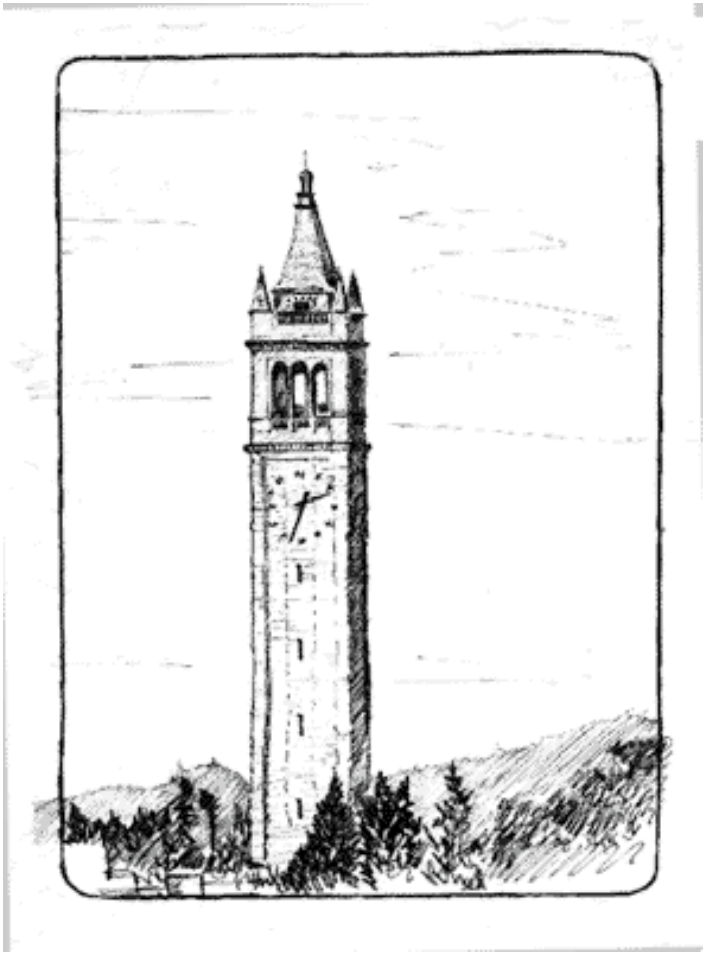
Cosmic Clocks:

Constraining the Equation of State of Dark Energy

Daniel Stern (JPL/Caltech)



UC Berkeley
2008 Feb. 26

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Constraining the Equation of State of Dark Energy

Daniel Stern (JPL/Caltech)

collaborators:
Raul Jimenez (Barcelona)
Marc Kamionkowski (Caltech)
Licia Verde (Barcelona)

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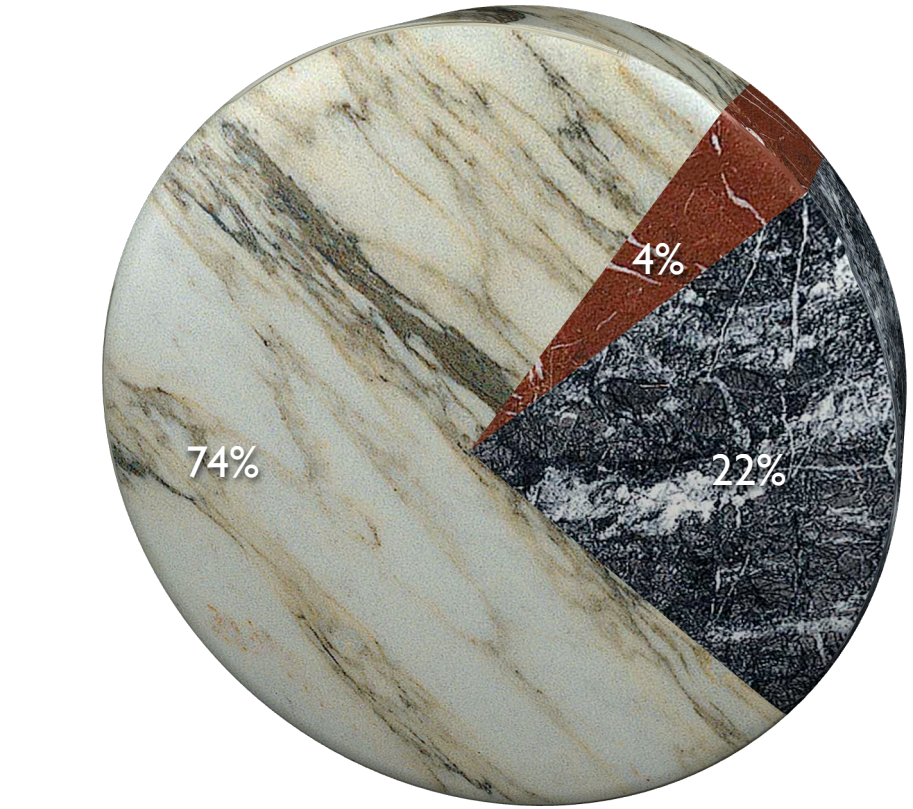
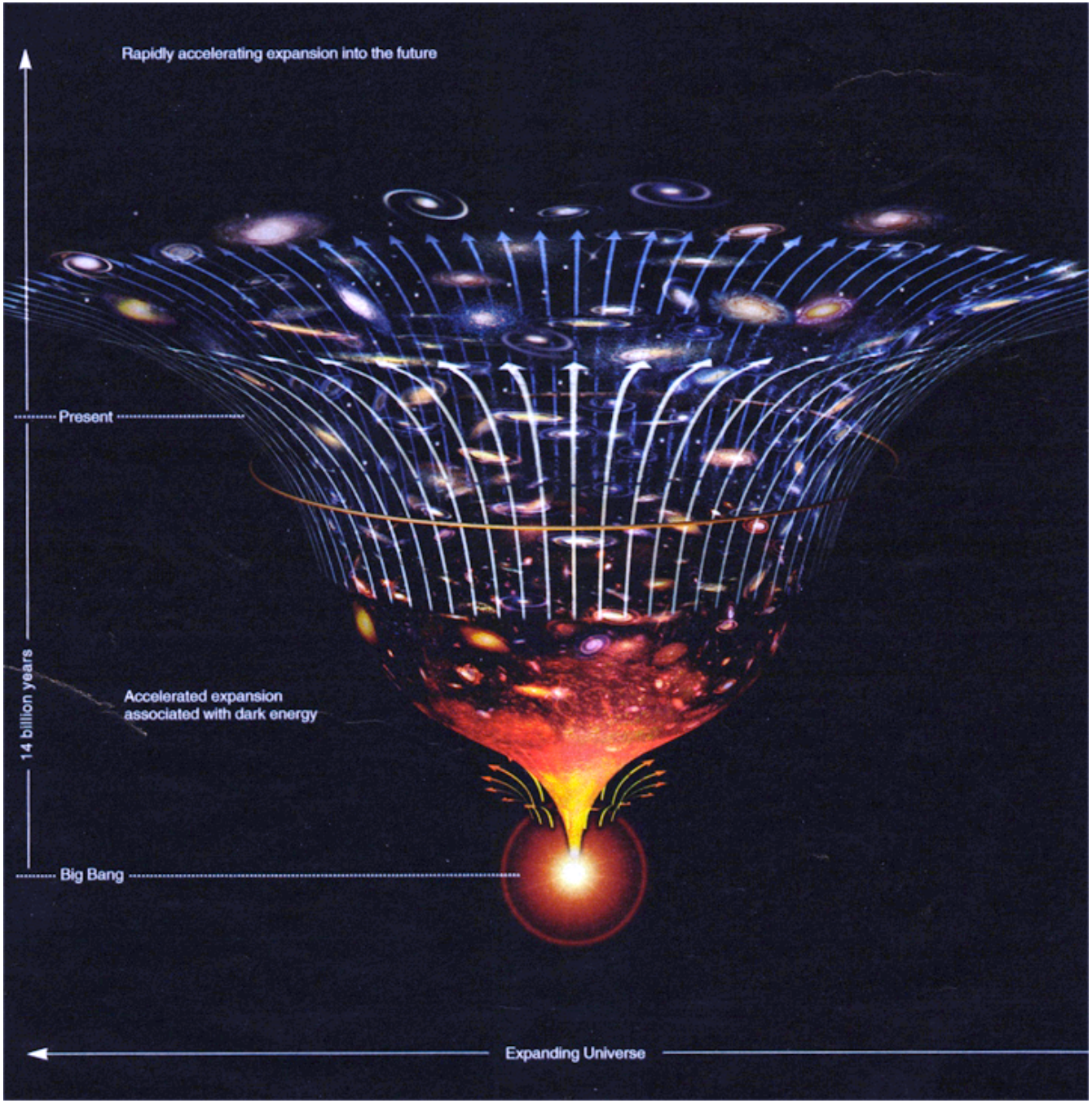

4%
22%
74%
Atoms
Dark Matter
Dark Energy


Rapidly accelerating expansion into the future
Present
14 billion years
Accelerated expansion
associated with dark energy
Big Bang
Expanding Universe

Λ

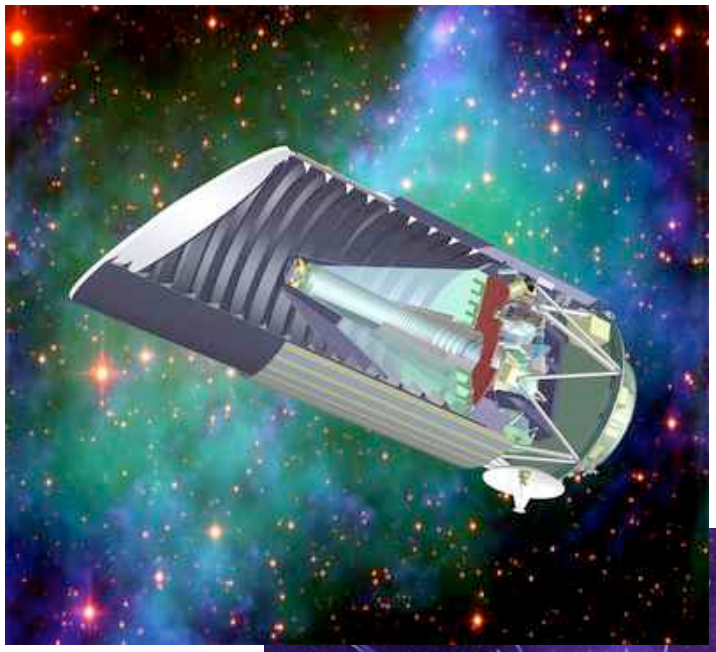
Equation of State of Dark Energy

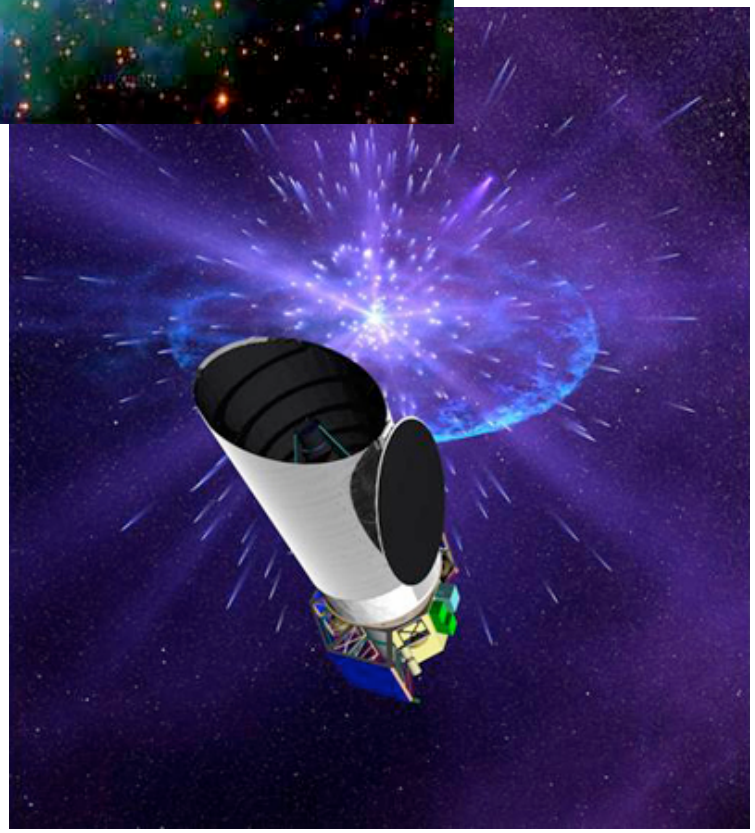
$$p = w \rho$$

- p - pressure
- w - equation of state parameter (w_Q)
- ρ - density

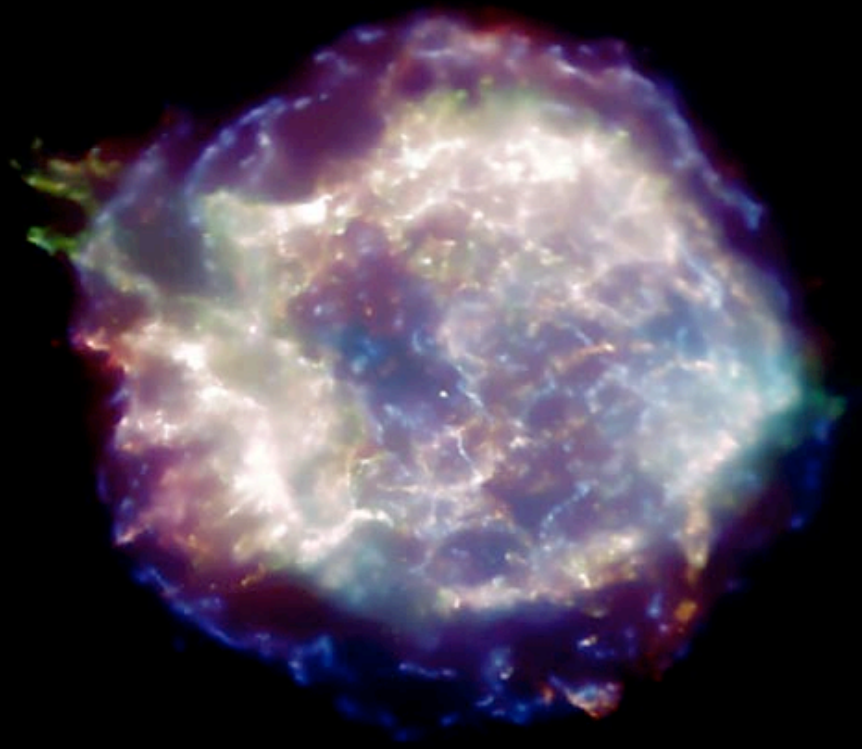
w = w(z)?

