Supernovae, Dark Energy, and the Accelerating Universe

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`http://supernova.LBL.gov`

High-Z Supernova Search Team

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A decade leading to an accelerating universe:

1988

1989 We knew or thought we knew…

1990

1991

1992 What we didn't know…

1993

1994

1995

1996 What we found…

1997

1998 Now what we don't know is…

1999

2000

2001 But we know how to find out…

We knew or thought we knew:

- ☐ The universe is decelerating
- ☐ Standard candles could measure deceleration
- ☐ Supernovae could in principle be standard candles at great distances;
- ☐ With HST, supernovae could be studied
- ☐ at cosmologically relevant distances — if we knew where to look.

What we didn't know:

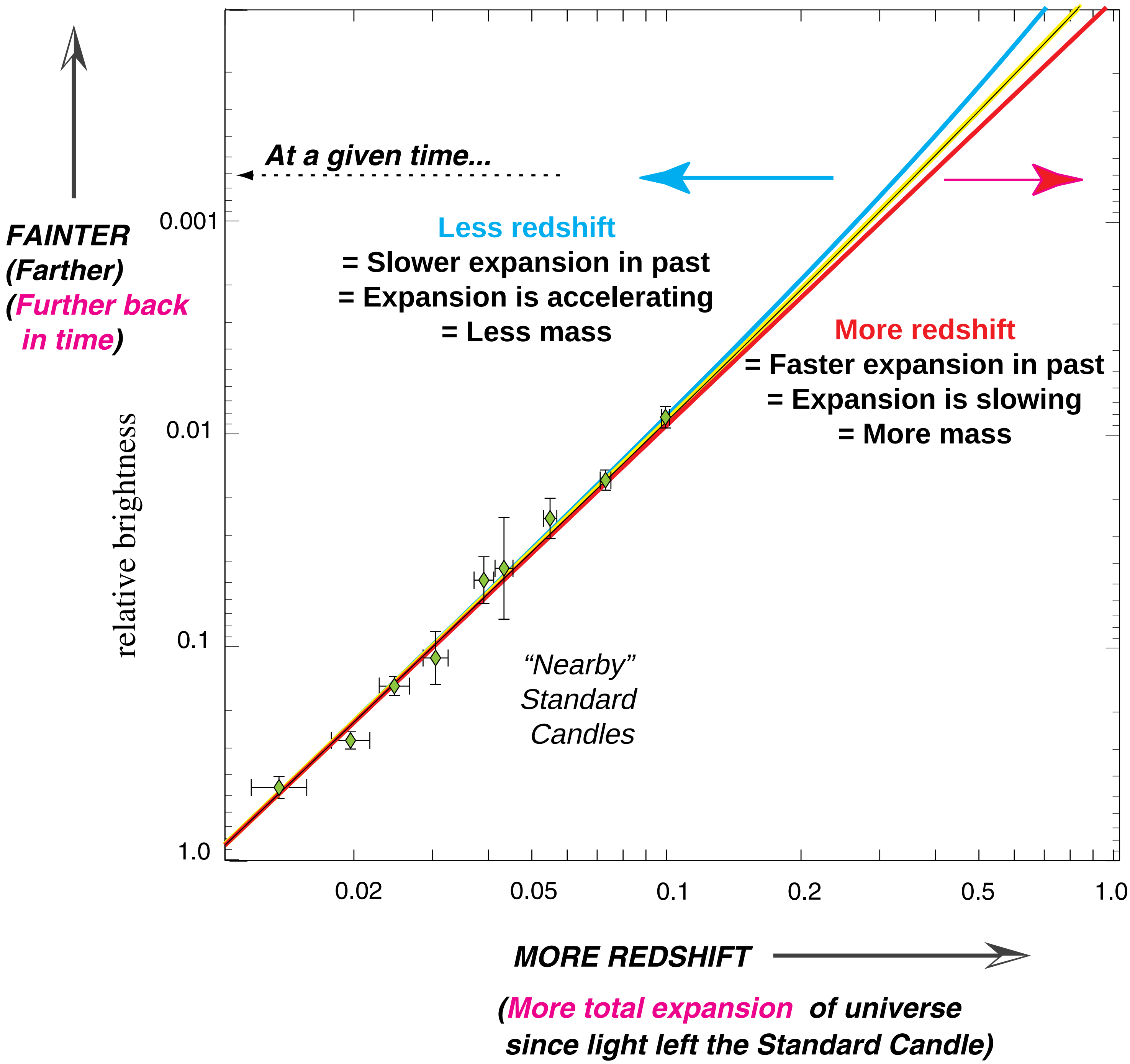
- ☐ The mass density of the universe
- ☐ ☐ = how much is the universe decelerating
- ☐ The current rate of expansion: the age of universe.
- ☐

What we found

☐

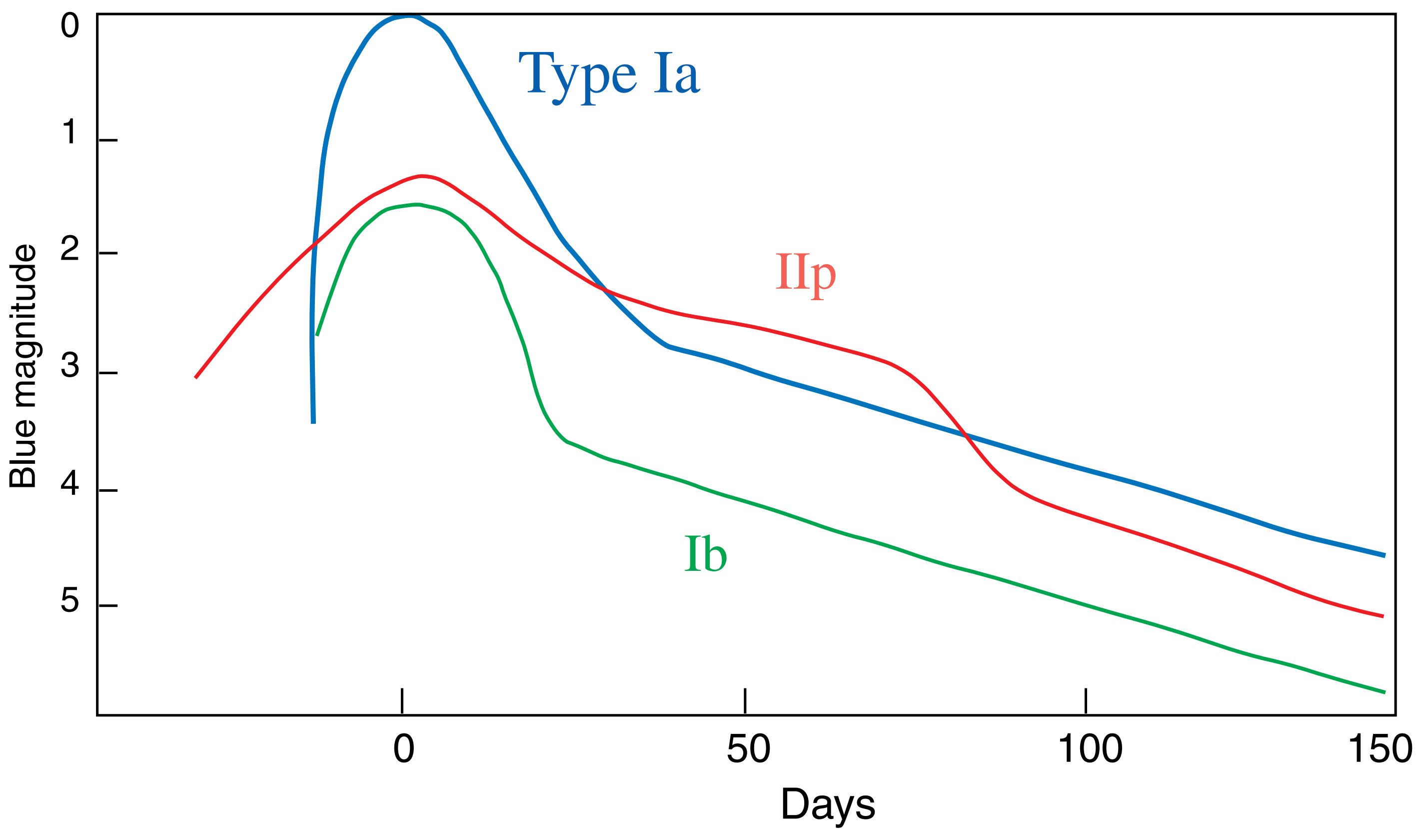
Now what we don't know is☐

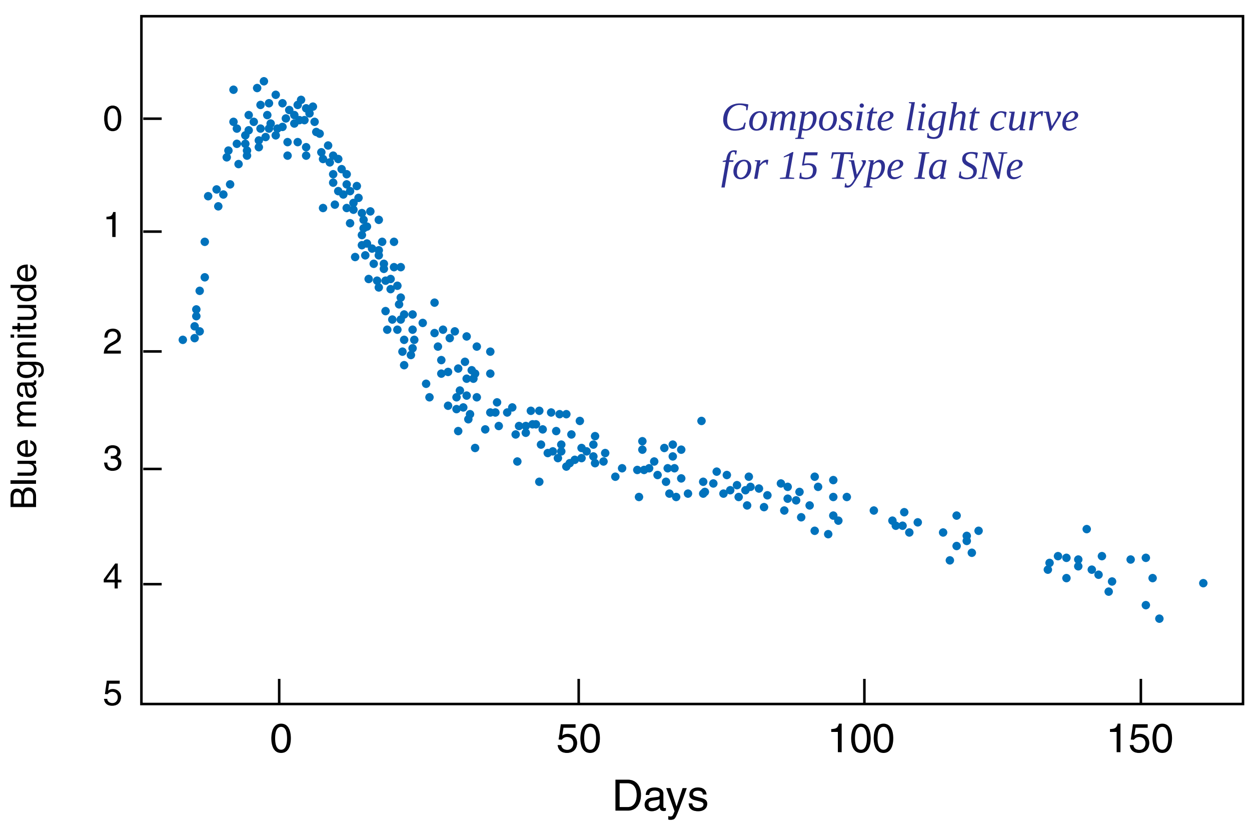
But we know how to find out



At a given time...
Less redshift
= Slower expansion in past
= Expansion is accelerating
= Less mass
More redshift
= Faster expansion in past
= Expansion is slowing
= More mass
FAINTER
(Farther)
(Further back
in time)
relative brightness
0.001
0.01
0.1
1.0
"Nearby"
Standard
Candles
0.02
0.05
0.1
0.2
0.5
1.0
MORE REDSHIFT
(More total expansion of universe
since light left the Standard Candle)

Supernova Light Curves





We knew or thought we knew…

What we didn't know:

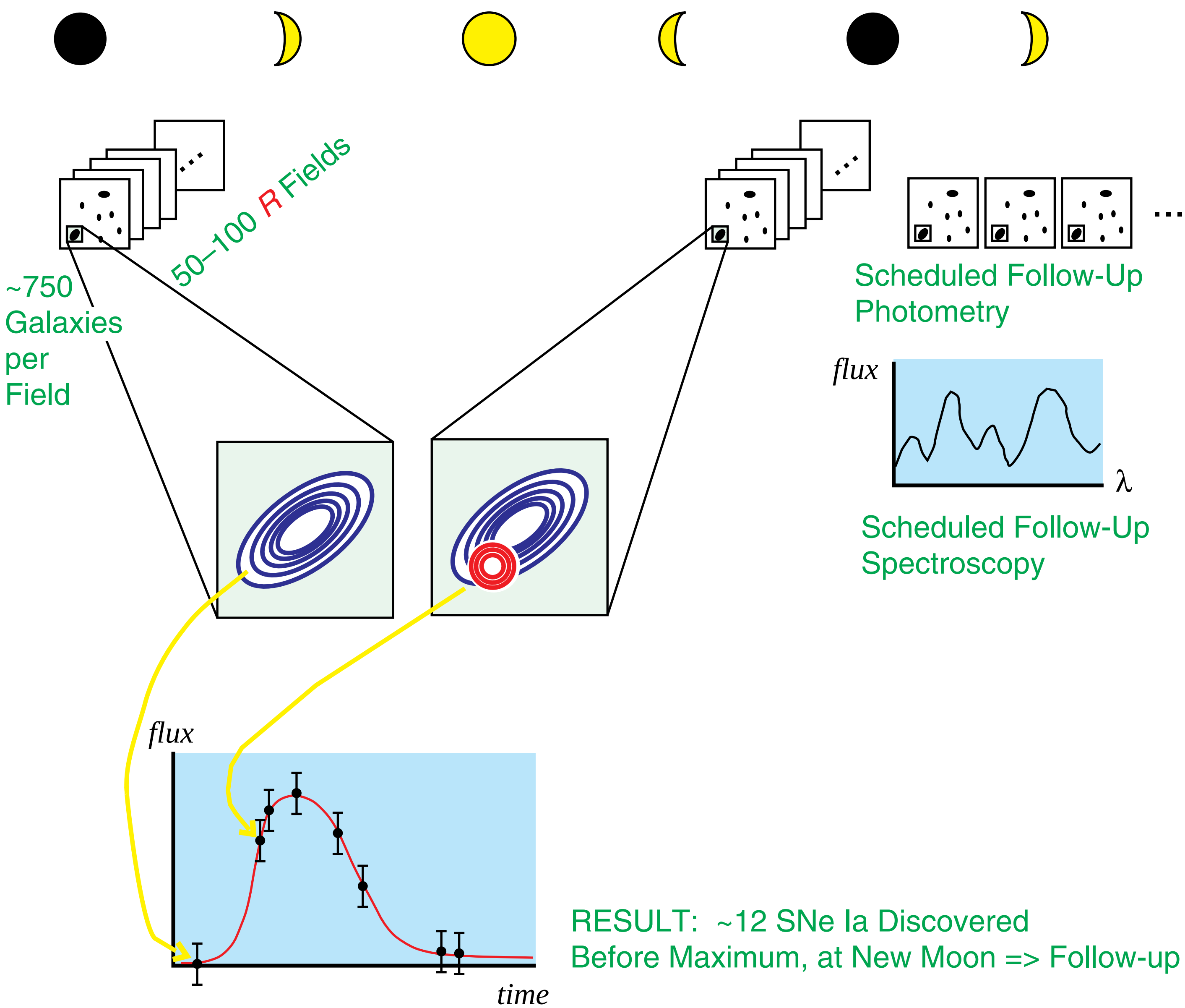
- ***about supernovae studies***
- that SNe could be found systematically
  - at cosmologically relevant distances ($z > 0.3$)
- that SNe could be identified spectroscopically at $z > 0.3$
- that SNe K-corrections could be handled at $z > 0.3$
- that extinction could be handled at $z > 0.3$
- that SNe could be calibrated (accounts for progenitor variation)

What we found…

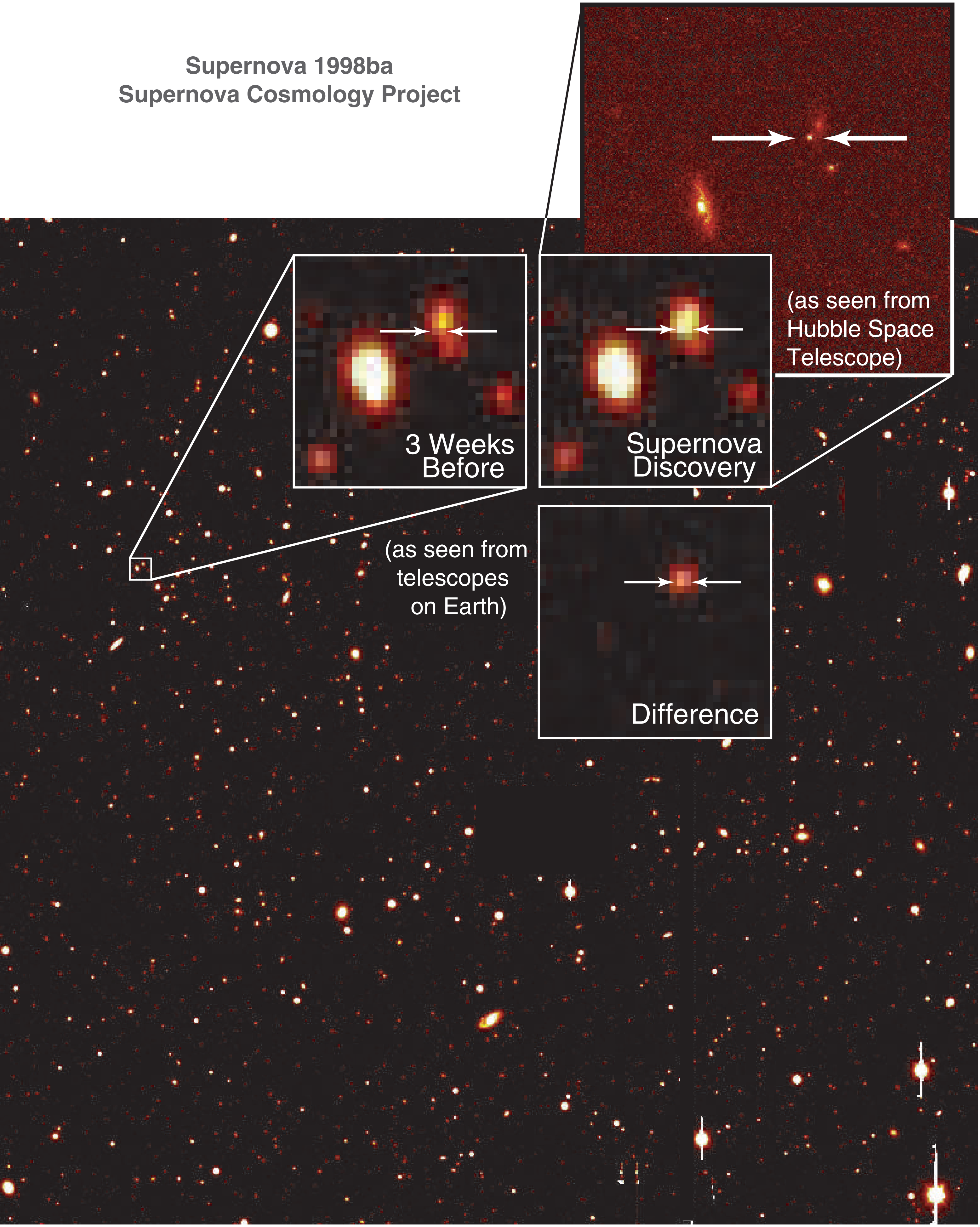
Now what we don't know is…

But we know how to find out…

Search Strategy Perlmutter et al. (1996a)



Supernova 1998ba
Supernova Cosmology Project



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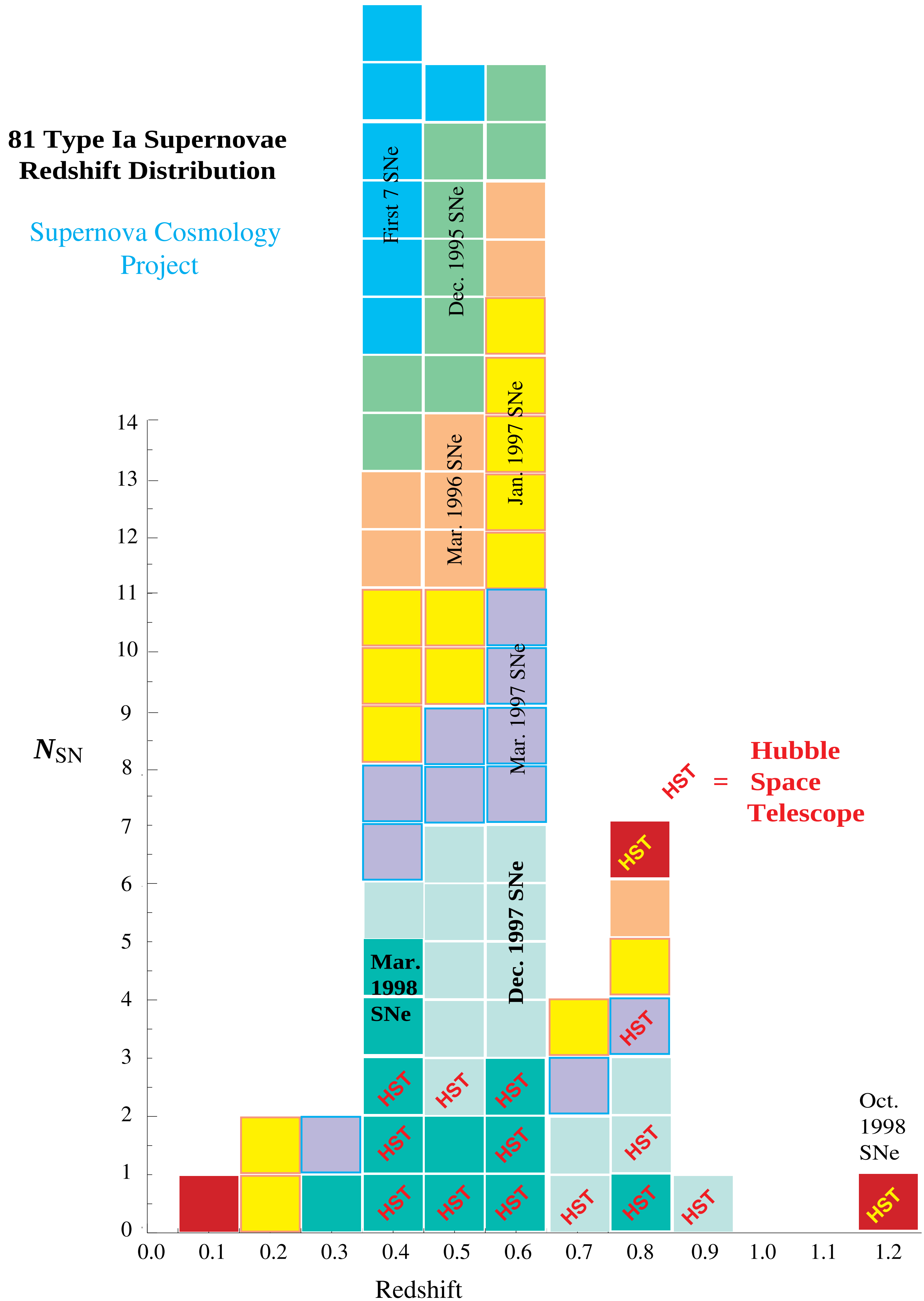
SUPERNOVAE

The Supernova Cosmology Project [S. Perlmutter, S. Deustua, G. Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, J. Melbourne, C. Pennypacker, and I. Small, Lawrence Berkeley Lab. and the Center for Particle Astrophysics; A. Goobar, Univ. of Stockholm; R. Pain, CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy, Cambridge; and B. Boyle, P. Bunclark, D. Carter, and M. Irwin, Royal Greenwich Obs.; with A. V. Filippenko and A. Barth (Univ. of California, Berkeley) at the Keck telescope; W. Couch (Univ. of N.S.W.) and M. Dopita and J. Mould (Mt. Stromlo and Siding Spring Obs.) at the Siding Spring 2.3-m telescope; H. Newberg (Fermi National Accelerator Lab.) and D. York (Univ. of Chicago) at the ARC telescope] report eleven supernovae found with the Cerro Tololo (CTIO) 4-m telescope in their 1995 High Redshift Supernova Search:

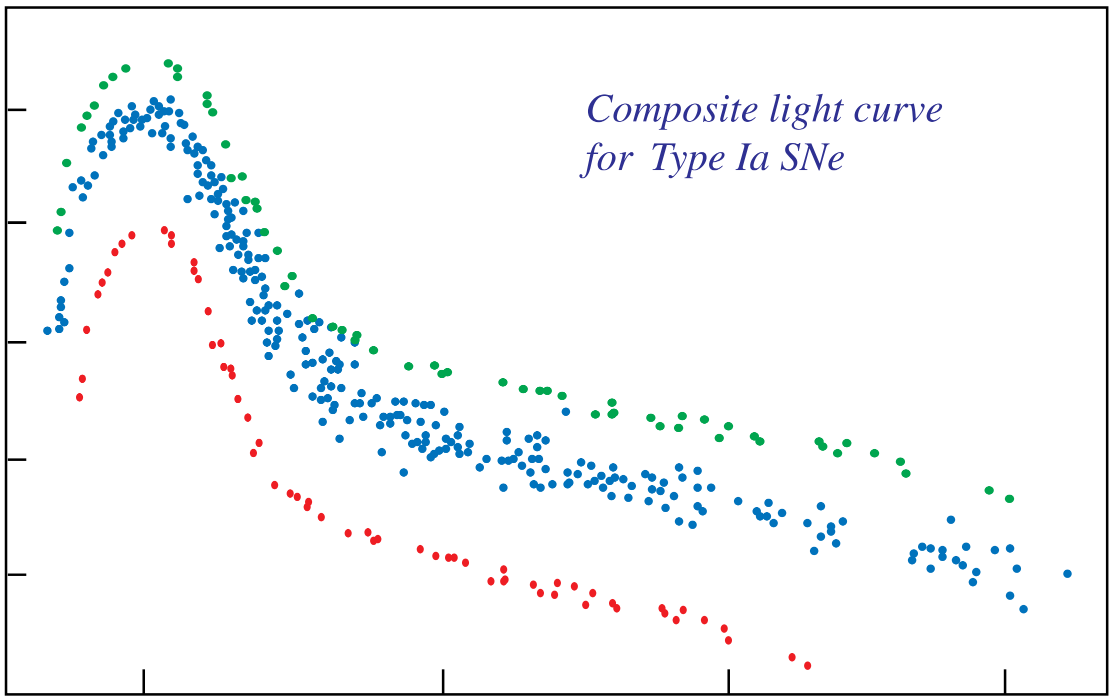
SN	1995 UT	R.A. (2000)	Decl.	R	Offset
1995aq	Nov. 19	0 29 04.26	+ 7 51 20.0	22.4	0".6 W, 1".4 S
1995ar	Nov. 19	1 01 20.41	+ 4 18 33.8	23.1	2".9 W, 0".5 S
1995as	Nov. 19	1 01 35.30	+ 4 26 14.8	23.3	0".7 W, 0".7 N
1995at	Nov. 20	1 04 50.94	+ 4 33 53.0	22.7	0".3 W, 0".4 S
1995au	Oct. 29	1 18 32.60	+ 7 54 03.5	20.7	1".4 E, 3".3 N
1995av	Nov. 20	2 01 36.75	+ 3 38 55.2	20.1	0".2 W, 0".0 N
1995aw	Nov. 19	2 24 55.54	+ 0 53 07.5	22.5	0".2 W, 0".2 S
1995ax	Nov. 19	2 26 25.80	+ 0 48 44.2	22.6	0".3 W, 0".2 S
1995ay	Nov. 20	3 01 07.52	+ 0 21 19.4	22.7	0".9 W, 1".4 S
1995az	Nov. 20	4 40 33.59	- 5 30 03.6	24.0	1".6 W, 1".7 N
1995ba	Nov. 20	8 19 06.46	+ 7 43 21.2	22.6	0".1 E, 0".2 N

The spectra (Keck, Nov. 26-28) are consistent with type-I supernovae (except SN 1995av, a probable type II) at the redshift of the host galaxy: z = 0.45, 0.46, 0.49 (preliminary type-I identification), 0.65, 0.16, 0.30, 0.4 (supernova redshift only), 0.61, 0.48, 0.45, 0.39. Photometry obtained on Nov. 21-23 at CTIO (A. Walker) and Nov. 23-27 at WIYN (D. Harmer, D. Willmarth) indicates that SNe 1995ar, 1995at, 1995av, 1995aw, 1995ay, and 1995az are now before or at maximum, while the others are slightly past maximum. The previous observations not showing the supernovae (to limiting mag about 24) were on Oct. 29-30 at the CTIO 4-m (except SN 1995au, on 1994 Sept. 29 at the Kitt Peak 4-m telescope). Continuing R, I, and B photometry is important. Contact saul@LBL.gov for finding charts.

1995 December 6 (6270) Daniel W. E. Green

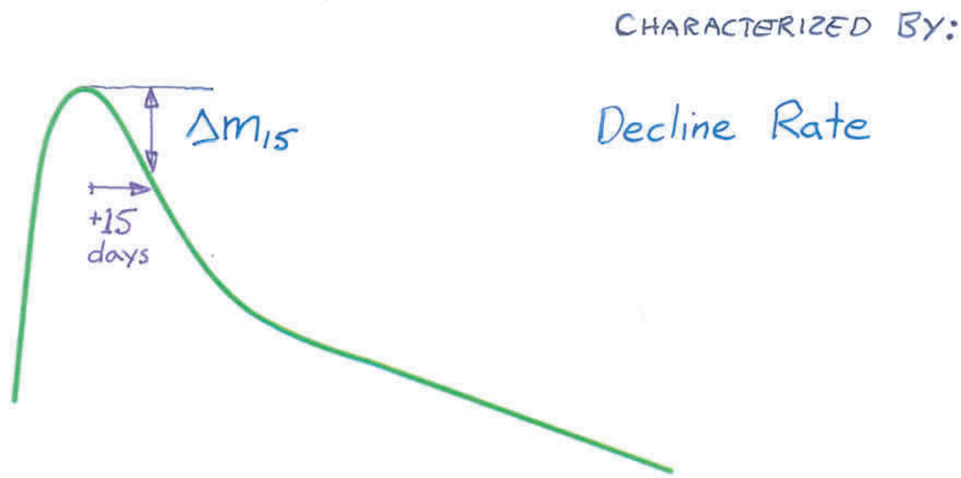


81 Type Ia Supernovae
Redshift Distribution
Supernova Cosmology Project
First 7 SNe
Dec. 1995 SNe
Mar. 1996 SNe
Jan. 1997 SNe
Mar. 1997 SNe
Dec. 1997 SNe
Mar. 1998 SNe
Oct. 1998 SNe
HST = Hubble Space Telescope
HST
N_{SN}
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Redshift

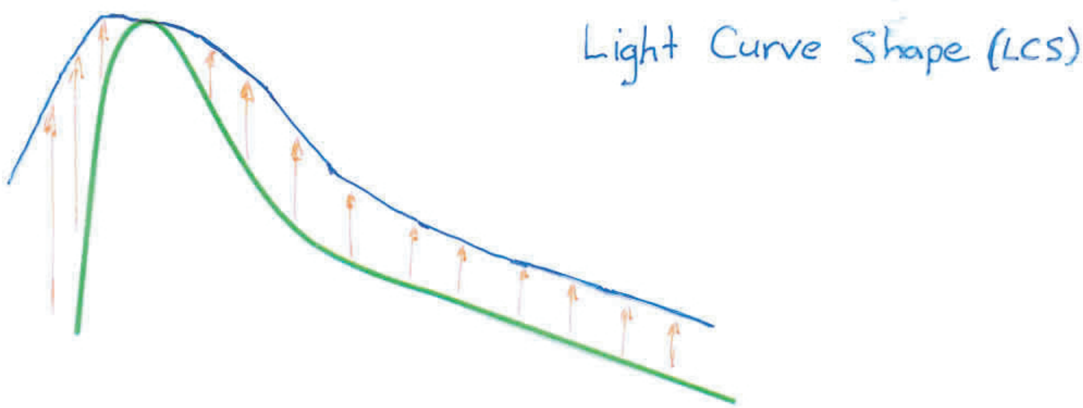

Composite light curve
for Type Ia SNe

Lightcurve Width-Luminosity Relation

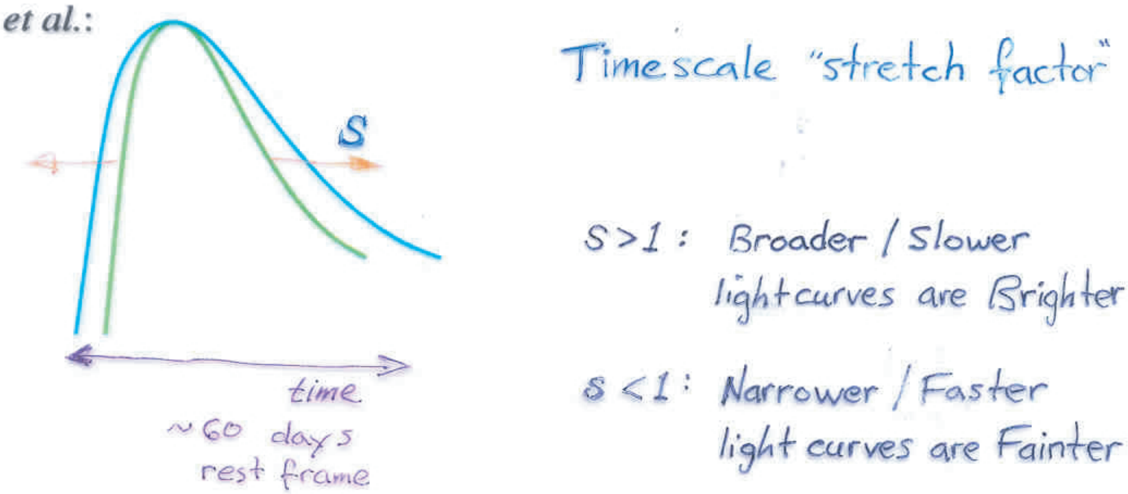
Phillips:
(1993—)

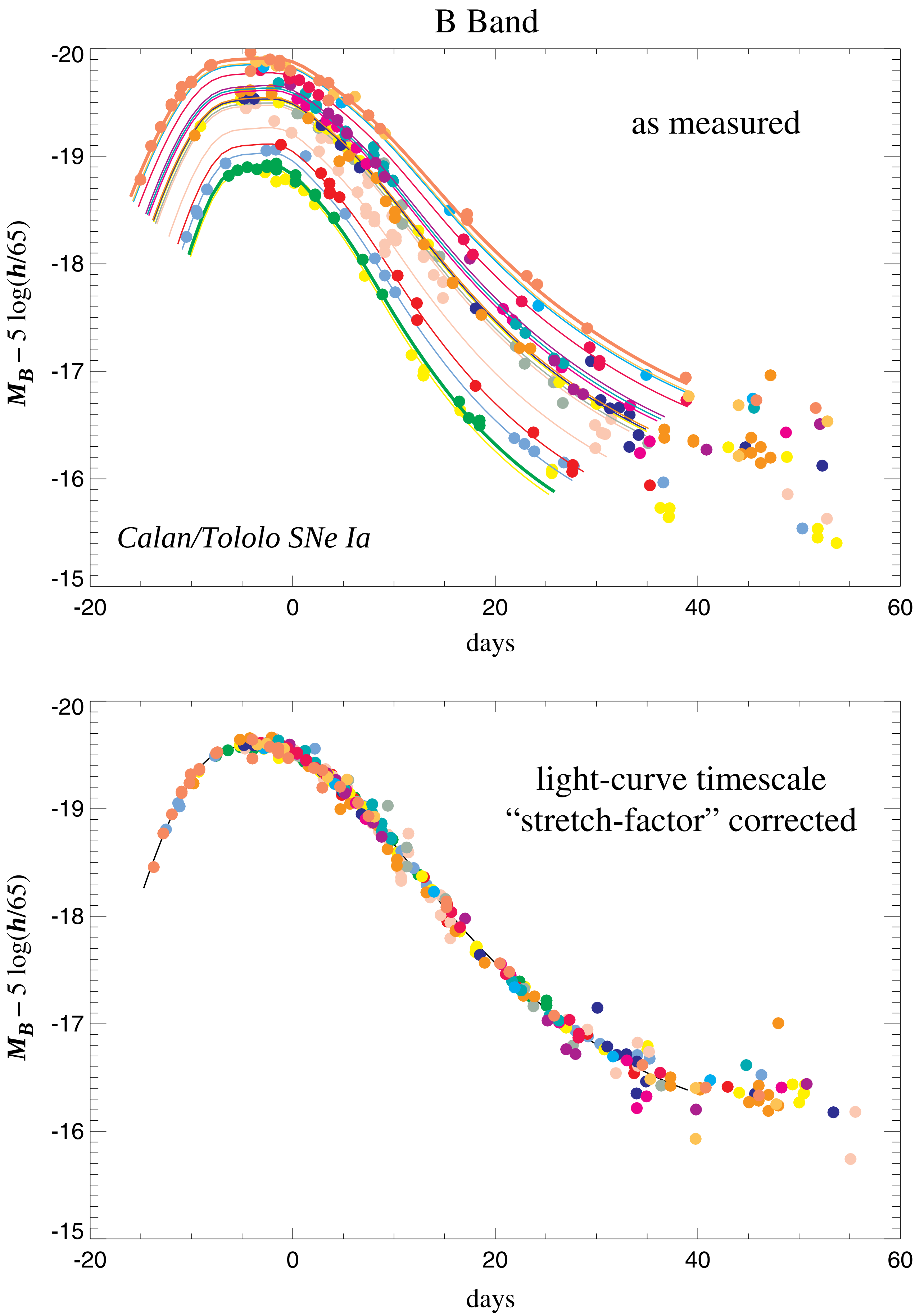


Riess, Press, & Kirshner:
(1995—)

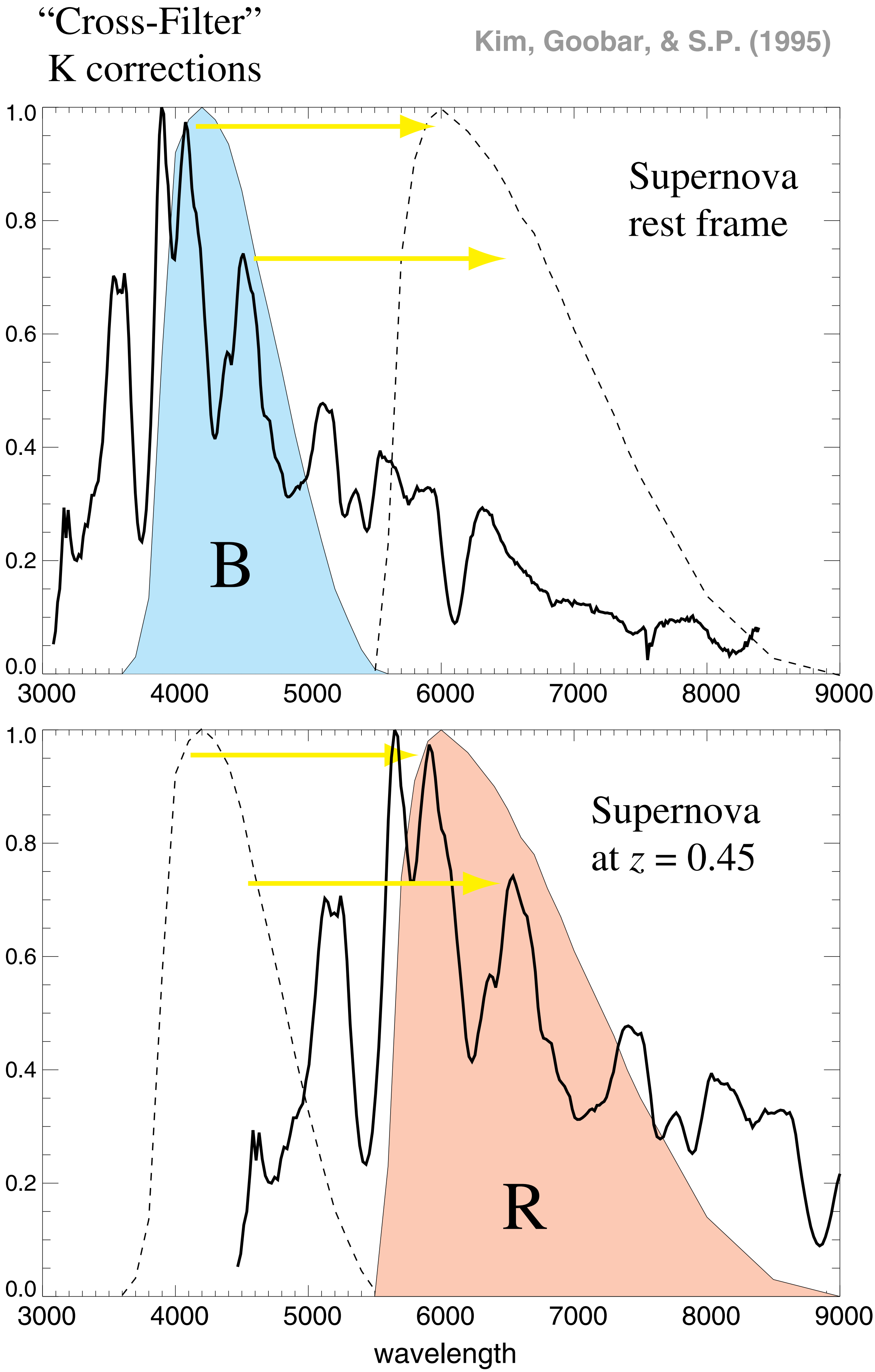


Perlmutter *et al.*:
(1996—)

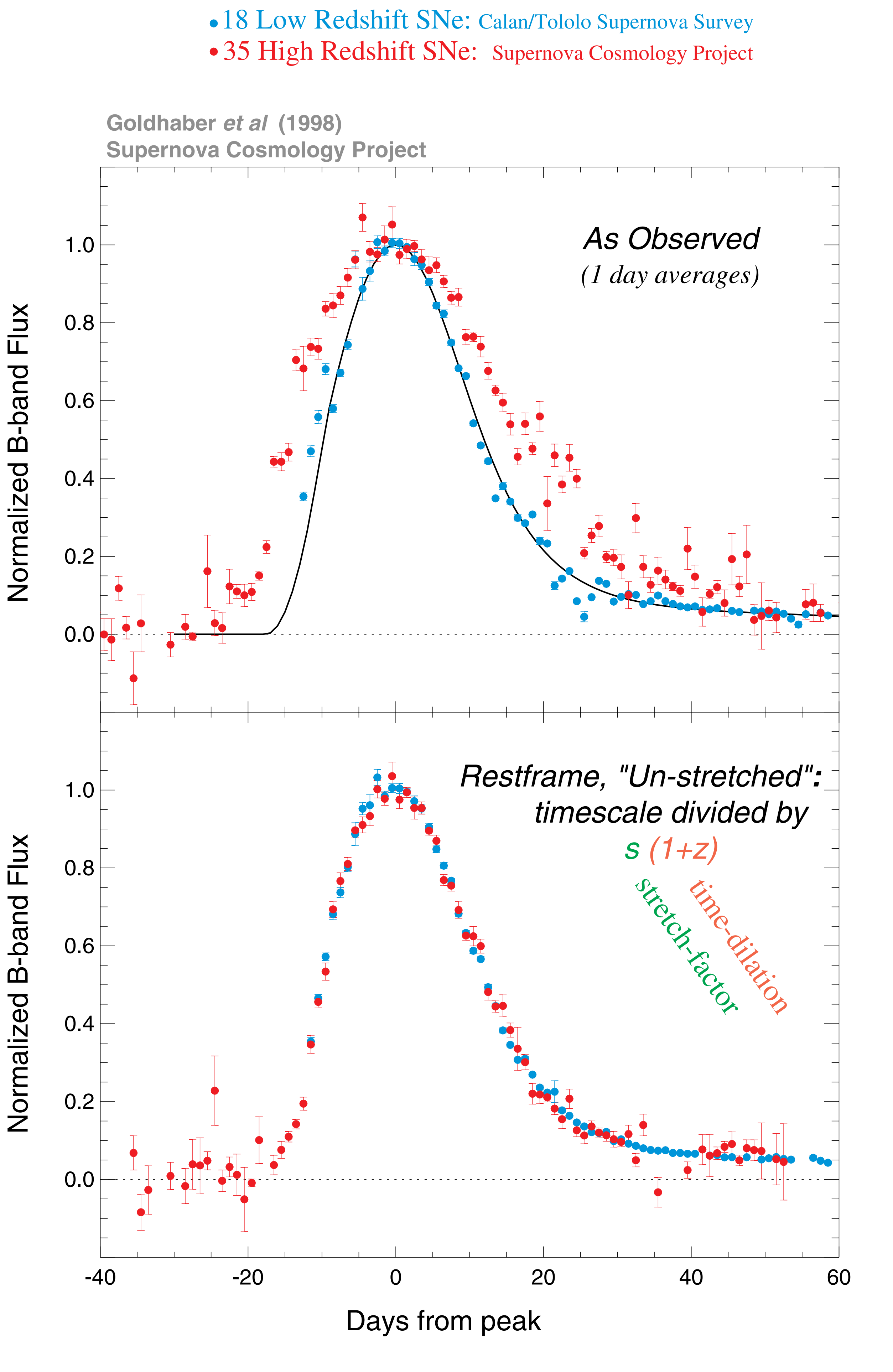




Kim, *et al.* (1997)



“Cross-Filter”
K corrections
Kim, Goobar, & S.P. (1995)
Supernova
rest frame
B
Supernova
at z = 0.45
R
1.0
0.8
0.6
0.4
0.2
0.0
3000
4000
5000
6000
7000
8000
9000
wavelength


• 18 Low Redshift SNe: Calan/Tololo Supernova Survey
• 35 High Redshift SNe: Supernova Cosmology Project
Goldhaber et al (1998)
Supernova Cosmology Project
As Observed
(1 day averages)
Restframe, "Un-stretched":
timescale divided by
s (1+z)
stretch-factor
time-dilation
Normalized B-band Flux
Days from peak
-40
-20
0
20
40
60
0.0
0.2
0.4
0.6
0.8
1.0

We knew or thought we knew…

What we didn't know:

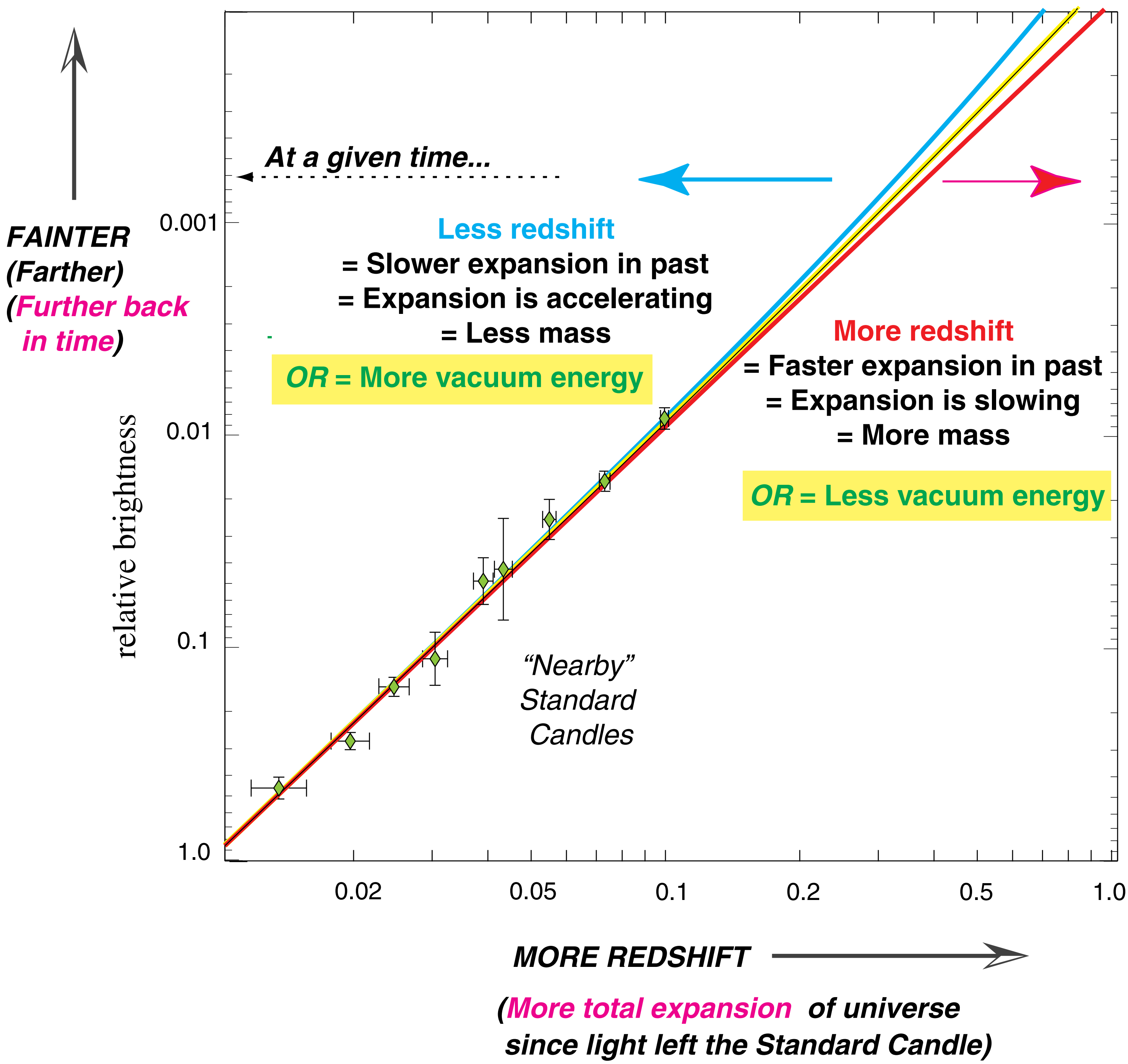
- ***about supernovae studies***
- that SNe could be found systematically
  - at cosmologically relevant distances ($z > 0.3$)
- that SNe could be identified spectroscopically at $z > 0.3$
- that SNe K-corrections could be handled at $z > 0.3$
- that extinction could be handled at $z > 0.3$
- that SNe could be calibrated(accounts for progenitor variation)

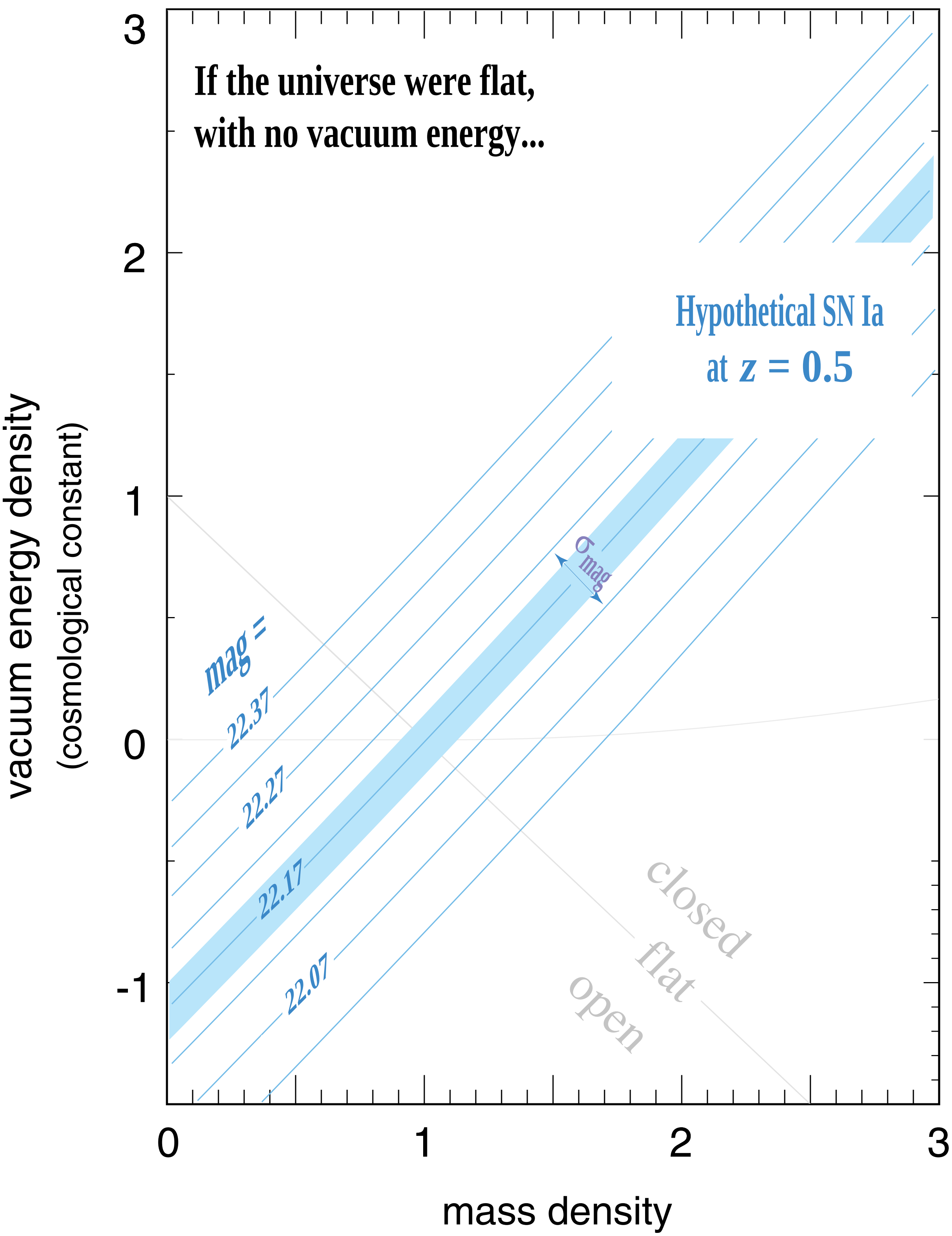
- ***about the universe***
- That the measurement of Ω_M could be separated
  - from the measurement of Ω_Λ

What we found…

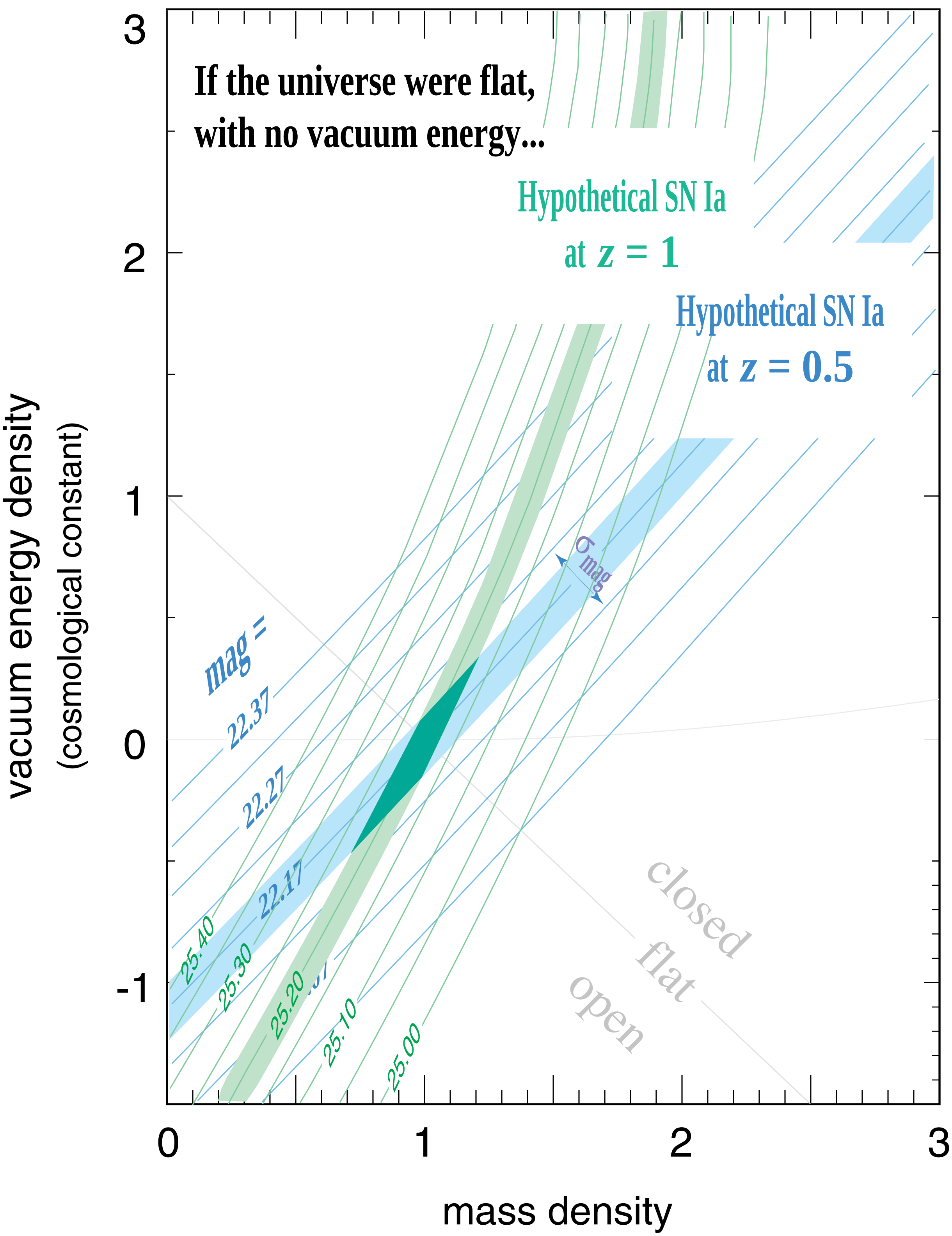
Now what we don't know is…

But we know how to find out…


FAINTER
(Farther)
(Further back in time)
relative brightness
0.001
0.01
0.1
1.0
At a given time...
Less redshift
= Slower expansion in past
= Expansion is accelerating
= Less mass
OR = More vacuum energy
More redshift
= Faster expansion in past
= Expansion is slowing
= More mass
OR = Less vacuum energy
"Nearby" Standard Candles
0.02
0.05
0.1
0.2
0.5
1.0
MORE REDSHIFT
(More total expansion of universe since light left the Standard Candle)



Goobar & Perlmutter
(Ap.J. 1995)



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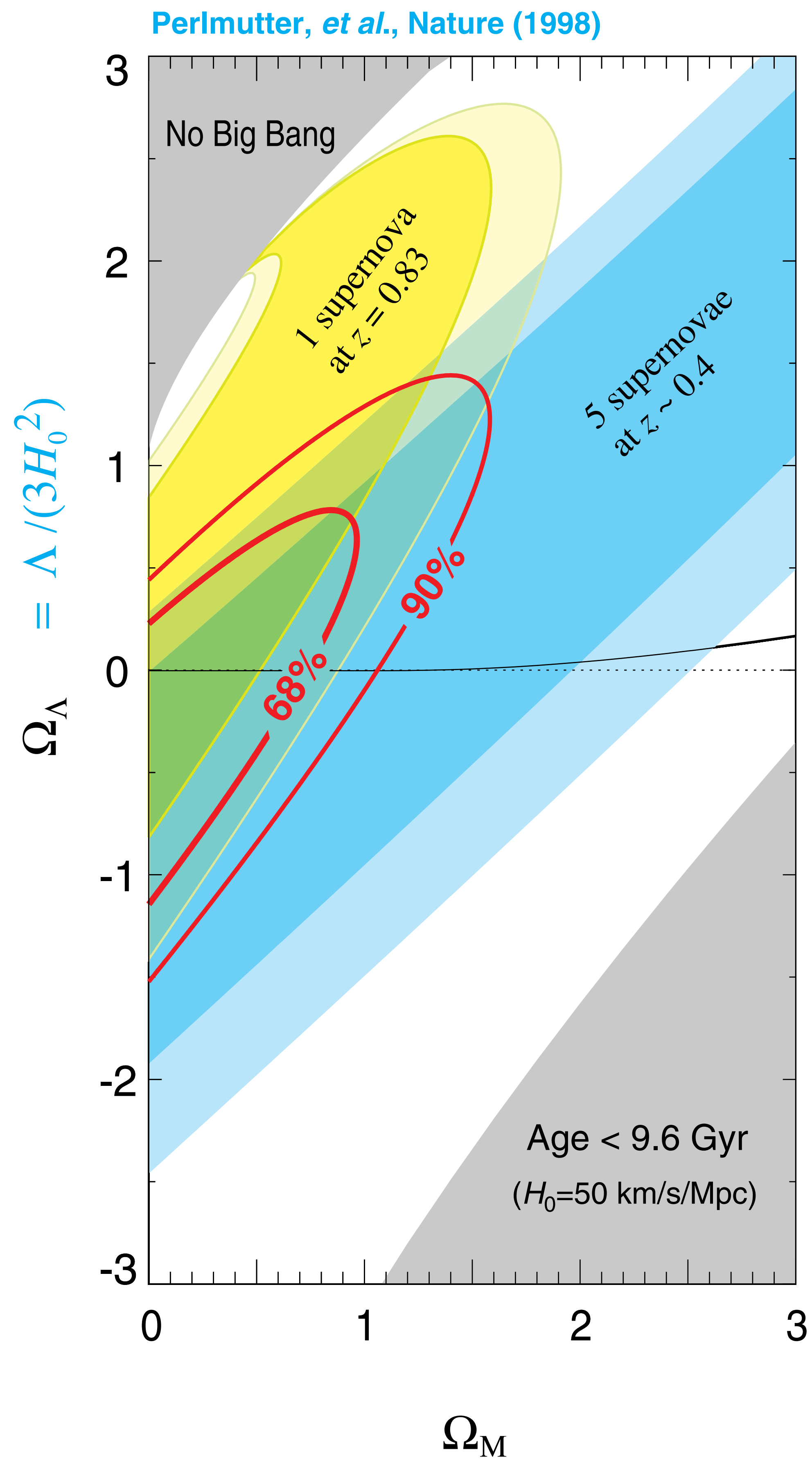


Perlmutter, et al., Nature (1998)
No Big Bang
1 supernova at z = 0.83
5 supernovae at z ~ 0.4
68%
90%
Age < 9.6 Gyr
(H0=50 km/s/Mpc)
ΩΛ = Λ /(3H0^2)
ΩM
3
2
1
0
-1
-2
-3
0
1
2
3

We knew or thought we knew…

What we didn't know…

What we found:

The universe is not decelerating, but accelerating.

Some unidentified negative-pressure energy density exists.

☐ This "dark energy" density dominates over mass density today.

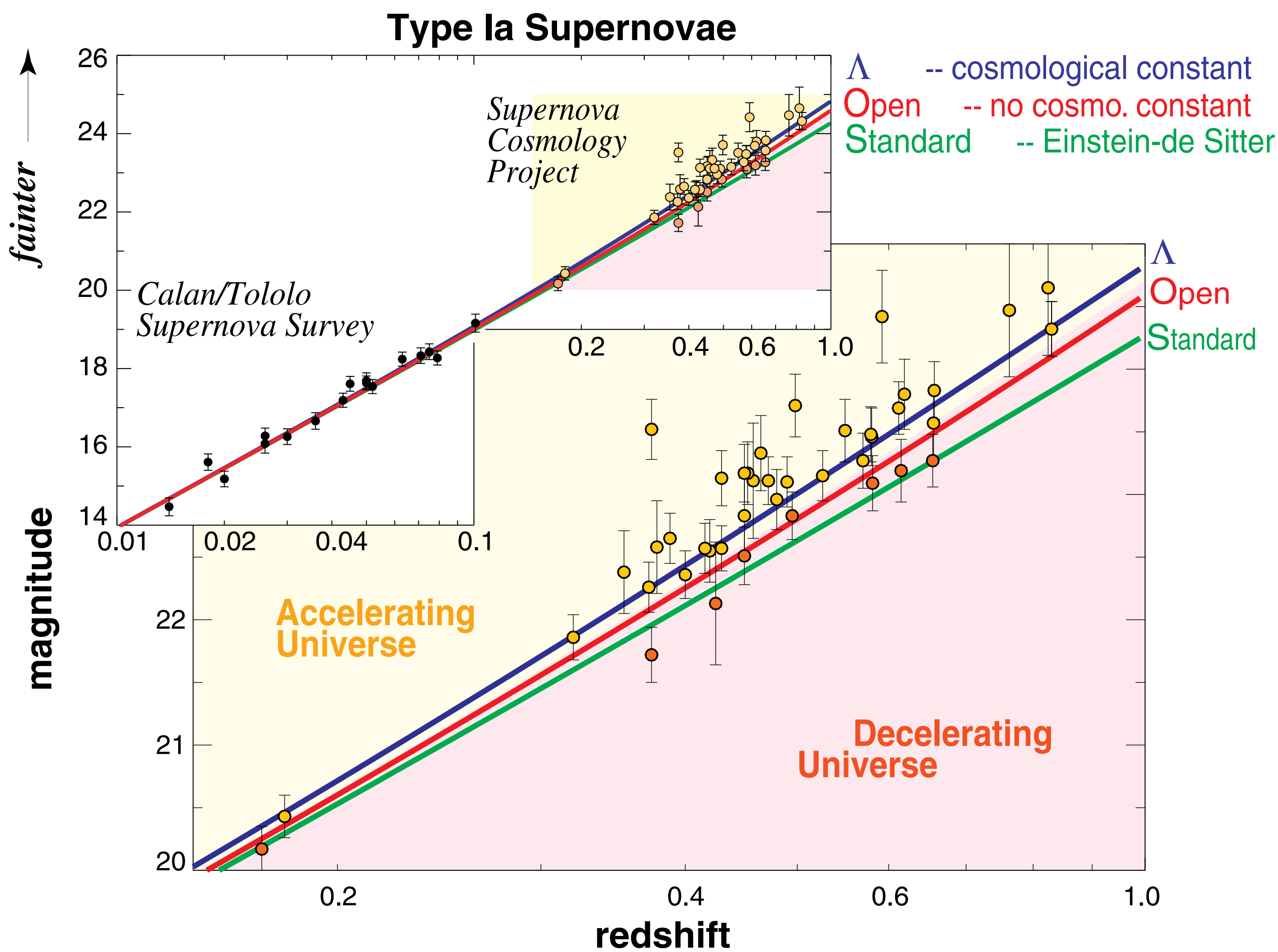
Now what we don't know is:

☐ the values of the "dark" and mass energy densities

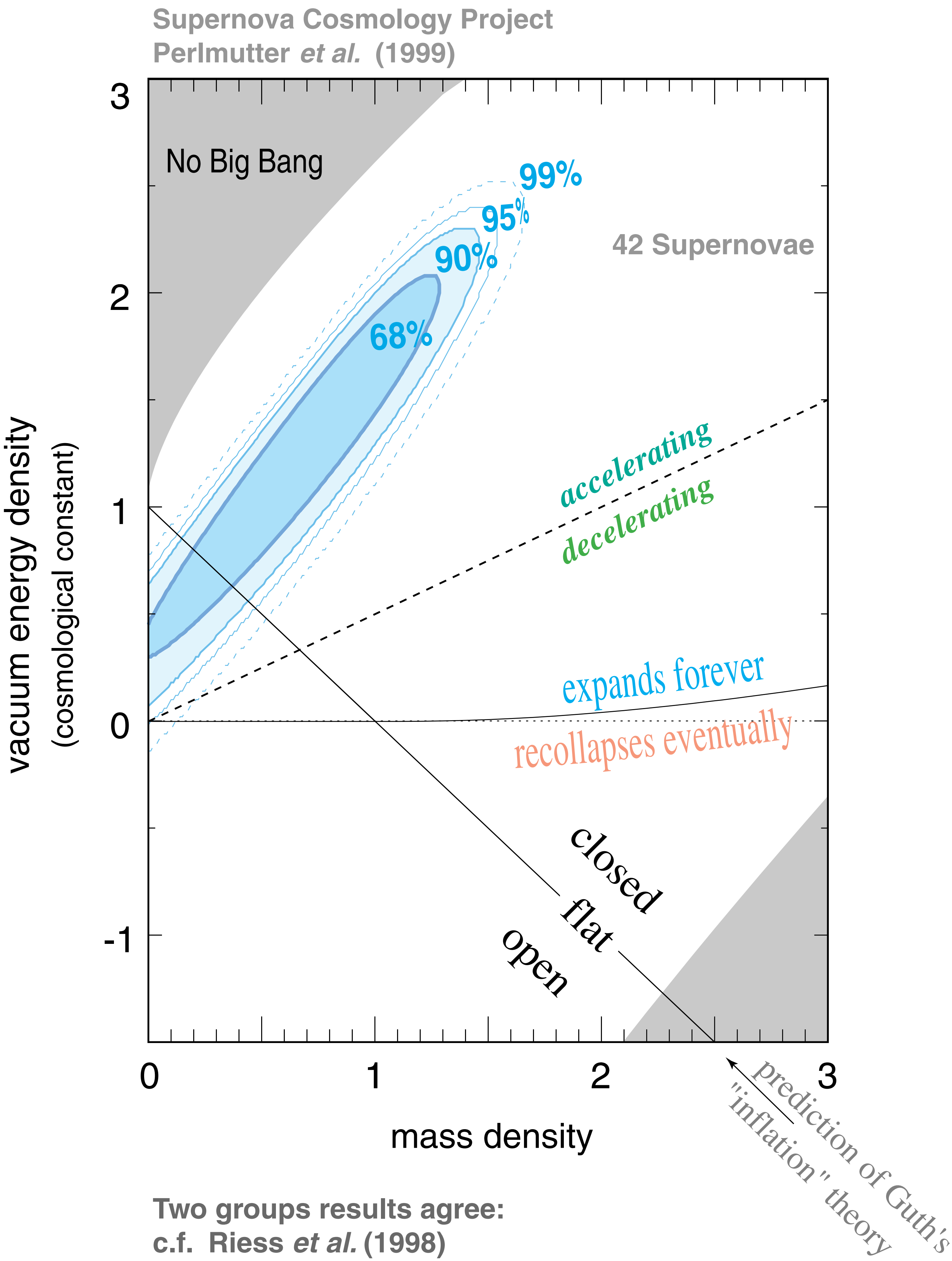
the curvature of space

the identity of the "dark energy"

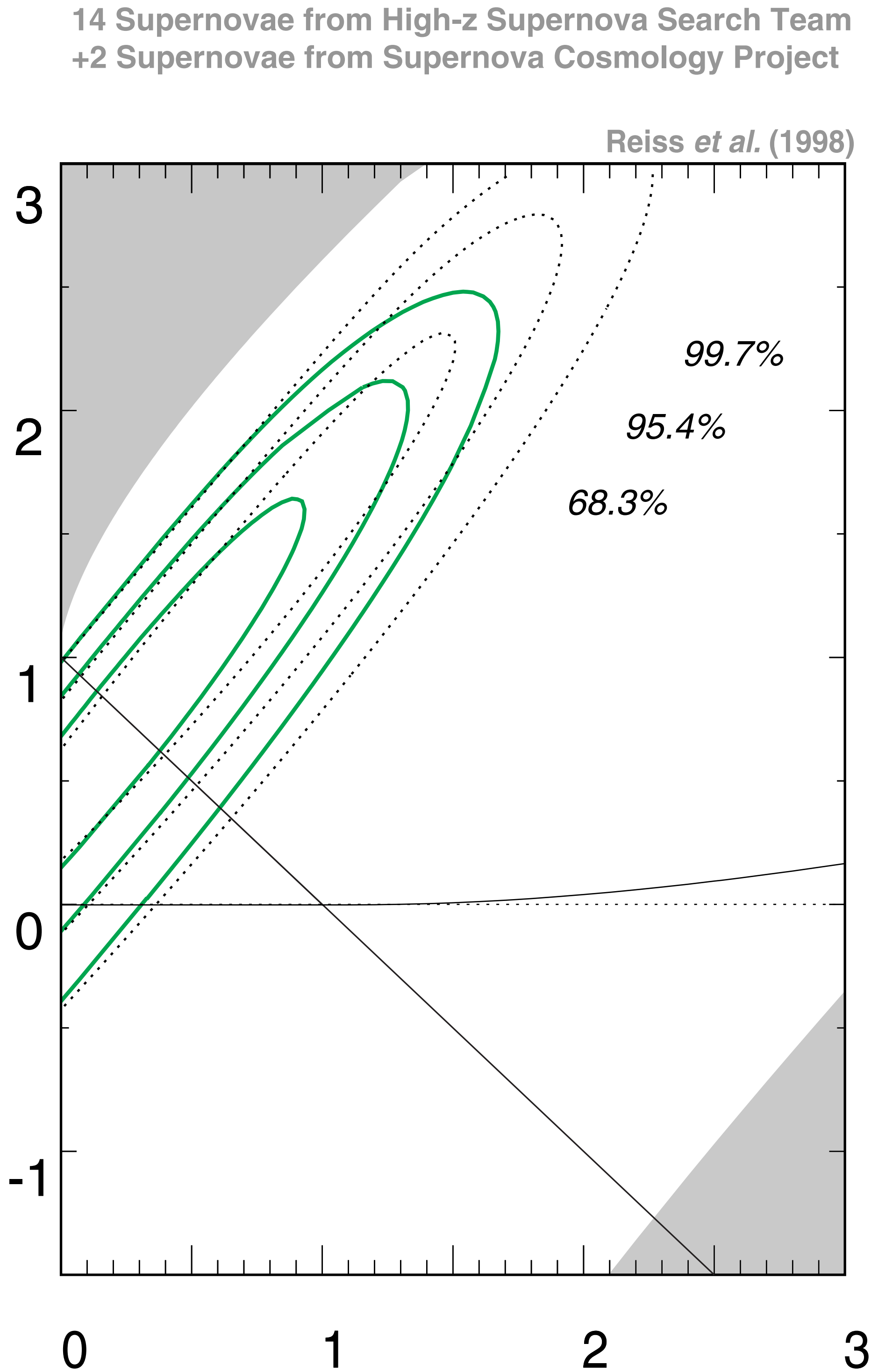
But we know how to find out…☐

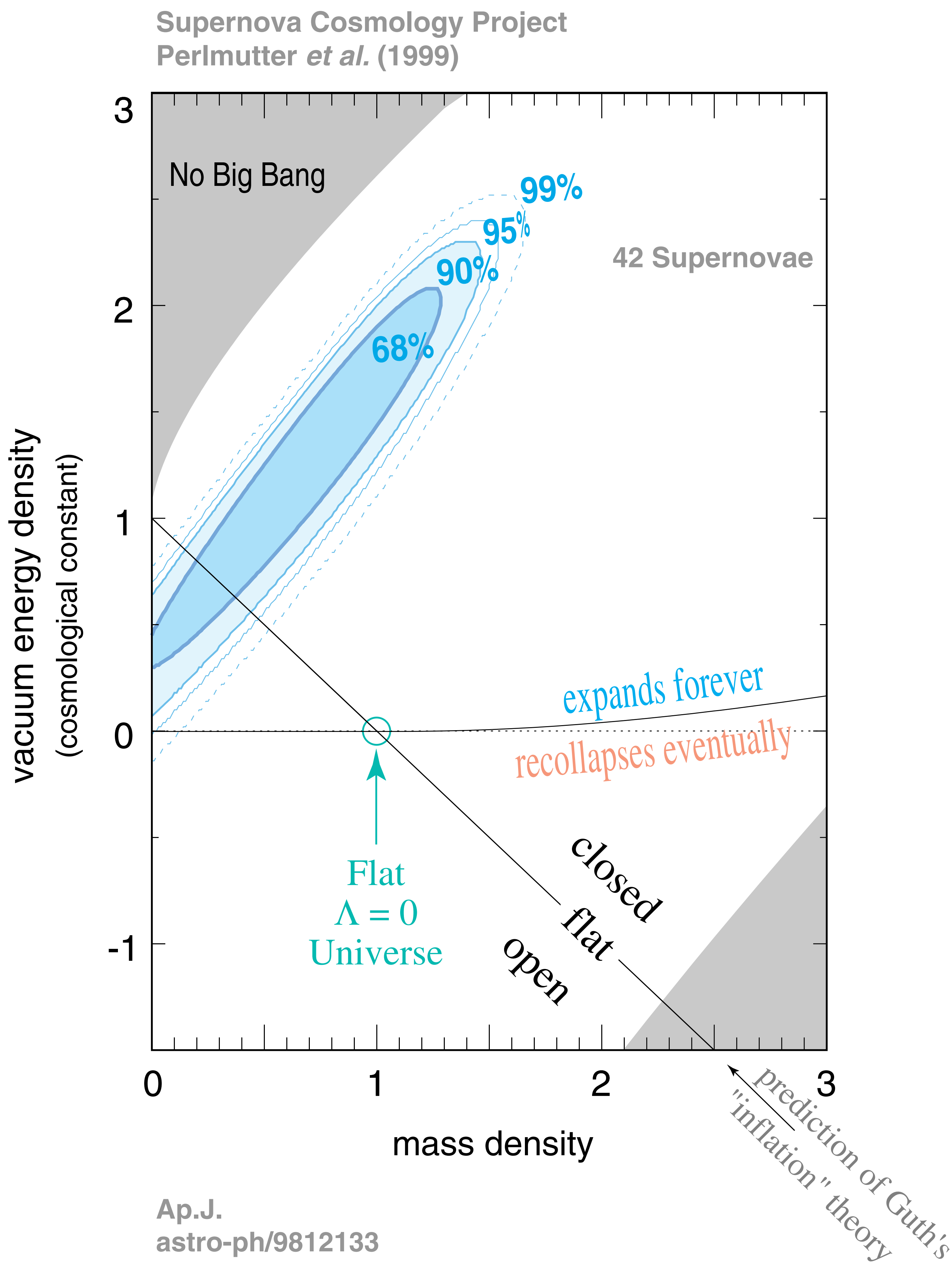


Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- Einstein-de Sitter
Supernova Cosmology Project
Calan/Tololo Supernova Survey
fainter
magnitude
redshift
Accelerating Universe
Decelerating Universe
Λ
Open
Standard
26
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
22
21
20
0.2
0.4
0.6
1.0

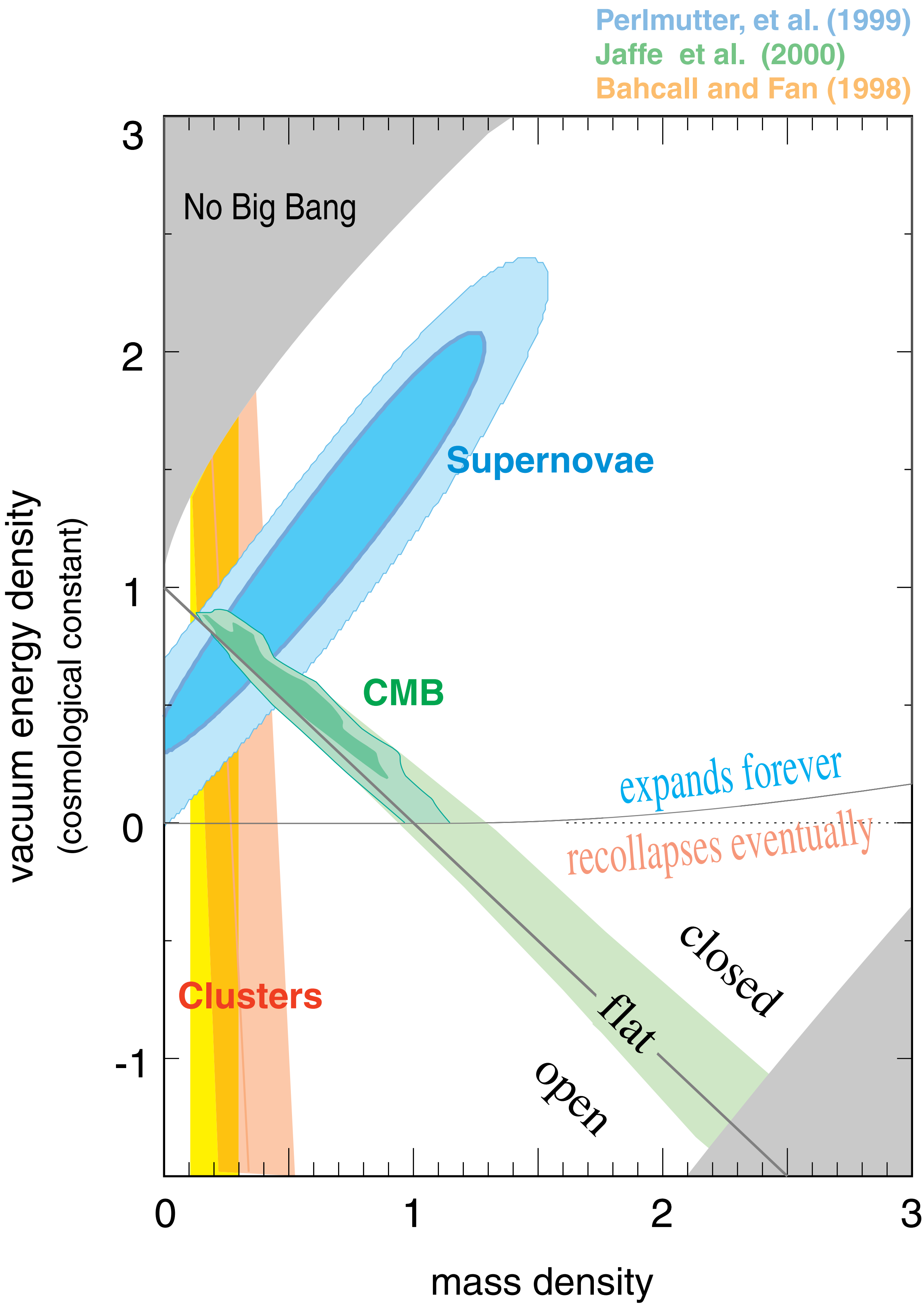


Supernova Cosmology Project
Perlmutter et al. (1999)
No Big Bang
99%
95%
90%
68%
42 Supernovae
accelerating
decelerating
expands forever
recollapses eventually
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3
prediction of Guth's
"inflation" theory
Two groups results agree:
c.f. Riess et al. (1998)


14 Supernovae from High-z Supernova Search Team
+2 Supernovae from Supernova Cosmology Project
Reiss et al. (1998)
99.7%
95.4%
68.3%
3
2
1
0
-1
0
1
2
3



Supernova Cosmology Project
Perlmutter et al. (1999)
No Big Bang
99%
95%
90%
68%
42 Supernovae
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
prediction of Guth's
"inflation" theory
Ap.J.
astro-ph/9812133



Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)
No Big Bang
Supernovae
CMB
expands forever
recollapses eventually
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

Systematic Error Checks

- Malmquist bias
- Extinction in SN-host galaxy or our Galaxy.

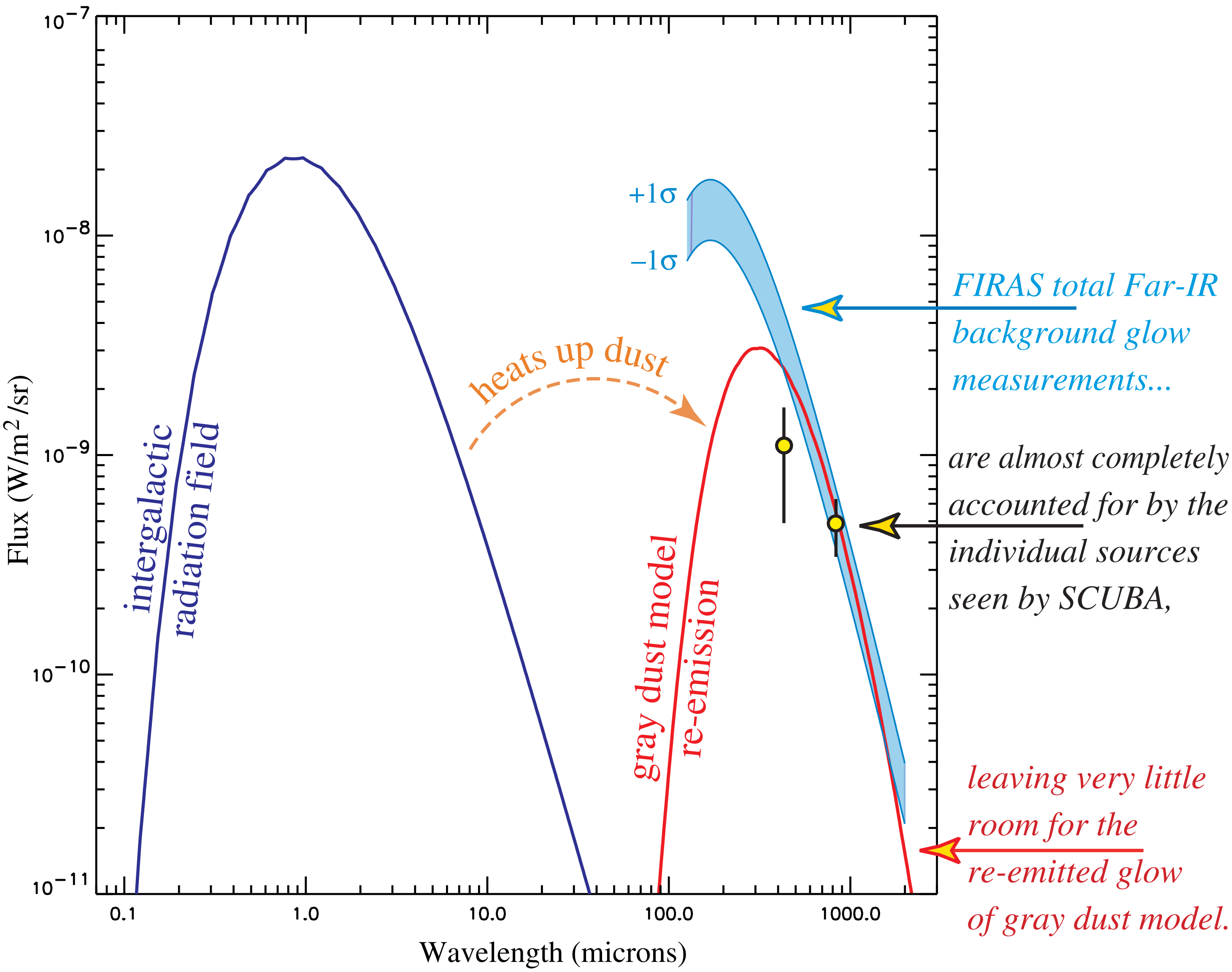
  Evolution of dust?
- Evolution of SNe Ia

  Shift in metallicity/progenitors? Calibratable?
- Local Hubble bubble

  Kim et al. (1996)
  Riess et al. (1997)
- Gravitational Lensing

  Frieman (1996)
  Wambsgans et al. (1996)
  Kantowski et al. (1994)
  Holz & Wald (1998)

Measurements by SCUBA at 850 μm
are already close to ruling out gray dust.

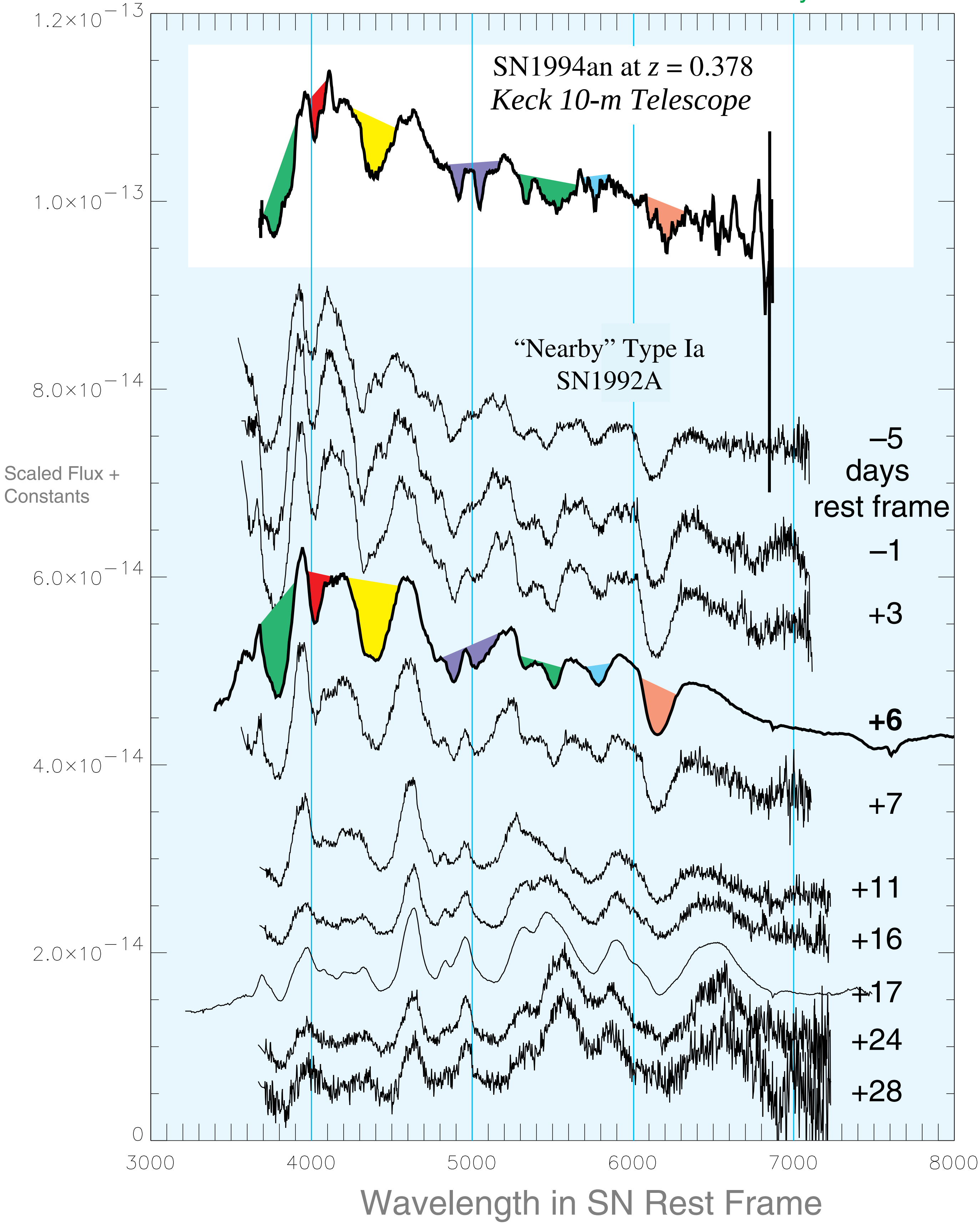


Aguirre & Haiman (1999)

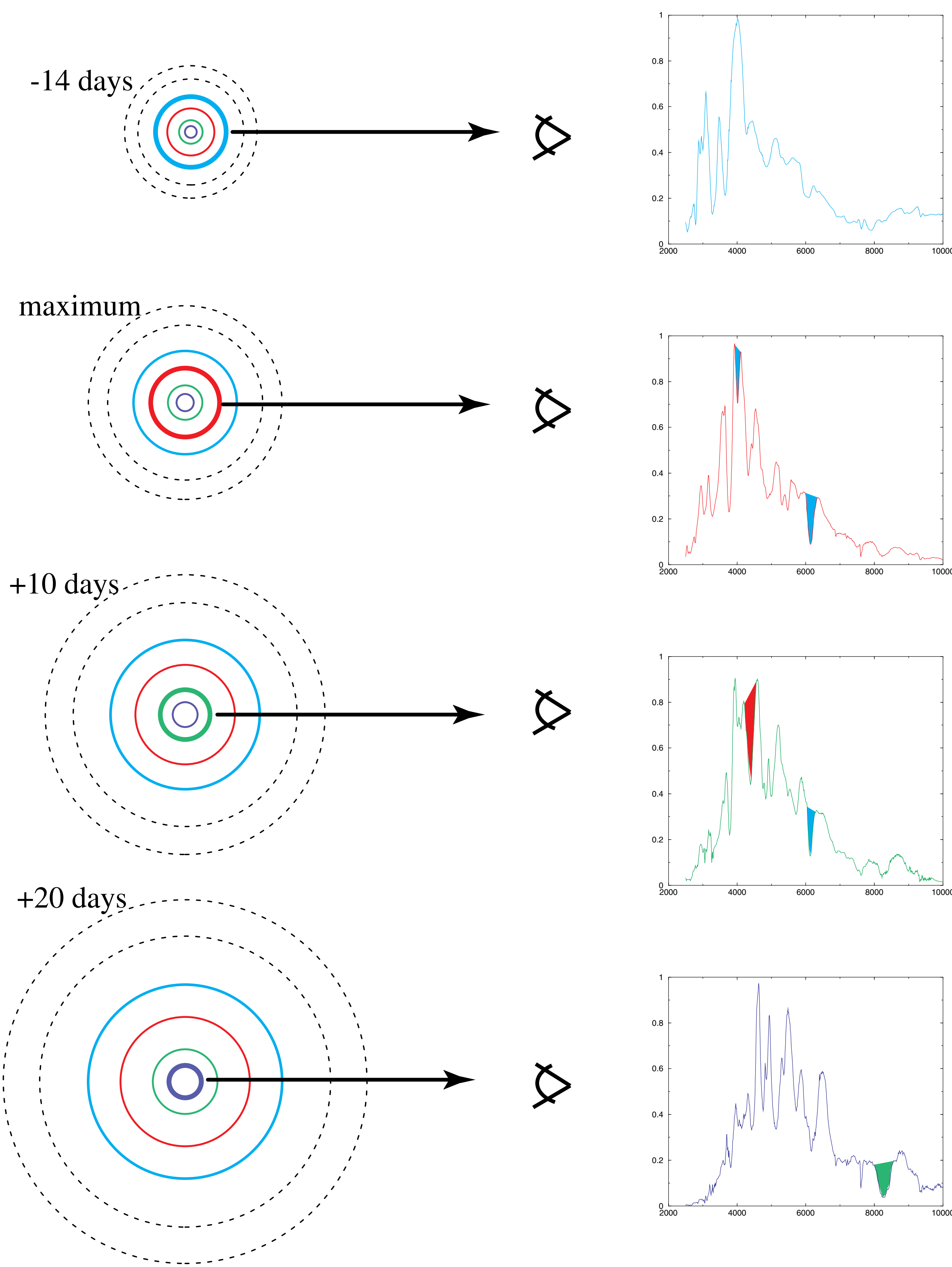
Spectra

An Example: SN1994an

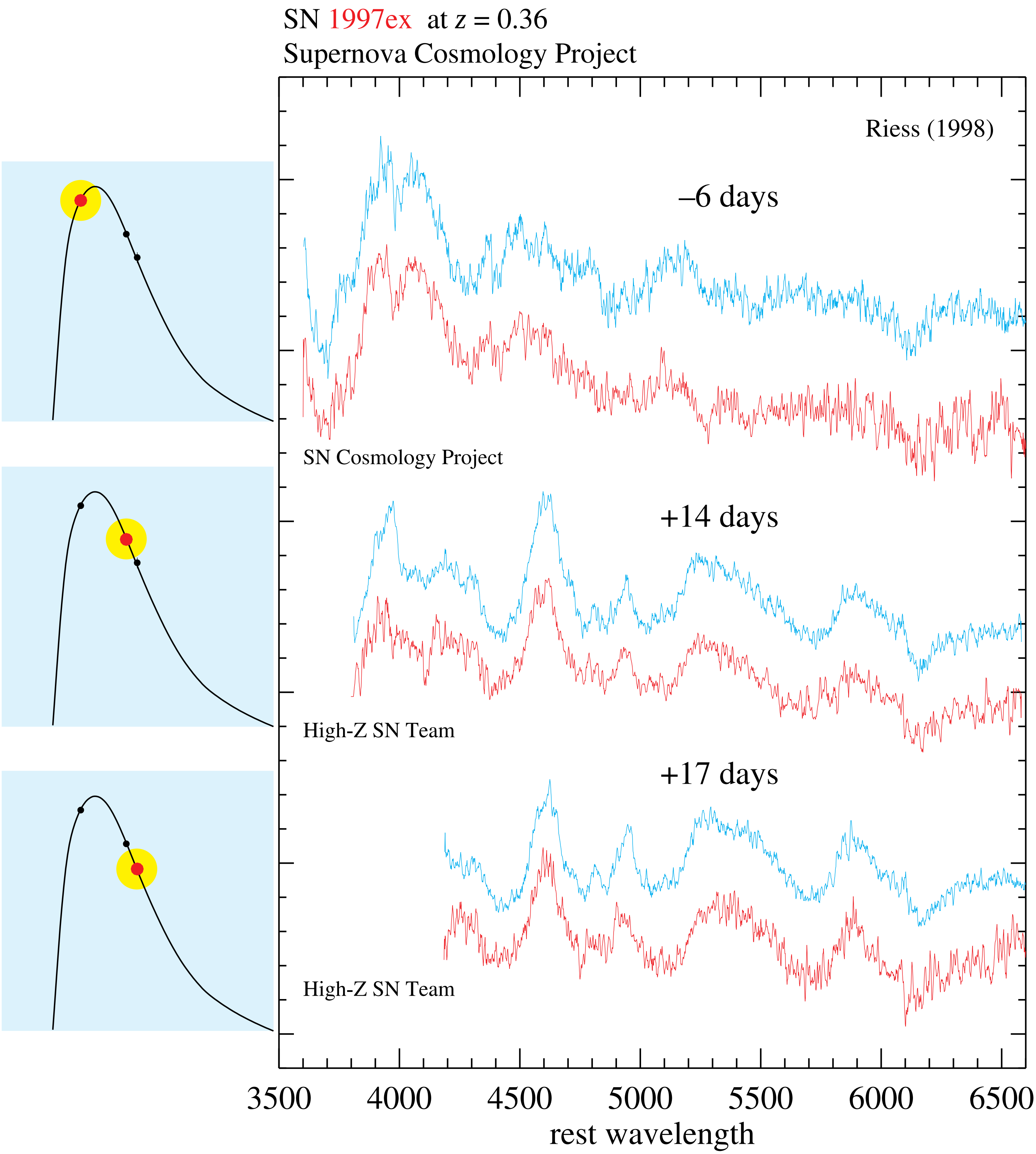
at $z = 0.378$
+9 days past max observer frame
= +6 days rest frame



The time series of spectra is a “CAT Scan” of the Supernova

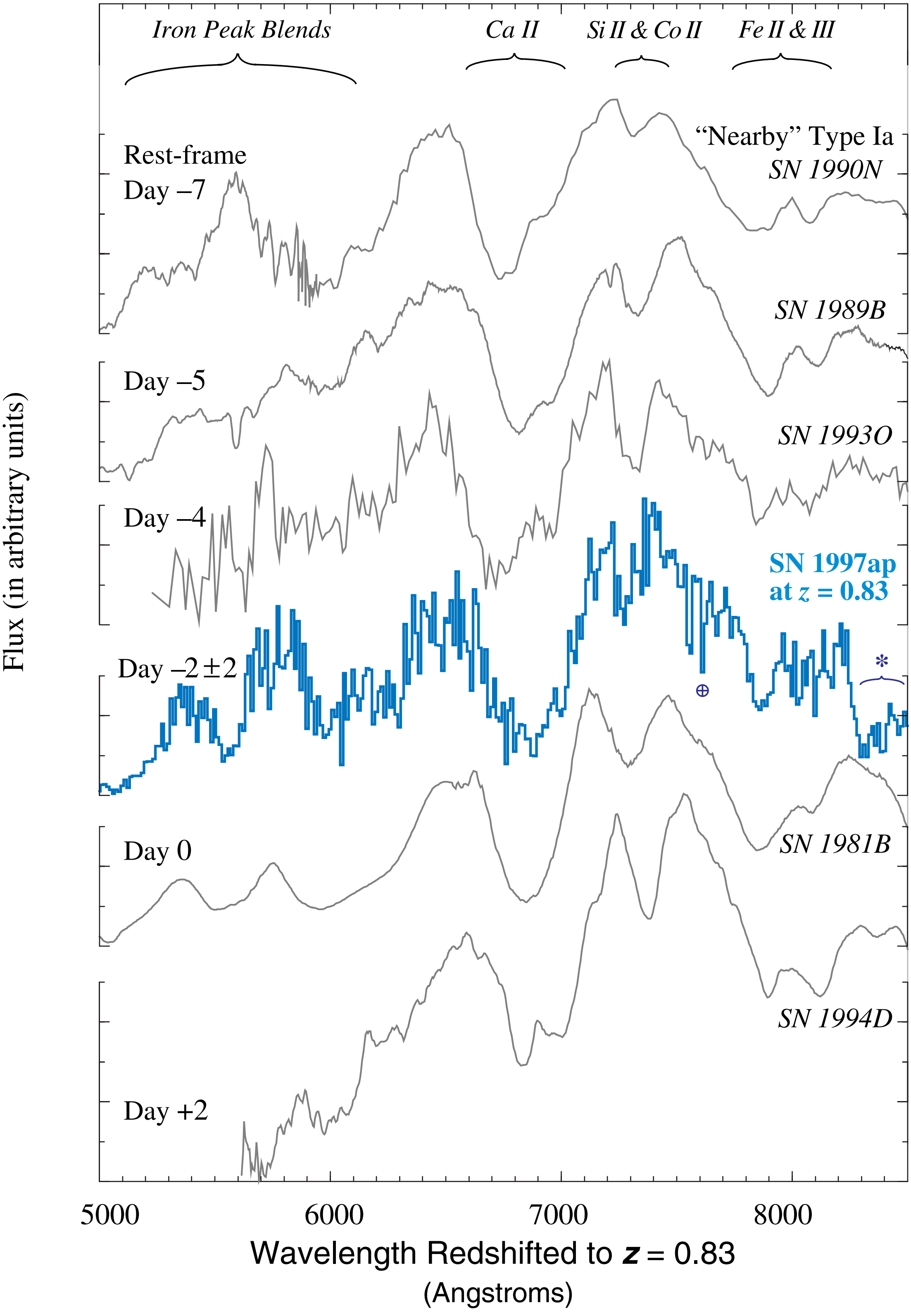


Time Series of Low-Redshift and High-Redshift Spectra



Supernova 1997ap at $z = 0.83$

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



Note: –4 days (before) max observer frame = –2 days rest frame

Score Card of Current Uncertainties

on $(\Omega_{M}^{flat}, \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

Statistical

☑	high-redshift SNe	0.05
☑	low-redshift SNe	0.065
	Total	***0.085***

Systematic

☑	dust that reddens $R_B(z=0.5) < 2\ R_B(\text{today})$	< 0.03
	evolving grey dust	
?	clumpy	
?	same for each SN	
☑	Malmquist bias difference	< 0.04
?	SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..	
☑	K-correction uncertainty including zero-points	< 0.025
	Total identified entities/processes	***0.05***

Cross-Checks of sensitivity to

☑	Width-Luminosity Relation	< 0.03
☑	Non-SN Ia contamination	< 0.05
☑	Galactic Extinction Model	< 0.04
☑	Gravitational Lensing by clumped mass	< 0.06

Perlmutter *et al.* (1998)
astro-ph/9812133

What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

- ***Why so small?***

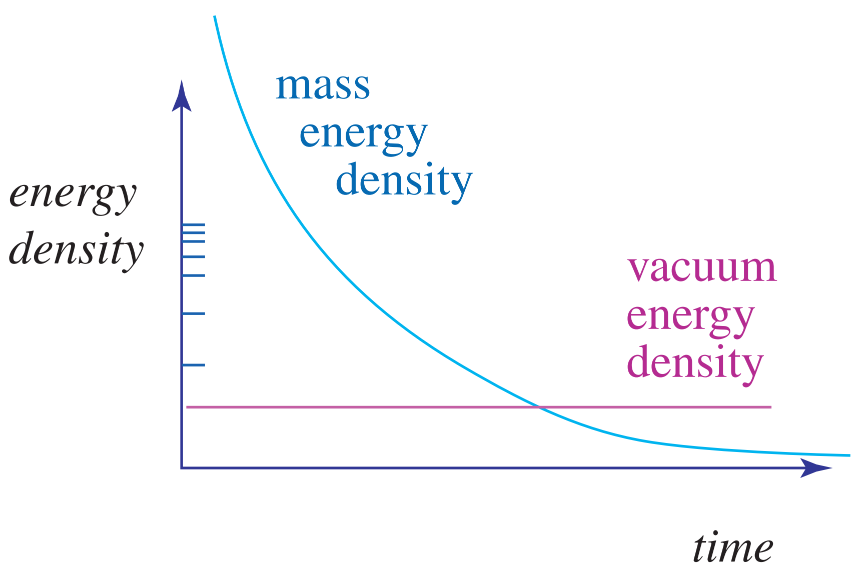
  Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{Planck}}$

  This is off by ~120 orders of magnitude!

- ***"Why now?"***

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

MATTER:	$p = 0$	$\rightarrow \rho \propto R^{-3}$
VACUUM ENERGY:	$p = -\rho$	$\rightarrow \rho \propto constant$



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MATTER:	$p = 0$	$\longrightarrow \rho \propto R^{-3}$
VACUUM ENERGY:	$p = -\rho$	$\longrightarrow \rho \propto \textit{constant}$

What are the alternatives?

New Physics:

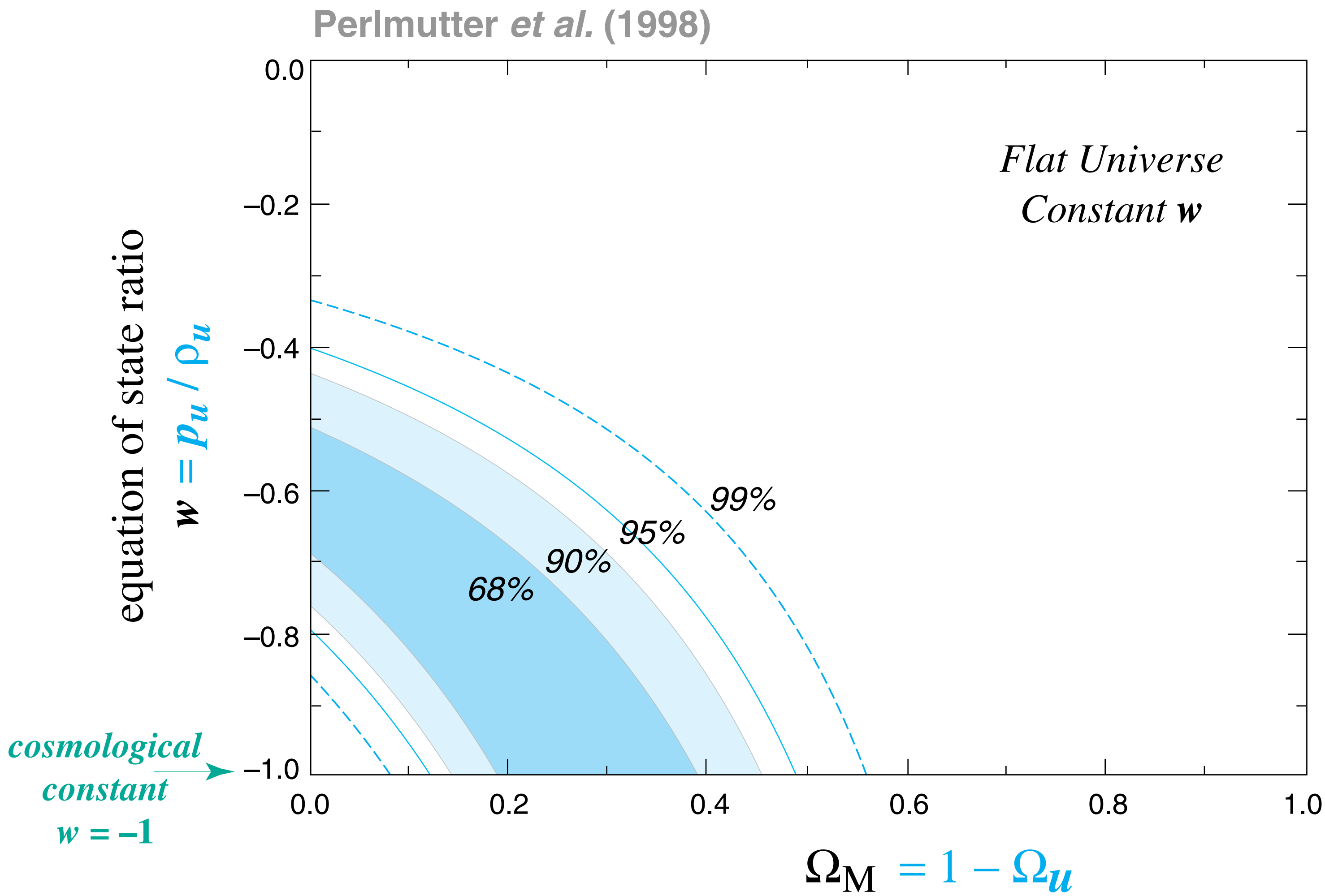
"Dark energy": Dynamical scalar fields, "quintessence",...

COSMIC STRINGS:	$p = -1/3\ \rho$	$\longrightarrow \rho \propto R^{-2}$
General Equation of State:	$p = w\rho$	$\longrightarrow \rho \propto R^{-3(1+w)}$

and w can vary with time

"Dark Energy"

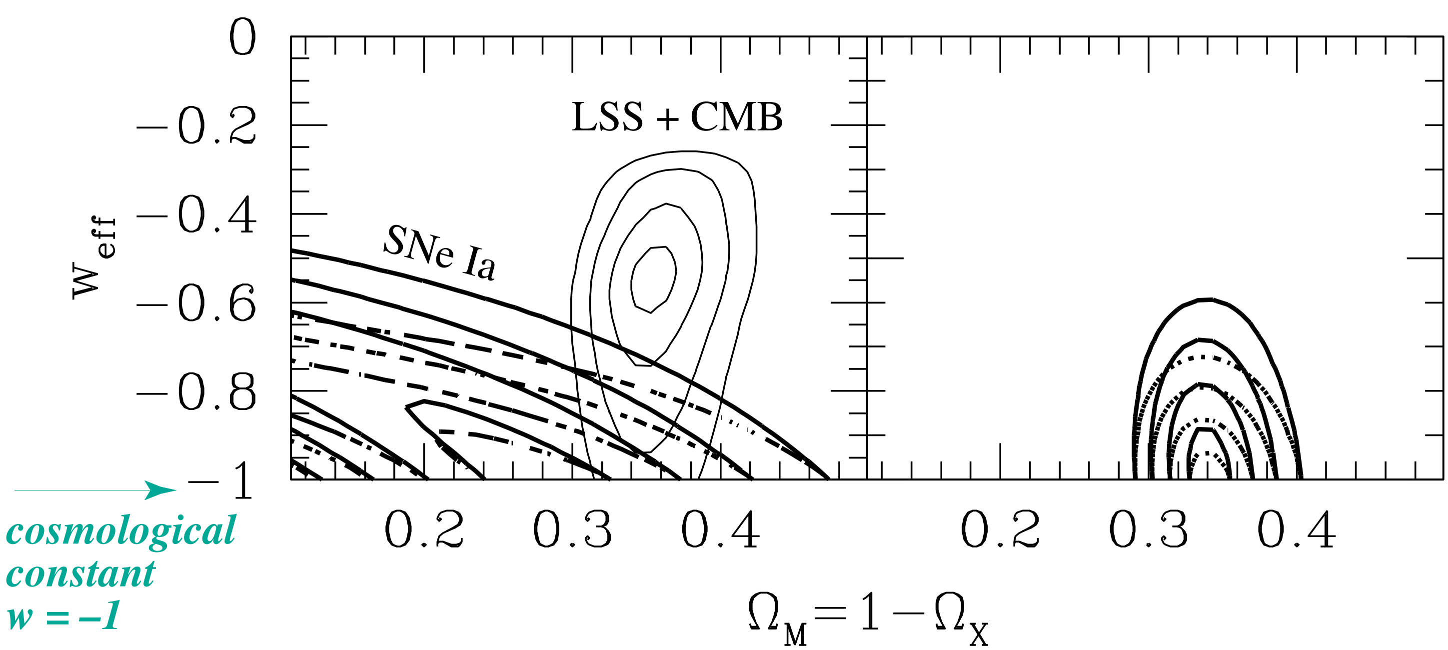
Unknown Component, Ω_u, of Energy Density



c.f. Garnavich et al. (1998)

astro-ph 9901052

Constraints on Equation of State of "Dark Energy"



S.P., Turner, & White (1999)
Phys. Rev. Lett.

We knew or thought we knew…

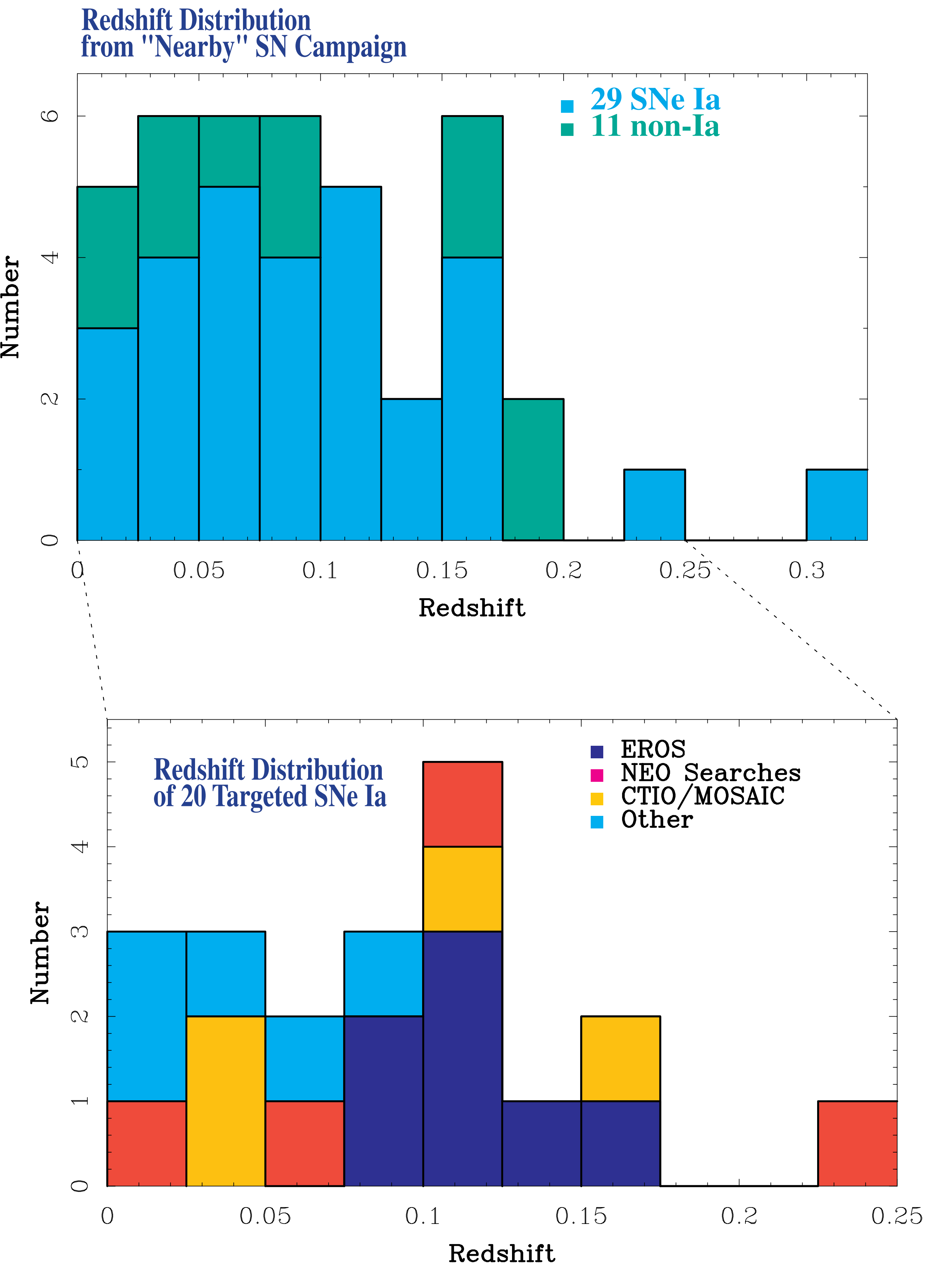
What we didn't know…

What we found…

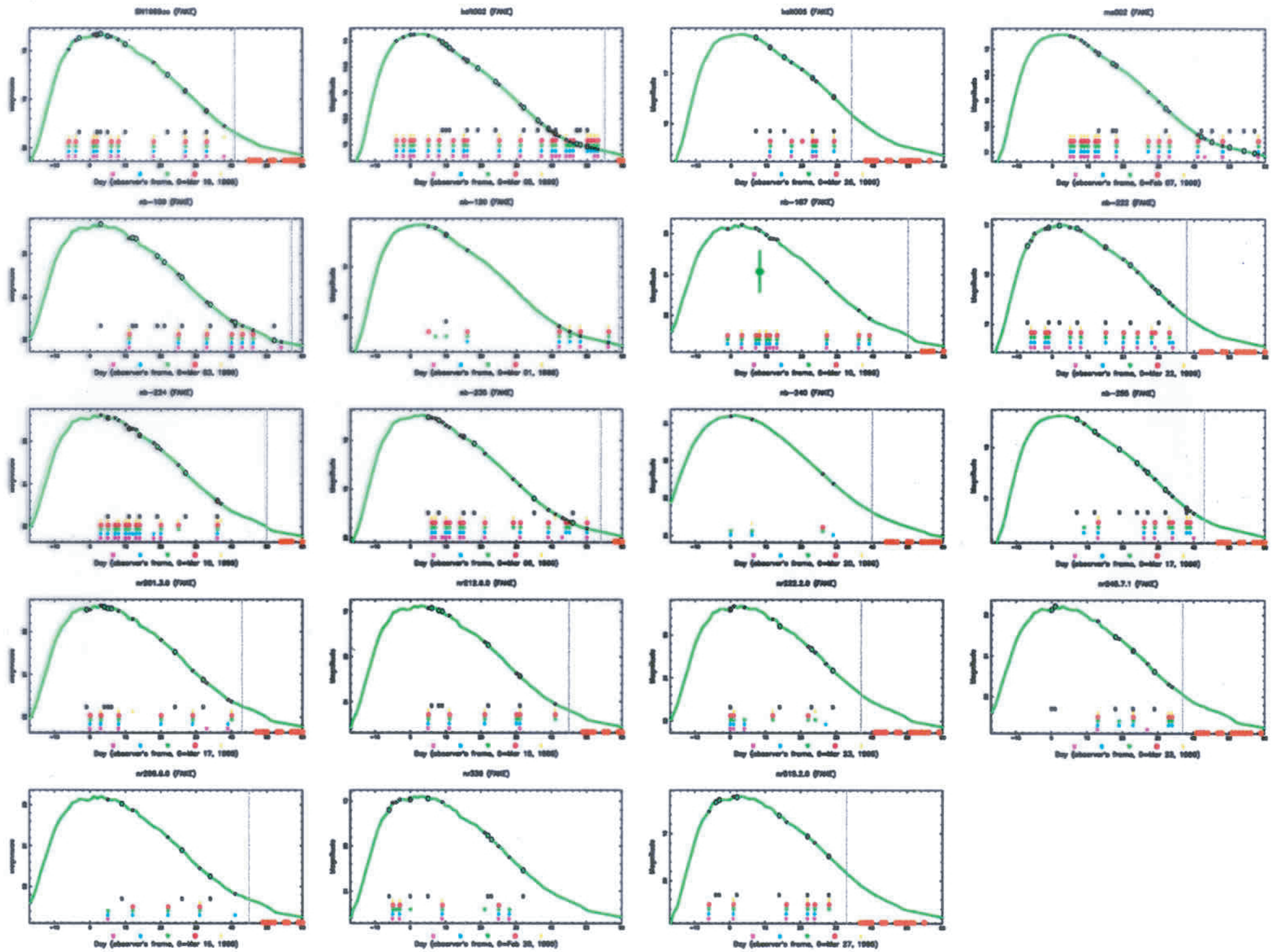
Now what we don't know is…□

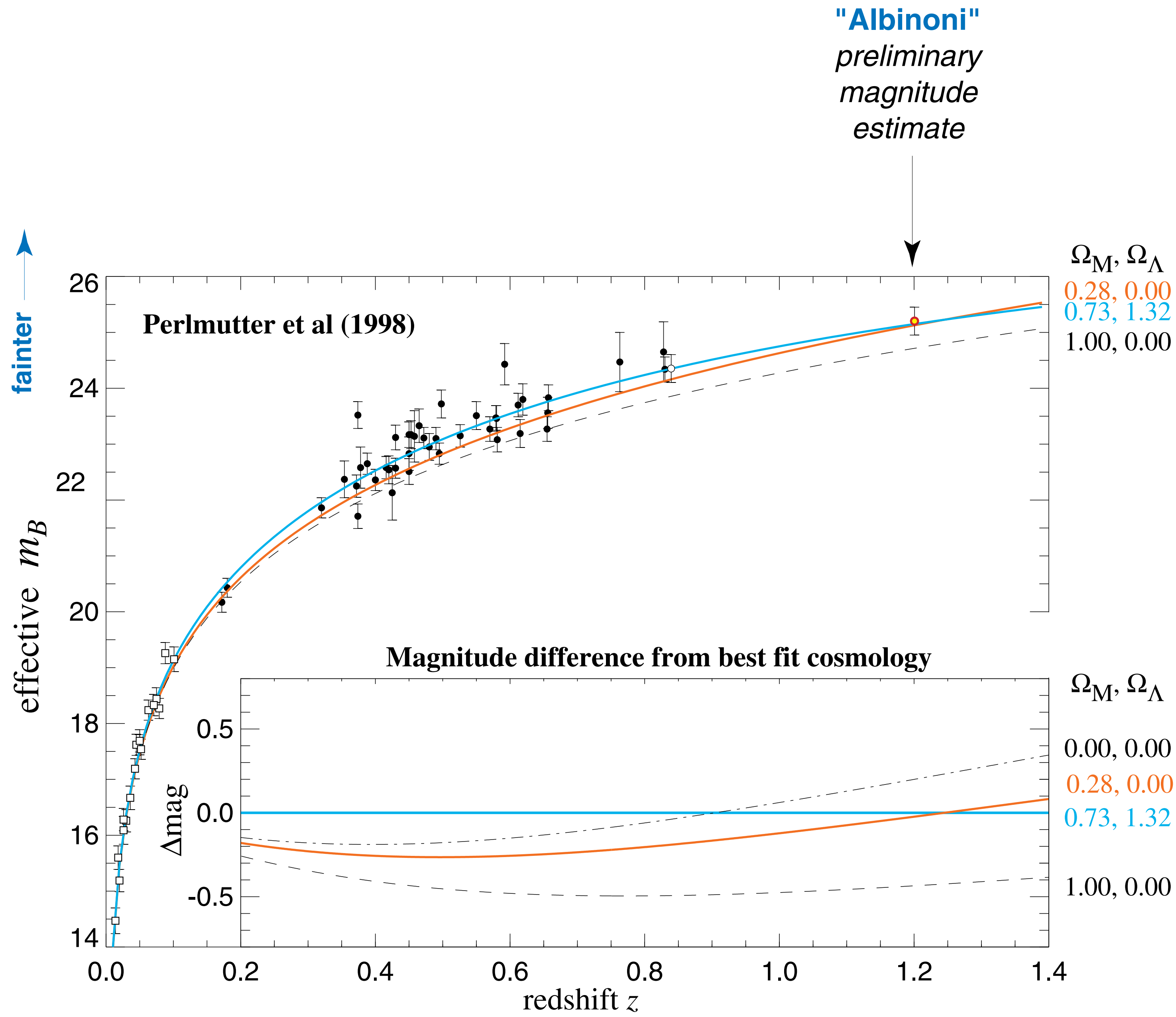
But we know how to find out:

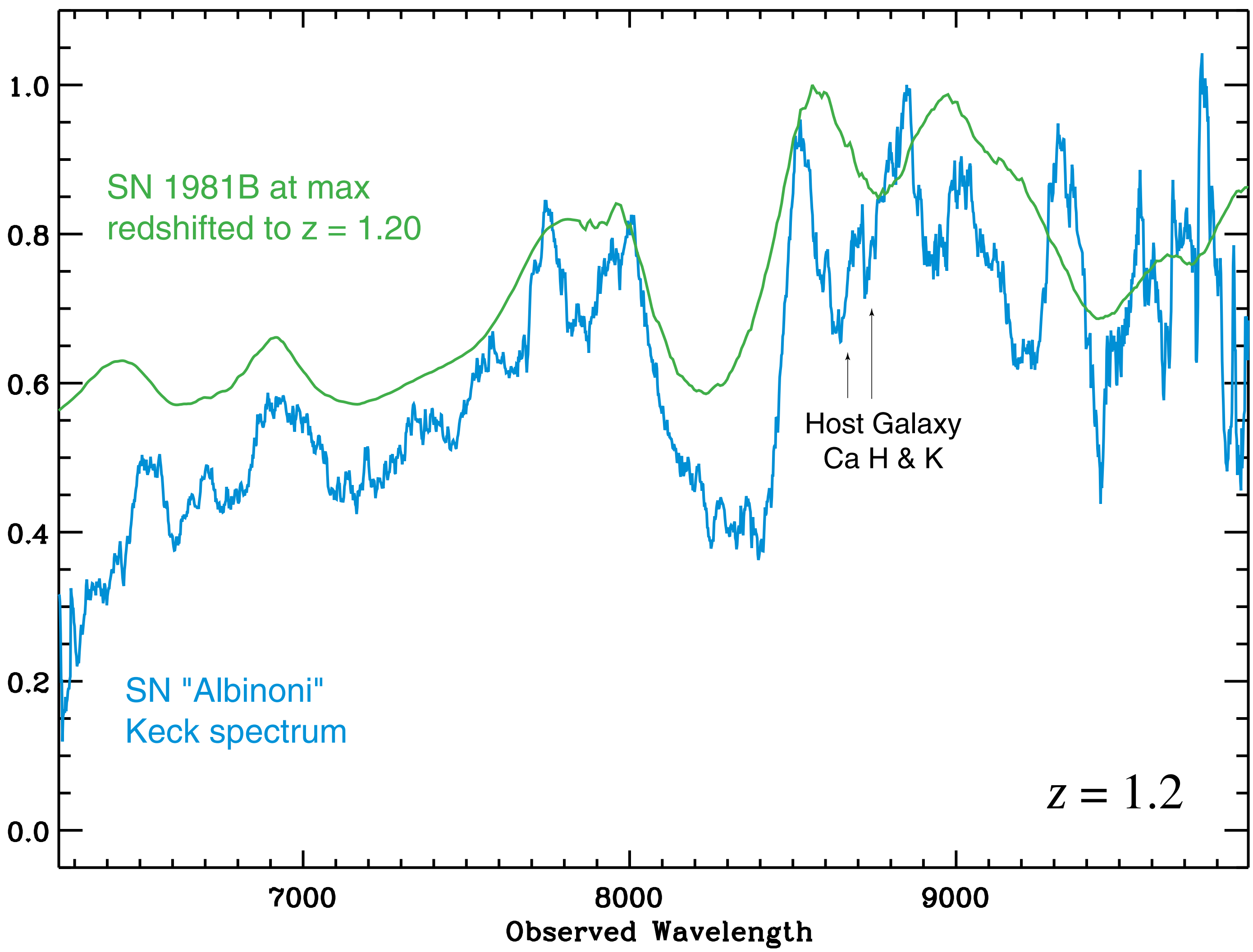
- We can systematically find low-redshift supernovae.
  - We can find and study supernovae at $z \sim 1.2$
- We can dramatically improve
  - statistics and systematics with a satellite.



Redshift Distribution
from "Nearby" SN Campaign
29 SNe Ia
11 non-Ia
Number
Redshift
0
2
4
6
0
0.05
0.1
0.15
0.2
0.25
0.3
Redshift Distribution
of 20 Targeted SNe Ia
EROS
NEO Searches
CTIO/MOSAIC
Other
Number
Redshift
0
1
2
3
4
5
0
0.05
0.1
0.15
0.2
0.25

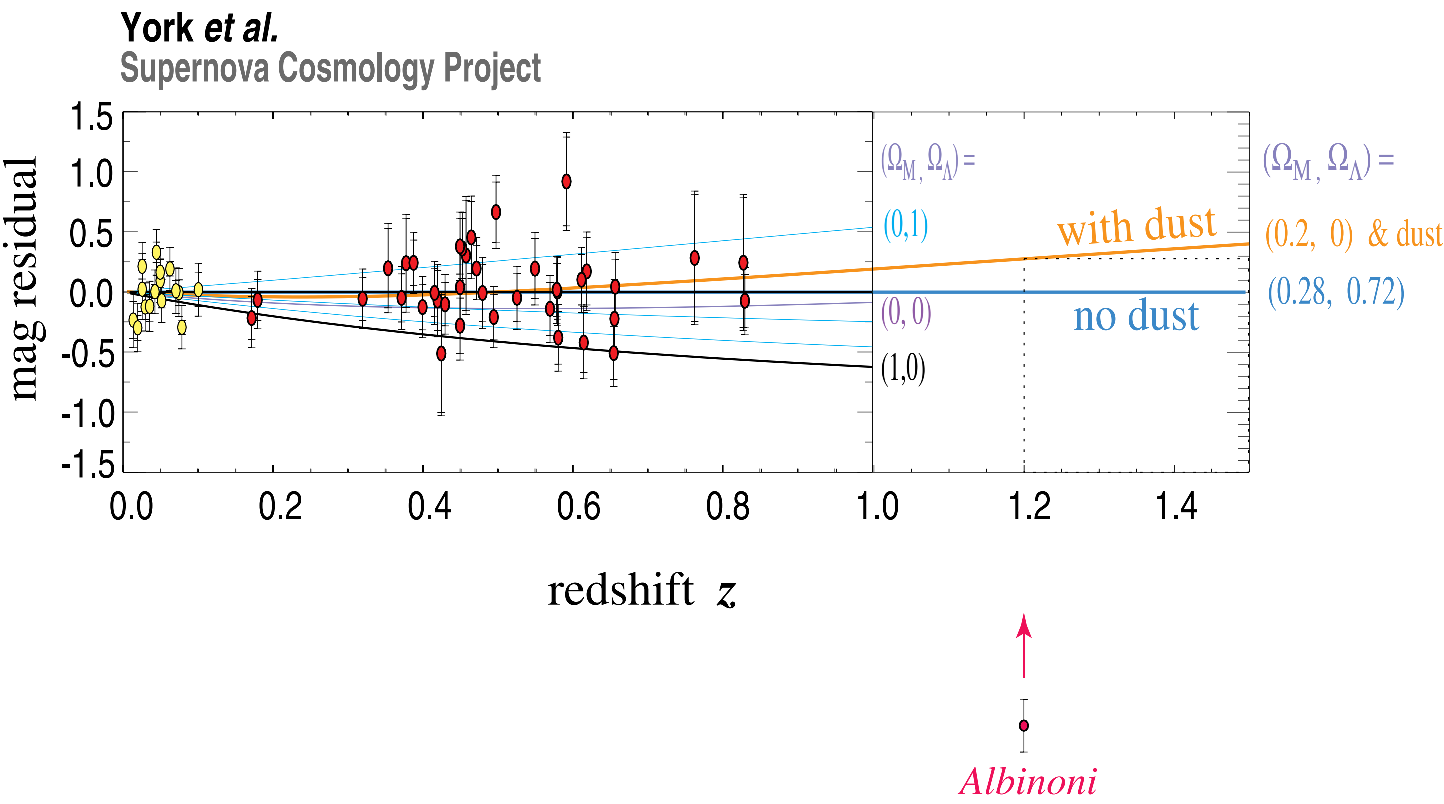



"Albinoni"
preliminary
magnitude
estimate
fainter
Perlmutter et al (1998)
effective m_B
26
24
22
20
18
16
14
Ω_M, Ω_Λ
0.28, 0.00
0.73, 1.32
1.00, 0.00
Magnitude difference from best fit cosmology
Δmag
0.5
0.0
-0.5
Ω_M, Ω_Λ
0.00, 0.00
0.28, 0.00
0.73, 1.32
1.00, 0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
redshift z



1.0
0.8
0.6
0.4
0.2
0.0
7000
8000
9000
Observed Wavelength
SN 1981B at max
redshifted to z = 1.20
SN "Albinoni"
Keck spectrum
Host Galaxy
Ca H & K
z = 1.2

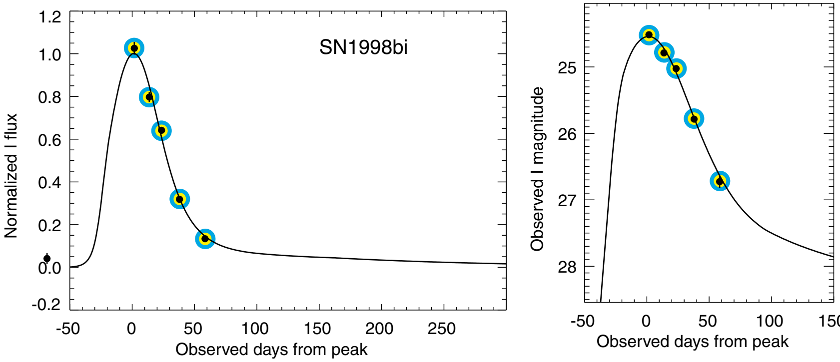
Recognizing
Intergalactic Grey Dust
Using SNe at Redshifts > 1



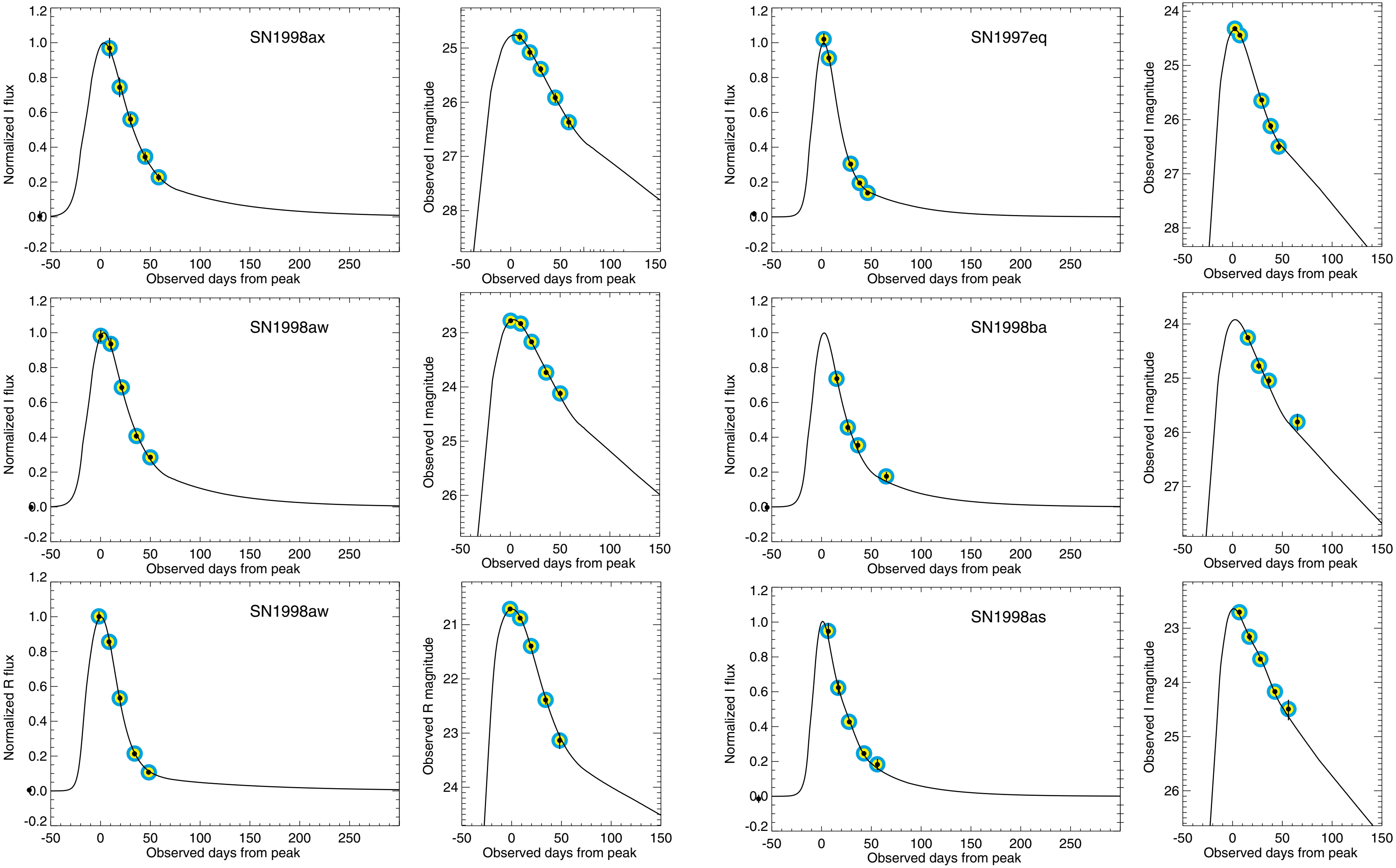
see Aguirre (1999)
astro-ph/9904319

PRELIMINARY

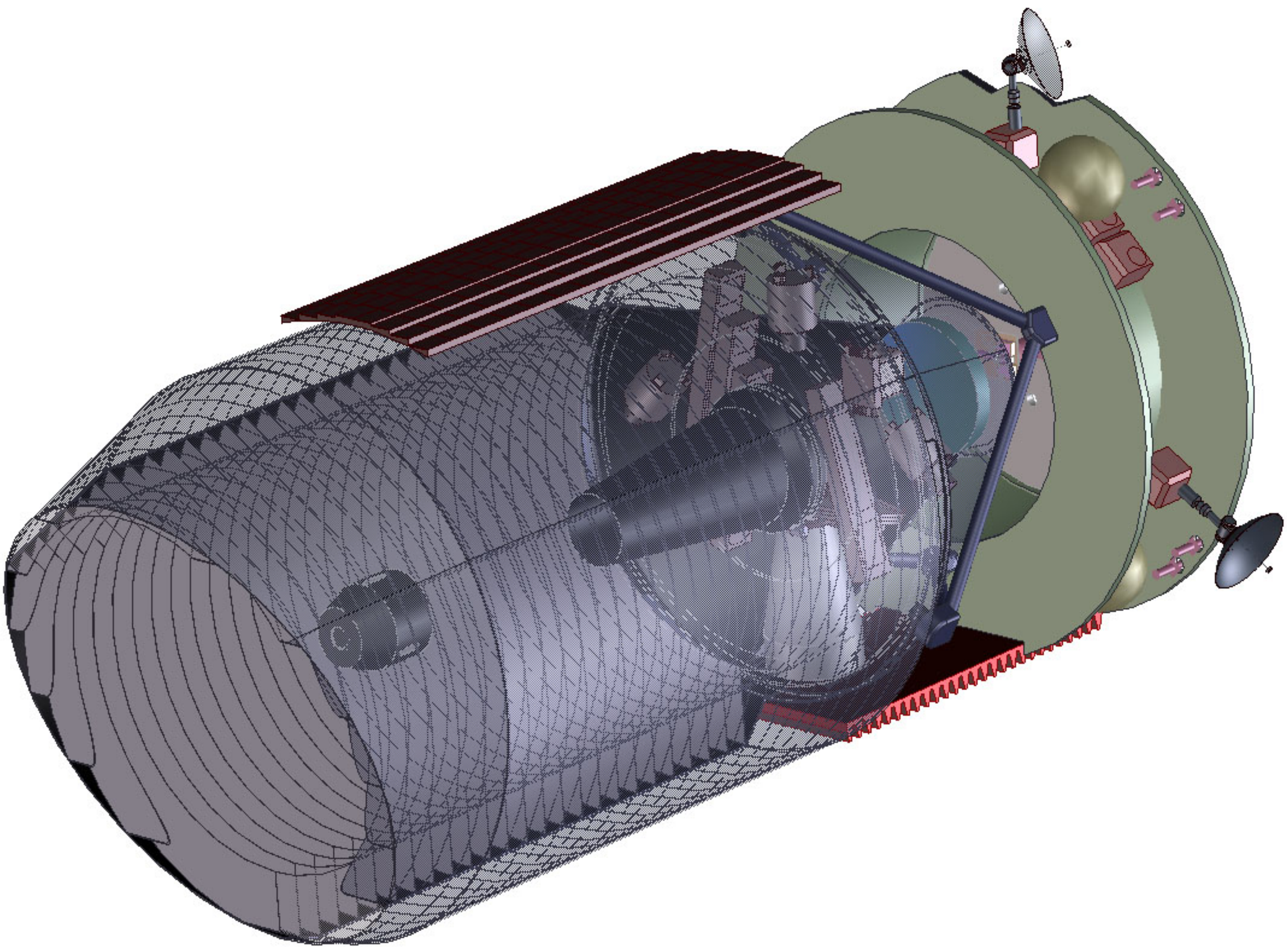
Hubble Space Telescope Lightcurves: High Redshift Type Ia Supernovae



Supernova Cosmology Project



SNAP SuperNova Acceleration Probe



SNAP SuperNova Acceleration Probe

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.

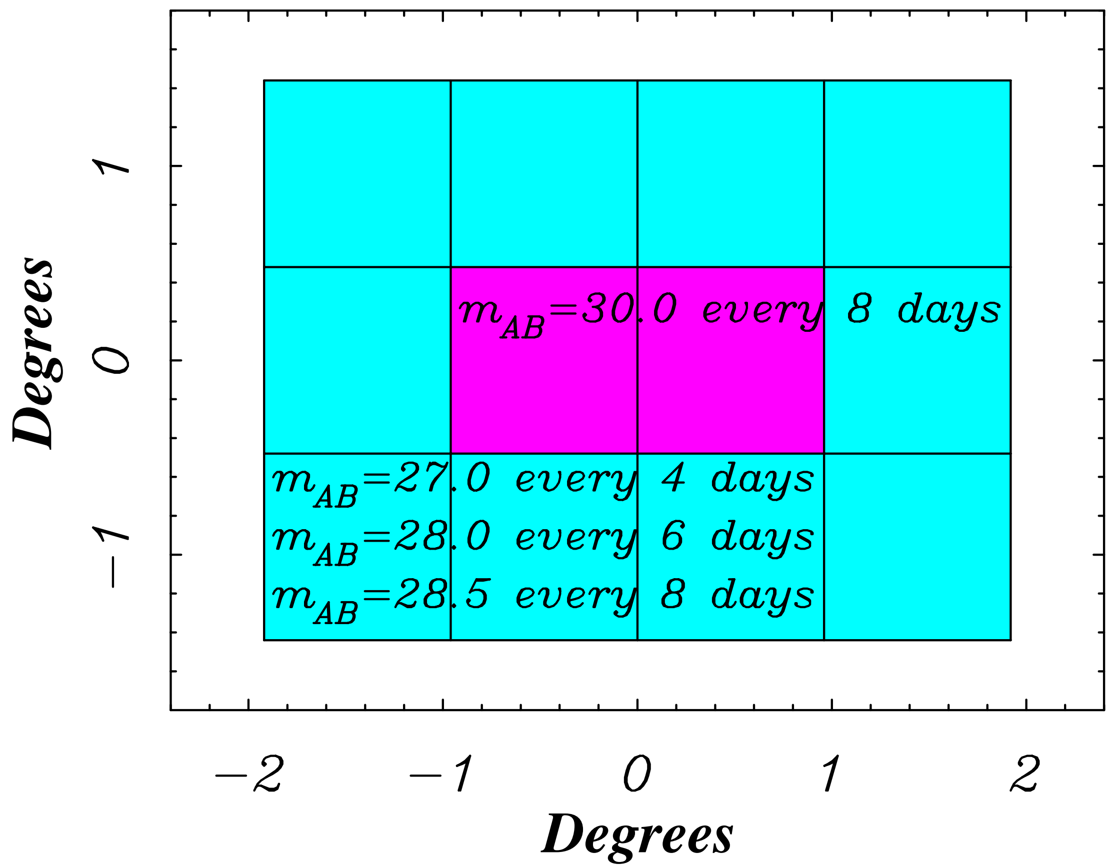
Designed to repeatedly observe an area of sky.

Essentially no moving parts.

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

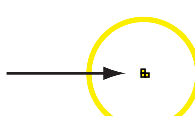
SNAP SuperNova Acceleration Probe

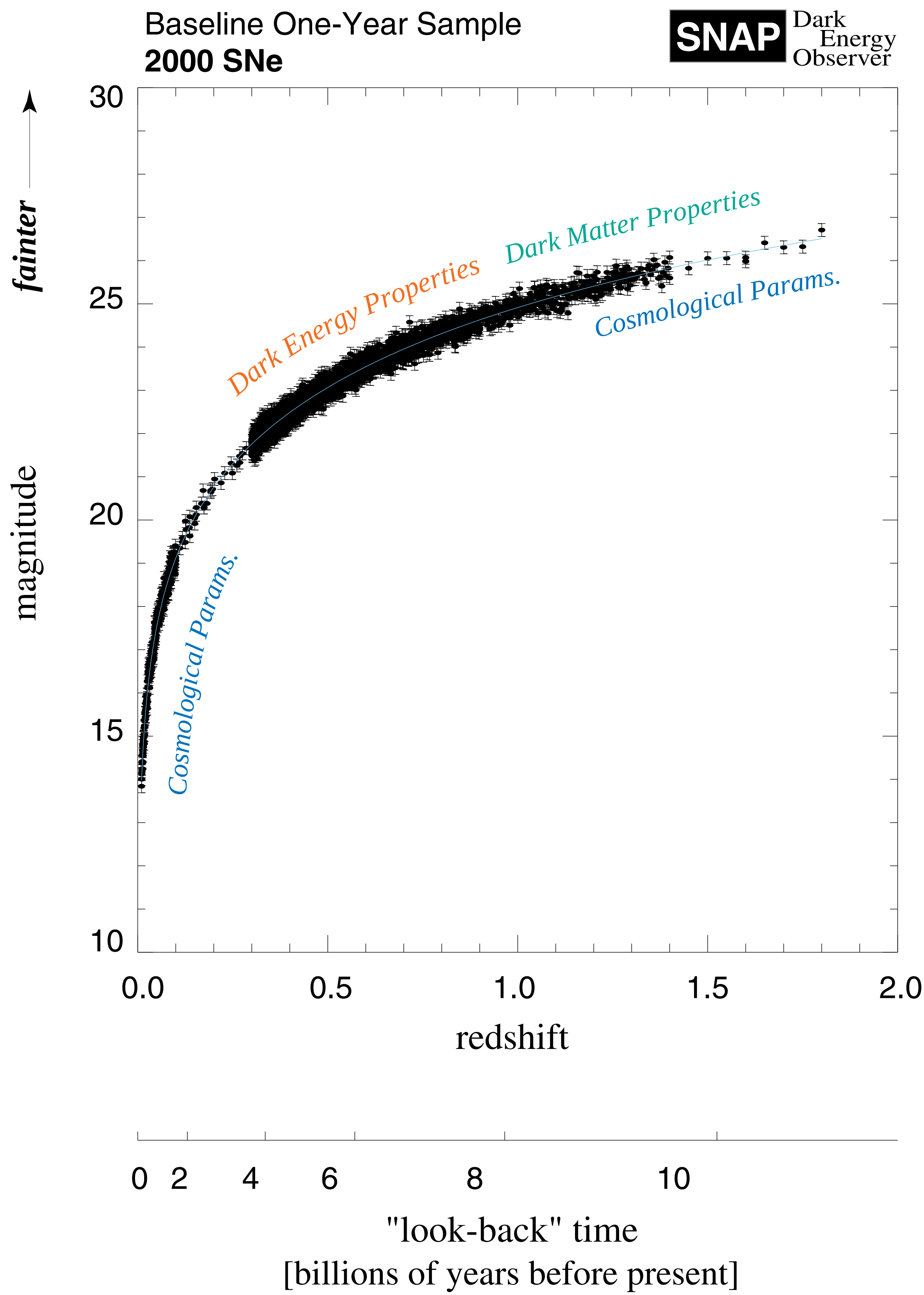
Search Strategy - Deep & Often



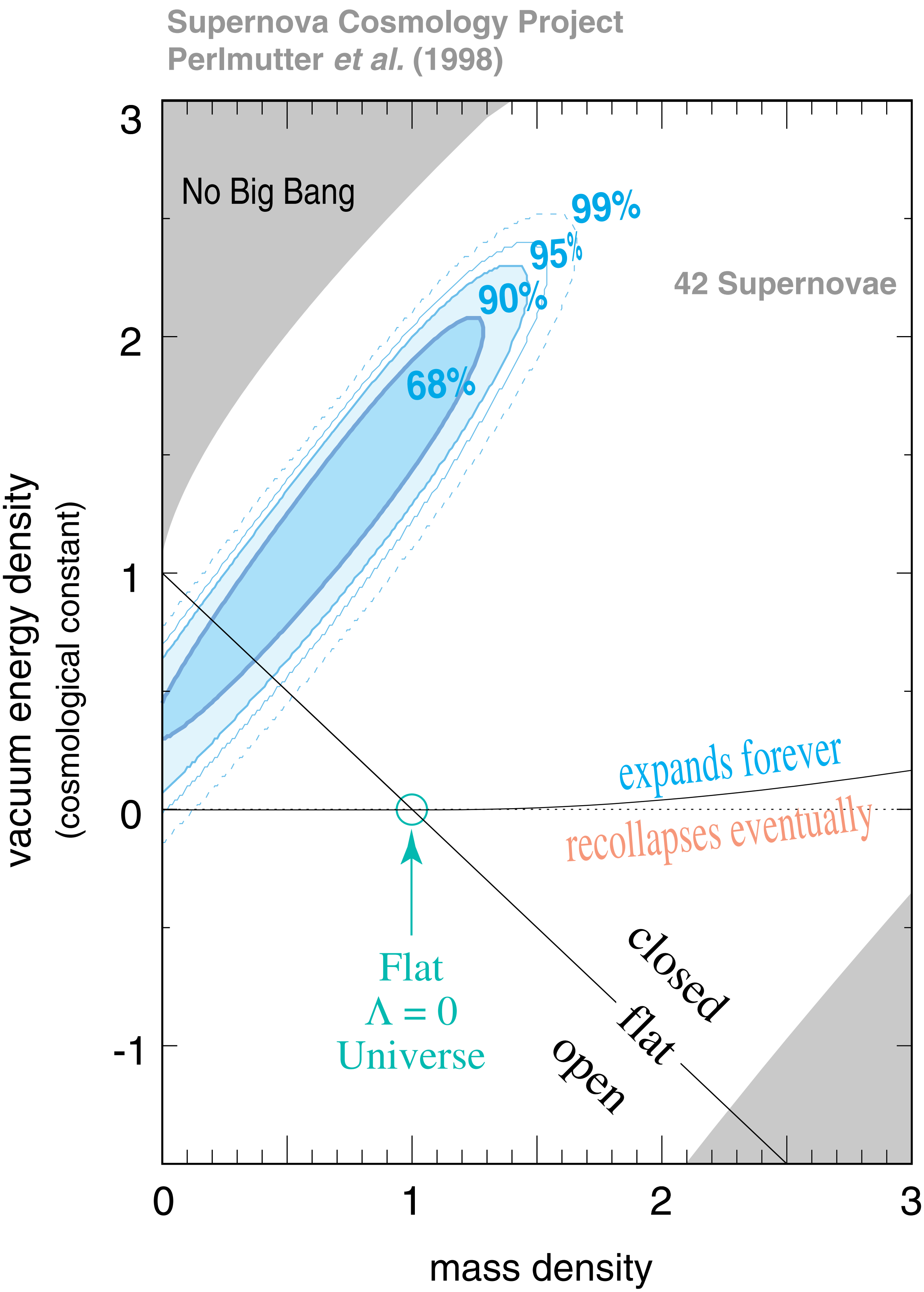
Co-added images: $\boldsymbol{m_{AB}}$ = 32.0 !

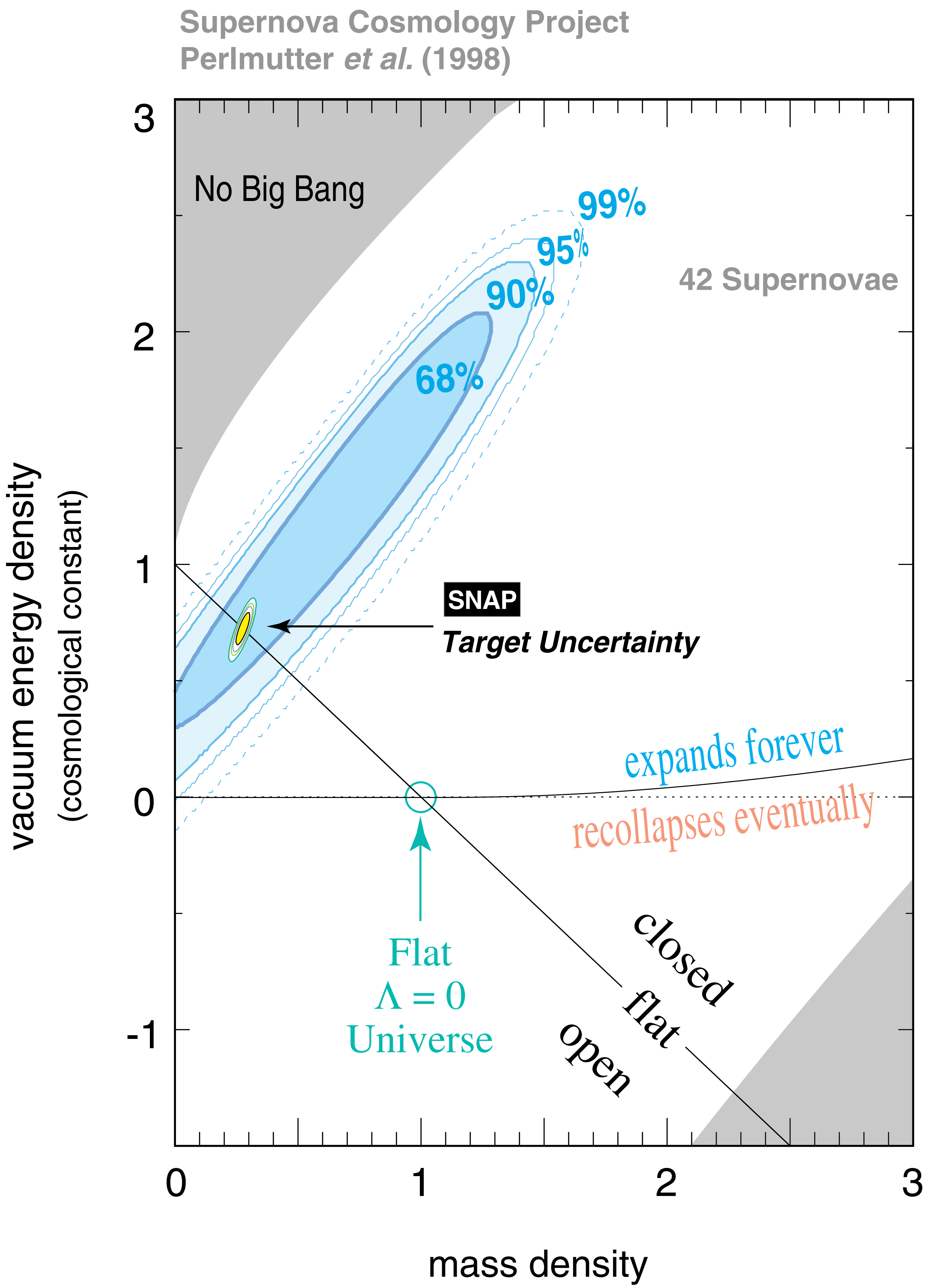
Size of
Hubble Deep Field





Baseline One-Year Sample
2000 SNe
SNAP Dark Energy Observer
fainter
magnitude
30
25
20
15
10
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
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
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


Supernova Cosmology Project
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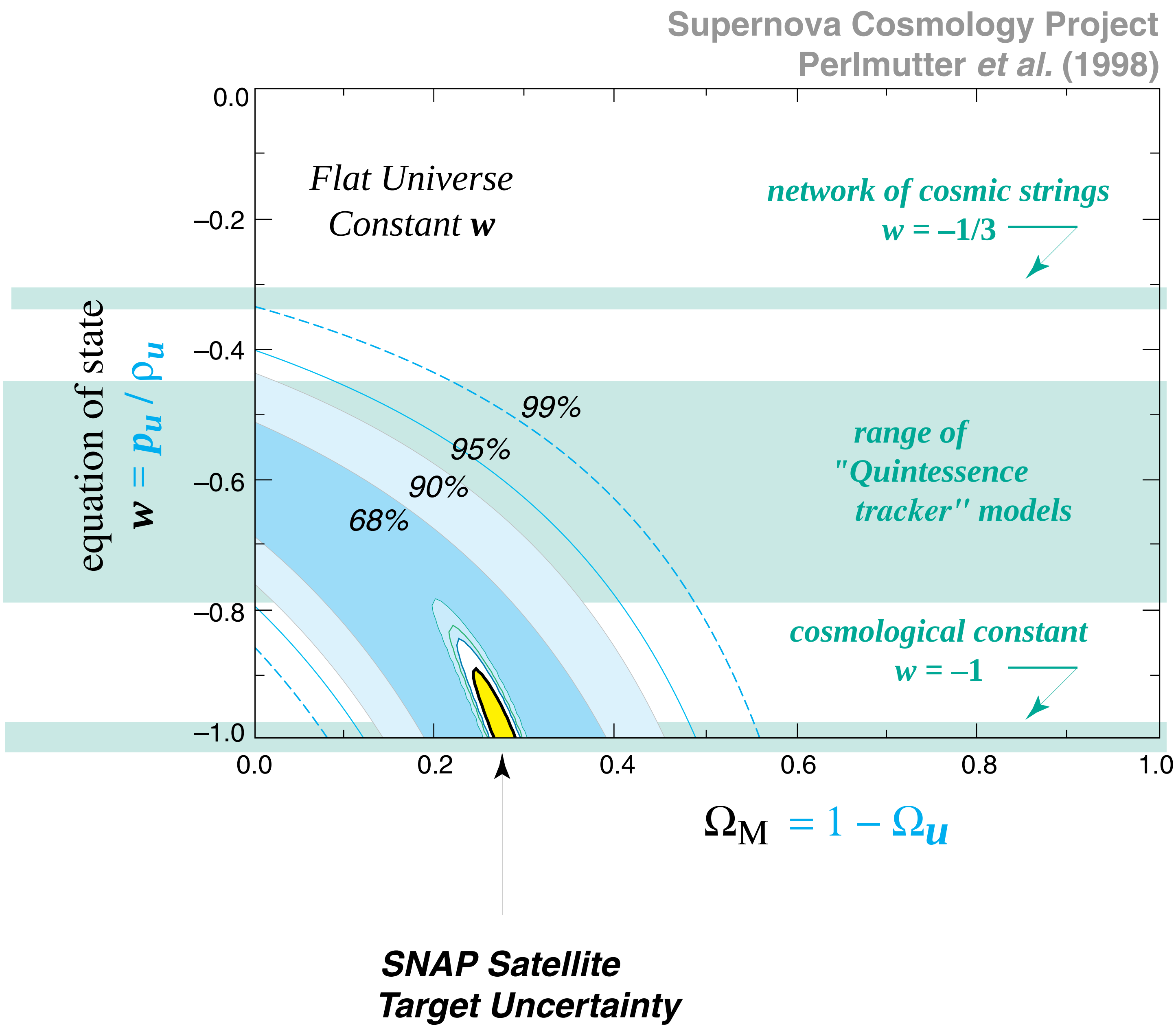
SNAP
Target Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

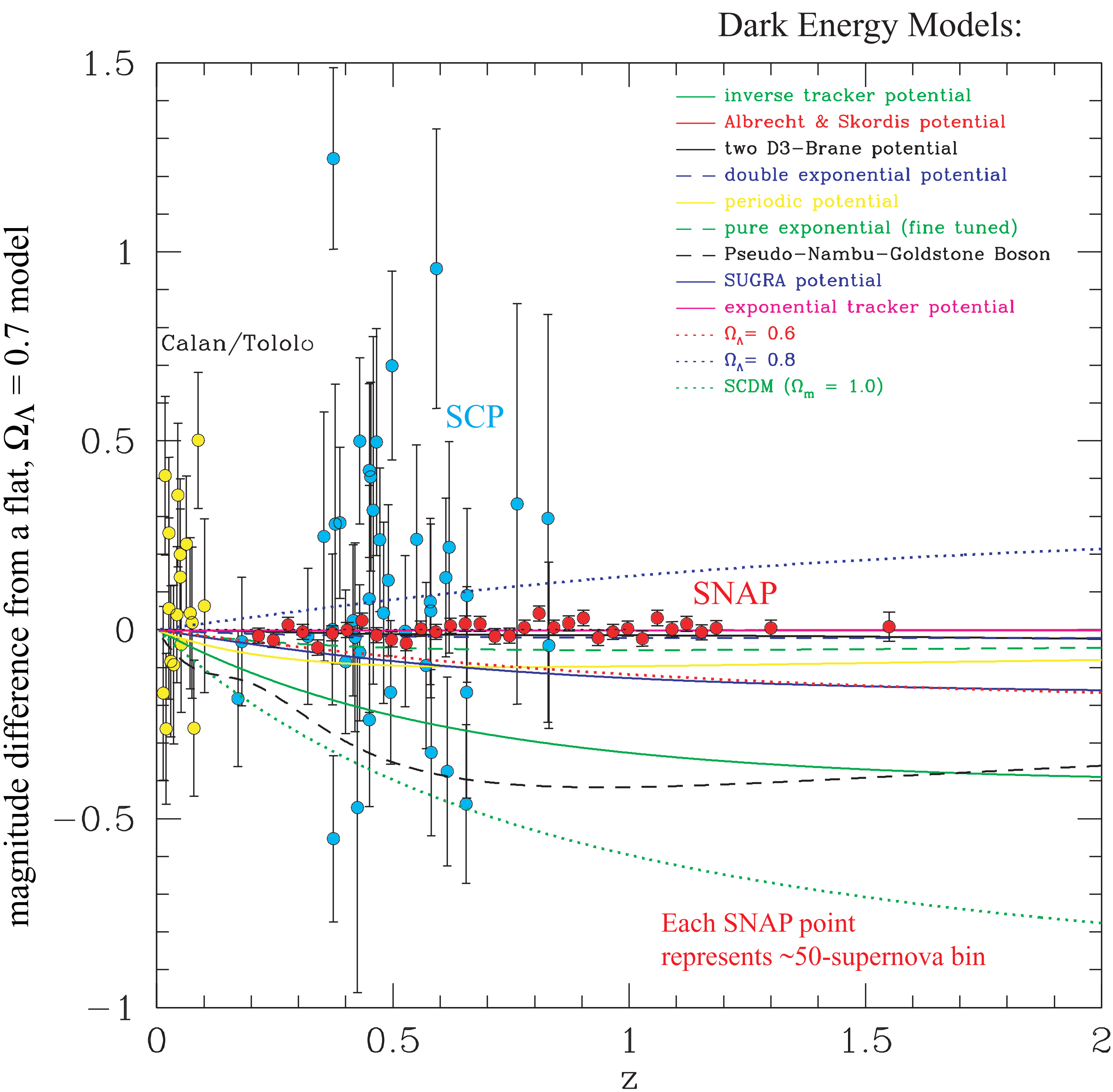
Dark Energy

Unknown Component, Ω_u, of Energy Density



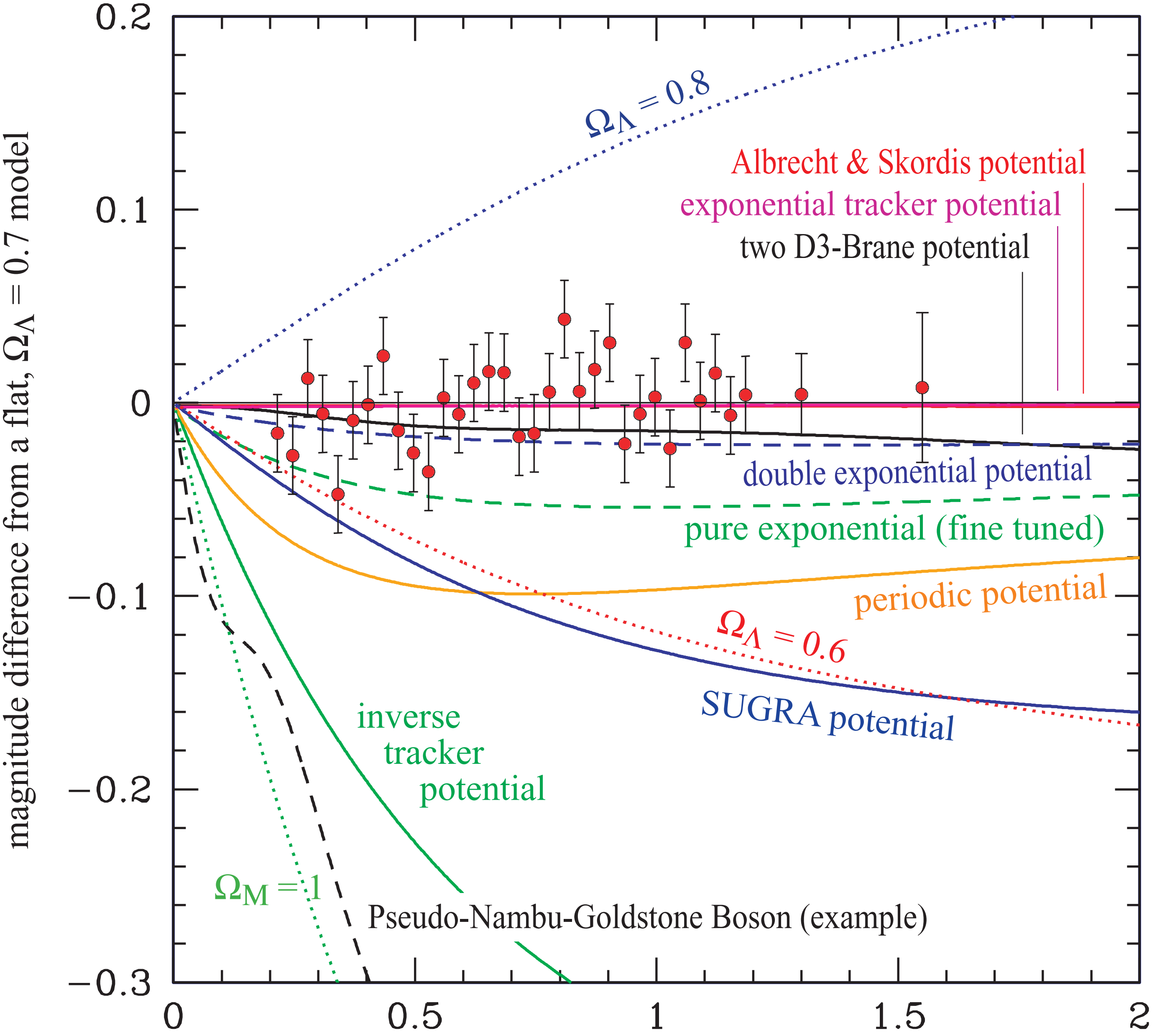
SNAP SuperNova Acceleration Probe

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

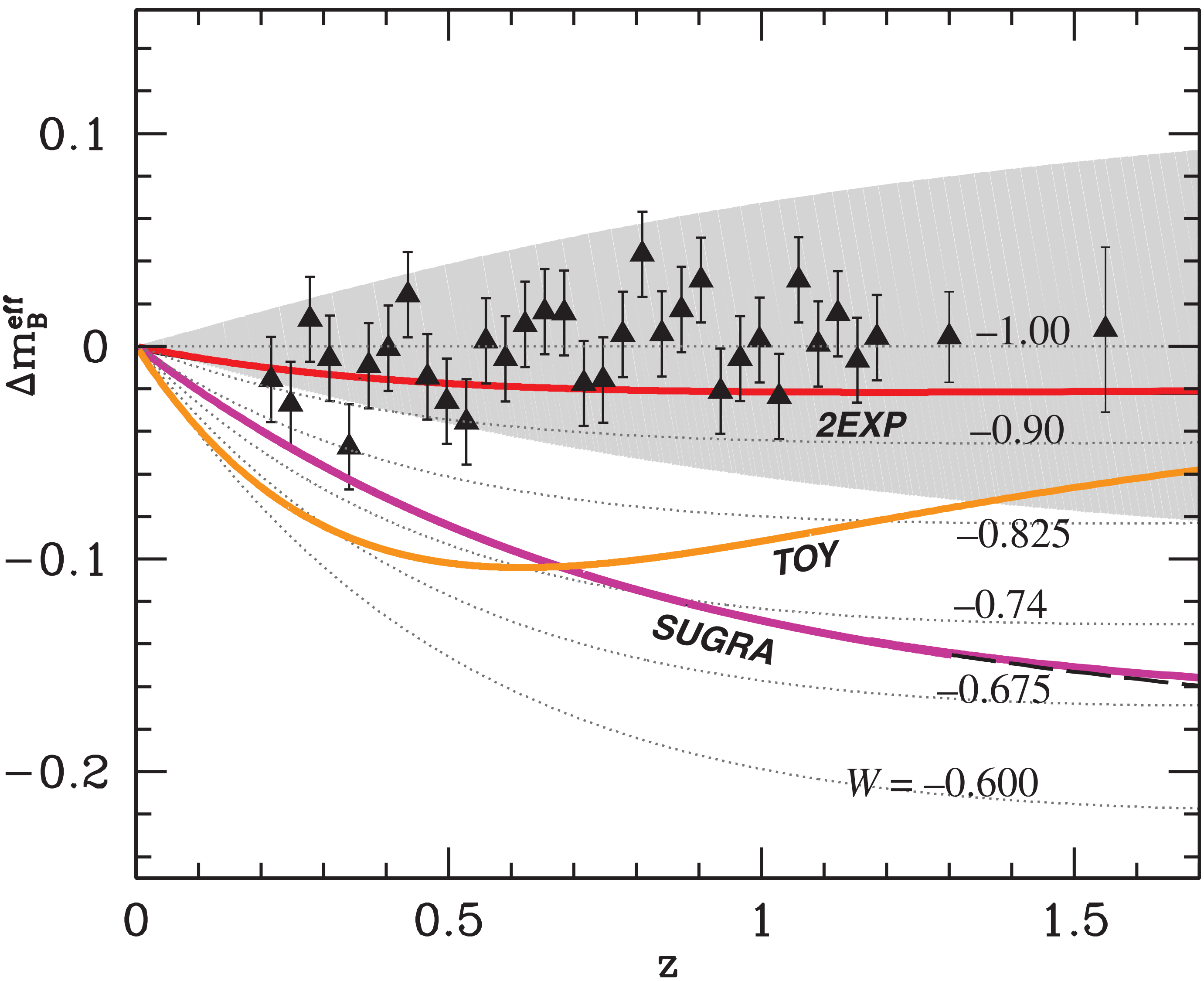


SNAP SuperNova Acceleration Probe

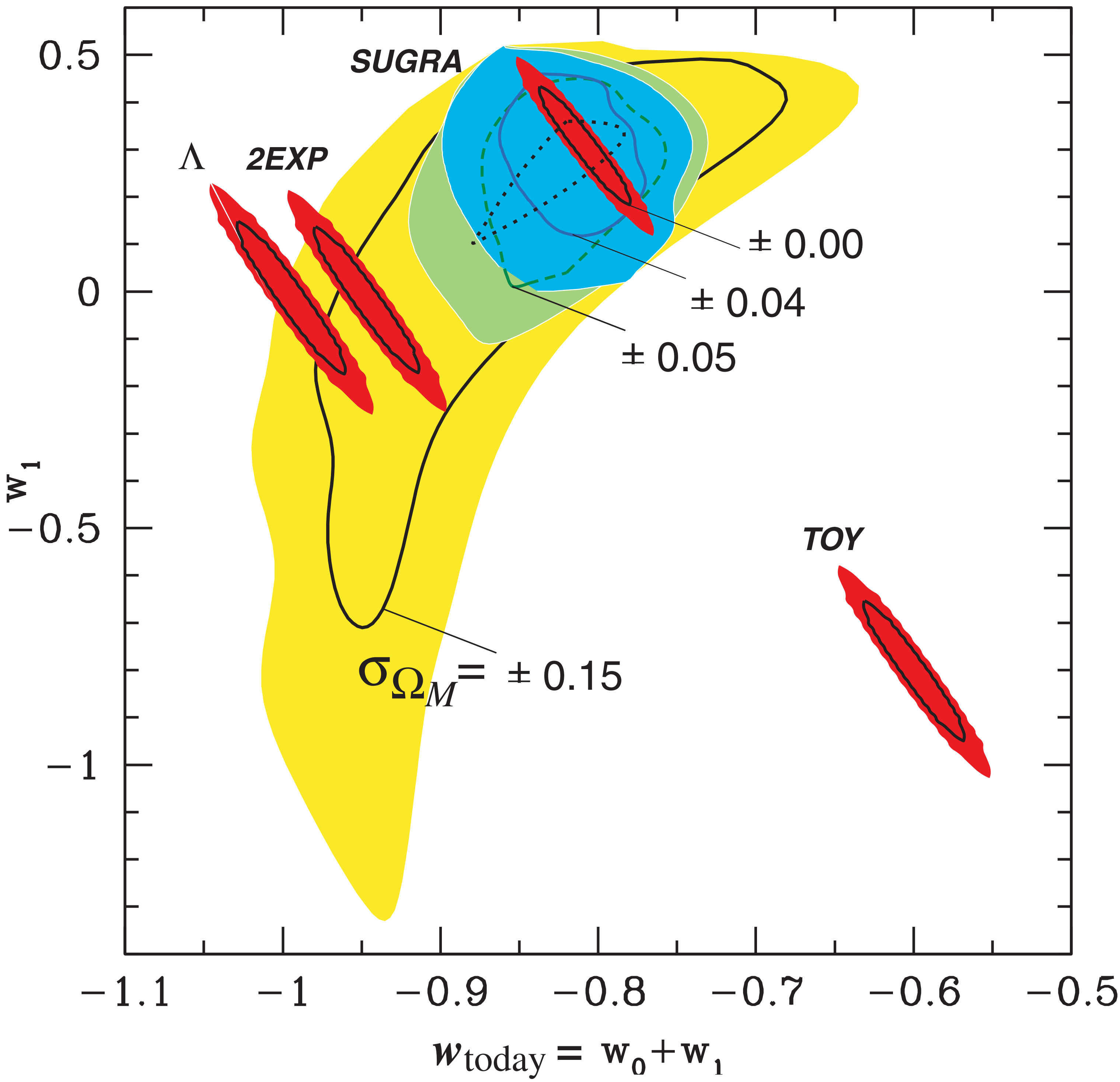
Binned simulated SNAP data compared with Dark Energy models currently in the literature.



Weller & Albrecht



0.1
0
−0.1
−0.2
Δm_B^{eff}
0
0.5
1
1.5
z
−1.00
2EXP
−0.90
−0.825
TOY
−0.74
SUGRA
−0.675
W = −0.600

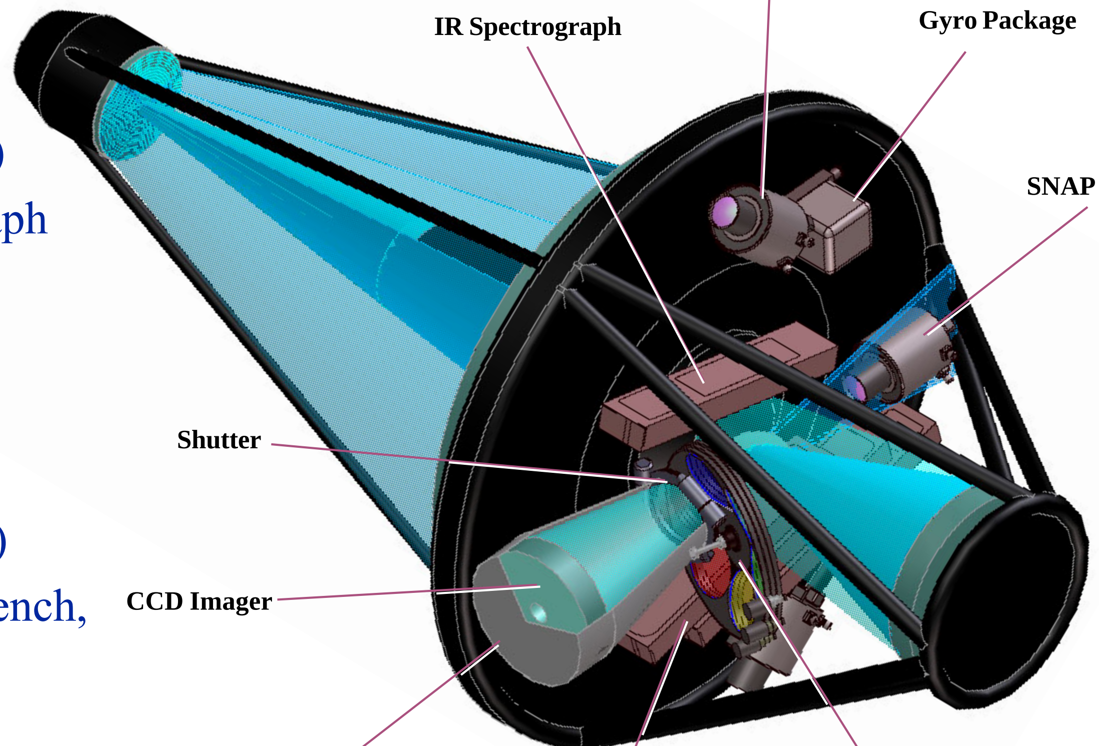


SUGRA
Λ
2EXP
TOY
± 0.00
± 0.04
± 0.05
$\sigma_{\Omega_M} = \pm 0.15$
0.5
0
−0.5
−1
−1.1
−1
−0.9
−0.8
−0.7
−0.6
−0.5
w_1
$w_{today} = w_0 + w_1$

Instrumentation Suite

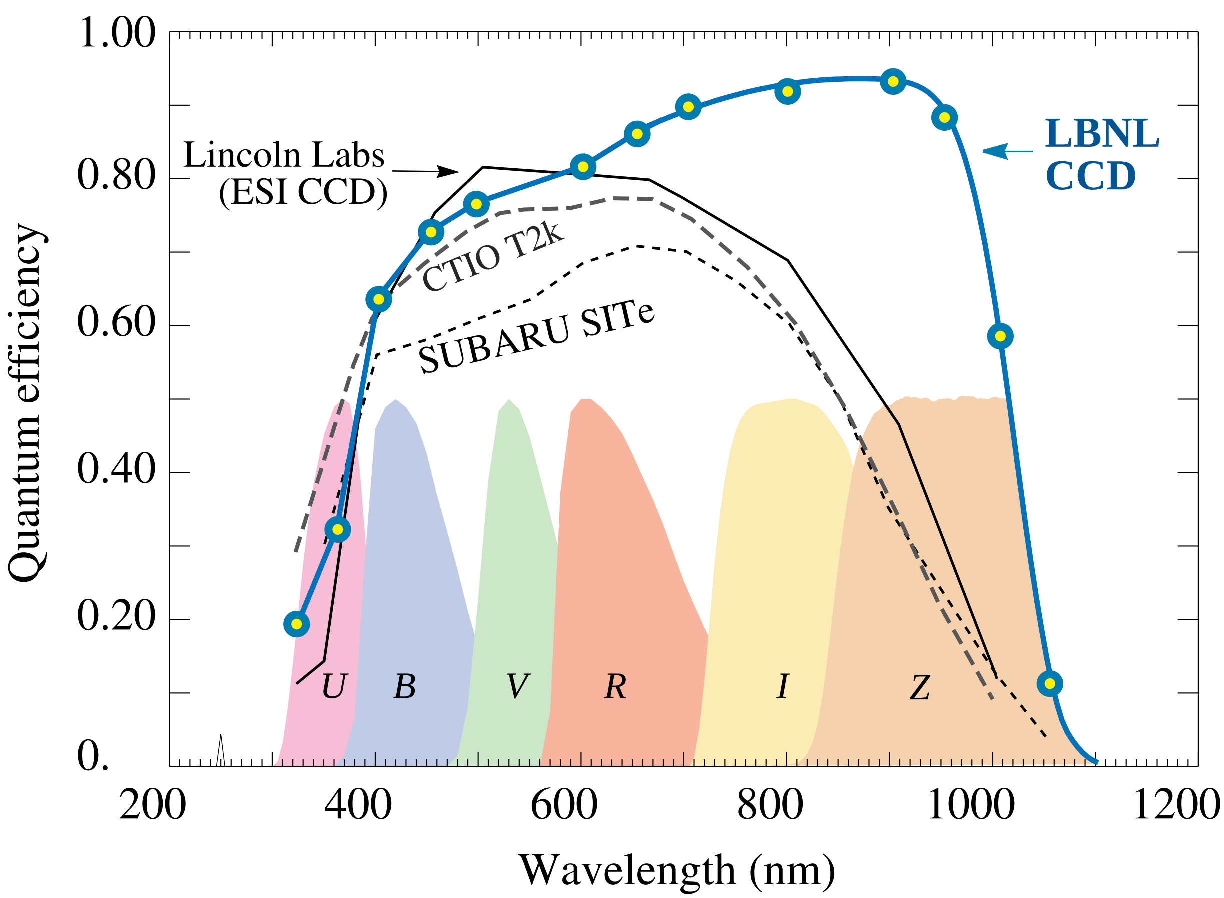
Key Instruments:

1) Wide Field Imager
   (one billion pixels)
2) IR Photometer
   (small field of view)
3) 3-channel spectrograph
   350-600 nm,
   550-1000 nm,
   900-1700 nm
4) Star Guider
   (image stabilization)
5) Telescope, Optics Bench,
   Filters, Shutters

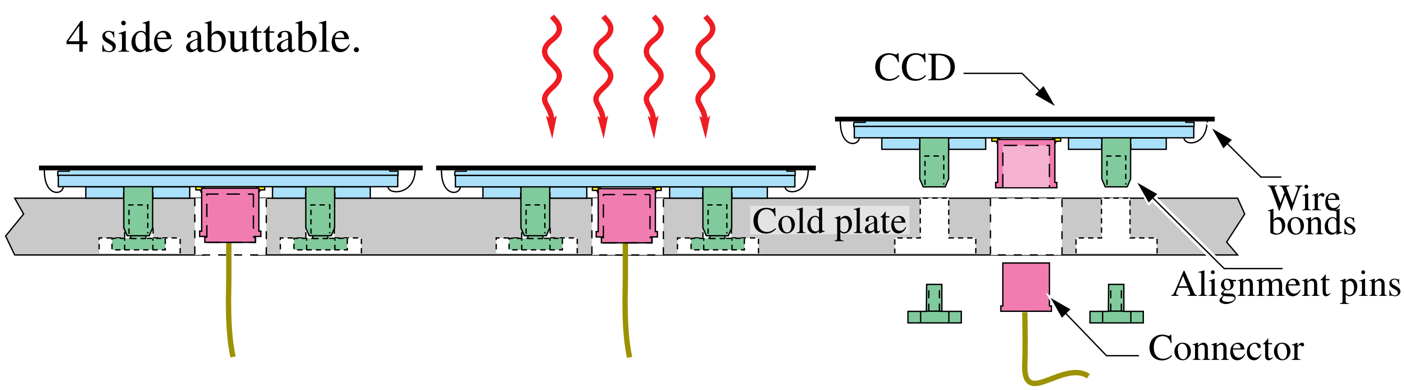


LBNL CCD Technology

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



4 side abuttable.



We knew or thought we knew:

- The universe is decelerating
- Standard candles could measure deceleration
- Type Ia SNe could in principle be standard candles at great distances;
- With HST ("ST" then) Type Ia supernovae could be studied
  - at cosmologically relevant distances — if we knew where to look.

What we didn’t know:

- ***about the universe***
- The mass density of the universe
  - = how much is the universe decelerating
- The current rate of expansion: the age of universe.
- That the measurement of mass density could be separated
  - from the measurement of the cosmological constant energy density

- ***about supernovae studies***
- that SNe could be found systematically
  - at cosmologically relevant distances ($z > 0.3$)
- that SNe could be identified spectroscopically at $z > 0.3$
- that SNe K-corrections could be handled at $z > 0.3$
- that extinction could be handled at $z > 0.3$
- that SNe could be calibrated (accounting for progenitor variation)

What we found:

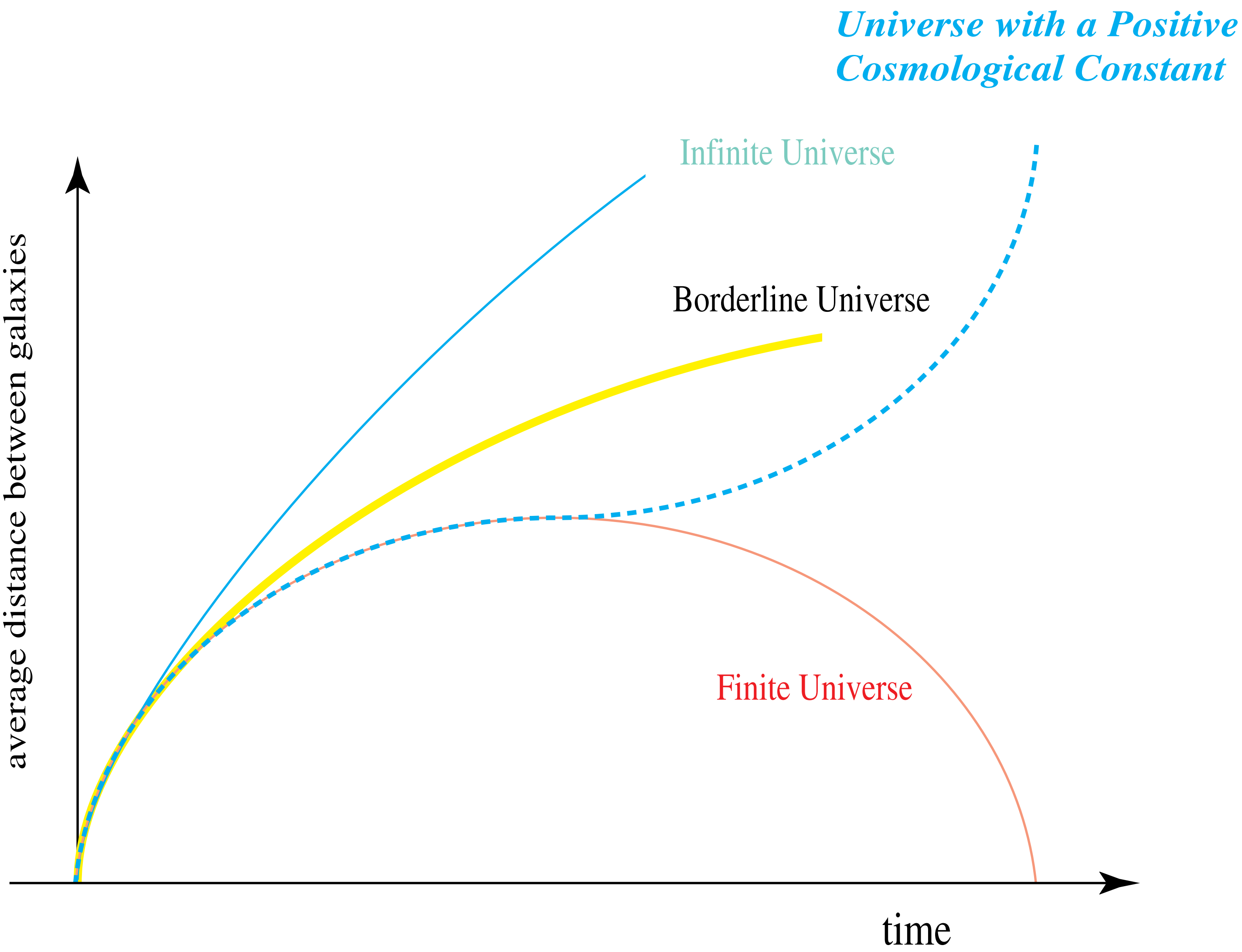
- The universe is not decelerating, but accelerating.
- Some unidentified negative-pressure energy density exists.
- This "dark energy" density dominates over mass density today.

Now what we don’t know is:

- the values of the “dark” and mass energy densities
- the curvature of space
- the identity of the “dark” energy

But we know how to find out:

- We can find and study supernovae at $z \sim 1.2$
- We can systematically find low-redshift supernovae
- We can dramatically improve statistics and systematics with a satellite.


Universe with a Positive
Cosmological Constant
Infinite Universe
Borderline Universe
Finite Universe
average distance between galaxies
time