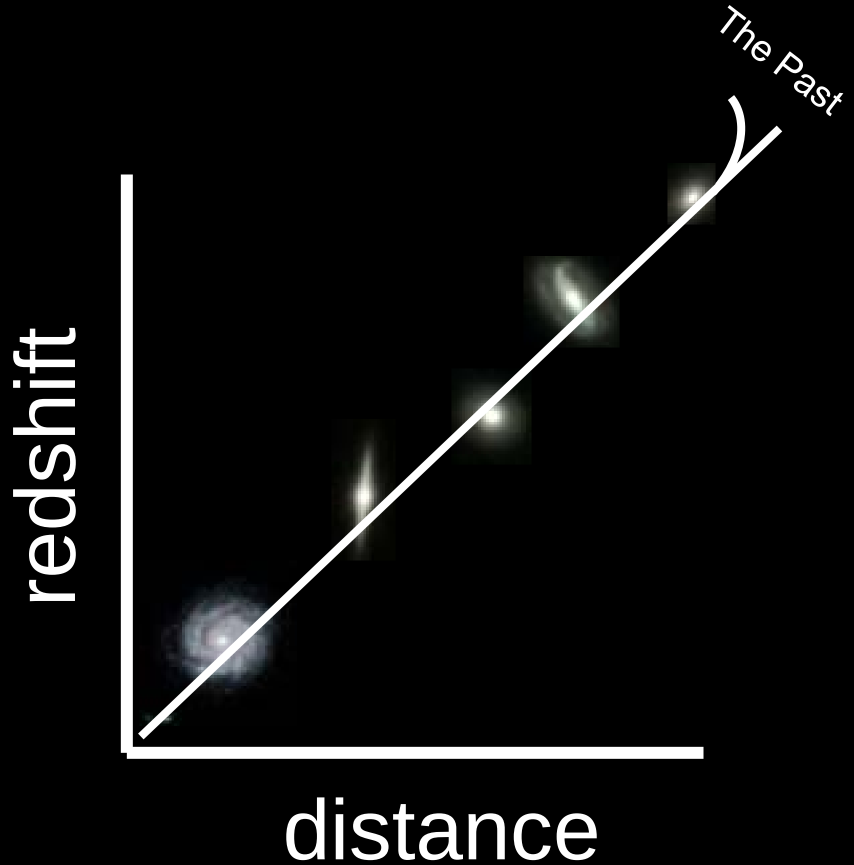
Johns Hopkins University
Space Telescope Science Institute
High-Z, Higher-Z Supernova Teams

Supernovae Reveal An Accelerating Universe (A Science Adventure Story)

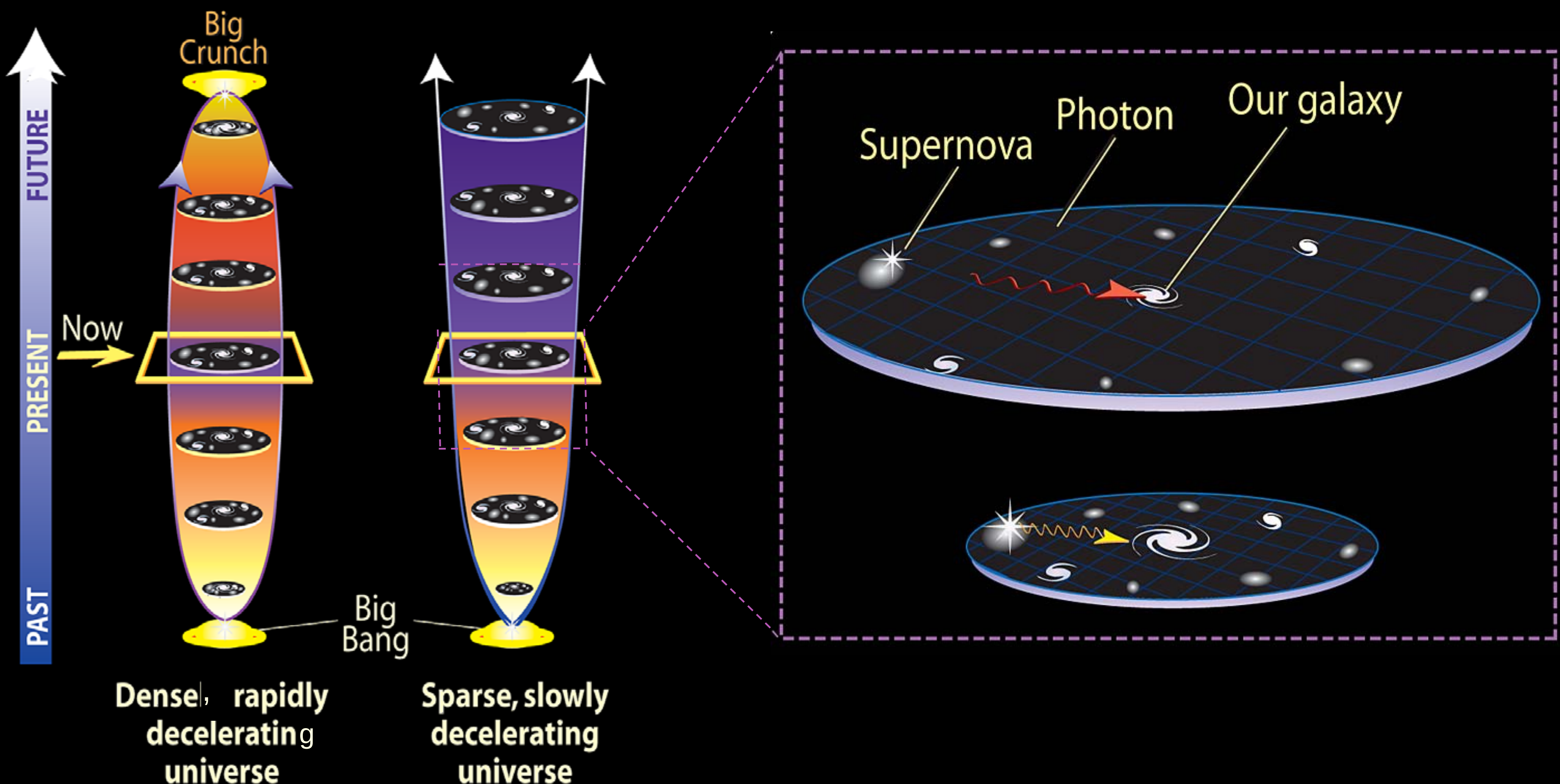
“If the Lord Almighty had consulted me before embarking on creation thus, I should have recommended something simpler.”—King Alfonso X

How big? How old? What next? Ask the Expanding Universe!



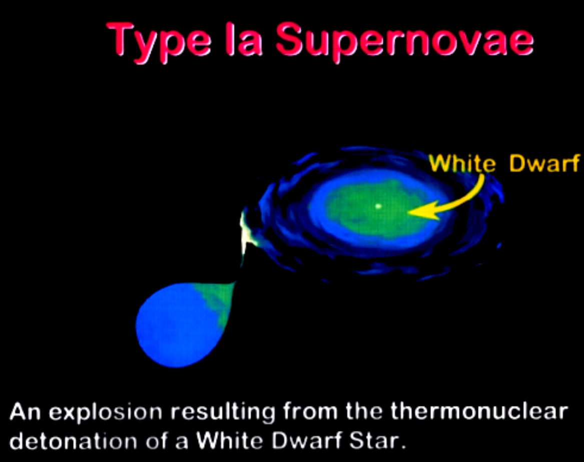
MODELS OF EXPANDING UNIVERSE – early 1990's

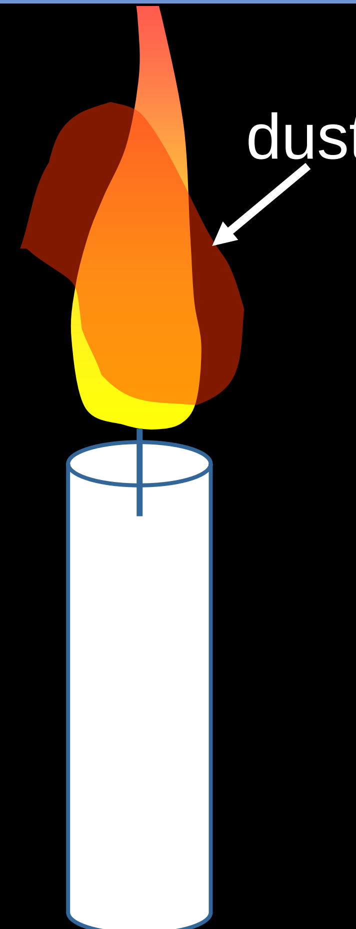
Heavy ($\Omega_M>1$) Lightweight ($\Omega_M<1$)



Measuring deceleration "weighs" Universe, ultimate fate!

Type Ia Supernovae, (imperfect) Standard Candles





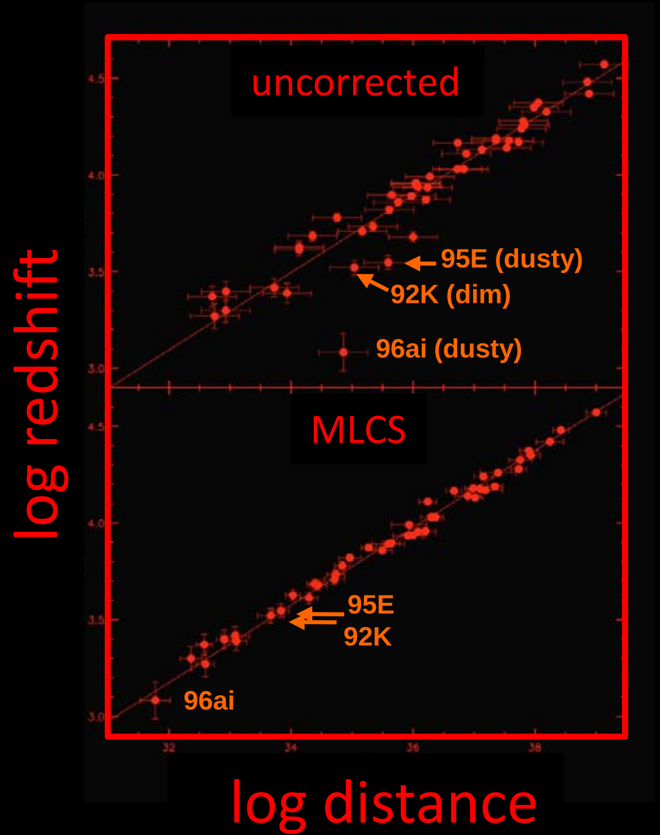
Bright=near faint=far

but not all the same…

faint & red=not so far!

1991 examples…Phillips 1993, Calan/Tololo Survey 1990-1993

Better Supernovae Distances-1994-1996



My "academic parents"

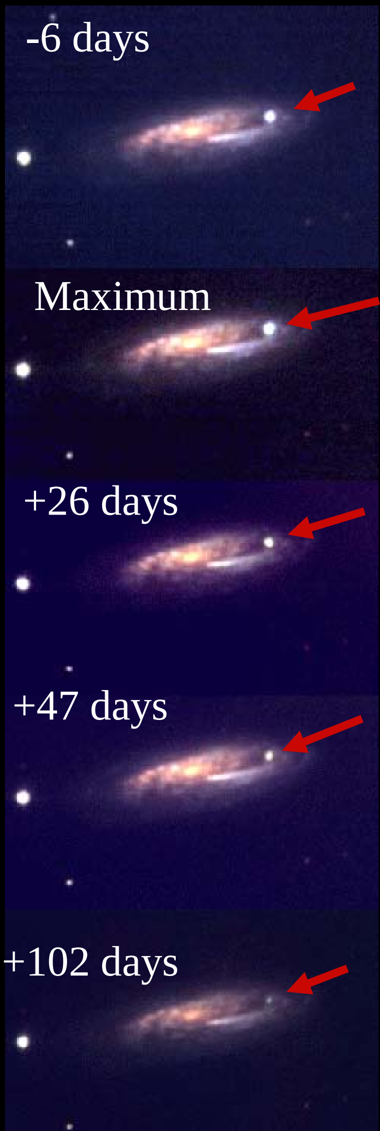
W. Press A.R. R. Kirshner

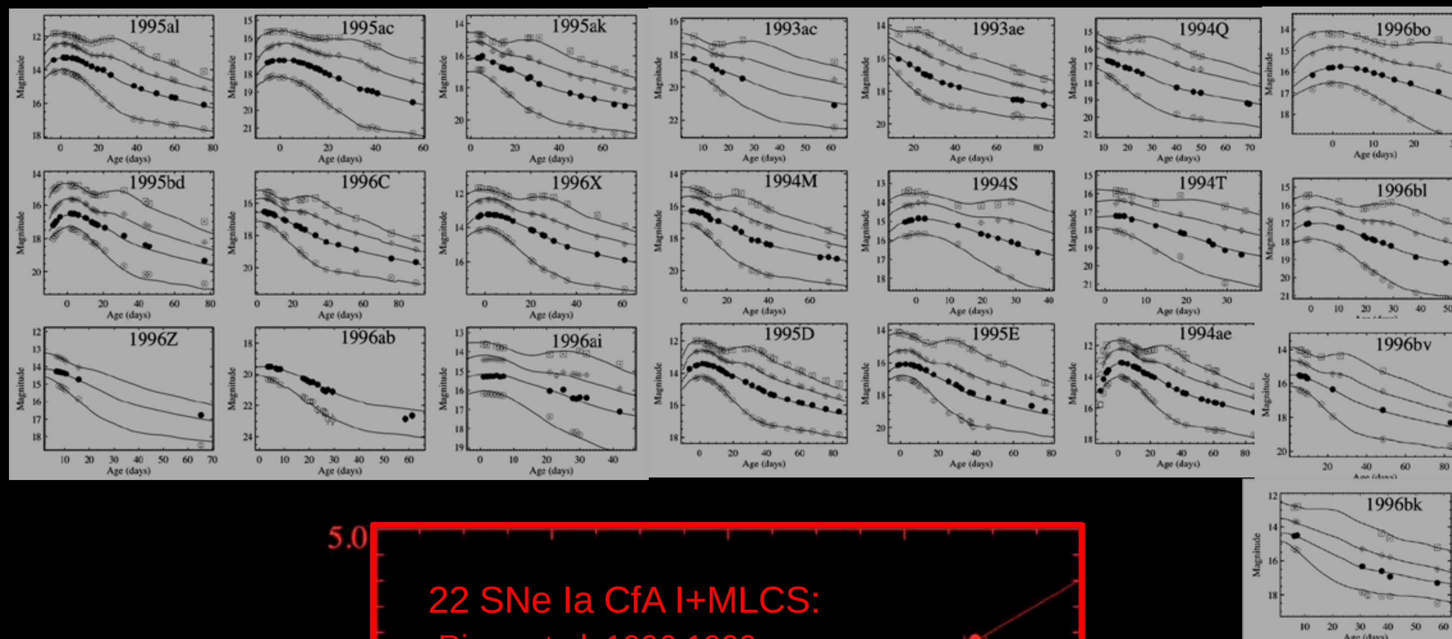
Thesis: Multicolor Light Curve Shape (MLCS) Method

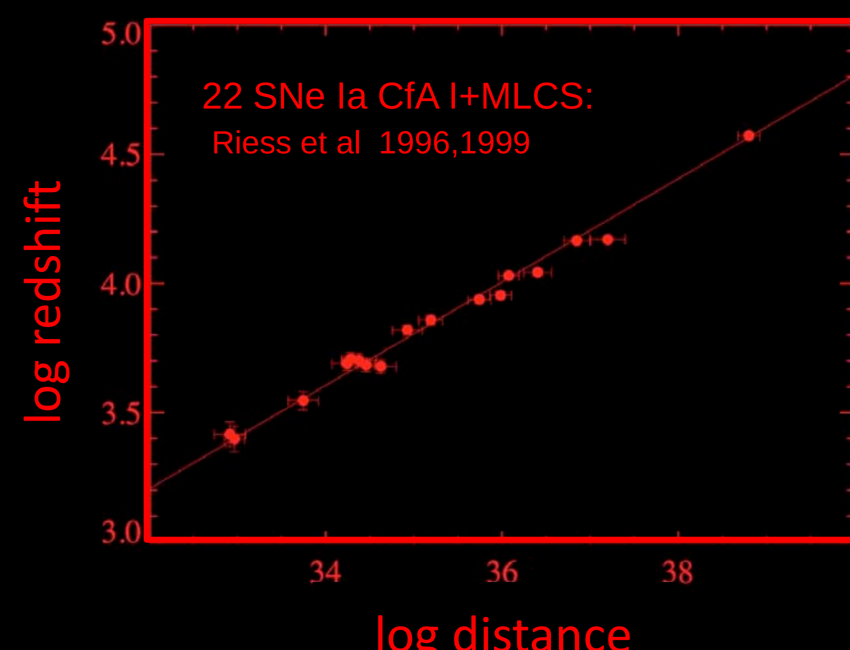
- Distinguish faint=far ***vs*** faint=intrinsically dim ***vs*** faint=dusty
- All ages, covariance, galaxy sims to improve dust measure
- For missing data: Snapshot method (1998)

CfA I Survey: A Northern Collection of SNe Ia; Expansion

1.2m Mt. Hopkins, 1200+ observations, 4 colors, 22 SN Ia, 1993-1996



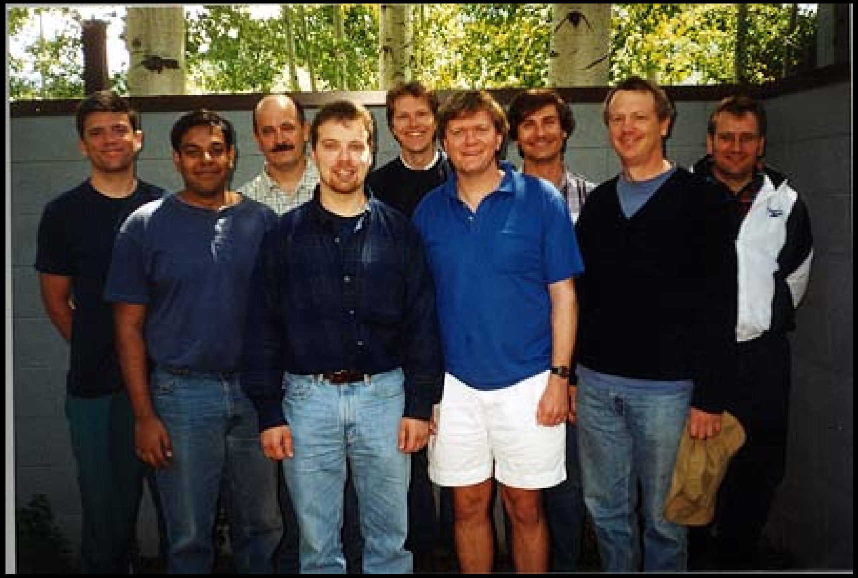




High-Z Supernovae Team

In 1994 the High-z Team was formed: "To Measure the Cosmic <u>Deceleration</u> of the Universe with Type Ia Supernovae"

To measure changes in the expansion rate, we sought the highest-redshift, most distant supernovae to compare to their nearby brethren we had already collected

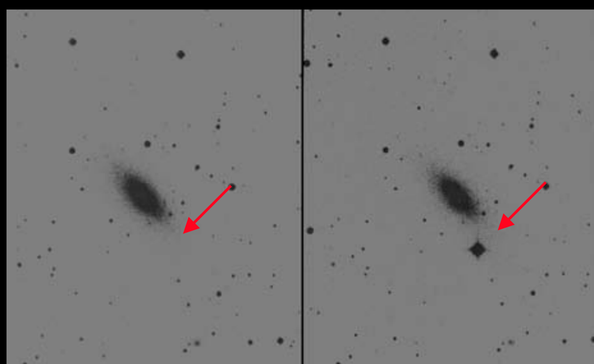


High-zers @ Aspen

High Redshift Supernovae—hard work!

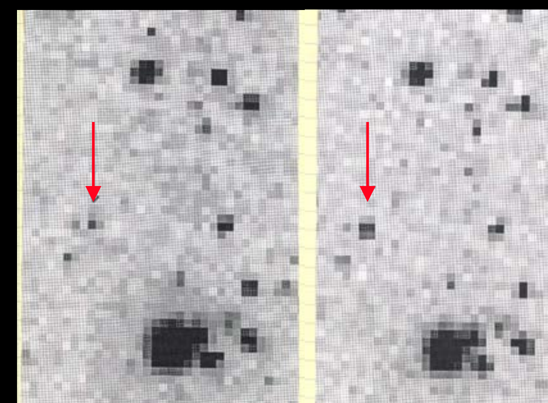
- Fall of 1996 went to Berkeley (nearby, nearly in SCP group)
- Observing for High-z at Keck with A. Filippenko, improving algorithms, reducing High-z supernova data (SN 95ao, 95ap, 96E, 96R, 96T, 96U)

SN Ia 1972E at 10 million light years



Before After

SN Ia 1996E at 6.6 billion light years



Before After

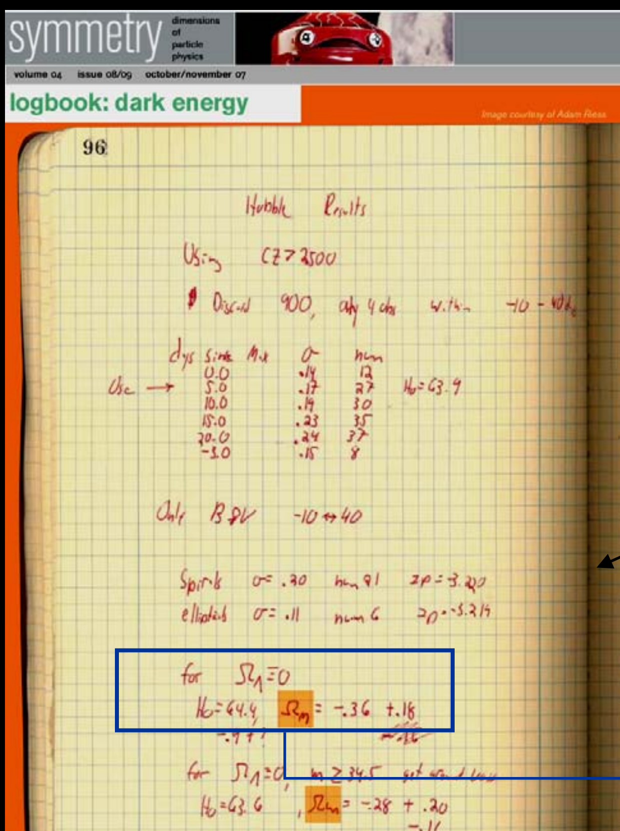
EUREKA!? In the Fall of 1997…

I has been picked to lead analysis of all data (16 SNe) to date….

$$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$$

"Eureka Moment" came when calculating the mass of Universe implied by the *deceleration (q_0>0)* of our supernovae, assuming no cosmological constant (Ω_Λ=0)

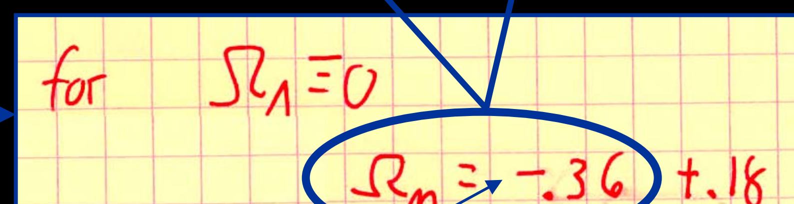
Adam's Lab book, Key Page, Fall 1997:



Negative Mass?

Actually the first indication of the discovery!

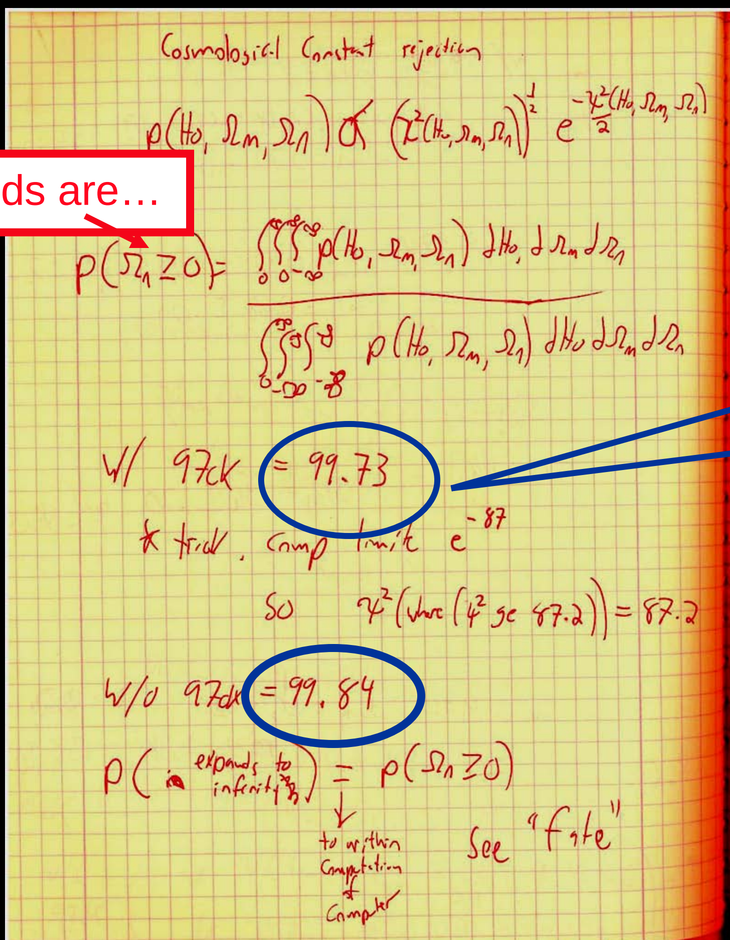
This negative sign means a negative deceleration *(q_0<0) which means acceleration*!



This negative sign represents 70% of Universe!

How? Looks like the Cosmological Constant (Dark Energy) …

Days later … What does this mean?
There cannot be negative mass, but would Einstein's Cosmological Constant explain this acceleration?



Odds are…

Yes!!! At least 99.73% sure something like Einstein's Cosmological Constant is needed!

After cross-checks, time to tell the team!

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: “Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer.”

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am “Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article if we are not very sure we are getting the right answer.”

B. Schmidt, Australia, 1/11/1998 7:13pm “I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…”

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: “I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don’t care and you’re just reporting the observations…It would be silly to say ‘we MUST have a nonzero [cosmological constant]’ only to retract it next year.”

M. Phillips Chile, 1/12/1998, 04:56 am: “…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant”

J. Tonry, Hawaii, 1/12/1998, 11:40 am: “…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …”

A. Filippenko 1/12/1998, 12:02 pm: “If we are wrong in the end, then so be it. At least we ran in the race.”

A. Riess Berkeley, CA 1/12/1998 6:36pm: “The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up…The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!”

A. Clocchiatti, Chile 1/13/1998 07:30pm: “If Einstein made a mistake with the cosmological constant…Why couldn’t we?”

N. Suntzeff Chile 1/13/1998 1:47pm: “I really encourage you [Adam] to work your butt off on this. We need to be careful…If you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting come your way in your lifetime.”

THE ACCELERATING UNIVERSE

SNe Ia near and far indicate acceleration equating to ~70% dark energy in Universe!

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OBSERVATIONAL ... ACCELERATING UNIVERSE
NT

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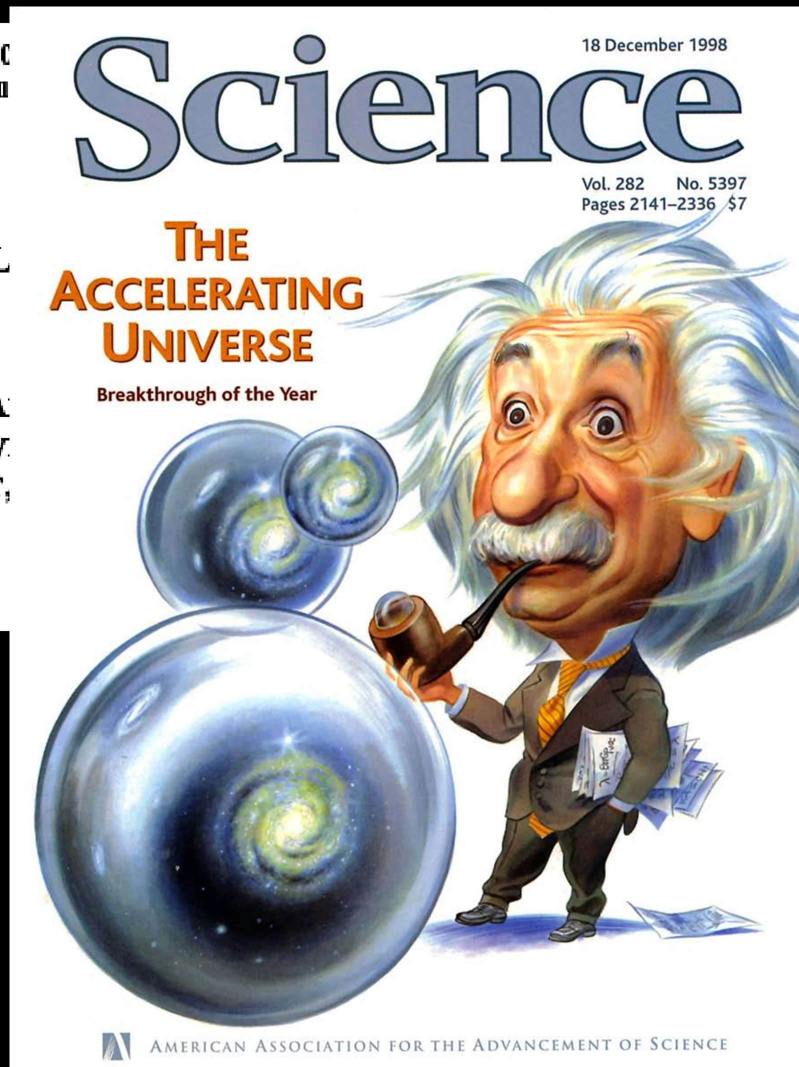
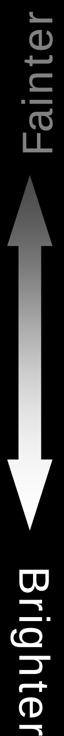
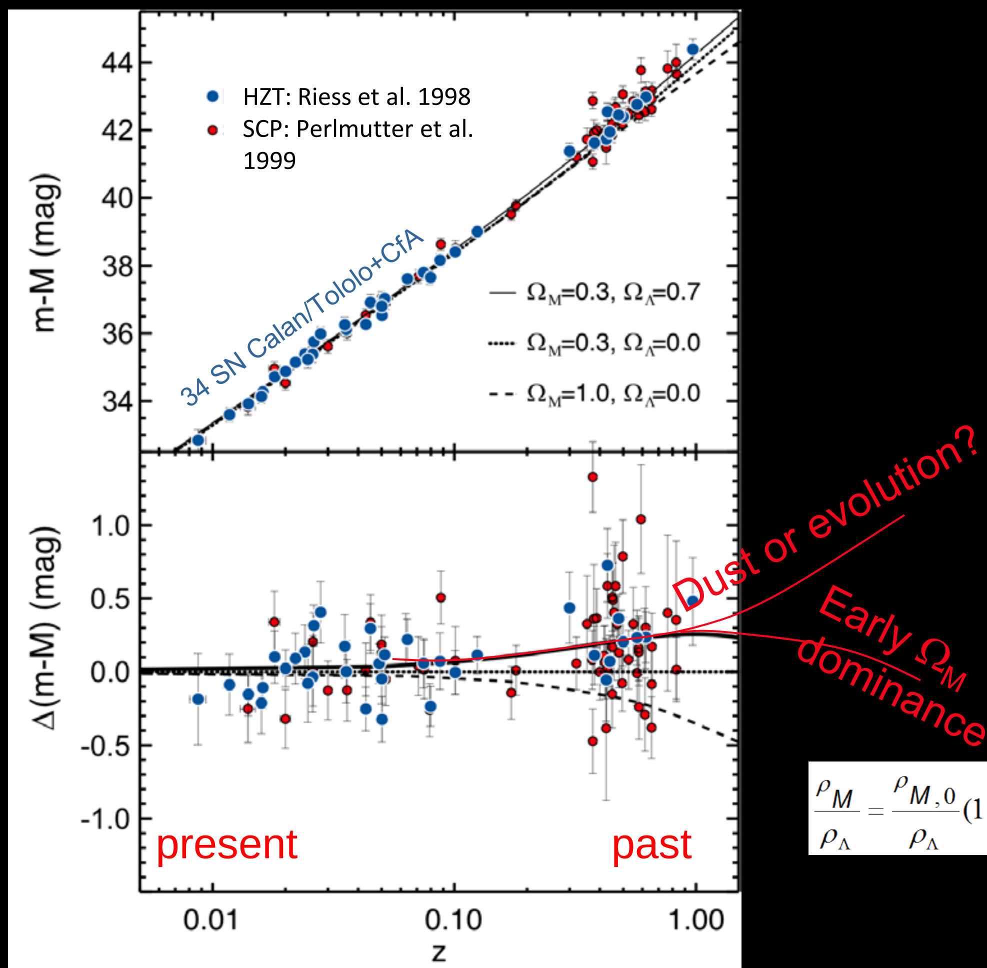


High-z,1998

Alternative Explanations for faint=far supernovae

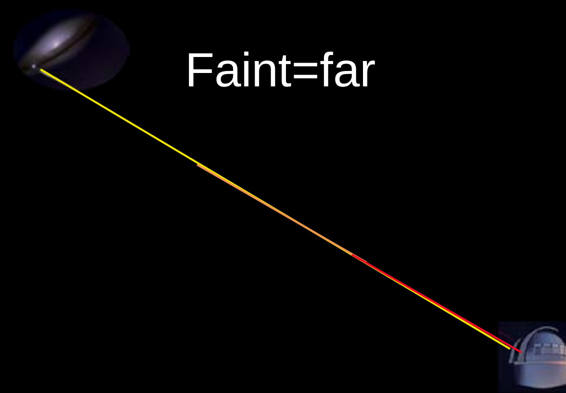
Steady dimming from grey dust or evolution instead?
Test: brighter at z>1 (i.e., prior deceleration)?





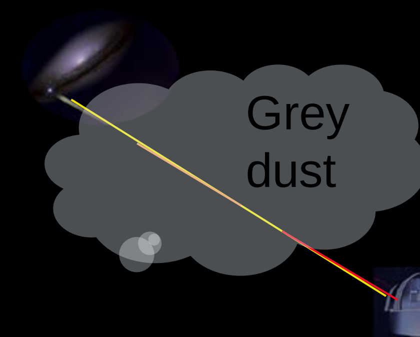
$$\frac{\rho_M}{\rho_\Lambda} = \frac{\rho_{M,0}}{\rho_\Lambda}(1+z)^3$$

Faint=far



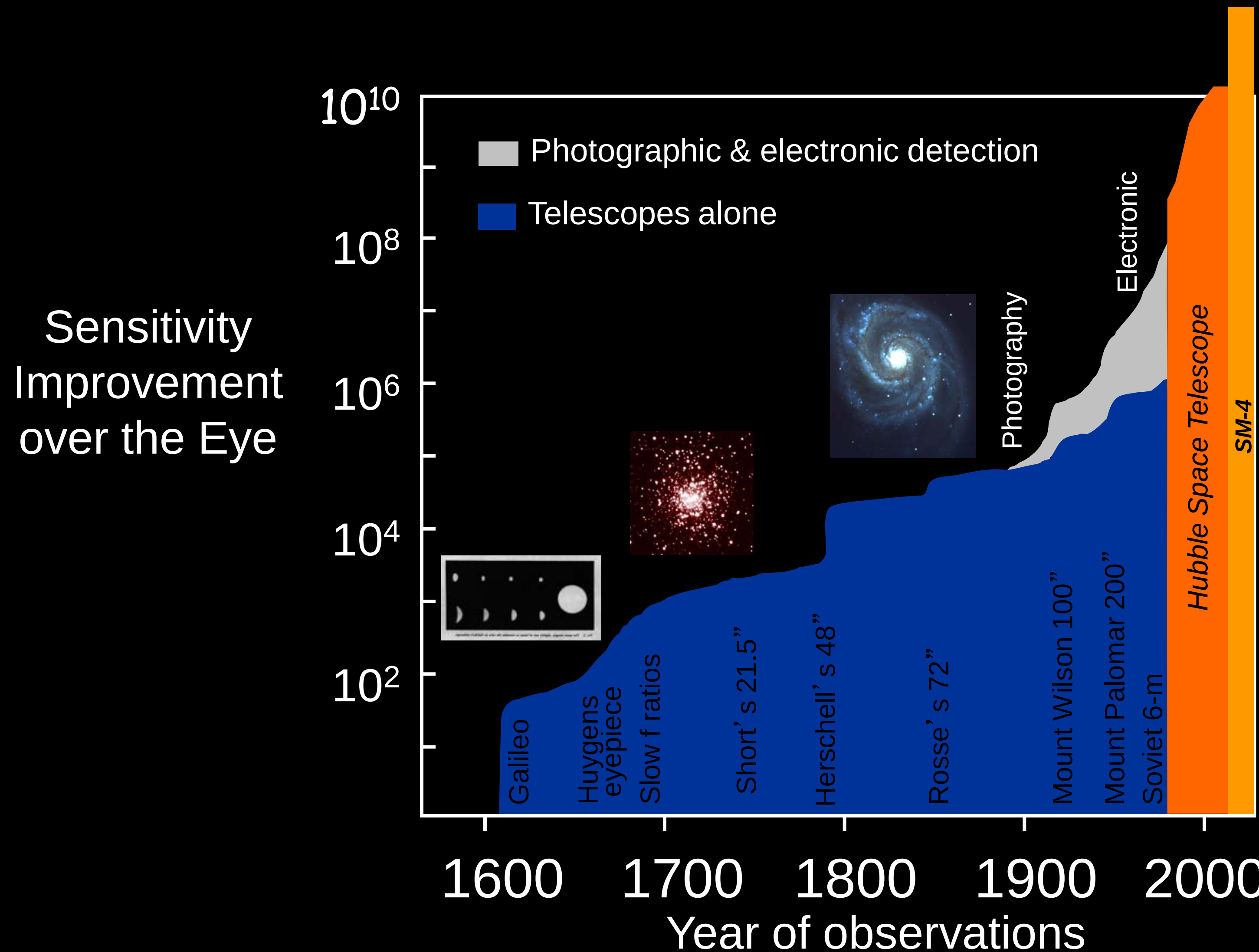
Universe accelerating

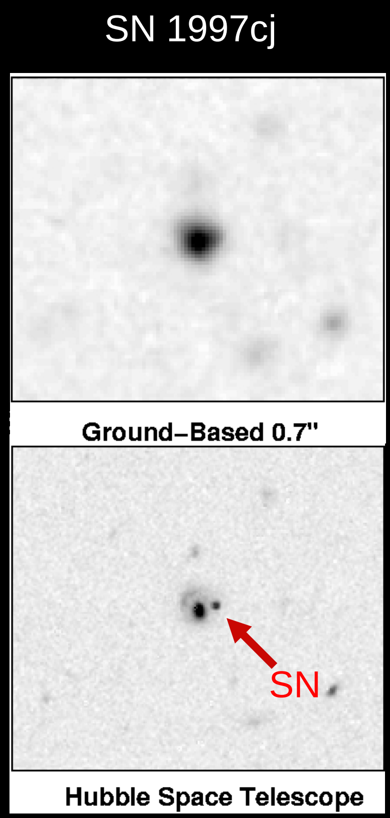
Faint=grey dust, not far



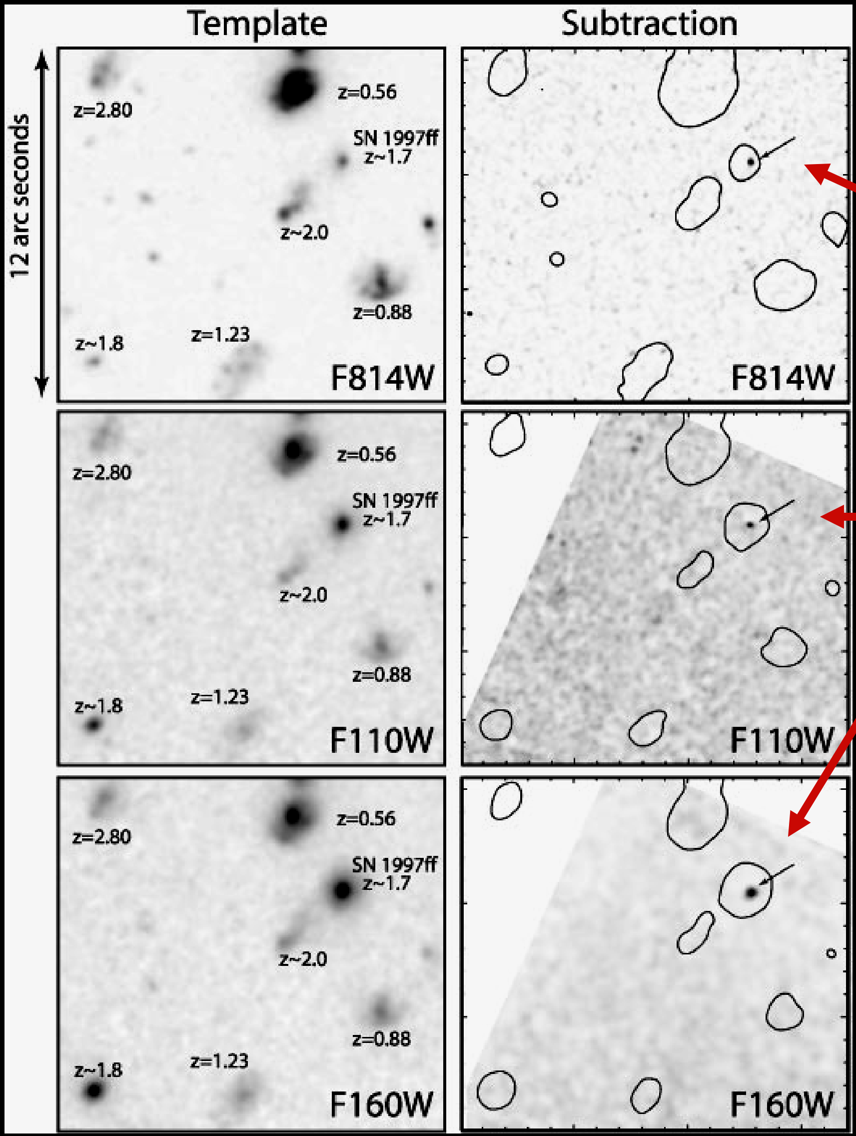
Not accelerating

Telescope sensitivity improves, we see farther…





A First Glimpse at Decelerating Universe…2001



SN Ia 1997ff, z=1.7

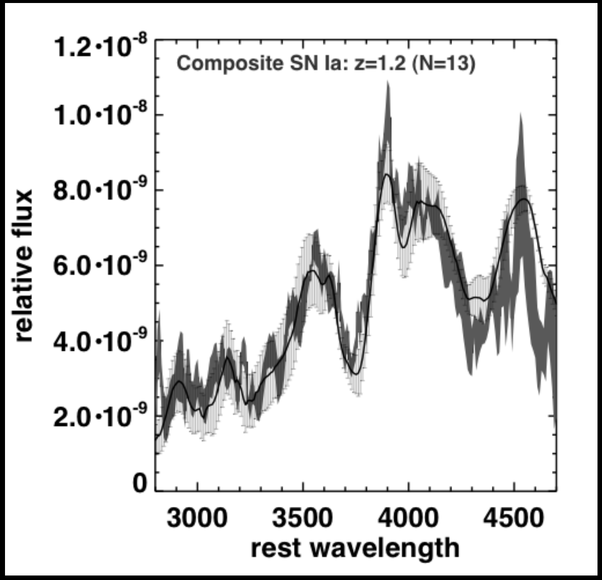
Discovery:
The Hubble Deep Field, WFPC2, 1997 (Gilliland & Phillips).

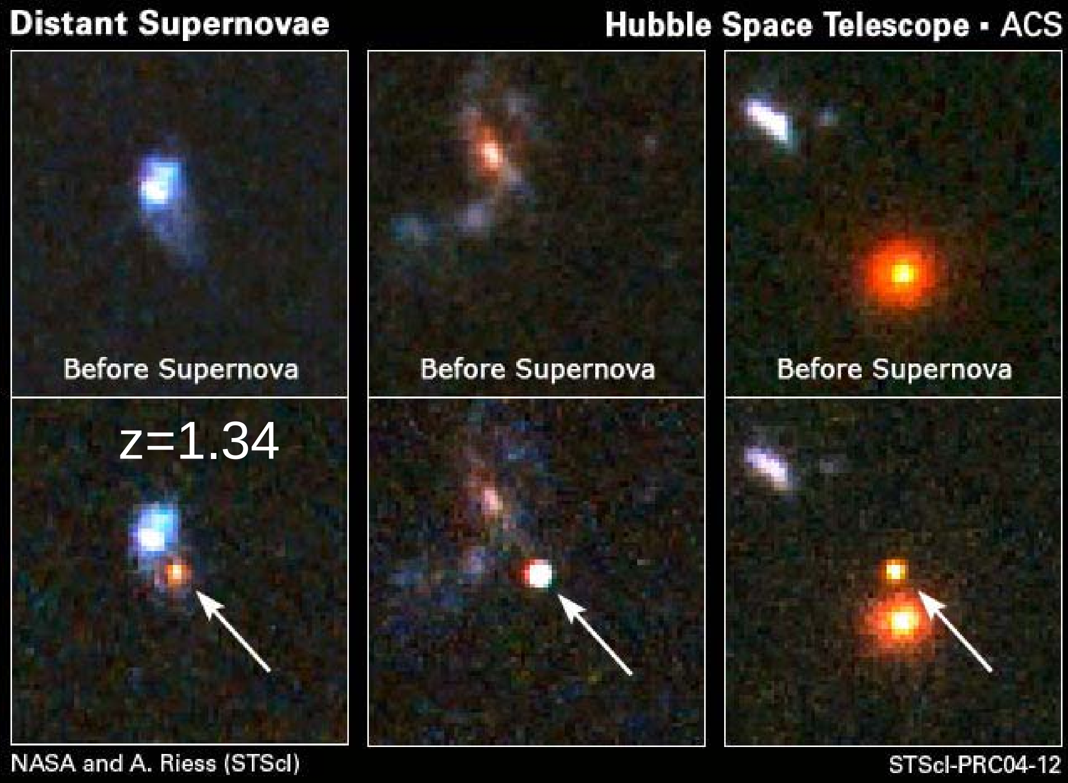
Rediscovery:
Light Curve Measured from ***Serendipitous*** Observations and timing of the NICMOS Near-Infrared Deep Field; (Riess et al 2001)

Results supported accelerating-interpretation of high-z SNe Ia, but with only one object conclusion not very robust

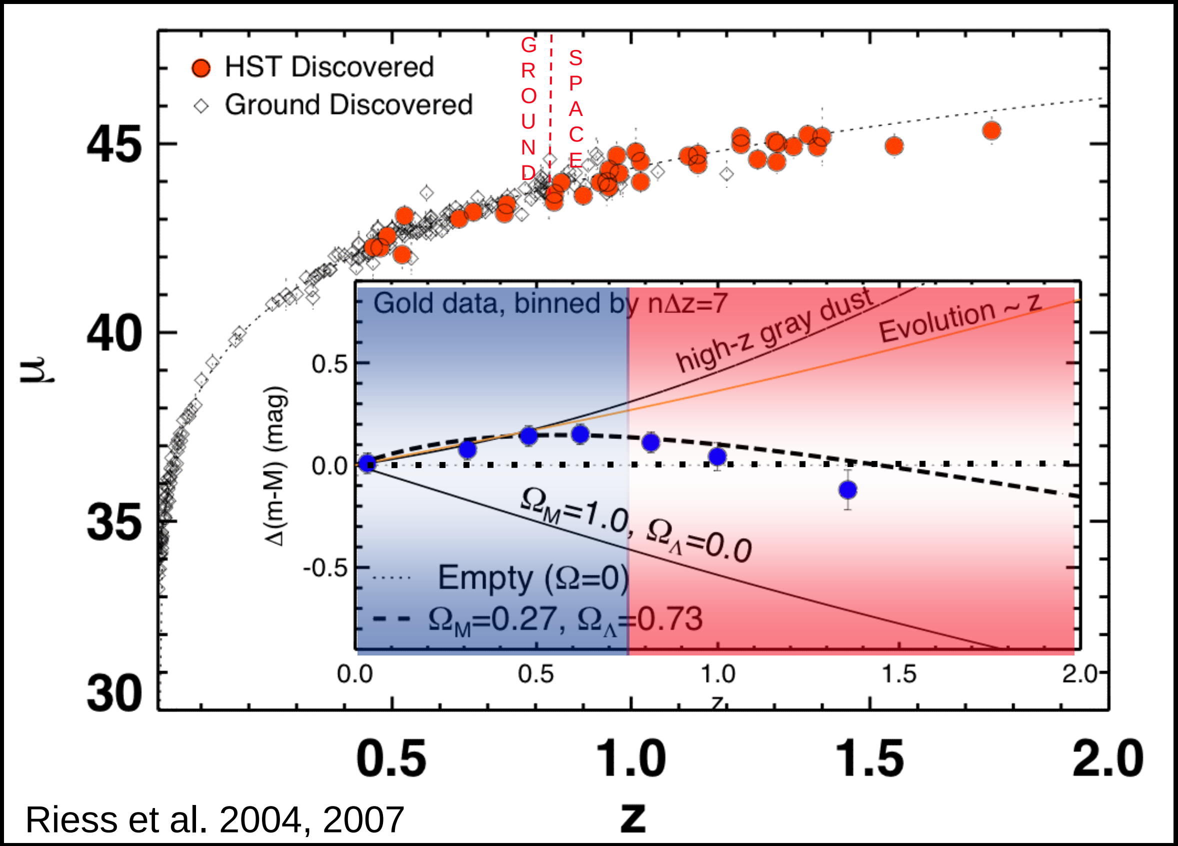
Hubble gets new camera, can measure SNe Ia at z>1, 2002

- In 2002 Astronauts install ACS
- From 2002-2007 the *Higher*-z Team measured 23 new SNe Ia at z>1



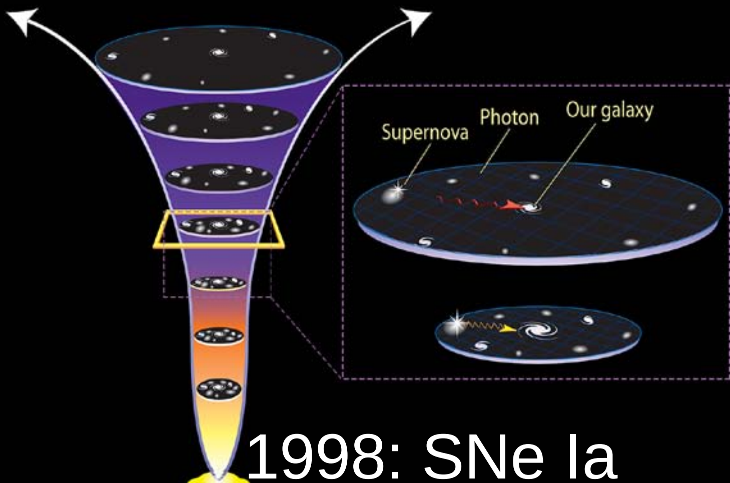


23 HST SN, see brightening/deceleration z>1, acceleration passes test!



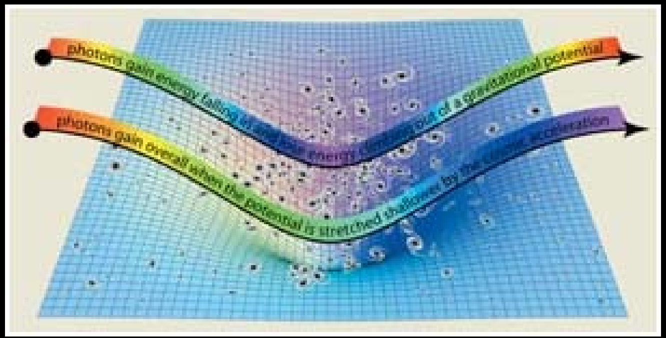
Not just supernovae require "dark energy"…

1 Expansion recently began Accelerating



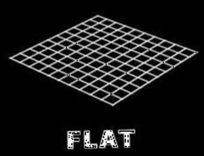
1998: SNe Ia

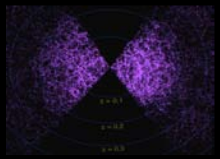
2 Galaxy potentials are being pried apart; passing photons gain energy



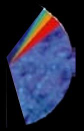
2003: late-time ISW Effect

3 Difference between Ω_{tot}=1 critical density, Ω_M=0.3 sub-critical is 0.7



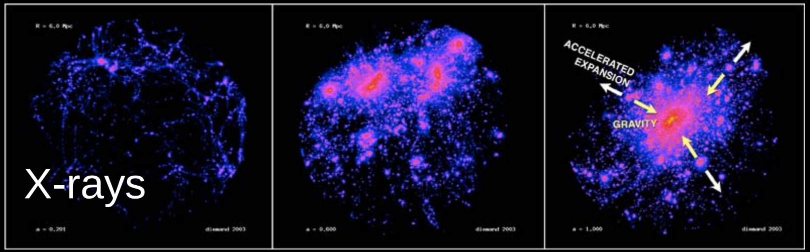


Ω_{DE}=0.7

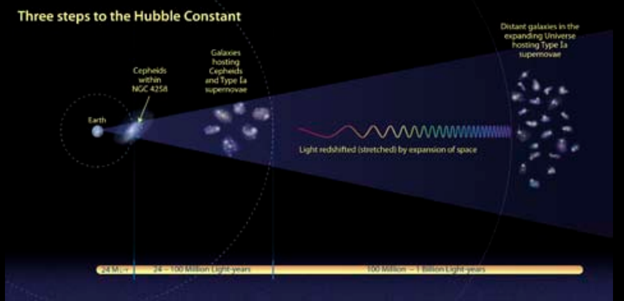
Ω=1 -  = 

2003: CMB & LSS,M/L,BAO,lensing

4 Arrested Growth Clusters, 2008



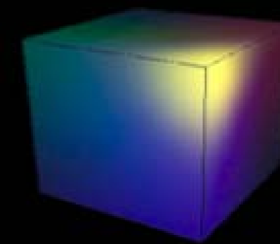
5 Change in *Absolute* Scale of Universe, z=1000-0, (WMAP+H_0=74±3), 2009



Why is the Universe Accelerating?

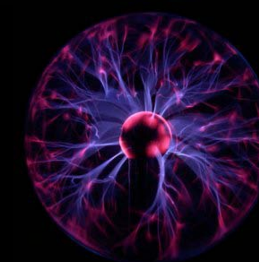
$$q_0 = \frac{\Omega_M}{2} + (1+3w)\frac{\Omega_{DE}}{2}$$

$w \equiv p/\rho$



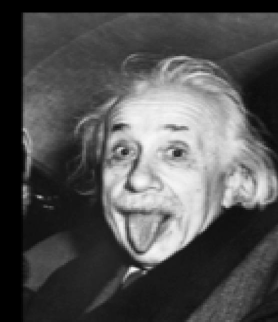
1. Static Vacuum Energy, (the cosmological constant)

A constant energy of empty space, expected in QM, consequence in GR--repulsive gravity, now $\Omega_{DE} \geq \Omega_M$ (but the coincidence problem & the 10^{120} problem)



2. Dynamical dark energy

A field with energy pervades space, changes with time (e.g., “inflation-lite”)



3. Modification to GR—long range

Maybe GR fails at long range, modification as scale approaches present horizon

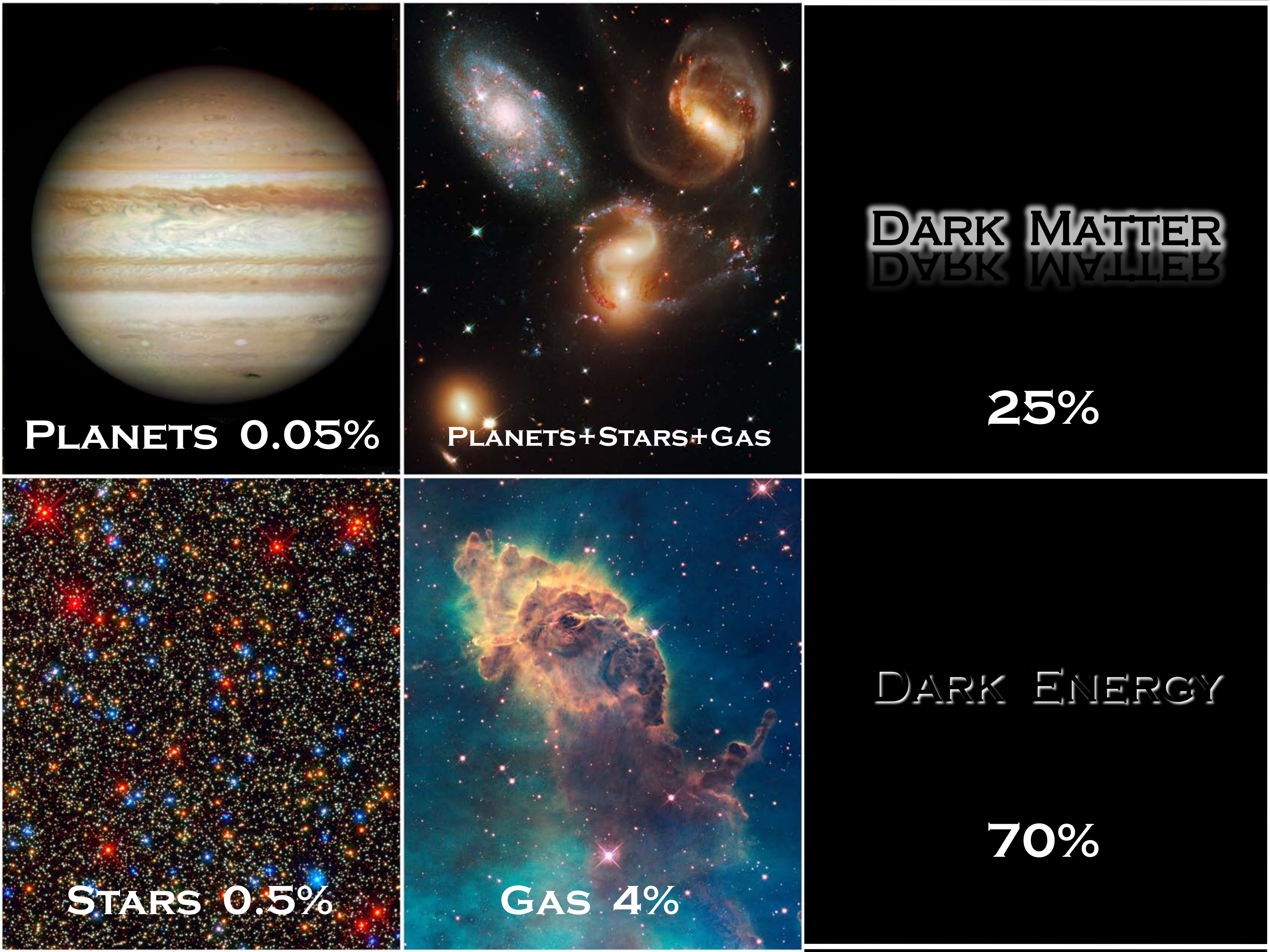
Tests of all 3: is DE strength constant, evolving, scale-dependent?

Last Upgrade for Hubble, install WFC3 in 2009

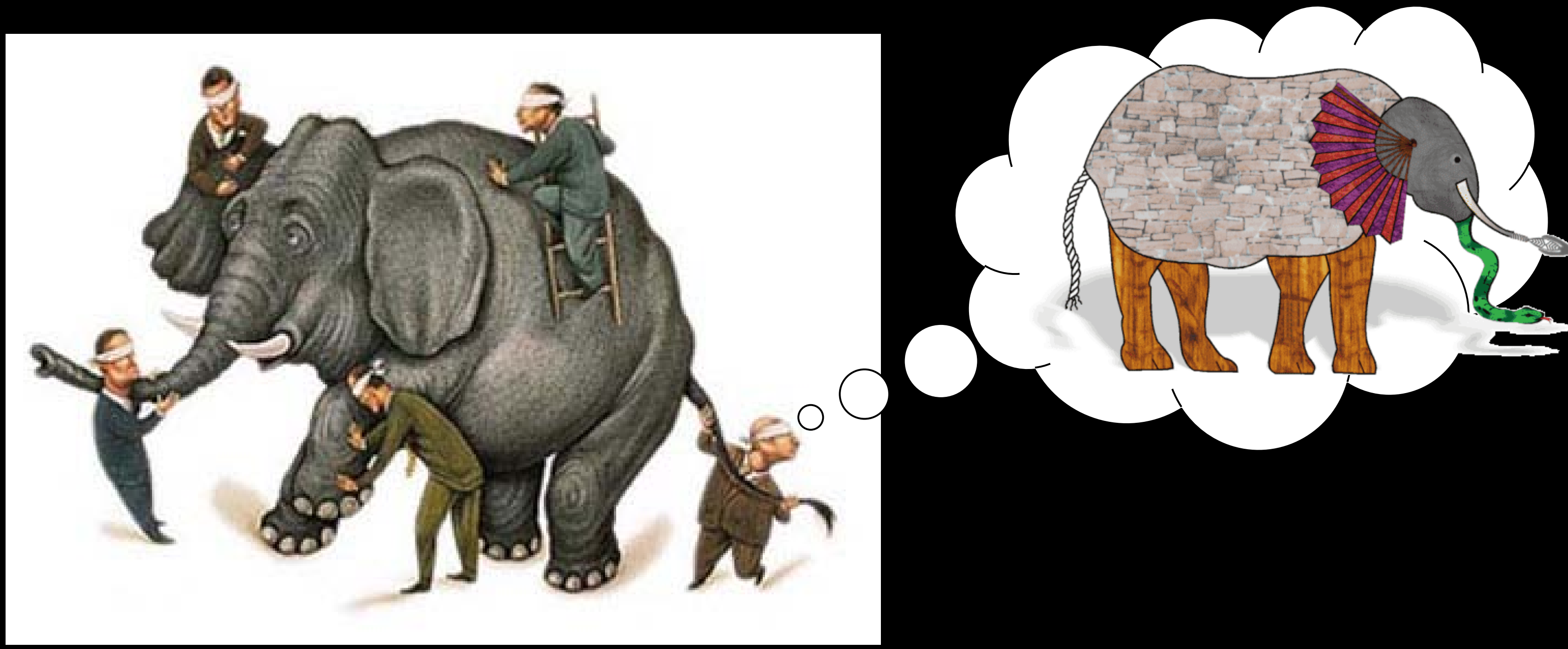
New studies to help understand dark energy

•Already increased precision in measuring H_0 (3.5%)

•A search for SNe at $1.5<z<2.3$, already found a few so far…

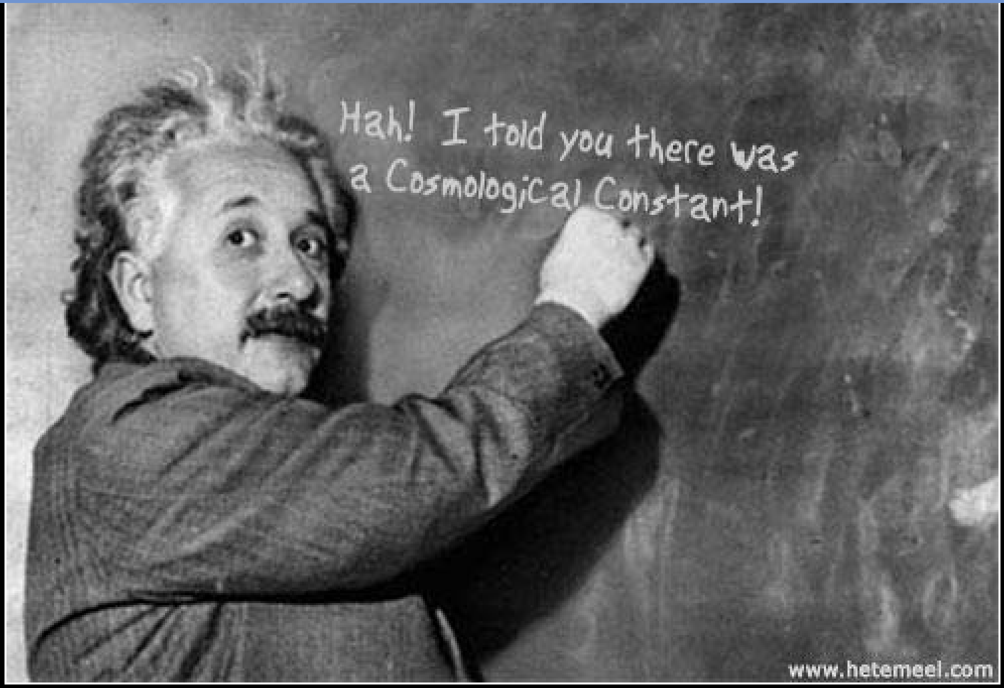

Planets 0.05%
Planets+Stars+Gas
Dark Matter
25%
Stars 0.5%
Gas 4%
Dark Energy
70%

Why is Dark Energy (cause of acceleration) so important?



- Its 70% of the Universe and we don't understand it!
- It will determine the fate (origin) of the Universe
- Touches the central pillars of modern physics (QM, GR, String) It's a clue and embarrassment, 10^{120}). It is likely to lead to something interesting…

SUMMARY

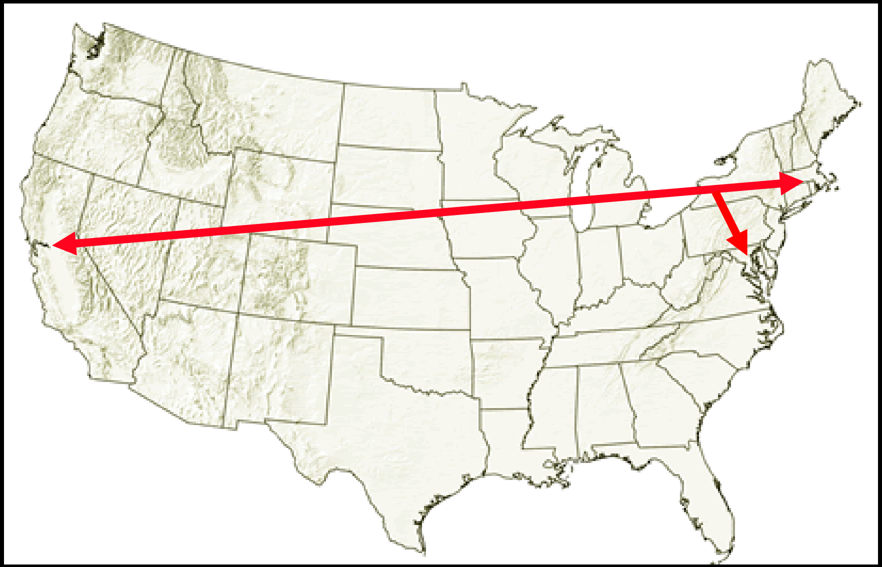


» We discovered accelerating expansion and dark energy in 1998. More distant supernovae seen with the Hubble Telescope test alternatives, confirm acceleration is real.

»Understanding dark energy lies in the critical path to understanding gravity, the fate and the origin of the Universe.

A Random Walk to the Discovery…

Bay Area, CA
Livermore Labs (92)
UC Berkeley (96-99)



Cambridge, MA
MIT (88-92),
Harvard U (92-96)

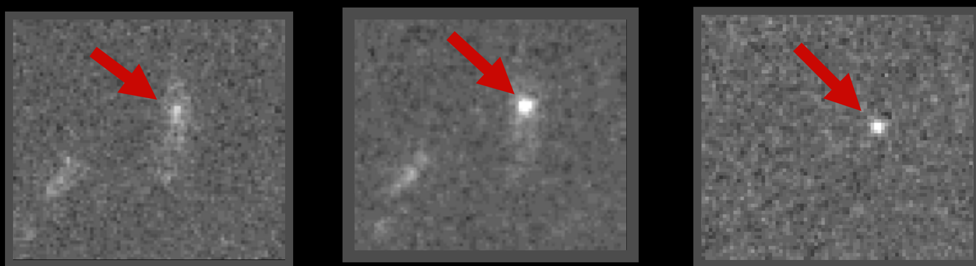
Baltimore,MD
STScI,JHU (99-)

• In 1992 I graduated MIT, summer at LLNL on MACHO project

• Fall, 1992: to Harvard (met Brian, fellow grad student), thesis on improving distances to Type Ia Supernovae with R. Kirshner.
(Began working with Brian and High-z Team on high-z SNe Ia, 1994)

Discovering the most distant supernovae with Hubble, 2002

Step 1: Detection at m_I>25, ACS

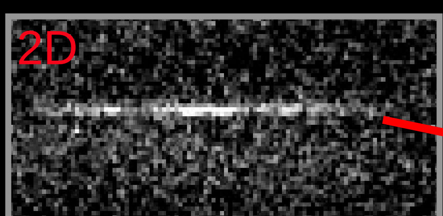


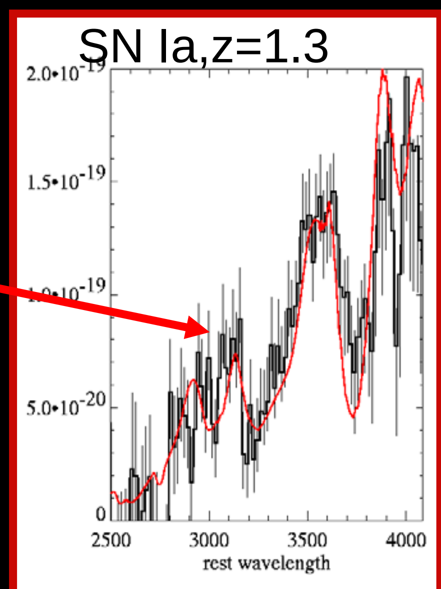
Step 2: Winnowing

SN Ia
are red
in UV

Step 3: Identification, redshift

ACS grism spectrum



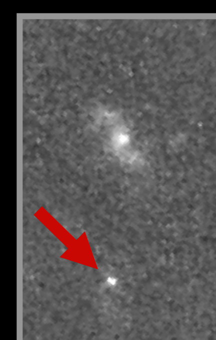


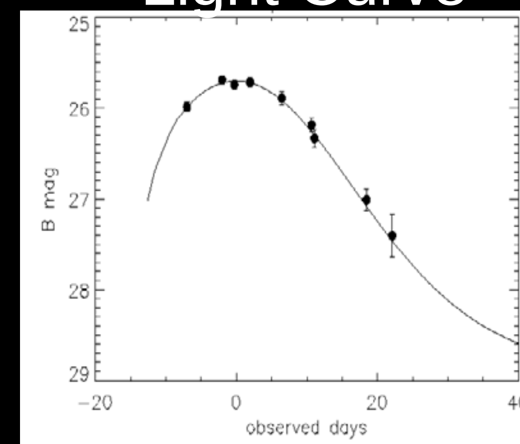
Ground has
never measured
redshift this high

Step 4: Follow-up, near-IR

Light Curve

NICMOS



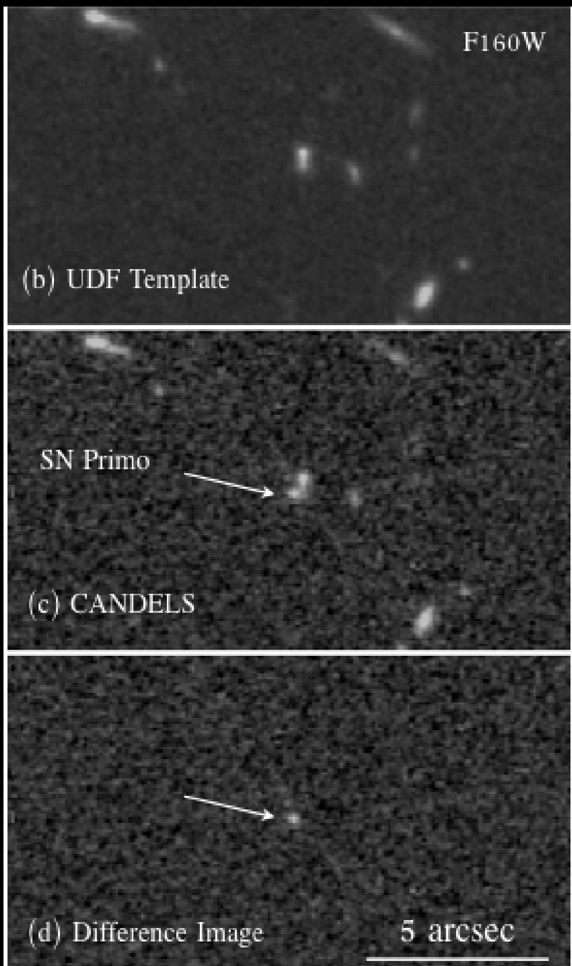


Peak and shape yields distance

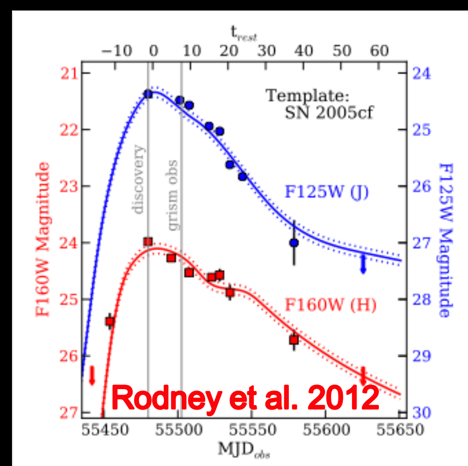
EXTENDING SNE IA TO $1.5 < z < 2.3$ WITH WFC3-IR

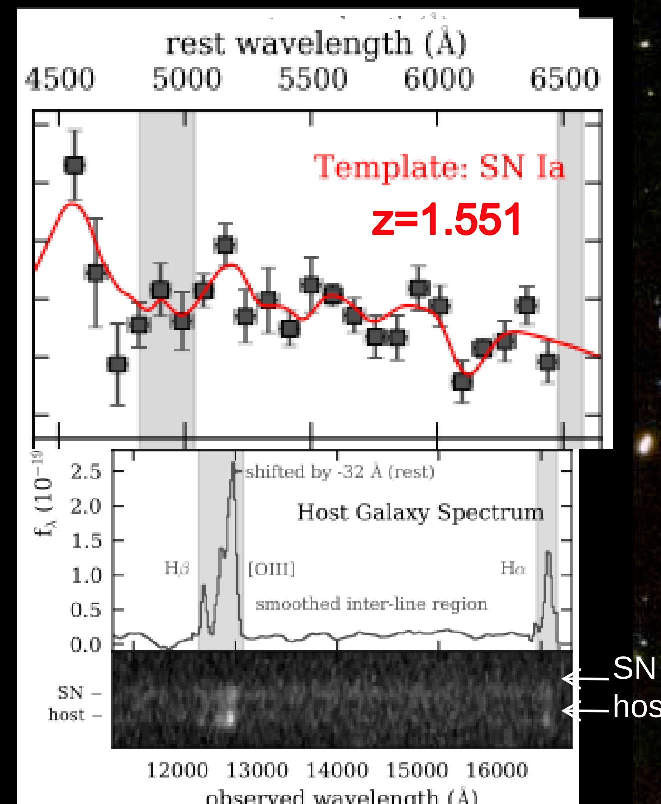
Higher-z Team

Discovery



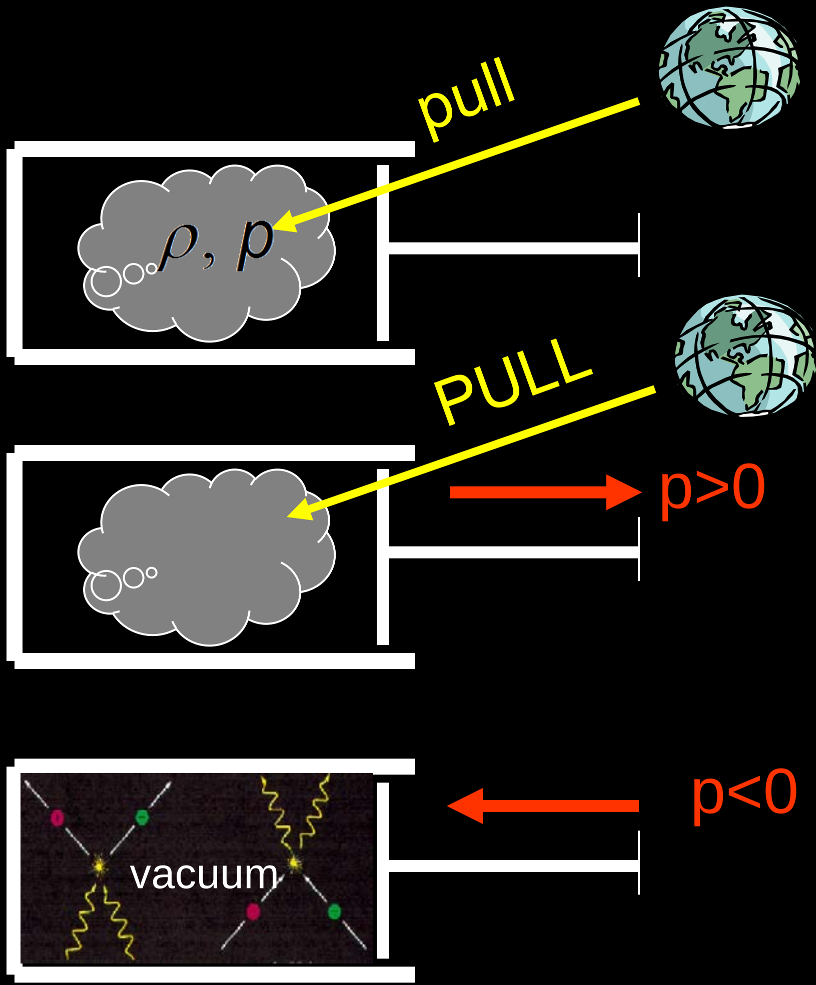
Follow-up





Most distant, spec. confirmed SN Ia

Why does the Vacuum Accelerate the Universe?



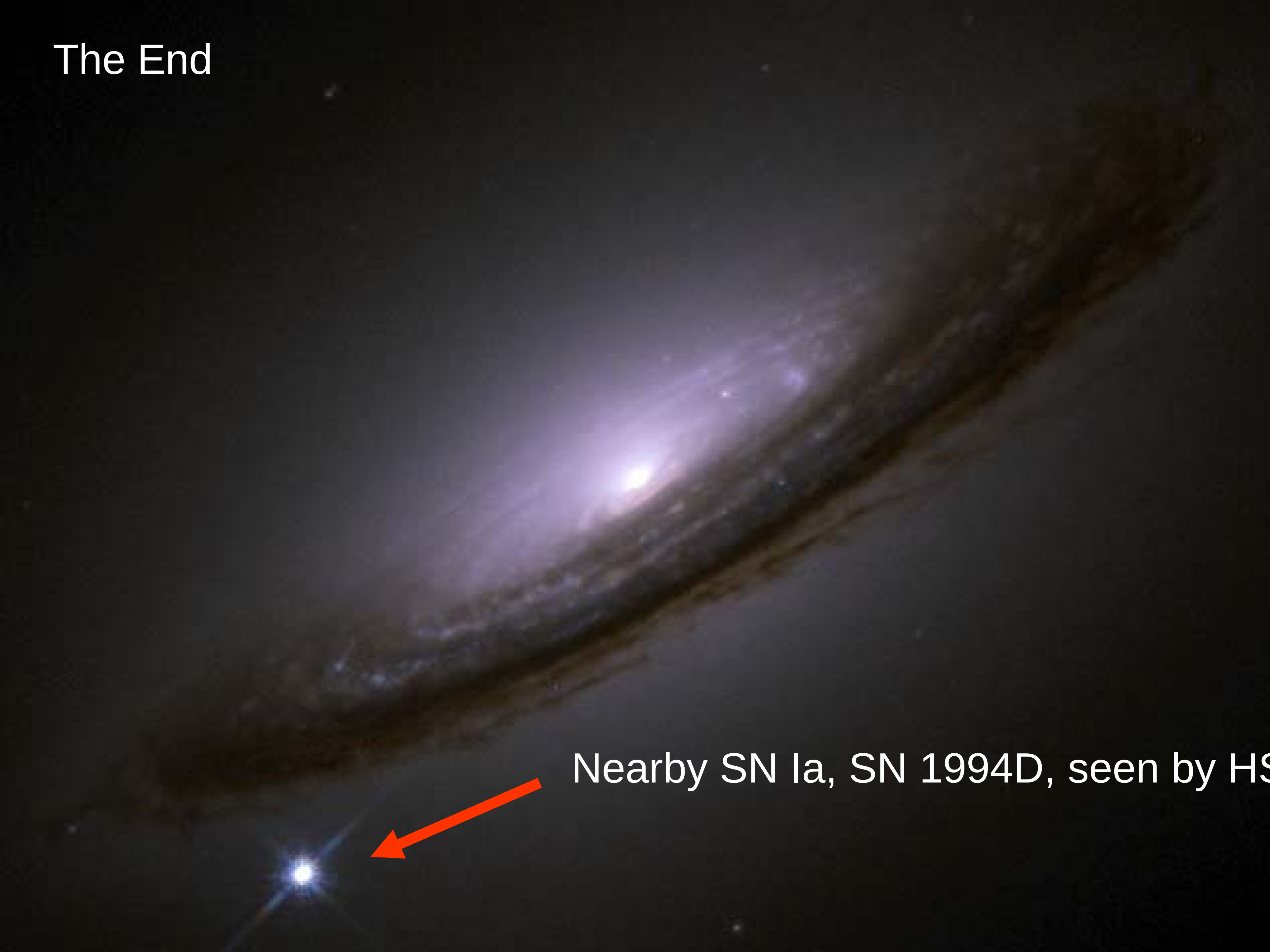
Newton: gravity $\propto \rho > 0$

Einstein: gravity $\propto (\rho + 3p) > 0$

Einstein: gravity $\propto (\rho - 3p) < 0$

QM: vacuum zp energy, do work
to expand U, so p<0, but
At present vacuum 120
Orders of magnitude off!

The End

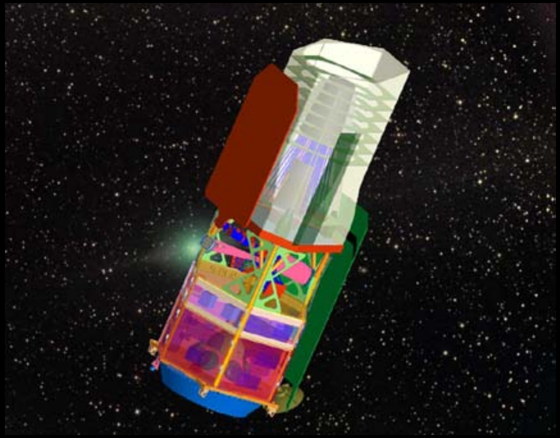


Nearby SN Ia, SN 1994D, seen by HS

Present and Future Studies of Dark Energy

The Goal: To measure if dark energy evolving & if General Relativity (Einstein's theory) works on large-scales.

- US Decadal Survey Picks, WFIRST, NASA to build for ~2020+ launch
- ESA selects EUCLID ~2019 launch
- Ground-based Plans: LSST, Big Boss, Subaru, etc. 2015-2025



WFIRST-Wide Field InfraRed Survey Telescope
1.5m, wide angle, Dark Energy via 3 methods