SUPERNOVAE!

DARK ENERGY

Robert Kirshner
Harvard-Smithsonian
Center for Astrophysics

Einstein™ & de Sitter (1932) [... of Λ]

"... an increase in the precision of data derived from observation will enable us in the future to fix its sign and determine its value."

337
523

JUST SIX NUMBERS

The Deep Forces that Shape the Universe

MARTIN REES

Plan of the Talk

- SN studies are thriving
- Doubled sample at low redshift
  explored U-band properties
- SNIa as the best standard candles H_0
- Hubble diagram for SNIa: evidence for Λ
- Measuring the cosmic equation of state

CTIO "ESSENCE": 200 SNIa @ $z \sim 0.5$

HST SN/GOODS SNIa @ z 1-1.8

w

SN Studies:

Nearby — automated search by KAIT

Weidong Li & Alex Filippenko UCB

	Kait	All others
1997	1	27
1998	20*	39
1999	40*	43
2000	38	47
2001	68*	70
2002	56 (4q15)	38

* world record

CfA: 1.5^m SPECTRA + 1.2^m LIGHT CURVES

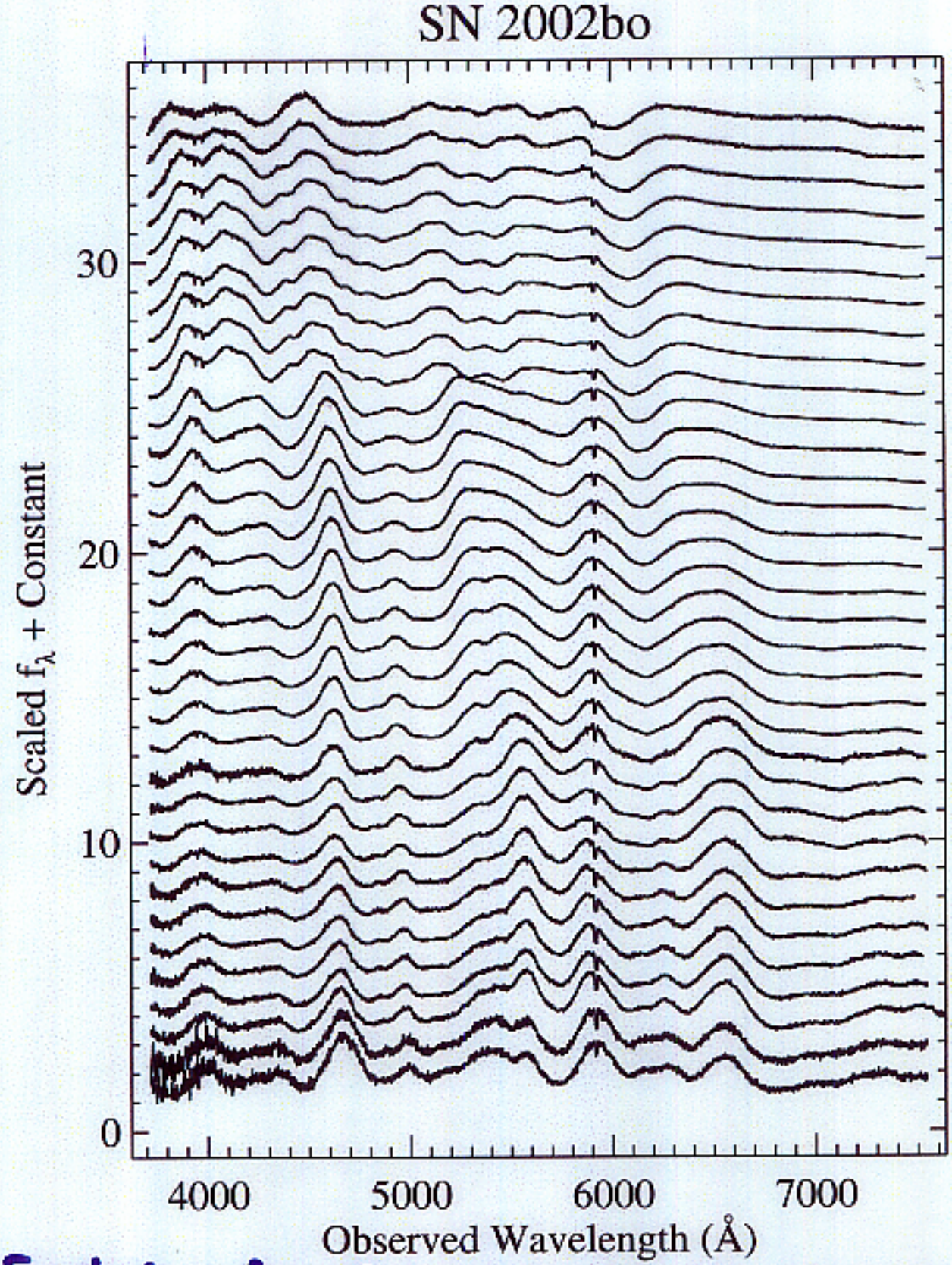
73 IAU Circulars in past year

SNIa: 93 SNII: 76 SNIIn: 12

SNIIb: 1 SNIb: 12 SNIc: 16

Unknown: 6

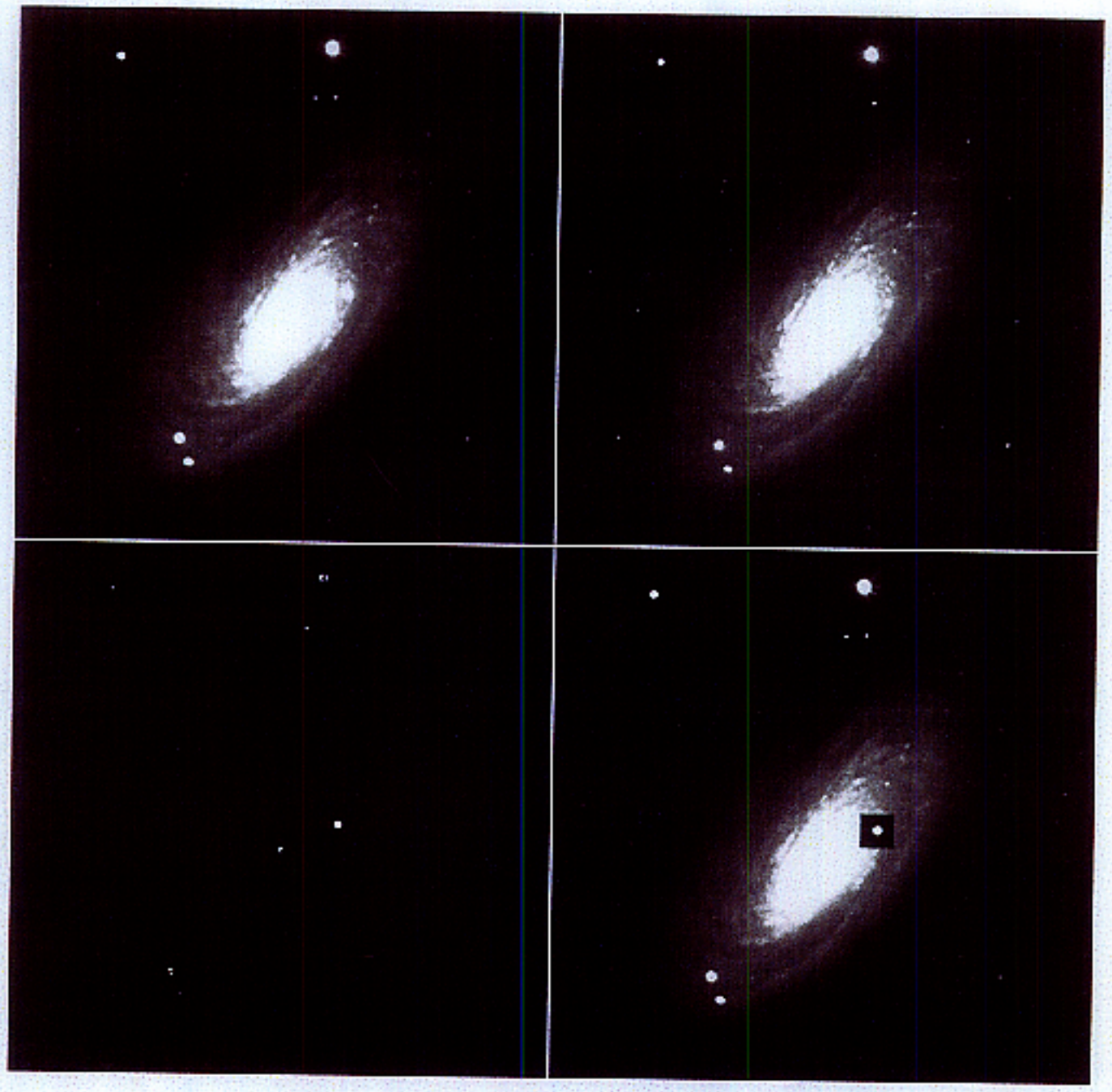
CfA: 34 Epochs of Spectroscopy for a SNIa

