Chap 17-18: Stellar Evolution – the Life and Death of a Star…

Here's the story we'll tell…

- Lowest mass stars and their evolution
- Medium mass star evolution
- High mass star evolution
- Stellar death, and stellar corpses
- The origin of the chemical elements beyond heliums – is stars

Stars: Nearly Always Born in Open Star Clusters

- To have the **Low temperature** requires shielding from the radiation of other stars; requires **dust** which requires a lot of mass, since dust is a relatively rare component of interstellar clouds
- Star clusters forming in today's environment are called "open star clusters", dozens to hundreds of stars…
- Our Galaxy makes about 2 or 3 stars per year on average

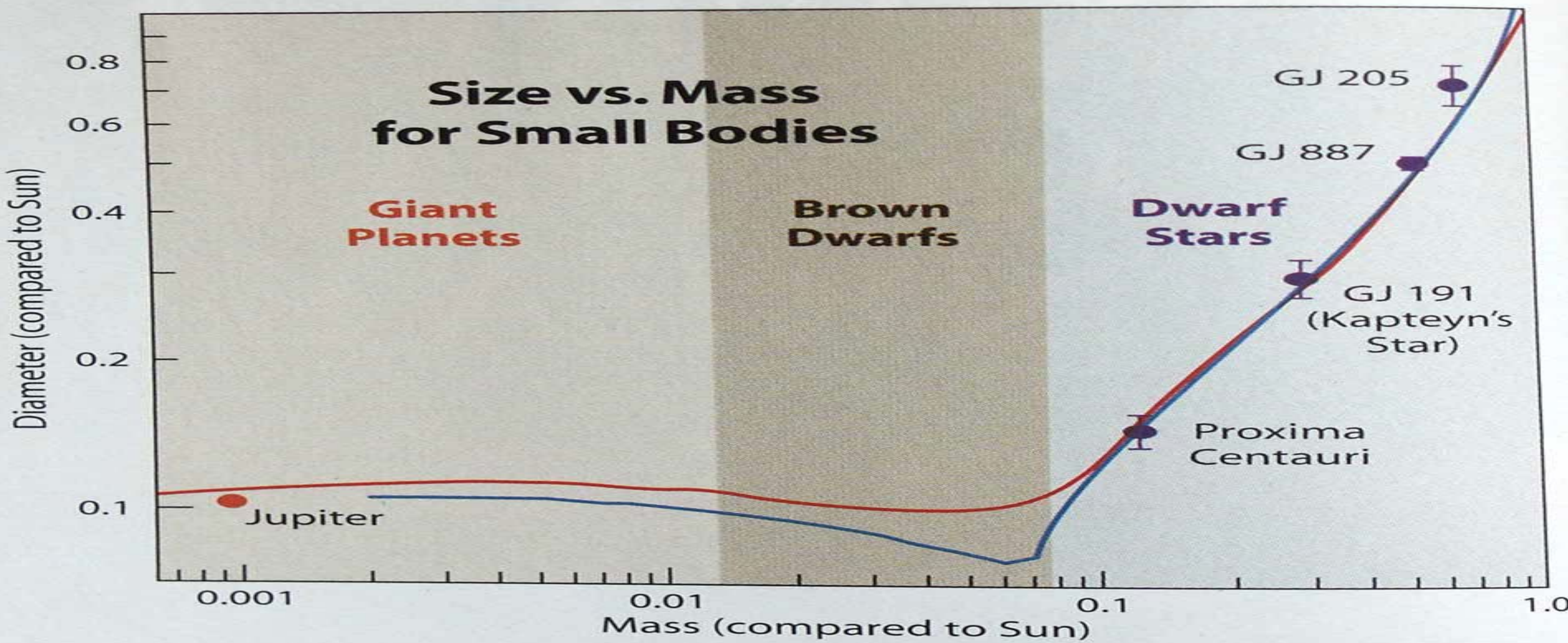
A rich open cluster, young and still dense

As Open Clusters Age…

- Since about half the initial mass of the giant molecular cloud that became the cluster, was blown away by stellar winds from the stars, the **clusters are usually not gravitationally well bound**.
- The stars inherit the turbulent motion of the original molecular cloud and so the stars are doing a sort of random "square dance" over time, and some stars sink closer to the center giving energy to others that are ejected from the cluster… **open star clusters eventually evaporate.**

Open Cluster M39 - A looser grouping

Add mass to a big gas giant planet, it'll actually get <u>smaller</u> as its gravity increases and compresses the gas – until it's up to $0.08M_{sun}$, and then you click over the engine of nuclear fusion, and now adding more mass will increase fusion and luminosity, puffing the star up and making it <u>bigger</u>



Theory predicts that red-dwarf stars, brown dwarfs, and giant planets will have very specific sizes depending on their masses. The curves show the predicted size-mass relation for objects 400 million years old (red line) and 5 billion years old (blue line). The four red dwarfs with sizes measured by the VLT Interferometer fall on or near these lines. Ob-

We will use Low, Medium, High Mass Star Classifications

- Our optional textbook has only 2 mass classes:
- - low mass: stars can fuse to helium and above, but not up to iron
- - high mass: fuse elements up through Iron, and end lives as supernovae
- ***<u>But Many stellar astronomer's, (me included) find it more compelling to think of 3 mass classes:</u>***
- - low mass stars; $M<0.5\ M_{sun}$: can only burn H->He
- - medium mass: Burn He to C and perhaps beyond that, up to but not including Iron
- - high mass stars; $M>8M_{sun}$: Fuse elements up through Iron, and end their lives as supernovae

A Quick Overview First…

- Stars burn through their core hydrogen, evolve off Main Sequence to become Red Giants, then die in various ways
- **Higher mass** stars evolve *rapidly*,… *and fuse in their cores heavier and heavier chemical elements as they evolve*
- **Lower mass** stars evolve *slowly, and make only a few of the lighter chemical elements before their cores cannot compress further.*

Evolution of Stars on the H-R Diagram

- Stars age at different rates, depending on their mass.
- Higher mass stars = faster evolution.
- The lowest mass stars will last on the main sequence for hundreds of billions of years. The highest mass stars only for a million years.

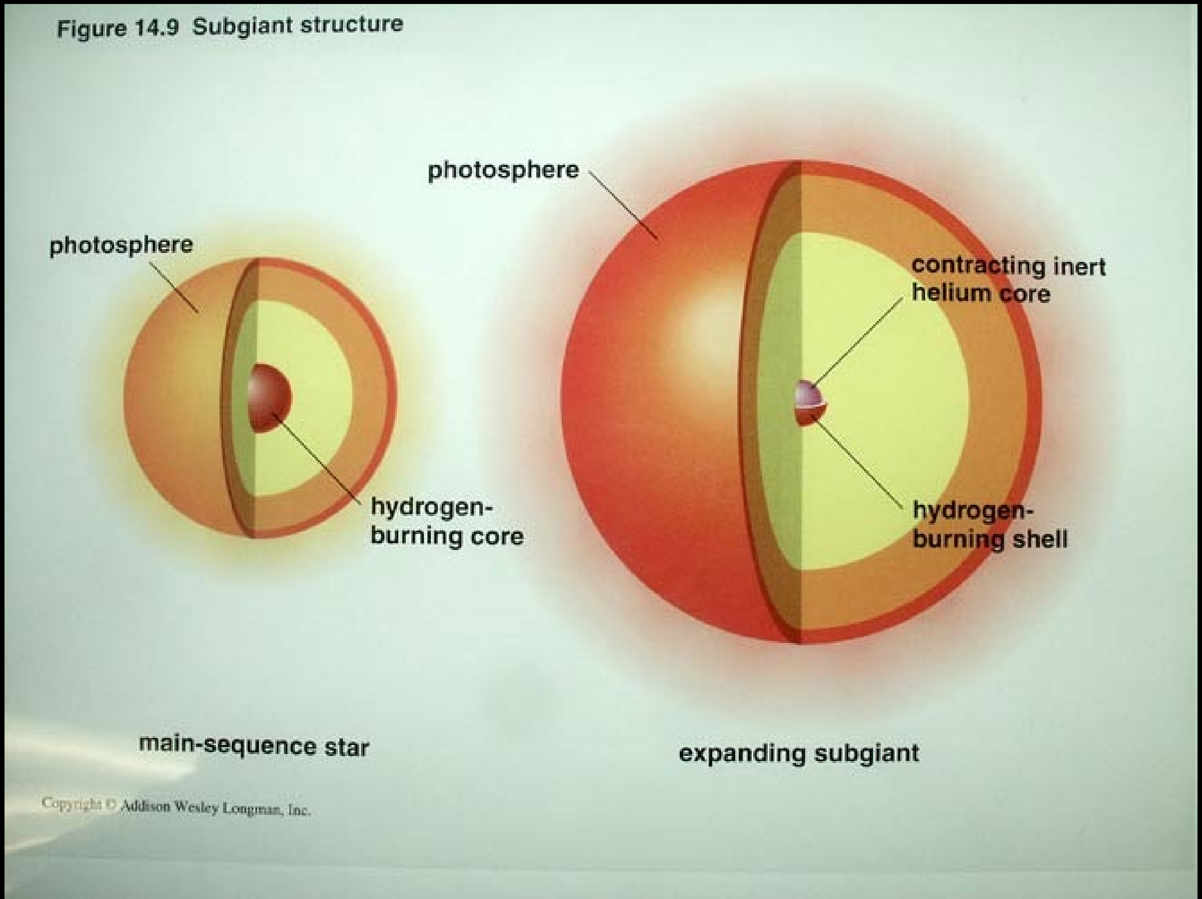
Evolution of the Lowest Mass Stars

- Begins with H burning in core
- When H runs out, core collapses under gravity
- This releases gravitational potential energy, adding to the star’s luminosity and puffing out the outer layers.

If the mass is less than 0.25 M_{sun}

- Then the star does not become a red giant or sub giant.
- The outer layers never get enough pressure to cause that kind of expansion
- So stars from 0.25 to 0.5 M_{sun} never burn helium, but they still reach the point of expanding their outer envelope and become smallish Red Giants.

The core shrinks as the hydrogen is converted to denser helium, and this collapse under gravity releases gravitational energy, puffing out the outer layers. So the star is both shrinking (deep inside) and expanding (outer layers) at the same time! True of all stars, not just the low mass stars



As the inner core has no more hydrogen…

- Hydrogen shell burning still proceeds in a shell outside the inner core
- When the core density reaches several tons per cubic inch, the electrons refused to squeezed any tighter.
- Essentially, the core becomes like an atom with all of its electron orbitals full.
- And just like the electron in the first orbital of hydrogen is forbidden to merge with the proton, so too do the electrons refuse to get packed tighter in this “electron degenerate” quantum state the entire star has become

The Outer Layers now fall back in

- If the star has less than 0.25 solar masses, it can’t become a red giant (see Medium Mass Evolution for red giants)
- No longer receiving gravitational potential energy (because the core’s now rigidly electron degenerate), then as the star continues to radiate light, the outer layers slowly sink inwards until the entire star is electron degenerate

The heat generated by the in-falling outer layers…

- Heats the surface and so the red dwarf becomes a “blue dwarf” star, smaller and dimmer than a main sequence star of the same temperature (Adams *et al* 2004)
- It falls along a curve towards the “cooling curve” for white dwarfs.
- A white dwarf is an electron degenerate star no longer producing energy, merely radiating the energy it produced earlier.

The lowest mass stars can't lift themselves above the Main Sequence, they peter out.

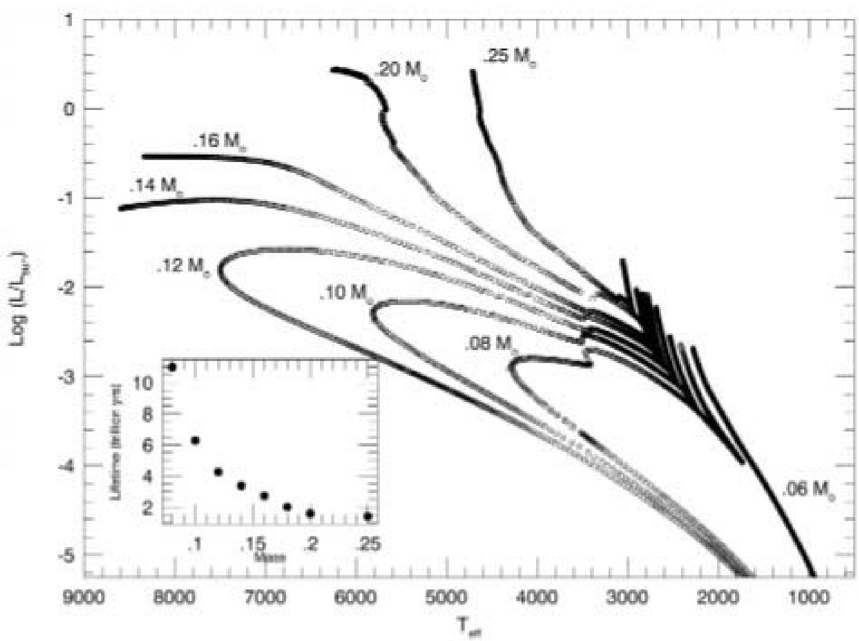


Fig. 2. The H-R diagram for red dwarfs with masses in the range $M_* = 0.08 - 0.25 M_\odot$ (from LBA). Stars with mass $M_* = 0.25 M_\odot$ are the least massive stars can can become red giants. The inset diagram shows the hydrogen burning lifetime as a function of stellar mass. Note that these small stars live for trillions of years.

