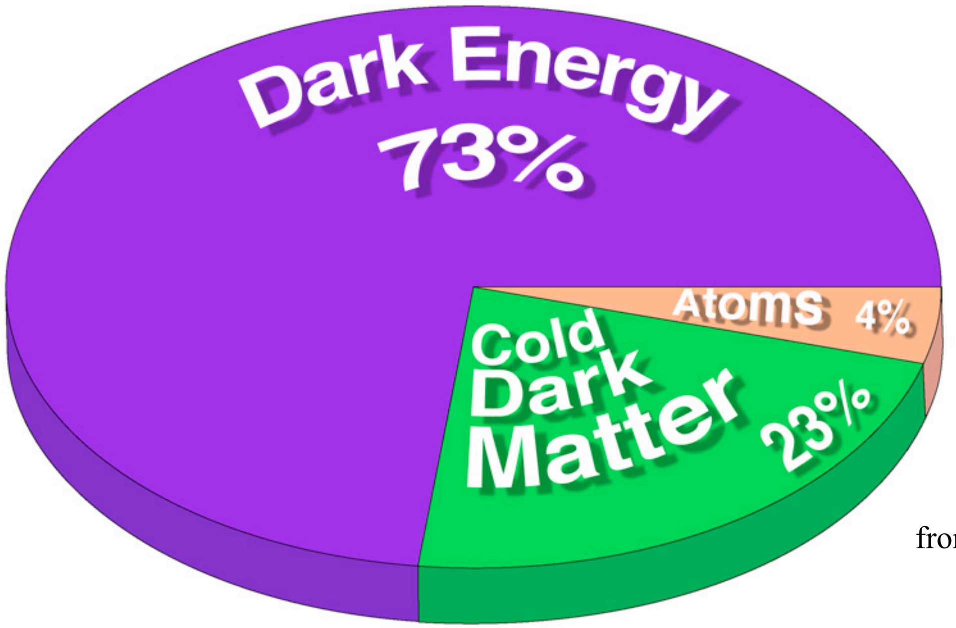
Observing dark energy (scalar field(s) ?)... in different ways



from WMAP web site

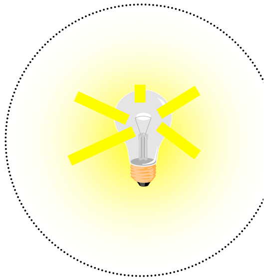
Raul Jimenez

University of Pennsylvania

www.physics.upenn.edu/~raulj

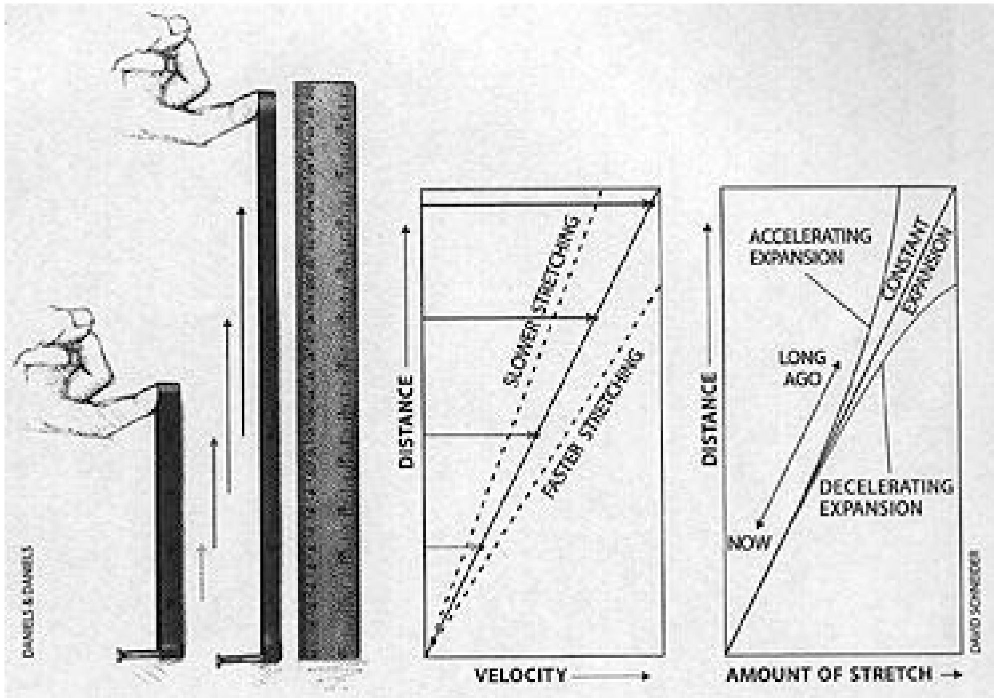
Supernovae

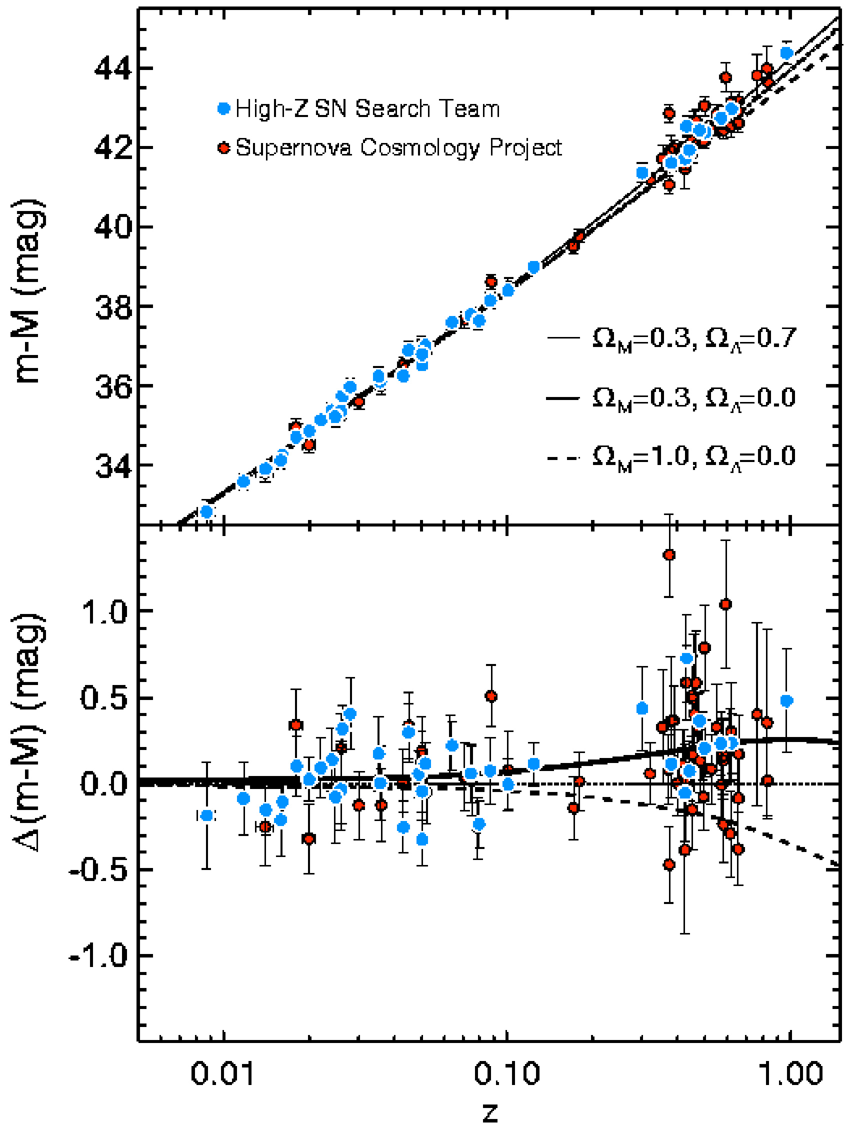
Standard candles



$$D_L = \sqrt{\frac{L}{4\pi F}}$$

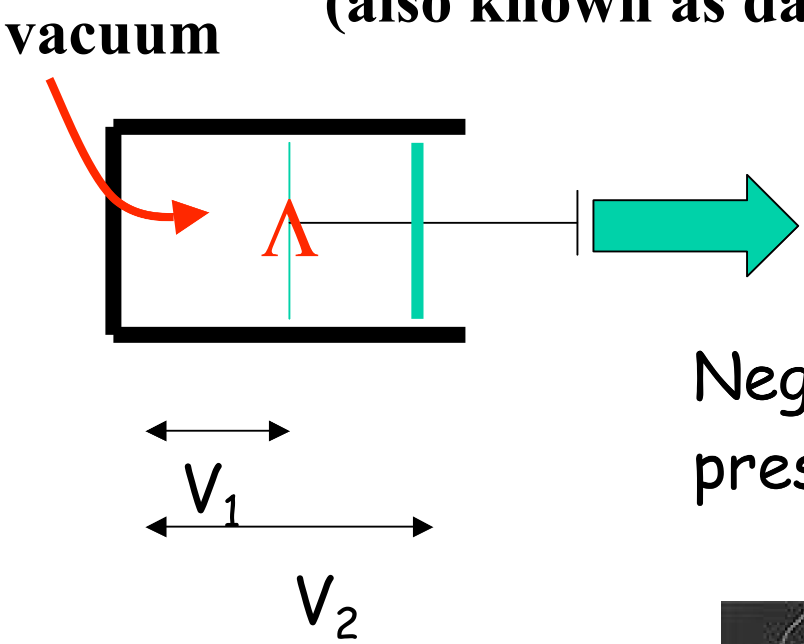
Function of geometry and
Content of Universe





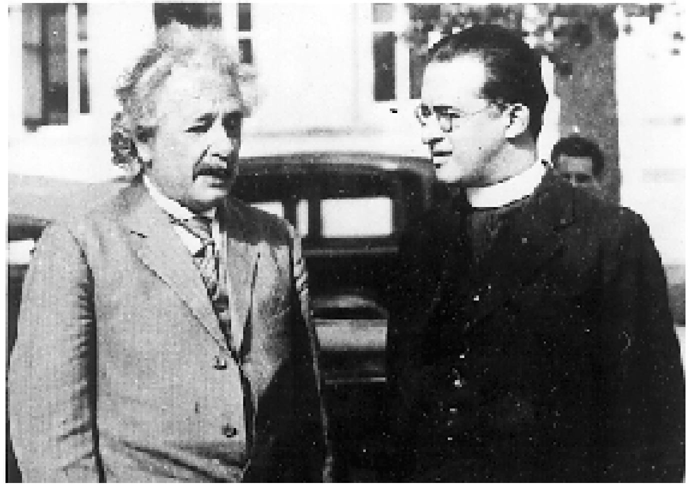
Vacuum energy Λ

(also known as dark energy or cosmological constant)



Negative pressure!

