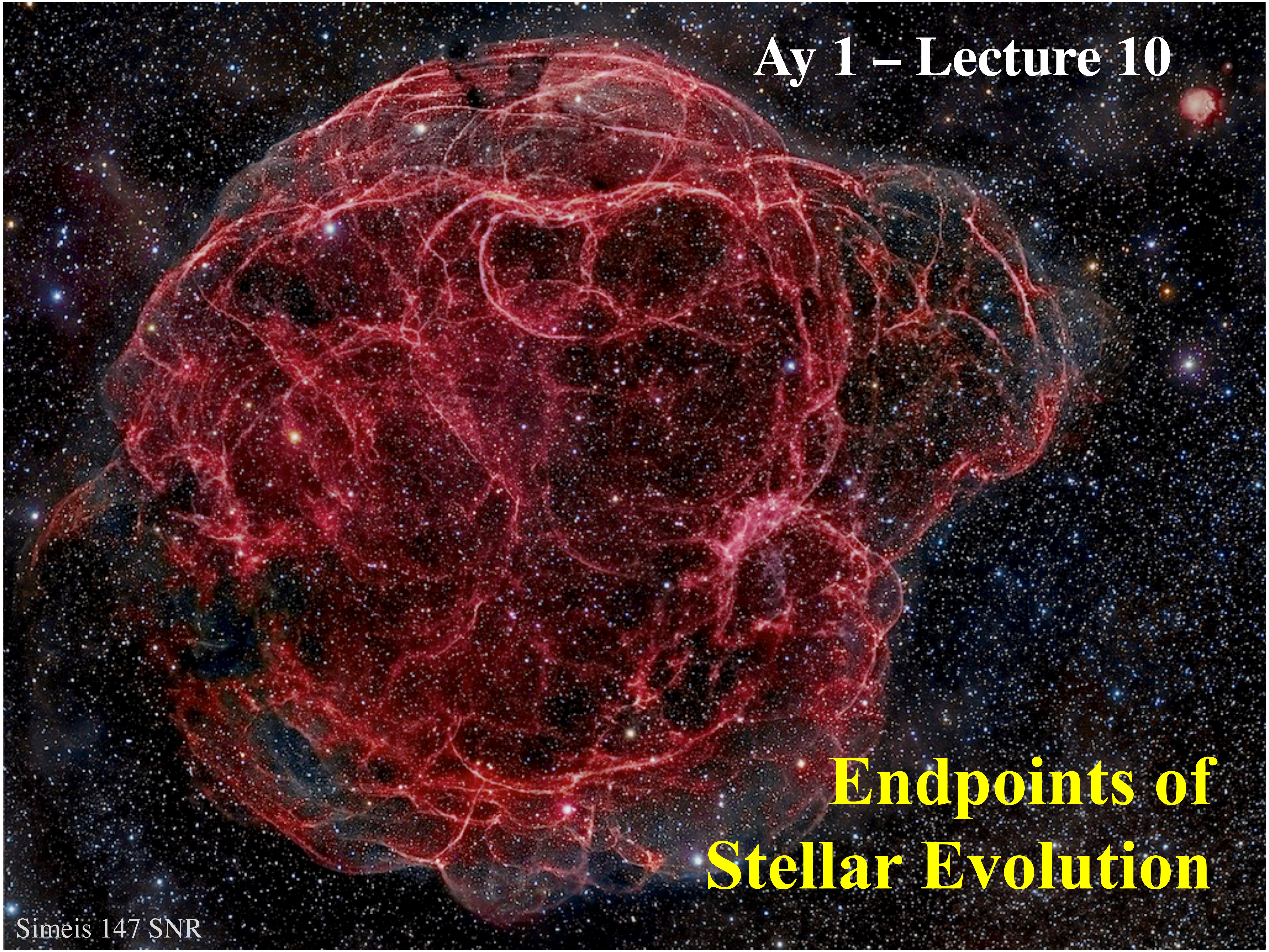
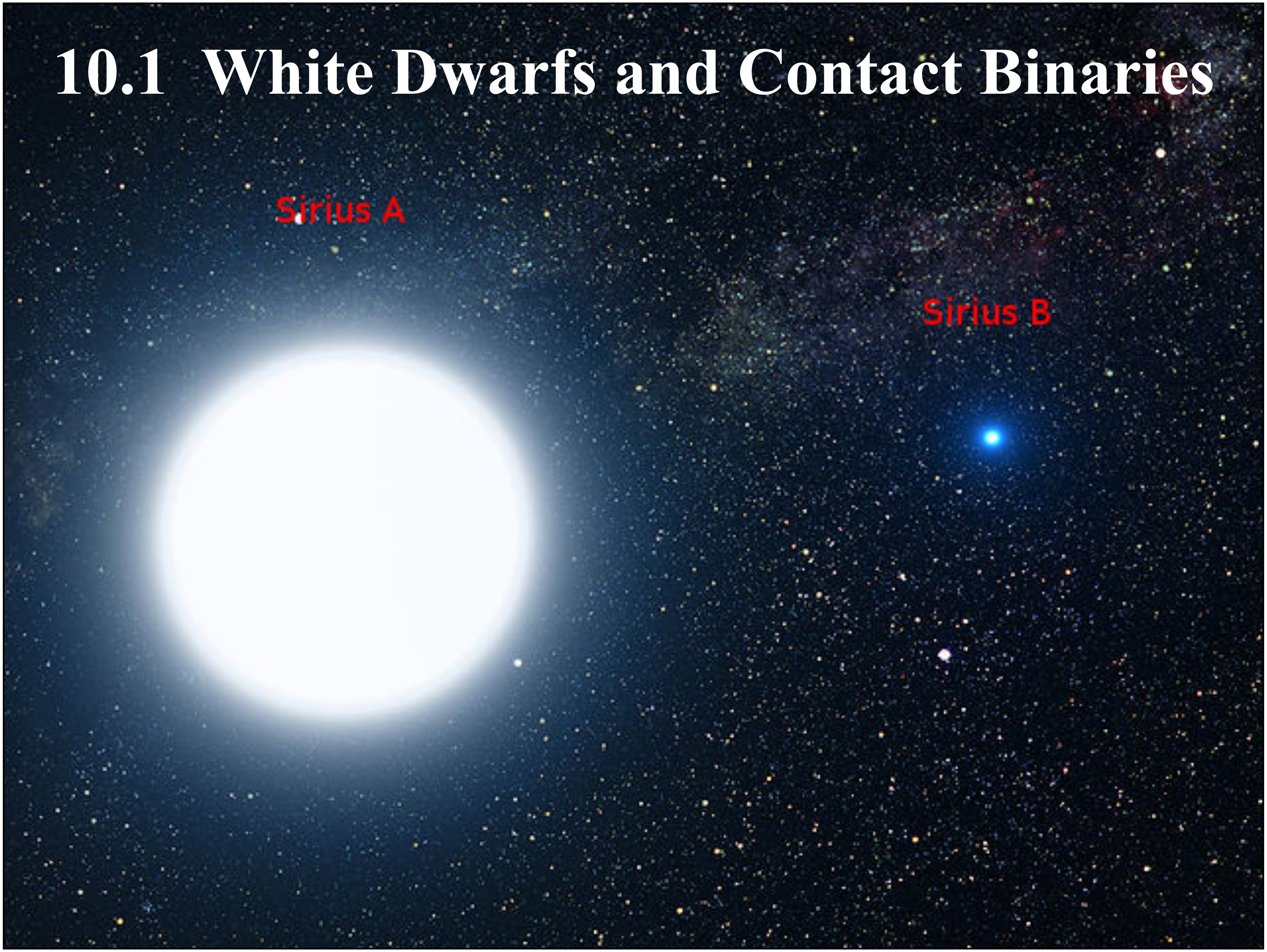