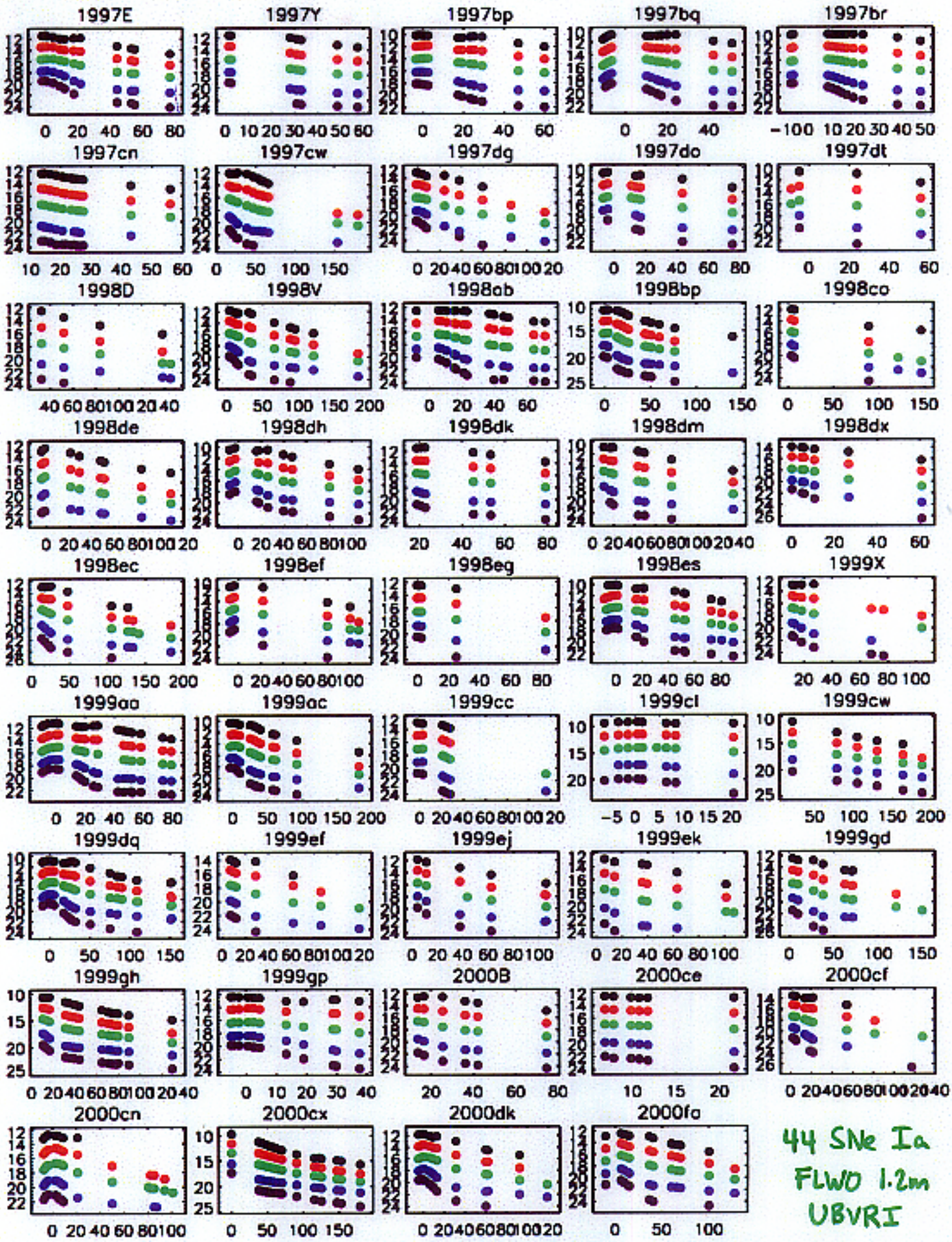


Explosion of a C-O white dwarf: NO HYDROGEN

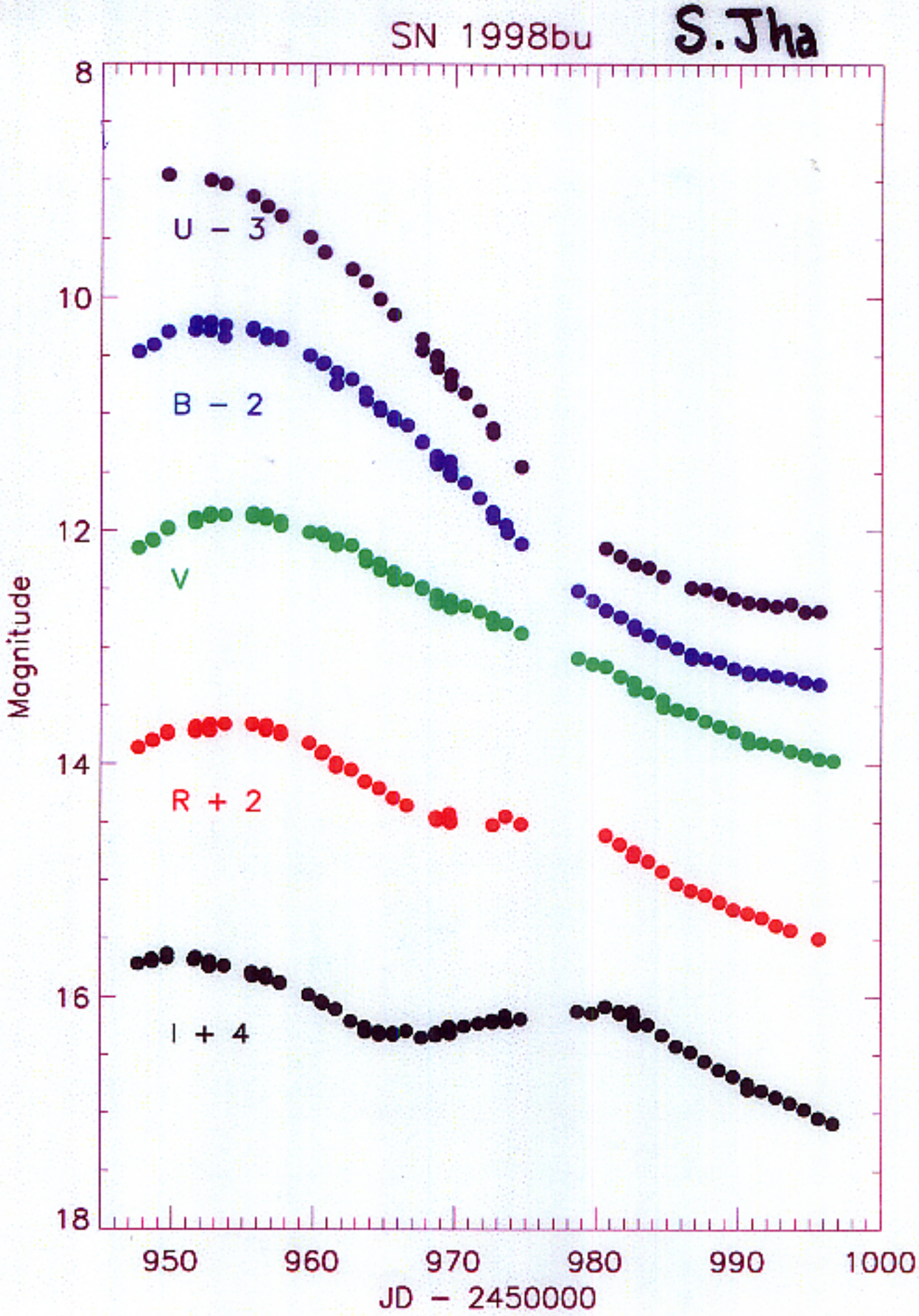
Saurabh Jha Ph.D. 2001 ⇒ MILLER

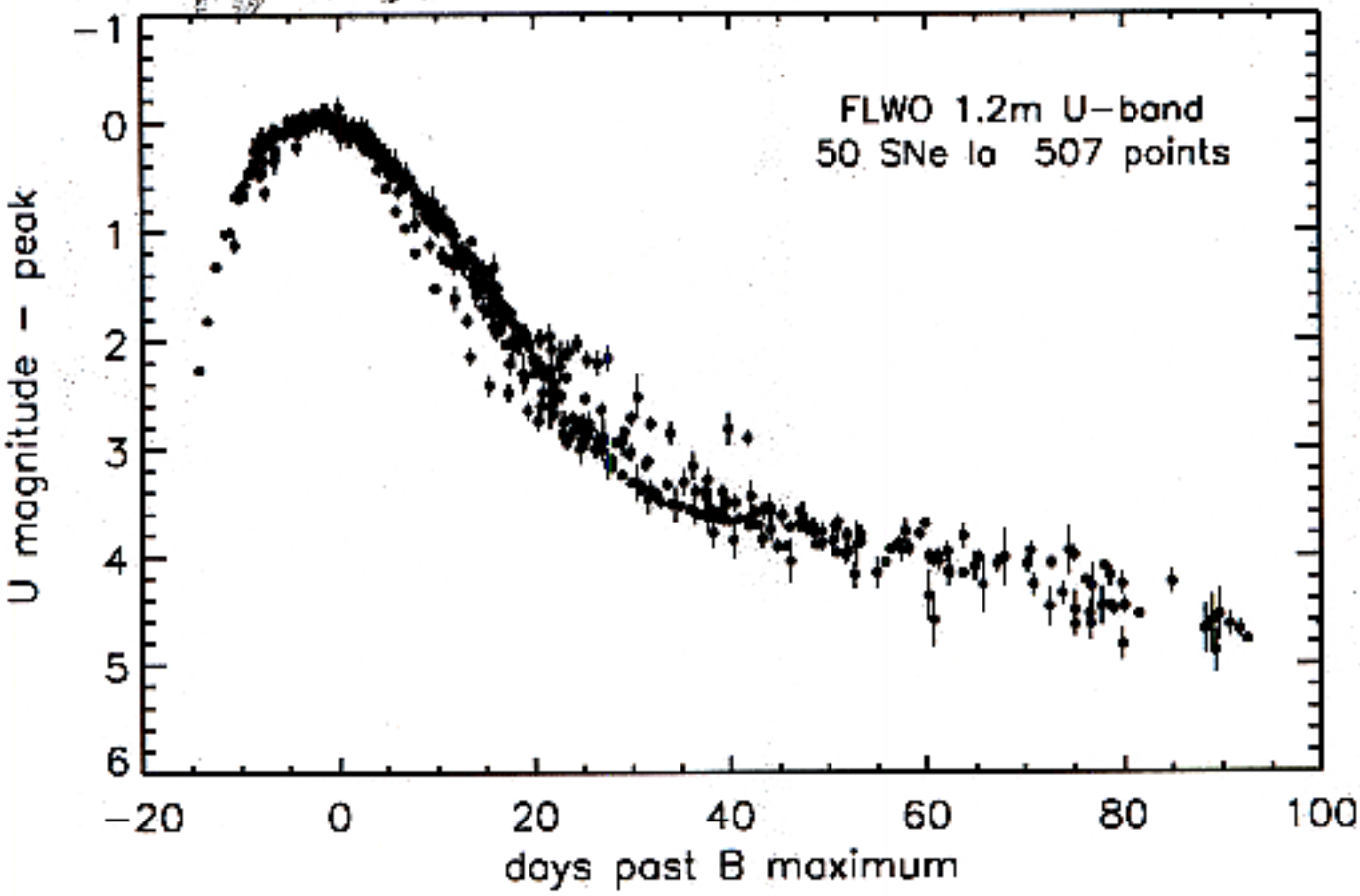
SN 1999cl in NGC 4501 (M88)



