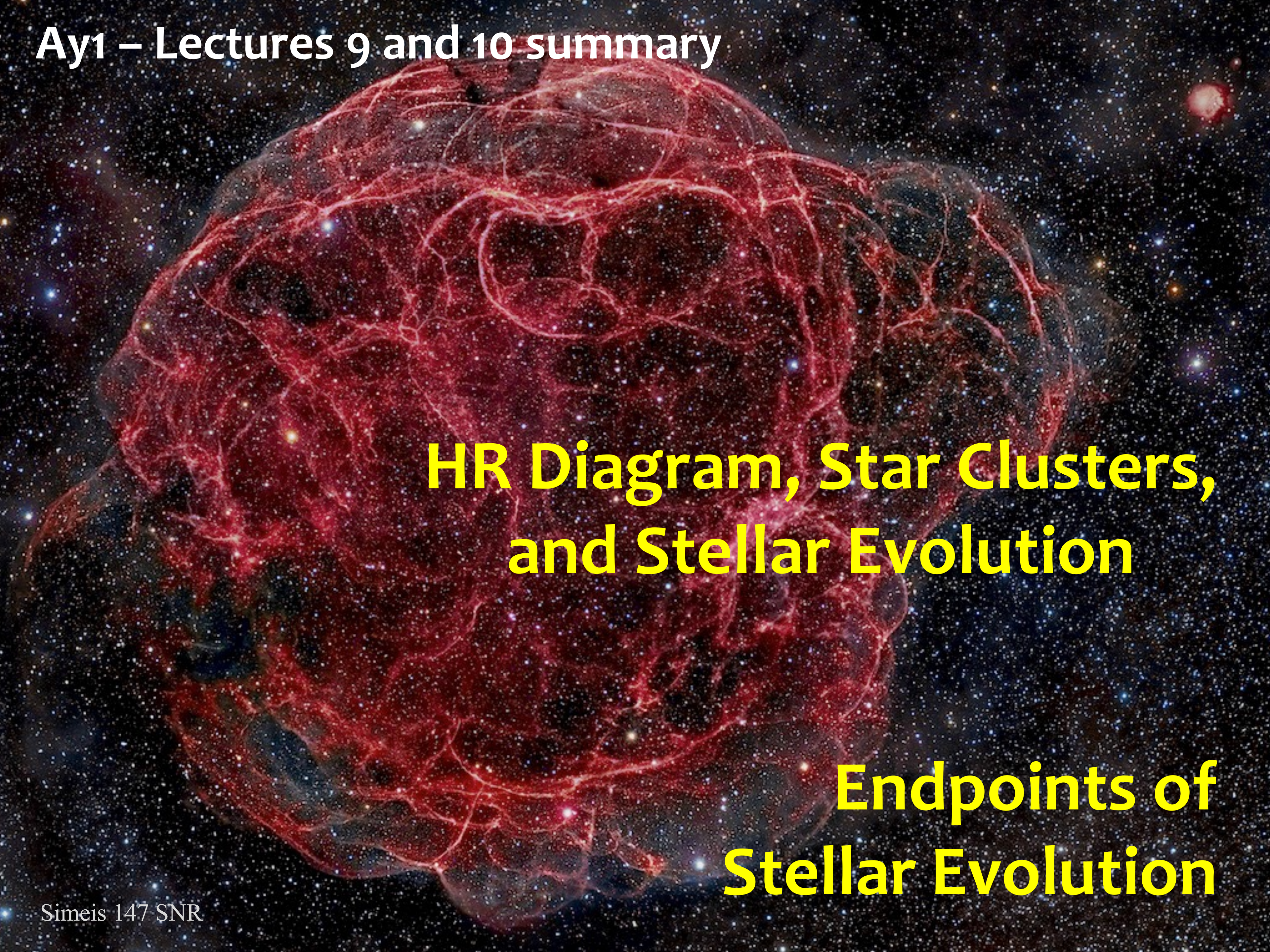
Ay1 – Lectures 9 and 10 summary



HR Diagram, Star Clusters, and Stellar Evolution

Endpoints of Stellar Evolution

Simeis 147 SNR

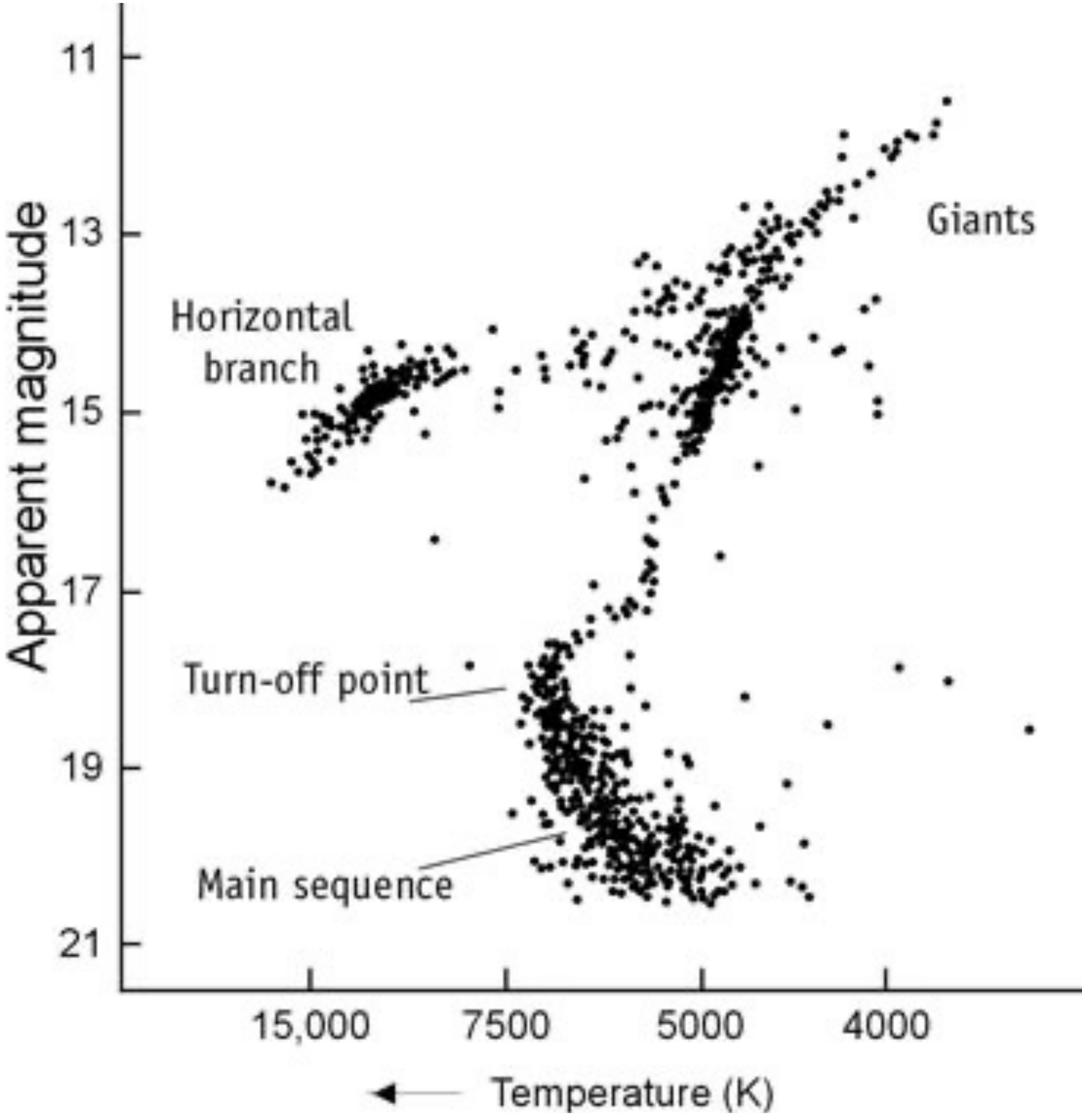
The Hertzsprung-Russel (HR) Diagram

It is a plot of stellar luminosity vs. temperature (~ spectral type)

Stars form ***distinctive sequences*** in the HR diagram

They correspond to different stages of the stellar evolution

This can used to test the stellar evolution models

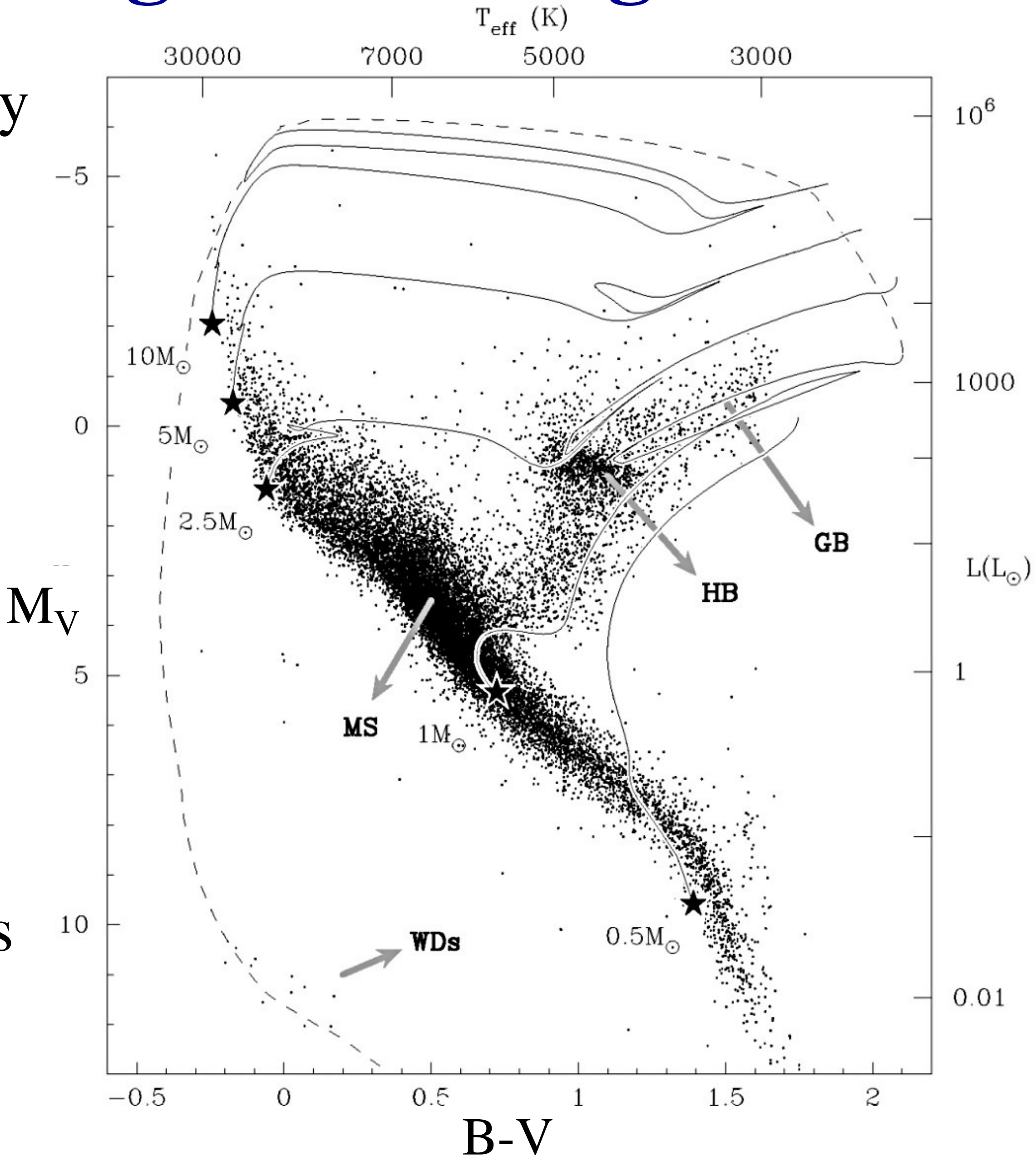


The Color-Magnitude Diagram

Stellar colors are typically used as a measure of the temperature

To get the absolute magnitudes (or luminosities), you must have *distances*

Need models of stellar atmospheres to convert these measured quantities into temperatures and bolometric luminosities



Star Clusters

Open (or Disk):

$N_\star \sim 10^2 - 10^3$

Ages ~ $10^7 - 10^9$ yr

Globular:

$N_\star \sim 10^4 - 10^7$

Ages ~ 10 - 13 Gyr

- Great "laboratories" for stellar evolution and dynamics
- Dynamical and evolutionary time scales < or << Galaxy's age, and a broad range of evolutionary states is present

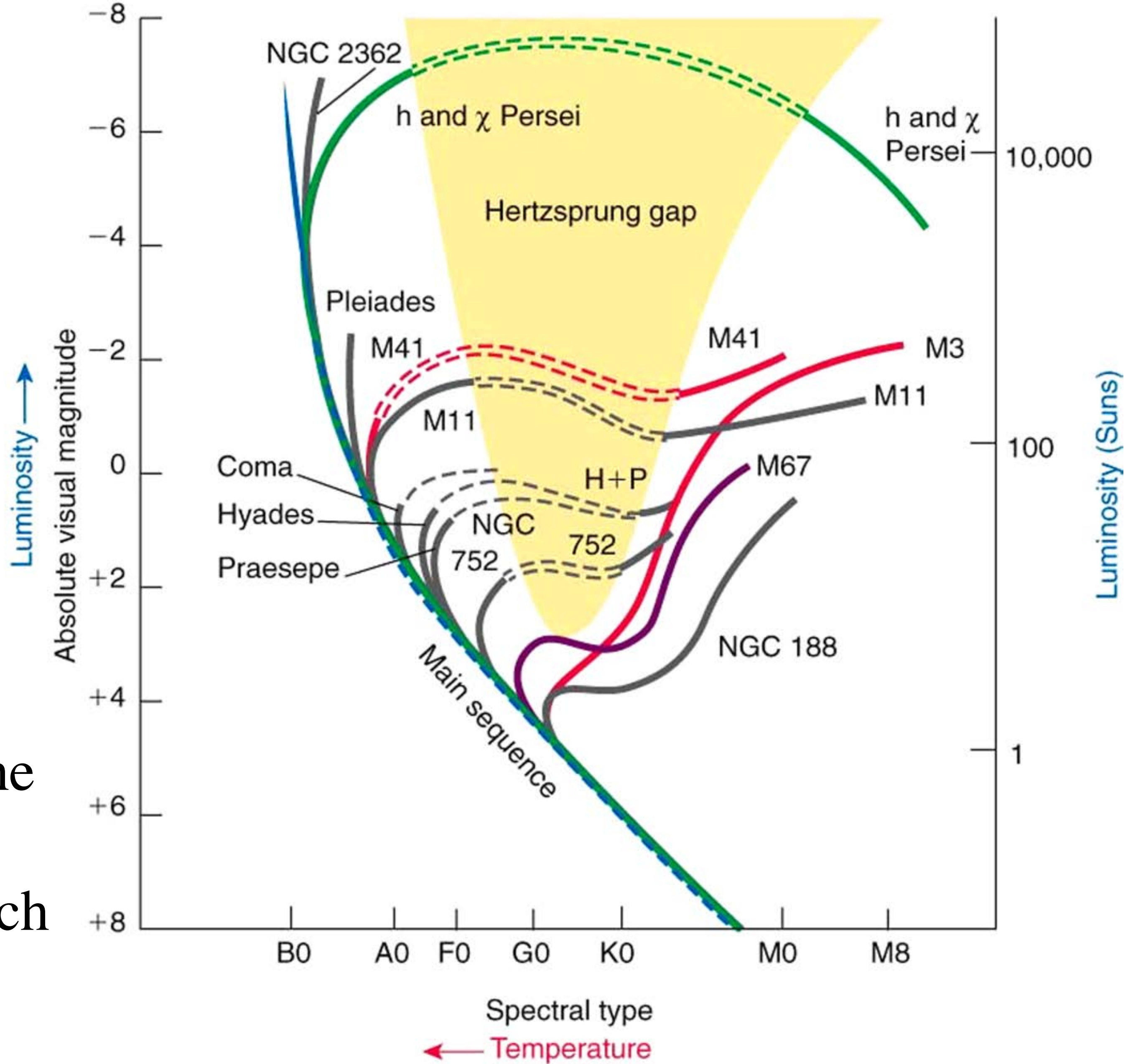
Testing Stellar Evolution

- The problem: stellar evolution happens on billion-year time scales
- The solution: use HR Diagrams of ***star clusters*** with a wide range of ages
  - Clusters contain 100's to 1000's of stars with a broad mass range
  - All stars are at the same distance, so it is easy to measure their relative luminosities
  - They have the same age, have the same chemical composition
- ***Each cluster thus provides a snapshot*** of what stars of different masses look like at the same age and composition (coeval populations)

