Measuring the Acceleration of the Cosmic Expansion Using Supernovae

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University of California, Berkeley
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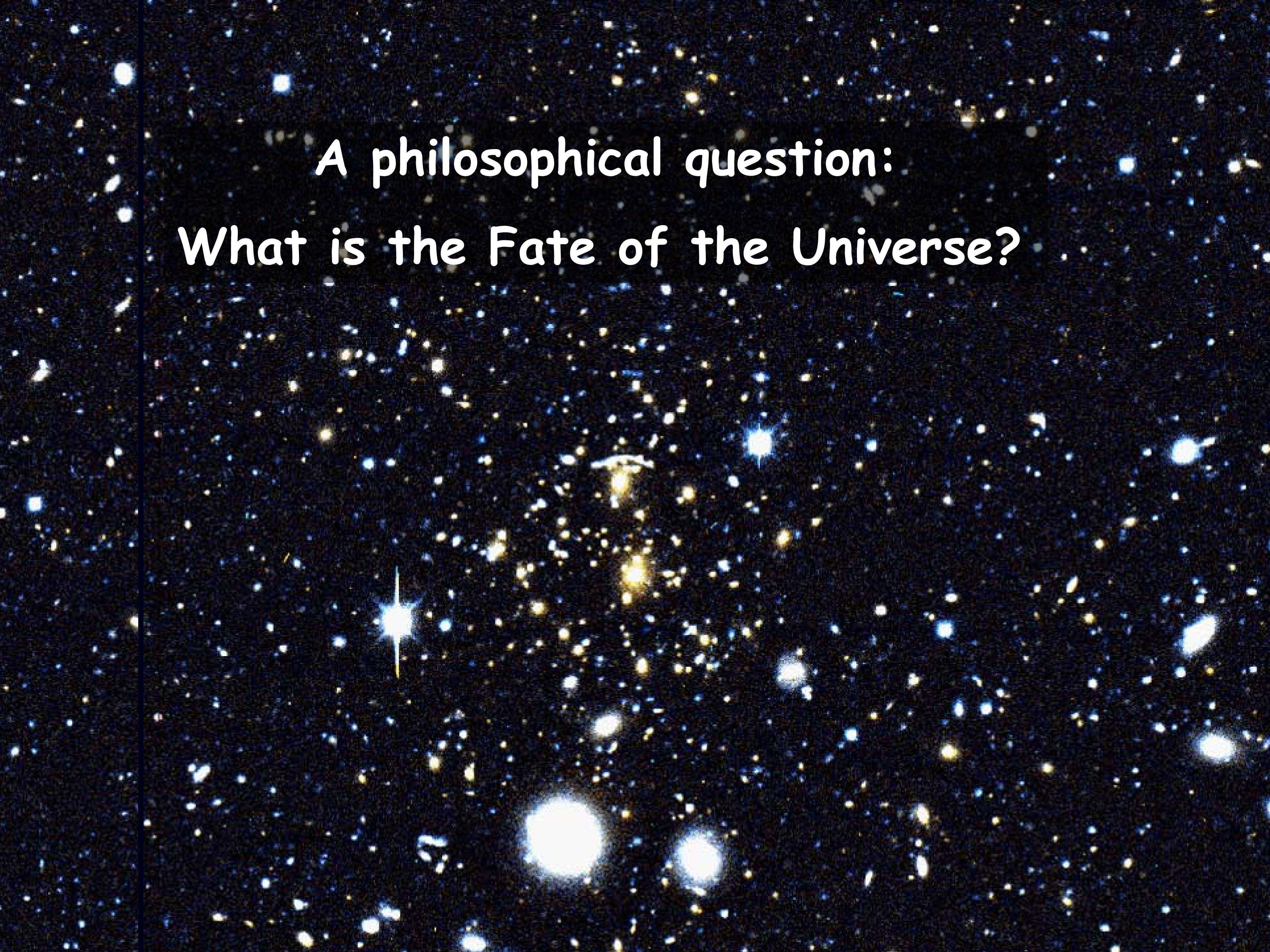
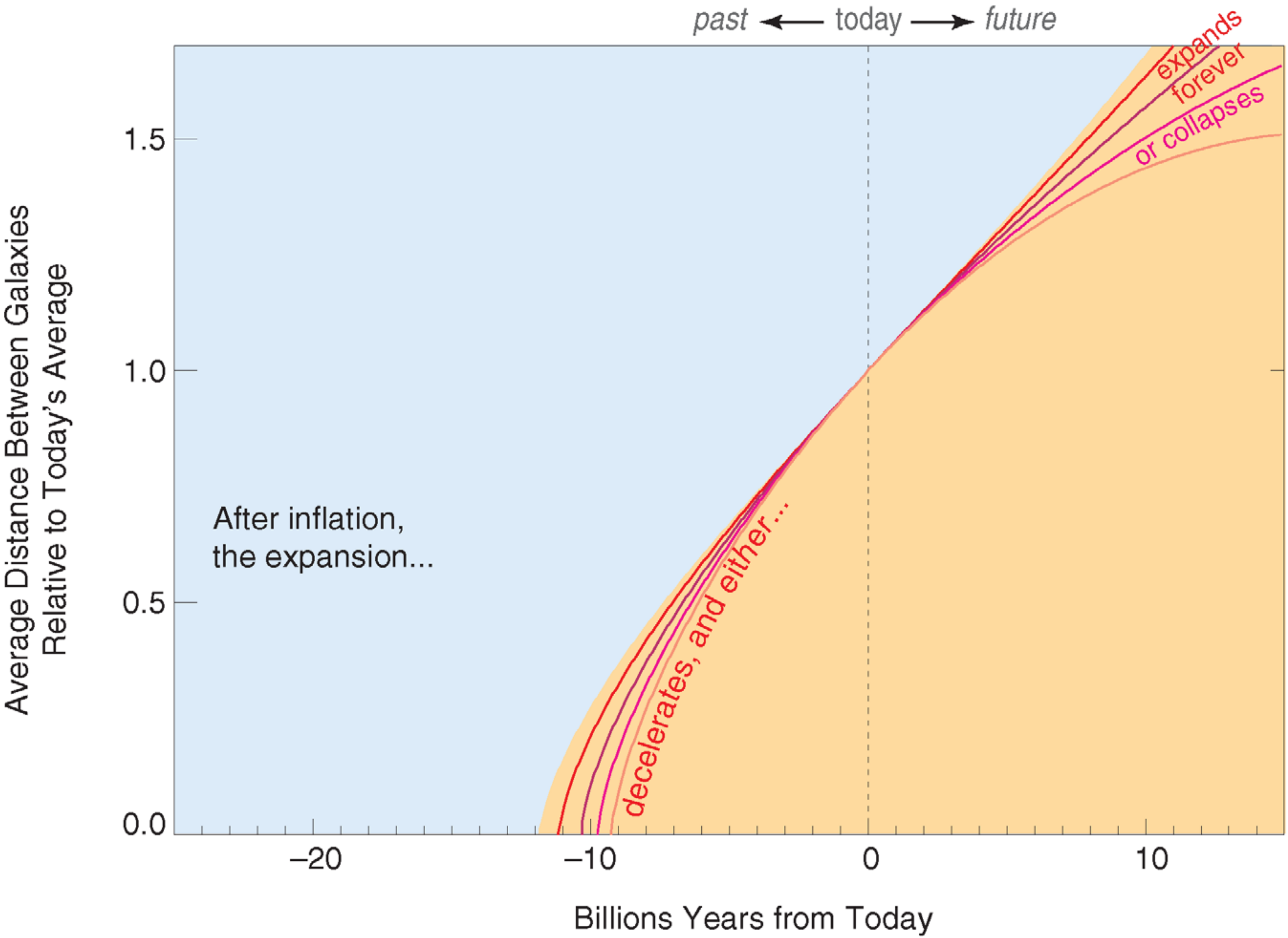
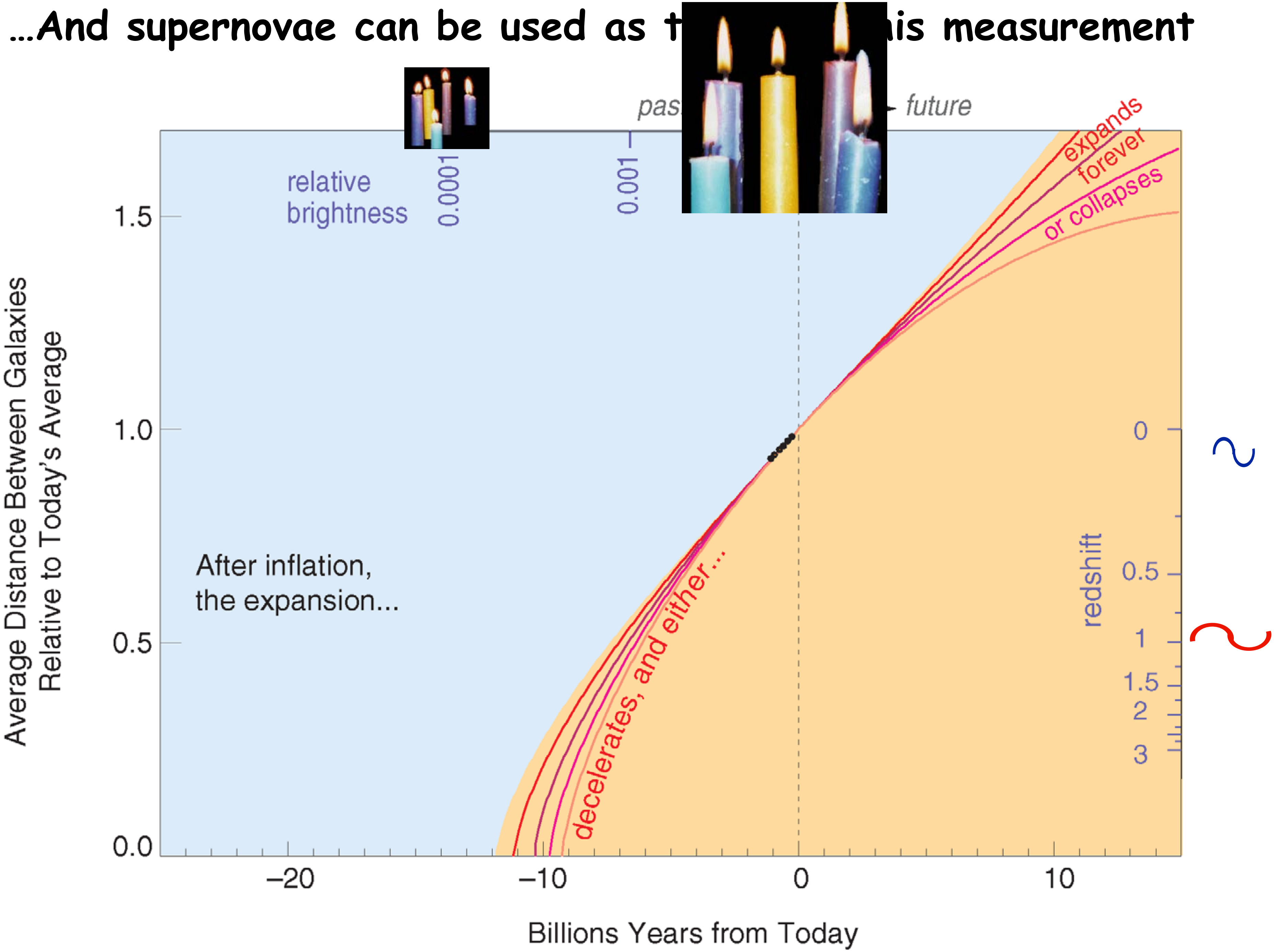
Nobel Lecture
Stockholm
December 2011


A philosophical question:
What is the Fate of the Universe?

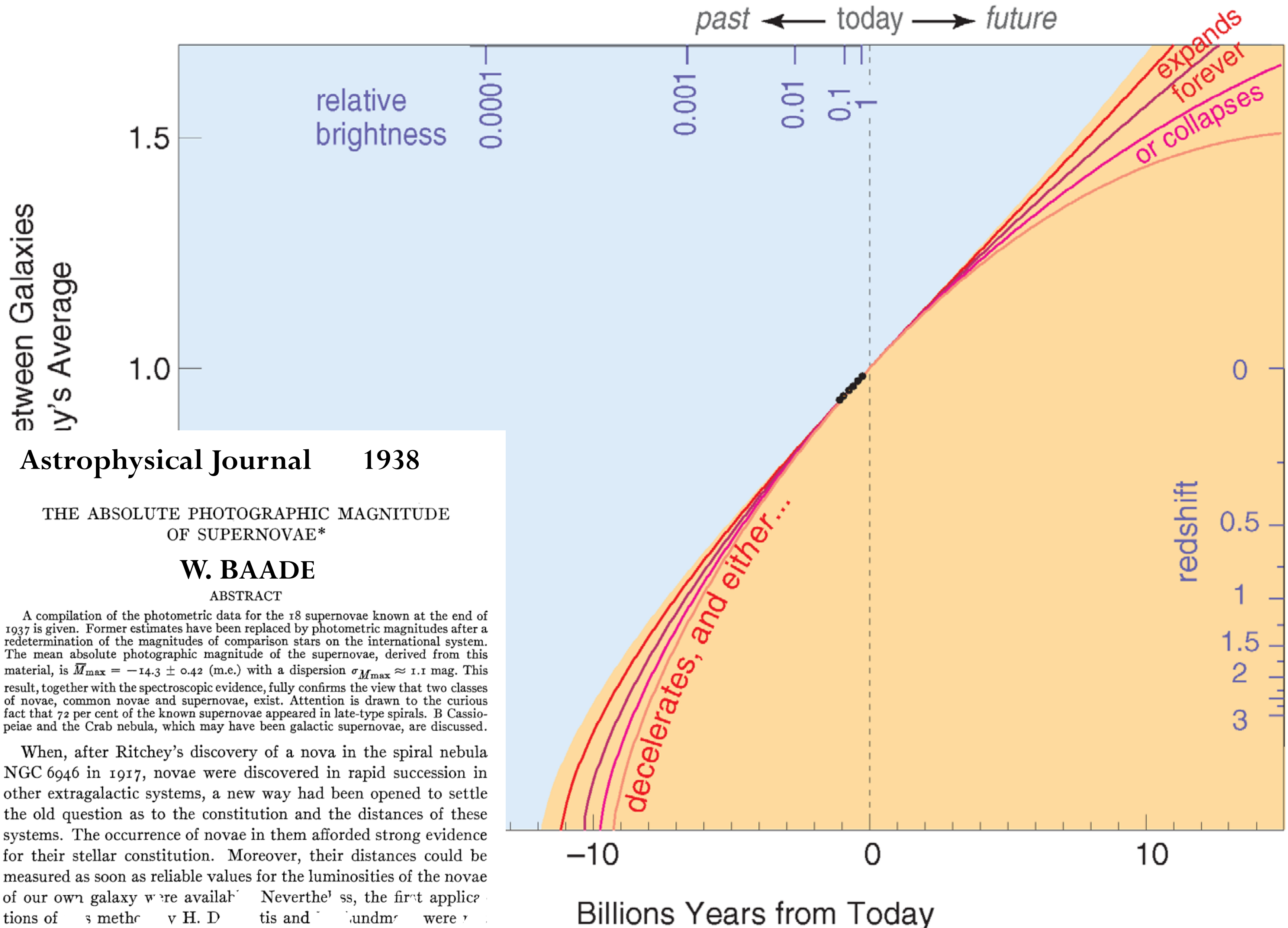
The Fate of the Universe can be determined from its history:



…And supernovae can be used as t … is measurement



Expansion History of the Universe



Astrophysical Journal 1938

THE ABSOLUTE PHOTOGRAPHIC MAGNITUDE OF SUPERNOVAE*

W. BAADE

ABSTRACT

A compilation of the photometric data for the 18 supernovae known at the end of 1937 is given. Former estimates have been replaced by photometric magnitudes after a redetermination of the magnitudes of comparison stars on the international system. The mean absolute photographic magnitude of the supernovae, derived from this material, is $\overline{M}_{max} = -14.3 \pm 0.42$ (m.e.) with a dispersion $\sigma_{M_{max}} \approx 1.1$ mag. This result, together with the spectroscopic evidence, fully confirms the view that two classes of novae, common novae and supernovae, exist. Attention is drawn to the curious fact that 72 per cent of the known supernovae appeared in late-type spirals. B Cassiopeiae and the Crab nebula, which may have been galactic supernovae, are discussed.

When, after Ritchey's discovery of a nova in the spiral nebula NGC 6946 in 1917, novae were discovered in rapid succession in other extragalactic systems, a new way had been opened to settle the old question as to the constitution and the distances of these systems. The occurrence of novae in them afforded strong evidence for their stellar constitution. Moreover, their distances could be measured as soon as reliable values for the luminosities of the novae of our own galaxy were availab[illegible] Neverthe[illegible]ss, the first applica[illegible] tions of [illegible] metho[illegible] H. D[illegible] tis and [illegible]undm[illegible] were [illegible] very s[illegible] tory [illegible] se t[illegible] data [illegible] rev[illegible]

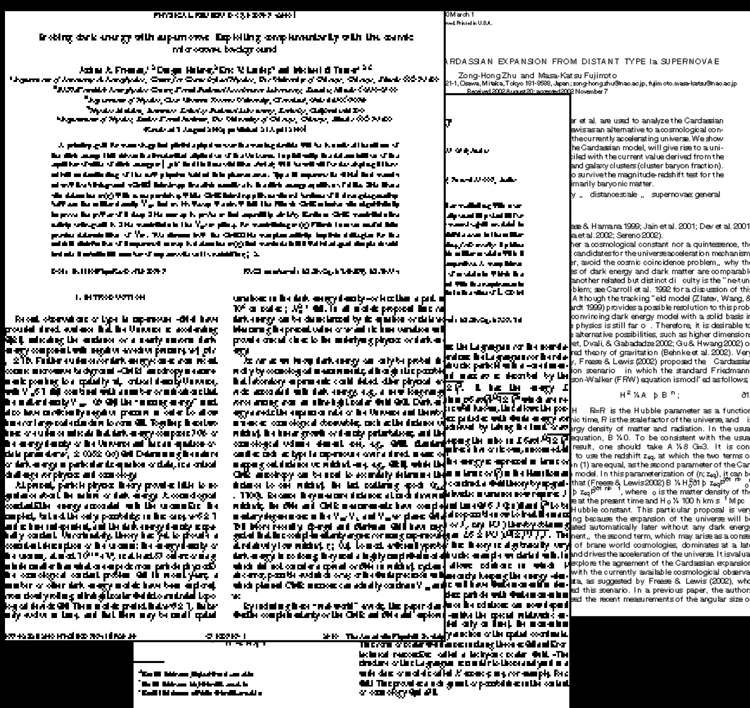
But supernovae were not quite good enough

"standard candles"

Mid - 1980's:

Two new developments

1 "Type Ia" supernovae:
a more standard candle



Panagia (1985)

Uomoto & Kirshner (1985)

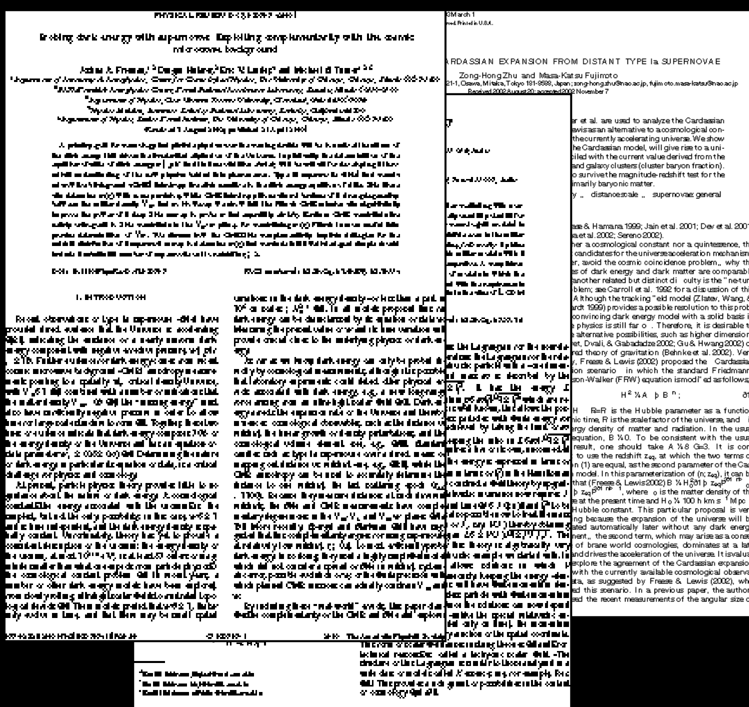
Wheeler & Levreault (1985)

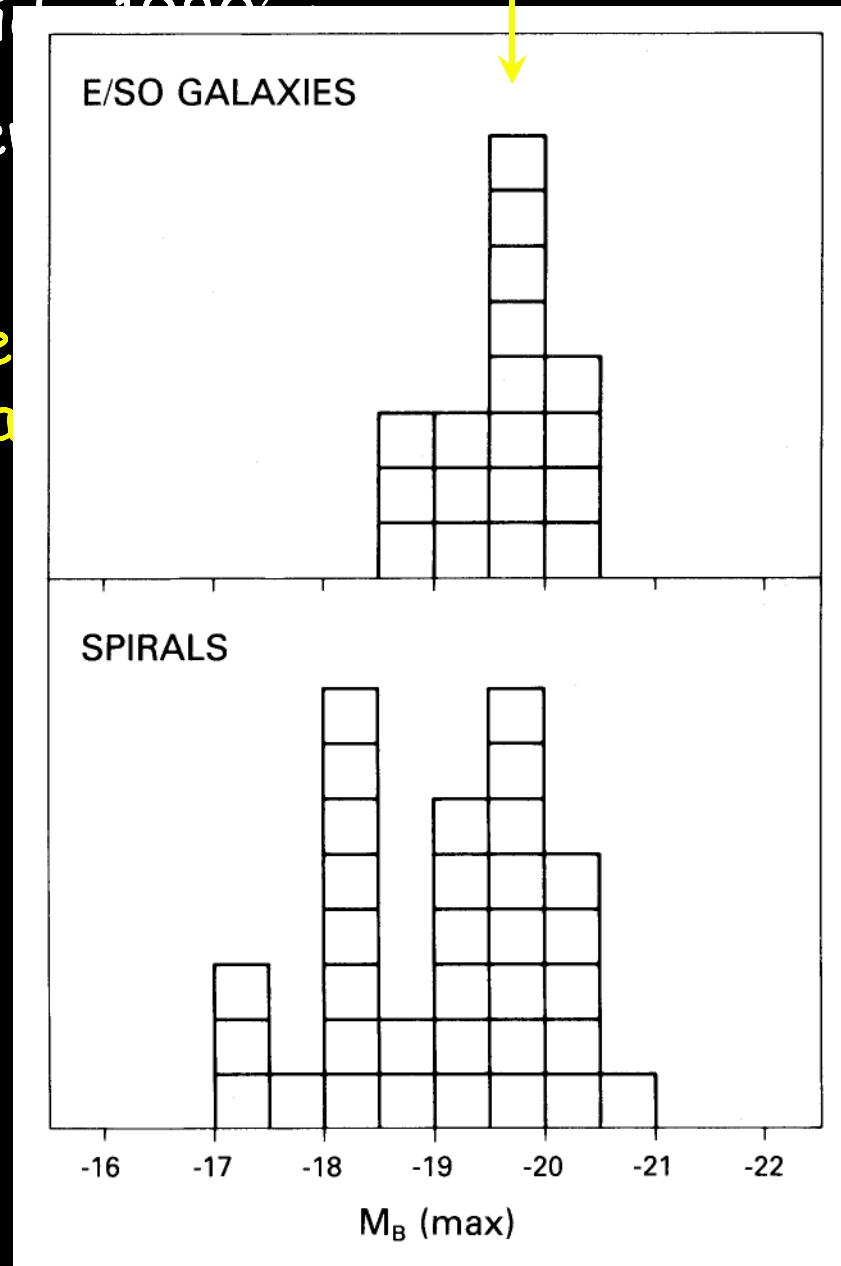
“Type Ia”?

