Life of a Star*

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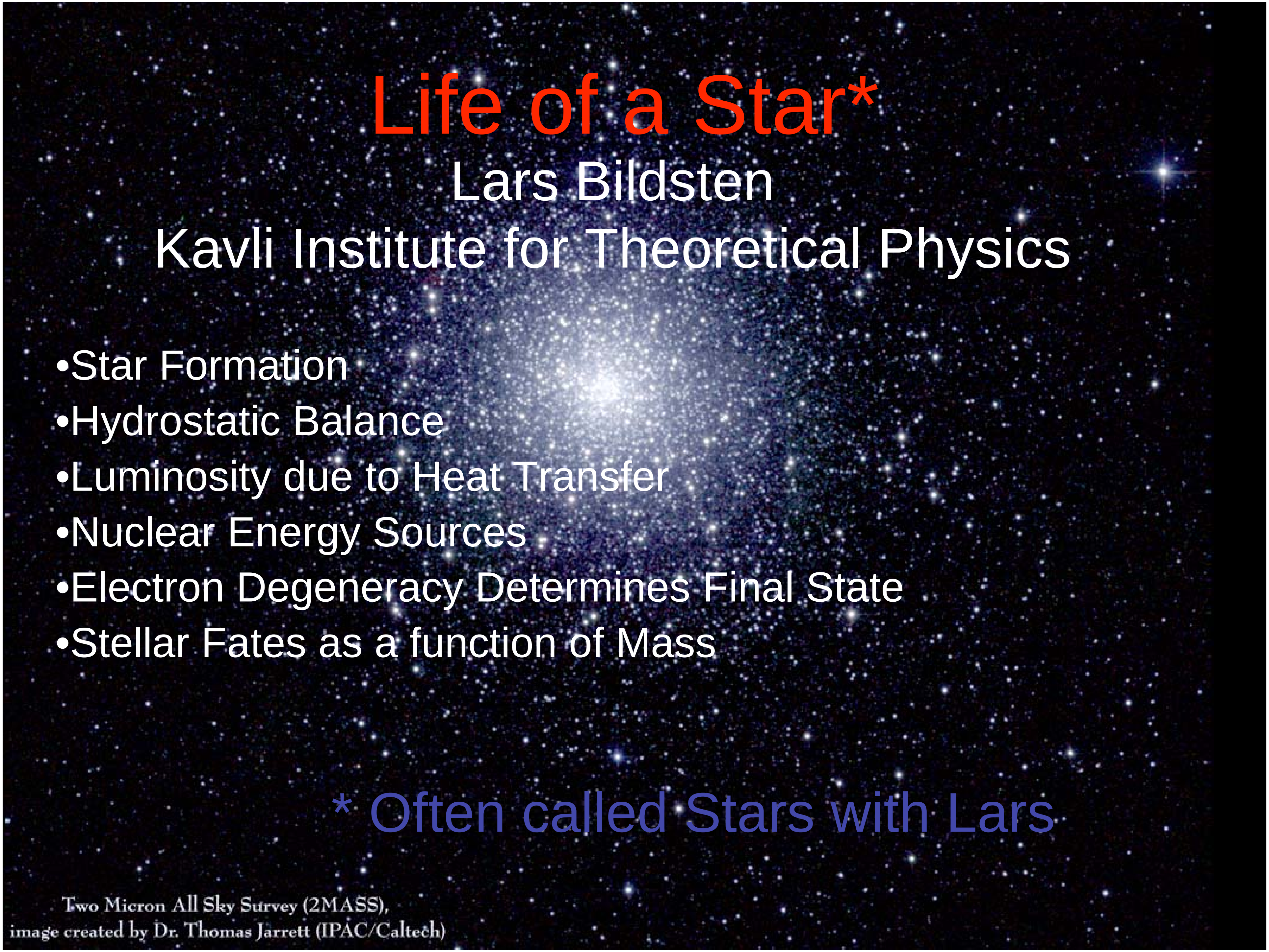
- Star Formation
- Hydrostatic Balance
- Luminosity due to Heat Transfer
- Nuclear Energy Sources
- Electron Degeneracy Determines Final State
- Stellar Fates as a function of Mass

* Often called Stars with Lars



Two Micron All Sky Survey (2MASS),
image created by Dr. Thomas Jarrett (IPAC/Caltech)

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IC 2944=Open Cluster about 10 Million Years old, 1.8 kpc

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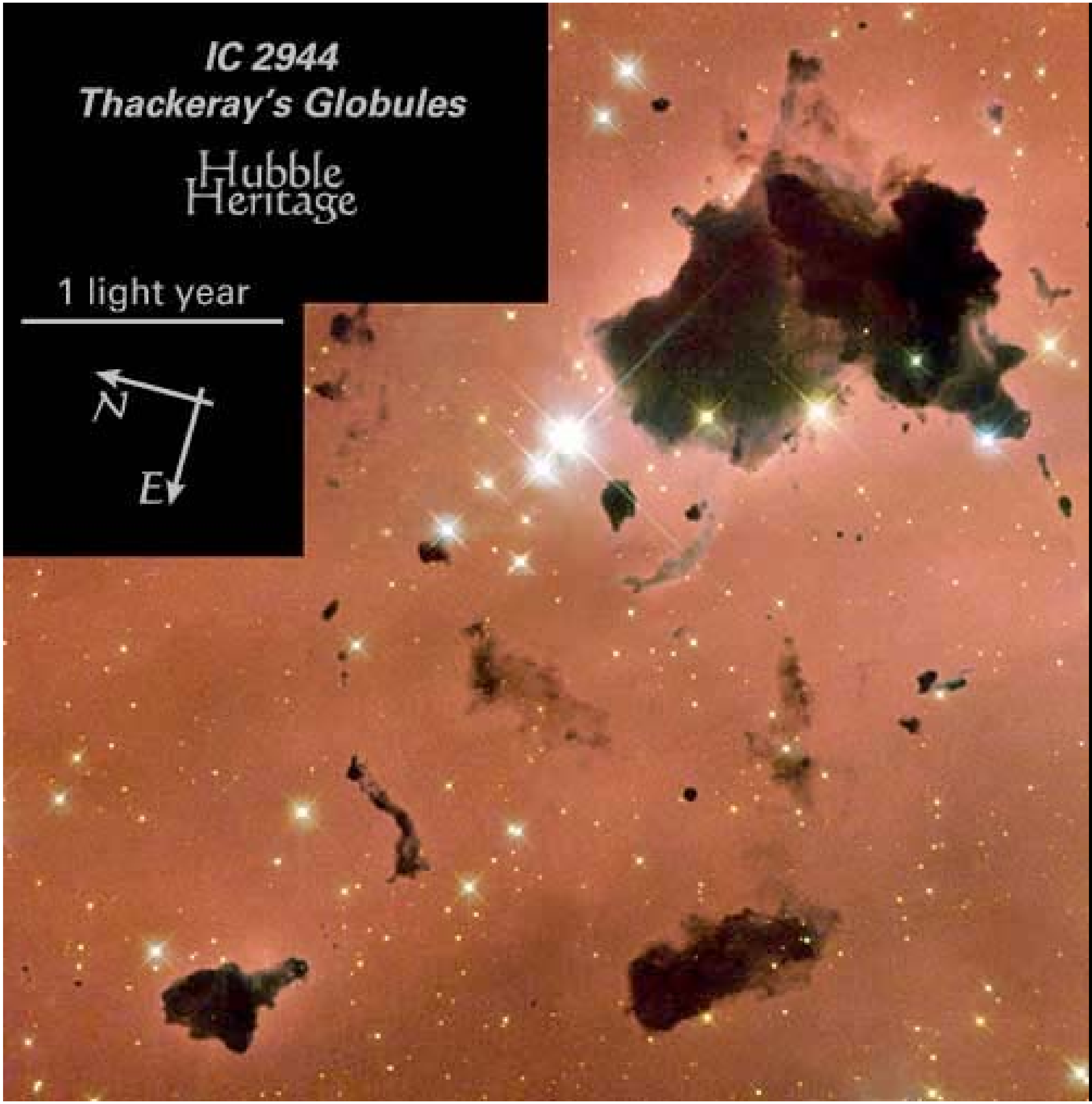
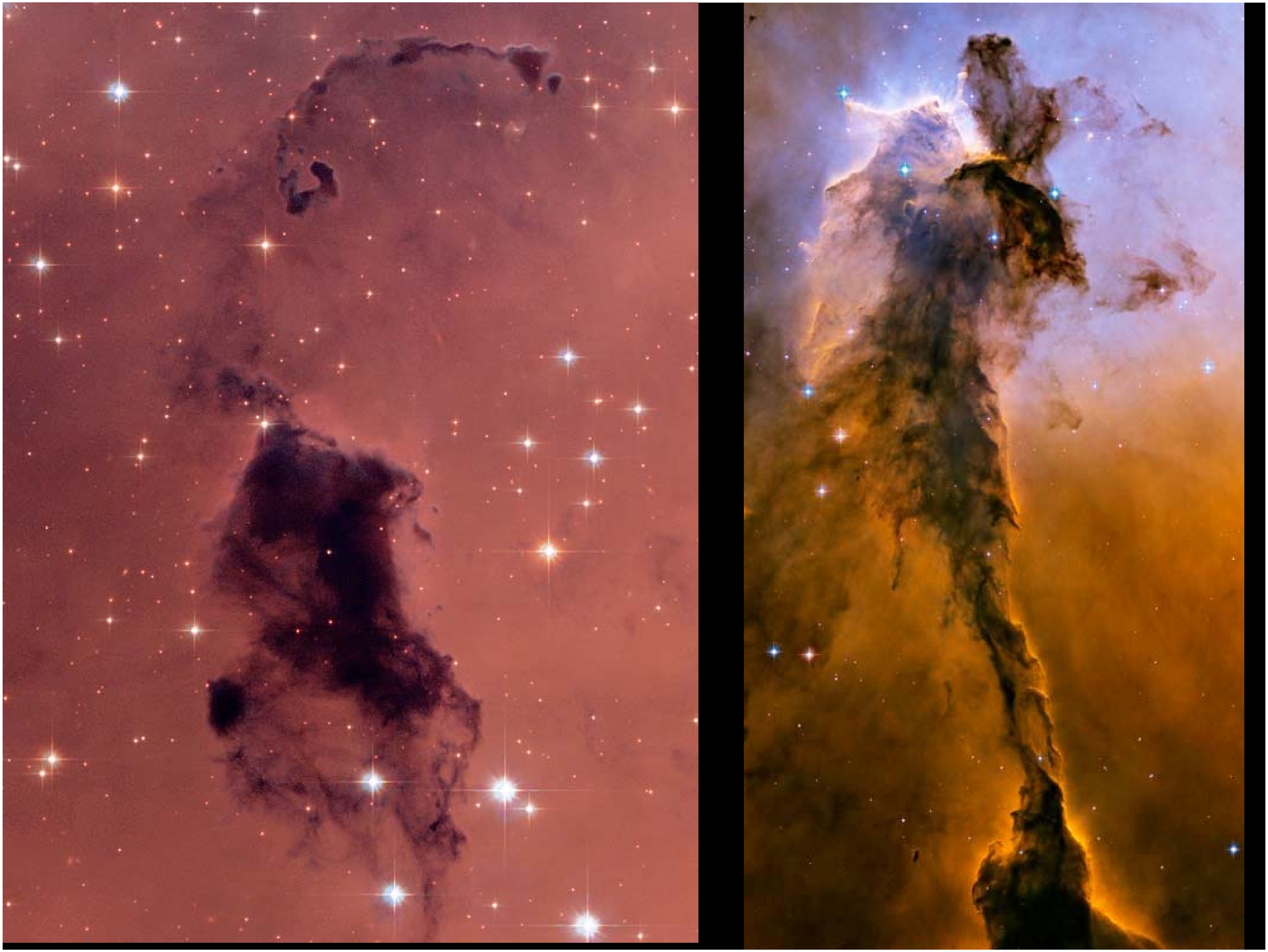
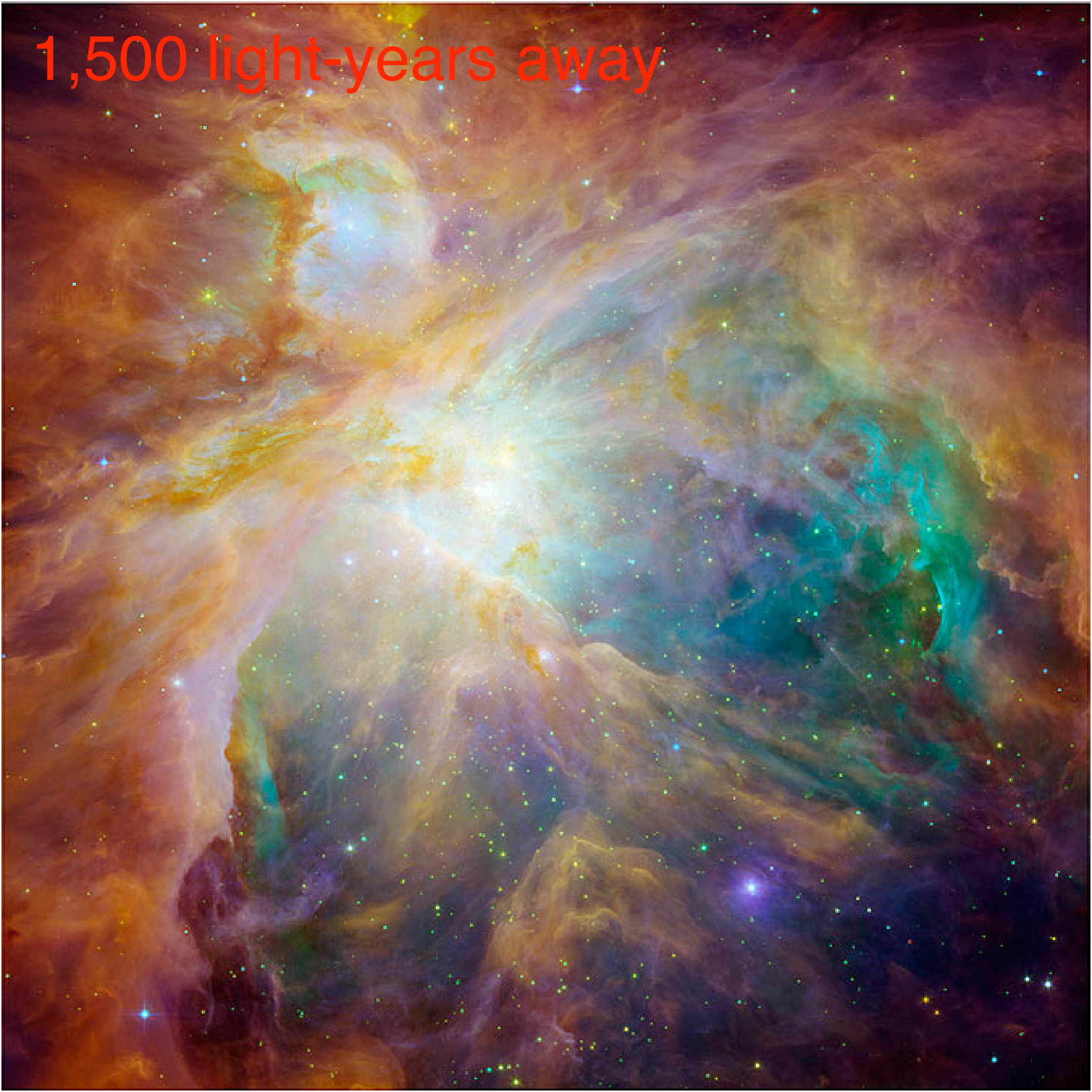


