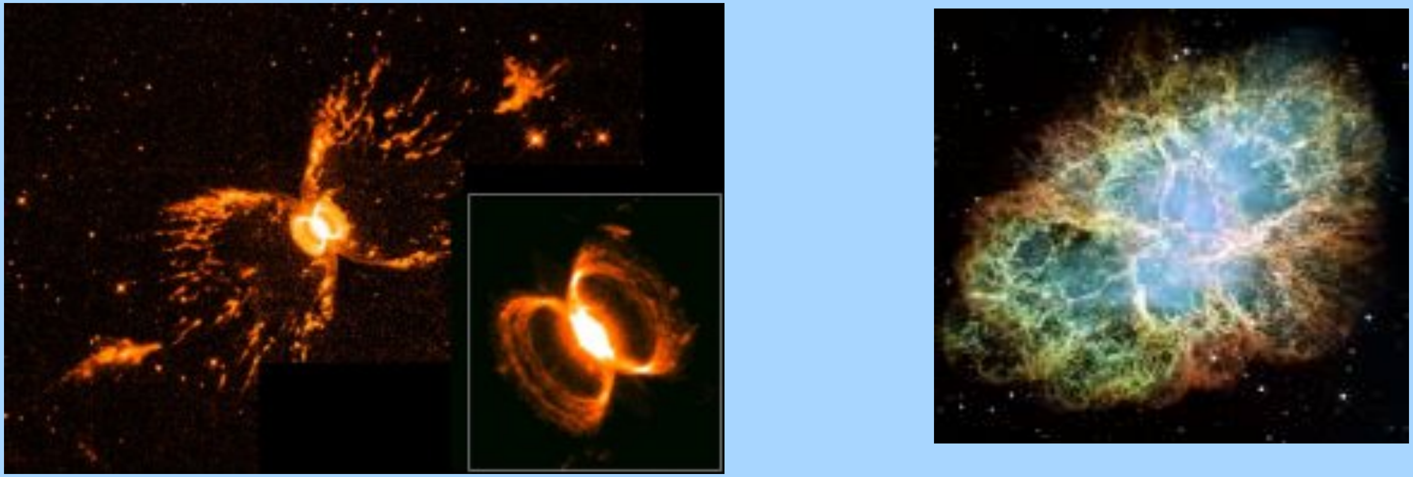
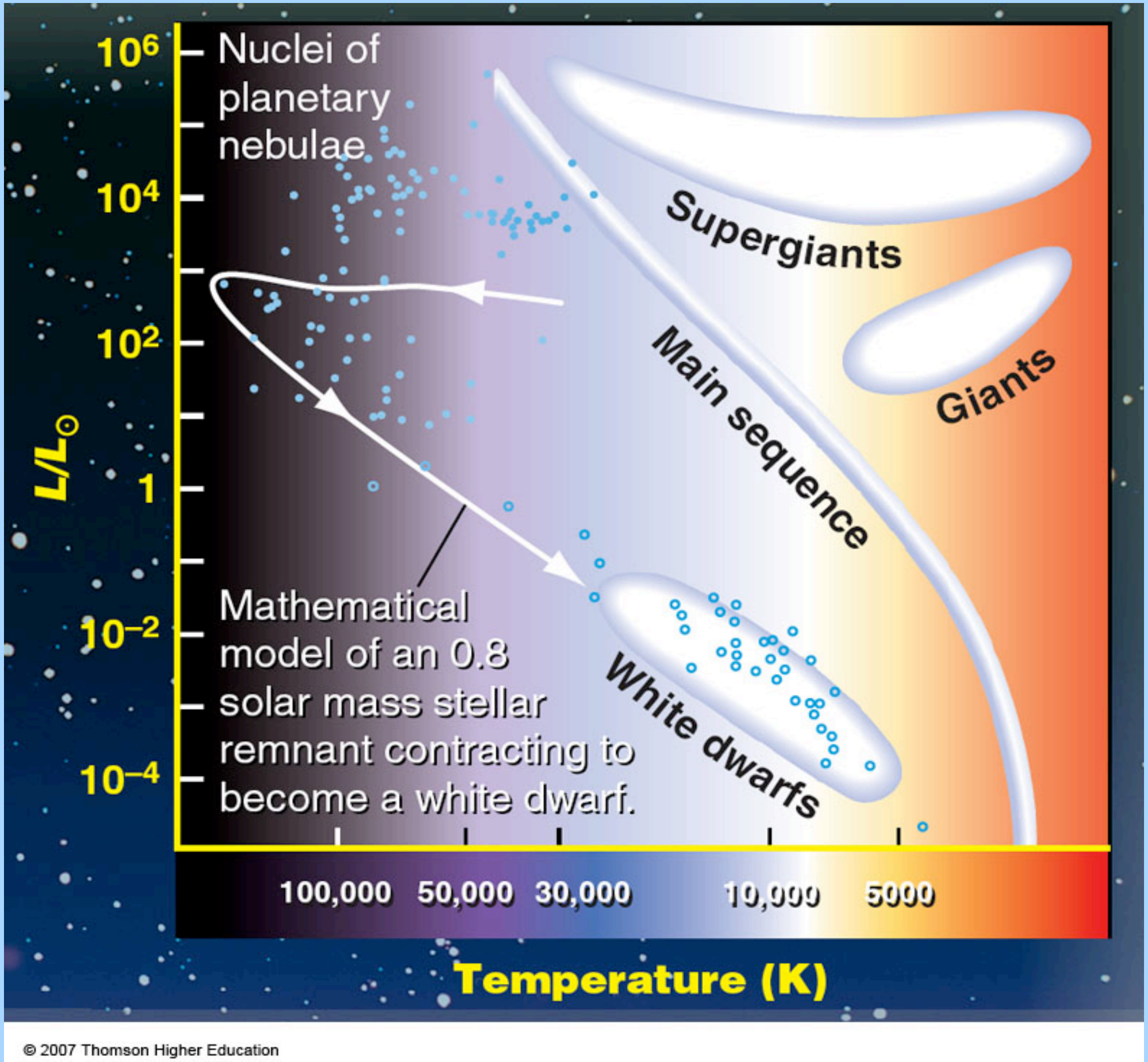
The Deaths of Stars



The Southern Crab Nebula (He2-104), a planetary nebula (left), and the Crab Nebula (M1; right), a supernova remnant.



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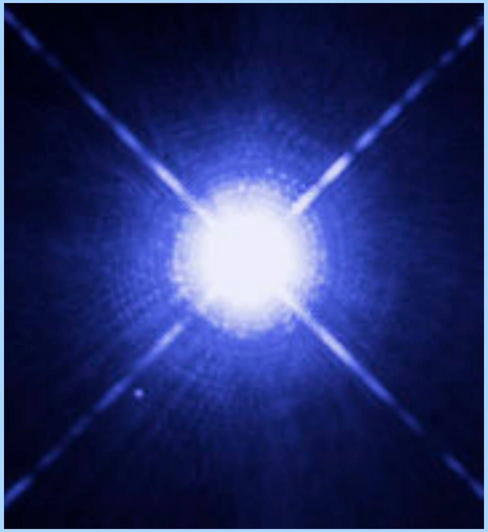
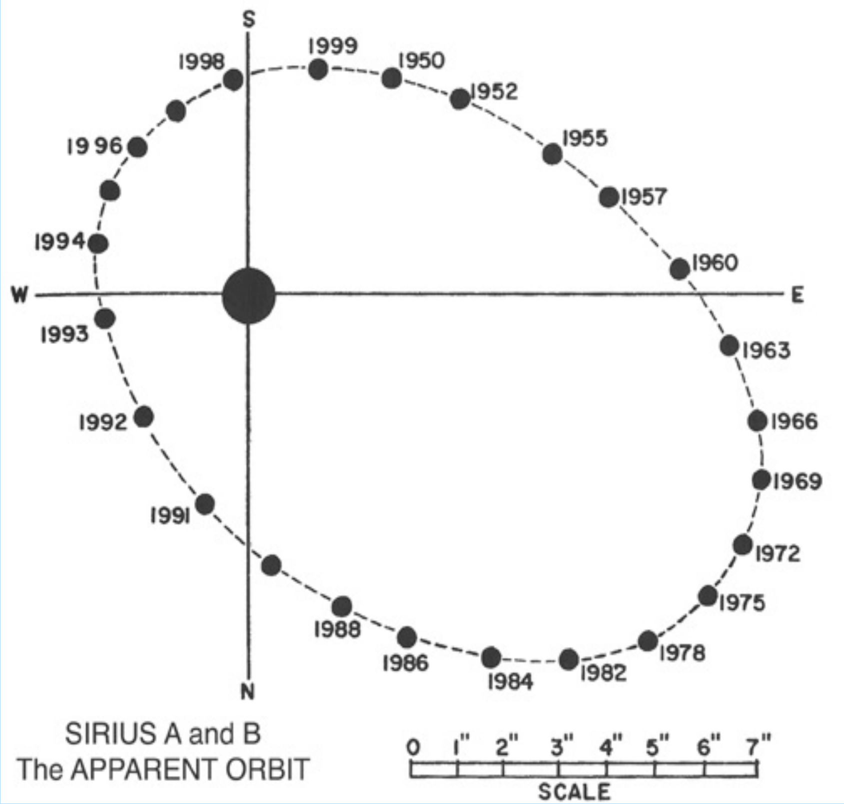
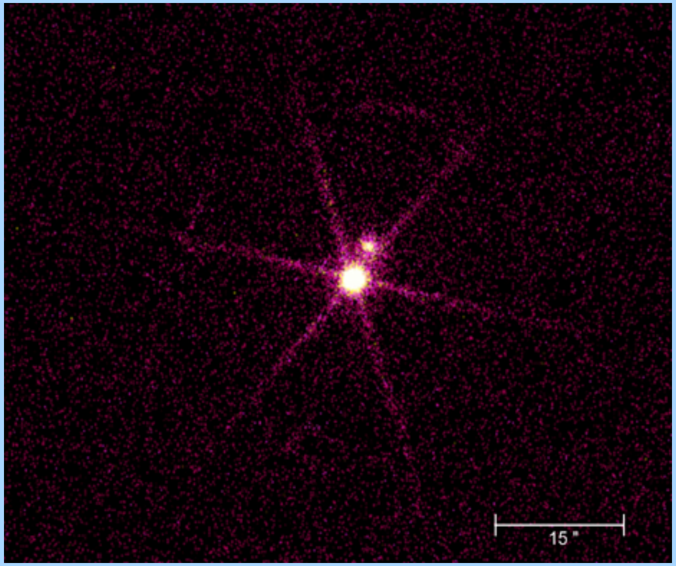
Once the giant phase of a medium-mass star ends, it exhales its outer layers, making a planetary nebula. The degenerate core is a white dwarf star.

In 1844 F. W. Bessel was investigating the proper motion and parallax of Sirius. He predicted that it had a faint, unseen companion.

In 1862 Alvan Graham Clark discovered this faint companion. It was the first known white dwarf star.