Mi… 1990’…

Two ne…

1 “Type Ia” supe…
a more standa…





Mid - 1980's:

Two new developments

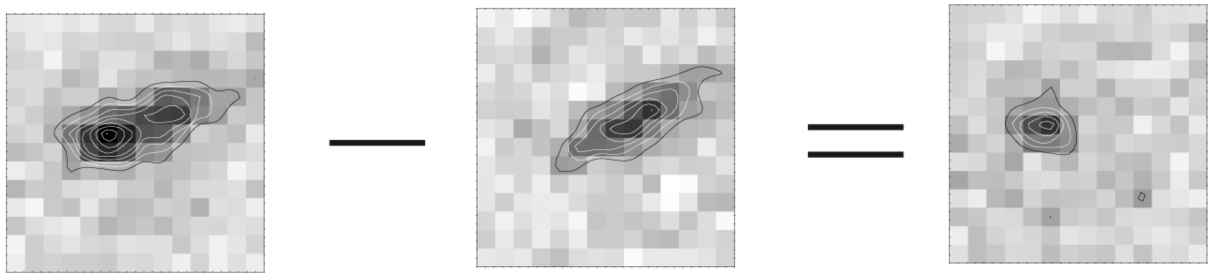
2 CCD detectors

& **computers** fast enough for image analysis

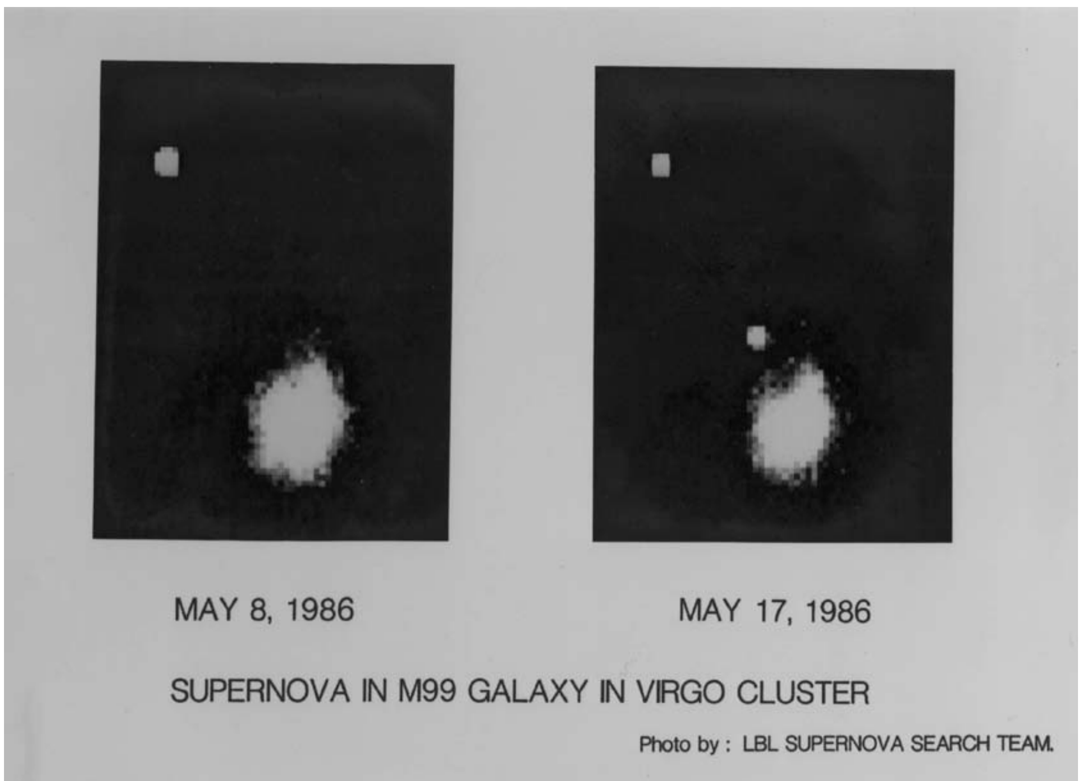
2

CCD detectors

& **computers** fast enough for image analysis



SN +Galaxy — Galaxy = SN



Luis Alvarez suggests to Rich Muller that it is time to re-do Stirling Colgate's robotic SN search

R. Muller:

Berkeley Automated Supernova Search

with C. Pennypacker and S.P.

Why is the supernova measurement *not* easy?

1. Can they be found **far enough** -- and **enough of them** -- for cosmology?
   Can they be found **early enough** to measure brightness over peak?

2. Can they be identified as Type Ia with spectra, despite how faint they will be?
   Can their brightness be compared with nearby ones, despite greatly "redshifted" spectra?

3. Are the supernovae standard enough?
   And how can one eliminate possible dust from diminishing their brightness?

4. Couldn't the supernovae evolve over 5 billion years?

Problems

with Type Ia Su

NB: Norgaard-Nielsen et al. searched intensively for over 2 years, and found just 1 Type Ia supernova several weeks past its peak.

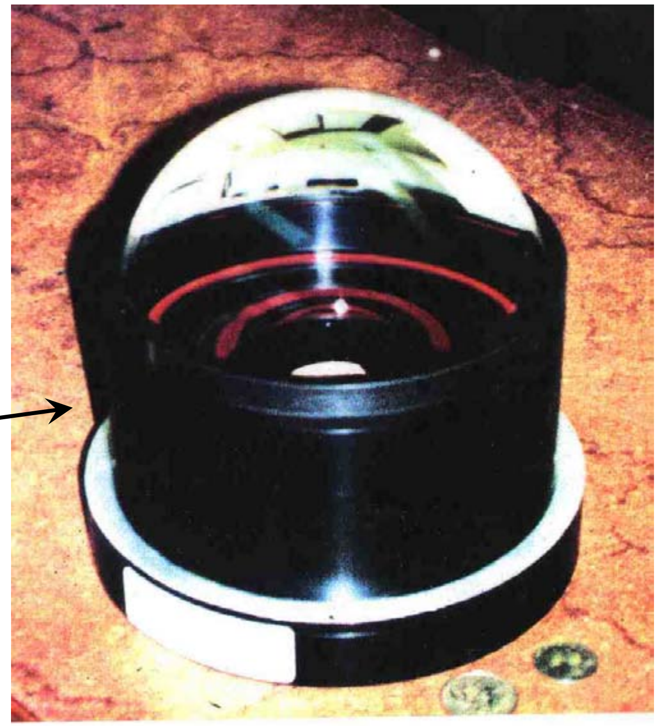
Rare

Random — can't schedule … or plan discoveries at new moon

Rapid — difficult to catch on the rise

Pennypacker & Perlmutter 1987 proposal:

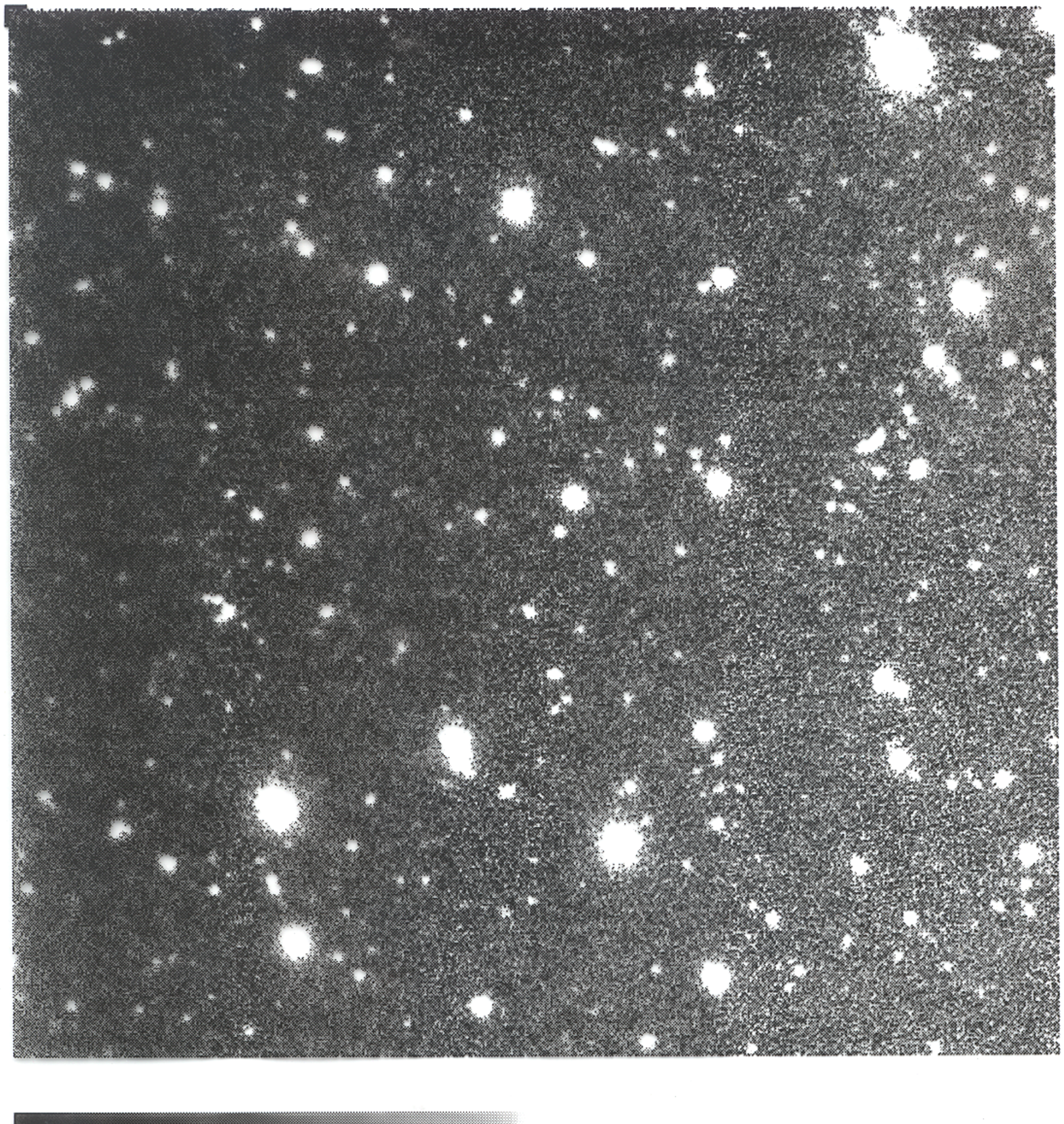
A novel F/1 wide-field CCD camera
for the Anglo-Australian 4-m telescope (AAT)



...A big enough telescope with a wide enough field to search for $z > 0.3$ Type Ia supernovae in 100s of galaxies with each image.

f855 7 01

Pennypacker & Perlmutter 1988 wide-field CCD camera at AAT



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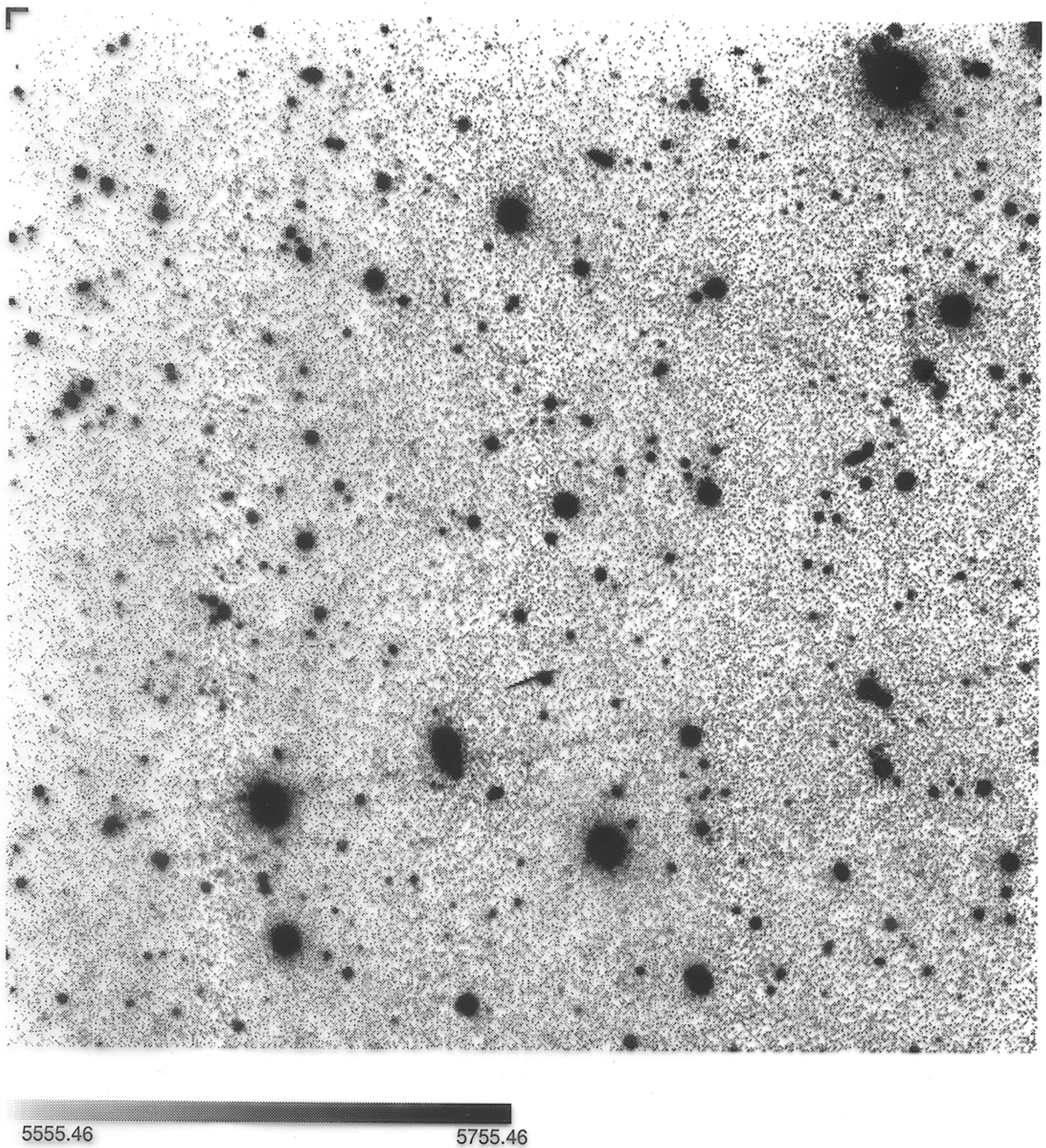

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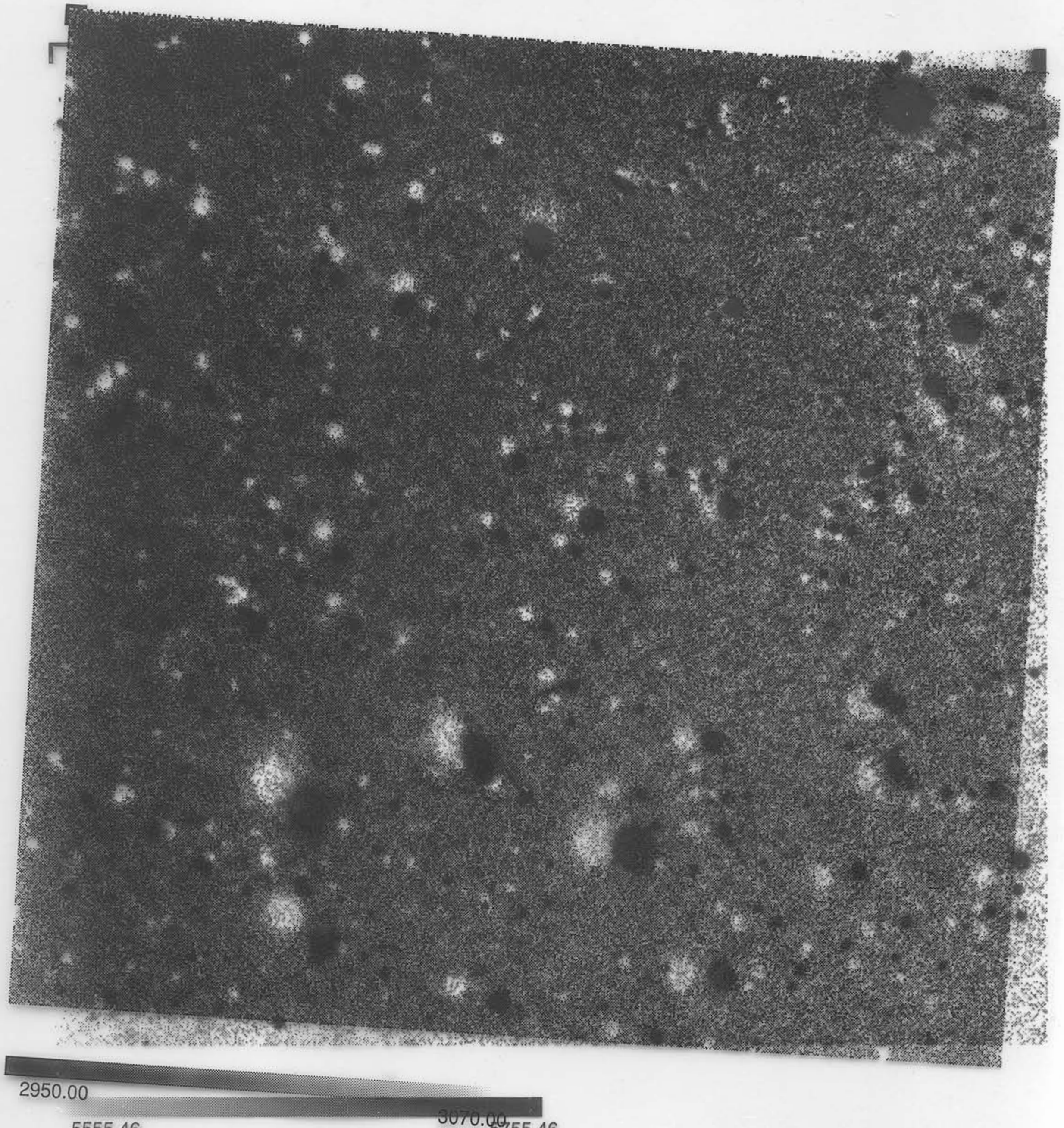
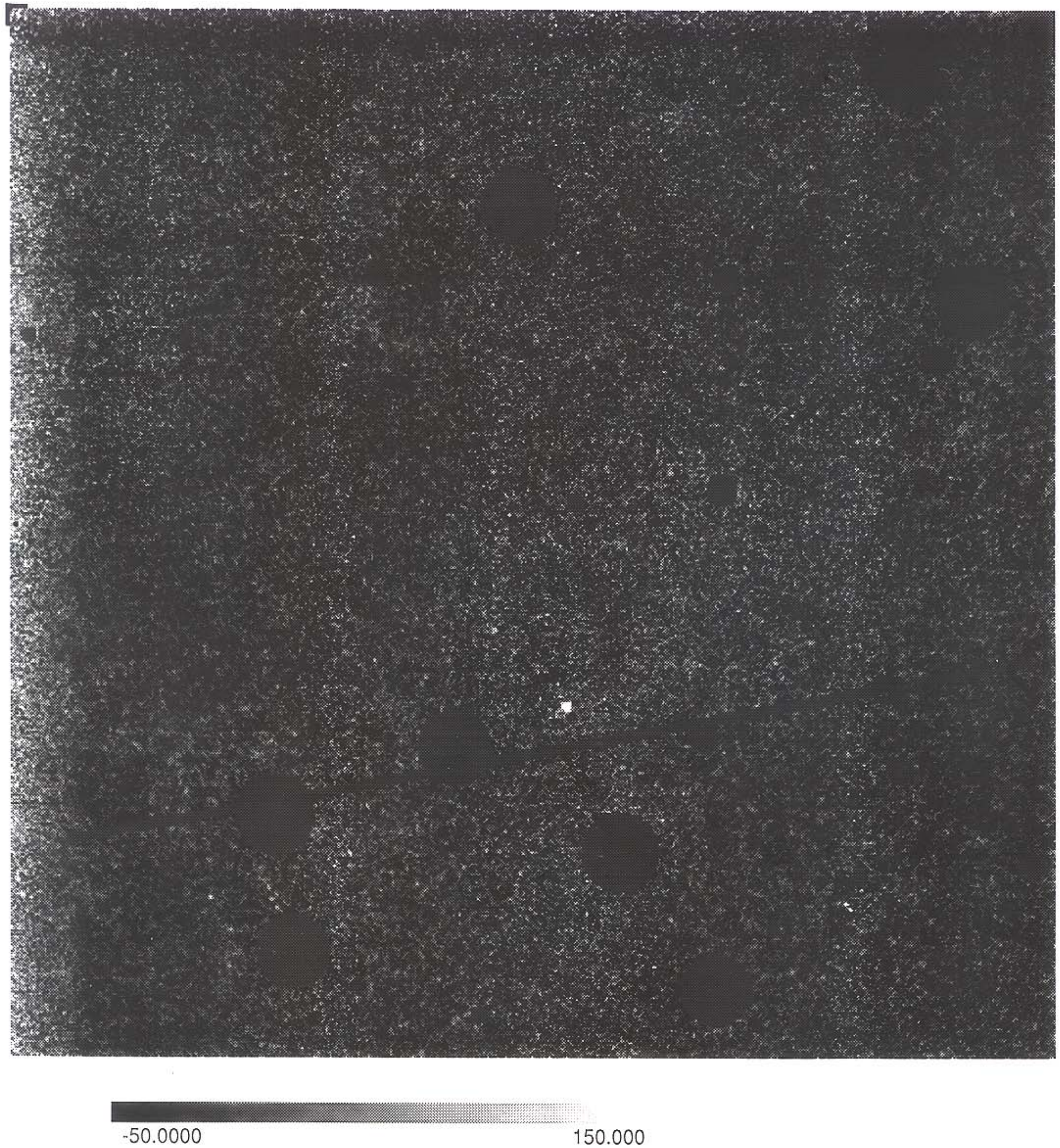


F855 7 01
1855 7 01

January 1990 — November 1989

F855 7 1990:01:23



Problems

with Type Ia Supernovae as a tool for cosmology

Rare ~1 / 500 years / galaxy

Random can't schedule telescope time or plan discoveries at new moon

Rapid difficult to catch on the rise

Hamuy et al. (*Astronomical Journal* 1993),
describing the Calan/Tololo Search for supernovae at much lower redshifts:

"Unfortunately, the appearance of a SN is not predictable. As a consequence of this we cannot schedule the followup observations a priori, and we generally have to rely on someone else's telescope time. This makes the execution of this project somewhat difficult."

