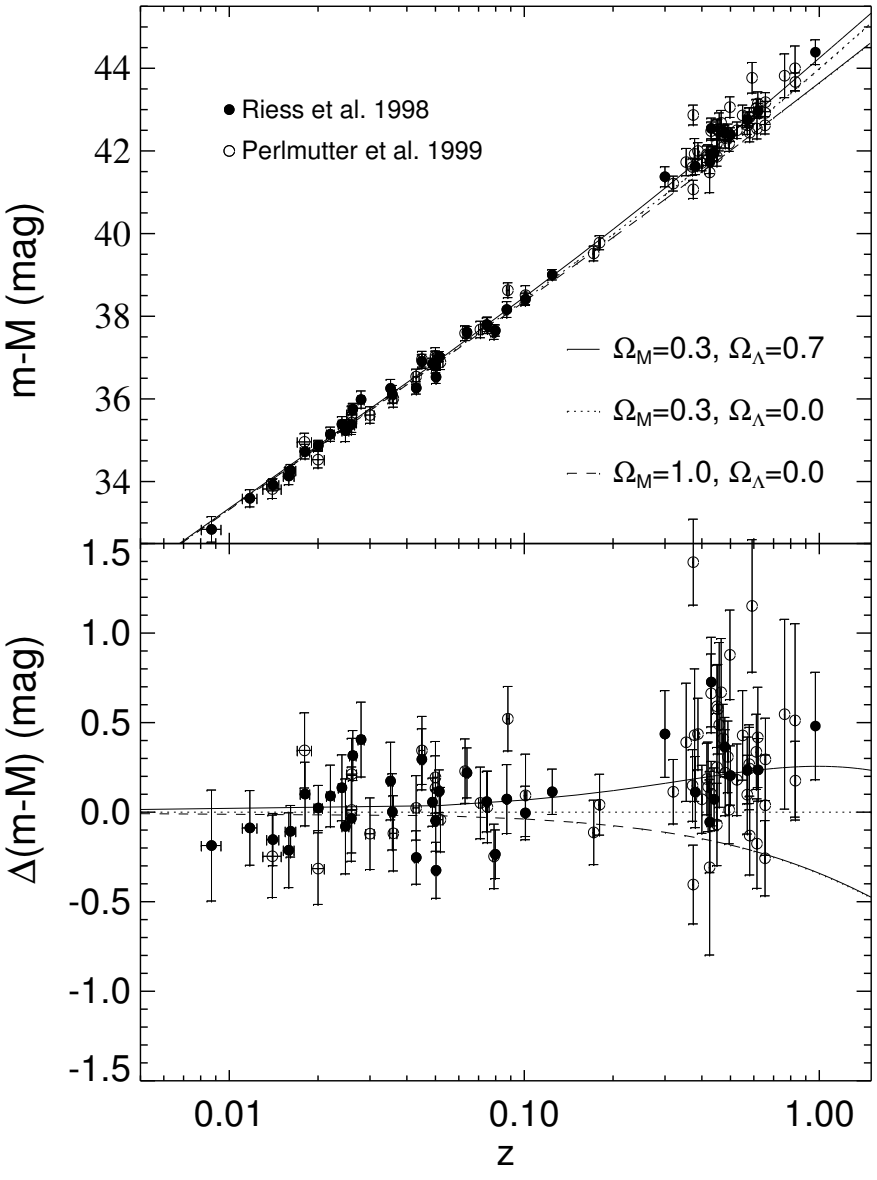
1995 : $C_l \Rightarrow \Omega_T \sim 1$

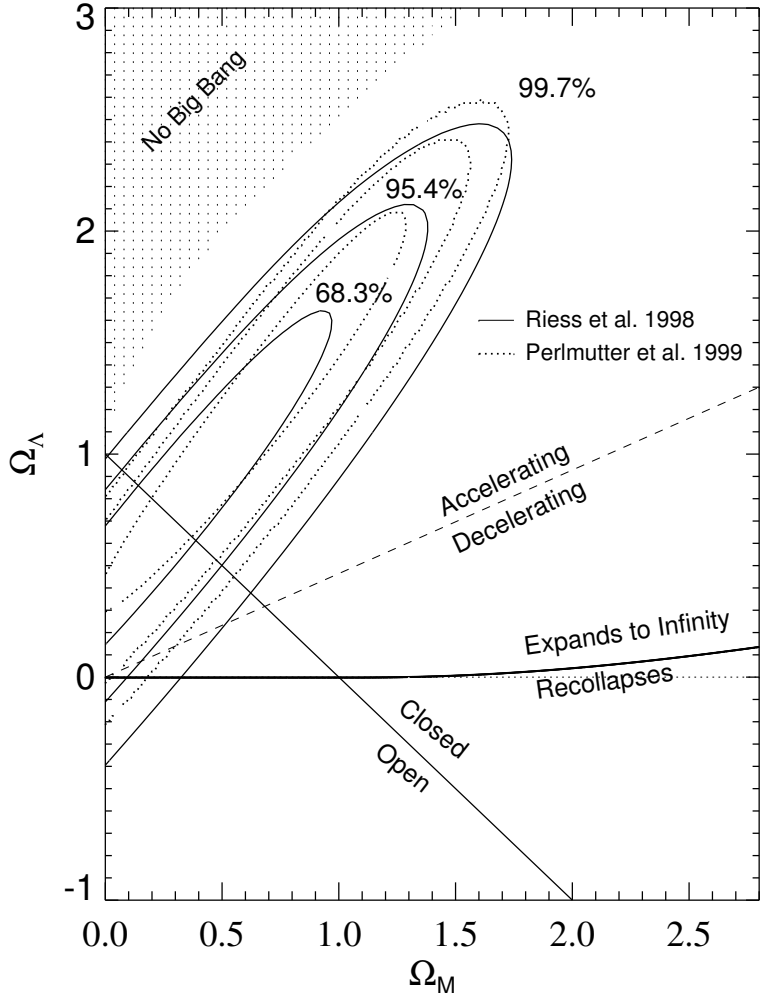
1994 : Kamionkowski, Spergel, Sugiyama : peak positions in C_l give Ω_T

1995 : Ostriker and Steinhardt announce $\Omega_T = 1 \Rightarrow \Lambda$CDM.



