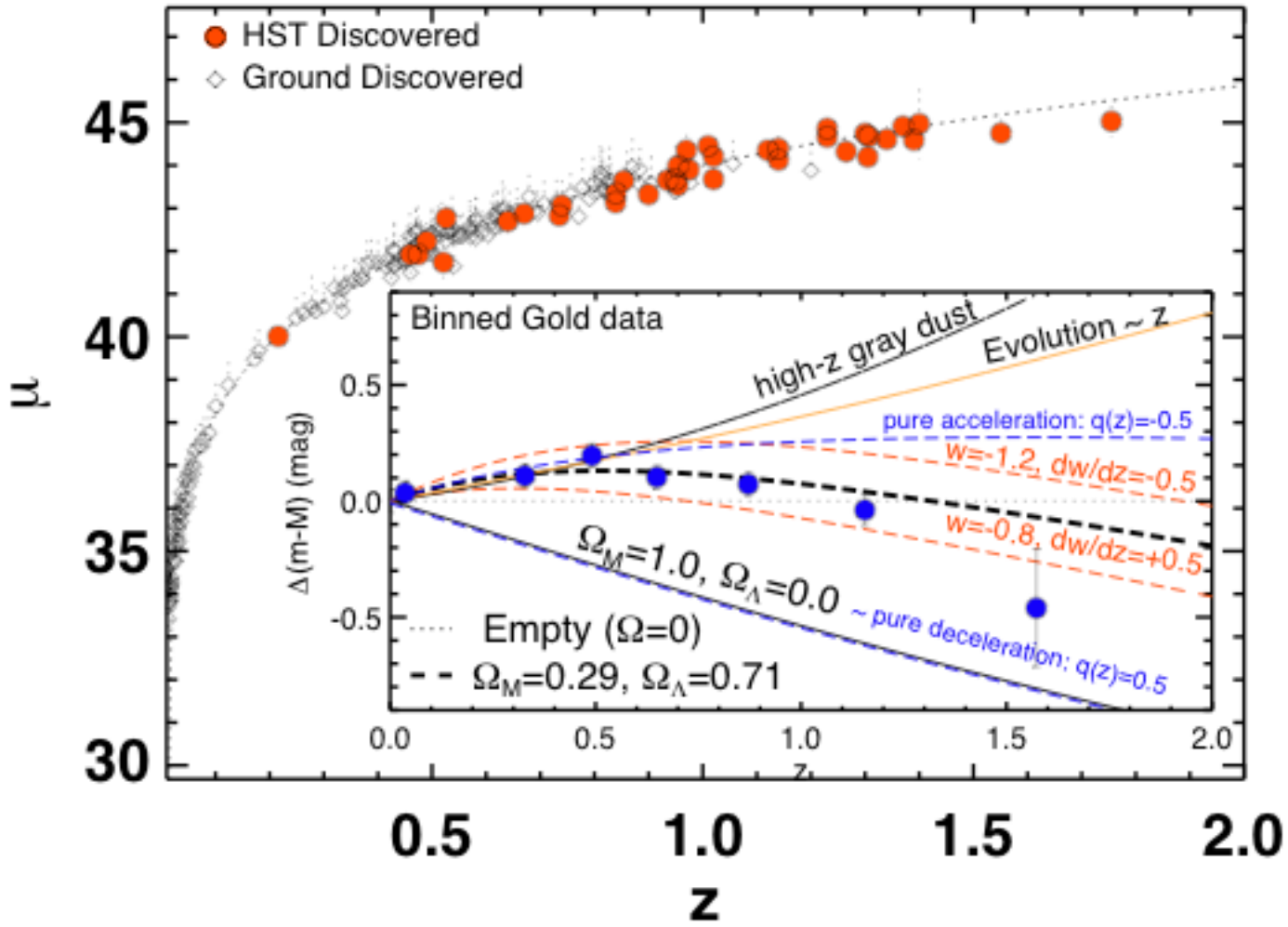
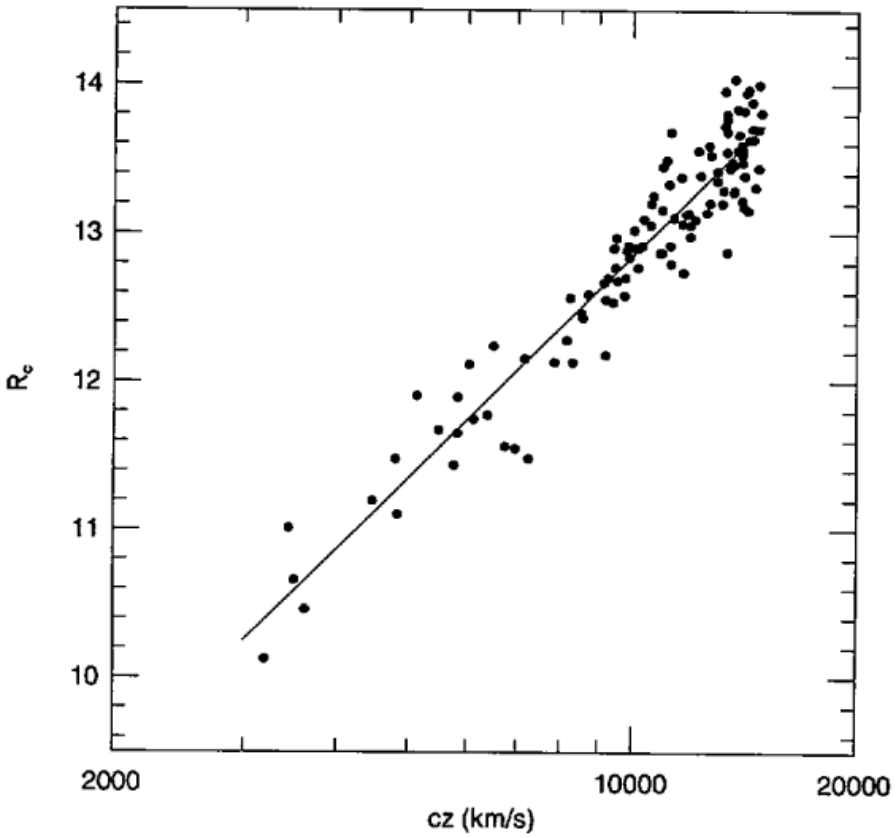
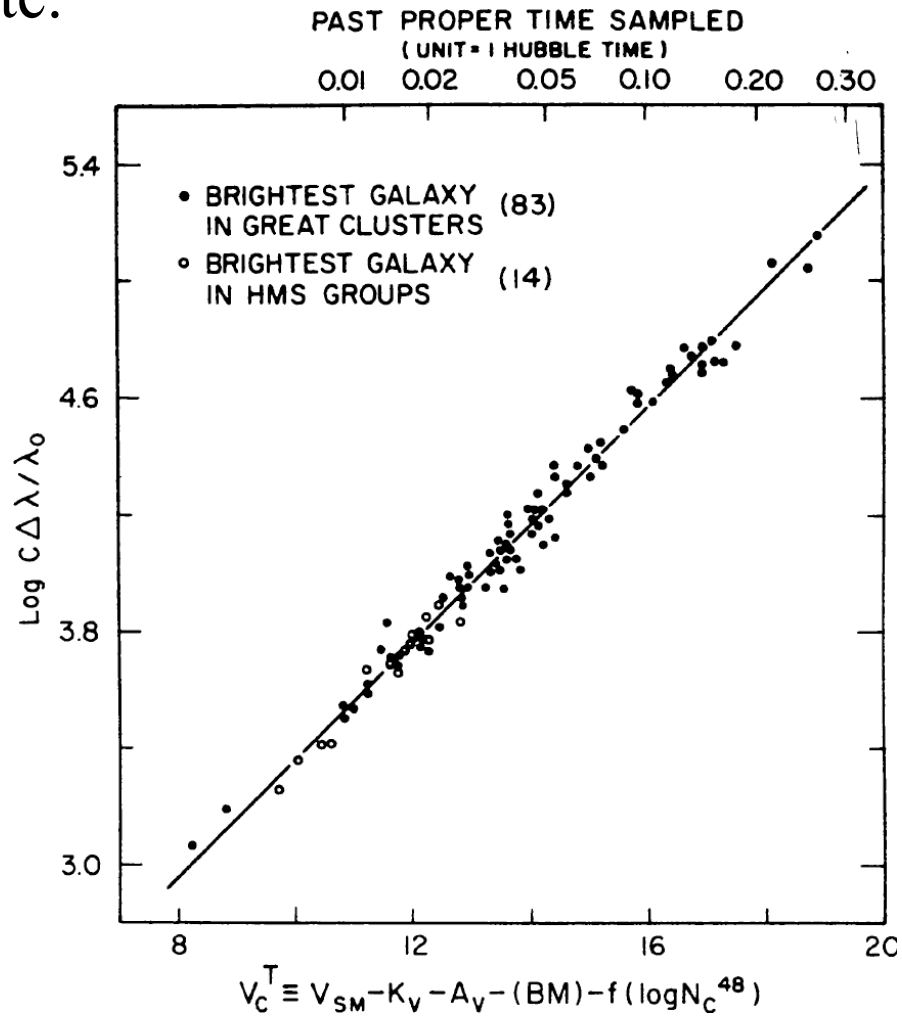
Hubble Diagram as a Cosmological Test



