Dark Energy: evidence, models and possible physical implications

Ed Copeland -- Nottingham University

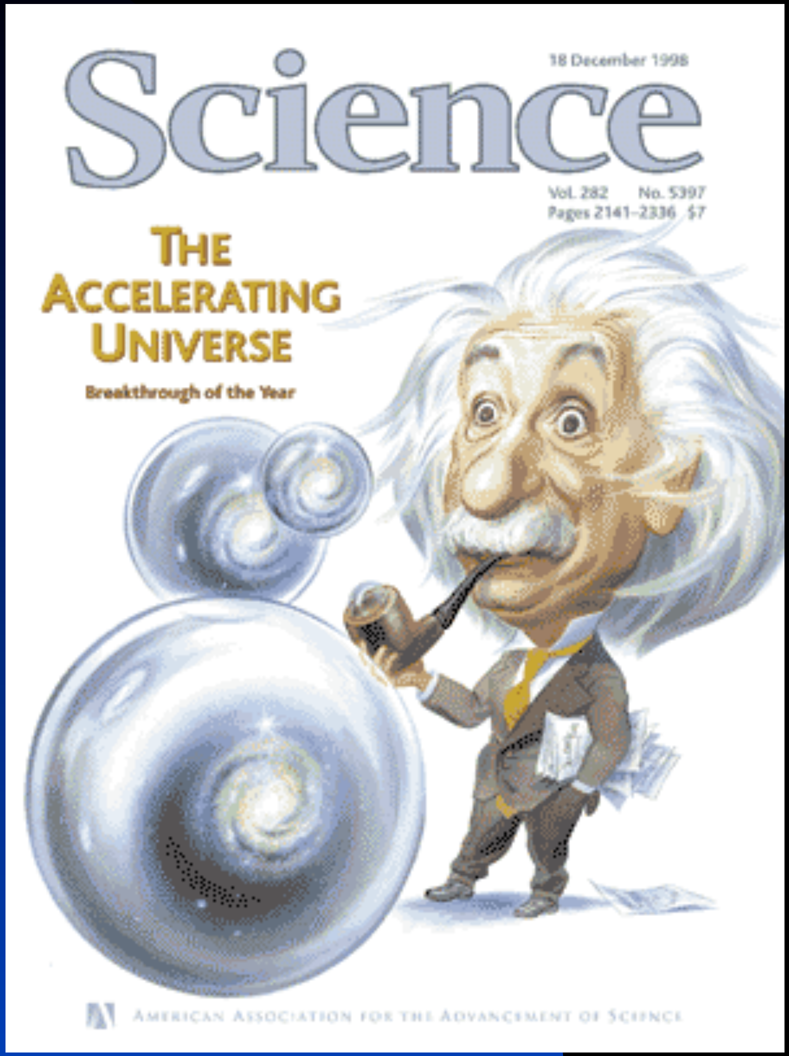
The plan which could evolve:

1. Evidence for Dark Energy --- Lecture 1
2. Models of Lambda --- Lecture 2
3. Scalar field models -- Lecture 3
4. Modified Gravity Models -- Lecture 4

School on Coarse Grained Cosmology

Galileo Galilei Institute - Firenze, Jan 26-29 2009

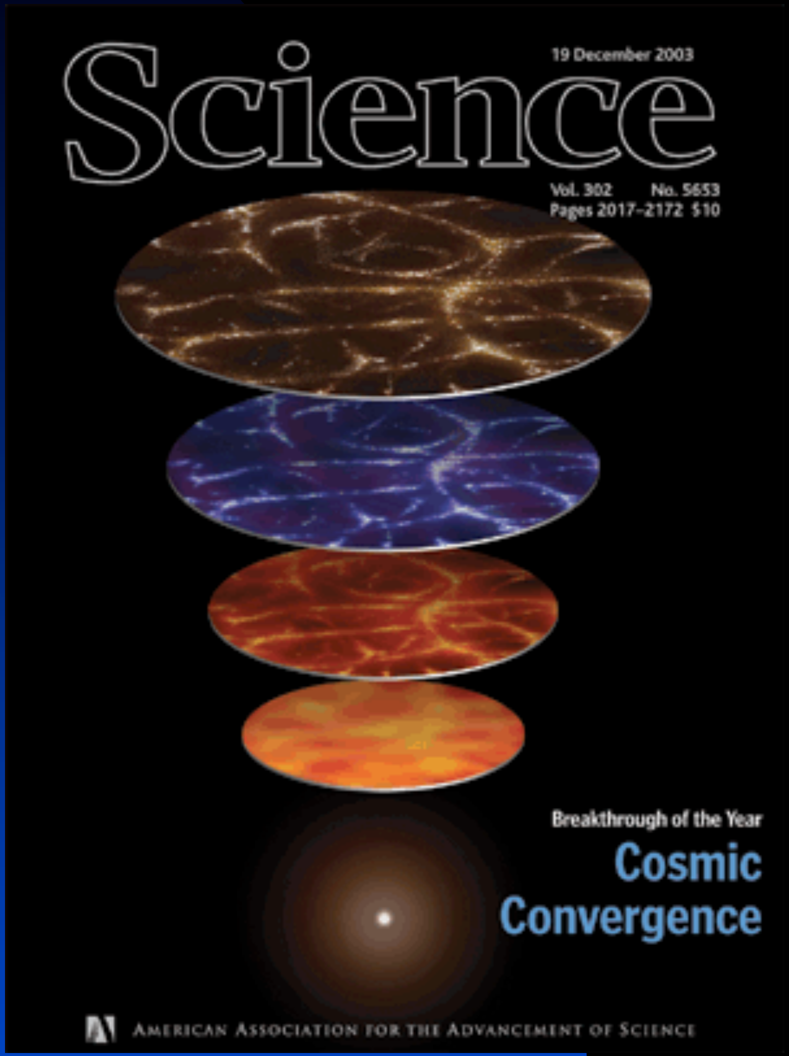
Science Magazine -- Breakthrough of the year -Dec 1998



``Einstein watches in surprise as a universe expands exponentially, its galaxies rushing apart ever faster.
Evidence for an accelerating universe, the Breakthrough of the Year for 1998, resurrects Einstein's discarded idea of an energy called lambda, or λ, which counteracts gravity and pushes space apart.''

So good -- they named it twice

Science Magazine -- Breakthrough of the year -Dec 2003



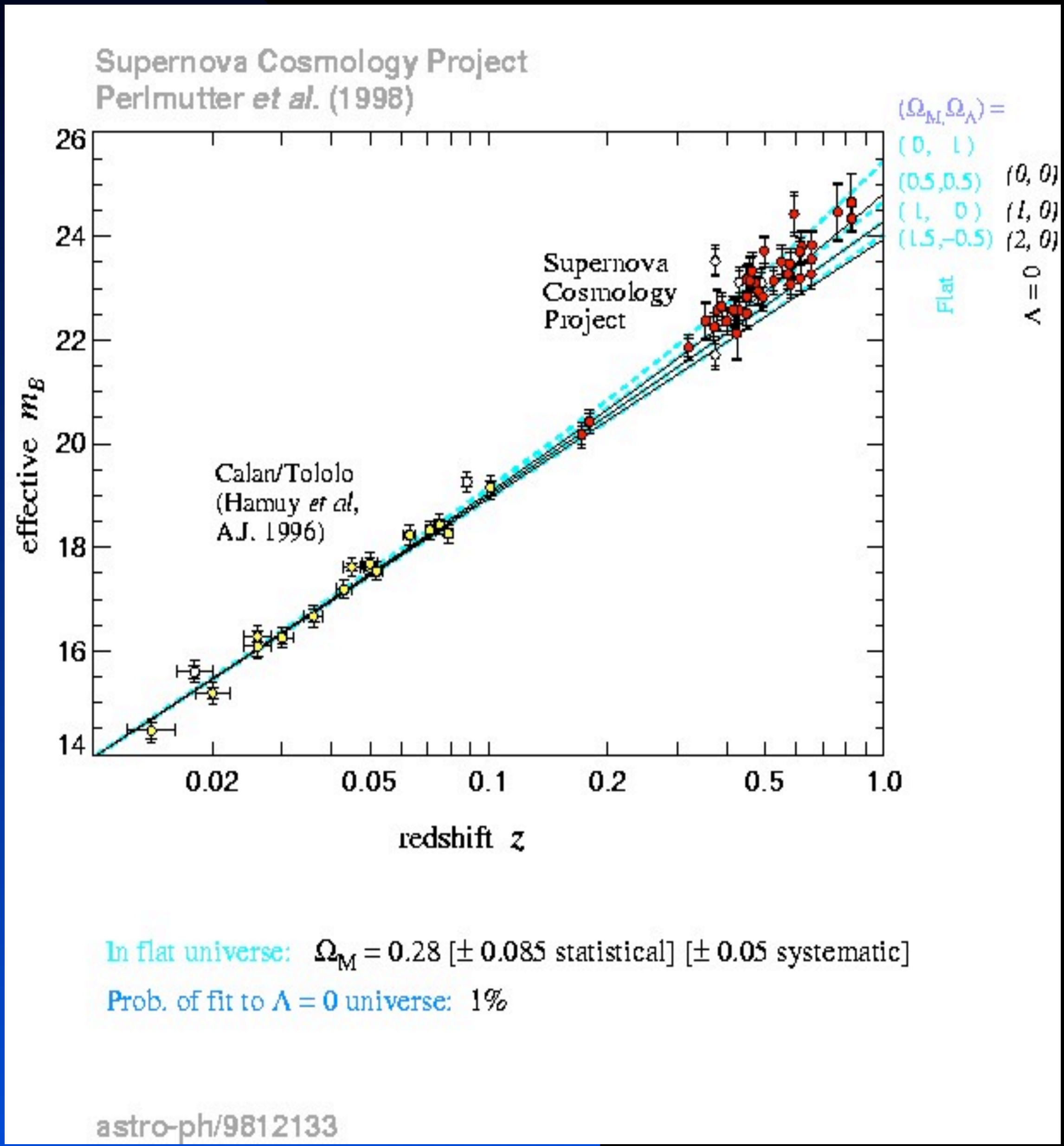
``Disks represent an aging and expanding universe.

Work this year confirmed a bizarre story of how the cosmos was born and what it is made of.

Dark energy is the primary ingredient in a universe whose expansion rate and age are now known with unprecedented precision.”

1. The Big Bang – (1sec → today)

The cosmological principle -- isotropy and homogeneity on large scales



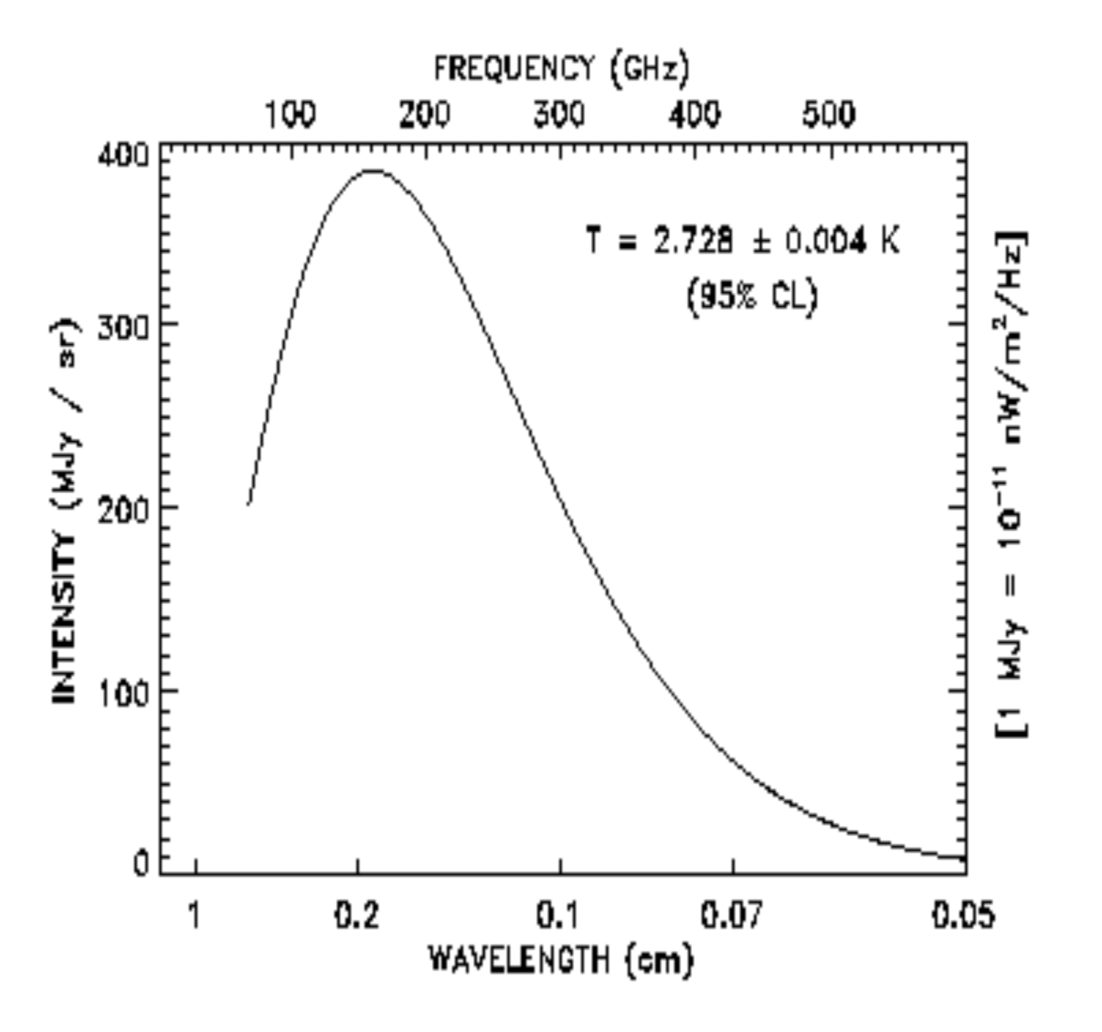
Test 1

- **The expansion of the Universe**

H_0=72±8 km s^{-1} Mpc^{-1}

(Freedman et al, 2001)

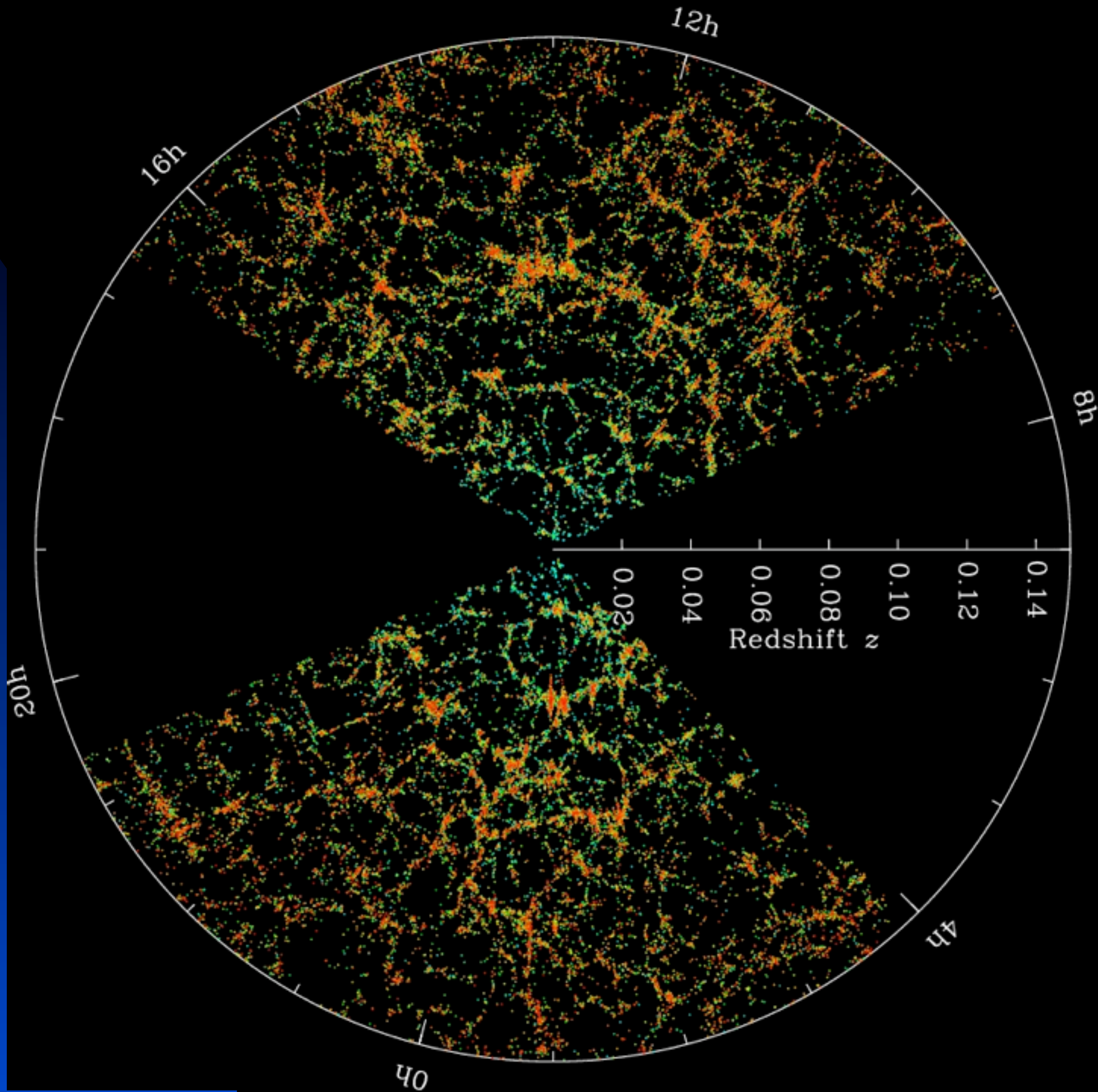
The Big Bang – (1sec → today)