Random — can't schedule telescope time or plan discoveries at new moon

Rapid — difficult to catch on the rise

Search Strategy

Perlmutter *et al* (1994)

time

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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

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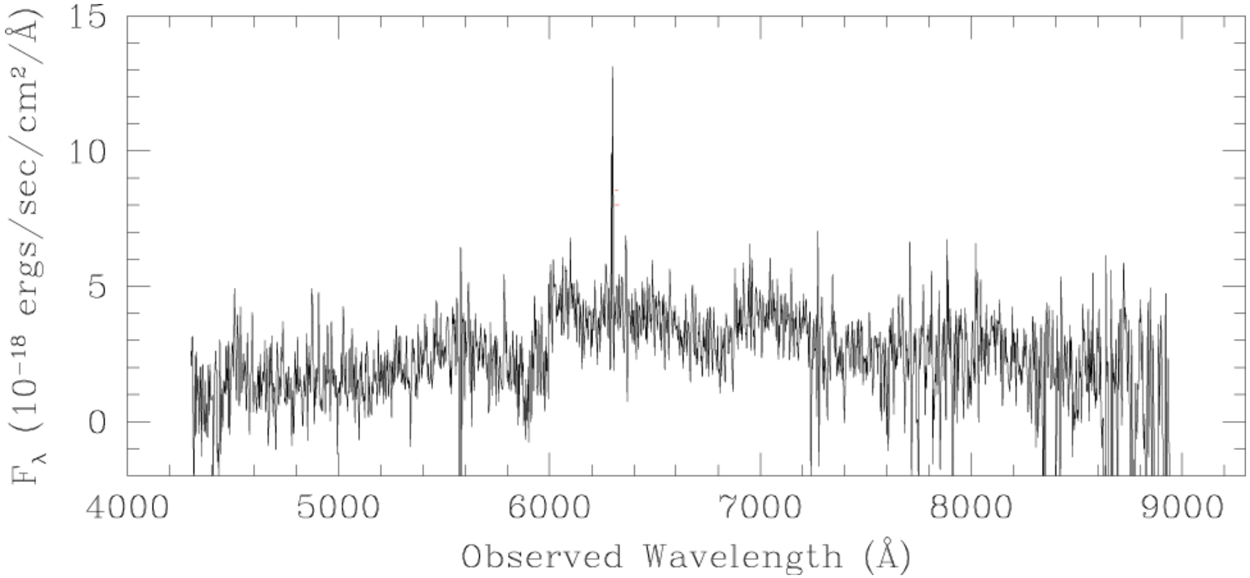
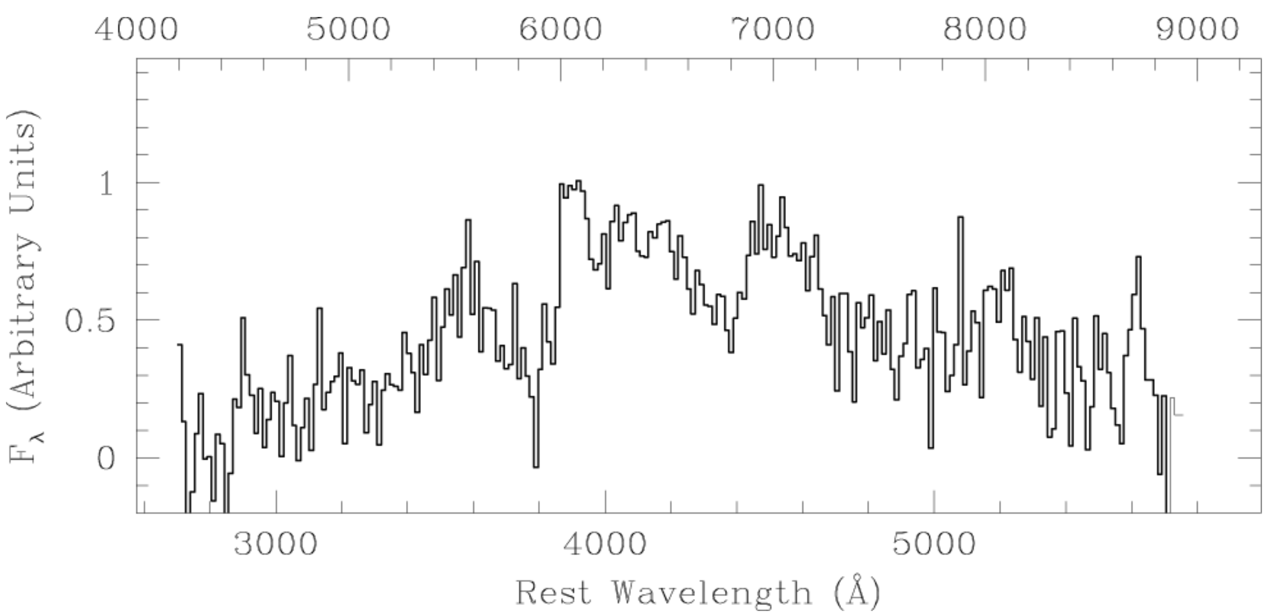
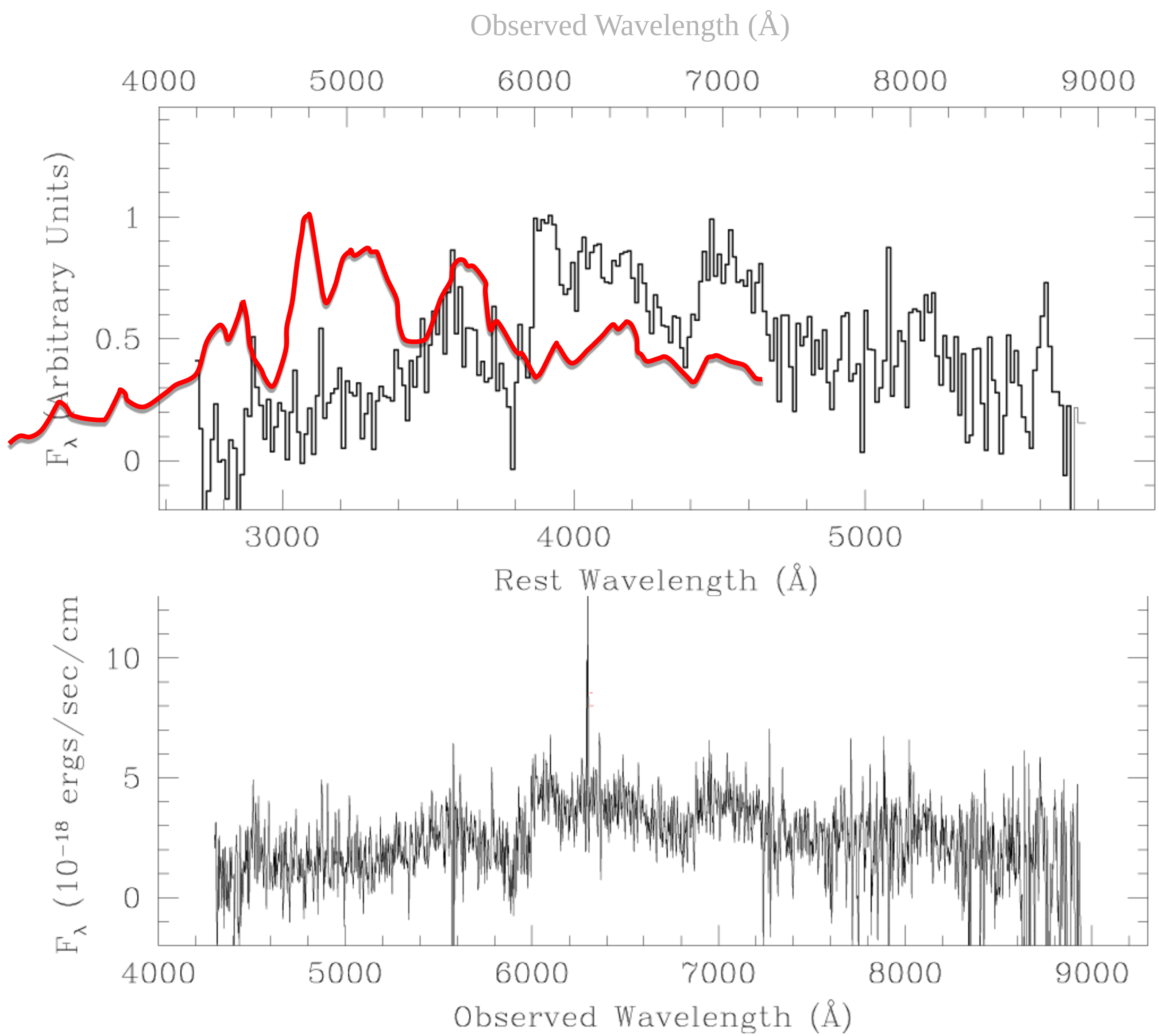
And, in fact, the spectra do look like noise

…until you know what you are looking for.

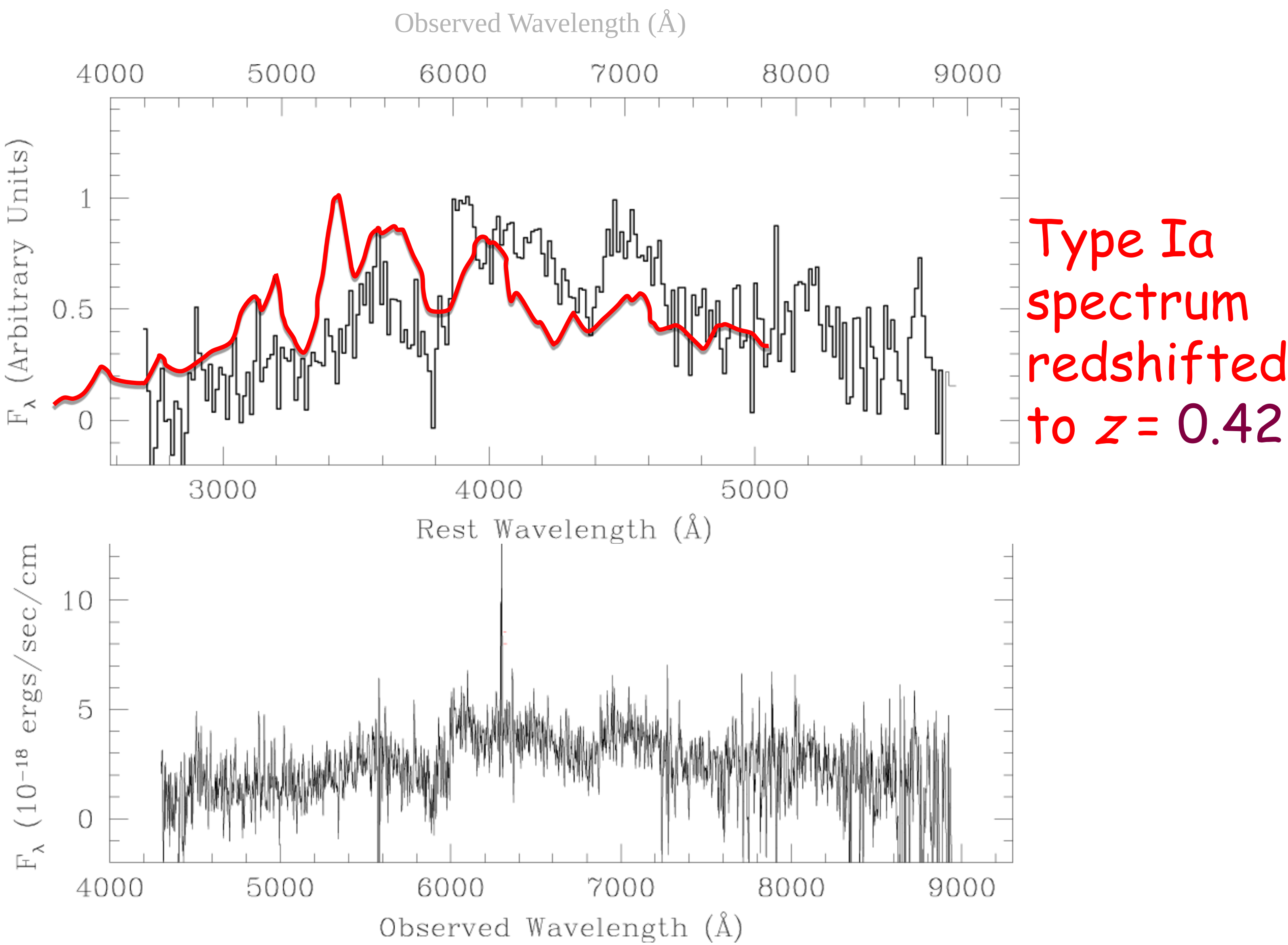


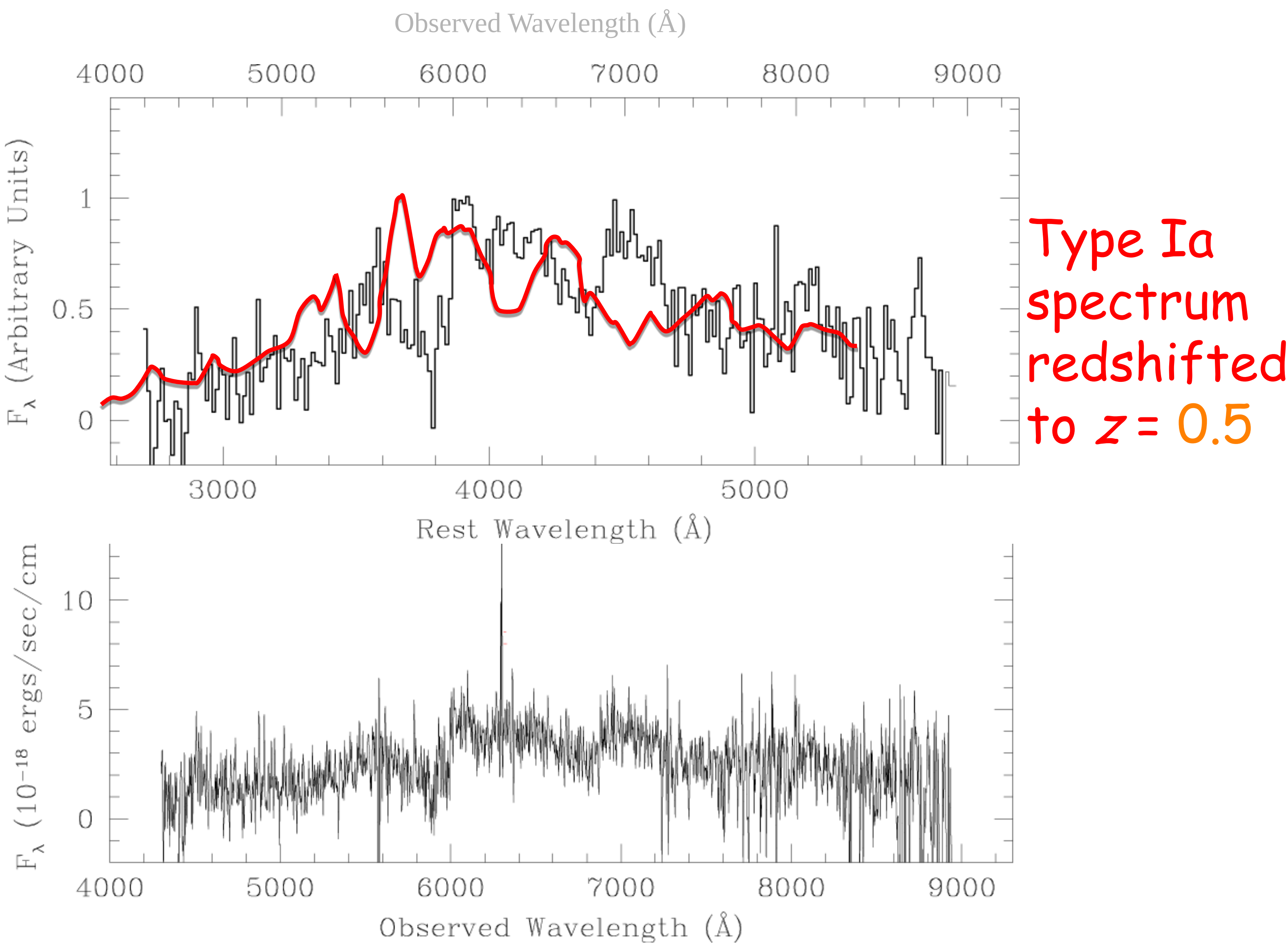
Observed Wavelength (Å)



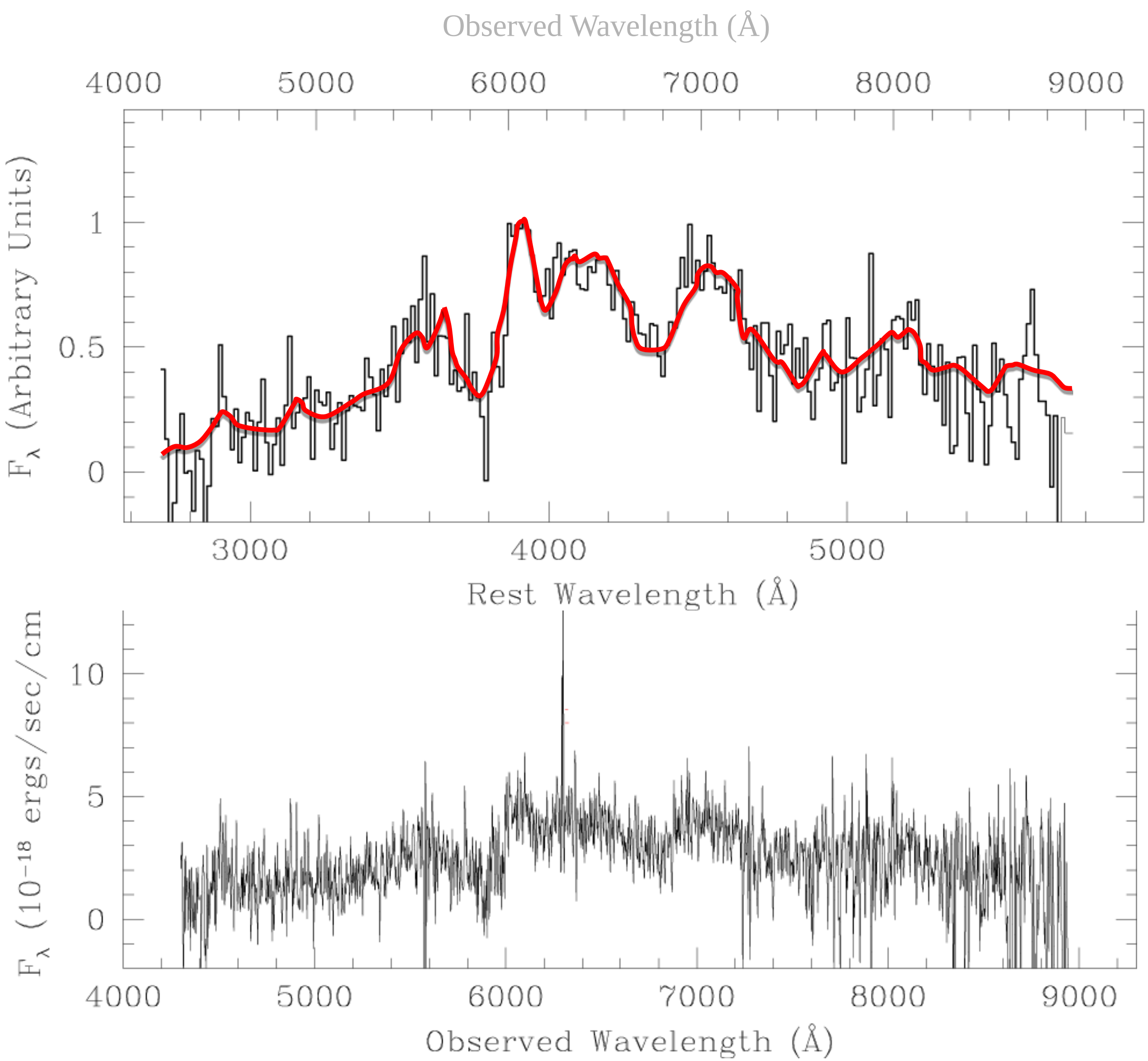


Type Ia spectrum redshifted to $z = 0.3$

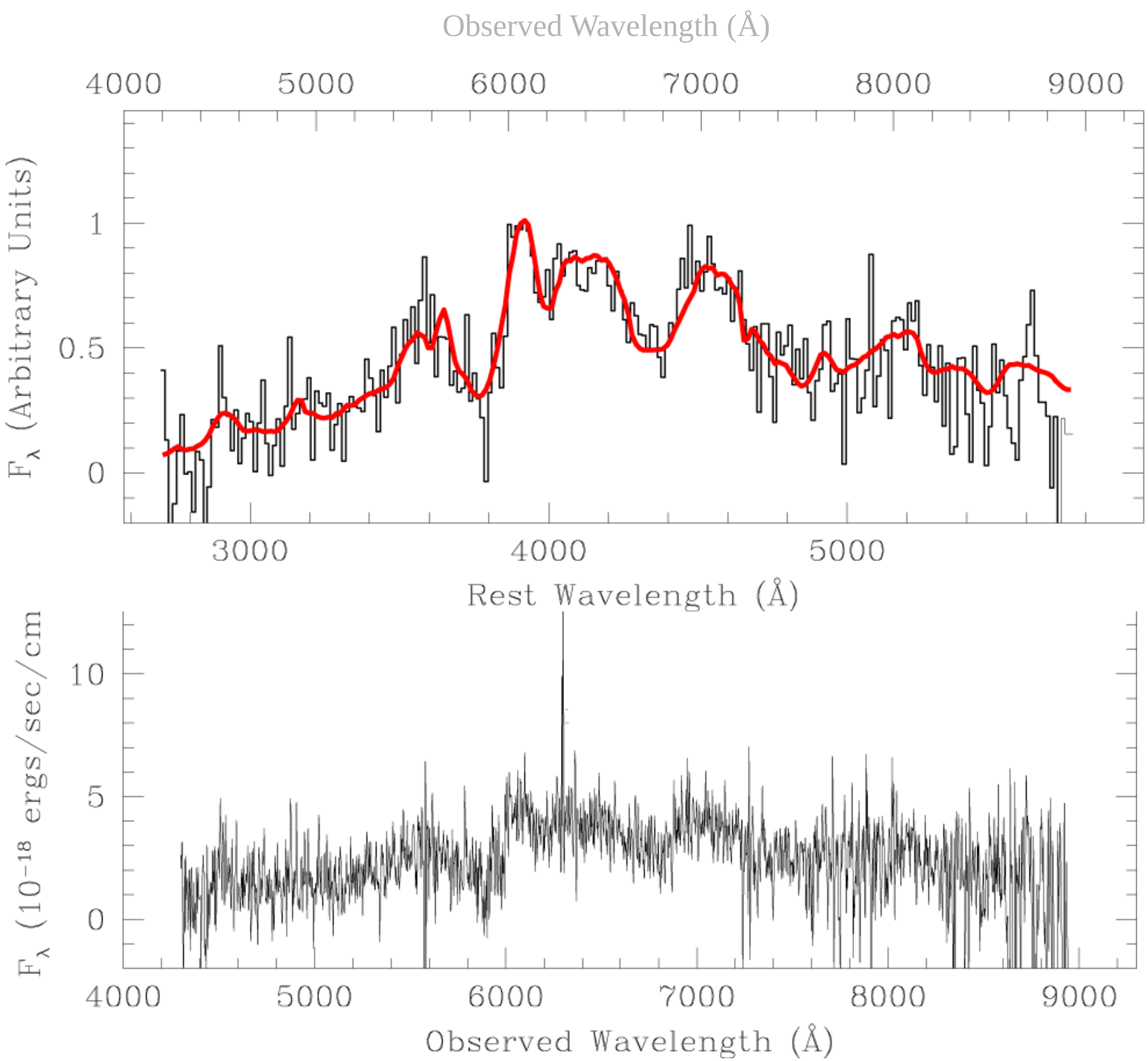

Observed Wavelength (Å)
4000
5000
6000
7000
8000
9000
1
0.5
0
F λ (Arbitrary Units)
3000
4000
5000
Rest Wavelength (Å)
Type Ia
spectrum
redshifted
to z = 0.42
10
5
0
F λ (10−18 ergs/sec/cm
4000
5000
6000
7000
8000
9000
Observed Wavelength (Å)



Observed Wavelength (Å)
4000
5000
6000
7000
8000
9000
1
0.5
0
F_λ (Arbitrary Units)
3000
4000
5000
Rest Wavelength (Å)
Type Ia spectrum redshifted to z = 0.5
10
5
0
F_λ (10^{-18} ergs/sec/cm
4000
5000
6000
7000
8000
9000
Observed Wavelength (Å)