Ay 1 – Lecture 10

Endpoints of Stellar Evolution

Simeis 147 SNR

10.1 White Dwarfs and Contact Binaries

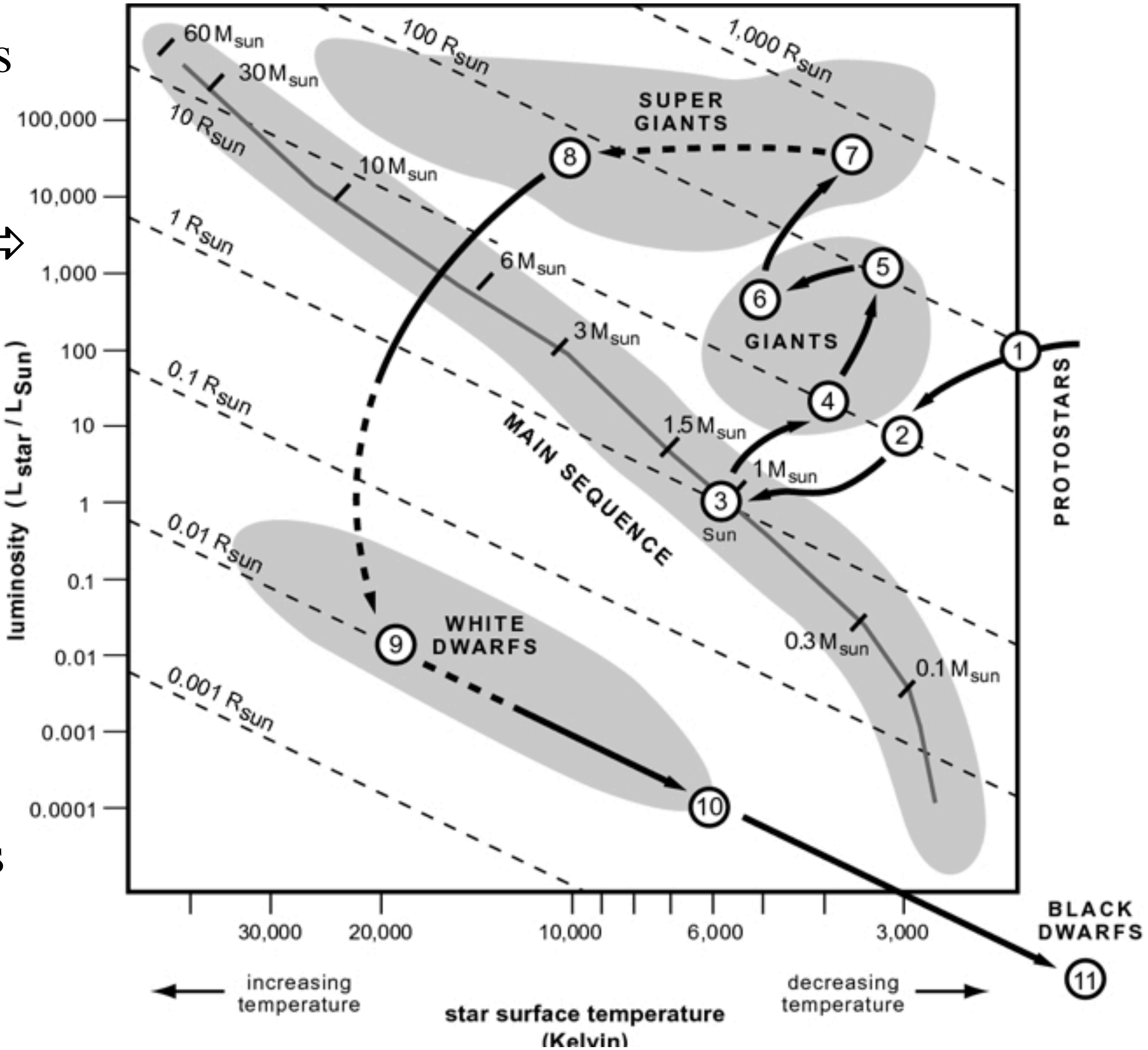


Low Mass Stars End Up as White Dwarfs

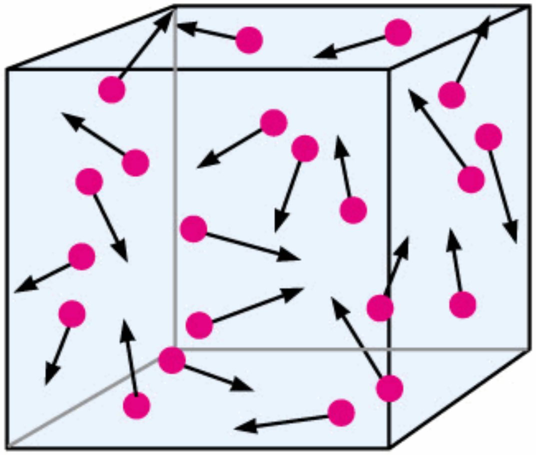
Red giant sheds its envelope, which becomes a planetary nebula ⇨

Hot, inert core becomes a white dwarf ⇨

White dwarf cools and becomes a black dwarf ⇨

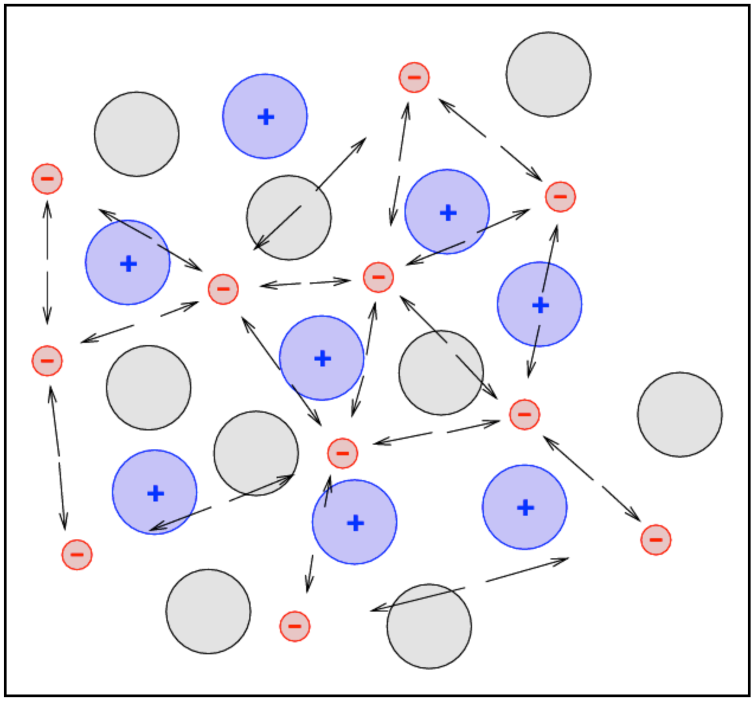


Degenerate Gas



In a normal gas, decreasing volume increases pressure and/or temperature

In a highly compressed gas, electrons and ions are packed close together

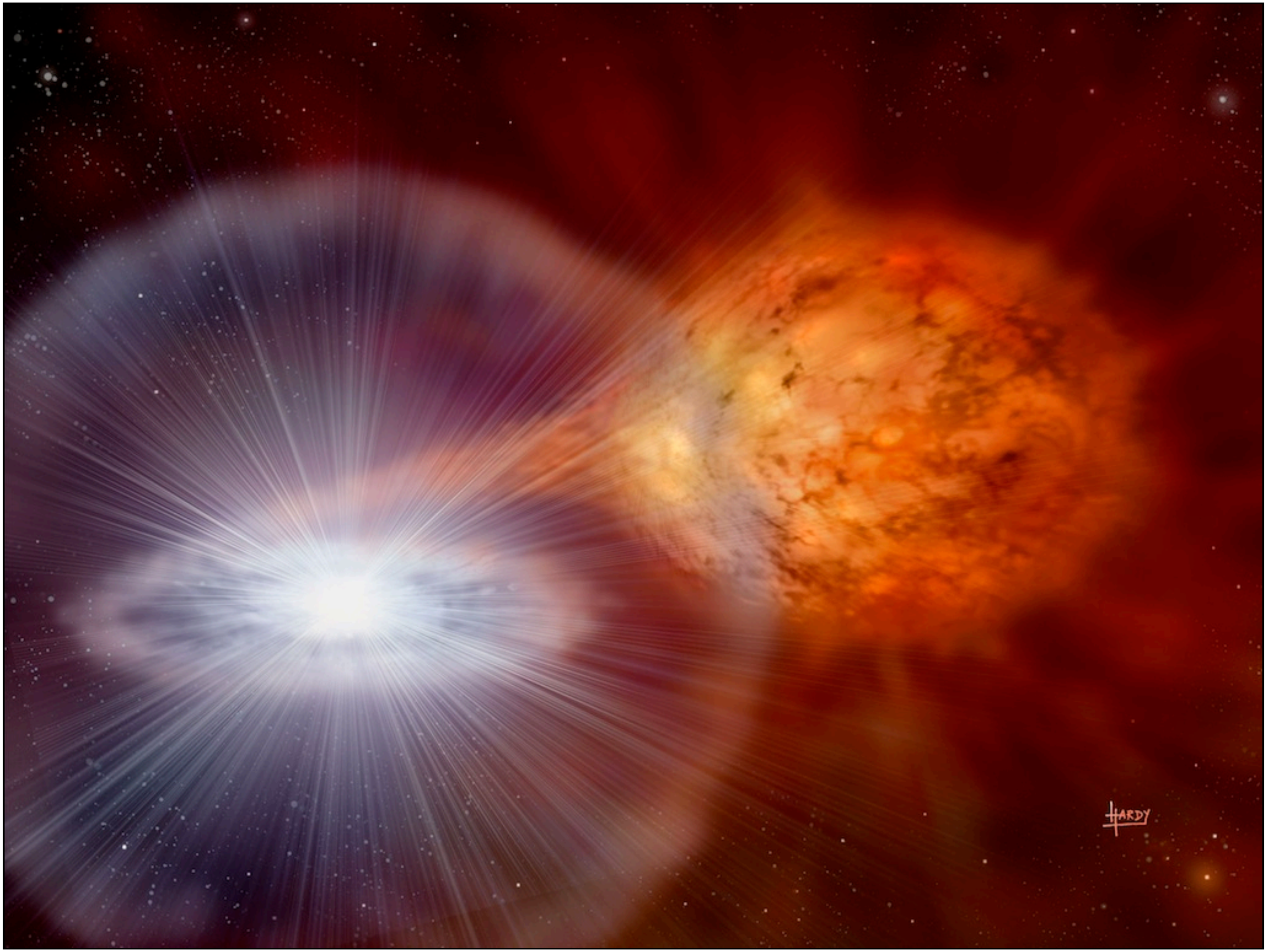


Pauli's exclusion principle states that in a given system, no two electrons can have the same energy state