Open Clusters: HR Diagrams

A systematic change with the cluster age:

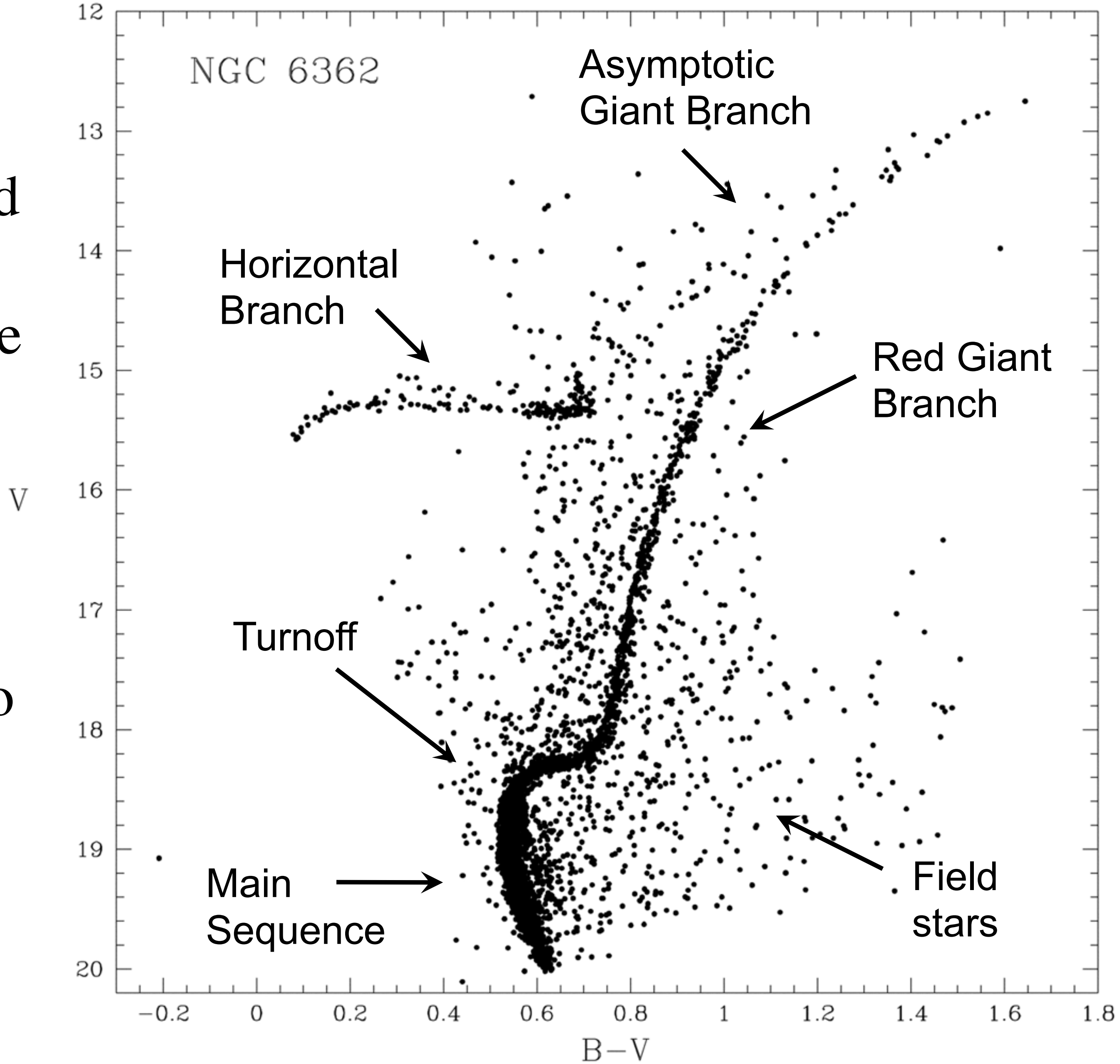
The MS turnoff moves to lower luminosities and temperatures as the cluster ages, and the red giant branch develops



Globular Clusters: HR Diagrams

Stars above the turnoff have evolved away, and other branches represent the more advanced stages of stellar evolution

We can use that to estimate the ages of the globular clusters, and thus of the Galaxy

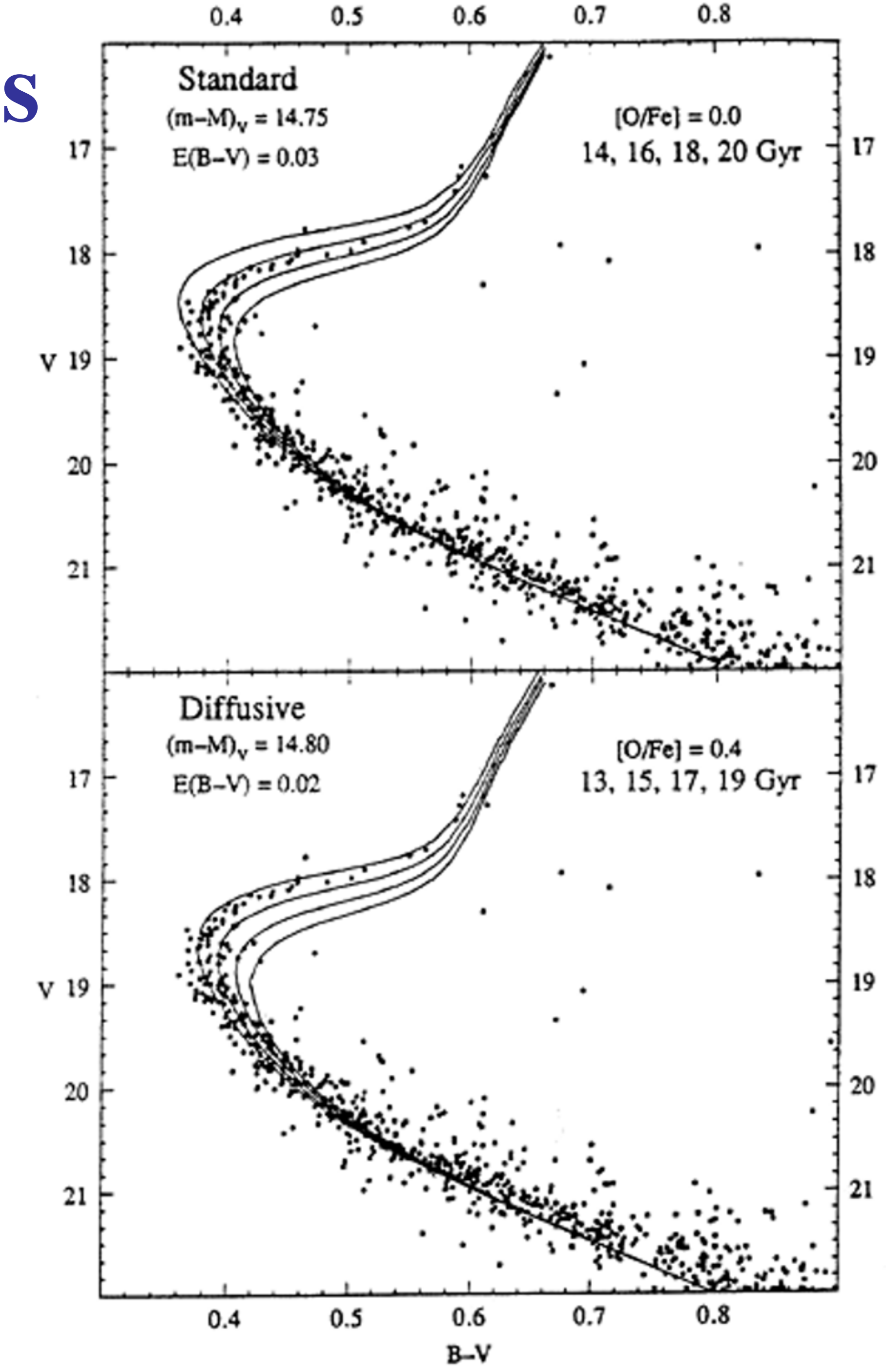


Globular Cluster Ages

Lines: ***Isochrones*** = theoretical models of the main sequence and the red giant branch (and others), at a given age, for a given chemical composition

Modern value for the mean globular cluster age in our Galaxy:

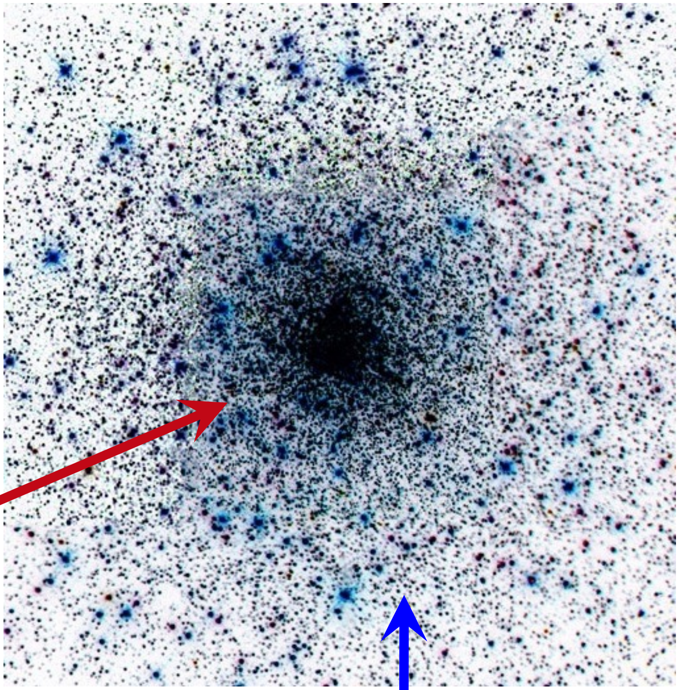
$$\text{Age} = 12.3^{+2.1}_{-2.5}\ \text{Gyr}$$



Dynamical Evolution of Star Clusters

1. Internal processes:

- ***Dynamical relaxation***: stars exchange energies in 2-body interactions, over a relaxation time



Stars in the core have lower energies and sink to the bottom of the potential well

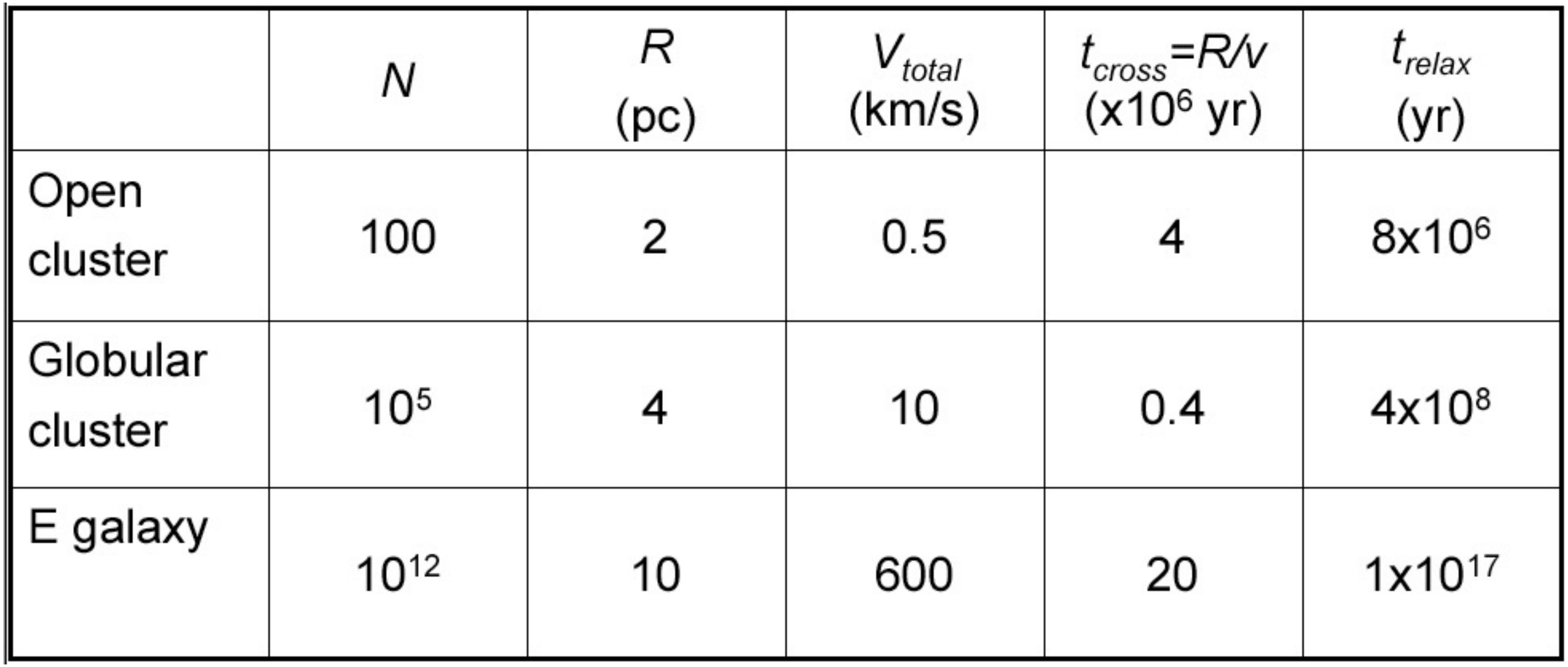
Stars with higher energies can reach large radii

- Core collapse, or gravothermal instability

2. External processes:

- Tidal shocks and evaporation

Dynamical Time Scales



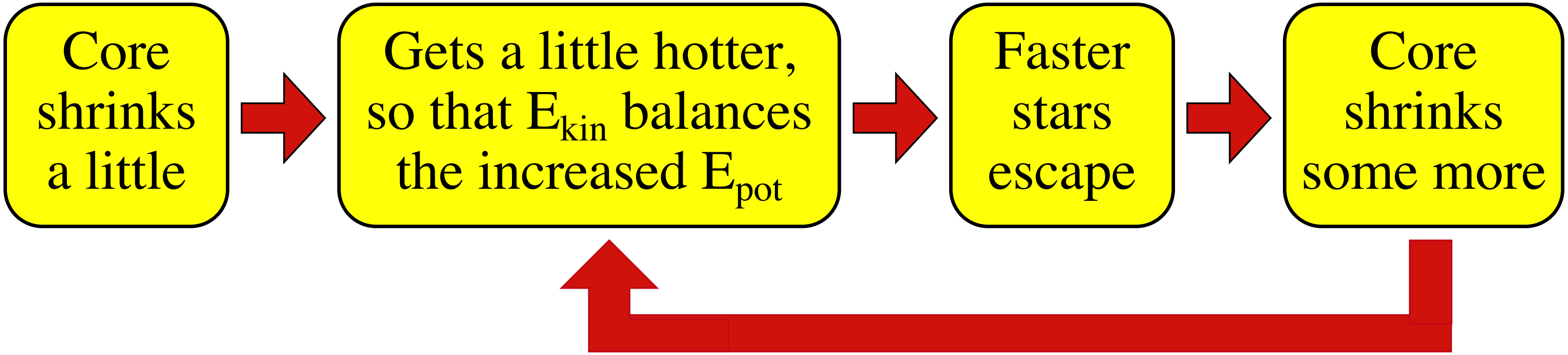
	N	R (pc)	V_{total} (km/s)	$t_{cross}=R/v$ ($\times 10^6$ yr)	t_{relax} (yr)
Open cluster	100	2	0.5	4	8×10^6
Globular cluster	10^5	4	10	0.4	4×10^8
E galaxy	10^{12}	10	600	20	1×10^{17}

Open clusters: $t_c \sim t_r < t_e$ ➞ quickly dissolved

Globular clusters: $t_c << t_r << t_e$ ➞ a variety of dynamical evolution states must be present

Elliptical galaxies: $t_c << t_r \sim t_e$ ➞ dynamical evolution not driven by 2-body relaxation

