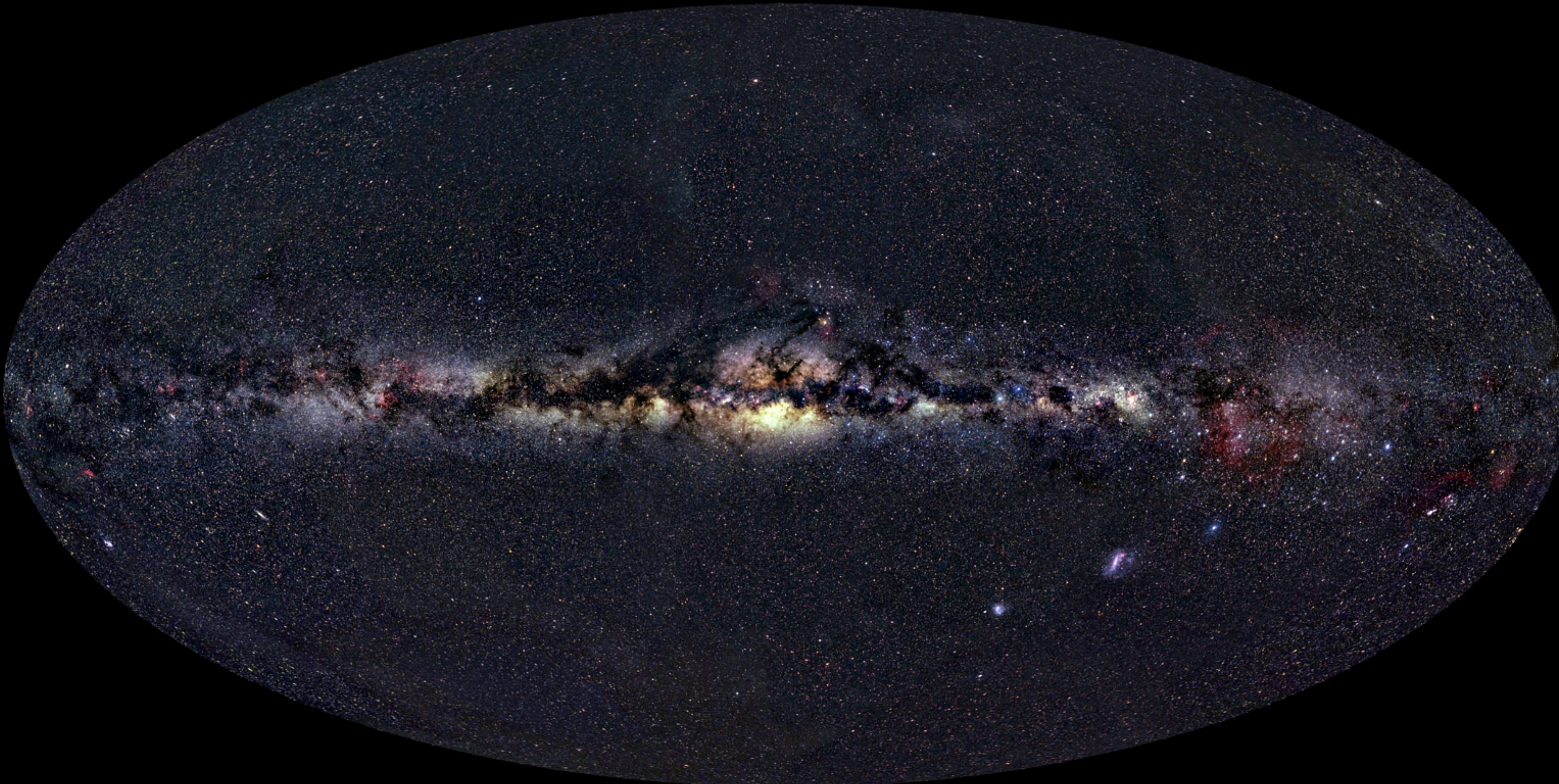
7th International Conference on
Gravitation and Cosmology
14-19 December 2011, Goa, India

A Nobel Surprise: Exploding Stars and the Accelerating Universe

Robert Kirshner

Harvard University



Milky Way = Universe

1917:

Einstein stuck in the cosmological constant to make a static Universe

theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.

Universe = Milky Way Galaxy

Edwin Hubble showed the Milky Way was **not** the whole Universe.

We live in a Universe of galaxies, each equivalent to the Milky Way.

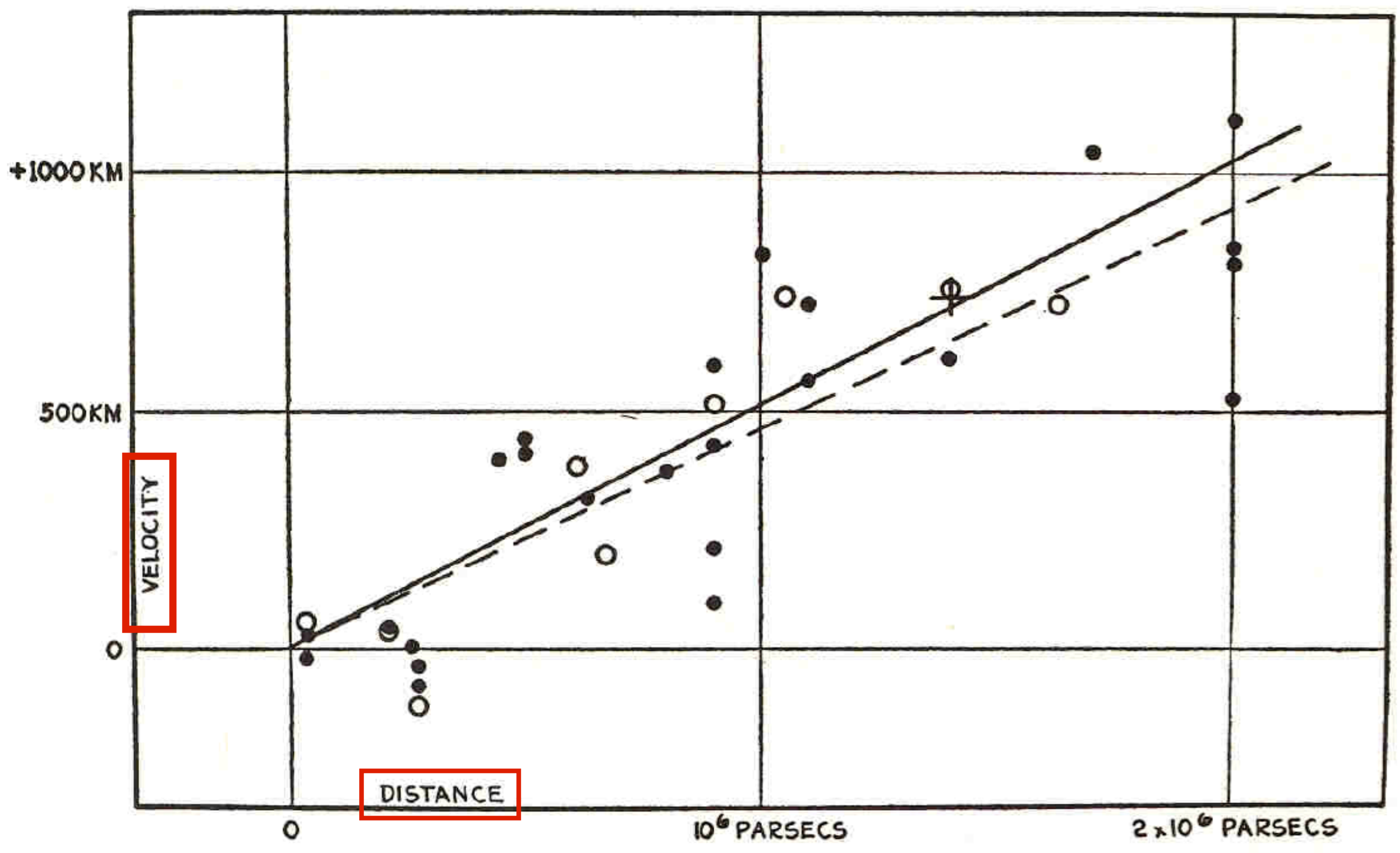
Vesto Melvin Slipher
Lowell Observatory

Measured spectra of the “nebulae”

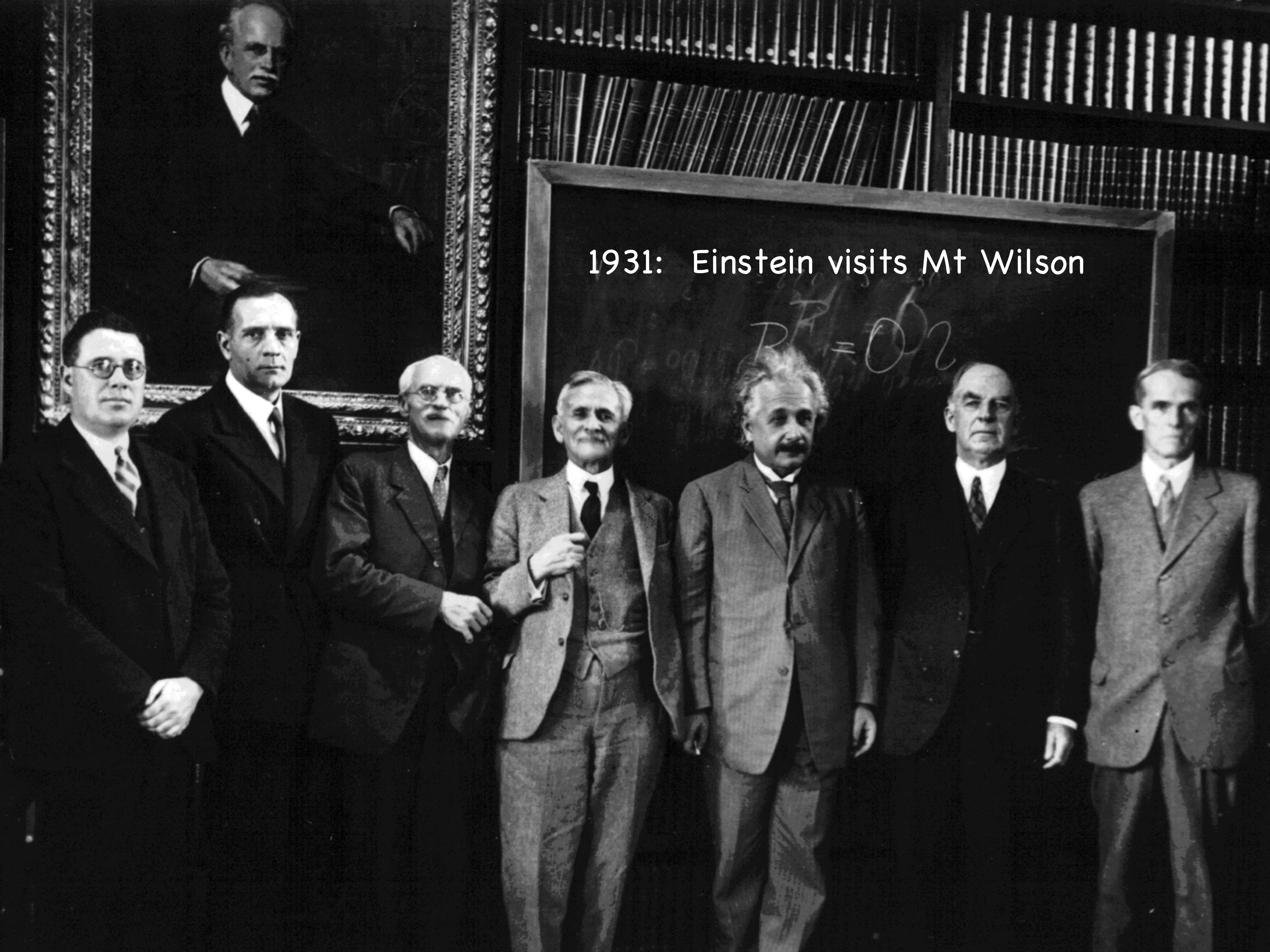
Found velocities much bigger than for stars in the Milky Way

Almost all of them away from us--redshifted

Hubble's Own 1929 Hubble Diagram



Redshift proportional to distance


1931: Einstein visits Mt Wilson

mann realized that this opened an entire new world of time-dependent universes: expanding, collapsing, and pulsating ones. Thus, Einstein's original gravity equation was correct, and changing it was a mistake. Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder he ever made in his life. But this "blunder," rejected by Einstein, is still sometimes used by cosmologists even today, and the cosmological constant denoted by the Greek letter Λ rears its ugly head again and again and again.

Gamow dubs a blunder

From *My World Line*

Georges Lemaître S.J. + MIT Ph.D.

"Everything happens as though the energy *in vacuo* would be different from zero…we associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmological constant λ."

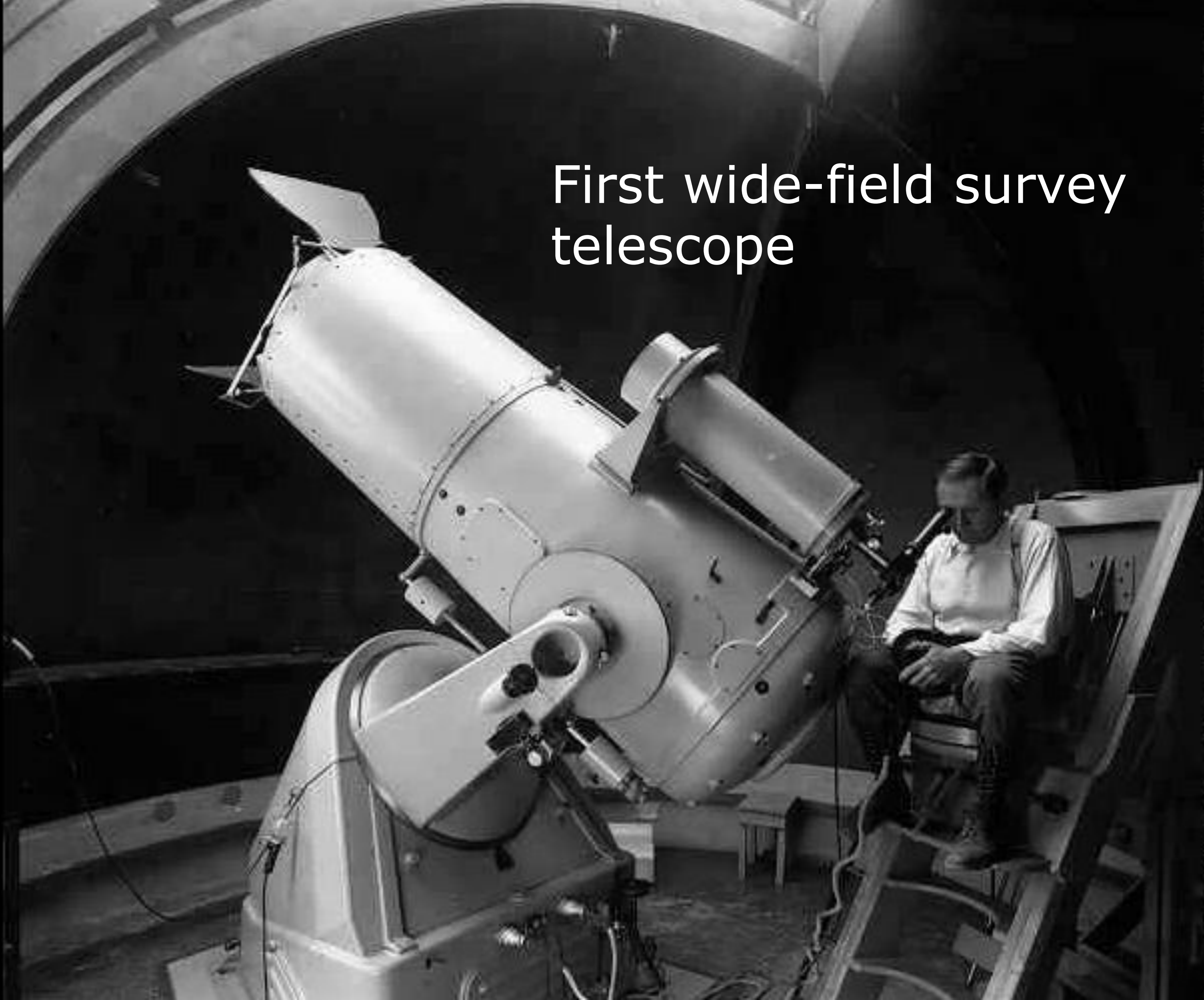
PNAS 20, 12 (1934)


No Λ!

Thermonuclear exploding stars
~ 4 x 10^9 Suns

10^6 brighter than Miss Leavitt's stars

~1 SNIa /century in a galaxy



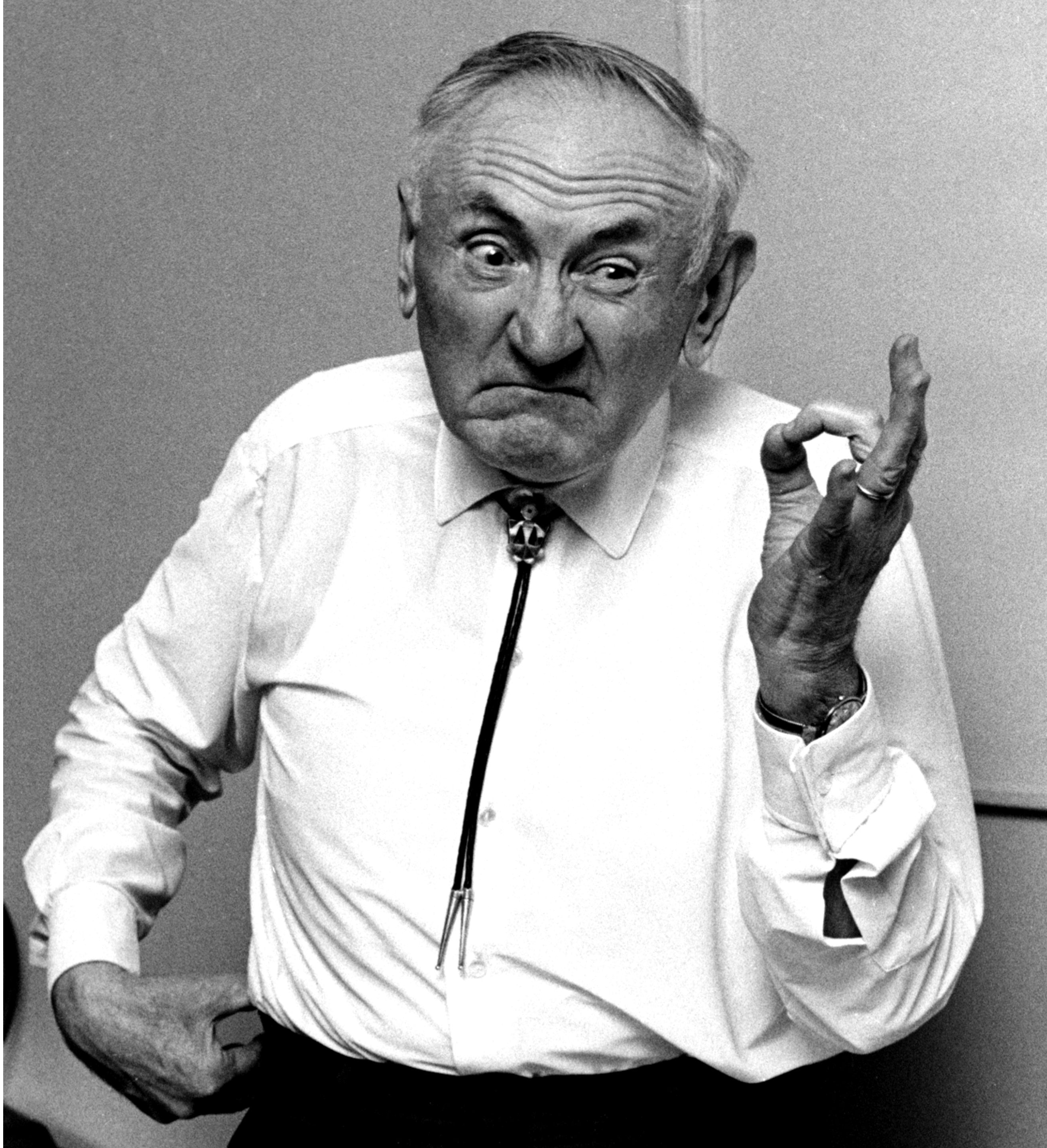
First wide-field survey telescope

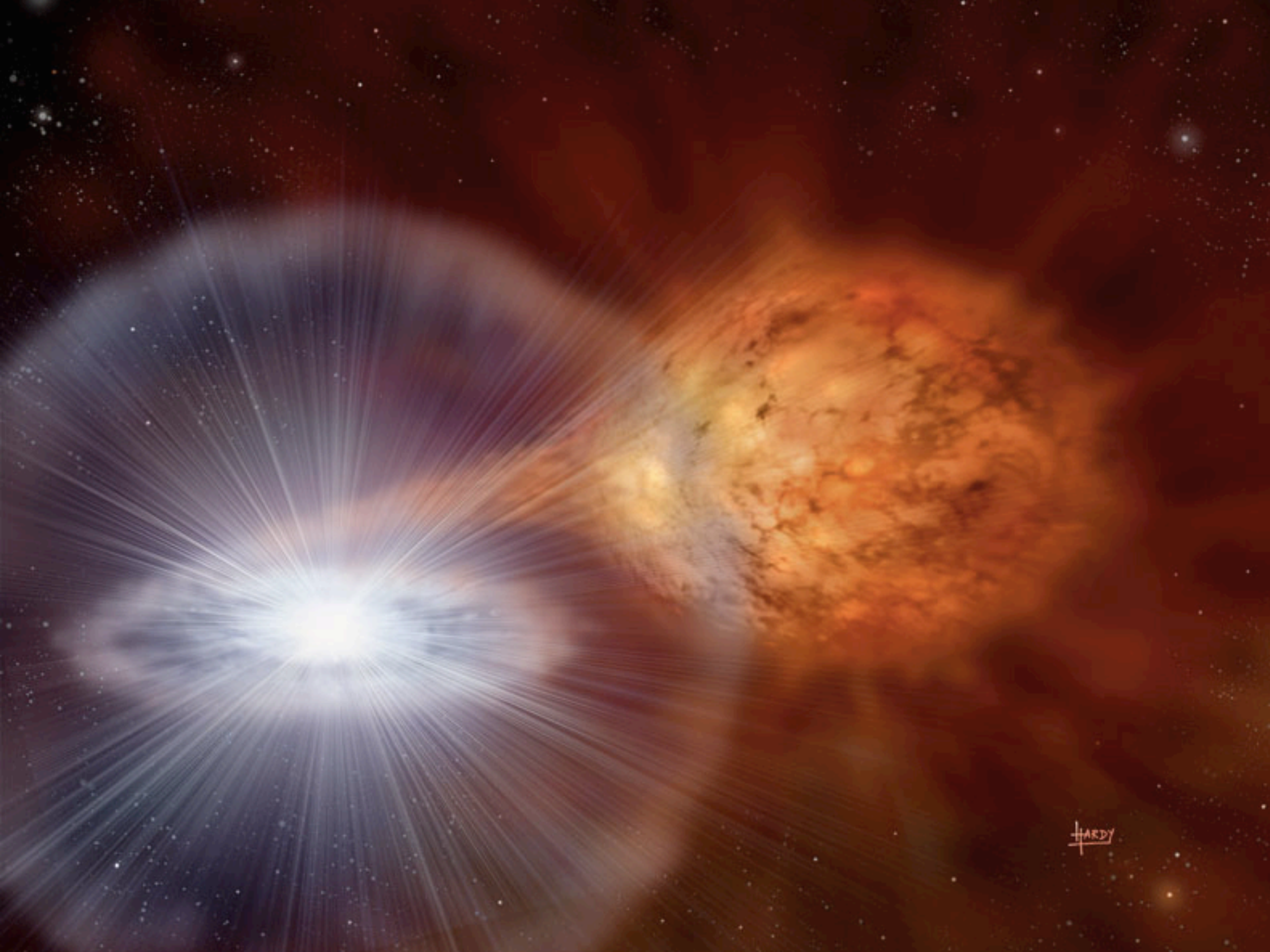
Fritz Zwicky:

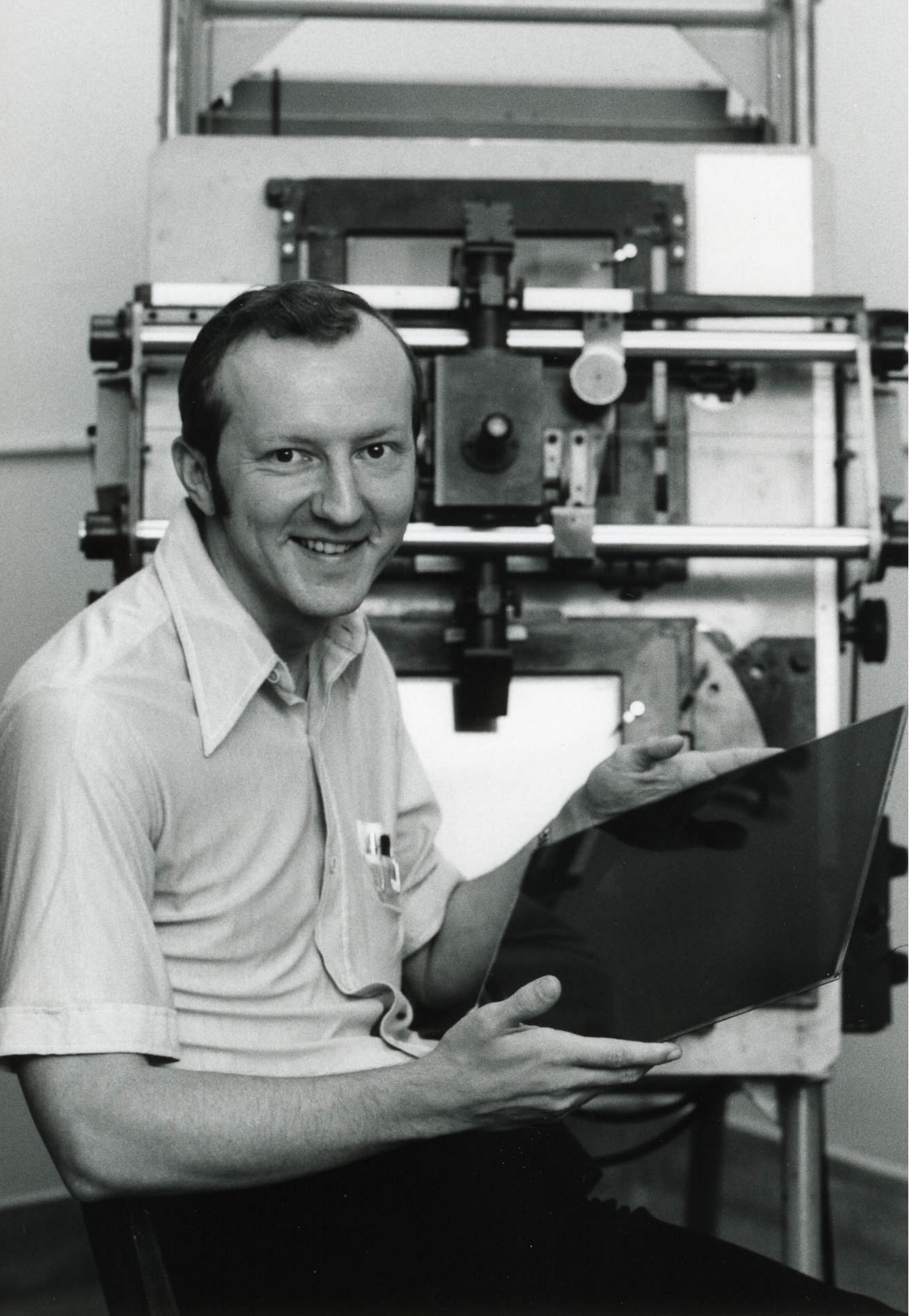
Supernova Pioneer

Dark Matter Pioneer

Gesture Pioneer




HARDY



The Beginning of Supernova Cosmology

Charlie Kowal
(1940-2011)

Note the imaging technology of 1968!

Monthly searches in the dark of the moon at Palomar with 48" and 18"

Paleolithic PanSTARRS

Kowal (1968)

- ✓ Had distances good to ~30% from SN I

Speculated that individual measurements might be good to 5-10%

“It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become availab for very distant supernovae

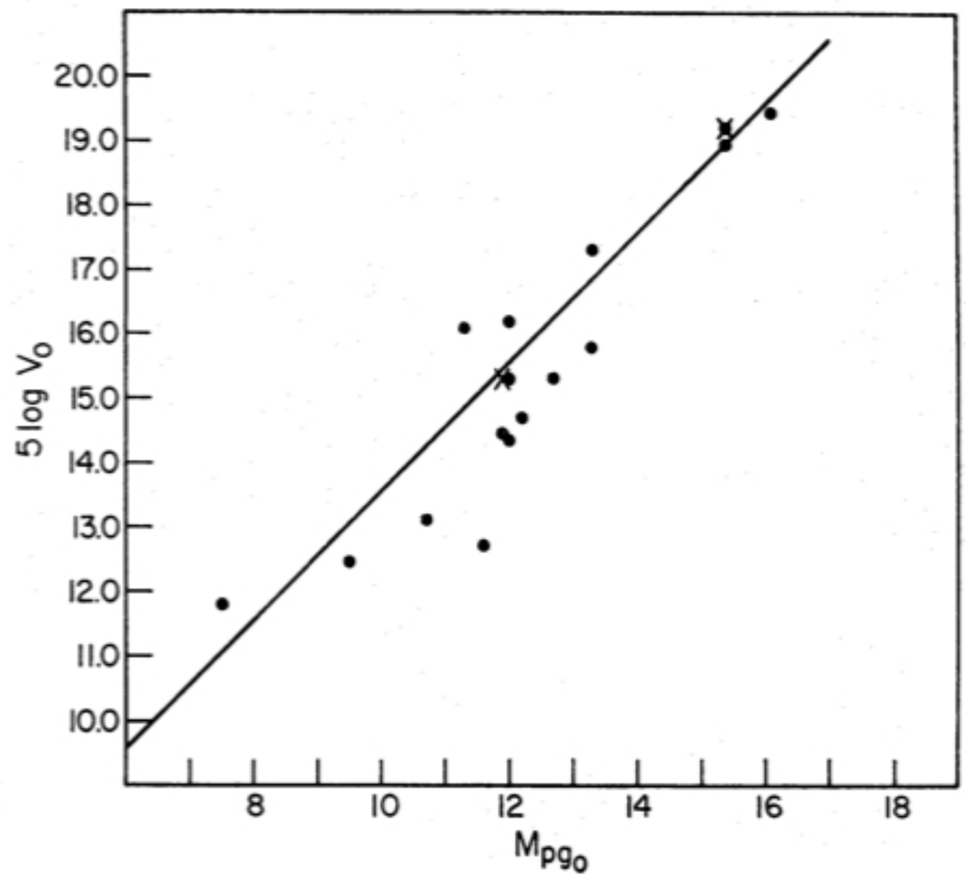
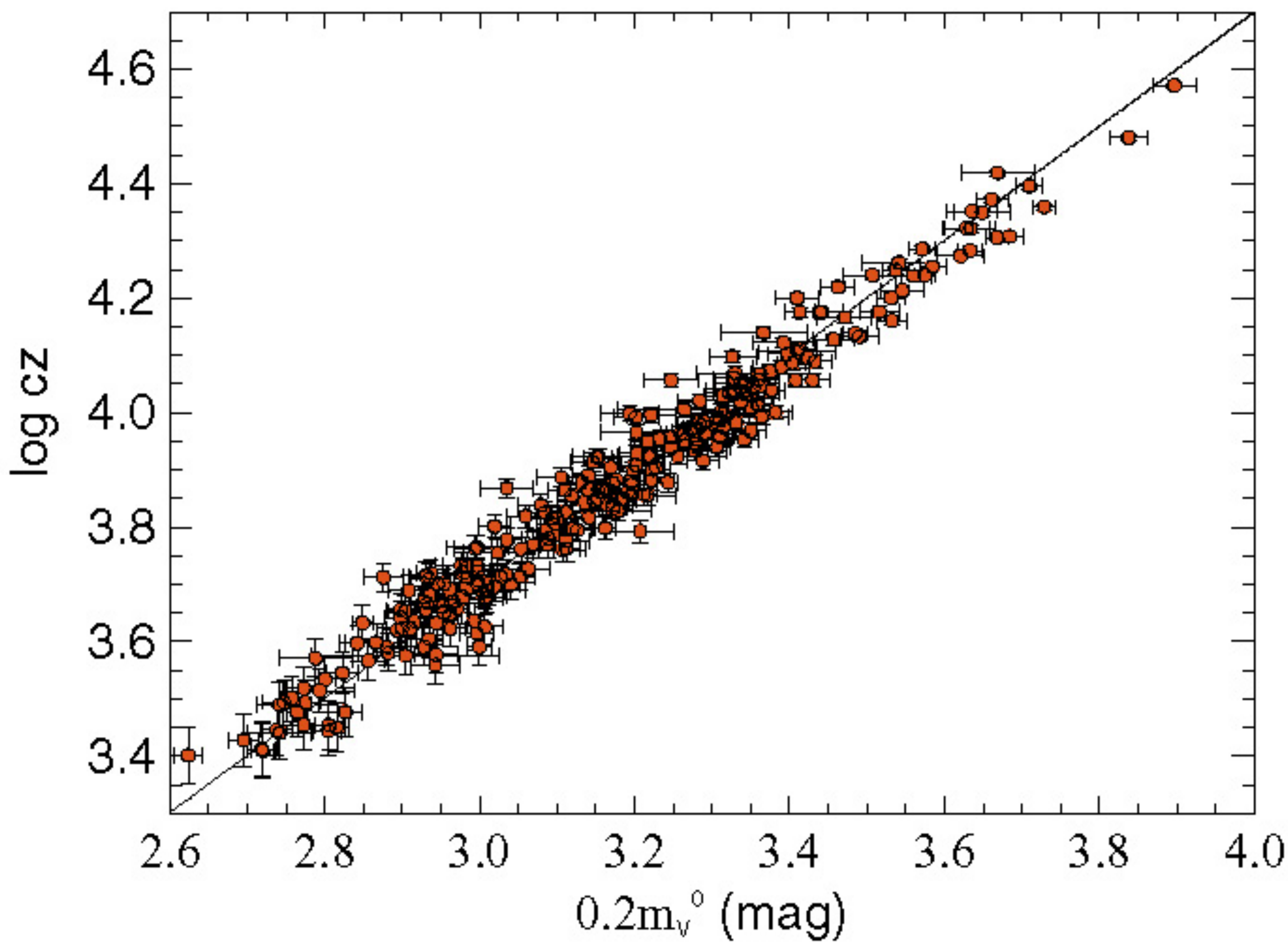


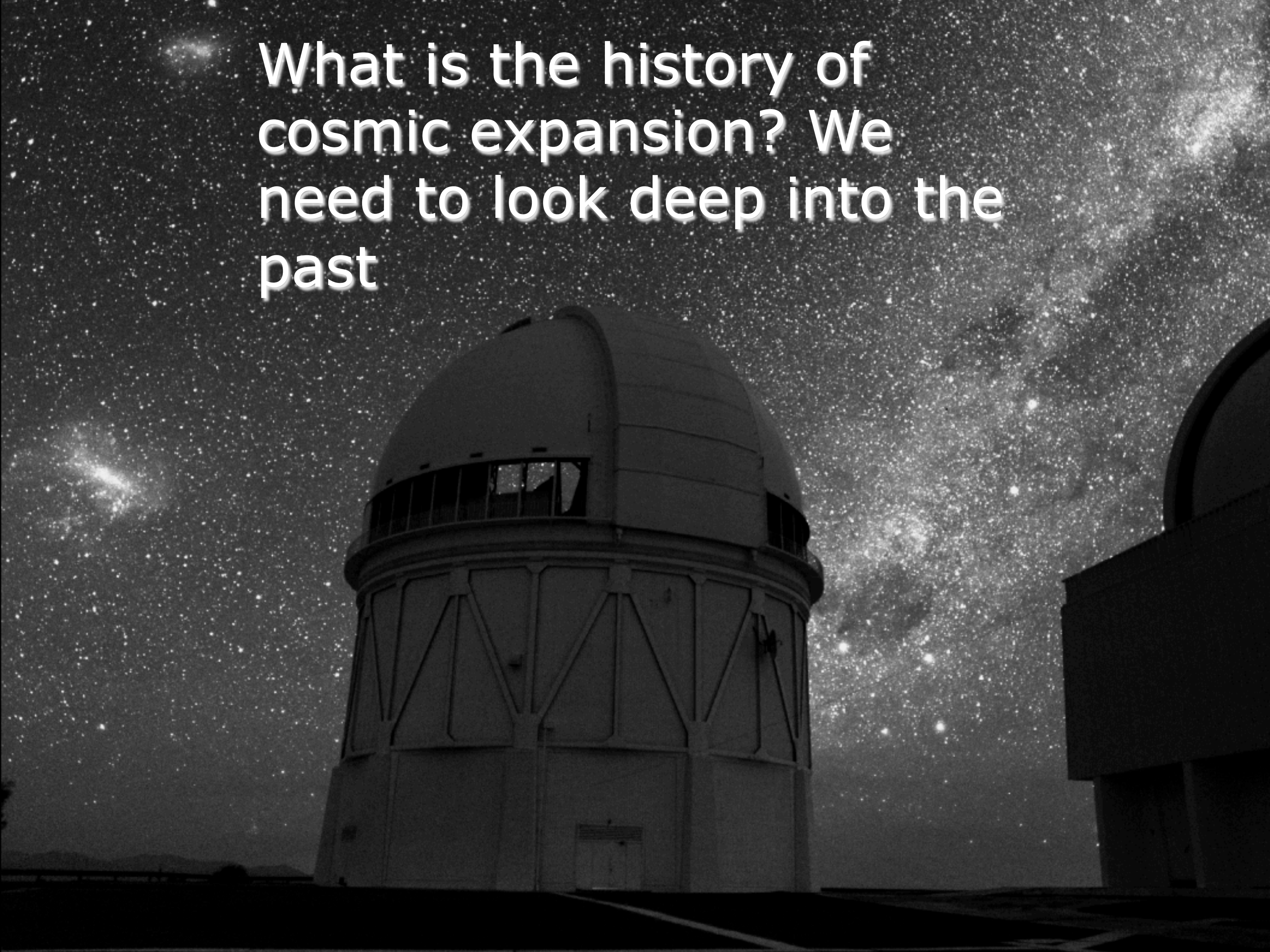
FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

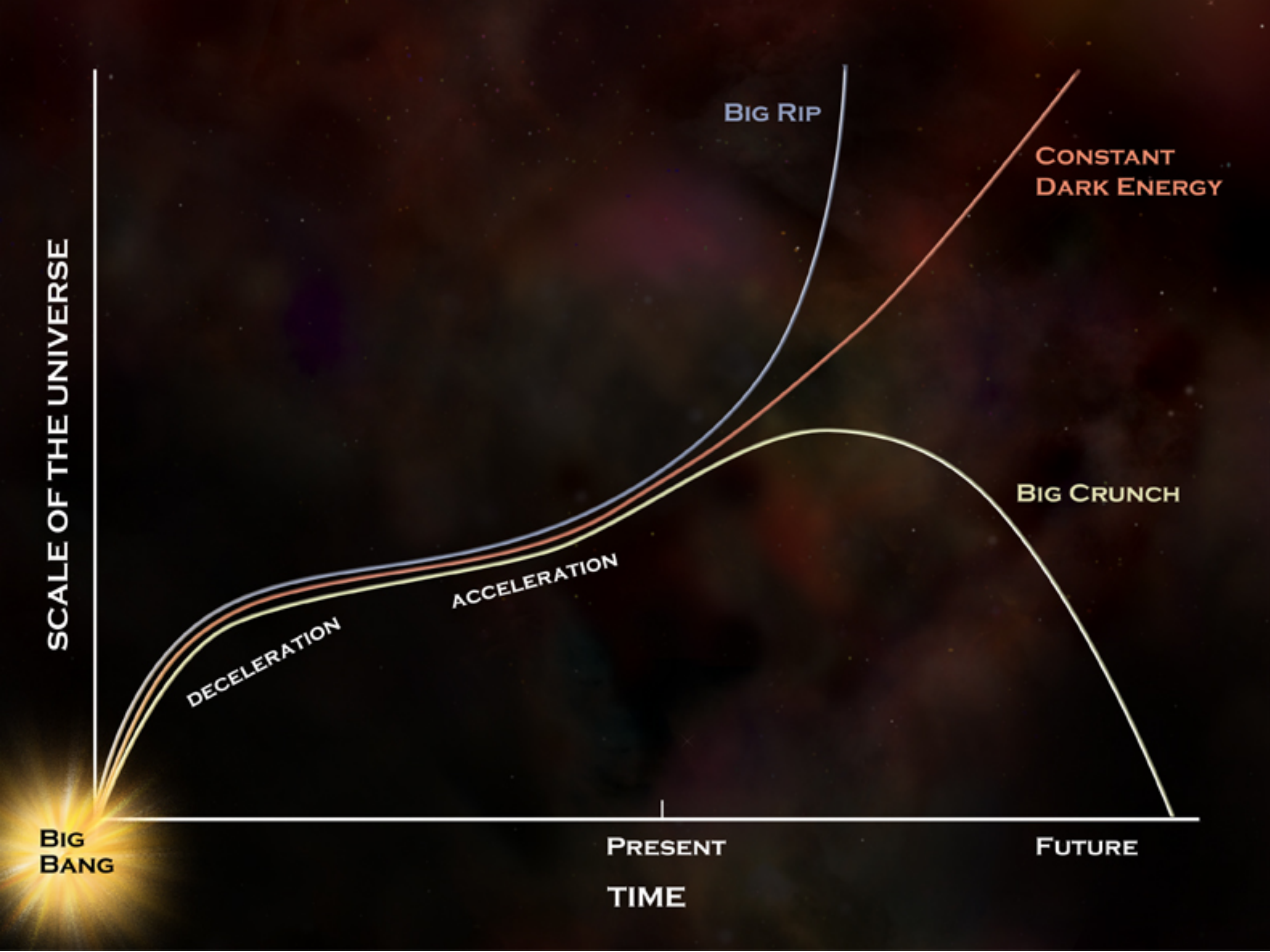
The intercept is well-determined: H_o

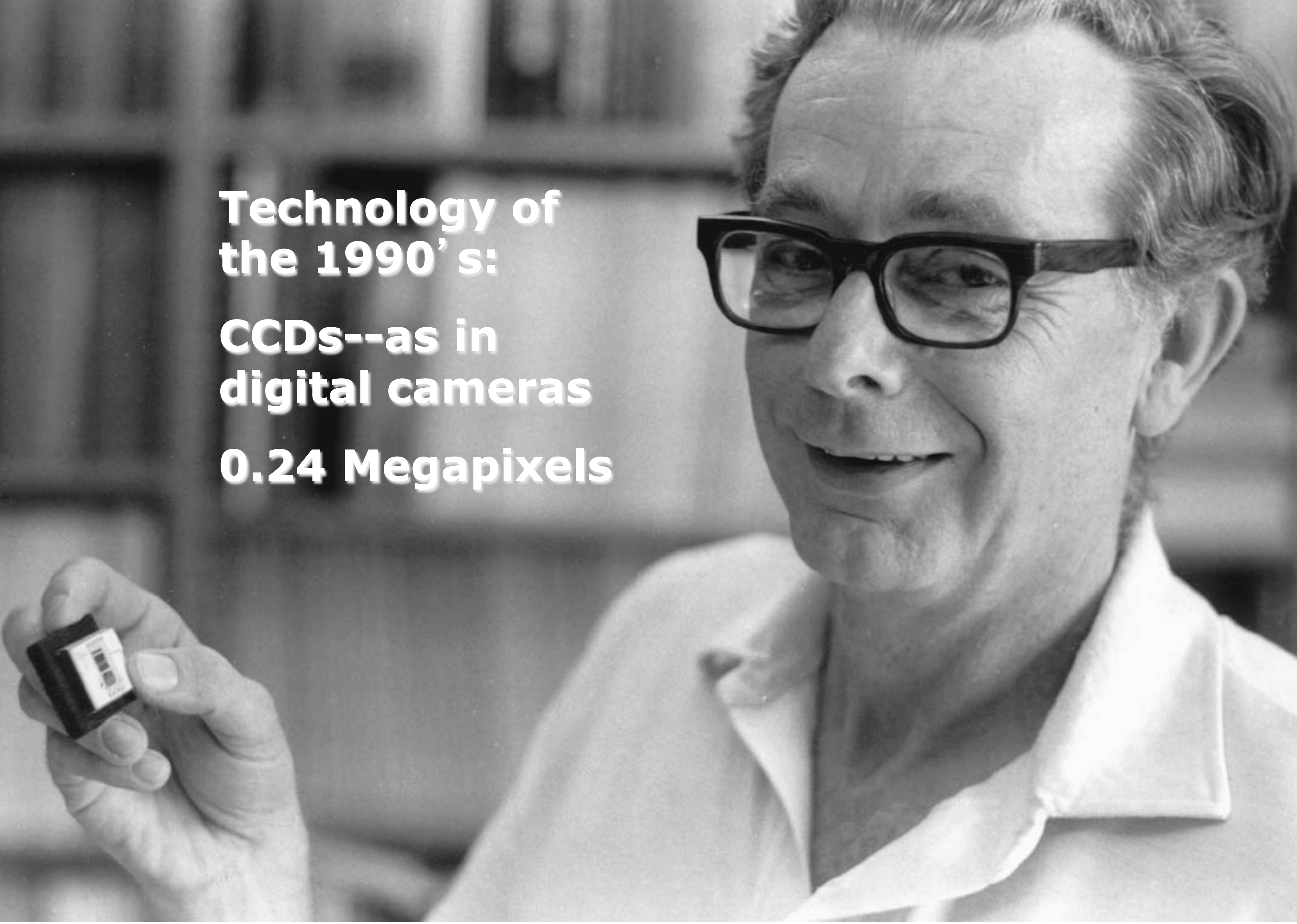
(Riess et al. 2009) 74.2 +/- 3.6 km/s/Mpc => $\Omega_m h^2$

