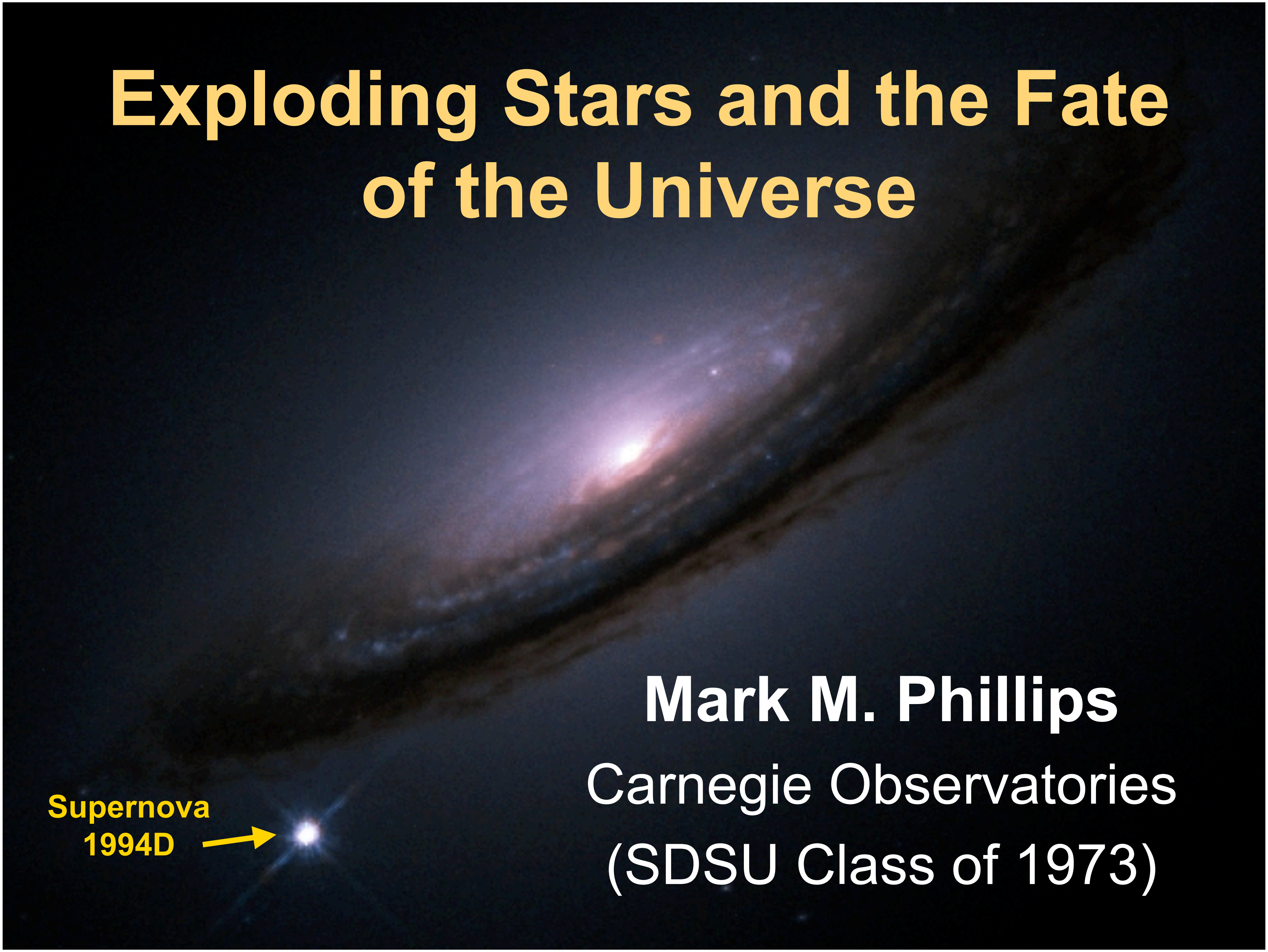
Exploding Stars and the Fate of the Universe



Mark M. Phillips
Carnegie Observatories
(SDSU Class of 1973)

Summary of Talk

- The Mystery of the “Guest Stars”
- How Do Stars Explode?
- Exploding Stars and the Fate of the Universe

Supernova 2006X: A star that exploded 60 million years ago

The Mystery of the "Guest Stars"

The “Guest Star” of 1054

In 1054, Chinese astronomers noted the appearance of a “Guest Star” in the constellation of Taurus

The star was also noted in Japanese and Arabian records, and may have been depicted by Anasazi artists in a pictograph at Chaco Canyon

The Guest Star of 1054 was 4 times brighter than Venus at maximum brightness, and was visible in daylight for 3 weeks

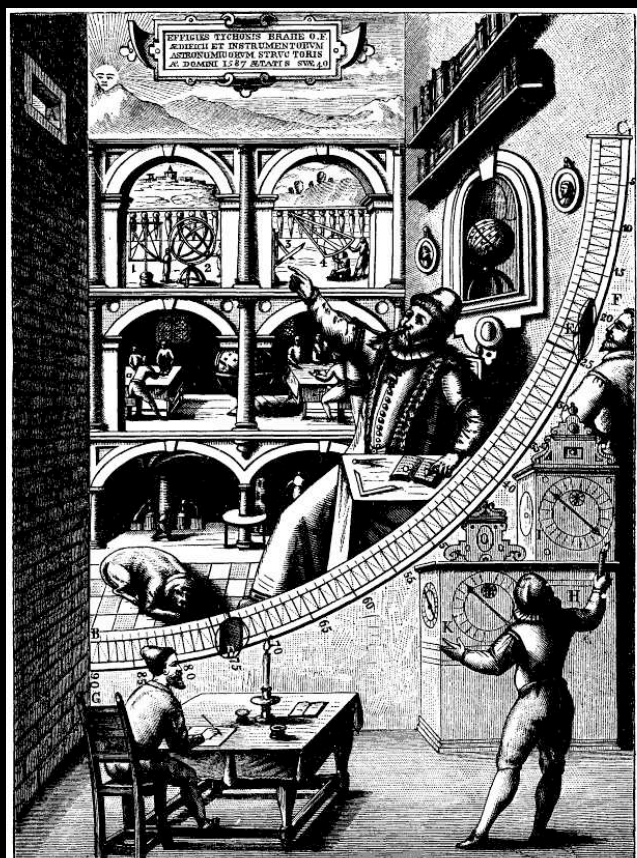
It was visible at night for more than 2 years

From the *Sung hui-yao* by Chang Te-hsiang:

"…during the fifth month of the first year of the Chih-ho reign period, [the Guest Star] appeared in the morning in the east guarding T'ien-Kuan [ζ Tauri]. It was visible in the day like Venus, with pointed rays in all four directions. The color was reddish-white... It was seen altogether for 23 days [as a daylight object]."

"…On the day Hsin-Wei [April 17, 1056] the third month in the first year of the Chia-yu reign period [March 19 - April 17, 1056] the Director of the Astronomical Bureau said, `The Guest Star has become invisible, which is an omen of the departure of the guest'."

Tycho Brahe (1546-1601)



A Danish nobleman famed for his accurate and comprehensive astronomical and planetary observations

On his way home the evening of November 11, 1572, he noticed a “new star” in the constellation of Cassiopeia

Tycho's "Nova Stella"

"I suddenly and unexpectedly beheld near the zenith an unaccustomed star with a bright radiant light. Astounded, as though thunderstruck by this astonishing sight, I stood still and for some time gazed with my eyes fixed intently upon this star.

It was near the stars, which have been assigned since antiquity to the asterism of Cassiopeia. I was convinced that no star like this had ever before shone forth in this location."

Tycho's new star was brighter than Venus at maximum, and was visible to the naked eye for 16 months

Johannes Kepler (1571-1630)

A great German astronomer and mathematician.

He was an assistant of Tycho Brahe, and used Brahe's observations to derive his famous laws of planetary motion.

Kepler is also famous for his observations of a "new star" that appeared in October 1604

Kepler's "Nova Stella"

Kepler did not actually discover the "new star", but carried out extensive observations of it.

Both Kepler and Galileo used parallax arguments to prove that the new star could not be close to the earth.

Galileo used the appearance of this new star in 1604 to argue against Aristotle's belief that the heavens were unchanging and immutable.

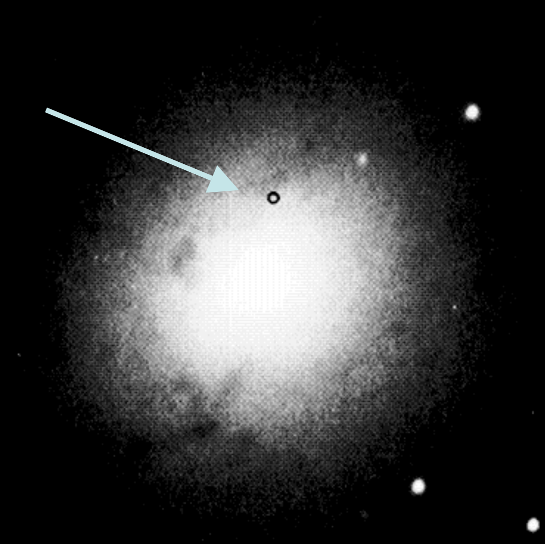
Kepler's new star was brighter than any other star at maximum brightness, and was visible to the naked eye for 12 months

Carl Ernst Albrecht Hartwig (1851-1923)

German astronomer who joined the staff of the Dorpat Observatory in Estonia in 1884

On August 20, 1885, Hartwig discovered a "new star" in the Andromeda Nebula (M 31)

S Andromeda in M 31



S Andromeda reached a maximum brightness of 6 magnitudes (not quite visible to the naked eye) and was observed for more than 100 days

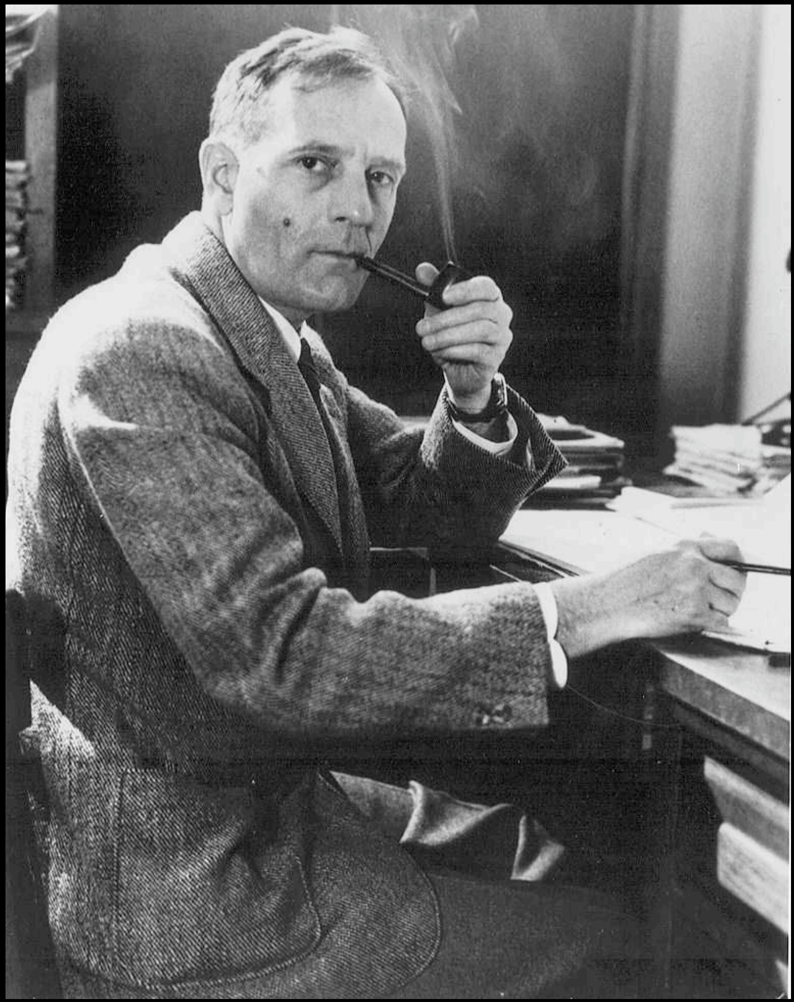
The appearance of this “new star” reactivated the debate over the nature of the “spiral nebulae” such as M 31

Edwin Hubble (1889-1953)

In 1923, an American astronomer with movie star looks, Edwin Hubble, used the new 100-inch telescope at the Mt. Wilson Observatory to photograph M31

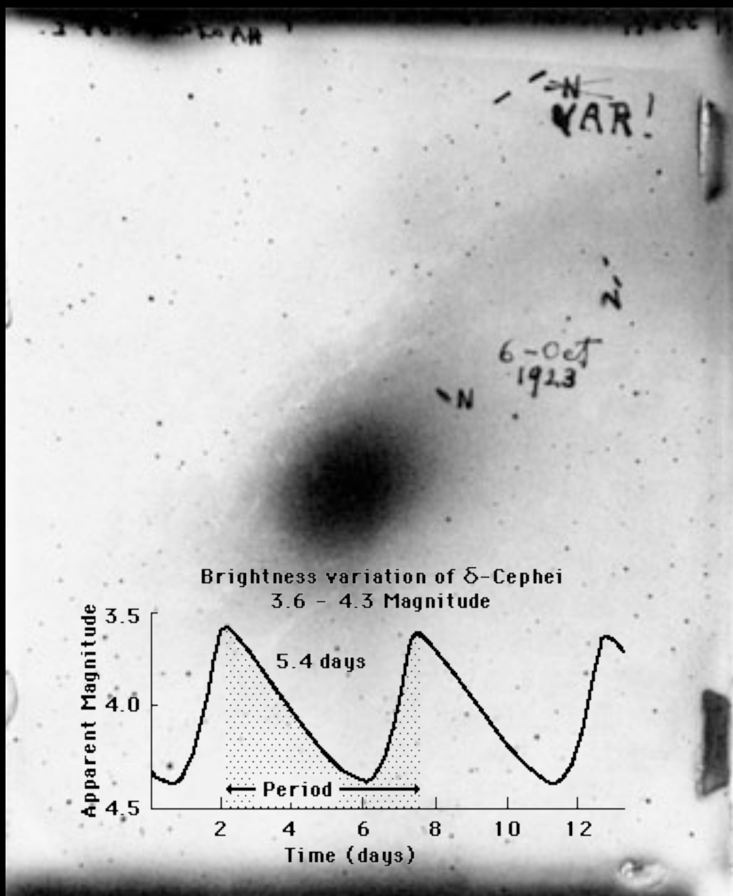
For the first time ever, it was possible to distinguish individual stars

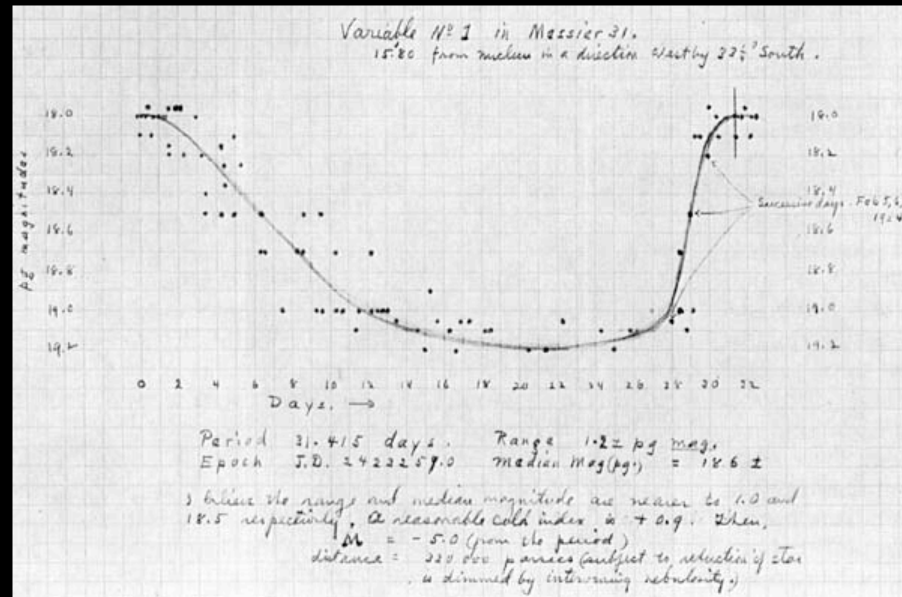
On October 6, 1923, Hubble realized that one of the stars in M31 was varying in brightness in a repeatable fashion



Hubble had discovered a Cepheid variable star, and was able to use it to measure the distance to M31

The Discovery of Cepheid Variable Stars in M31





Cepheid variable stars are named after δ Cephei, one of the nearest examples in the Milky Way

They are thousands of times more luminous than our sun

In 1912, Henrietta Leavitt discovered that the period of the brightness variations for Cepheids was correlated with their luminosities

Henrietta Leavitt (1868-1921)

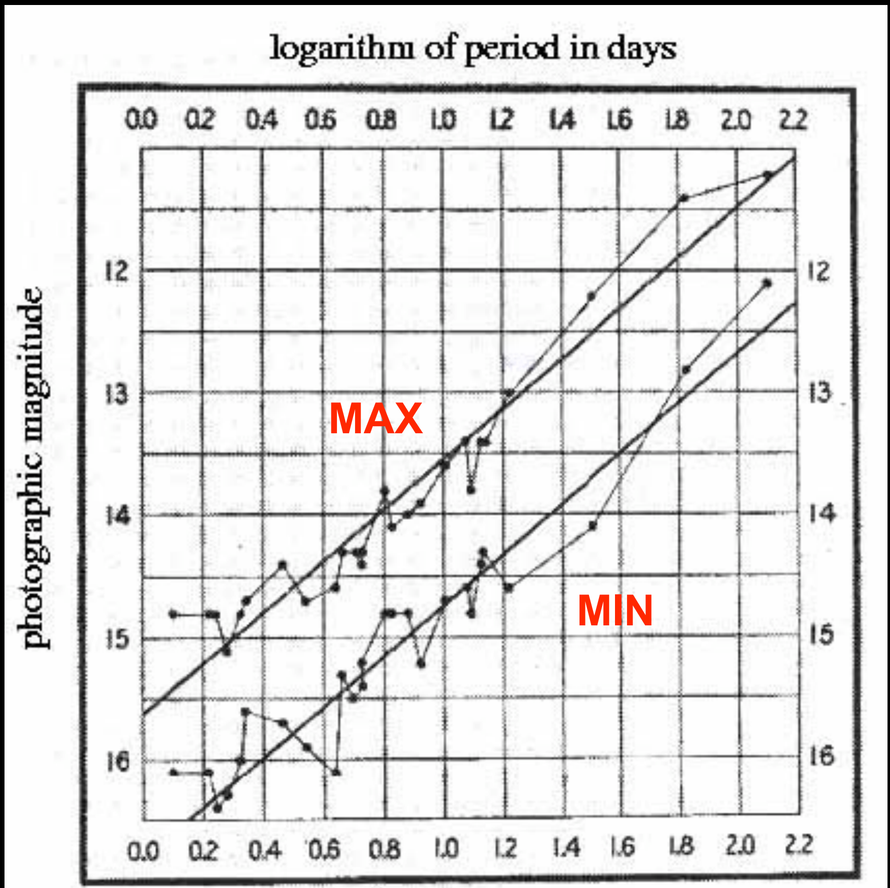


FIG. 2.

Henrietta Leavitt worked at the Harvard College Observatory for 28 years

Her discovery of the Period-Luminosity relationship for Cepheid variables provided a powerful yardstick for measuring distances in the Universe

How to Measure Distances using Cepheid Variable Stars

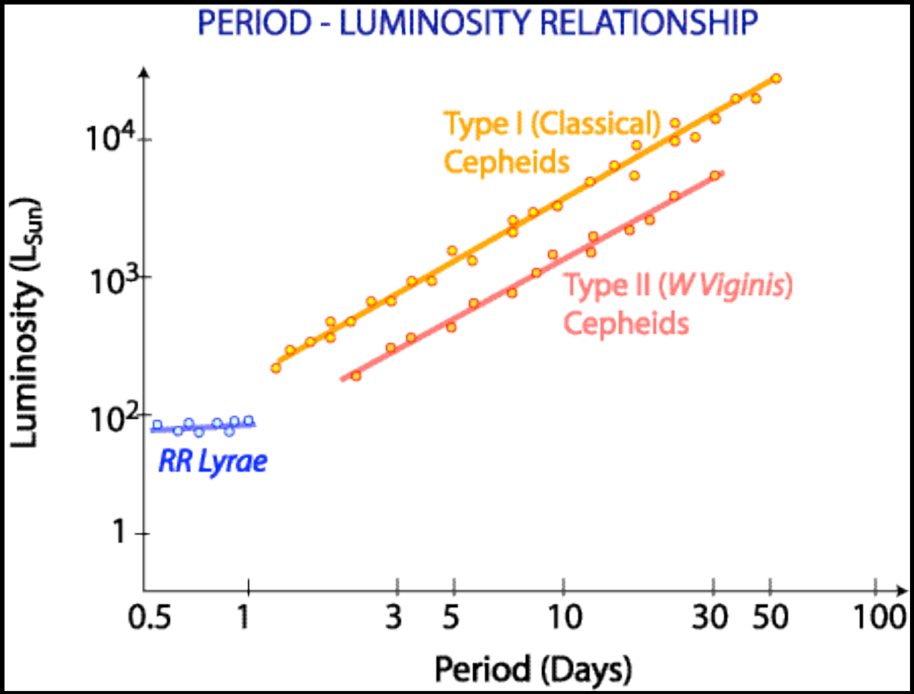
1. Measure the period of the brightness variations of the Cepheid which gives the luminosity of the star
2. Measure the average apparent brightness over one period
3. Use the Inverse Square Law of Brightness to derive the distance to the Cepheid

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

B = apparent brightness

L = luminosity

d = distance



The Distance to M31 and the Nature of S Andromeda

Based on observations of 12 Cepheid variable stars in M31, Hubble derived a distance of 930,000 light years

Modern determinations give a much greater value of 2.5 million light years

In any case, such a large distance implied a huge luminosity for the “new star” S Andromeda discovered in 1885 by Hartwig

2.7 billion times the luminosity of the Sun!

Supernovas

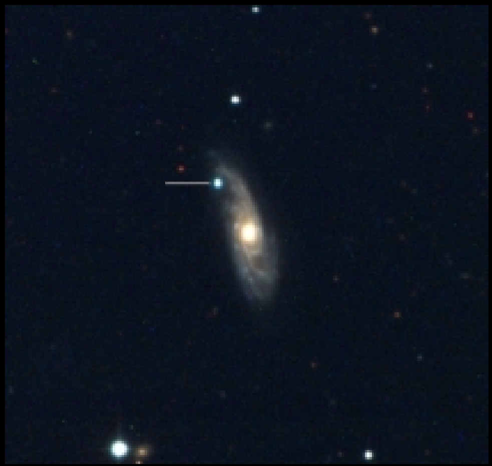
S Andromeda, the “guest star” of 1054, and Tycho’s and Kepler’s “stella nova” are all members of a class of objects that became known as “Supernovas”

Supernovas occur approximately 1-3 times per century in a typical spiral galaxy like the Milky Way

We now understand that they are the explosive deaths of stars

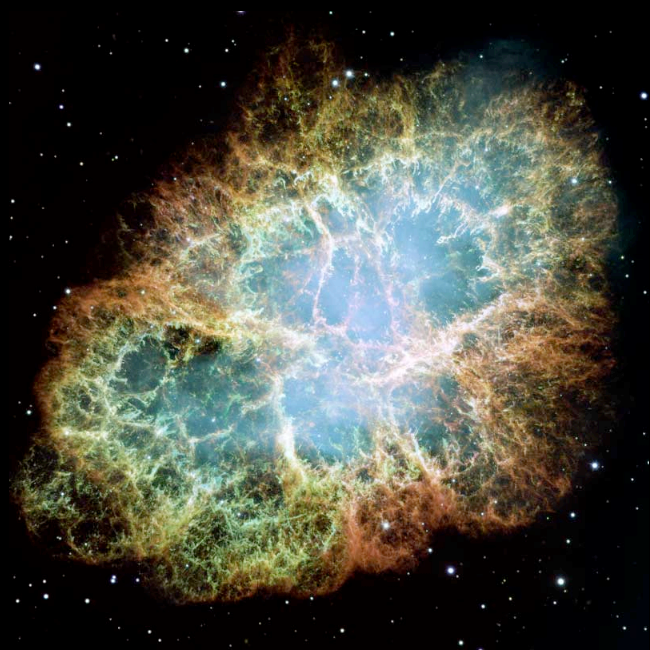
SN 2004dt

SN 2005bf

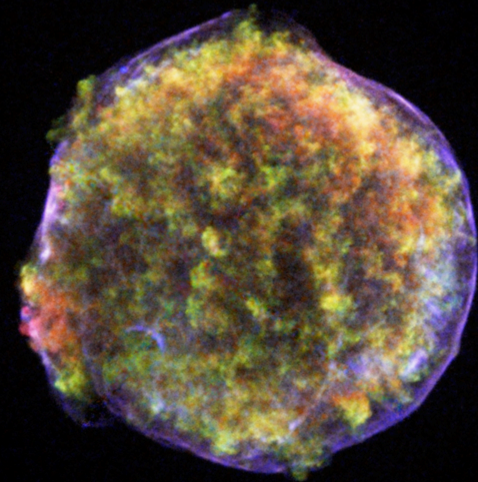


SN 2005eq

Remnants of Supernova Explosions



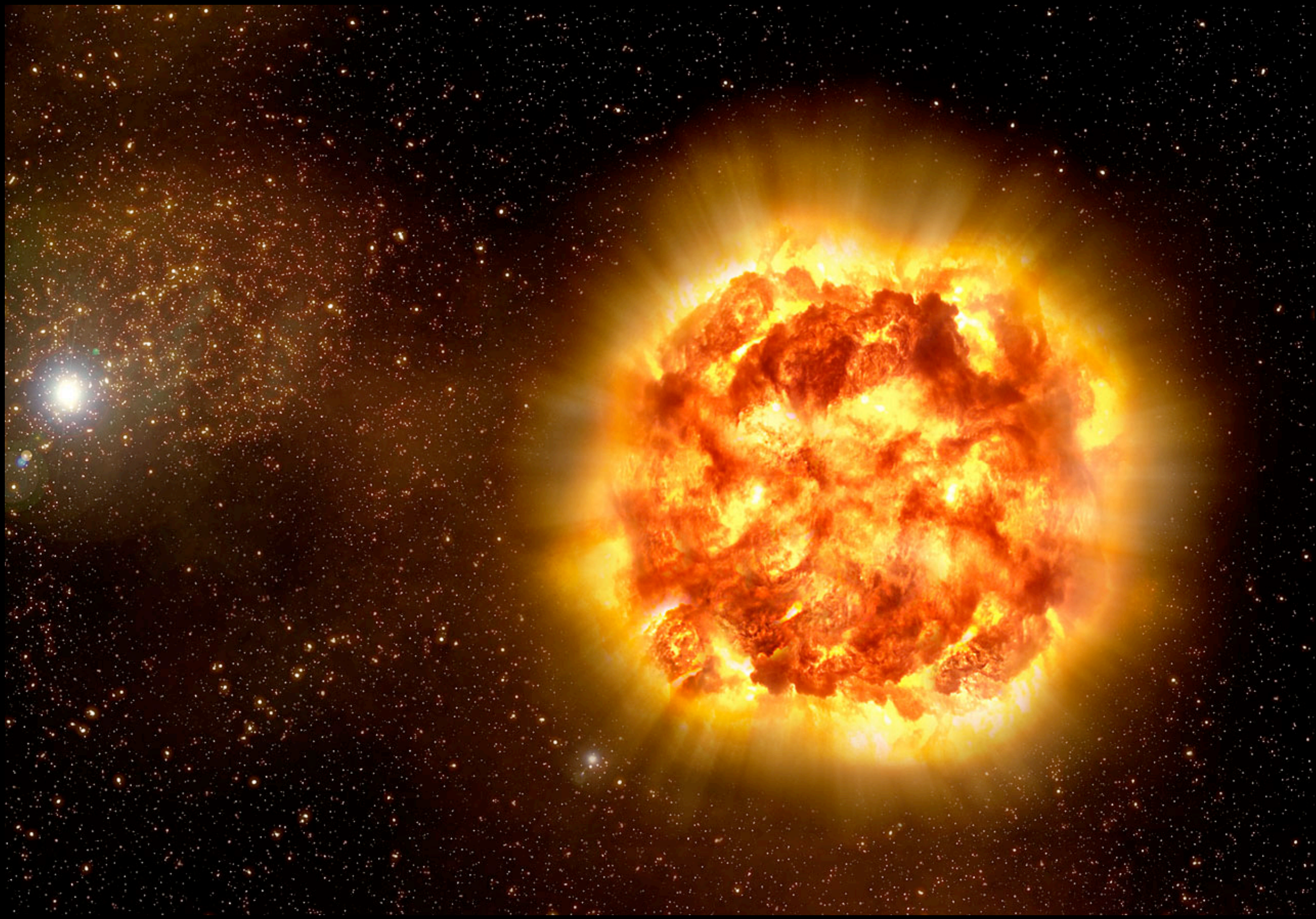
The “Crab Nebula” -- remnant of SN 1054 -- as seen by Hubble Space Telescope



The remnant of Tycho’s SN as seen in X-rays

The remnant of Kepler’s SN as seen in X-rays

How Do Stars Explode?



Two Different Types of Supernova

There are two major categories of supernovas:

1. **Core-Collapse supernovas**

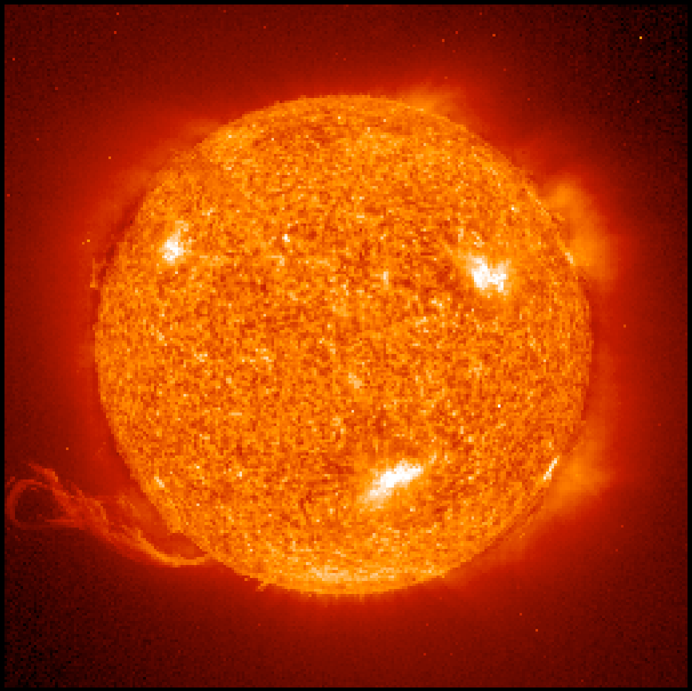
   These are produced by a massive star (> 8-9 solar masses) that runs out of fuel at its center, producing a sudden collapse and explosion

2. **Thermonuclear supernovas**

   These are thought to be the runaway explosion of a white dwarf star as it accretes mass from a binary companion

A Short History of the Sun - I

The Sun is a typical star, composed mostly of hydrogen (74% by mass), helium (24-25% by mass), and trace quantities of the other elements



The Sun is currently powered by nuclear fusion reactions in its center which convert hydrogen into helium

The Sun is currently 4.6 billion years old, and has burnt about half of the hydrogen fuel in its core

In another 5-6 billion years, the Sun will have exhausted the remaining hydrogen in its center

As the core contracts and heats up, helium fusion reactions producing carbon will begin as hydrogen continues to burn in a shell surrounding the helium core

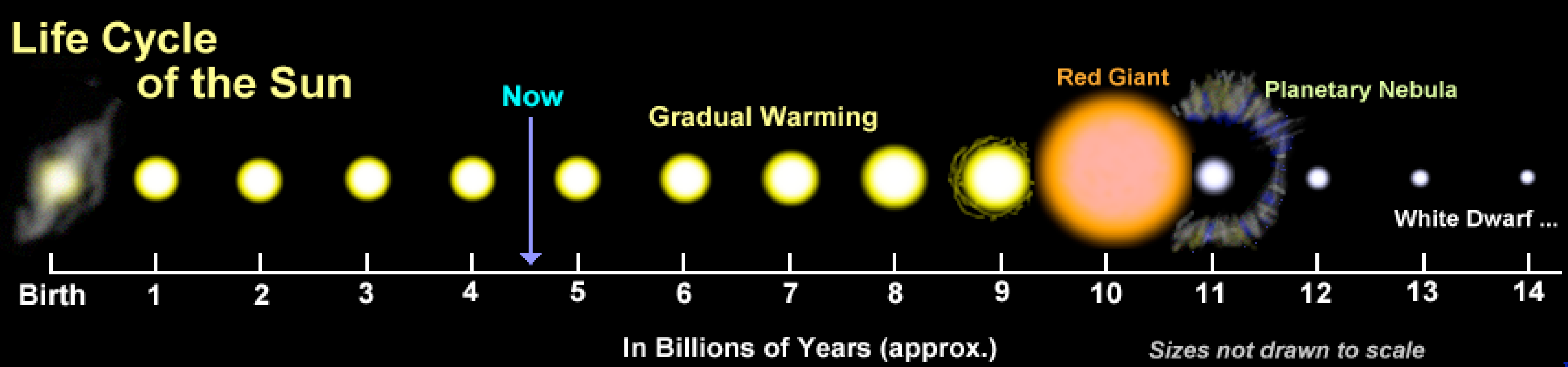
A Short History of the Sun - II

During this helium-burning phase, the Sun will become a “red giant” as its outer layers swell to beyond the Earth’s current orbit

This phase lasts only 100 million years, at which point the helium in the Sun’s core will be exhausted

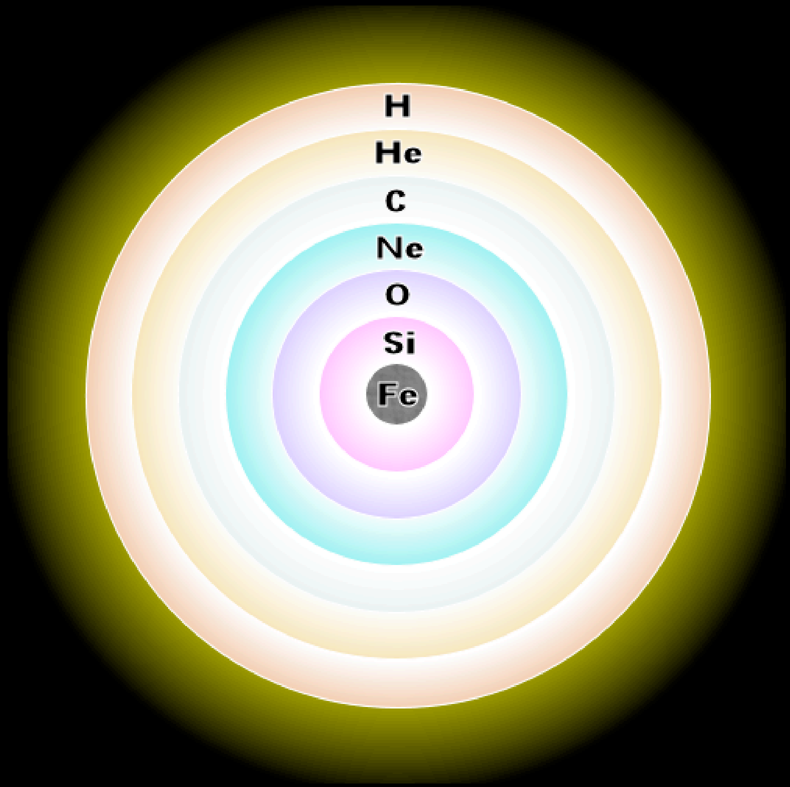
Following the “red giant” phase, the Sun will lose a significant fraction of its outer envelope in several thermal pulses, forming a “planetary nebula”

Unable to sustain further fusion reactions, the Sun will contract and slowly cool to become a “white dwarf” the size of the earth



The Evolution of Massive Stars - I

The initial evolution of massive stars (> 8-9 times the mass of the Sun) follows that of the Sun, with the star first burning hydrogen in its core, and then helium



However, unlike the Sun, massive stars are able to reach central temperatures that are high enough to continue to burn more and more massive nuclei in a succession of fusion reactions

The star becomes layered like an onion, with the lightest elements outside, building up to an iron-nickel core at the center

Fusion reactions can no longer be sustained with the formation of the iron-nickel core

The Evolution of Massive Stars - II

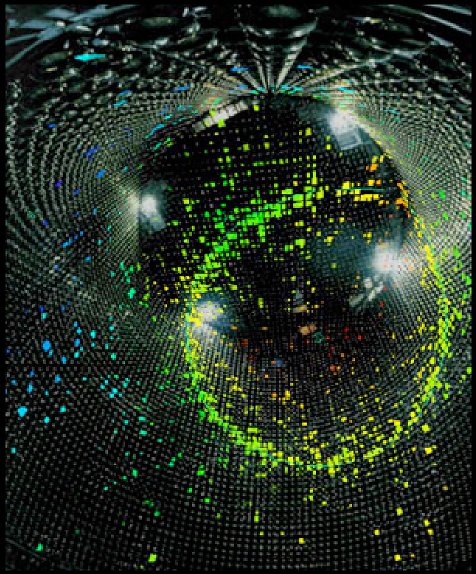
The core can no longer withstand the pressure of the outer layers of the star, and collapses catastrophically on itself at velocities reaching 20% of the speed of light

In a matter of seconds, the iron-nickel core undergoes photodisintegration (a sort of “reverse fusion”)

Electrons and protons merge to form a neutron core of 1.4-2.1 solar masses and only 30 kilometers in diameter

A powerful burst of neutrinos escapes from the star, signaling the formation of the neutron core

The instantaneous energy released by these neutrinos is equal to the luminous energy emitted by all of the galaxies in the Universe at that moment



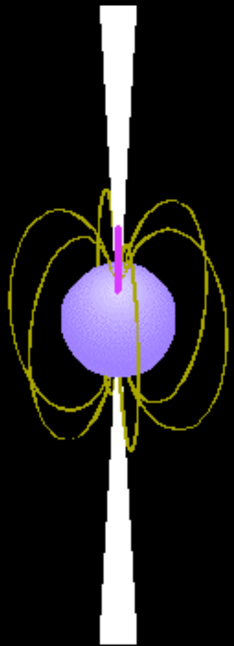
The Evolution of Massive Stars - III

The infalling outer layers of the star collide with the neutron core and rebound producing an explosion and accompanying shock wave

The neutron core is left behind and becomes a “neutron star”

This is what we call a Core-Collapse supernova

The “guest star” of 1054 was a Core-Collapse supernova which produced a rapidly rotating neutron star called a “pulsar”



The Evolution of Massive Stars - IV

Although massive stars have more fuel, they also burn at a much faster rate due to the higher temperatures in their centers

The massive stars that produce core-collapse supernovas have lifetimes of only millions of years

Core-collapse supernovas therefore trace the youngest generation of stars in galaxies

The appearance of SN 1987A in the Large Magellanic Cloud provided a unique opportunity to test these ideas

SN 1987A

Appeared suddenly on Feb. 23, 1987 in the Large Magellanic Cloud, our closest galaxy neighbor (165,000 light years distant)

It was the first “naked-eye” supernova since Kepler’s SN in 1604 (and the first since the invention of the telescope!)

After Before

The star that exploded was observed beforehand, and was know to be a massive star (20 solar masses)!

A burst of neutrinos was observed consistent with the formation of a neutron star!

Although we are still working to understand some of the details revealed by observations, SN 1987A provided stunning confirmation of our basic ideas concerning Core-Collaspe supernovas

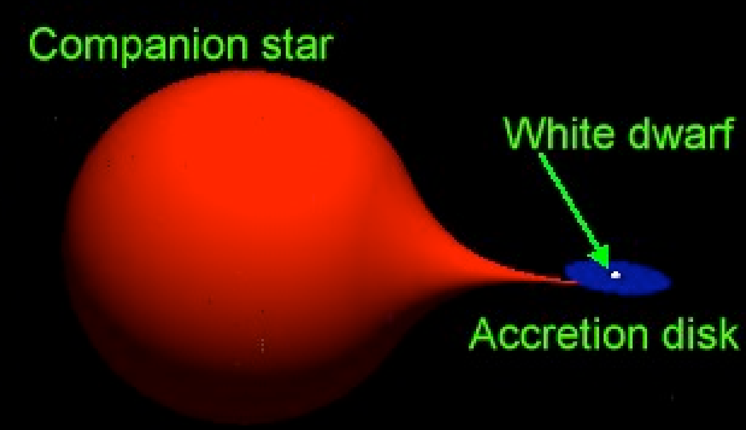
What About Thermonuclear Supernovas?

Certain supernovas show spectra completely lacking in hydrogen, the most common element in the Universe

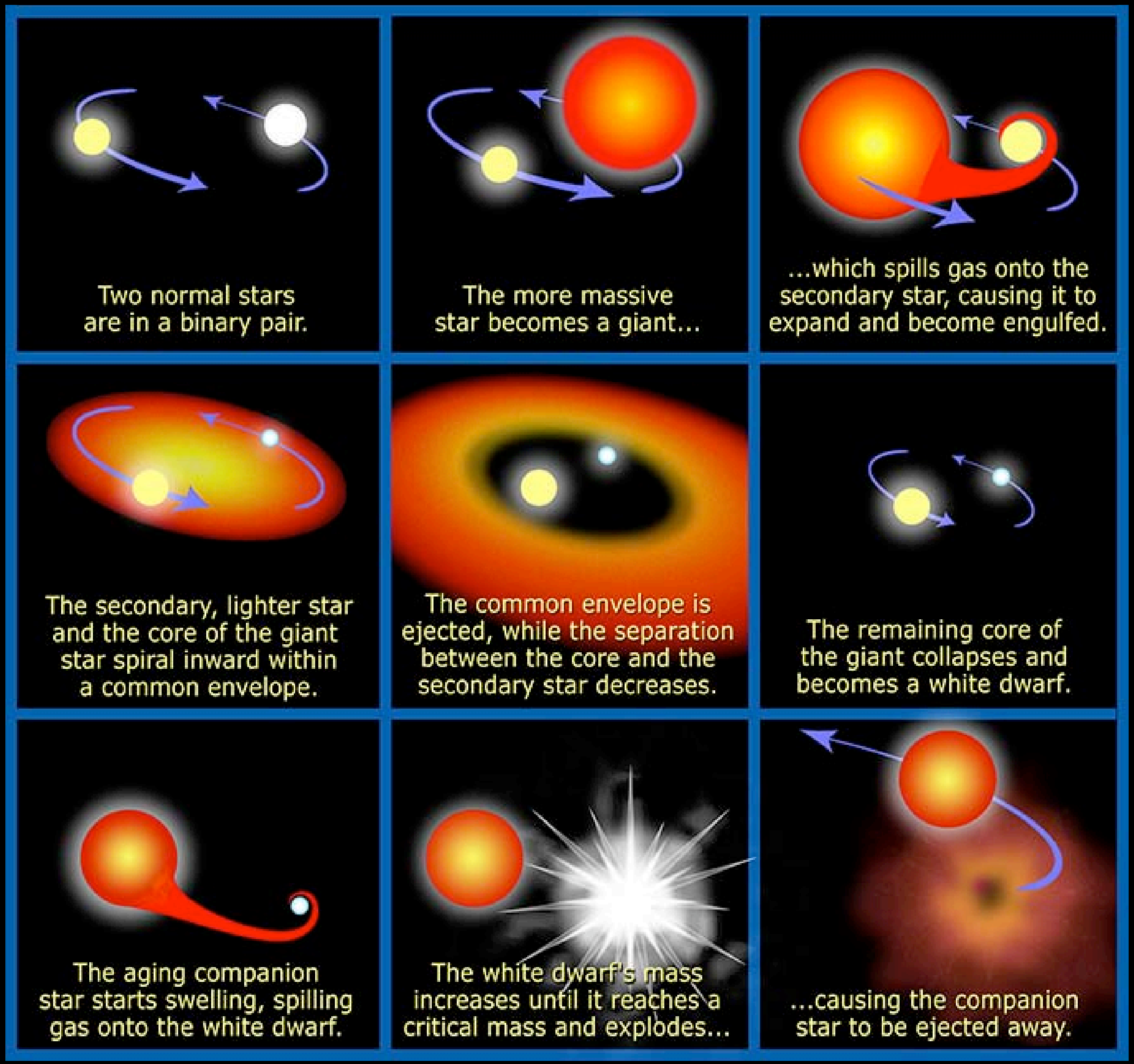
This strange situation is difficult to produce, except in a double star system (a “binary pair”)

The large luminosities of these supernovas can be explained by the sudden thermonuclear detonation of a white dwarf star, caused by mass from the secondary star accreting onto the white dwarf

Unlike Core Collapse supernovas, thermonuclear supernovas completely destroy the white dwarf progenitor



A Possible Scenario…



More About Thermonuclear Supernovas

Thermonuclear supernovas are extremely luminous, and display a remarkable resemblance from one to another

Recent observations suggest that thermonuclear supernovas may arise from both older and younger stellar populations

Tycho's "nova stella" was almost certainly a thermonuclear supernova

The evidence suggests that **Kepler's "nova stella"** was also a thermonuclear supernova, but perhaps one arising from a younger progenitor

Supernovas and the Origin of the Elements

About 14 billion years ago, the Universe began in a gigantic explosion called the “Big Bang”

Hydrogen, helium, and a small amount of lithium were created in the first minutes of the Big Bang

All the other elements were produced in stars and supernova explosions

Core-collapse supernovas produced most of the oxygen in the Universe, without which life as we know it would not be possible

Thermonuclear supernovas produced most of the iron in the Universe

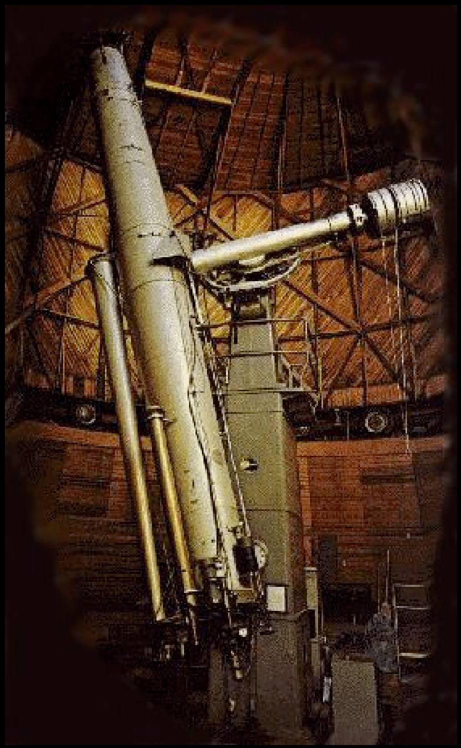
All elements heavier than iron (e.g., gold, mercury, lead, uranium) were produced only in supernova explosions

Exploding Stars and the Fate of the Universe

Vesto Slipher

In 1912, Vesto Slipher was the first astronomer to obtain the spectrum of a spiral nebula

Over the next 10 years at Lowell Observatory, he patiently labored to obtain spectra of more of these objects



These observations required as much a 80 hours exposure time per nebula!

By the mid-1920s, he had observed 45 spiral nebulas

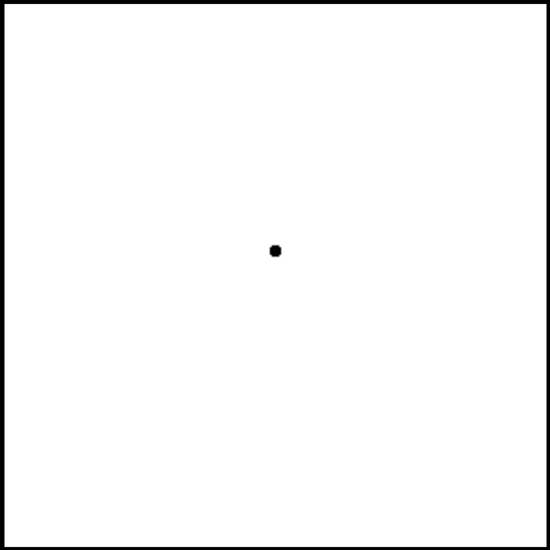
With the exception of only one object (M31), he made the startling discovery that all were moving away from us at huge velocities (up to 1,000 kilometers per second)

How Did Slipher Measure Velocities?

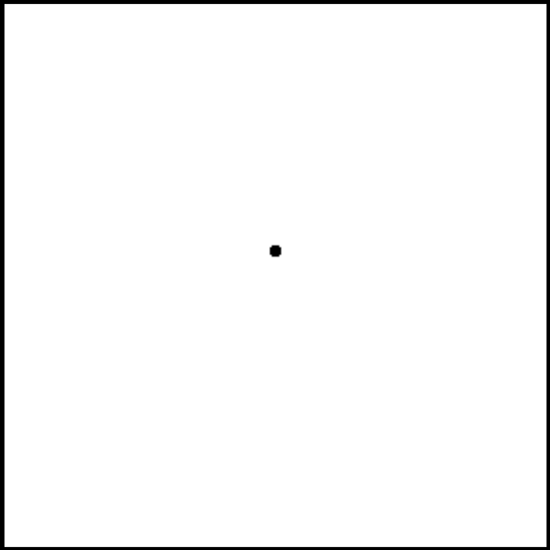
Slipher used the Doppler effect to measure the velocities of stars and galaxies

If a galaxy is moving toward us, the light will appear to have a shorter wavelength -- this is called a “blueshift”

If a galaxy is moving away from us, the light will appear to have a longer wavelength -- this is called a “redshift”



Stationary Source



Moving Source

The Redshift

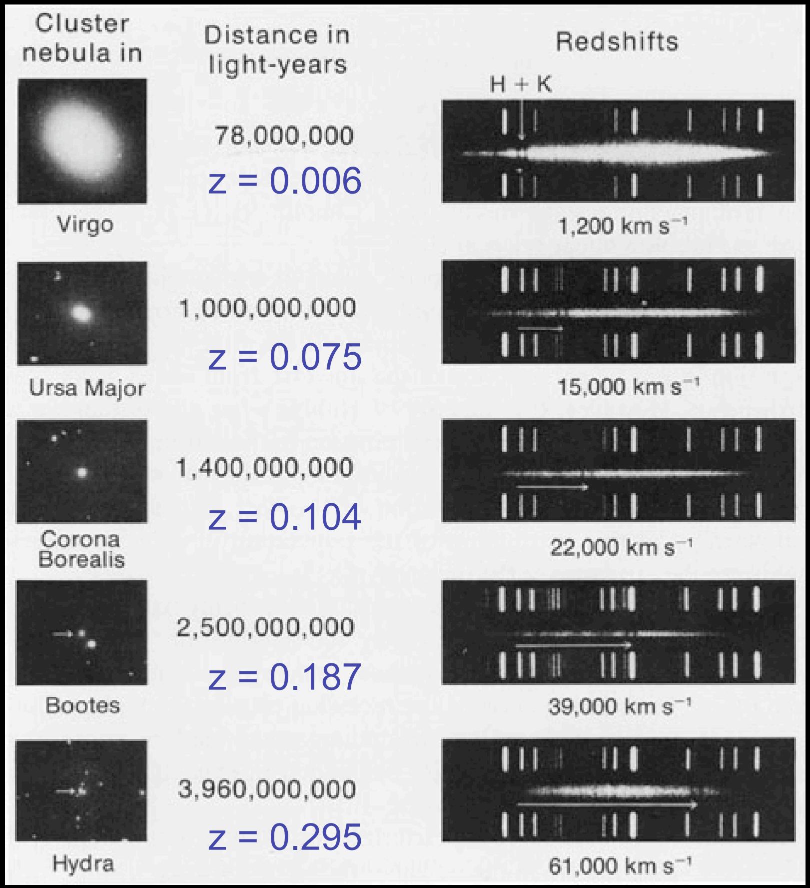
Slipher was able to identify absorption features in the spiral nebulas that are also observed in the spectra of normal stars

He found that these features were "redshifted", and was able to calculate the velocity from the relation

$$v \approx c \times z$$

where the redshift "z" is defined as

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$



Hubble's Discovery of the Expansion of the Universe

Hubble's discovery of Cepheid variable stars in M31 showed that the spiral nebulas were at great distances from the Milky Way

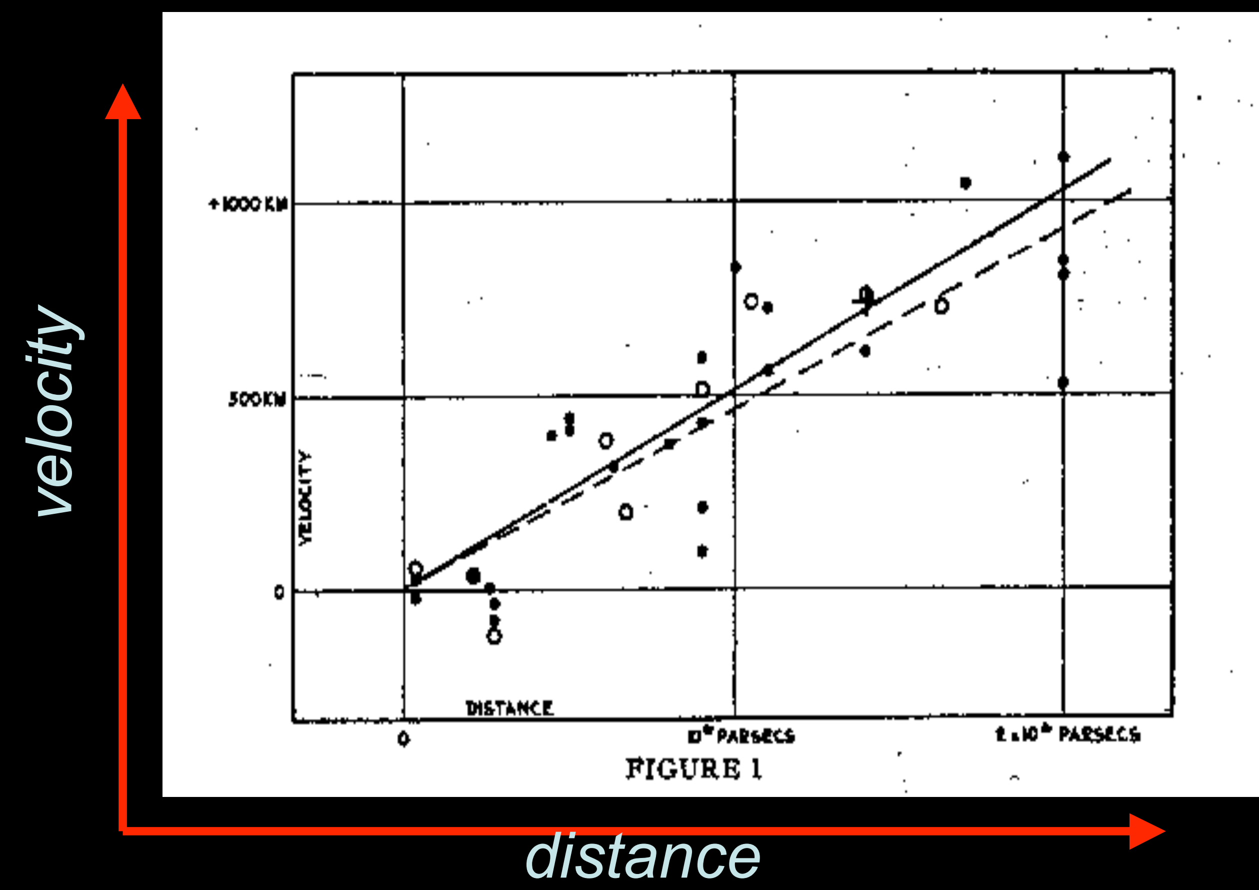
In a moment of inspiration, Hubble took Slipher's velocity measurements of the spiral nebulas, supplemented by his own observations, and plotted them versus distances that he had derived for the same nebulas using Cepheid stars or other distance indicators (e.g., the brightest stars)

Hubble found that the more distant the spiral nebula, the greater its velocity, thereby discovering the expansion of the Universe

The Hubble Diagram

Hubble's diagram showed that $v = H_o \times d$

The slope of this relation, H_o, is called the "Hubble constant", and measures the current rate of expansion of the Universe

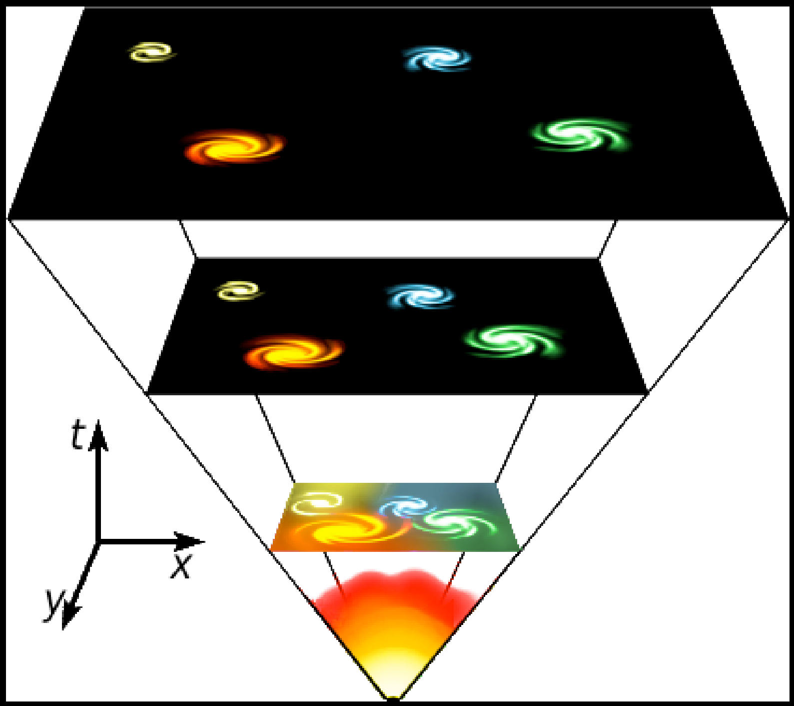


The Big Bang

Hubble's finding revolutionized our concept of the Universe, and marked the beginning of the modern age of cosmology

If the Universe is seen to be expanding today, then it must have been smaller, denser, and hotter in the past

This gave rise to the idea that the expansion of the Universe began in a tremendous explosion known as "The Big Bang"



During the remainder of the 20th century, the challenge for astronomers was to determine whether the Universe would expand forever, or if gravity would eventually overcome the expansion, and cause the Universe to collapse

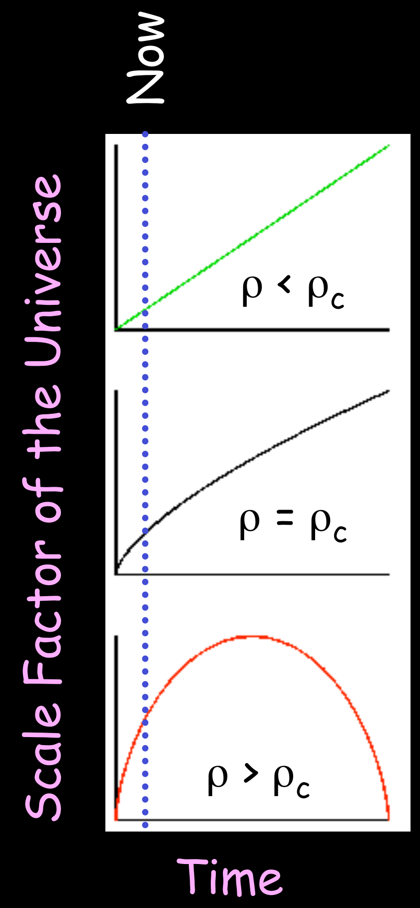
The Fate of the Universe

It is possible to measure the geometry and eventual fate of the Universe via the Hubble diagram by comparing the velocity of the expansion now and when the Universe was much younger

For this it is necessary to determine the distances to very distant galaxies

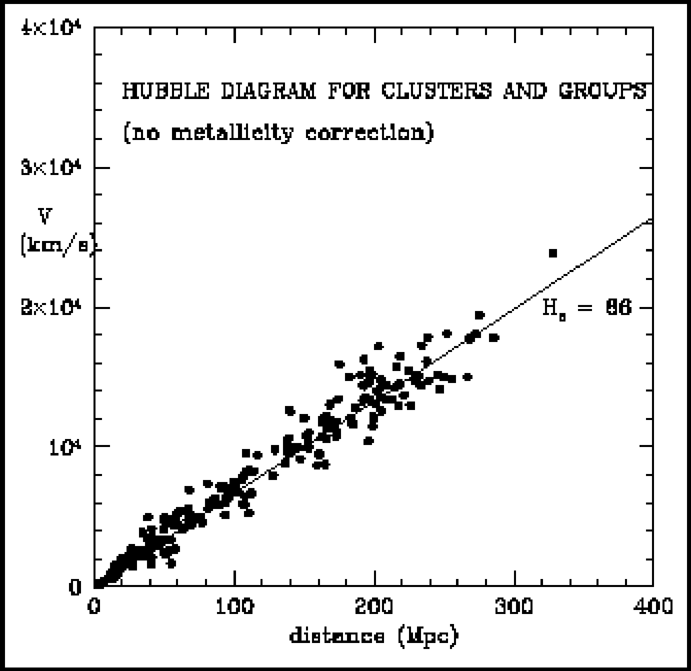
The average density of matter, ρ, determines the fate of the universe

- **If ρ is less than the "critical density", ρ_c, the universe is open, infinite, and will expand forever.**
- **If ρ is greater than ρ_c, the universe is closed, finite, and will eventually re-collapse**
- **If ρ is exactly equal to ρ_c, the universe is flat, infinite, and will expand forever**
- The parameter $\Omega = \rho / \rho_c$ is a convenient way of expressing these alternatives



Measuring Distances to Very Distant Galaxies

Between 1956-1975, Allan Sandage and others attempted to use the brightest galaxies in clusters since these show only a 12% dispersion in luminosity in the local Universe



However, it was eventually realized that the luminosities of galaxies change with time

Galaxies were brighter when they were younger due to the evolution of their constituent stars

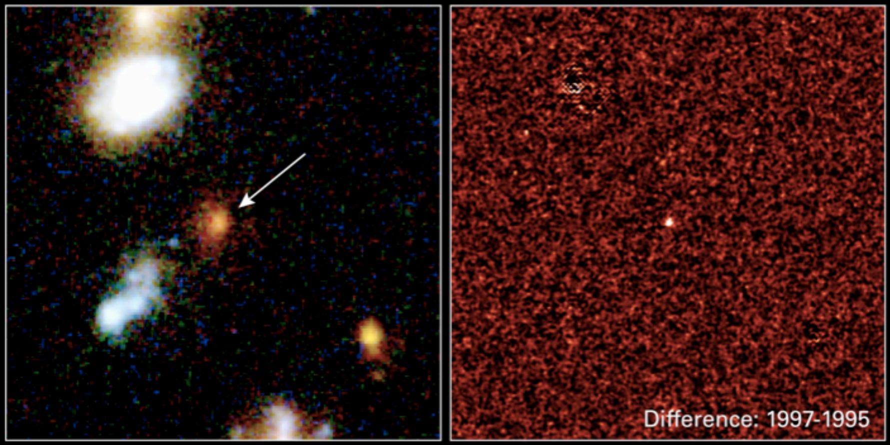
The size of this aging effect is larger than the small differences in the Hubble diagram due to the changing expansion of the Universe

Supernovas Should Be Better

Galaxies are poor standard candles because they are conglomerations of many stars of different masses, ages, and chemical abundances

Single stars make much better standard candles, but even the brightest stars cannot be observed beyond the distance of the Virgo Cluster (the nearest rich galaxy cluster to the Milky Way)

The exceptions to this rule are the supernovas, which can be observed to distances where the Universe was 1/3rd its present age



SN 1997ff (z~1.7) in the Hubble Deep Field

Thermonuclear Supernovas (a.k.a. Type Ia Supernovas)

Since the 1930s, the light curves of thermonuclear supernovas have been known to be remarkably similar

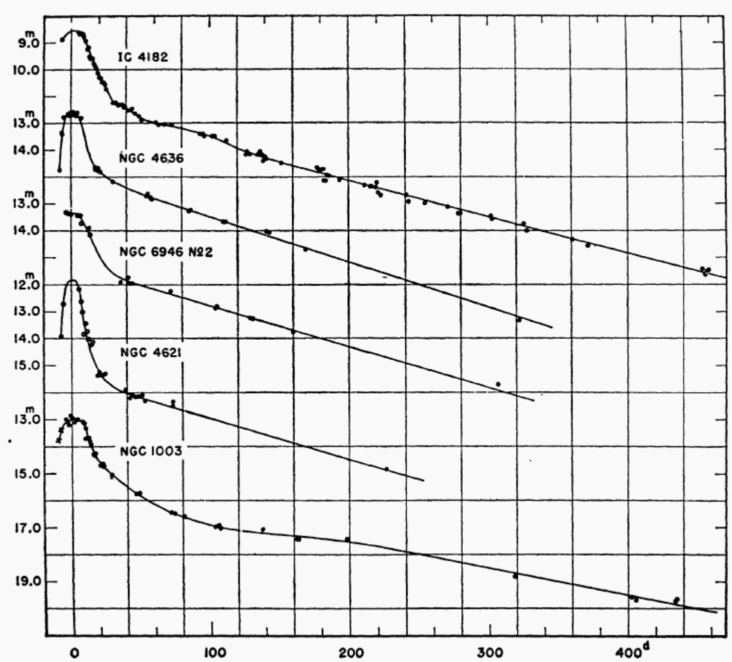
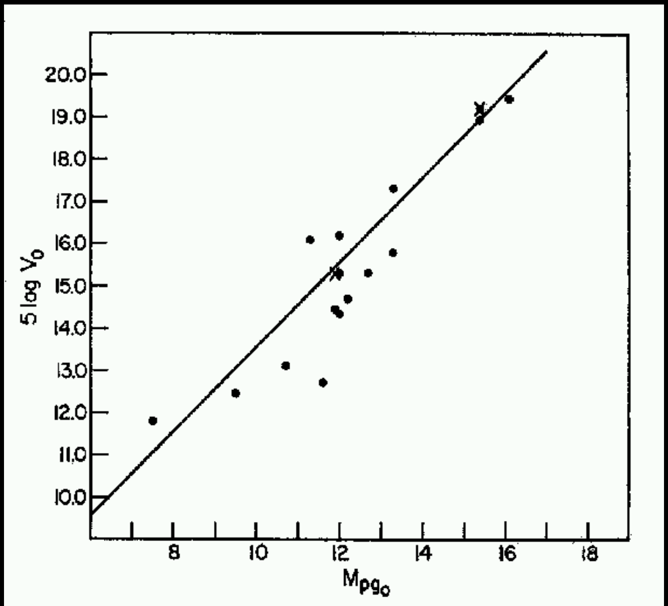


FIG. 1. Photographic light curves of supernovae of type I.

In 1938, Carnegie astronomer Walter Baade first suggested that these supernovas, which astronomers now call "Type Ia", could be used as cosmological standard candles

Perfect Standard Candles?

In 1968, Charles Kowal published a Hubble diagram for 22 Type Ia supernovas with 30% in distance, demonstrating the potential utility of these events as cosmological “standard candles”



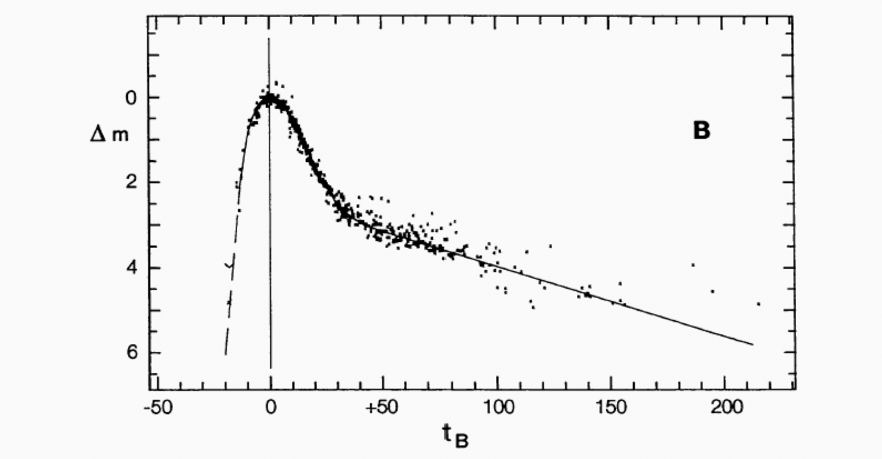


Figure 2 The standard *B* light curve (adapted from Cadonau 1987), based on observations of 22 SNe Ia.

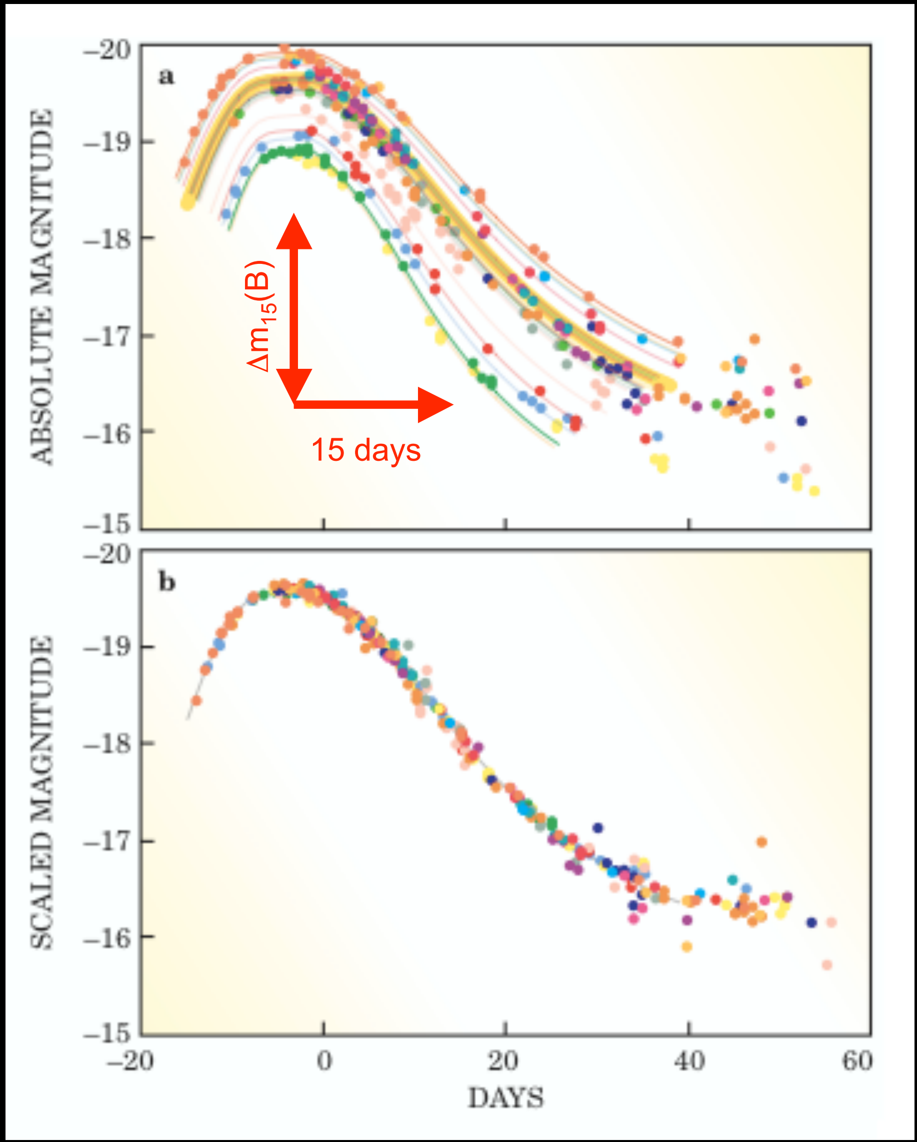
Work by Sandage, Tammann, and others in the early-1980s suggested that Type Ia supernovas might be perfect standard candles, with identical light curves and luminosities

Bad News and Good News

Unfortunately, modern data have shown that Type Ia supernovas are not perfect standard candles, but range in maximum luminosity by a factor of 2 or more!

Fortunately, however, a tight correlation exists between the width of the light curve and the luminosity at maximum

This relationship can be used to correct the peak luminosity of any Type Ia supernova to a standard value, allowing them to be used to measure distances to galaxies with an accuracy of 10% or better!

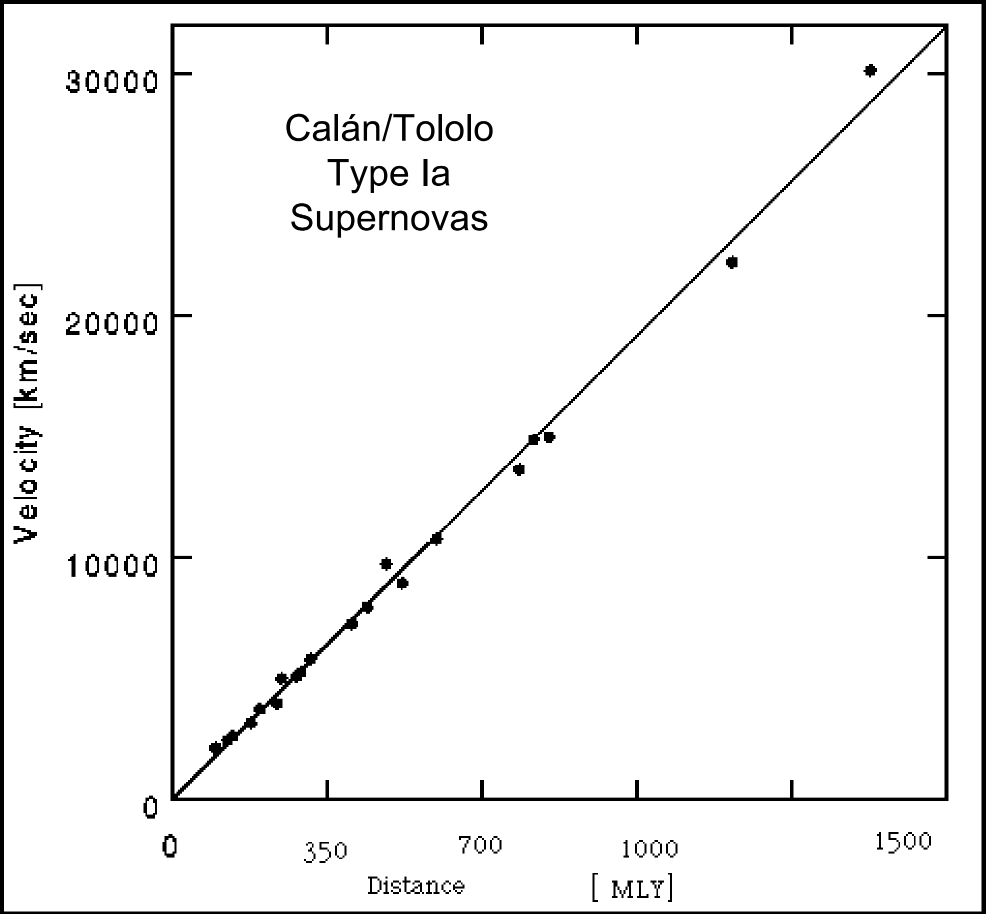


How Well Do They Work?

The Calán/Tololo survey was carried out in Chile in the early 1990s with the idea of testing the precision of distances obtained from Type Ia supernovas

The results were even better than expected, yielding a relative precision of 5% for the distance of a single object

Combining these results with Cepheid distances obtained to nearby galaxies that hosted Type Ia supernovas yields a Hubble constant of 73 km/s/Mpc



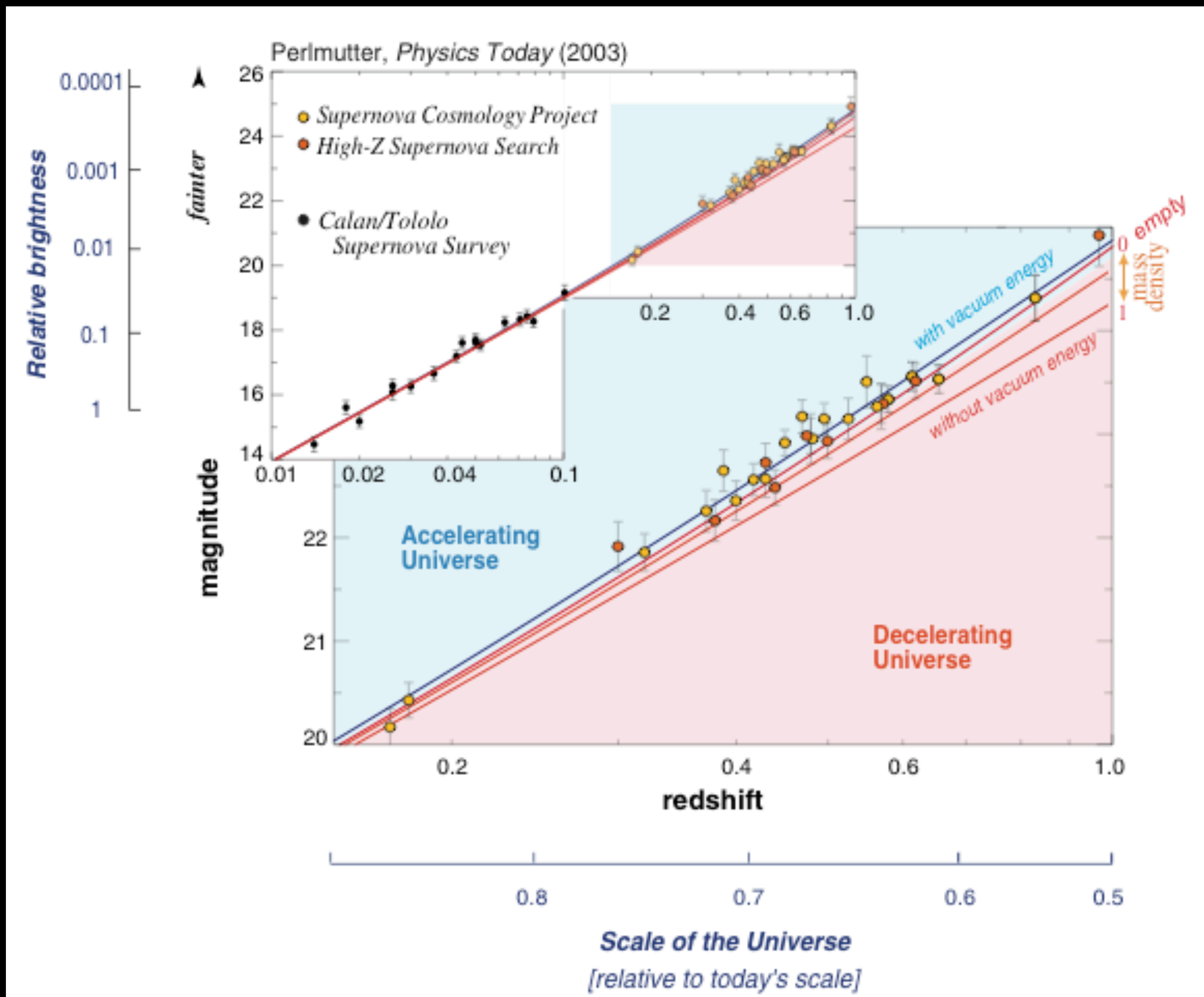
The Race to Determine the Fate of the Universe

- First distant (z = 0.3) Type Ia supernova discovered in 1988 by Norgaard-Neilsen et al.
- Seven distant (z ~ 0.4) Type Ia supernovas discovered in 1994 by Supernova Cosmology Project (SCP)
- First distant (z ~ 0.5) Type Ia supernova discovered in 1995 by High-Z SN Search Project (High-Z SN)
- In 1998-1999, the High-Z SN and SCP teams independently publish their first Hubble diagrams of distant Type Ia supernovas
- **Unexpectedly, both teams found that…**

Saul Perlmutter
(P.I. SCP)

Brian Schmidt
(P.I. High-Z SN)

The Expansion of the Universe is Accelerating!



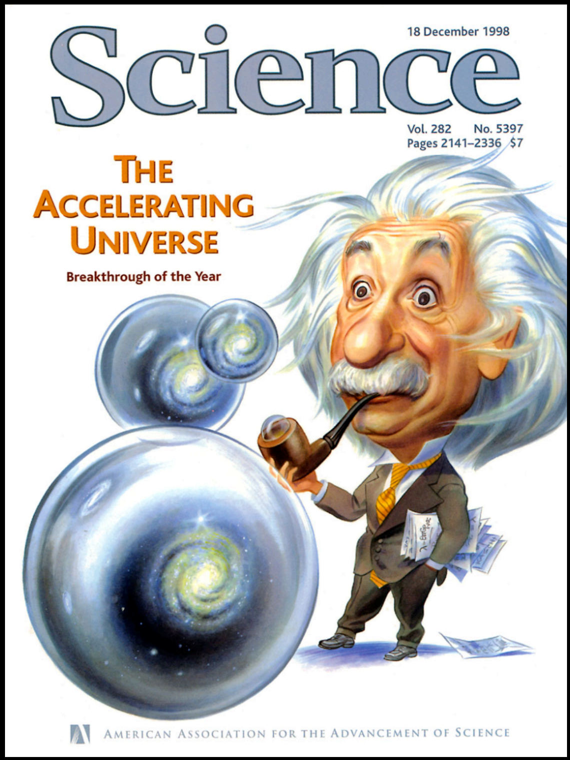
Guess Who Predicted This!

Shortly after Albert Einstein invented General Relativity in 1915, he calculated what the theory would predict for the evolution of the Universe

To his consternation, he found that the Universe should either be expanding or contracting

Since this contradicted the standard wisdom at that time, he included an “anti-gravity” term called the “Cosmological Constant” in his equations which balanced gravity to create a static Universe

When Einstein heard that Hubble had discovered that the Universe was expanding, he quickly retracted the “Cosmological Constant”, calling it the greatest blunder of his career



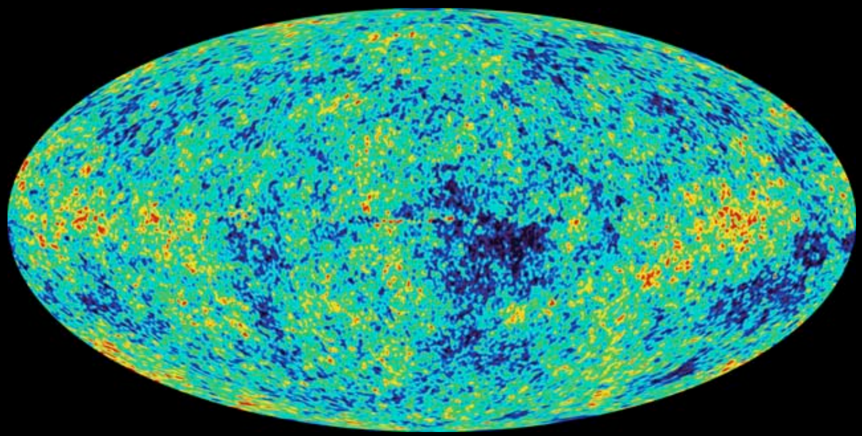
December 1998

Dark Energy

Amazingly, the observed Type Ia supernova Hubble diagram can be perfectly explained if we put the Cosmological Constant back in Einstein's equations

However, the observations do not yet rule out other possible forms of repulsive energy -- hence, we lump them all together by attributing the acceleration to "Dark Energy"

In recent years, detailed observations of the Cosmic Microwave Background radiation (a remnant of the Big Bang) have completely confirmed this picture of a Universe which is dominated today by Dark Energy



So What is the Fate of the Universe?

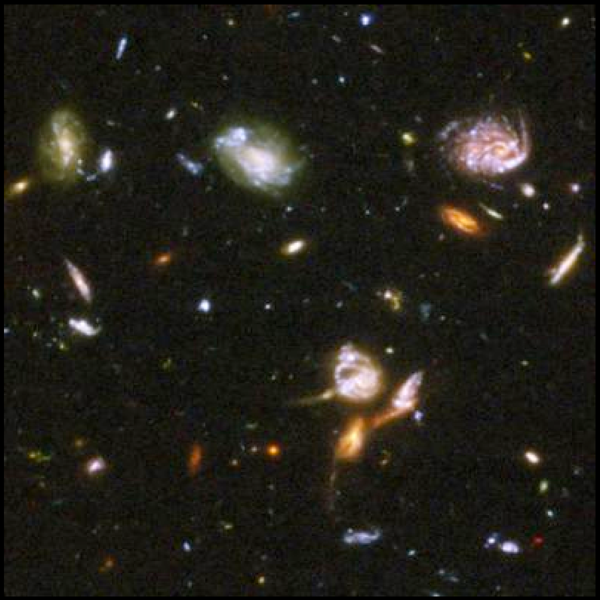
We can now say with considerable certainty that the Universe will expand forever

This is a philosophically profound statement since it implies that our Universe has not existed forever

If the acceleration of the expansion remains constant over time, consistent with Einstein's Cosmological Constant, the Universe will expand forever to a state of "infinite dilution"

In a 100 billion years, only a tiny fraction of the known galaxies in the Universe will be observable

The Universe as we know it will become a very lonely place…



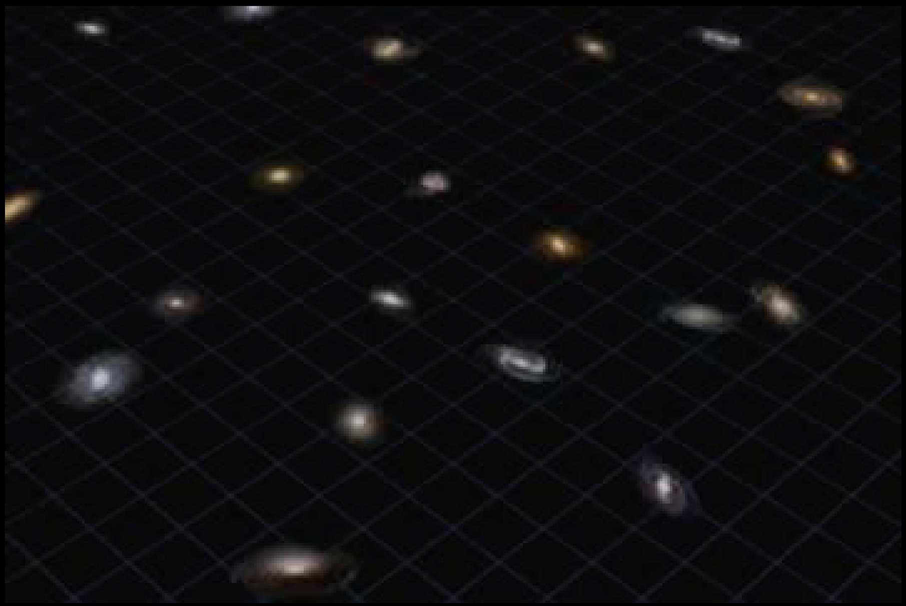
A Big Rip?

A less likely but more exotic possibility is that the Dark Energy grows much stronger with time, eventually leading to the “Big Rip”

In this scenario, as the Dark Energy grows, its repulsive force becomes strong enough to rip all bound systems apart -- first galaxy clusters, then galaxies, stars, planets, and finally atoms

Astronomers are working hard now to try to determine if the Dark Energy is, indeed, changing with time

In any case, the earliest that this could happen is in another 22 billion years or so…



Thanks to SDSU…
… and special thanks to John Schopp