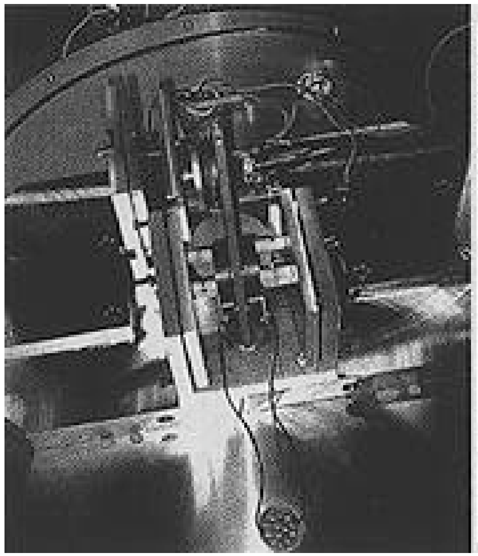
1917

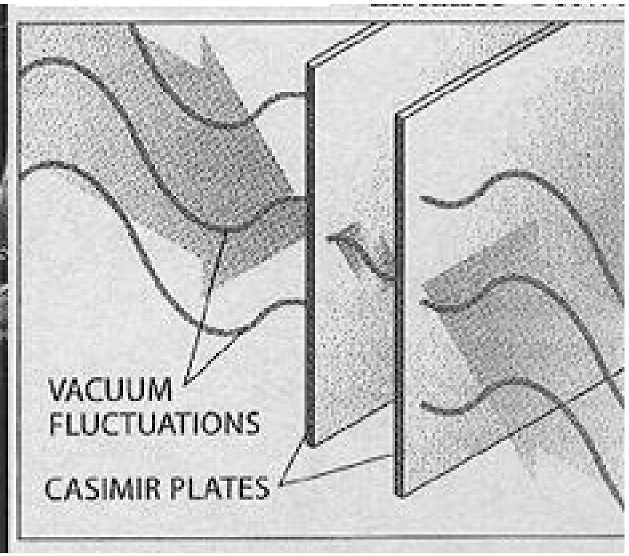


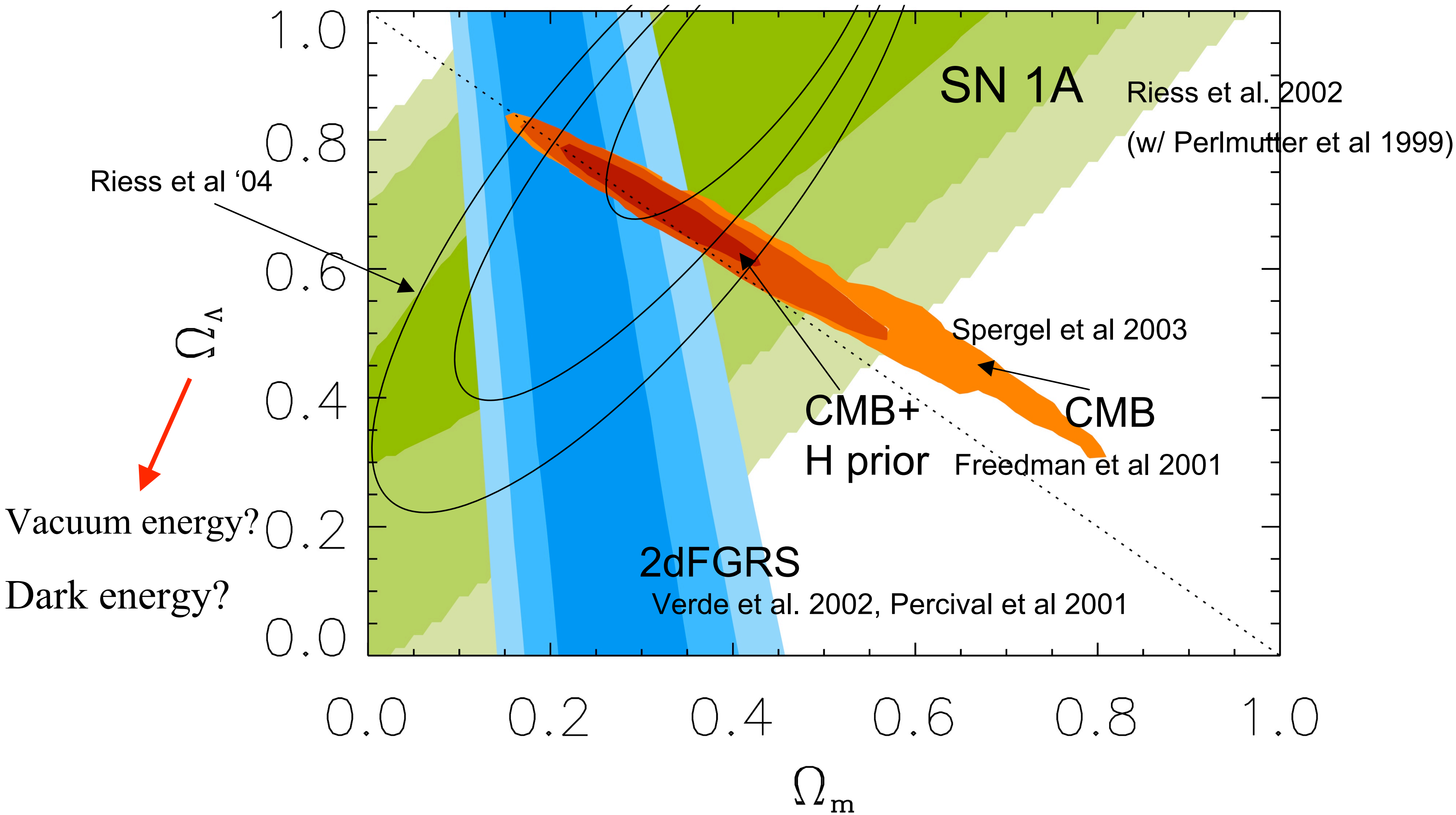
$E_1 = \rho_V V_1$

$E_2 = \rho_V V_2$

$E_2 > E_1$







from Verde (2003)

We can "measure" dark energy because of its effects on the expansion history of the universe: a(t)

$$\frac{\dot{a}(t)}{a(t)} = H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

$$H^2 = H^2{}_0[\rho(z)/\rho(0)]$$

$$\dot{\rho}_Q = -3H(z)(1+w(z))\rho_Q$$

SN: measure d_L

$$d_L = (1+z)\int_z^0 (1+z')\frac{dt}{dz'}dz'$$

CMB: θ_A and ISW → a(t)

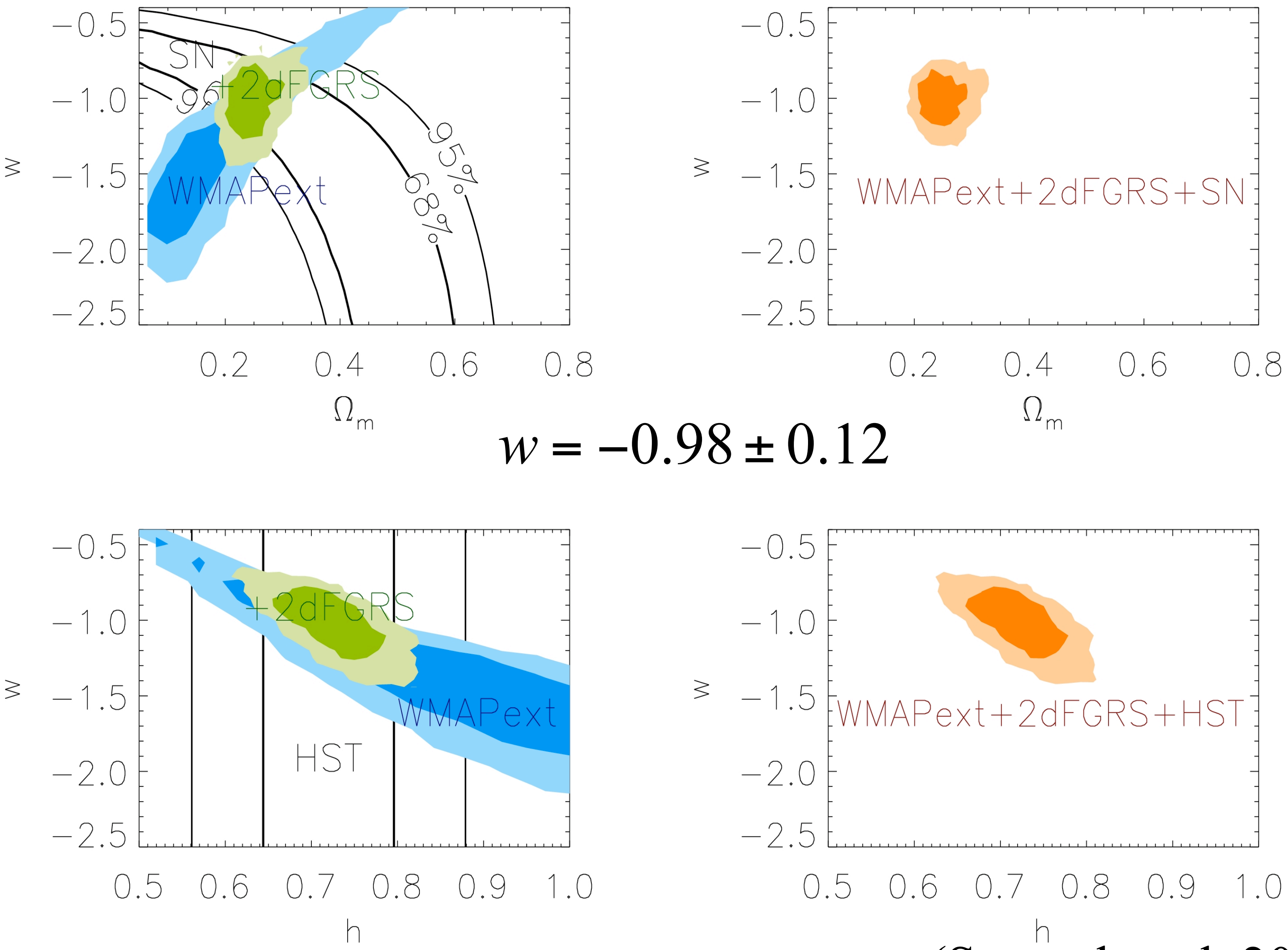
LSS or LENSING: g(z) or r(z) → a(t)

AGES: H(z) → a(t)

$$H_0^{-1}\frac{dz}{dt} = -(1+z)^{5/2}\{\Omega_m(0) + \Omega_Q(0)\exp[3\int_0^z \frac{dz'}{(1+z')} w_Q]\}^{1/2}$$

1a:WMAP+external data sets: Constraints on Quintessence (?)