CfA3 data set




What is the history of cosmic expansion? We need to look deep into the past


Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Acceleration
Deceleration
Big
Bang
Present
Future
Time


Technology of the 1990’s:
CCDs--as in digital cameras
0.24 Megapixels

The discovery of a type Ia supernova at a redshift of 0.31

Hans U. Nørgaard-Nielsen*, Leif Hansen†, Henning E. Jørgensen†, Alfonso Aragón Salamanca‡, Richard S. Ellis‡ & Warrick J. Couch§

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† Copenhagen University Observatory, Øster Voldgade 3, DK-1350 Copenhagen K, Denmark
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§ Anglo-Australian Observatory, Epping Laboratory, PO Box 296, Epping, New South Wales 2121, Australia

OBSERVATIONS indicate that nearby supernova of type Ia have similar peak brightnesses, with a spread of less than 0.3 mag (ref. 1), so that they can potentially be used as 'standard candles' to estimate distances on a cosmological scale. As part of a long-term search for distant supernovae, we have identified and studied an event that occurred in a faint member of the distant galaxy cluster AC118, at a redshift of $z = 0.31$. Extensive photometry and some spectroscopy of the event strongly supports the hypothesis that we have detected a type Ia supernova whose time-dilated light curve matches that of present-day supernovae of this class. We discuss the precision to which its maximum brightness can be ascertained, and indicate the implications that such deep supernovae searches may have for observational cosmology.

Although supernovae are not as luminous as the brightest galaxies in clusters, they are events rather than objects and so should be less affected by the evolutionary and dynamical complications that have plagued determinations, by magnitude-redshift tests based on first-ranked cluster galaxies, of the deceleration parameter q_0. If a sufficient number of supernovae could be found and if they revealed a closely distributed (tight) Hubble diagram, precise photometry of a sufficiently deep sample could provide an interesting constraint on q_0. The effect of a change in q_0 from 0.1 to 0.5 is only 0.13 mag at $z = 0.3$, rising to 0.22 mag at $z = 0.5$, so many accurately measured supernovae would be required. Our distant-supernova search programme has been described previously[2,3]. Our recent estimate of the frequency of occurrence of type Ia supernovae[3] lies at the lower end of the range determined in nearby galaxies[4-6]. Furthermore, even at maximum light such type Ia supernovae would be fainter than $V \approx 21.5$ mag, and thus any search strategy needs to reliably detect an absolute change in a galaxy's flux equivalent to $V \approx 23$ mag.

Using the 1.5-m Danish telescope at La Silla, Chile, we have monitored ~60 clusters in the redshift interval $0.2 < z < 0.5$ over a period of two years. One-hour CCD exposures in good conditions were taken during most months in the period August–April and were immediately compared with suitable frames taken at earlier epochs, by forming difference frames (after smoothing to the same seeing and scaling to the same object intensity)[2]. We have already discussed[3,7] the discovery of a probable type II supernova at $z = 0.28$. That particular event was very faint but demonstrated our ability to find genuine events at $V \approx$ 23.6 mag, a limit more than adequate for detecting type Ia supernovae to $z \approx 0.5$. Here we report the first detection of a type Ia supernova (SN1988U)[8], the most distant so far discovered. Photometry of this object allows us to comment on the feasibility of estimating q_0 from a reasonable sample of such events.

The new event was identified in a faint galaxy in the field of the rich cluster AC118. This cluster was identified as part of the southern Abell catalogue[9] and has since been extensively studied spectroscopically[10,11], although no previous spectrum exists of the galaxy in which this supernova occurred; the cluster redshift is 0.307. The event was found with the Danish 1.5-m telescope on 8 and 9 August 1988 by comparing a V CCD frame with one taken in good conditions during 1986 (Fig. 1). Observations at the 4.2-m William Herschel Telescope (WHT) on 9 August 1988 confirmed both the photometric detection and offsets measured at La Silla. Furthermore, the excess light has the same full width at half maximum (FWHM) as that for other stellar objects in the field. Subsequently, the cluster was observed several times on both the WHT and the 1.5-m Danish telescope when conditions and instrumentation permitted; a complete photometric record is given in Table 1.

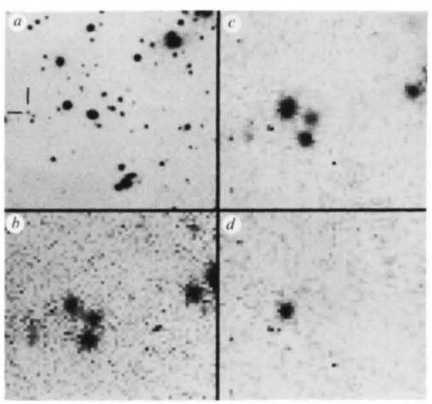


FIG. 1 Detection of the candidate supernova in the distant cluster AC118. *a*, 1-hour V exposure on the Danish 1.5-m telescope on 30 August 1986. *b*, 30 × 30-arcsec enlargement of *a* around the galaxy containing the event. *c*, Same enlargement of a 1-hour V exposure taken on 8 and 9 August 1988. *d*, Subtracted image ($c - b$) after scaling and allowing for slightly different seeing on the two exposures. Analysis of the difference frame shows that the excess light is offset 0.5 arcsec east and 0.7 arcsec south of the galaxy nucleus. The galaxy position at right ascension $\alpha = 00^h 11^m 56.69^s$, declination $\delta = -30° 41' 45.3''$ (1950.0). The galaxy has a redshift of $z = 0.31$ and $V = 22.35 \pm 0.03$ mag; the event was detected with $V = 22.05 \pm 0.05$ mag.

TABLE 1 Photometric record

Julian date (minus JD 2447373.5)	Aperture (m)	Seeing (arcsec)	Supernova V (mag)	ΔV
9.28	1.5	1.7	22.05	0.05
10.21	1.5	1.6	22.18	0.05
11.20	4.2	1.1	22.30	0.09
11.28	1.5	2.1	22.29	0.07
12.20	4.2	1.5	22.43	0.09
13.16	4.2	1.3	22.32	0.08
14.20	4.2	1.2	22.38	0.08
15.35	1.5	1.8	22.67	0.08
16.34	1.5	1.6	22.74	0.10
36.08	4.2	1.3	24.02	0.43
37.23	1.5	1.3	29.30	0.25
38.24	1.5	1.0	24.20	0.31
67.20	1.5	1.5	>24.4	—
			R	ΔR
11.20	4.2	1.2	21.94	0.07
12.20	4.2	1.6	22.17	0.08
37.32	1.5	2.3	>24.1	—*
70.12	1.5	1.1	>24.4	—

* Estimated from frame taken in standard Gunn r filter[21].

Like the Vikings, the Danes were there a long time ago! 1989

SN1988U:

SN Ia z=0.31

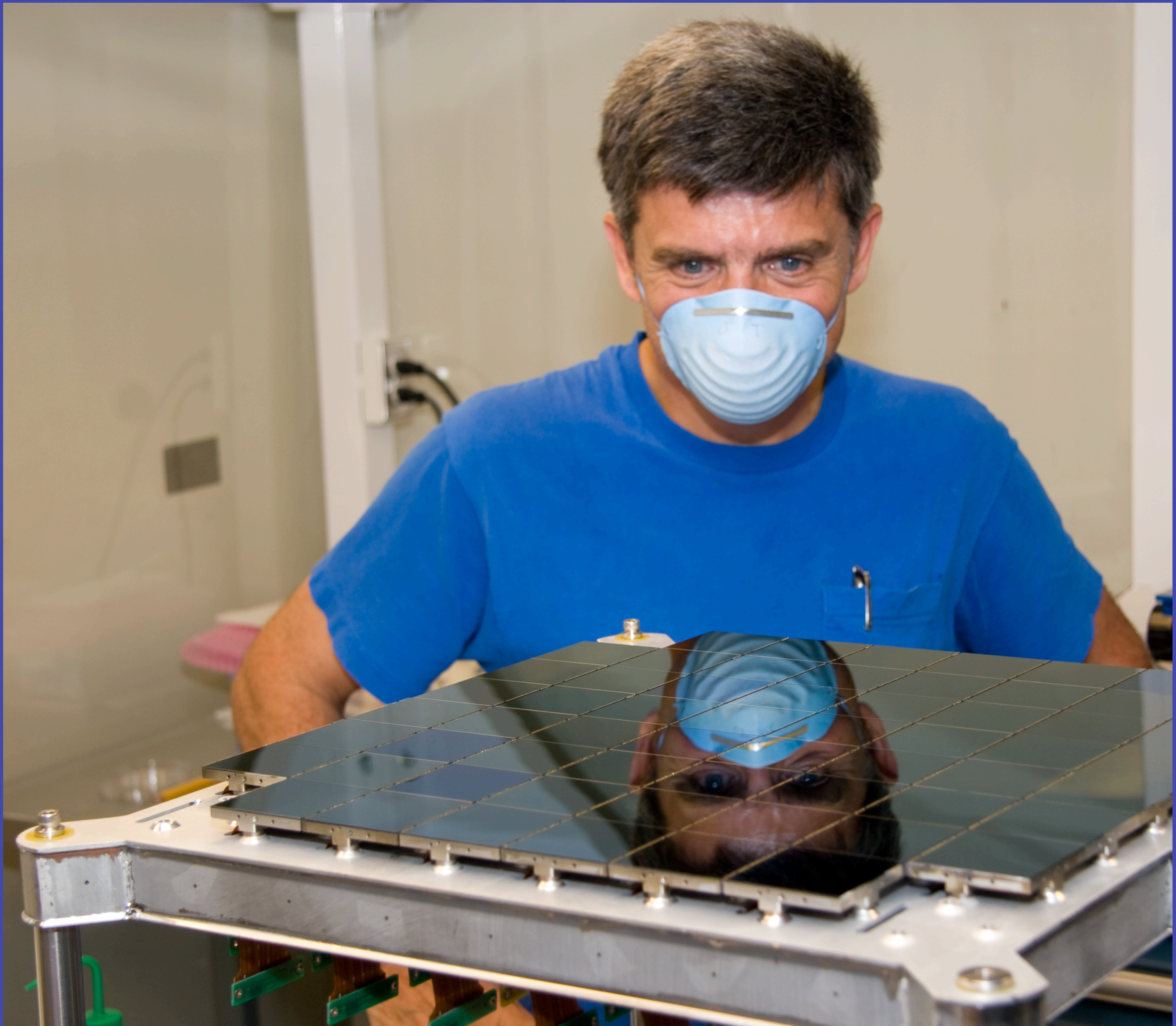
For cosmology!

Real-time image registration, scaling,subtraction

Monthly searches

Scheduled follow-up

Today: gigapixel cameras!

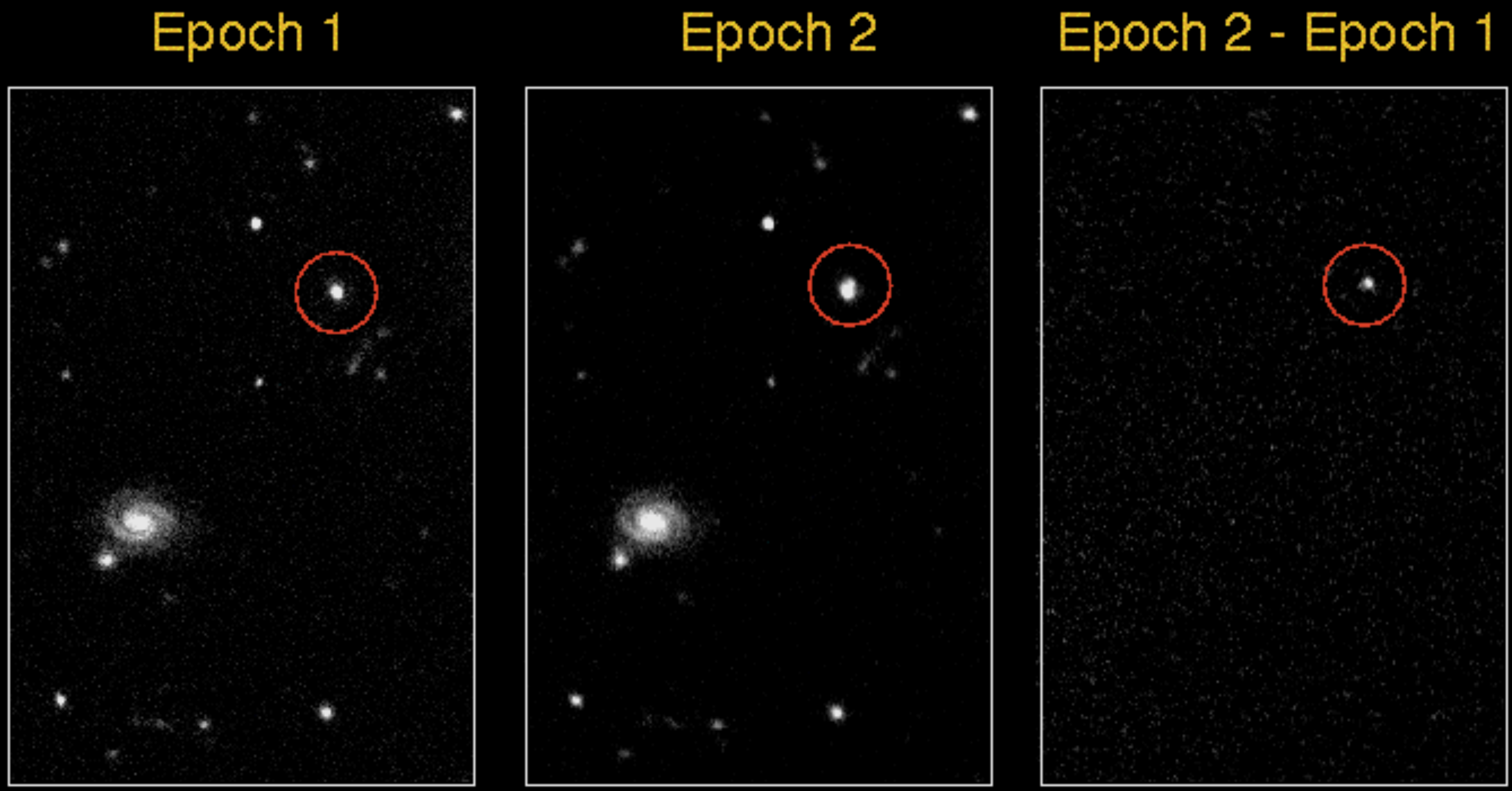


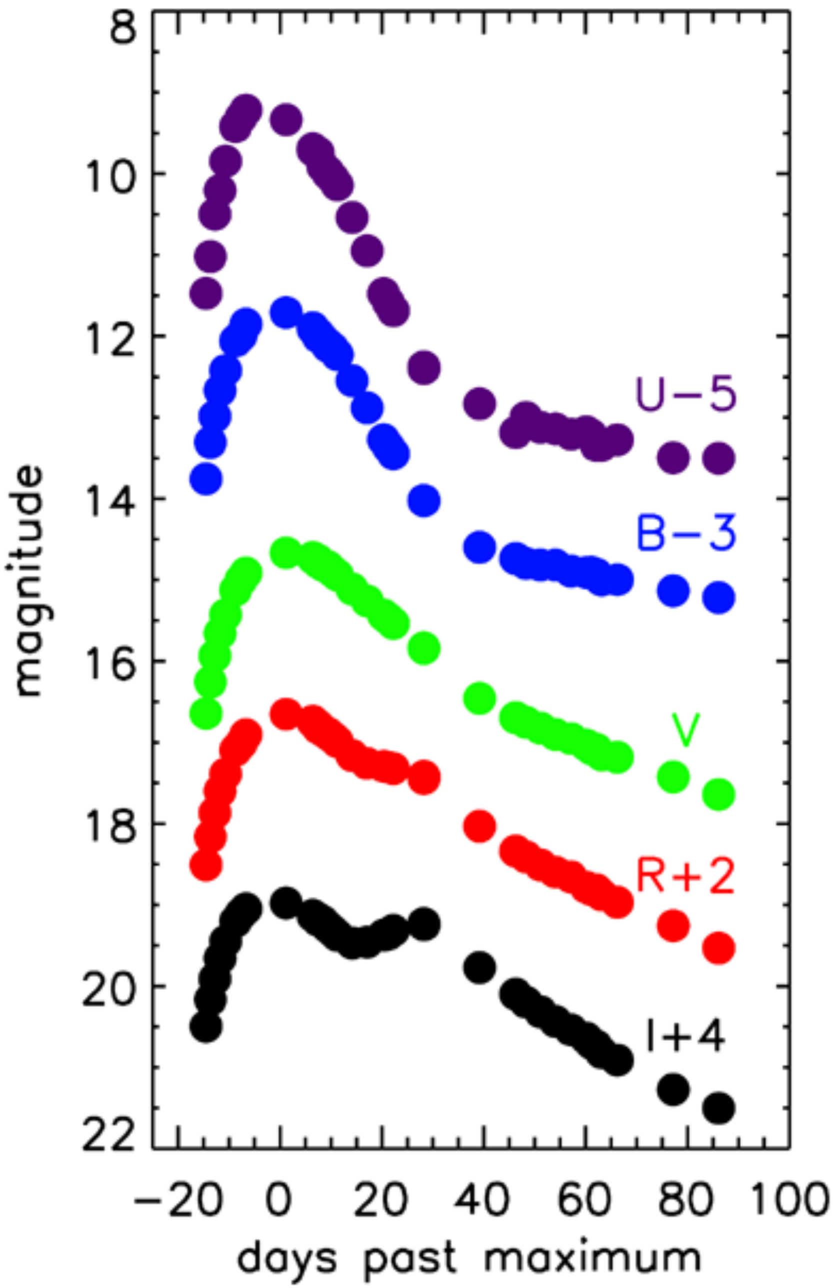
Brian Schmidt explains to his thesis advisor how easy this will be

Front Back

Searching by Subtraction

inexpensive labor under careful supervision--
computers!





