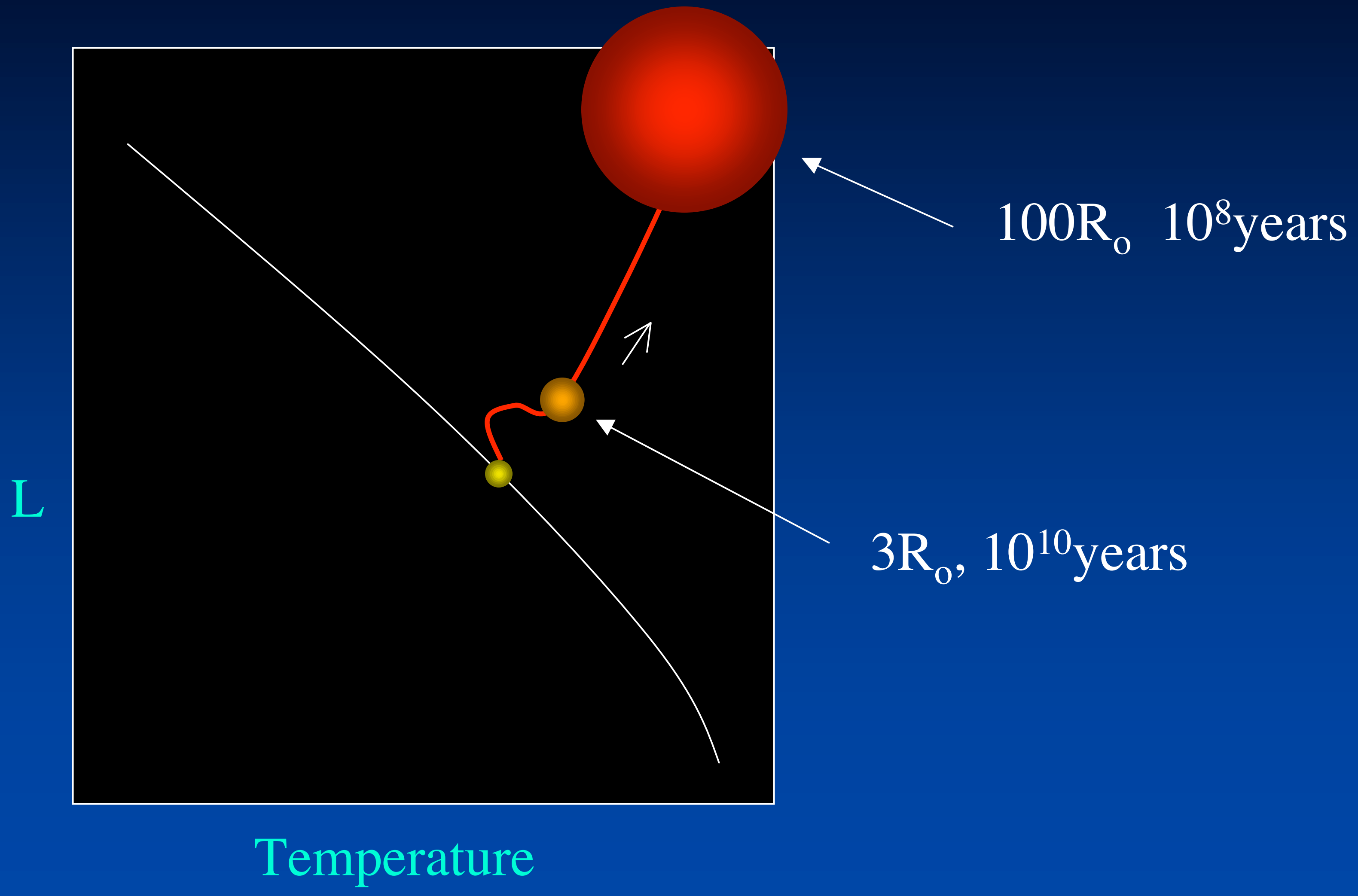
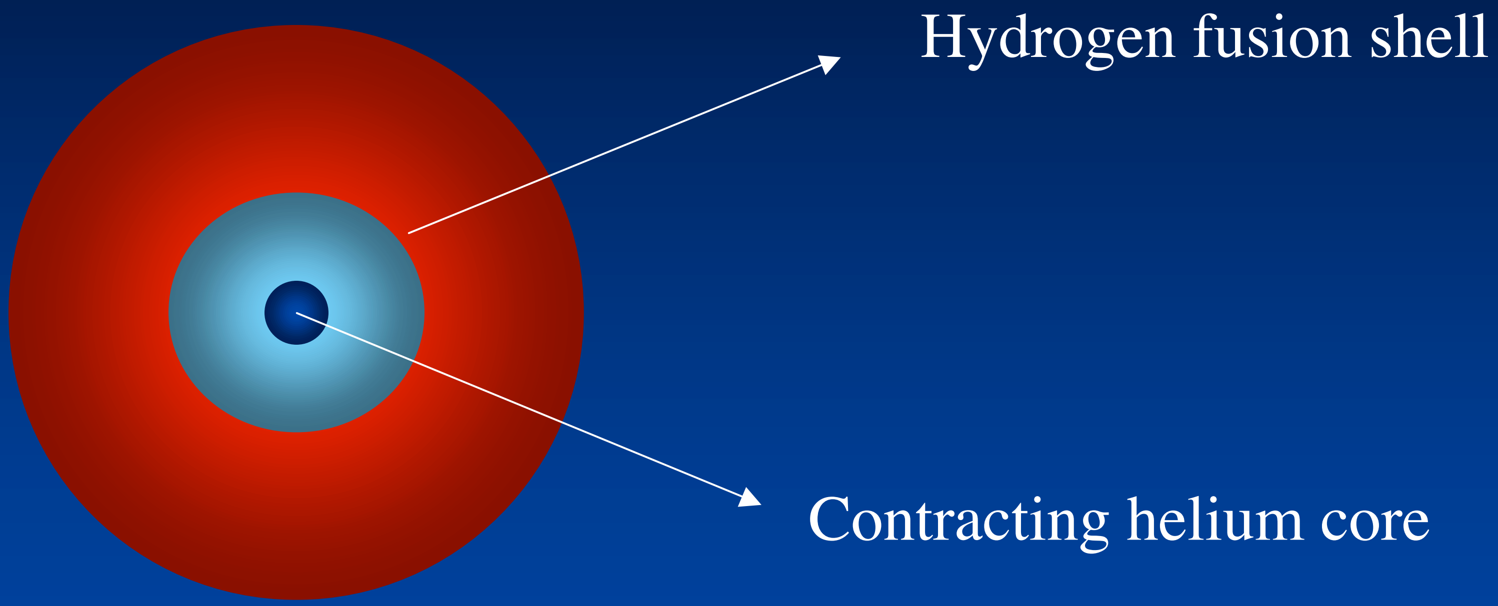
Next Session

- Stellar evolution
  - Low-mass stars
  - Binaries
  - High-mass stars
- Supernovae
- Synthesis of the elements

Red Giant



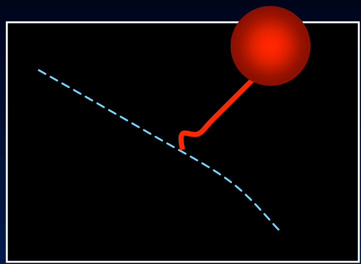
Red Giant



Electron Degeneracy

- Pauli Exclusion Principle says that you can only have two electrons per unit 6-D phase-space volume in a gas.

$$\boxed{\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z}$$



Red Giants

- RG Helium core is support against gravity by electron degeneracy
- Electron-degenerate gases do not expand with increasing temperature (no thermostat)
- As the Temperature gets to 100 x 10^6K the "triple-alpha" process (Helium fusion to Carbon) can happen.

Helium fusion/flash

Helium fusion requires two steps:

$$\boxed{\begin{array}{c} He^4 + He^4 \rightarrow Be^8 \\ Be^8 + He^4 \rightarrow C^{12} \end{array}}$$

The Berylium falls apart in 10^{-6} seconds so you need not only high enough T to overcome the electric forces, you also need very high density.

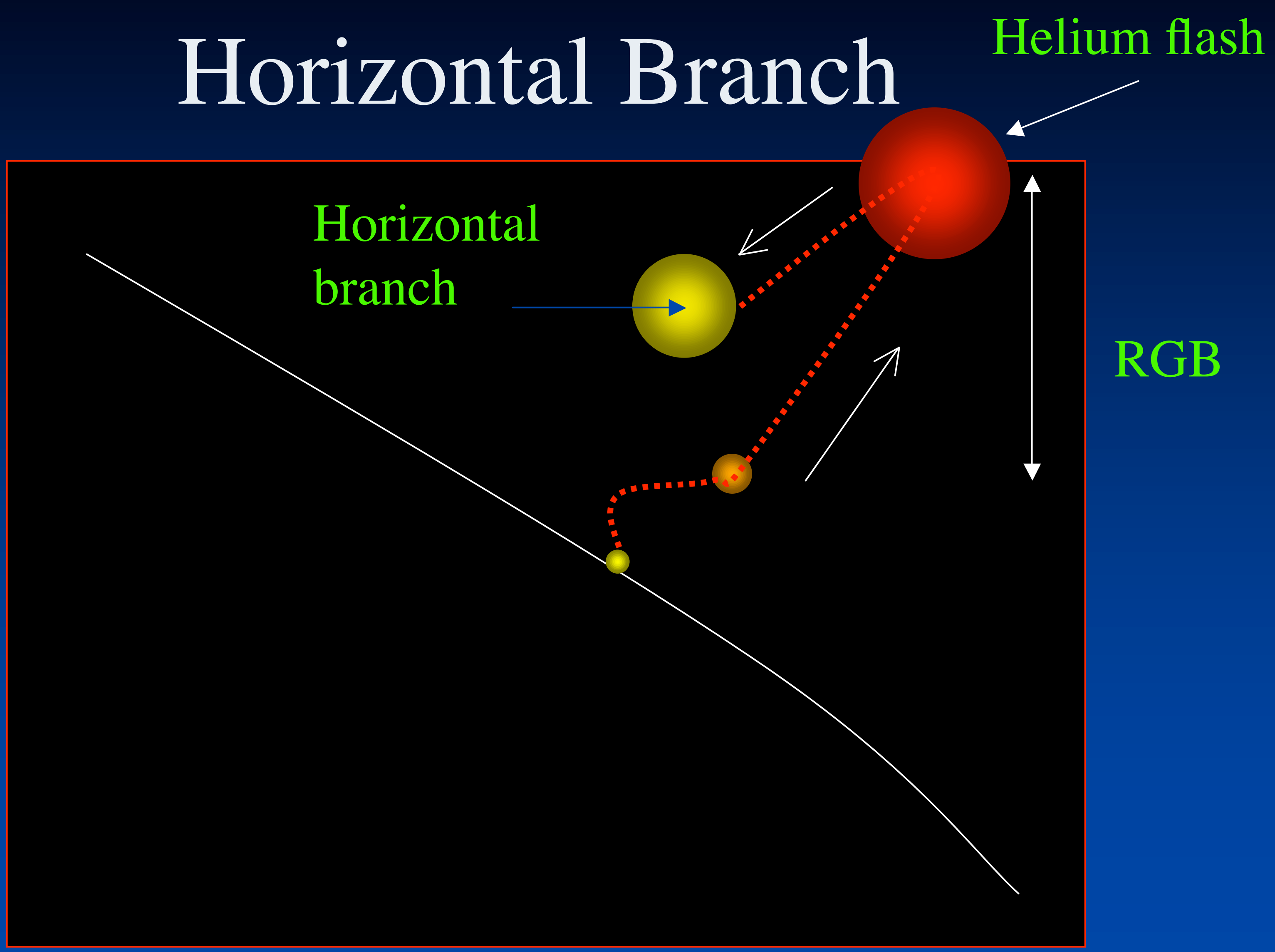
Helium Flash

- The Temp and Density get high enough for the triple-alpha reaction as a star approaches the tip of the RGB.
- Because the core is supported by electron degeneracy (with no temperature dependence) when the triple-alpha starts, there is no corresponding expansion of the core. So the temperature skyrockets and the fusion rate grows tremendously in the `helium flash'.

Helium Flash

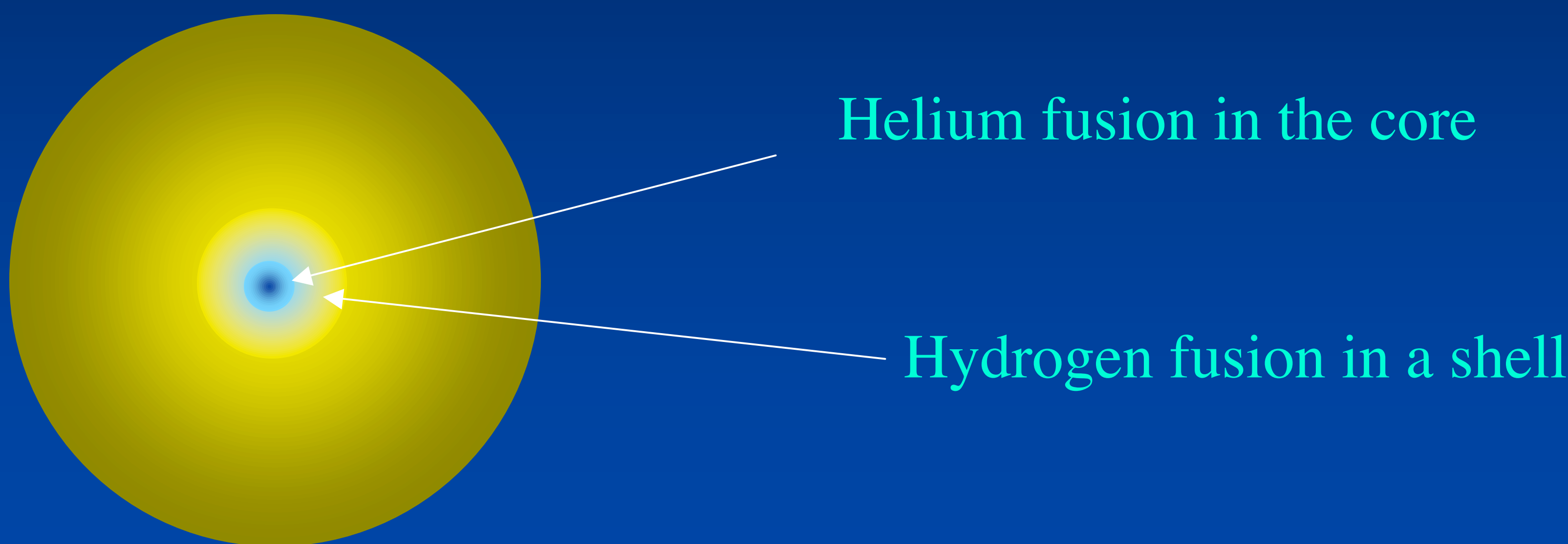
- The big increase in the core temperature adds momentum phase space and within a couple of hours of the onset of the helium flash, the electrons gas is no longer degenerate and the core settles down into `normal' helium fusion.
- There is little outward sign of the helium flash, but the rearrangment of the core stops the trip up the RGB and the star settles onto the *horizontal branch*.

Horizontal Branch



Horizontal Branch

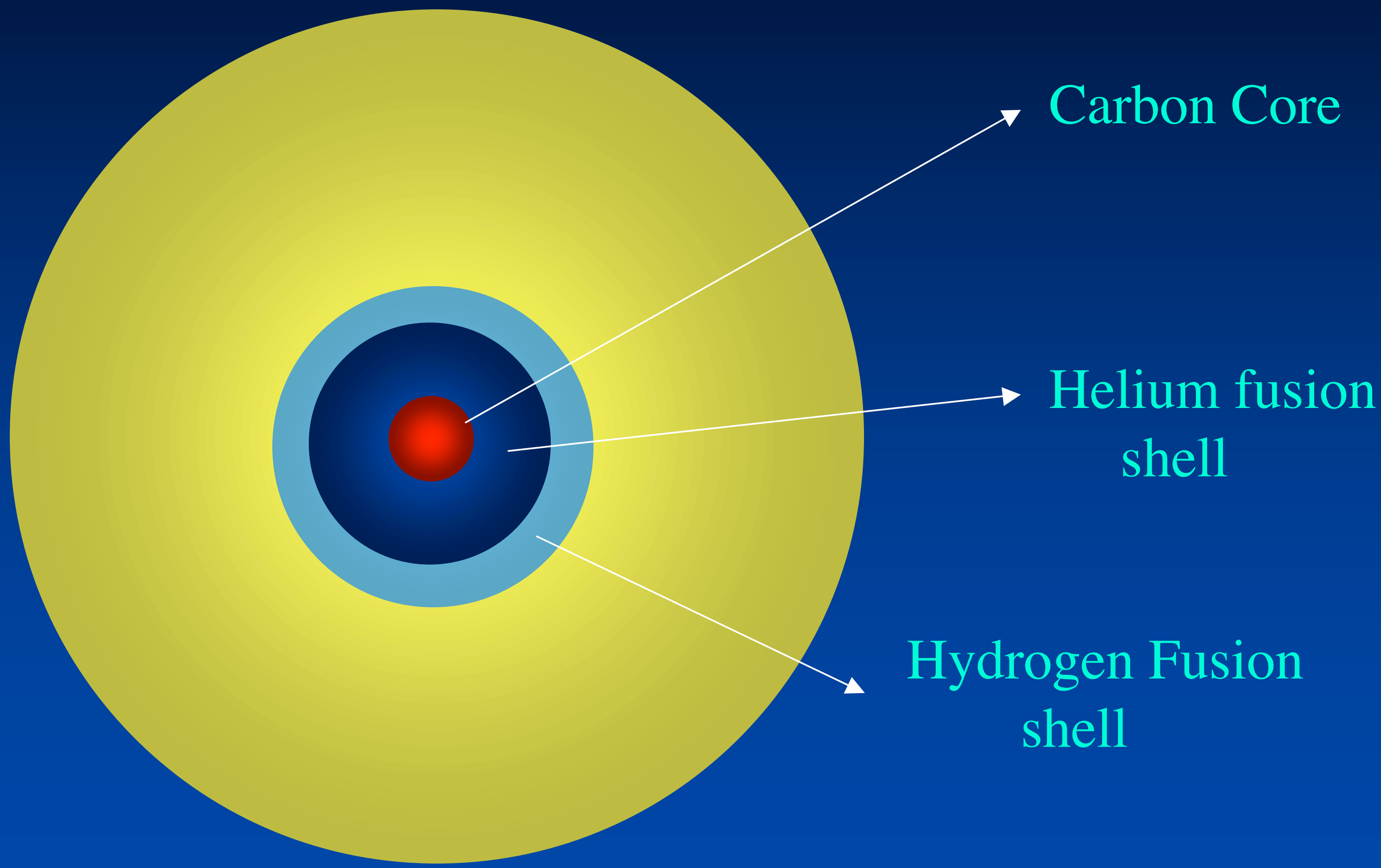
- Stars on the horizontal branch have similarities to main-sequence stars



The Second Ascent Giant Branch

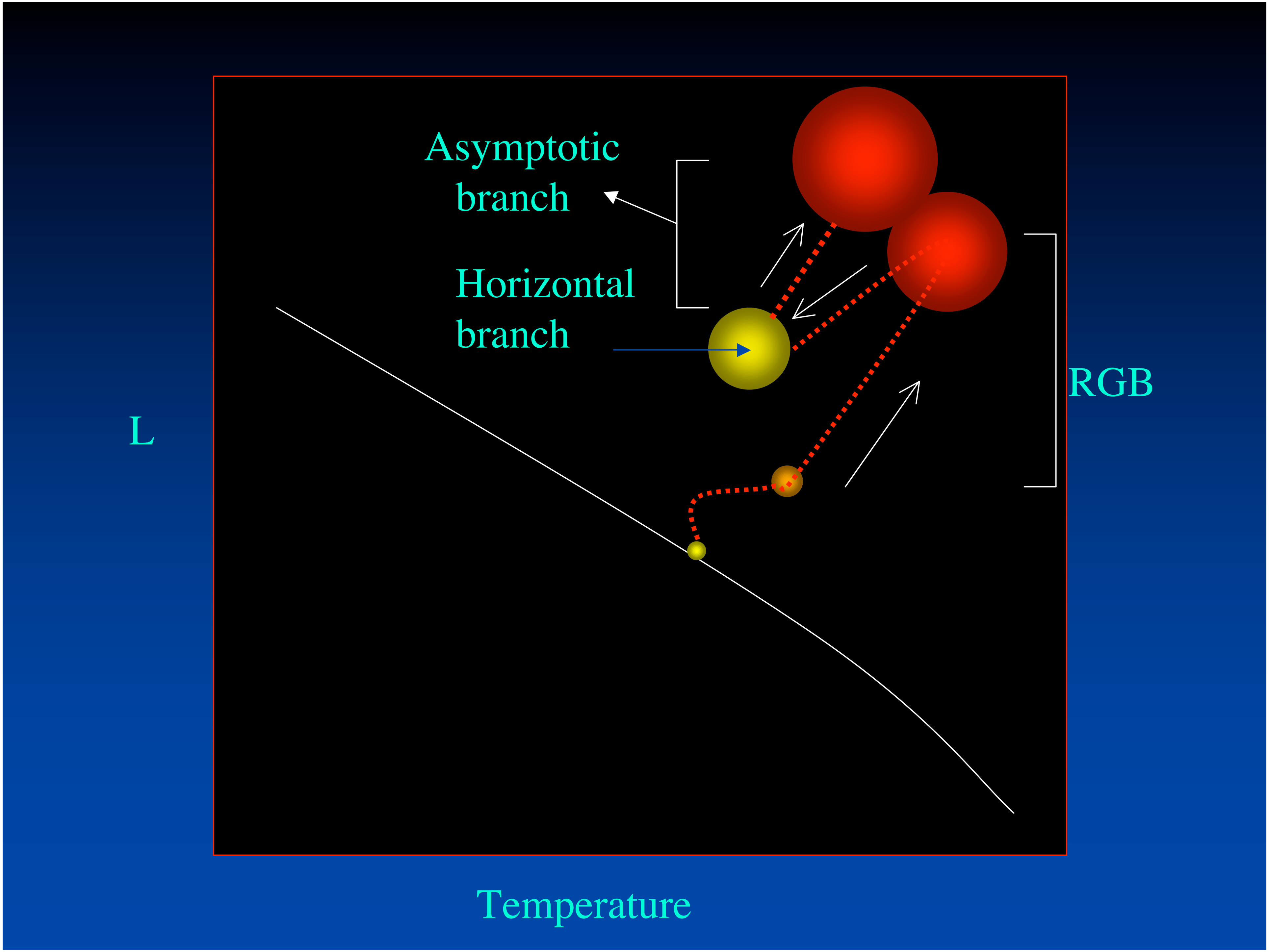
- Horizontal-branch stars (like main-sequence stars) begin to use up their fuel in the core.
- In this case, the star is building up a Carbon core. *For stars near $1M_o$ the temperature never gets high enough for Carbon fusion.*
- The core begins to contract, releasing gravitational potential energy and increasing the fusion rates in the He and H fusion shells. Does this sound familiar?