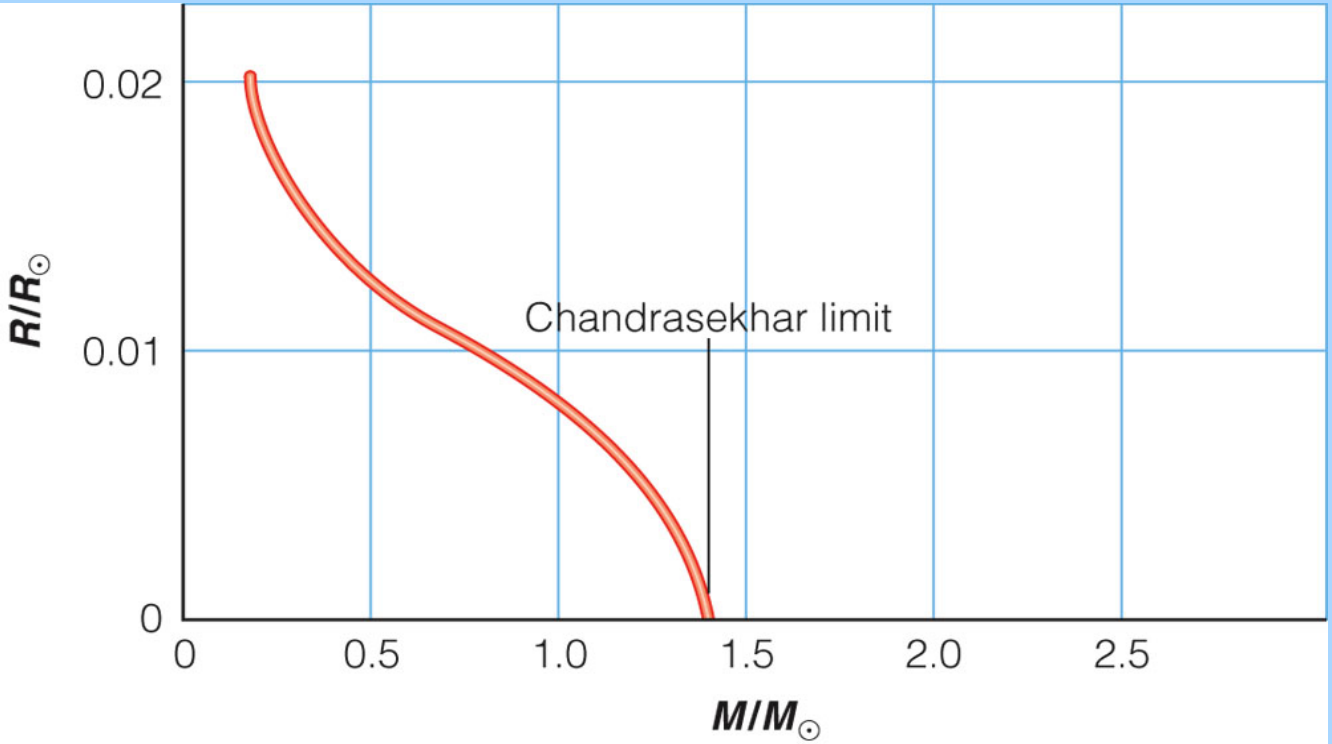


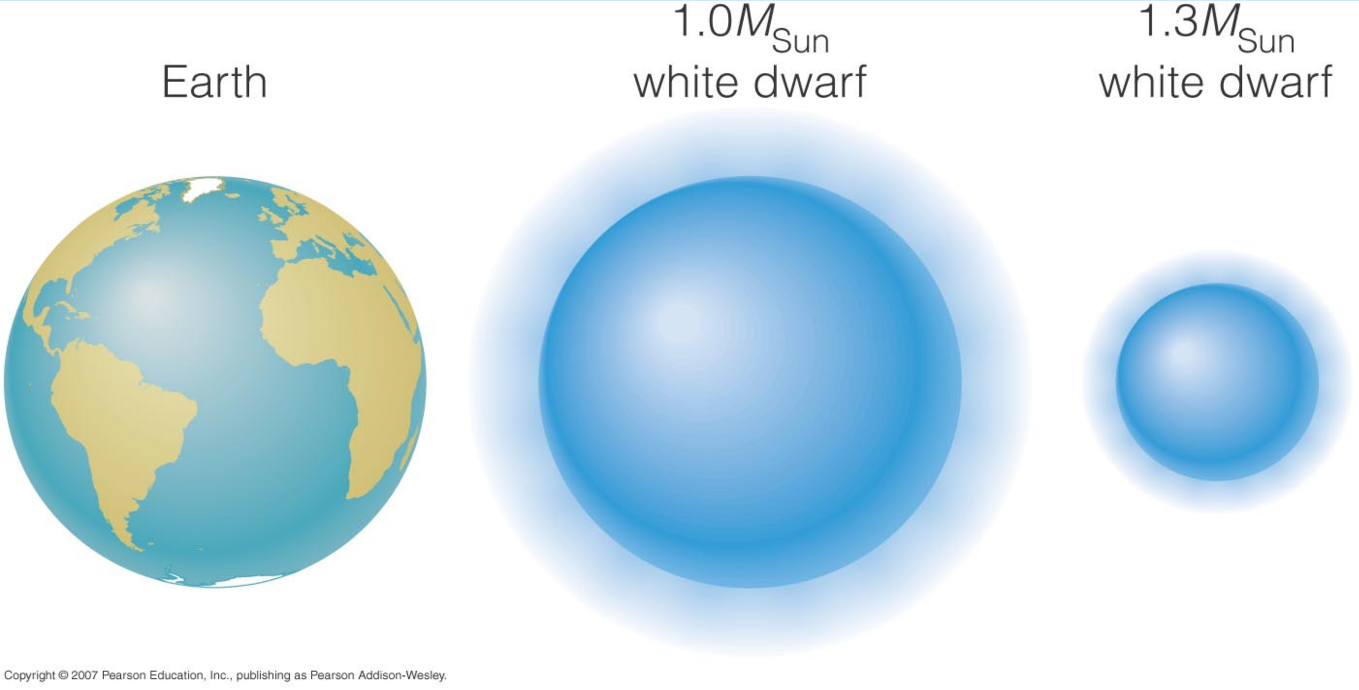




Sirius A and B at optical wavelengths (top left), and in X-rays (left).

In 1930 the young Indian physicist Subrahmanyan Chandrasekhar (1910-1995) discovered that a white dwarf star can have a mass no greater than 1.4 solar masses.





A white dwarf star is comparable in size to the Earth. More massive white dwarfs are smaller than less massive white dwarfs.

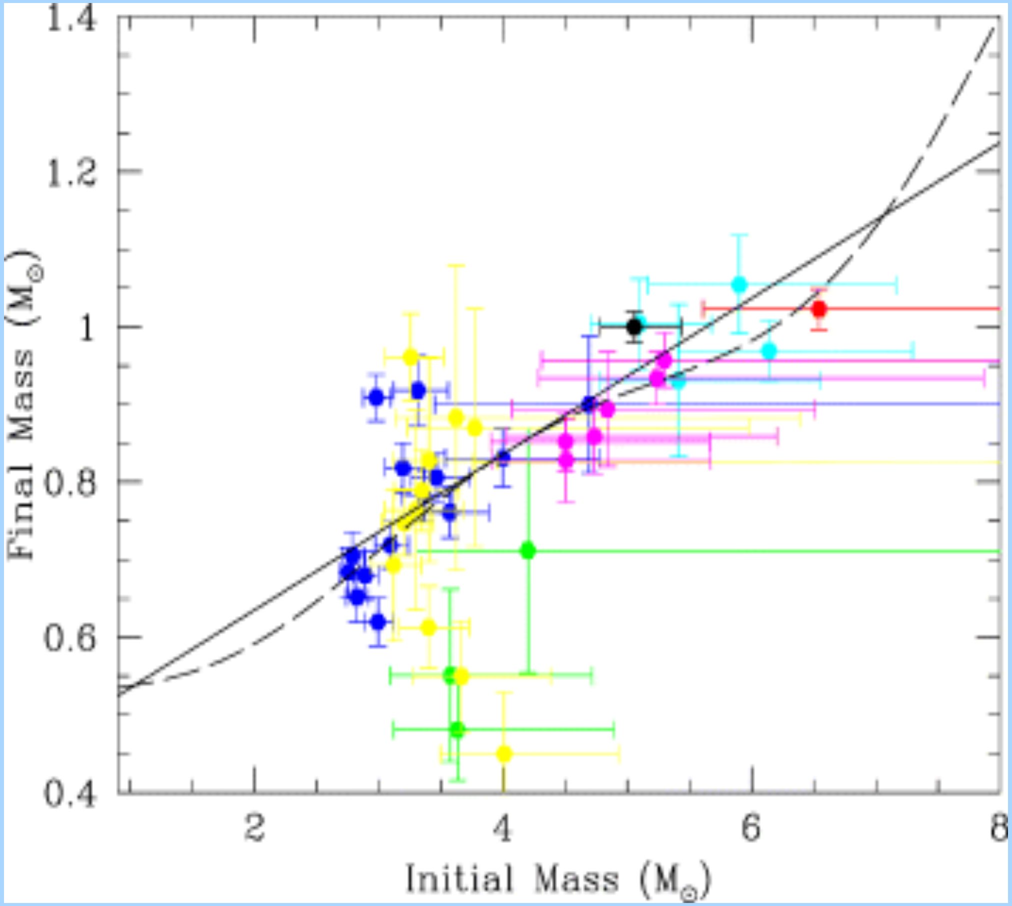
Three routes to an end state:

less than 0.4 solar masses – because they are fully convective, they use up all their mass slowly converting H to He. Do not become red giants.

0.4 to 8 solar masses – lose mass due to stellar winds during giant phase, exhale atmospheres (which become planetary nebulae), leave white dwarf remnant at center of planetary nebula

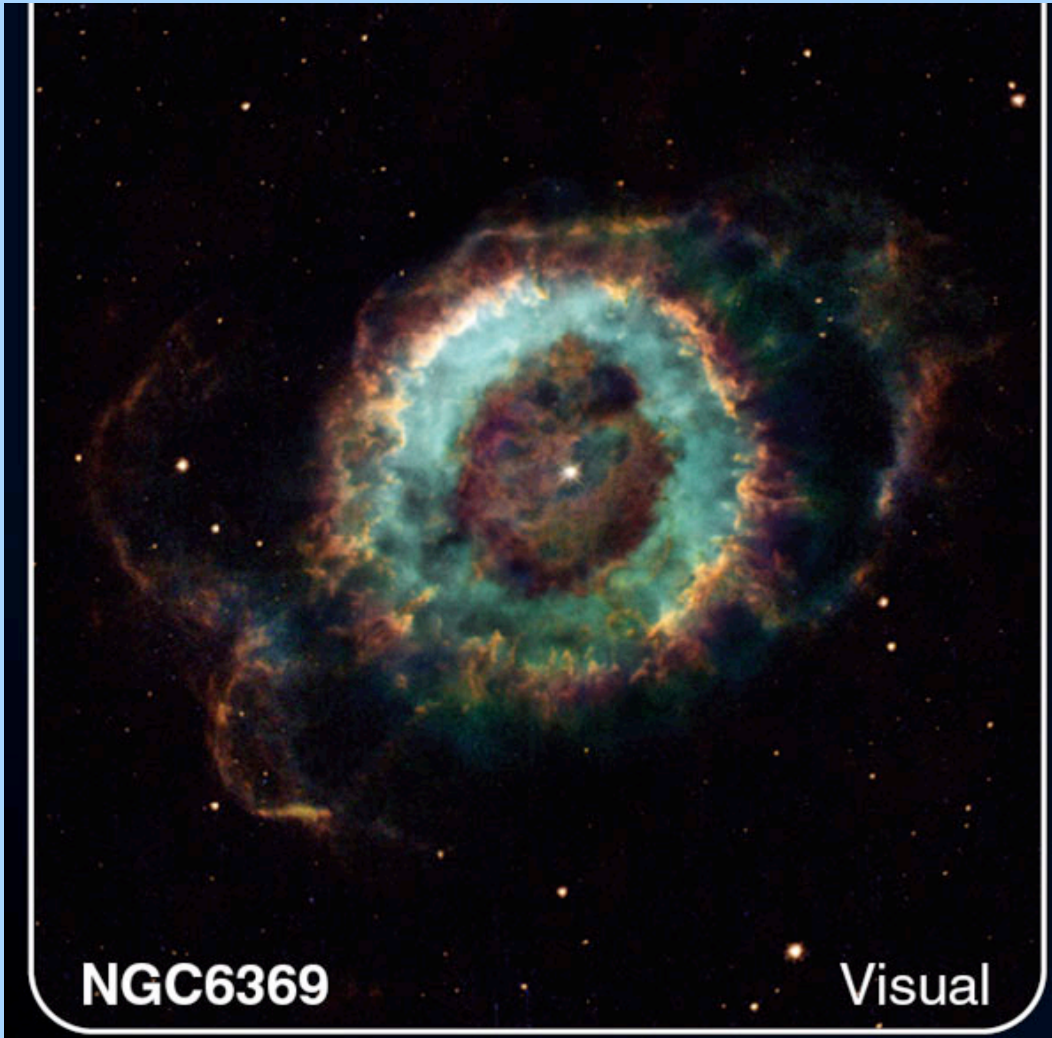
8 or more solar masses – explode as Type II supernovae, leaving behind black holes, neutron stars, or pulsars

Occultation of Venus by the Moon, 19 June 2020



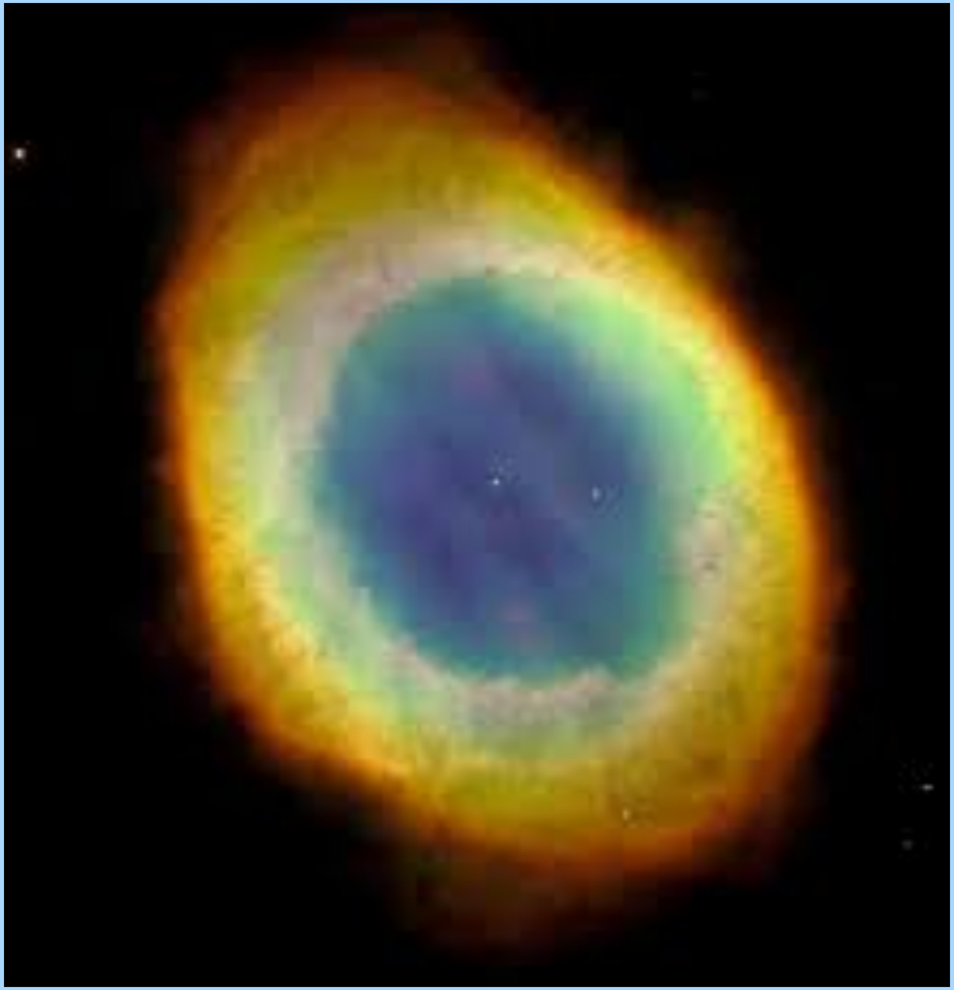
Somehow or other, intermediate mass stars “know” they must shed sufficient mass to have less than 1.4 solar masses.