alk

Light Curves: Clues to Luminosity

Related to ^{56}Ni produced in the explosion

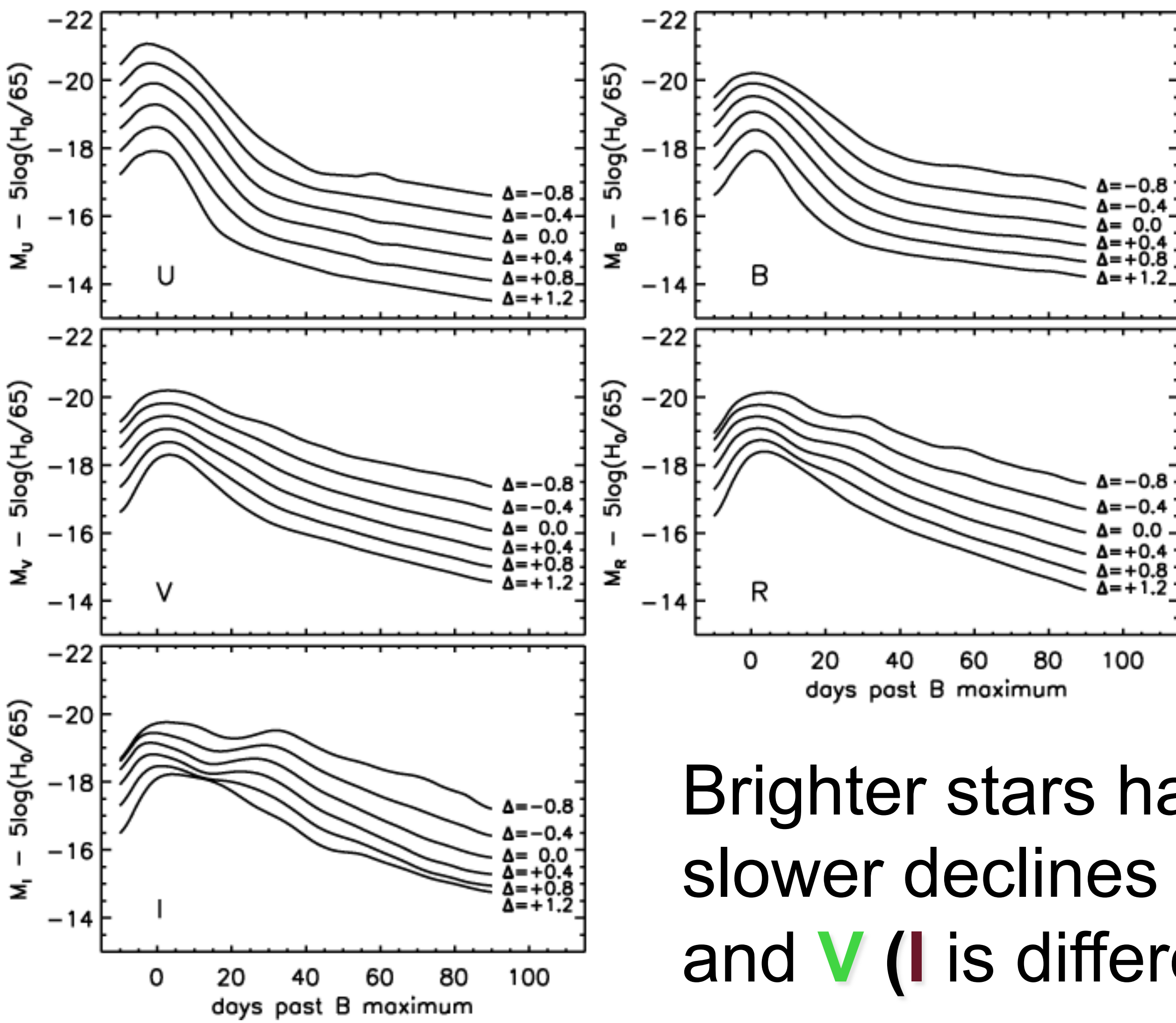
Mark Phillips (1992)

Riess, Press & Kirshner (1995, 1996)

Goal: better distances, determination of extinction by dust

SALT, Sifto…

Light Curve Shapes => L



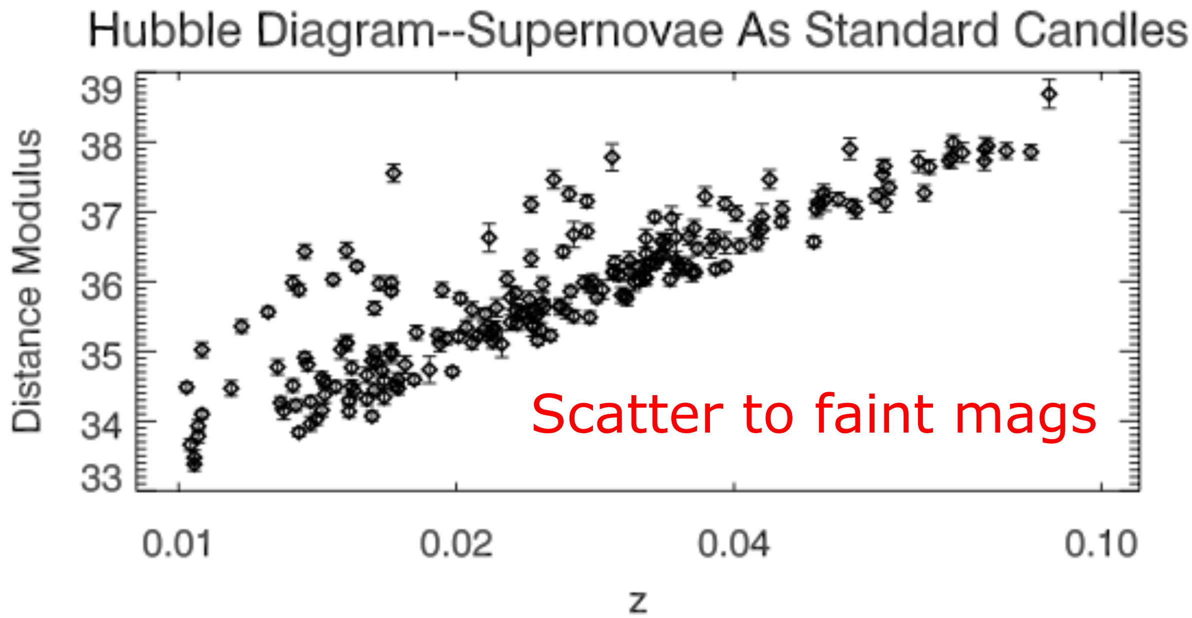
Brighter stars have slower declines in **B** and **V** (**I** is different)

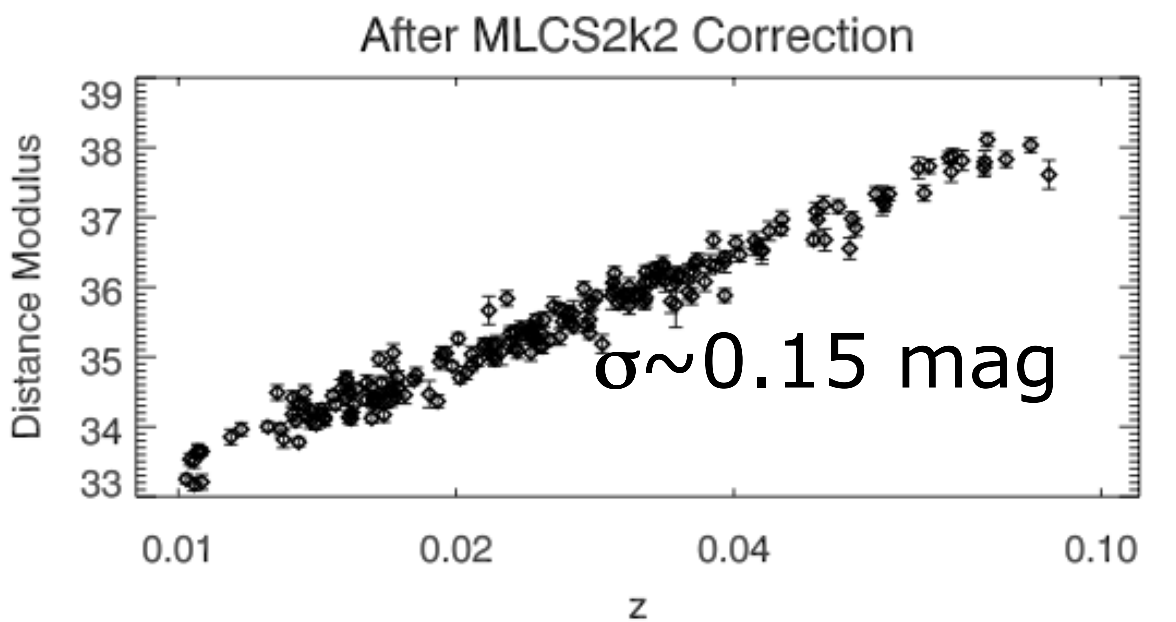

Dust both dims and reddens:
Adam Riess showed how to
account for this

N~200
Approaching the end of statistical limits-- now the errors are systematic.

The largest of these is due to light curve fitting + dust properties.

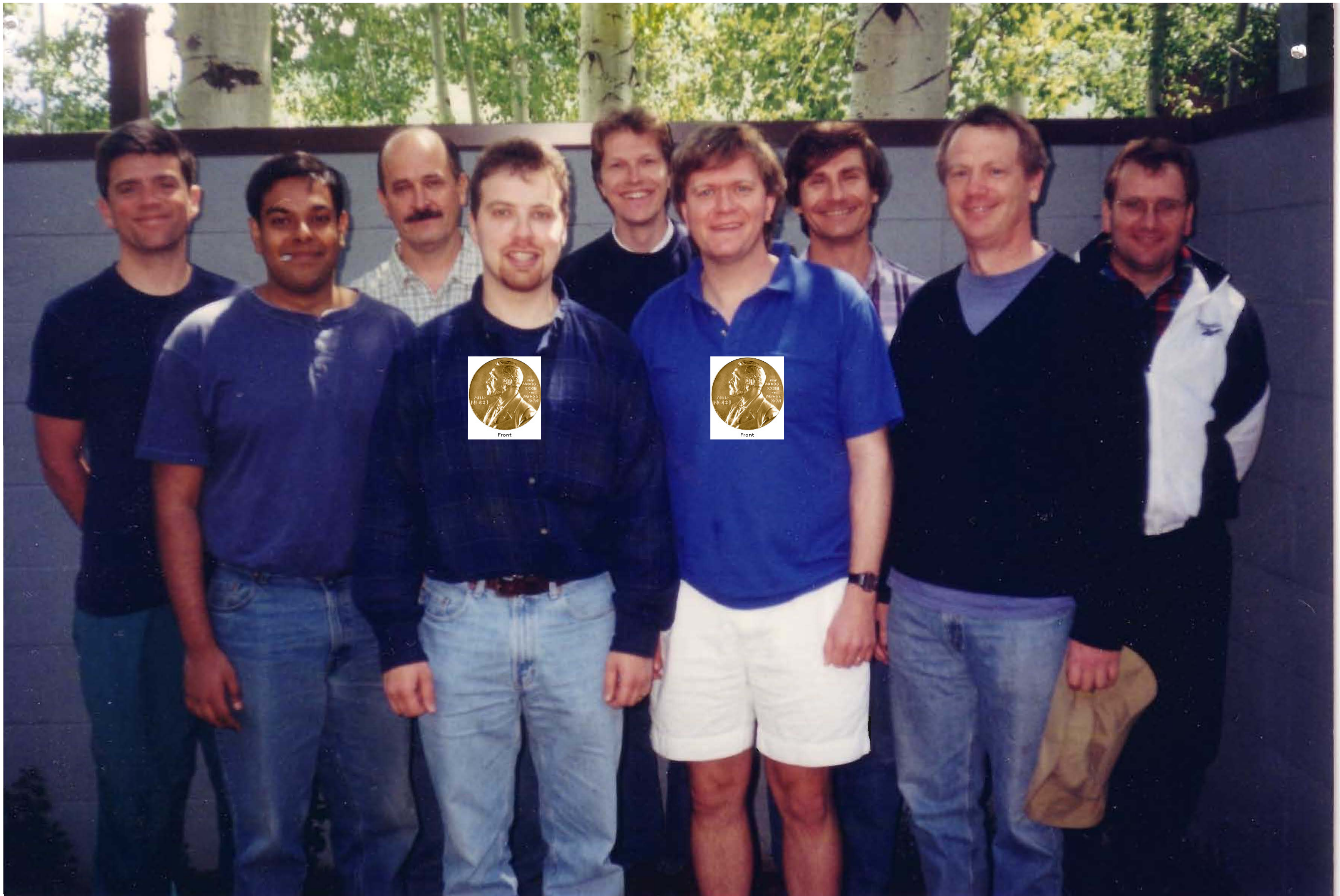
Conley et al (2007)
Kessler et al (2009)





1/100 years ~ 1/5000 weeks => 5000 galaxies

Also fabricated in supernovae: High-Z Team



Searching for cosmic deceleration

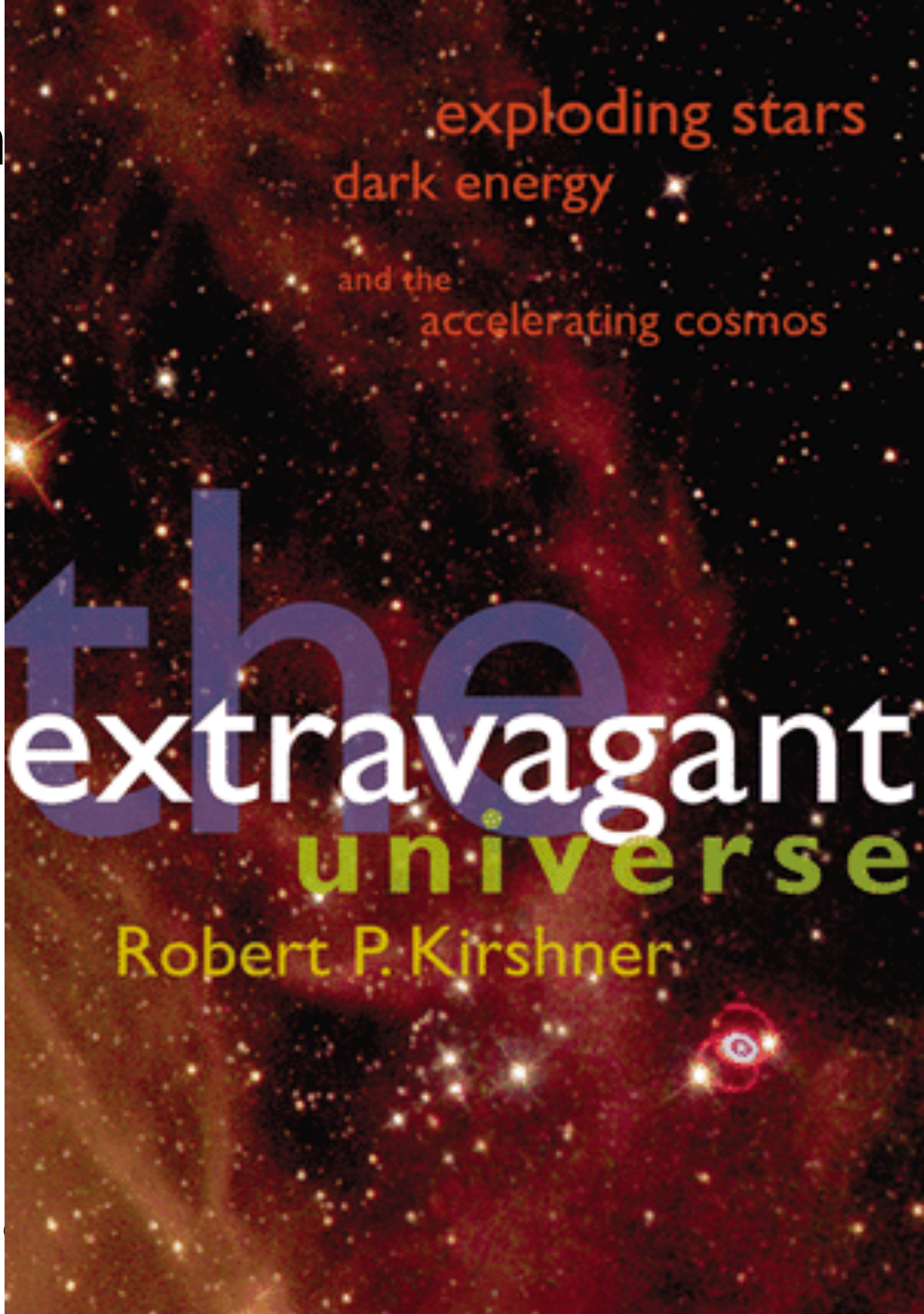
$a'' \sim q_o \sim -(\Omega_m/2 + \Omega_\Lambda)$

So, for $\Omega_\Lambda = 0$, expect to see deceleration

Front

Back

If you are interested in the details of the discovery-- I cannot recommend a better book.



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THE ASTROPHYSICAL JOURNAL, 483:565–581, 1997 July 10

July 1997 Ap.J.:SCP: No Λ

MEASUREMENTS[1] OF THE COSMOLOGICAL PARAMETERS Ω AND Λ FROM THE FIRST SEVEN SUPERNOVAE AT $z \geq 0.35$

S. PERLMUTTER,[2,3] S. GABI,[2,4] G. GOLDHABER,[2,3] A. GOOBAR,[2,3,5] D. E. GROOM,[2,3] I. M. HOOK,[3,6]
A. G. KIM,[2,3] M. Y. KIM,[2] J. C. LEE,[2] R. PAIN,[2,7] C. R. PENNYPACKER,[2,4] I. A. SMALL,[2,3]
R. S. ELLIS,[8] R. G. MCMAHON,[8] B. J. BOYLE,[9,10] P. S. BUNCLARK,[9] D. CARTER,[9]
M. J. IRWIN,[9] K. GLAZEBROOK,[10] H. J. M. NEWBERG,[11] A. V. FILIPPENKO,[3,6]
T. MATHESON,[6] M. DOPITA,[12] AND W. J. COUCH[13]
(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1996 August 26; accepted 1997 February 6

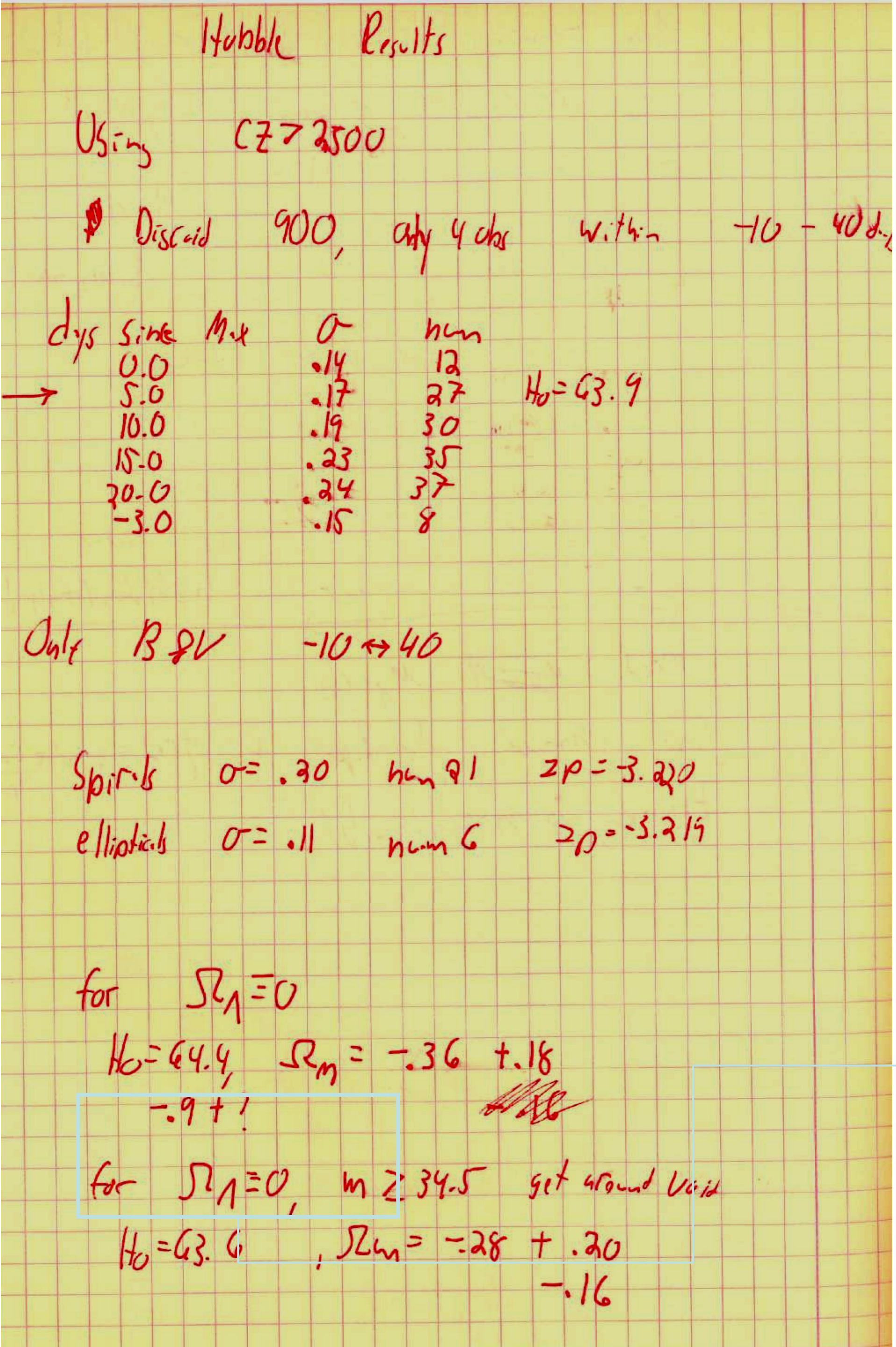
ABSTRACT

We have developed a technique to systematically discover and study high-redshift supernovae that can be used to measure the cosmological parameters. We report here results based on the initial seven of more than 28 supernovae discovered to date in the high-redshift supernova search of the Supernova Cosmology Project. We find an observational dispersion in peak magnitudes of $\sigma_{M_B} = 0.27$; this dispersion narrows to $\sigma_{M_B,\rm corr} = 0.19$ after "correcting" the magnitudes using the light-curve "width-luminosity" relation found for nearby ($z \leq 0.1$) Type Ia supernovae from the Calán/Tololo survey (Hamuy et al.). Comparing light-curve width–corrected magnitudes as a function of redshift of our distant ($z = 0.35$–0.46) supernovae to those of nearby Type Ia supernovae yields a global measurement of the mass density, $\Omega_M = 0.88^{+0.69}_{-0.60}$ for a $\Lambda = 0$ cosmology. For a spatially flat universe (i.e., $\Omega_M + \Omega_\Lambda = 1$), we find $\Omega_M = 0.94^{+0.34}_{-0.28}$ or, equivalently, a measurement of the cosmological constant, $\Omega_\Lambda = 0.06^{+0.28}_{-0.34}$ (<0.51 at the 95% confidence level). For the more general Friedmann-Lemaître cosmologies with independent Ω_M and Ω_Λ, the results are presented as a confidence region on the Ω_M-Ω_Λ plane. This region does not correspond to a unique value of the deceleration parameter q_0. We present analyses and checks for statistical and systematic errors and also show that our results do not depend on the specifics of the width-luminosity correction. The results for Ω_Λ-versus-Ω_M are inconsistent with Λ-dominated, low-density, flat cosmologies that have been proposed to reconcile the ages of globular cluster stars with higher Hubble constant values.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