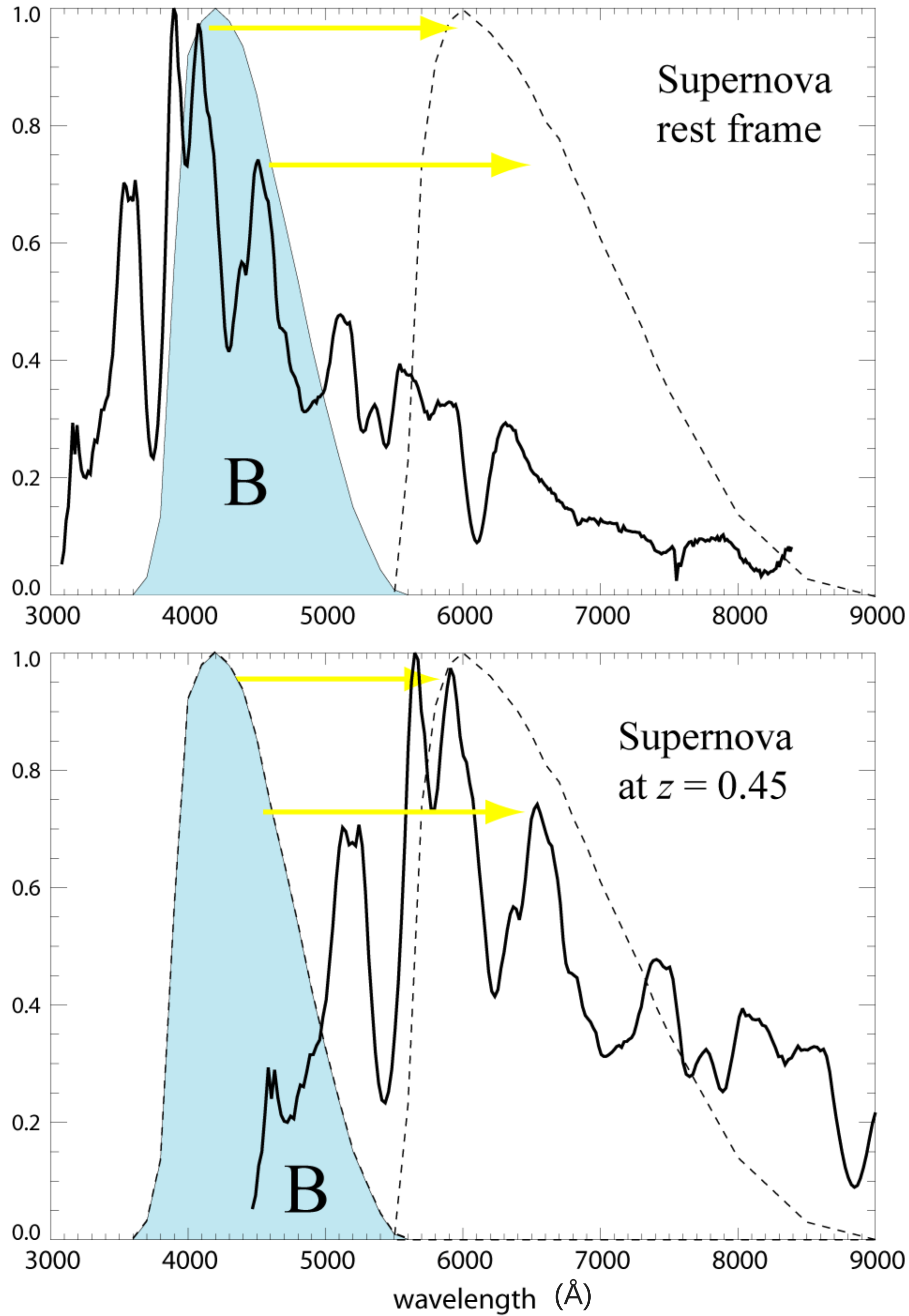
Type Ia spectrum redshifted to $z = 0.55$



Type Ia spectrum redshifted to $z = 0.55$

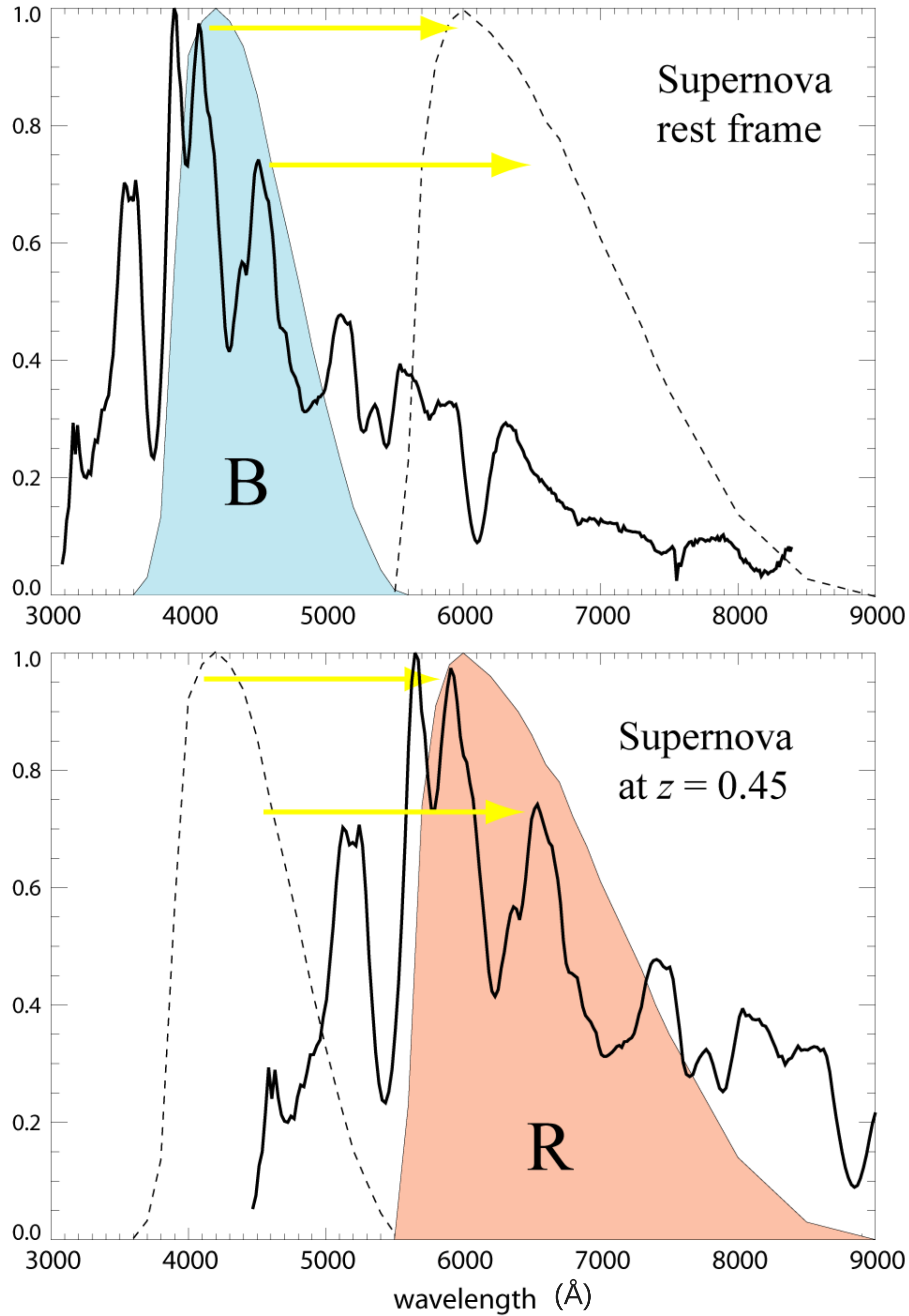
Standard
K corrections

Leibundgut, A&A (1990)



“Cross-Filter” K corrections

Kim, Goobar, & Perlmutter (1995)



Why is the supernova measurement *not* easy?

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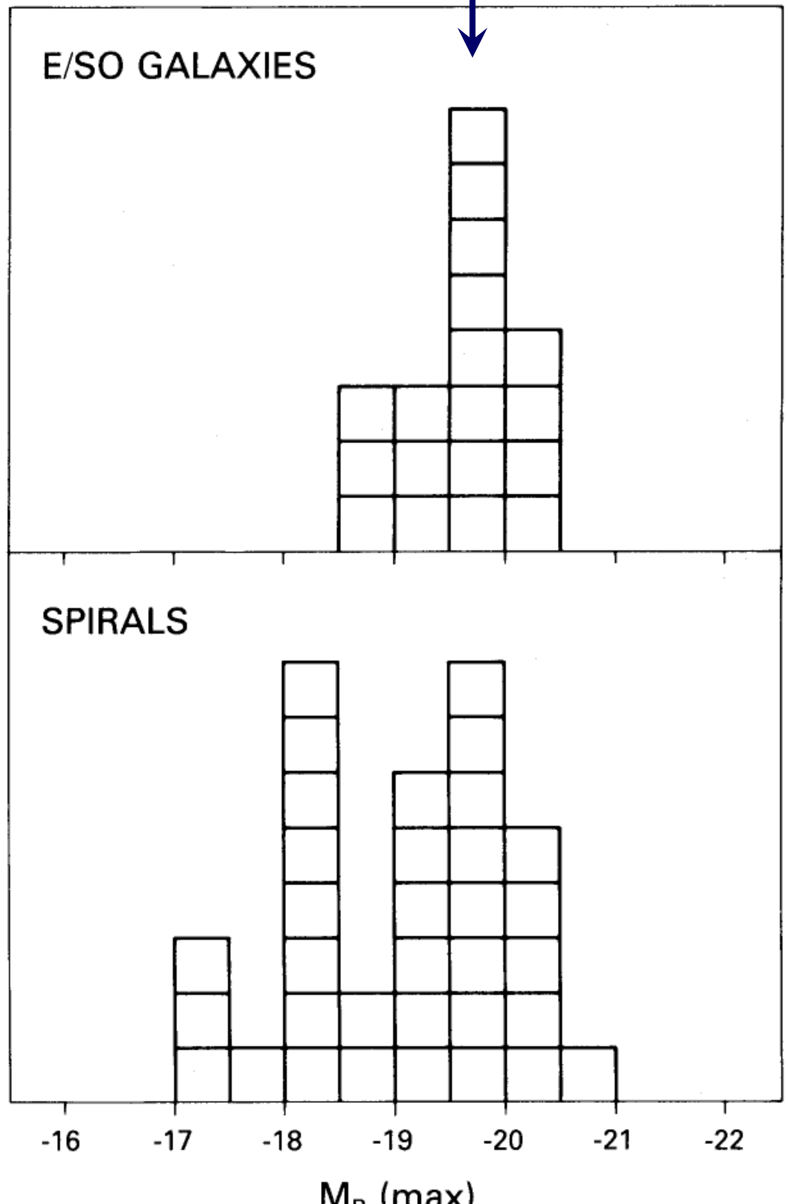
“Type Ia”?

Panagia (1985)



The Astrophysical Journal, 585:52–56, 2003 March 1

CONSTRAINTS ON CARDASSIAN EXPANSION FROM DISTANT TYPE Ia SUPERNOVAE

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ABSTRACT

The distant Type Ia supernovae data compiled by Perlmutter et al. are used to analyze the Cardassian expansion scenario, which was recently proposed by Freese & Lewis as an alternative to a cosmological constant (or more generally a dark energy component) in explaining the currently accelerating universe. We show that the allowed intervals for n and z_{eq}, the two parameters of the Cardassian model, will give rise to a universe with a very low matter density, which can hardly be reconciled with the current value derived from the measurements of the cosmic microwave background anisotropy and galaxy clusters (cluster baryon fraction). As a result, this Cardassian expansion proposal does not seem to survive the magnitude-redshift test for the present Type Ia supernovae data, unless the universe contains primarily baryonic matter.

Subject headings: cosmological parameters — cosmology: theory — distance scale — supernovae: general

1. INTRODUCTION

A major development in modern cosmology is the discovery of the acceleration of the universe through observations of distant Type Ia supernovae (Perlmutter et al. 1998, 1999; Riess et al. 1998, 2001; Leibundgut 2001). It is well known that all known types of matter with positive pressure generate attractive forces and decelerate the expansion of the universe—conventionally, a deceleration factor is always used to describe the status of the universe's expansion (Sandage 1988). Given this, the discovery from the high-redshift Type Ia supernovae indicates the existence of a new component with fairly negative pressure, which is now generally called dark energy, such as a cosmological constant (Weinberg 1989; Carroll, Press, & Turner 1992; Krauss & Turner 1995; Ostriker & Steinhardt 1995) or an evolving scalar field (referred to by some as quintessence: Ratra & Peebles 1988; Wetterich 1988; Frieman et al. 1995; Coble, Dodelson, & Frieman 1997; Caldwell, Dave, & Steinhardt 1998; Gong 2002). While current measurements of the cosmic microwave background anisotropies favor a spatially flat universe with cold dark matter (de Bernardis et al. 2000; Lange et al. 2001), both the deuterium abundance measured in four high-redshift hydrogen clouds seen in absorption against distant quasars (Burles & Tytler 1998a, 1998b) (combined with the baryon fraction in galaxy clusters from X-ray data: see White et al. 1993 for the method) and the large-scale structure in the distribution of galaxies (Bahcall 2000; Peacock et al. 2001) have made a strong case for a low-density universe (for a recent summary, see Turner 2002a). It seems that all these observations can be concordantly explained by the hypothesis that there exists, in addition to cold dark matter, a dark energy component with negative pressure in our universe (Turner 2002b). The existence of this component has also been independently indicated by other observations such as the angular size–redshift relations for compact radio sources (Guivits, Kellermann, & Frey 1999; Vishwakarma 2001; Lima & Alcaniz 2002; Chen & Ratra 2003) and FR IIb radio galaxies (Guerra, Daly, & Wan 2000; Daly & Guerra 2002; Podariu et al. 2003), the age estimates of old high-redshift galaxies (Dunlop et al. 1996; Krauss 1997; Alcaniz & Lima 1999), and gravitational lensing (Kochaneck 1996; Chiba & Yoshii 1999; Futamase & Hamana 1999; Jain et al. 2001; Dev et al. 2001; Ohyama et al. 2002; Sereno 2002).

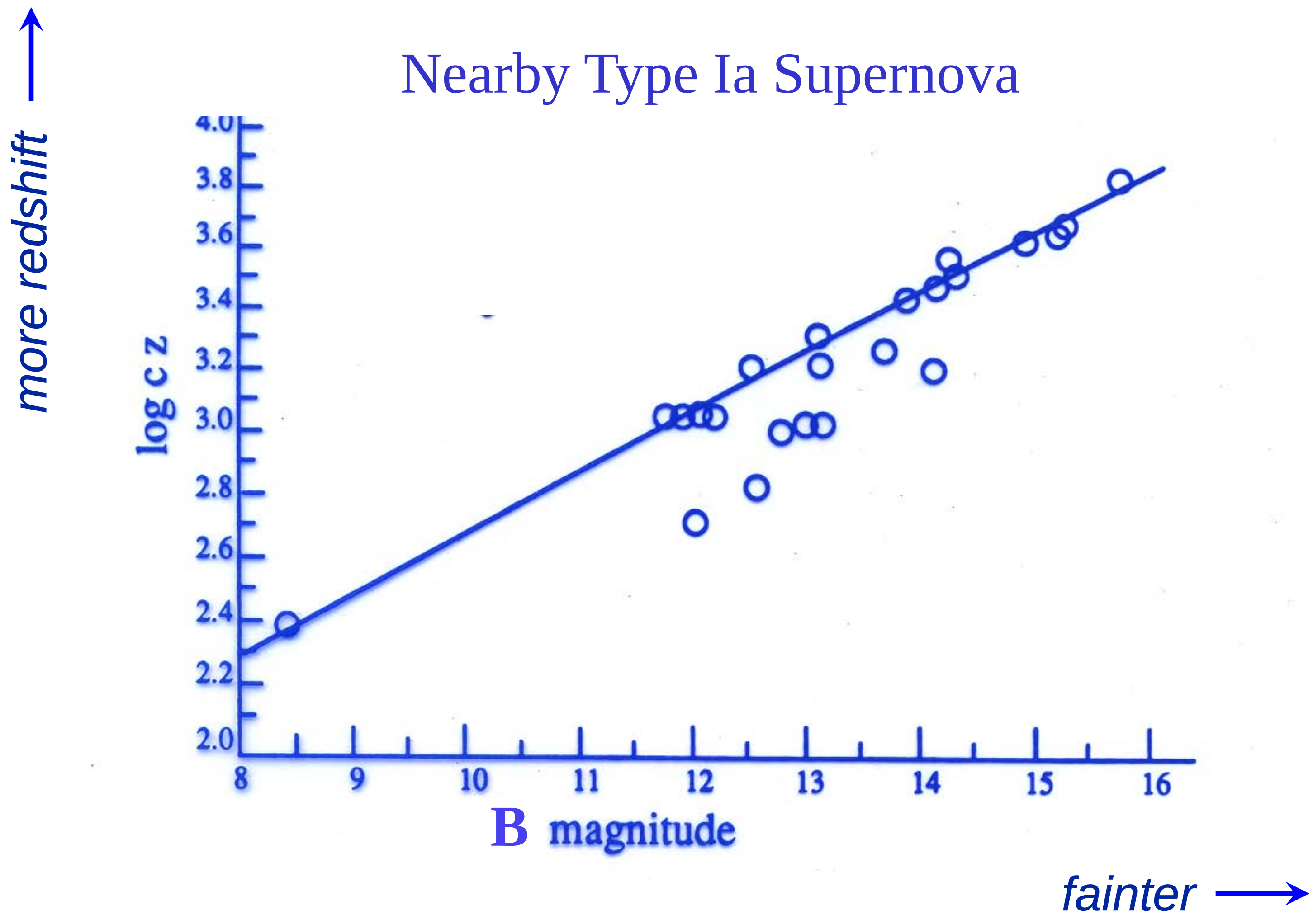
Neither a cosmological constant nor a quintessence, the present candidates for the universe acceleration mechanism, however, avoid the cosmic coincidence problem—why the densities of dark energy and dark matter are comparable today (another related but distinct difficulty is the "fine-tuning problem; see Carroll et al. 1992 for a discussion of this point). Although the tracking field model (Zlatev, Wang, & Steinhardt 1999) provides a possible resolution to this problem, a convincing dark energy model with a solid basis in particle physics is still far off. Therefore, it is desirable to explore alternative possibilities, such as higher dimensions (Deffayet, Dvali, & Gabadadze 2002; Gu & Hwang 2002) or an altered theory of gravitation (Behnke et al. 2002). Very recently, Freese & Lewis (2002) proposed the "Cardassian expansion scenario" in which the standard Friedmann-Robertson-Walker (FRW) equation is modified as follows:

$$H^2 = A\rho + B\rho^n ; \qquad (1)$$

where $H \equiv \dot{R}/R$ is the Hubble parameter as a function of cosmic time, R is the scale factor of the universe, and ρ is the energy density of matter and radiation. In the usual FRW equation, $B = 0$. To be consistent with the usual FRW result, one should take $A = 8\pi G/3$. It is convenient to use the redshift z_{eq}, at which the two terms of equation (1) are equal, as the second parameter of the Cardassian model. In this parameterization of $(n; z_{eq})$, it can be shown that (Freese & Lewis 2002) $B = H_0^2 (1 + z_{eq})^{3(1-n)} \Omega_0^{1-n} [2 + (1 + z_{eq})^{3(1-n)}]^{-1}$, where Ω_0 is the matter density of the universe at the present time and $H_0 = 100\ h$ km s^{-1} Mpc^{-1} is the Hubble constant. This particular proposal is very intriguing because the expansion of the universe will be accelerated automatically later without any dark energy component—the second term, which may arise as a consequence of brane world cosmologies, dominates at a late epoch and drives the acceleration of the universe. It is valuable to explore the agreement of the Cardassian expansion model with the currently available cosmological observation data, as suggested by Freese & Lewis (2002), who proposed this scenario. In a previous paper, the authors have used the recent measurements of the angular size of

Leibundgut & Tammann
A&A (1990)

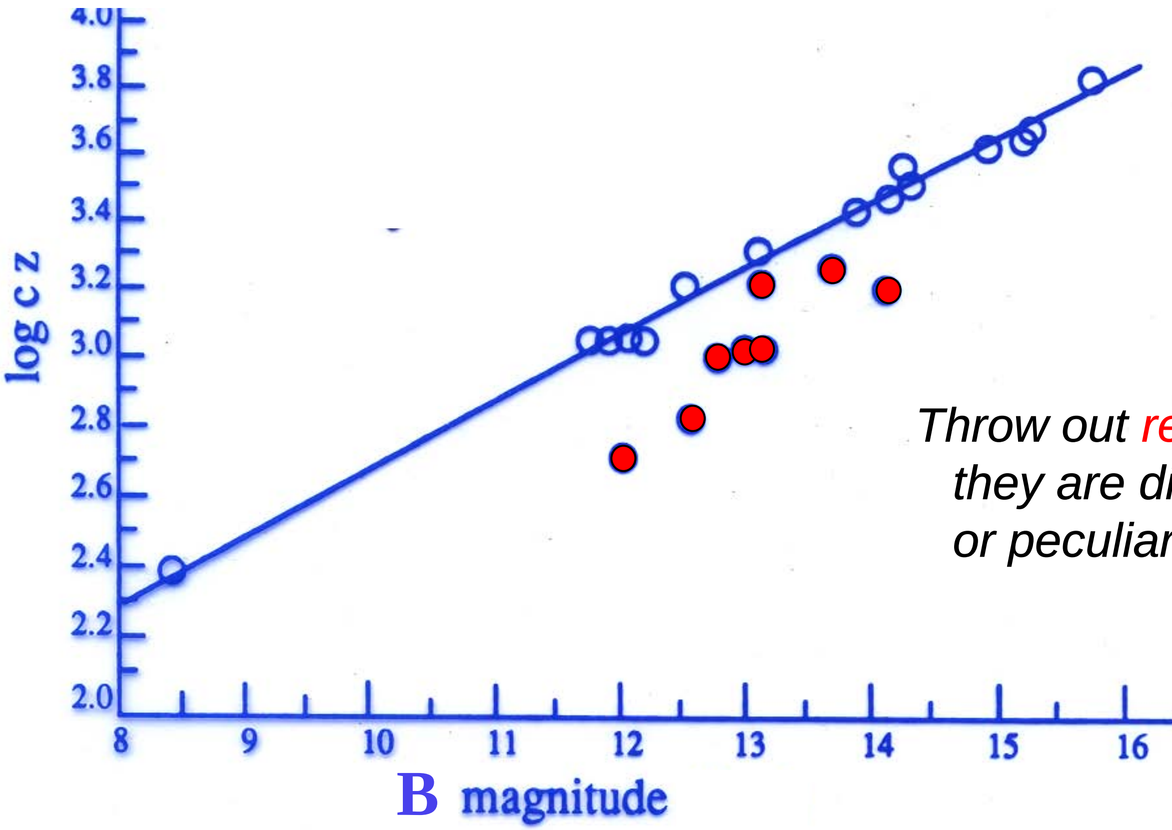
Vaughan, Branch, Miller, & S.P. (1995)



Vaughan, Branch, Miller, & S.P. (1995)

more redshift

Nearby Type Ia Supernova



Throw out red supernovae: they are dimmed by dust or peculiar

fainter

Observed dispersion of nearby Type Ia peak brightness:

Branch & Miller (1993)

Vaughan, Branch, Miller, & S.P. (1995)

40% -- 50% observed dispersion

reduced to 30% dispersion by selection based on color

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1. INTRODUCTION

Hamuy, Maza, Phillips, Suntzeff et al (1993)

“Calan/Tololo Supernova Search”

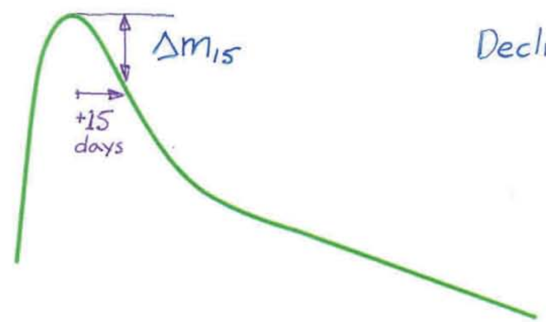
A beautiful, well-measured set of nearby supernova

now observed dispersion goes down to ~18% after color selection

Lightcurve Width-Luminosity Relation

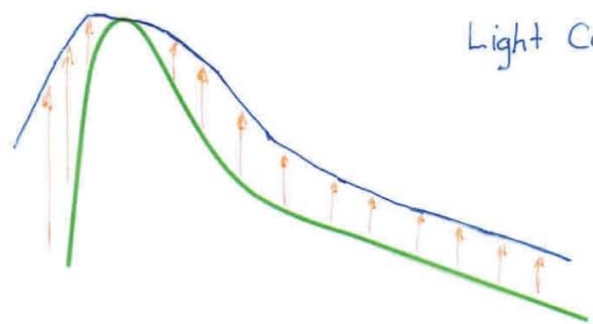
CHARACTERIZED BY:

Phillips:
(1993–)



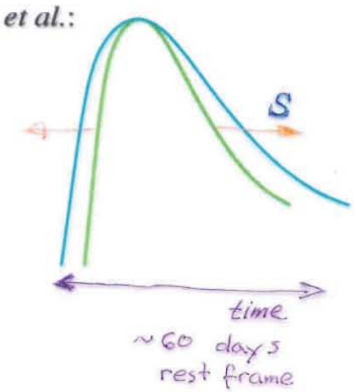
Decline Rate

Riess, Press, & Kirshner:
(1995–)



Light Curve Shape (LCS)