Asymptotic Giant Branch



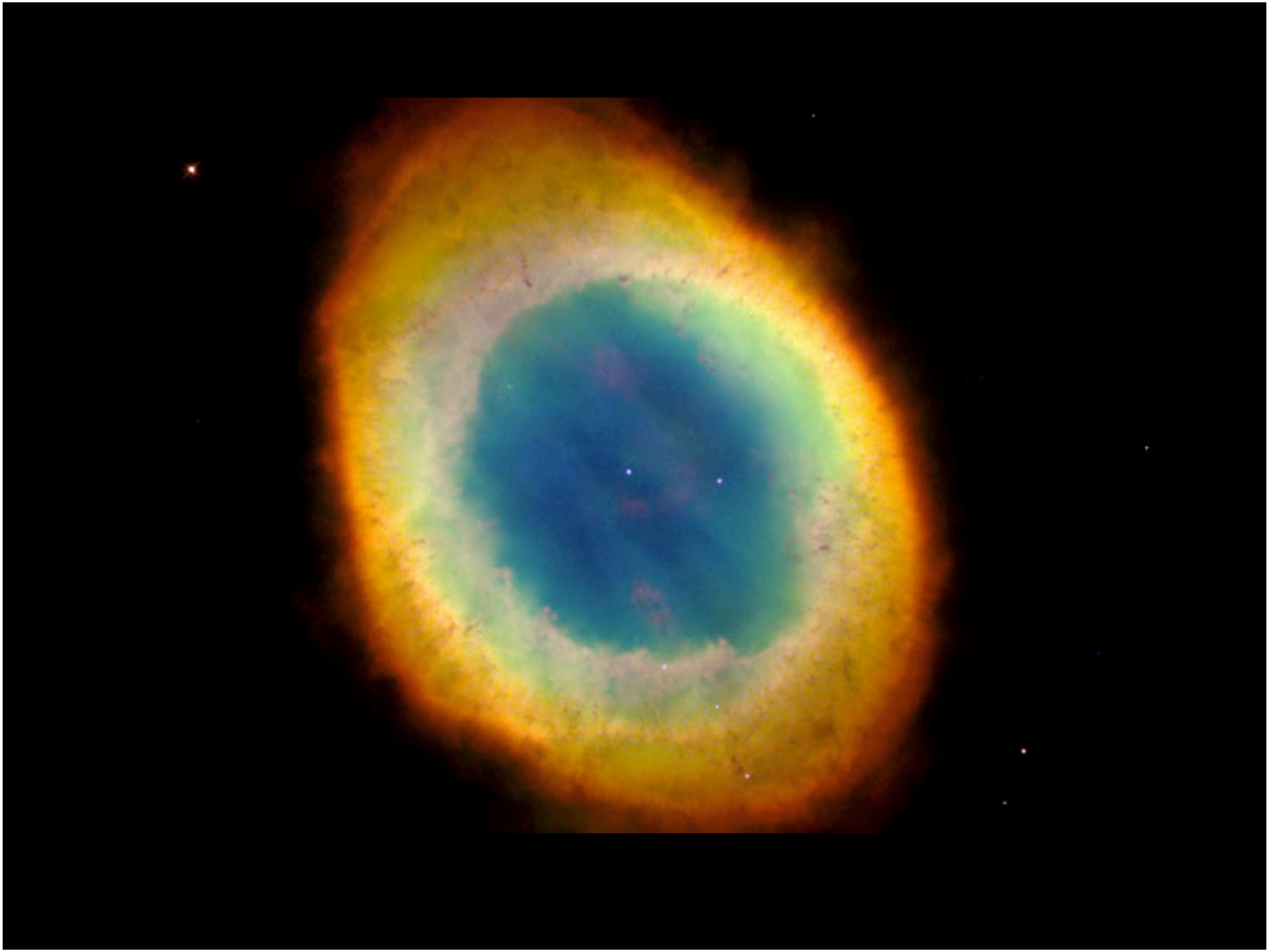
Asymptotic Giant Branch

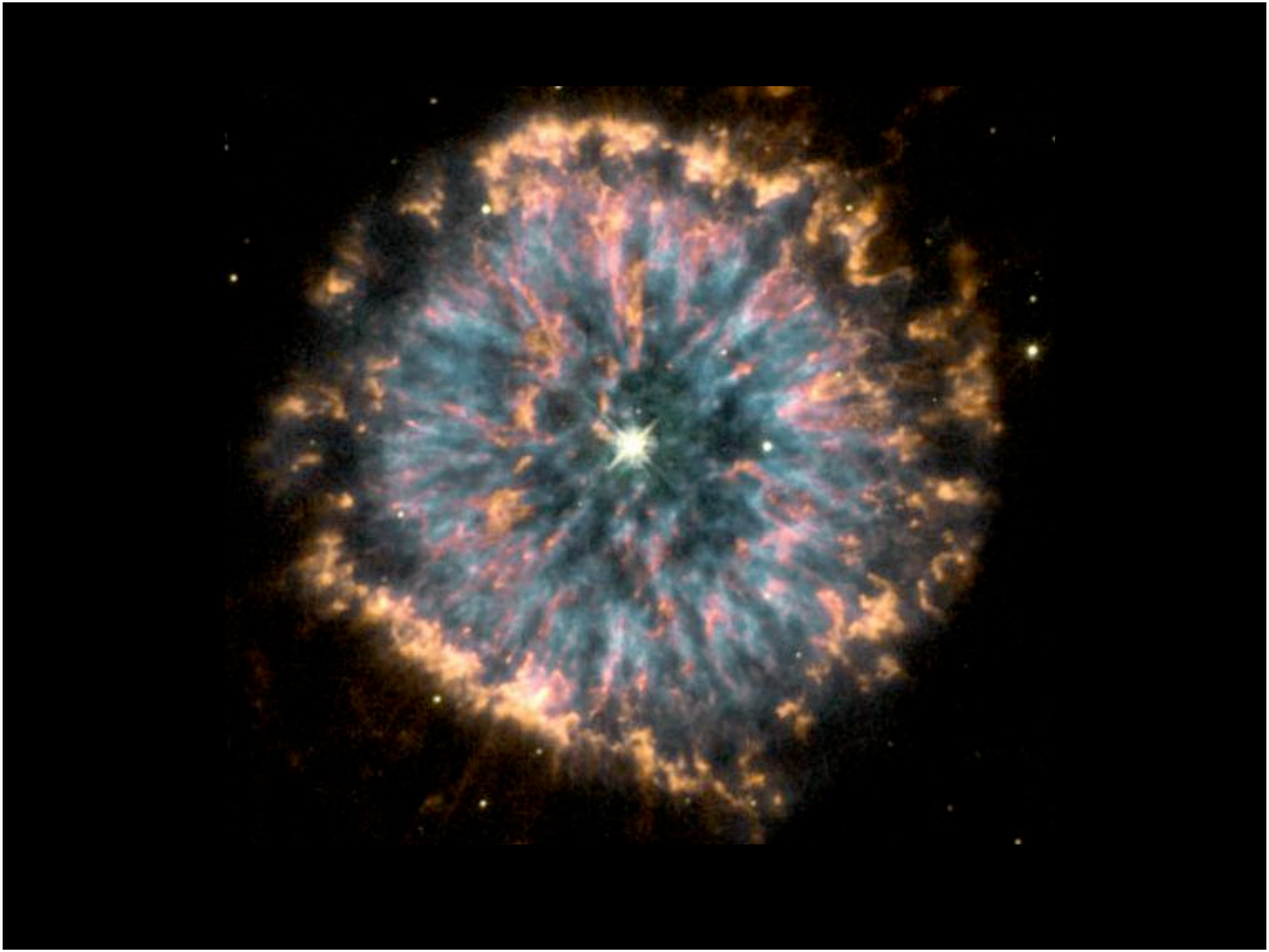
- This is like the transition from the main sequence to the Red Giant Branch.
- Stars evolve off the HB up and right in the HR-Diagram on a track parallel and above the RGB. Now, the energy generation is much more erratic. The triple-alpha process rate scales with T^{30}(!). AGB stars undergo `Shell flashes'.

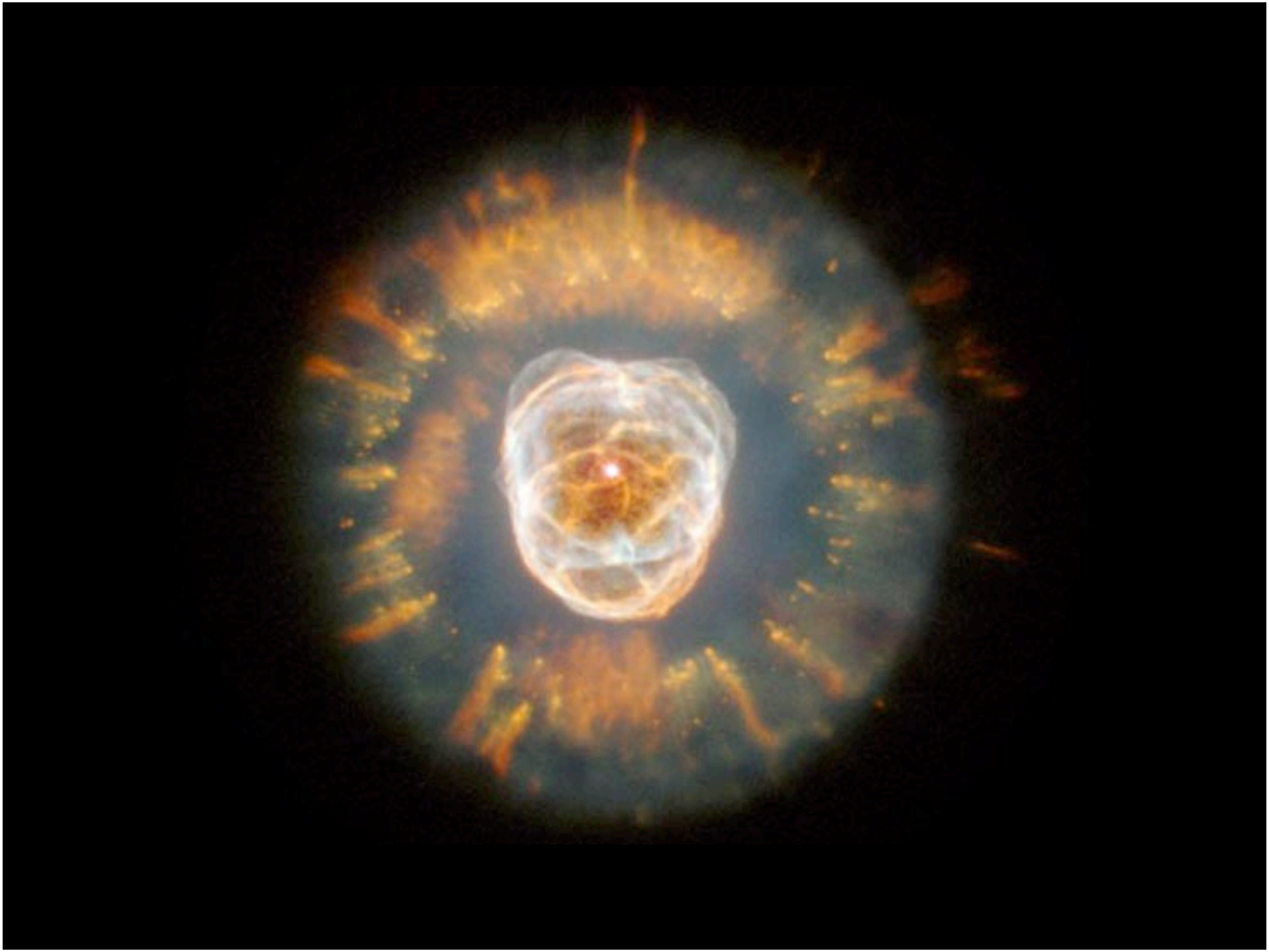

Asymptotic
branch
Horizontal
branch
RGB
L
Temperature

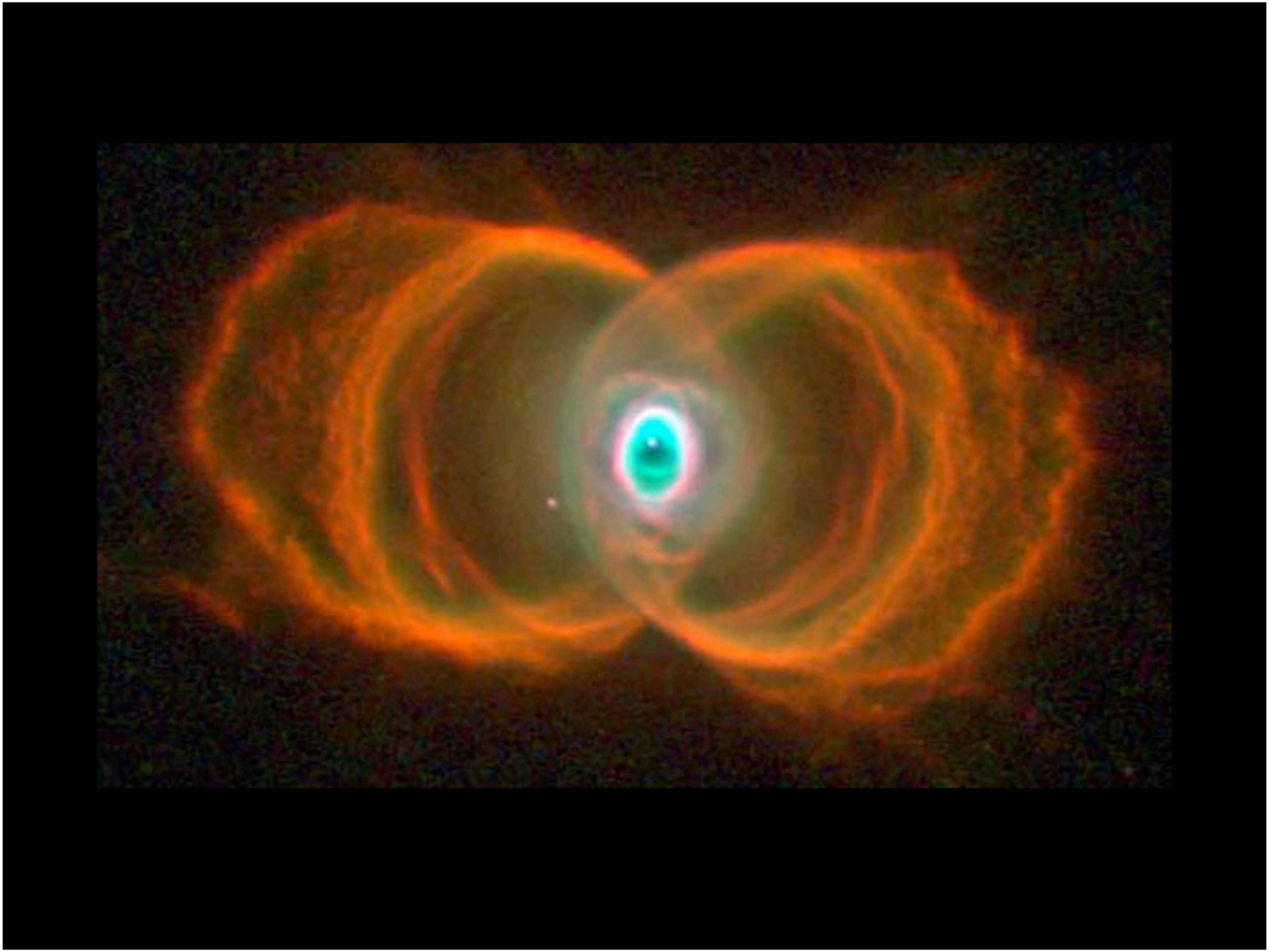
Planetary Nebula Stage

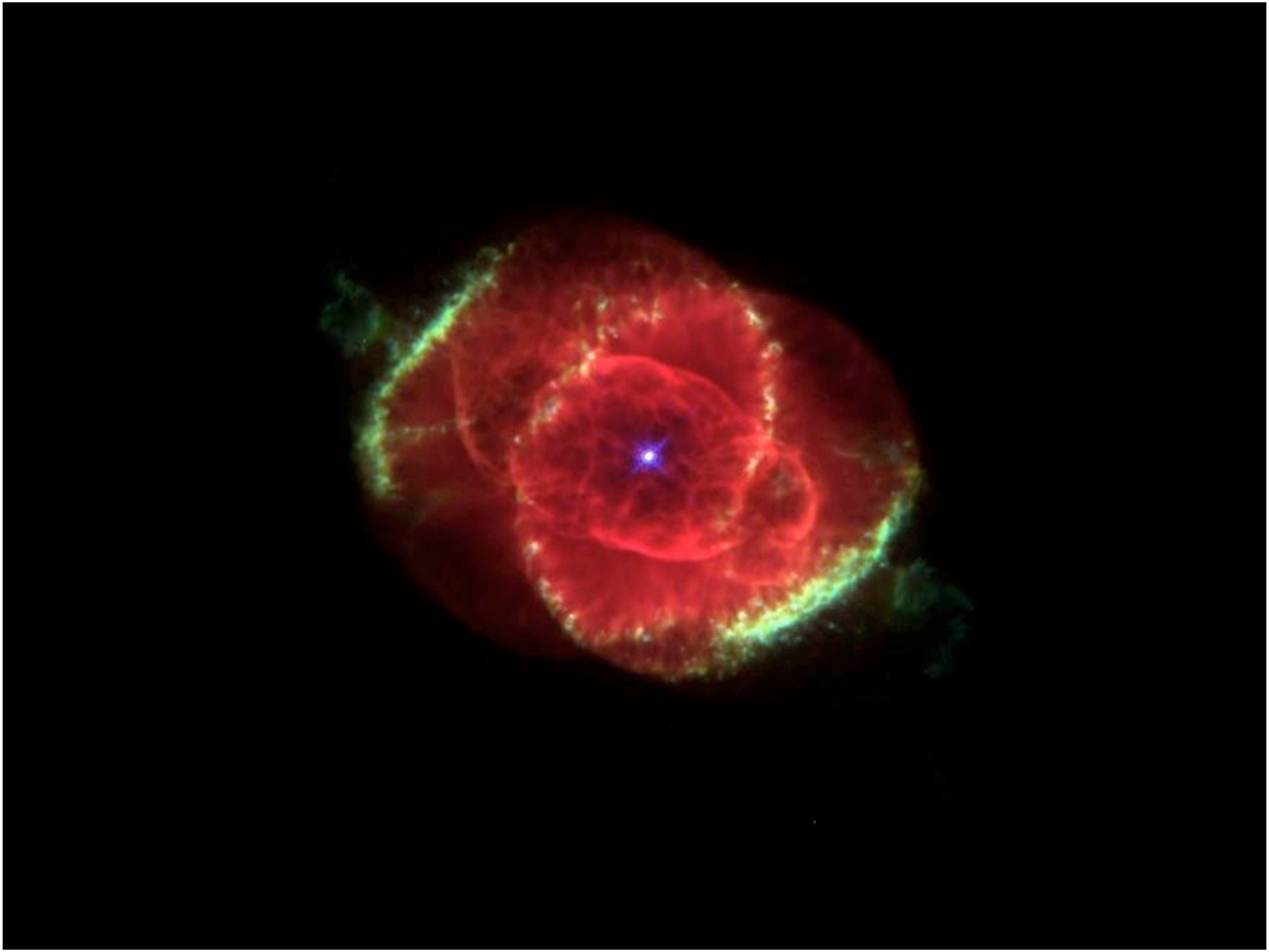
- The trip up the AGB (or `second ascent giant branch') gets terminated when the star's outer envelope becomes detached and begins to drift off into space. (!!)
- The former envelope shines in the light of emission lines.
- As the envelope expands and becomes transparent the very hot core of the AGB star can be seen at its center.





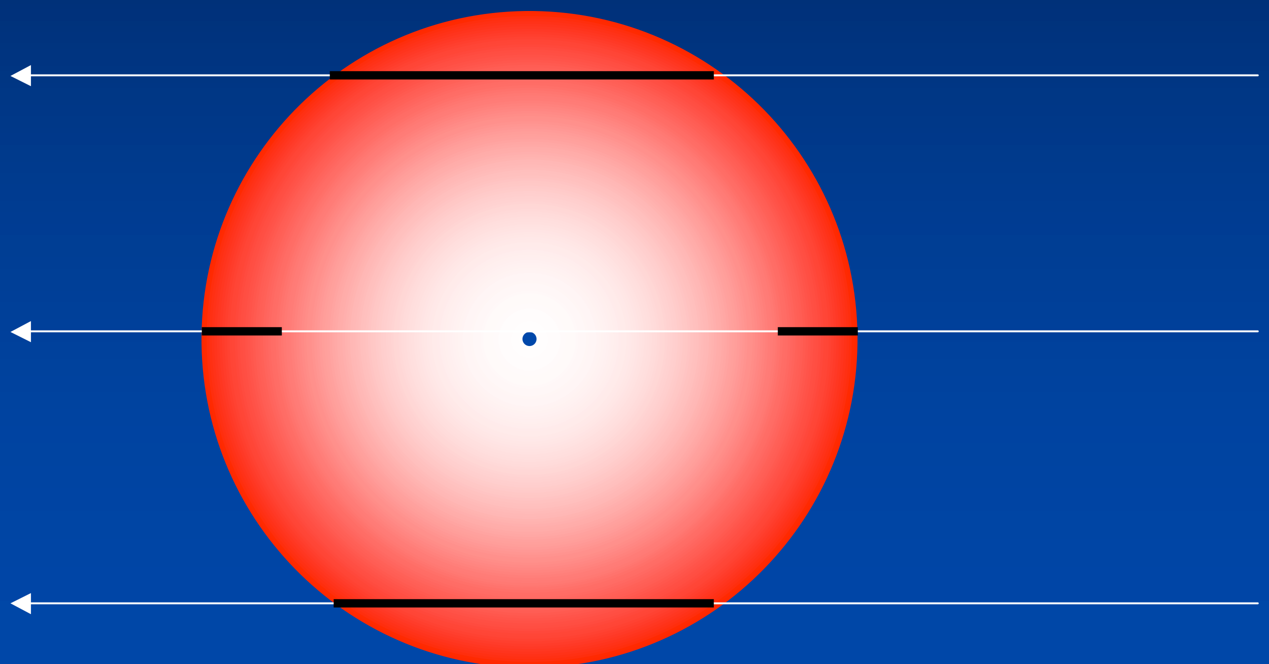






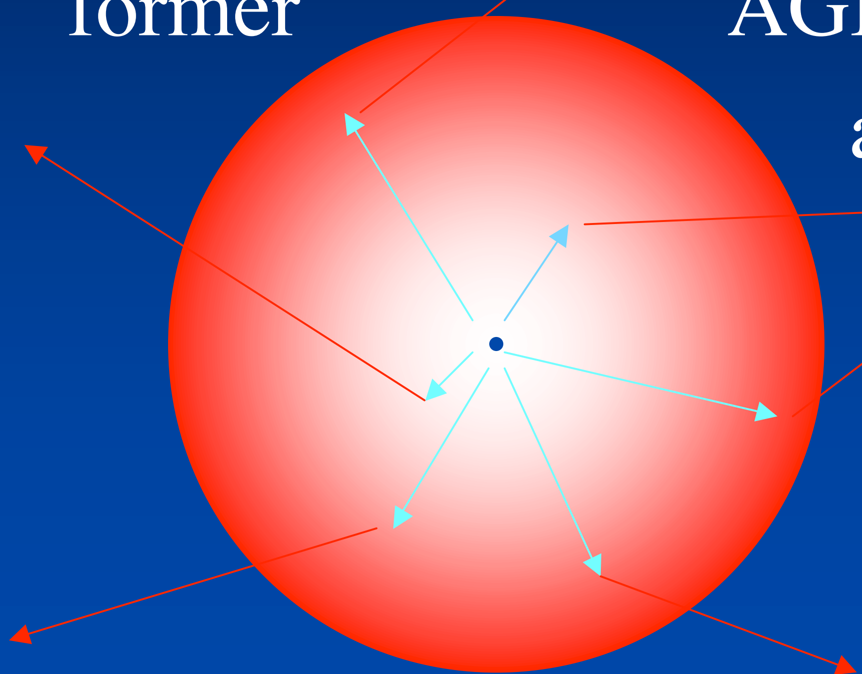
Planetary Nebulae

- The outer envelope expanding out as a shell appears as a ring in the sky.



Planetary Nebulae

- The emission is similar to that from HII regions. Ultraviolet photons from the hot former AGB-star core ionize atoms in the shell. On recombination, photons are produced.



Planetary Nebulae Shells

- The ejection mechanism for the shell is a combination of winds from the core, photon pressure, perhaps the shell flashes and the large radius of the star.
- The shell expands into space at relatively low speed (20 km/sec).
- Approximately 50% of the AGB star mass is ejected.

Planetary Nebulae Shell

- The shell expands and is visible for about 30,000 years growing to a size of more than a light year.
- The shell is enhanced in the abundance of He, Carbon, Oxygen (because of convection during the AGB phase). This is one of the means by which `Galactic Chemical Evolution' proceeds.
- There are about 30,000 PN in the Galaxy at any time.

Planetary Nebulae Central `Star'

- The object in the center of the nebula is the former core of the AGB star.

(1) It is hot! T>150,000k initially

(2) Supported by e- degeneracy

(3) Mass ~ $0.6M_o$

(4) Radius ~ 6000km (Earth)

(5) Density ~ 10^9 kg/m^3

A thimble of material at this density would weight about 5 tons on Earth.

Planetary Nebulae Central `Star’

- The central `star’ isn’t a star because it has no energy source. This is a white dwarf.
- Supported against gravity by e- degeneracy.
- Lots of residual heat, no energy source, a white dwarf is like a hot ember. As it radiates energy into space, the white dwarf cools off.
- There is an upper limit to the mass of a WD set by e-degeneracy. $1.4M_o$ is the Chandrasekar Limit.

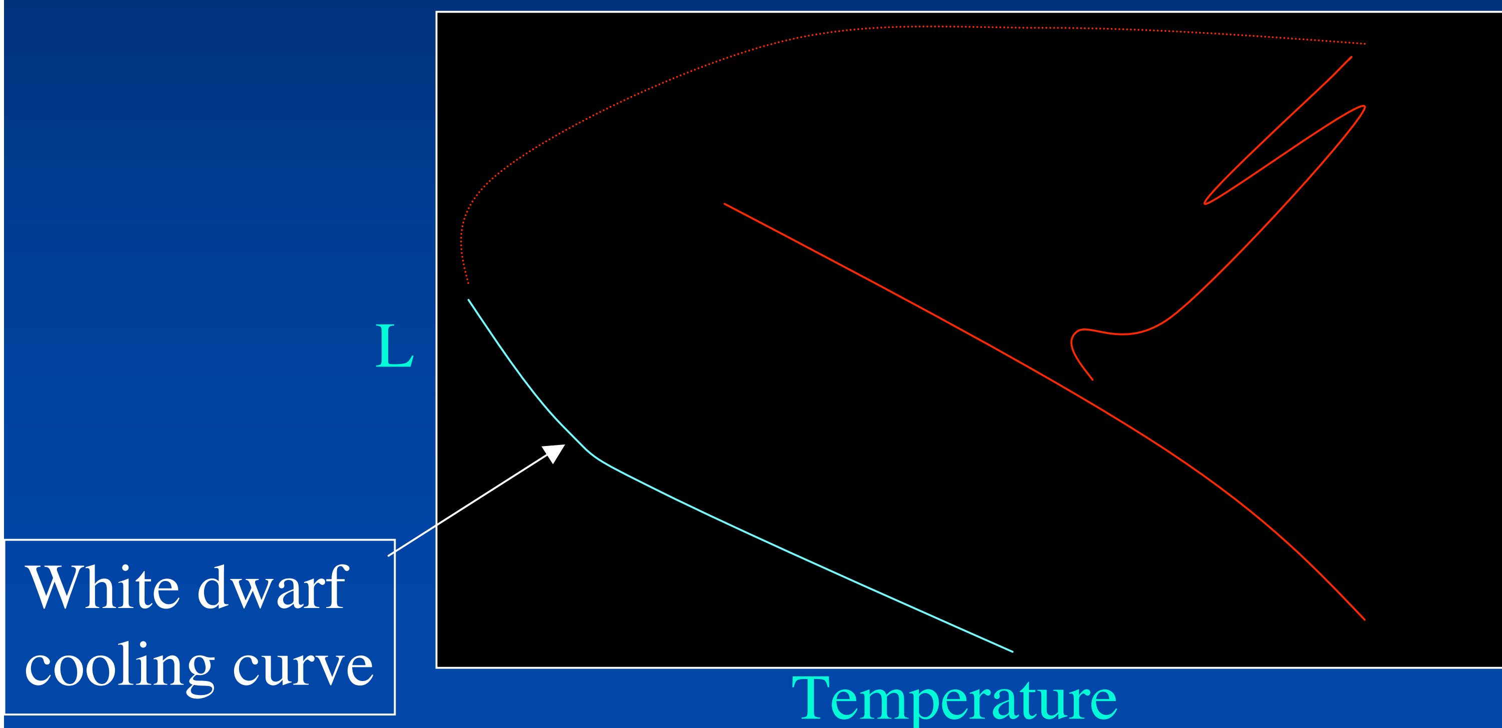
White Dwarf

- Energy source: none
- Equilibrium:
  e- degeneracy vs gravity

•Size: 6000km (Earth)

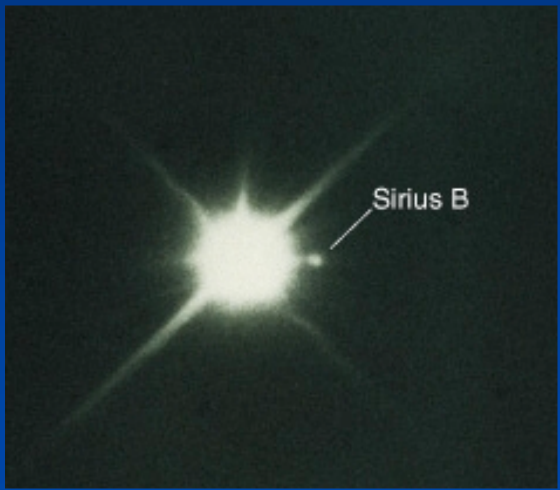
White Dwarfs

- WDs appear in the HR-Diagram in the upper right during the Planetary Nebula phase and VERY rapidly (30,000 years) evolve downward and to the left. After that the slowly cool down and to the right over billions of years.