Test 2

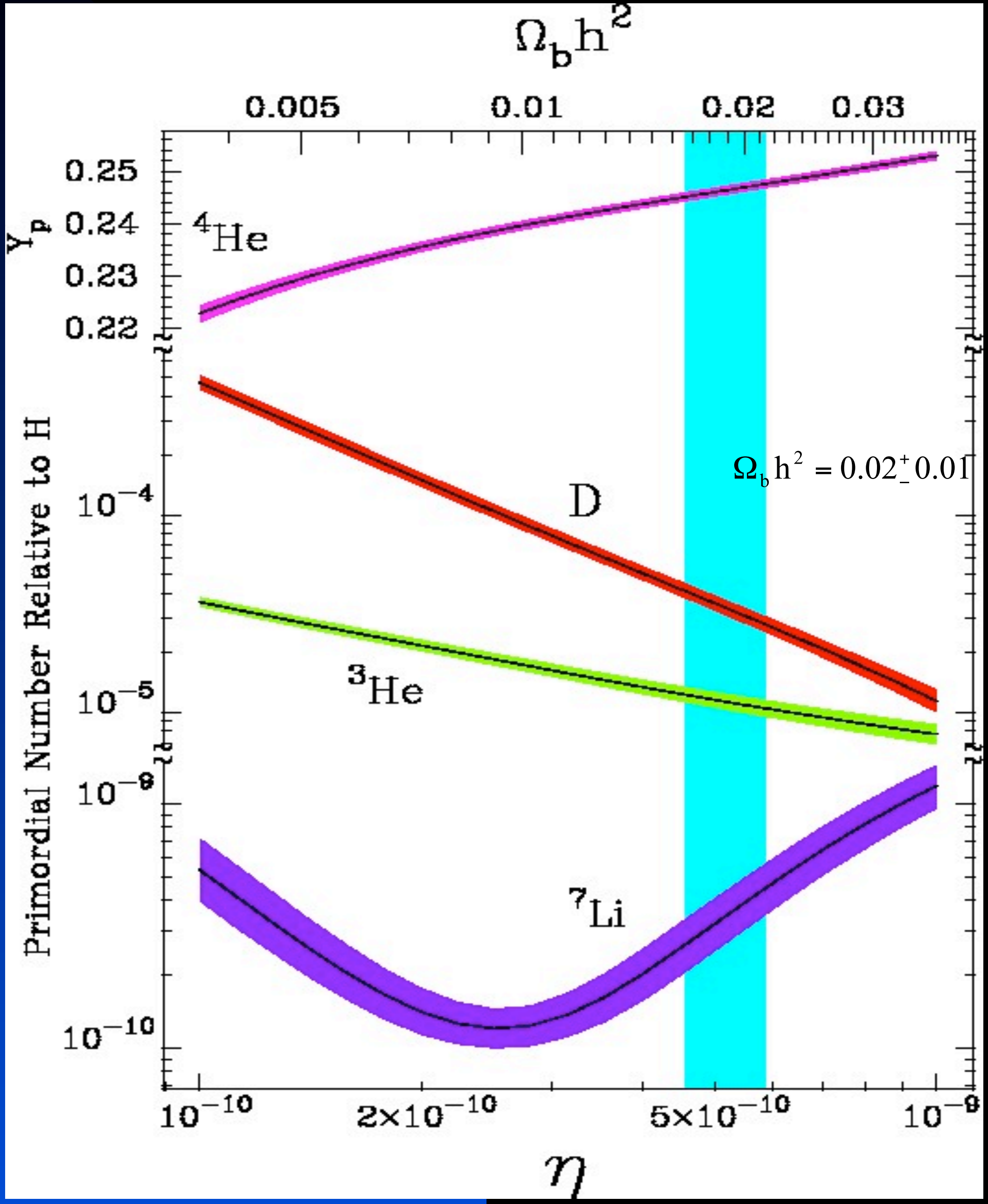
- **The existence and spectrum of the CMBR**
- **$T_0 = 2.728 \pm 0.004$ K**

Sloan Digital Sky Survey



Homogeneous on large scales?

The Big Bang – (1sec → today)



Test 3

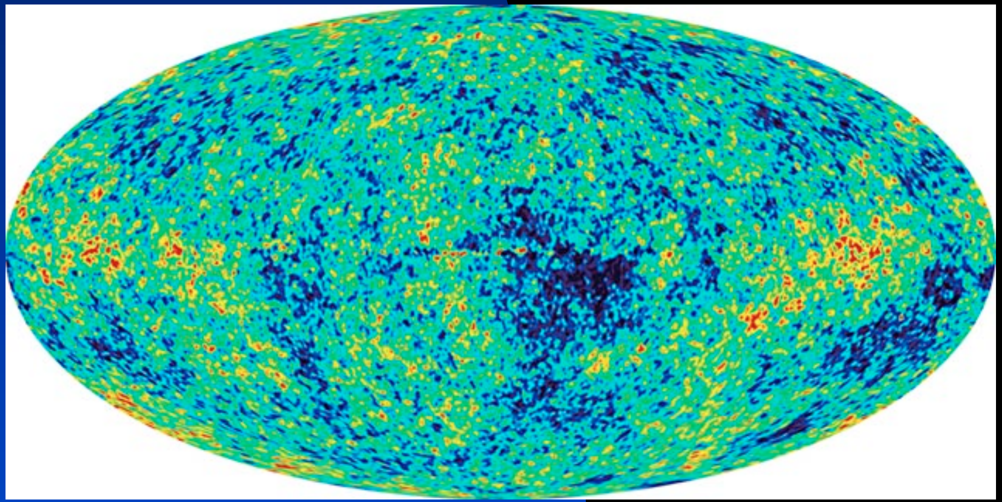
- **The abundance of light elements in the Universe.**
- **Most of the visible matter just hydrogen and helium.**

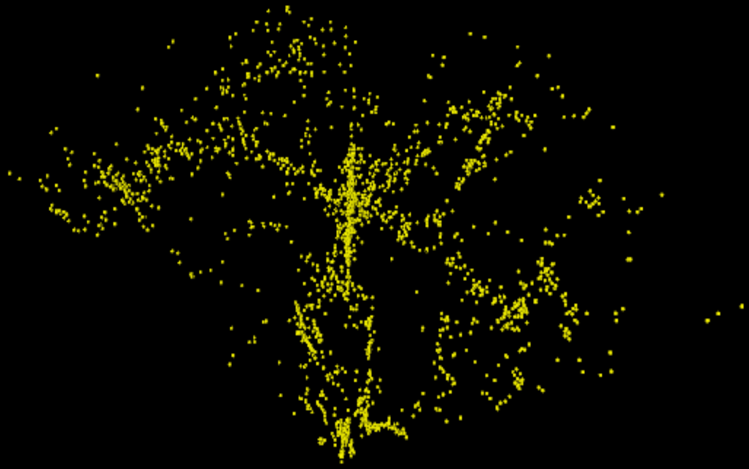
$$\Omega_b h^2 = 0.02^{+0.01}_{-0.01}$$

The Big Bang – (1sec → today)

Test 4

- **Given the irregularities seen in the CMBR, the development of structure can be explained through gravitational collapse.**





Some basic equations

Friedmann:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3}G\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

a(t) depends on matter.

Energy density $\rho(t)$: Pressure $p(t)$

Related through : $p = w\rho$

w=1/3 – Rad dom: w=0 – Mat dom: w=-1– Vac dom

Eqns (Λ=0):

Friedmann + Fluid conservation

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3}G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

Combine

$$\frac{\ddot{a}}{a} = -\frac{8\pi}{3} G(\rho + 3p) --- Accn$$

$$If \;\; \rho + 3p < 0 \Rightarrow \ddot{a} > 0$$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho - \frac{k}{a^2}$$

$$\dot{\rho} + 3(\rho + p)\frac{\dot{a}}{a} = 0$$

$$\rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3(1+w)} \quad ; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3(1+w)}}$$

$$\mathrm{RD} \quad : \quad w = \frac{1}{3} : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-4} \quad ; \; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{1}{2}}$$

$$\mathrm{MD} \quad : \quad w = 0 : \rho(t) = \rho_0 \left(\frac{a}{a_0}\right)^{-3} \quad ; \; a(t) = a_0 \left(\frac{t}{t_0}\right)^{\frac{2}{3}}$$

$$\mathrm{VD} \quad : \quad w = -1 : \rho(t) = \rho_0 \;\; ; \; a(t) \propto e^{Ht}$$

A neat equation

$$\rho_c(t) \equiv \frac{3H^2}{8\pi G} \quad ; \quad \Omega(t) \equiv \frac{\rho}{\rho_c}$$

Friedmann eqn

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$$\rho_c(t_0) \equiv 1.88h^2 * 10^{-29}\,\mathrm{gcm}^{-3}$$

Critical density

Current bounds on H(z) -- Komatsu 2008 - (WMAP5+BAO+SN)

$$\mathbf{H^2(z) = H_0^2\left(\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{de}\exp\left(3\int_0^z \frac{1+w(z')}{1+z'}dz'\right)\right)}$$

(Expansion rate) -- $H_0 = 70.5 \pm 1.3$ km/s/Mpc

(radiation) -- $\Omega_r = (8.5 \pm 0.3) \times 10^{-5}$

(matter) -- $\Omega_m = 0.274 \pm 0.015$

(curvature) -- $\Omega_k < 0.008$ (95%CL)

(dark energy) -- $\Omega_{de} = 0.726 \pm 0.015$

(de eqn of state) -- $1+w = -0.006 \pm 0.068$

If allow variation of form : $w(z) = w_0 + w' z/(1+z)$ then $w_0 = -1.04 \pm 0.13$ and $w' = 0.24 \pm 0.55$ (68% CL)

Weighing the Universe

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

$1. \Omega_m$

a. Cluster baryon abundance using X-ray measurements of intracluster gas, or SZ measurements.

b. Weak grav lensing and large scale peculiar velocities.

c. Large scale structure distribution.

d. Numerical simulations of cluster formation.

$$\Omega_m h^2 = 0.1369 \pm 0.0037$$

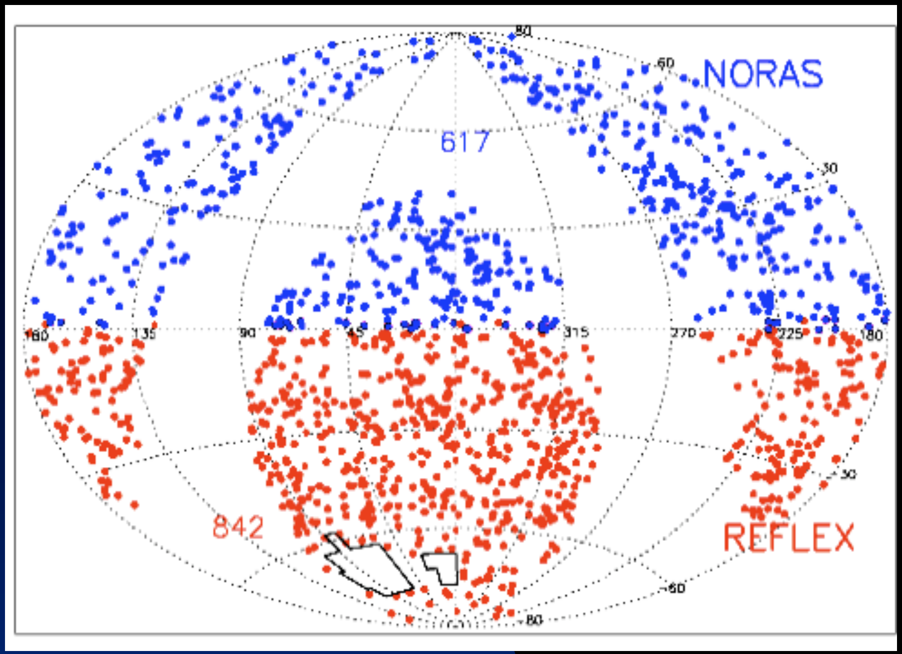
$$\Omega_m << 1$$

(Komatsu et al, 2008) (WMAP5)

$H_0 = 70.1 \pm 1.3$ km s^{-1} Mpc^{-1}

X-ray Cluster Surveys: REFLEX & NORAS: 1600 clusters

Boehringer 2008



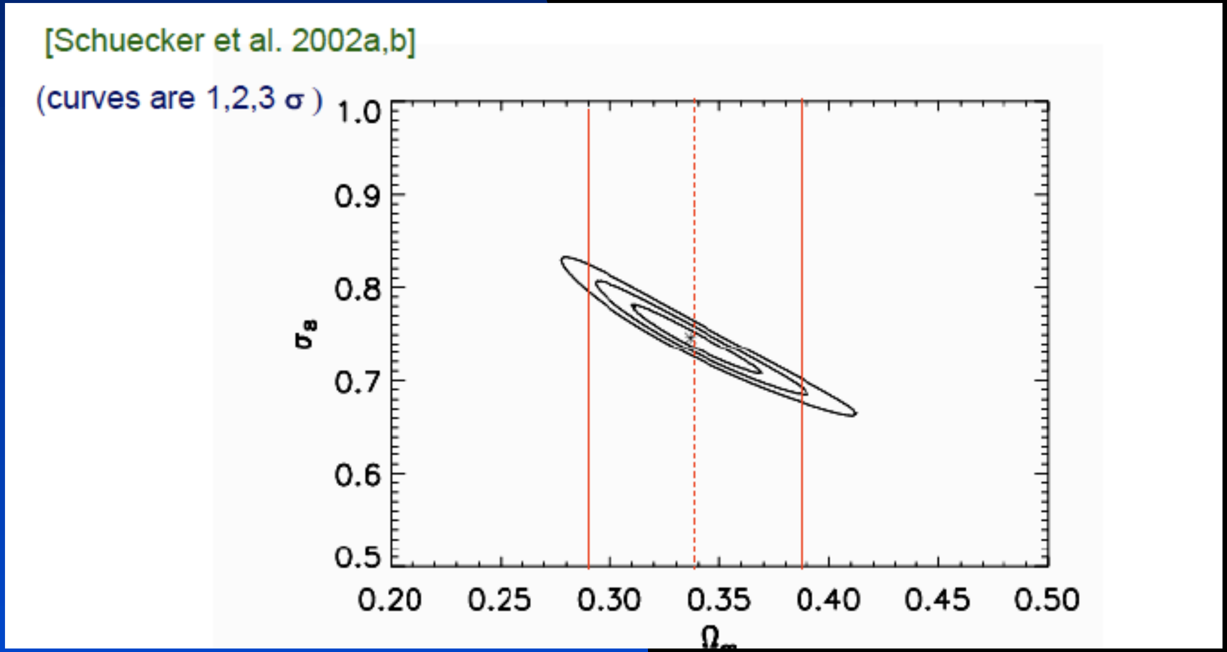
Galaxy clusters -- largest well defined objects in the universe. Coma cluster