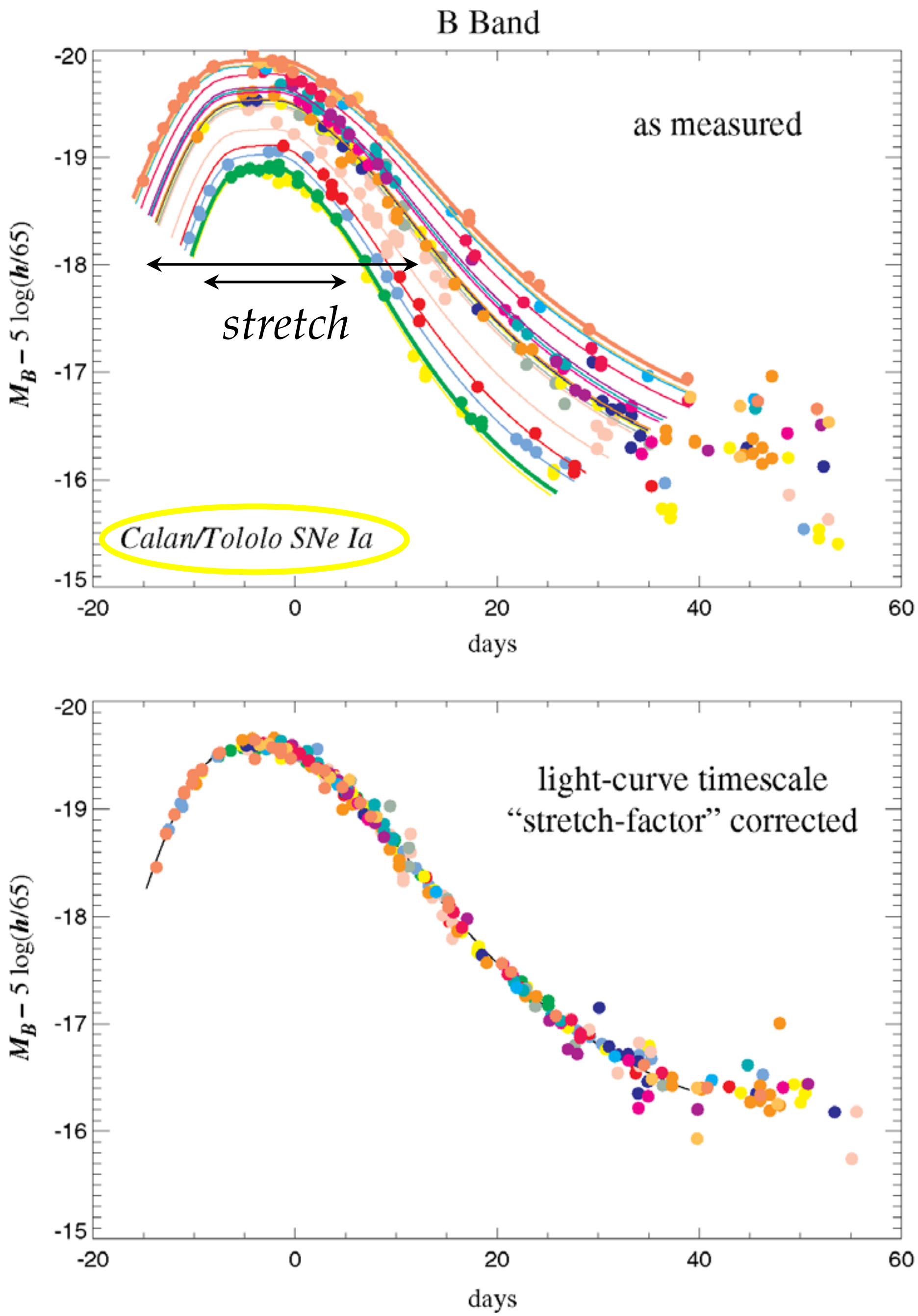
Perlmutter *et al.*:
(1996–)



Timescale "stretch factor"

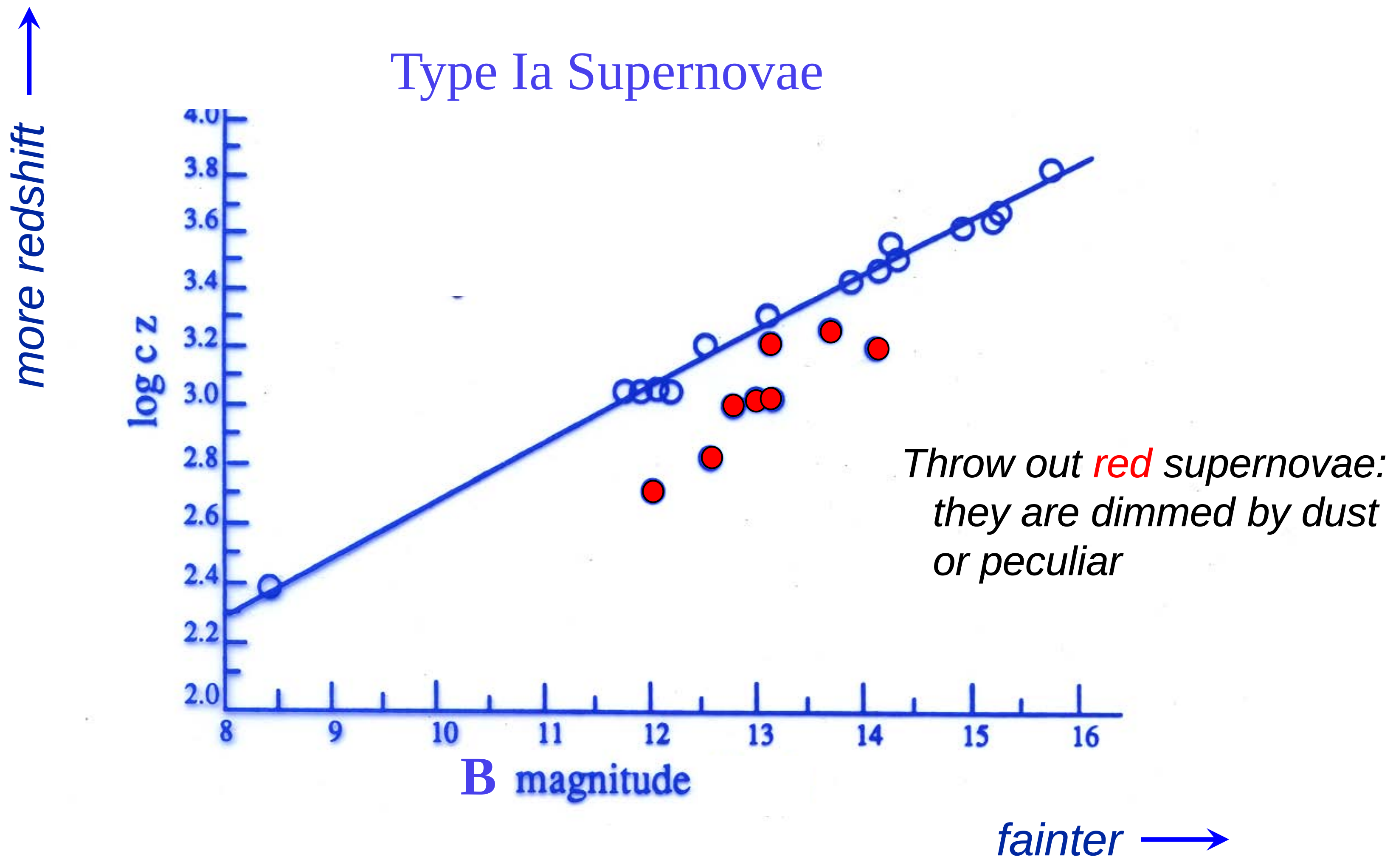
s > 1 : Broader / Slower lightcurves are Brighter

s < 1 : Narrower / Faster light curves are Fainter



B Band
as measured
stretch
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
$M_B - 5\log(h/65)$
days

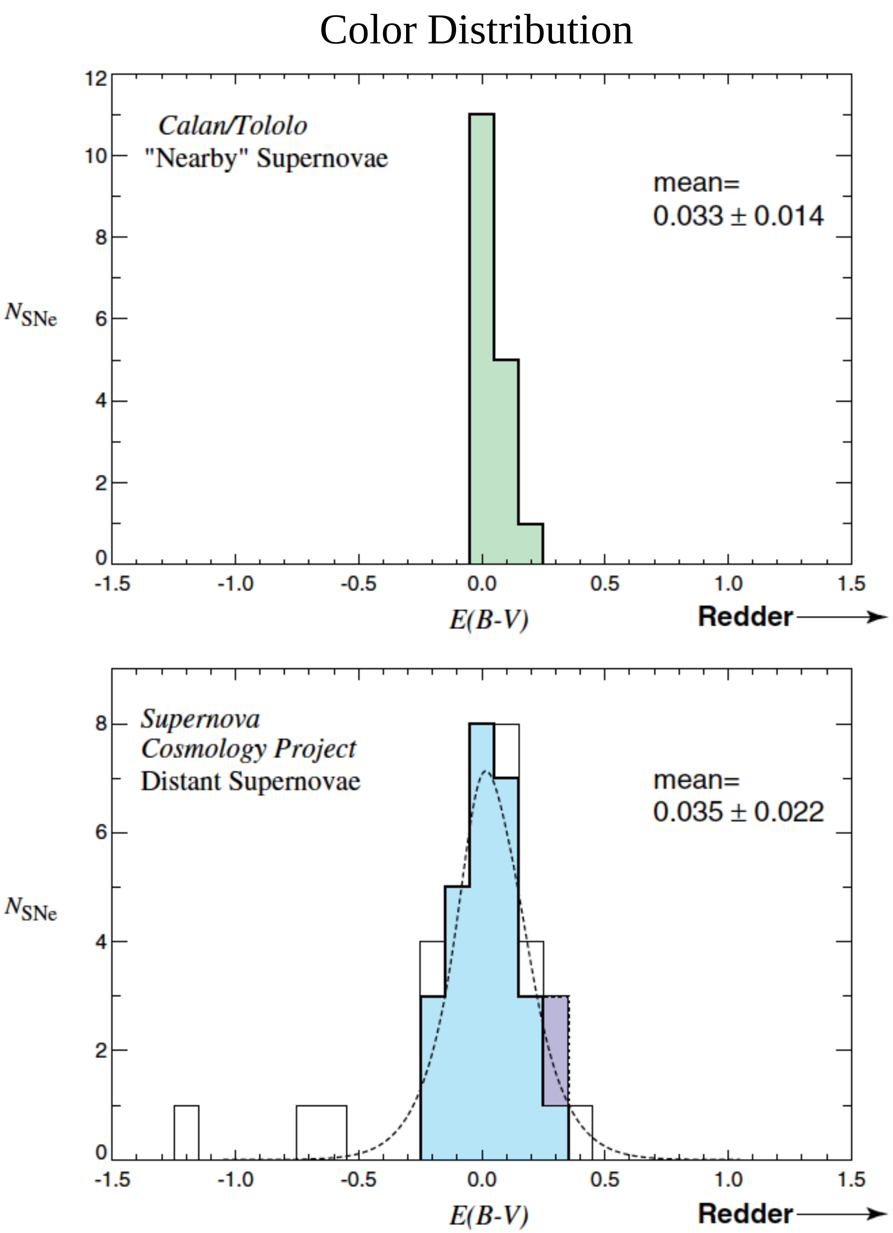
A. Kim et al.



Type Ia Supernovae
more redshift
log c z
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
8
9
10
11
12
13
14
15
16
B magnitude
fainter
Throw out red supernovae:
they are dimmed by dust
or peculiar

Compare color distributions,

or correct each SN individually for its color, assuming a dust color law.



Why is the supernova measurement *not* easy?

1. Can they be found **far enough** -- and **enough of them** -- for cosmology?
   Can they be found **early enough** to measure brightness over peak?

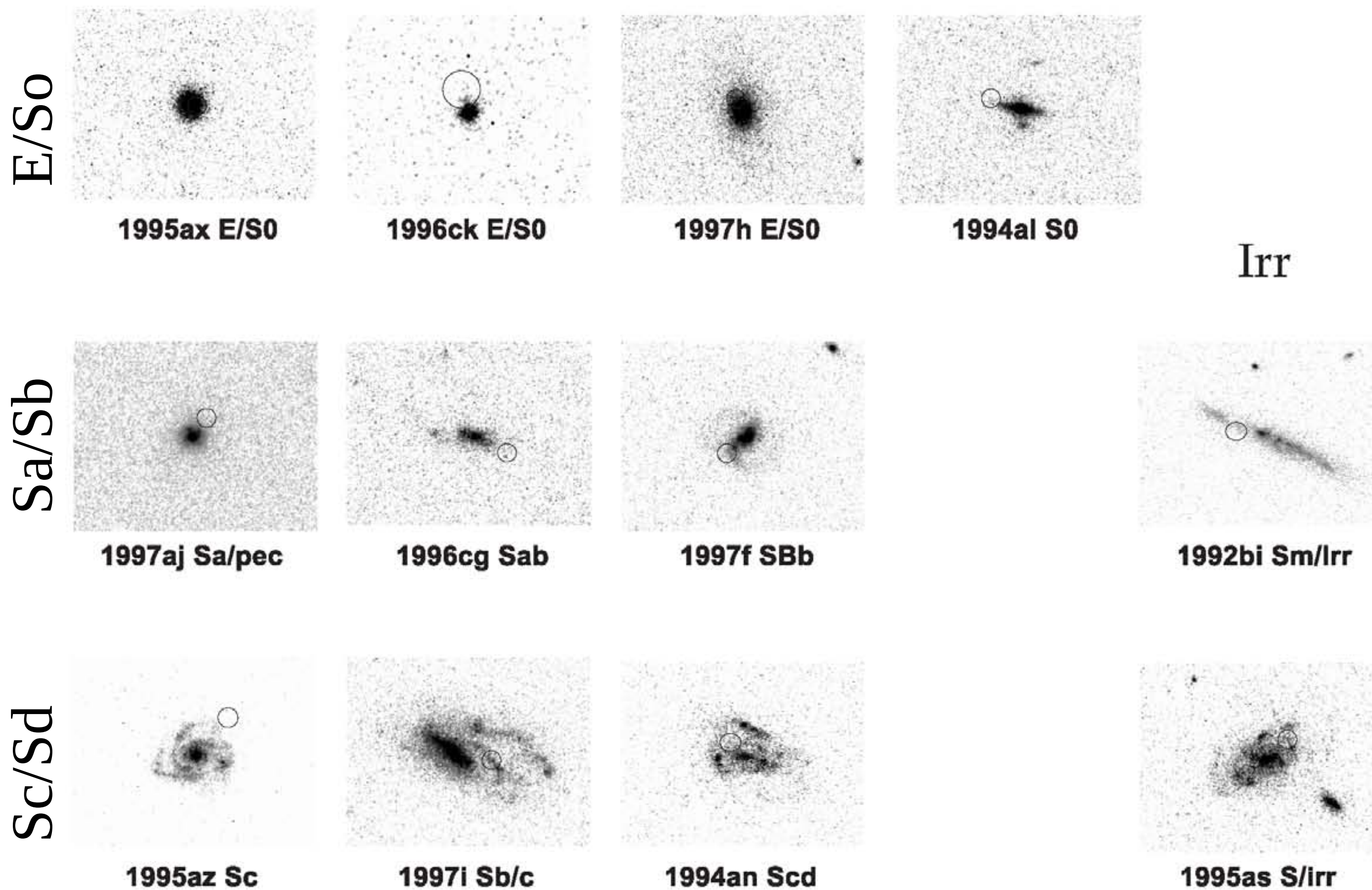
2. Can they be identified as Type Ia with spectra, despite how faint they will be?
   Can their brightness be compared with nearby ones, despite greatly "redshifted" spectra?

3. Are the supernovae standard enough?
   And how can one eliminate possible dust from diminishing their brightness?

4. Couldn't the supernovae evolve over 5 billion years?

Sullivan, et al. (2002)
Supernova Cosmology Project

SN Ia Host Galaxies: Morphological Classification with HST/STIS Imaging



Why is the supernova measurement *not* easy?

1. Can they be found **far enough** -- and **enough of them** -- for cosmology?
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4. Couldn't the supernovae evolve over five billion years?

Why is the supernova measurement ***not*** easy?

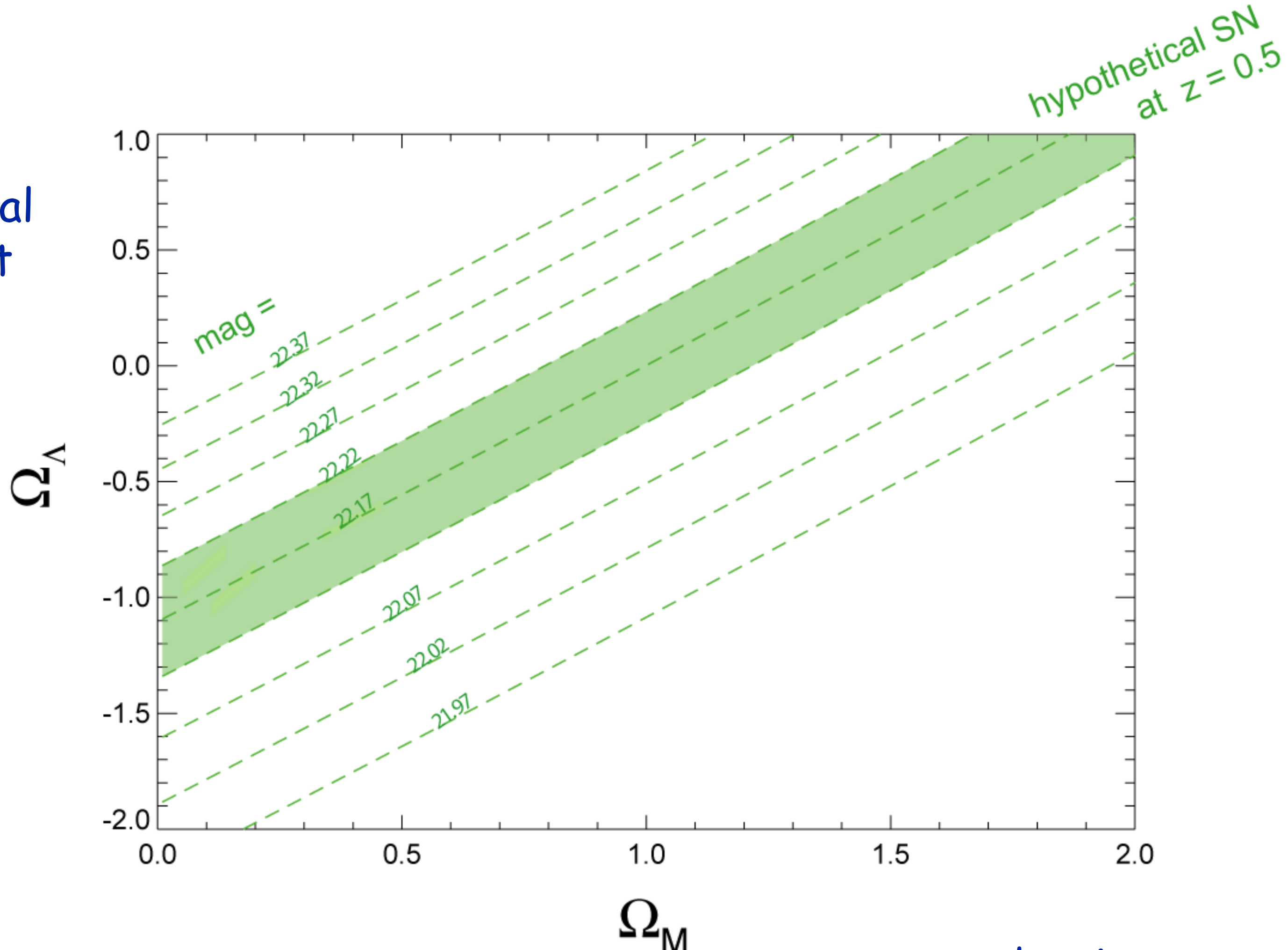
a "new" problem

5. What if Einstein's "Cosmological Constant" (Λ) exists? It will fight against gravity due to mass (M) in the universe

-- how can you tell if there is less M or more Λ or vice versa?

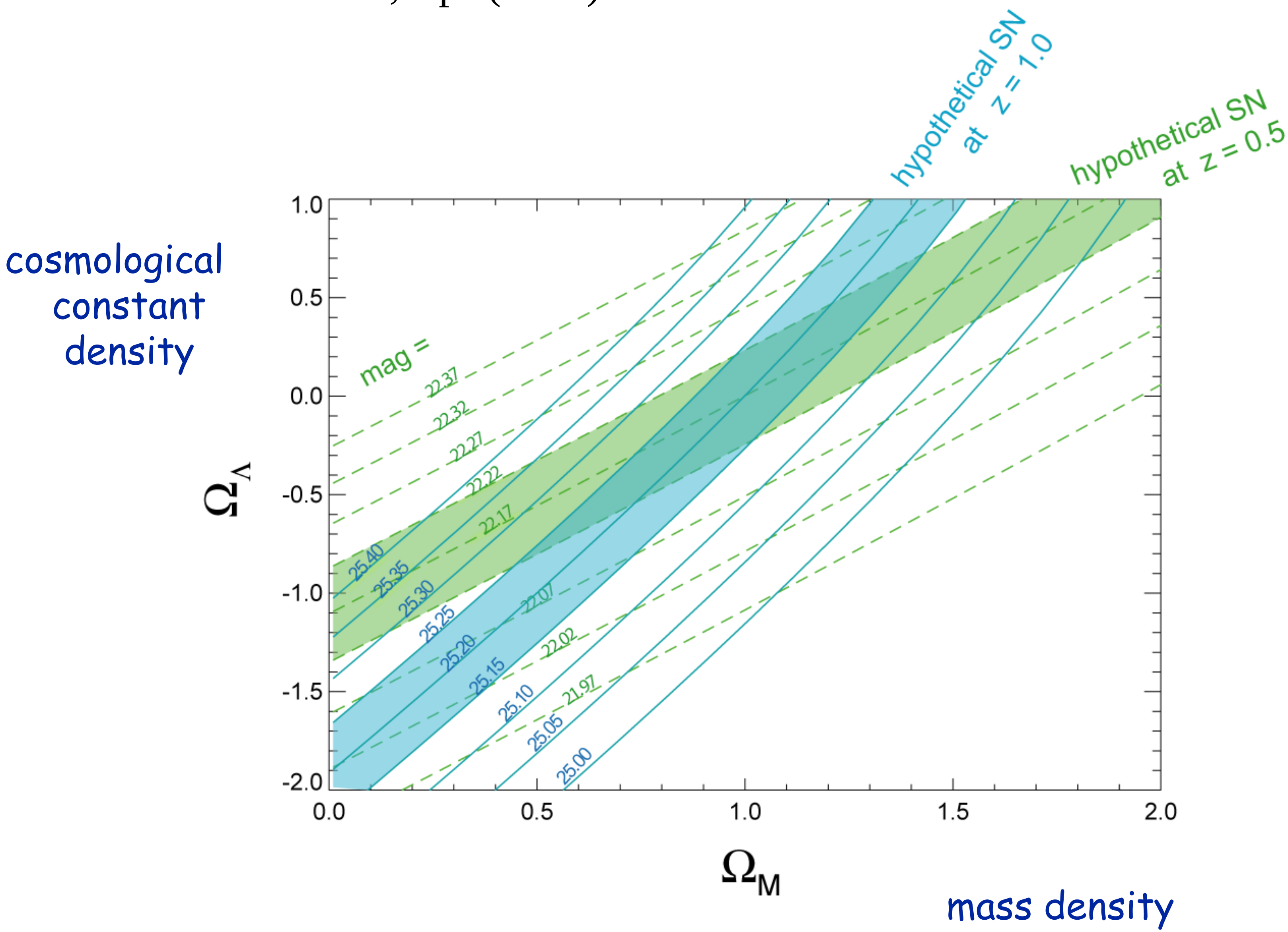
Goobar & Perlmutter, ApJ (1995)