The Hubble Diagram: Early Work

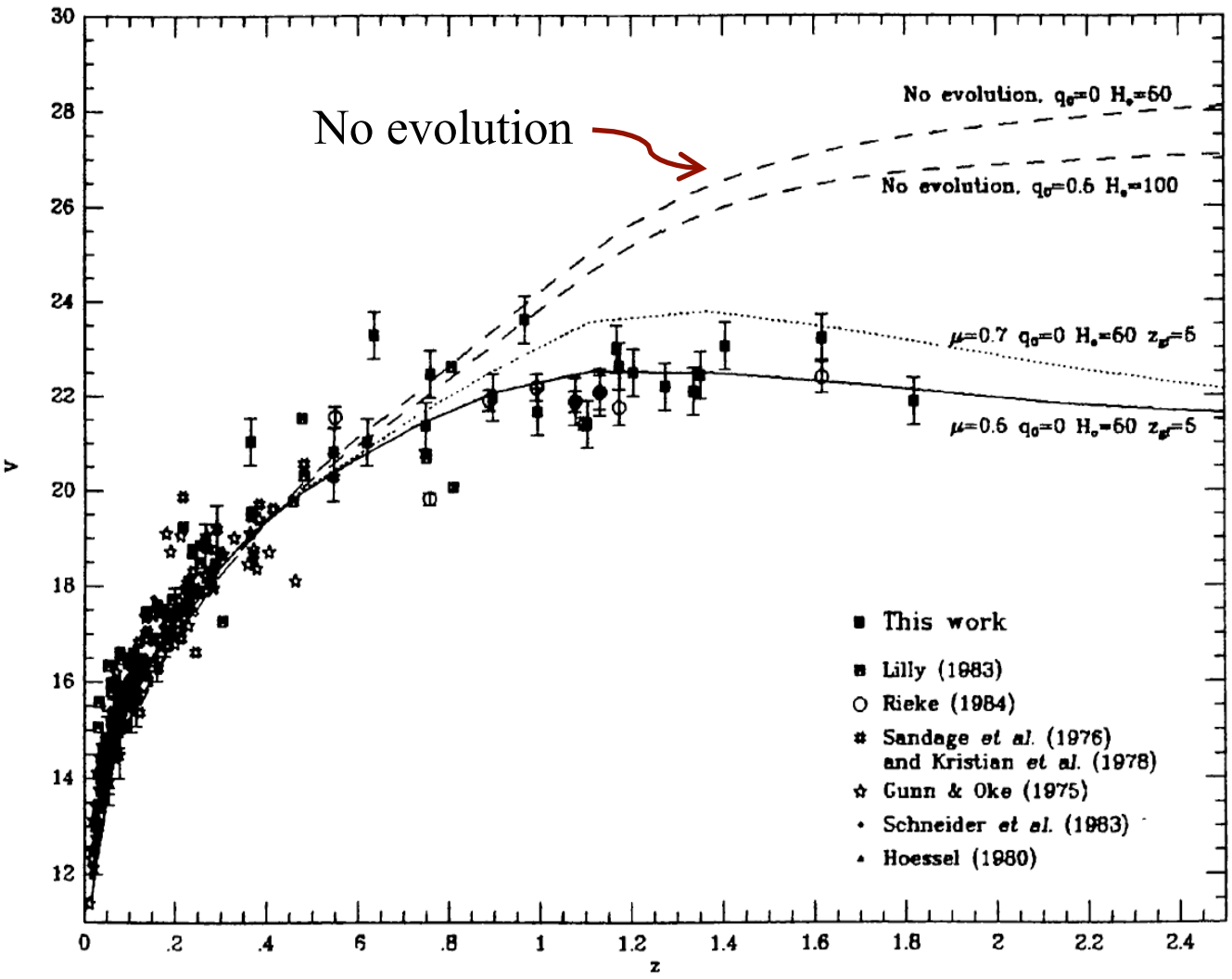
- Mostly done at Palomar by Sandage and collaborators, and by Gunn and collaborators, using brightest cluster ellipticals, with corrections for cluster richness etc.
- Foiled by galaxy evolution!





Effects of Galaxy Evolution

- Alas, galaxies were generally brighter in the past, since there was more star formation, and young, luminous, massive stars have short lifetimes
- This tends to overwhelm the cosmological effects, especially in the bluer bands

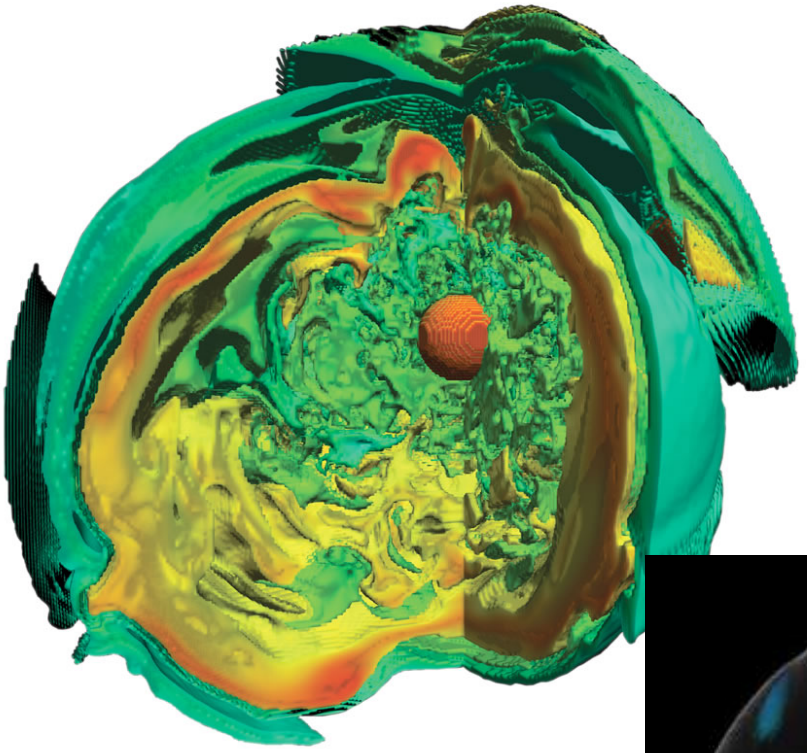


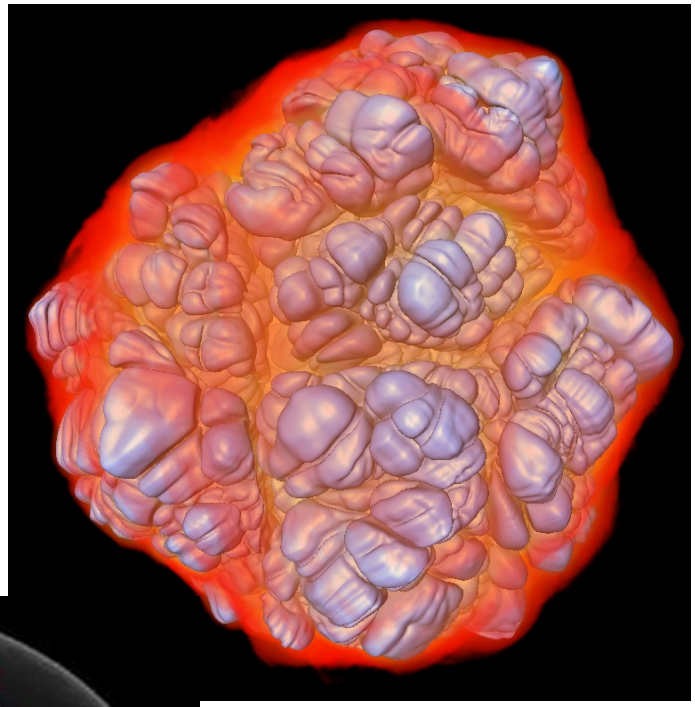
The Hubble diagram → for powerful radio galaxies (Djorgovski et al.)