- The cooling curve for a white dwarf joins these curves as the make a sharp left and head back down in luminosity, as the star becomes completely electron degenerate

At this point, the star would be about the size of the Earth

- But weigh tons per cubic inch.
- Now, no low-mass star has ever done this!
- Why? The Universe is not old enoughyet for any low mass star to have reached the age that they would go completely electron degenerate.
- But our stellar and nuclear physics understanding is quite good. Patience!

Onward to…
Medium Mass Star Evolution

- **H** burning until all core **H** is **He**, then core contracts, releasing gravitational potential energy, raising luminosity and expanding the star ~ x100 times
- Core density and temperature rises until 180 million K. Then…..
- Well, you tell me – what are the options for further fusion? We have **H** and **He** floating around in the core…

The Lithium Beryllium Roadblock

- A main sequence star always has Hydrogen and Helium bouncing around in its core. What can it make from these??
- H^1+He^4 = Li^5 But, this is unstable and will immediately fall apart.
- He^4 + He^4 = Be^8 But, this too is unstable and will immediately fall apart
- The only solution is for the density and temperature to rise 10x higher (to 180M Kelvin), to the point that two He^4 can collide making Be^8 and instantly before it falls apart, get hit with another He^4
- He^4 + He^4 + He^4 = C^{12}, which is ordinary, stable carbon. The “Triple Alpha” process. Helium fusion to make carbon! But, it takes more gravity than the lowest mass stars can muster.
- Medium mass stars like the sun can do it

There are several different ways to produce Helium from Hydrogen fusion

- The Proton-Proton chains (PP2, PP2, and PP3
- For heavier stars than the sun, the CNO cycles, which involve carbon, nitrogen, and oxygen in intermediate steps, is much more complicated even than the PP chains, but whose ultimate net is 4H into 1He, just like the PP chains

This graph shows how tightly bound is the nucleus (for the most common isotope of each element). Iron is the tightest of all.

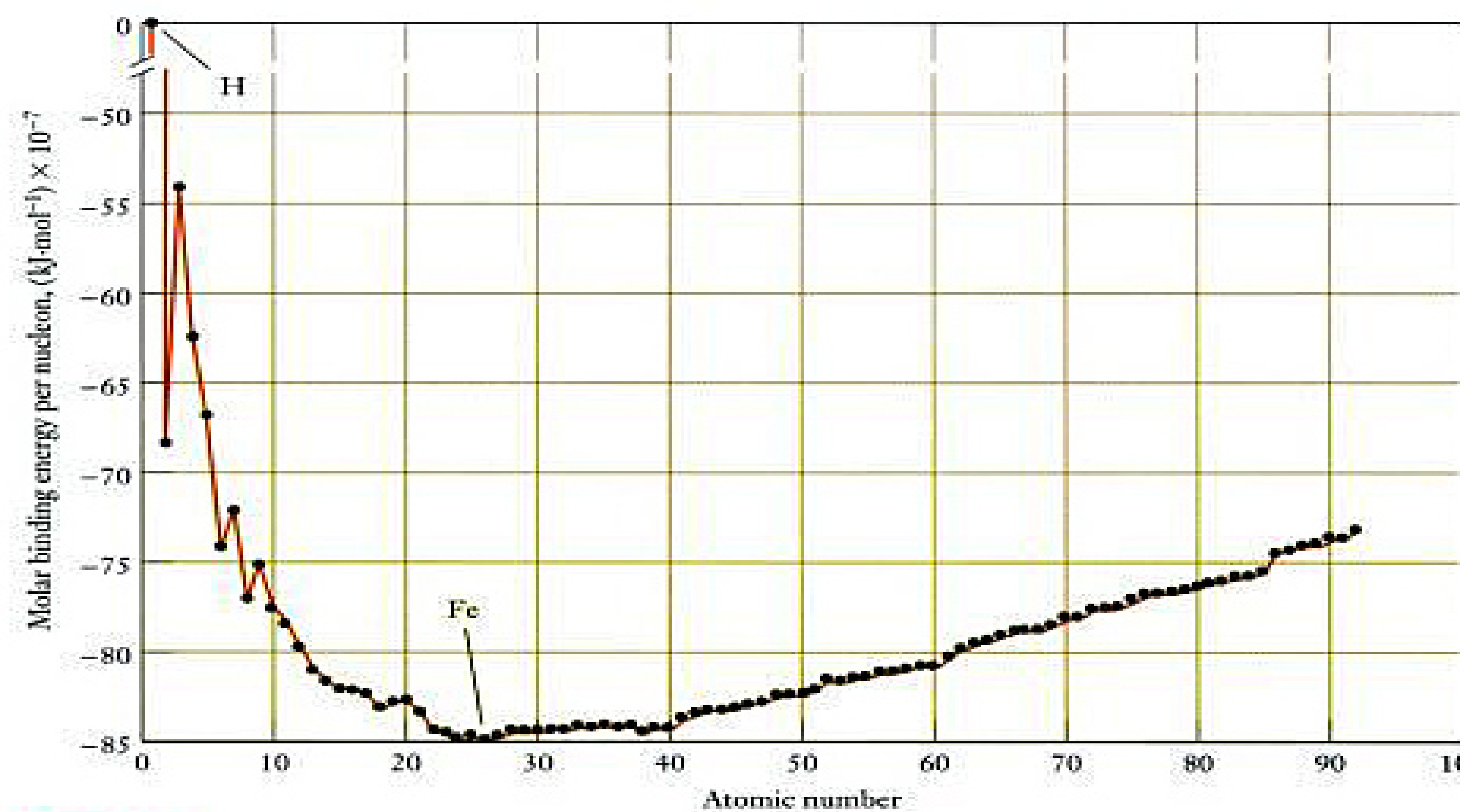
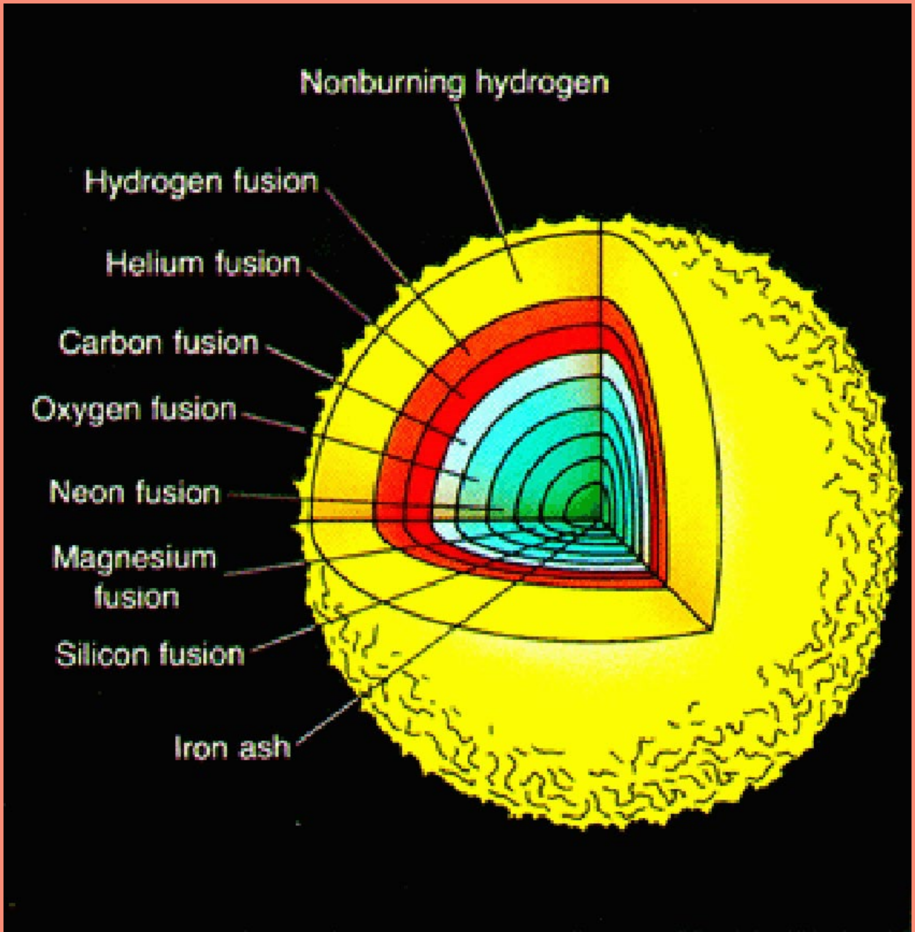


Figure 3.18.

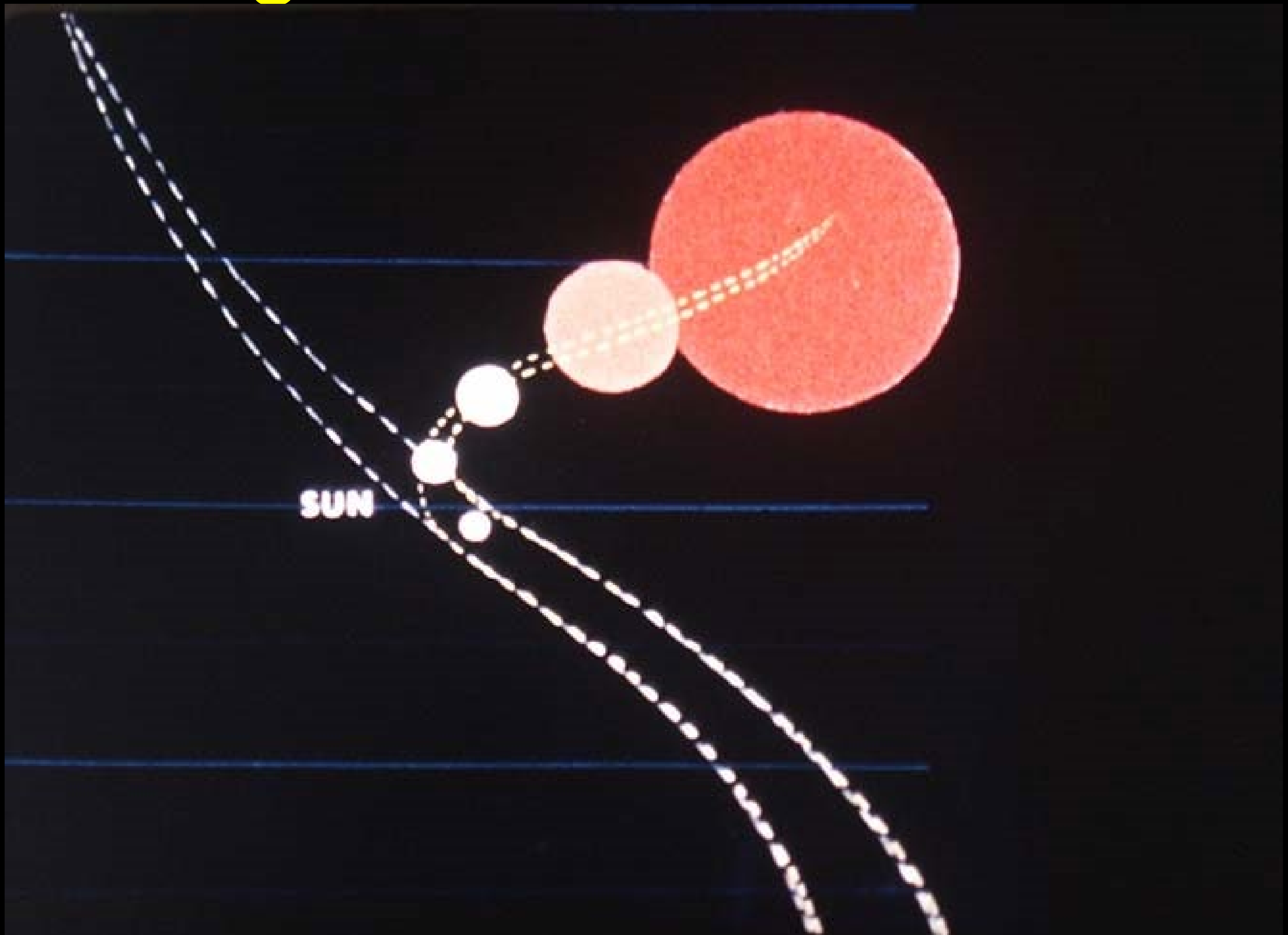
Nuclear binding energy per nucleon. Zero energy on this plot is for hydrogen, $Z = 1$. The lowest energy, most stable nucleus is iron, $Z = 26$.

The core develops like an onion, with layers of heavier fusion elements deeper



- As a fuel becomes entirely converted to a heavier fusion product, that fusion product requires a higher temperature and density for it to fuse into a yet heavier element, which can only happen when the core contracts further

The sun's track, simplified, on the HR Diagram towards a Red Giant



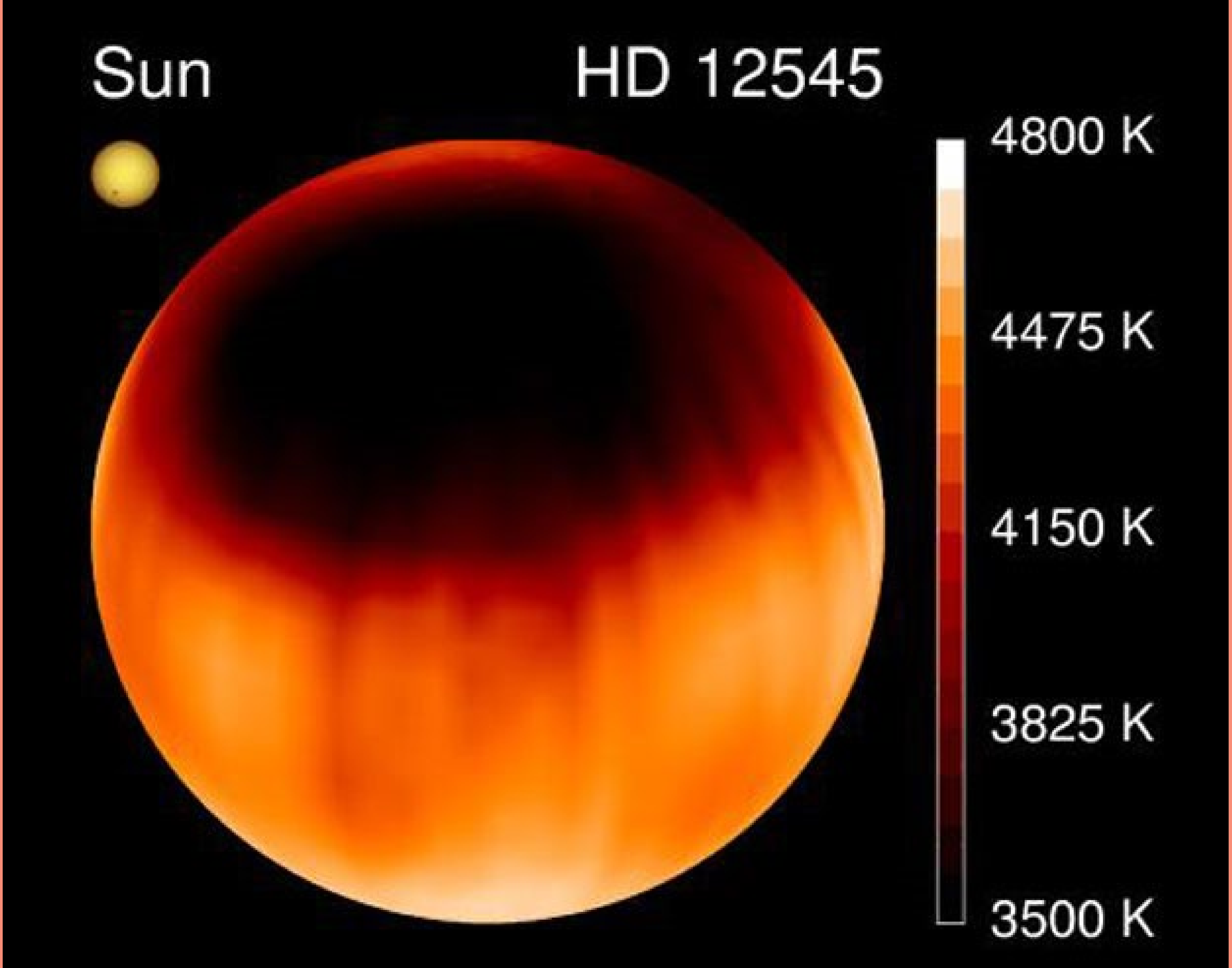

SUN
6,000°C
RED GIANT STA
3,000°C

The Sun isn’t the only star showing magnetic fields and star spots

- Magnetic field activity on the sun is relatively mild compared to many stars, even stars of similar mass and surface temperature. On average, the sun has less variance than most of our similar stellar brothers
- But by far the most dramatic example of star spots is HD 12545 – a chromospherically active star which has had huge spots in the past – star spots!
- And it was discovered right here at Cabrillo Observatory, in early 1990’s! Spawned some good scientific journal papers.

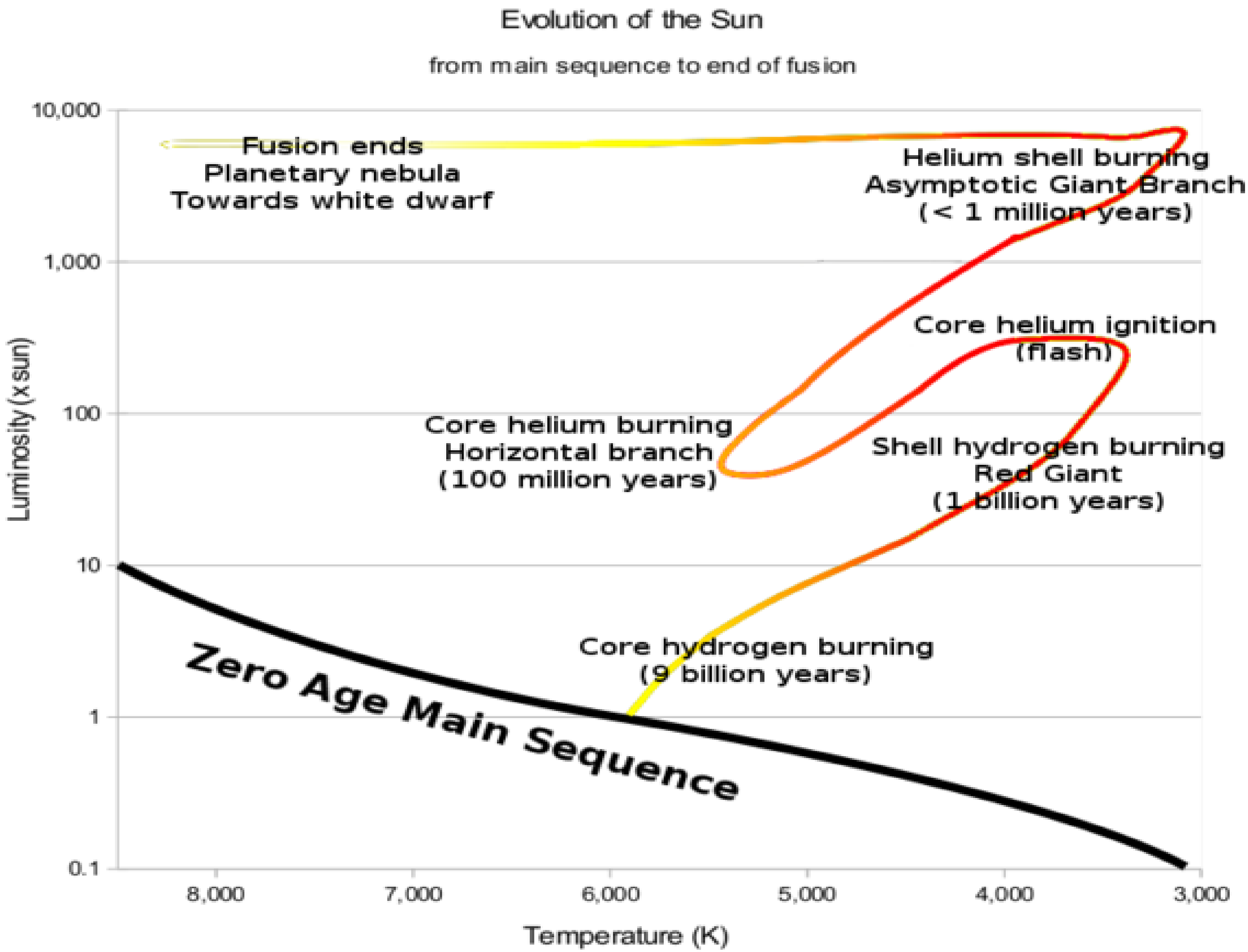
Red Giants Can Have Deep Convection Zones, with Possibility for Large “Star Spots”

- The largest star spot every discovered – was discovered HERE, at Cabrillo College, by me in 1989.
- HD 12545, has a star spot covering MOST of one hemisphere, dropping it’s brightness in HALF especially in the Blue and less so in the Red (star spots are areas of cooler, hence more IR centered light)


Sun
HD 12545
4800 K
4475 K
4150 K
3825 K
3500 K

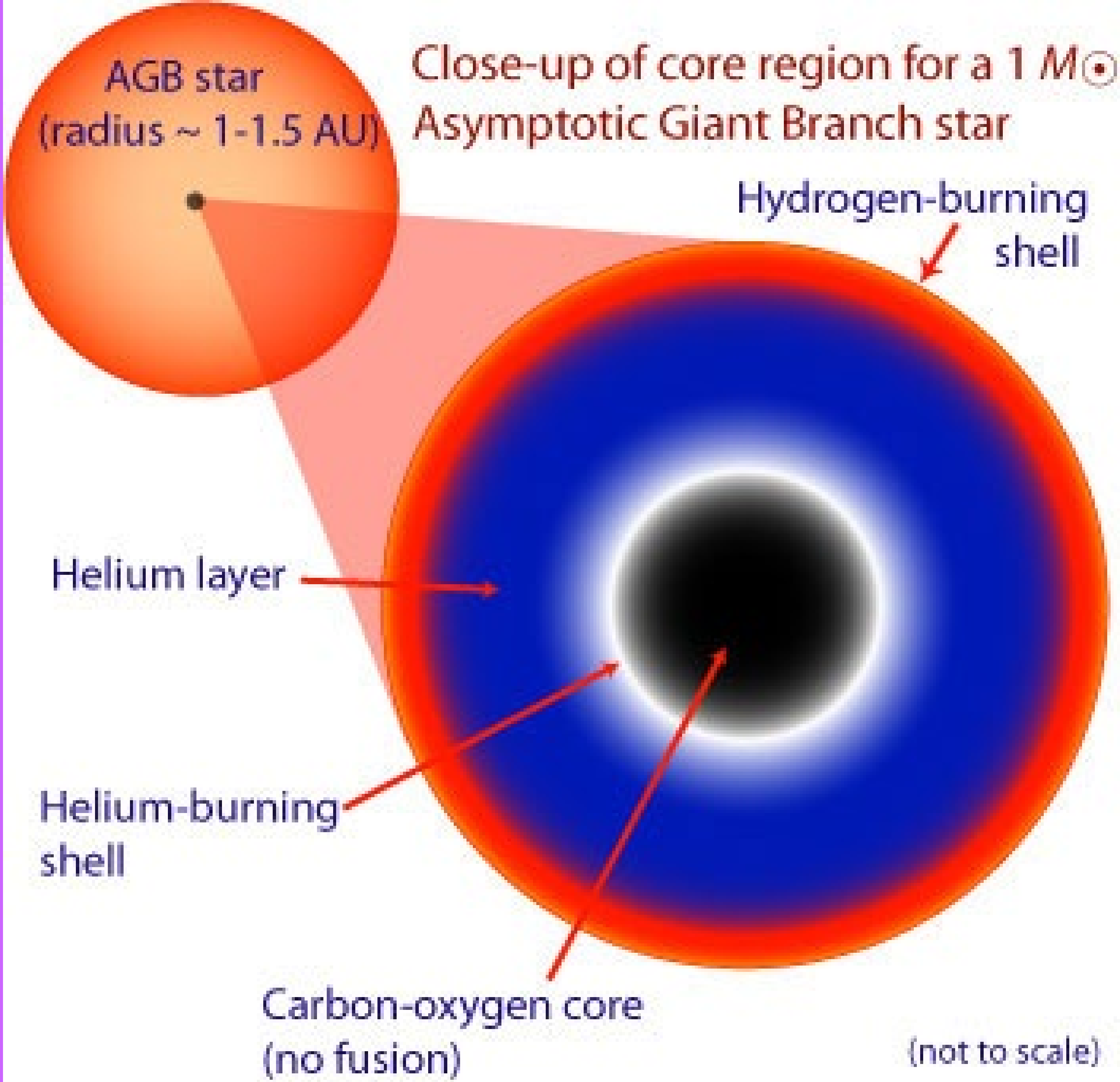
And a Recent new discovery of a large star spot is on XX Triangulum

- Red giant, mapped with “Doppler Imaging”, making use of different parts of star coming towards/away from us at different velocities, allow us to see where the cool *vs* warm areas must be on the star, even though you cannot SEE the disk of the star
- **YouTube reconstruction of rotating XX Tri**


Evolution of the Sun
from main sequence to end of fusion
10,000
1,000
100
10
1
0.1
Luminosity (x sun)
8,000
7,000
6,000
5,000
4,000
3,000
Temperature (K)
Fusion ends
Planetary nebula
Towards white dwarf
Helium shell burning
Asymptotic Giant Branch
(< 1 million years)
Core helium ignition
(flash)
Core helium burning
Horizontal branch
(100 million years)
Shell hydrogen burning
Red Giant
(1 billion years)
Core hydrogen burning
(9 billion years)
Zero Age Main Sequence

Some highlights of previous graph

- Inert helium core develops, held up by degeneracy pressure, with its temperature rising. Rising temp does not cause expansion of core because normal gas pressure is not the support, it's electron degeneracy.
- When temp reaches helium fusion point of ~180M Kelvin, fusion does not cause core expansion because again, it's not held up by normal gas pressure but by degeneracy pressure. So no expansion and no quenching of helium fusion – you instead get runaway fusion "Helium Flash", which then finally breaks the degeneracy. This flash expands the outer envelope so rapidly it cools the hydrogen burning shell, shutting off hydrogen fusion and so the outer luminosity actually goes DOWN temporarily.
- As the helium fusion luminosity rises through higher layers, hydrogen shell burning resumes, luminosity rises, and we have an "asymptotic giant branch" star.
- Helium fuses to carbon, to oxygen, and then onward.
- Most stars in the disk of our galaxy inherit heavy elements like iron from earlier generations of stars which went through advanced fusion stages and exploded. These heavy elements can act as seeds, and neutrons freed in the fusion processes (mainly starting with C^{13} and Ne^{22}) slamming into these heavy element seeds, can create about half of the isotopes of elements heavier than iron, by the S-Process . Follow link for more details.

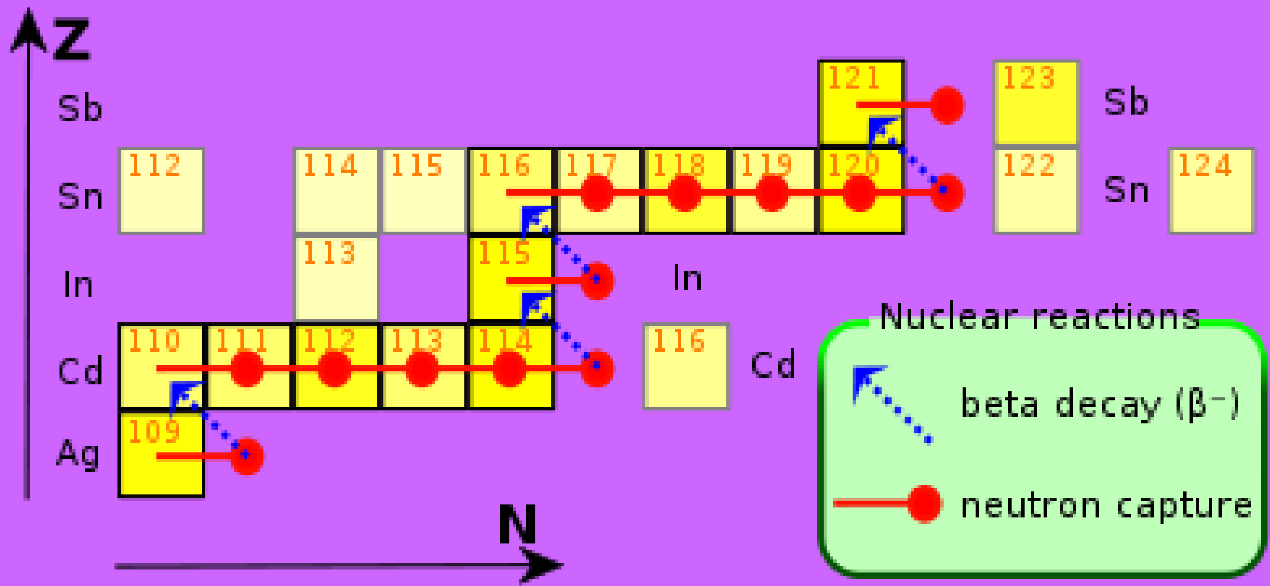


Close-up of core region for a 1 $M_\odot$
Asymptotic Giant Branch star
AGB star
(radius ~ 1-1.5 AU)
Hydrogen-burning
shell
Helium layer
Helium-burning
shell
Carbon-oxygen core
(no fusion)
(not to scale)

Three Processes of Nuclear Fusion

- "**s-Process**": the "slow" process, capture of neutrons slowly, involves radioactive decay between steps and so a different path upward through the Periodic Table, common in AGB Red Giants
- **"r-process":** the "rapid" process – nuclei are hit with neutrons so fast they can't radioactively decay, and neutron-rich nuclei can be made this way. Supernovae (see later) involve a lot of this
- "**p-process**": similar to the r-process, but it's protons, not neutrons, hitting the nuclei.

S-Process; an example starting with Silver (Ag) as the seed, to Antimony



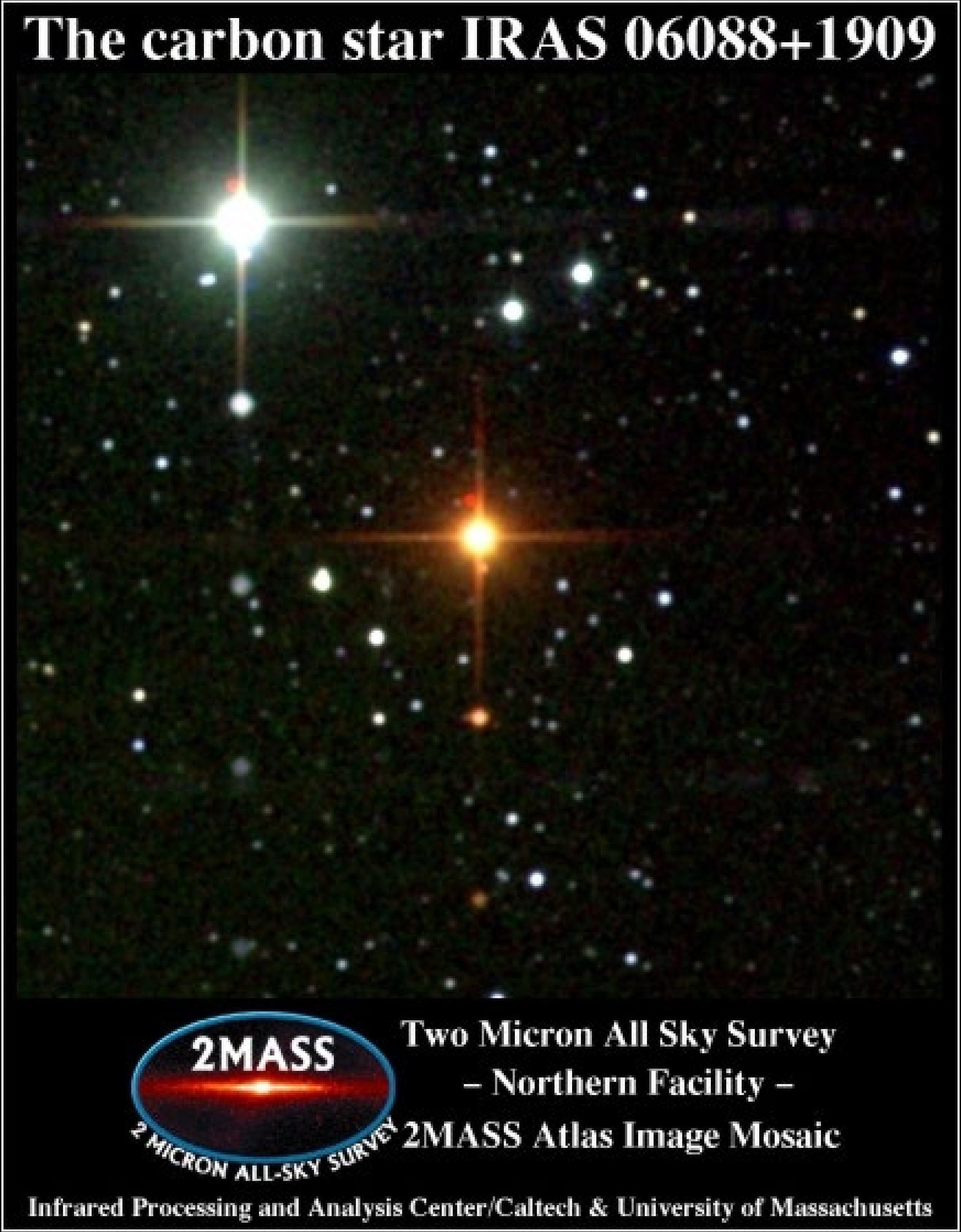
- What do you need to remember of red giant details for exams? Very little – just that **medium mass stars can nuclear fuse elements up to but not including iron**, and **each reaction takes higher temperature and delivers less luminosity so it goes quicker**.
- Know H, He, C, and importance of Iron.

Stages of the Evolution of the Sun and Other 1 Solar Mass Stars

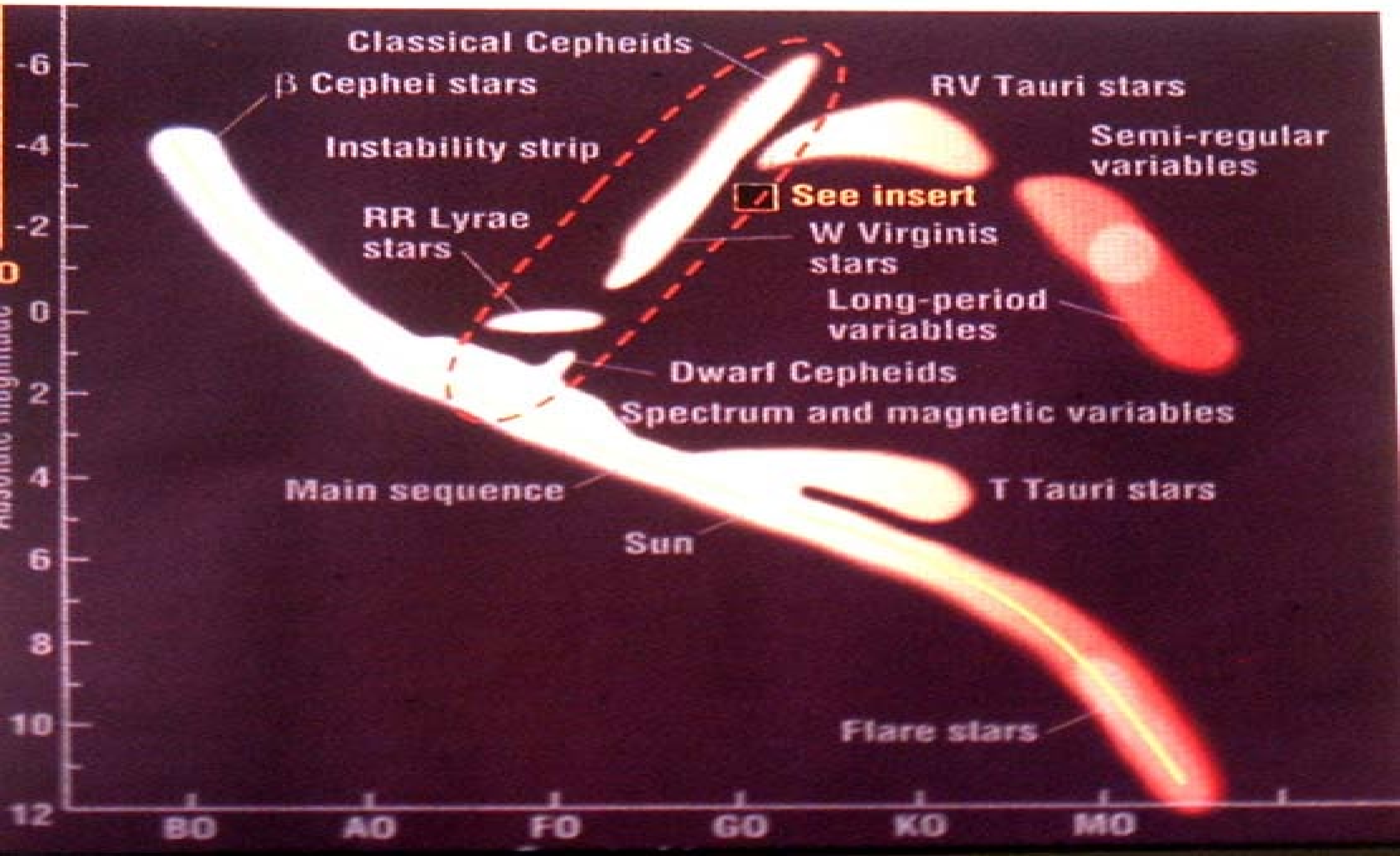
- Main Sequence Star: 11 Byr
- Red Giant Star: 1.3 Byr
- Horizontal Branch Star: 100 Myr
- Asymptotic Giant Branch Star: 20 Myr
- Thermal Pulsation Phase: 400,000 yr
- Planetary Nebula Phase: ~10,000 yr
- 0.54 solar mass White Dwarf: final state
- Notice the sun will lose ~half its mass before ending as a white dwarf
- Animated GIF of HR evolution

Carbon Stars

- Some red giants very deep convection zones, all the way down to the core, and have excess carbon *vs.* oxygen.
- The carbon is dredged up by convection to the surface during the complex later stages of shell burning.
- Stellar winds blow this carbon outward.
- The oxygen is entirely used up making CO, leaving the remaining carbon to make graphite
- These graphite grains are dust, and much like “PigPen” from the “Peanuts” cartoon, they shroud themselves in their own dust, reddening the star dramatically
- **<u>Since carbon is essential for life, carbon stars are very important to getting carbon out of stars and into the interstellar medium where it can become part of later generations of stars, as happened with our solar system – WE are made of carbon, after all!</u>**

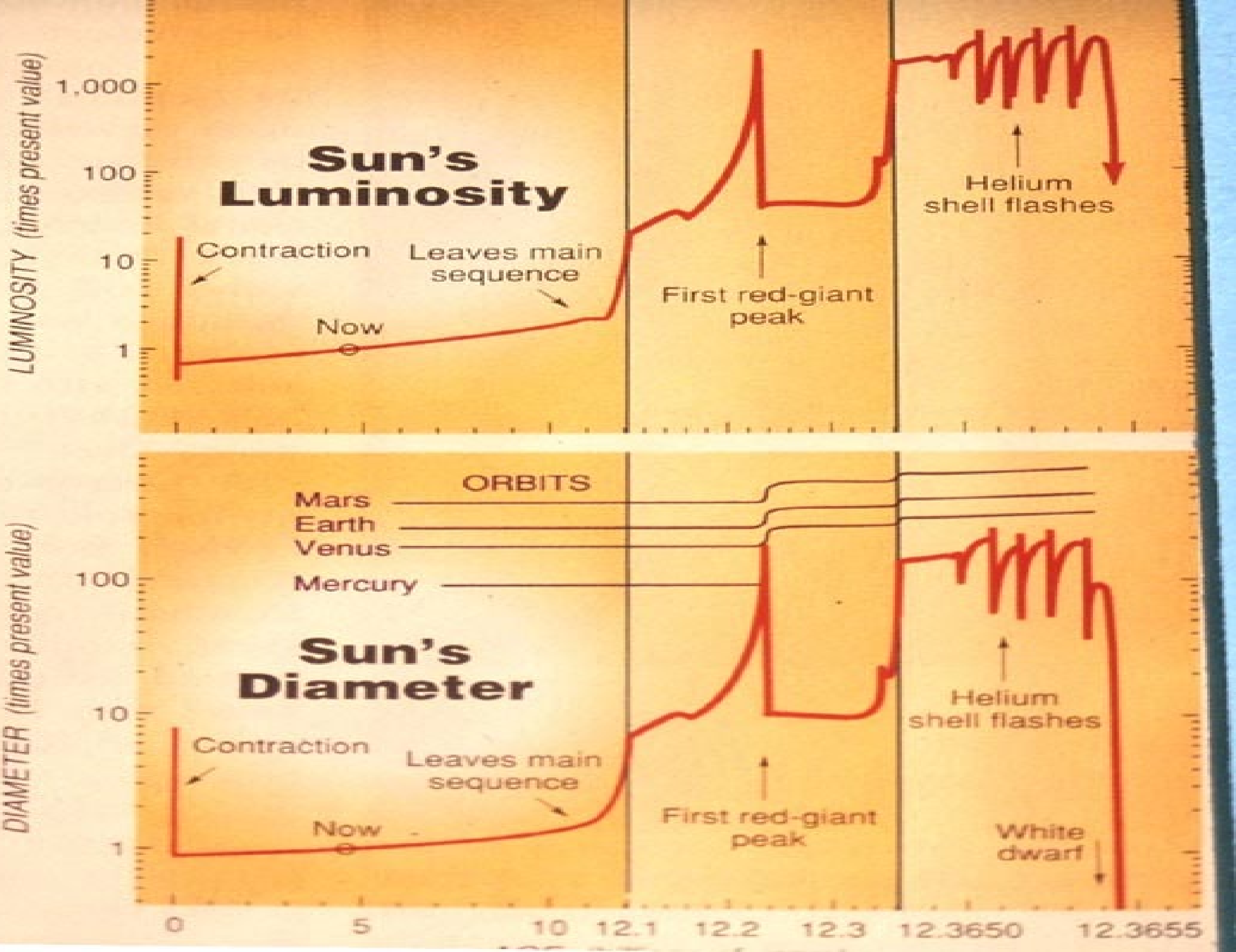

The carbon star IRAS 06088+1909
2MASS
2 MICRON ALL-SKY SURVEY
Two Micron All Sky Survey
– Northern Facility –
2MASS Atlas Image Mosaic
Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Red dotted Area: The Instability Strip, where stars will pulsate. Too many types to remember; but do remember Cepheids (we'll cover later)



The End of the Line for Medium Mass Stars like the Sun…

- Added luminosity is so strong, it lifts the red giant’s low density outer envelope completely off the star.
- As it expands, its opacity drops and we see to a deeper and deeper and hotter and hotter depth, so the star moves left on the HR diagram
- Until… we see the ***electron degenerate*** core; the new white dwarf created at the center
- This core can now cool, as it can’t collapse further and it is exposed to the cold of outer space.
- Thus, it follows the cooling curve of a white dwarf; down and to the right on the HR diagram
- So, what we see is a hot stellar corpse surrounded by an expanding and thinning cloud of fluorescent gas = ***a Planetary Nebula***


LUMINOSITY (times present value)
1,000
100
10
1
Sun's Luminosity
Contraction
Leaves main sequence
Now
First red-giant peak
Helium shell flashes
DIAMETER (times present value)
100
10
1
ORBITS
Mars
Earth
Venus
Mercury
Sun's Diameter
Contraction
Leaves main sequence
Now
First red-giant peak
Helium shell flashes
White dwarf
0
5
10
12.1
12.2
12.3
12.3650
12.3655

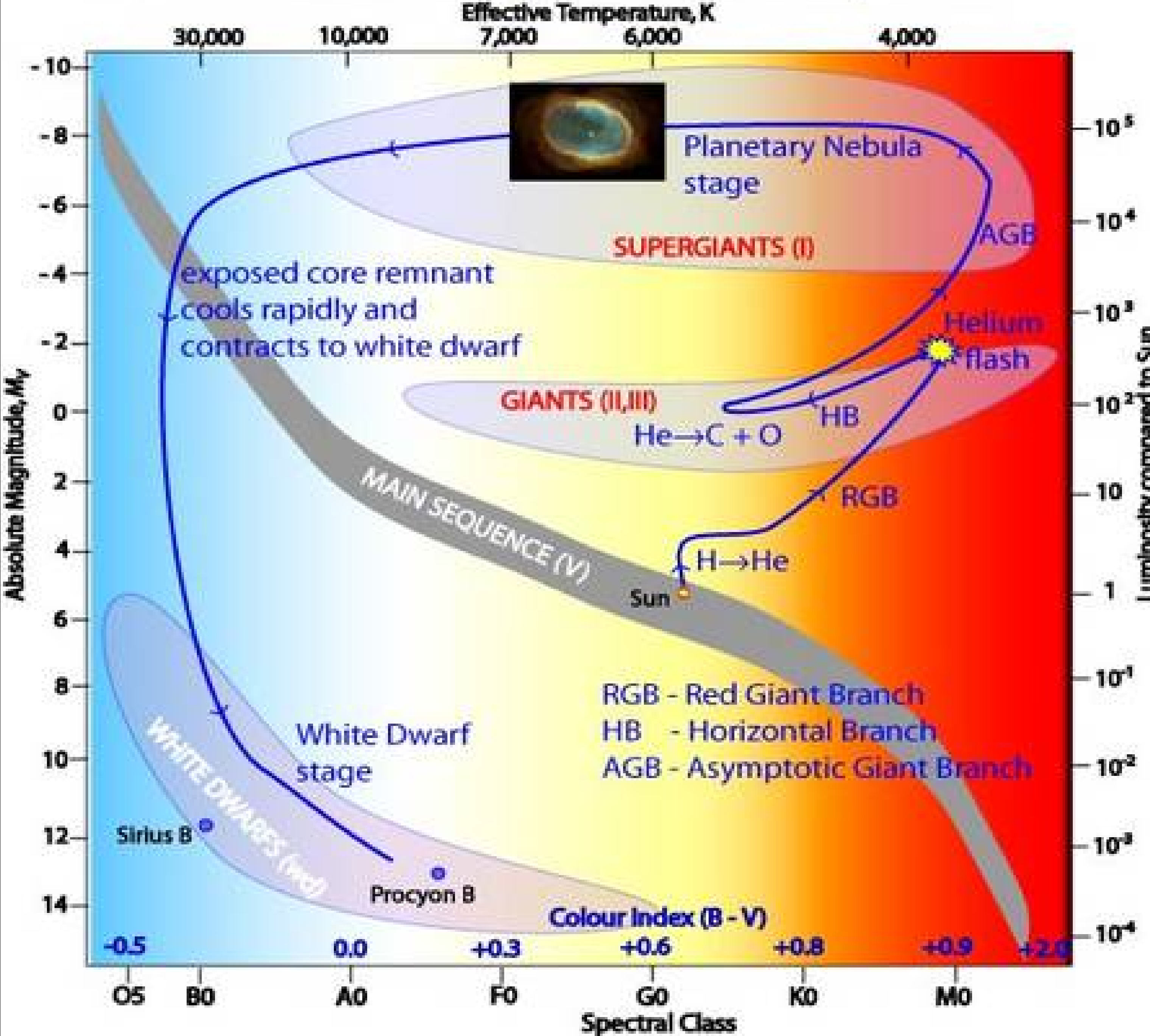
ew billion years from now, with atmosphere and ocean boiled away by a growing post-main-sequence Sun, lif
ne to an end. Humankind — or whatever it has evolved into — may flourish elsewhere in the galaxy. But as I
The Last Three Minutes, we can't run forever. Painting © 1991 David A. Hardy/Astro Art.

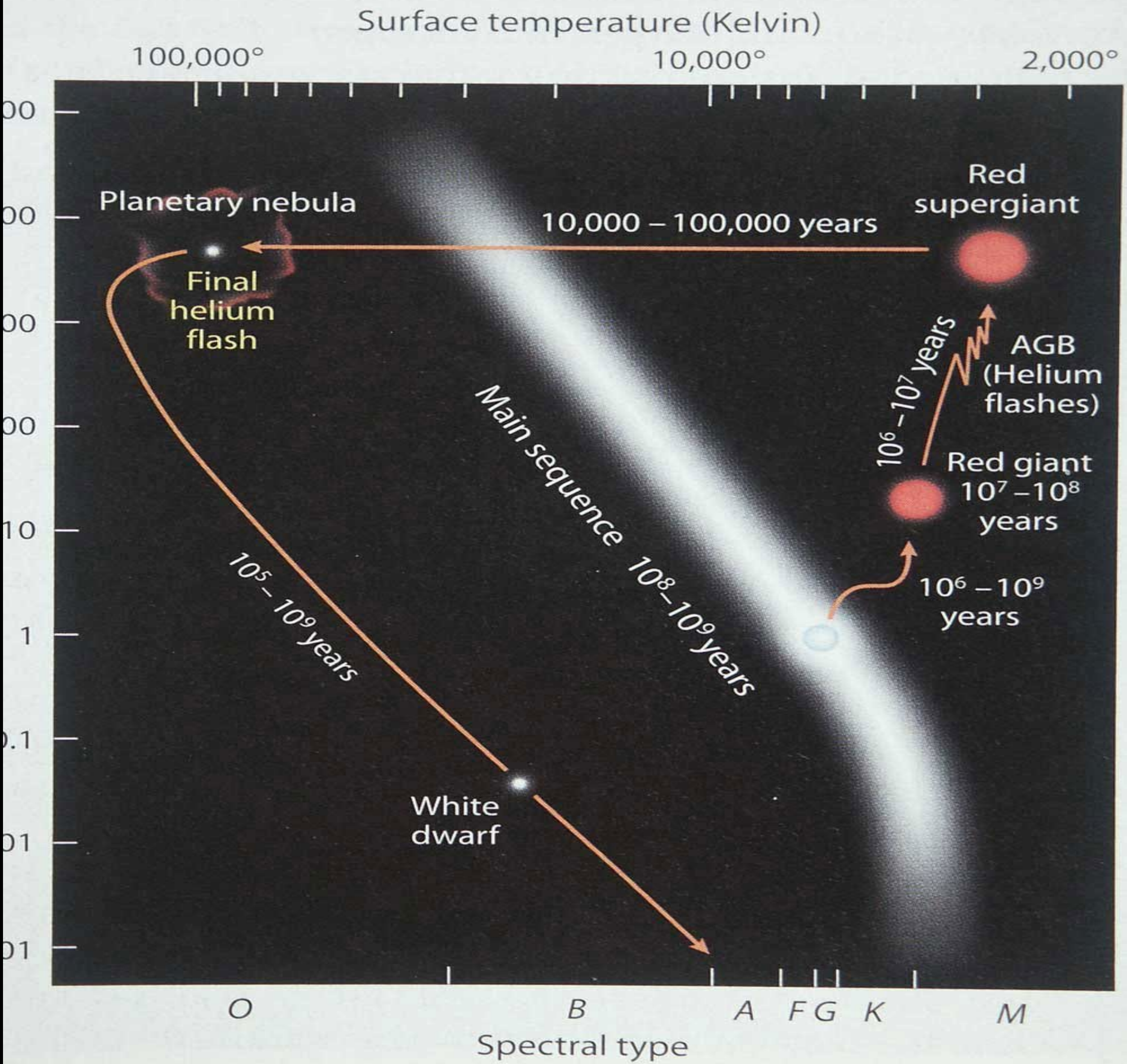
We're All Doomed!

“Planetary Nebula??”

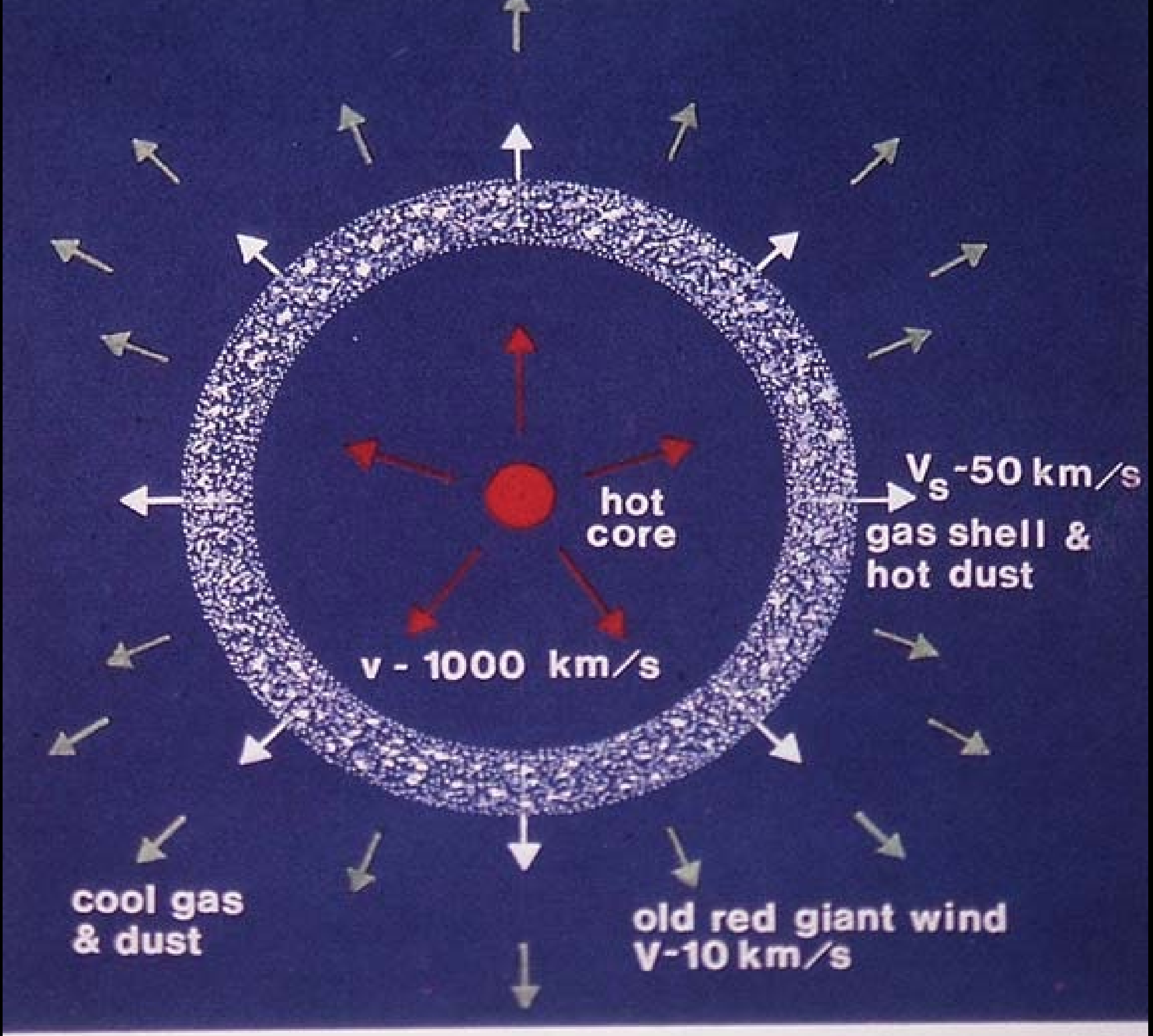
- The name can be misleading – it’s a nod to the history of their discovery.
- One of the first discovered was the Eskimo Nebula, a little greenish disk that looks remarkably like the planets Uranus and Neptune, in 18th century telescopes (as we’ll see)
- Some early discoverers got excited thinking they’d discovered a new planet! The Eskimo Nebula is in Gemini, on the ecliptic plane where the other planets live, and so it’s not a ridiculous notion for the time
- But, they’ve actually got NOTHING to do with planets.

Sun's Post-Main Sequence Evolutionary Track



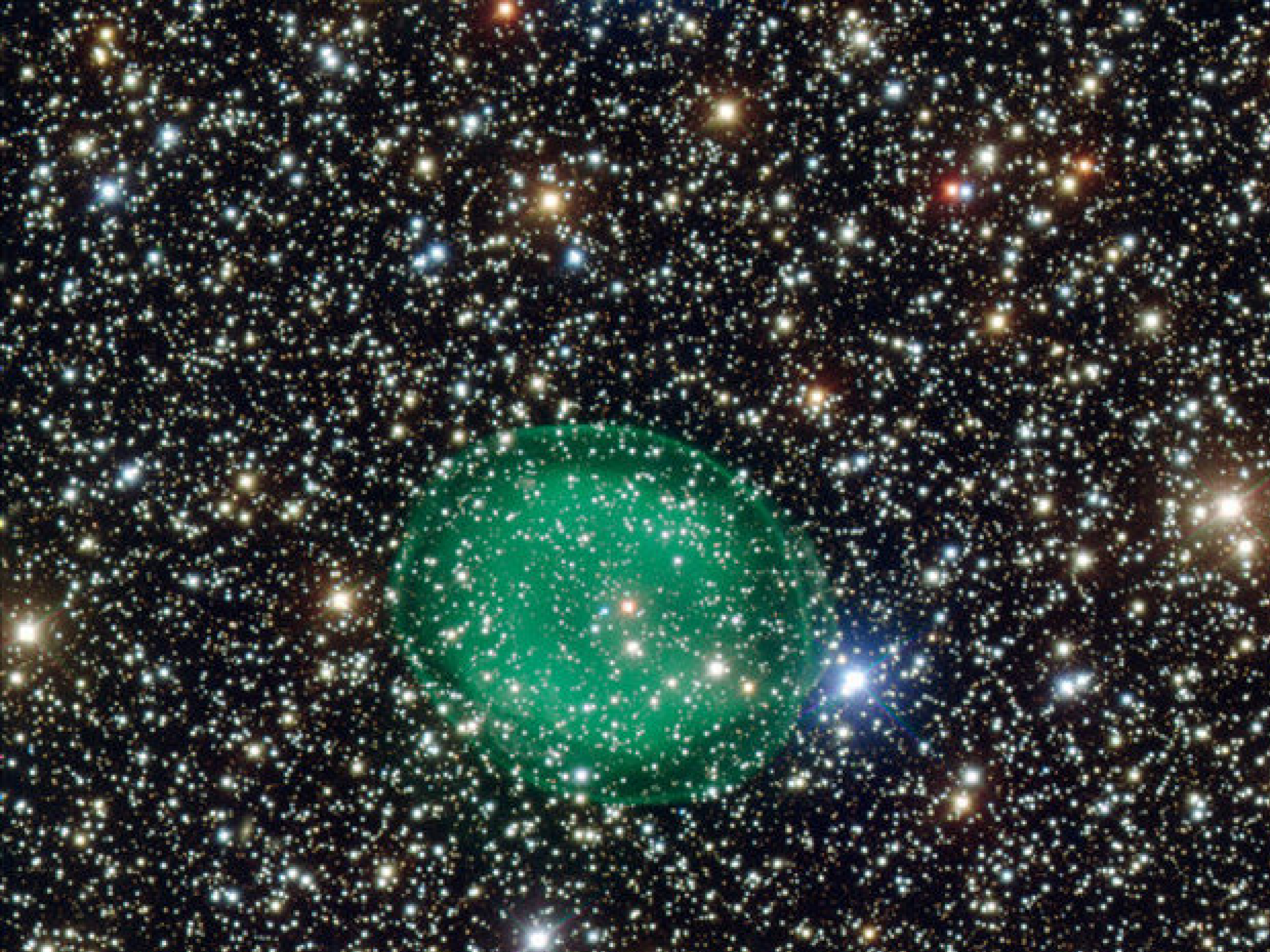


Surface temperature (Kelvin)
100,000°
10,000°
2,000°
Planetary nebula
Final
helium
flash
10,000 – 100,000 years
Red
supergiant
AGB
(Helium
flashes)
10⁶–10⁷ years
Red giant
10⁷ –10⁸
years
10⁶ –10⁹
years
Main sequence 10⁸–10⁹ years
10⁵– 10⁹ years
White
dwarf
10
1
O
B
A
F
G
K
M
Spectral type

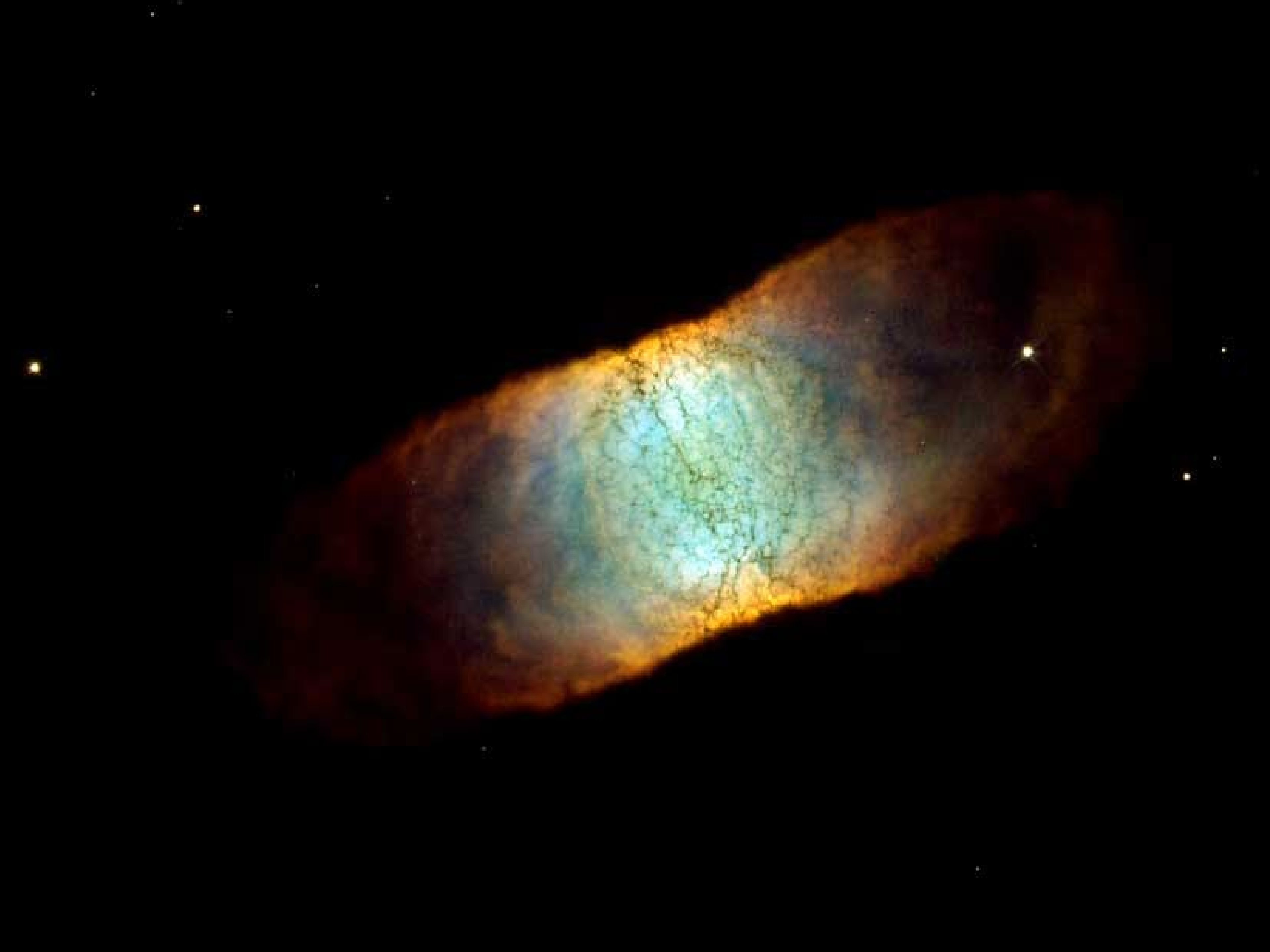


This schematic diagram illustrates the "snowplow" model of planetary nebula formation. The green arrows represent the remnant low-speed stellar wind ejected during the previous red-giant phase, while the red arrows show the newly developed fast wind from the recently exposed hot core of the giant. The white material is the high-density pileup of gas at the interface of the two winds, which we observe as a planetary. Courtesy Sun Kwok.

