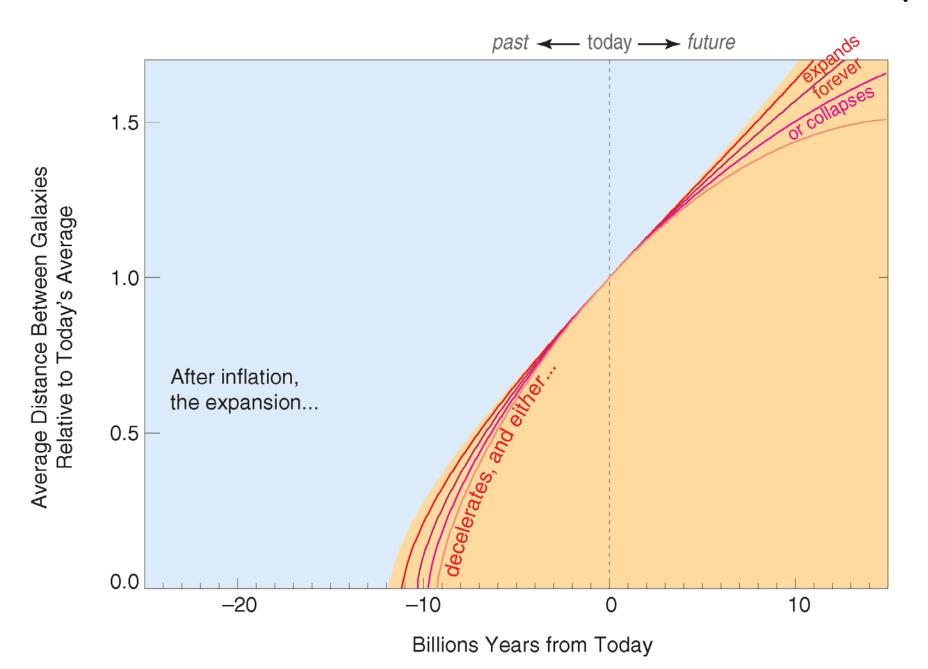
Measuring the Acceleration of the Cosmic Expansion Using Supernovae

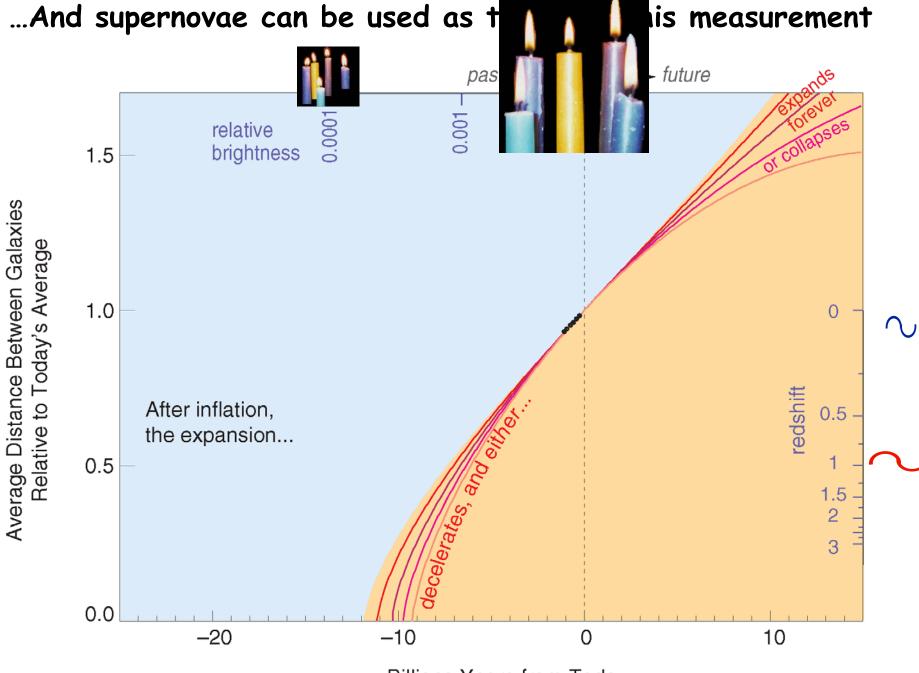
# Saul Perlmutter

University of California, Berkeley Lawrence Berkeley National Laboratory

Nobel Lecture Stockholm December 2011 A philosophical question: What is the Fate of the Universe?

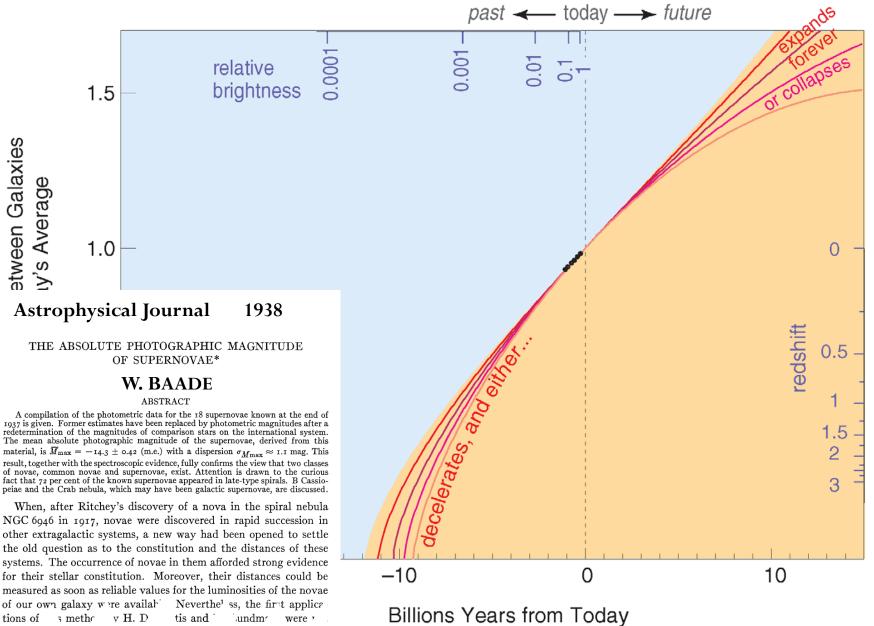
## The Fate of the Universe can be determined from its history:





Billions Years from Today

### **Expansion History of the Universe**



verys tory se t' lata rev n v

But supernovae were not quite good enough "standard candles"





## Mid - 1980's:

## Two new developments

## "Type Ia" supernovae: 1 a more standard candle

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Achar A, Frenza J, "Denge Halery," Dr. V. Lesiej," and Hockel & Tener M. Market A. Strandowski, "Den y Hannes Market Andreas Market Andreas Market Andreas Market Market Andreas Market And Charles Stands (00 m) Sector 21 August 2009 pr Milder 21 April 200

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2010 The Astronomy President Davids

Zong-Hong Zhu and Masa-Katsu Fujimoto J. Osava, Mitaka, Tokyo 181-8888, Japan ponghong Judi ar et al. are used to analyze the Cardassian avisasian alternative to accsmological con-the currently accelerating universe. We show he Cardassian model, will give rise to a uniled with the current value derived from the nd galaxy clusters (cluster baryon fraction). survive the magnitude radshift test for the marily baryonic matter. No. 10.000 Aug.

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Uomoto & Kirshner (1985)

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# "Type Ia"?

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## "Type Ia" supe 1 a more standa

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Joshu J., Franz J., <sup>1</sup>Ozga J., Mary C. W. V. Levin, *et al.* 1997 and McKell J. Theore <sup>1,4</sup> (Josenwa J., Leving J., <sup>1</sup>Ozen J. K. V. K. Markov, J. K. Harts, <sup>1</sup>O Kan, <sup>1</sup>Olan, <sup>1</sup>Ol Wards at 7 August 200 pr Wide St April 200

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Mid - 1980's: Two new developments

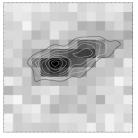


CCD detectors

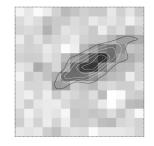
& computers fast enough for image analysis



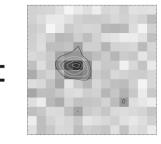
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SN +Galaxy



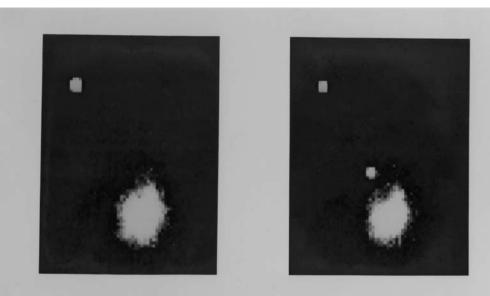
Galaxy



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.



MAY 8, 1986

MAY 17, 1986

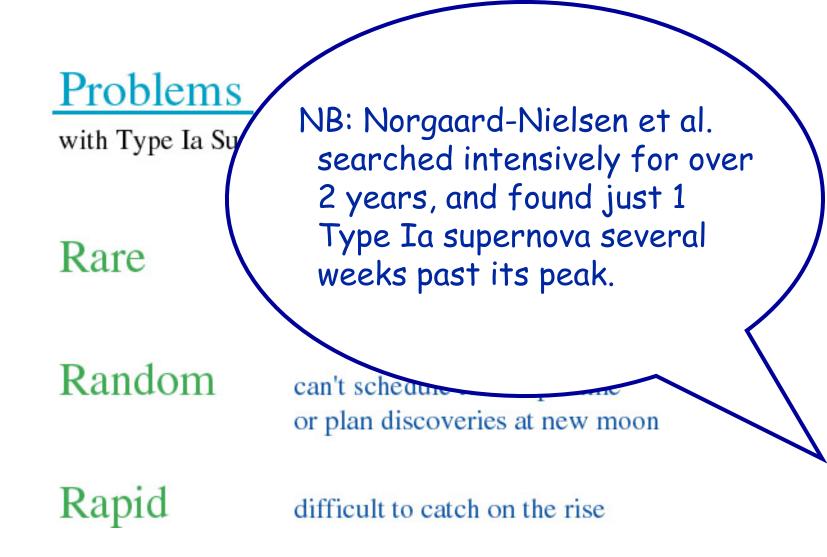
SUPERNOVA IN M99 GALAXY IN VIRGO CLUSTER

Photo by : LBL SUPERNOVA SEARCH TEAM.



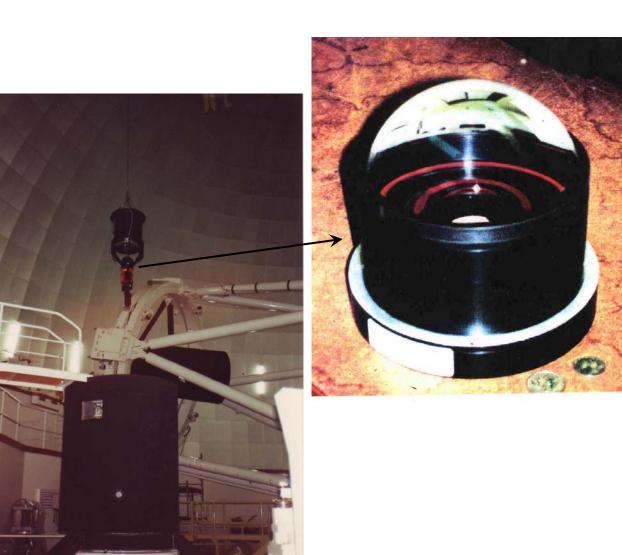
# Why is the supernova measurement *not* easy?