82-87% -- Dark matter

11-13% -- hot gas

2-5% -- galaxies

Poss and Rosat all sky survey



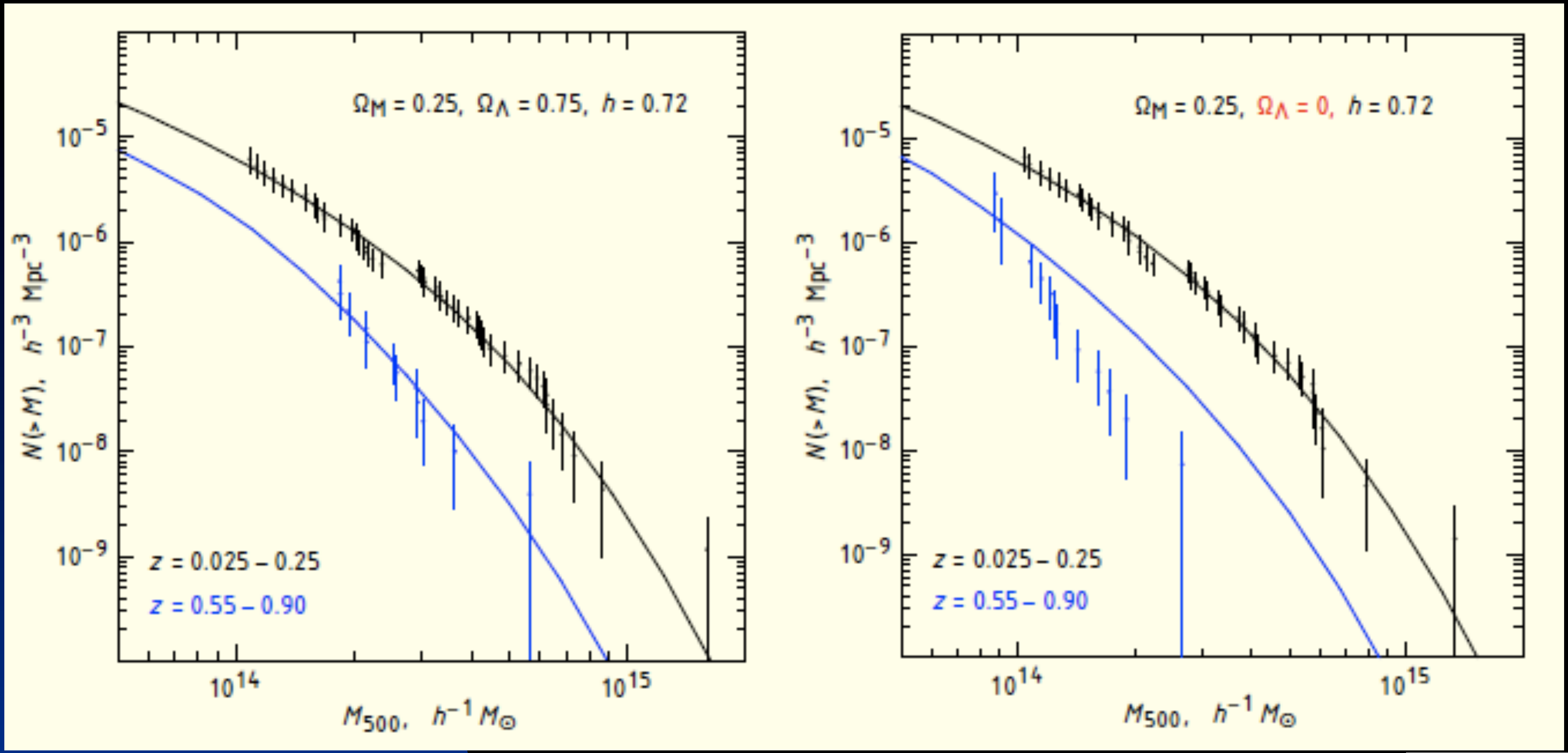
Schuecker et al 2002

REFLEX Cluster Surveys: Ω_m=0.3±0.05 (2σ)

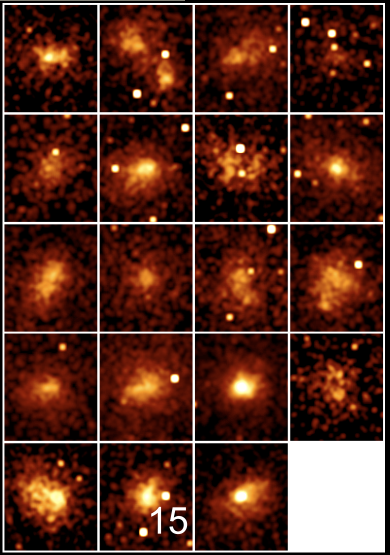
Use constancy of the baryon-to-total mass ratio as a standard ruler

Chandra X-ray Surveys led to 100’s of clusters

Vikhlinin 2008



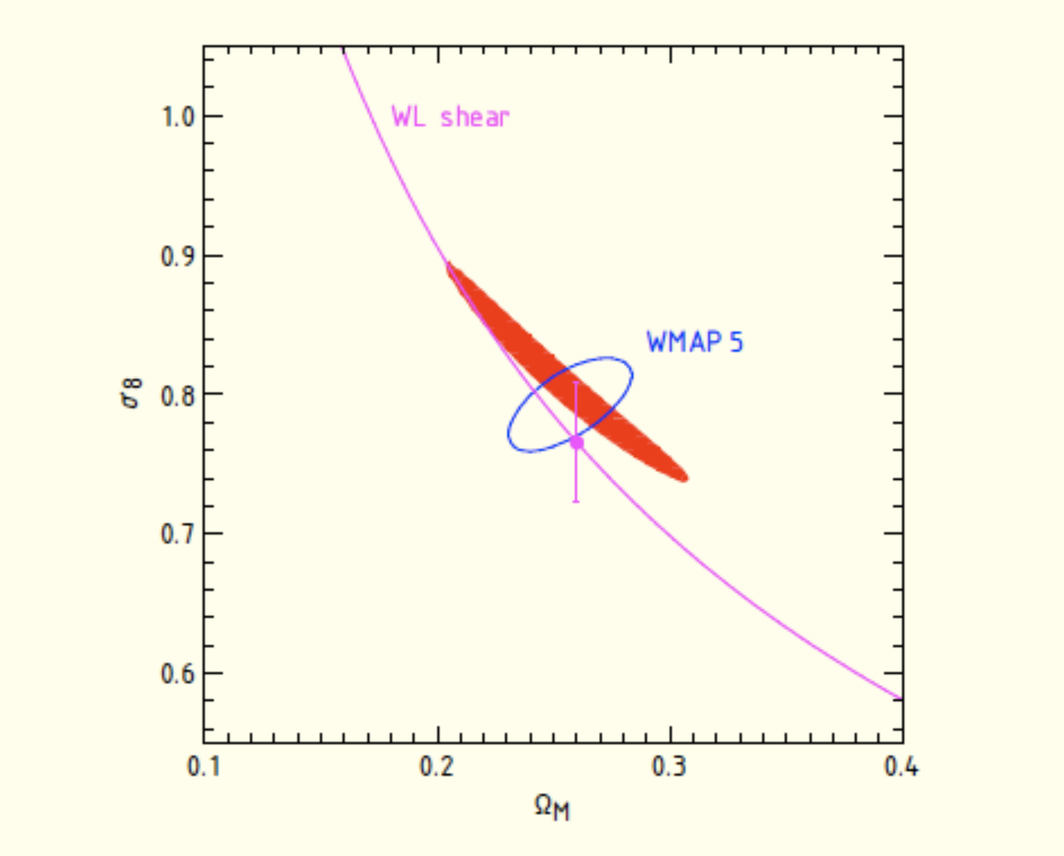
Led to recent claim of detection of Λ based on evolution of number density of clusters.



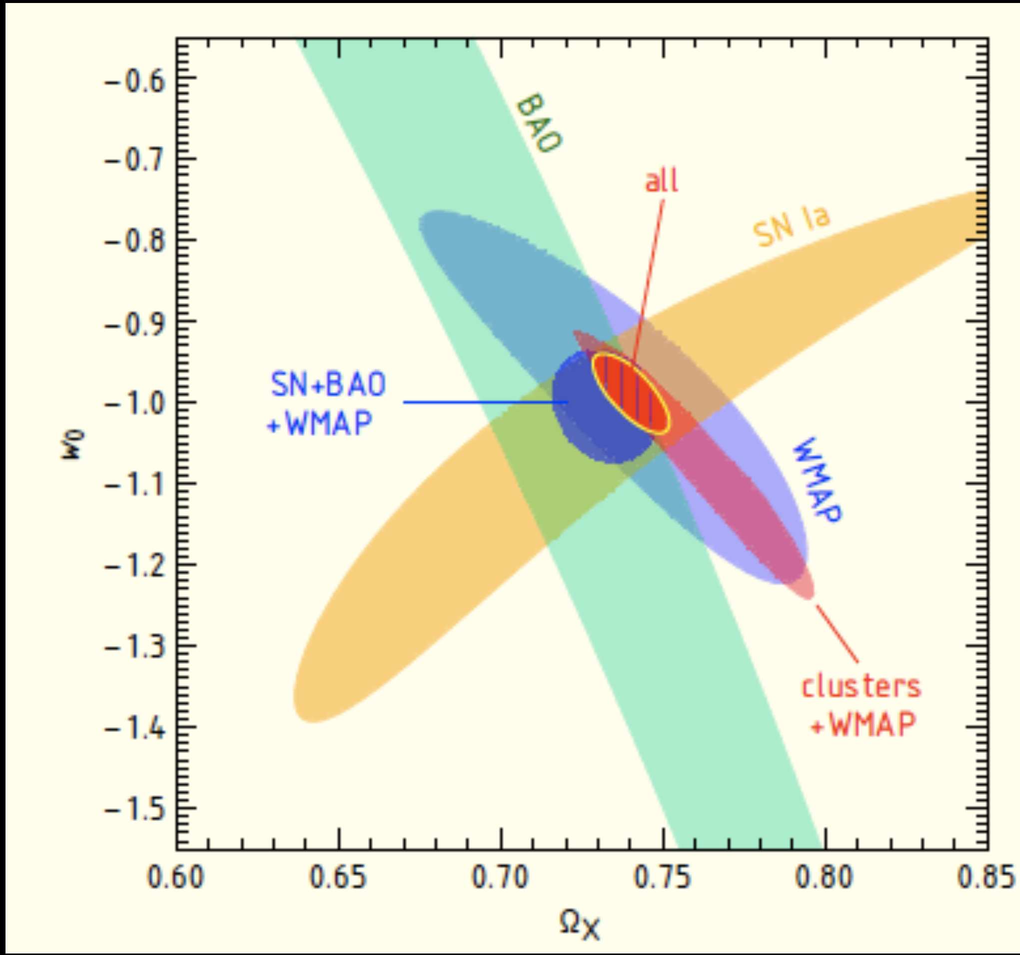
Chandra archive

Chandra X-ray Surveys

Vikhlinin 2008

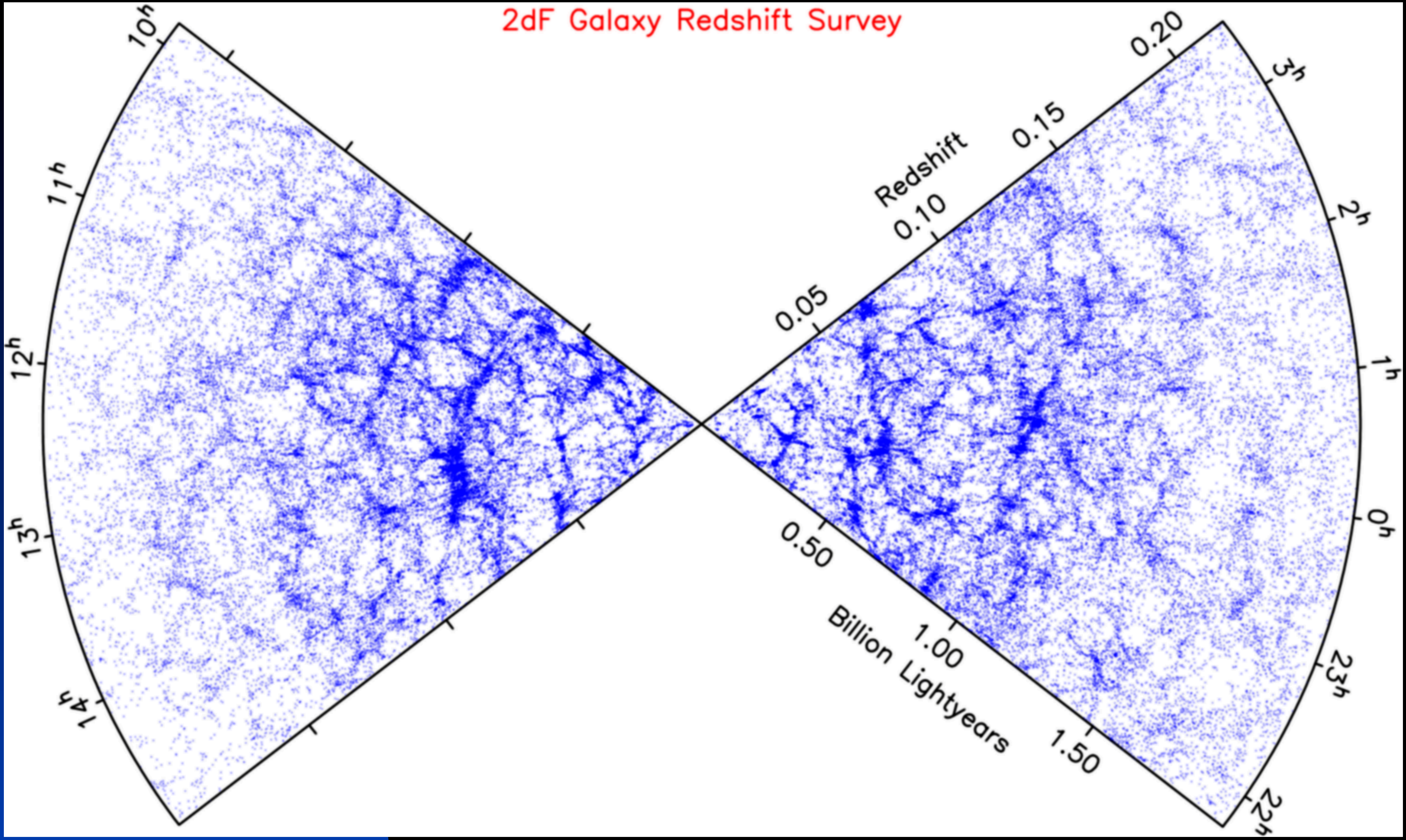


For Ω_m=0.25: σ_8=0.813 ±0.013



CMB+SN+BAO+clusters:
w_0=-0.99±0.045

Final 2dFGRS Power Spectrum:



Cole, Percival, Peacock, Baugh, Frenk +2dFGRS 05

Growth of structure by gravity -- sensitive to dark matter and dark energy

- Perturbations can be measured at different epochs hence probe different physics contributions:

1. CMB z=1000
2. 21cm z=10-20 (?)
3. Ly-alpha forest z=2-4
4. Weak lensing z=0.3-2
5. Galaxy clustering z=0-2

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta \rightarrow \delta(t)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2}$$