1998 : SNIa ⇒ acceleration



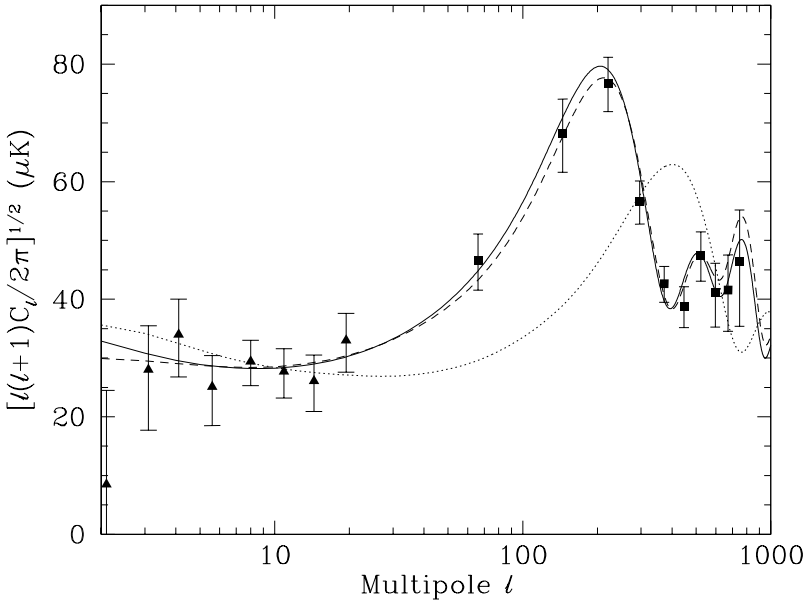


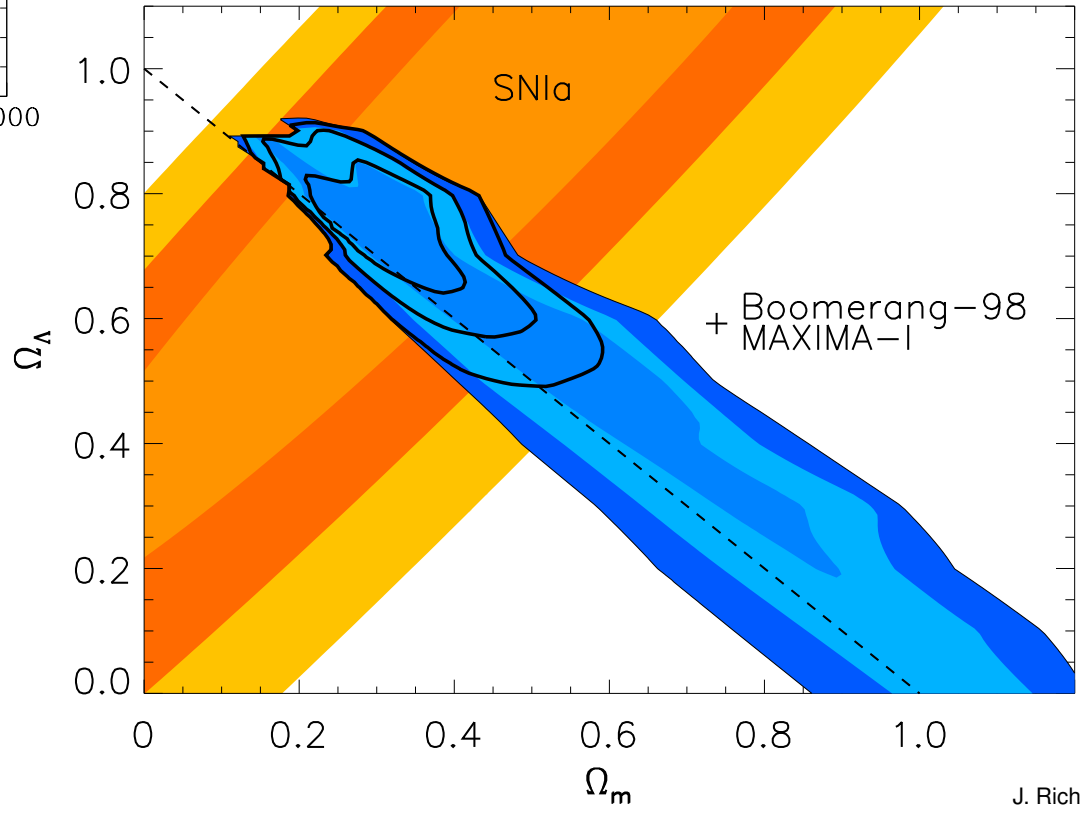
Some comments on SNIa

- SNIa 40% dimmer at $z = 0.5$ than for $\Omega_M = 1$.
- Acceleration independent of applicability of Friedmann Eqn.
- Empirical models of $L_{Ia}(stretch, color)$
- Achromatic dimming by dust ?
- SNIa luminosity evolution ?

