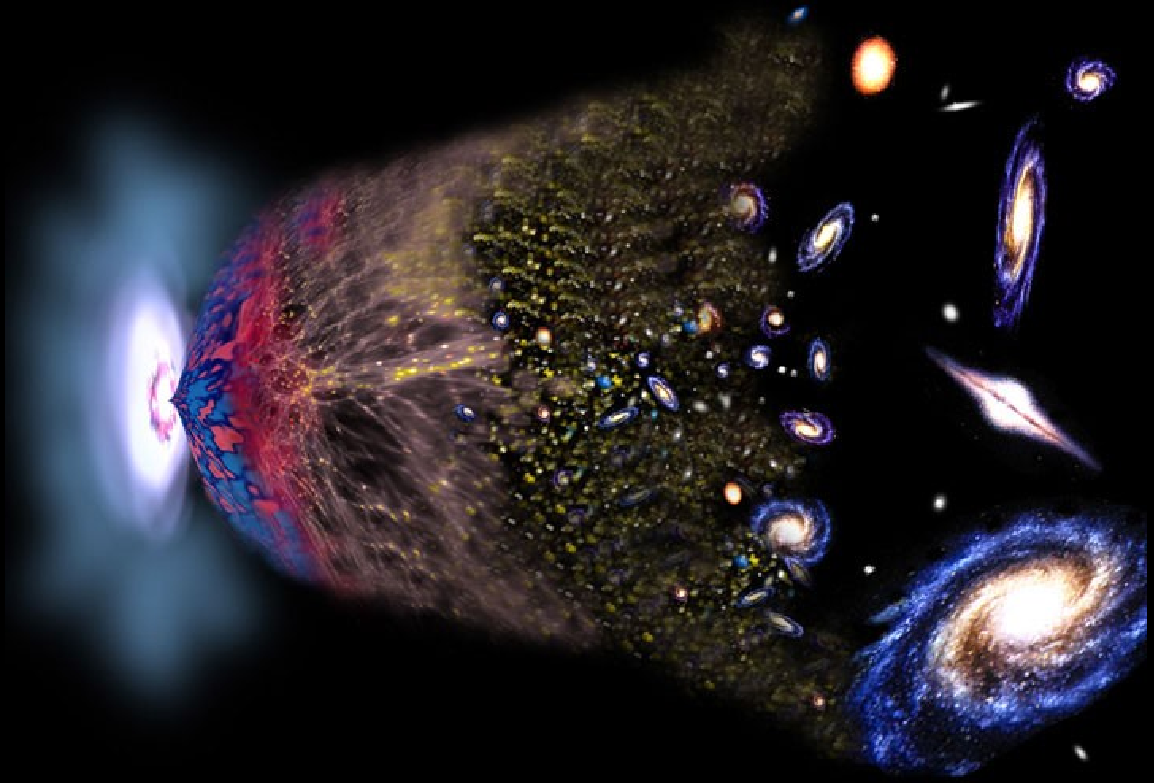
Challenges of the accelerating Universe: Measuring the expansion rate



Raul Jimenez
www.ice.csic.es/personal/jimenez

The basics

Action describing the dynamics of the universe is:

$$S = \int dt d^3x \sqrt{-g} \left\{ -\frac{m_p^2}{16\pi} \left(R + f\left(R, R^{\mu\nu} R_{\mu\nu} \right) \right) + \frac{g^{\mu\nu}}{2} \partial_\mu q \partial_\nu q - V(q) + S_{matter} \right\}$$

Consider quintessence a perfect fluid:

$$\rho_Q = \frac{1}{2}\dot{q}^2 + V(q)$$

$$p_Q = \frac{1}{2}\dot{q}^2 - V(q)$$

Which has conservation law:

$$\dot{\rho}_q + 3H(\rho_q + p_q) = 0$$

For full treatment see Simon, Verde, RJ (2005)

All left now is use Einstein eq:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_p^2}(\rho_m + \rho_q)$$

And Klein-Gordon equation:

$$\ddot{q} + 3H\dot{q} + V' = 0$$

What I want to know is shape of potential V

$$\varepsilon_1 = -\frac{\dot{H}}{H^2};\ \varepsilon_2 = \frac{\dot{\varepsilon}_1}{H\varepsilon_1}$$

$$V(z) = (3-\varepsilon_1)\frac{H^2}{m_p} - \frac{1}{2}\sum_i (1-w_i)\rho_i - \frac{1}{2}(\rho_f - p_f)$$

But what I really need is V(q)

$$V(q) = \varepsilon_1 \frac{H^2}{m_p} - \frac{1}{2}(\rho_T + p_T)$$

We can "measure" dark energy because of its effects on the expansion history of the universe and the growth of structure

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

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

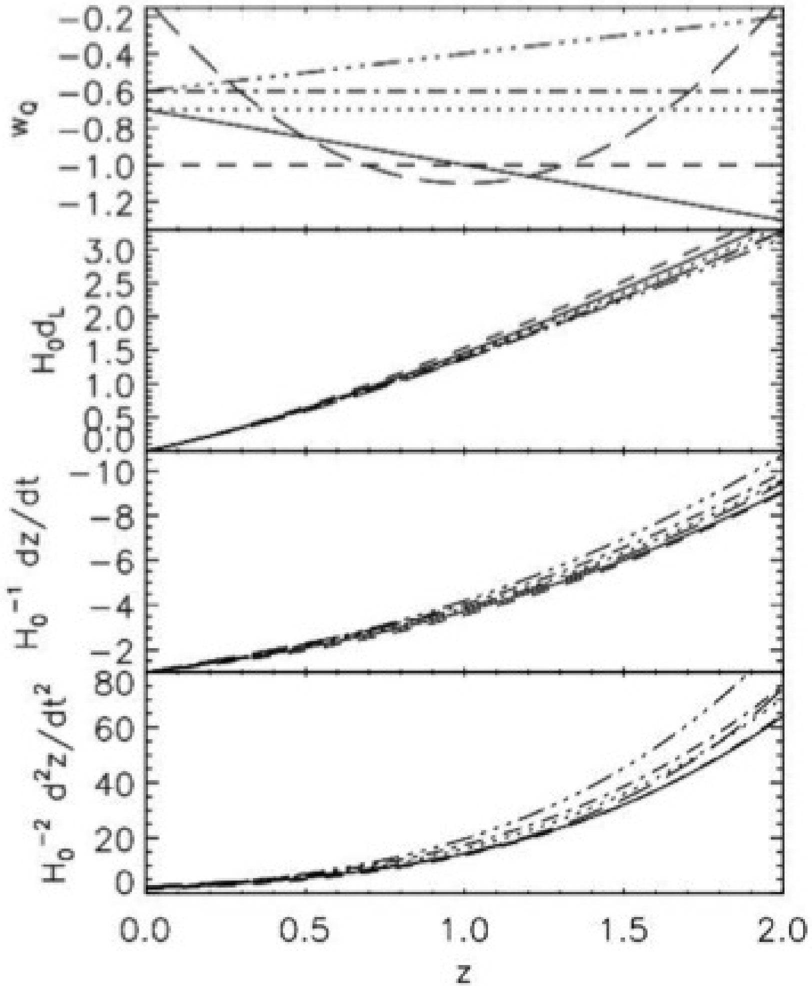
$$\dot{\rho}_Q = -3H(z)(1+w(z))\rho_Q$$

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

CMB: θ_A and ISW → a(t)

LSS or LENSING: g(z) or r(z) → a(t)

AGES: H(z) → a(t) $\quad H_0^{-1}\frac{dz}{dt} = -(1+z)^{5/2}\{\Omega_m(0) + \Omega_Q(0)\exp[3\int_0^z \frac{dz'}{(1+z')} w_Q]\}^{1/2}$



30% variation in *w(z)* corresponds to:

- 5% variation in d_L
- 10% variation in *dz/dt*
- 30% variation in d^2z/d^2t

Jimenez & Loeb (2002; ApJ, 537, 37)

Challenge n2: is it dynamical?

Theoretical physicists: which parameterization?

To give you a flavor, assume it is a slowly rolling potential and think about inflation

$$\varepsilon_1 = -\frac{\dot{H}}{H^2} = 1 - \frac{\ddot{a}}{a} H^{-2} = \frac{dH}{dz}\frac{(1+z)}{H}$$

Similar to horizon flow parameters (from Simon, Verde, RJ PRD 2005)

$$V(z) = (3 - \varepsilon_1)\frac{H^2}{\kappa} - \frac{1}{2}\rho_m$$

H(z)

$\dot{H}$(z)

$$K(z) = \varepsilon_1 \frac{H^2}{\kappa} - \frac{1}{2}\rho_m$$

Just integrate to get ϕ(z)

But if you have a parameterization (or a model)

$$3H^2(z) - \frac{1}{2}(1+z)\frac{dH^2(z)}{dz} = \kappa\left(V(\alpha_i,\, z) + \frac{1}{2}\rho_m(z)\right) \equiv g(\alpha_i,\, z)$$

Can be integrated analytically!

Unfortunately….