- for cold matter (solids), w=0
- for radiation, w=1/3
- for cosmological constant (Λ), w=-1
- for quintessence, w=w(z)

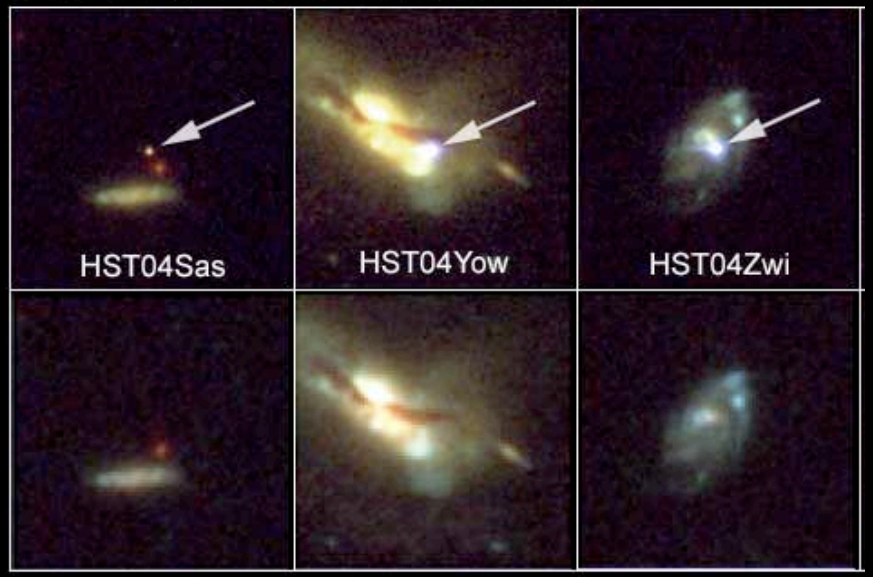




Standard Candle

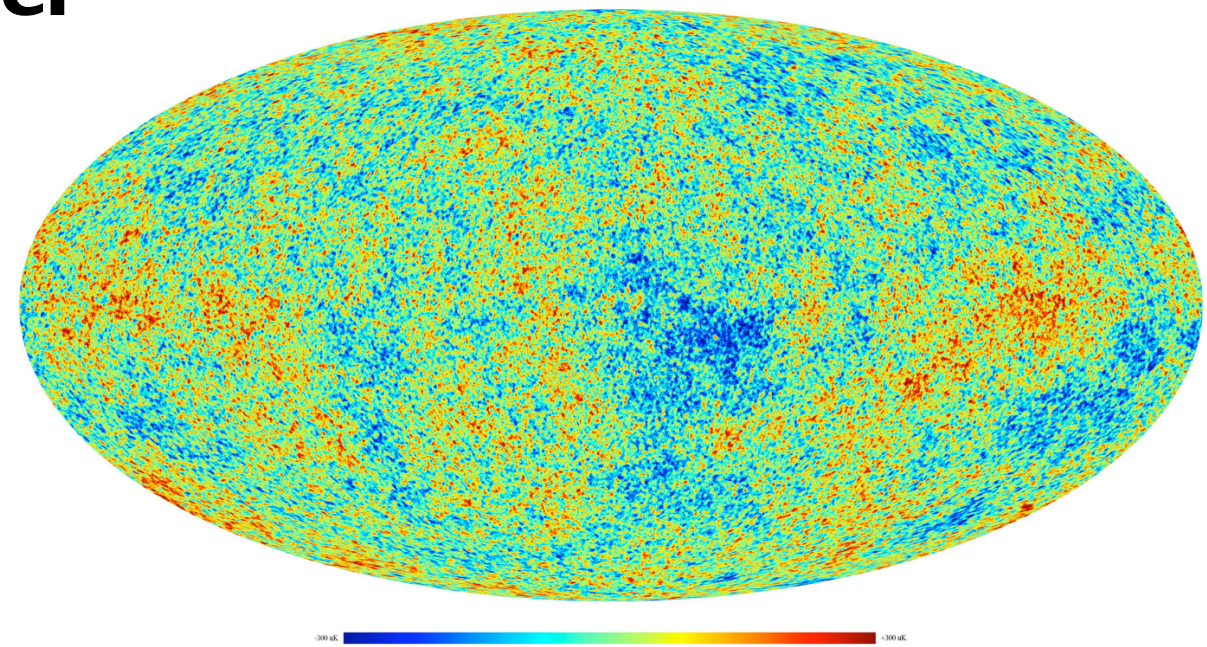


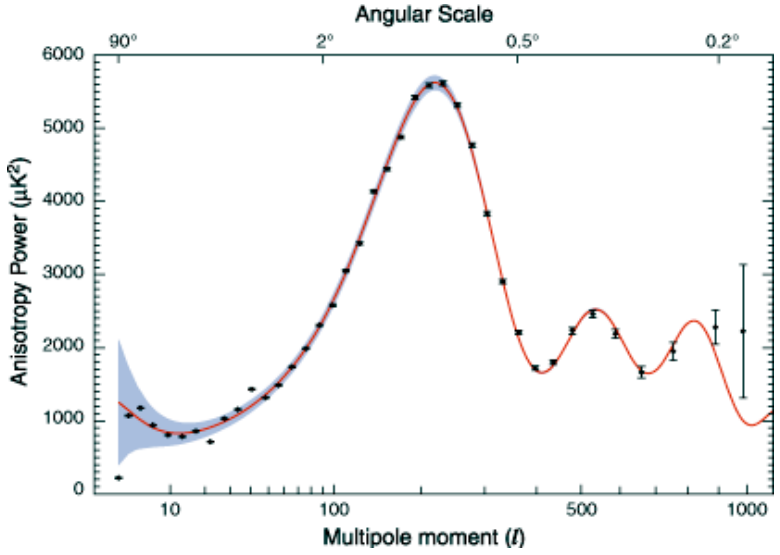
Host Galaxies of Distant Supernovae



NASA, ESA, and A. Riess (STScI)

Standard Ruler

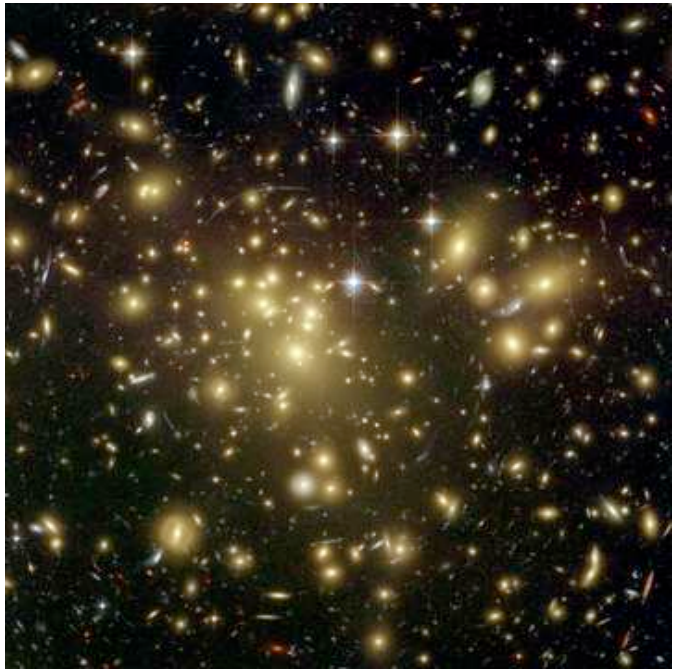


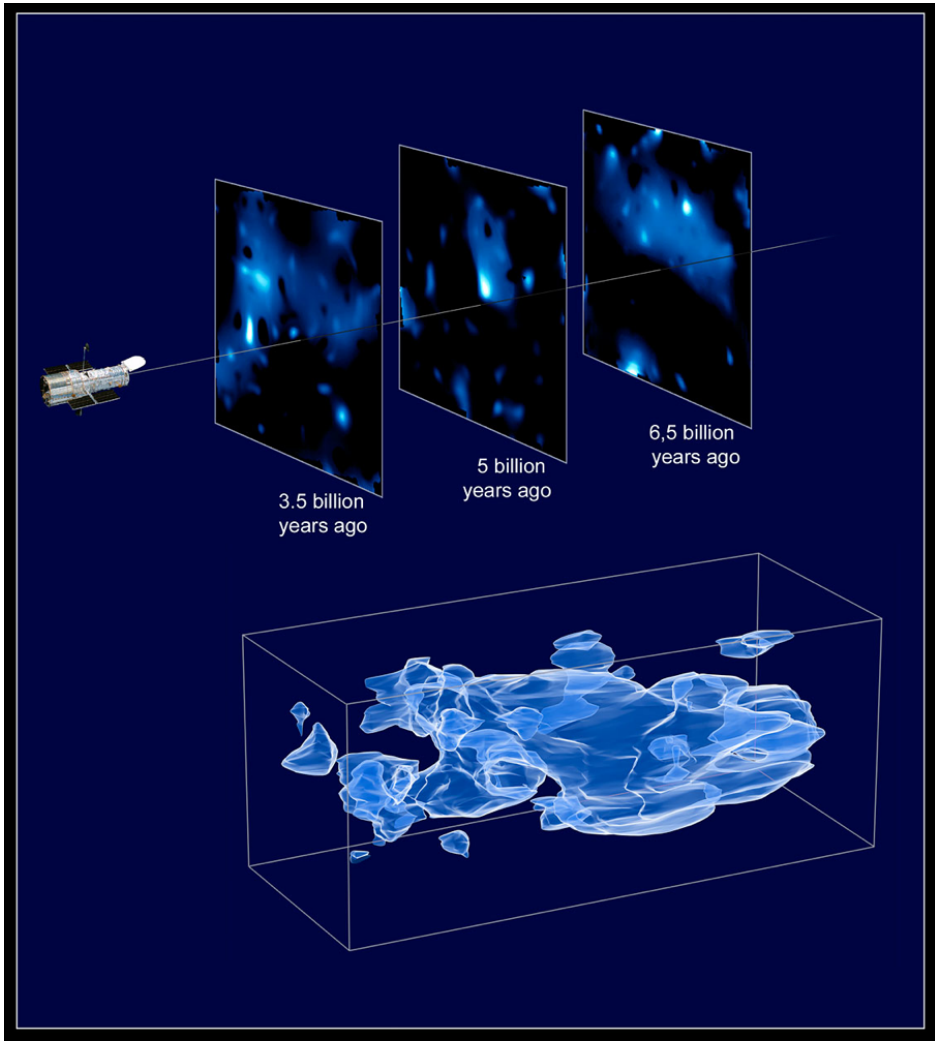


baryon acoustic oscillations
(radio galaxies)

Structure Formation

weak lensing
galaxy clusters





Standard Clock

early-type galaxies

Theory

• using supernovae to probe *w(z)* is compromised by the integral nature of the dependence of luminosity distance $d_L(z)$ on *w(z)*:

$$d_{\rm L} = (1+z)\int_z^0 (1+z')\frac{dt}{dz'}dz',$$

where *t(z)*, the age of the universe at redshift *z*, is a function of *w(z)*.

• goal will be to probe the integrand directly, *(dt/dz)*; in particular, the *differential age method* will be less subject to systematics than an absolute age determination.

• also, since

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

this method can also be used to determine the Hubble constant.