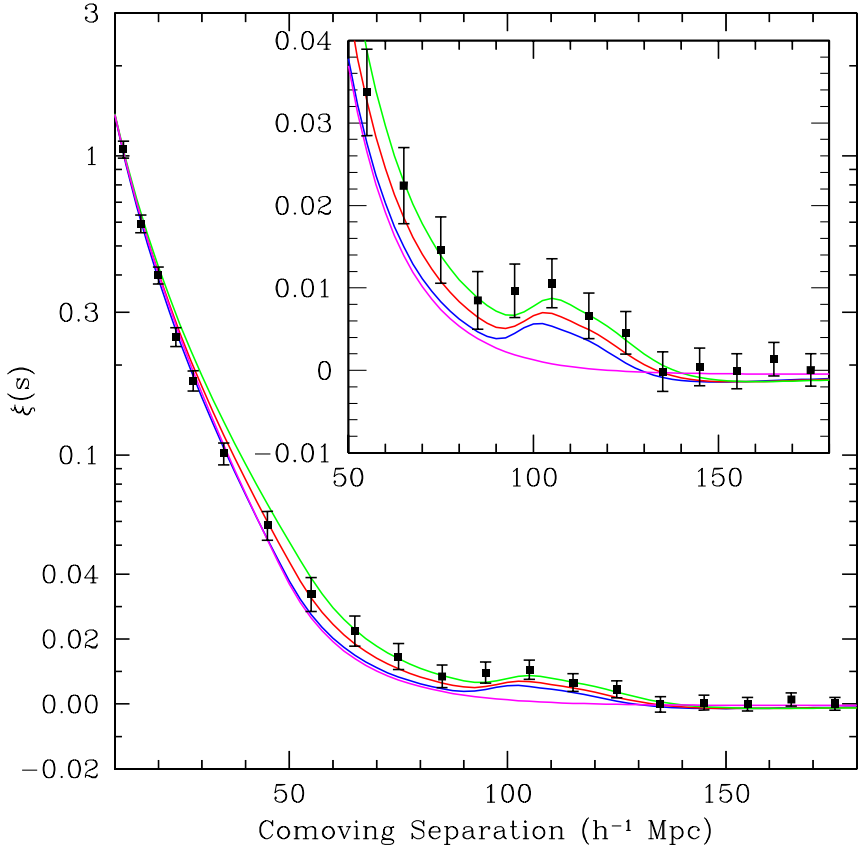
Last two issues layed to rest with the discovery of BAO in 2006 but may be important for “precision cosmology”.