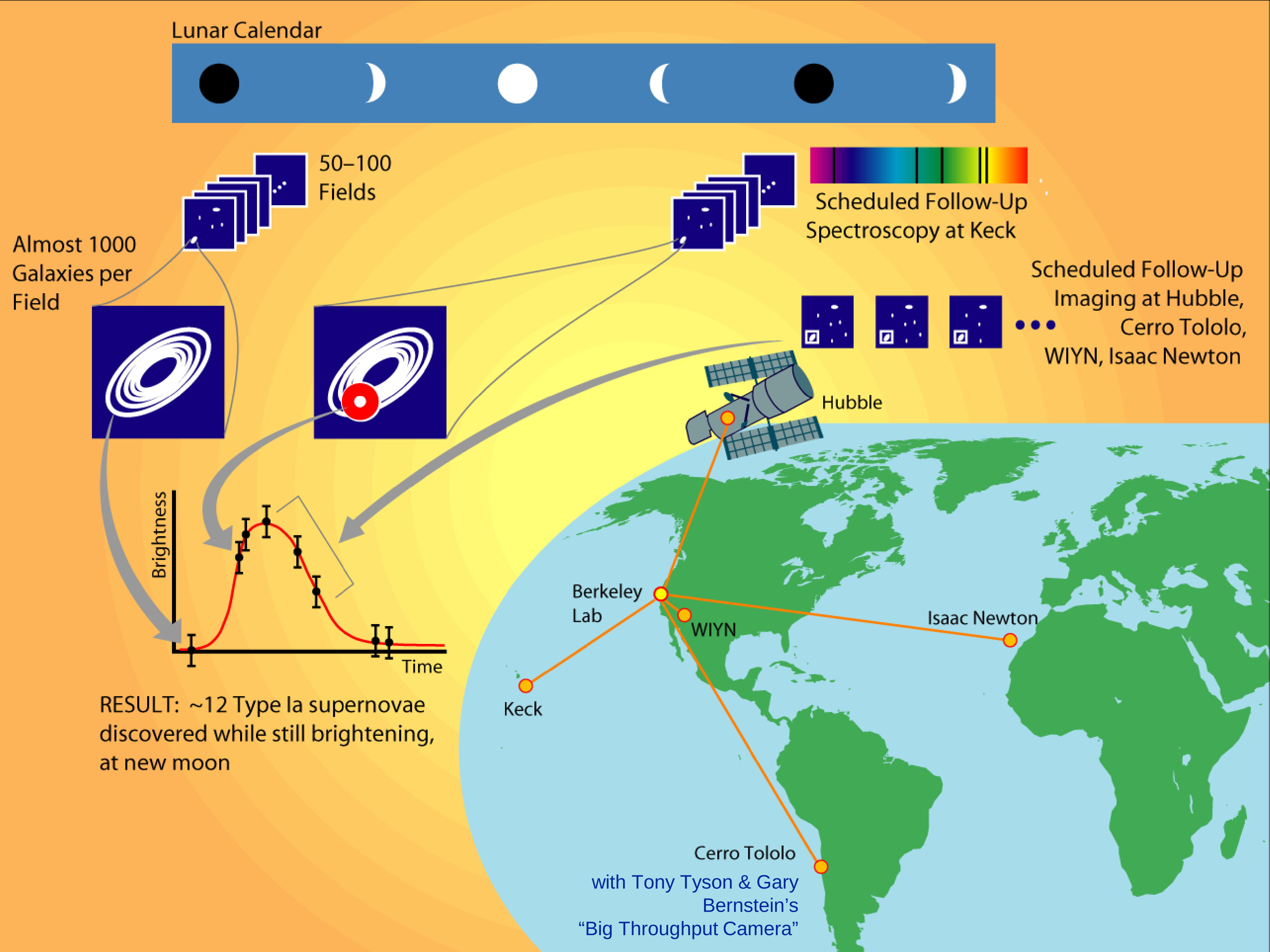
cosmological
constant
density



mass density

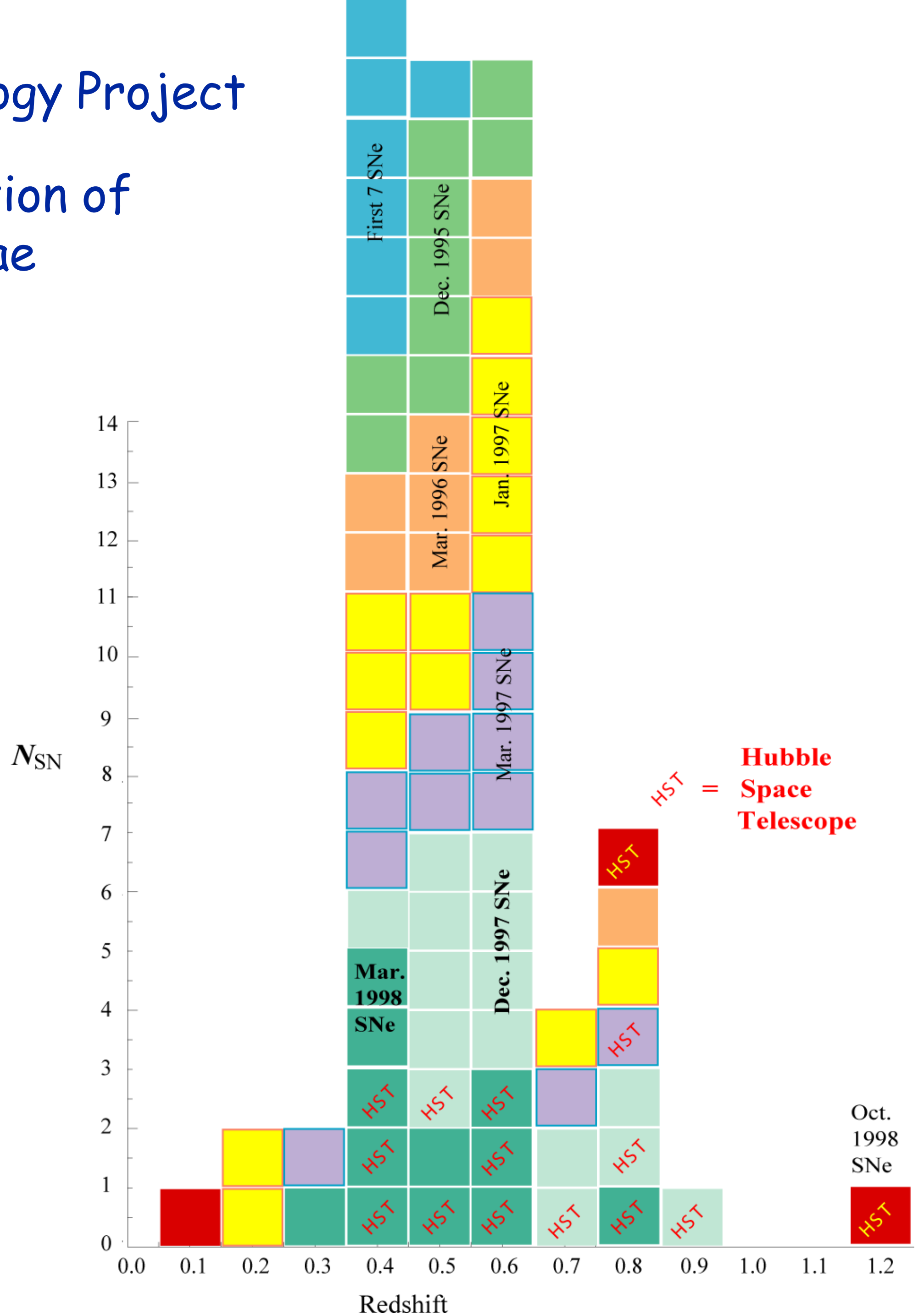
Goobar & Perlmutter, ApJ (1995)

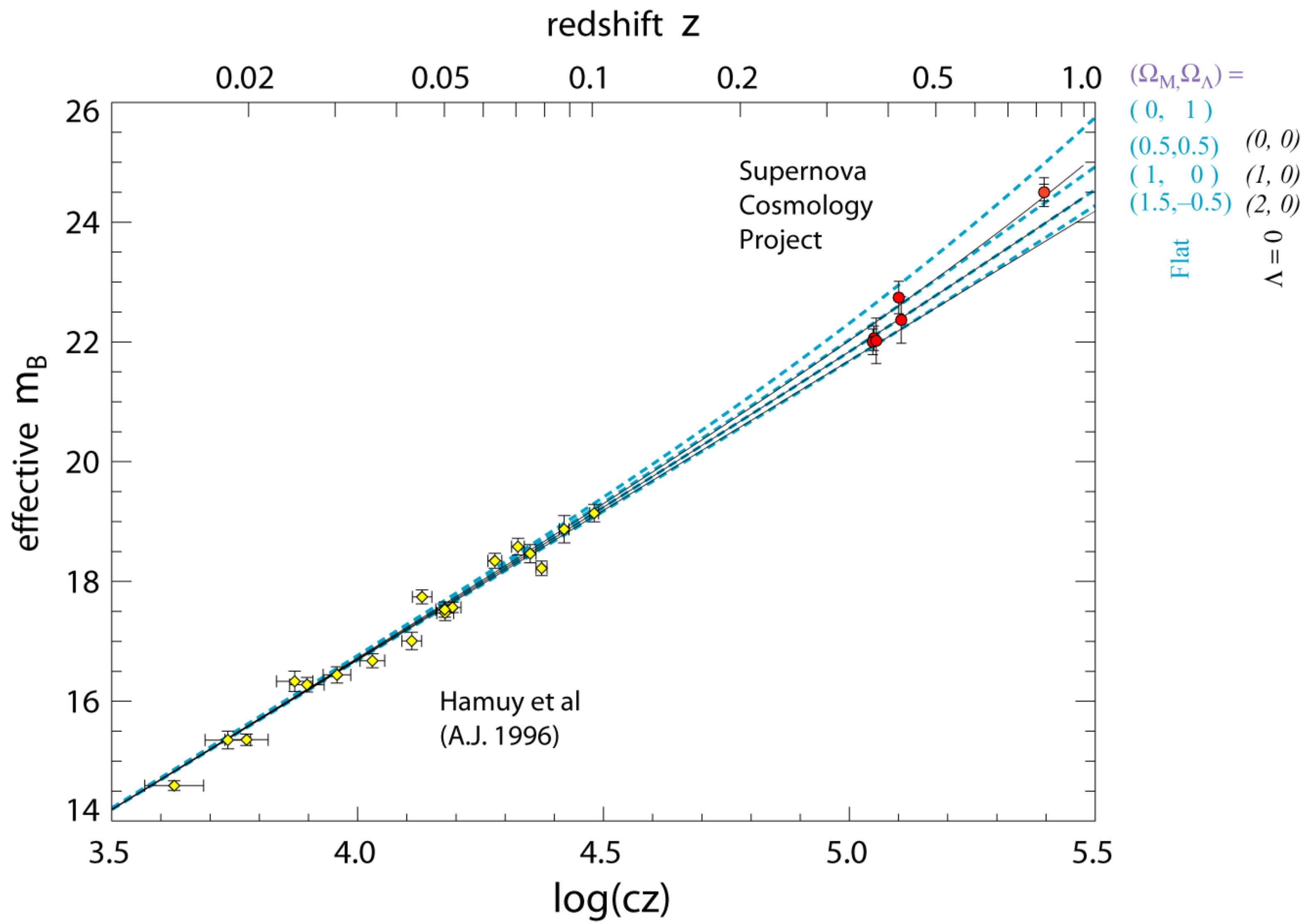



Lunar Calendar
50–100
Fields
Almost 1000
Galaxies per
Field
Scheduled Follow-Up
Spectroscopy at Keck
Scheduled Follow-Up
Imaging at Hubble,
Cerro Tololo,
WIYN, Isaac Newton
Hubble
Brightness
Time
RESULT: ~12 Type Ia supernovae
discovered while still brightening,
at new moon
Berkeley
Lab
WIYN
Isaac Newton
Keck
Cerro Tololo
with Tony Tyson & Gary
Bernstein's
"Big Throughput Camera"

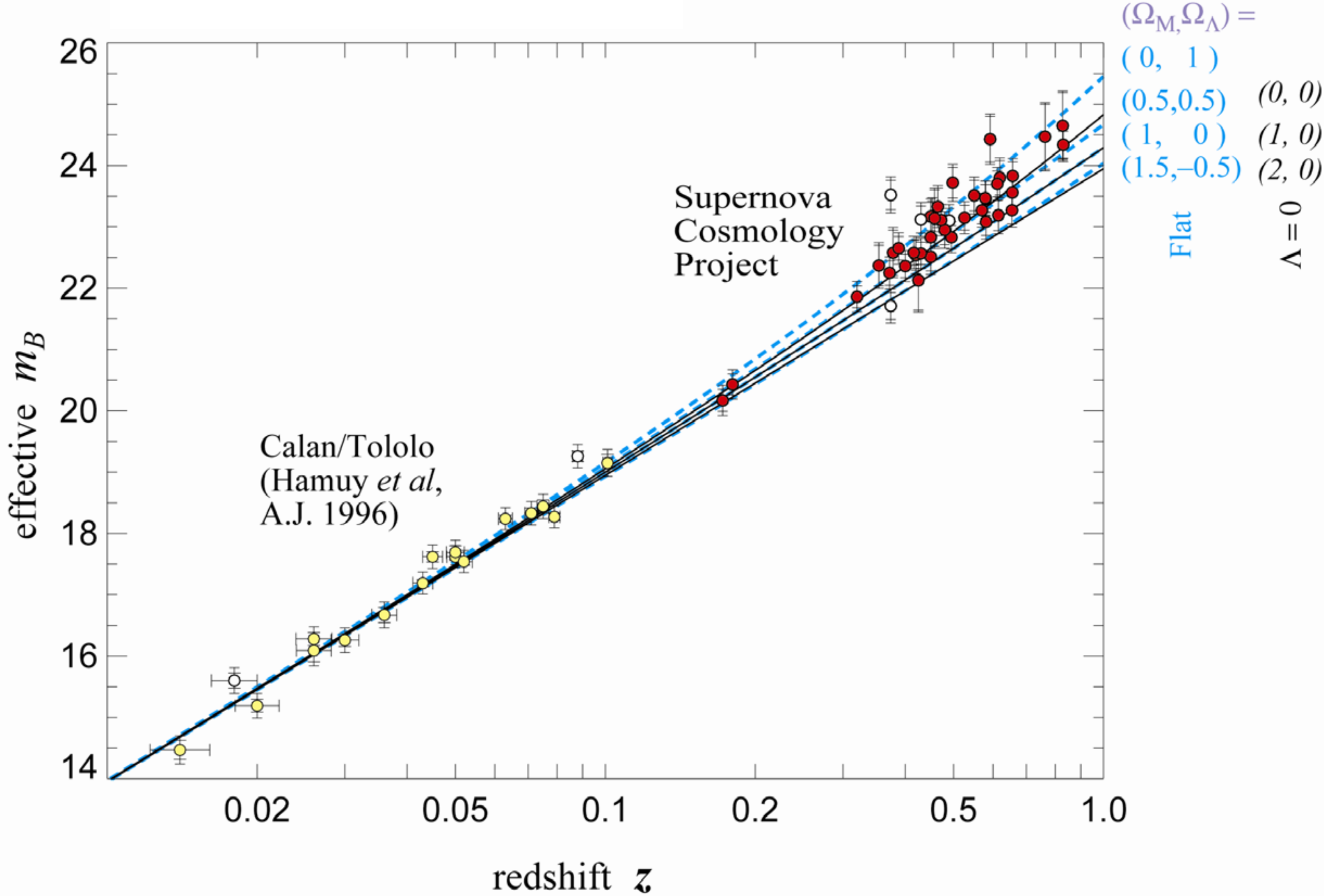
Supernova Cosmology Project

redshift distribution of
Type Ia supernovae
as of 1998

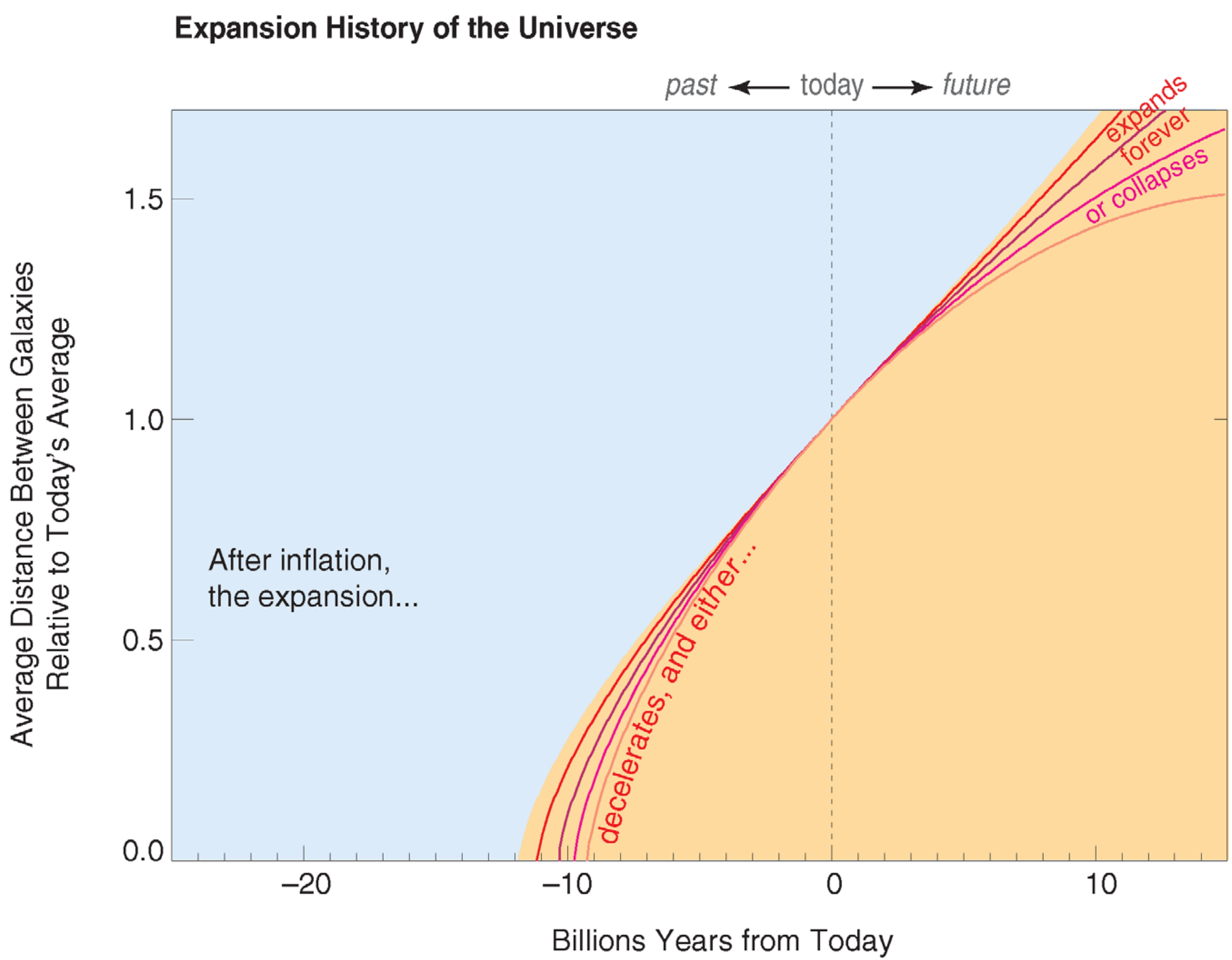




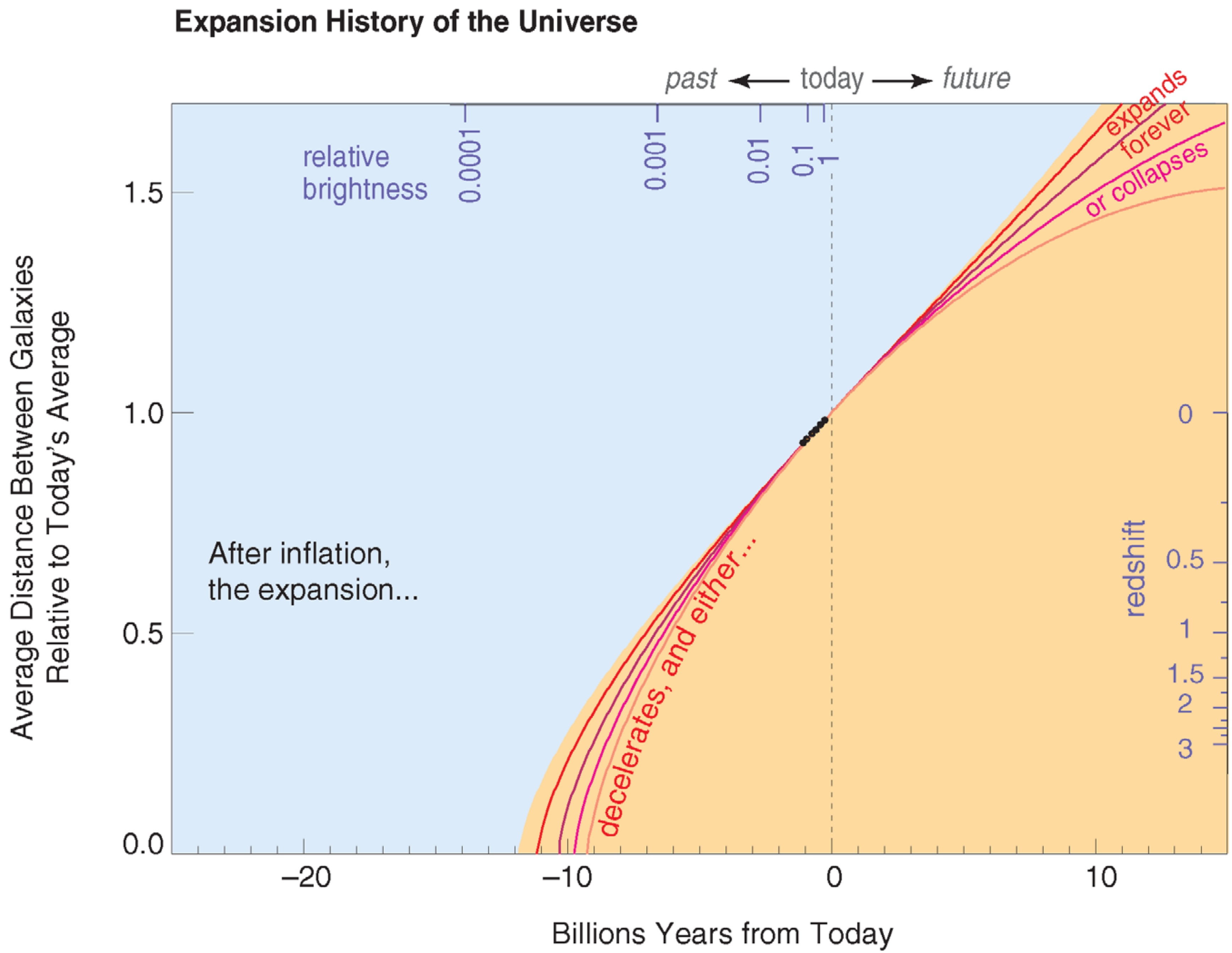
Perlmutter, et al.
Nature (1998)