Ferrario et al. (2005)

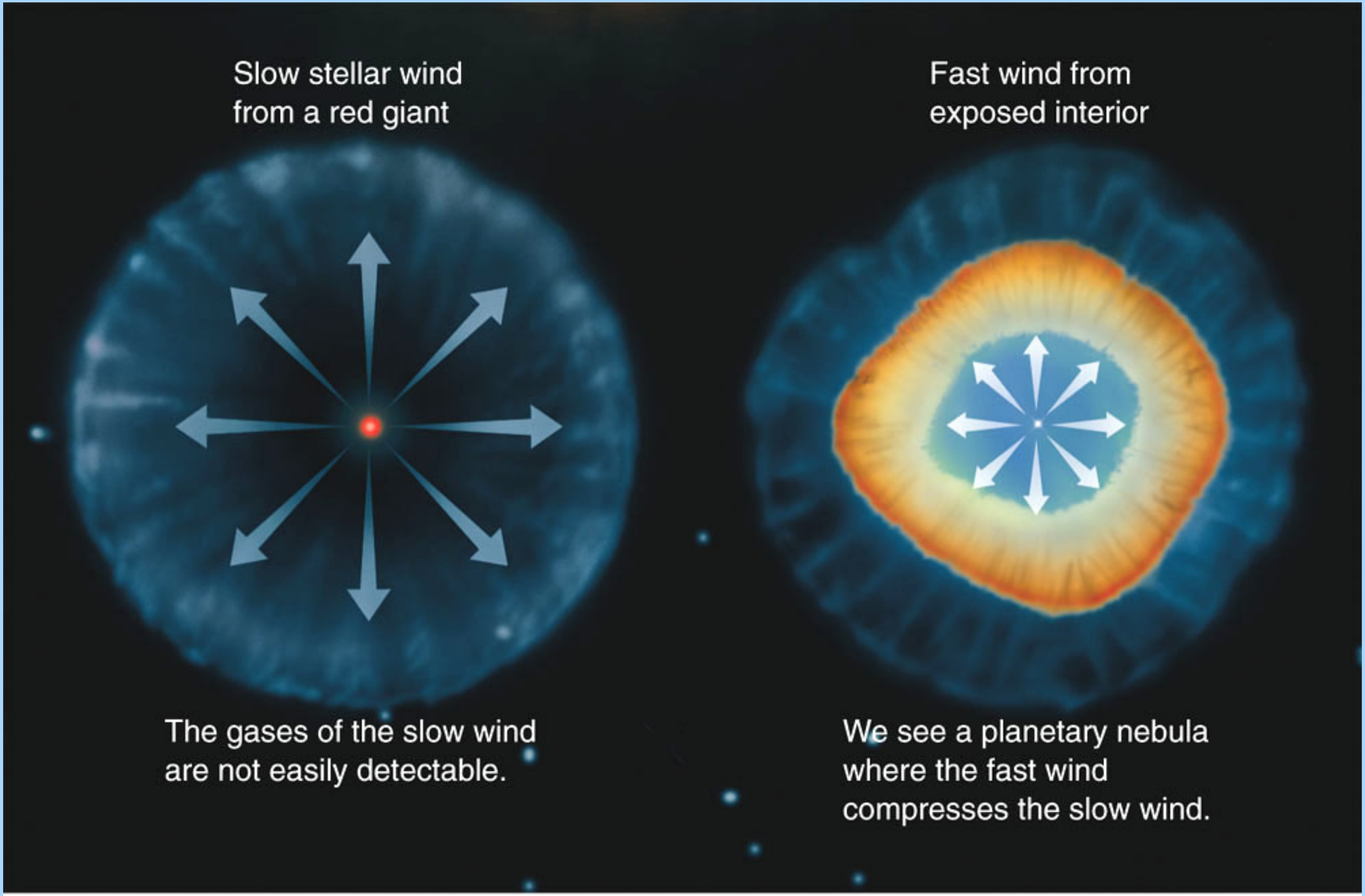


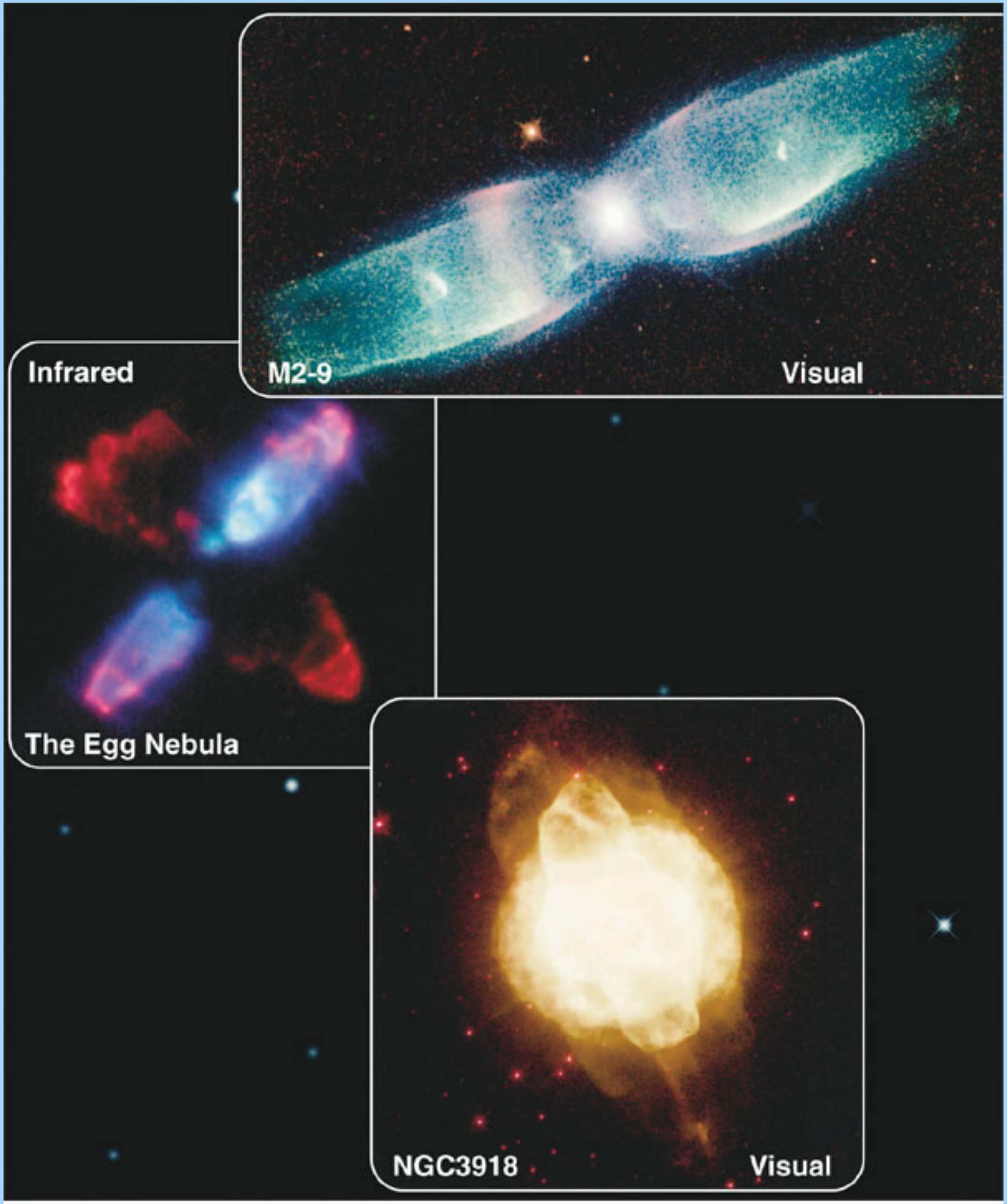
Hubble Heritage Team, STScI/AURA/NASA

This nearly spherical planetary nebula has a low-luminosity outer envelope and a highly excited inner region.

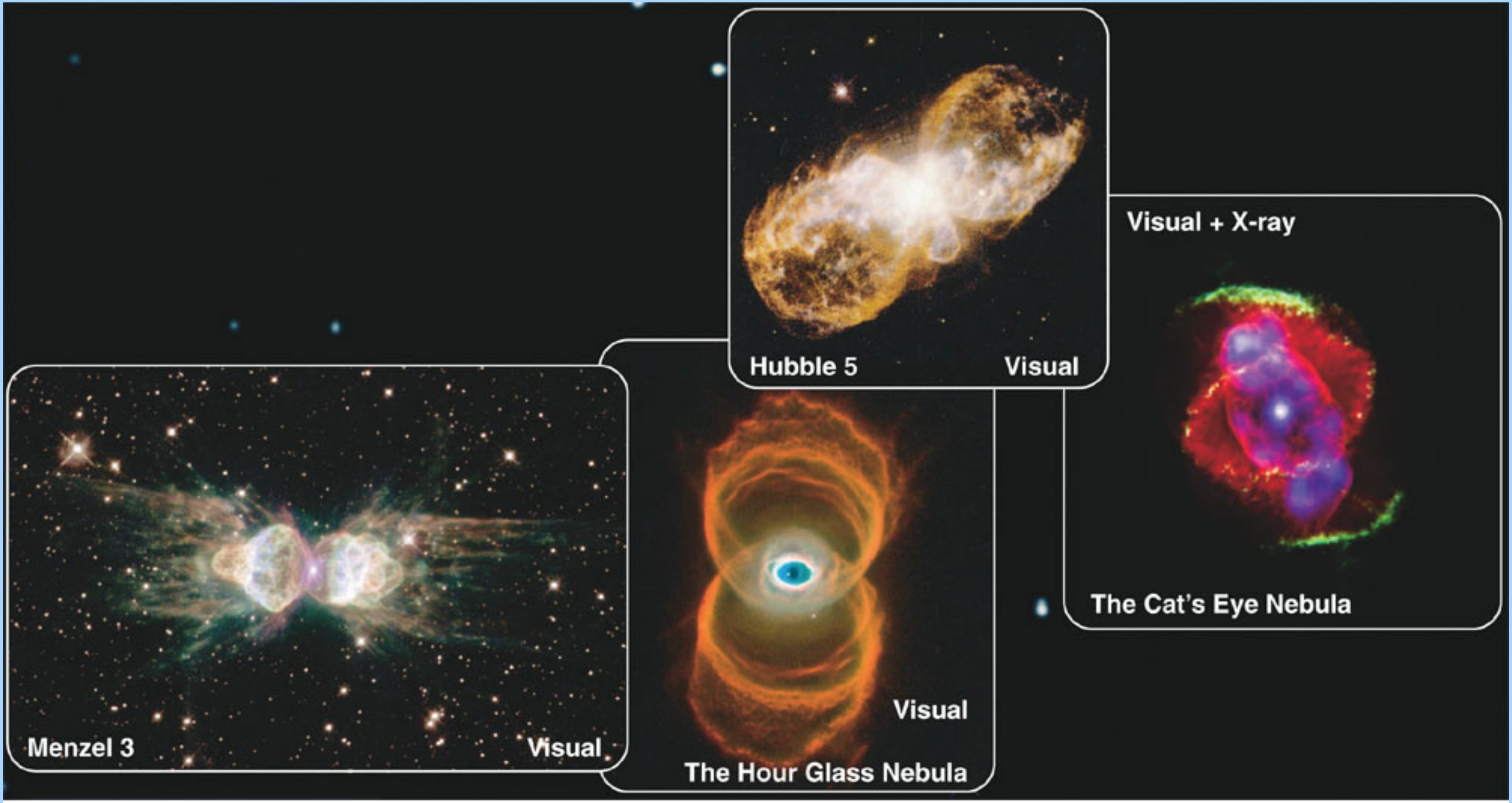


Ring Nebula in Lyra (M 57). Note white dwarf in center.


Slow stellar wind from a red giant
Fast wind from exposed interior
The gases of the slow wind are not easily detectable.
We see a planetary nebula where the fast wind compresses the slow wind.



Three lovely planetary nebulae.



More planetary nebulae.

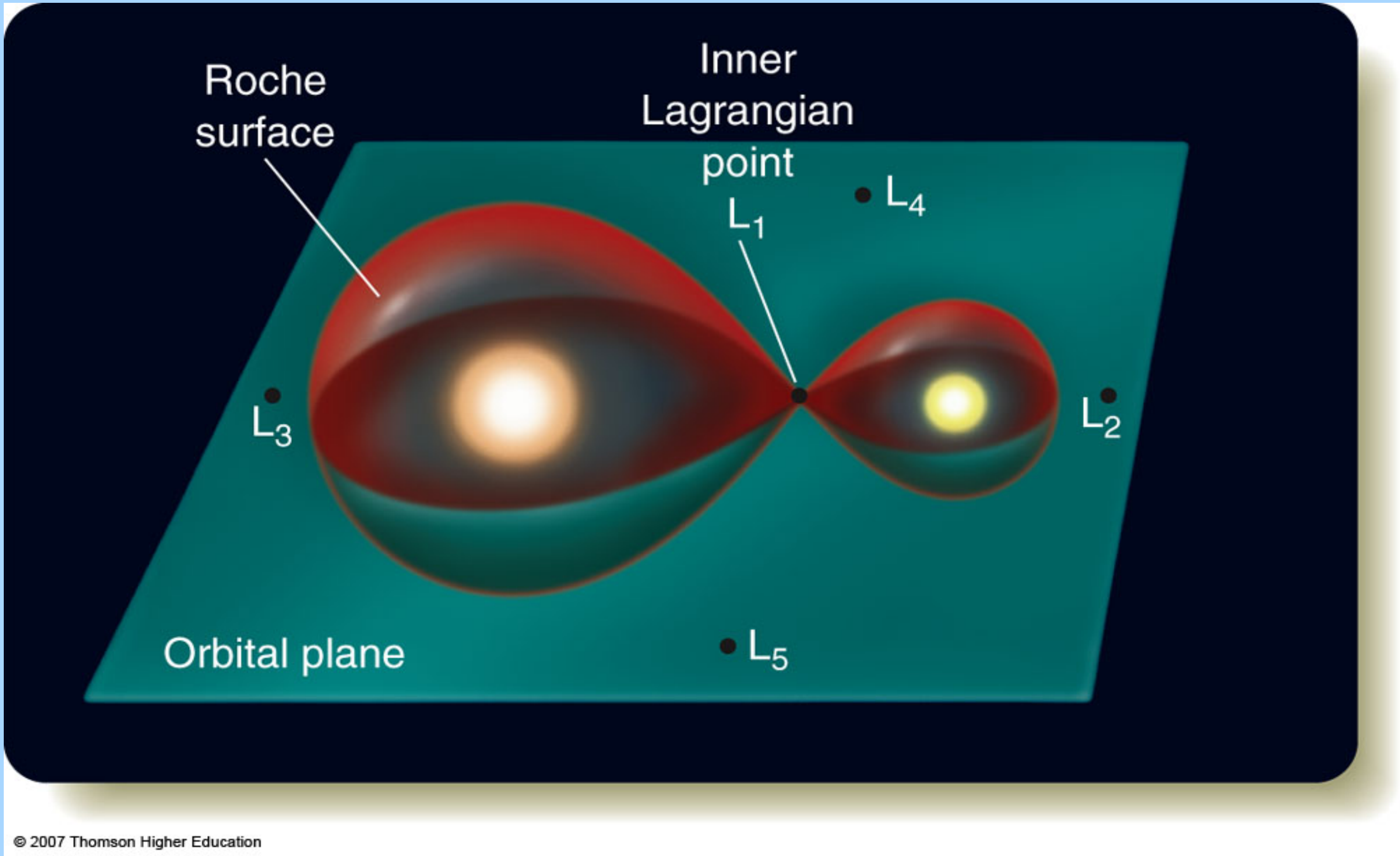
The final end state of a single star with *less than* 8 solar masses is:

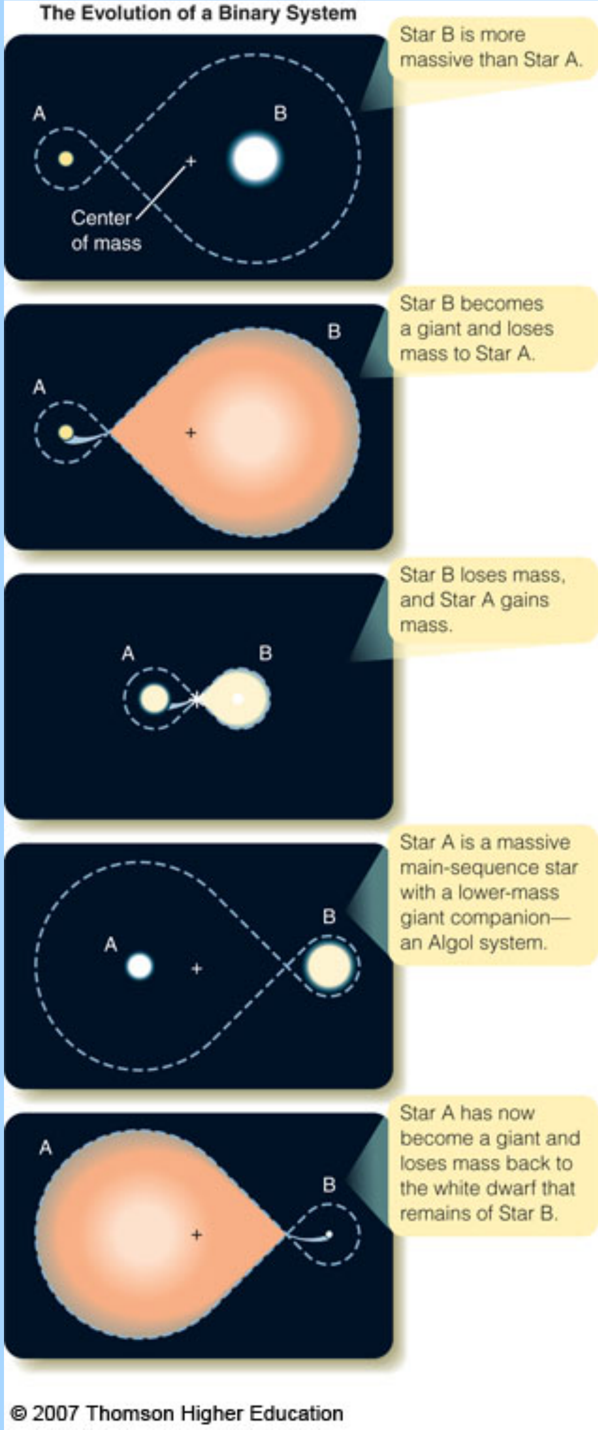
a) red giant star
b) white dwarf star
c) Type Ia supernova (exploding white dwarf)
d) Type II supernova (core collapse SN)

The final end state for a star with *more than* 8 solar masses is:

a) supergiant star
b) white dwarf star
c) Type Ia supernova (exploding white dwarf)
d) neutron star or black hole

Close binary stars have different evolution than single stars. Mass can be passed from one star to the other.





The Evolution of a Binary System

Star B is more massive than Star A.

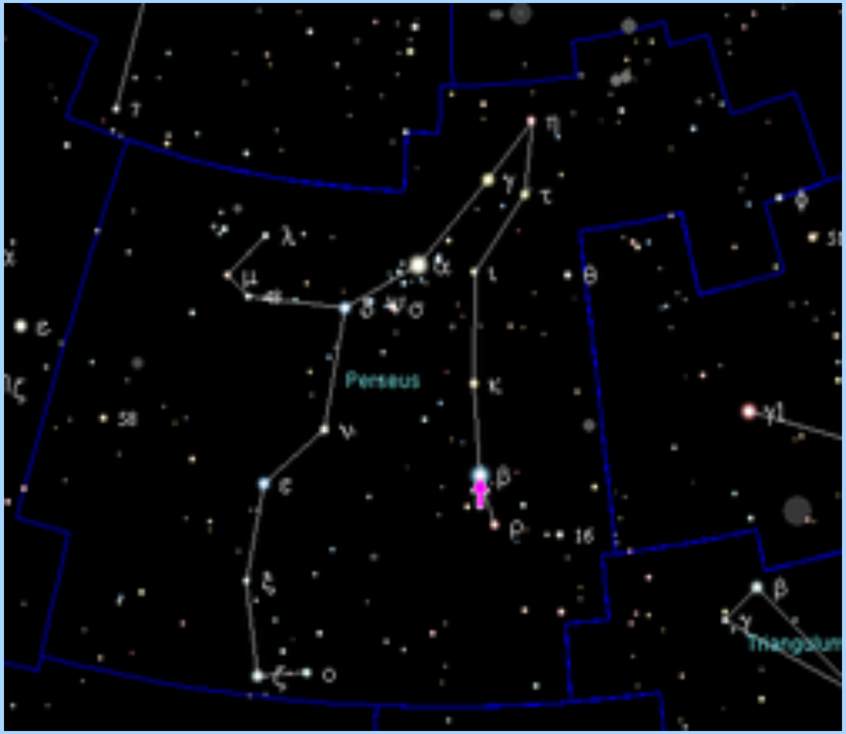
Star B becomes a giant and loses mass to Star A.

Star B loses mass, and Star A gains mass.

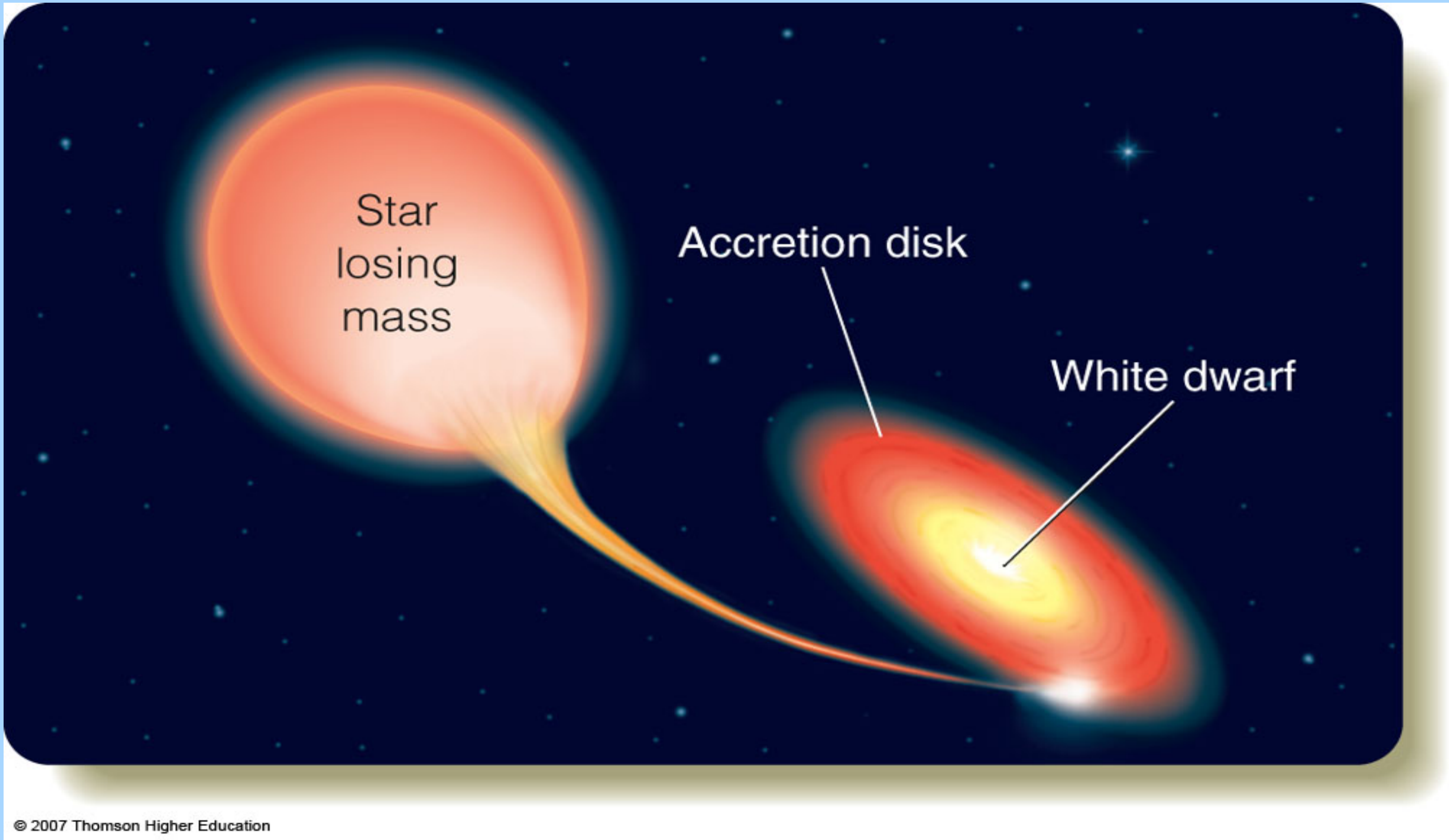
Star A is a massive main-sequence star with a lower-mass giant companion—an Algol system.

Star A has now become a giant and loses mass back to the white dwarf that remains of Star B.

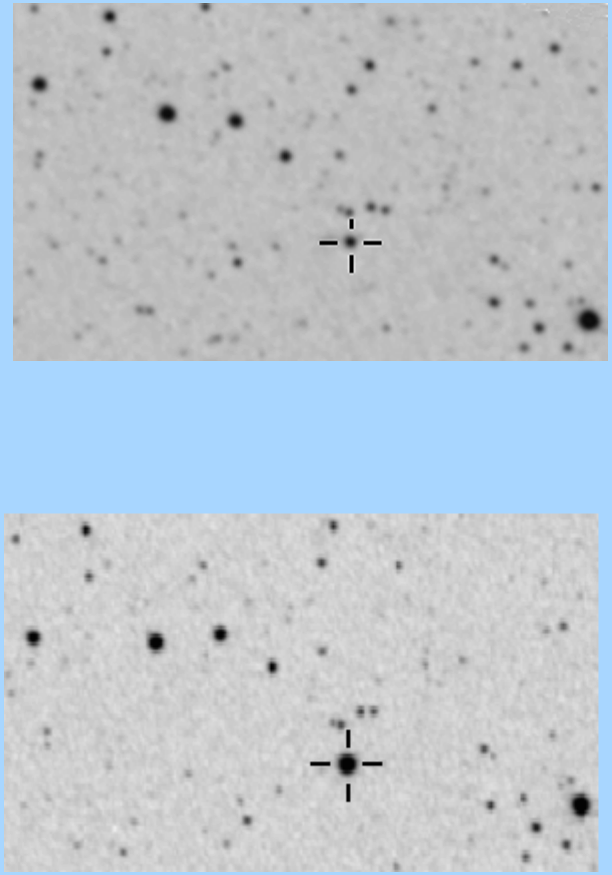
As the more massive star swells to become a red giant, a lot of mass can be transferred to the formerly less massive star. Ironically, the originally less massive star can be the one to reach its end state first.



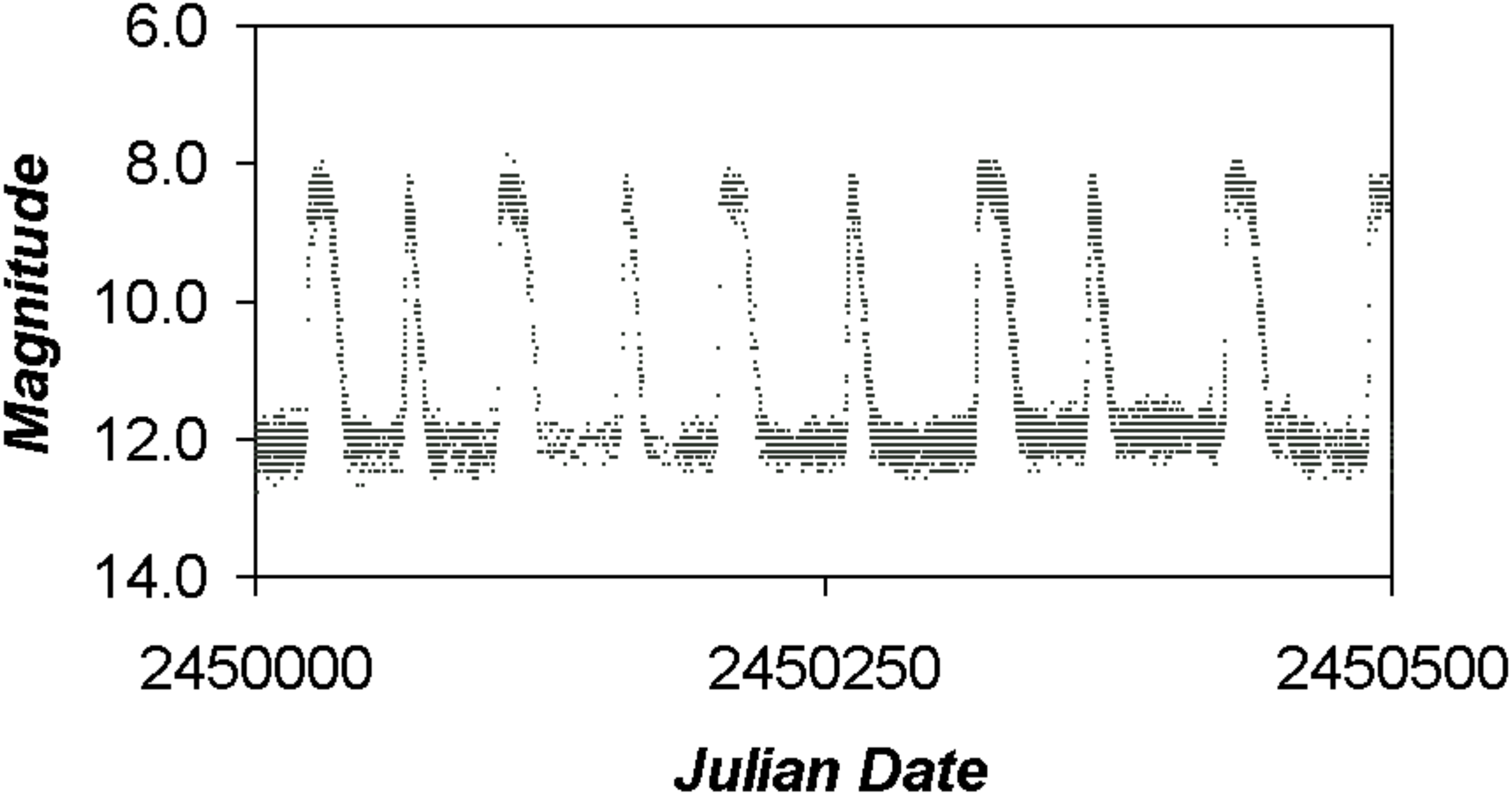
The star Algol (β Persei, marked with pink arrow) is an eclipsing binary in which the original less massive star has evolved to become a red giant, which the original more massive star is still on the main sequence.