Effective w

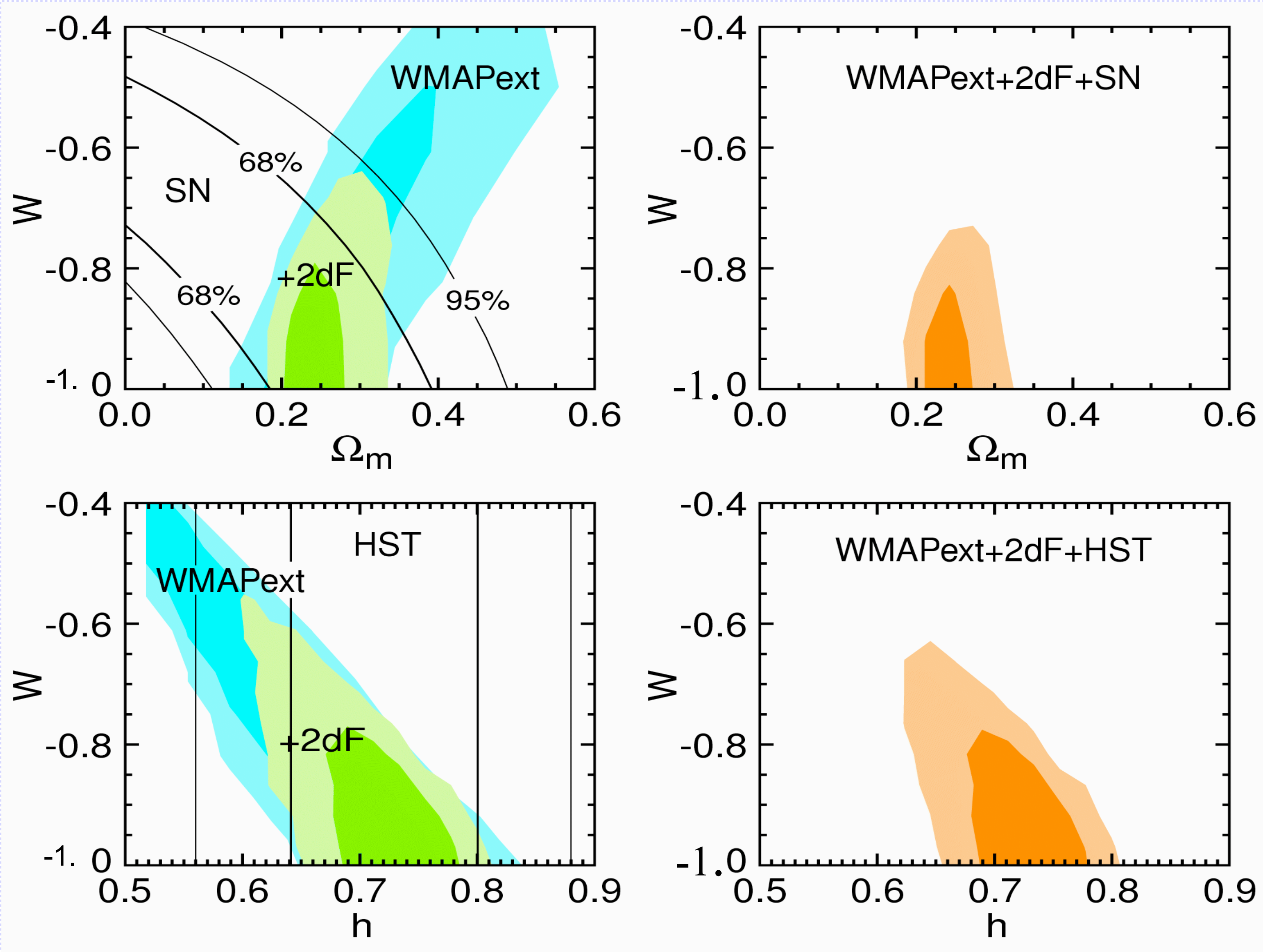


$$w = -0.98 \pm 0.12$$

(Spergel et al. 2003)

WMAP+external data sets: **Constraints on Quintessence**

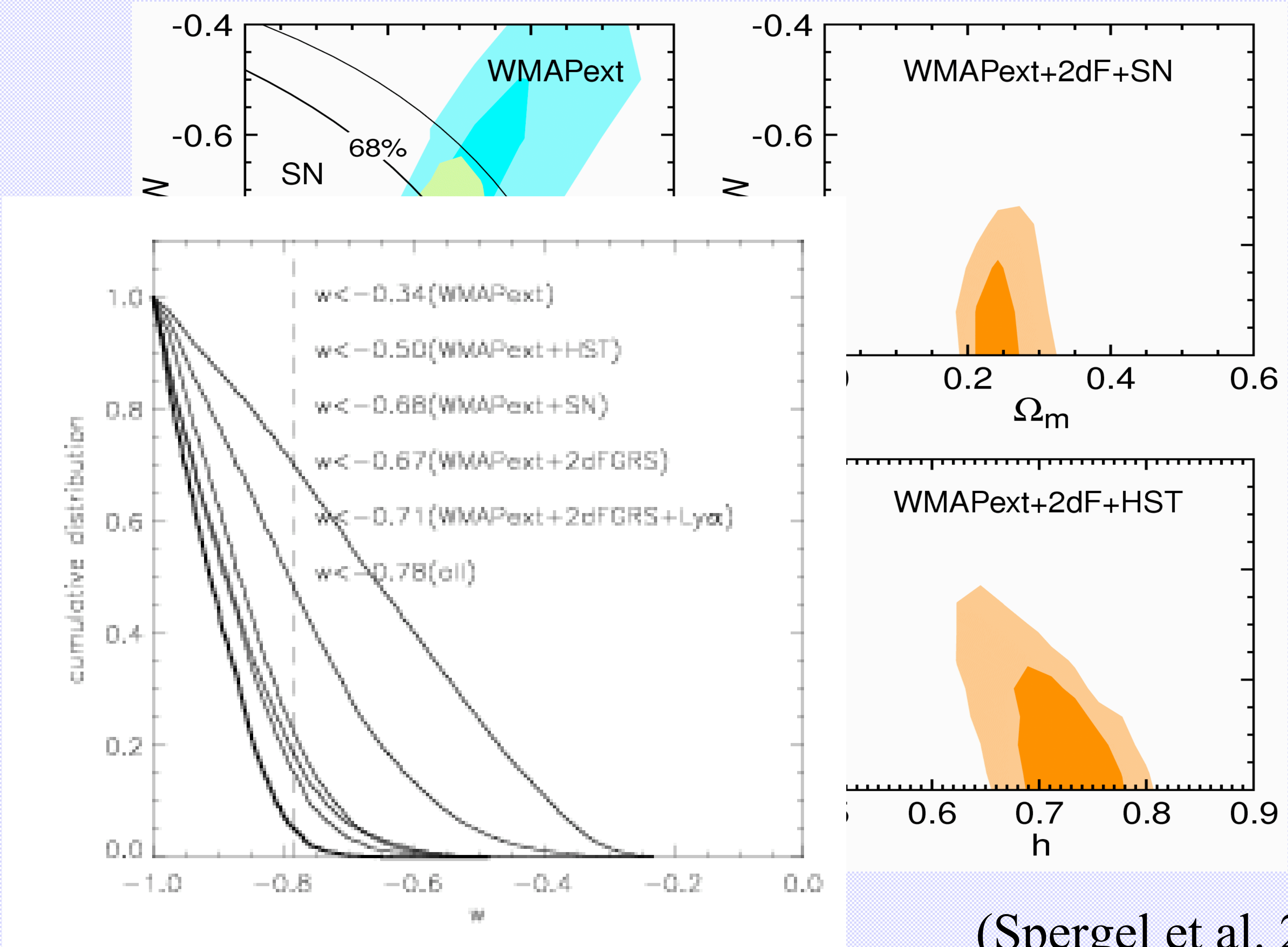
Effective w



(Spergel et al. 2003)

WMAP+external data sets: **Constraints on Quintessence**

Effective w



(Spergel et al. 2003)

LARGE SCALES: **1:CMB and Large scale structure**

1a- **WMAP + external data sets results** results

(WMAP team 2003)

1b- **CMB X lensing X Rees Sciama** *Future:ACT*

(Verde & Spergel 2002)

SMALL SCALES: **2: A cosmologist's use of stars**

2a- **Globular clusters ages** results

(in collaboration with L. Verde, T. Treu, D. Stern 2003)

2b- **Non-parametric w(z) (dz/dt) ?** *preliminary*

(in collaboration with Joan Simon, L. Verde 2003-2004)

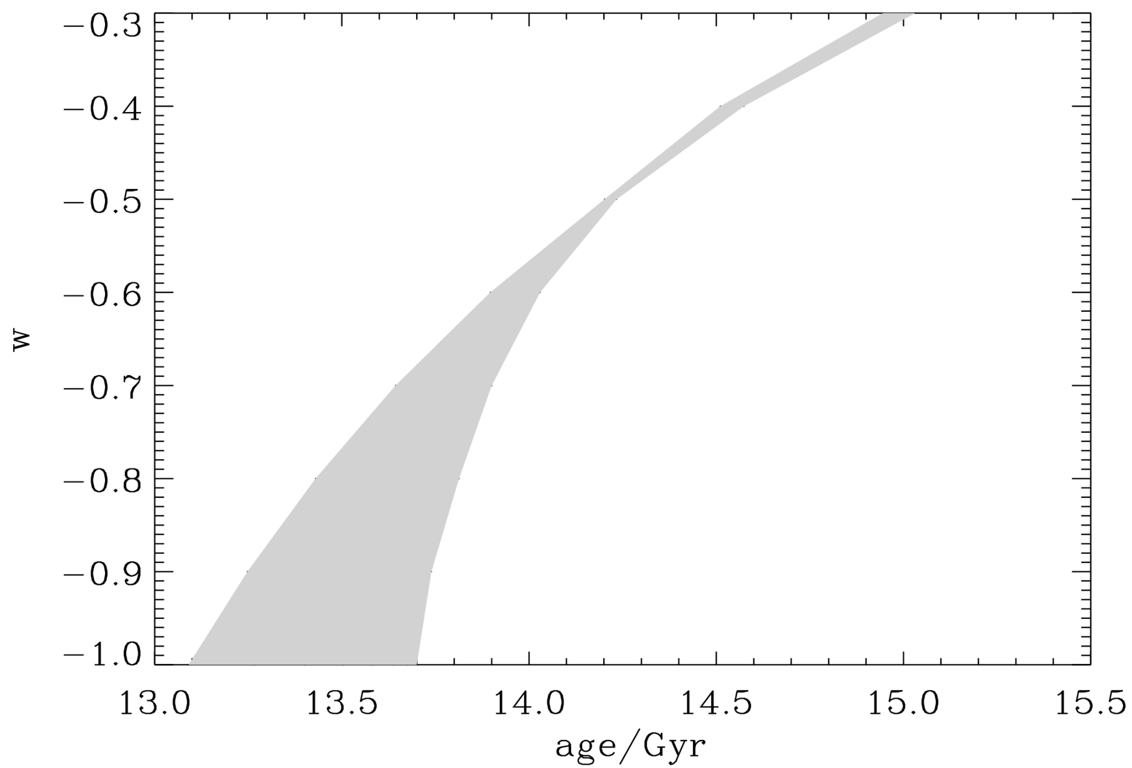
2a:Globular clusters ages: THEORY

Assume the universe to be **flat**: ℓ_1 depends on w and age

l1=sound horizon(decoupling)/angular diameter distance (decoupling)

for a fixed value of w, a change in $\_{m}h^2$ that keeps ℓ_1 fixed will also keep age unchanged (Cadwell et al. 1998, Knox et al. 2001, Hu et al. 2001)

