PHAS 1102
Physics of the Universe

5 - Stellar evolution

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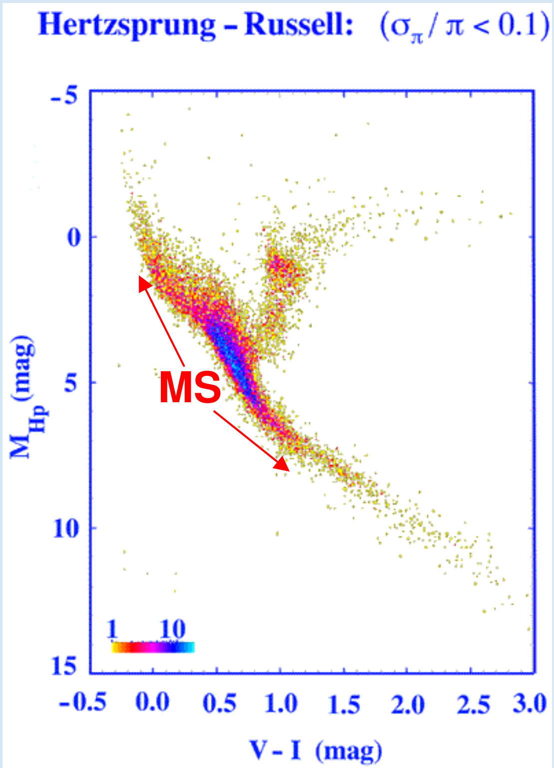
<u>*Stellar evolution*</u> *(ZG Ch.16, FK Ch. 21)*

Study of physical changes taking place in stars as their composition is altered because of thermonuclear reactions.

General sequence: Protostar → Pre-Main Sequence (PMS) → Main Sequence (MS) → post-Main Sequence

Main physical parameter determining evolution: MASS

Evolutionary track: Plot of points showing <u>time sequence of evolutionary stages</u> of a star on an H-R diagram (which is collection of <u>star snapshots</u> - may use colour, or spectral type, instead of temperature, and magnitude in place of luminosity).



The birth and evolution of stars

Most (90%) of stars lie on the MS, where stars burning H to He (PP or CNO cycles) are in hydrostatic equilibrium.

How do stars get on to the MS, and what happens afterwards?

Stars are born from huge interstellar clouds of gas (mostly in the form of molecular H, i.e. H_2) and dust, which are massive enough to contract gravitationally: collapse starts in free-fall (particles do not collide → no internal pressure): protostar

As density increases, cloud's core traps (becomes opaque to) IR radiation from dust heated by collisions with molecules, collapse slows down, hydrostatic equilibrium established:

Pre-Main Sequence star

Takes ~ 1 million years to form a PMS star of 1 solar mass

Giant Molecular Clouds ('stellar nurseries')

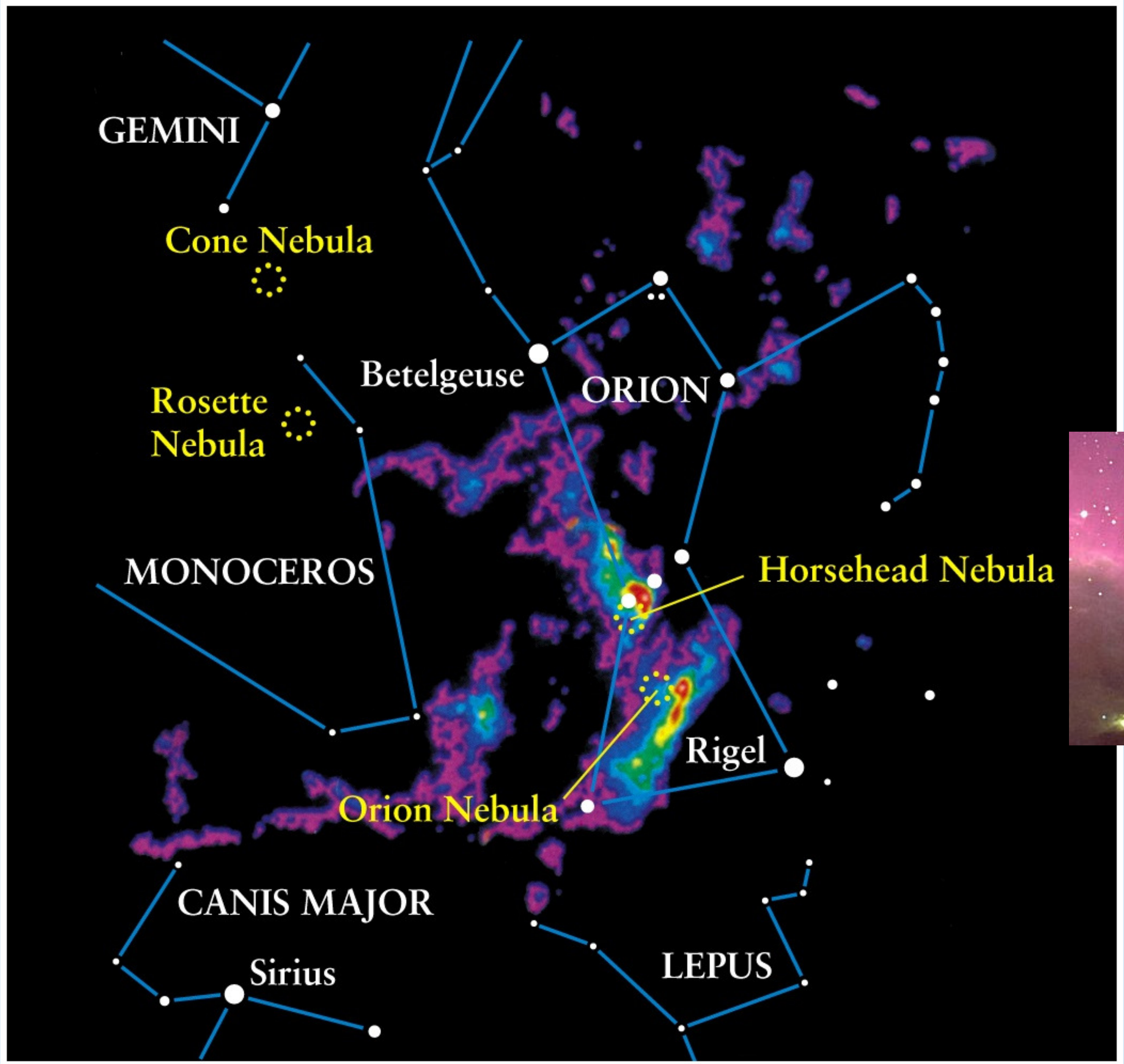
Radii: 10s of parsec
Masses: $10^4 - 10^6$ solar masses
Temperature: Few 10s of K

Densities from 10^7 up to 10^{12} particles m^{-3} in cloud cores

Collapse to form stars with 0.1 – 100x solar mass

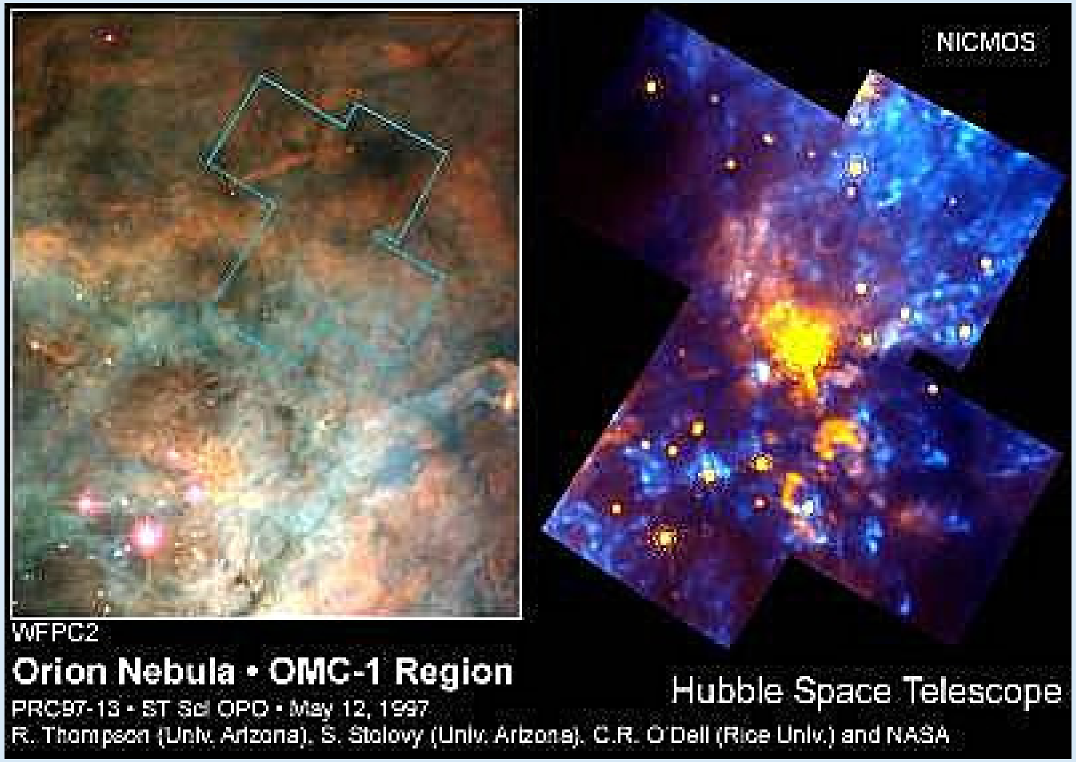
Examples: Orion Nebula in the Milky Way
30 Doradus in the Large Magellanic Cloud
GMCs in the Andromeda galaxy …