Core Collapse, aka
The Gravothermal Catastrophe



Core shrinks a little

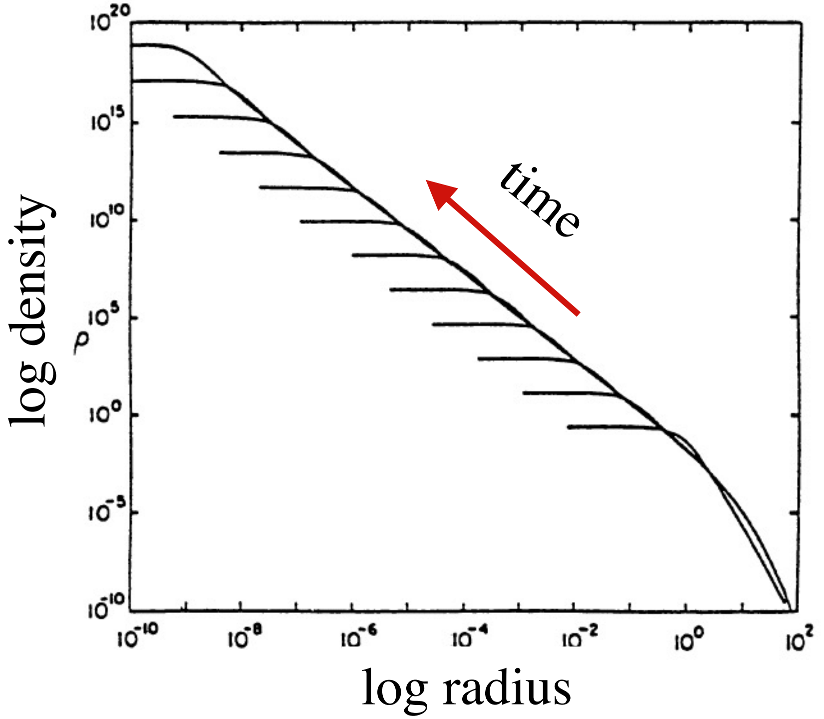
Gets a little hotter, so that E_{kin} balances the increased E_{pot}

Faster stars escape

Core shrinks some more

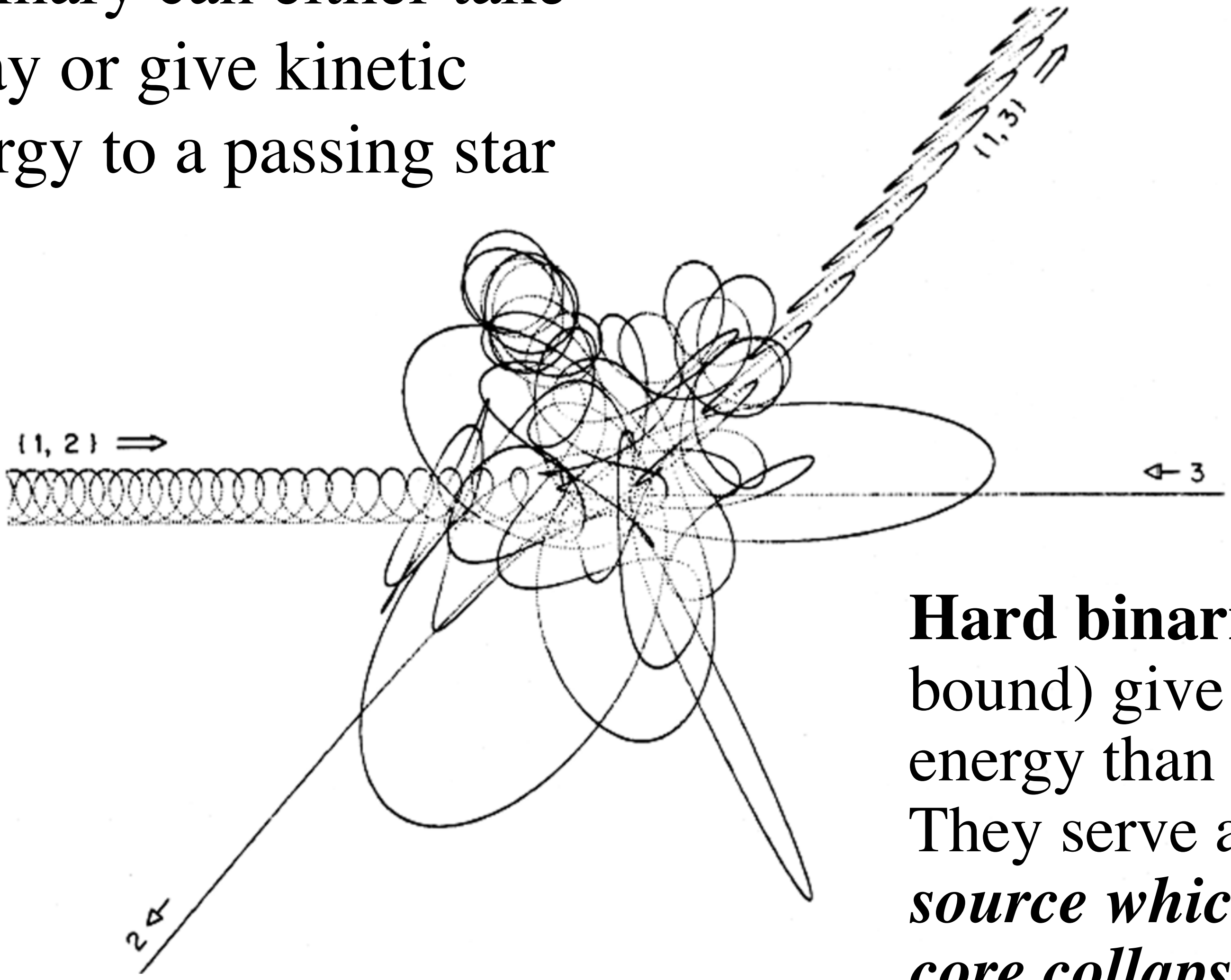
The only way to arrest the collapse is to provide *a source of energy* in the center, to replace the escaped heat. In the case of (proto)stars, this is accomplished by thermonuclear reactions.

In the case of globular clusters, it is accomplished by ***hard binaries***.



Binaries as a Source of Energy

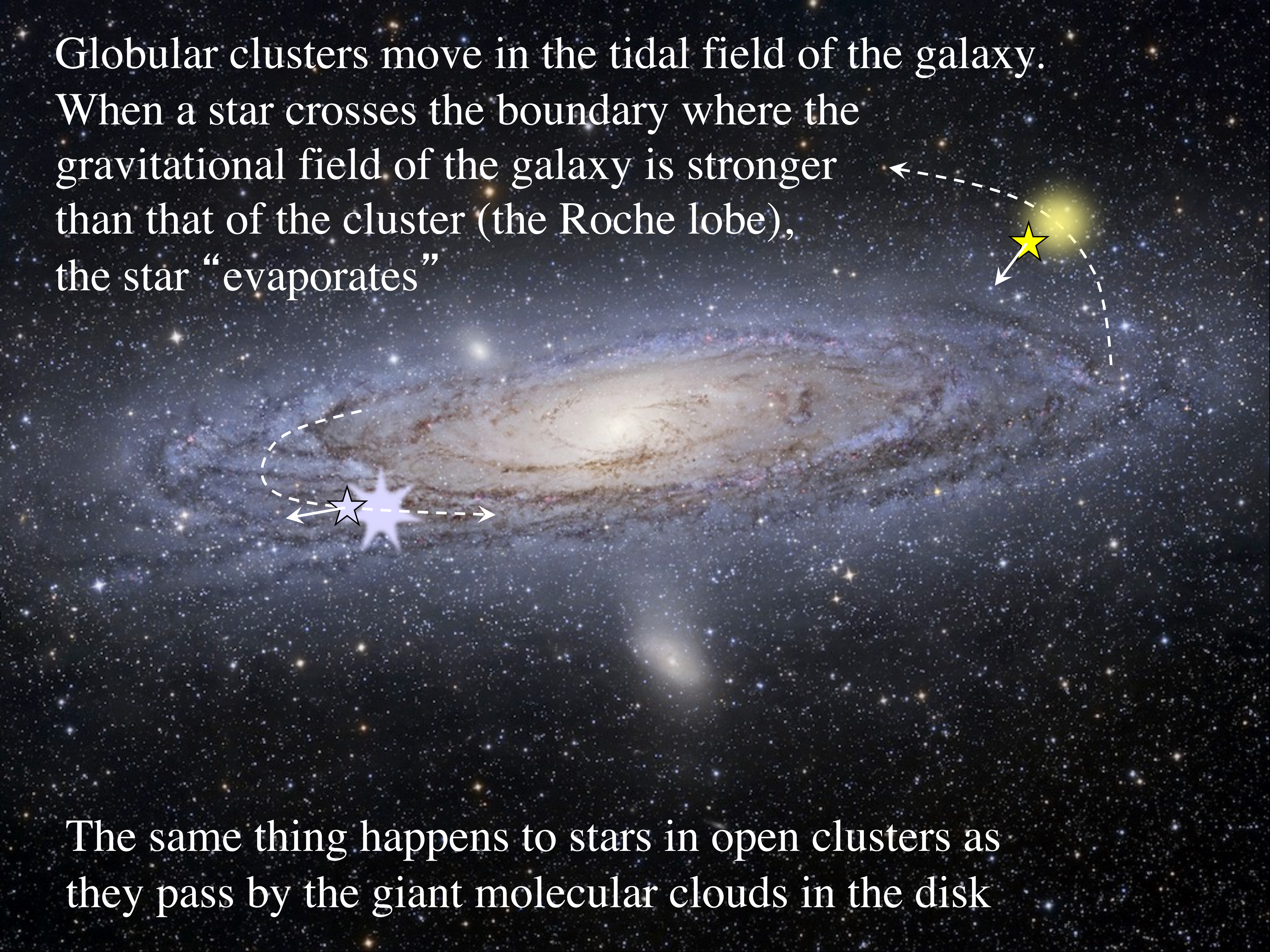
A binary can either take away or give kinetic energy to a passing star



Hard binaries (tightly bound) give away more energy than they absorb. They serve as the ***energy source which arrests the core collapse*** and stabilize the cluster

(Numerical simulation by P. Hut and J. Bahcall)

Globular clusters move in the tidal field of the galaxy. When a star crosses the boundary where the gravitational field of the galaxy is stronger than that of the cluster (the Roche lobe), the star "evaporates"



The same thing happens to stars in open clusters as they pass by the giant molecular clouds in the disk

Main Sequence (MS) and the Range of Stellar Masses

- MS is defined as the locus where stars burn H into He in their cores
- That is where they spend most of their lifetime
- It is ***a sequence of stellar masses*** – by far the most dominant parameter that determines stellar properties
- The lower mass end is set by the objects which cannot reach the necessary [T,ρ] to ignite fusion, because of their ***low mass*** ($M_\star < 0.08\ M_\odot$): **brown dwarfs** (new spectral types: L, T, Y)
- The ***high-mass end*** of the stellar family is set by the **Eddington limit**

Eddington Limit

Electrons/ions at a stellar surface feel radiation pressure that is proportional to luminosity, and that can drive a ***stellar wind***

When the radiation pressure matches the gravitational pull of the star, we have a limiting,
Eddington luminosity:

$$L = \frac{4\pi G c m_p}{\sigma_e} M$$

A more luminous star at a given mass would blow itself apart.

$$= 1.26 \times 10^{38} \left(\frac{M}{M_{sun}} \right) \text{ erg s}^{-1}$$

This is the *maximum luminosity* which an isotropically emitting source with a mass *M* could have

Invert the formula:

$$M_E = 8 \times 10^5 \left(\frac{L}{10^{44} \text{ erg s}^{-1}} \right) M_{sun}$$

Evolution on the Main Sequence

Star burns H in core, core composition slowly changes from H to He. Small changes in the external properties (L, T_e, R)

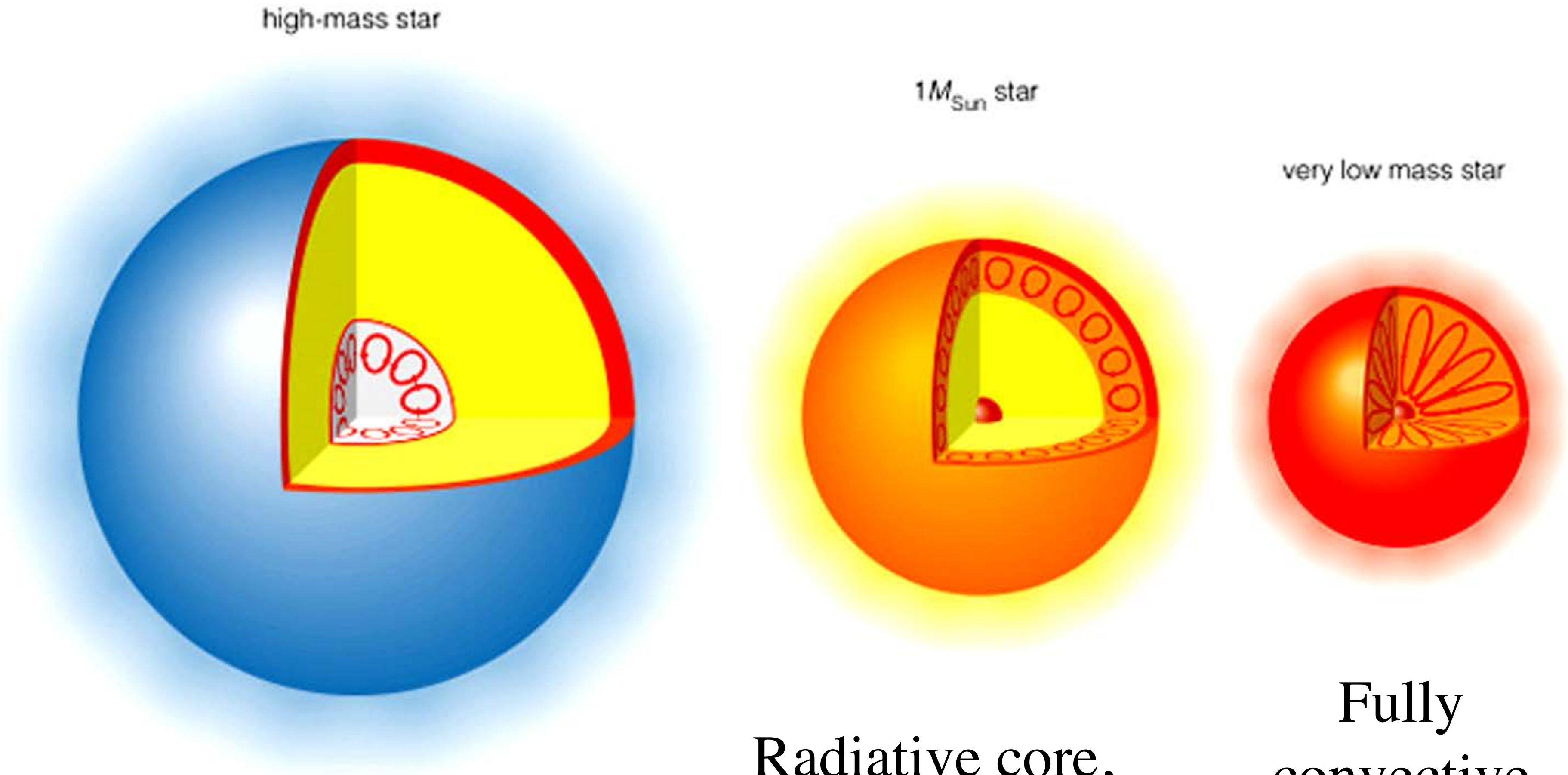
Main-sequence lifetime is strongly mass-dependent, since the more massive stars:

- sustain higher core temperatures
- have higher rates of nuclear fusion
- are more luminous and exhaust H fuel more quickly

$$L \propto M^{3.5} \rightarrow t_{ms} \propto M^{-2.5}$$

Star leaves the main sequence when it stops burning hydrogen in the core that is now pure He (but it continues burning it in a shell around the core). This leads to *expansion* of the envelope, and the formation of a **red giant**