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

Theory

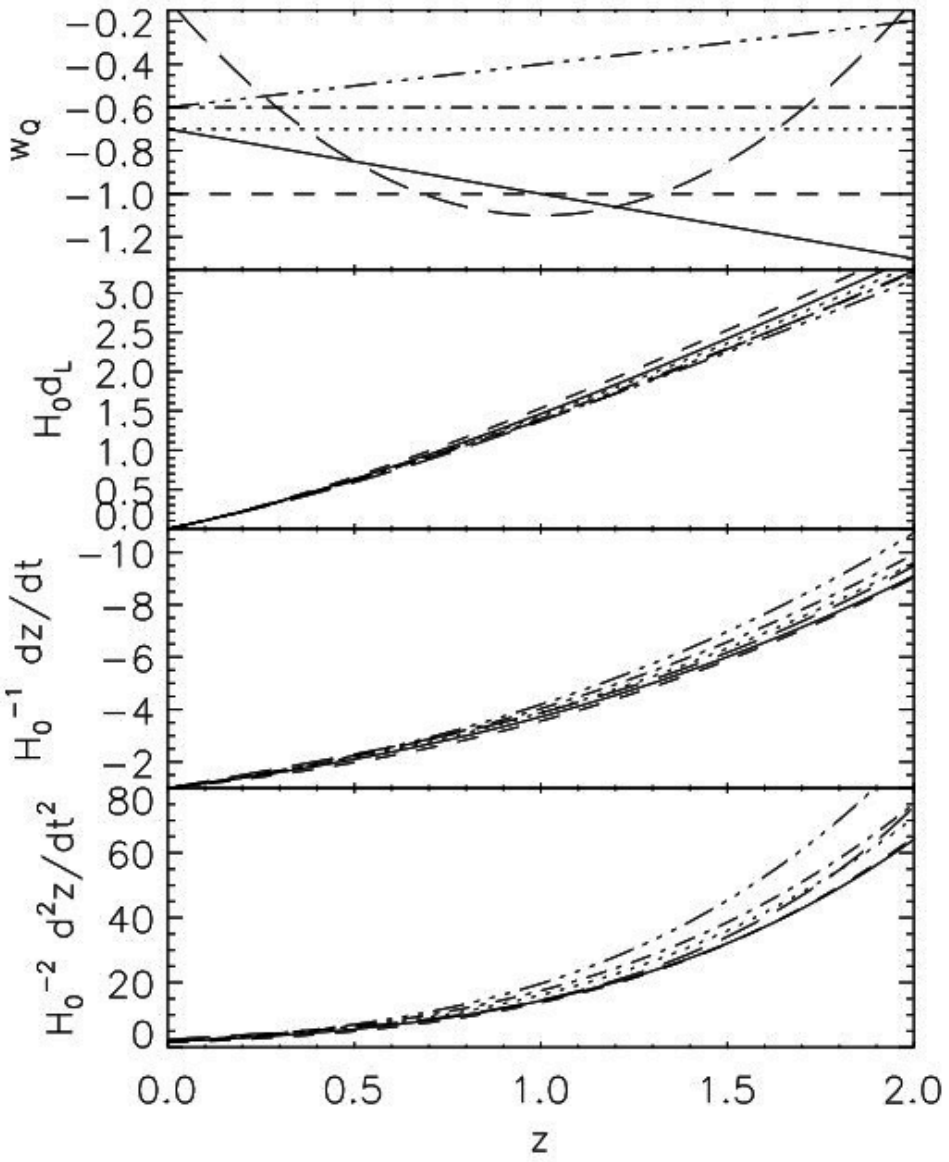
- in particular, *dz/dt* is related to *w(z)* through a single integration:

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

- and d^2z/d^2t depends explicitly on *w(z)*:

$$H_0^{-2}\frac{d^2z}{dt^2} = \frac{[H_0^{-1}(dz/dt)]^2}{(1+z)}\left[\frac{5}{2} + \frac{3}{2}w_Q(z)\right] - \frac{3}{2}\Omega_m(0)(1+z)^4 w_Q(z)$$

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



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)

Standard Clock?

early-type galaxies

Experimental concerns

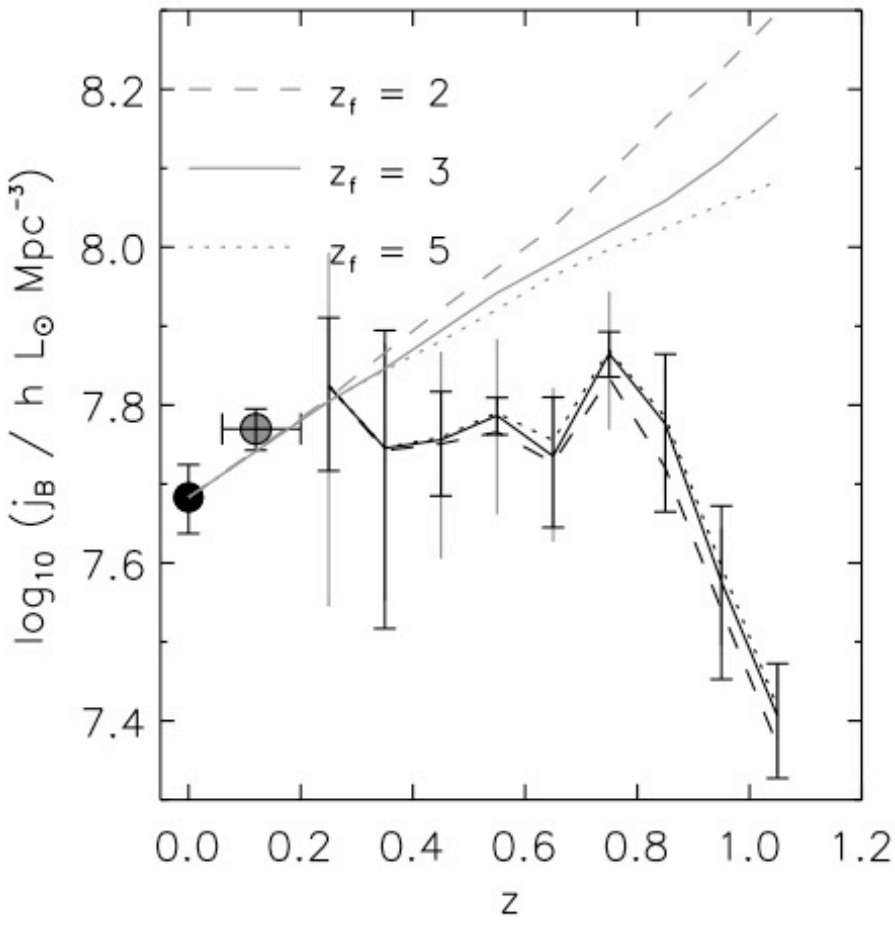
How well can gE's be approximated as passively evolving, old systems?
- mergers; early-type galaxies still assembling at $z<1$?
- on-going star formation ("frosting")

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

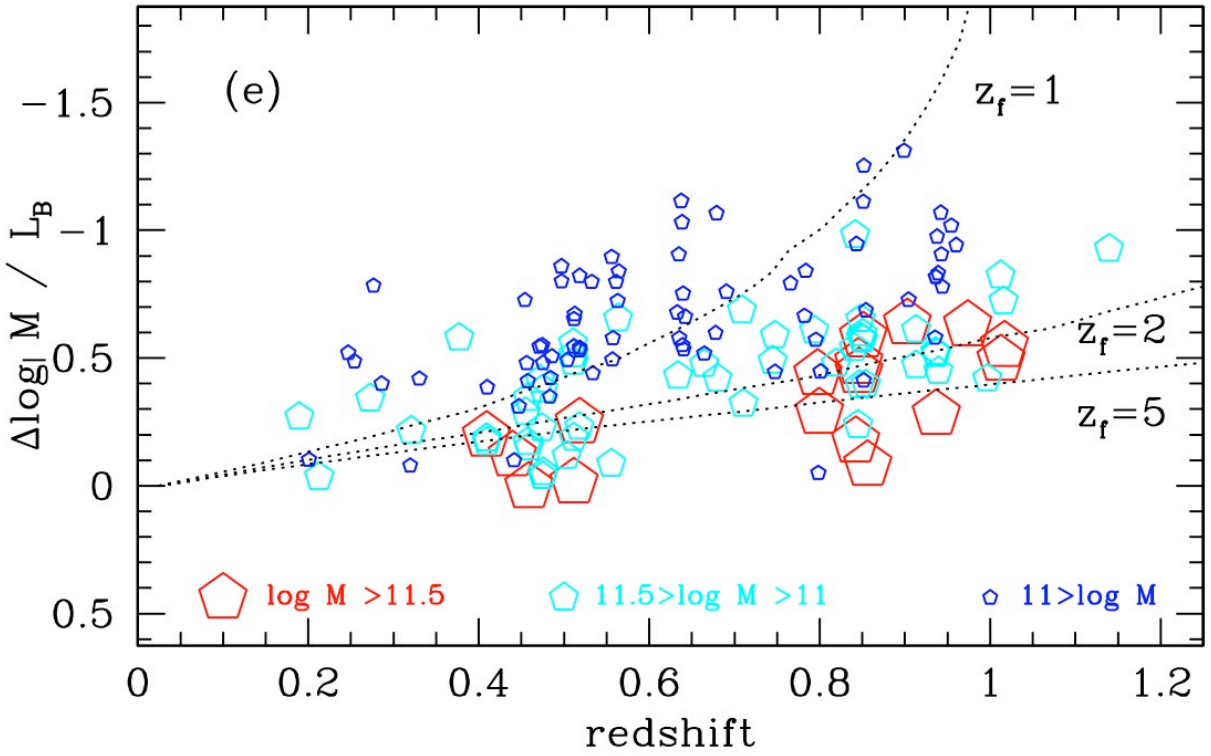
substantial assembly (e.g., luminosity evolution) since z~1 (as predicted by hierarchical ΛCDM models)



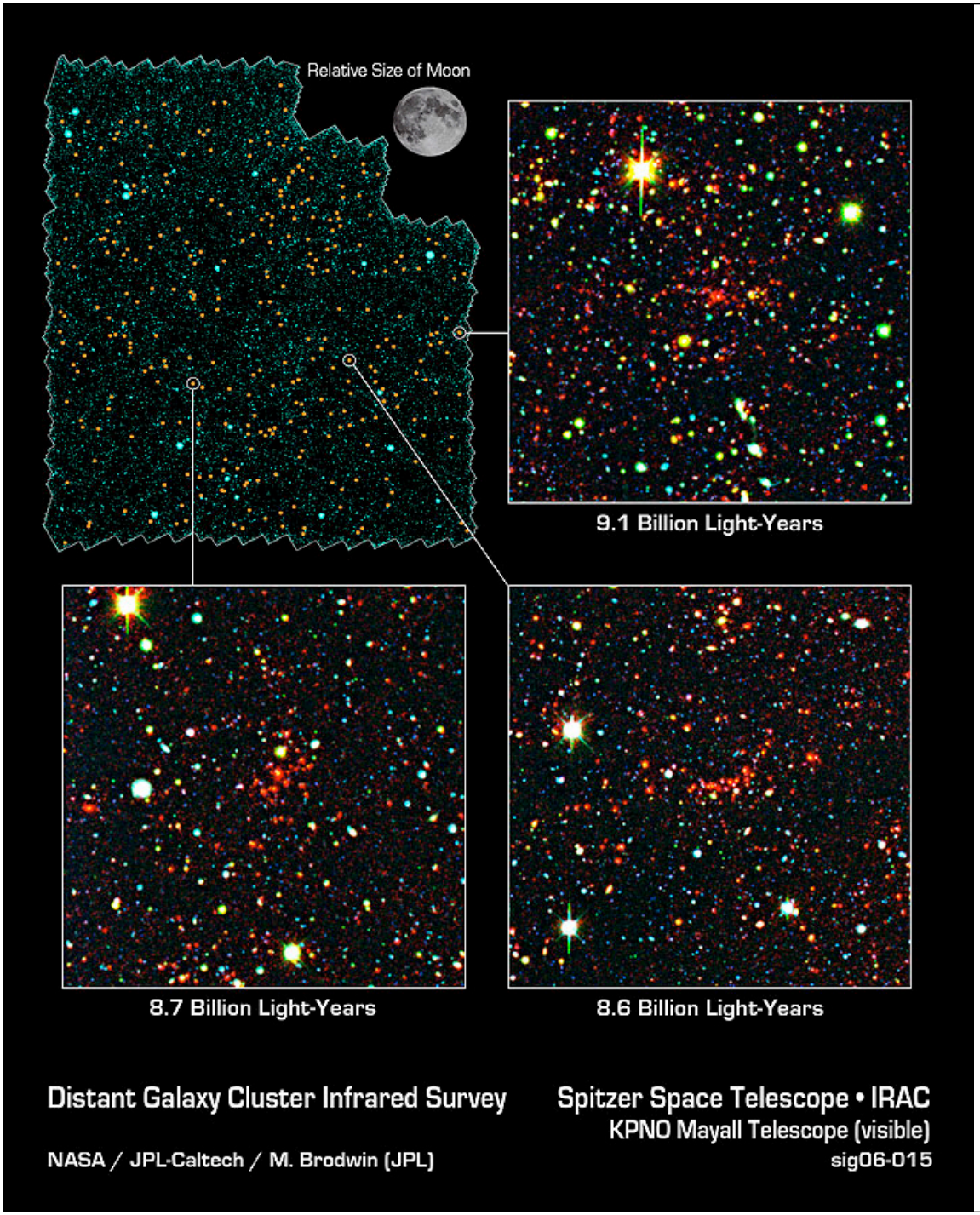
Bell et al. (2004; ApJ, 608, 752)