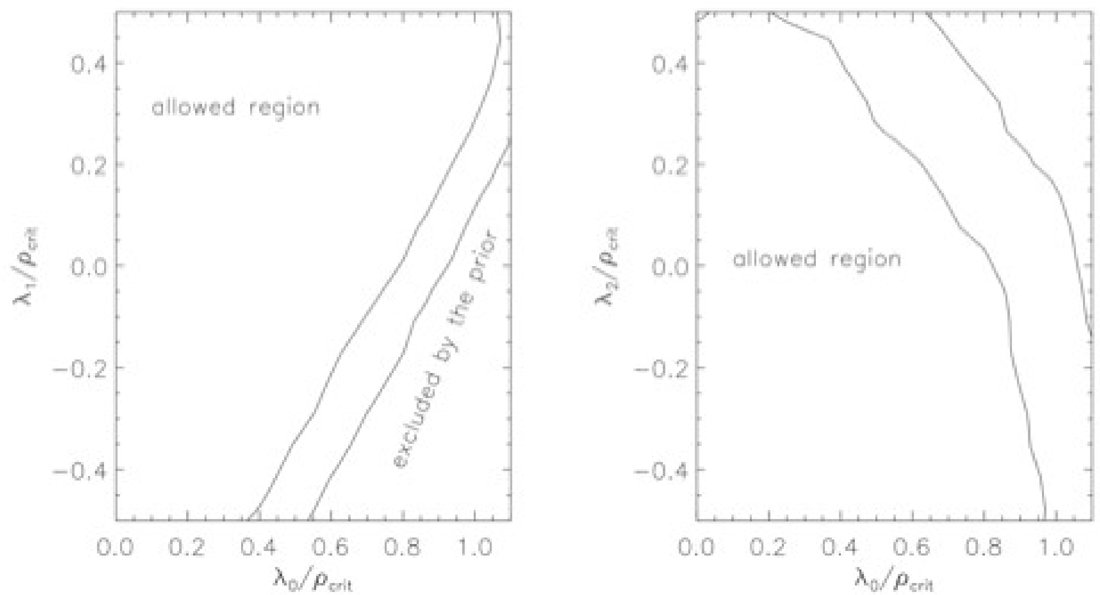
Data are not yet good enough for a fully non-parametric reconstruction

Chebyshev to the rescue…

$$V(z) = \sum_{n=0}^{M} \lambda_n T_n[x(z)], \qquad x(z) = \frac{2z}{z_{\max}} - 1$$

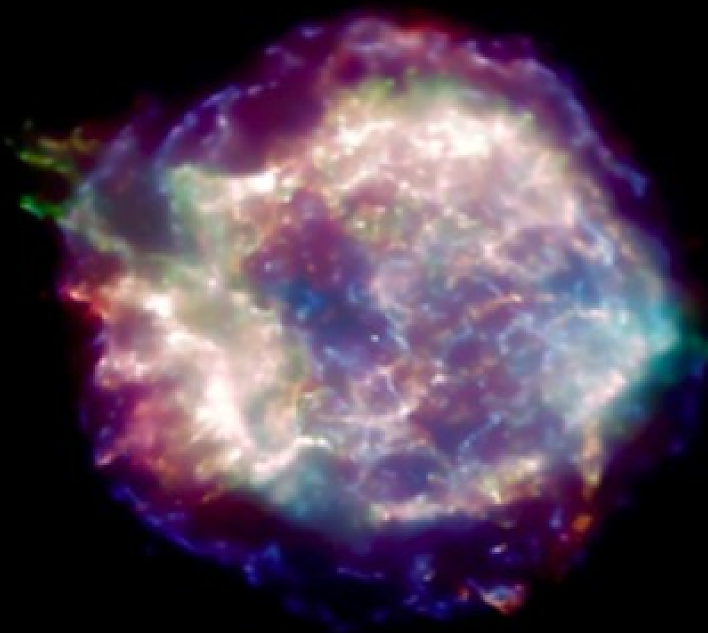
No data, priors only

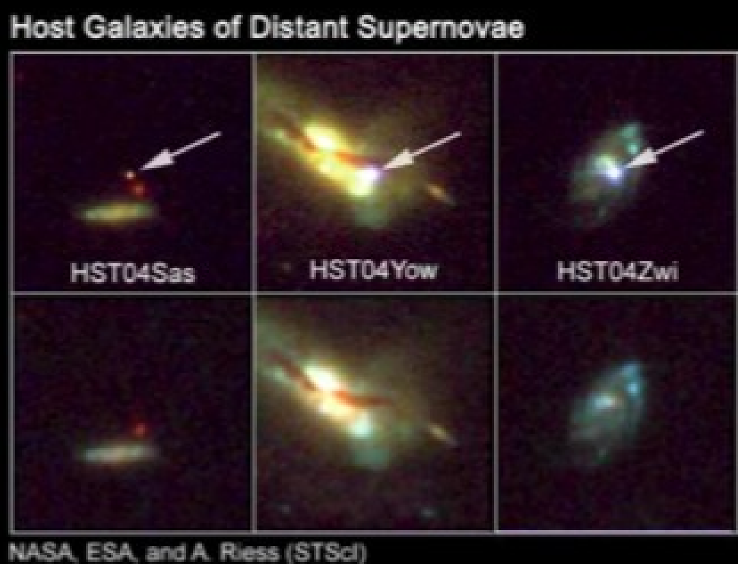
$K > 0$ $\rho_T > 0$ that is $H^2 > 0$ $V_0 + K_0 = \Omega_{Q,0}\rho_c$ Flatness



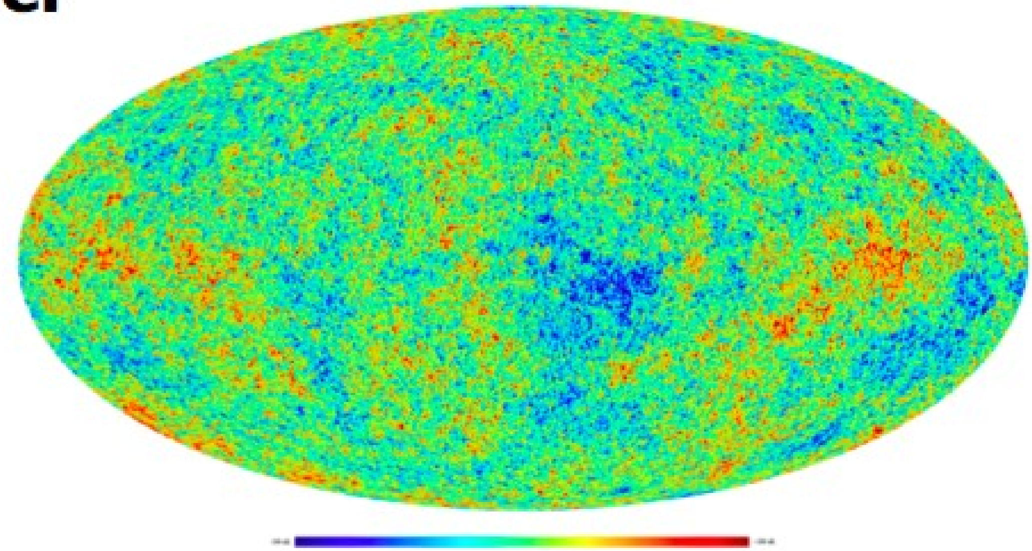
$\Omega_{m,0} = 0.27 \pm 0.07$ From large-scale structure !

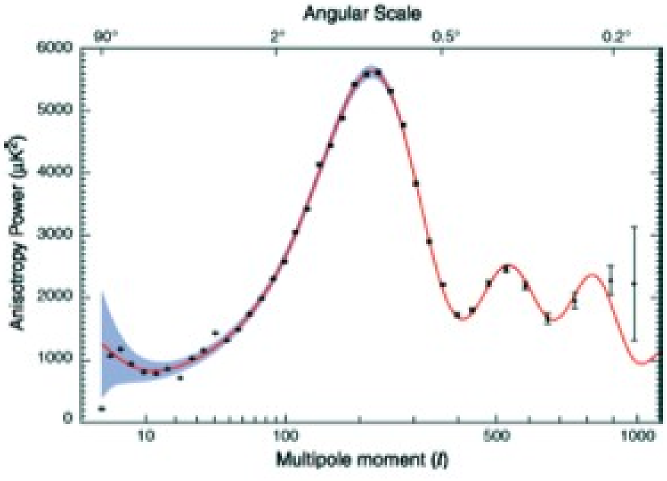
Standard Candle





Standard Ruler

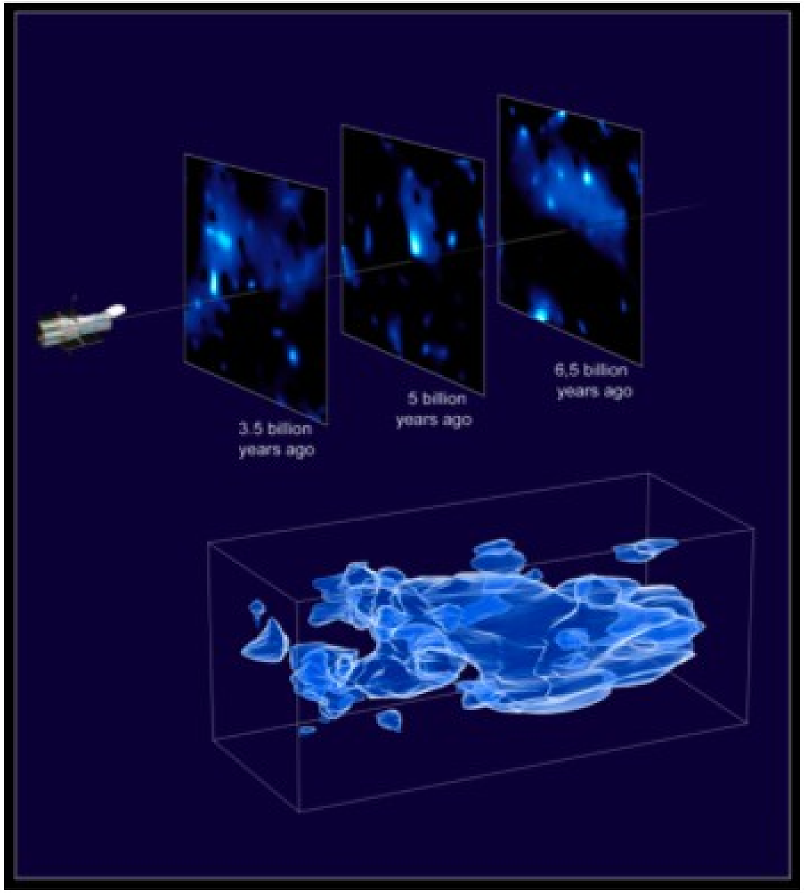




baryon acoustic oscillations
(radio galaxies)