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



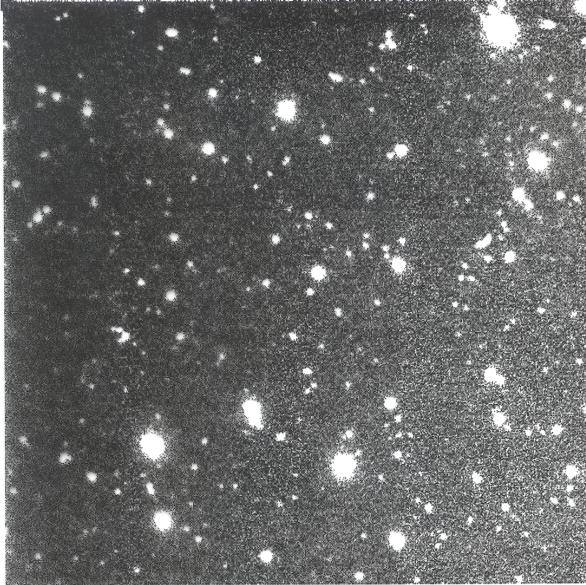
Pennypacker & Perlmutter 1987 proposal:

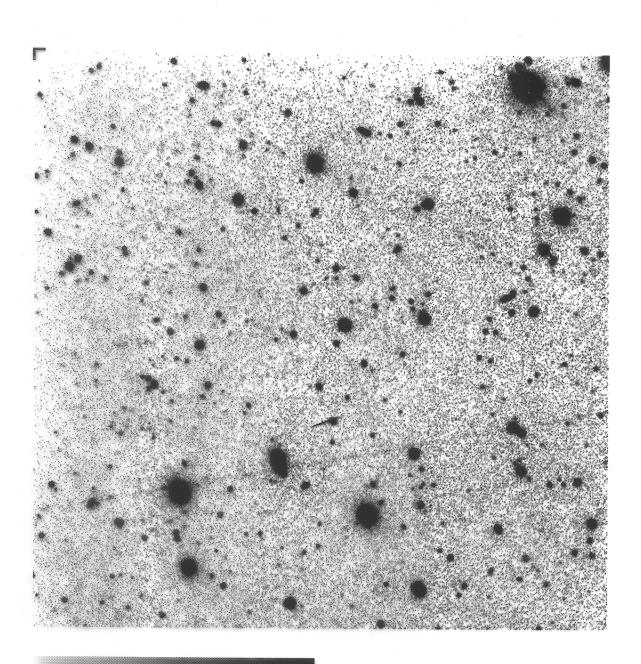
# A novel F/1 wide-field CCD camera for the Anglo-Australian 4-m telescope (AAT)

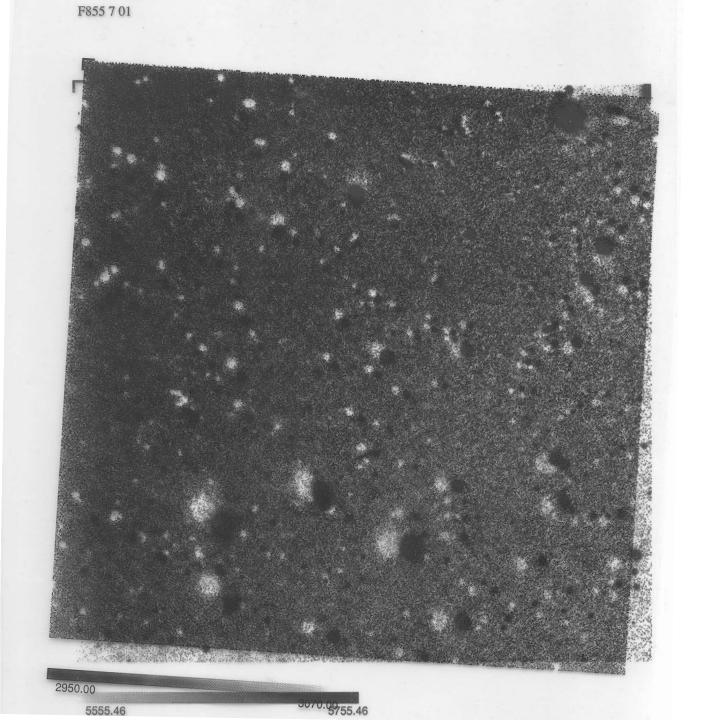


...A big enough telescope with a wide enough field to search for z > 0.3 Type Ia supernovae in 100s of galaxies with each image.

# Pennypacker & Perlmutter 1988 wide-field CCD camera at AAT



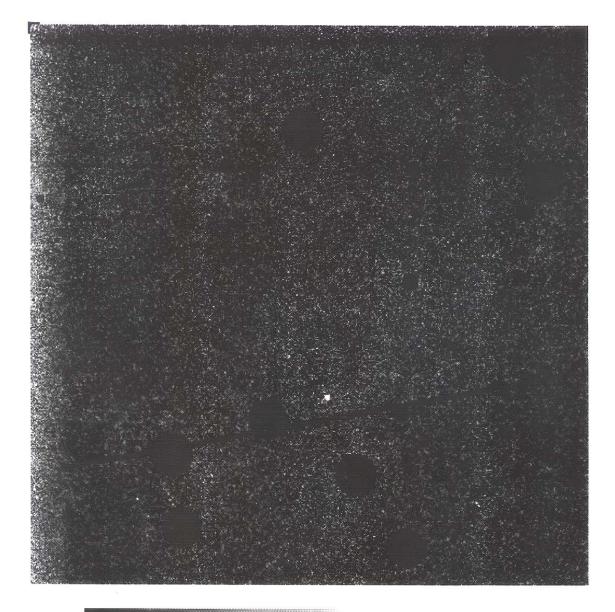








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# Problems

with Type Ia Supernovae as a tool for cosmology



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

difficult to catch on the rise

Rapid

# Search Strategy Perlmutter et al (1994) Image: Perlmutter et al (1994)

Central Bureau for Astronomical Telegrams INTERNATIONAL ASTRONOMICAL UNION Postal Address: Central Bureau for Astronomical Telegrams Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A. IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions) BMARSDEN@CFA.HARVARD.EDU or DGREEN@CFA.HARVARD.EDU (science) Phone 617-495-7244/7440/7444 (for emergency use only)

#### 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 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

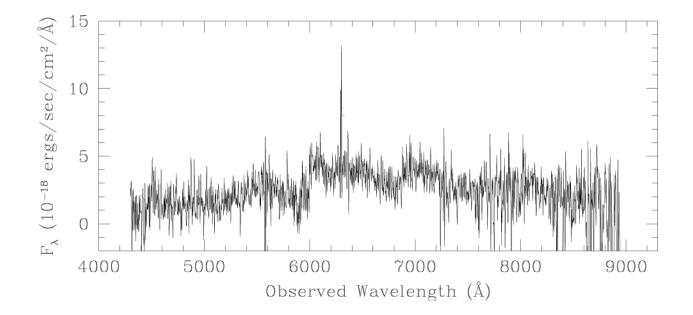
The spectra (Keck, Nov. 26-28) are consistent with type-I supernovae (except SN 1995av, a probable type II) at the redshift of the host galaxy: z = 0.45, 0.46, 0.49 (preliminary type-I identification), 0.65, 0.16, 0.30, 0.4 (supernova redshift only), 0.61, 0.48, 0.45, 0.39. Photometry obtained on Nov. 21-23 at CTIO (A. Walker) and Nov. 23-27 at WIYN (D. Harmer, D. Willmarth) indicates that SNe



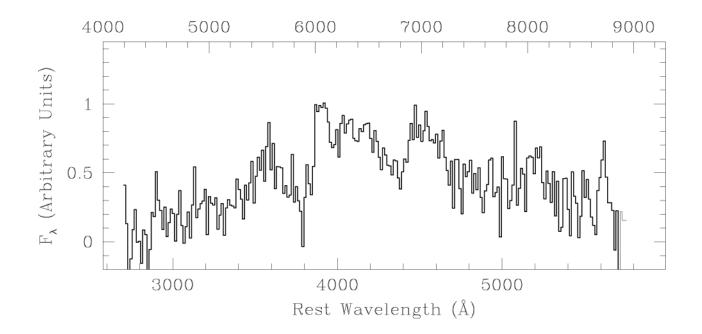
# Why is the supernova measurement *not* easy?

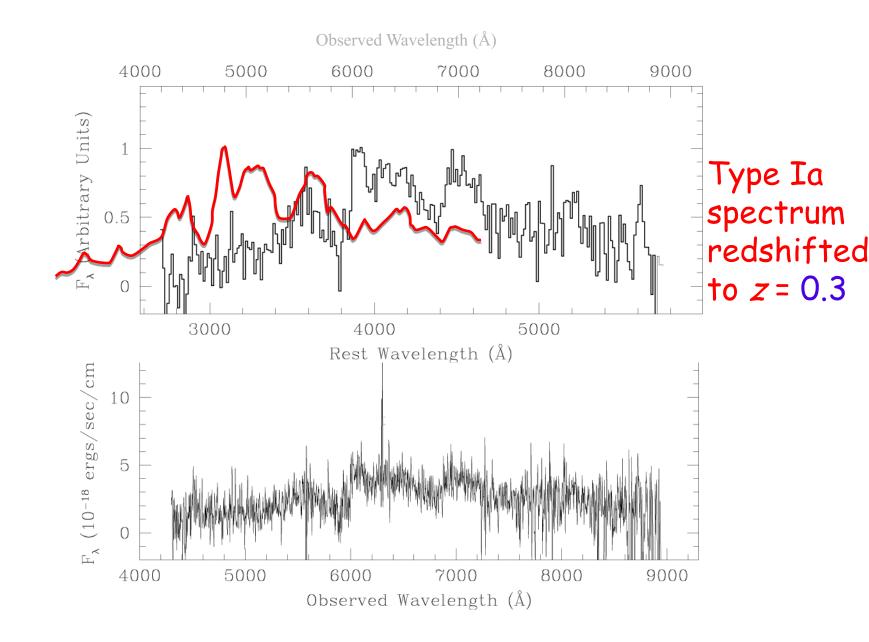
- Can they be found far enough -- and enough of them -- for cosmology?
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- 3. Are the supernovae standard enough? And how can one eliminate possible dust from diminishing their brightness?
- 4. Couldn't the supernovae evolve over 5 billion years?

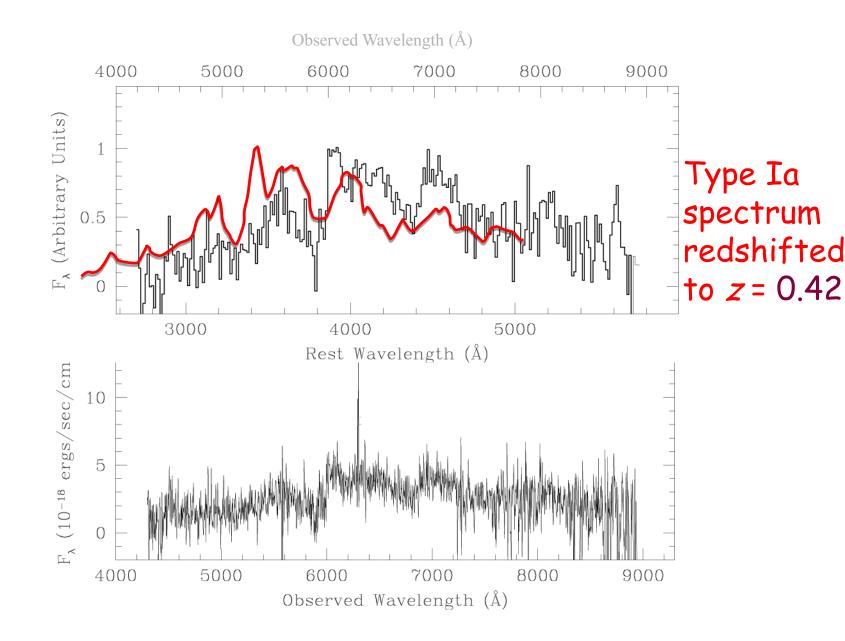
And, in fact, the spectra do look like noise ...until you know what you are looking for.