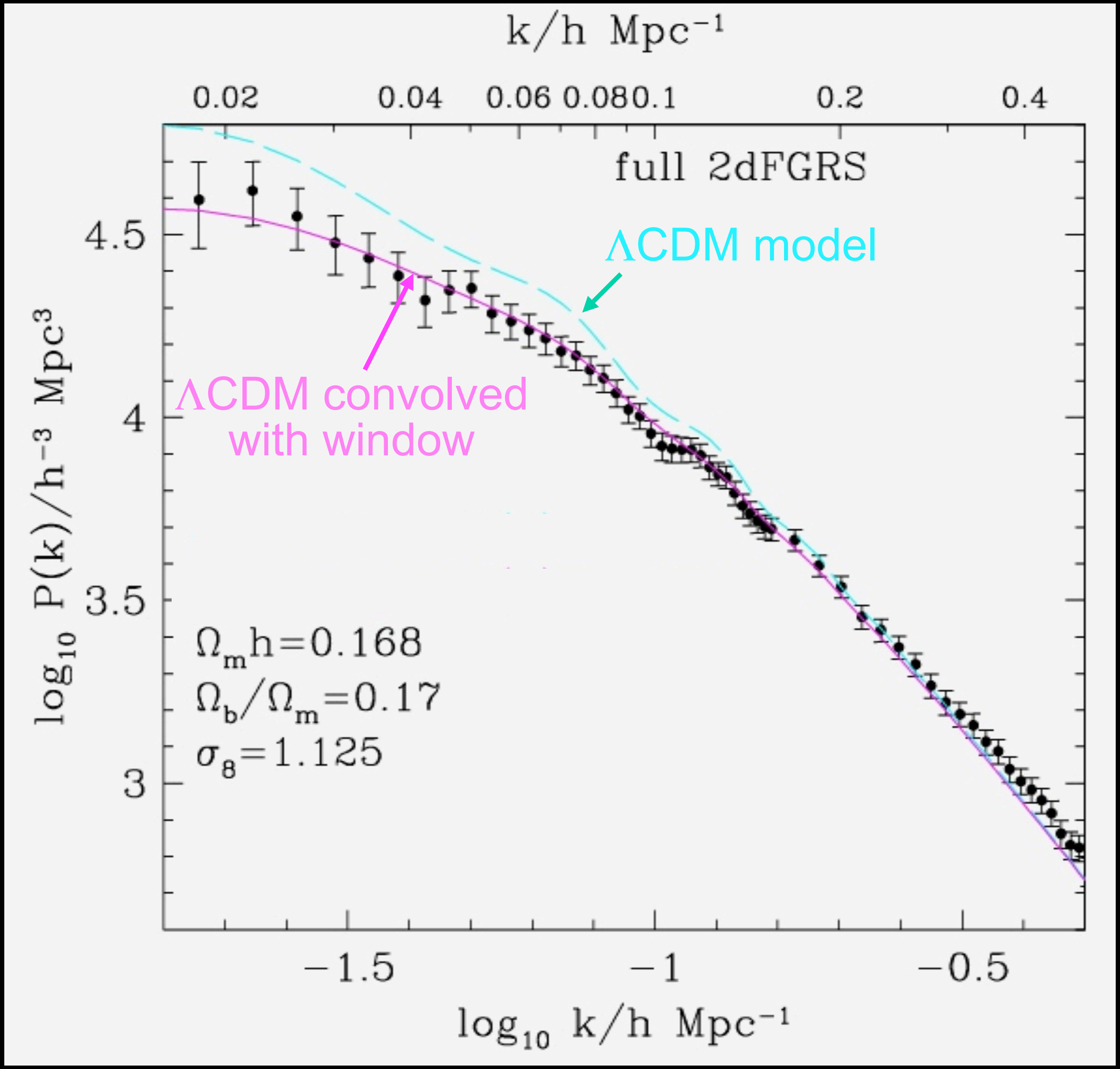
$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

Final 2dFGRS Power Spectrum:

Well fitted with ΛCDM convolved with window function.

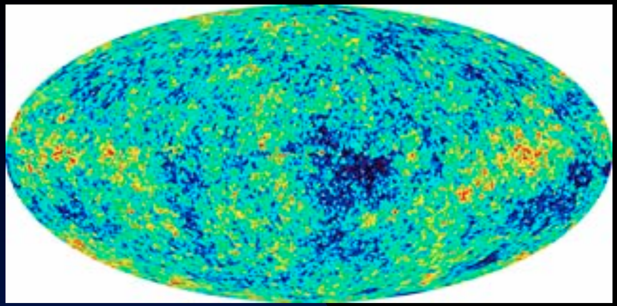
$\Omega_m h = 0.168$
$\Omega_b/\Omega_m = 0.17$

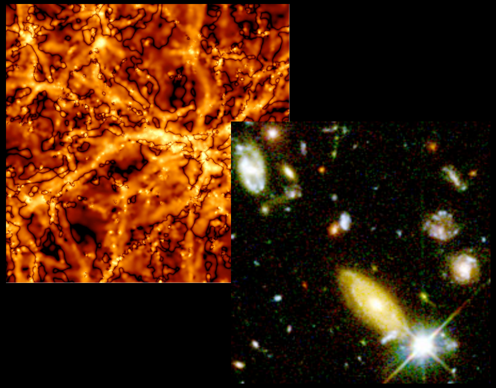
Cole, Percival, Peacock, Baugh, Frenk +2dFGRS 05

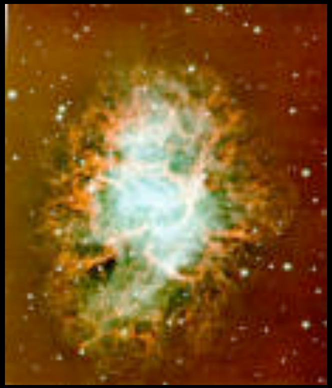


Cosmic probes

Linder







CMB: direct probe of quantum fluctuations

Time: 0.003% of the present age of the universe.

LSS: less direct probes of expansion

Pattern of ripples, clumping in space, growing in time.

3D survey of galaxies and clusters.

Supernovae: direct probe of cosmic expansion

Time: 30-100% of present age of universe

$2. \Omega_b$

BBN → $\Omega_b h^2 = 0.02^{+0.01}_{-0.01}$

Majority of baryonic matter dark.

$\Omega_b << \Omega_m$

Require Dark matter !!

CDM	HDM – strongly constrained
Axions	Neutrinos
Neutralinos	
PBH's	
Supermassive relics …	

Supersymmetry and dark matter

Neutrinos not likely unless almost degenerate in mass, require 5-40eV.

WIMPS such as neutralinos, axions, axinos, gravitinos…

Interactions with matter vary enormously in strength: neutralinos (10^{-2}) – gravitinos (10^{-33}).

Neutralino- well motivated, LSP (assumption), gives closure for range of SUSY masses below a few TeV.

Ex: **Gaugino** like neutralino has allowed mass in range 30-150 GeV.

Evidence for Dark Energy?

Enter CMBR:

$$3.\ \Omega_0 = \Omega_m + \Omega_\Lambda$$

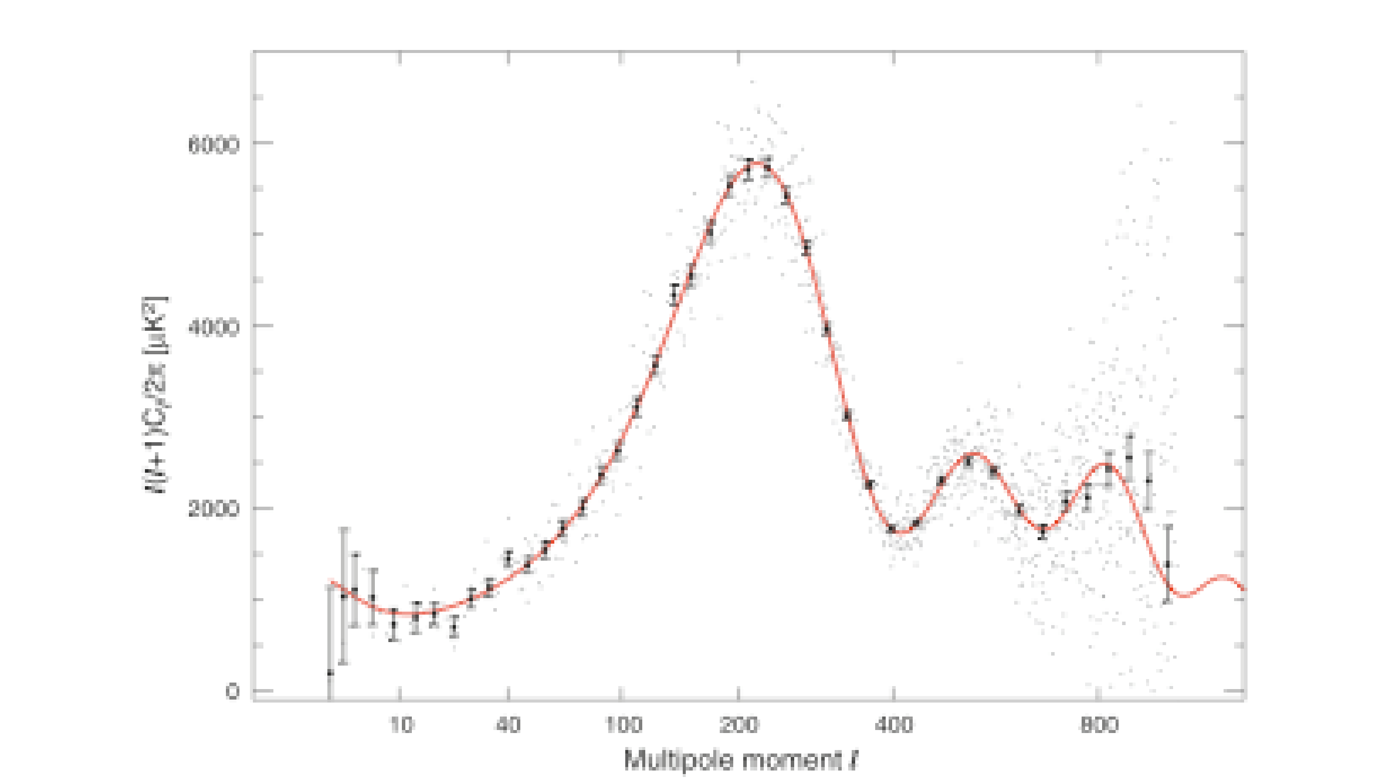
Provides clue. 1st angular peak in power spectrum.

$$l_{peak} \approx \frac{220}{\sqrt{\Omega_0}}$$

$$|1 - \Omega_0| = 0.03^{+0.026}_{-0.025}$$

WMAP3-Depends on assumed priors

Spergel et al 2006



$$-0.0175 < \Omega_k < 0.0085$$

Dunkley et al 2008 (WMAP5)

WMAP3 and dark energy

Assume flat univ + SNLS:

$w = -0.97^{+0.07}_{-0.09}$

Rules out frustrated networks of walls:

If assume w= -1, then with SNLS:

$\Omega_k = -0.015^{+0.020}_{-0.016}$.

WMAP + HST:

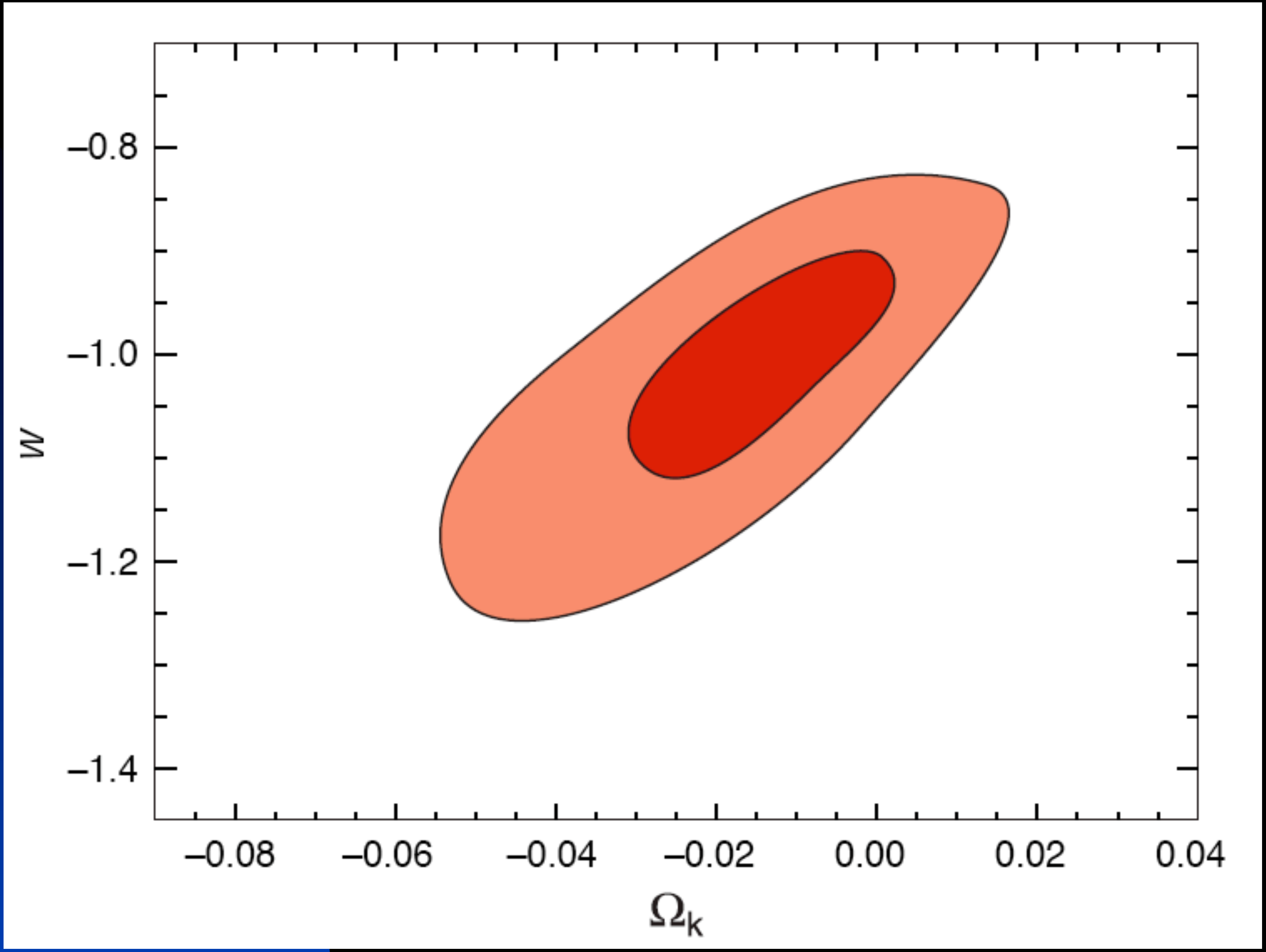
$\Omega_K = -0.010^{+0.016}_{-0.009}$ and $\Omega_\Lambda = 0.72 \pm 0.04$.

Drop prior of flat univ: WMAP + LSS + SNLS:

$w = -1.06^{+0.13}_{-0.08}$.

Spergel et al 2006

Relax the prior of spatial flatness.