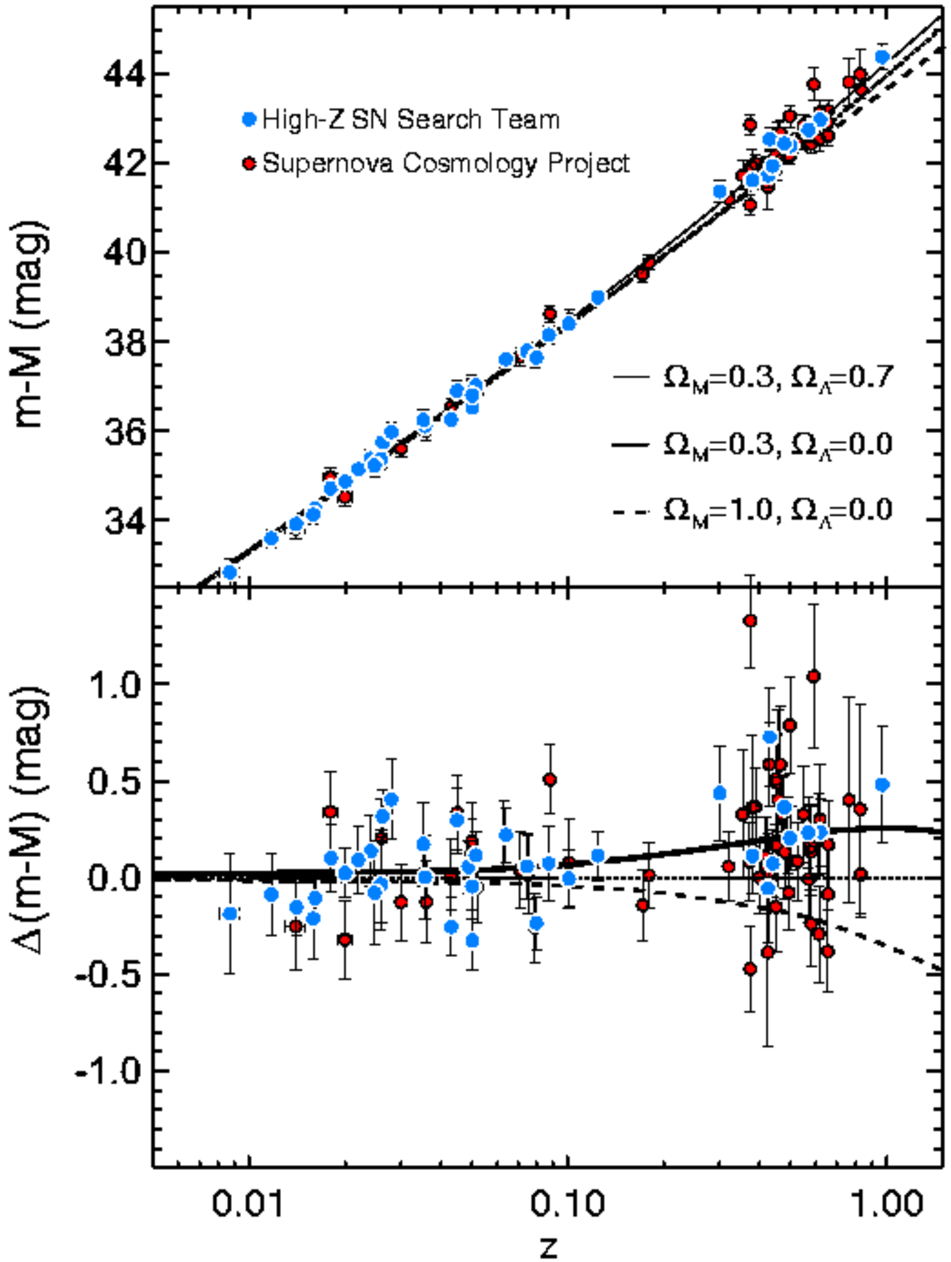
The classical magnitude-redshift diagram for a distant standard candle remains perhaps the most direct approach for measuring the cosmological parameters that determine the fate of the cosmic expansion (Sandage 1961, 1989). The first standard candles used in such studies were first-ranked cluster galaxies (Gunn & Oke 1975; Kristian, Sandage, & Westphal 1978) and the characteristic magnitude of the cluster galaxy luminosity function (Abell 1972). More recent measurements have used powerful radio galaxies at higher redshifts (Lilly & Longair 1984; Rawlings, Lacey, & Eales 1994). Both the early programs (reviewed by Tammann 1983) and the recent work have proved particularly important for the understanding of galactic evolution but are correspondingly more difficult to interpret as measurements of cosmological parameters. The Type Ia supernovae (SN



Eureka! or
“What’s wrong with this?”
Adam Riess’s notebook
Fall 1997

Negative Mass?
That seemed strange!
Universe is **not** slowing
down-- it’s speeding up!

Talk



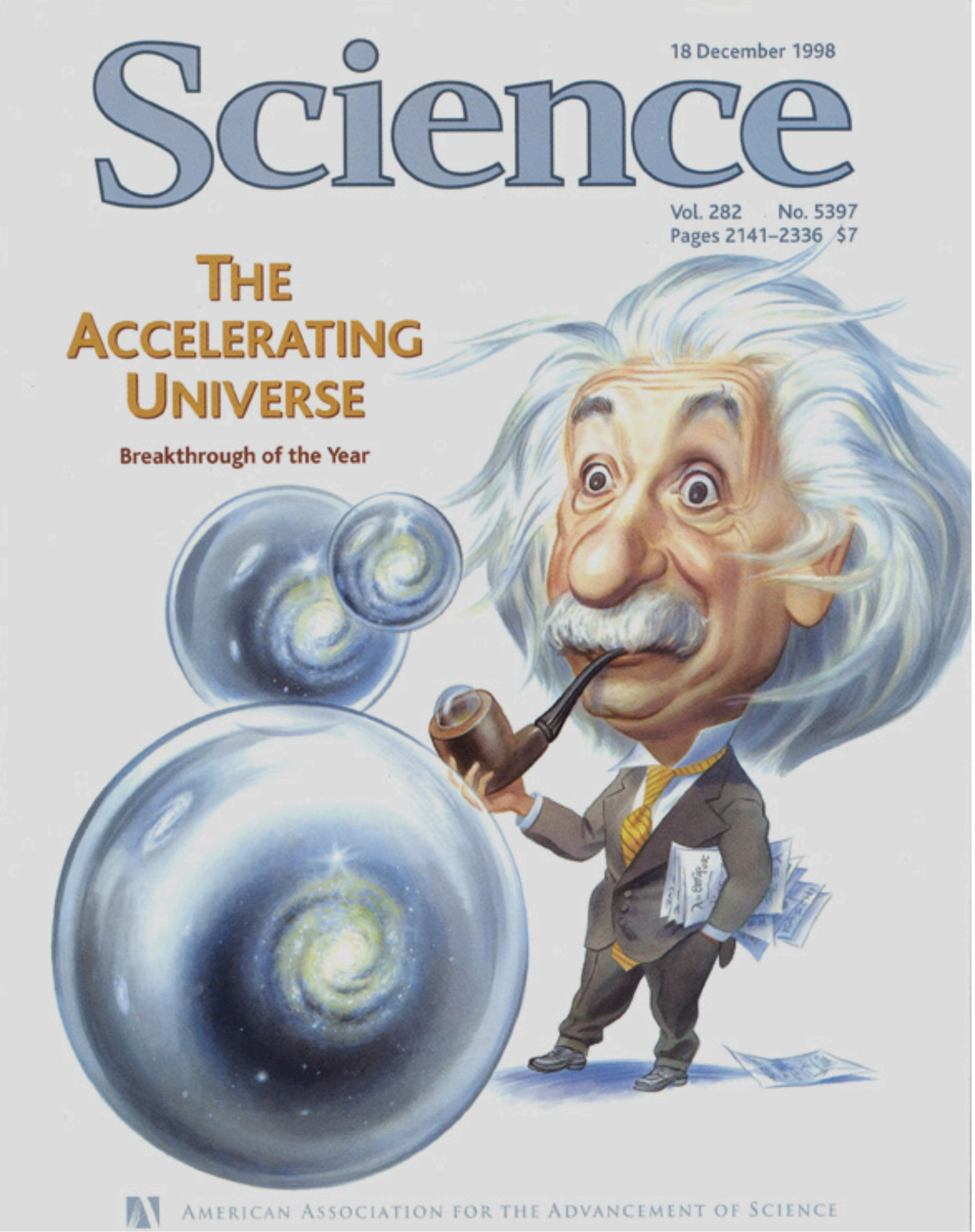
1998 Data:

Riess et al.
Astronomical Journal

September 1998

Perlmutter et al.
Astrophysical Journal

June 1999



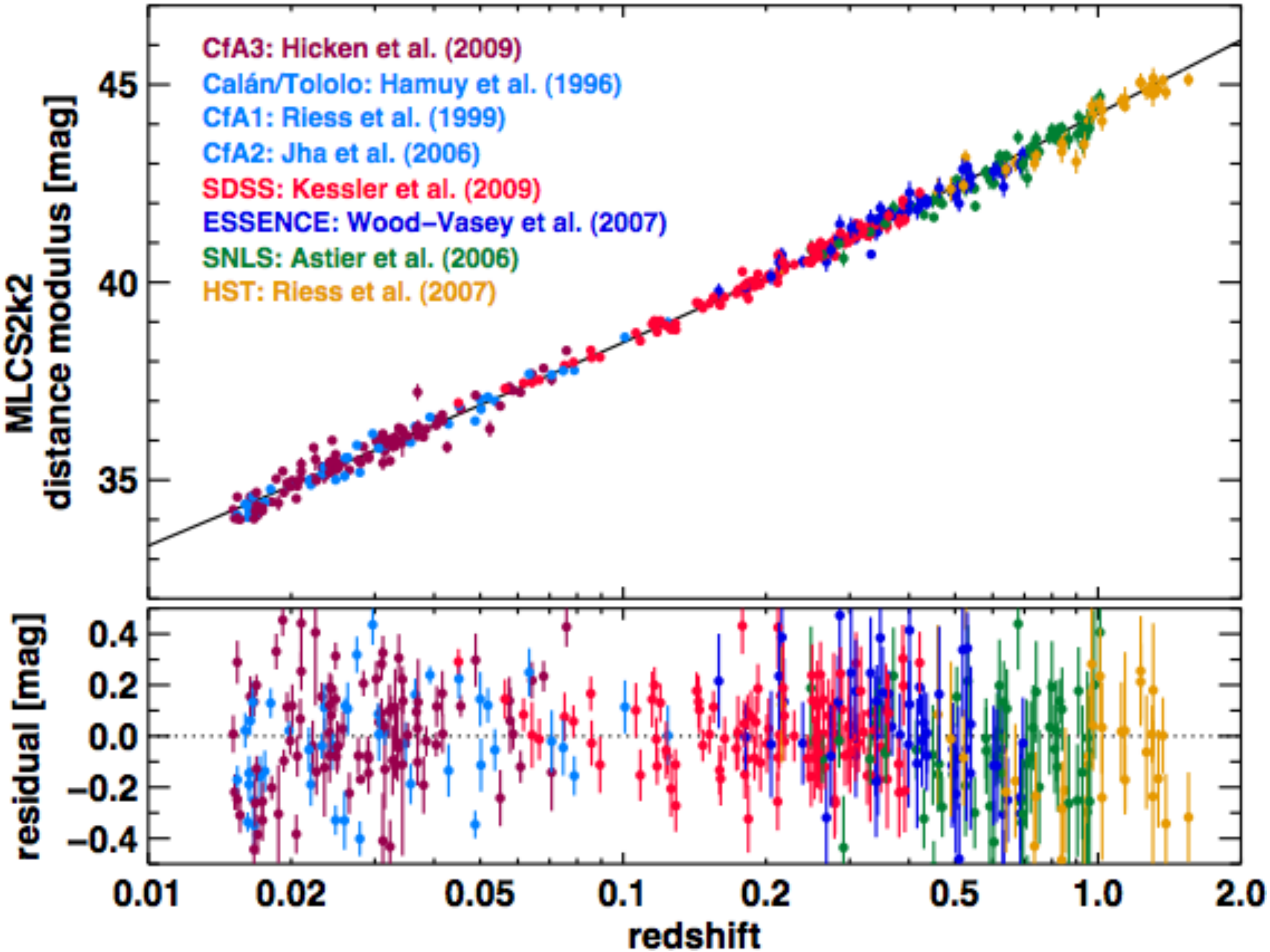
Improvements since 1998:

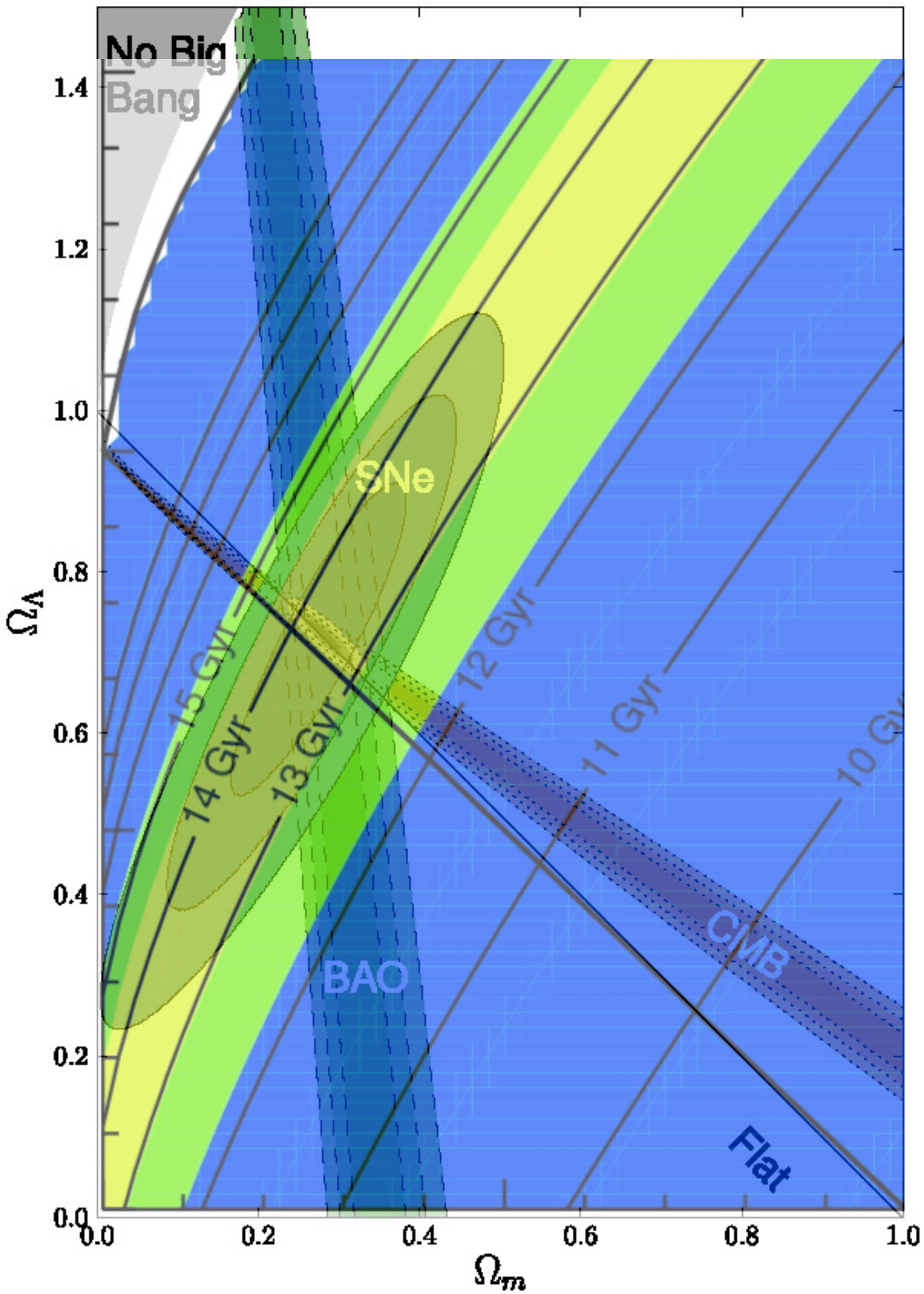
Bigger samples

Higher redshift

Lower systematic errors: the IR

Today's Sample~500 SN Ia





What do the supernovae measure?

Cosmic Age!

$\Omega_\Lambda - \Omega_m$:

the difference between the acceleration due to the dark energy and the braking due to gravitation

Perpendicular to CMB which measures

$\Omega_\Lambda + \Omega_m$

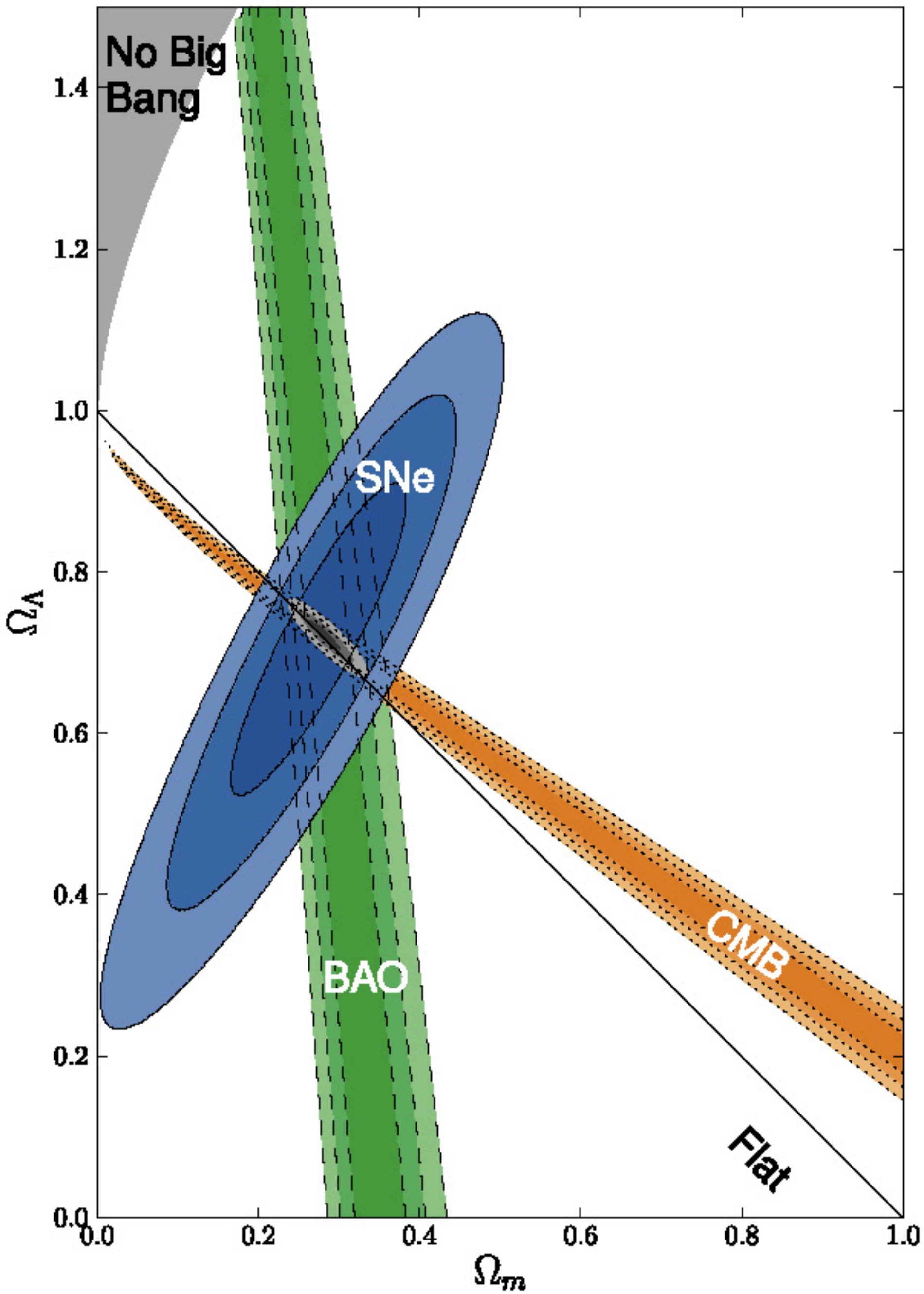
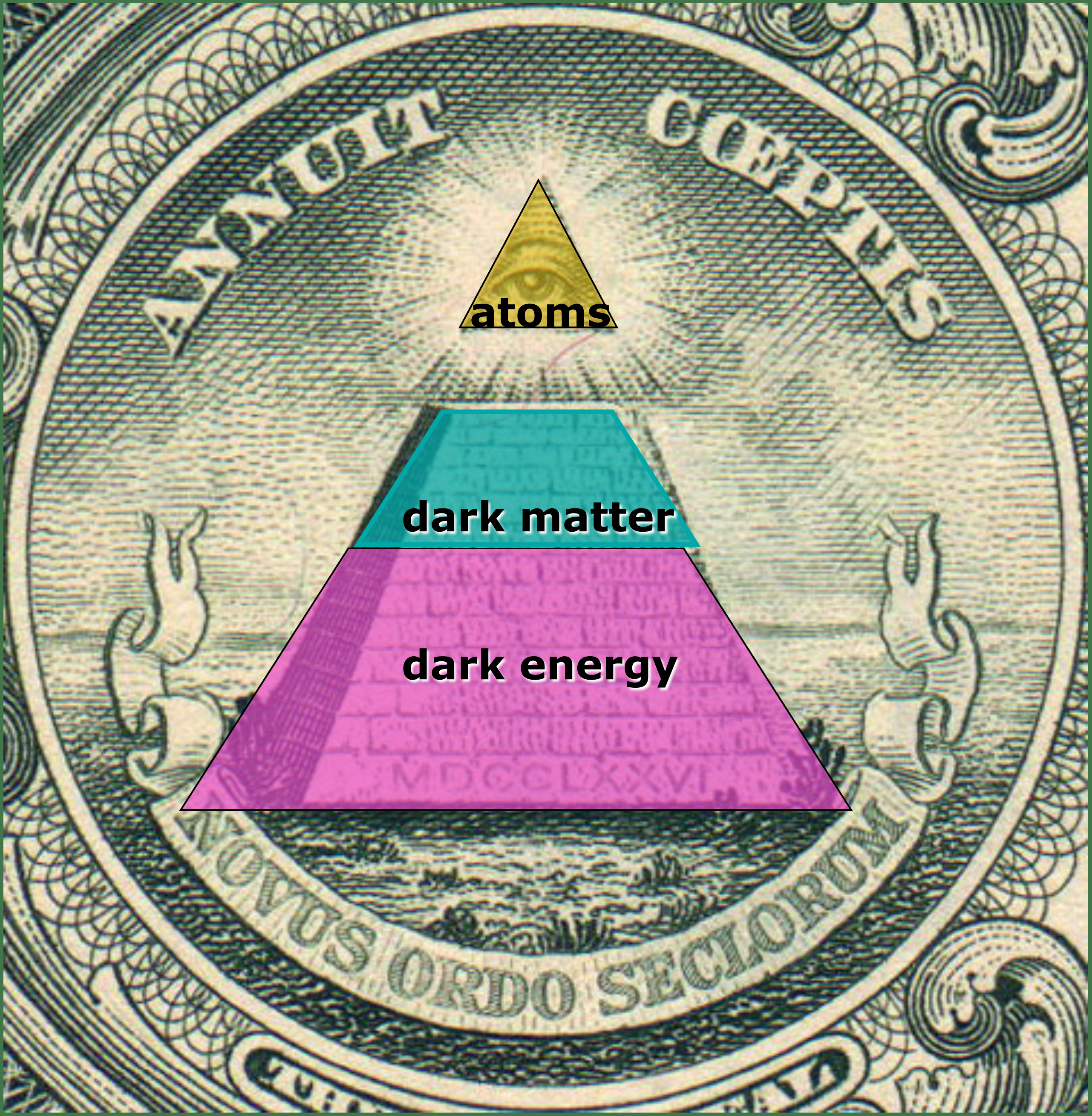


