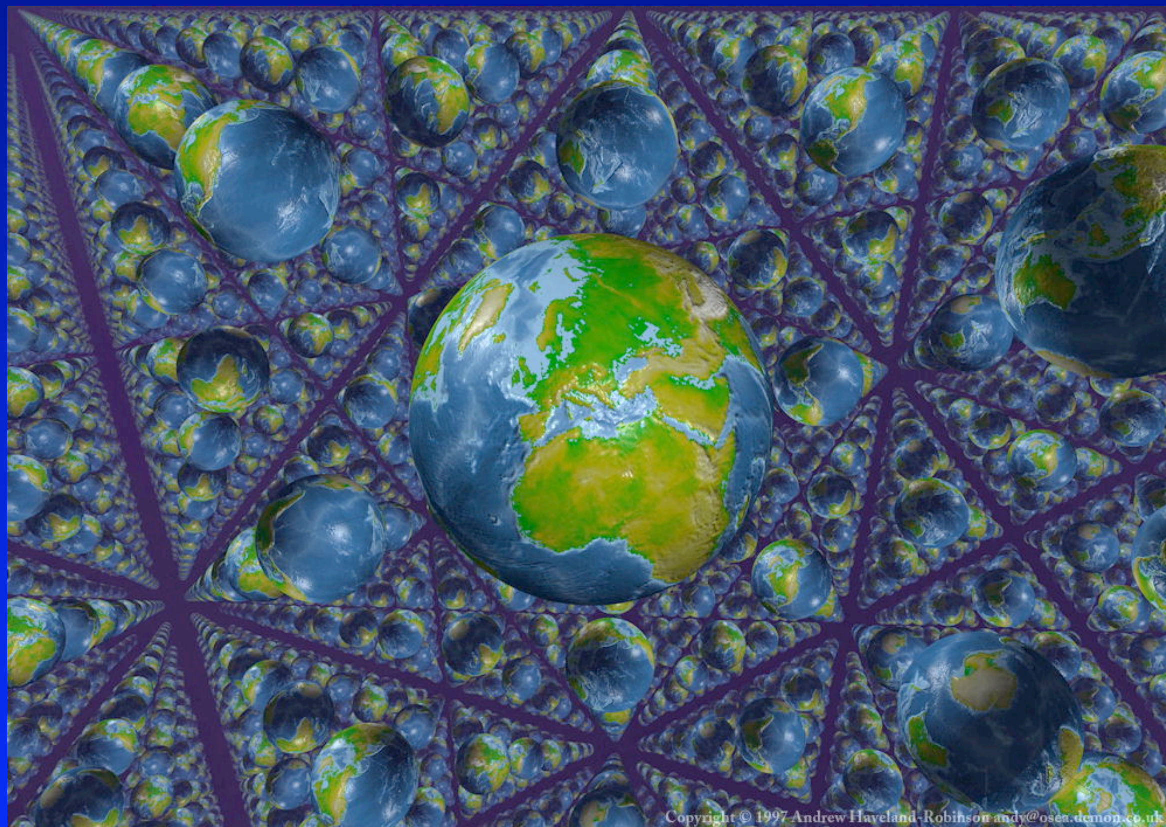
Our Place In Space

Exploding Stars, the Expansion of the Universe, Cosmic Anti-Gravity, and the Search for Extra-Terrestrial Intelligence



Andrew Friedman & Jason Gallicchio

Harvard Department of Astronomy, Harvard Department of Physics

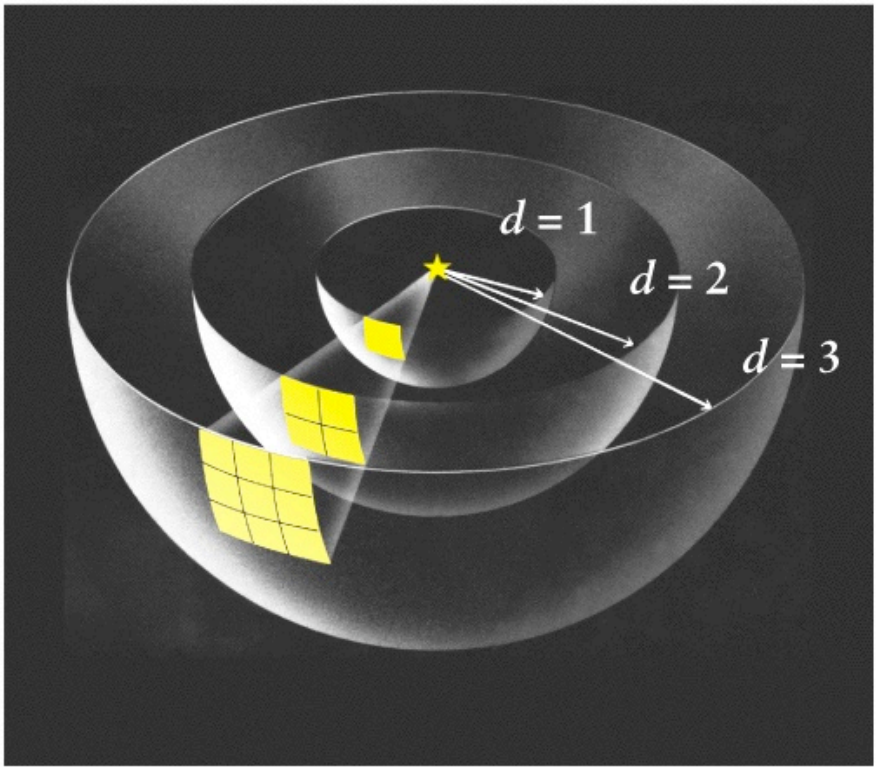
Dudley House Crosstalk: Thursday, March 6th 2008

Outline

- **Measuring Distances in Astronomy**
- Einstein, Hubble, and Cosmic **Expansion**
- Cosmic **Acceleration**
- My **Research**: Using Supernovae to Measure Distances and Cosmic Acceleration

Distances in Astronomy

Inverse Square Law



F = flux (or brightness)
L = luminosity (or power)
d = distance

$$F = \frac{L}{4\pi d^2}$$

Standard Candles

A **Standard Candle** is a theoretical astronomical object of known intrinsic luminosity *L*, like a 100 Watt light bulb in space

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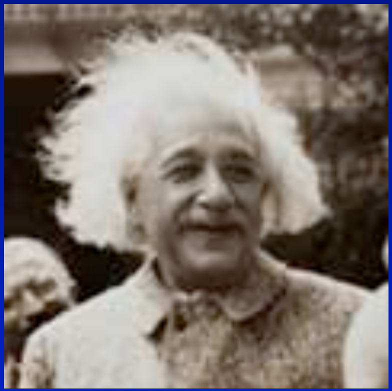
The Size of the Known Universe in 1915

Λ The Cosmological Constant Λ

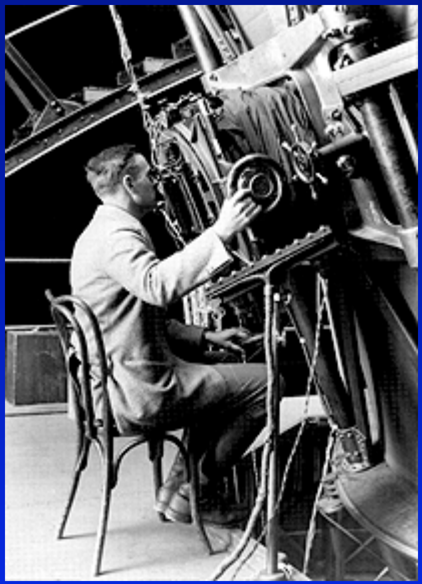
- In 1917, Einstein introduced the cosmological constant Λ to allow for a static universe, the favored theory of the time.

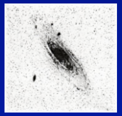


$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

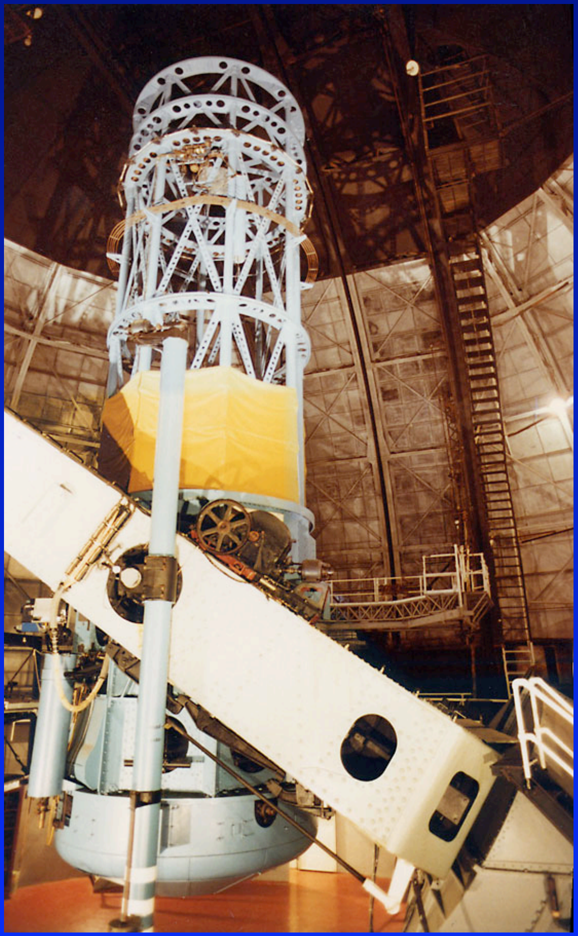
Edwin Hubble (1889-1953)

Edwin Hubble





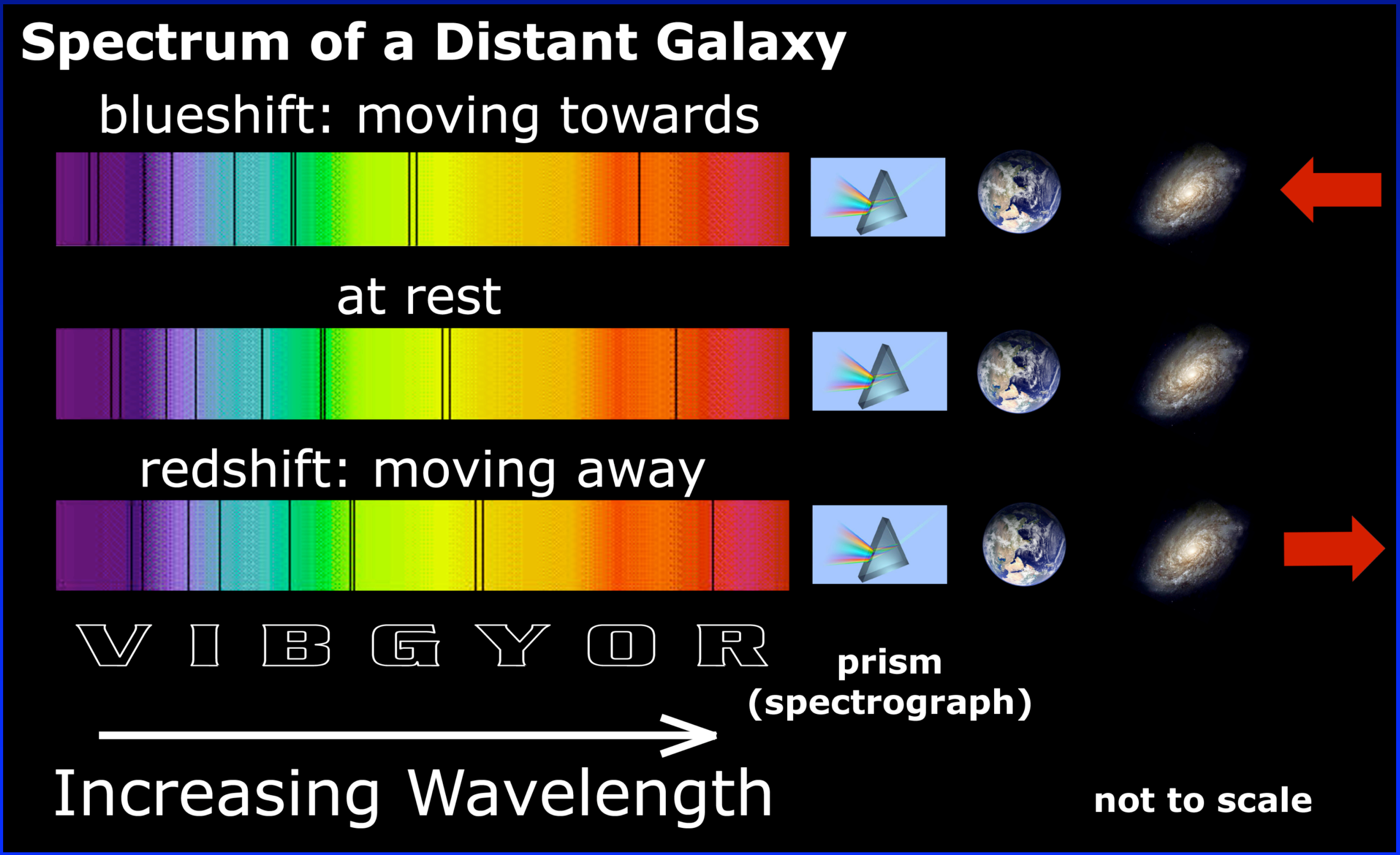
Measuring the velocities and distances of “spiral-nebulae”



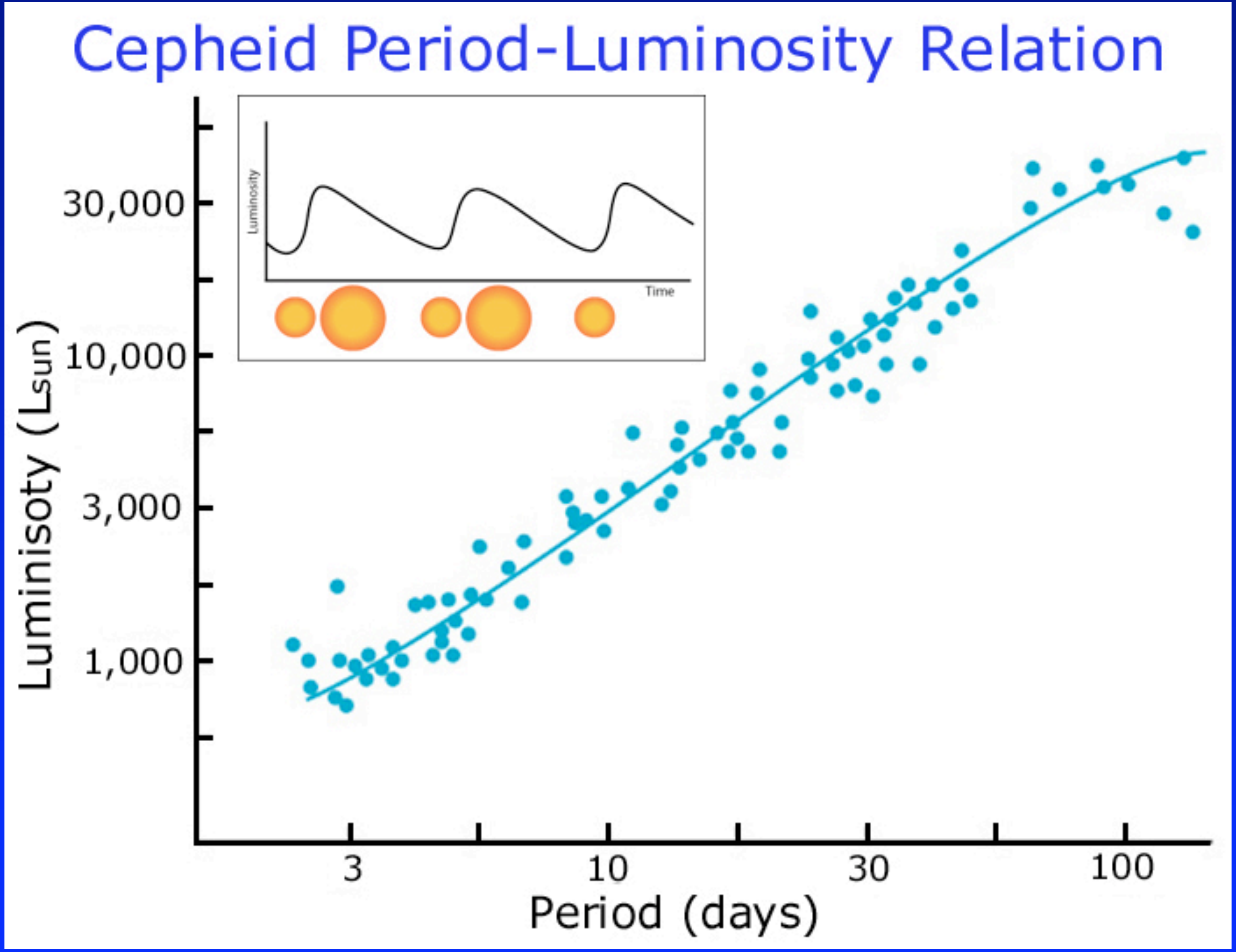
The 100 inch Hooker telescope at the Mt. Wilson Observatory

Hubble Space Telescope 1990 – ????

Redshift

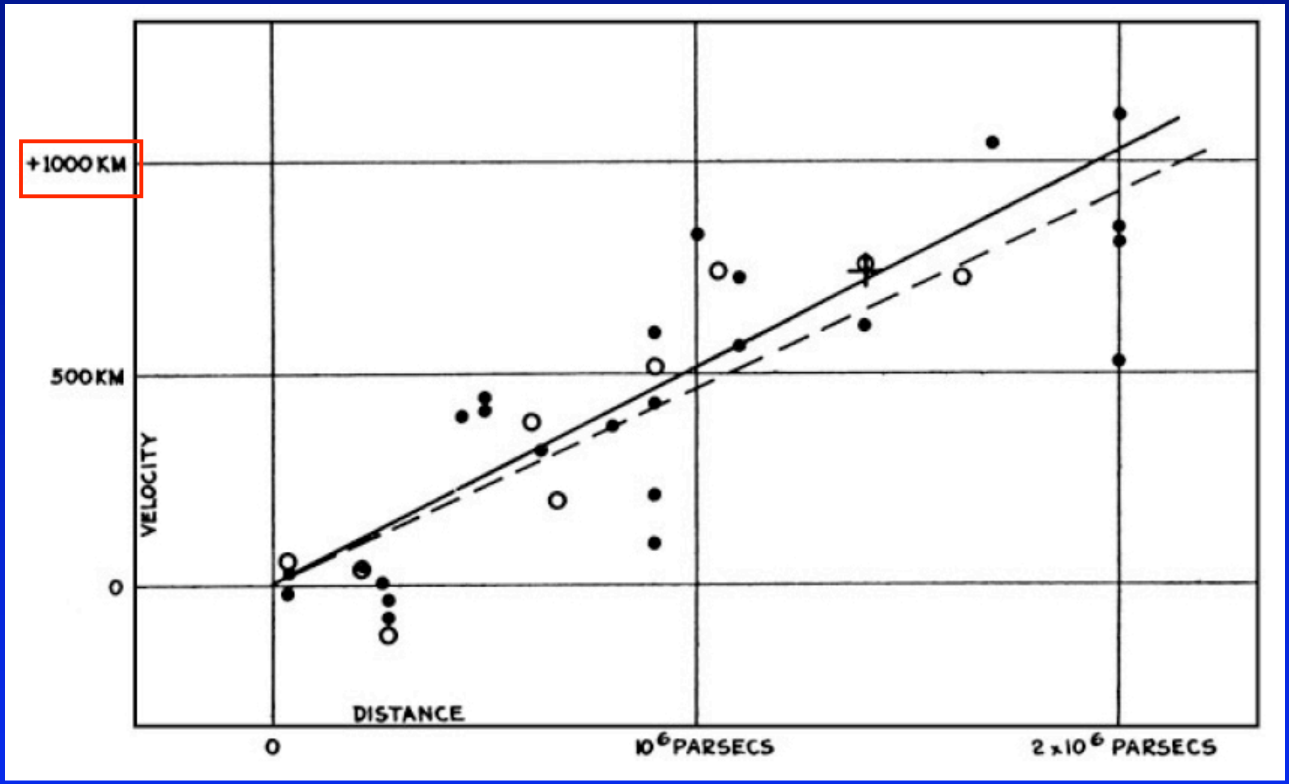

Spectrum of a Distant Galaxy
blueshift: moving towards
at rest
redshift: moving away
V I B G Y O R
prism
(spectrograph)
Increasing Wavelength
not to scale

Cepheid Variable Stars



Hubble's Diagram (1929)

velocity (v)

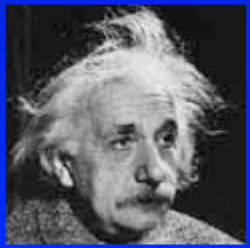


distance (d)

Most galaxies are redshifted (positive velocity)
The more distant ones move faster.
Exactly what you'd expect for a Big Bang!

Einstein's Biggest Blunder?

Λ



- If Einstein hadn't been so insistent on a static universe, he could have **predicted** the Big Bang and the expansion of the universe years before Hubble's 1929 discovery.