Differences in Stellar Structures Regarding the Energy Transport

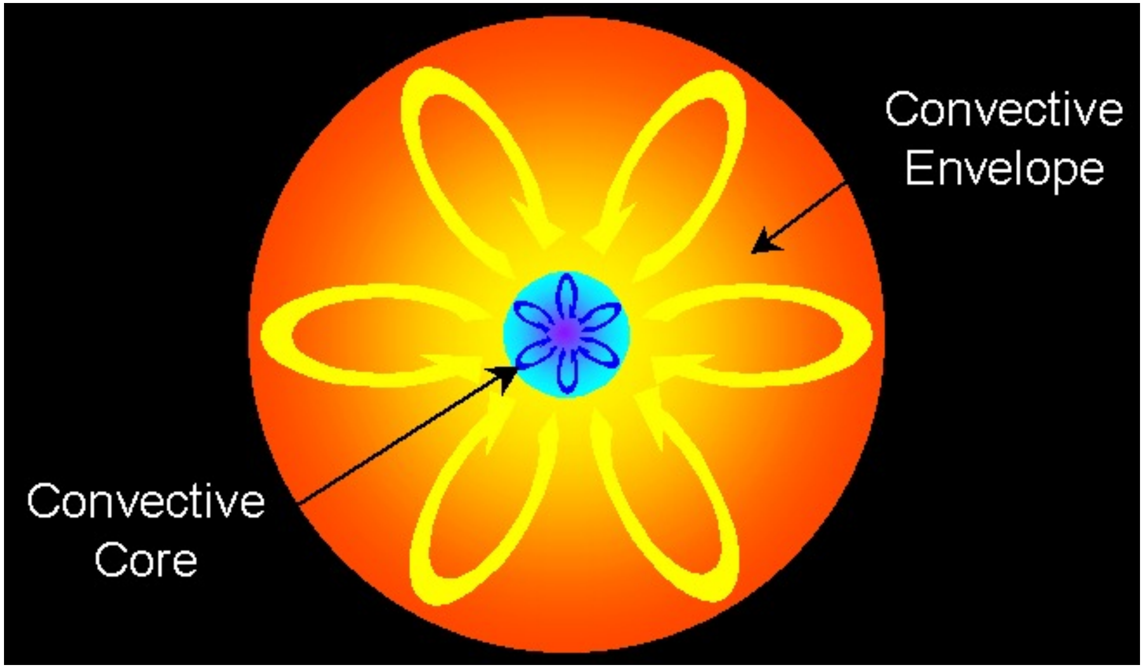


Convective core,
radiative envelope

Radiative core,
convective envelope

Fully
convective

Very Low Mass Stars: Red Dwarfs

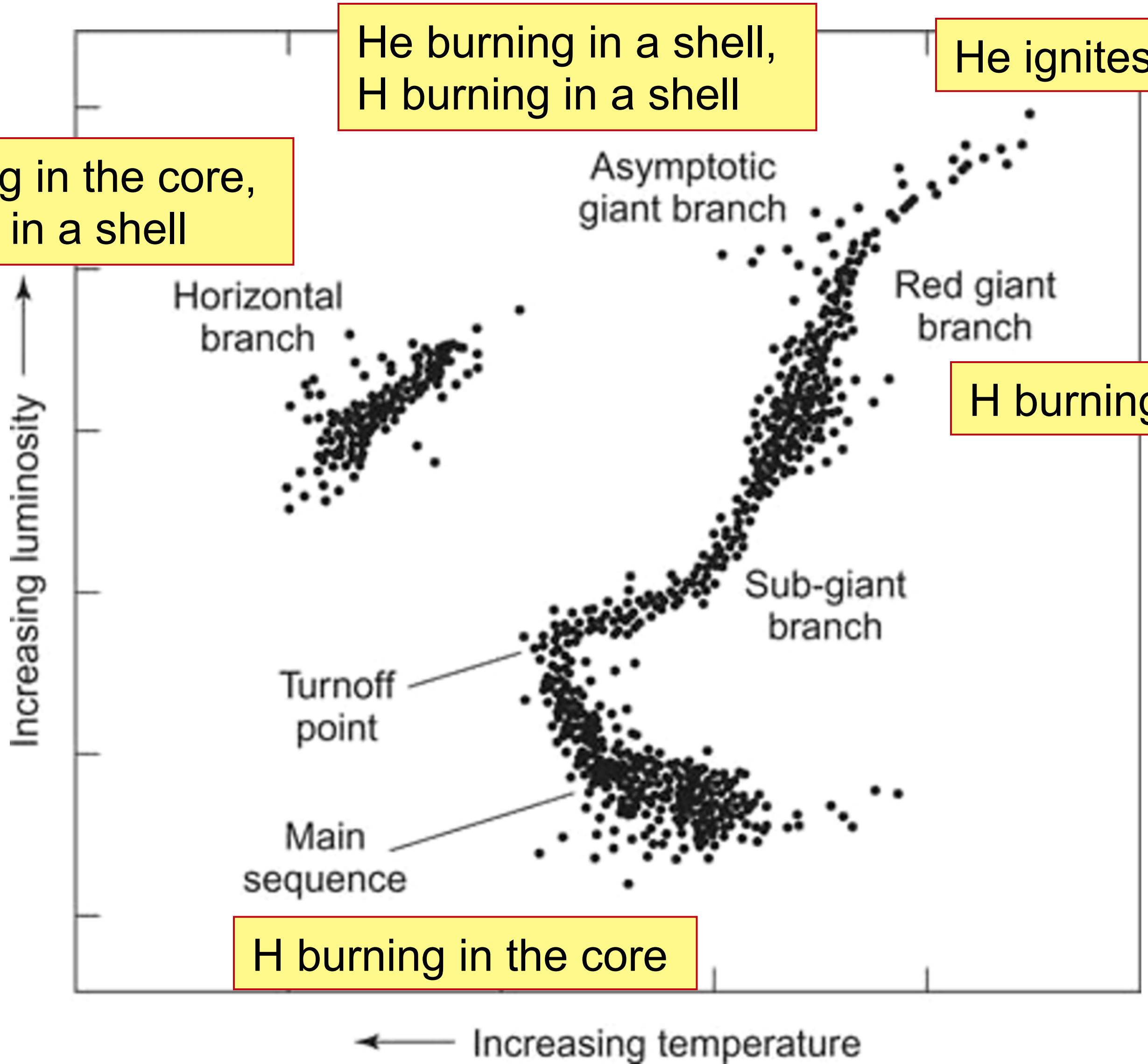


- Mass < 0.4 $M_{\odot}$
- Their structure is all convection zone, H and He is mixed throughout the star
- The star burns H slowly
- Will never build up a He core, and never ignite He
- Could perhaps survive on the MS for a 100 Gyr!
- Then just fade as a White dwarf

The End of the MS Phase

- On the MS, a star is in a hydrostatic equilibrium, and its core is sufficiently hot to fuse H into He
- Now the star has two chemically distinct zones, a core of inert He surrounded by an H envelope - the core of a MS star is not sufficiently hot for He burning
- When the core becomes pure He, a new evolutionary phase stars - the ascent to the ***Red Giant Branch*** (RGB)
- Without energy generation, the core cannot support itself against gravitational collapse and so it begins to shrink; as it collapses it heats up
- This heat is transferred to a thin shell of H around the core which reaches a temperature in which H fusion can occur

Stellar Evolution is a Sequence of Different Thermonuclear Reactions



He burning in a shell,
H burning in a shell

He ignites in the core

He burning in the core,
H burning in a shell

H burning in a shell

H burning in the core

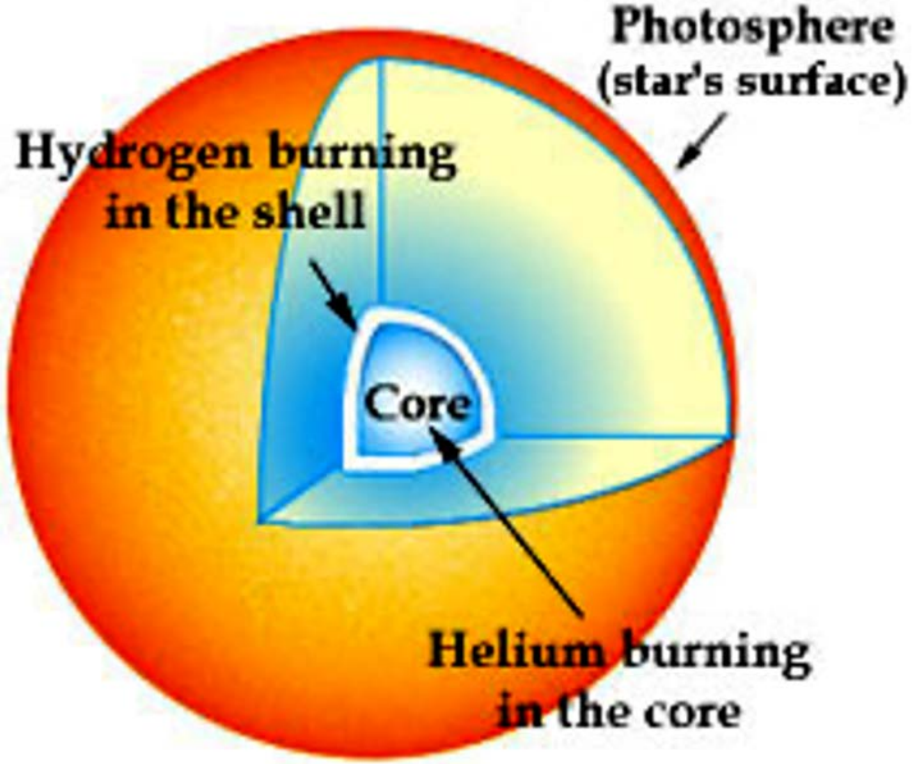
Becoming a Red Giant

- As the core continues to collapse, the temperature in the H fusing shell continues to rise and thus the luminosity in the shell increases as does the pressure
- The entire star is no longer in a hydrostatic equilibrium, and the envelope begins to expand
- As they expand these outer layers cool - the star becomes redder, while its luminosity increases: the star slowly ascends the RGB
- Our Sun will swell to about the size of the Earth's orbit
- This imbalance will continue until the star again finds a source of core energy generation, i.e., He fusion

Structure of a Red Giant

- Now the core has heated to T ~ 10^8 K, which is the threshold temperature for the fusion of He into C
- The star is in a quasi-static equilibrium. The lifetime of a star as a Red Giant is about 10% of its MS lifetime

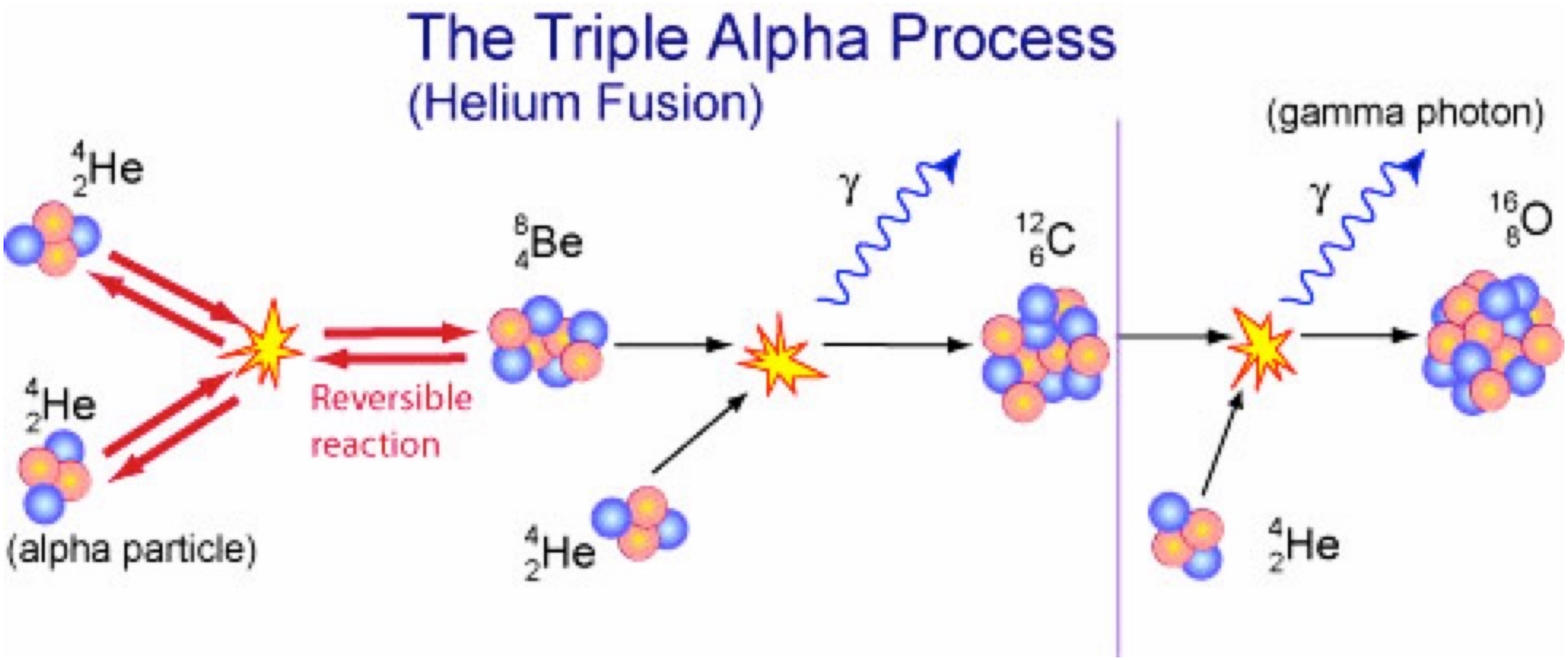
- The luminosity generated by the core fusion of He into C is far greater than the shell luminosity associated with the fusion of H into He



Helium Flash: The End of the RGB

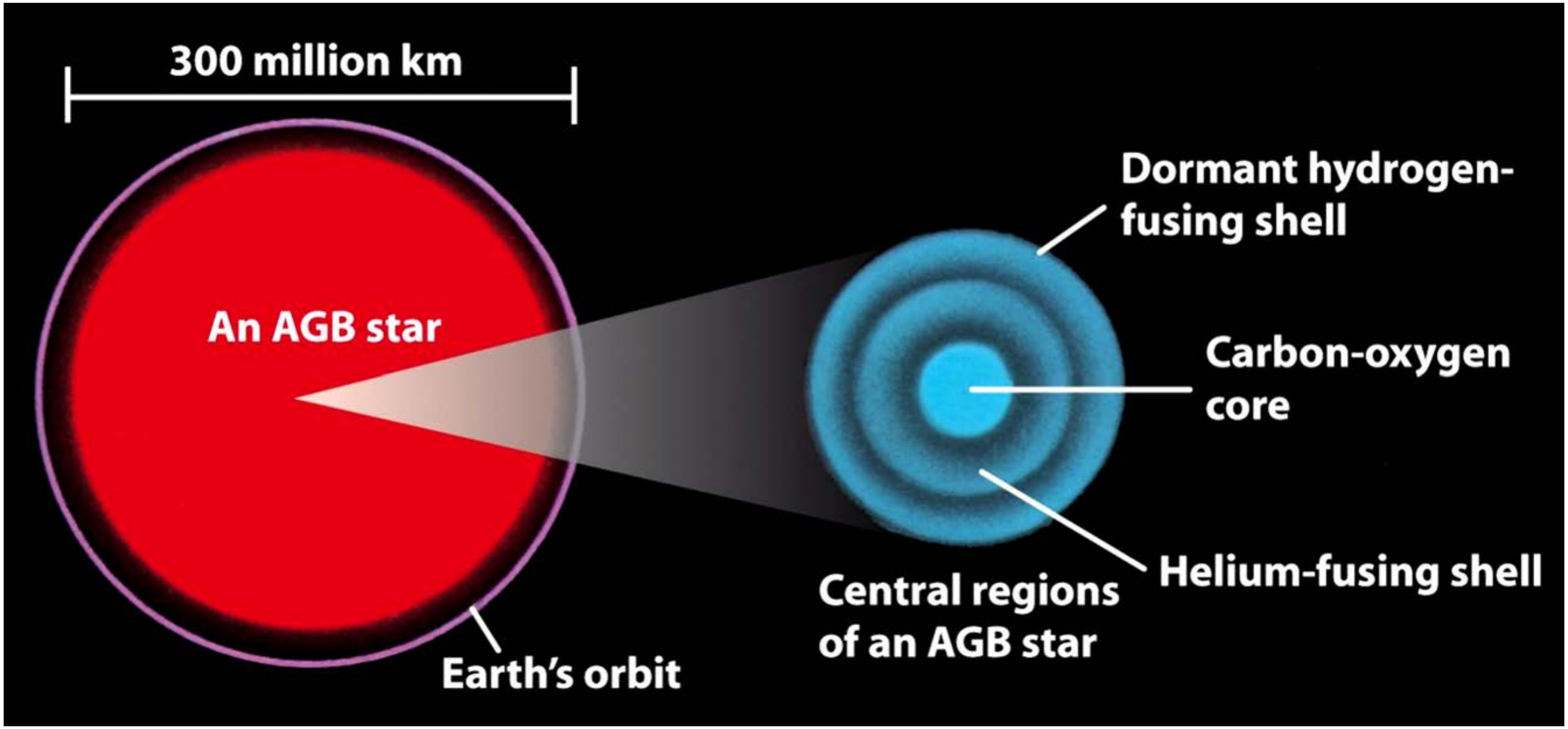
- H fusion leaves behind He ash in the core of the star which cannot begin to fuse until the temperature of the core reaches 100 million K. How a star begins He fusion depends on its mass:
- $M > 3\ M_{\odot}$ stars contract rapidly, their cores heat up, and He fusion begins gradually
- Less massive stars evolve more slowly and their cores contract so much that degeneracy occurs in the core
- When the temperature is hot enough He fusion begins to make energy and the T rises, but pressure does not increase due to degeneracy
- Higher T increases He fusion even further resulting in a runaway explosion: the **Helium Flash** which for a few minutes can generate more luminosity than an entire galaxy. The flash does not destroy the star: the envelope absorbs the energy

