Class 10 :
Life and Death of Stars

ASTR350 Black Holes (Spring 2022)

Cole Miller

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 ($M>8M_{sun}$)

Muddiest points

Any astro questions?

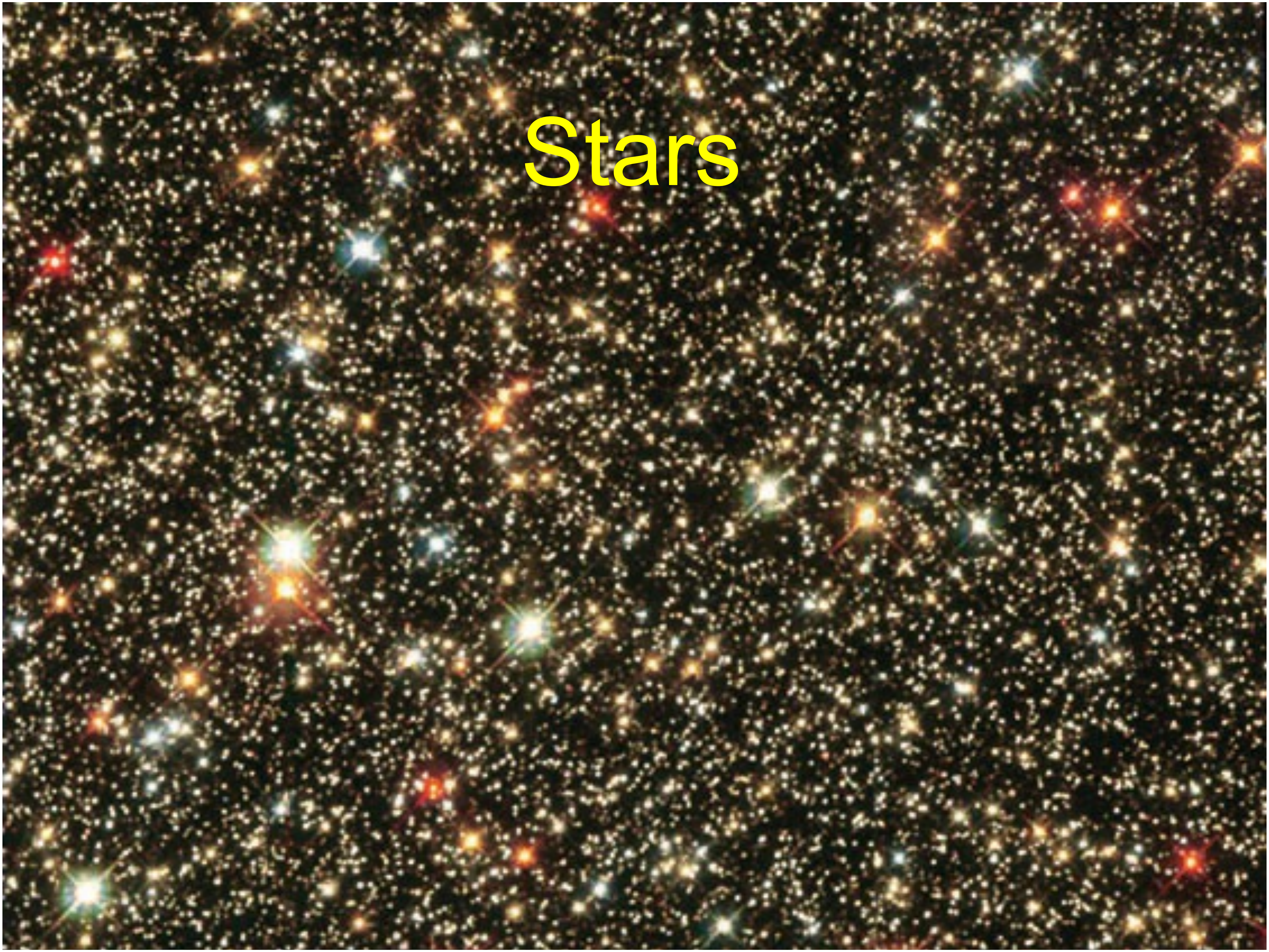
RECAP

- Kerr black holes
  - No-hair theorem – any (isolated) black hole is determined purely by its mass, spin and electric charge (and electric charge is irrelevant for astrophysical black holes).
  - 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 (ISCO)
    - Photon circular orbit

From Theory to Observation

- What properties of the astronomical objects imply/require that they are black holes?
  - how are these objects found?
  - what sort of data can be used?
  - how are black holes formed?
  - how are black holes visible?
- How can we use astronomical data to 'test' general relativity?
  - is general relativity the 'correct' theory of gravity?
  - how do general relativity and quantum theory interact?

Stars



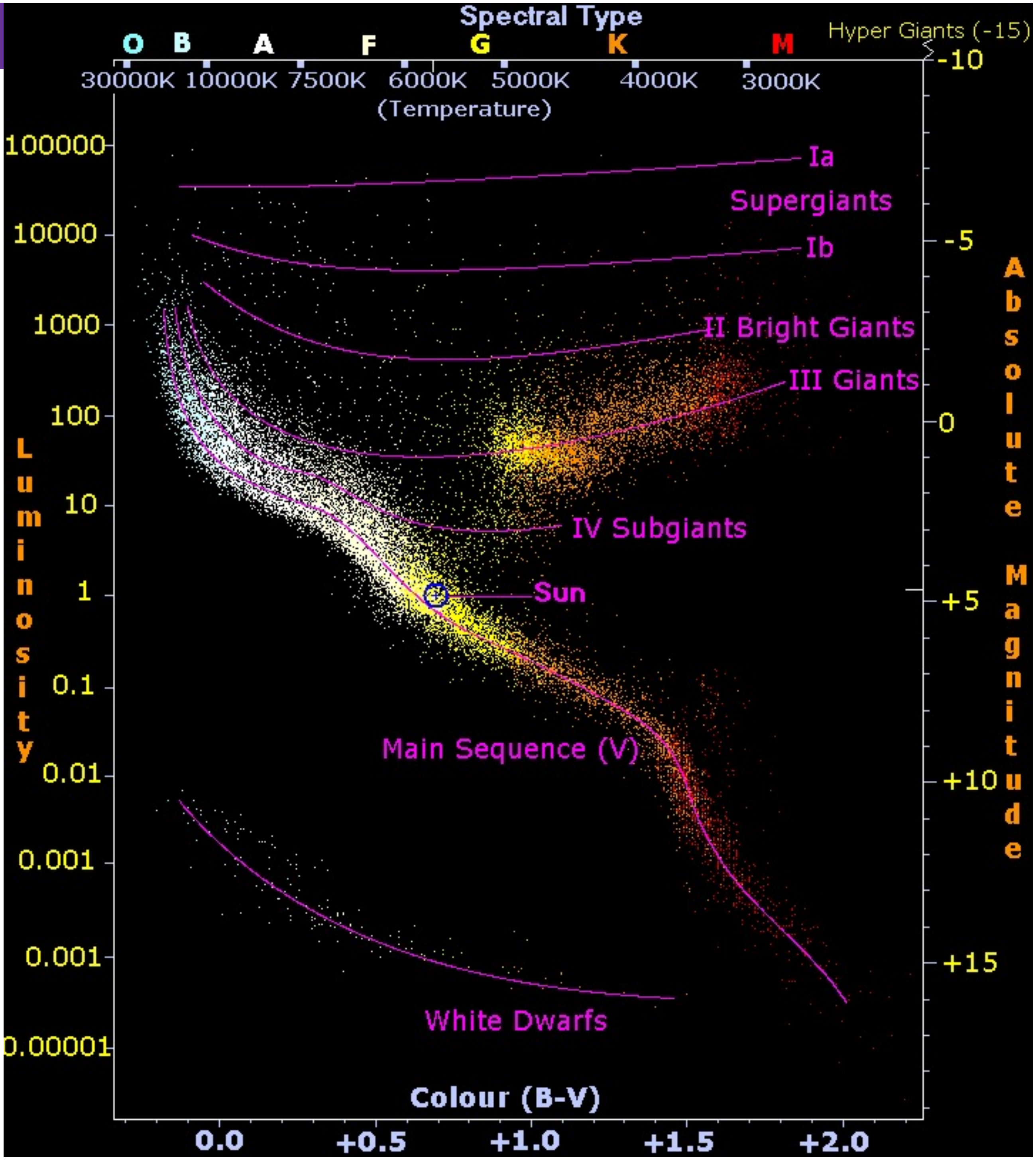
I : Some reminders about stars

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

*** the color of a star is related to its temperature**

Hertzsprung-Russell Diagram

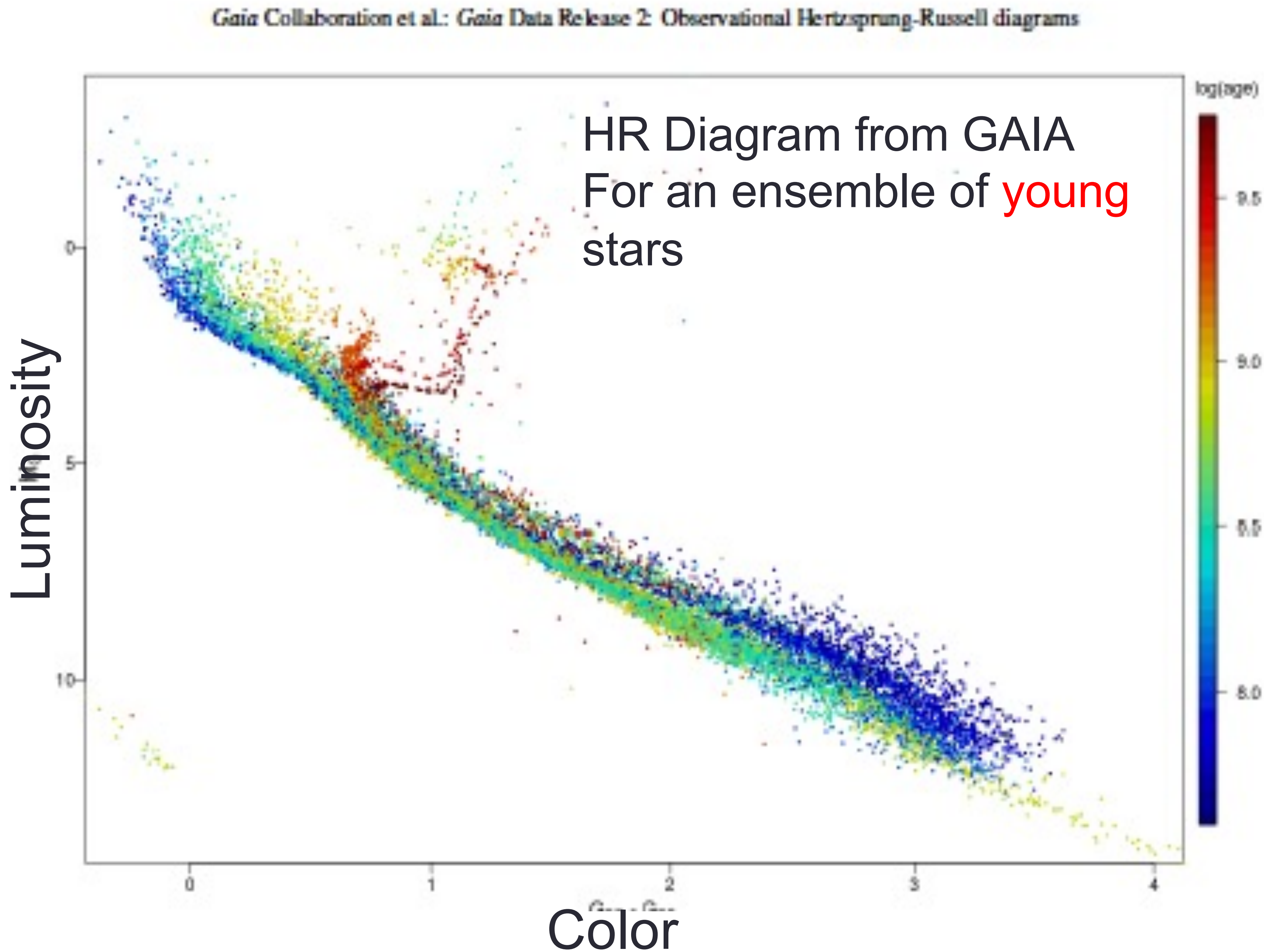
- 'Color' vs Luminosity (in solar units)
- Points are actual stars
- Notice main sequence



I : Some reminders about stars

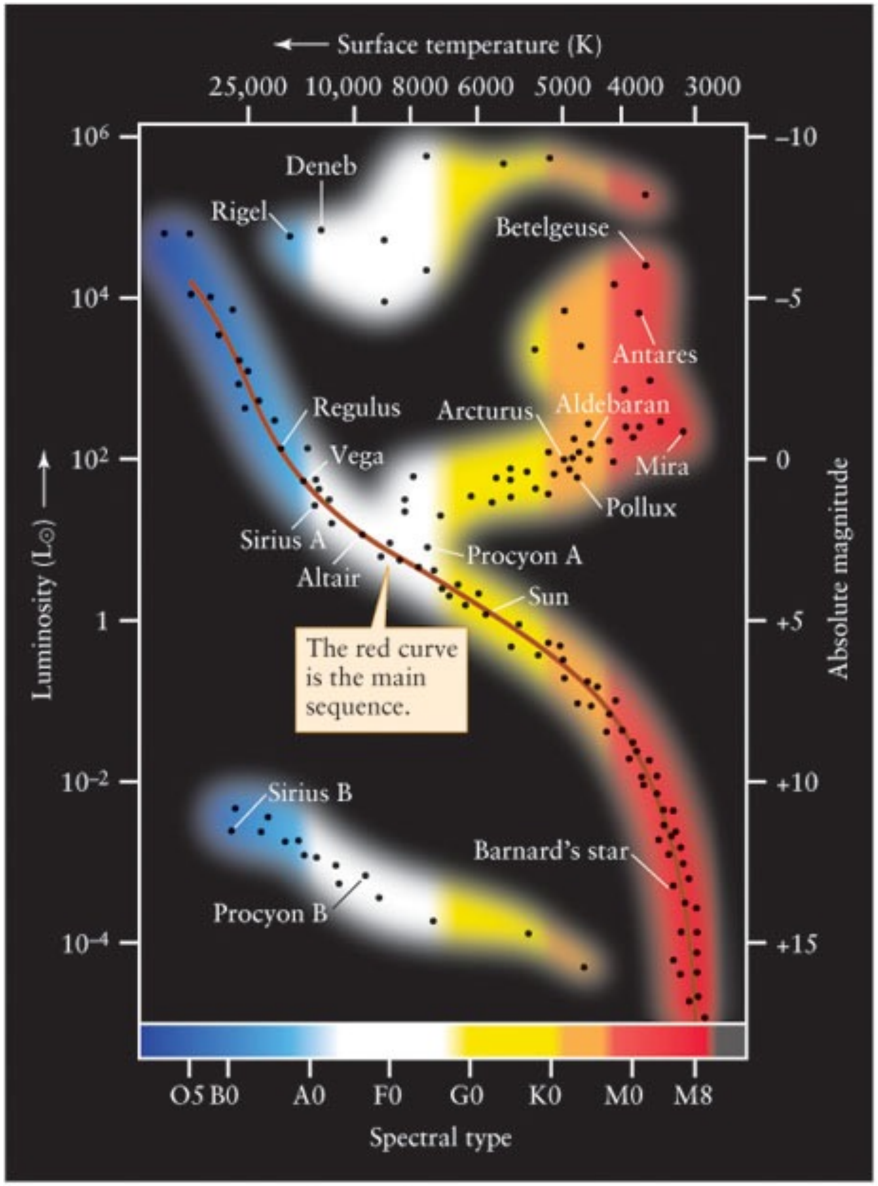
- Differences between stars is mostly due to **mass** and **age** of star:
  - **Main sequence** is the normal/long-lived part of the star's life. This is the H➔He fusion phase.
  - Location on main sequence determined by mass (high-mass = hot and luminous,

    low-mass = cool and dim).
  - Stars leave the main sequence and move around the HR-diagram as they age.
    - high mass stars have short life
    - low mass stars have long life

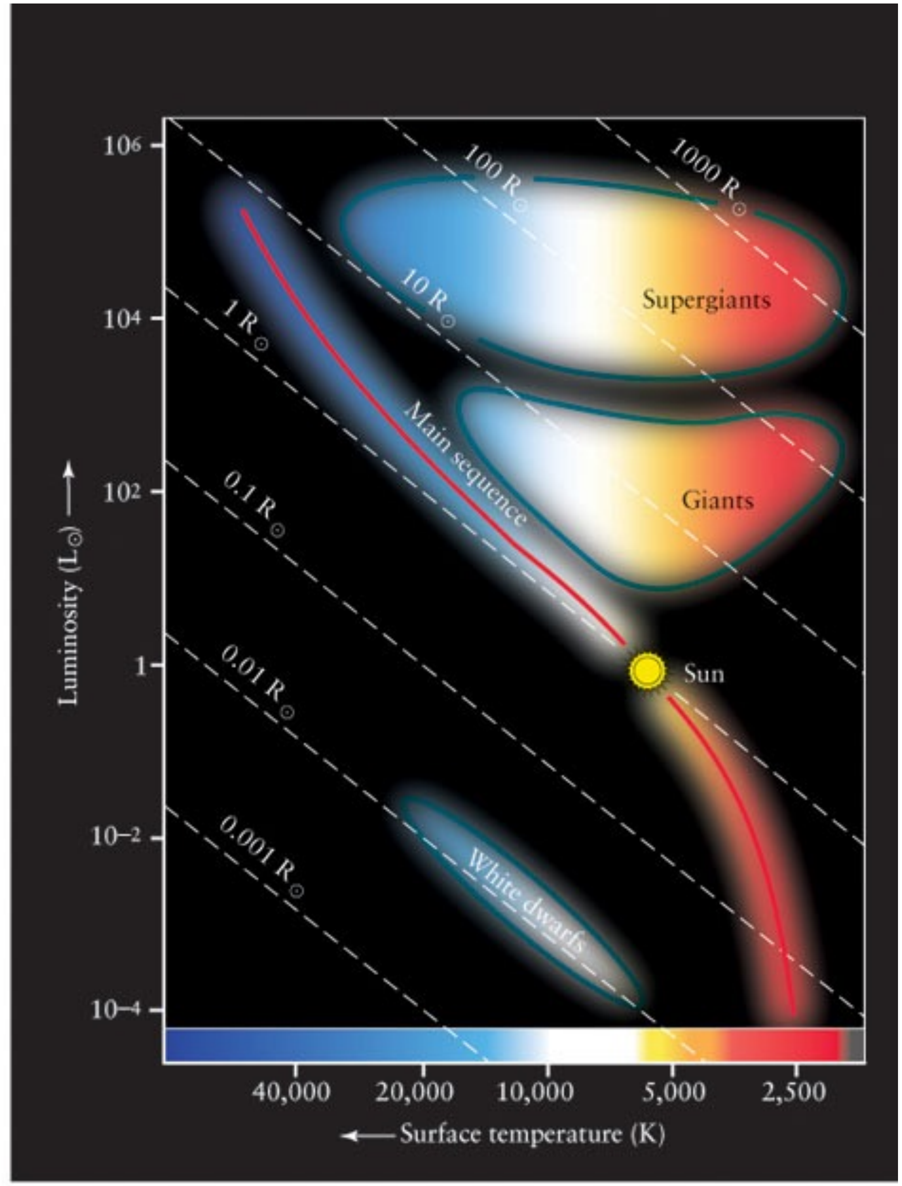


Gaia Collaboration et al.: Gaia Data Release 2: Observational Hertzsprung-Russell diagrams
HR Diagram from GAIA
For an ensemble of young stars
Luminosity
Color
log(age)
9.5
9.0
8.5
8.0
0
5
10
0
1
2
3
4

Location of famous stars on H-R Diagram



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



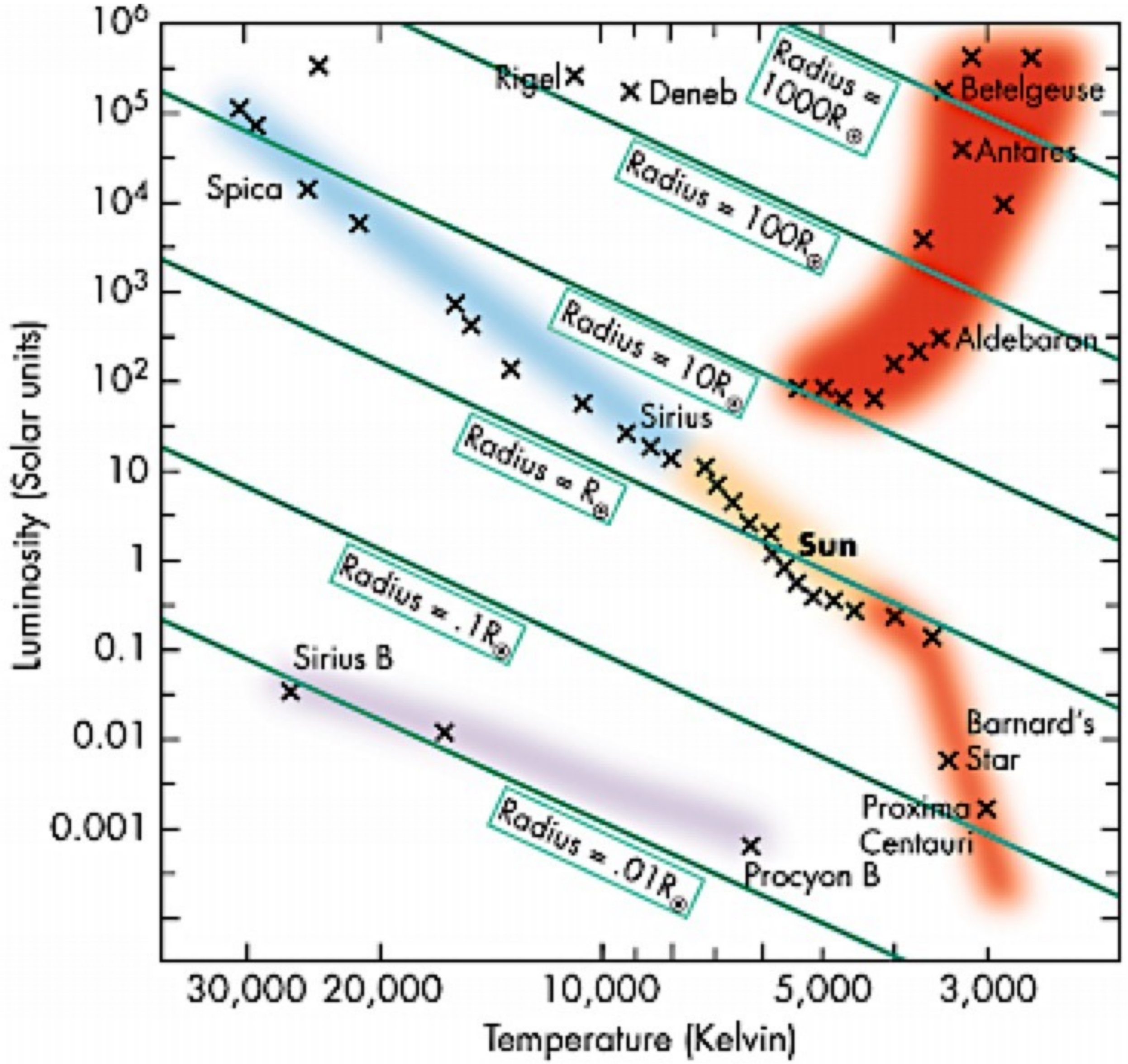
(b) The sizes of stars on an H-R diagram

Stellar Sizes/Luminosity/Temperature

Stefan-Boltzmann law- Lines $L \sim AT^4$

(T= temperature, A= area)

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

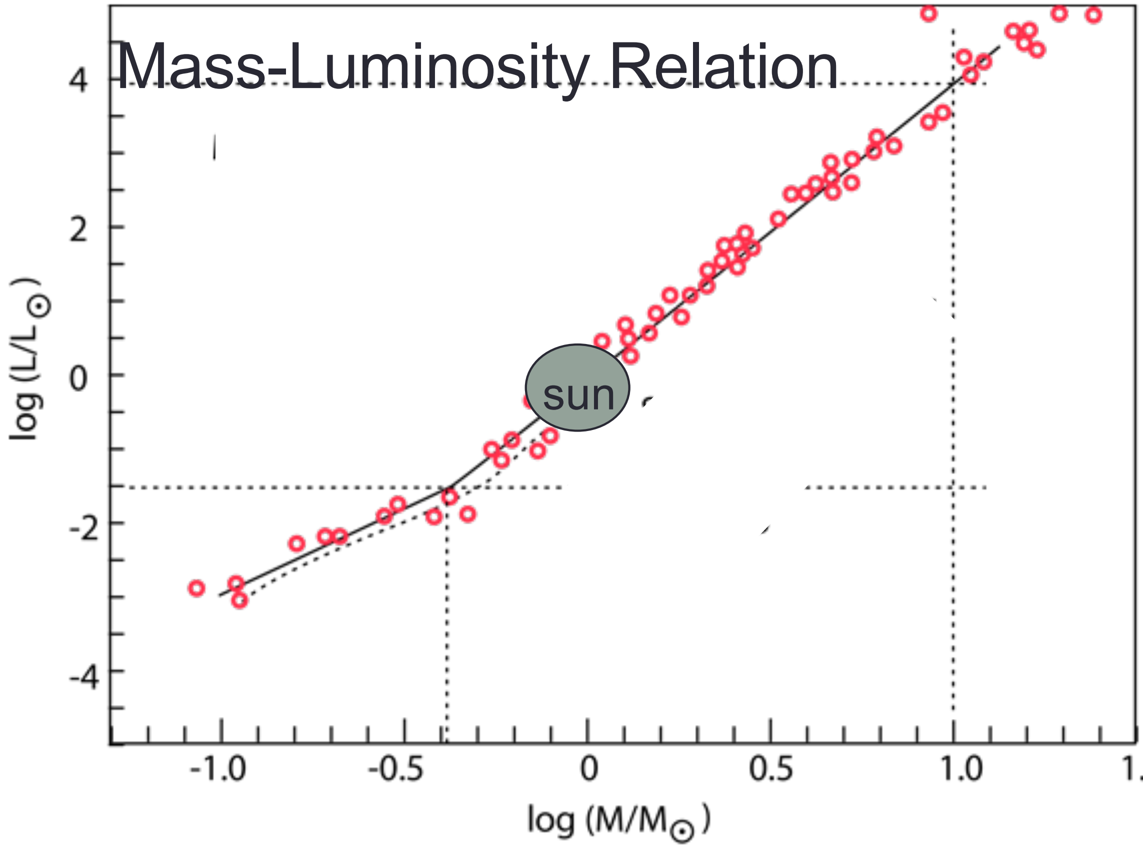


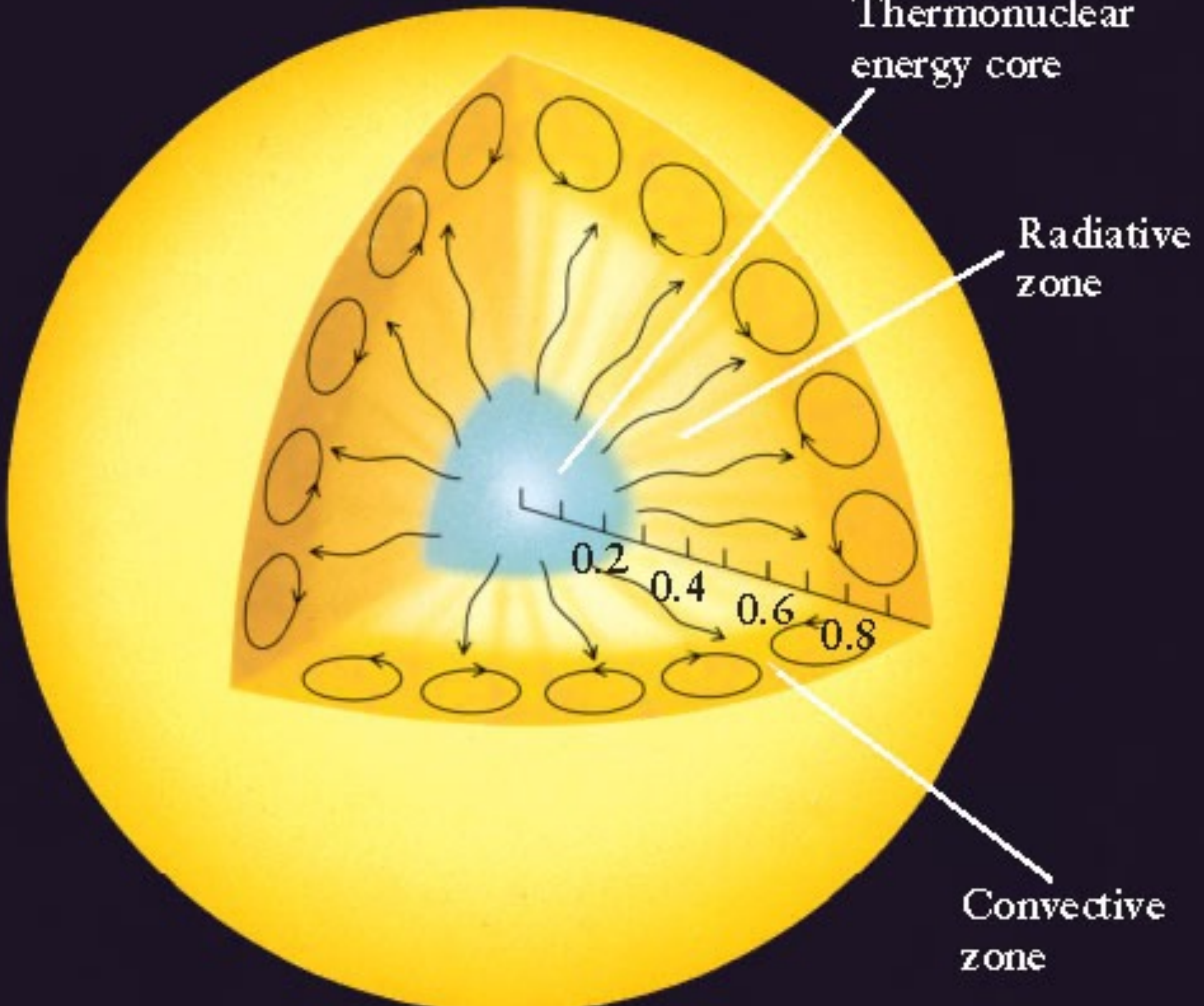
http://www.physics.isu.edu/~hackmart/spectral_class.pdf

Mass- Luminosity and Mass-Lifetime

- $L \sim L_{sun}(M/M_{sun})^{3.5}$ (not too far from $M=M_{sun}$)
- Life on the main sequence

$\tau \sim 10^{10}\,(M/M_{sun})^{-2.5}$ years (also not too far from $M=M_{sun}$)





Inside the Sun

II : Hydrogen 'burning' (actually fusion!)

- Basic process during main sequence: $4H \rightarrow {}^4He$
  - **0.7% of rest mass is converted to energy**… (0.007: James Bond!)

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

  - 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

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

"ASTROPHYSICS IS A FIGHT BETWEEN GRAVITY AND EVERYTHING ELSE"

My quote! I think it summarizes a great deal of astrophysics...

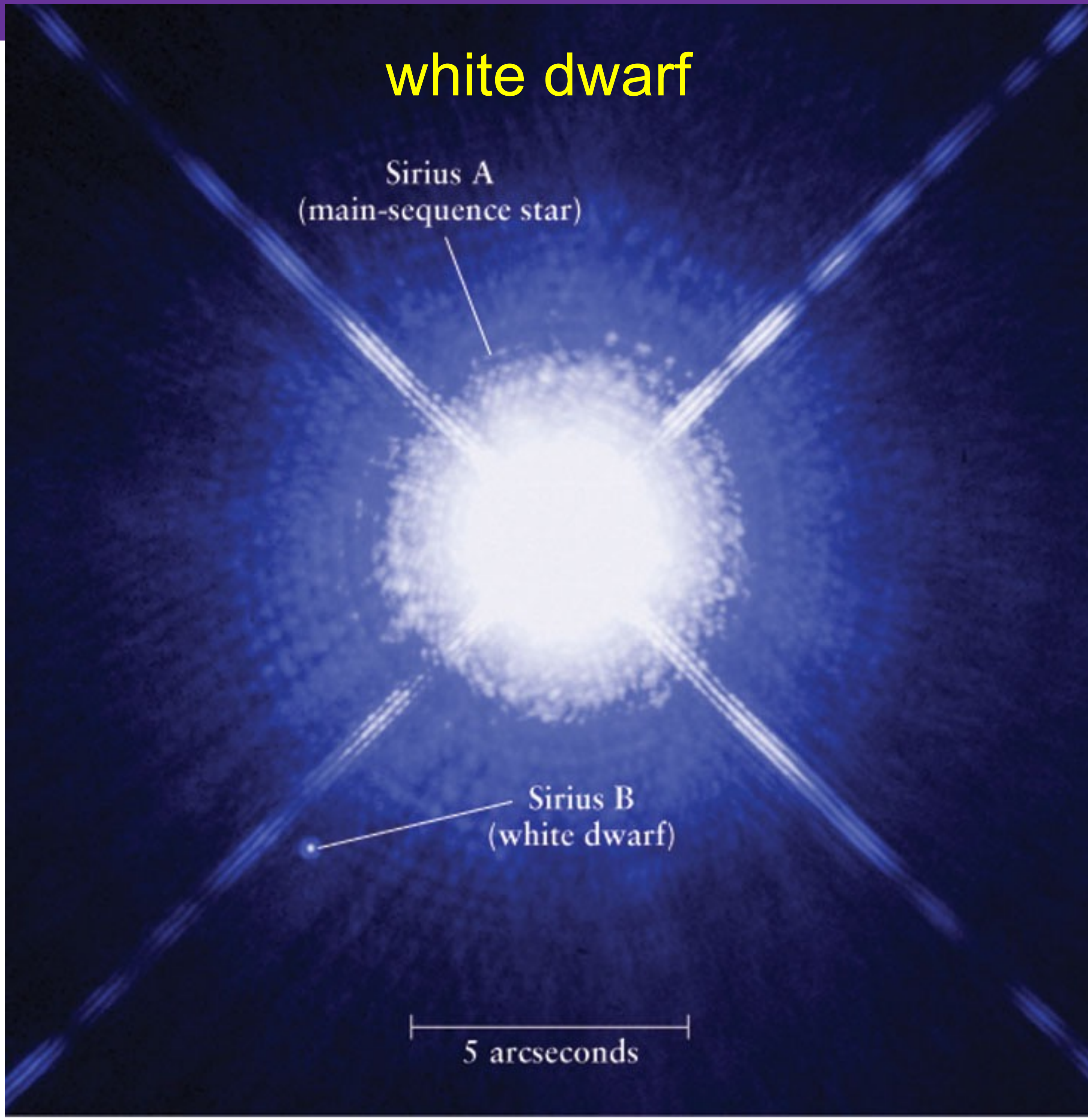
III : Post-MS evolution of low-mass star ($M<8M_{sun}$)

- 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 $M>0.4M_{sun}$)

$$3He \rightarrow C$$

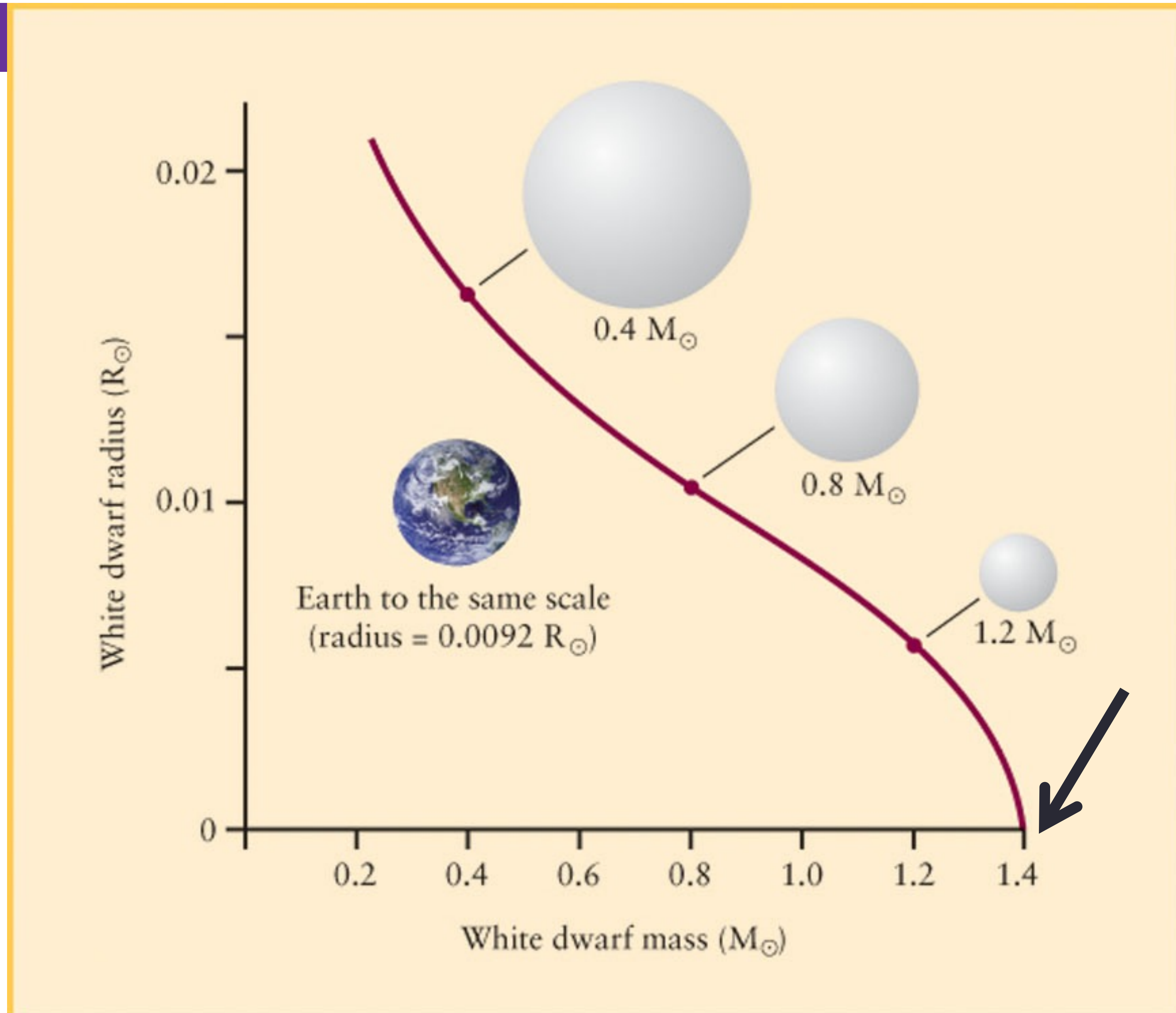
  - Star expels envelope in series of explosive events (nova) ➔ planetary nebula
  - He or C core remains as a **white dwarf** (stellar mass but size of Earth)

white dwarf


Sirius A
(main-sequence star)
Sirius B
(white dwarf)
5 arcseconds

As white dwarf increases in mass it gets smaller!

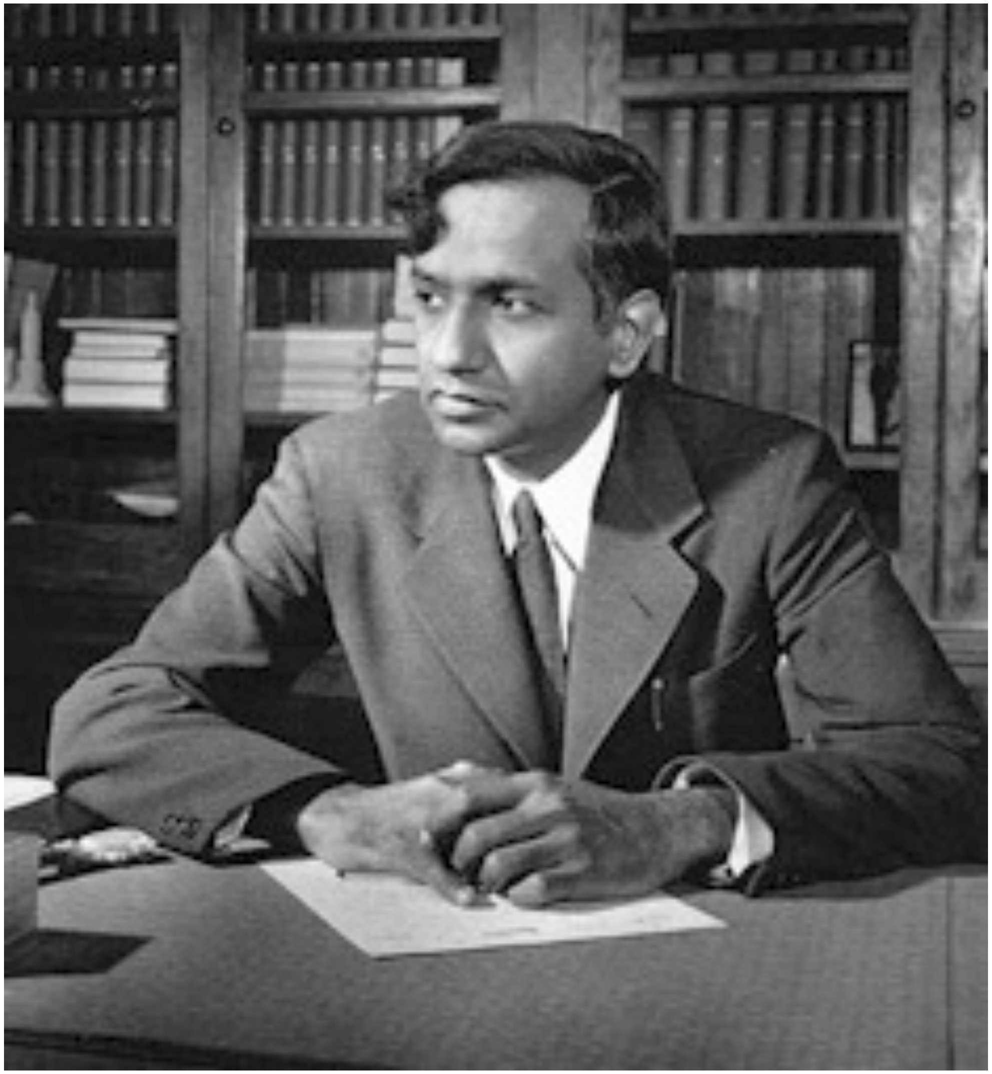
white dwarfs are supported against gravity by relativistic electron degeneracy



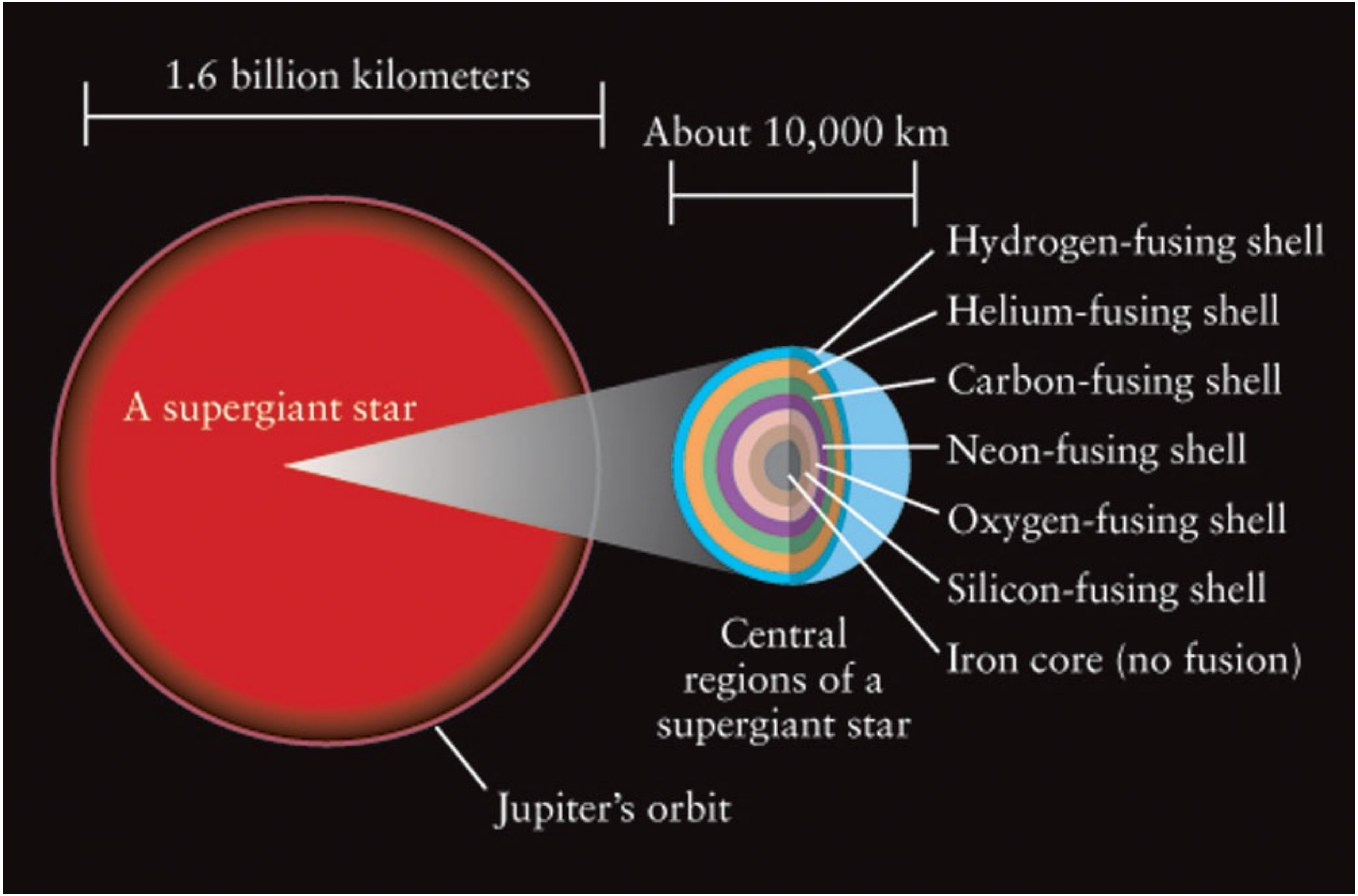
This produces a maximum mass which can be supported:
the **Chandrasekhar Limit** $M_{ch} \sim 1.4\ M_{sun}$

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



Big star: pre-Supernova Stellar Structure



What happens next?

- Once iron is reached, fusion stops in core
- Without energy production, core gets crushed
- When M_{core}~$1.4M_{sun}$, pressure forces become incapable of supporting core… core undergoes catastrophic gravitational collapse (in less than a second)- Chandrasekhar mass (more or less; there are always details!)

What happens next?

- Energetics of core collapse…
  - releases about 10^{46} Joules (~10^{12} years of Sun's luminosity)
  - 99% of energy 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

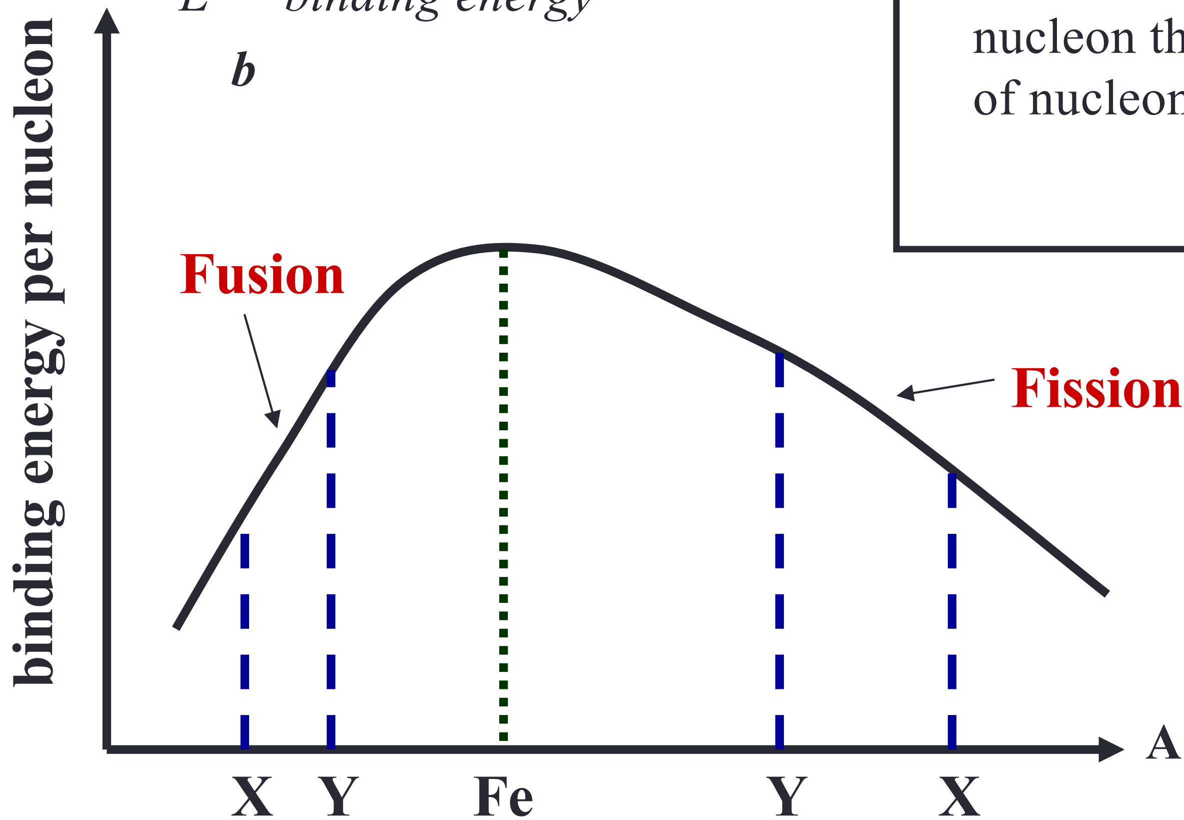
- Fusion reactions during the supernova responsible for producing many of the elements heavier than iron; but some/most might come from colliding neutron stars!

Binding energy of Nuclei - why stellar burning stops generating energy

A=total no. nucleons

Z=total no. protons

E = binding energy



Change from X to Y emits energy since Y is more tightly bound per nucleon than X. This is a function of nucleon mass

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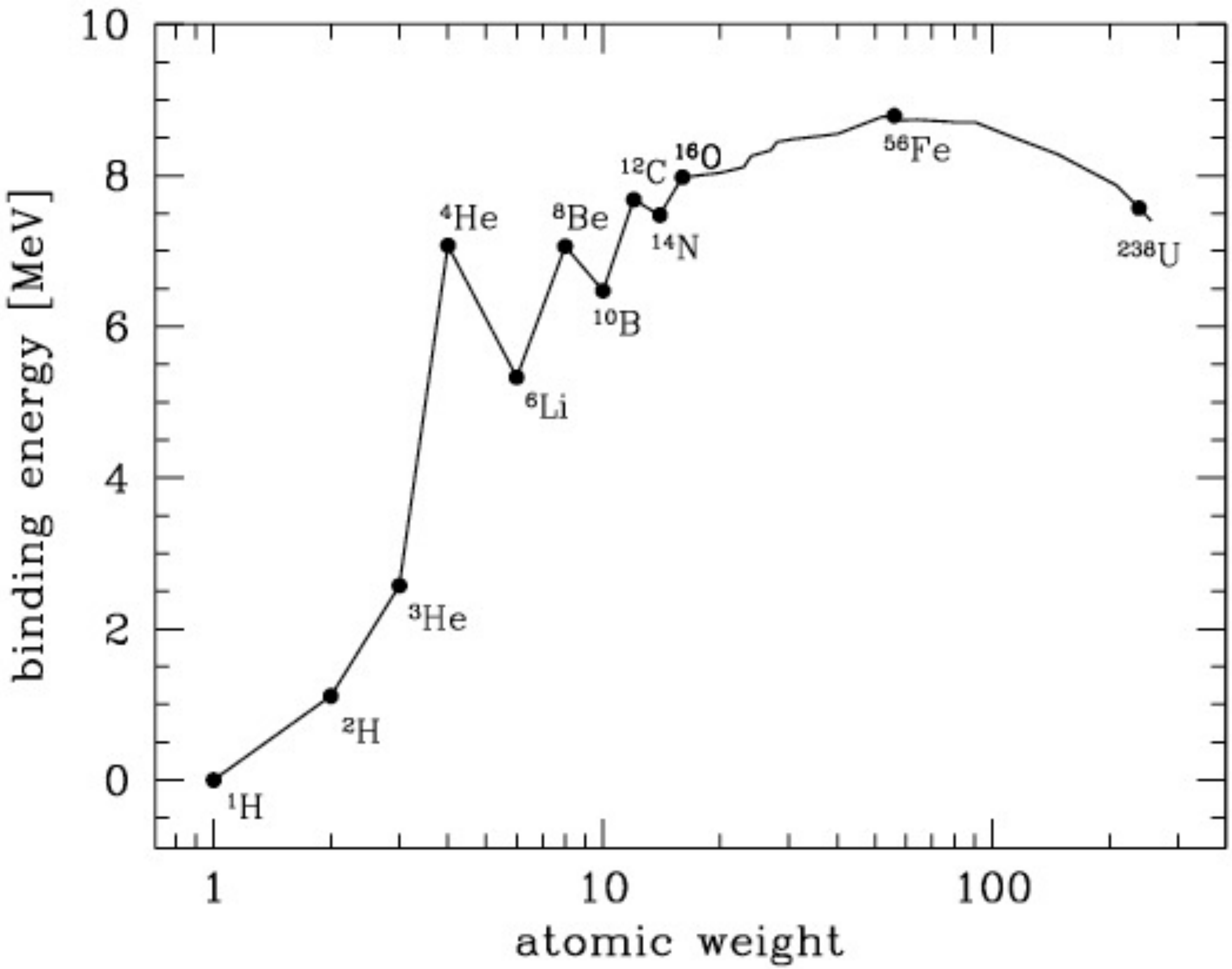
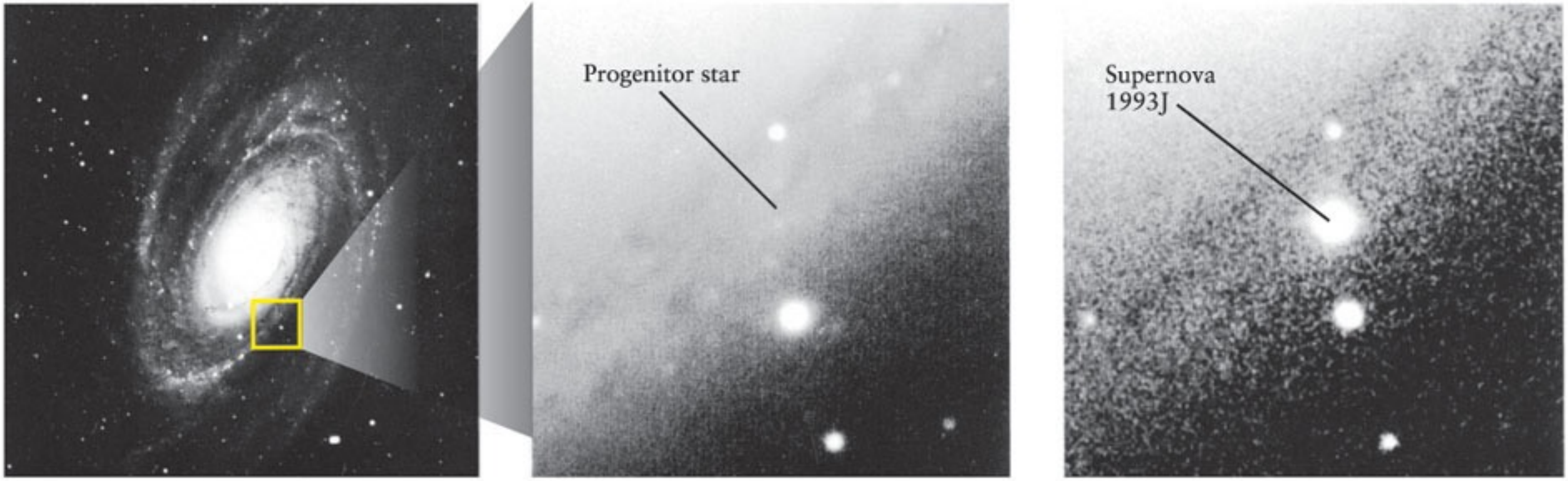
http://www.mssl.ucl.ac.uk/

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
Can be seen very far away- used for cosmology

What happens to the core?

- If $M<20M_{sun}$
  - Probably becomes a **neutron star** ($M\sim1.4$-$2.3M_{sun}$, $R\sim10$km)
  - Matter gets "neutronized"

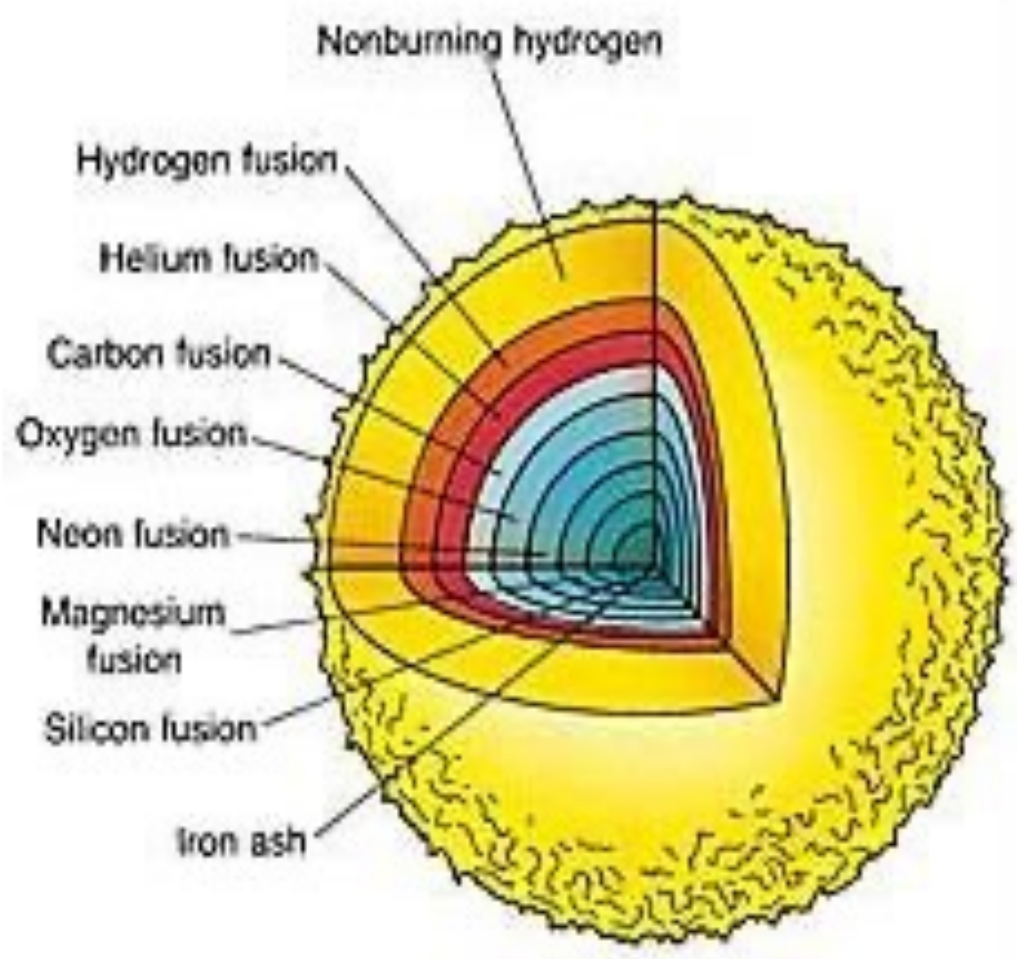
$$p + e^- \rightarrow n + \nu$$

- If $M>20M_{sun}$
  - Core can collapse all the way to a **black hole** (maybe sometimes NS?)
  - $M\sim3$-$20M_{sun}$, $R_{Sch}=5$-60km

  - 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 happens when the gravitational attraction exceeds the degeneracy pressure?
- We know of no physics that can prevent a <u>total</u> gravitational collapse of the core to a BH



Massive Star Collapse - SN

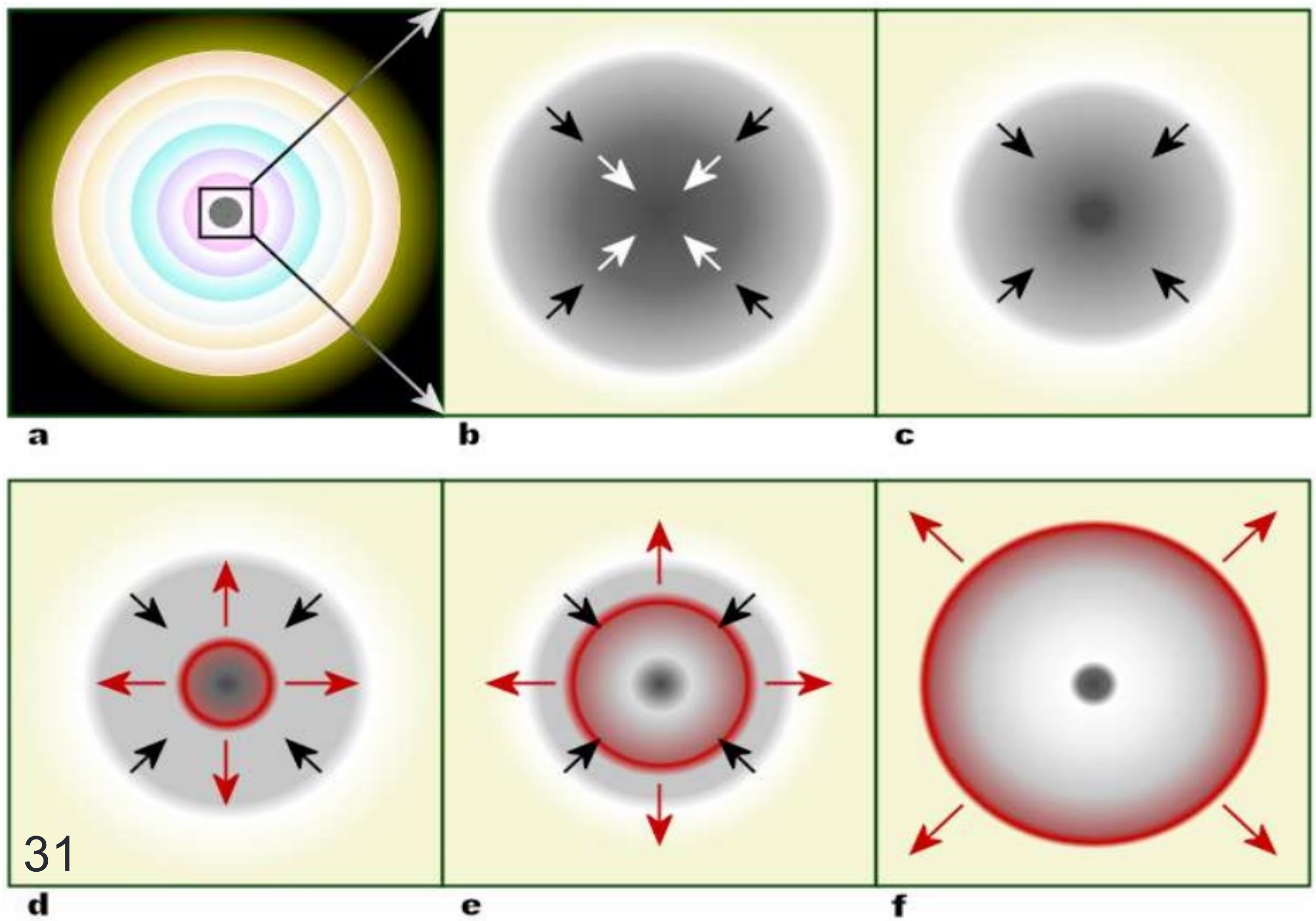
- Collapse of a massive star- the cores mass 'burns' into iron nuclei and has a maximum mass determined by the Chandrasekhar limit, ~1.4 $M_{\odot}$.
- Natural from stellar evolution
- Leaves NS or **BH** or maybe no remnant
- Wide range of masses, metallicities, binarity etc. make for wide range of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