Once all available energy states are filled, the gas cannot be compressed further – this creates a **degeneracy pressure**, a consequence of quantum mechanics

White Dwarfs

- Gravity is balanced by the electron degeneracy pressure
- The sizes are ~ the size of the planet Earth
  - Densities ~ 10^6 g/cm^3
- The masses are up to ~ 1.4 $M_\odot$ = the ***Chandrasekhar limit***
- Beyond that mass, pressure cannot balance the gravity, and the star collapses into a neutron star or a black hole
- Increasing the mass *decreases* the radius: $R \sim M^{-1/3}$
- Typical composition: C and/or O
- Neutron stars are the equivalent of white dwarfs, but the degeneracy pressure is provided by neutrons, not electrons
- The star cools passively as it radiates its latent heat,becoming fainter and cooler, and at some point it crystalises
- Cooling time ~ many billions of years

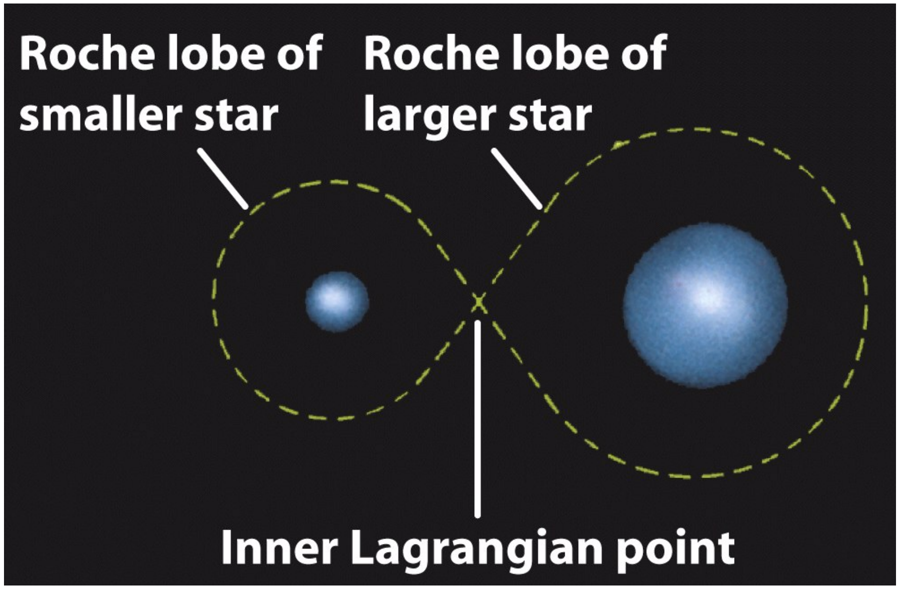

HARDY

Stars in Close (Contact) Binaries

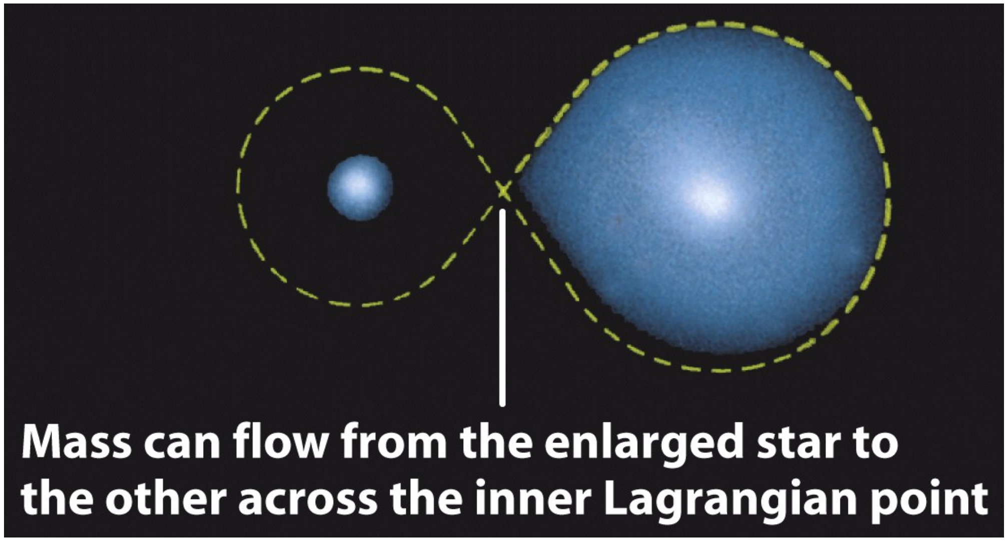
They can interact (exchange mass), and that can significantly affect their evolution

Roche lobe: the surface where the gravitational potential of the two stars is equal

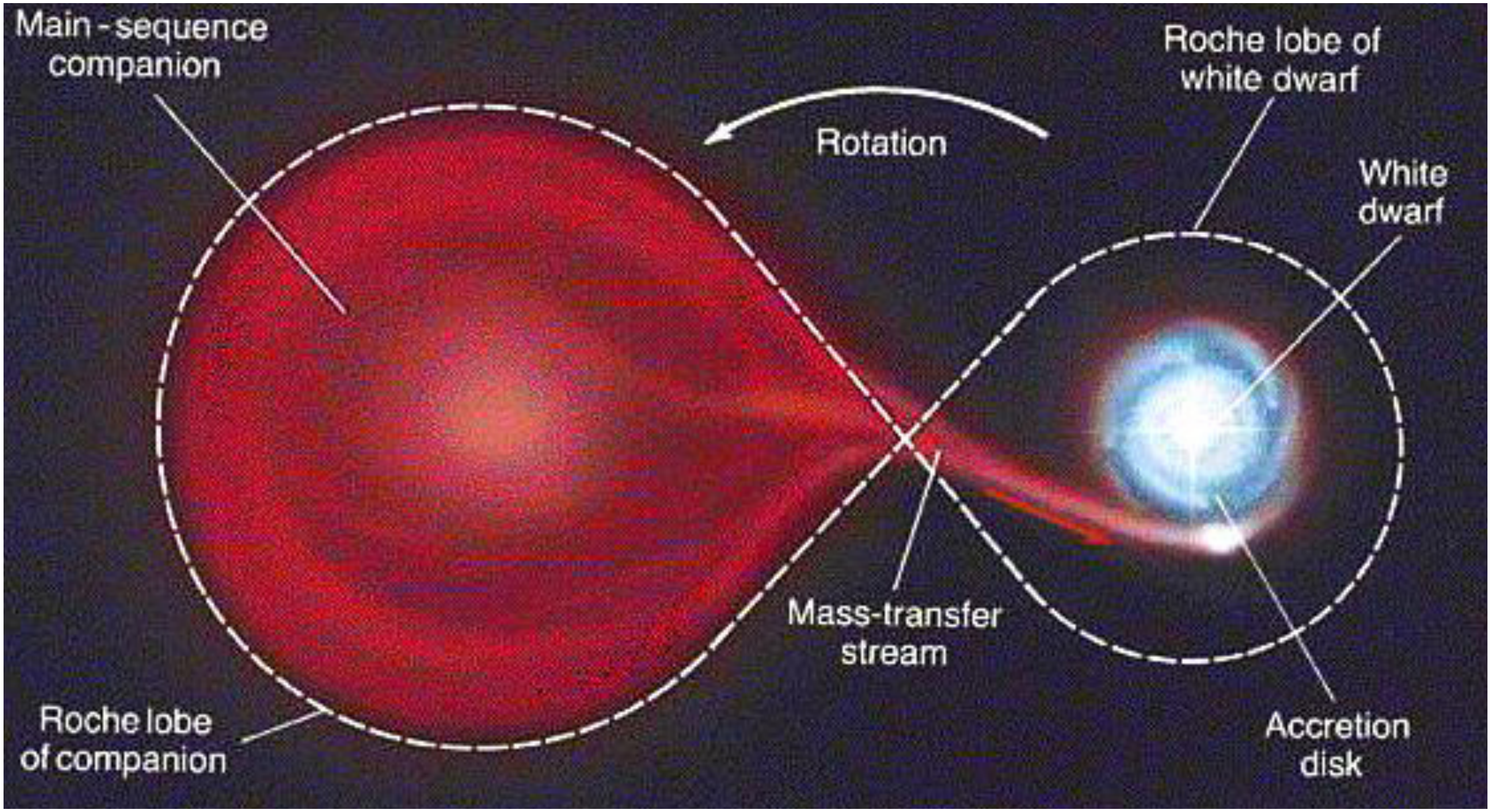
Inner Lagrange Point: the point between them where the two lobes connect



Mass transfer in a close binary system occurs when at least one star overflows its Roche lobe


Mass can flow from the enlarged star to the other across the inner Lagrangian point

