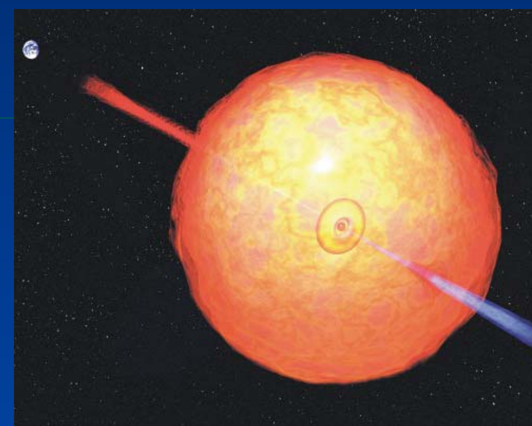
Measuring the Expansion and Acceleration of the Universe with Supernovae and Gamma-Ray Bursts



Andrew Friedman

Department of Astronomy, Harvard University

The Summer Science Program

SSP TA '02

Ojai California, July 3, 2006

Outline

- **Measuring Distances in Astronomy**

- Einstein, Hubble, and the **Expansion** of the Universe

- Type Ia Supernovae and the **Acceleration** of the Expansion of the Universe.

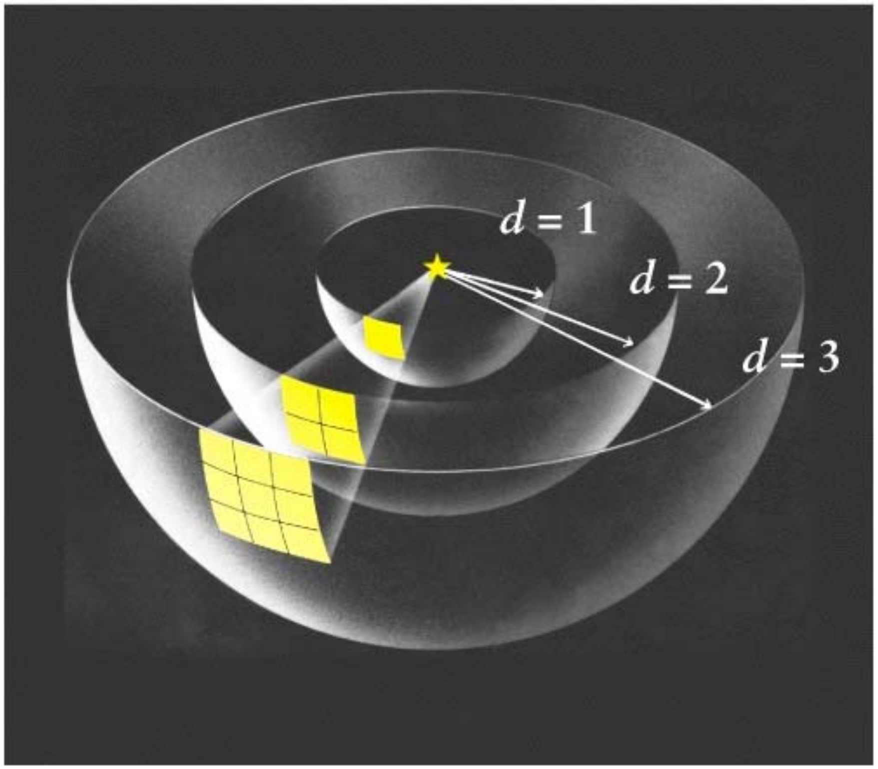
- My **Research**: Developing New Distance Measurement Methods

  Type Ia Supernovae at Infrared Wavelengths

  Gamma-Ray Bursts (GRBs)

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

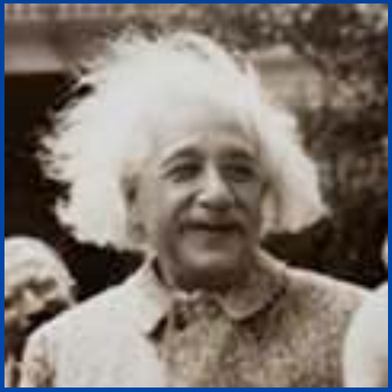
$$G_{\mu\nu} + \boxed{\Lambda} g_{\mu\nu} = 8\pi T_{\mu\nu}$$

The Cosmological Constant
Cosmic Anti-Gravity Term

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

"That term [the cosmological constant] 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."

(Einstein, 1917)



Edwin Hubble

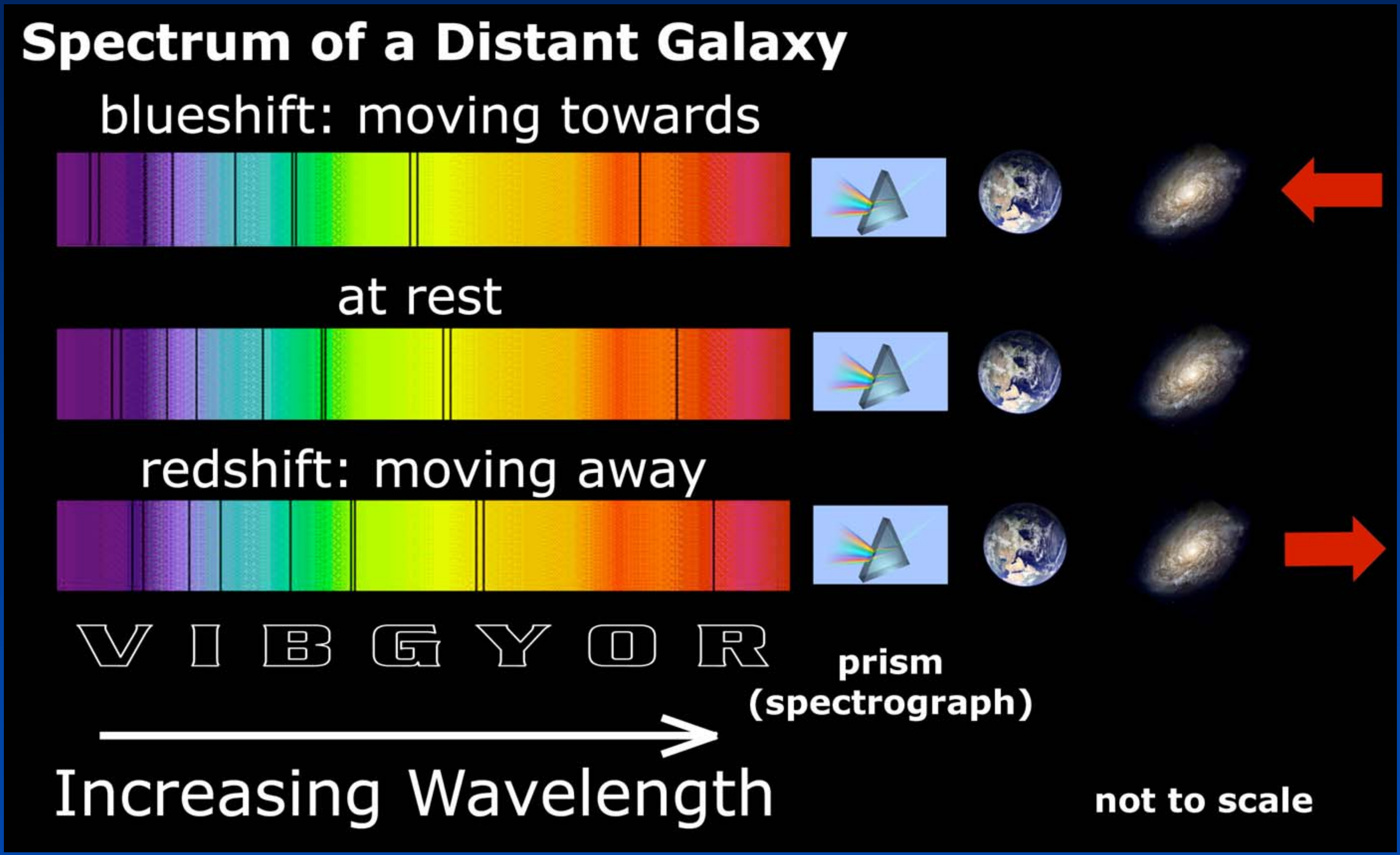
Edwin Hubble
1889-1953

Hubble Space Telescope
1990 – ????

Measuring the velocities and distances of “spiral-nebulae”

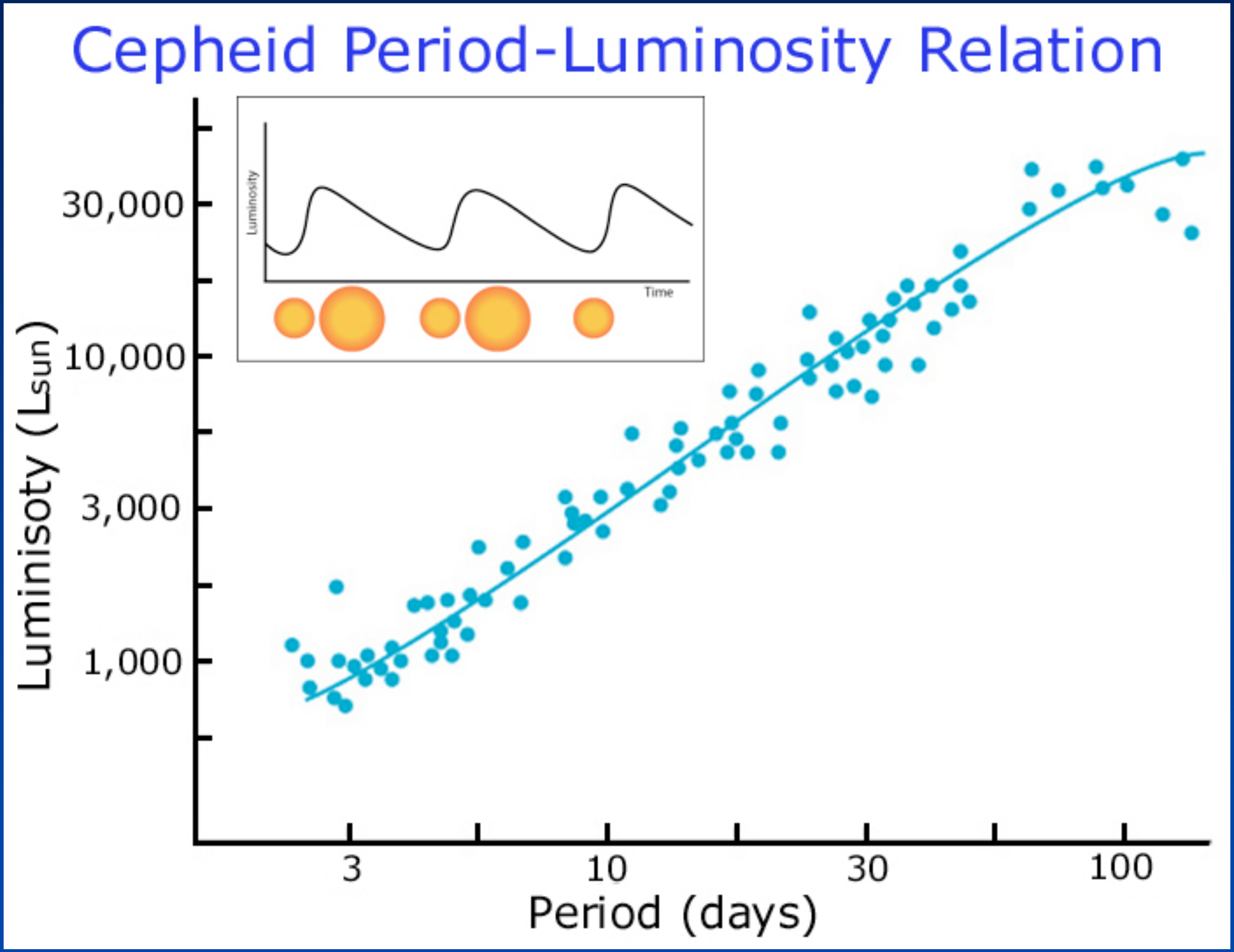
The 100 inch Hooker telescope at the Mt. Wilson Observatory

Redshift



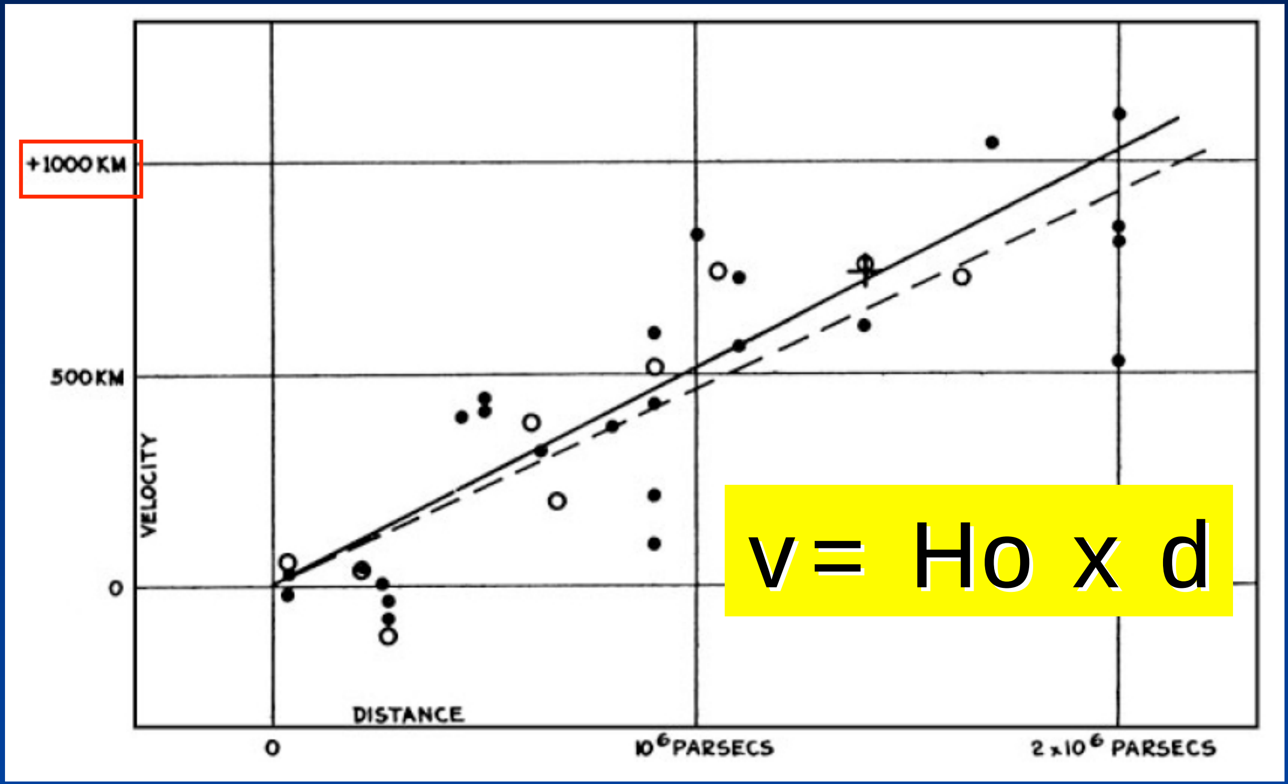
Spectrum of a Distant Galaxy
blueshift: moving towards
at rest
redshift: moving away
V I B G Y O R
prism
(spectrograph)
Increasing Wavelength
not to scale

Cepheid variable stars



Hubble's Diagram (1929)

velocity (v)

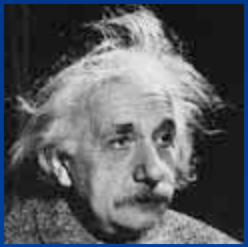


v = Ho x d

distance (d)

Most galaxies are redshifted (moving away)
The more distant ones move faster.
H_o = Hubble Constant. $T_o = 1/H_o$ ~age of universe

Einstein's biggest blunder?