Enough mass in the globules for about 15 stars like the sun. . .



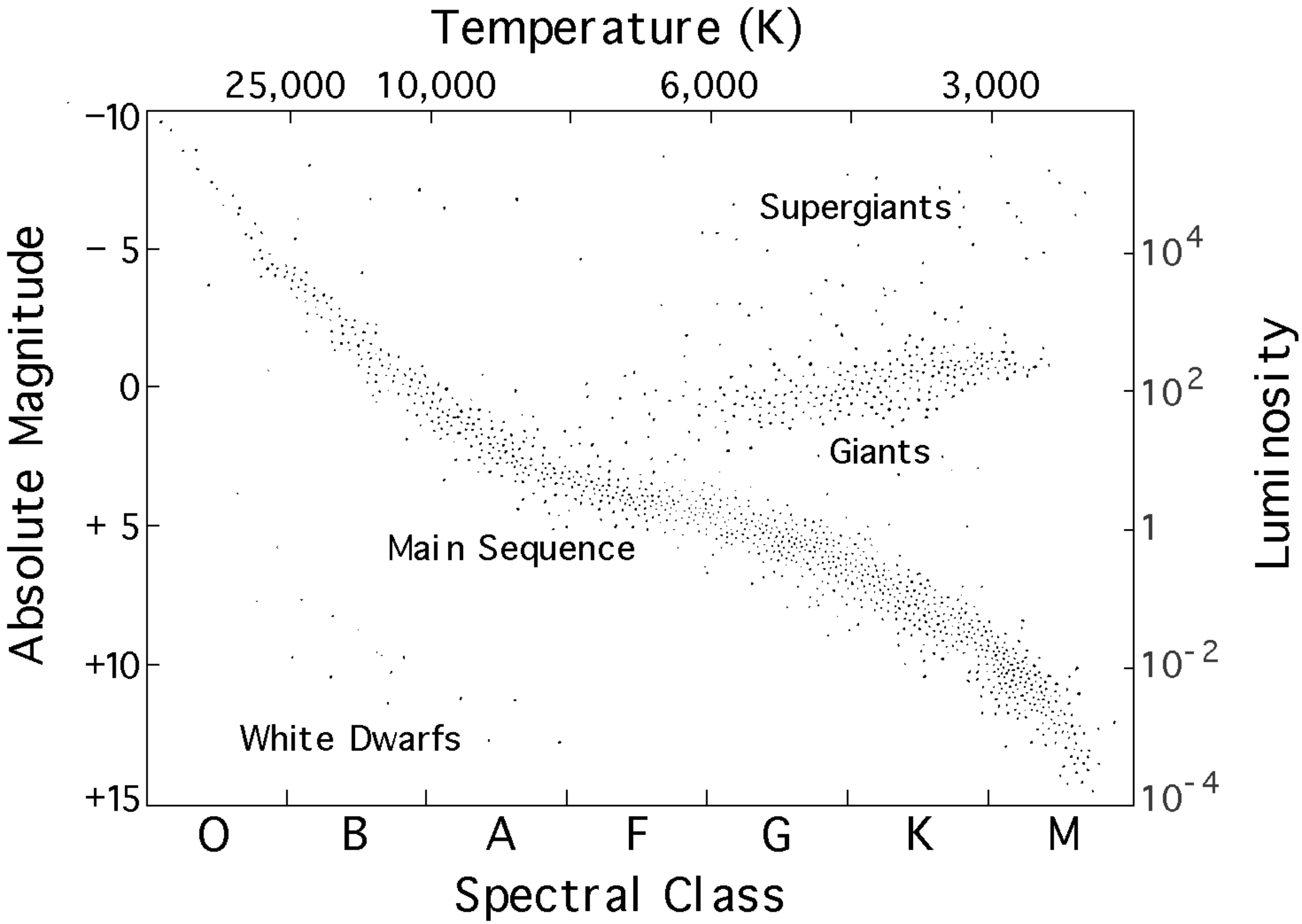


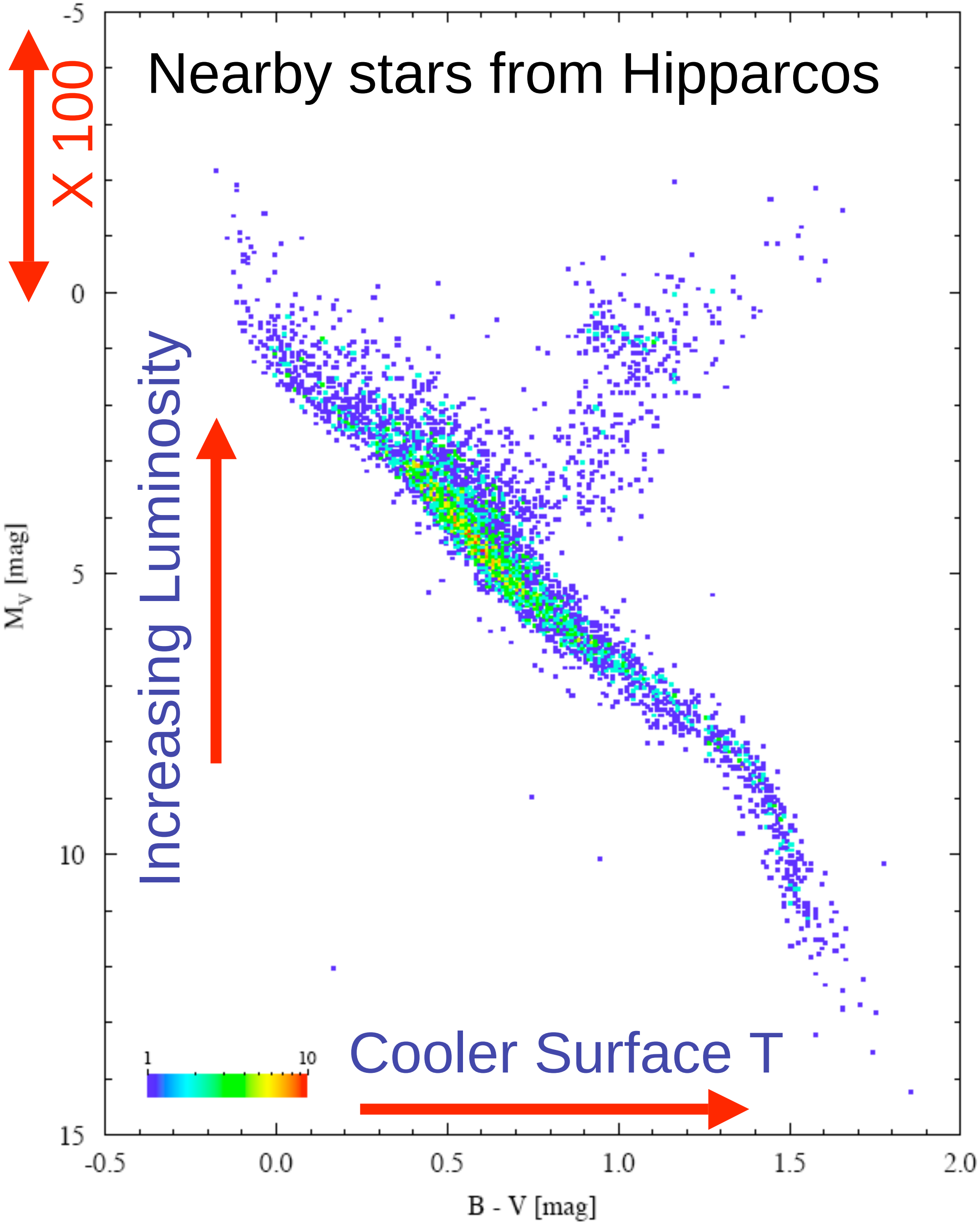
The Orion Nebula

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • WFI

NASA / JPL-Caltech / T. Megeath (University of Toledo) & M. Robberto (STScI) ssc2006-21a

Hertzsprung Russell Diagram





The outcome of star formation is construction of 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 cheat, and assume that at a typical place in the star, m=total mass M, r=radius R, then 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

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

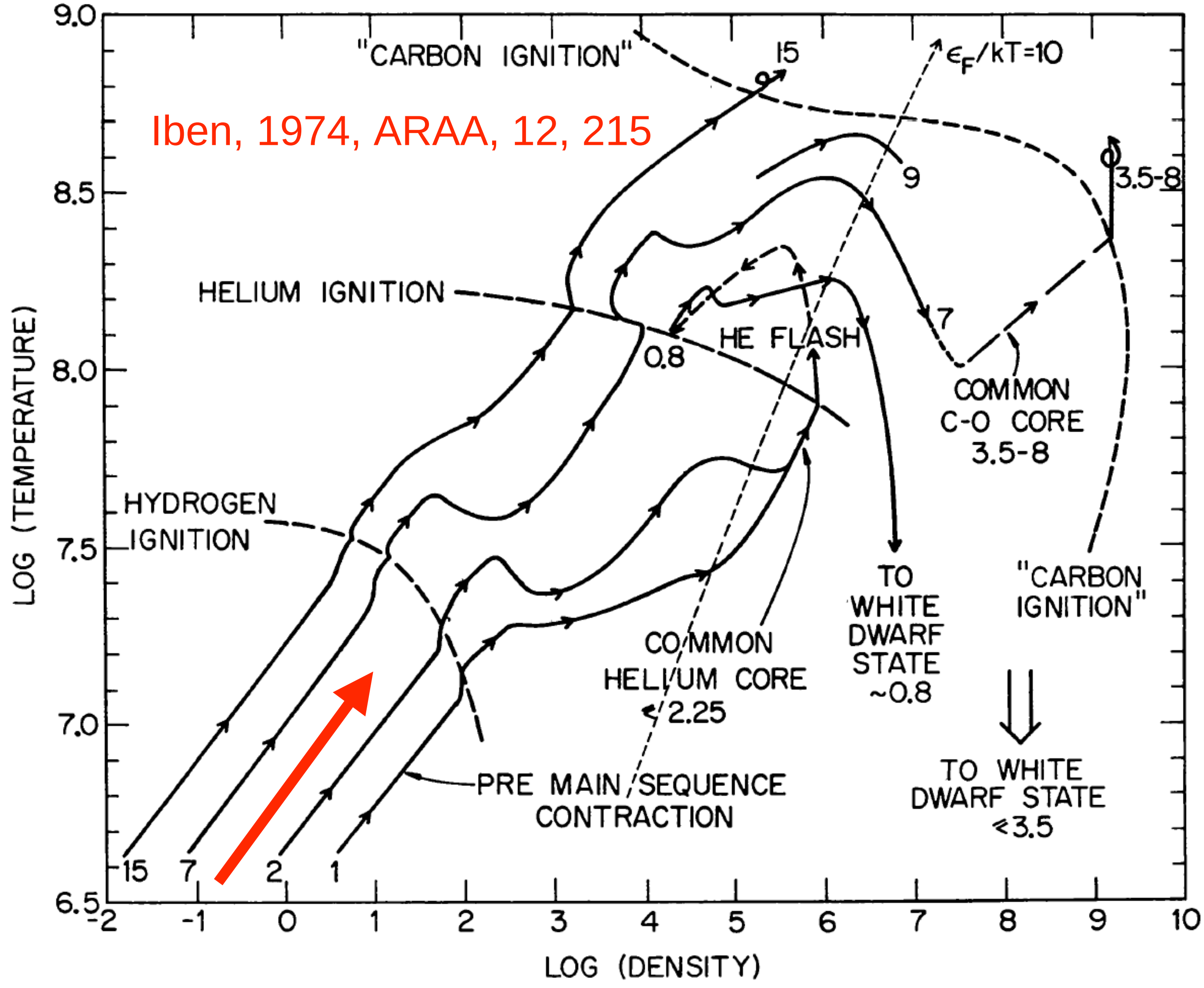
More on Hydrostatic Balance

$$k_B T_c \approx \frac{G M m_p}{R}$$