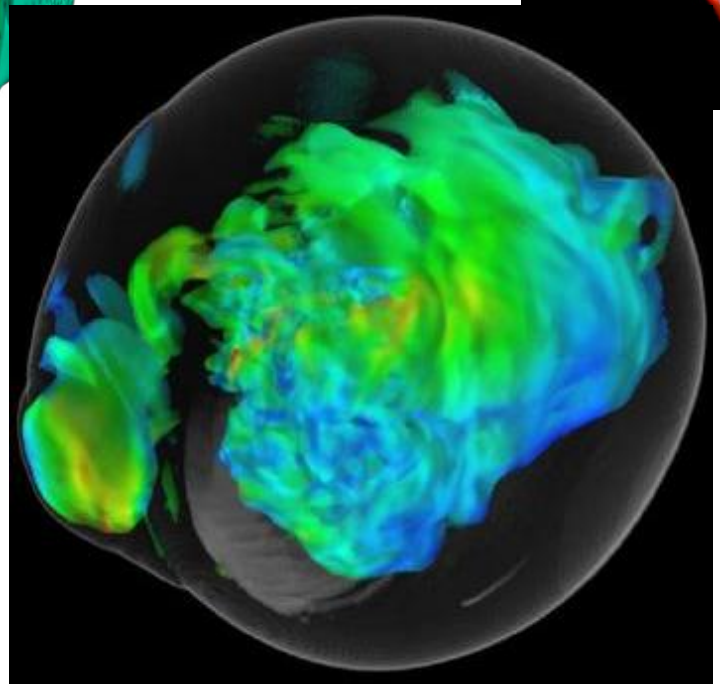
The Supernova Ia Hubble Diagram

- The field was reborn with the advent of the SN Ia Hubble diagram, following the standardization of their peak brightness using light curve shapes
- There are still some unknowns:
  - Explosions not fully understood; many possible models: Chandrasekhar-mass models, deflagrations vs. detonations
  - Progenitor systems not known: white dwarfs yes, but double degenerate vs. single degenerate binaries …
- SN Ia are not really standard candles …
  - There are large variations in light curve shapes, colors, spectral evolution, and some clear outliers; possible differences in physical parameters, e.g, Ni mass
- But they ***are*** good distance indicators, after the empirical correction for light curve shapes
- Do they evolve (e.g., due to metallicity)? Maybe a little

Warning! SNe are a Messy Phenomenon!







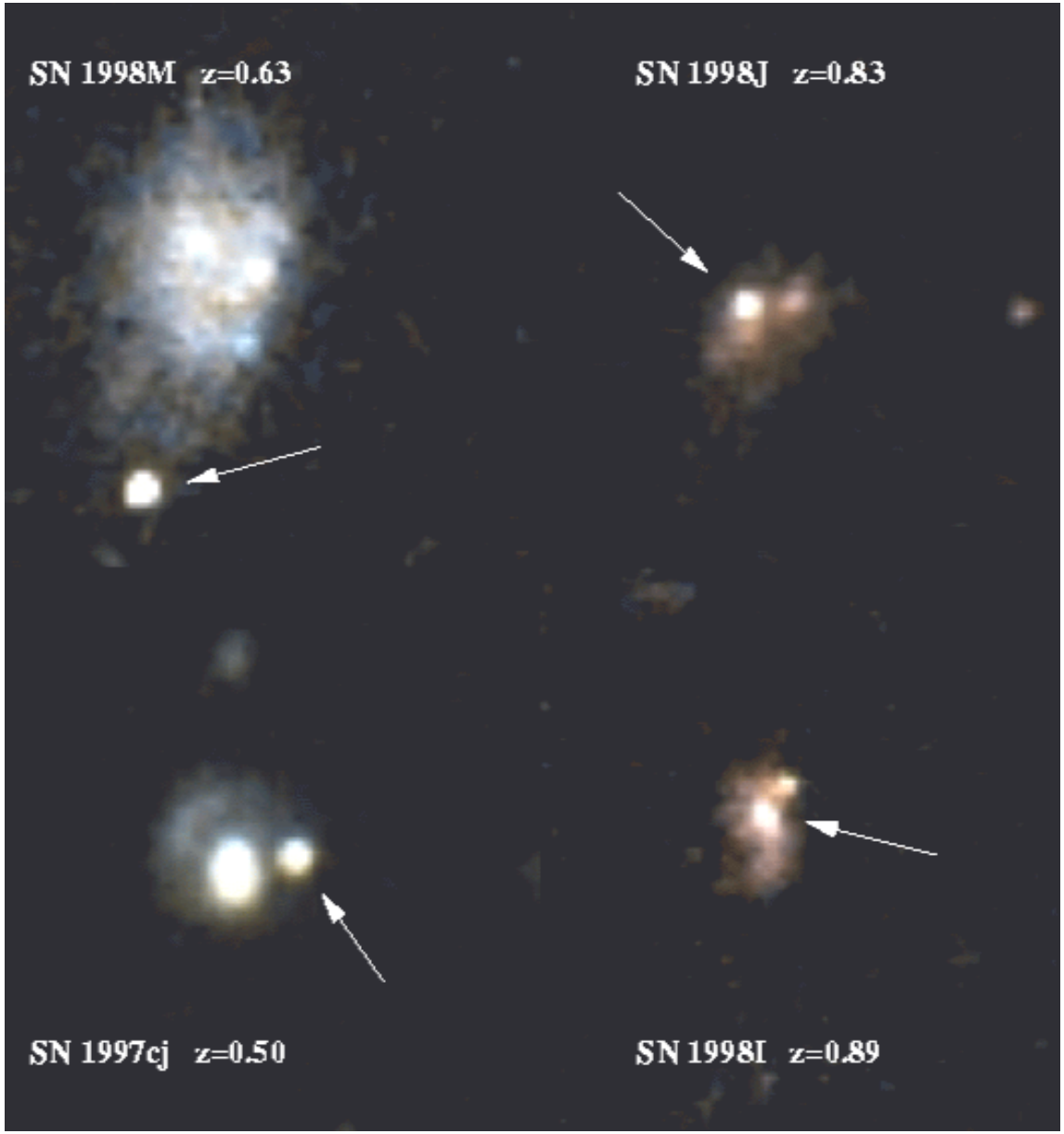
Various numerical simulations of SN explosions