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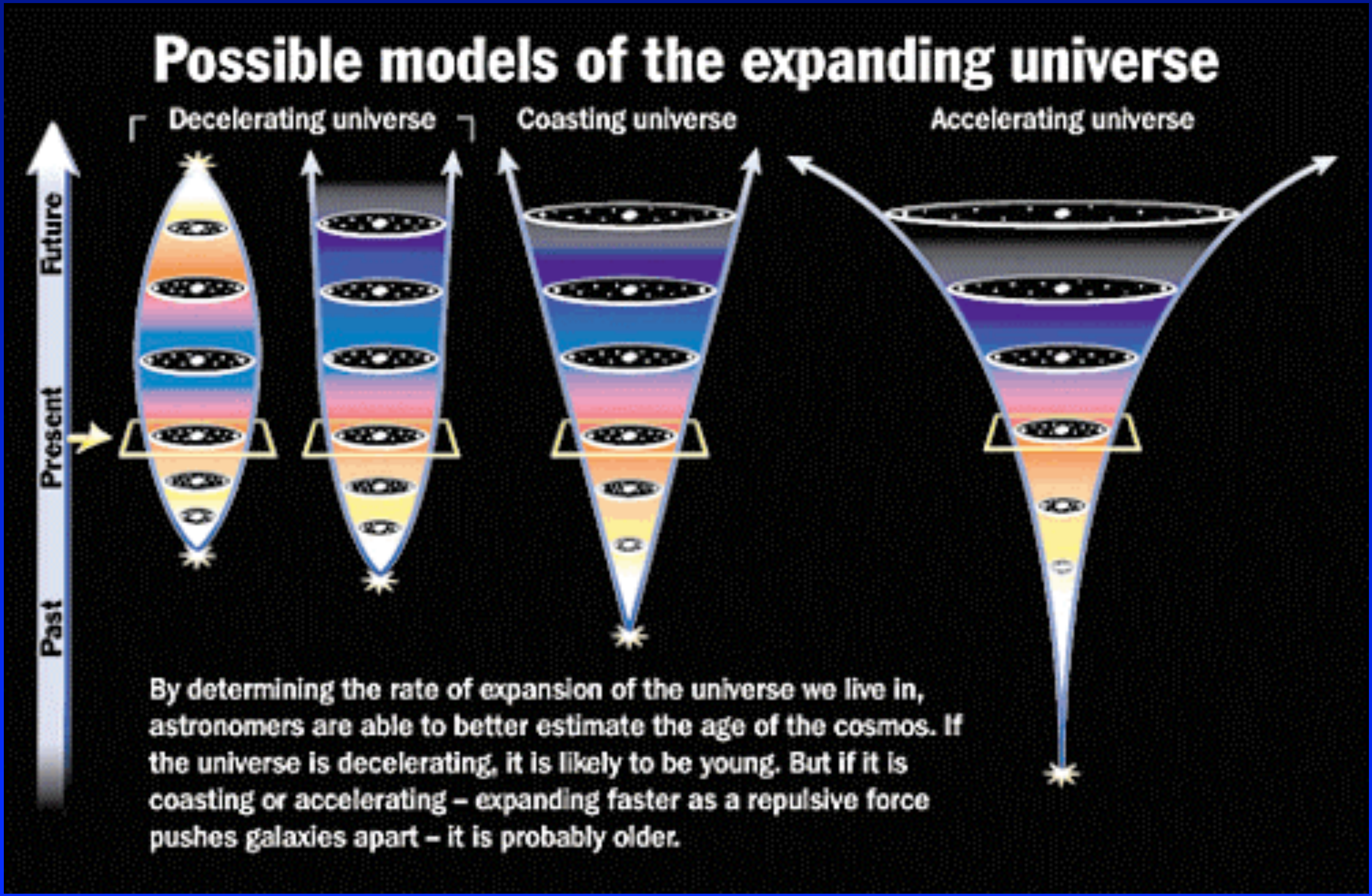
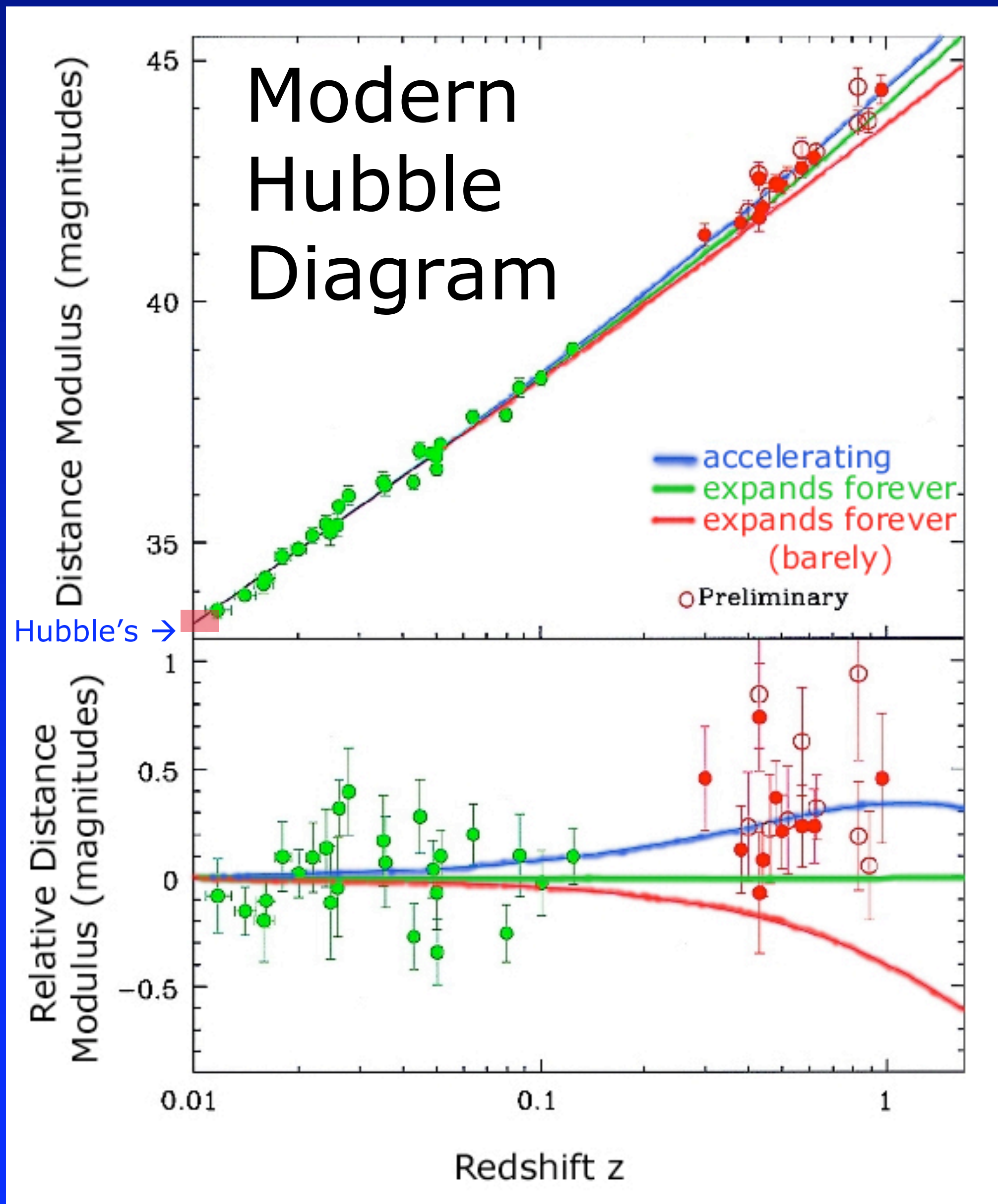
The Universe as a Time Machine

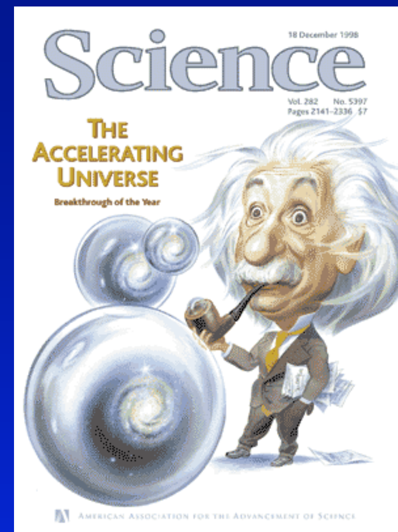
- Distant objects give us snapshots of the universe in the past.
- The redshift tells us how much the universe has expanded since the light left the object.
- Measure redshift and distance for many objects, reconstruct a movie of the cosmic expansion history.

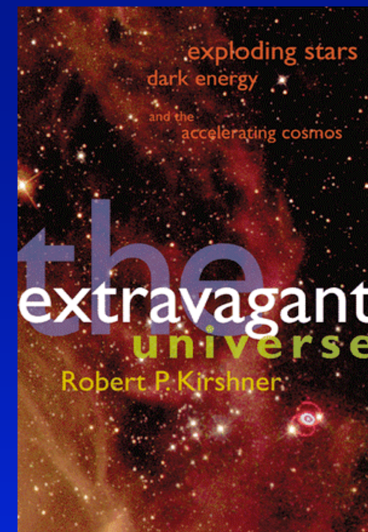
Possible Expansion Histories



The Accelerating Universe (1998)







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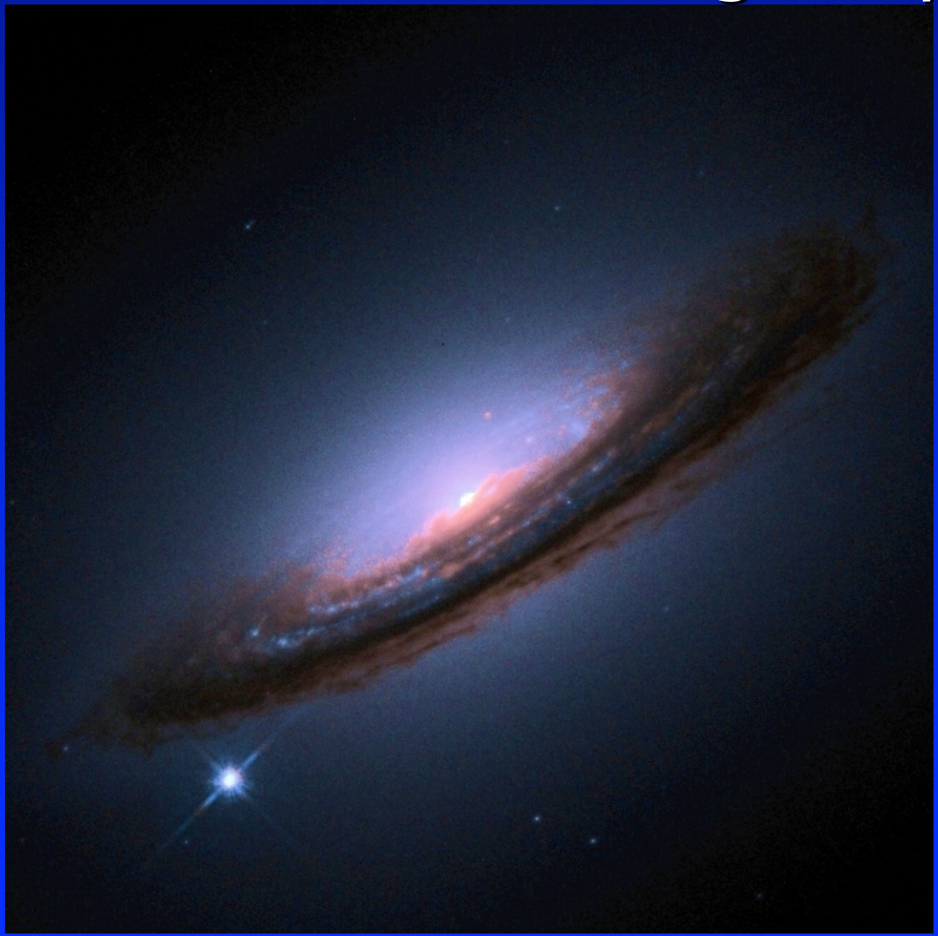
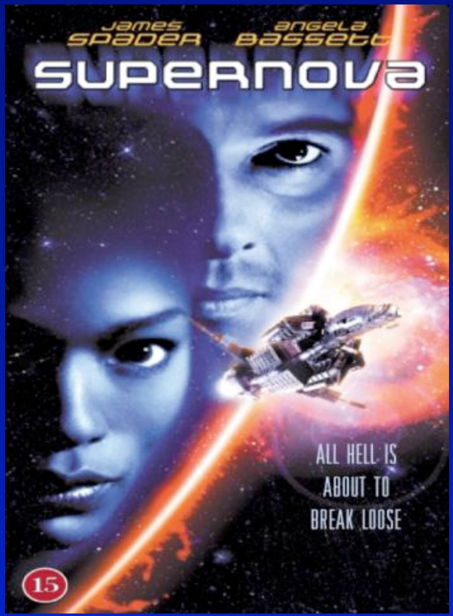
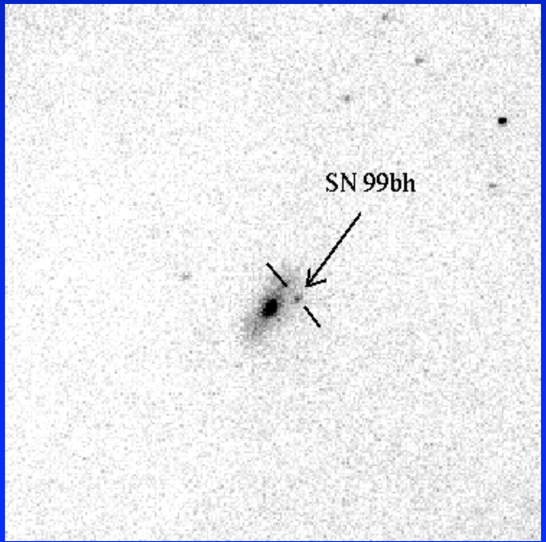
Supernova

A single exploding star can outshines an entire galaxy!



SN 1994d – Hubble Space Telescope



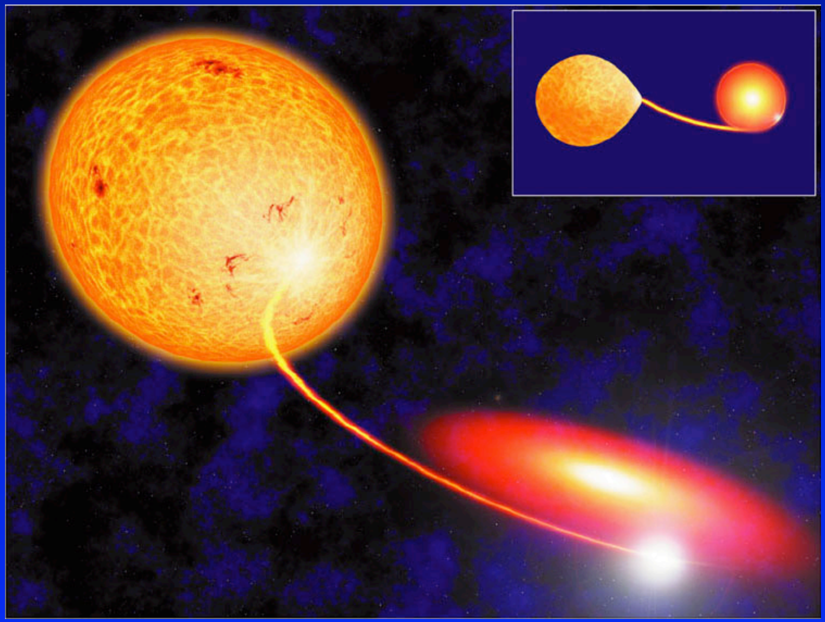


SN 1999bh – Katzmann Automated Imaging Telescope & Andy

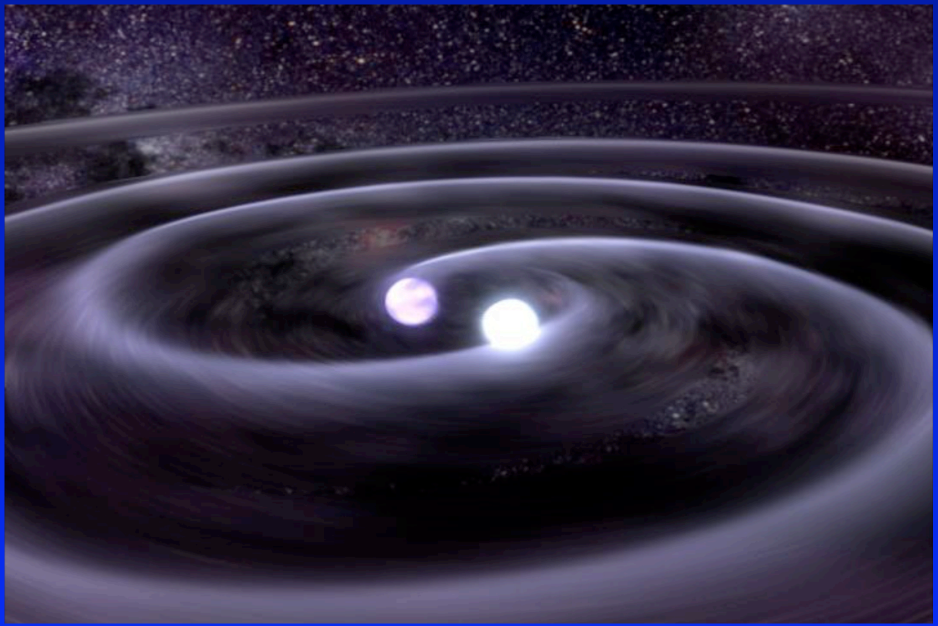
Type Ia Supernovae

Thermonuclear Bombs in Space!

Explosions of White Dwarfs in Binary Systems



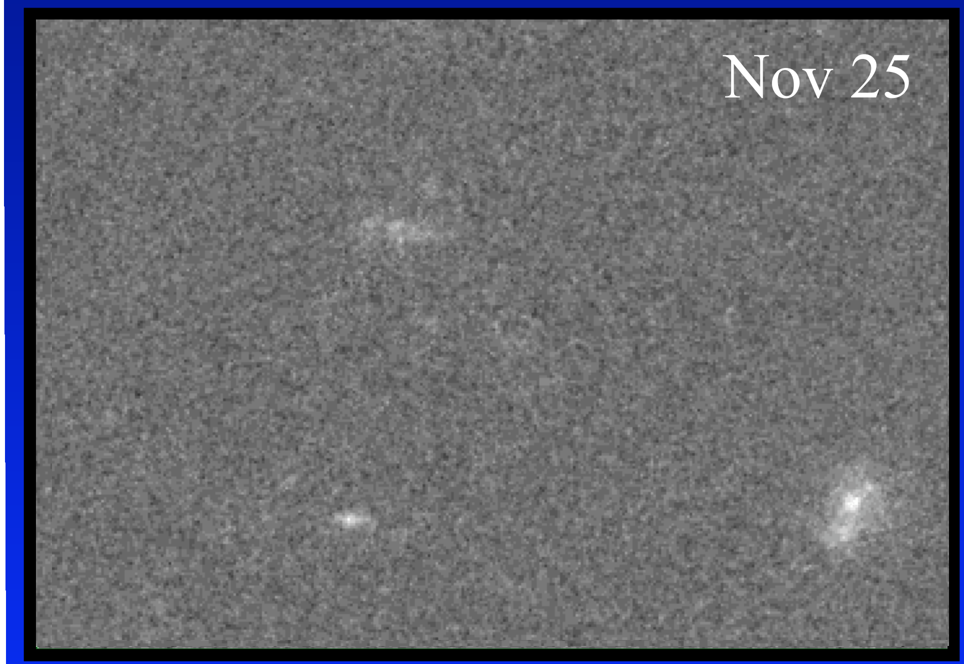
WD Accretion From Main Sequence Companion