gE's as passively evolving, old systems

the most massive early-type galaxies are the oldest



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



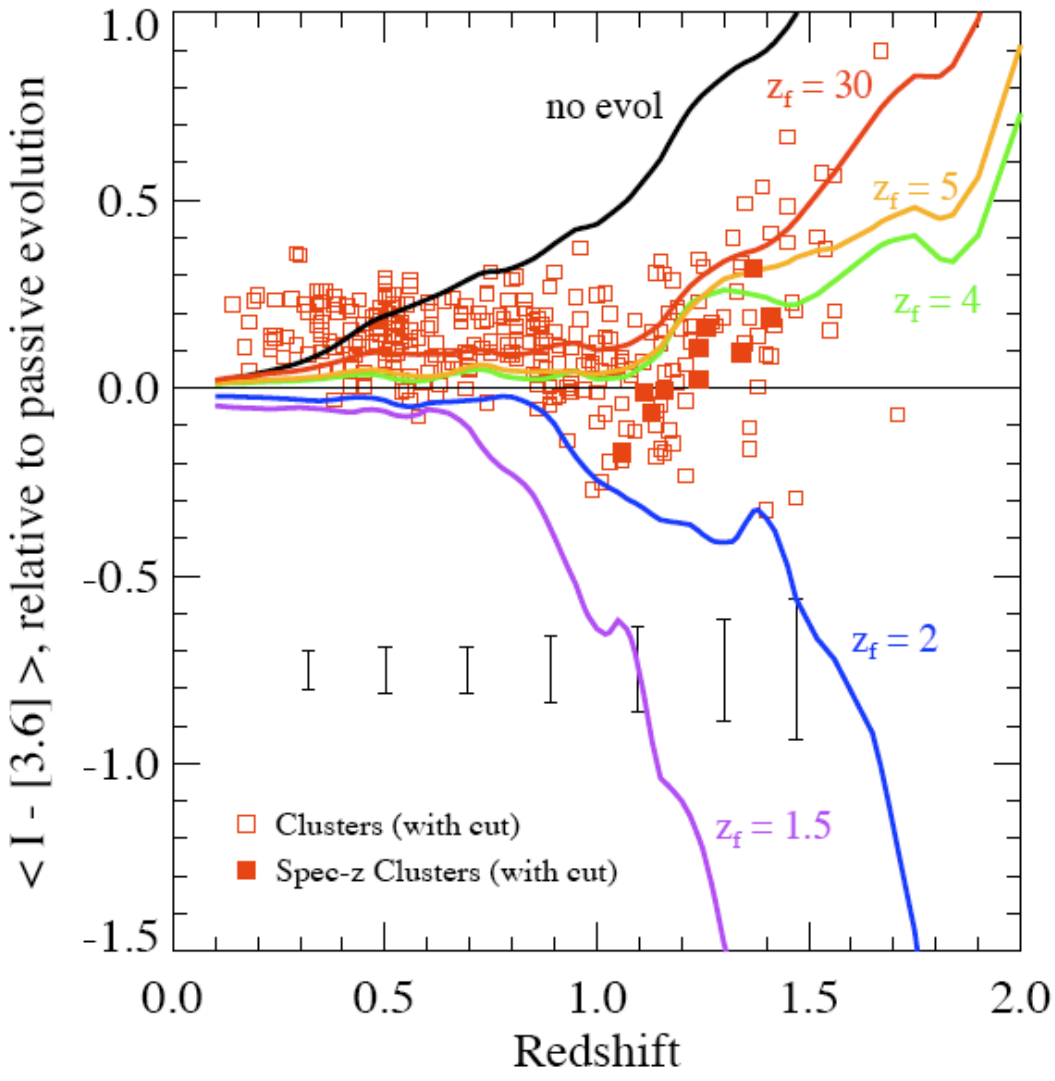
IRAC Shallow Cluster Survey (Boötes field)

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)



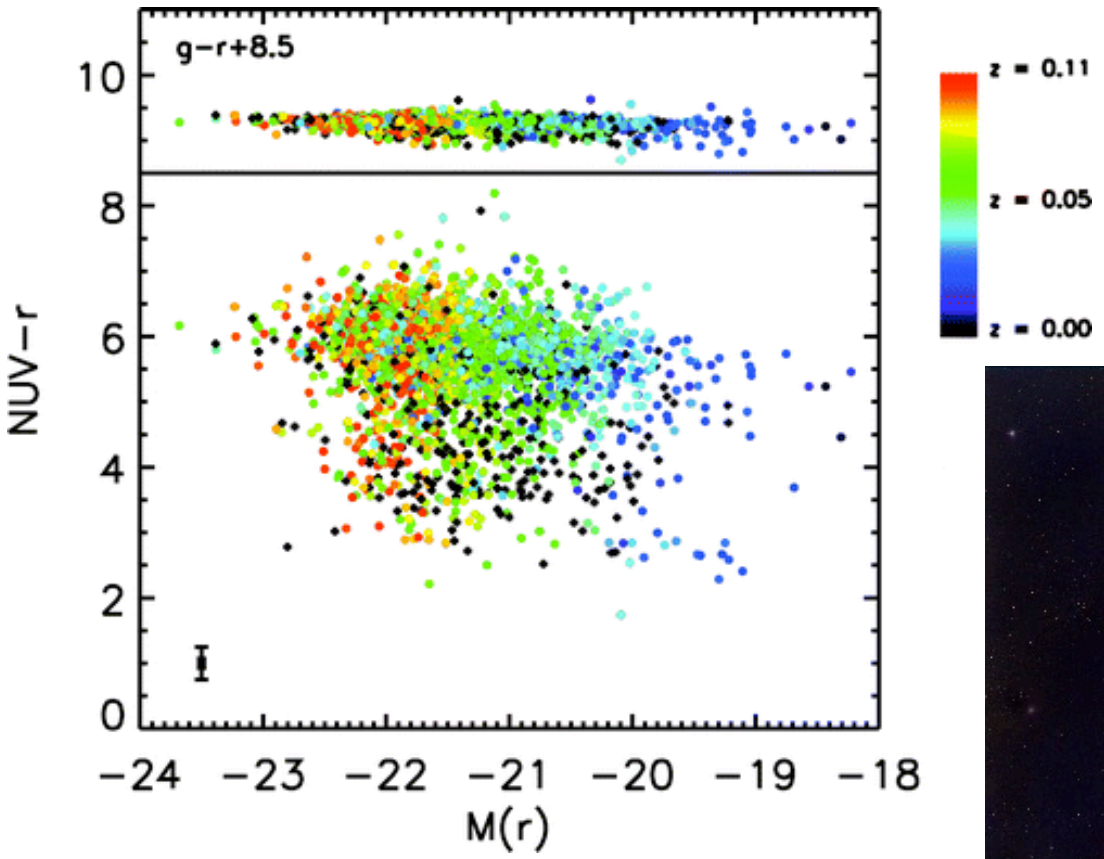
Eisenhardt et al. (ApJ, submitted)

gE's as passively evolving, old systems

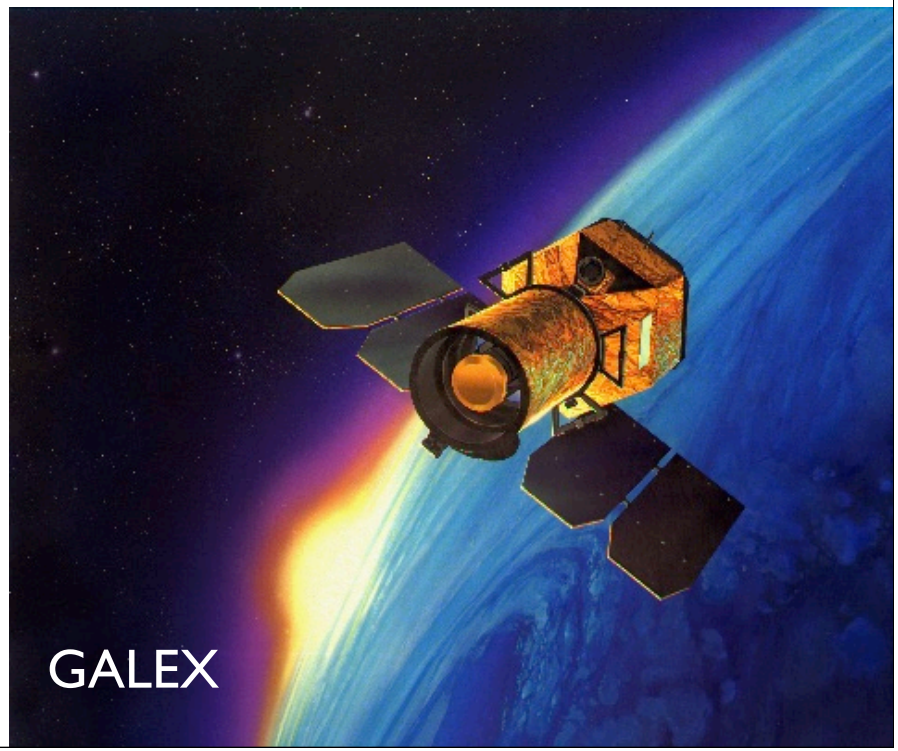
solution:
dry mergers

van Dokkum (2005; AJ, 130, 2647)

gE's as passively evolving, old systems

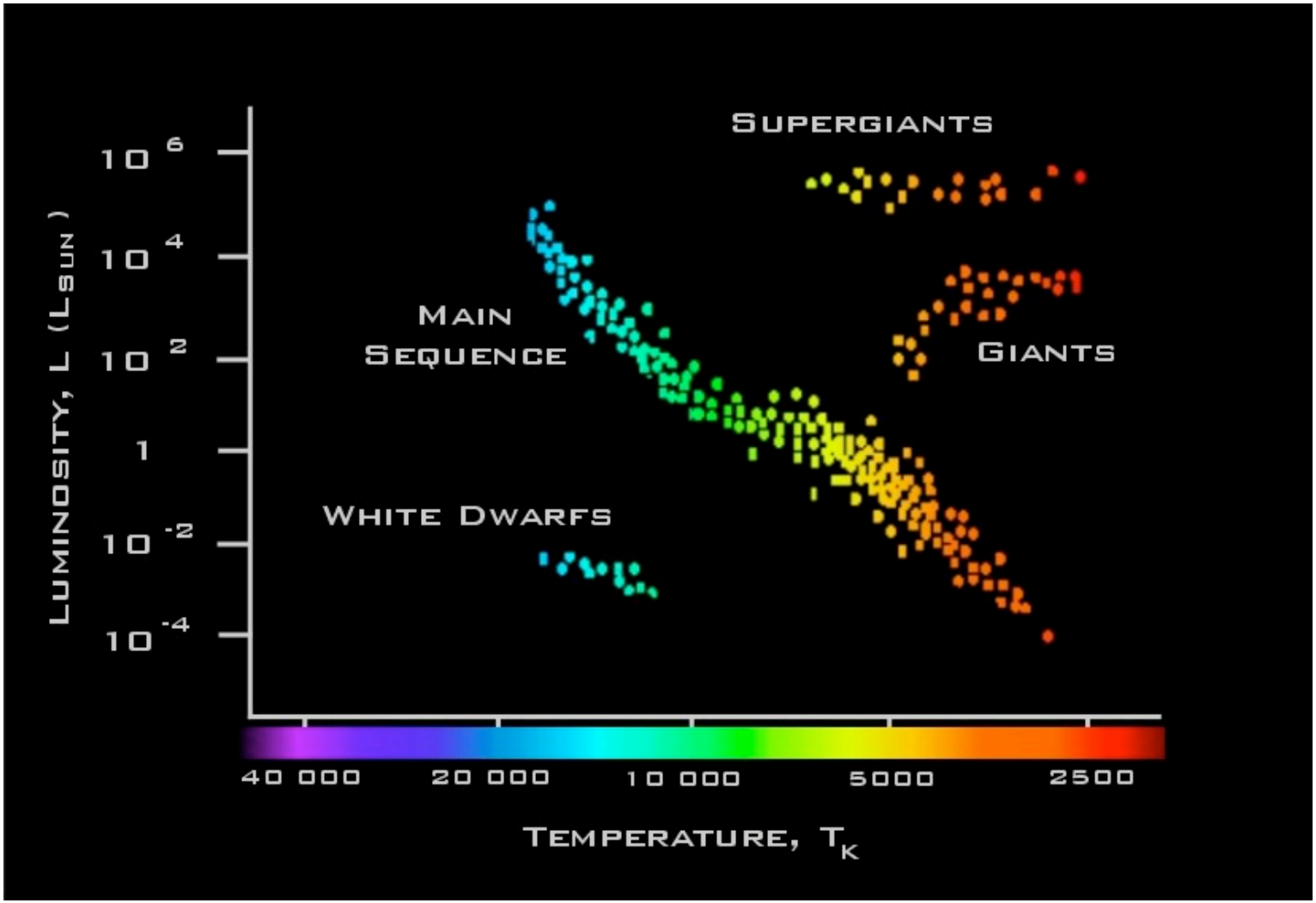


- 15% of local, bright ellipticals show "frosting" of recent (< 1 Gyr) star formation
- only 1-2% by mass
- "downsizing": less frosting in most massive galaxies