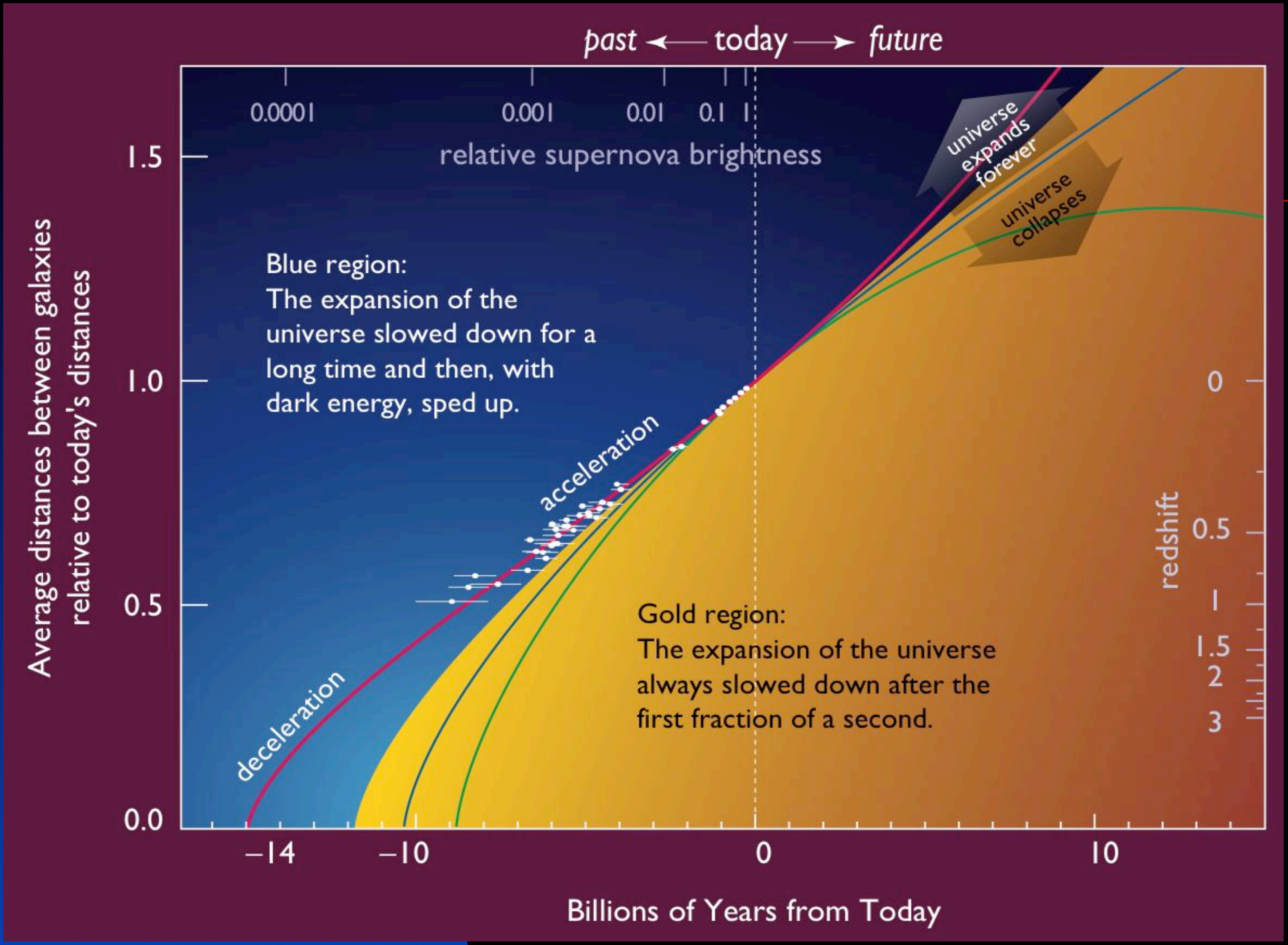


WMAP+LSS+SN

Spergel et al 2006

Best fit values: $w = -1.062^{+0.128}_{-0.079}$ **and** $\Omega_k = -0.024^{+0.016}_{-0.013}$

Evidence for Acceleration



data from Supernova Cosmology Project (LBL)

graphic by Barnett, Linder, Perlmutter & Smoot (for OSTP)

Exploding stars – supernovae –bright beacons that allow us to measure the expansion over the last 10 billion years.

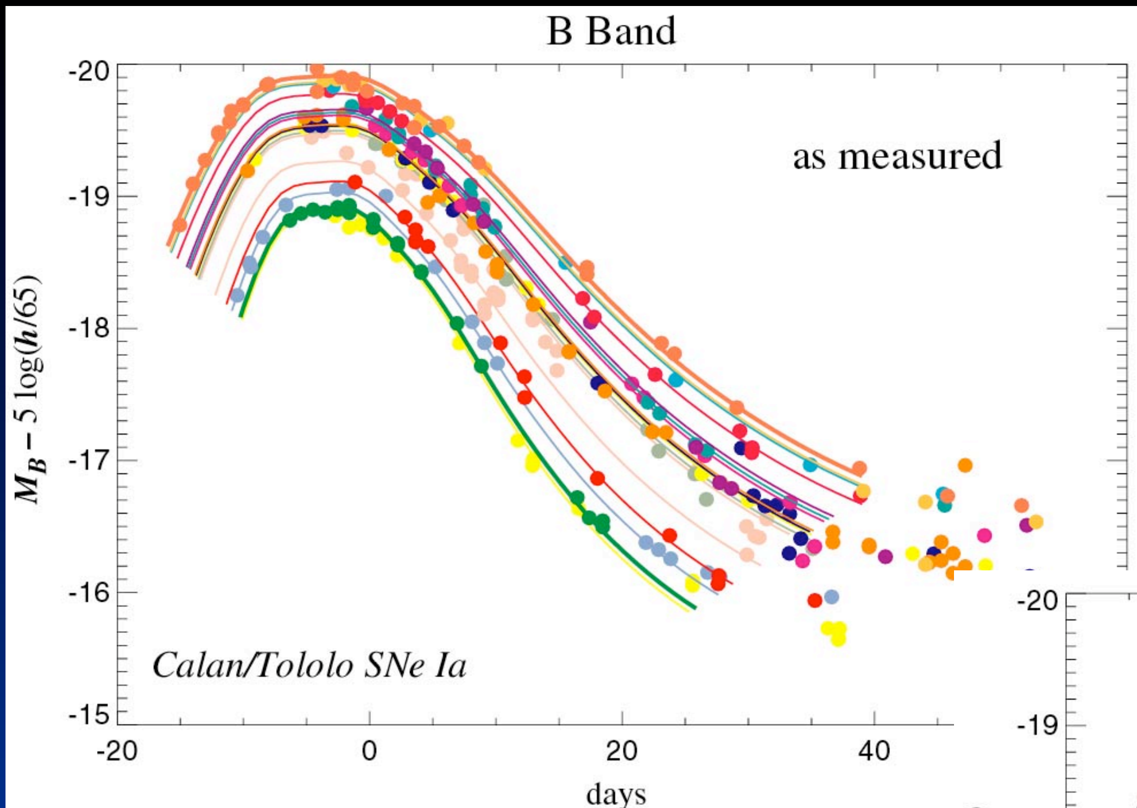
Type Ia Supernovae

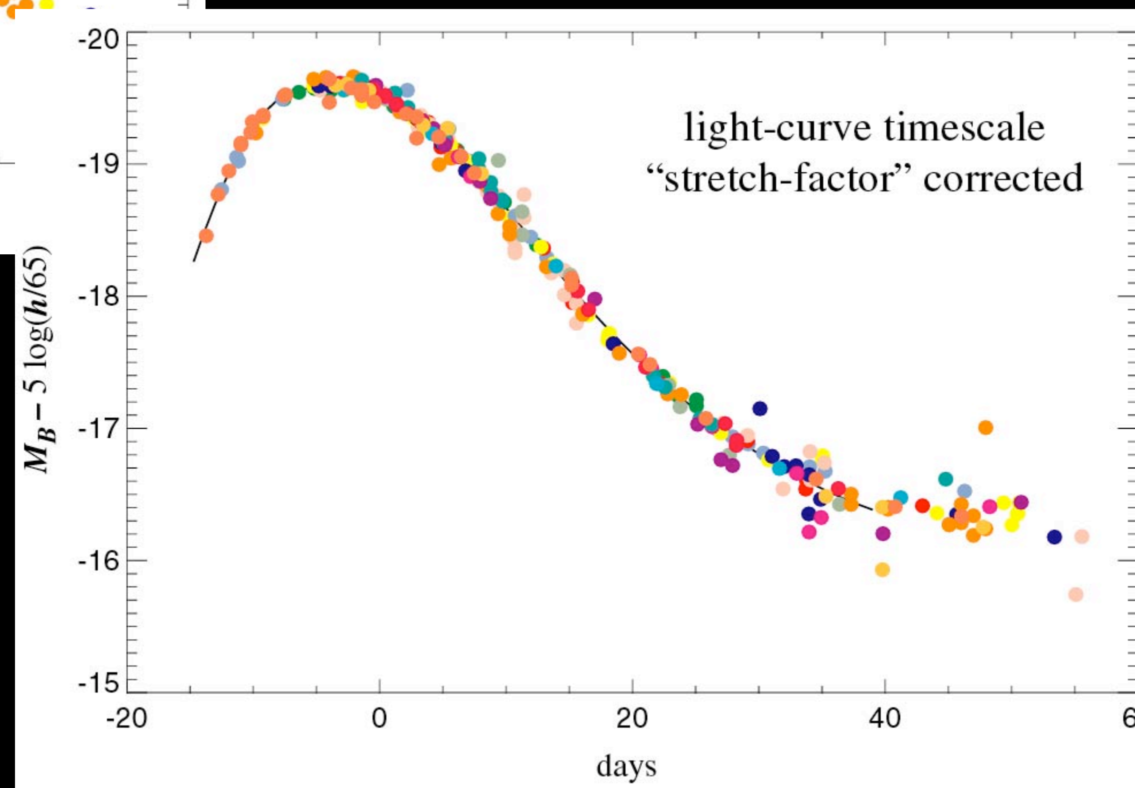
- Exploding star, briefly as bright as an entire galaxy
- Characterized by no Hydrogen, but with Silicon
- Gains mass from companion until undergoes thermonuclear runaway

Standard explosion from nuclear physics

Standard Candle

Linder





Kim, *et al.* (1997)

Brightness tells us distance away (lookback time)

Redshift measured tells us expansion factor (average distance between galaxies)

Relating the expansion rate to distance in the Hubble diagram.

Object intrinsic luminosity L, the measured energy flux F defines the luminosity distance d_L to the object (i.e. distance inferred from inverse square law)

$$d_L(z) \equiv \sqrt{\frac{L}{4\pi F}} = (1+z)r(z)$$

$$r(z) = \int_0^z \frac{dz'}{H(z')} \qquad (k=0) \qquad \text{comoving distance}$$

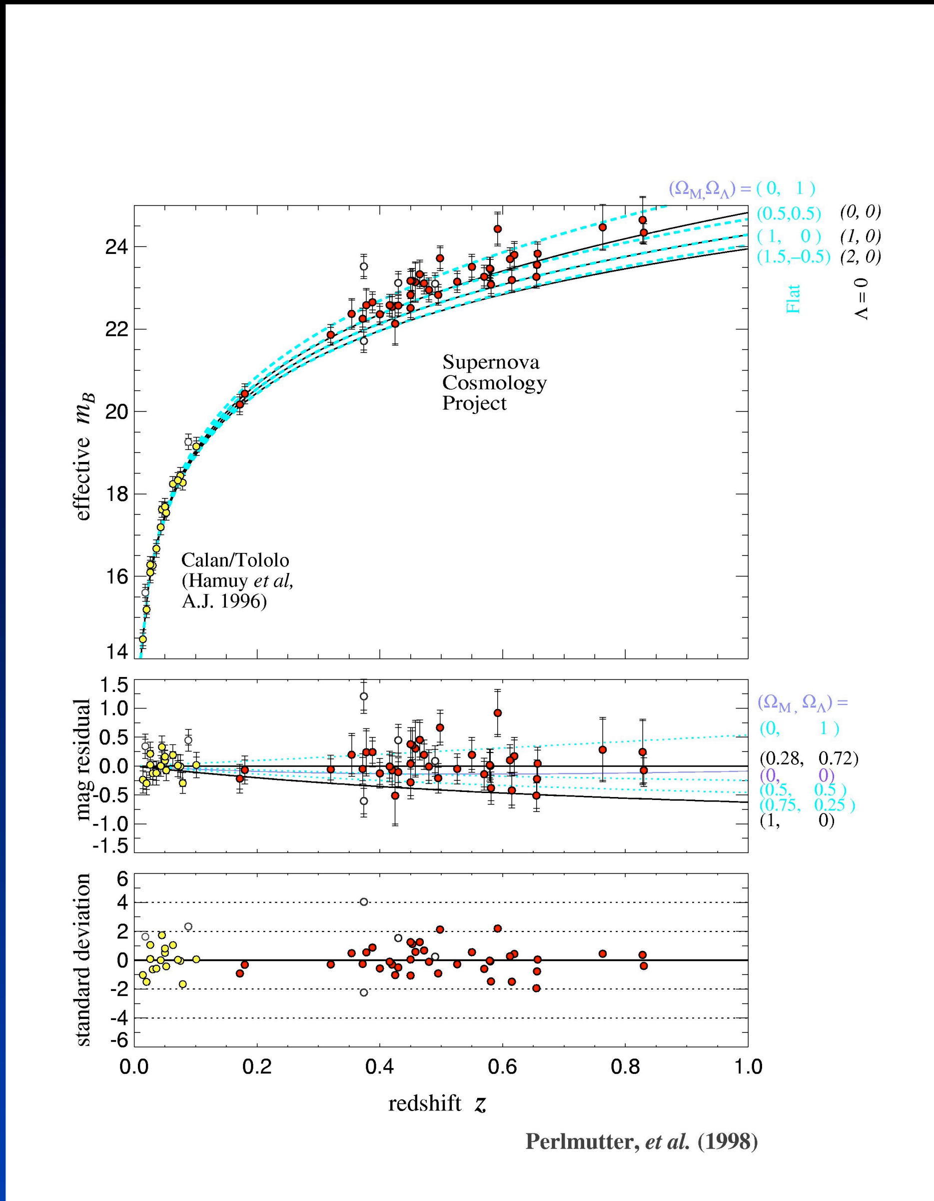
$$\mathbf{H^2(z) = H_0^2 \left(\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{de} \exp\left(3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right) \right)}$$

Luminosity distance related to distance modulus μ:

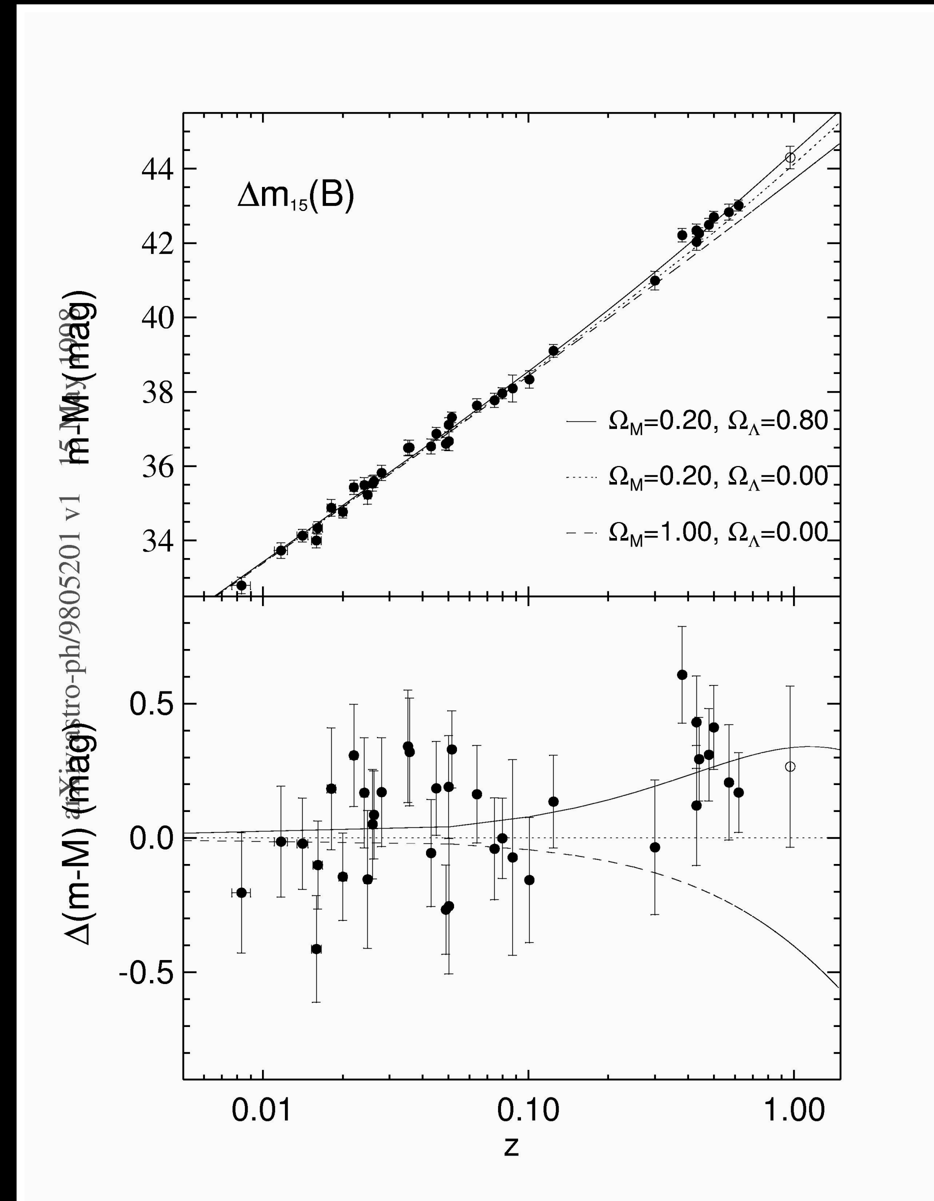
$$\mu(z) \equiv m - M = 5\log_{10}(d_L/10\ \mathrm{pc}) = 5\log_{10}((1+z)r(z)/\mathrm{pc}) - 5$$

where m is apparent magnitude (prop to log of Flux) and M is the absolute magnitude (prop to log of Intrinsic luminosity).
Standard Candles : objects of fixed M. So by measuring m we constrain the cosmological model.