Material from the accretion disk in a nova (or dwarf nova) settles onto the white dwarf. This can lead to *periodic* explosions in the system.



SS Cygni is a dwarf nova that has an outburst just about every 52 days. In the upper image at left it is in its faint stage. In the lower image at left it is having an outburst.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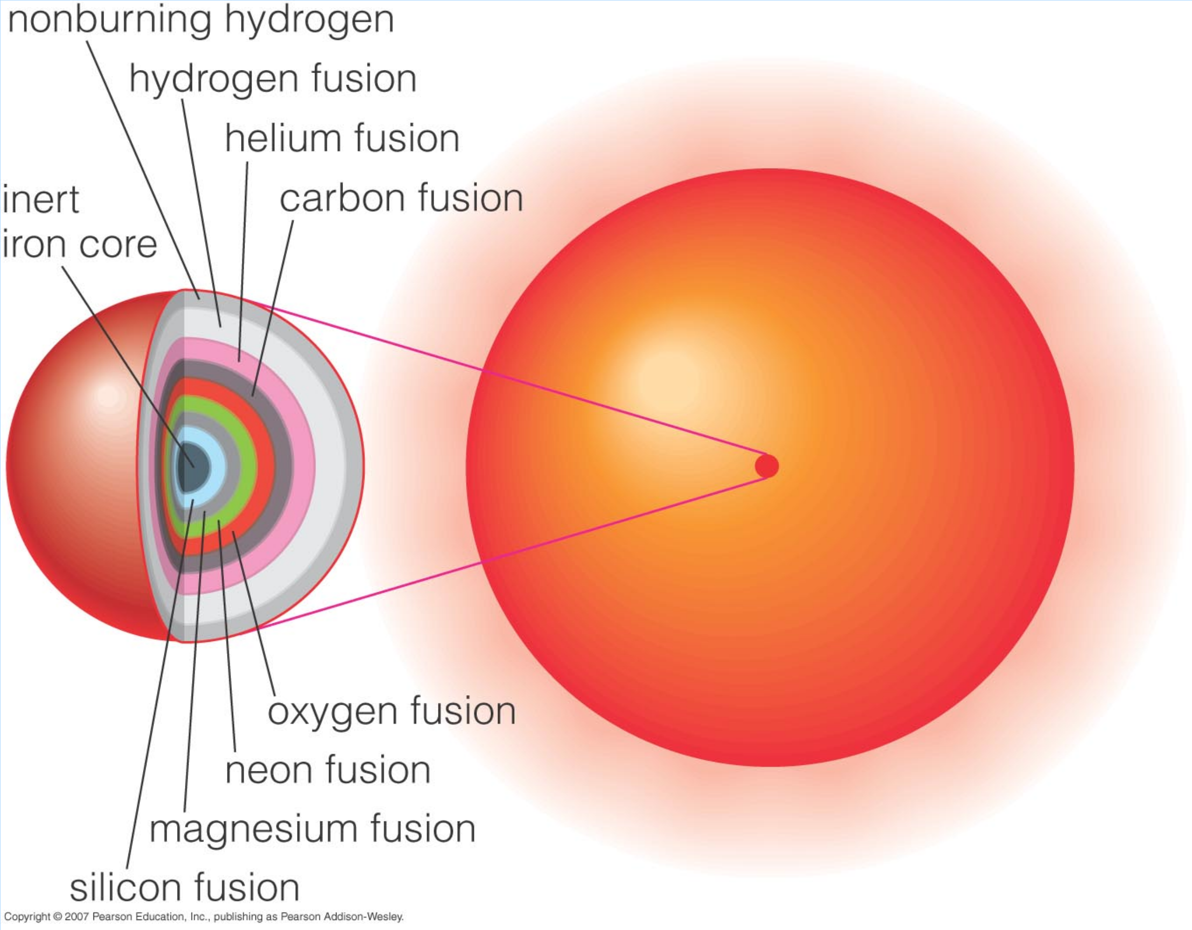
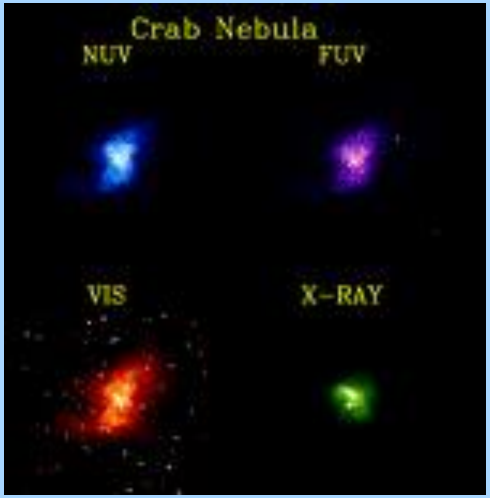
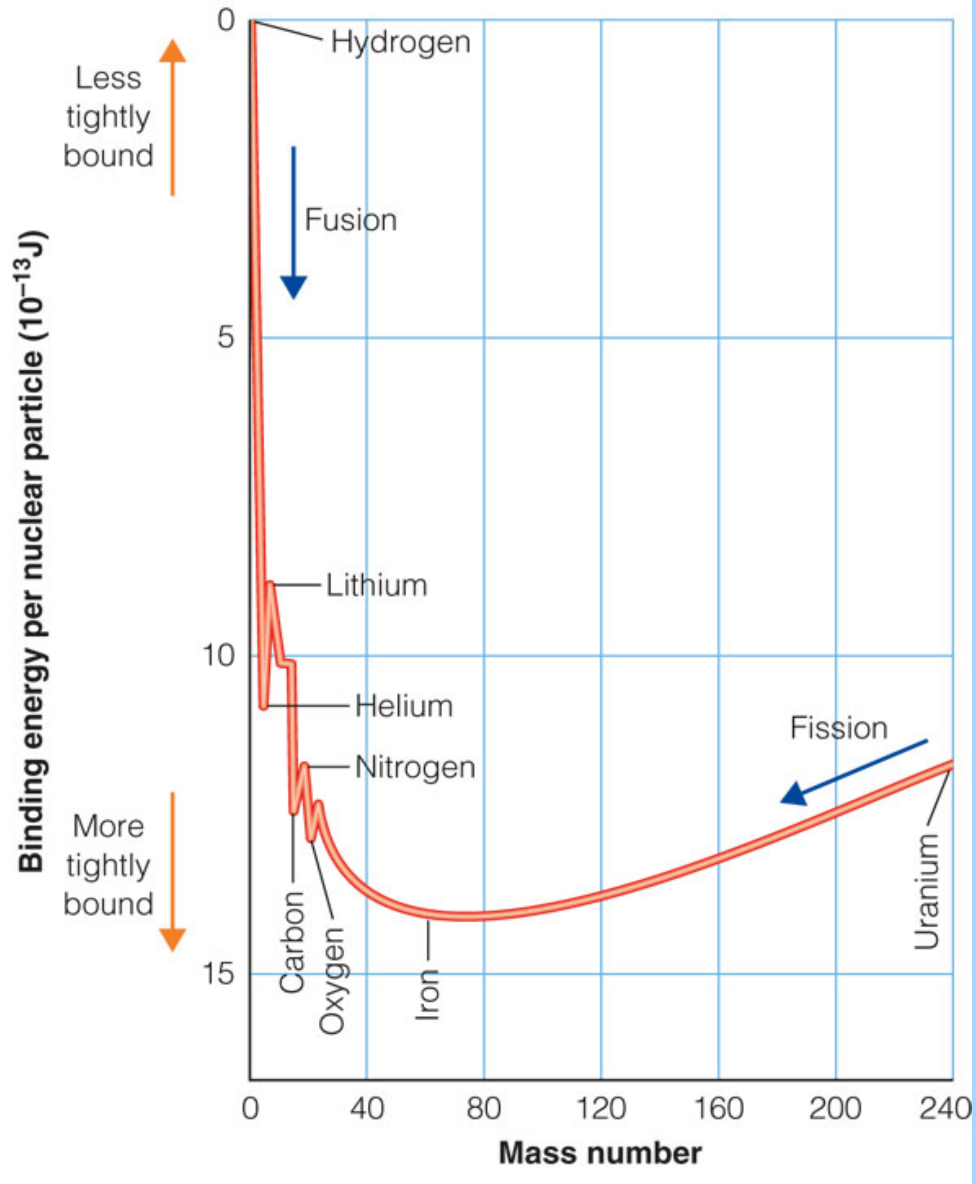
Stars with 8 or more solar masses end up with a many-layered structure, eventually with an iron core.

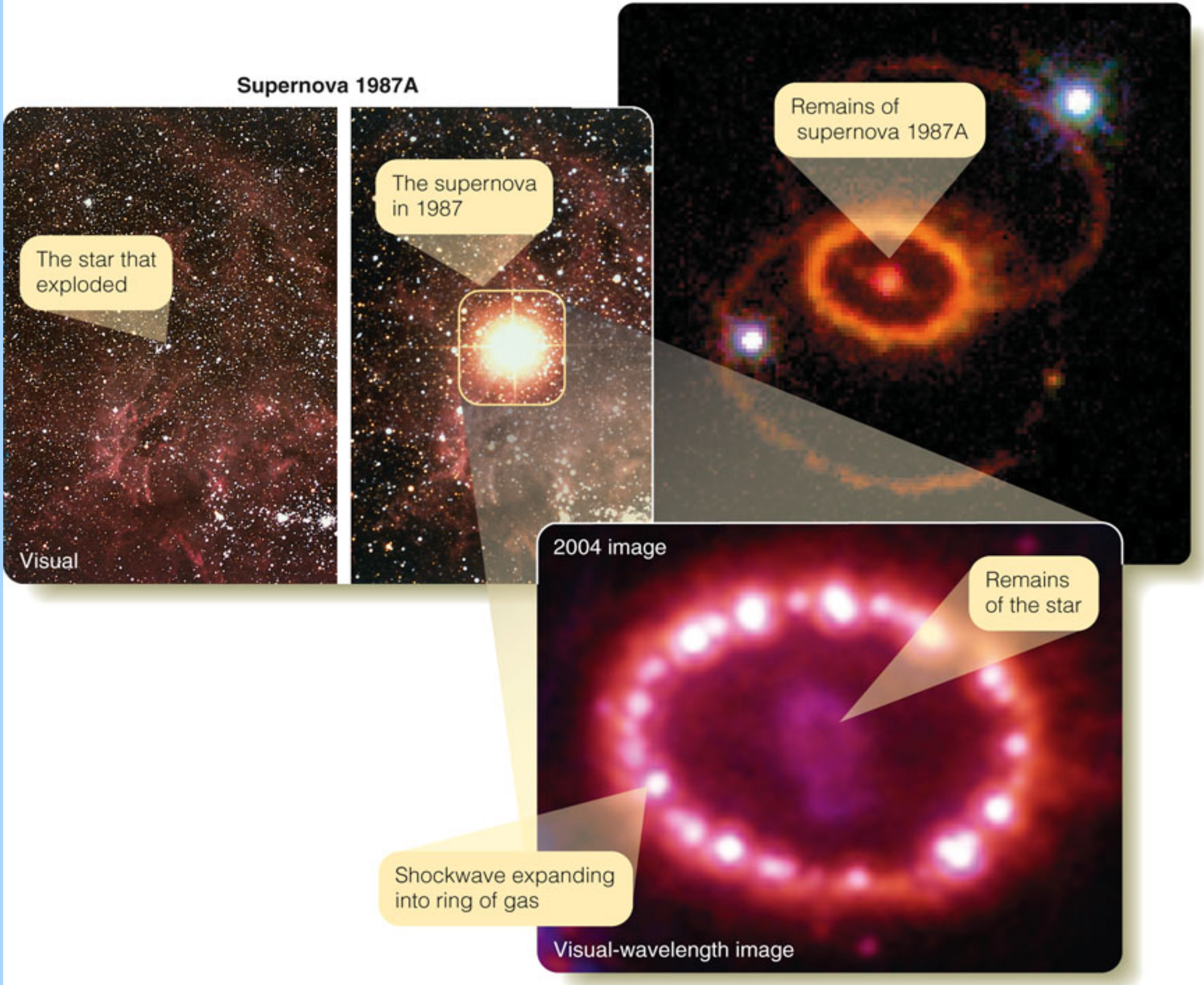




The Crab Nebula in Taurus is a SN remnant of an object visible in the year 1054.



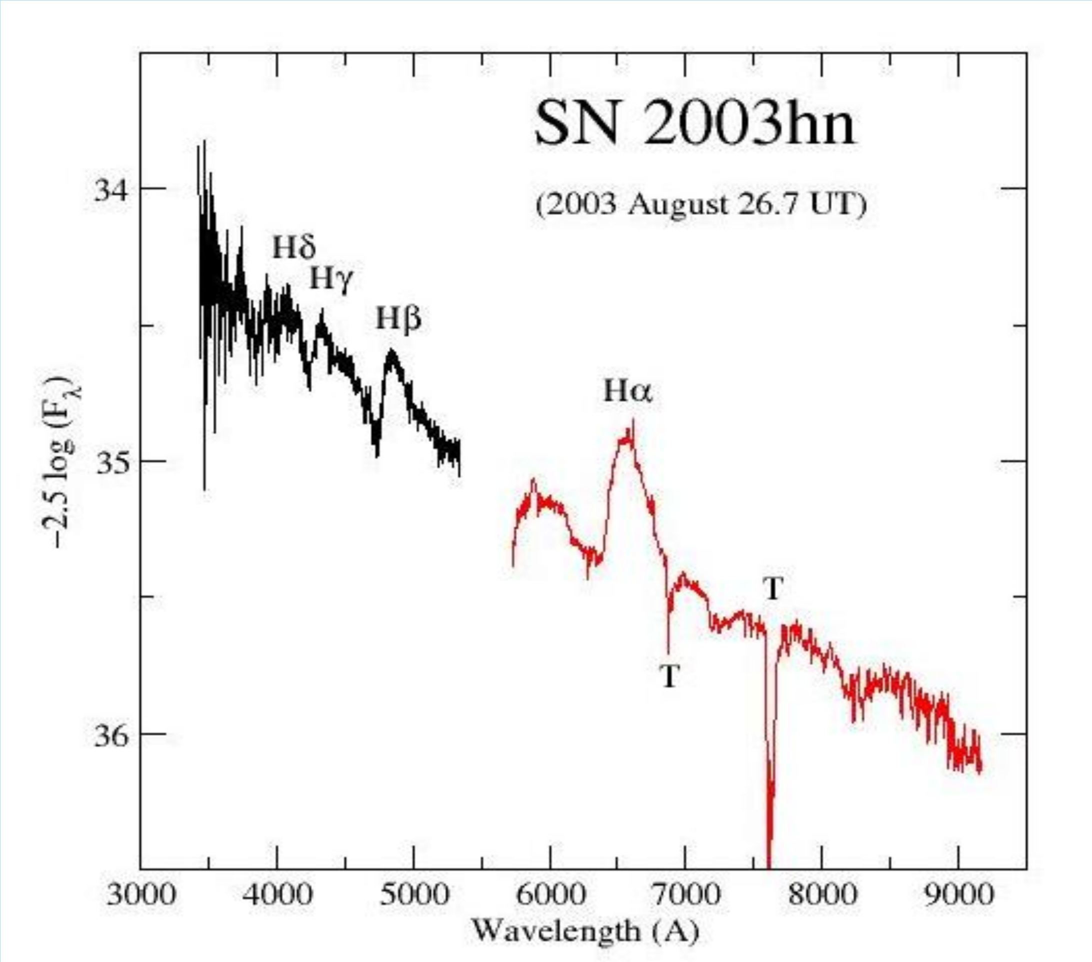
Iron is the mostly tightly bound nucleus. Nuclear reactions to form heavier atoms would use up more energy than they would produce. The outer layers squeeze down onto the iron core and the star explodes as a Type II supernova.


Supernova 1987A
The star that exploded
The supernova in 1987
Remains of supernova 1987A
Visual
2004 image
Remains of the star
Shockwave expanding into ring of gas
Visual-wavelength image

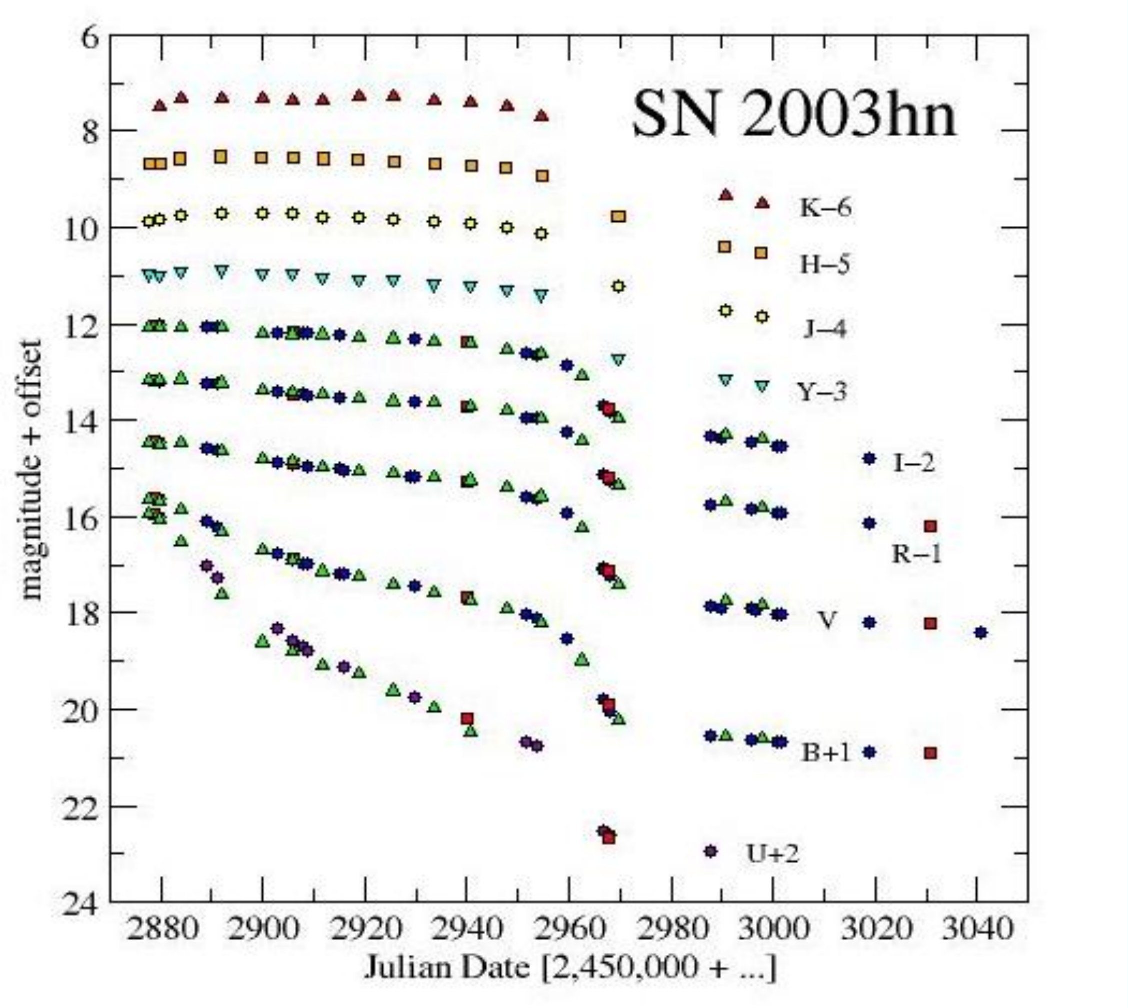
SN 1987A was the explosion of blue supergiant star in the Large Magellanic Cloud, a satellite galaxy of our Milky Way.

Neutrinos from this explosion were detected on the Earth.

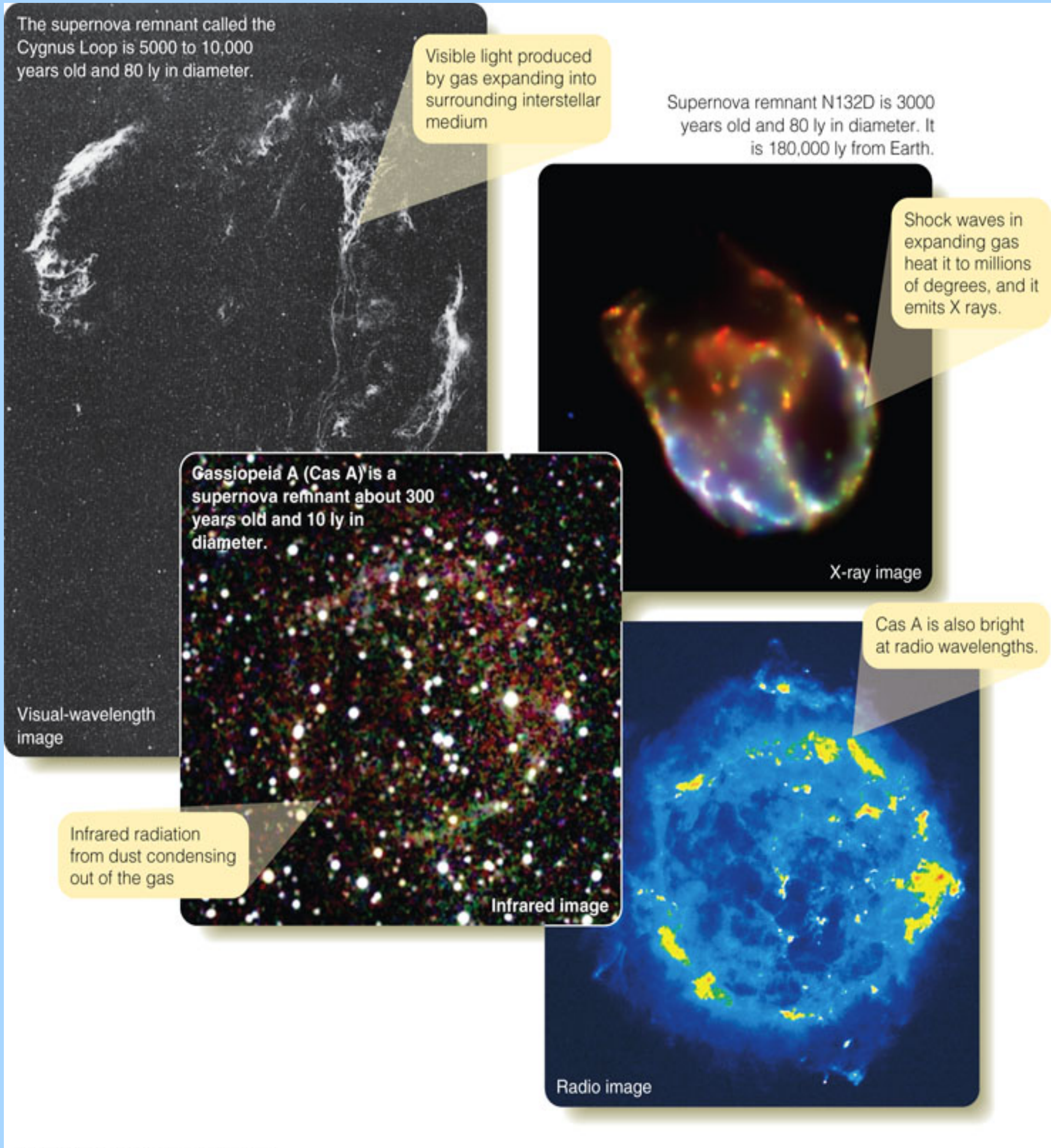
As the ejecta of the SN plow into the interstellar medium, an expanding ring of shocked gas is observed.



Spectrum of the Type II SN 2003hn. At least four emission lines due to atomic hydrogen are visible.



Infrared and optical light curves of the Type II-P SN 2003hn.



The supernova remnant called the Cygnus Loop is 5000 to 10,000 years old and 80 ly in diameter.

Visible light produced by gas expanding into surrounding interstellar medium

Supernova remnant N132D is 3000 years old and 80 ly in diameter. It is 180,000 ly from Earth.

Shock waves in expanding gas heat it to millions of degrees, and it emits X rays.

Cassiopeia A (Cas A) is a supernova remnant about 300 years old and 10 ly in diameter.

Cas A is also bright at radio wavelengths.

Infrared radiation from dust condensing out of the gas

We can find many supernova remnants in our Galaxy.

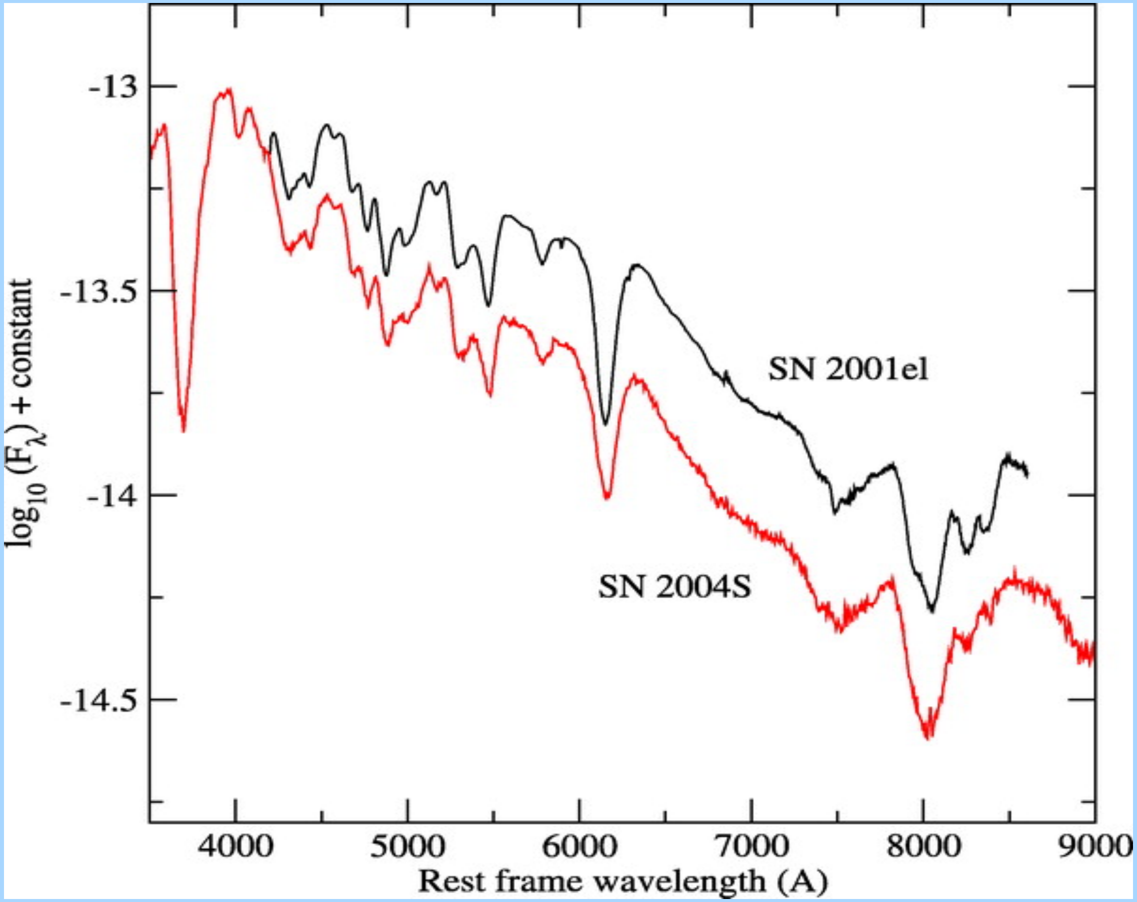
There are two basic ways to make a supernova:

1) explosion of a single massive star

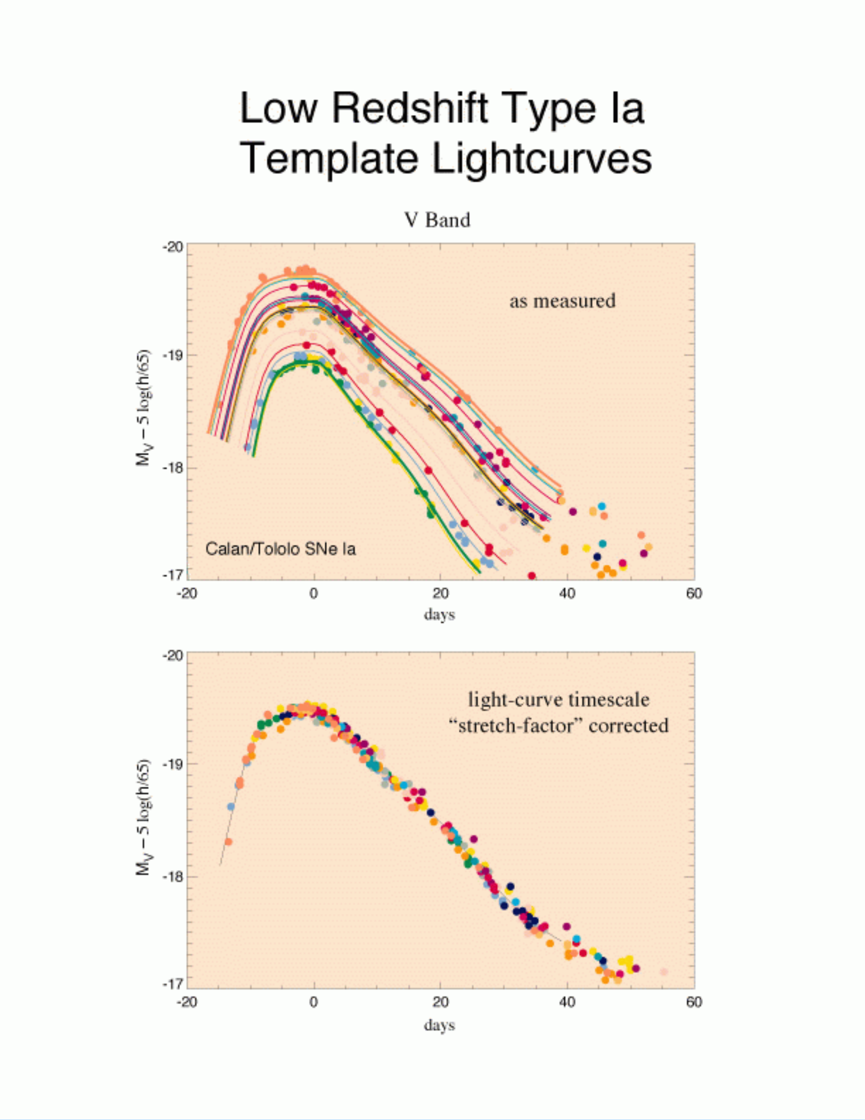
2) mass transfer to a white dwarf star (If the mass of the WD approaches 1.4 solar masses, the star explodes.)

Supernovae with hydrogen emission in their spectra are called Type II. They are explosions of single, massive stars.

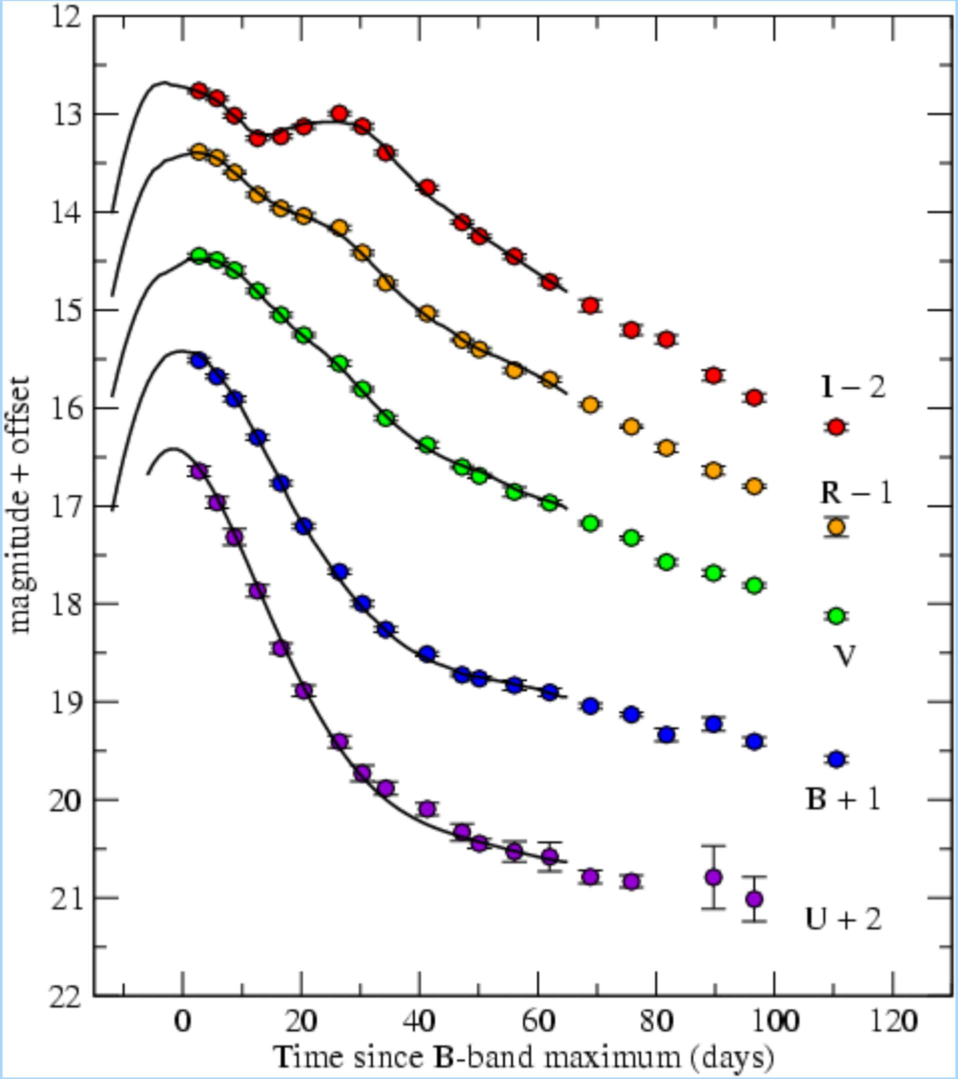
Supernovae without hydrogen emission, but with silicon absorption are Type Ia SNe They are explosions of C-O white dwarf stars.



Note how similar the spectra of these two Type Ia supernovae are!



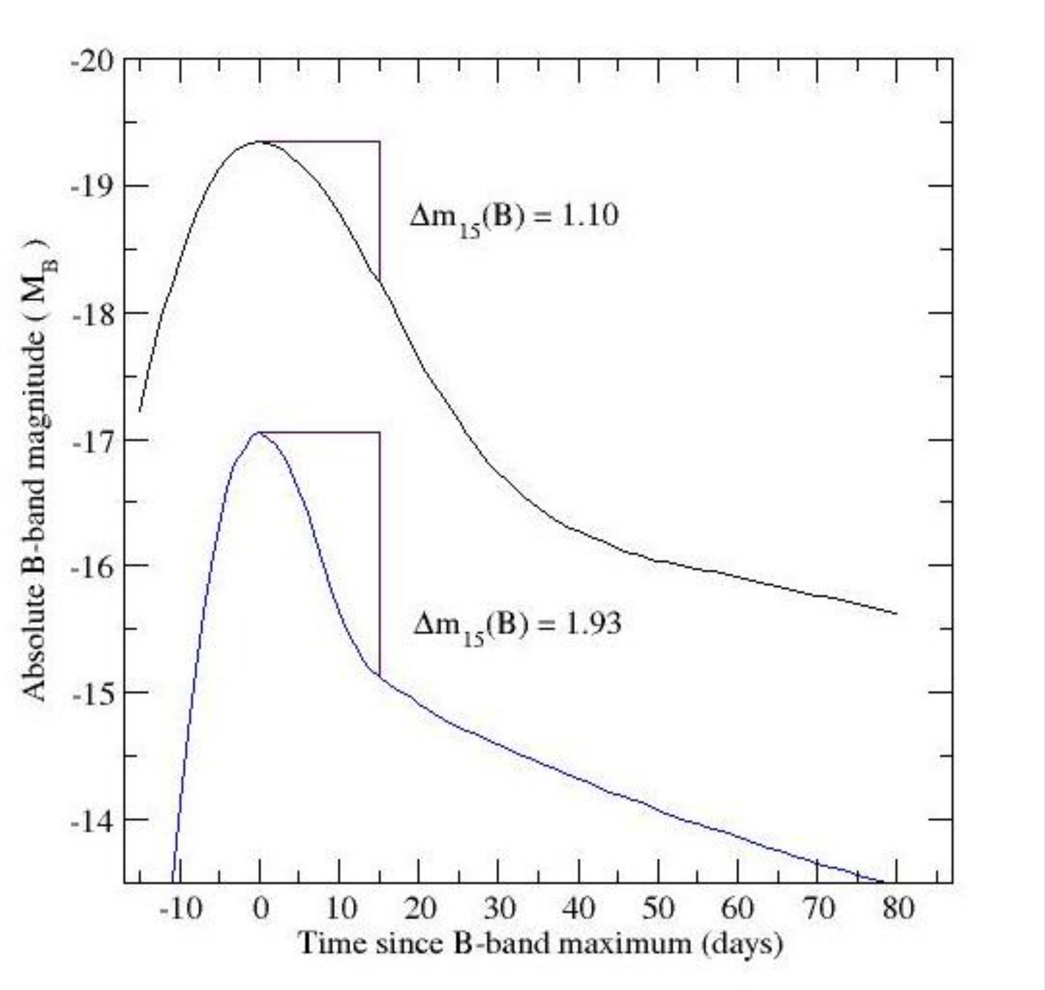
Type Ia supernovae have very similar light curves in the B-band and V-band. But the objects that are brighter at maximum light have light curves that decline more slowly.



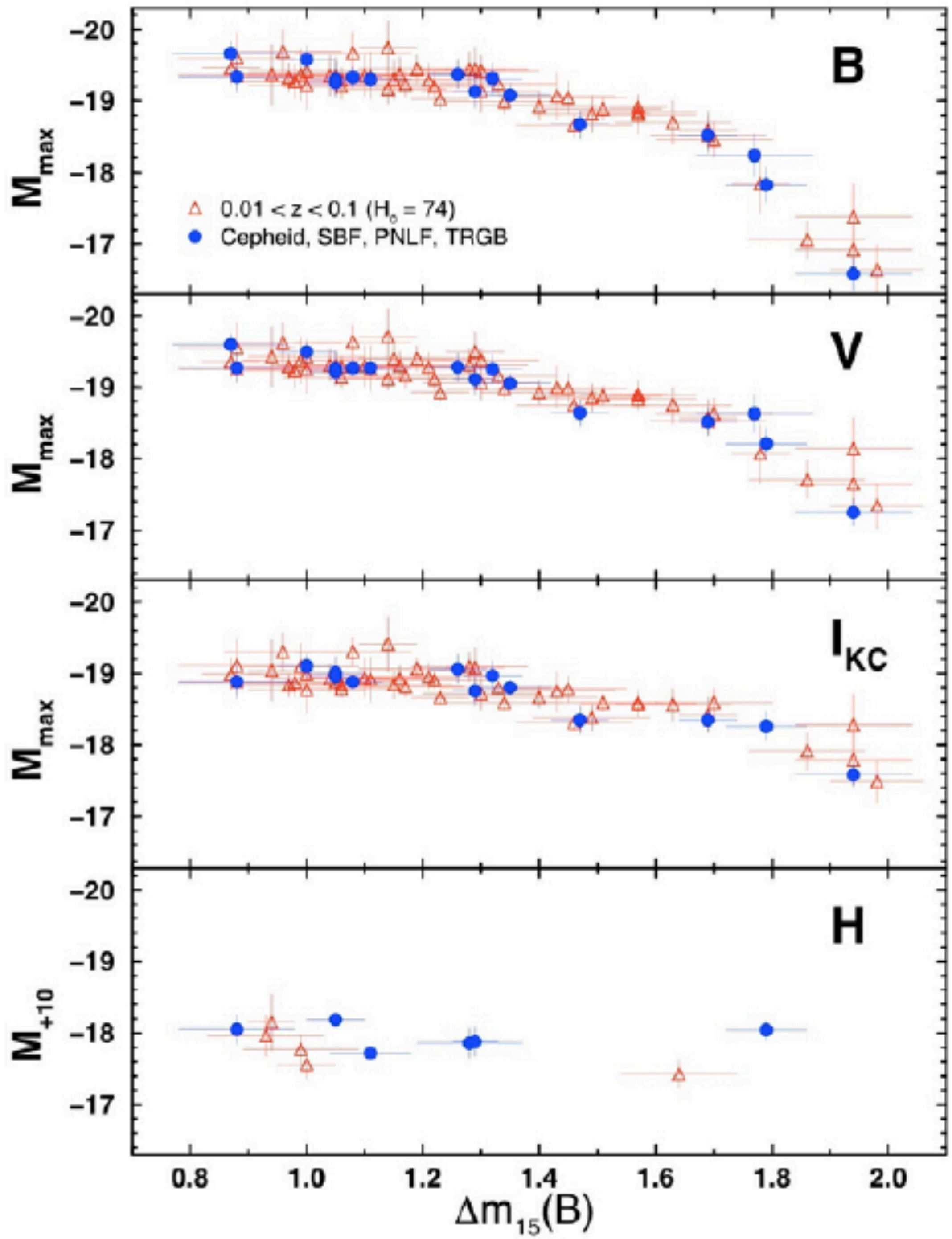
Optical light curves of the Type Ia supernova 2004S.