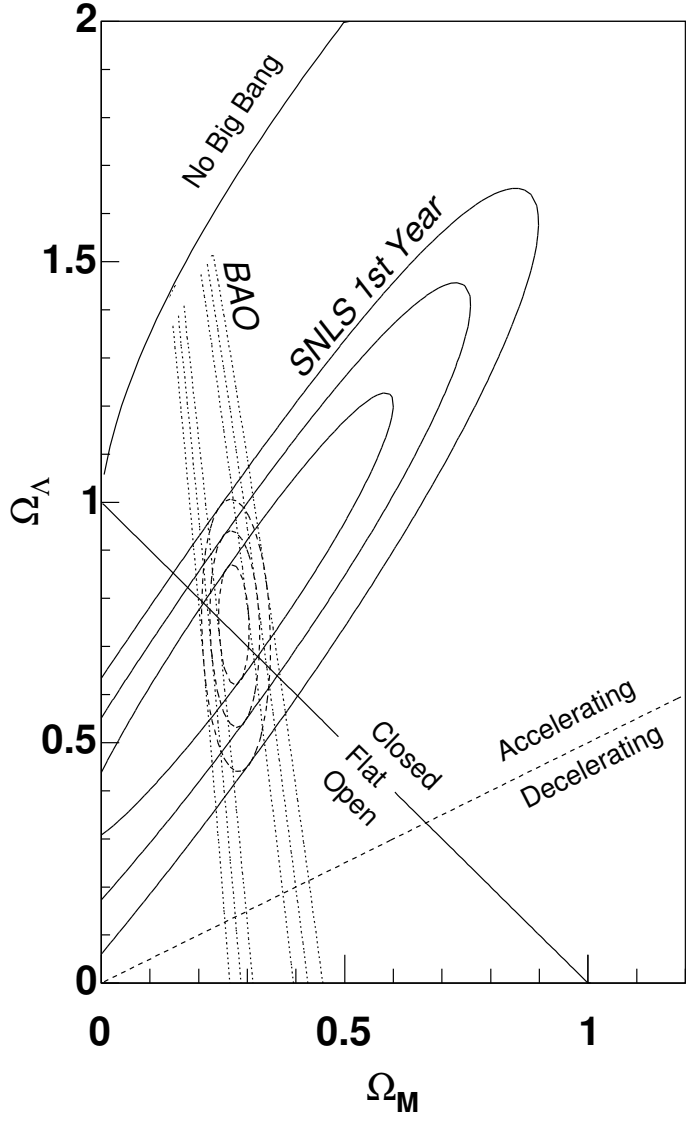
2000 : Boomerang and Maxima



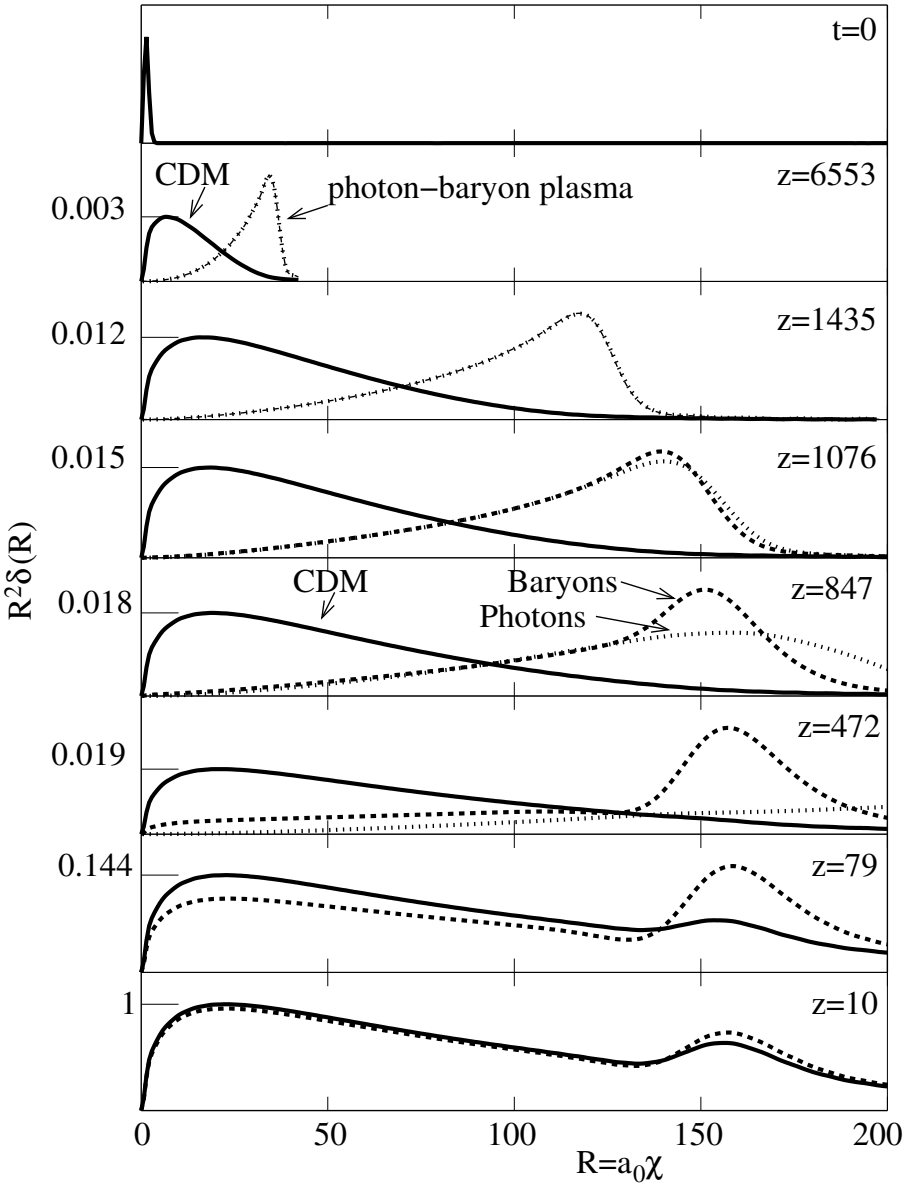


2006 : BAO


3
1
0.3
0.1
0.04
0.02
0.00
−0.02
ξ(s)
50
100
150
Comoving Separation (h⁻¹ Mpc)
0.04
0.03
0.02
0.01
0
−0.01
50
100
150


2
1.5
1
0.5
0
0
0.5
1
Ω_Λ
Ω_M
No Big Bang
BAO
SNLS 1st Year
Closed
Flat
Open
Accelerating
Decelerating