Giant Molecular Clouds in Orion



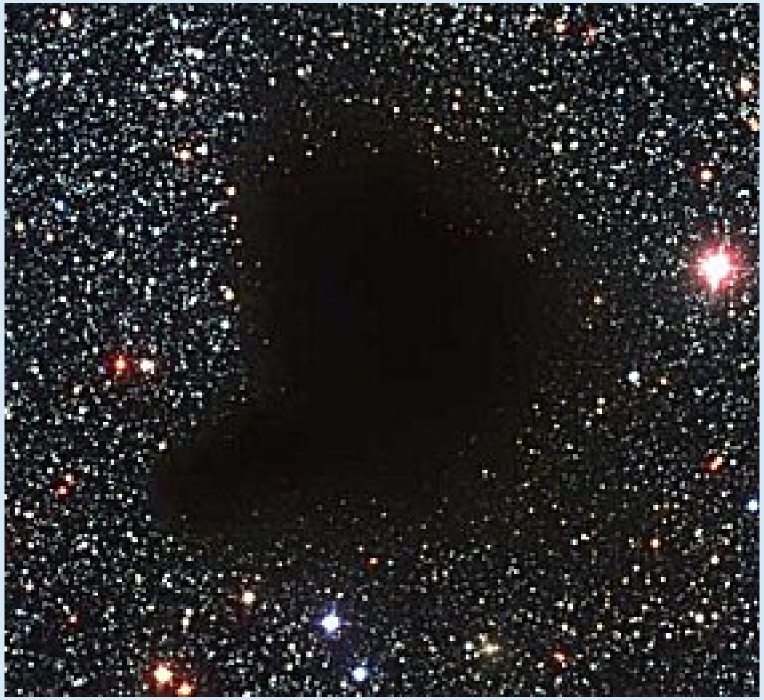
Giant Molecular Clouds

Orion Nebula

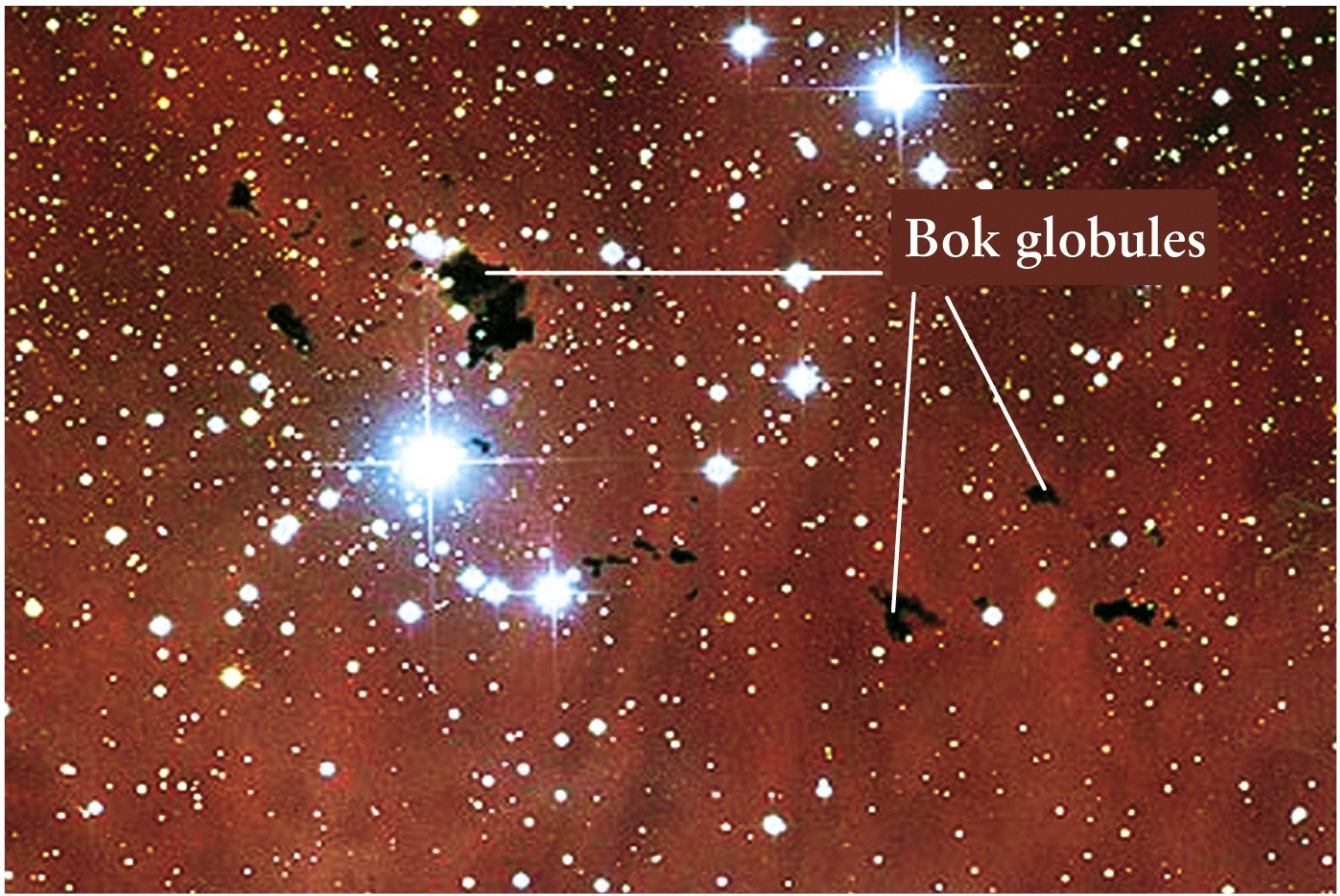


Optical Infrared

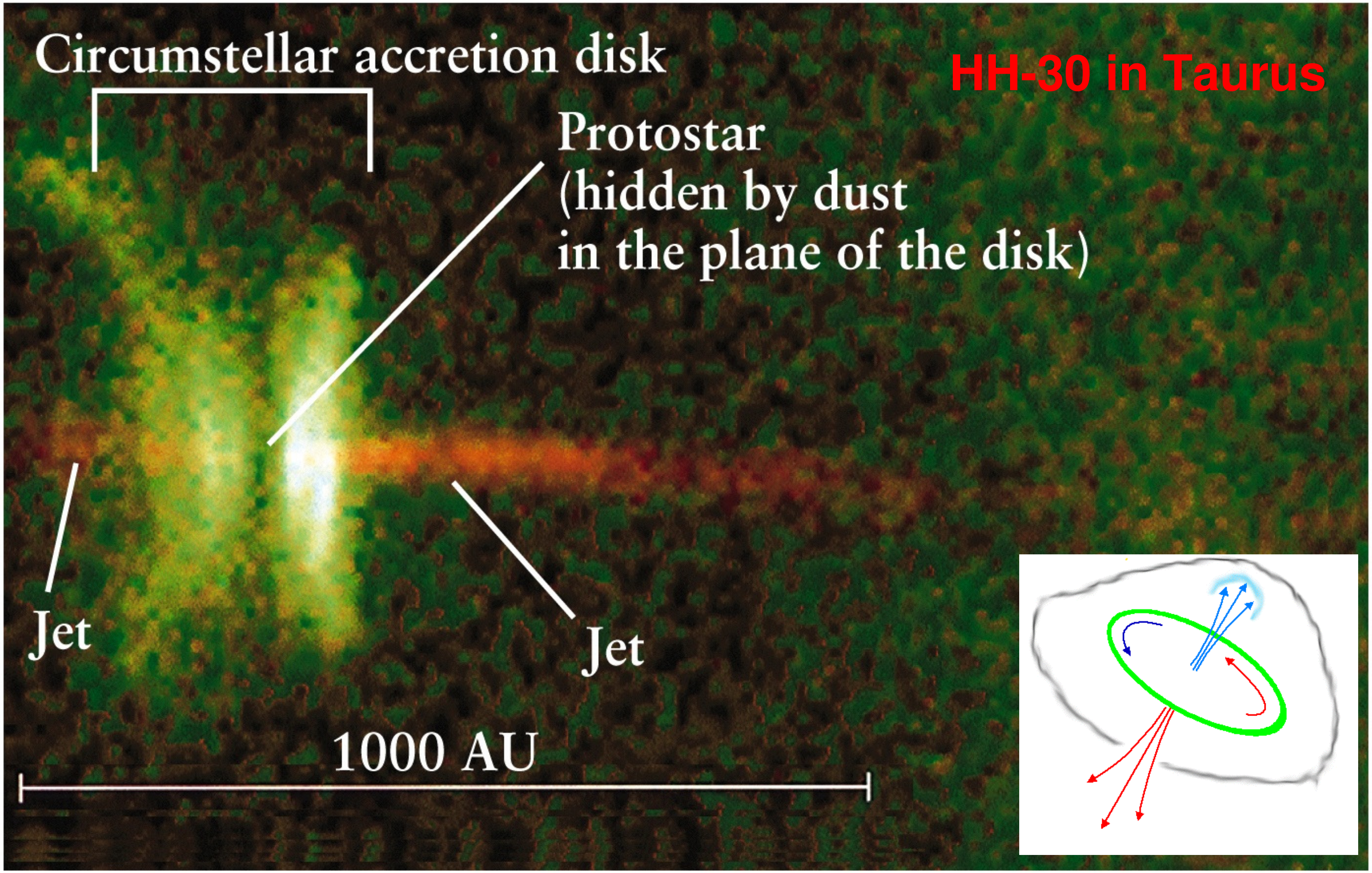
Barnard 68



Small Molecular Clouds



Protostars (and proto-planetary disks)



From PMS to MS stars

PMS star shines by slowly contracting, while matter accretes onto its core and the central temperature raises.

Finally, central temperature high enough to start H burning, collapse halts and star is now a real MS star.

Hydrostatic equilibrium maintained by heat from thermonuclear reactions: Zero-Age Main-Sequence (ZAMS) star (before any substantial amount of H is fused to He)

Takes ~ 20 million years from initial collapse to ZAMS star

Higher mass stars arrive on MS with higher luminosity and temperature.

Main Sequence evolution (1)

Main Sequence phase: entire phase of H burning in the core (converting H → He via PP and CNO)

Duration of MS phase (τ_{MS}) depends on star's store of energy (amount of H, i.e. its mass) and the rate at which energy consumed (luminosity).

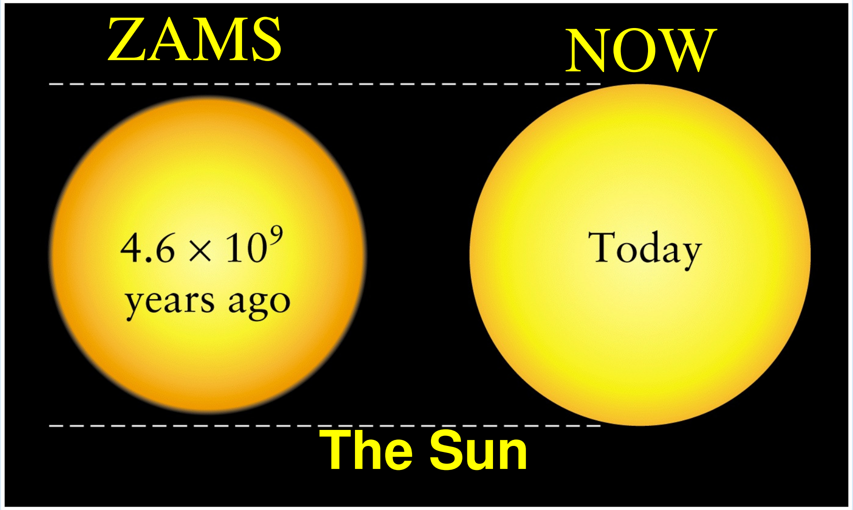
Evolution faster for more massive stars: more massive stars have higher central temperatures, thus nuclear reactions occur faster. So:

$\tau_{MS} \sim 10^{10}$ yr for a 1 solar mass star
$\tau_{MS} \sim 10^{7}$ yr for a 15 solar mass star

Main Sequence evolution (2)

For 1 solar mass star, Main Sequence lifetime 10^{10} years (ZAMS → MST, or Main Sequence Turnoff)

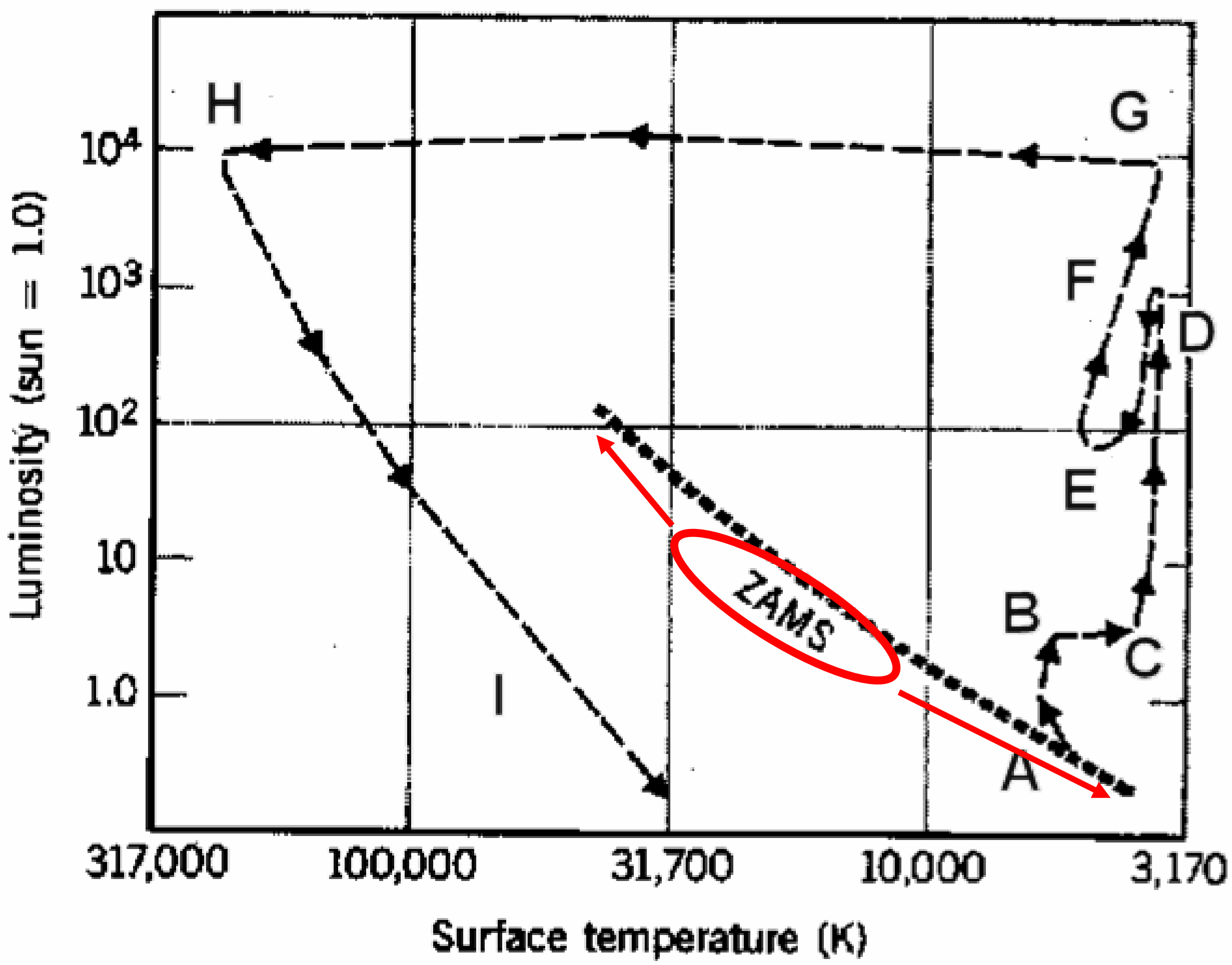
As 4 H → 1 He, number of particles falls
pressure drops
core contracts
core temperature rises → pressure rises
→ increased luminosity, increased envelope radius
('Mirror law': shrinking core → expanding envelope!)



Surface temperature rise = 300K
Luminosity up by 40%
6% increase in radius

Post-Main Sequence evolution (1 solar mass star)

Evolution implies composition and size change, thus luminosity and temperature change too.