Structure Formation

weak lensing
galaxy clusters



Rotate Image Right

Standard Clock

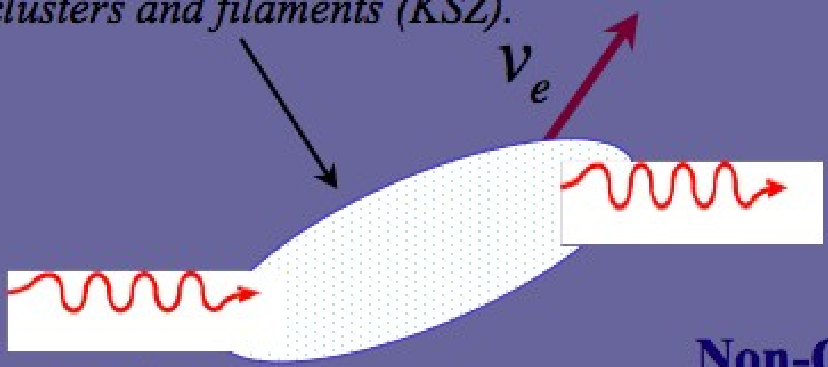
early-type galaxies

Kinetic SZ/Ostriker-Vishniac (OV)

$$\delta T_{kSZ} \propto \; n_e \, \mathbf{v_e} \cdot \mathbf{n}$$

Bulk *Velocity of hot electrons.*

Bulk velocity of *HOT electrons from ionization by the first stars (OV) or in clusters and filaments (KSZ).*



CMB photon

Amplitude of OV signal determines epoch of reionization.

OV power spectrum measures the density and velocity fluctuations at reionization.

KSZ measures cluster bulk velocity field at low z.

Non-Gaussian but with CMB frequency spectrum. Spatially distinguishable. Requires a high fidelity map.

Using the KSZ signal

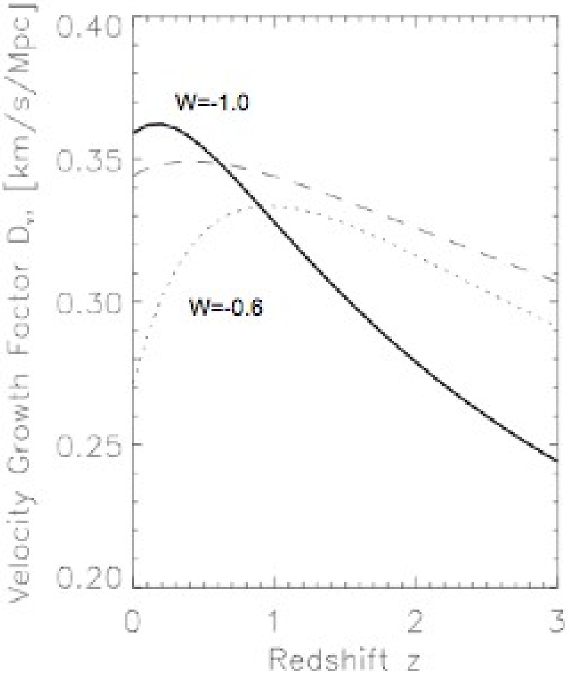
(Hernandez-Monteagudo, Verde, RJ, Spergel 2005)

The peculiar velocity field is sensitive to the onset of the late acceleration of the Universe.

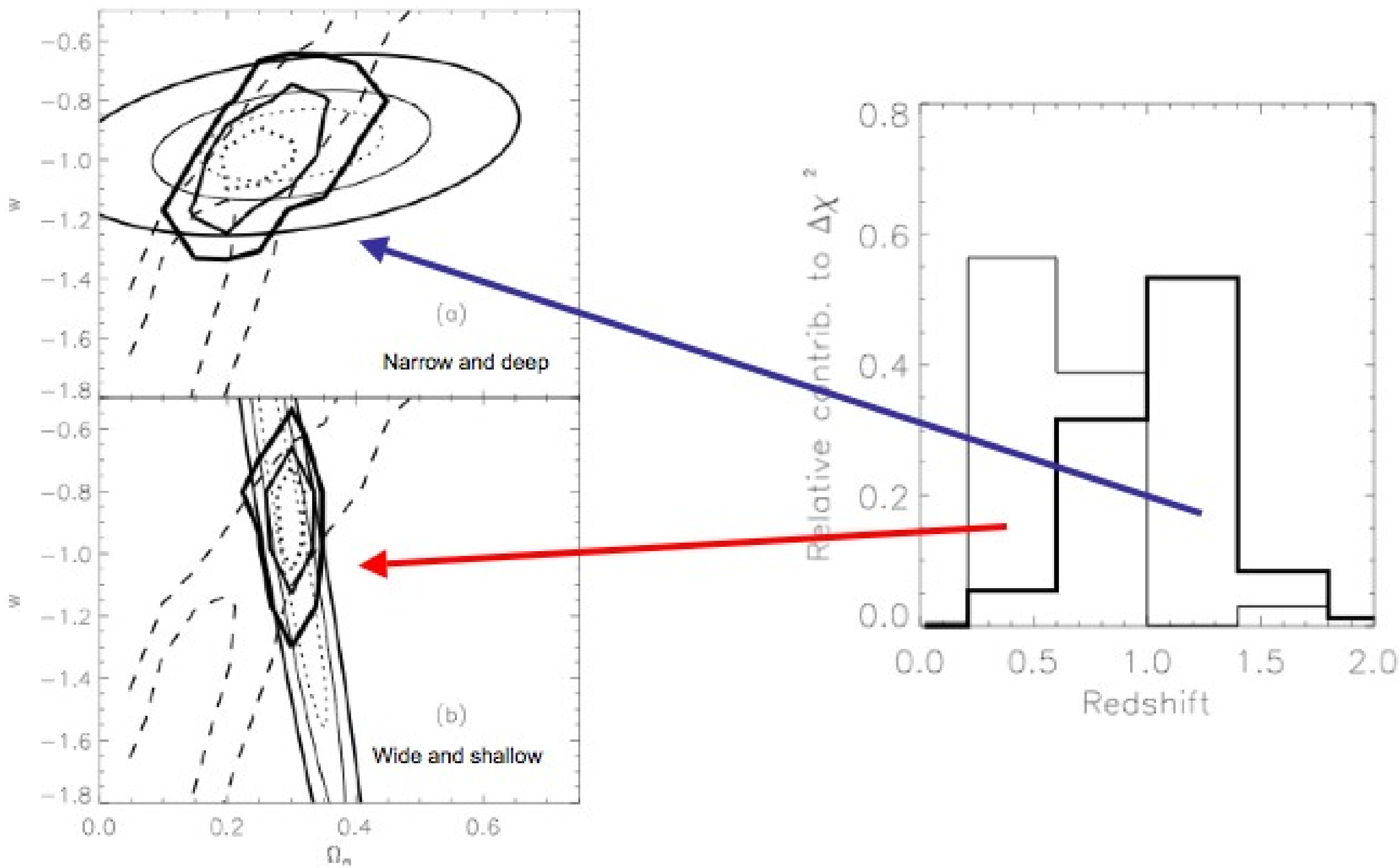
Recall that KSZ $\delta T_{kSZ} \propto n_e \mathbf{v_e} \cdot \mathbf{n}$

The power spectrum of the velocities is

$$P_{vv}(k) = \left(\underbrace{H(z) \left| \frac{d\mathcal{D}_\delta}{dz} \right|} \right)^2 \frac{P_m(k)}{k^2} = \mathcal{D}_v^2 \frac{P_m(k)}{k^2},$$



KSZ sensitivity to w

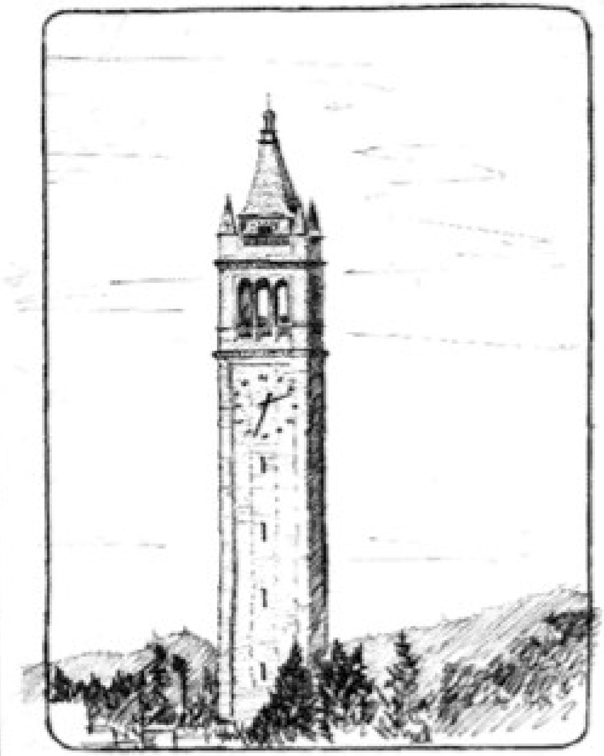


(from Hernandez-Monteagudo et al.2005)

Cosmic Clocks:

Constraining the Equation of State of Dark Energy

with Dan Stern (JPL/Caltech)
Marc Kamionkowski (Caltech)
Licia Verde (Barcelona)