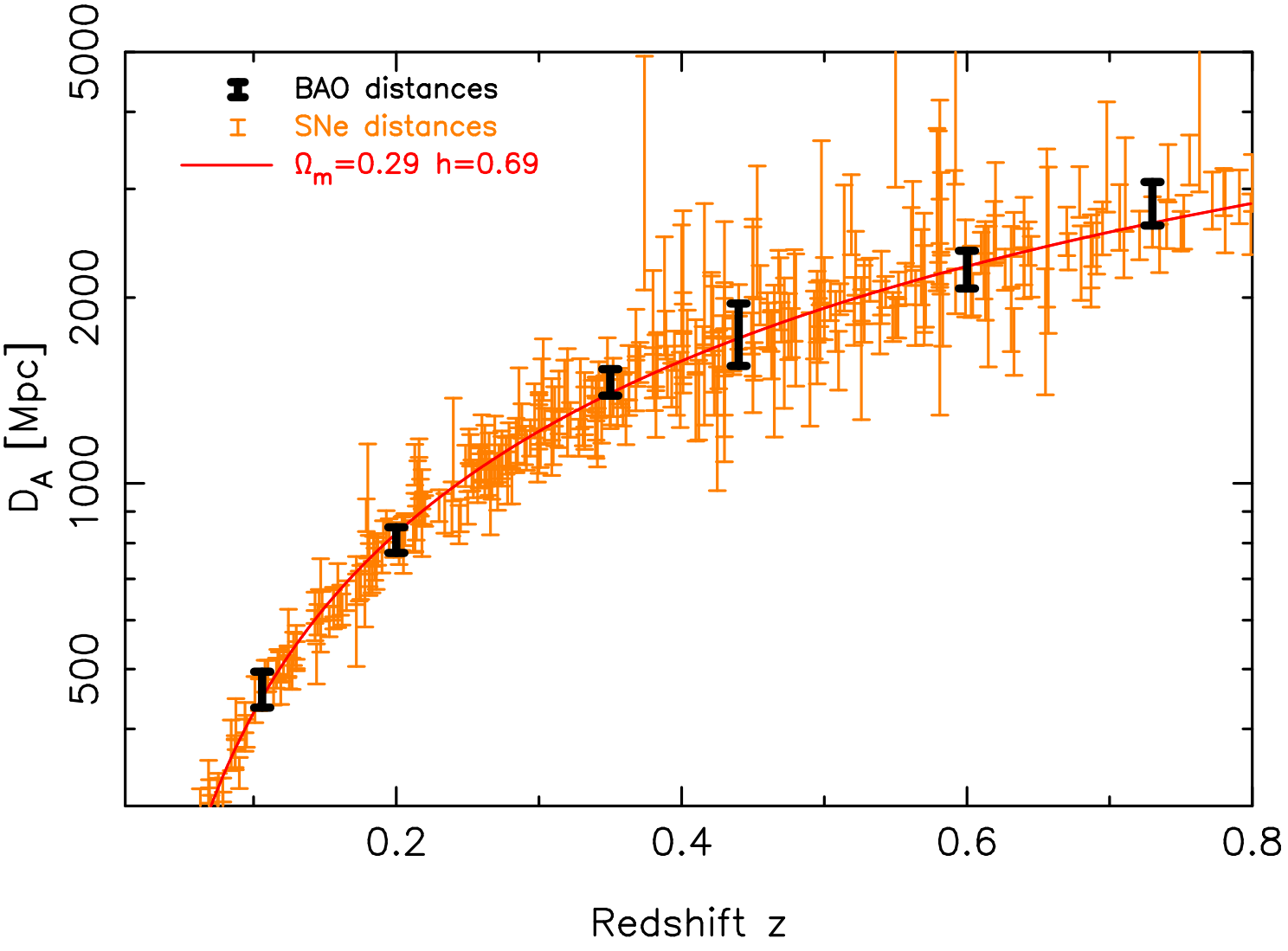
BAO



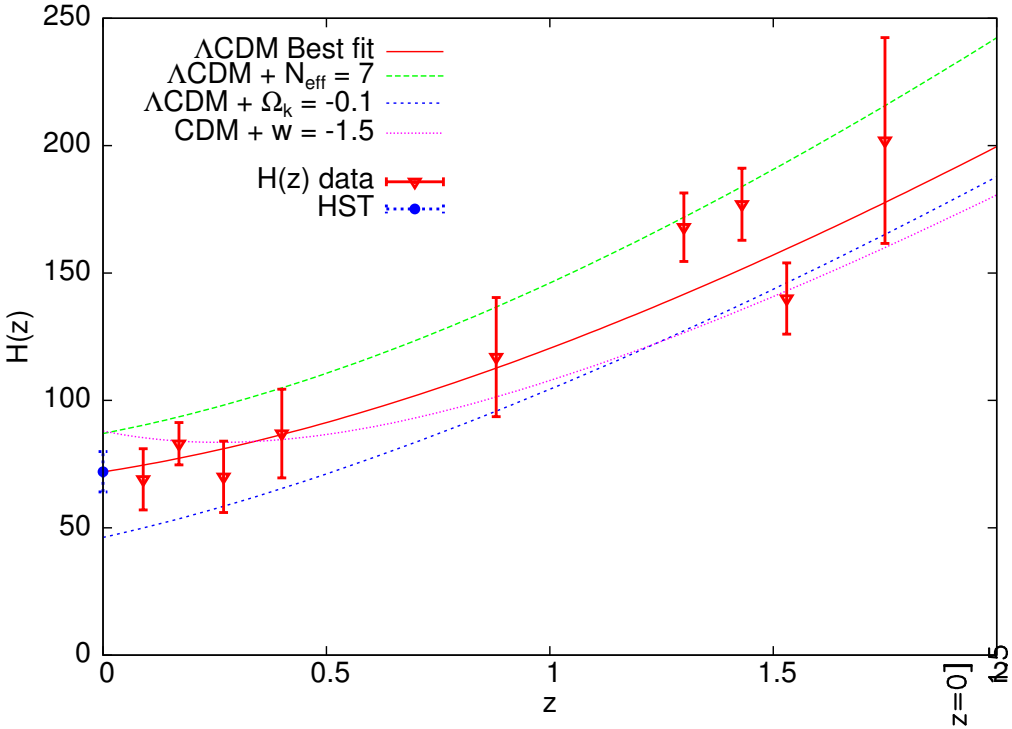
- An awe-inspiring vision of the early universe
- correlation length at $z = 0$
  $\rightarrow \Omega_M$
- transverse correlation
  $\rightarrow D_A(z)$
- longitudinal correlation
  $\rightarrow c/H(z)$
- present measurements
  $\rightarrow [D_z^2 c/H]^{1/3}$
- theoretical uncertainties
  $\sim 1\%$

