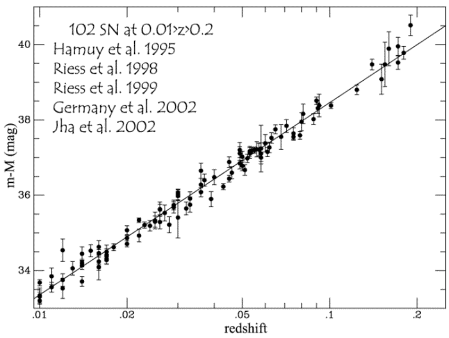
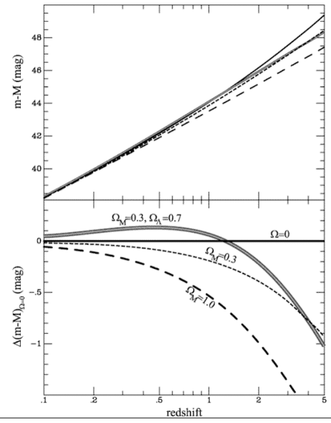




The Standard Model: 1995

Universe is Made up of normal matter

Choice A (Theorists)
- Universe is Flat
- Inflation is correct
- Hubble Constant less than 60

Choice B (Observers)
- Universe is Open
- Inflation is wrong
- Hubble Constant less than 80

Choice C (people with few friends)
- Universe is Flat
- Universe is dominated by Cosmological Constant

High-Z SN Ia History

Zwicky's SN Search from 1930s-1960s giving Kowal's Hubble Diagram in 1968

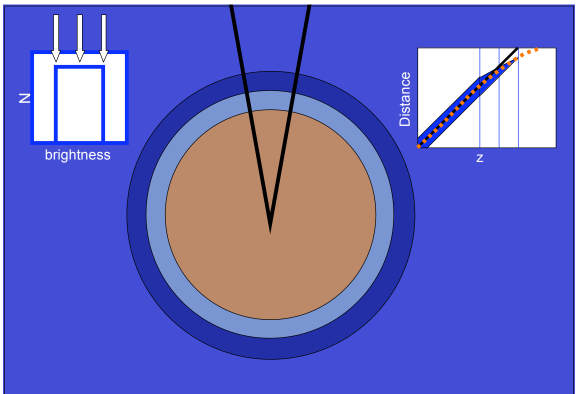
Ib/Ic SN Contamination realised in 1984/5

1st distant SN discovered in 1988 by a Danish team (z=0.3)

- 7 SNe discovered in 1994 by Perlmutter et al. at z = 0.4
- Calan/Tololo Survey of 29 Nearby SNe Ia completed in 1994

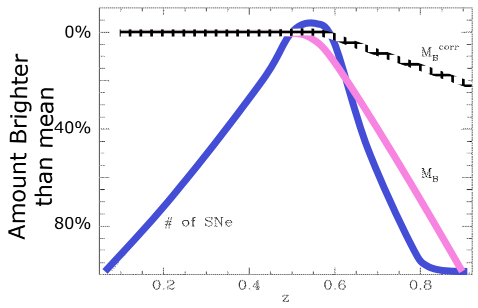
Potential Pitfalls to High-Z SNe Ia Distances

- Extinction
  - *Are the Extinction Properties of High-Z and low-Z SNe the same?*
- Evolution
  - *Are the SNe Seen today the same as the SNe of yesterday?*
- Selection Effects?
  - *Are the corrections larger than the measurement?*
- K-corrections
  - *How accurately can we transform to the restframe?*
- Gravitational Lensing
  - *Does Weak Lensing significantly bias the measurement?*



Selection Effects/Malmquist Bias

Selection Effects
Monte Carlo Simulation

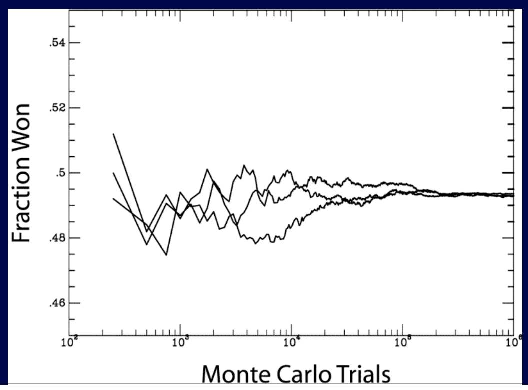


Monte Carlo Simulations

- Play through complicated scenarios on a computer.
- Do many trials to lower you uncertainty
- Easy way to learn simulate very complicated situations

- Example : Craps
  - Rules. On first roll of two dice, 7,11 you win…2,3,12 you lose. Otherwise, you need to match your first roll before rolling another 7 (or you lose). What are your odds?