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

"*Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the **biggest blunder** of his life.*"

-George Gamow, My World Line, 1970

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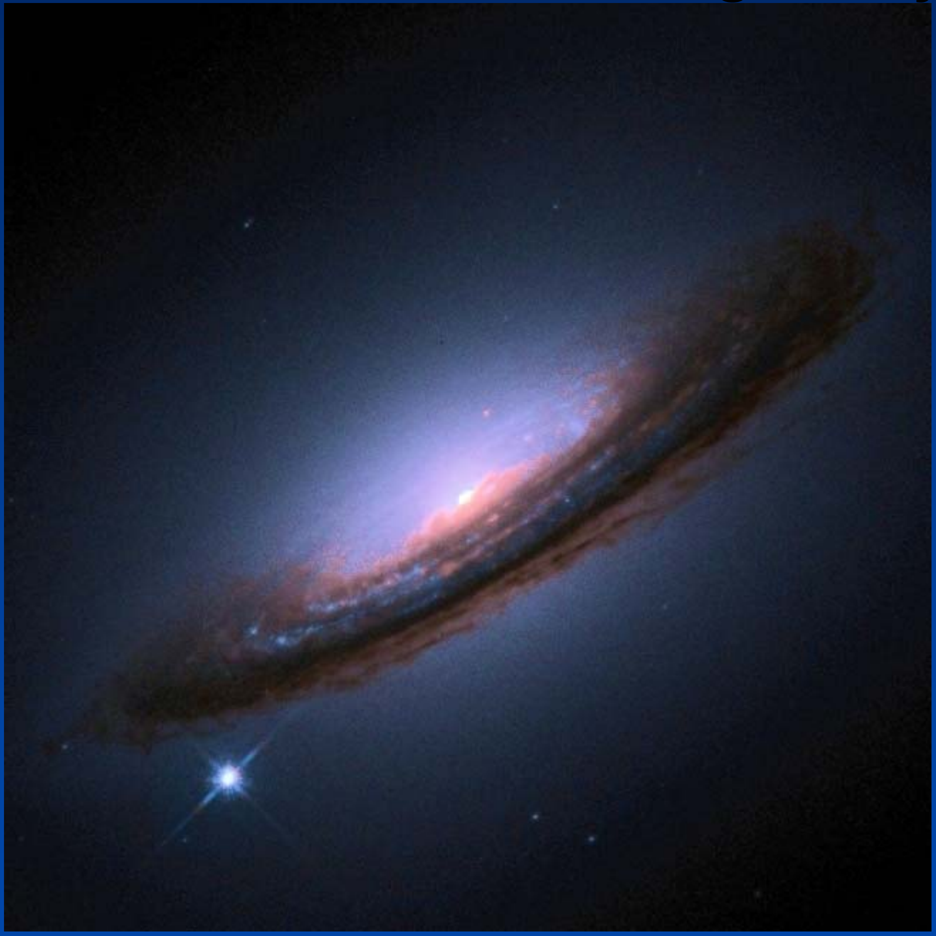
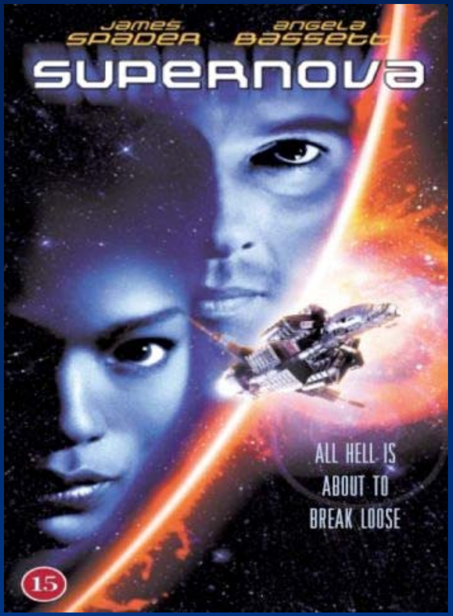
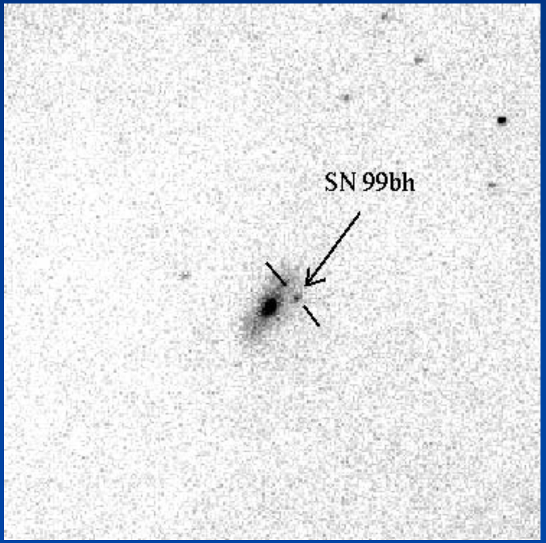
Supernova

A single exploding star can outshines an entire galaxy!



SN 1994d – Hubble Space Telescope



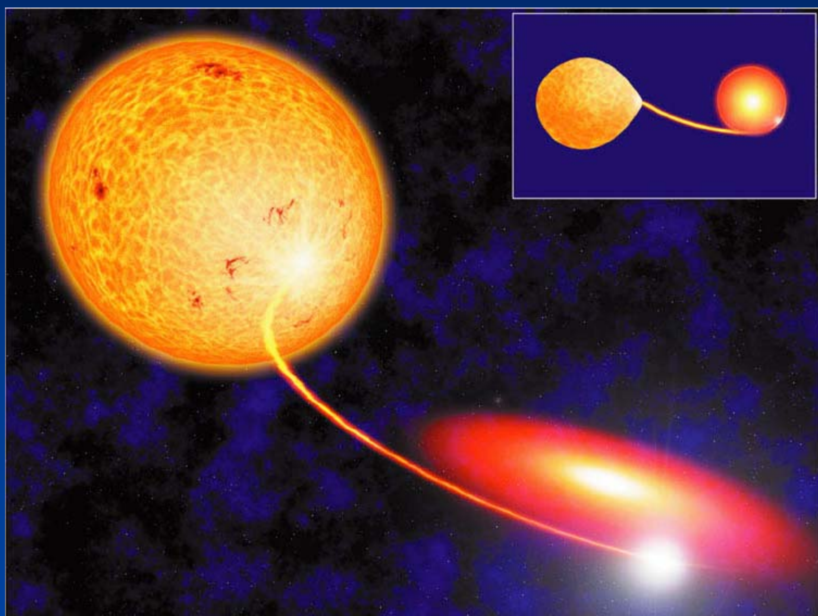


SN 1999bh – Katzmann Automated Imaging Telescope & Andy

Type Ia SupernovaE

Thermonuclear Bombs in Space!

Explosions of White Dwarfs in Binary Systems

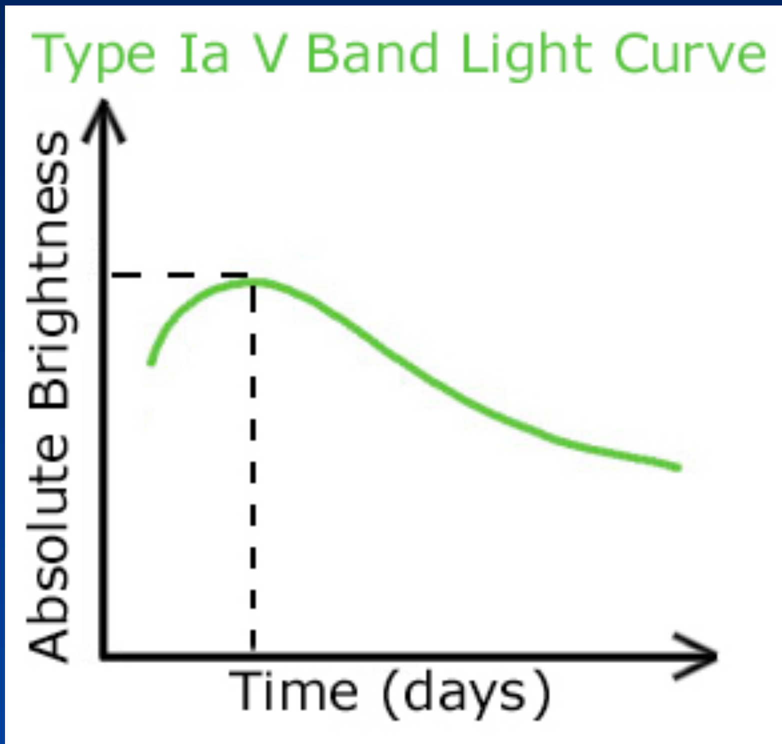


WD Accretion From Main Sequence Companion

Merger of 2 White Dwarfs

If the total mass of the WD system exceeds ~1.4 M_{sun} (the Chandrasekhar mass), it goes supernova