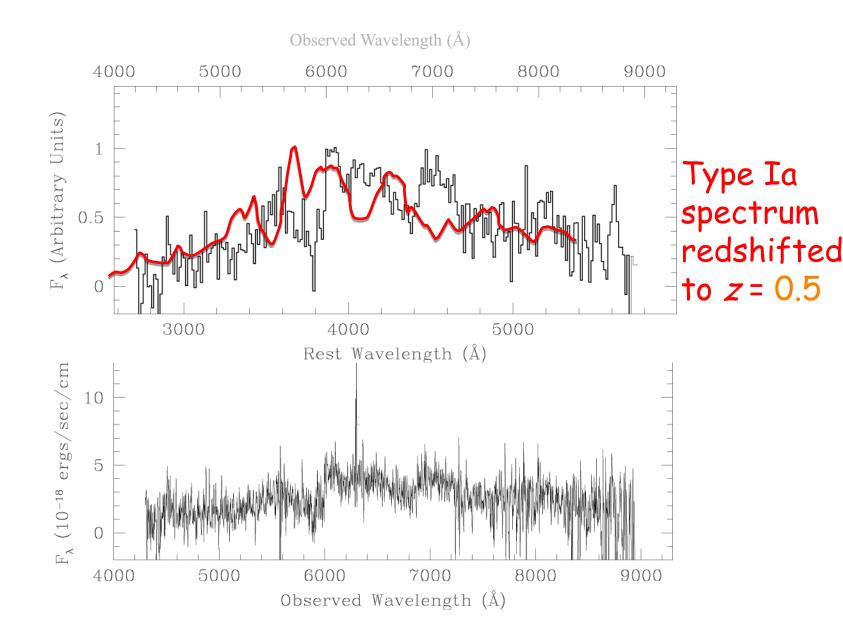


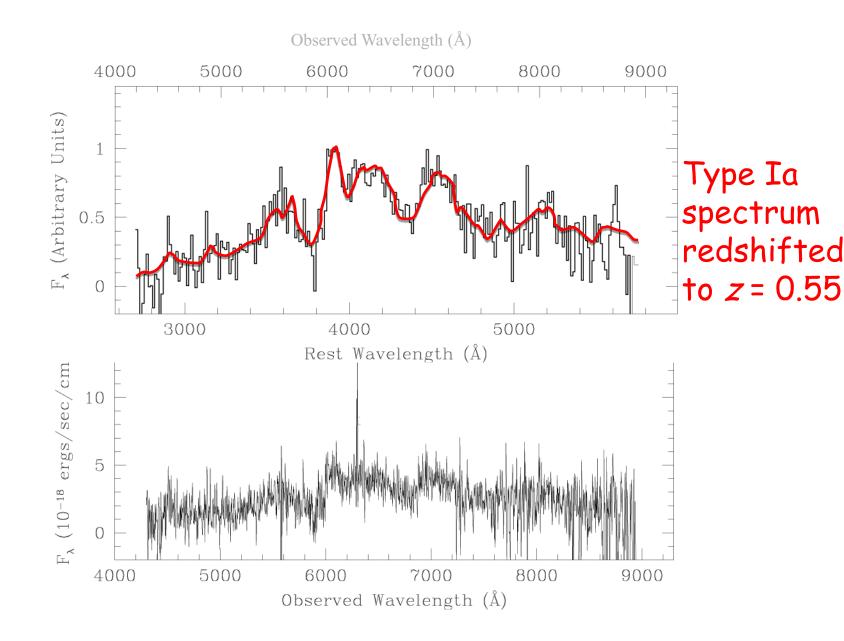
Observed Wavelength (Å)

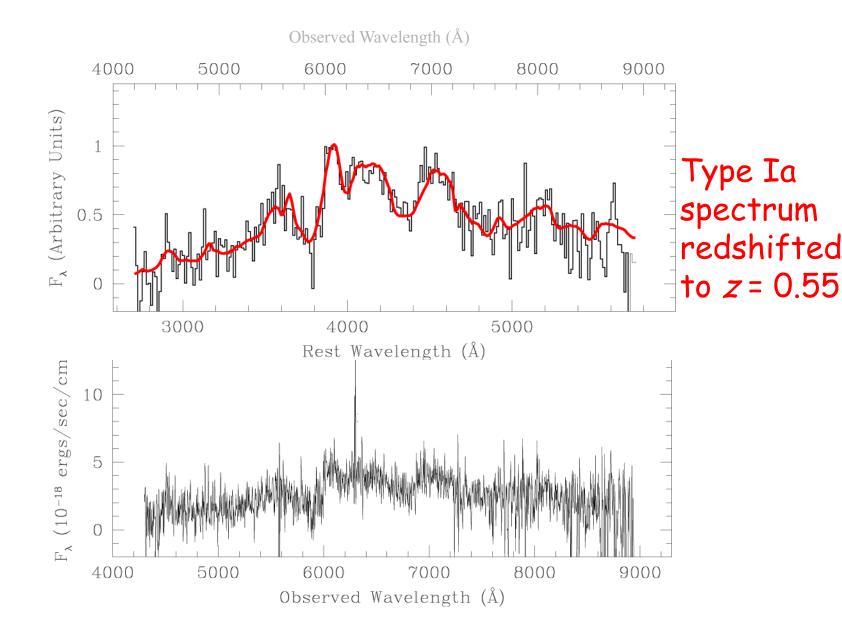


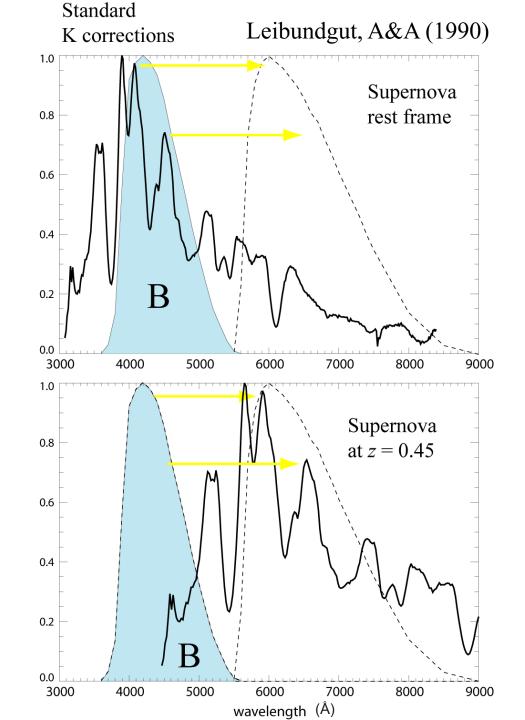


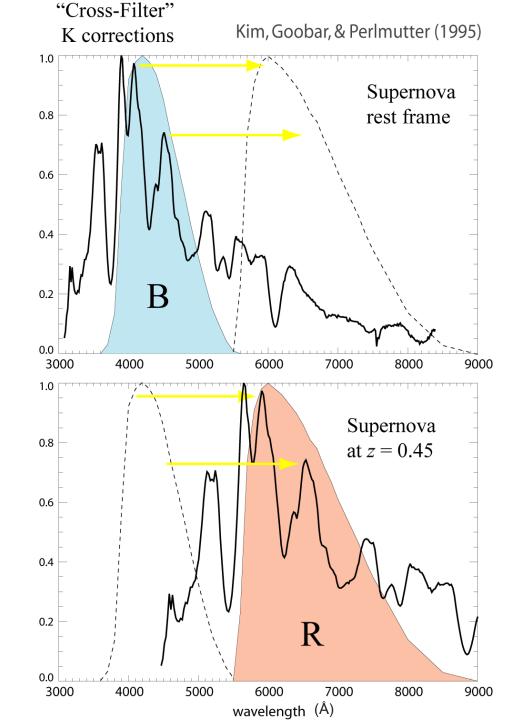








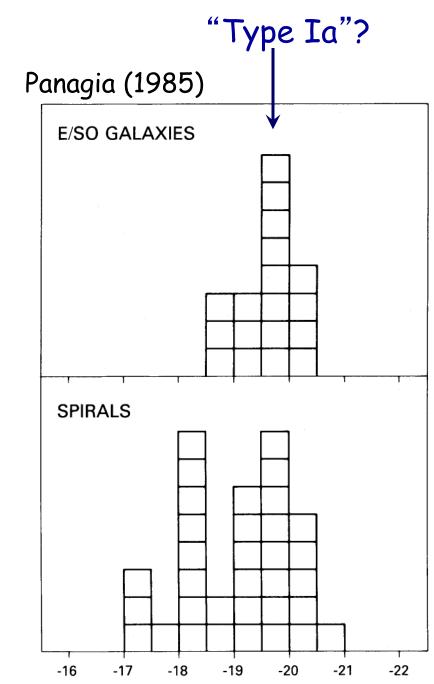






# Why is the supernova measurement *not* easy?

- Can they be found far enough -- and enough of them -- for cosmology?
   Can they be found early enough to measure brightness over peak?
- 2. If found, they won't be bright enough to identify as Type Ia with spectrum.
  And how can their brightness -- greatly redshifted -- be compared with nearby ones?
- 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?



 $M_{\rm B}$  (max)

Astrophysical Journal , 585,52,55,2003 March 6. The Instantian I are social & day, 10 righteneous Piktel Freine die U.S.K.

CONSTRAINTS ON CARDASSIAN EXPANSION FROM DISTANT TYPE IS SUPERNOVAE Zong-Hong Zhu and Masa-Katsu Fujimoto National Astronomical Obstructury, 2:21-1, Dava, Mileka, Telyo 181-9533, Japan zmoghong shu Strao acip, Ayim oto mas-katsu Shao acip Revised 2020 Avust 20:3 accorded 2020 Avust 20:3 accorded 2020 Avust 20:3 accorded 2020 Avust 20:3 accorded 202

#### ABSTRACT

The distant Type Is supernovae data compiled by Perimetra et al. are used to analyze the Cardiastian exgransion semanic, which ware recently proposed by Prease & Lewissean alternative to a comological con-tant (or more speciarily dark's energy component) in explaining the surrently accessing users. We show that the allowed intervals for nod 2a<sub>2</sub>, the two parameters of the Cardiastian model, will give rais to autr-ment with any two matter density, which can hardly be encoding with the compression area given and from the mean with any two matter density, which can hardly be encoding with the compression area given and the other sections of the Cardiastian model, will give rais to autr-density and the constant density which can hardly be encoding with the compression area given and the form the sections of the section of the complexity of the complexity the section of the complexity the the complexity of the section of the complexity of the complexity of the complexity of the complexity the section of the complexity o releasements every down and er betrang, when can narby be reconnaid when released with the contract value betrang information measurements of the cosmic microware beauging round an isotropy and galaxy clustes (cluster larger of narbio). A sar result, the Candassian expansion proposal does not seen to survive the magnitude radshift test for the present Type I subpervice addat, where the universe contains primarily targonic matter. Subject headings: cosmological parameters \_ cosmology: theory \_ distancescale \_ supernovae: general