Craps – simulation…3 different goes…

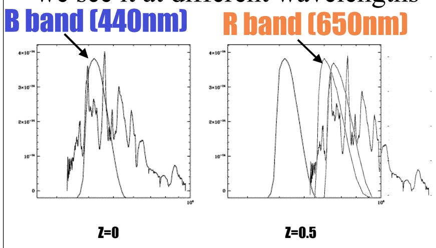


Precision

- Monte Carlo simulations are just like an experiment…
- Precision increases as the sqrt(measurements).
- You will have a problem in the second round where you need to do a Monte Carlo Calculation.

K-Corrections

As the light of an object become redshifted, we see it at different wavelengths



Photometry and K-corrections

1 $m_i = M_i + 5\log(D_L/10pc)$ — definition of absolute mag

2 $(m - M) \equiv 5\log\left(\frac{D_L}{10pc}\right)$ — definition of distance modulus

3 $F(\lambda,z)d\lambda = \frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}$ — Flux of redshifted source

4 $m_i = Z_i - 2.5\log\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}$ — definition of mag

5 $M_i = Z_i - 2.5\log\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}\left(\frac{1}{4\pi(10pc)^2}\right)$

6 $m_i(z) = Z_i - 2.5\log\frac{\int S_i(\lambda)\frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}}{\int S_i(\lambda)d\lambda}$

7 $(m_i(z) - M_i) = \left(Z_i - 2.5\log\frac{\int S_i(\lambda)\frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}}{\int S_i(\lambda)d\lambda}\right) - \left(Z_i - 2.5\log\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}\left(\frac{1}{4\pi(10pc)^2}\right)\right)$

8 $(m_i(z) - M_i) = 2.5\log\left(\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}\right) + 5\log\left(\frac{D_L}{10pc}\right)$

9 $(m - M) = (m_i(z) - M_i) - K_i$

where,

10 $K_i(z) = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)L\left(\frac{\lambda}{(1+z)}\right)d\lambda}\right]$

analagous for two different filters is

11 $(m - M) = (m_i(z) - M_j) - K_{ij}(z),$

where

12 $K_{ij}(z) = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_j(\lambda)L(\lambda/(1+z))d\lambda}\right] + Z_j - Z_i$

e.g SN Ia at z=0.5 has R=22.2 and K-Corr (R->B) =–0.75 and M_B =-19.5
its (m-M) = 22.2 + 0.75 + 19.5 = 42.45

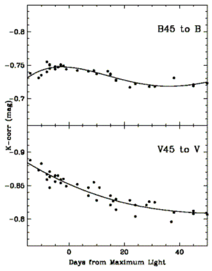
K-Corrections

$$m_i = Z_i - 2.5\log\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}$$

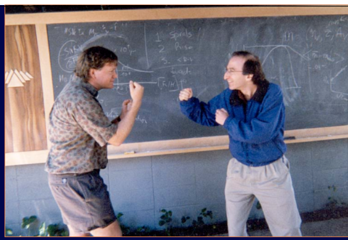
$$K_i = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)F(\lambda/(1+z))d\lambda}\right]$$

$$K_{ij} = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_j(\lambda)F(\lambda/(1+z))d\lambda}\right] + Z_j - Z_i$$

$$(m-M) = m_j - K_{ij} - M_i$$



Kim et al. 1996



The Supernova Cosmology Project

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro, G. Goldhaber, D. Groom,
A. Kim, M. Kim, R. Knop, P. Nugent, (LBL & CfPA)
N. Walton (Isaac Newton Group)
A. Fruchter, N. Panagia (STScI)
A. Goobar (Univ of Stockholm)
R. Pain (IN2P3, Paris)
I. Hook, C. Lidman (ESO)
M. Della Valle (Univ of Padova)
R. Ellis (CalTech)
R. McMahon (IofA, Cambridge)
B. Schaefer (Yale)
P. Ruiz-Lapuente (Univ of Barcelona)
H. Newberg (Fermilab)
C. Pennypacker