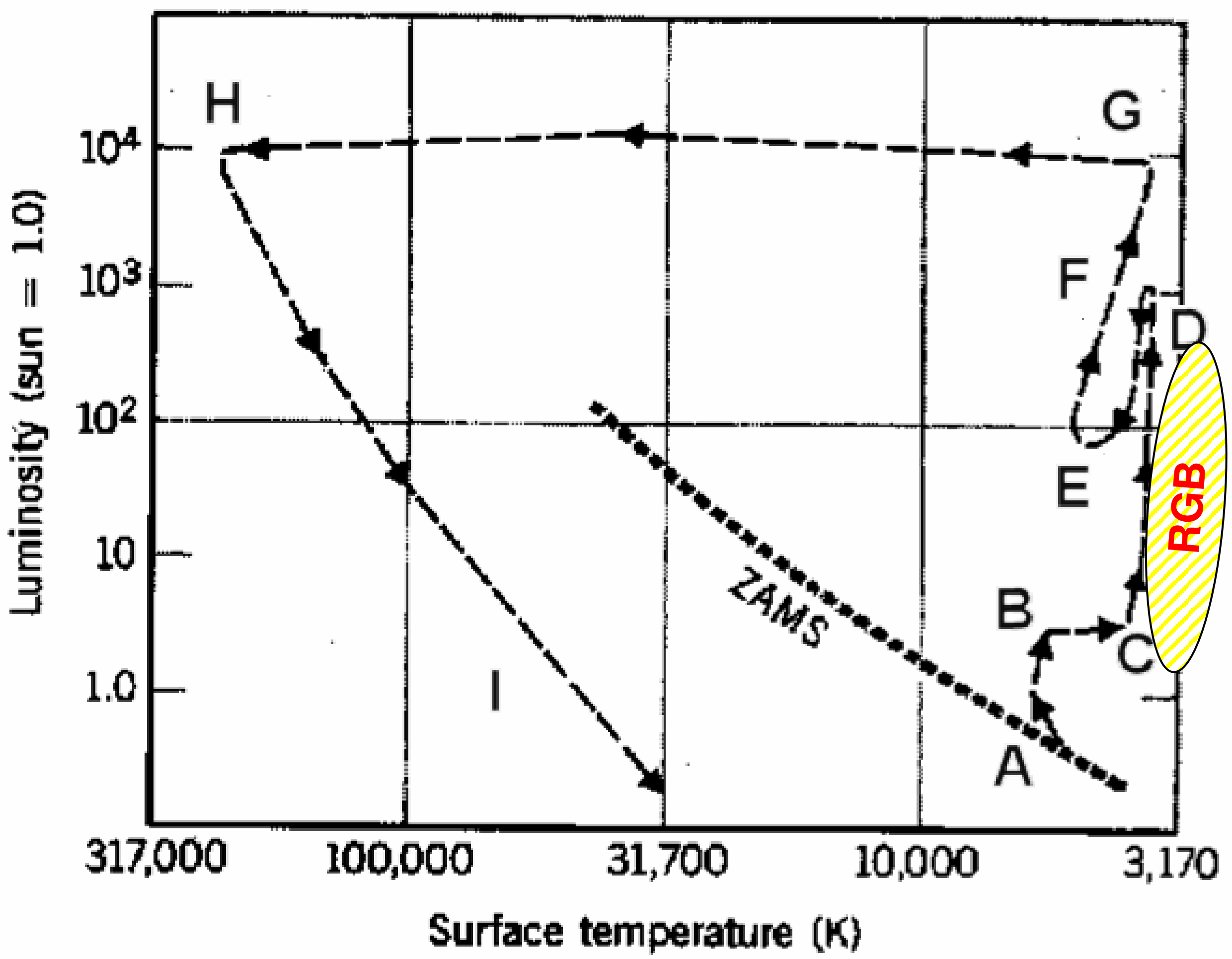


A-B: H → He,
star's core shrinks, core temperature up, luminosity up

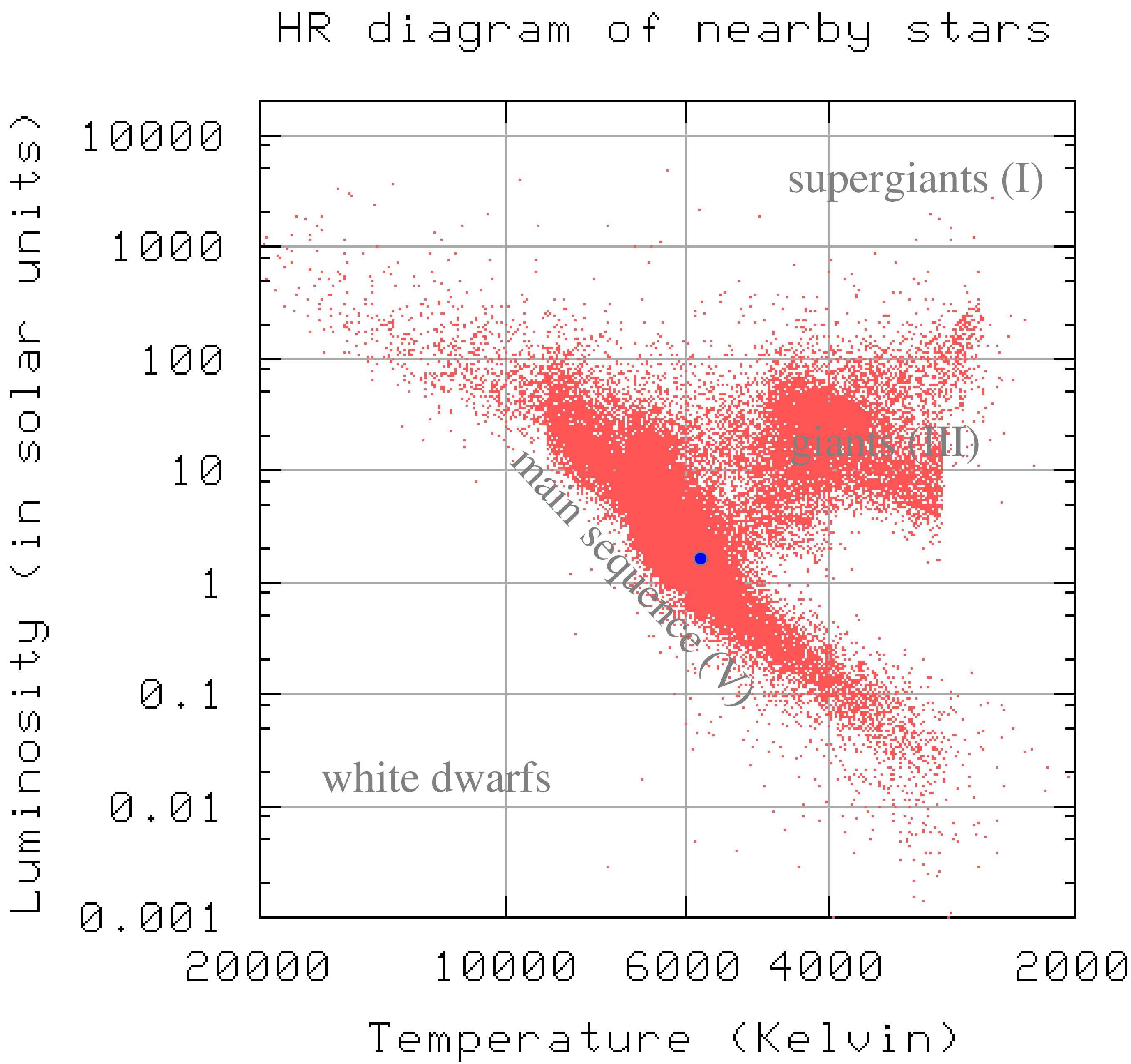
B-C: H exhausted in core, but burns in outer shell, envelope expands, surface temperature down

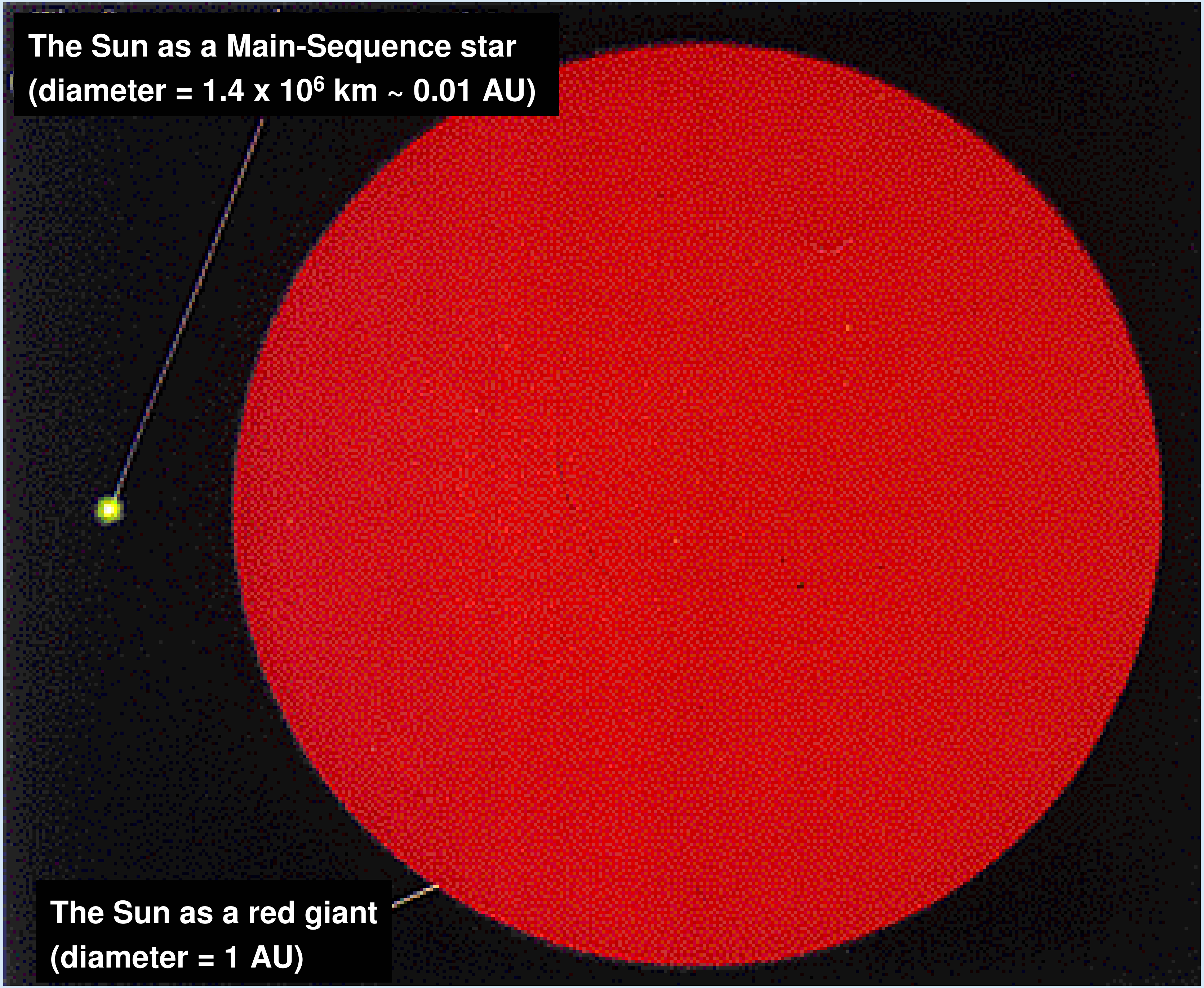
Post-Main Sequence evolution (1 solar mass star)

C-D: Convection carries most energy into envelope → Luminosity increases greatly → Red Giant, R~100 x MS radius (star moves along Red Giant Branch, RGB)

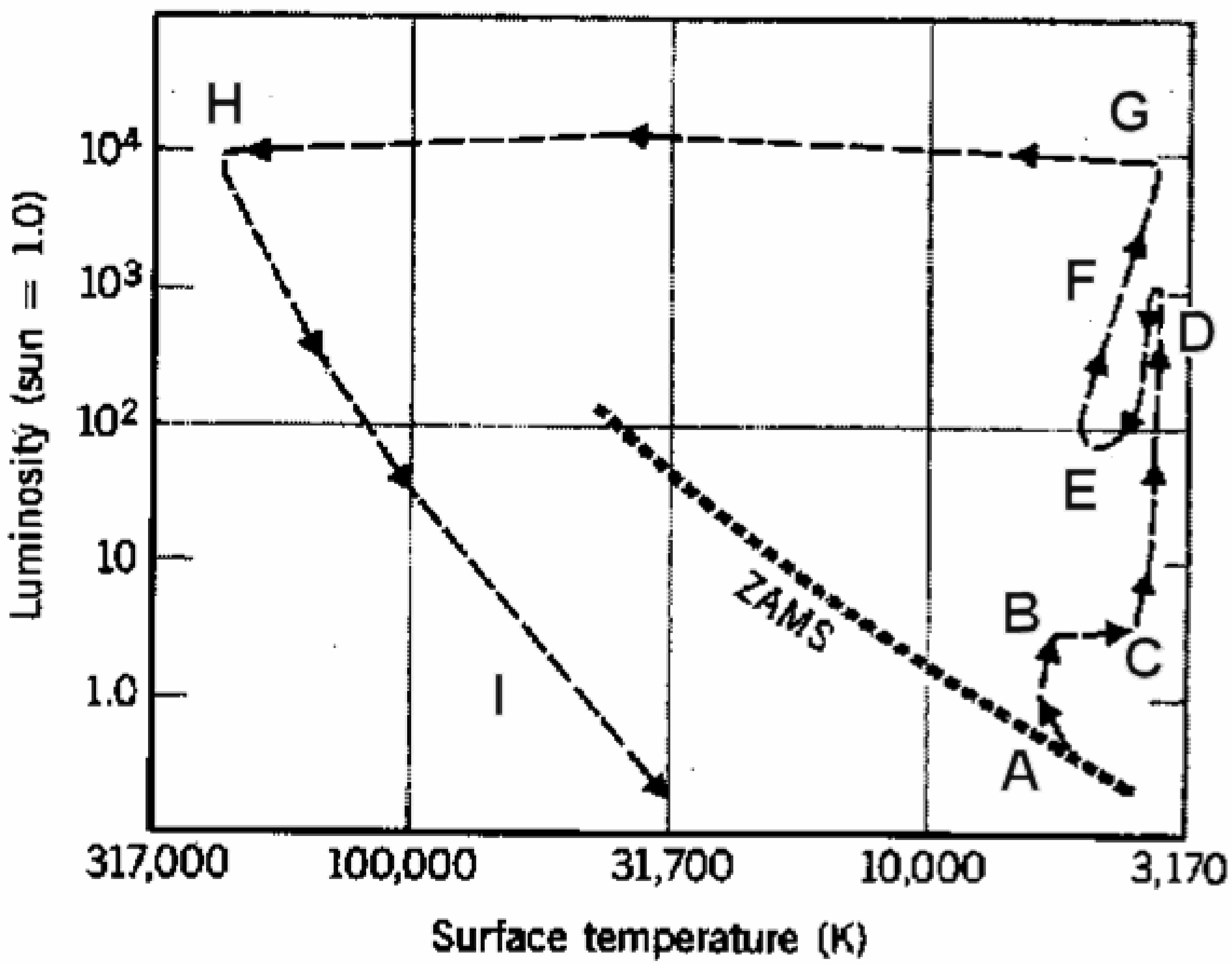


Core density so high that electrons form a degenerate gas (degenerate pressure depends on density, not on temperature) → balances gravity in place of nuclear reactions


HR diagram of nearby stars
supergiants (I)
giants (III)
main sequence (V)
white dwarfs
10000
1000
100
10
1
0.1
0.01
0.001
20000
10000
6000
4000
2000
Temperature (Kelvin)
Luminosity (in solar units)


The Sun as a Main-Sequence star
(diameter = 1.4 x 10^6 km ~ 0.01 AU)
The Sun as a red giant
(diameter = 1 AU)

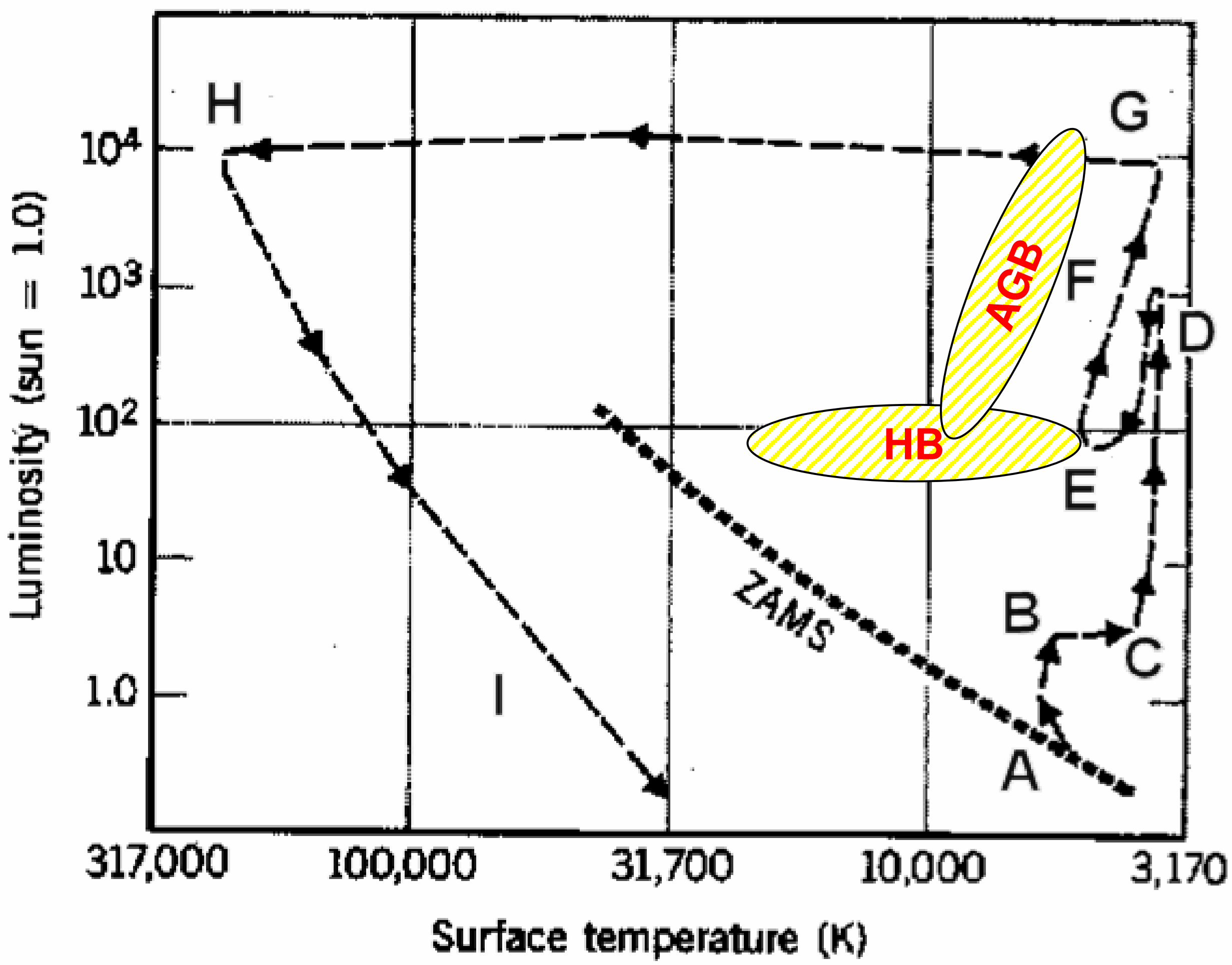
Post-Main Sequence evolution (1 solar mass star)