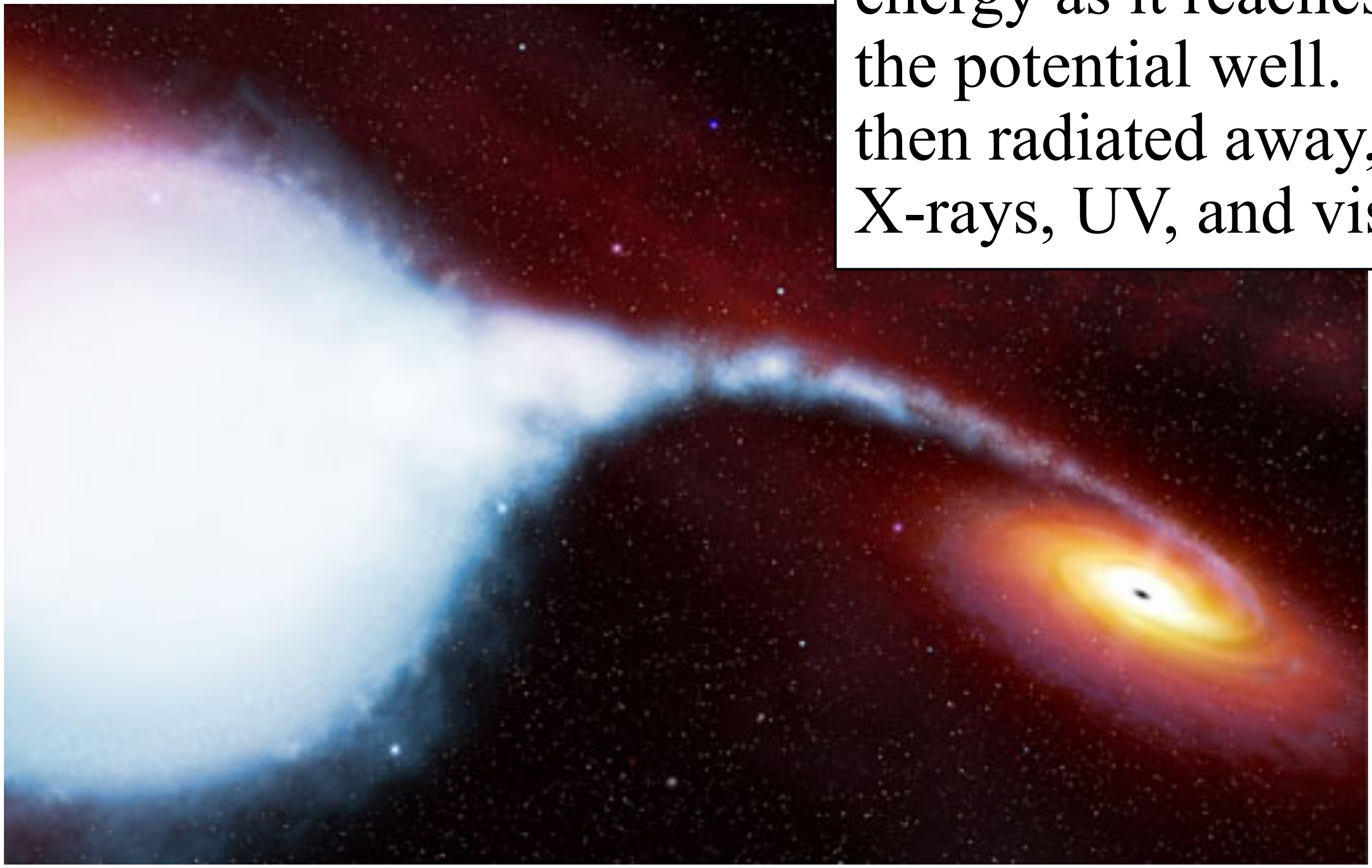
Accretion to a Compact Companion



If the accreting companion is a compact object (WD, NS, BH), the infalling material will form an **accretion disk**, which soaks up the excess angular momentum

Accretion Power

The material acquires a kinetic energy as it reaches the bottom of the potential well. This energy is then radiated away, typically in X-rays, UV, and visible

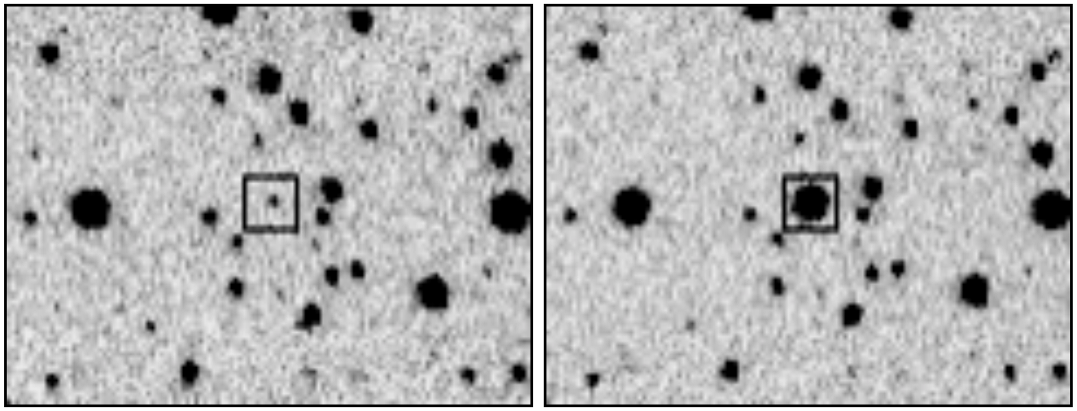


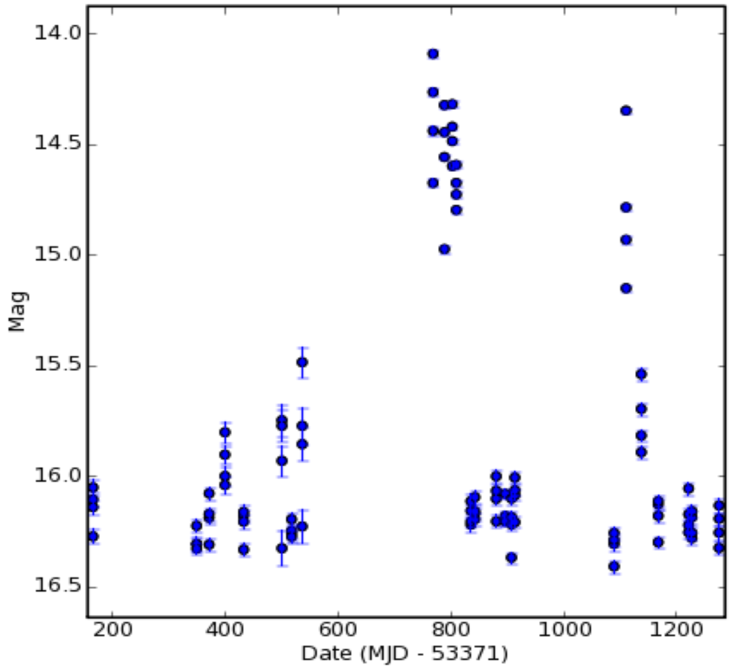
$E_{kin} = \Delta E_{pot} \approx GM/R_{accr}$ $\quad$ $\text{Luminosity} = dE/dt = G\dot{M}/R_{accr}$