Experimental concerns

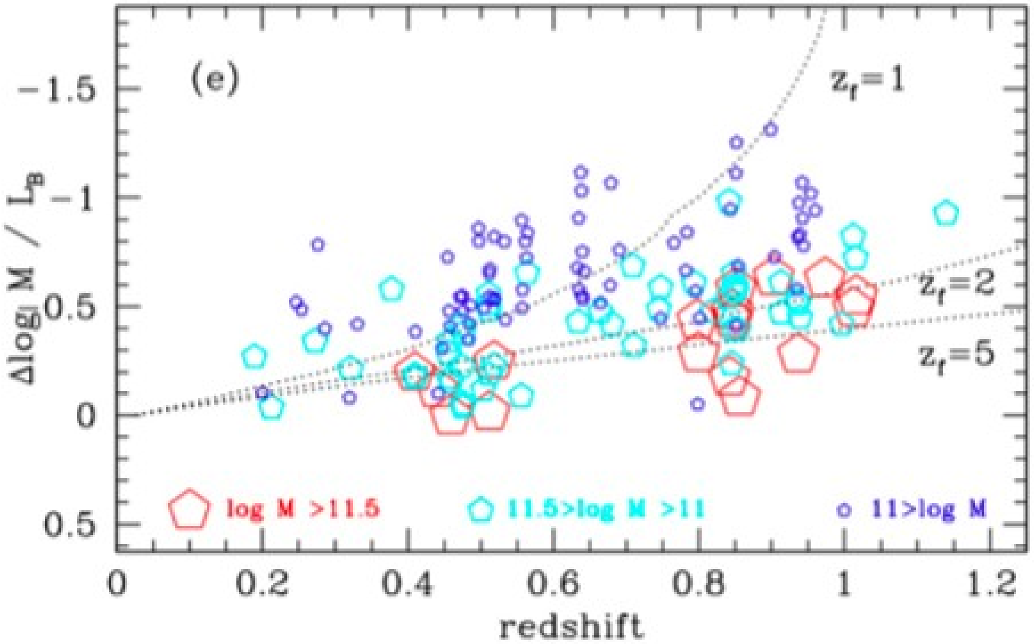
How well can gE's be approximated as passively evolving, old systems?
- mergers; early-type galaxies still assembling at $z<1$?
- on-going star formation ("frosting")

How can we best model the stellar ages?
- systematics between stellar synthesis models

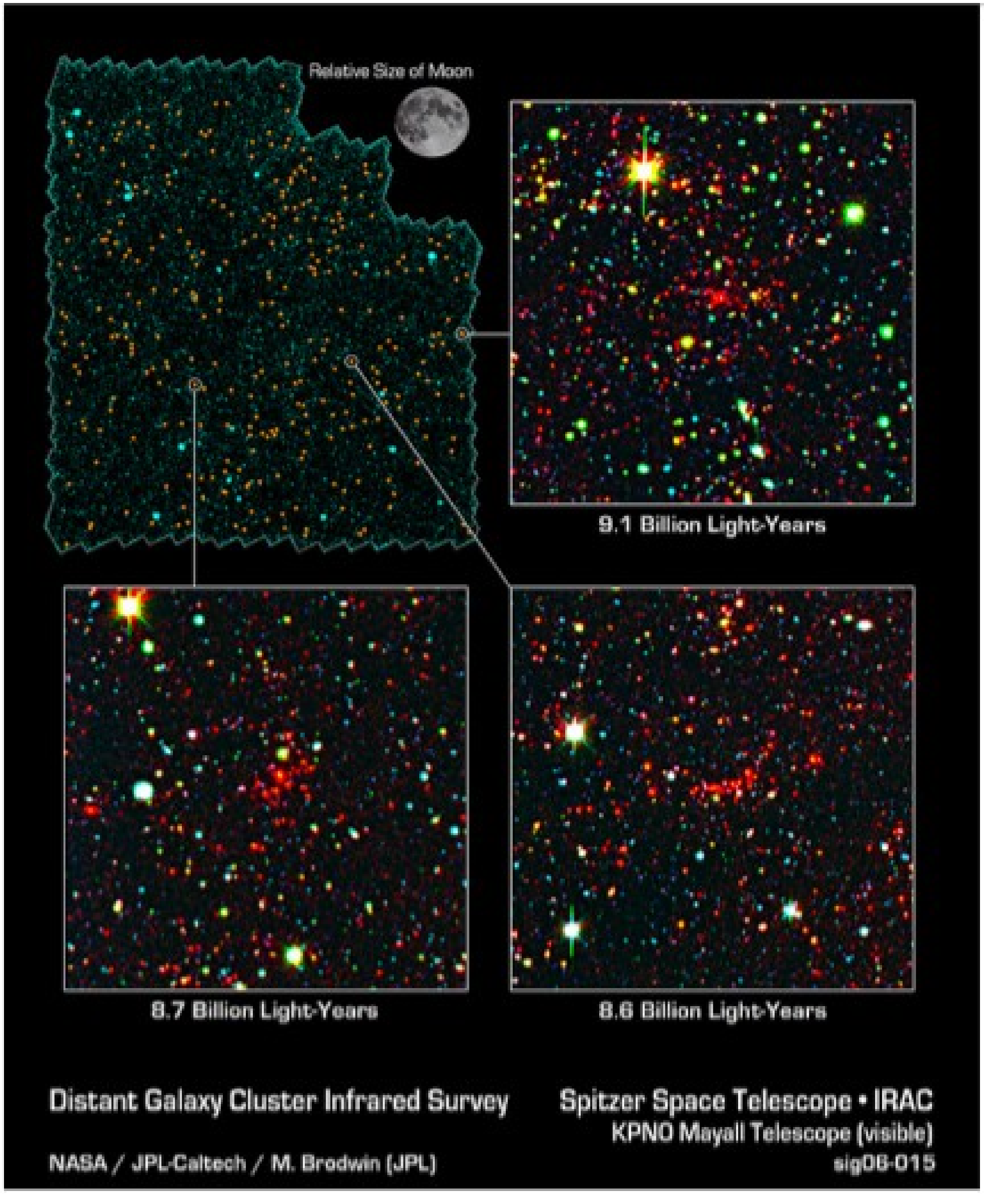
How can we best measure the stellar ages?
- ability to measure accurate stellar ages
- efficiency at obtaining spectra

gE's as passively evolving, old systems

the most massive early-type galaxies are the oldest



Treu et al. (2005; ApJ, 622, L5)



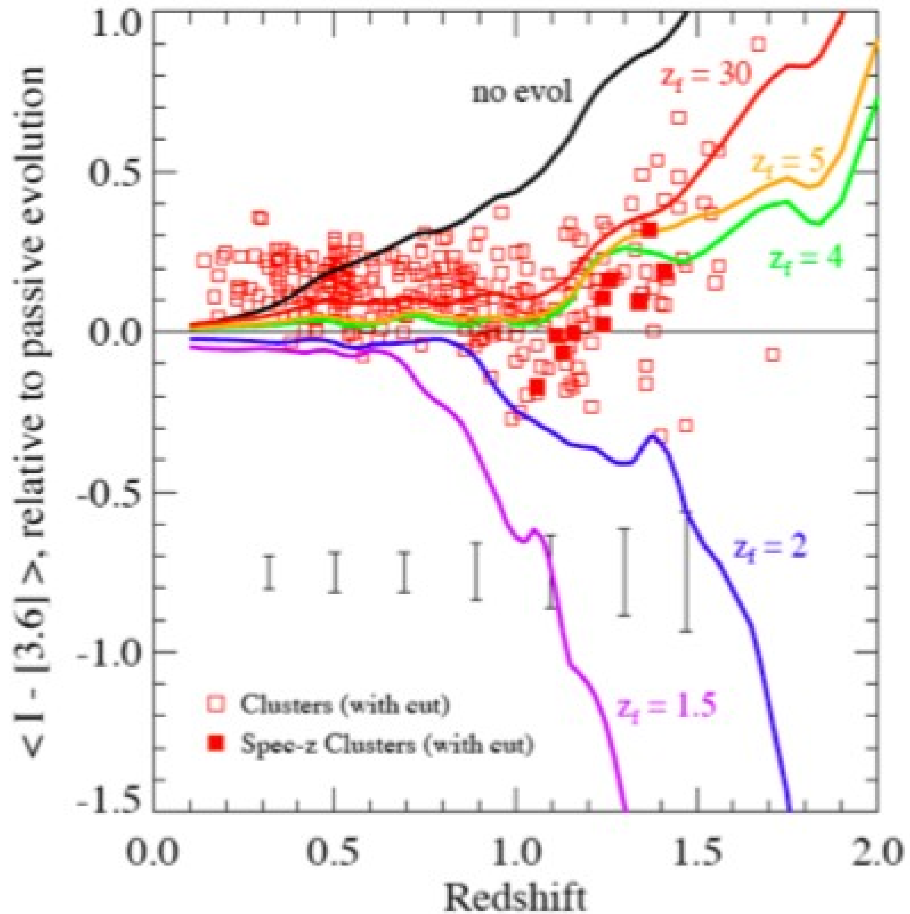
IRAC Shallow Cluster Survey (Boötes field)

14 confirmed
galaxy clusters at z>1

- Stanford et al. 2005, ApJL, 634, L129
- Elston et al. 2006, ApJ, 639, 816
- Brodwin et al. 2006, ApJ, 651,
- Brodwin et al. 2007, ApJL, 671, L93
- Eisenhardt et al., ApJ, submitted
- Galametz et al., in preparation

gE's as passively evolving, old systems

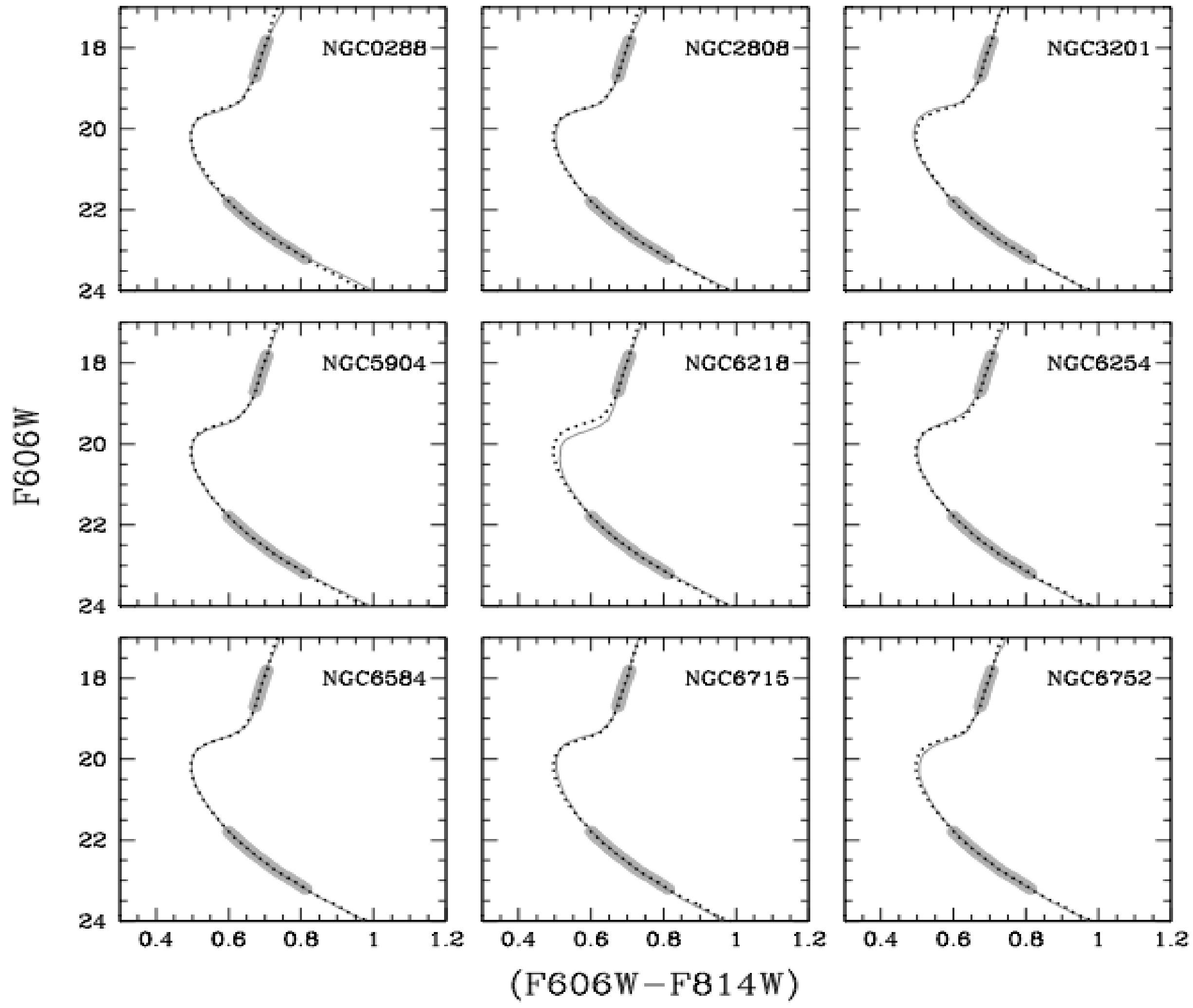
colors indicate a high formation redshift (for cluster gE's)



Eisenhardt et al. (ApJ, submitted)

A Lesson from the past: Globular Cluster **RELATIVE AGES**

"This method provides relative ages to a formal precision of 2–7%. We demonstrate that the calculated relative ages are independent of the choice of theoretical model." (0812.4541)

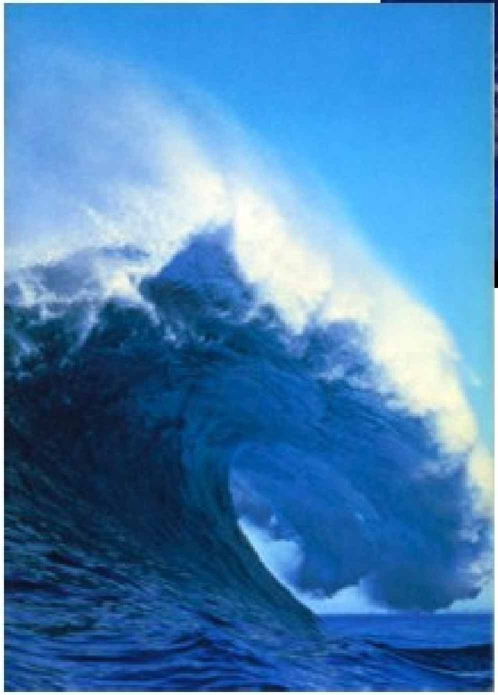


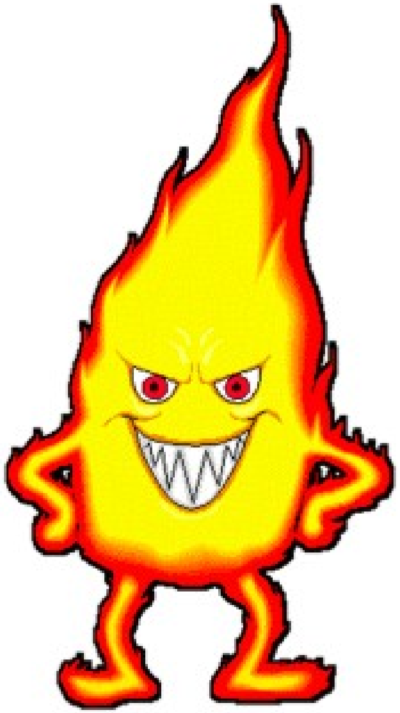
First attempt in 2004 ... failed at the proposal stage

2005 thru mid-2007 ... lots of bad weather

UT 2007 Aug 15-16

- Hurricane Flossie
- two earthquakes (5.4 & 4.0)
- fire
- tsunami warning



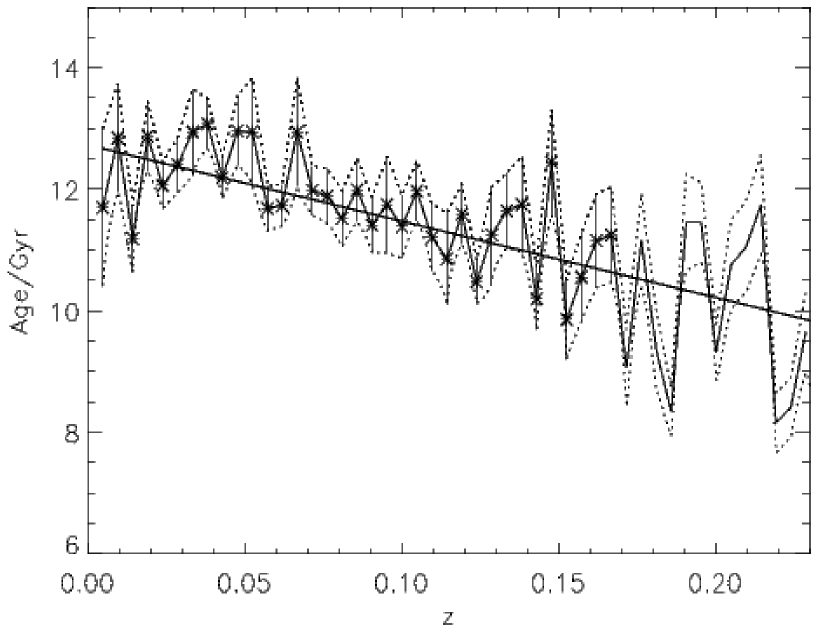


Reconstruct w(z): RELATIVE GALAXY AGES

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

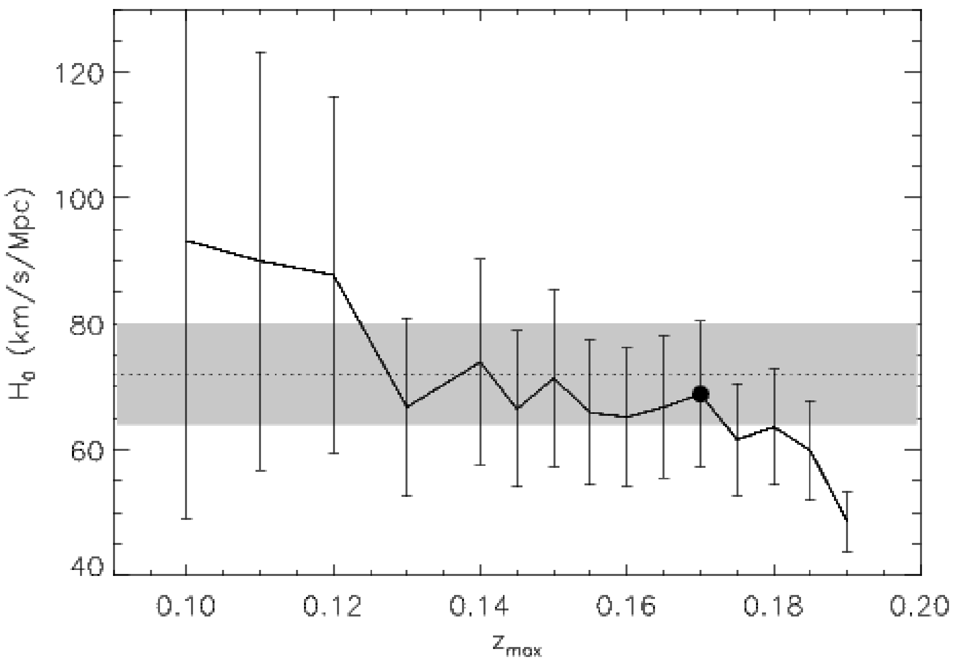
$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

(Jimenez et al. 2003)



The edge for z<0.2

(Jimenez et al. 2003)

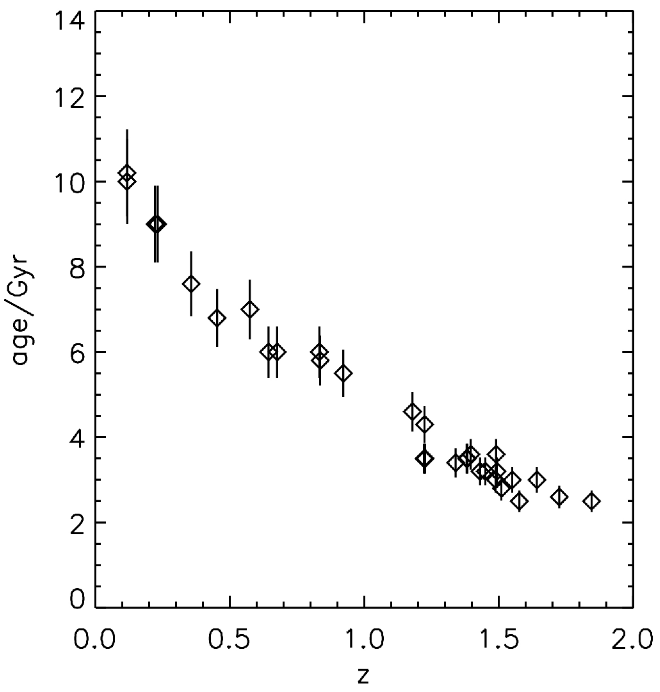


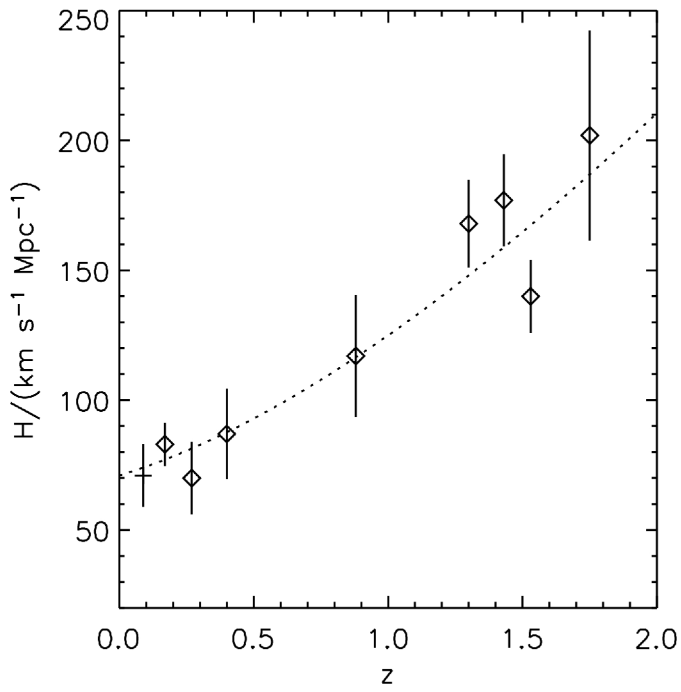
Similar trend found by Bernardi et al. (astro-ph/0509360) using alpha-enhanced models

The value of H0

GDDS

+high z radiogalaxies + Treu et al. 2000 sample

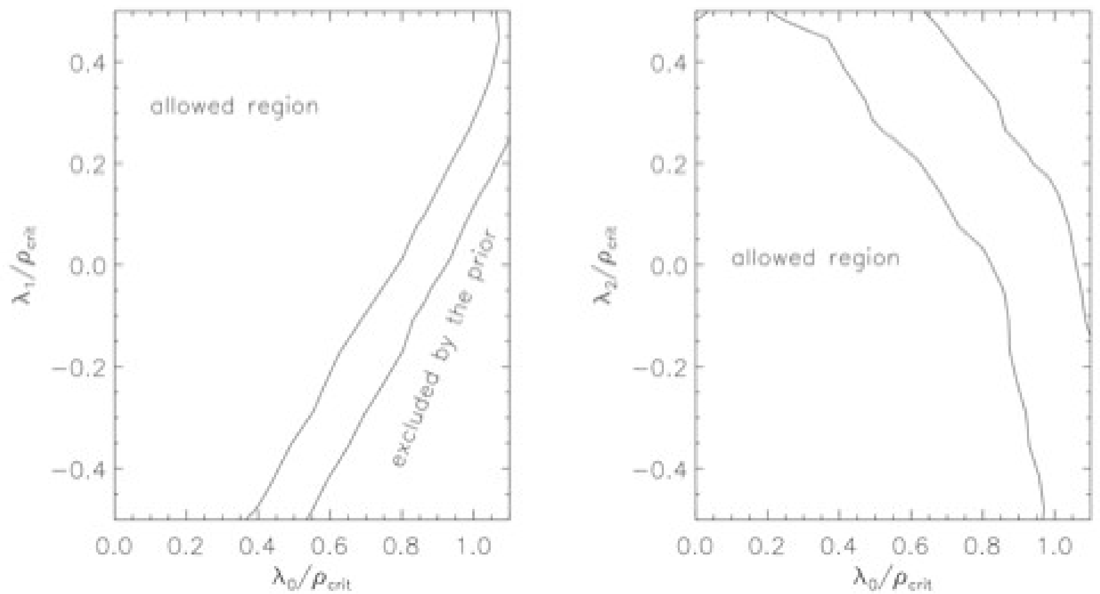




From Simon, Verde, RJ (2005)

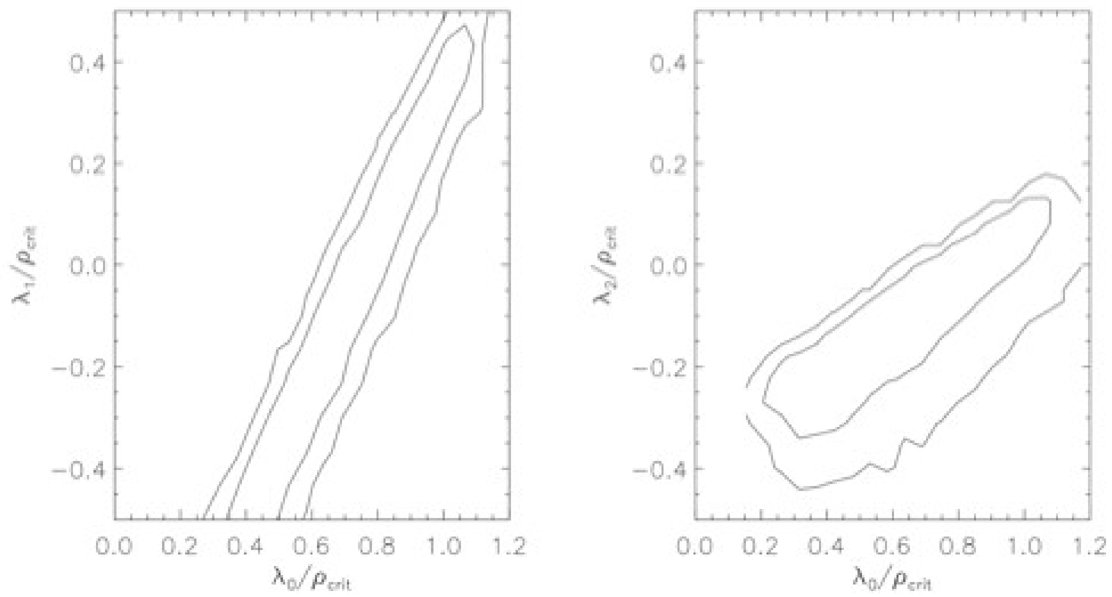
No data, priors only

$K > 0$ $\rho_T > 0$ that is $H^2 > 0$ $V_0 + K_0 = \Omega_{Q,0}\rho_c$ Flatness

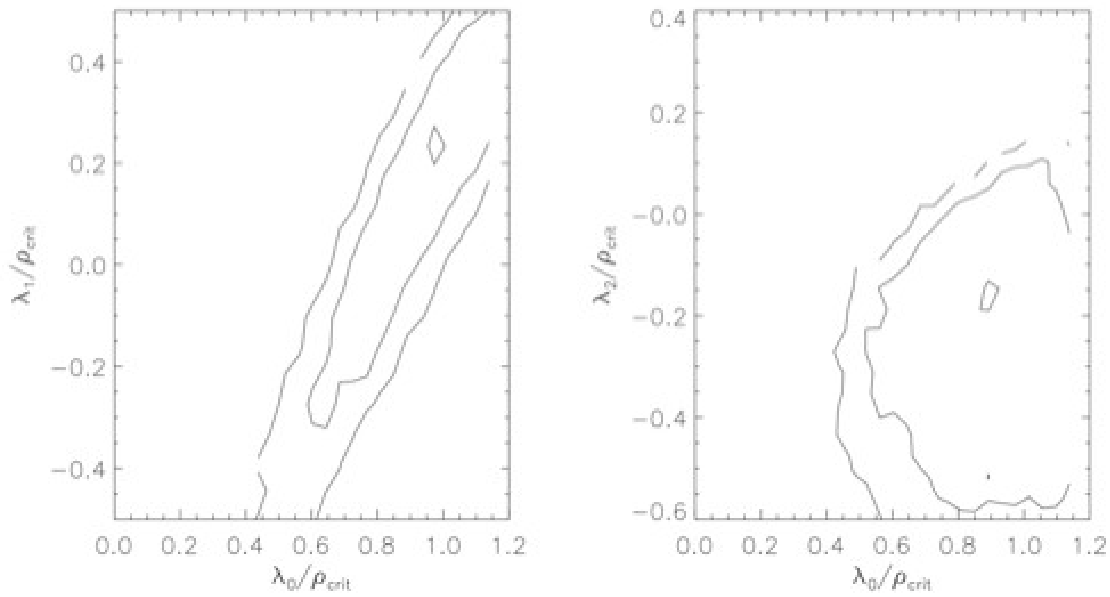


$\Omega_{m,0} = 0.27 \pm 0.07$ From large-scale structure !

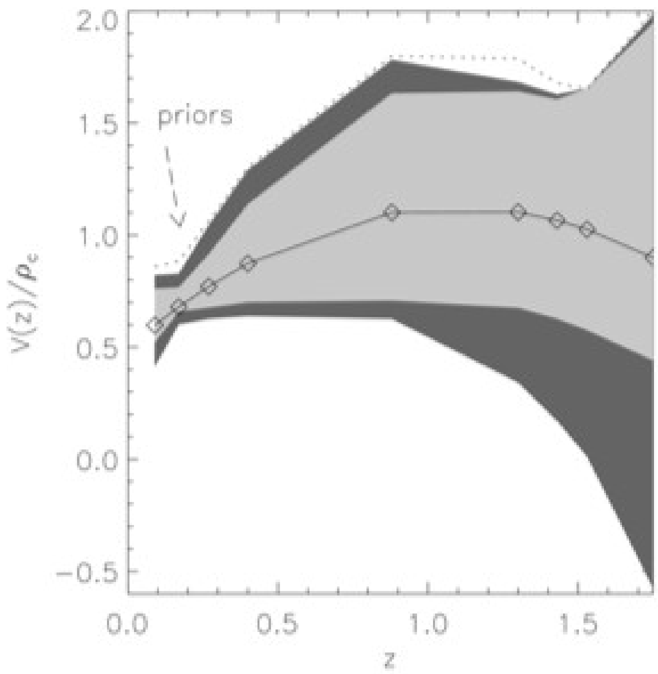
As a benchmark let's consider the Supernovae



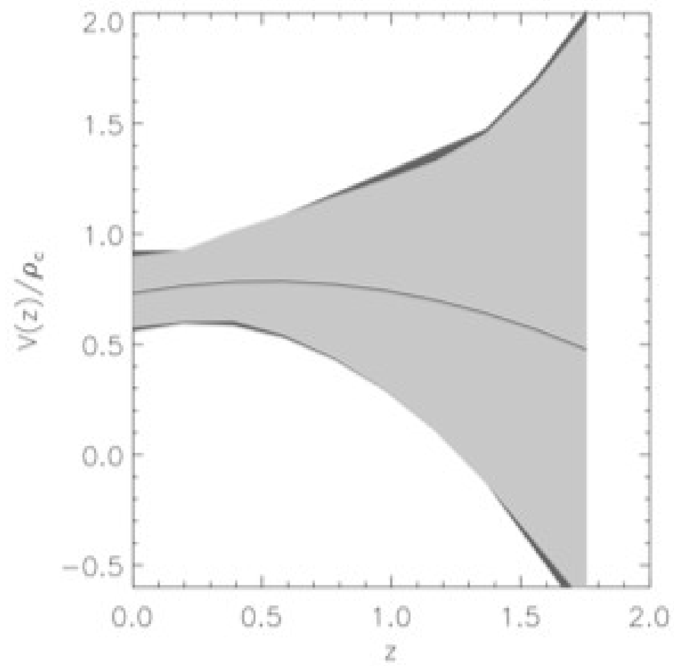
Using galaxy ages



From Simon, Verde, RJ (2005)

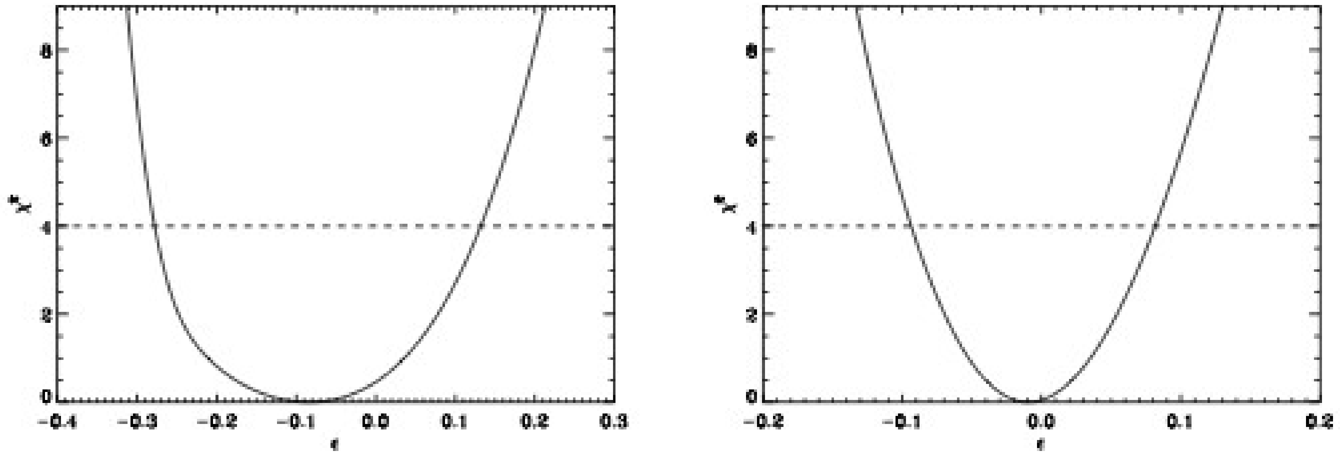


Galaxies

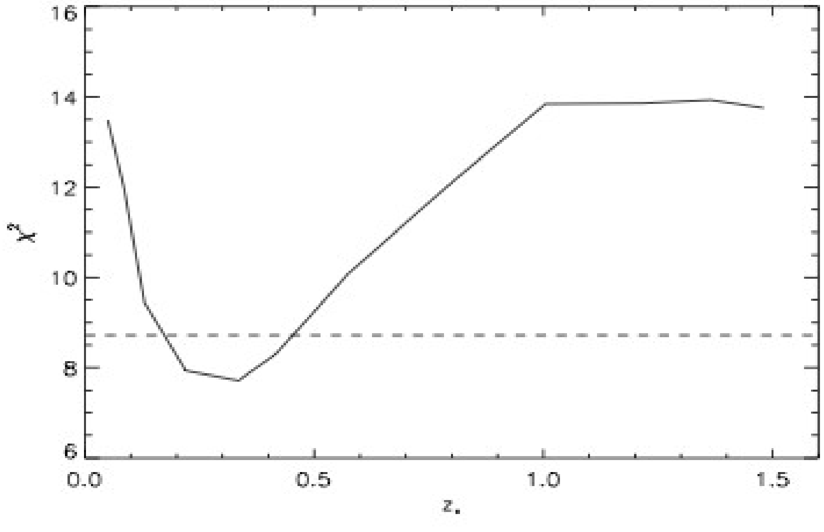


SN1A, Riess et al '04

Multiple uses of H(z)

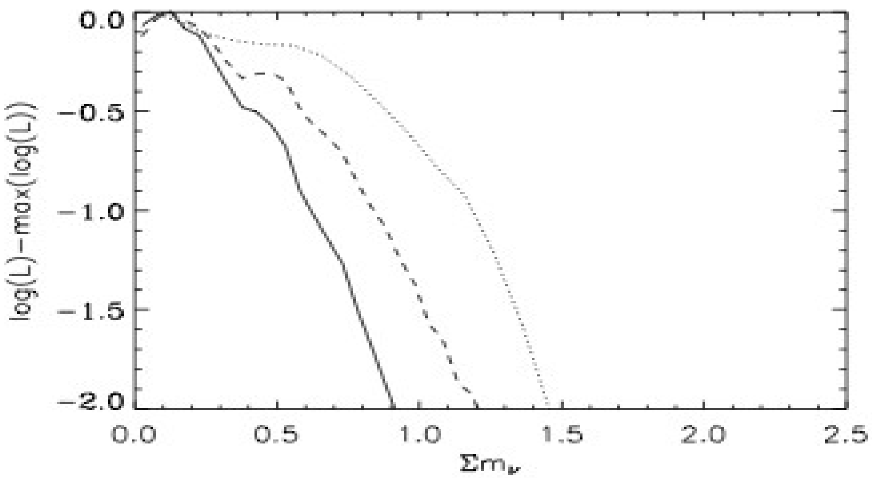


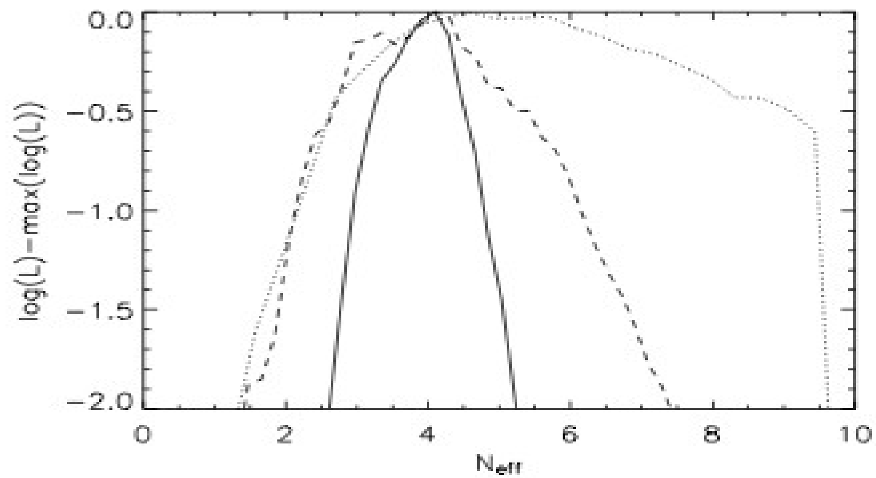
A factor 5 improvement on universe transparency (Avgoustidis, Verde, RJ arXiv:0902.2006)