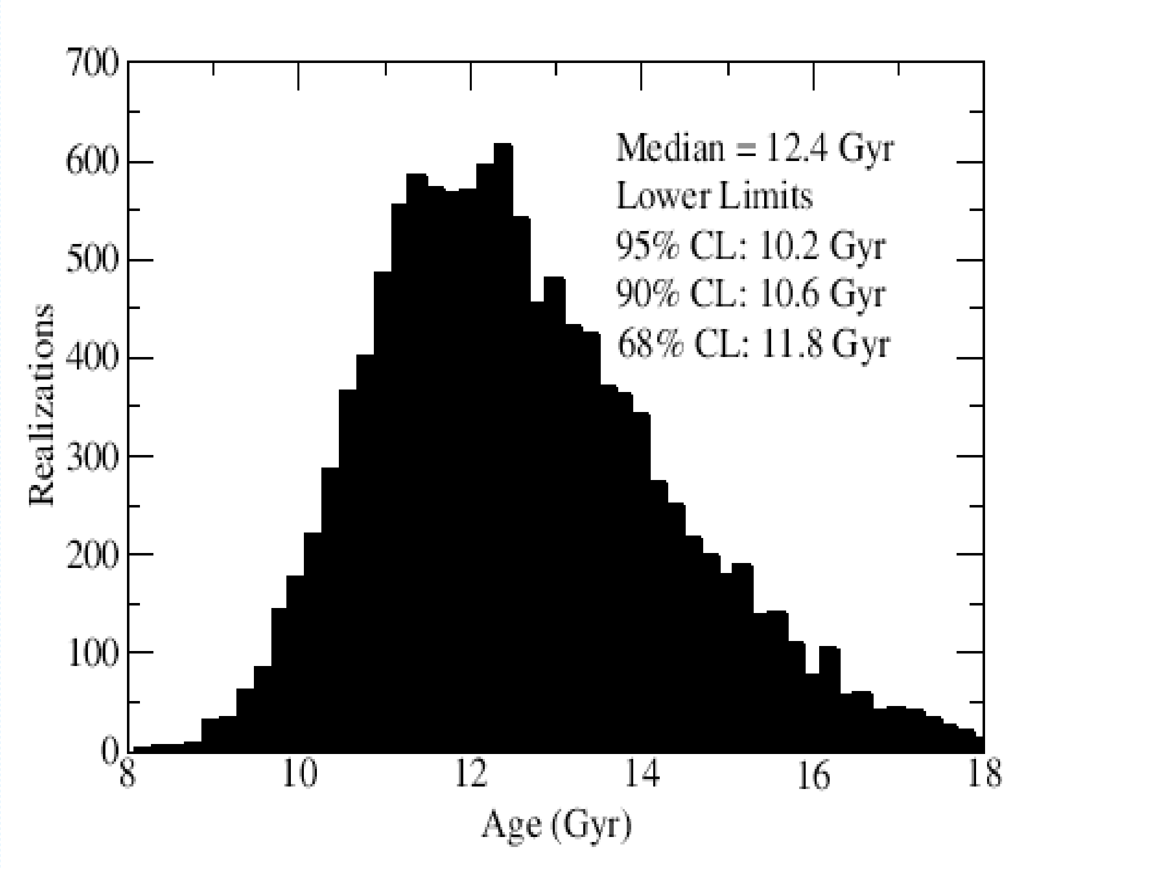
Effective w



2a: Globular clusters ages: independent age estimate

Monte Carlo for age of oldest GC paying careful attention to systematics

From Krauss & Chaboyer 2003

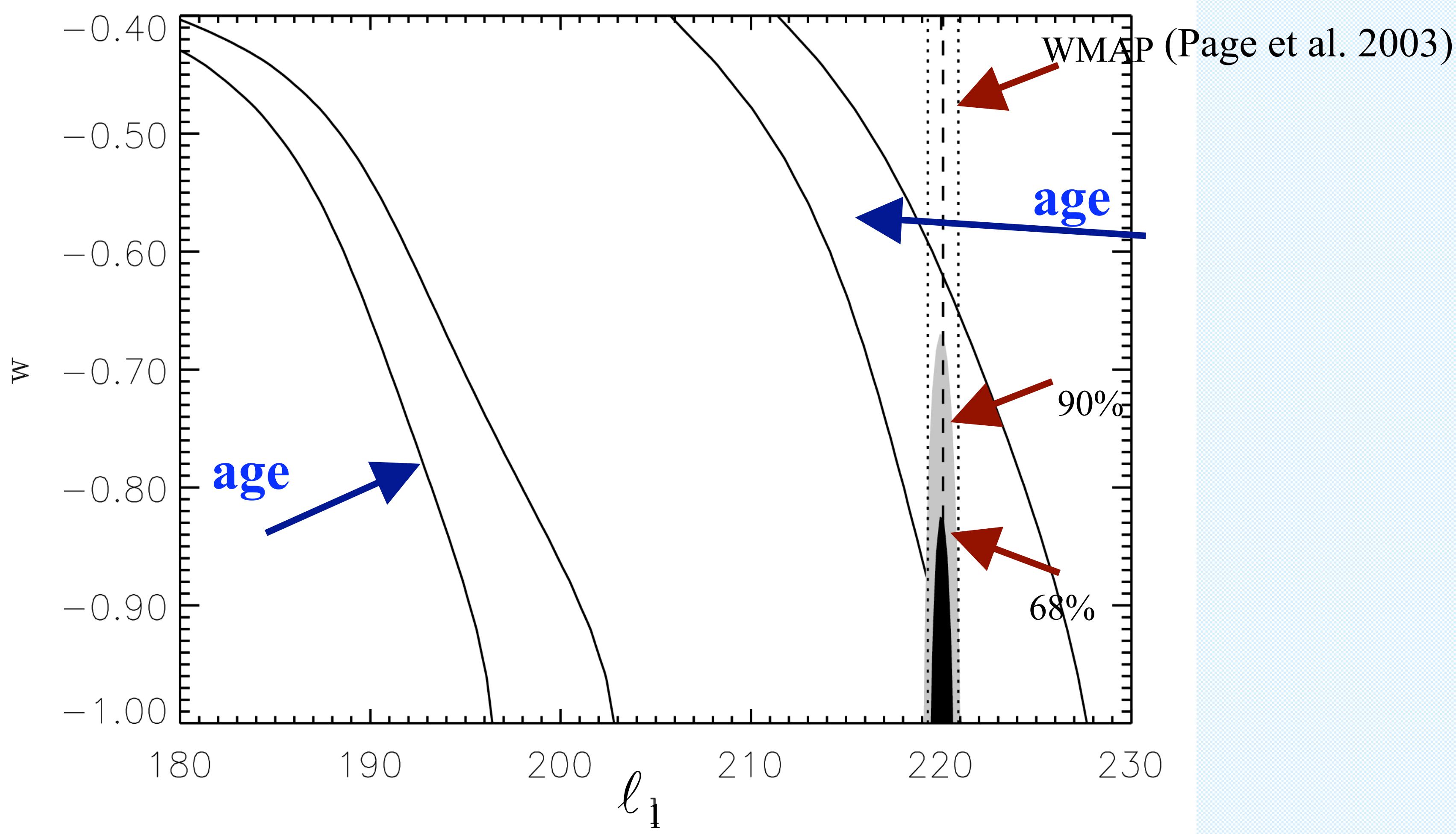


M92

$$P(t) = \frac{A}{\sigma(t-T)} \exp[-\ln[(t-T)/m]^2 / 2\sigma]$$

OFFSET

2a:Globular clusters ages: Constraint on "effective" w



(Jimenez , Verde, Treu, Stern, 2003)

Very weak priors on 50 < H < 95

0 < _ m < 0.5

1b:Dark energy and secondary CMB

(Verde, Spergel 2002,PRD)

$$\left.\frac{\Delta T}{T}\right|_{\gamma} \cong \frac{\Delta T^{P}}{T} + \underbrace{\frac{\Delta T^{P}}{T} \bullet \nabla\Theta}_{\text{Lensing}} + \frac{\Delta T^{NL}}{T} + SZ + \ldots$$

High z (low l)

Rees-Sciama

Gravitational potential

$$\Theta(\gamma) = -2\int_0^{r_*} \frac{r_* - r}{r_* r} \Phi(r, \gamma r) dr$$

Depends on Ω_0, w

ISW, but non-linear

$$\frac{\Delta T^{NL}}{T} = 2\int \frac{\partial}{\partial t} \Phi^{NL}(r, \gamma r) dr$$

Low z
(high l)

1b: Bispectrum :

Luo 1994,…. Spergel Goldberg 1999, Goldberg, Spergel 1999, Komatsu, Spergel 2001 etc…

to couple the high z universe (low ℓ) to the low z universe (high ℓ) via the weak lensing signal

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} = \langle a^{m_1}_{\ell_1} a^{m_2}_{\ell_2} a^{m_3}_{\ell_3} \rangle = \begin{pmatrix} \ell_1 \ell_2 \ell_3 \\ m_1 m_2 m_3 \end{pmatrix} B_{\ell_1 \ell_2 \ell_3}$$

Consider primordial, lensing & Rees-Sciama:

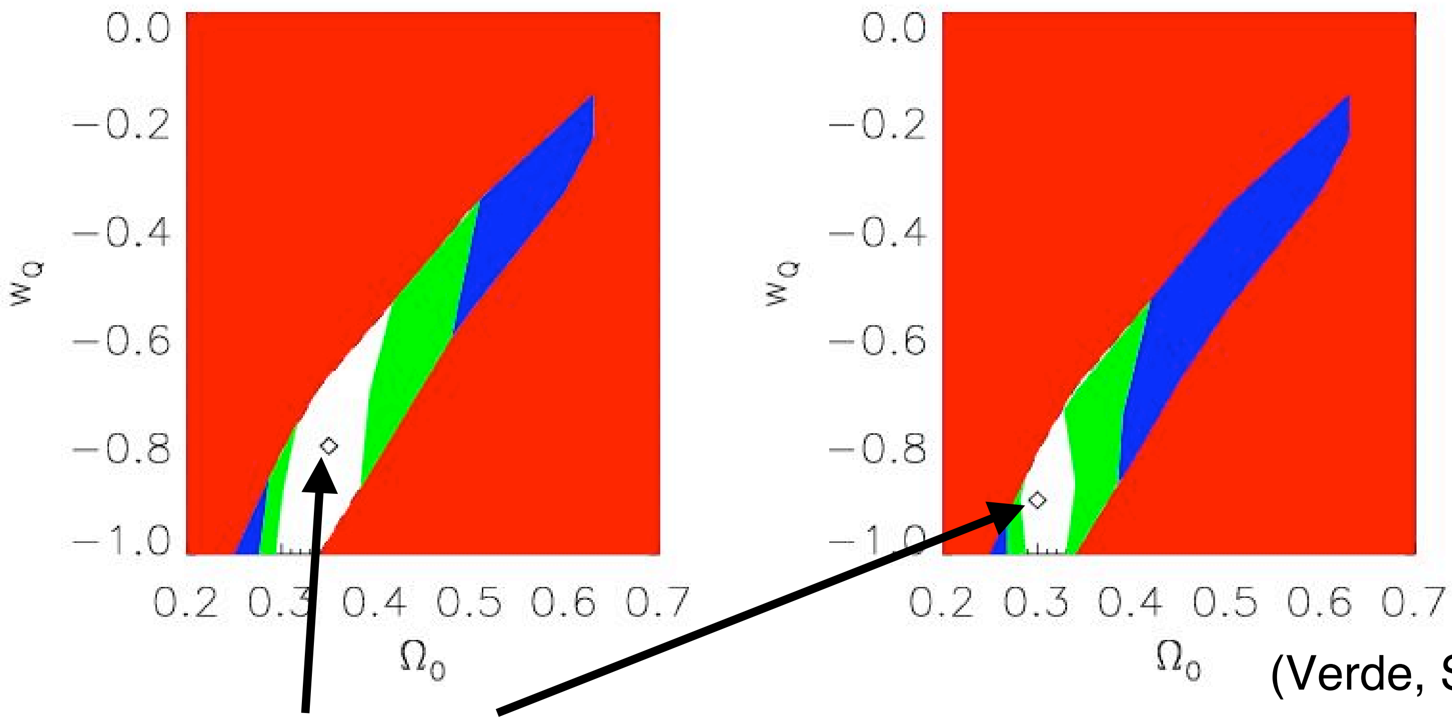
Balance of 2 competing contributions:

- **Decay of gravitational potential** **(non Einstein de Sitter Universe)**
- **Amplification due to non-linear gravitational evolution**

Balance depends on Ω_m and w

Bispectrum: Cross correlating primordial-lensing-Rees Sciama

ACT+WMAP2yr data

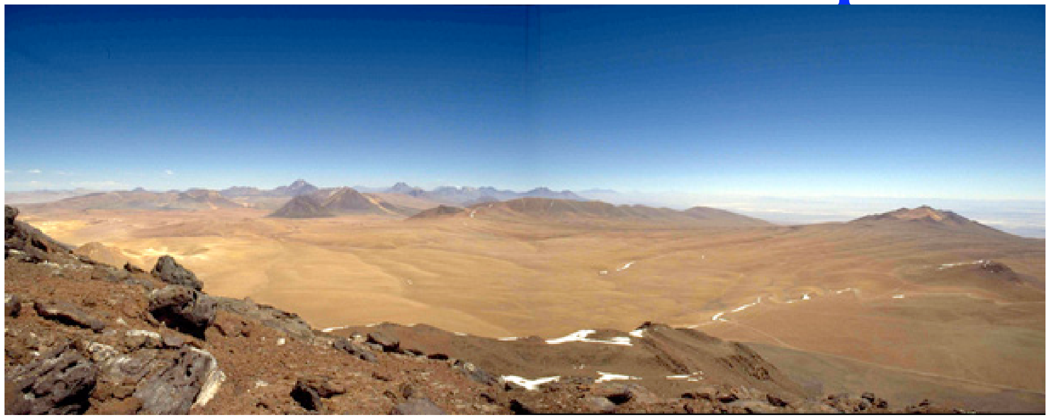


(Verde, Spergel 2002)

Fiducial model

See also Giovi Baccigalupi, Perrotta 2003 for w(z)

The ACT telescope



The Atacama in Chile

5200 meter elevation, dry, low turbulence, close to ALMA

More info: http://www.physics.upenn.edu/act

6 m telescope

CCD like array of bolometers

100 sq degrees

3 frequencies for SZ

145, 220, 270 GHz

1.7’ beam

P.I. Lyman Page

PENN

RUTGERS

Princeton

Toronto

CUNY

Drexel University

NIST National Institute of Standards and Technology

Columbia

Católica

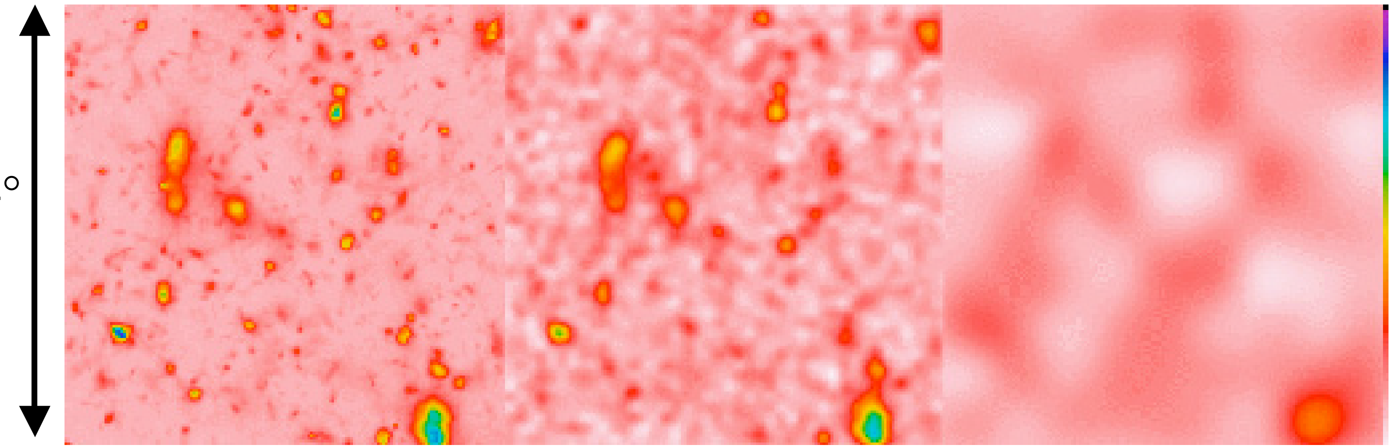
Haverford

NASA Goddard Space Flight Center

Arcminute Resolution mm-wave Observations

150 GHz

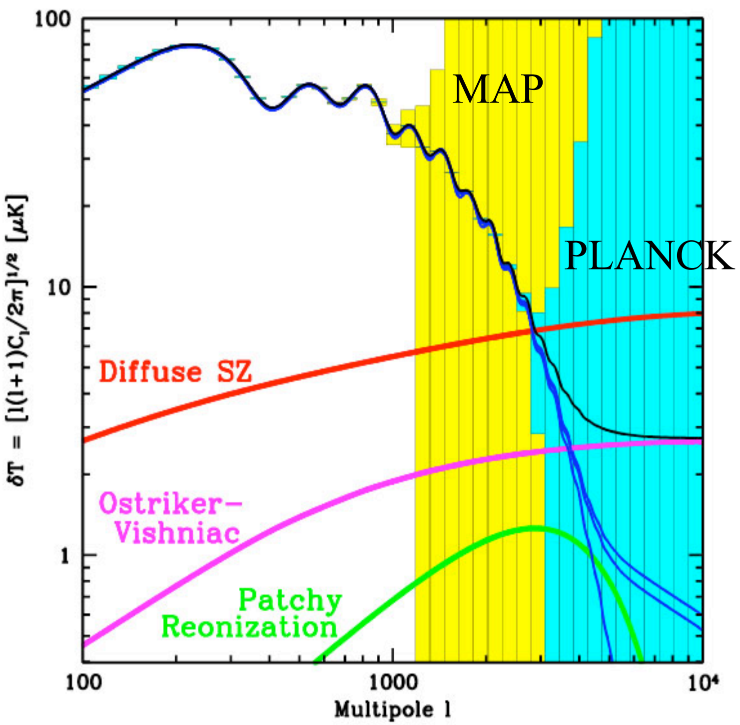
1.4°

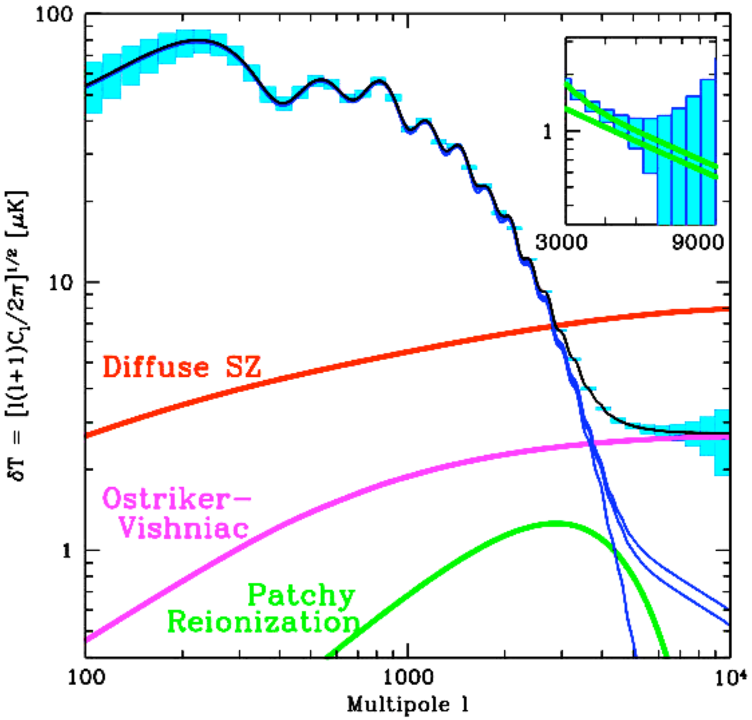


< 1% of survey area

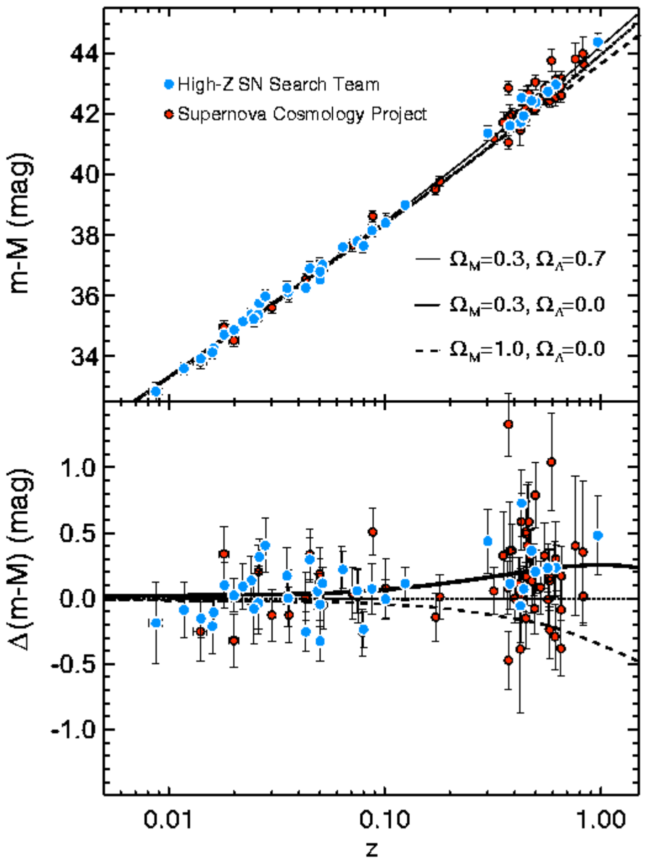
~2% of high quality area

SZ Simulation | **MBAC on ACT 1.7' beam w/ 2X noise** | **PLANCK**

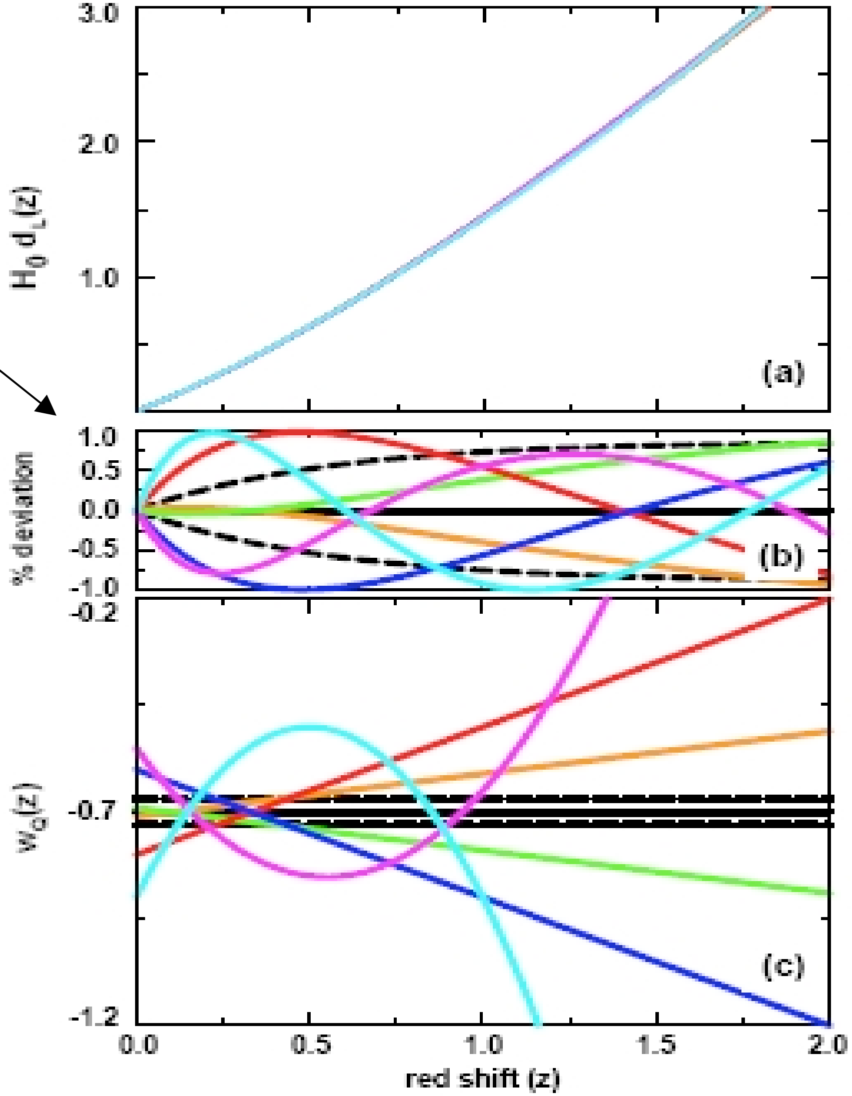




Reconstructing w: a difficult task



SNAP error



from Maor et al. 2000

2b:Reconstruct w(z): use dz/dt

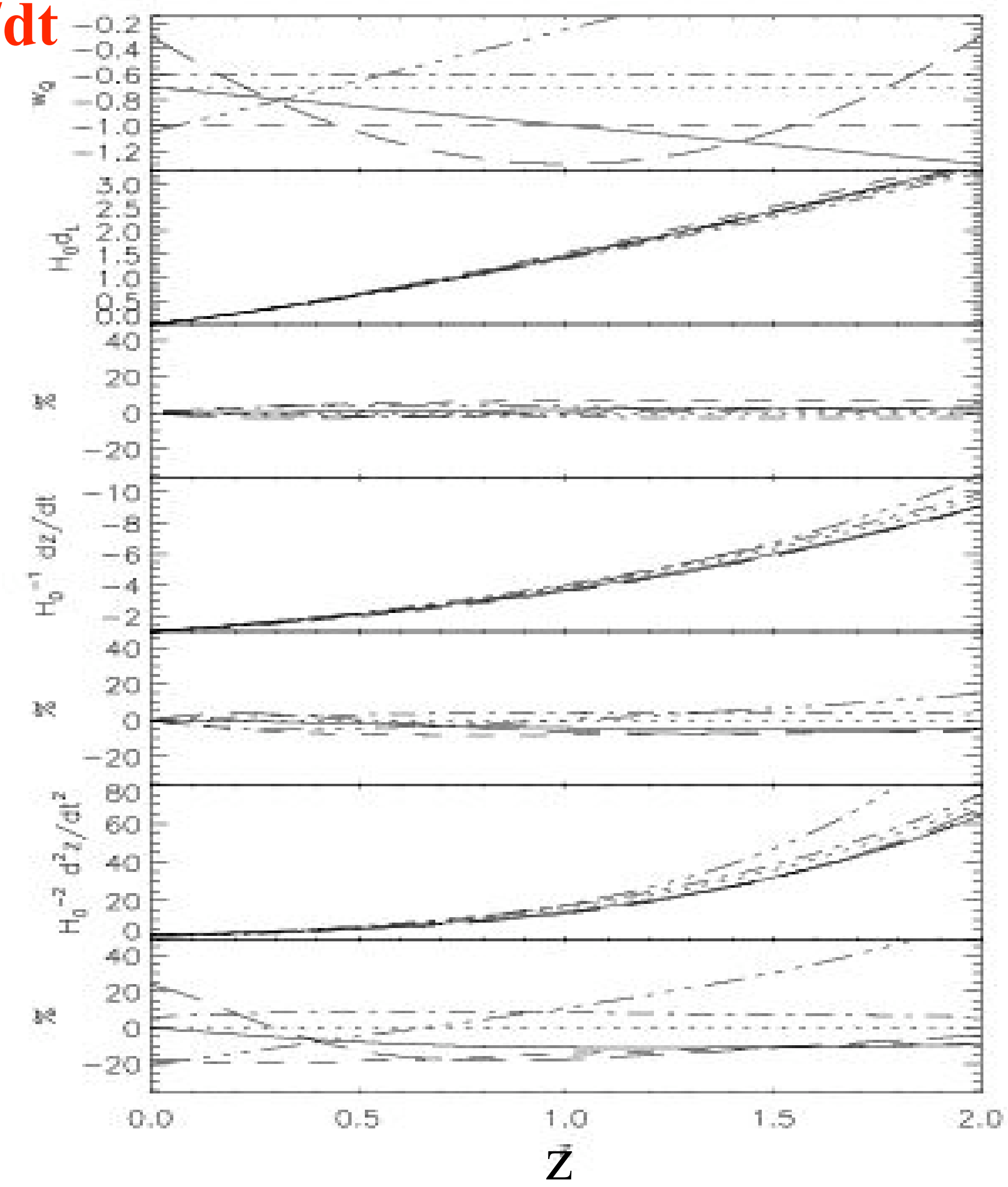
Non-parametric!

Note: $d_L = (1+z)\int_z^0 (1+z')\frac{dt}{dz'}dz'$

$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

w(z) in here

$$\frac{d^2z}{dt^2} = \left(\frac{dz}{dt}\right)^2 (1+z)^{-1}\left(\frac{5}{2}+\frac{3}{2}w(z)\right) - \frac{3}{2}\Omega_m (1+z)^4 w(z)$$



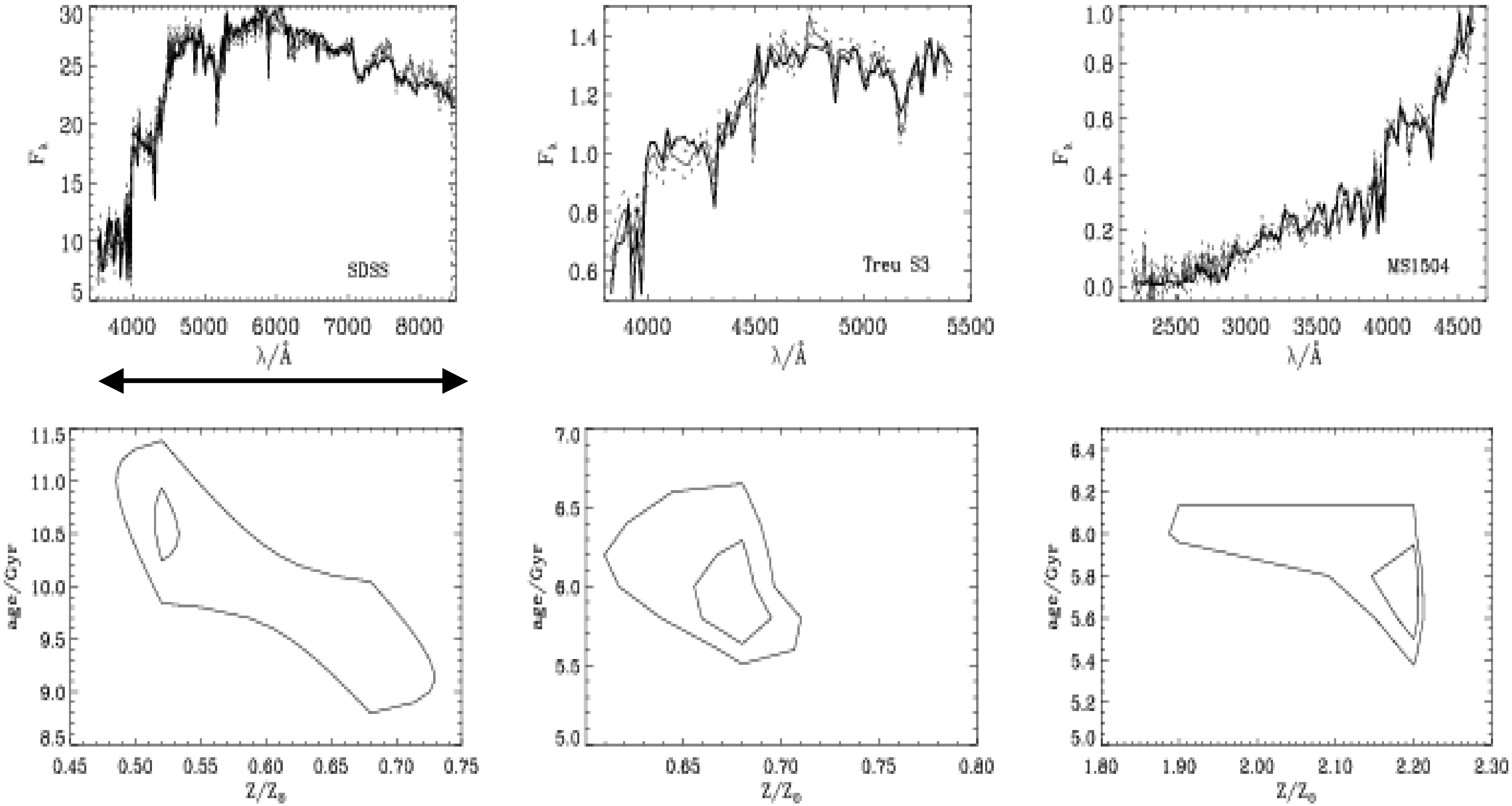
(from Jimenez & Loeb 2002)

2b:Reconstruct w(z): cosmic chronometers

The Red Envelope

Is it possible to obtain accurate ages?

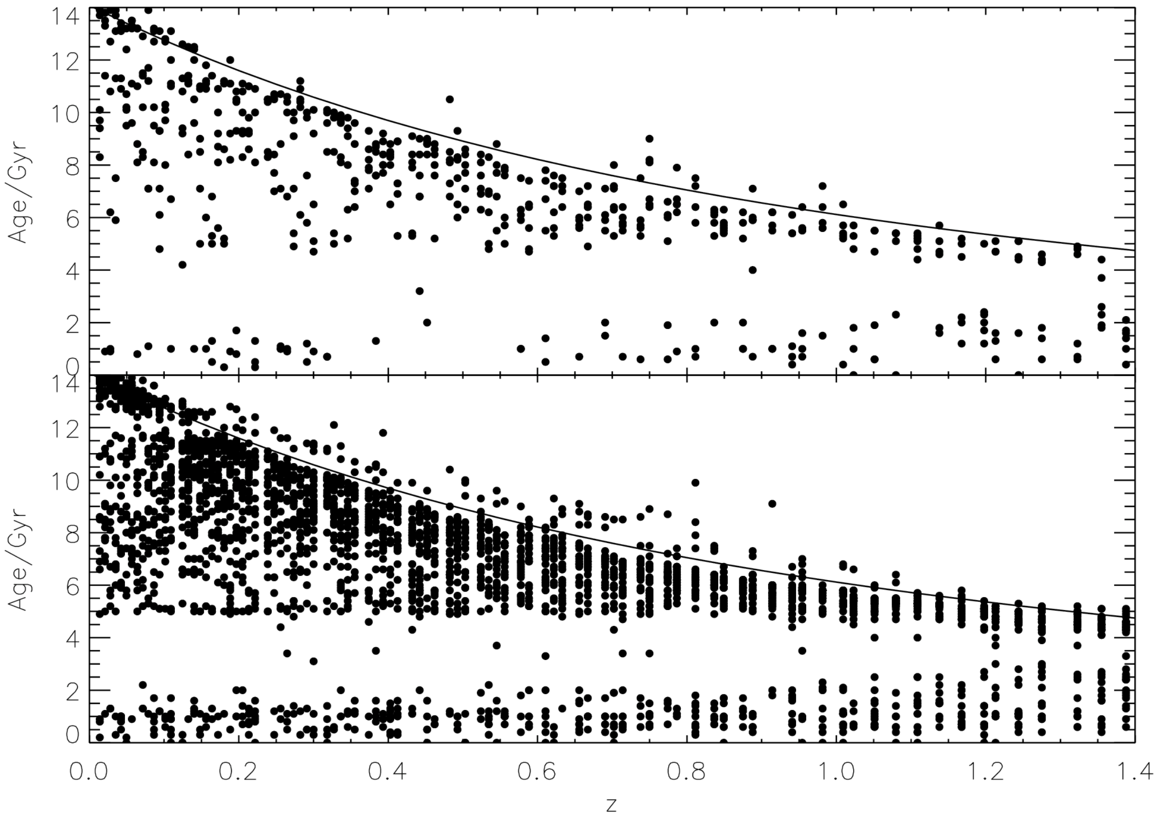
Old, passively evolving galaxies



(From Jimenez, LV, Treu, Stern 2003)

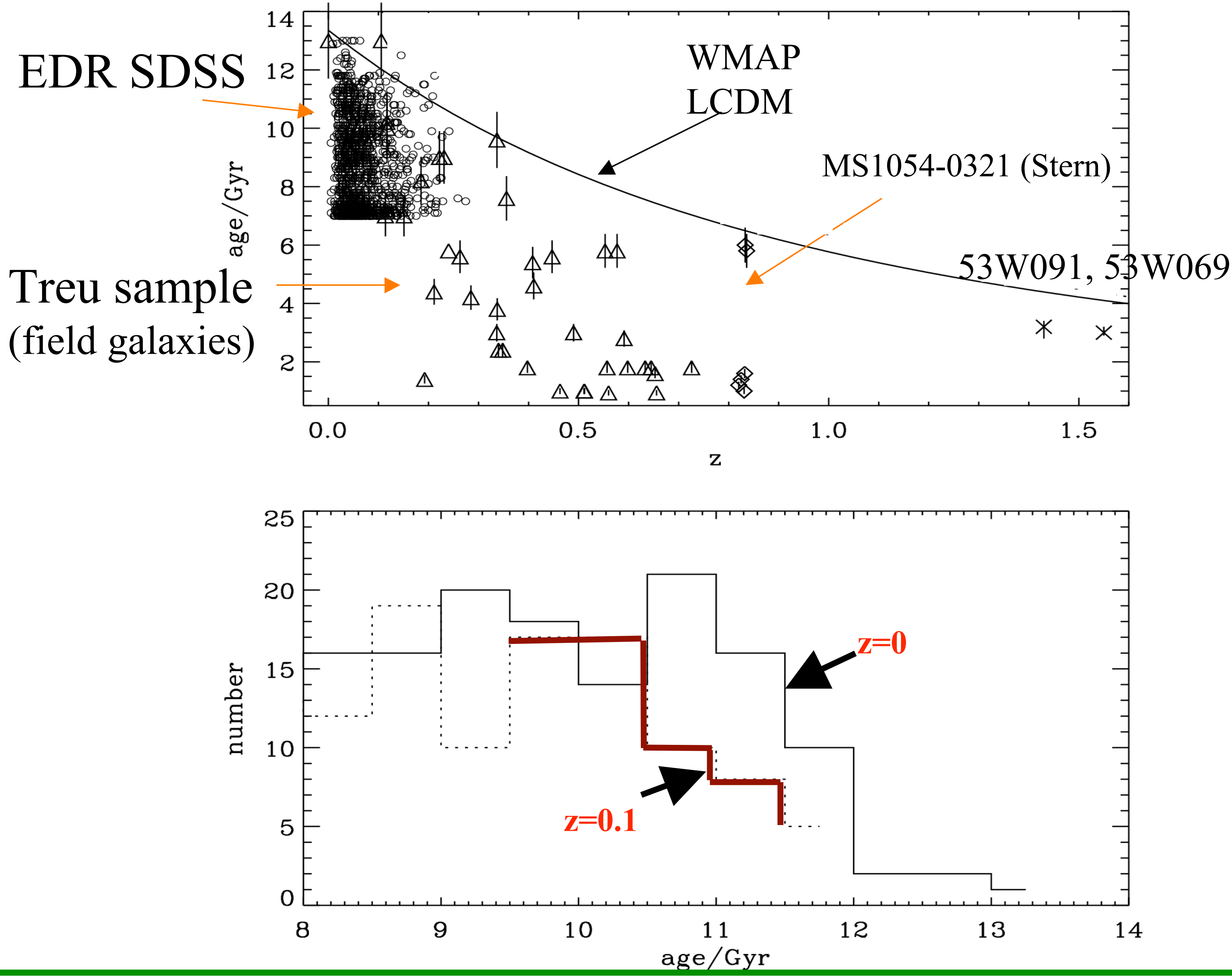
2b:Simulating the “edge”, error budget, tests for sistematics

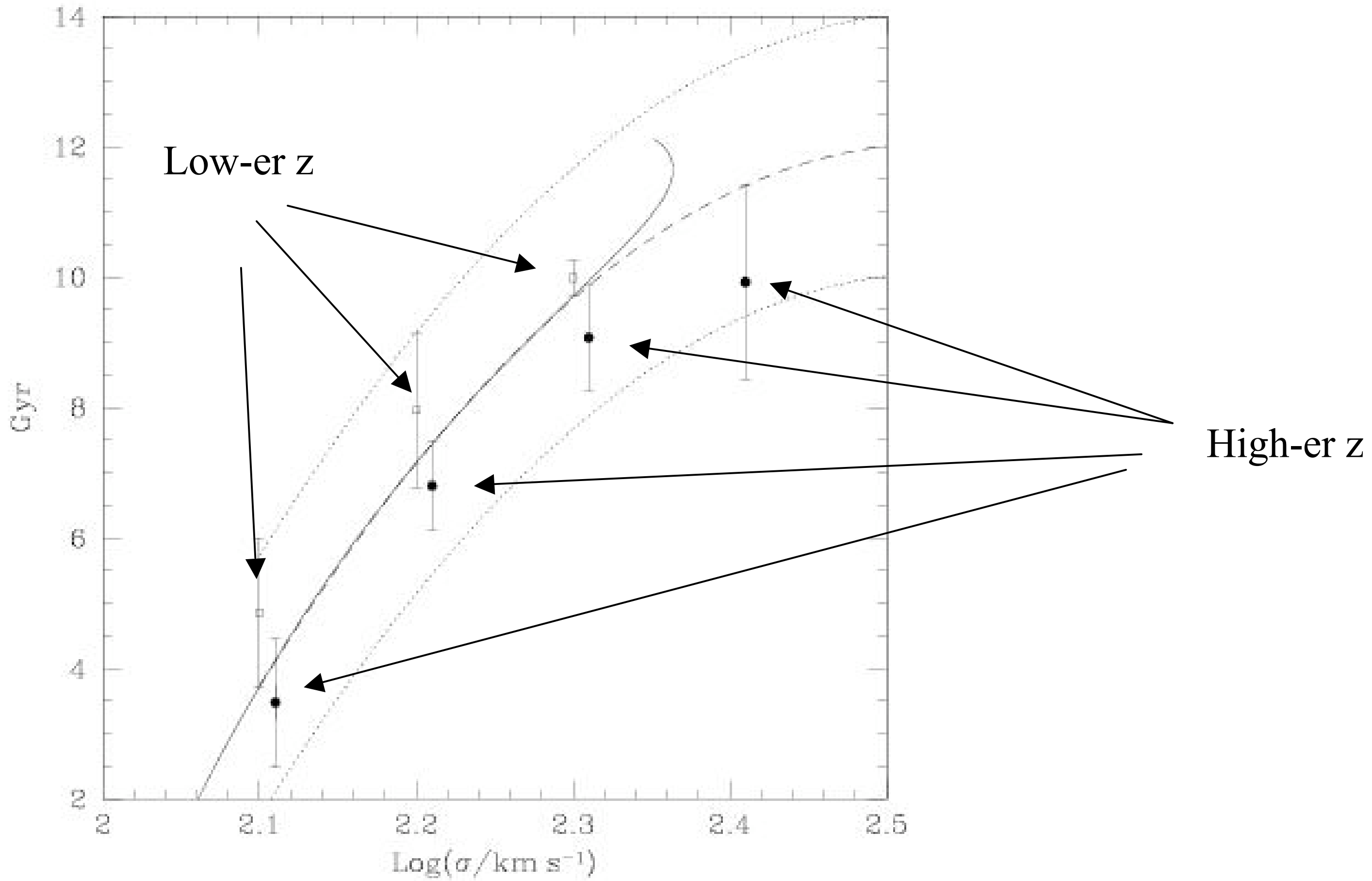
Small burst of SF?



See also Jimenez & Loeb 2001

2b:Reconstruct w(z): Age-redshift relation





From Bernardi et al. 2003

2b:Reconstruct w(z) with dz/dt: Difficult, BUT:

- Relative ages !!!
- Battery of tests for effects possible systematics
  (Jimenez & Loeb 2002, Jimenez , LV, Treu, Stern 2003)
- At $z \approx 1$ the rest frame UV spectrum of ellipticals is dominated by main sequence stars

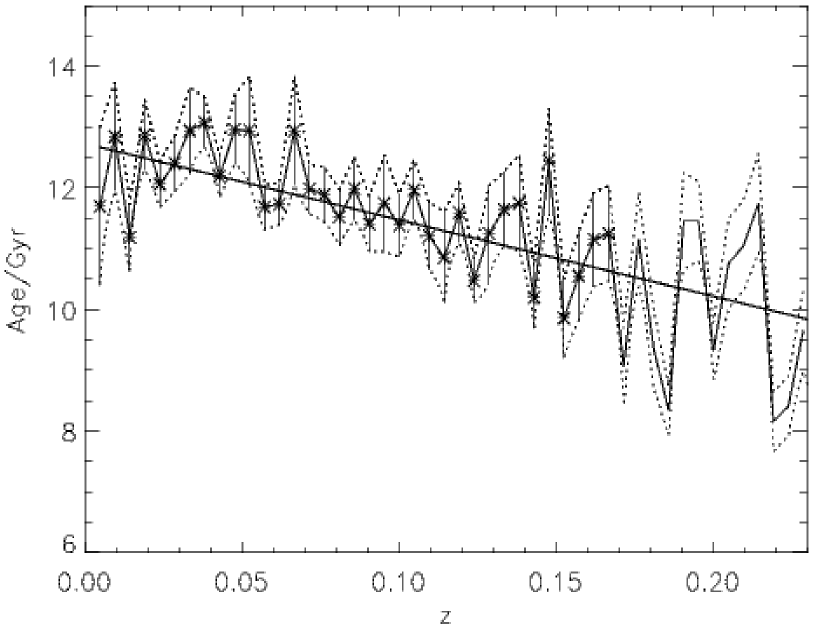
Neutrinos lesson

- You've got to be honest with uncertainties
- Many high S/N spectra will help improve the statistics.

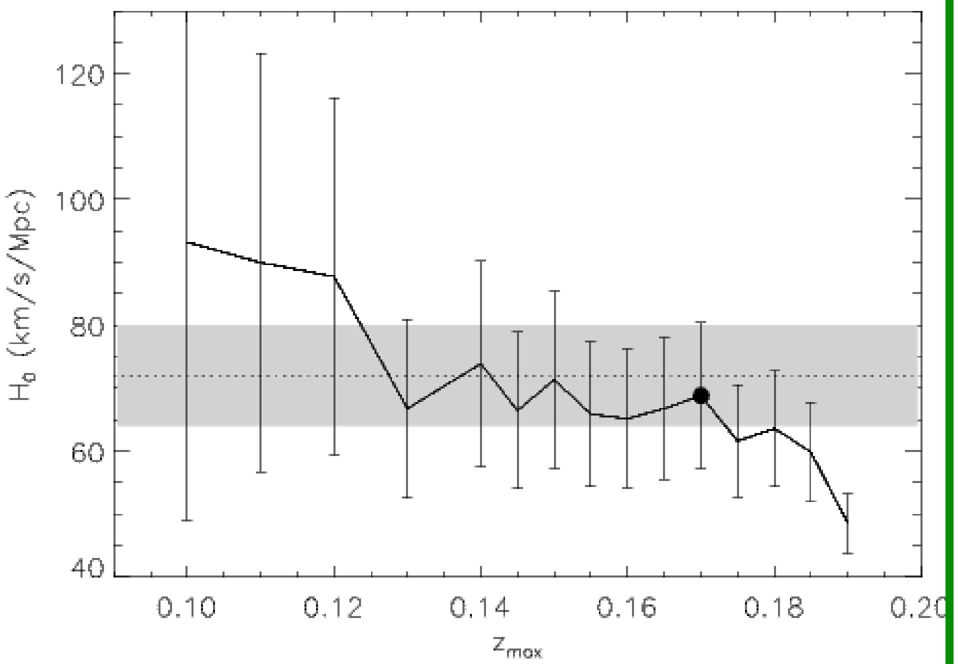
2b:Reconstruct w(z):   CAN IT work?

At z=0 dz/dt gives Ho and we have SDSS galaxies:

$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$



The edge for z<0.2



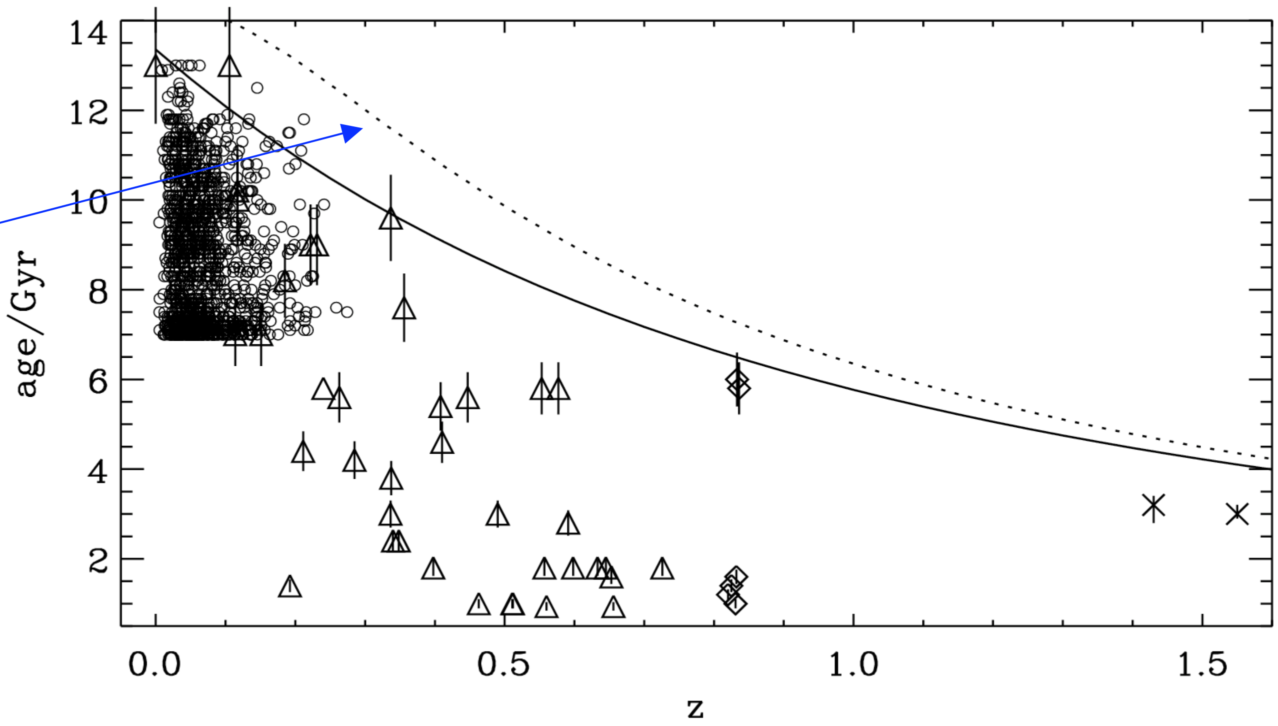
The value of H0

2b: Reconstruct w(z): Age-redshift relation

preliminary

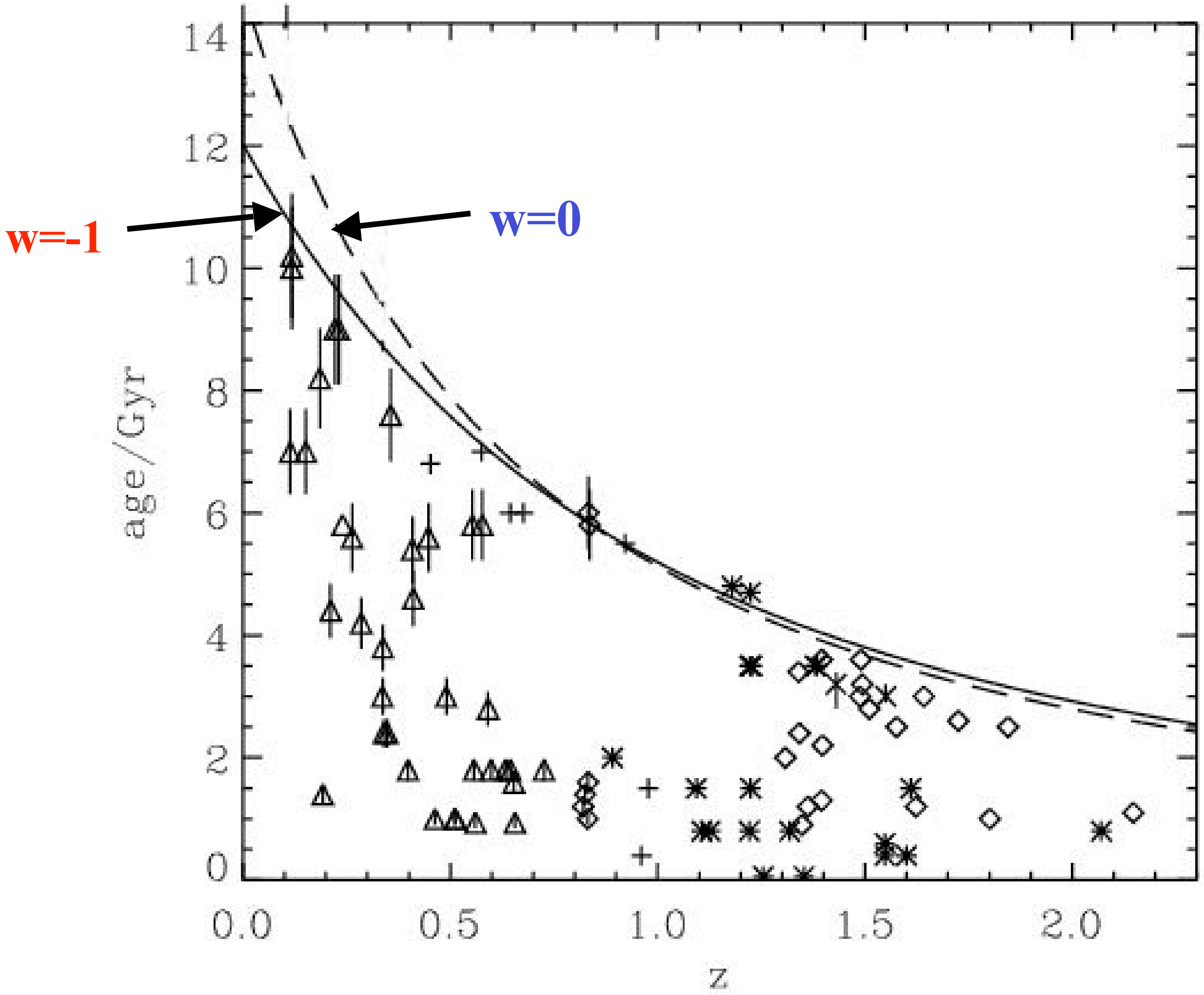
$w = -2$ z>1

Linearly to w=0 for 0<z<1



Every high-z spectrum helps: Please give generously!

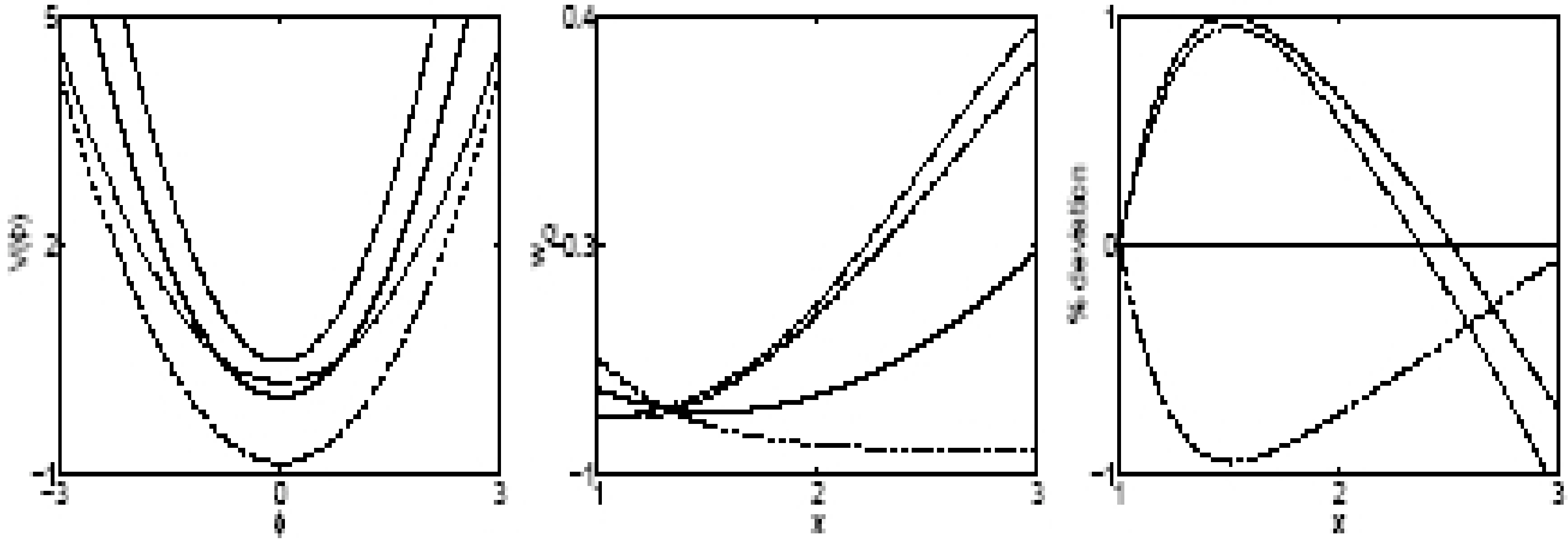
New data at high-z



Models with arbitrary H0

ACT will observe about 1000 clusters (50000 spectra up to z ~ 1)

The almost "impossible" task of reconstructing the potential



from Maor et al. 2002

CONCLUSIONS

The effective w is around –1.
It's important to beat systematics by using cross checks.

WMAPext: $w = -0.98 \pm 0.12$ CG ages: w< -0.8

SDSS consistent

For the moment, looks like dark energy is consistent with Λ

The next challenge is to track w(z) possibly in a non-parametric way

I have shown a preliminary attempt to do just this using relative ages

More data are needed