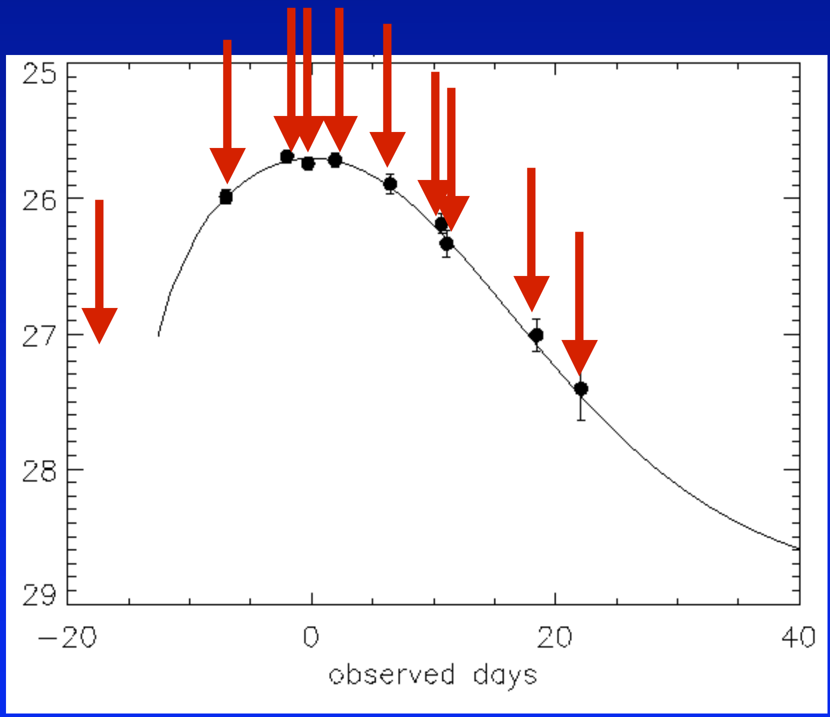


Merger of 2 White Dwarfs

Artist's Conceptions

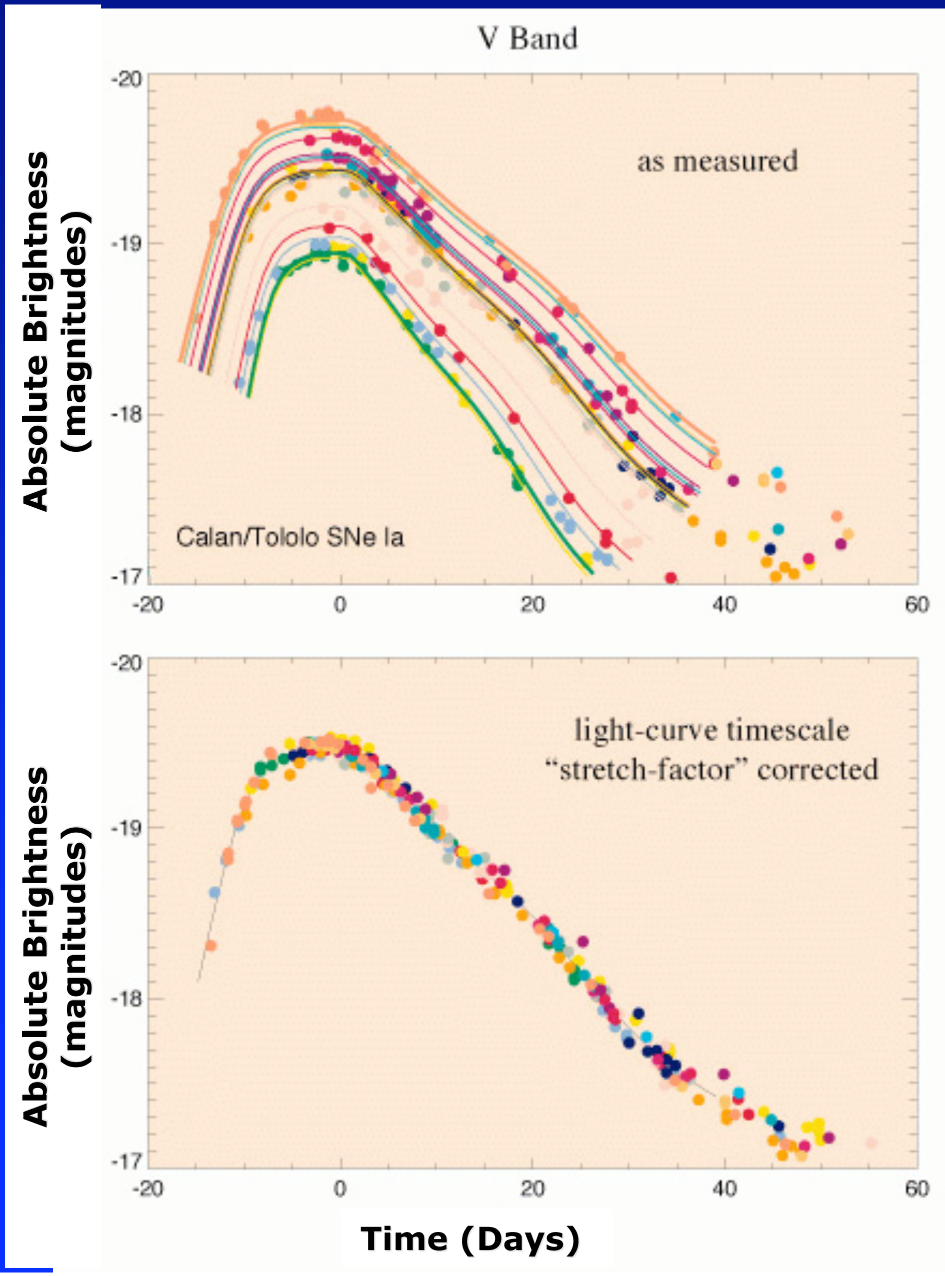
The Rise and Fall of Aphrodite





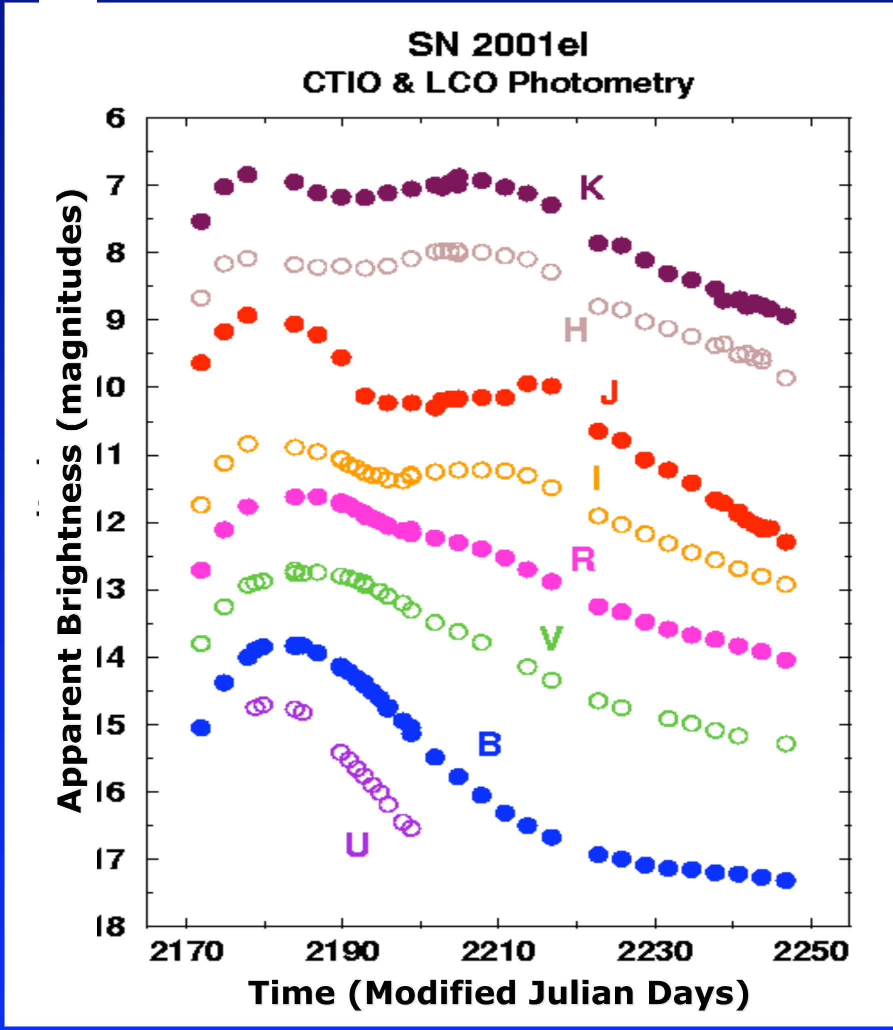
Courtesy: Robert P. Kirshner

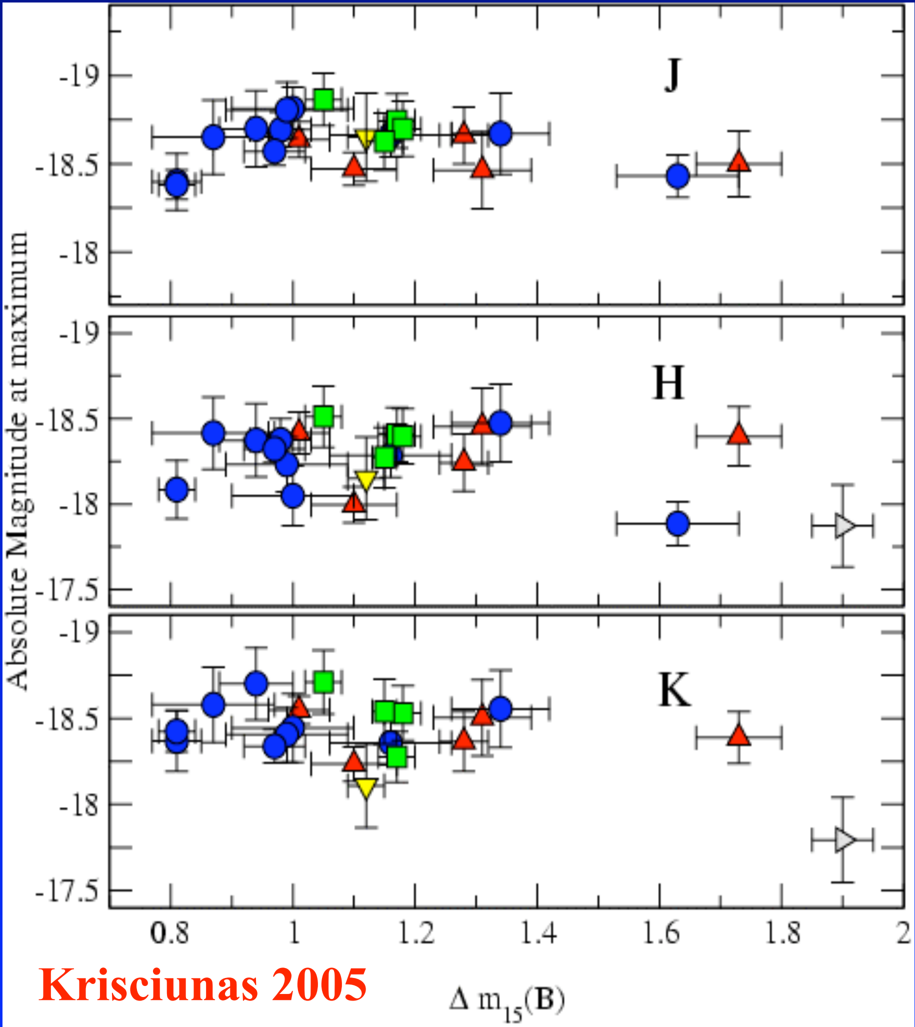
Type Ia SNe: *Optical Light Curves*



- Type Ia SNe are not perfect standard candles at optical wavelengths
- Fortunately the brightest ones decline slowest
- True at optical wavelengths

Type Ia Sne: *Infrared Light Curves*



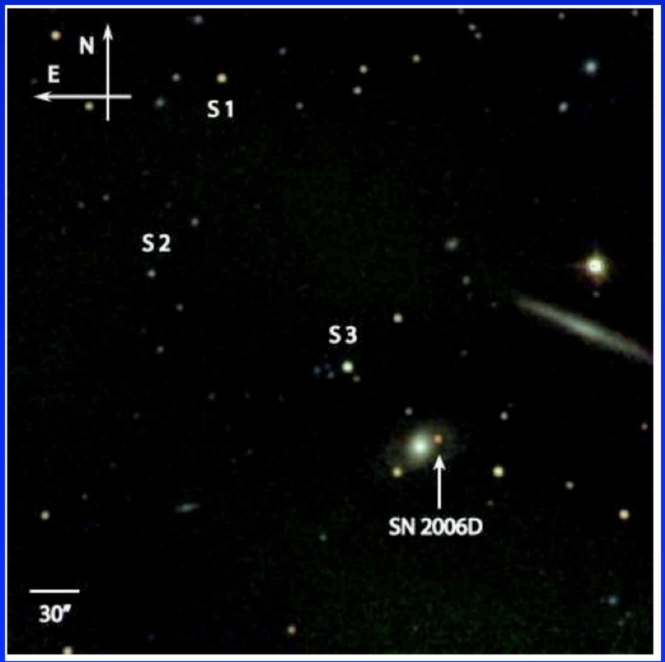


(left) Typical Light Curves. (right) SNe Ia may be better standard candles at infrared wavelengths (1-2 μm) vs. optical wavelengths.

The Peters Automated InfraRed Imaging TELescope

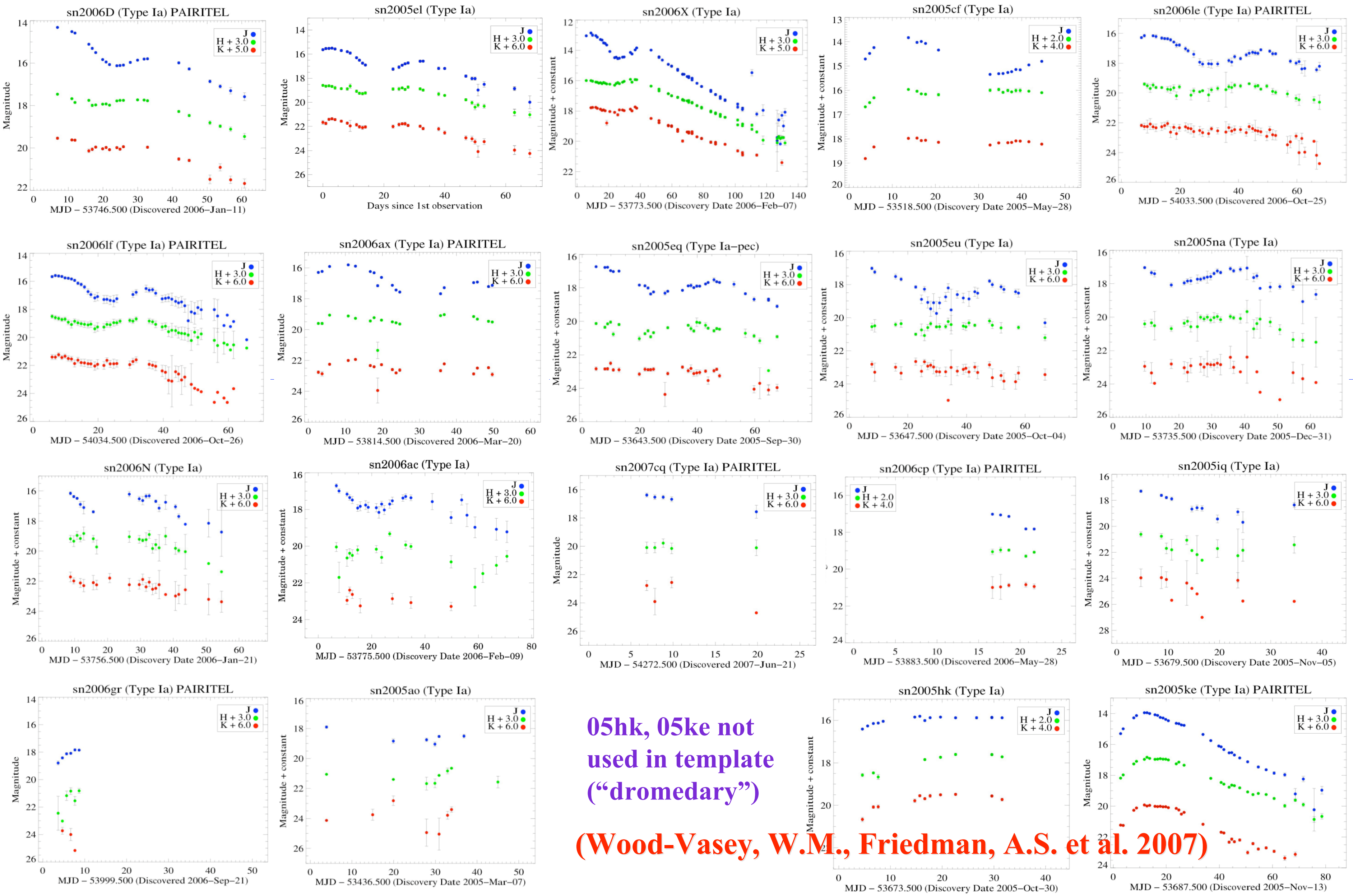
PAIRITEL
PETERS AUTOMATED INFRARED IMAGING TELESCOPE

www.pairitel.org



Fred Lawrence Whipple Observatory, Mount Hopkins, Arizona

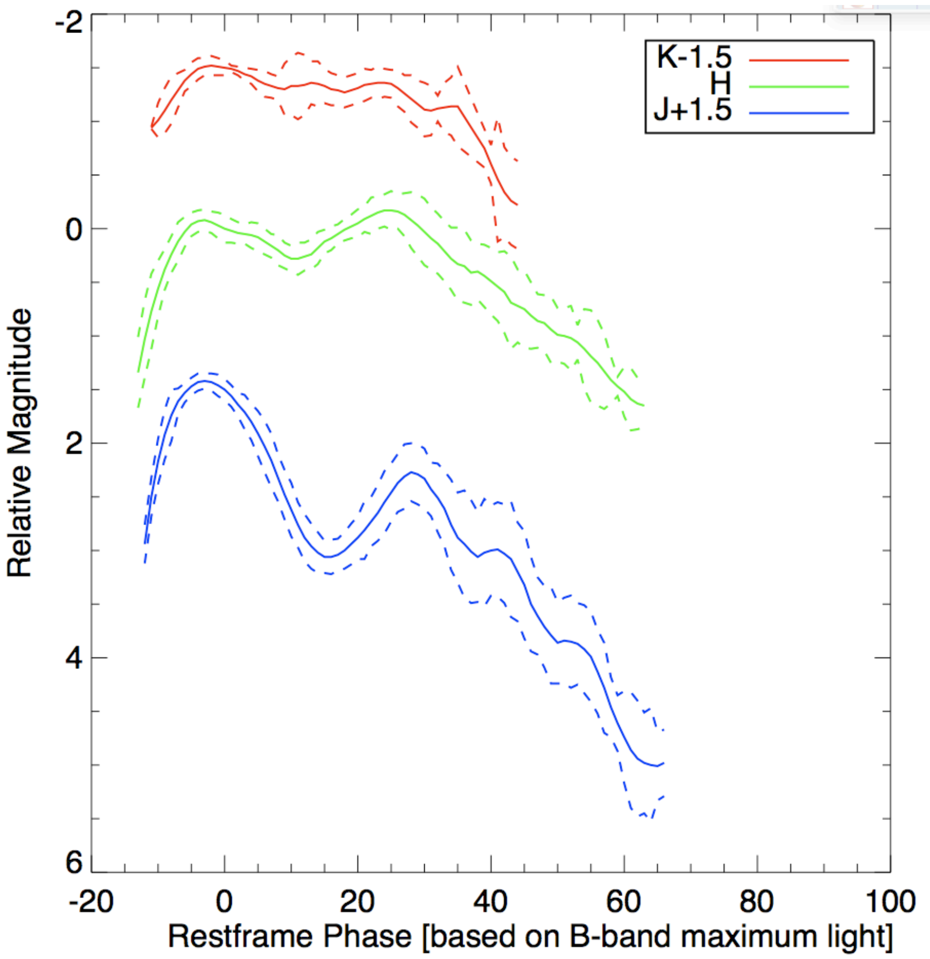
Sample Infrared Light Curves from PAIRITEL (3 years of data)



05hk, 05ke not used in template ("dromedary")

(Wood-Vasey, W.M., Friedman, A.S. et al. 2007)

Infrared Light Curve Templates



- Dashed line shows how uncertain the standard light curve is
- Most Standard in H Band (green)
- Very little wiggle room (dashed lines) around the solid curve, especially between days -10 and 30.

Wood-Vasey, Friedman et al. 2007 (FIG 2)

NASA/DOE Joint Dark Energy Mission

DESTINY

Dark Energy

Space

Telescope

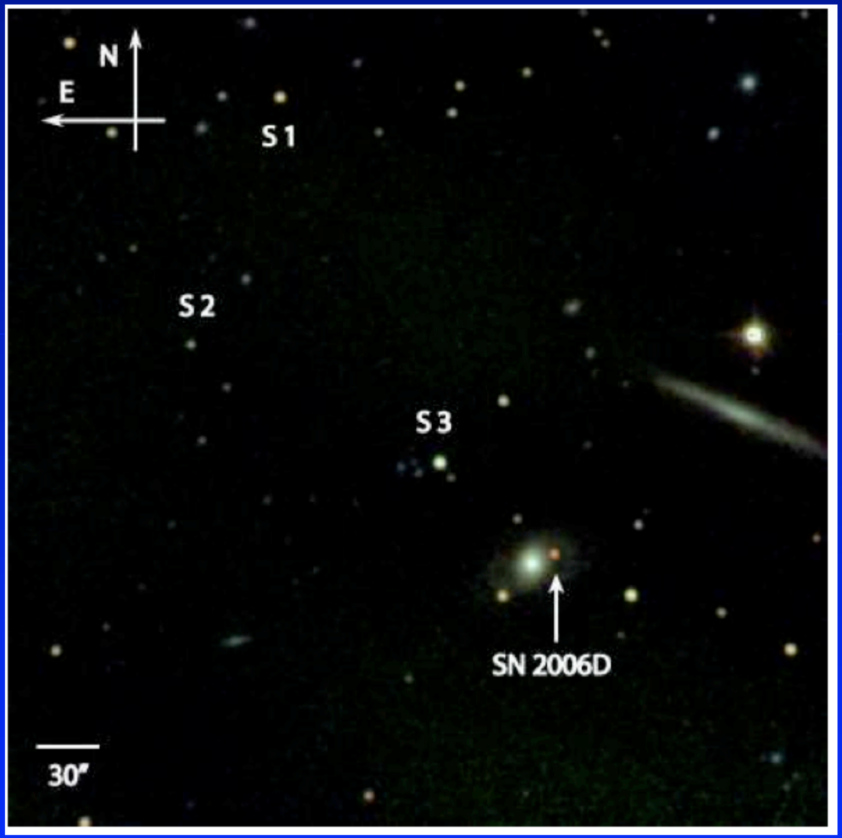
Will study thousands of Supernovae at optical/infrared wavelengths

100 Billion Years of Solitude

The Observable Universe Now

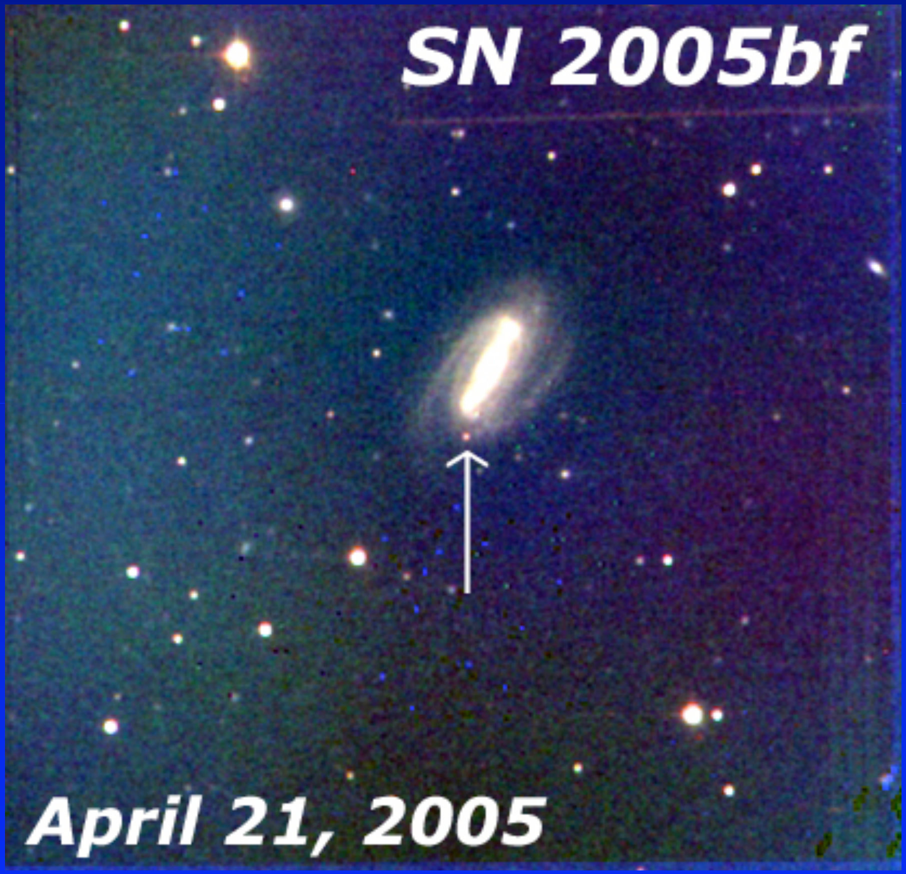
100 billion years later

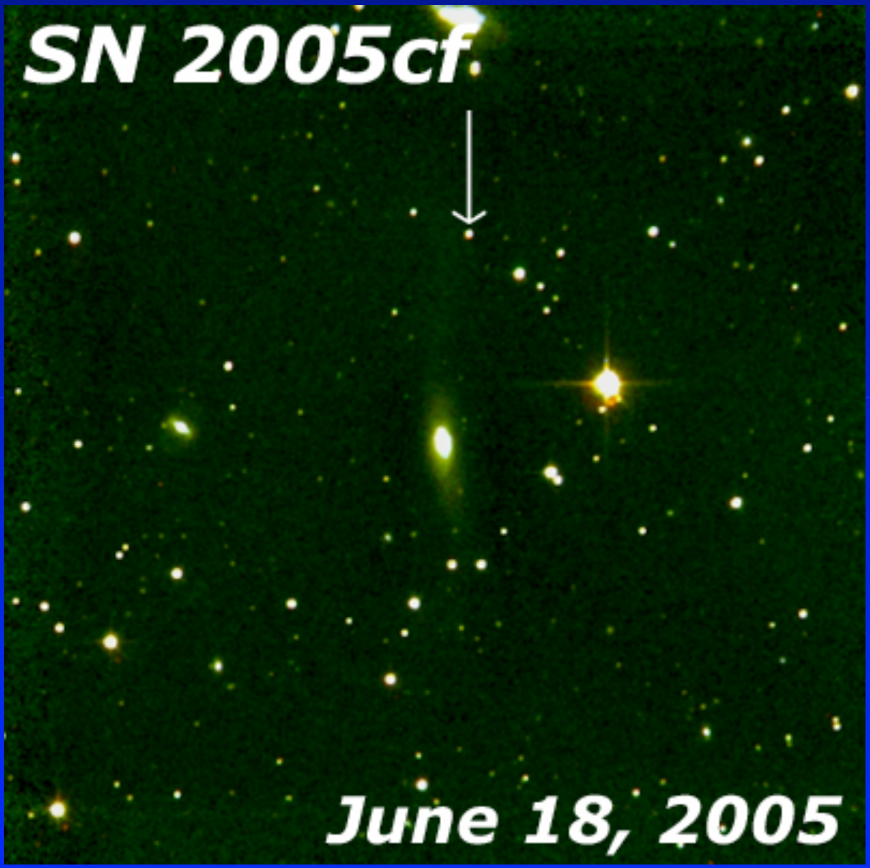
PAIRITEL JHK_s Images: 06D, 05ls



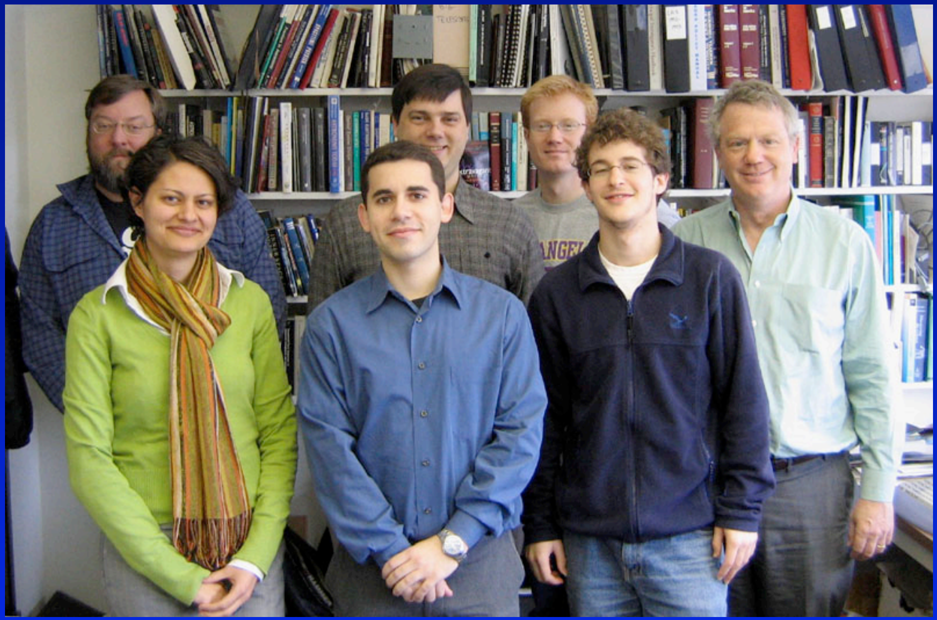
Wood-Vasey, Friedman et al. 2007
(astro-ph/0711.2068v1)

False Color PAIRITEL JHK Images





Research Collaborators



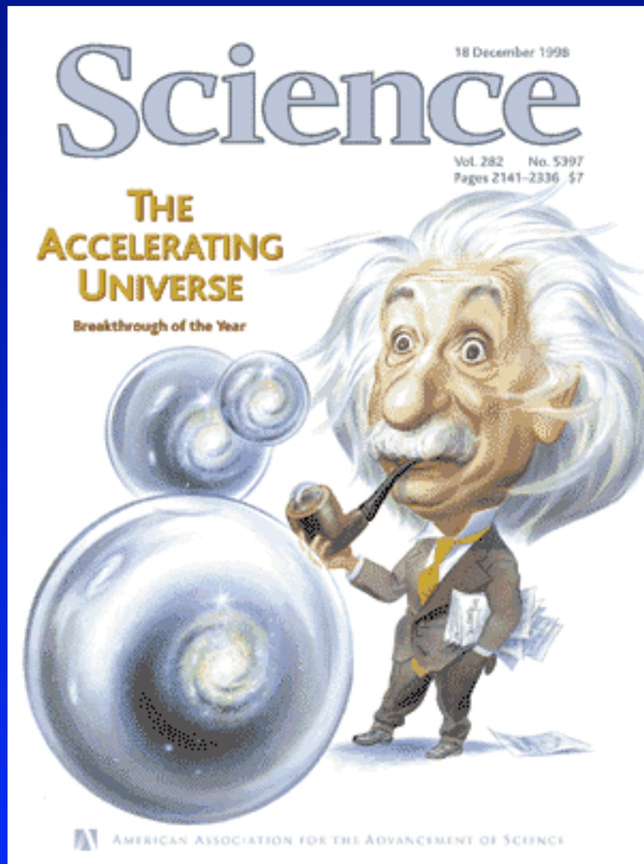
CfA Supernova Group

Robert Kirshner, Christopher Stubbs, Stephane Blondin, W. Michael Wood-Vasey, Pete Challis, Malcolm Hicken, Andrew Friedman, Kaisey Mandel, Gautham Narayan, (Harvard), Maryam Modjaz (UC Berkeley)

PAIRITEL Project

Joshua Bloom, Dan Starr (UC Berkeley), Cullen Blake, Emilio Falco, Andy Szentgyorgi (Harvard), Mike Skrutskie (Virginia)

The accelerating universe

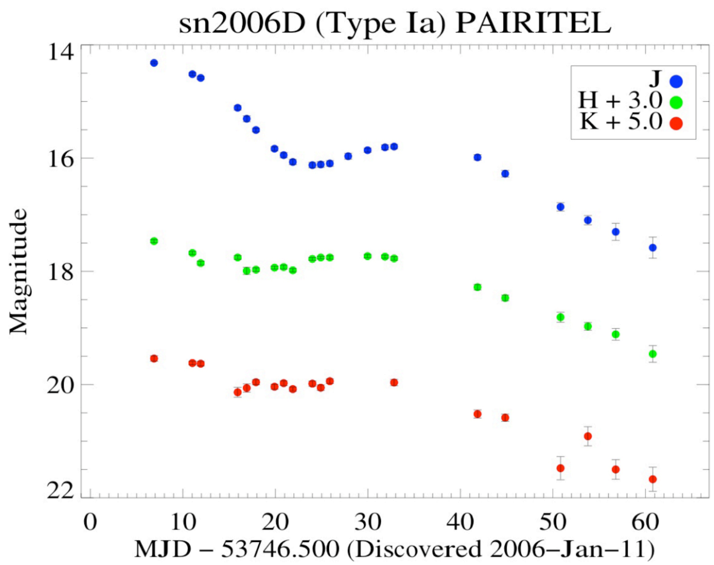


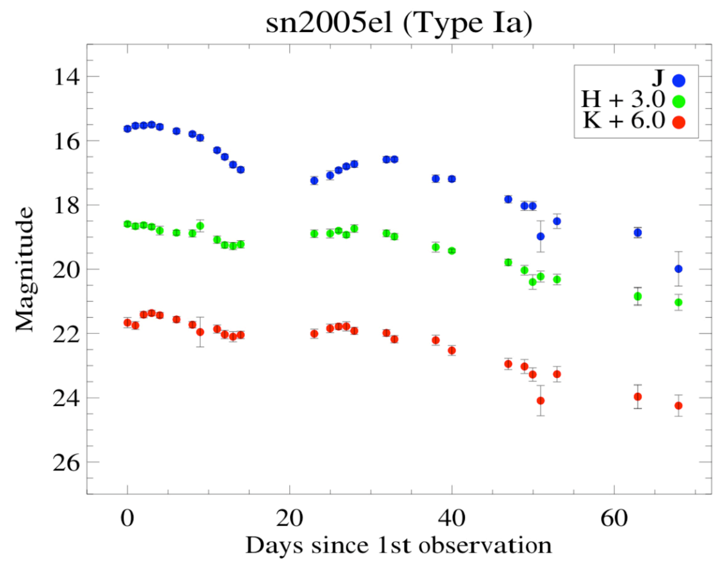
Return of the cosmological constant?

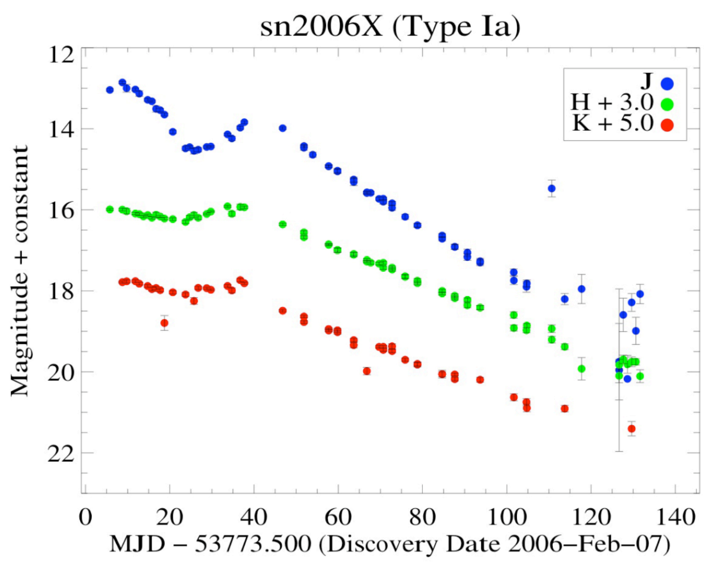
Λ

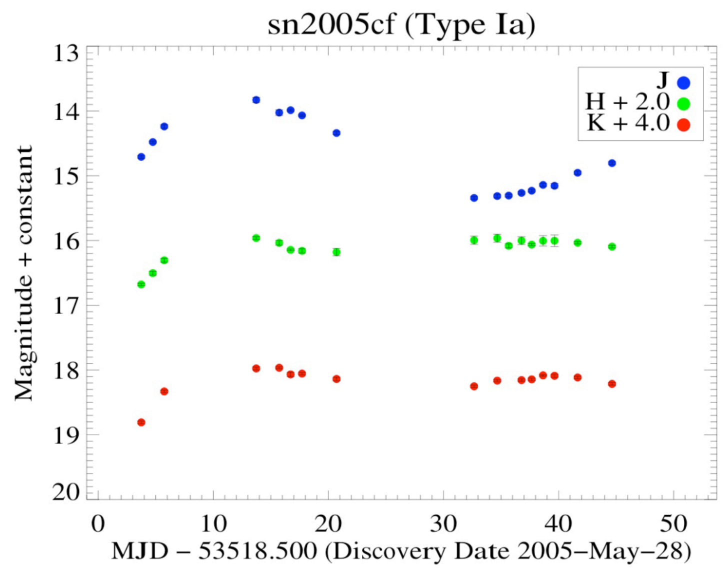
Dark Energy

PAIRITEL SNe Ia Light Curves

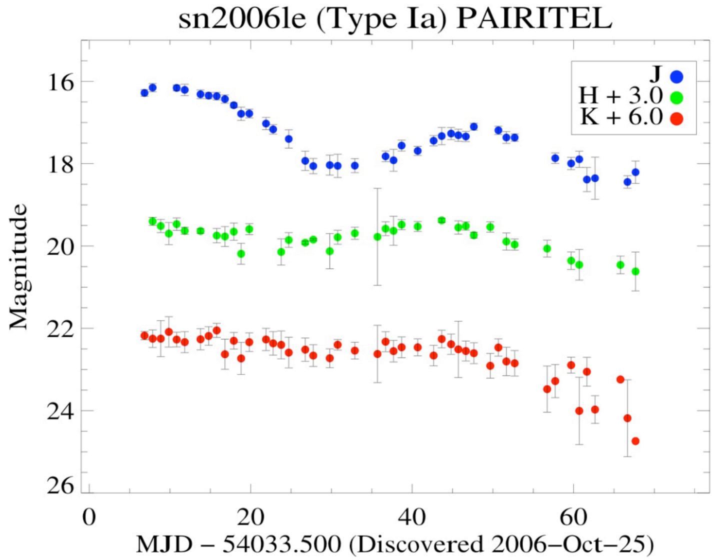


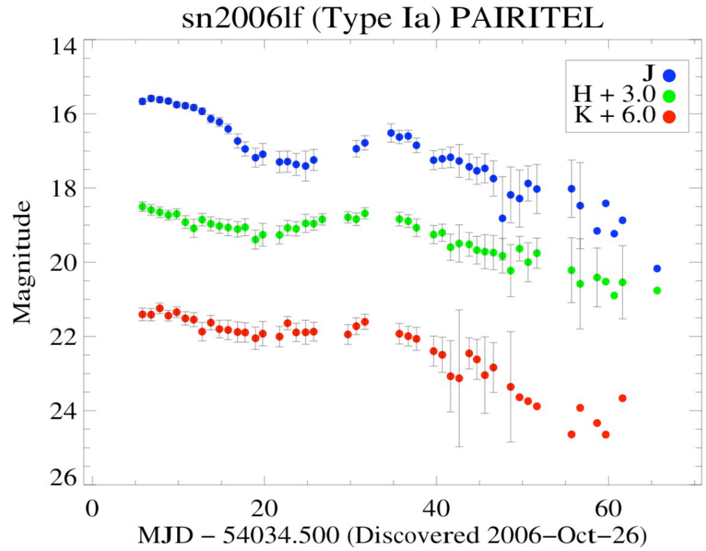


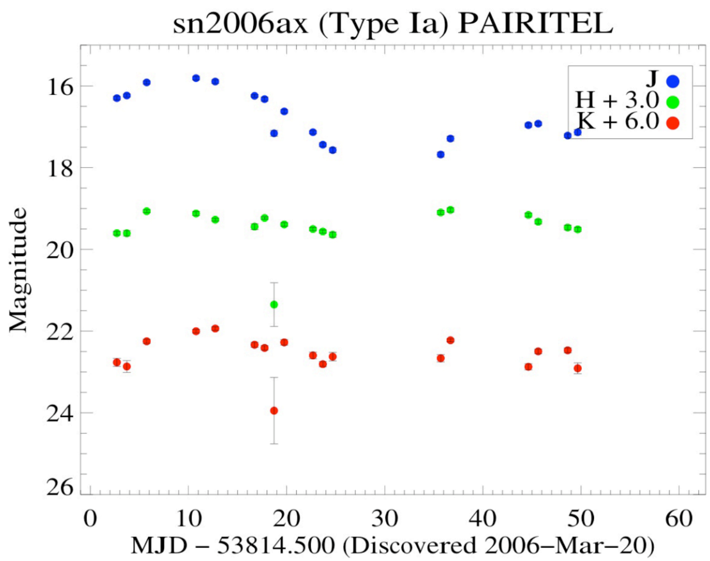


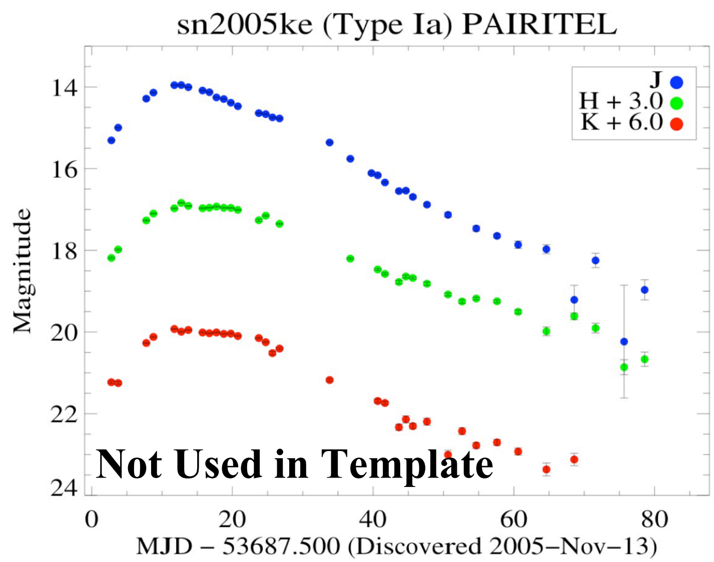


PAIRITEL SNe Ia Light Curves









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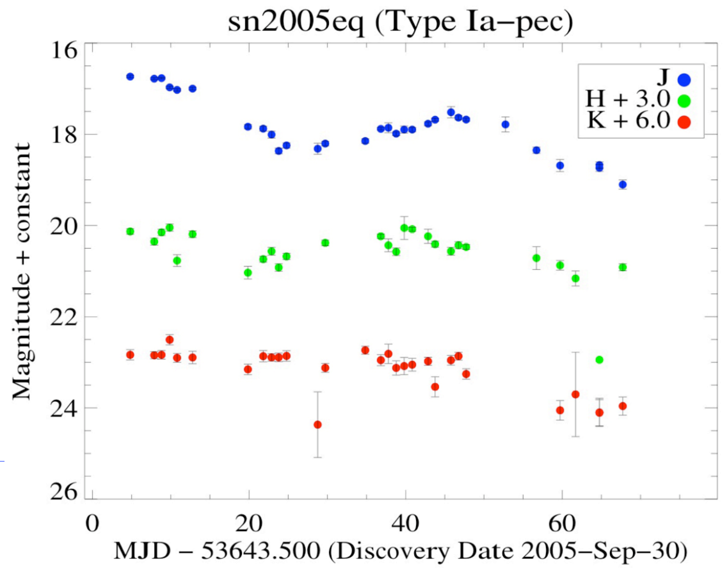

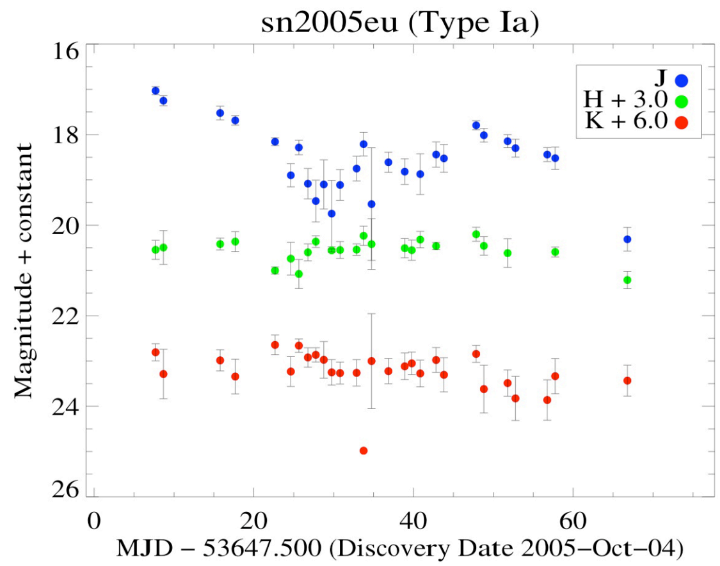

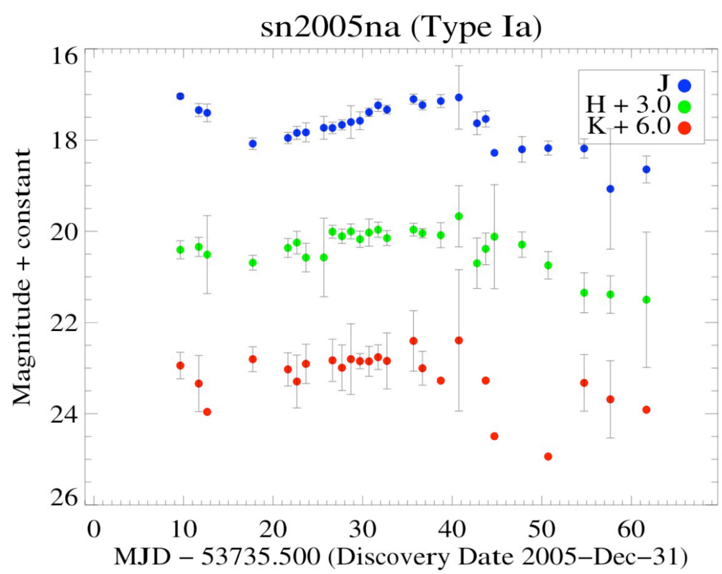

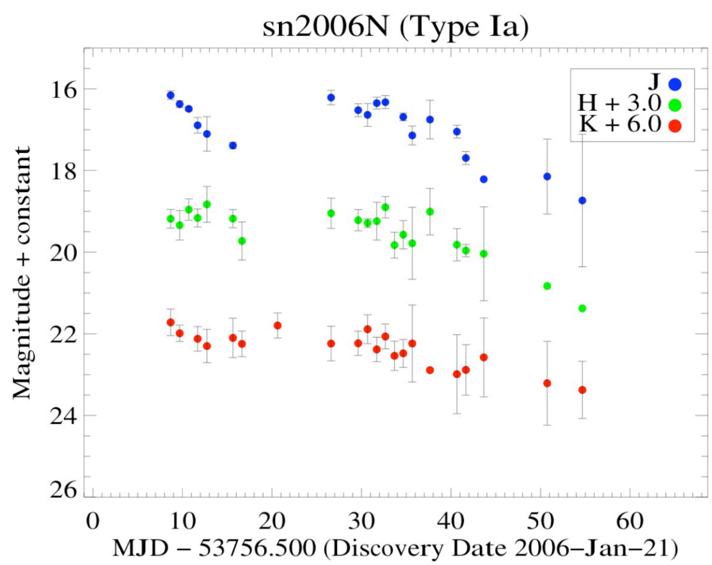

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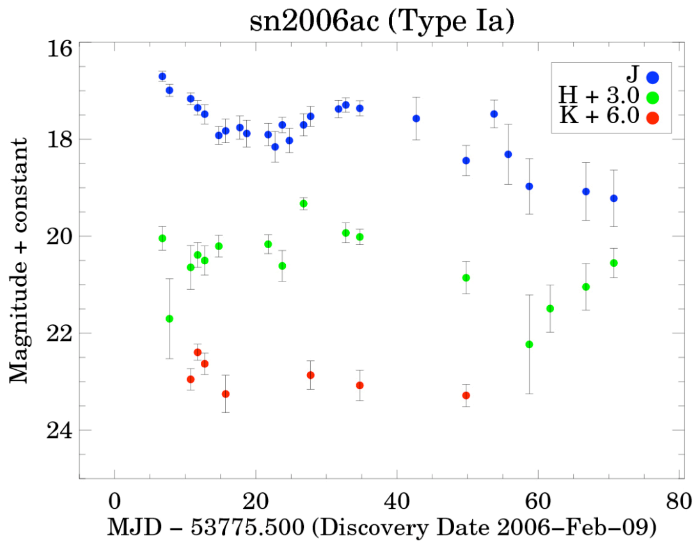
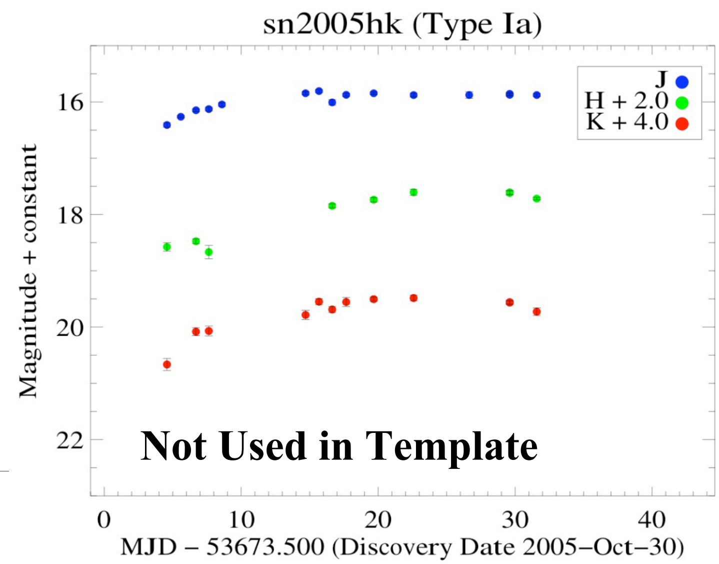
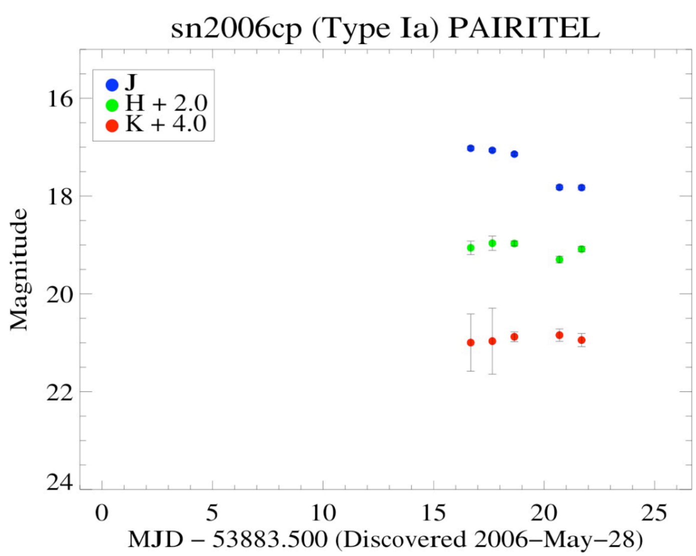
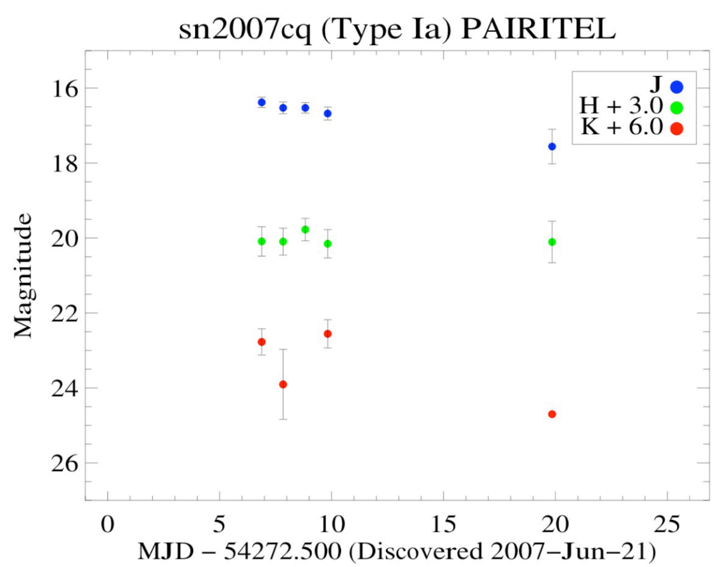
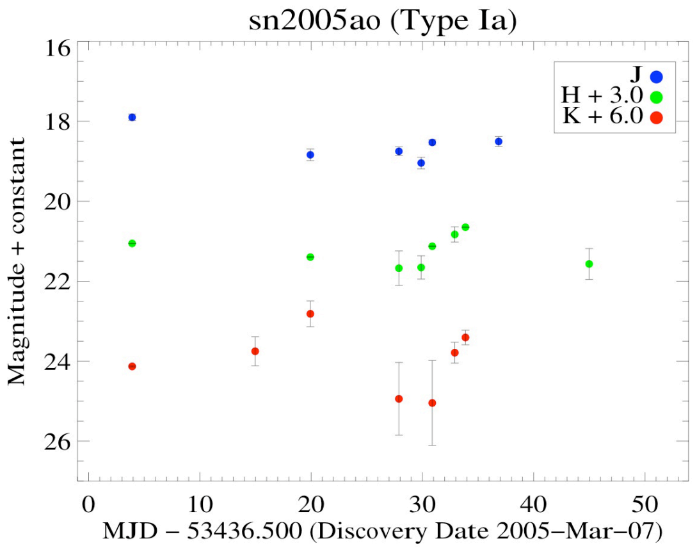


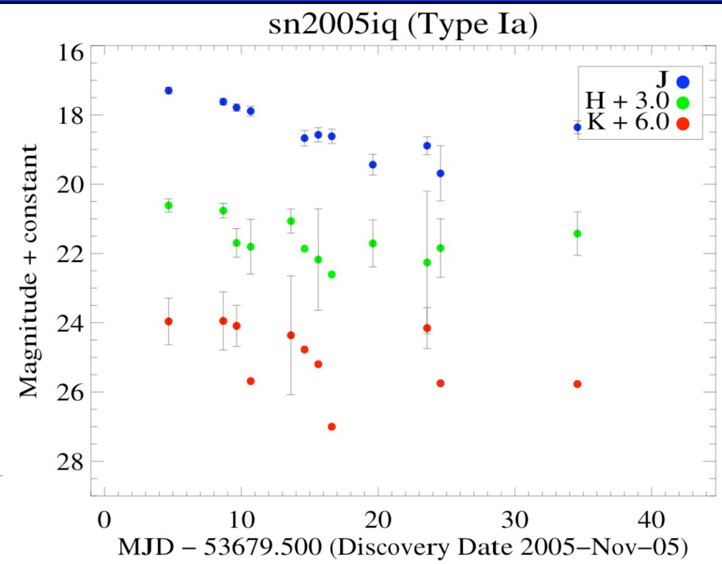


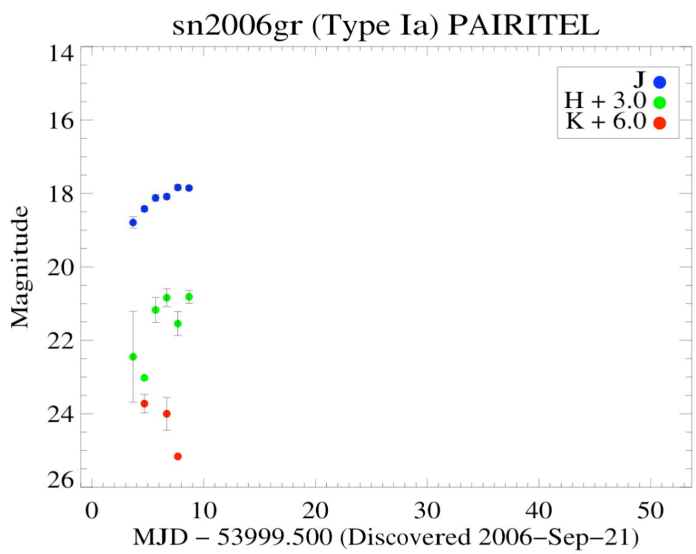


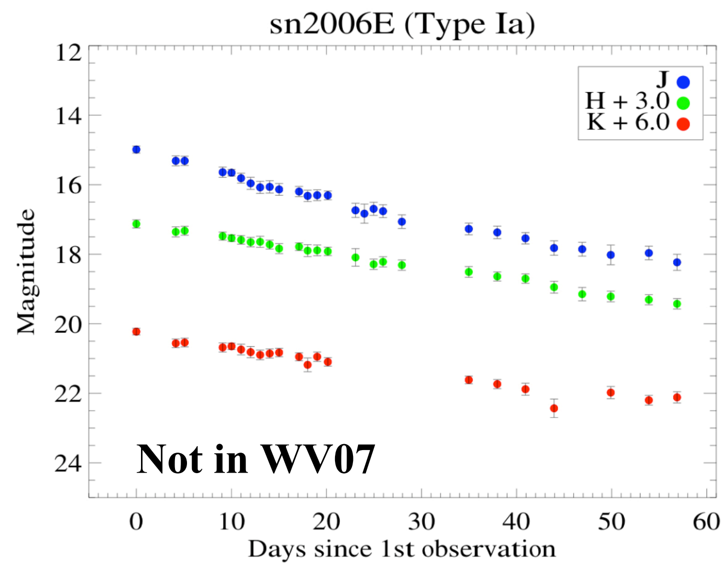


PAIRITEL SNe Ia Light Curves

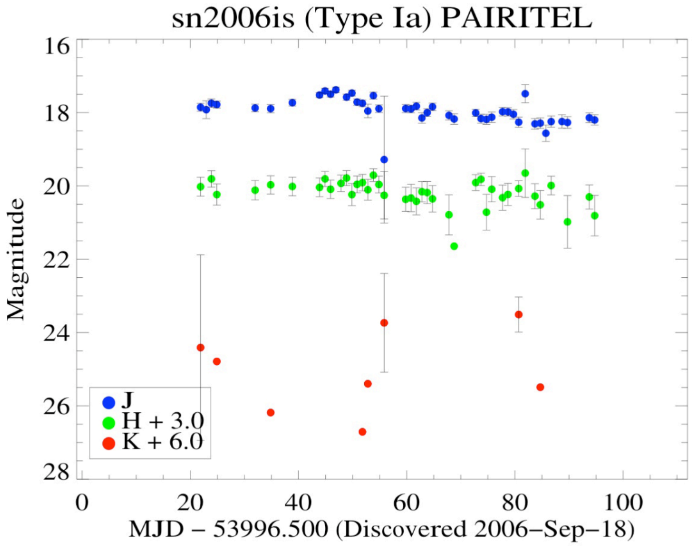


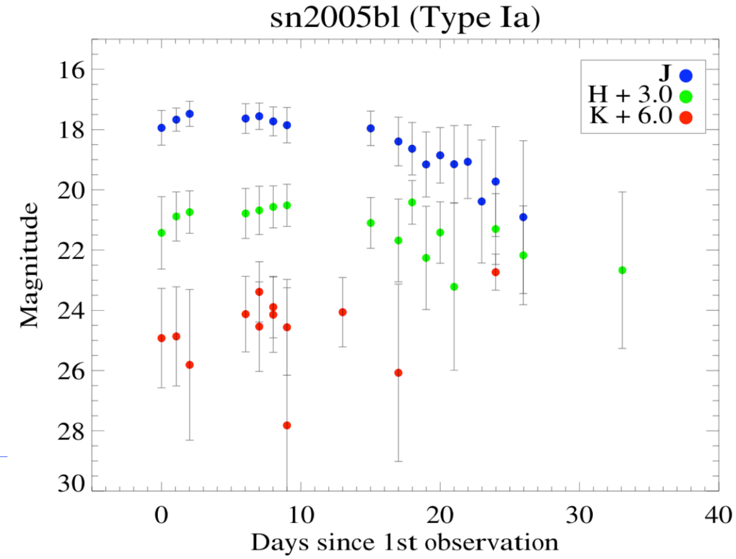


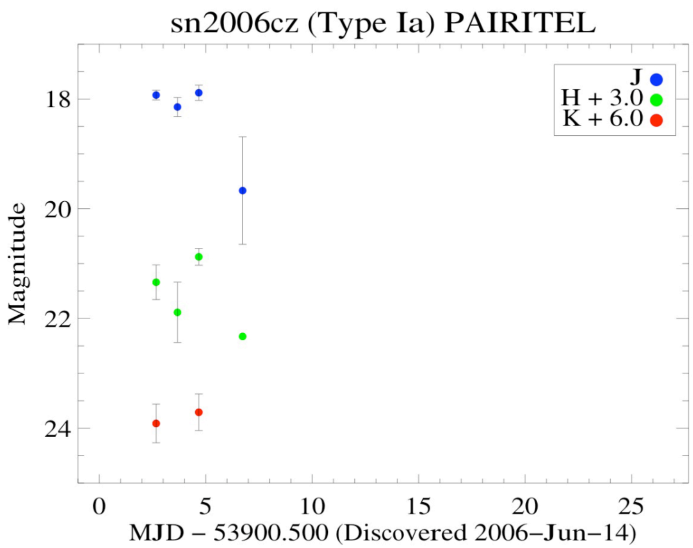


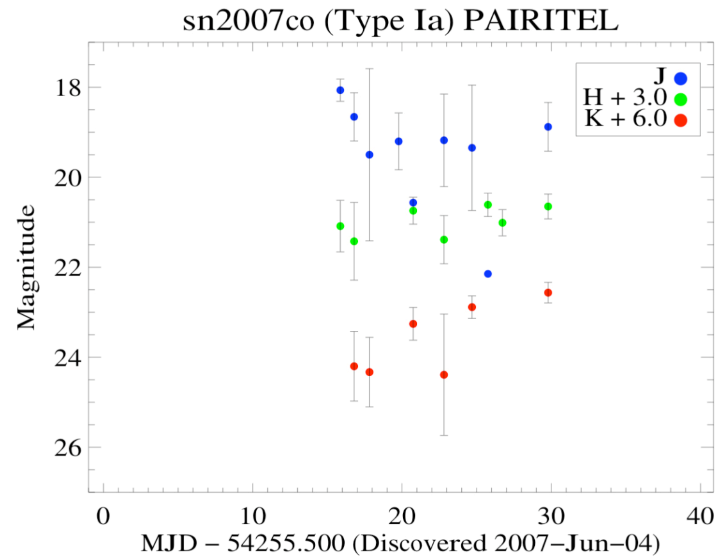


Sample LCs: Preliminary (Not in WV07)









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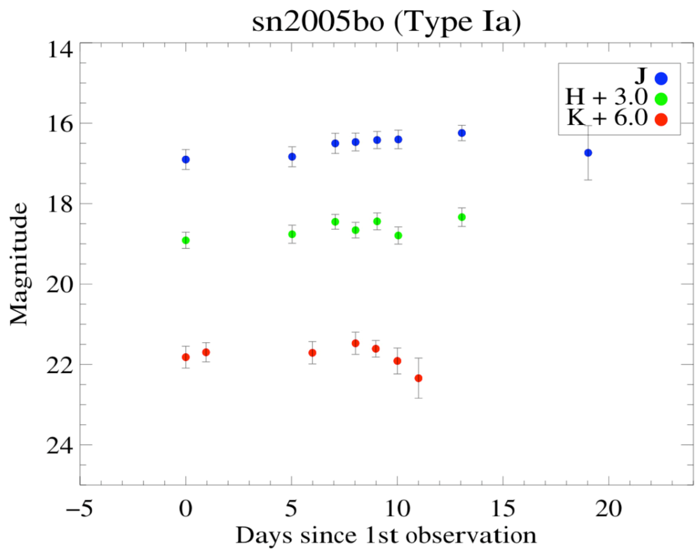

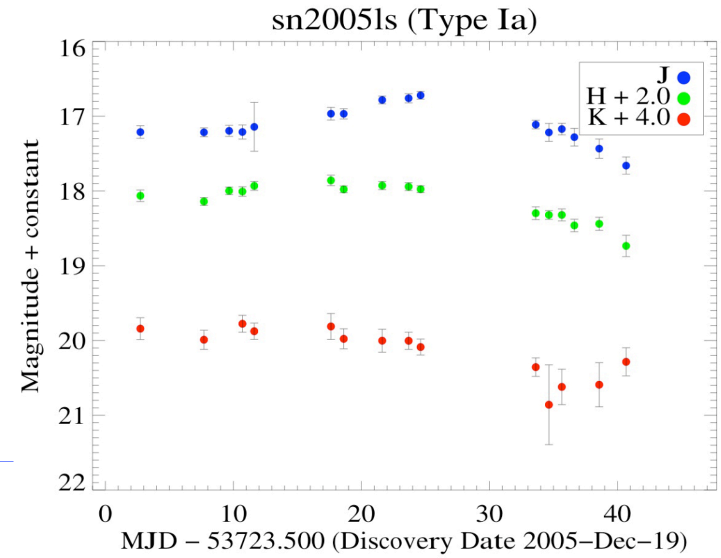

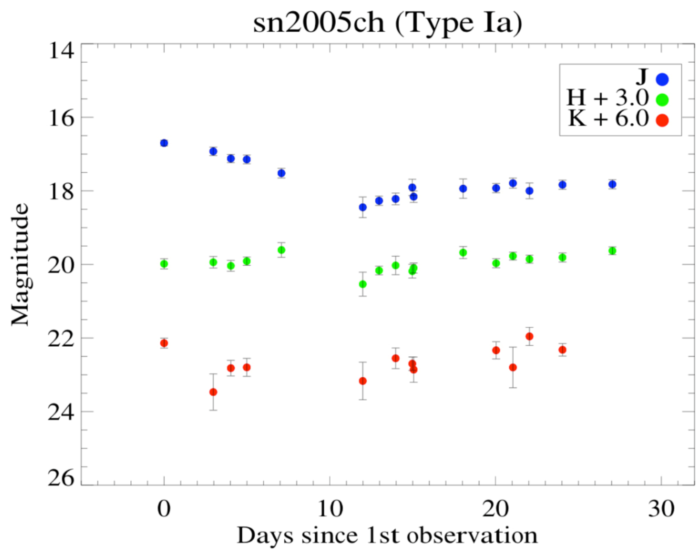

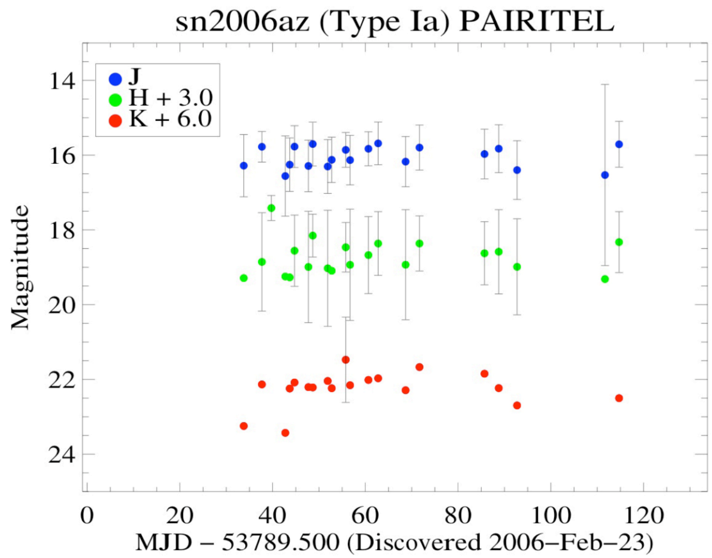

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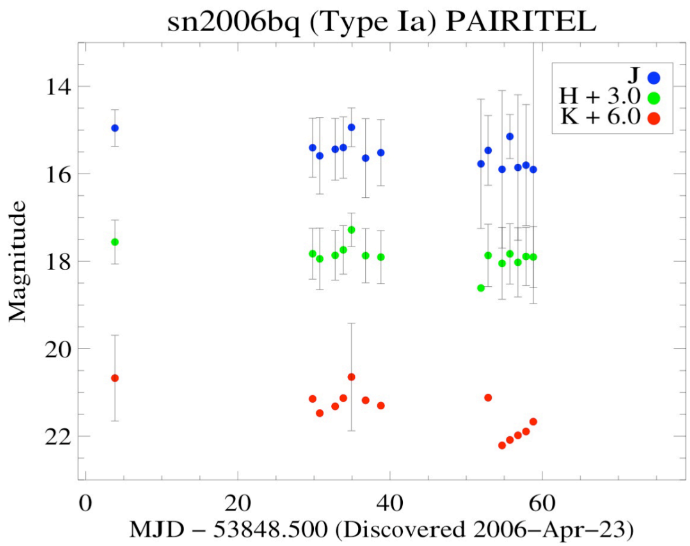
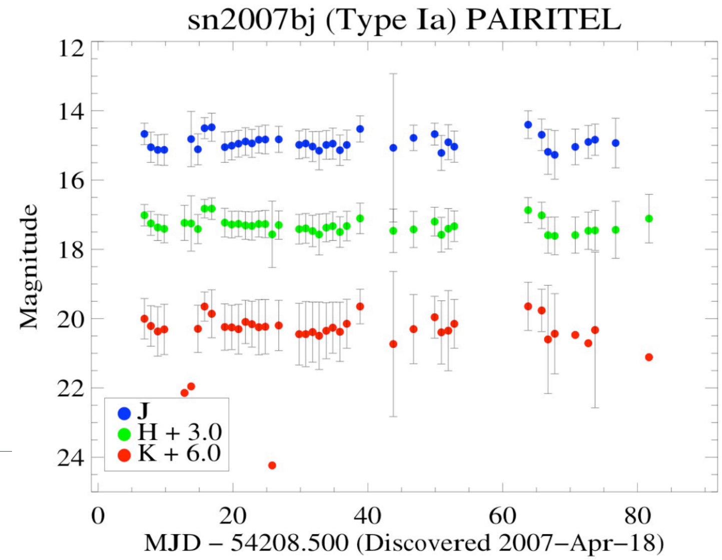




The Friedmann equations

Solutions to Einstein's Field Equations of General Relativity, which describe an expanding (or contracting) universe.

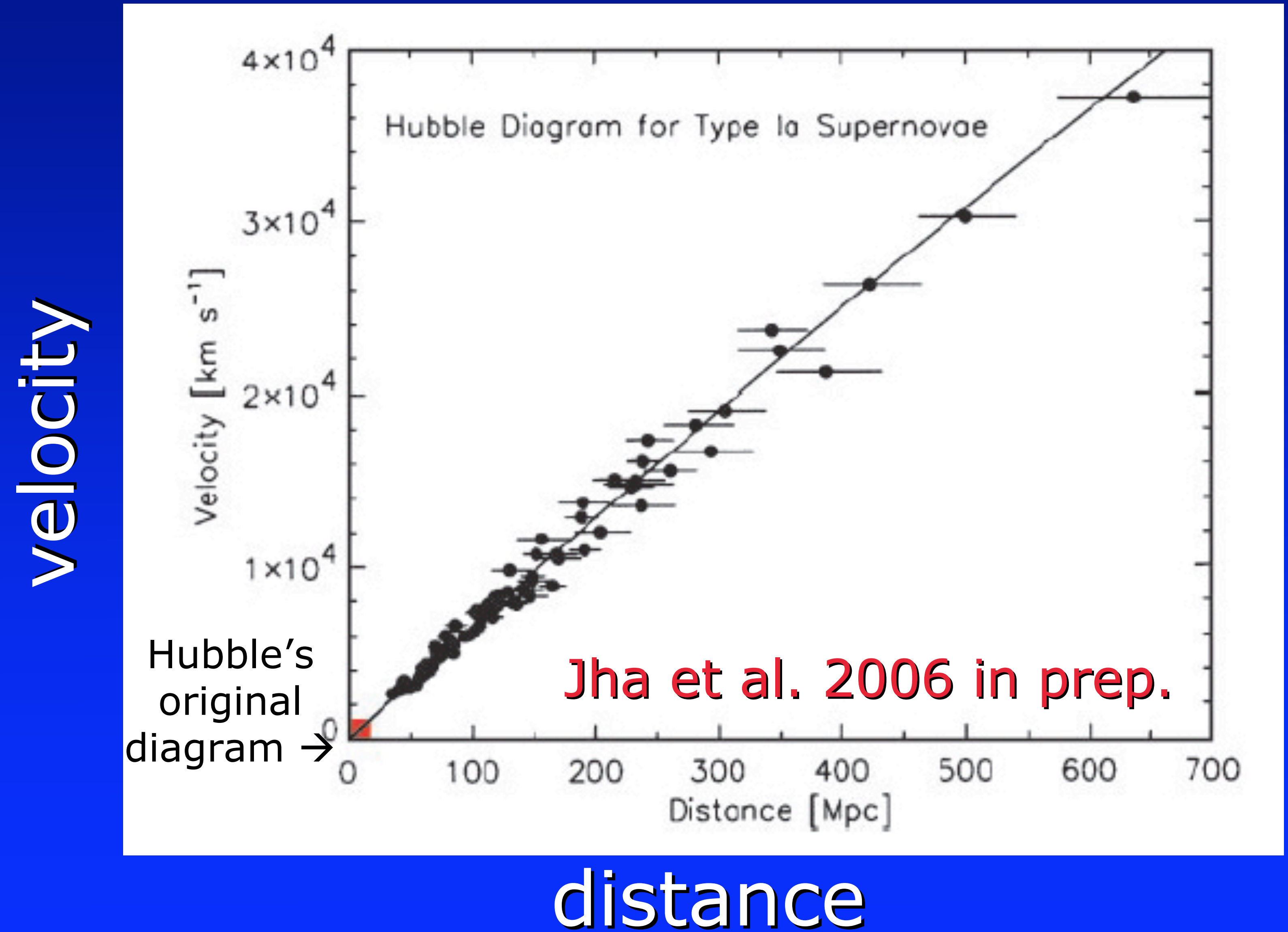
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

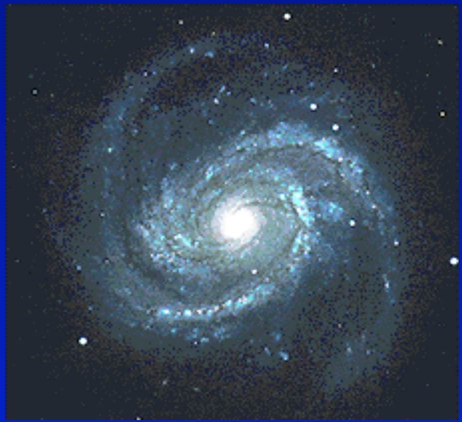
Alexander Friedmann 1888-1925

Einstein introduced General Relativity in 1915 but these solutions were not found until 1922, by Friedmann

Modern Hubble Diagram



A universe of galaxies





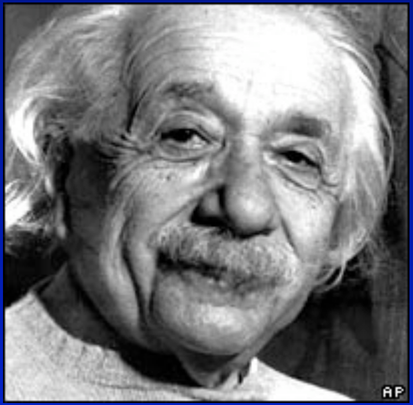

HISTORICAL SUPERNOVAE

Year	Report	Status
185AD	China	Identification in doubt (Chin and Huang 1994)
386	China	unknown
393	China	unknown
1006	China, Japan, Korea, Arab lands, Europe	Identified with radio SNR
1054	**China, Japan**	**Crab Nebula**
1181	China, Japan	Possible identification with radio SNR 3C58
1572	Europe (Tycho Brahe), China, Japan	Tycho's remnant
1604	Europe (Kepler), China, Japan, Korea	Kepler's remnant
1987	**SN 1987A – southern hemisphere**	**Large Magellanic Cloud**

Einstein's theory of gravity

Einstein's Field Equation

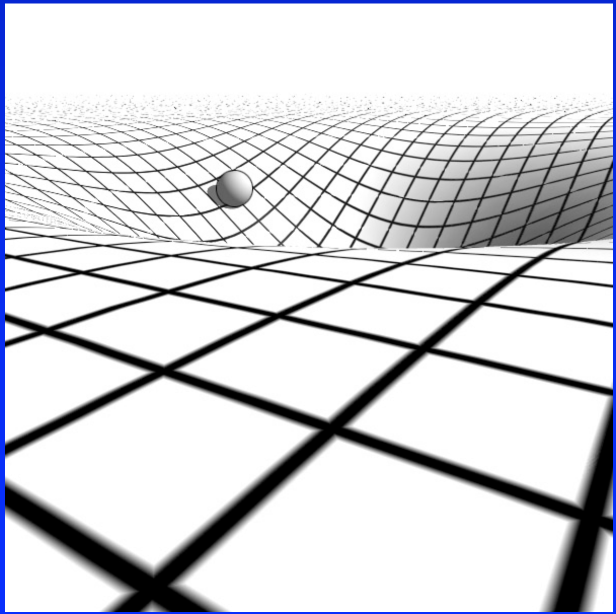
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



The curvature of space-time

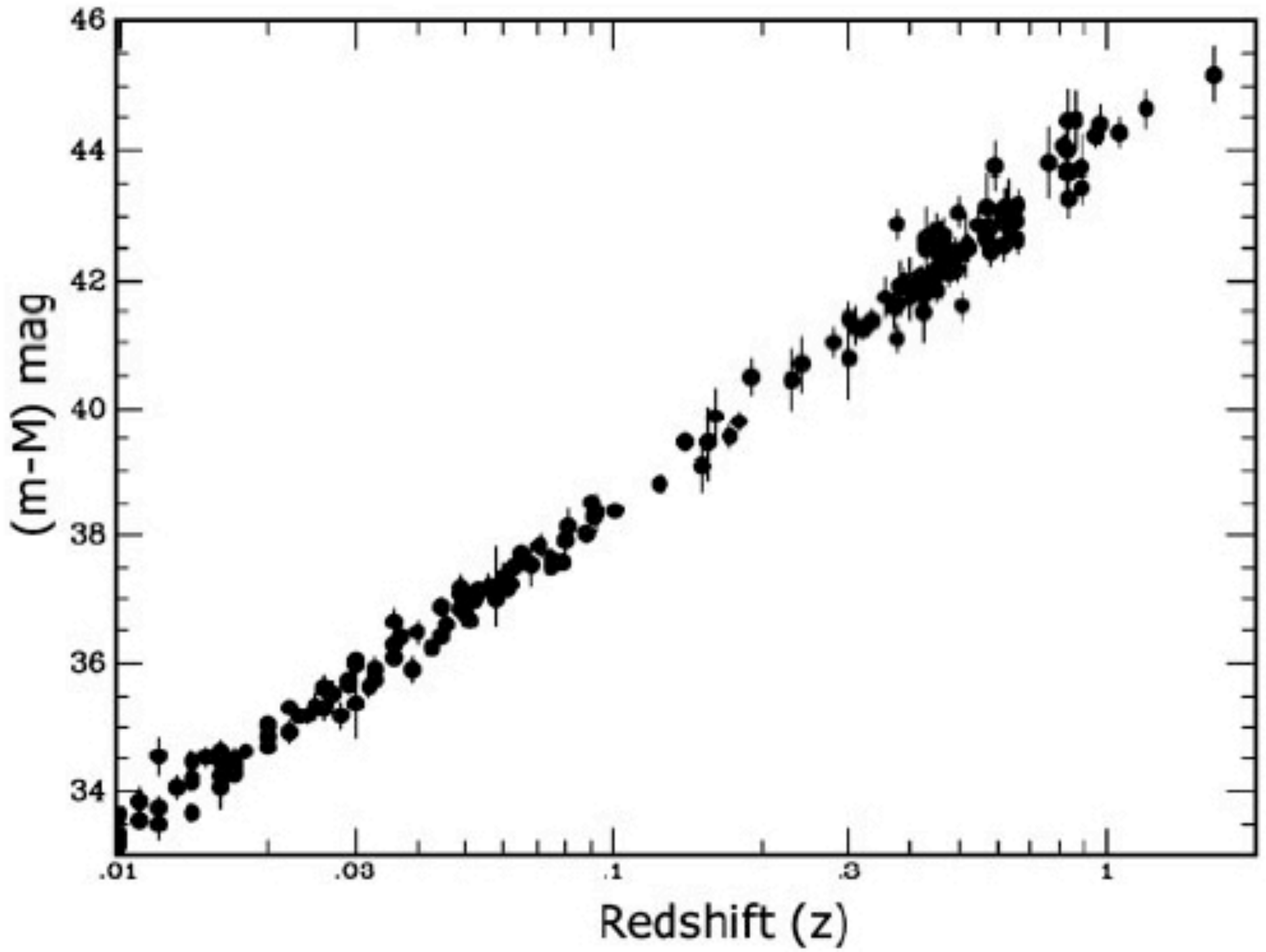
The matter energy content of space-time

- Matter and Energy tell space and time how to curve.
- The curvature of space and time tells matter and energy how to move.
- In general relativity, **gravity is curved space-time**!



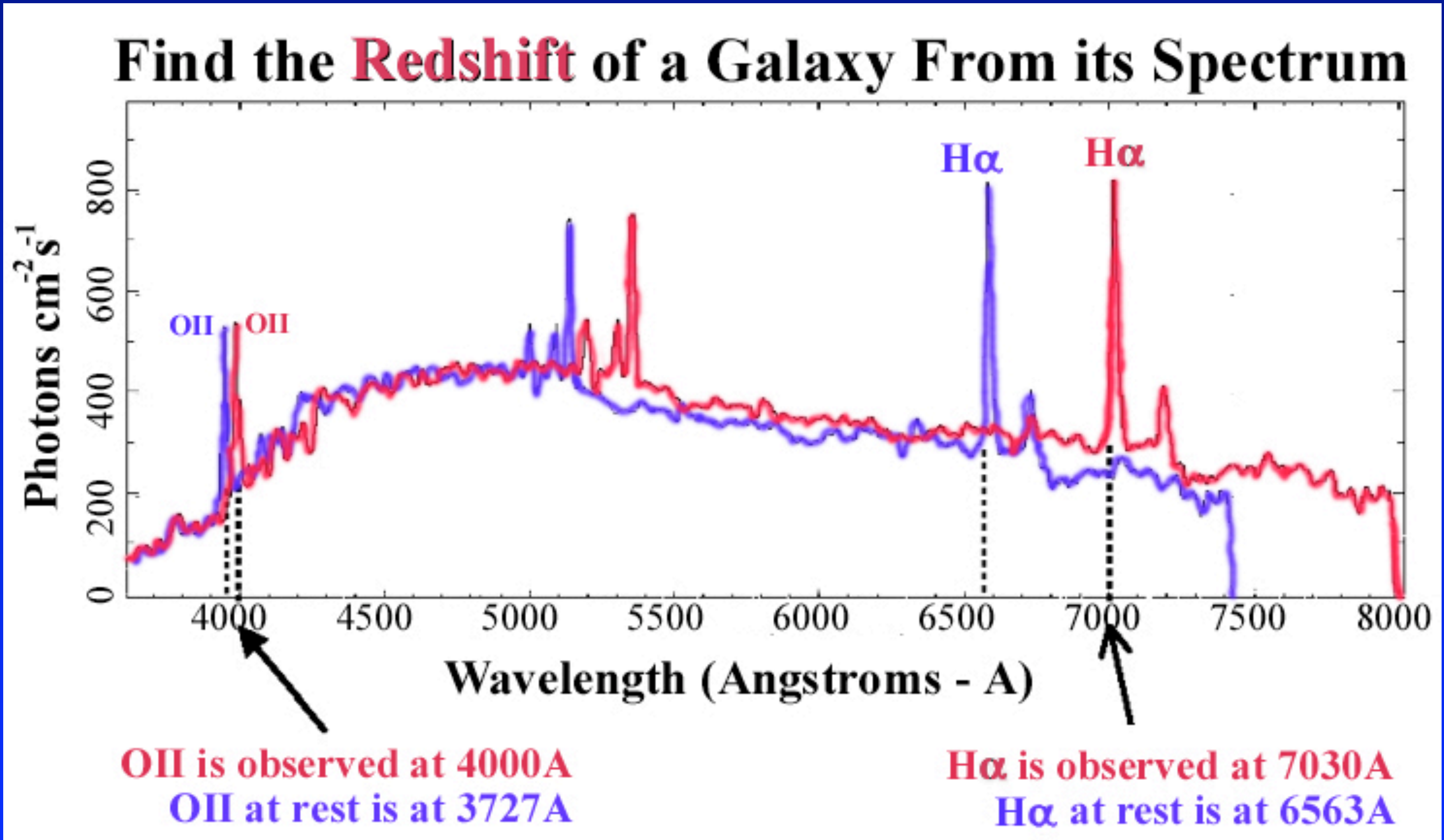
High redshift Hubble diagram

Distance modulus



Redshift (i.e. velocity)

Redshift



Find the Redshift of a Galaxy From its Spectrum
Hα
Hα
OII
OII
Photons cm^{-2} s^{-1}
0
200
400
600
800
4000
4500
5000
5500
6000
6500
7000
7500
8000
Wavelength (Angstroms - A)
OII is observed at 4000A
OII at rest is at 3727A
Hα is observed at 7030A
Hα at rest is at 6563A

Cosmological Inverse sq. law

7. Differential Flux and Luminosity in a Finite Observed Bandpass

To avoid confusion, lab frame (observed) quantities have an $_o$ subscript as in ν_o while rest frame (emitted) quantities have an $_e$ subscript as in ν_e. Quantities with no subscripts like νF_ν represent arbitrary frames of reference (i.e. the observed frame, rest frame, or any other frame). Traditionally, $z_o \equiv 0$ is not specified explicitly and $z_e \equiv z$ by convention for clarity. In other words, examples of $(1+z)/(1+z_o) \equiv (1+z)$ and $(1+z_o)/(1+z) \equiv 1/(1+z)$ since $1+z_o \equiv 1$. The observed flux per unit frequency F_{ν_o} (per unit wavelength F_{λ_o}) in units of [erg cm^{-2} s^{-1} Hz^{-1}] ([erg cm^{-2} s^{-1} Hz]) are given by equations 13, 14 respectively.

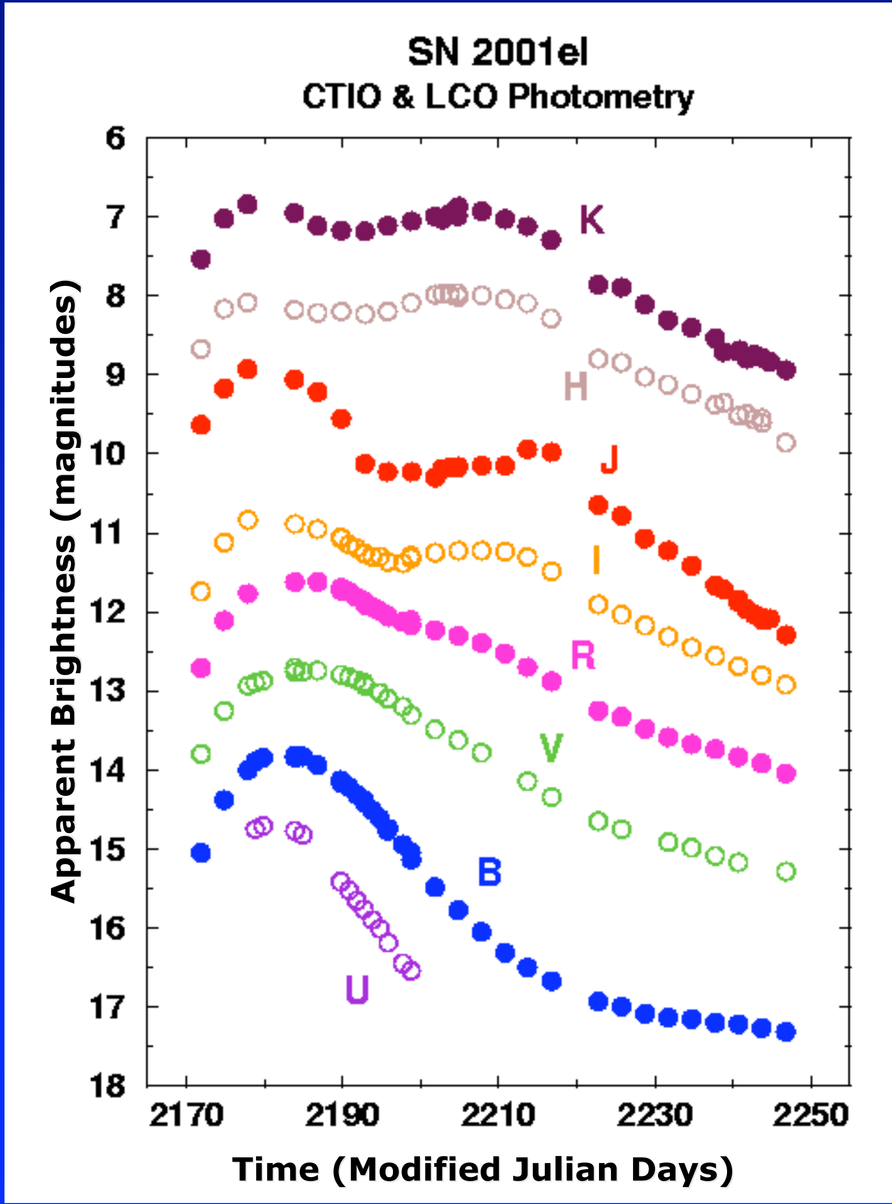
$$F_{\nu_o} = (1+z)\frac{L_{\nu_e}}{4\pi D_L^2} = (1+z)\frac{L_{\nu_e}}{L_{\nu_o}}\frac{L_{\nu_o}}{4\pi D_L^2} \qquad (13)$$

$$F_{\lambda_o} = \frac{1}{(1+z)}\frac{L_{\lambda_e}}{4\pi D_L^2} = \frac{1}{(1+z)}\frac{L_{\lambda_e}}{L_{\lambda_o}}\frac{L_{\lambda_o}}{4\pi D_L^2} \qquad (14)$$

where $\nu_e = (1+z)\nu_o$ and $\lambda_e = \lambda_o/(1+z)$. Note that $\lambda\nu = c$ and $\nu F_\nu = \lambda F_\lambda$. Differential flux per unit log frequency is the most natural flux unit for which there is no redshifting of the bandpass.

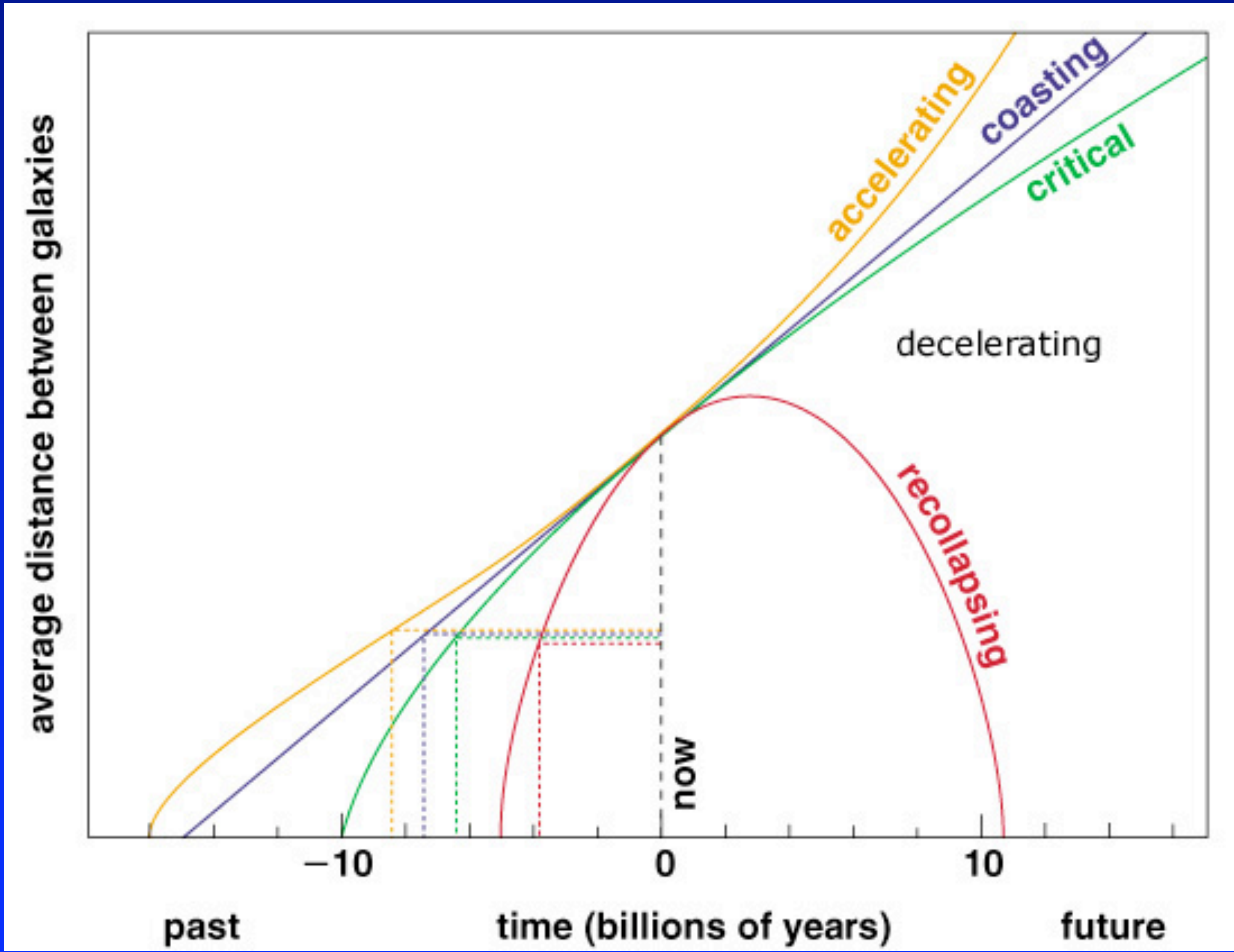
$$\nu_o F_{\nu_o} = \frac{\nu_e L_{\nu_e}}{4\pi D_L^2} = \lambda_o F_{\lambda_o} = \frac{\lambda_e L_{\lambda_e}}{4\pi D_L^2} \qquad (15)$$

Type Ia light curves

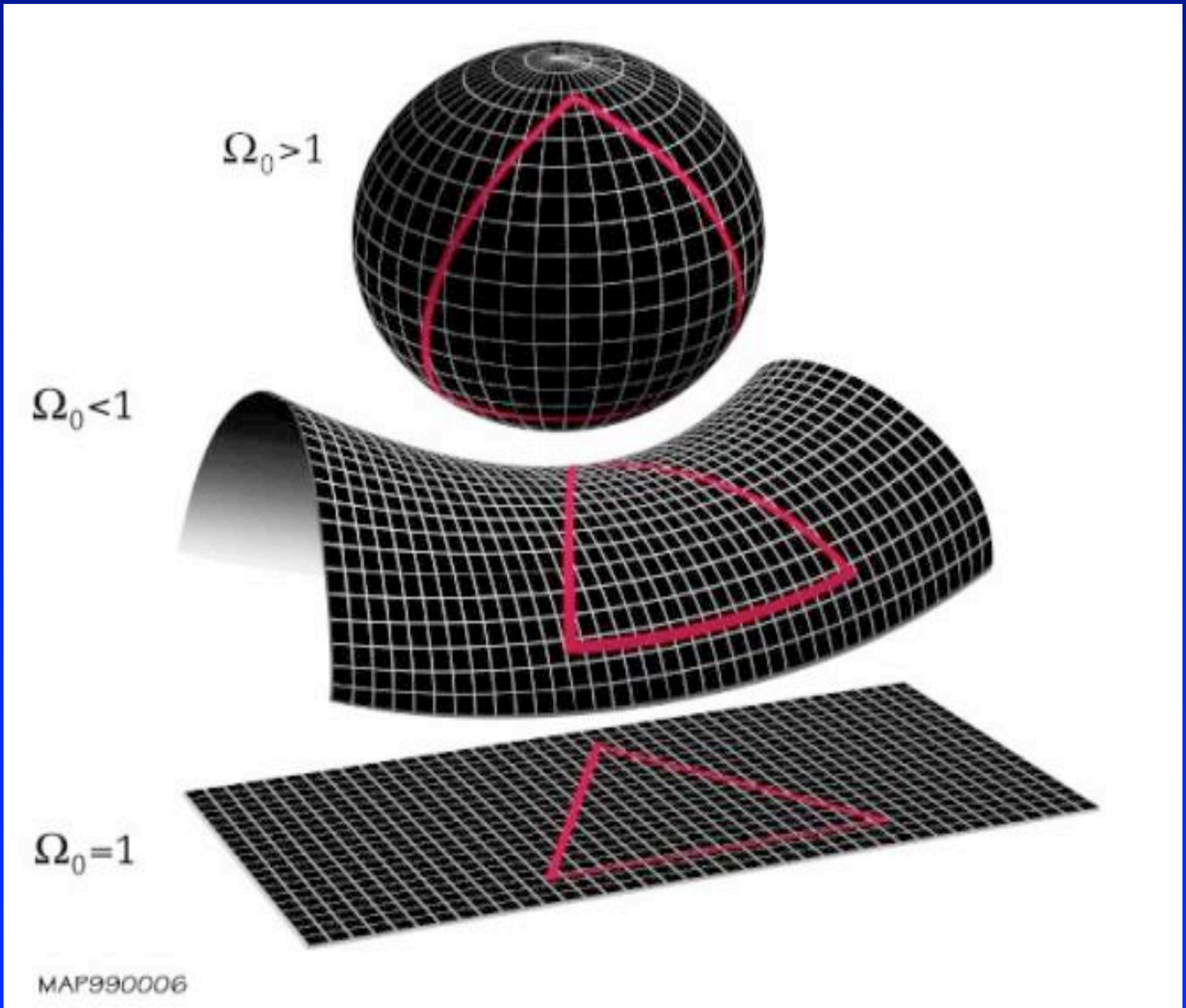


- We observe the SN through different filters that only let through colors in some range.
- UBVRI are names for color ranges at optical wavelengths
- JHK are infrared color ranges

