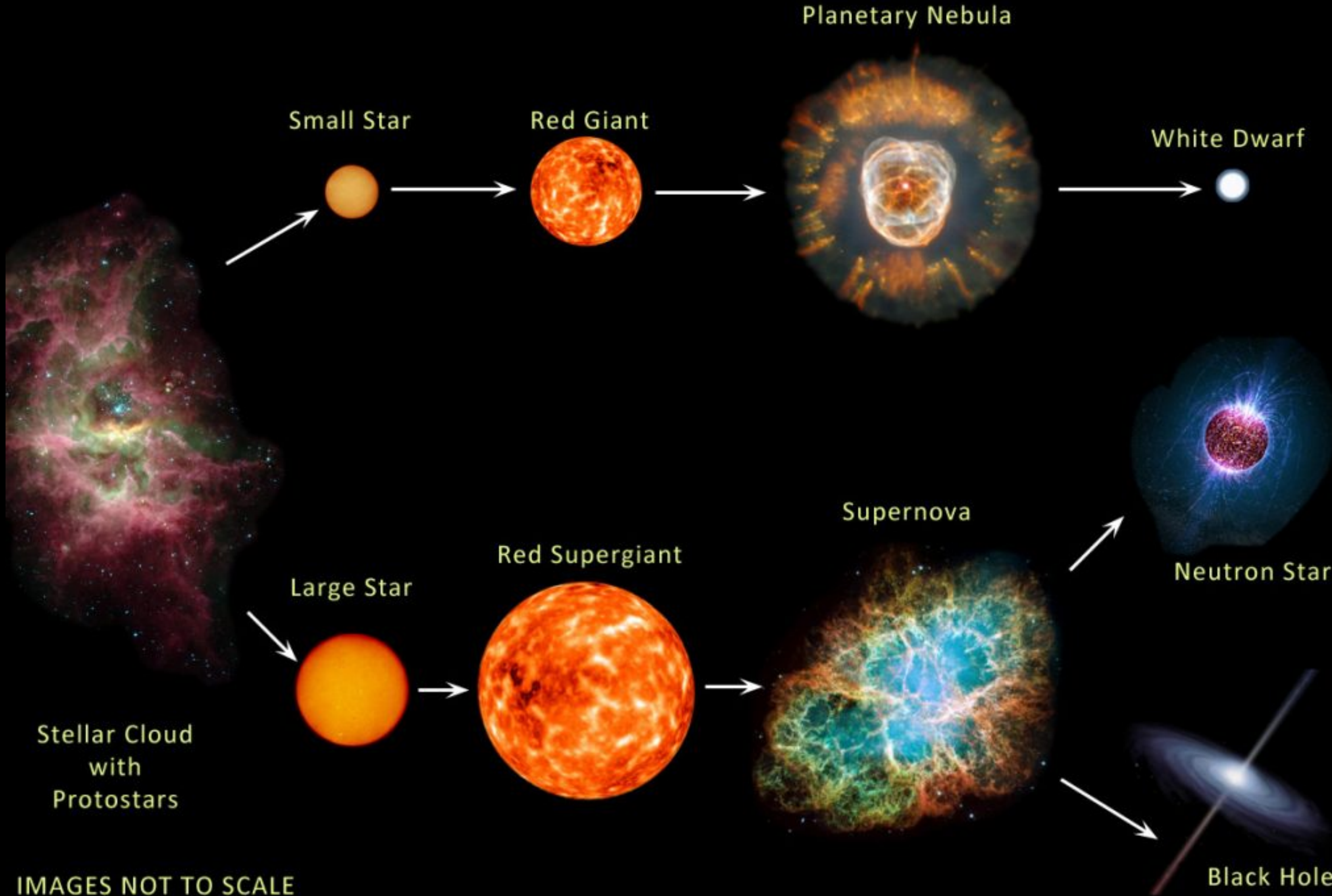
Phys 321: Lecture 7

Stellar Evolution



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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_2 cloud with $T = 10$ K and $n_{H2} = 10^{10}$ m^{-3}, $M_J \sim 8$ 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***

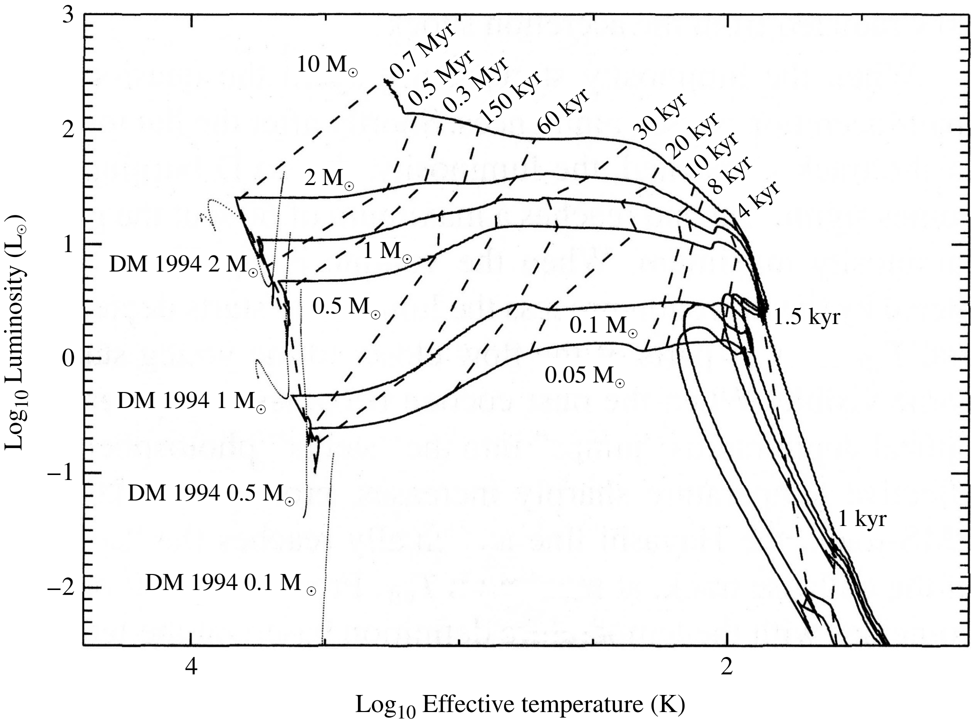
Free-fall time, or the time takes for a particle to fall from any point of the cloud freely:

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

Again for the dense molecular H_2 cloud with T = 10 K and $n_{H2} = 10^{10}$ m^{-3}

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

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

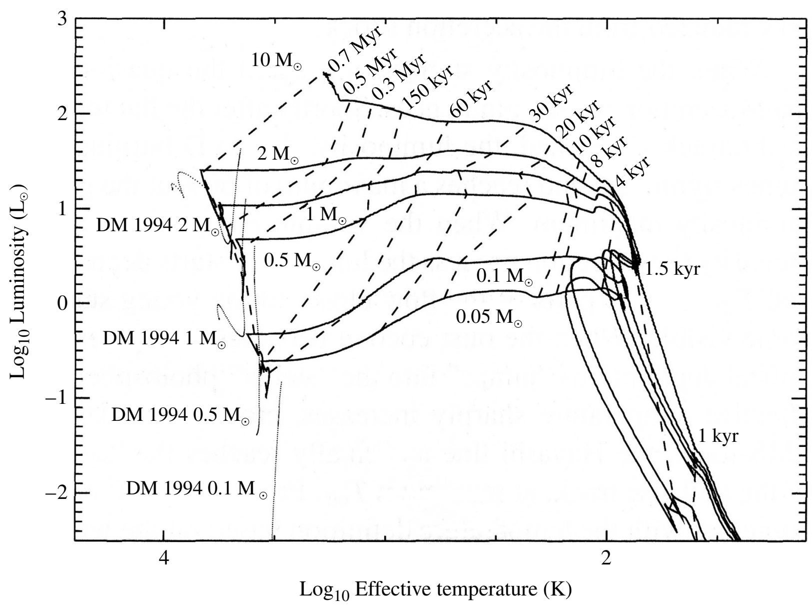
Some electrons are ionized from heavier elements

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***

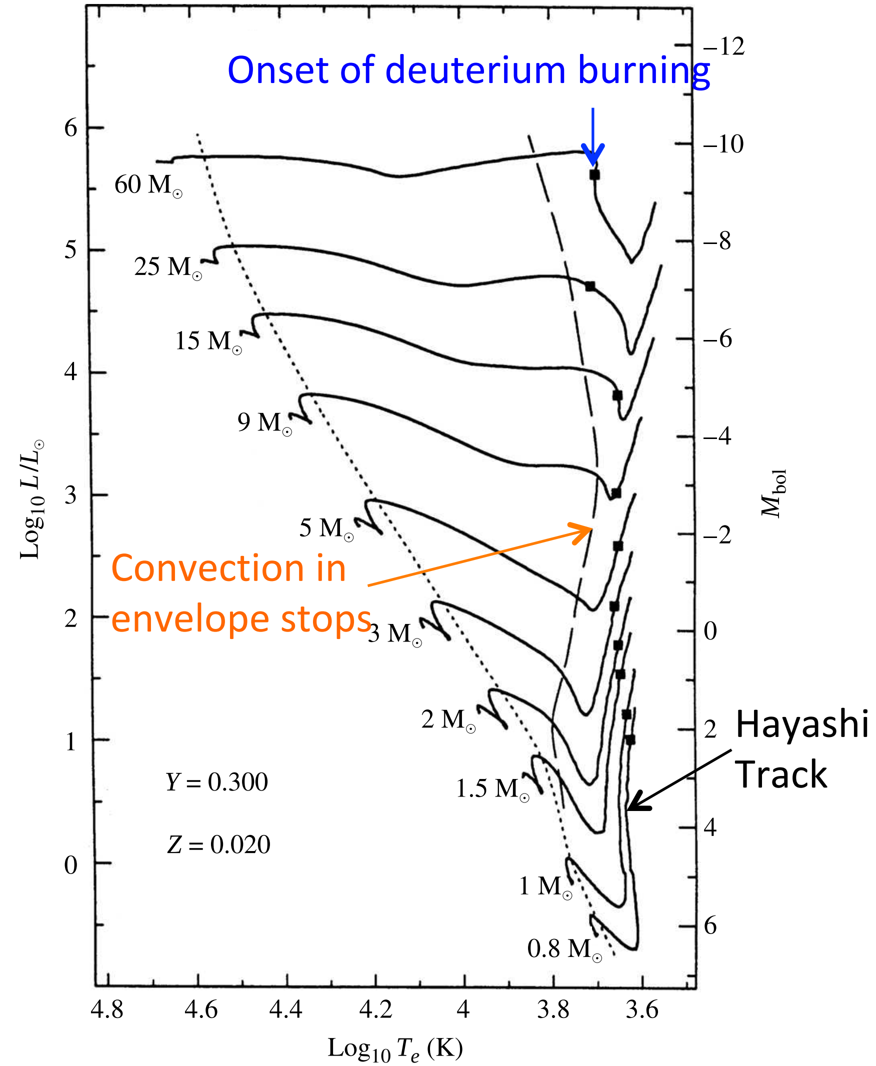


- Slightly increasing effective temperature
- Quickly decreasing luminosity

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

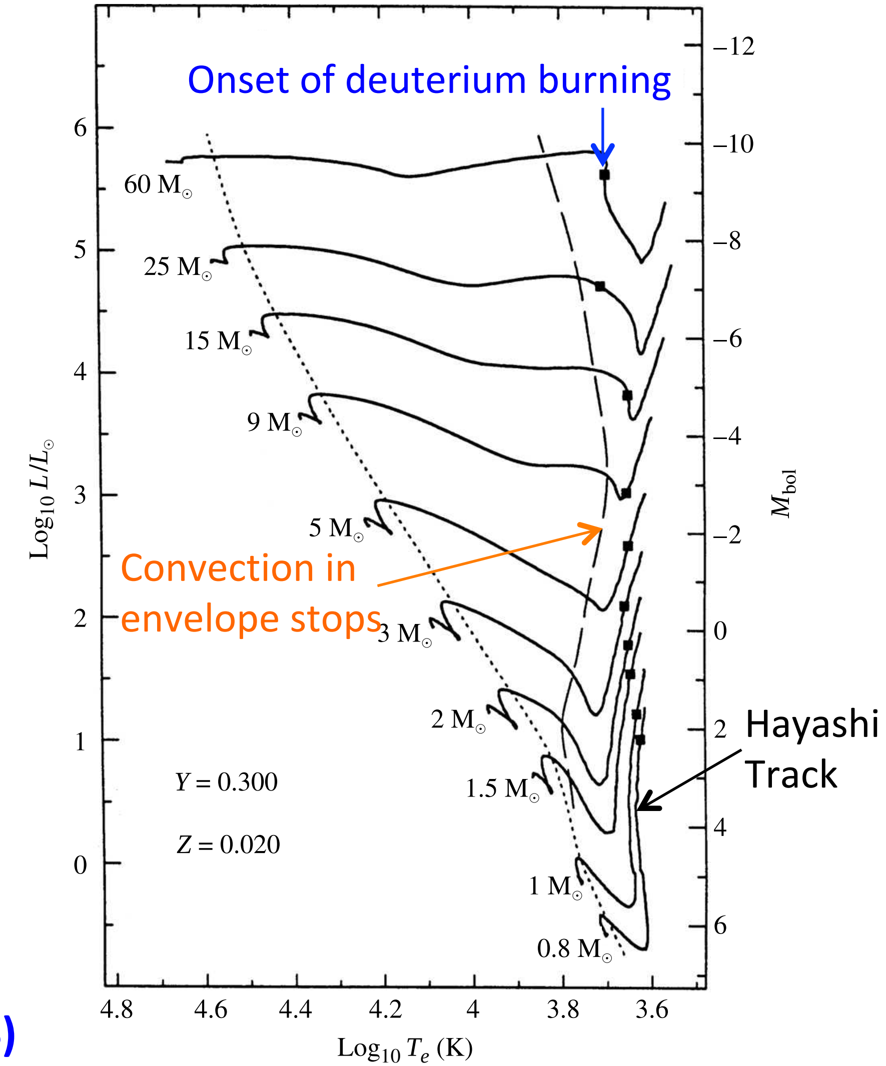


Pre-main-sequence Evolution

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 -> 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 -> enters the main sequence

Zero-age main-sequence stars (ZAMS)

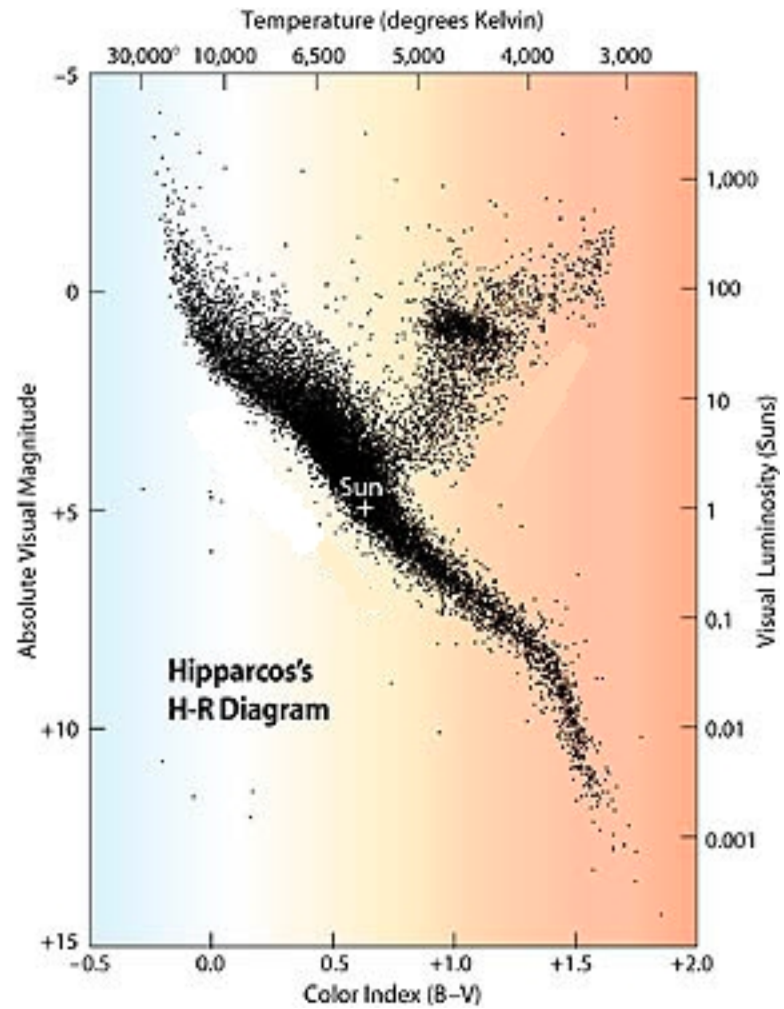


H-R diagram of stars in the solar neighborhood

- Timescale governed by nuclear reactions
  - ~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

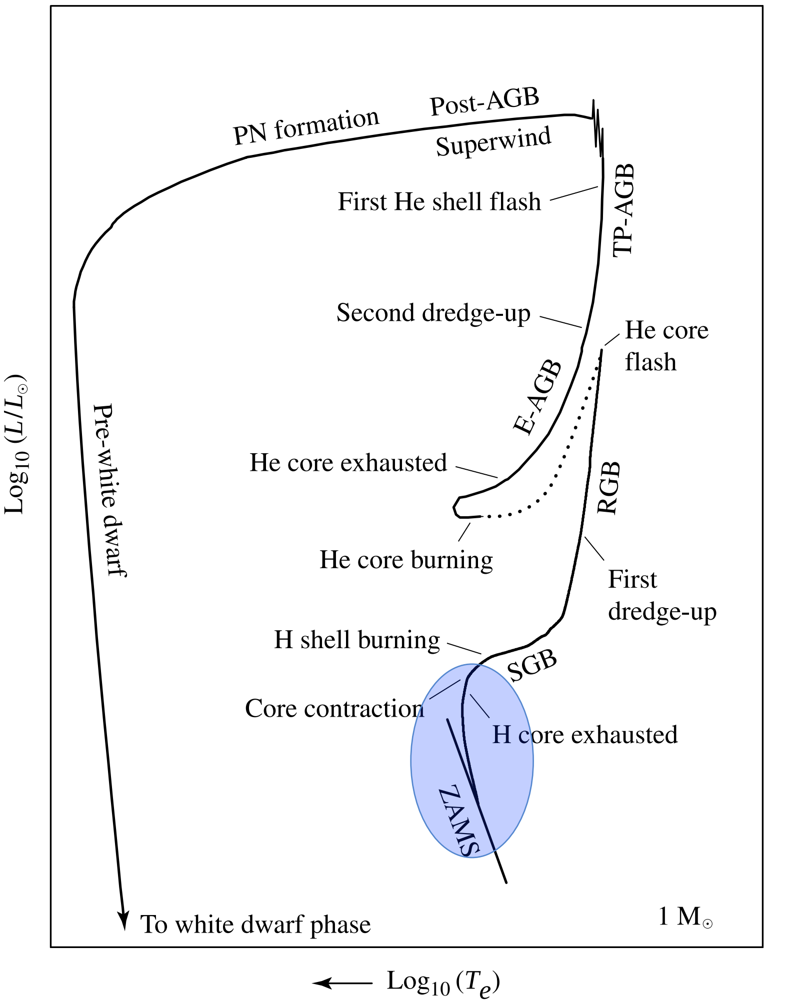


Main-sequence evolution

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

$$P_t = \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4$$ 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



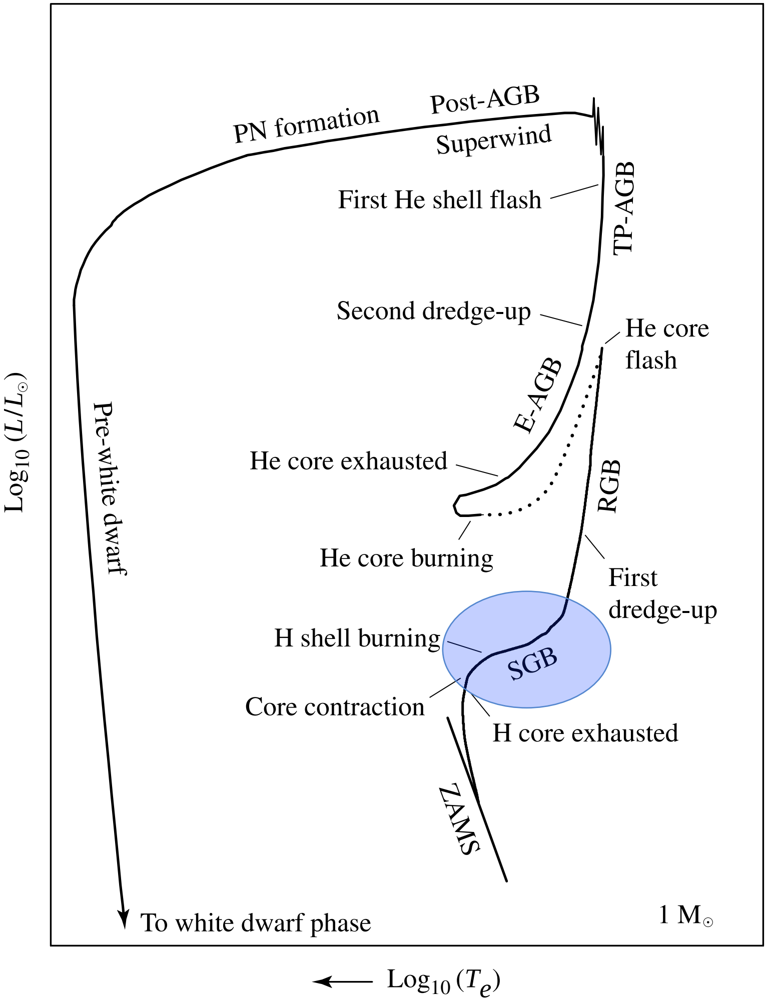
Evolution off the main sequence I

- 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)**



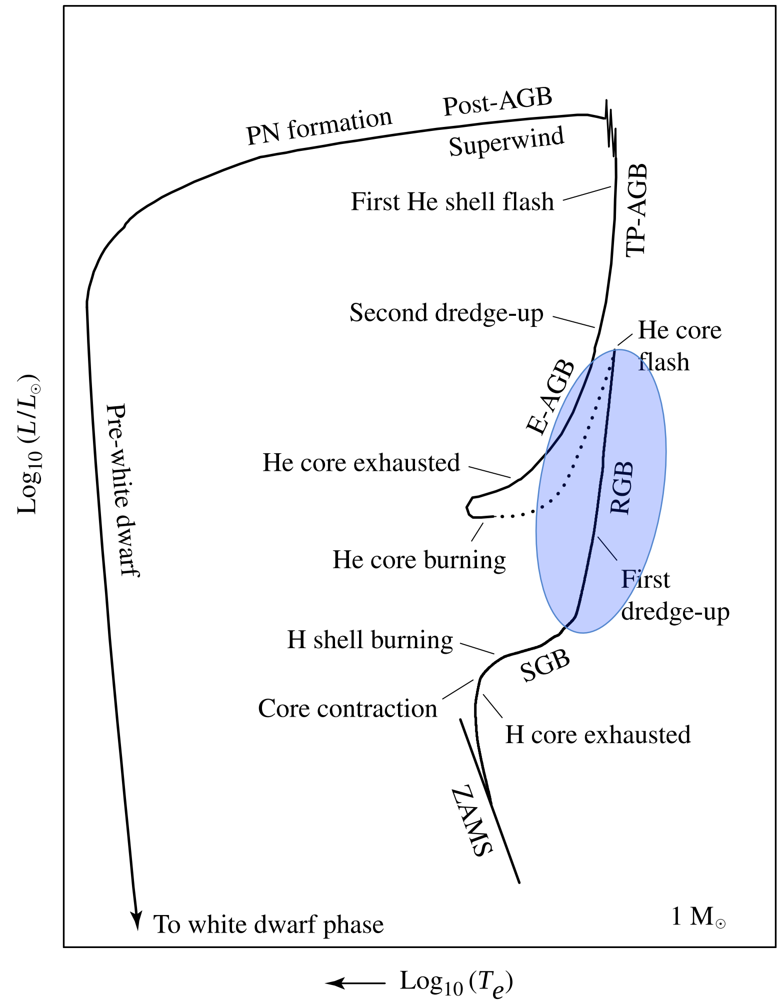
Evolution off the main sequence II

- 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

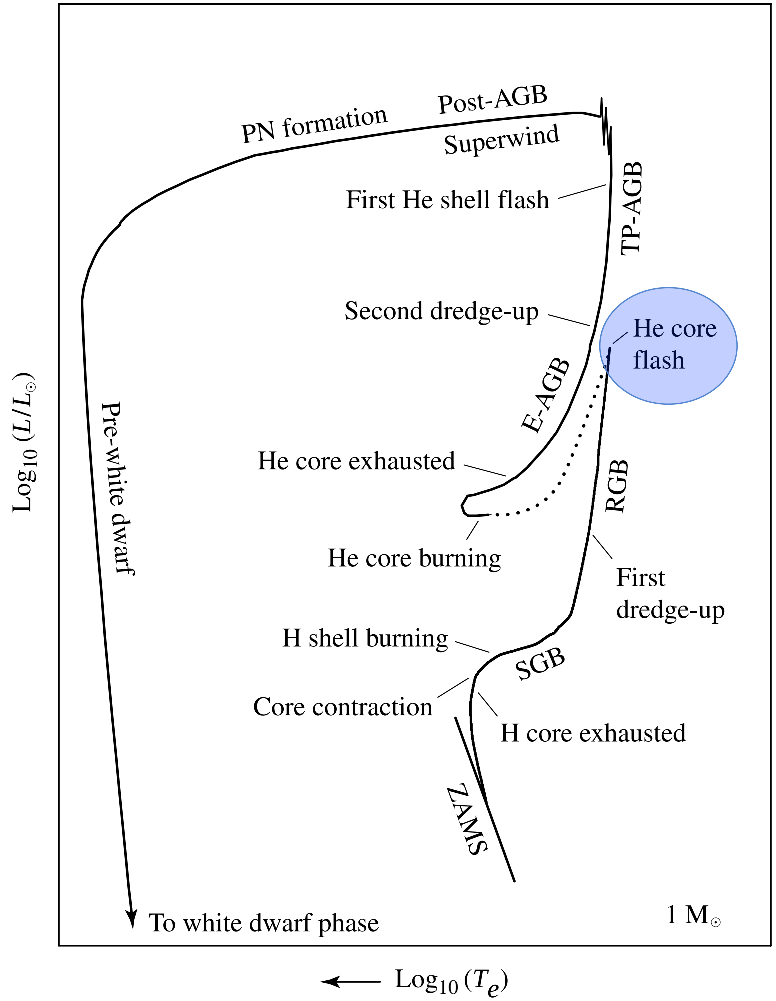
⇨ **Red Giant Branch (SGB)**



Evolution off the main sequence III

- For low-mass stars (<~ 1.8 M_{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 -> no expansion to dissipate the energy -> more efficient helium burning -> 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”**

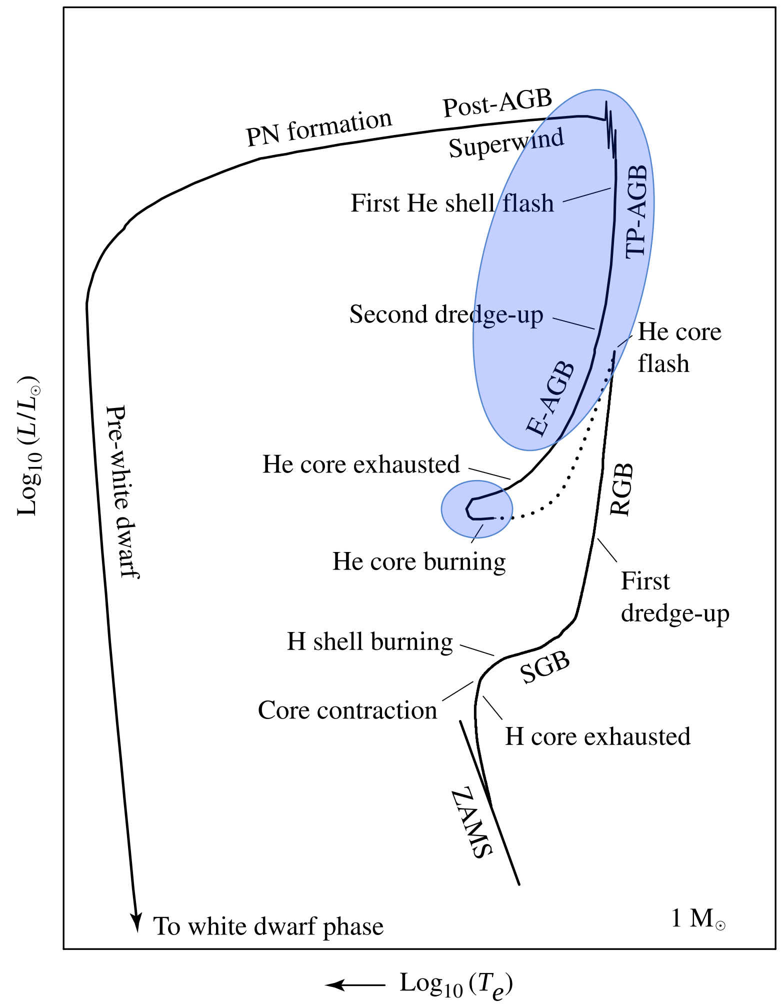
But the lifetime is much shorter

- 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**

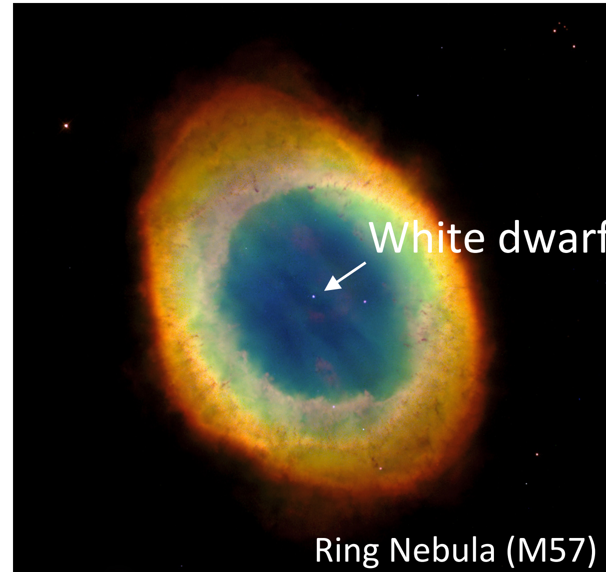
- He shell burning during the AGB phase is highly temperature dependent and unstable, and intermittent helium shell flashes occur
- AGB stars have extremely low surface gravity and suffer high mass loss

⇨ **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 19th century
  - Owes the appearance to the ultraviolet light emitted by the hot, condensed central star
  - UV light absorbed by the gas sounding the star, causing atoms to become excited/ionized
  - Excited electrons cascade back to lower energy levels, making the nebula glow in visible light

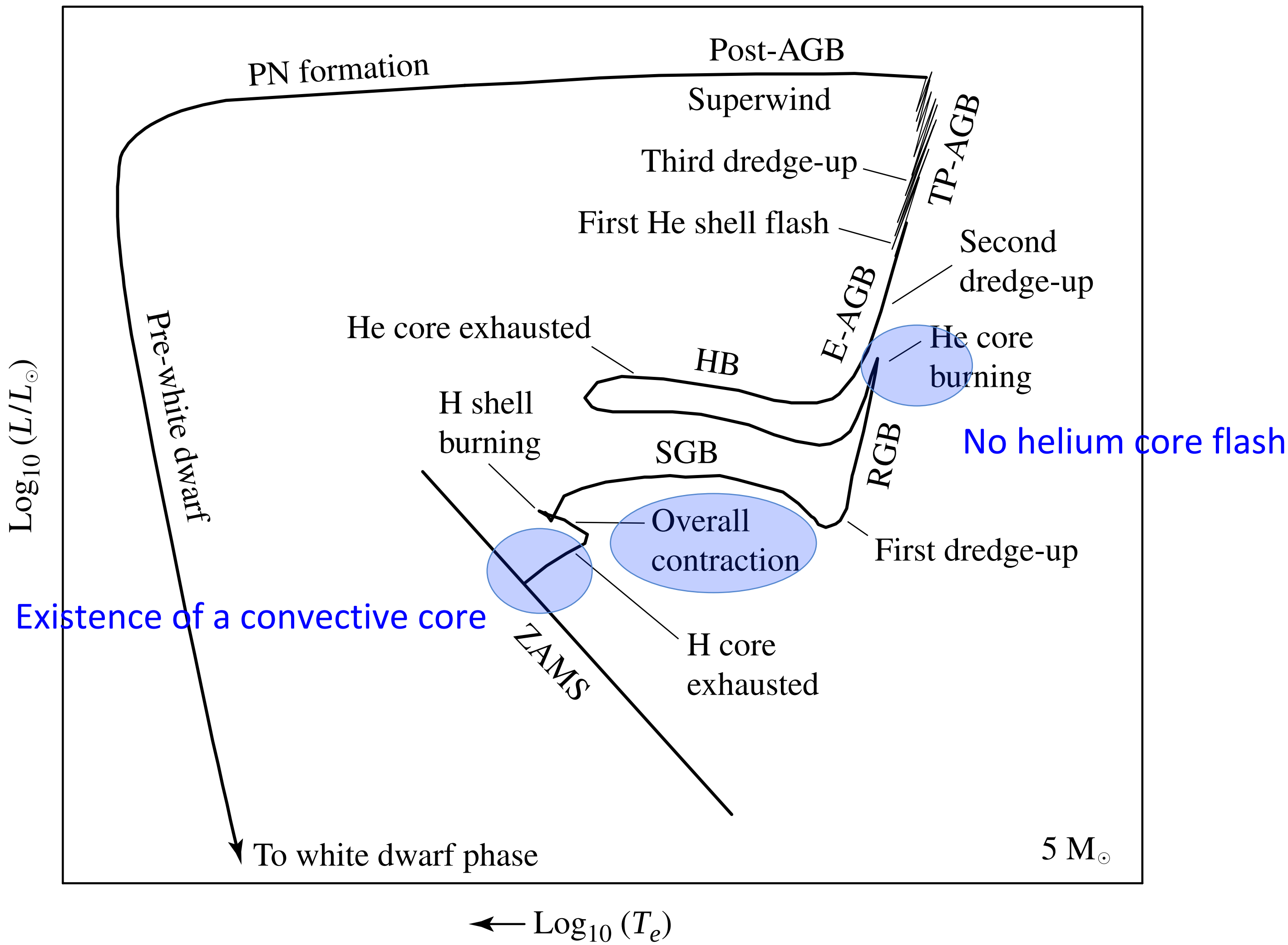


Red: Nitrogen, G Oxygen, Blue: Helium

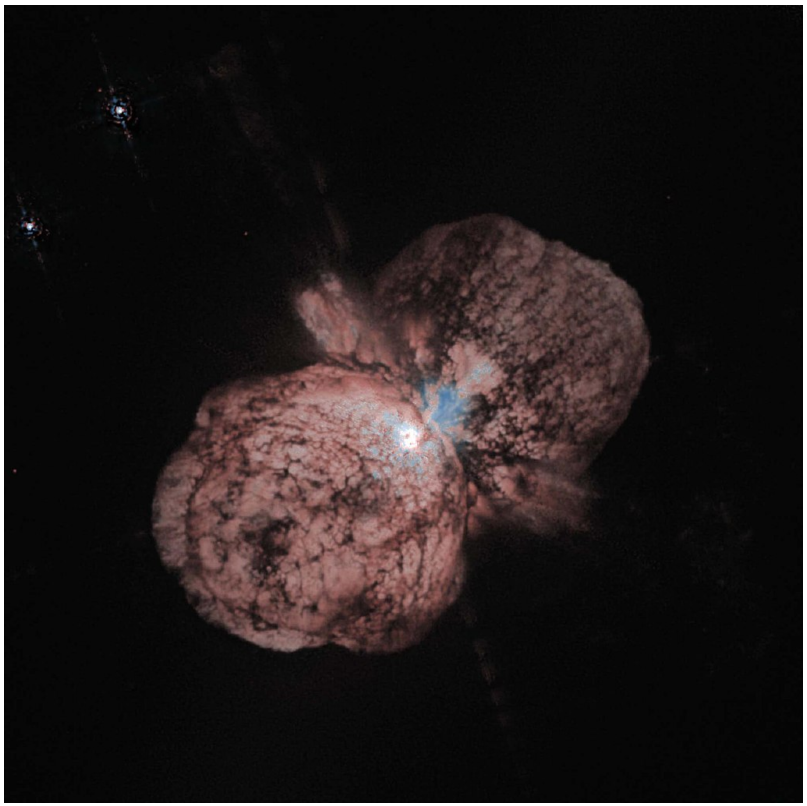
Death of low-mass stars

- Crash course by Phil Plait

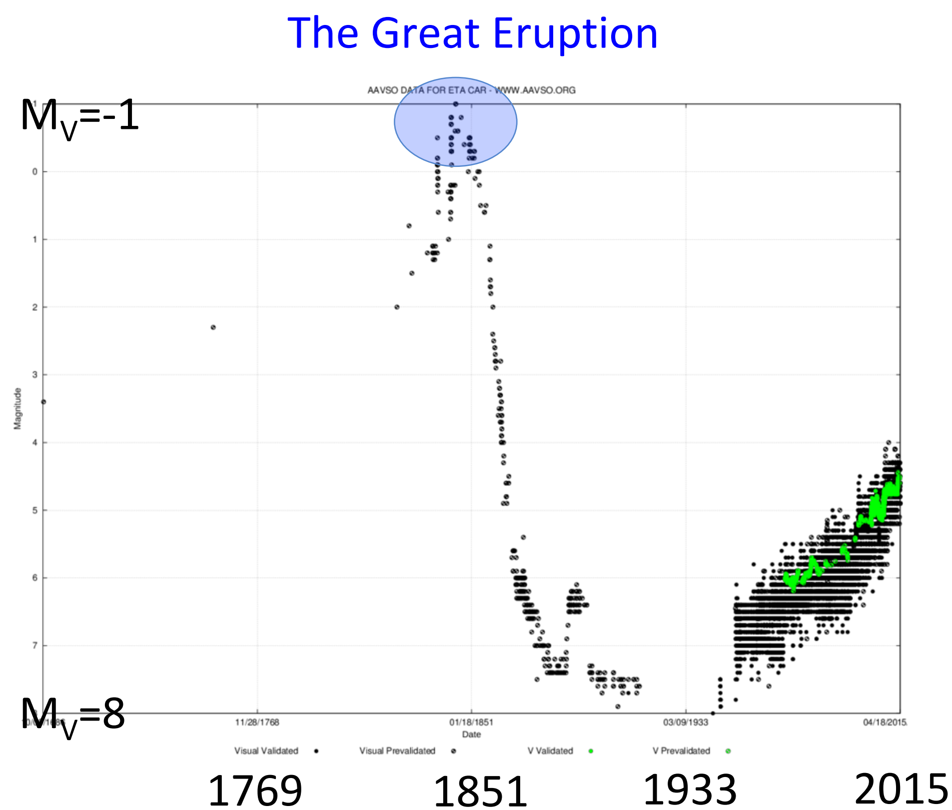
Evolution of stars with intermediate mass



Observations of massive stars: Luminous Blue Variables (LBVs)



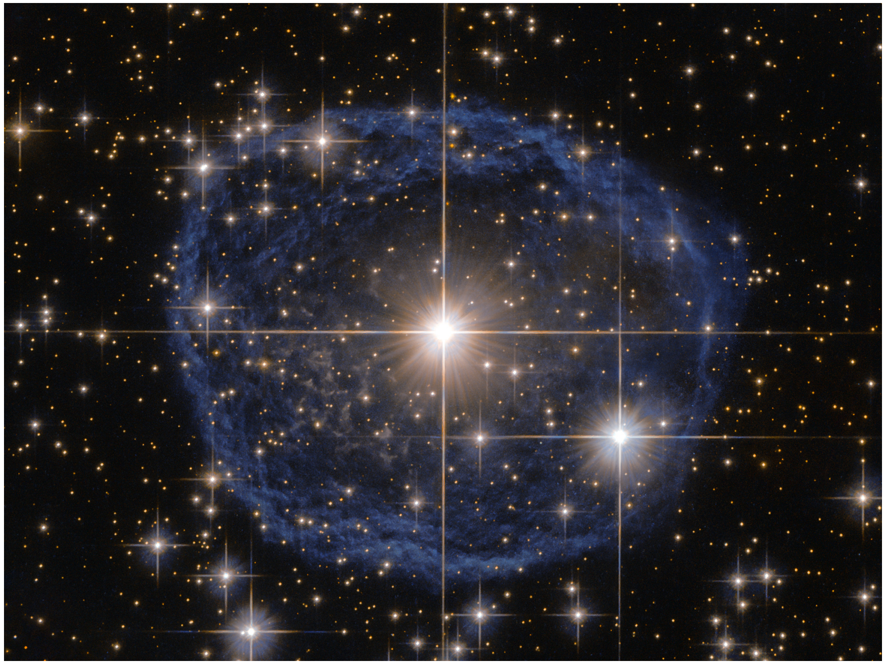
η Carinae: an 120-solar-mass star surrounded by a large nebula consisting of two lobes, each ~0.1 pc across



Historical visual magnitude of η Carinae

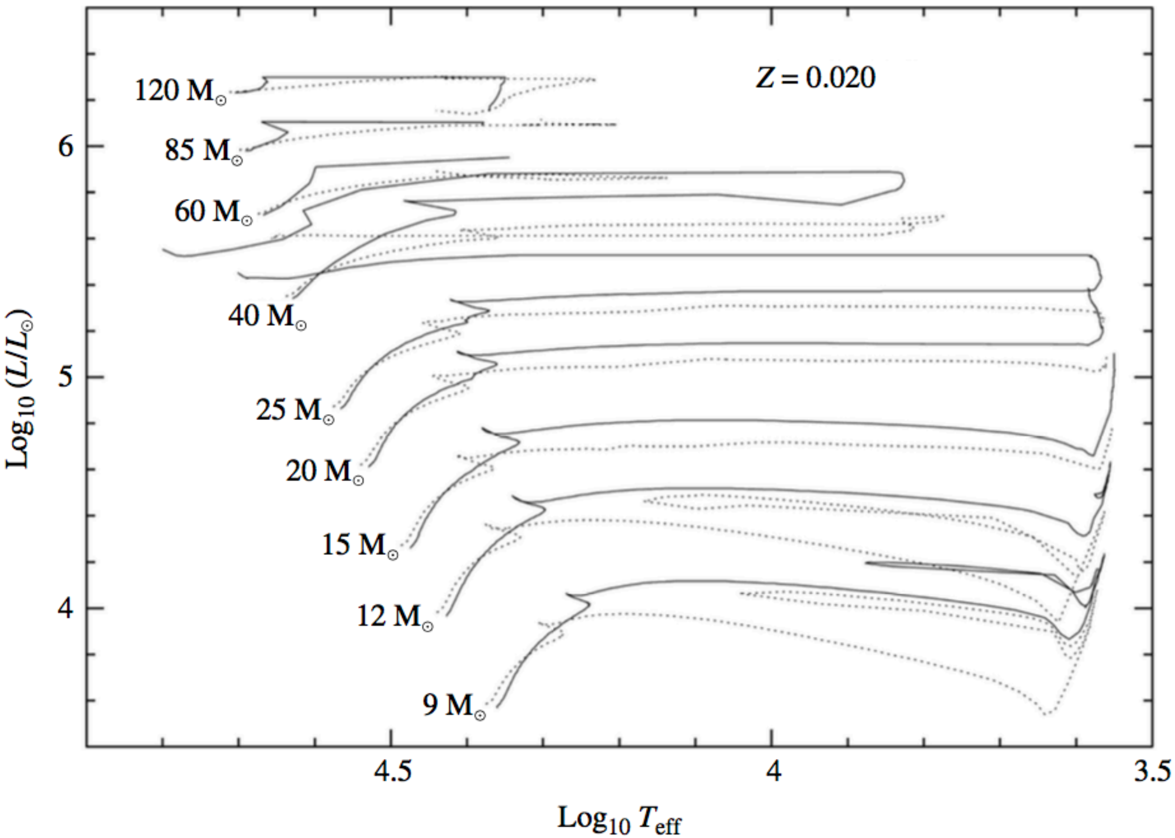
Observations of massive stars: Wolf-Rayet Stars

- Very hot, massive stars
- Effective temperature 25,000 K to 100,000 K
- Extreme mass loss ~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 ~315x solar mass



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

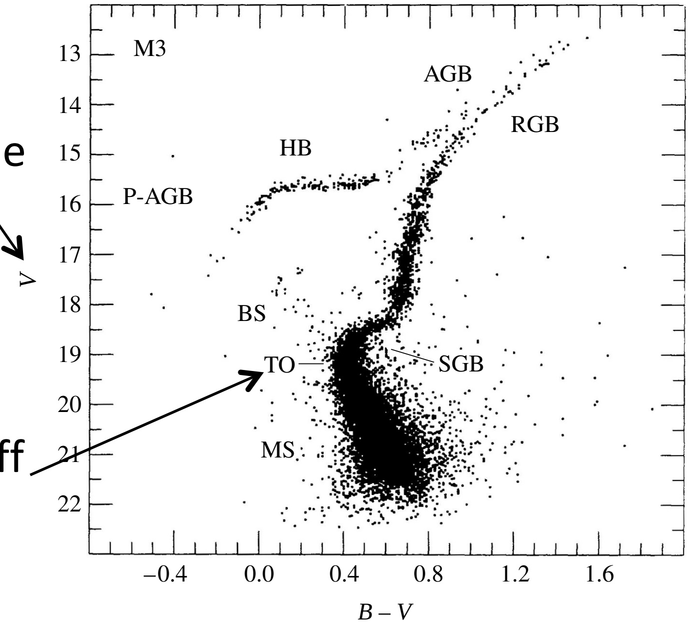
Evolution of massive stars



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

Stellar clusters

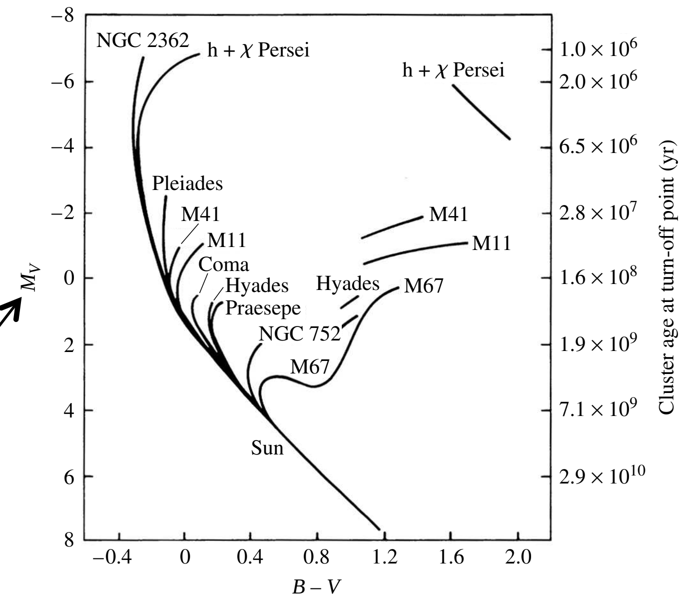
HR diagram of M3



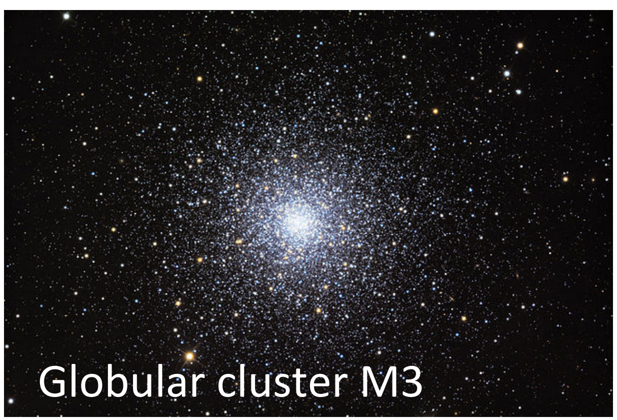
Apparent magnitude

Turn-off point

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



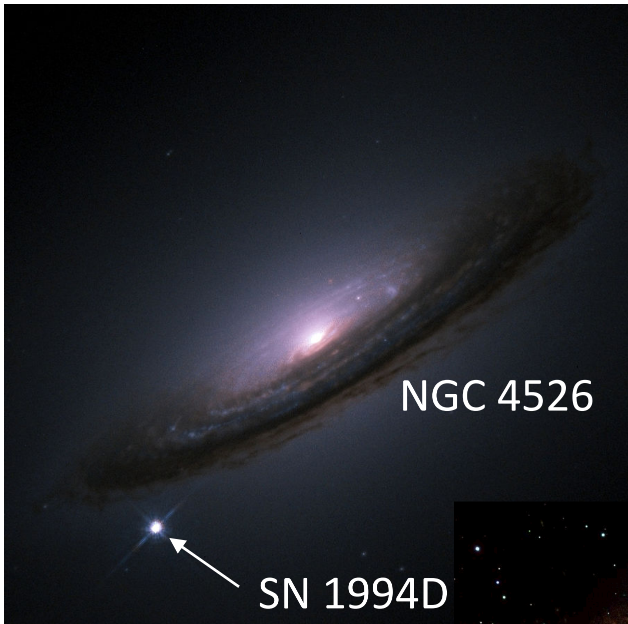
Absolute magnitude

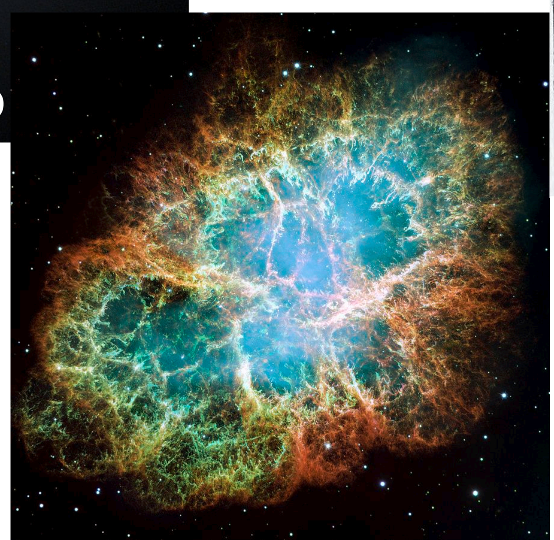


Fate of massive stars

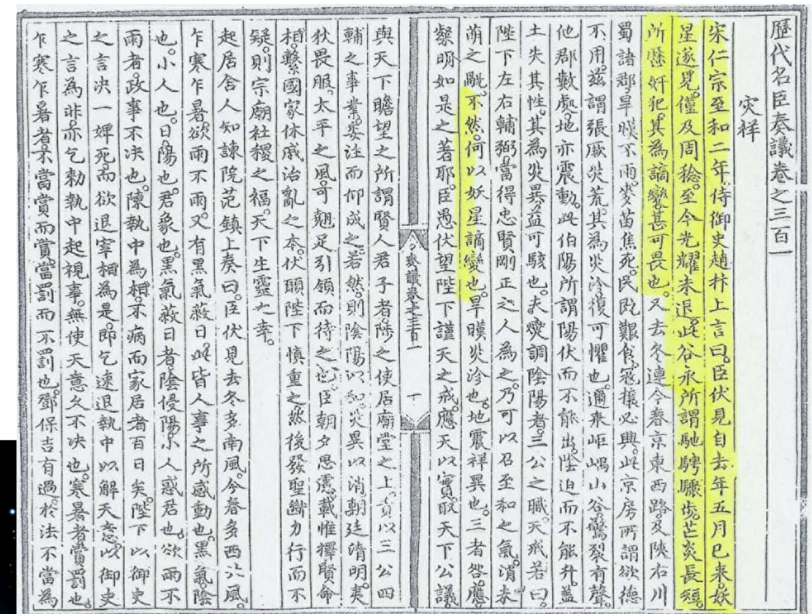
Fate of massive stars: Supernovae

Transient, but titanic explosions in the Universe



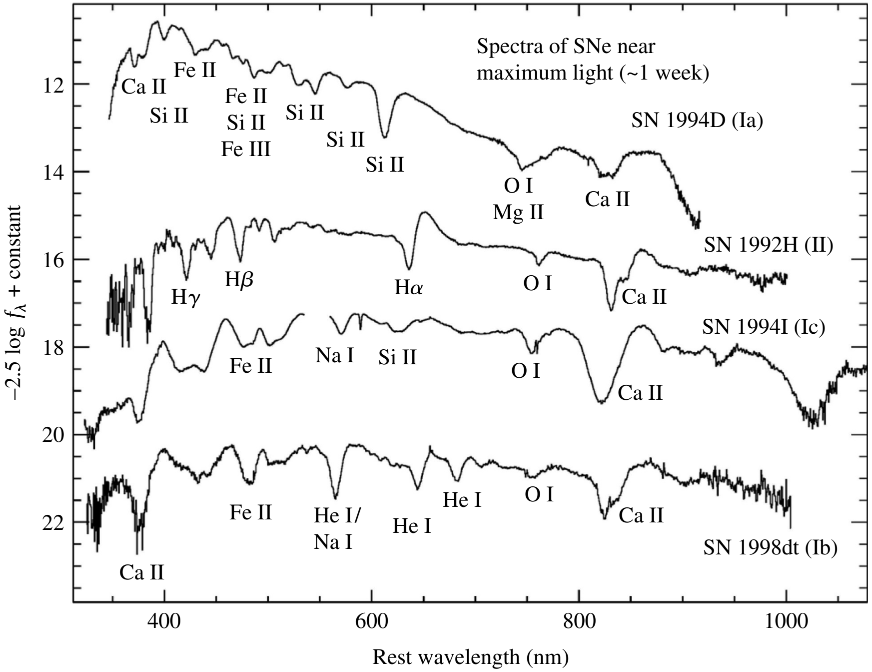


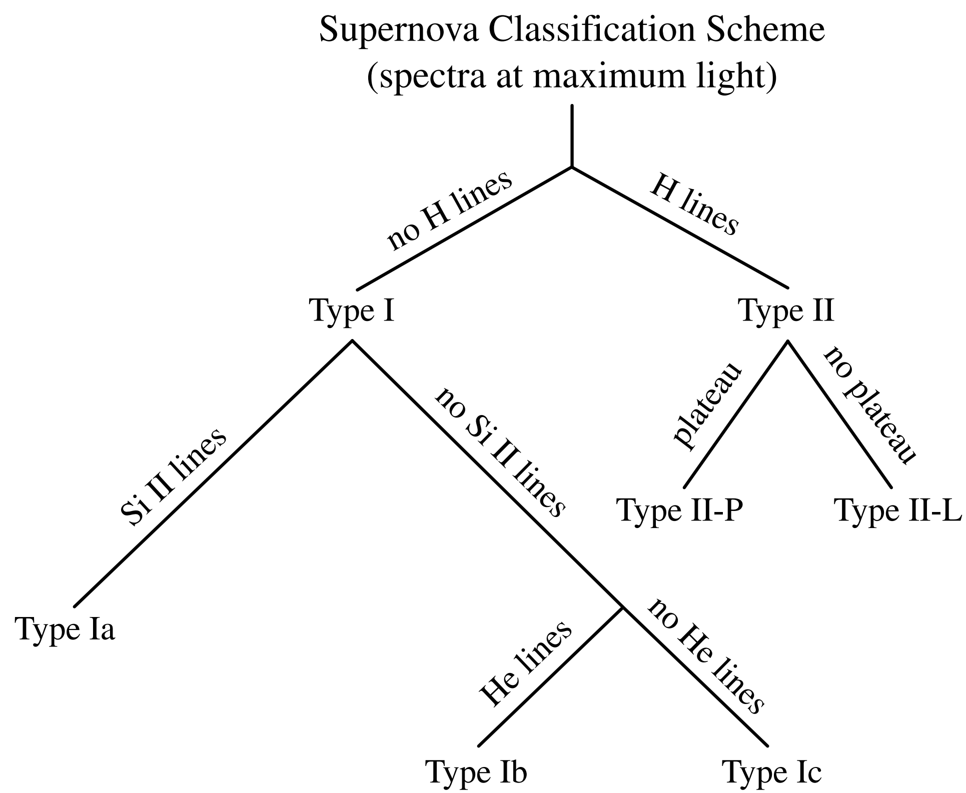
The Crab Nebula


歷代名臣奏議卷之三百一
災祥
宋仁宗至和二年。侍御史趙抃上言曰。臣伏見自去年五月巳來。妖
星遂見。僅及周朞。至今光耀未退。此谷永所謂馳騁驟步。芒炎長類。
所懸奸犯。其為譴變甚可畏也。又去冬連今春京東西路及陝右川
蜀諸郡旱暵不雨。麥苗焦死。民既艱食。寇攘必興。此京房所謂欲德
不用。茲謂張厥災荒。其為災沴複可懼也。邇來岷嵎山谷。驚裂有聲。
他郡數處地亦震動。此伯陽所謂陽伏而不能出。陰迫而不能升。蓋
土失其性。其為災異益可駭也。夫變調陰陽者。三公之職。天戒若曰。
陛下左右輔弼。當得忠賢剛正之人為之。乃可以召至和之氣。消未
萌之亂。不然。何以妖星譴變也。旱暵災沴也。地震祥異也。三者咎應。
粲明如是之著耶。臣愚伏望陛下謹天之戒。應天以實。取天下公議
奏議卷之三百一 十
與天下瞻望之所謂賢人君子者。陟之使居廟堂之上。責以三公四
輔之事業。委注而仰成之。若然。則陰陽以和。災異以消。朝廷清明。天
下晏服。太平之風。可翹足引領而待之也。臣朝夕思慮。載惟擇賢命
相。繫國家休戚治亂之本。伏願陛下慎重之。然後發聖斷。力行而不
疑。則宗廟社稷之福。天下生靈之幸。
起居舍人知諫院范鎮上奏曰。臣伏見去冬多南風。今春多西北風。
乍寒乍暑。欲雨不雨。又有黑氣蔽日。此皆人事之所感動也。黑氣陰
也。小人也。日陽也。君象也。黑氣蔽日者。陰侵陽。小人惑君也。欲雨不
雨者。政事不決也。陳執中為相。不病而家居者百日矣。陛下以御史
之言決一婢死。而欲退宰相為是邪。乞速退執中。以解天意。以御史
之言為非邪。乞勑執中起視事。無使天意久不決也。寒暑者賞罰也。
乍寒乍暑者。不當賞而賞。當罰而不罰也。鄧保吉有過。於法不當為

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

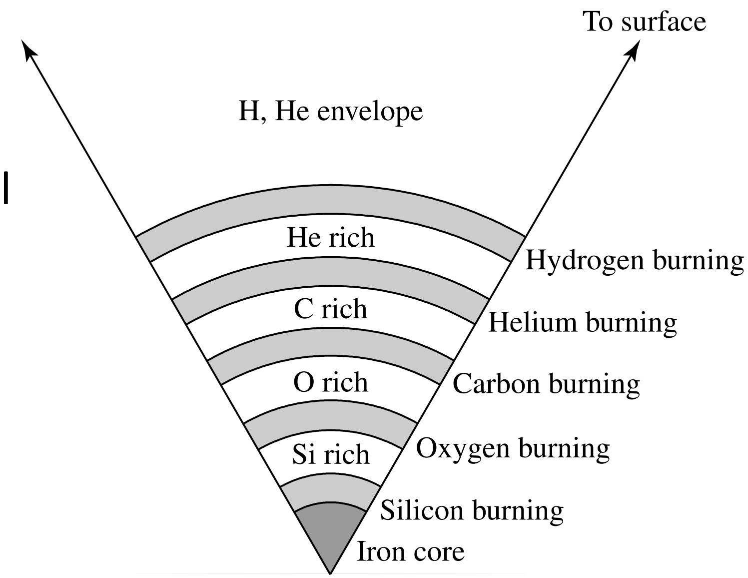
$$^{56}_{26}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}_{2}\mathrm{He} + 4n$$

$$^{4}_{2}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n.$$

Neutron formation

$$p^{+} + e^{-} \rightarrow n + \nu_{e}.$$

- 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

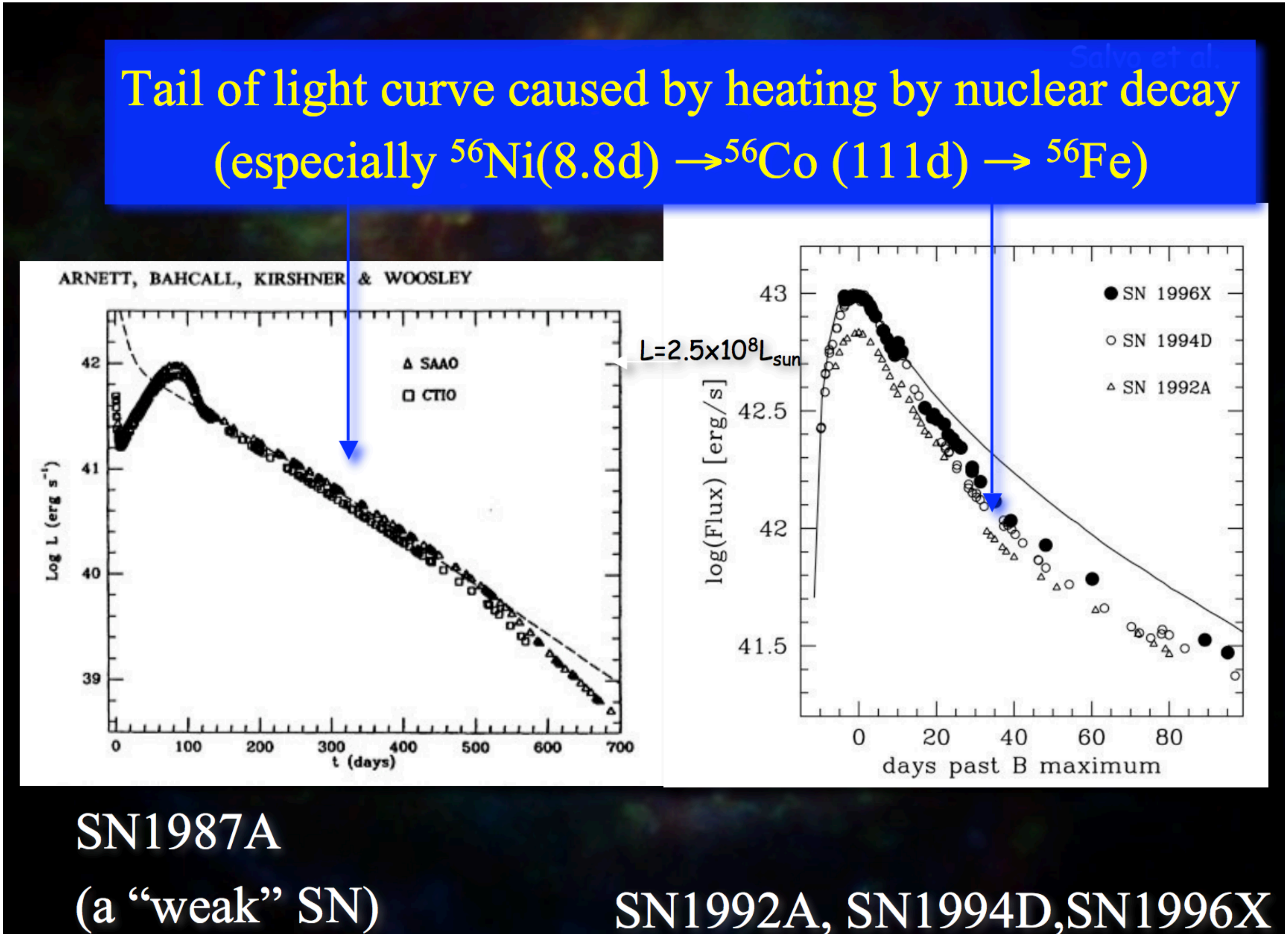
Core-collapse supernovae: Energy release

- During the collapse, speeds can reach 70,000 km/s (~0.2 c)
- Within <1 s, a volume of the size of Earth can been compressed down to ~50 km, ~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!

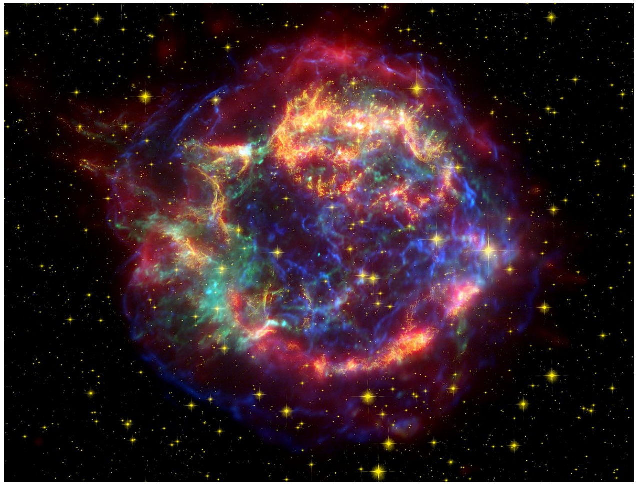
Supernova Explosion

- 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 10^9x solar luminosity, capable of competing with the brightness of the entire galaxy!

Supernova lightcurves

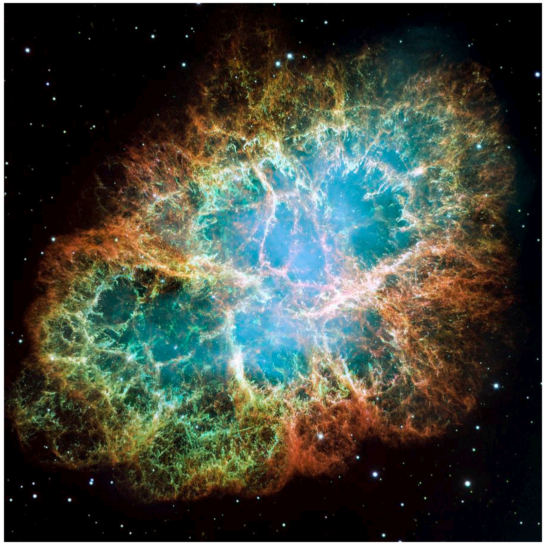


Supernova Remnants



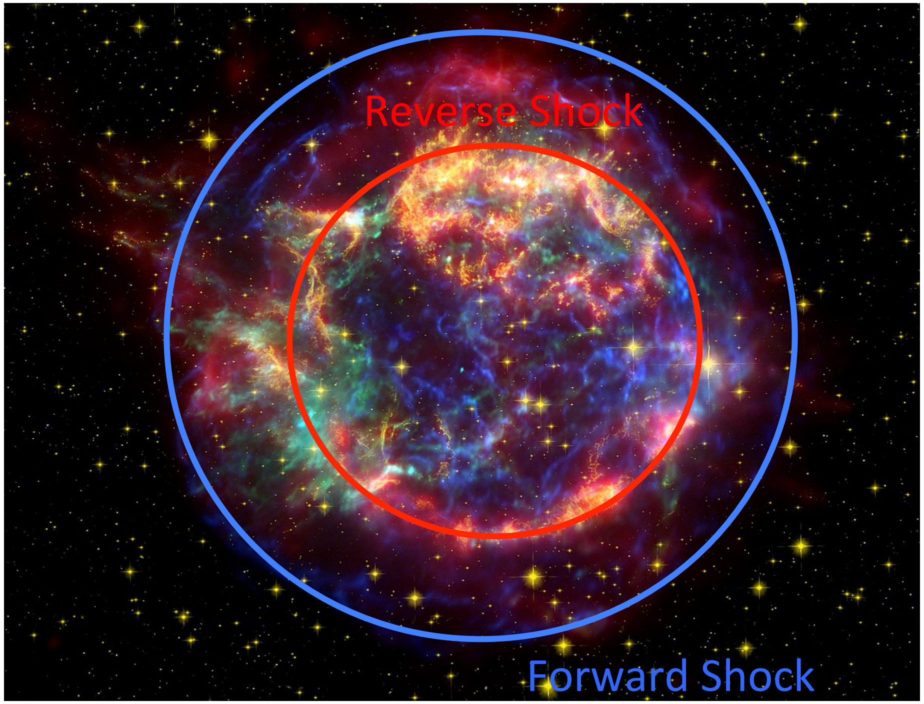
Cassiopeia A (SN 1671A?)

Crab Nebula (SN 1054A)



SN 1987A (in LMC)

Supernova Remnants



Cassiopeia A

Shocked ISM

Shocked Ejecta