Doubly Ionized Oxygen produces a Green Emission Line at 501nm, if core is very hot, like here, in **the Eskimo Nebula**

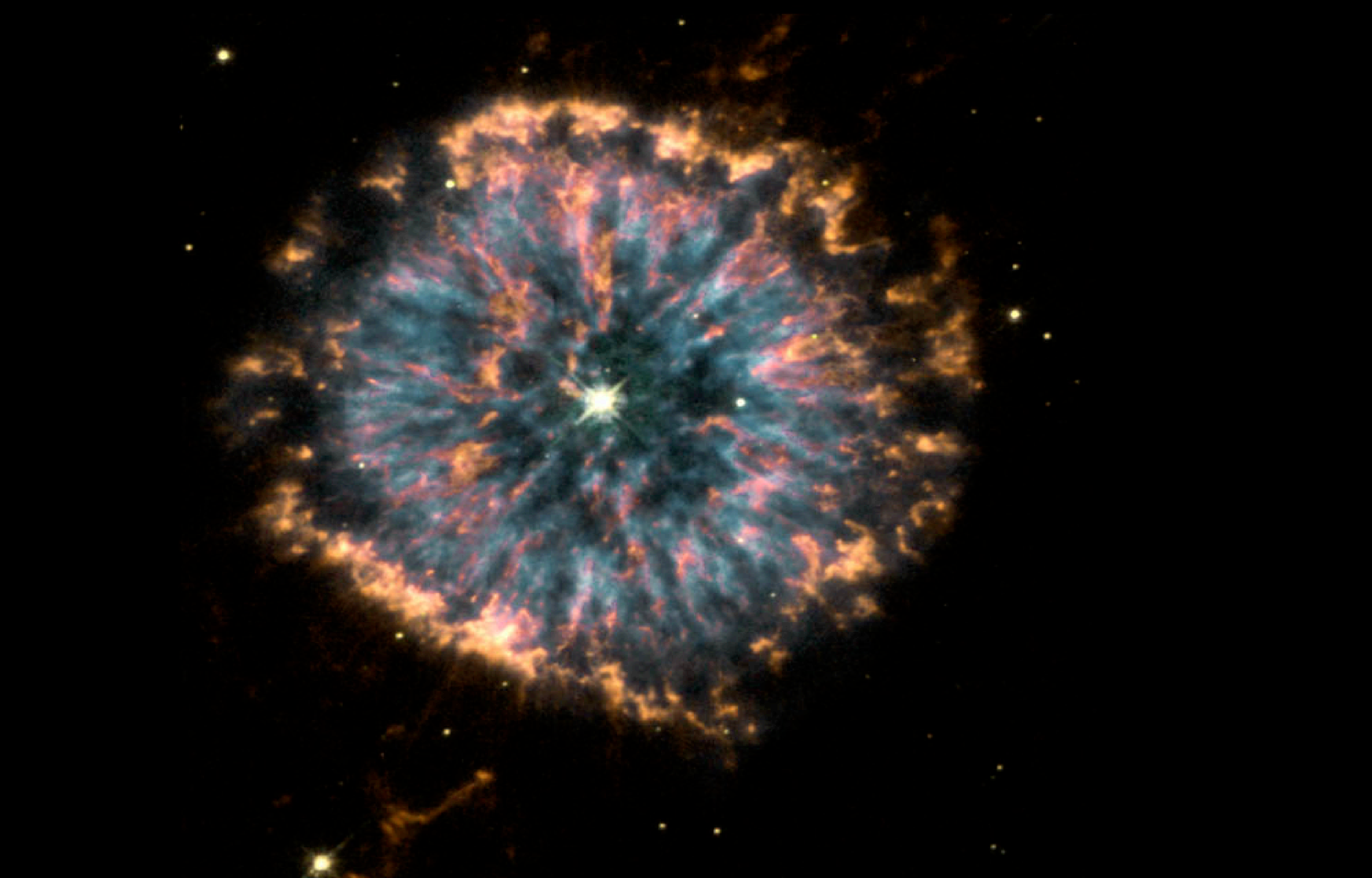


Hubble

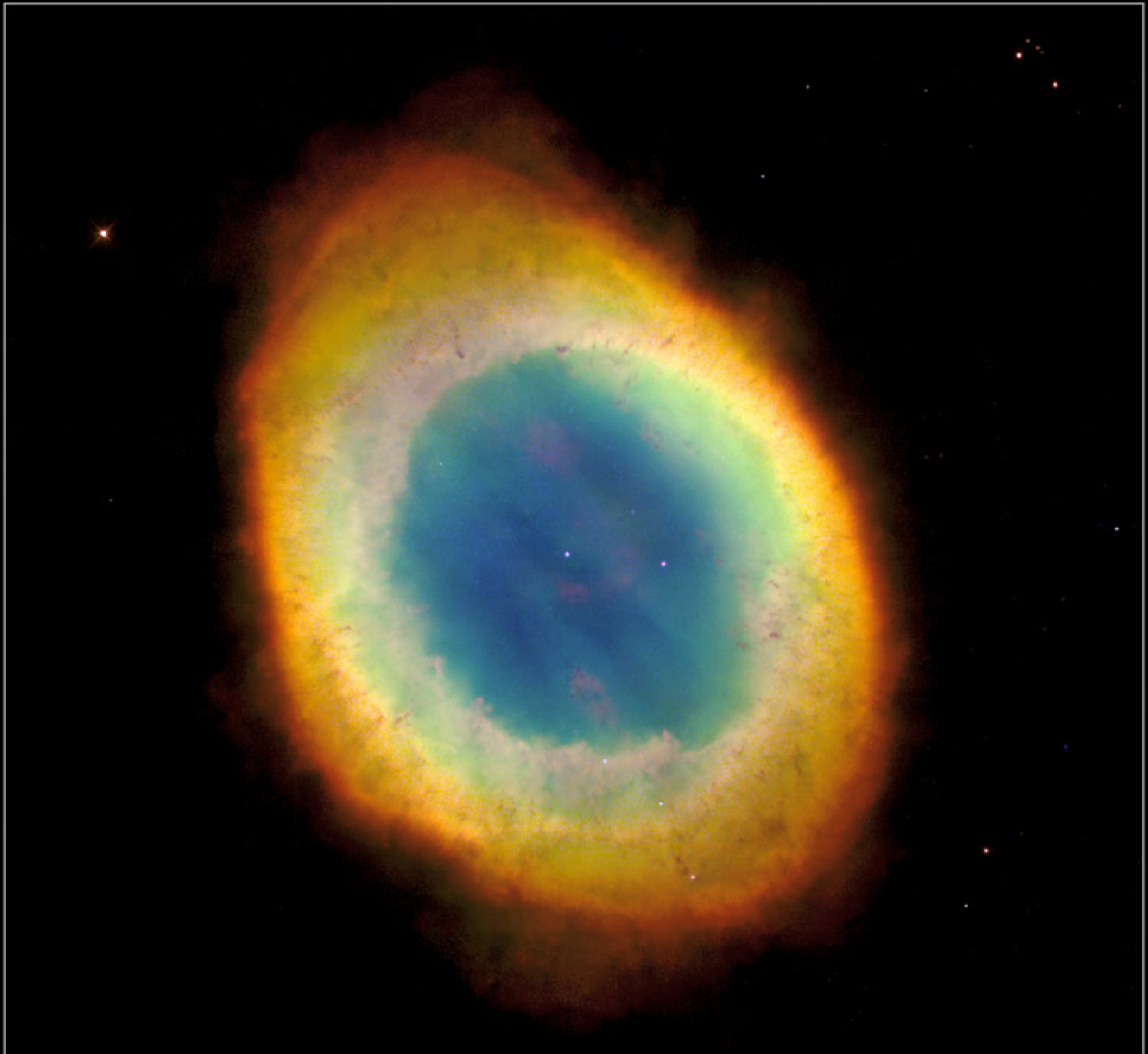


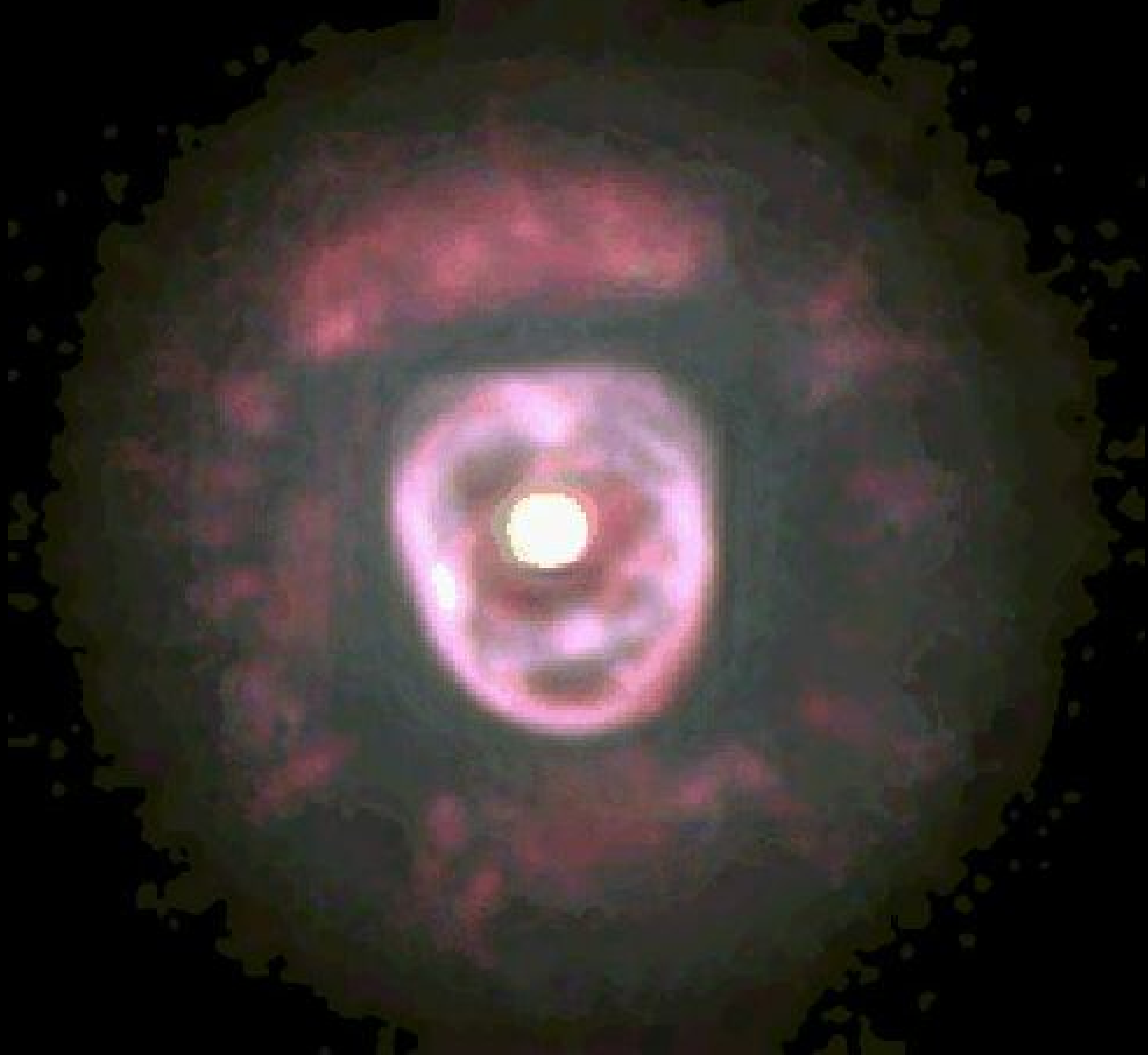
NGC 2440

Planetary Nebula NGC 6751



Ring Nebula



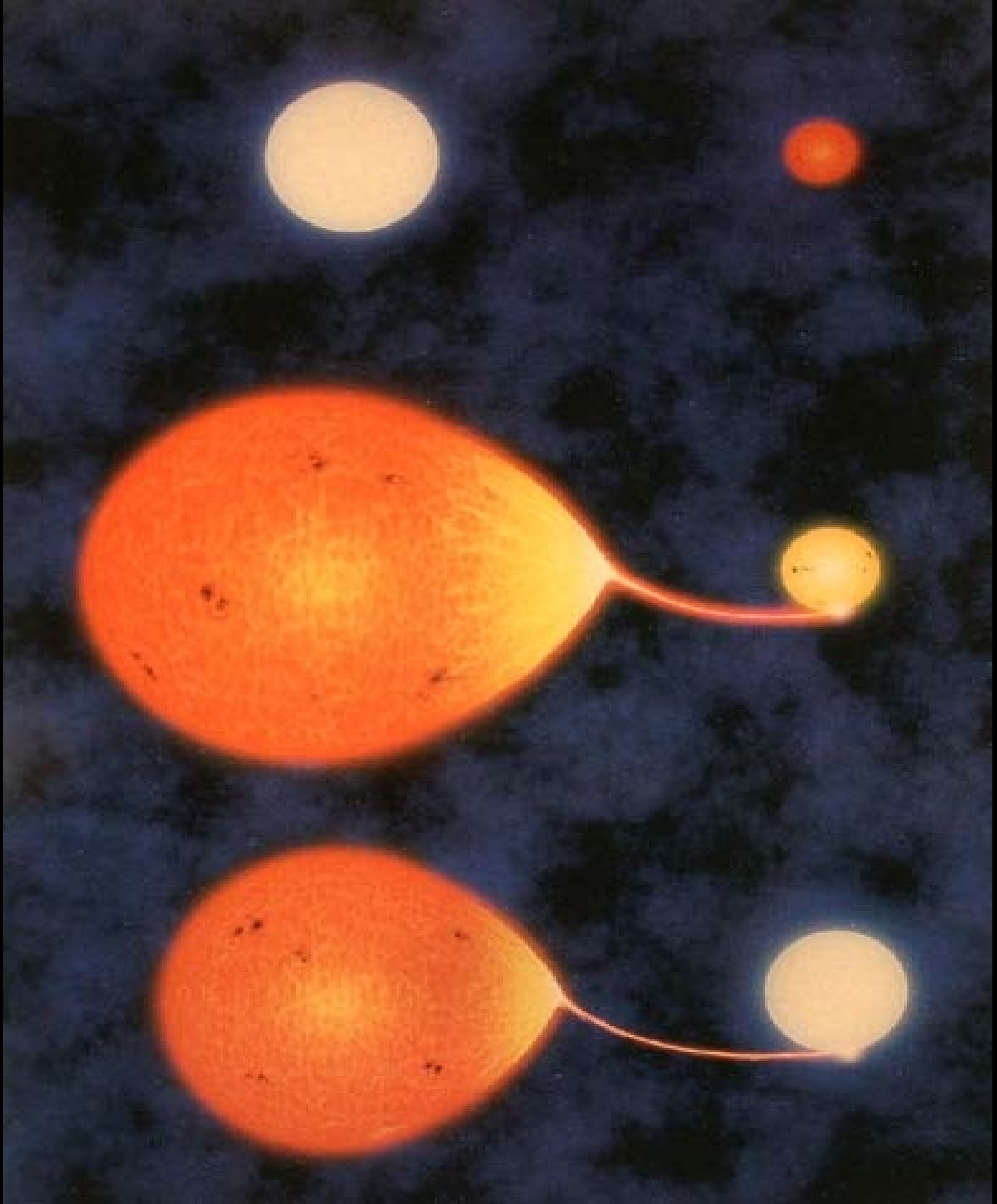


What Happens to old White Dwarfs?

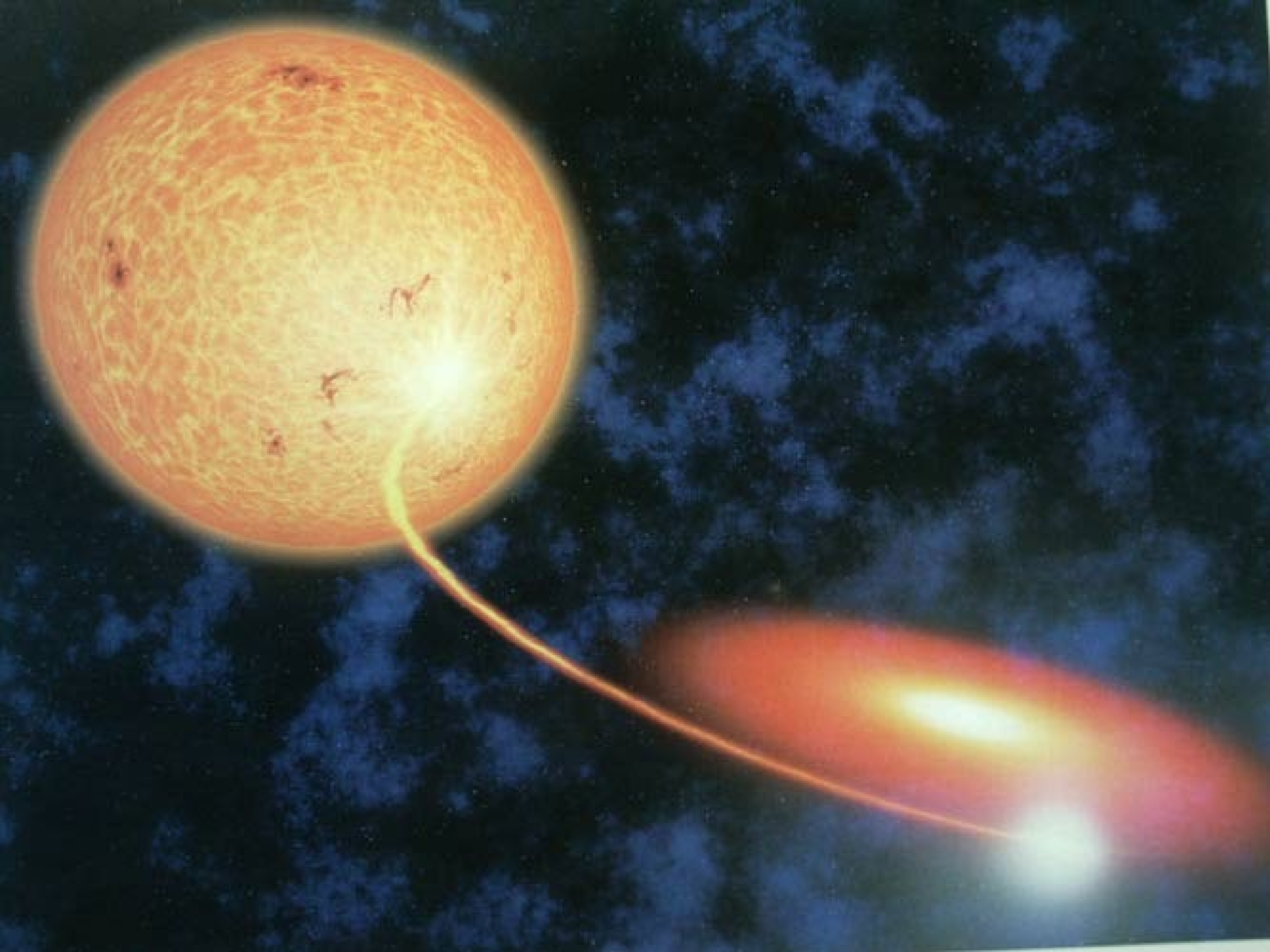
- “They just …..fade away”
- Medium mass star white dwarfs (the only ones around today) are made mostly of carbon, and as they cool, the carbon can crystallize into… diamond!