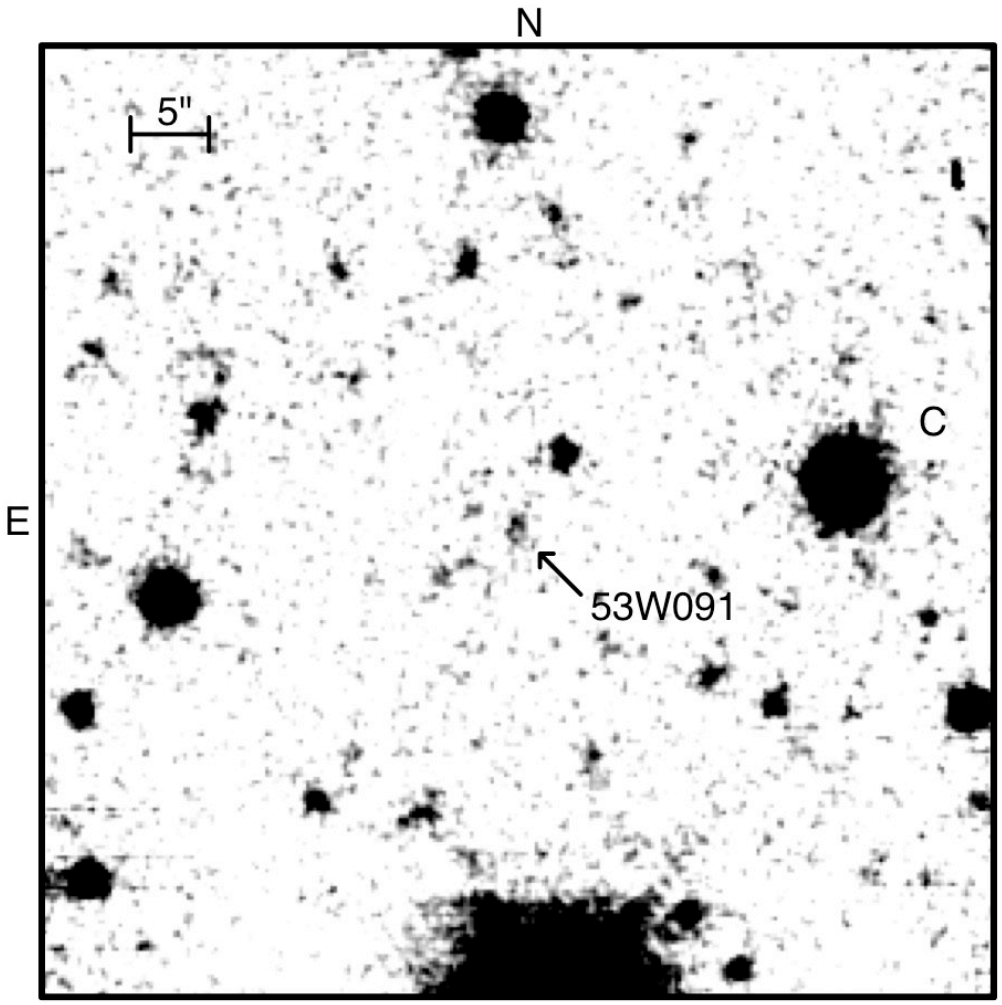


Yi et al. (2005; ApJ, 619, L111)
Kaviraj et al. (2007; ApJS, 173, 619)
Jimenez et al. (2007; ApJ, 669, 947)

measuring age of stellar population



measuring age of stellar population

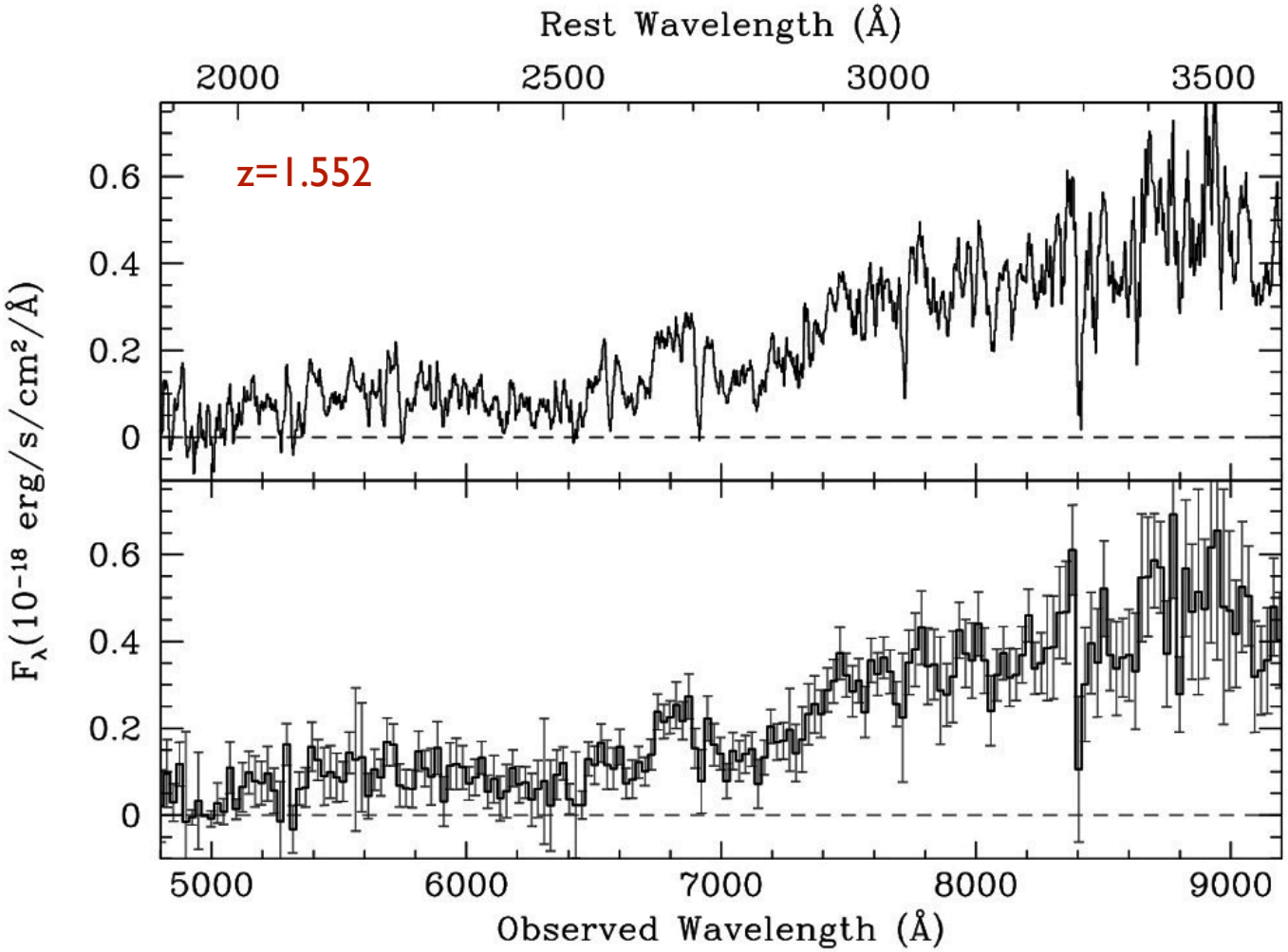


LBDS 53W091

faint, red radio galaxy

Spinrad, Dey, Stern et al. (1997; ApJ, 484, 581)

measuring age of stellar population



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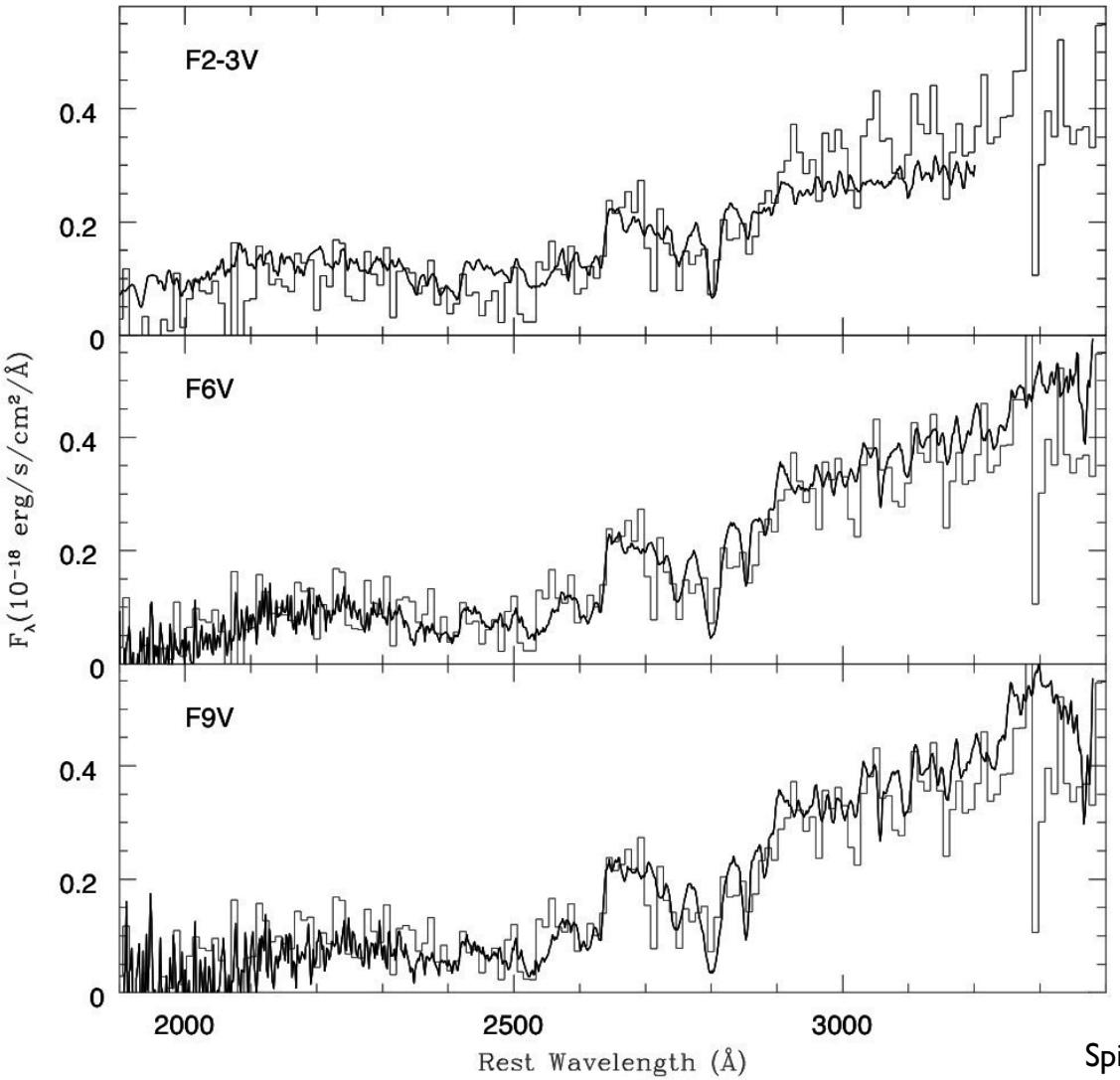
measuring age of stellar population