The Next Step: Burning Helium Into Carbon



- Requires much higher temperatures, T ~ 10^8 K
- Enabled by the “exact right” energy resonance for carbon

Dredge-ups bring the products of nuclear fusion to a giant star’ s surface

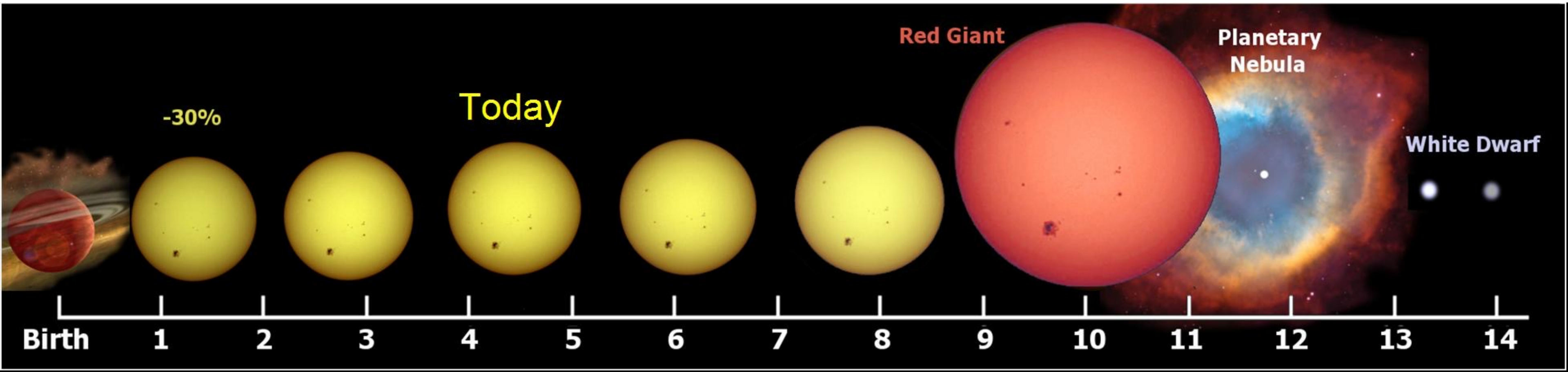


- As a low-mass star ages, convection occurs over a larger portion of its volume
- This takes heavy elements formed in the star’ s interior and distributes them throughout the star

The End Phases of Stellar Evolution

- The evolution and eventual fate of stars critically dependent on their mass:
- Stars with initial masses of *less* than ~ 8 $M_\odot$ end as ***white dwarfs.*** The star sheds its RG envelope, which becomes a ***planetary nebula***, and the inert, degenerate core cools passively
- Stars with initial masses *greater* than ~ 8 $M_\odot$ explode as ***supernovae.*** The stellar remnants are ***neutron stars*** or ***black holes***

The fate of our Sun

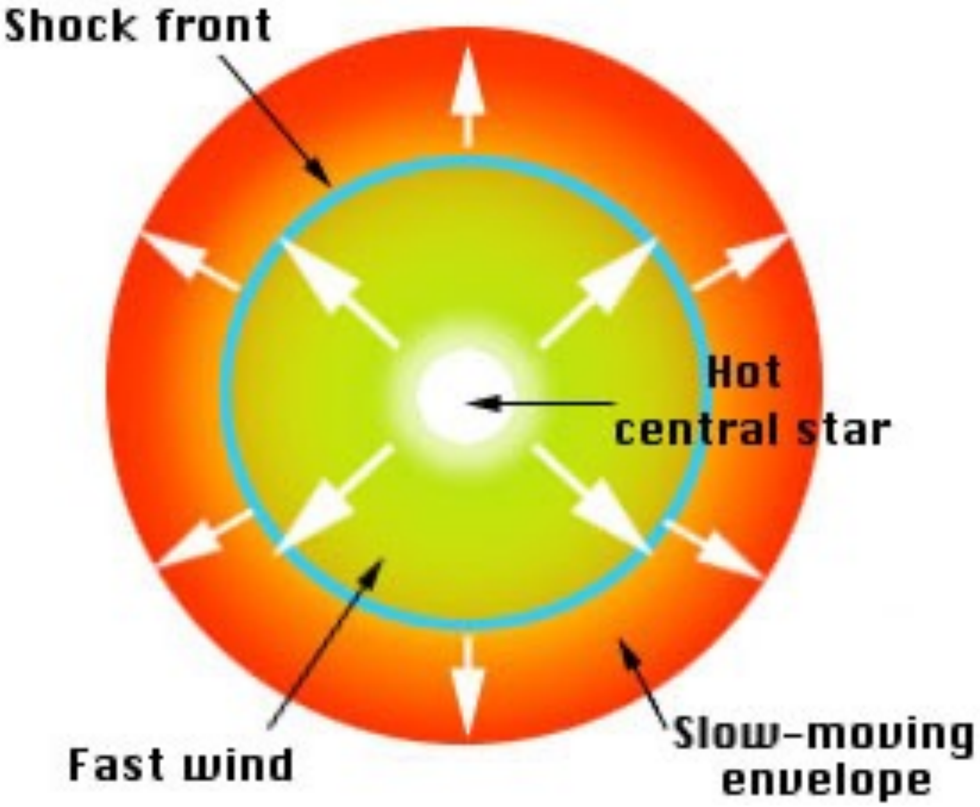


Planetary Nebula Formation

- A RG brightens by a factor of between 1,000 and 10,000. The outer, hydrogen-rich envelope swells up to a few au radius, with T ~ 2,000 - 3,000 K
- A strong stellar wind begins to blow from the star's surface (akin to the Sun's solar wind, but much stronger), and, in the course of the star's RG life, carries away most of the H envelope
- During the final shedding of its envelope, when the mass loss is the greatest, the star becomes unstable and pulsates, with periods ~ few months to > 1 yr. Such stars are called ***long-period variables***.
- The envelope material ejected by the star forms an expanding shell of gas that is known as a ***planetary nebula (PN)***

Formation of Planetary Nebula

Planetary nebulae typically have masses ~ 0.2 $M_\odot$, although some are considerably more massive. They expand V ~ 10 - 20 km/s, and plow into the surrounding *interstellar medium,* contributing to its chemical enrichment.



Their central stars (degenerate cores of progenitors) provide photoionization for the nebulae.

Planetary Nebulae Imaged by the HST

Eskimo Nebula

Ring Nebula

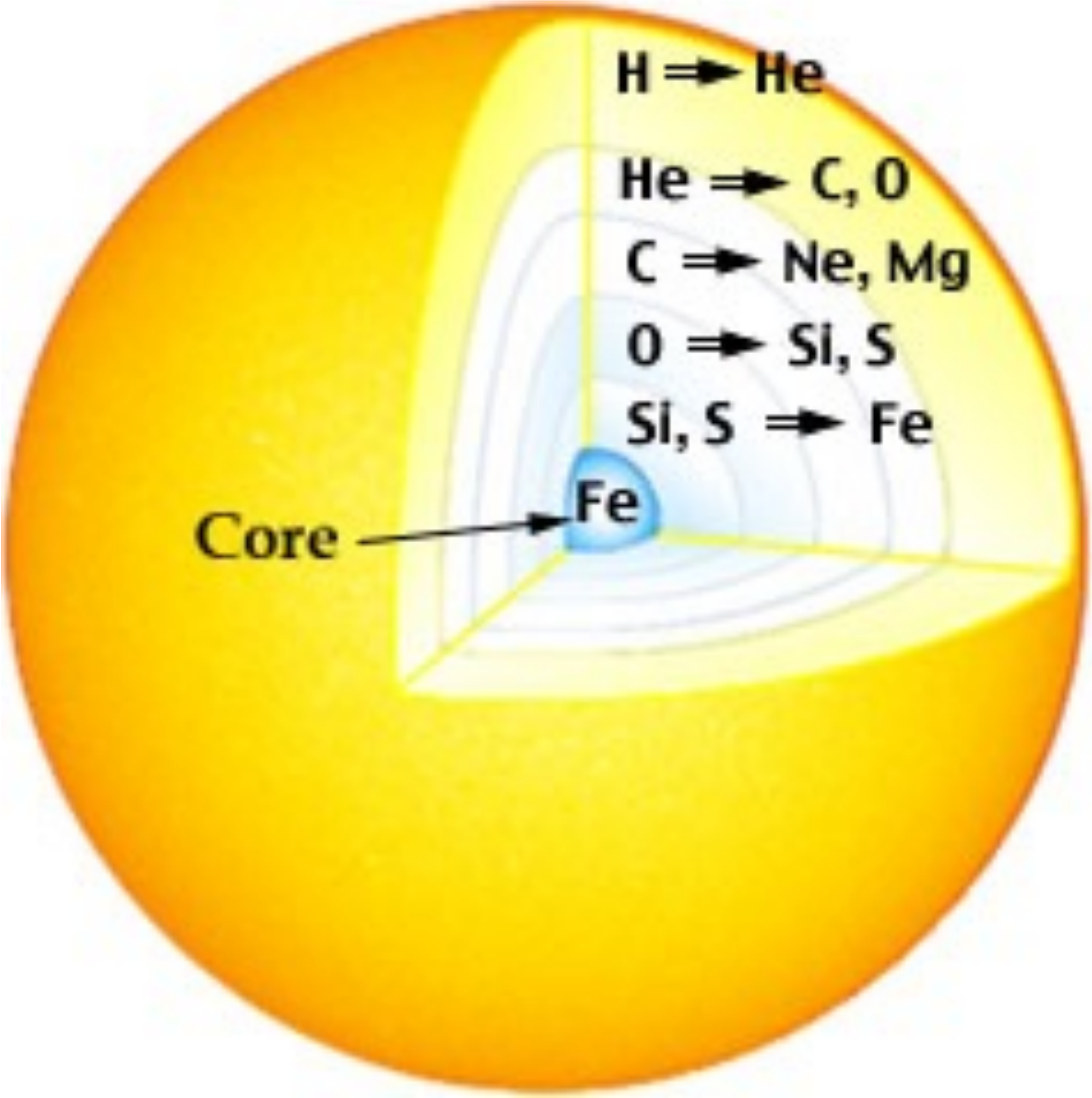
Necklace Nebula

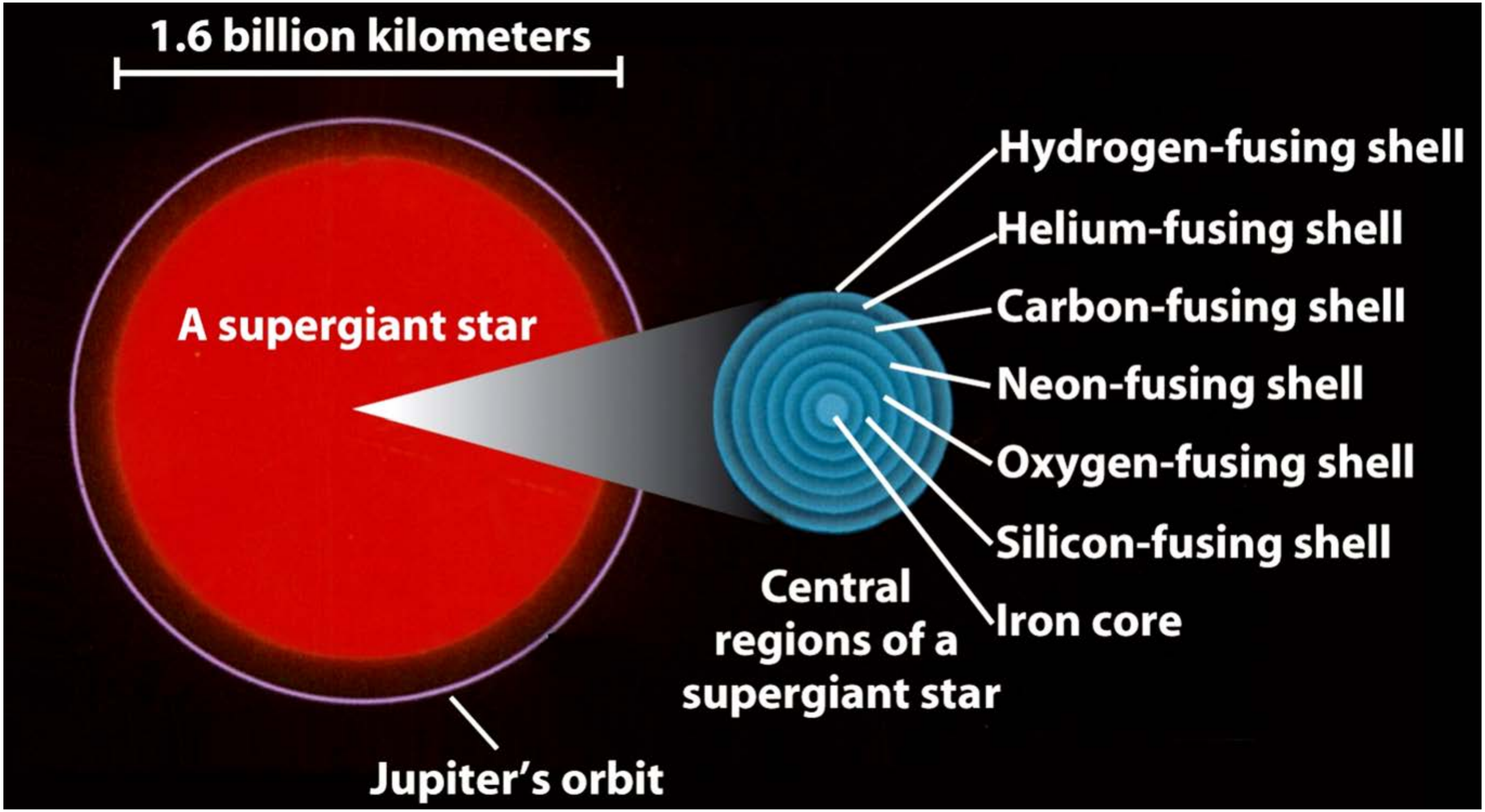
Spirograph Nebula (IC 418)

Cat’s Eye Nebula

Hour Glass Nebula

Highly Evolved Star Structure

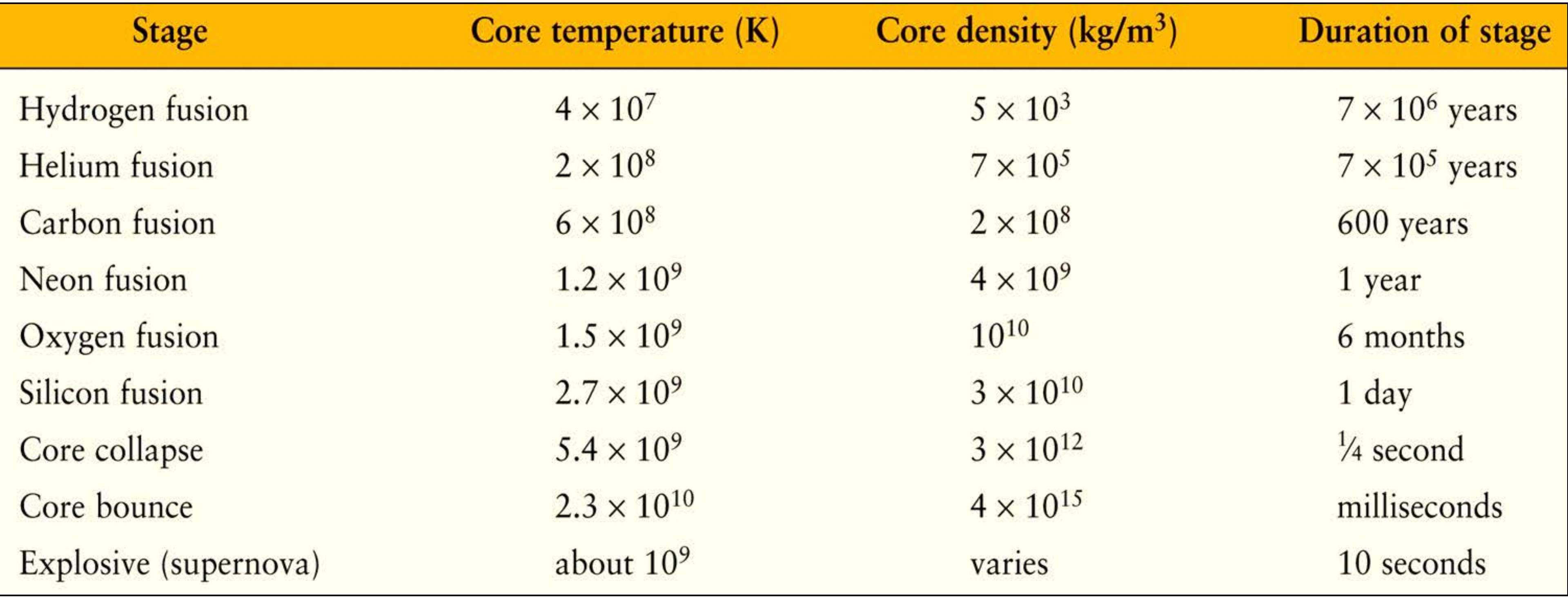




- In the last stages, a high-mass star has an Fe-rich core surrounded by concentric shells hosting the various thermonuclear reactions
- The sequence of thermonuclear reactions stops here, because the formation of elements heavier than Fe requires an input of energy rather than causing energy to be released