Compact object mass $\quad$ Accretion radius $\quad$ Mass accretion rate

Cataclysmic Variables

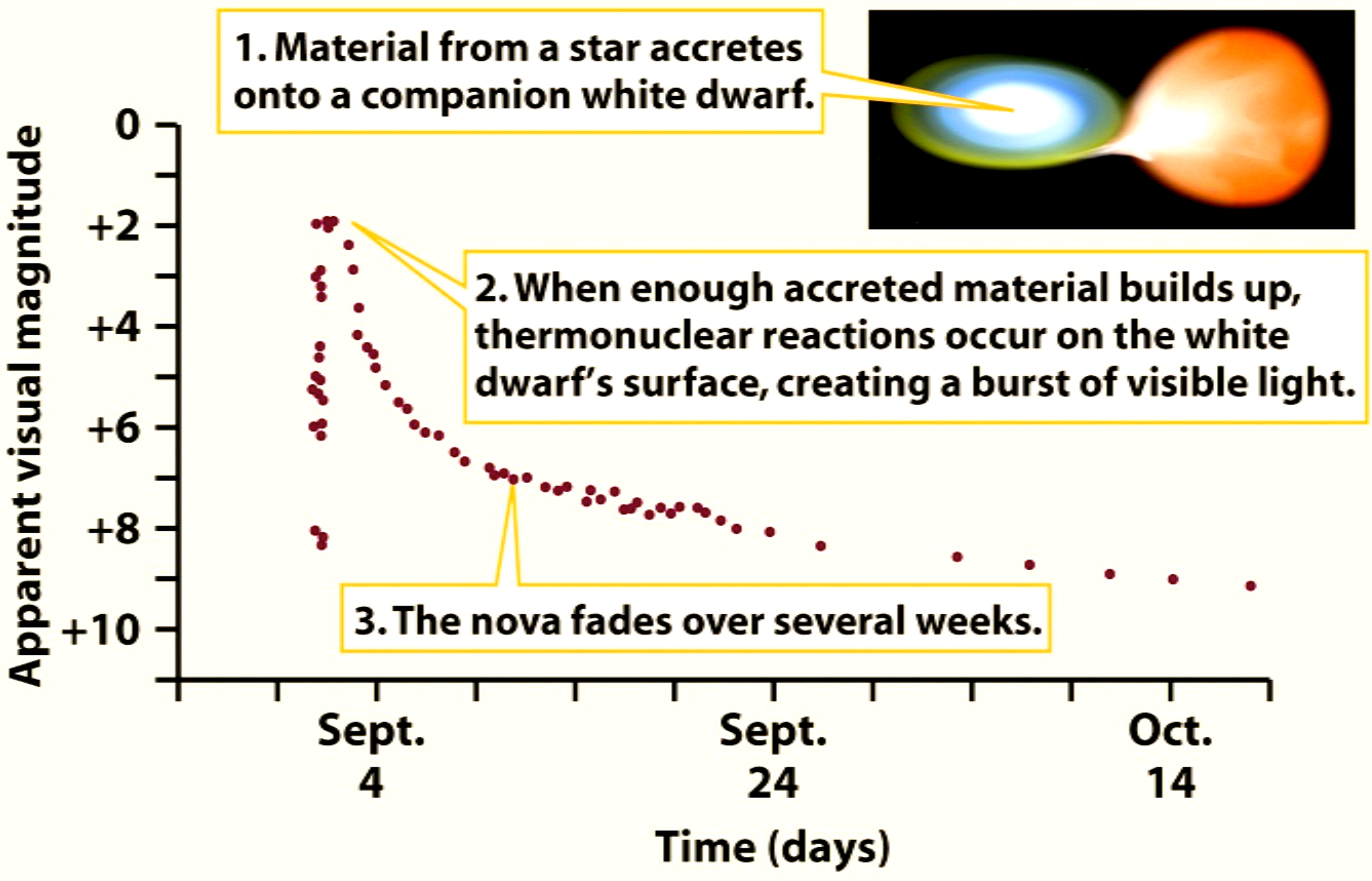
- Variation in the mass accretion translate into variations in luminosity, that can be dramatic. Such objects are called **cataclysmic variables**





- In addition, material can fall onto the surface of the white dwarf or neutron star to produce a layer in which *thermonuclear reactions can explosively ignite*
- This sudden increase in luminosity is called a **nova**; they have peak luminosities of ~10^{-4} of that of a supernova

Novae

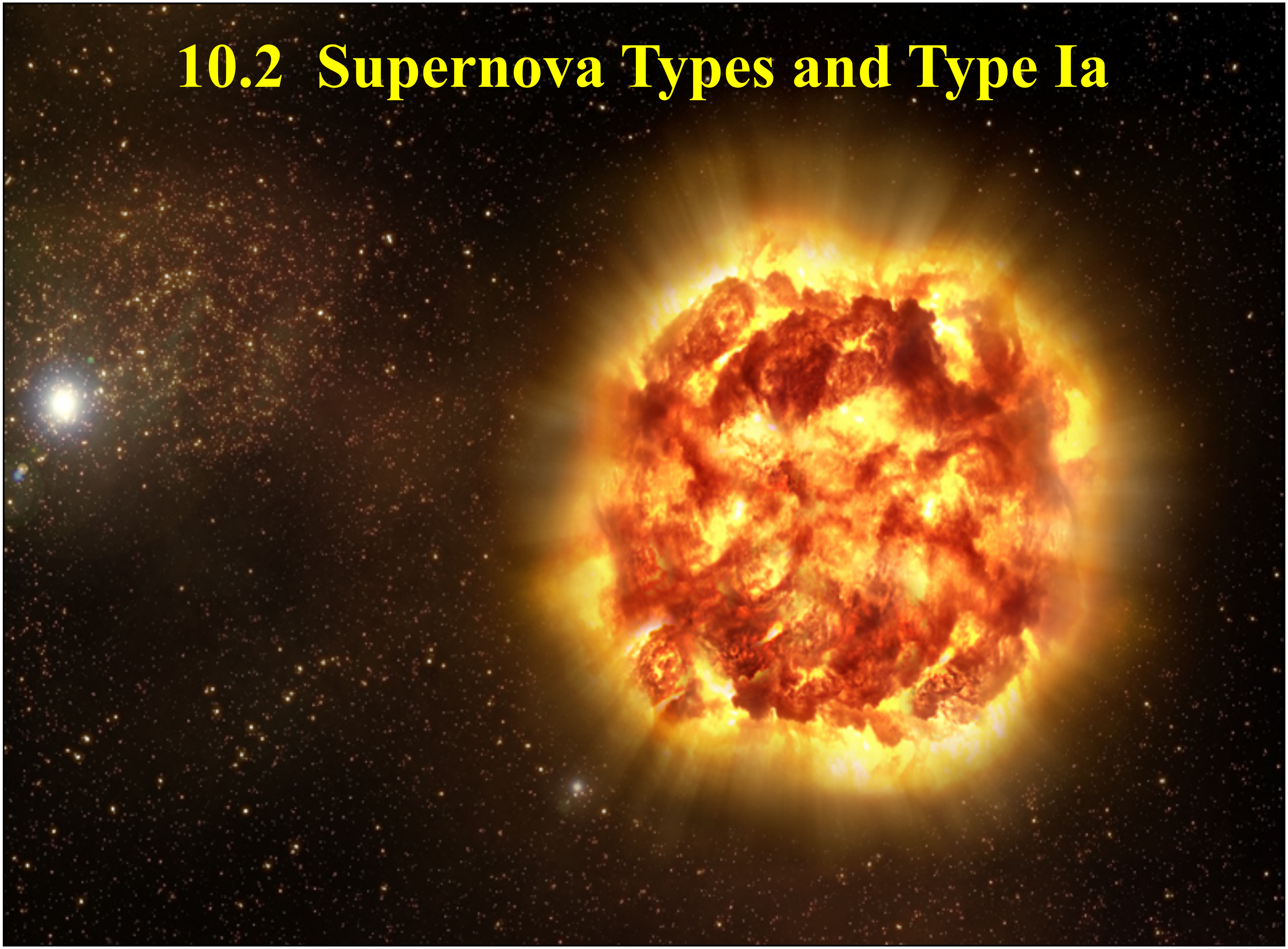


1. Material from a star accretes onto a companion white dwarf.

2. When enough accreted material builds up, thermonuclear reactions occur on the white dwarf's surface, creating a burst of visible light.

3. The nova fades over several weeks.

10.2 Supernova Types and Type Ia



Supernovae (SNe): Exploding Stars

- Two basic types and several sub-types, which differ in spectroscopic properties, light curves, locations, progenitors, etc.
- Previously normal star suddenly (~ few days to weeks) becomes *much* more luminous (up to $\sim 10^{10}\ L_\odot$), rivals entire galaxy in brightness for a few weeks! Fades over months to years
- Most energy (~ 99%, up to $\sim 10^{54}$ erg) in neutrinos; kinetic energy ~ 1% (typically $\sim 10^{51}$ erg); visible light only ~ 0.1% of the total
- Gas expands at $V \geq 10{,}000$ km/s!
- Leave a nebular remnant, and a compact remnant (neutron star or a black hole)

Supernova Classification

Type I: no lines of H in the spectrum
Occur in all types of galaxies

Type II: lines of H seen in spectrum
Occur in star-forming galaxies only

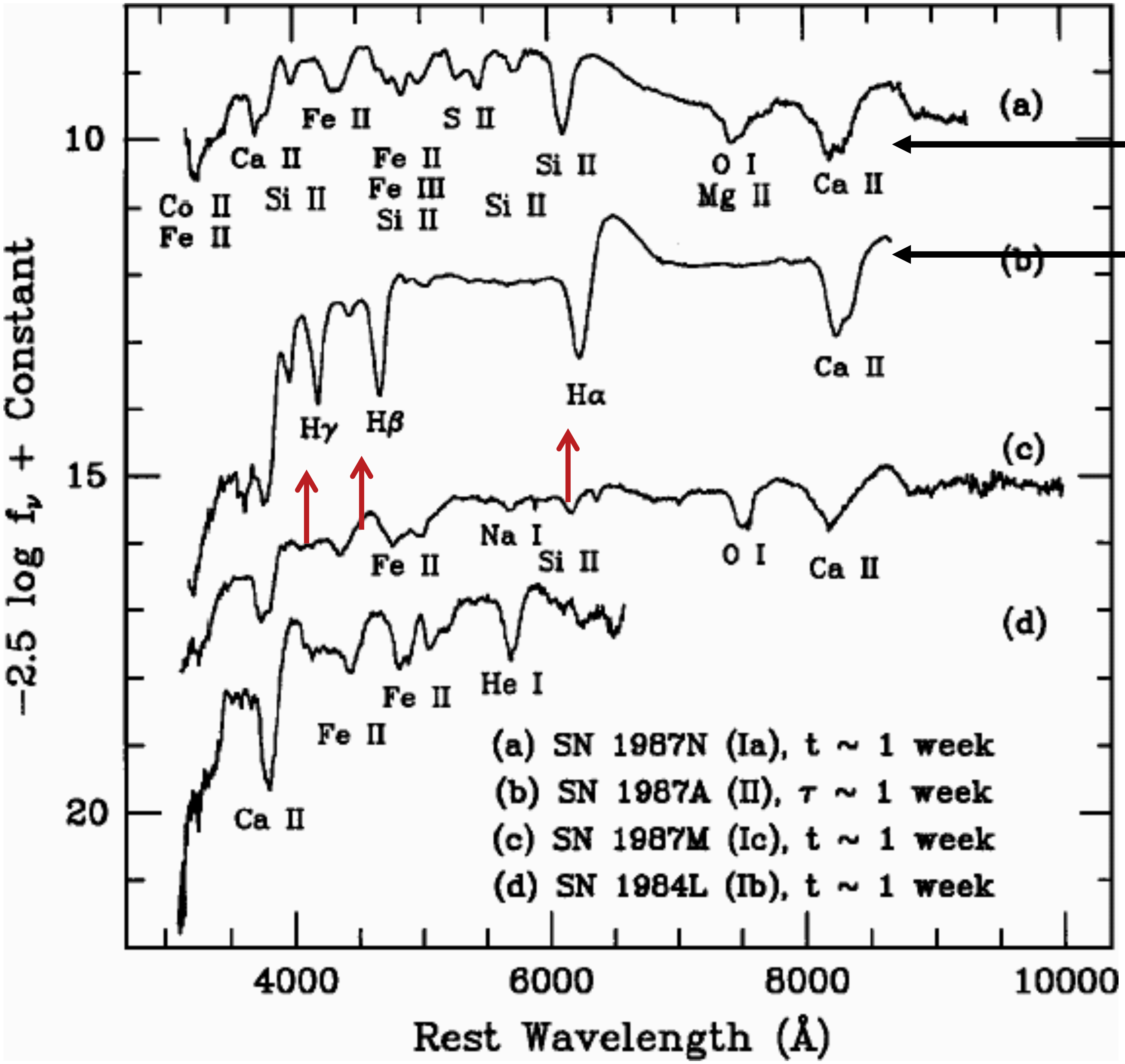
Typical rate ~ 1 per galaxy per century

Type I's are further divided into subclasses (Ia, Ib, Ic) based on their spectral properties. There are also "peculiar" cases

Type Ia SNe are believed to result from explosions of Chandrasekar mass white dwarfs. All other types are thought to result from the collapse of massive stars

There may be two mechanisms for Type II SNe, core collapse of a massive star, or annihilation of e+ e– pairs

SN Spectra Comparison

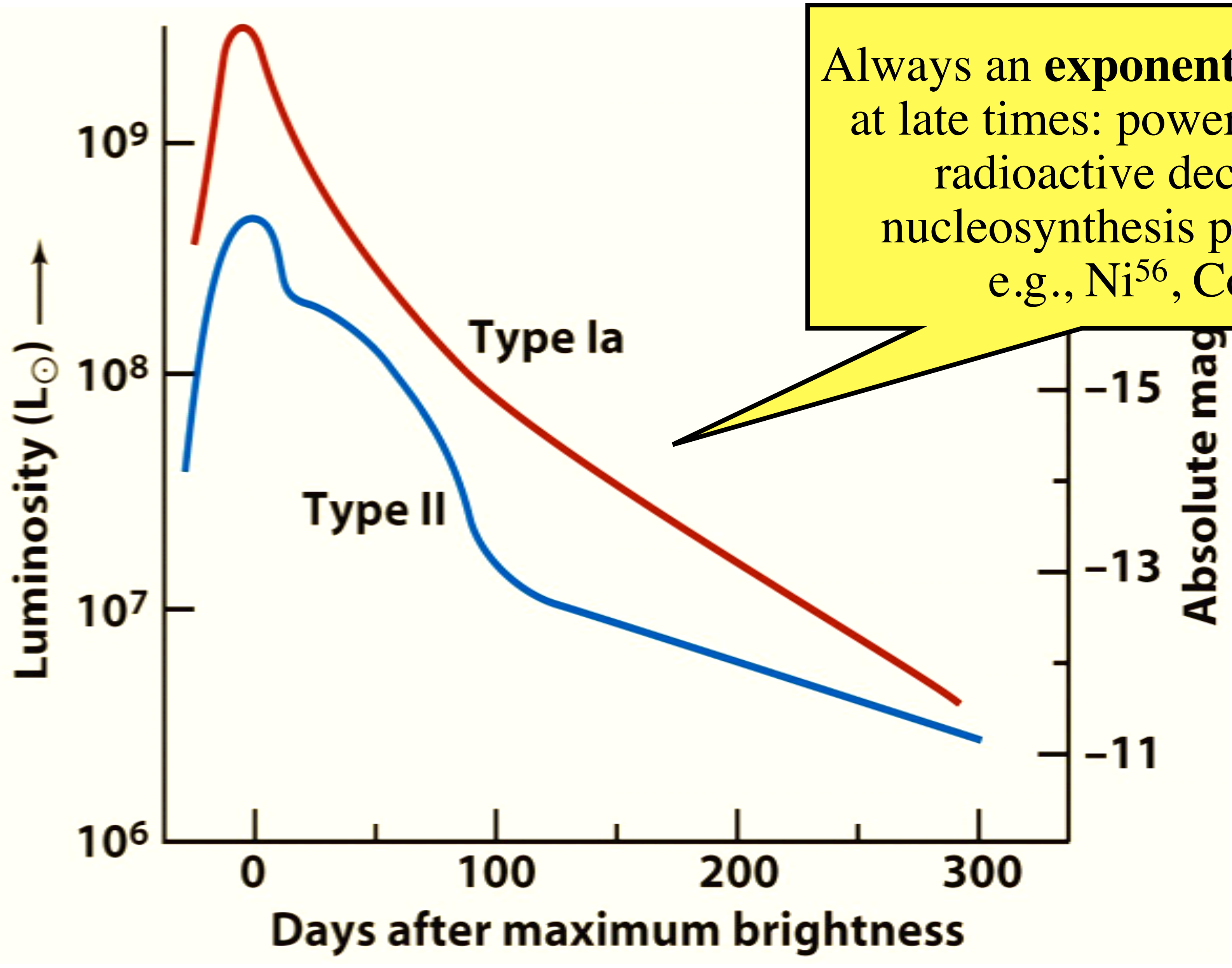


Type Ia

Type II

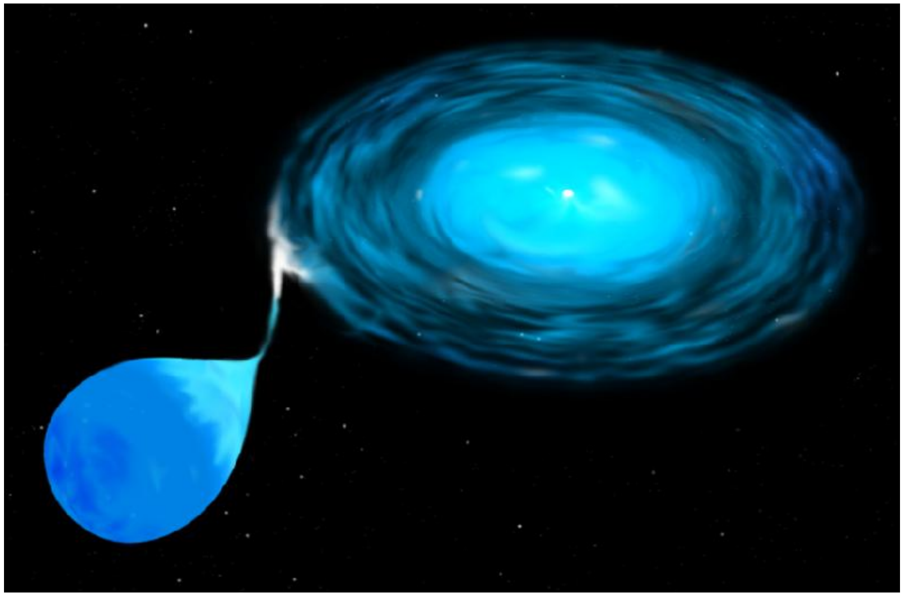
Clear lines of hydrogen in spectrum

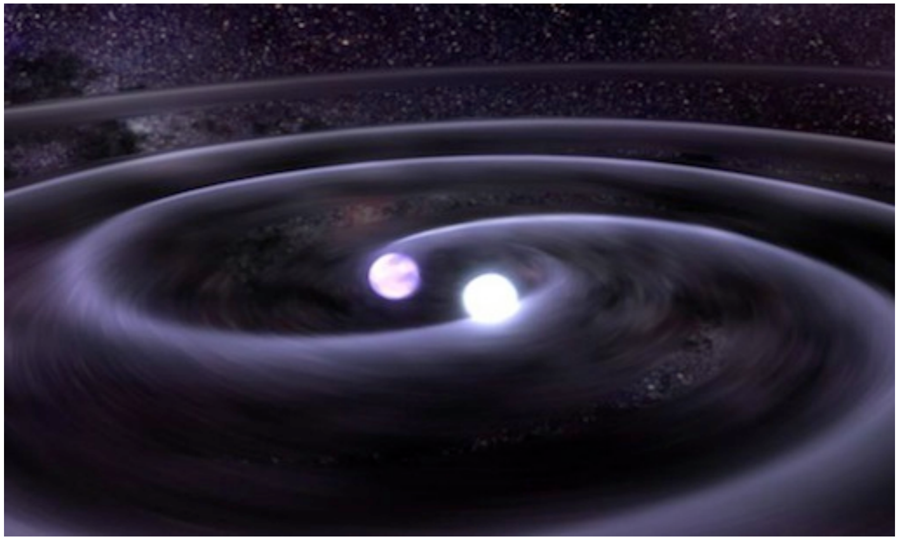
SN Types: Light Curve Differences



Always an **exponential decline** at late times: powered by the radioactive decay of nucleosynthesis products, e.g., Ni^{56}, Co^{56}

Type Ia SNe: produced by accreting white dwarfs in close binaries





Once the white dwarf accretes enough mass to push it over the Chandrasekhar limit,

$$M_{Ch} \approx 1.4 M_{sun}$$

degenerate gas pressure can no longer support the star against the gravity, and the star collapses

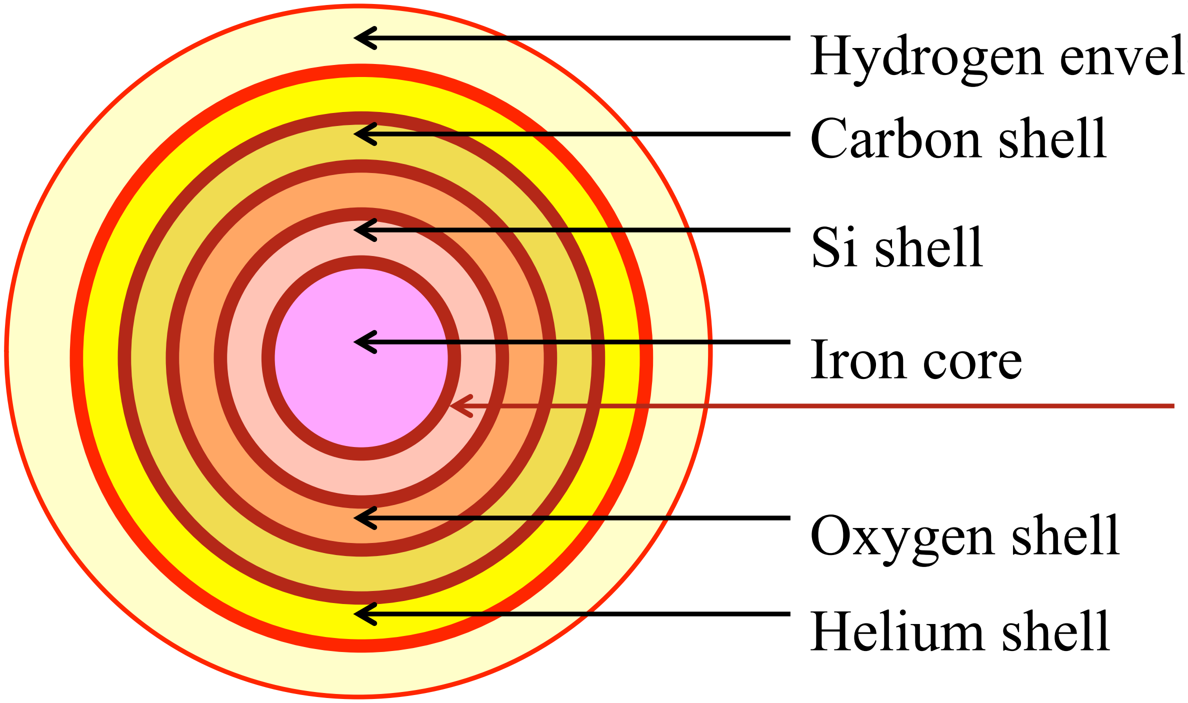
An alternative mechanism is a spiral-in and merger of a binary white dwarf

10.3 Core-Collapse Supernovae

Core Collapse in Massive Stars

In a massive star, core temperature can be high enough that nuclear burning of Si to Fe can occur. Beyond Fe, further fusion is *endothermic*, and will not occur *under equilibrium conditions*. As an iron core develops, other reactions still proceed at larger radii:

“Onion shell” structure



Hydrogen envelope

Carbon shell

Si shell

Iron core

Oxygen shell

Helium shell

Separated by zones in which nuclear fusion is occurring - **shell burning,** e.g. Si burning to Fe just outside the iron core

Core Collapse in Massive Stars

Eventually Fe core becomes too massive to be supported by electron degeneracy pressure, and **core collapses**

Once collapse starts, it proceeds very rapidly:

Photodisintegration

$$^{56}\text{Fe} + \gamma \rightarrow \text{lighter elements}$$

Needs high energy gamma rays

Inverse beta decay

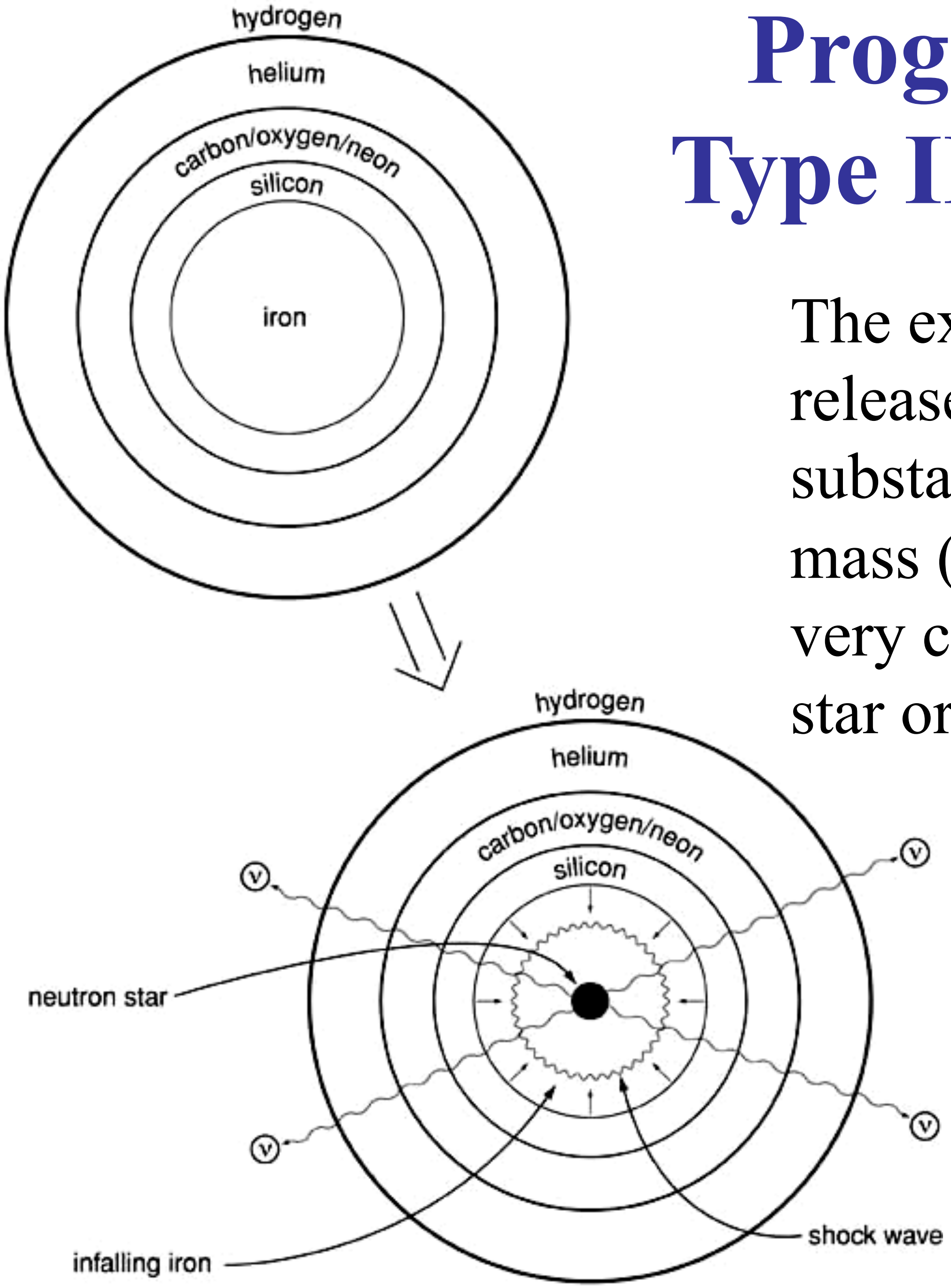
$$e^{-} + p \rightarrow n + \nu_e$$

Needs e^- and p to have enough energy to overcome mass difference between neutron and proton

These processes rob the core of pressure support, accelerate the collapse, and drive the composition toward neutron rich matter

Core collapse produces a shock wave that actually explodes the star

Progenitor of a SN Type II: Core Collapse



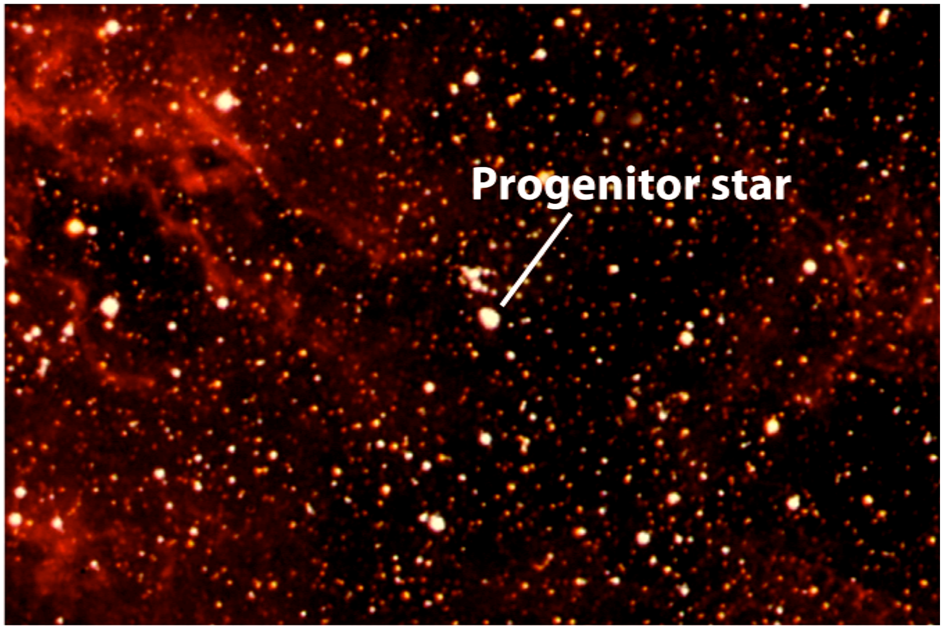
The explosion is powered by the release of the binding energy, as a substantial fraction of the star's mass (> 2 M_{sun}) collapses into a very compact remnant, a neutron star or a black hole

The bulk of the energy is carried out by neutrinos generated by the inverse beta decay

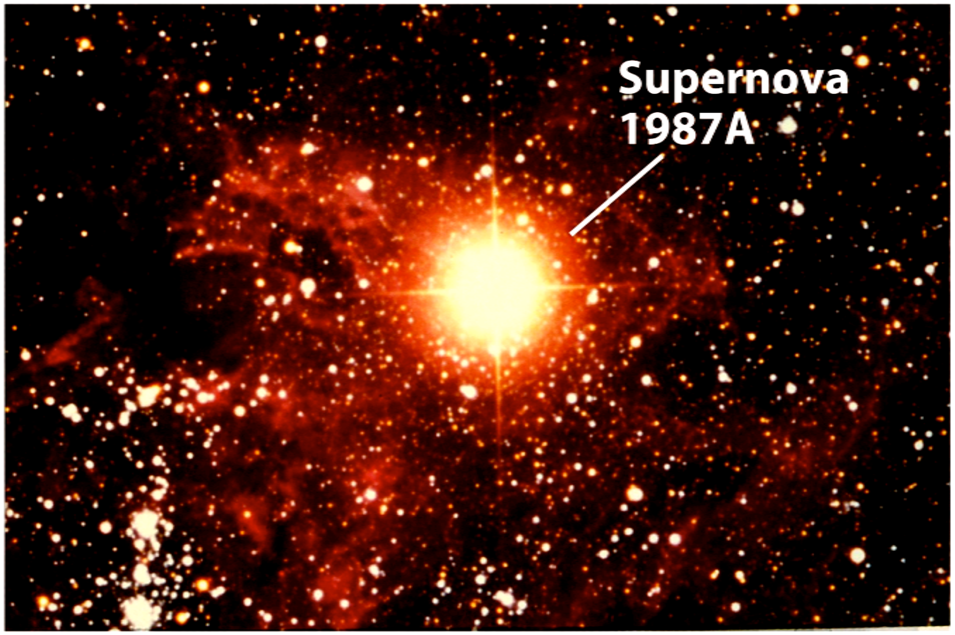
A nearby supernova 1987A in LMC gave us the forst and only modern close-up look at the death of a massive star …

… Including the first detection of extra-Solar neutrinos, thus confirming our basic model for core-collapse SNe:

> 99% of the total SN energy emerges in neutrinos!



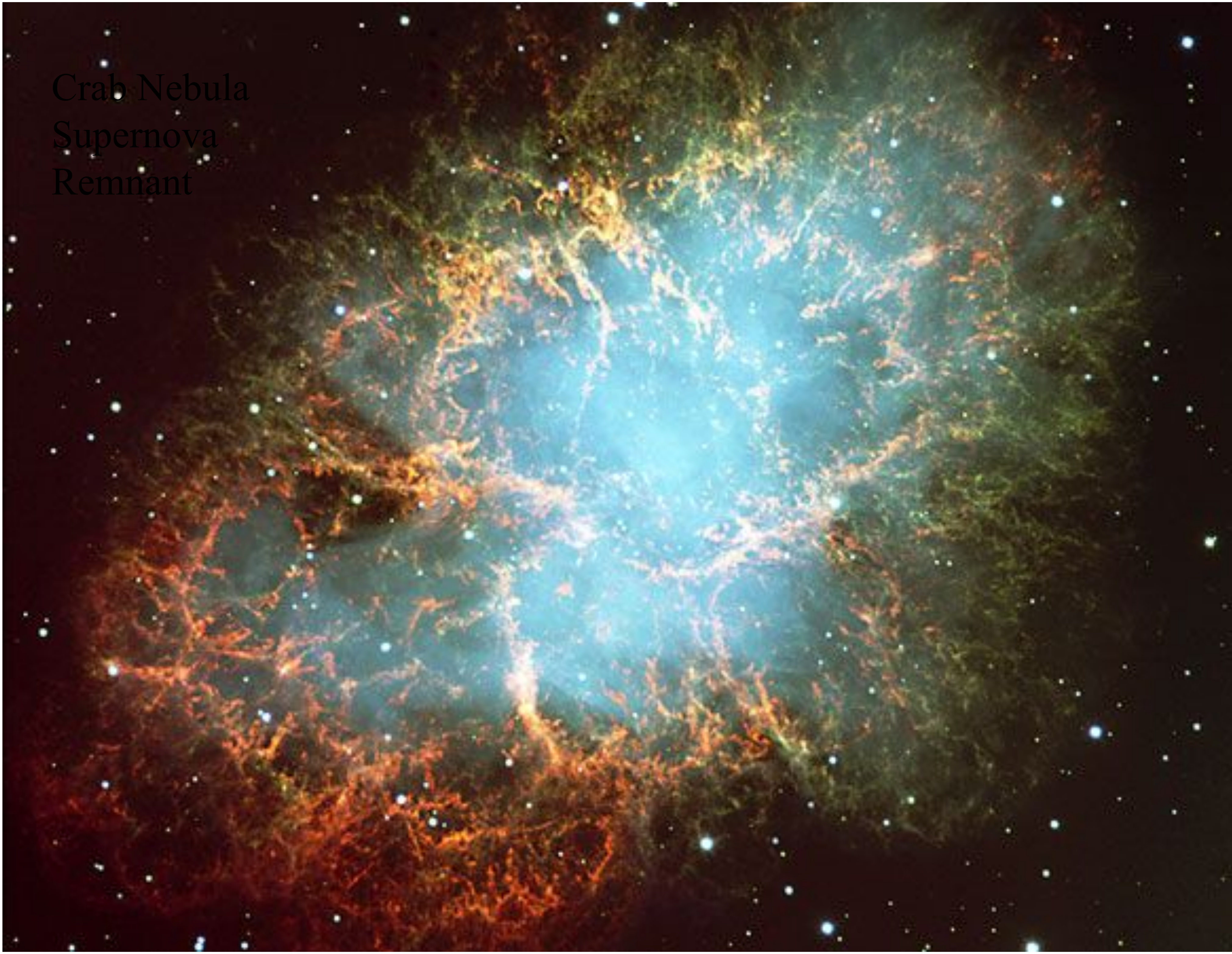
Before the star exploded



After the star exploded

Supernova Remnants

- The gaseous shell ejected by a supernova plows into the surrounding interstellar medium at $V > 10^4$ km/s, compresses it, intermingles with it, enriches it with freshly synthesized heavy elements, and forms what is called a supernova remnant
- Supernova remnants may be observed for hundreds of thousands of years as often beautiful, visual objects, but also as emitters of radio waves and X-rays
- Close to 150 supernova remnants have been detected in the Milky Way and more than a hundred are being discovered every year in distant galaxies



Crab Nebula
Supernova
Remnant

The Crab Nebula

- The result of a supernova that, according to Chinese and Japanese chronicles, exploded in 1054. Despite a distance of about 7,000 light-years, the supernova was brighter than Venus for weeks before fading from view after nearly two years. Interestingly, almost no European records of the event have been found ("The Dark Ages are called that not because the light fails to shine, but because people refuse to see it")
- The nebula is still expanding at V > 1300 km/s and emits synchotron radiation in all wavelengths, from gamma rays to radio waves
- And of course, it is the home of the Crab Pulsar

Cas A: remnant of a supernova that exploded in 1658