6dFGS, SDSS, WiggleZ

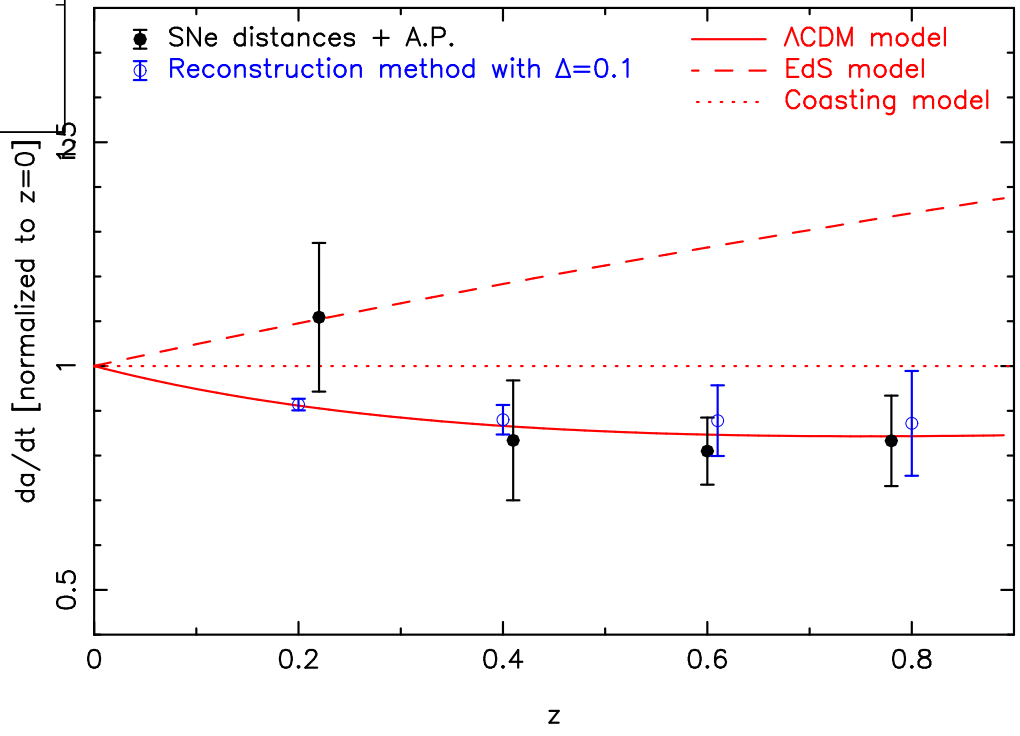
Blake et al., arXiv :1108.2635



$H(z)$ from stellar clocks and BAO

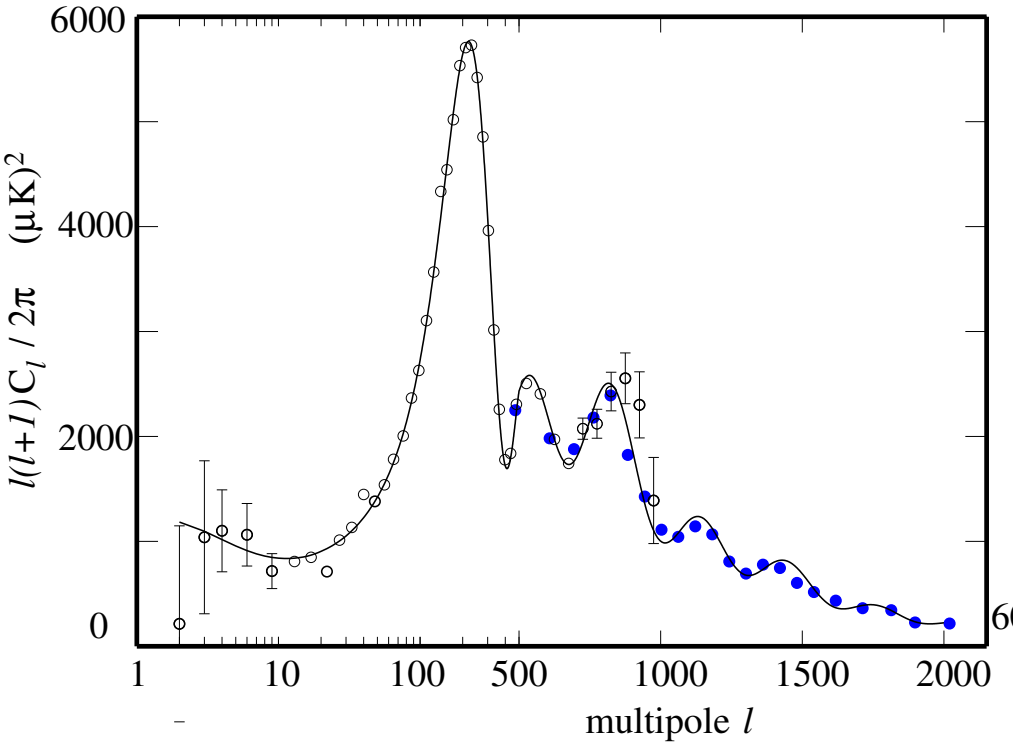


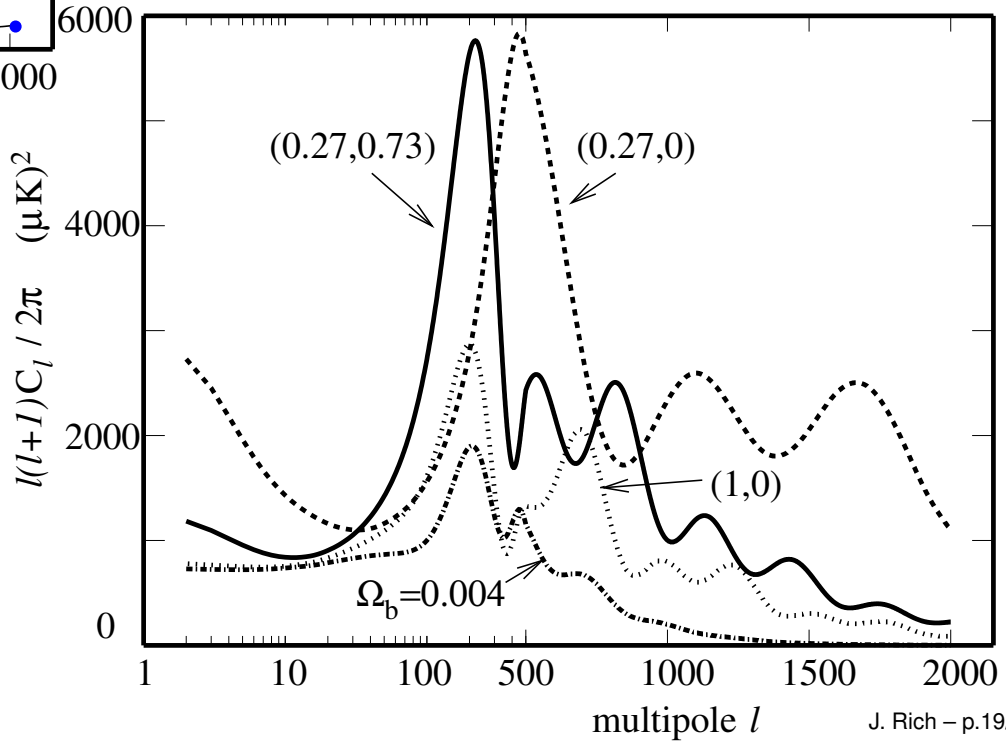
arXiv :0807.0039
Figueroa et al.



arXiv :1108 :2637
Blake et al.