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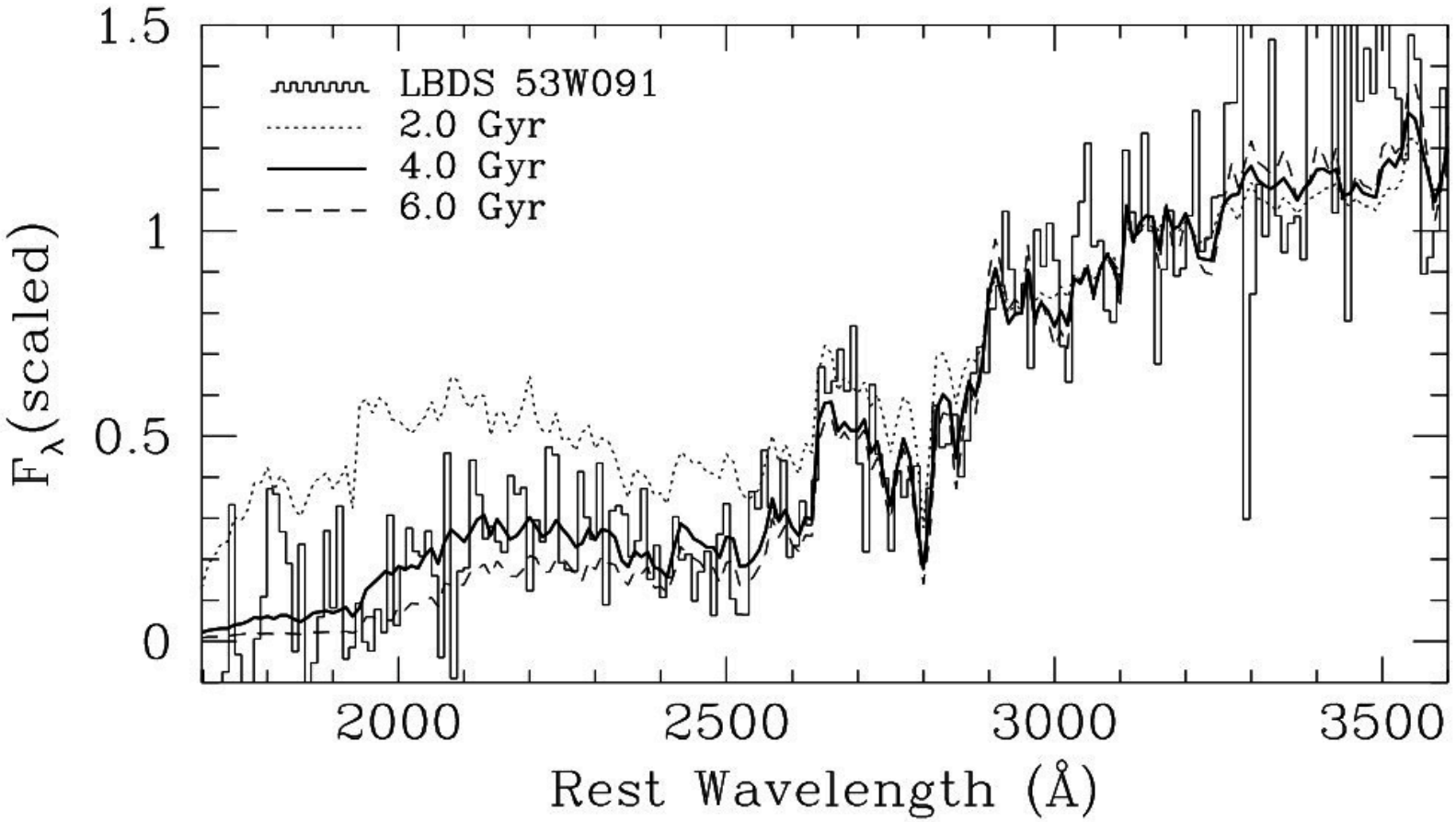
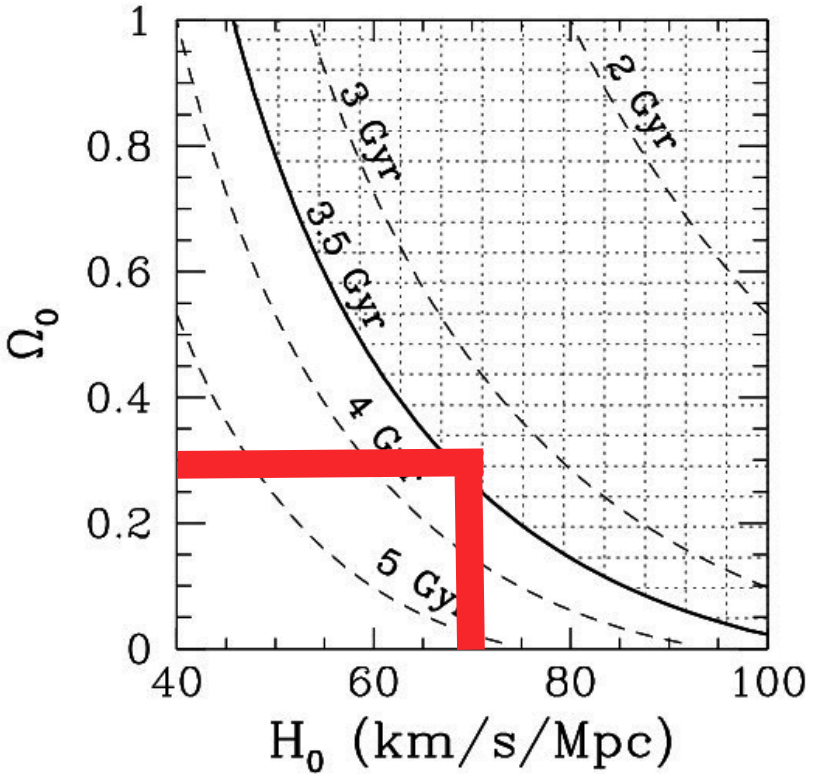


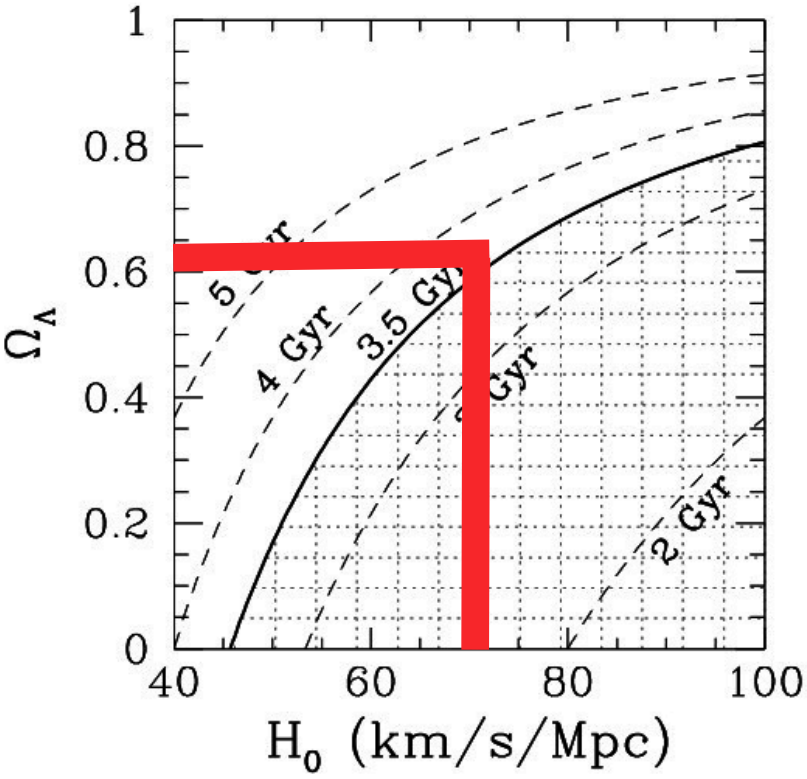
best fit age:

3.5 Gyr (at z=1.552)

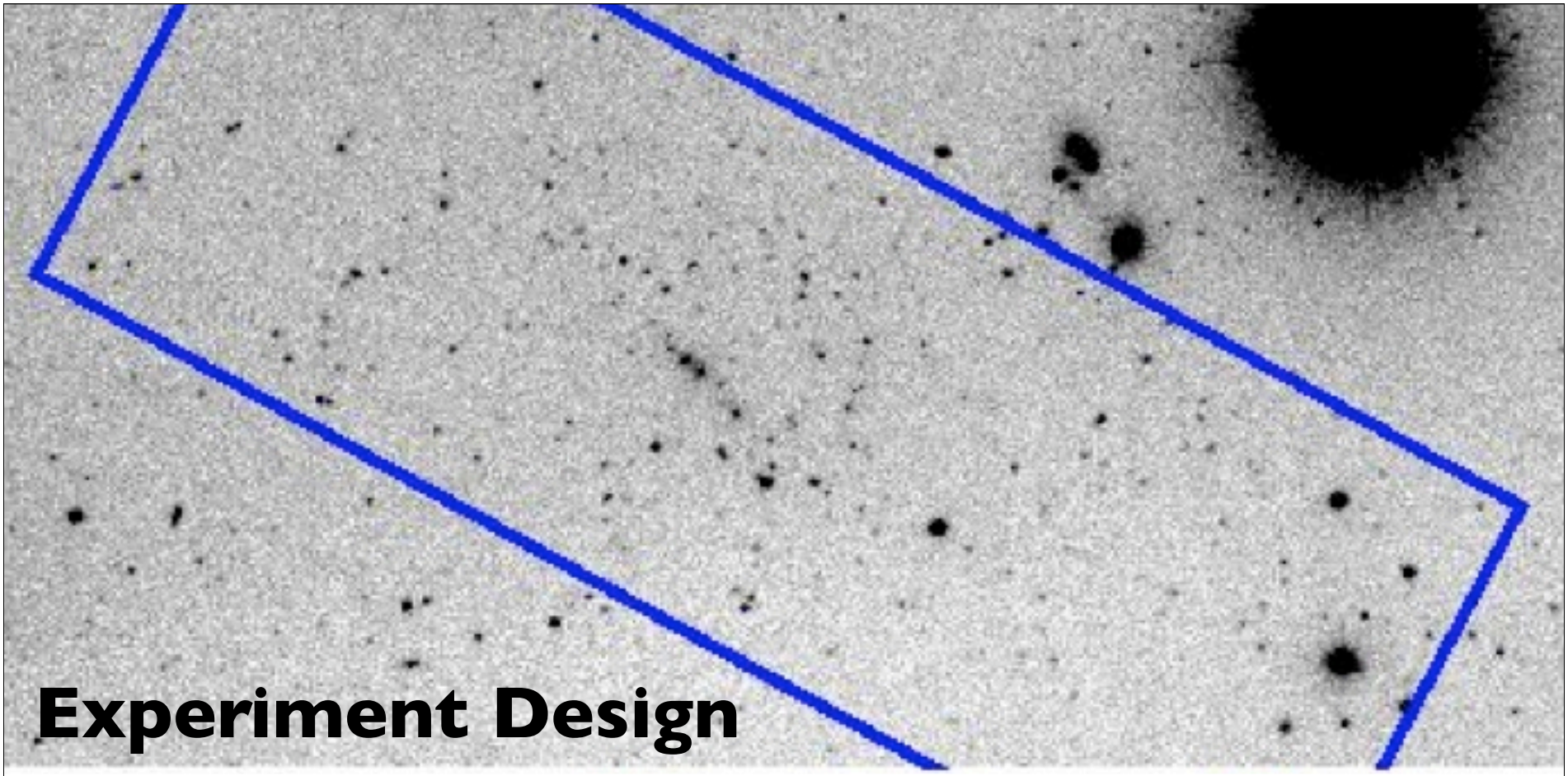
Spinrad, Dey, Stern et al. (1997; ApJ, 484, 581)

measuring age of stellar population





Spinrad, Dey, Stern et al. (1997; ApJ, 484, 581)

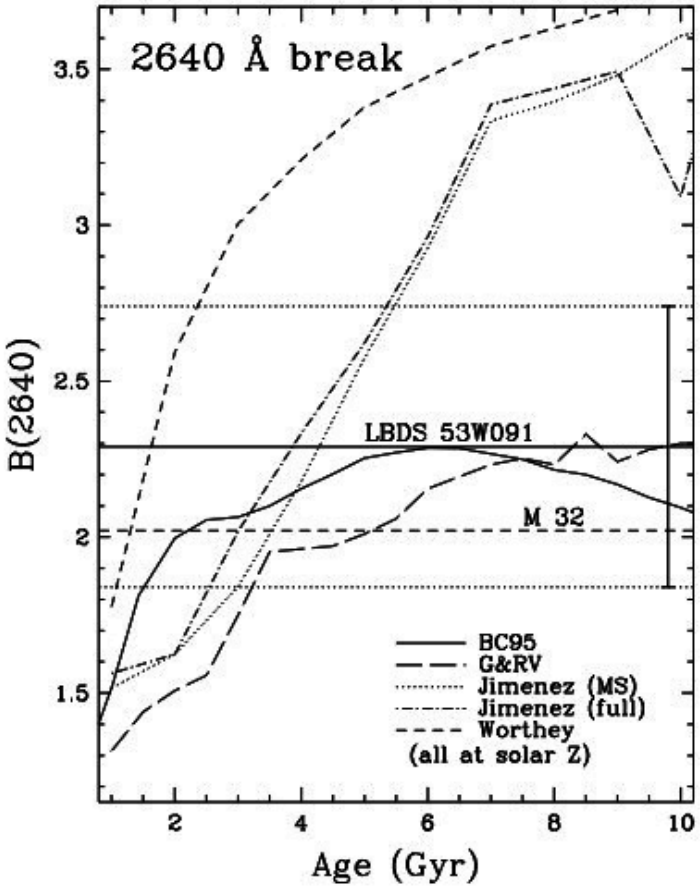


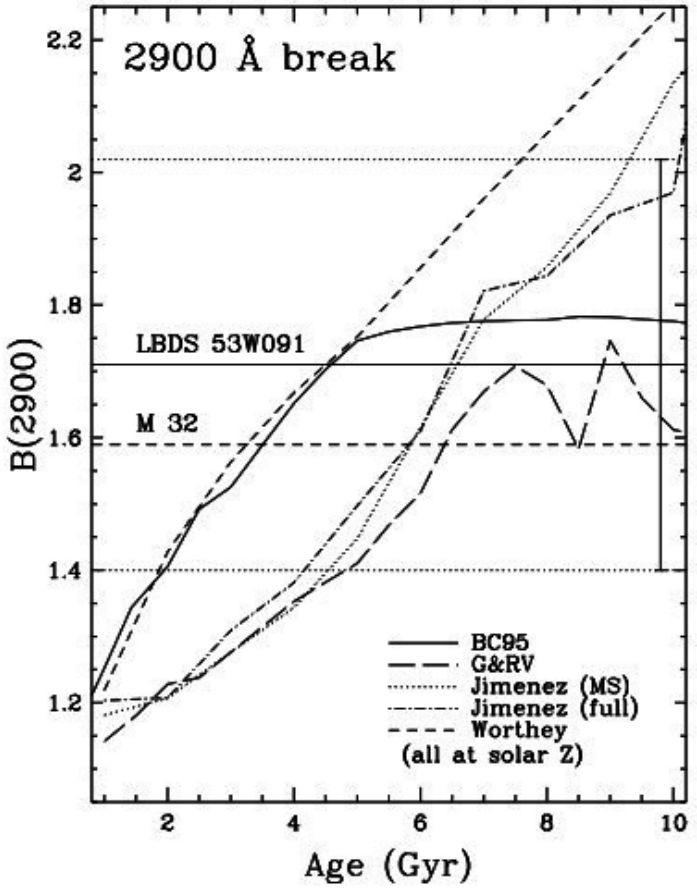
Experiment Design

- want high S/N spectra of ellipticals
- cluster ellipticals better than field ellipticals
- more luminous ellipticals better than less luminous
- spectra biased to blue wavelengths better
- multiplexing would be better