D: Core reaches a temper. of ~10^8 K
→ He burning starts
→ temper. goes up in the core, but pressure does not (degenerate gas)
→ He burning rate goes up
→ temper. goes up
➔ He flash
(He burning spreads through core in few min because of gas high thermal conductivity)

Post-Main Sequence evolution (1 solar mass star)

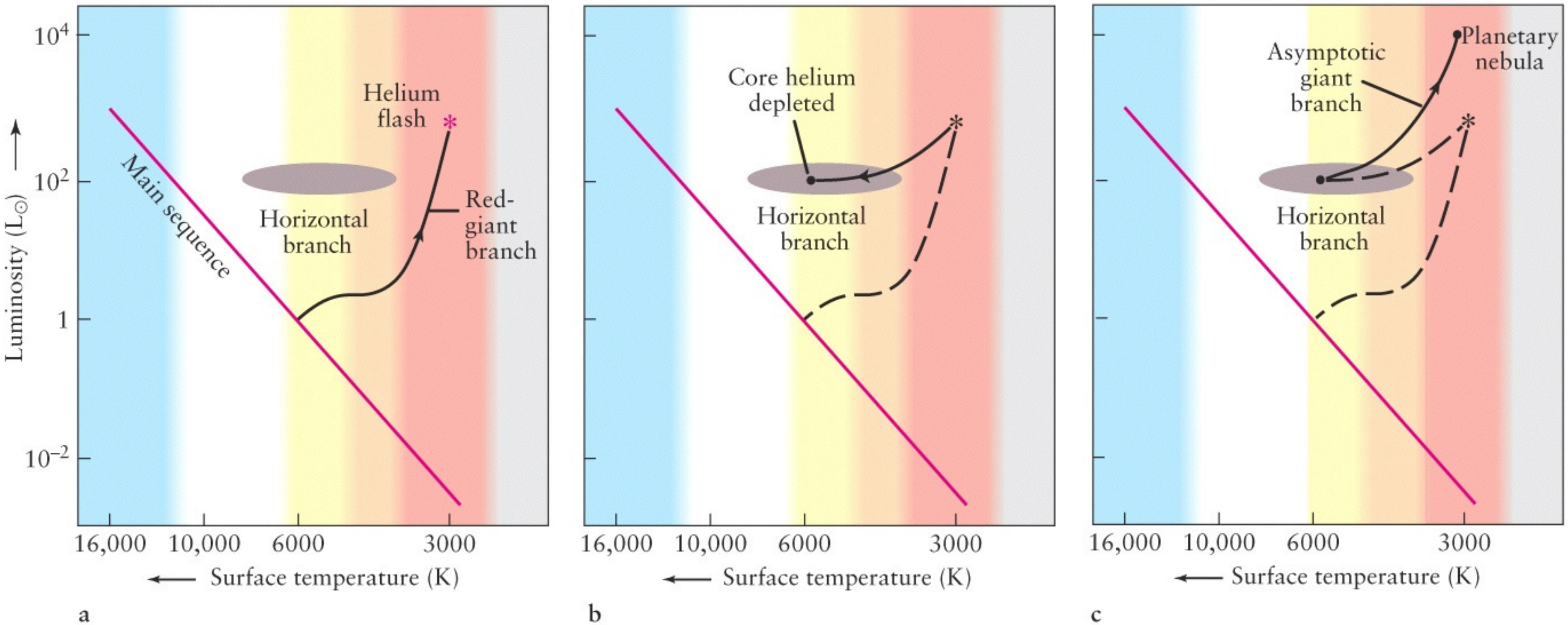
D-E: When core gets to ~3.5 x 10^8 K, electrons become non-degenerate, core expands and cools → stable He burning phase with H shell burning (star joins Horizontal Branch, HB)



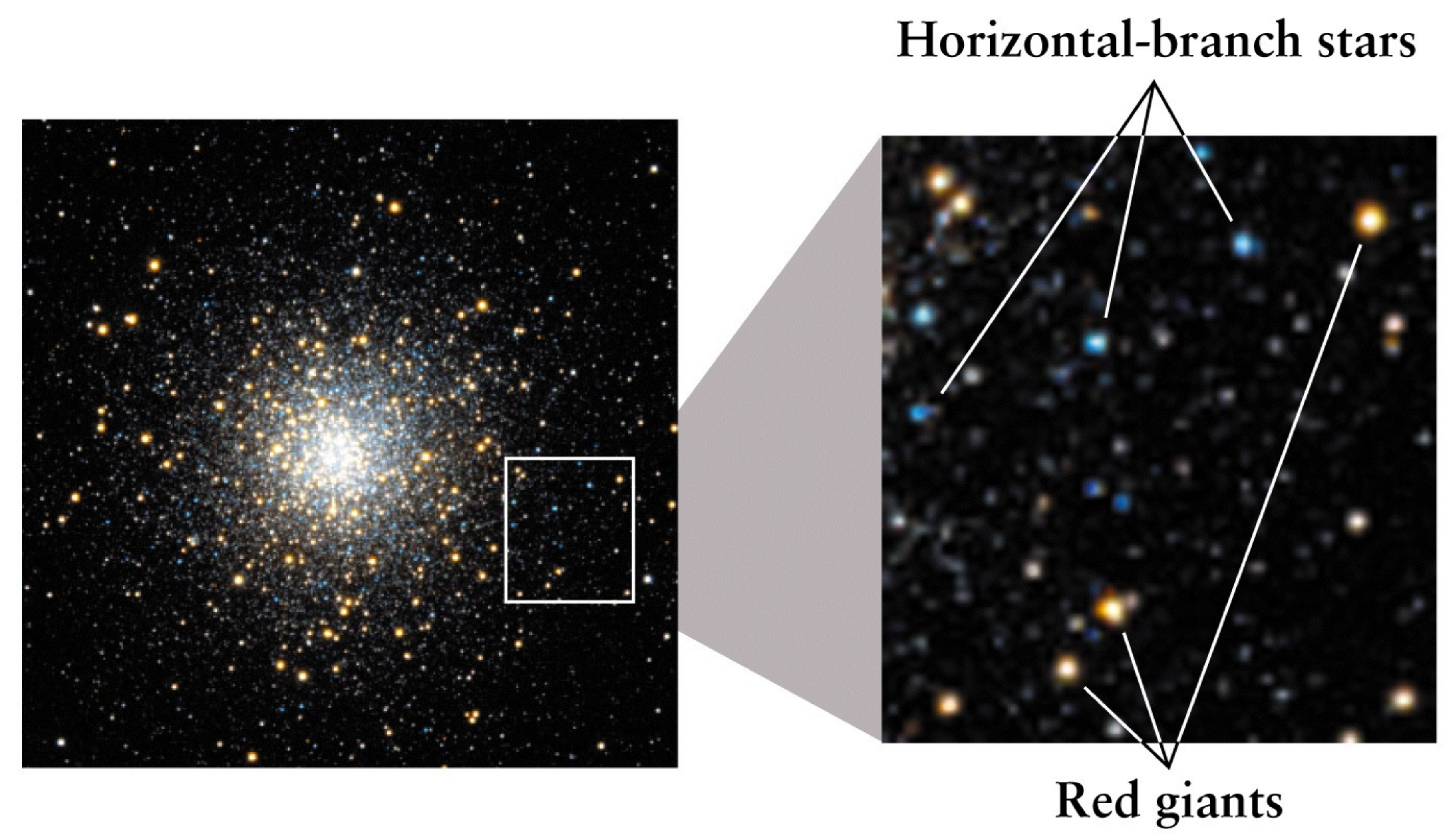
F: He exhaustion, C core contracts (degenerate gas) → envelope expands, second Red Giant phase (Asymptotic Giant Branch, AGB)

Horizontal Branch

Part of the H-R diagram where stars appear after having undergone He flash, and after beginning to burn He steadily in the core and Hydrogen in a surrounding shell

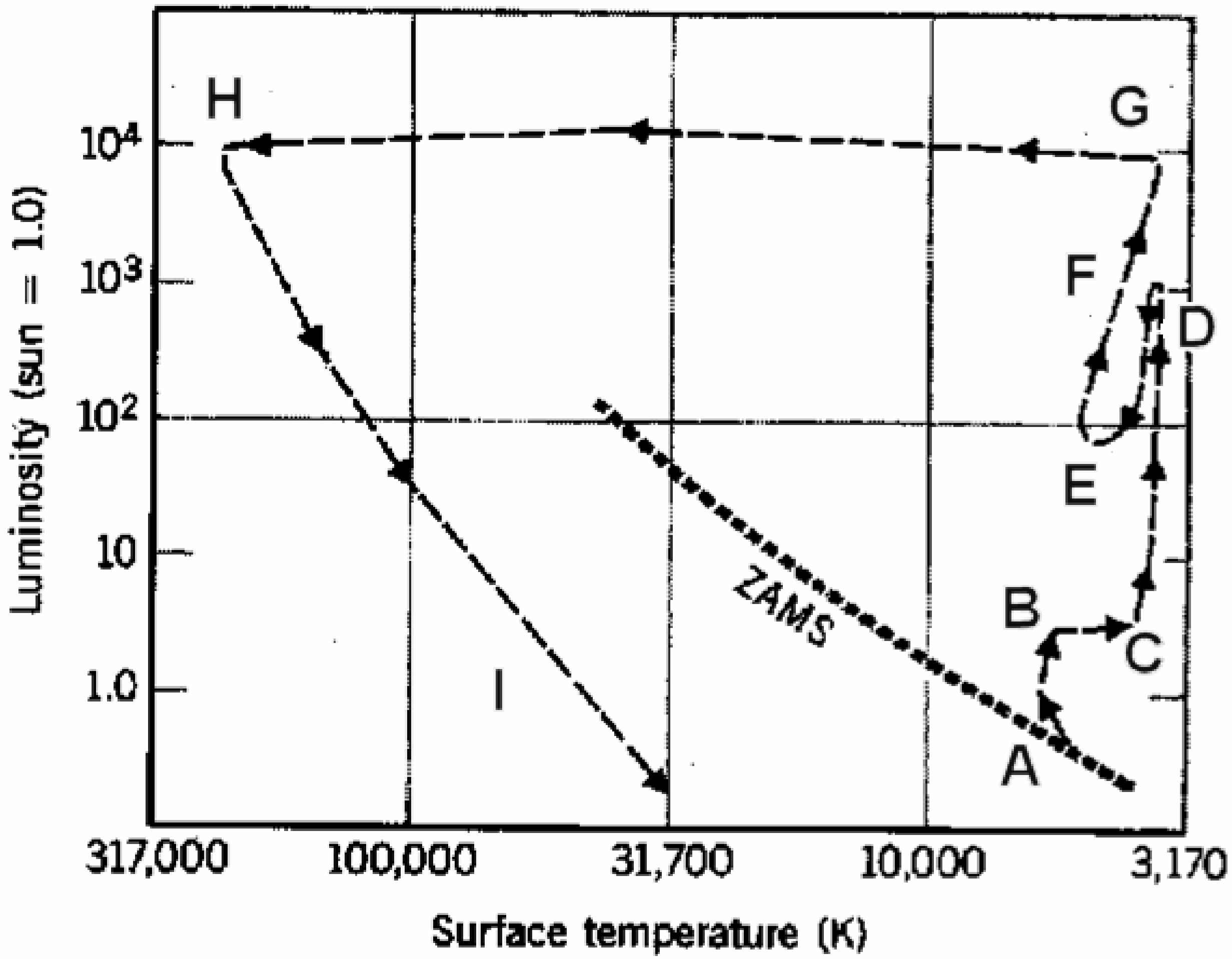


Globular cluster M10 in Ophiuchus



Post-Main Sequence evolution (1 solar mass star)