#### 1. INTRODUCTION

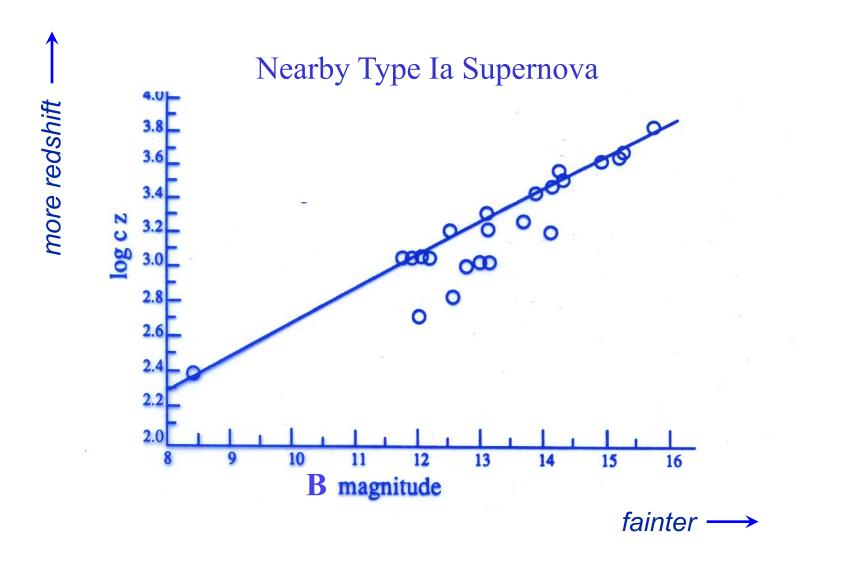
A major devotes in moderno contrology is the discov-ery of the acceleration of the universe through observations of datars Type langemone (Printmet et al. 1086, 2007). Filteret al. 1086, 2007), Labourdopy 1000(1), It is well known and an article trefore the discovery of the activity of the verse, conventionally, a deviation to factor is always used to describe the status of the ultimet of the high-relating Type 1988), Ginen this the discovery from the high-relating Type 1989, Dirent this the discovery from the high-relating Type It a supernovae indicates the existence of a new component with fairly negative pressure, which is now generally called bard energy, but as a cosmological constant (Warhego Construints, Schwart, Schwart, Schwart, Schwart, Schwart, Orsteins, Schwart, Schwart, Schwart, Schwart, Schwart, Inderend to by some acquinessence. Rarra & Paubles 1965; Vertreich 1987; Caldwell, Dawe, & Seinhardt 1956; Gong 2023; White currert measurements of the cosmic micro Frierren 1927, Caldwell, Davis, Steinhart 1958, Coog 2020, White course the access the construction access the construction of the construction with cold ark matrix (b6 farmache at 2020, Languer at 2020), both the device interface at 2020, Languer at 2020, Loss the device in splank values means of in four the structure of the structure interface at 2020, Languer at 2020, Loss the device in splank values (Section 2020, Section 1998), and the structure interface at 2020, Languer at 2020, Loss the device in splank values (Section 2020, Section 1998), and the structure interface at 2020, Languer at 2020, Languer (Burles 6, Triffer 3026), Tok estimates provide at al. 2020, The end at structure (Barbard 2020, 1998), and the structure interface (Barbard 2020, 1998), and the structure (Barb

Futurnam & Harrana 1999; Jain et al. 2001; Dev et al. 2001; Ohyama et al. 2002; Serano 2002). Neither a cosmological constant nor a quintemene, the present candidaterior the universamcederation mechanism, however, avoid the cosmic solveidence problem, why the distribution of task appears and dark metter are conceptible. Intervente, audo tiña comito cionedarios problem, with the context people data segure para tabal qui ne terme assessante la context people data segure para tabal qui ne terme assessante ing problem, ase Carcello et al. (2021 for a dissuession of the data segure para tabal qui ne terme assessante assessante data hardar 1000 processante para terme assessante anna tabal qui ne terme qui ne data segure data segure para segure para tabal qui ne terme qui ne data segure para segure para tabal qui ne terme qui ne data segure para segure para tabal qui ne terme qui ne data segure para segure para tabal qui ne terme qui ne data segure para segure para segure para segure qui ne data segure para segur

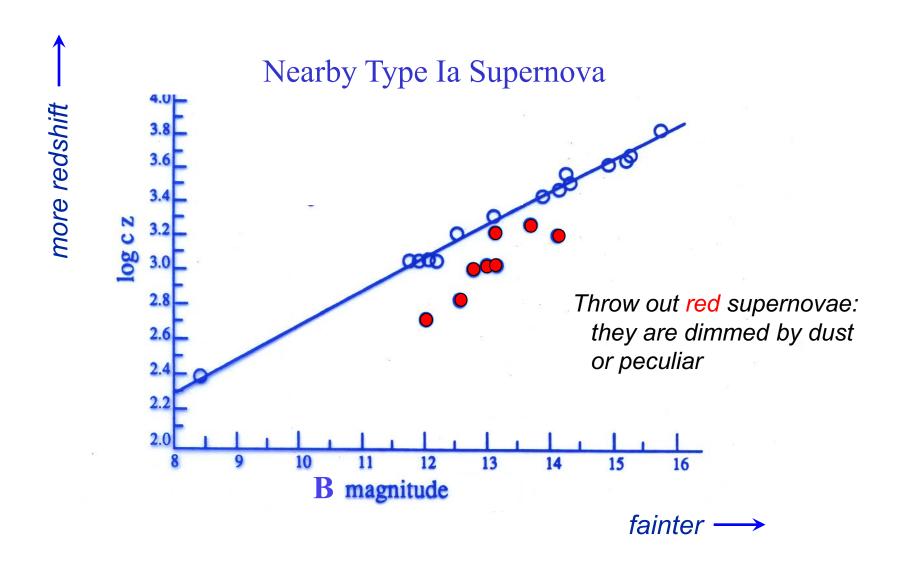
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Vaughan, Branch, Miller, & S.P. (1995)



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



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# 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

CONSTRAINTS ON CARDASSAN EXPANSION FROM DISTANT TYPE In SUPERNOVAE Zong-Hong Zhu and Mana-Katsu Fujimoto Natona Astrona id Charnetery, 2211, Josen, Milles Johg 1918-1988, January Darga Manaka asja, Ajin do nas-latu Shaoas

RSTRACT

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1. INTRODUCTIO

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#### tamase & Hamana 1999; Jain et al. 200

• should as a particle back dots. Note that the should be also be als

where H EHF is the Hubble parameter as is (uncold the original density of matter and radiation. In the user density of the transmission of radiation is the energy density of matter and radiation. In the user density of the energy density of matter and radiation. In the user density of the energy density of matter and the energy density of the energy density density of the energy density of the explored and the e

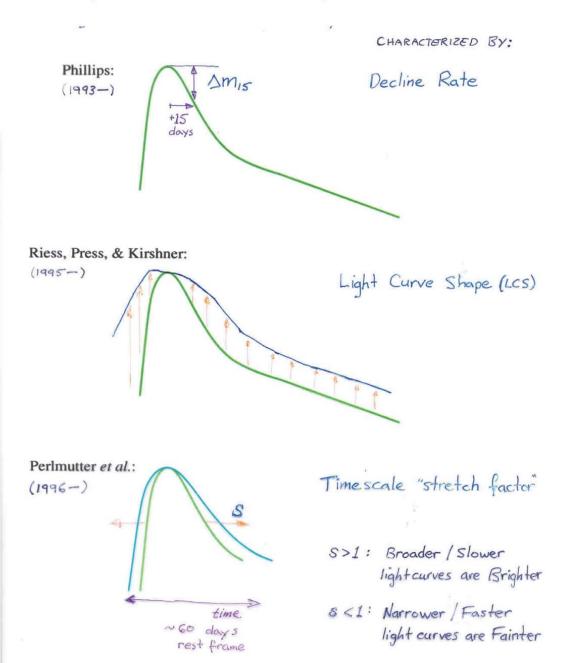
Hamuy, Maza, Phillips, Suntzeff et al (1993)

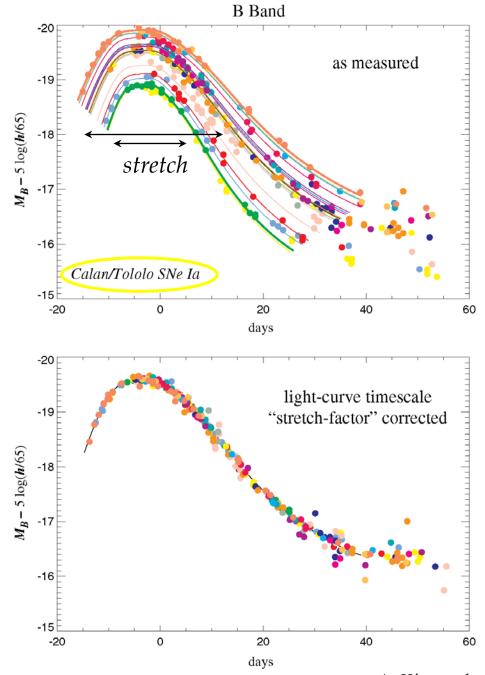
"Calan/Tololo Supernova Search"

A beautiful, well-measured set of nearby supernova

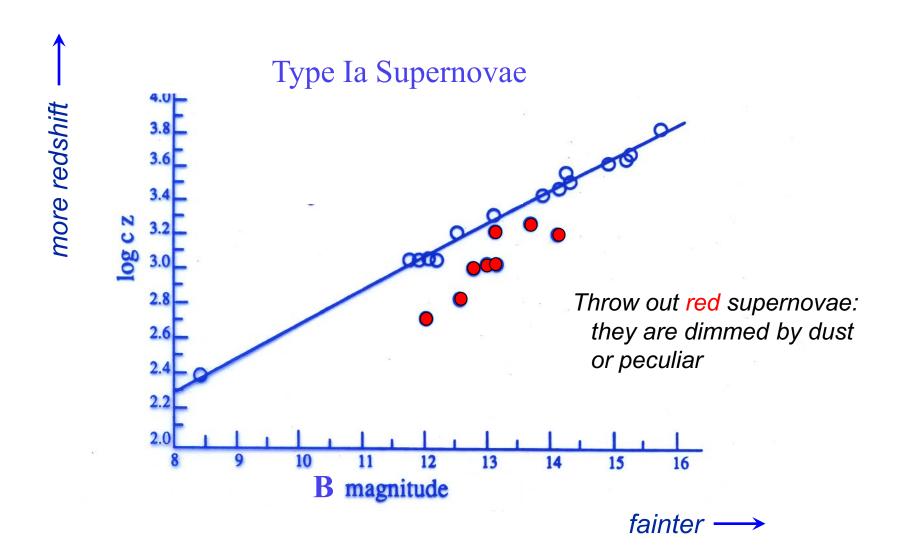
now observed dispersion goes down to ~18% after color selection