LRIS-B

systematics in modeling





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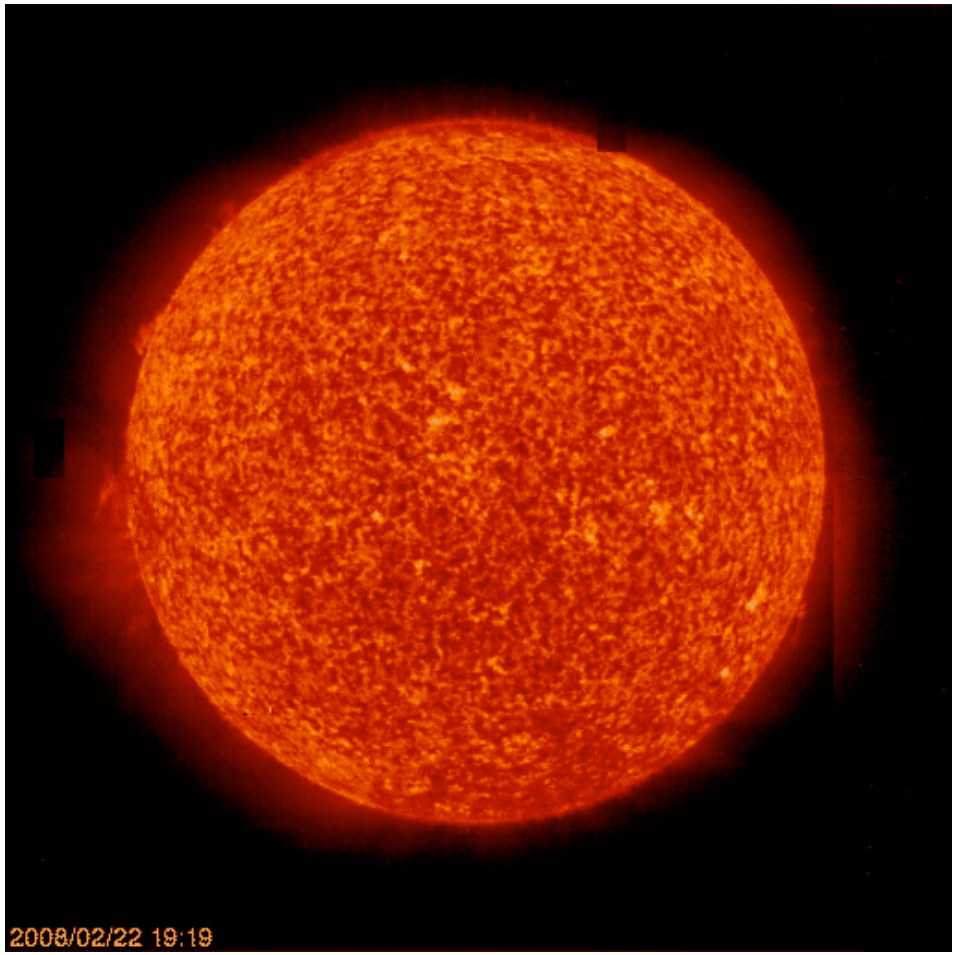
systematics in modeling



Yi et al. (2000; ApJ, 533, 670):

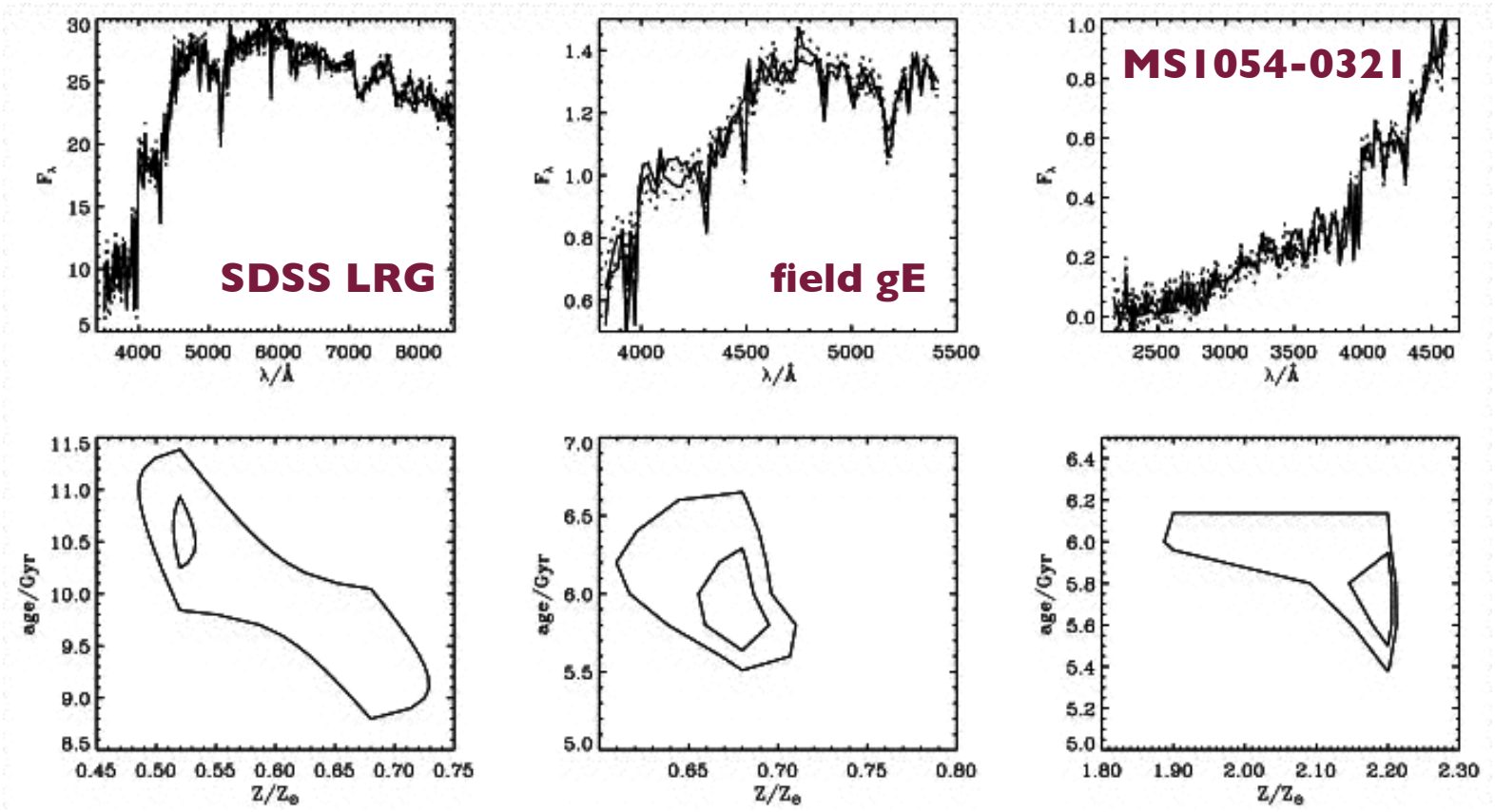
Sun is ~5 Gyr old

Nolan, Dunlop, & Jimenez (2001; MNRAS, 323, 385):

Sun is ~10 Gyr old

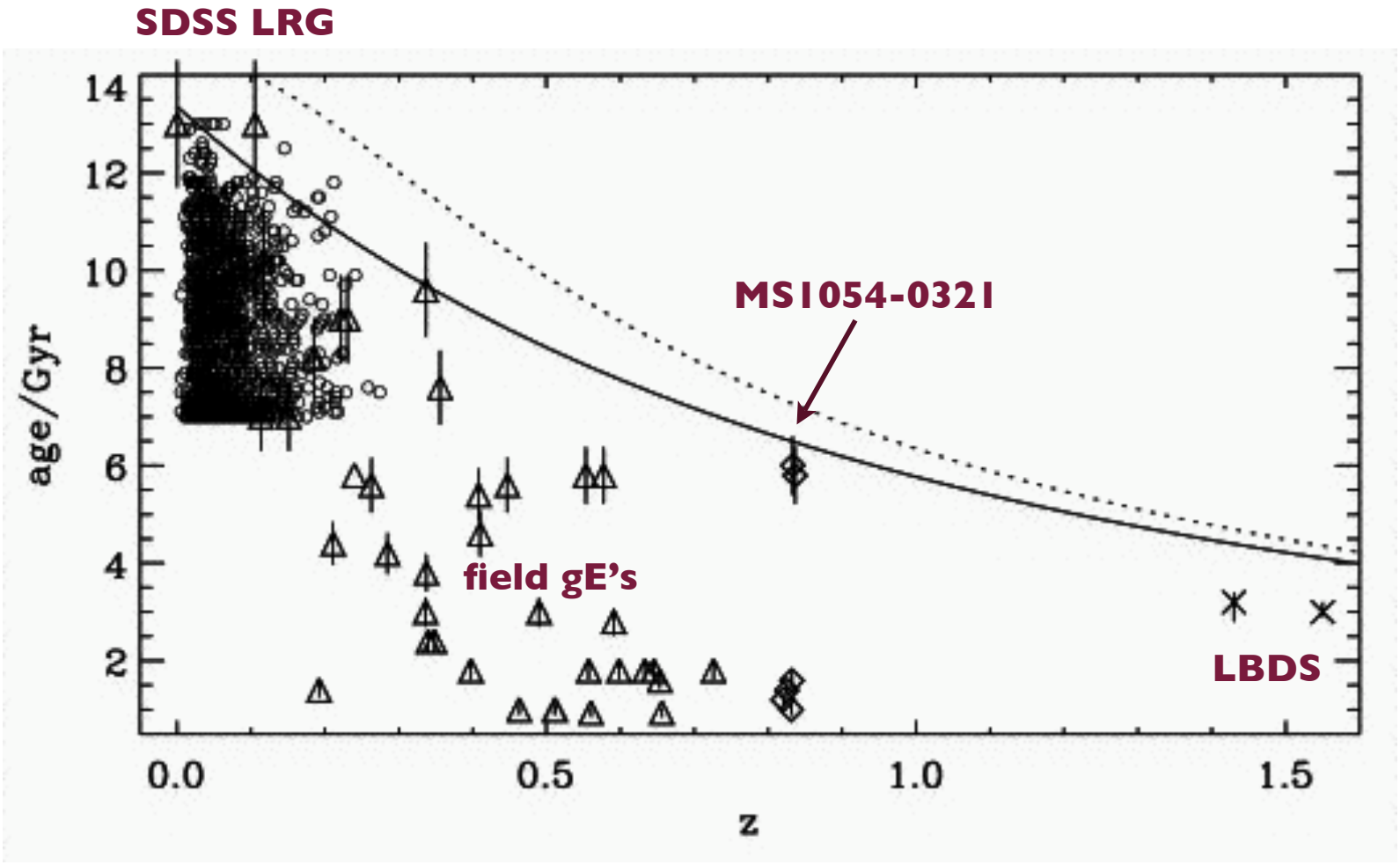
on the other hand, *dt/dz* is more robust than *t(z)*: galaxies simulated with Jimenez code, then modeled with BC03 had 10% systematic differences in absolute ages, but only 2-3% systematics in relative ages

a worked example



Jimenez, Verde, Treu, & Stern (2003; ApJ, 593, 622)