White Dwarfs

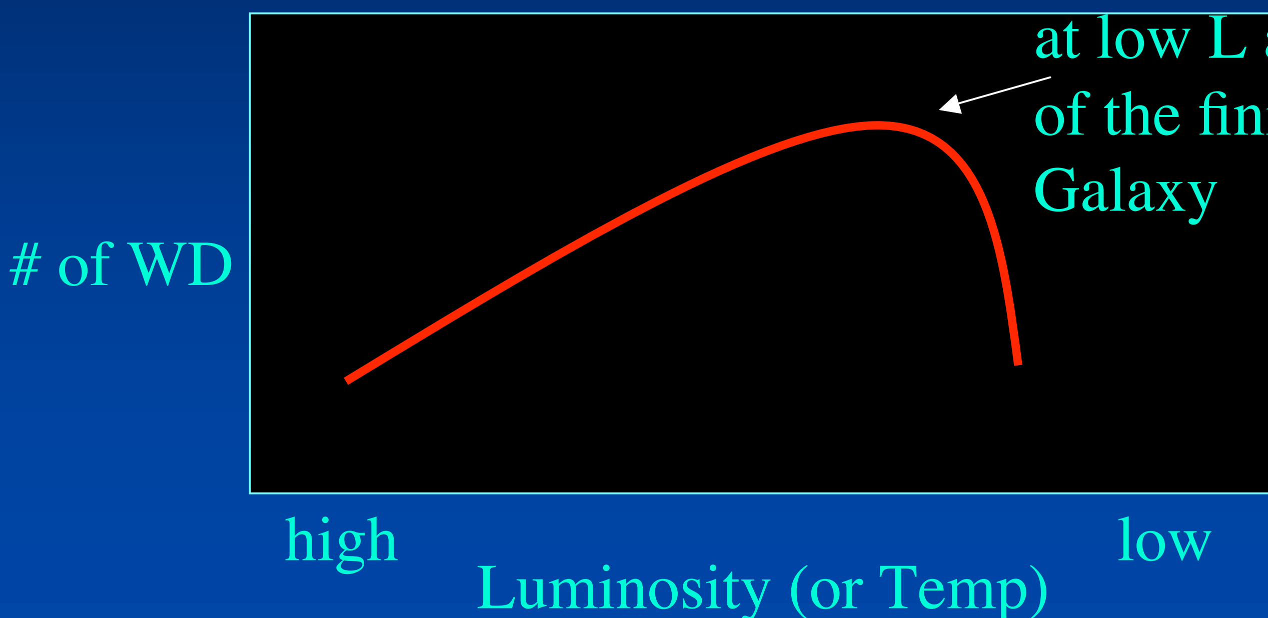
- At least 15% of the stellar mass in the solar neighborhood is in the form of WDs. They are very common, though hard to see.



White Dwarf Cosmochronology

- The WDs in the solar neighborhood have an interesting story to tell:

This drop off in WDs at low L and T is because of the finite age of the Galaxy



White Dwarfs in the Galaxy

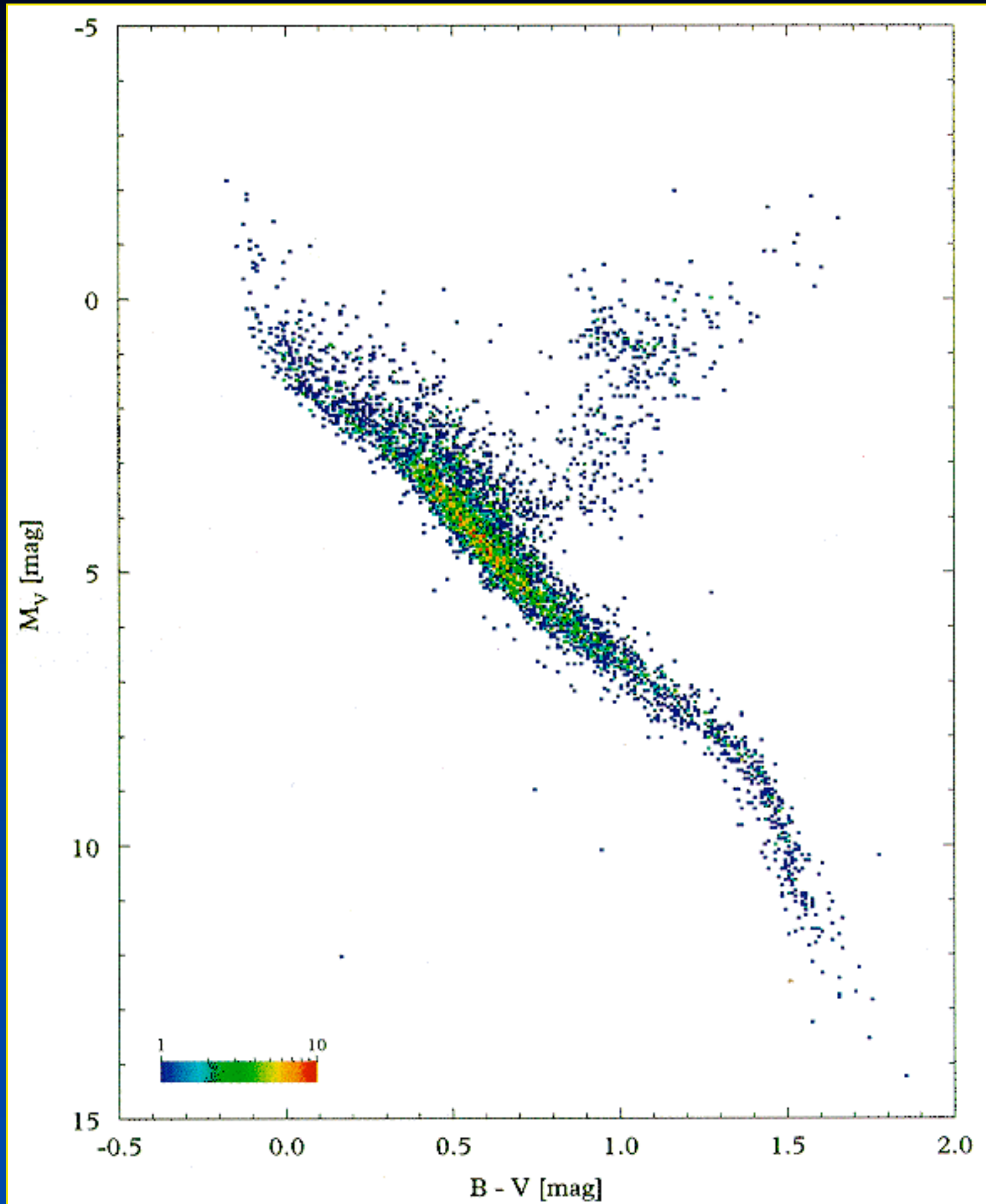
- We think that all stars with initial main-sequence mass less than around $7M_o$ become white dwarfs.
- When we look at the number of WDs at different luminosity (or temperature) there are some interesting bumps and wiggles AND a dramatic dropoff at the Luminosity that corresponds to a cooling age of 11 Gyr.

Evolution of $1M_o$ Star

Protostar	Grav. contraction	5×10^7 years
Main Sequence	Core H fusion	10×10^9 years
Red Giant	Core contraction and shell H fusion	5×10^8 years
Horizontal Branch	Core He fusion and shell H fusion	5×10^7 years
AGB	Core contr + He fusion + H fusion	1×10^6 years
White dwarf	none	A very long time

Evolution of $1M_o$ Star

- The time spent in a particular evolutionary phase is related to the number of stars of that type we see in the sky of that type. (although you have to be careful)
- When the Sun is an AGB star, its envelope will extend out to the orbit of Mars, the H-fusion shell will reach the orbit of the former Earth.
- $1M_o$ main-sequence star becomes a $0.6M_o$ WD made mostly of C with a little H, He.



-5
0
5
10
15
-0.5
0.0
0.5
1.0
1.5
2.0
B - V [mag]
M_V [mag]
1
10

Evolution of $4M_o$ Stars

- For stars less than $6M_o$ these last slides describe the evolution pretty well. There are some differences in the details that depend on the initial main-sequence mass.
- For stars that start with > $4M_o$, it gets hot enough in the cores to (1) avoid the helium flash and (2) to start carbon fusion.
- The WD remnant contains Ne, Mg and Si and the amount of enriched material returned to the ISM is larger.

Do we have all this right?

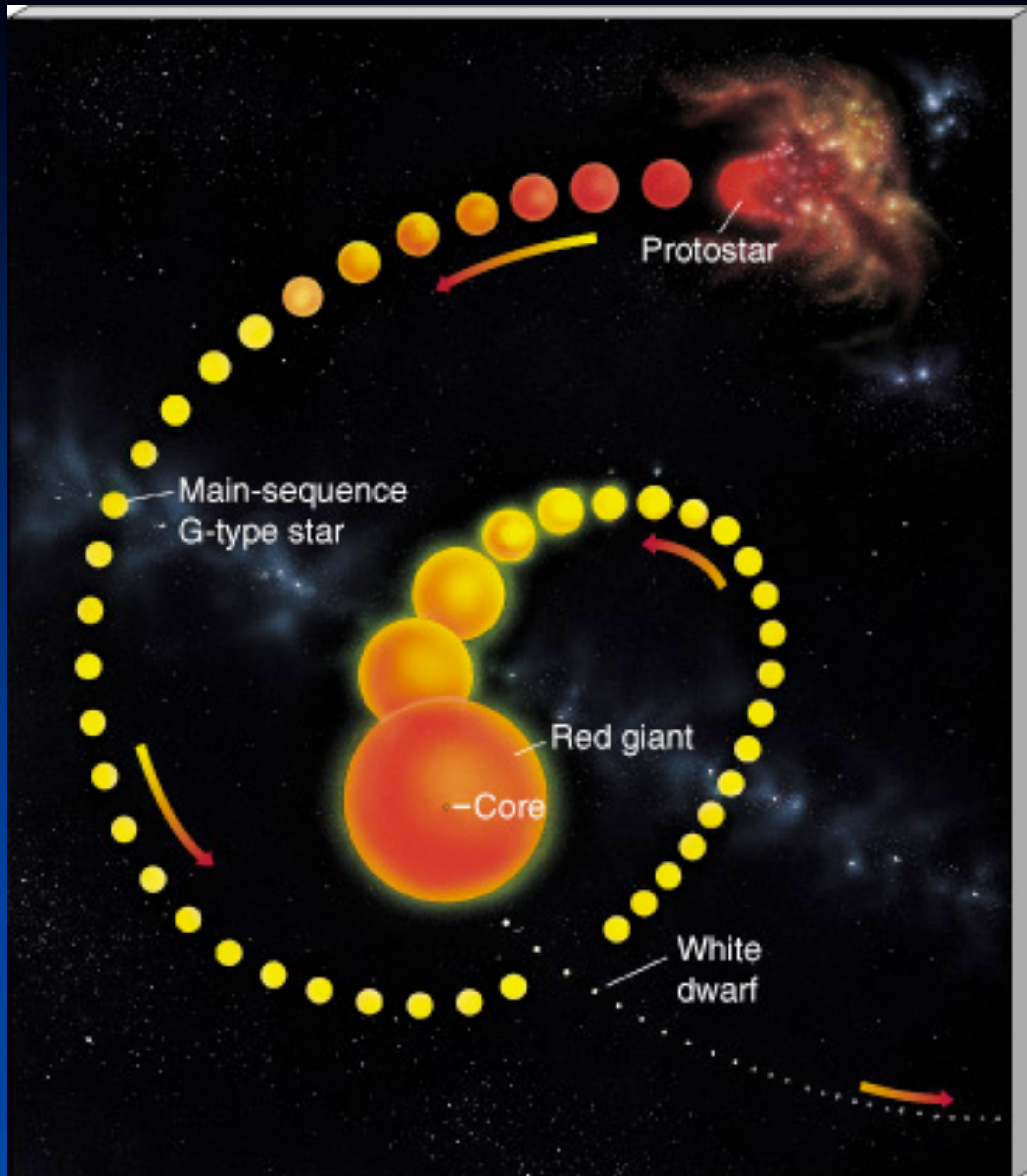
- How do we check all this out?

  (1) Star clusters are perfect because they contain stars in many of the evolutionary phases. Can test timescale, surface temperature and luminosity predictions. After 30 years of testing, it looks like we understand the basic evolution of stars very well.

  (2) My personal favorite test is the measurement of radioactive Tc in AGB stars.

Technecium$_{43}$

- Tc is an element with no stable isotopes and the longest-lived isotope (Tc^{98}) has a half-life of 4.2 million years.
- Models for AGB stars, predict that Tc will be synthesized inbetween shell flashes and convected to the surface.
- In 1952 Tc was detected for the first time in a star and now is routinely found in the spectra of AGB stars. This is direct proof of nucleosynthesis in stars and a powerful verification of stellar models.


Protostar
Main-sequence
G-type star
Red giant
Core
White
dwarf

Evolution of Close Binary Systems

- Before going on to the evolution of massive stars and supernovae II, we'll think about the evolution of close binary systems.
- There are many multiple star systems in the Galaxy, but for the vast majority, the separation of the stars is large enough that one star doesn't affect the evolution of the other(s).

The Algol Mystery

- Algol is a double-lined eclipsing binary system with a period of about 3 days (very short). The two stars are:

  Star A: B8, 3.4M_o main-sequence star

  Star B: G5, 0.8M_o `subgiant’ star

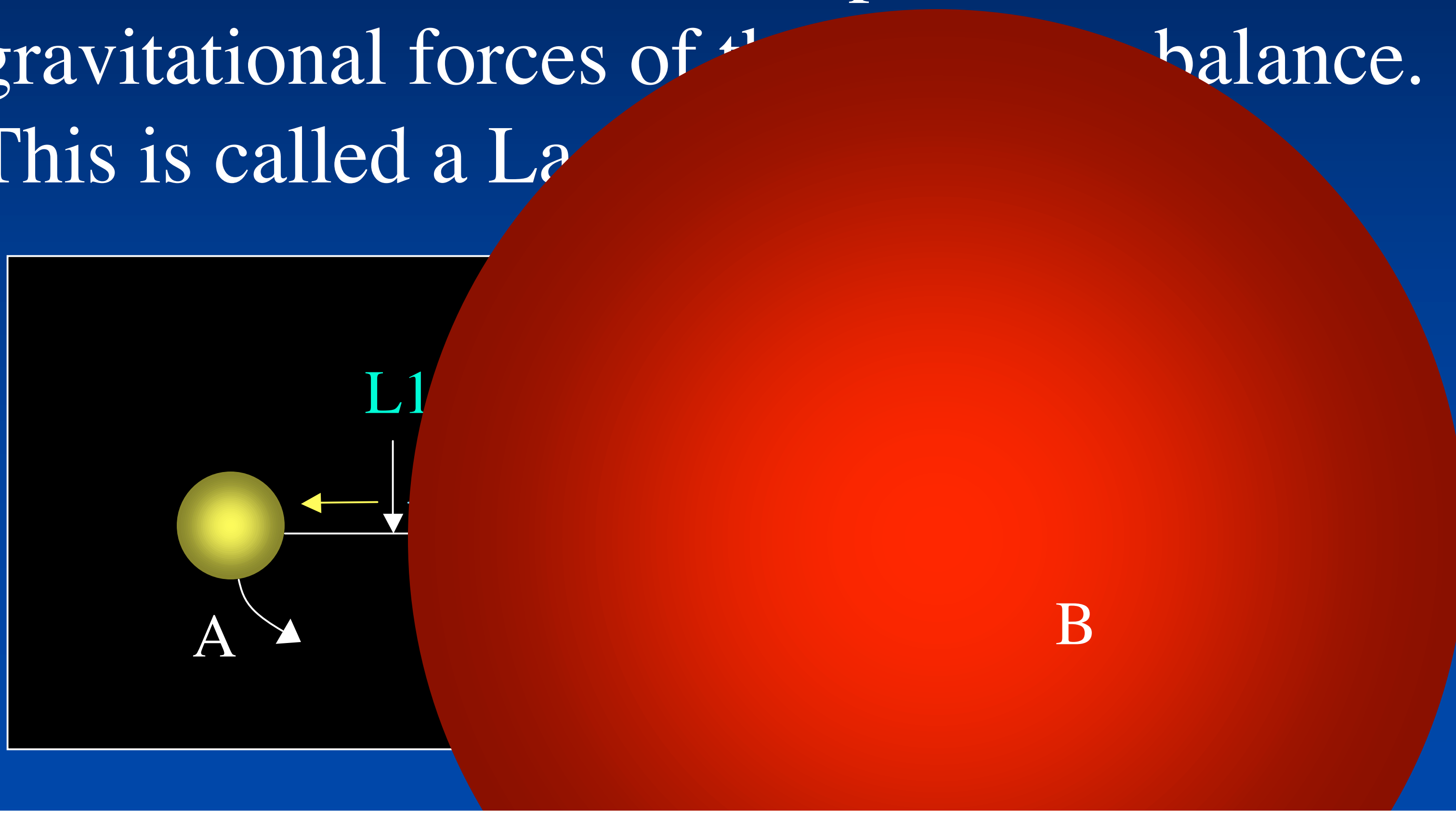
What is wrong with this picture?

Algol

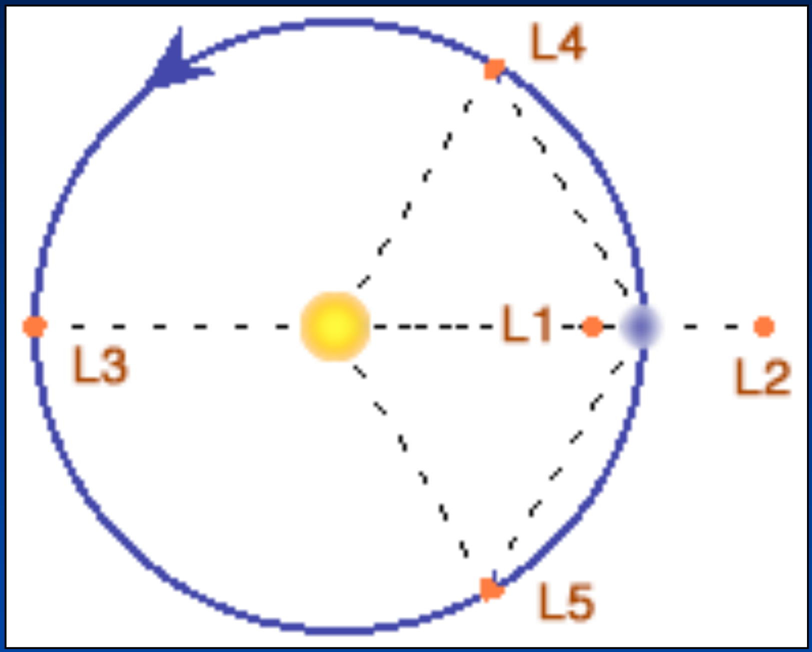
- The more massive star (A) should have left the main sequence and started up the RGB before the less massive star (B).
- What is going on here?
- The key is the short-period orbit.

The Algol Story

- Originally the system contained Star A at $1.2M_o$ and Star B at $3.0M_o$.
- Between the two stars is a point where the gravitational forces of th balance. This is called a La

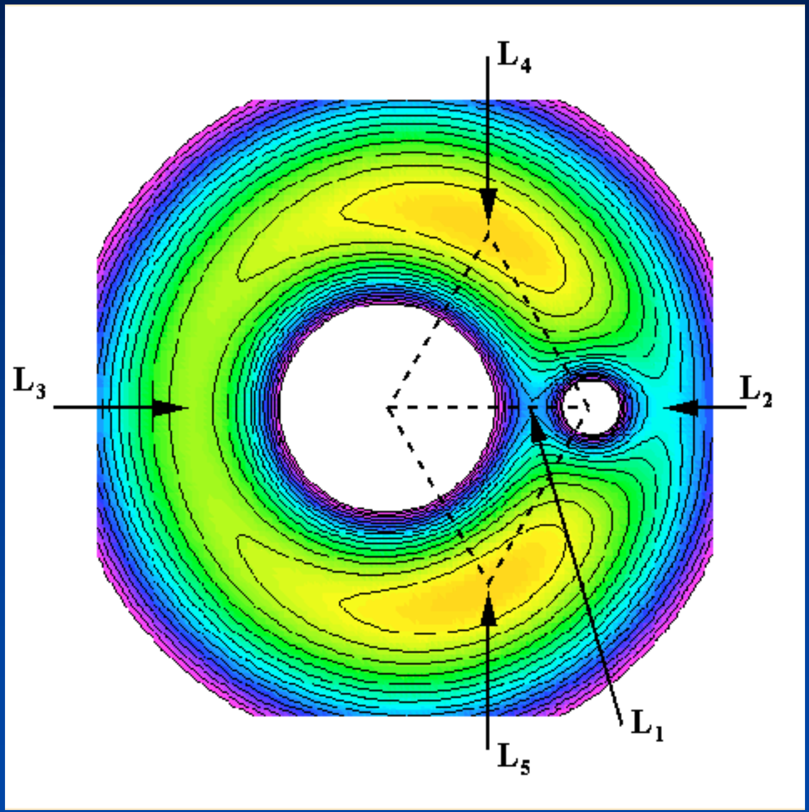


Lagrange Points



- There are 5 Lagrange points in the Earth/Sun system. L1, L2 and L3 are unstable on a timescale of 23 days
- L3 is a popular spot for Vulcan.
- L2 is the proposed orbit forJWST
- L4 and L5 are stable and collect stuff

Lagrange Points



- You should be a little confused about how this all works.
- The Lagrange Points are only obvious in a rotating reference frame.

Algol cont.

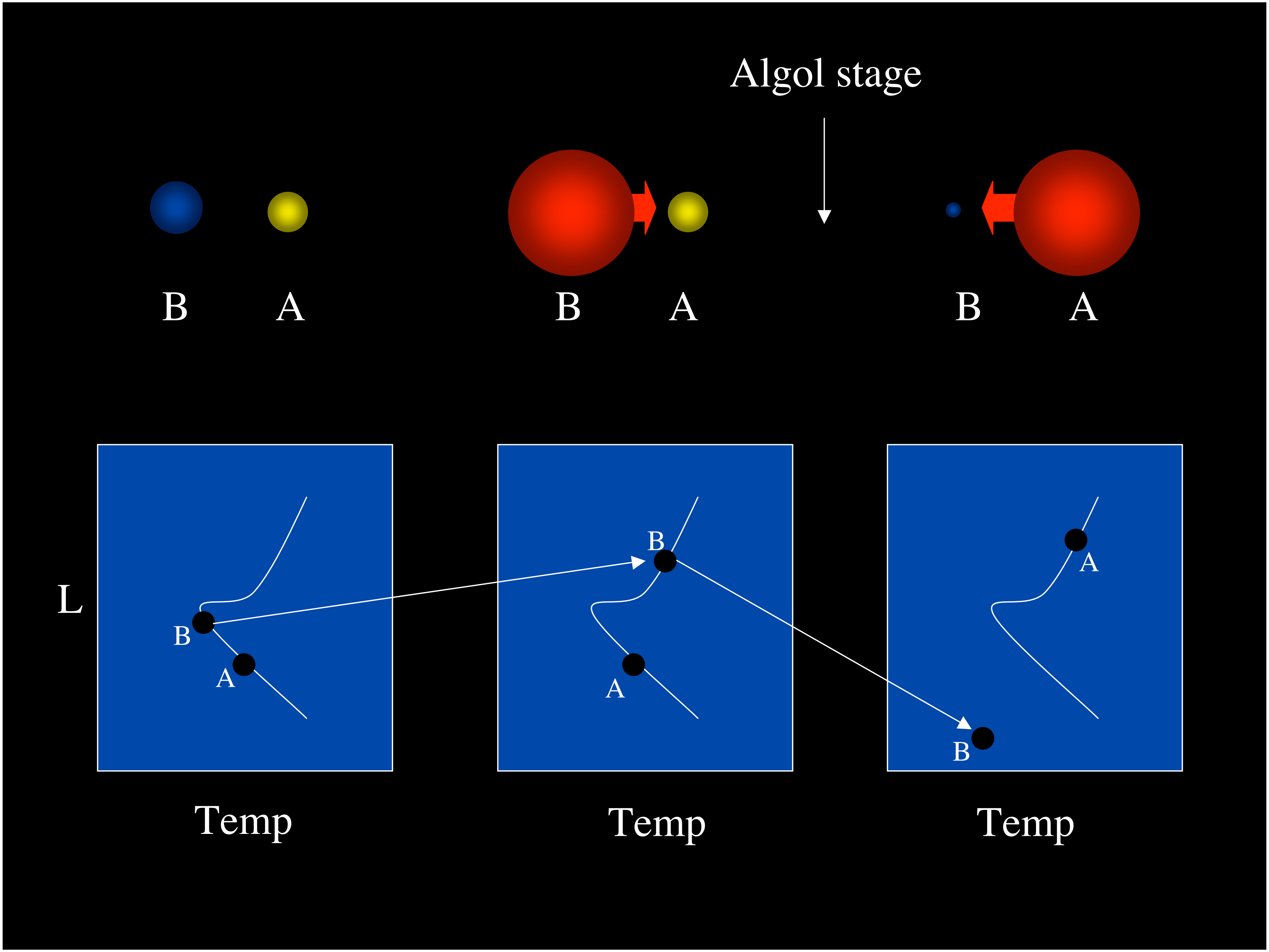
- Back to Algol. As Star B evolves and expands as it heads up the RGB.
- When its radius equals the distance of the L1 point (called the Roche Radius) the material in Star B's envelope feels a stronger attraction to Star A and there is mass transferred from B to A.

Mass Transfer in Binaries

- In the case of Algol, Star B transferred $2.2M_o$ of material to Star A.