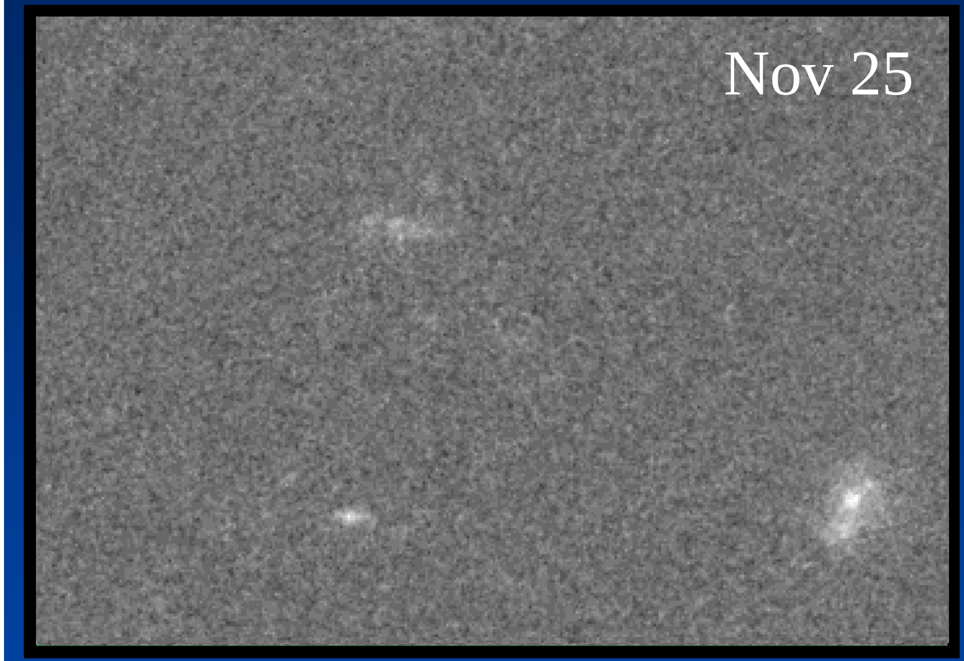
Type Ia light curves

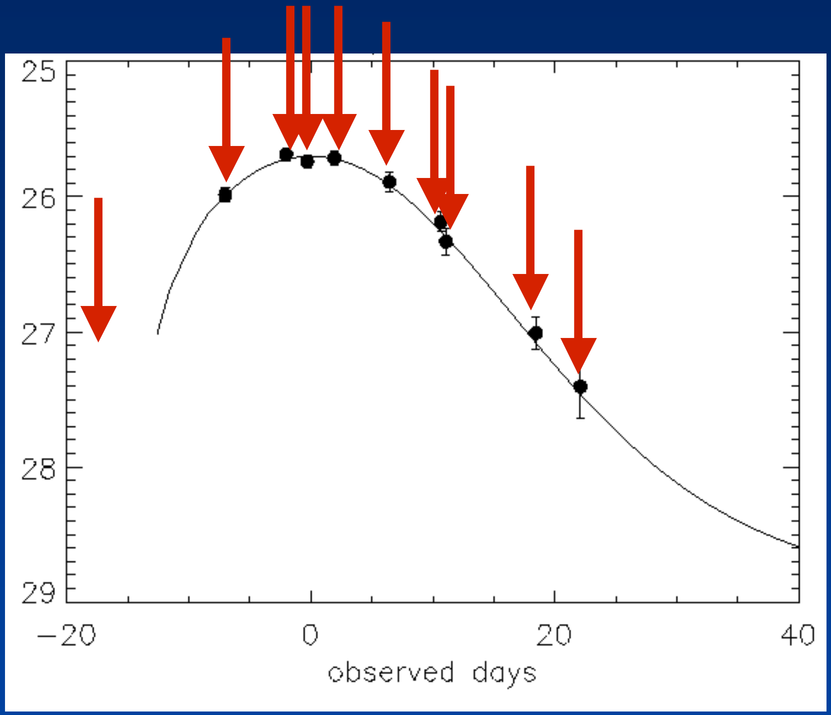


$$F = \frac{L}{4\pi d^2}$$

- 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*

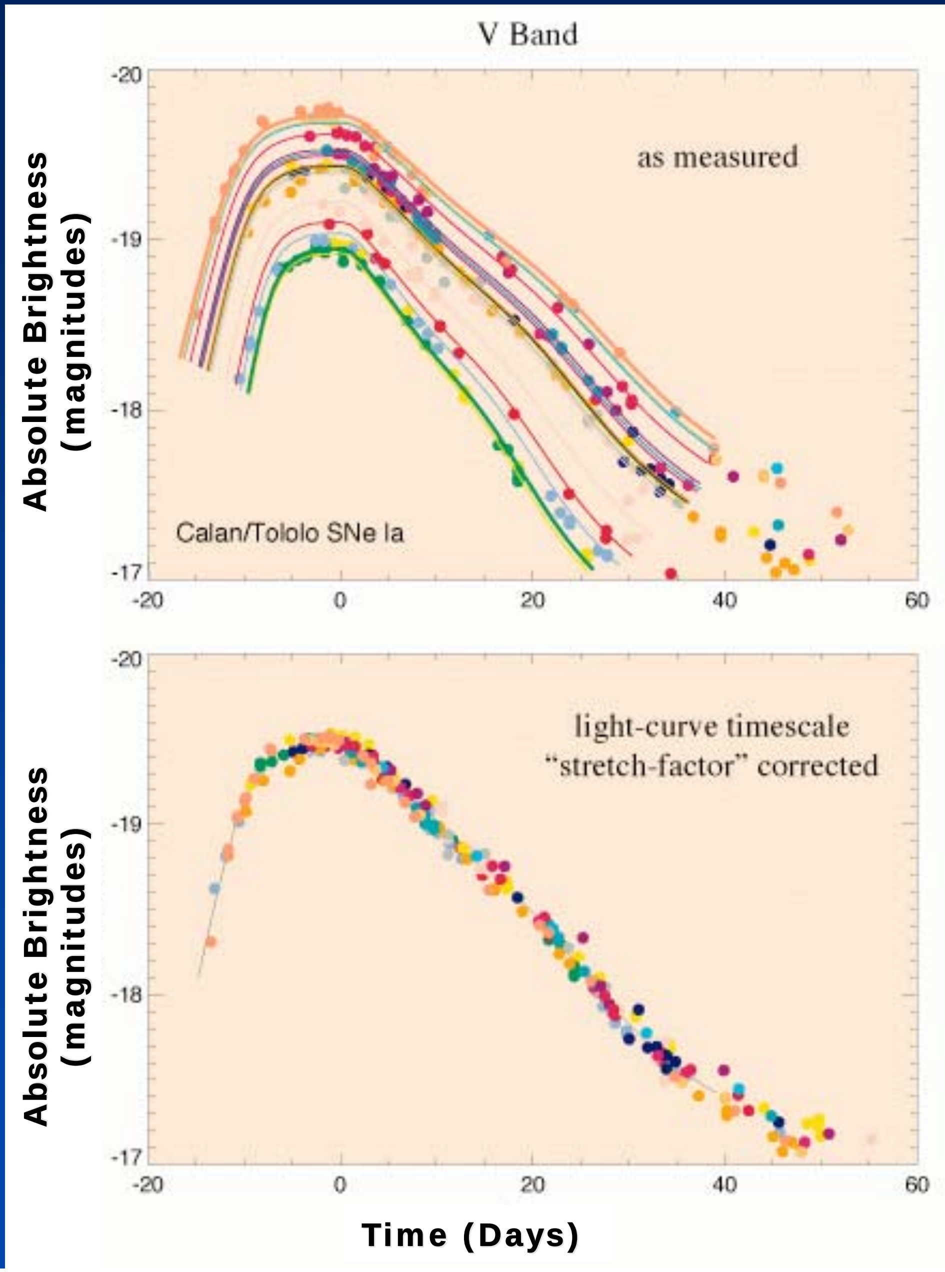
The Rise and Fall of Aphrodite





Courtesy: Robert P. Kirshner

Type Ia *Standardizable* candles

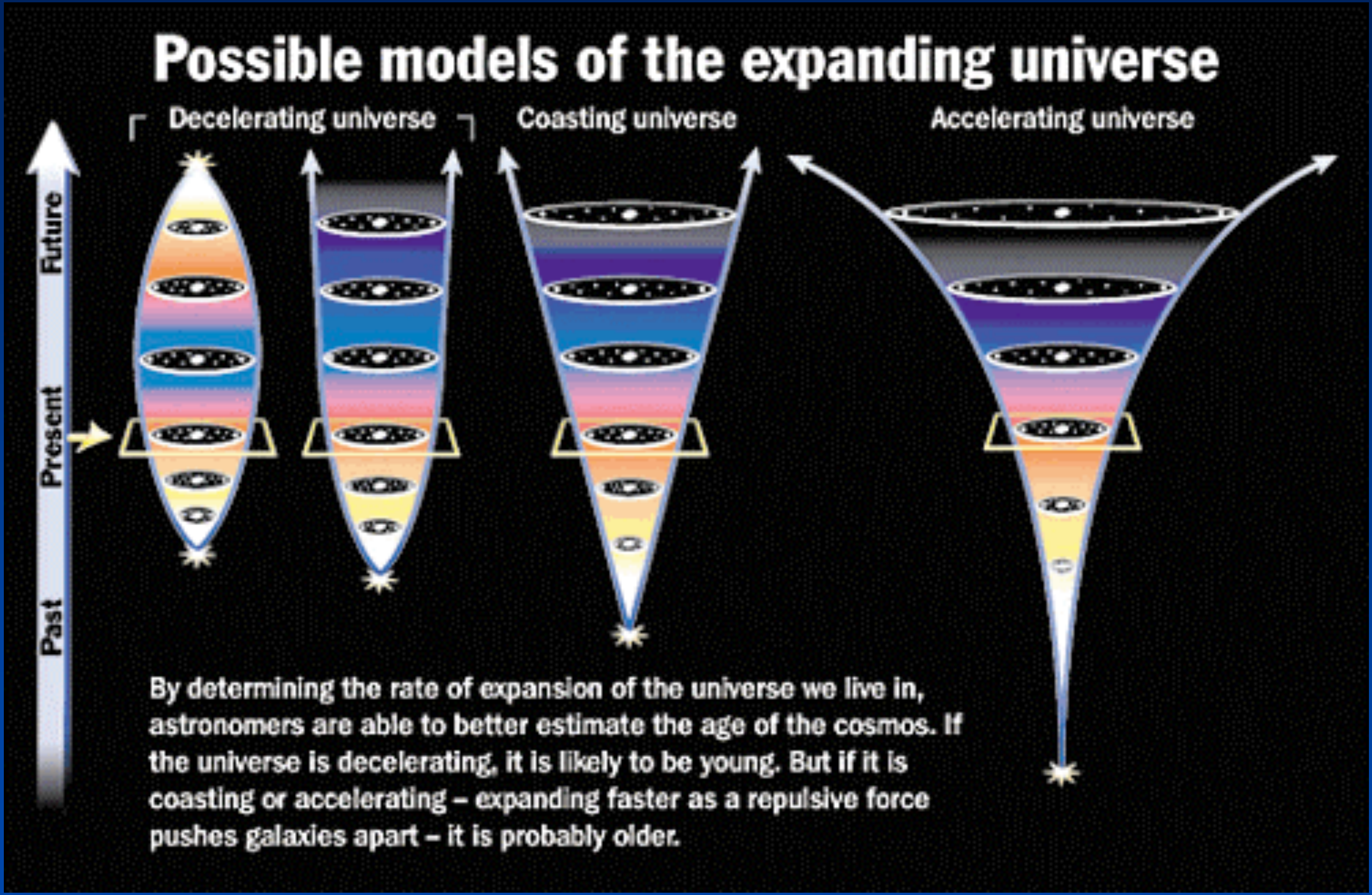


- Type Ia SNe are not perfect standard candles at optical wavelengths
- Fortunately the brightest ones decline slowest

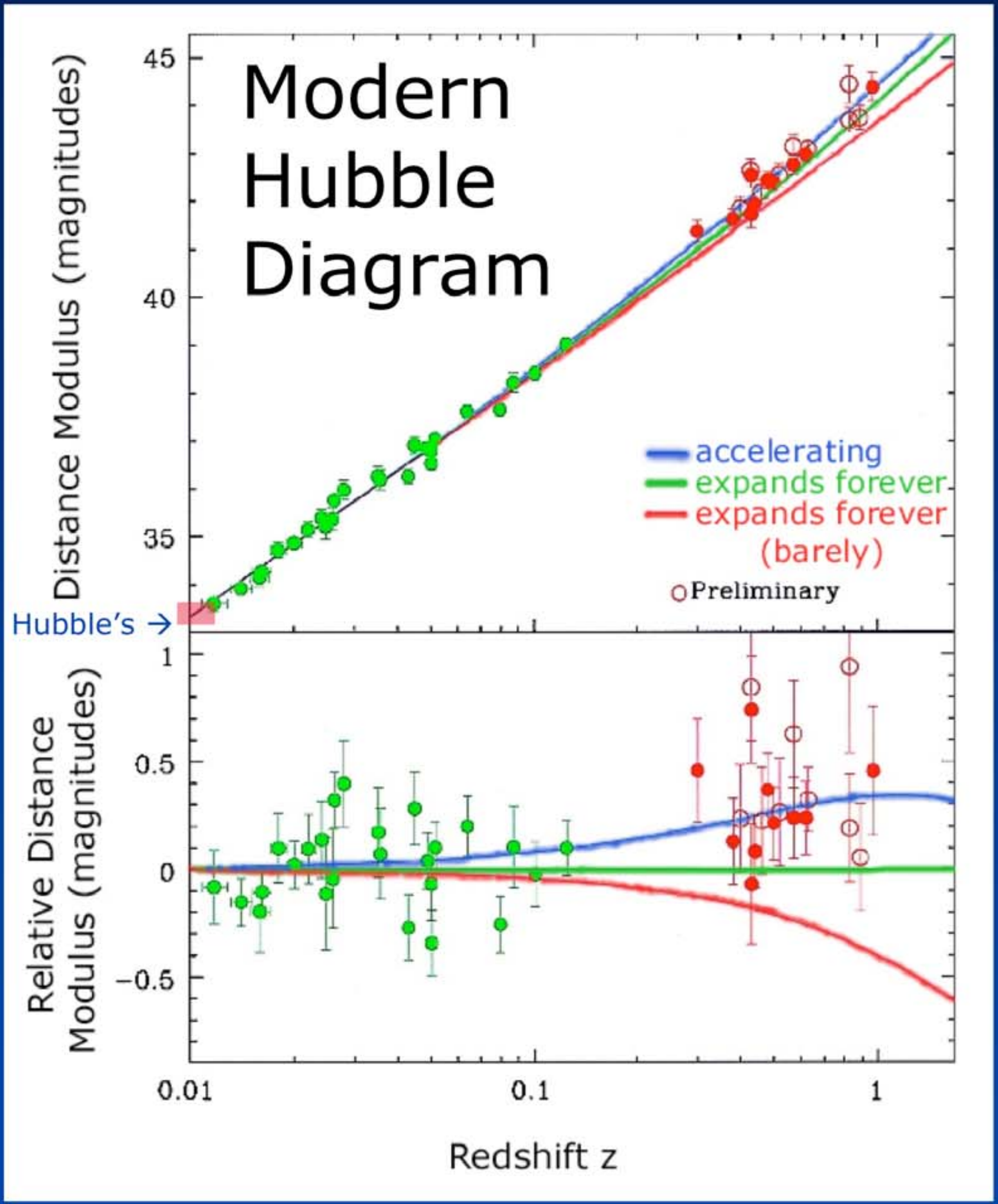
The universe as a time machine

- The speed of light is finite.
- Objects at different distances give us snapshots of the universe at the time that the light left.
- The redshift tells us how much the universe has expanded in that time.
- If we measure the redshift and distance for that snapshot, we can reconstruct a movie of the expansion for each epoch in cosmic history.

possible expansion histories



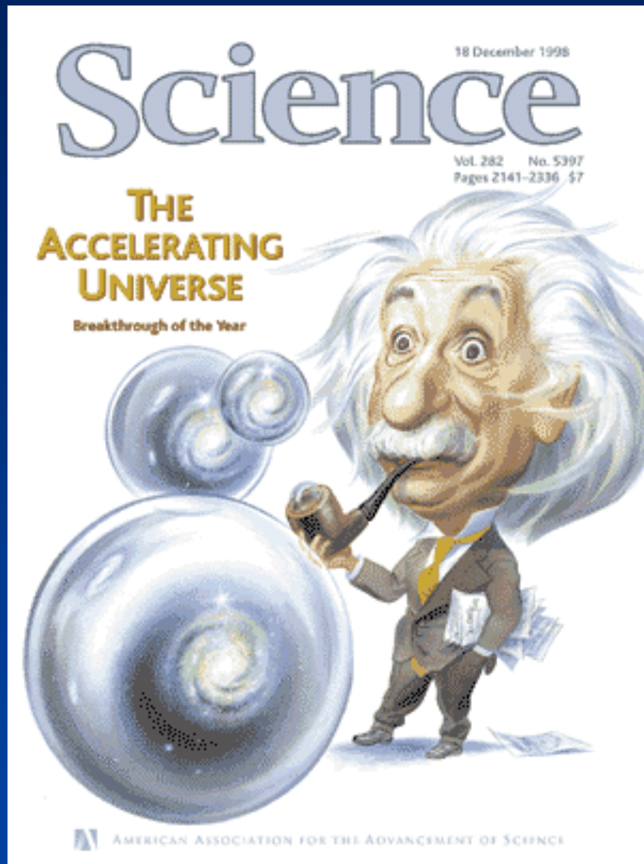
The accelerating universe

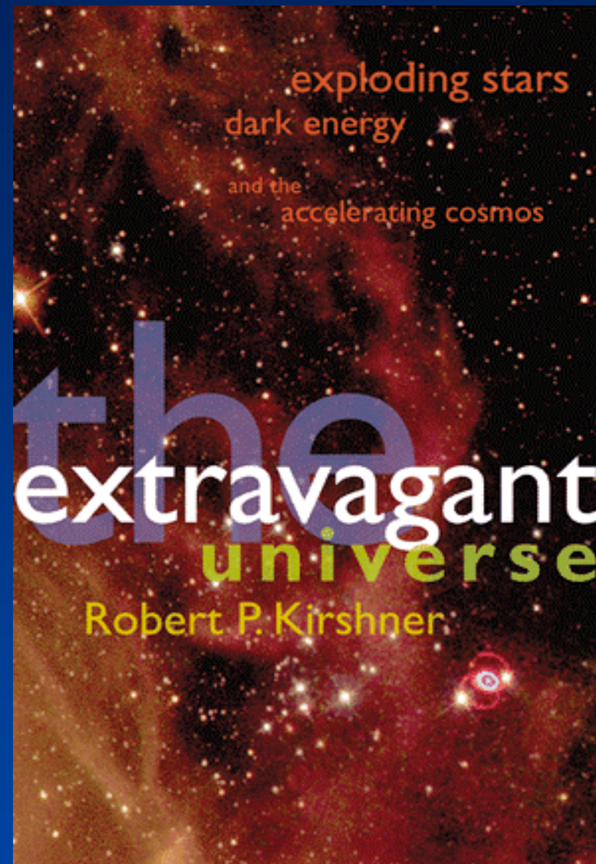


The unexpected 1998 discovery by 2 independent teams, the High-z SN Search Team (HZT) and the Supernova Cosmology Project (SCP).

only the HZT results are shown here

The accelerating universe





Return of the cosmological constant?