Figure from Suzuki et al. astro-ph 1105.3470

Based on Low z: (Calan-Tololo + CfA1 +CfA2 + CfA3 + Sloan) + 8 from SCP (Kowalski 2008)

ESSENCE + SNLS + Higher-Z+ 6 from SCP "Union 2"

Ω_m = 0.27 +/- 0.01
Ω_Λ = 0.73


ANNUIT CŒPTIS
atoms
dark matter
dark energy
MDCCLXXVI
NOVUS ORDO SECLORUM

INTERNATIONAL BROTHERHOOD OF THEORISTS

LOCAL 137

cogito ergo sum

UNION CARD

Robert Kirshner

MEMBER IN GOOD STANDING

UC CHAPTER

THE · UNIVERSITY · OF · CALIFORNIA · 1868 · LET THERE BE LIGHT

valid to ∞

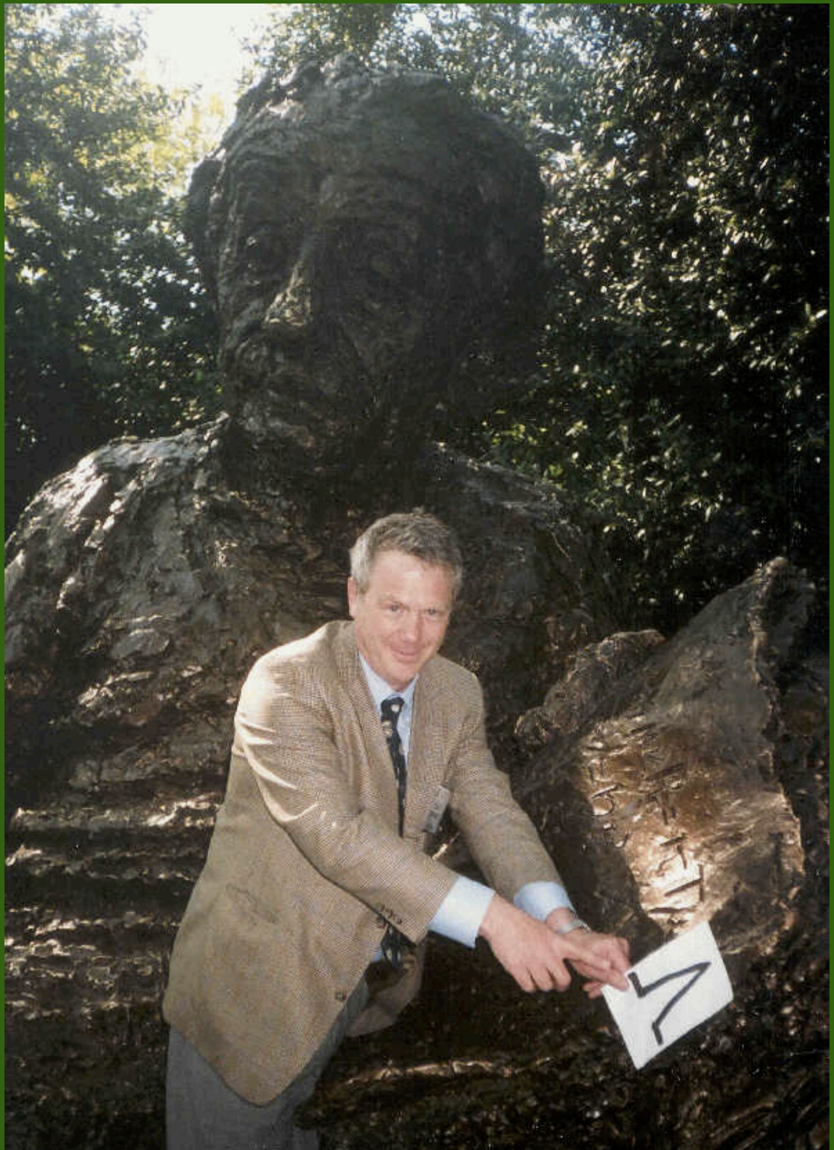
David Gross

President

Lars Bildsten

Shop Steward

Putting Λ on the Right Hand Side



Is the Dark Energy the Cosmological Constant?

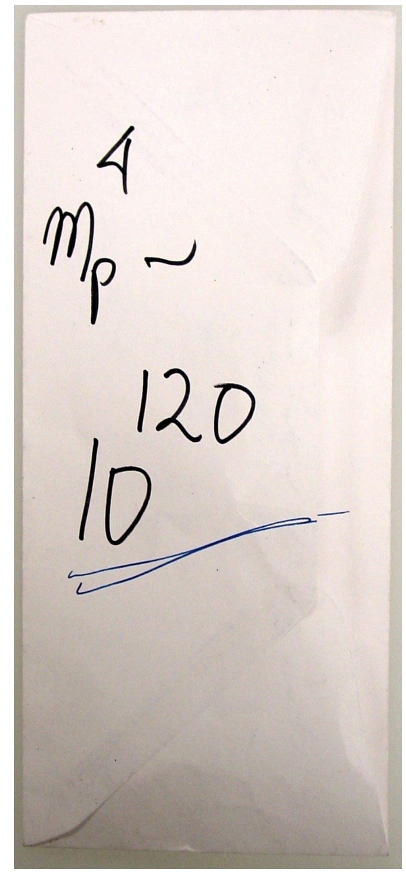
Not good quantitative agreement!

Other possibilities: something that is not constant

Modifications to gravity?

Cannot tell from expansion history alone

Need other information-- growth of structure



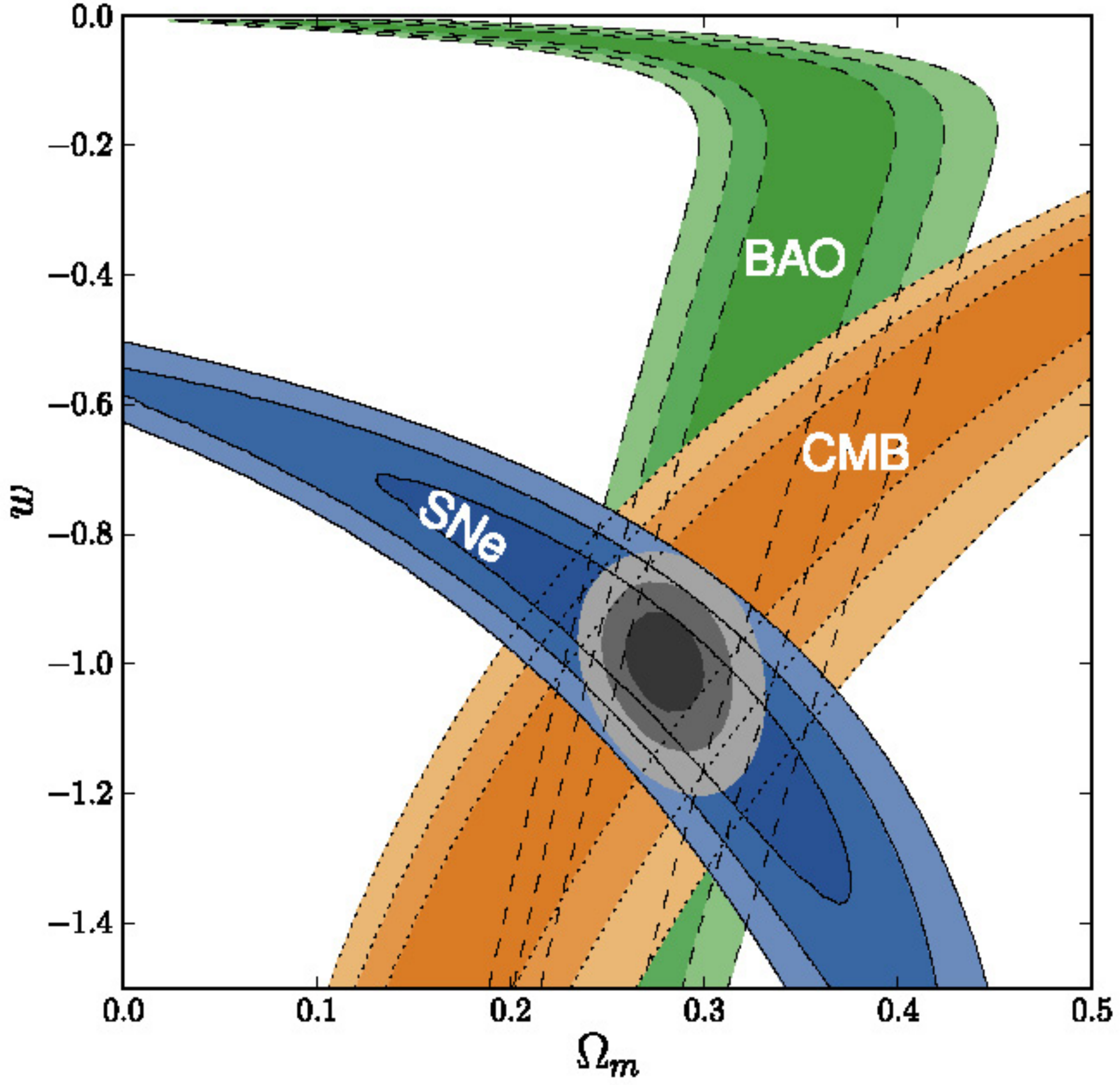


Figure from Suzuki et al. (2011)

1 + w = -0.01 +/-0.06 **+/- 0.10 (sys)**

Consistent with a cosmological constant--but does not rule out modifications of gravity

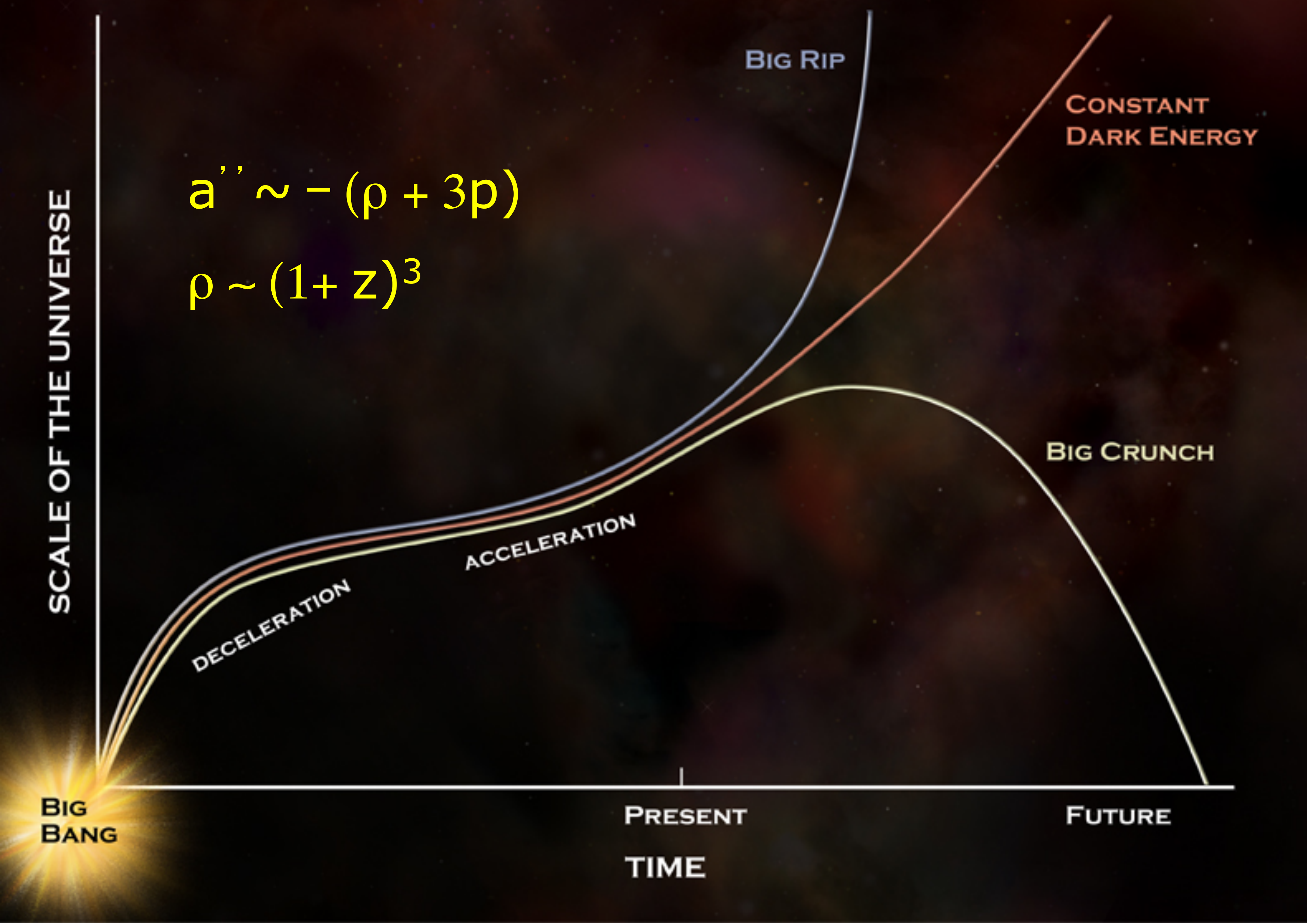
How do we diminish the systematic errors?

Use information about host galaxies, from spectra, and avoid problems with dust!

Most promising:
NIR observations

$$\ddot{a} \sim -(\rho + 3p)$$

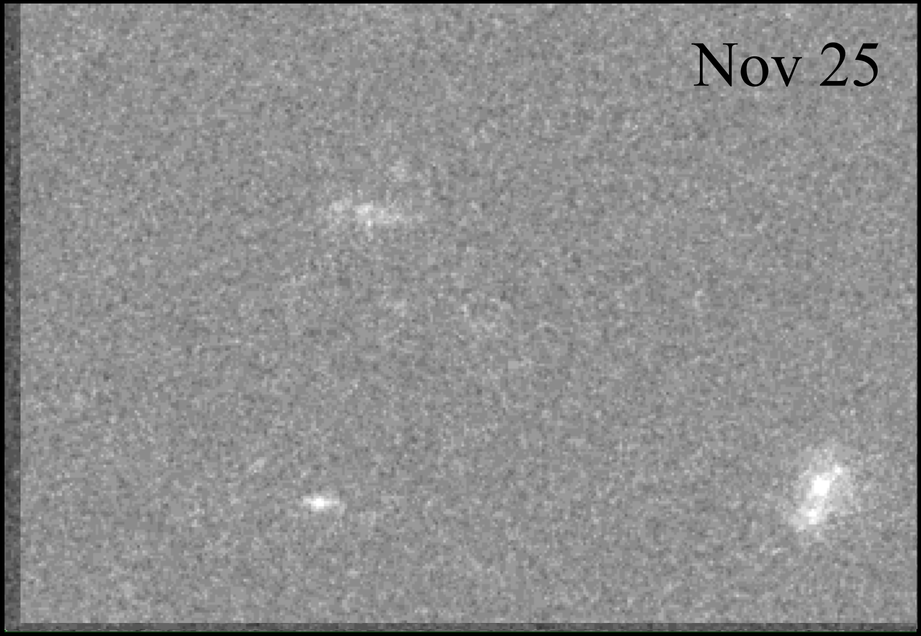
$$\rho \sim (1+z)^3$$

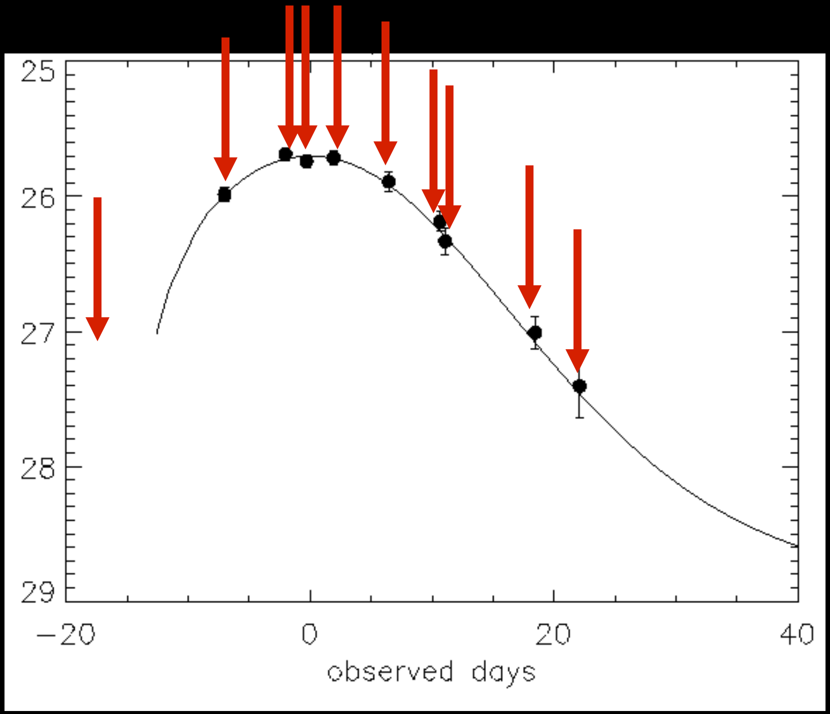


Searching for Supernovae with HST

Back to the age of ***de***celeration

The Rise and Fall of a Distant Supernova





A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of

Front

Back

important step in figuring out just what the dark energy is.

"He gave us information about when the universe hit the gas pedal," said Dr. Michael S. Turner, a cosmologist at the University of Chicago who is director of mathematics and

the universe speed up 5 billion years ago.

If that was the case, supernovas even

"It's great to see it," Dr. Riess said.

In Dr. Lykken's words, and as borne out by discussions at the meeting here, "theorists don't have a clue" about the identity of the dark energy that is so important.