a worked example



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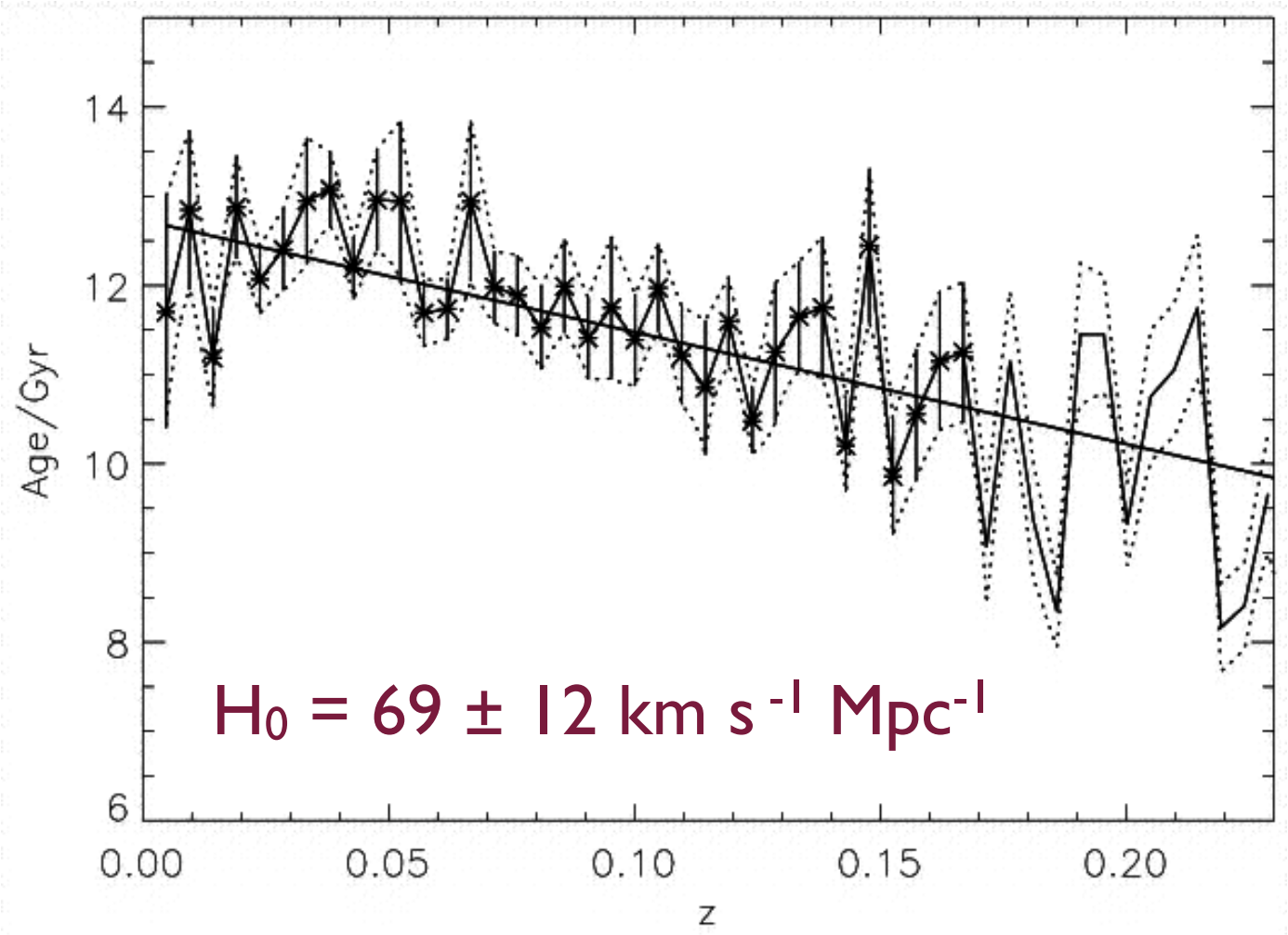
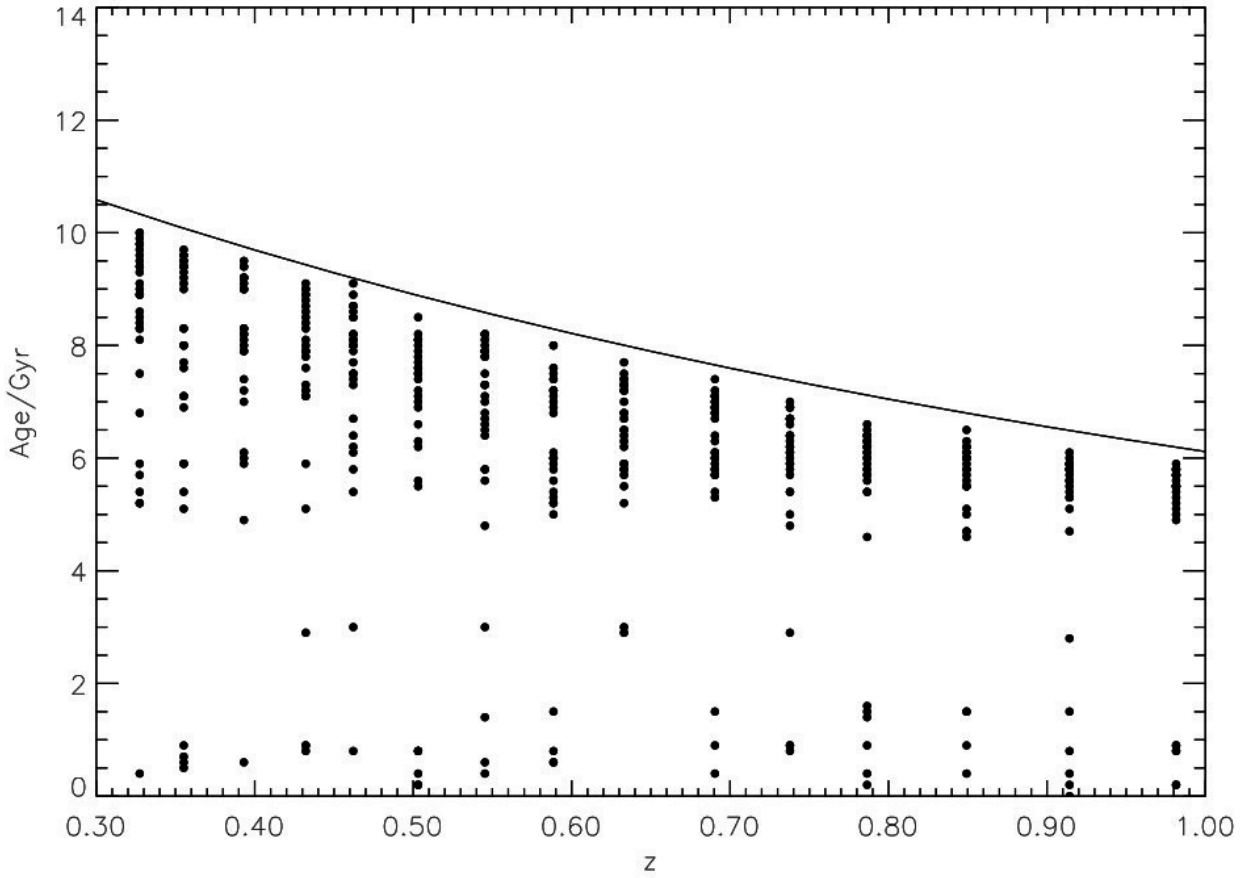
a worked example



Jimenez, Verde, Treu, & Stern (2003; ApJ, 593, 622)

proposed observations



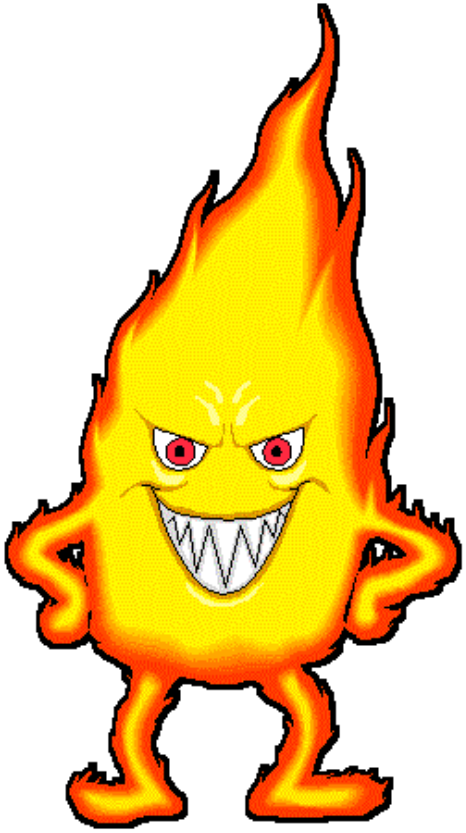
15 clusters @ 0.2<z<1; 15 galaxies per cluster
random secondary bursts accounting for 10% of the galaxy mass

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

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

UT 2007 Aug 15-16

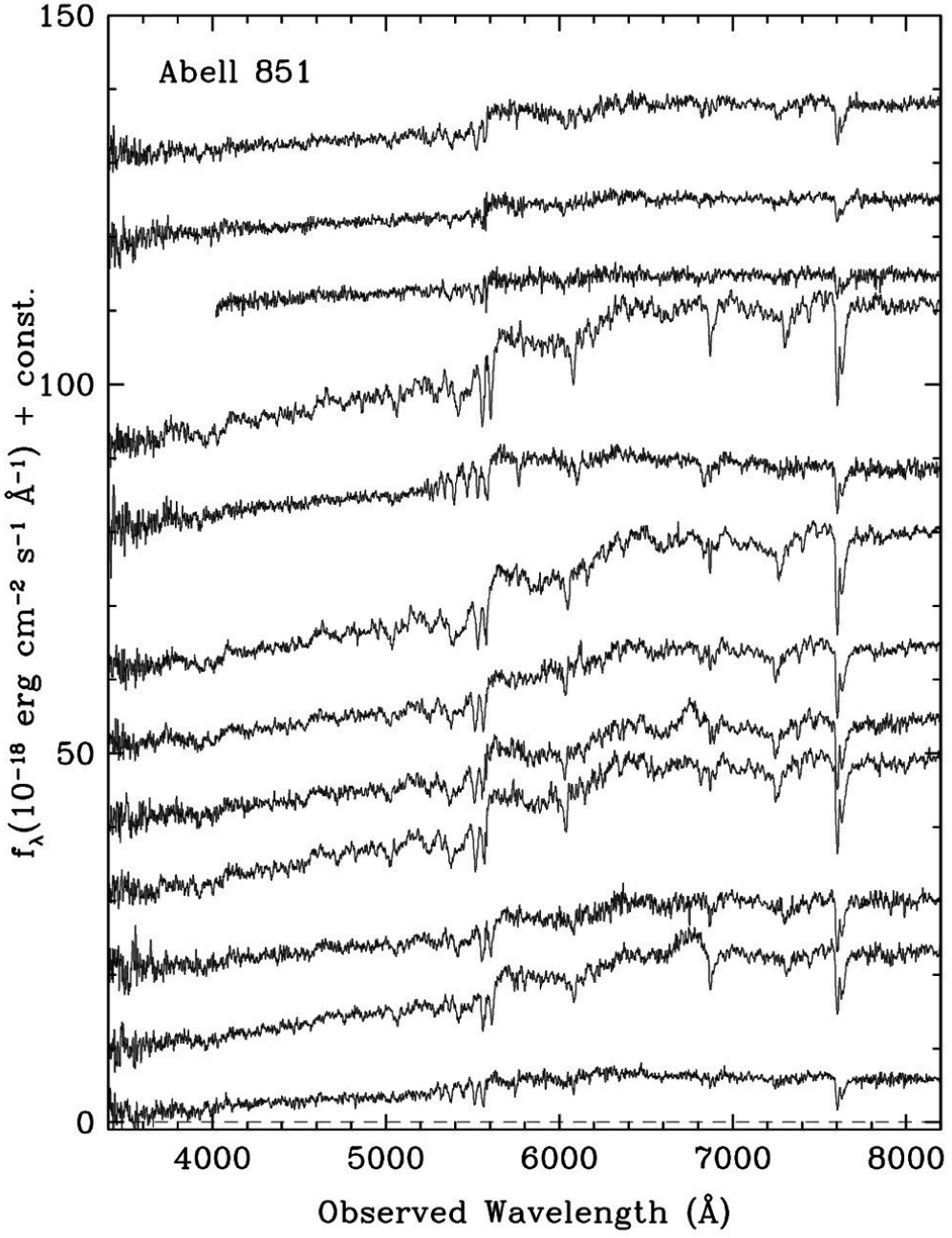
- Hurricane Flossie
- two earthquakes (5.4 & 4.0)
- fire
- tsunami warning



UT 2007 Dec 17 -18

- ~40% dark
- cirrus to clouds
- seeing 1.1" - 2.7" (avg. ~1.4")

- observed 10 clusters



Conclusions

stay tuned to see how effective of a cos(m)ology probe cluster ellipticals can be

but worked example already shows robustness of the technique; measured H_0 to precision of 12 km s^{-1}, and showed w=-1 (e.g., Λ) is consistent with the cluster ellipticals as cosmic chronometers

Asher Stern