Λ

Dark Energy

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  Type Ia Supernovae at Infrared Wavelengths

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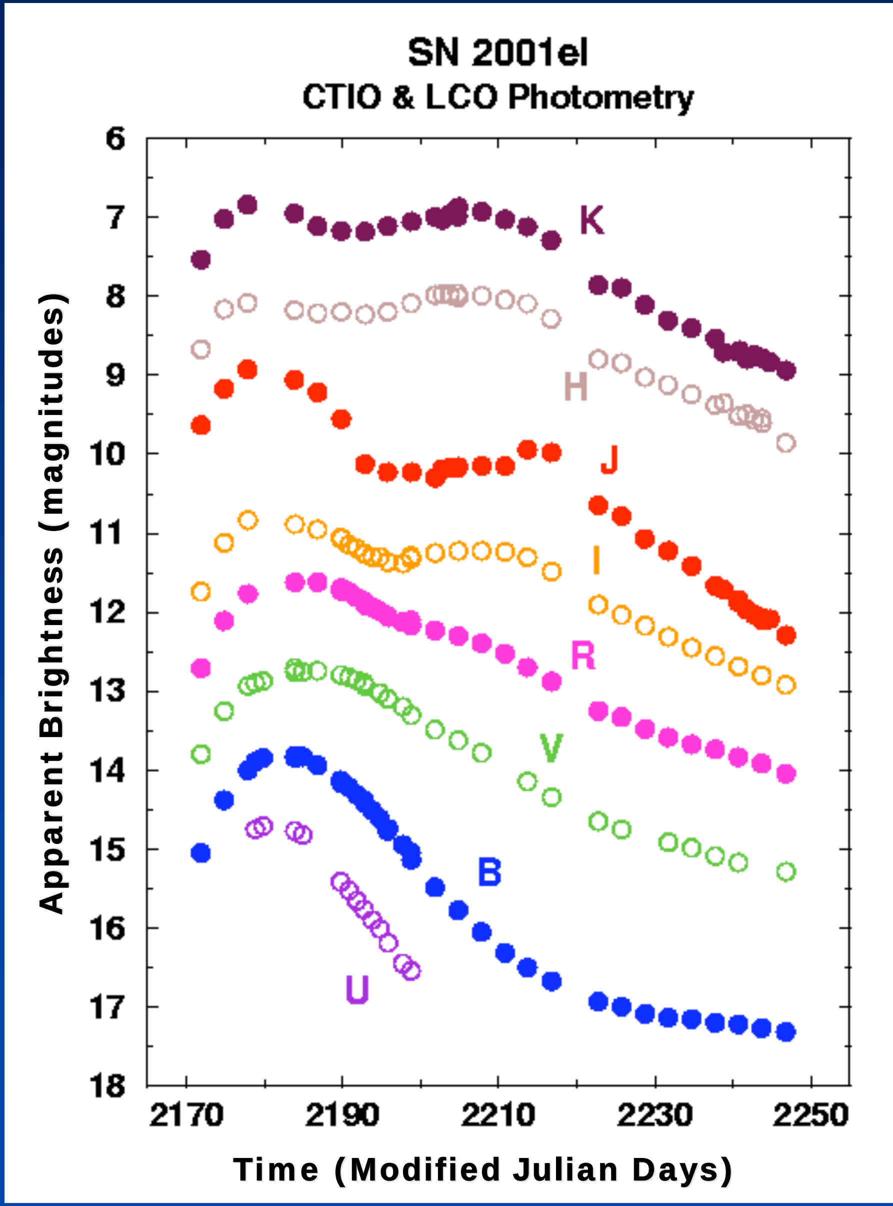
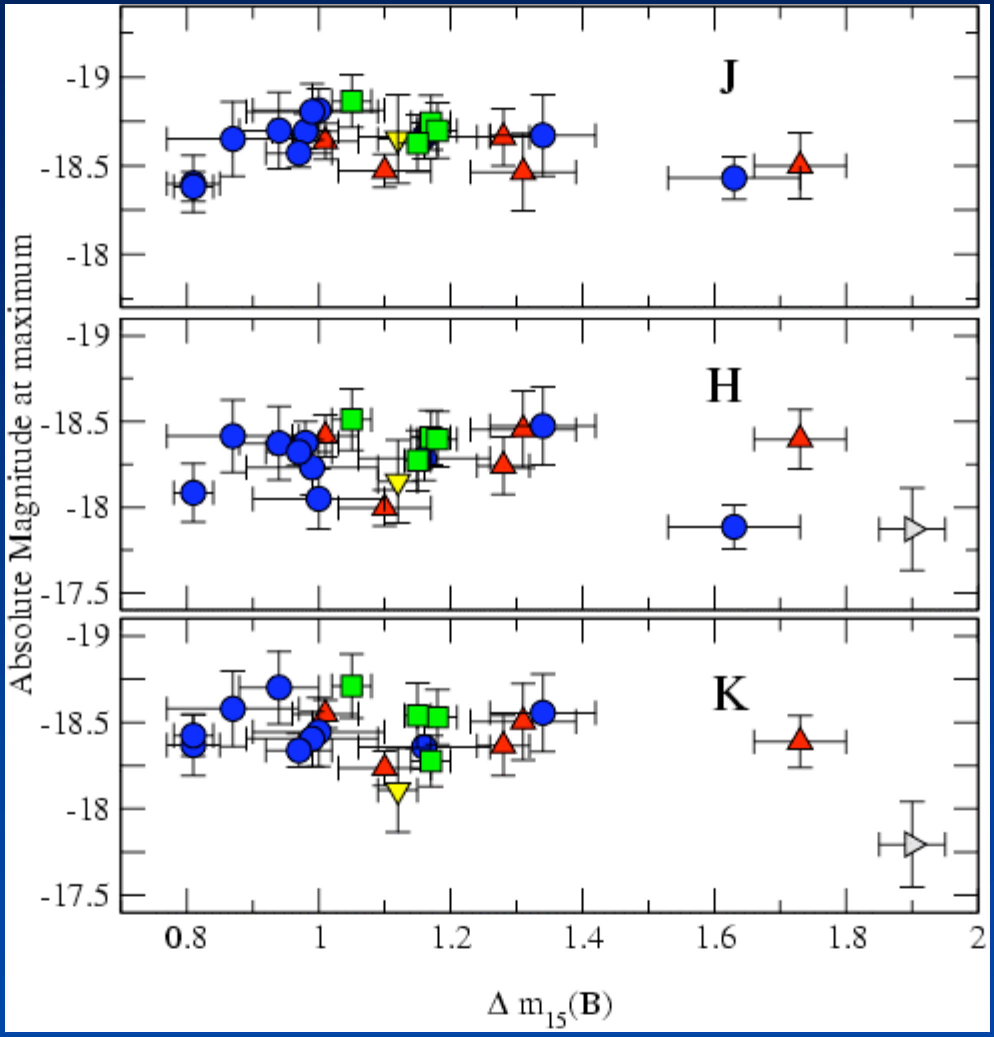
Type Ia light curves



- 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

Infrared Type Ia Supernovae



Type Ia Supernovae may be better standard candles at infrared wavelengths vs. optical wavelengths.

Krisciunas et. al 2005

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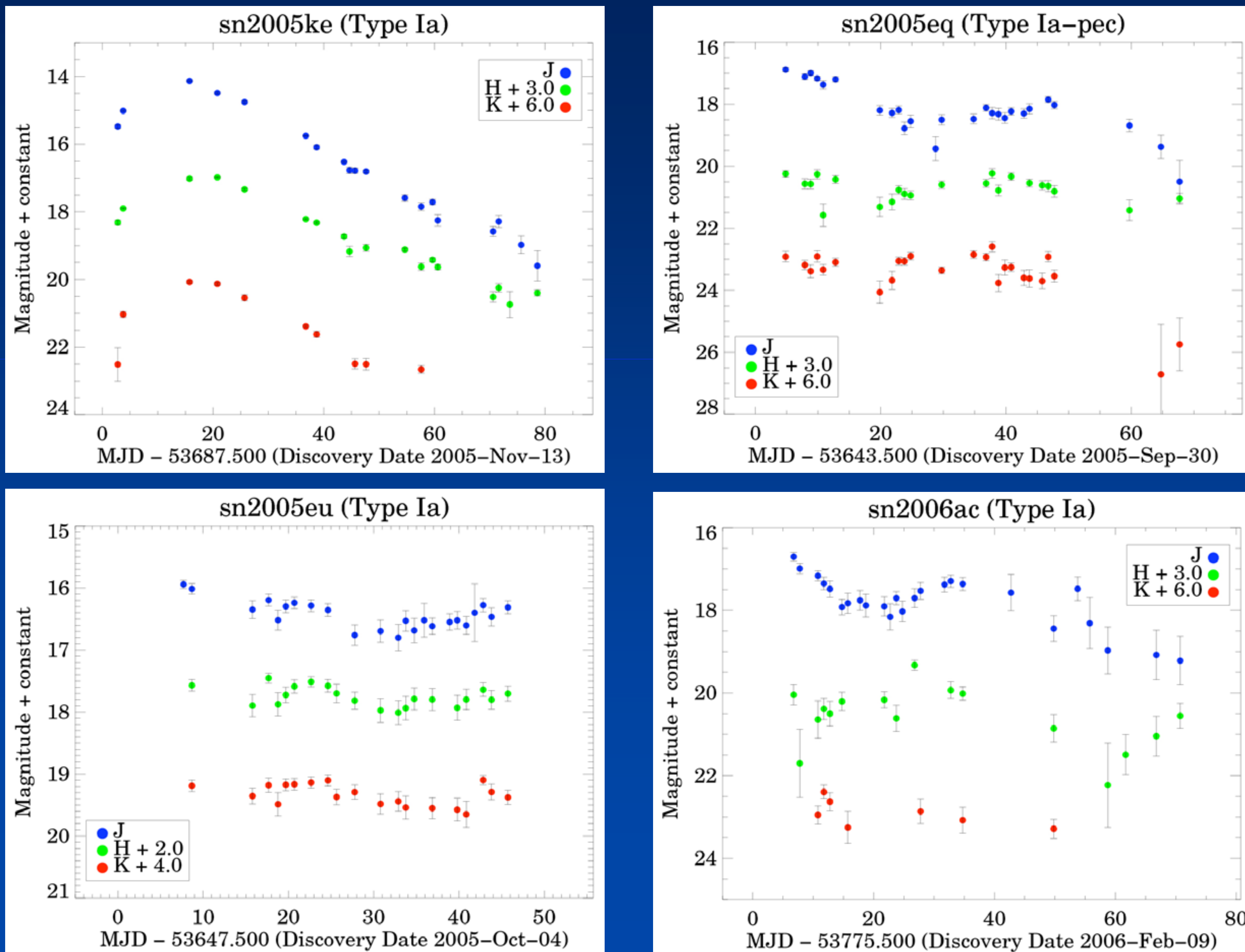
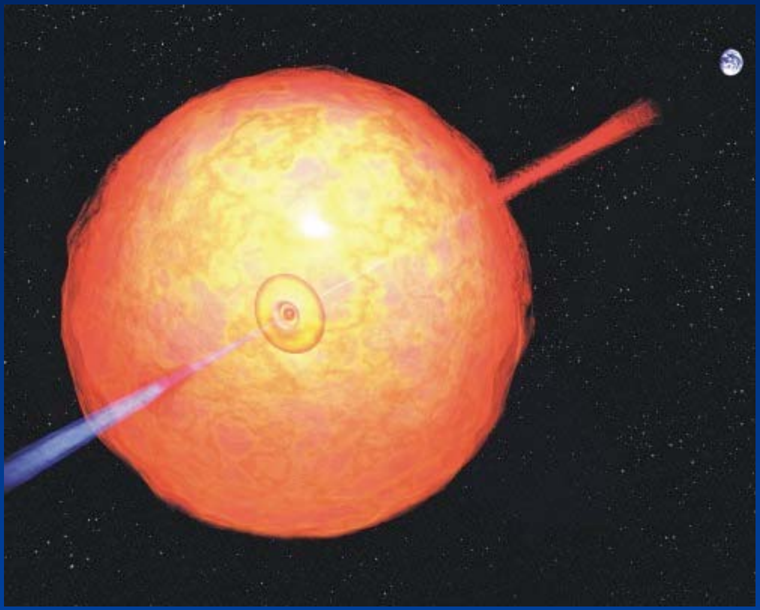
Mount Hopkins, Arizona

Infrared Type Ia Light Curves

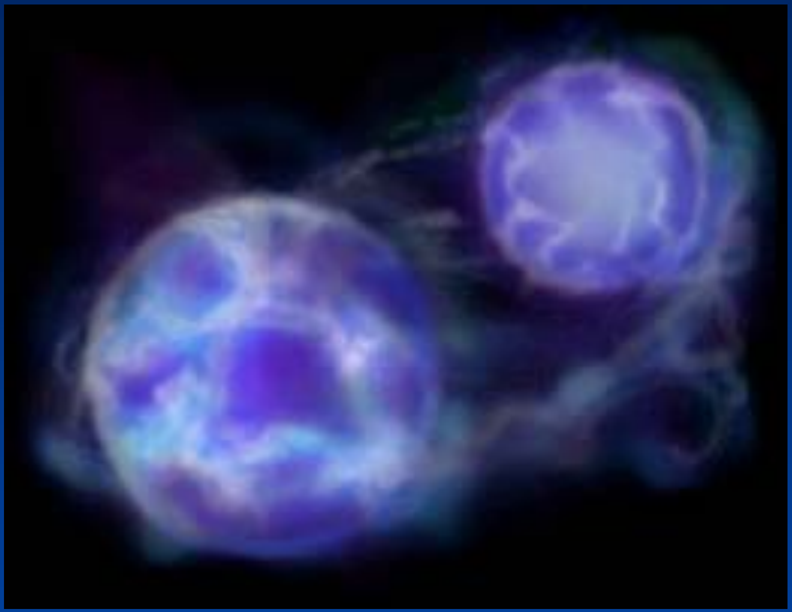


Gamma-ray bursts (GRBs)

The Brightest Explosions in the Universe!



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



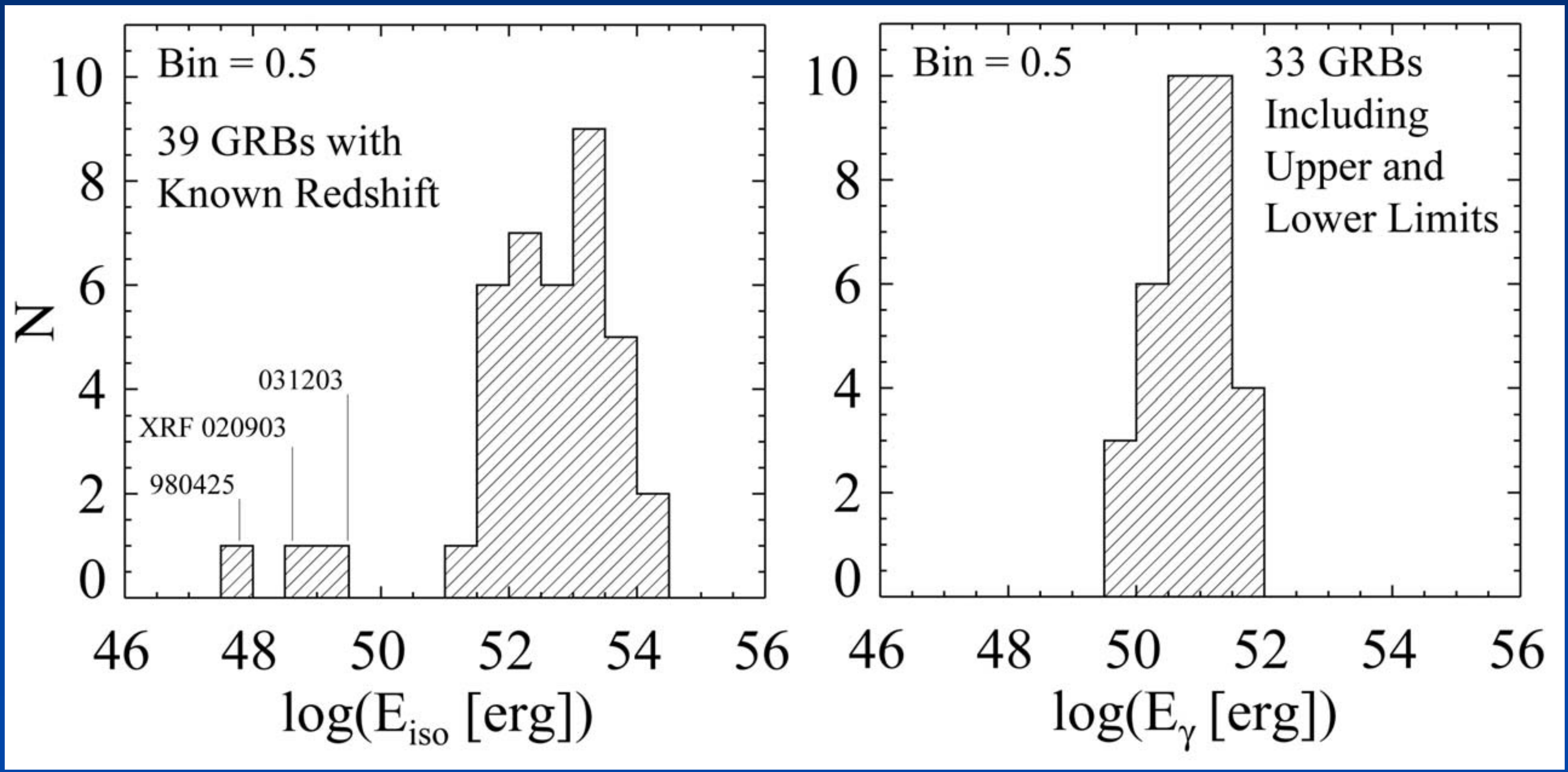
Short GRBs – Probably Merging Neutron Stars

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

GRB Energetics

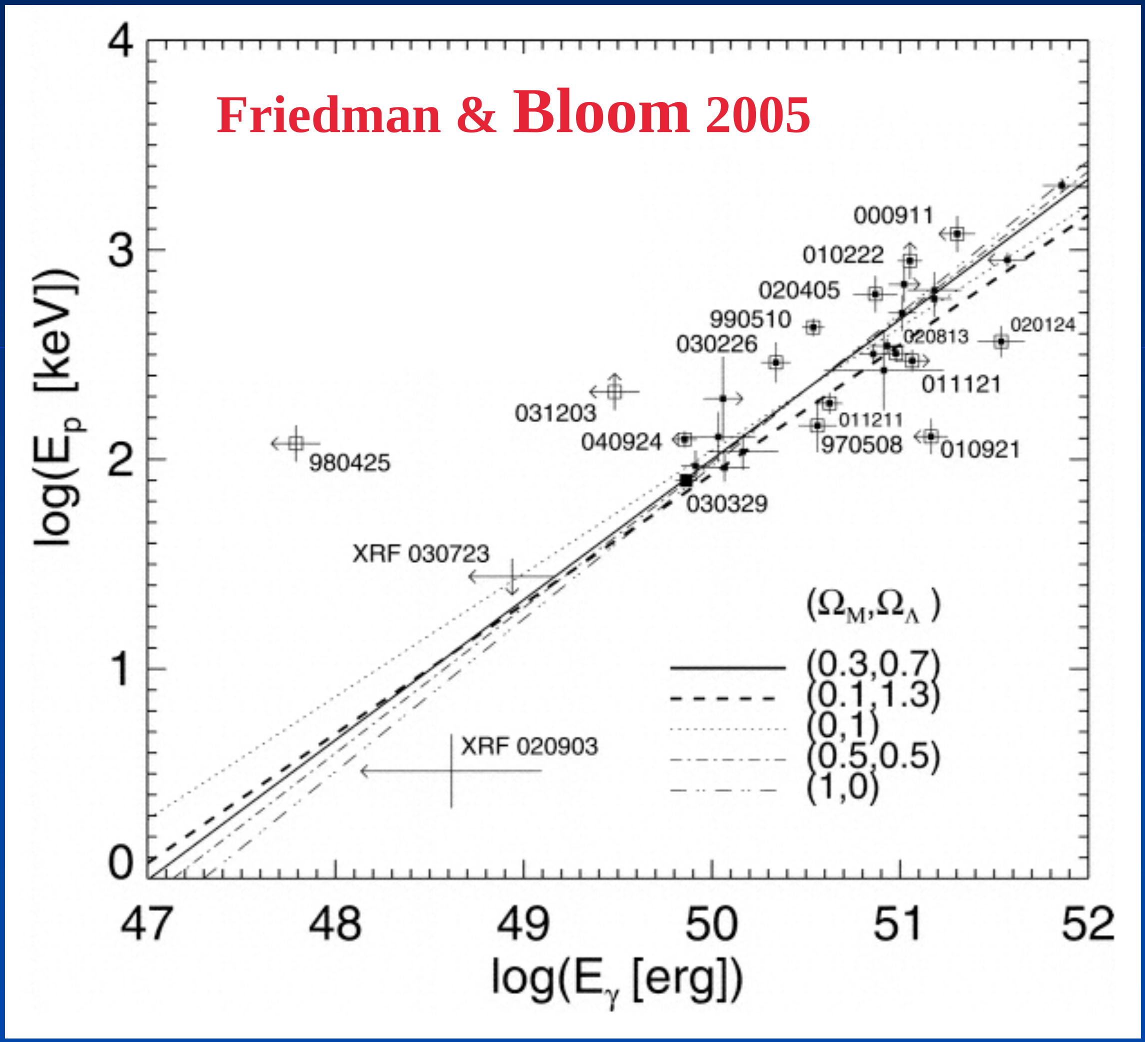
The isotropic equivalent gamma-ray energy E_{iso} is a ***bad*** *standard candle*

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



Data from: Friedman & Bloom 2005

Grb standardized candles

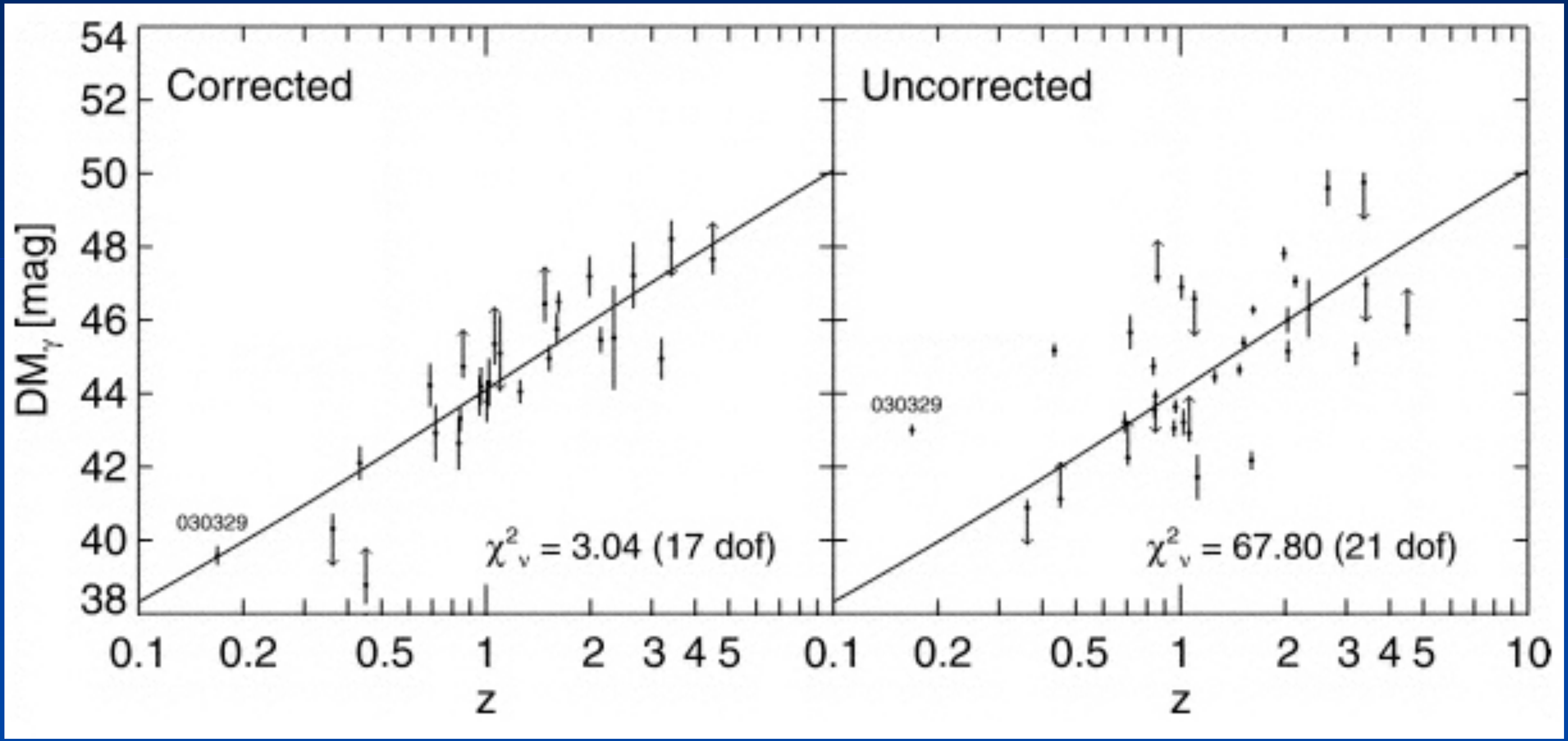


Y-axis: Ep
The peak energy at which most of the gamma-ray light is emitted (*this is like the dominant gamma-ray color of the GRB*)

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

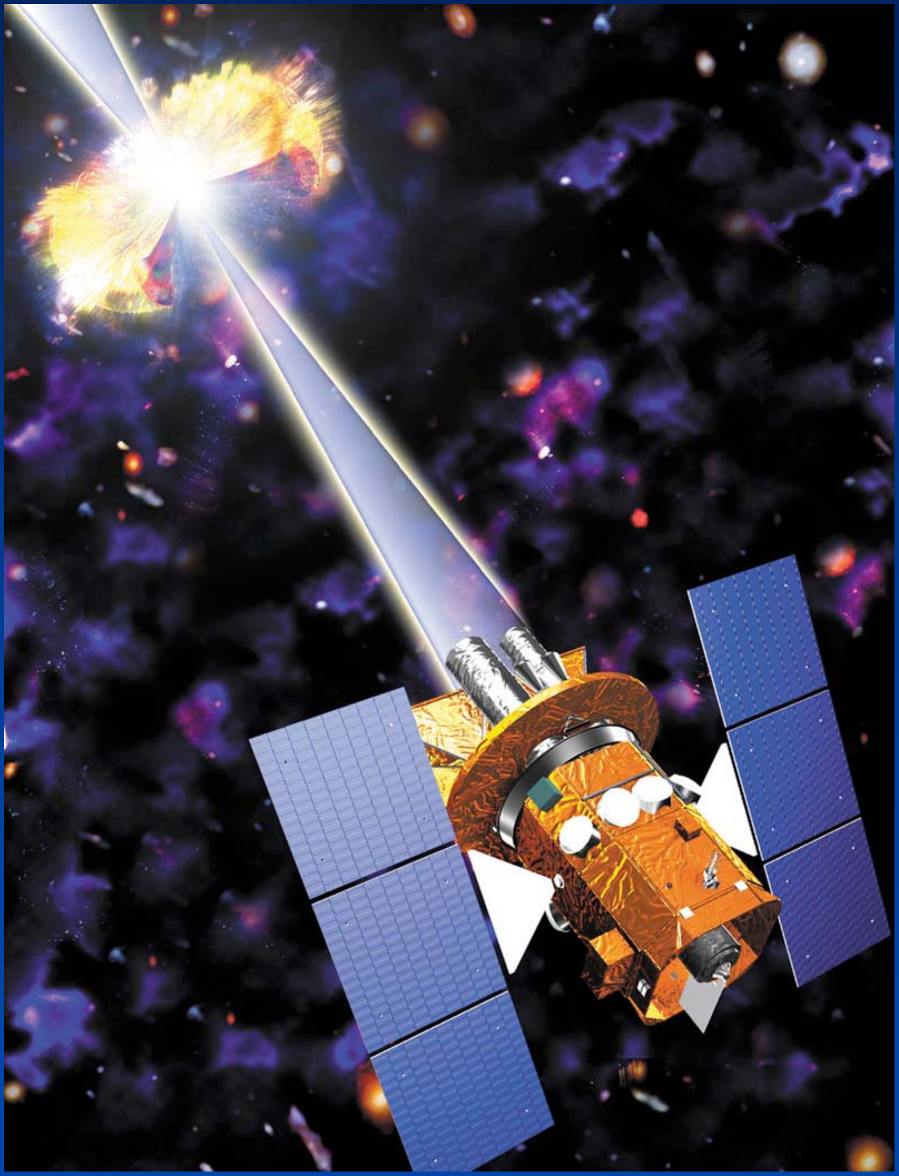
Grrb Hubble diagram

E_p and E_γ **E_γ**

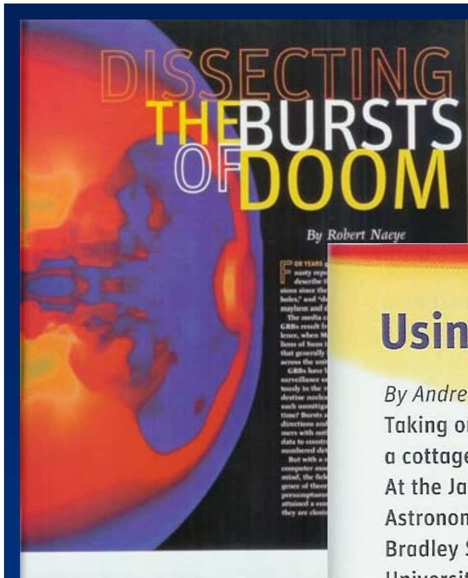


Friedman & Bloom 2005

Nasa swift satellite



Sky & Telescope, Aug 2006



SKY & TELESCOPE

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.*

100 billion years of solitude

The Friedmann equations

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

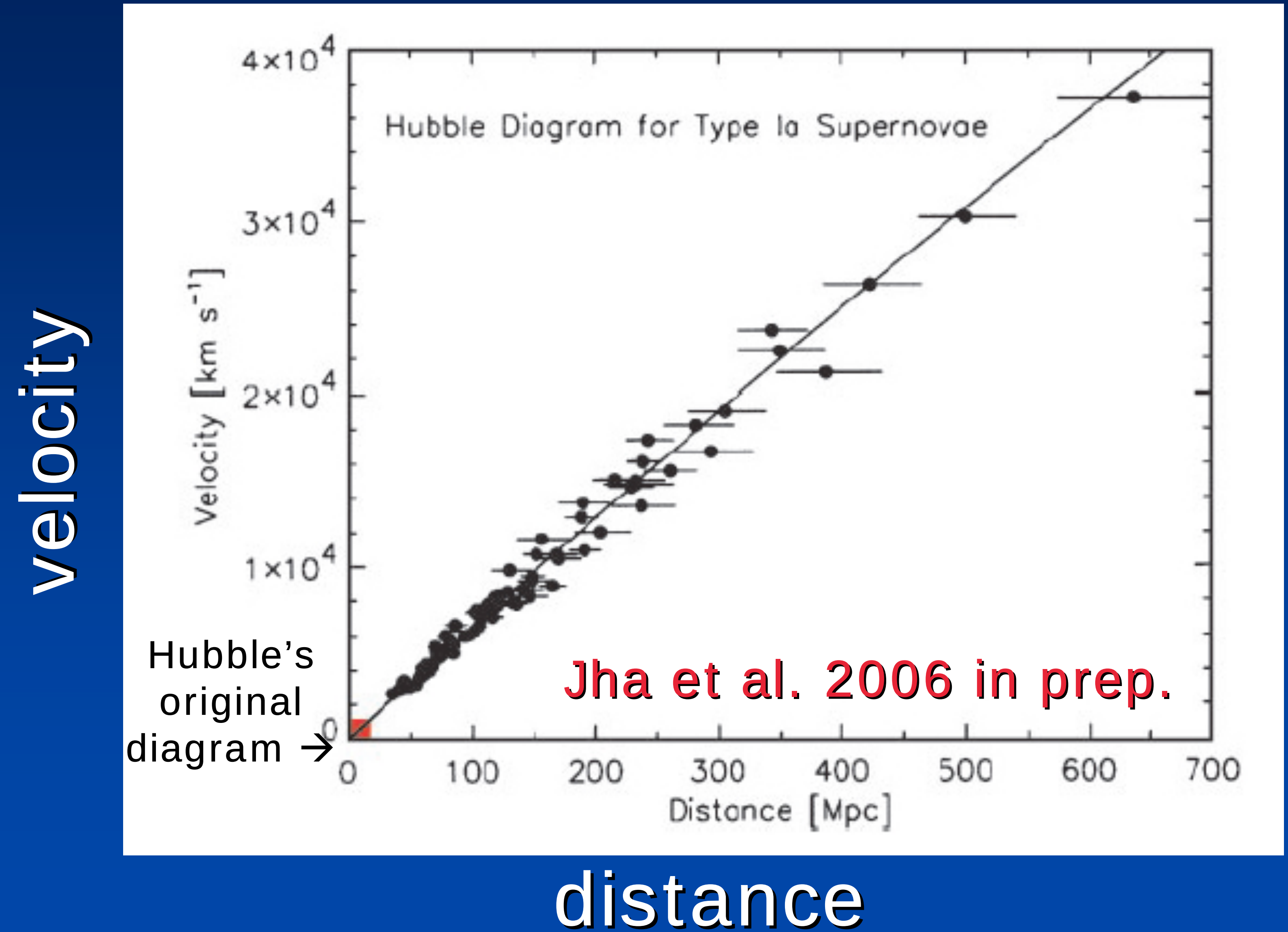
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

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

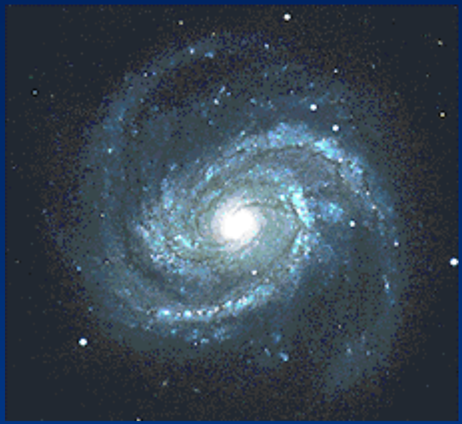
Einstein introduced General Relativity in 1915 but these solutions were not found until 1922, by Friedmann

Alexander Friedmann 1888-1925

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**

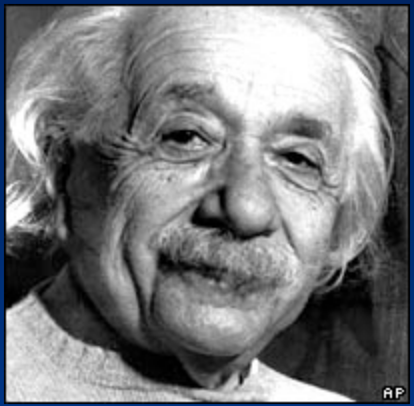
Einstein's theory of gravity

Einstein's Field Equation

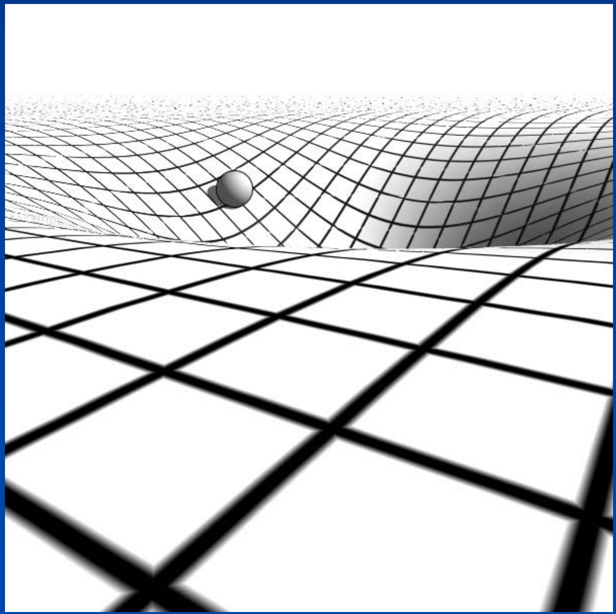
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

The curvature of space-time

The matter energy content of space-time

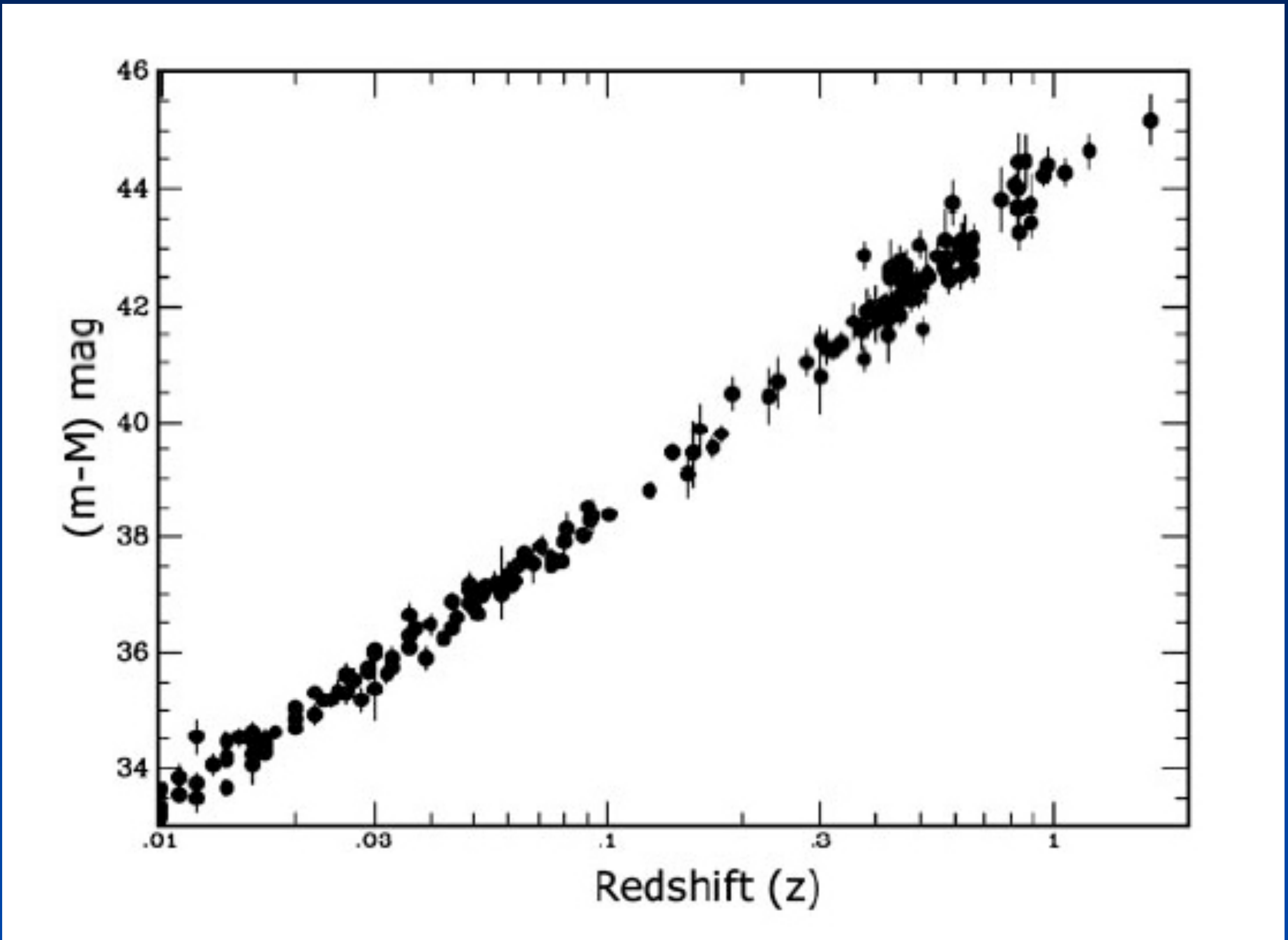


- Matter and Energy tell space and time how to curve.
- The curvature of space and time tells matter and energy how to move.
- In general relativity, **gravity is curved space-time**!



High redshift Hubble diagram

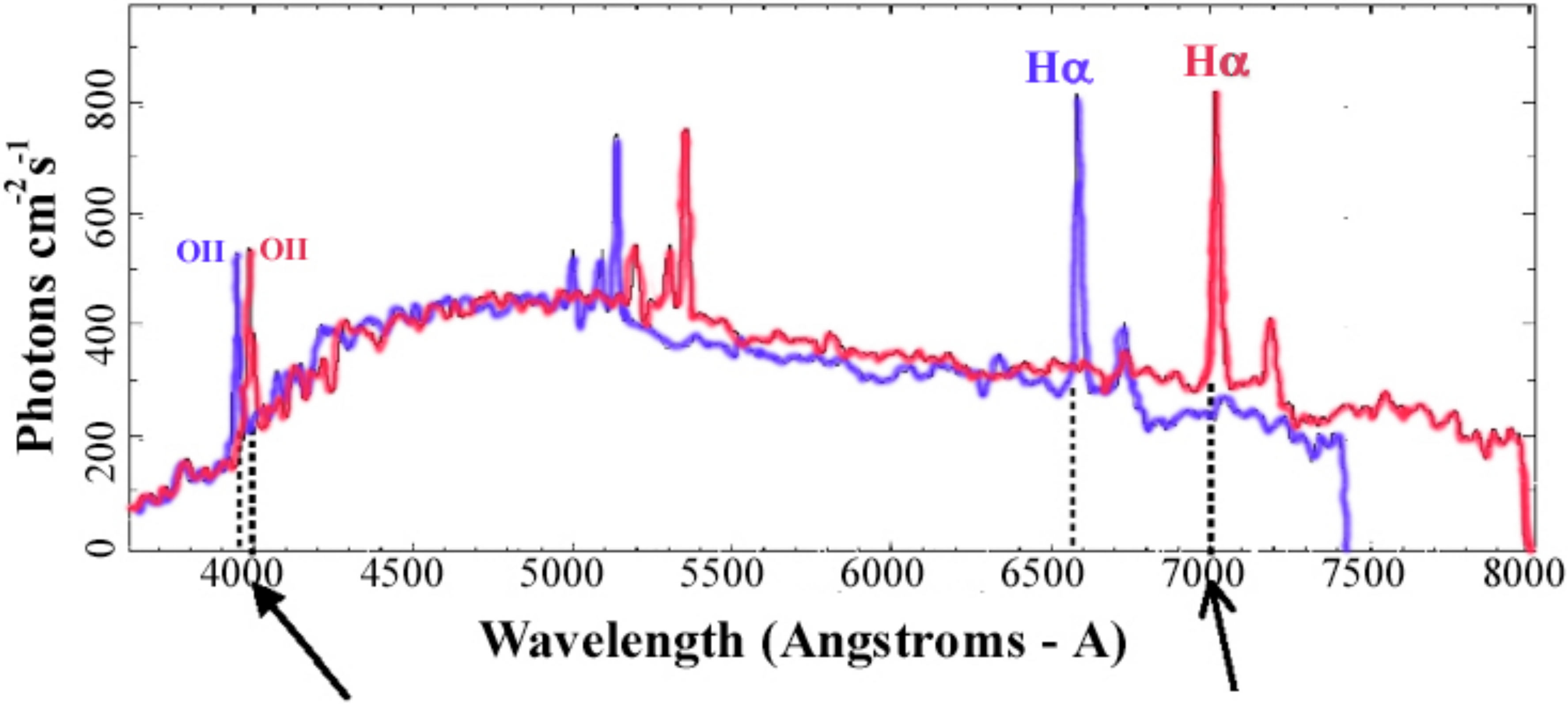
Distance modulus



Redshift (i.e. velocity)

Redshift

Find the Redshift of a Galaxy From its Spectrum



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.

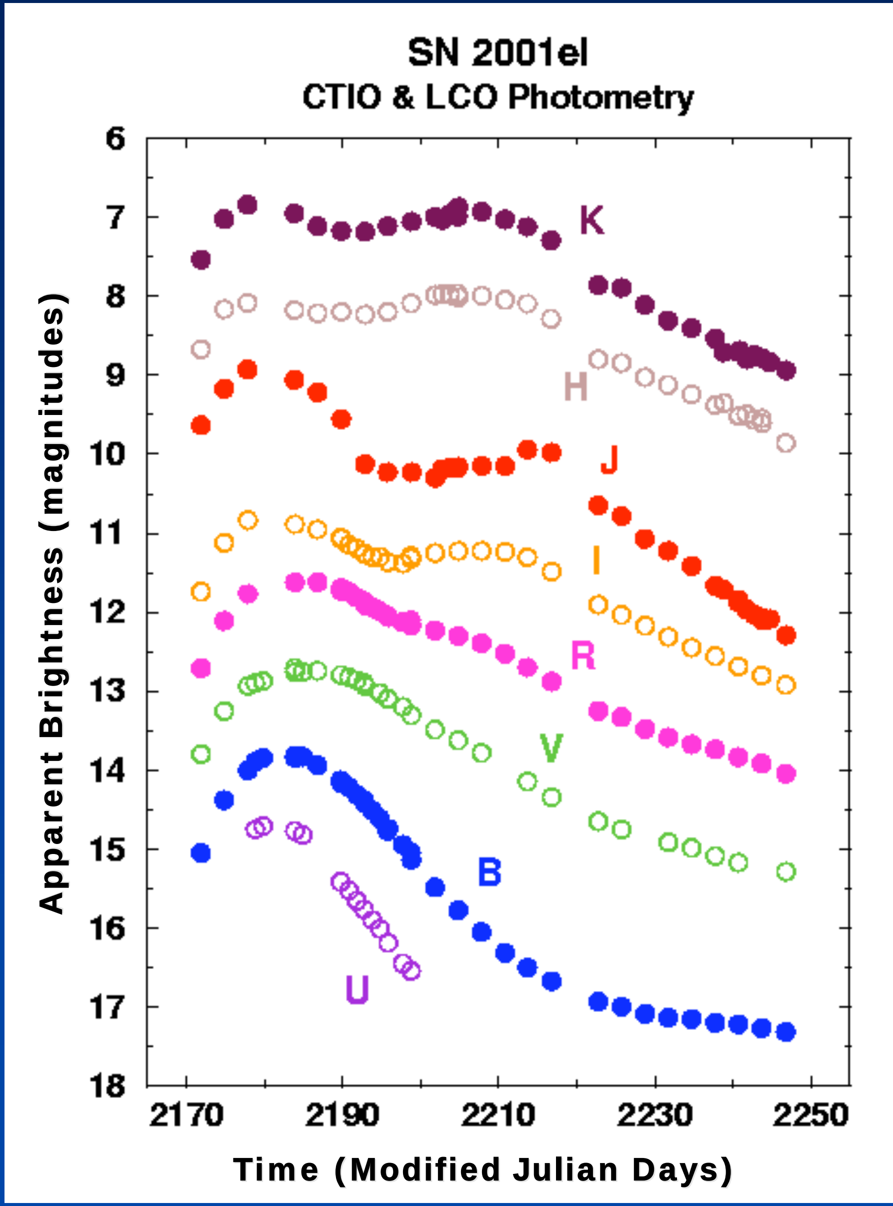
$$F_{\nu_o} = (1+z)\frac{L_{\nu_e}}{4\pi D_L^2} = (1+z)\frac{L_{\nu_e}}{L_{\nu_o}}\frac{L_{\nu_o}}{4\pi D_L^2} \tag{13}$$

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

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.

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

Type Ia light curves



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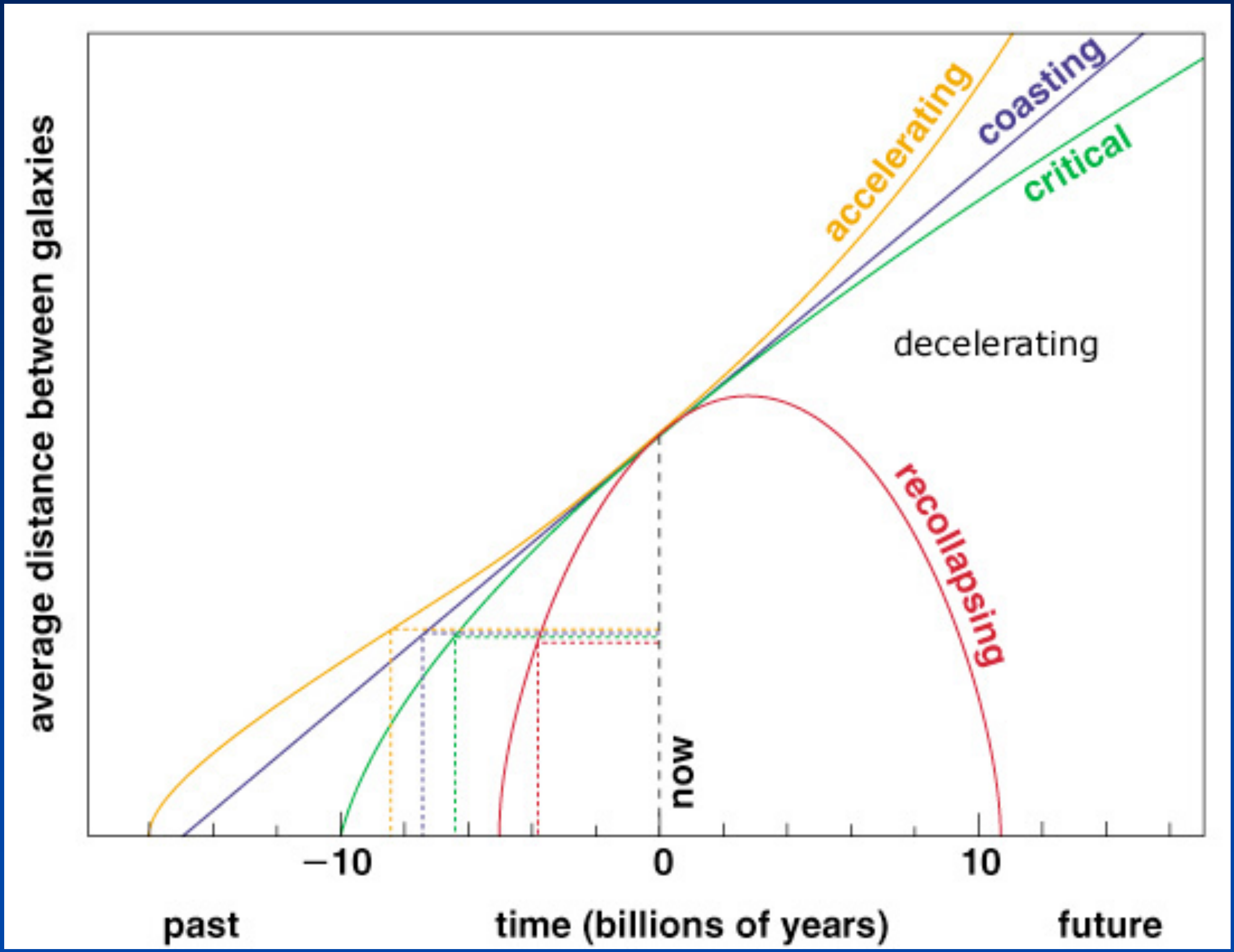
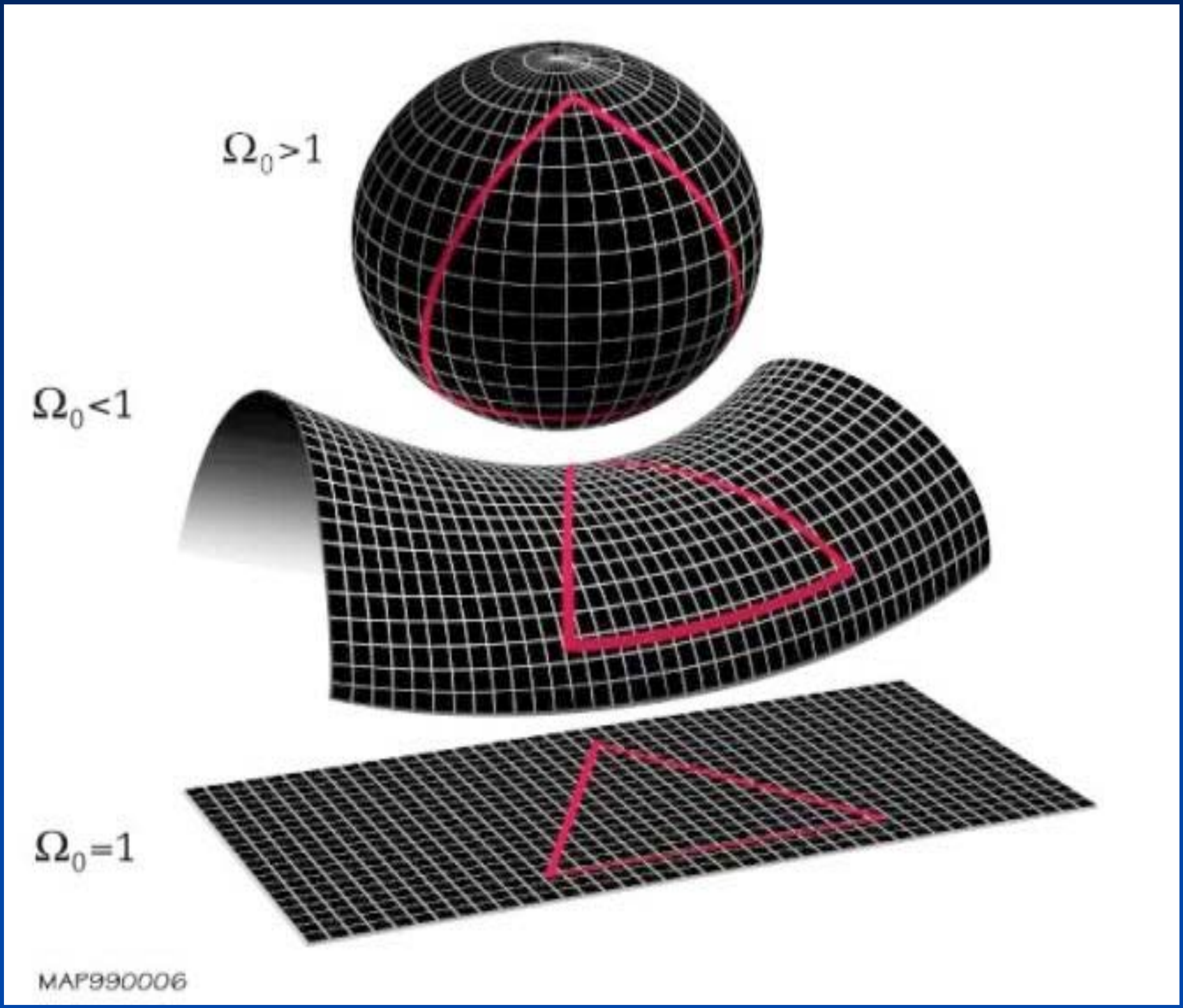
possible expansion histories