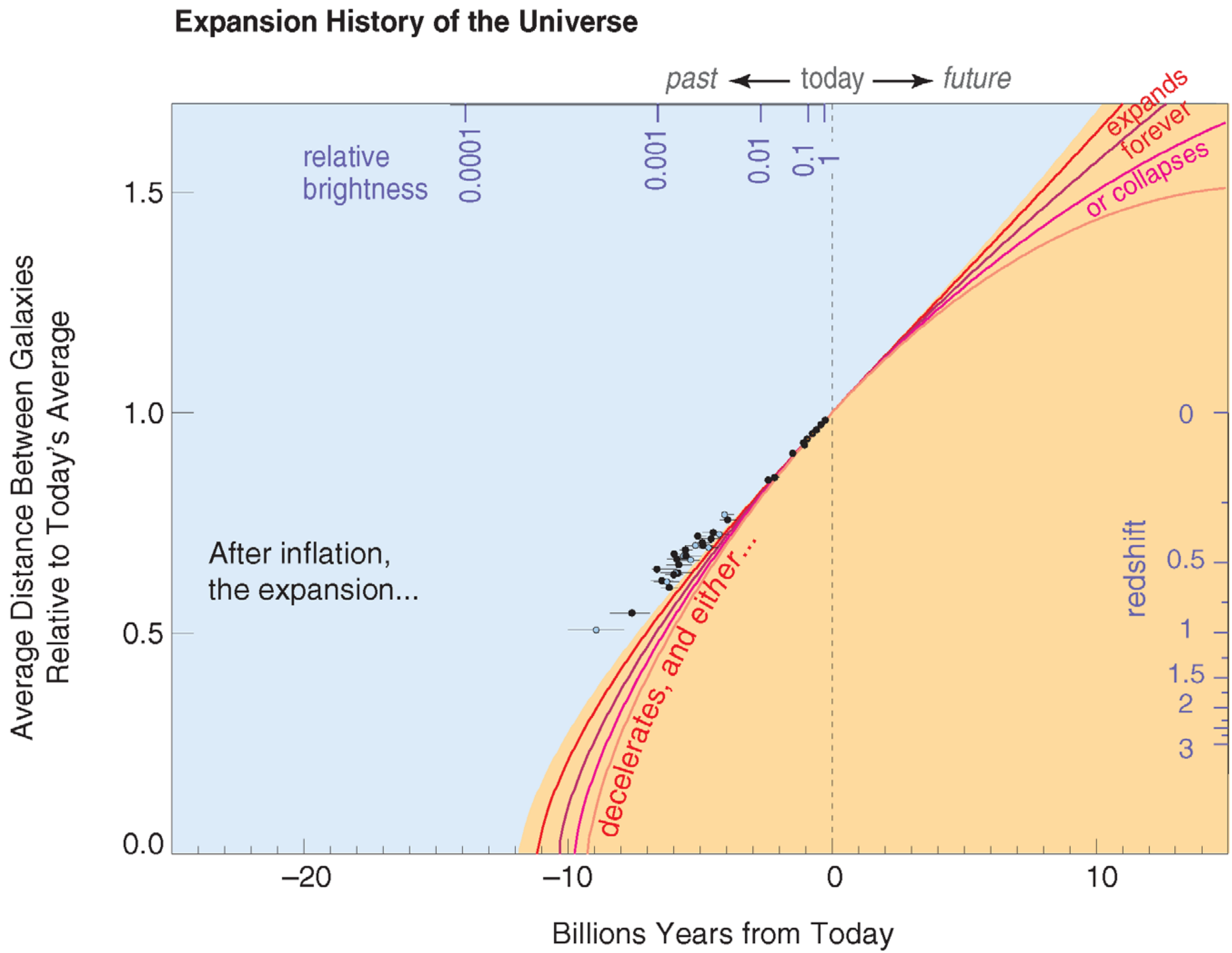
effective m_B
redshift z
26
24
22
20
18
16
14
0.02
0.05
0.1
0.2
0.5
1.0
Supernova Cosmology Project
Calan/Tololo (Hamuy *et al*, A.J. 1996)
$(\Omega_M, \Omega_\Lambda)$ =
(0, 1)
(0.5,0.5)
(1, 0)
(1.5,–0.5)
(0, 0)
(1, 0)
(2, 0)
Flat
$\Lambda = 0$



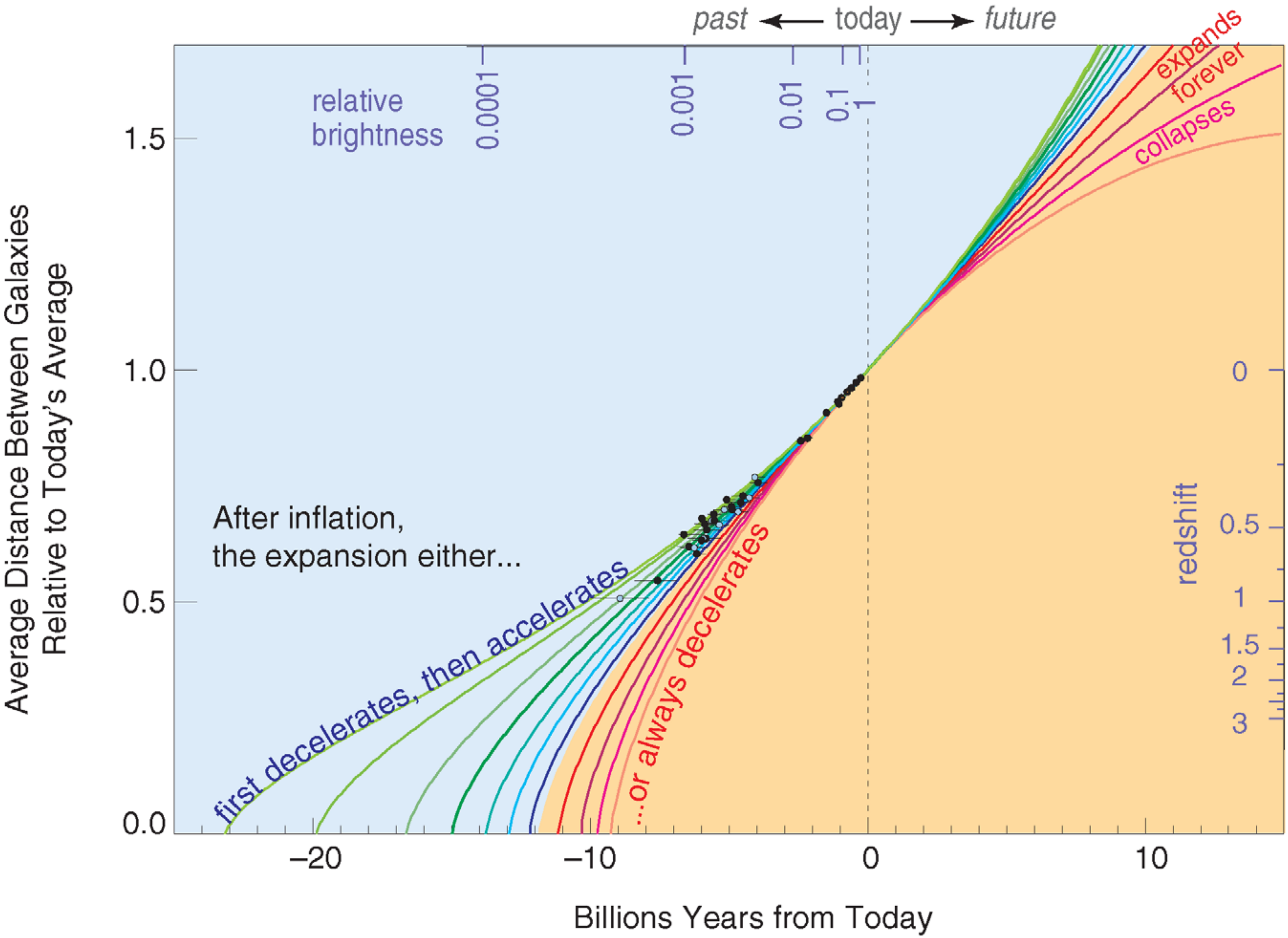
Expansion History of the Universe
past
today
future
expands
forever
or collapses
decelerates, and either...
After inflation,
the expansion...
Average Distance Between Galaxies
Relative to Today's Average
1.5
1.0
0.5
0.0
–20
–10
0
10
Billions Years from Today

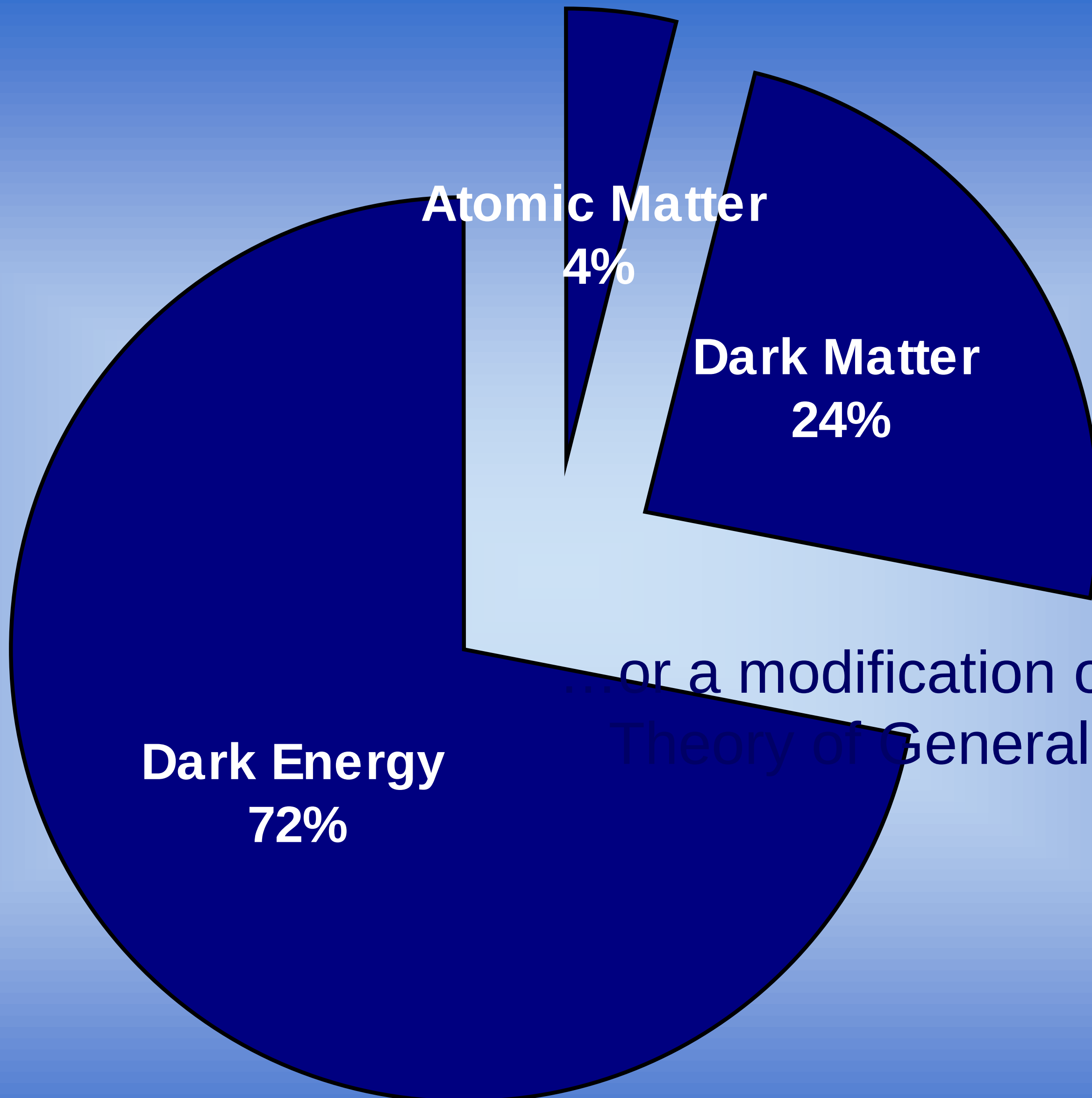


Expansion History of the Universe
past
today
future
relative
brightness
0.0001
0.001
0.01
0.1
1
expands
forever
or collapses
1.5
1.0
0.5
0.0
Average Distance Between Galaxies
Relative to Today's Average
After inflation,
the expansion...
decelerates, and either...
0
redshift
0.5
1
1.5
2
3
–20
–10
0
10
Billions Years from Today


Expansion History of the Universe
past ← today → future
relative brightness
0.0001
0.001
0.01
0.1
1
expands forever or collapses
After inflation, the expansion...
decelerates, and either...
redshift
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
–20
–10
0
10
Billions Years from Today

Expansion History of the Universe





…or a modification of Einstein's Theory of General Relativity?

Dark Energy

Quintessence

Supergravity

K-essence

Cyclic Universe

Phantom Energy

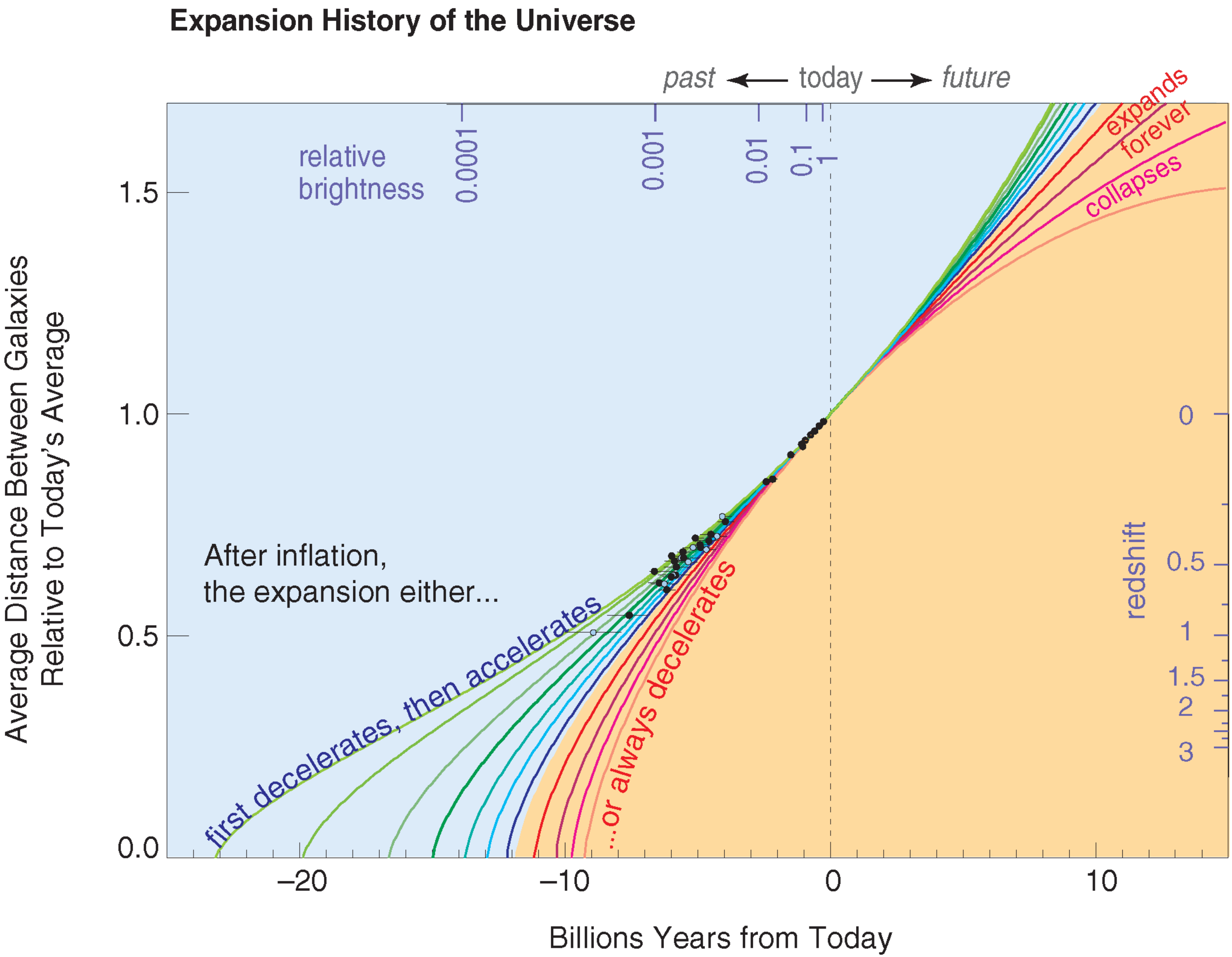
Extra Dimensions

Big Rip Cosmology

Ekpyrotic Universe

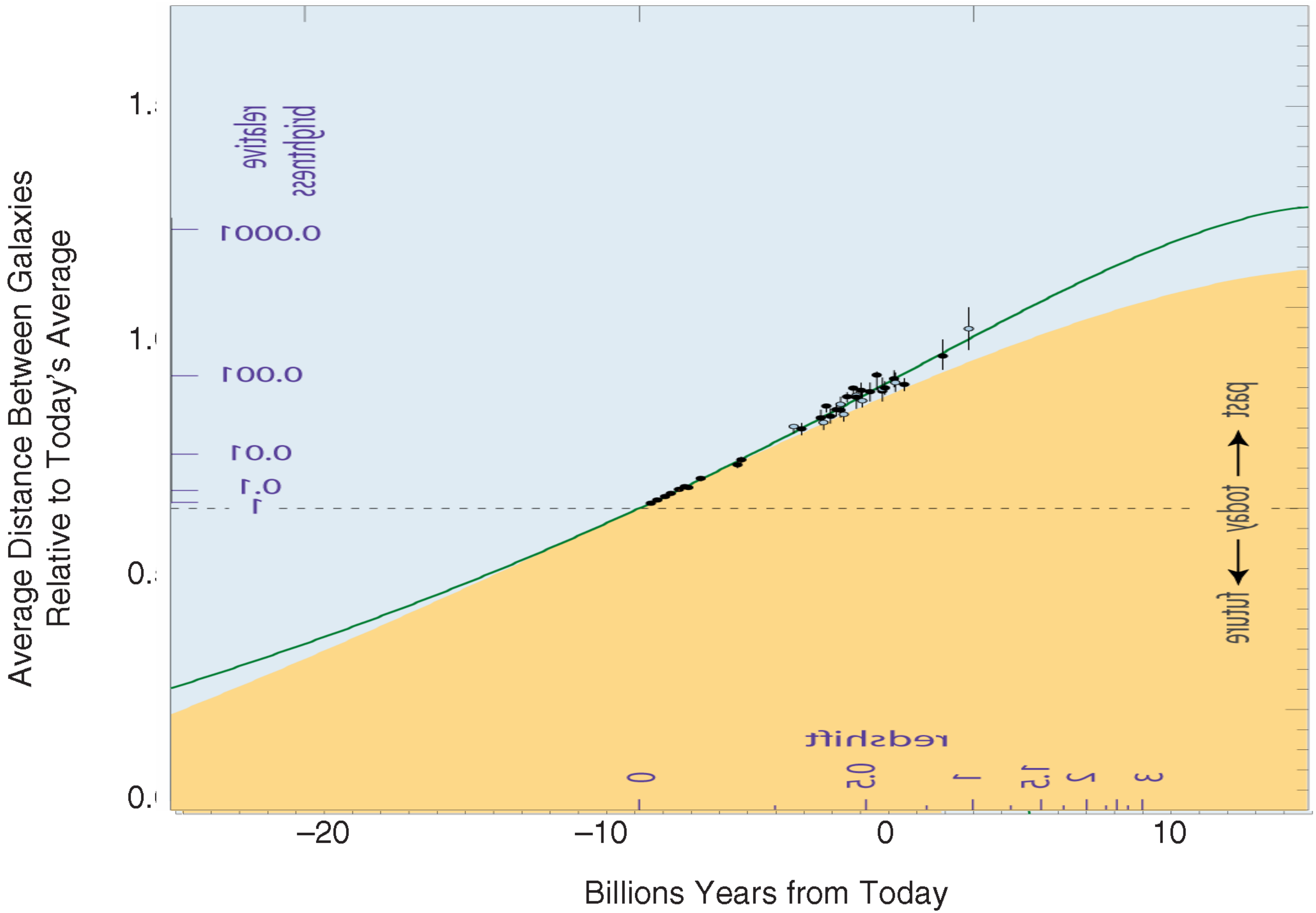
Photon-axion oscillations

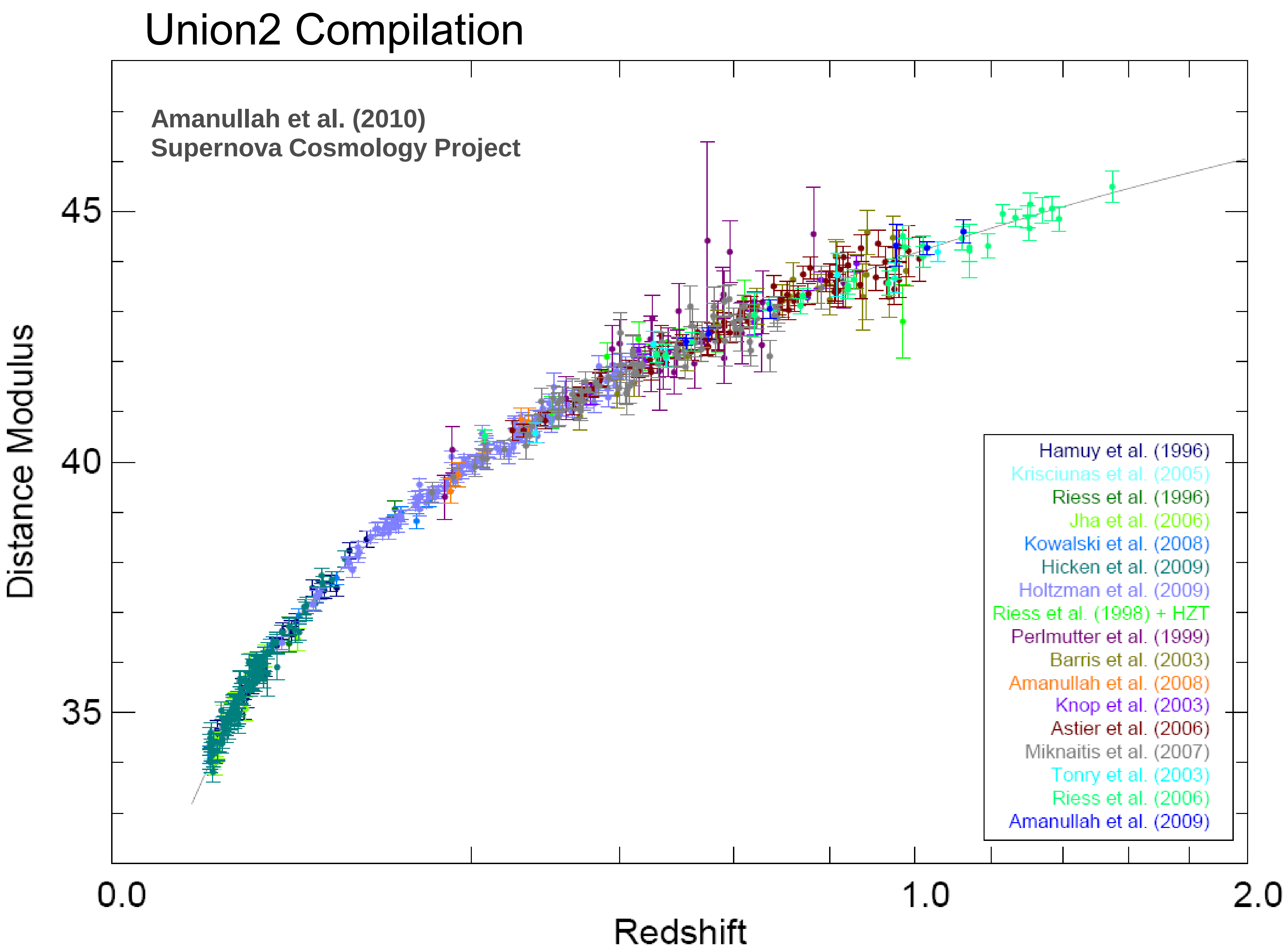
Everybody talks about the dark energy,
but nobody does anything about it.