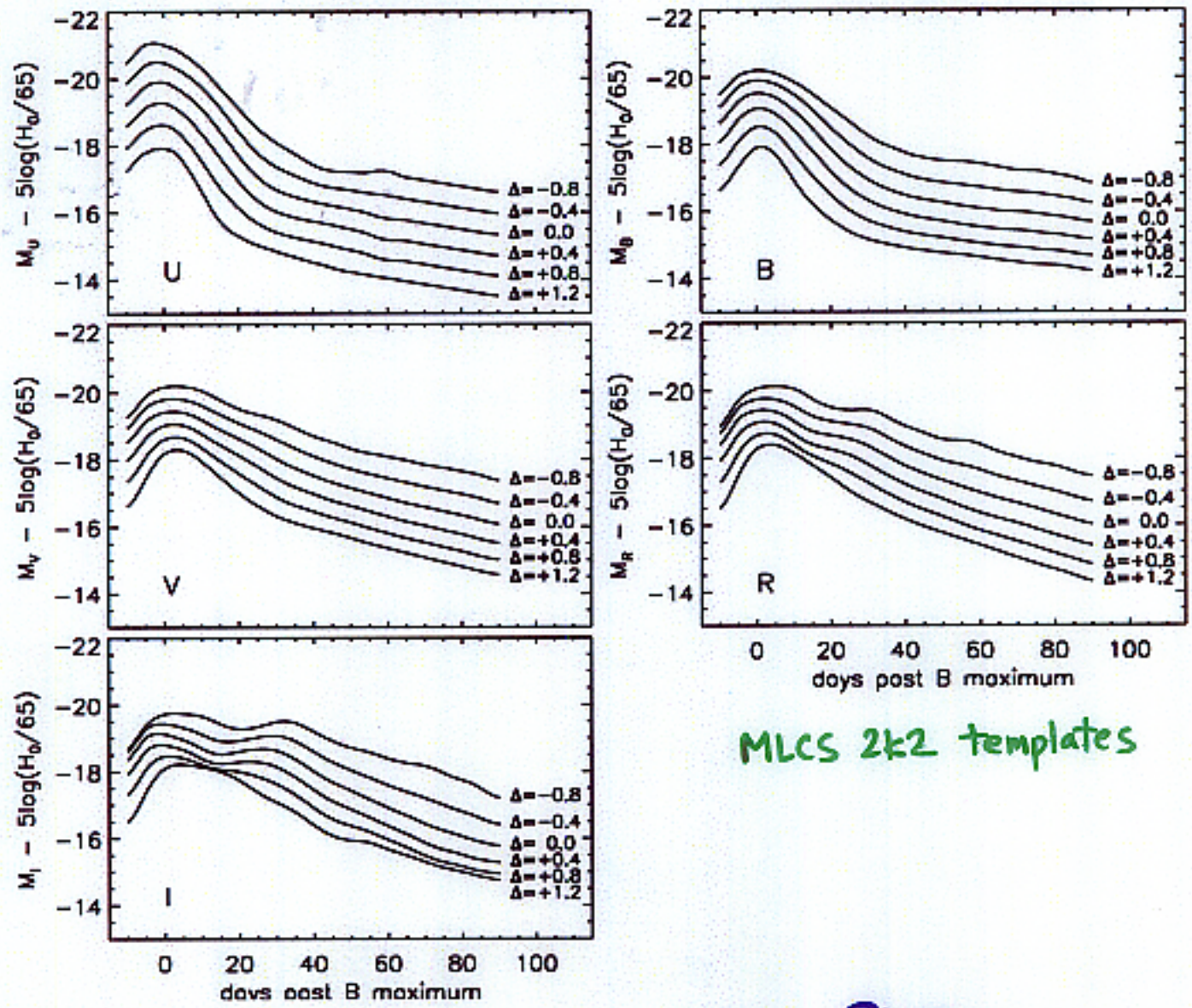


44 SNe Ia
FLWO 1.2m
UBVRI


SN 1998bu
S.Jha
U − 3
B − 2
V
R + 2
I + 4
Magnitude
JD − 2450000
8
10
12
14
16
18
950
960
970
980
990
1000


FLWO 1.2m U−band
50 SNe Ia 507 points
U magnitude − peak
days past B maximum
−1
0
1
2
3
4
5
6
−20
0
20
40
60
80
100

Saurabh Jha, Ph.D.



MLCS 2k2 templates

Δm_{15} Phillips
Hamuy

SCP-"stretch"

Emitted Frame

UBVRI

1.0 0.7 0.5 0.2 0

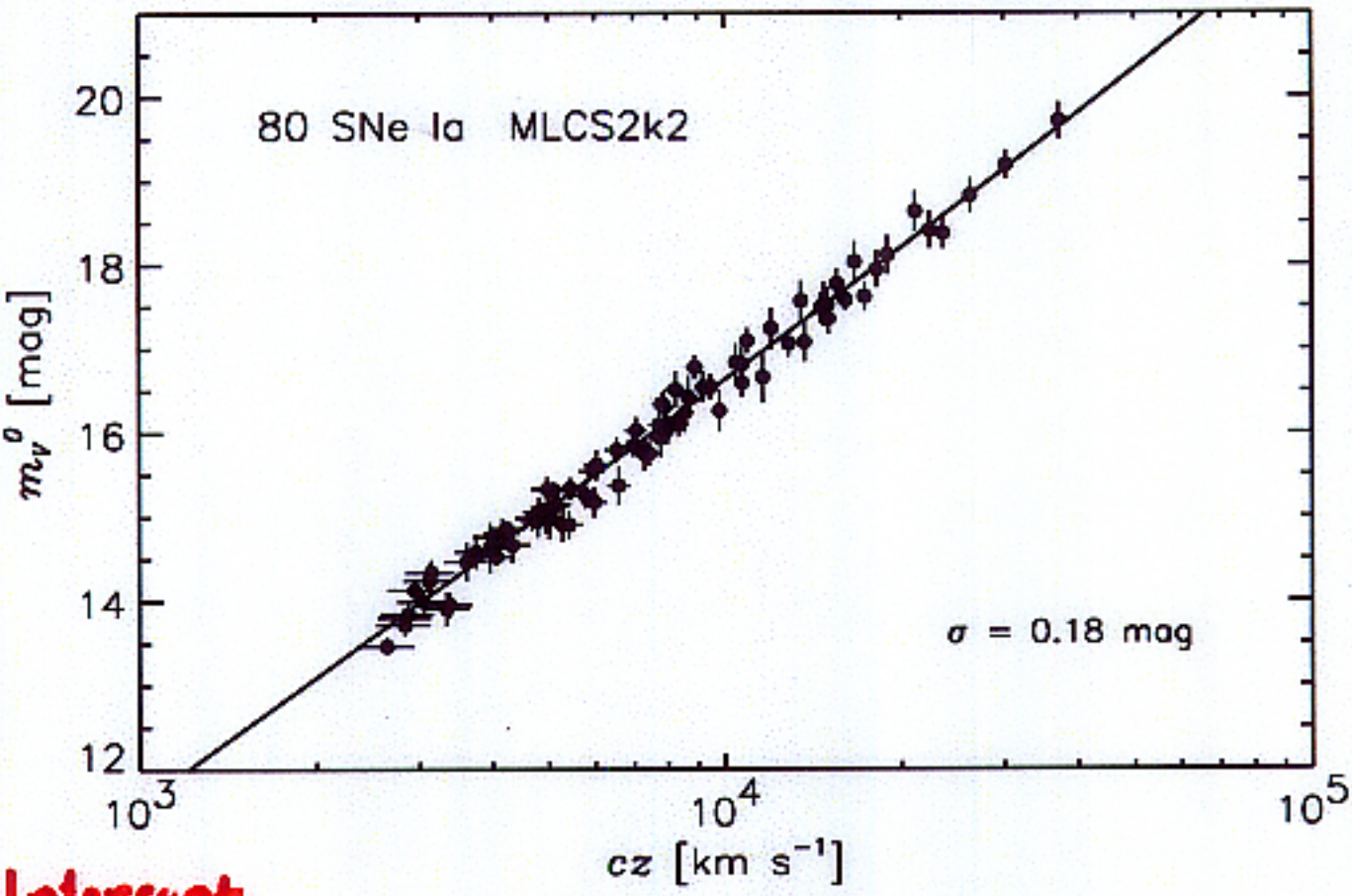
Observed Frame

U B V R I z

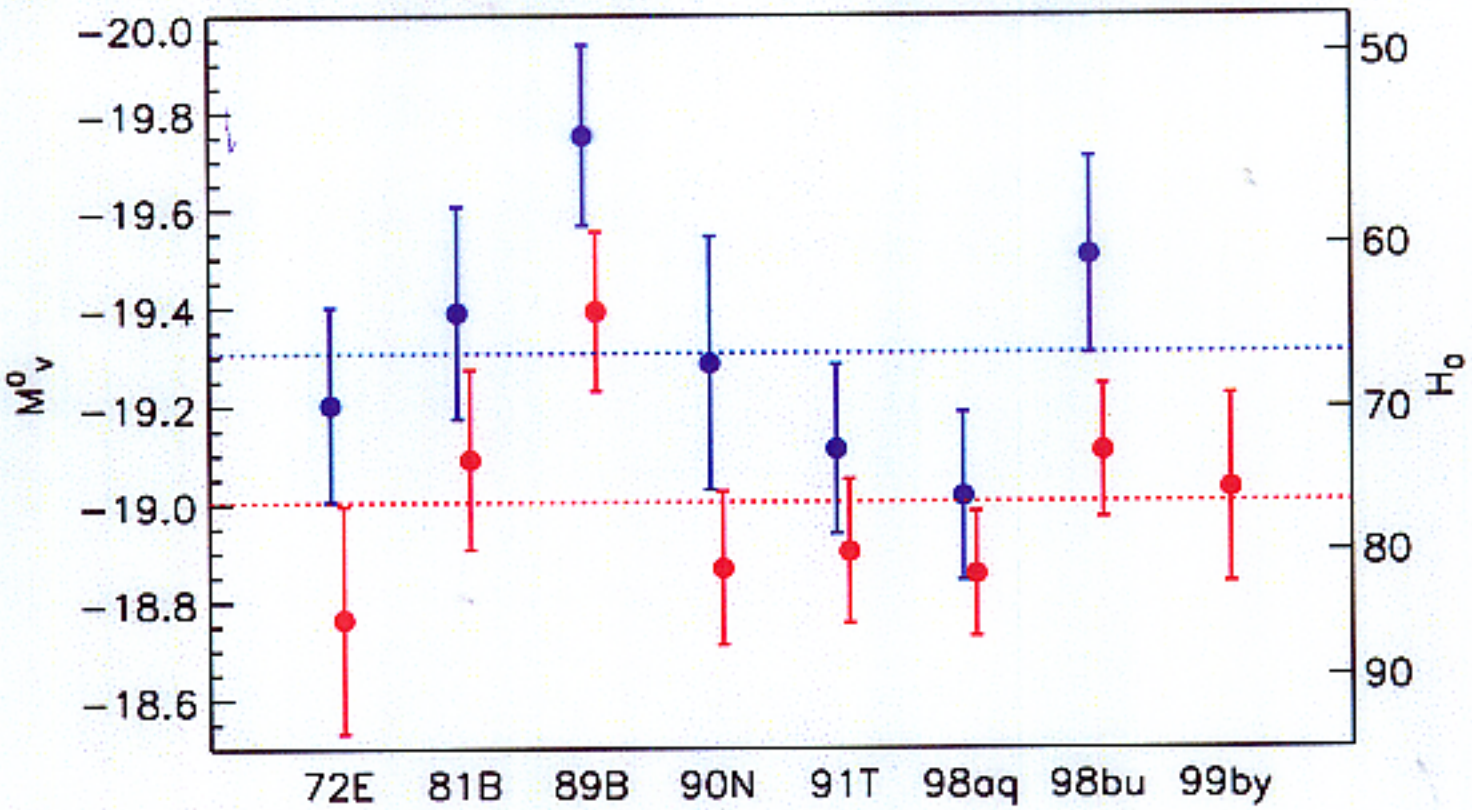
z = REDSHIFT

~ 20 in 1995

~ 40 in 1998



Intercept gives H_0 (if you know the luminosity of a SNIa)