Evidence for a change in cosmic acceleration: '**cosmic**

tion

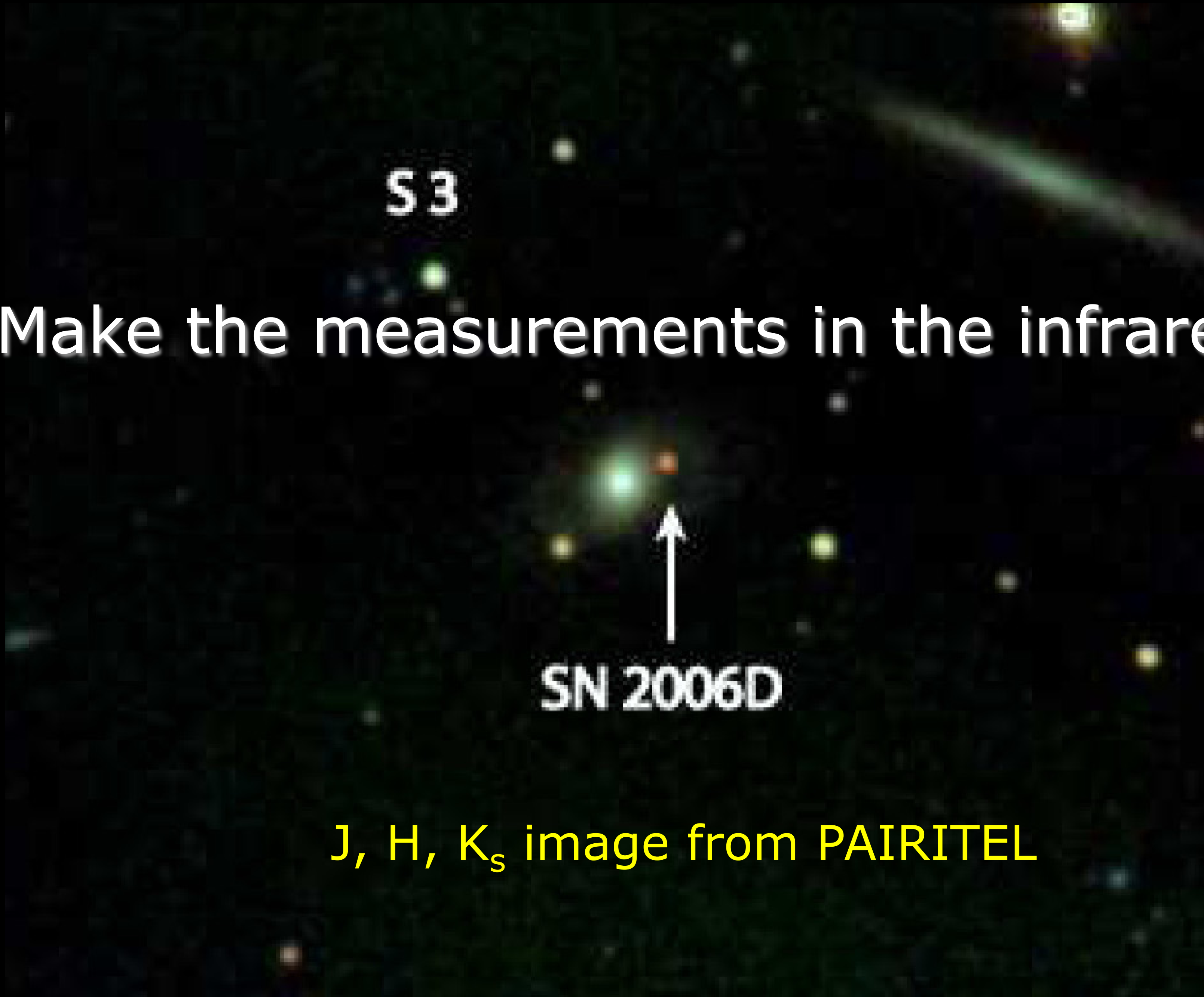
Big rip?

The Future

The biggest uncertainties now are **systematic errors** and the worst of these come from dust and light curve fitters

Dust both dims and reddens -- but less so in the infrared

Make the measurements in the infrared!



J, H, K_s image from PAIRITEL

Kaisey Mandel

Using a Bayesian model to combine optical and IR data for SN Ia, predict distances, and determine dust properties.

BayeSN inference : Kaisey Mandel

ApJ 704, 629 (2009)

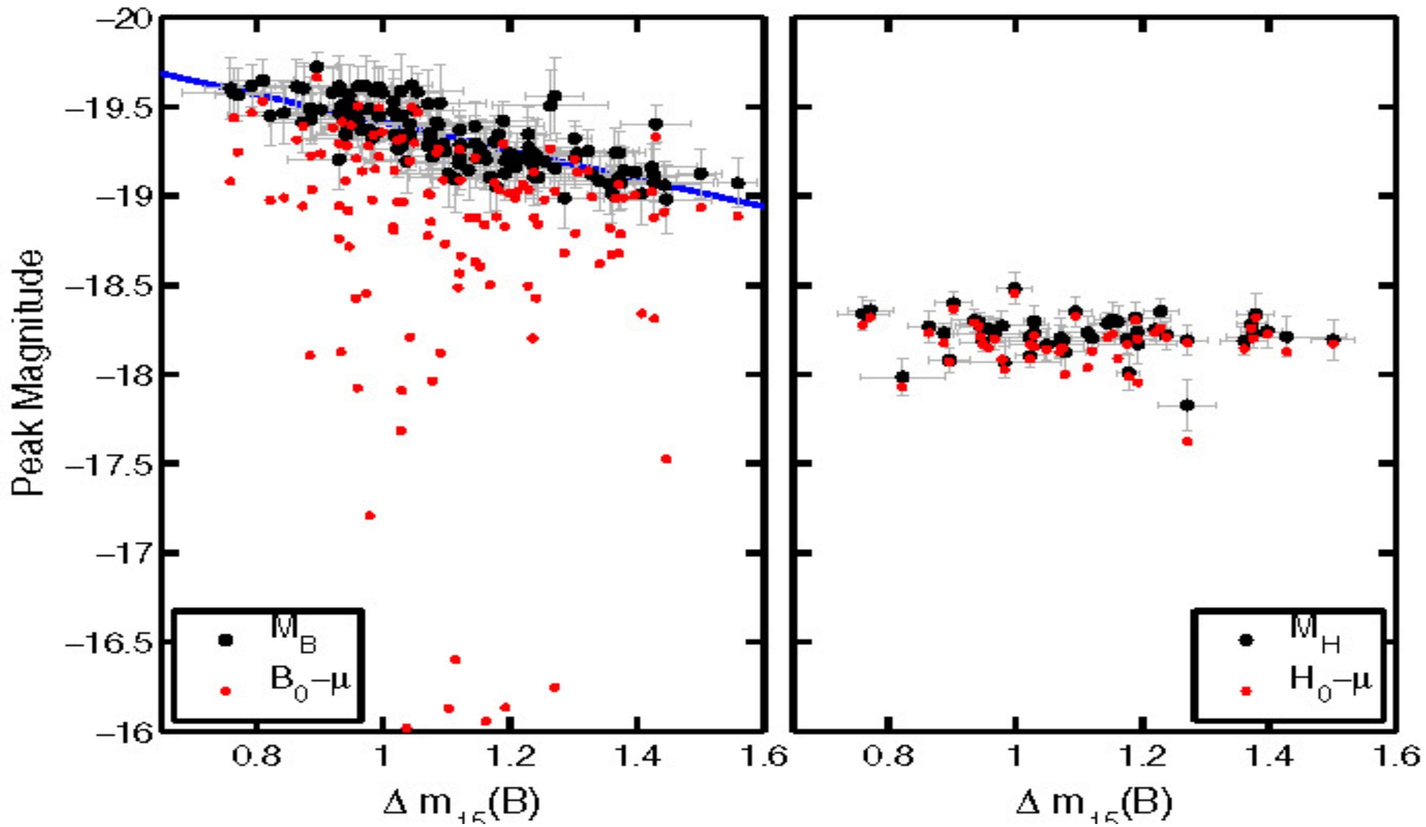
Needs Job!

ApJ 731, 120 (2011)

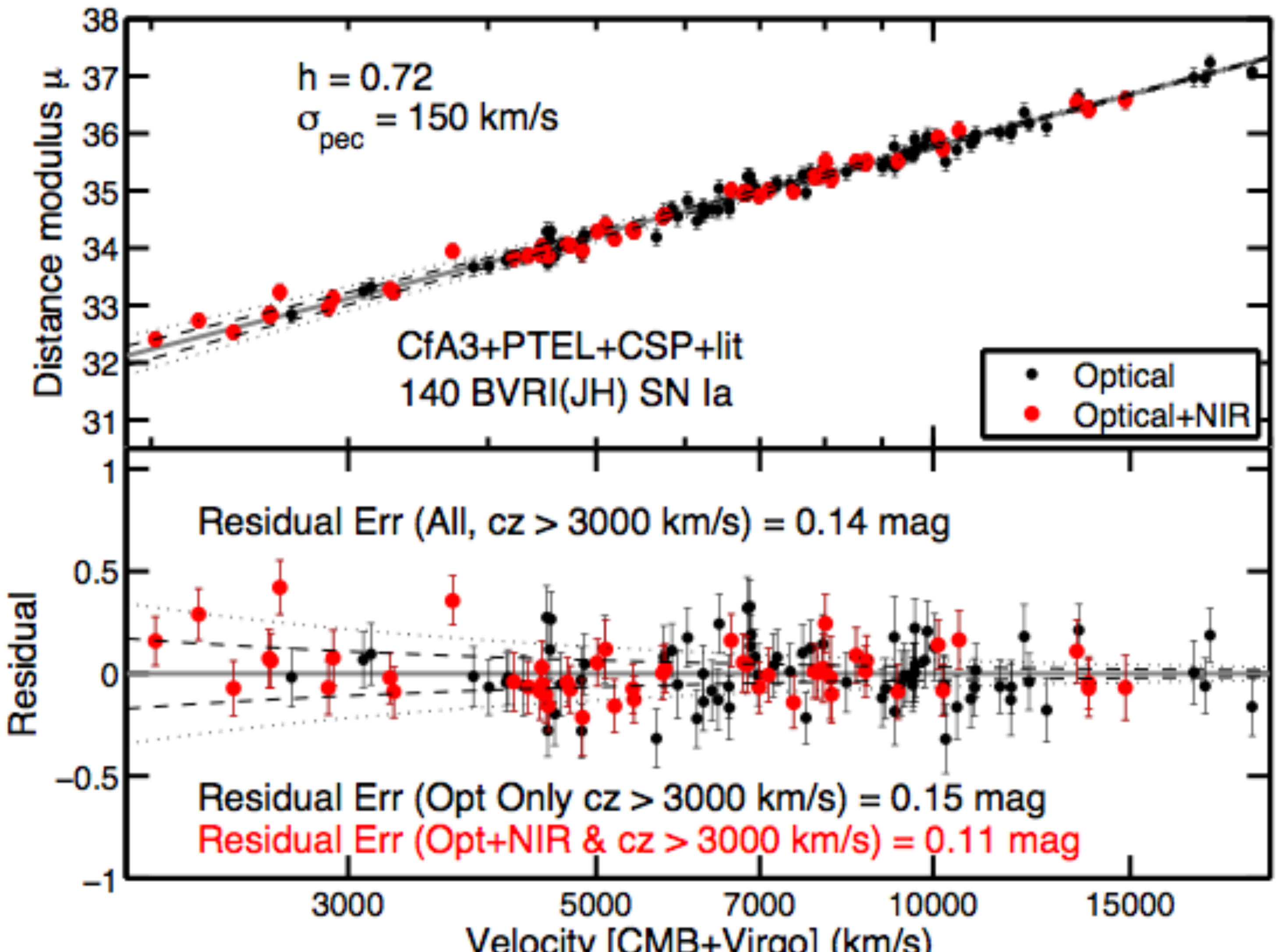
Optical: standardizable candles

IR: standard candles! (and less trouble with dust!)

THE ASTROPHYSICAL JOURNAL, 731:120 (26pp), 2011 April 20

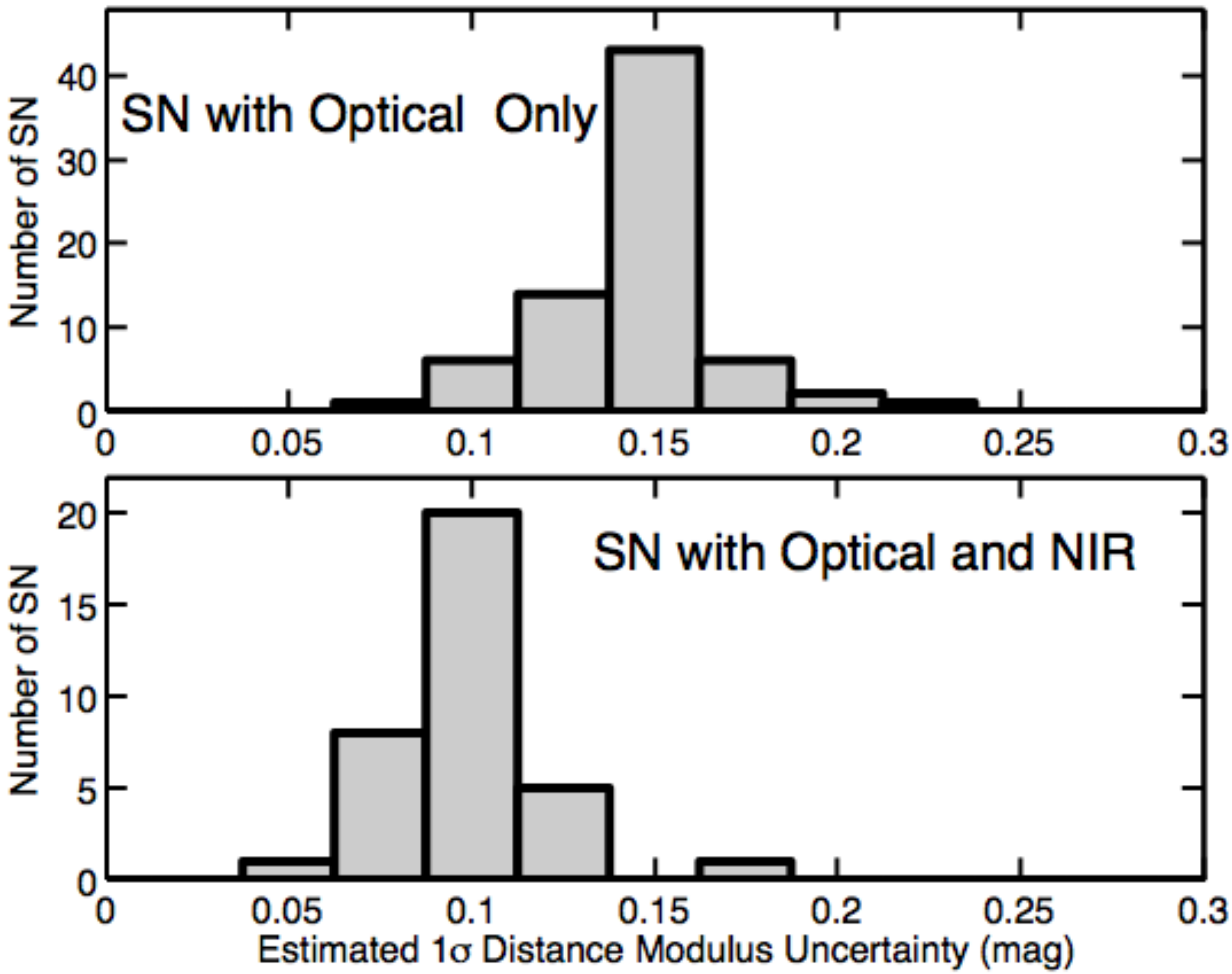


The Payoff



h = 0.72
σ_{pec} = 150 km/s
CfA3+PTEL+CSP+lit
140 BVRI(JH) SN Ia
Optical
Optical+NIR
Distance modulus μ
38
37
36
35
34
33
32
31
Residual Err (All, cz > 3000 km/s) = 0.14 mag
Residual Err (Opt Only cz > 3000 km/s) = 0.15 mag
Residual Err (Opt+NIR & cz > 3000 km/s) = 0.11 mag
Residual
1
0.5
0
−0.5
−1
3000
5000
7000
10000
15000
Velocity [CMB+Virgo] (km/s)

Could we get this advantage for the high-z supernovae? RAISIN



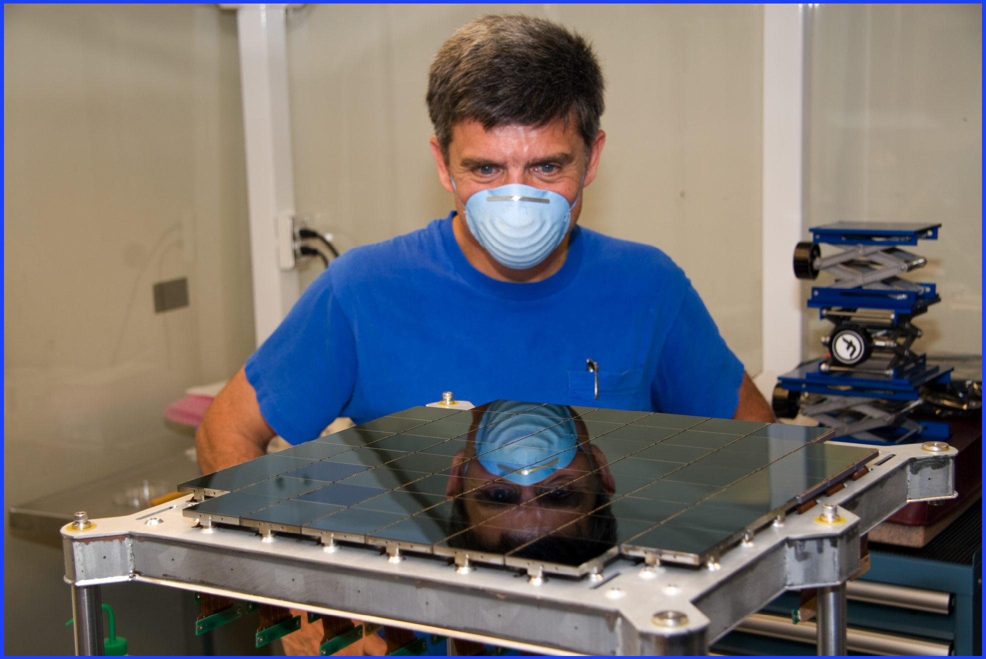
Use WFC3 to get rest frame IR of moderate redshift SN Ia!

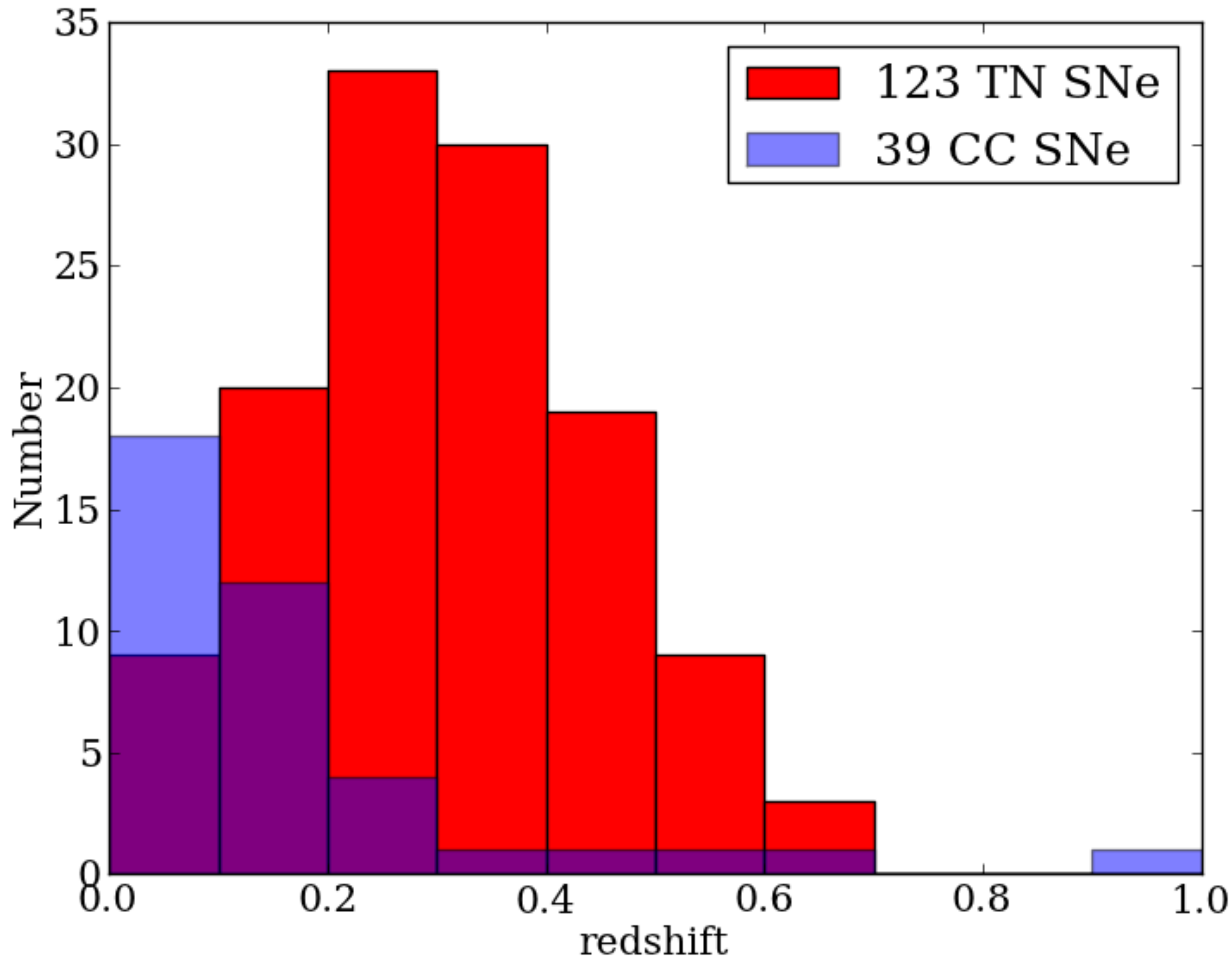
SNIA in the IR = RAISIN

Pan-STARRS

Medium-Deep Fields

Good light curves at z~0.4
Real production now
7 square degrees
0.26 "/pixel





Spectra from Magellan, MMT, Gemini

Key to the RAISIN program to get restframe IR of SN Ia

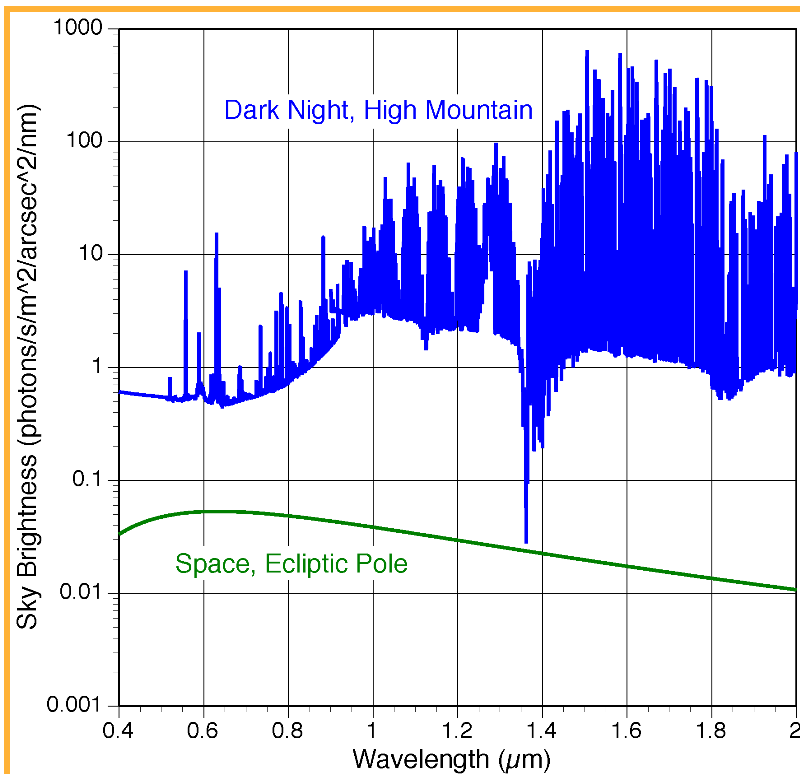
Only in space!

