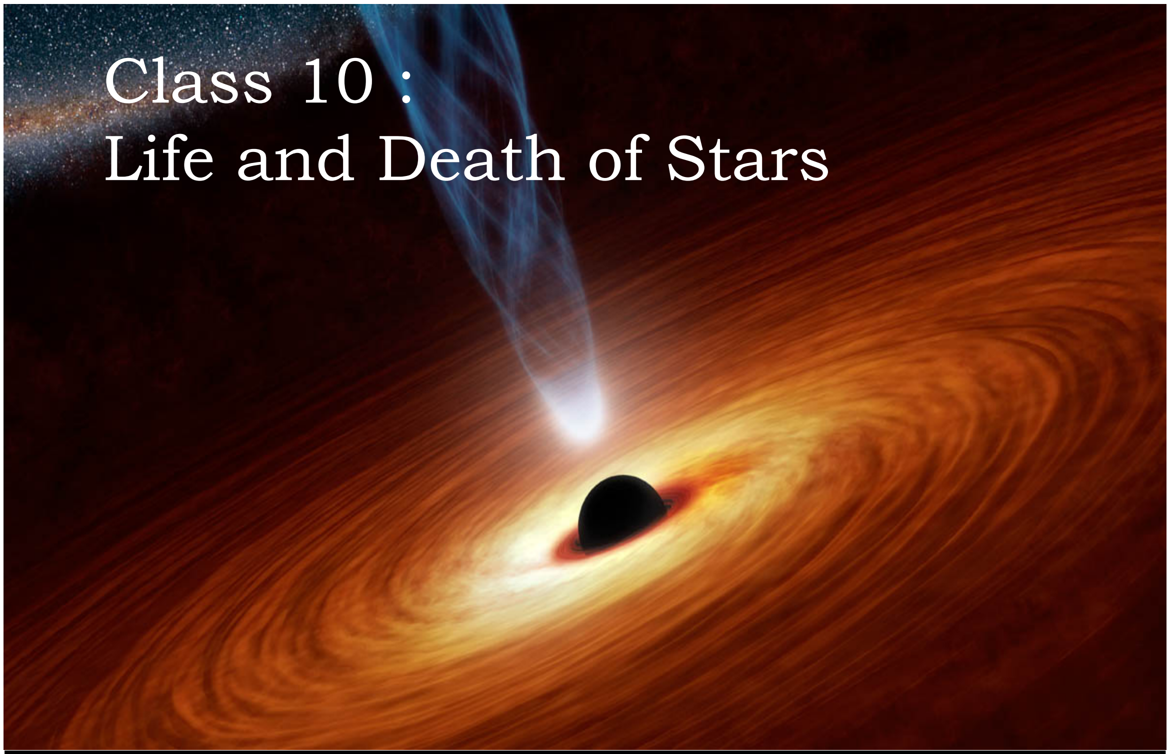
Class 10 : Life and Death of Stars



ASTR350 Black Holes (Spring 2020)
Prof. Richard Mushotzky

RECAP

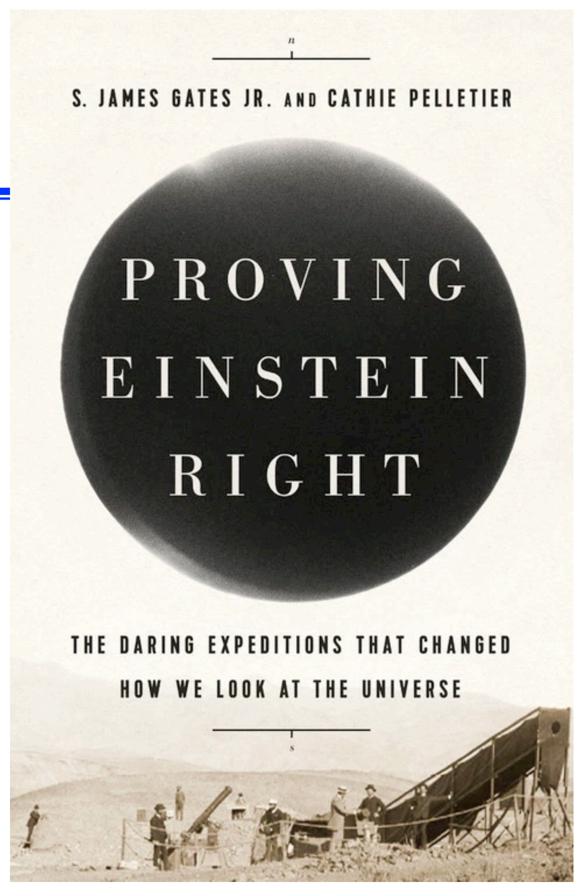
- Kerr black holes
  - No hair theorem – any (isolated) black hole is determined purely by its mass, spin and charge.
  - Ergosphere – region containing energy of rotation. Impossible to stand still there… must rotate in same sense as the black hole
  - Event horizon is smaller for spinning black holes. No horizon at all for a>1 (superspinners), although these may not exist
  - Can extract more energy from Kerr black holes
  - Special orbits around black holes
    - Innermost stable circular orbit
    - Photon circular orbit

This class

- Start the discussion of real black holes
- Focus on "stellar mass black holes"
- Come from the death of stars… *so must first study the life of stars!*
- Two case studies…
  - Low mass star ($M<8M_{sun}$)
  - High mass star ($M>8M_{sun}$)

- **Homework 4 due, Homework 5 see ELMS Due March 5**

New Book by U of MD Prof. S. Gates

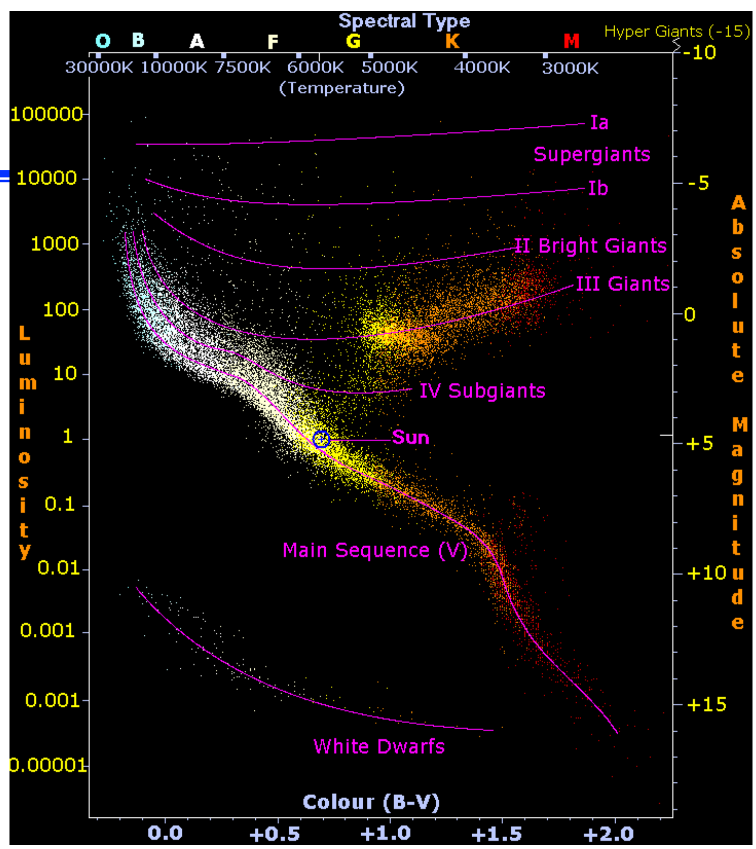


I : Some reminders about stars

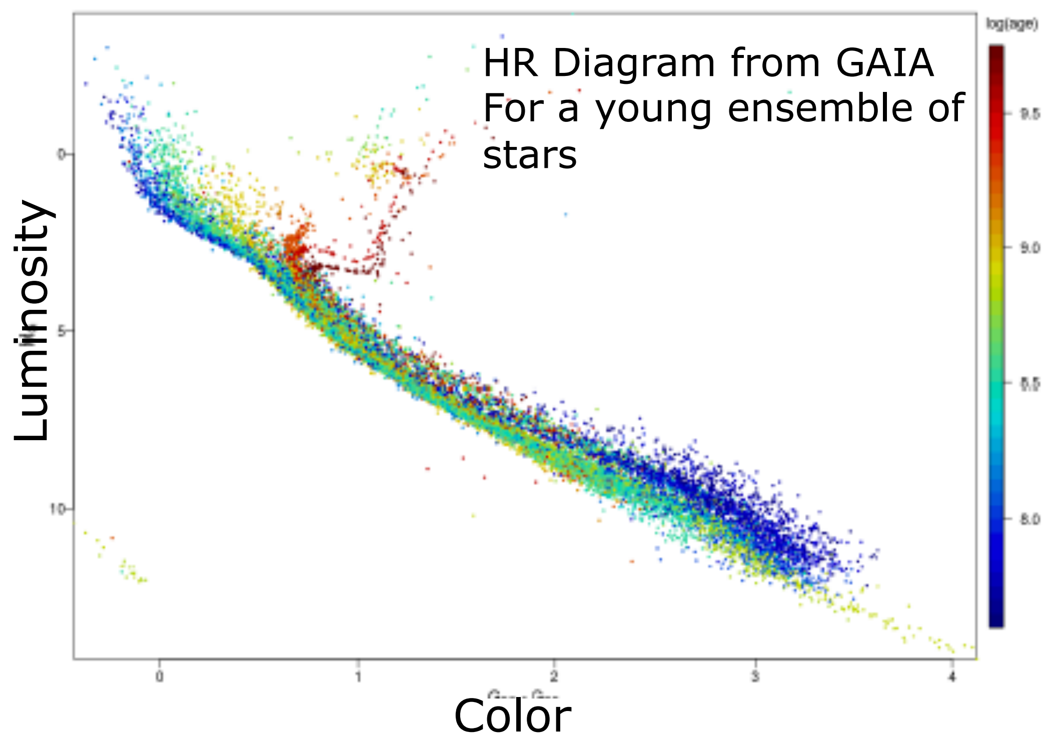
- Stars have variety of…
  - Colors (Temperature; 3000K-30000K)
  - Luminosities ($0.001L_{sun}$ – $100{,}000L_{sun}$)
  - If we plot the luminosity and temperature/color of a collection of stars (Hertzsprung-Russell Diagram), we find distinct patterns emerging… most stars lie on a line called the **main sequence.**

I : Some reminders about stars

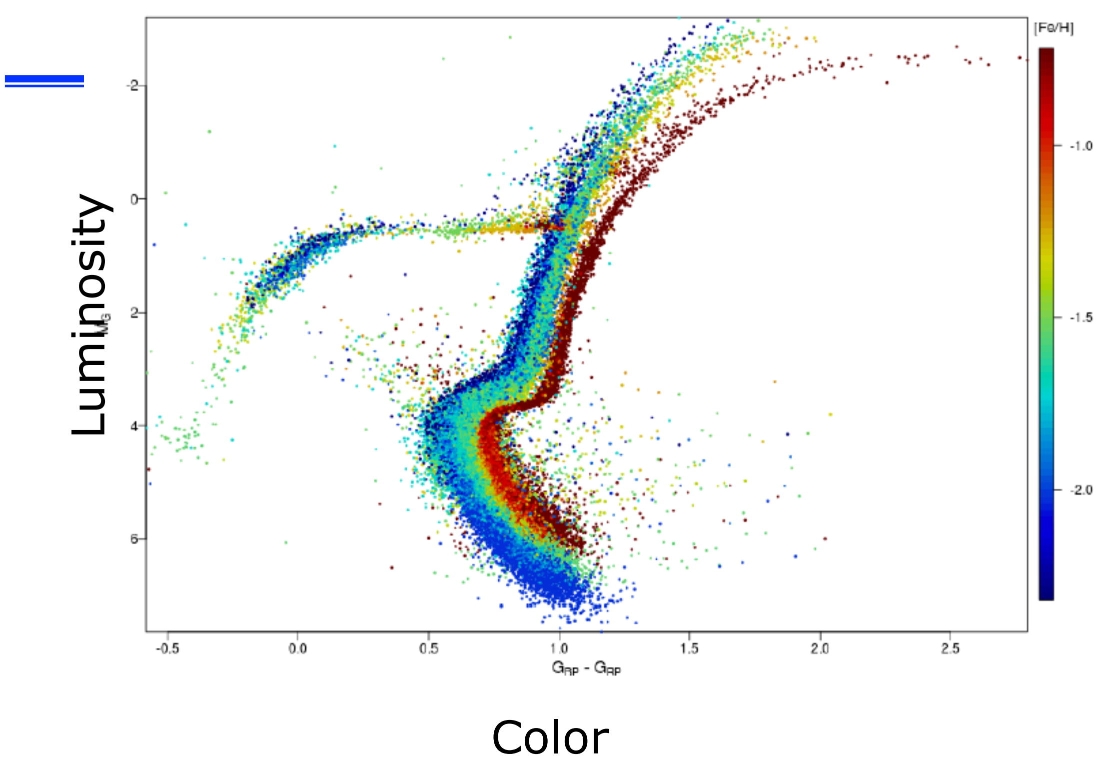
- Differences mostly due to **mass** and **age** of star:
  - **Main sequence** is the normal/long-lived part of the stars live. This is the H➔He fusion phase.
  - Location on main sequence determined by mass (high-mass = hot and luminous low-mass = cool and dim).
  - Stars leave the main sequence and move around the HR-diagram as they age.



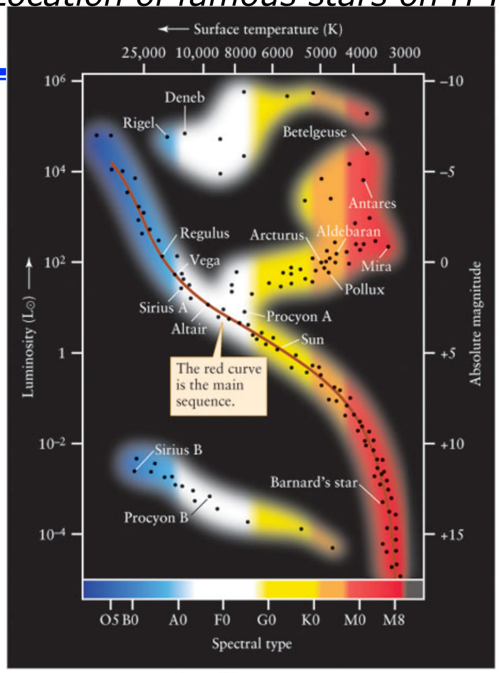
Gaia Collaboration et al.: *Gaia* Data Release 2: Observational Hertzsprung-Russell diagrams



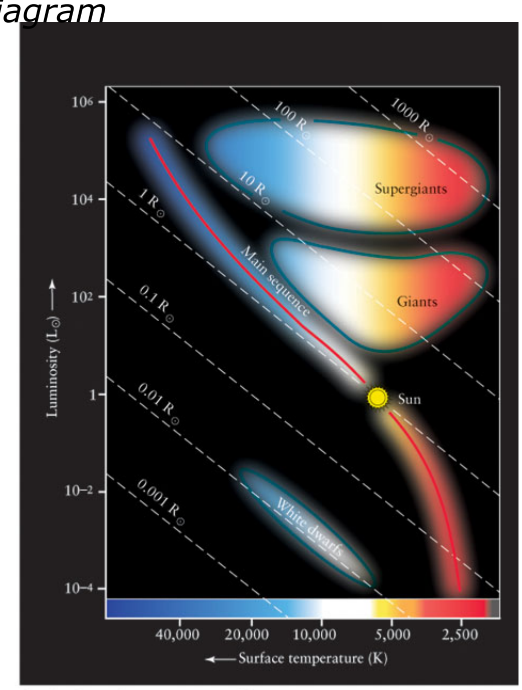
HR Diagram from GAIA-For a old ensemble of stars – color coded by metallicity



Location of famous stars on H-R Diagram



(a) A Hertzsprung-Russell (H-R) diagram

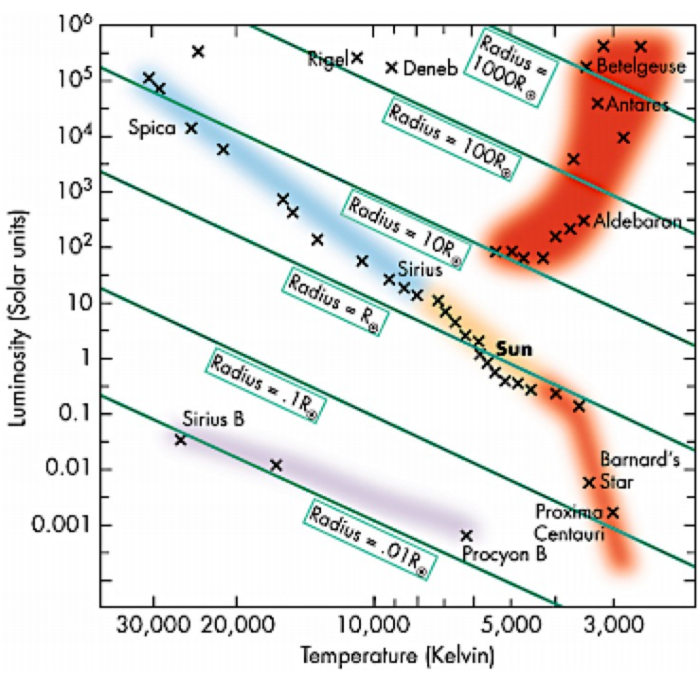


(b) The sizes of stars on an H-R diagram

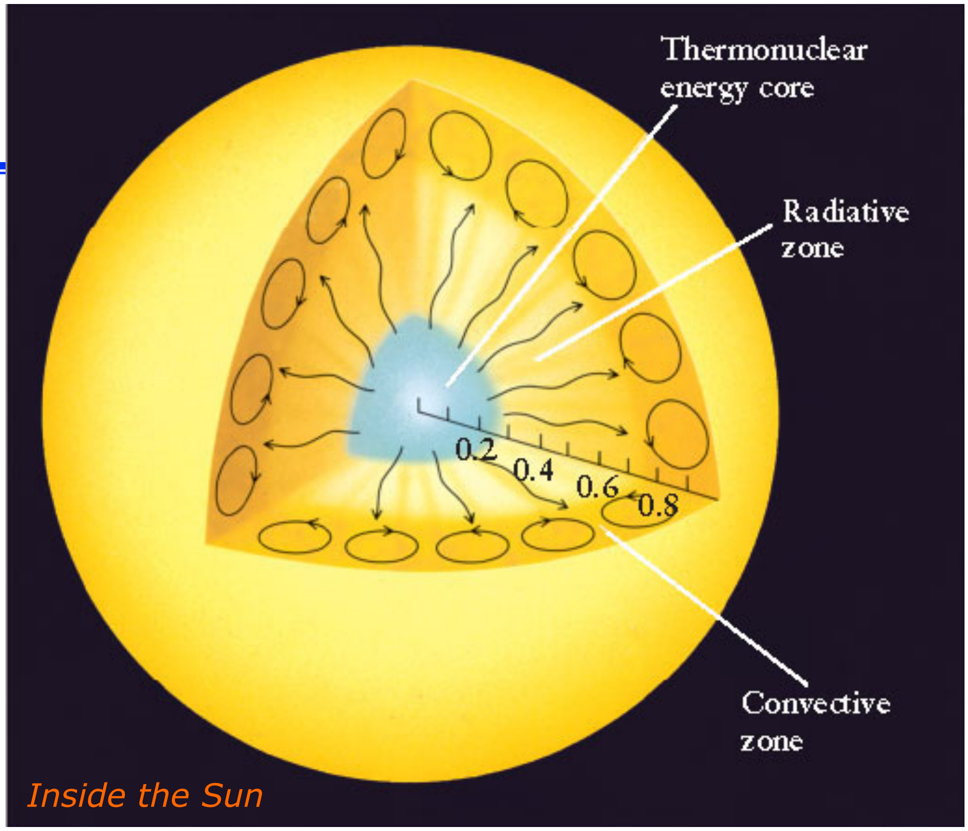
Stellar Sizes/Luminosity/Temperature

Stefan-Boltzman law- Lines L~AT⁴ (T= temperature, A= area)

- Over a wide range in luminosity stars radiate close to a Black body spectrum in the optical band



http://www.physics.isu.edu/~hackmart/spectral_class.pdf



II : Hydrogen burning

- Basic process during main sequence: 4H → ^{4}He
  - **0.7% of mass is converted to energy**…

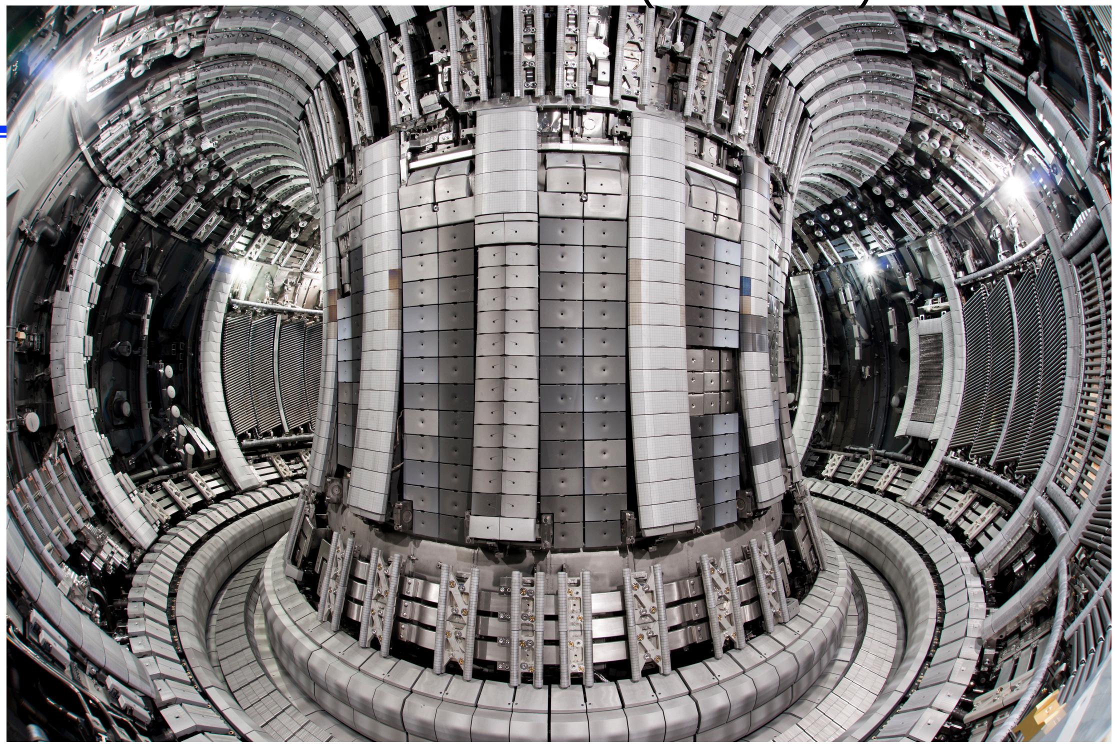
$$\text{efficiency} = \frac{\text{energy released}}{(\text{total mass processed})c^2}$$

  - About 10^6 times more efficient than chemical burning

- But, eventually, the star runs out of hydrogen in its core. For all but the most massive stars, the time until the star runs out of hydrogen is

$$\tau \approx 1.0 \times 10^{10} \left(\frac{M}{M_\odot}\right)^{-2.5} \text{yr}$$

A fusion reactor (tokomak)



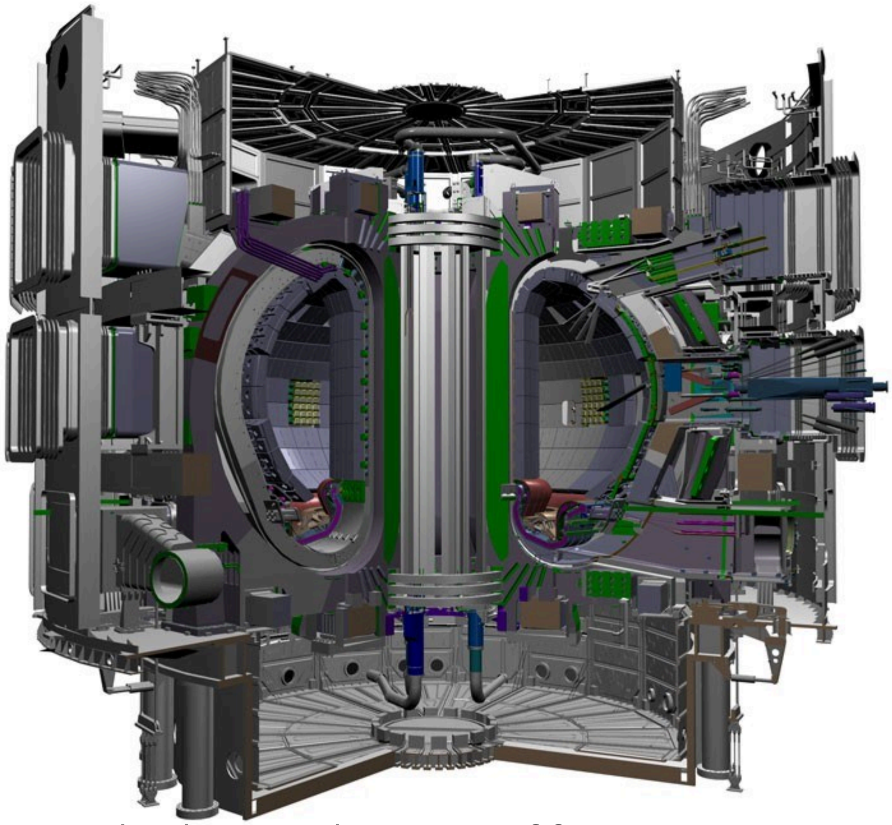
Fusion Power

UNLIMITED ENERGY

Fusion, the nuclear reaction that powers the Sun and the stars, is a potential source of safe, non-carbon emitting and virtually limitless energy.
~10^6 times more energy per gram than burning oil/gas.

So far 16 MW for less than a second) by the fusion of about 0.5 g of deuterium/tritium (isotopes of Hydrogen)

Conditions need a temperature of ~10^8 k



ITER-designed to harness the energy of fusion

“Astrophysics is a fight between gravity and everything else”

Prof. Cole Miller (UMd)

III : Post-MS evolution of low-mass star ($M<8M_{sun}$)

- Once hydrogen runs out in core after millions of years…
  - Energy production stops
  - Core contracts (gravity no longer balanced by outward flow of energy)
  - Envelope of star expands ➔ Red Giant
  - Core contraction ➔ heating ➔ helium fusion! (provided that $M>0.4M_{sun}$)

$$3He \rightarrow C$$

  - Star expels envelope in series of explosive events (nova) ➔ planetary nebula
  - He or C core remains as a **white dwarf** (stellar mass but size of Earth)

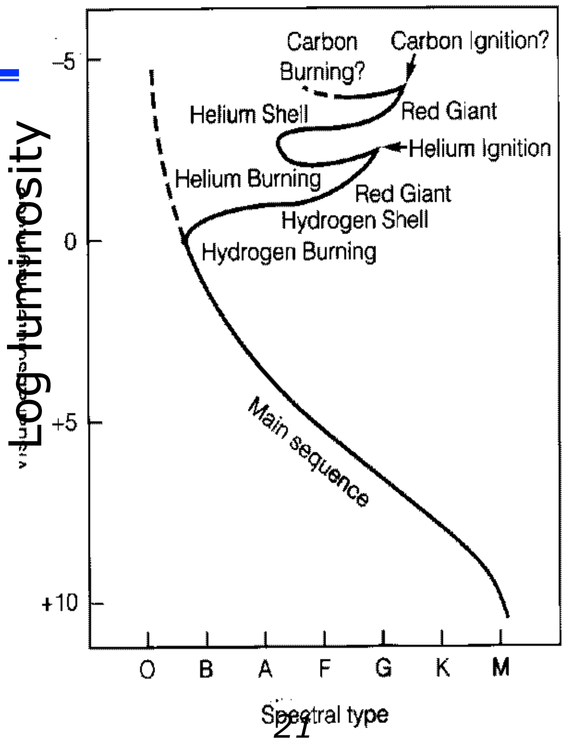
Off the MS

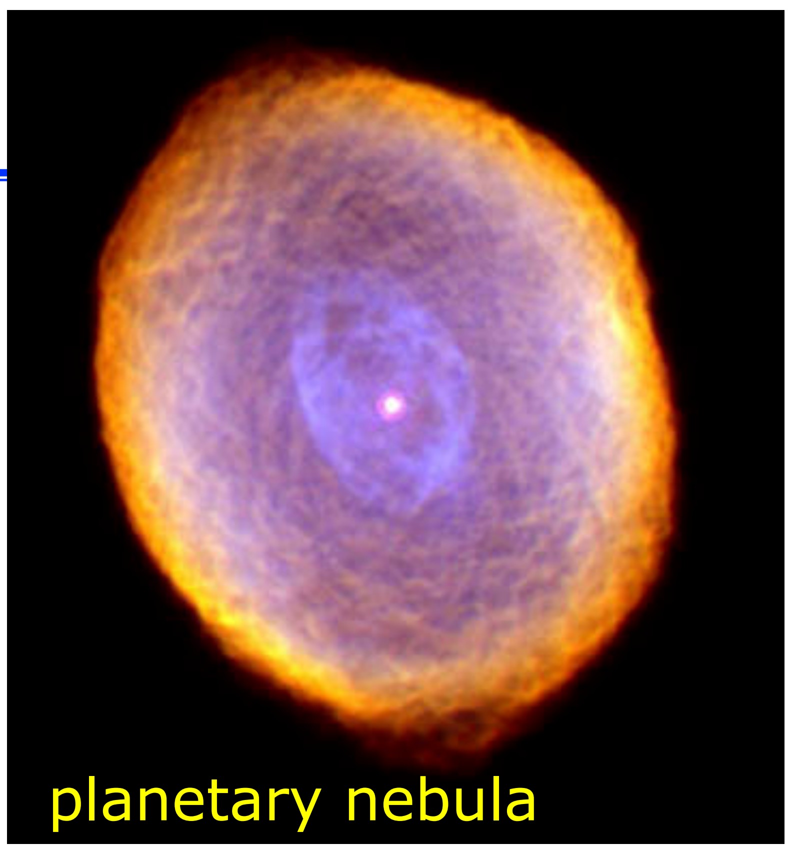
- He burning only releases ~20% of the energy that H burning produces

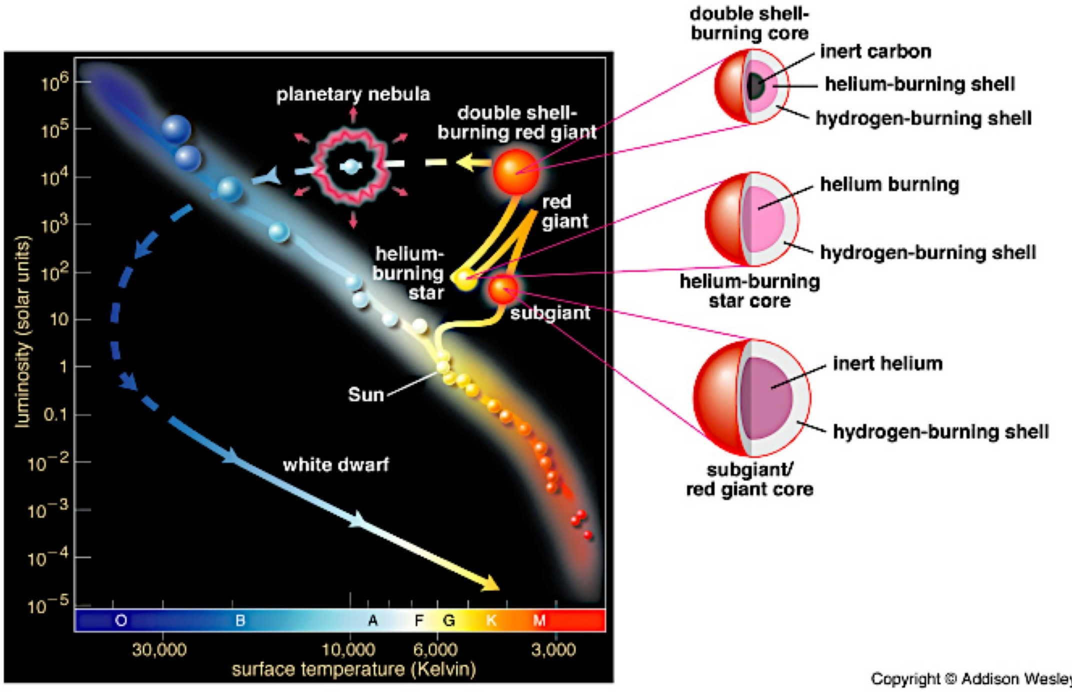
- Lifetime in the He burning phase is short...

~ 2×10^9 yrs for a solar mass star

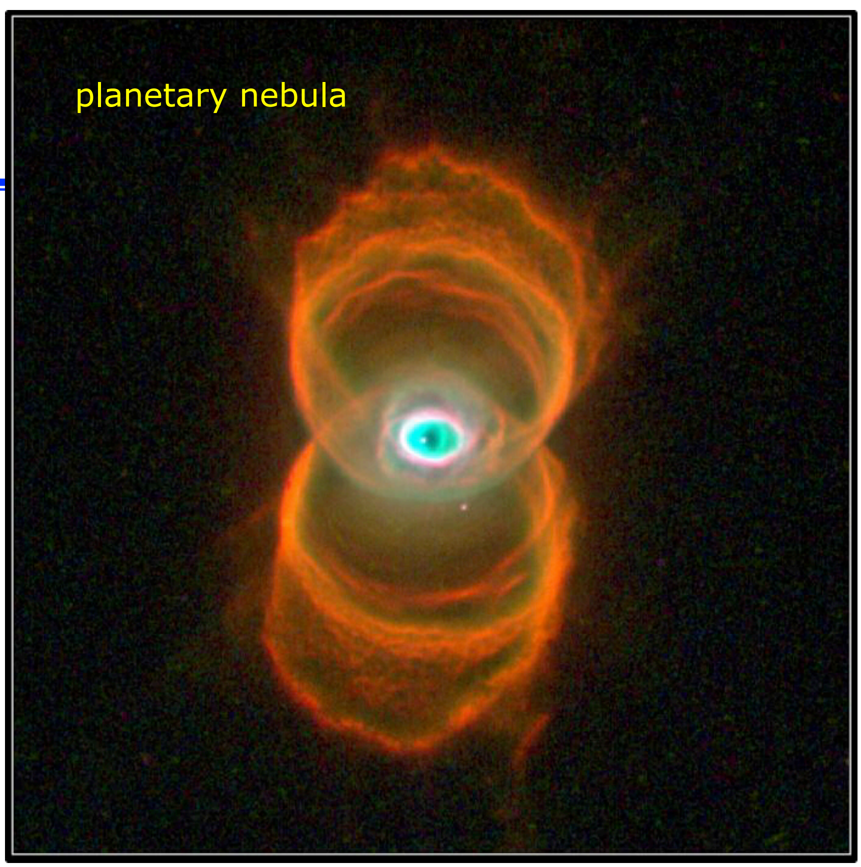
- Stars on the giant branch are ***very*** luminous

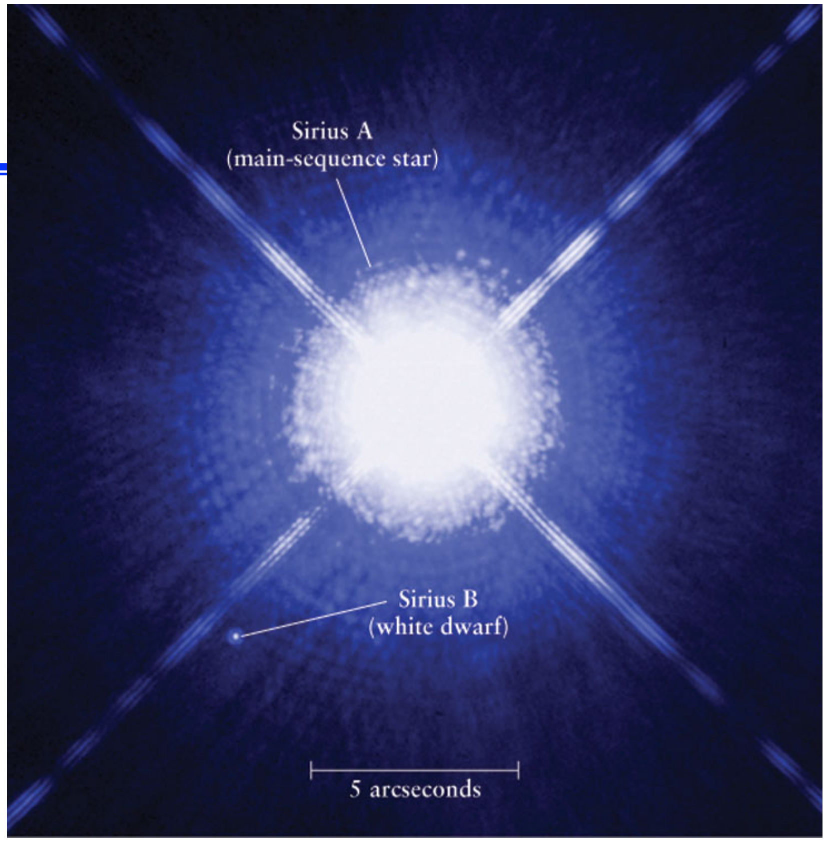


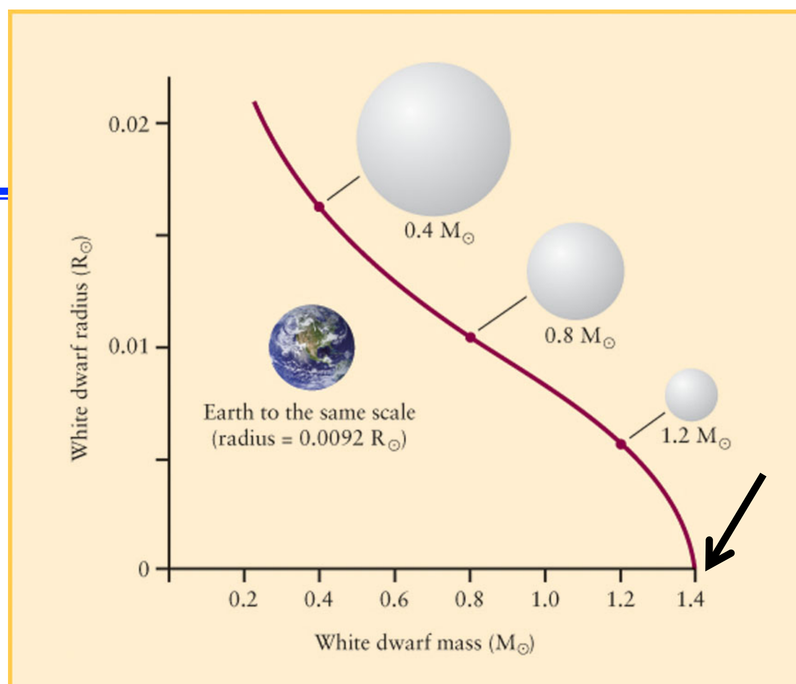




http://astronomyonline.org Copyright Addison Wesley







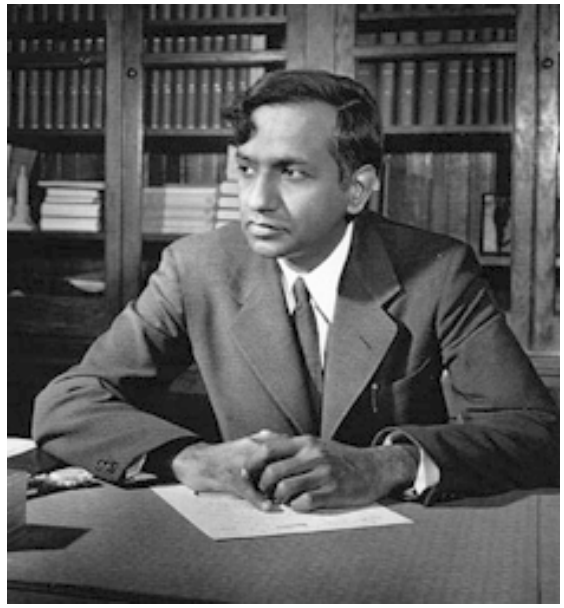
As white dwarf increases in mass it gets smaller-

white dwarfs are supported against gravity by relativistic electron degeneracy

This produces a maximum mass which can be supported known as the ***Chandraskhar Limit****, and is* $\mathbf{M_{ch} = 1.44\ M_{sun}}$

Subrahmanyan Chandrasekhar

- Important work on understanding of stellar structure, white dwarfs, stellar dynamics, radiative transfer, quantum theory of the hydrogen anion, hydrodynamic and hydromagnetic stability, turbulence, general relativity, mathematical theory of black holes and theory of colliding gravitational waves



A Little History

http://www-news.uchicago.edu/releases/95/950822.chandrasekhar.shtml

In 1930, at the age of 19, Chandrasekhar completed college and boarded a boat to England for postgraduate study at Cambridge University.

While on the voyage, he developed a theory about the nature of stars for which he would be awarded the Nobel Prize 53 years later. His theory challenged the common scientific notion of the 1930s that all stars, after burning up their fuel, became faint, planet-sized remnants known as white dwarfs. He determined that stars with a mass greater than 1.4 times that of the sun–now known as the "Chandrasekhar mass"– must eventually collapse past the stage of a white dwarf into an object of such enormous density that "one is left speculating on other possibilities," he wrote.

Initially his theory was rejected by peers and professional journals in England. The distinguished astronomer Sir Arthur Eddington publicly ridiculed his suggestion that stars could collapse into such objects, which are now known as black holes.

Chandrasekhar Mass

Combined general relativity with quantum mechanics to derive the maximum mass of a white dwarf (1.4 M_{sun})

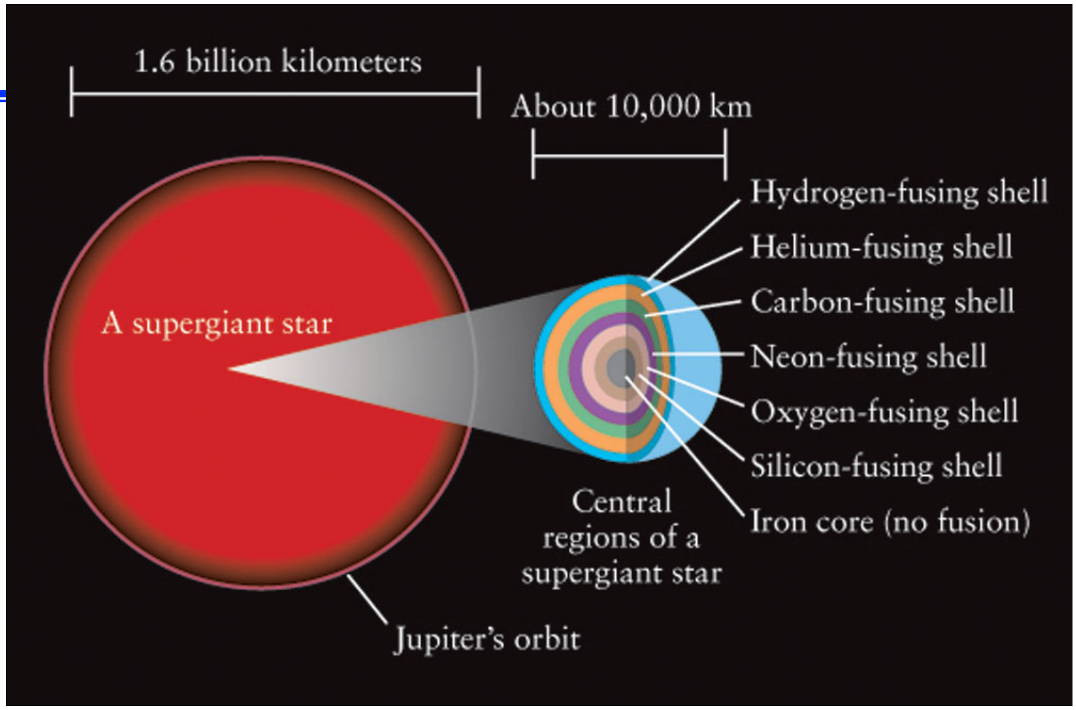
Above this mass it must collapse either into a neutron star or a black hole

Chandrasekhar's work on the limit aroused controversy, owing to the opposition of the British astrophysicist Arthur Eddington. Eddington was aware that the existence of **black hole**s was theoretically possible, and also realized that the existence of the limit made their formation possible. However, he was unwilling to accept that this could happen. After a talk by Chandrasekhar in 1935, he replied:
The star has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few km radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace. … I think there should be a law of Nature to prevent a star from behaving in this absurd way![25]

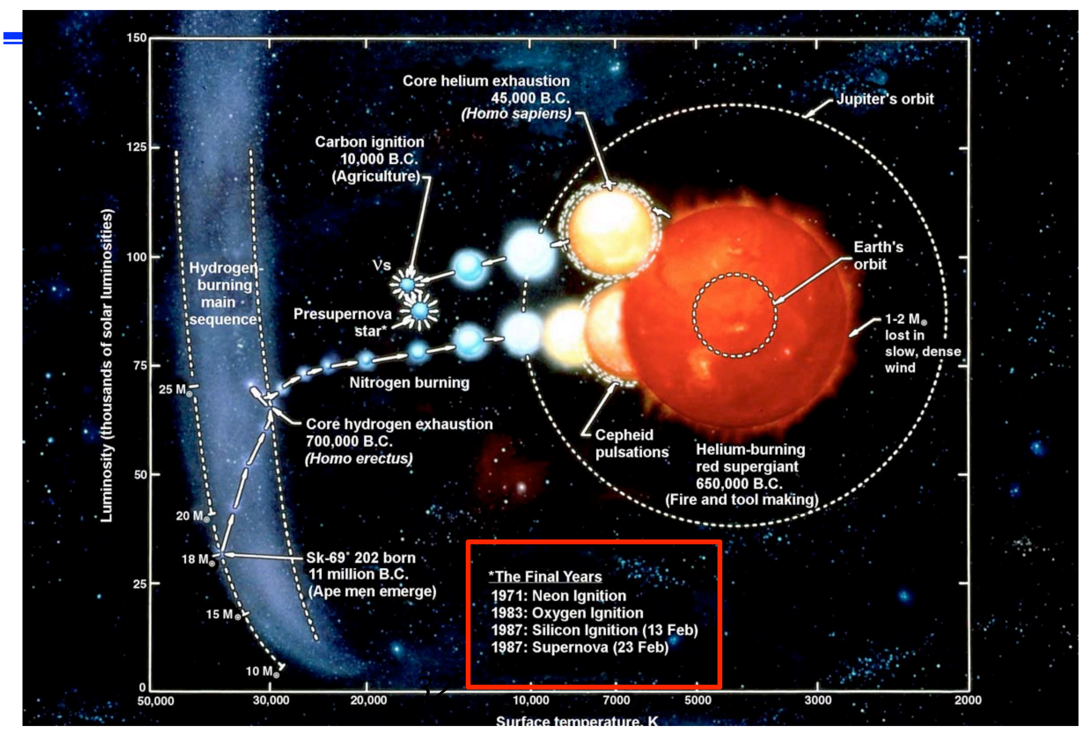
II : Evolution of a high-mass star

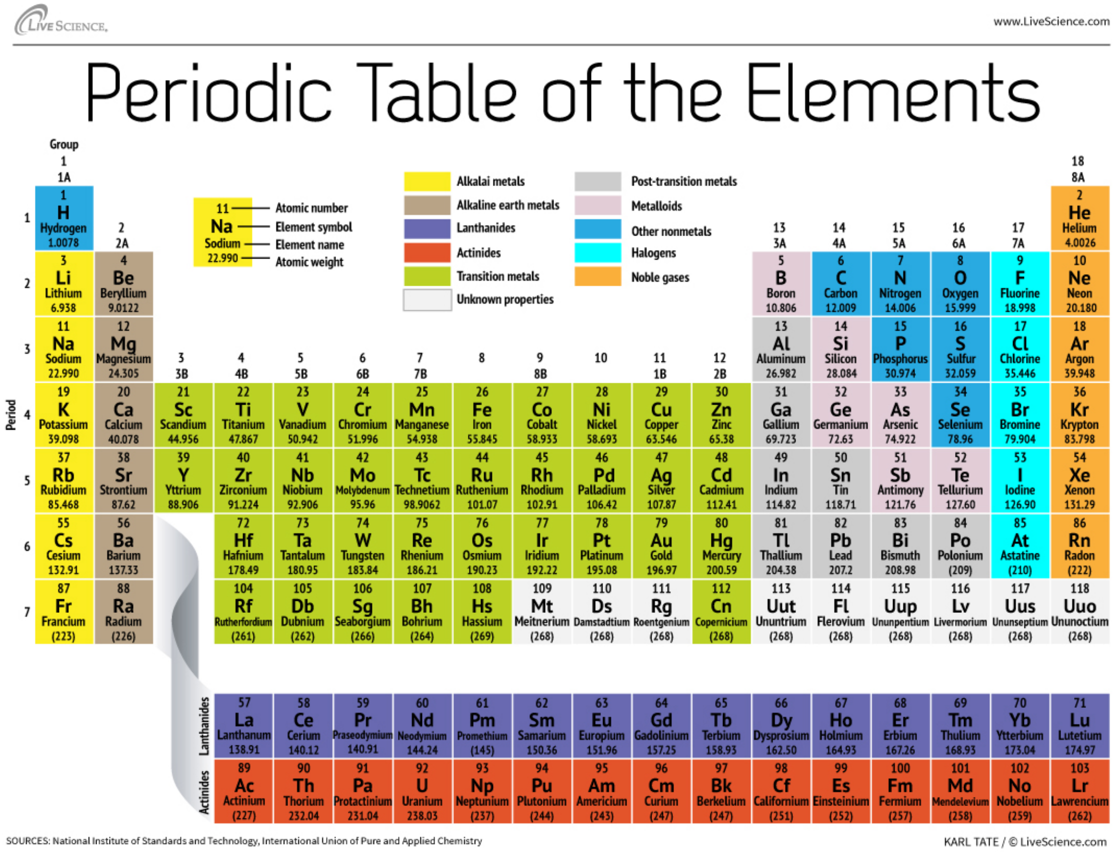
- Stars with $M>8M_{sun}$ take a different path… core gets hot enough that nuclear burning can proceed beyond Carbon
  - There is a sequence of reactions that go all of the way from H to Fe (iron)
  - The fusion reactions get less and less efficient as the sequence proceeds… mass must be processed as a progressively faster rate in order to satisfy stars demand for energy
  - **Iron is the end of the road**… it has the most stable nucleus and so you cannot extract energy by fusing it
  - Star ends up with a onion-like structure… an iron core surrounded by a shell of Si→Fe burning, which is surrounded by a shell of O→Si burning etc.

Pre-Supernova Stellar Structure

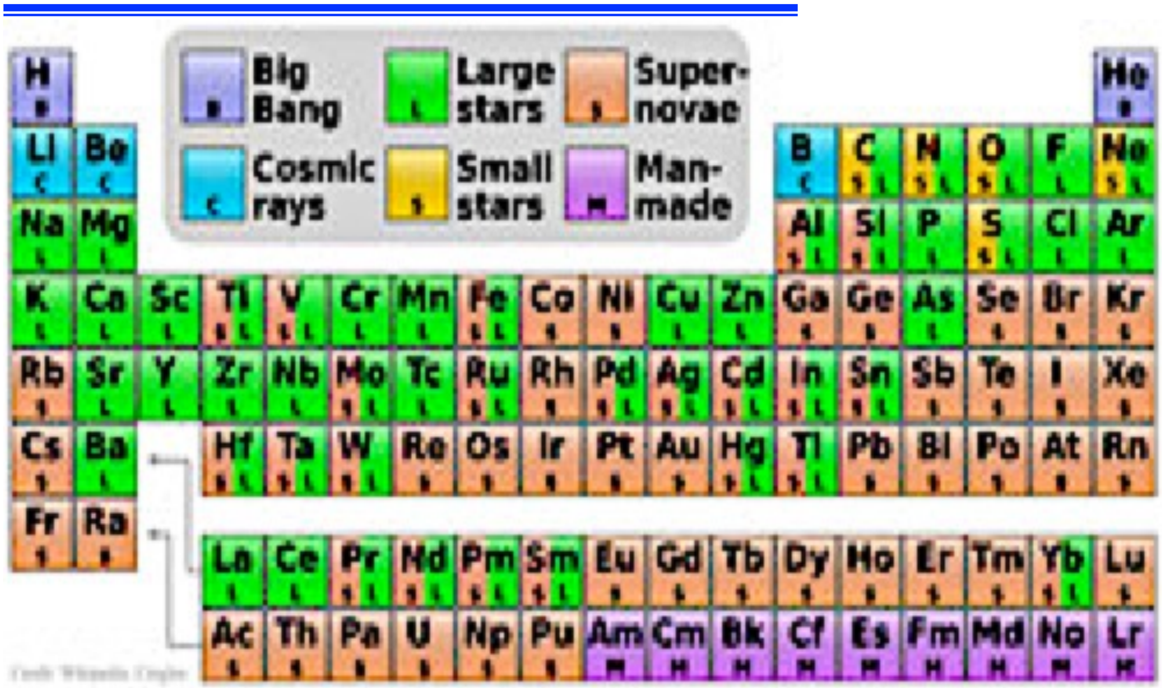


SN1987A- AKA SK-69-202 - Short But Exciting Life
Original Mass = 18 $M_\odot$





Which elements are made where



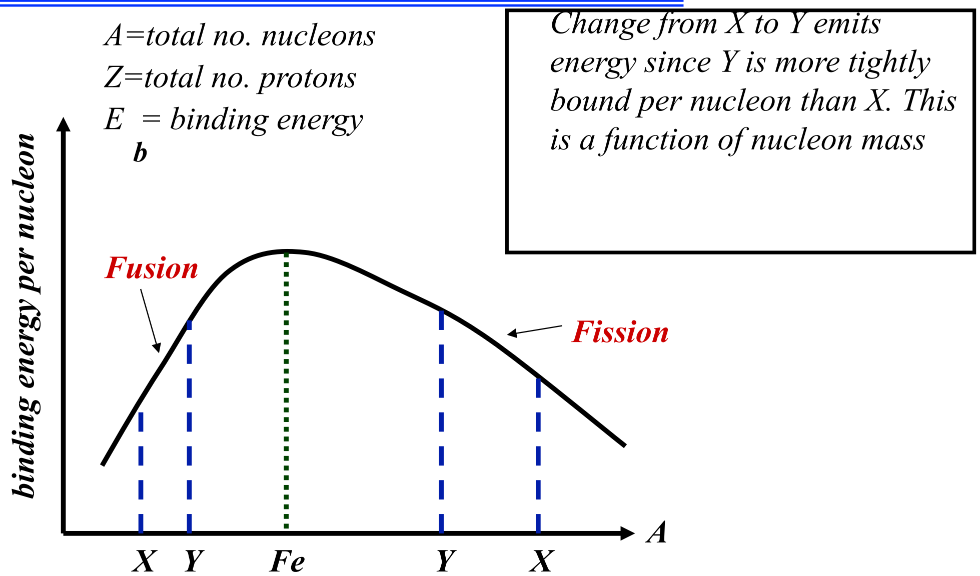
What happens next?

- Once iron is reached, fusion stops in core
- Without energy production, core gets crushed
- When $M_{core} \sim 1.4 M_{sun}$, pressure forces become incapable of supporting core… core undergoes catastrophic gravitational collapse (in less than a second)- Chandrasekhar mass

What happens next?

- Energetics of core collapse…
  - releases about 10^{46} watts-(~10^{12} years of suns luminosity)
  - 99% emerge as neutrinos
  - Star is blown apart… **core collapse supernova**
  - 1% of energy (10^{44}J) emerges as radiation and kinetic energy- as bright as all the stars in the MilkyWay for a few weeks
- Fusion reactions during the supernova responsible for all elements heavier than iron

Binding energy of Nuclei - why stellar burning stops generating energy



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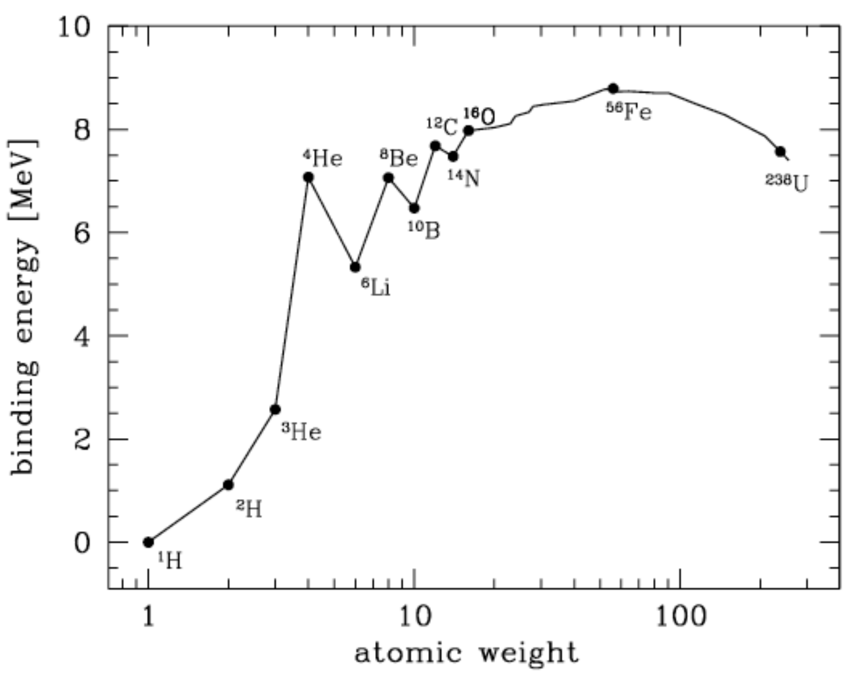
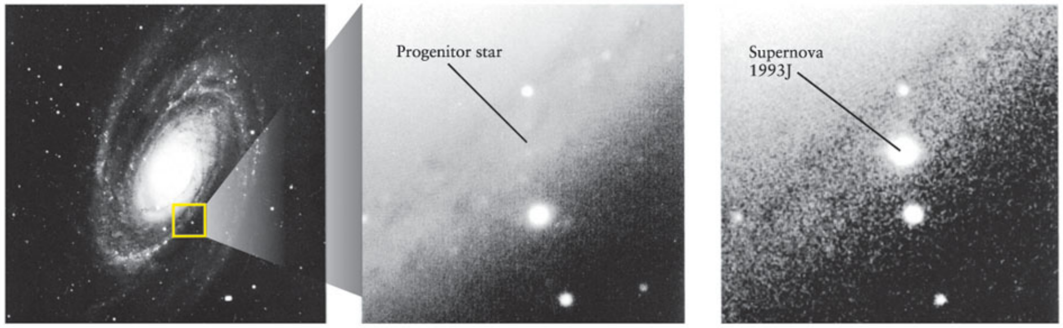
http://www.mssl.ucl.ac.uk/

Why nucleosynthesis stops at Fe





(a) Spiral galaxy M81 (b) Before the explosion (c) After the explosion

Luminosity of SN ~ that of the host galaxy

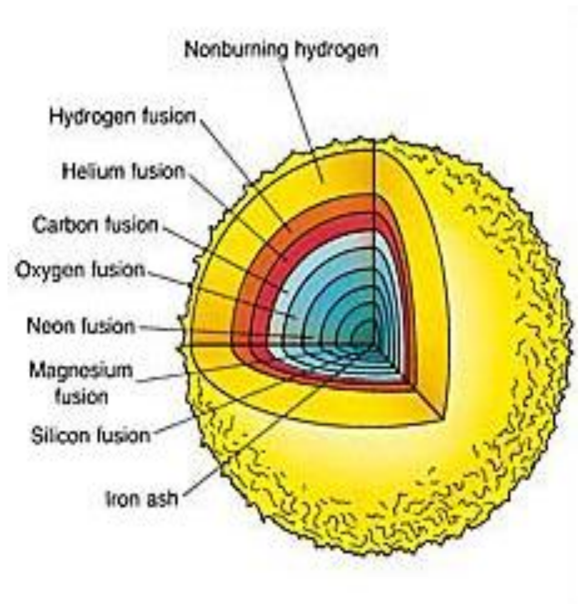
- What happens to the core?
- If $M<20M_{sun}$
  - Can become a **neutron star** ($M\sim1.5\text{-}2M_{sun}$, $R\sim10$km)
  - Matter gets "neutronized"

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

- If $M>20M_{sun}$
  - Core can collapse all of the way to a **black hole**
  - $M\sim3\text{-}20M_{sun}$, $R_{Sch}=5\text{-}60$km
  - Actually recent research shows that both NS and BHs can form from a wide range of mass.

Beyond neutron stars…

- Suppose collapsing core has mass that exceeds maximum mass for a neutron star
- What then when the gravitational attraction exceeds the degeneracy pressure?
- We know of no physics that can prevent a total gravitational collapse of the core ➡ BH



Massive Star Collapse-Type II SN

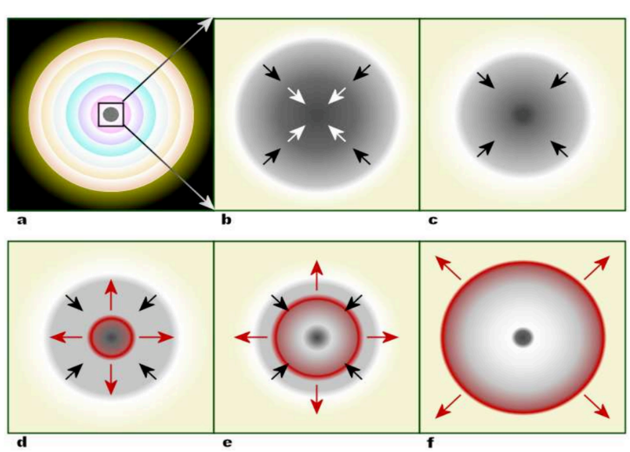
- Collapse of a massive star- the cores mass 'burns' into iron nuclei and has a maximum mass determined by the Chandrasekhar limit, ~1.4 $M_{\odot}$.
- Natural from stellar evolution
- Leaves NS or BH or maybe no remnant
- Wide range of masses, metallicities, binarity etc make for wide range of properties

Physics of explosion is VERY complex

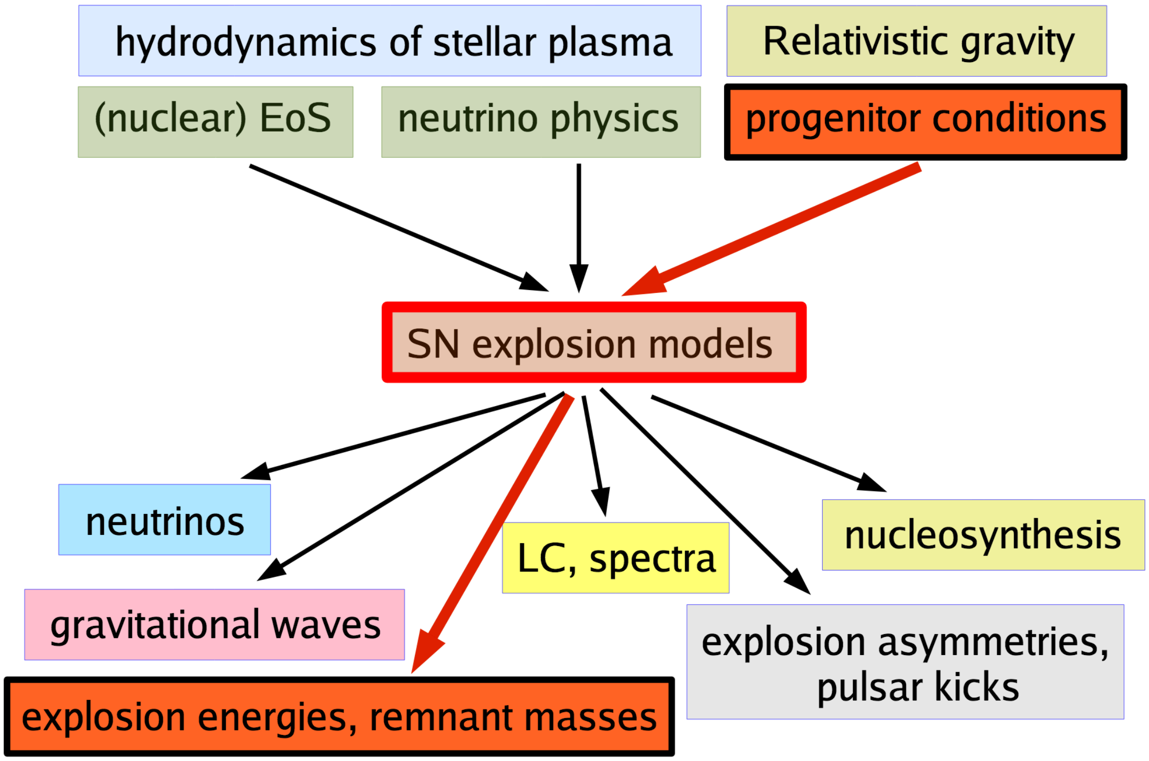
•Most of the explosion energy is carried away by neutrinos-

•Nobel prize 2002

• Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields



How Massive Stars Explode- T-H Janke

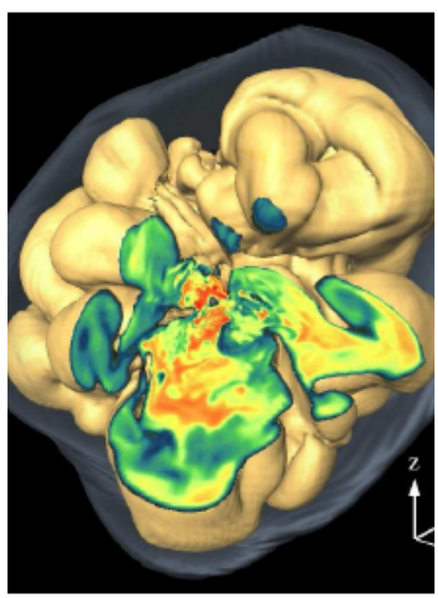


It Ain't Simple

- implosion of stellar cores
- Violent, large-scale nonradial mass motions are generic in supernova cores
- We are made of stuff that was once in the middle of a massive star.