## Lightcurve Width-Luminosity Relation



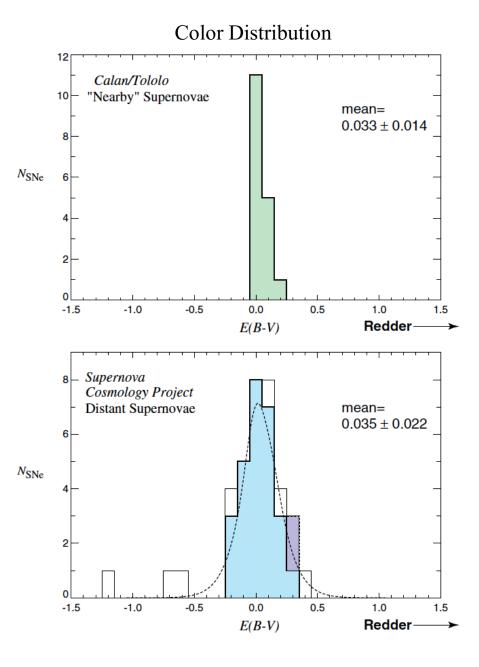


A. Kim et al.



# Compare color distributions,

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



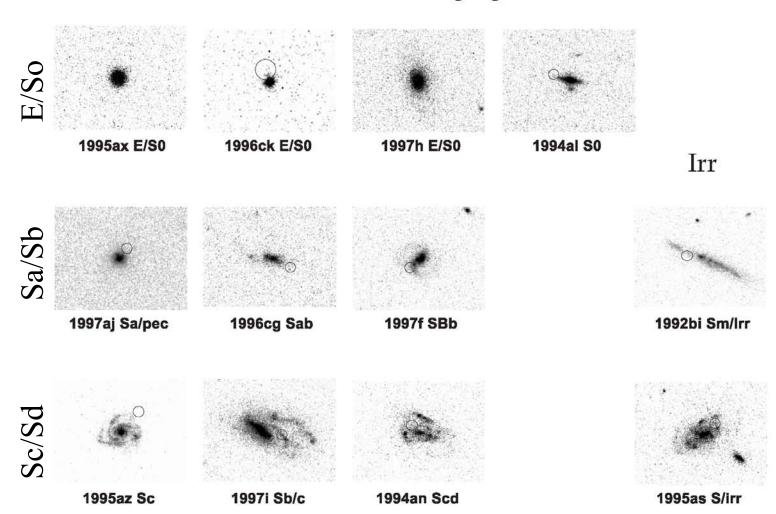


# Why is the supernova measurement *not* easy?

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

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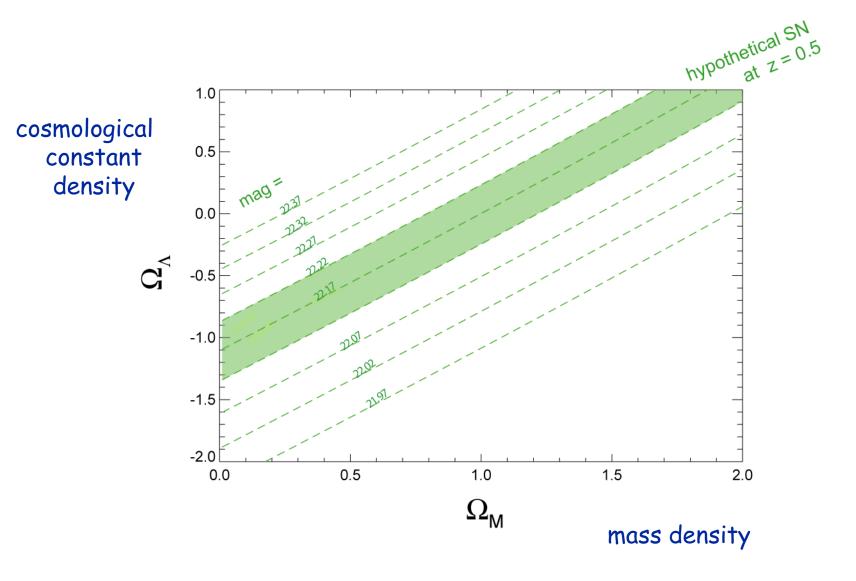
# Why is the supernova measurement *not* easy?

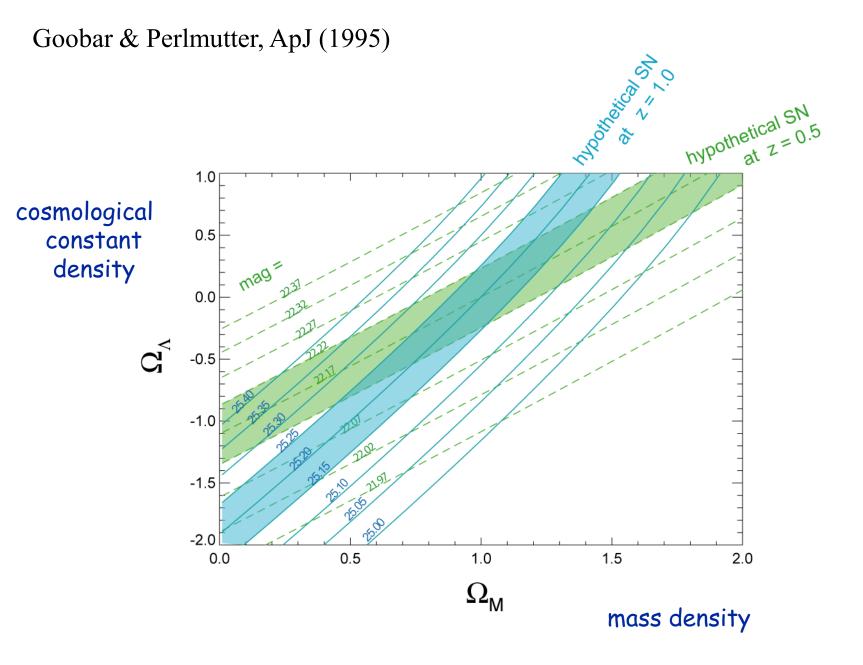


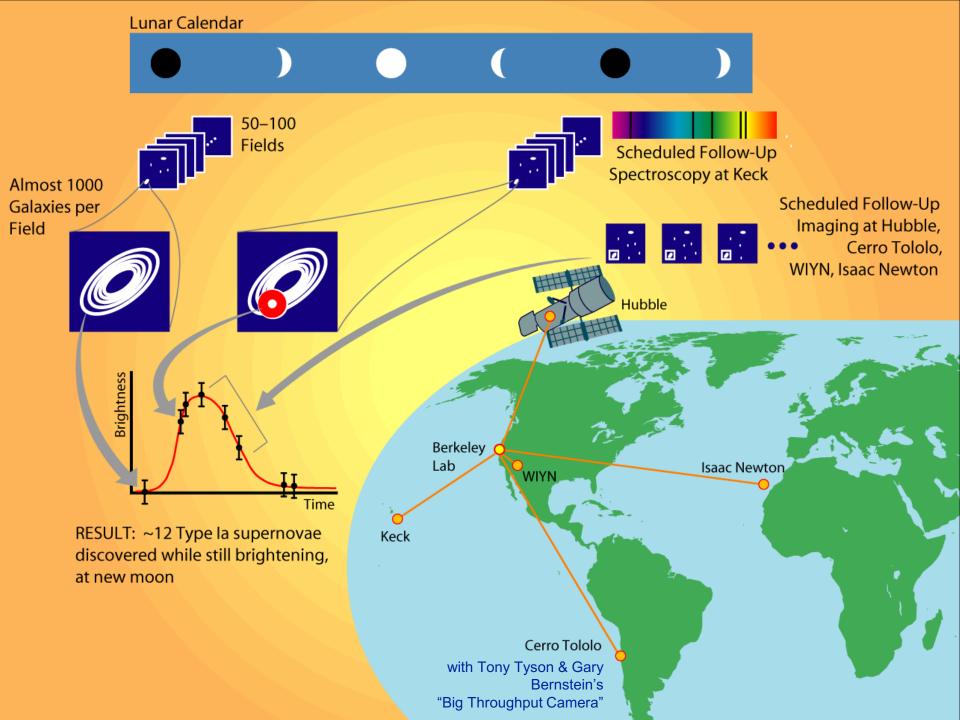
5. What if Einstein's "Cosmological Constant" (Λ) exists? It will fight against gravity due to mass (M) in the universe

-- how can you tell if there is less M or more  $\Lambda$  or vice versa?

Goobar & Perlmutter, ApJ (1995)