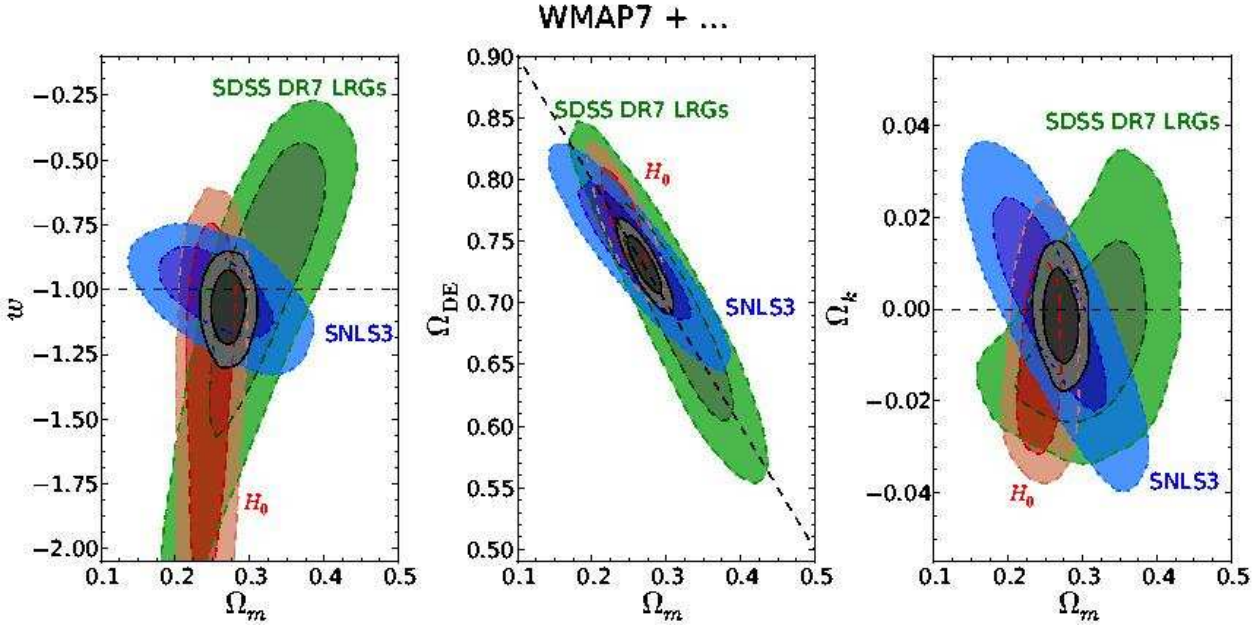
2009 : WMAP7+AcBar



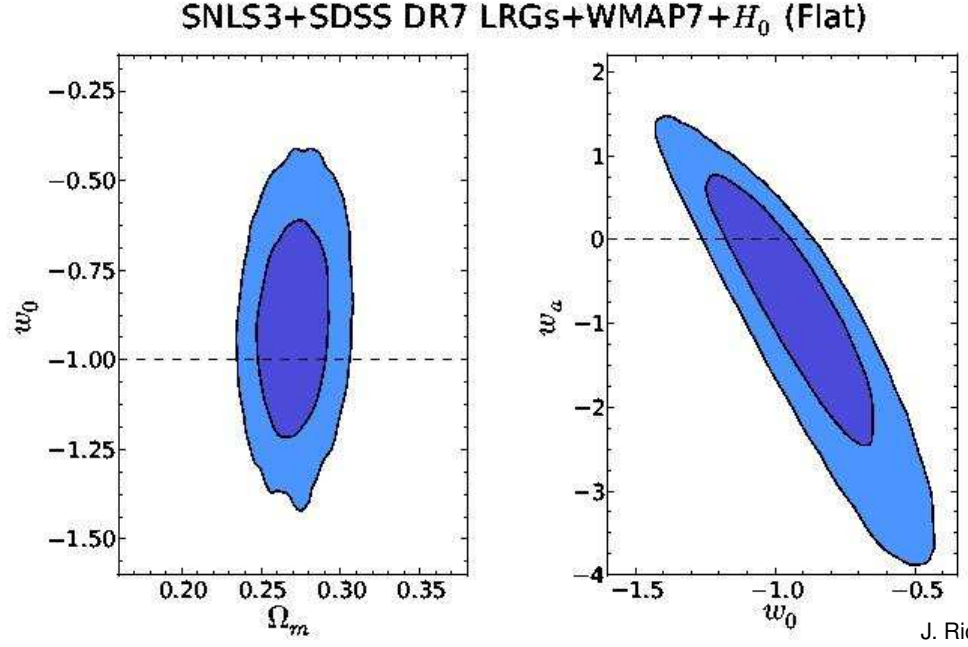


2011 : WMAP7+SNLS+BAO+H_0

Sullivan et al., arXiv :1104.1444



$$w = p_{de}/\rho_{de}$$



$$w(z) = w_0 + w_a z/(1+z)$$

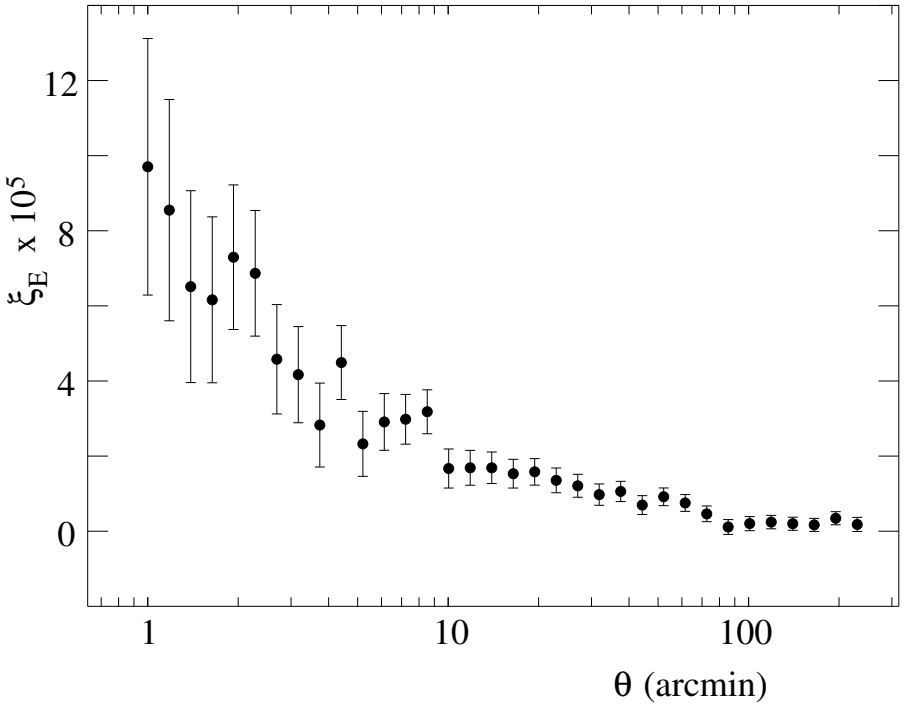
$$\rho_\Lambda = (1.50 \pm 0.05) \times 10^{-15} kWH/m^3 \,\mathbf{?}$$

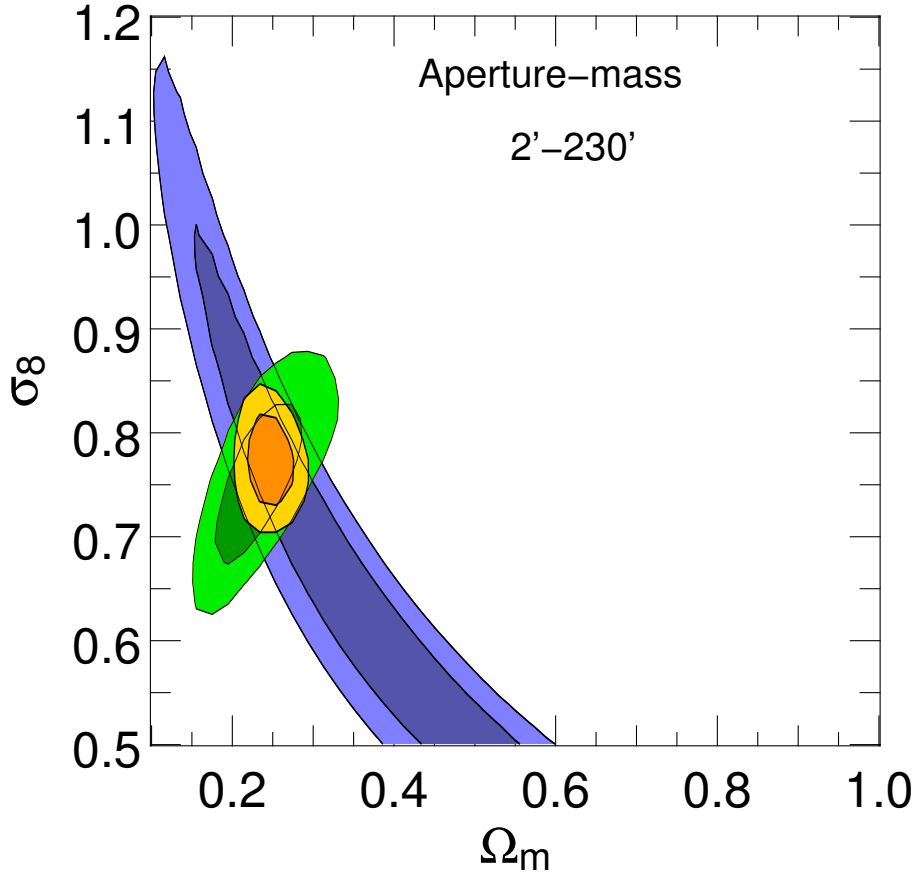
But what about :

