Evidence for the accelerated expansion of the universe based on type Ia supernovae

G. Goldhaber

A Study of the Universe with Supernovae

GERSON GOLDHABER of the

SUPERNOVA COSMOLOGY PROJECT[1]

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and Lawrence Berkeley National Laboratory

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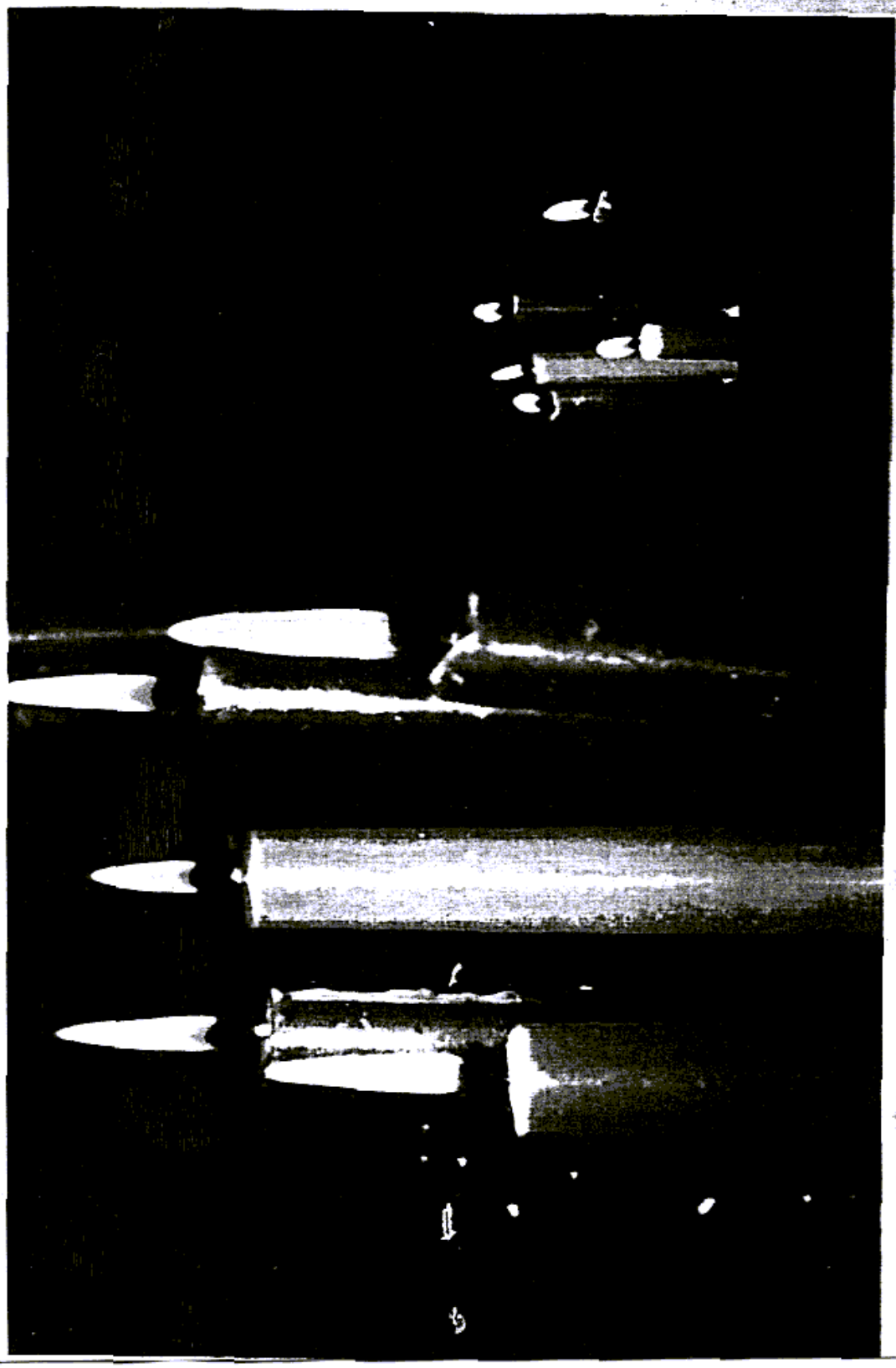
- When the mass reaches a critical value – about 1.4 times the mass of our Sun (known as the Chandrasekhar limit) – the White Dwarf collapses and starts "burning" carbon and oxygen mainly to Nickel. This happens in a few seconds and is the SUPERNOVA EXPLOSION (Type IA). 0.6 M⊙ of ^{56}Ni are produced in the explosion.

- Since all these Supernovae start at the same mass, 1.4 M⊙, they turn out to be of about the same brightness – standard candles.

- The radioactive decay of ^{56}Ni and its daughter ^{56}Co supply the energy for the SN light curve.



The principle

Measure the distance to a galaxy in which a Supernova has exploded

from the SN brightness

Measure the expansion of the Universe since this SN has exploded

from the Red Shift

Compare with different models of the Universe

Gives: Matter Density Ω_M

Dark energy density - Einstein's Cosmological Constant Ω_Λ

An Empirical Result

Type Ia Supernovae are "Standard Candles"

small variations can be calibrated

The Experiment

Find Supernovae

in NEARBY Galaxies (less than 100 million light-years)

in DISTANT Galaxies - Early galaxies (5 - 9 Billion light-years)

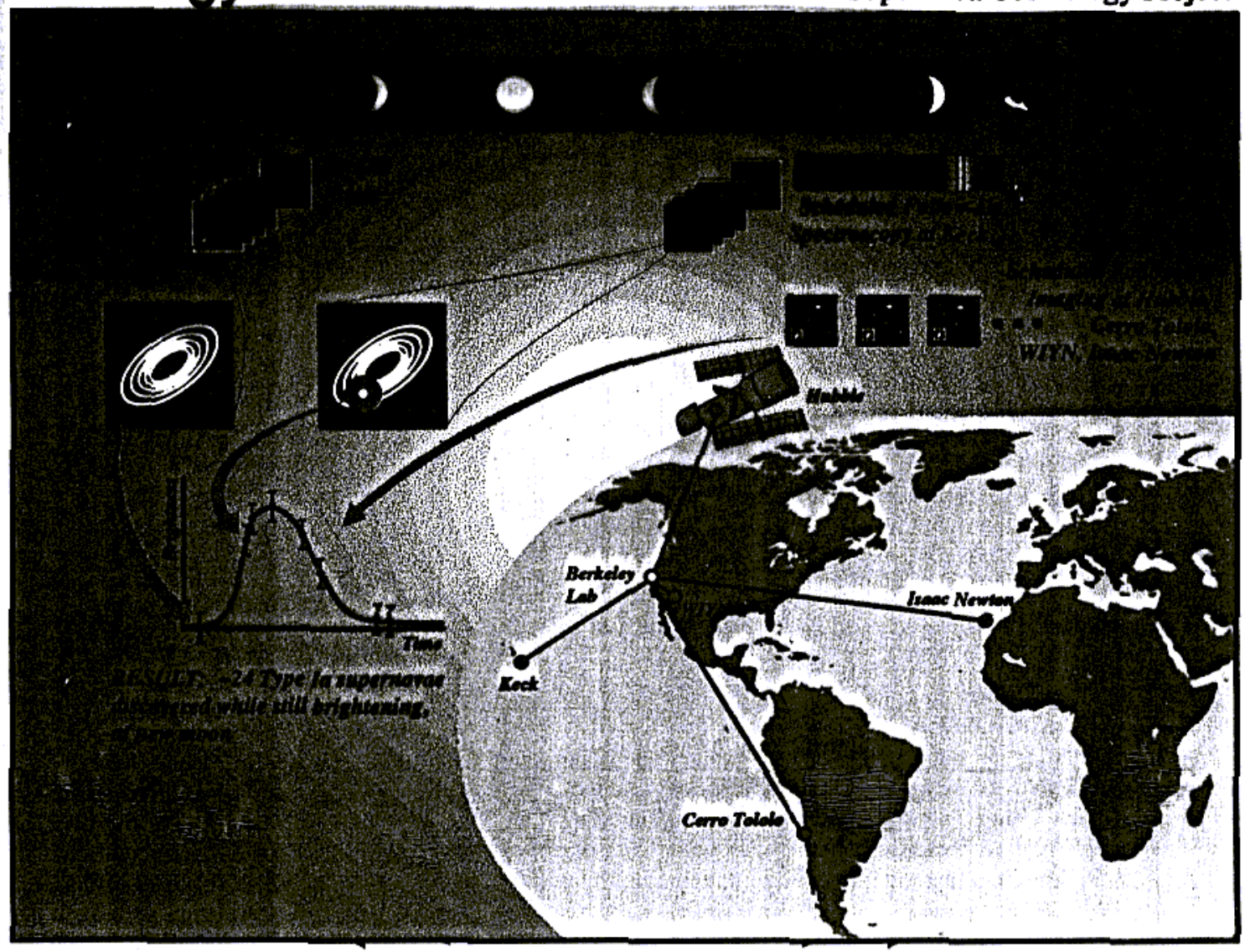
Measure Red Shift (from Spectrum)

Measure Light Curve (PHOTOMETR

Strategy

Supernova Cosmology Project

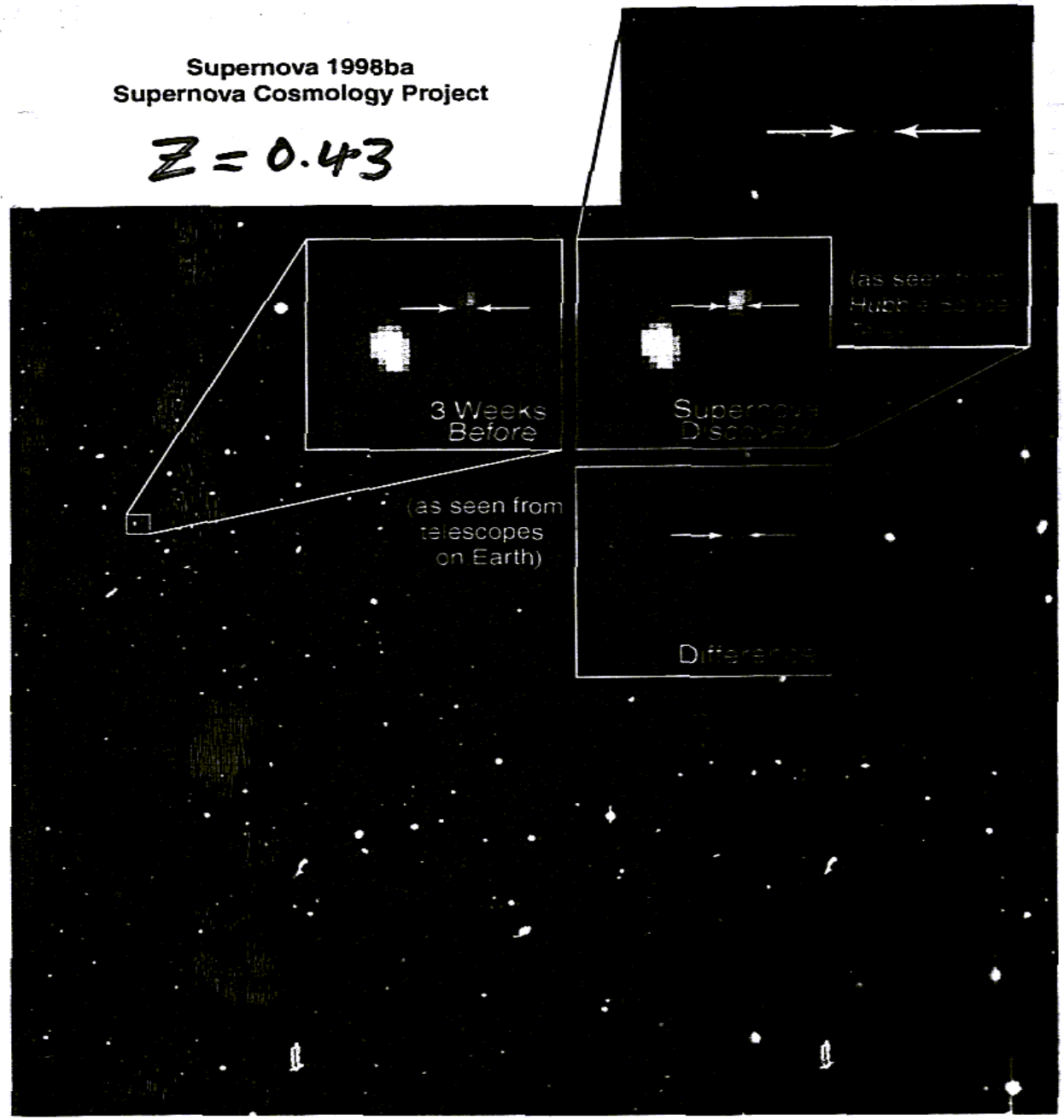
CCD
2Kx2K
15μ
Pixels



Perlmutter, *et al.*, in *Thermonuclear Supernovae*, NATO ASI, v. 486 (1997)

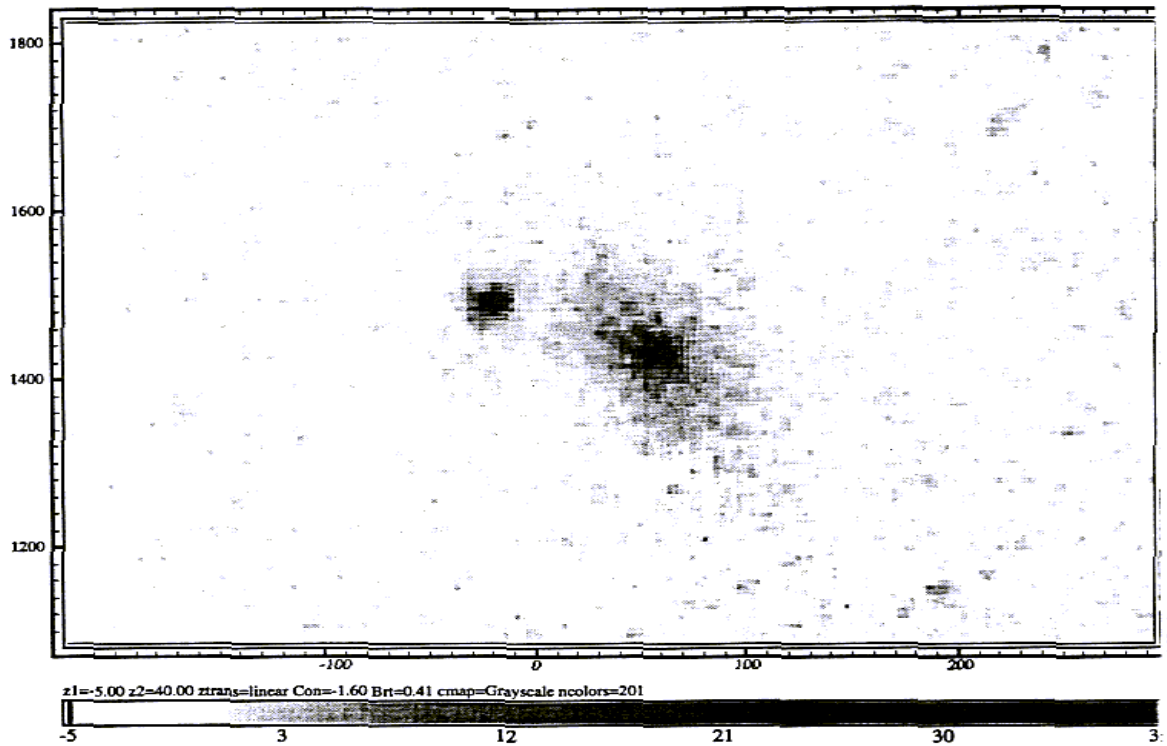
Supernova 1998ba
Supernova Cosmology Project

$z = 0.43$



HST z = 0.74

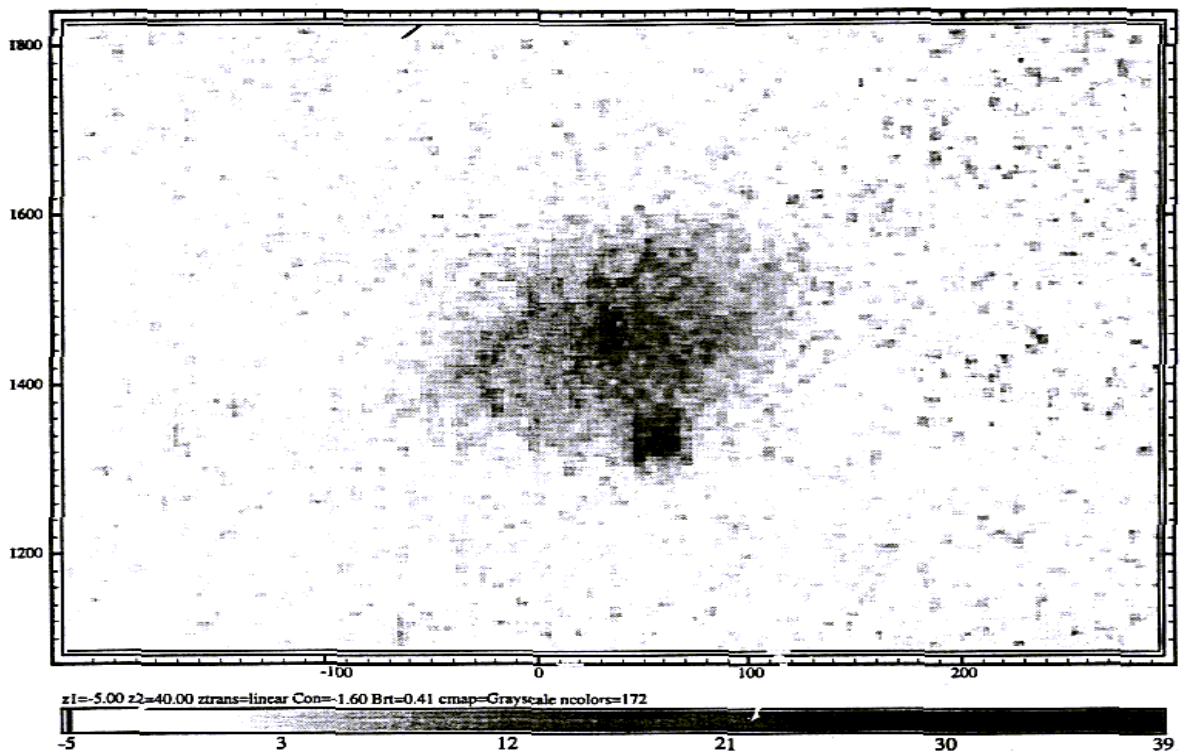
sn981 2.hhh - SN98142[1/1]



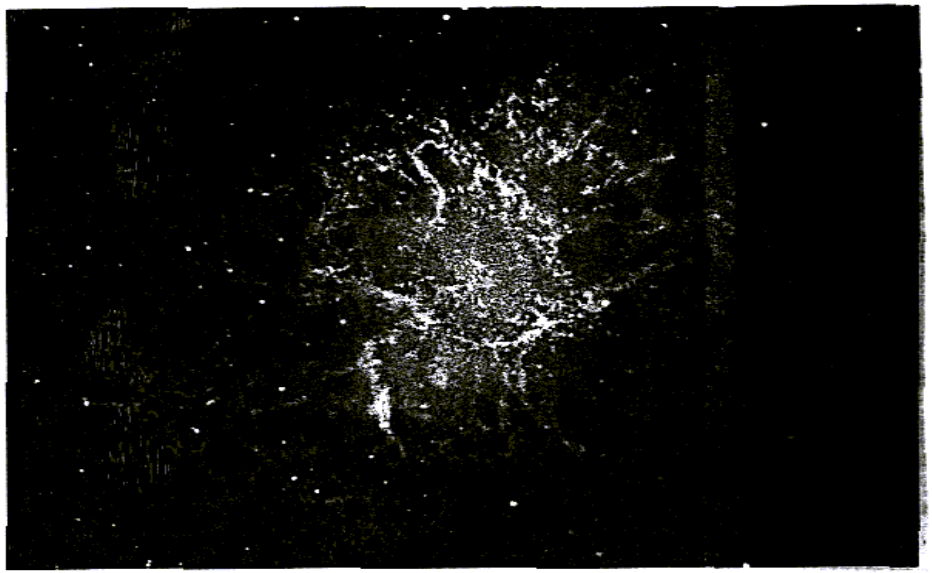
NOAO/IRAF aldering@mama' w.lbl.gov Tue Sep 8 10:16:25 1998

HST z=0.355

sn98122.hhh - SN98122[1/1]



NOAO/IRAF aldering@mamalan.lbl.gov Tue Sep 8 10:15:31 1998



CRAB NEBULA IN OUR GALAXY

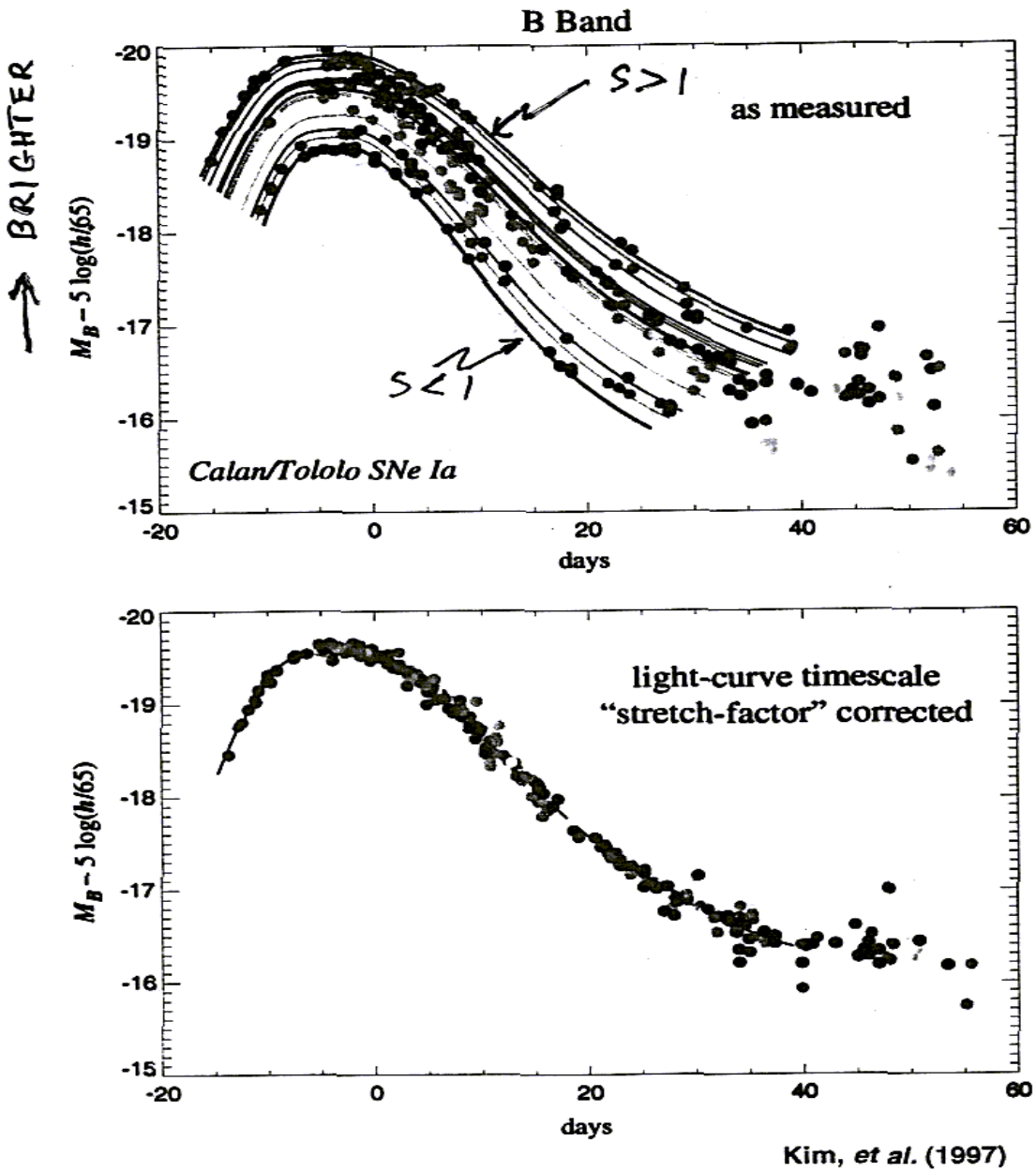
REMNANT OF SN 1056

OBSERVED BY CHINESE & ANASAZI

SDSS-II SN Light Curves

$$\text{Width} = (1+z)^2 \times \text{FWHM}$$

$$\text{FWHM} = \text{Width}_{max} \times (1+z)^{-2}$$

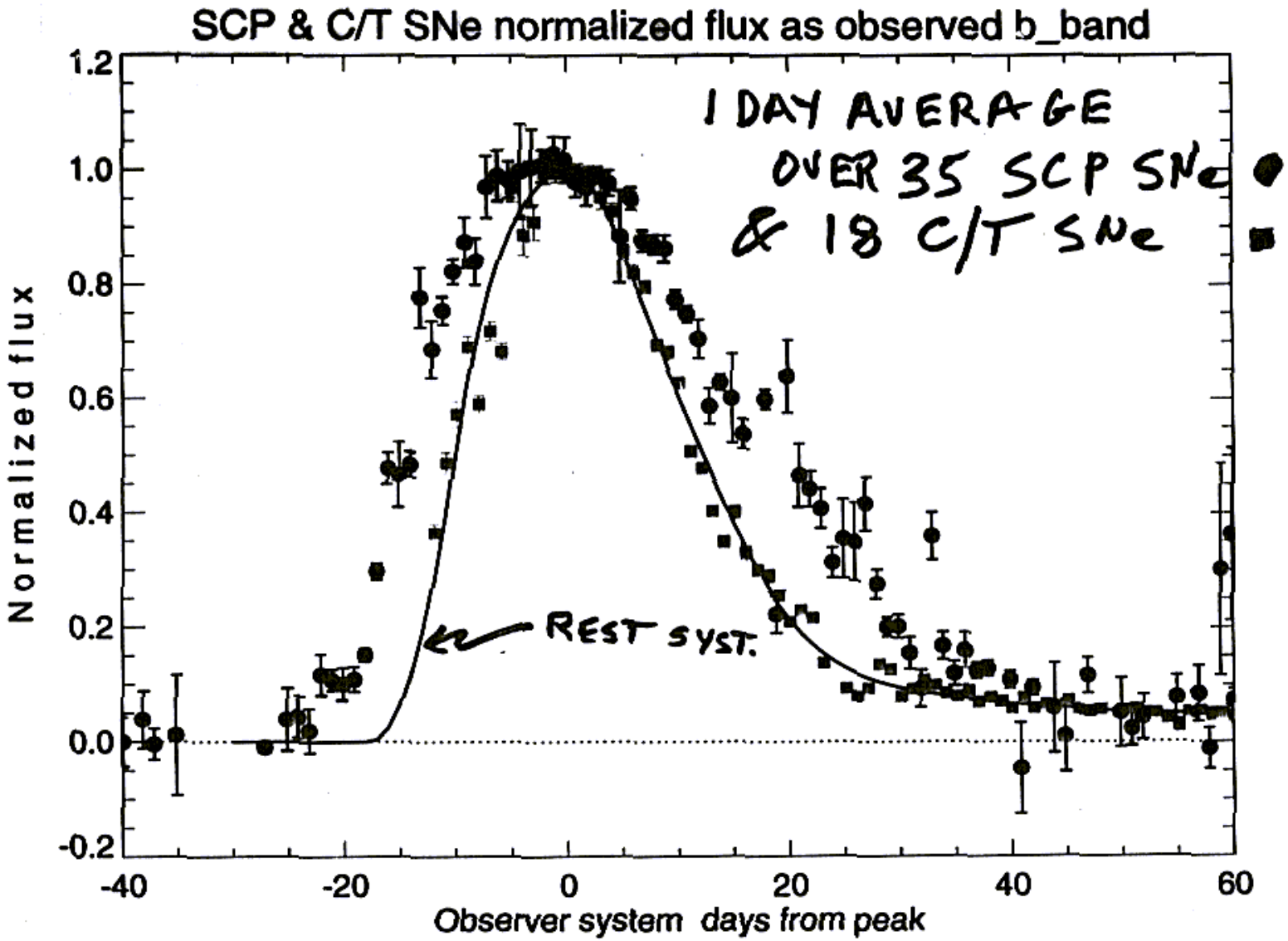


Kim, *et al.* (1997)

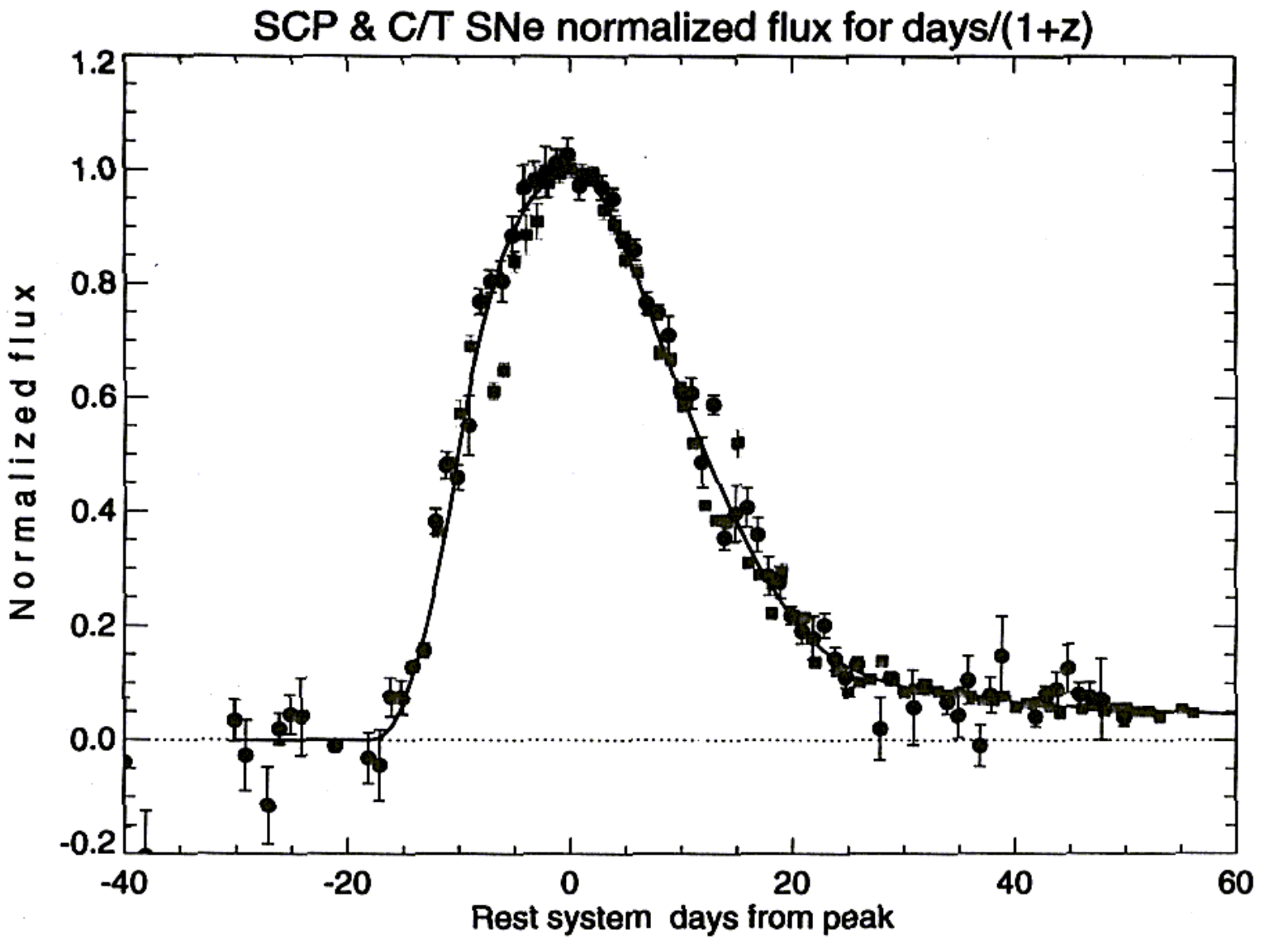
Normalized flux
Observer system days from peak
Rest system days from peak
(a)
(b)
(c)
(d)
(e)
(f)
(g)

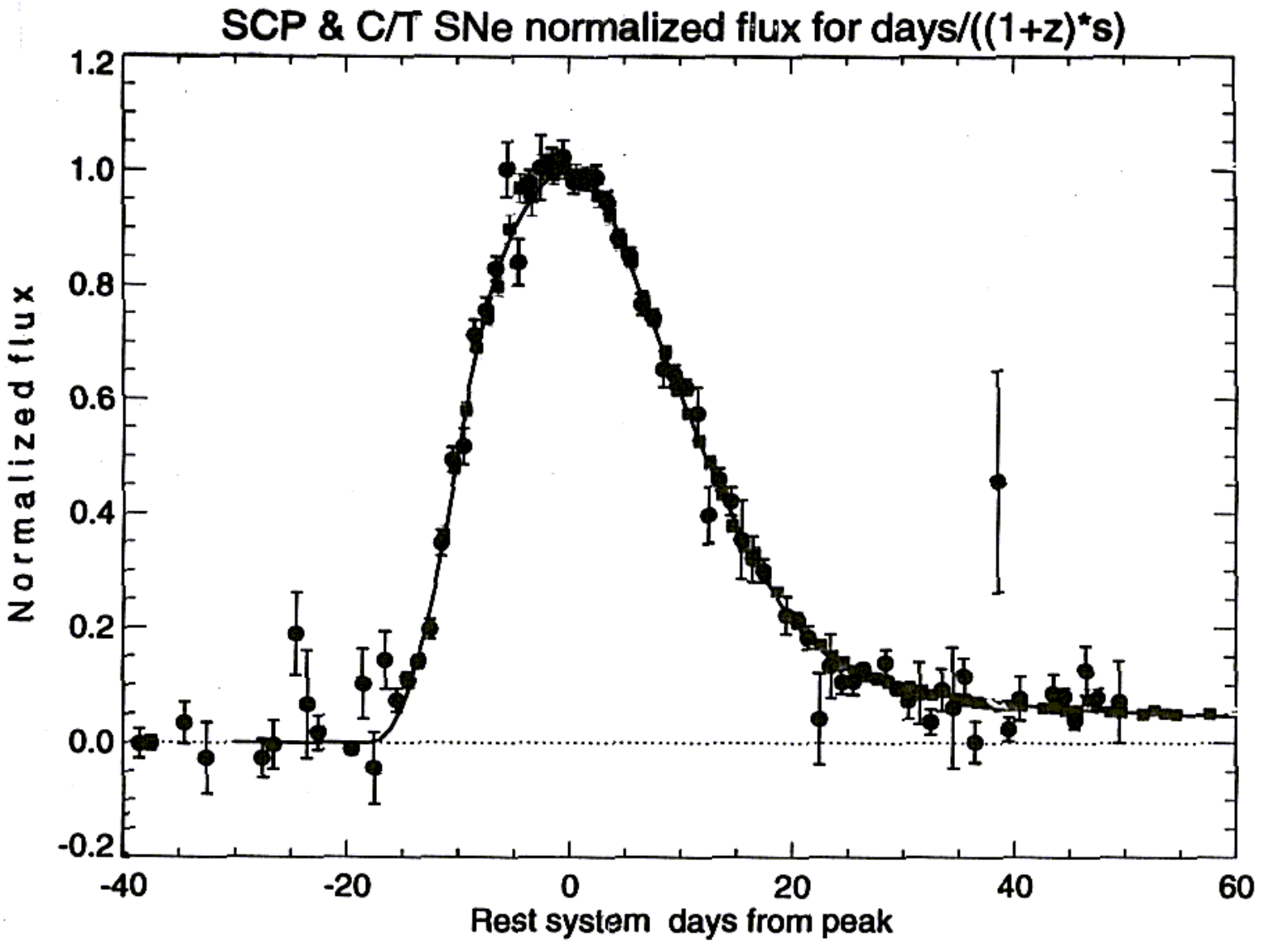
INDIVIDUAL

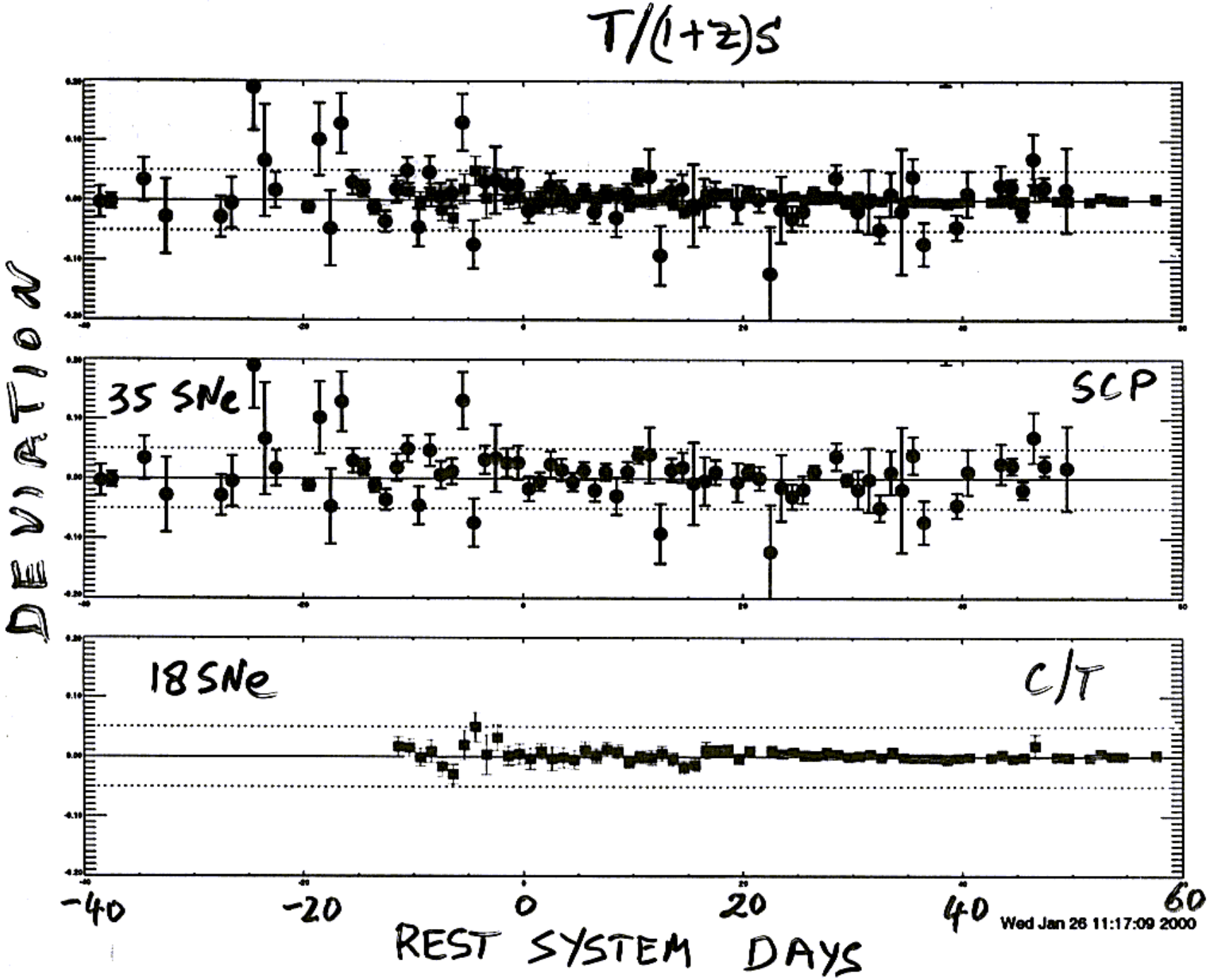
AVERAGE



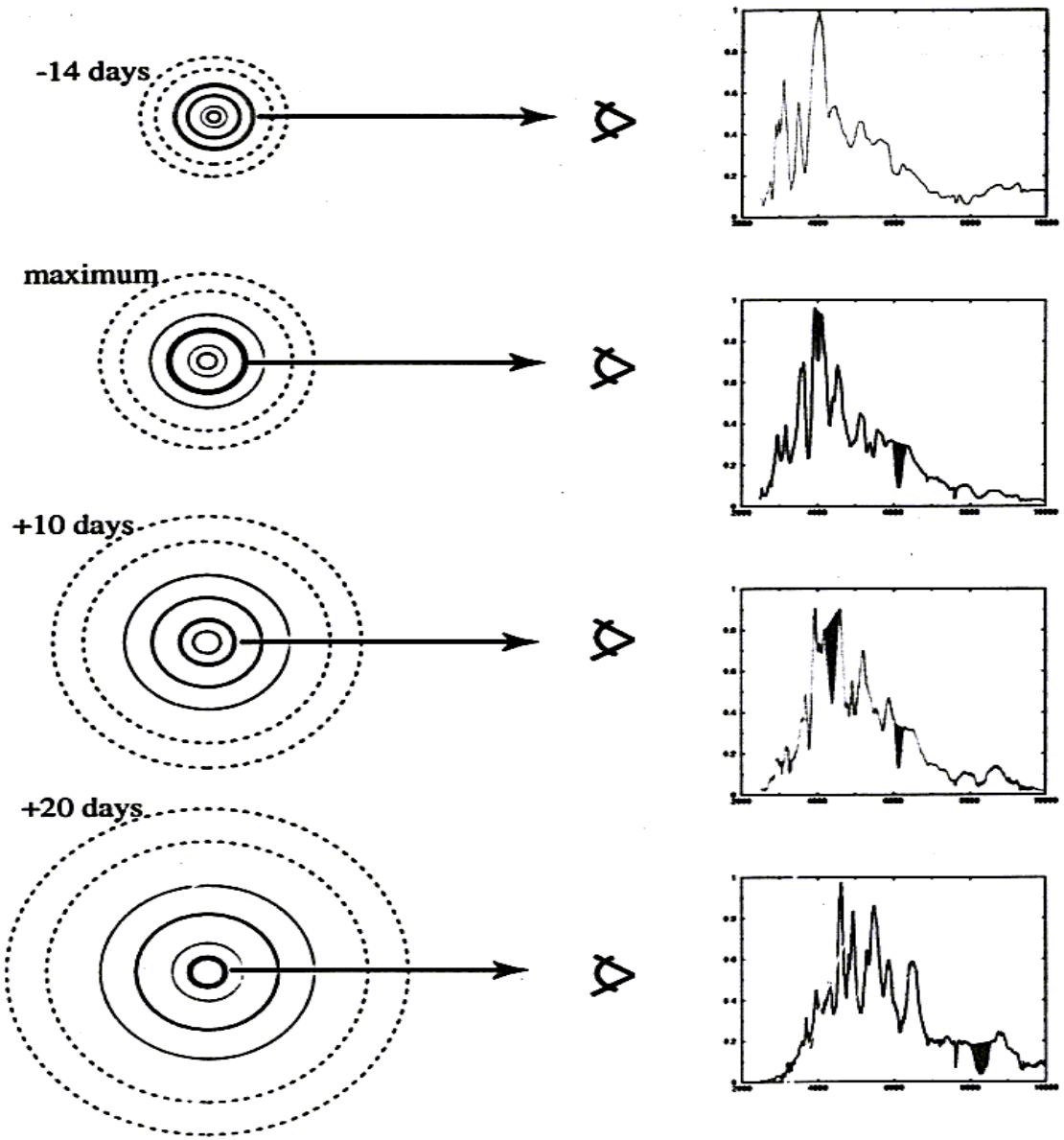
Wed Jan 26 11:19:45 2000


SCP & C/T SNe normalized flux for days/(1+z)
Normalized flux
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-40
-20
0
20
40
60
Rest system days from peak
Tue Jan 25 13:51:50 2000

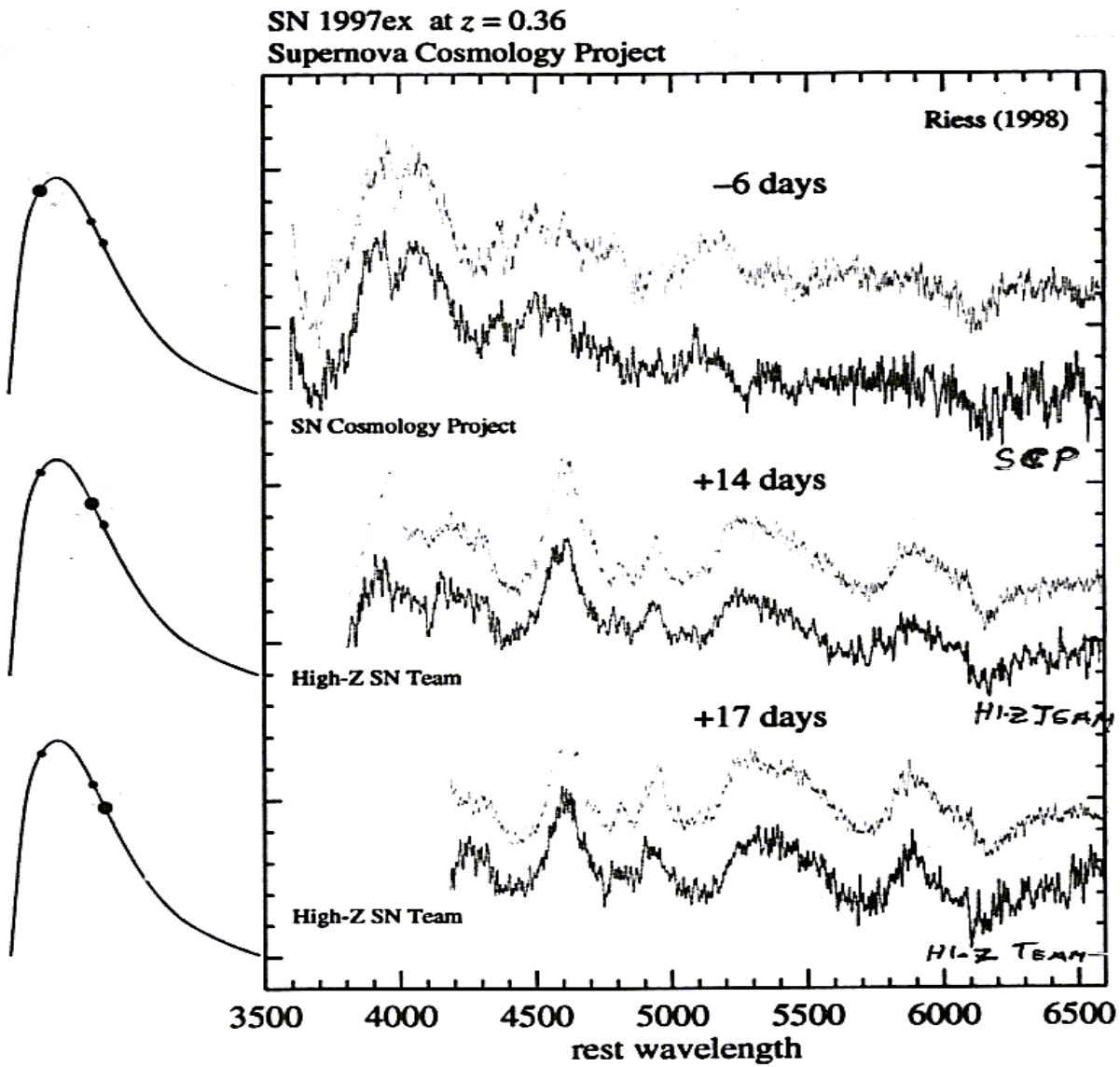

SCP & C/T SNe normalized flux for days/((1+z)*s)
Normalized flux
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-40
-20
0
20
40
60
Rest system days from peak
Wed Jan 26 11:07:47 2000


T/(1+z)s
DEVIATION
35 SNe
SCP
18 SNe
C/T
-40
-20
0
20
40
60
Wed Jan 26 11:17:09 2000
REST SYSTEM DAYS

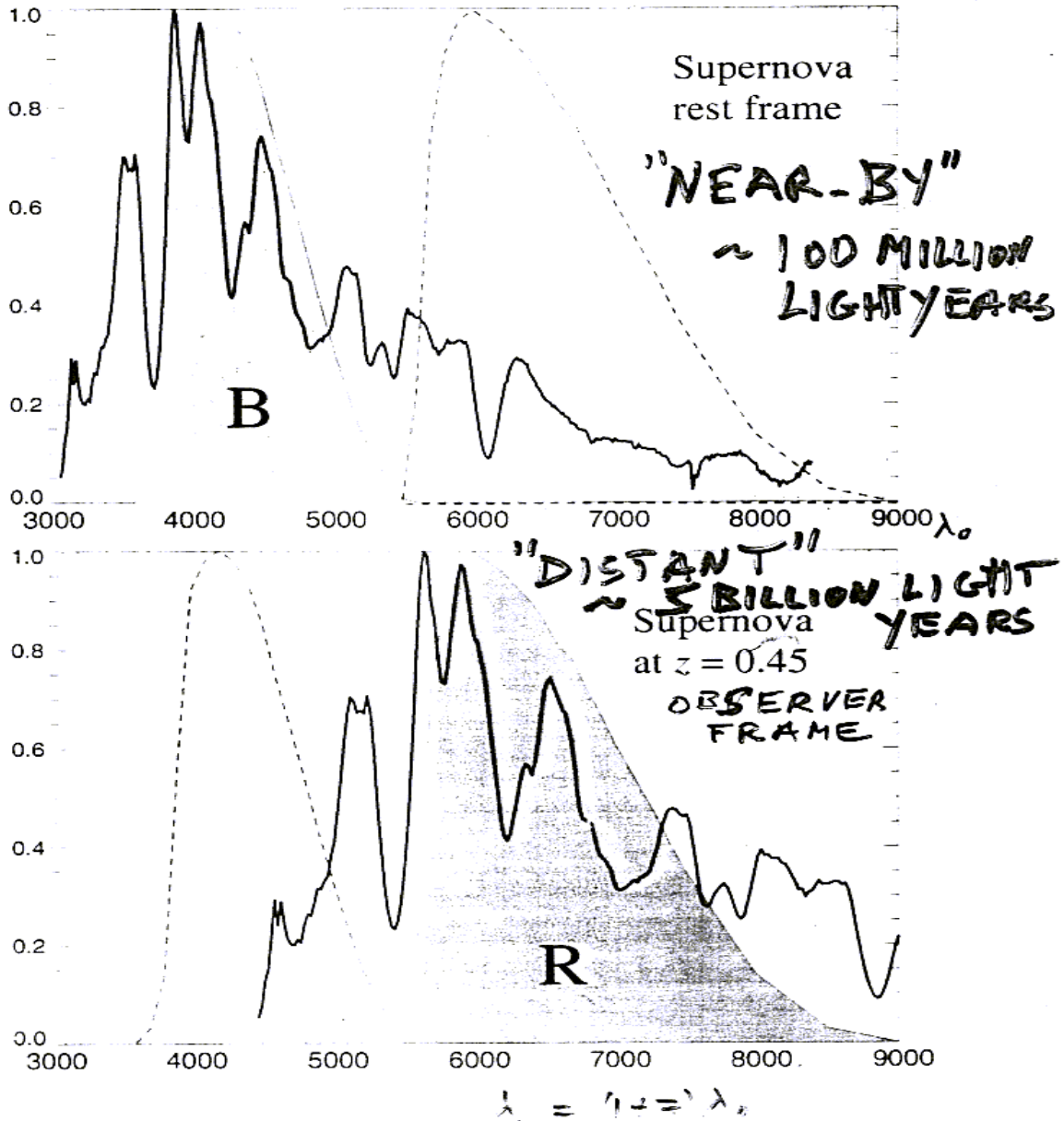
The time series of spectra is a "CAT Scan" of the Supernova



Time Series of Low-Redshift and High-Redshift Spectra



K corrections



Luminosity Distance

Goobar & Perlmutter (1995):

$$d_L(z;\Omega_M,\Omega_\Lambda,H_0) = \frac{(1+z)}{H_0\sqrt{|\kappa|}} \quad X$$

$$\mathcal{S}\left(\sqrt{|\kappa|}\int_0^z \left[(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda\right]^{-\frac{1}{2}} dz'\right),$$

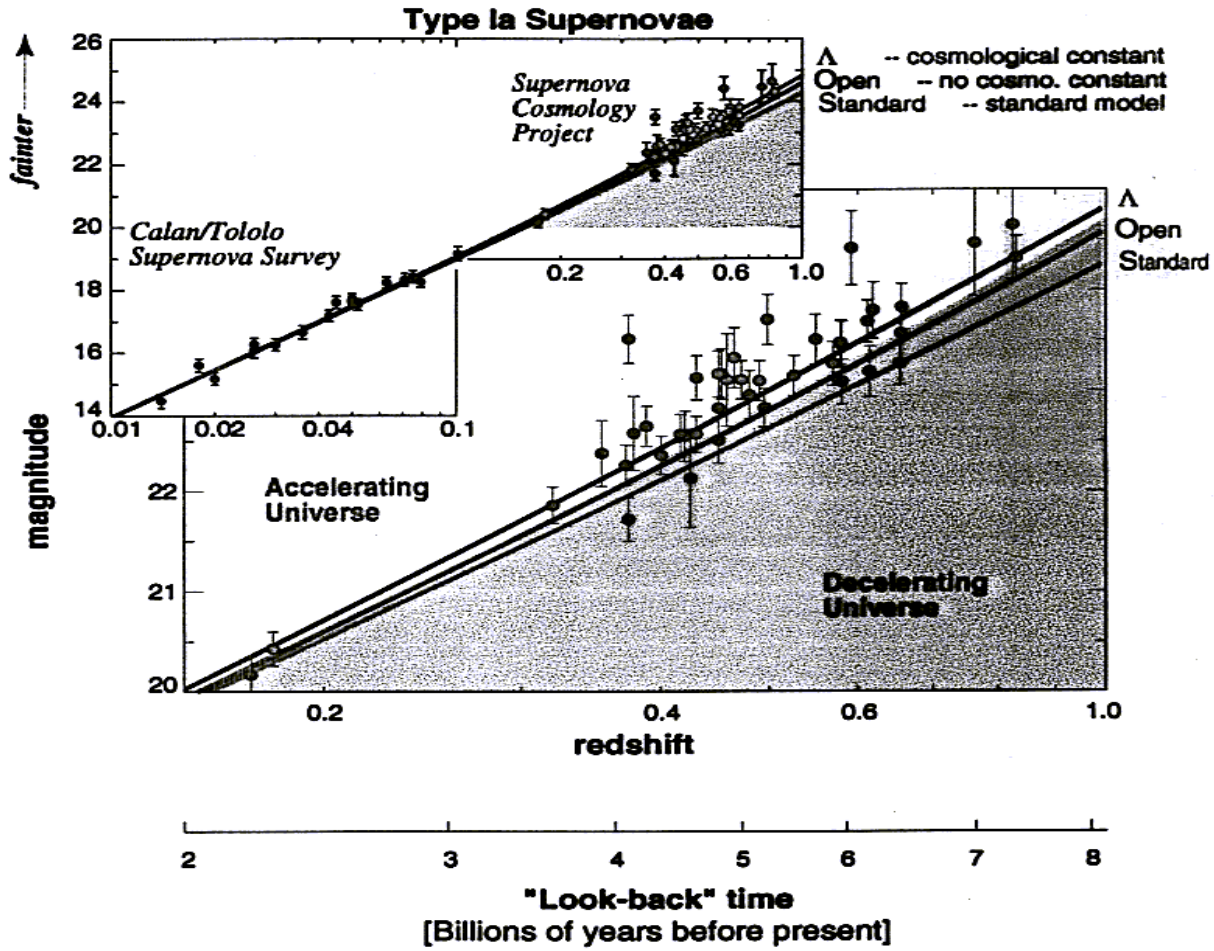
for $\Omega_M + \Omega_\Lambda > 1$, $\mathcal{S}(x)$ is defined as $\sin(x)$

and $\kappa = 1 - \Omega_M - \Omega_\Lambda$ POSITIVE CURVATURE

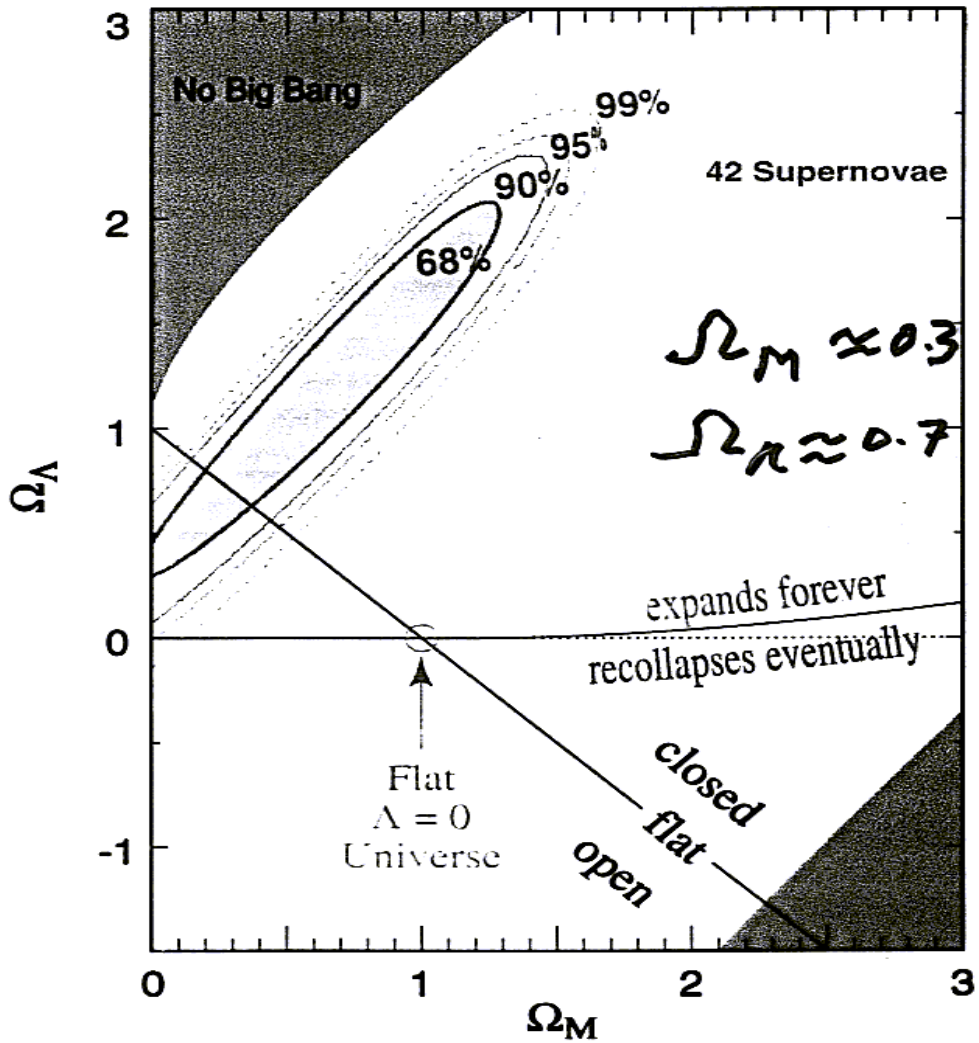
for $\Omega_M + \Omega_\Lambda < 1$, $\mathcal{S}(x) = \sinh(x)$

and $\kappa = 1 - \Omega_M - \Omega_\Lambda$; NEGATIVE CURVATURE

for $\Omega_M + \Omega_\Lambda = 1$, $\mathcal{S}(x) = x$ and $\kappa = 1$. FLAT


Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
Supernova Cosmology Project
Calan/Tololo Supernova Survey
fainter
magnitude
Accelerating Universe
Decelerating Universe
redshift
"Look-back" time
[Billions of years before present]

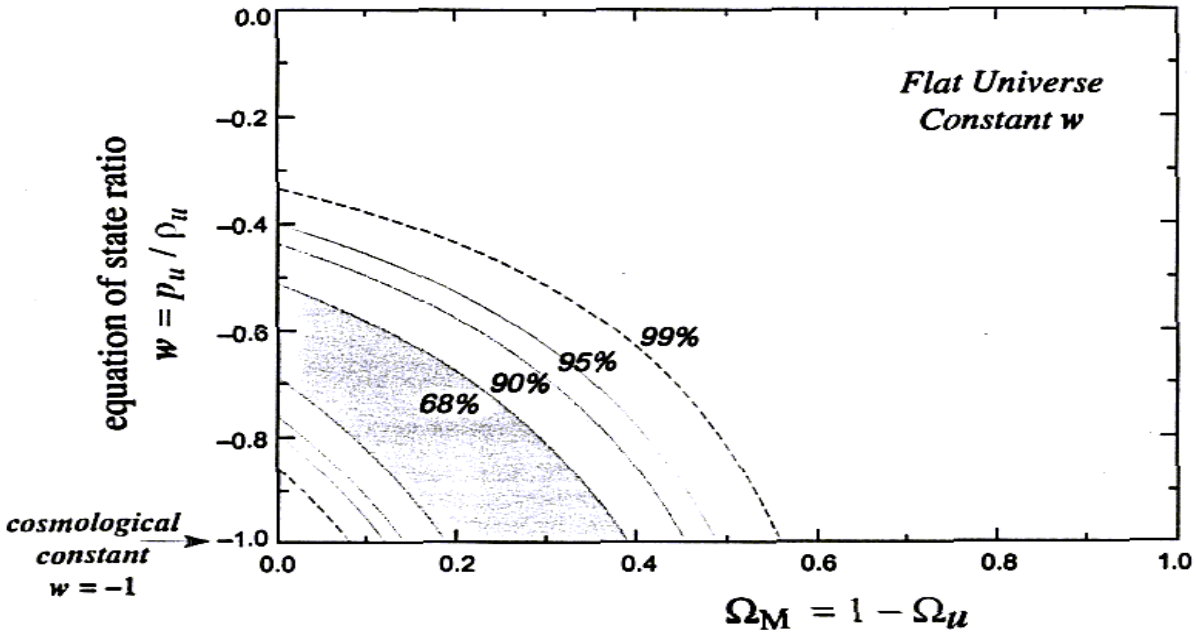
Supernova Cosmology Project
Perlmutter *et al.* (1998)



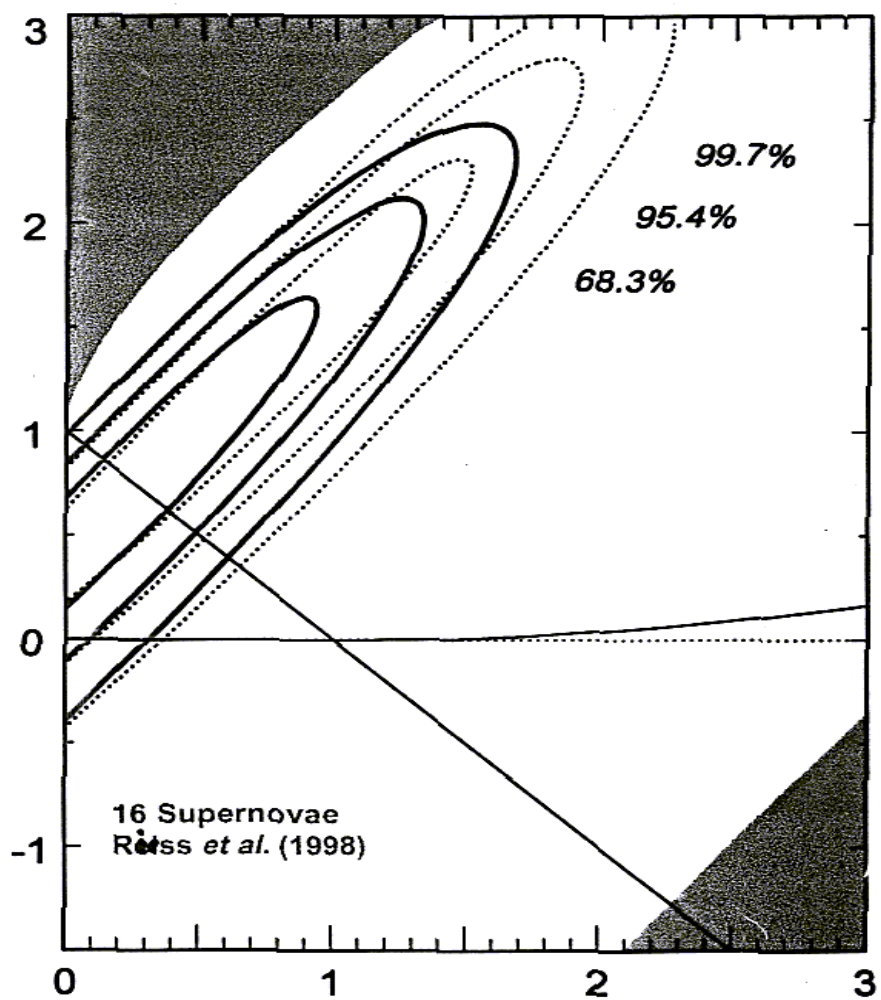
Ap.J.
astro-ph/9812133

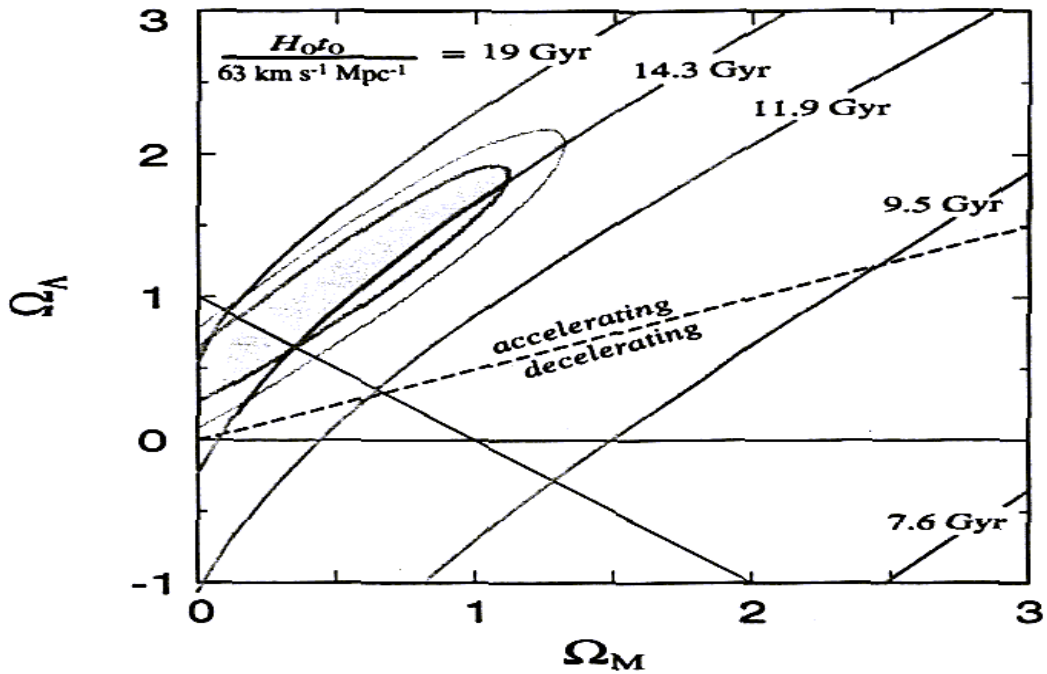
Unknown Component, Ω_u, of Energy Density

Perlmutter *et al.* (1998)

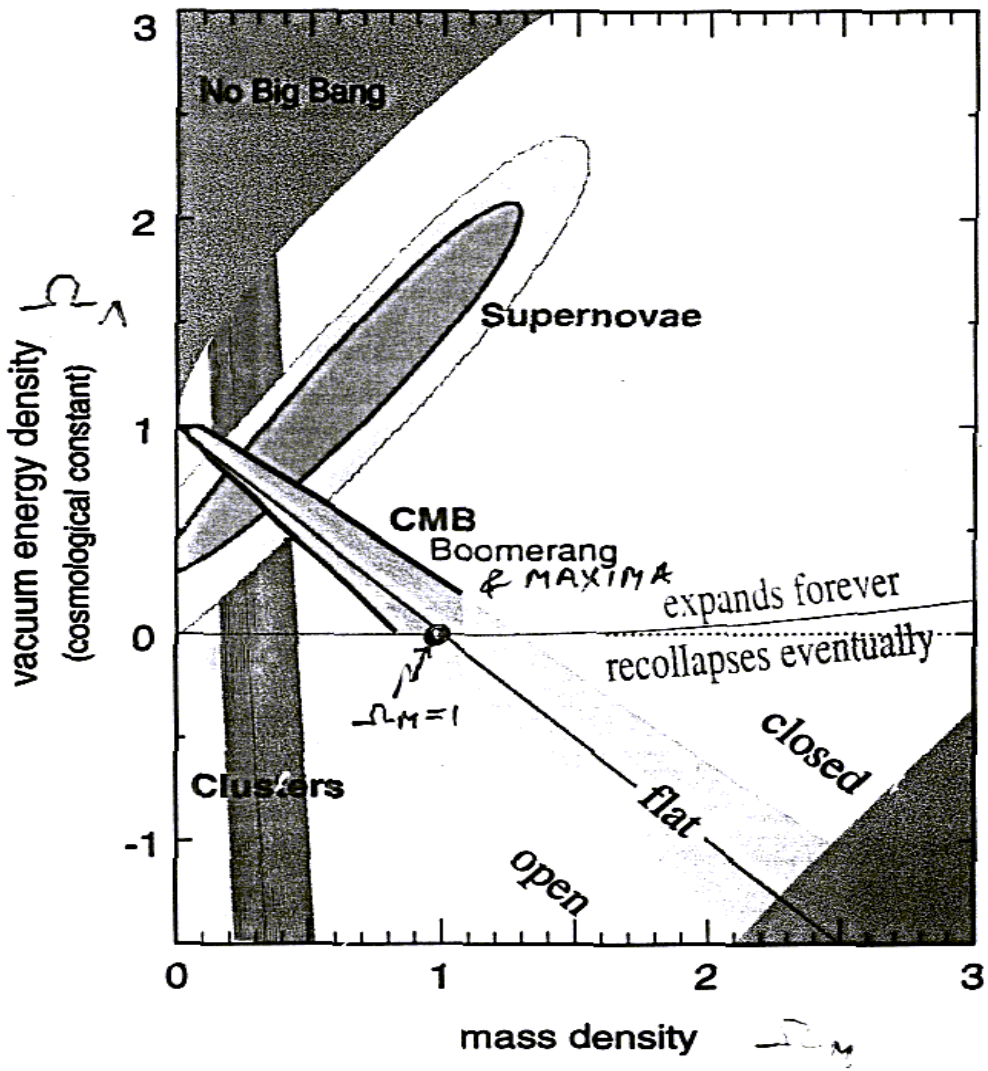


c.f. Garnavich et al. (1998)

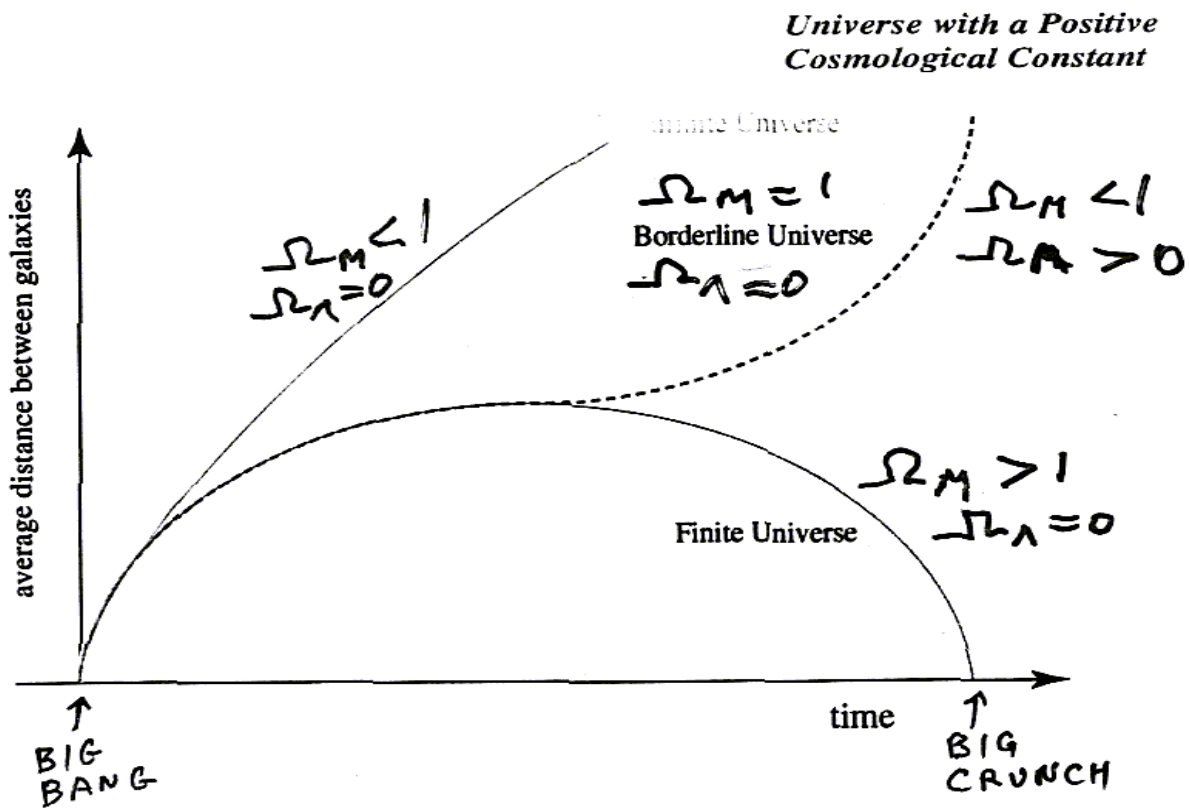

3
2
1
0
-1
0
1
2
3
99.7%
95.4%
68.3%
16 Supernovae
Riess et al. (1998)

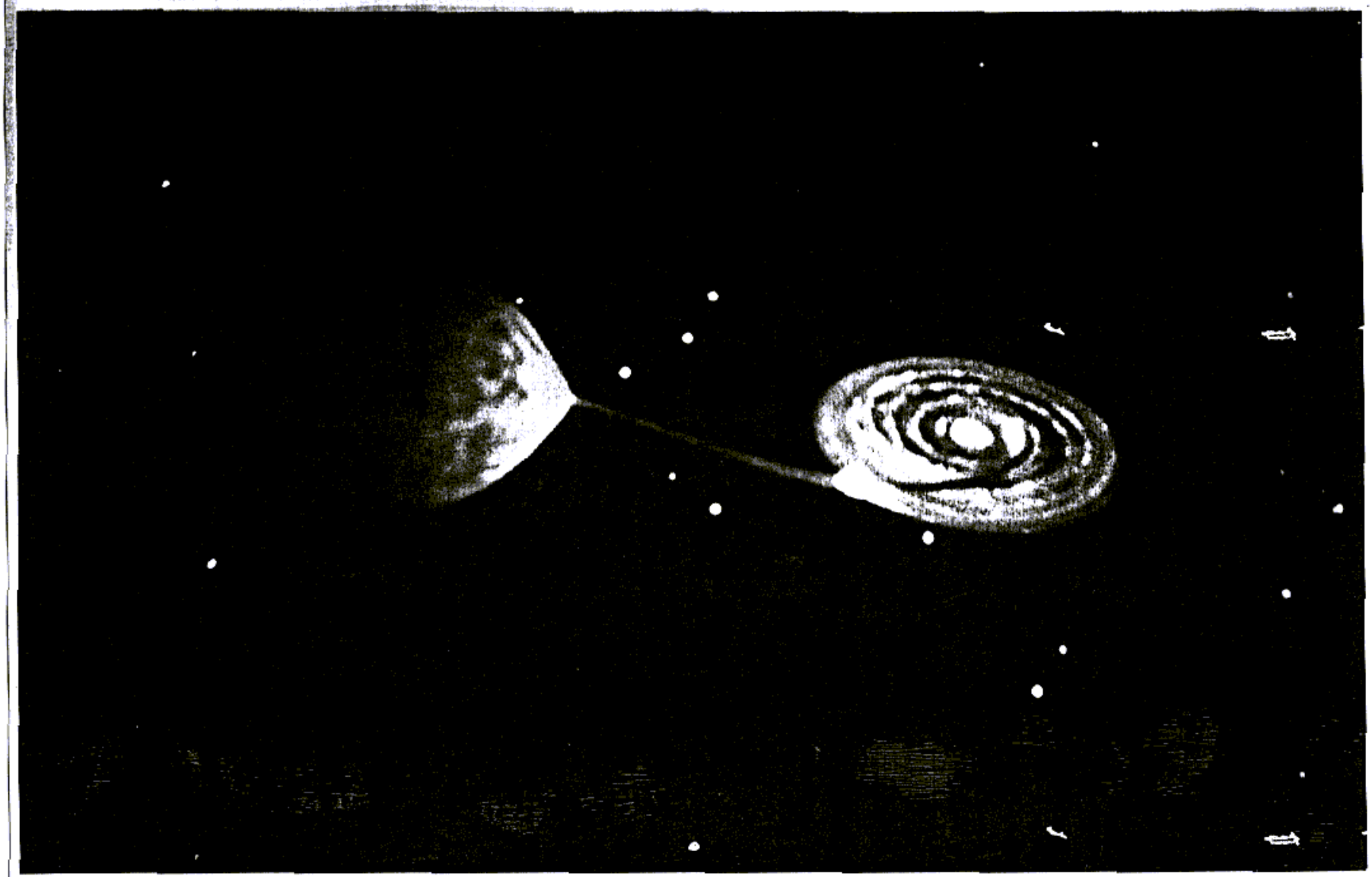


UNIVERSE
NO LONGER TOO YOUNG
FOR GLOBULAR CLUSTERS


No Big Bang
Supernovae
CMB
Boomerang
& MAXIMA
expands forever
recollapses eventually
closed
flat
open
Clusters
$\Omega_M = 1$
vacuum energy density
(cosmological constant)
Ω_Λ
mass density
Ω_M
3
2
1
0
-1
0
1
2
3

WHY NOW ?


Universe with a Positive Cosmological Constant
average distance between galaxies
$\Omega_M < 1$
$\Omega_\Lambda = 0$
$\Omega_M = 1$
Borderline Universe
$\Omega_\Lambda = 0$
$\Omega_M < 1$
$\Omega_\Lambda > 0$
$\Omega_M > 1$
$\Omega_\Lambda = 0$
Finite Universe
time
BIG BANG
BIG CRUNCH



Photographic Services
BD 9505-
LAWRENCE BERKELEY LABORATORY

CHALLENGES

C. WHY NOW?

1. FROM PARTICLE PHYSICS

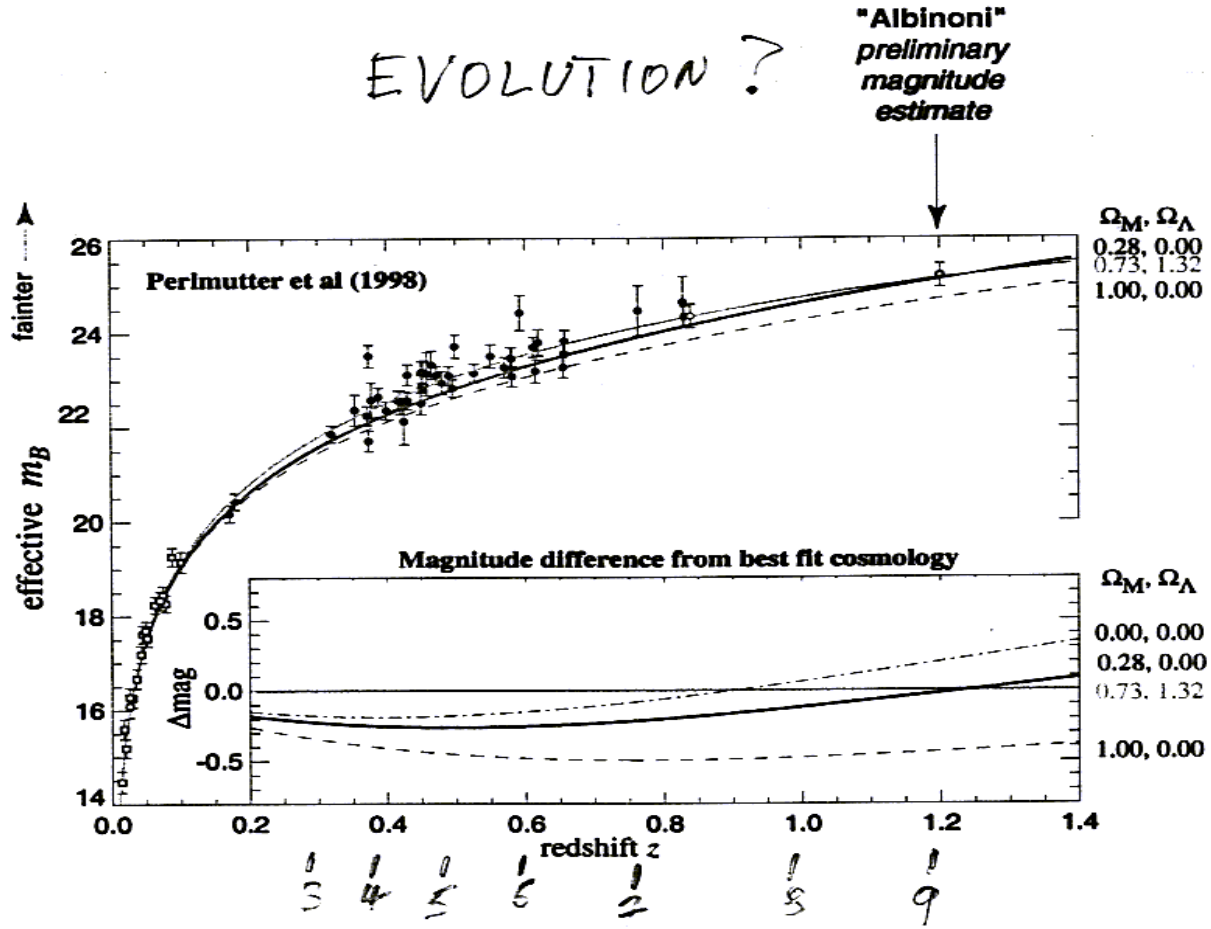
   Λ WHICH IS ASSOCIATED WITH THE VACUUM ENERGY DENSITY IS PREDICTED AS $\sim 10^{120}$ LARGER THEN OBSERVED – HENCE ASSUMED $\Lambda = 0$

2. GREY DUST

3. EVOLUTION

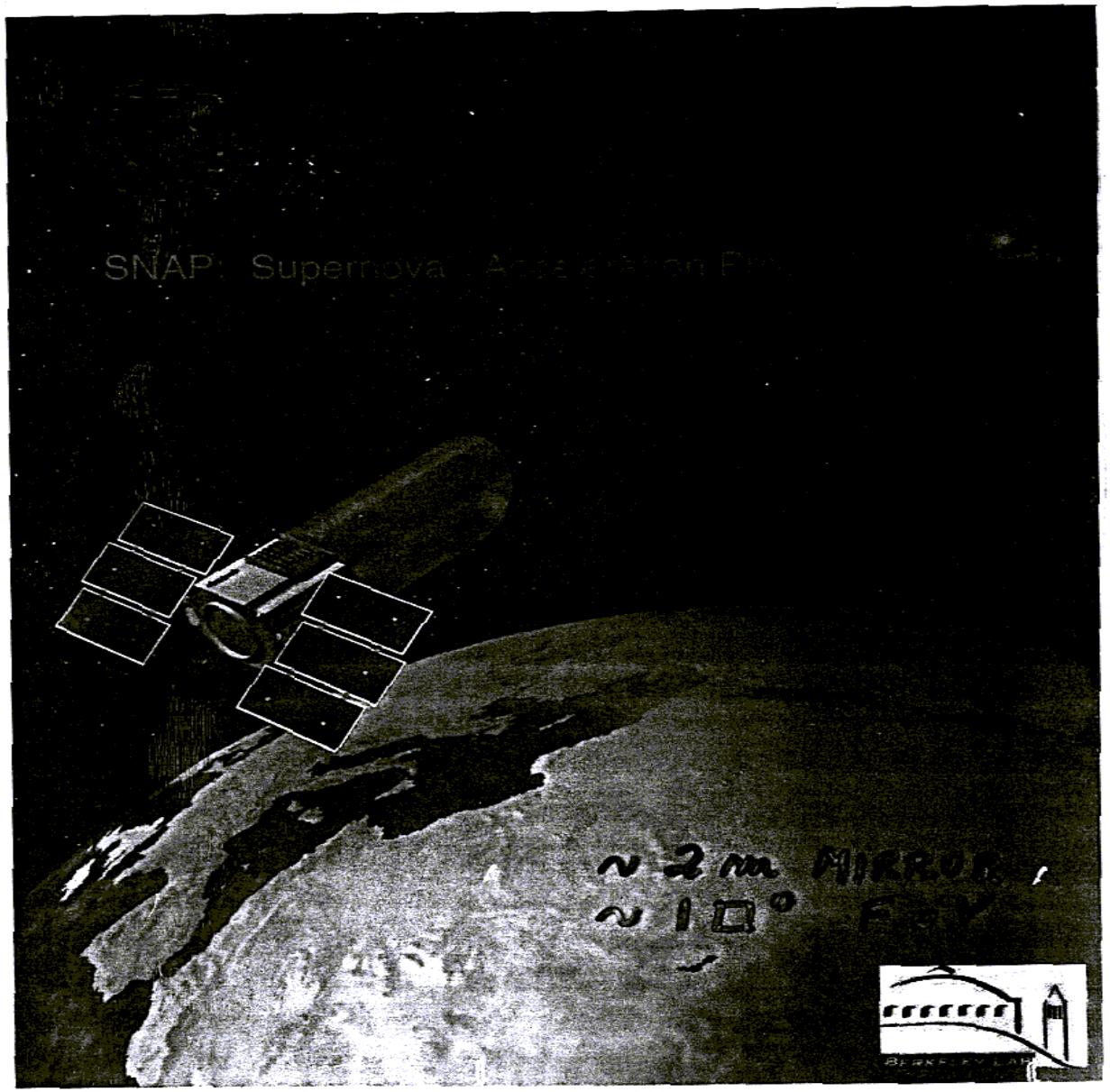
4. RISE TIME DIFFERENCE (SOLVED)

EVOLUTION ?



LOOK BACK TIME

BILLION YEARS


SNAP: Supernova
~2 m MIRROR
~1 □°

SuperNova / Acceleration Probe (SNAP)

An Experiment to Measure the Properties of the Dark Energy of the Universe

The Institutions of the SNAP Collaboration

Lawrence Berkeley National Laboratory
Space Sciences Laboratory
CNRS-IN2P3, LPNHE, and College de France
University of Maryland, College Park
University of California, Berkeley
University of Chicago
Space Telescope Sciences Institute
California Institute of Technology
Gemini Observatory
European Southern Observatory
University of Stockholm
[redacted] Lisbon Inst. Superior Tecnico

November 24, 1999

http://snap.lbl.gov

SNAP SuperNova Acceleration Probe

SAUL PERLMUTTER PI
MIKE LEVI CO-P.

satellite overview

Instruments:

- **~2 m aperture telescope**
  Can reach very distant SNe.
- **1 square degree mosaic camera, 1 billion pixels**
  Efficiently studies large numbers of SNe.
- **3-channel spectroscopy, 0.3um – 1.7um**
  Detailed analysis of each SN.

Satellite:

Dedicated instrument.

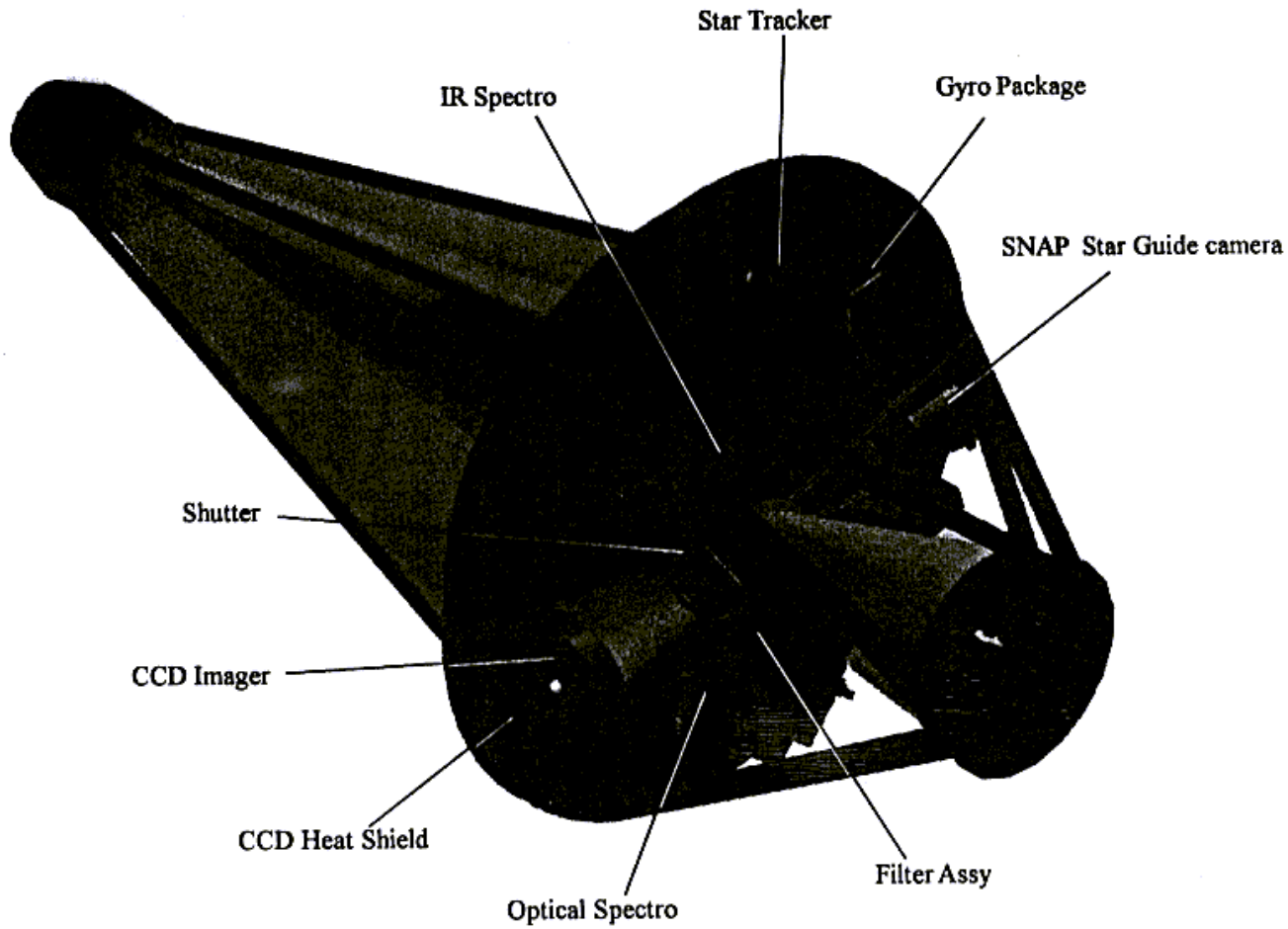
Designed to repeatedly observe an area of sky.

Essentially no moving parts.

4-year construction cycle.
3-year operation for experiment
(lifetime open-ended).

[redacted]

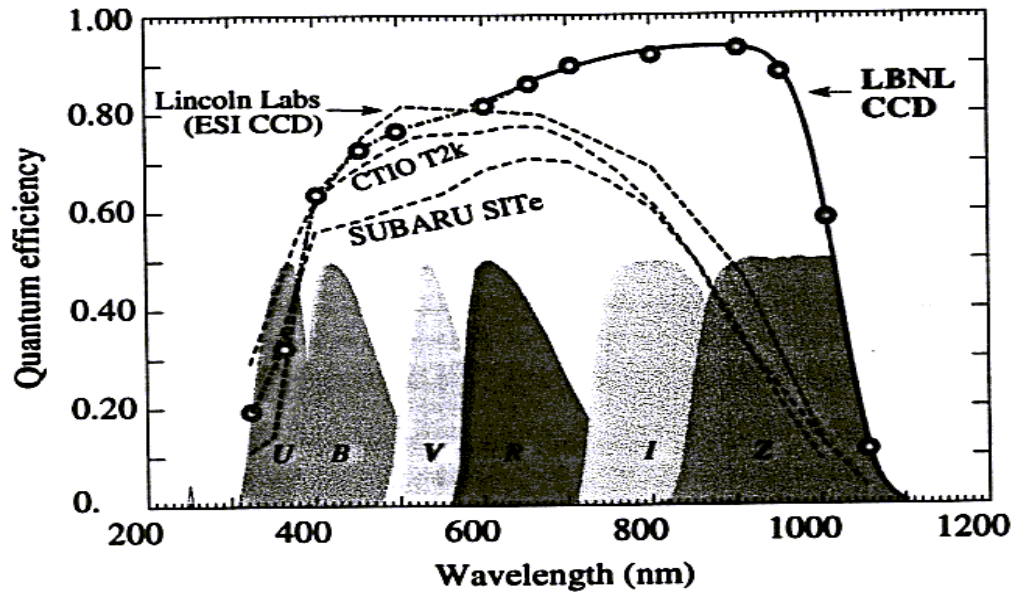
Instrument Deck
TMA-43 Beam Envelope
Mk3 Optical Bench
(Main Baffles and shrouds not shown)



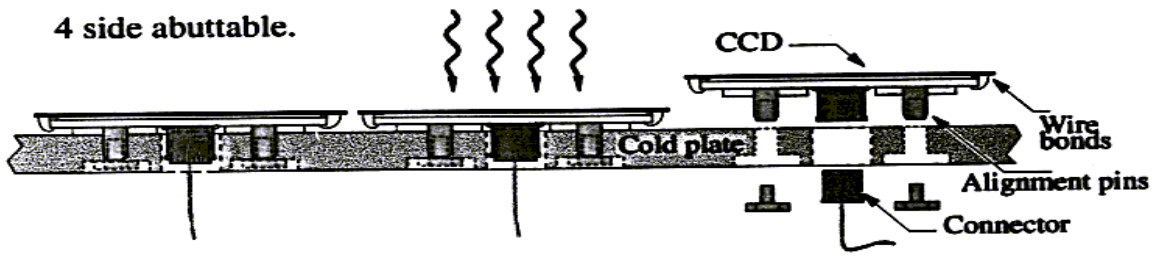
LBNL CCD Technology

high resistivity, 300μ thick fully depleted.

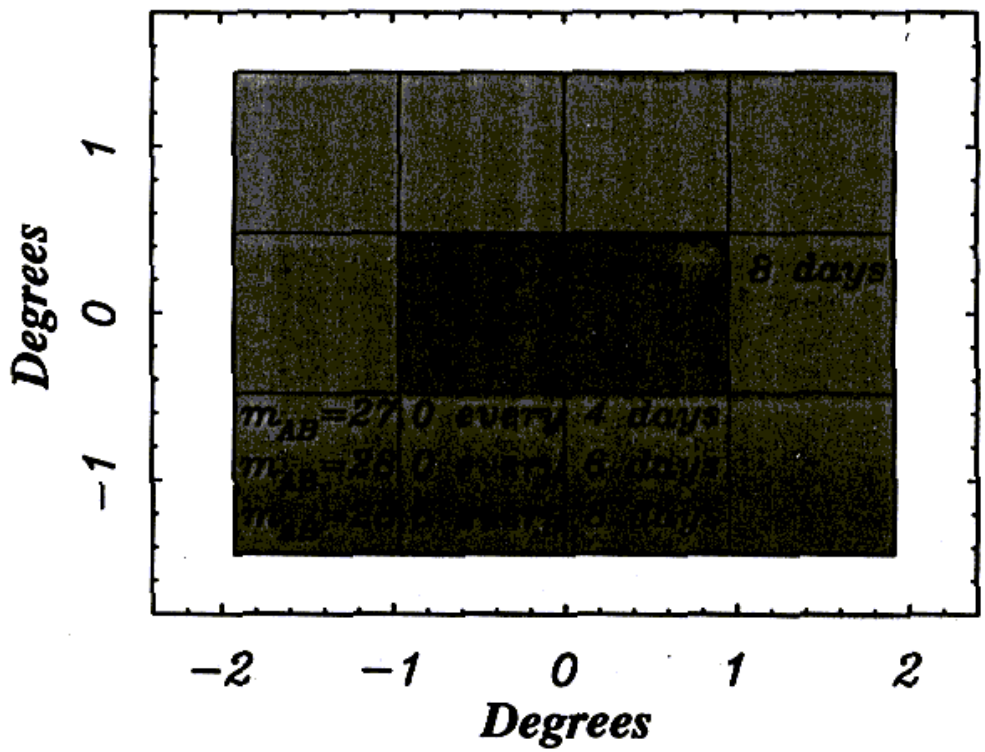
High quantum efficiency from near UV to near IR
No thinning, no fringing.
High yield.
Radiation hard.



4 side abuttable.



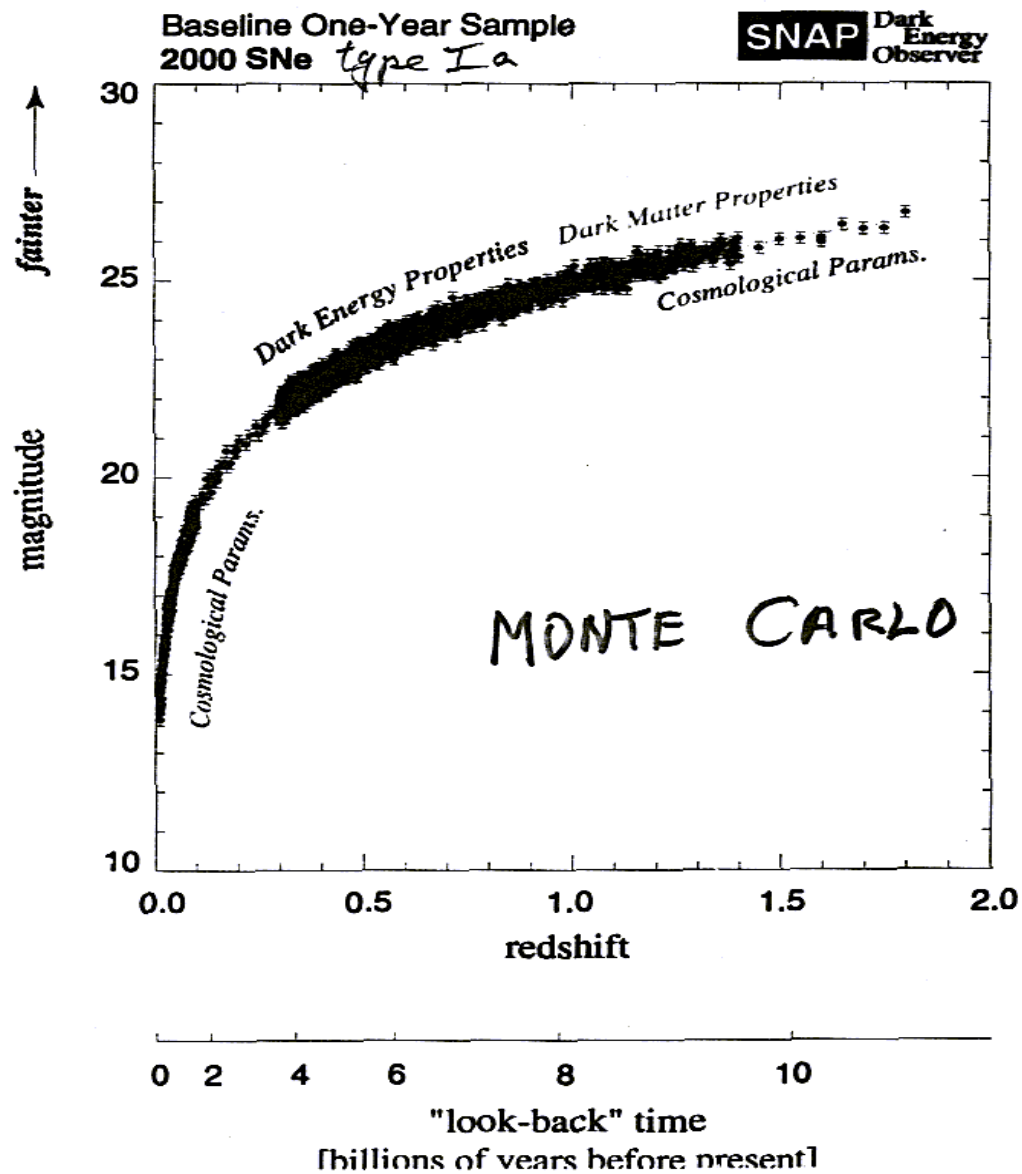
SNAP Search Strategy - Deep & Often

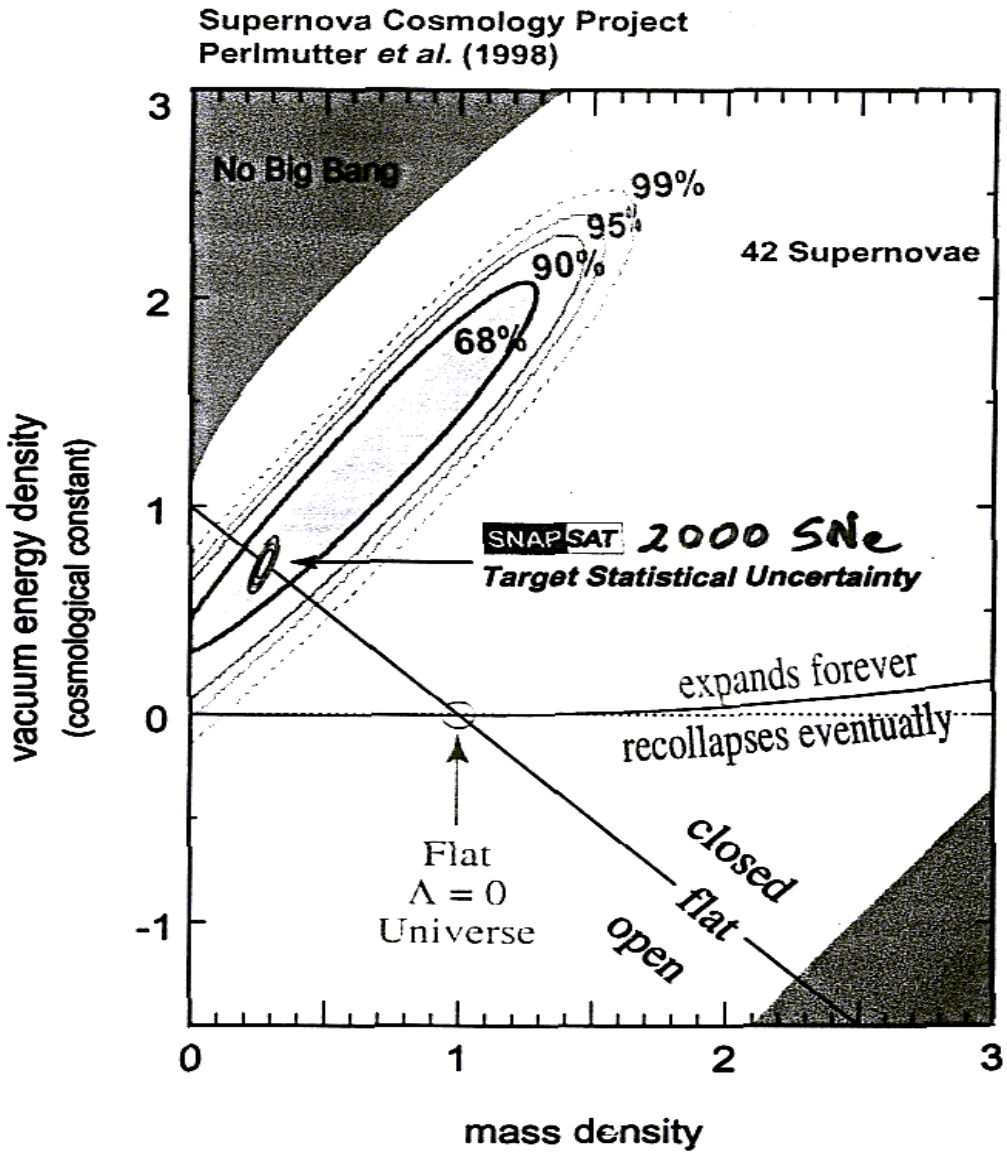


SNAP FOV equals:

- 679× HST+WFPC2
- 507× HST+WFPC3
- 319× HST+ACS
- 225× NGST

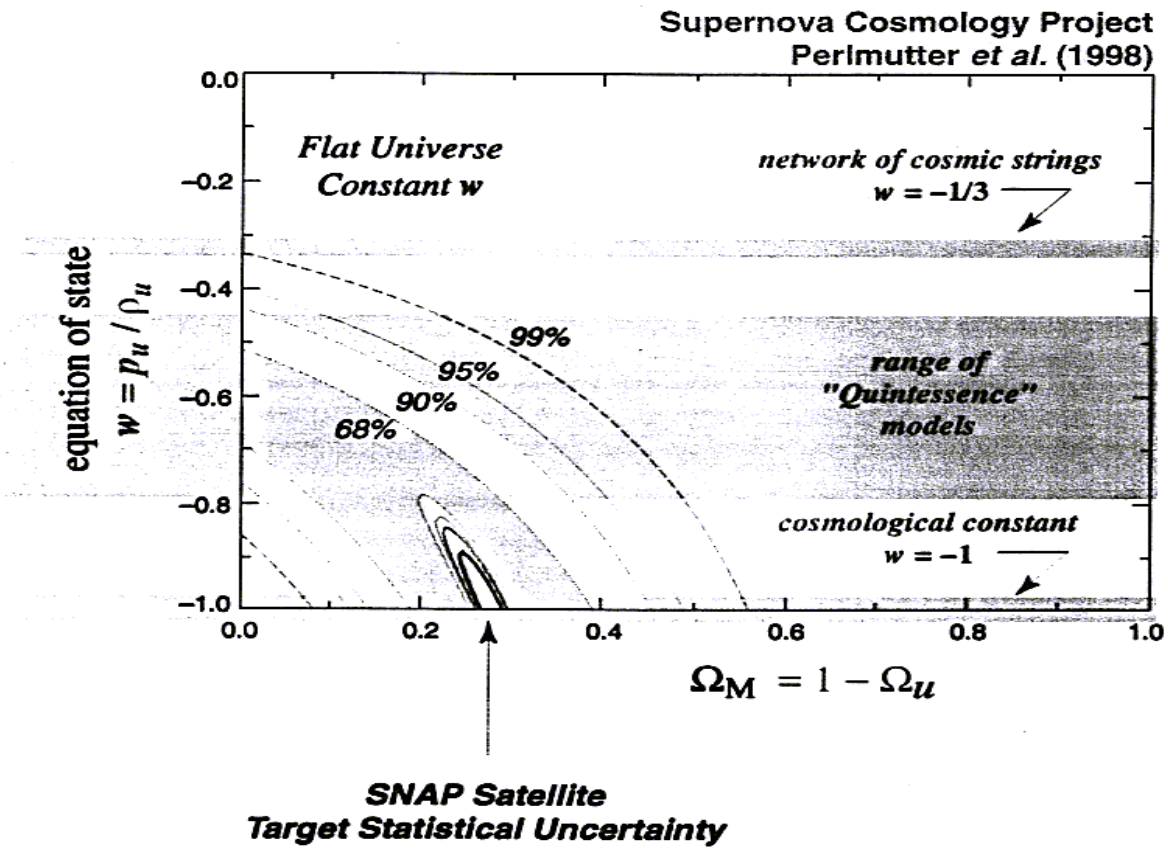
SNe


Baseline One-Year Sample
2000 SNe type Ia
SNAP Dark Energy Observer
fainter
magnitude
30
25
20
15
10
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
MONTE CARLO
0.0
0.5
1.0
1.5
2.0
redshift
0
2
4
6
8
10
"look-back" time
[billions of years before present]


Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAP SAT 2000 SNe
Target Statistical Uncertainty
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

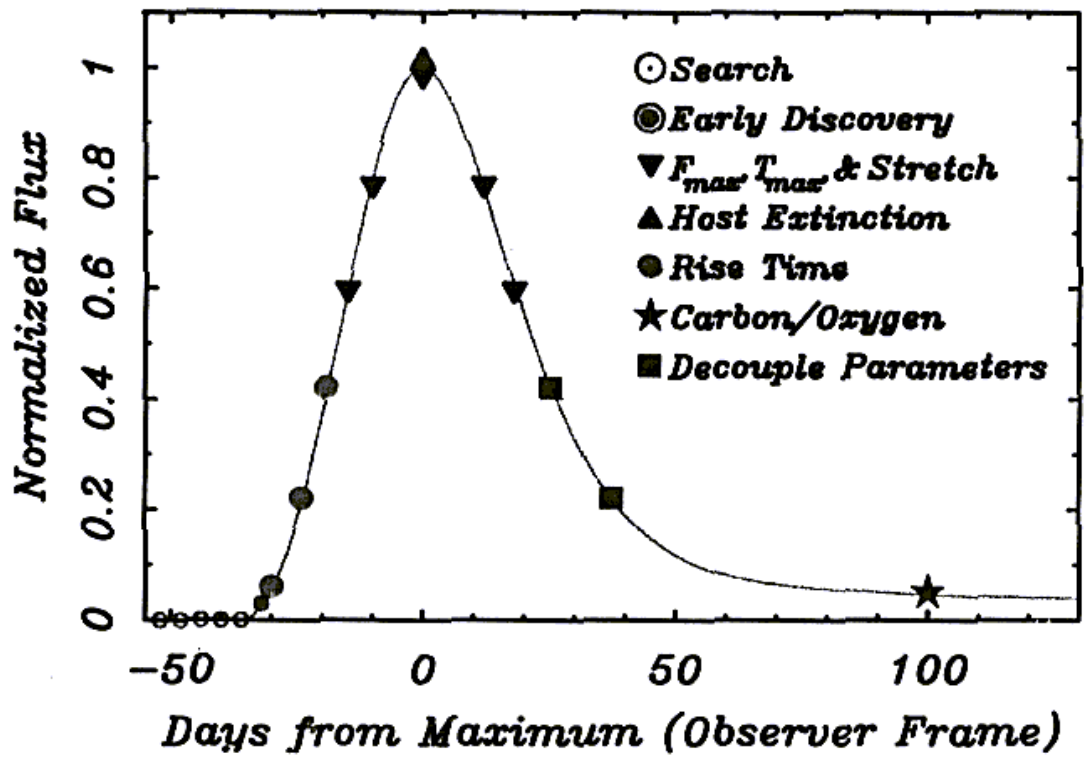
Dark Energy

Unknown Component, Ω_u, of Energy Density

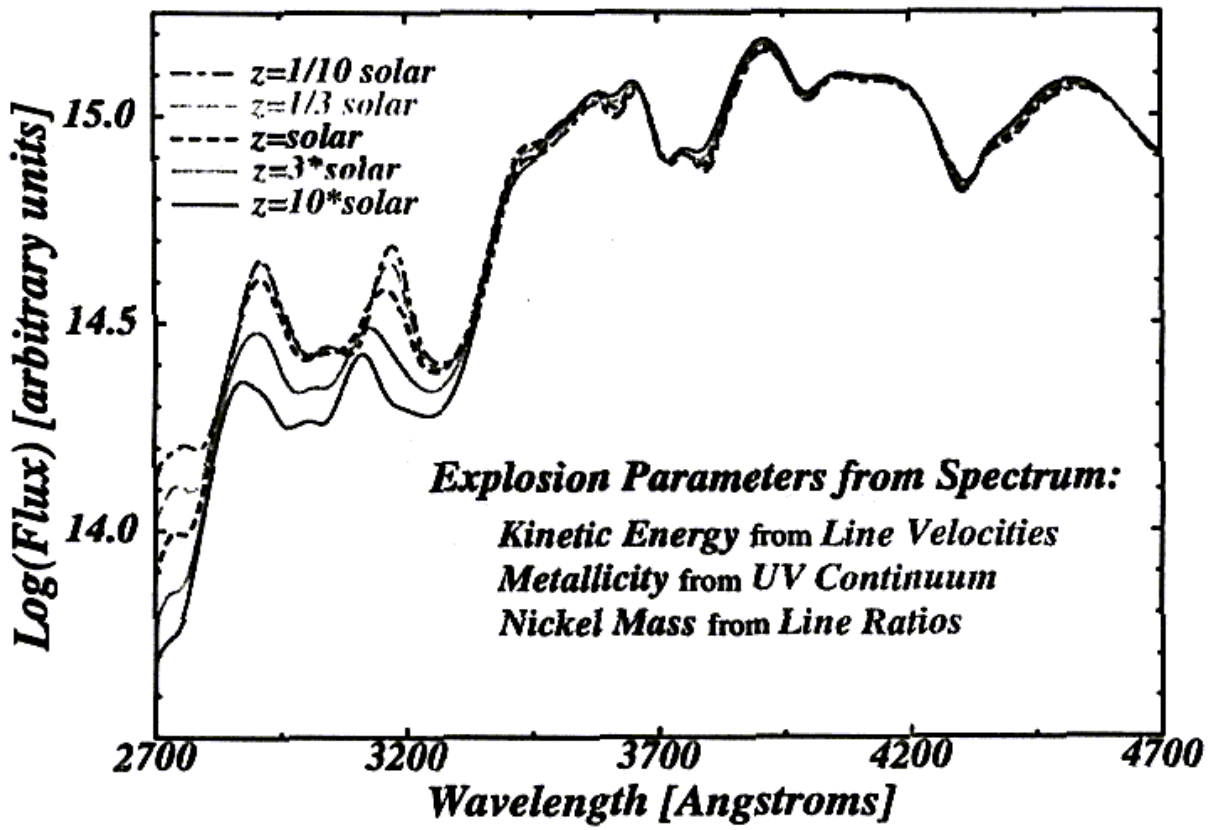


Measure Light Curve from 2 days to 80 days in Rest frame

B−band Lightcurve Photometry for z = 0.8 Type Ia

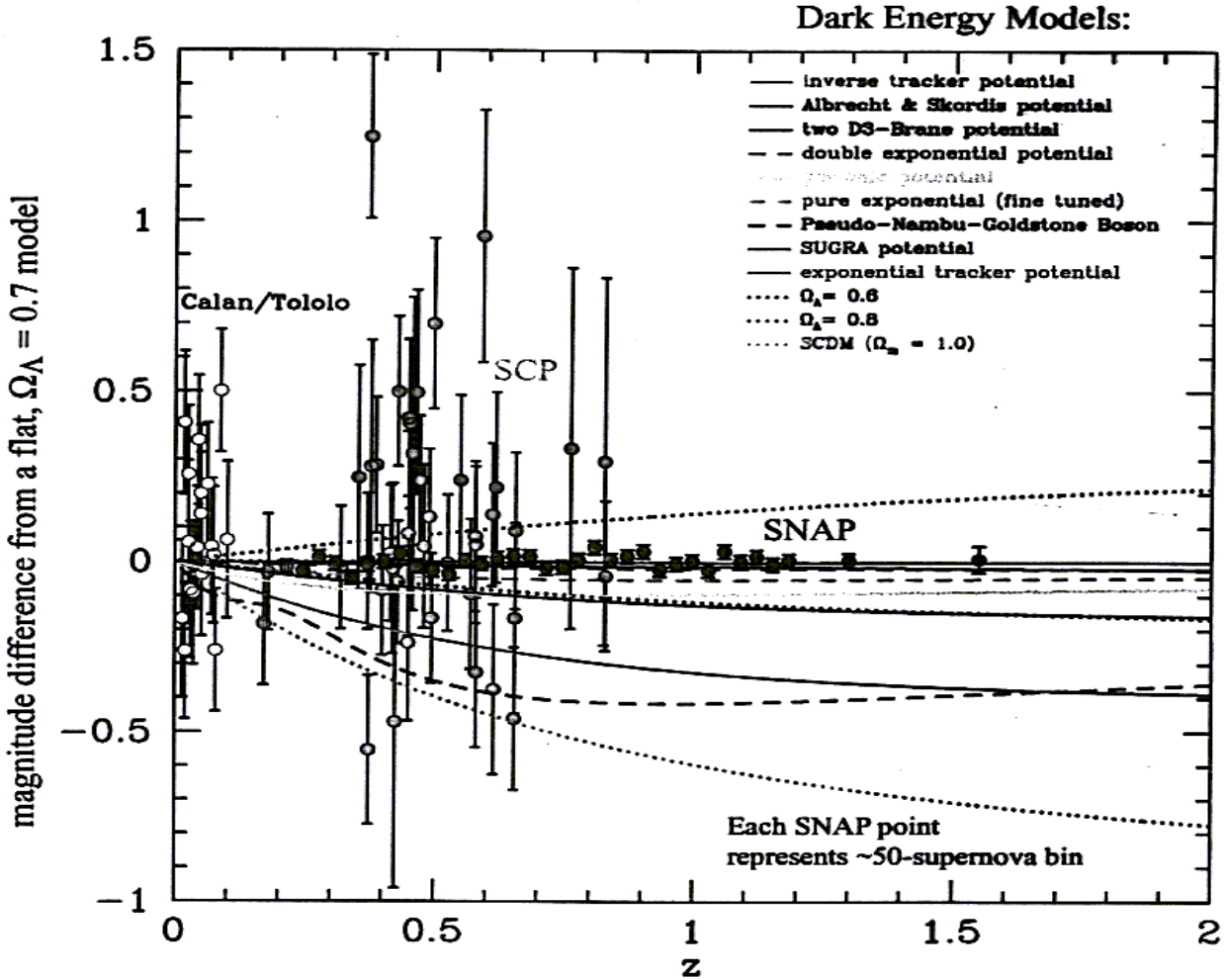


METALICITY


z=1/10 solar
z=1/3 solar
z=solar
z=3*solar
z=10*solar
15.0
14.5
14.0
Log(Flux) [arbitrary units]
2700
3200
3700
4200
4700
Wavelength [Angstroms]
Explosion Parameters from Spectrum:
Kinetic Energy from Line Velocities
Metallicity from UV Continuum
Nickel Mass from Line Ratios

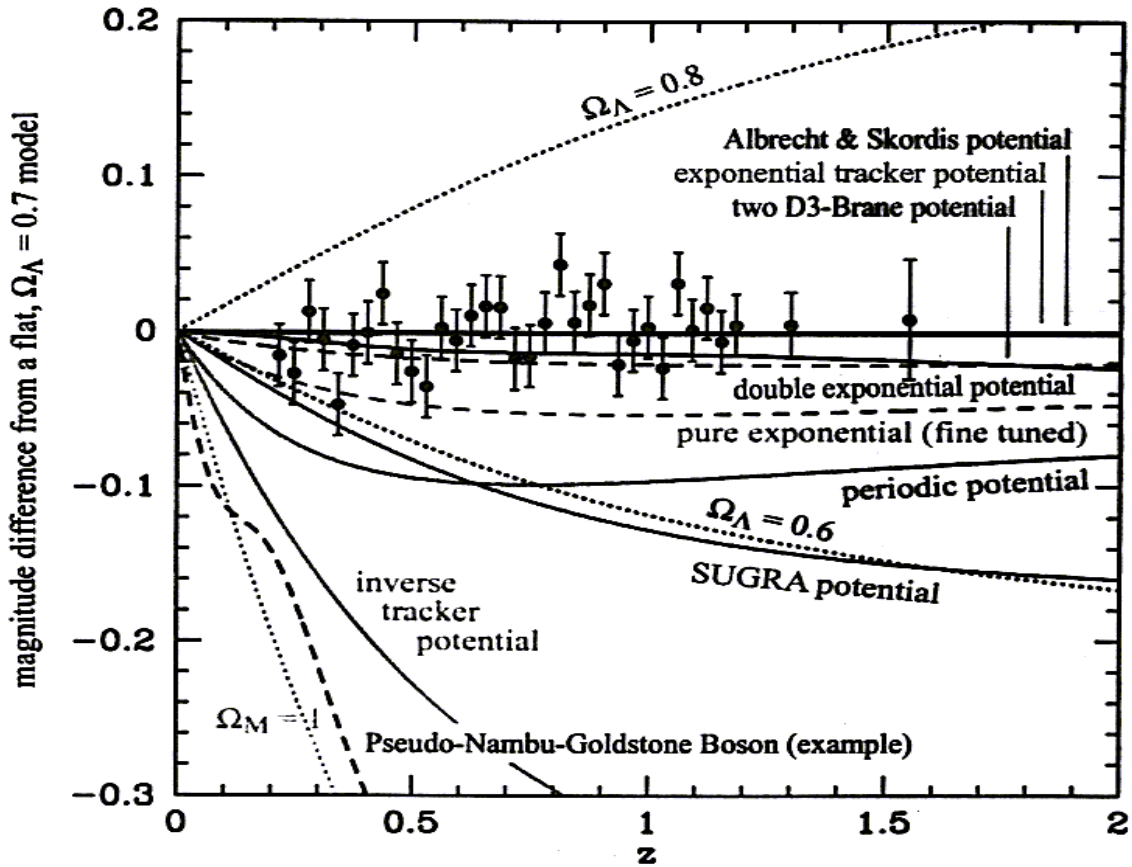
SNAP SuperNova Acceleration Probe

Current ground-based data
compared with binned simulated SNAP data.



SNAP SuperNova Acceleration Probe

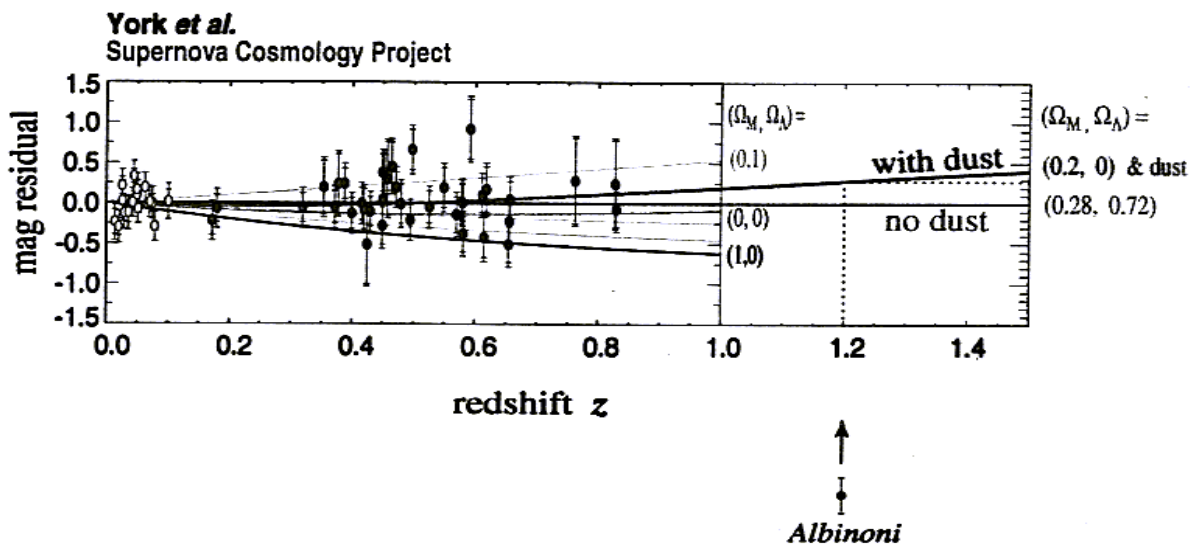
Binned simulated SNAP data compared with Dark Energy models currently in the literature.



Weller & Albrecht

Recognizing Intergalactic Grey Dust Using SNe at Redshifts > 1

?



see Aguirre (1999)
astro-ph/9904319

≃ 9 BILLION YEARS

BIG BANG ≈ 14 " "

WHEN DID THE MATTER-DOMINATED UNIVERSE BECOME Λ DOMINATED?

$$(1 + z)^3 \Omega_M = \Omega_\Lambda$$

$z = 0.37$ ~3.5 billion years ago

WHEN DID DECELERATION TURN TO ACCELERATION OF THE UNIVERSE?

$$q = \frac{\Omega_M}{2} - \Omega_\Lambda$$

$$(1 + z)^3 \frac{\Omega_M}{2} = \Omega_\Lambda$$

$z = 0.73$ ~6 billion years ago

BOTH OCCURRED DURING THE PERIOD OUR SNe WERE EXPLODING!