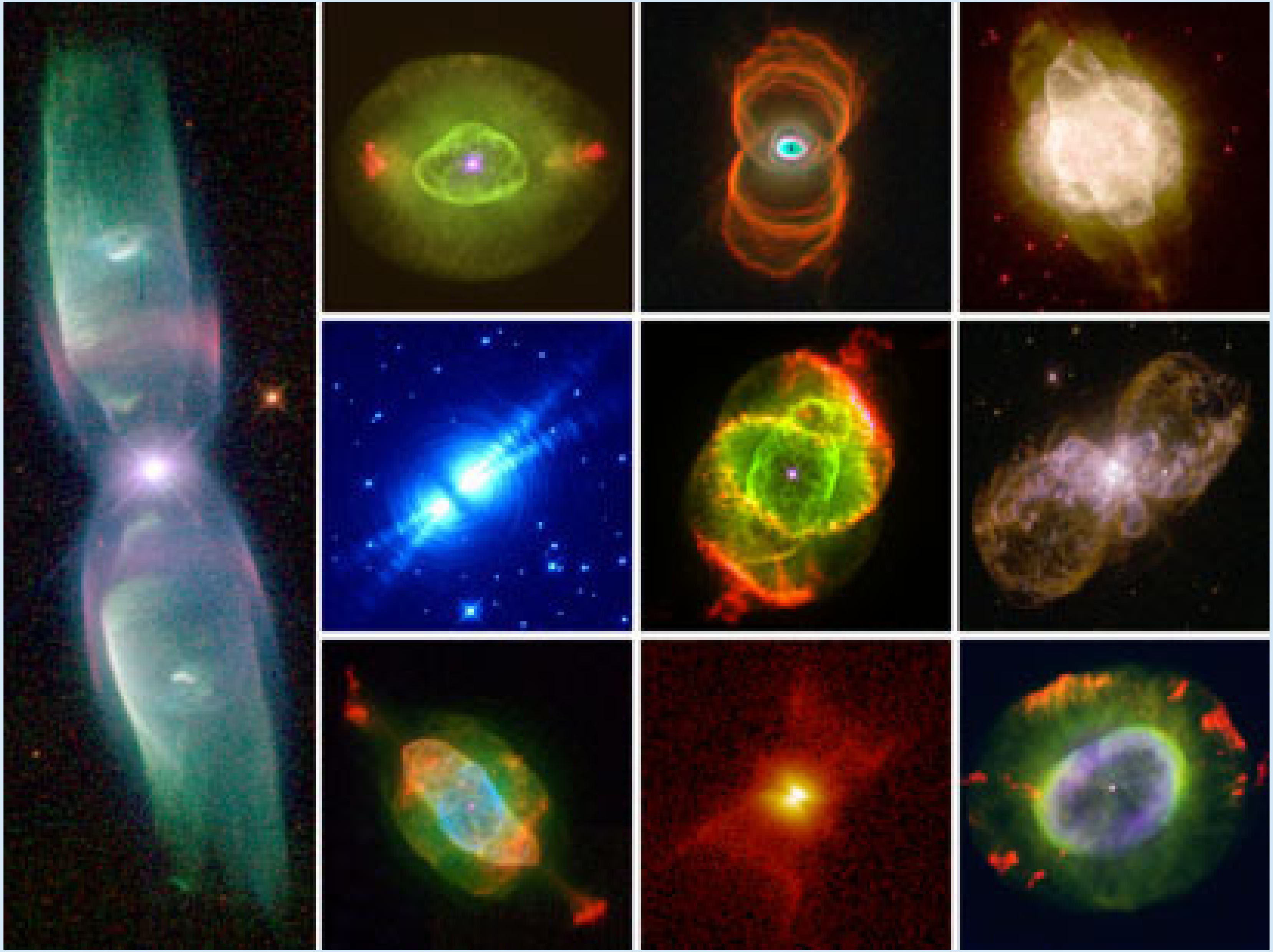
Star not massive enough to ignite C …



G: He burning to C (triple-α process) very sensitive to temperature → He burning (now in a shell) causes star to become unstable → star pulsates and ejects outer layers

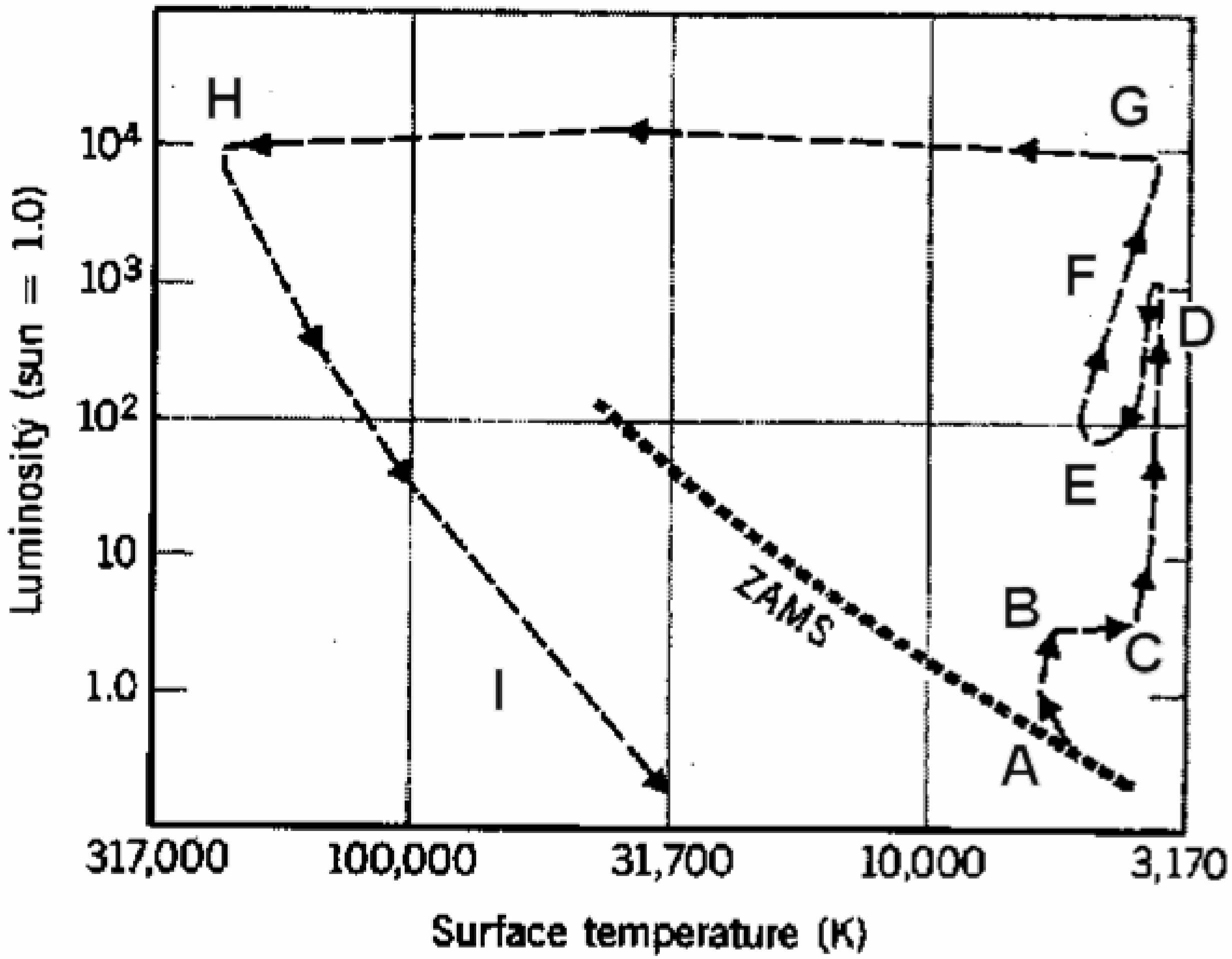
G-H: Core exposed as a very hot star, ejected envelope forms a nebula for ~10^4 yr (Planetary Nebula phase)

Planetary Nebulae from the Hubble Space Telescope



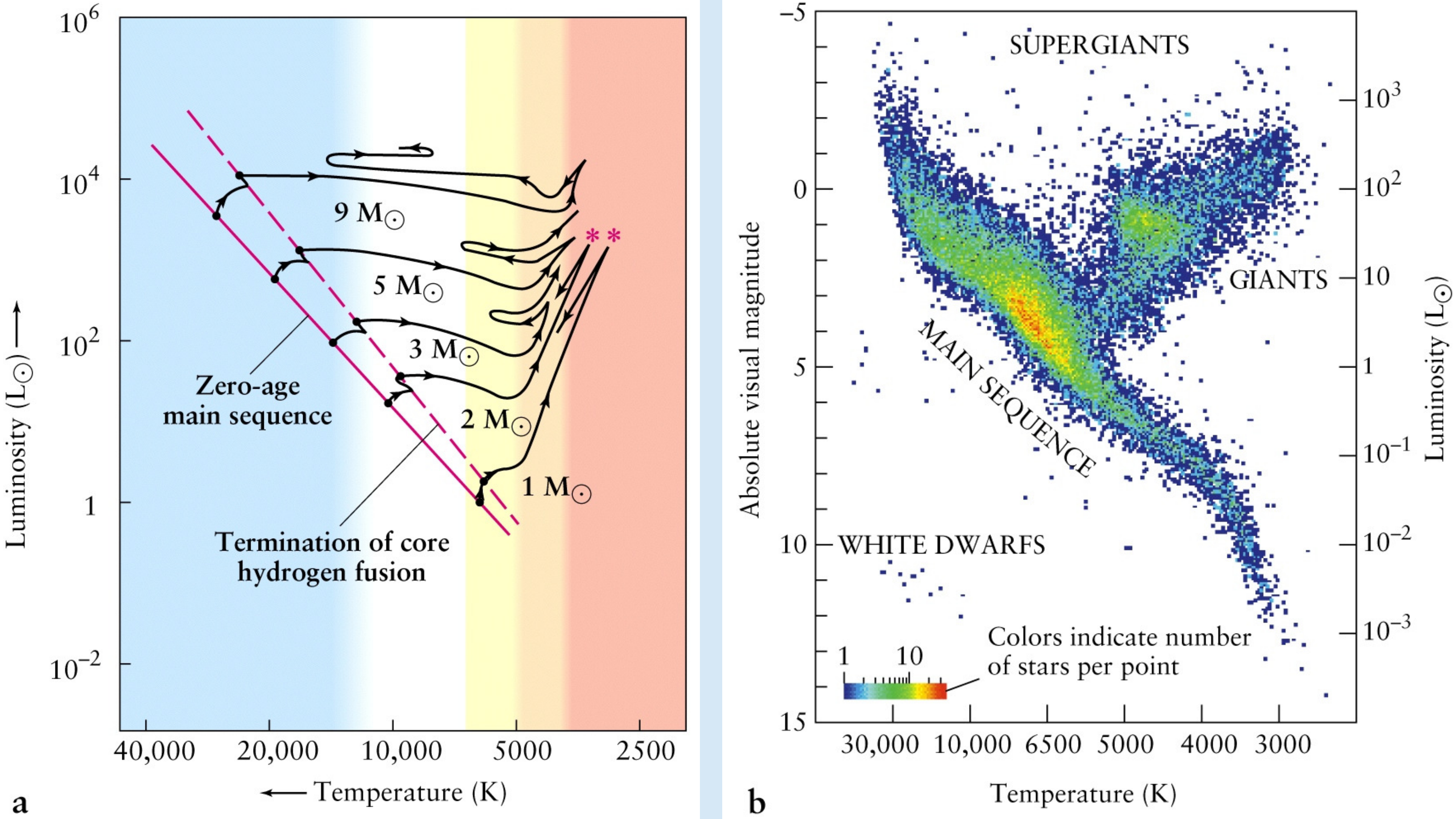
Post-Main Sequence evolution (1 solar mass star)

Planetary Nebula keeps expanding until it dissipates in the Interstellar Medium.



I: C core supported by electron degenerate pressure → star (~ Earth's size) never gets to C ignition temper.
→ C white dwarf
→ cools off to black dwarf in a few 10^9 yr

Stellar evolution for various stellar masses



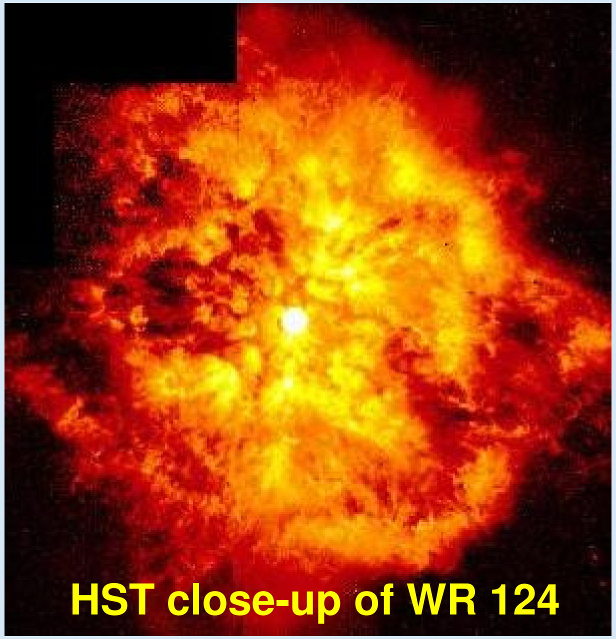
Stellar evolution of extremely massive stars

Extremely massive stars (50 – 100 solar masses; radiation pressure prevents formation of higher >100 masses) lose mass by stellar winds, which slow their evolution

Sun loses ~ 10^{-14} of its mass per year in the solar wind
Massive O stars may lose 10^{-7} to 10^{-6} solar mass per year

Extremely massive stars lose 50-60% of their mass by end of MS phase: outer layers stripped off
→ core is revealed, may not turn into Red Giant because no outer shell

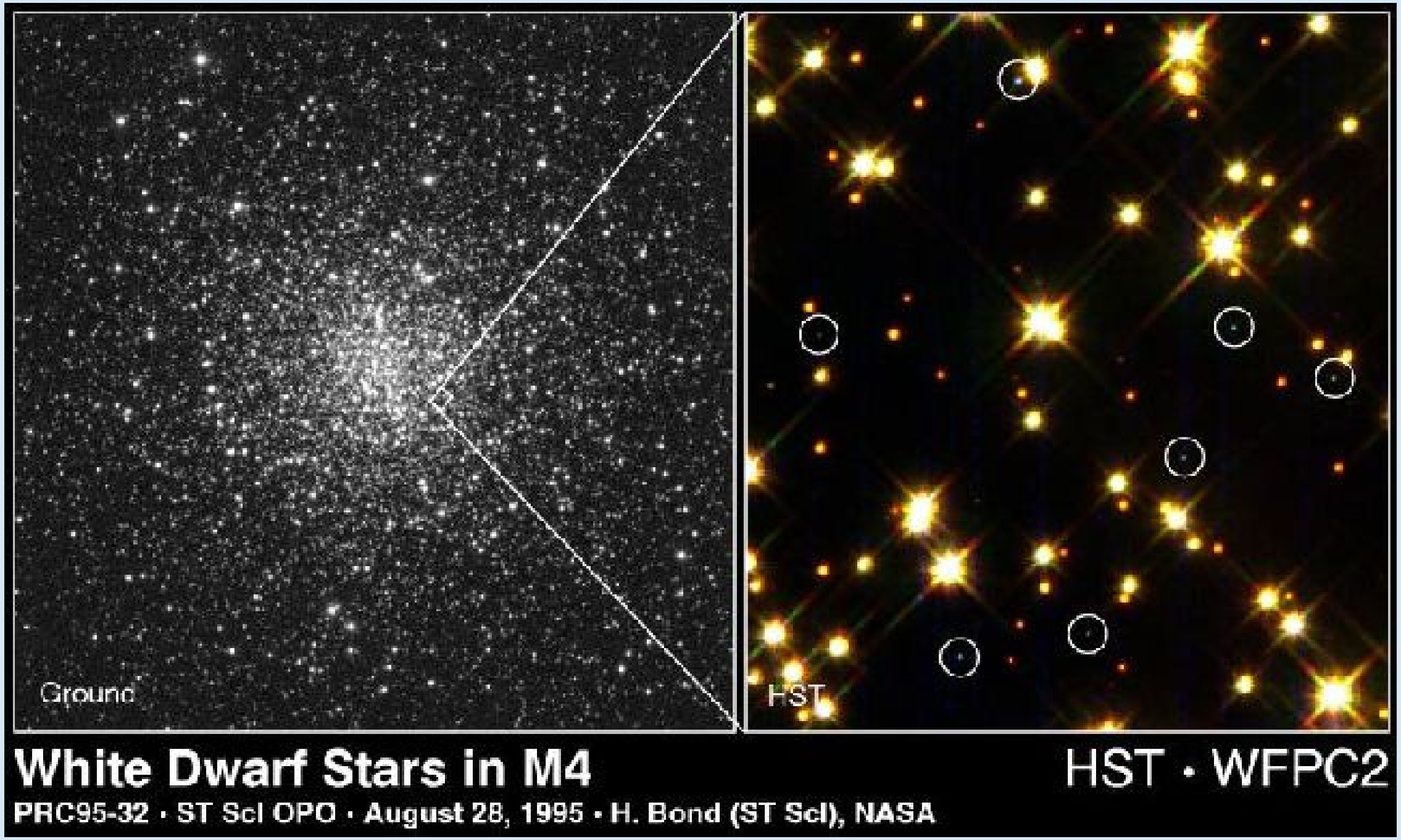
→ Wolf-Rayet stars (strong N and O emission lines)
→ Supernova (named Type Ib)