As R shrinks (e.g. 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 (the Kepler problem), 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

$$t_{\mathrm{Kelvin}} \approx \frac{G M^2 / R}{L} \approx 10^7 \mathrm{yr}$$



Iben, 1974, ARAA, 12, 215

$$T_c \approx 2 \times 10^6 \mathrm{K} \left(\frac{M}{M_\odot}\right)^{2/3} \left(\frac{\rho_c}{\mathrm{gr\ cm^{-3}}}\right)^{1/3}$$

Stellar Luminosity

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

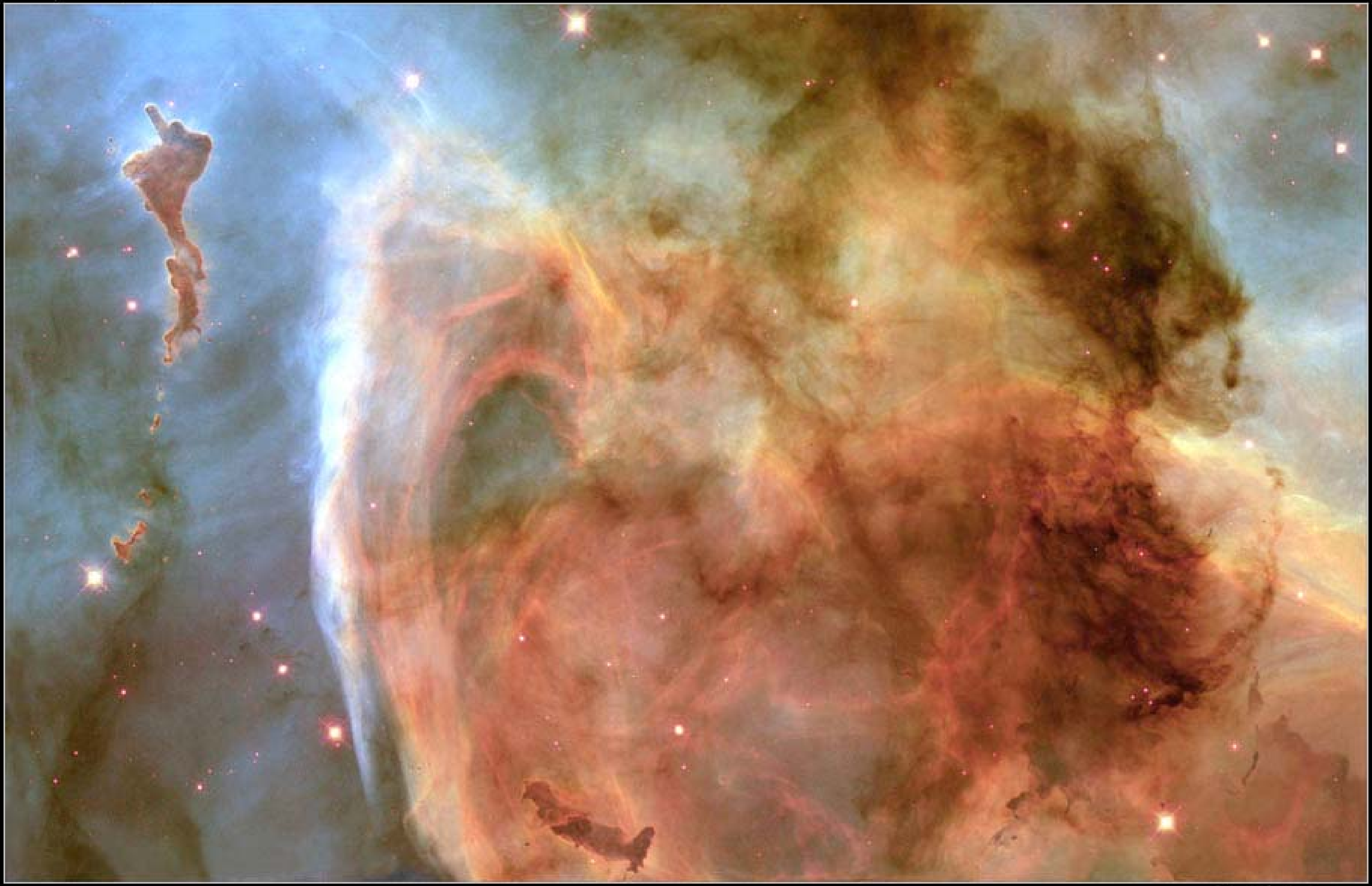
The luminosity of the star is determined by heat transport, since the core is hot, and the surface is cold (VACUUM!). Unlike in your house, the heat is transported by diffusion of photons, which have a mean free path l, giving:

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

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 50 solar masses. . . . .

But what sets the stellar radius?

Keyhole Nebula



Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06

Nuclear Burning

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

$$p + p \rightarrow D + e^{+} + \nu_e$$

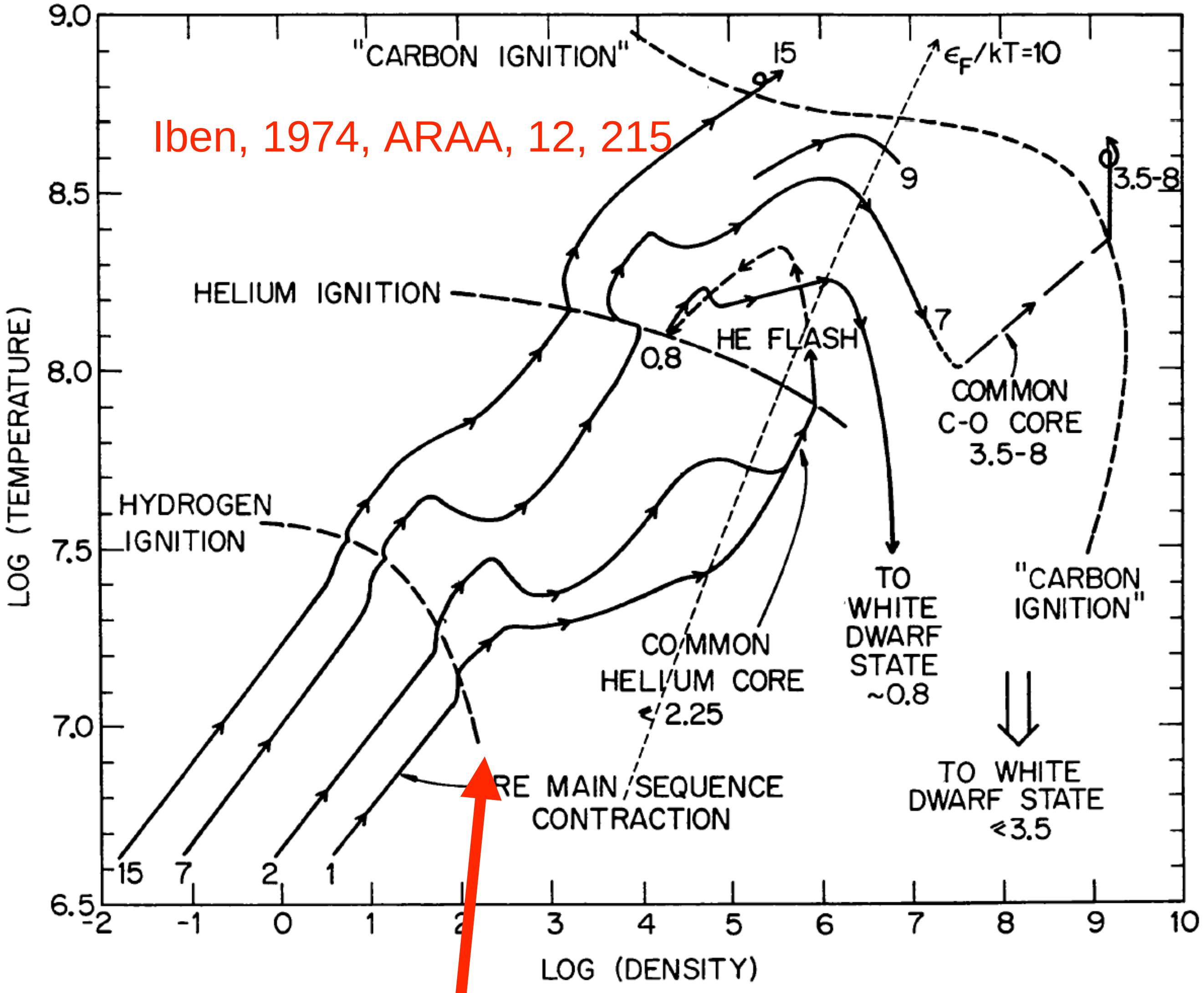
$$p + D \rightarrow {}^3\,\mathrm{He} + \gamma$$

$$^3\mathrm{He} + {}^3\,\mathrm{He} \rightarrow {}^4\,\mathrm{He} + p + p$$

This reaction rate is very temperature sensitive, so once a certain T_c is reached, the energy generation rate MATCHES that lost. This fixes the stellar radius, R, and lifetime

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

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



Iben, 1974, ARAA, 12, 215

$$T_c \propto M/R$$

Since burning is so temperature sensitive, the core temperature changes little across the main sequence, so we get (roughly)

$$R \propto M$$

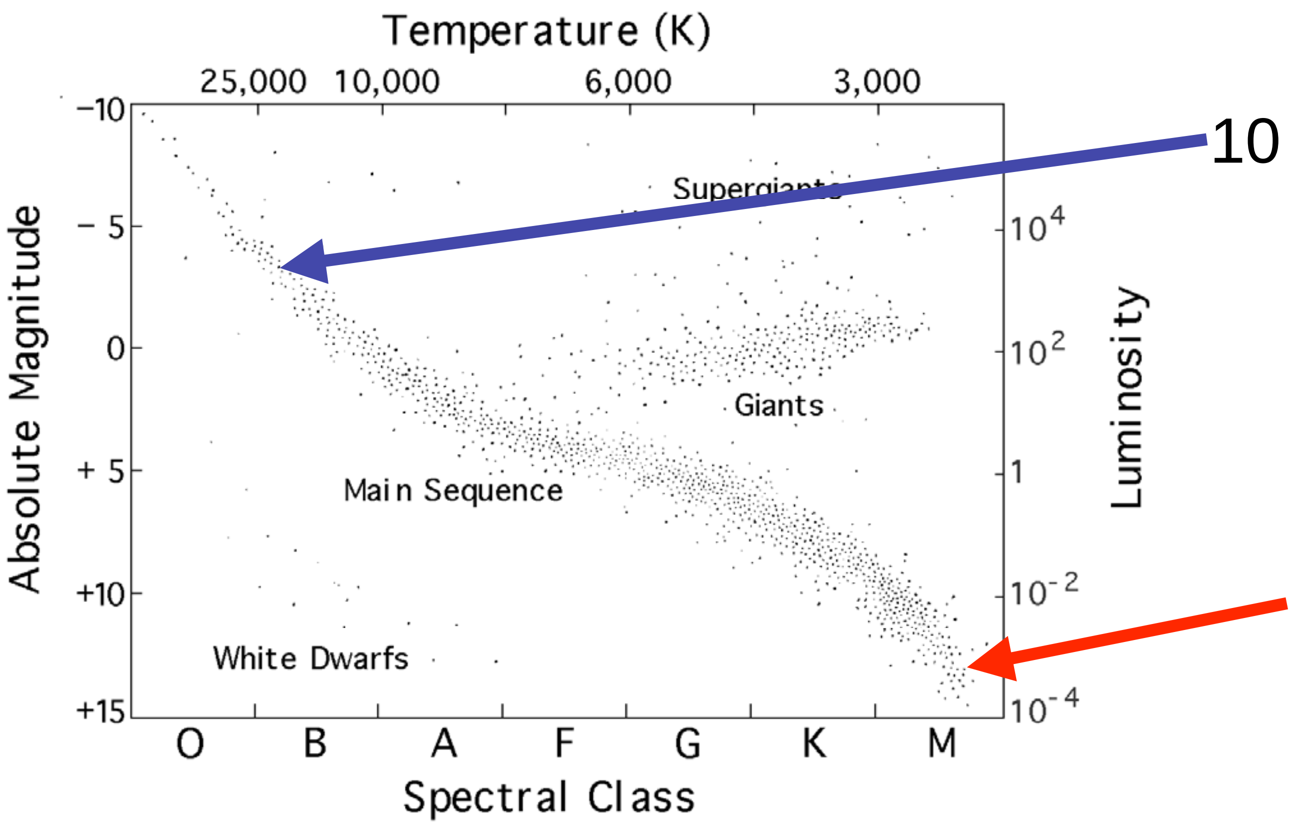
Hydrogen Burning “Main Sequence” goes down to 0.08 solar masses ..

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

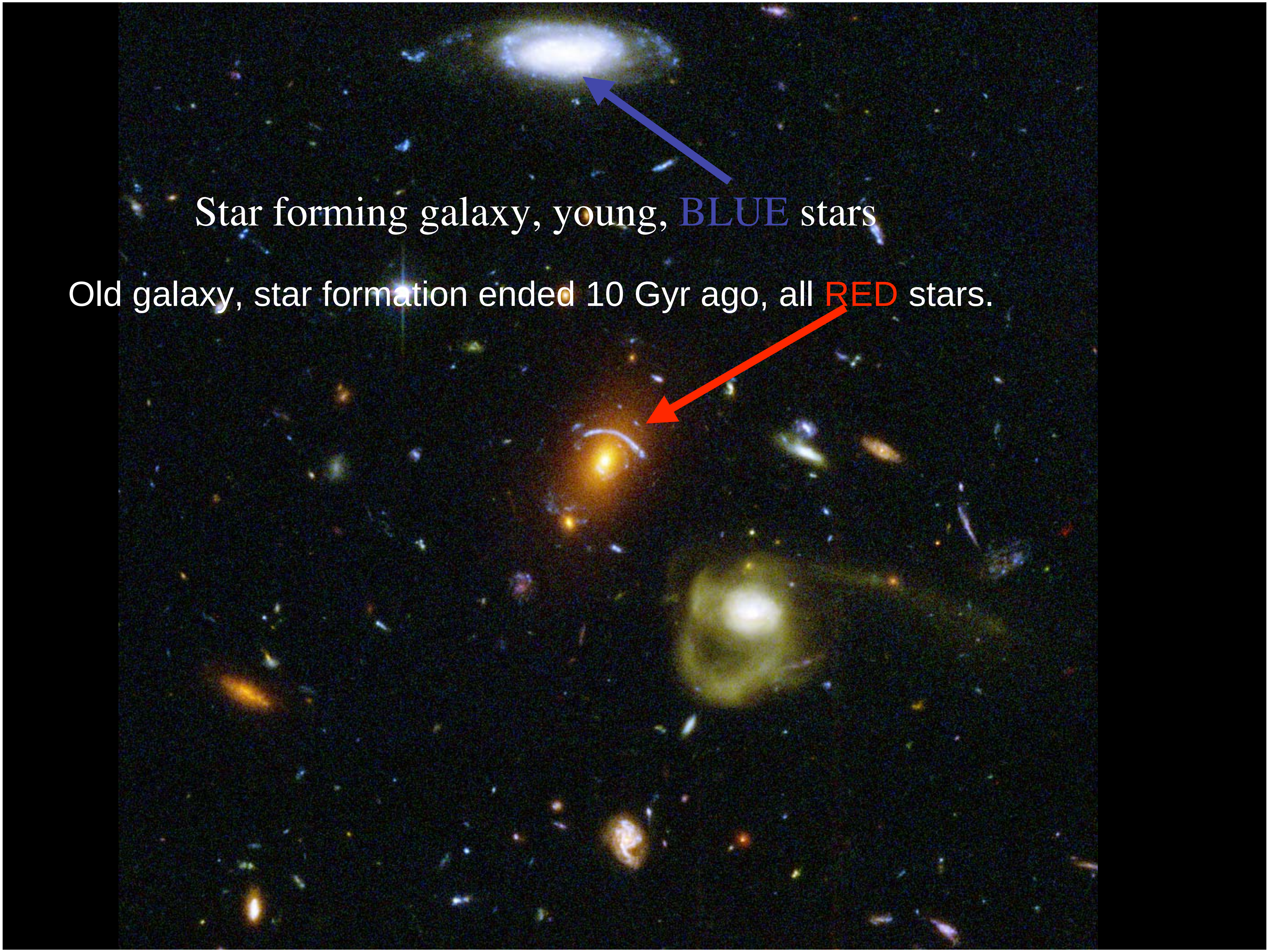
$$L = 4\pi R^2 \sigma_{SB} T_{\mathrm{eff}}^4 \propto M^3 \rightarrow T_{\mathrm{eff}} \propto M^{1/4}$$

More massive stars are more luminous and have a higher effective temperature. The formula above implies a factor of five change in T_eff from 0.1 to 60 solar masses.