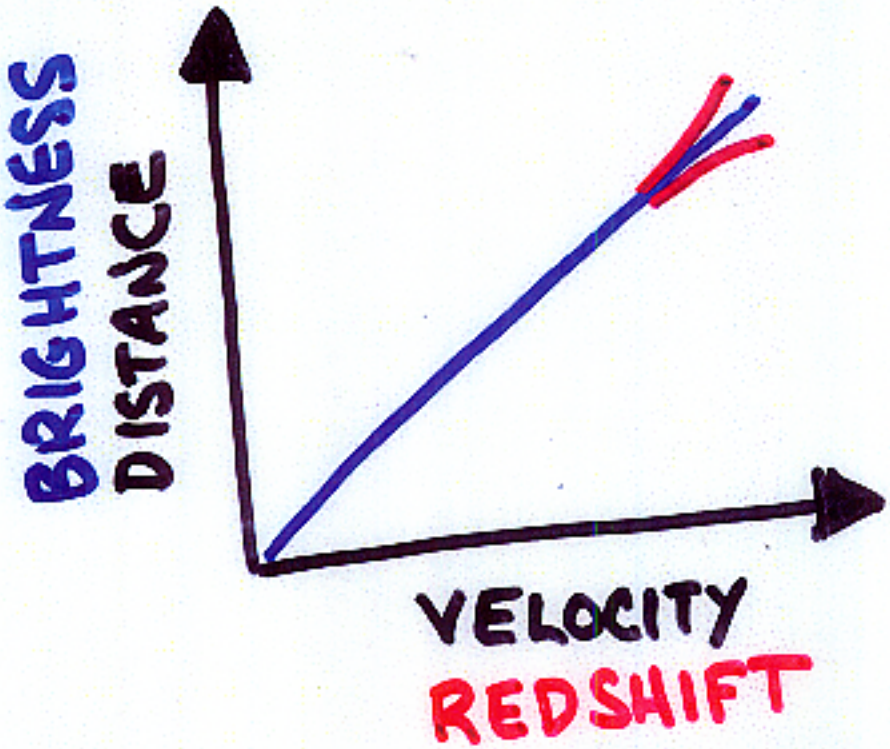
SN Ia Project (Saha et al. 2001)

Key Project (Freedman et al. 2001)

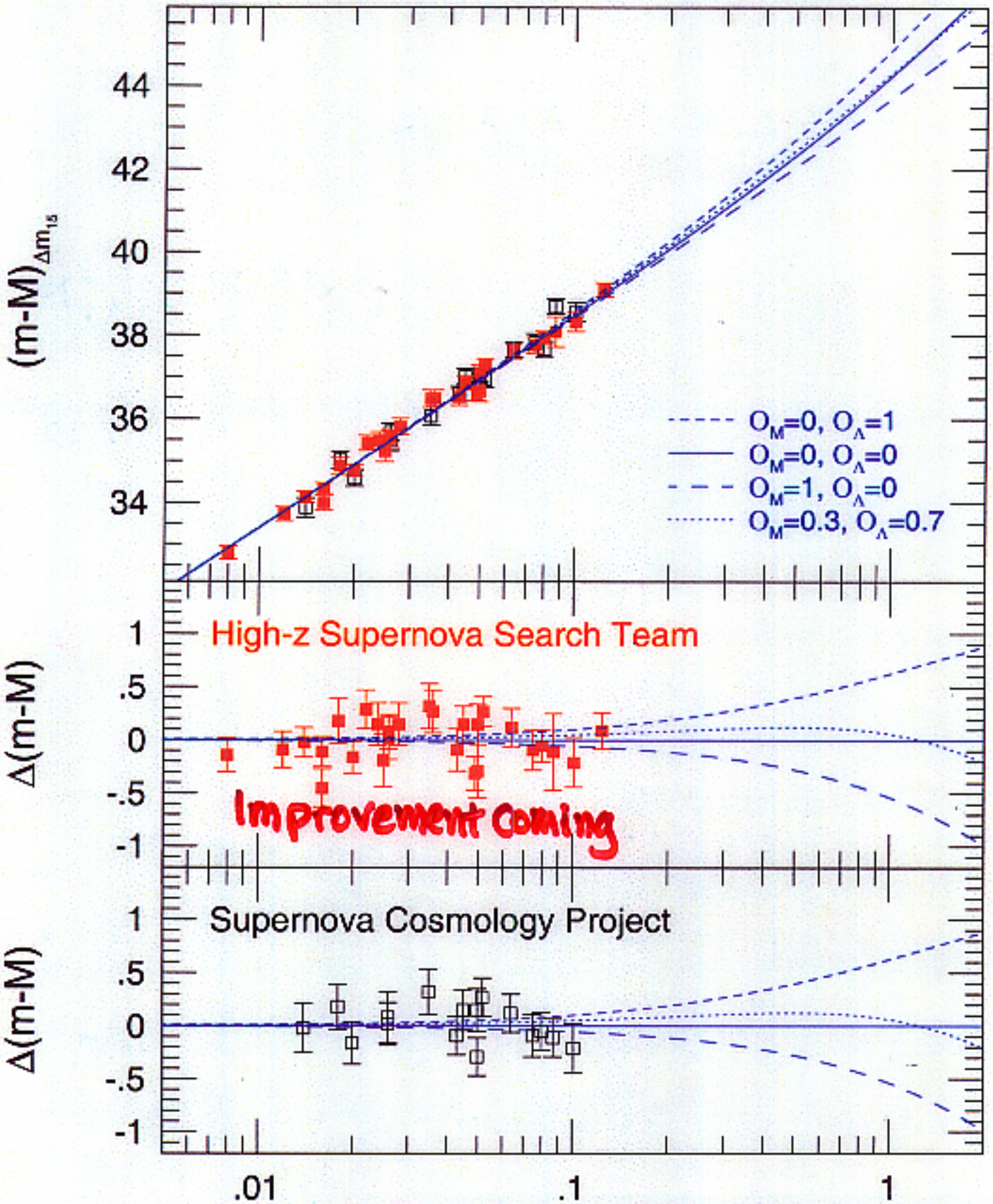
All the uncertainty is in the Cepheid distances!

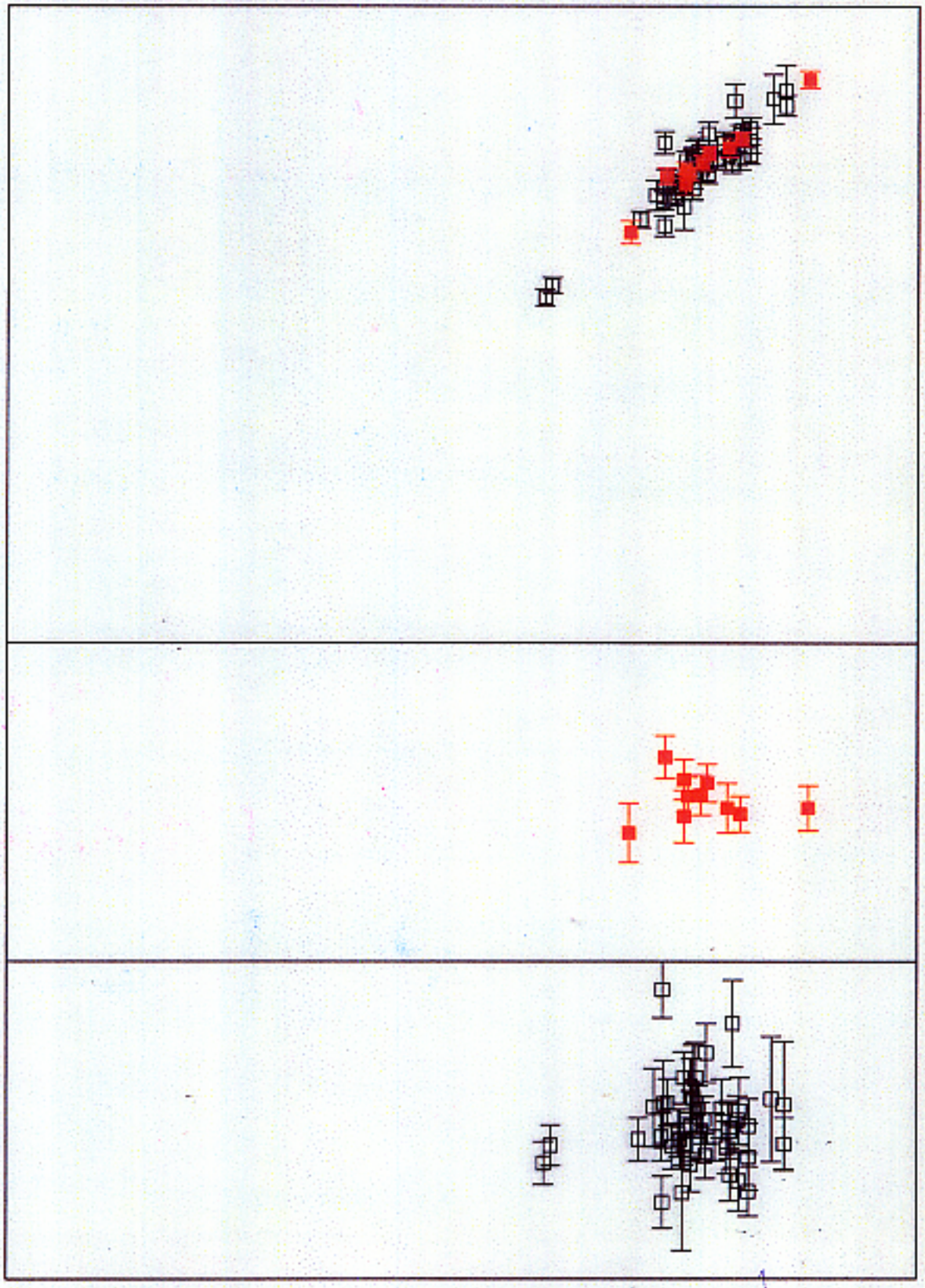
[Also distance to the Large Magellanic Cloud]

A GLOBAL TEST:



NEED A VERY BRIGHT AND RELIABLE STANDARD CANDLE


(m-M)$_{\Delta m_{15}}$
44
42
40
38
36
34
O_M=0, O_Λ=1
O_M=0, O_Λ=0
O_M=1, O_Λ=0
O_M=0.3, O_Λ=0.7
High-z Supernova Search Team
Δ(m-M)
1
.5
0
-.5
-1
Improvement Coming
Supernova Cosmology Project
Δ(m-M)
1
.5
0
-.5
-1
.01
.1
1



High z: few points but smaller errors

Supernovae
CMB
Dark Energy (Ω_Λ)
Matter (Ω_M)
0
1
0
1

SUPERNOVA OBSERVATIONS

PROVIDE THE ONLY EVIDENCE

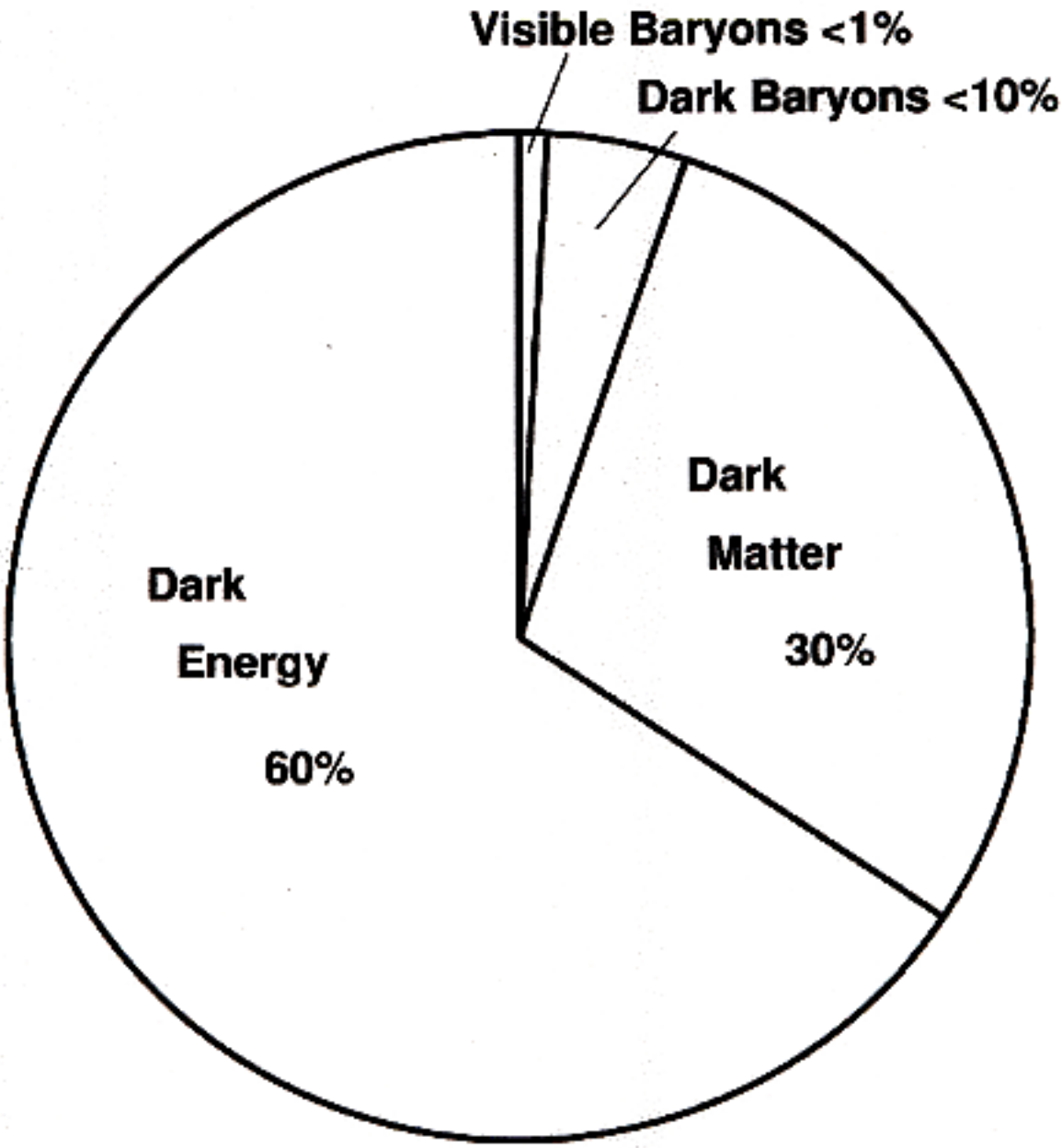
FOR ACCELERATION. ($p<0$!)

COMBINING CMB + SNIa $\Rightarrow$

A CONSISTENT PICTURE

$$\Omega_m \sim 0.3 \quad \Omega_\Lambda \sim 0.7$$

Cluster dynamics $\Rightarrow \Omega_m \sim 0.3$



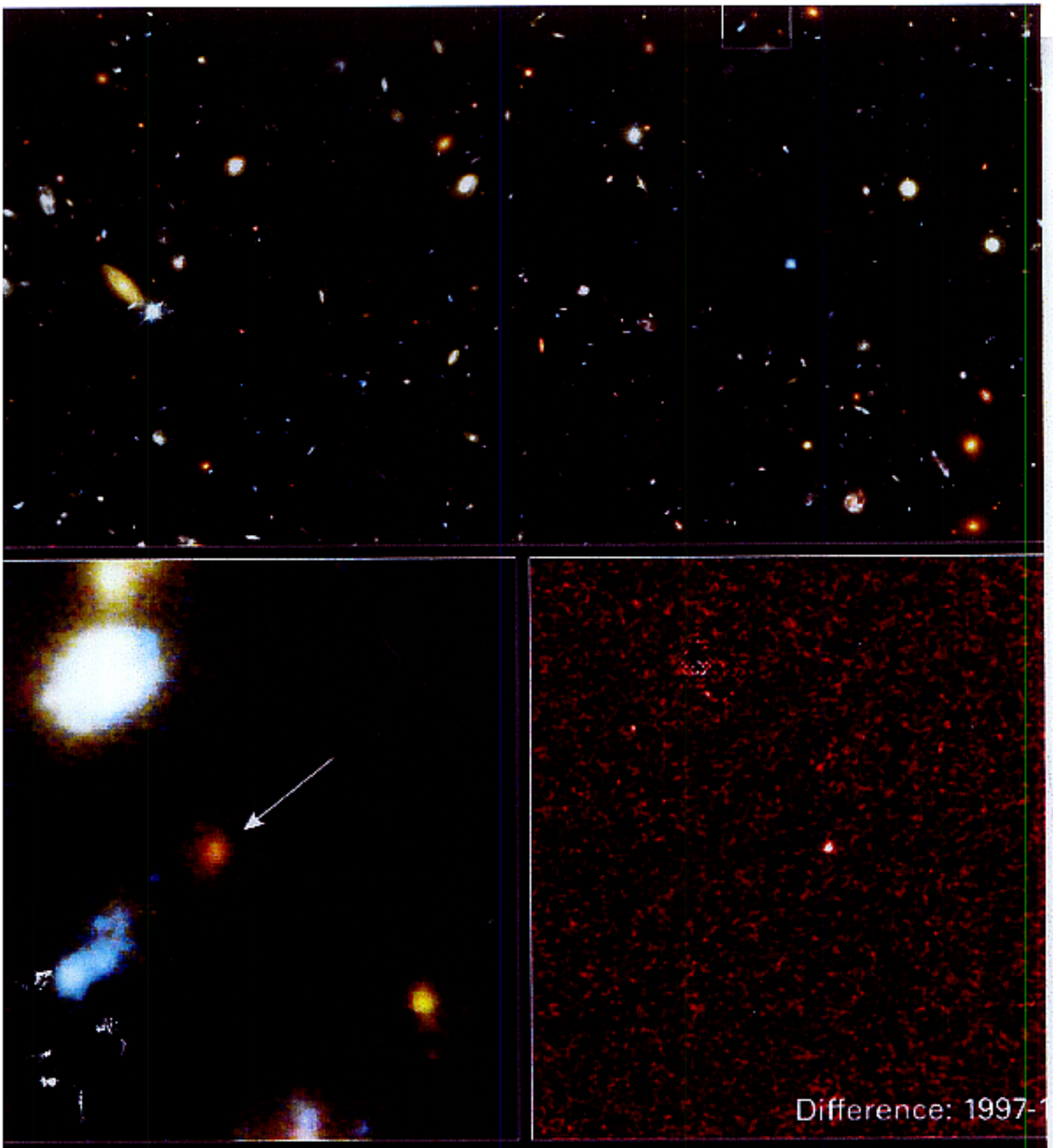
Contents of the Universe

Go To Higher z!

$$\rho_m \sim (1+z)^3$$

See <u>deceleration</u> by $z \sim 1$

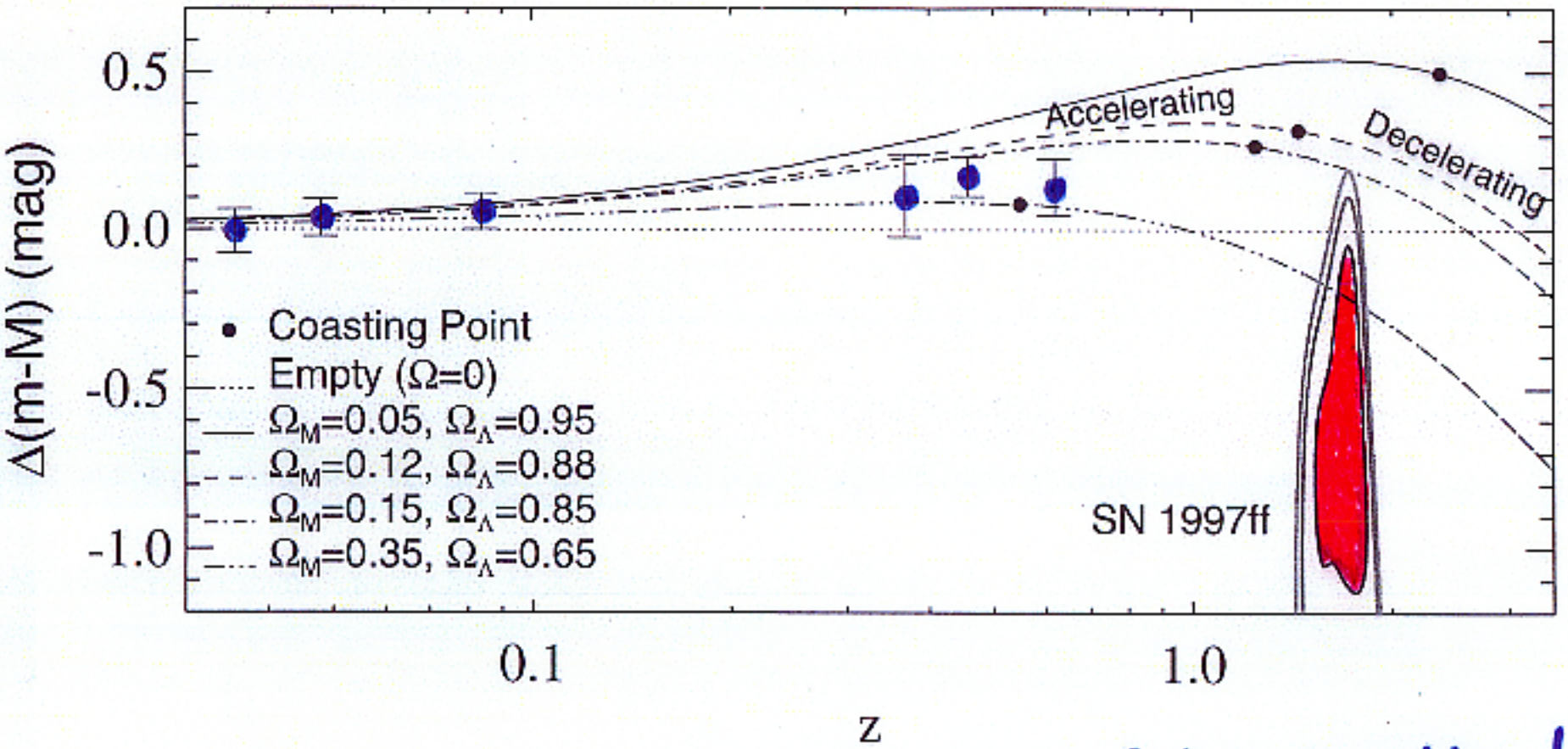
Change of <u>sign</u> for effect on SNIa magnitudes



Distant Supernova in the Hubble Deep Field

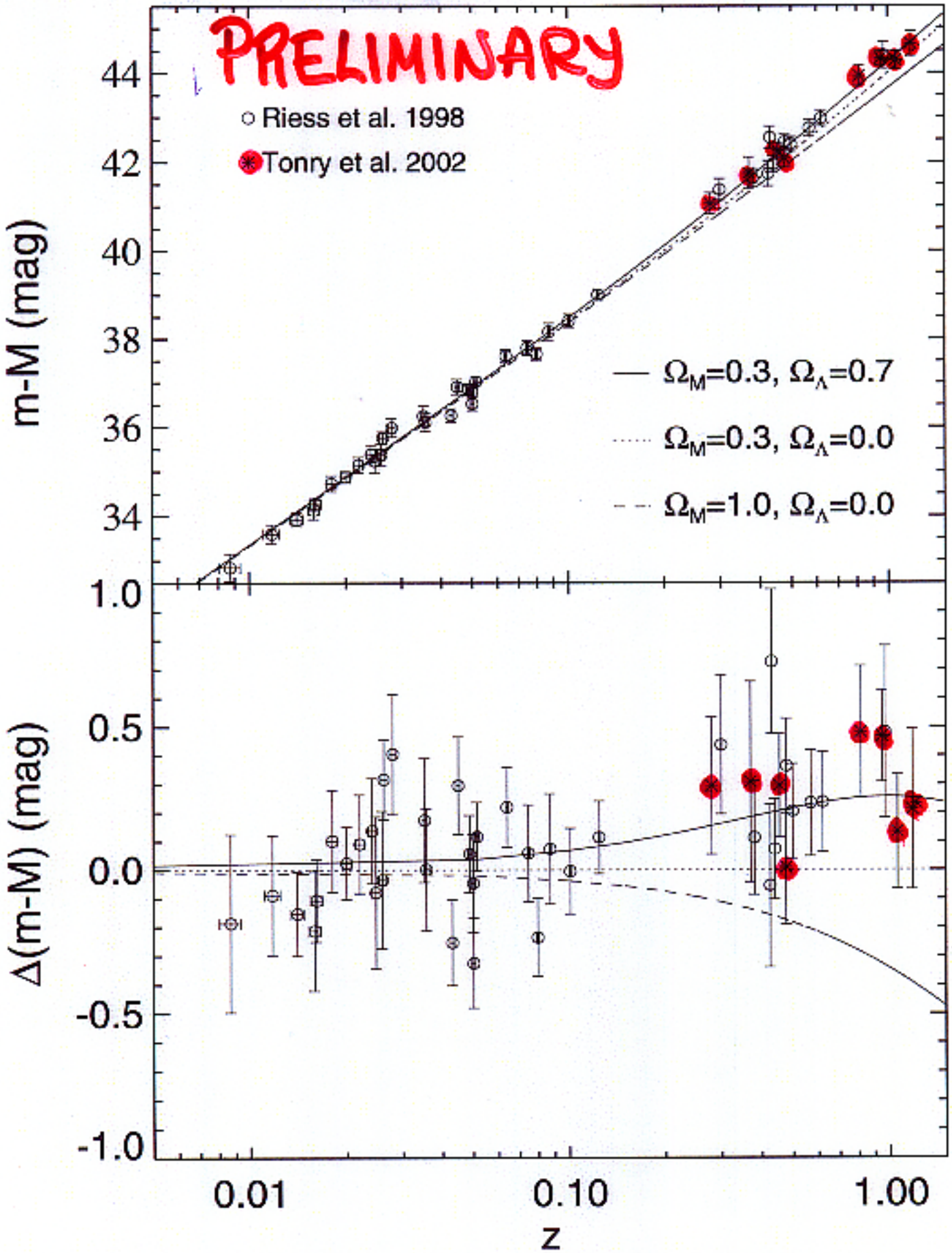
Hubble Space Telescope • WFPC2

Riess et al. astro-ph/0104445

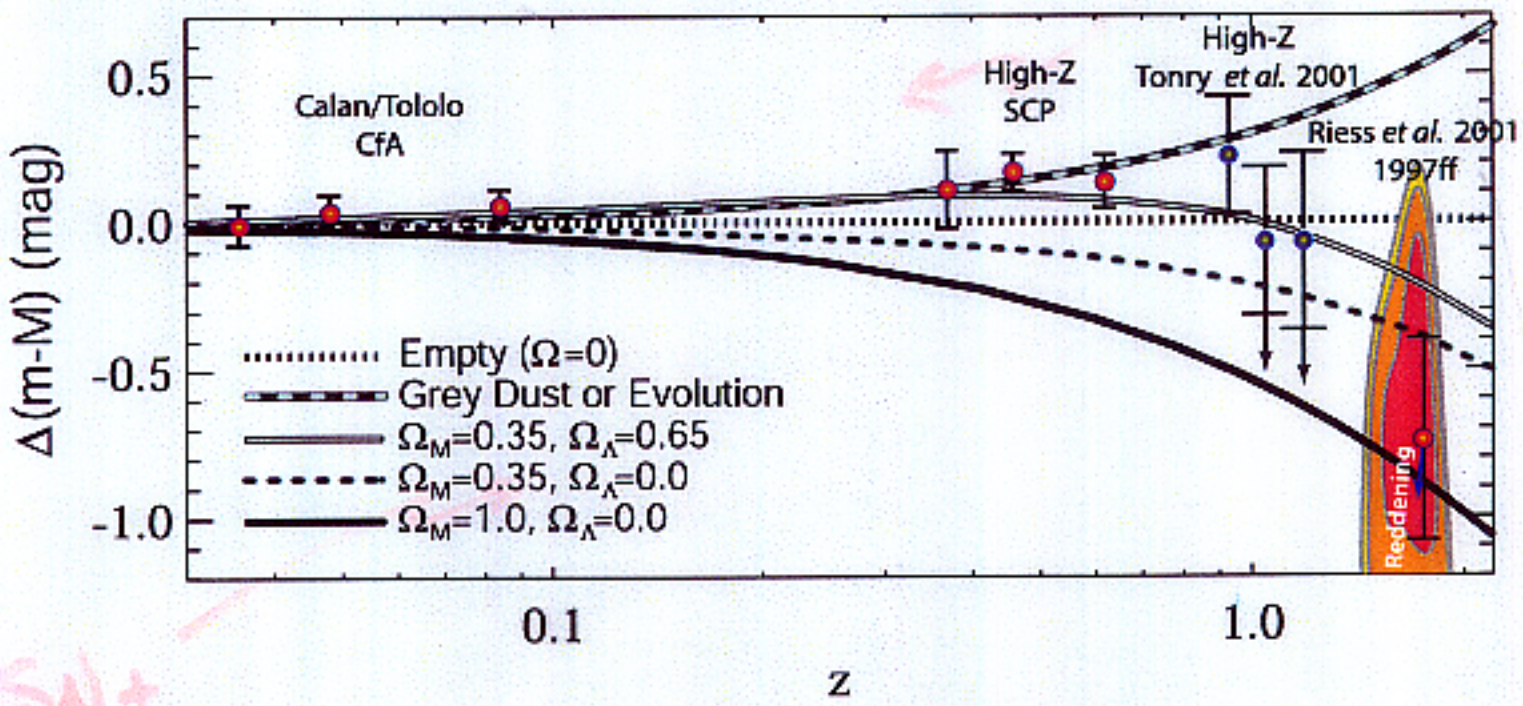


SN @ z=1.7 from the epoch of deceleration!

arXiv:astro-ph/0104455 27 Apr 2001


PRELIMINARY
Riess et al. 1998
Tonry et al. 2002
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
44
42
40
38
36
34
Δ(m-M) (mag)
1.0
0.5
0.0
-0.5
-1.0
0.01
0.10
1.00
z

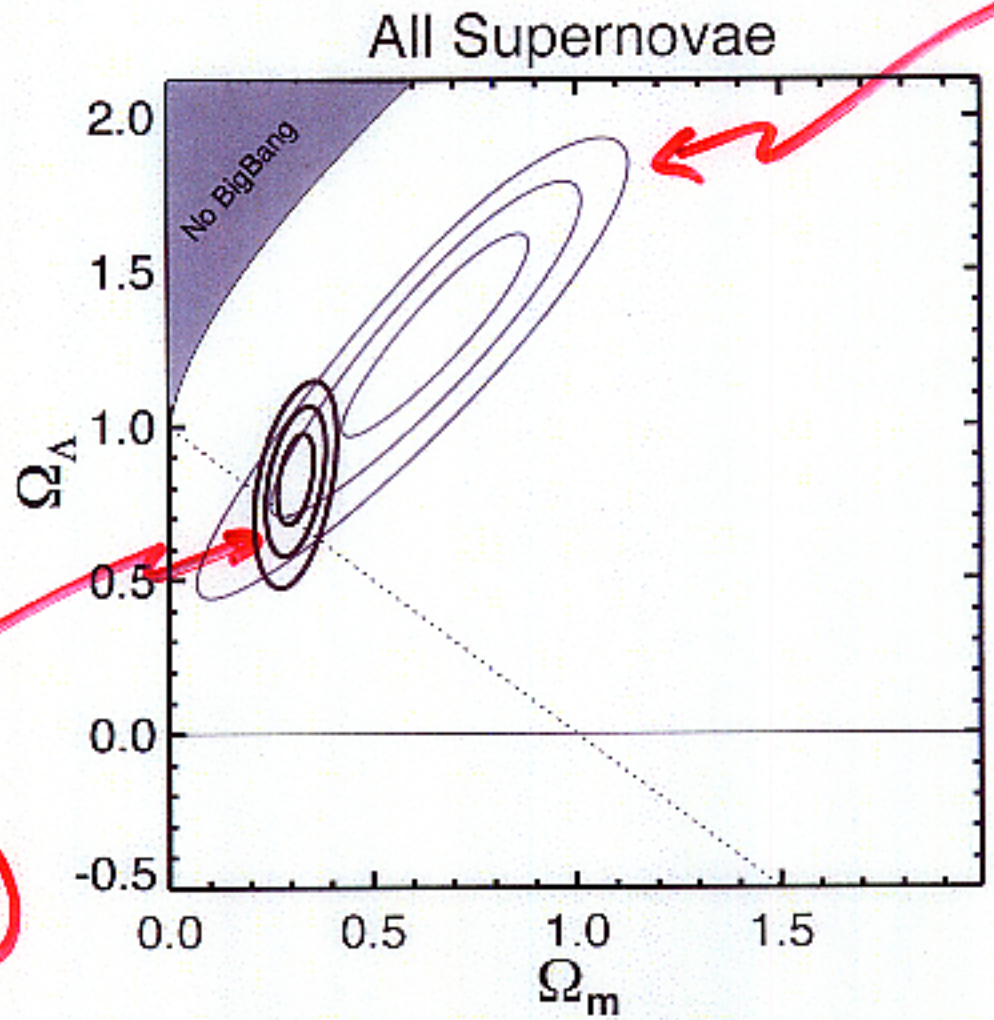
PRELIMINARY SN ONLY



SN + CMB ($\Omega_{TOT} \geq 1$)

PRELIMINARY

SN ONLY



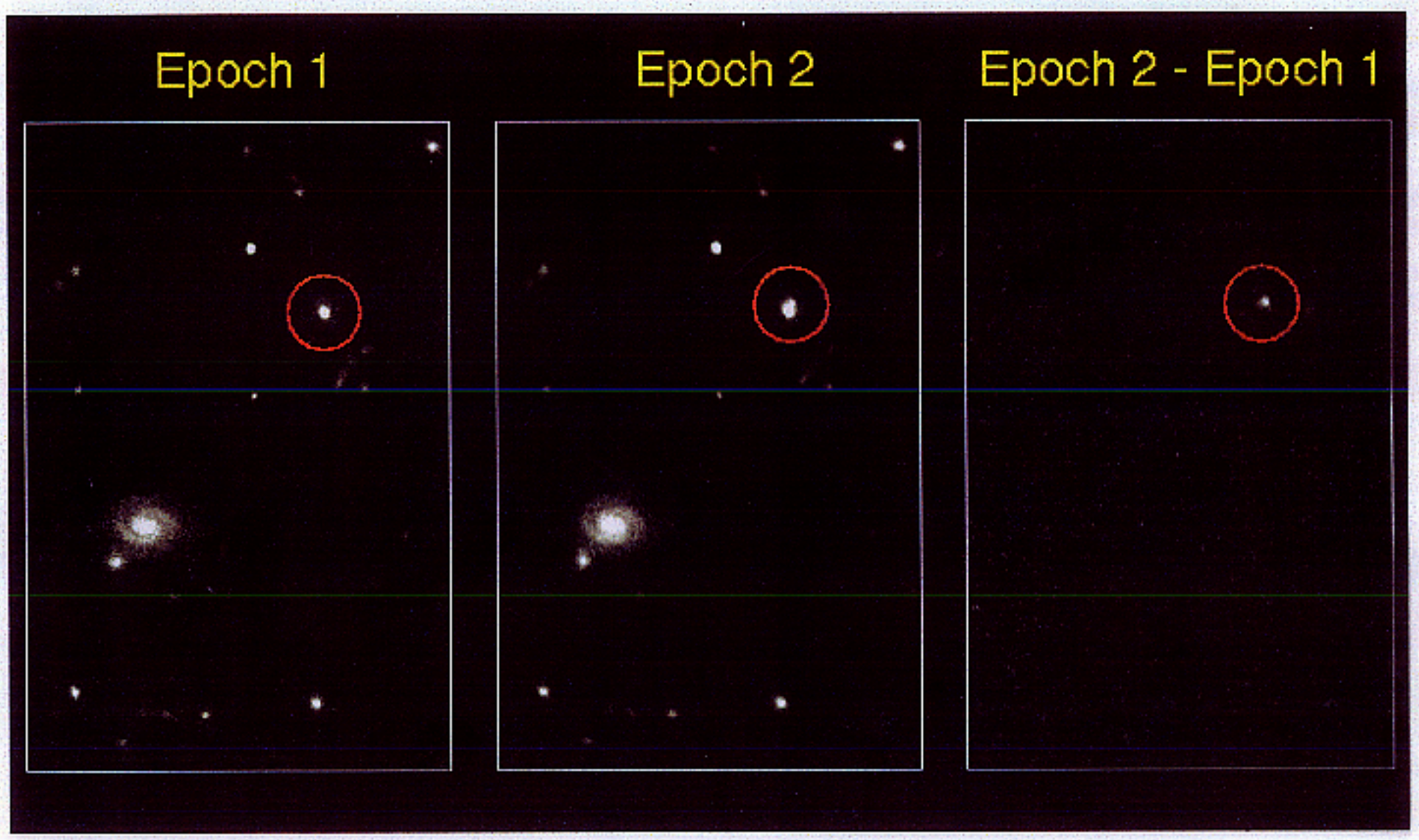
SN + CMB ($\Omega_{TOT} = 1$)

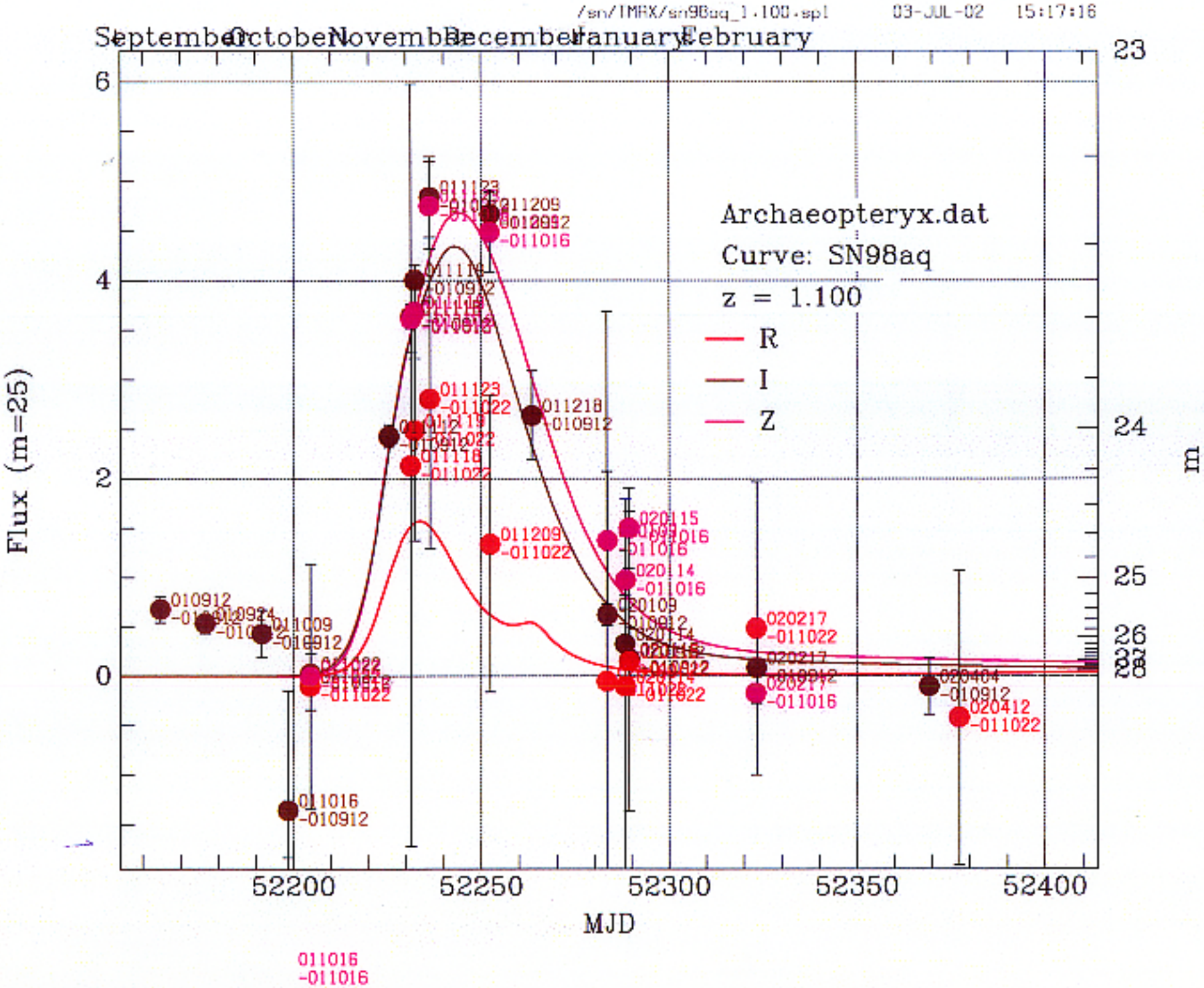
$H_0 t_0 \sim 1 \pm 0.05$!

BUILDING UP THE SAMPLE

NOT JUST "BEFORE" AND "AFTER" ⇒ A CAMPAIGN TO MONITOR SN

JOHN TONRY
BRIAN BARRIS } 2001 @ SUBARU


Epoch 1
Epoch 2
Epoch 2 - Epoch 1


/sn/IMRX/sn98aq_1.100.spl 03-JUL-02 15:17:16
September
October
November
December
January
February
Archaeopteryx.dat
Curve: SN98aq
z = 1.100
R
I
Z
Flux (m=25)
m
MJD
52200
52250
52300
52350
52400
6
4
2
0
23
24
25
26
011016
-011016

COMING SOON

"ESSENCE"

Nick Suntzeff, Brian Schmidt, Chris Stubbs ...

CTIO 4^m + MOSAIC CCD

1/2 a night every other night

~200 SNIa $0.3 < z < 0.8$

Higher precision on equation of state by building up the sample where the effect of dark energy is largest

Onset of acceleration

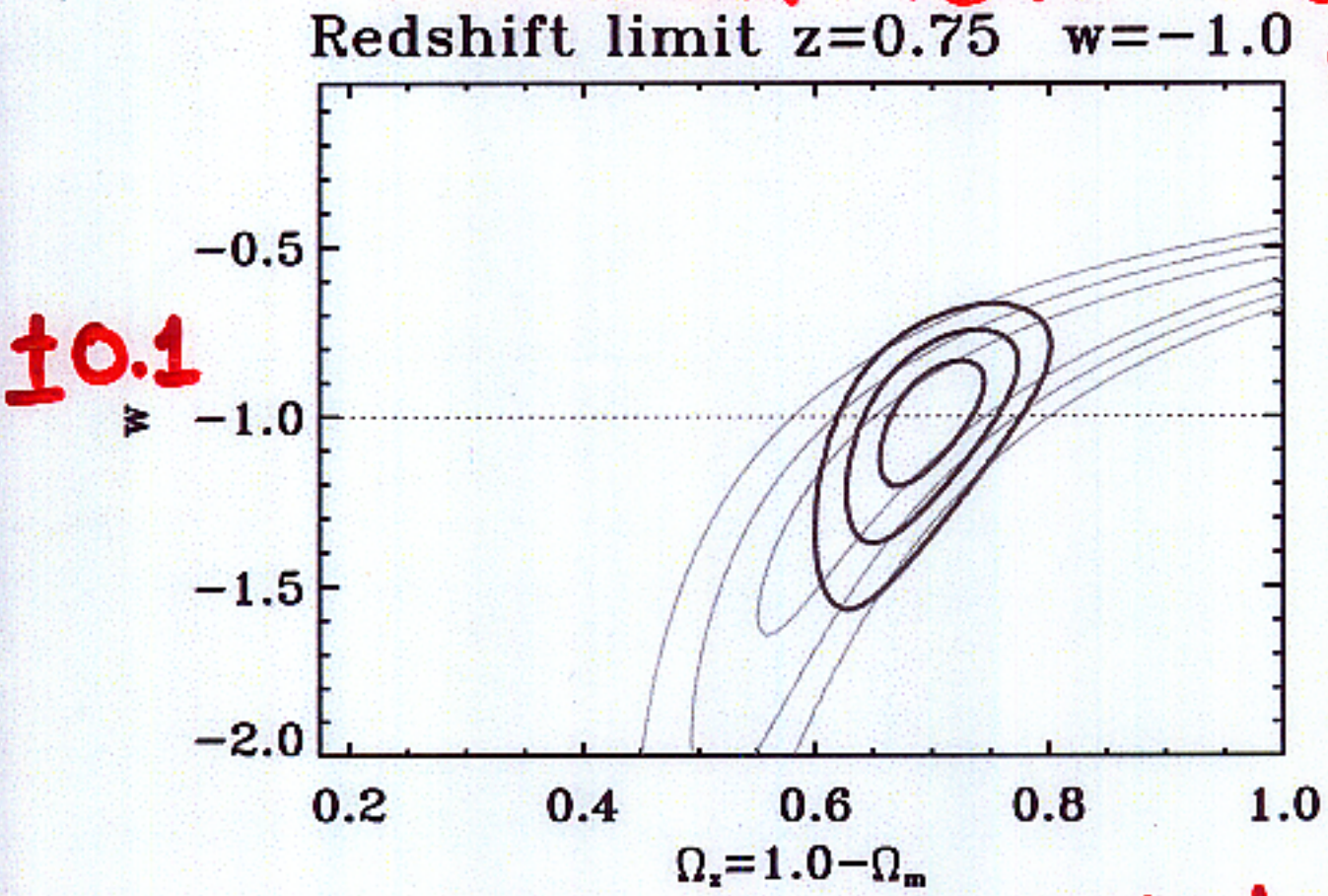
First data: Oct 2002

Measuring w

P/ρ -1 = cosmo constant

Garnavich et al. 1998

SIMULATION - NOT REAL



If w=-1, good. If w≠-1 better!

But what about

$w(z)$?

Go deep!

Adam Riess @ STSCI

use the new camera on HST to find very distant Supernovae (z: 1.0 – 1.8)

U-band light curves with CCD camera

B, V with Infrared Camera NICMOS on HST

The GOODS ACS Supernova Survey

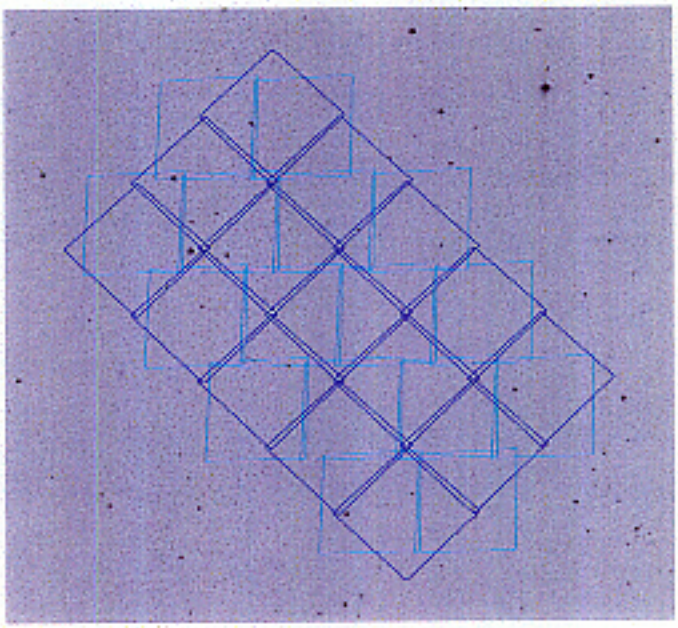
Each 3x5 mosaic will be observed every ~45 days in the z-band (m~26.5) in 5 epochs

Simultaneous V,i colors

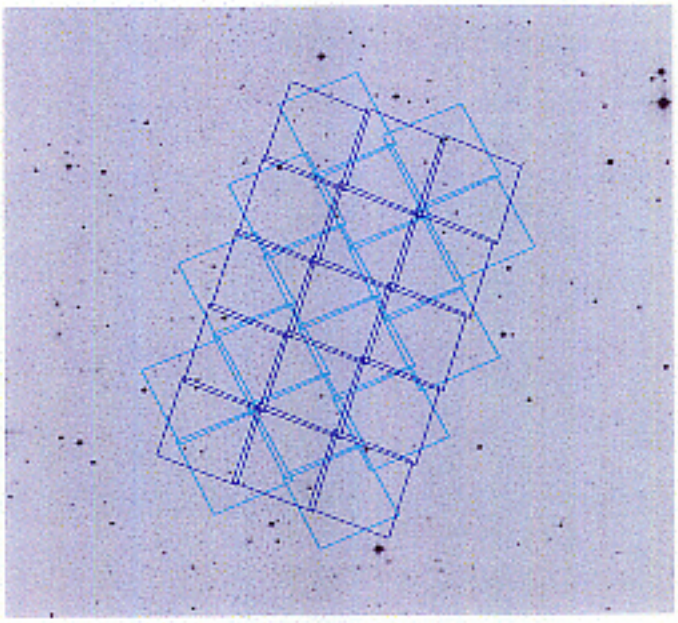
Photometric redshifts available from near-IR optical, and UV data

6 ToO triggers with HST for follow-up of SNc Ia at $1.0 < z < 1.8$

Hubble Deep Field North



Chandra Deep Field South



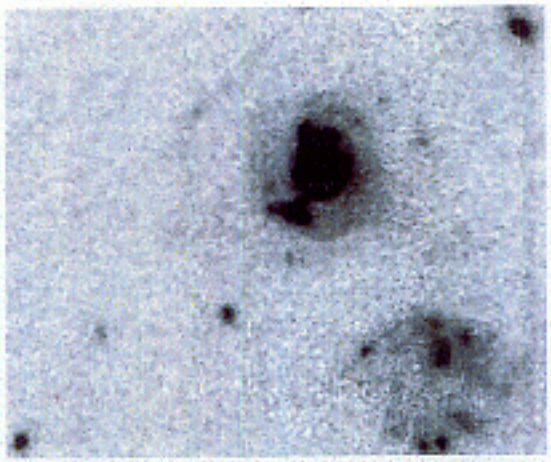
A Higher-z Supernova Search by Piggybacking on the GOODS ACS Survey

The GOODS survey includes 5 z-band epochs of a 3x5 mosaic of the HDFN and CDFS (including simultaneous colors and photo-z's)

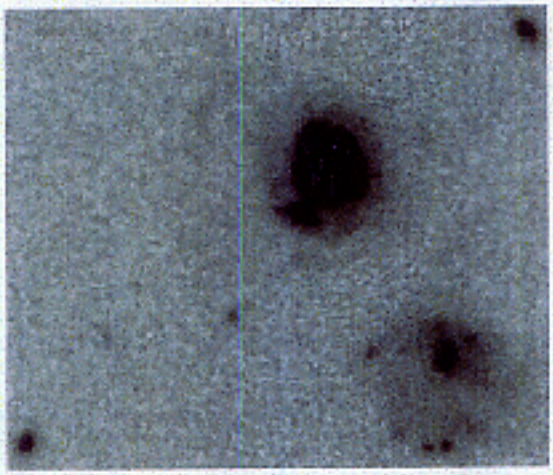
The SN follow-up consists of 6 TOO for SNe Ia at $1.0 < z < 1.8$

GTO SN Ia at z=1.06 in HDFN

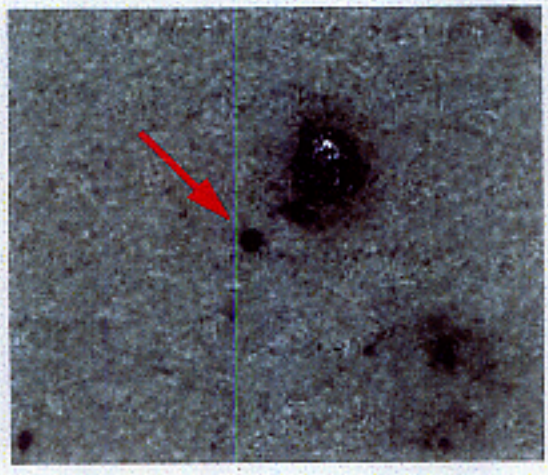
Original HDFN
F814W



Original HDFN
F606W



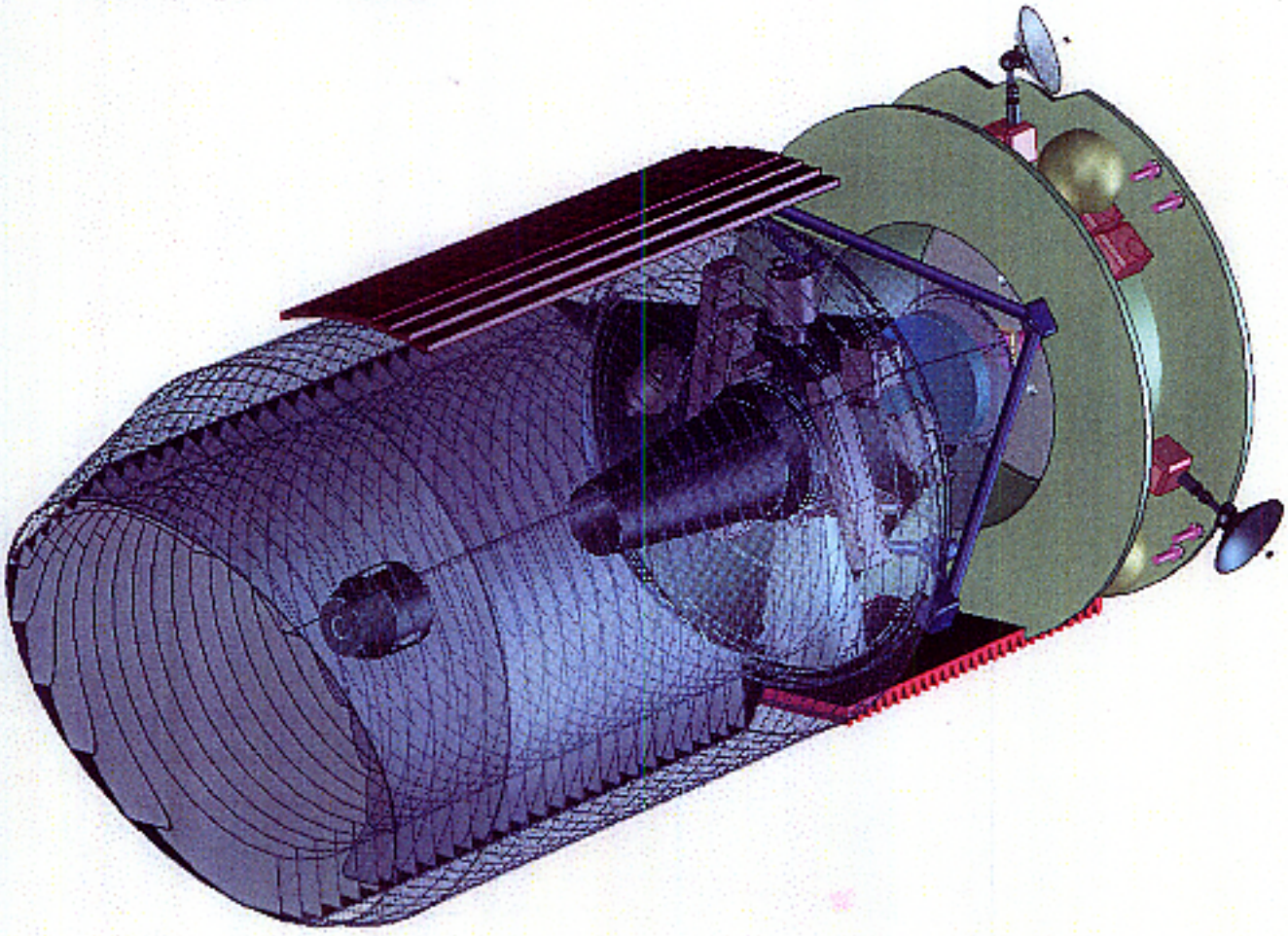
GTO HDFN
May, 2002
F775W



ACS:
smaller pixels = better photometry
.05"

High-z program starts Oct 2002

SNAP SuperNova Acceleration Probe



LBL
Perlmutter & Co.

SUMMARY

- low z data improving 2x + U-band
- Middle z data being published soon!
  - looks good
- ESSENCE to get w to ±0.1
- HST SN to see SN at z ~ 1-1.8

[SNAP to do this better]

Concordance of SNIa, CMB, Ω_m from clusters more convincing than any single approach.