- Do we live in a void ?
  No ! KSZ effect
  Shang and Stebbins PRL 107(2011)
- Friedmann equation applies to a clumpy universe ?
  Who knows ? !
- Does GR apply at cosmological scales ?
  Need to study cosmic structure growth :
  weak shear
  redshift distortions

weak-shear on LSS

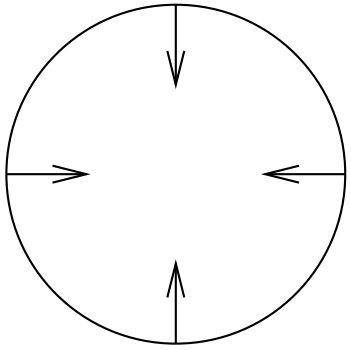
Fu et al., A&A 479 (2008)



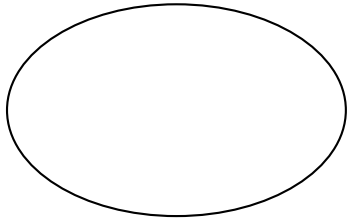


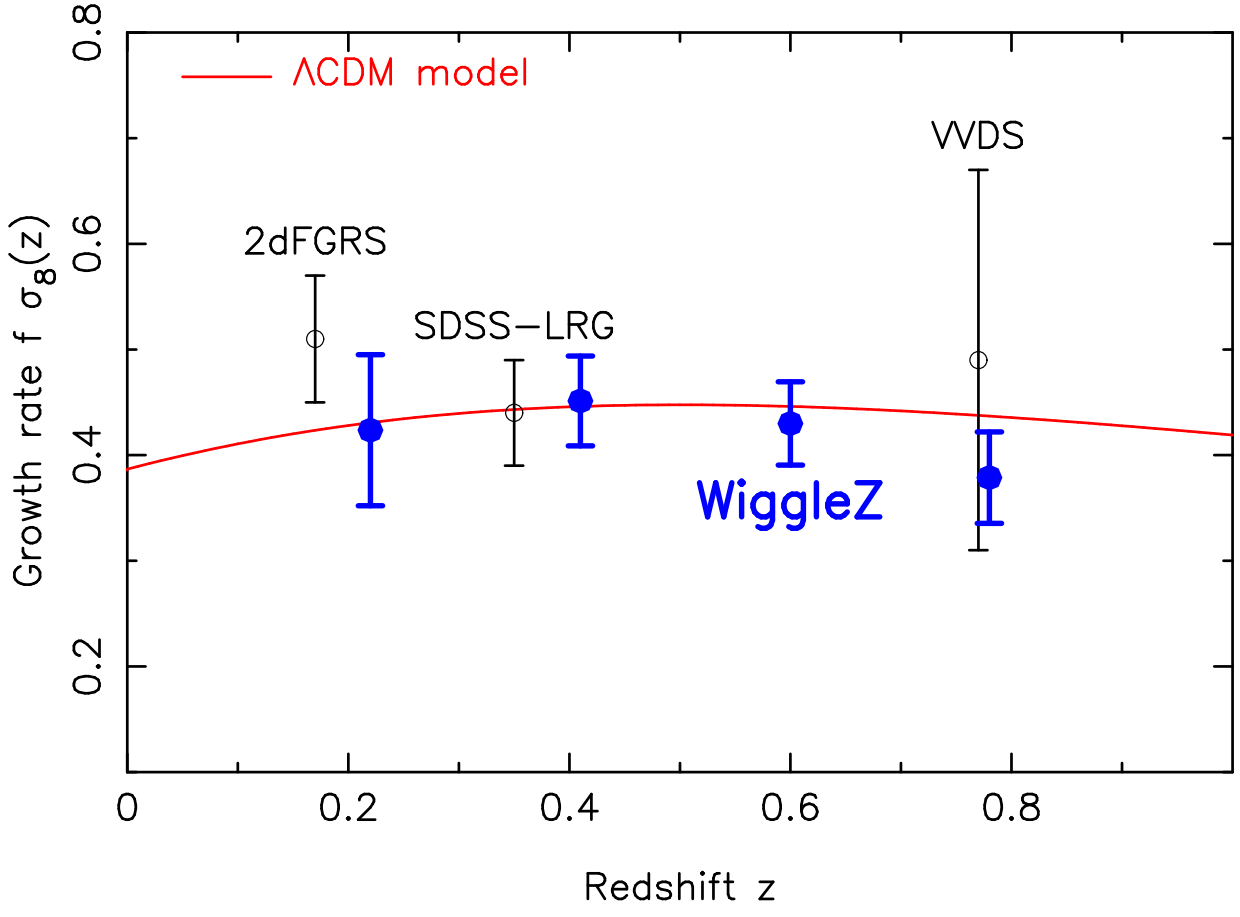
z-distortions $\rightarrow$ growth rate

real space



redshift space





arXiv :1104 :2948
Blake et al.