Geometry of the universe



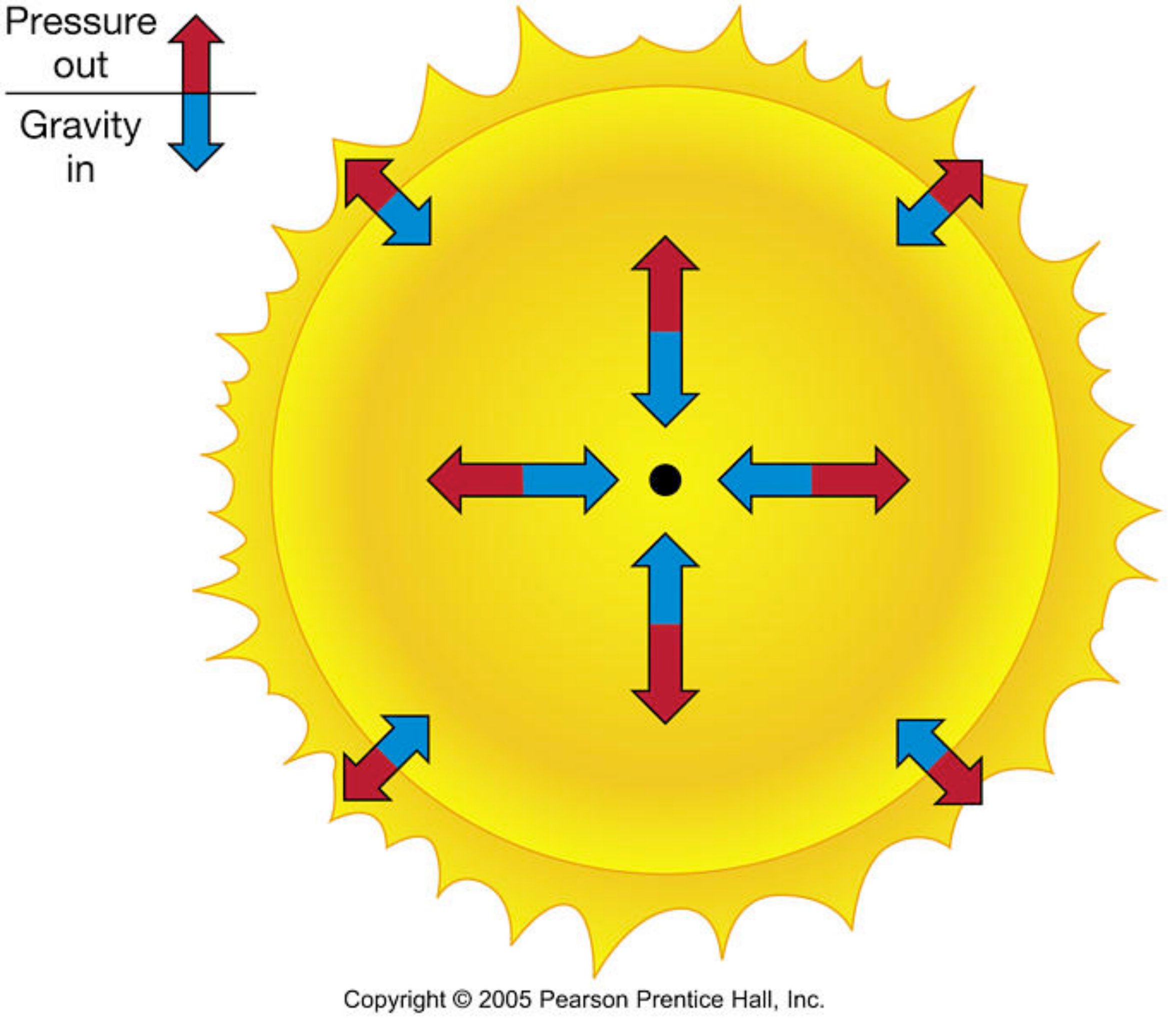
Closed

Open

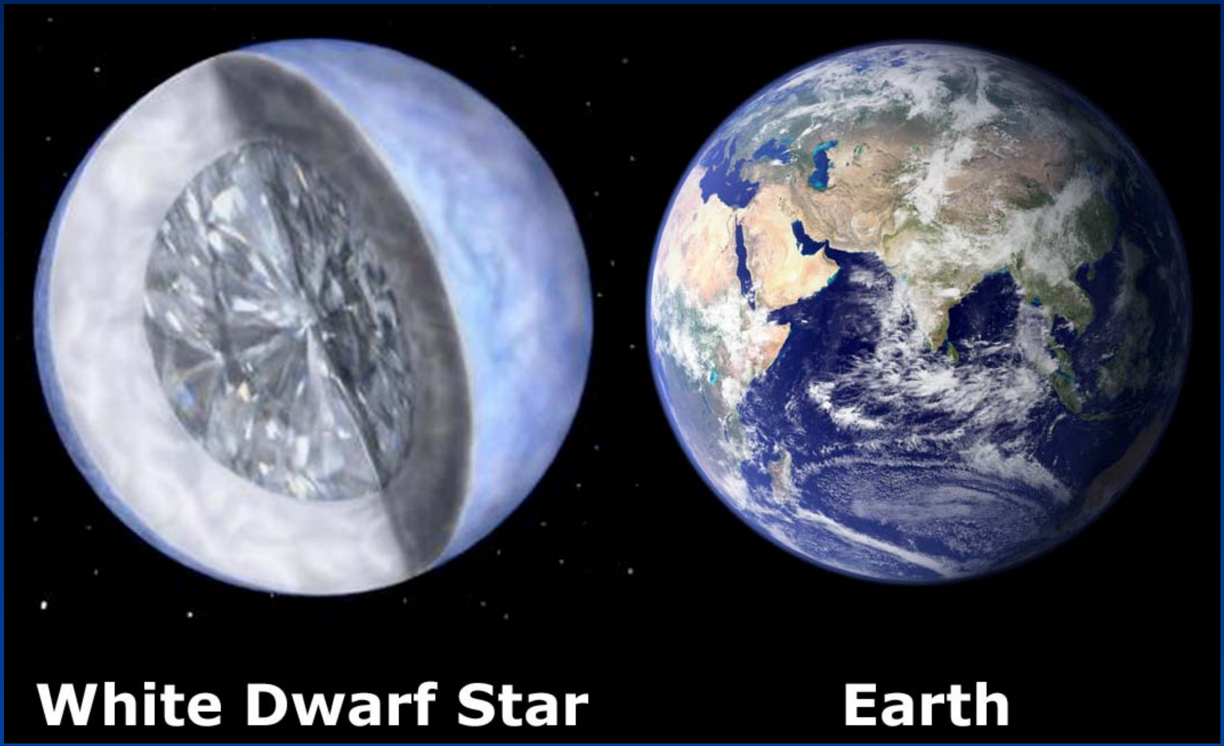
Flat

Star wars

• Gravity vs. pressure.



White dwarfs

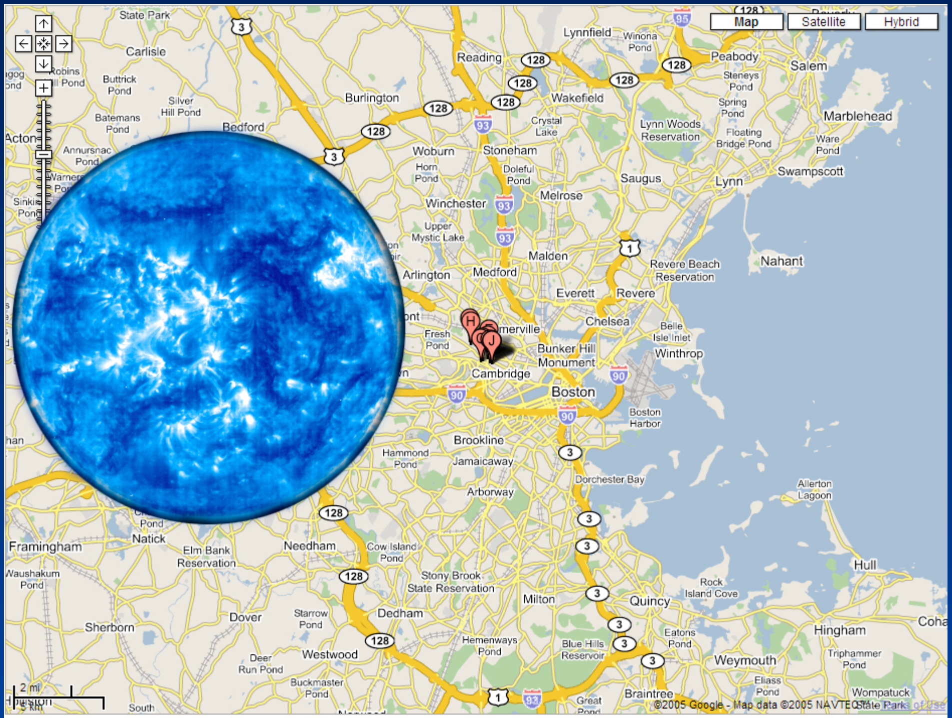


- A White Dwarf star is a dead star (i.e. no nuclear fusion), about as massive as the sun, but shrunk to the size of the Earth.
- WDs are held up by the pressure from the mutual repulsion of their electrons

White dwarfs

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

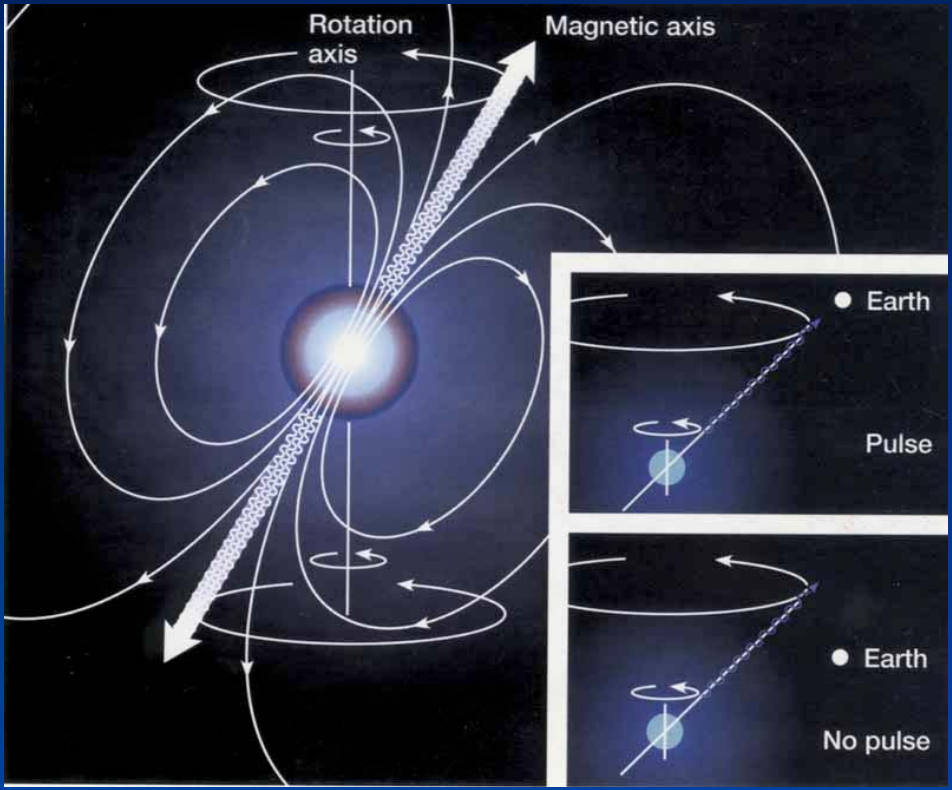
Neutron stars



Neutron Star to Attend Harvard

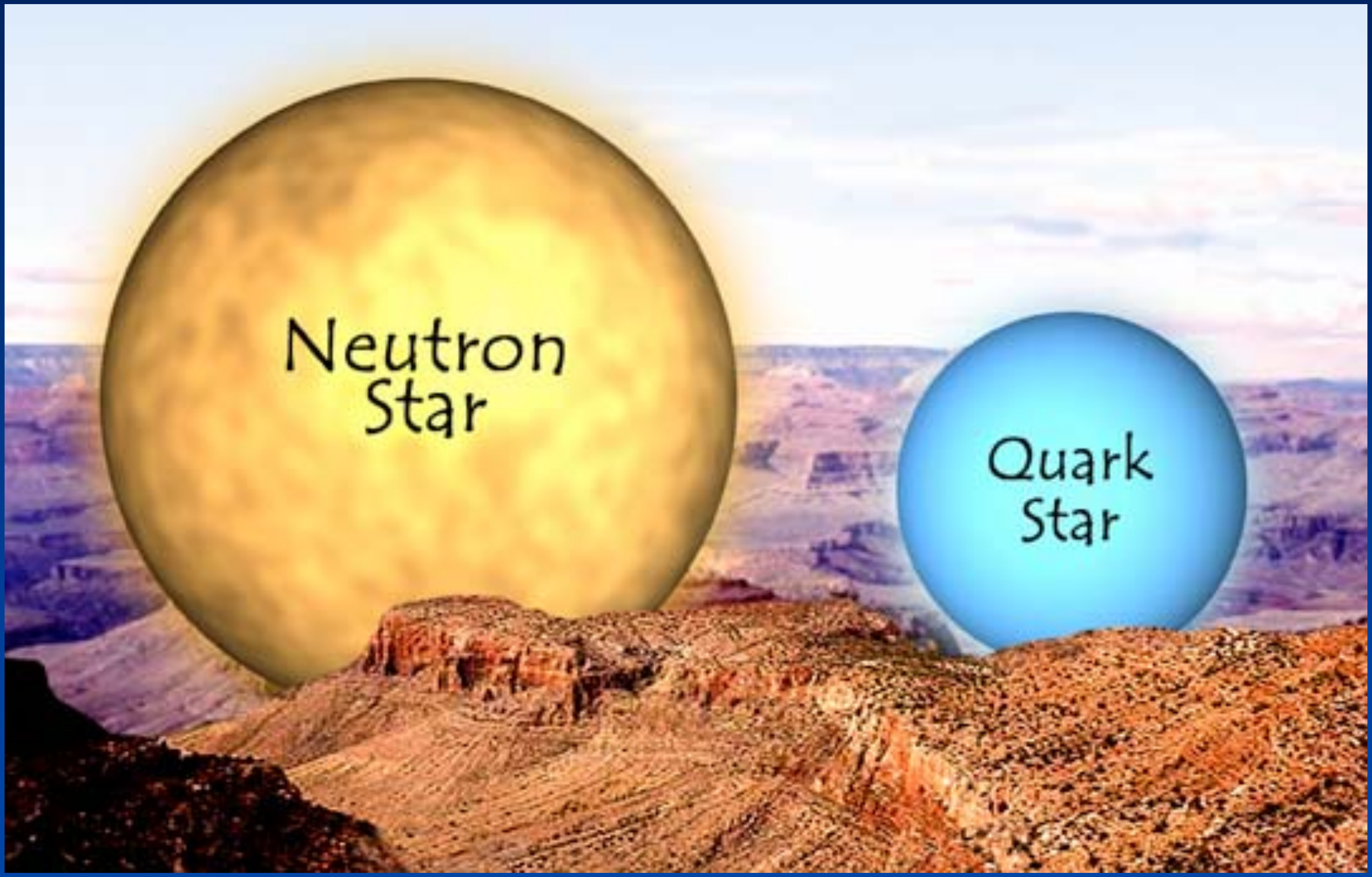
- A Neutron Star (NS) is a dead star (no fusion) as massive as the sun, but the size of a city.
- NSs are held up by the pressure from the mutual repulsion of their neutrons

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

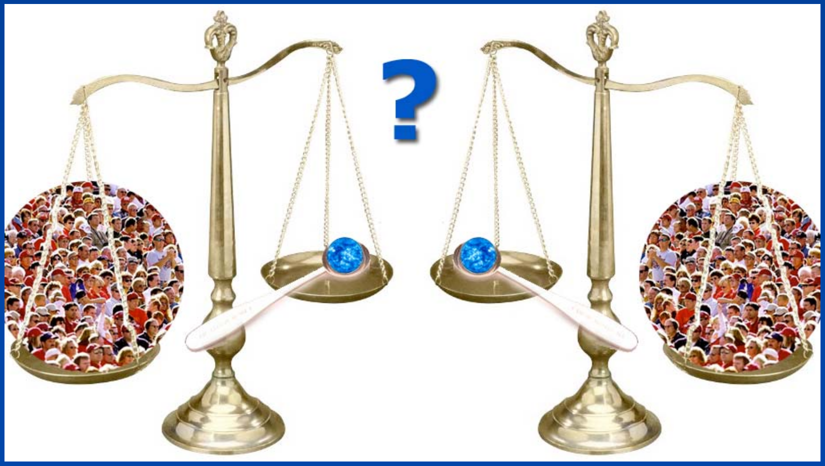
Star wars

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?

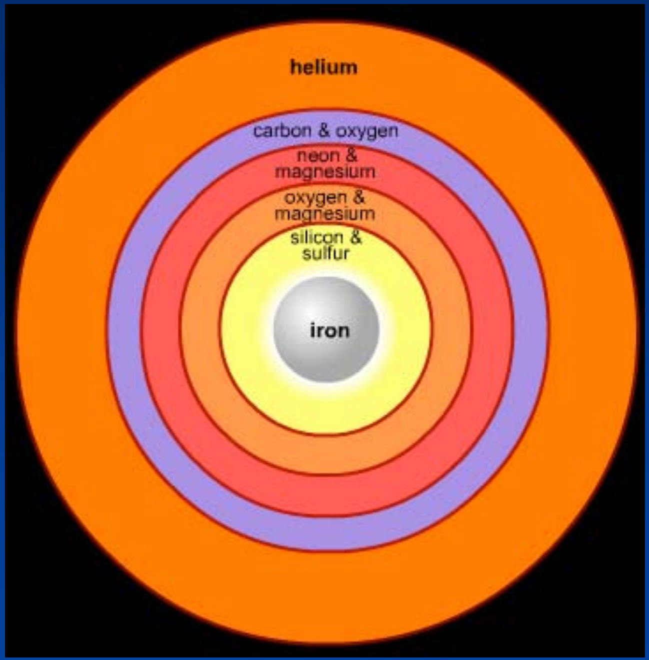
- The guest lecturer
- A teaspoon of material from the sun's core
- A teaspoon of white dwarf material
- A teaspoon of neutron star material
- The mass of all six billion human beings on Earth



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

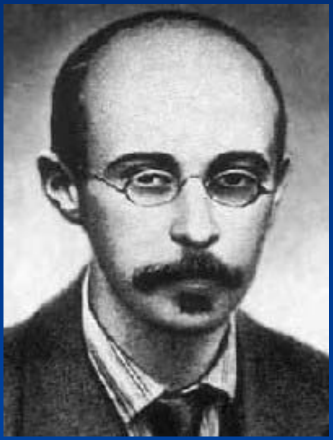
The Friedmann equations

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