Star A: $1.2M_o$ -> $3.4M_o$

Star B: $3.0M_o$ -> $0.8M_o$

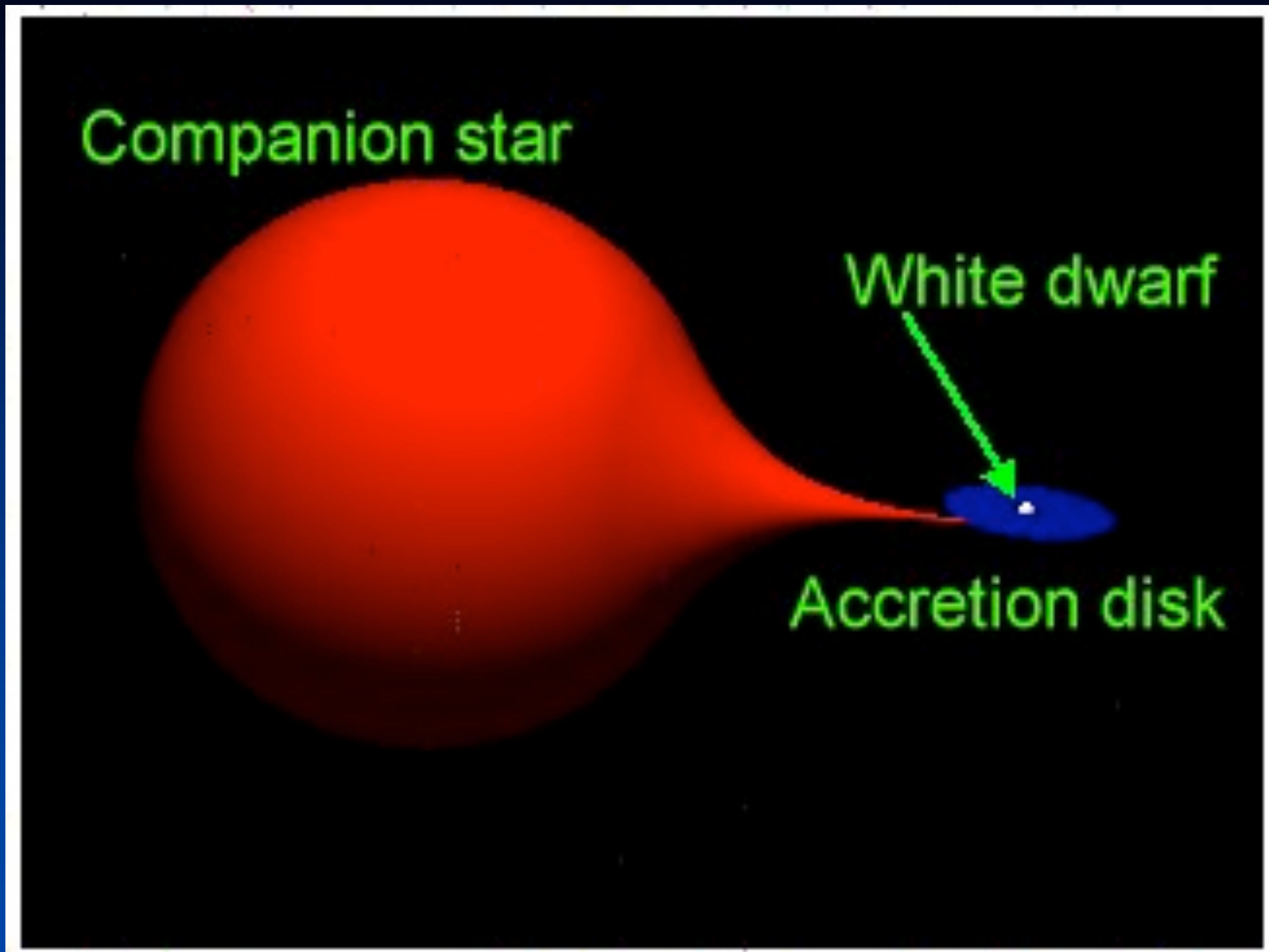

Algol stage
B
A
B
A
B
A
L
B
A
B
A
A
B
Temp
Temp
Temp

Mass Transfer Binaries

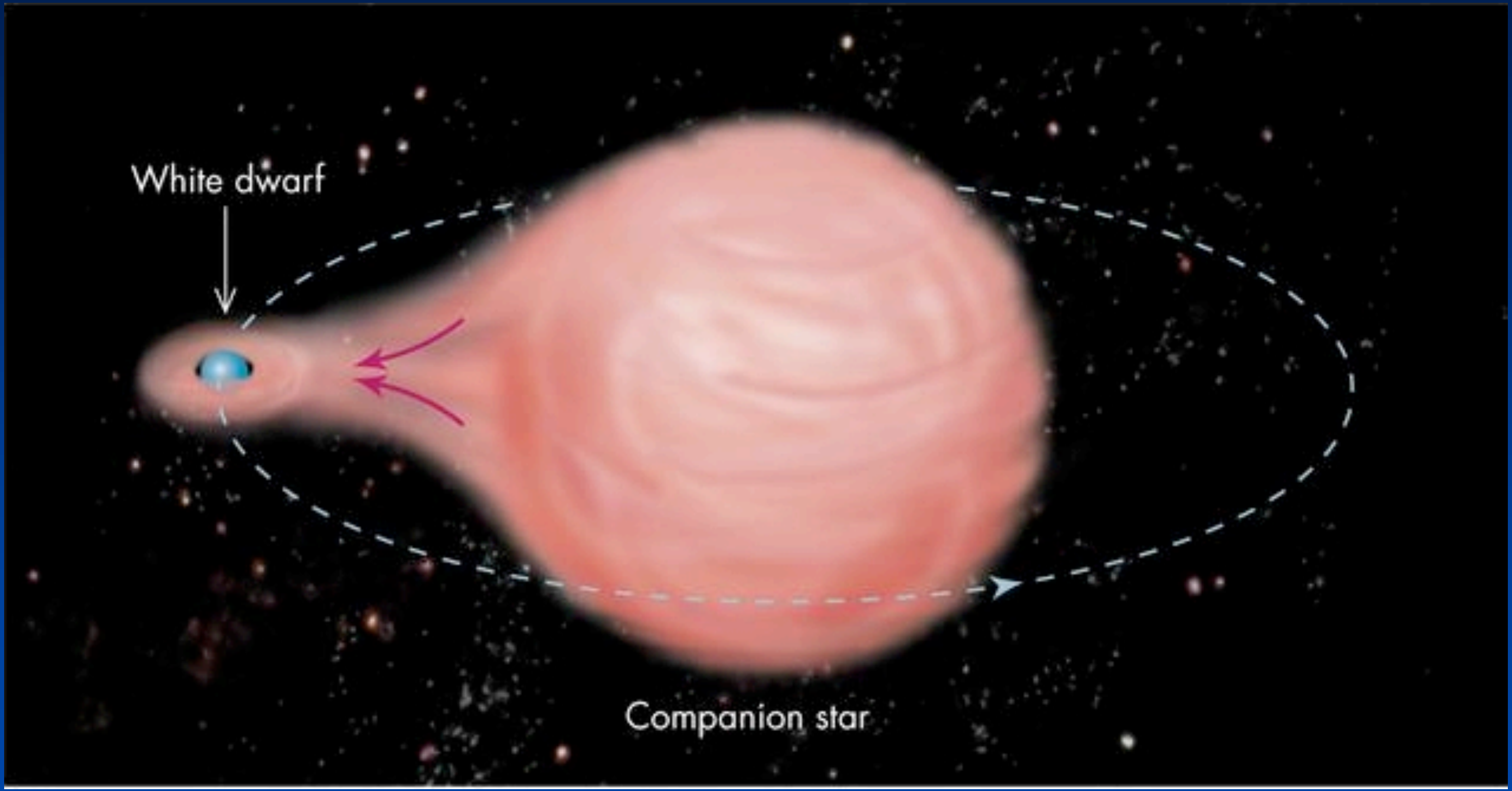
- Think about the continued evolution of Algol and you have the explanation for novae.
- If the original primary transfers most of its mass to the original secondary, you are left with a massive main-sequence star and a helium WD.
- When the original secondary starts to evolve up the RGB, it transfers some material back onto the helium WD.

Novae

- As the fresh hydrogen accumulates on the surface of the helium WD it is like an insulating blanket -- the temperature rises to 10^7k and there is a Hydrogen fusion explosion.
- The star brightens by anywhere from a factor of 10 to a factor of 10,000.
- In some cases, this takes a star from too-faint to see to bright-enough to see so these objects were called Nova -- new star.


Companion star
White dwarf
Accretion disk

Novae/Supernovae I

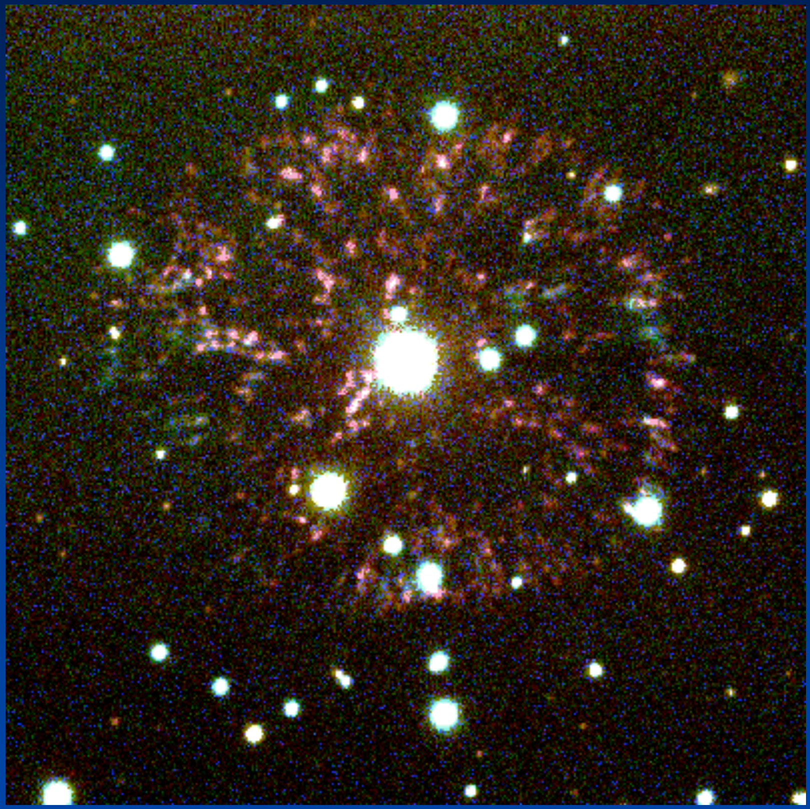


Note! Not to scale!

Novae

- Nova Vel 1998 (3rd magnitude)

Novae

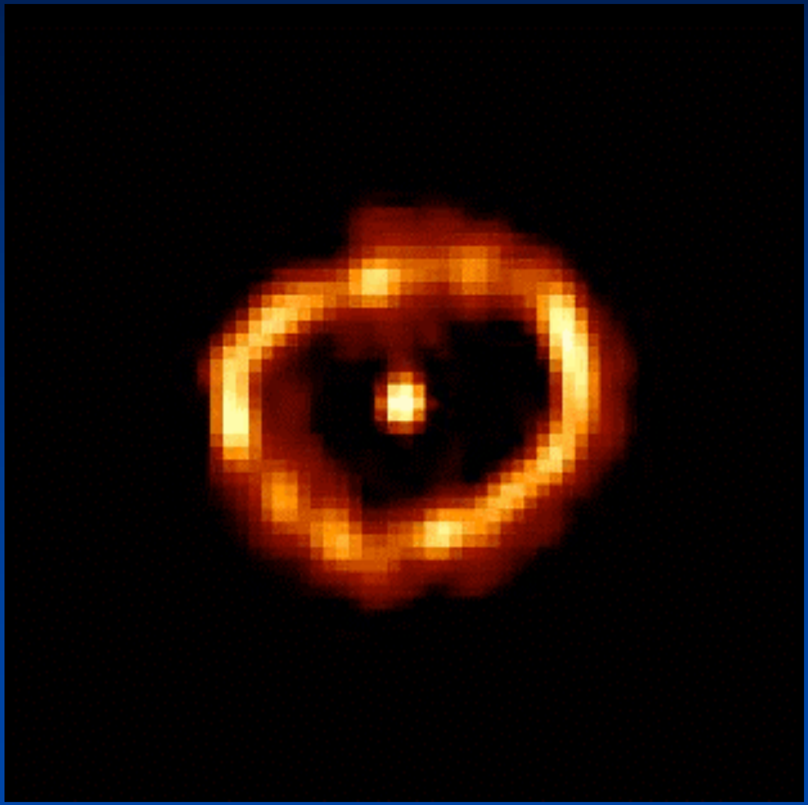


- Nova Persei became one of the brightest stars in the sky in 1901. Look there now and see the expanding shell from the explosion. The velocity of the material is ~2000km/sec

Novae

- Nova Cyg (1992) illuminated a cloud of nearby Hydrogen gas.
- The expanding shell of the nova could be seen a few years later with HST.

Novae



- Nova Cyg in 1994.
- Most nova are \`recurrent'.
- Every year there are 20 - 30 novae observed in the Galaxy. \`Naked eye' nova occur more like one per decade.

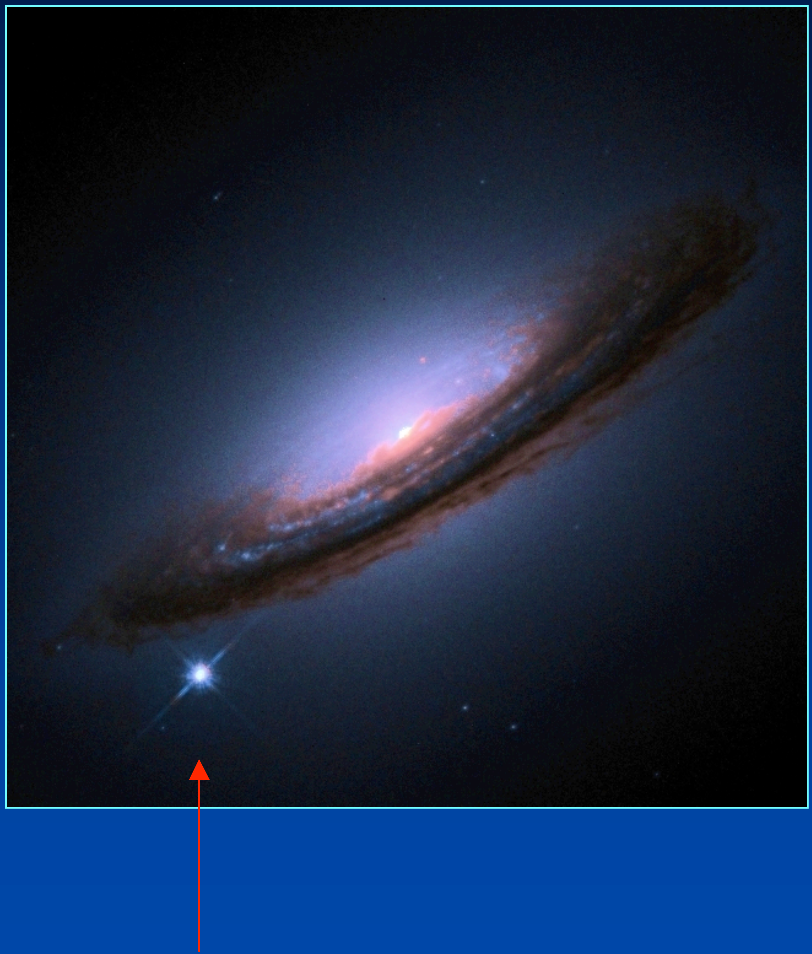
Mass Transfer in Binaries

- The scenario that leads to nova explosions can produce an even wilder phenomenon.
- In the early 1900s `novae' were sometimes observed in other galaxies and were used to help set the distances to galaxies.
- But, when it became clear that even the nearest galaxies were much further away than anyone had thought this suggested that the extragalactic `nova' were much brighter than Galactic nova -- the term *supernova* was coined.

Supernova Type I

- Supernova are very luminous -- a bright as the combined light of all the stars in a small galaxy!
- They rise in brightness very quickly and then fade over timescales of months.

Supernova



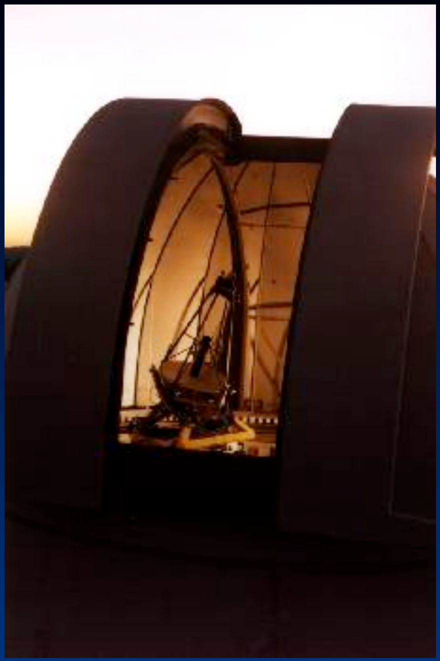
- Early on it was realized there were two distinct types of SN.
- SN I have no hydrogen in their spectra and are seen in all types of galaxies
- SN II have hydrogen and are only seen in spiral galaxies and near star-forming regions

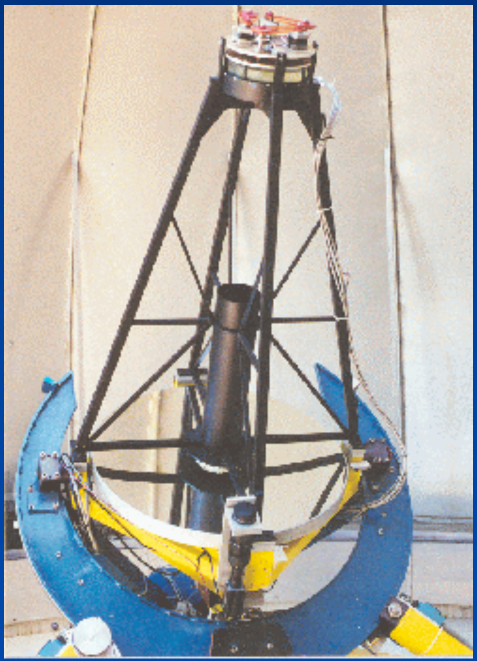
Supernova I

- No hydrogen in the spectra
- Seen in all types of galaxies
- Seen everywhere within galaxies (halo and disk)
- Maximum brightness: $6 \times 10^9 L_o$
- A decade ago, 15 - 20 were discovered per year, last year 166

Supernova I

- There is a robotic telescope up at Mt. Hamilton that does an automatic search for SN every clear night.
- Take images of lots of galaxies, digitally subtract them, look for any residual.





Supernova I

- What is going on here? It took a long time to sort this out.
- Remember WD mass transfer binaries and the Chandrasekar limit.
- What would happen if mass transfer nudged the mass of a WD above the $1.4M_o$ limit for degenerate electron gas pressure?

Supernova I

- When a WD exceeds the Chandrasekar limit there is a violent version of the helium flash.
- The temperature skyrockets and within a second a fusion chain reaction fuses elements all the up to radioactive nickel.
- *This star has exploded in a runaway thermonuclear catastrophe!*

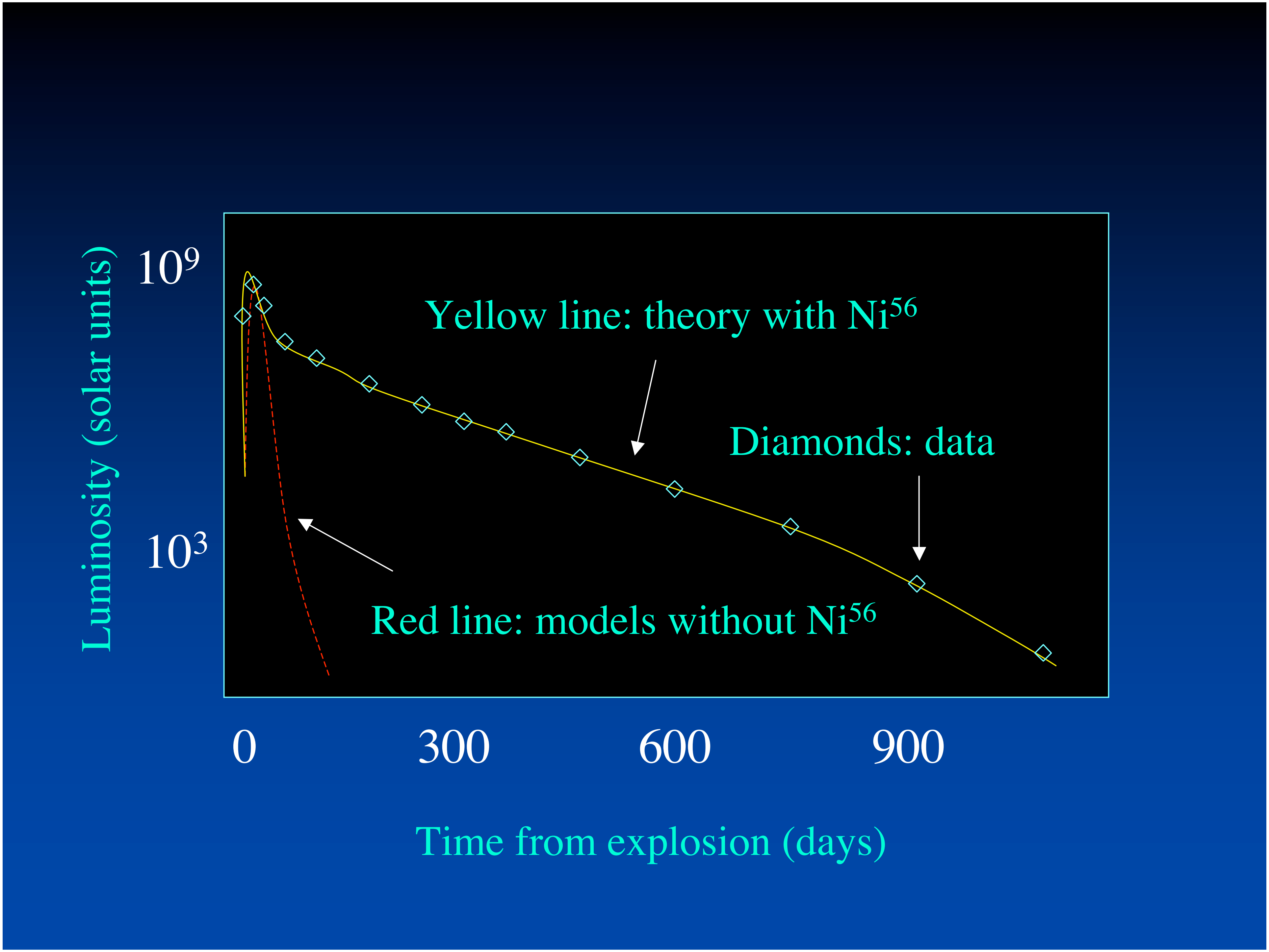
Supernova I

- What is RIGHT about this theory?

(1) Will see these objects in `old' populations.

(2) Models for the detonation of a $1.4M_o$ WD give the right total energy

(3) The predicted amount of radioactive Ni^{56} in the explosion fit the light curve perfectly



Yellow line: theory with Ni56
Diamonds: data
Red line: models without Ni56
10^9
10^3
Luminosity (solar units)
0
300
600
900
Time from explosion (days)

SN I

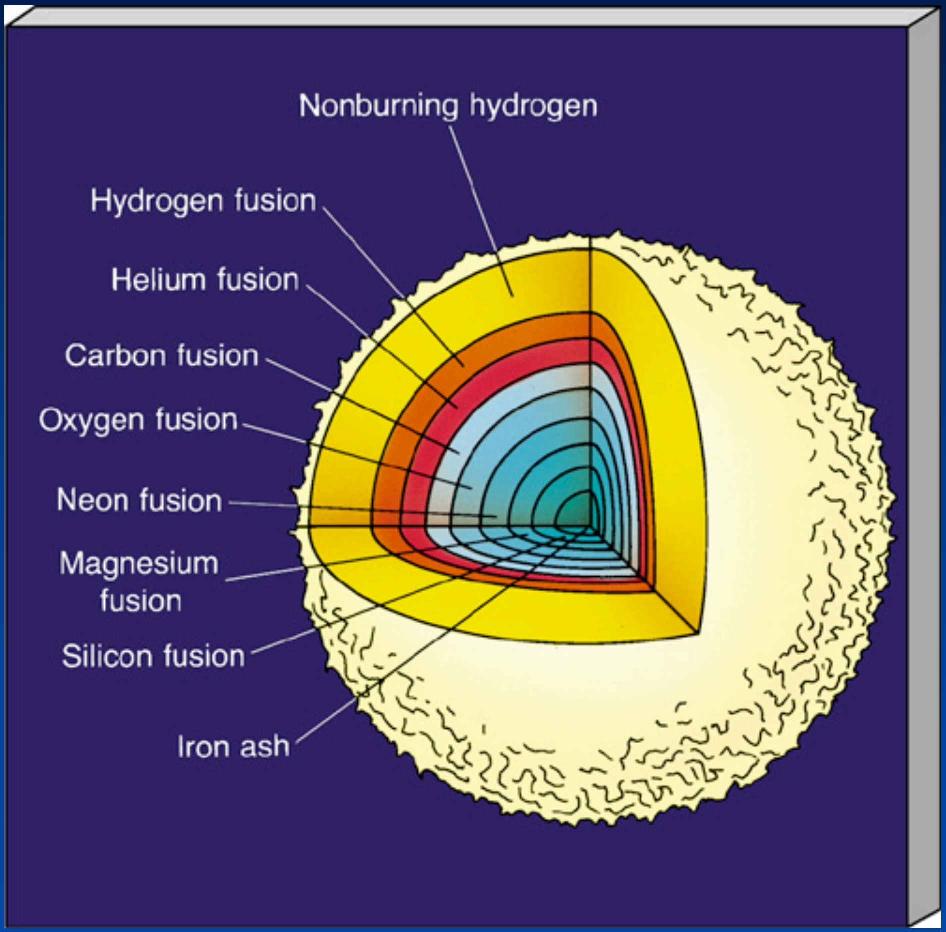
- What’s WRONG with this theory?
- Five years ago, the answer went like this.
- The accreted mass of a Red Giant onto a WD would be hydrogen rich, yet the signature of SN I is no hydrogen. Obvious solution is to have the merger of two $0.7M_o$ helium WDs. Problem was, didn’t have an examples of close helium-WD pairs!
- Now, we do.