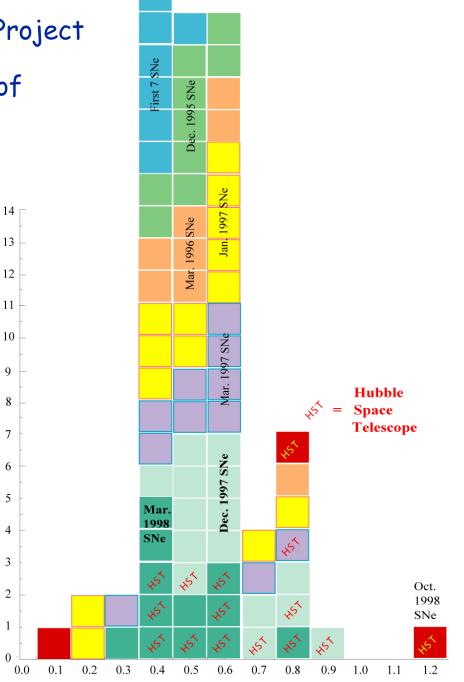




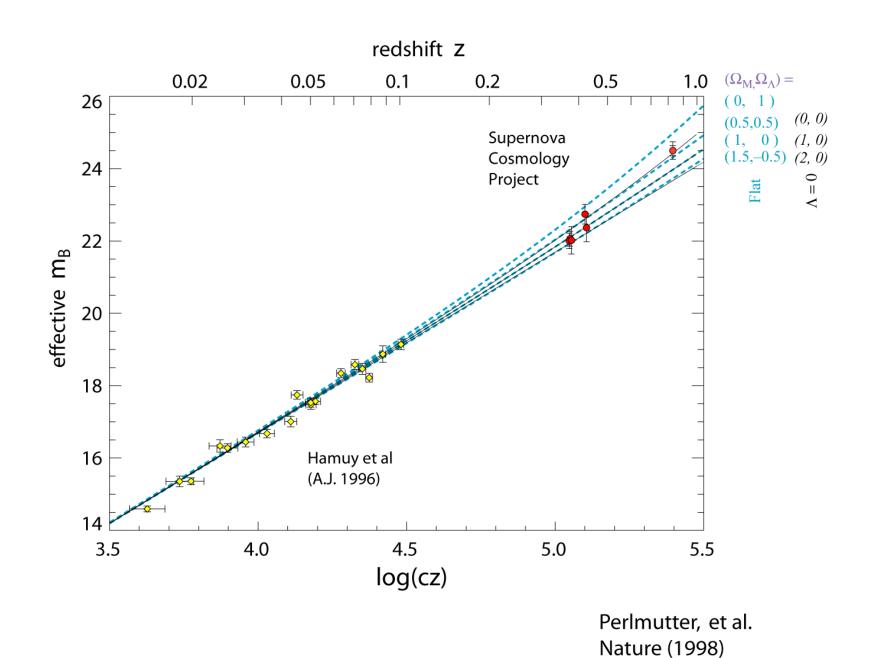
Supernova Cosmology Project

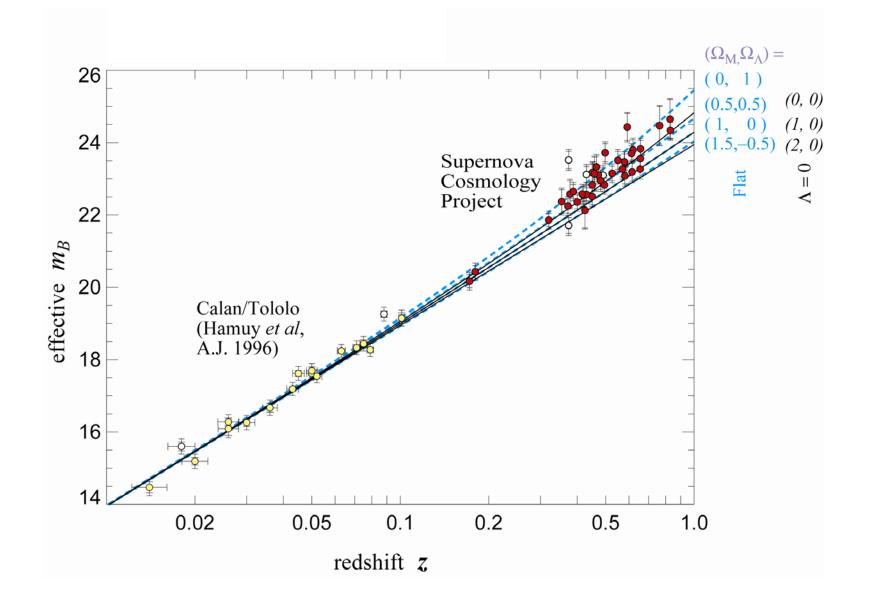
 $N_{\rm SN}$ 

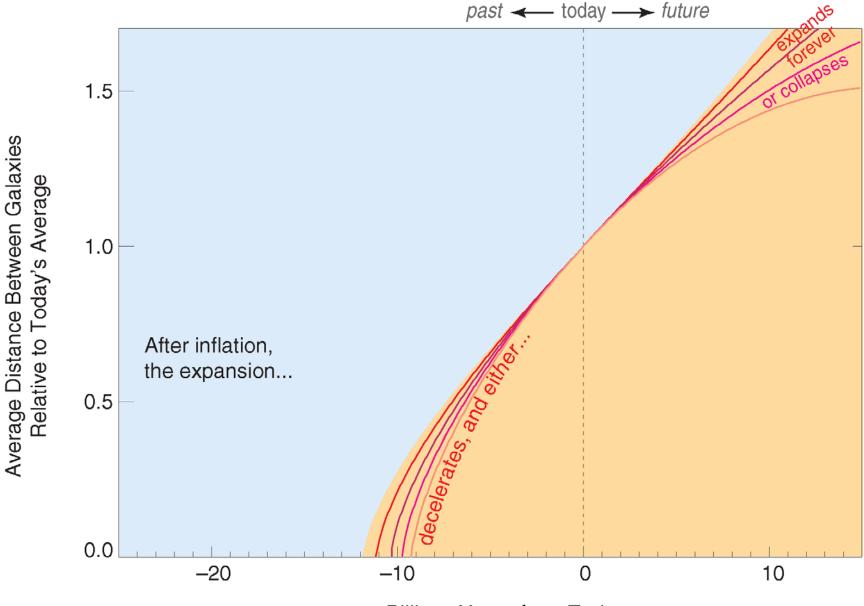
redshift distribution of Type Ia supernovae as of 1998



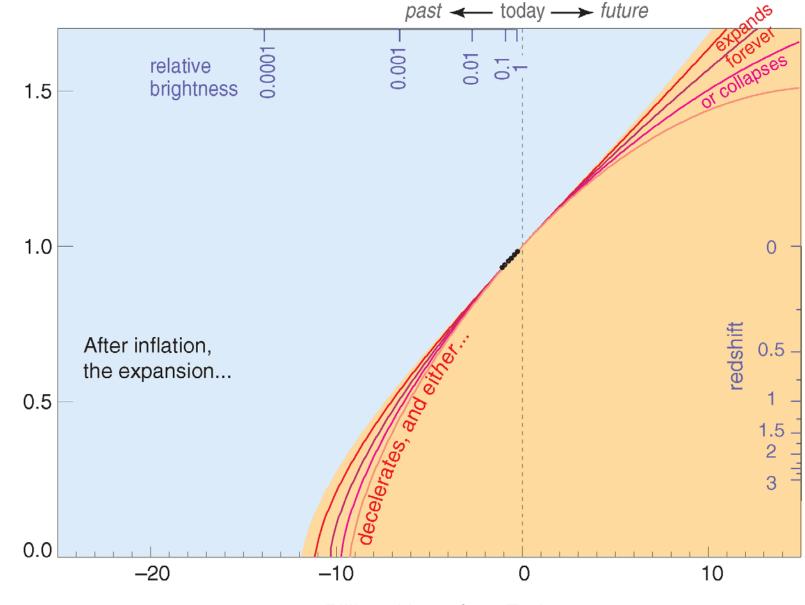
Redshift





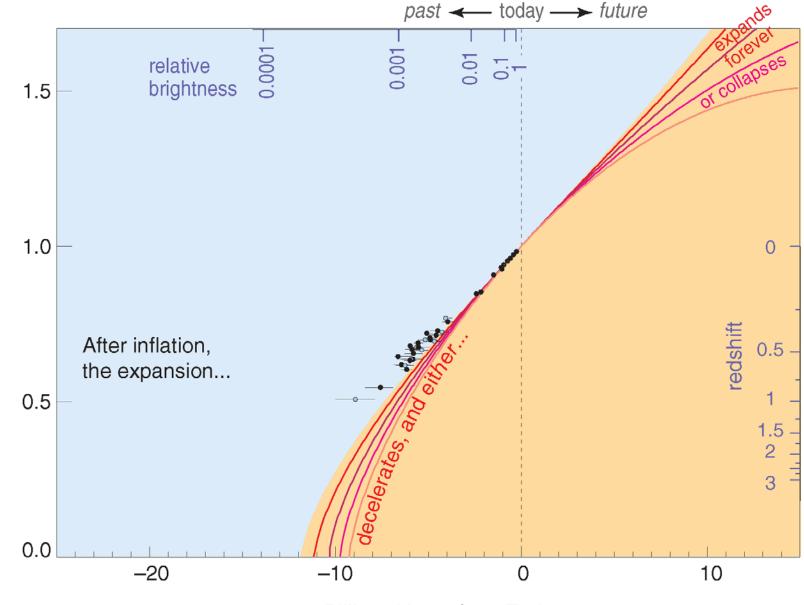


Billions Years from Today



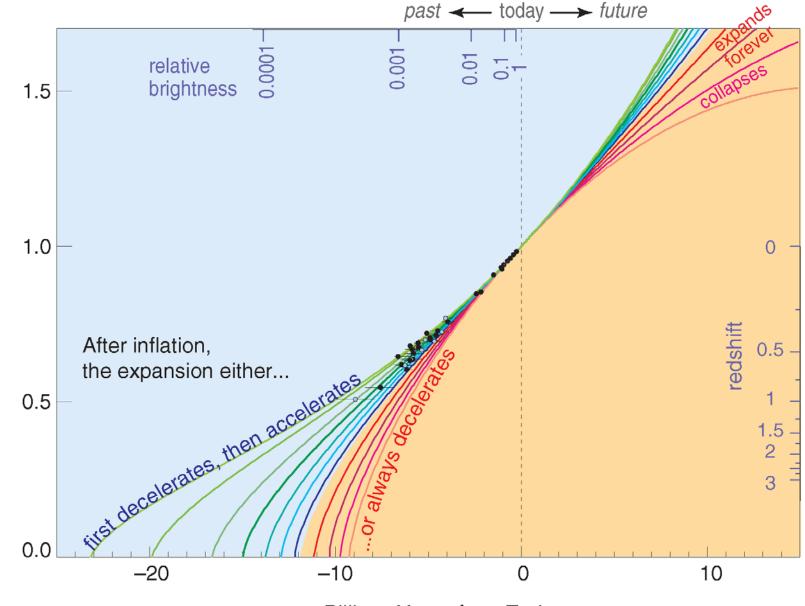
Billions Years from Today

Average Distance Between Galaxies Relative to Today's Average



Billions Years from Today

Average Distance Between Galaxies Relative to Today's Average



Billions Years from Today

Average Distance Between Galaxies Relative to Today's Average

## Atomic Matter

**4**%

Dark Matter 24%

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

Dark Energy 72%

A sa result, this Cardassian expansion proposal does not seem to survive the magnitude redshift test for the present Type lasupernovaedata, unless the universe contains primarily baryonic matter. Subject headings cosmological parameters , cosmology: theory , distancescale , supernovae general

> Futamase & Hamana 1999; Jain O hyama et al. 2002; Sereno 2002

Neither a cosmological const

Beinhardt 1999) provides a possib

per use physics is still far o . . . erefore explore alternative possibilities och a (De ayet, Dvali, & Gabadadze 2) an altered theory of ormitation

lem, a convincing dark energy particle physics is still far o

where H B=R is the Hubble

of cosmic time, R is the scale factor of the energy density of matter a

FRW equation, B %0. To be cons

shown that (Freese & Lewis 2002) B ½ b ½ þ ð1 þ z<sub>og</sub> p<sup>öt ne</sup> 1, where o**g t**he

second group of models assume an evolving scalar Geldpos-

essing a negative pressure and cold dark matter. It also @ts

ell the observational constraints, and seems rather natural

but it is not clear whether it really solves the coincidence

substratum not as simple as a pressureless perfect juid, there

eem to be no *a priori* reasons to exclude a coupling between

tional deshown to provide qualitatively new reatures which may be the mode

both components. Interacting quintessence models have been 🗮 🗰 🖬 🗰

Most of the QCDM models assume at the

has been demonstrated that a suitable coulding ma

to a stable constant ratio of the energy d

moments which is compatible with an a

and the scalar Geldcomponents evolve a specific experiment aver, given that the physical nature or to quintesses is still unknown and also that the dark matter may w

intriguing because the expansion accelerated automatically later w

however, avoid the cosmic coincidence prob

densities of dark energy and dark matter are comparable

today (another related but distinct di culty is the "ne-tun

ing problem; see Carroll et al. 1992 for a discussion of this

point). Although the tracking "eld model (Zlatev, Wang, &

an altered theory of gravitation (Behnke et al. 2002)

H<sup>2</sup> % A F

FRW result, one should take A 1/48 G=3. It is

recently, Freese & Lewis (2002) proposed the Gardassian

expansion spenario in which the standard Eriedmann

Robertson-Walker (FRW) equation ismodi' ed asfollows

tion to this pro

present candidates for the univer

#### 1. INTRODUCTION

A major development in modern cosmolociu is the dispoverv of the acceleration of the universe through observations of distant Type I a supernovae (Perlmutter et al. 1998, 1999; Riesset 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 secondarian (Sandare 1988) Given this the discovery from the high-redshift Tyrus la 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 "eld (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 anisot ropies favor a spatially "at universe with cold dark matter (de Bernardis et al. 2000) Lance 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 lowdensity 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, Dalv. & Wan 2000; Dalv & Guerra 2002; Podari u et al. 2003). the age estimates of old high-redshift galaxies (Dunlop et al. 1995; Kirauss 1997; Albaniz & Lima 1999), and gravitational lensing (Kochaneck 1995: Chiba & Yoshii 1999:

> anthoge-disposed unit, the 25% protessorme. Ainland D. View components happens to be of the same order toda Because the application of a protessorme Generic, #5 Ke inhibitor to the pistil also impairs the rejection of self pollen, the targets of ARC1 ubiquitination must be degraded by this Cosm ology multi-enzyme.complex. A just problem for a recent review see OH.