The Supernova breakthrough 1998

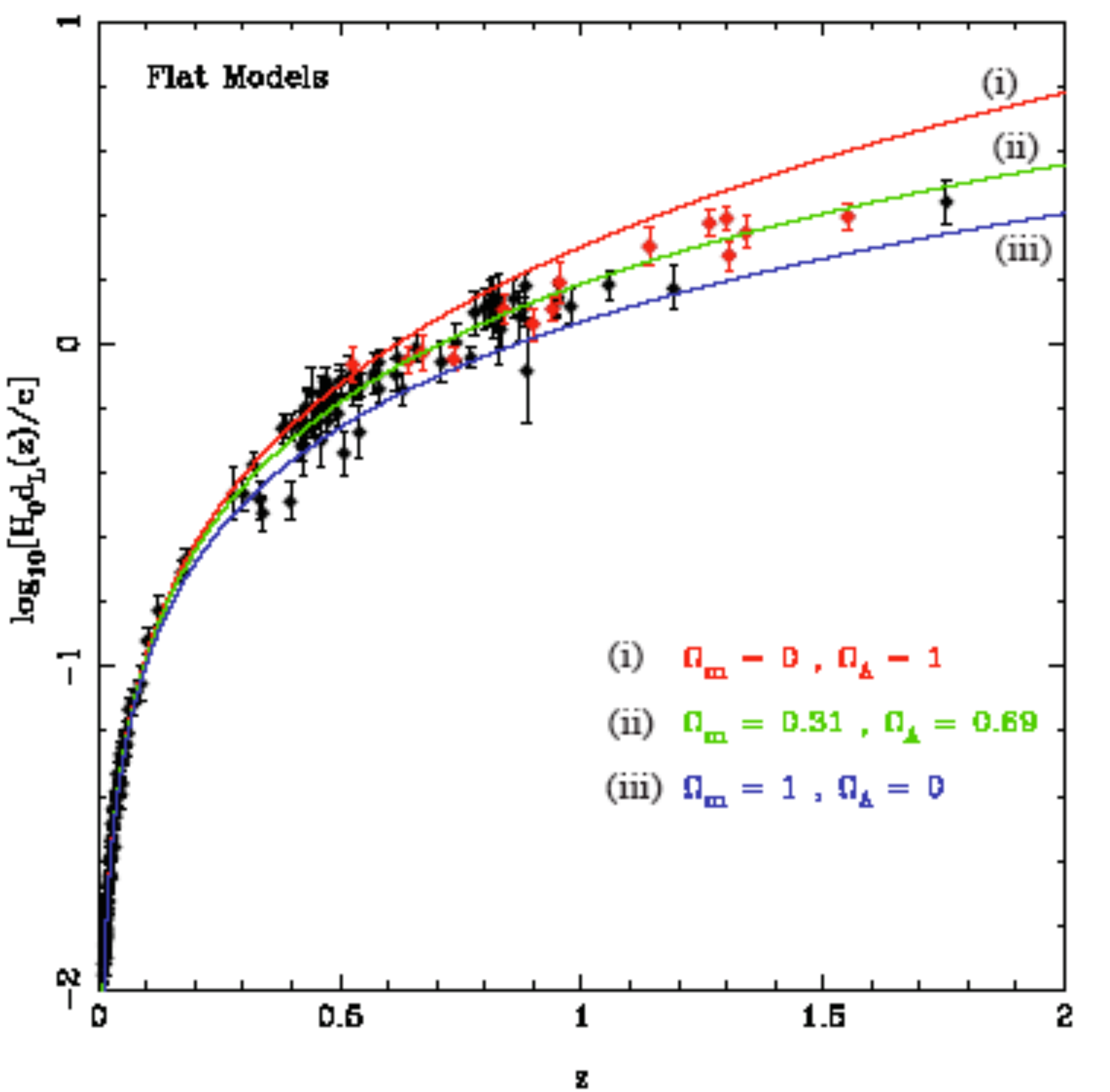


Perlmutter et al 1999



Riess et al 1998

Type Ia Luminosity distance v z [Reiss et al 2004]

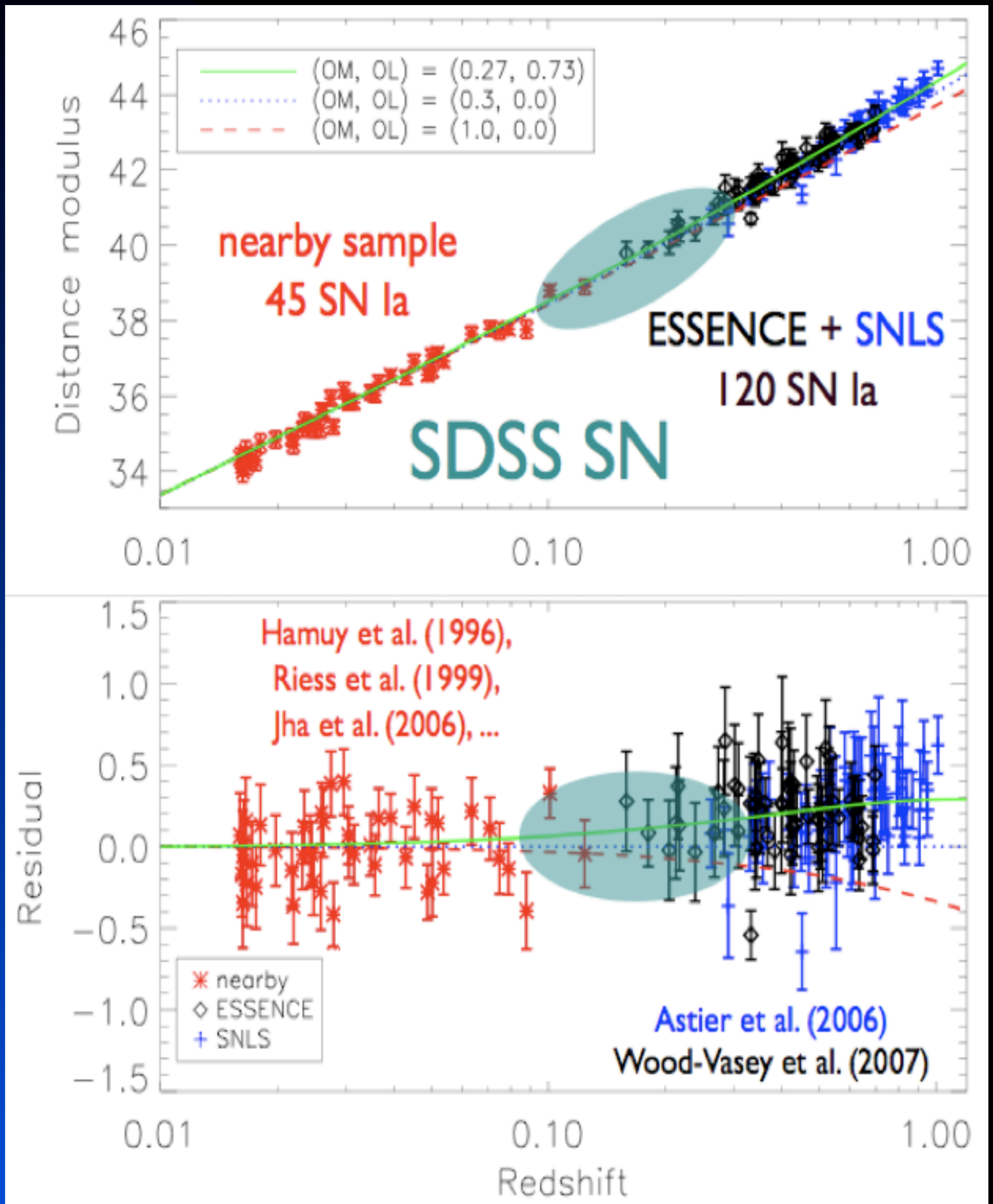


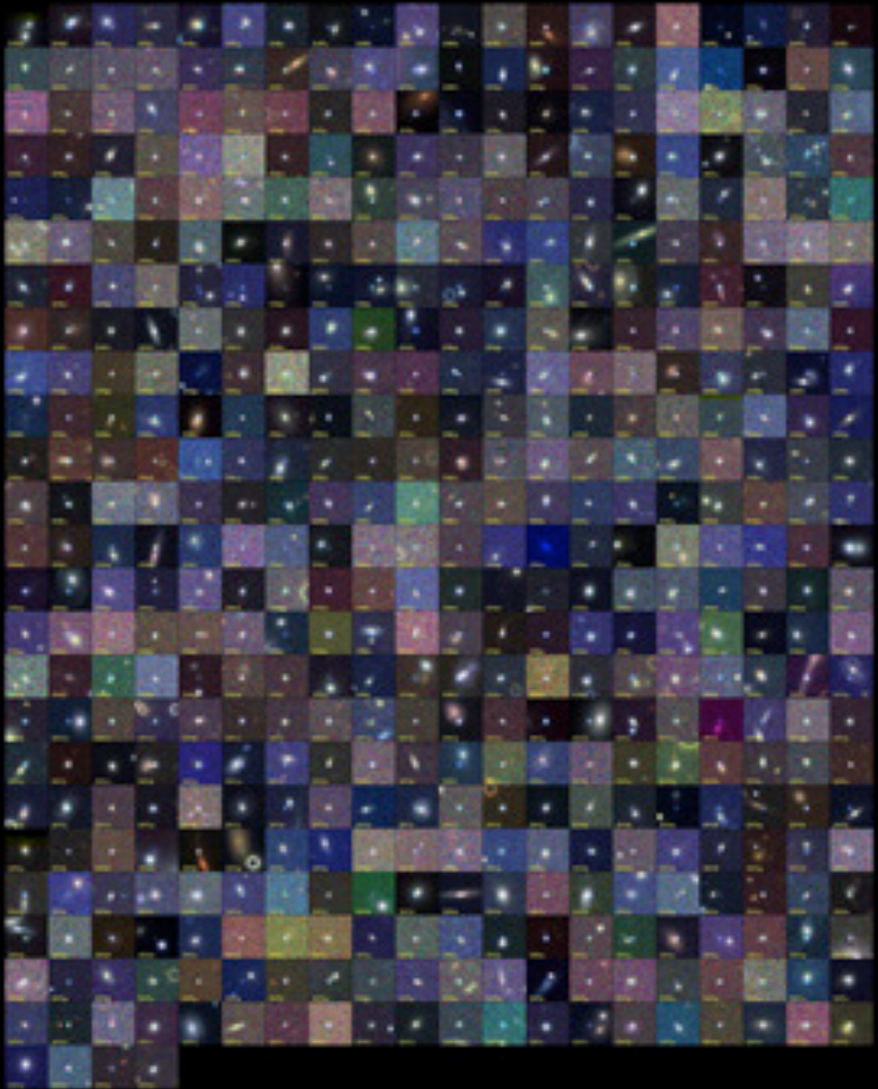
Flat model
Black dots -- Gold data set
Red dots -- HST

$$(i)\Omega_m = 0,\ \Omega_\Lambda = 1 \quad (ii)\Omega_m = 0.31,\ \Omega_\Lambda = 0.69 \quad (iii)\Omega_m = 1,\ \Omega_\Lambda = 0$$

SDSS II -- Supernova Survey:
Sept-Nov : 2005-2007
Leads to continuous Hubble diagram.

Friemann et al 2008

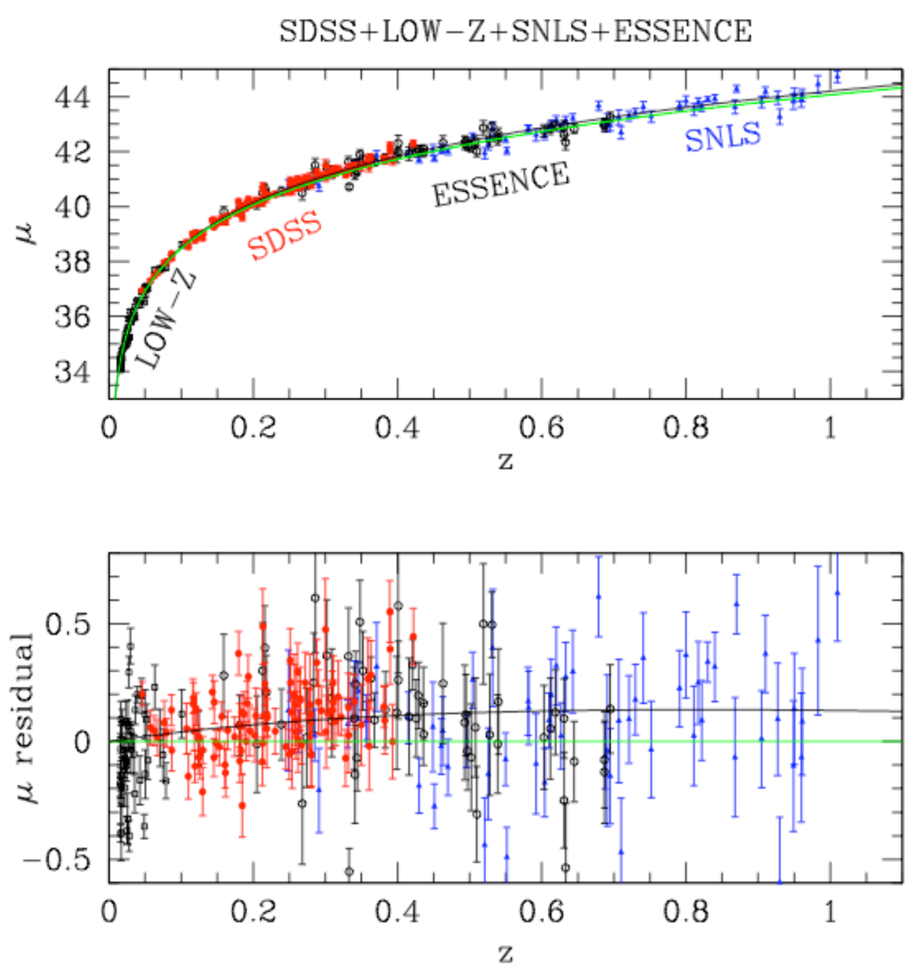


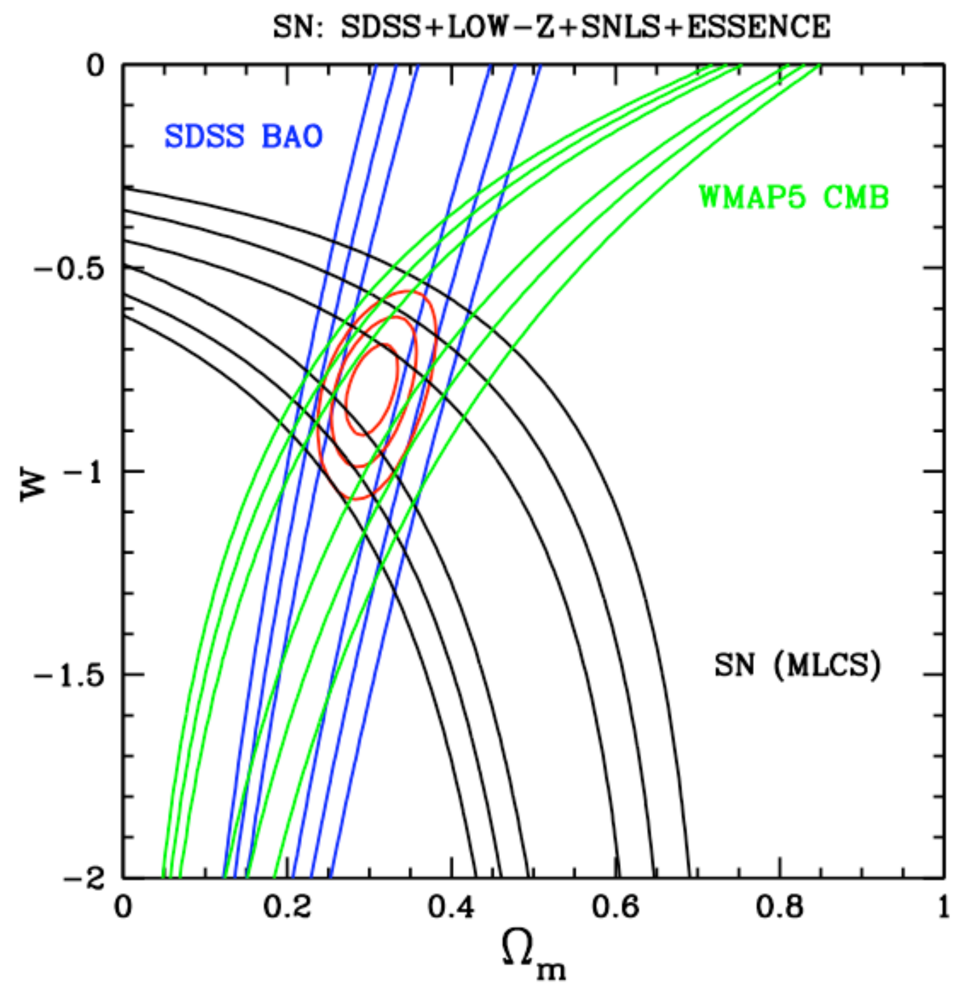


Fill in the redshift desert z~0.04-0.5 with ~500 Type 1a SN.