The Evolution of High-mass Stars

- For stars with initial main-sequence mass greater than around $7M_o$ the evolution is much faster and fundamentally different.

$1M_o$	10×10^9 years
$3M_o$	500×10^6 years
$15M_o$	15×10^6 years
$25M_o$	3×10^6 years

Massive Star Evolution



- The critical difference between low and high-mass star evolution is the core temperature.
- In stars with $M > 7M_o$ the central temperature is high enough to fuse elements all the way to Iron (Fe)

Nucleosynthesis in Massive Stars

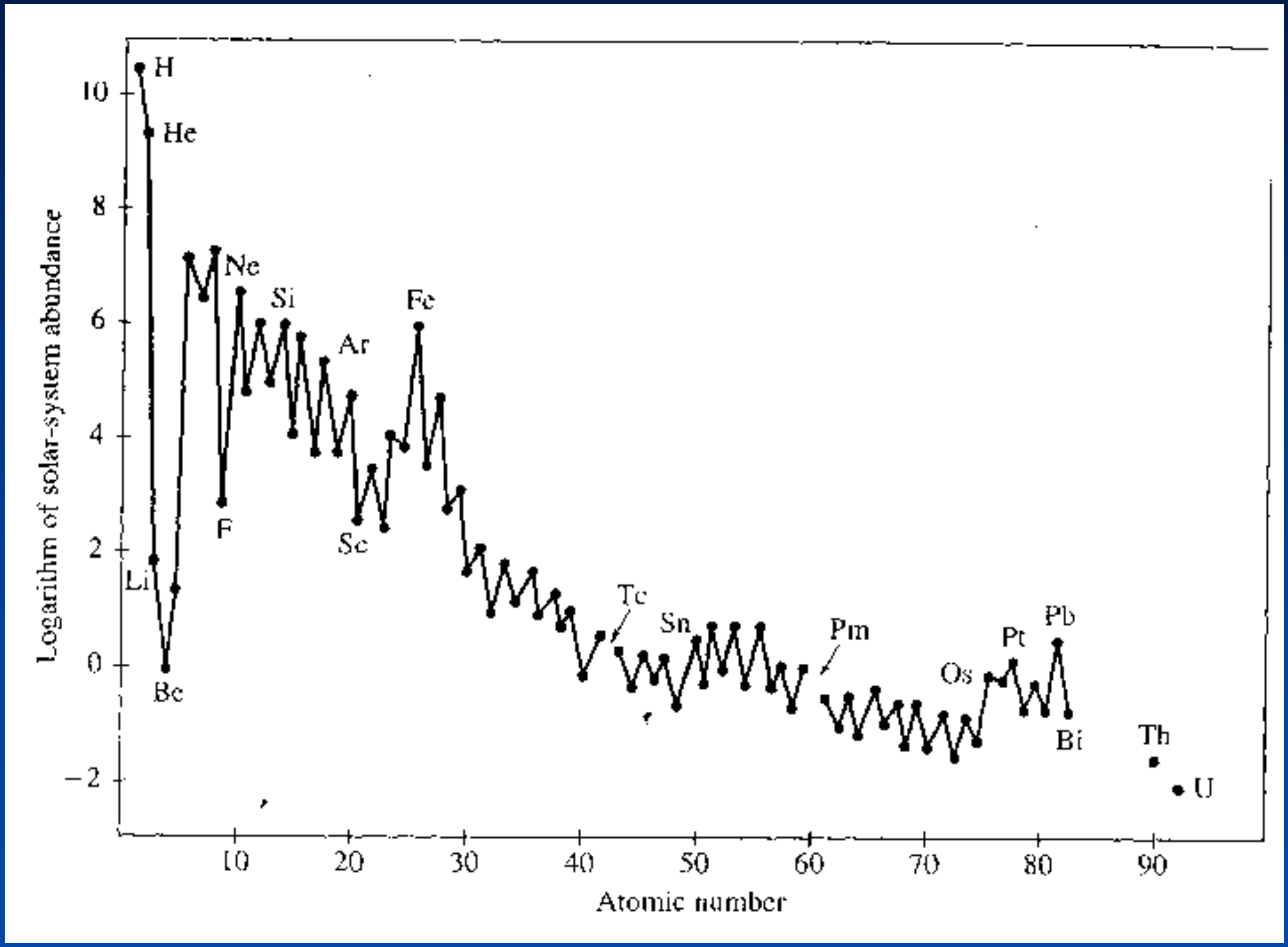
- Fusing nuclei to make new elements is called nucleosynthesis.

Temperature	Fusion reaction
15 million K	H -> He^4
100 million K	He^4-> C^{12}
600 million K	C^{12}-> O^{16} (Mg^{24})
15000 million K	O^{16}-> Ne^{20} (S^{32})
etc	etc

Massive Star Nucleosynthesis

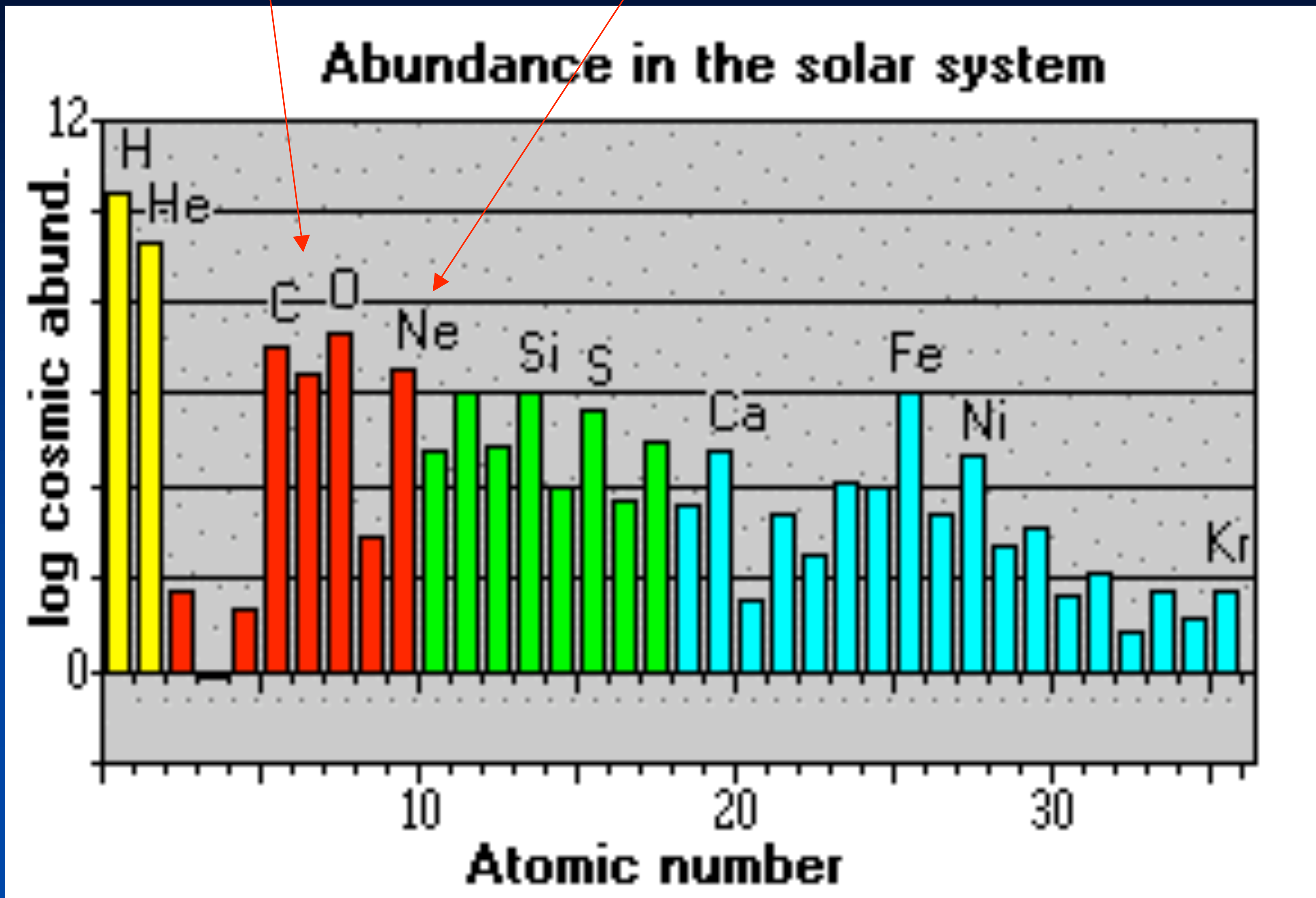
- In a $25M_o$ star nucleosynthesis proceeds quickly to Fe (why it stops there we will get to in a minute).
- The most common reaction is called the `alpha process' and it is fusing He^4 to existing nuclei. This process is reflected in to abundance of various elements in the Universe today.

Nucleosynthesis in Massive Stars



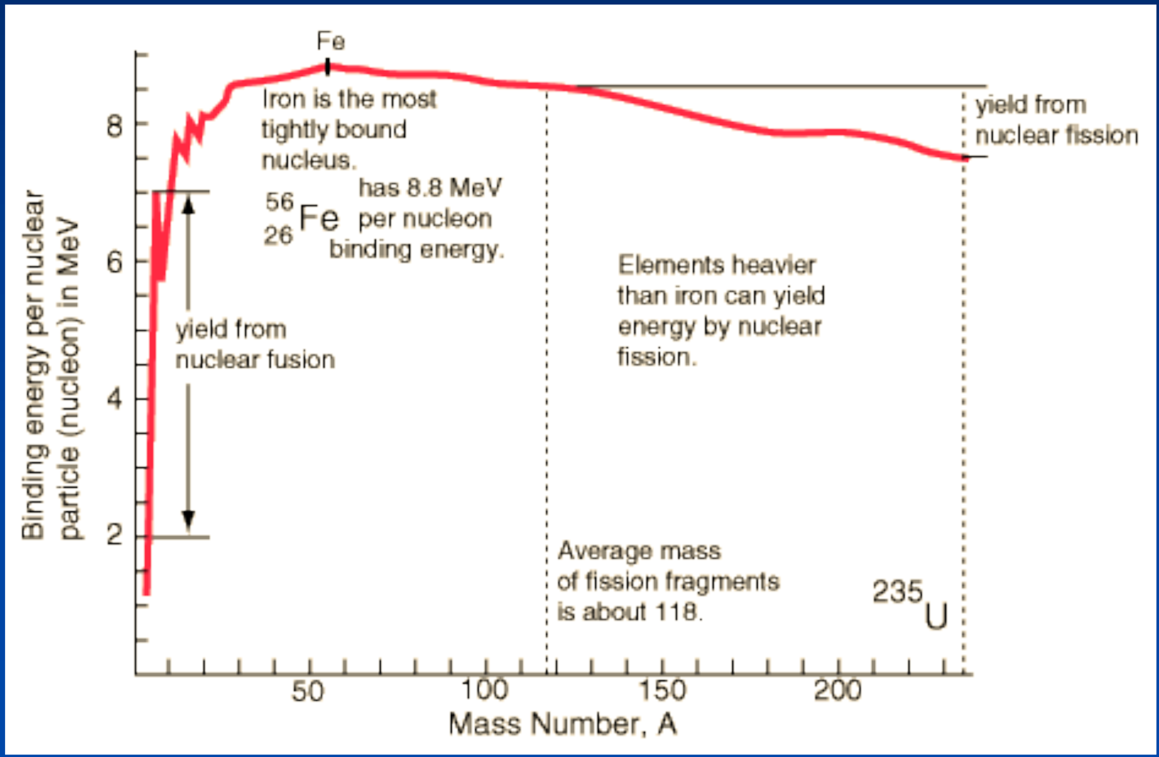
C+He-> O

O+He->Ne


Abundance in the solar system
log cosmic abund.
12
0
H
He
C
O
Ne
Si
S
Ca
Fe
Ni
Kr
10
20
30
Atomic number

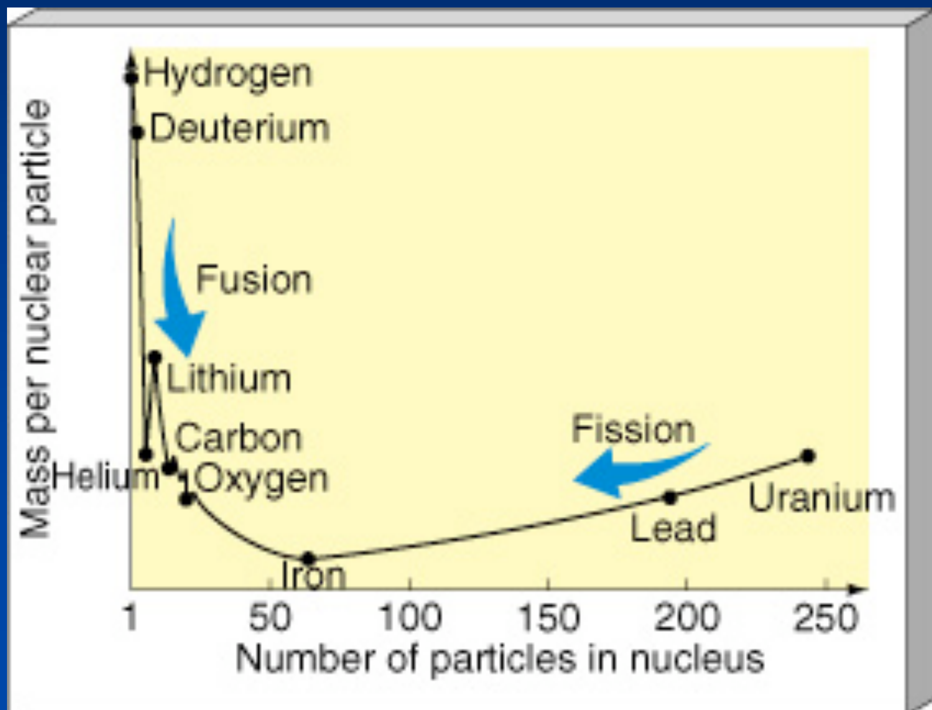
What is special about Fe?

- Fe is at the peak of the `curve of binding energy'



Fe

- An easier way to think about this is in the mass/nucleon for a given nucleus:



Nucleosynthesis

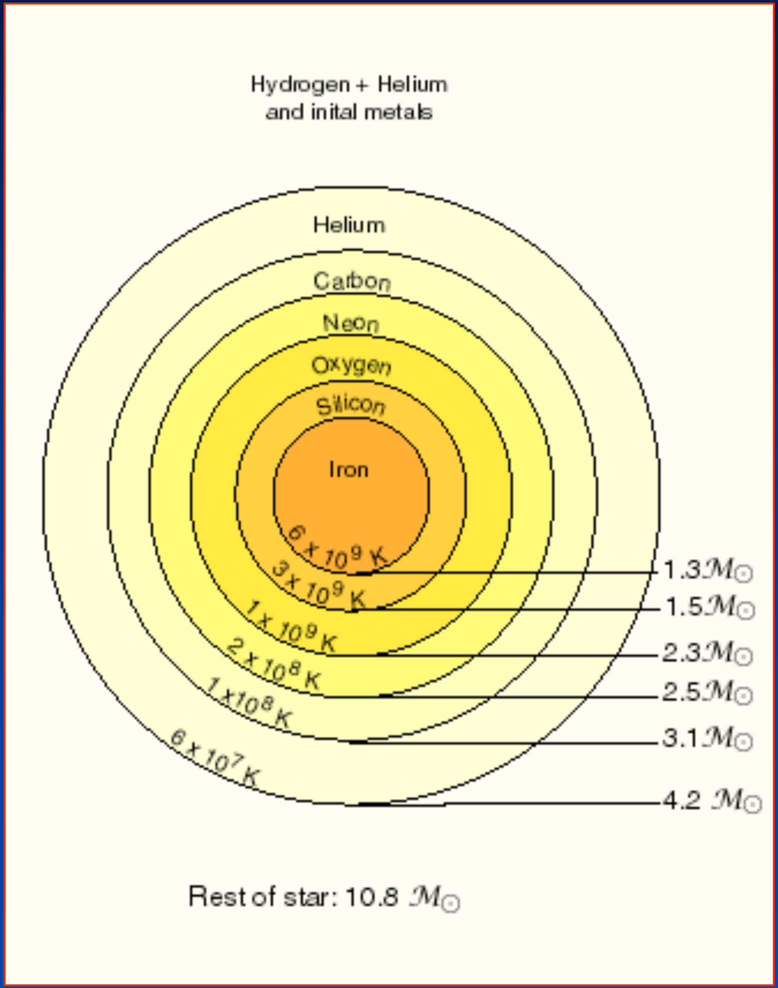
- Fusing light elements together results in more nuclear binding energy and less mass per nucleon. When the mass disappears, it is converted to energy so light-element fusion produces energy.
- But, when fusing any element to Fe, you now need to PROVIDE some energy to be converted into mass and Nature doesn't like to do this.
- On the other hand, elements heavier than Fe can break apart and go to less mass/nucleon and release energy.

Stage	Central T	Duration (yr)
H fusion	40 million K	7 million
He fusion	200 million K	500 thousand
C fusion	600 million K	600
O fusion	1.2 billion K	1
Ne fusion	1.5 billion K	6 months
Si fusion	2.7 billion K	1 day

Core Collapse

- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the $1.4M_o$ Chandrasekar limit.
- On a timescale less than a second the core implodes and goes through a series of events leading to a tremendous explosion.

Massive-star Evolution



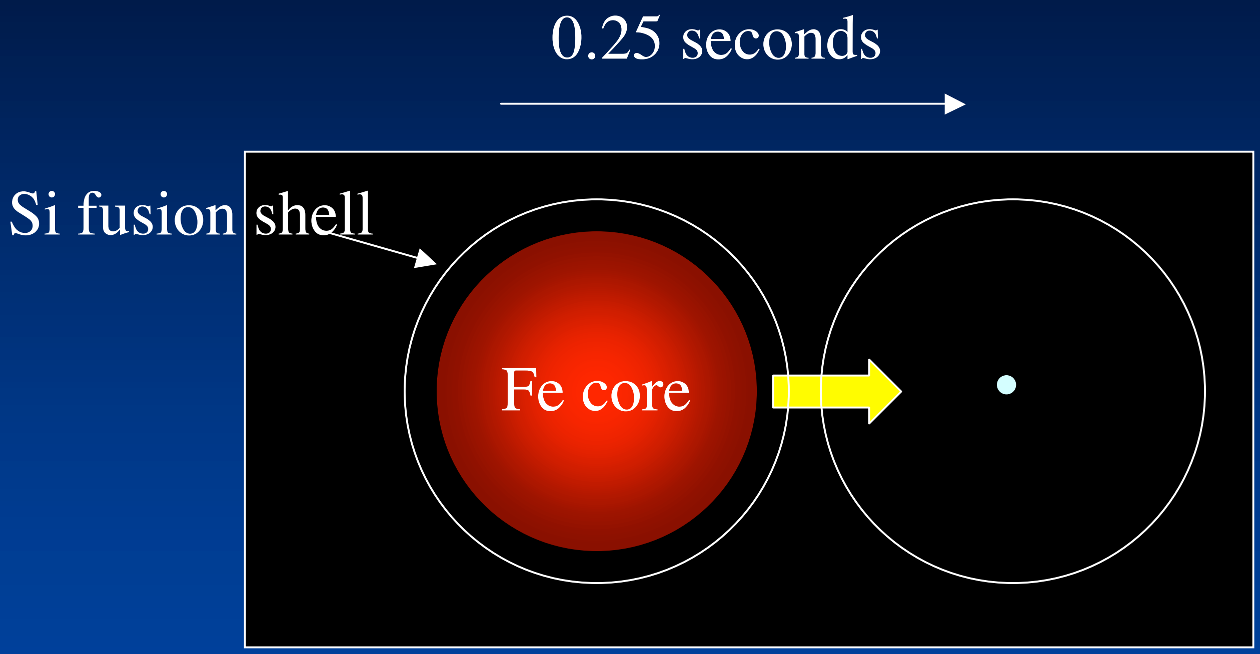
Core Collapse

1) Exceed the Chandrasekar limit
2) Temperature reaches 10 billion K
3) Fe nuclei photodisintegrate, cooling the core and speeding the collapse
4) The gravitational pressure is so high that neutronization occurs converting the electrons and protons into neutrons and releasing a blast of neutrinos

0.1 sec

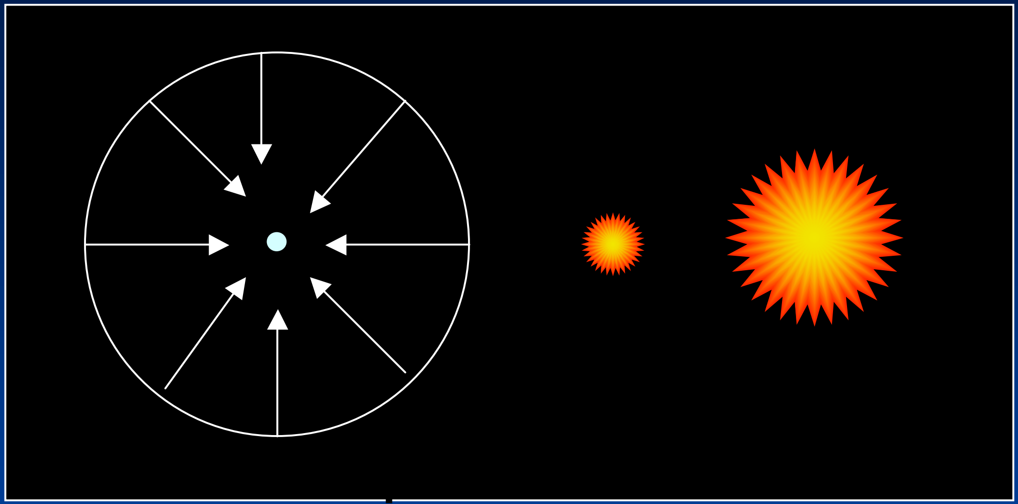
0.2 sec

Core-Collapse in Massive Stars



1) Fe core exceeds 1.4M and implodes
2) Temp reaches 5 billion K and photodisintegration begins to blast apart the Fe nuclei
3) Neutronization occurs: $e^- + p^+ \rightarrow n^0$ + neutrino

Core-Collapse in Massive Stars



4) Neutron ball is at `nuclear density' (>10^{17} kg/m^3) and is much harder than any brick wall.
5) Infalling layers crash into neutron ball, bounce off, create a shock wave and, with help from the neutrinos, blast off the outer layers of the star at 50 million miles/hour.

SNII Bounce Shock wave

Core-collapse Supernovae

- The resulting explosion is called a SNII
- Expect:
  - Rapidly expanding debris
  - 10^8 times the optical luminosity of the Sun
  - Chemically enriched debris
  - Association with massive stars/star formation
  - Extremely dense 1.4 solar mass neutron ball

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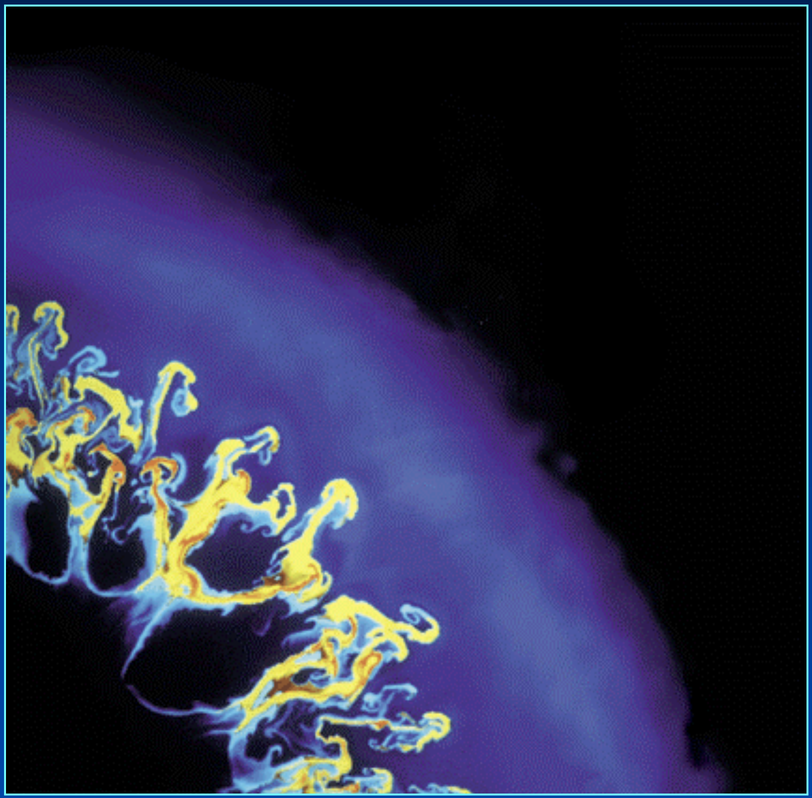
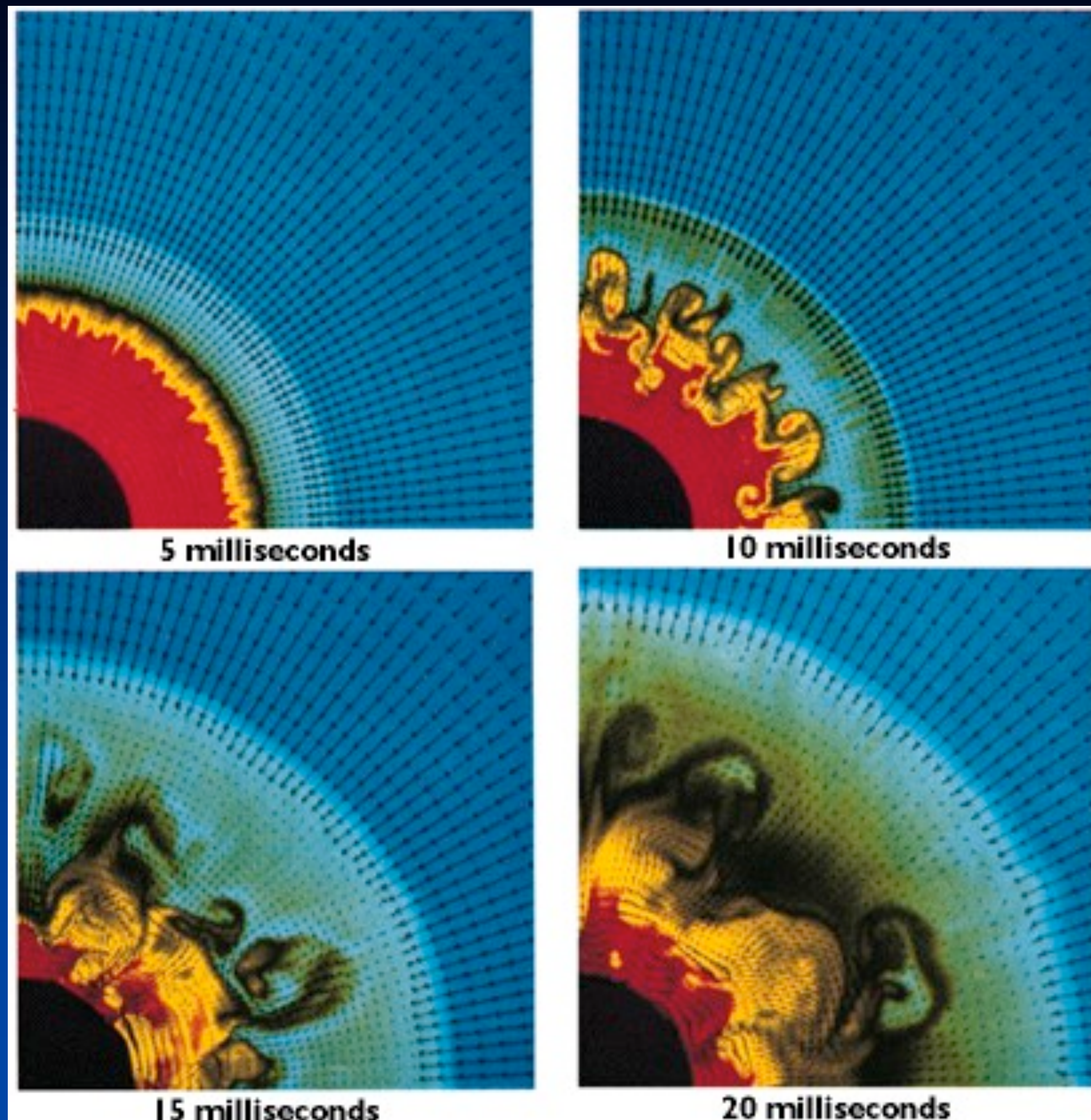
Supernova II



- This is a wild event.
- In the explosion the models predict:
- Many rare elements will be manufactured in non-equilibrium reactions
- A rapidly expanded debris shell
- An extremely dense ball of neutrons will be left behind

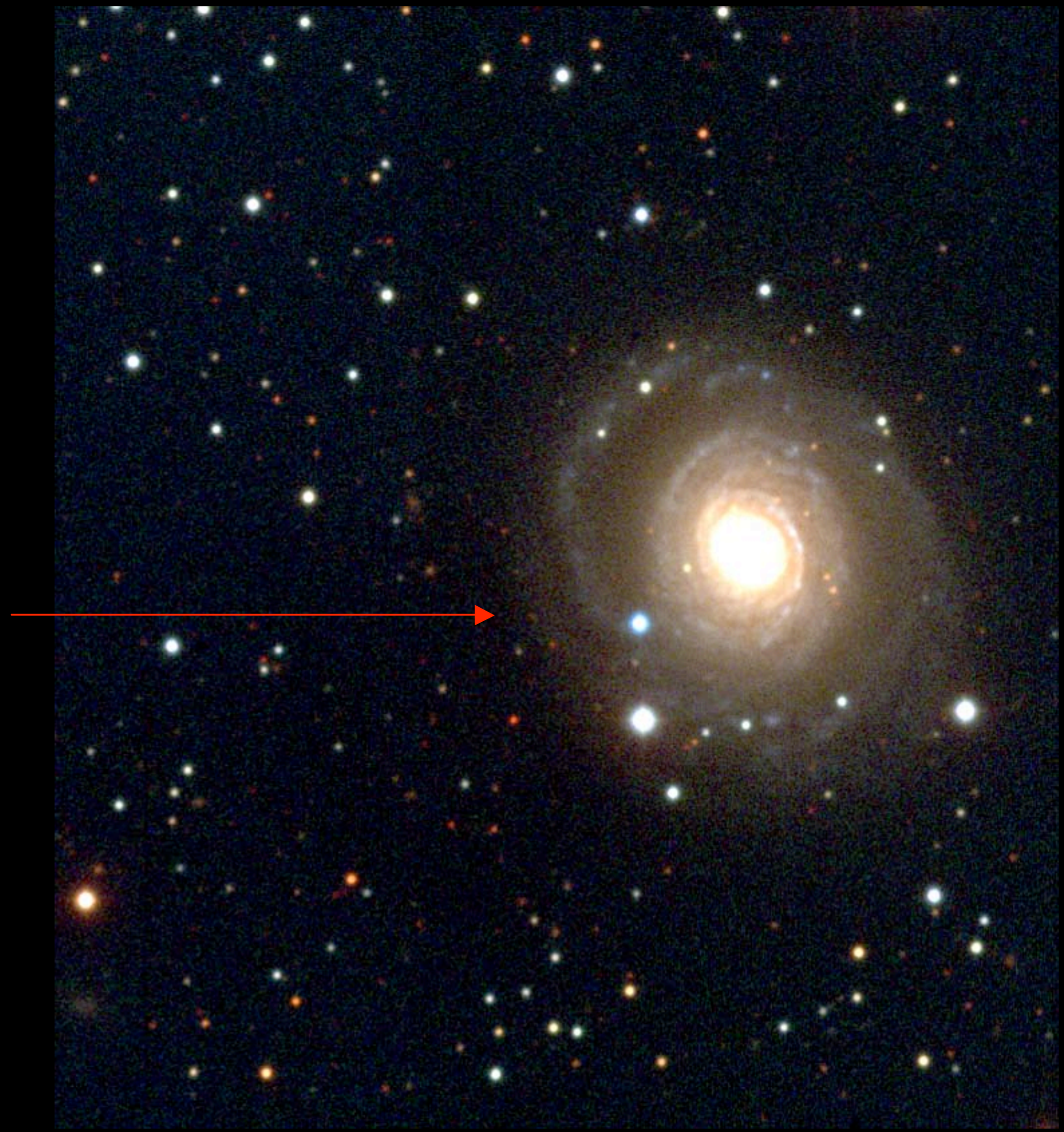

5 milliseconds
10 milliseconds
15 milliseconds
20 milliseconds

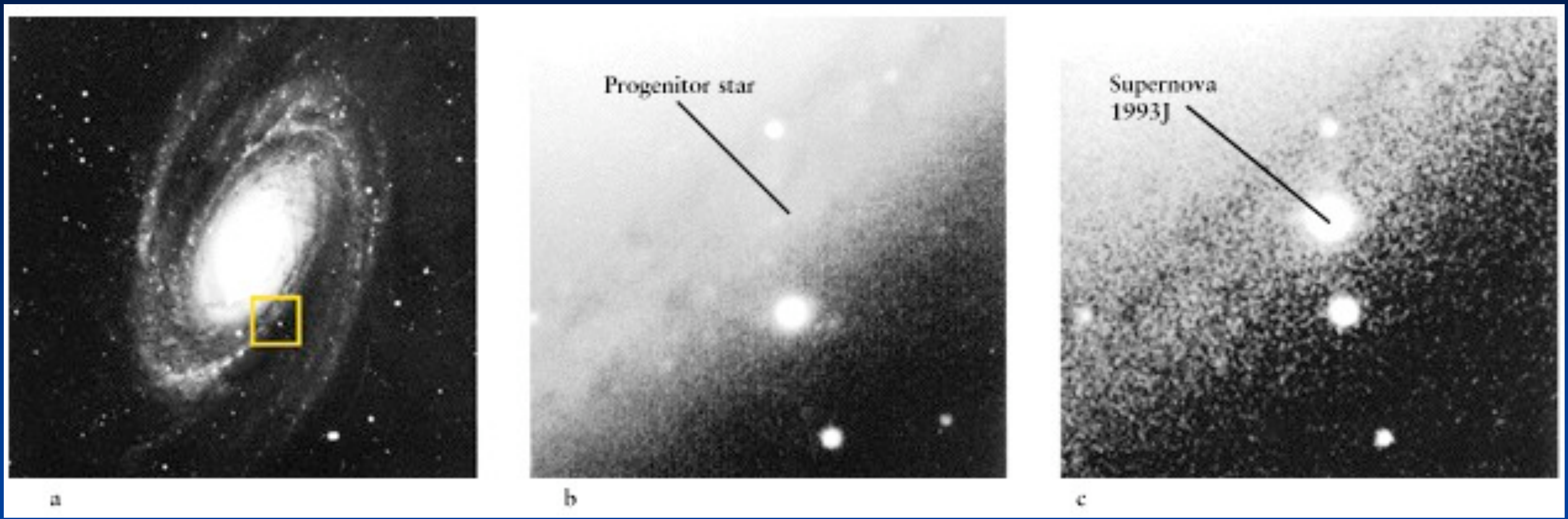
Supernova II

- Any reasons to believe this story?
- Many!

1) SN II have been seen in many galaxies in the last 100 years and always near star-formation regions:

Guilt by association!



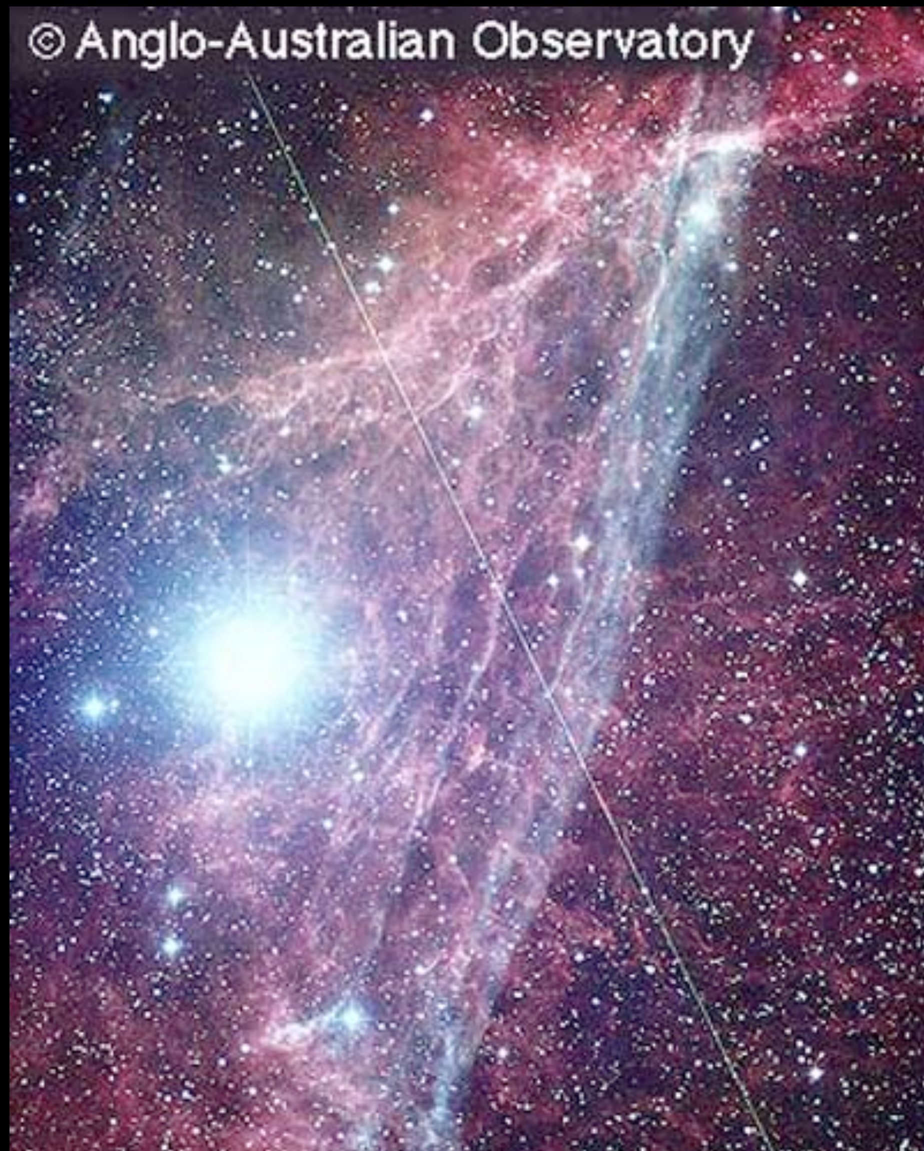

Progenitor star
Supernova
1993J
a
b
c

SNII

2) Predicted peak luminosity of $10^8 L_o$ is observed

3) Predicted expansion velocity of 10,000 to 20,000 km/sec is observed

4) In the Galaxy, when we point our telescopes at historical SN, we see chemically-enriched, rapidly expanding shells of gas


© Anglo-Australian Observatory

NGC 1850 in LMC

SN 1987a

- There was a major breakthrough in 1987.
- 165,000 years ago in a nearby galaxy called the Large Magellanic Cloud, a star blew up as a SNII.
- The first indication was a neutrino `burst'. About 10 billion neutrinos from SN1987a passed through every human on Earth. Neutrino detectors caught about 14 of them.
- 99% of a SNII energy is released as neutrinos.

SN1987a

- The second indication, about 4 hours after the neutrinos arrived was a new naked-eye star in the LMC

SN1987a

- For the first time, the progenitor star of a SNII was identified:

$\boxed{20M_o \text{ Supergiant -- bingo!}}$

- The final prediction of SNII theory is that there should be a very dense ball of neutrons left behind in the center of a SNII remnant. More later.

Historical Supernovae

- There are more than 2500 SN that have been seen in other galaxies in the last 100 years. Based on other spiral galaxies, a big spiral like the Galaxy should have about:

0.5 SNI per century

1.8 SNII per century

Historical SN

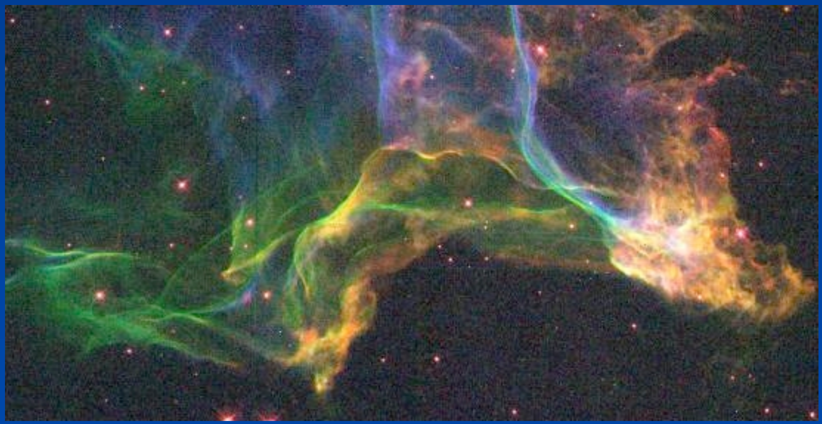
- We miss many in the Galaxy because of dust obscuration.
- From radio surveys for SN remnants, we have discovered 49 remnants for an inferred rate of 3.4 SN/century.
- There are several `historical supernovae' -- bright new stars that appeared in the sky and were recorded by various people.

Historical SN

- 1006, 1054, 1181, 1572, 1604 and 1658 were years when bright `guest stars’ were widely reported

Historical SN

- For all the guest stars, point a modern telescope at the position and see a rapidly-expanding shell of material.
- In two cases, the remnant was discovered before the historical event

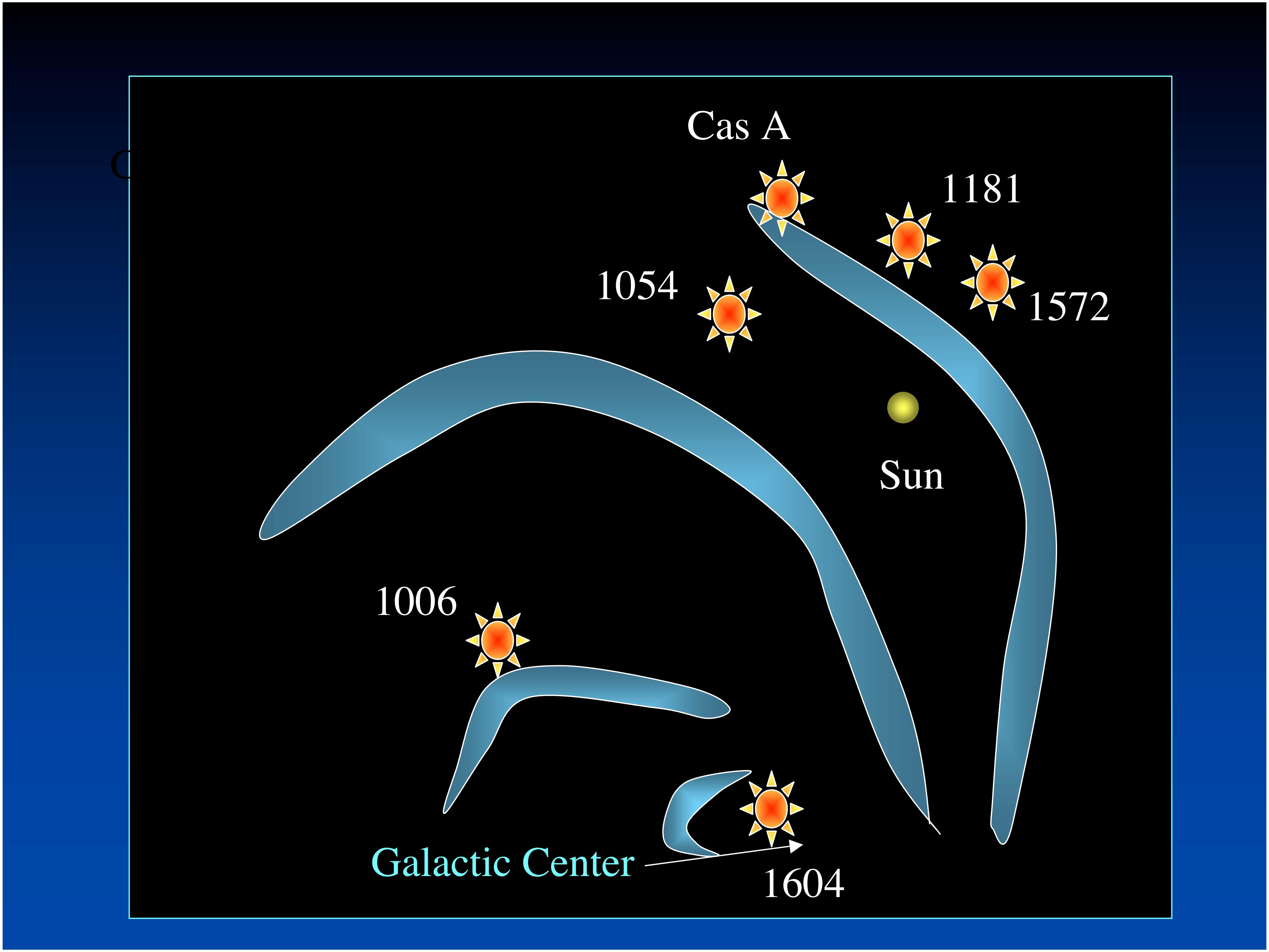


Historical SN

- The 1054AD event was so bright it cast shadows during the day -- this is the position of the Crab Nebula

Historical SN

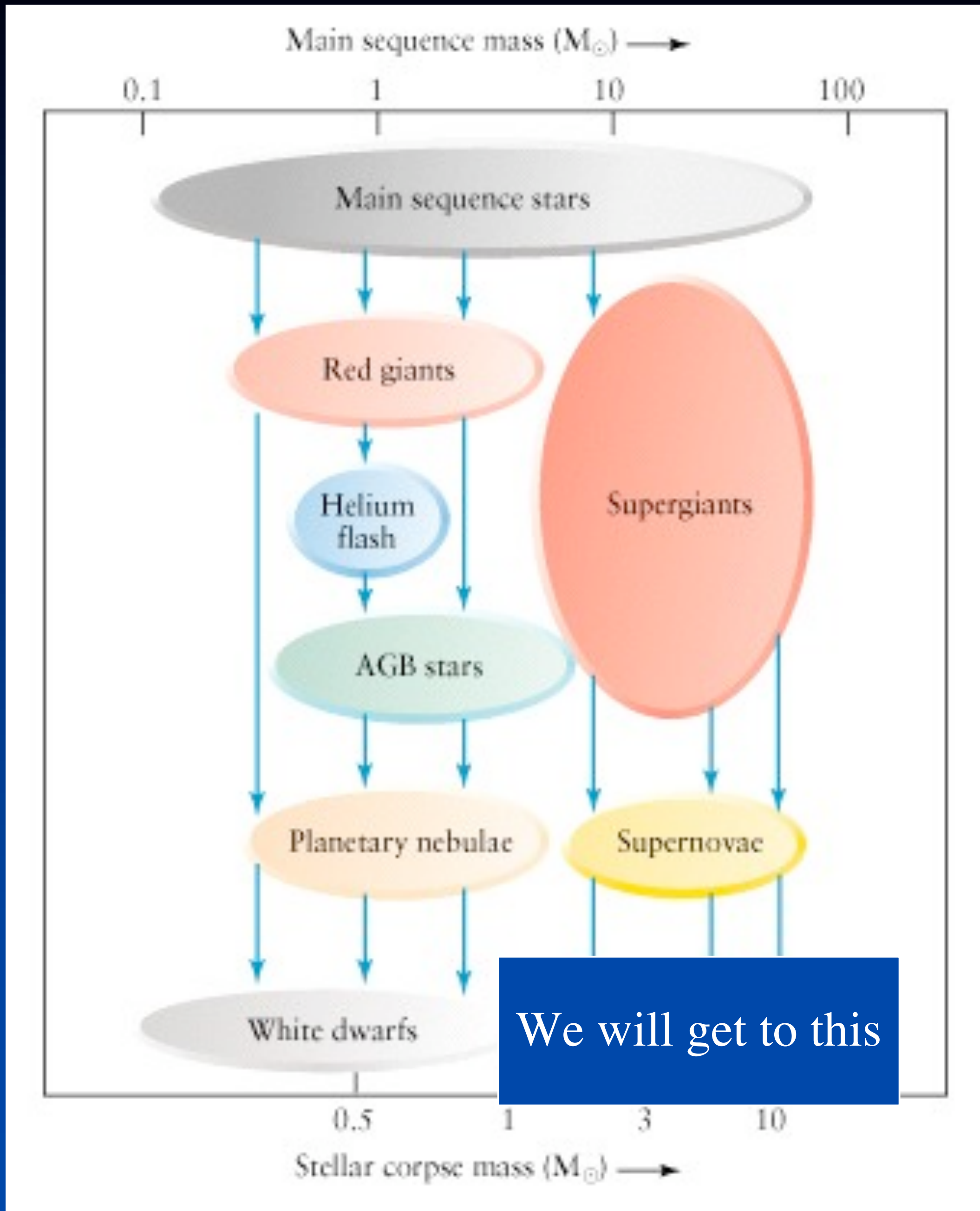
- The nearest SN remnant is the `Gum' nebula from around 9000BC. Four times closer than the Crab, it would have been as bright as the full moon.
- A mystery is `Cas A' -- this was a SN at about 1600AD, should have been very bright, but no records of it exist.


Cas A
1181
1054
1572
Sun
1006
Galactic Center
1604

Supernovae in the Galaxy

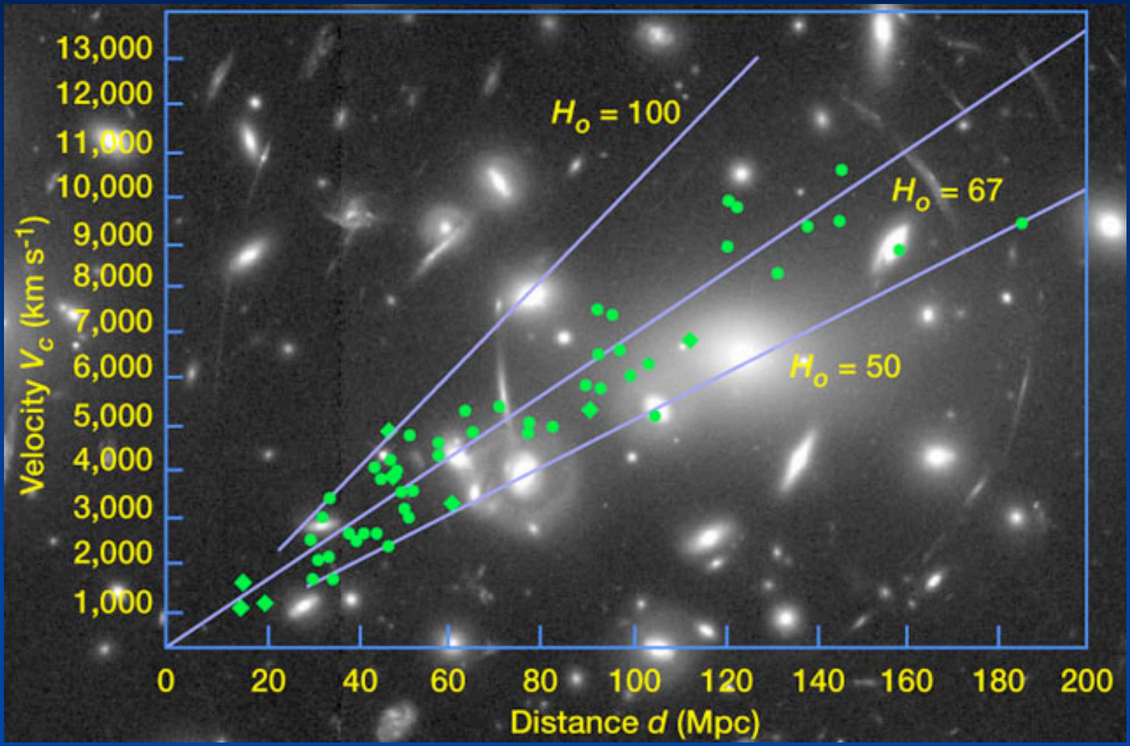
- We are long overdue for a bright Galactic Supernova.
- For a while, a nearby SN was a valid candidate for the source of the demise of the dinosaurs.
- There are the products of short-lived radioactive isotopes locked up in primitive meteorites which suggest a SN in the vicinity of the Solar System about 100,000 years before the Sun formed. A SN may have triggered the collapse of the proto-Sun.

Next Galactic SN?



We will get to this

Sidetrip - the Expansion of the Universe

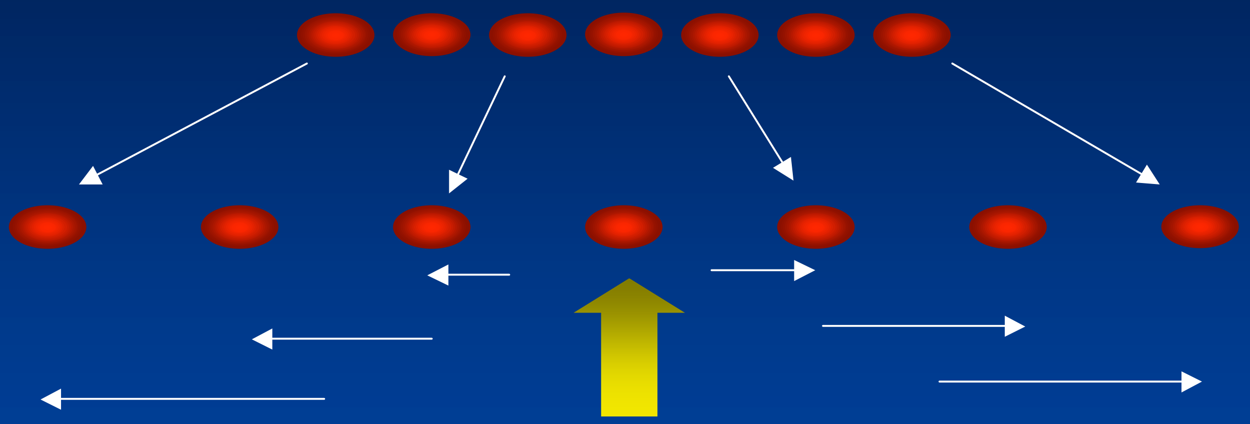


- The first hint of the Big Bang was the discovery in the 1930s that the Universe is expanding

The Expanding Universe

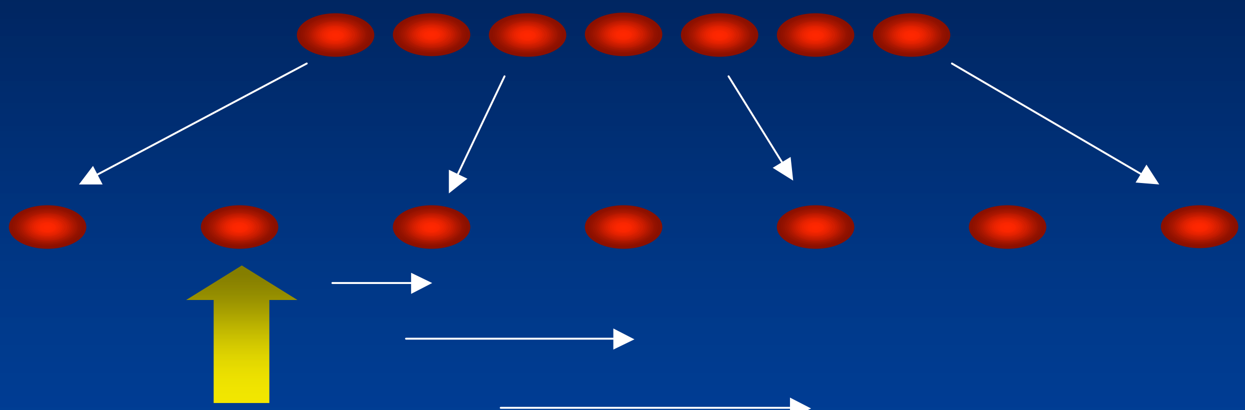
- Although the most naïve interpretation of all galaxies expanding away is we are at the center of the Universe, when you think about the *Hubble Law*, it is clear that the entire Universe is expanding (right?).
- More distant objects are moving faster.
- Observers at every galaxy look out and see the other galaxies rushing away.

The Expanding Universe



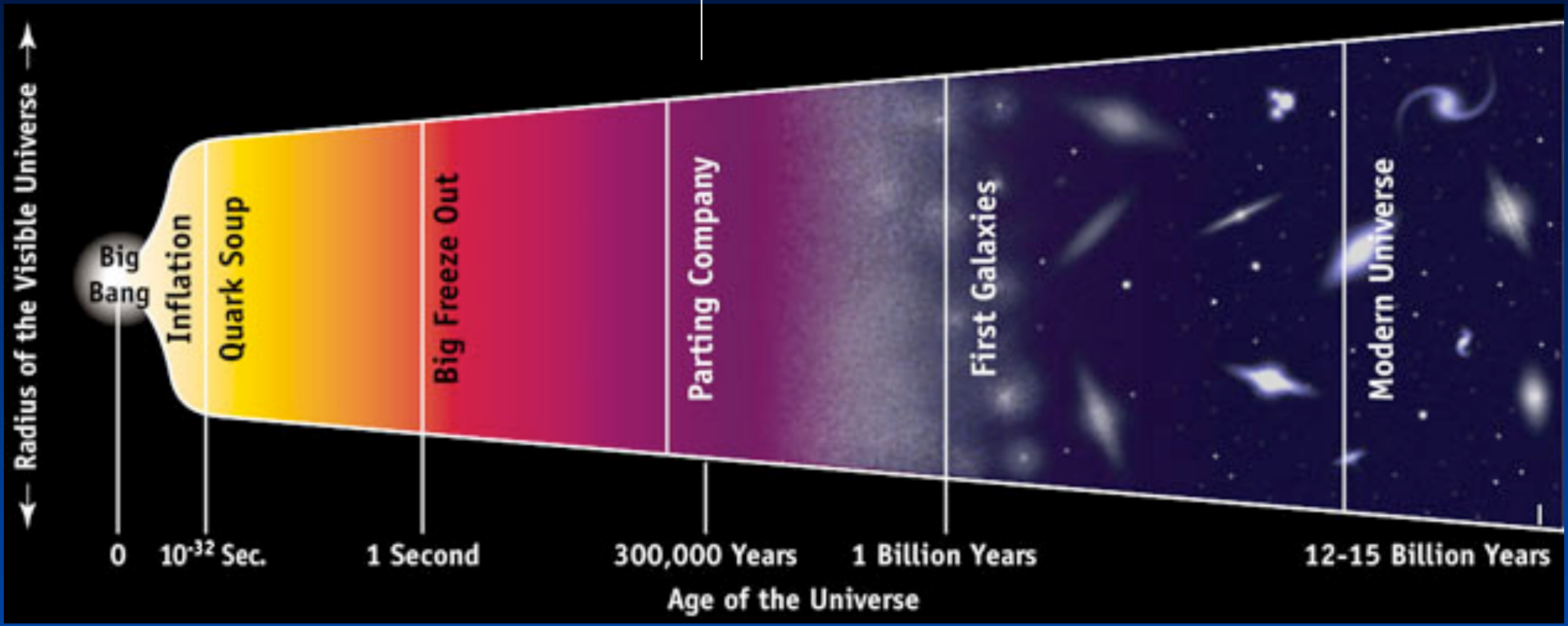
These people measure their nearest neighbors to have moved one unit, the next galaxies to have moved 2 units…

The Expanding Universe



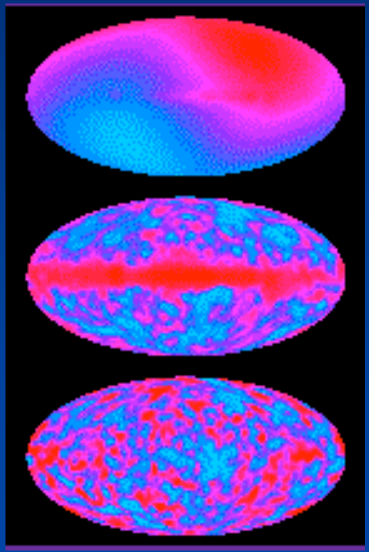
These people measure their nearest neighbors to have moved one unit, the next galaxies to have moved 2 units…

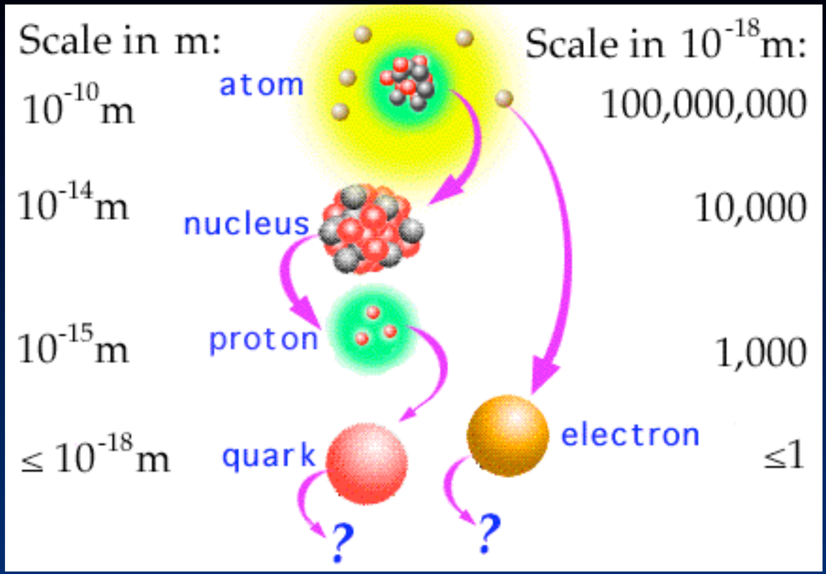
Universe ionized



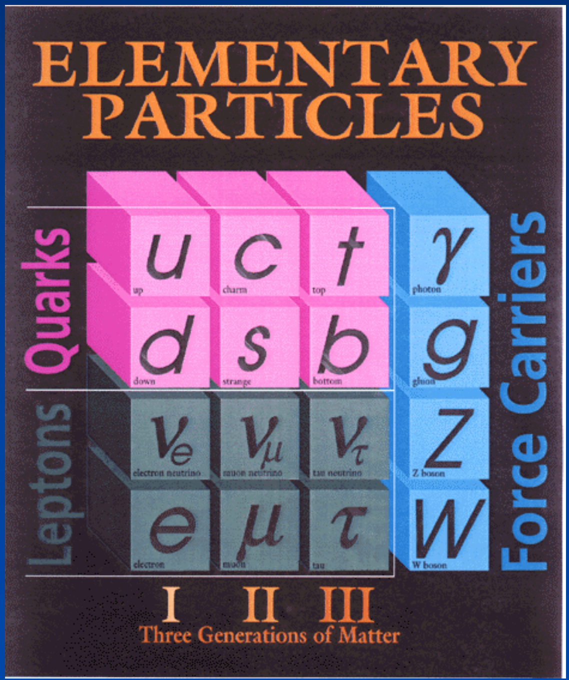
The Temperature of the Universe

- We also know the temperature of the current-day Universe from the ***Cosmic Microwave Background***
- This is the radiation that pervades the entire Universe and as the Universe expands it gets cooler.





Subatomic levels

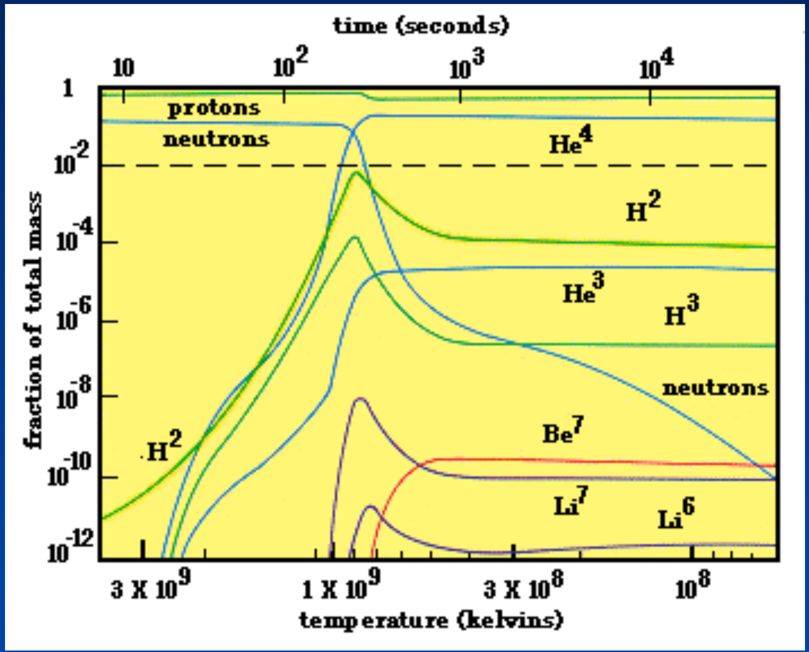


Elementary particle periodic table

The Synthesis of the Elements

- In the beginning, there was only H and He. Early in the Big Bang, it was a soup of elementary particles. As the Universe expanded and cooled, there was a period of proton fusion into Helium.
- The Universe ran into the Be problem. Red giant cores get past this via the Triple-Alpha process, but the Universe expands right through this possibility and the density/temperature are quickly too low to synthesis any additional elements.

Big Bang Nucleosynthesis



- BB+1 second: electrons, photons, neutrons, protons
- BB+2 minutes: some H^2 (p+n) produced
- BB+4 minutes: He production+tiny amount of Be, B and Li
- That's all! Universe has expanded to 10^9K and a density of only 10 g/cm^2

Big Bang Nucleosynthesis

- Is this story right?
- Seems to be. The oldest stars in the Galaxy are deficient in the abundance of elements heavier than Helium (but show the predicted amount of He)
- The current record holder has Fe/H about 200,000 times smaller than the solar value.
- Not quite down to Big Bang abundances, but we are getting pretty close and still looking.

Chemical Evolution of the Universe

- So we need to find the sources of the vast majority of elements in the Periodic Table of the elements.
- We already know about some of the sources.

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

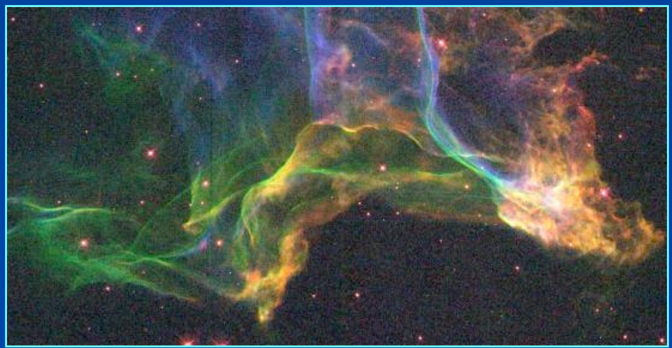
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Chemical Evolution

- Low-mass stars synthesize `new' He, C, O during the main-sequence, RGB, HB and AGB phases.
- These freshly-minted elements are brought to the surface via convection and re-distributed via stellar winds and planetary nebulae into the interstellar medium to be incorporated into later generations of stars.

Chemical Evolution II

- For more massive stars, `equilibrium' fusion reactions produce elements all the way up to Fe.
- Freshly made elements are delivered via stellar winds or, sometimes more spectacularly via supernova explosions



Chemical Evolution III

- What about the trans-Fe elements?
- Equilibrium fusion reactions of light elements don’t proceed past Fe because of Fe’s location at the peak of the curve of binding energy.
- However, in certain circumstances, supernovae for example, non-equilibrium reactions can build elements beyond Fe in the Periodic Table. Many of these are radioactive, but some are stable.

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

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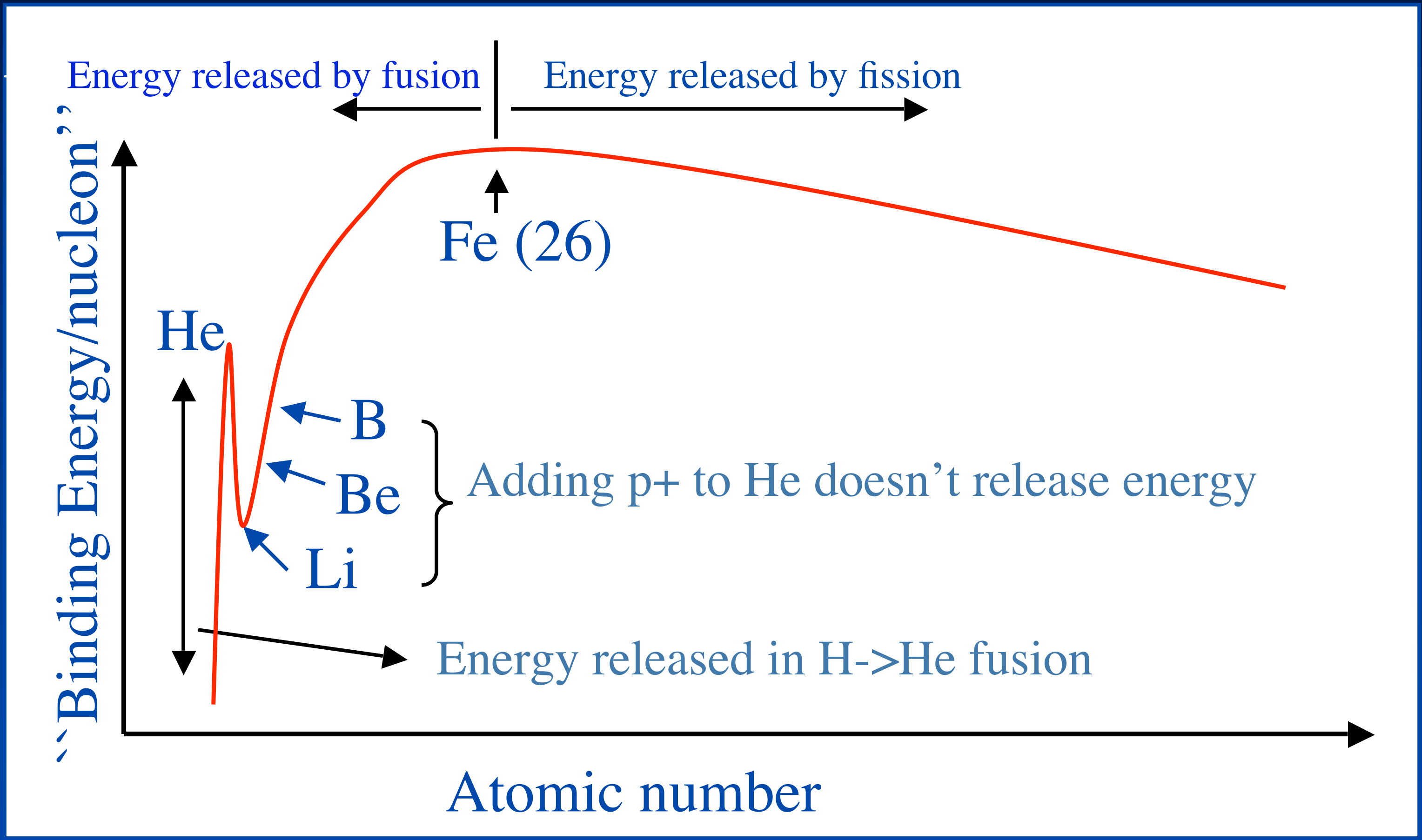
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

The `curve of binding energy'

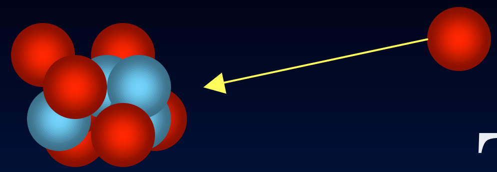


Neutron Capture Elements

- There are two principle paths to building the elements heavier than Fe. Both use the addition of neutrons to existing `seed' nuclei (neutrons have no charge so are much easier to add to positively-charged nuclei).

  S-process (slow addition of neutrons)

  R-process (rapid addition of neutrons)



The S-process

- The S-process stands for the Slow addition of neutrons to nuclei. The addition of a n° produces heavier isotope of a particular element. However, if an electron is emitted (this is called beta-decay), the nucleus moves one step up the periodic table.

S-Process

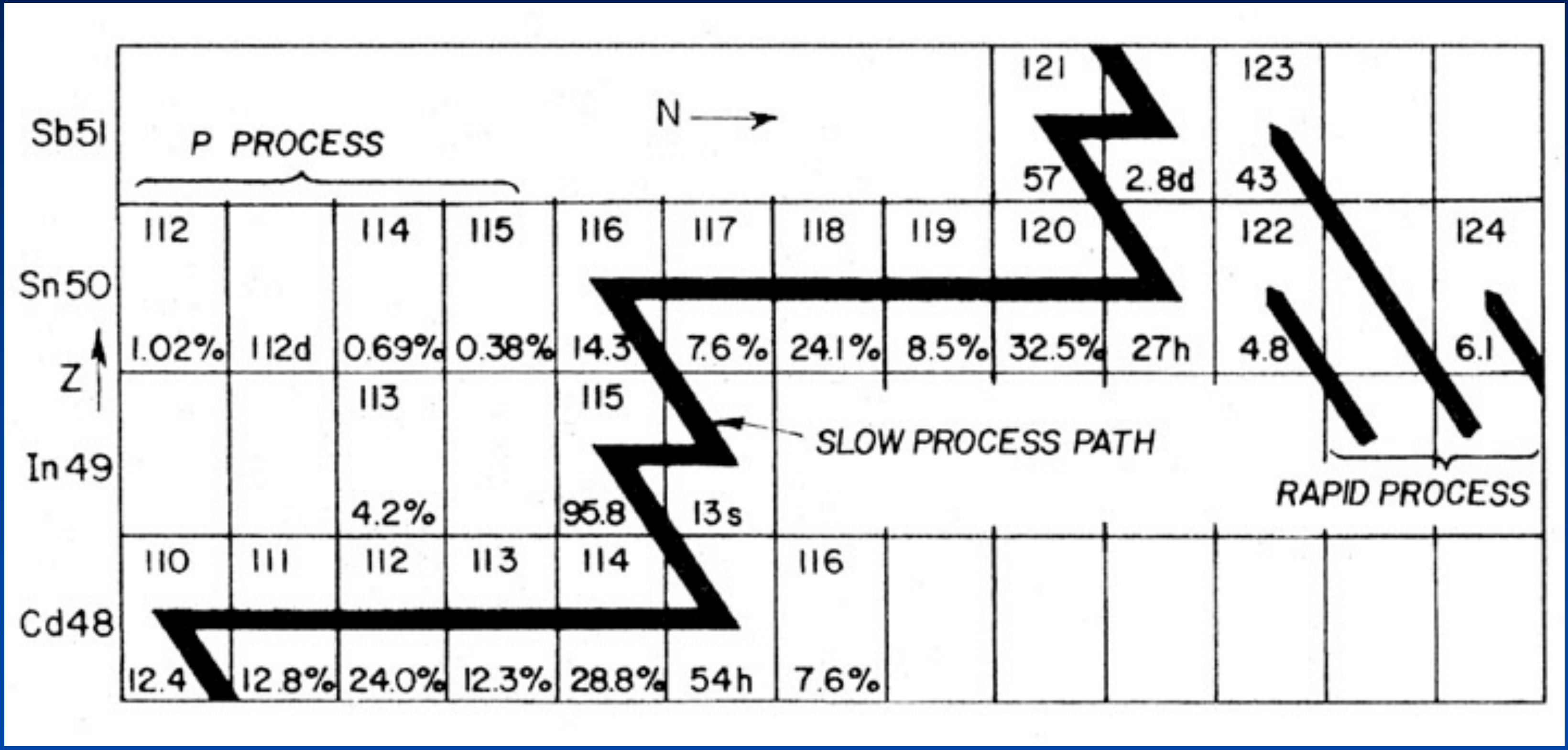
- `Slow' here means that rate of n^o captures is low compared to the beta-decay rate.
- It really is slow, sometimes 100's of years go by between neutron captures.

$$_{26}Fe^{56} + n^o \dashrightarrow {}_{26}Fe^{57}$$
$$_{26}Fe^{57} \dashrightarrow {}_{27}Co^{57} + e^-$$

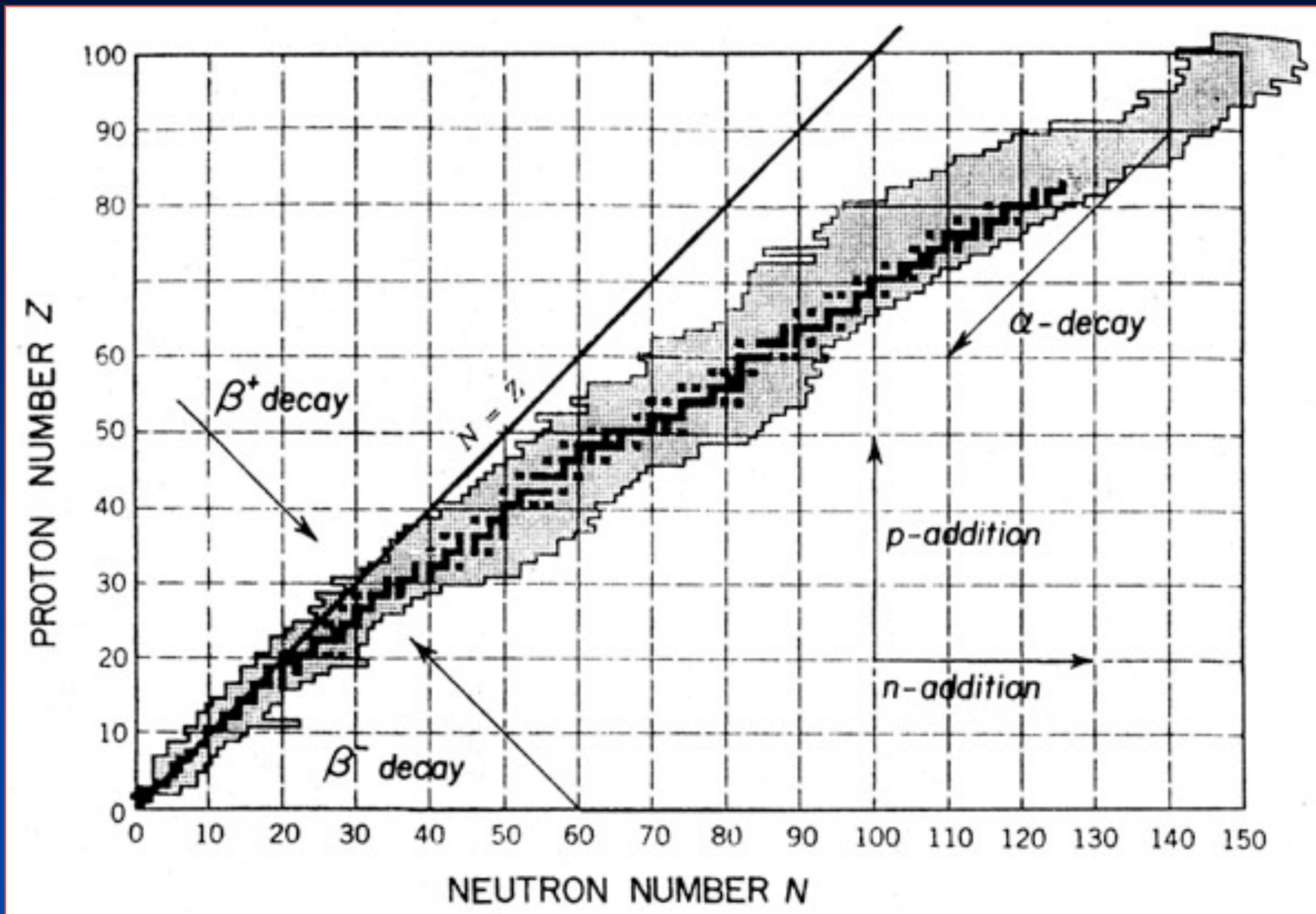
Here a neutron changed into a proton by emitting an electron

- The S-process can produce elements up to #83 - Bismuth. There are peaks in the Solar System abundance of heavy elements at ^{38}Sr, ^{56}Ba and ^{82}Pb. These are easily understood in the context of the S-process and `magic' numbers of neutrons.
- The site of the S-process is AGB stars during and between shell flashes. The n° source is a by-product of $C^{13}+He^{4} \rightarrow O^{16}$
- ^{43}Tc is an s-process nucleus and proof that it is in operation in AGB stars.