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Thesubstrate(s) of ARC1 ubiquitination, and how SRK affects ARC 1 activity, pervain unknown. Unfortunetely, ARC1 is unlike any other known U-box protein, so guilt by association cannot be used to predict its target. The large increase in ubiquitinated proteins observed after a self-pollination suggests that a marked shift in target selection occurs in the papilla cell. But how does this shift cause the changes seen during clien rejection? Regues 1 shows some possibilities. ARC1 zero has challen and the coincidence problem GO pollen rejection?

rnight target proteins in the papilla cell that the way we th no mally promote pollen commination and reconsidering direct them to the protessome for breakultimate fat down. Degradation must somehow be significantcheor the Universe Gil# On the other hand. metricited to new where the popula celland involves a negativer the question of how such a stationary solution can be elf pollen grain touch, so a no ther possibility upod to be an endeted to ubiquitin@rolein vesiclesorting: mentioned in ubiquitination of specific transport proteins helps to direct the flow of vesicles to approprintecellular destinctions'. Consistent with this notion was the finding by Stone et al. that when ARC1 is phosphoryleted by SRK it is no longer mostly in the nucleus but enters the cytop learn, where it seems to easociete with the endoplearnic reticulum and fish they might up nder why it use full of on fundame secreto ny system. Focused secreto ny activity at the contact effected localized localencing of around to observe itld. the papilla cell wall are even to seen soon after a compatible pollination". ARC1 ubiquitination could present the delivery of proteins seriously is that it goes against the grain. However, Bjorken Ň a particle theories and other molecules that are essential for Most physicists have hoped that an ultimate Ň notes that a cosmological constant pro germination or wallloosening to the contact

. Meofelfoollen Stone and colleaguesOvork constitutes a step forward in our understanding of brassica self-incompatibility. But is there a bigger picture to well? Other plant families have evoked self-incompatibility mechanisms Standard Model/Bjorken propose a new that are noised, different to that found in Scaling Canasta, based on well-stablished breasings. Selfincompatible species in the Romene fimily, which includes apple and anthropically viable a small cosmological light and so causal contact will be lost. This correcther fruit trees, uses differentS-locus- constant might be. encoded enzyme Ň a ribonuclease Ň to in hibit the growth of self pollen. What is the but non-zero, cosmological constant might of an infinite clears the S-locus product that identifies self exist has changed physicists O interest in like expan pollen. Two tantalizing reports have shown anthropic explanations of nature precisely

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it does, rather than why it more often than

Jarnes Bjorken. In a paper<sup>o</sup> published in Phyr

notions in particle theory, to rexploring how

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#### Cosmology with Ladryon Geldae dark energy



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Luis P. Chimento,<sup>1</sup> Alejandro S. Jakubi,<sup>1</sup> Diego Pawła,<sup>2</sup> and Winfried Zimdahl<sup>3</sup>

1428 Buenos Aires, Argentina

simultaneously solve the coincidence problem of our present Universe. For this purpose we study the evolution

of the energy density ratio of these two components. We demonstrate that a stationary attractor solution is

compatible with an accelerated expansion of the Universe. We extend this study to account for dissipation

Nowadays there is a wide consensus among observational — solvable model for a smooth transition from a matter domi-

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present paper we clarify this point and establish an exactly

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may simultaneously help to drive acceleration and so

coincidence problem 62# A negative pressure arises natu

rally from bulk viscous dissipation, quantum particle produc

tion or self-interaction in the matter component G3# Here

verse can be realized in a commercatively simple menner

The paper is organized as follows. Section II introduces

the basic equations of the model. Section III explores the

dynamics of the energy density ratio, including the stabi

parameter. In Sec. V the available magnitude-redshirt data of

primordial nucleosynthesis data to restrict the parameters of

the model. Section 57 presents our conclusions and fina-

within the framework of general relativity.

ons in the dark matter "uid. Finally, type Ia supernovae 💒 primoritial nucleosyn thesis

The Astrophysical Journal , 595:52, 56, 2003 March . 005. The American Astronomical Society. All right seven ved. Frinted in U.S.A

#### CONSTRAINTS ON CARDASSIAN EXPANSION FROM DISTANT TYPE IS SUPERNOVAE

Zong-Hong Zhu and Masa-Katsu Fujimoto National Astronomical Observatory, 2-21-1, Osava, Mitaka, Tokyo 191-5558, Japan ; zong-hongshu5khao.acjp, fujimoto.maa-katsu5khao.acjp Received 2002 August 20; accepted 2002 November 7

#### ABSTRACT

The distant Type Ia supernovae data compiled by Perlmutter et al. are used to analyze the Cardassian expansion stenario, which was recently proposed by Freeze & Lewis as an alternative to accosmological 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 an isotropy and galaxy clusters (cluster baryon fraction). A sa result, this Cardassian expansion proposal does not seem to survive the magnitude-redshift test for the present Type lasupernovaedata, unless the universe contains primarily baryonic matter.

Subject headings cosmological parameters , cosmology: theory , distancescale , supernovae general

#### 1. INTRODUCTION

A major davelopment in modern cosmology is the discov-pery of the acceleration of the universe through observations of distant Type I a supernovae (Perfmutter et al. 1938, 1999; Please tai 1393, 2007; Lebry to be prediced a last, and the set of the set of

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2001), both the deuterium abundance measured in four whether the set of the urles & Tytler 1998a, 1998b) (combined action in galaxyclusters from X-raydata: 1993 for the method) and the large-scale distribution of galaxies (Bahcall 2000; 101) have made a strong case for a low <sup>1</sup>Denantamento de Fôrica. Facultad de Generias Exactas y ilatural es Universidad de Buenos Aires Gudad Universitaria, Pabellón J. for a recent summary, see Turner 2002a). these observations can be concordantly vpothesisthat there exists, in addition to a dark energy component with negative iverse (Turner 2002b). The existence of as also been independently indicated by ns such as the angular size..redshift pact radio sources (Guivits, Kellermann hwakarma 2001: Lima & Alcaniz 2002 03) and FR IIb radio galaxies (Guerra. ); Daly & Guerra 2002; Podariu et al. 2003), of old high-redshift galaxies (Dunlop s 1997; Albaniz & Lima 1999), and grav-Kochaneck 1995; Chiba & Yoshii 1999;

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024-6961/2002/75/295594499825.00

Futamase & Hamana 1999: Jain et al. 2001: Dev et al. 2001: Obcarra 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 di culty is the "ne-tuning problem; see Carroll et al. 1992 for a discussion of this point). A lthough the tracking "eld model (Zlater, Wang, & Steinhardt 1999) provides a possible resolution to this prob lem, a convincing dark energy model with a solid basis in particle physics is still far o . Therefore, it is desirable to explore alternative possibilities, such as higher dimensions (De avet, 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 ismodi' ed asfollows

#### H<sup>2</sup> ¼A b B <sup>n</sup>:

ð18

where H R=R is the Hubble parameter as a function of cosmic time, R is the scale factor of the universe, and is the energy density of matter and radiation. In the usual FRW equation, B ¼0. To be consistent with the usual FRW result, one should take A %48 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 (Freeze & Lewis 2002) B ½ H<sub>0</sub><sup>201</sup> fp  $z_{eq}$ <sup>201</sup>  $r^{o1}$  of ½ þ ði þ  $z_{eq}$ <sup>201</sup>  $r^{o1}$ , where  $_0$  is the matter density of the universe at the present time and H o ¼ 100 h km s <sup>1</sup> M pc <sup>1</sup> 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 enoch and drives the appeleration of the universe. It isvaluable 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

NTENTS		<ol> <li>The redshift angulanesize and redshift- magnitude relations</li> </ol>
		4 Galaxy counts
I Introduction	\$59	6. The gravitational lensing rate
A. The issues for observational cosmology	\$60	7. Dynamics and the mean mass density
B. The opportunity for physics	361	8. The baryon mass fraction in clusters of
C. Some explanations	\$52	ത്രിയാക
I Basic Concepts	<b>6</b> 63	<ol> <li>The cluster mass function</li> </ol>
A. Friedmann-Lemañoe model	<b>363</b>	<ol> <li>Bissing and the development of nonlinear</li> </ol>
B. the cosmological constant	565	mass density " us trations
n" ation and dark energy	\$66	<ol> <li>The aniso tropy of the cosmic microwave</li> </ol>
I storical Remarks	\$67	background rediation
Einstein's thoughts	\$67	12. The mass autocorrelation function and
2. The development of ideas	369	nonbaryonic mattee
<ol> <li>Early indications of L</li> </ol>	\$69	<ol> <li>The gravitational inverse-square law</li> </ol>
<ol><li>The coincidences augument against L</li></ol>	\$70	C. The state of the cosmological tests
3. Vacuum energy and L	\$70	V. Concluding Remarks
C. In ation	\$72	Note added in proof
1 The scenario	\$72	Acknowledgments Appendisc Recent Dark-Energy Scalar Field Research
<ol> <li>In ation in a low-density universe</li> </ol>	\$73	A ppendix: Recent Dark-Energy Scalar Field Research References
The cold-dark-matter model	\$74	Relations
E Dark energy	\$76	
<ol> <li>The XCDM parametrization</li> </ol>	\$76	
<ol><li>Decay by emission of matter or radiation</li></ol>	\$77	I. INTRODUCTION
<ol> <li>Cosmic @ald defects</li> </ol>	\$78	I. INTRODUCTION
<ol> <li>Dark-energy scalar Geld</li> </ol>	\$78	There is significant observational evidence for the o
V. The Cosmological Tests	580	tection of Einstein's cosmological constant. L. or a co
A. The theories	\$90	ponent of the material content of the universe that v
General relation	\$80	ies only slowly with time and space and so acts like
The cold dock enter model for along ture		
		all use the term <i>dark energy</i> for L or a component acts like it. Detection of dark energy would be
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erng pom bis of we biggo		new ue to an old puzzle: the gravitational effect of t
		point energies of particles and Gelds. The total w
<ol><li>Light-element abundances</li></ol>	585	other energies, that are close to homogeneous a
<ol> <li>Expansion times</li> </ol>	\$96	nearly independent of time, acts as dark energy. What

52



physical explanation of pality would explain vides a fund why the Universement look precisely the way that asympt vene: the not would not. Into the fmy has entered (what Bior and Review D, entitled @Cosmology and the objects raced proportional to their distance beyond a certain, fixed distance, all obje will recede at velocities greater than that of

The realization that an extremely small, c he recterize that a gene encoding another component of because the value it seems to take is otherwise dimensional



alerated exp

articular it

However, Bjorken N a particle theorist

distance, the de Sitter horizon, therefor

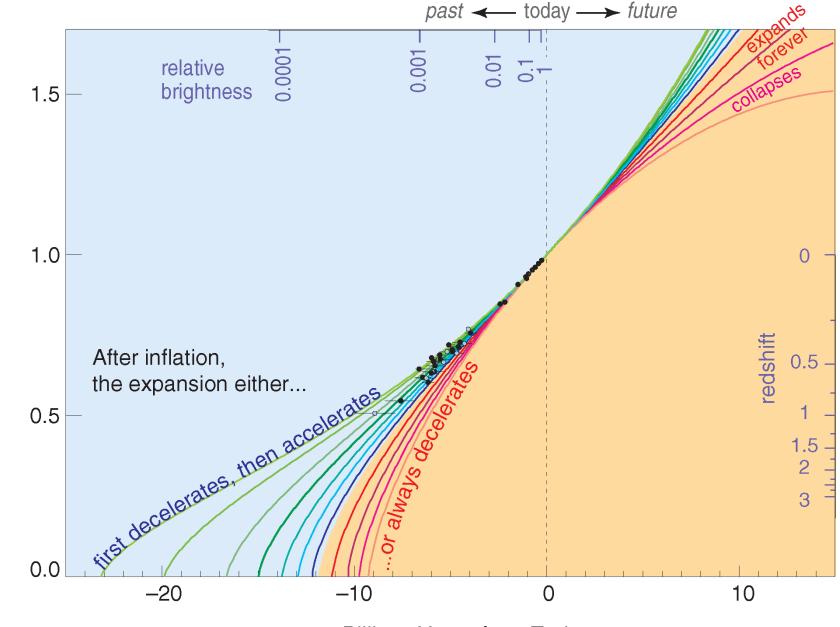


component., the second term, which may arise as a conse quence of brane world cosmologies, dominates at a late of Lenge at avdiv or and up with epoch and drives the acceleration of the universe. It is value that a state of the universe of the uni ble to explore the agreement of the Cardassian expansion and a solution of a solution of the Cardassian expansion and a solution of the Cardassian expansion and the solution of the solution of the Cardassian expansion and the solution of the Cardassian expansion and the solution of the Cardassian expansion and the solution of the model with the currently available ological observa**li, e mud pod el posteze** or e tion data, as suggested by Fre rious pape tsof the a proposed this scenario. In a p have used the recent measurem