Massive Star Collapse-Type II SN

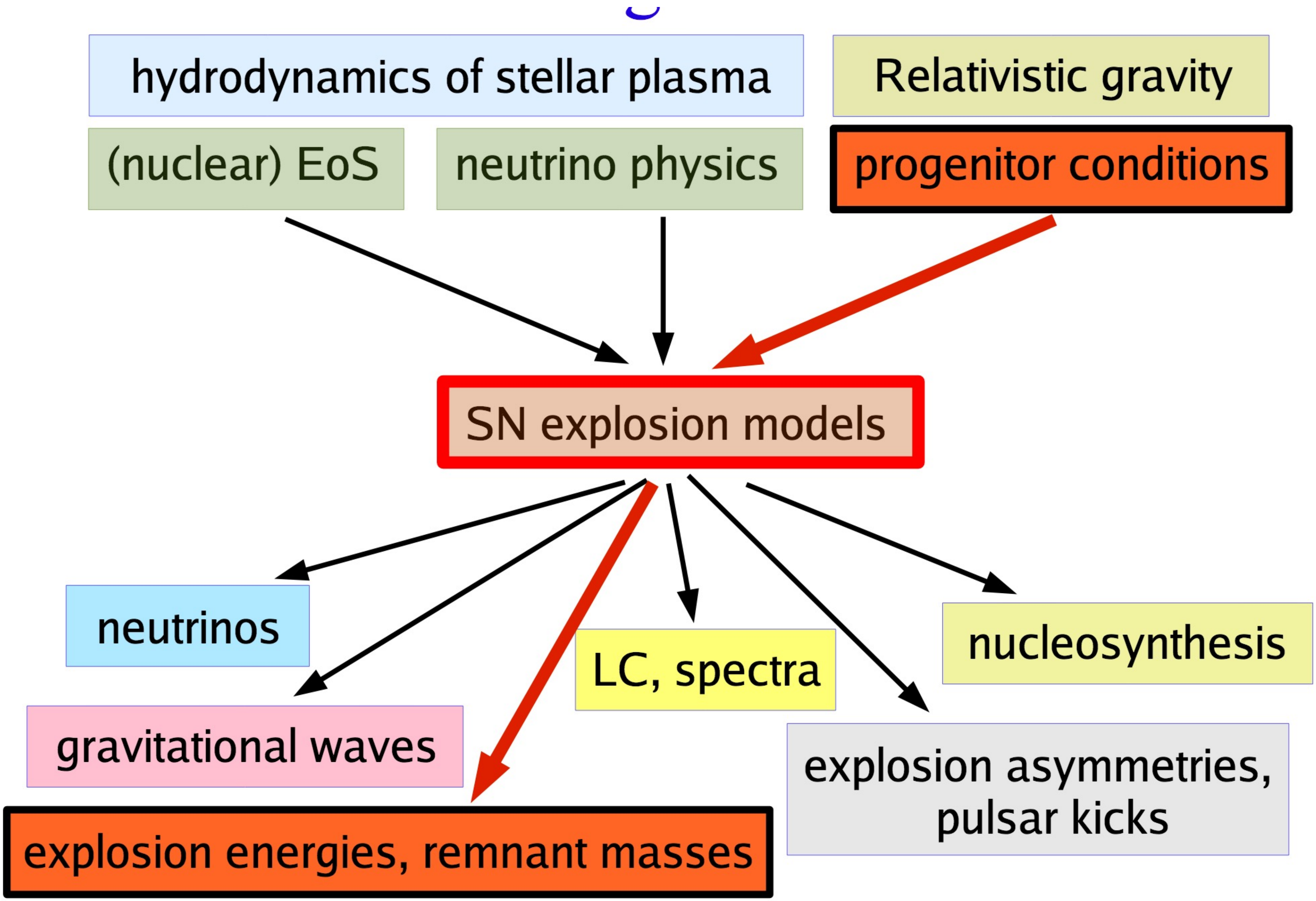
Physics of explosion is VERY complex

- **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



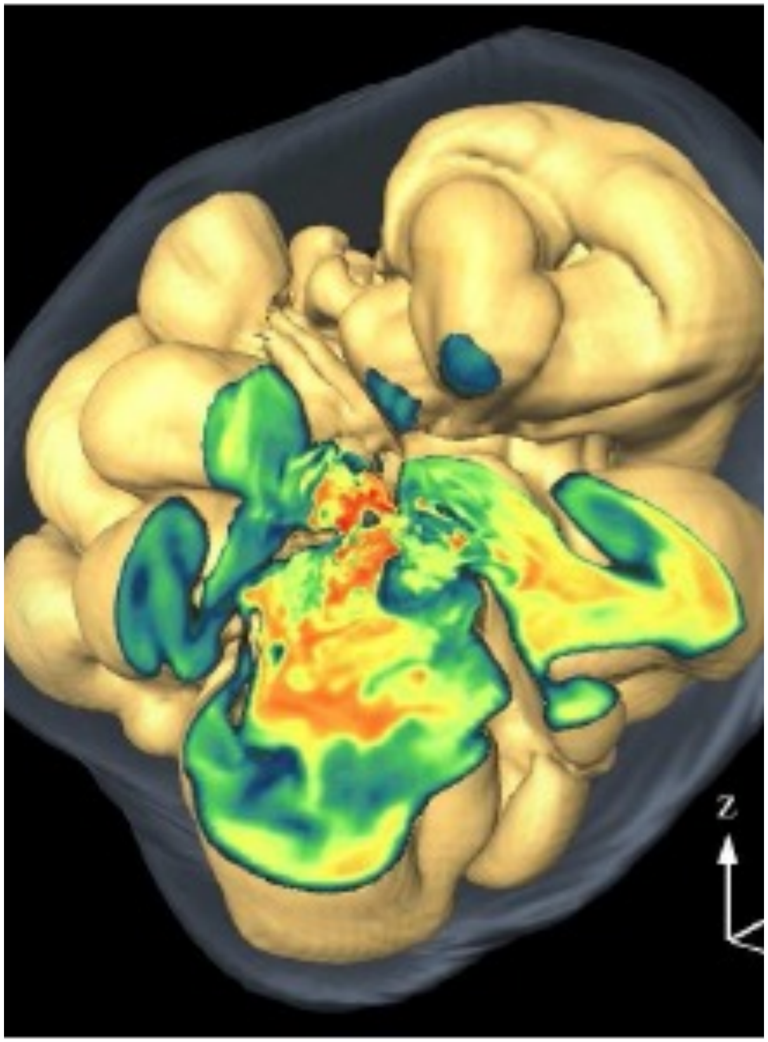
How Massive Stars Explode- T-H Janke



It Ain't Simple

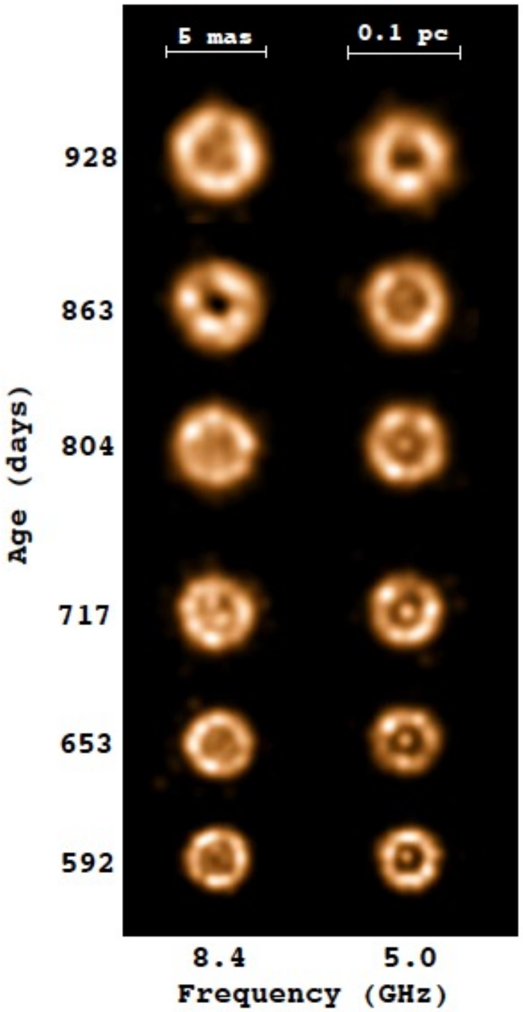
- implosion of stellar cores
- Violent, large-scale nonradial mass motions are generic in supernova cores
- We are made of stuff that was once in the middle of a massive star.

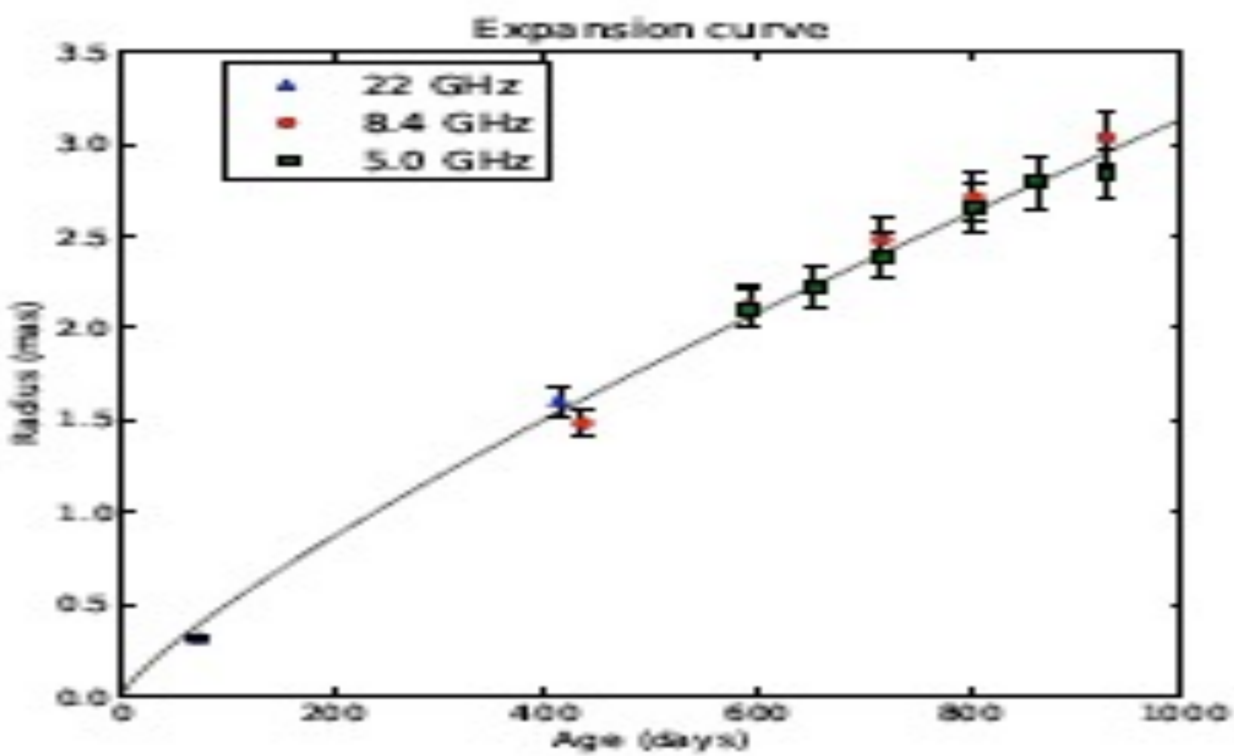
Simulation of SN a few seconds after explosion



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

    The kinetic energy ~10^{51}erg



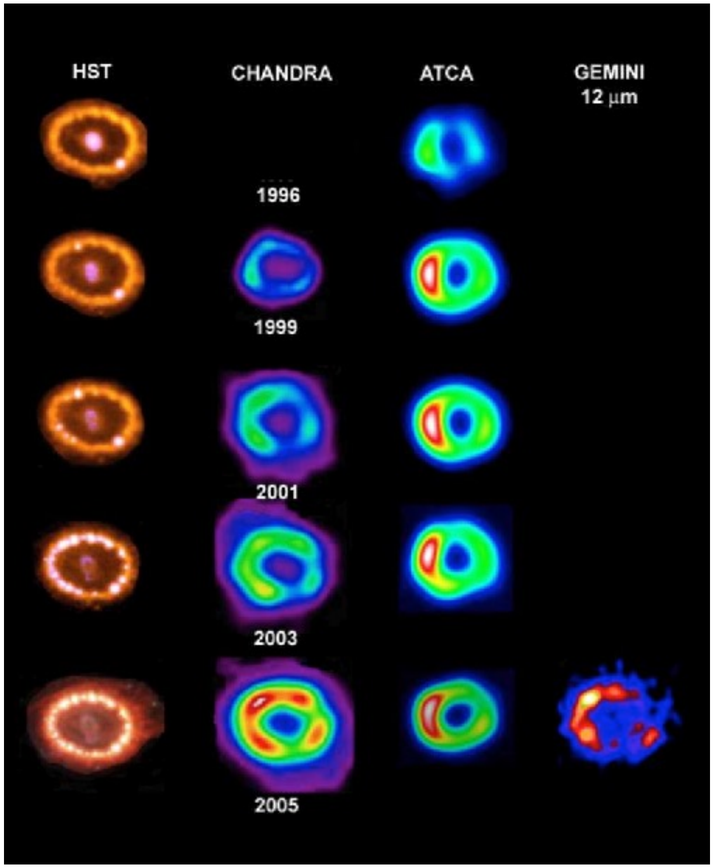


size vs. time after explosion from high resolution radio data

Supernova Remnants

What's left after the explosion

- Supernova remnants are
  powered by expansion energy of
supernova ejecta,
- Dissipated as the debris collides with interstellar material generating shocks which creates hot gas
  (T ~ 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

Masses of Compact Objects

- Astronomers can measure the masses of compact objects observed as x-ray or radio sources (next lecture)
- Find two populations
  - NS with a narrow range of masses but always less than 2.3 $M_\odot$
  - Heavier objects with a wide range of masses up to ~20$M_\odot$

Observed 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: >100 via GW