Rapid Final Stages of a Massive Star Evolution

- A high mass star undergoes an extended sequence of thermonuclear reactions in its core and shells: C fusion, Ne fusion, O fusion, and Si fusion, all the way to Fe



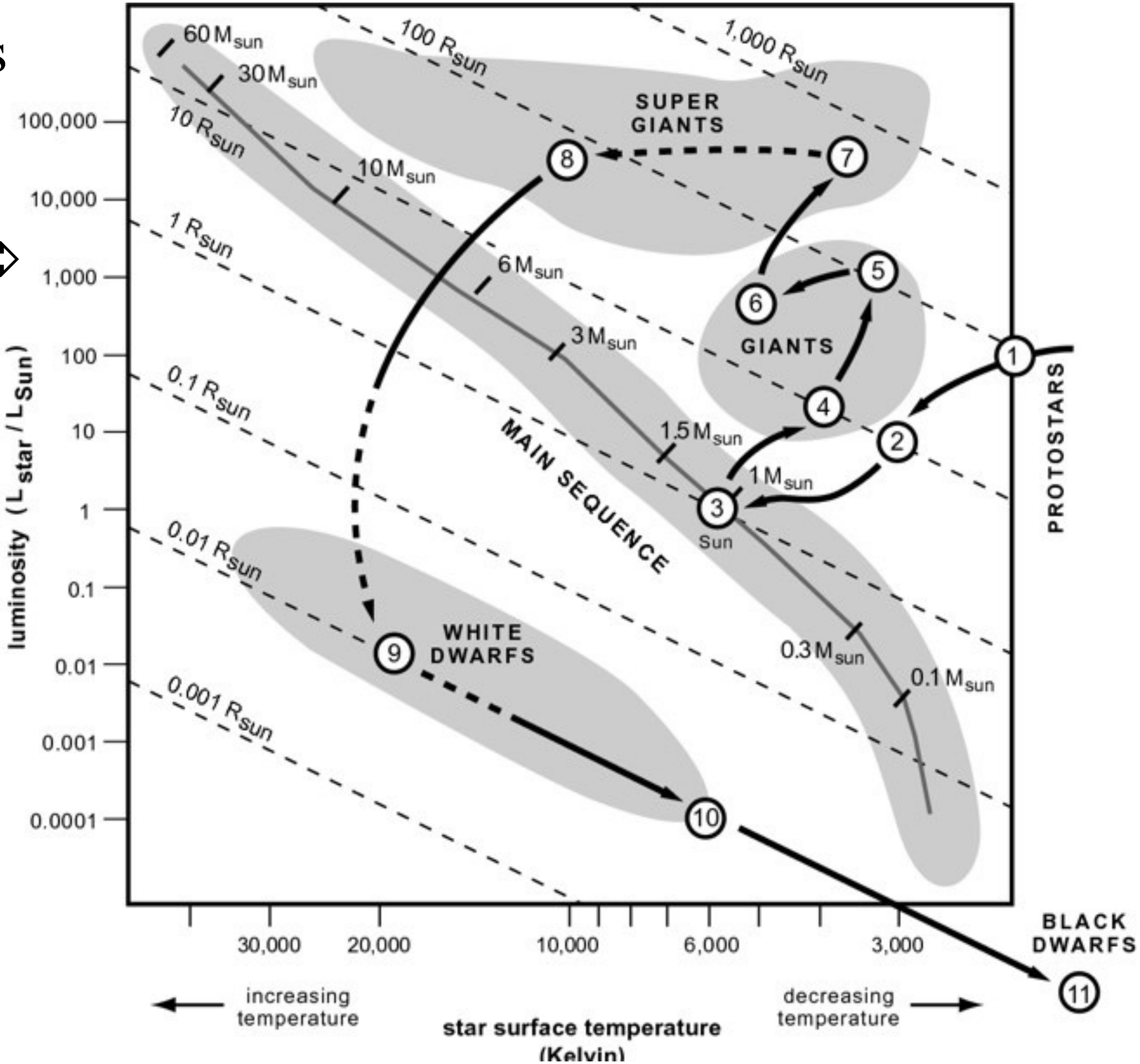
Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Low Mass Stars End Up as White Dwarfs

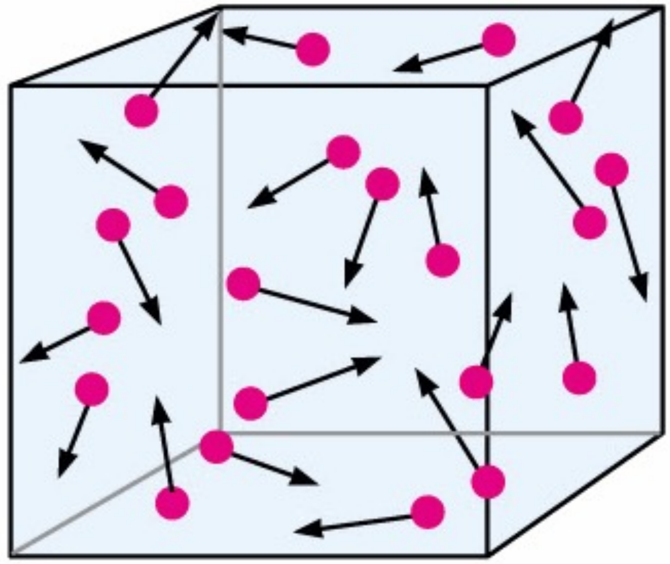
Red giant sheds its envelope, which becomes a planetary nebula ⇨

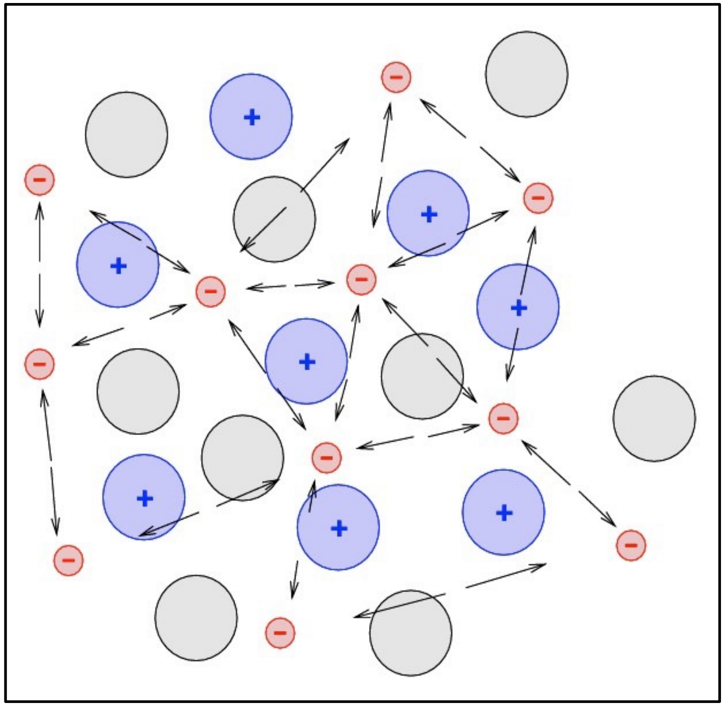
Hot, inert core becomes a white dwarf ⇨

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

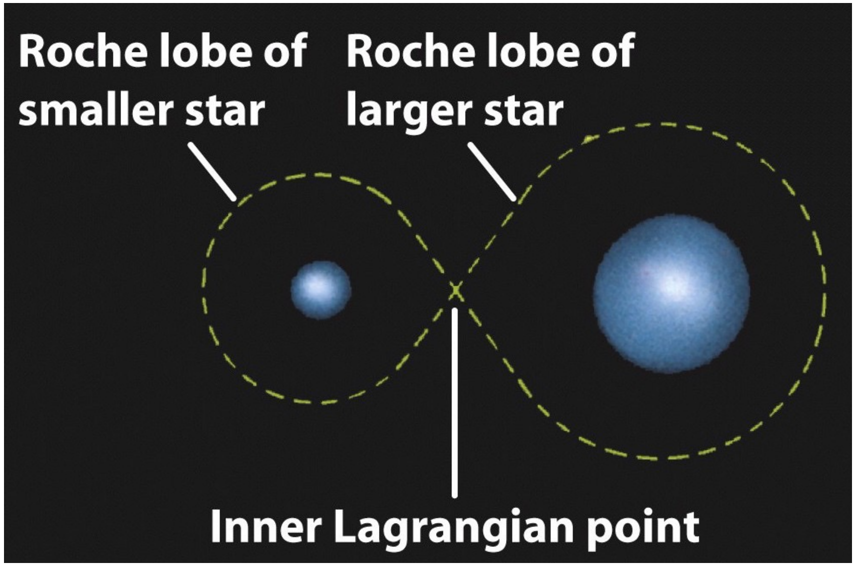
- Gravity is balanced by the electron degeneracy pressure
- The sizes are ~ the size of the planet Earth
  - Densities ~ 10^6 g/cm^3
- The masses are up to ~ 1.4 $M_\odot$ = the ***Chandrasekhar limit***
- Beyond that mass, pressure cannot balance the gravity, and the star collapses into a neutron star 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

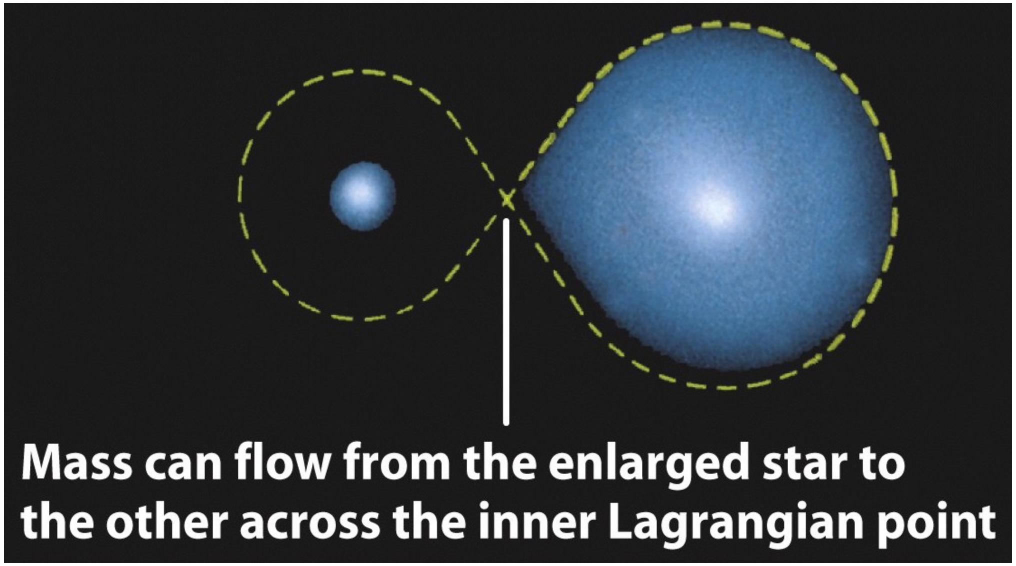
Stars in Close (Contact) Binaries

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

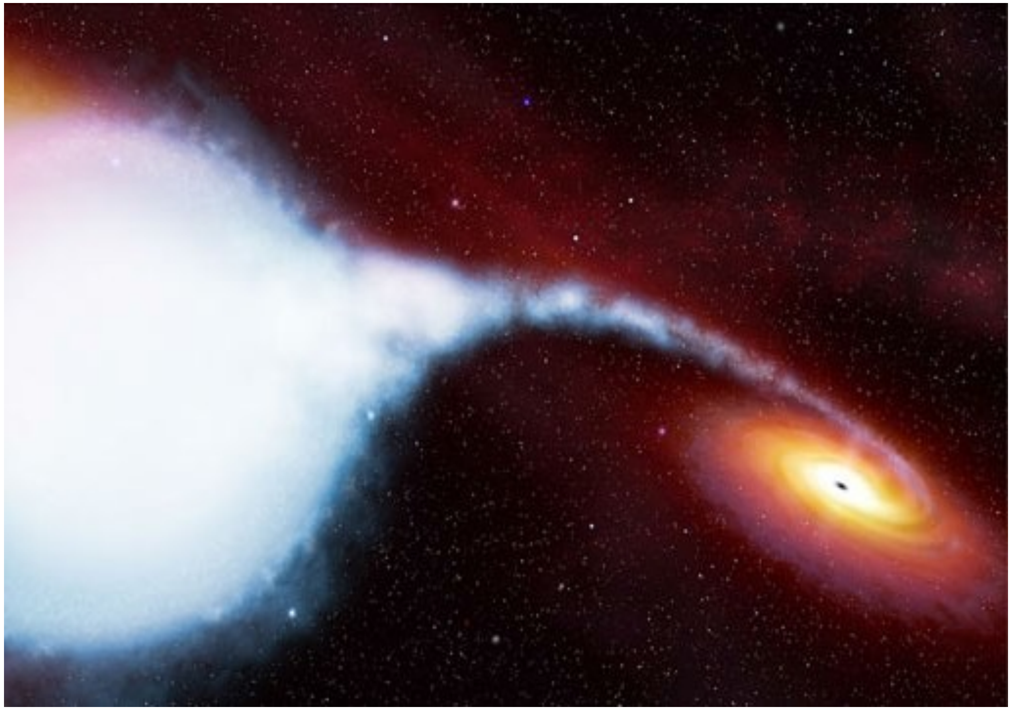
Inner Lagrange Point: the point between them where the two lobes connect




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

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

Accretion to a Compact Companion



(WD, NS, BH)

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

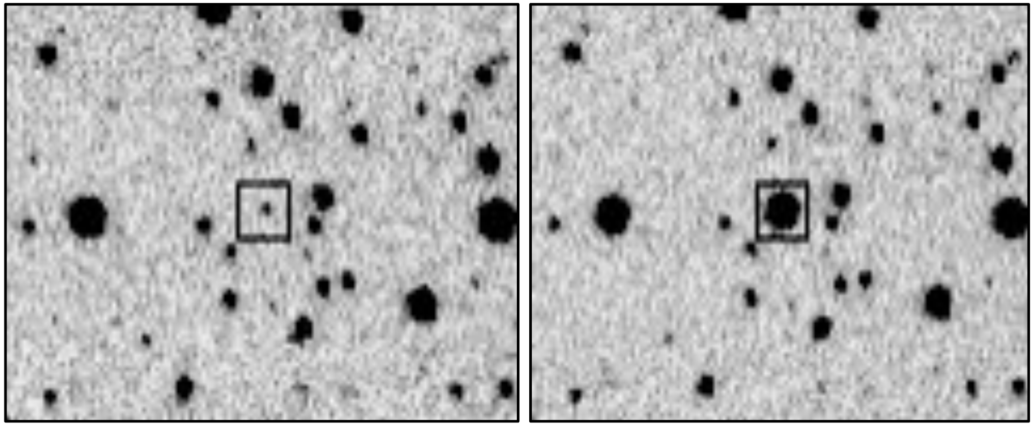
$E_{kin} = \Delta E_{pot} \approx GM/R_{accr}$ Luminosity = dE/dt $= G\dot{M}/R_{accr}$