10 Solar masses

0.1 Solar masses



Star forming galaxy, young, BLUE stars

Old galaxy, star formation ended 10 Gyr ago, all RED stars.

Minimum Mass Star that Burns H

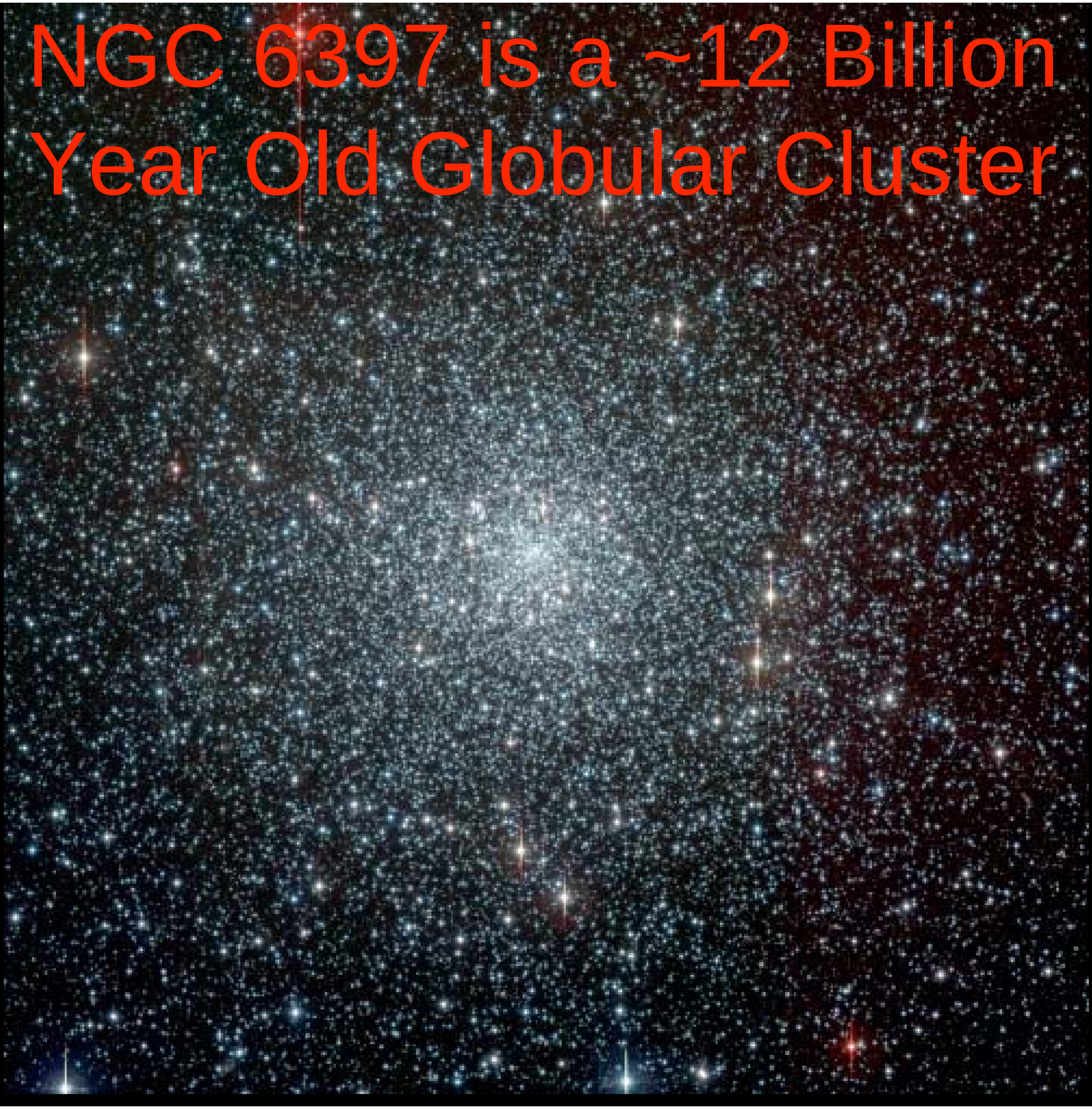
As a star contracts, the density becomes large enough that the spacing of electrons equals their De Broglie wavelength. In terms of density and temperature, this happens once

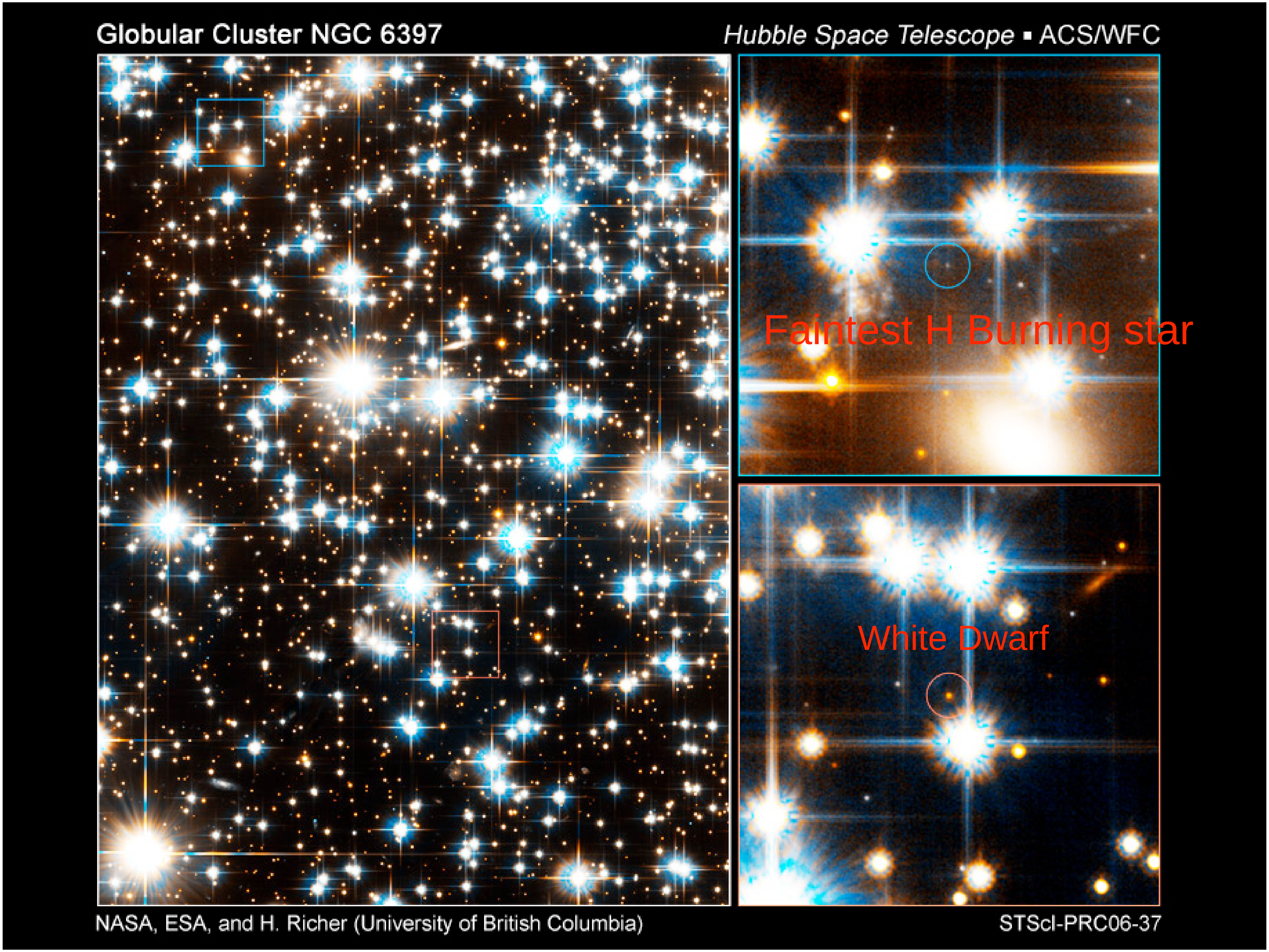
$$T < 10^7\mathrm{K}\left(\frac{\rho}{10^4\mathrm{gr\ cm}^{-3}}\right)^{2/3}$$

The pressure needed to hold up the star is then supplied by “Degeneracy” pressure, or the fact that the Pauli exclusion principle forces the electrons to have more and more energy as the density increases ==> The temperature no longer rises