possible expansion histories



Geometry of the universe



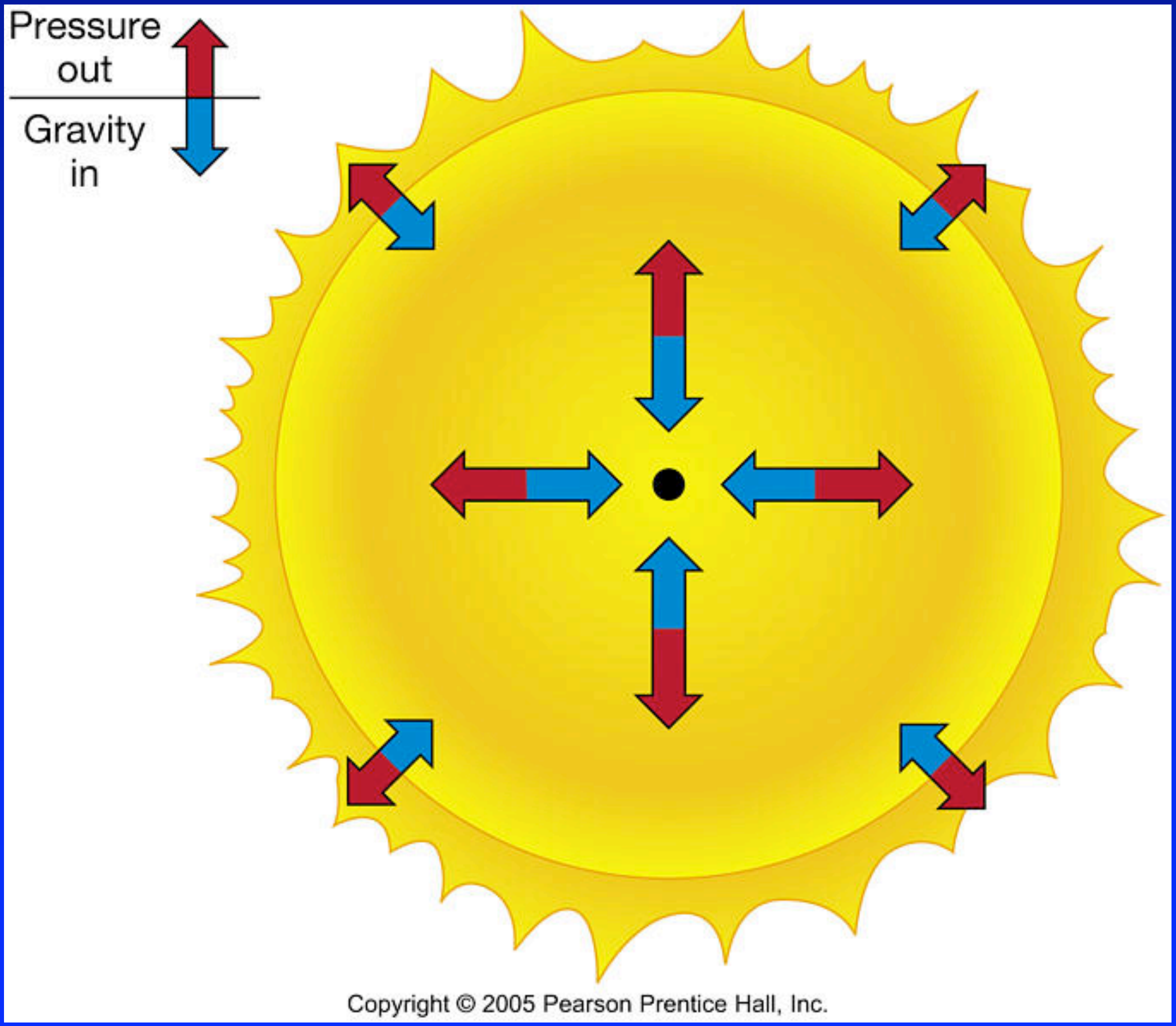
Closed

Open

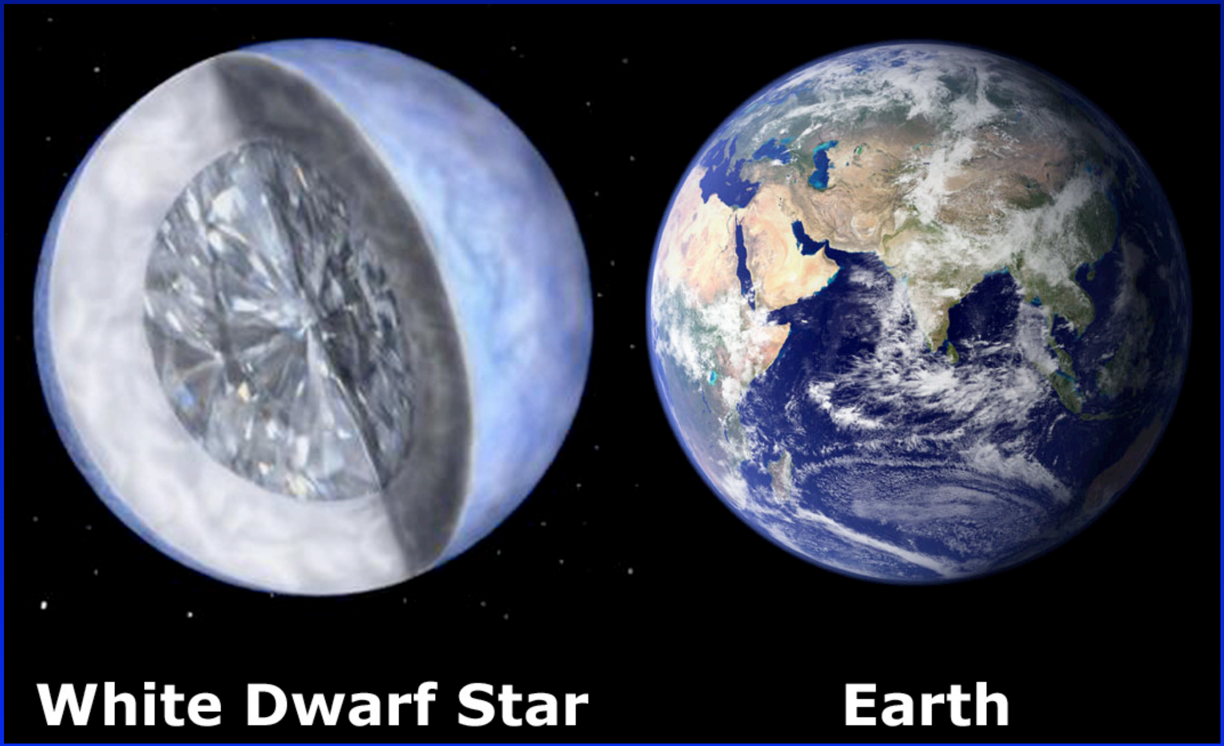
Flat

Star wars

- Gravity vs. pressure.



White dwarfs

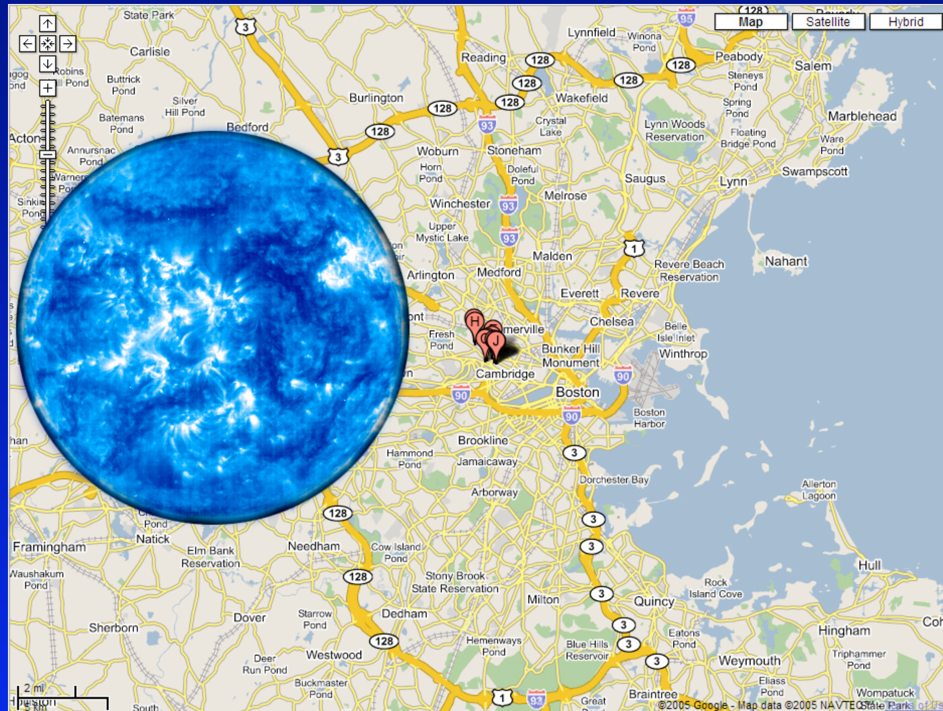


- A White Dwarf star is a dead star (i.e. no nuclear fusion), about as massive as the sun, but shrunk to the size of the Earth.
- WDs are held up by the pressure from the mutual repulsion of their electrons

White dwarfs

A White Dwarf (WD) star exists in a so-called *degenerate* state of matter. WDs shrink when you add mass to them.

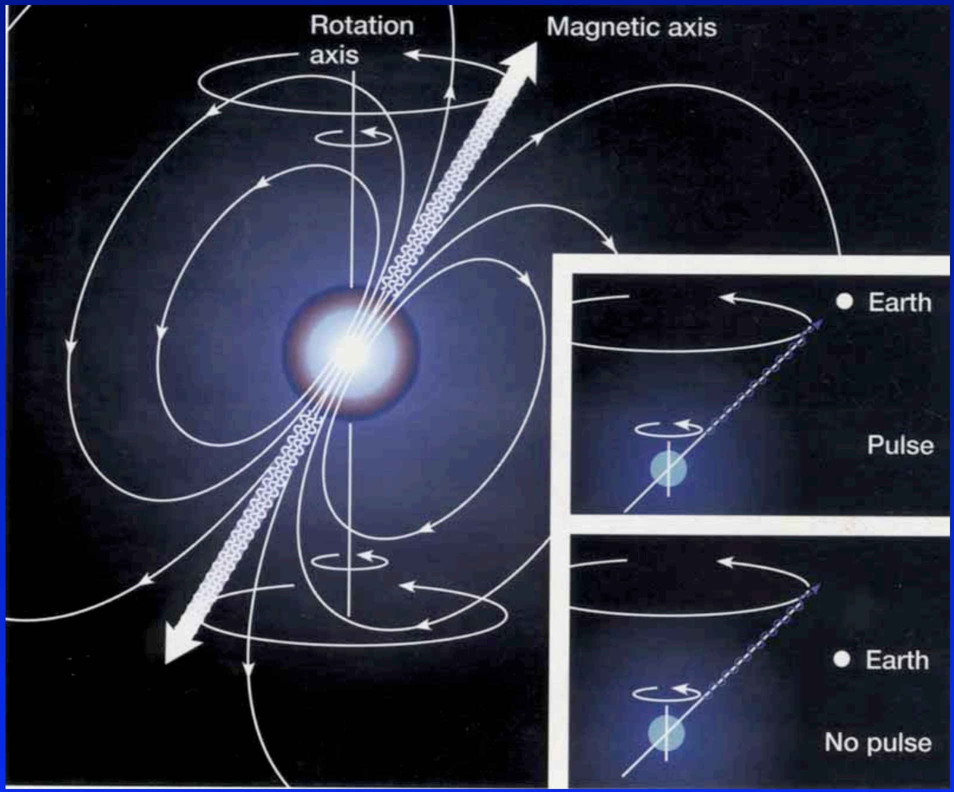
Neutron stars



Neutron Star to Attend Harvard

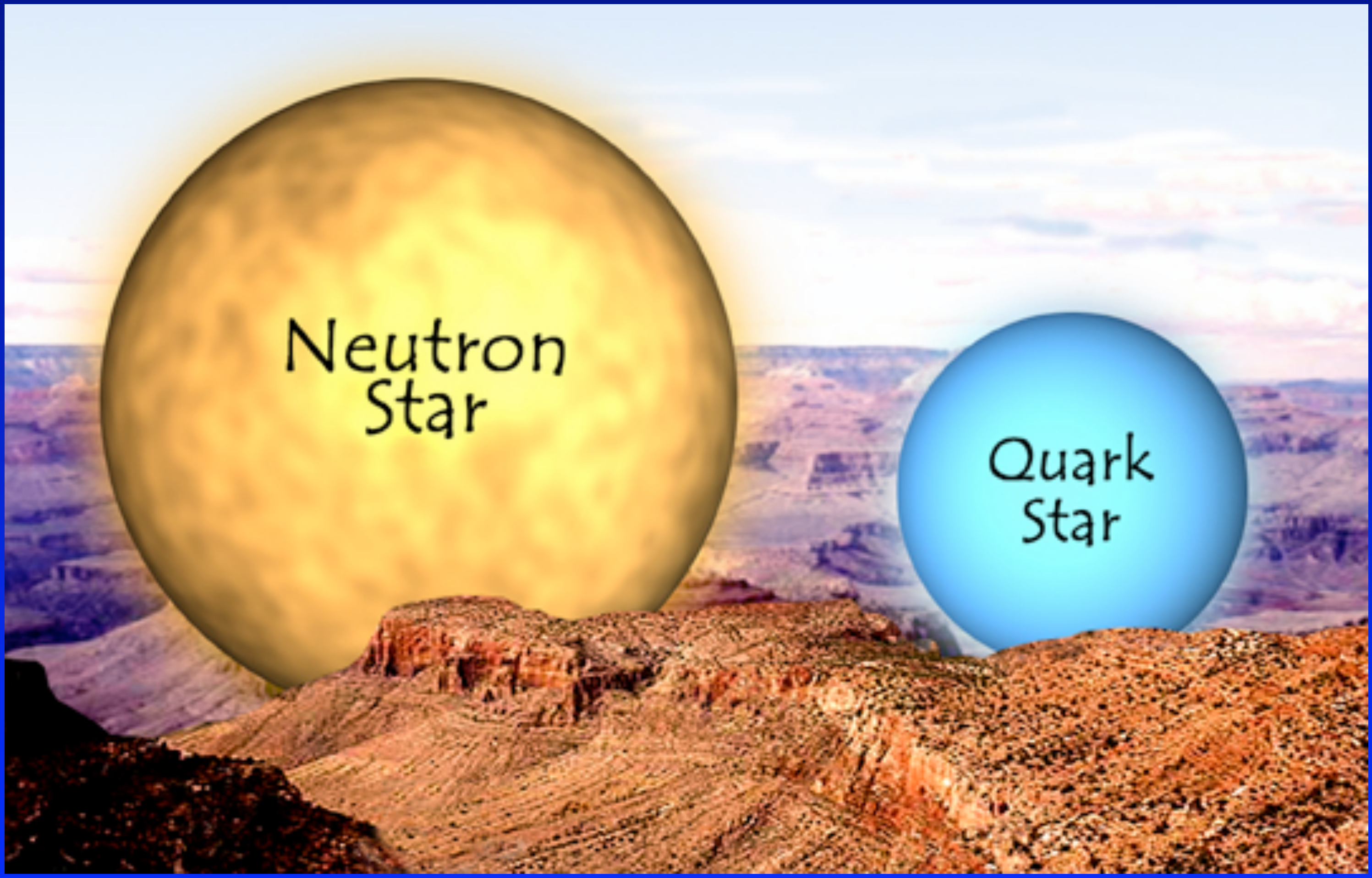
- A Neutron Star (NS) is a dead star (no fusion) as massive as the sun, but the size of a city.
- NSs are held up by the pressure from the mutual repulsion of their neutrons

PULsars



•Pulsars are rapidly rotating neutron stars with radio or X-ray beams like lighthouses
•Pulsars rotate with precise regularity that beats our best atomic clocks.

Quark stars ?



- A Quark Star may be held up by the pressure from the mutual repulsion of its quarks

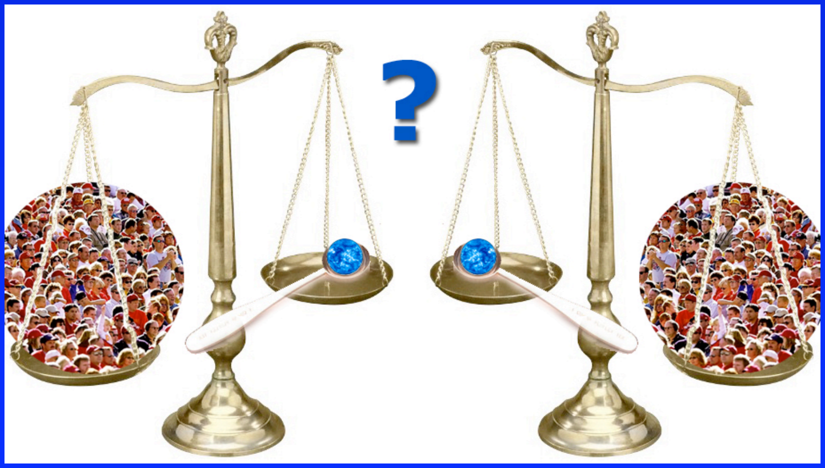
Star wars

Astrophysical Object	Force Fighting Gravity
People	Electromagnetism
Planets	Electromagnetism
Protostars	Thermal Pressure (gravitational contraction)
Main Sequence Stars	Thermal Pressure (nuclear fusion)
White Dwarfs	electron degeneracy pressure
Neutron Stars	neutron degeneracy pressure
Quark Stars	quark pressure?
Black Holes	NOTHING!

question #1

A Neutron Star has an average density of about 10^{14} g/cm^3. A teaspoon has a volume of about 5 cm^3. Assuming an average person weighs 50kg, which of the following has the most total mass?

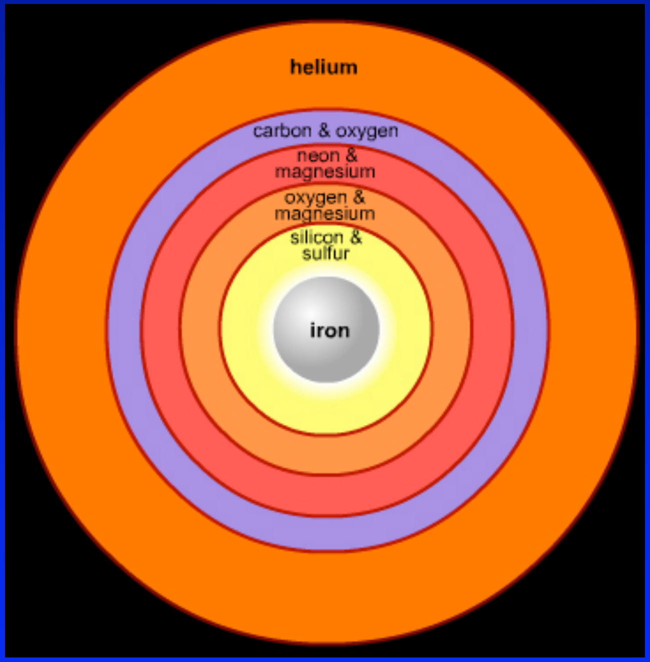
- The guest lecturer
- A teaspoon of material from the sun’s core
- A teaspoon of white dwarf material
- A teaspoon of neutron star material
- The mass of all six billion human beings on Earth



Type I i Supernovae

Gravity Bombs!

Gravitational Core Collapse of Massive Stars



- For stars with $M > 8\ M_{sun}$ main sequence nuclear fusion results in an onion-like structure w/ an Iron core

- Star can't get any more energy from fusing Iron

Once the pressure support from fusion disappears, the star's core collapses, leading to a supernova as the outer layers fall in and rebound

DEMO

Stellar Explosion MOVIEs

Core Collapse
Supernova Movie

Gamma Ray Burst Movie

Leftover COMpact objects

Type of Stellar Explosion	**Compact Remnant**
Type Ia	NOTHING!
Failed Type Ia	*NEUTRON STAR?*
Type II	NEUTRON STAR
	BLACK HOLE
Gamma-Ray Burst	BLACK HOLE

The Friedmann equations

Solutions to Einstein’s Field Equations of General Relativity, which describe an expanding (or contracting) universe.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

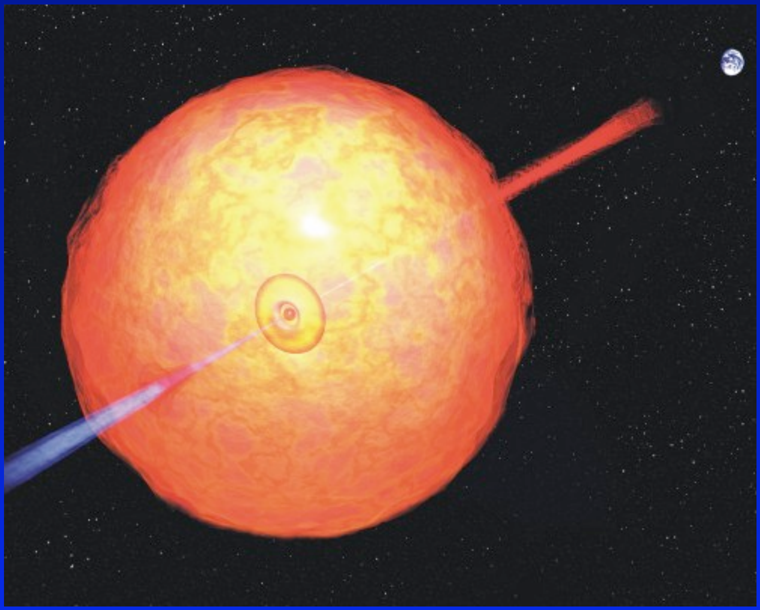
Einstein introduced General Relativity in 1915 but these solutions were not found until 1922, by Friedmann

Alexander Friedmann
1888-1925

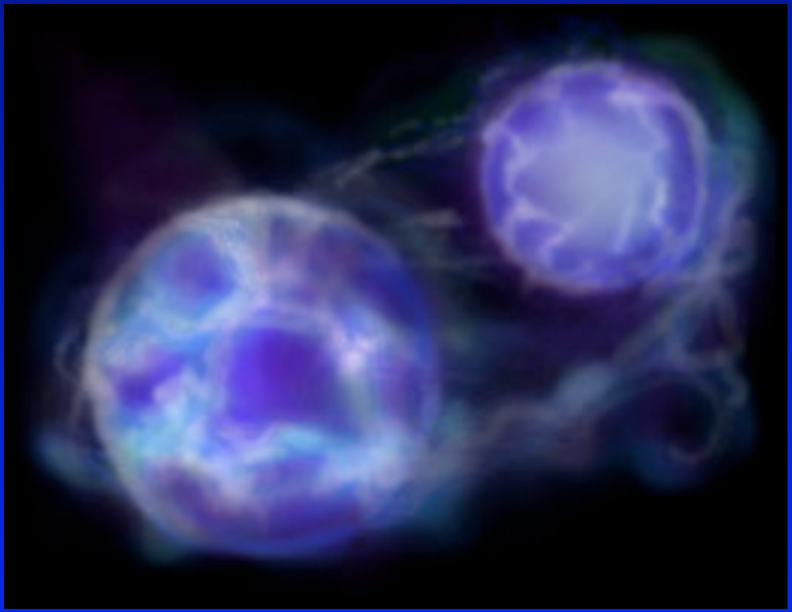
George Lemaitre
1894-1966

Gamma-ray bursts (GRBs)

The Brightest Explosions in the Universe!



Long GRBs - Related to core collapse Supernovae of Some Massive Stars



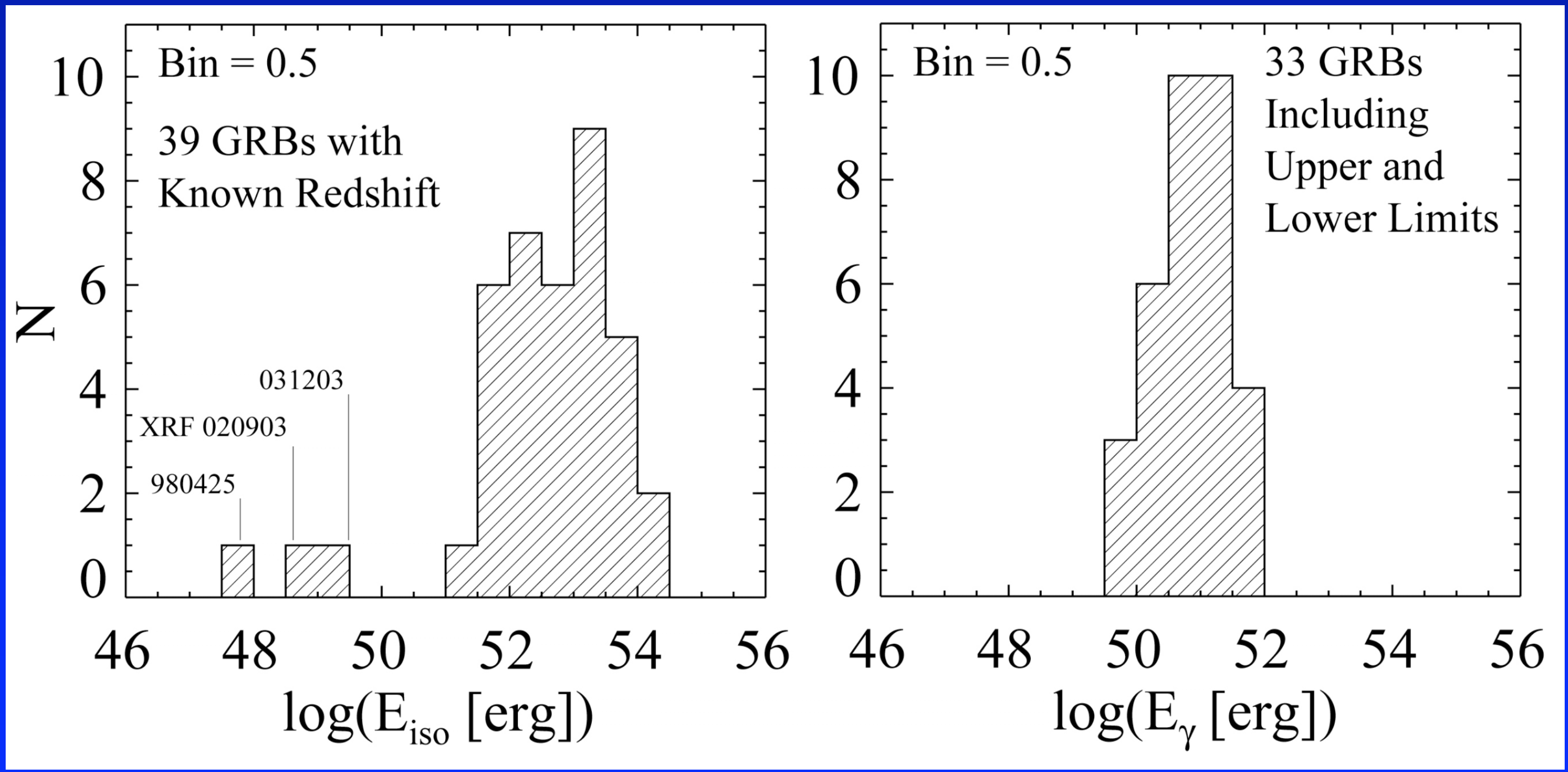
Short GRBs – Probably Merging Neutron Stars

A short-lived accretion disk forms around newly formed black hole. High velocity jets produced which emit paired beams of gamma-rays.