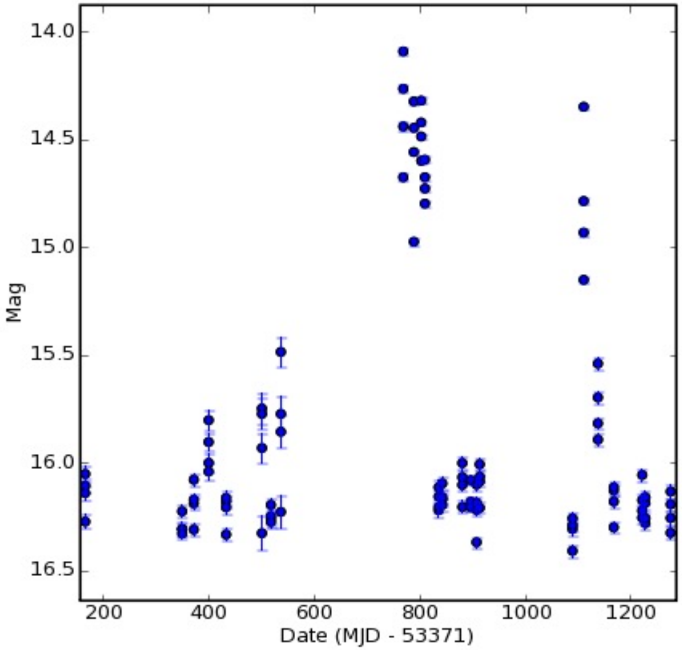
Compact object mass Accretion radius Mass accretion rate

The infalling material will form an **accretion disk**, which soaks up the excess angular momentum

Cataclysmic Variables

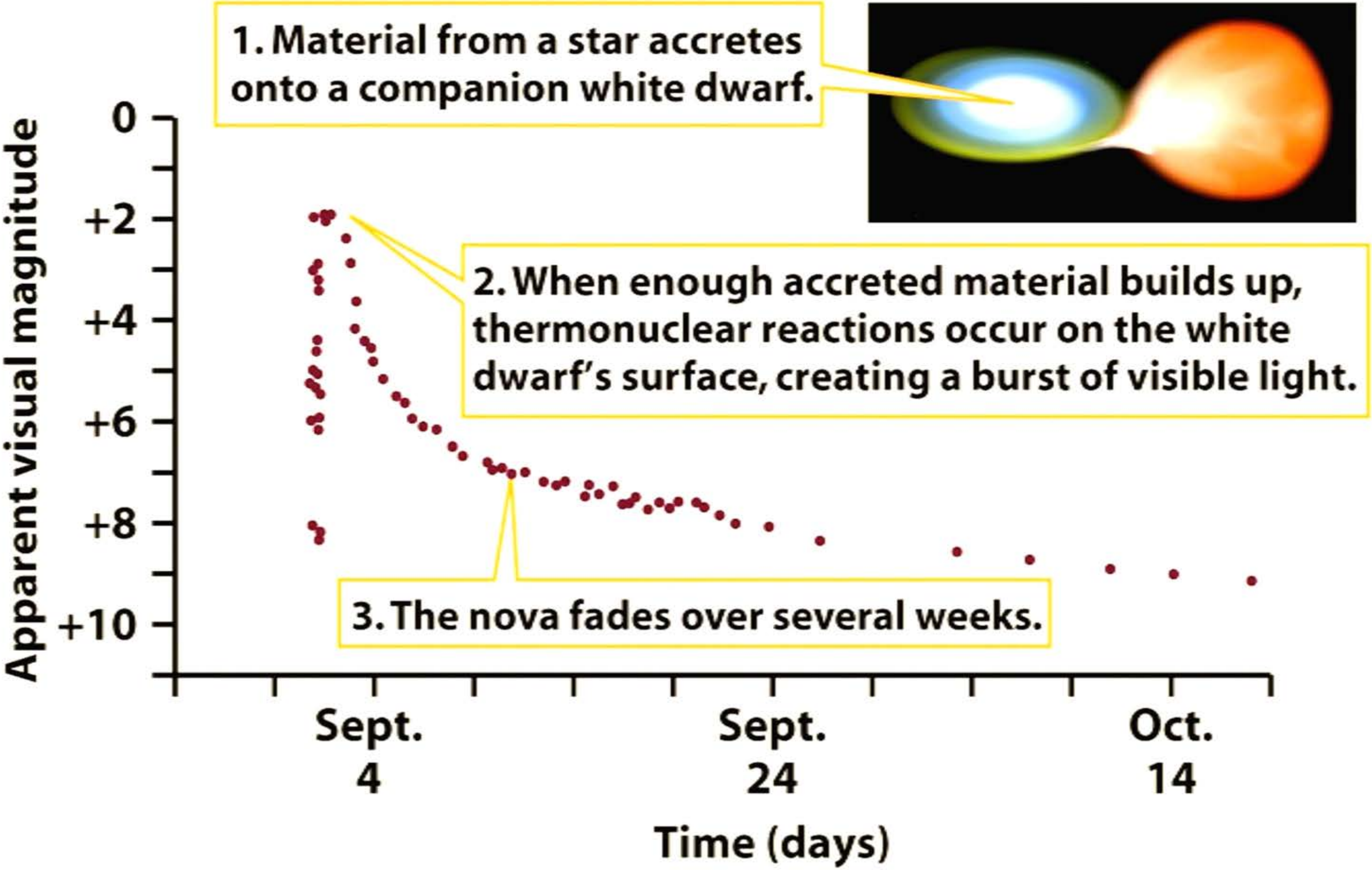
- Variation in the mass accretion translate into variations in luminosity, that can be dramatic. Such objects are called **cataclysmic variables**





- 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.

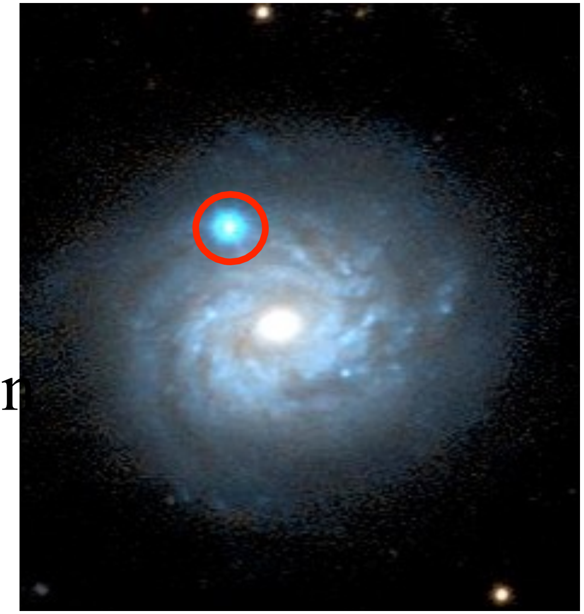
2. When enough accreted material builds up, thermonuclear reactions occur on the white dwarf's surface, creating a burst of visible light.

3. The nova fades over several weeks.

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 i
star-forming galaxies only

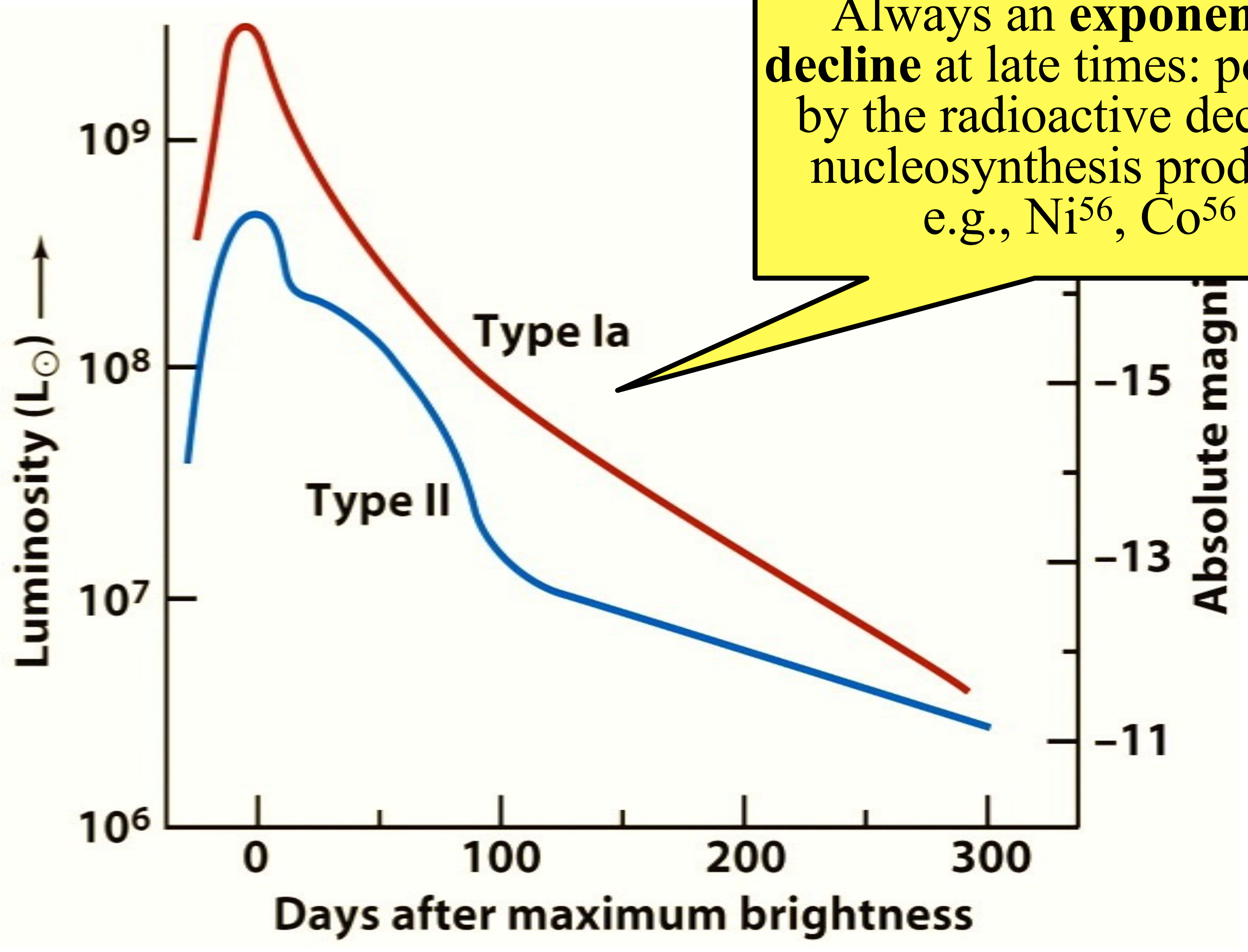
Typical rate ~ 1 per galaxy per century

They are further divided into subclasses (Ia, Ib, Ic, IIn, IIp, etc.) based on their spectral properties. There are also “peculiar” cases (i.e., rare/unusual). More are still being found.

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

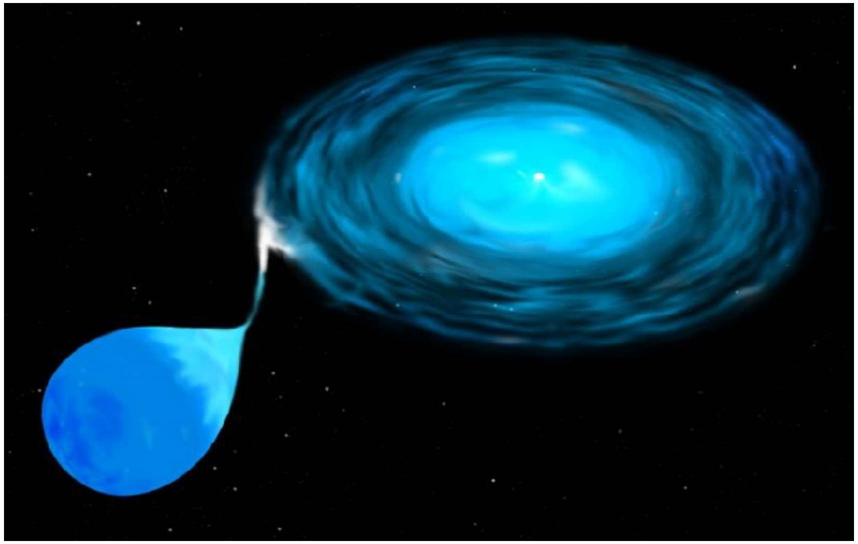
There may be two mechanisms for Type II SNe, core collapse of a massive star, or annihilation of e+ e– pairs.

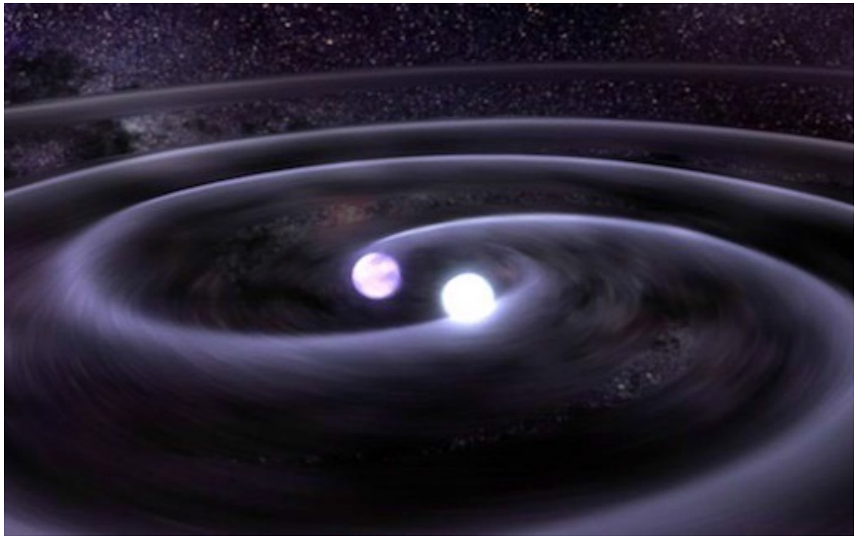
SN Types: Light Curve Differences



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,

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

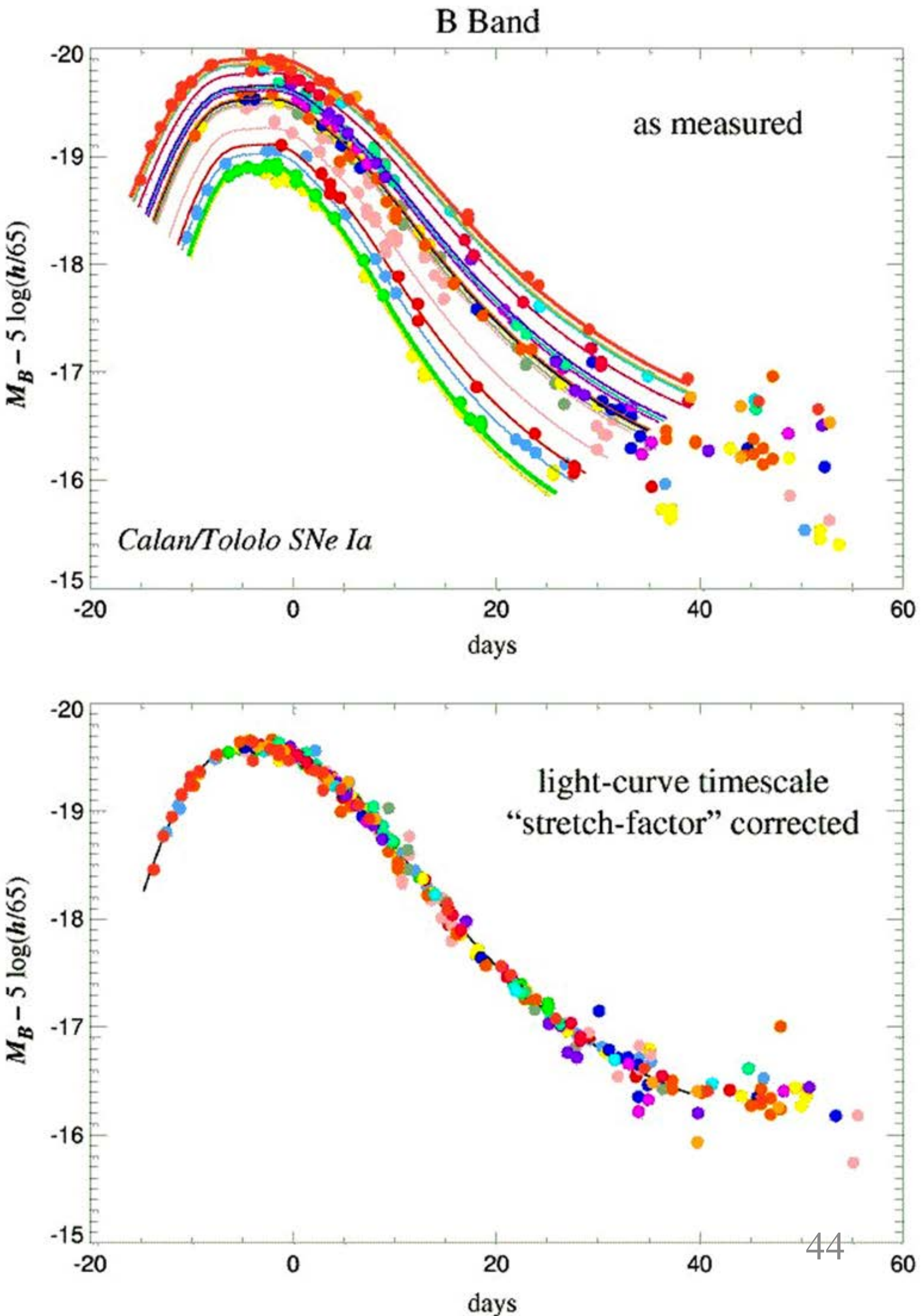
degenerate gas pressure can no longer support the star against the gravity, and the star collapses