Expansion History of the Universe
past ← today → future
relative brightness
0.0001
0.001
0.01
0.1
1
1.5
1.0
0.5
0.0
Average Distance Between Galaxies Relative to Today's Average
expands forever
collapses
0
0.5
1
1.5
2
3
redshift
After inflation, the expansion either...
first decelerates, then accelerates
...or always decelerates
−20
−10
0
10
Billions Years from Today

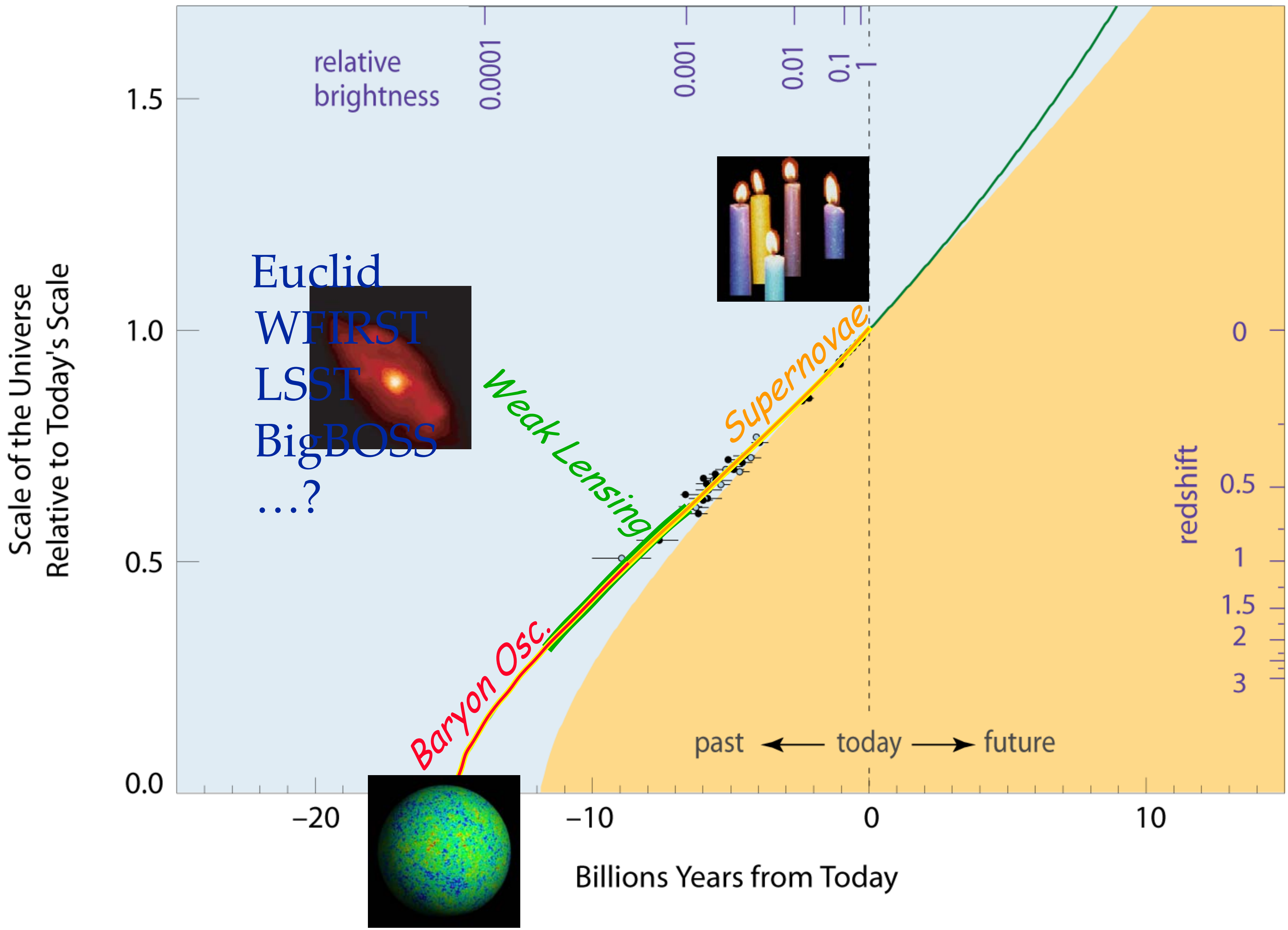
Expansion History of the Universe

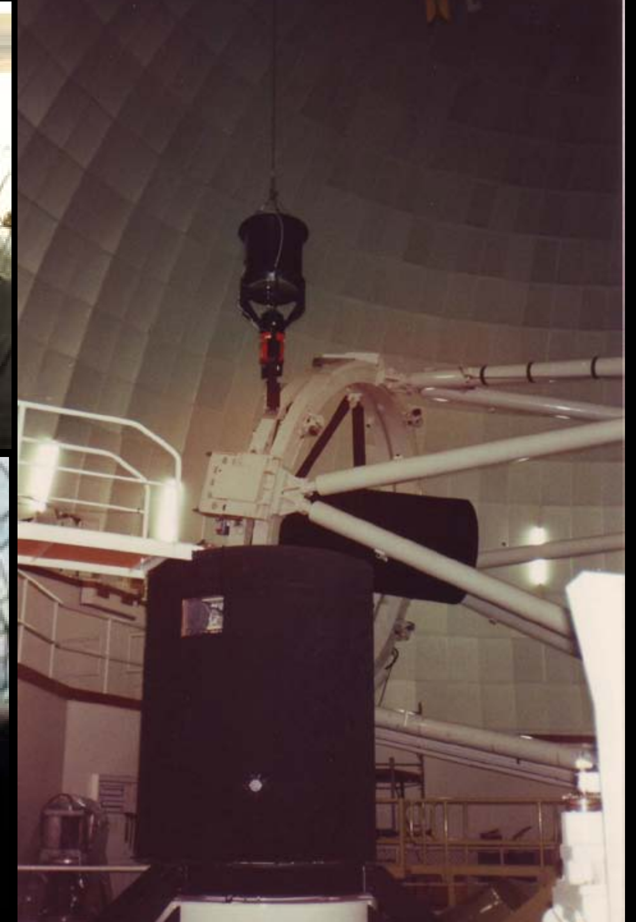




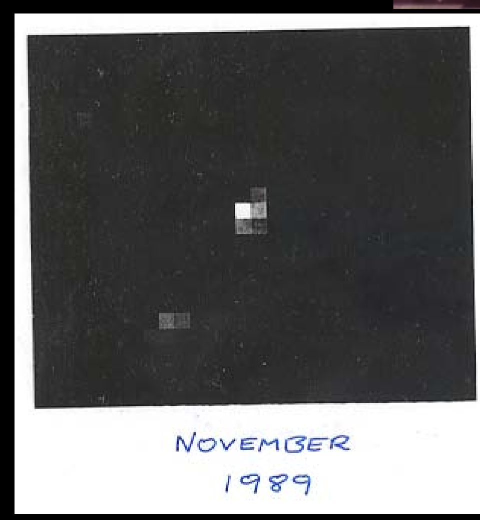
Union2 Compilation
Amanullah et al. (2010)
Supernova Cosmology Project
Distance Modulus
45
40
35
0.0
1.0
2.0
Redshift
Hamuy et al. (1996)
Krisciunas et al. (2005)
Riess et al. (1996)
Jha et al. (2006)
Kowalski et al. (2008)
Hicken et al. (2009)
Holtzman et al. (2009)
Riess et al. (1998) + HZT
Perlmutter et al. (1999)
Barris et al. (2003)
Amanullah et al. (2008)
Knop et al. (2003)
Astier et al. (2006)
Miknaitis et al. (2007)
Tonry et al. (2003)
Riess et al. (2006)
Amanullah et al. (2009)

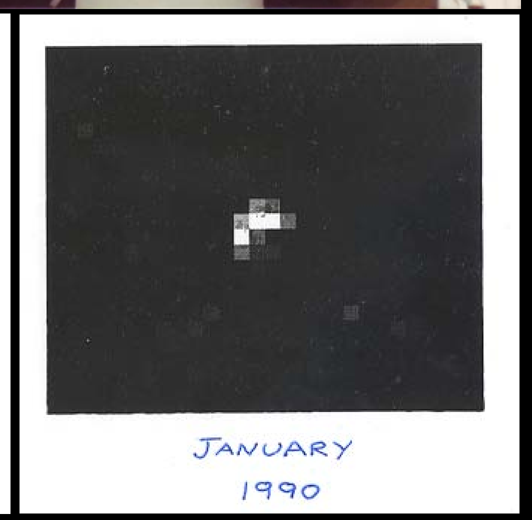
Expansion History of the Universe



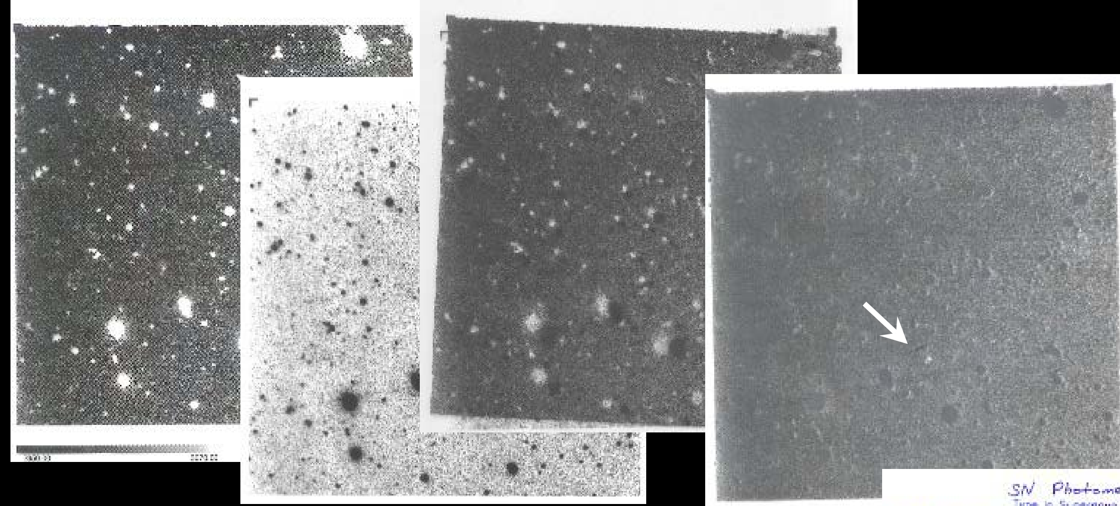


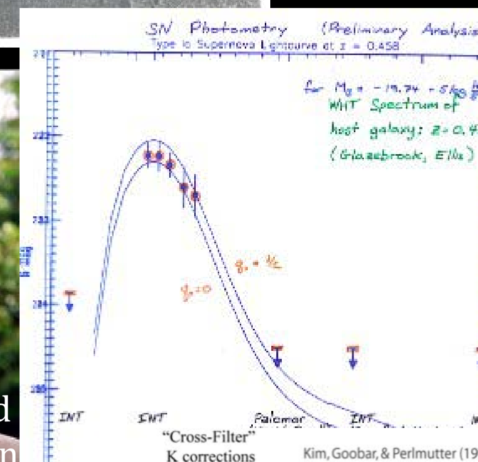
Carl
Pennypacker

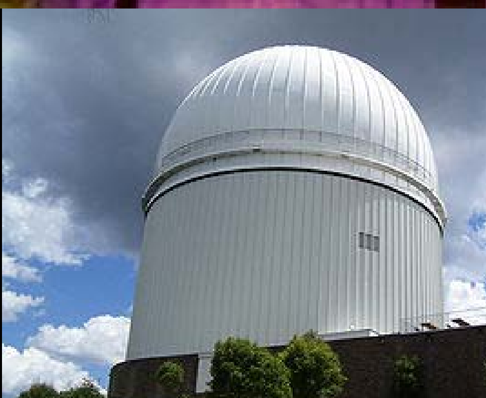





Gerson
Goldhaber
(1924-2010)

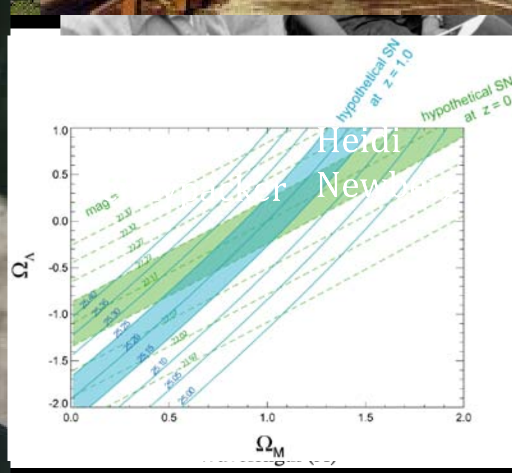



SN Photometry (Preliminary Analysis
Type Ia Supernova Lightcurve at z = 0.458
INT
INT
Palomar

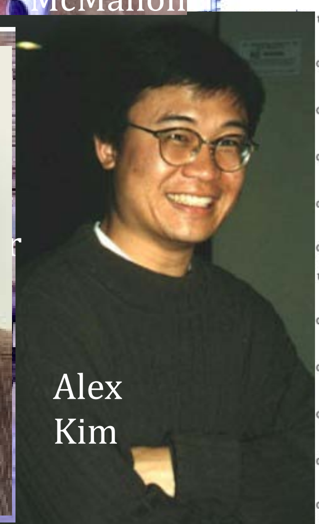


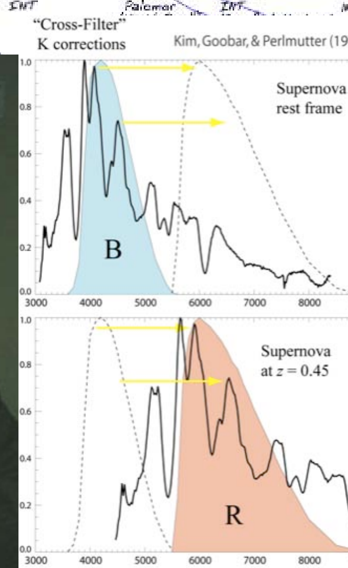

Richard
McMahon

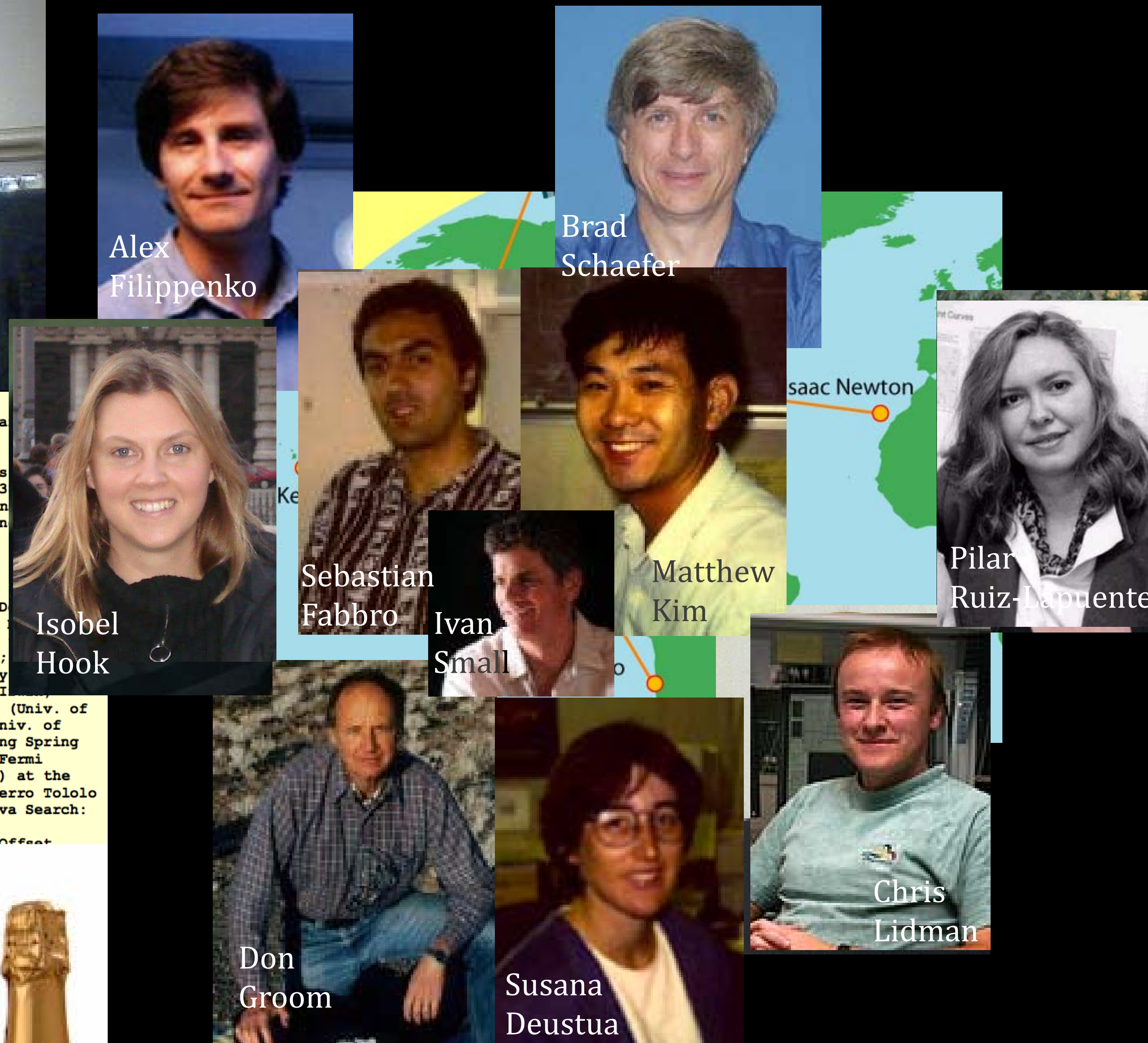

Richard
Ellis

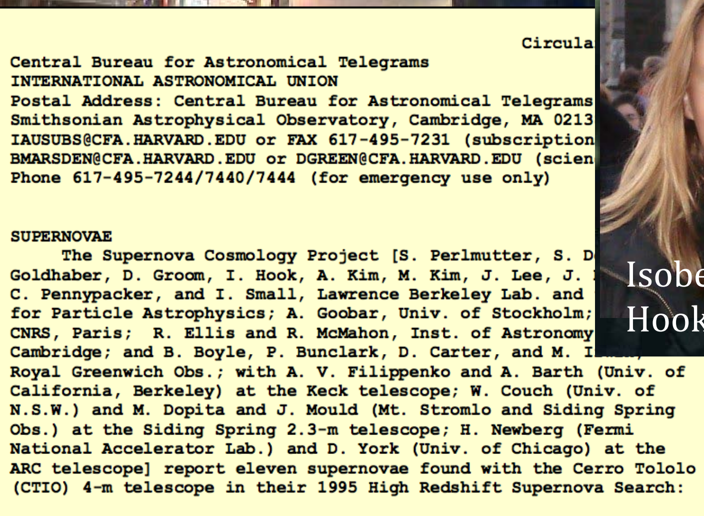

hypothetical SN
at z = 1.0
Heidi
mag =
Ω_Λ
Ω_M


Ariel
Goobar


Alex
Kim


"Cross-Filter"
K corrections
Supernova
rest frame
B
Supernova
at z = 0.45
R



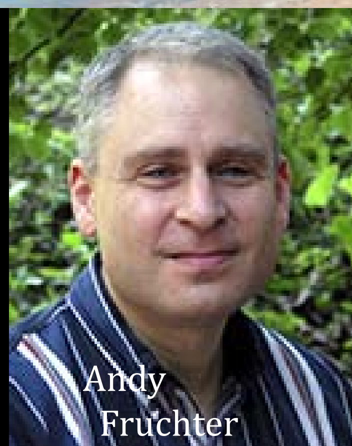

Circula

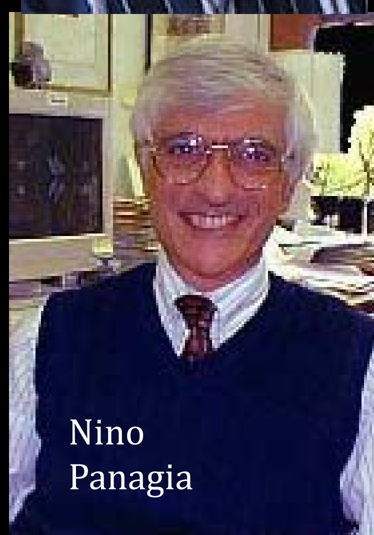
Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
Postal Address: Central Bureau for Astronomical Telegrams
Smithsonian Astrophysical Observatory, Cambridge, MA 0213
IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscription
BMARSDEN@CFA.HARVARD.EDU or DGREEN@CFA.HARVARD.EDU (scien
Phone 617-495-7244/7440/7444 (for emergency use only)

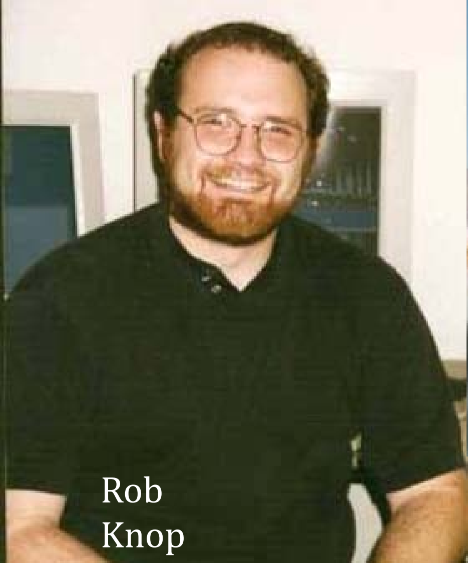
SUPERNOVAE

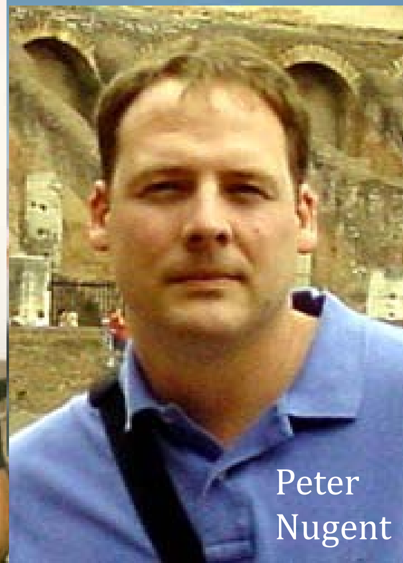
The Supernova Cosmology Project [S. Perlmutter, S. D
Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, J.
C. Pennypacker, and I. Small, Lawrence Berkeley Lab. and
for Particle Astrophysics; A. Goobar, Univ. of Stockholm;
CNRS, Paris; R. Ellis and R. McMahon, Inst. of Astronomy
Cambridge; and B. Boyle, P. Bunclark, D. Carter, and M. I
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:



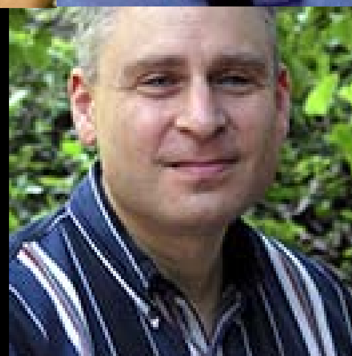

Andy
Fruchter

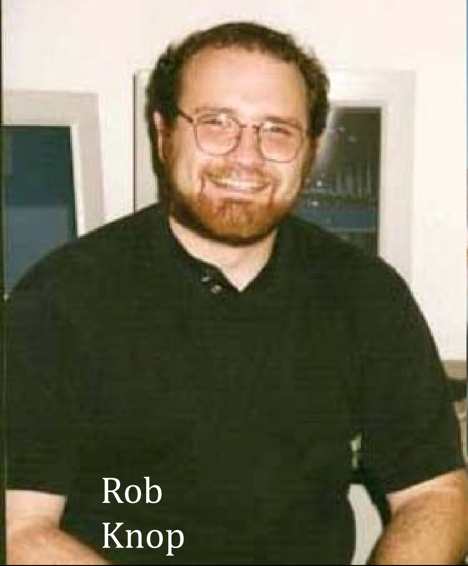

Nino
Panagia



Rob
Knop


Peter
Nugent

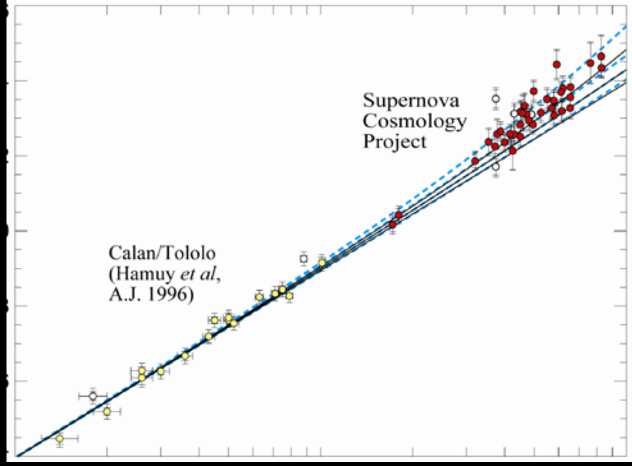

Greg
Aldering




Rob
Knop


Peter
Nugent

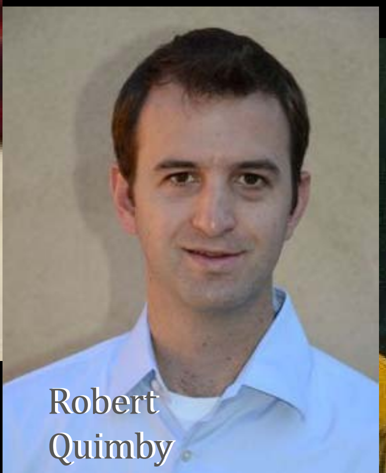

Greg
Aldering


Supernova
Cosmology
Project
Calan/Tololo
(Hamuy *et al*,
A.J. 1996)


Julia
Lee


Nelson
Nunes

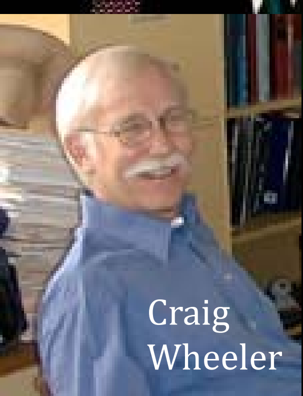

Patricia
Castro


Robert
Quimby


David
Branch


Mario
Hamuy


José
Maza


Craig
Wheeler


Gustav
Tammann