The High-Z SN Search

The High-Z Team

- Brian Schmidt (ANU)
- Nick Suntzeff, Bob Schommer, Chris Smith (CTIO)
- Mark Phillips (Carnegie)
- Bruno Leibundgut and Jason Spyromilio (ESO)
- Bob Kirshner, Peter Challis, Tom Matheson (Harvard)
- Alex Filippenko, Weidong Li, Saurabh Jha (Berkeley)
- Peter Garnavich, Stephen Holland (Notre Dame)
- Chris Stubbs (UW)
- John Tonry, Brian Barris (University of Hawaii)
- Adam Reiss (Space Telescope)
- Alejandro Clocchiatti (Catolica Chile)
- Jesper Sollerman (Stockholm)

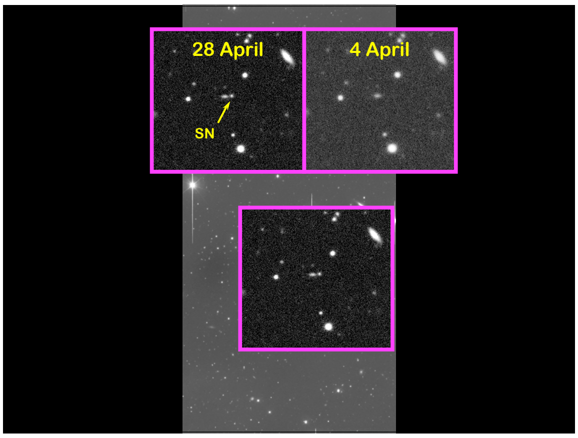
The High-Z SN Search

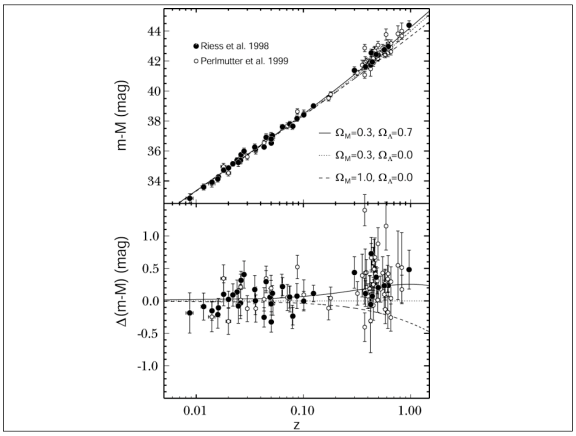
4M TELESCOPE SECUENCE

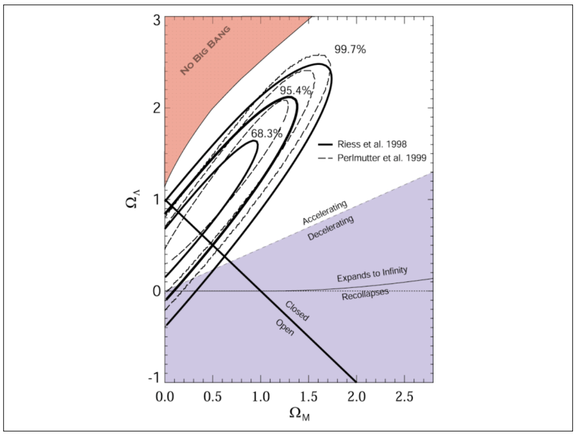
CERRO TOLOLO

INTER-AMERICAN OBSERVATORY

ROGER SMITH MARIO CACERES

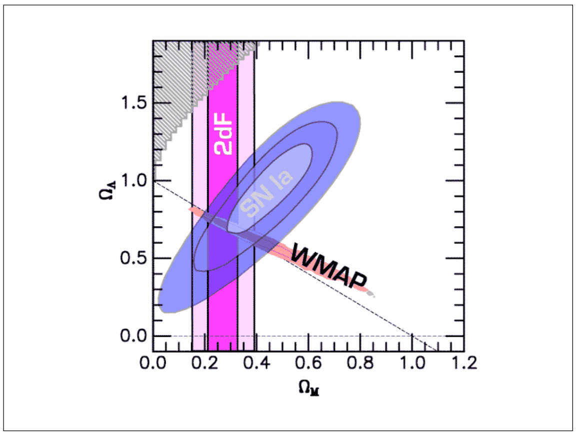






6 More Years of Work

150 Supernova later...

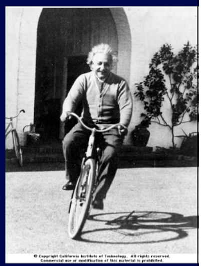


So What is the Dark Energy?