Rest frame IR measurements of z~1 supernovae are not possible from the ground

Go as far into the IR as technically feasible!

Sky is very bright in NIR: >100x brighter than in space

Sky is not transparent in NIR: absorption due to water is very strong and extremely variable



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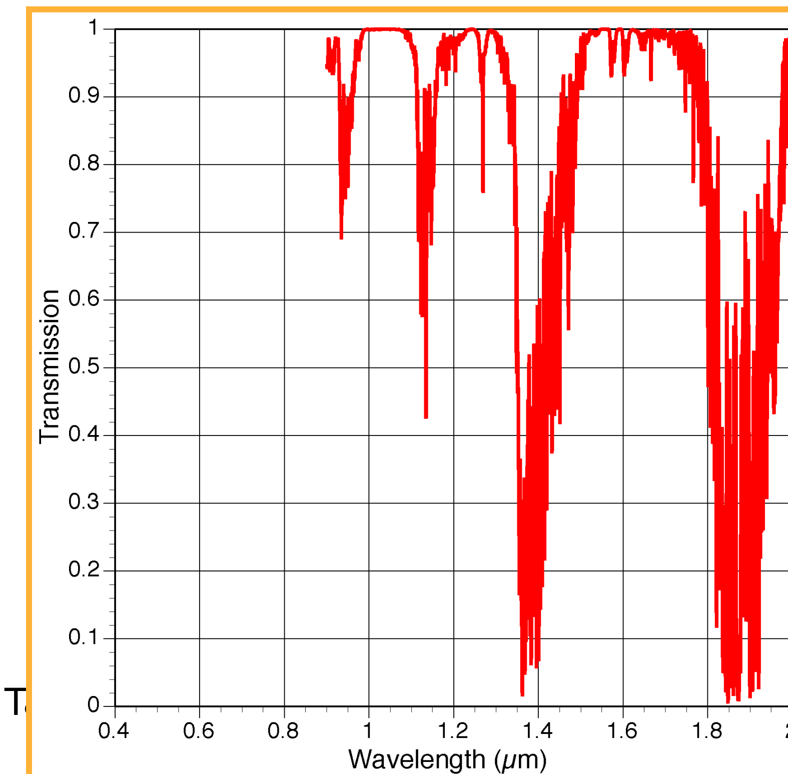
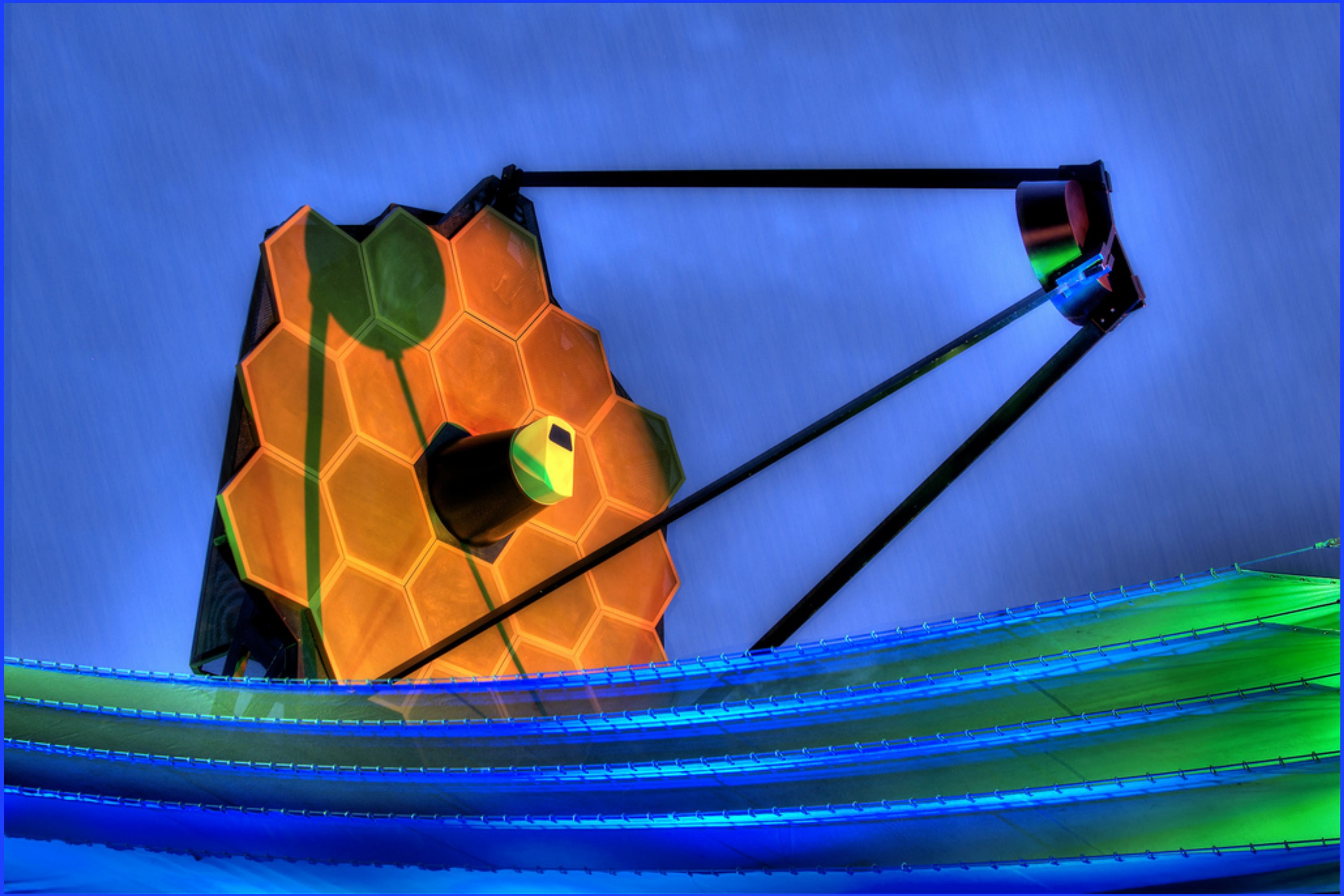
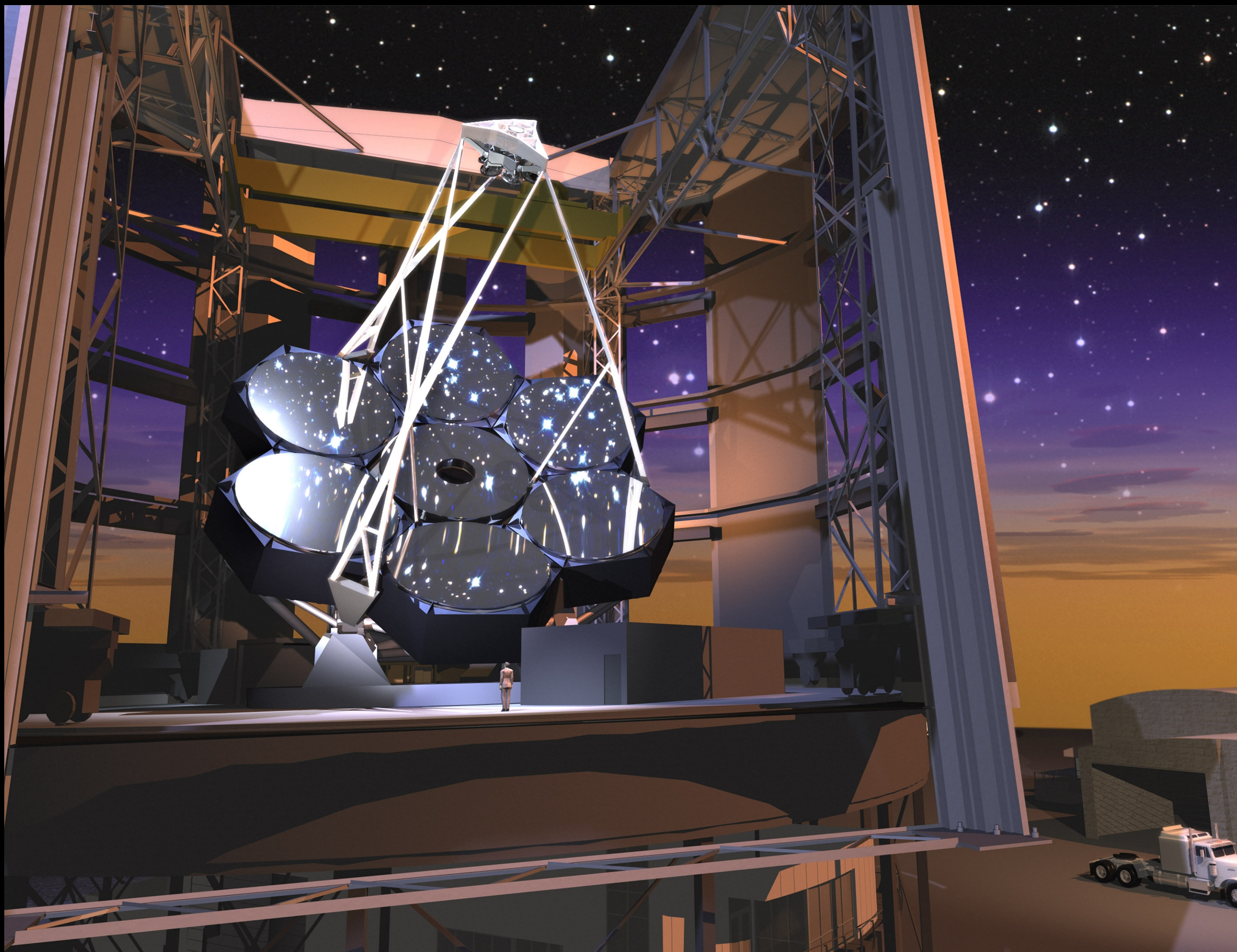




JWST will be excellent for the rest frame IR of SN Ia at $0.2 < z < 1$

Giant Magellan Telescope



Compared to Eye--

Area: 10^8

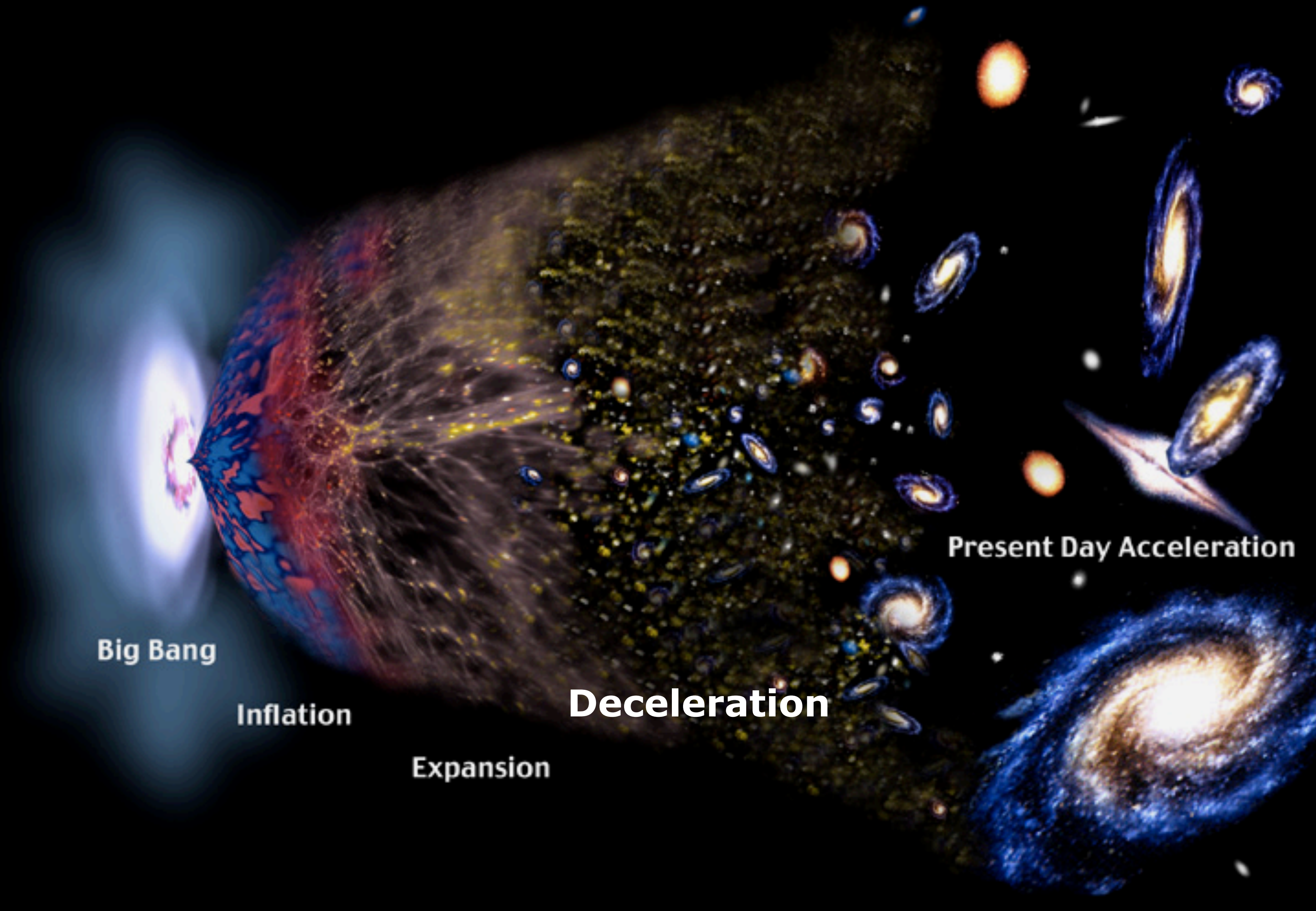
Resolution: 10^4

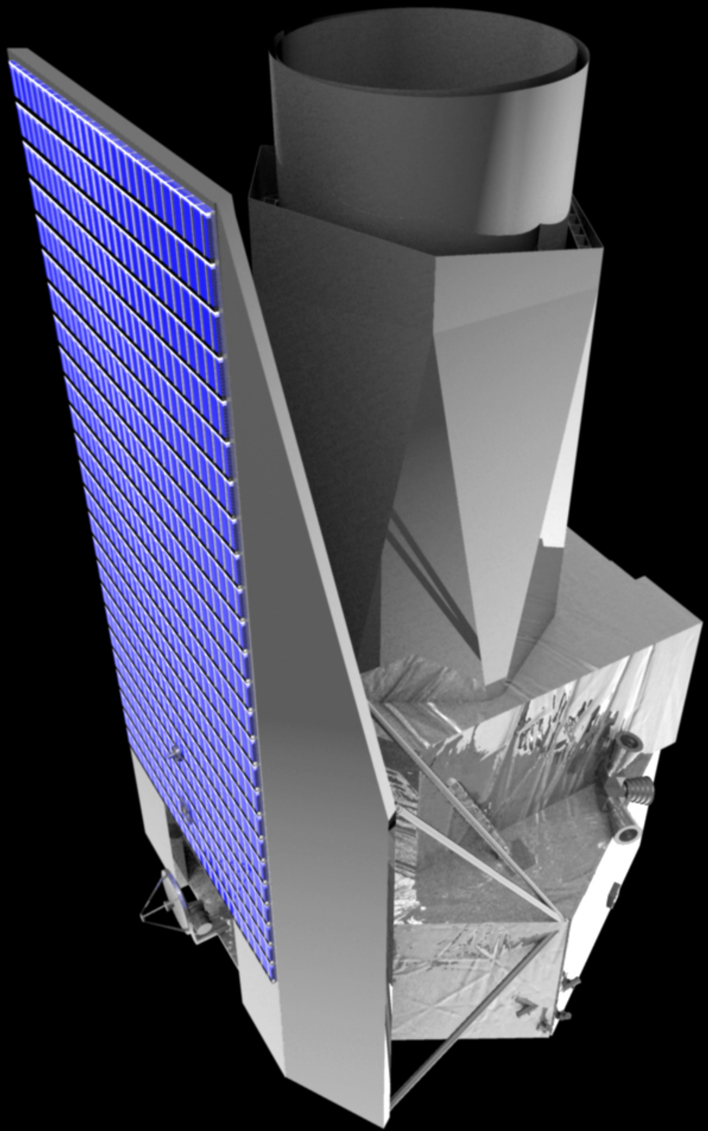
Compared to HST--

Area: 10^2

Resolution: 10

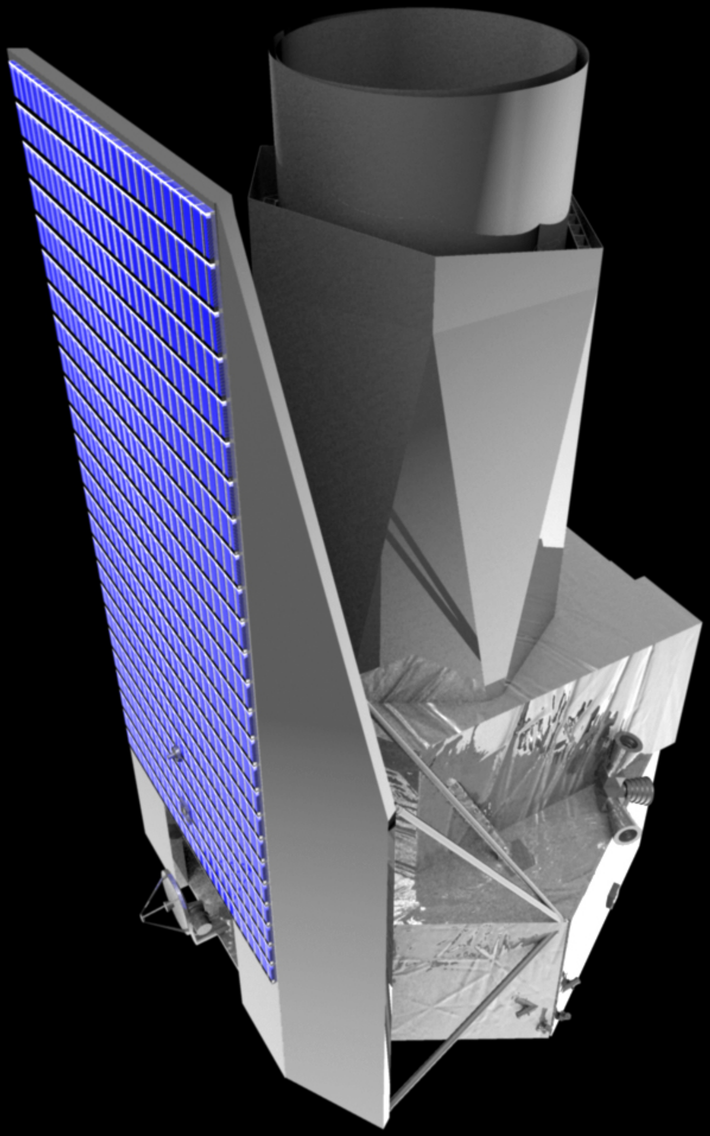
Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!





EUCLID

Baseline:
Baryon
Oscillations
Weak Lensing



SNEUCLID

Baseline:
Baryon
Oscillations
Weak Lensing

Could do a
good job
with
supernove

Our Future?

Our future?

Milky Way = Universe!?