(see http://astronomyonline.org/Stars/Papers/AlexNervosaSupernova.pdf)

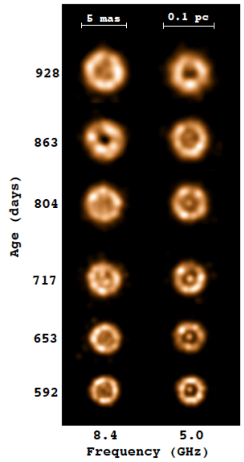
Simulation of SN a few seconds after explosion

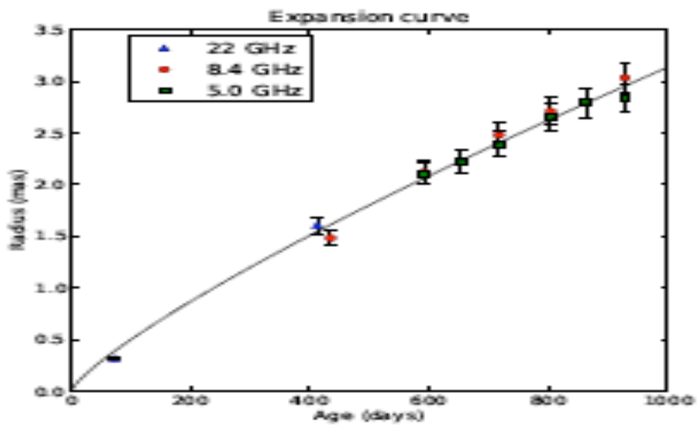


Type IIs

- total "optical" energy ~10^{49}erg radiated as photons.
- several solar masses ejected at ~1%c- expands rapidly

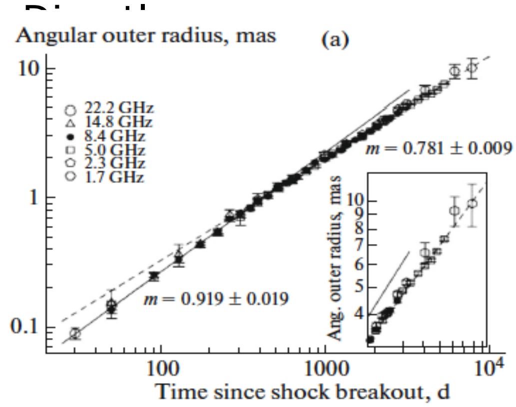
  The kinetic energy ~10^{51}erg

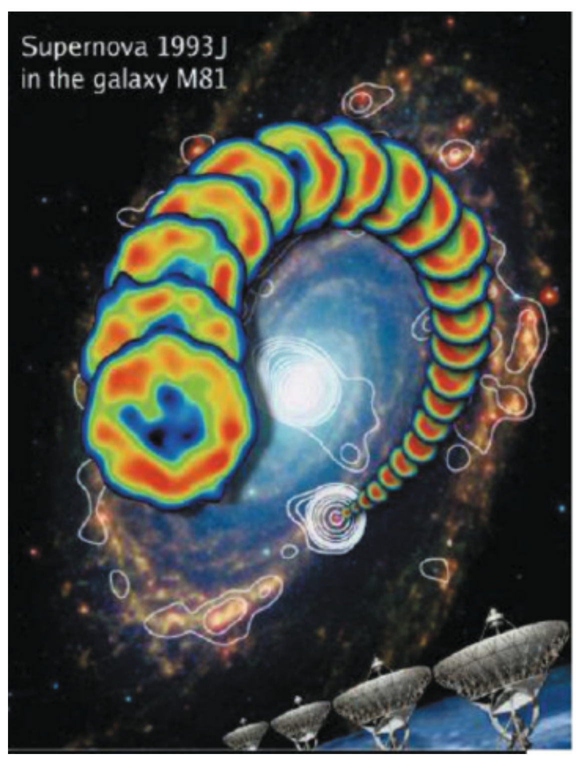




Evolution into a SNR-Radio Emission

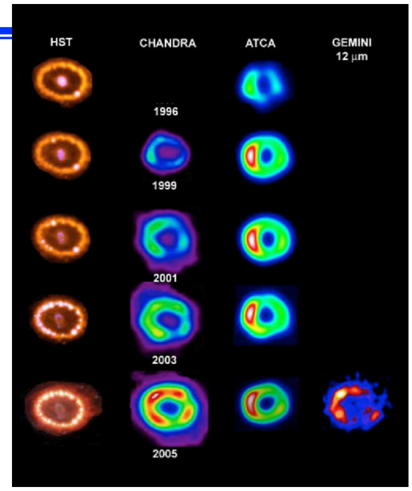
- Radio VLBI has the sensitivity and resolution to map nearby SN as they turn into SNR (Bartel et al Astronomy Reports 2017 61,299)
- 50d-8 years of images of SN 1993J





SuperNova Remnants

Whats left after the explosion
Supernova remnants
powered by expansion energy of supernova ejecta,
dissipated as the debris collides with interstellar
material generating shocks
$T \sim 10^{6-7}$ K
characteristic thermal emission is X-rays
timescale ~100-10,000 years



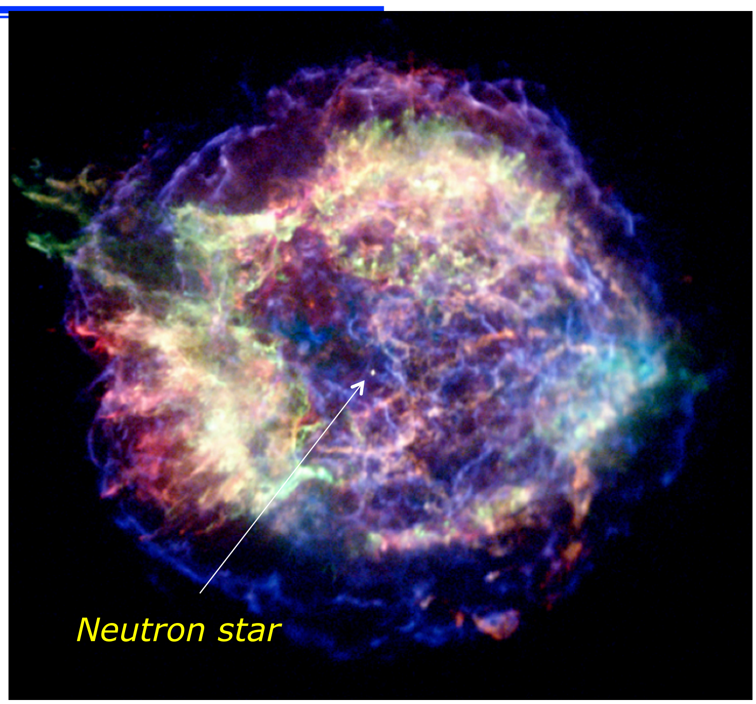
Evolution of 1987A
in optical, x-ray,radio and IR-*Still no central point source (NS or BH) visible*

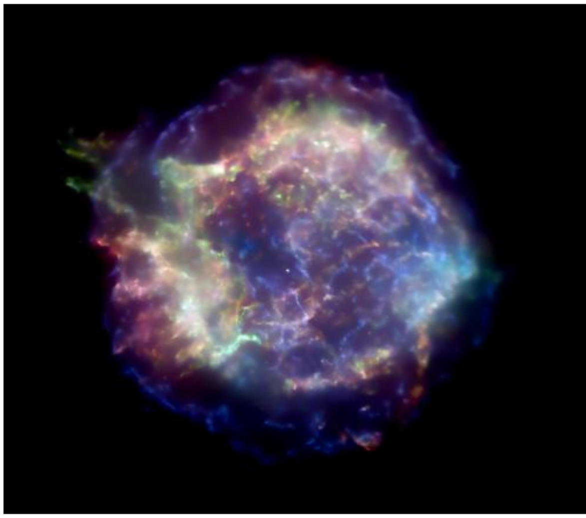
SuperNova Remnant Cas-A

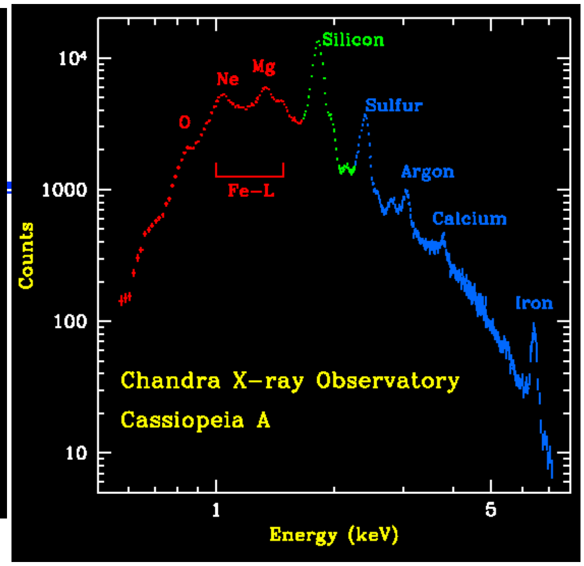
Exploded in ~1670
But not seen

Each color in this x-ray image corresponds to emission by a different element (e.g. O,Ne,Mg,Si,S,Fe)

type II SN **ejects** the previously made elements+heavier elements made in the explosion







- Type II produces: mainly O -- high O/Fe ratio

Plot of NS/BH Progenitor Masses from Supernova

- NS masses in purple, black hole in gray
- (progenitor star mass in orange, core in green)

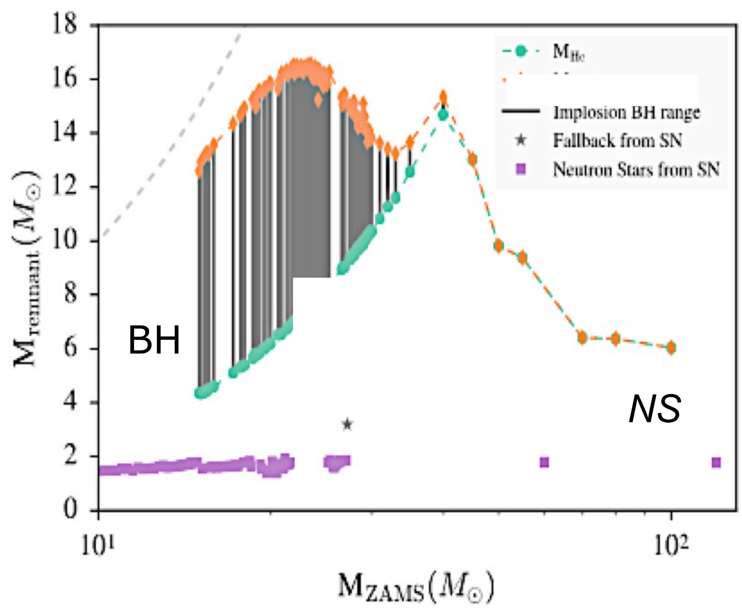


FIG. 1.— Baryonic remnant masses as a function of the progenitor ZAMS mass, for the central engine W18. Neutron star remnant masses from successful explosions are shown in purple. The range

Masses of Compact Objects

- Masses of NS cluster around $1.4M_{sun}$ (some up to 2 M_{sun})
- Separate population of objects *BHs
- ~20 black holes with a dynamical measurement of the mass+>10 via GW