Early cosmology results:

Friemann et al 2008





Kessler, Becker, et al. 2008

Coincidence problem – why now?

Recall: $\frac{\ddot{a}}{a} \geq 0 <-> = (\rho + 3p) \leq 0$

If: $\rho_x = \rho_x^0 \, a^{-3(1+w_x)}$

Universe dom by Quintessence at: $z_x = \left(\frac{\Omega_x}{\Omega_m}\right)^{\frac{1}{3w_x}} - 1$

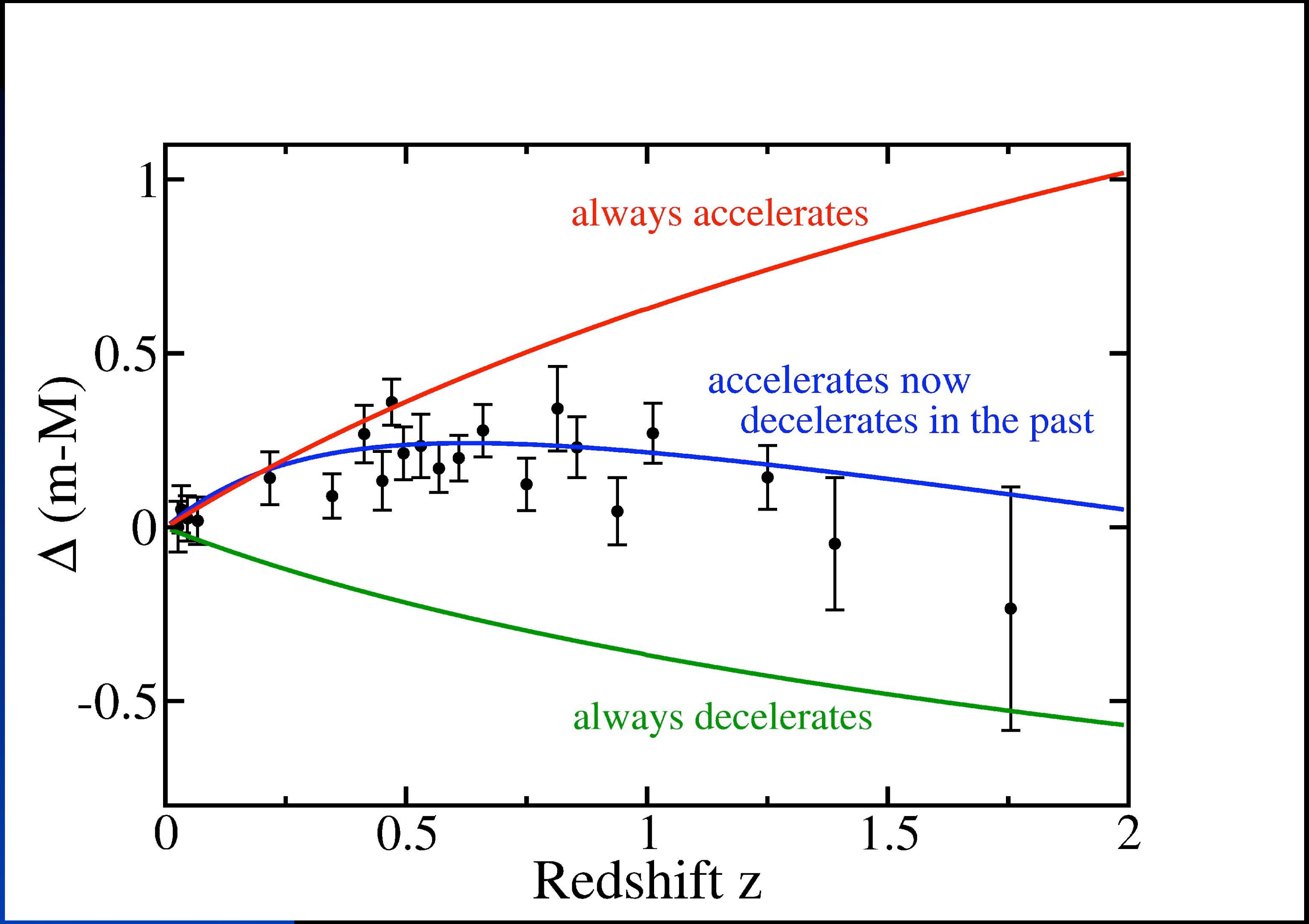
$$\left(\frac{\Omega_x}{\Omega_m}\right) = \frac{7}{3} \to z_x = 0.5,\ 0.3 \text{ for } w_x = -\frac{2}{3},\ -1$$

Univ accelerates at: $z_a = \left(-(1+3w_x)\frac{\Omega_x}{\Omega_m}\right)^{\frac{-1}{3w_x}} - 1$

$$z_a = 0.7,\ 0.5 \text{ for } w_x = -\frac{2}{3},\ -1$$

Constraint: $-0.11 < 1 + w < 0.14$ **Komatsu et al 2008 (WMAP5)**

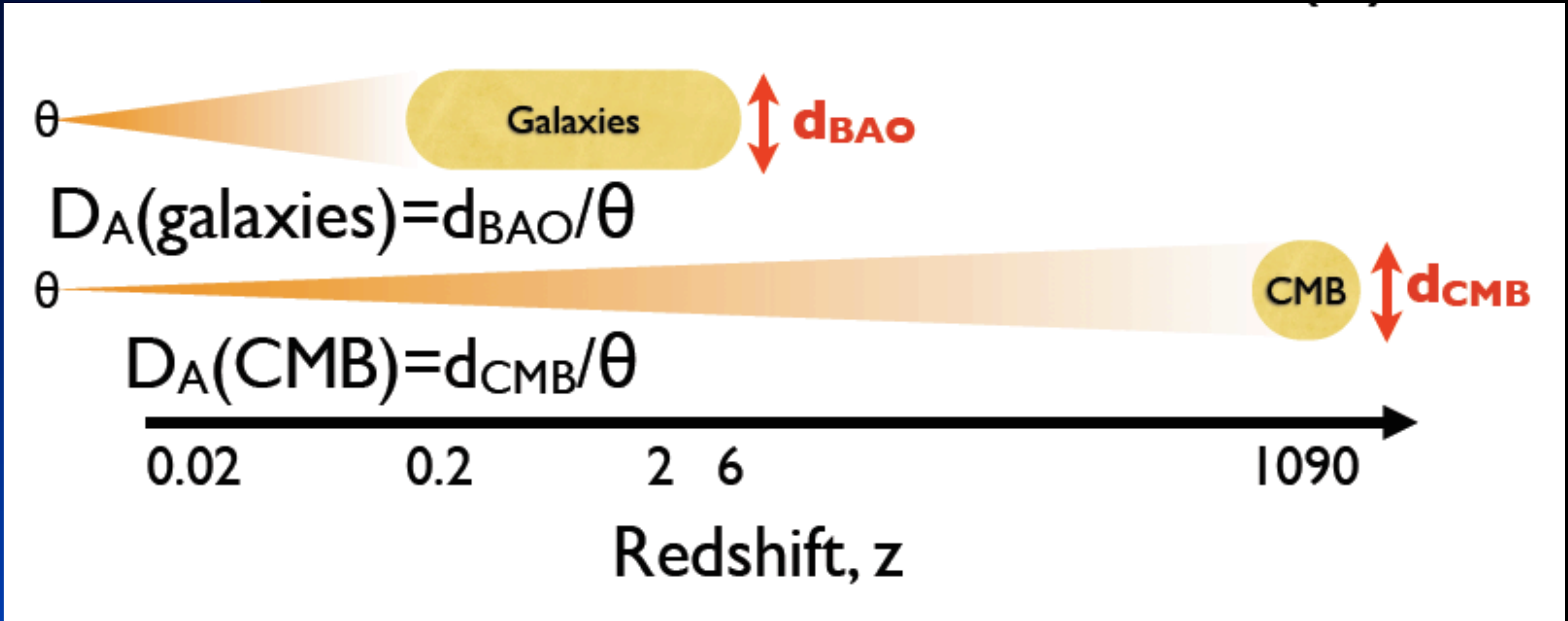
The acceleration has not been forever -- pinning down the turnover will provide a very useful piece of information.



As well as luminosity distance, have angular distance scale:

$$d_A(z) = (1+z)^{-2} d_L(z)$$

Offer possibility of measuring deeper into universe -- through Galaxies BAO (z<6) and CMB spots (z~1090):

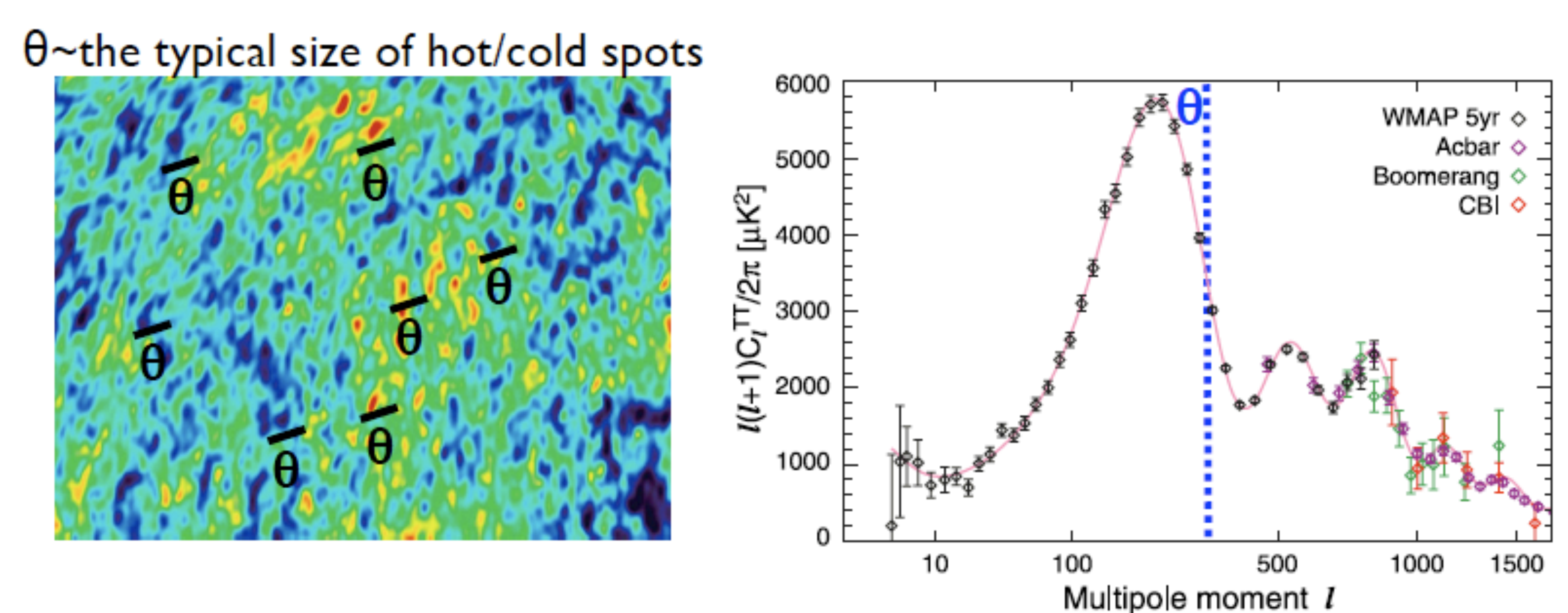


Komatsu 2008

If we know intrinsic physical size d_{CMB} can measure ang distance and this can be used to give us more information on geometry of universe.

Use CMB and BAO as a Standard Ruler

Komatsu 2008



Idea - spots in real space lead to oscillations in Fourier space. Physical spot size, d_{CMB} , governed by physical distance travelled by sound wave between big bang and decoupling of photons (z~1090).

$$d_H(t_{\rm CMB}) = a(t_{\rm CMB})\int_0^{t_{\rm CMB})} \frac{cdt}{a(t)} - -\text{causal (photon) horizon}$$

$$d_s(t_{\rm CMB}) = a(t_{\rm CMB})\int_0^{t_{\rm CMB})} \frac{c_s(t)dt}{a(t)} - -\text{sound horizon}$$

where c_s - time dep speed of sound of photon-baryon fluid

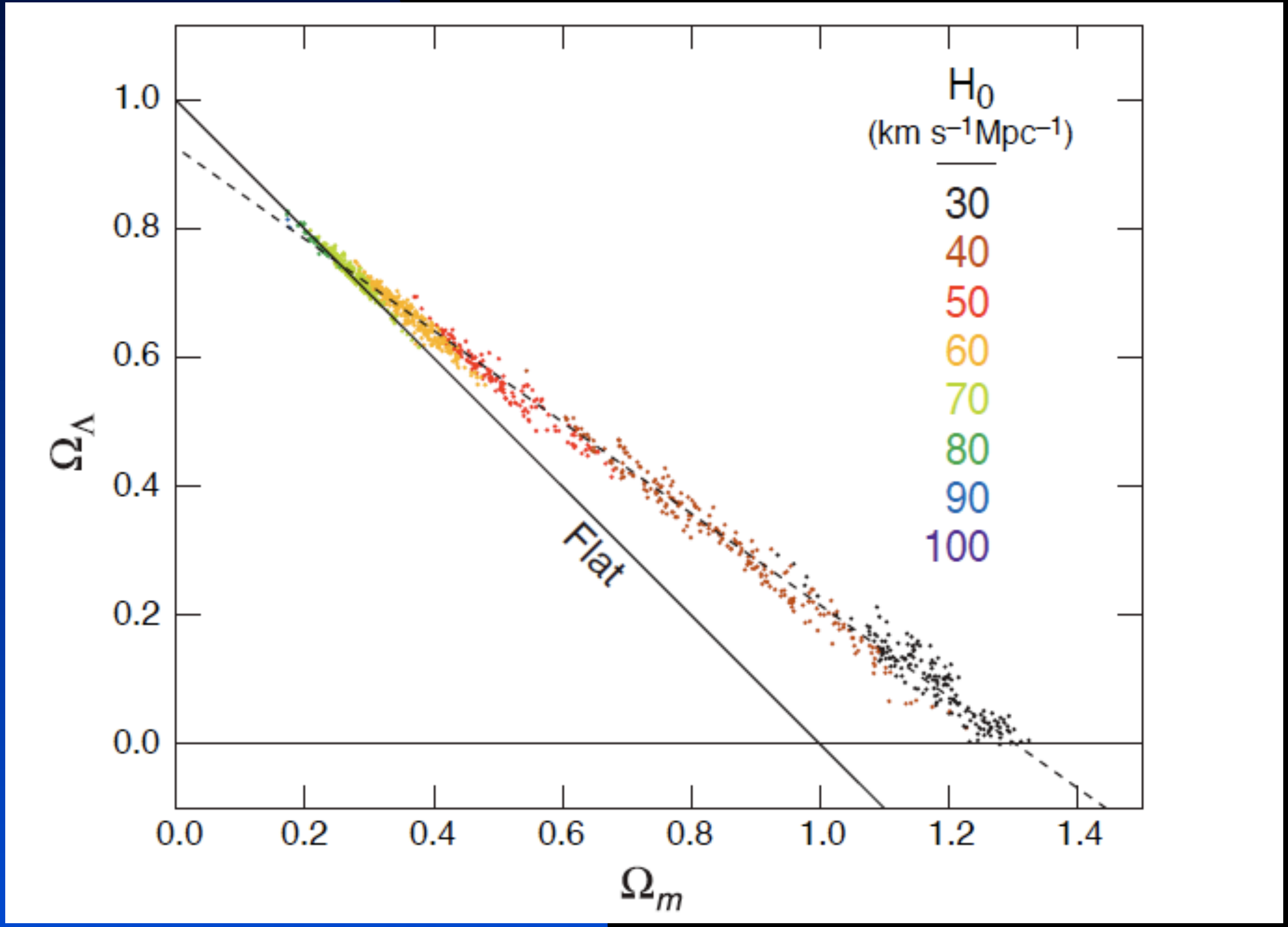
WMAP 5 year data gives:

Komatsu 2008

$l_{CMB} = \pi/\theta = \pi\, d_A(z_{CMB})/d_s(z_{CMB}) = 302.45 \pm 0.86$

$r_s(z_{CMB}) = (1+z_{CMB})\, d_s(z_{CMB}) = 146.8 \pm 1.8$ (comoving distance)

Can use ratio $d_A(z_{CMB})/d_s(z_{CMB})$ to constrain geometry of universe.