An astronomical "standard candle" is an object whose absolute magnitude we can deduce, such as from its variations of brightness (e.g. a Cepheid variable star) or from the decline rate of its light curve (e.g. a Type Ia supernova).

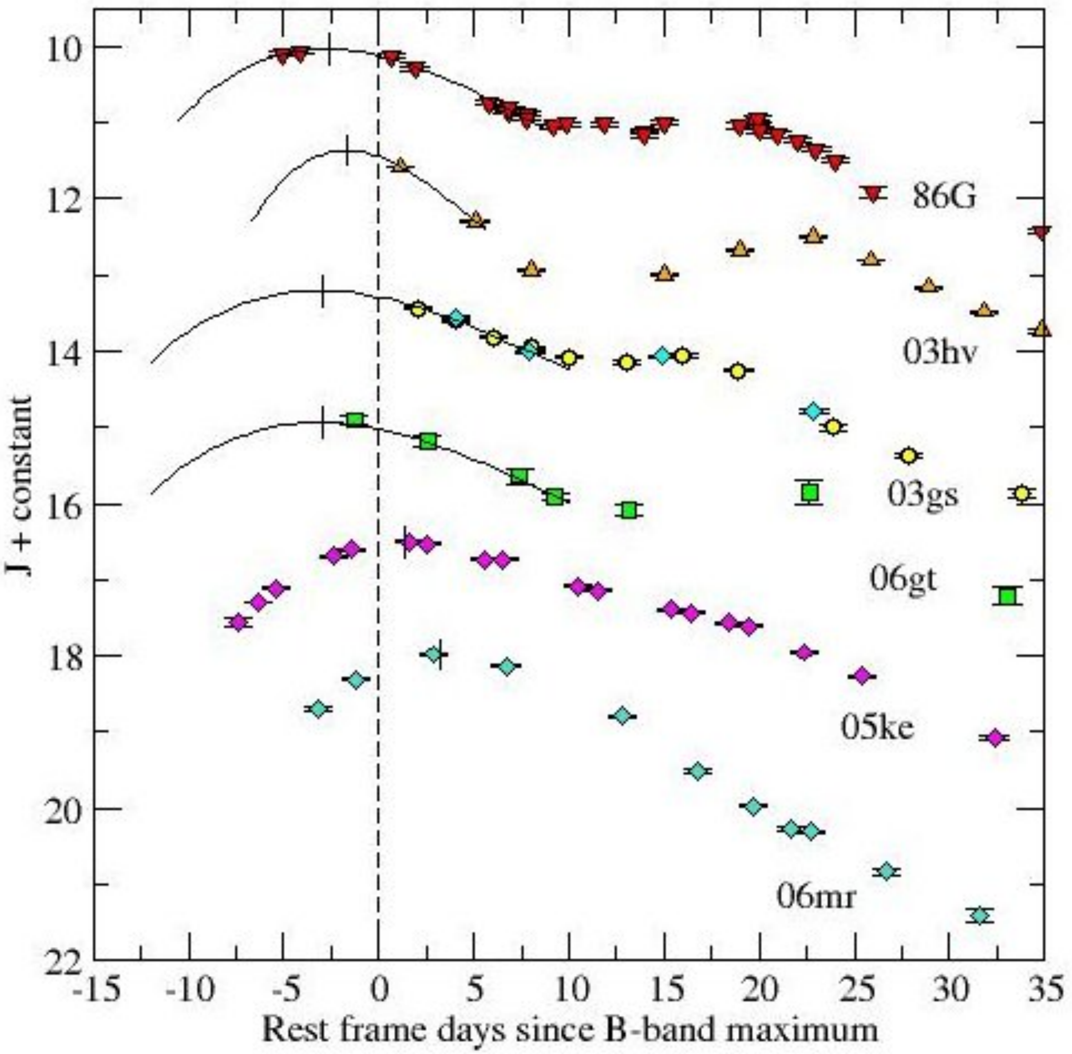
Then, with a measurement of its apparent brightness, we can derive its distance.



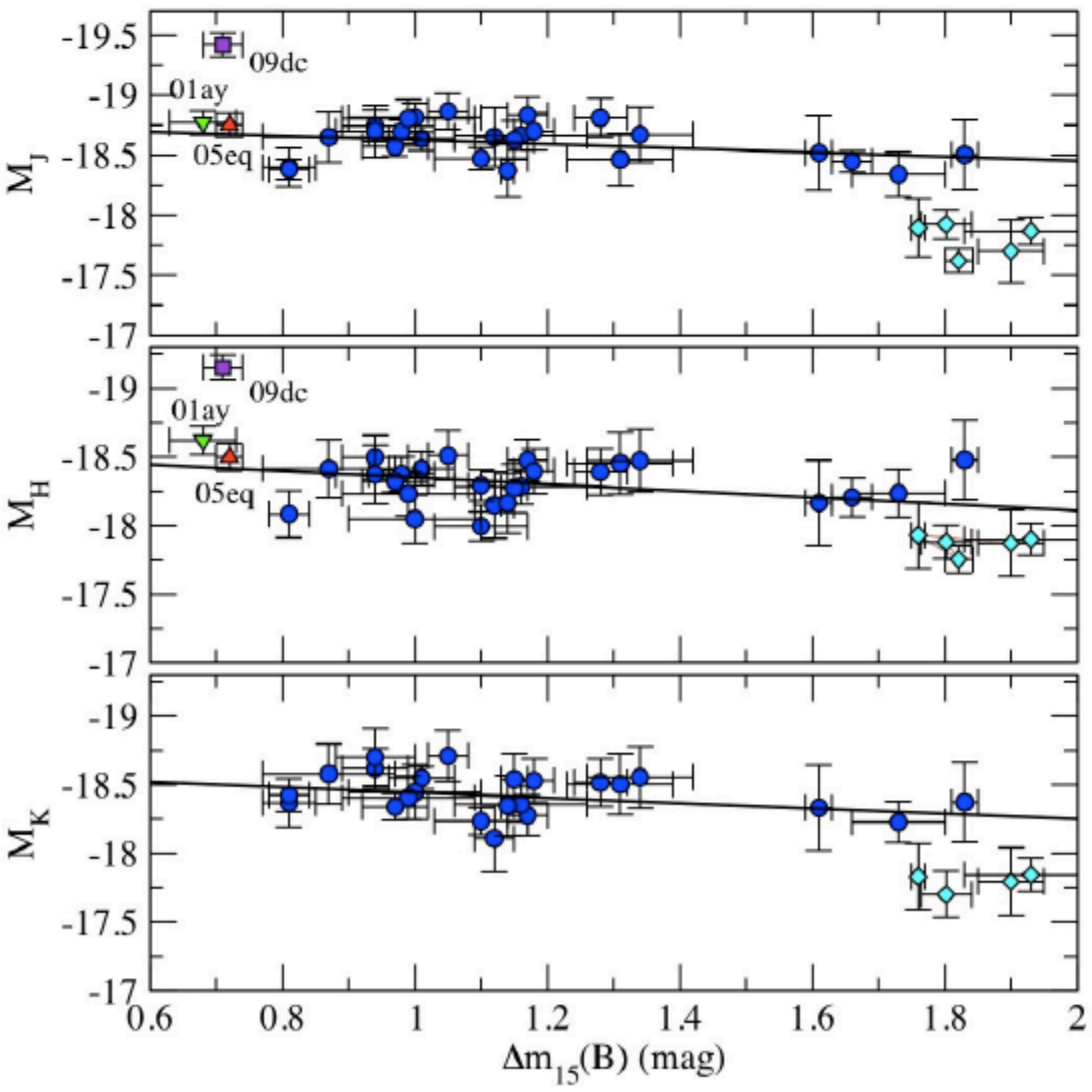
The "decline rate" is the number of magnitudes that a Type Ia supernova gets fainter in the blue band over the first 15 days after maximum brightness. Faster decliners are less luminous. The objects are standardizable candles.



Decline rate relations of Type Ia Sne in three optical bands and the near-IR H-band (ca. 2003).

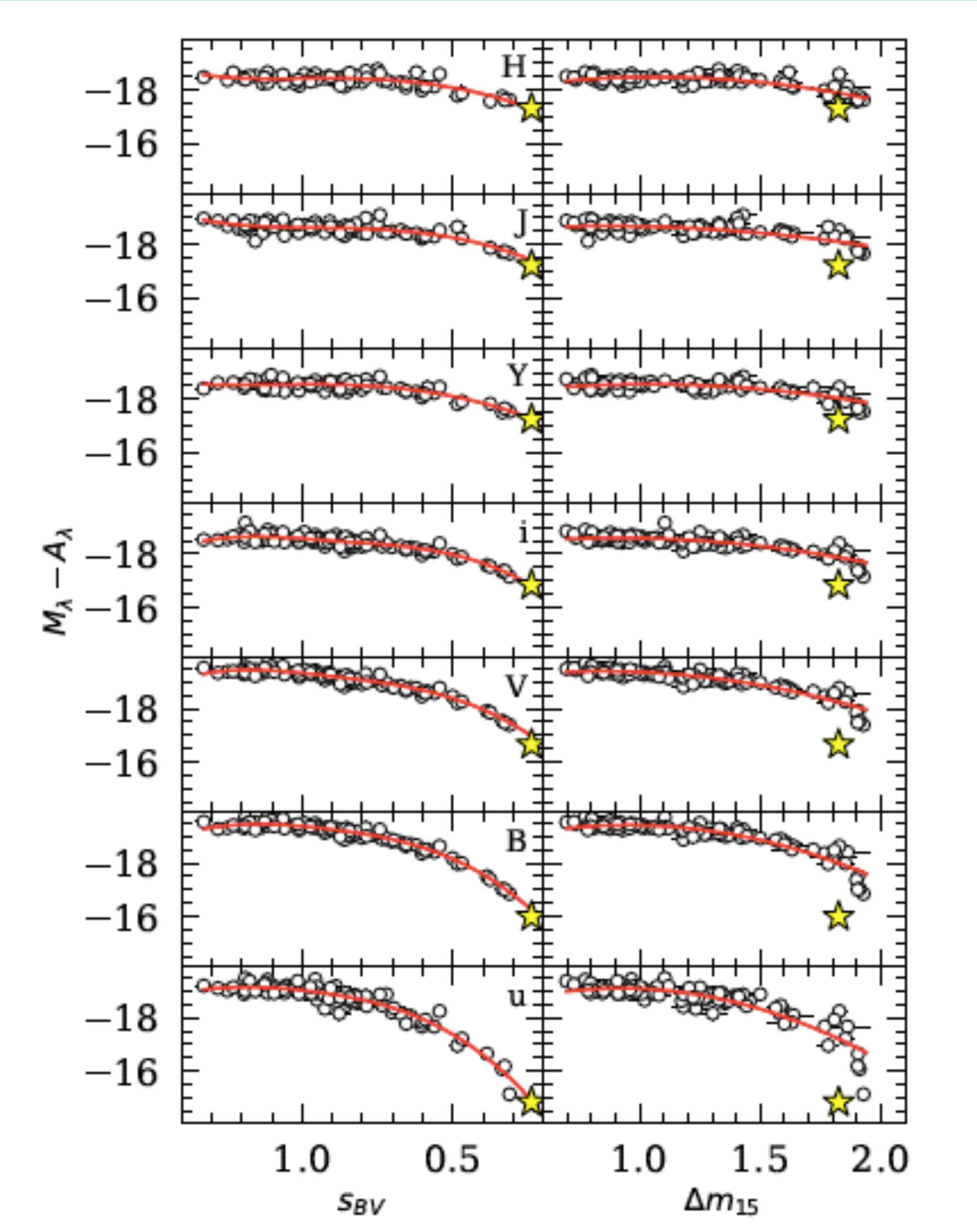


The top 4 SNe shown here are intrinsically brighter than the bottom two.
The top 4 peak in the near-IR a couple days prior to the time of *B*-band max.
Note the different strengths of the 2ndary maxima.



Absolute mags of Type Ia supernovae in the near-IR, vs. the optical B-band decline rate.

Except for those that peak in the near-IR after B-band maximum, they are essentially "standard candles"



The absolute magnitude of Type Ia SNe is correlated with two measures of the “decline rate”.

Burns et al. (2018)

SN 1994D

Because Type Ia supernovae are so bright (4 billion times brighter than the Sun!) and because we can determine their absolute magnitudes, we can use them to determine distances to galaxies halfway across the visible universe.

What would happen to the orbit of the Earth if the Sun somehow became a black hole?

a. The Earth's orbit would be unchanged.
b. The Earth would get sucked into the black hole.
c. The Earth would be ejected from the solar system.
d. We have no idea.

An astronomical “standard candle” is an object whose absolute magnitude we know by one means or another.

Then, by measuring its apparent magnitude, we can determine its distance using the standard formula

$$M = m + 5 - 5 \log_{10} (d_{pc}) \quad \text{or}$$

$$\log_{10} (d_{pc}) = (m + 5 - M) / 5 \quad \text{and}$$

$$d_{pc} = 10^{(\log d)}$$

Examples of astronomical standard candles:

1) A main sequence star of known spectral type (e.g. Sirius), which is an A0 star with $M_V \sim 0.0$.

2) An exploding white dwarf star measured in the near-infrared at the time of its infrared maximum brightness.

2) The mean brightness of an RR Lyrae star ($M_V \sim +0.7$).

An astronomical “standardizable candle” is an object
that can have a large range of intrinsic luminosity,
but that can be determined from easily obtained data.

Examples:

1) Cepheid variable stars have mean luminosities ranging from about 600 to 25,000 times that of the Sun. Using the period-luminosity relation discovered by Leavitt we can estimate the mean intrinsic luminosity of such a star.

2) Exploding white dwarf supernovae observed in the optical B- and V-bands have maximum luminosities that depend on the decline rate after maximum light. This is known as the Phillips relation.