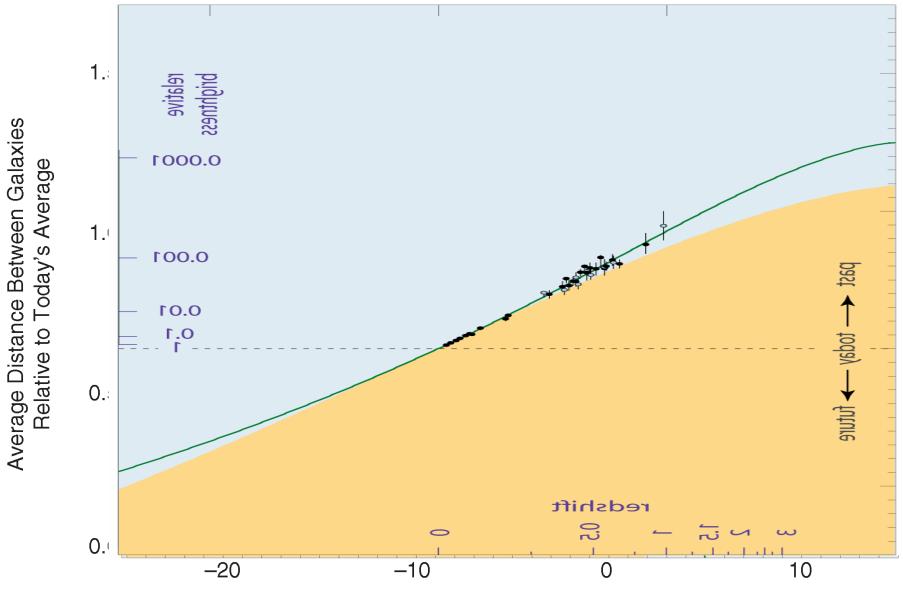
#OTOTOET1

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

Average Distance Between Galaxies Relative to Today's Average

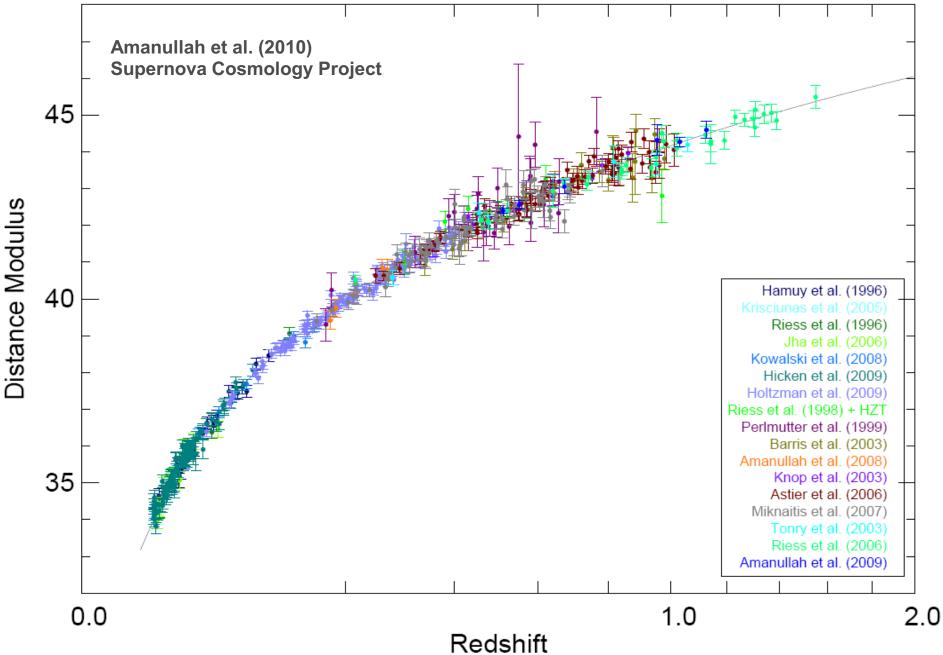


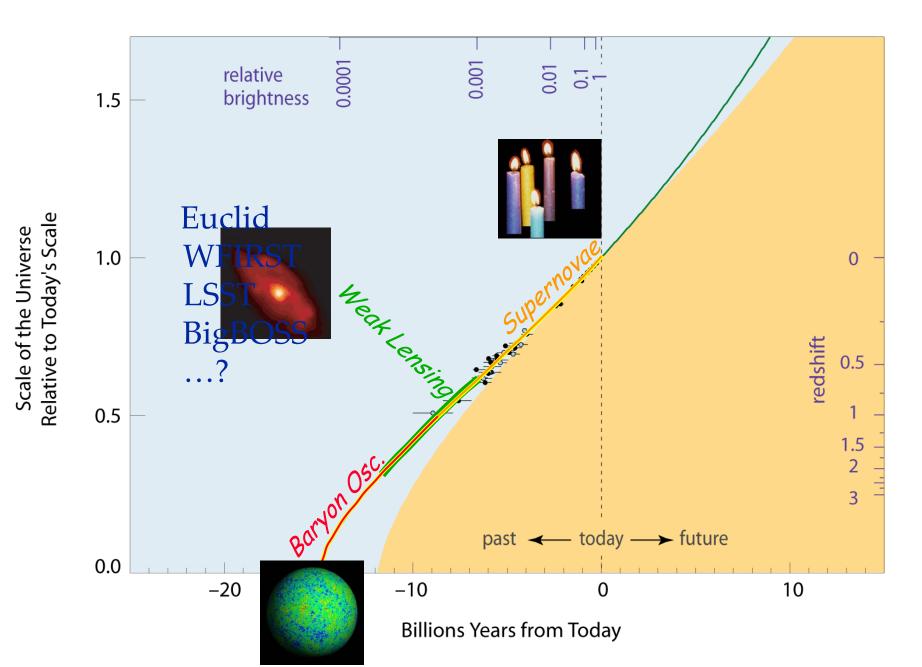
Billions Years from Today

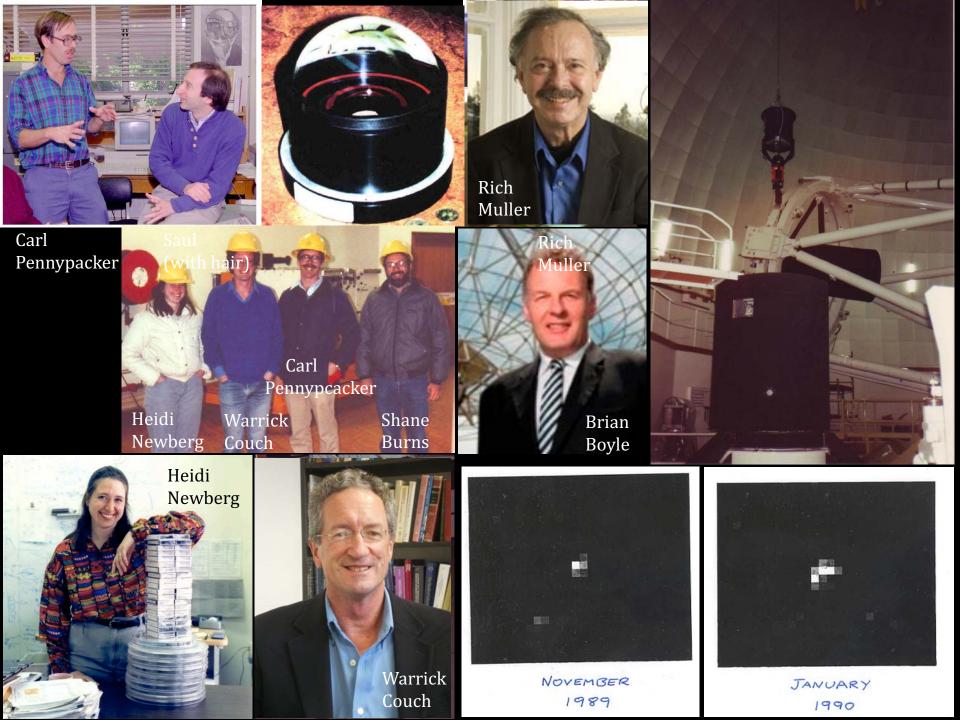


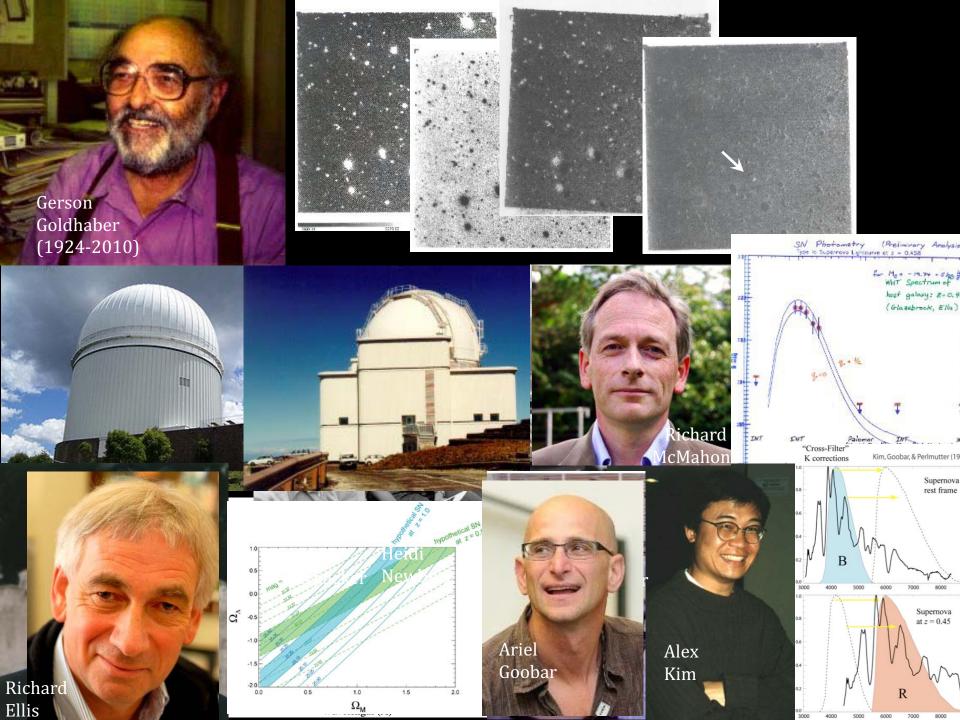
Billions Years from Today

# **Union2** Compilation













Sebastian

Fabbro Ivan

Smal

Susana

Deustua

Brad Schaefer

saac Newton

Matthew

Kim

Pilar Ruiz-

Lidman

lente

Circula

Isobel

Hook

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Don

Groom

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#### 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:



