

# Nuclear Physics and Astrophysics of Exploding Stars

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# It's all about Energy!

- **Gravity** . . . The release of energy as the star 'falls' onto itself
- **Nuclear** . . . The release of energy from fusing the Hydrogen and Helium made in the big bang to heavier elements like Carbon, Oxygen, . . . Iron. .

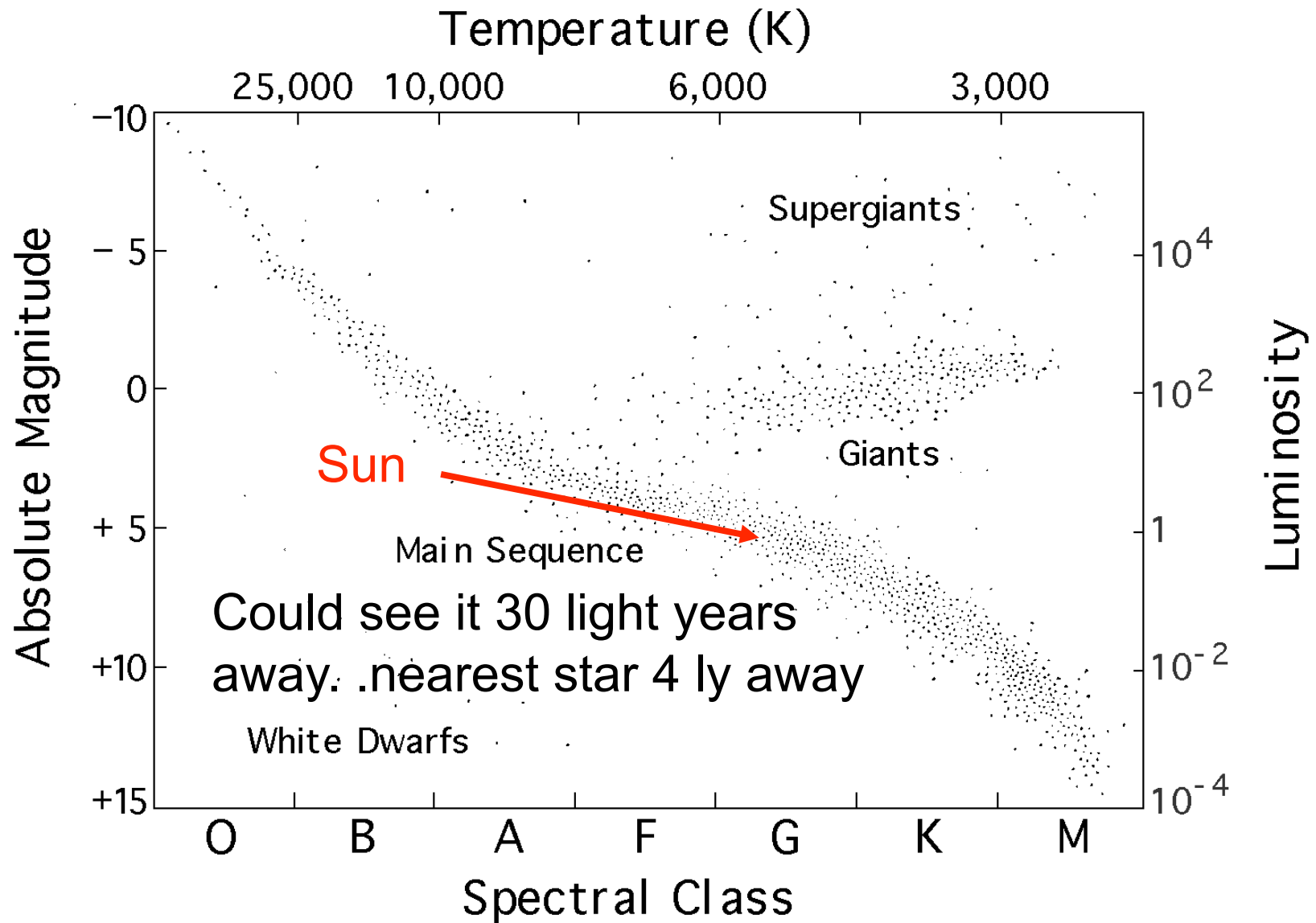
**Stars** tap into both of these energy sources, but only at the rate needed to match that lost from the surface.

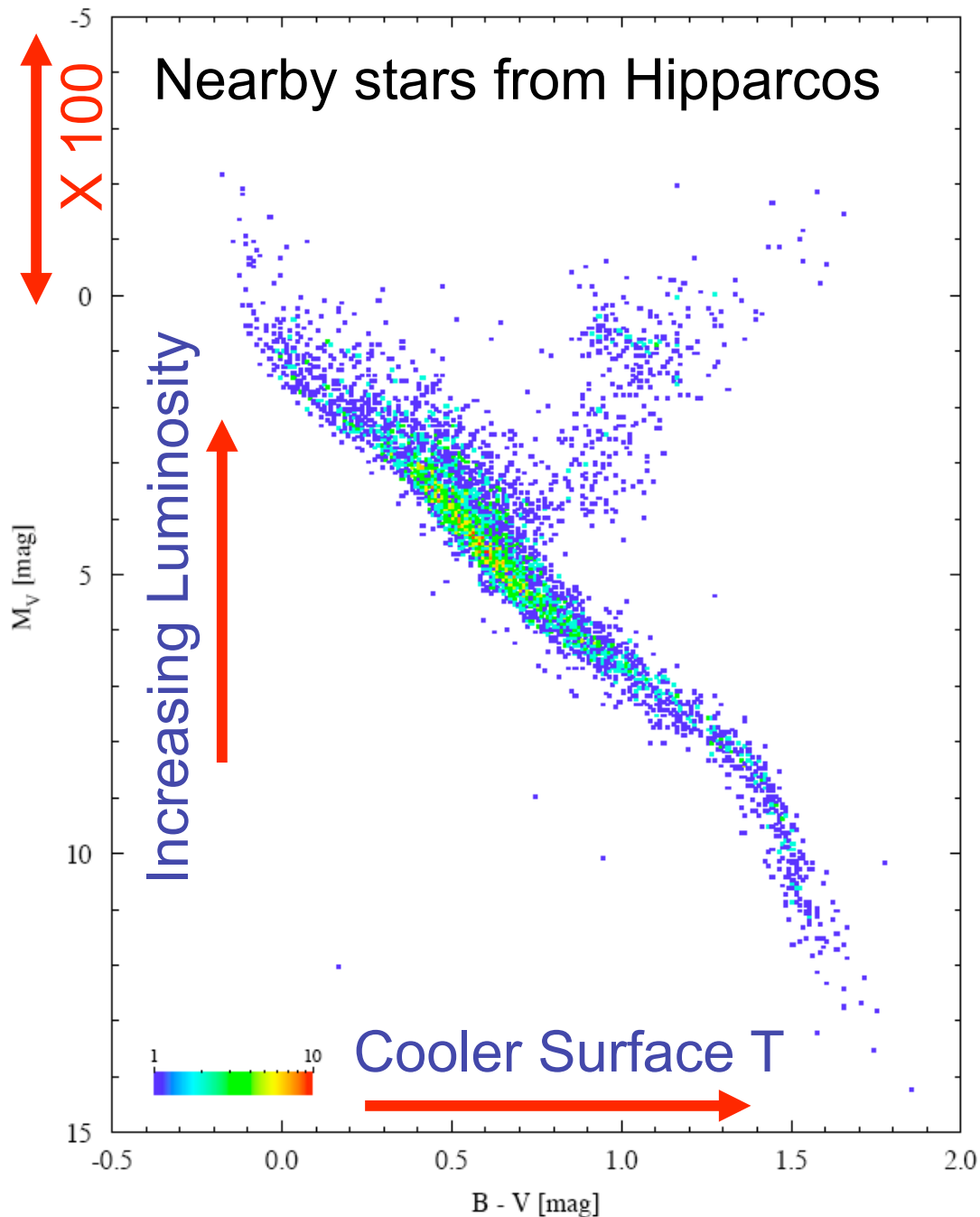
**Supernovae** do the opposite. They release the energy so rapidly that the object explodes, completely disintegrating.

# Four Lectures

1. Basics of Stellar Structure and Evolution:  
Setting the Stage
2. Understanding Supernovae Lightcurves and  
the New Surveys
3. Thermonuclear Supernovae
  - Type Ia Supernovae: Progenitor Puzzles
  - New kinds of events from Helium Detonations?
4. Supernovae from Gravitational Collapse
  - Most explode from  $10\text{-}20M_{\odot}$  stars => IIP's
  - Unusual events also occur. . Jets? Magnetars?

# Hertzprung Russell Diagram





The outcome of star formation are stars that only occupy certain regions of this diagram.

- Why?
- What is the controlling parameter?
- How do stars evolve in time?
- What do they become?

# Hydrostatic Balance

Since sound waves travel around a star in an hour or so, there is plenty of time for hydrostatic balance to apply:

$$\rightarrow \frac{dP}{dr} = -\rho g, \text{ where } g(r) = \frac{Gm(r)}{r^2}$$

We now assume that at a typical place in the star,  $m$ =total mass  $M$ ,  $r$ =radius  $R$ , so that hydrostatic balance gives

$$\frac{P}{R} \sim \rho \frac{GM}{R^2}, \text{ combine with ideal gas } P \approx \frac{\rho k_B T}{m_p}$$

Where  $m_p$ =proton mass (everything is ionized). This allows us to find the relation between the central temperature,  $T_c$ , and the mass and radius

$$k_B T_c \approx \frac{GMm_p}{R}$$

# More on Hydrostatic Balance

$$k_B T_c \approx \frac{GMm_p}{R}$$

As  $R$  shrinks (i.e. as the star contracts from the large cloud it started in), the core temperature rises! This is the same as what happens to a particle in orbit, as it loses energy (**radiates!**), it moves in (**radius shrinks!**), and moves faster (**higher temperature!**).

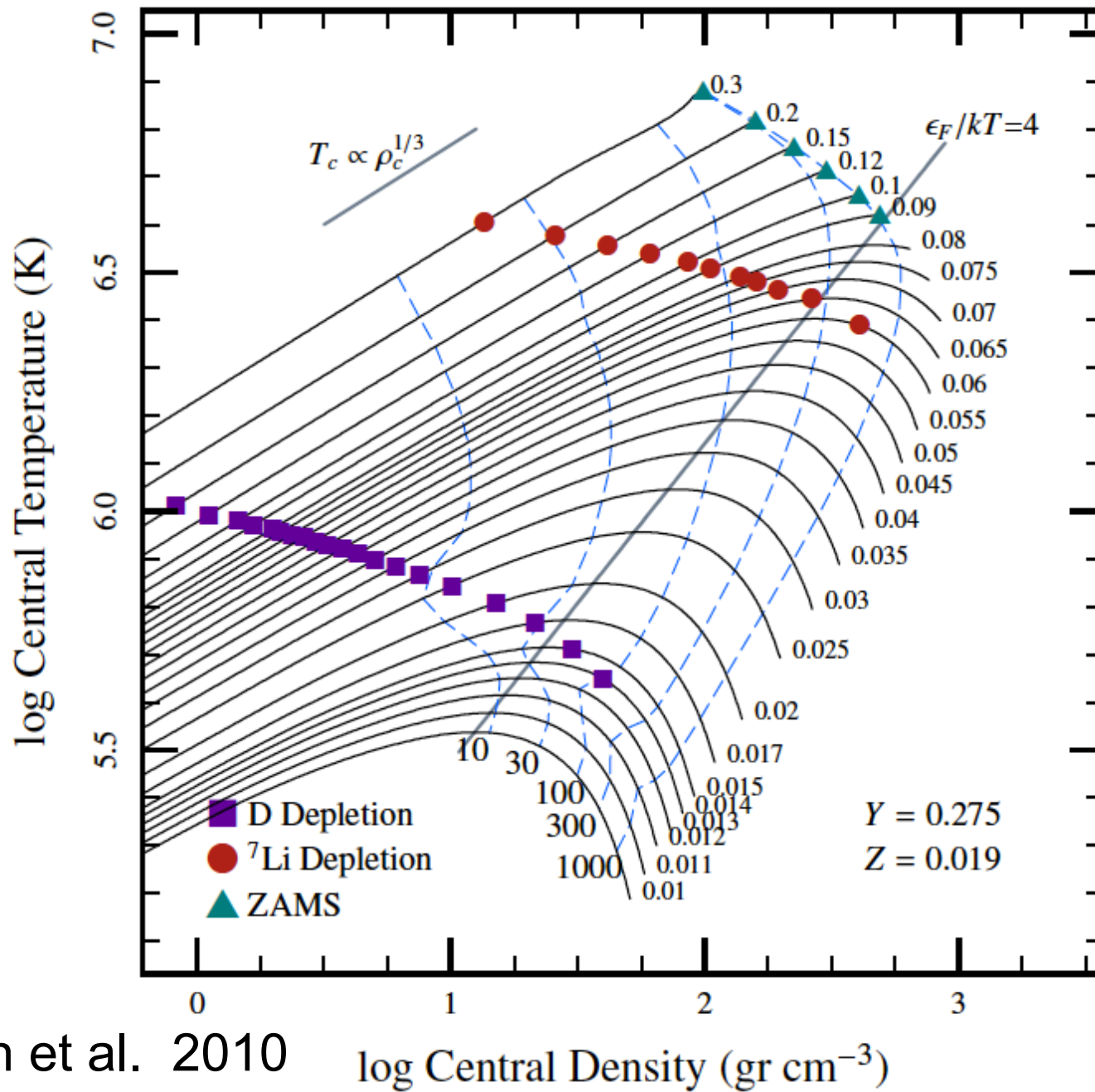
Prior to ignition of any nuclear energy source, the loss of energy (at luminosity  $L$ ) leads to a slow contraction of the star. If the Sun were powered this way, it would change its radius on a time

$$t_{\text{Kelvin}} \approx \frac{GM^2/R}{L} \approx 10^7 \text{ yr}$$

# HW Problem One

- How does the answer change when the electrons start to become degenerate?





Paxton et al. 2010

log Central Density ( $\text{gr cm}^{-3}$ )

# Stellar Luminosity

$$k_B T_c \approx \frac{GMm_p}{R}$$

The luminosity of the star is determined by heat transport, since the core is hot, and the surface is cold (VACUUM!). Unlike in your house, the heat is transported by diffusion of photons, which have a mean free path  $l$ , giving:


$$\text{Heat Flux} \approx cl \frac{d(aT^4)}{dr} \rightarrow \text{Luminosity} \propto M^3$$

This tells us that the luminosity of a star is mostly dependent on its mass,  $M$ , and has a large dynamic range, as stars range in mass from  $0.08$  to  $50M_\odot$ .

But what sets the stellar radius?

# Keyhole Nebula



8000 light years away, image is 9 light years across. 

# Nuclear Burning

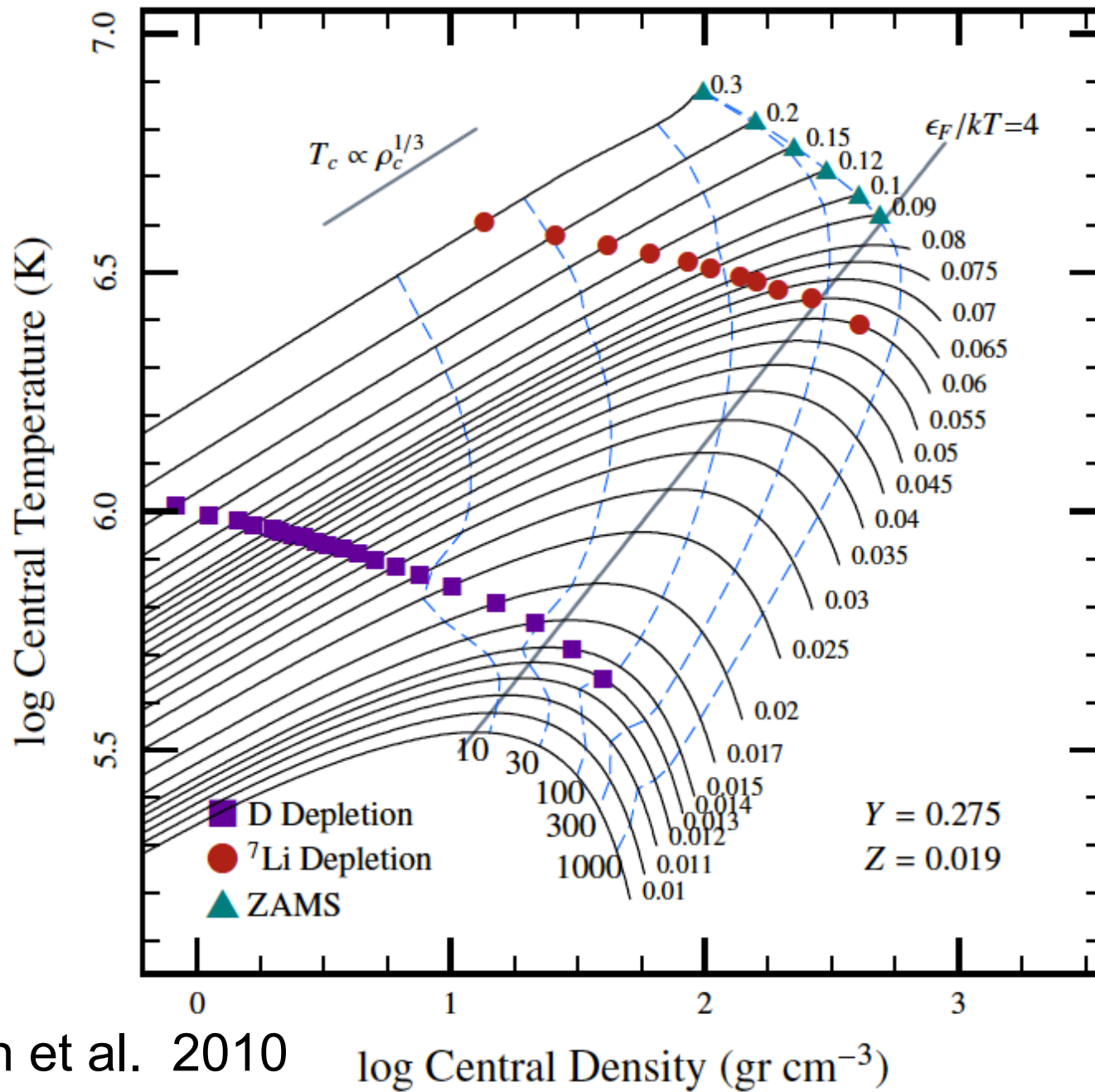
Since the Sun would only live for ~ 10 Million years in the absence of an energy source, a more robust energy source was needed. Quantum mechanics allowed for tunnelling into the nucleus giving the fusion reactions of Hydrogen=>Helium:



This reaction rate is temperature sensitive, so once a certain  $T_c$  is reached, the energy generation rate MATCHES that lost. This fixes the stellar radius  $R$  (proportional to  $M$ ), and lifetime

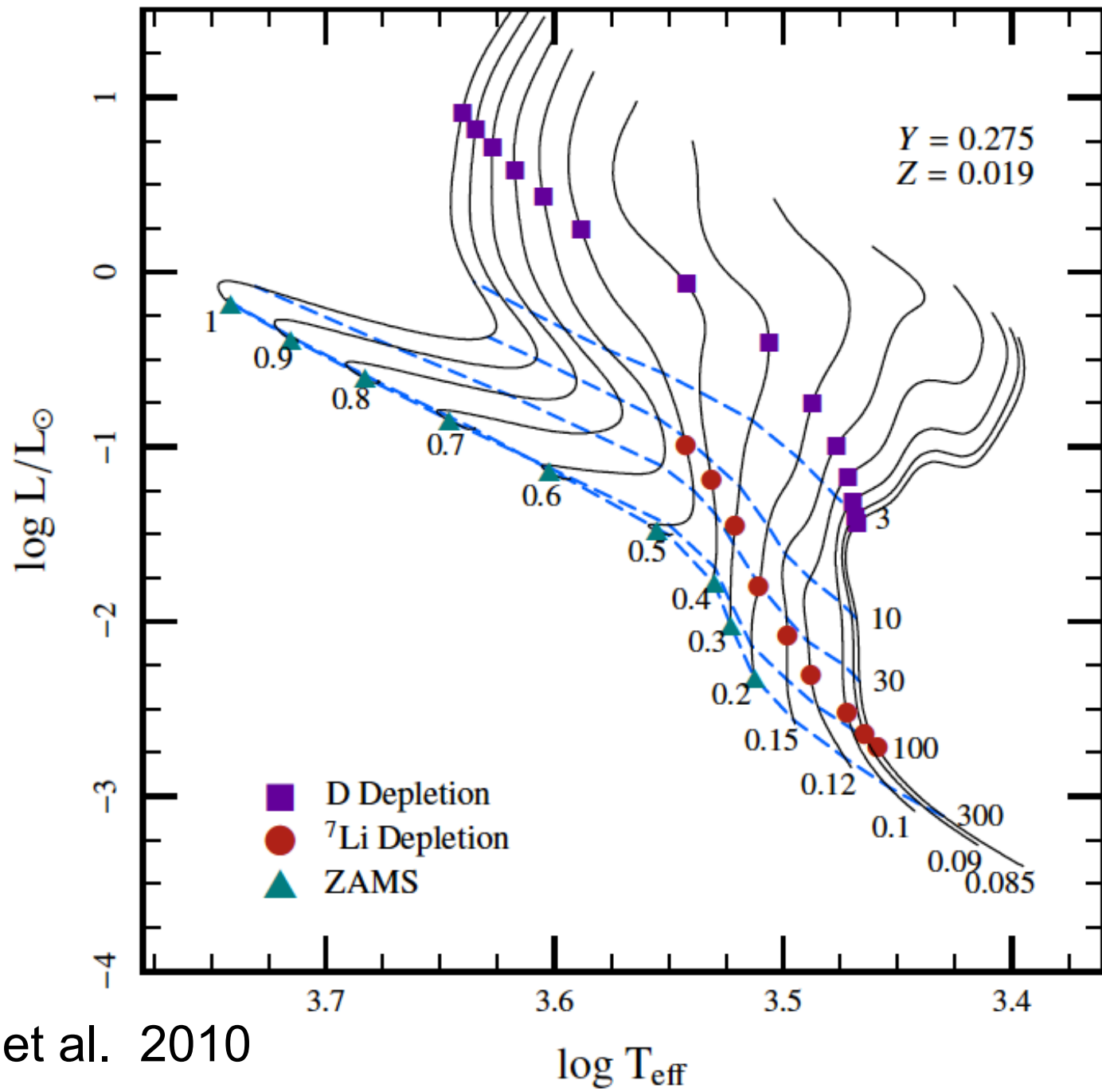
$$\text{Lifetime} = \frac{\text{Nuclear Energy}}{\text{Luminosity}} \approx 10 \text{ Gyr} \left( \frac{M_\odot}{M} \right)^2$$

Brightest stars have the shortest lives (not unlike Hollywood!)



Paxton et al. 2010

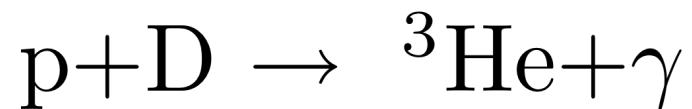
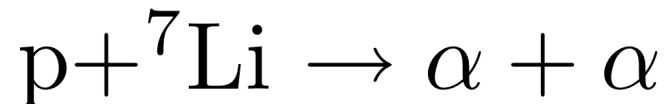
log Central Density ( $\text{gr cm}^{-3}$ )



Paxton et al. 2010

# HW Problem Two

- Why is it easier for the star to burn Deuterium and Lithium than Hydrogen??????



Massive, most luminous stars burn their fuel the fastest, so we get the age of an Open Cluster like Pleiades from the absence of even brighter stars ==> 120 Myr

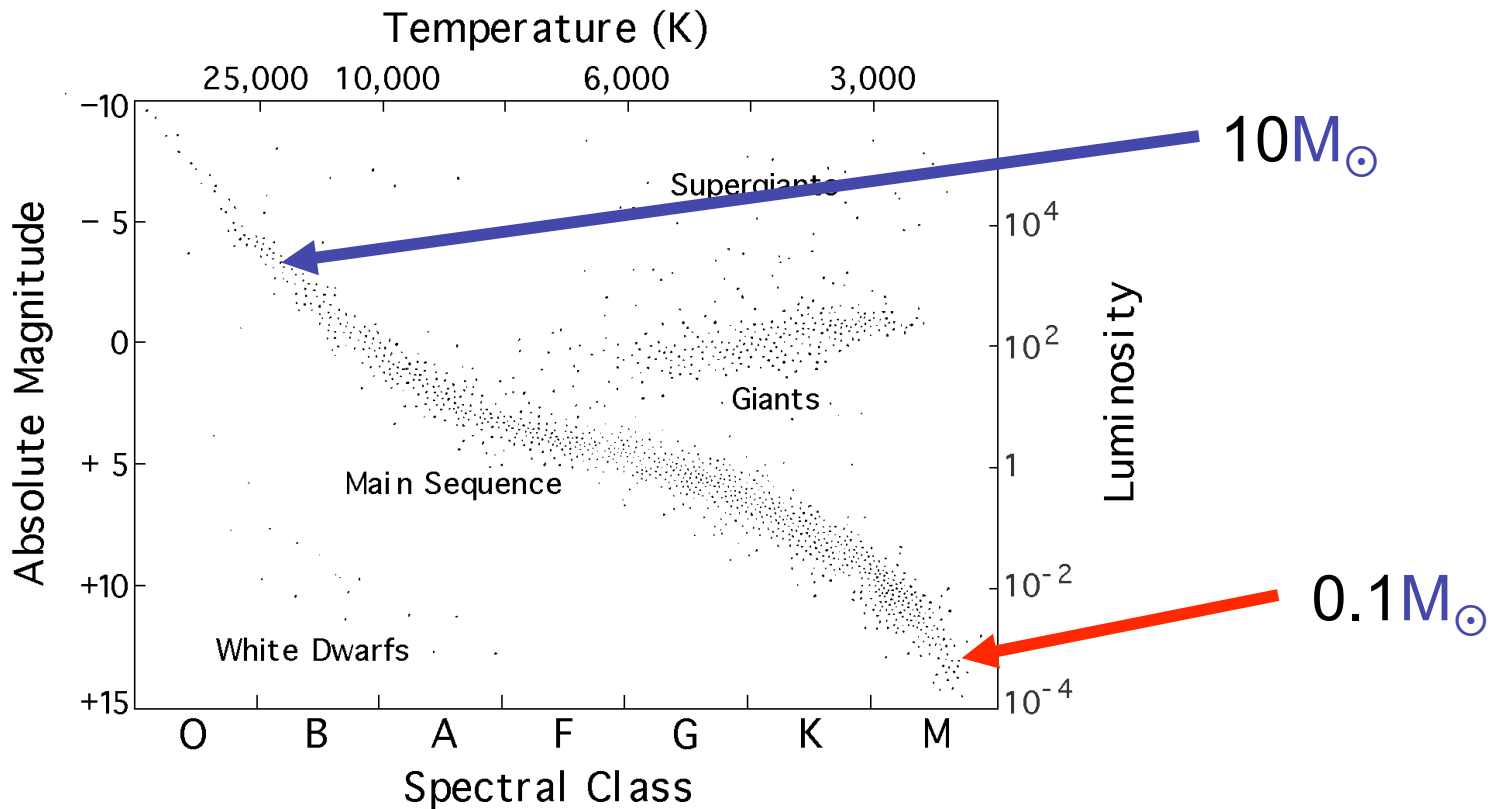




# Surface Temperature Scale

$$L = 4\pi R^2 \sigma_{SB} T_{\text{eff}}^4 \propto M^3 \rightarrow T_{\text{eff}} \propto M^{1/4}$$

More massive stars are more luminous and have hotter surface temperatures. The formula implies a factor of five change in  $T_{\text{eff}}$  (surface value) from  $0.1 M_{\odot}$  to  $60 M_{\odot}$ .



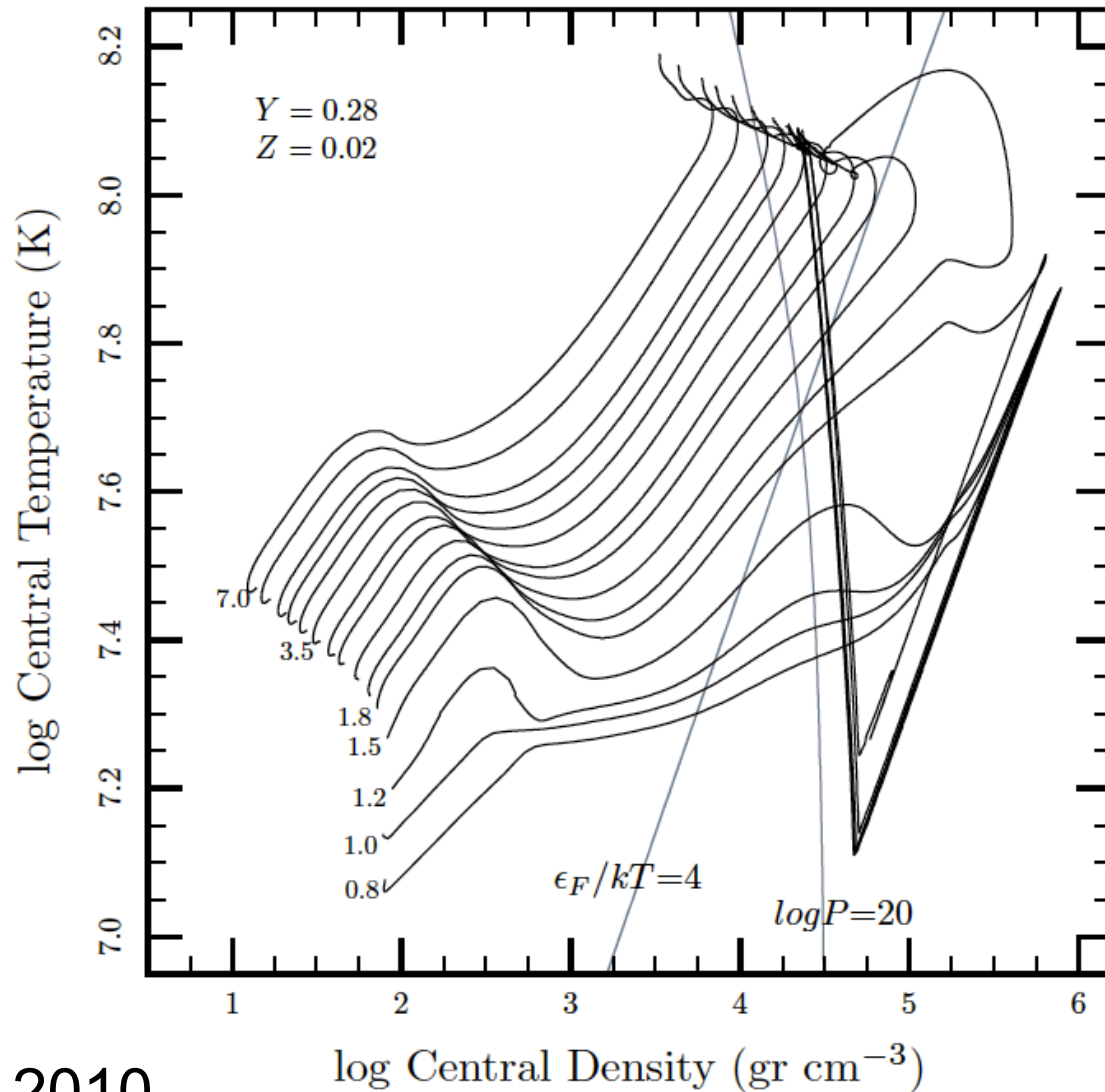
# Helium Burning

Eventually the star runs out of Hydrogen, having converted it all to Helium in the core. However, nuclear energy remains. If only it could be understood how to convert Helium into a heavier element, then stars could live longer and produce CARBON.

The problem was that  $\text{He} + \text{He} \Rightarrow {}^8\text{Be}$  an unstable element.. Hence had to understand how to do it in multiple steps, which was solved, finding a path  $\text{He} + \text{He} + \text{He} \Rightarrow \text{Carbon}$ .

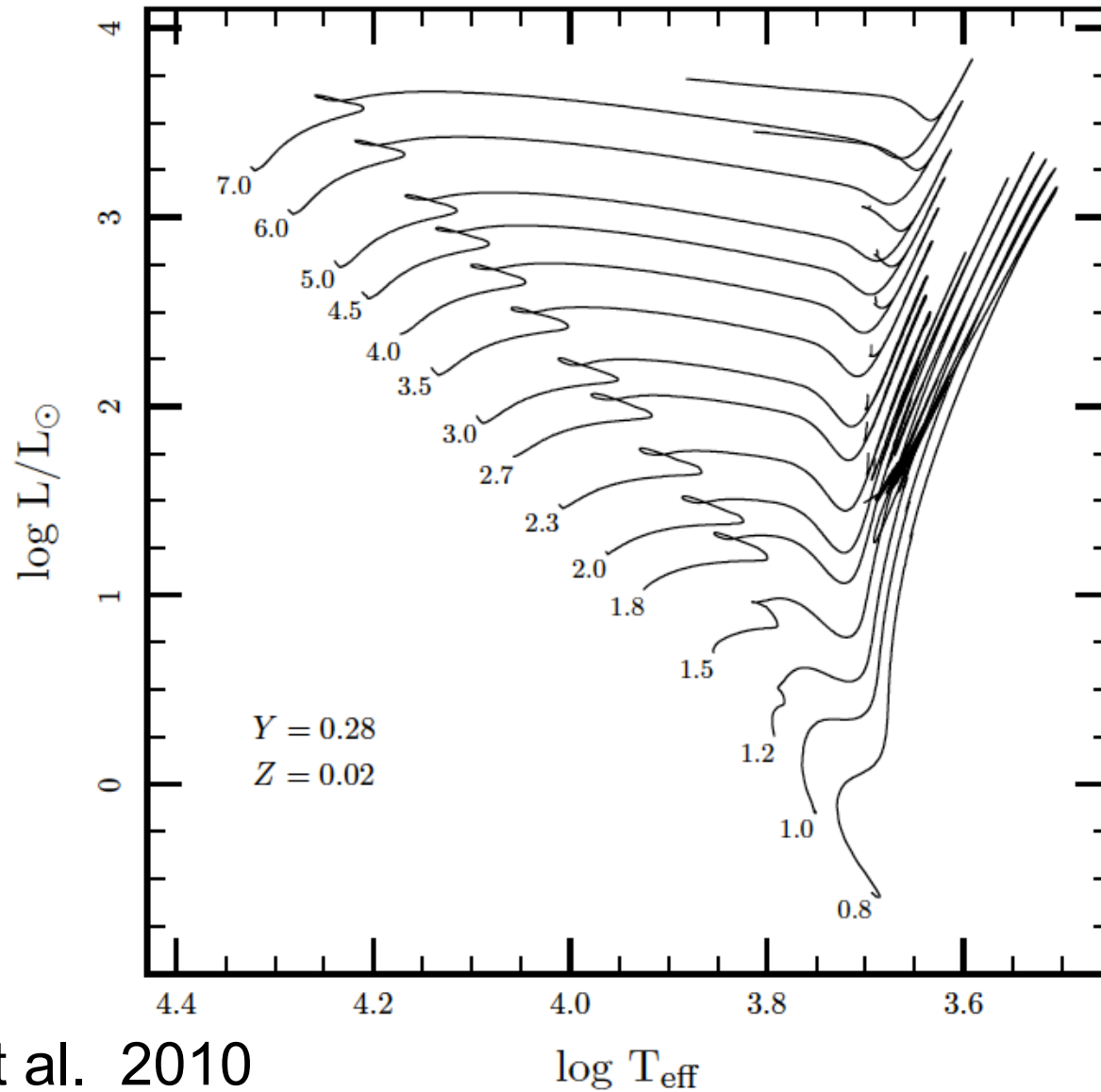
Helium Burning makes Carbon and Oxygen in the Stellar Core, and stars with mass  $< 6-8M_{\odot}$  never burn the carbon, simply cooling to become  $0.6-1.0M_{\odot}$  white dwarfs, the rest of the star leaves in a 5-10 km/second wind!.

# Hydrogen Burning to Helium Ignition



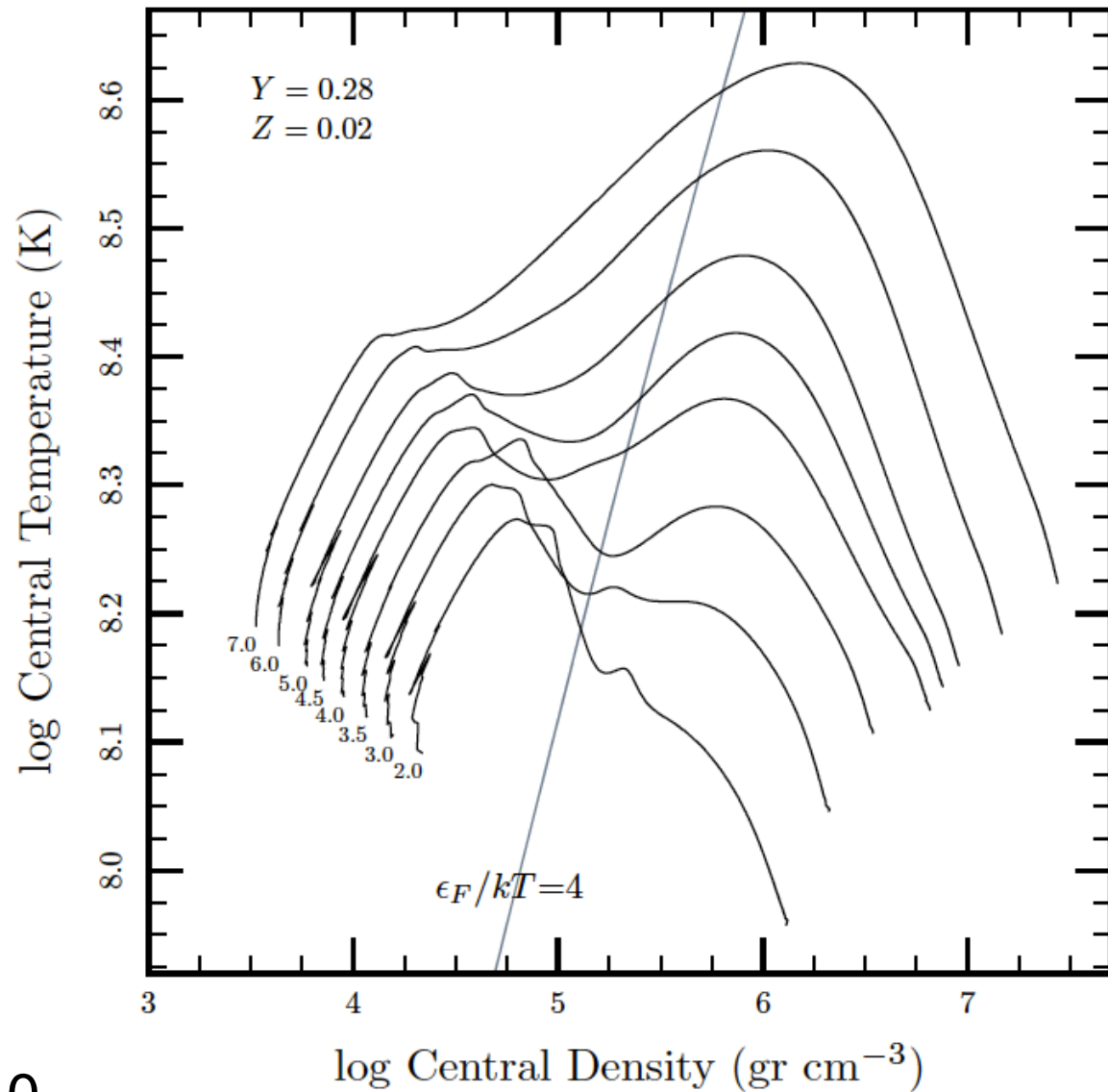
Paxton et al. 2010

# Hydrogen Burning to Helium Ignition



Paxton et al. 2010

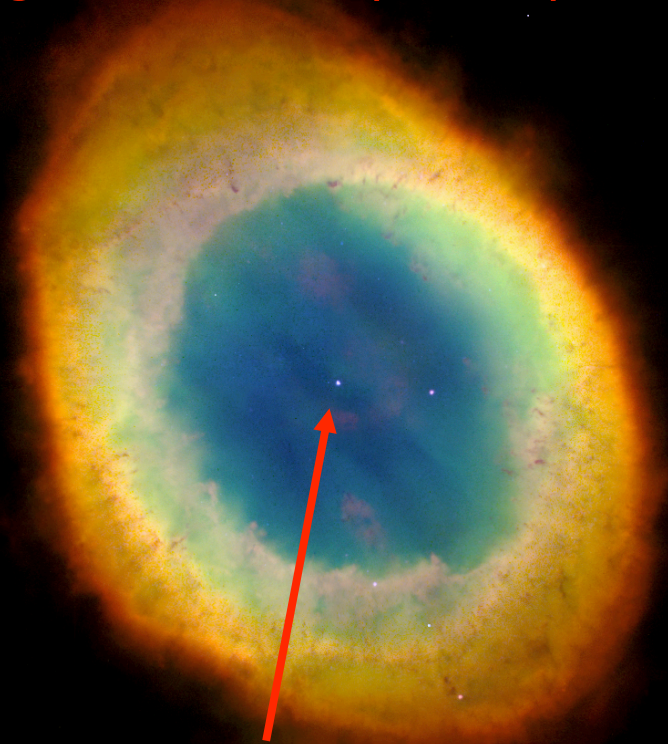
# Carbon Oxygen White Dwarf Formation



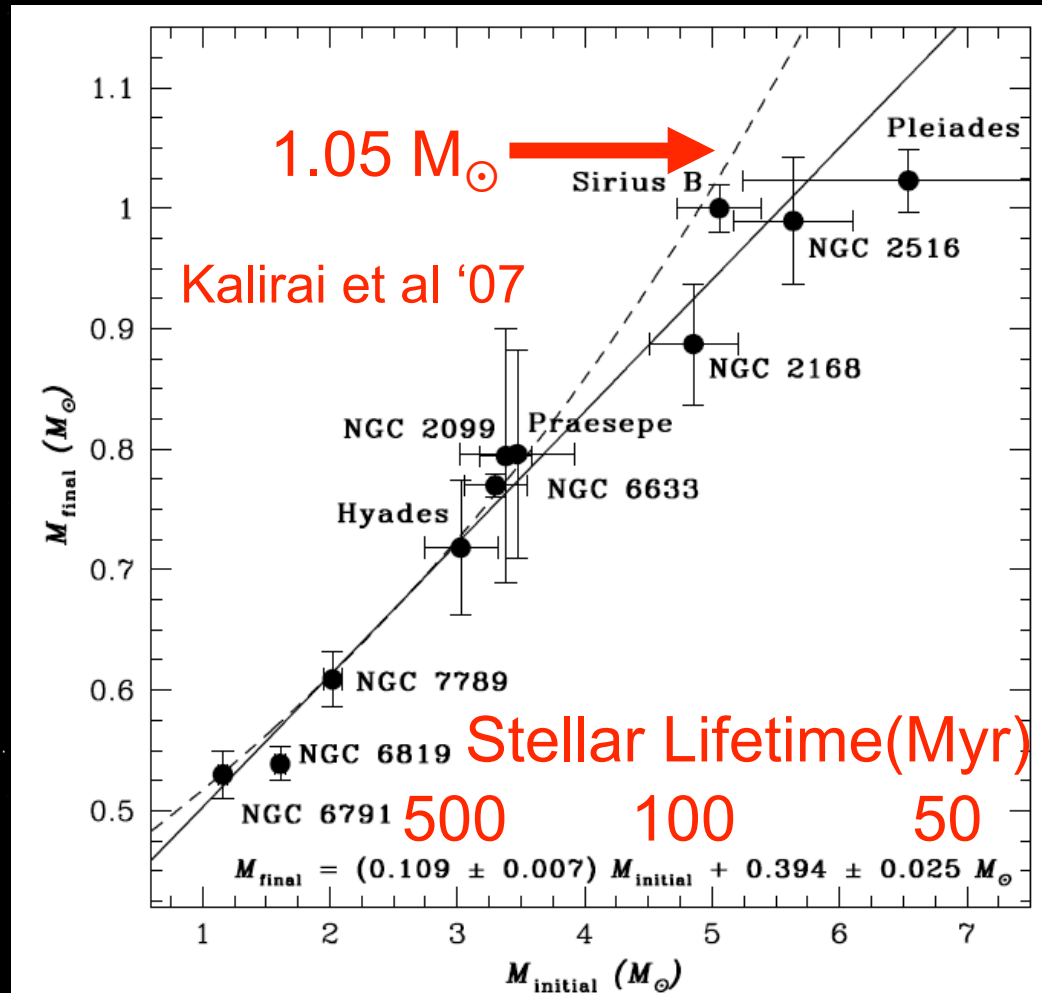
Paxton et al. 2010

Stars with  $< 6-8 M_{\odot}$  make  $0.5-1.0 M_{\odot}$  Carbon/Oxygen white dwarfs with radius  $\sim$  Earth and central densities  $> 10^6 \text{ gr/cm}^3$  that simply cool with time.

## Ring Nebulae (M 57)



Young White Dwarf



# HW Problem Three

What's the mass-radius relation when the degenerate electrons provide ALL the pressure support???

# White Dwarf Basics

As the WD cools, the electrons become degenerate, supplying a pressure

$$P_e \approx n_e E_F \approx n_e \frac{\hbar^2 k_f^2}{2m_e} \quad P_e \propto \rho^{5/3} \propto (M/R^3)^{5/3}$$

that balances the hydrostatics  $\frac{dP}{dr} = -\rho \frac{Gm(r)}{r^2}$   $P_e \sim \frac{GM^2}{R^4}$

to give a mass-radius relation:

$$R \propto 1/M^{1/3} \rightarrow \rho \propto M^2$$

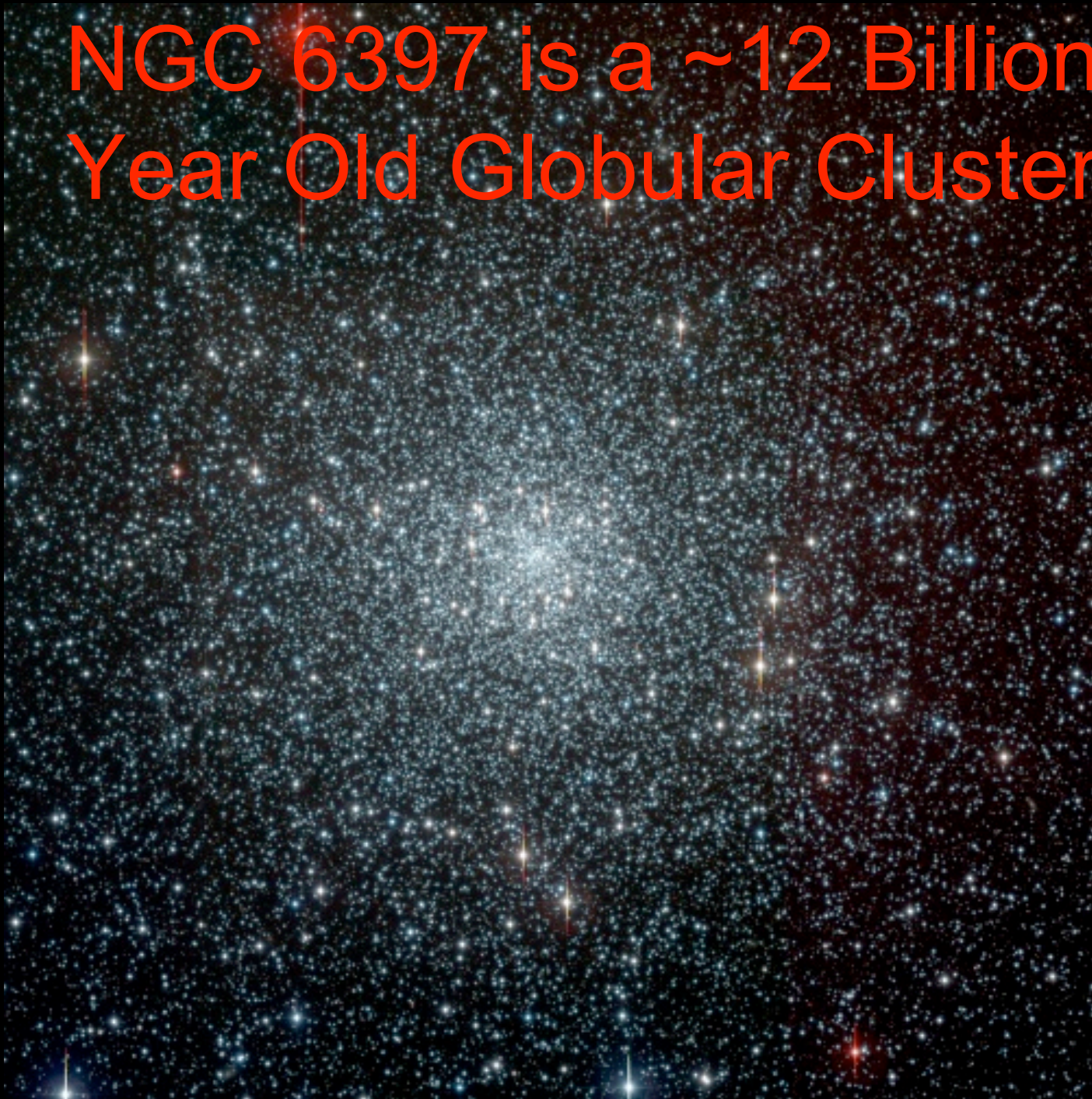
The density rises with mass, and the electrons become relativistic, giving  $E_F = p_F c \rightarrow P \propto \rho^{4/3}$  which means the radius is indeterminate, and there is a critical mass, called the Chandrasekhar mass

$$M_{Ch} = 1.46 M_{\odot} \left( \frac{2Z}{A} \right)^2$$

No stable WDs can exist with masses greater than this!

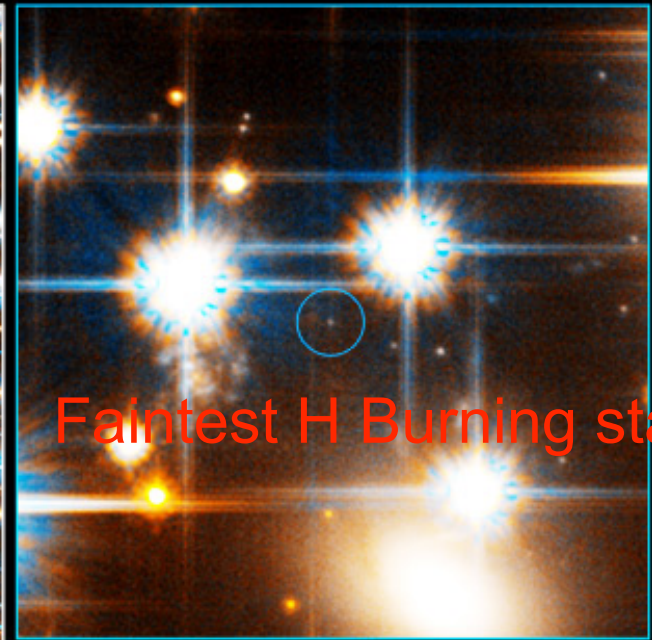
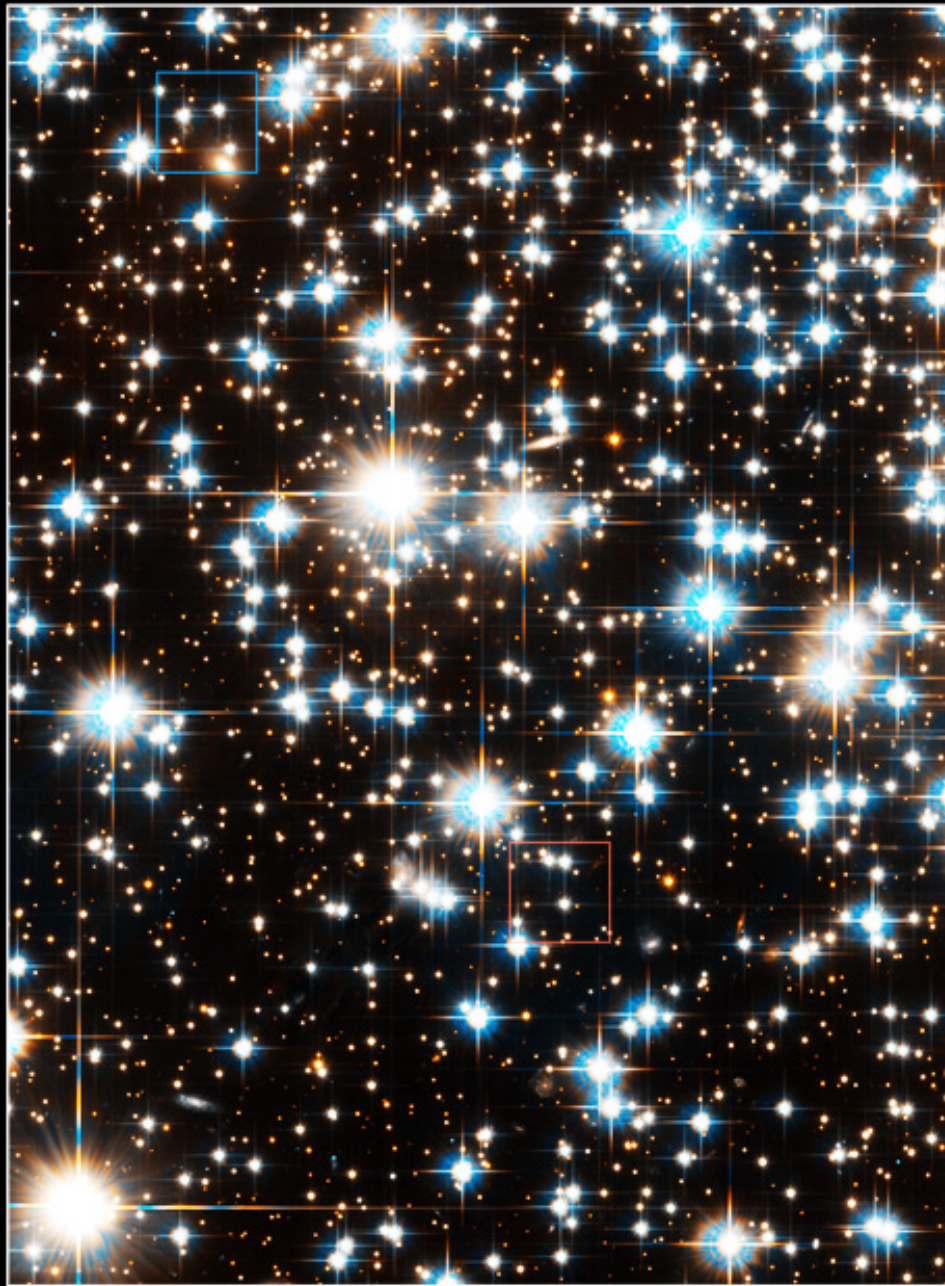


NGC 6397 is a ~12 Billion  
Year Old Globular Cluster

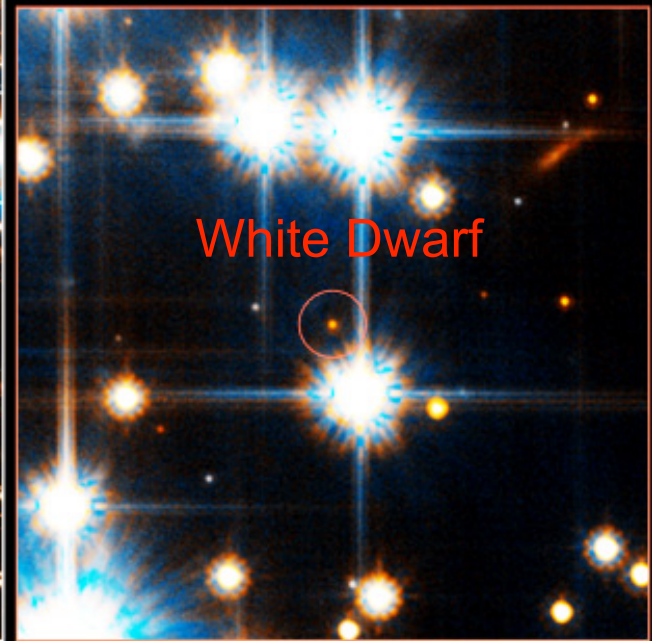


Globular Cluster NGC 6397

Hubble Space Telescope ■ ACS/WFC

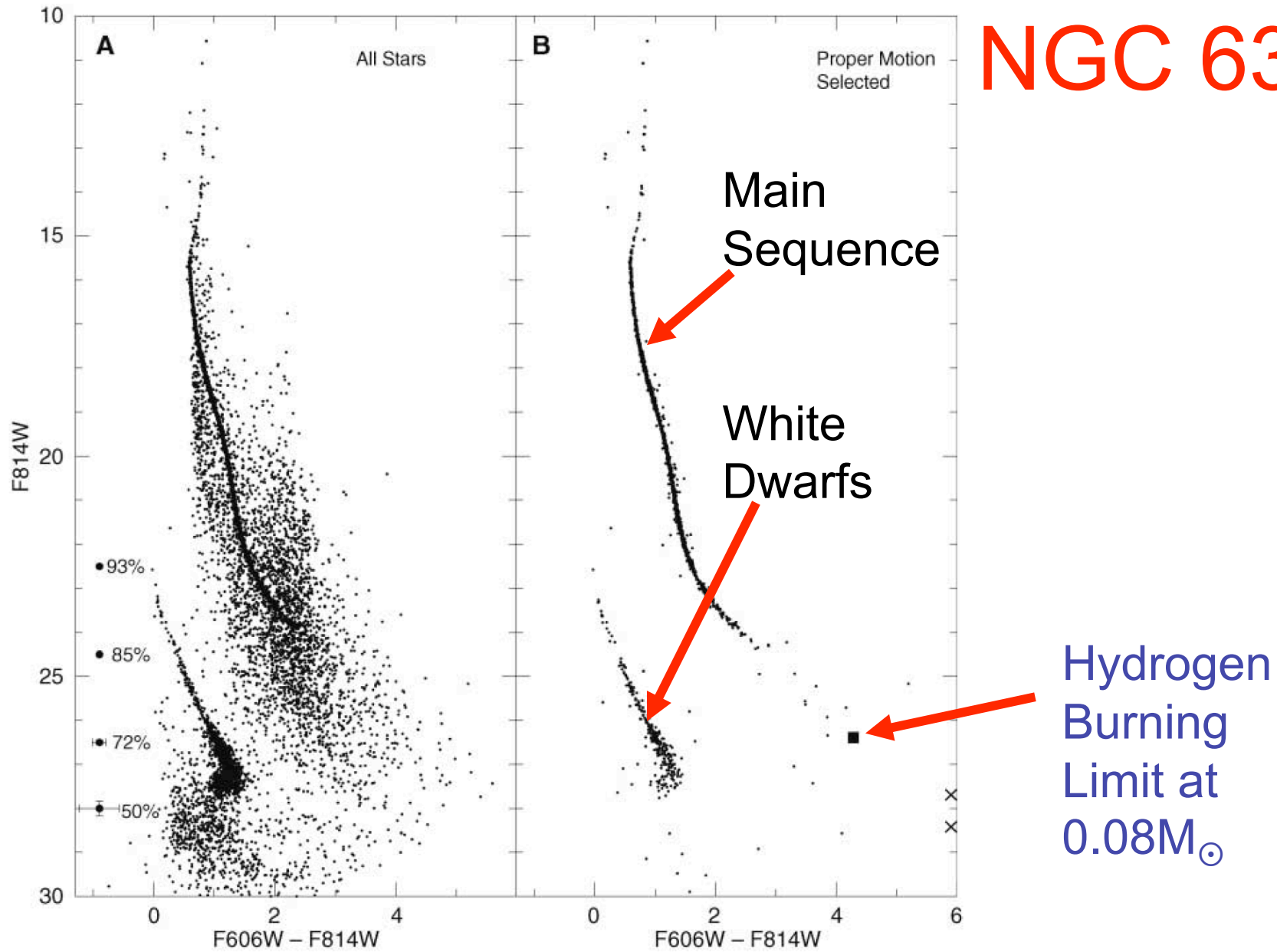


Faintest H Burning star



White Dwarf

# NGC 6397



Richer et al 2006, Science, 313, 936

# Outcomes so Far

$M < 0.08$ : Never got hot enough to ignite Hydrogen Burning

$0.08 < M < 0.8$ : Still Burning Hydrogen to Helium after 12 Gyrs

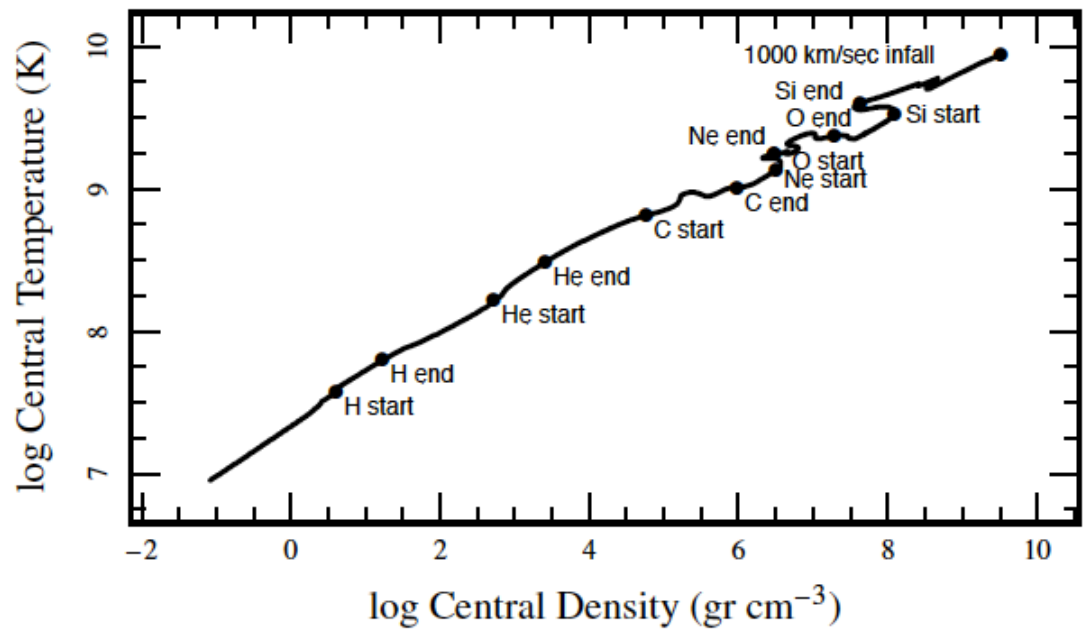
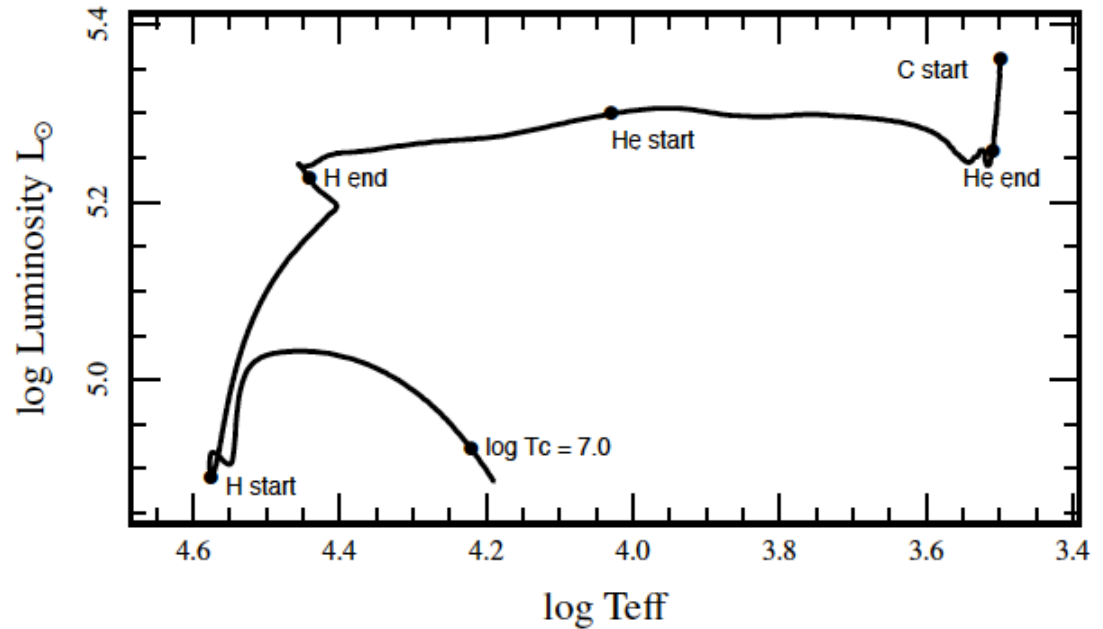
$0.8 < M < (6-8)$ : Burn  $H \Rightarrow He$ , and  $He \Rightarrow C/O$ , then leaves a compact remnant white dwarf of  $0.55 \Rightarrow 1.1 M_{\odot}$  some nucleosynthesis occurs in the exiting matter, but not much.

Stars more massive than 6-8 times the Sun get to burn all the way up to the most stable nucleus,  $^{56}\text{Fe}$ , at least in their core.

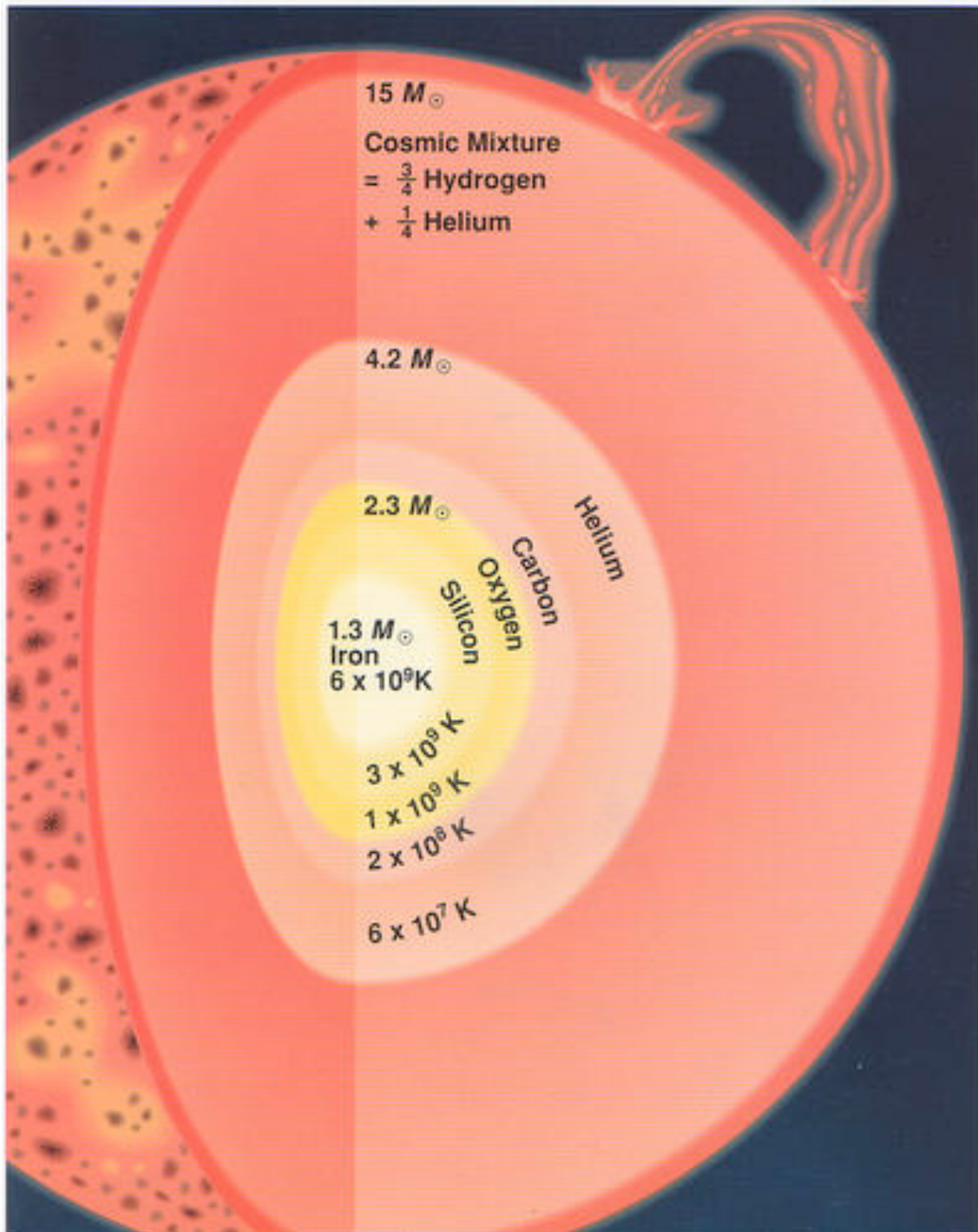
After that has happened, no further nuclear burning can halt the gravitational contraction... . . . Leading to a catastrophic collapse to densities comparable to that of a nucleus!  $\Rightarrow$  Type II Supernovae

# Life of a 25 Solar Mass star

- Central conditions allow for a more complete burn
- End up with a nearly pure  $^{56}\text{Fe}$  core of mass near  $M_{\text{ch}}$



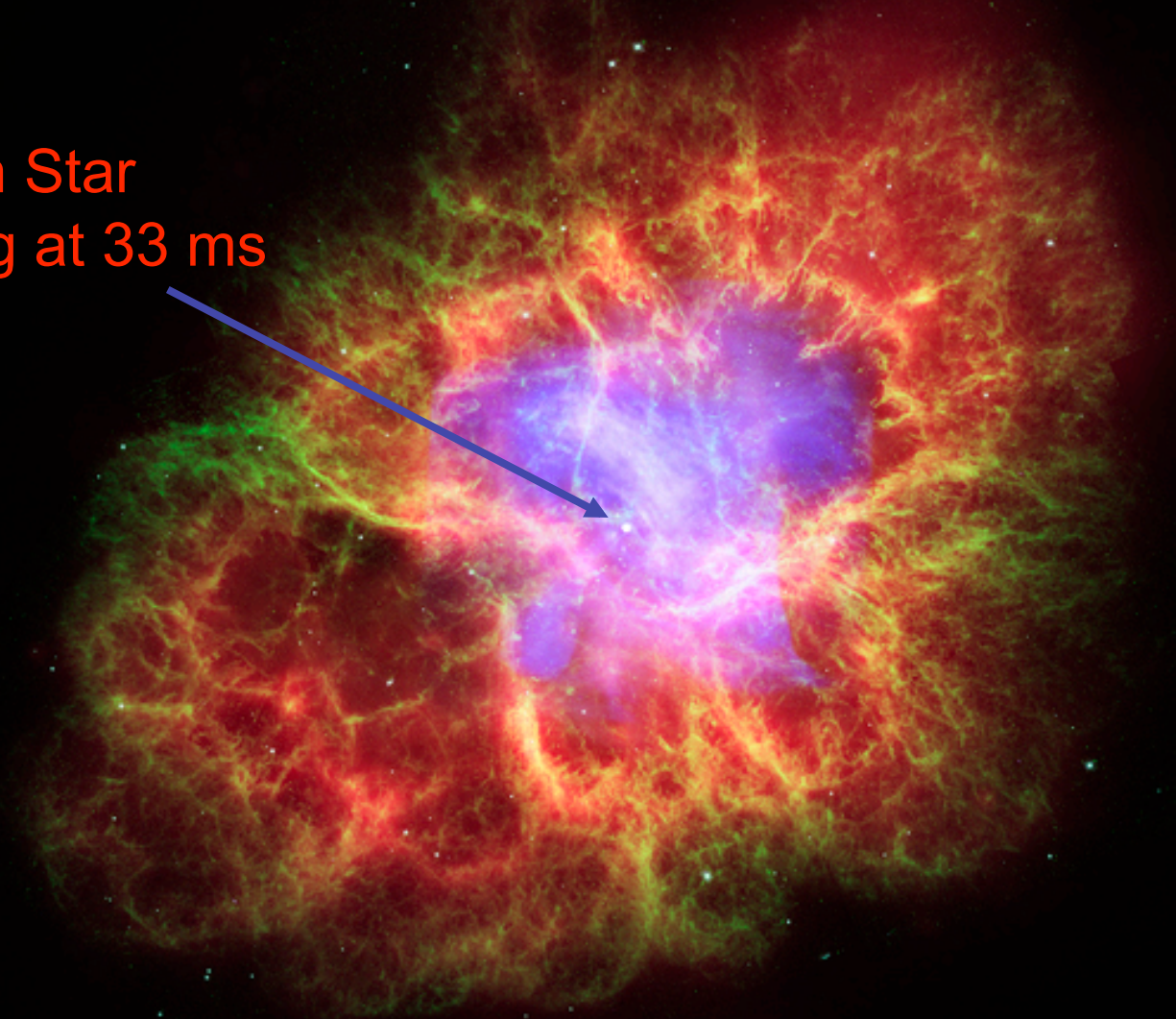
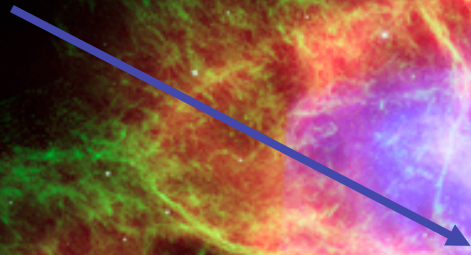
Paxton et al. 2010



- The shells of matter get ejected, enriching the matter between stars.
- These events make most of the elements like Carbon, Oxygen, Silicon. . . But only some of the Iron.
- The remnant left from the collapse is either a **Neutron Star** or a **Black Hole**.

# Crab Nebula from the supernova of 1054 AD

Neutron Star  
spinning at 33 ms



End lecture one