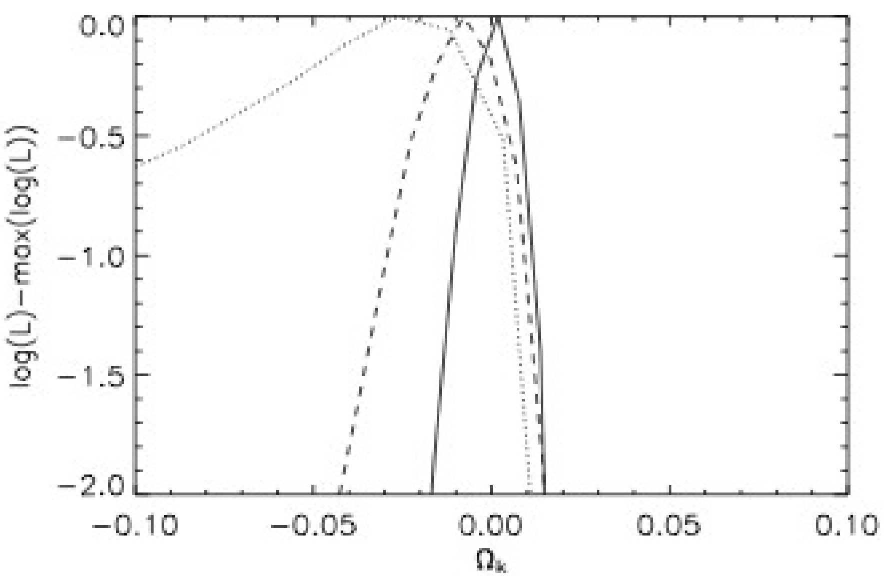
Detection of aceleration/deceleration (Avgoustidis, Verde, RJ arXiv:0902.2006)

Multiple uses of H(z)





Constraints on the mass and number of relativistic particles (de Bernardis et al. JCAP0803:020,2008 Figueroa, Verde, RJ JCAP0810:038,2008) and on the curvature

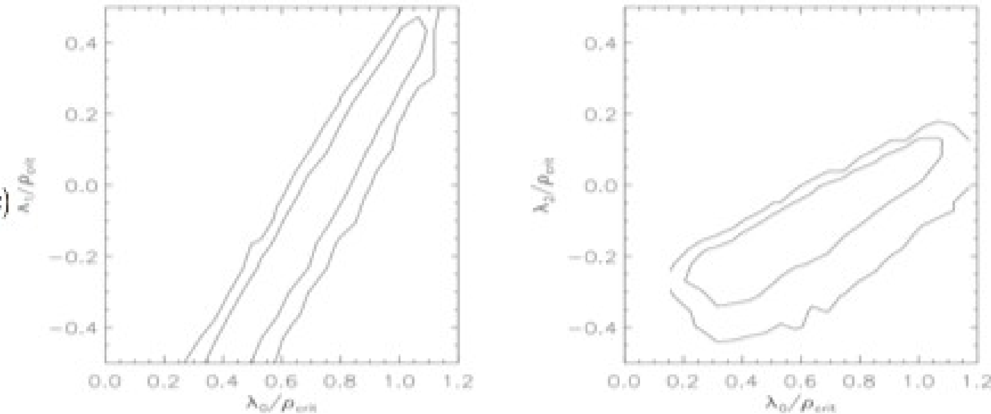


Current constraints (SN)

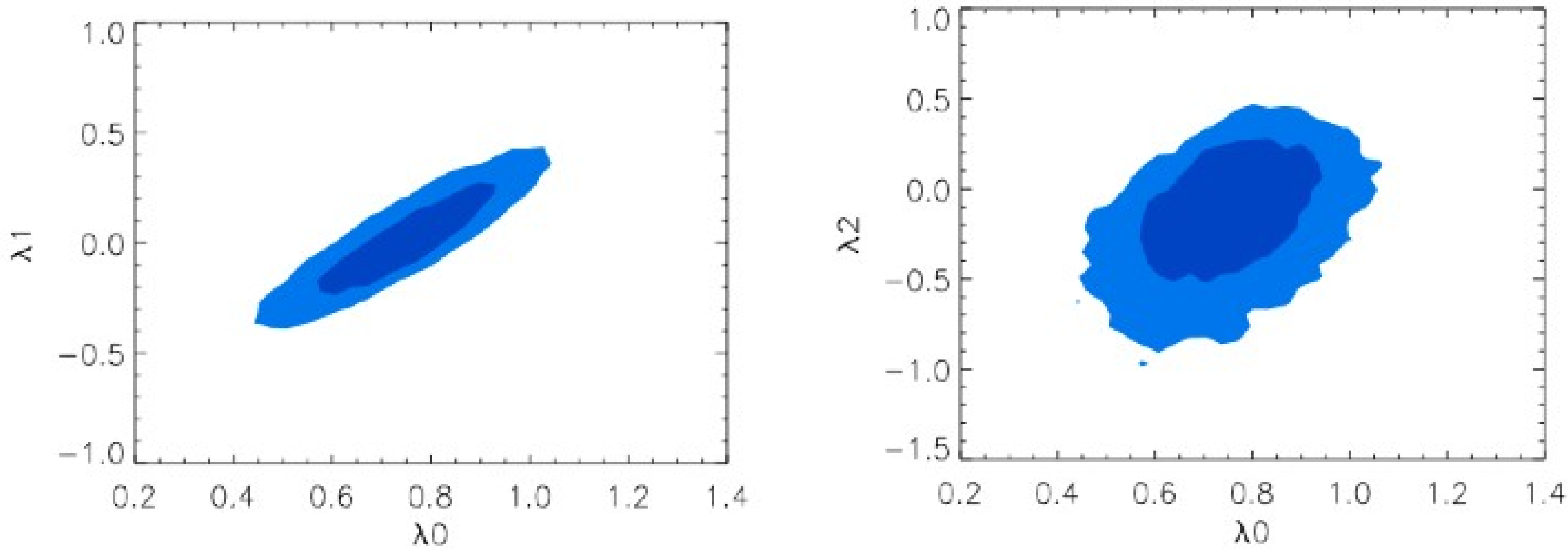
Simon, Verde, RJ '05

$$3H^2(z) - \frac{1}{2}(1+z)\frac{dH^2(z)}{dz} = \kappa\left(V(\alpha_i, z) + \frac{1}{2}\rho_m(z)\right) \equiv g(\alpha_i, z)$$

Use Chebyshev expansion of V



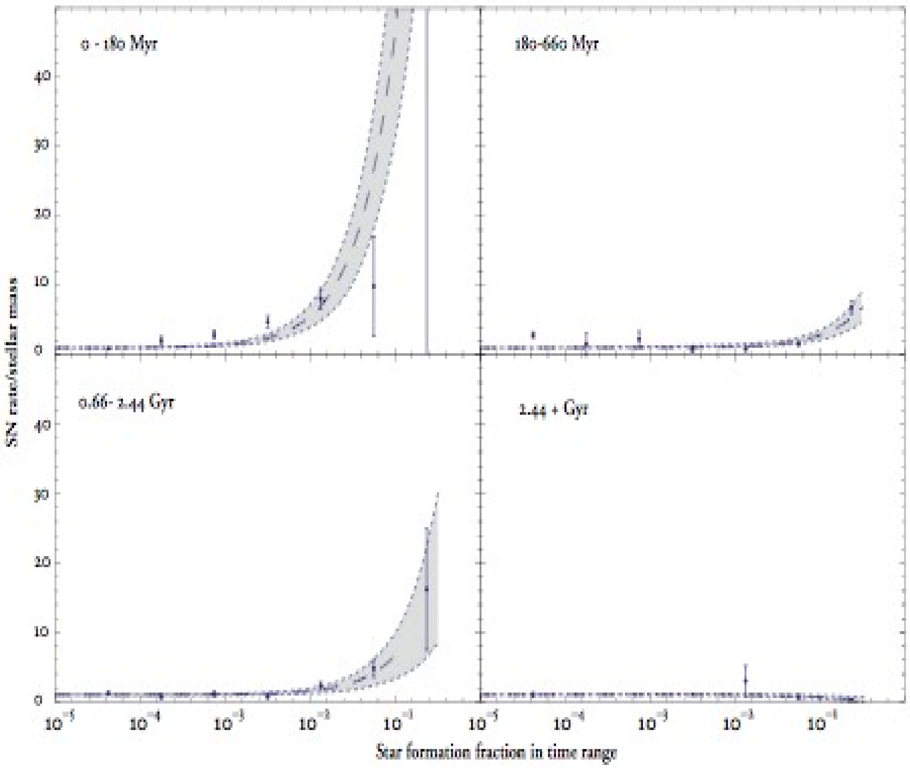
Fernandez-Martinez, Verde '08 W BOSS (no flatness prior!)

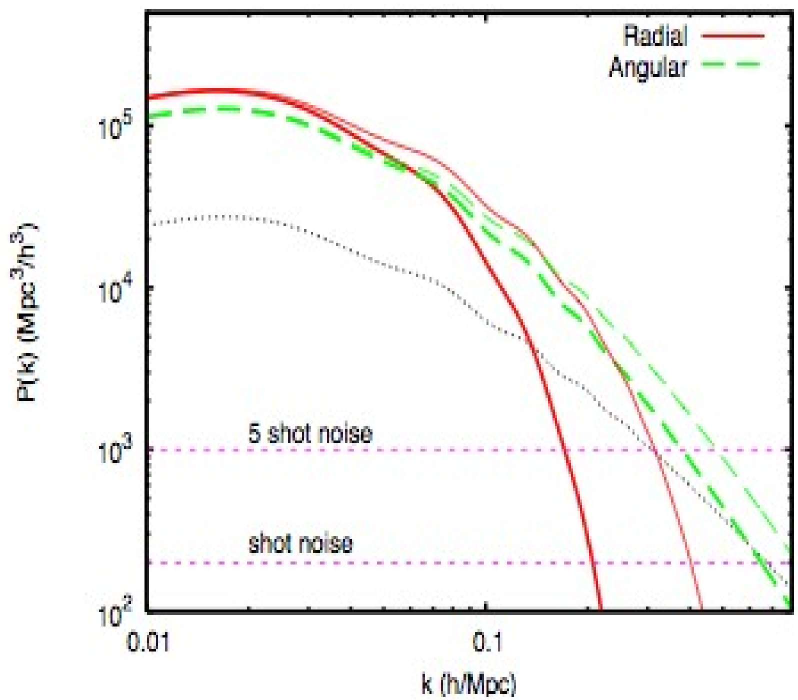


The importance of having high S/N spectra

Spectra of SN Ia hosts may help to tighten the H diagram

If you want to do radial BAOs you do need spectra





Aubourg et al. (2008)

Roig et al. (2009)