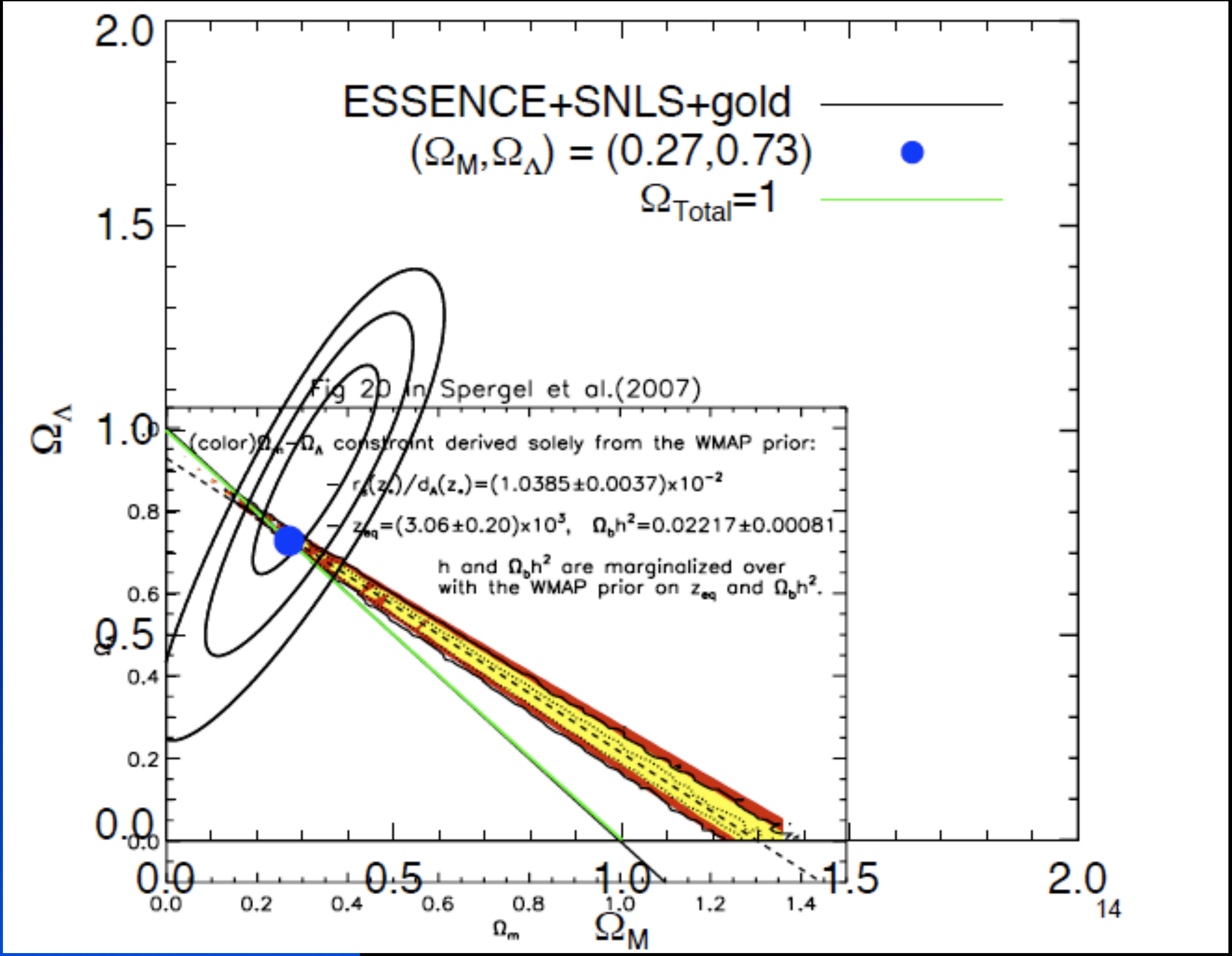
Spergel et al 2007

All models in figure are power-law CDM + DE but without flatness constraint, and fit WMAP 3 year data. Note degeneracy line: $\Omega_k = 1 - \Omega_m - \Omega_\Lambda =$ $-0.3040 + 0.4067\Omega_\Lambda$

Need H_0 to break it.

WMAP 5 +SN1a to break degeneracy :

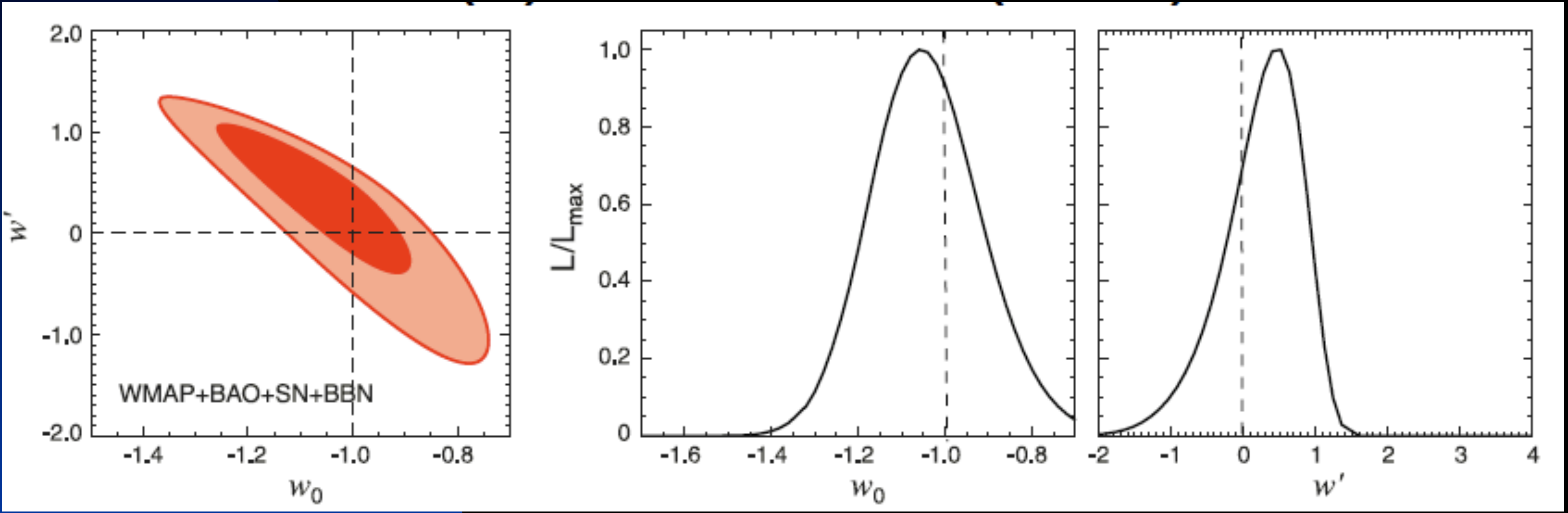
Komatsu 2008



The dark energy equation of state is constrained by a number of approaches, but we need to remain aware of the assumptions we make in parameterising it, and in the background cosmology. More on this later.

$$w(z) = w_0 + w'(z)\frac{z}{1+z}$$

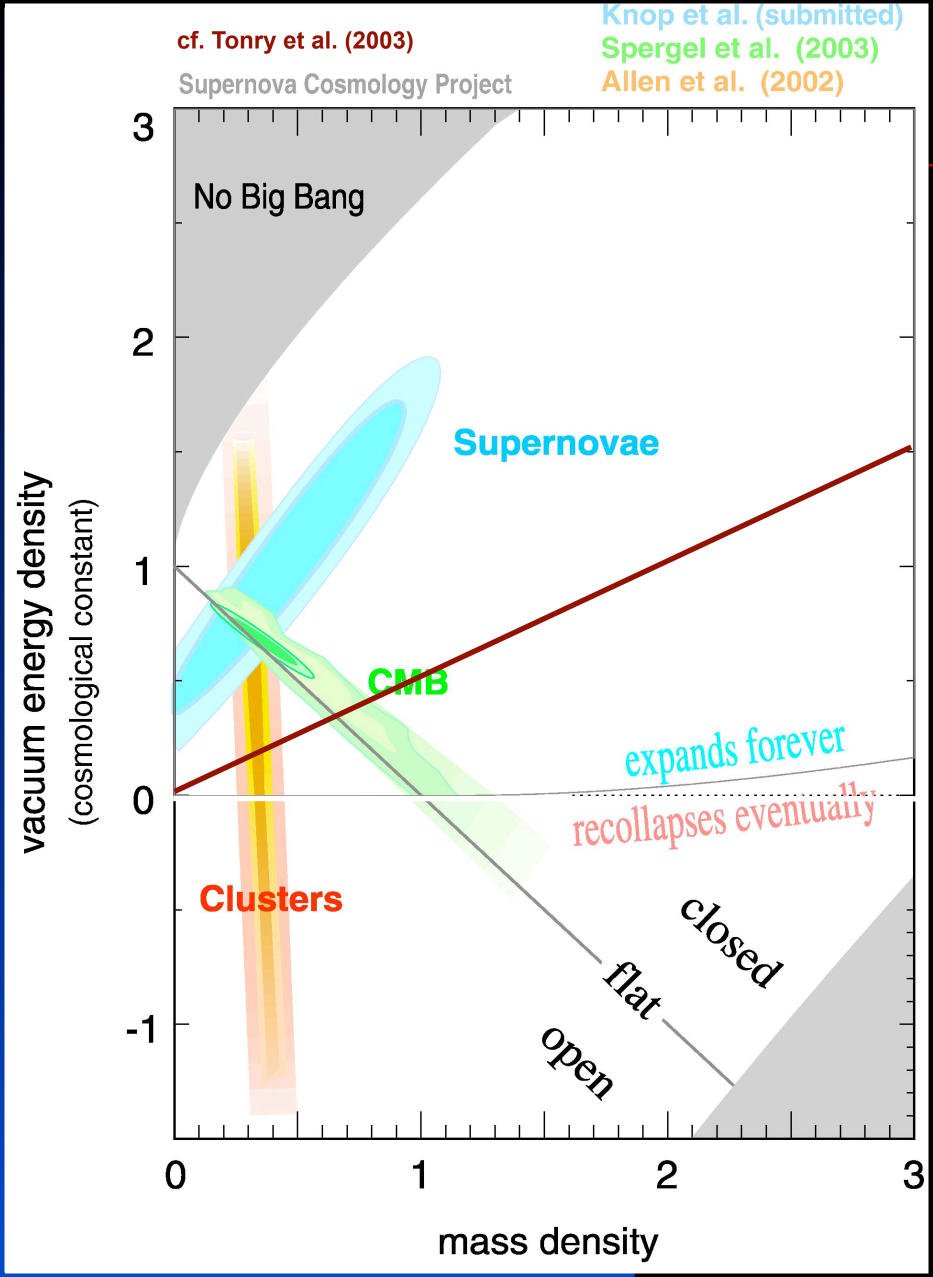
Komatsu 2008



Looks to be consistent with a cosmological constant:

$$w_0 = -1.04 \pm 0.13 \text{ and } w' = 0.24 \pm 0.55 \; (68\% CL)$$

Cosmic Concordance --2003



- ***Supernovae alone***

⇒ **Accelerating expansion**

⇒ **Λ > 0**

- ***CMB (plus LSS)***

⇒ **Flat universe**

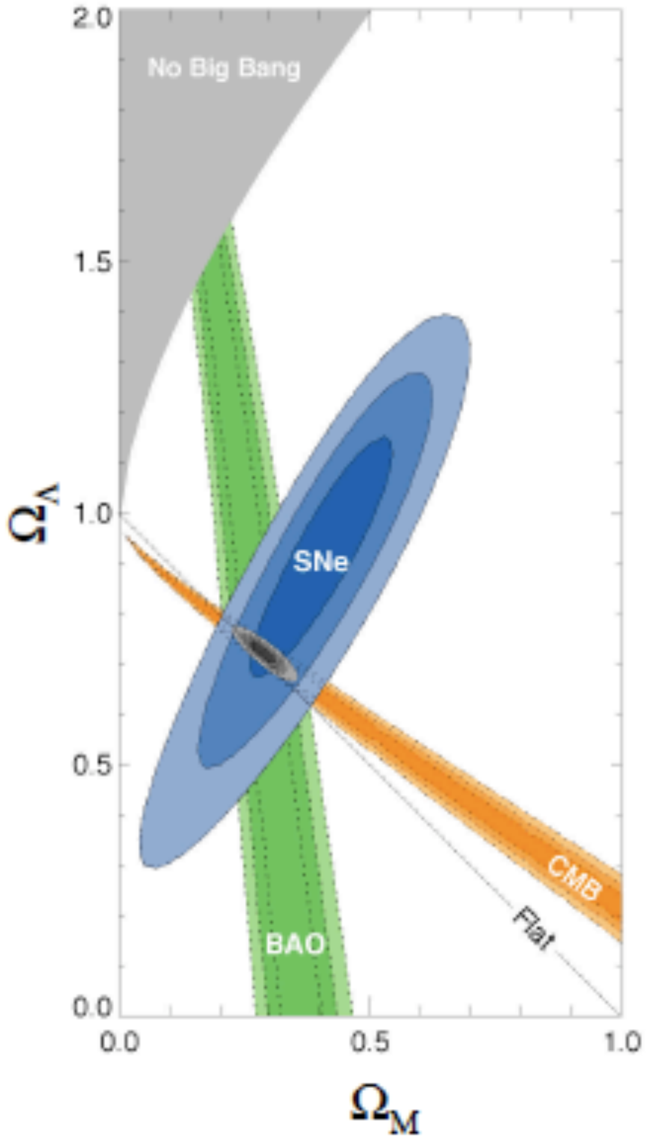
⇒ **Λ > 0**

- ***Any two of SN, CMB, LSS***

⇒ **Dark energy ~75%**

Kowalski et al 2008

Results: Cosmological fit parameters



Combination of SNe with:
BAO (Eisenstein et. al., 2005)
CMB (WMAP-5 year data, 2008)

For a flat Universe:

$$\Omega_m = 0.274 \pm 0.016(\text{stat}) \pm 0.012(\text{sys})$$

… and with curvature:

$$\Omega_m = 0.285 \pm 0.020(\text{stat}) \pm 0.010(\text{sys})$$

$$\Omega_k = -0.010 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$$

$$\Omega_\Lambda = 0.76 \pm 0.02$$

including Union Sne compilation