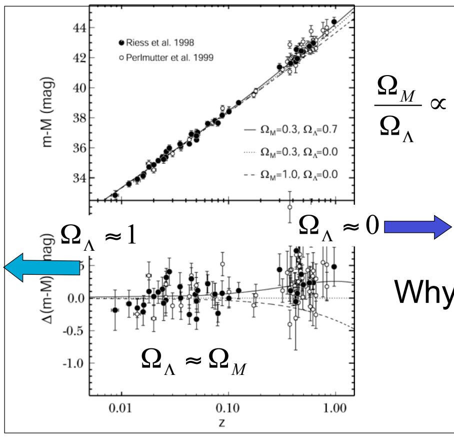
One possibility is that the Universe is permeated by an energy density, constant in time and uniform in space.

Such a “cosmological constant” (Lambda: Λ) was originally postulated by Einstein, but later rejected when the expansion of the Universe was first detected.

General arguments from the scale of particle interactions, however, suggest that if Λ is not zero, it should be very large, larger by more than 10^{50} than what is measured.



If dark energy is due to a cosmological constant, its ratio of pressure to energy density (its equation of state) is $w = P/\rho = -1$ at all times.



$$\frac{\Omega_M}{\Omega_\Lambda} \propto (1+z)^3$$

Why Now?

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

Unfortunately none of these theories has any particularly sound basis, and most spend much of their time looking like a Cosmological Constant.

So What is the Dark Energy?

An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model is incorrect.

Whether general relativity is incorrect or the Universe is filled with an unanticipated form of energy, exploration of the acceleration of the Universe’s expansion might profoundly change our understanding of the composition and nature of the Universe.

Dark Energy Ideas

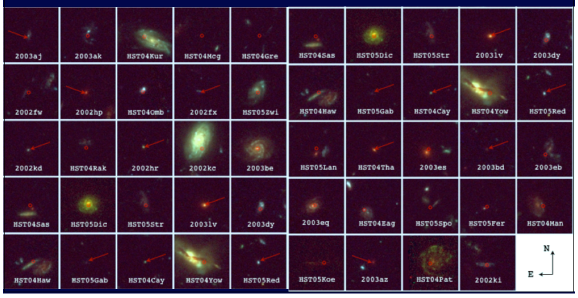
Tracker Quintessence, single exp Quintessence, double exp Quintessence, Pseudo-Nambu-Goldstone Boson Quintessence, Holographic dark energy, cosmic strings, cosmic domain walls, axion-photon coupling, phantom dark energy, Cardassian model, brane cosmology (extra-dimensions), Van Der Waals Quintessence, Dilaton, Generalized Chaplygin Gas, Quintessential inflation, Unified Dark matter & Dark energy, superhorizon perturbations, Undulant Universe, various numerology, Quiessence, general oscillatory models, Milne-Born-Infeld model, k-essence, chameleon, k-chameleon, f(R) gravity, perfect fluid dark energy, adiabatic matter creation, varying G etc, scalar-tensor gravity, double scalar field, scalar+spinor, Quintom model, SO(1,1) scalar field, five-dimensional Ricci flat Bouncing cosmology, scaling dark energy, radion, DGP gravity, Gauss-Bonnet gravity, tachyons, power-law expansion, Phantom k-essence, vector dark energy, Dilatonic ghost condensate dark energy, Quintessential Maldacena-Maoz dark energy, superquintessence, vacuum-driven metamorphosis, wet dark fluid...

