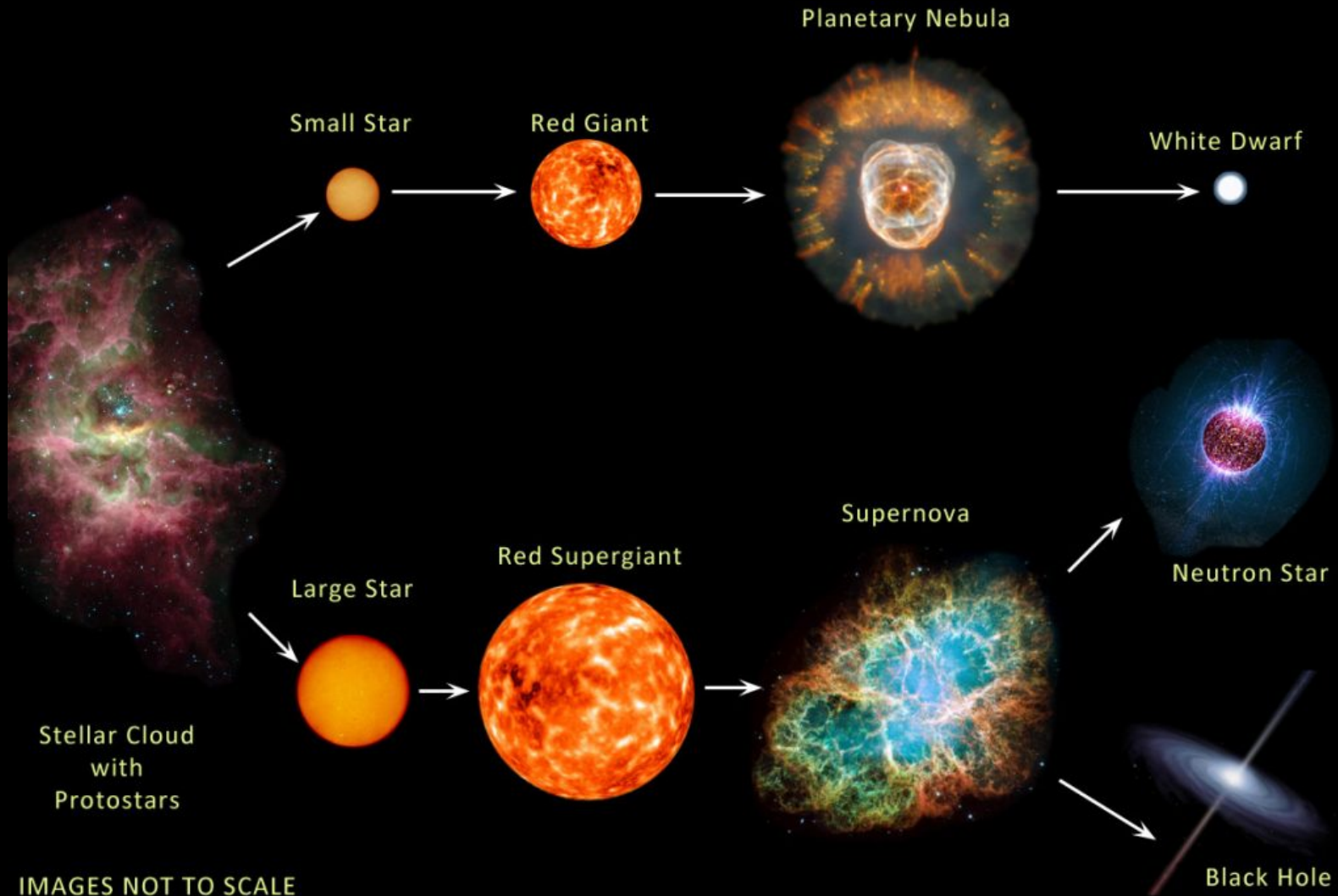


# Phys 321: Lecture 7

## Stellar Evolution



# Stellar Evolution

- Formation of protostars (covered in Phys 320; briefly reviewed here)
- Pre-main-sequence evolution (this lecture)
- Evolution on the main sequence (this lecture)
- Post-main-sequence evolution (this lecture)
- Stellar death (next lecture)

# Formation of protostars

- Clouds of gas and dust collapse and form Young Stellar Objects (YSOs)

Condition for spontaneous collapse to occur:

$M_c > M_J$     Where     $M_J \simeq \left( \frac{5kT}{G\mu m_H} \right)^{3/2} \left( \frac{3}{4\pi\rho_0} \right)^{1/2}$     is the **Jeans mass**

↑  
Mass of the cloud

For a typical dense molecular H<sub>2</sub> cloud with  
T = 10 K and n<sub>H2</sub> = 10<sup>10</sup> m<sup>-3</sup>, M<sub>J</sub> ~ 8 Msun

This is the consequence of the virial theorem:

For a system in **equilibrium**:  $2K + U = 0$

For a system to **collapse**:  $2K < |U|$     Internal energy is too low -> pressure  
can not support against gravity

# Formation of protostars

- Once spontaneous collapse occurs, the time scale is set by the *free-fall time*

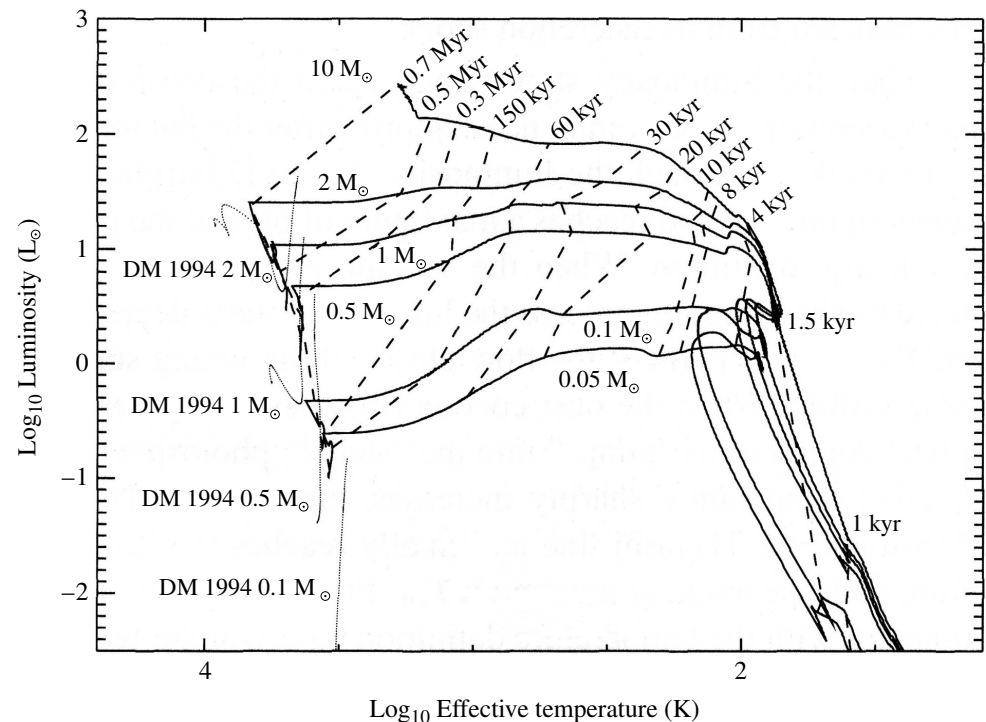
Free-fall time, or the time takes for a particle to fall from any point of the cloud freely:

$$t_{\text{ff}} = \left( \frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}.$$

Again for the dense molecular  $\text{H}_2$  cloud with  $T = 10 \text{ K}$  and  $n_{\text{H}_2} = 10^{10} \text{ m}^{-3}$

$$t_{\text{ff}} = 3.8 \times 10^5 \text{ yr}$$

This is a very rapid process





# Pre-main-sequence evolution

- The free-fall process is ended when a quasi-static **protostar** is formed, i.e., it is now under hydrostatic equilibrium
- The rate of evolution is now controlled by the rate at which the star can **thermally** adjust to the contraction
- Gravitational potential energy is released over time and is the source of the protostar's luminosity

# What is the time scale for the pre-main-sequence evolution of an one solar mass protostar?

Note this answers below are just orders of magnitude estimates

- A. 1 kyr
- B. 0.1 Myr
- ☒ C. 10 Myr
- D. 1 Gyr
- E. 10 Gyr



This time scale is just the **Kelvin-Helmholtz** timescale discussed in the previous lecture: Time for the gravitational potential energy to liberate by the contraction

# Pre-main-sequence contraction times

Initial Mass ( $M_{\odot}$ )	Contraction Time (Myr)
60	0.0282
25	0.0708
15	0.117
9	0.288
5	1.15
3	7.24
2	23.4
1.5	35.4
1	38.9
0.8	68.4

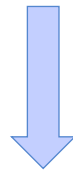
# The Hayashi track

Protostar contracts



Gravitational potential energy liberates

Effective temperature steadily increases



Some electrons are ionized from heavier elements

Opacity increases due to  $H^-$  ion



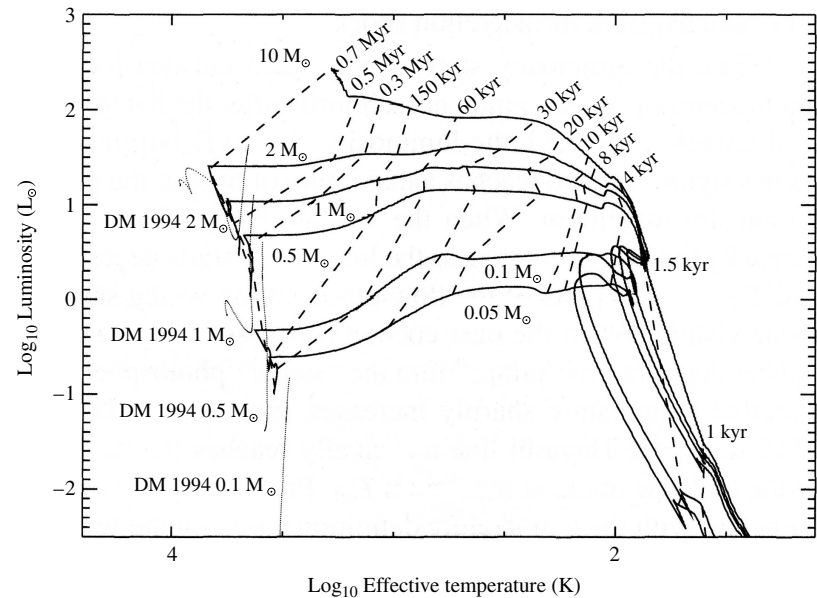
Temperature gradient required for energy transfer by radiation becomes too large



A large portion of the protostar becomes **convective**



Evolution follows the nearly vertical **Hayashi Track**

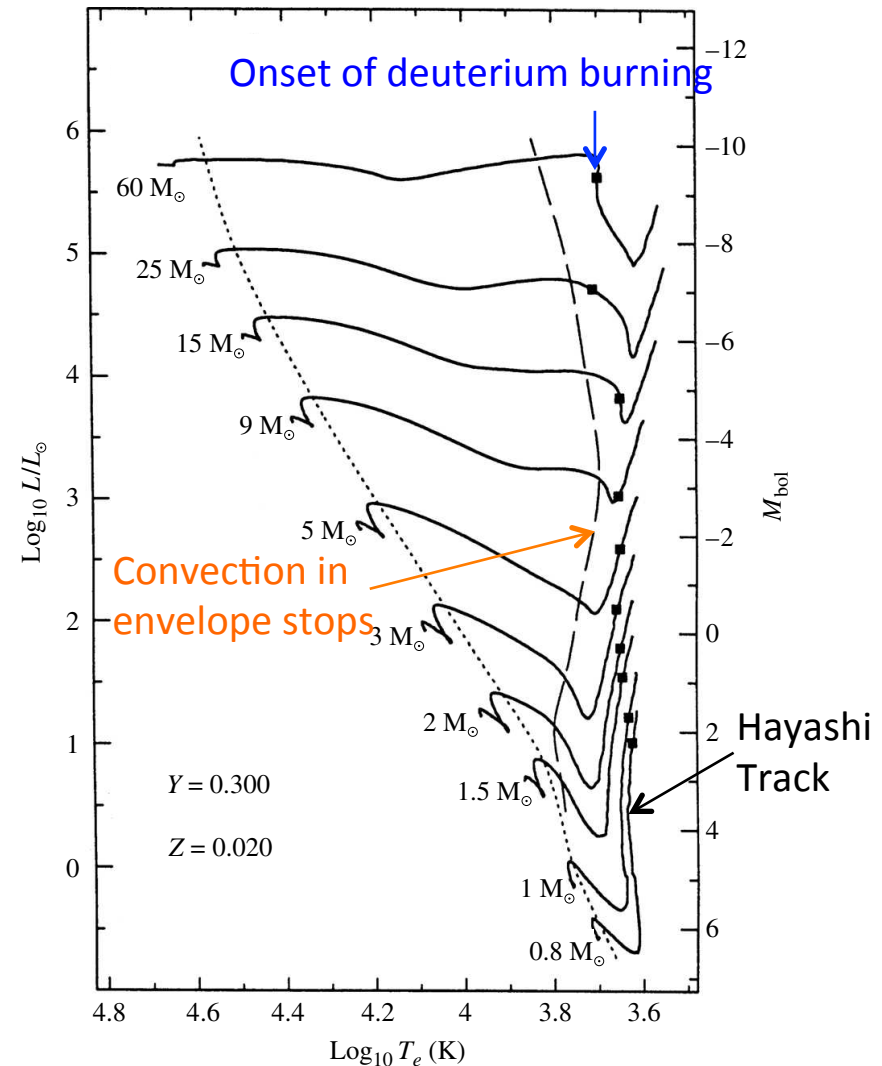


- Slightly increasing effective temperature
- Quickly decreasing luminosity

# Pre-main-sequence evolutionary tracks

## Evolution tracks

- A plot of the location of an object on an H-R diagram at **different times** during its lifetime is called an **evolutionary track**
- Evolutionary tracks for pre-main-sequence (PMS) objects depend on the initial mass of the protostar
- They reach the main sequence at different points

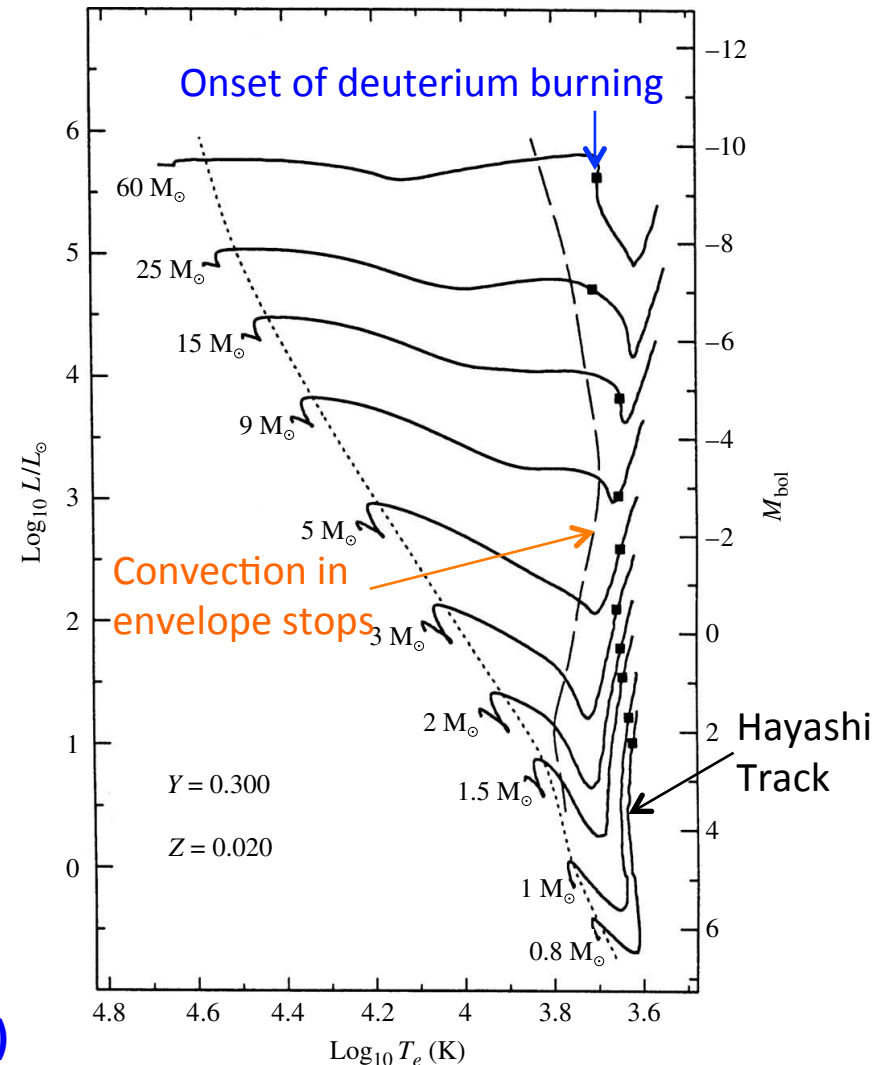


# Pre-main-sequence Evolution

## Evolution stages for solar mass stars

- Protostar collapse with a large convection envelope: Hayashi track
- Deuterium burning starts
- Rising temperature increases ionization and decreases opacity  $\rightarrow$  radiation core develops and gradually encompasses more of the star's mass
- More energy is released into the convective envelop, increases the luminosity
- Effective temperature continue to increase as the star is still contracting
- Temperature at the center becomes high enough for nuclear reactions to begin  $\rightarrow$  enters the main sequence

➡ Zero-age main-sequence stars (ZAMS)



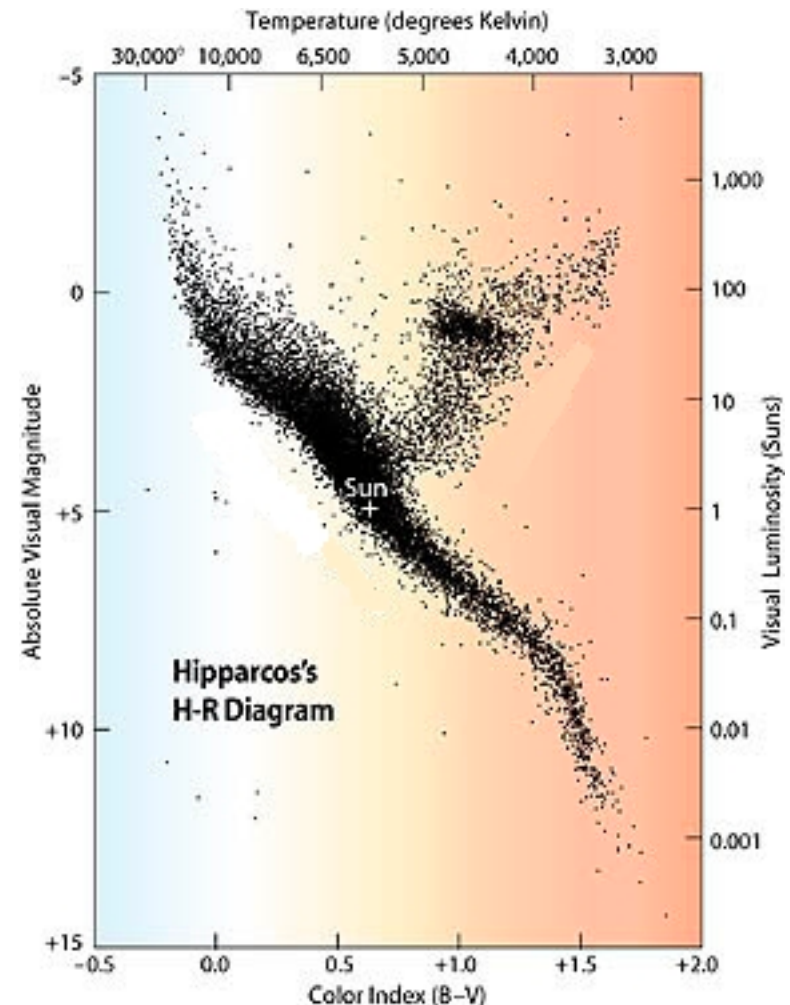
# H-R diagram of stars in the solar neighborhood

- Timescale governed by nuclear reactions

- $\sim 10^{10}$  years for the Sun
- Stars

$$t_{star} / t_{sun} \approx (M_{star} / M_{sun})^{-2.3}$$

- 80–90% of all stars in the solar neighborhood are main-sequence stars
- Width of the main sequence
  - Small, but nonzero
  - Possible causes:
    - Observational errors
    - Differing chemical compositions
    - Varying stages of evolution

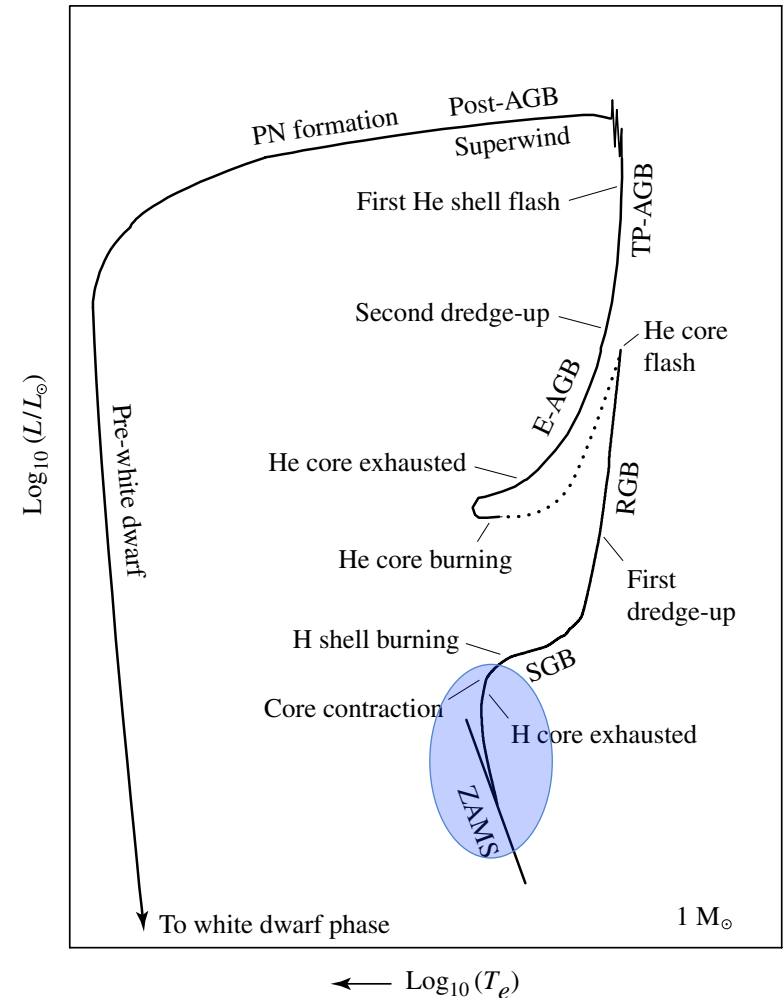


# Main-sequence evolution

- Hydrogen burns into helium
- Mean molecular weight  $\mu$  increases in the core
- If nothing else changes, what does the pressure do?

$$P_t = \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4. \quad \text{Decrease!}$$

- Insufficient pressure to support overlying layers
- Core gets slowly compressed
- Virial theorem: half of the gravitational energy goes into heat
- Core temperature increases
- More efficient nuclear reaction
- Both luminosity and effective temperature increase





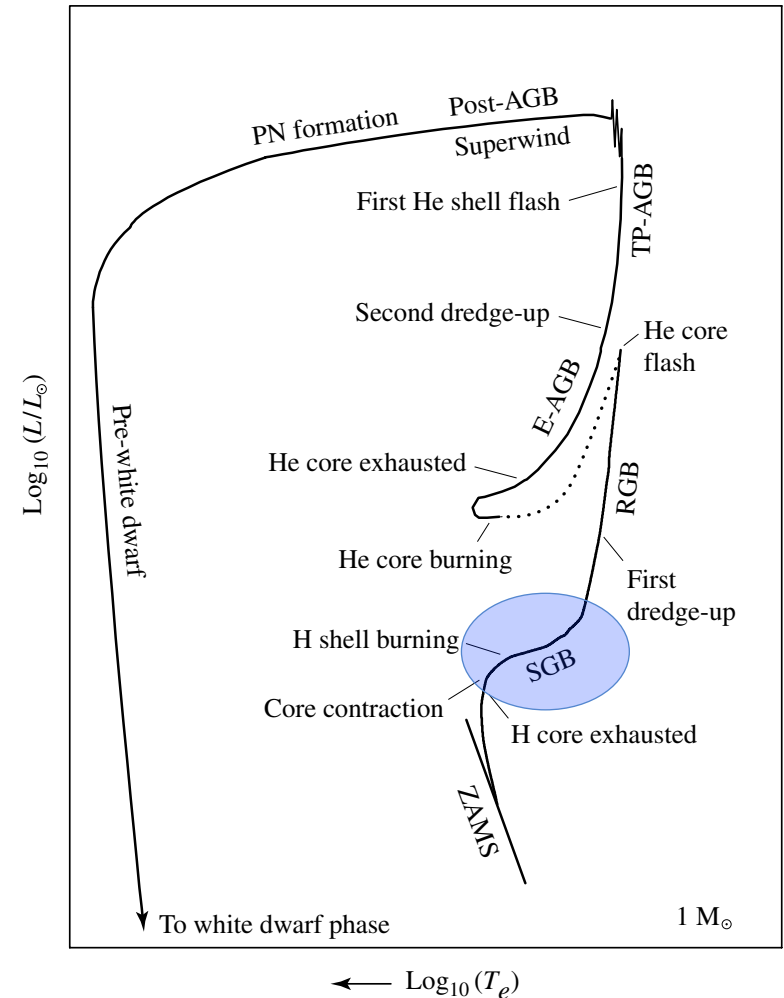
# Evolution off the main sequence I

- Star uses up its initial supply of H in the core
- Core contracts, temperature and density in the region around the core increases and ignites H burning in a shell

➡ **Hydrogen shell burning**

- Helium core steadily increases in mass but the temperature is not high enough to ignite helium nuclear reaction
- Eventually the helium core cannot support the outer layers (Schönberg-Chandrasekhar limit) and contract rapidly on the Kelvin-Helmholtz timescale
- Gravitational energy released, envelop of the star expands, effective temperature decreases

➡ **Subgiant branch (SGB)**



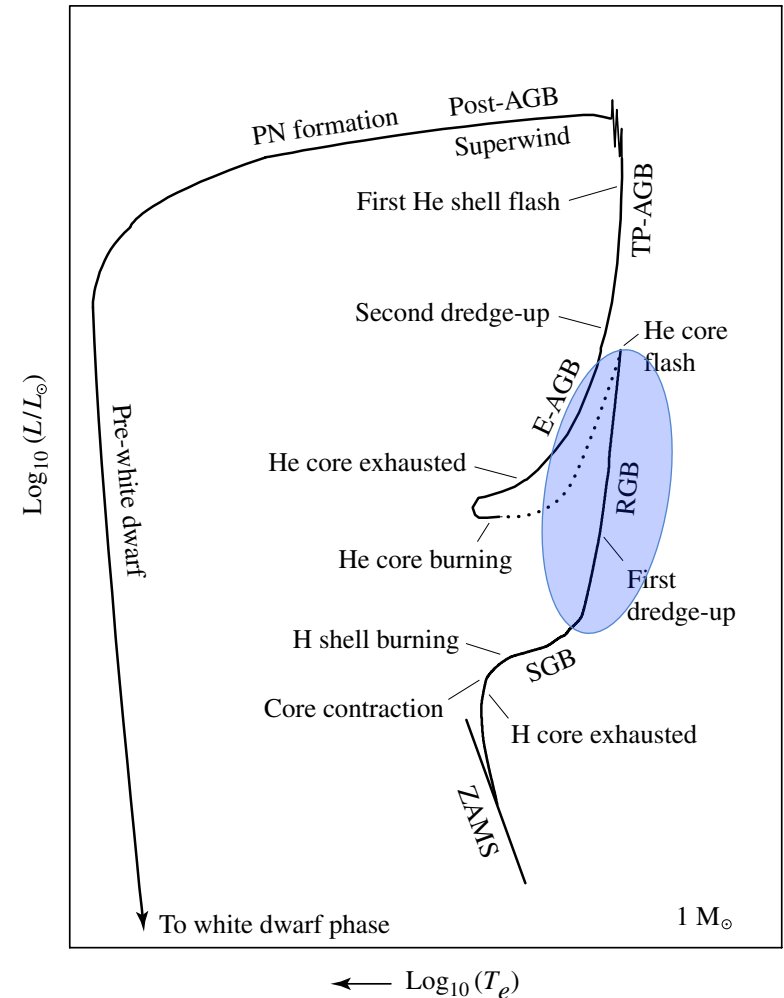
# Evolution off the main sequence II

- Stellar envelope further expands, effective temperature further decreases
- Opacity increases due to the additional contribution of the  $H^-$  ion

$$dT / dr = - \frac{-3\kappa(r)\rho(r)}{4acT^3} \frac{L(r)}{4\pi r^2}$$

- Temperature gradient required for energy transport by radiation is large enough for convection to kick in
- Convection zone develops throughout the stellar interior
- Evolution follows the Hayashi track of the pre-main-sequence star, but upwards!
- Star rapidly expands and in the meantime, cools down

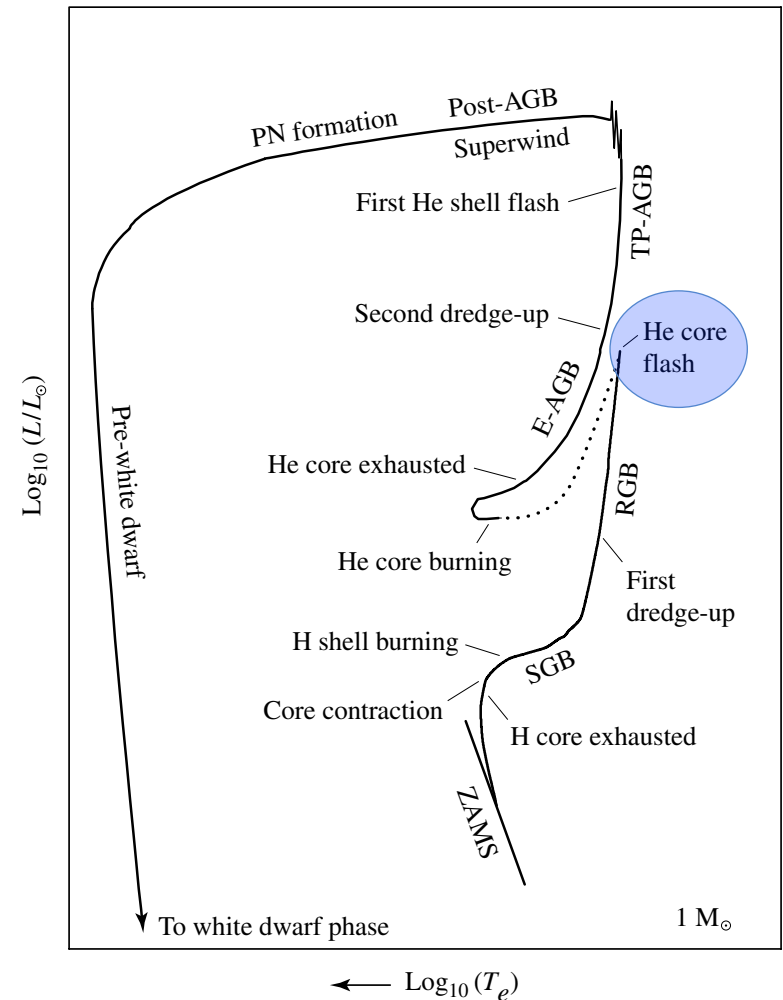
➡ **Red Giant Branch (SGB)**



# Evolution off the main sequence III

- For low-mass stars ( $< \sim 1.8 M_{\text{sun}}$ ), the helium core continues to collapse during evolution to the tip of the RGB branch
- Temperature and density continue to increase in the helium core
- Electrons are forced to occupy the lowest energy levels possible.
  - Electrons are fermions, and they cannot all occupy the same quantum state
  - They stacked into progressive higher energy states, and the core becomes **electron-degenerate**
  - Pressure of a completely degenerate electron gas is  $P_e = K\rho^{5/3}$ .
- Ultimately the temperature/density become high enough to ignite helium burning ( $10^8$  K)
- Temperature rapidly increases, yet the pressure of the degenerate electron gas does not increase  $\rightarrow$  no expansion to dissipate the energy  $\rightarrow$  more efficient helium burning  $\rightarrow$  explosive energy release!

 **Helium Core Flash**



# Evolution off the main sequence IV

- Helium core flash “lifts” the degenerate electron gas in the core
- Dramatic changes in the stellar interior
- Helium core burning stabilizes

## ➡ Helium-core-burning “main sequence”

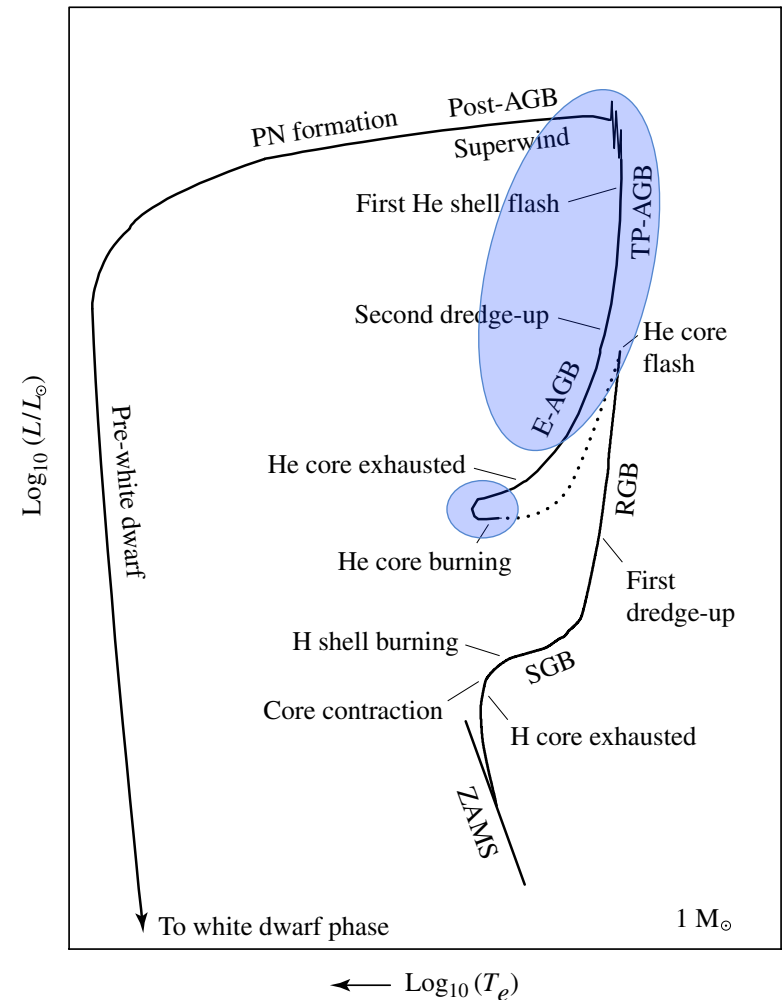
But the lifetime is much shorter

- When helium is exhausted in the core, the star begins to burn He in a shell around the now carbon core (resulted from the triple alpha process) -> evolution is very similar to the hydrogen burning SGB and RGB branch

## ➡ Asymptotic Giant Branch

- He shell burning during the AGB phase is highly temperature dependent and unstable, and intermittent **helium shell flashes** occur
- AGB stars have extremely low surface gravity and suffer high mass loss

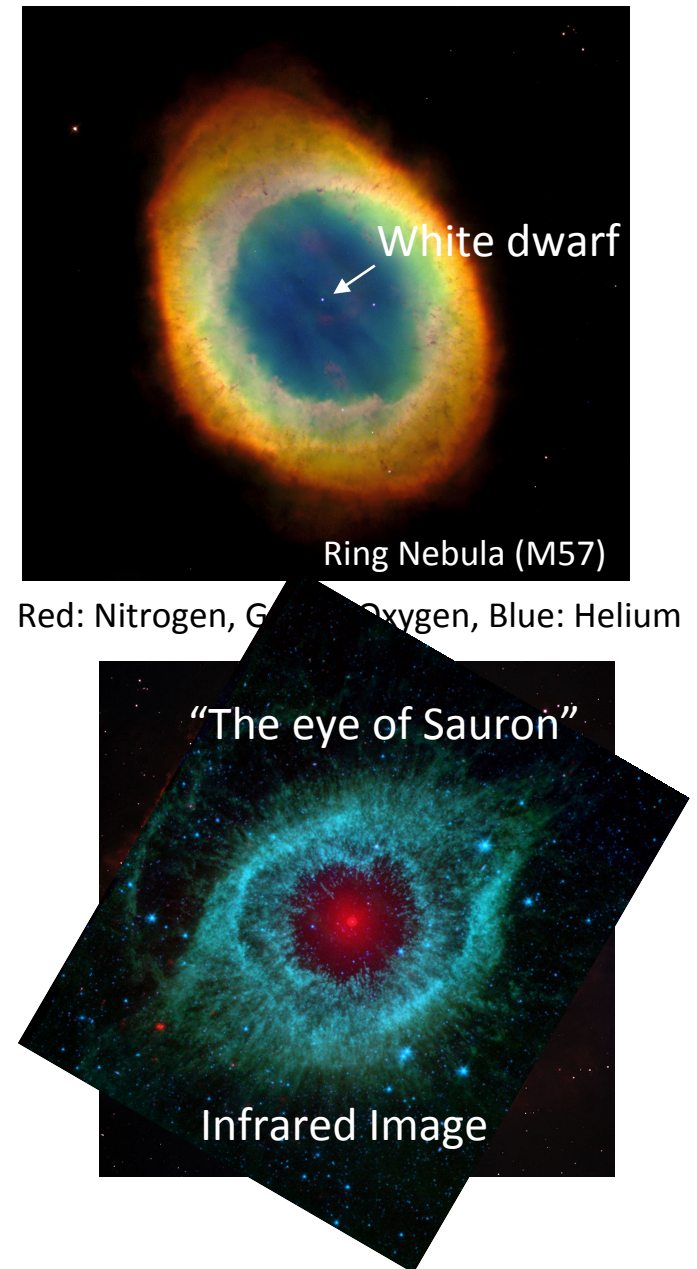
## ➡ Superwind and formation of planetary nebulae



# Planetary Nebulae

- **Planetary nebulae**

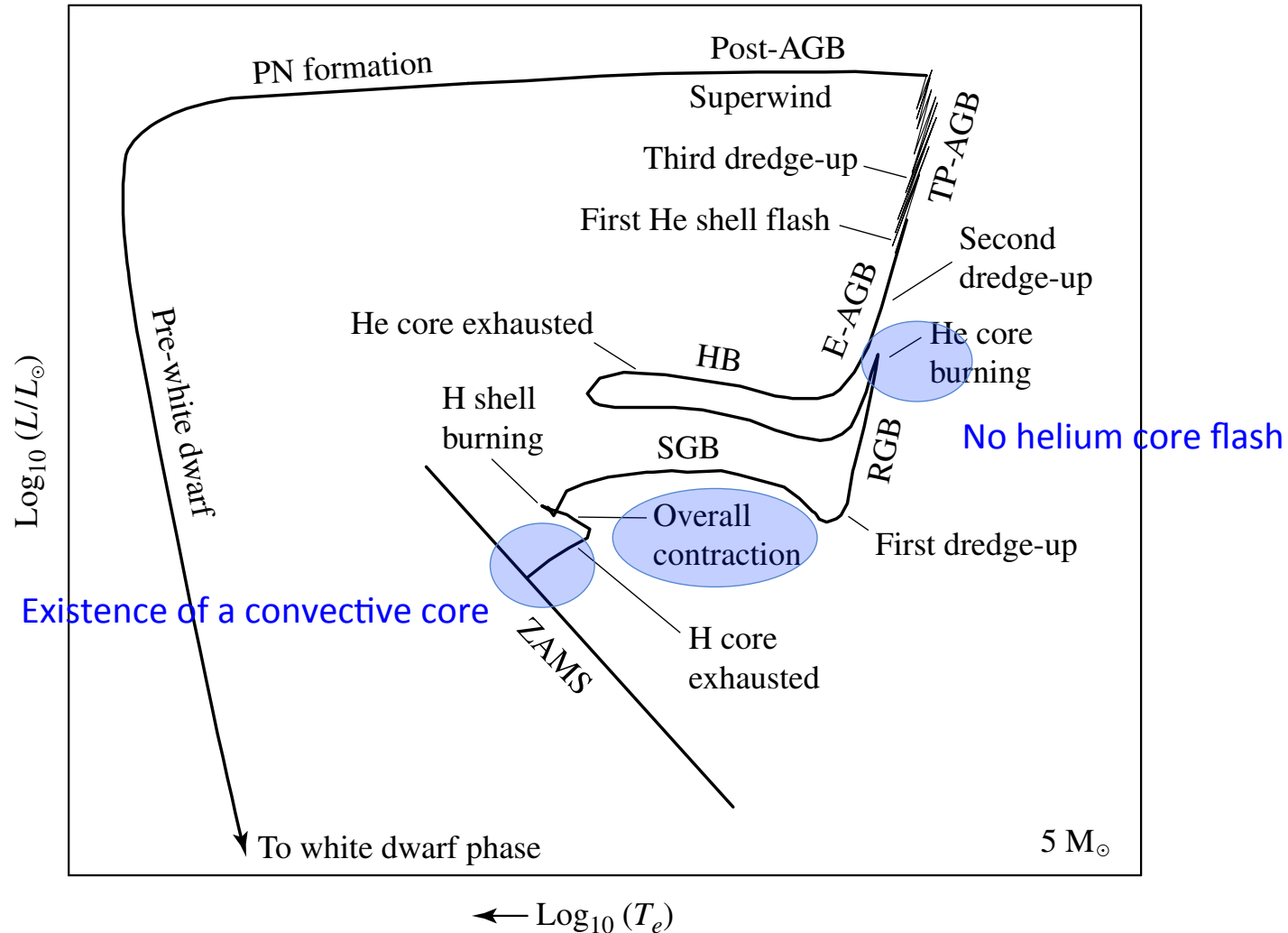
- Formed by the expanding gas around a white dwarf progenitor
- Got the name as they look like giant gaseous planets when viewed through a small telescope in the 19<sup>th</sup> century
- Owes the appearance to the ultraviolet light emitted by the hot, condensed central star
- UV light absorbed by the gas surrounding the star, causing atoms to become excited/ionized
- Excited electrons cascade back to lower energy levels, making the nebula glow in visible light



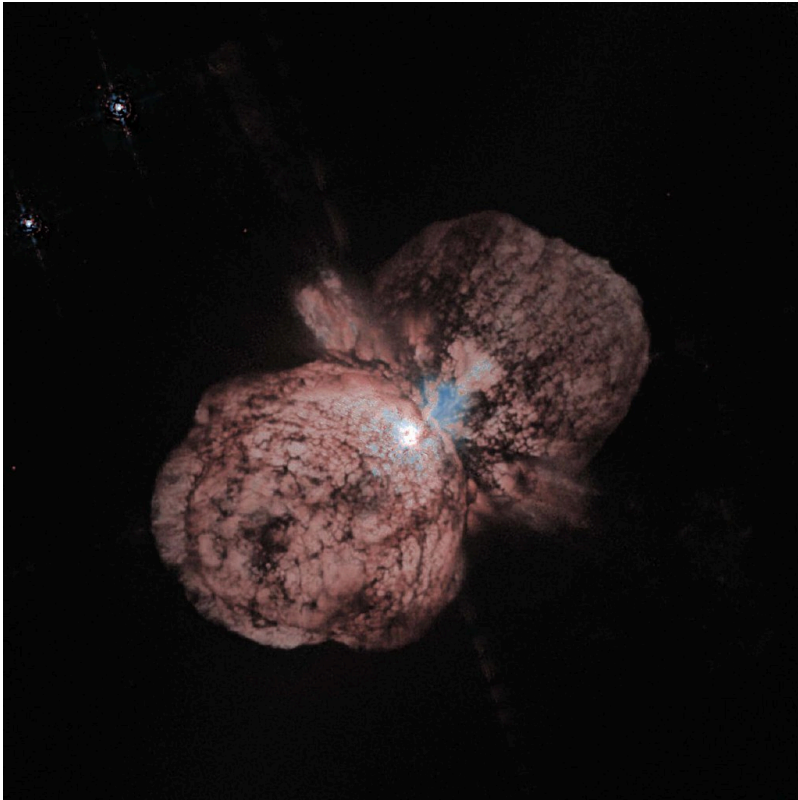
# Death of low-mass stars

- [Crash course by Phil Plait](#)

# Evolution of stars with intermediate mass

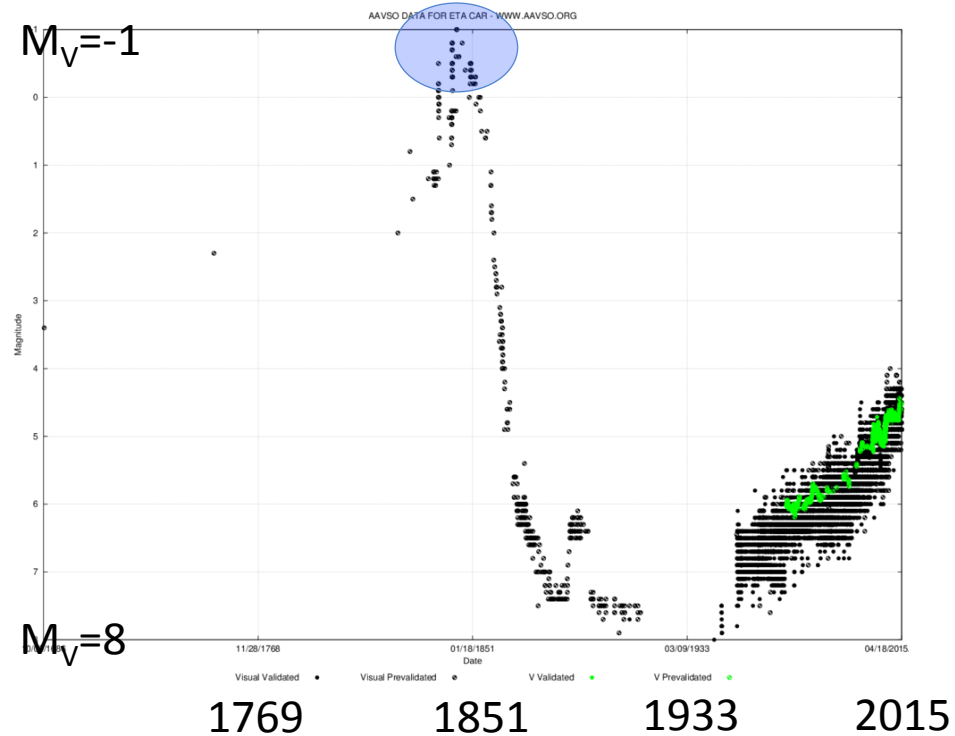


# Observations of massive stars: Luminous Blue Variables (LBVs)



η Carinae: an 120-solar-mass star surrounded by a large nebula consisting of two lobes, each ~0.1 pc across

## The Great Eruption

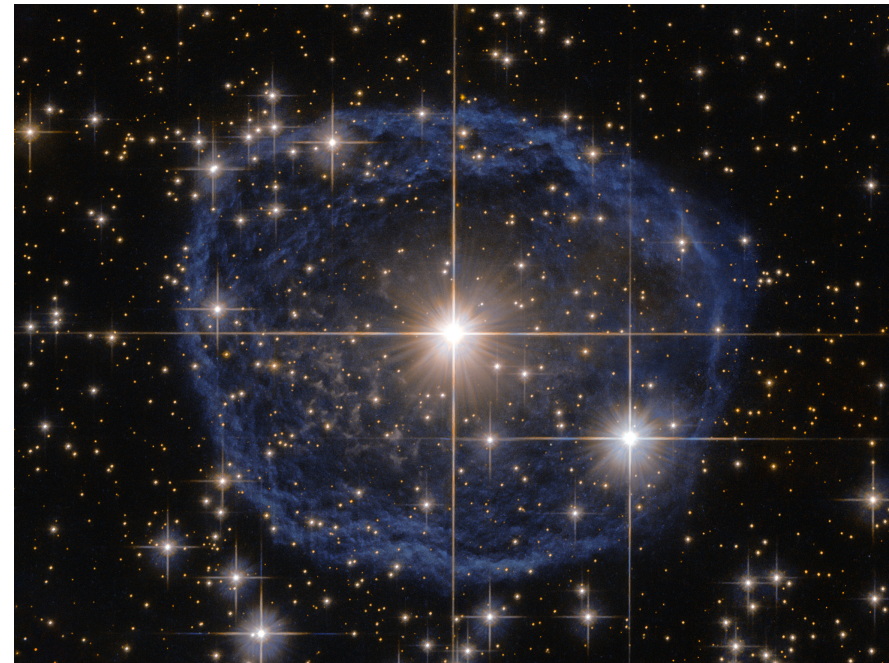


Historical visual magnitude of η Carinae



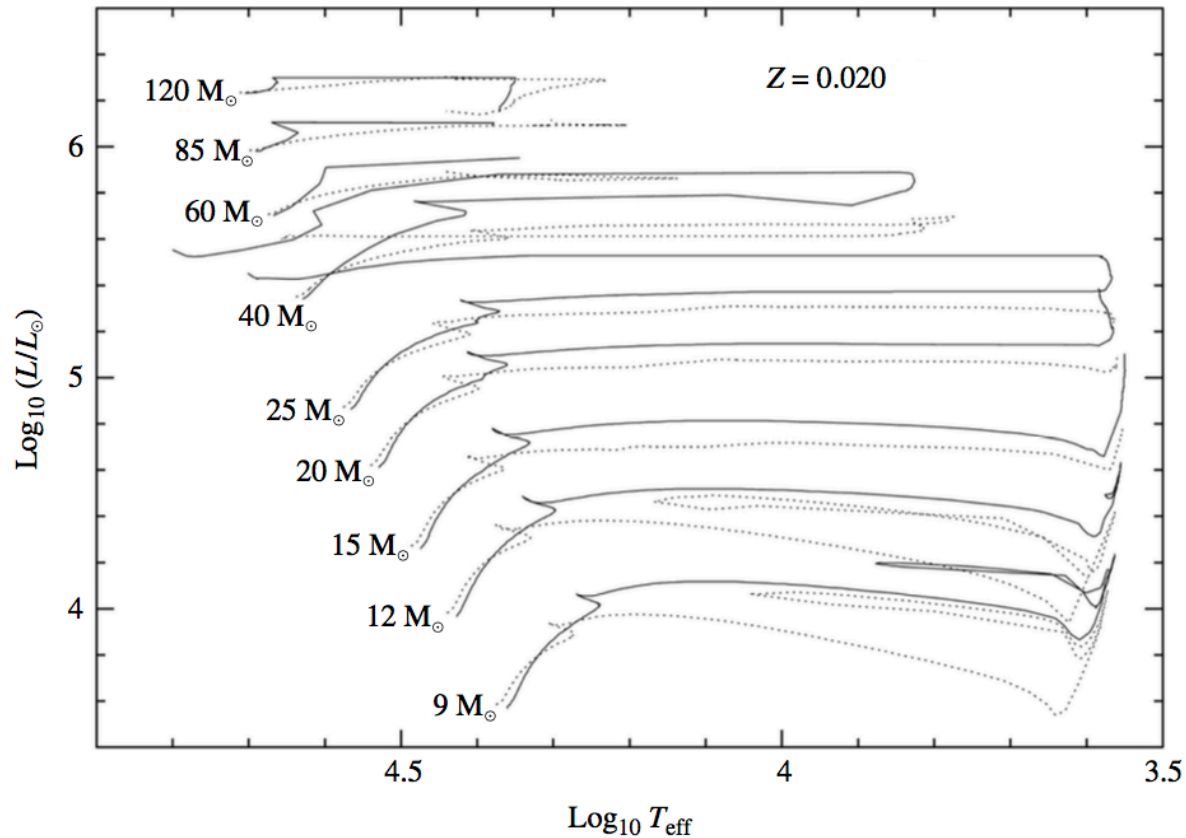
# Observations of massive stars: Wolf-Rayet Stars

- Very hot, massive stars
- Effective temperature 25,000 K to 100,000 K
- Extreme mass loss  $\sim 10^{-5}$  solar mass per year with powerful stellar winds
- The most massive star known to date, R136a1, is a Wolf-Rayet star, estimated to be  $\sim 315$  solar mass



WR 31a, surrounded by a blue bubble nebula from powerful stellar wind impacting surrounding material

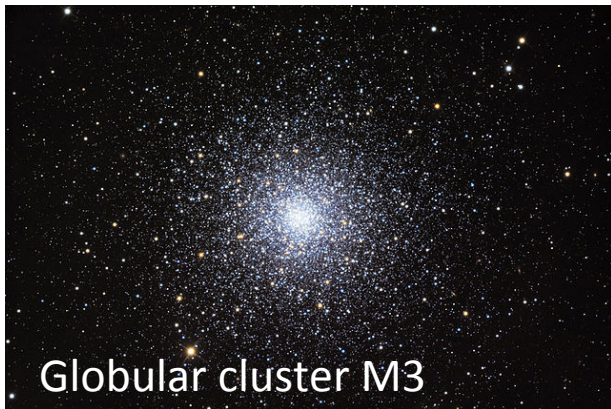
# Evolution of massive stars



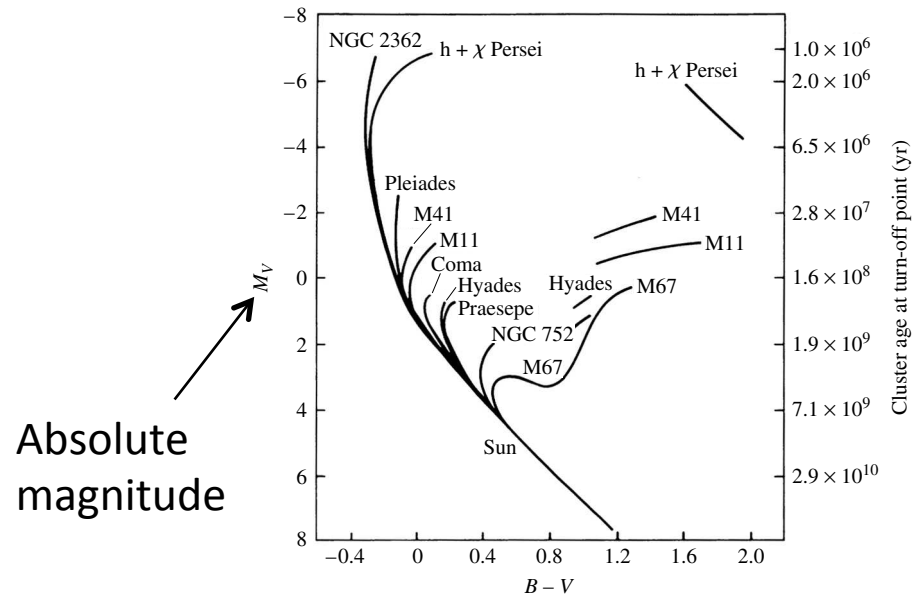
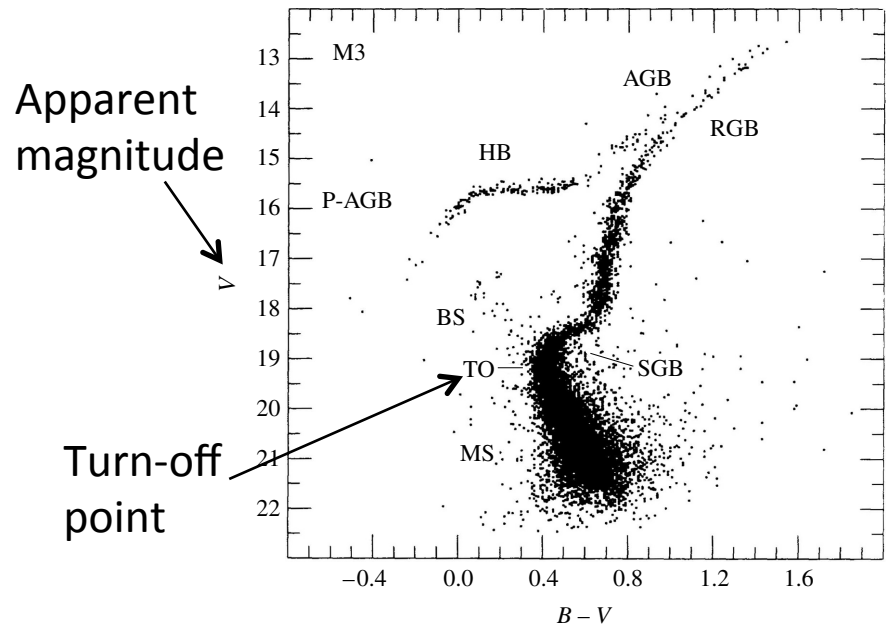
All massive stars with  $>\sim 8$  solar mass probably end their life in a **supernova explosion**

# Stellar clusters

- Very useful in studying stellar evolution, as the stars are
  - at the same distance
  - born at the same time and with the same composition
- Can be used to find out **distance** and **age** of the cluster



HR diagram of M3



# Fate of massive stars

31

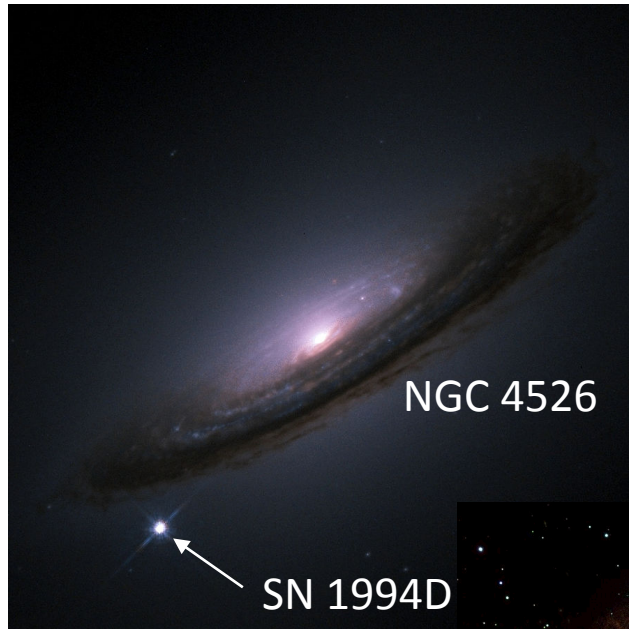


***HIGH  
MASS STARS***



# Fate of massive stars: Supernovae

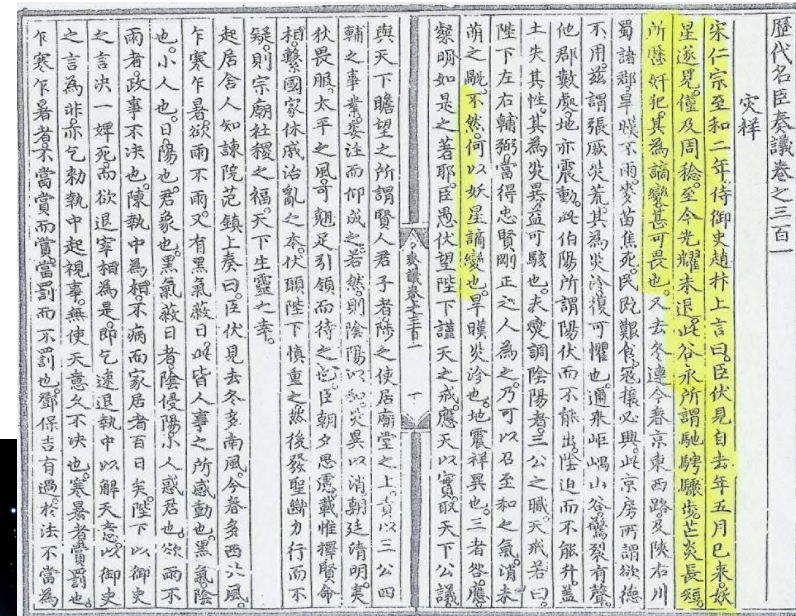
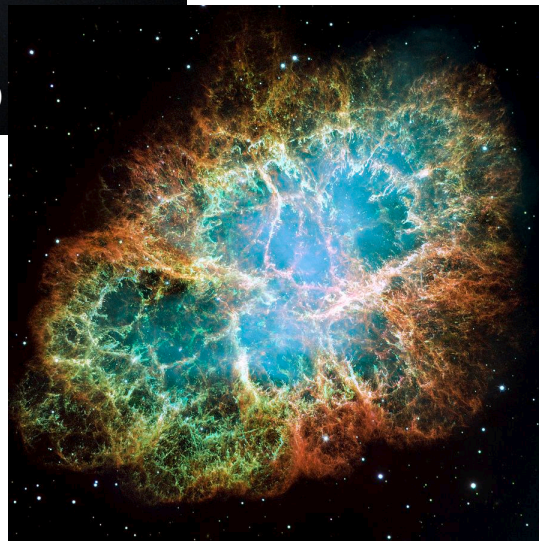
Transient, but titanic explosions in the Universe



NGC 4526

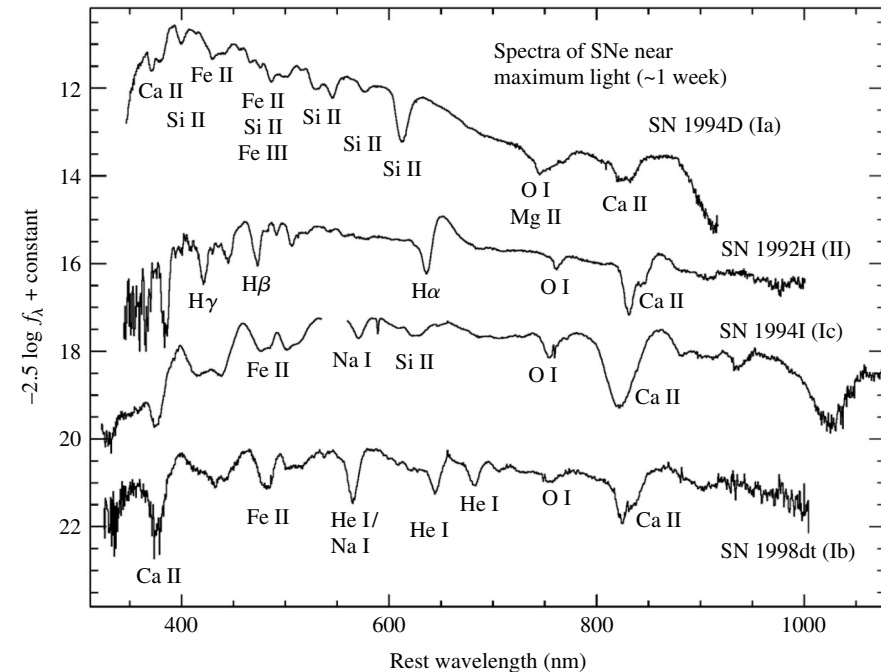
SN 1994D

The Crab Nebula

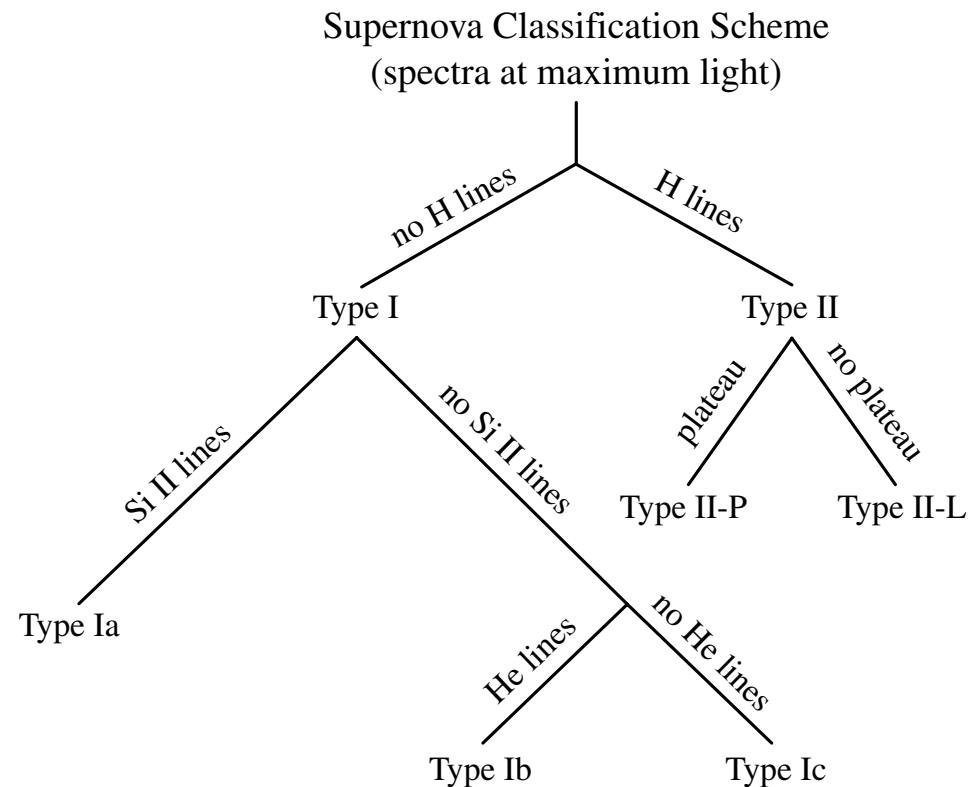


Reported by Chinese Astronomers  
in 1054 AD as a “Guest Star”

# The classification of supernovae



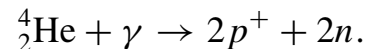
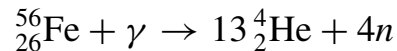
- Type II, Type Ib, and Type Ic supernovae are **core-collapse supernovae** associated with the death of massive stars



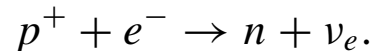
# Core-collapse supernovae mechanism

- Recall Fe is located at the peak of the binding energy per nucleon curve, nuclear fusion stops to release energy at iron
- The core has very high T, supported by thermal electron degeneracy pressure, and electrons in the core have extremely high energies – but no additional energy input
- Under this extreme conditions, two processes occur

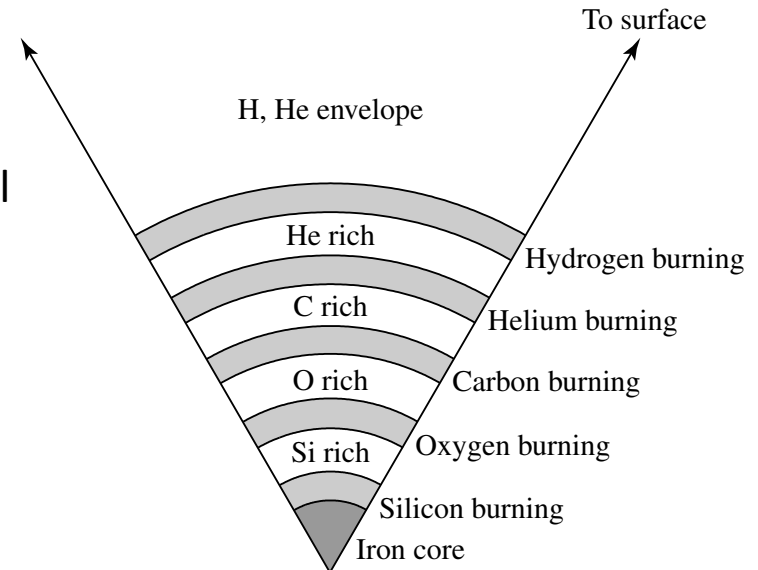
## Photodisintegration



## Neutron formation



- Photodisintegration removes thermal pressure; Neutron formation removes electron degeneracy pressure – nothing supports the entire envelop of the star!
- Core goes through homologous free-fall collapse in a very short time!



The onion-like interior of an evolved massive star through core silicon burning

# Core-collapse supernovae:

## Energy release

- During the collapse, speeds can reach 70,000 km/s ( $\sim 0.2 c$ )
- Within  $< 1$  s, a volume of the **size of Earth** can be compressed down to  $\sim 50$  km,  **$\sim$ size of Rhode Island**
- Releases energy of  $\sim 10^{46}$  J (homework problem) in days/months, equivalent to the total output of the 100 Sun-like stars for its entire lifetime, 10 billion years!

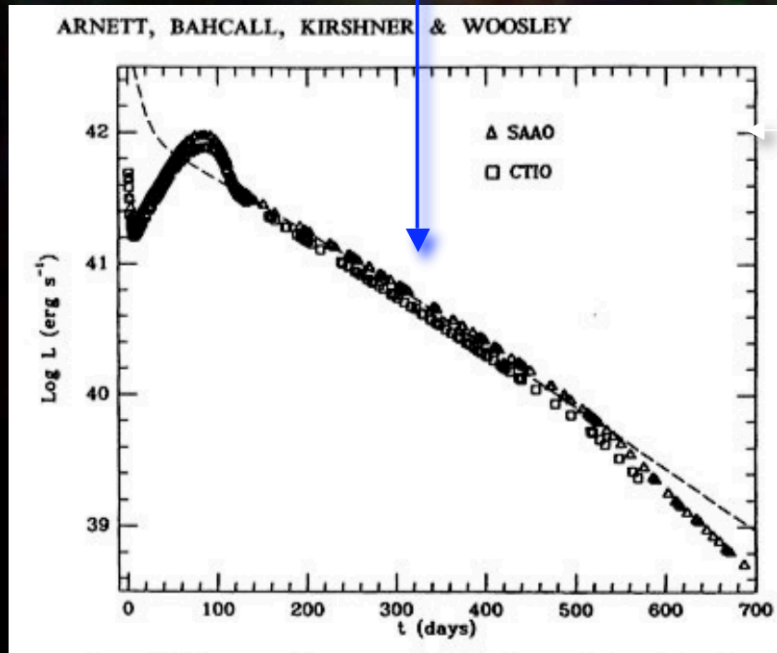


# Supernova Explosion

- Catastrophic core collapse results in a blast wave sweeping outward as a shock
- Shock encounters the infalling outer material and becomes an accretion shock
- The accretion shock continues to march through the star's envelope, drive the materials outward, and heats them up
- When the materials become optically-thin, a tremendous optical display results, with a peak (visible) luminosity of  $10^9$ x solar luminosity, capable of competing with the brightness of the entire galaxy!

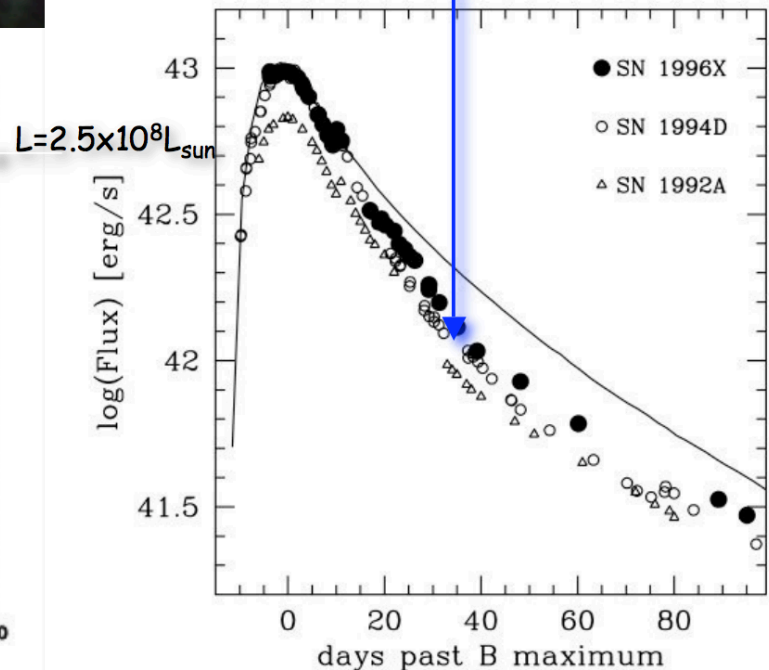
# Supernova lightcurves

Tail of light curve caused by heating by nuclear decay  
(especially  $^{56}\text{Ni}(8.8\text{d}) \rightarrow ^{56}\text{Co}(111\text{d}) \rightarrow ^{56}\text{Fe}$ )



SN1987A

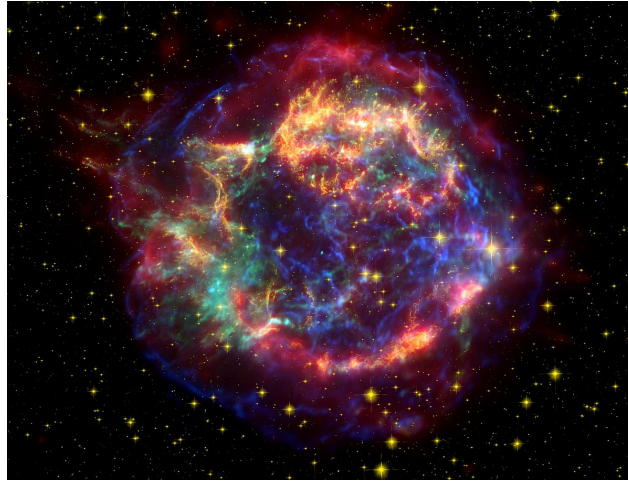
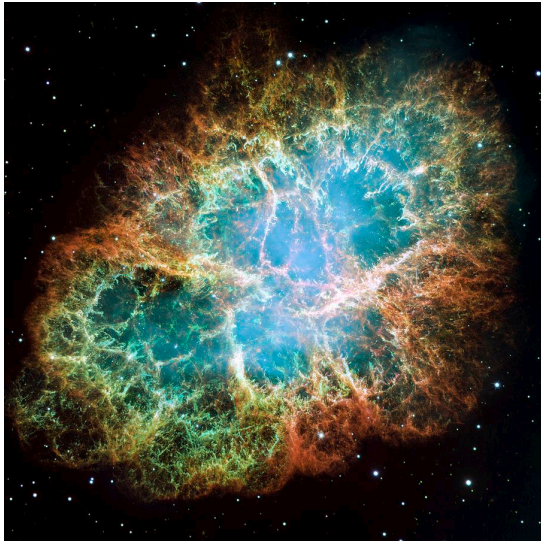
(a “weak” SN)



SN1992A, SN1994D, SN1996X

# Supernova Remnants

Crab Nebula (SN 1054A)

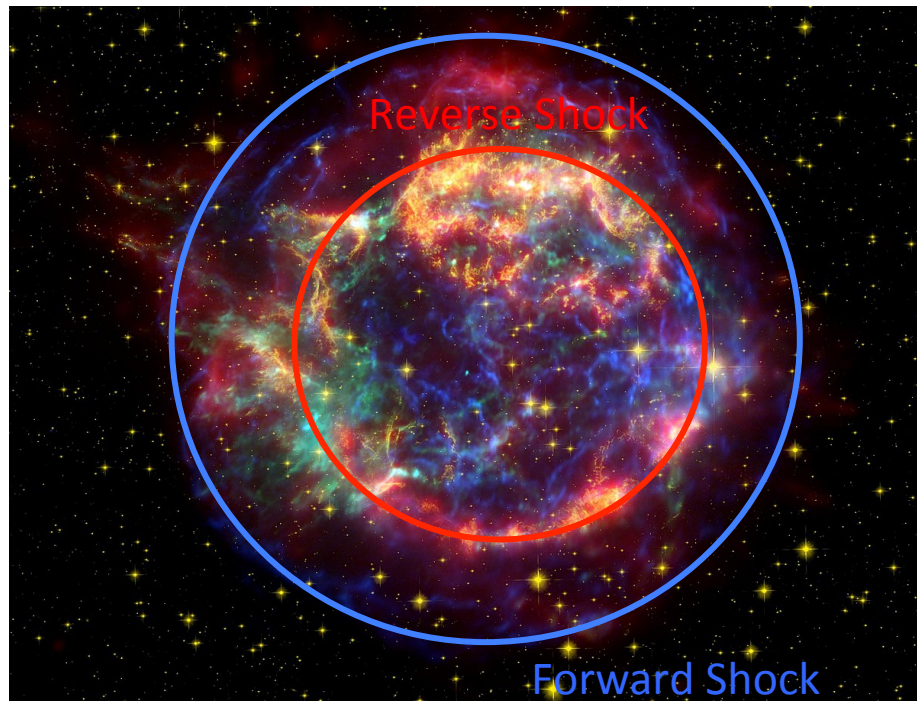


Cassiopeia A (SN 1671A?)

SN 1987A (in LMC)



# Supernova Remnants



Cassiopeia A

Shocked ISM      Shocked Ejecta