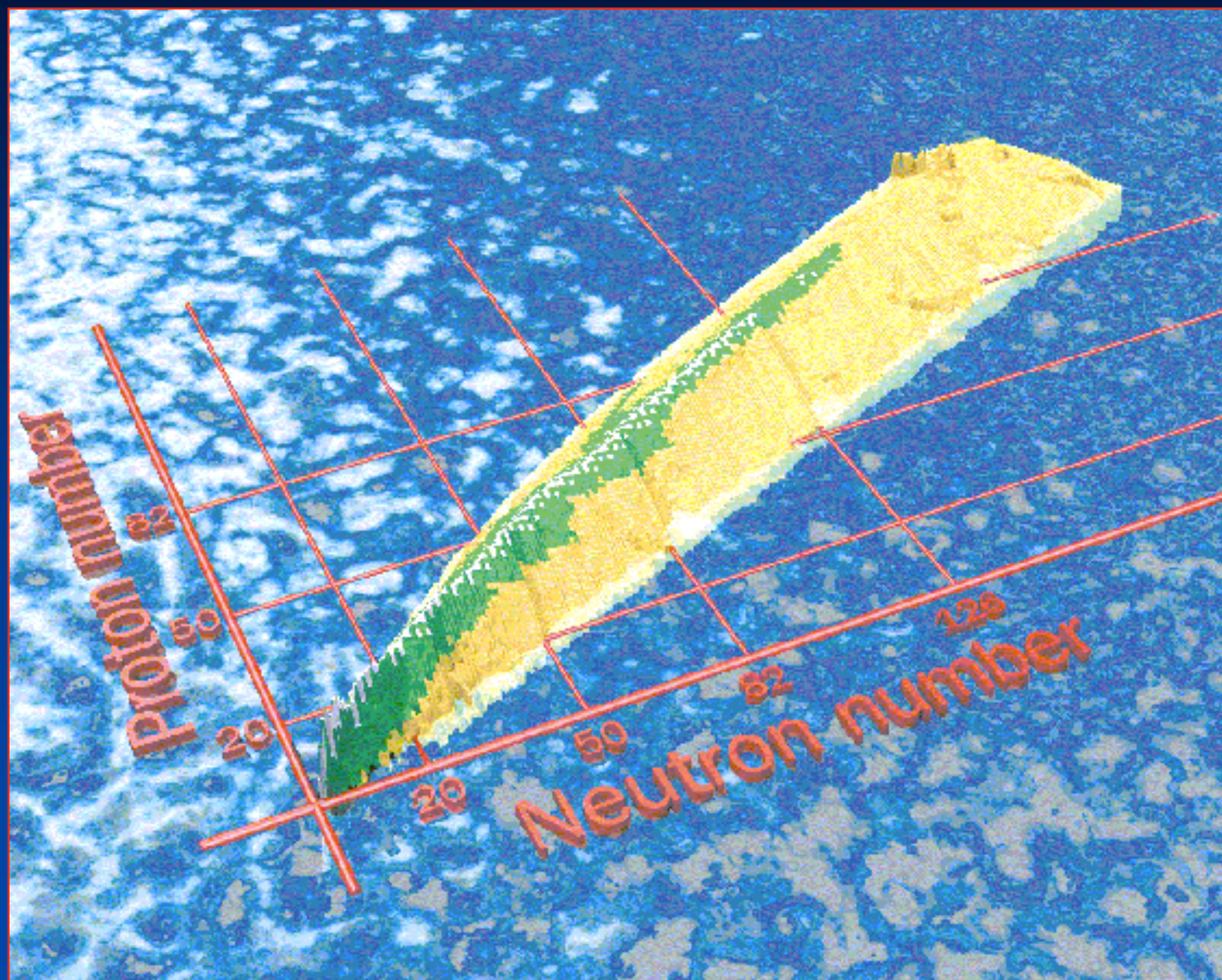
S-process path



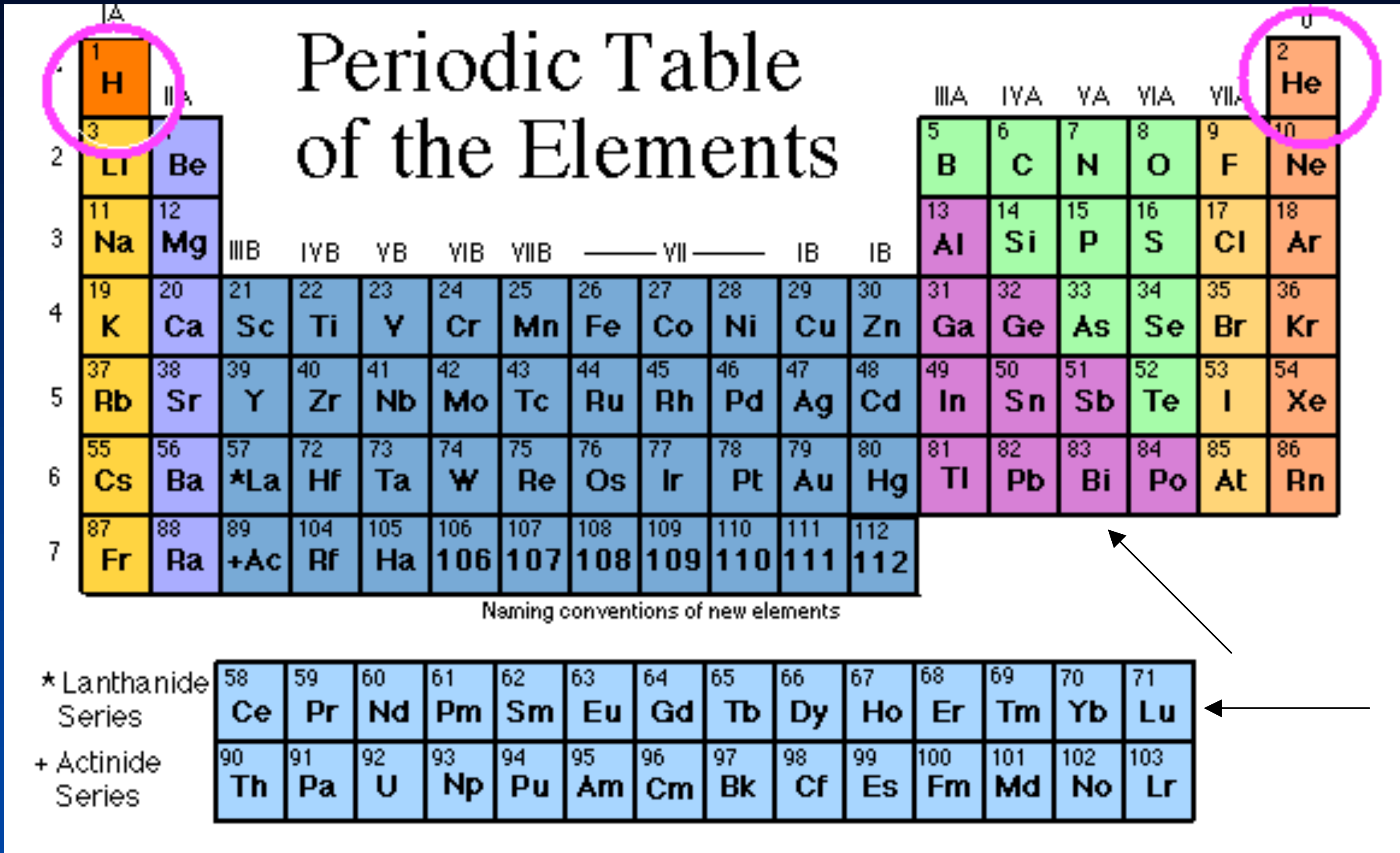
Nuclear mass - neutrons+protons



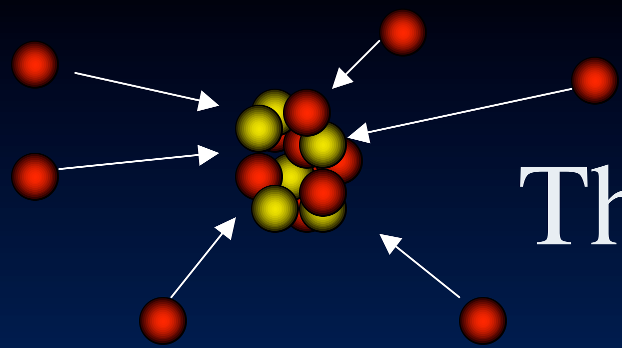
PROTON NUMBER Z
NEUTRON NUMBER N
N = Z
β⁺ decay
β⁻ decay
α - decay
p-addition
n-addition
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150



Proton number
82
50
20
Neutron number
20
50
82
126

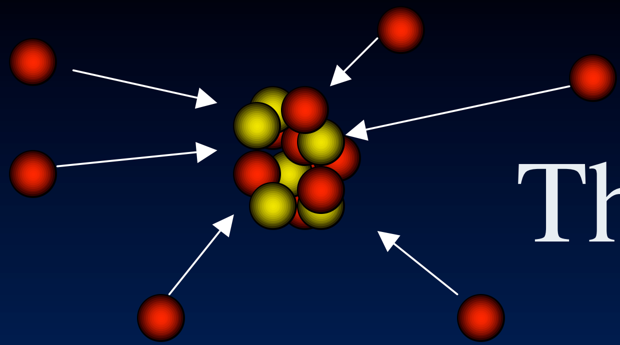


Add 5 neutrons to Fe and undergo 2 beta-decays. What element?



The R-process

- The R-process is the Rapid addition of neutrons to existing nuclei. Rapid here means that many neutrons are added before a beta-decay occurs.
- First build up a VERY heavy isotope, then as beta-decays occur you march up in atomic number and produce the REALLY HEAVY STUFF.



The R-process

- For this to happen need a big burst of neutrons. The most promising place with the right conditions is in a SNII explosion right above the collapsed core.
- We see an overabundance of R-process elements in the oldest stars. As the early chemical enrichment of the Galaxy was through SNII, this is evidence of SNII as the source of r-process elements

R-process

- If we look at the Crab Nebula or other SNII remnants we don’t see r-process elements.
- We DO see regions of enhanced O, Si, Ne and He which appear to reflect the `onion skin’ structure of the massive star progenitor.

Solar Composition by Mass

H ……….78.4%
He………19.8%
O ………. 0.8%
C ……….. 0.3%
N ……….. 0.2%
Ne ……… 0.2%
Si ………. 0.04%
Fe ………. 0.04%

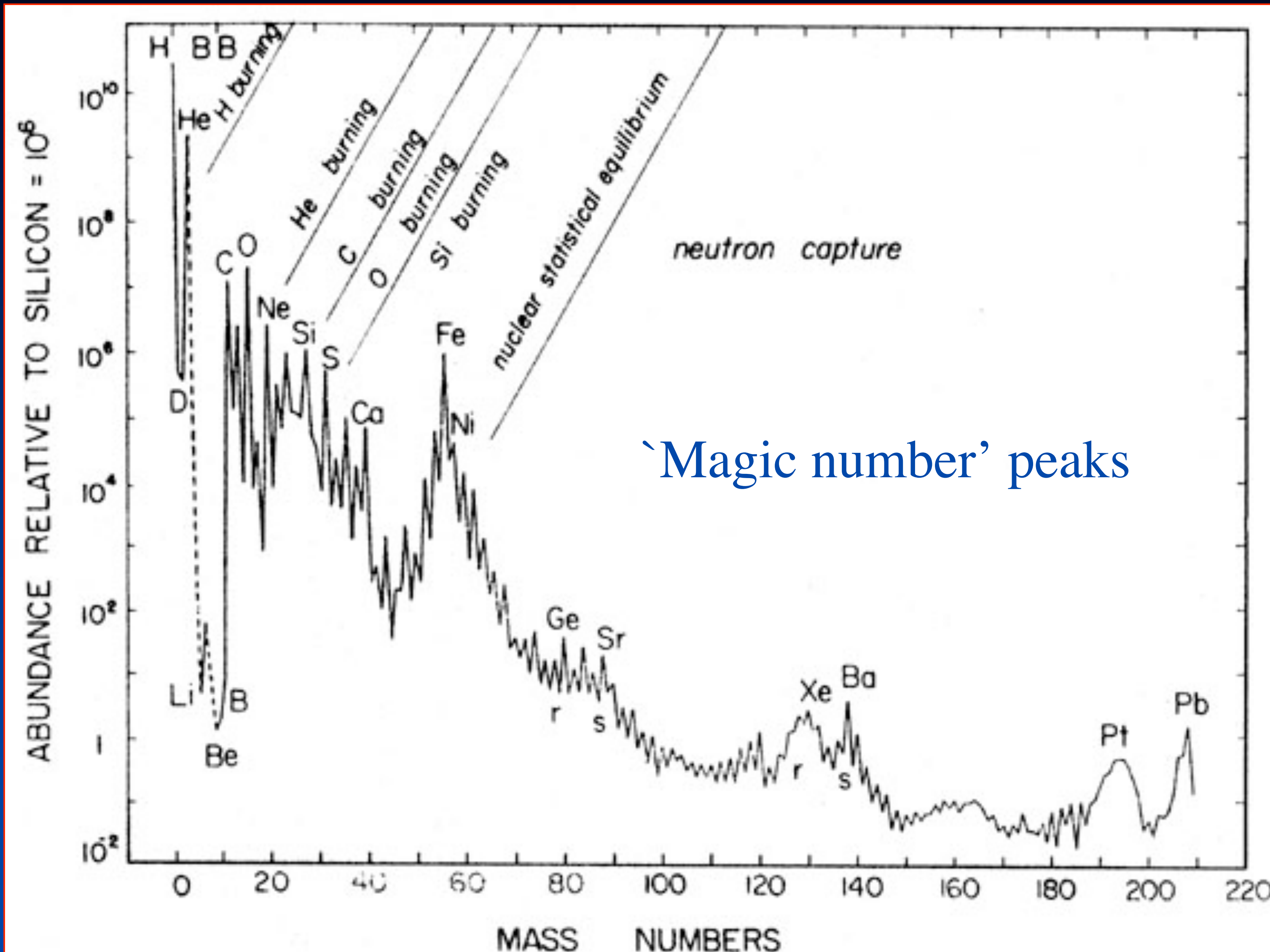
Big Bang

Low-mass stars

High-mass stars

Gold……..0.000000009%
($2.1 x 10^{24} at $300/ounce)

R-process
S-process



`Magic number' peaks

- What does a good doctor do for his patient?
- Helium
- Or, Curium
- What does a bad doctor do for his patient?
- Barium
- What did the Mafia do to the innocent bystander?
- Cesium
- Dysprosium
- Barium

- How was class last time?

- How was class last time?
- A little boron…

Last Time

- For a 1 solar mass star, order the phases of evolution:

(1) Protostar

(2) main sequence

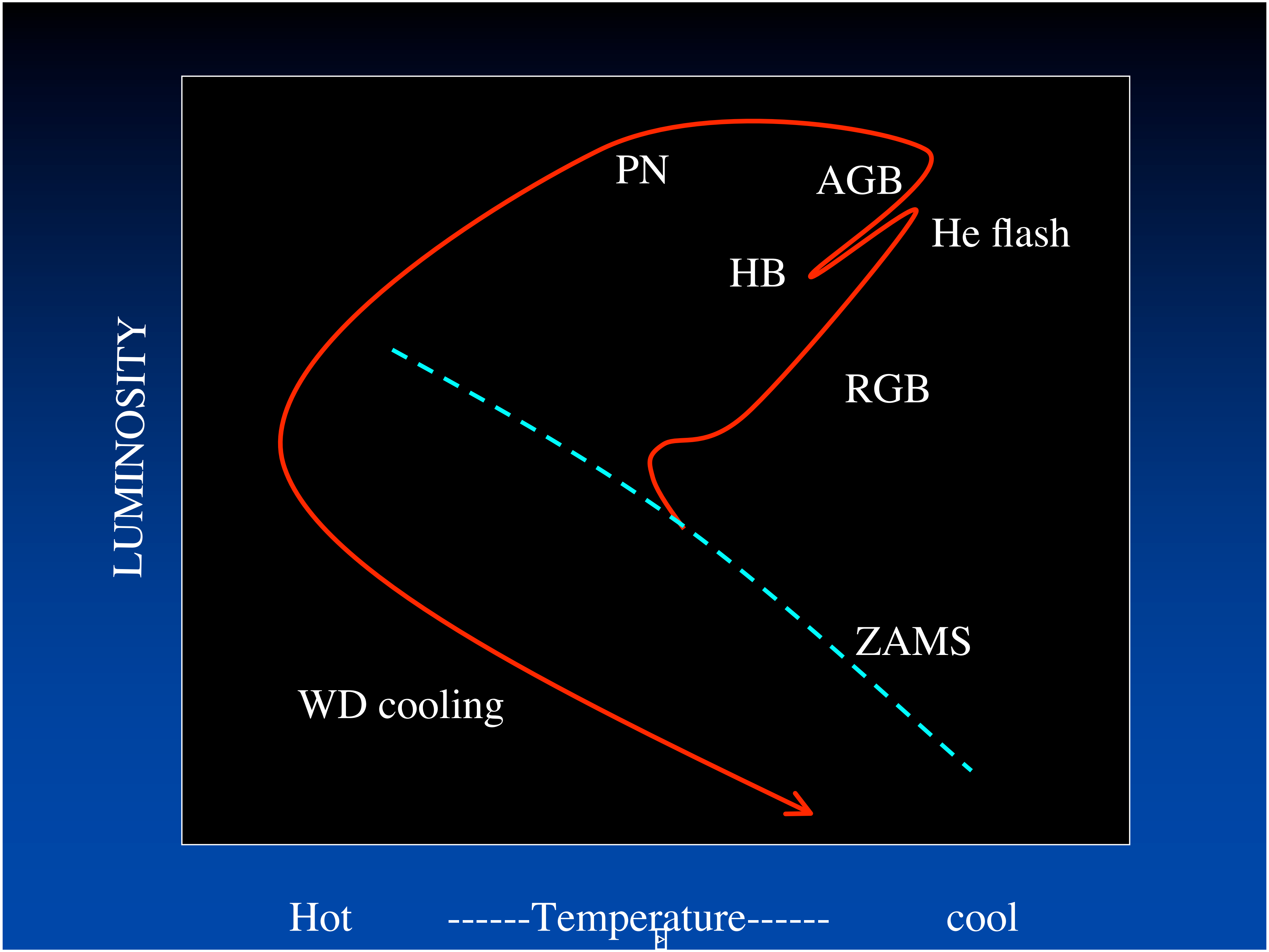
(3) RGB

(4) Horizontal Branch

(5) AGB

(6) Planetary Nebula

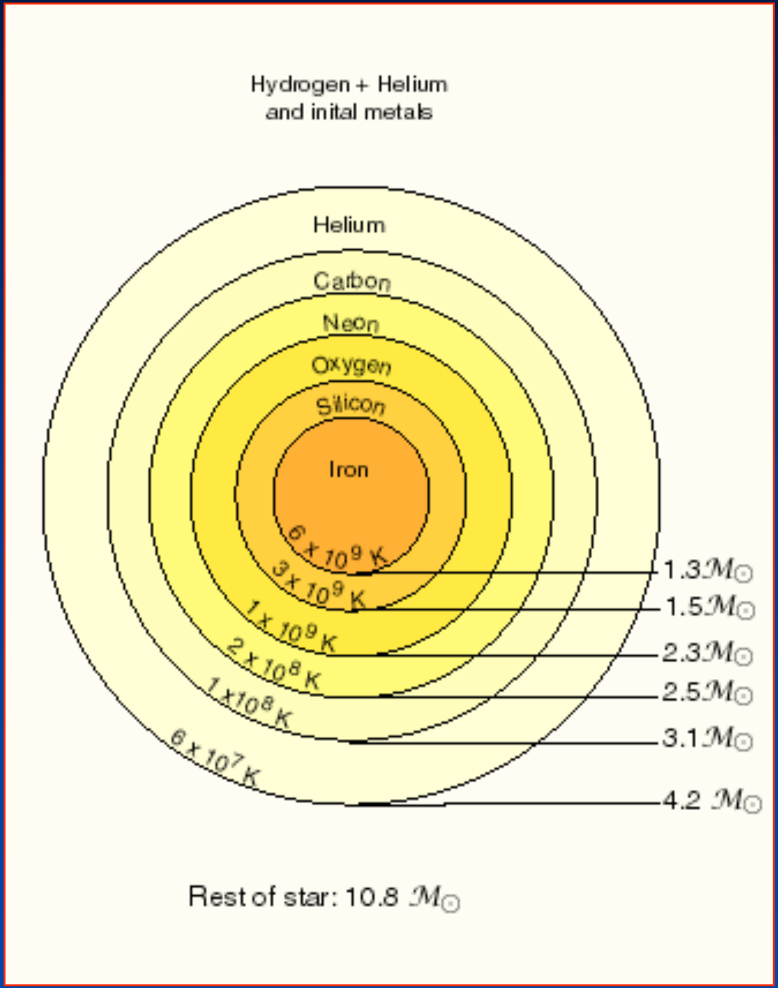
(7) White Dwarf


PN
AGB
He flash
HB
RGB
ZAMS
WD cooling
LUMINOSITY
Hot ------Temperature------ cool

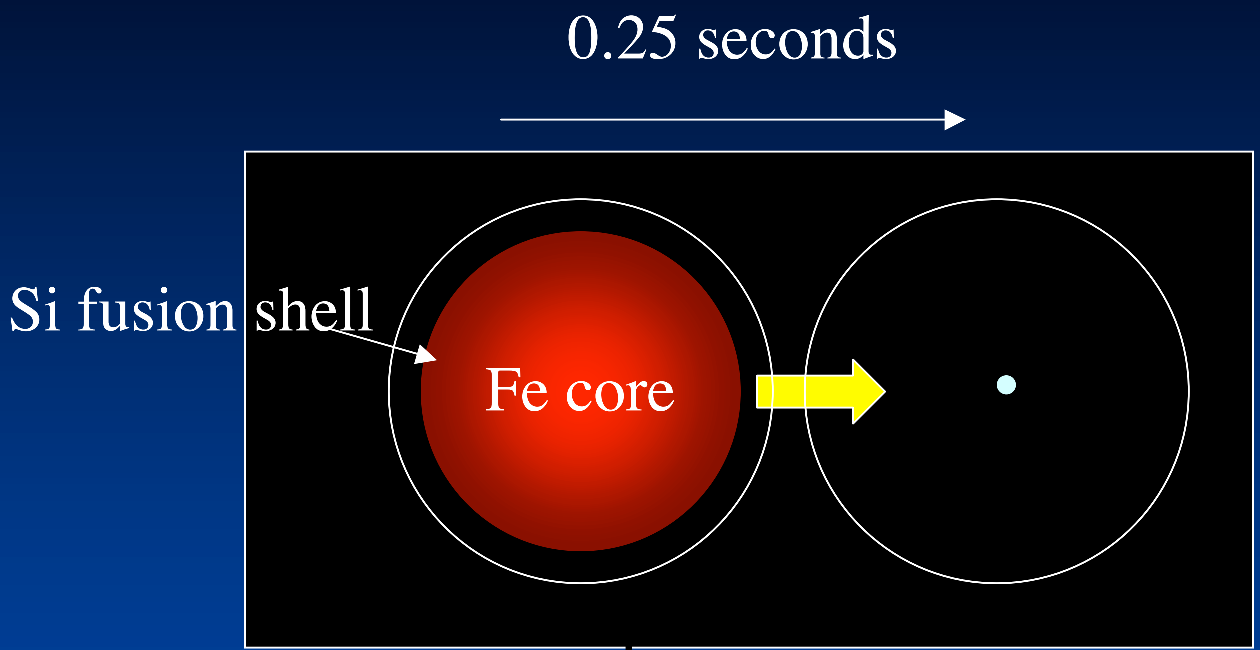
Review: Mass-transfer Binaries

- Novae - mass transfer from RGB star to its WD companion. Hydrogen accumulates on surface of WD, has a small runaway thermonuclear explosion.
- Supernovae Type I - WD accumulates enough mass to exceed the Chandrasekar (1.4 solar mass) limit. Collapse and simultaneous nuclear detonation of entire WD.
  - $>10^9$ solar luminosity
  - Production of elements up to radioactive Ni^{56}
  - Seen in old and intermediate-age populations

Massive-star Evolution



Core-Collapse in Massive Stars



1) Fe core exceeds 1.4M and implodes
2) Temp reaches 5 billion K and photodisintegration begins to blast apart the Fe nuclei
3) Neutronization occurs: $e^- + p^+ \rightarrow n^0$ + neutrino
4) Neutron core, bounce, shockwave, explosion

SN1987a

- Nearest SN since telescope invented.
  - Neutrino blast detected
  - Precursor identified: 20 solar mass supergiant!