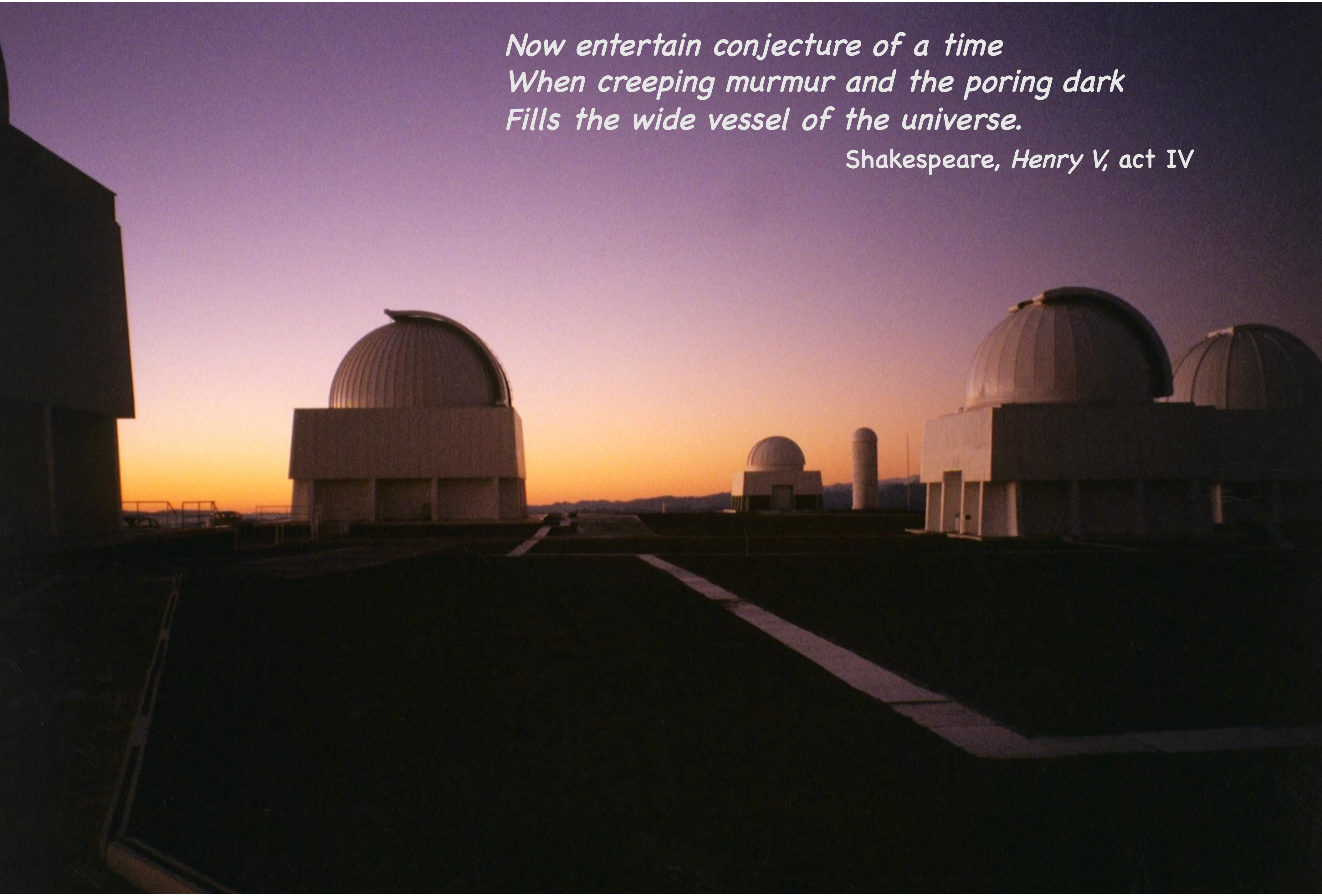

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.
Shakespeare, Henry V, act IV

"Anyone can do astronomy when it is clear."

– Olin Eggen, 1980

The Accelerating Universe

Nicholas B. Suntzeff

Mitchell Institute for Fundamental Physics & Astronomy
Department of Physics & Astronomy
Texas A&M University
University of Texas/Austin

50th Anniversary of NOAO

17 March 2010

NOAO

"No important science has ever been done at the National Optical Observatory."

Famous National Academy astronomer - 1992

NOAO

"I could run this place for $300,000 per year."

Said by an astronomer on an NSF site review panel of CTIO around 1998.

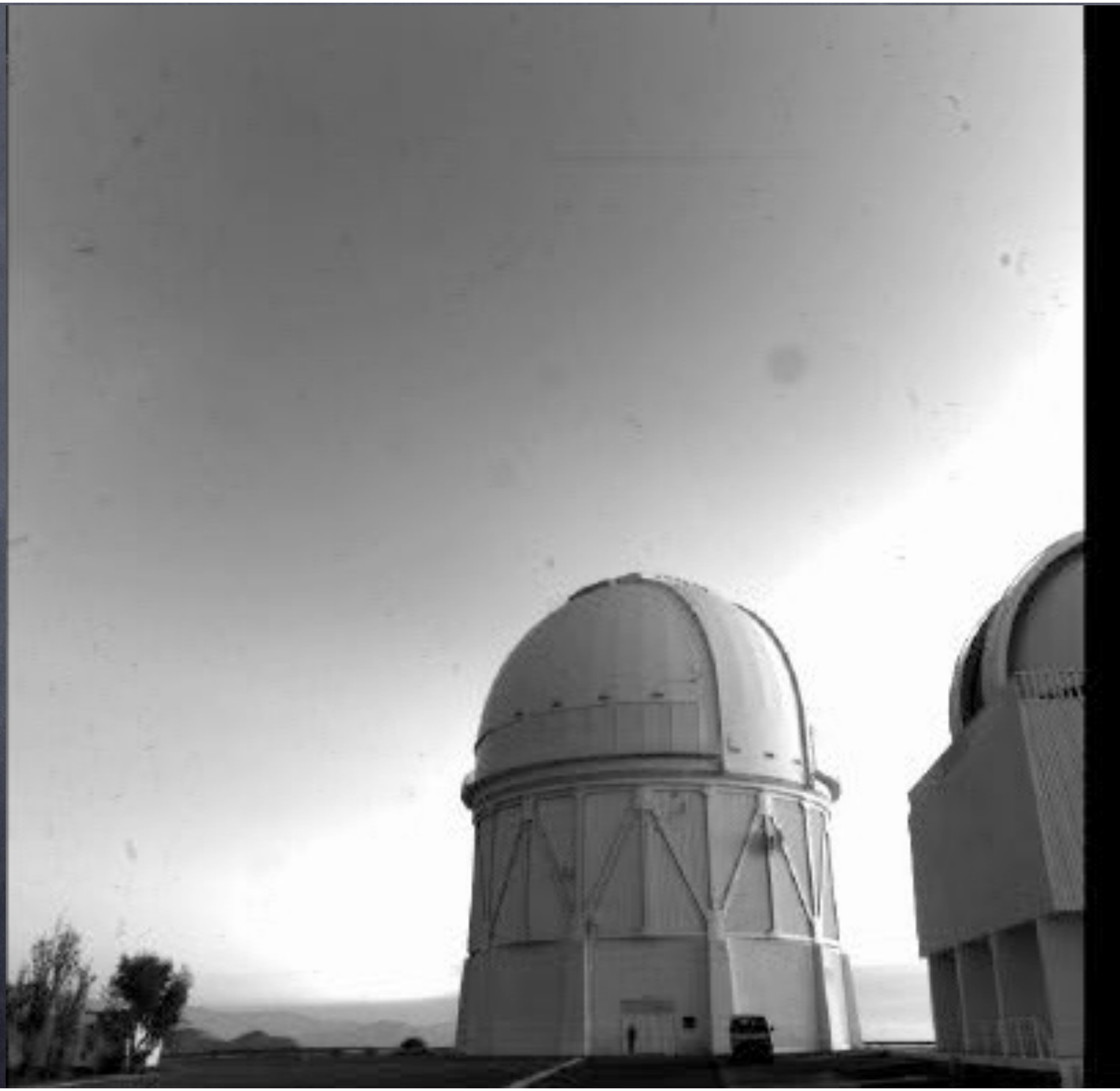
NOAO

"We should shut down NOAO and give the money to the better observatories."

Said by a different famous NAS astronomy member, 1992

"NOAO – that is a place where a Lick graduate would go."

Said by an astronomer when they heard that Suntzeff was going to CTIO. 1982



My version of the history of Dark Energy

Rashoman effect

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 133 | MARCH 1961 | NUMBER 2

THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

Allan Sandage

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology

Received October 14, 1960; revised November 5, 1960

ABSTRACT

The present paper reviews several tests which can be performed to decide between world models. Each test is discussed in terms of the capabilities of the 200-inch Hale telescope. The tests include (1) the deviation from linearity of the red-shift–magnitude relation, (2) the galaxy-count–magnitude relation, (3) the angular-diameter–red-shift relation treated for both metric and isophotal diameters, and (4) the time scale. Selected exploding models of the Friedman type and the steady-state model are considered. The object of the tests is to determine observationally the deceleration parameter q_0. Once q_0 is known, the world model follows from equations given in Section I.

It appears possible to find q_0 from the magnitude–red-shift relation. At a red shift $(\Delta\lambda/\lambda_0)$ of $z = 0.5$, a difference of 0.9 mag. exists in the $[m, z]$ relation between a closed, elliptical universe with $q_0 = +1$ and the steady-state model with $q_0 = -1$. Such a difference can possibly be detected if the aperture effect for the measurement of intensities and if the Scott effect of observational selection can be allowed for. The value of q_0 is presently estimated to lie between 0 and +3. The most probable value is $q_0 = 1 \pm \frac{1}{2}$. The predictions of steady-state cosmology would appear to be inconsistent with present information.

The $N(m)$ relation for galaxy counts is derived for all models considered. Galaxy counts are insensitive to the model. At the limit of the 200-inch, an observational error of only $\Delta m_R = 0.28$ mag. can change the counts from indicating a closed universe with $q_0 = +1$ to an open, empty model with $q_0 = 0$. There seems to be no hope of finding q_0 from the $N(m)$ counts because the predicted differences between the models are too small compared with the known fluctuations of the distribution.

The angular diameters of clusters of galaxies and of galaxies themselves are discussed. The angular diameter subtended by a linear distance y is shown to change with z in a different way than the isophotal diameters. Both types of diameters are considered, and a test for q_0 seems to be possible with the 200-inch, but the test will be difficult and perhaps marginal

Equations for the time t_0 since the beginning of the expansion are derived. It is shown that t_0 is a function of the Hubble parameter H_0 and q_0 alone for exploding models with $\Lambda = 0$. The present value of H_0 and the age of the oldest stars are shown to be incompatible. If $q_0 = +1$, then $t_0 = 0.571\ H_0^{-1} = 7.42 \times 10^9$ years (assuming $H_0 = 75$ km/sec 10^6 pc). However, the age of the oldest stars in our Galaxy is computed to be greater than 15×10^9 years if the most recent stellar models of Hazelgrove and Hoyle are used. These values are too uncertain to claim that exploding models with $\Lambda = 0$ are incorrect, but the data, as given, would so require. It is shown in the final section that exploding models of the Lemaitre-Eddington type approach asymptotically $q_0 = -1$ and are therefore like the steady-state model. In the limit both models predict the same $[m, z]$ and $[\theta, z]$ relations Consequently, tests of the type considered in this paper cannot decide between these particular models Appeal to the time independence of the steady-state model must then be made for a test. Appendix A gives the explicit equations for $N(m)$ for various q_0 values.

THE ASTROPHYSICAL JOURNAL, 214:L5–L7, 1977 May 15

DETERMINING q_0 FROM SUPERNOVAE*

ROBERT V. WAGONER
Institute of Theoretical Physics, Department of Physics, Stanford University
Received 1977 January 18; revised 1977 February 10

ABSTRACT

It is shown how Baade's method for determining the distance to variable stars can be applied to distant supernovae to obtain the deceleration parameter q_0 (as well as the Hubble constant H_0). In contrast to other methods, these cosmological quantities are expressed *solely* in terms of *observable* properties of any particular supernova. The assumptions upon which this analysis is based can be tested from the observations. Spectrophotometry of supernovae with apparent magnitudes $m_V \gtrsim 23$ is required, probably necessitating a space telescope.

Subject headings: cosmology — stars: supernovae

I. INTRODUCTION

It has become obvious from recent studies of evolutionary effects on galaxies (Ostriker and Tremaine 1975) that the classical redshift-magnitude relation cannot be used to obtain the cosmological deceleration parameter q_0 unless the luminosity evolution of the galaxies employed can be independently *observed*. Petrosian (1976) has suggested using measurements of the ratio of average surface brightness to limiting surface brightness as a way to learn about surface brightness evolution. However, this method does not directly provide information on the integrated luminosity evolution, unless a specific model is chosen. In particular, it is not sensitive to the evolution of galactic size which could be present in dense clusters. The use of methods other than the redshift-magnitude relation which also employ "standard candles," "standard sizes," etc., faces similar difficulties because the evolution of such "standards" can never be known with certainty.

That is, our analysis is valid within any metric theory of gravity (Misner, Thorne, and Wheeler 1973).

B) The cosmological principle is statistically valid. Therefore, the large-scale geometry is described by the Robertson-Walker metric (Weinberg 1972)

$$ds^2 = c^2dt^2 - R^2(t)[(1 - ku^2)^{-1}du^2 + u^2(d\theta^2 + \sin^2\theta d\phi^2)] \,, \quad (1)$$

where u is a comoving radial coordinate ($k = 0, \pm 1$). The effects of inhomogeneities in the mass distribution (due to galaxies, etc.) on the propagation of photons (cf. Dyer and Roeder 1972; Weinberg 1976) may be included in the following analysis if necessary. The only modifications would occur in equations (5) and (9), with equation (8b) remaining valid through the order indicated.

C) During the 40 days following maximum brightness, the bulk of the radiation from a supernova is in the form of a thermal continuum, resembling that from

Can Type Ia Supernovae be used to measure distances?

DES OF SUPERNOVAE 1023

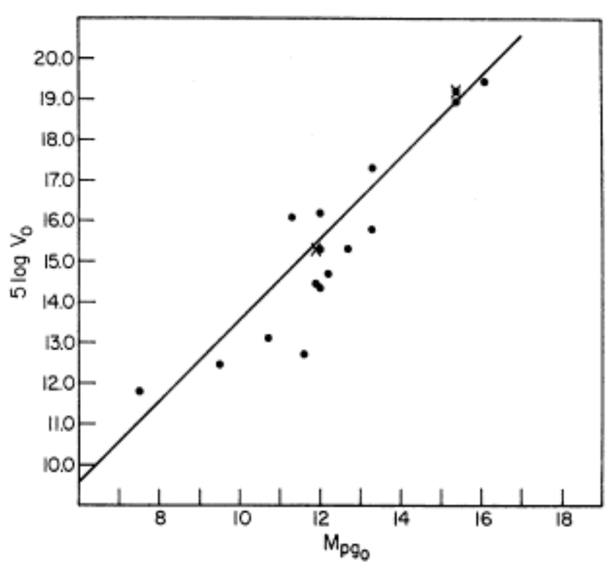


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

Kowal (1968)

SUPERNOVAE AS A STANDARD CANDLE FOR COSMOLOGY

STIRLING A. COLGATE

New Mexico Institute of Mining and Technology, and Los Alamos Scientific Laboratory

Received 1978 September 5; accepted 1979 March 9

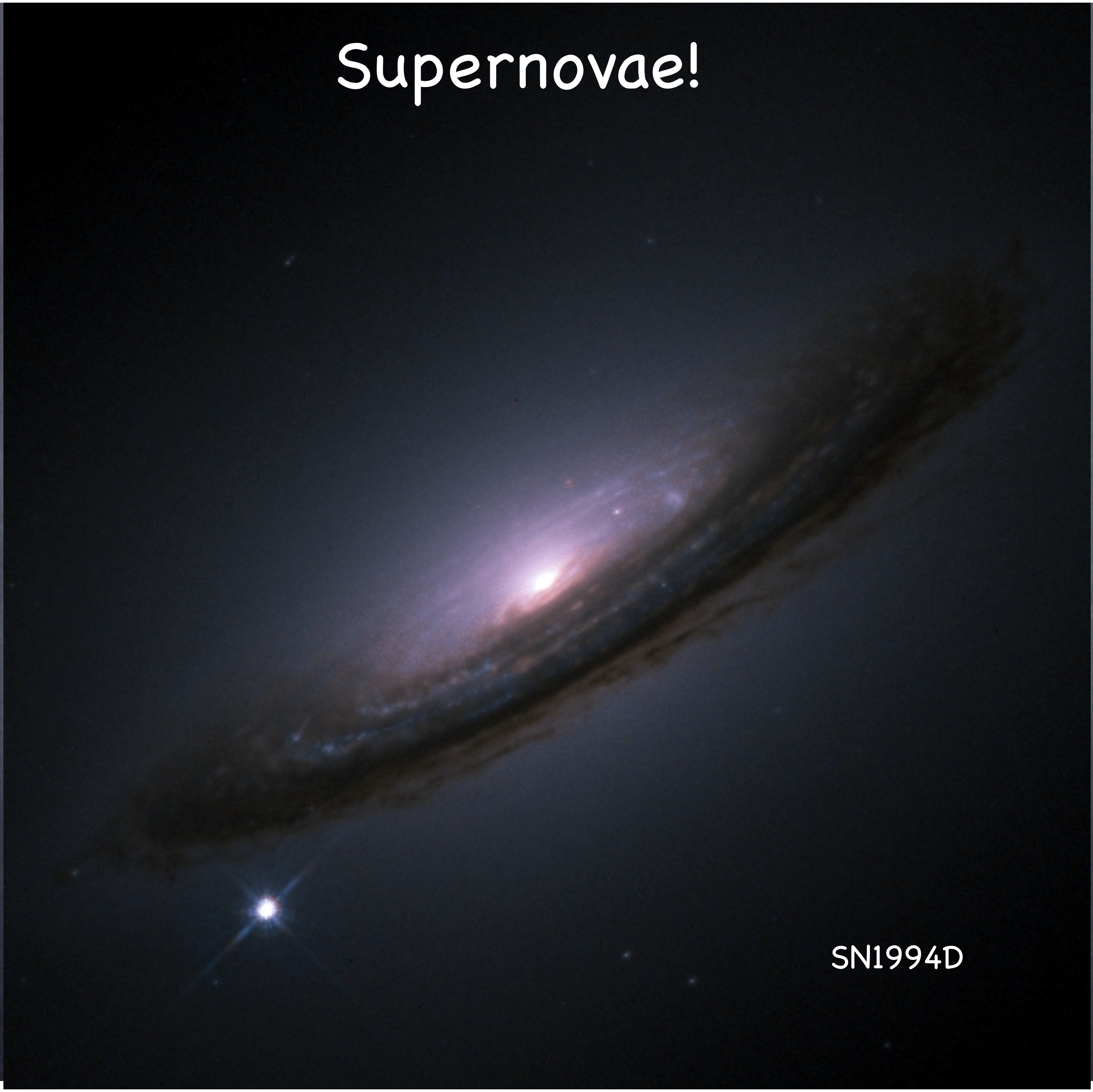
ABSTRACT

Supernovae can perhaps be found at $Z \approx 1$ using the Space Telescope and the Focal Plane Camera (cryogenic charge coupled devices) at a rate of approximately four per week using 3 hours per week of viewing time. If Type II supernovae are used as a self-calibrating candle at $Z \ll 1$, then Type I's can be calibrated from Type II's as a secondary standard candle (2 mag brighter) and used instead of Type II's for a less difficult determination of q_0. This assumes all Type I's are the same independent of Z whereas each Type II is self-calibrated. Adequate statistics of supernovae in nearby galaxies $Z \lesssim 1$ can further verify the uniqueness of Type I's. Three-color wide-band photometry performed over the period of the maximum luminosity of a Type I gives the time dilation $\propto (1 + Z)^{-1}$, color shift $\propto (1 + Z)^{-1}$, and apparent luminosity $\propto Z^{-2}[1 + 0.5(1 + q_0)Z + O(Z)]^{-2}(1 + Z)^{-2}$. A Type I supernova at maximum and $Z = 1$, $H_0 = 50$, should give rise to a statistically meaningful maximum single pixel signal of ~ 250 photoelectrons compared to an average galaxy center background of ~ 25 photoelectrons for an 80 s integration time. An average of ~ 100 large galaxies ($10^{10}\ L_\odot$) per field allows $\sim 10^4$ galaxies to be monitored using 3 hours of viewing time. Z can be determined by time dilation and color shift sufficiently accurately that the determination of q_0 will have twice the error of the calibration of Type I as a standard candle.

Subject headings: cosmology — stars: supernovae

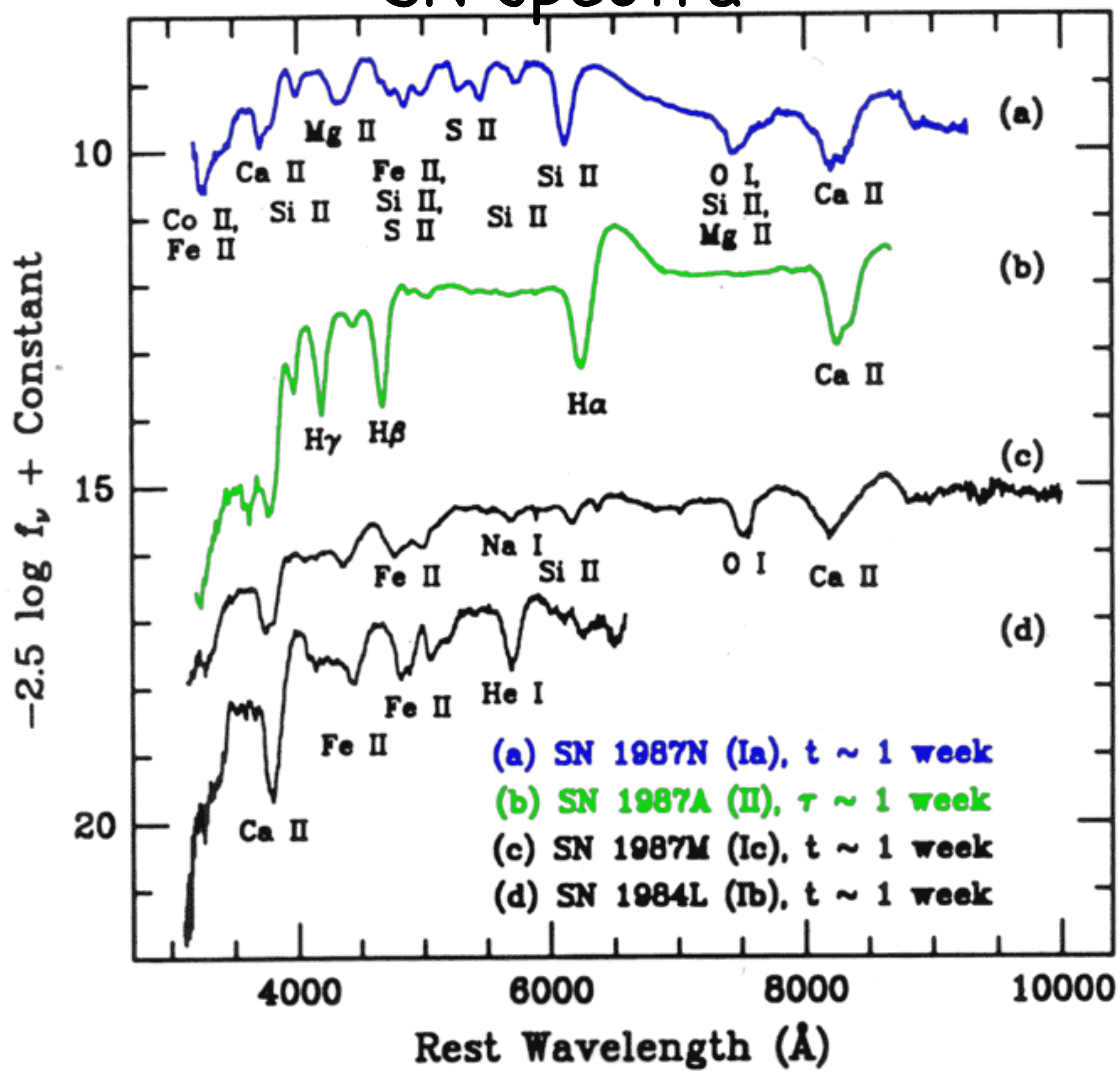
Colgate (1979)

Supernovae!



P. Challis
CfA & NASA

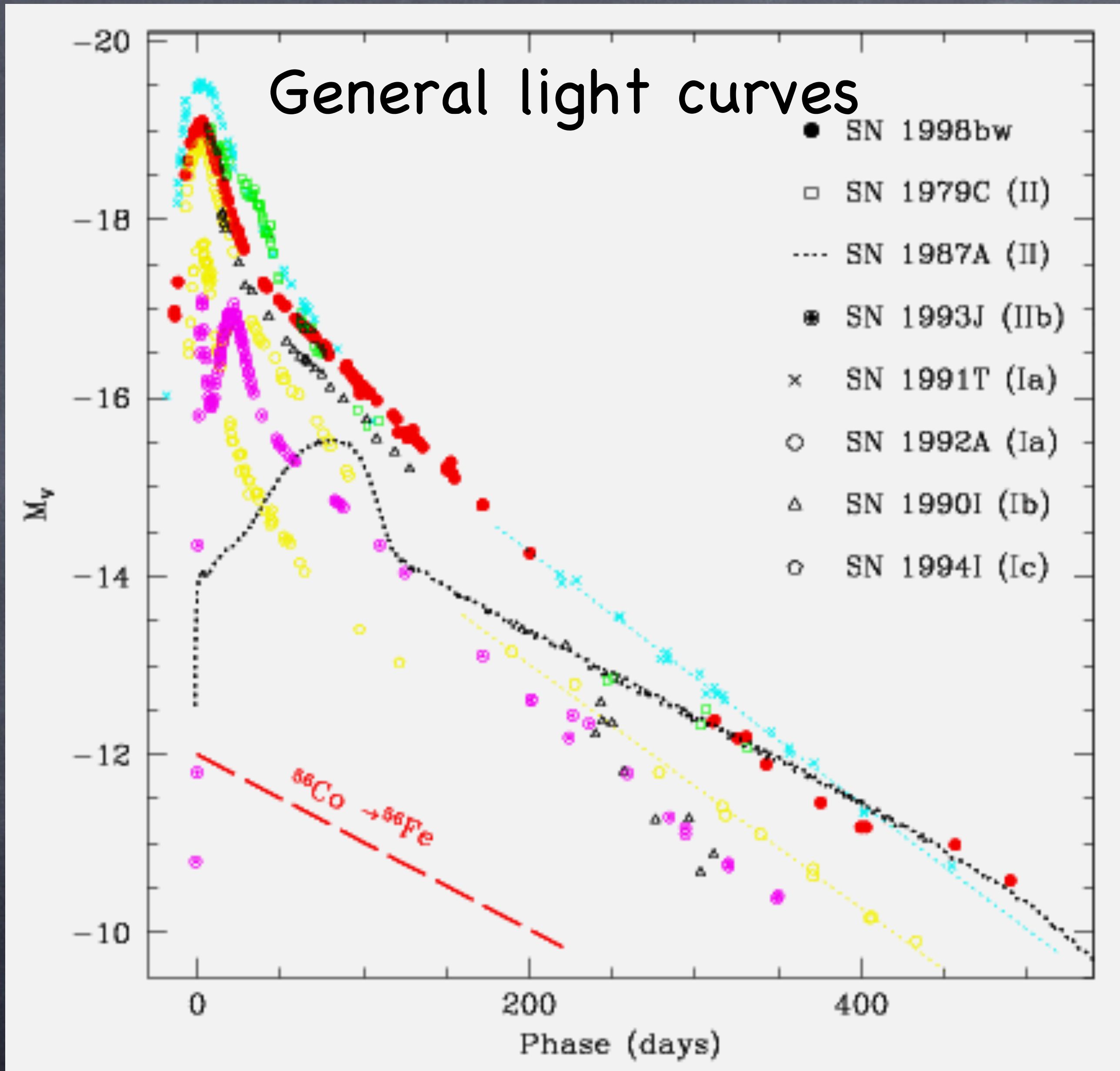
SN spectra



Type Ia

Core Collapse

Type Ib/c & Type II



^{56}Ni →
^{56}Co →
^{56}Fe

Leibundgut & Suntzeff 98

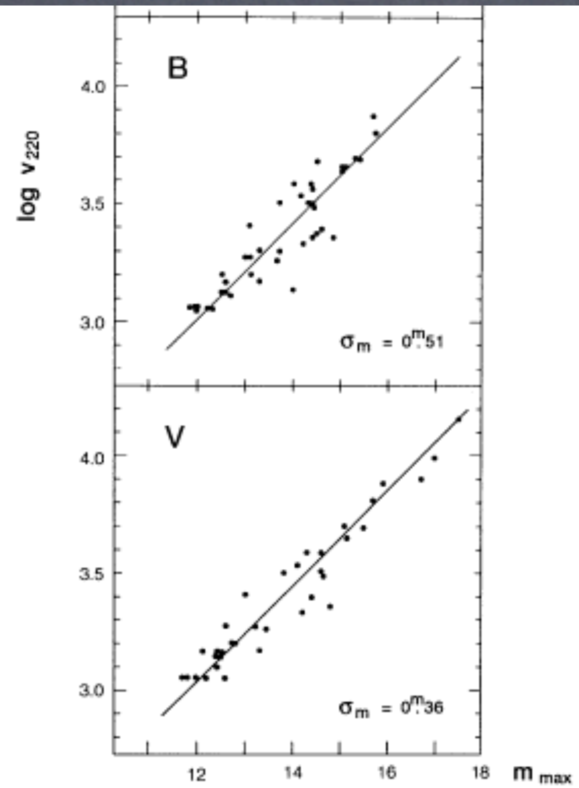


FIG. 1.—The Hubble diagrams in m_{pg}, B, and V. The data for the diagrams in m_{pg} and in B are from Tammann & Leibundgut (1990). The data of the diagram in V are from Table 1 here. The lines through the data have an assigned slope of $d \log v/dm = 0.2$, required if the redshift-distance relation is linear.

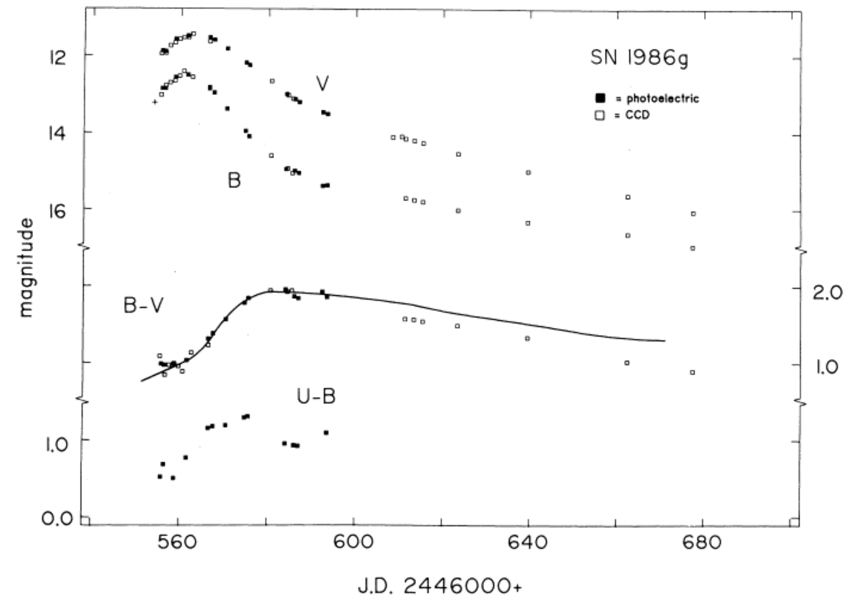


FIG. 2–B, V, $(B-V)$, and $(U-B)$ observations of SN 1986G in NGC 5128 plotted as a function of time. The solid line corresponds to Pskovskii's (1984) mean $(B-V)$ curve for Type Ia supernovae with $\beta = 12$, shifted by an amount equal to $E(B-V) = 0.82$.

Phillips, M.M. et al 1987 – first CCD light curve. Used A. Phillips software

Sandage & Tammann 1993

Calán/Tololo Survey

1985 Sandage and Tammann give up their SN survey. Sandage urges Suntzeff to consider a CCD study for light curves

1986-9 SN1986G and SN1989B show that Type Ia SNe are not the same.

1987 – SN1987A!

1989 – UC Santa Cruz meeting where redoing the Maza survey is discussed

1990-1996 - The Calan/Tololo Survey

1994 - Brian Schmidt and Suntzeff form the High-Z Team.

NOAO

"Suntzeff has now fallen in with the devil*, and he had such a good career ahead of him."

In a letter to Olin Eggen from Allan Sandage, 1990.

* Mark Phillips

IRAF

Fill in the blank:

"IRAF is total ****"

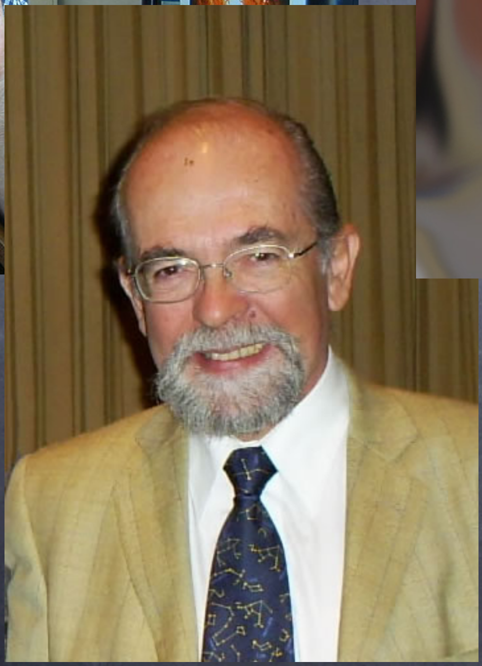
"*** is way better than IRAF."

"Anyone that uses IRAF is a(n) ********."

"We don't use IRAF at C**tech"

All I can say to that is "flpr."

Calán/Tololo Survey



Calán/Tololo

- Use Schmidt plates or films - 25 sq-deg
- Send the next morning to UChile on the bus to be scanned for new SNe.
- Follow-up possible SNe starting the next night on the 0.9m/1.5m/4m
- CCD follow-up scheduled *before* the SNe were discovered. This was NOT invented by SCP.
- Use Drew Phillips kernel matching in IRAF for image subtraction (made for SN1987A). Once again, this was NOT invented by the SCP

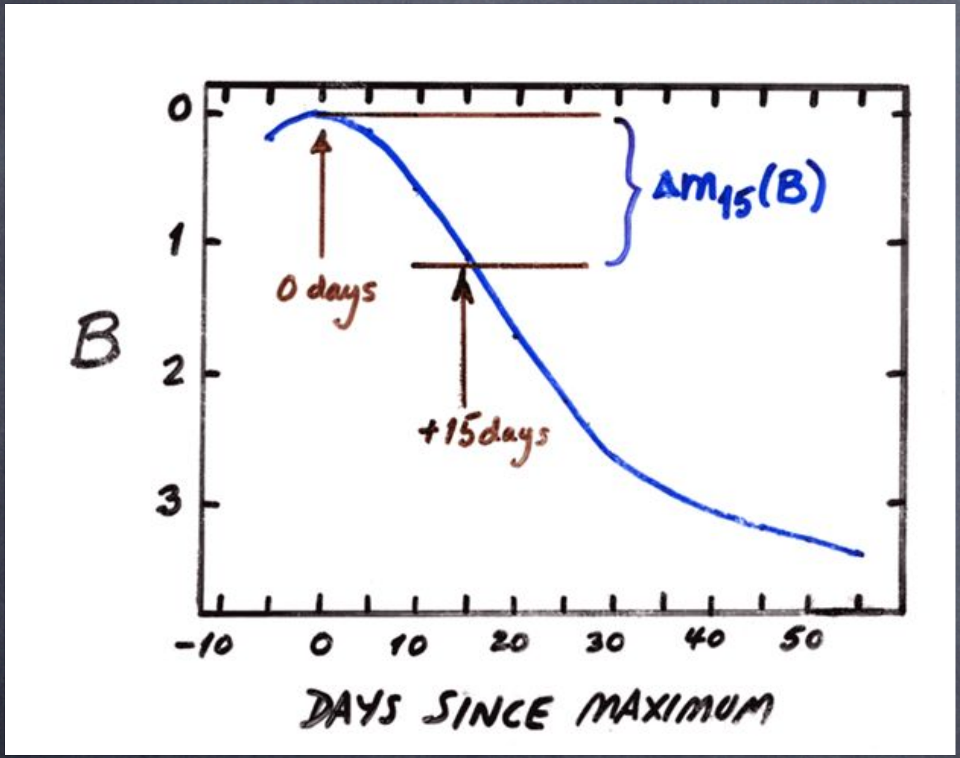
Calán/Tololo

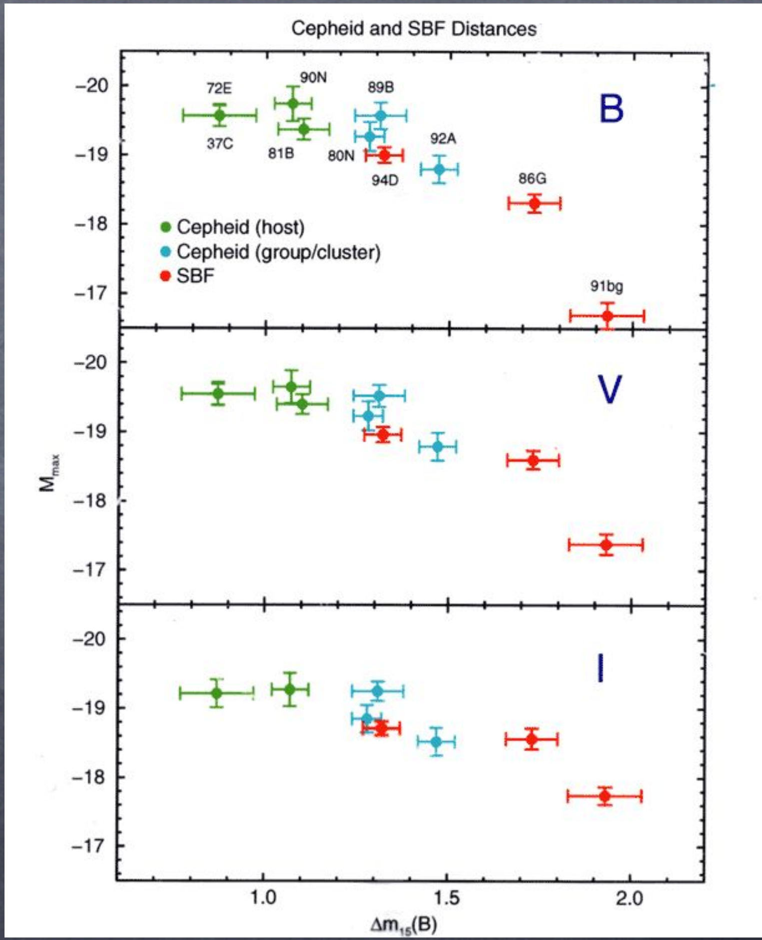
- The Calán/Tololo goal was to provide the best calibration of distances to Type Ia SNe.
- Combined with this calibration, and the HST Cepheid calibration project by Saha/Sandage/Tammann, we could measure the most accurate value of H_0.
- By 1996, we had measured a precise Hubble diagram in the quiet Hubble flow

Calán/Tololo

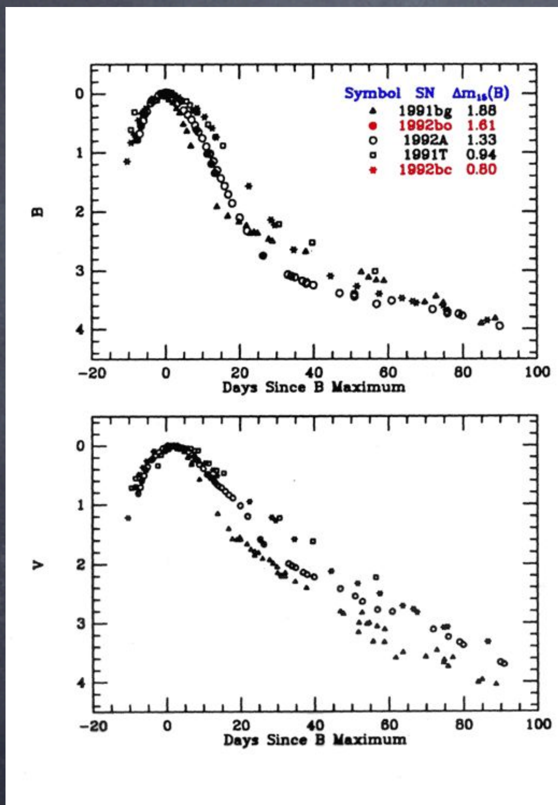
- We also provided CCD light curves to host galaxies with HST Cepheid distances.
- Ultimately the Saha/Sandage/Tammann data were subsumed by the H_0 Key Project of Kennicutt, Mould, and Freedman.
- In their now famous 2002 paper, Freedman et al combined their distances to host galaxies of Type Ia SNe, our measurements of light curves of SNe in these galaxies, and our quiet Hubble flow to derive the most accurate value of their Hubble constant.

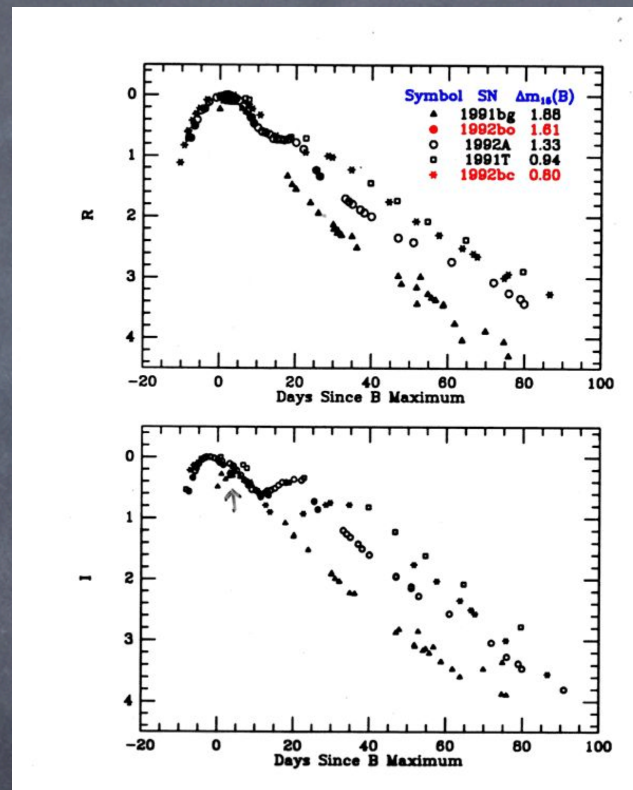
Phillips 1993 breakthrough





CCD light curves - Lira





Paulina Lira

Suntzeff (1994)

Calán/Tololo

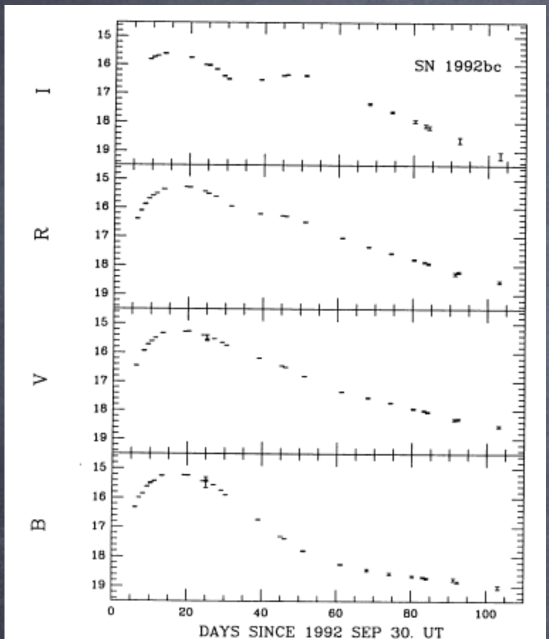
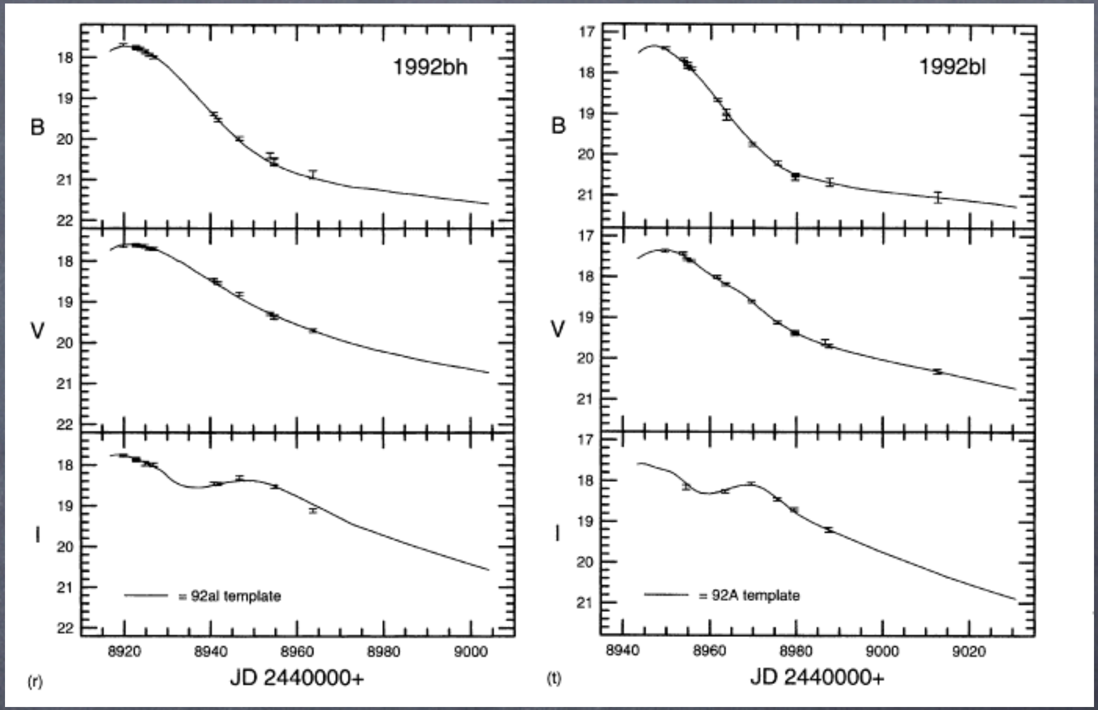


FIG. 1.—B, V, R, and I light curves of SN 1992bc



Maza et al 1994

Hamuy et al 1996

Calan/Tololo

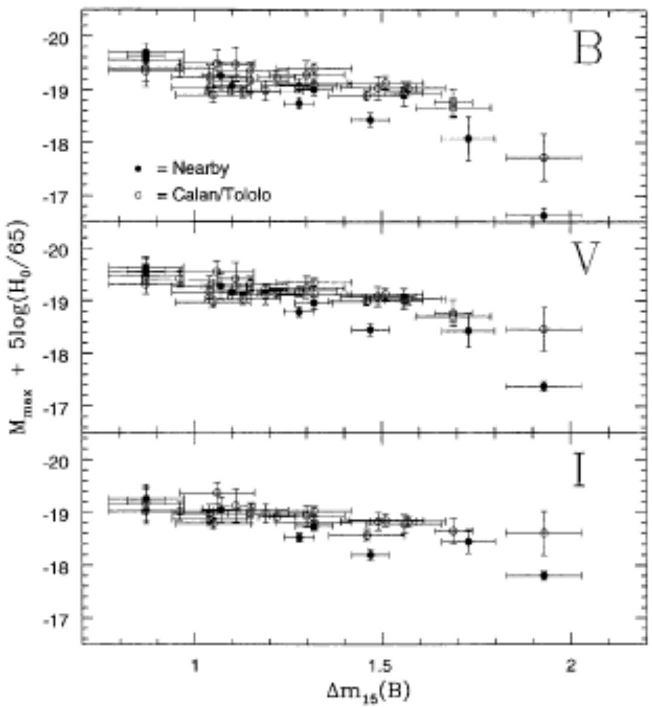


FIG. 2. As in Fig. 1, but with the open circles corresponding to the Calán/Tololo sample (excluding the two possibly reddened SNe 90Y and 93H), and the filled circles to the nearby sample (from Table 2).

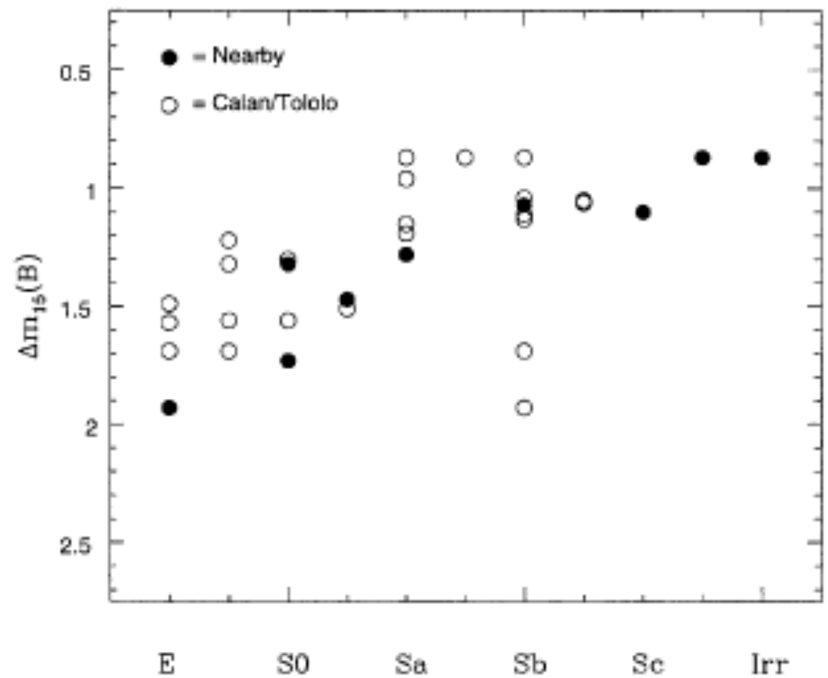


FIG. 4. The decline rate of the B light curve [$\Delta m_{15}(B)$] of both the Calán/Tololo (open circles) and nearby (filled circles) samples of SNe Ia plotted as a function of the morphological types of their host galaxies.

Hamuy et al 1996

Indicates that there are two populations of Ia SNe

Hubble Constant

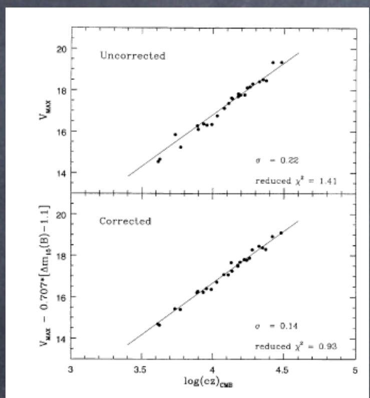
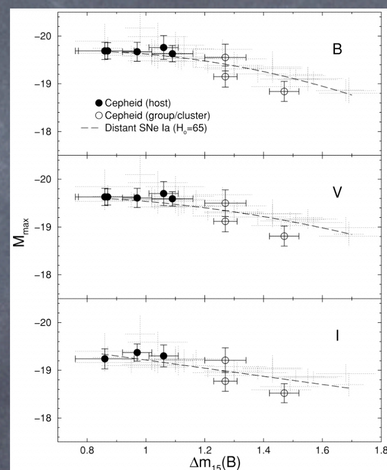


FIG. 5. (top panel) The Hubble diagram in V for the SNe Ia in the Calán/Tololo sample with $B_{MAX}-V_{MAX} \leq 0.20$. (bottom panel) The Hubble diagram for the same 26 events after correction for the peak luminosity-decline rate dependence.

Hamuy et al 1996

+

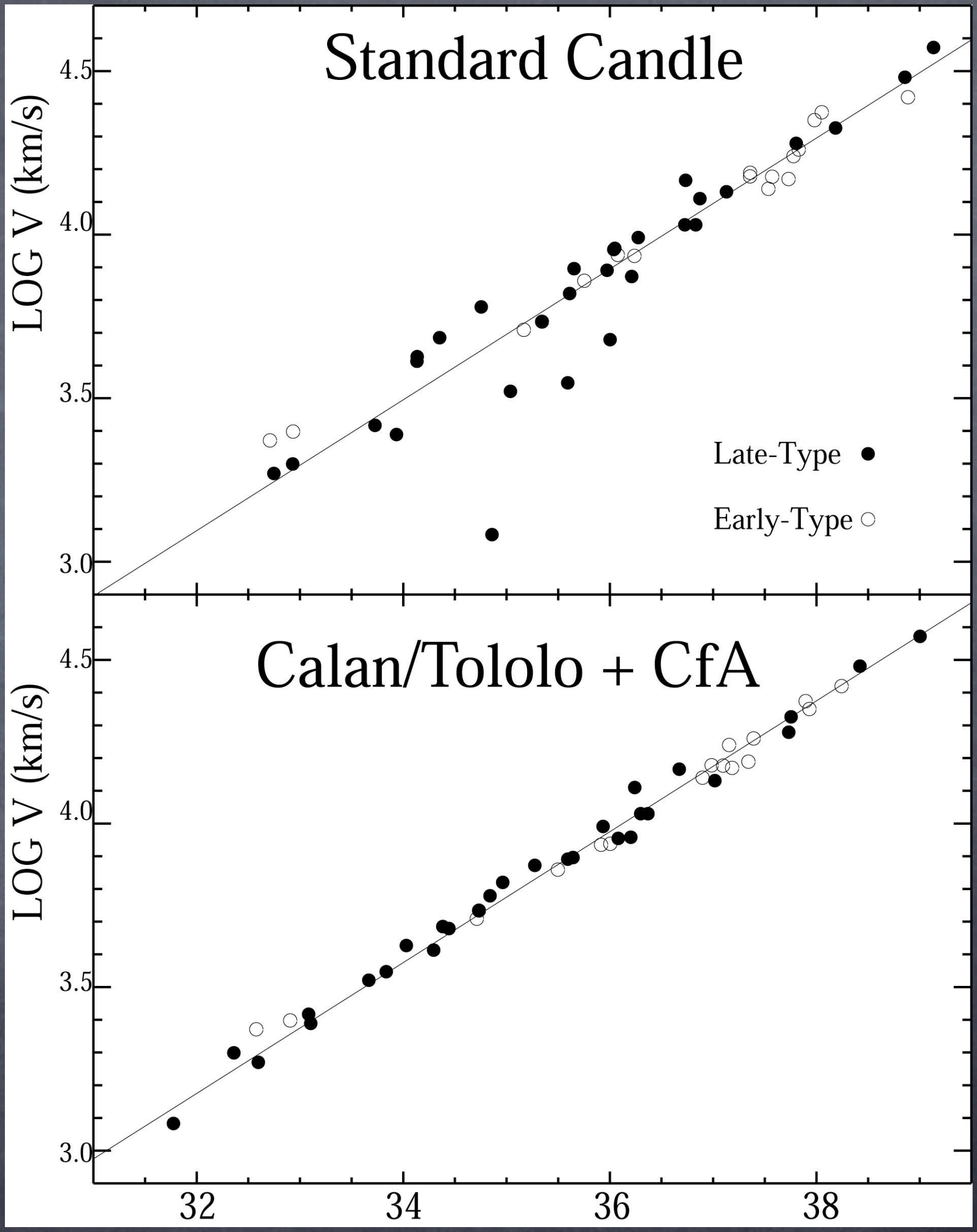


Suntzeff et al 1999

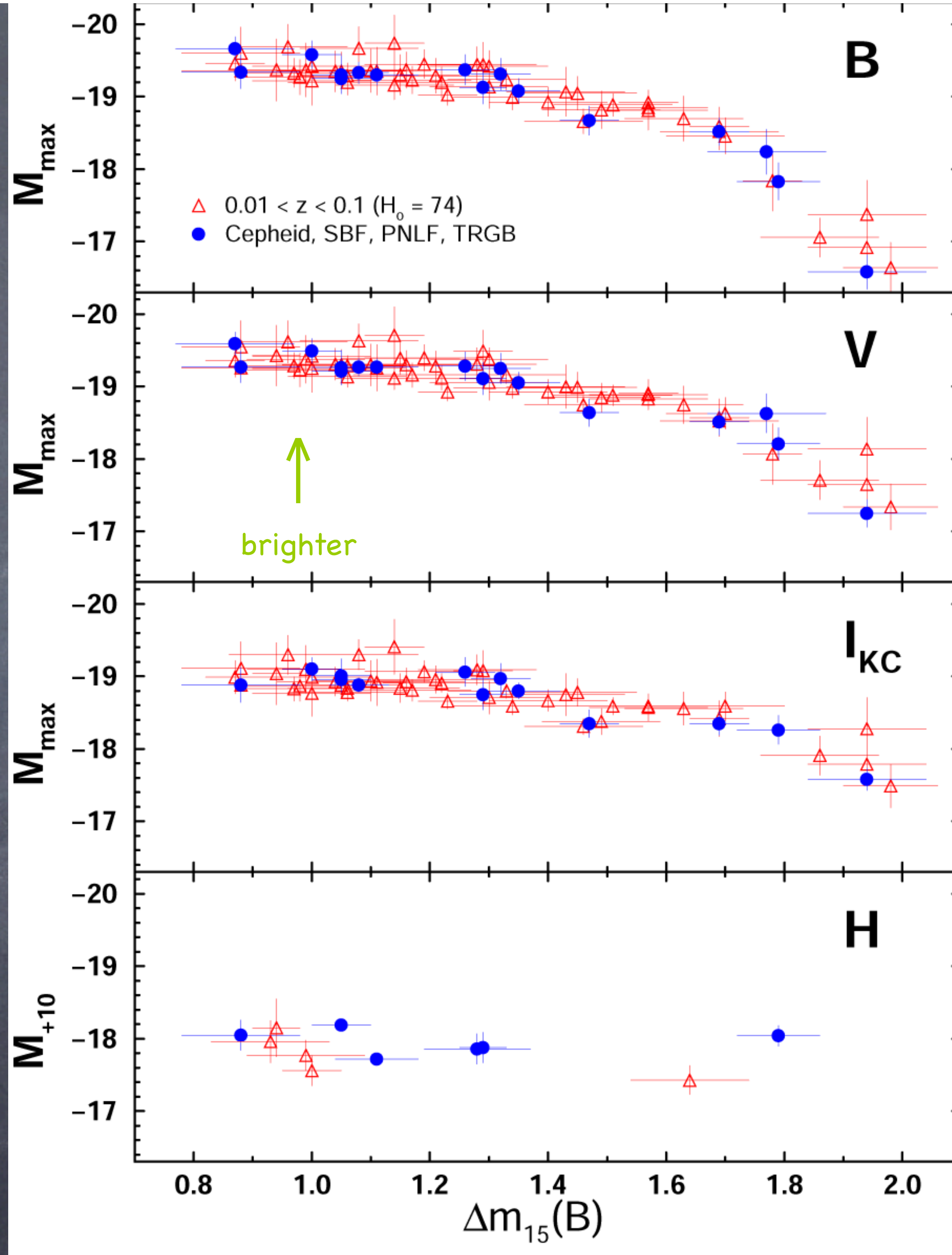
+ HST Cepheid calibration

$= H_0$

Effects of correction to Δm_{15}



Absolute magnitudes of Type Ia SNe



H, K probable standard candles, Krisciunas etal 2003. →

High-Z Supernova Team

- Brian Schmidt & Nicholas Suntzeff 1994
  - Brian writes the software – "three months, maximum"
  - I would run the observing program at CTIO
- We would be a small team to compete with the SCP

High-Z SNe

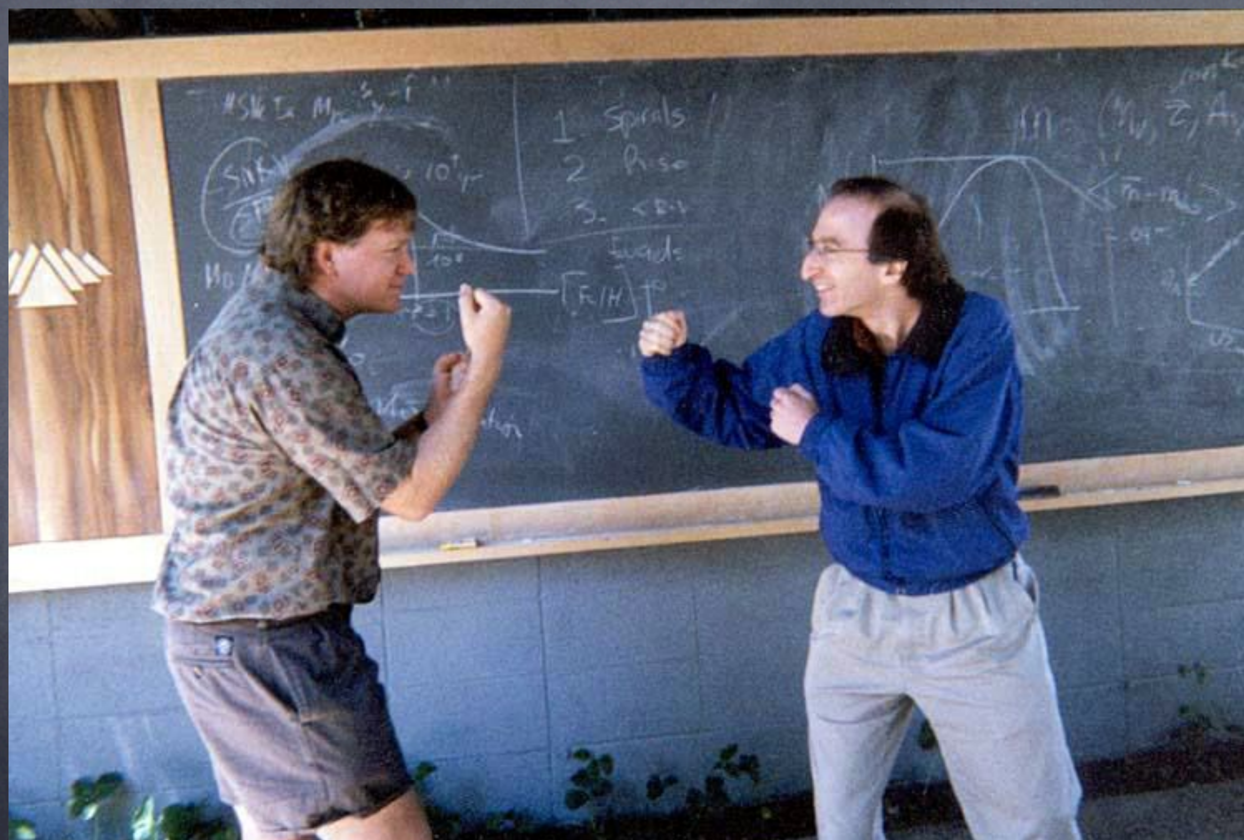
- We had the luminosity calibration from C/T
- We had the experts - Phillips, Hamuy, Leibundgut, Garnavich, Spyromilio, Riess, Schmidt
- We had the image subtraction software from Drew Phillips
- The numbers were that we should find around 4 SNe per sq-deg per month
- We figured we could easily catch up to the SCP
- And we were pure anarchy

The rules...

- The person who did the most work would be first author
- Every semester the whole "team" would work for the next institution on the list: AAO, ESO, Harvard, Washington, Berkeley - and they would publish
- Brian would be in charge of the software and overall project anarchy and I would be in charge of the observing and photometry

The High-Z Team

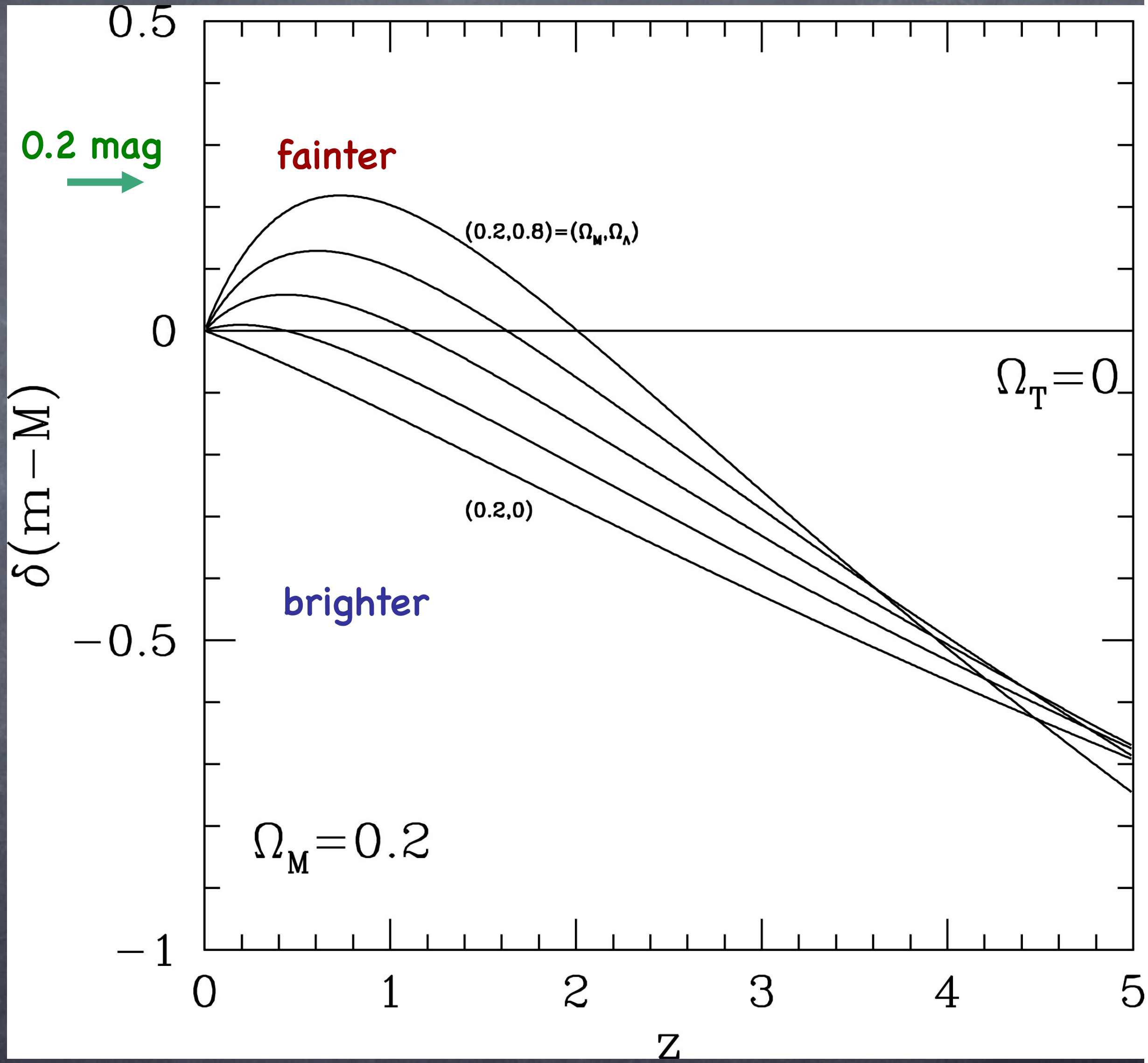
The Cosmology



Distance Modulus II

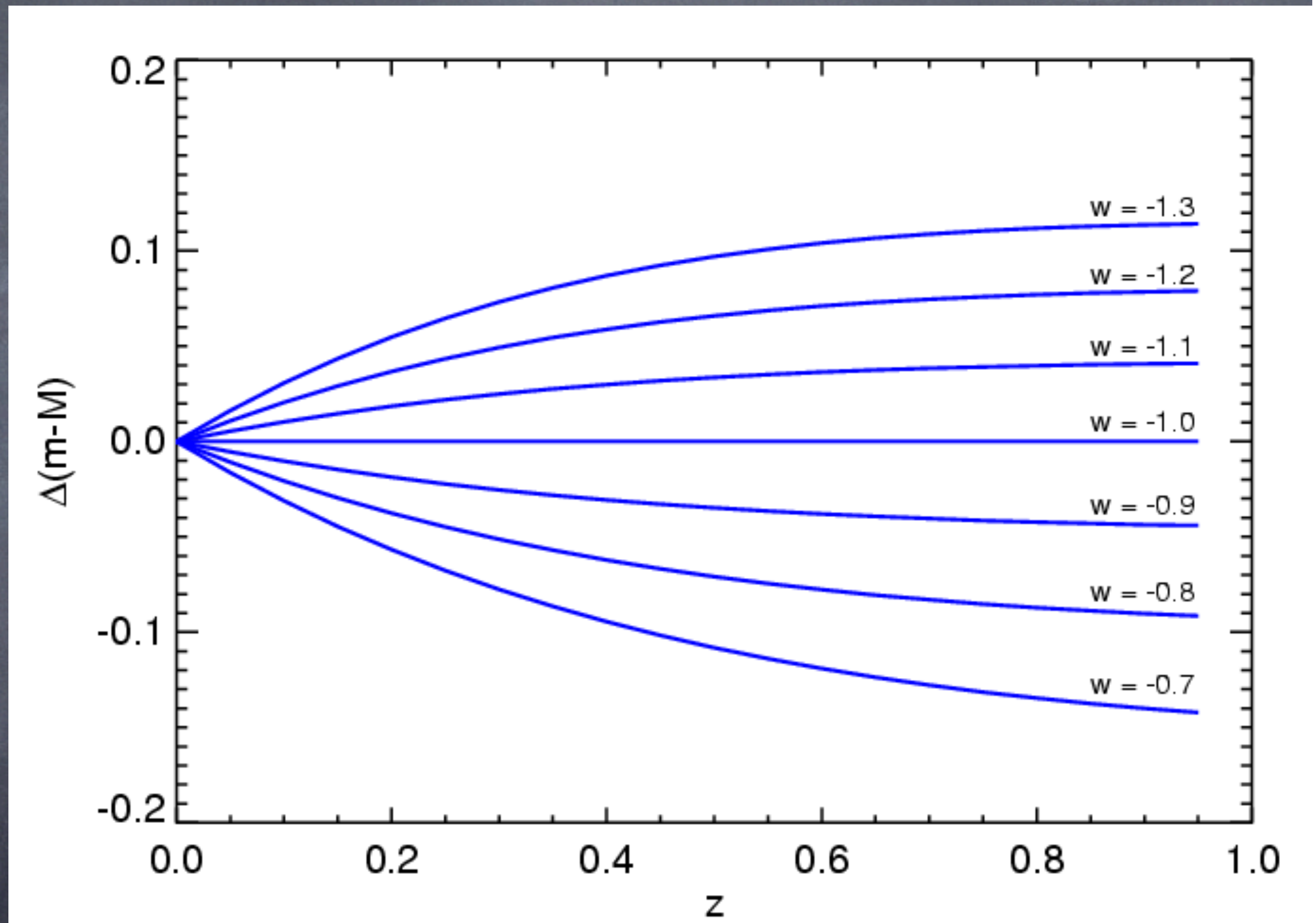
Peak effect for L is at about z~0.8.

We are looking for about a 0.25m effect.



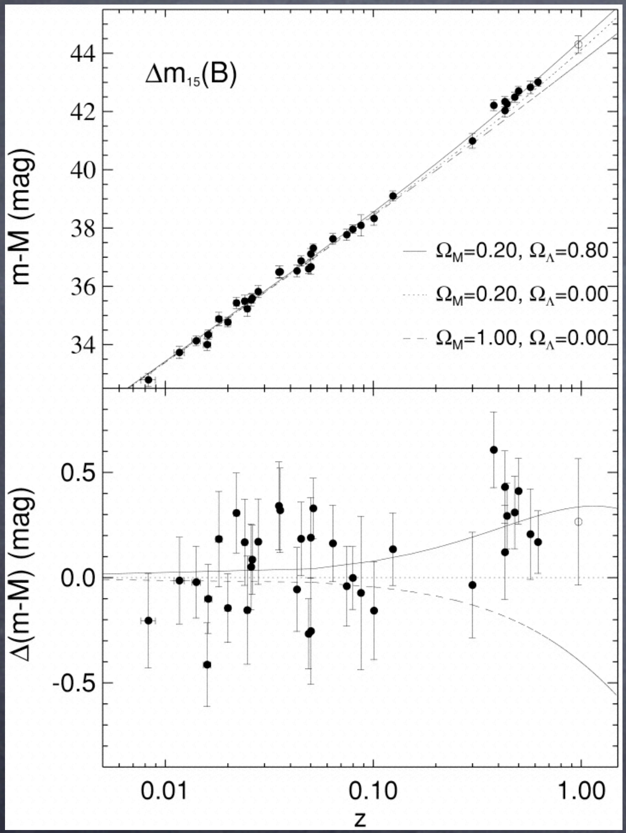
Equation-of-State Signal

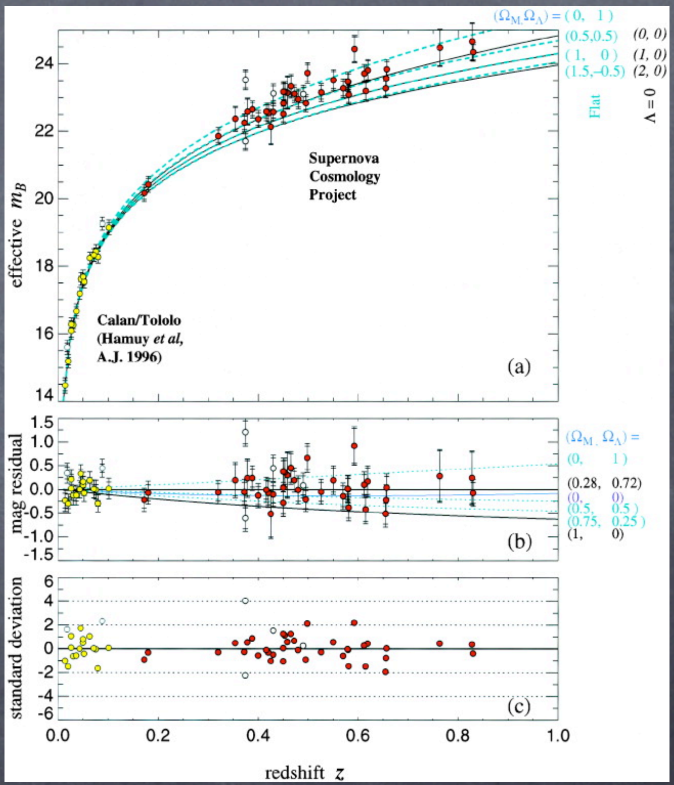
Assume
$P = w\rho c^2$



Difference in apparent SN brightness vs. z
Ω_Λ=0.70, flat cosmology

Acceleration





Riess et al 1998

Perlmutter et al 1999

The Basic Question:

Is a cosmological constant model consistent with the data?

Is $w=-1$?

The ESSENCE Survey

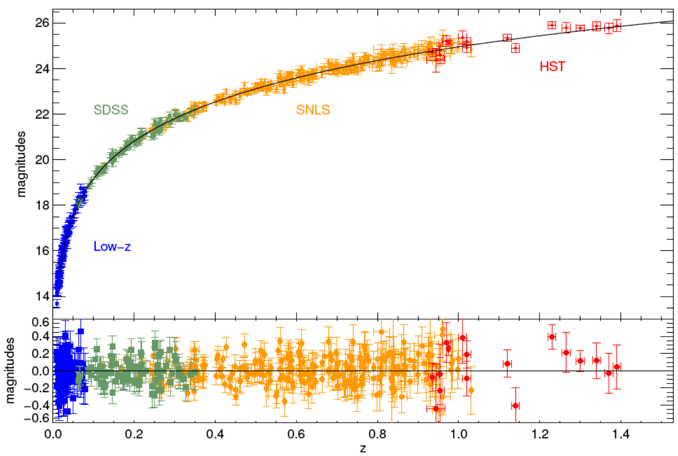
- Determine w to 10% or w!=-1
- 6-year project on CTIO/NOAO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, $0.2<z<0.8$
- Data and SNeIa public real-time

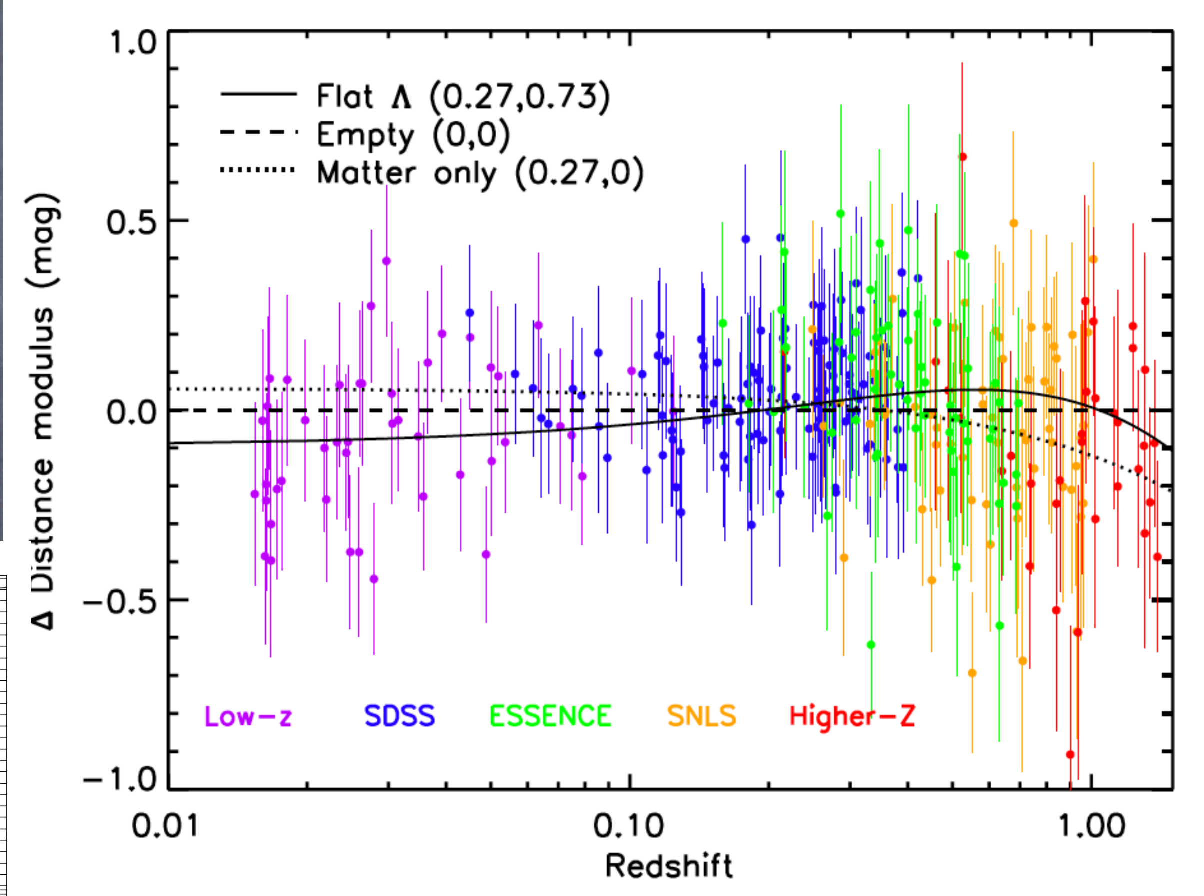
Gold⇒Union⇒Constitution⇒ what the **** set

SDSS SN plot

Lesson in plotting

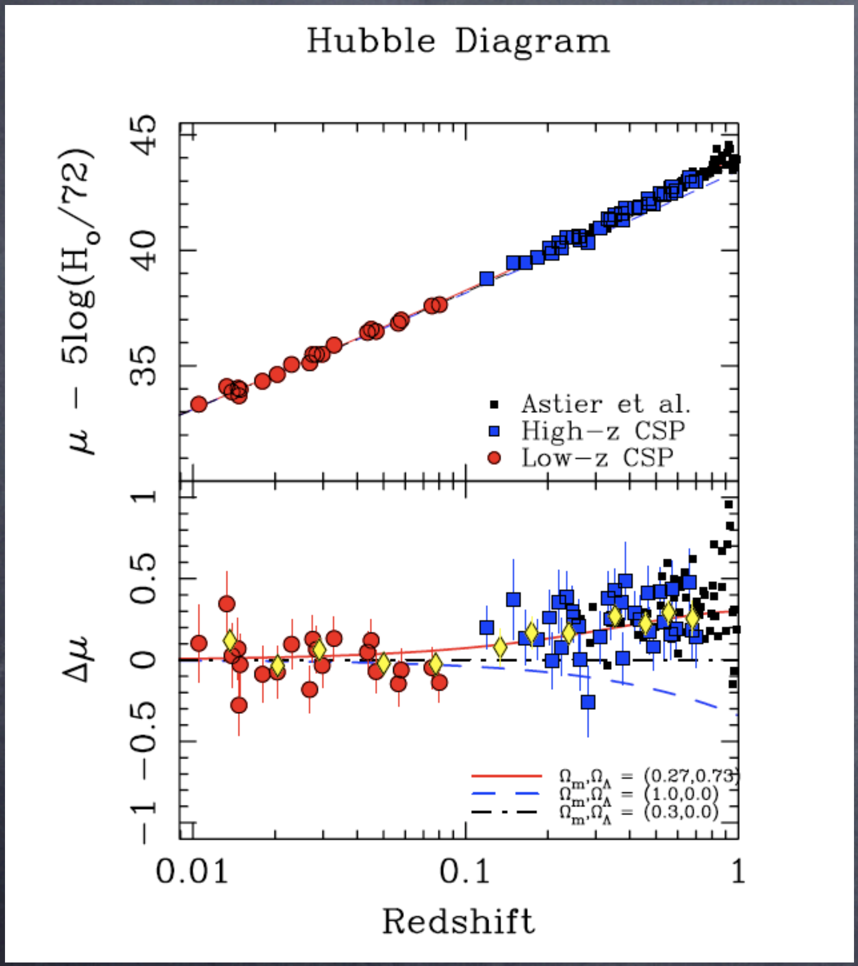
⇓

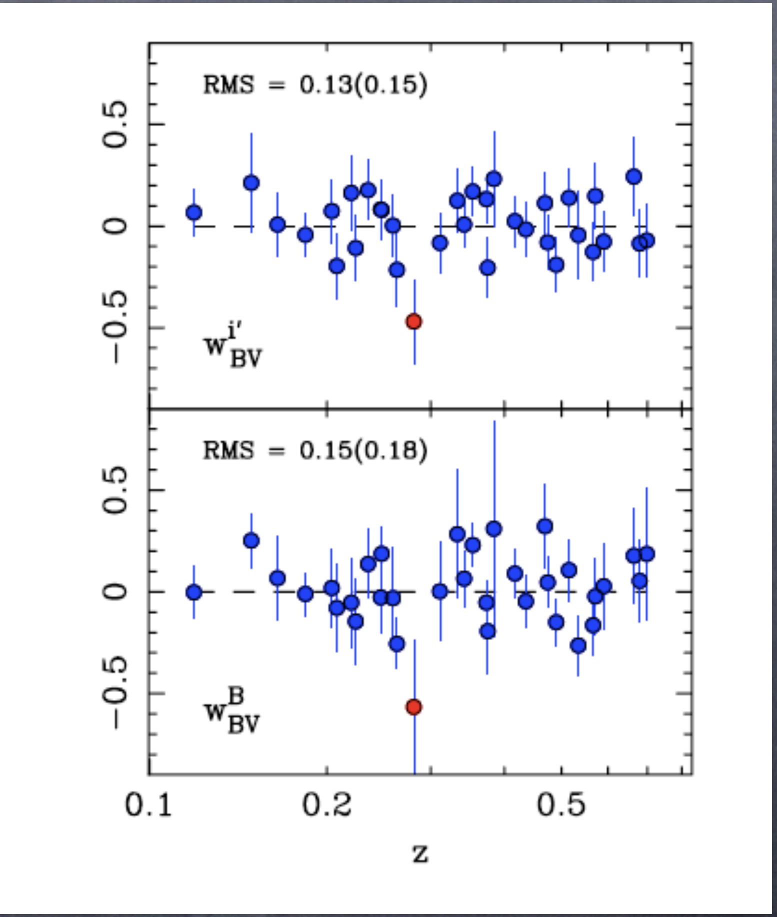




Being from Texas, I suggest the Confederate Set is next

High-z project





I-band measurements

Hicken et al 2009

state parameter, w. The CfA3 sample is added to the Union set of Kowalski et al. (2008) to form the Constitution set and, combined with a BAO prior, produces $1 + w = 0.013^{+0.066}_{-0.068}(0.11 \text{ syst})$, consistent with the cosmological constant. The CfA3 addition makes the cosmologically-useful sample of nearby SN Ia between 2.6 and 2.9 times larger than before, reducing the statistical uncertainty to the point where systematics play the largest role. We use four light curve fitters to test for systematic differences: SALT, SALT2, MLCS2k2 ($R_V = 3.1$), and MLCS2k2 ($R_V = 1.7$). SALT produces high-redshift Hubble residuals with systematic trends versus color and larger scatter than MLCS2k2. MLCS2k2 overestimates the intrinsic luminosity of SN Ia with $0.7 < \Delta < 1.2$. MLCS2k2 with $R_V = 3.1$ overestimates host-galaxy extinction while $R_V \approx 1.7$ does not. Our investigation is consistent with no Hubble bubble. We also find that, after light-curve correction, SN Ia in Scd/Sd/Irr hosts are intrinsically fainter than those in E/S0 hosts by 2σ, suggesting that they may come from different populations.

SNe and GRB's

Wright (2007)

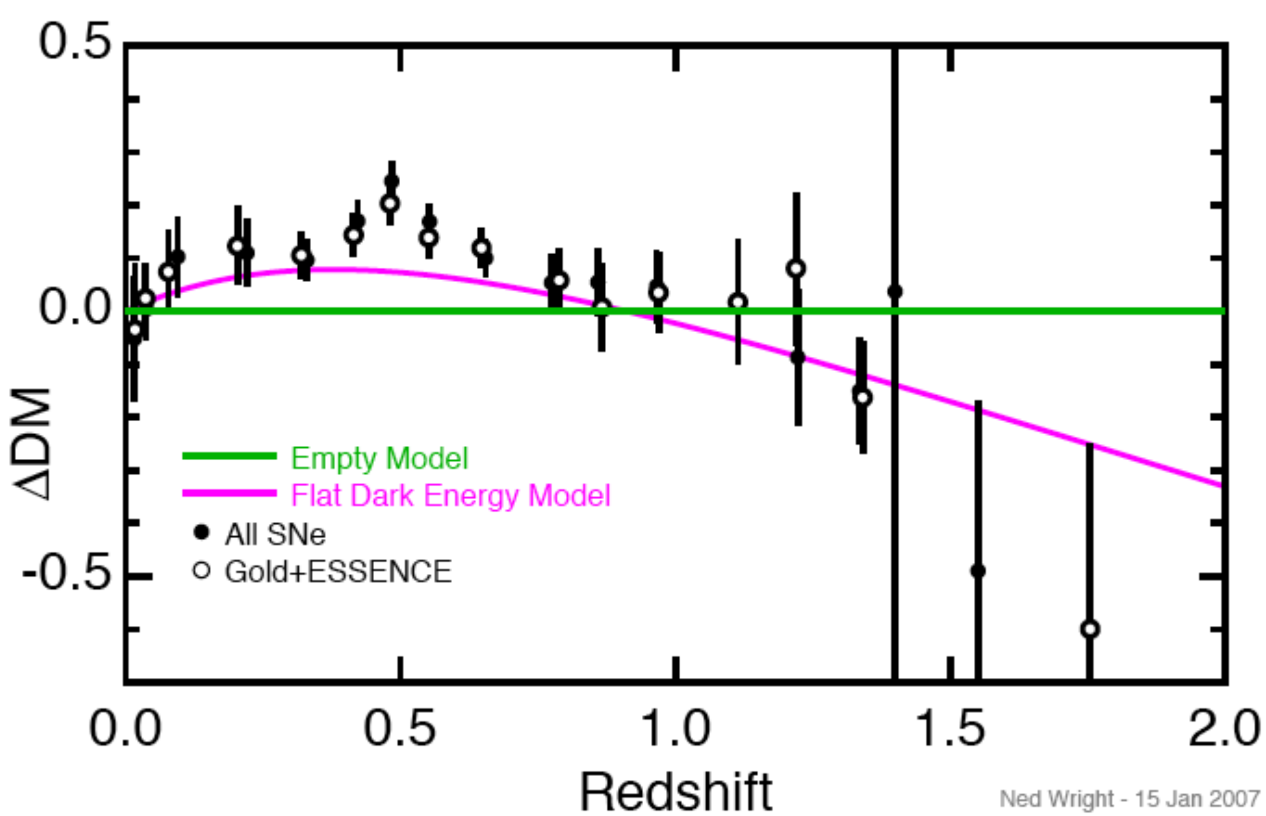
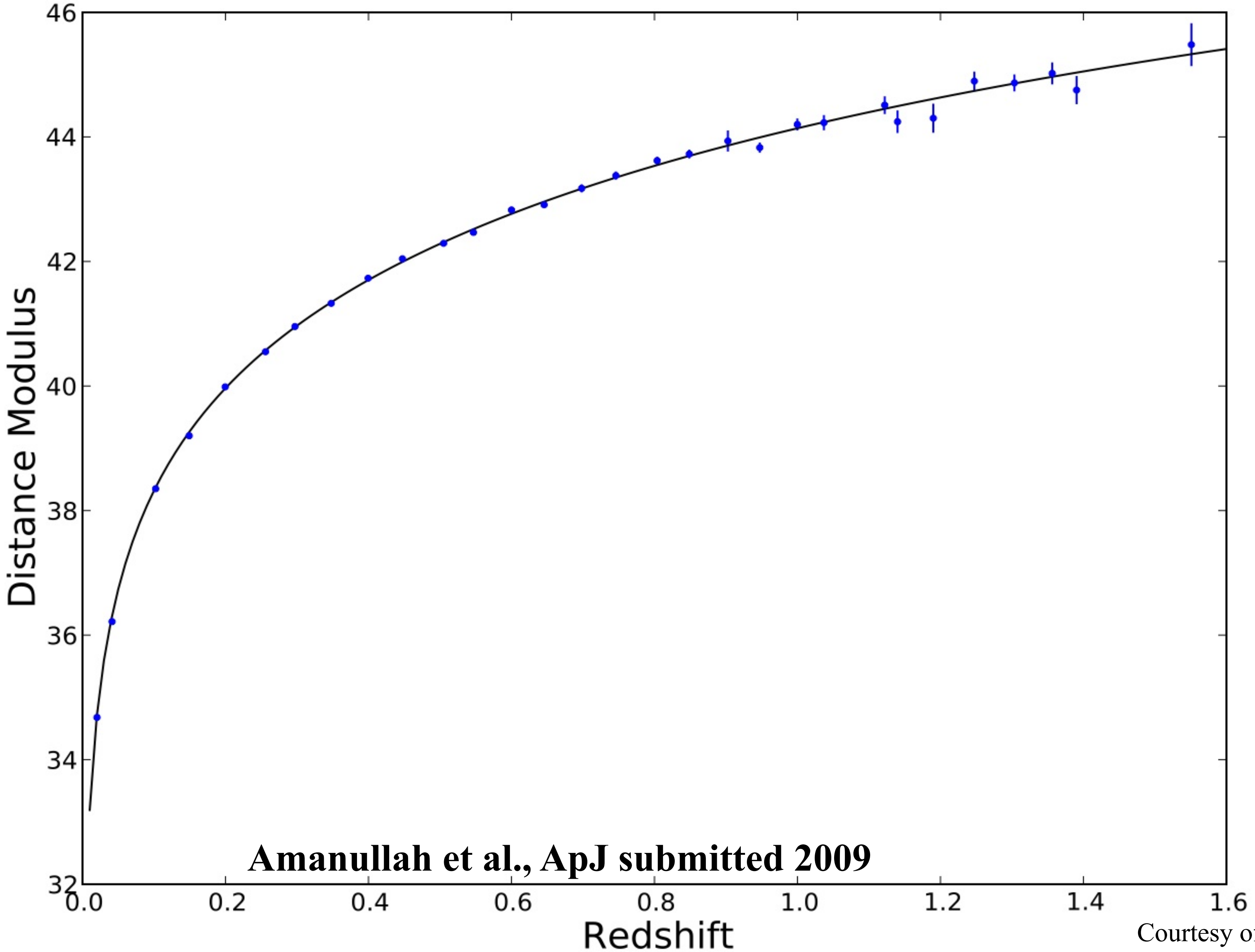


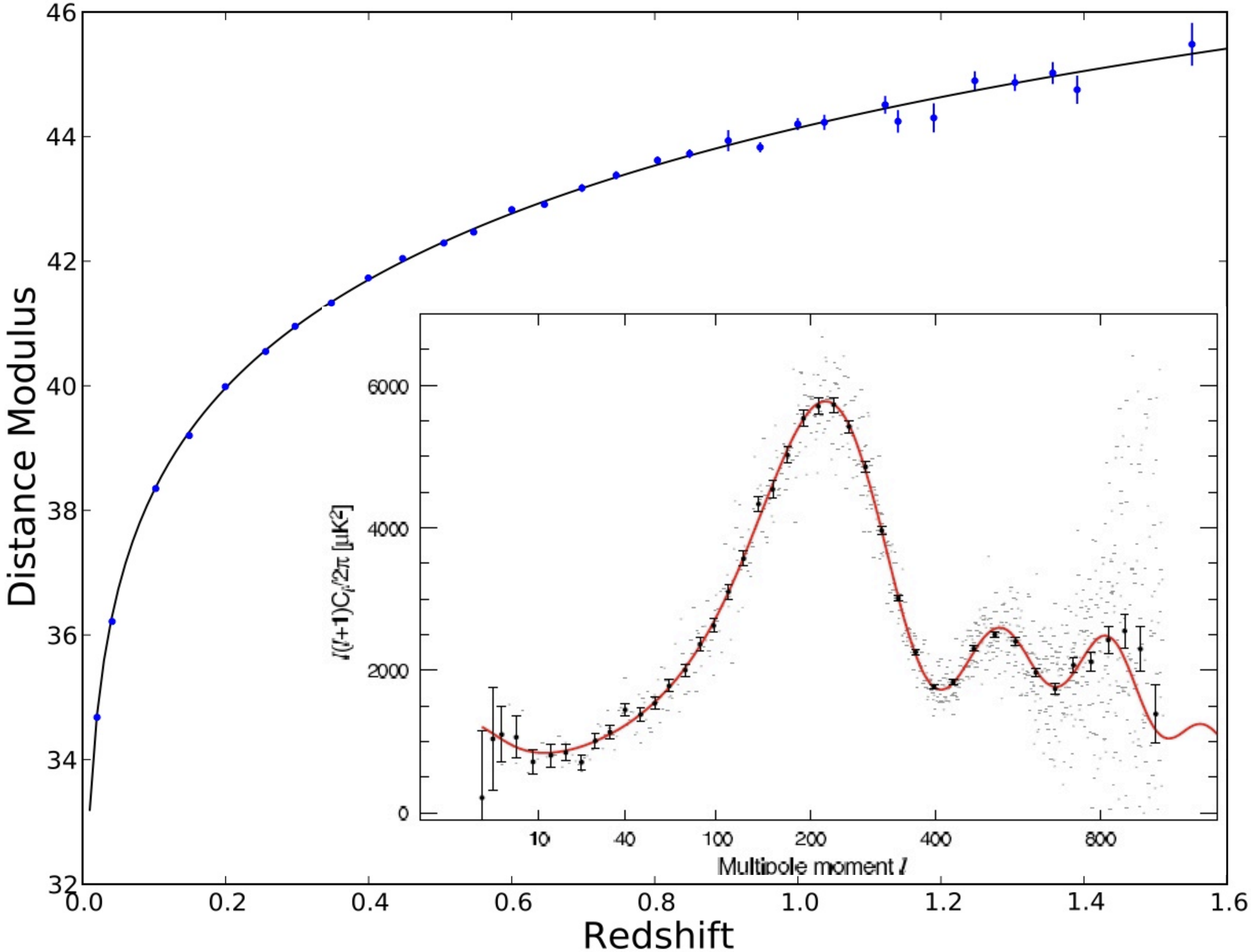
Fig. 2.— Binned supernova data *vs.* redshift compared to a flat ΛCDM model with $\Omega_M = 0.369$. The filled circles are binned points from the full dataset, while the open circles have omitted the "Silver" subset.

Current Data: World



Courtesy of D.Rubin

Cosmology Fit



Cosmic Coincidence

Why not just settle for a cosmological constant Λ?

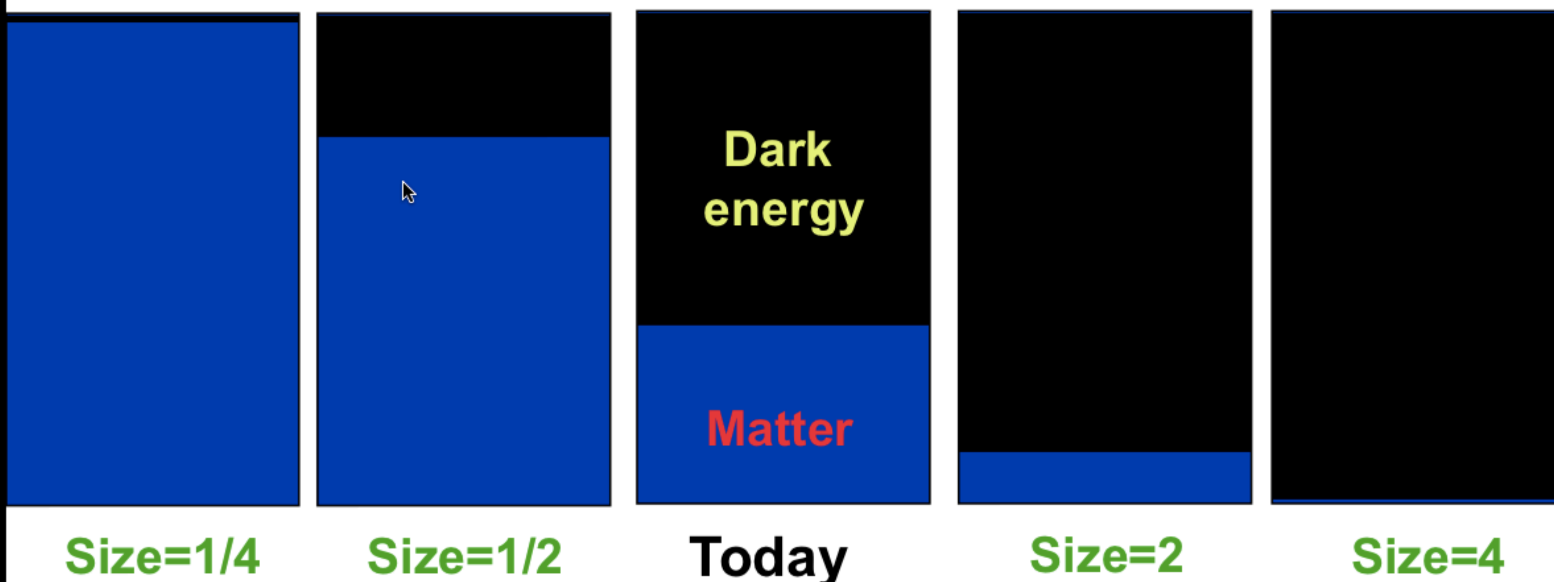
→ For 90 years we have tried to understand why Λ is at least 10^{120} times smaller than we would expect – *and failed*.

→ We know there *was* an epoch of time varying vacuum once – inflation.

Courtesy of E. Linder

Cosmic Coincidence

We cannot calculate the vacuum energy to within 10^{120}. But it gets worse: Think of the energy in Λ as the level of the quantum "sea". At most times in history, matter is either drowned or dry.



Courtesy of E. Linder

On Beyond Λ!

***We need to explore further frontiers* in high energy physics, gravitation, and cosmology.**

New quantum physics? Does nothing weigh something?

Einstein's cosmological constant, Quintessence, String theory

New gravitational physics? Is nowhere somewhere?

Quantum gravity, extended gravity, extra dimensions?

Courtesy of E. Linder

Dark Energy + 12

12 years after today, where will we be?

CMB: Planck data, ground based polarization and CMB lensing

BAO: BOSS (on sky), WiggleZ, SuMIRe, HETDEX…

Clusters: SZ Effects - ACT, SPT

Supernovae: *smarter*, not just more

Multiprobe: DES, KDUST? (Dome A), GMT?

NASA/DOE JDEM? ESA Euclid? LSST?

Stage IV from the ground - BigBOSS

Courtesy of E. Linder

Future of Dark Energy

Today we know the dark energy equation of state, *constant* w to ~10%.

Future experiments look bright for dark physics. We must test for varying w (no real theory predicts constant w).

If w(a) ~ -1, is Λ the conclusion?

No! Many, diverse physics theories give w(a)~-1.

Approaching Λ: Microphysics, High Energy Physics, Gravity.

Courtesy of E. Linder

Λ from Microphysics

Barotropic fluids are defined through an explicit equation of state $P=p(\rho)$.

The dynamics is related to microphysics

$$w' = -3(1+w)(c_s^2-w)$$

Since this has an attractor solution at $w=-1$, it may motivate $w\sim-1$ today.

For analysis, just need stability/causality condition

$$0 \leq c_s^2 \leq 1$$

Interesting results ensue…

Linder & Scherrer 2009

Courtesy of E. Linder

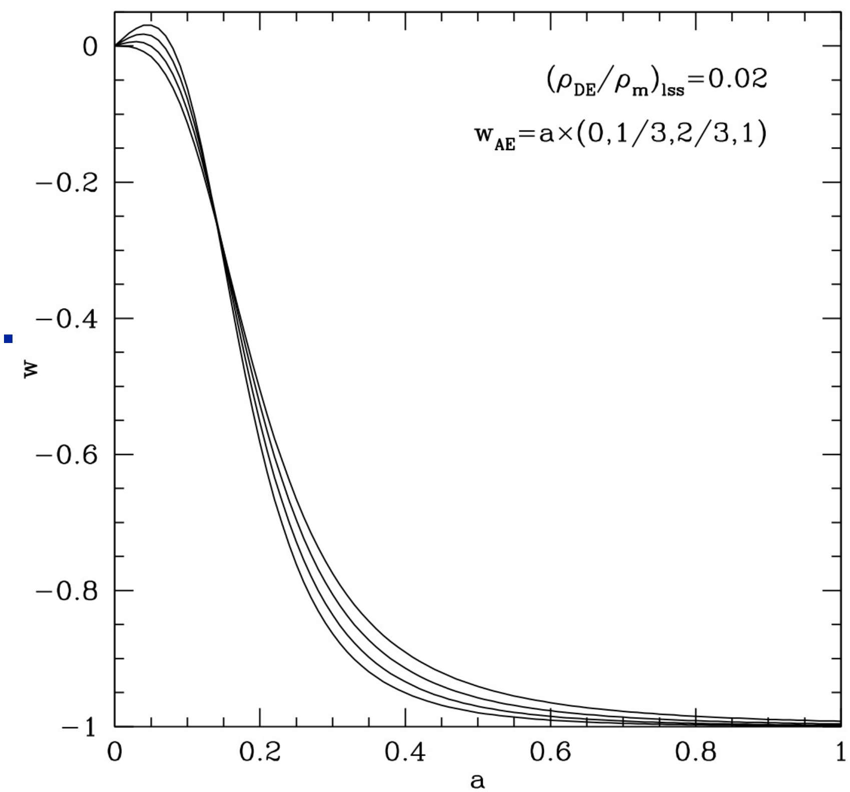
Aetherizing Lambda

At high z, barotropic DE tracks the matter - no fine tuning problem!

Then barotropic DE evolves rapidly (w decreases from -0.1 to -0.9 in a factor <4 of expansion) - no coincidence problem!

So $w_0 \approx -1$ is easily achievable (unlike for tracking quintessence).

Barotropic DE "predicts" $w_0 \approx -1$.



Courtesy of E. Linder

Λ from High Energy Physics

One of the main problems in coming up with a dark energy theory is making it look natural.

Why aren't the initial conditions characteristic of the high energy universe?

How is it protected against quantum corrections?

The cosmological constant suffers both problems.

Some quintessence solutions avoid the first through attractor solutions, e.g. exponential, inverse power law. Some quintessence avoid the second through symmetries, e.g. PNGB.

DBI action solves both with relativistic kinematics.

DBI Action

Dirac-Born-Infeld (DBI) action arises from volume traced out by 3-brane in 10D spacetime.

$$\mathcal{L} = -T\sqrt{1-\dot{\phi}^2/T} + T - V$$

Silverstein & Tong 2004 Alishahiha, Silverstein & Tong 2004

Define $\gamma = (1-\dot{\phi}^2/T)^{-1/2}$

just like Lorentz boost factor.

Quintessence lagrangian recovered when

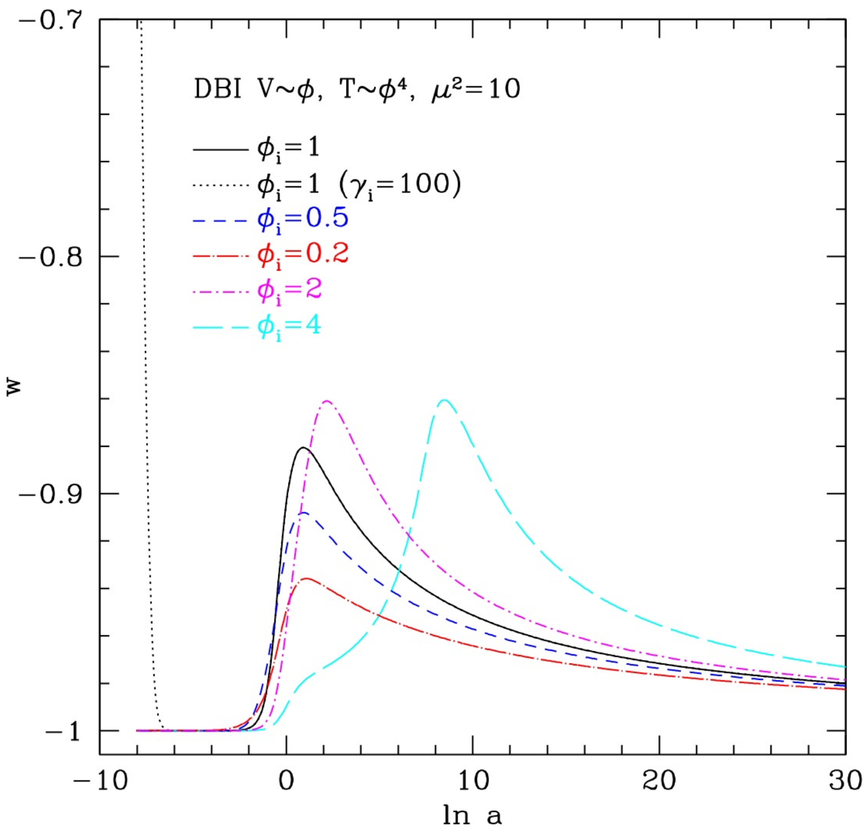
$K = (1/2)\dot{\phi}^2 \ll T$ i.e. $\gamma - 1 \ll 1$

DBI-type action applied to many scenarios in different approximations, e.g. rolling tachyon (Chaplygin gas), k-essence, k-inflation, etc.

Courtesy of E. Linder

Λ Attractor

Class 1 leads to cosmological constant attractor, despite no nonzero ground state.



1+w ~ 1/(ln a)

w=-1 in past, and attracted toward w~-1 in future. So today, not so far from w=-1.

Deviation from w=-1 related to "mass" $\mu^2=(V/T)_{Pl}$.

Directly constrain string theory physics.

Courtesy of E. Linder

Λ from Gravity

GR has spacetime curvature as the essential dynamical variable.

The Einstein-Hilbert action is

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \quad R$$

Consider a generalization, called f(R) theories:

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \, [R + f(R)]$$

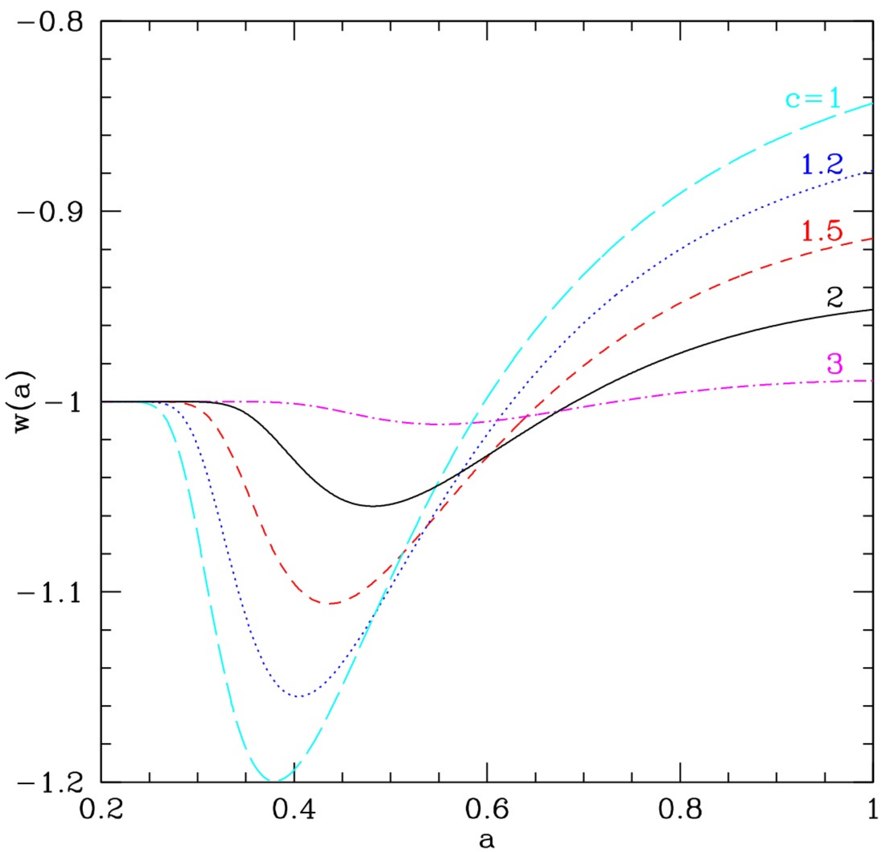
f = constant is a cosmological constant term, e.g. **R-2Λ**
f_R (linear term) acts to redefine G_{Newton} f_{RR} is key new element, with $f_{RR}>0$ to avoid pathologies.

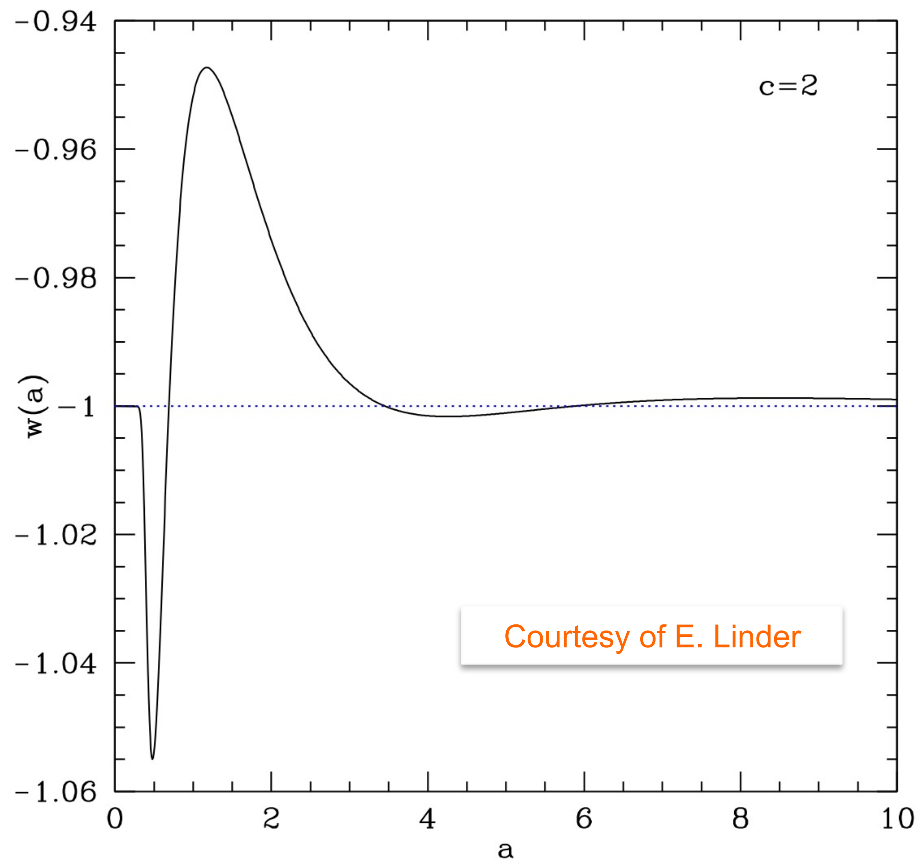
see reviews by Durrer & Maartens 0811.4132, Sotiriou & Faraoni 0805.1726

Effects on Expansion

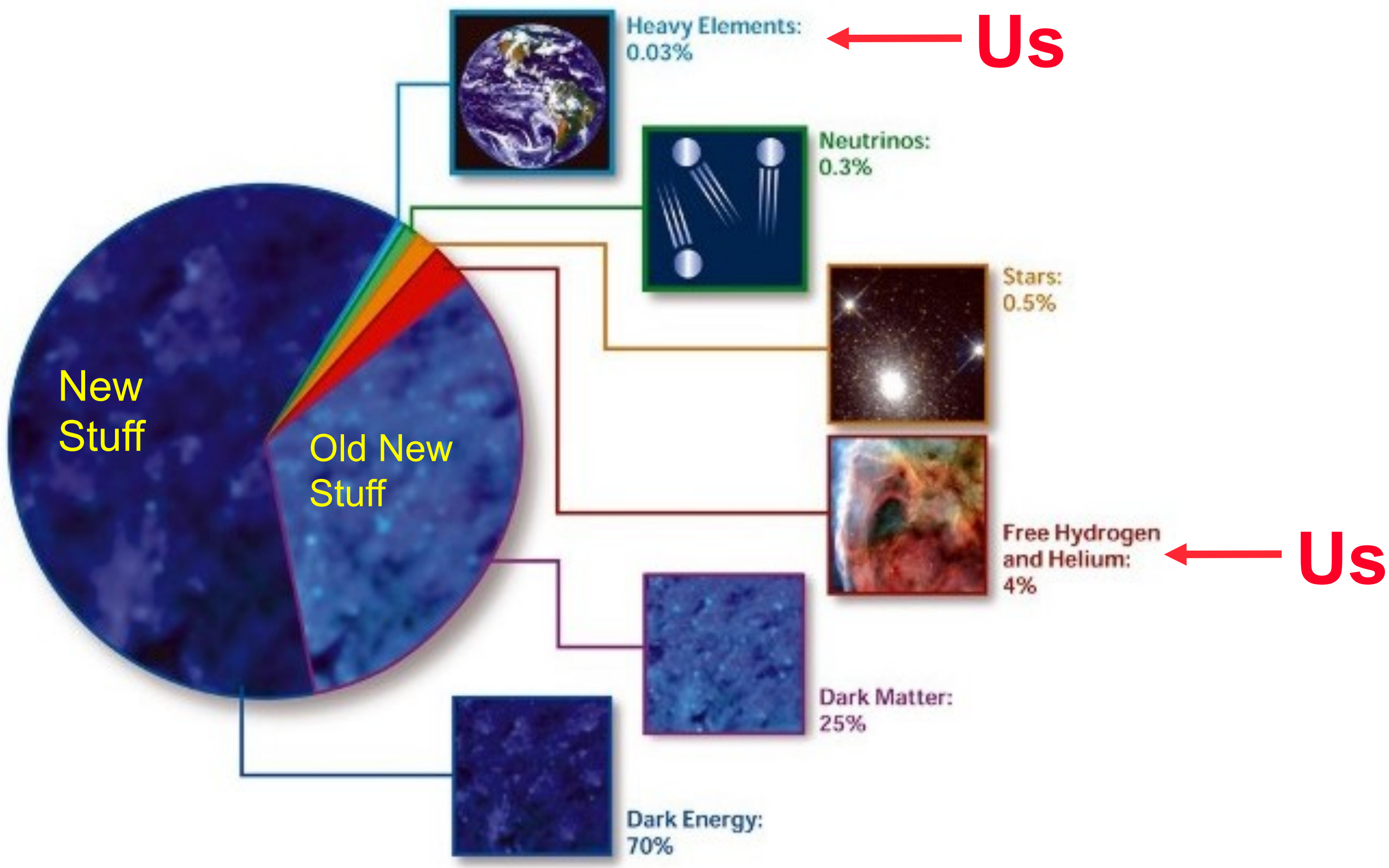
Combination cr is determined by the matter density today Ω_m, so there is one more free parameter, c.

R approaches a constant in the future - de Sitter.





Describing Our Universe



STScI

95% of the universe is unknown!

NOAO

"No important science has ever been done at the National Optical Observatory."

Famous National Academy astronomer - 1992