Stellar evolution of low mass stars (1)

Stars of mass much lower than the Sun do not get to burn much He to C before they expel their envelope

They end up as white dwarfs, composed mostly of He

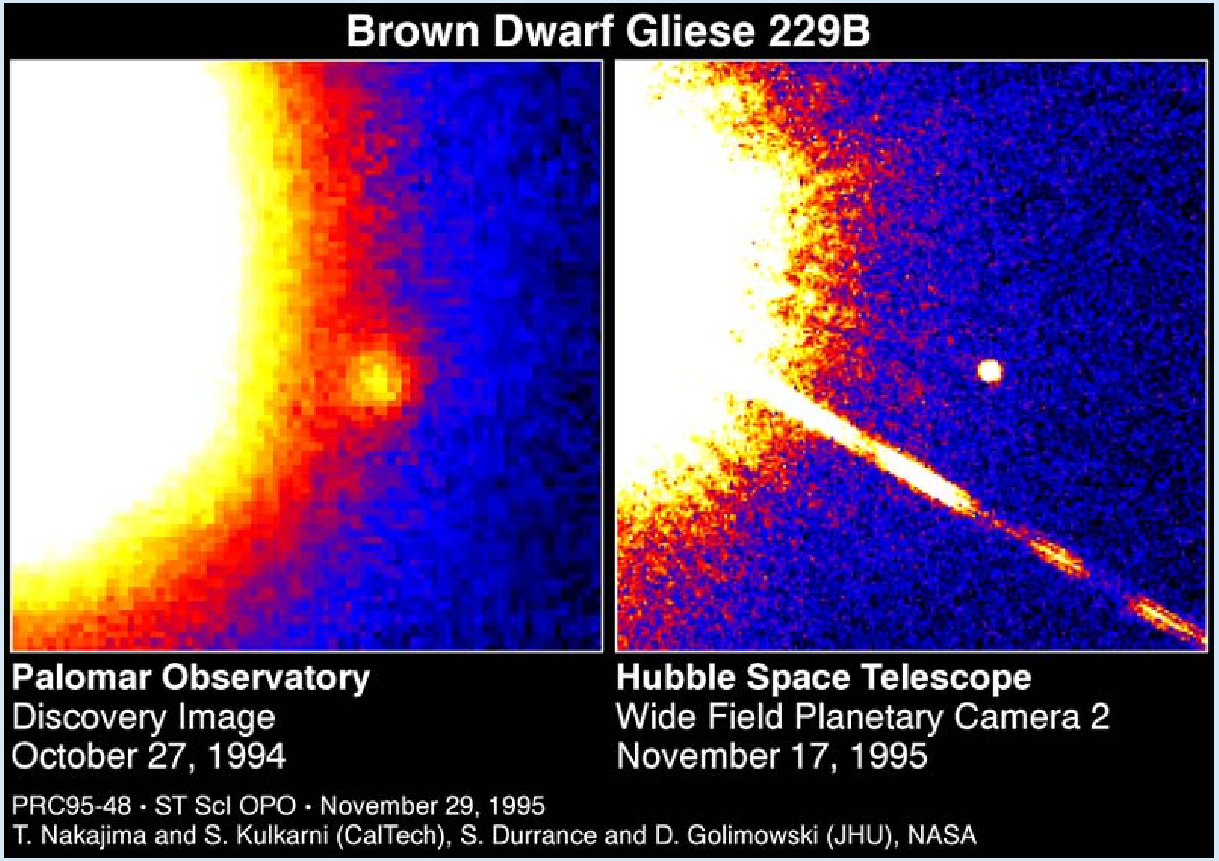


Stellar evolution of low mass stars (2)

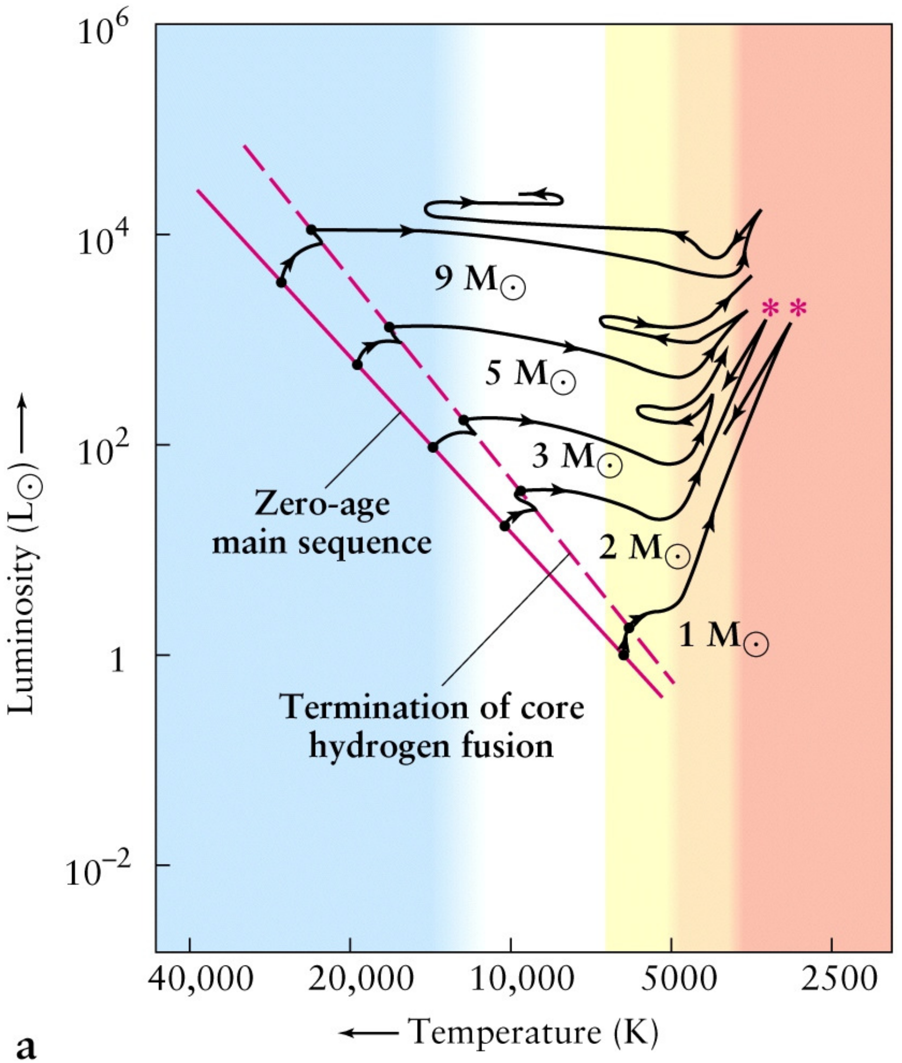
Stars of < 0.08 solar masses:

- central temperature never high enough to start H burning
- central density so high that matter becomes degenerate, preventing further contraction and nuclear ignition

➔ star cools off to become a brown dwarf



Stellar evolution for >1 solar mass stars

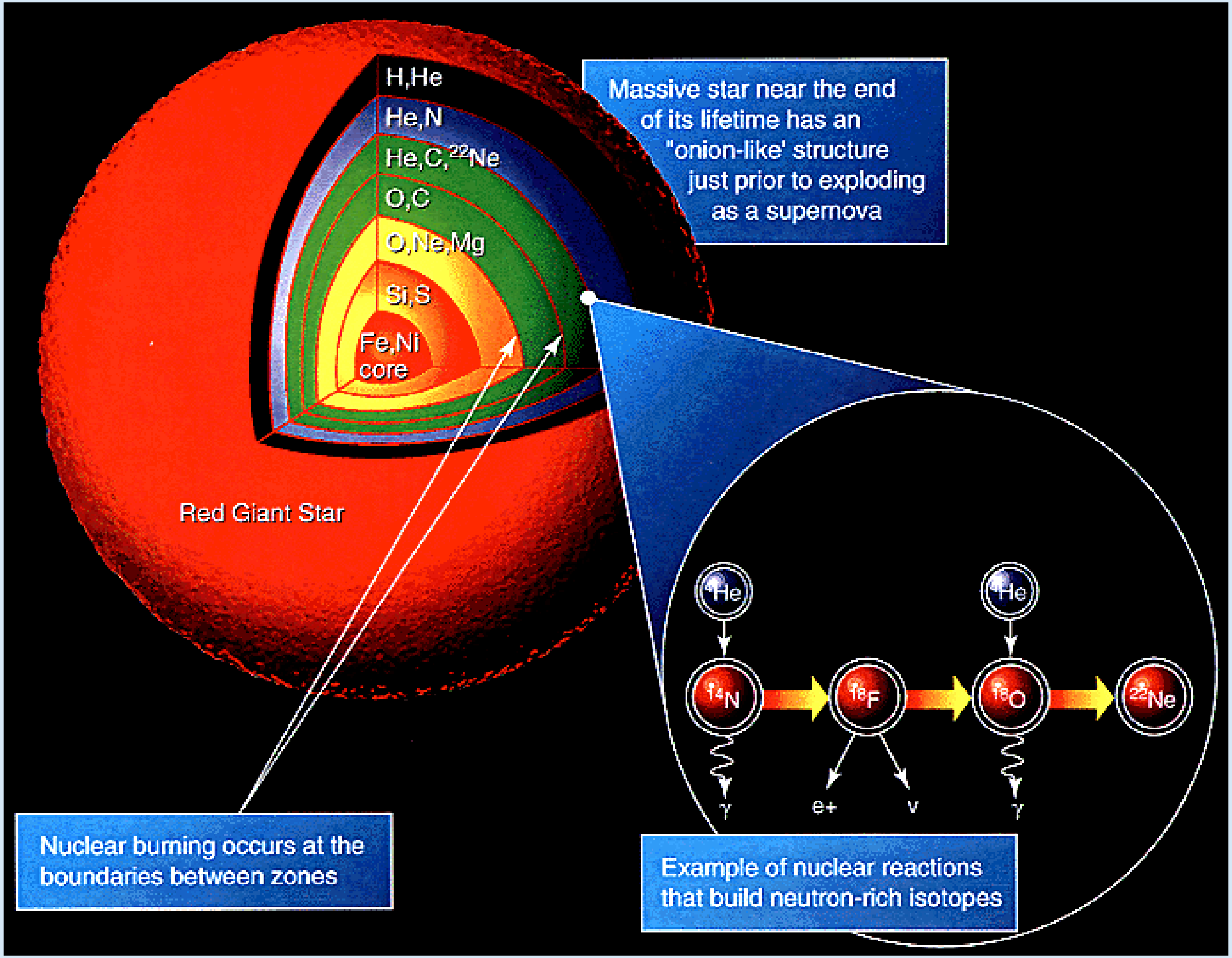


On MS, H burning by CNO cycle
(higher mass, hotter core)
Post-MS, similar to 1 solar mass, but:
Core temper. higher → burning of further elements occurs

No He flash, core not degenerate

Successive Red Giant phases; after each core burning stage, reaction continues in a shell
→ 'onion-like' structure, shells with different reactions

< 8 M_{Sun}: Evolution similar to that of 1 solar mass star
> 8 M_{Sun}: Nuclear burning → Fe core → collapse → Supernova


H,He
He,N
He,C,^{22}Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Red Giant Star
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
Nuclear burning occurs at the boundaries between zones
^{4}He
^{4}He
^{14}N
^{18}F
^{18}O
^{22}Ne
γ
e+
ν
γ
Example of nuclear reactions that build neutron-rich isotopes

Nucleosynthesis

At > 8 solar mass, Ne burning (~10^9 K), then
O burning (2 x 10^9 K)
Si burning (3 x 10^9 K) → S → Fe (Ni)
Faster and faster!! (C: few hundred years; Si, a day)

Massive stars are rare, but <u>most important</u>: they fuse heavy elements and spread them back into the interstellar medium via Supernovae.

Red Giants play major role in nucleosynthesis:
Thermal pulses in He burning shell encourage formation of neutron-rich isotopes.
<u>Convection</u> pulls up elements formed in the core by H burning
(→ 'dredge-up')

FAQ: Frequently Asked Questions!

Have black dwarfs been detected? A black dwarf is an hypothetical astronomical objects: a white dwarf so old that it has cooled down, so that it no longer emits significant heat or light. None expected to exist yet, since the time required for a white dwarf to cool down is calculated to be longer than the age of the Universe.

What is degenerate matter? Matter which has sufficiently high density that its (degeneracy) pressure arises from the Pauli exclusion principle (which forbids two particles to occupy identical quantum states; thus, compressed in little volume, they must occupy higher energy levels than normal → pressure).

Why do fusion reactions accelerate at the end of the star's evolution? Nuclear reaction rates strongly depend on temperature; since the stellar core temperature, and density, increase all the time, and the amount of fuel for each step is smaller, it takes a shorter time to use it all up.

Where are heavier elements that Fe formed? In explosive nucleosynthesis (→ extreme temperatures) during supernovae, and by neutron capture via the the r(apid)-process in core collapse supernovae, and the s(low)-process in AGB stars.

The path to Supernova ***(ZG Ch. 18, FK Ch. 22)***

So called 'Type II Supernovae' arise from evolved stars of > 8 solar mass (O and B spectral type), and occur only in spiral galaxies, especially in spiral arms (regions of strong star formation).

Such massive stars can fuse elements up to Fe

→ Fe core grows (Fe cannot fuse and release energy), supported by electron degeneracy pressure
→ when core size reaches the Chandrasekhar limit (1.44 solar mass, or 3×10^{30} kg) degeneracy pressure no longer sustains it
→ core contracts and gets hotter

➔ Catastrophic collapse ('core collapse' supernova)

Core collapse Supernova (Type II)

At ~ 6 x 10^9 K, photodissociation of Fe (in ¼ second):

$^{56}Fe + \gamma \rightarrow 13\ ^4He + 4n$ (absorbs 100 MeV, core collapses faster)

$^4He \rightarrow 2p + 2n$

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

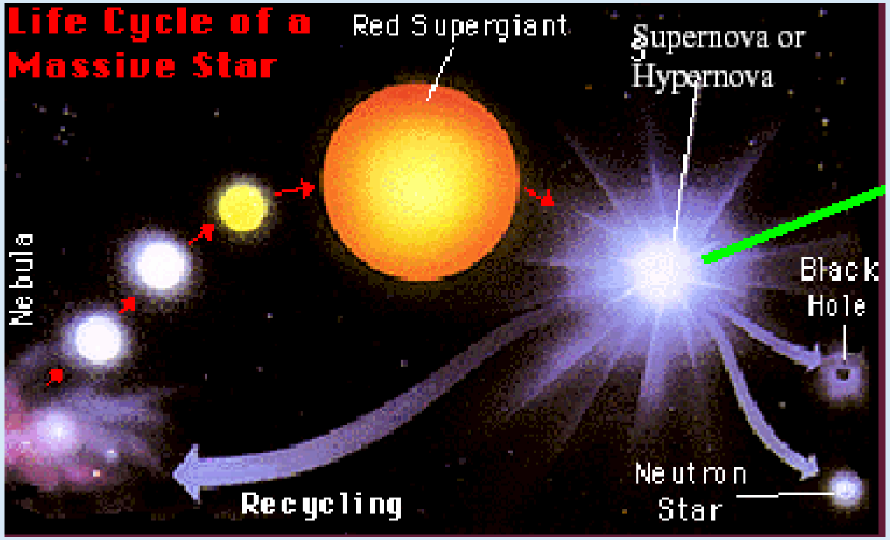
Proton and electrons 'squeezed' together to form neutrons, emitting pulse of neutrinos (which carry energy away, accelerate core collapse, are absorbed by outer layers, and accelerate their expulsion) in milliseconds!

Collapse eventually halted by short-range repulsive neutron-neutron interactions involving <u>degenerate neutron gas pressure</u> as well as the <u>strong nuclear force</u> → neutron star forms

Core collapse to a black hole

Neutron stars of > 3 solar mass are unstable against further collapse to a black hole (object predicted by Einstein's General Relativity with a gravitational field so strong that nothing can escape from it - not even light)

→ Collapse of 25 - 50 solar mass stars
with a core size > 3 solar mass
can lead to formation of black holes



'Bounceback'

Once collapse stops, innermost core bounces back somewhat, infalling outer layers rebound, producing shock wave (crossing star in a few hours) that blows off the rest of the star's material (at speeds of 5000 – 30000 km s^{-1})

Total energy released ~ 10^{46} Joule (ν), 10^{44} Joule (kinetic = energy Sun will produce over 10^{10} yrs)

➔ Supernova Remnant (SNR)

Outer layers still contain fuel for nucleosynthesis (explosive)

→ flood of energetic neutrons, absorbed by heavy nuclei

For example, within several minutes

$$^{56}Fe \rightarrow {}^{61}Fe$$

$$^{61}Fe \rightarrow {}^{61}Co + e^- + \nu$$

One major product of Supernova explosion is expected to be radioactive ^{56}Co, with half life of 77 days → γ-rays from its decay heat expanding envelope

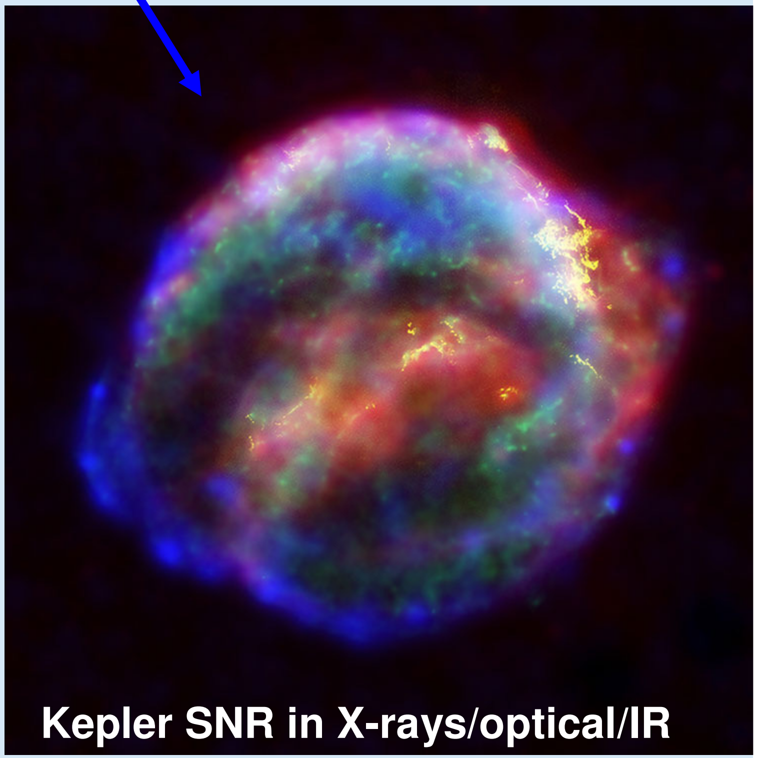
Supernova → Supernova Remnant

Supernovae are quite rare occurrences, ~1 per 50 – 100 yrs in our Galaxy (but none observed since 1604)

→ seen mainly in other galaxies, e.g. SN1994D in NGC4526

Visible brightness can increase by up to x10^8, then decays over several yrs

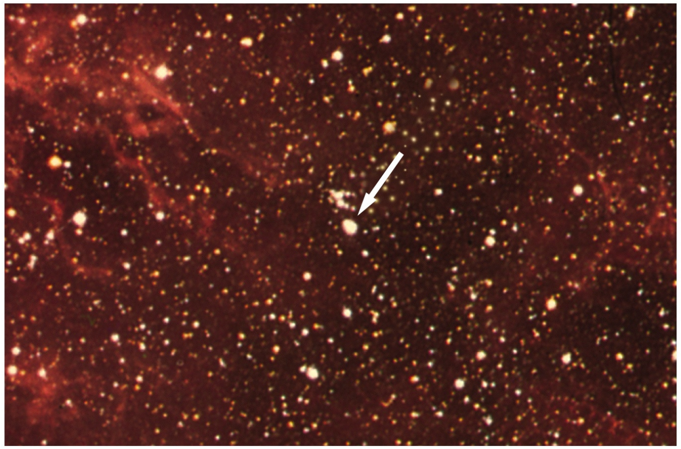
Kinetic energy of expanding outer layers heats interstellar medium, shell of gas keeps shining in X-ray, visible and radio wavelengths for up to 100,000 yrs, with material slowly cooling off



Kepler SNR in X-rays/optical/IR

(http://apod.oa.uj.edu.pl/apod/ap041008.html)

When SNR central density dropped sufficiently, neutron star at its core may appear (hot → X-rays, visible, radio)



a Before

SN1987A

In the Large Magellanic Cloud, at 51.4 kpc from Earth, on 23 Feb. 1987 (but really ~168,000 yrs before …)

Brightest SN for 400 yrs

Most intensely studied Supernova!

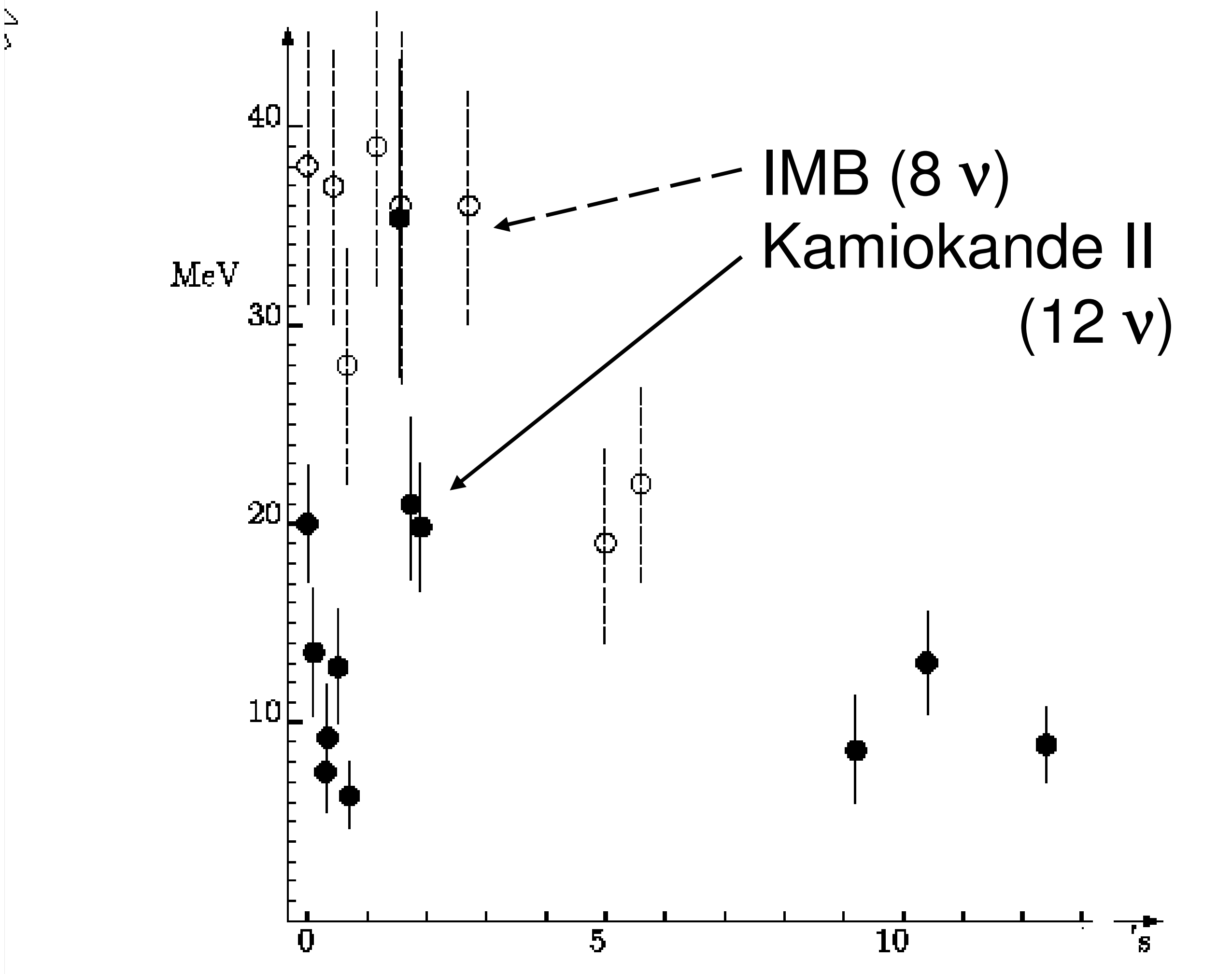
Progenitor: presumed 18 solar mass blue supergiant

Reached apparent magnitude +3

b Immediately after

Neutrinos from SN1987A

~3 hours before visible light reached Earth, burst of neutrinos (24) detected at three separate observatories

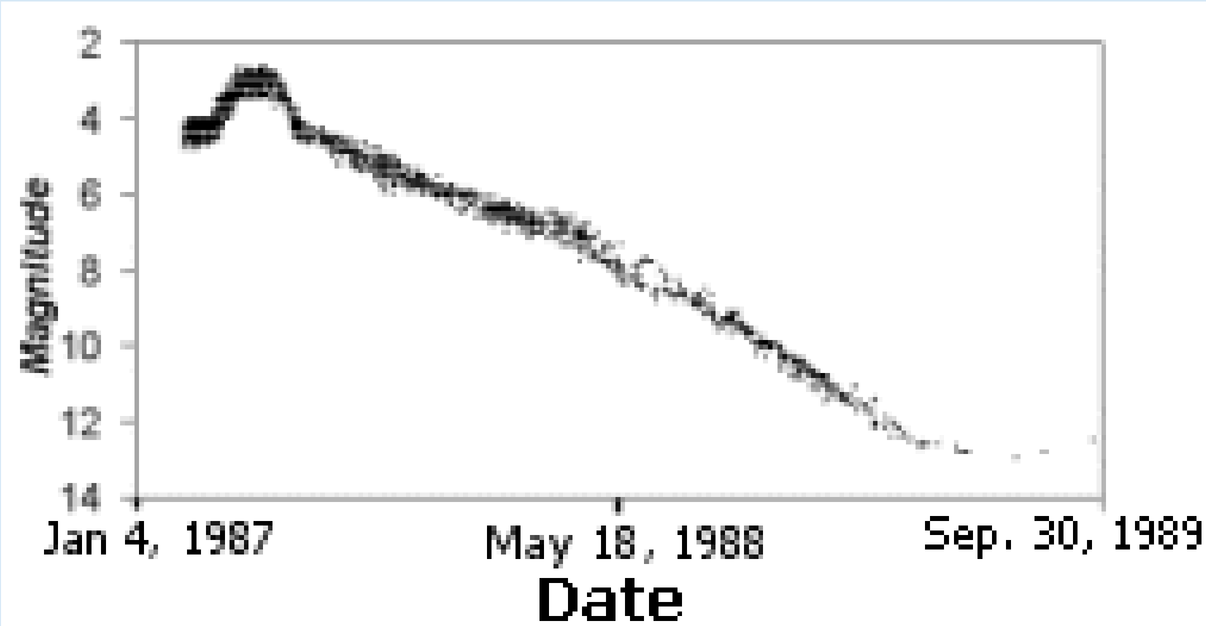


Remarkable confirmation that SN theory is correct, by observation of a neutron star formation!

Neutrino astronomy (extra-solar) was born!