Things could still go wrong …

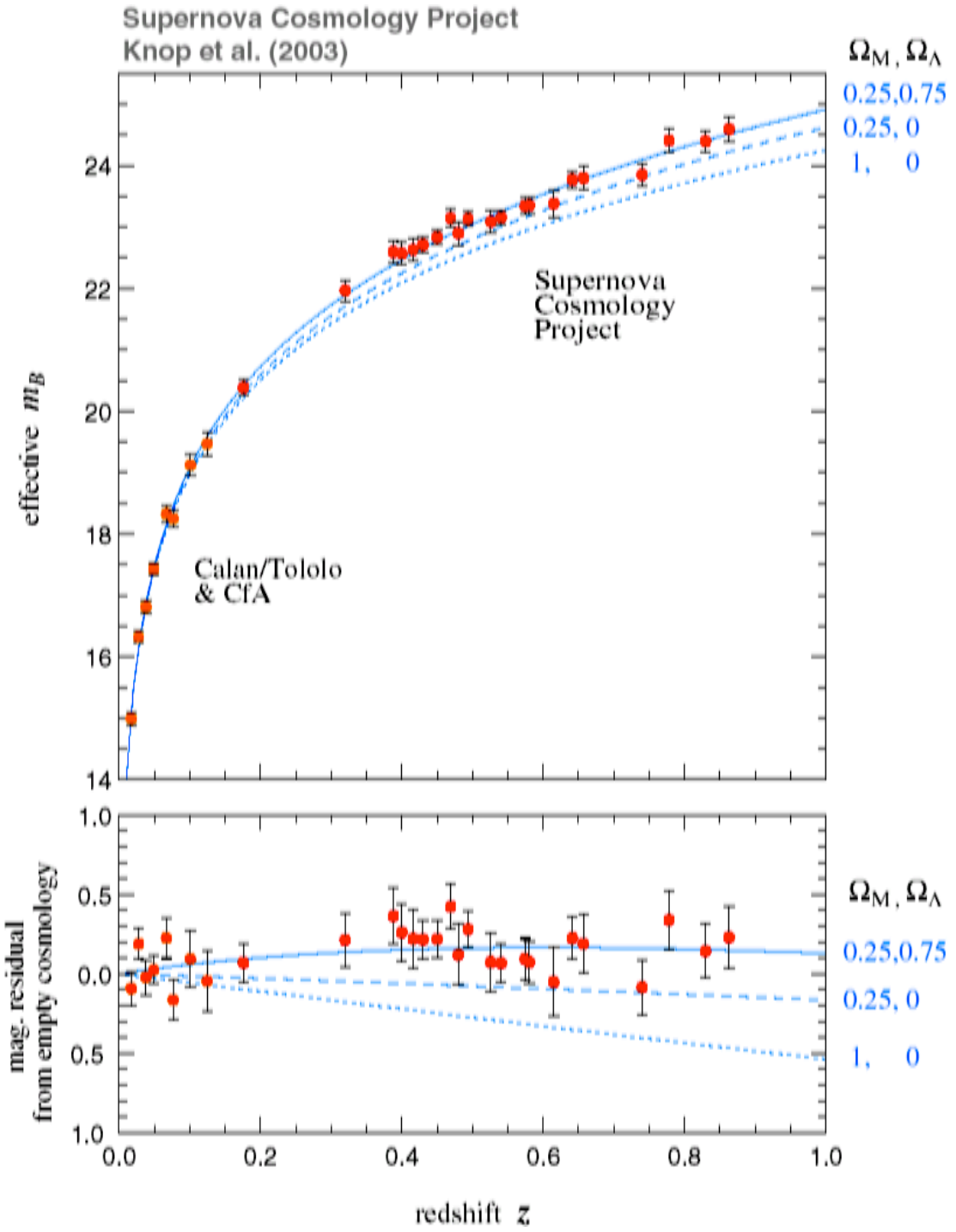
Examples of High-Redshift SNe

HST observations of SNe in distant galaxies
(Riess et al.)

Note: you need to …
- Detect them
- Measure the light curves
- Do the K-corrections
- Get the redshifts

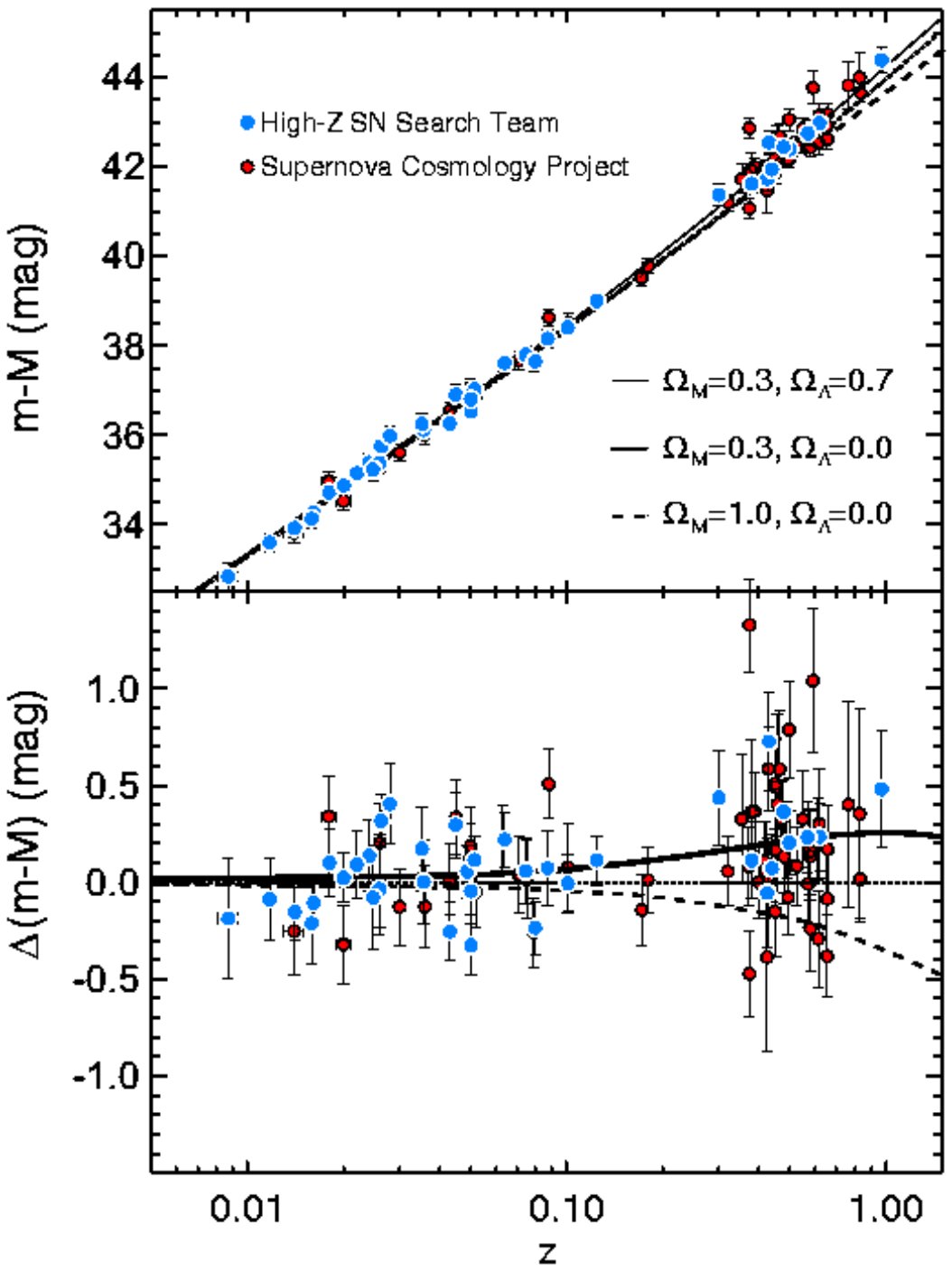


This yielded the **evidence for an accelerating universe and the positive cosmological constant,** independently and simultaneously by two groups:
The Supernova Cosmology Project at LBL (Perlmutter et al.), and …

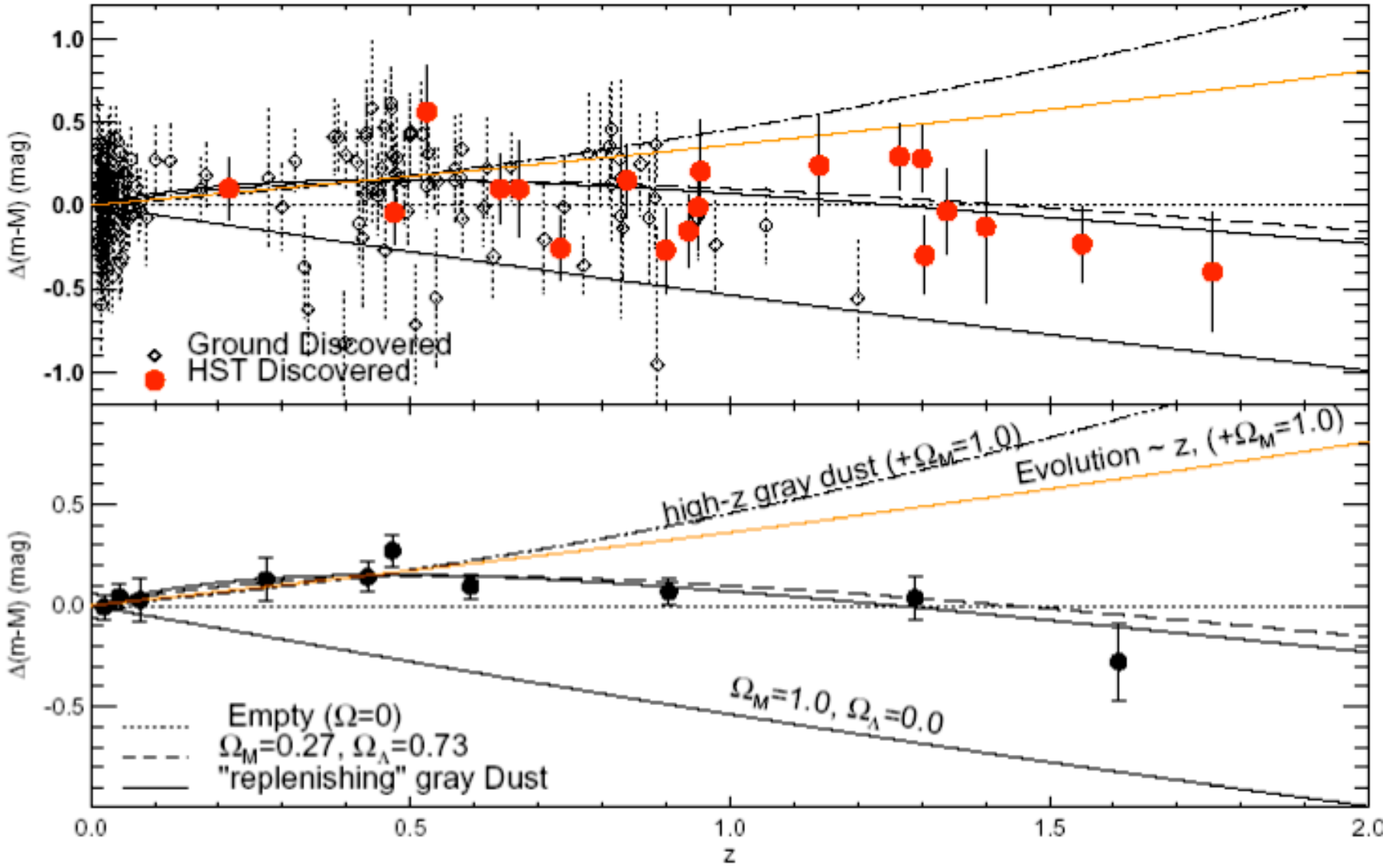


… and by the High-Z Supernova Team
(B. Schmidt, A. Riess, et al.)

Both teams found very similar results …



Current Evidence Points to $\Omega_\Lambda \sim 0.7$

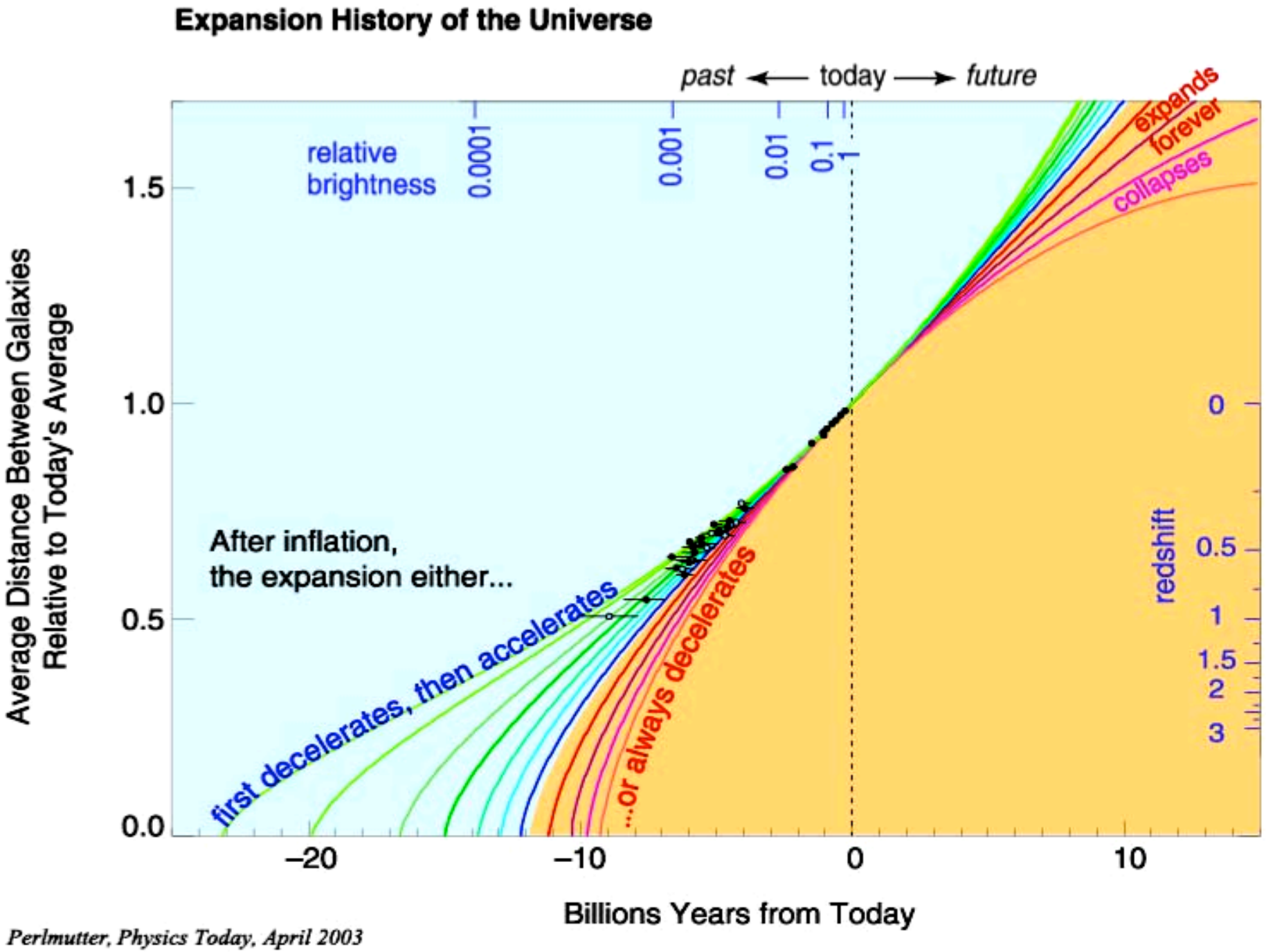


… So They Got a Nobel Prize

A. Riess

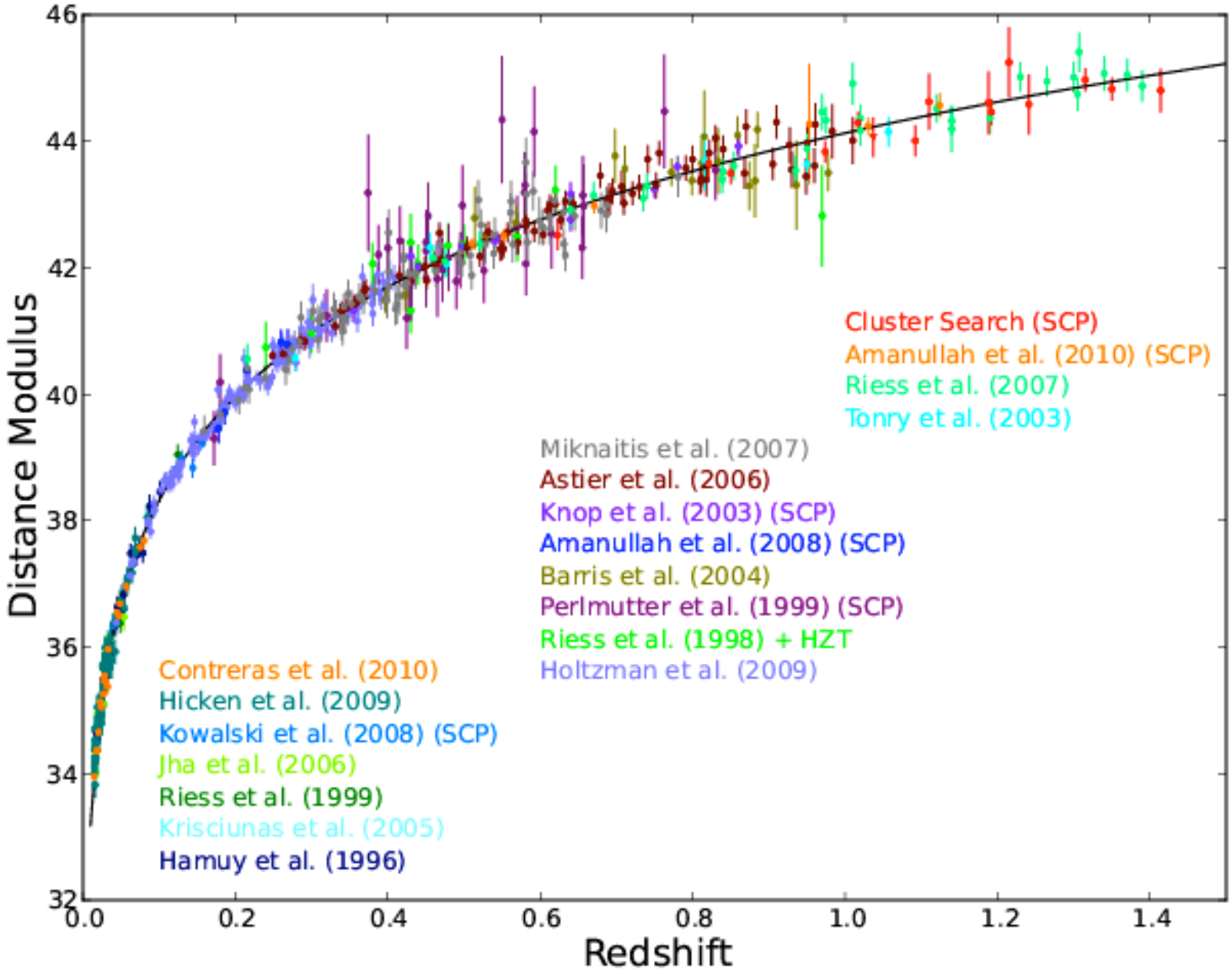
S. Perlmutter

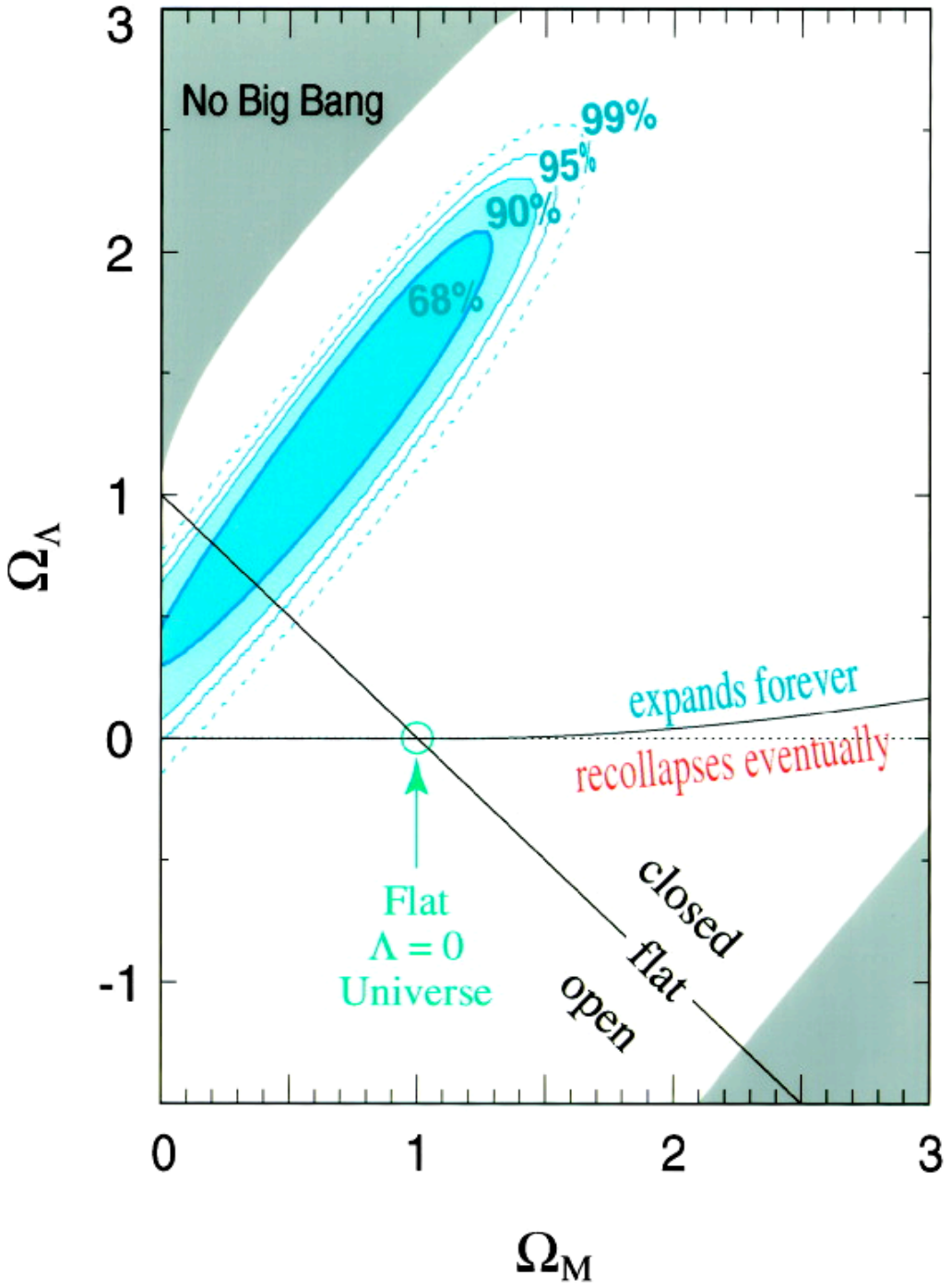
B. Schmidt



Perlmutter, Physics Today, April 2003

A Modern Version of the SN Hubble Diagram



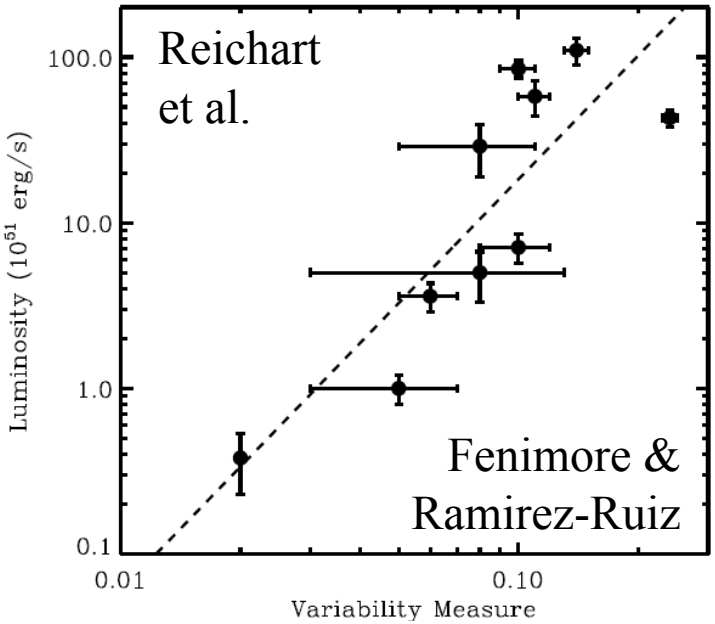


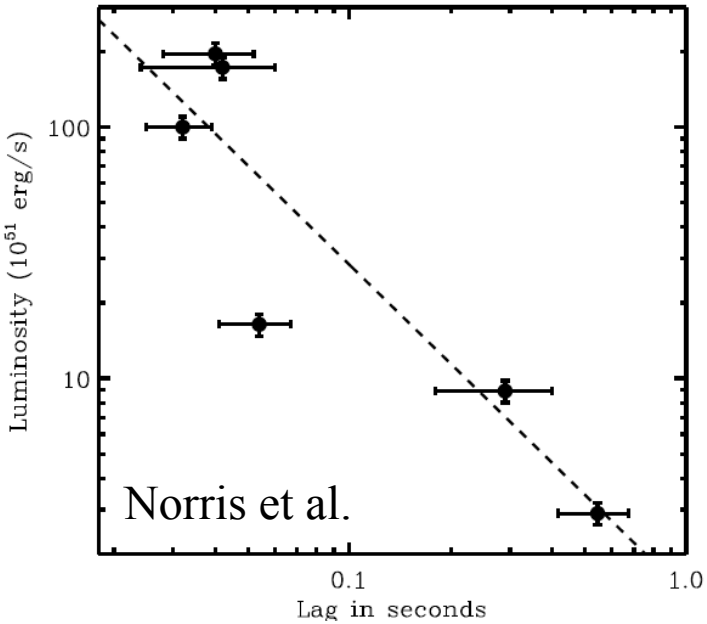
SN measurements on their own actually define an allowed region in the plane of [Ω_m , Ω_Λ]

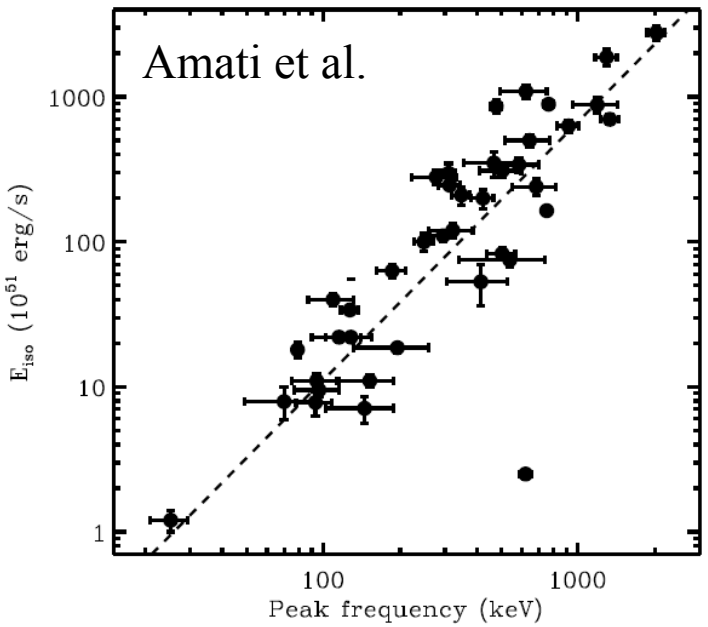
Example of **degeneracy**: distinct universes produce identical results for this cosmological test

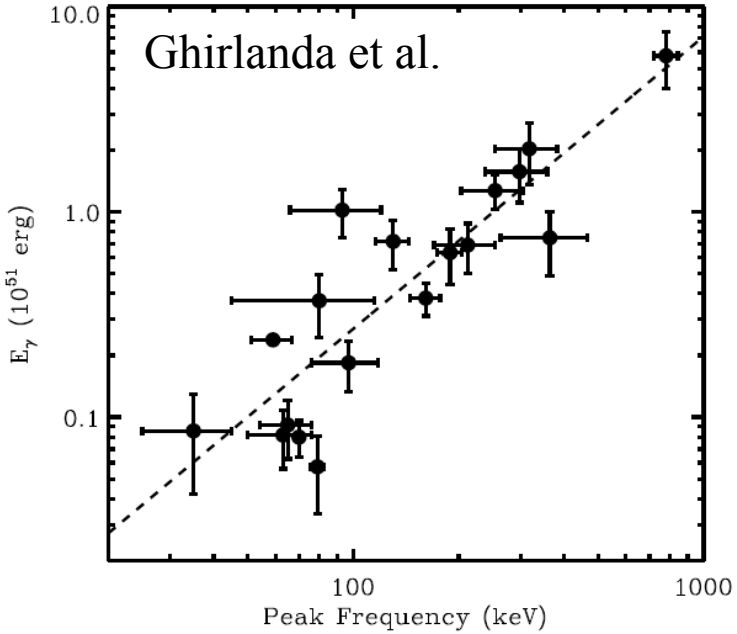
We need some additional, constraints (e.g., flatness) to pin down the actual value of Ω_Λ

GRBs as Standard Candles?



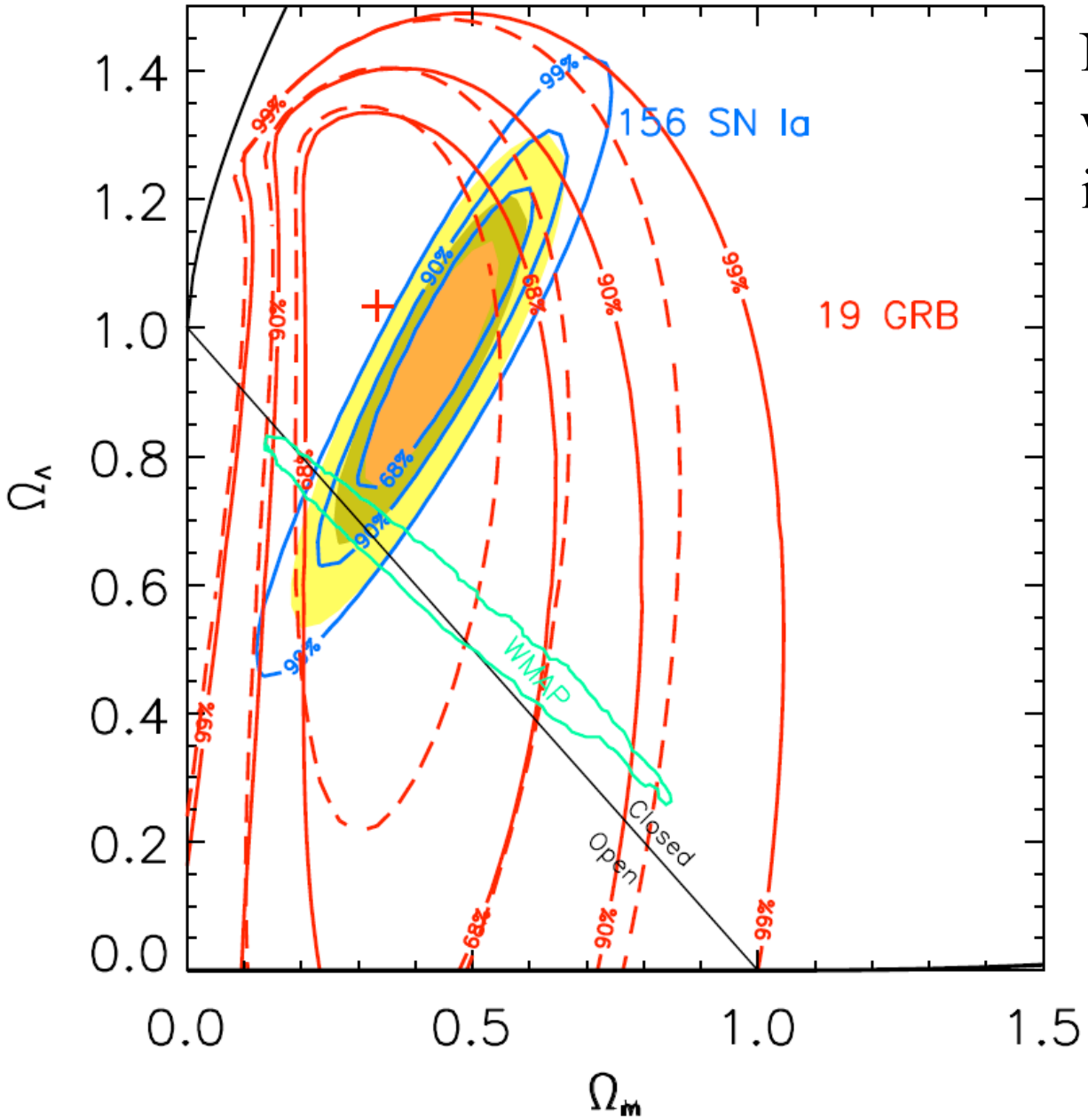






Various distance-independent burst parameters correlate with the total apparent isotropic energy or luminosity

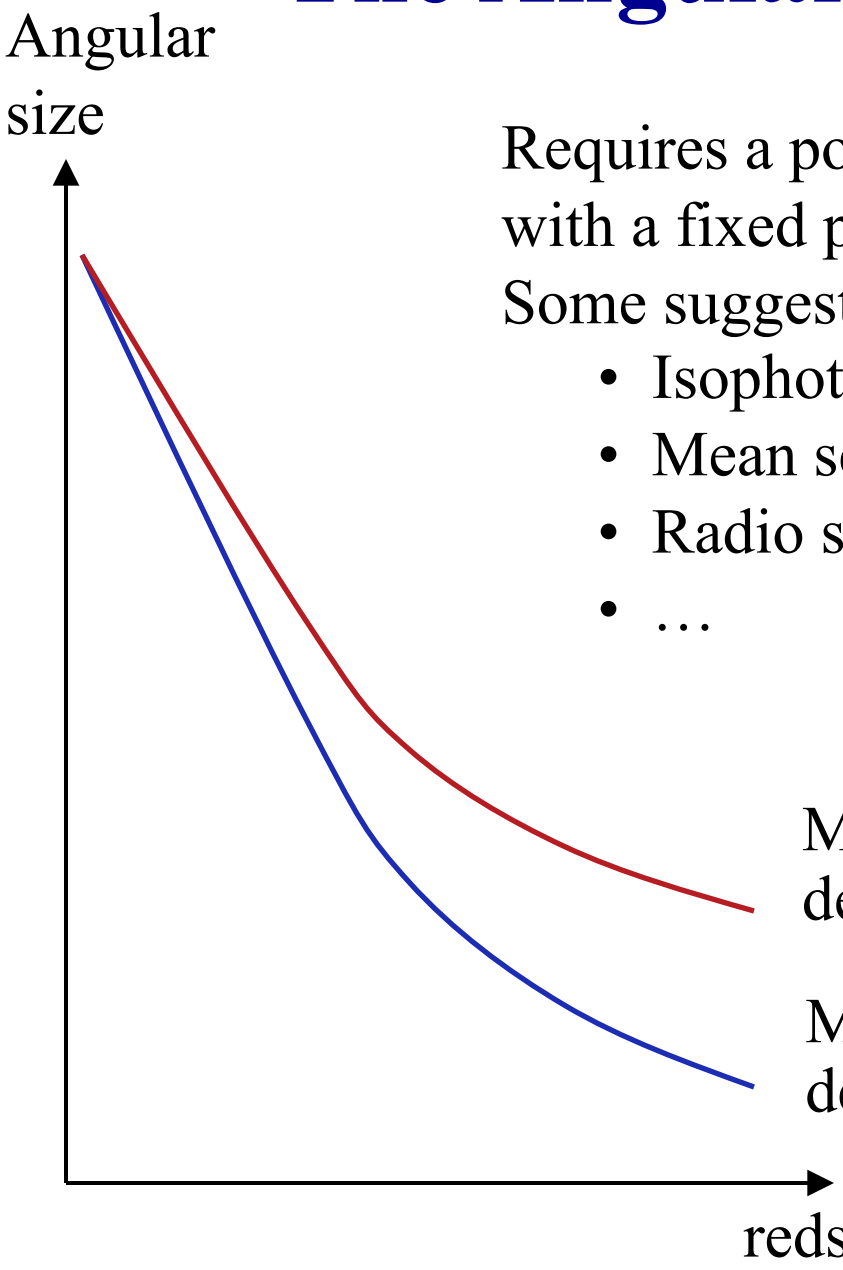
GRBs as Standard Candles?



Not quite competitive with SNe yet, but there is a promise…

(Figure from Lazzati et al.)

The Angular Diameter Test



Requires a population on non-evolving sources with a fixed proper size - "standard rulers".
Some suggested candidates:

- Isophotal diameters of brightest cluster gal.
- Mean separation of galaxies in clusters
- Radio source lobe separations
- …

Model with a higher density and/or $\Lambda \leq 0$

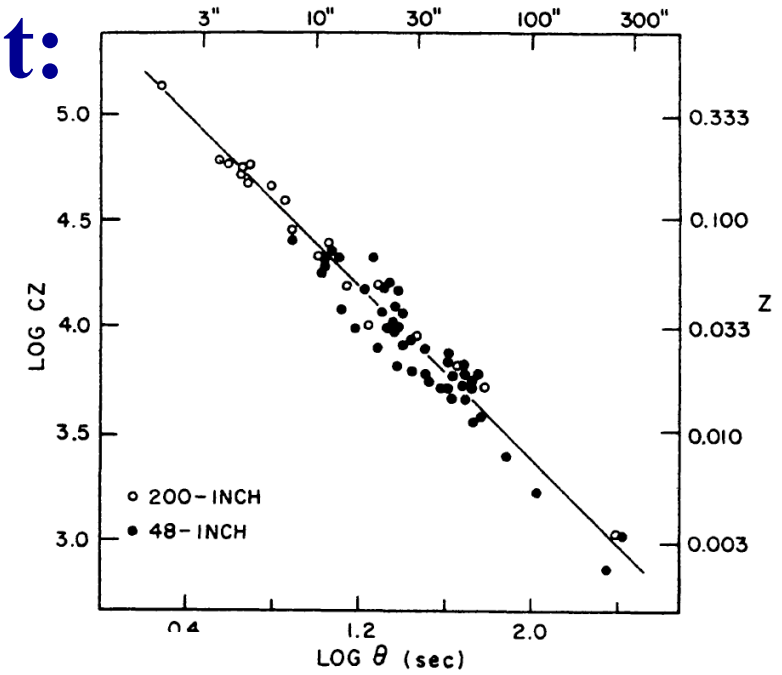
Model with a lower density and/or $\Lambda > 0$

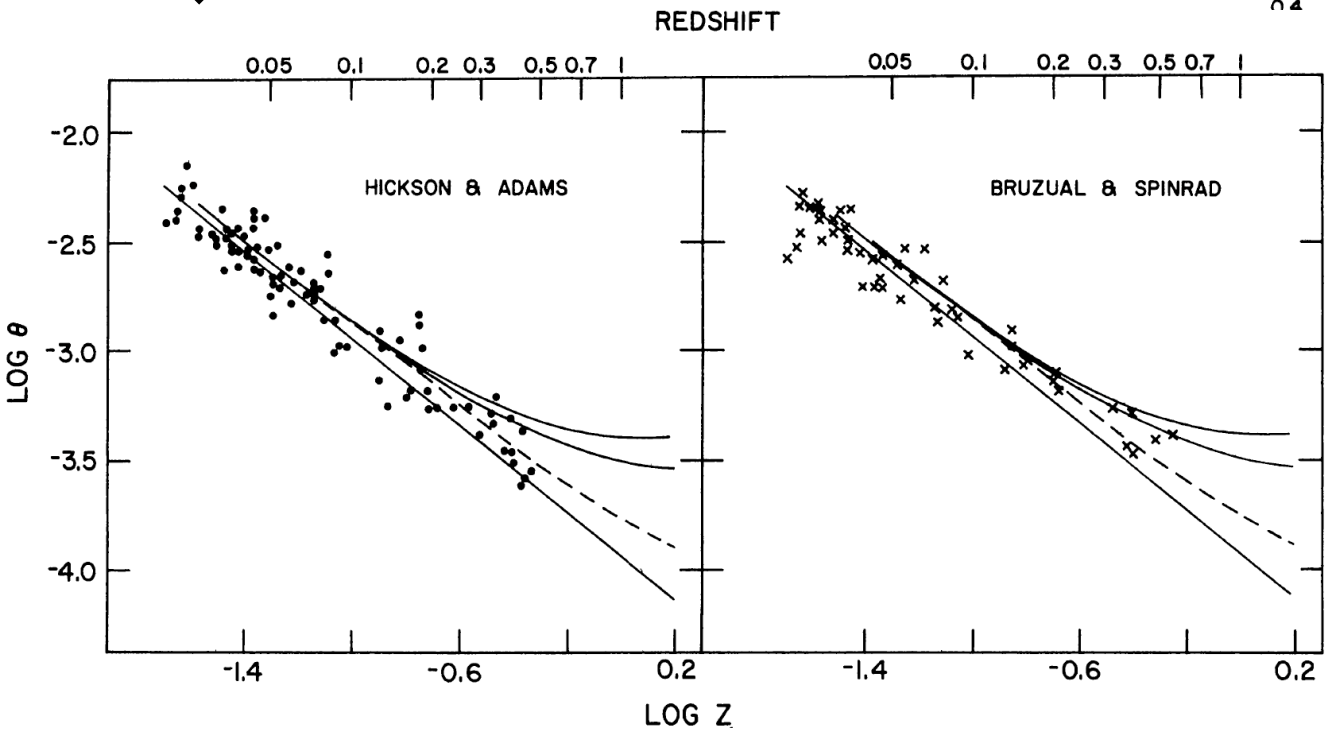
The Angular Diameter Test: Some Early Examples

Brightest cluster ellipticals →

Clusters of galaxies

↓





Again, **evolution** overwhelms the cosmological effects …

Next:
Cosmology With the Cosmic Microwave Background