Astroparticle Physics
Lecture 4

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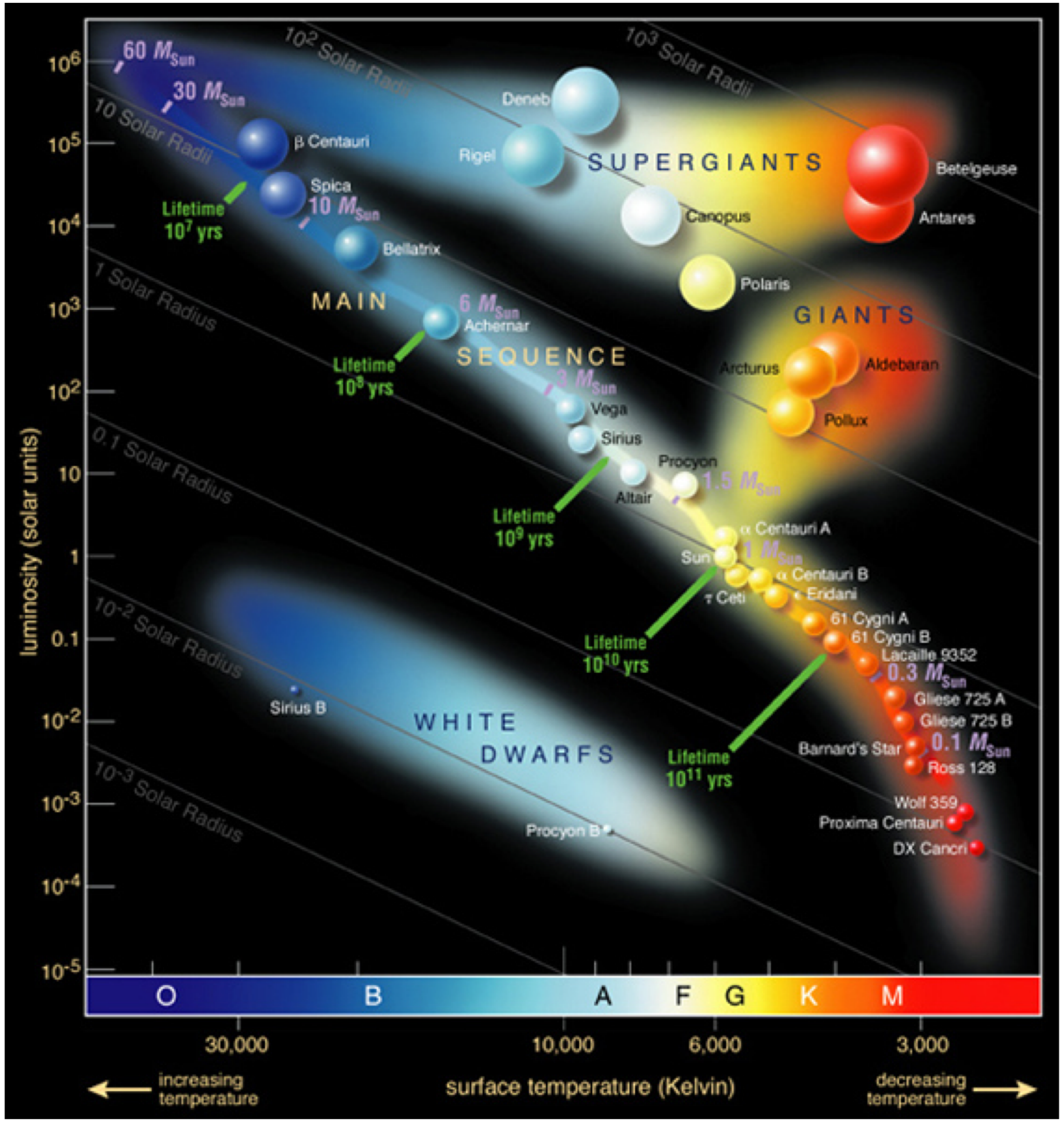
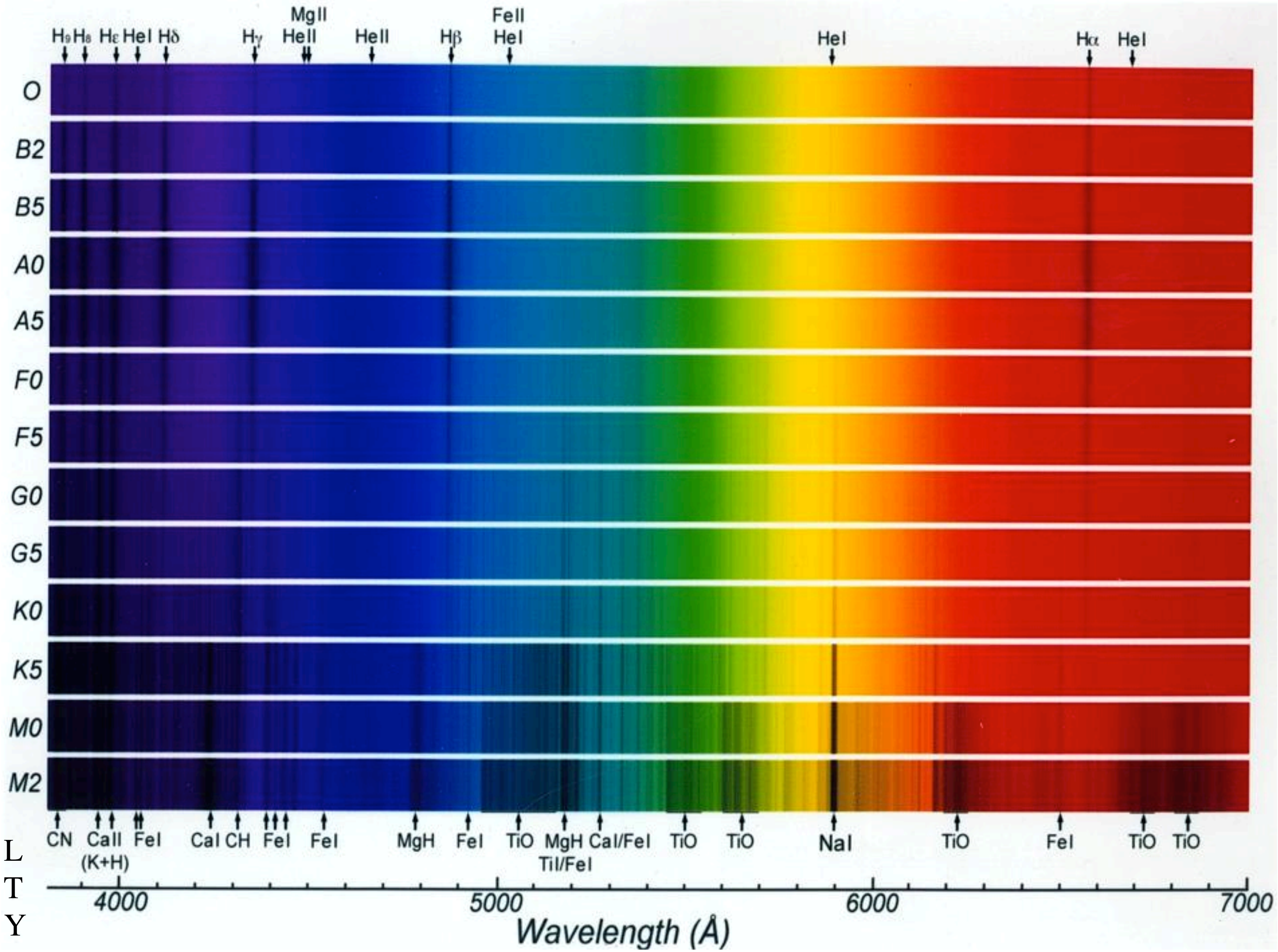
DHEP

The Hertzsprung Russel Diagram



Stellar Spectral Types

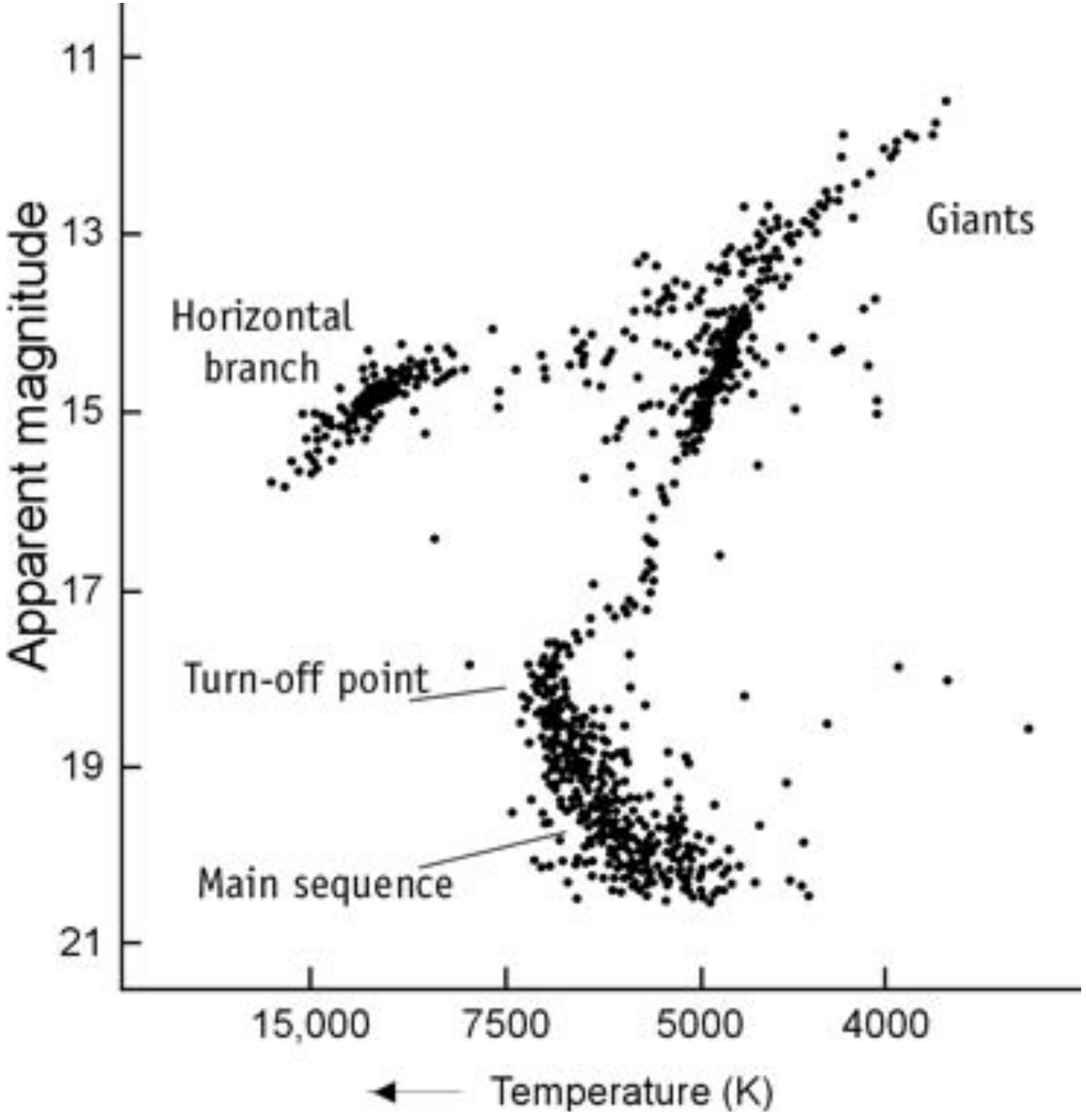


L
T
Y

Temperature

The Hertzsprung-Russel (HR) Diagram

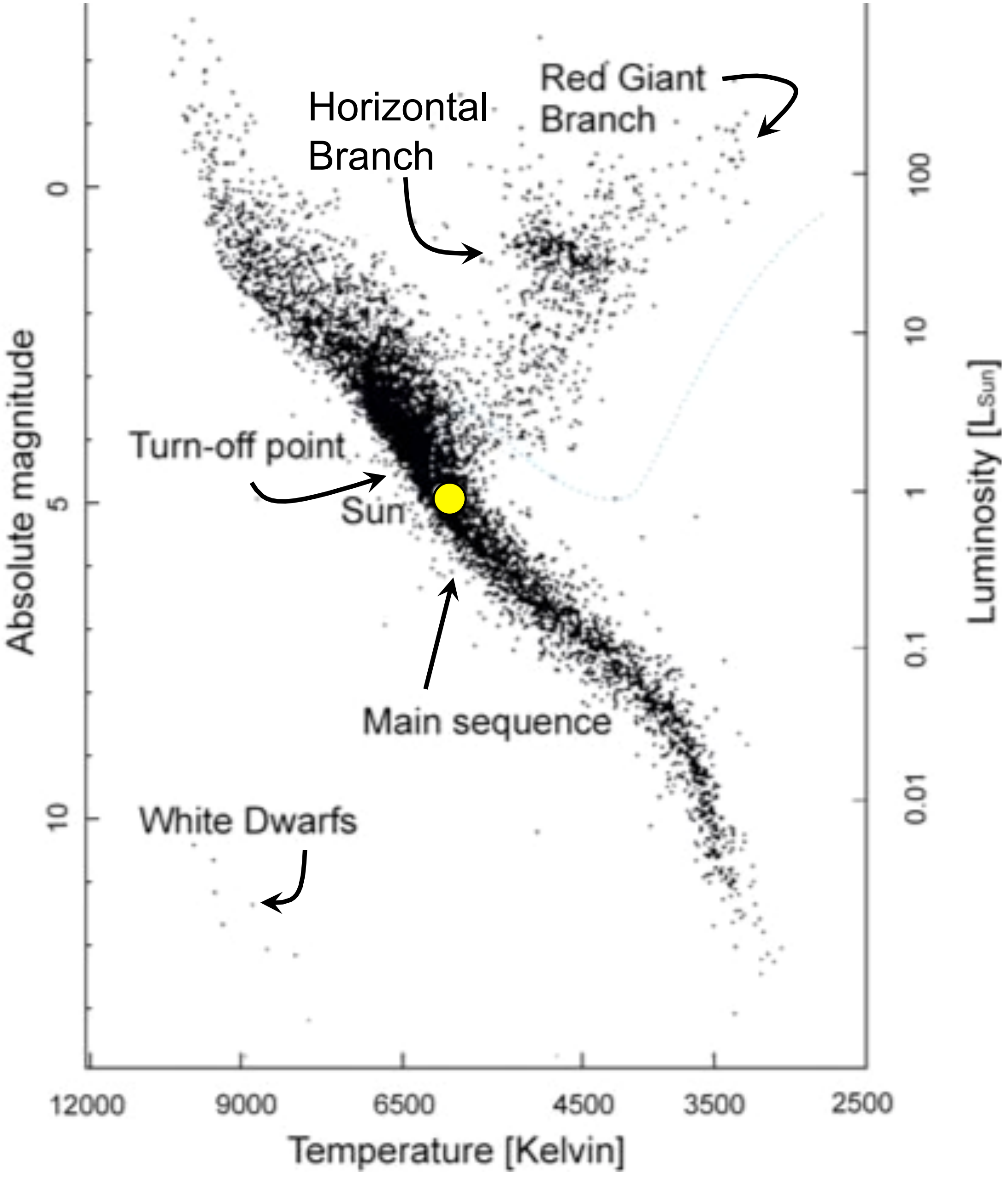
Stars form ***distinctive sequences*** in the HR diagram



This can be understood in the context of the stellar evolution models, and used to test them

The Principal Sequences

They correspond to different stages of the stellar evolution

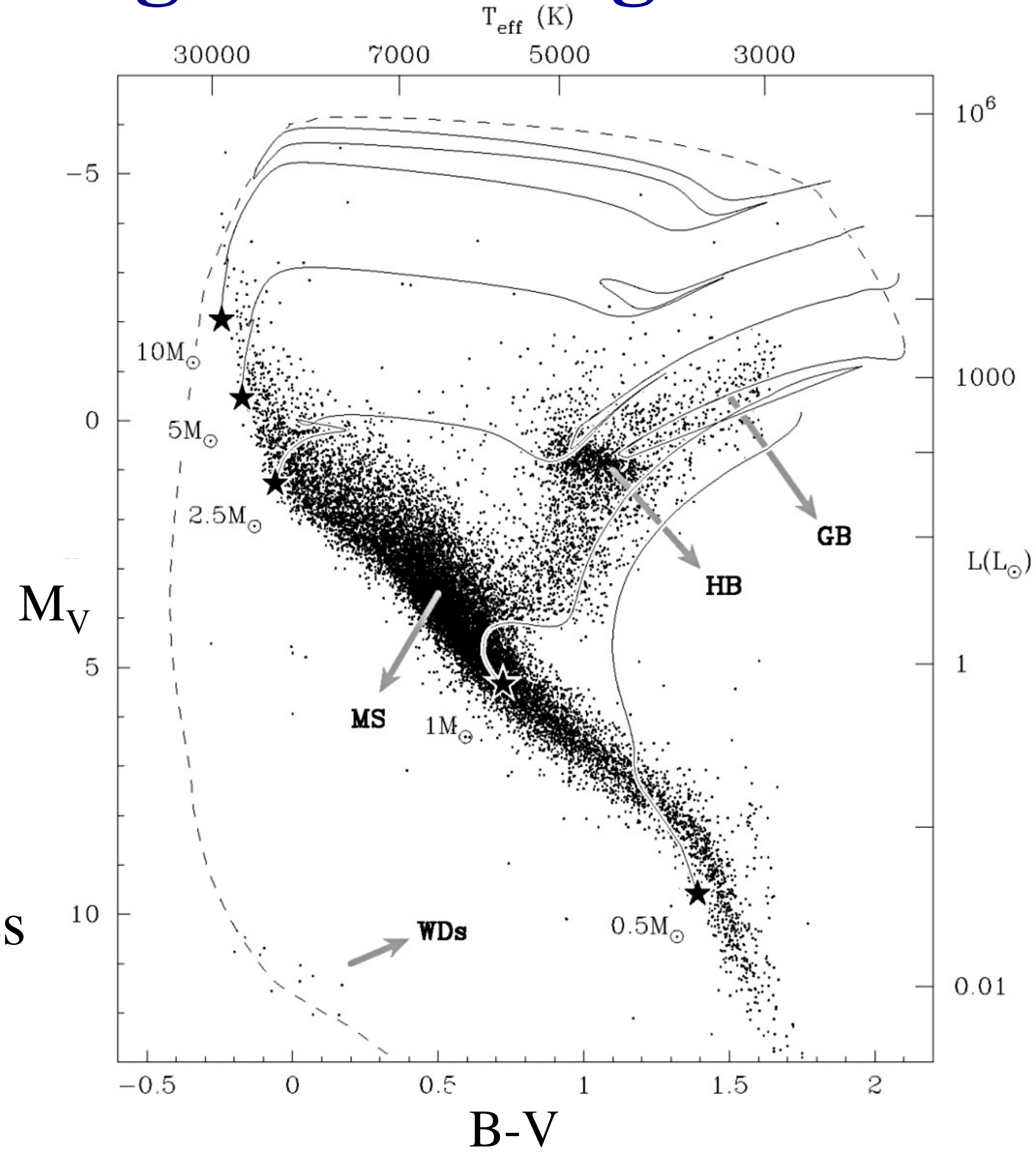


Note: to get the absolute magnitudes (or luminosities), you must have *distances*

The Color-Magnitude Diagram

Generally, photometric colors re used on the X axis, as a measure of temperature, e.g., (B-V) = difference in magnitudes in two different filters (B and V)

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 $\sim 10^7 - 10^9$ 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

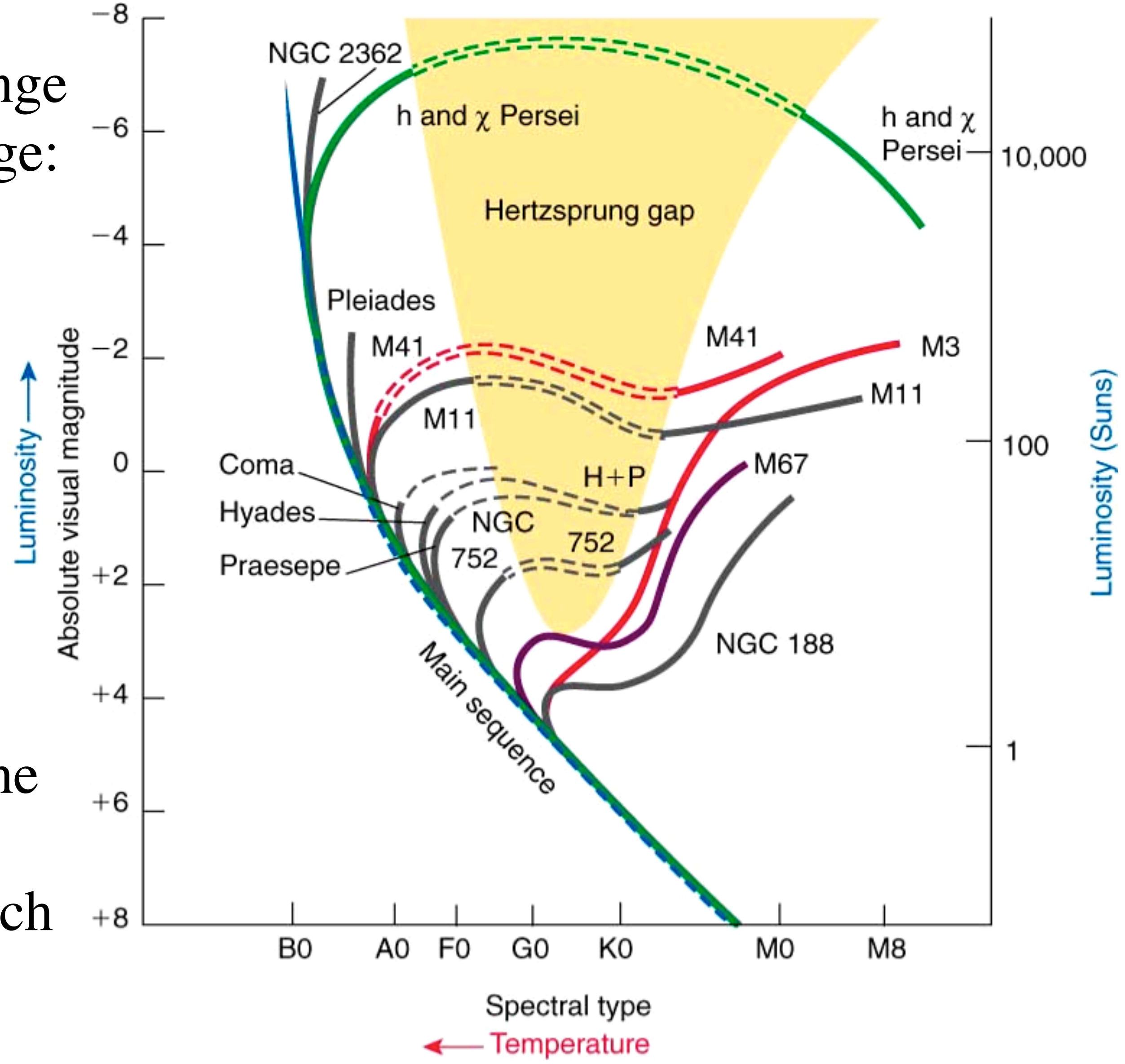
Testing Stellar Evolution

- 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:

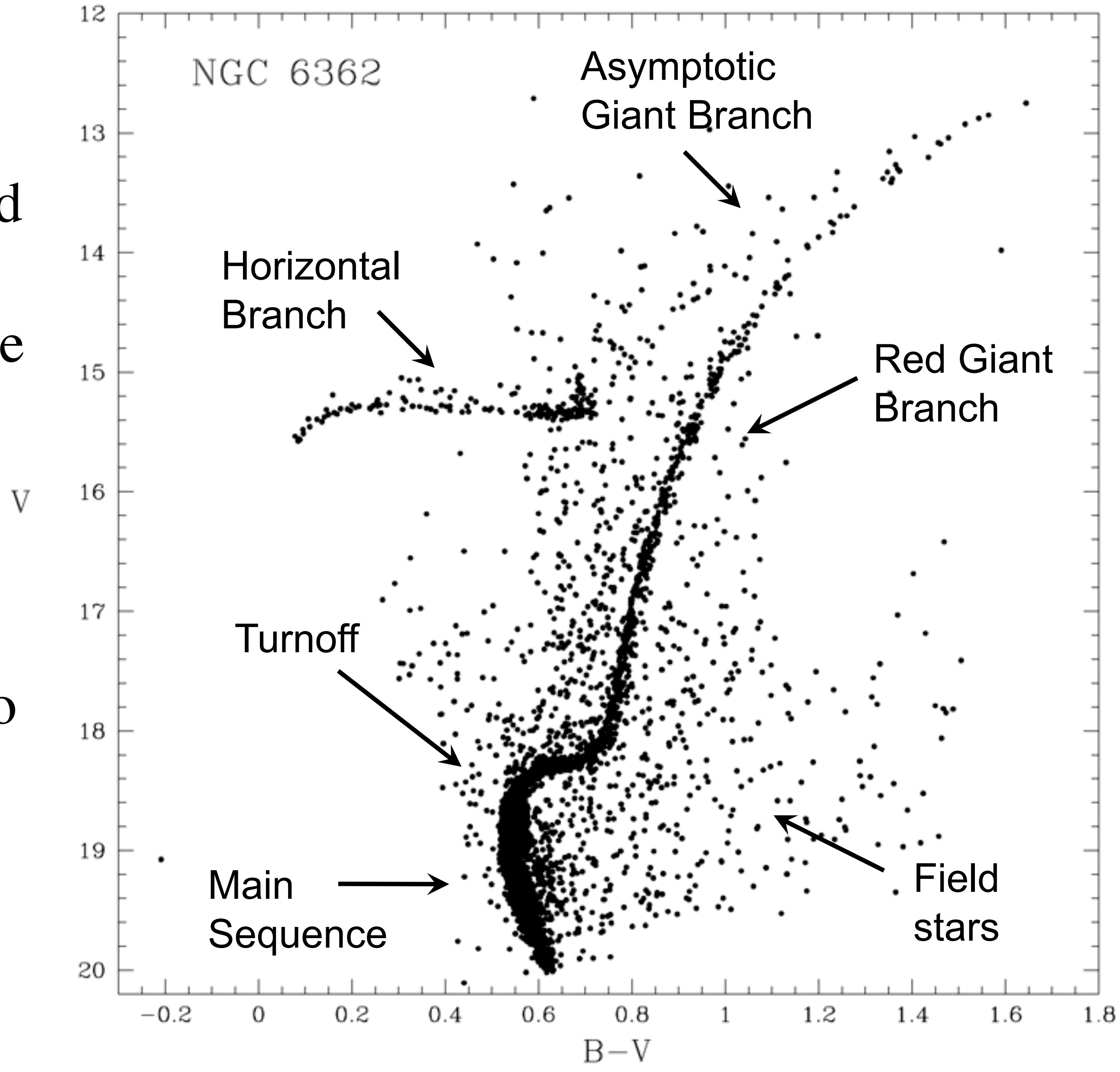
The MS turnoff moves to lower luminosities and temperatures as the cluster ages, and the red giant branch develops



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

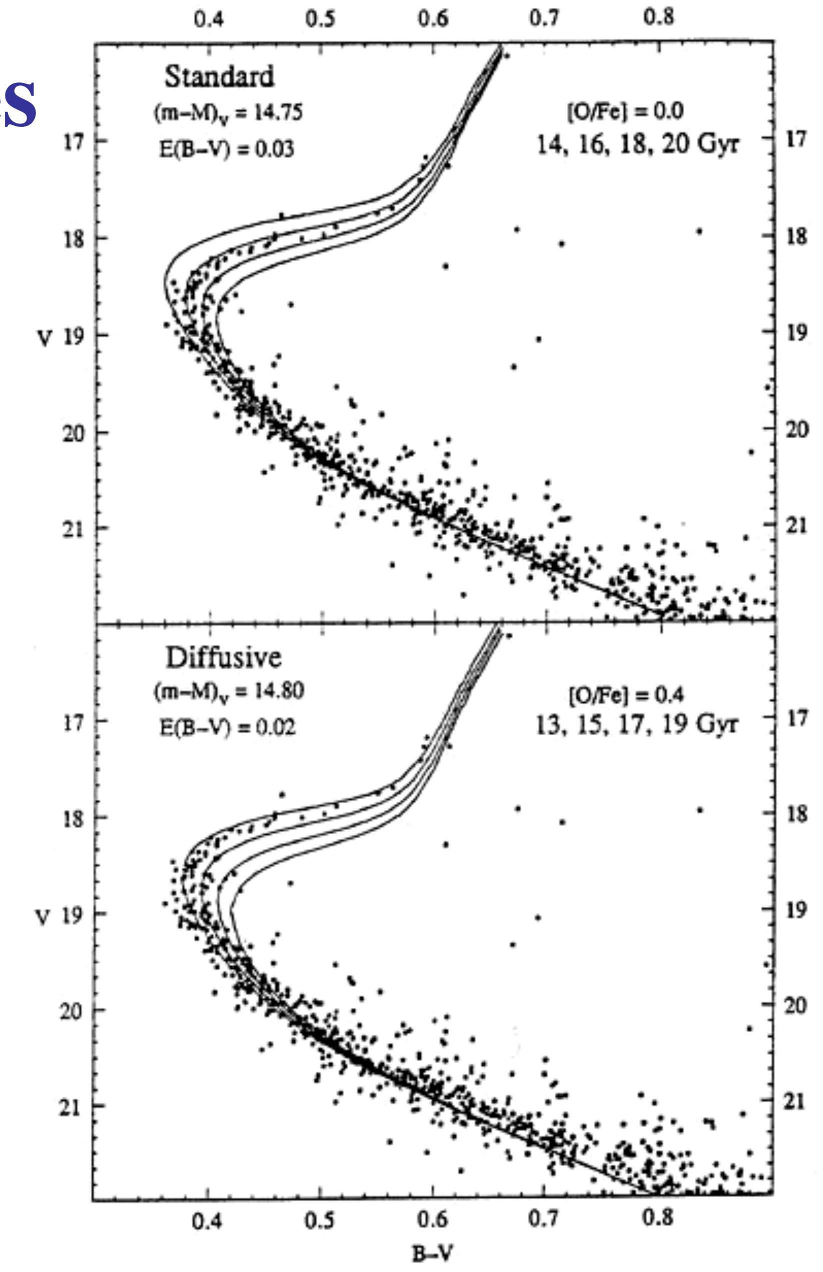


Globular Cluster Ages

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:

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



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**

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:

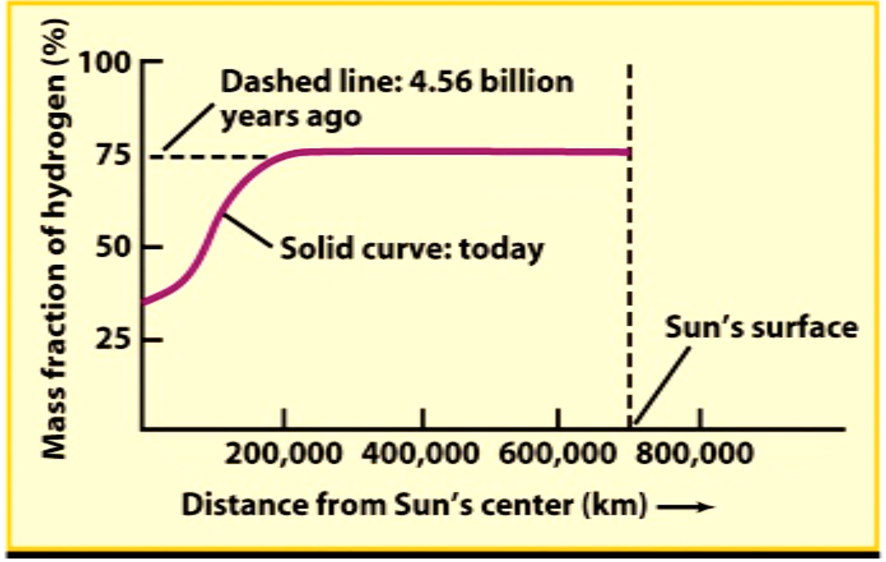
- sustain higher core temperatures
- have higher rates of nuclear fusion
- are more luminous and exhaust H fuel more quickly

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

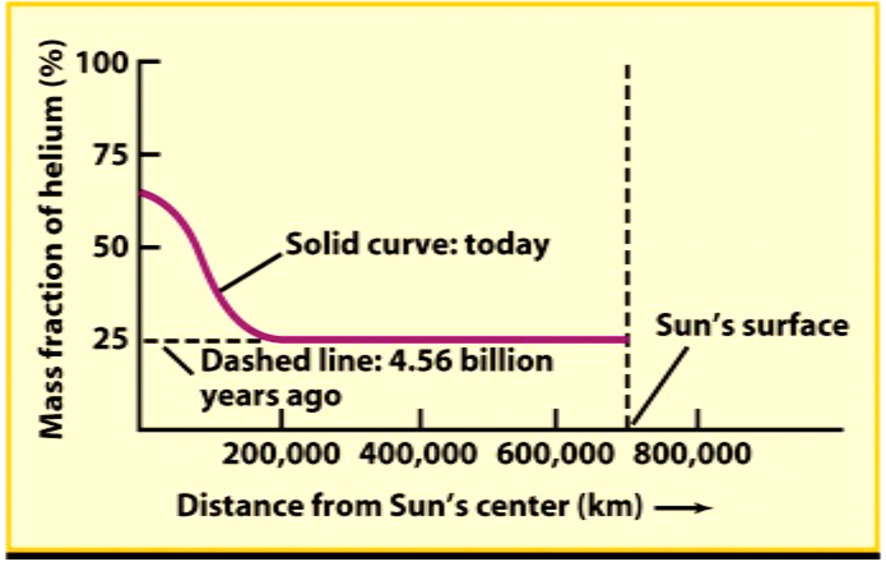
Star leaves the main sequence when it stops burning hydrogen in the core that is now pure He (but it continues burning it in a shell around the core). This leads to *expansion* of the envelope, and the formation of a **red giant**

Stellar Lifetimes on the Main Sequence

Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000



(a) Hydrogen in the Sun's interior



(b) Helium in the Sun's interior

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:**

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

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

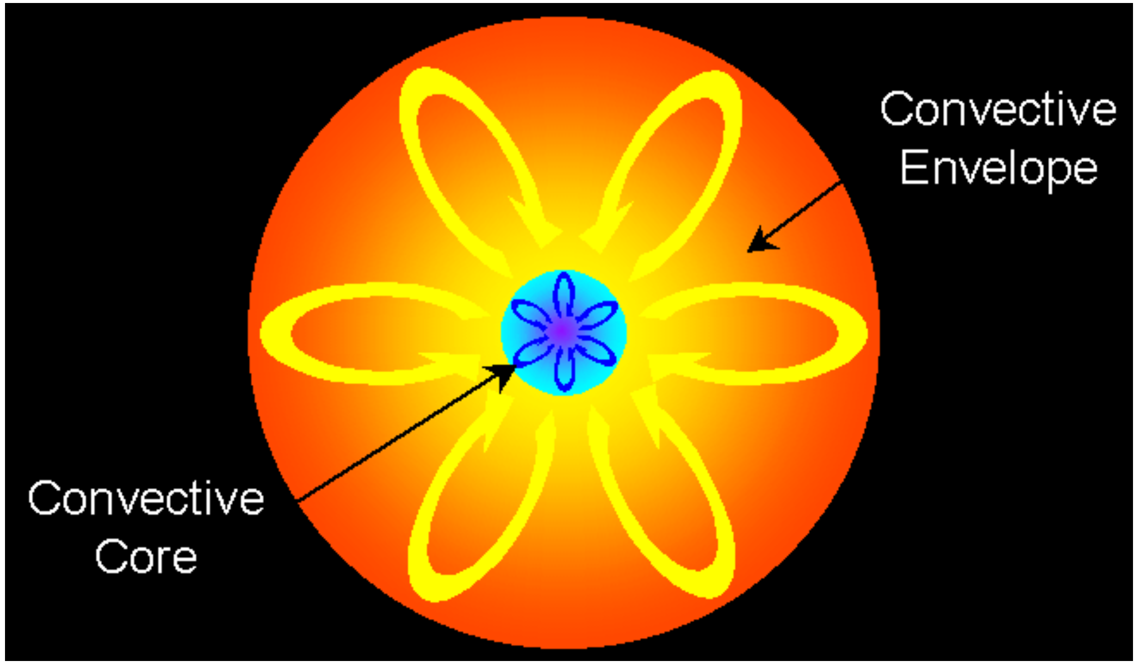
A more luminous star at a given mass would blow itself apart.

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

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

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

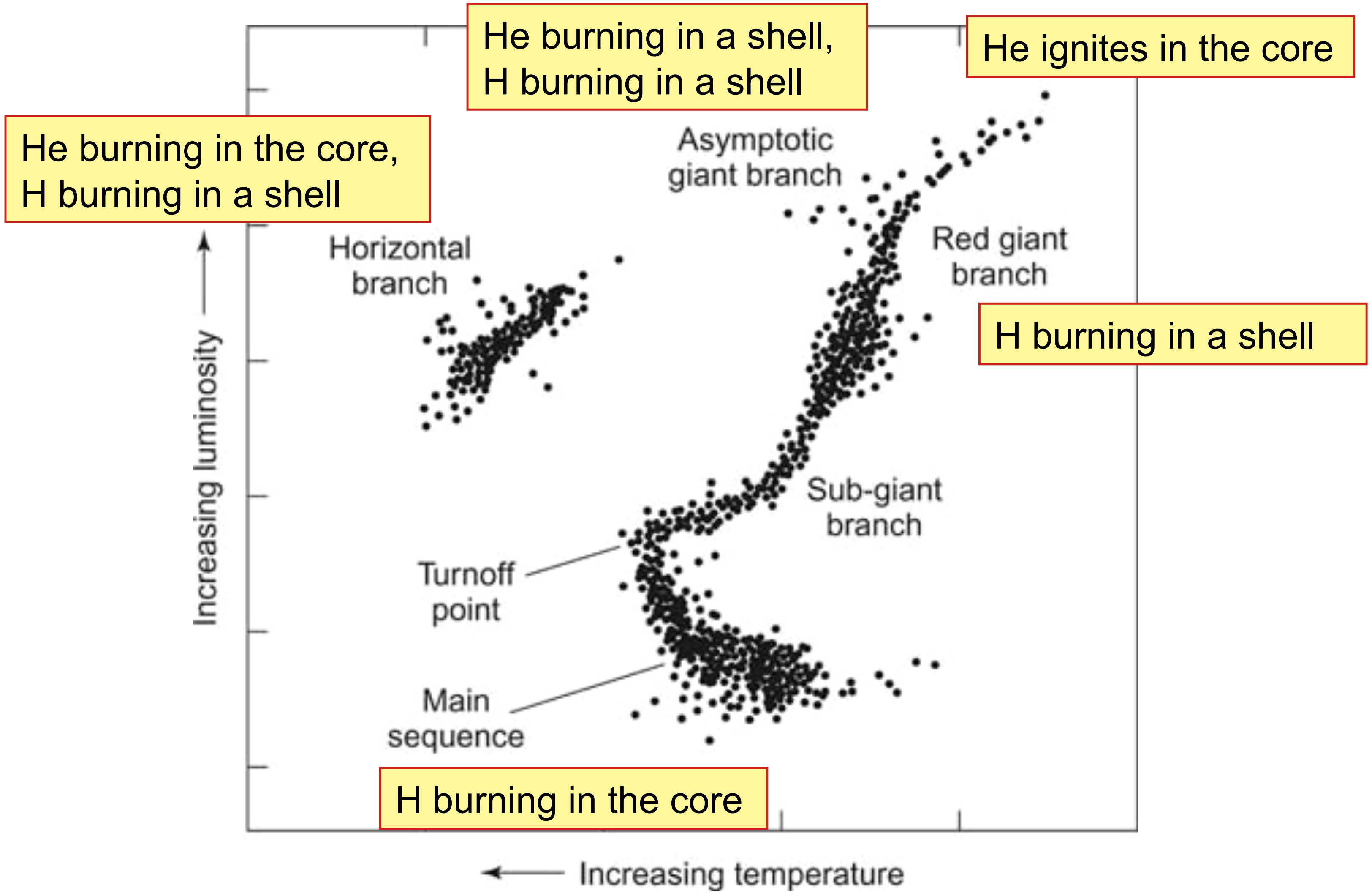


- Will never build up a He core, and never ignite He
- Could perhaps survive on the MS for a 100 Gyr!
- Then just fade as a White dwarf

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



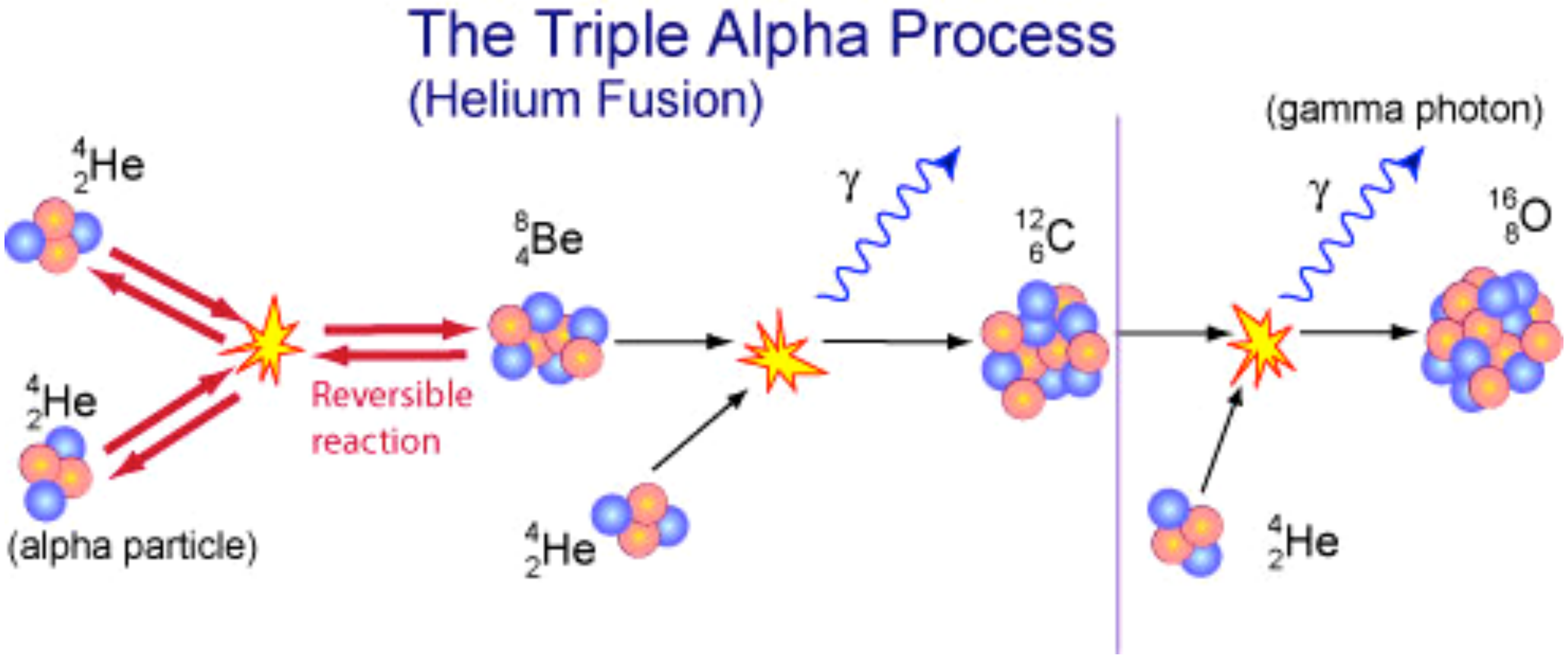
Becoming a Red Giant

- 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

Helium Flash: The End of the RGB

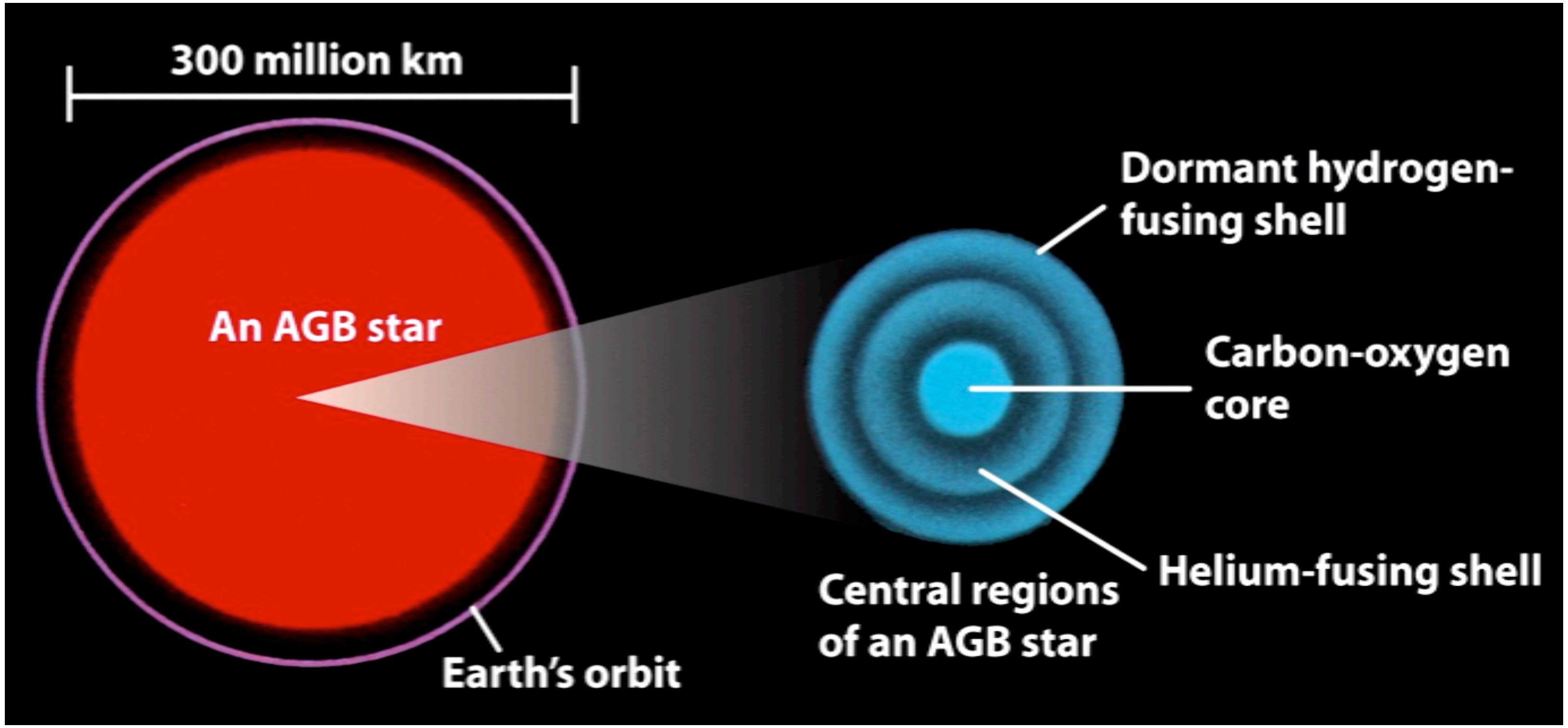
- H fusion leaves behind He ash in the core of the star which cannot begin to fuse until the temperature of the core reaches 100 million K. How a star begins He fusion depends on its mass:
- $M > 3\ M_{\odot}$ stars contract rapidly, their cores heat up, and He fusion begins gradually
- Less massive 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



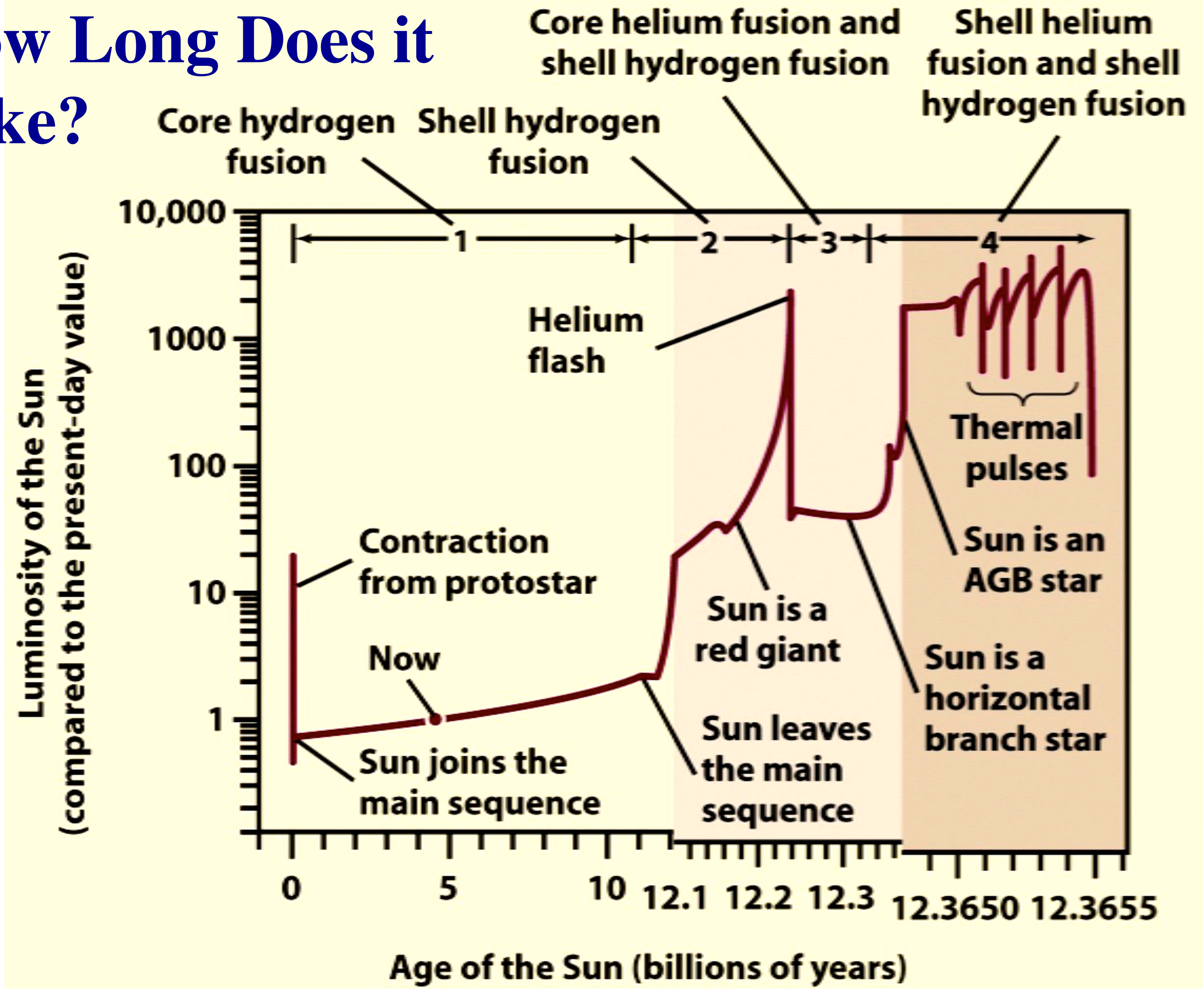
- Requires much higher temperatures, T ~ 10^8 K
- Enabled by the “exact right” energy resonance for carbon

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

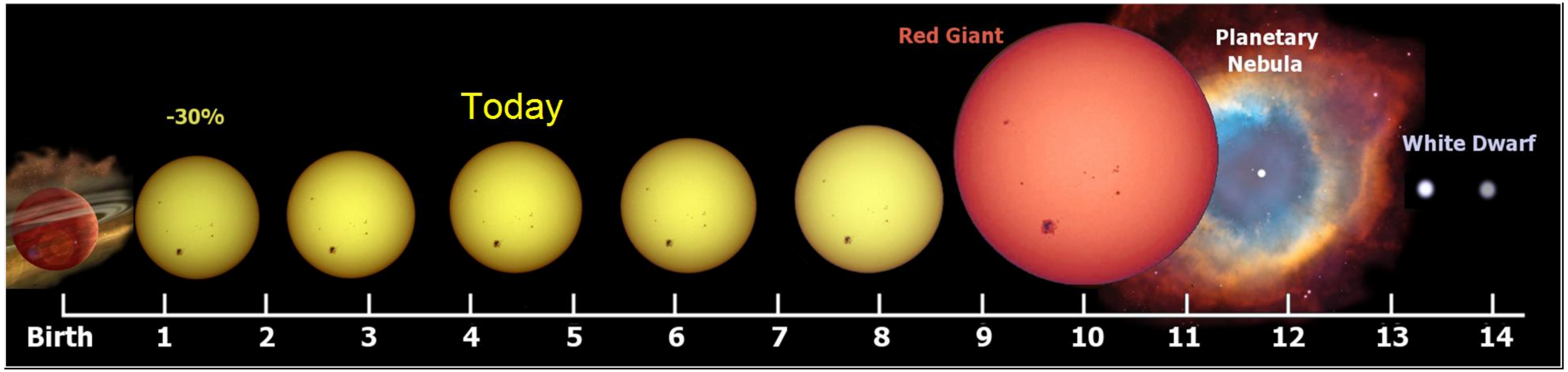
How Long Does it Take?



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

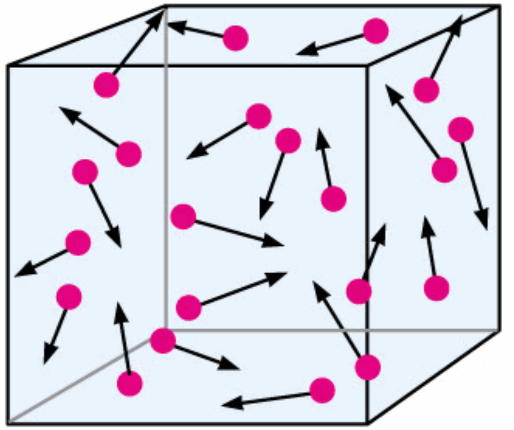


Rapid Final Stages of a Massive Star Evolution

- 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

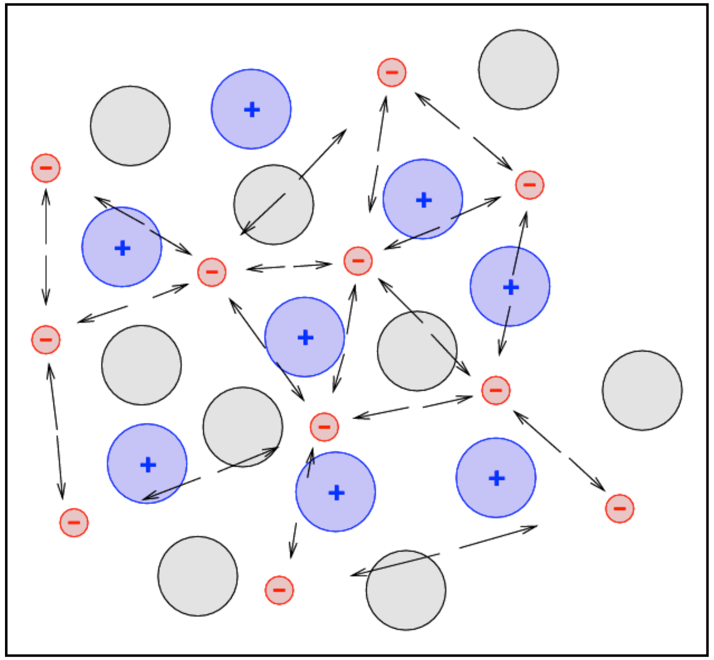
Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
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

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

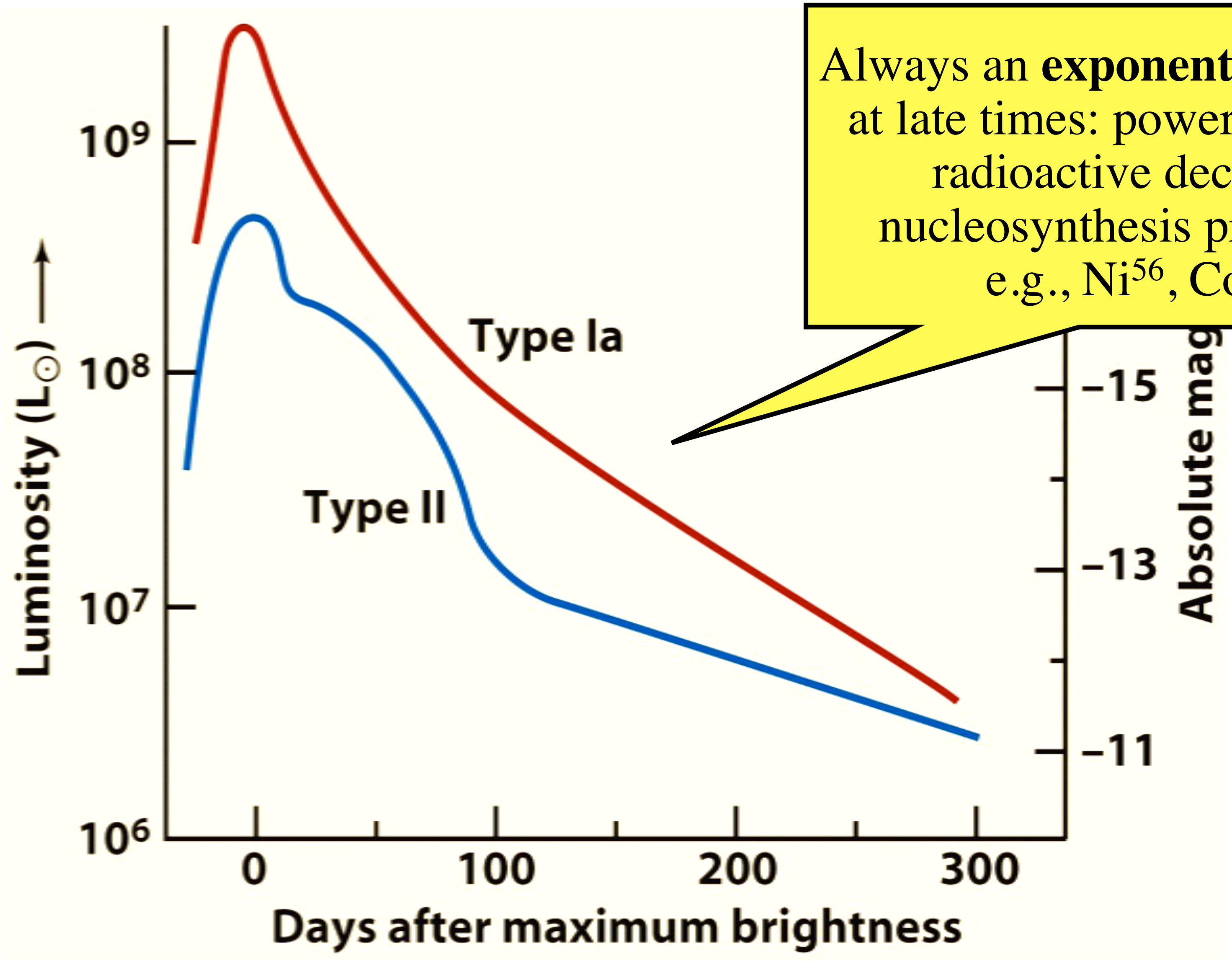
White Dwarfs

- 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

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 ~ 10^{54} erg) in neutrinos; kinetic energy ~ 1% (typically ~ 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)

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}

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

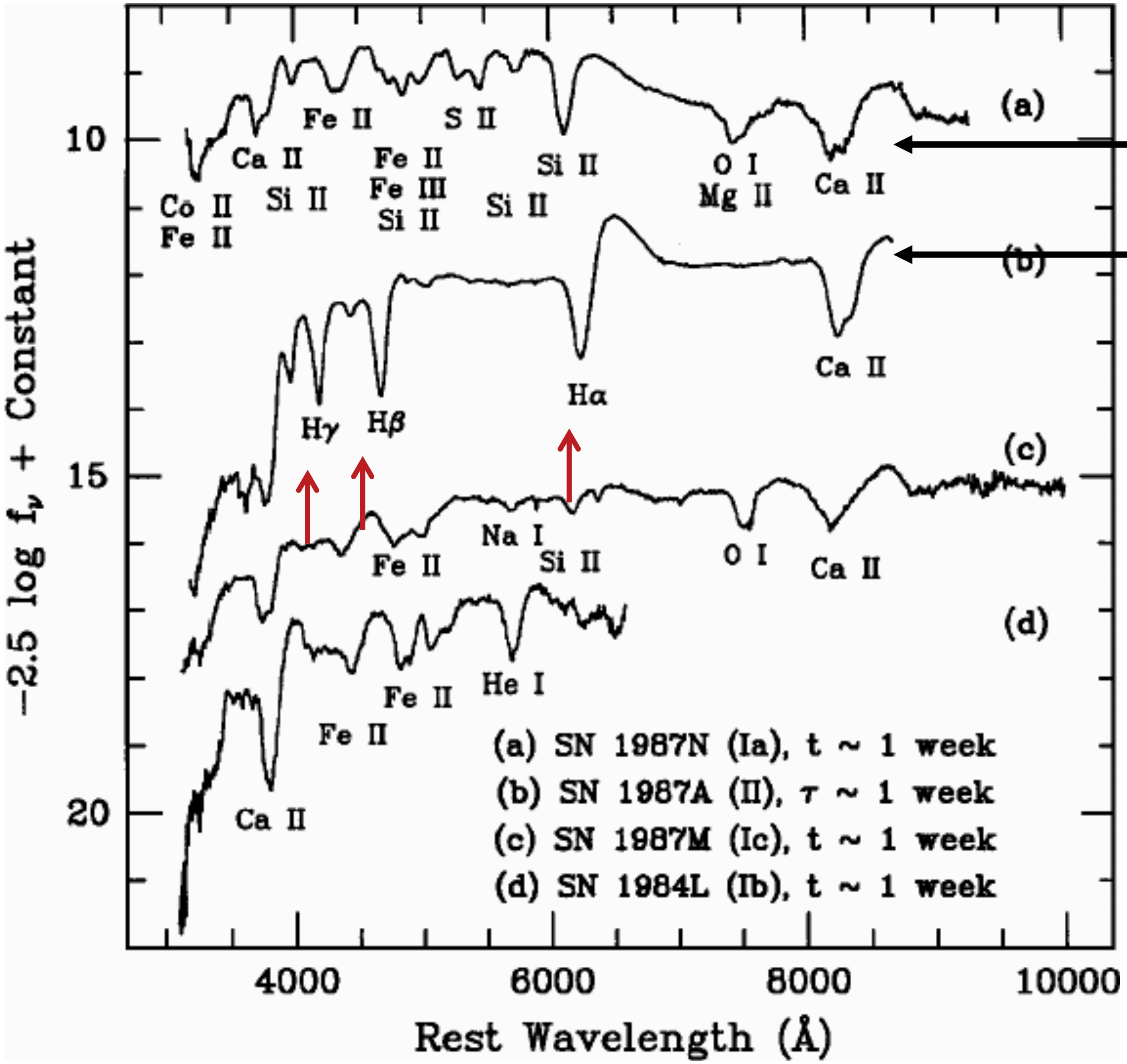
Typical rate ~ 1 per galaxy per century

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

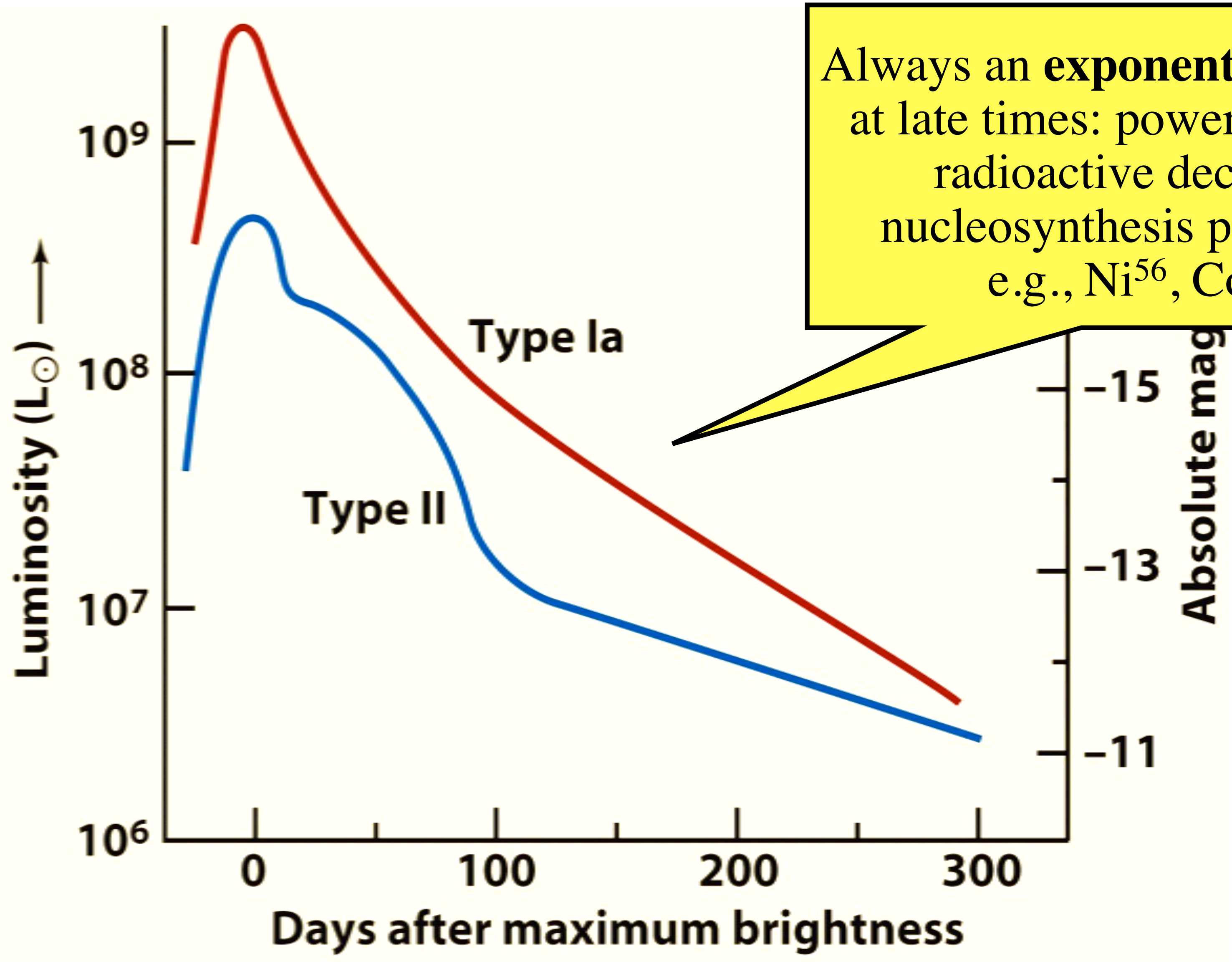


Type Ia

Type II

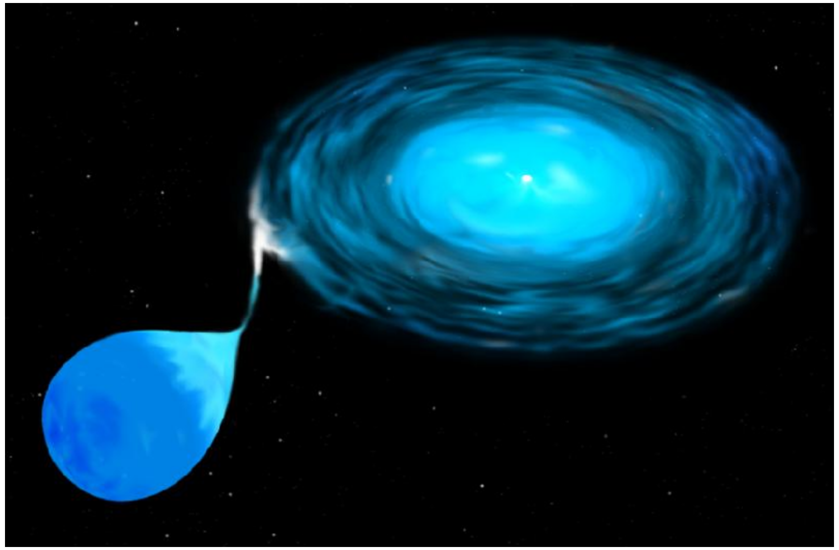
Clear lines of hydrogen in spectrum

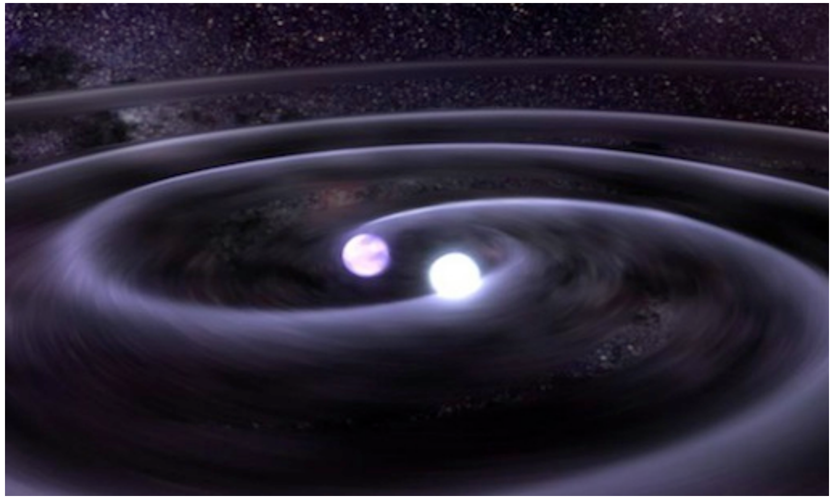
SN Types: Light Curve Differences



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

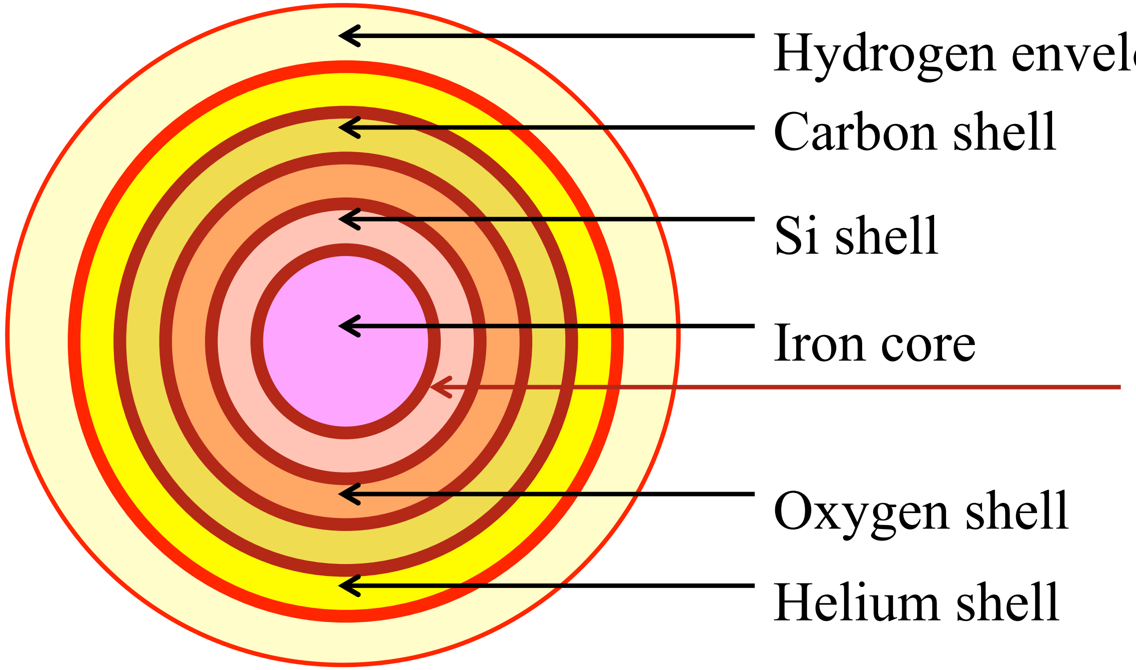
An alternative mechanism is a spiral-in and merger of a binary white dwarf

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



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

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

Needs high energy gamma rays

Inverse beta decay

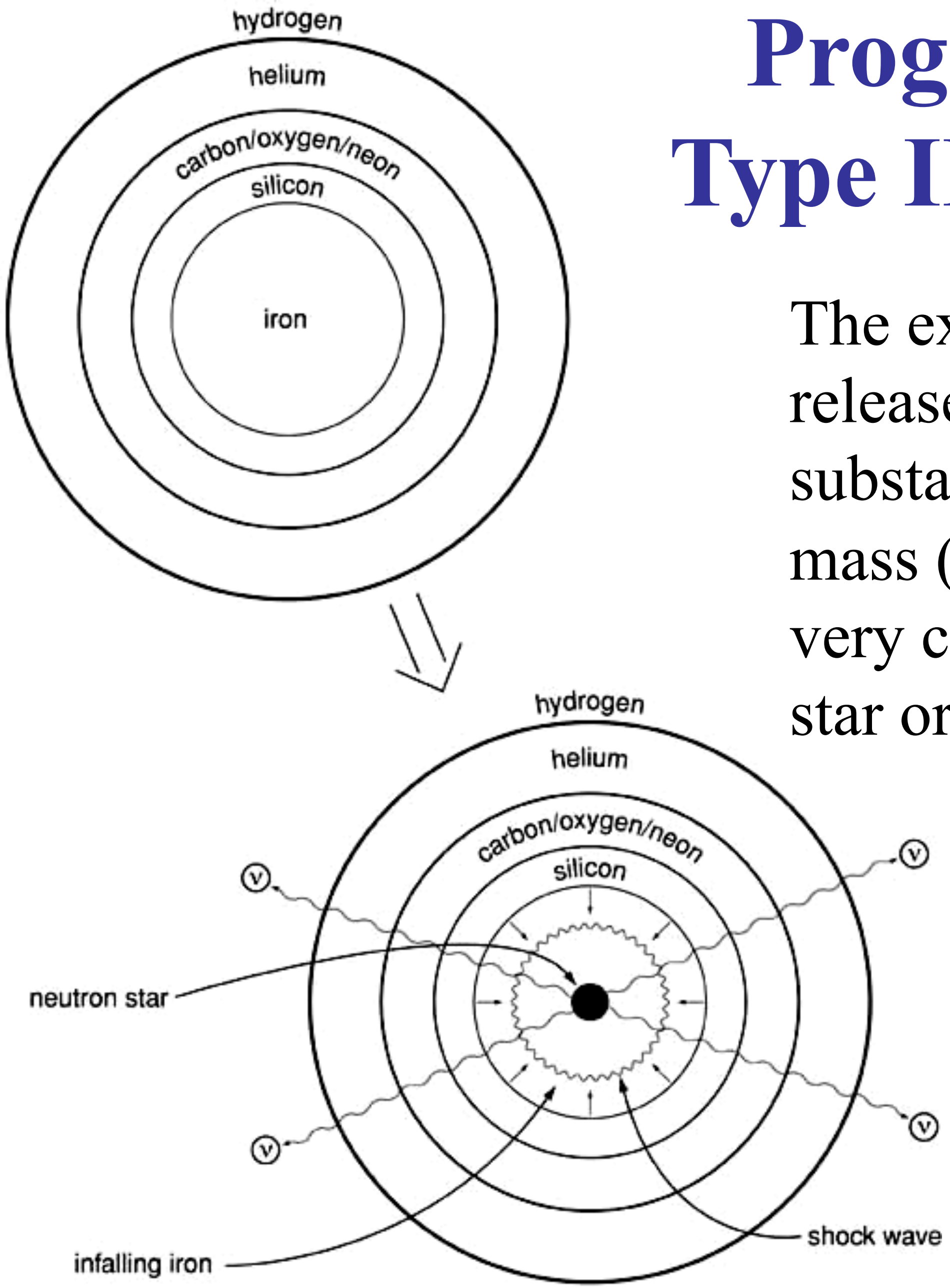
$e^{-} + p \rightarrow n + \nu_e$

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

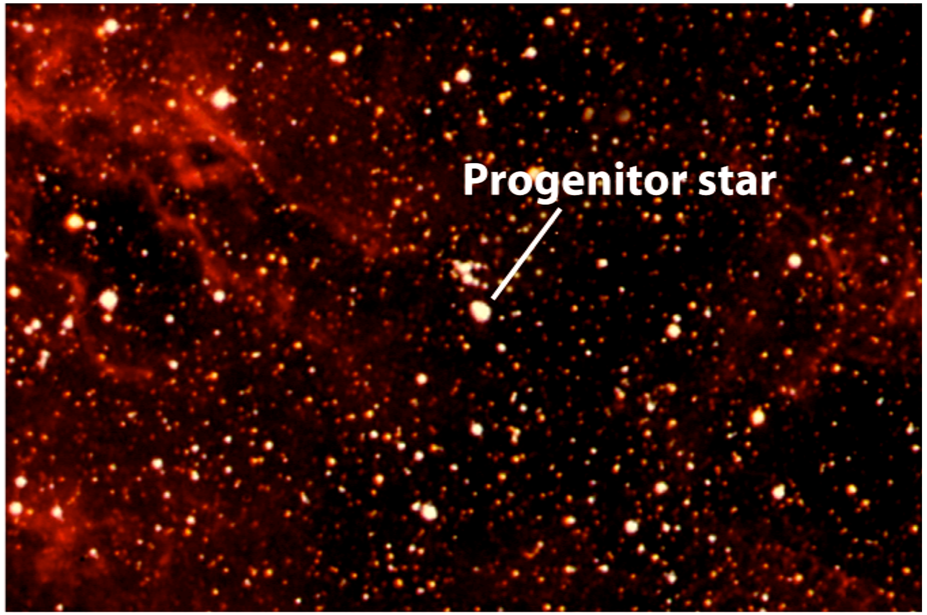


The explosion is powered by the release of the binding energy, as a substantial fraction of the star's mass (> 2 M_{sun}) collapses into a very compact remnant, a neutron star or a black hole

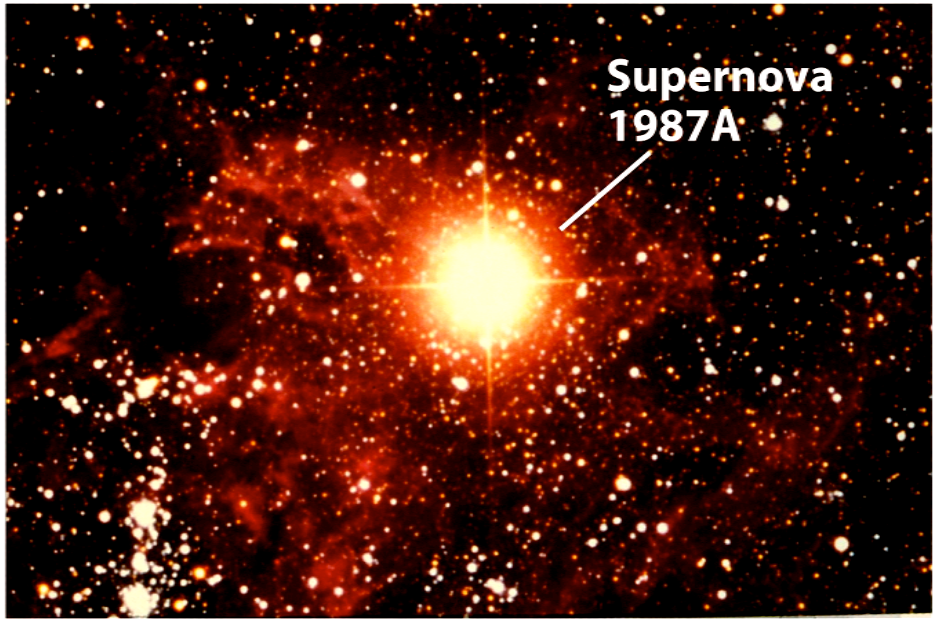
The bulk of the energy is carried out by neutrinos generated by the inverse beta decay

A nearby supernova 1987A in LMC gave us the 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!



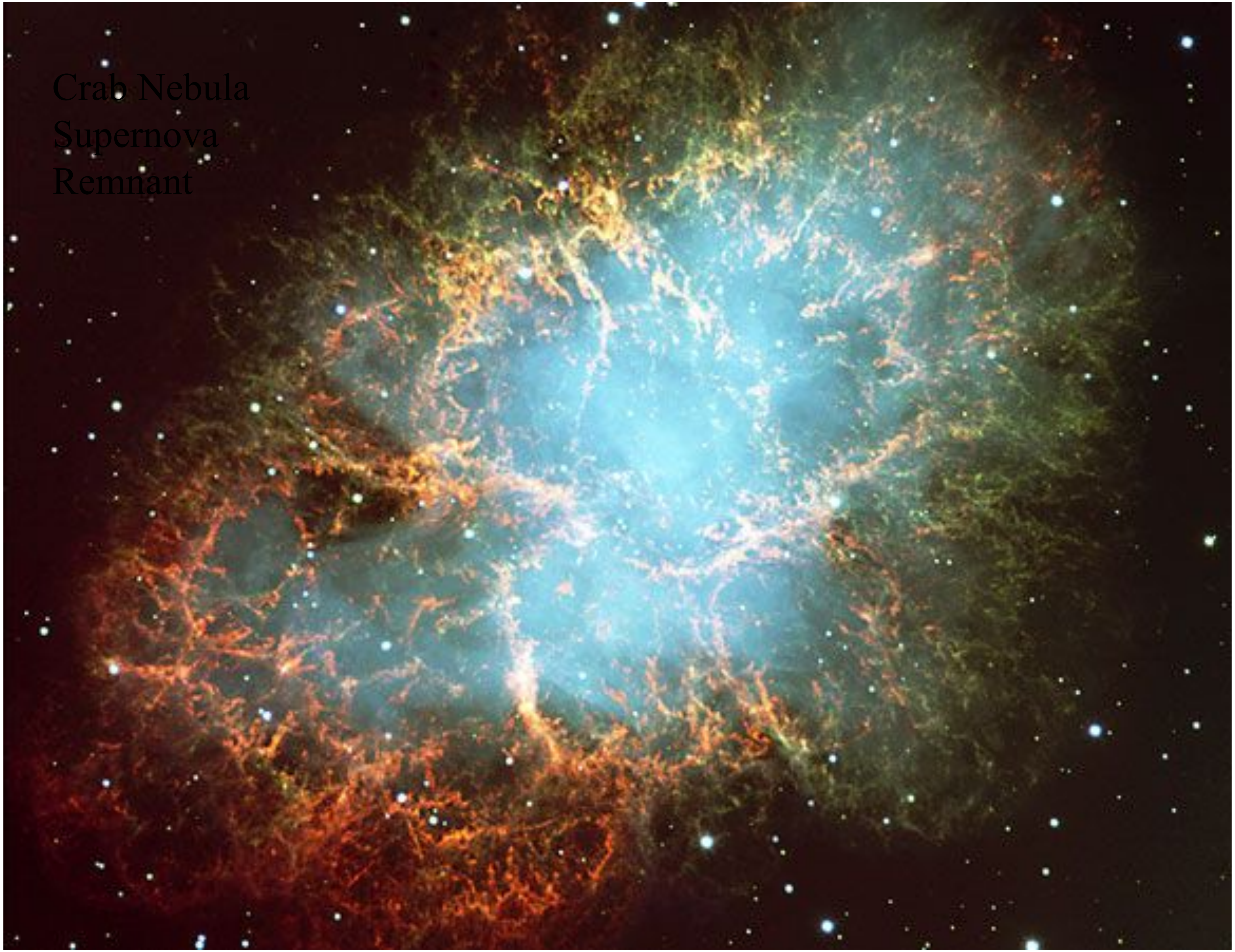
Before the star exploded



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


Cas A: remnant of a supernova that exploded in 1658

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

(1) The intensity of cosmic rays is practically independent of time. This fact indicates that the origin of these rays can be sought neither in the sun nor in any of the objects of our own Milky Way.

(2) The decrease in intensity of cosmic rays in equatorial regions has successfully been explained by assuming that at least a part of the rays consists of very energetic, positively or negatively charged particles. These particles must be of extra-terrestrial origin, as otherwise the distance traversed by them would not be long enough for the earth's magnetic field to produce the observed dip in intensity at the equator.

From the fact that in the cloud-chamber experiments no protons or charged particles heavier than electrons have been observed in any considerable number, one might conclude that the corpuscular component of cosmic rays consists of positive or negative electrons, or both. The characteristics of the east-west effect indicate that the positively charged particles far outnumber the negatives. However, whether or not these particles are electrons cannot as yet be said with certainty, since the electrons which are observed in cloud chambers may all be secondary particles formed in the earth's atmosphere by different primaries.

Zwicky's basic argument

- $\boldsymbol{W_{CR} = \frac{\rho_E \pi R^2 D}{\tau} = 3 \times 10^{41} J\ yr^{-1}}$
- $\rho_E = 1\ eV\ cm^{-3}$
- $R = 15 kpc, D = 0.3 kpc$
- $\tau = 3 \times 10^6$yrs
- $\boldsymbol{W_{SN} = 10^{43} J yr^{-1}}$
- Type II SNe typically eject 10 solar masses with velocity $10^7 ms^{-1}$
- Observed SNe rate : ~ 3 SNe/Galaxy/century
- An efficiency of a few % in the acceleration process is sufficient to power CRs using SNe