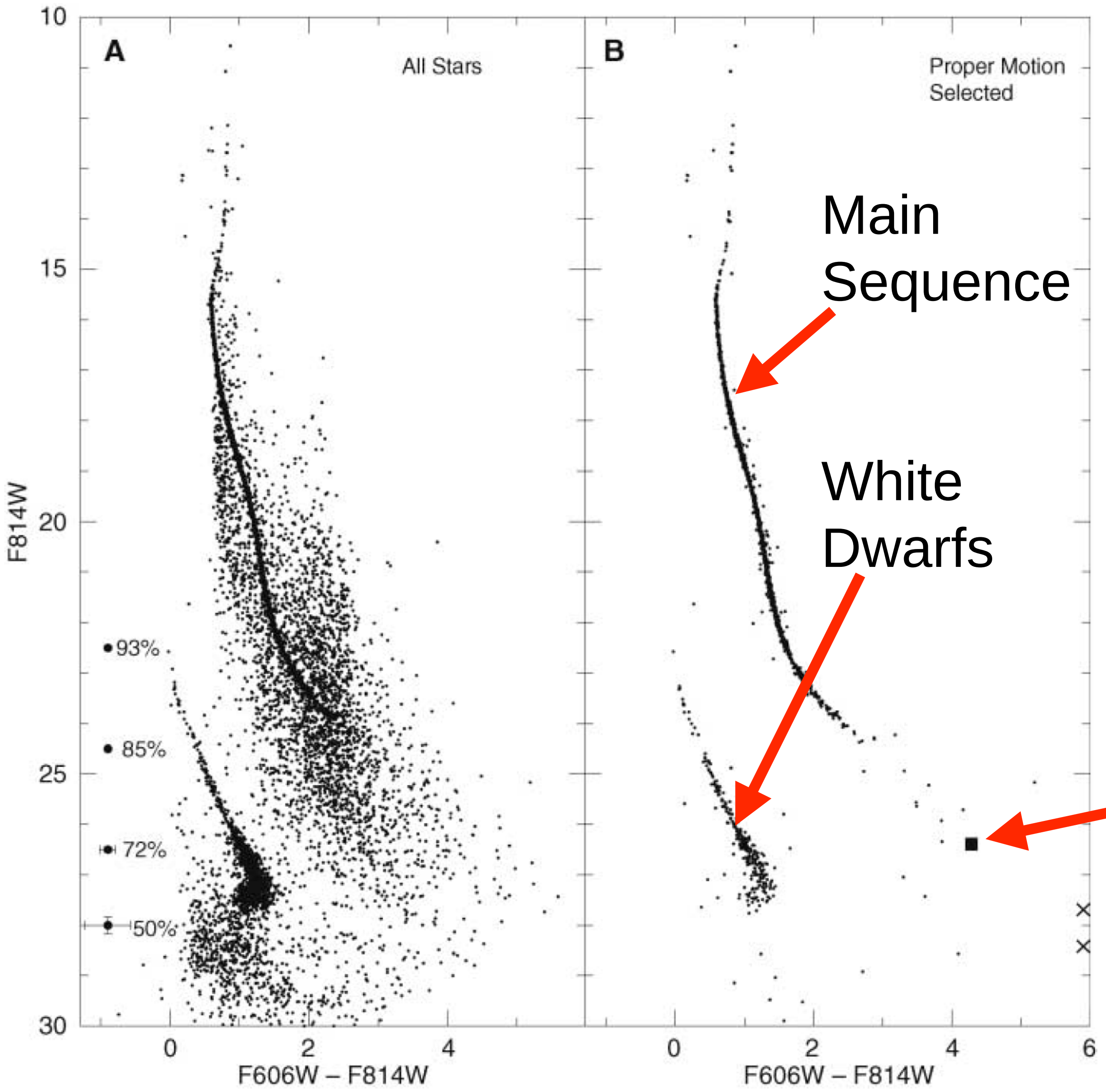
Setting a maximum temperature as a function of stellar mass. For H burning this requires M>0.08M_sun. Lower mass stars just cool forever, never igniting H==> Brown Dwarfs/Jupiter.

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
NASA, ESA, and H. Richer (University of British Columbia)
STScI-PRC06-37

NGC 6397

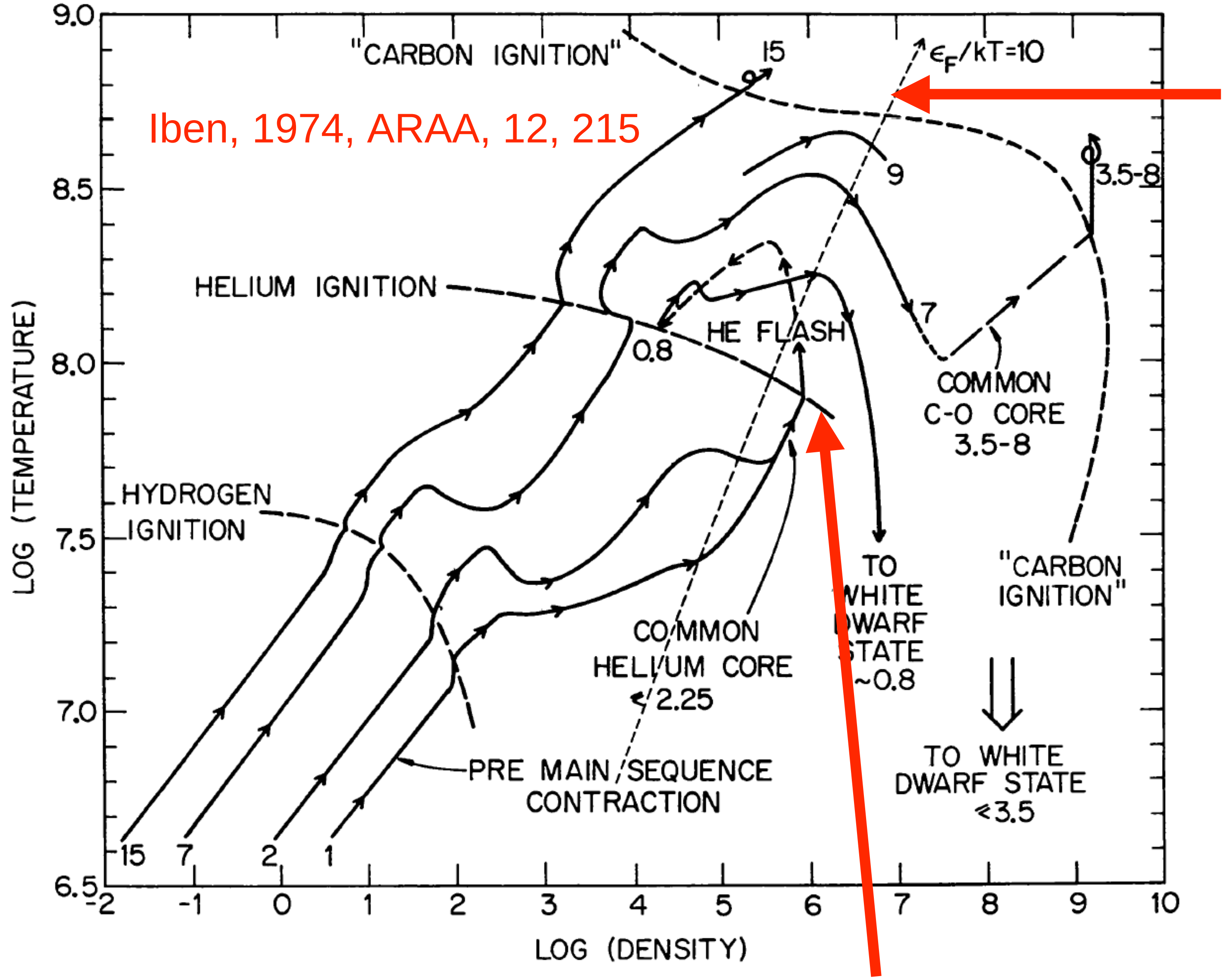


Main Sequence

White Dwarfs

Hydrogen Burning Limit

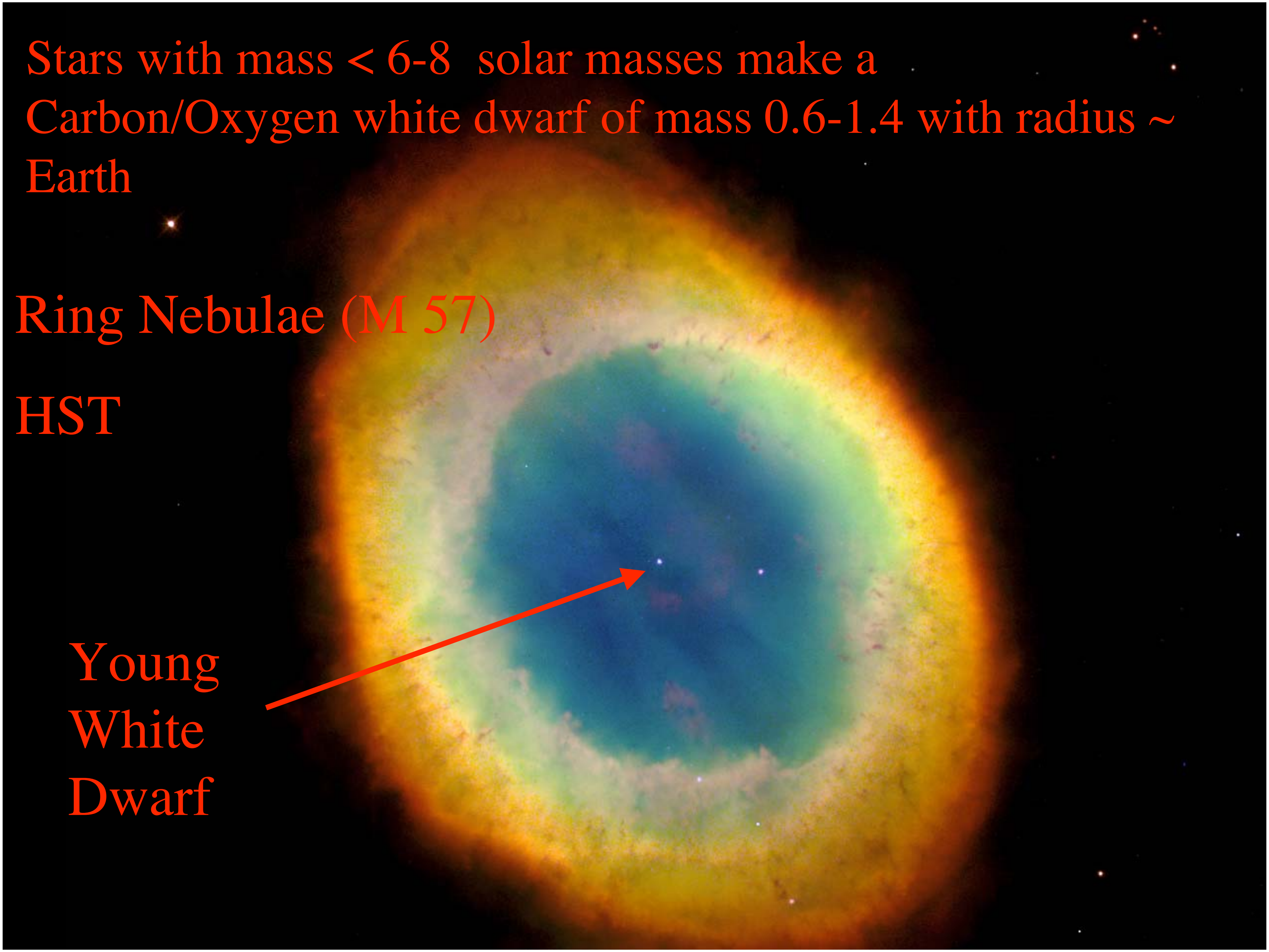
Richer et al 2006, Science, 313, 936


Iben, 1974, ARAA, 12, 215

Stars with mass < 6-8 solar masses never burn the carbon and cool to become White Dwarfs of mass 0.6-1.0 .. The rest goes out in a slow wind. . .