GRB Energetics

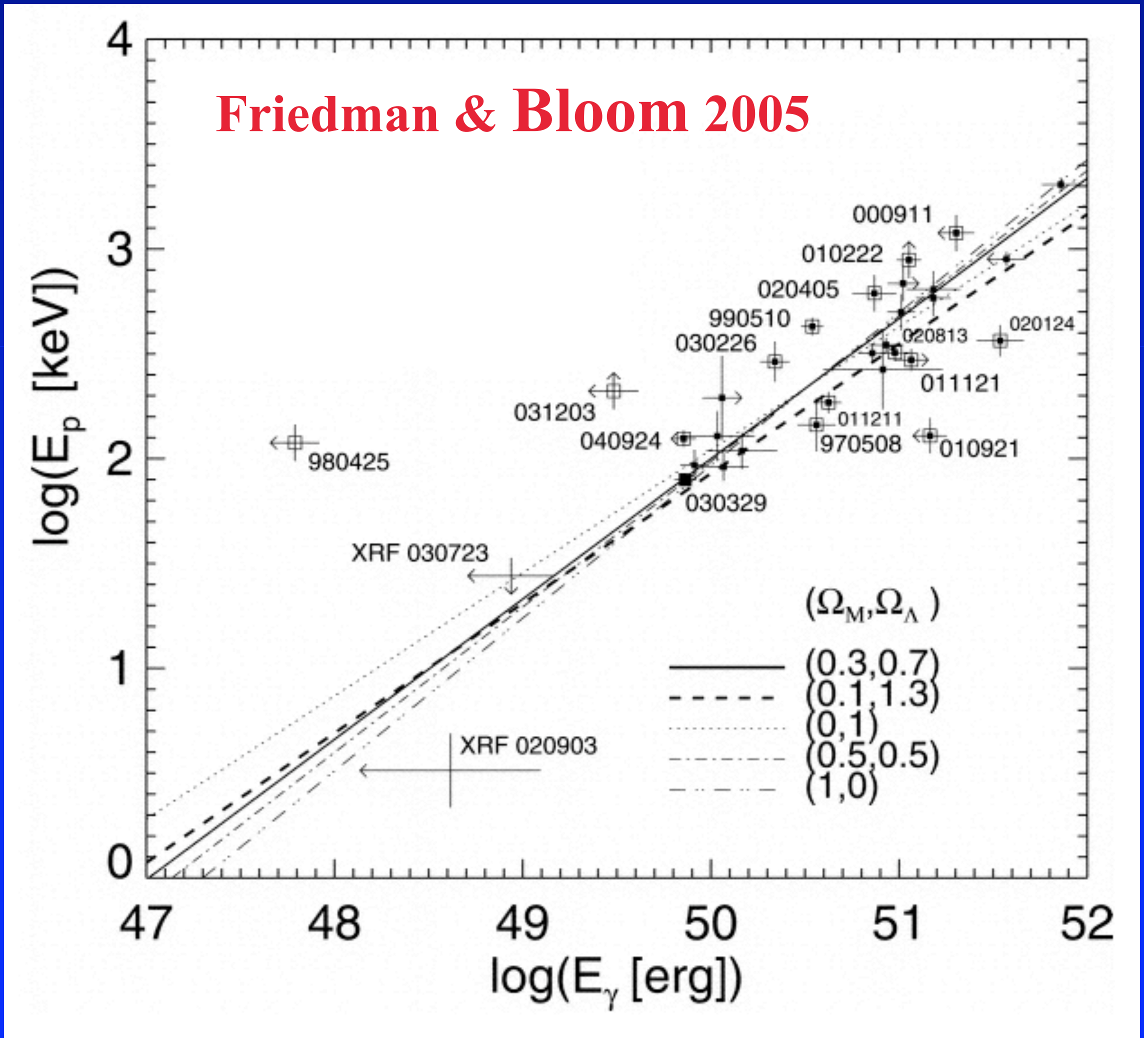
The isotropic equivalent gamma-ray energy E_{iso} is a ***bad*** *standard candle*

The beaming corrected gamma-ray energy Eγ is a ***better*** *standard candle*



Data from: Friedman & Bloom 2005

Grb standardized candles



Y-axis: Ep

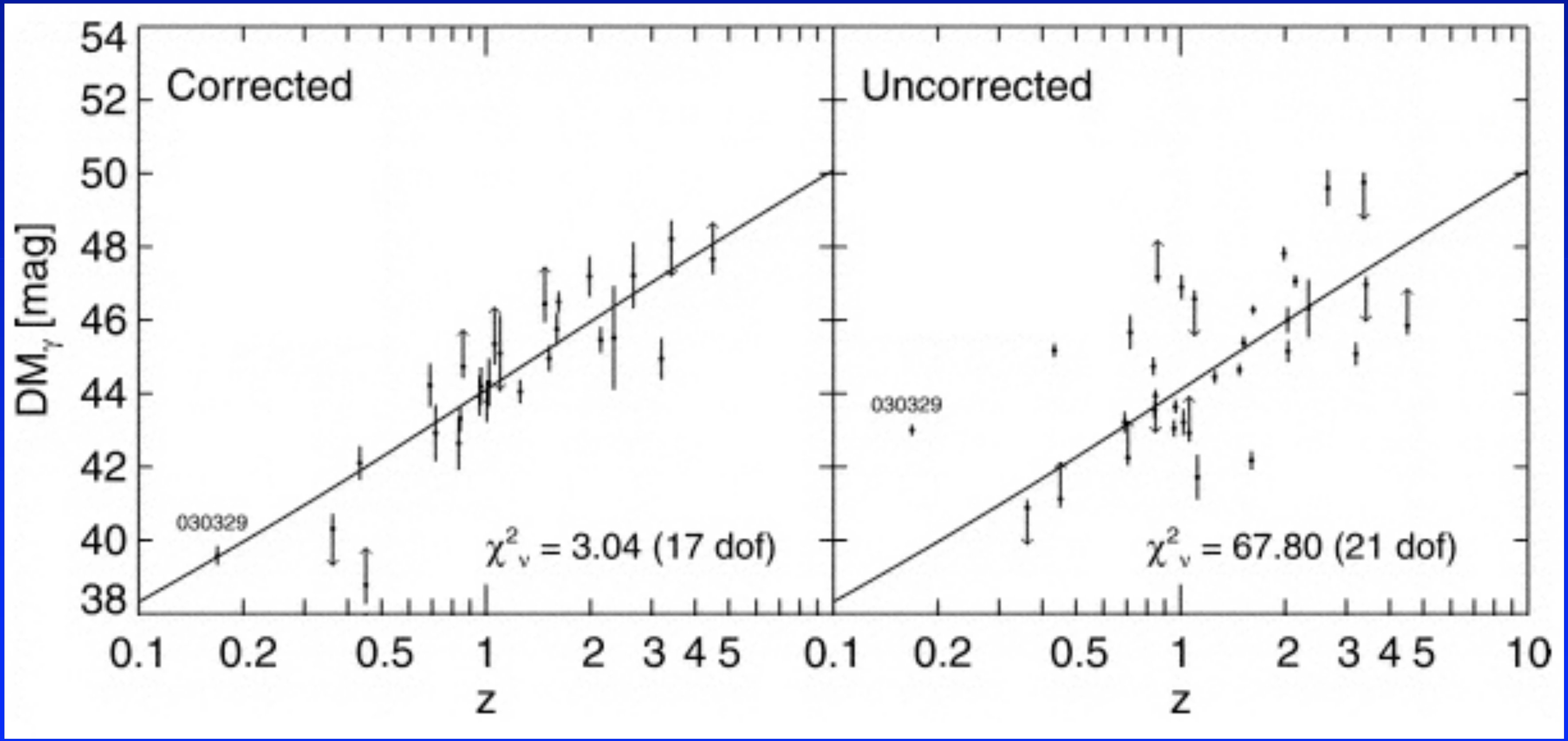
The peak energy at which most of the gamma-ray light is emitted (*this is like the dominant gamma-ray color of the GRB*)

X-axis: Eγ

The total energy emitted in gamma rays, corrected for beaming (*this is related to the intrinsic luminosity of the GRB*)

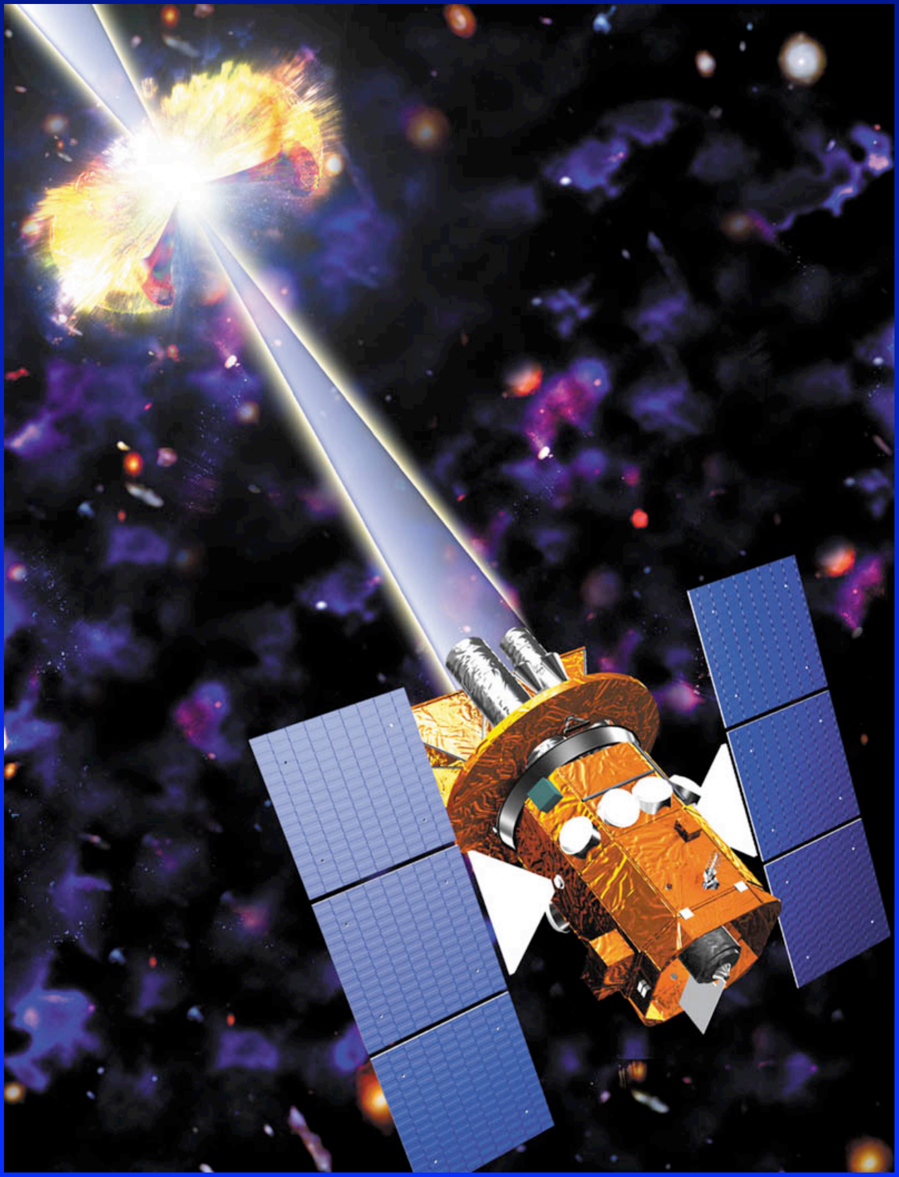
Grb Hubble diagram

E_p and E_γ **E_γ**

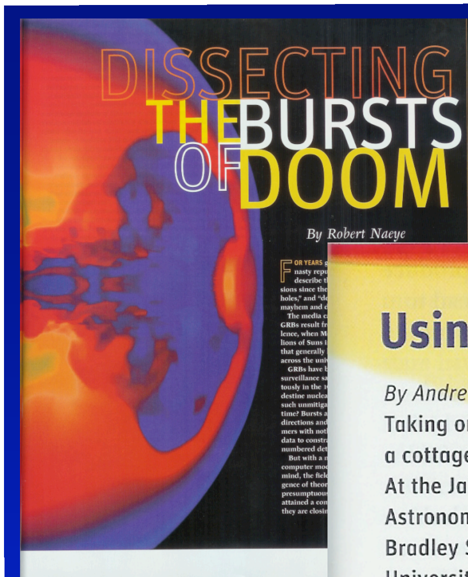


Friedman & Bloom 2005

Nasa swift satellite



Sky & Telescope, Aug 2006



Using GRBs for Cosmology

By Andrew Samuel Friedman

Taking on Einstein has become a cottage industry for scientists. At the January 2006 American Astronomical Society meeting, Bradley Schaefer (Louisiana State University) reported that he had used long-duration gamma-ray bursts (GRBs) as standard candles (distance indicators of known luminosity) to measure the universe's expansion history. Schaefer boldly concluded that the dark energy responsible for accelerating the expansion had changed in strength over time. This result called into question the constancy of one of Einstein's most storied concepts, the cosmological constant (June issue, page 22). Schaefer's effort exemplifies the excitement and controversy surrounding the emerging field of GRB cosmology.

For the past decade, two competing teams have used supernovae of the Type Ia class as standard candles. With their extraordinary luminosities, these white-dwarf explosions can be seen across billions of light-years, which allowed the teams to make their remarkable 1998 discovery that the universe's expansion is accelerating. This surprising result resurrected Einstein's cosmological constant.

Could GRB standard candles be the new game in town? GRBs are much more luminous than Type Ia supernovae, so they can be seen further back in time. But they suffer from a host of problems. In contrast to Type Ia supernovae, which have relatively uniform properties, GRB luminosities vary by a factor up to a million when not adjusted for beaming. To correct for this wide variation, astronomers must correlate several observed properties, such as the burst's peak gamma-ray energy and the time when the afterglow exhibits a sharp decrease in brightness. Astronomers have developed several other GRB standardization methods, but each has its own pitfalls that could undermine accurate distance estimates. This is of particular concern when different methods are combined, as in Schaefer's analysis.

While hundreds of Type Ia supernovae have measured distances, only about 20 GRBs can be placed on a reliable Hubble diagram — a graph that plots distance versus redshift (Schaefer used about 50). Swift, combined with other satellites, is contributing some of the higher-redshift bursts that most constrain the current Hubble diagram. But there haven't been enough GRBs nearby to calibrate their luminosities. This problem has long been resolved for Type Ia supernovae because they have been well studied in nearby galaxies, some with independent distance measurements from Cepheid variable stars. Unfortunately, the paltry few nearby GRBs have exhibited low energies and strange properties, suggesting that their progenitors differ from their more-distant cousins. Without local calibration, GRBs have limited utility for tracking dark energy's behavior through time.

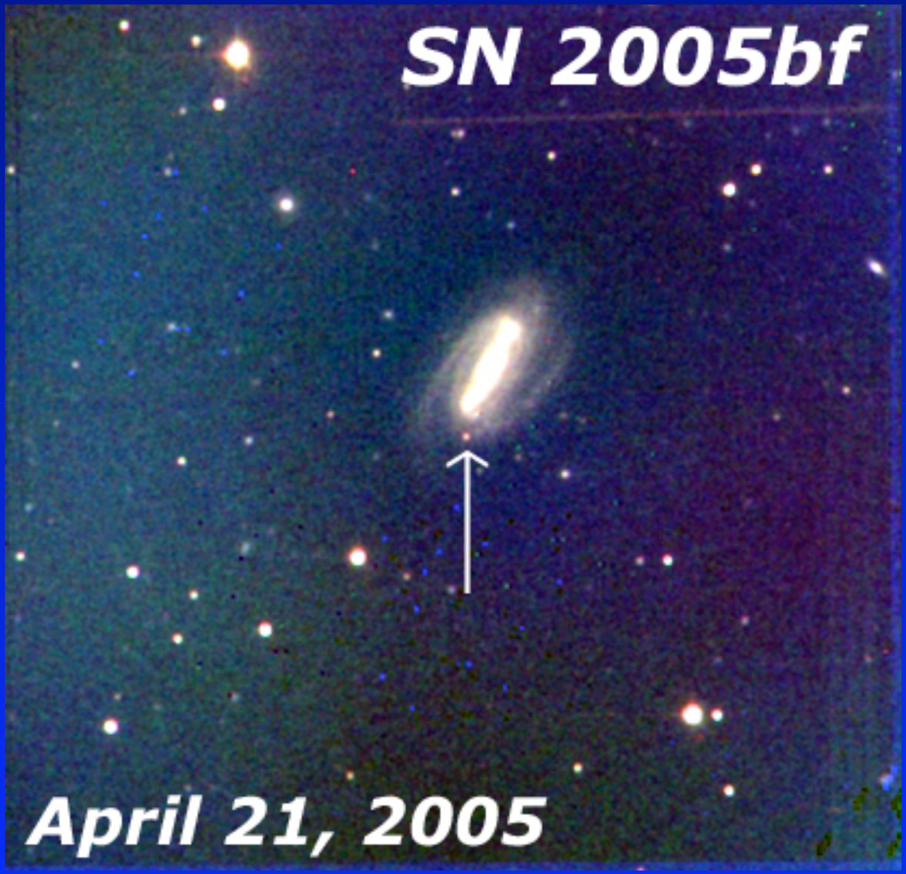
Still, since gamma rays penetrate dust and GRB spectra are simpler than supernova spectra, GRB standard candles could avoid some of the problems that have plagued Type Ia supernova distance estimates. Moreover, since GRBs can be detected at much greater distances, astronomers could, in principle, map the expansion history out to a time when the universe was less than a billion years old. But the early universe's expansion was dominated by matter's gravitational attraction, not dark energy's repulsion — which took over only within the past few billion years. This also limits GRBs' usefulness for studying dark energy.

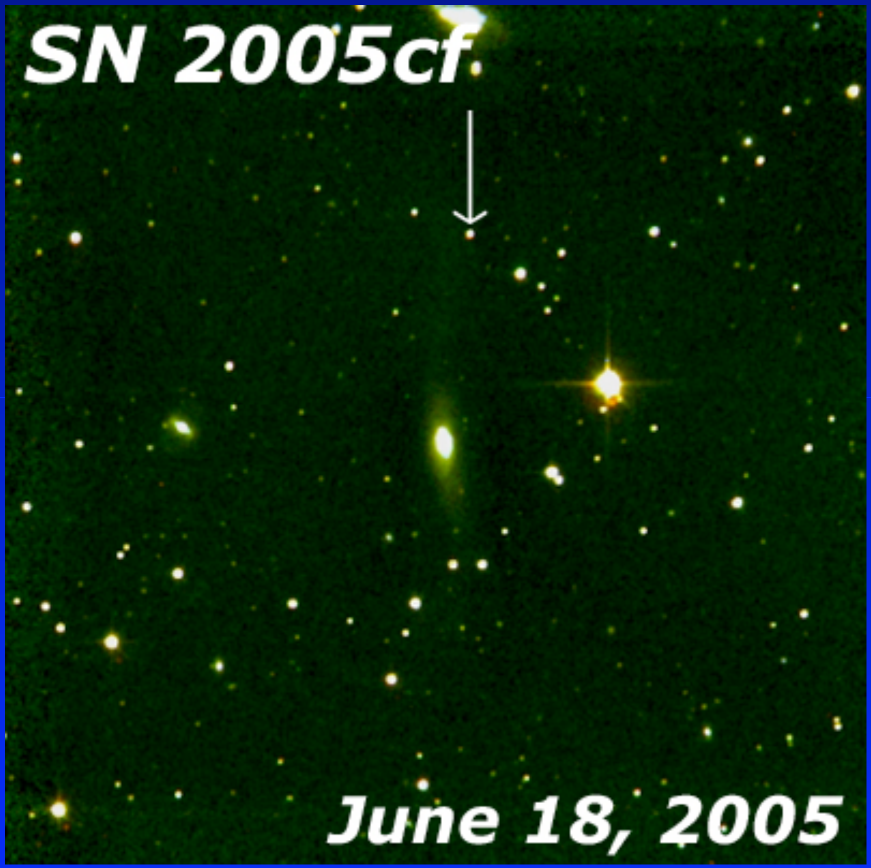
Rather than pointing to the evolution of dark energy's strength, Schaefer's results are more convincingly interpreted as indirect evidence for the evolution of GRB luminosity, with more-distant GRBs yielding higher-energy explosions (though this was already suspected). Our knowledge of GRBs is not yet mature enough to draw conclusions on dark energy's time variation. Although GRBs may not have Einstein turning over in his grave, it is safe to say that if he were alive today, the brightest explosions in the universe would certainly have piqued his interest.

Harvard PhD student ANDREW SAMUEL FRIEDMAN*'s research involves developing novel standard candles such as GRBs and supernovae at near-infrared wavelengths as tools to map cosmic expansion history.*

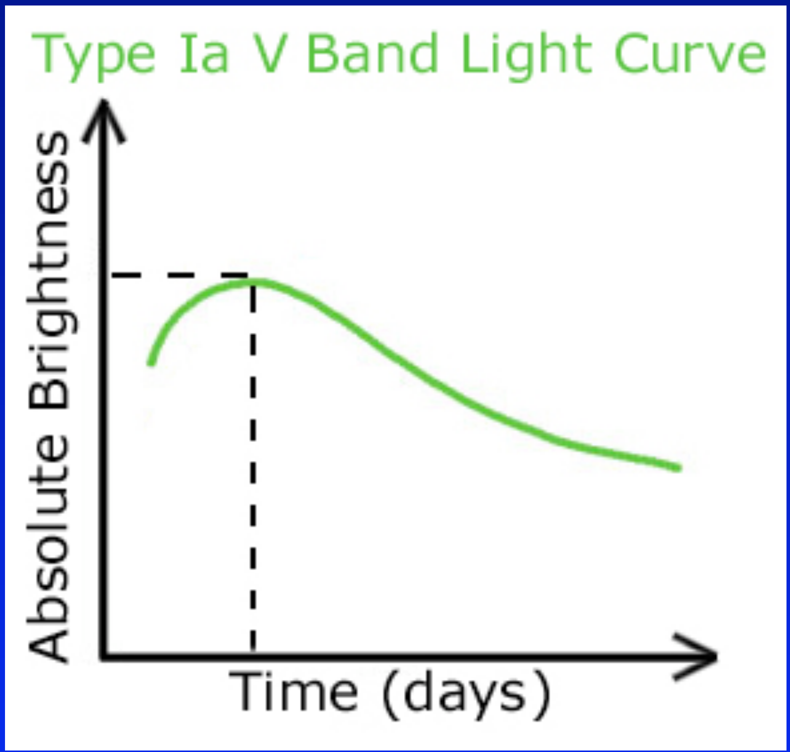
SKY
& TELESCOPE

False Color PAIRITEL JHK Images





Type Ia light curves



$$F = \frac{L}{4\pi d^2}$$

- The peak absolute brightness (or luminosity *L*) of a Type Ia supernova is *roughly* constant from event to event
- If we measure the apparent brightness (or flux *F*), we can infer the distance *d* if we somehow know *L*