Stolen from Karl Glazebrook

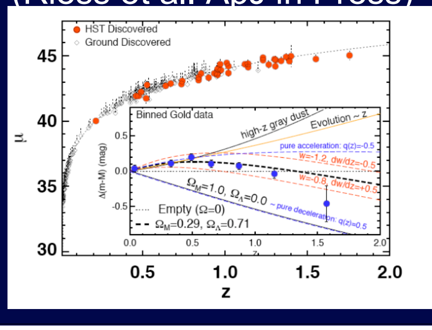
Current Results on w

- Supernova measurements of DL from z=0 to z=1.5 (Nearby, SCP, High-Z, CFHTLS, Essence, Higher-Z)
- BAO (+CMB constraint of acoustic scale at z=1089) measurement of 4% by SDSS at <z=0.35>
- Ω_M measurement of 0.27± 0.03 via 2dF+SDSS
- WMAP + LSS combined constraints

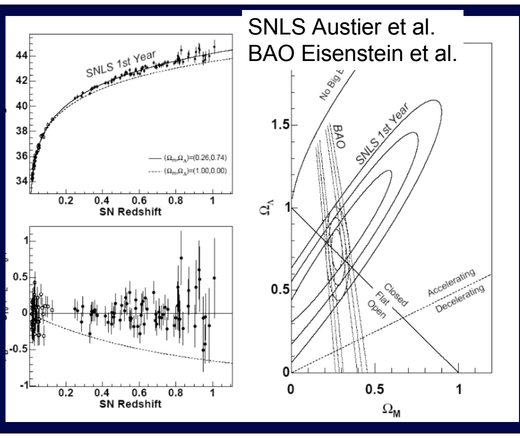
Hubble has found 50 new Supernovae
Half beyond the reach of the ground

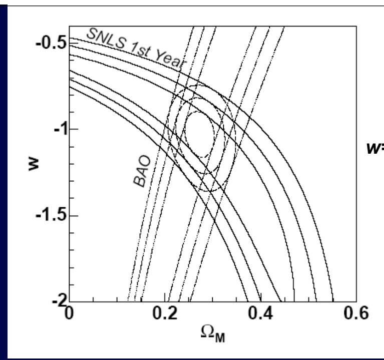


Higher-Z
(Riess et al. ApJ in Press)



SNLS Austier et al.
BAO Eisenstein et al.

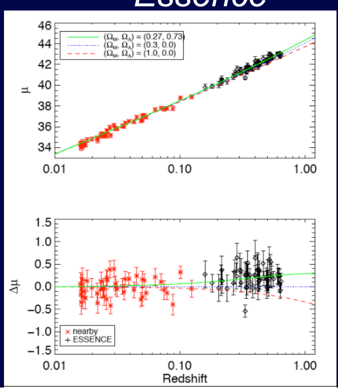




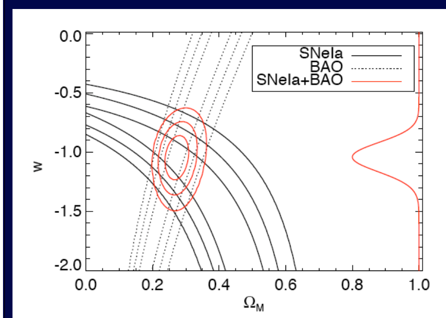
w=-1+/-0.1

Austier et al. CFHT Legacy Survey – assumes Flat Universe And uses CMB + BAO measurement.

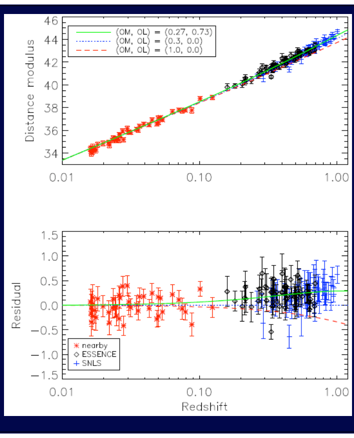
Essence



Michael Wood-Vasey et al. ApJ Submitted



w=-1.05±.13
(0.13 mag sys)



SNLS+Essence using MLCS2k2 w=1.07 ±0.09

Dark Energy looks like Λ

- As near as we can tell the Universe is expanding just as a Cosmological Constant would predict. (based on luminosity distance between z=0 to z=1.5 from SN Ia - and Angular-size distance (modified) between z=0.35 and z=1089) and power spectrum info from LSS+CMB.