Helium Burning makes Carbon and Oxygen in the Stellar Core

Stars with mass < 6-8 solar masses make a Carbon/Oxygen white dwarf of mass 0.6-1.4 with radius ~ Earth



Ring Nebulae (M 57)

HST

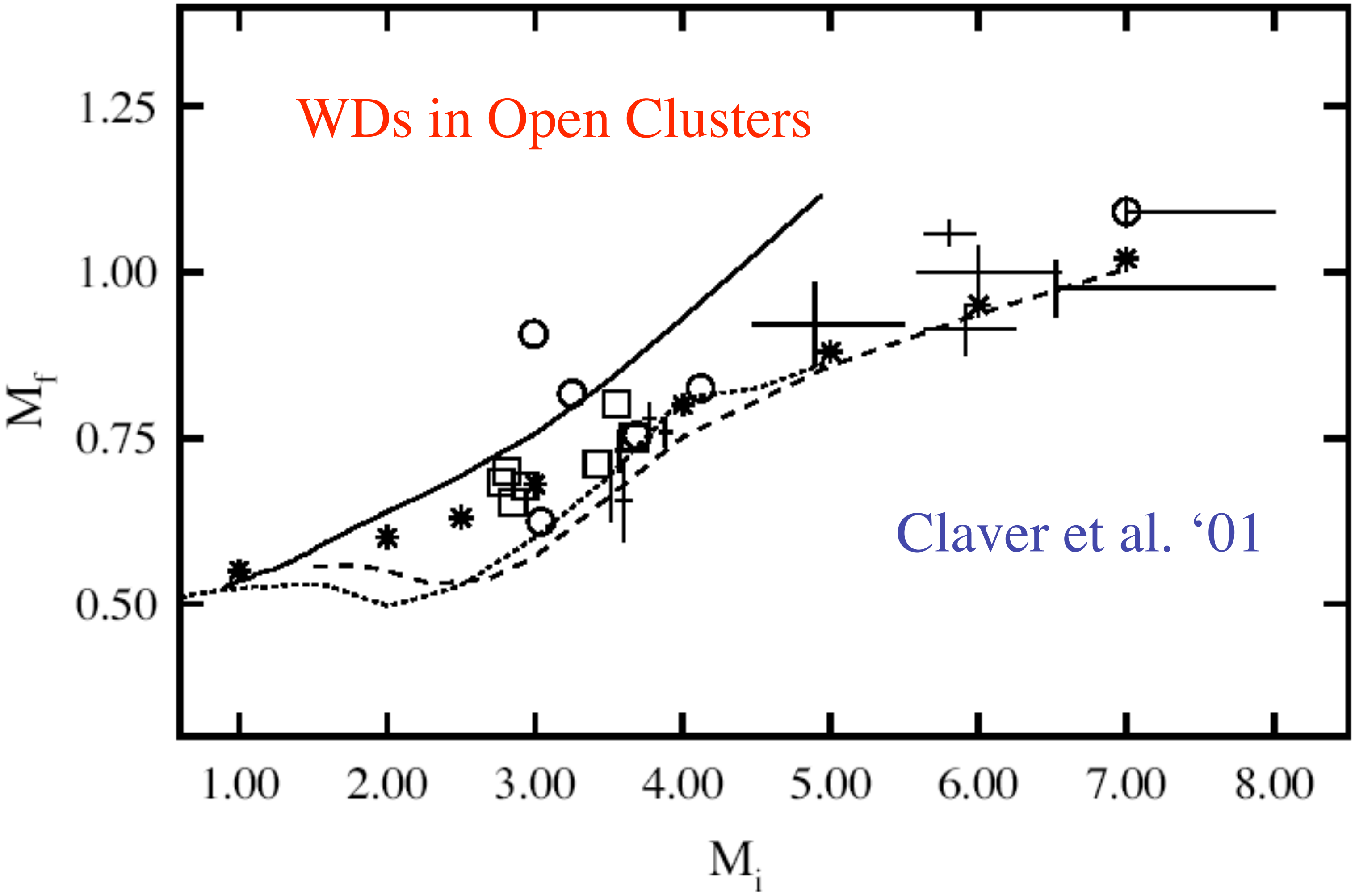
Young White Dwarf

The Helix Nebula

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS

NASA / JPL-Caltech / ESA

ssc2006-01b



WDs in Open Clusters

Claver et al. ‘01

FIG. 11.—Initial-final mass relation for the nearby cluster white dwarfs: Praesepe (*open circles*) and Hyades (*open squares*). The highest mass open circle is the Pleiad LB 1497, plotted at its lower limit. The error bars correspond to WDs in NGC 2516 (near $M_i \sim 6\ M_\odot$) and NGC 3532 (near $M_i \sim 4\ M_\odot$). The errors do *not* include uncertainties in the cluster distances and ages. Also shown are the theoretical initial-final mass relation

Outcomes so Far

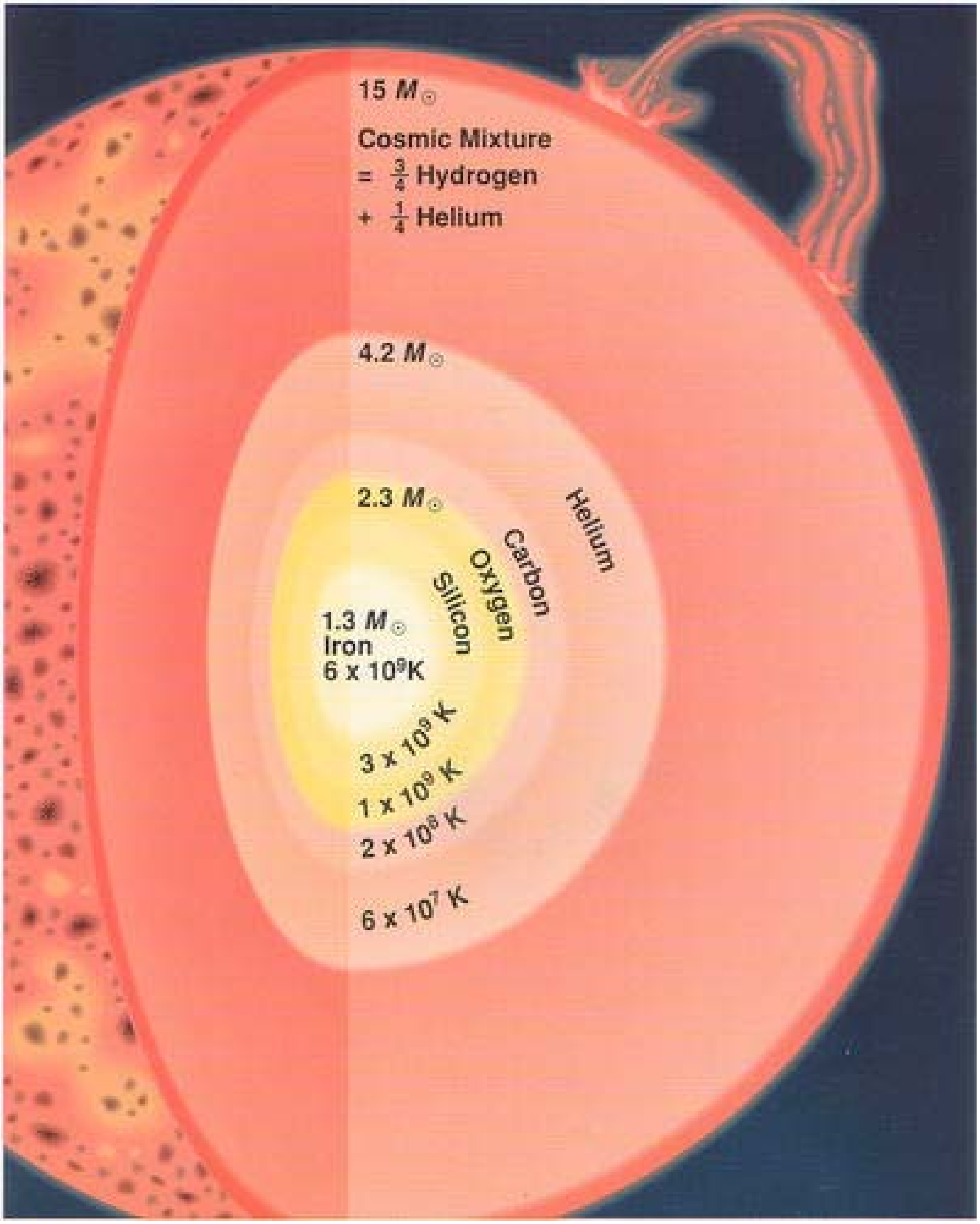
$M<0.08$: Never got hot enough to ignite Hydrogen Burning

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

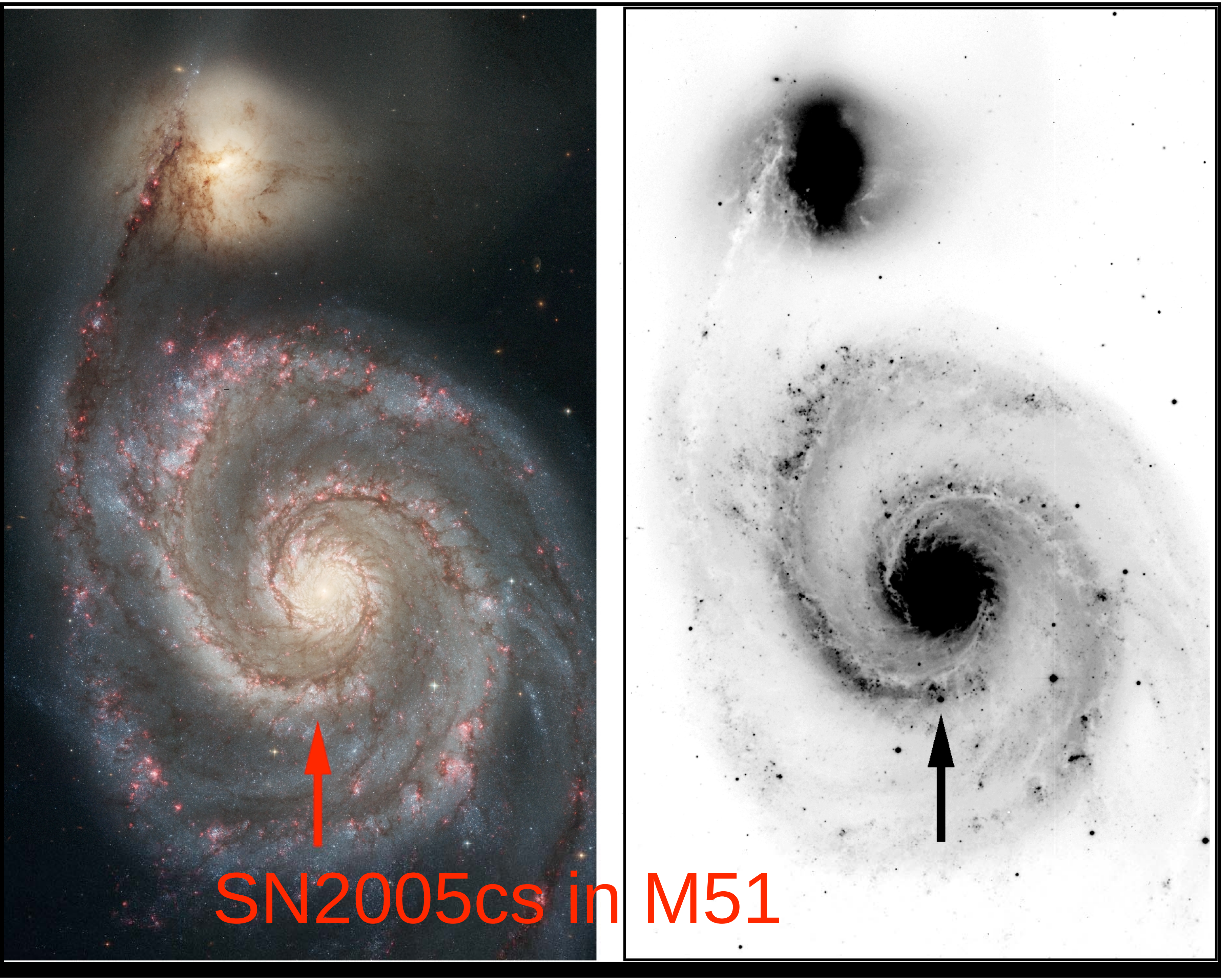
$0.8<M<(6\text{-}8)$: Burn H=>He, and He=>C/O, then leaves a compact remnant white dwarf of 0.55=>1.1 solar masses, some nucleosynthesis occurs in the exiting matter, but not much.

Stars more massive than 6-8 times the Sun get to burn all the way up to the most stable nucleus, 56Fe, 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! ==> Type II Supernovae

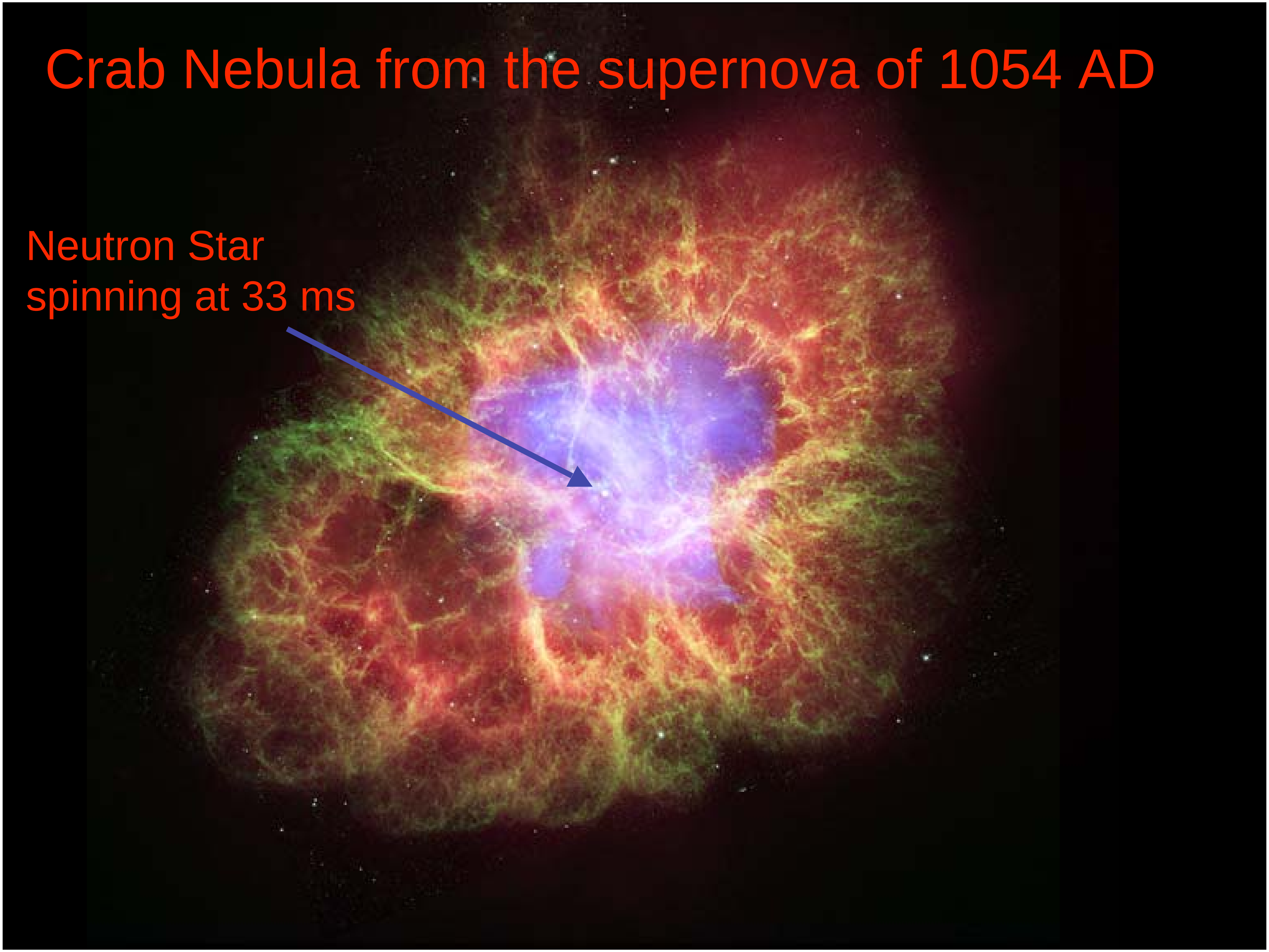


- The shells of matter get ejected, enriching the matter between stars.
- These events make most of the elements like Carbon, Oxygen, Silicon. . . But only some of the Iron.
- The remnant left from the collapse is either a Neutron Star or a Black Hole.

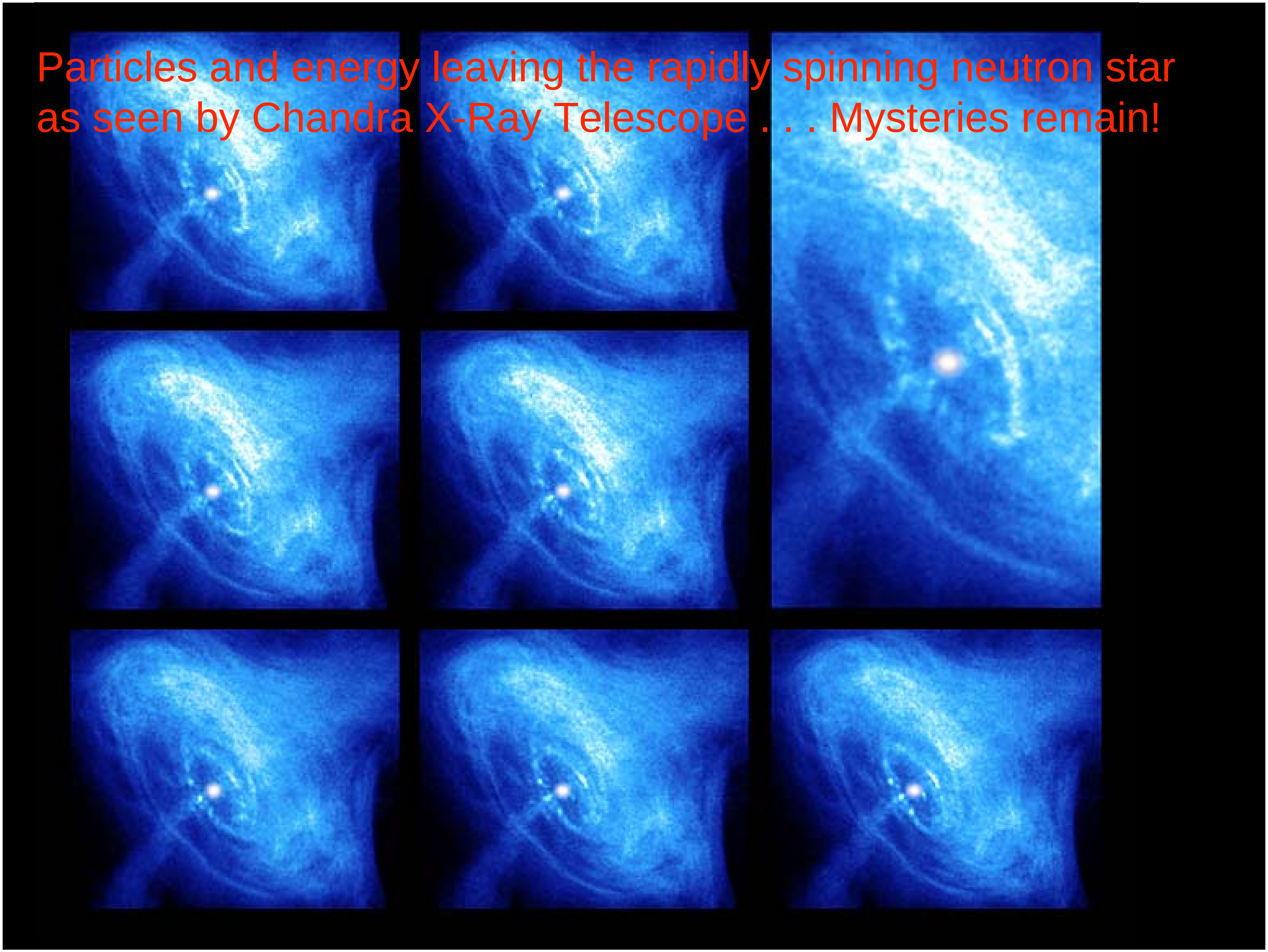


SN2005cs in M51

Crab Nebula from the supernova of 1054 AD



Neutron Star
spinning at 33 ms



Particles and energy leaving the rapidly spinning neutron star as seen by Chandra X-Ray Telescope . . . Mysteries remain!

Questions??