The decay of SN1987A

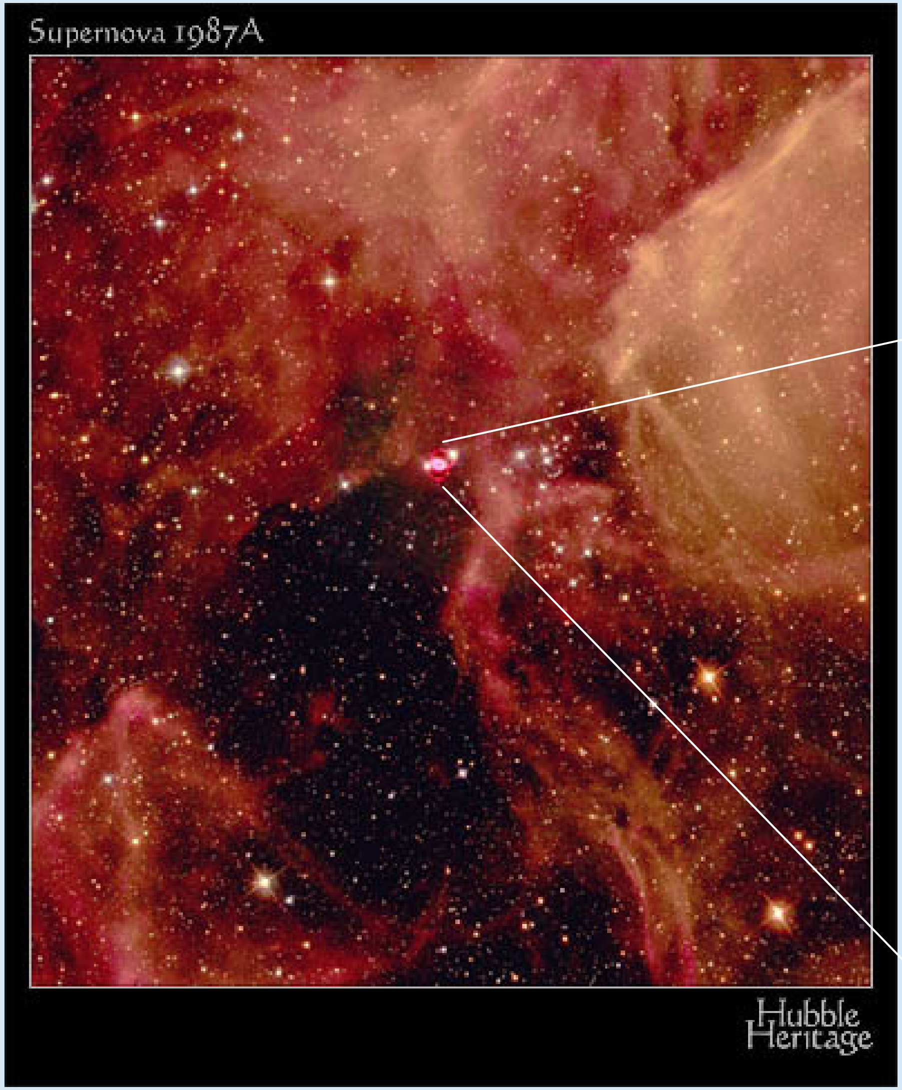
Peak visible brightness in May 1987, then exponential decay from July to November exactly matches that expected for ^{56}Co, again confirming theory

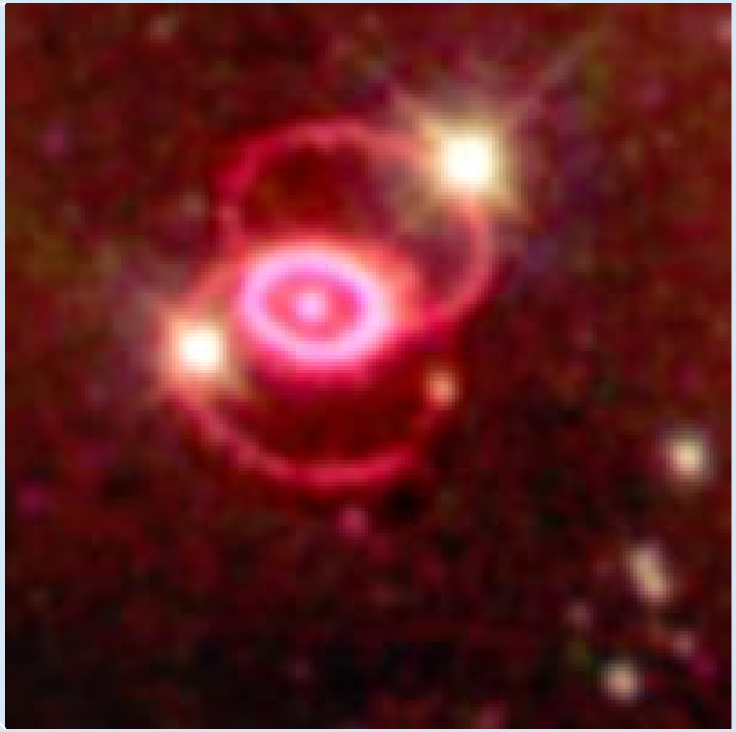


Observations over subsequent ~ 20 years were to raise some surprises …

SN1987A ring structures

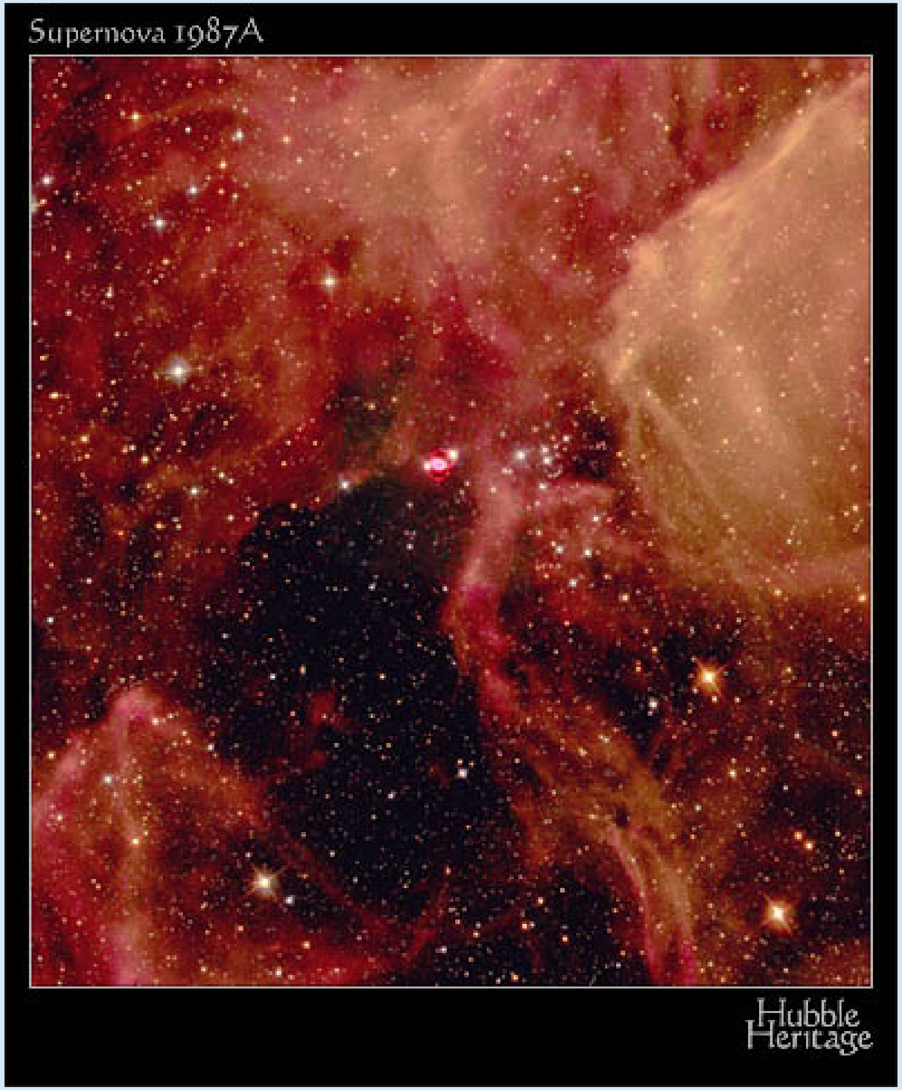
Since 1990, HST has kept an attentive eye on SN 1987A, observing it at least once a year → SNR (in the centre) is surrounded by inner and outer ring structures → measured expansion speeds of 30 – 40 km s^{-1}, 100-1000x less than SN

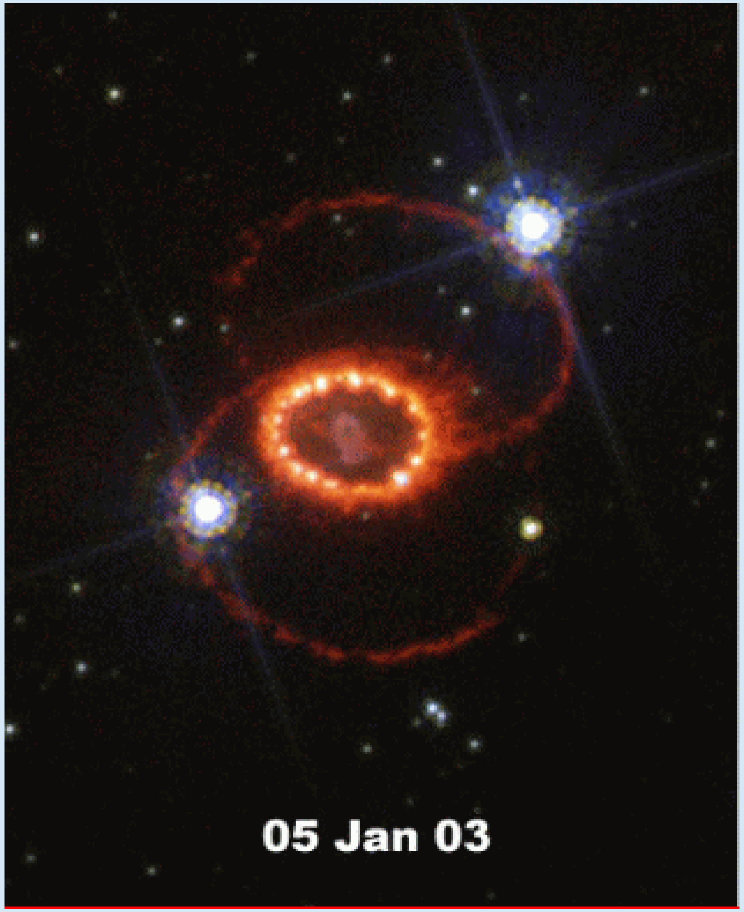




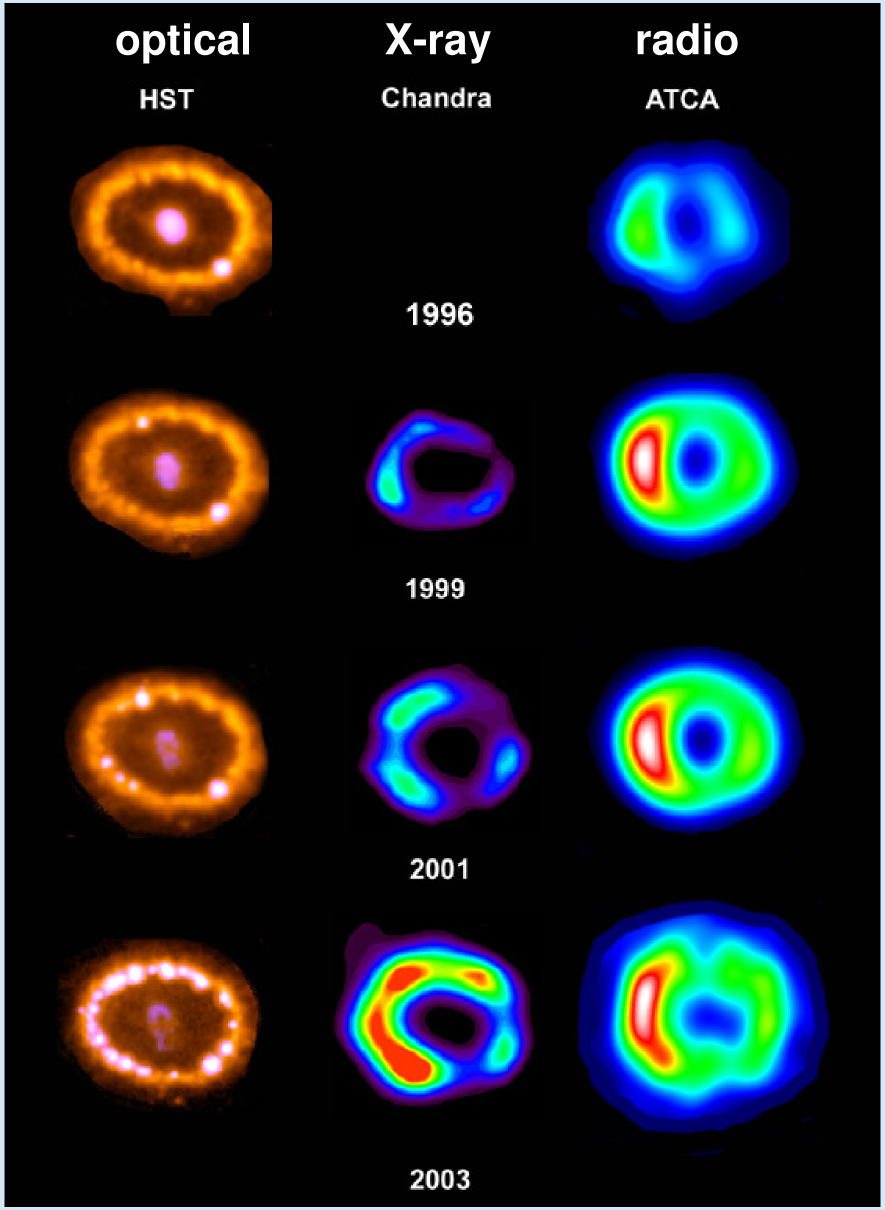
SN1987A ring brightening

HST has also observed 'hot spots' developing in the inner ring structure, which has become generally brighter with time (the two bright stars are unrelated)





SN1987A ring expansion



Inner ring structure also studied in X-ray and radio band

Origin of ring structure still a mistery: spectra show unusual N enrichment + low speeds
→
Material expelled by progenitor supergiant 10-20,000 yr before SN (and now glowing because of SN UV flash)? But why not in all directions, rather than <u>puffing rings like a pipe smoker</u>?

→ see model
on the course Website!