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

SNe Ia as Standard Candles

- The peak brightness of a SN Ia correlates with the shape of its light curve (steeper → fainter)
- Correcting for this effect standardizes the peak luminosity to ~10% or better

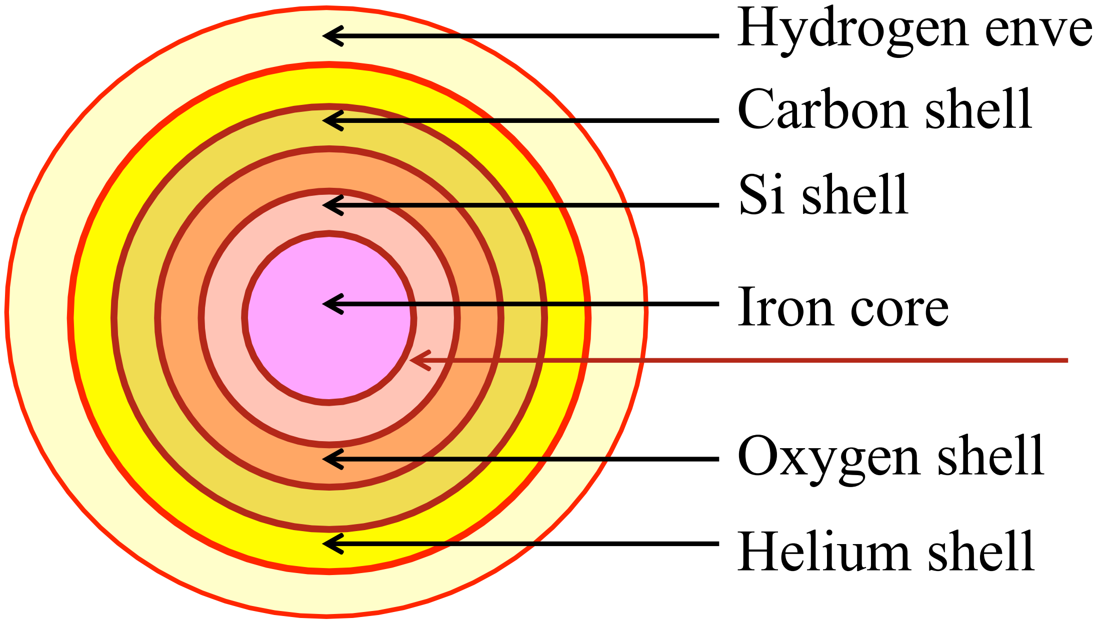
- This makes the SNe Ia very useful as cosmological probes:
- Their observed



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

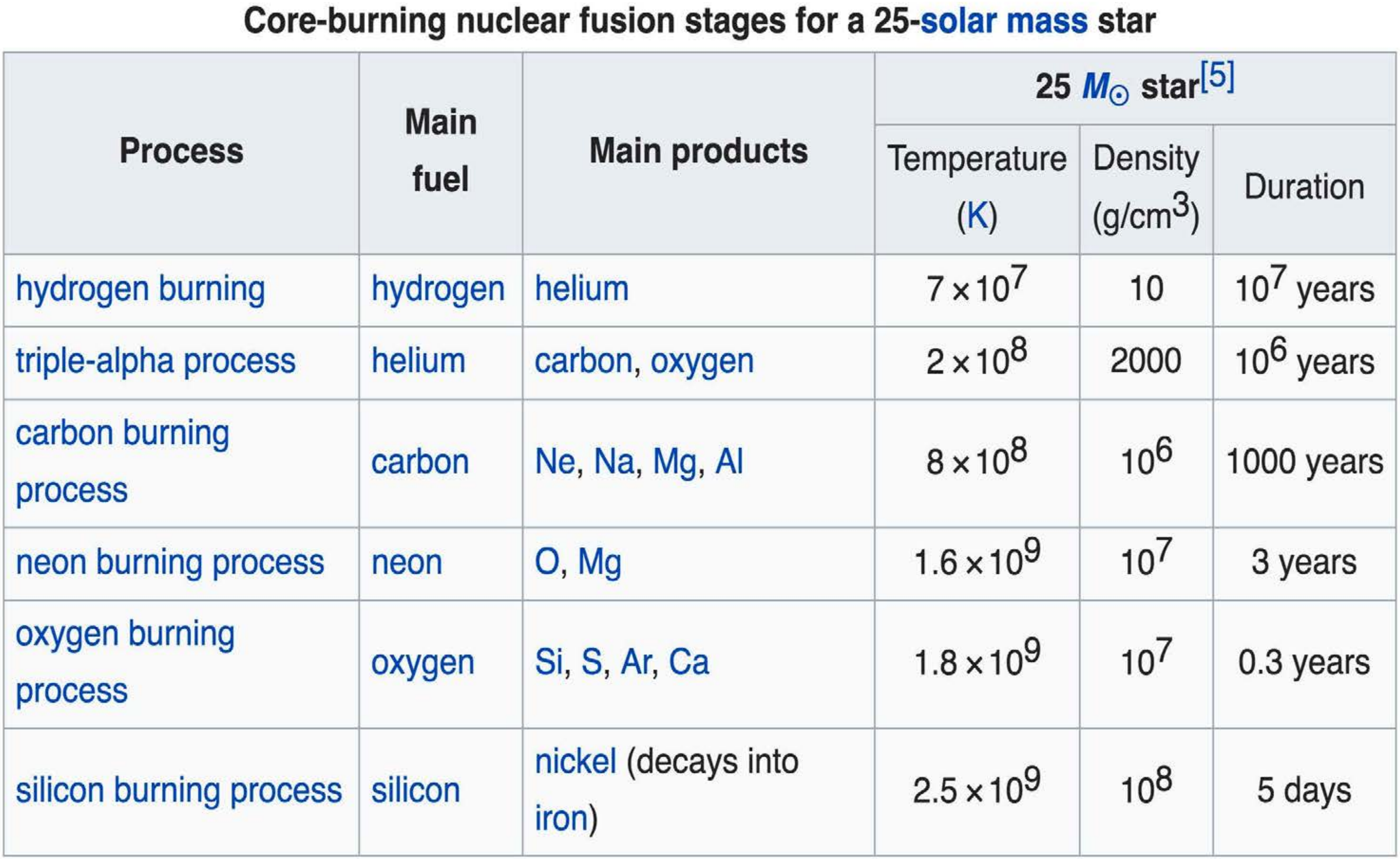
Iron core

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

Accelerated Thermonuclear Evolution



Core-burning nuclear fusion stages for a 25-solar mass star

Process	Main fuel	Main products	25 $M_\odot$ star[5]		
			Temperature (K)	Density (g/cm^3)	Duration
hydrogen burning	hydrogen	helium	7×10^7	10	10^7 years
triple-alpha process	helium	carbon, oxygen	2×10^8	2000	10^6 years
carbon burning process	carbon	Ne, Na, Mg, Al	8×10^8	10^6	1000 years
neon burning process	neon	O, Mg	1.6×10^9	10^7	3 years
oxygen burning process	oxygen	Si, S, Ar, Ca	1.8×10^9	10^7	0.3 years
silicon burning process	silicon	nickel (decays into iron)	2.5×10^9	10^8	5 days

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

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

Needs high energy gamma rays

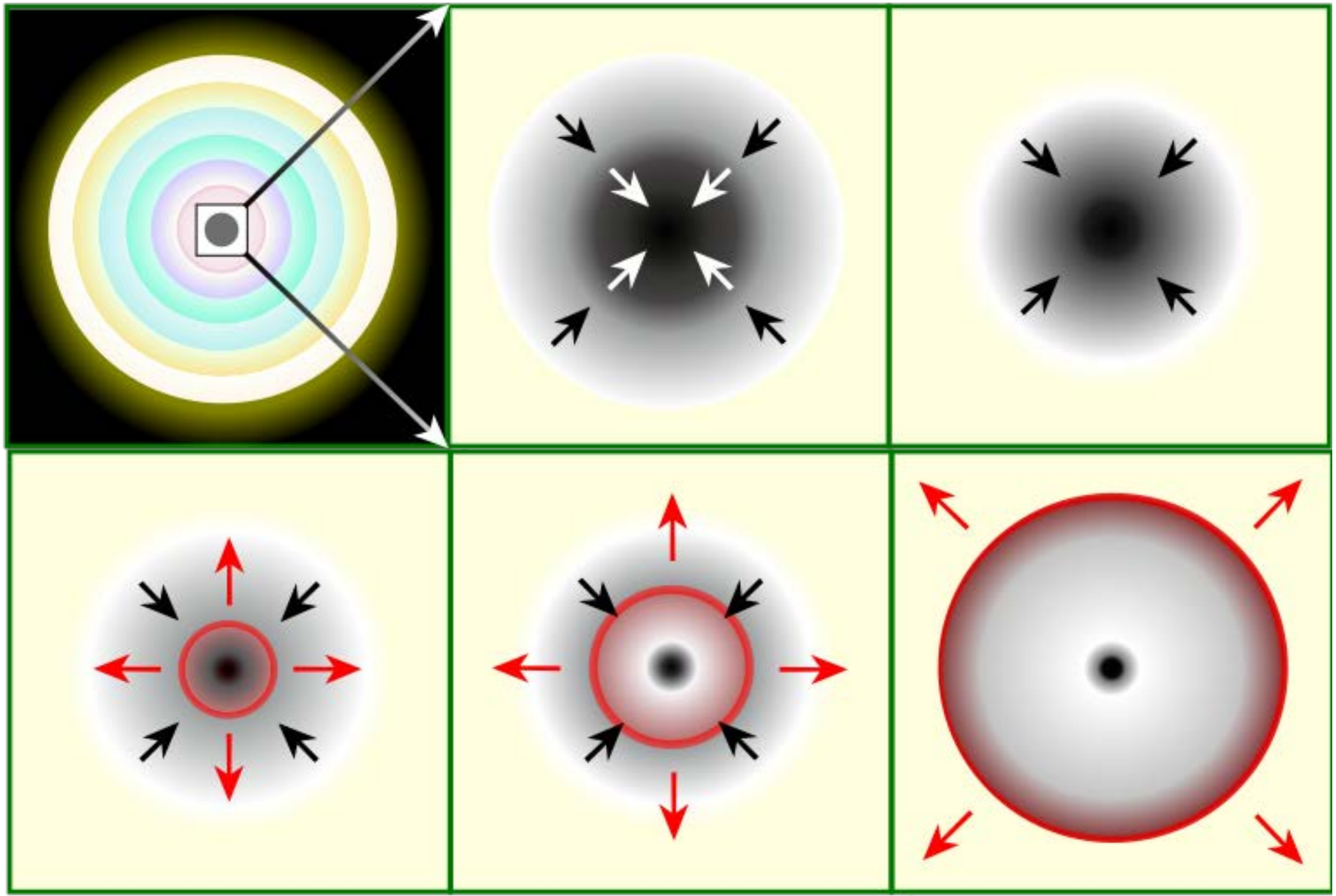
Inverse beta decay

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

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



Fe core reaches the Chandrasekhar mass, and starts to collapse…

The inner core is compressed into neutrons

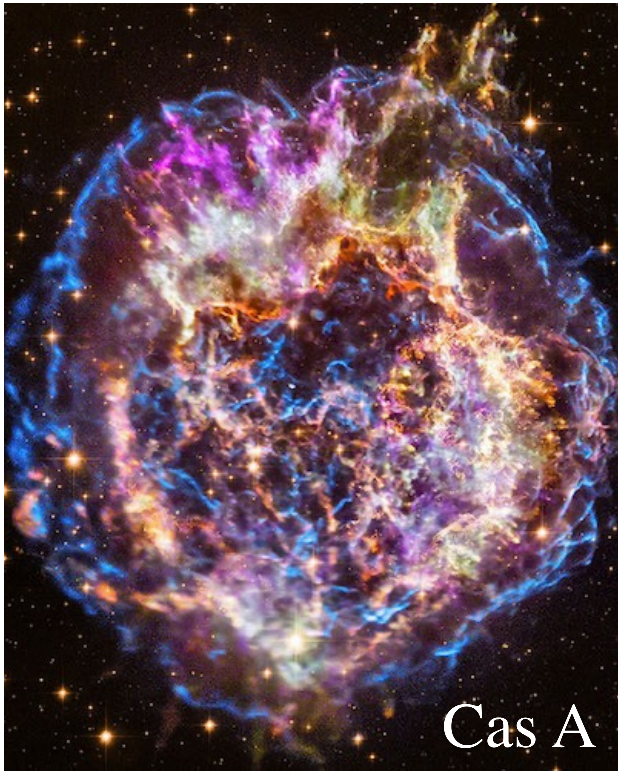
That causes the infall to bounce…

… and form an outward going shock wave …

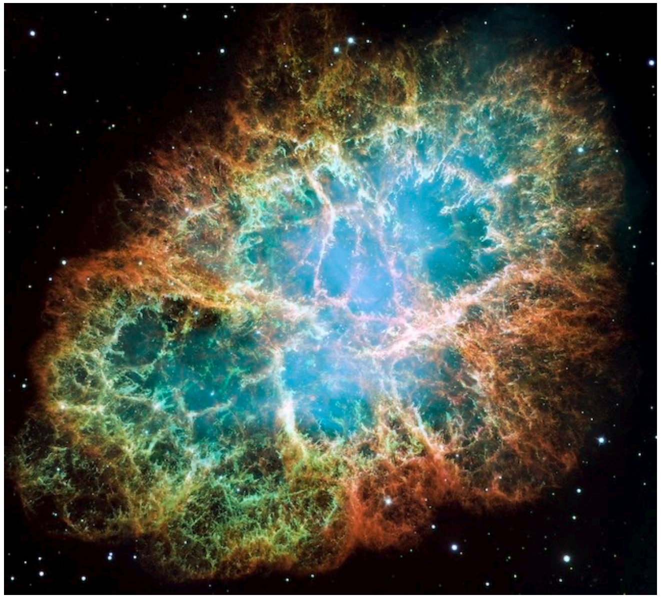
… which explodes the star

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



The Crab Nebula



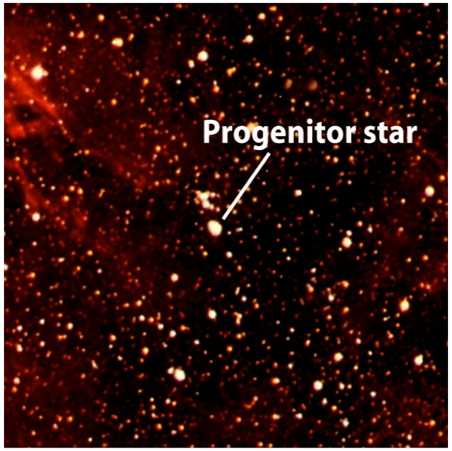
- The result of a supernova that, according to Chinese and Japanese chronicles, exploded in 1054. Despite a distance of ~2 kpc, the supernova was brighter than Venus for weeks before fading from view after nearly two years.

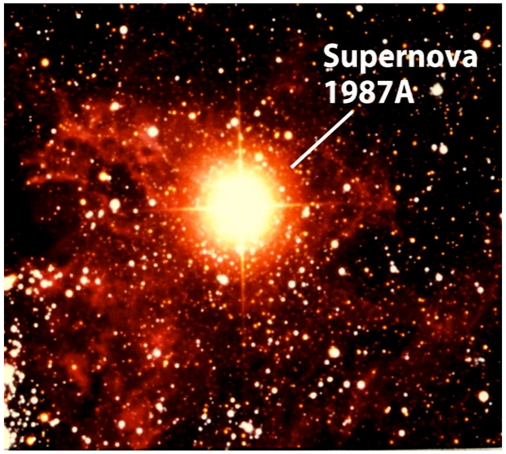
  Interestingly, almost no European records of the event have been found ("The Dark Ages are called that not because the light fails to shine, but because people refuse to see it")
- The nebula is still expanding at V > 1300 km/s and emits synchotron radiation in all wavelengths, from gamma rays to radio waves
- And of course, it is the home of the Crab Pulsar

A nearby supernova 1987A in LMC gave us the first 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!





Its evolving remnant: