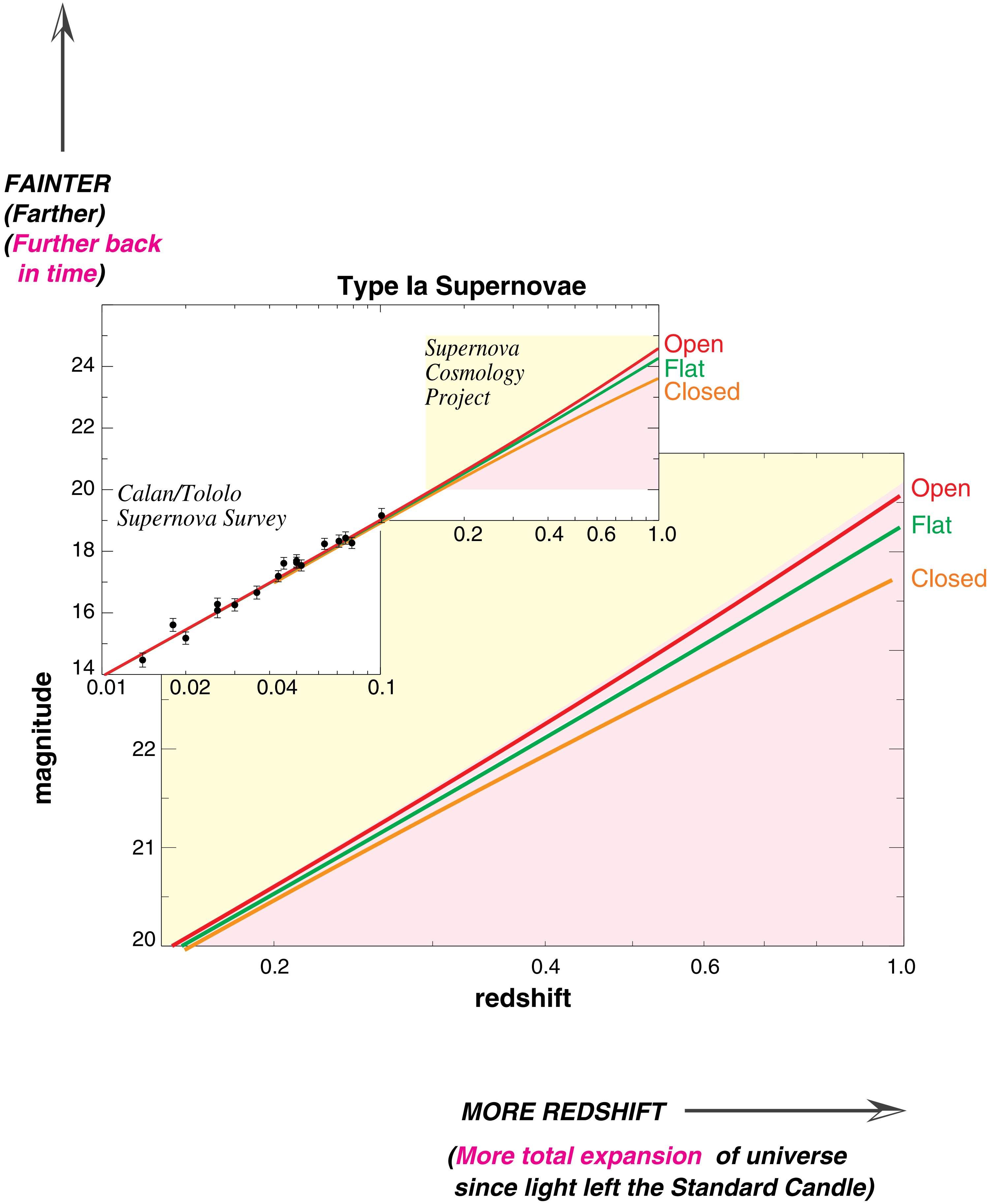
SuperNova / Acceleration Probe
DOE Review:
Science Overview

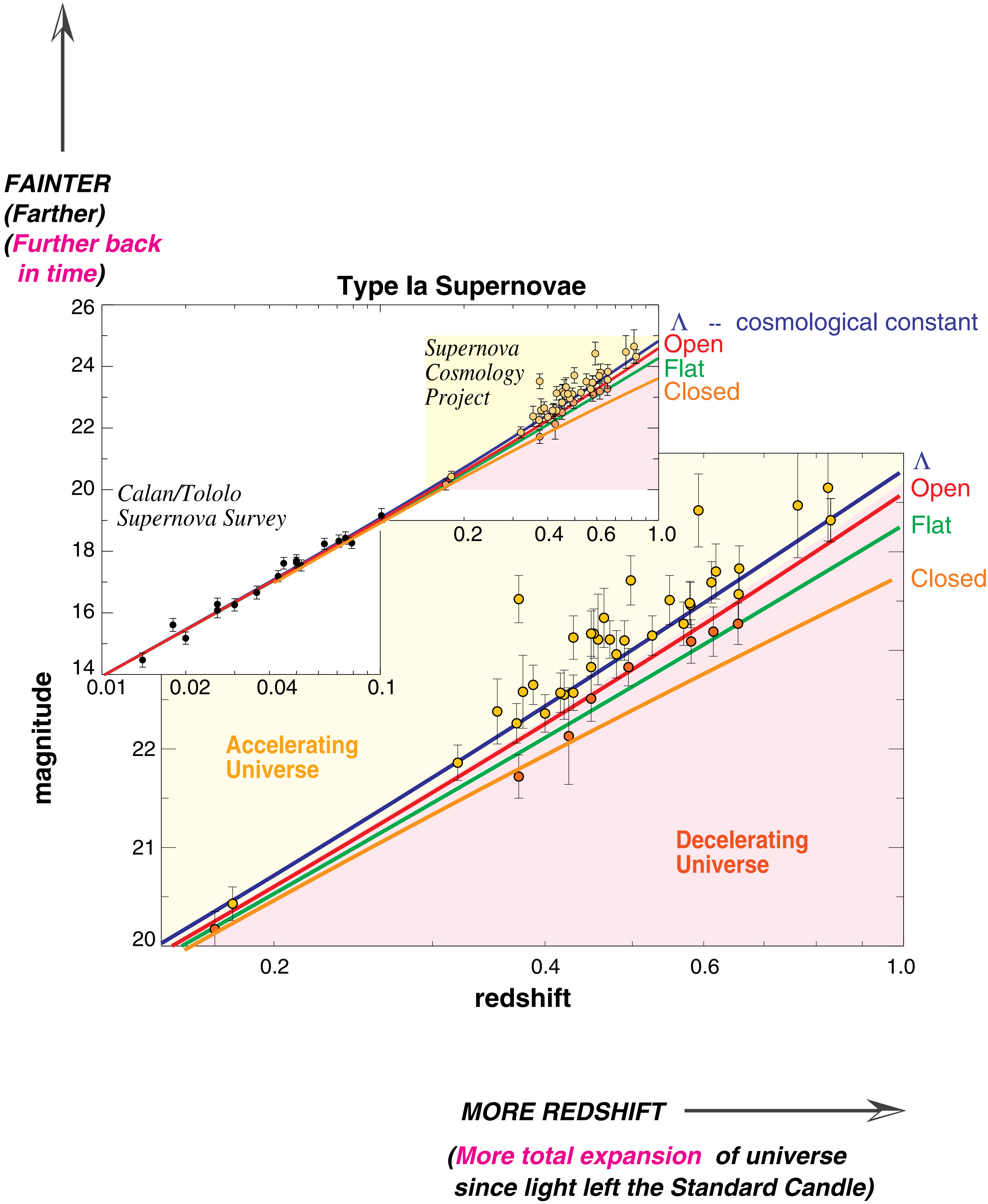
Lawrence Berkeley Laboratory
July 2002

Saul Perlmutter

0. Background: cosmology/dark energy measurements from supernovae.
1. A really hard goal: $w'(z)$.
2. An exhaustive list of systematics.
3. An unusual tool for cosmology.
4. How this tool can address systematics.
5. Project status and reviews.



FAINTER
(Farther)
(Further back
in time)
Type Ia Supernovae
Supernova
Cosmology
Project
Open
Flat
Closed
Calan/Tololo
Supernova Survey
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
magnitude
22
21
20
0.2
0.4
0.6
1.0
redshift
Open
Flat
Closed
MORE REDSHIFT
(More total expansion of universe
since light left the Standard Candle)


FAINTER
(Farther)
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Type Ia Supernovae
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Λ -- cosmological constant
Open
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Λ
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Accelerating
Universe
Decelerating
Universe
magnitude
redshift
26
24
22
20
18
16
14
0.01
0.02
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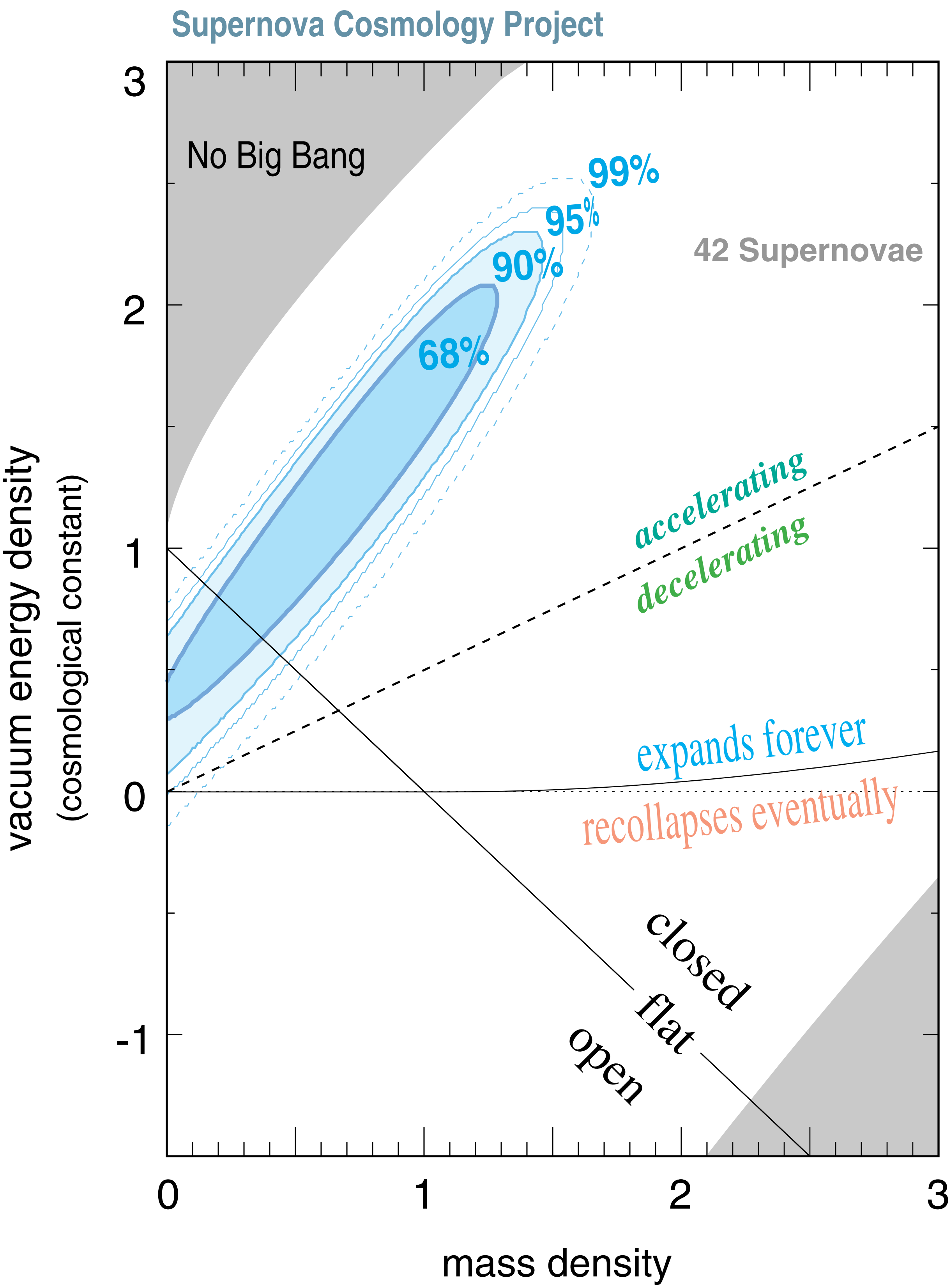
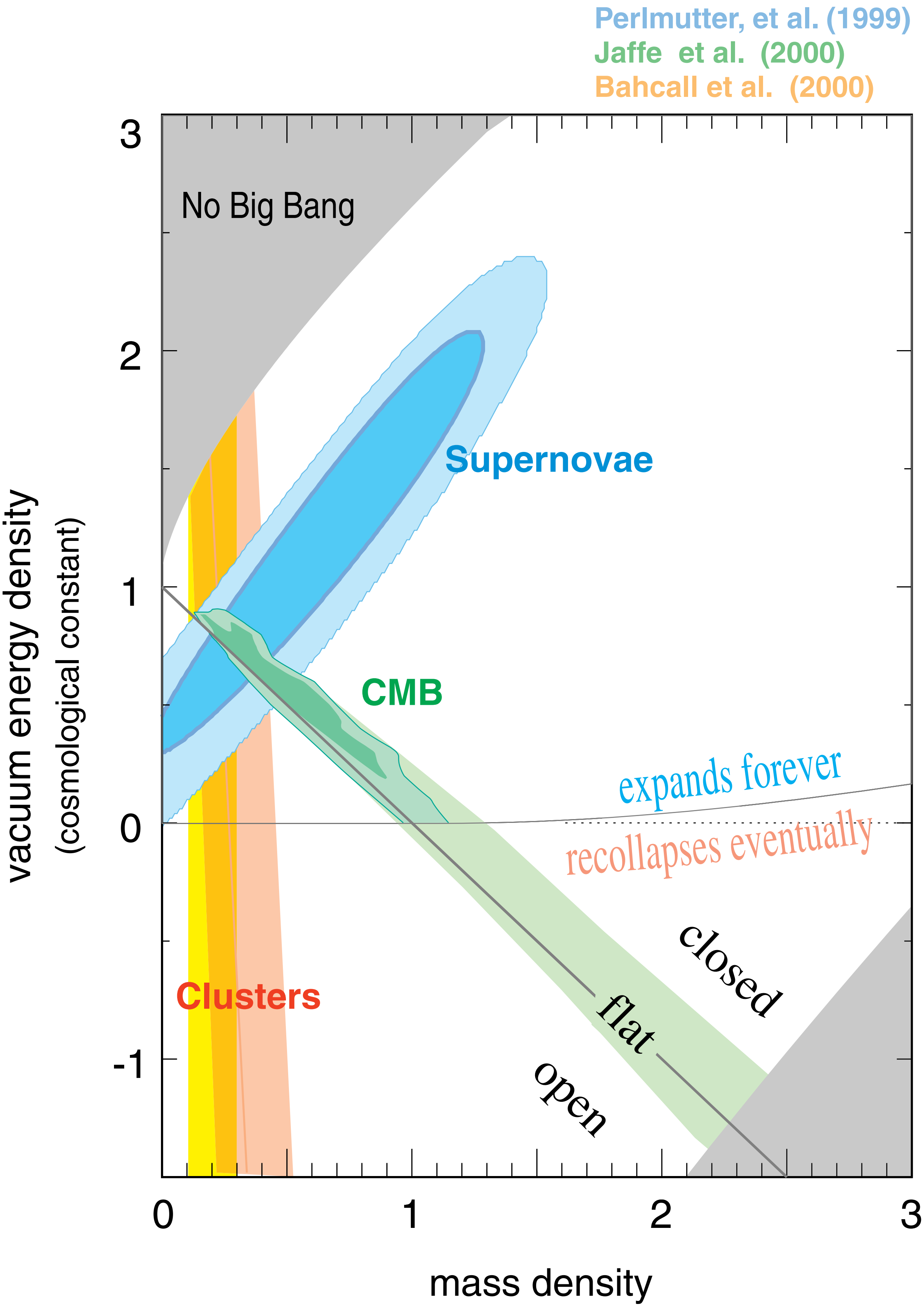


Perlmutter *et al.*
(Ap.J. 1999)
astro-ph/98 12133


Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall et al. (2000)
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

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: $p = 0 \longrightarrow \rho \propto R^{-3}$

VACUUM ENERGY: $p = -\rho \longrightarrow \rho \propto \textit{constant}$

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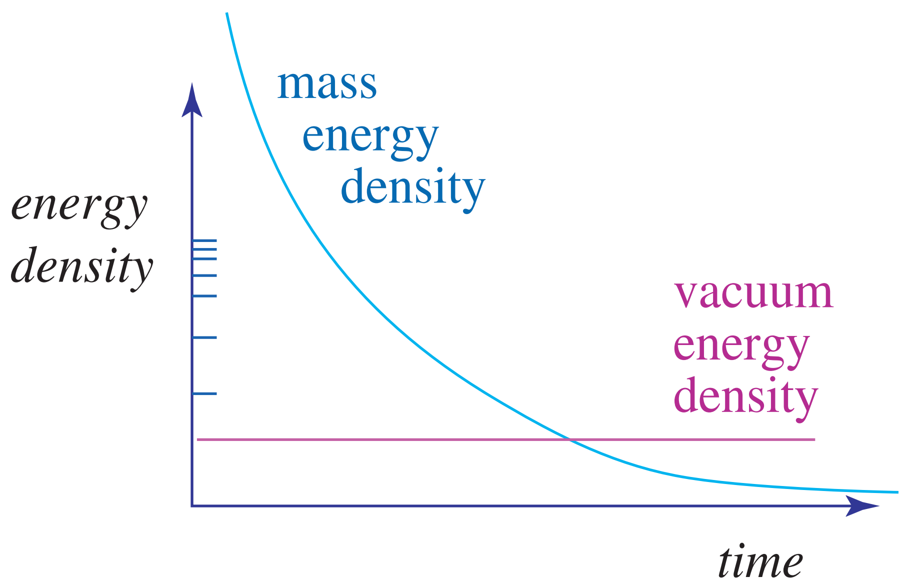

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VACUUM ENERGY: $p = -\rho \longrightarrow \rho \propto constant$

What are the alternatives?

New Physics: "Dark energy":

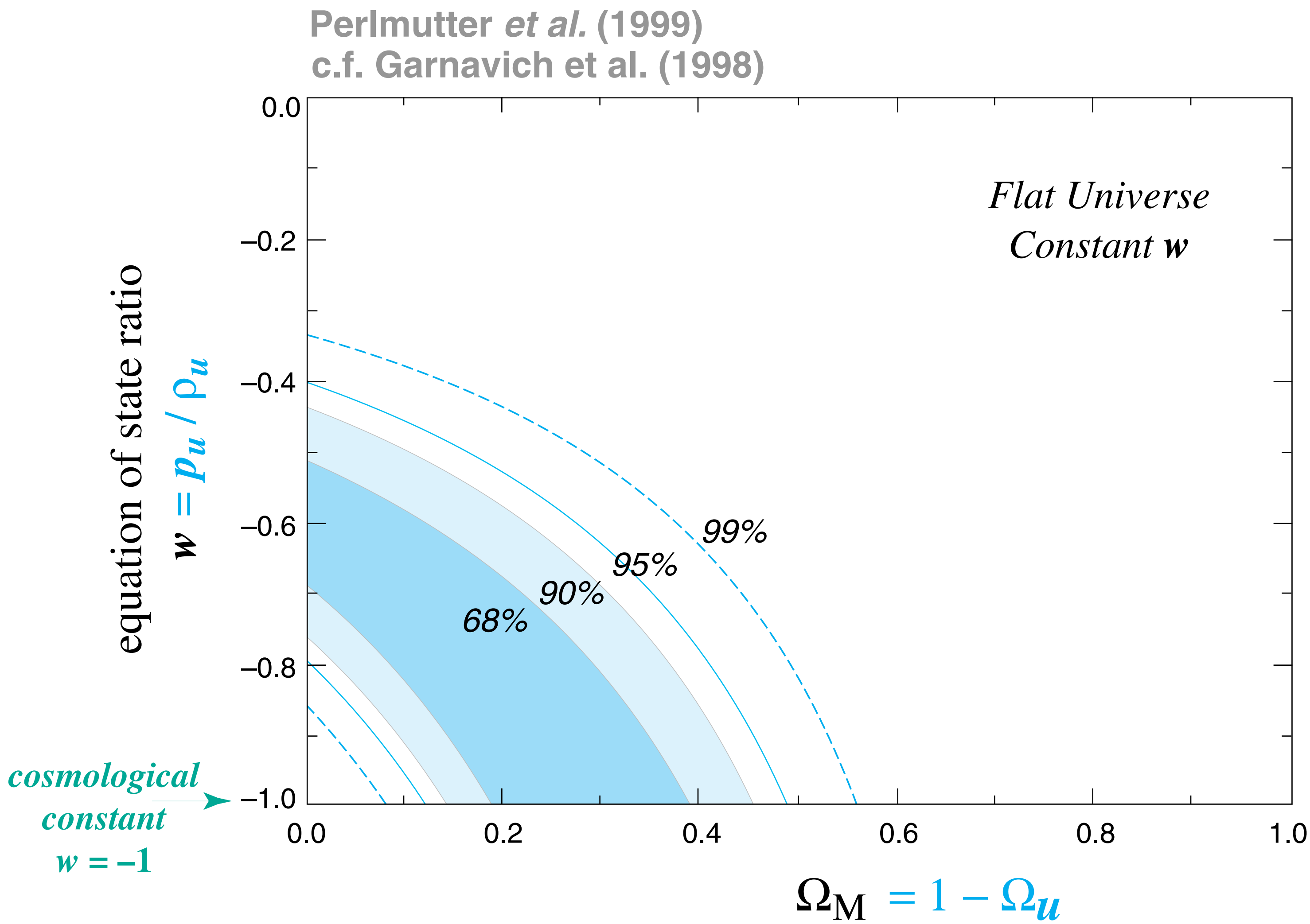
Dynamical scalar fields, "quintessence",...

General Equation of State:

$$p = w\rho \longrightarrow \rho \propto R^{-3(1+w)}$$

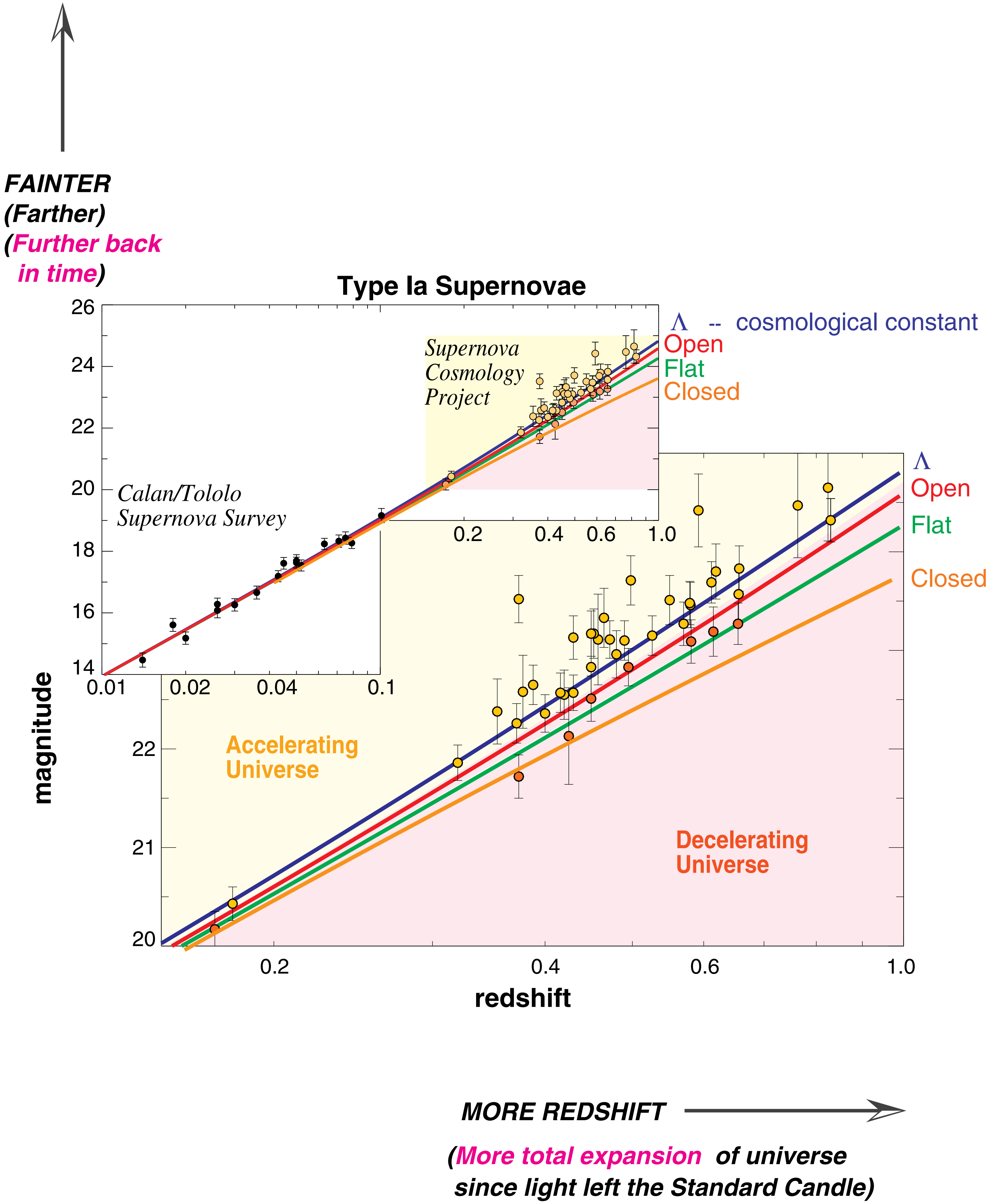
and w can vary with time

Unknown Component, Ω_u, of Energy Density



1. A Really Hard Goal: $w'(z)$

A measurement of the expansion history of the universe with enough accuracy that a measurement of a *change* in the properties of the dark energy, e.g. $w' \neq 0$, would be trusted.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redshift
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MORE REDSHIFT
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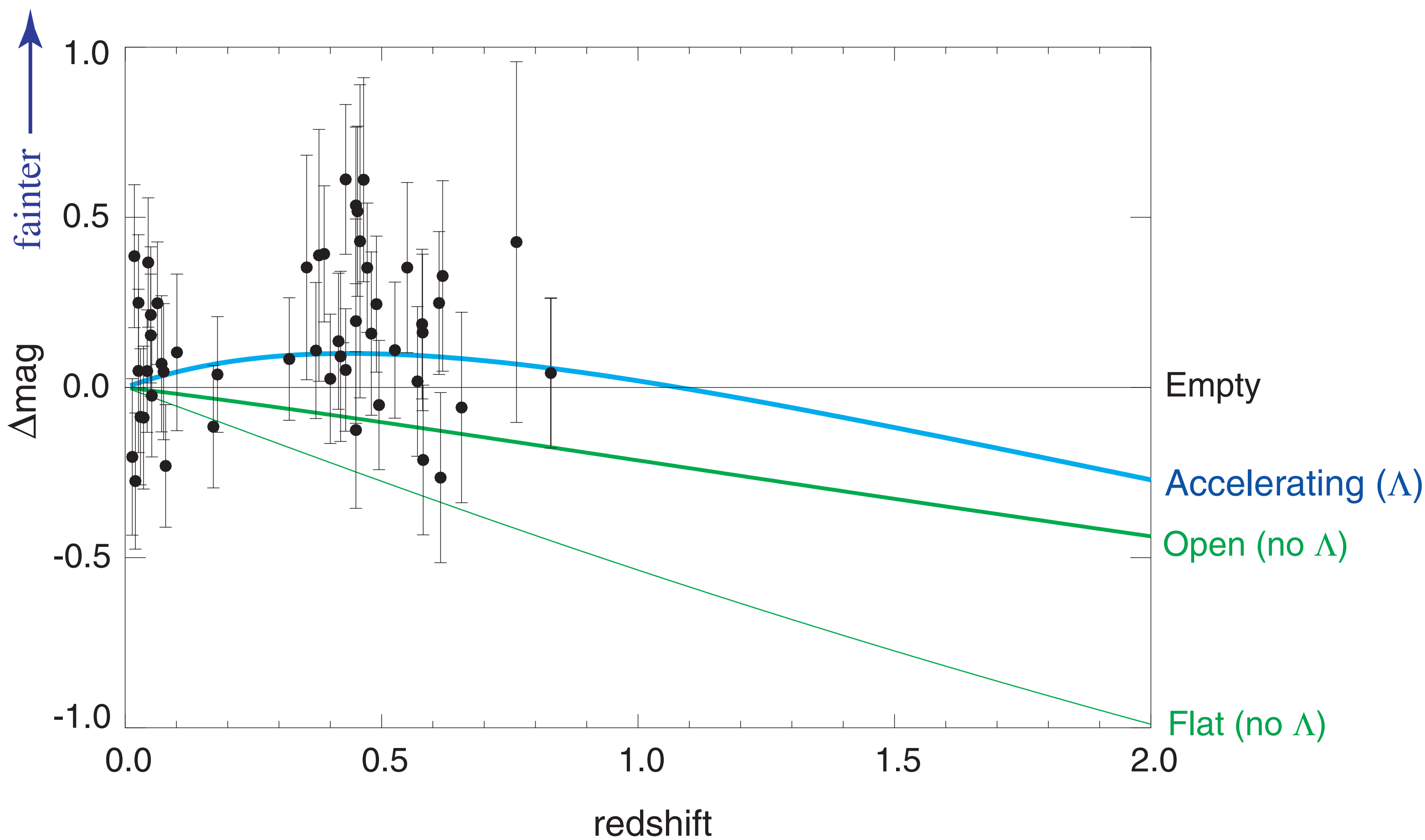
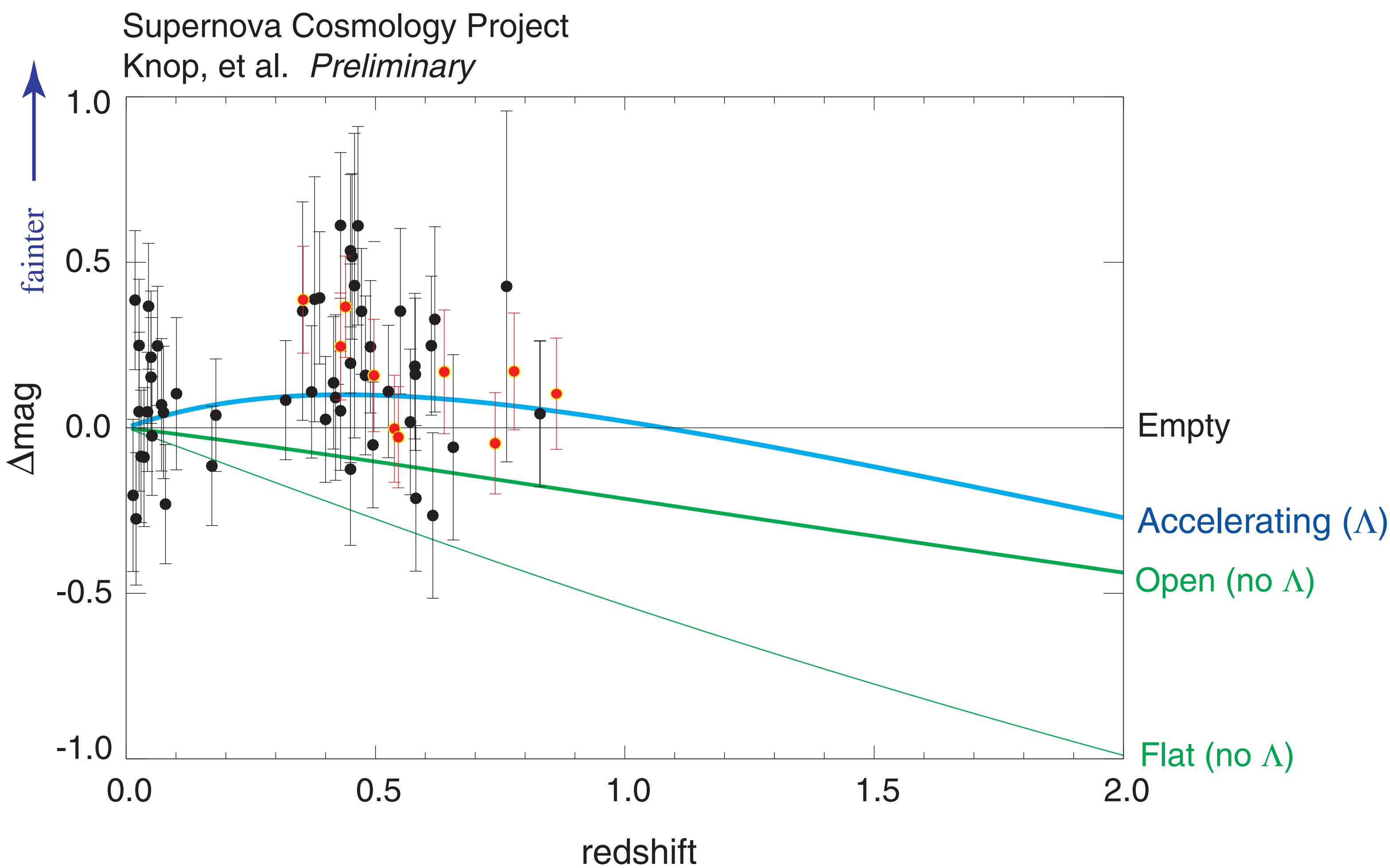
1998: Acceleration

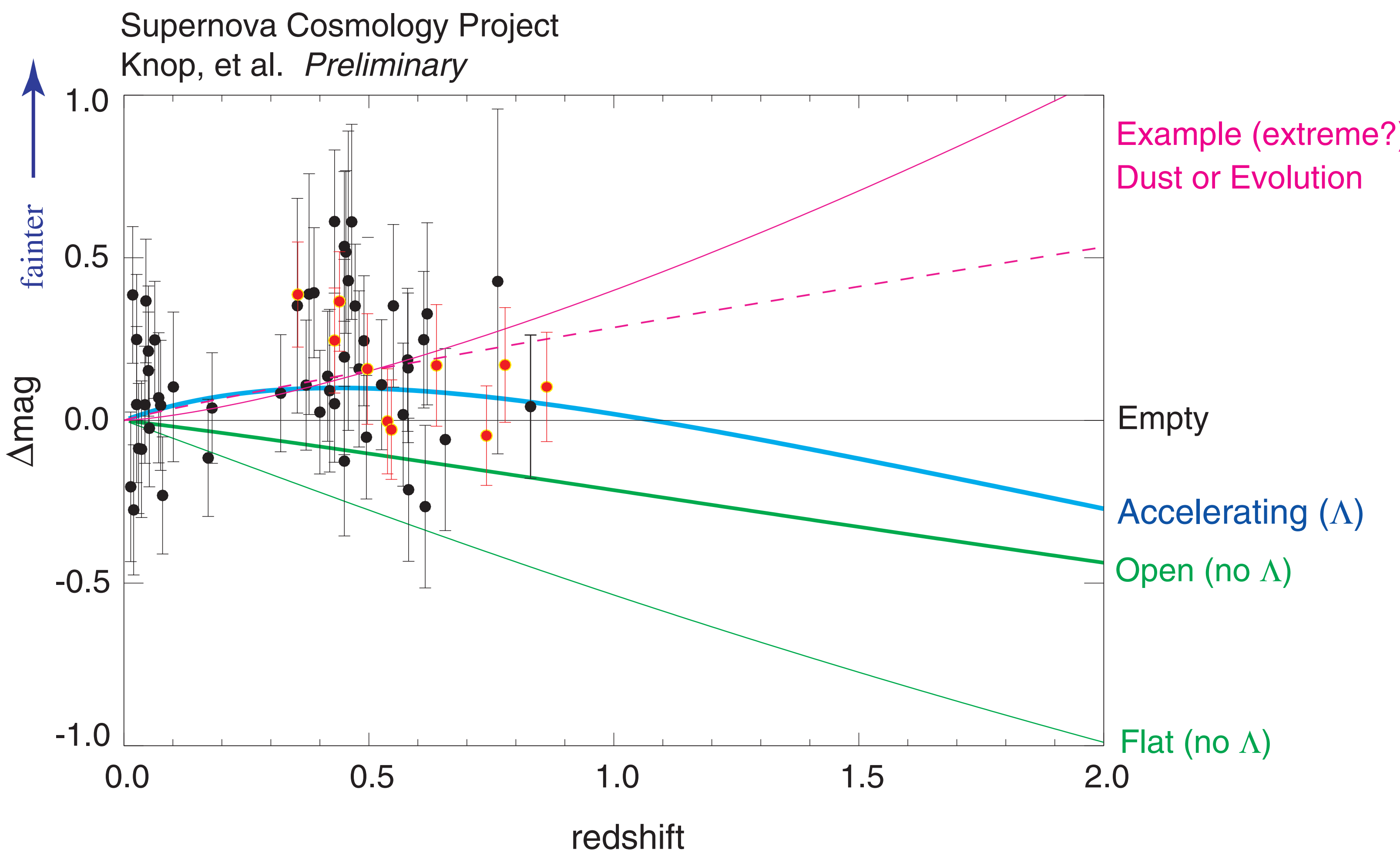


New HST data



Supernova Cosmology Project
Knop, et al. *Preliminary*
fainter
Δmag
1.0
0.5
0.0
-0.5
-1.0
0.0
0.5
1.0
1.5
2.0
redshift
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)

New HST data



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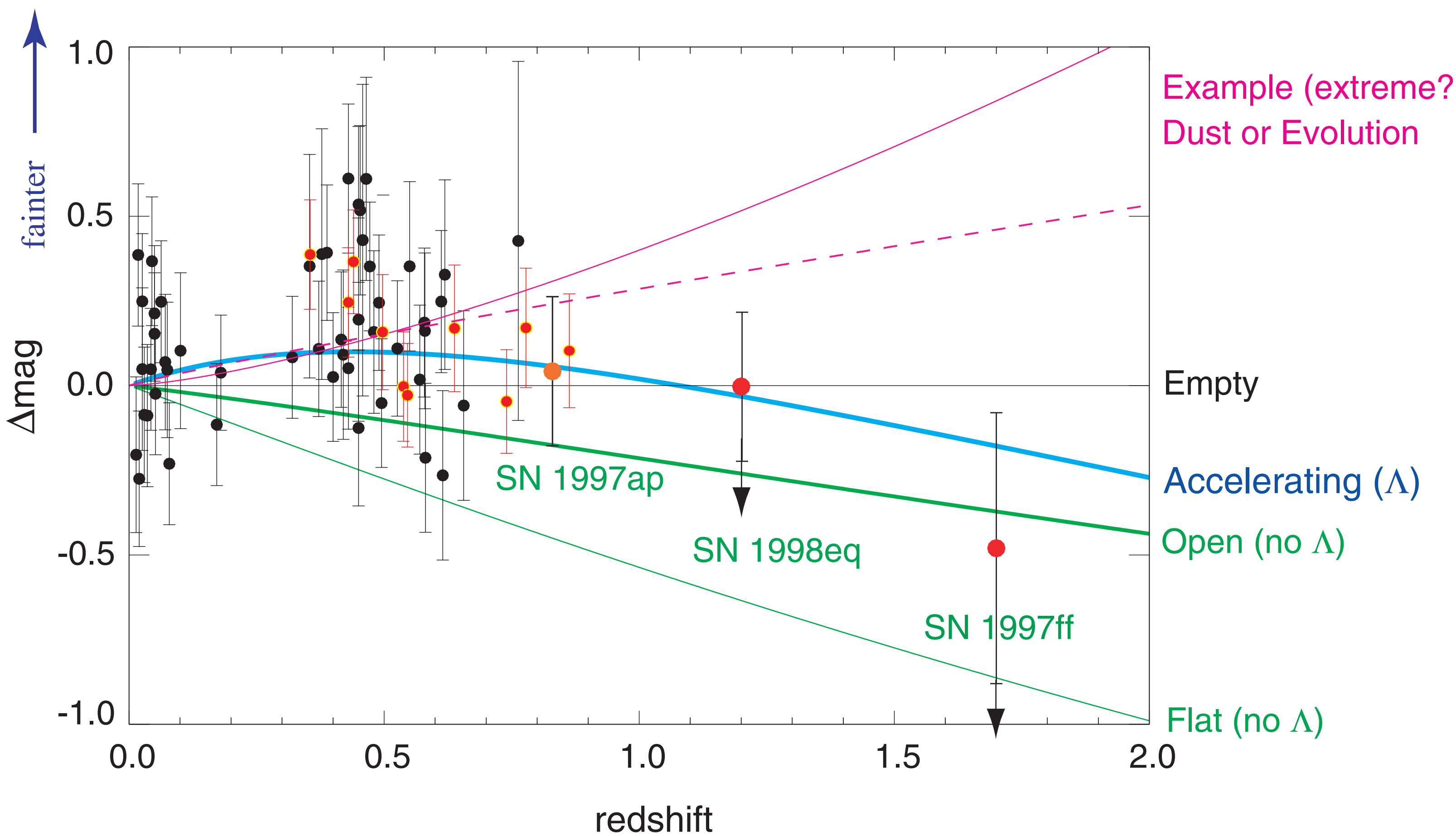
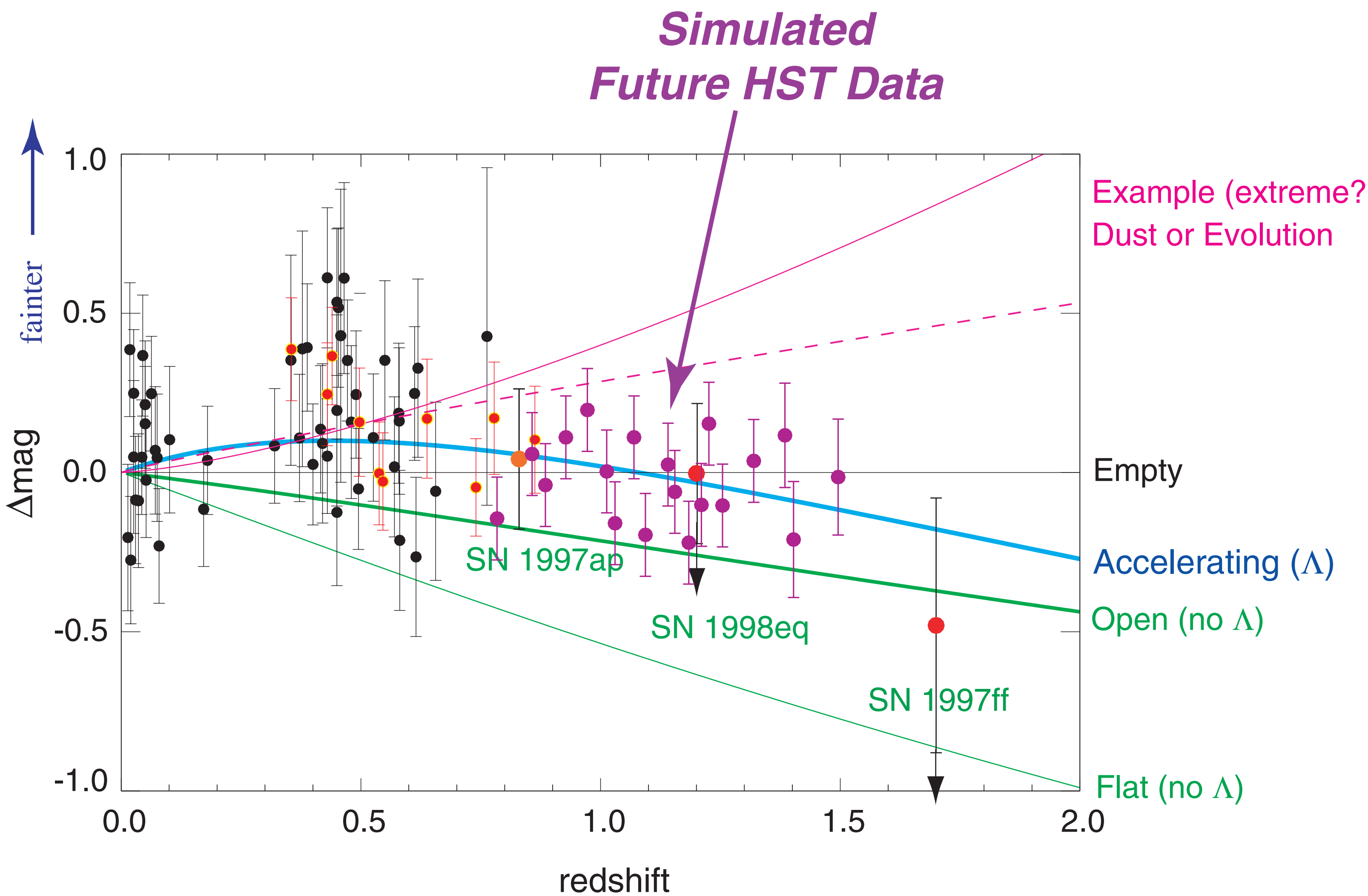
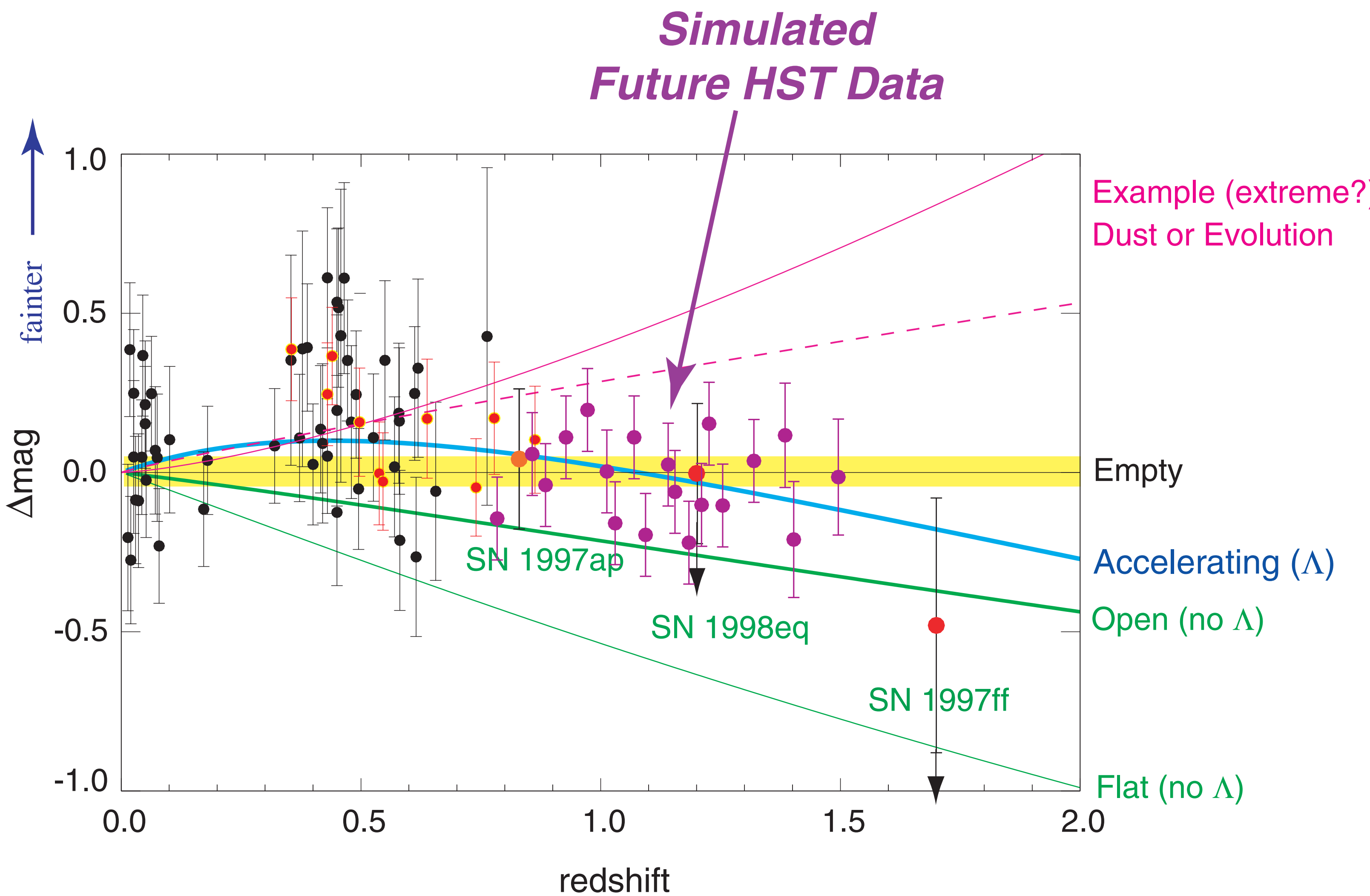
redshift
Example (extreme?)
Dust or Evolution
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)

Supernovae probing the *deceleration* era with IR measurements





Simulated
Future HST Data
fainter
Δmag
1.0
0.5
0.0
-0.5
-1.0
0.0
0.5
1.0
1.5
2.0
redshift
Example (extreme?)
Dust or Evolution
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)
SN 1997ap
SN 1998eq
SN 1997ff



Simulated
Future HST Data
fainter
Δmag
1.0
0.5
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redshift
Example (extreme?)
Dust or Evolution
Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)
SN 1997ap
SN 1998eq
SN 1997ff

Current statistical uncertainties from supernova measurements are almost good enough that they are limited by systematic uncertainties:

Uncertainties on Ω_M or Ω_Λ in flat cosmology:

Statistical	
high-redshift SNe	0.05
low-redshift SNe	0.065
Total	***0.085***
Systematic Total	
identified entities/processes	***0.05***

Significant advances in these measurement uncertainties will require **much better constraints on the systematics.**

Perlmutter et al. (1999)

2. An exhaustive list of systematics.

What makes the supernova measurement special?

An exhaustive accounting of sources of SN systematic uncertainties:

SN Ia Evolution

- o shifting distribution of
  progenitor mass/metallicity/C-O
- o shifting distibution of SN physics params:
  - -- amount of Nickel fused in explosion
  - -- distribution of Nickel
  - -- kinetic energy of explosion
  - -- opacity of atmosphere's inner layers
  - -- metallicity

Gravitational Lensing (de)amplification

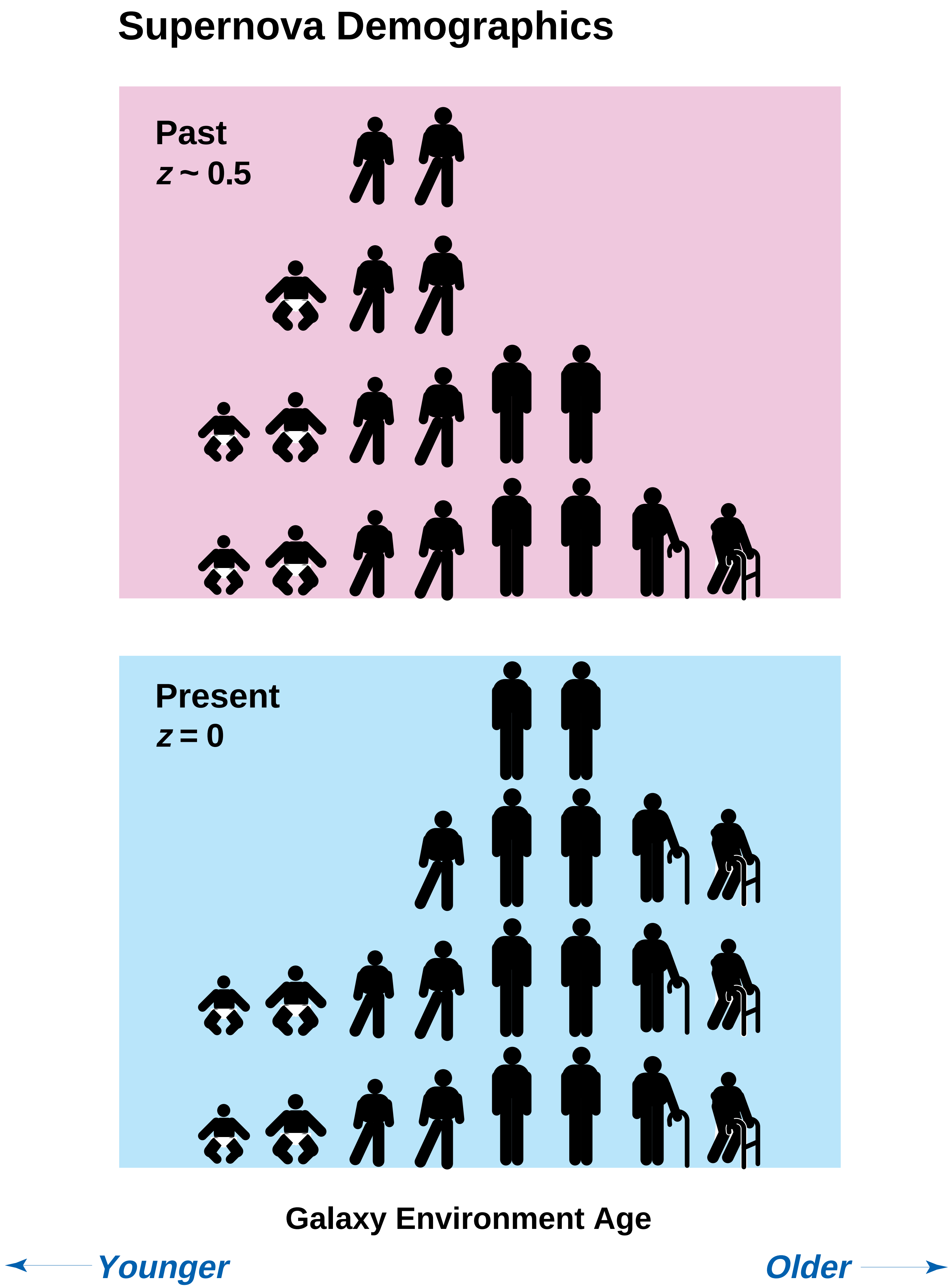
Dust/Extinction

- o dust that reddens
- o evolving gray dust
  - -- clumpy
  - -- homogeneous
- o Galactic extinction model

Observational biases

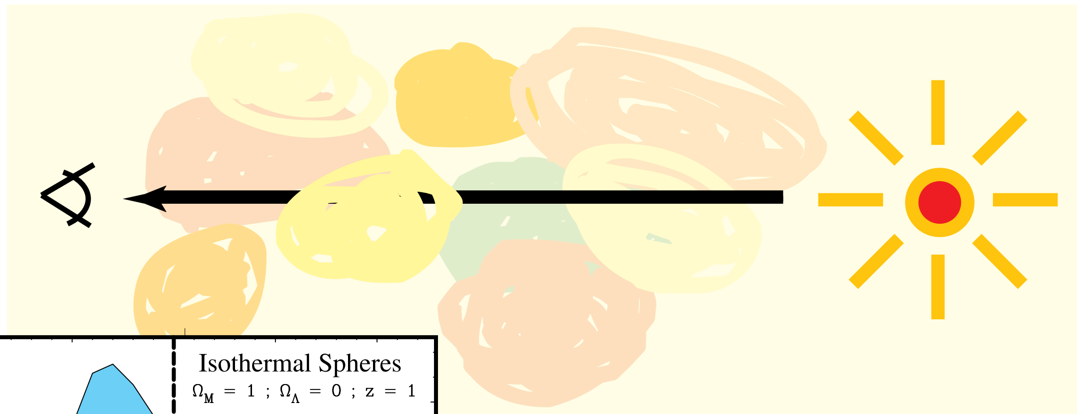
- o Malmquist bias differences
- o non-SN Ia contamination
- o K-correction uncertainty
- o color zero-point calibration

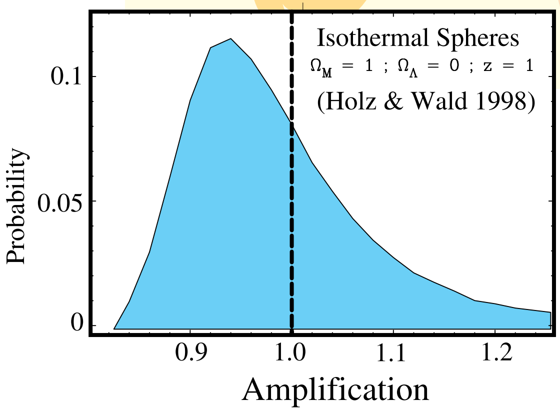
Perlmutter et al. (1999)


Supernova Demographics
Past
z ~ 0.5
Present
z = 0
Galaxy Environment Age
Younger
Older

Gravitational Lensing in a Clumpy Universe

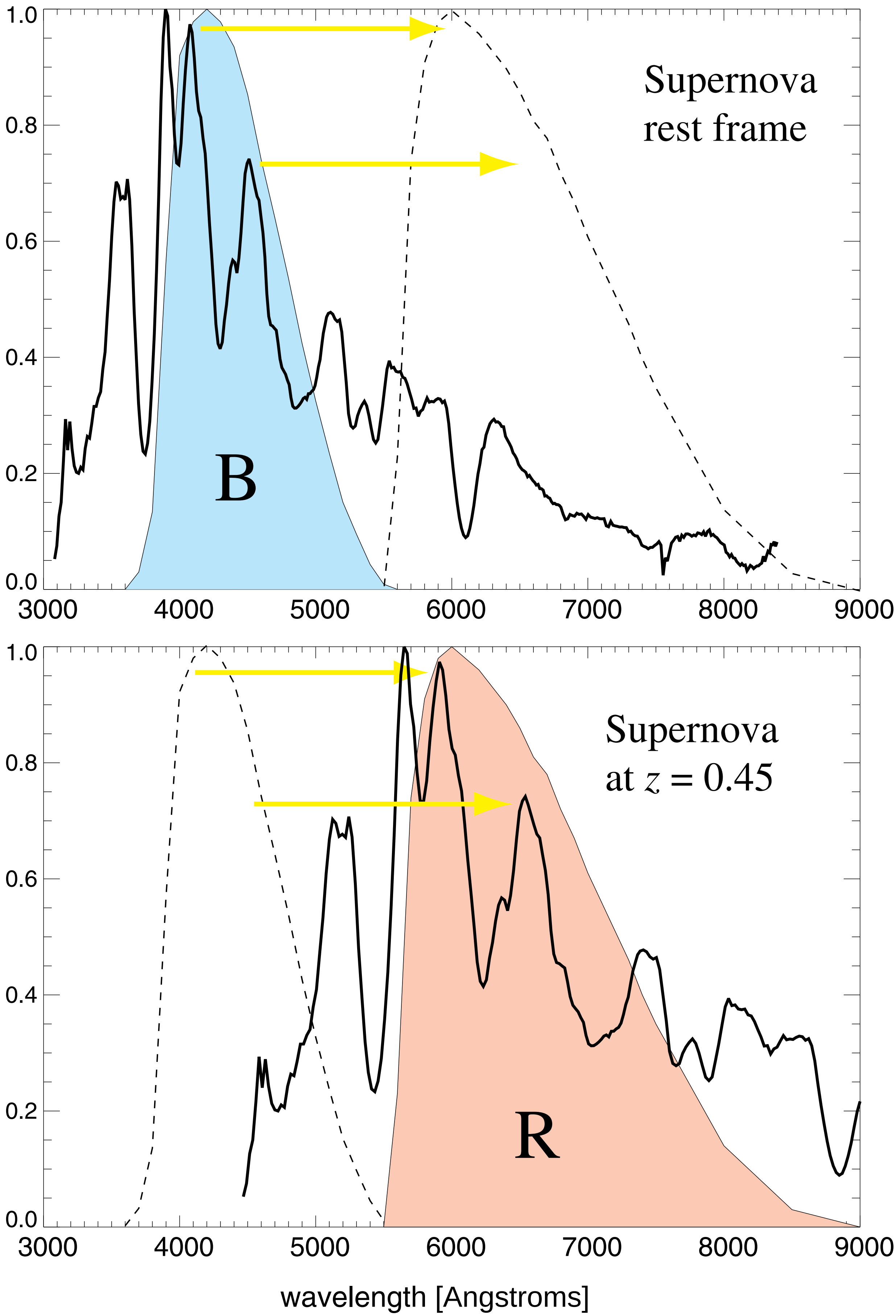
"Weak Lensing" Approx:
Power spectrum of mass density in relatively smooth universe.



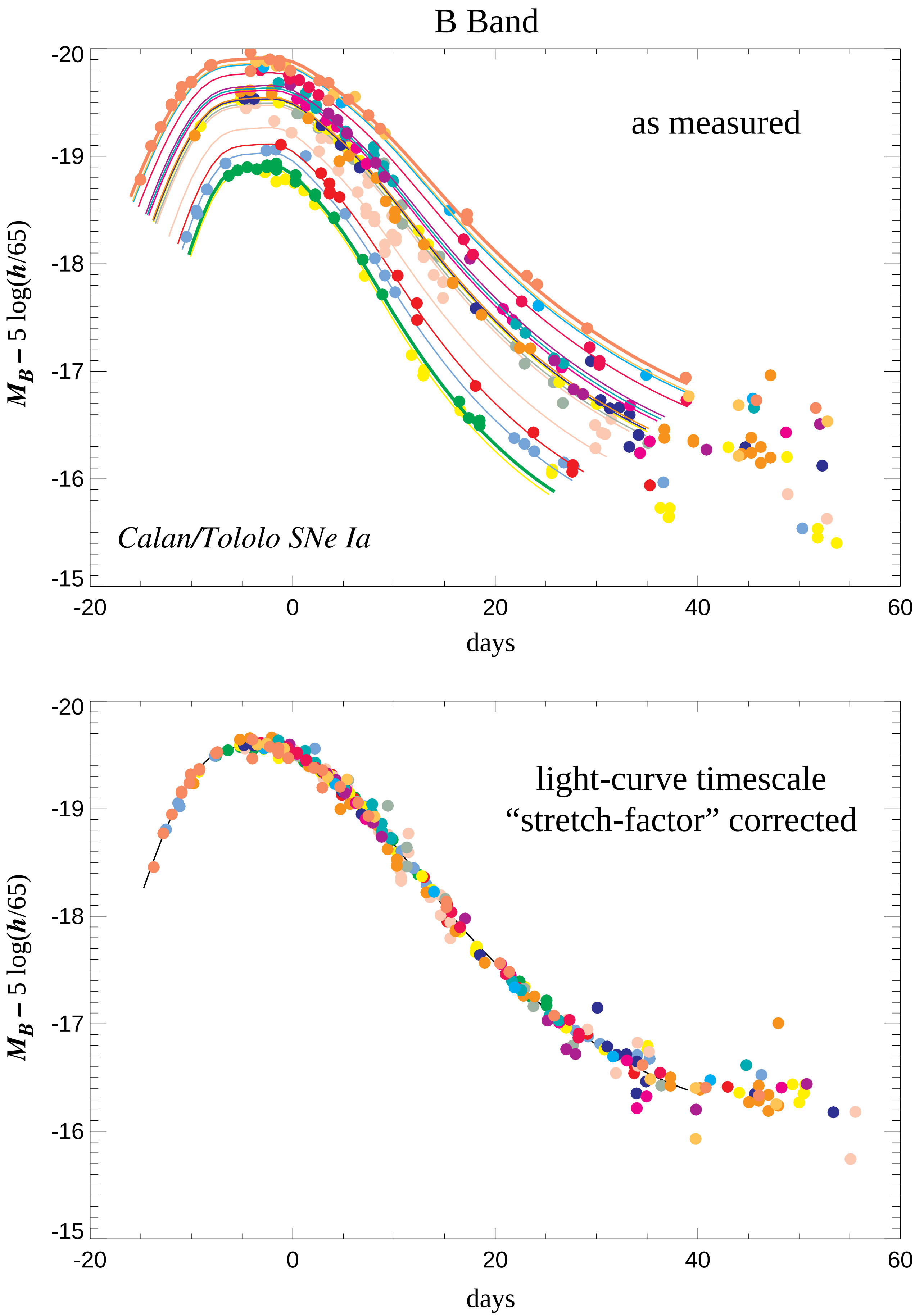


“Cross-Filter”
K corrections

Kim, Goobar, & Perlmutter (1995)

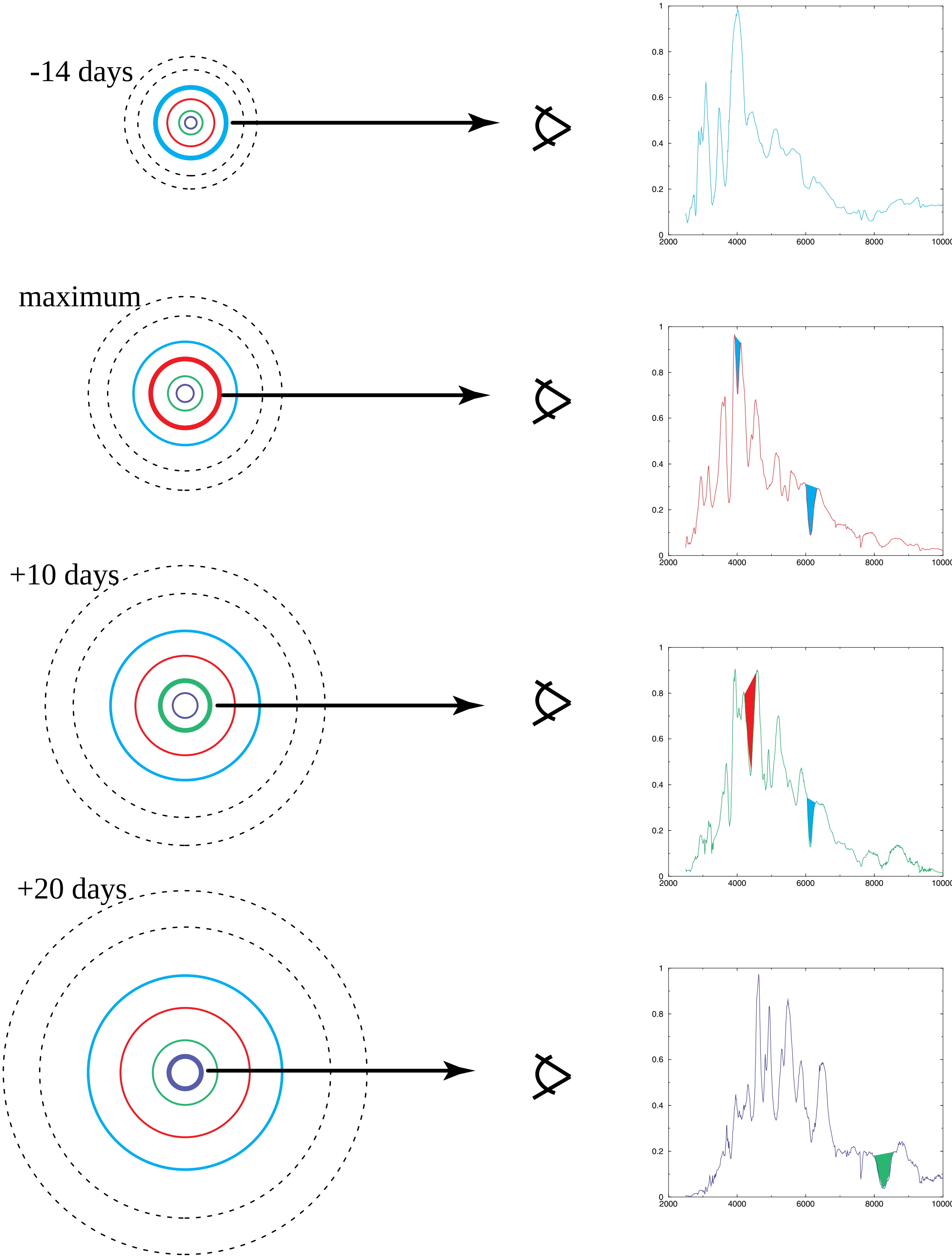


3. SN Ia: An unusual tool for cosmology.

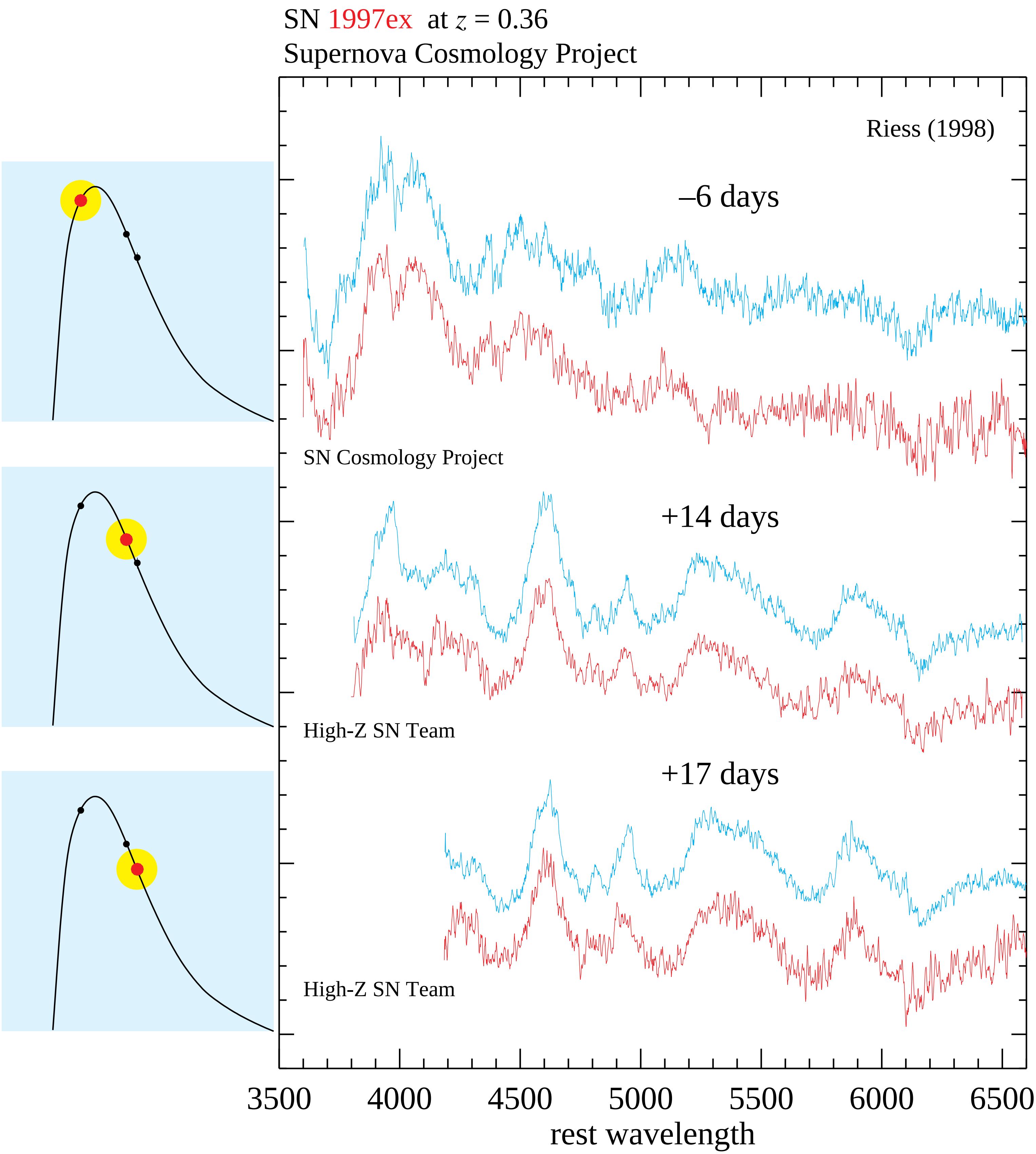


Kim, *et al.* (1997)

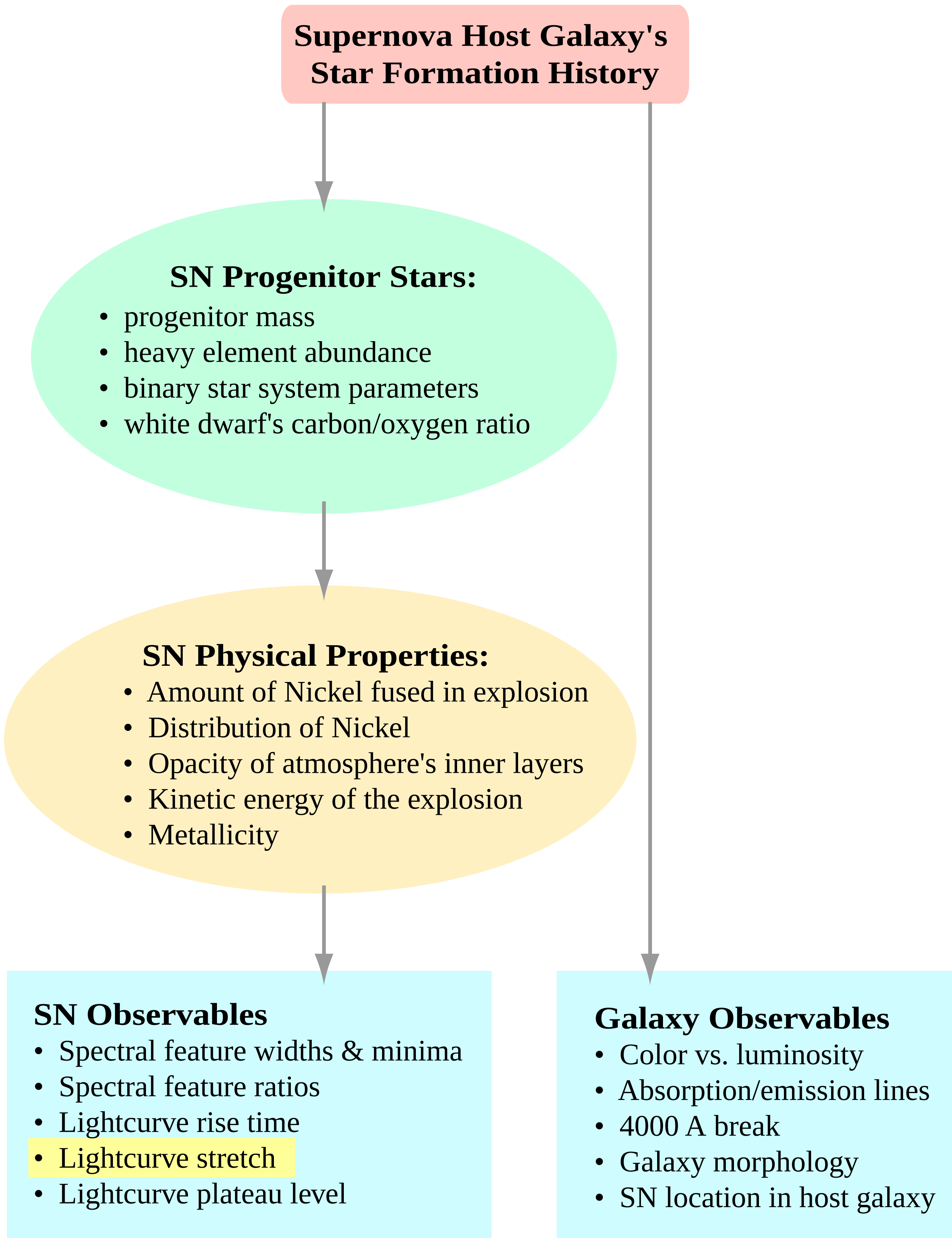
The time series of spectra is a “CAT Scan” of the Supernova



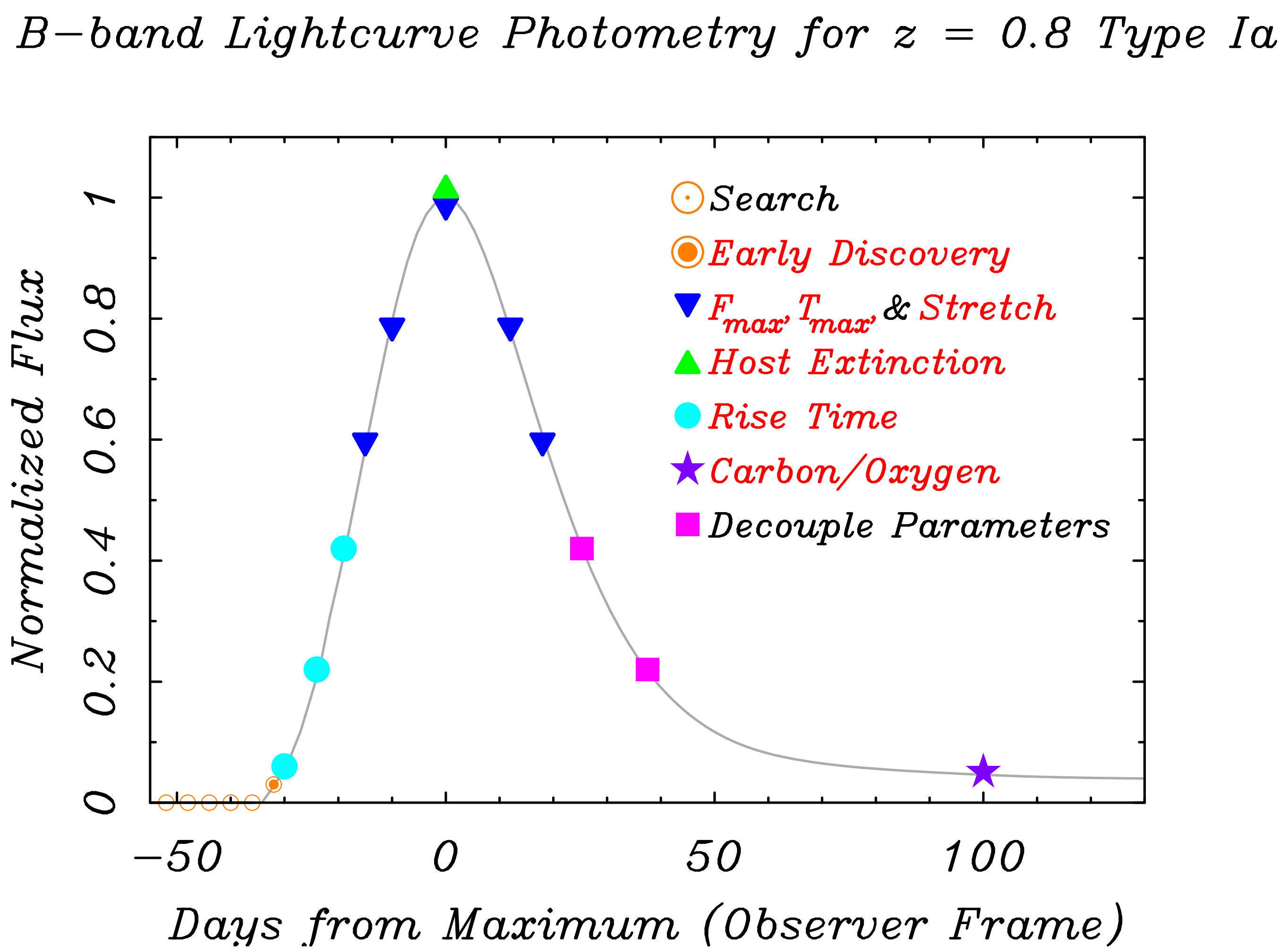
Time Series of Low-Redshift and High-Redshift Spectra



Control of Evolution Systematics: Matching Supernovae



SNAP SuperNova Acceleration Probe



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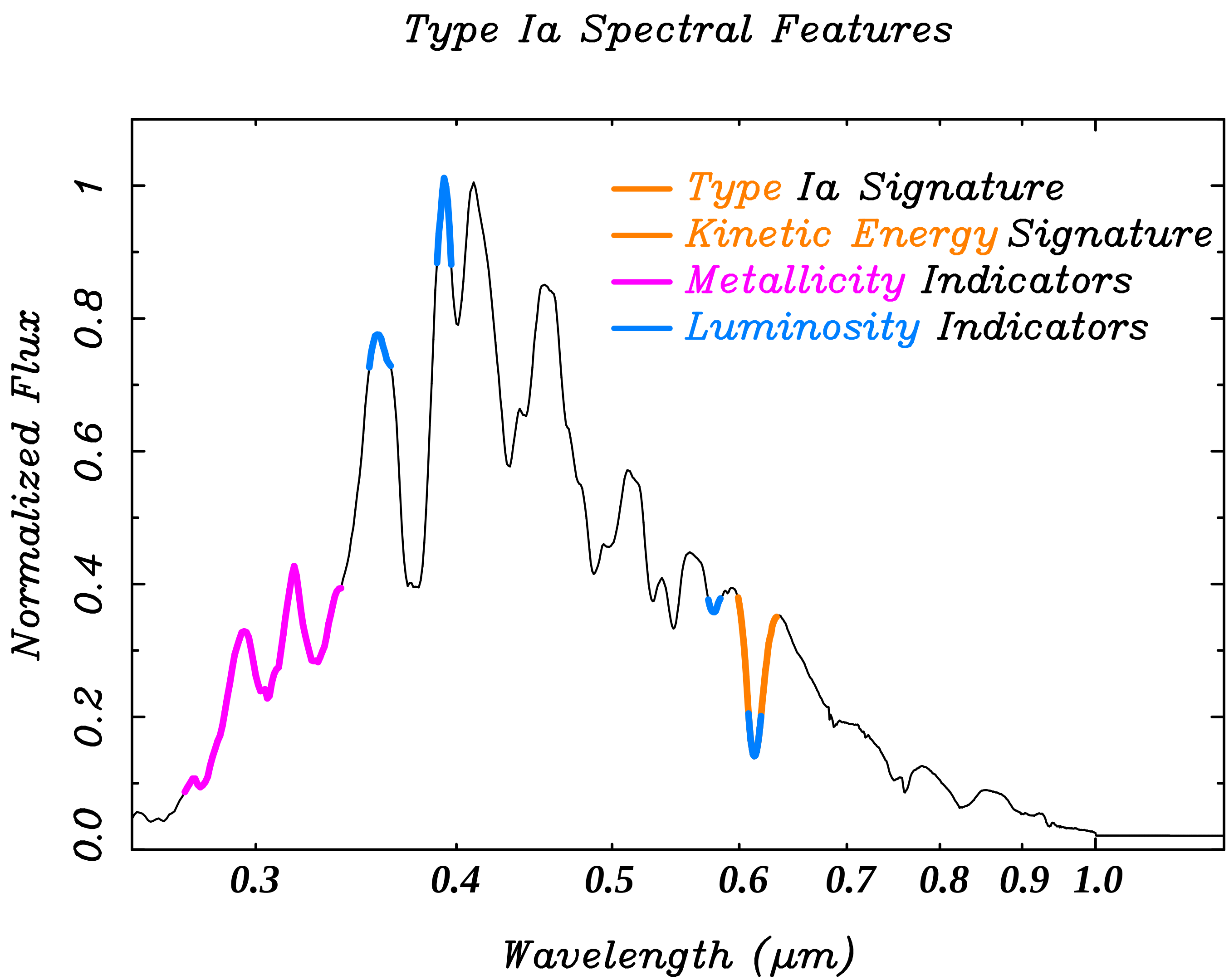

Control of Evolution Systematics:
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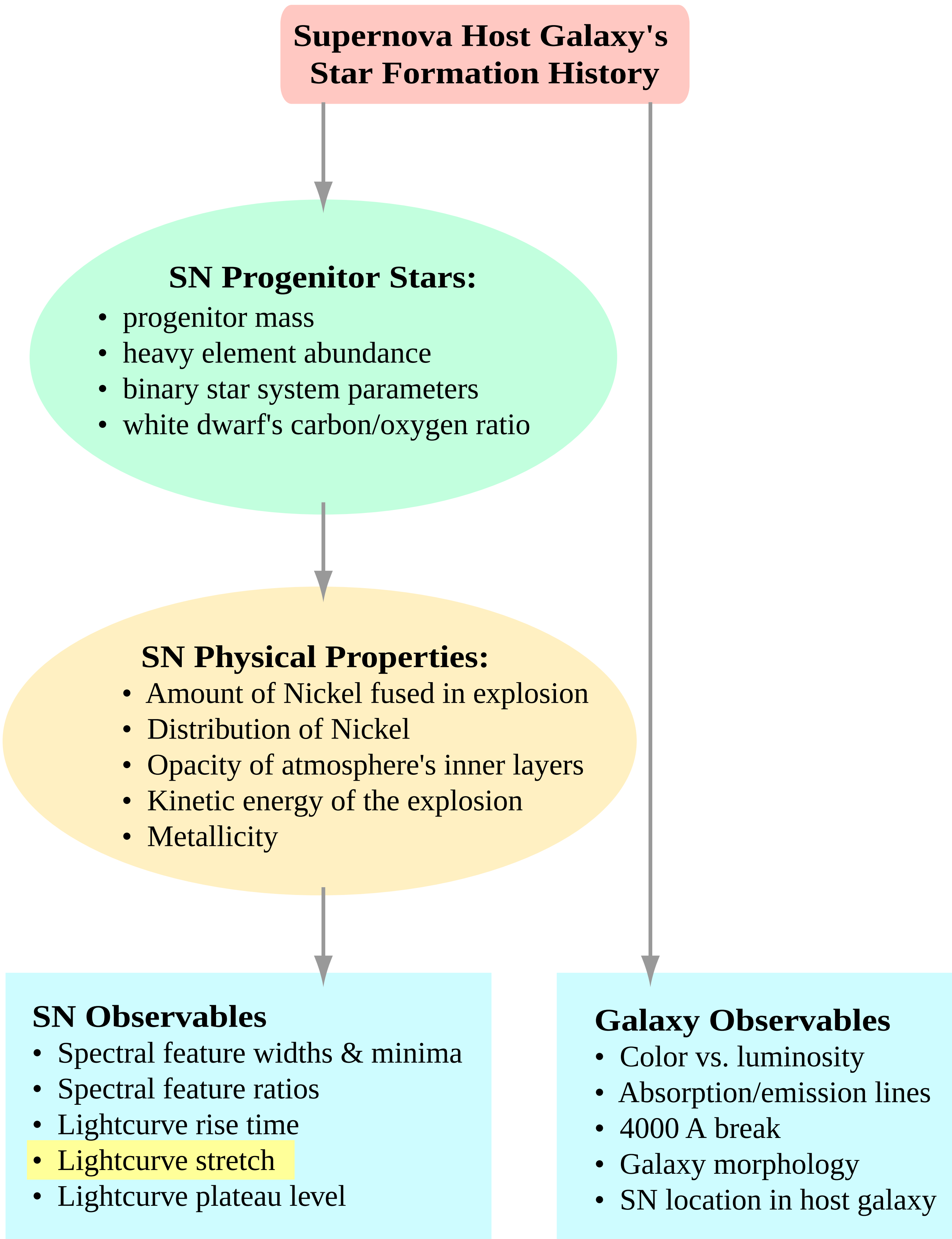
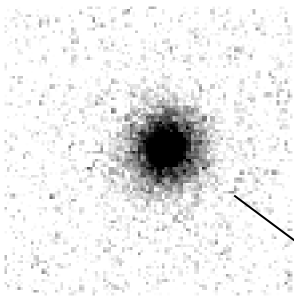


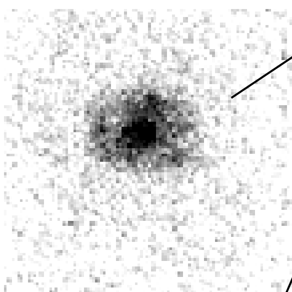
Host galaxy morphology, from space-based imaging with HST / STIS

Result from elliptical host galaxy subsample agrees with flat, $\Omega_\Lambda = 0.72$ result from whole dataset. (Elliptical best flat universe fit: $\Omega_\Lambda = 0.58 \pm 0.2$)

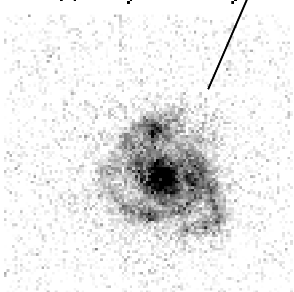
SN1995ax, z=0.615, E/S0



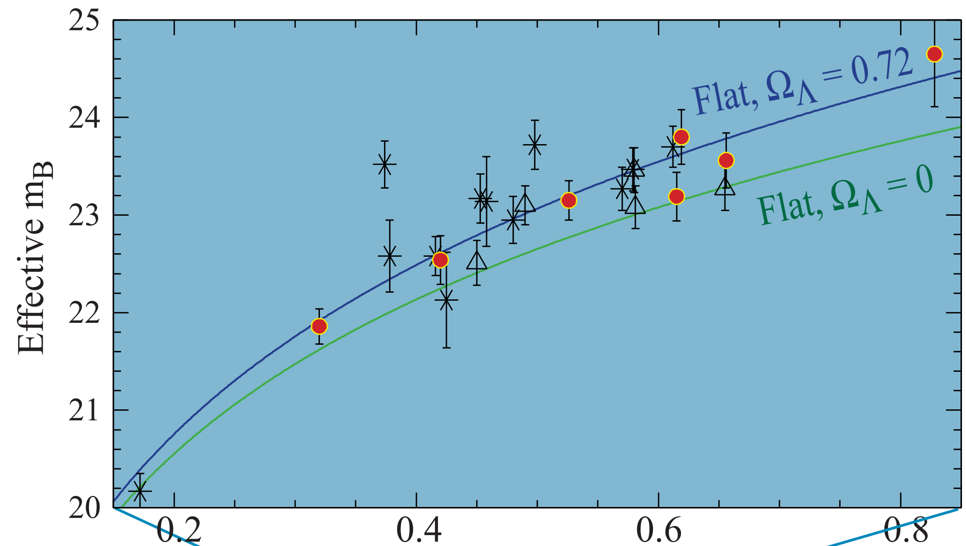
SN1997eq, z=0.540, Sab

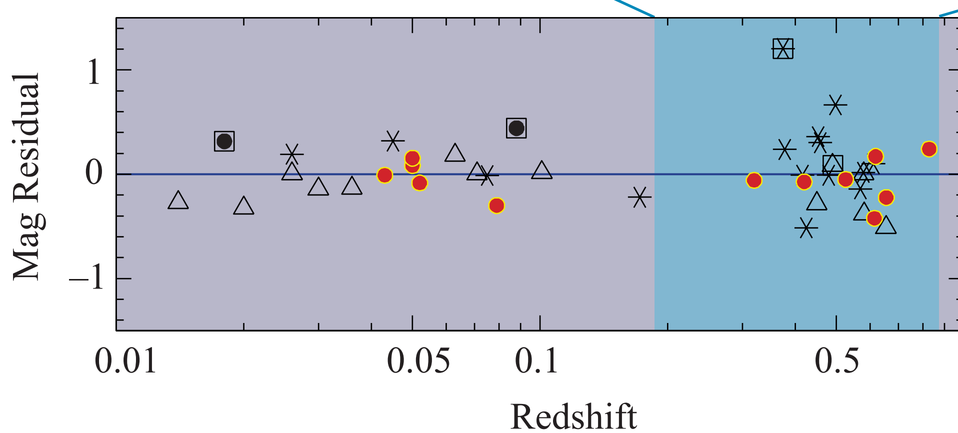


SN1995az, z=0.450, Scd



galaxy type	dispersion from flat, $\Omega_\Lambda = 0.72$
● Elliptical: E/S0	$\sigma = 0.19$ mag
△ Spiral: Sa/Sb/Sc	$\sigma = 0.27$ mag
⚹ Late/Irregular: Scd/Irr	$\sigma = 0.30$ mag

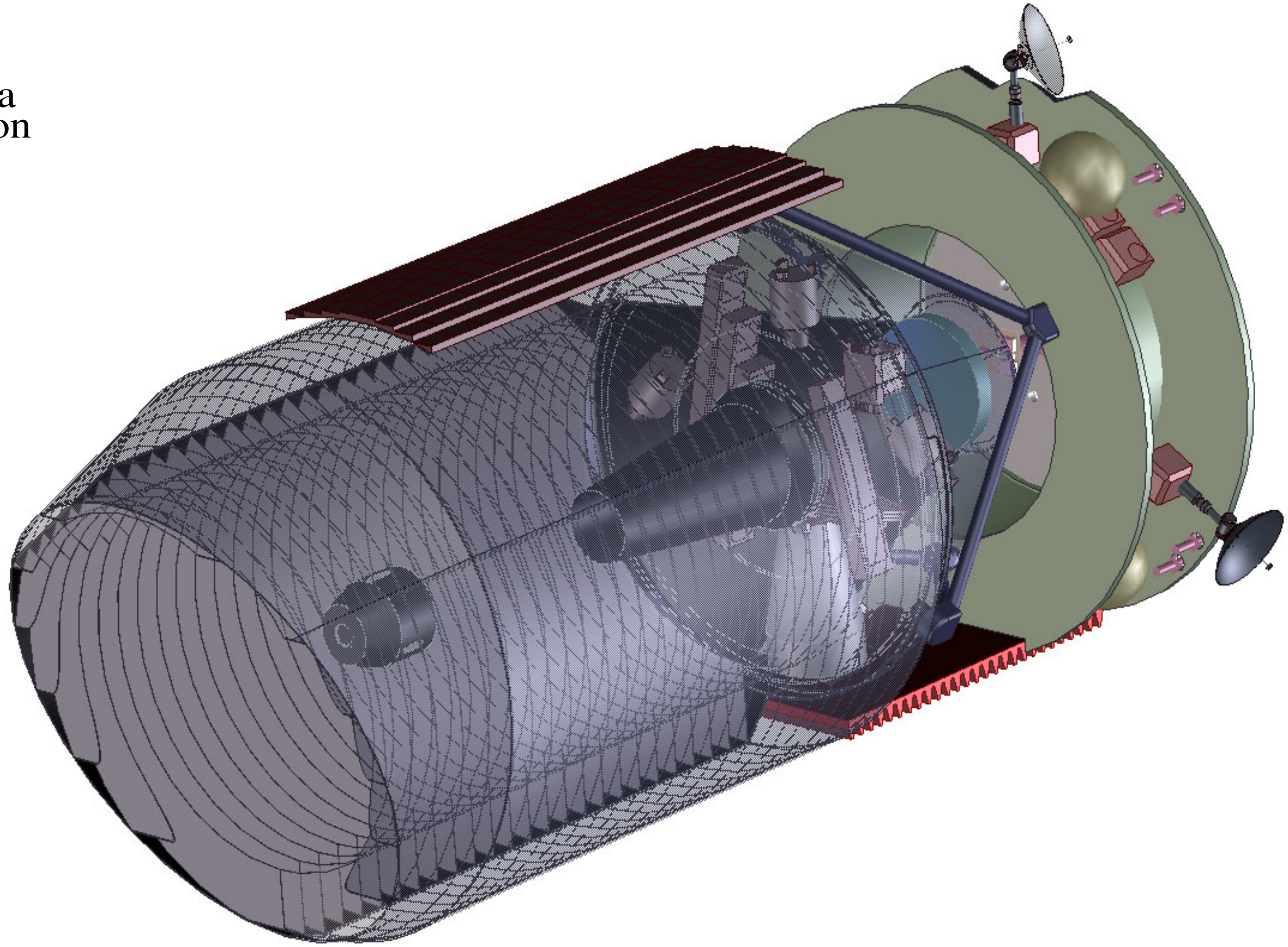




Ellis et al. (astro-ph/0011369)
Supernova Cosmology Project

4. How this tool can address systematics.

SNAP SuperNova Acceleration Probe



- **~2 m aperture telescope**

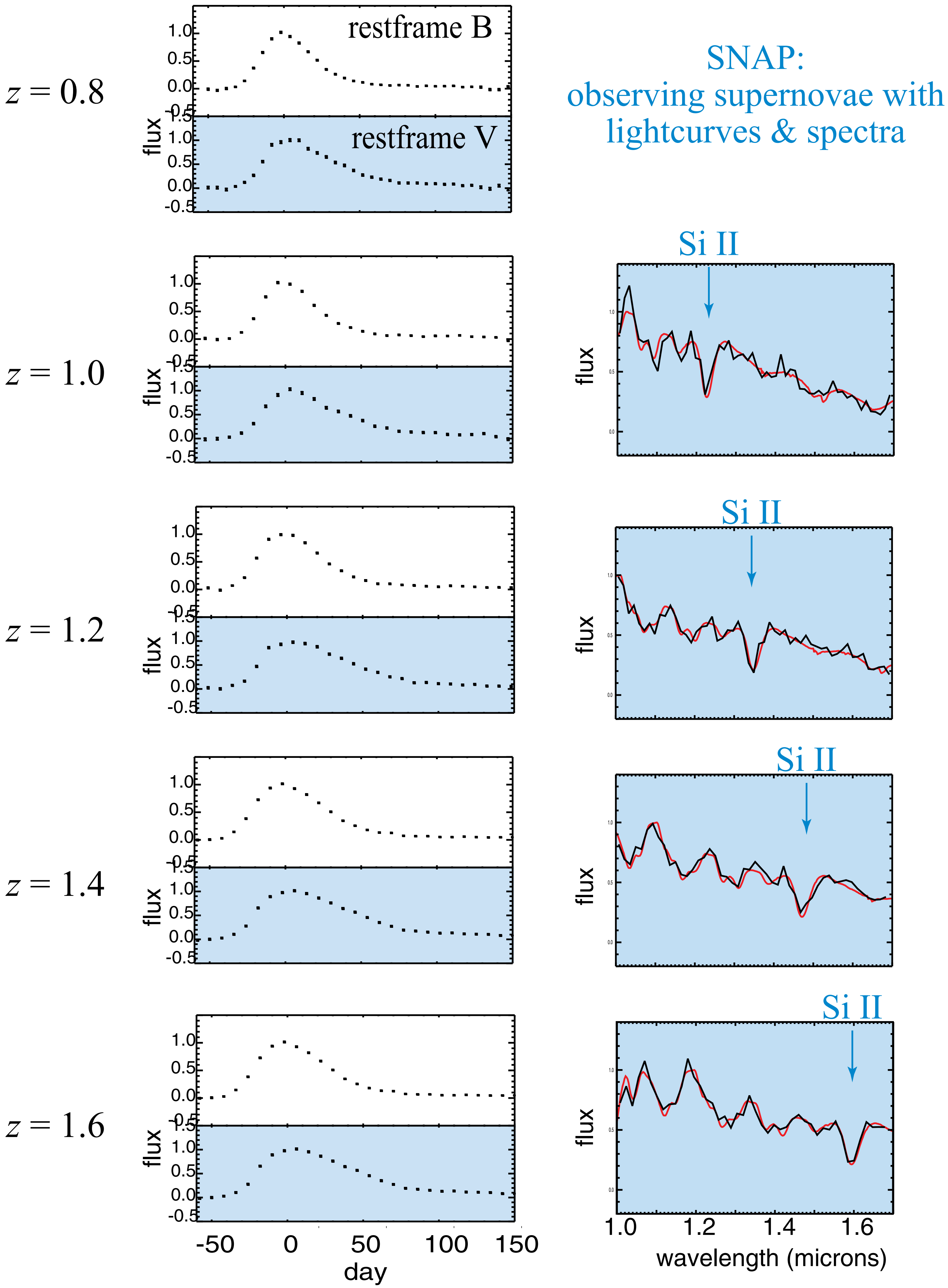
  Can reach very distant SNe.

- **1 square degree mosaic camera, ~1 billion pixels**

  Efficiently studies large numbers of SNe.

- **0.35um -- 1.7um spectrograph**

  Detailed analysis of each SN.



SNAP:
observing supernovae with
lightcurves & spectra
z = 0.8
z = 1.0
z = 1.2
z = 1.4
z = 1.6
restframe B
restframe V
flux
day
-50
0
50
100
150
Si II
wavelength (microns)
1.0
1.2
1.4
1.6

An exhaustive accounting of sources of SN systematic uncertainties:

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- o shifting distribution of
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- o shifting distibution of SN physics params:
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- o dust that reddens
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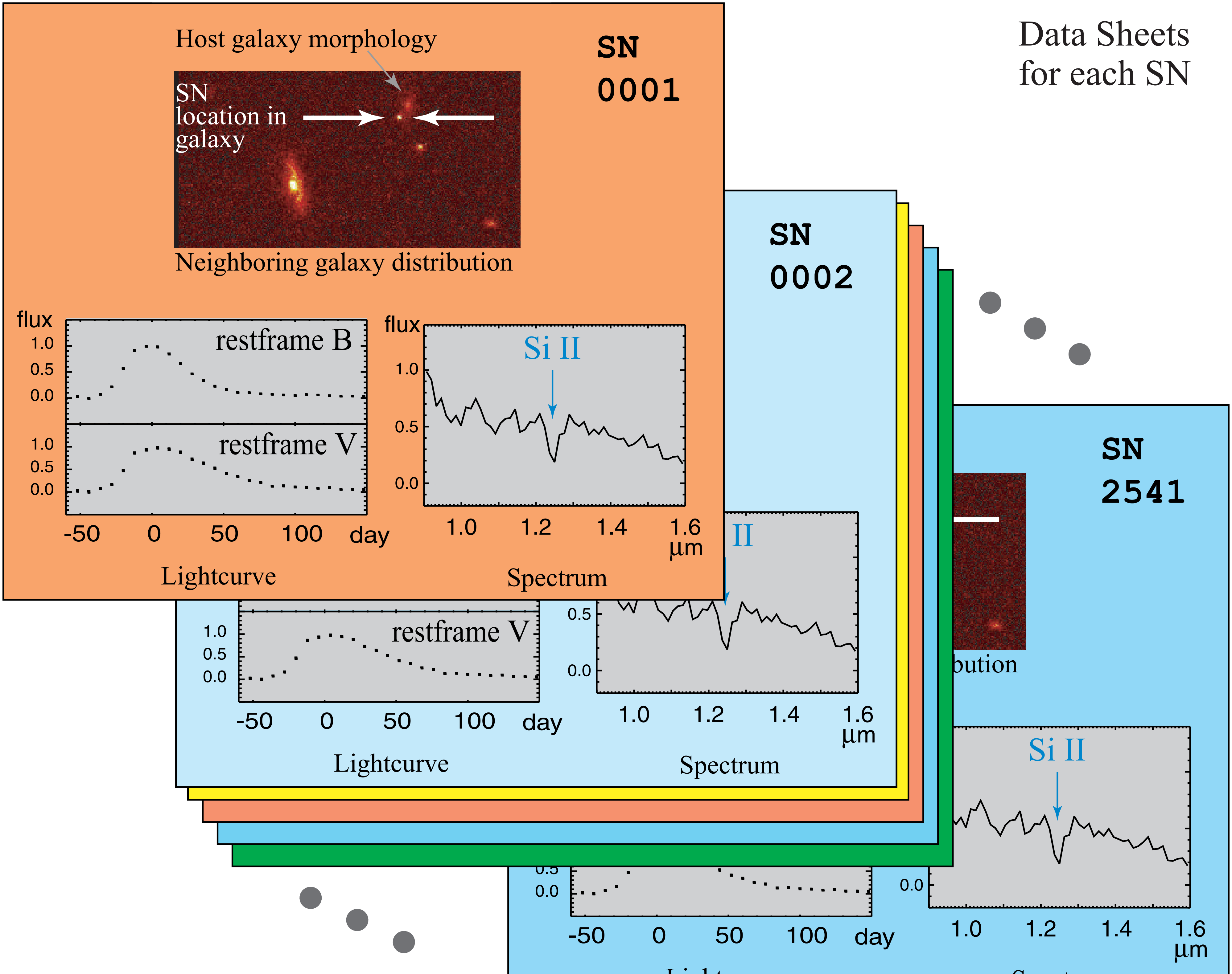


Data Sheets
for each SN
SN
0001
Host galaxy morphology
SN
location in
galaxy
Neighboring galaxy distribution
flux
restframe B
restframe V
day
Lightcurve
Si II
µm
Spectrum
SN
0002
SN
2541

1

Sort into Like Subsets

Group A:
* Si II in spectrum: type Ia
* elliptical host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

Group B:
* Si II in spectrum: type Ia
* in core of late-type spiral host
* faint UV: high metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

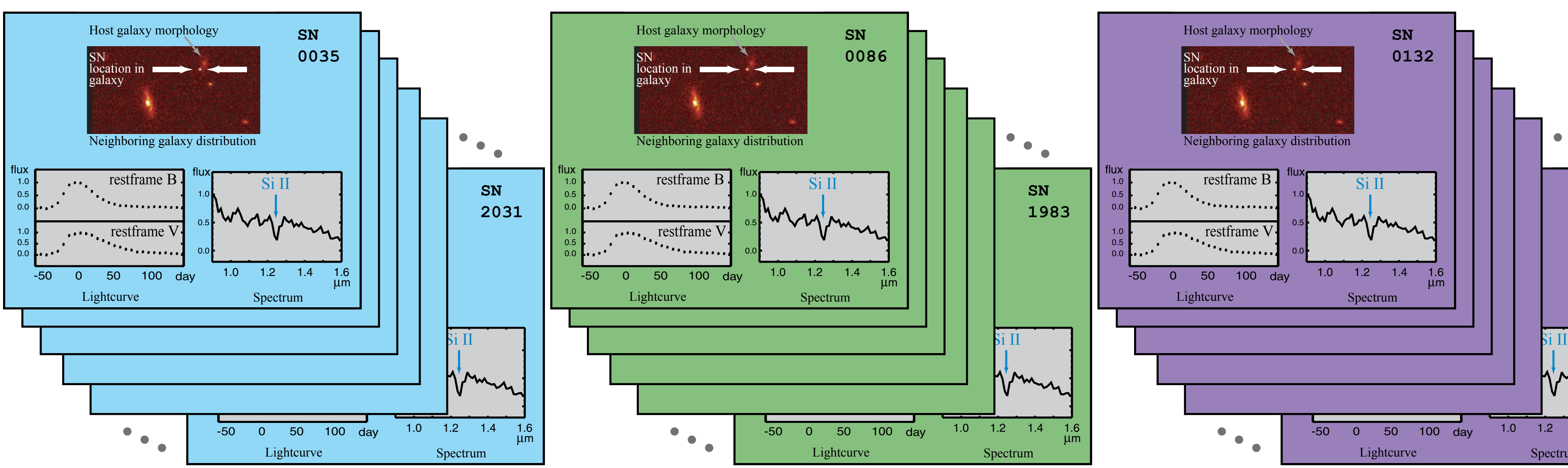
⋮

Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities 8000 < v < 9500 km/s

⋮

• • •

Gro
* Si II i
* in core
* bright
* short
* spectr 8000



2

Each subset gets its own extinction-corrected Hubble diagram:

Group A:
* Si II in spectrum: type Ia
* elliptical host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

Group B:
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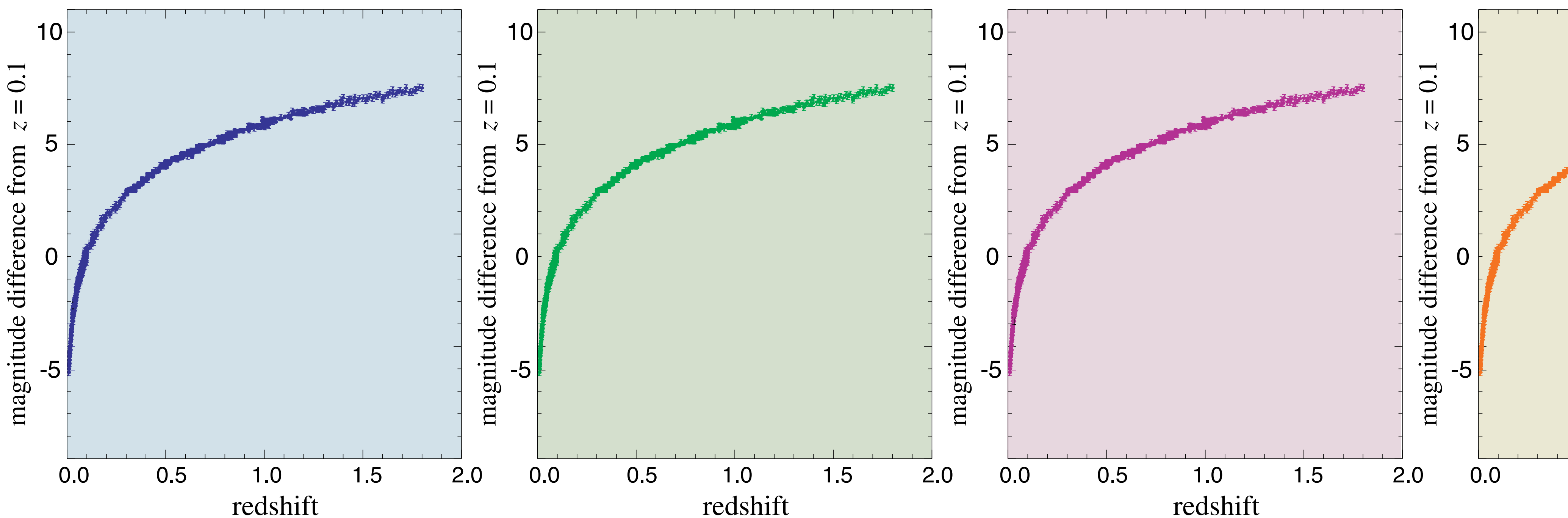
⋮

Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities 8000 < v < 9500 km/s

⋮

• • • **Gro**
* Si II i
* in core
* brigh
* short
* spectr
8000



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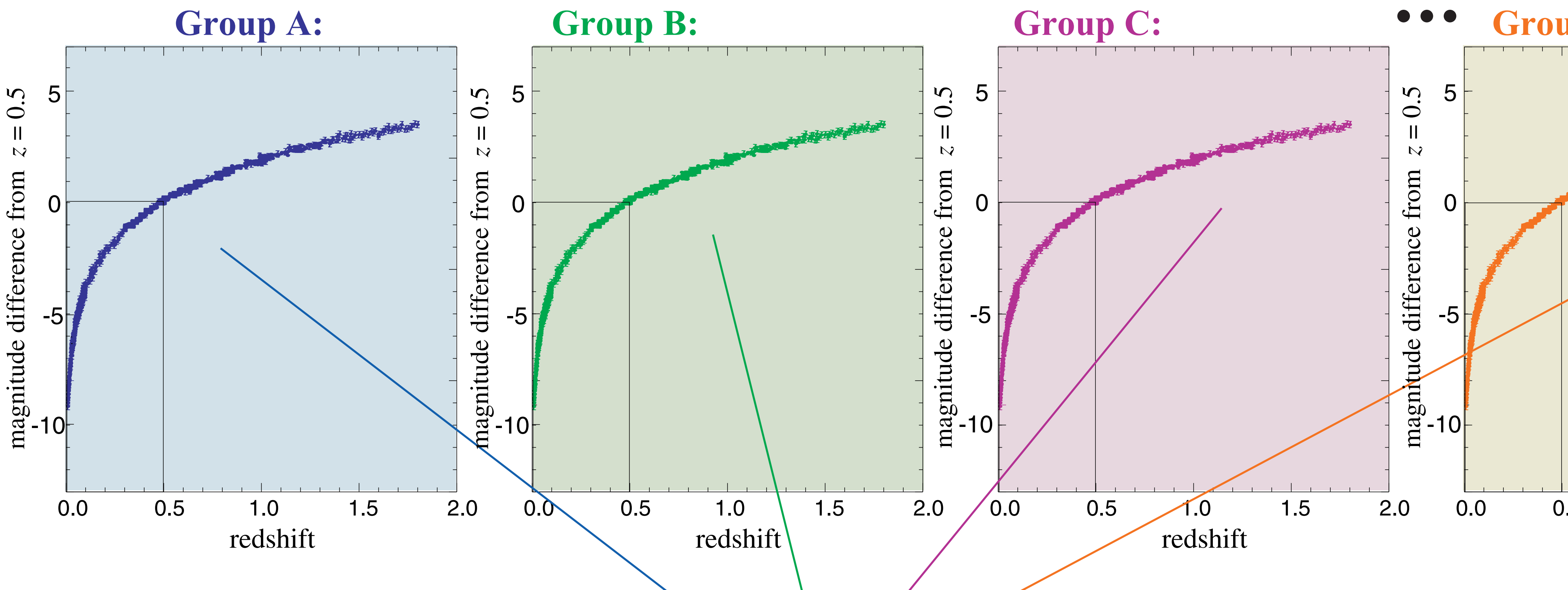
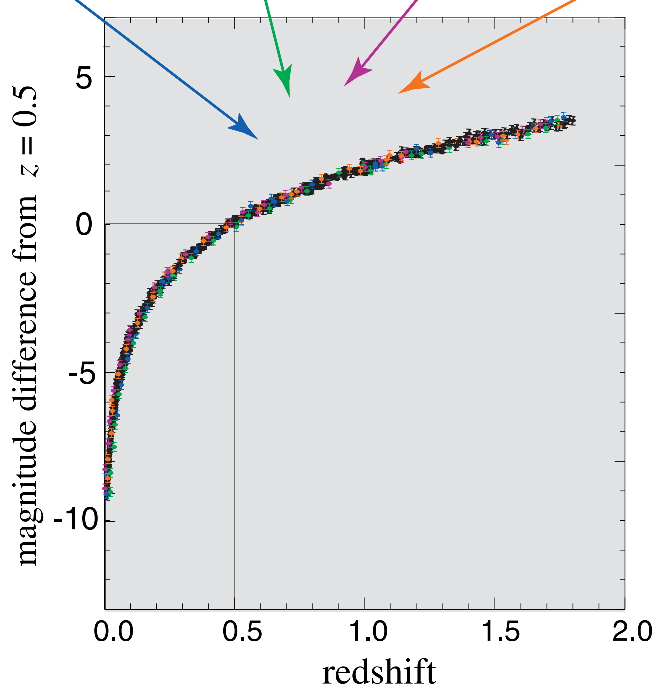


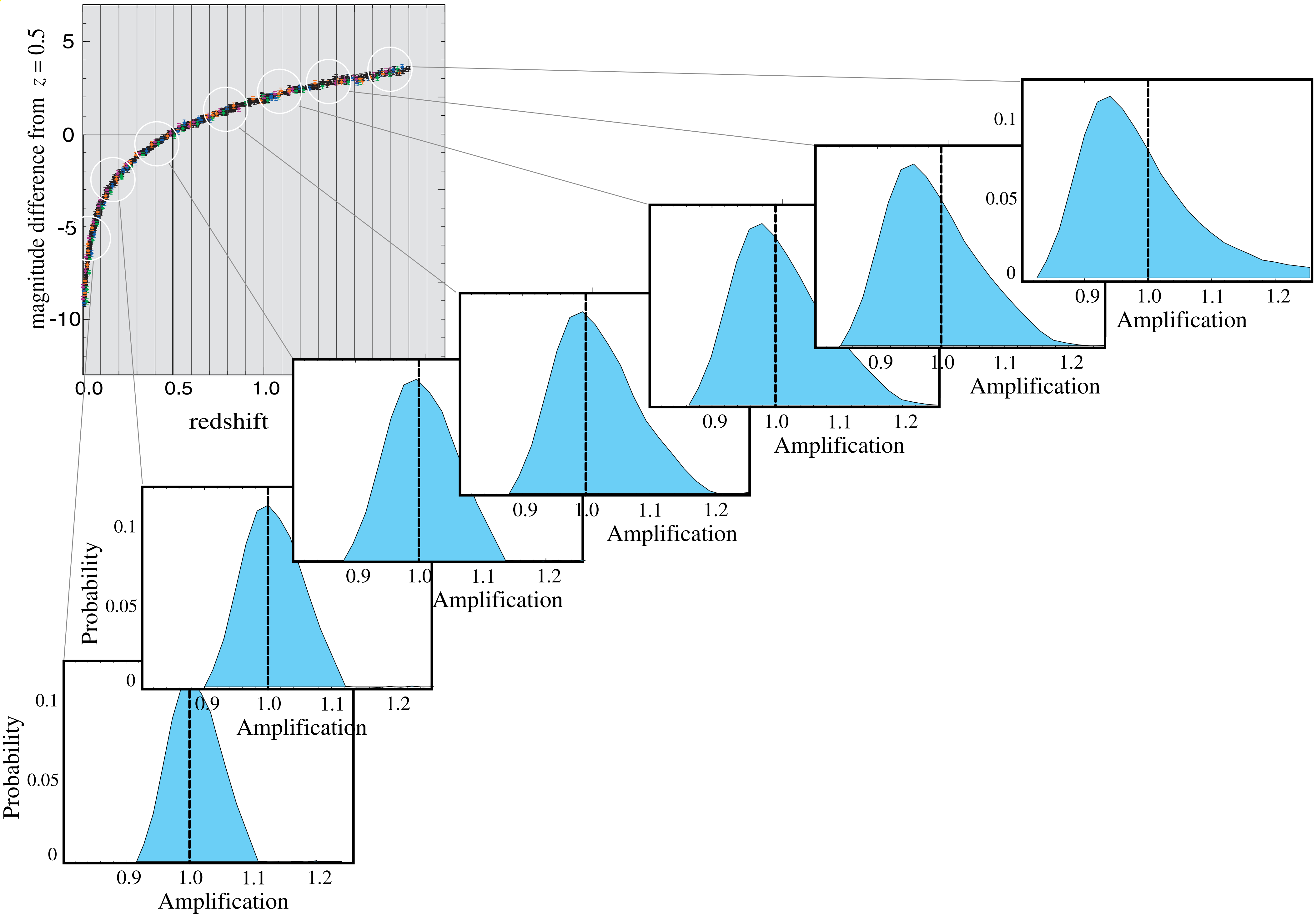
Combine into one Hubble diagram

with magnitude difference from $z = 0.5$



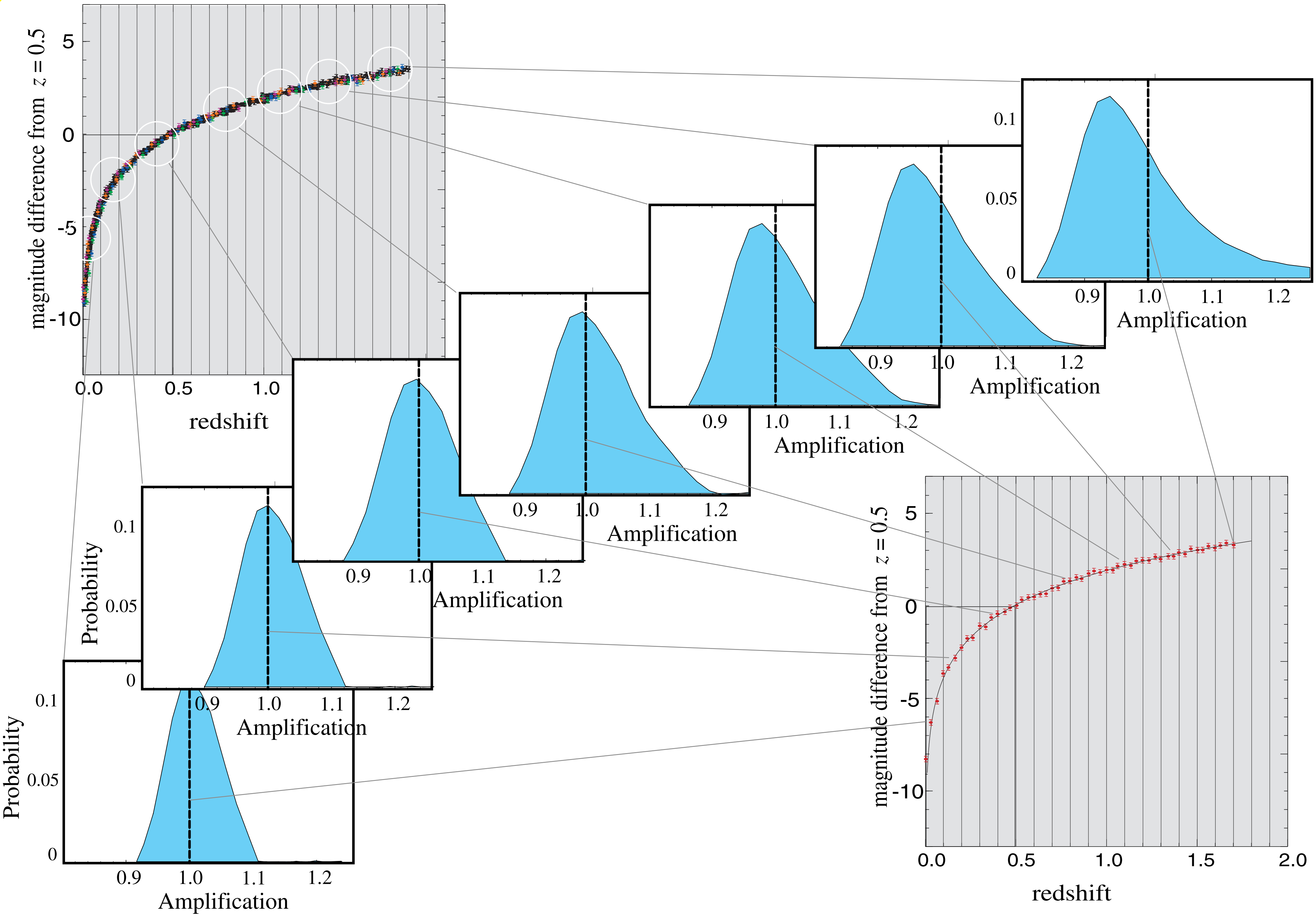
3

Break Hubble diagram into *z* slices to study lensing (de)amplification distribution:



3

Fit/average lensing distributions to construct redshift-binned Hubble diagram:



Example Measurement Requirements for Each Step

1 Sort into Like Subsets

Spectrum:

Si II feature — $\lambda/\Delta\lambda \sim 100$ resolution

UV features 5σ per bin

Lightcurve:

Rise time — 3σ measurement, 3.8 mag before max

Peak fit — 15σ measurement, 2 mag after max

Image:

Host galaxy morphology — <0.1" dithered resolution

2 Extinction-corrected Hubble diagram

Spectrum & Lightcurve:

Cross-wavelength calibrated colors for photometry and spectroscopy from near-UV to near-IR (0.35 -- 1.7 μm)

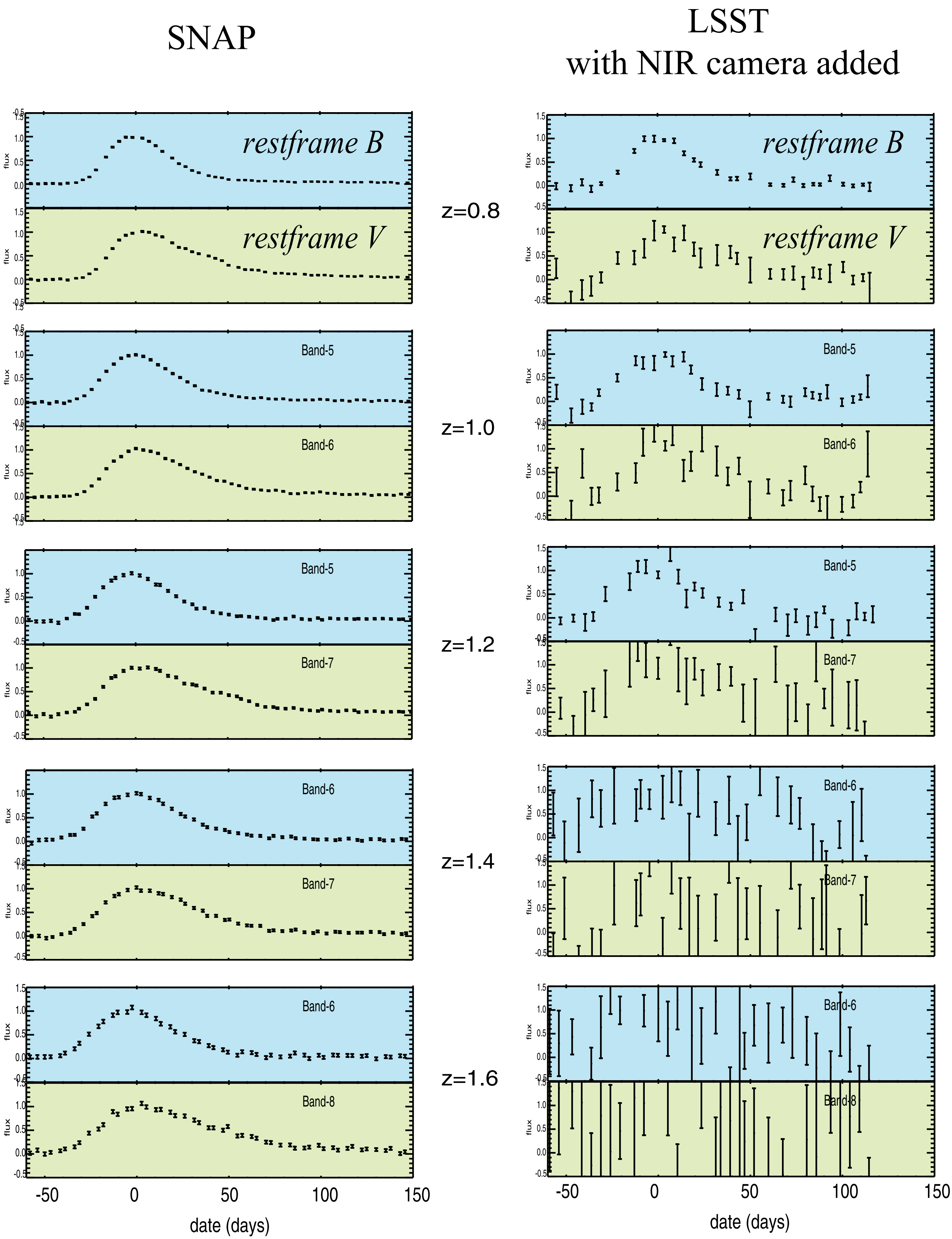
3 Correct for lensing distributions

Image quality:

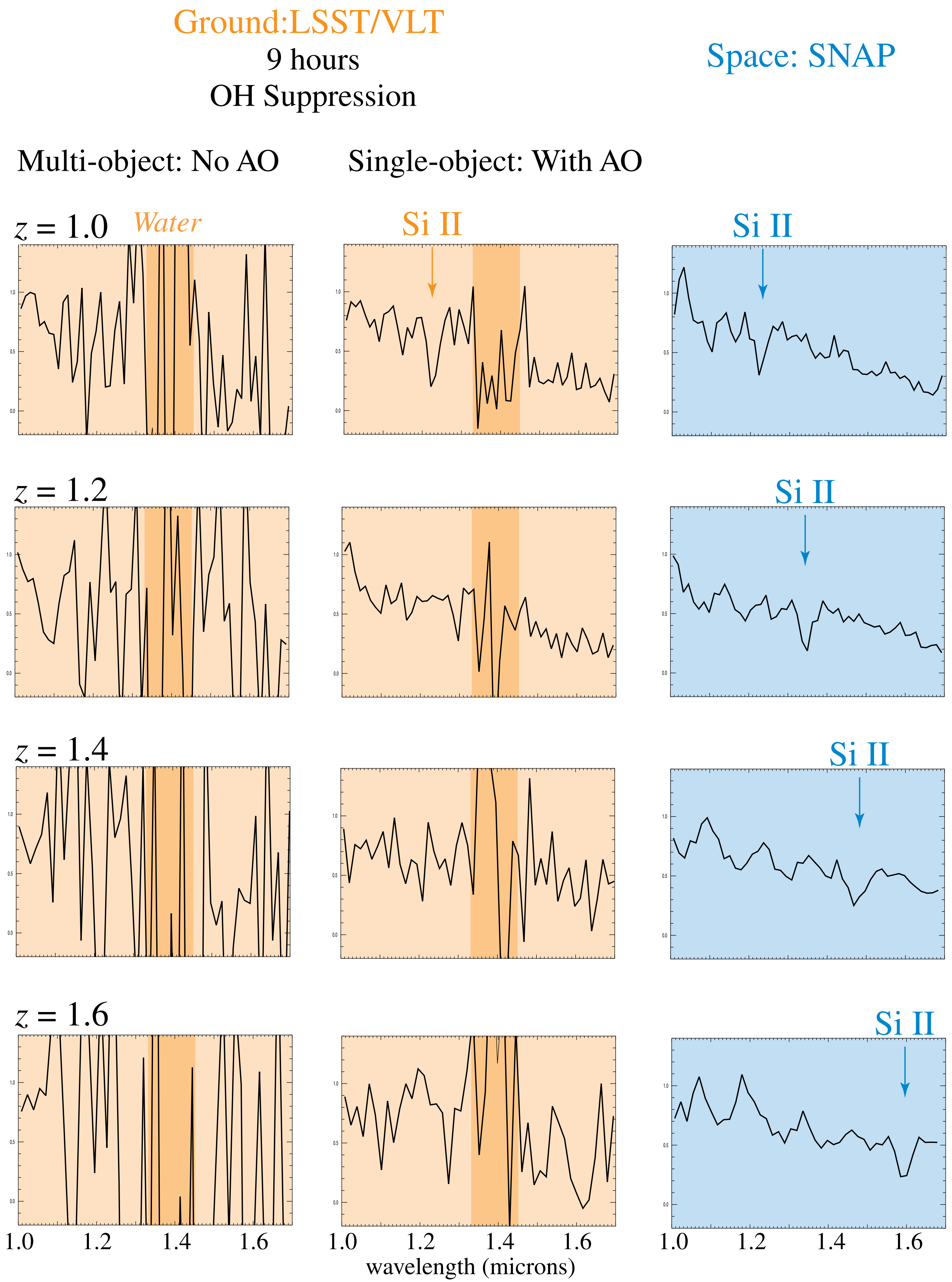
<0.1" dithered resolution for neigboring galaxy gravitational lensing map

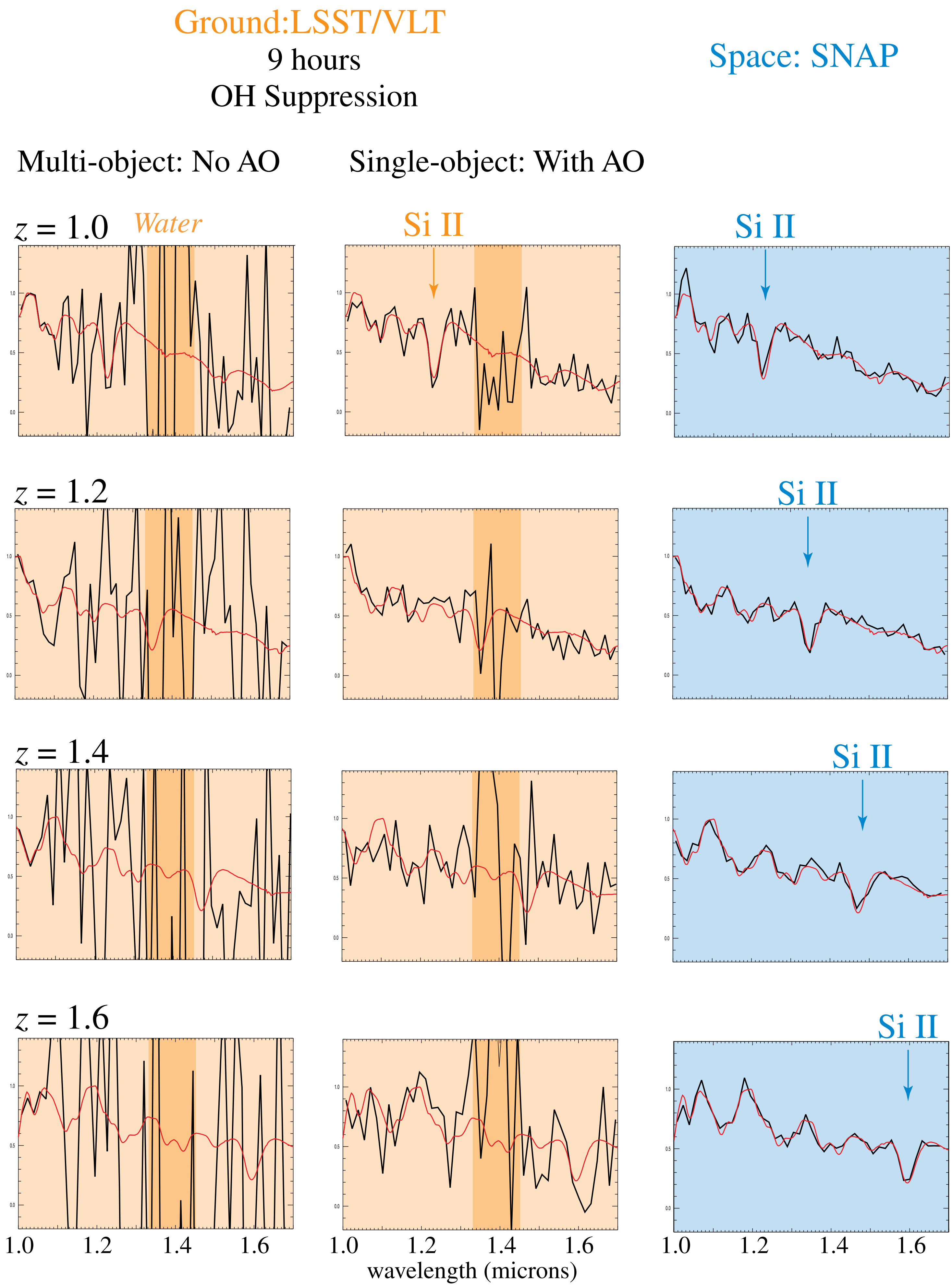
Redshift range & statistics:

>~50 SNe per bin to obtain lensing distribution



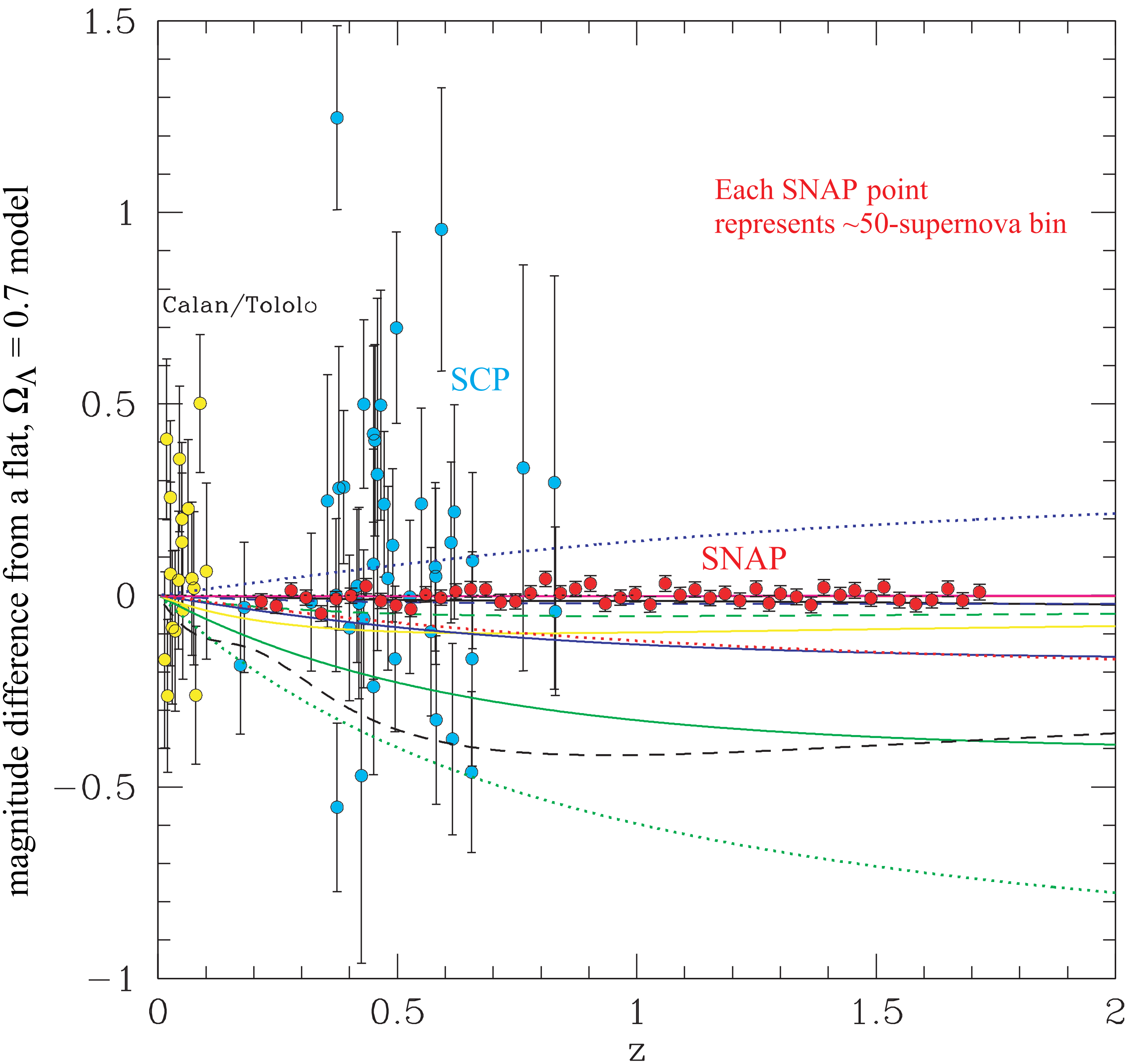
SNAP
LSST
with NIR camera added
restframe B
restframe V
z=0.8
Band-5
Band-6
z=1.0
Band-5
Band-7
z=1.2
Band-6
Band-7
z=1.4
Band-6
Band-8
z=1.6
flux
date (days)


Ground:LSST/VLT
9 hours
OH Suppression
Space: SNAP
Multi-object: No AO
Single-object: With AO
z = 1.0
Water
Si II
Si II
z = 1.2
Si II
z = 1.4
Si II
z = 1.6
Si II
1.0
1.2
1.4
1.6
wavelength (microns)


Ground:LSST/VLT
9 hours
OH Suppression
Space: SNAP
Multi-object: No AO
Single-object: With AO
z = 1.0
Water
Si II
Si II
z = 1.2
Si II
z = 1.4
Si II
z = 1.6
Si II
1.0
1.2
1.4
1.6
wavelength (microns)

SNAP SuperNova Acceleration Probe

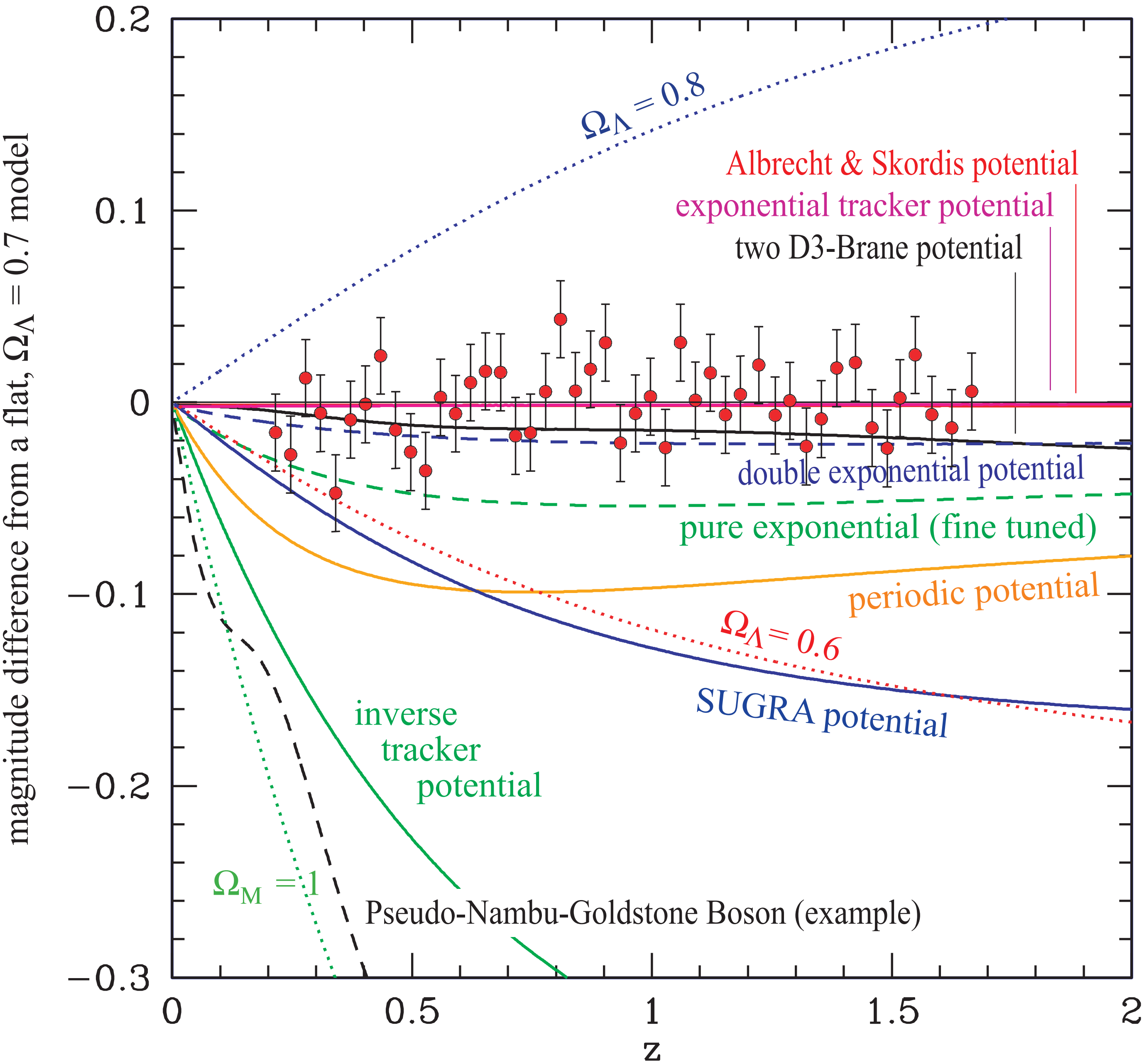
Current ground-based data compared with binned simulated SNAP data and a sample of Dark Energy models.



based on Weller & Albrecht (2001)

SNAP SuperNova Acceleration Probe

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

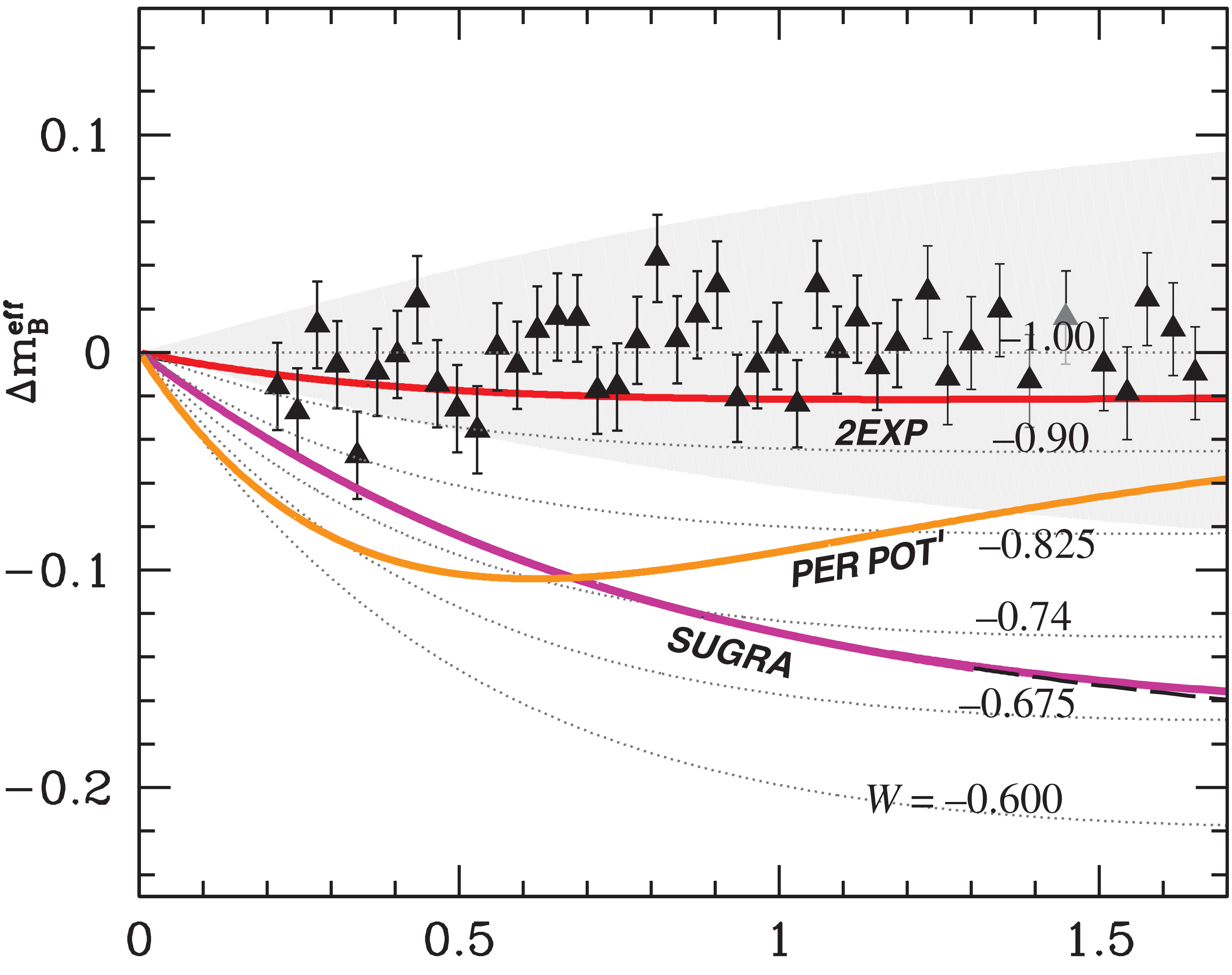


based on

Weller & Albrecht (2001)

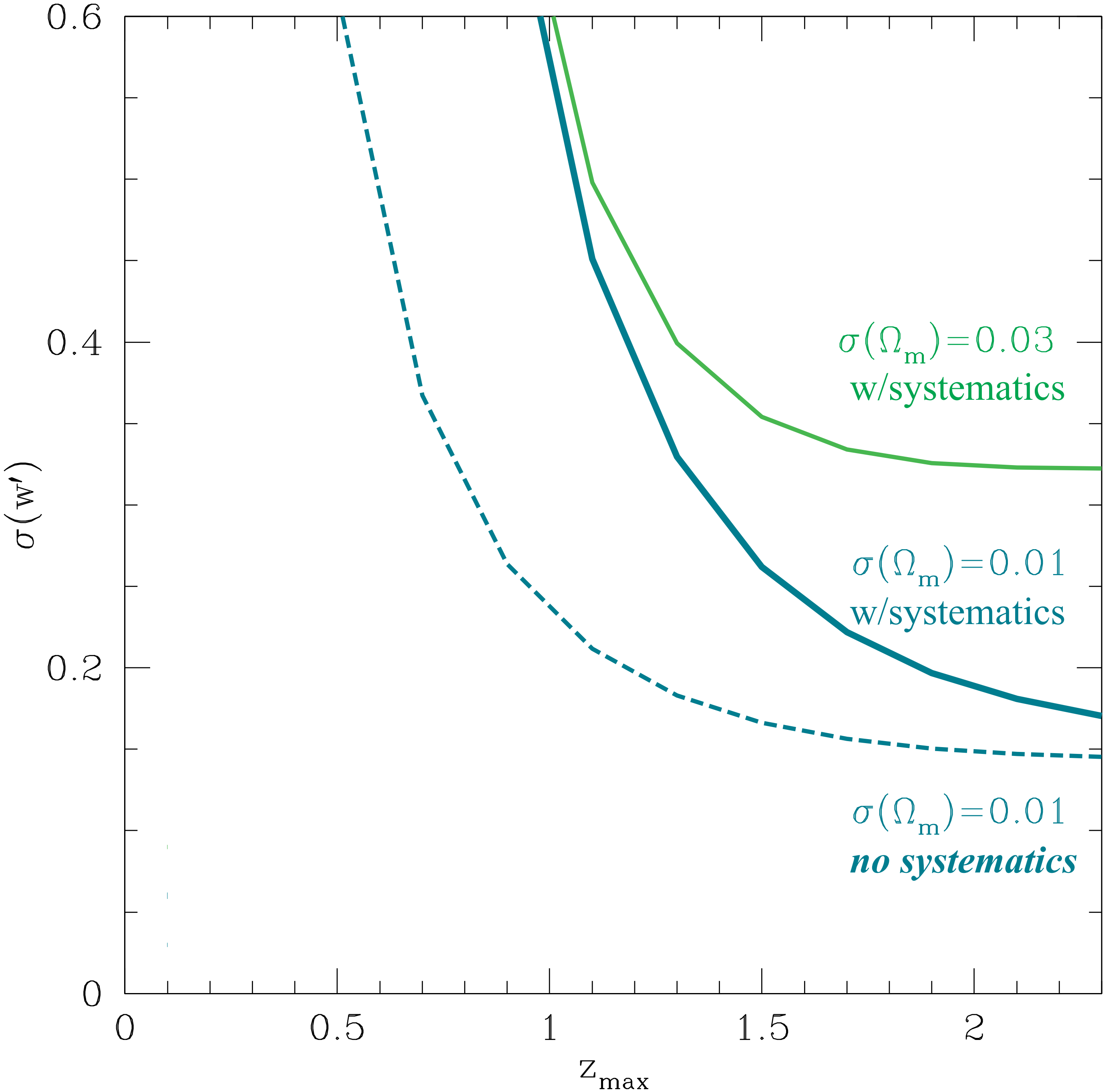
SNAP SuperNova Acceleration Probe

Binned simulated SNAP data
compared with Dark Energy models.



based on
Weller & Albrecht (2000)

How the uncertainty improves as we extend the redshift range.



SNAP SuperNova Acceleration Probe

Primary Science Mission

Requiring complementary measurements of cosmological parameters, Dark Matter, Dark Energy,...

Type Ia supernova calibrated candle:

Hubble diagram to $z = 1.7$

Type II supernova expanding photosphere:

Hubble diagram to $z = 1$ and beyond.

Weak lensing:

Direct measurements of $P(k)$ vs z

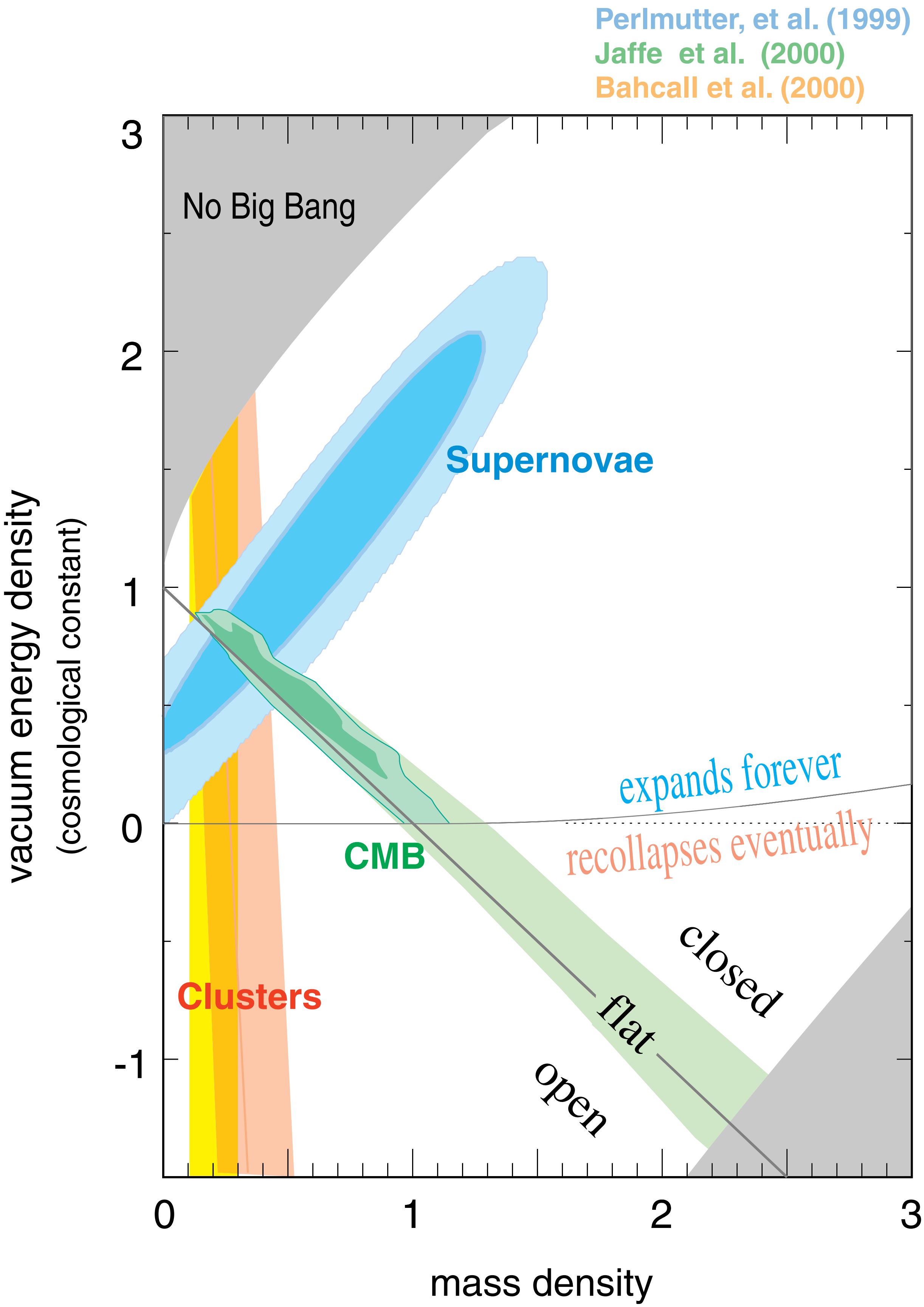
Mass selected cluster survey vs z

Strong lensing statistics: Ω_Λ

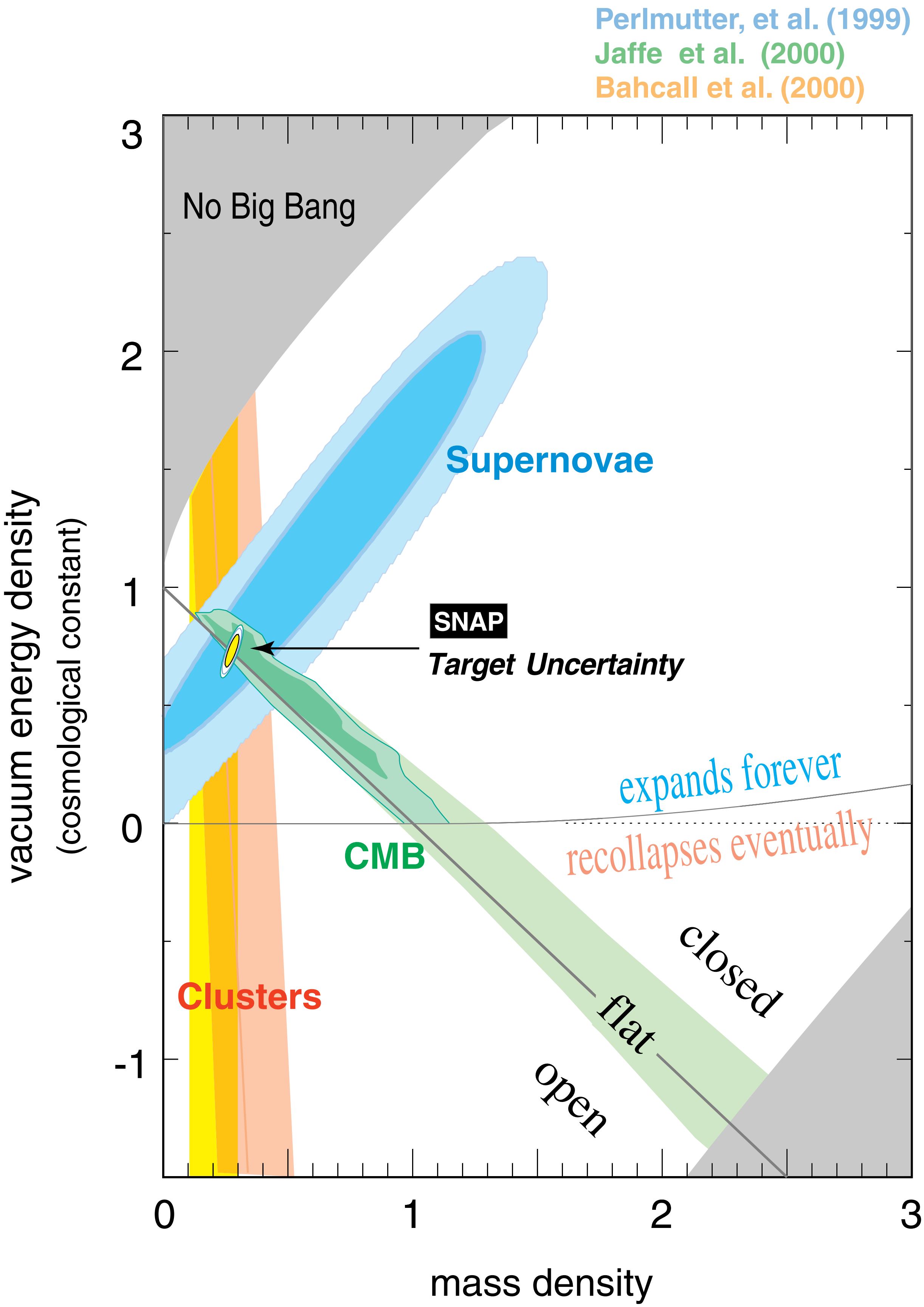
10x gains over ground based optical resolution, IR channels + depth.

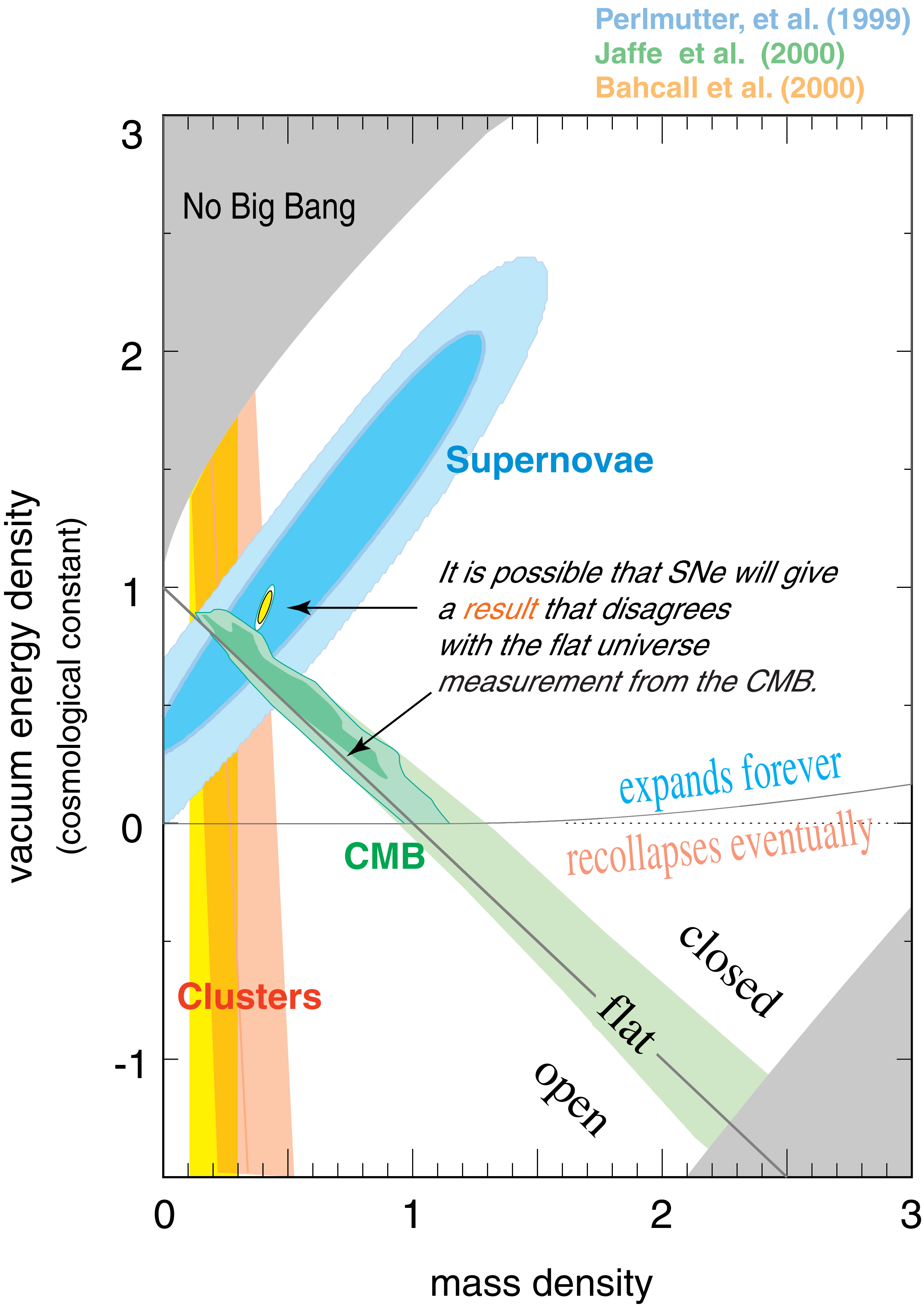
Galaxy clustering:

$W(\Theta)$ angular correlation vs redshift from 0.5 to 3.0



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


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


Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall et al. (2000)
No Big Bang
Supernovae
It is possible that SNe will give
a result that disagrees
with the flat universe
measurement from the CMB.
expands forever
recollapses eventually
CMB
Clusters
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

5. Project status & reviews.

SNAP SuperNova Acceleration Probe

Active members of the SNAP collaboration

G. Aldering, C. Bebek, J. Bercovitz, W. Carithers, C. Day, S. Deustua*, R. DiGennaro, D. Groom, S. Holland, D. Huterer*, A. Karcher, A. Kim, W. Kolbe, B. Krieger, R. Lafever, M. Levi, E. Linder, S. Loken, P. Nugent, H. Oluseyi, S. Perlmutter, K. Robinson, A. Spadafora, J. Walder (Lawrence Berkeley National Laboratory)

M. Bester, E. Commins, G. Goldhaber, S. Harris, P. Harvey, H. Heetderks, M. Lampton, J. Lamoureux, D. Pankow, C. Pennypacker, R. Pratt, M. Sholl, G. F. Smoot (UC Berkeley)

C. Akerlof, G. Bernstein*, D. Levin, T. McKay, S. McKee, M. Schubnell, G. Tarle , A. Tomasch (U. Michigan)

R. Ellis, R. Massey*, J. Rhodes, A. Refregier* (CalTech)

C. Bower, N. Mostek, J. Musser, S. Mufson (Indiana)

A. Fruchter (STScI)

P. Astier, E. Barrelet, A. Bonnissent, A. Ealet, J-F. Genat, R. Malina, R.Pain, E. Prieto, G. Smadja, D. Vincent (France: CNRS/IN2P3, CNRS/INSU)

R. Amanullah, L. Bergström, M. Eriksson, A. Goobar, E. Mörtsell (U. Stockholm)

** Affiliated with the listed institution for organizational purposes*

SNAP SuperNova Acceleration Probe

Project Chronology: Reviews & Studies

First public presentation of idea at Fermilab "Inner Space/Outer Space" symposium.	**May 1999**
SAGENAP review 1 for DOE & NSF-Physics	**March 2000**
NASA Structure and Evolution of the Universe (SEU) subcomittee	**Nov 2000**
NAS/NRC Committee on Astronomy and Astrophysics	**Dec 2000**
DOE-HEP R&D review	**Jan 2001**
DOE HEPAP	**March 2001**
NASA Integrated Mission Design Center	**June 2001**
NAS/NRC Committee on the Physics of the Universe	**July 2001**
CNES (France Space Agency)	**Nov 2001**
NASA/SEU Strategic Planning Panel	**Dec 2001**
NASA Instrument Synthesis & Analysis Lab	**Dec 2001**
SAGENAP review 2	**March 2002**
CNES review (scheduled)	**Oct 2002**

Project History and Status

Peer review of science (260 page proposal) by
DOE & NSF's SAGENAP panel, March 2000:

Strong endorsement of science,
and recommendation for study funding.

DOE/Science & R&D Review (Jan 2001):

"SNAP is a science-driven project with compelling scientific goals."
"SNAP will have a unique ability to measure the variation in the equation of state of the universe."
"Implications for particle physics: We believe that it is not an overstatement to say that the Type Ia supernova measurements will uniquely address issues at the very heart of the field…"

SNAP SuperNova Acceleration Probe

Three National Prioritization Panels' Recommendations

Astronomy & Astrophysics

NRC Decadal Survey:

"One of the most exciting developments of the past decade has been the discovery that the cosmological constant may not be zero — our universe appears to be filled with dark energy."

"The committee identified several key problems that are particularly ripe for advances in the coming decade. These problems are … properties of the universe: the amount and distribution of its matter and energy, its age, and the history of its expansion."

SNAP was formulated after the Decadal Survey's data collection phase.

Physics

HEPAP 20-Year Planning Report:

"Modern cosmology is closely connected with particle physics. For example, cosmological measurements of dark energy and particle dark matter have direct implications for particle physics."

"Dark energy can be probed by a number of techniques. Among the most powerful are measurements of the expansion rate of the universe from observations of Type Ia supernovae."

Report gives a strong endorsement for continued development of SNAP.

Intersection of Physics and Astronomy

NRC Committee on the Physics of the Universe:

"Deciphering the nature of dark matter and dark energy is one of the most important goals in the physics of the universe. Resolving both puzzles is key to advancing our understanding not only of cosmology but also fundamental physics."

"Observations of distant supernovae can probe the detailed expansion history directly back to redshifts of around 2.... Large-field-of-view telescopes are needed to find larger and more uniform samples of supernovae."

Committee reviewed SNAP in July 2001 as part of their Phase II study of specific projects (released this spring).

Report of the NRC's
Commitee on the Physics of the Universe
(The Turner Panel)

Recommendation:

"The discovery that the expansion of the universe is speeding up and not slowing down has revealed the presence of a mysterious new energy form that accounts for two-thirds of all the matter and energy in the universe. Because of its diffuse nature, it can only be probed through its effect on the expansion of the universe.

"The NRC's most recent astronomy decadal survey has recommended building the Large Synoptic Survey Telescope to study transient phenomena in the universe; it will also have significant ability to probe dark energy. To fully characterize the expansion history and probe the dark energy will require a wide-field telescope in space (such as the Supernova/Acceleration Probe)."

Recommendation: "The Committee further recommends that NASA and DOE work together to construct a wide-field telescope in space to determine the expansion history of the universe and fully probe the nature of the dark energy."

NASA's strategic plan

- NASA updates its strategic plan this year,
  - —Presented SNAP to NASA Structure and Evolution of the Universe (SEU) in November 2000 and again to strategic planning sub-panel in December 2001, SNAP white paper & technology roadmap.
- Turner Panel report had major impact on planning process.
- NASA/SEU Roadmap now has a SNAP-like mission
  - —Three "cosmic probes" new ~$500M mission starts every three years, one for dark energy. Will require new NASA initiative and request for funds (SEU FY03 budget $21M).
  - —Initiative is called *"Beyond Einstein"*.
  - —SEU Roadmap promulgated in ~September.
  - —Unknown which of the three cosmic probes would go first (Dark Energy, Black Holes, CMB-Polarization).
  - —They are very aware of the keen interest from DOE.
- We are assuming that SNAP will be funded either: 1) 100% by DOE (including paying NASA for a launch and other services), or 2) a 50/50 partnership DOE/NASA through the SEU process. DOE is aggressively pursuing new project lines – see R. Orbach "Occassional Paper on Dark Energy".

SNAP SuperNova Acceleration Probe

Science Goals for The First Wide-field Survey in Space

A Resource for the Science Community:
The *only* wide-field deep survey in space -- with HST resolution.

- SNAP main survey will be 4000x larger (and somewhat deeper) than the biggest HST deep survey, the ACS survey
- Complementary to NGST: target selection for rare objects
- Can survey 3000 sq. deg in a year to I = 29 or J = 28 (AB mag) .

→ Archive data distributed

→ Guest Survey Program

Whole sky can be observed every few months

SNAP SuperNova Acceleration Probe

January 2001 AAS meeting
1 dedicated session, 9 talks, 4 posters
January 2002 AAS meeting
2 dedicated sessions, 18 talks, 7 posters:

Grass-roots Support

Oral Session 111. Science with Wide Field Imaging in Space:

The Astronomical Potential of Wide-field Imaging from Space	S. Beckwith (Space Telescope Science Institute)
Galaxy Evolution: HST ACS Surveys and Beyond to SNAP	G. Illingworth (UCO/Lick, U. of California)
Studying Active Galactic Nuclei with SNAP	P.S. Osmer (OSU), P.B. Hall (Princeton/Catolica)
Distant Galaxies with Wide-Field Imagers	K. M. Lanzetta (State U. of NY at Stony Brook)
Angular Clustering and the Role of Photometric Redshifts	A. Conti, A. Connolly (University of Pittsburgh)
SNAP and Galactic Structure	I. N. Reid (STScI)
Star Formation and Starburst Galaxies in the Infrared	D. Calzetti (STScI)
Wide Field Imagers in Space and the Cluster Forbidden Zone	M. E. Donahue (STScI)
An Outer Solar System Survey Using SNAP	H.F. Levison, J.W. Parker (SwRI), B.G. Marsden (CfA)

Oral Session 116. Cosmology with SNAP:

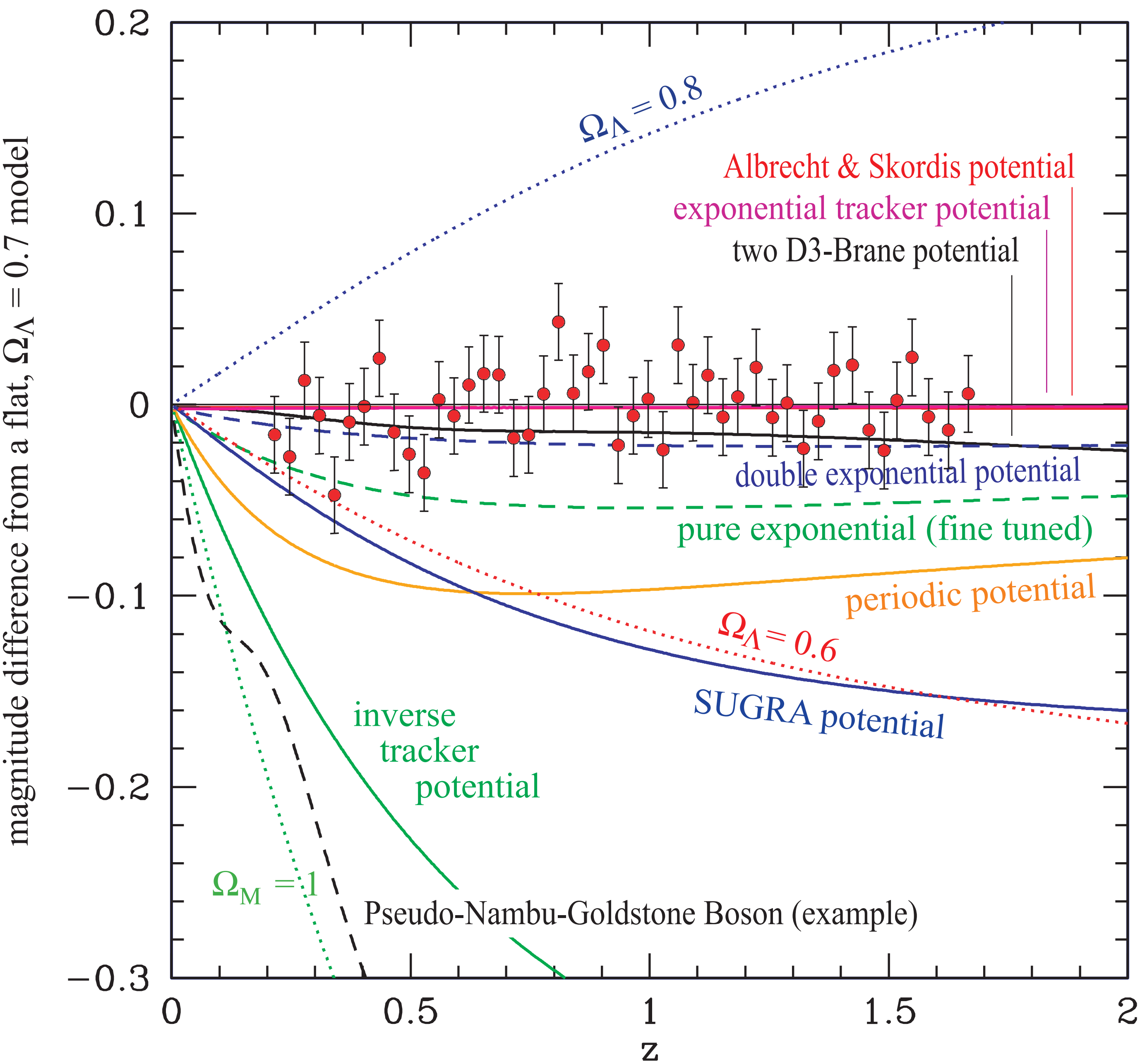
Dark Energy or Worse	S. Carroll (University of Chicago)
The Primary Science Mission of SNAP	S. Perlmutter (Lawrence Berkeley Laboratory),
The Supernova Acceleration Probe:mission design & core survey	T. A. McKay (University of Michigan)
Sensitivities for Future Space- and Ground-based Surveys	G. M. Bernstein (Univ. of Michigan)
Constraining the Properties of Dark Energy using SNAP	D. Huterer (Case Western Reserve University)
Type Ia Supernovae as Distance Indicators for Cosmology	D. Branch (U. of Oklahoma)
Weak Gravitational Lensing with SNAP	A. Refregier (Cambridge), Richard Ellis (Caltech)
Strong Gravitational Lensing with SNAP	R. D. Blandford, L. V. E. Koopmans, (Caltech)
Strong lensing of supernovae	D.E. Holz (ITP, UCSB)

Poster Session 64. Overview of The Supernova/Acceleration Probe:

Supernova / Acceleration Probe: An Overview	M. Levi (LBNL)
The SNAP Telescope	M. Lampton (UCB)
SNAP: Science with Wide Deep Fields in Space	E. Linder (LBNL)
SNAP: An Integral Field Spectrograph for Supernova Identification	R. Malina (Marseille,INSU), A. Ealet
Supernova / Acceleration Probe: GigaCAM - A Billion Pixel Imager	C. Bebek (LBNL)
Supernova / Acceleration Probe: Cosmology with Type Ia Supernovae	A. Kim (LBNL)
Supernova / Acceleration Probe: Education and Outreach	S. Deustua (LBNL)

SNAP SuperNova Acceleration Probe

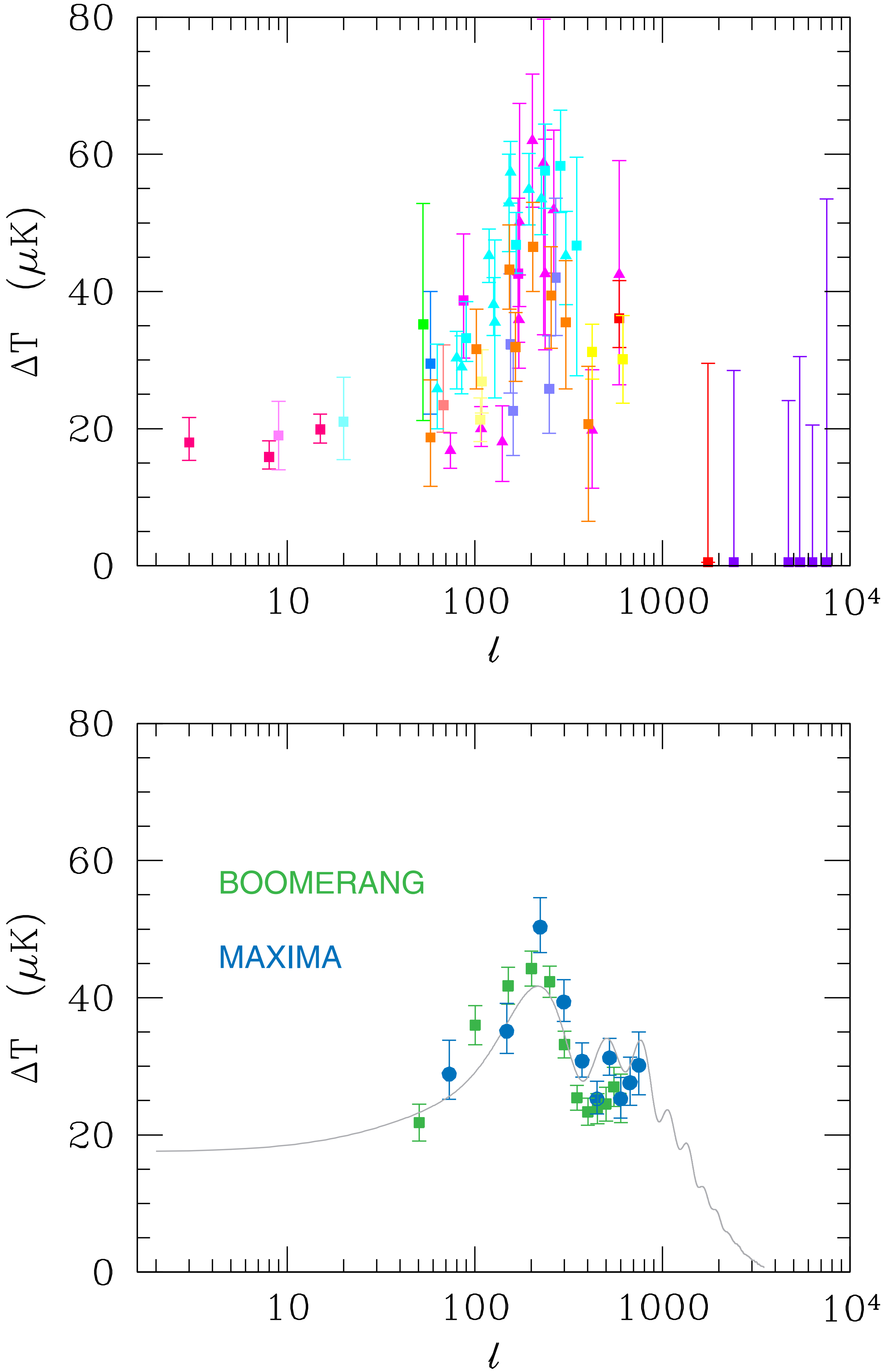
Binned simulated SNAP data compared with Dark Energy models currently in the literature.



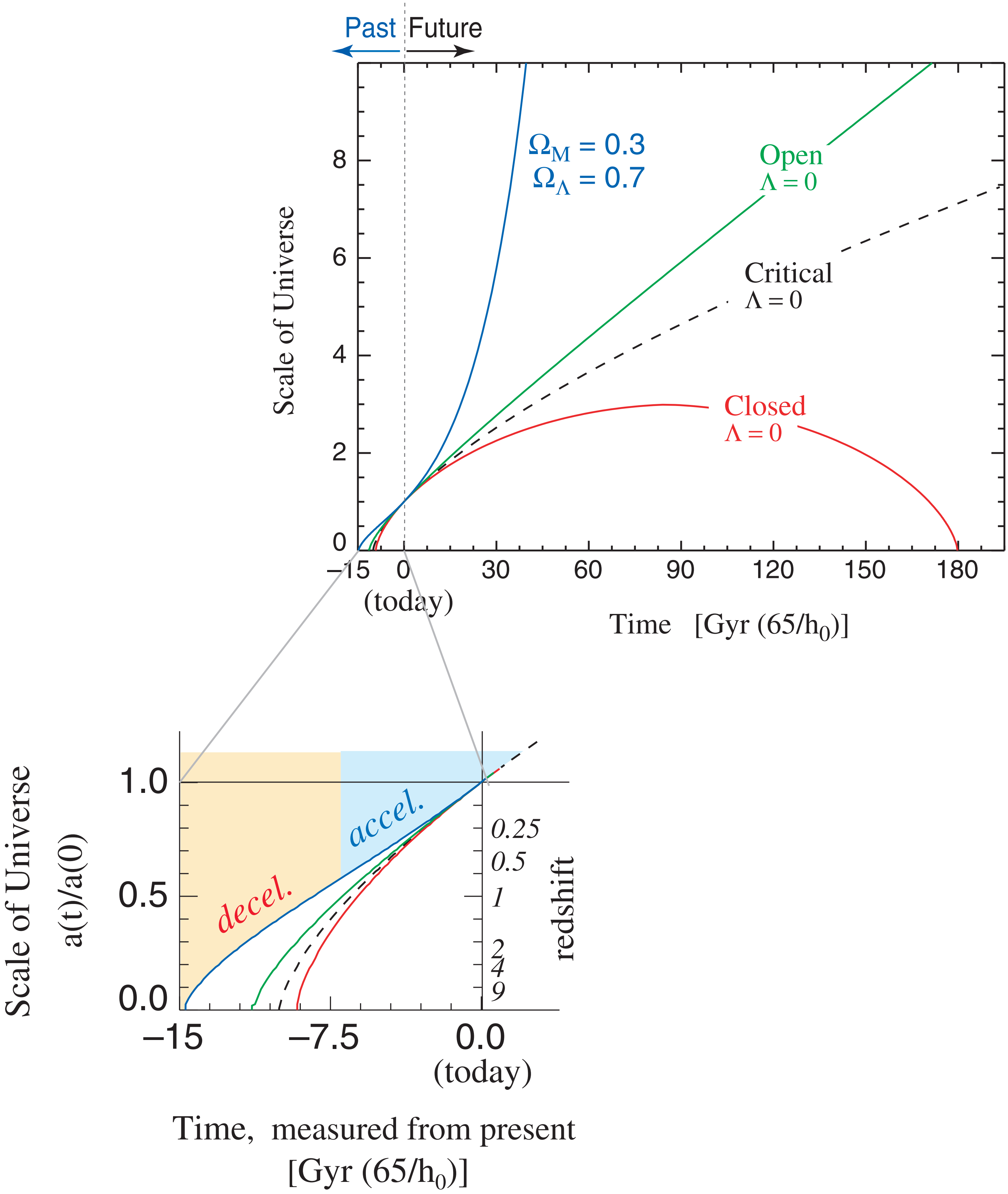
based on

Weller & Albrecht (2001)

CMB data before BOOMERANG and MAXIMA



Expansion History of the Universe



END