- We actually see vibrations in some white dwarfs which tell us it’s transforming into crystalline carbon – a form of diamond
- Diamonds in the sky!

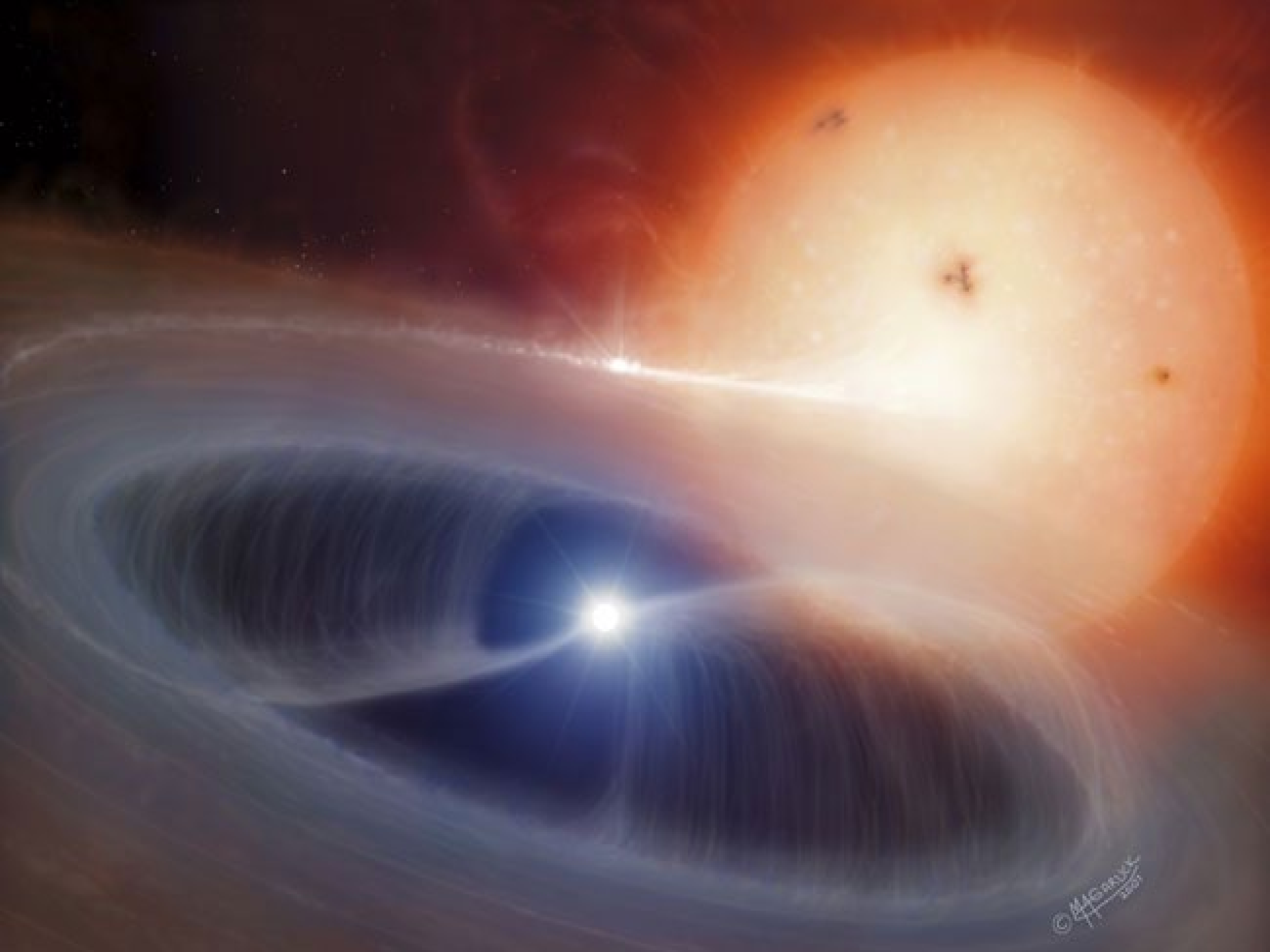
What happens if the stars are in a close binary system?

- This happens a lot. Nearly half the stars in our Galaxy are members of binary star systems
- ***Roche lobe*** defines gravitational "backyard" for each star



A Mass transfer binary. Red Giant overfills Roche Lobe and dumps onto compact companion

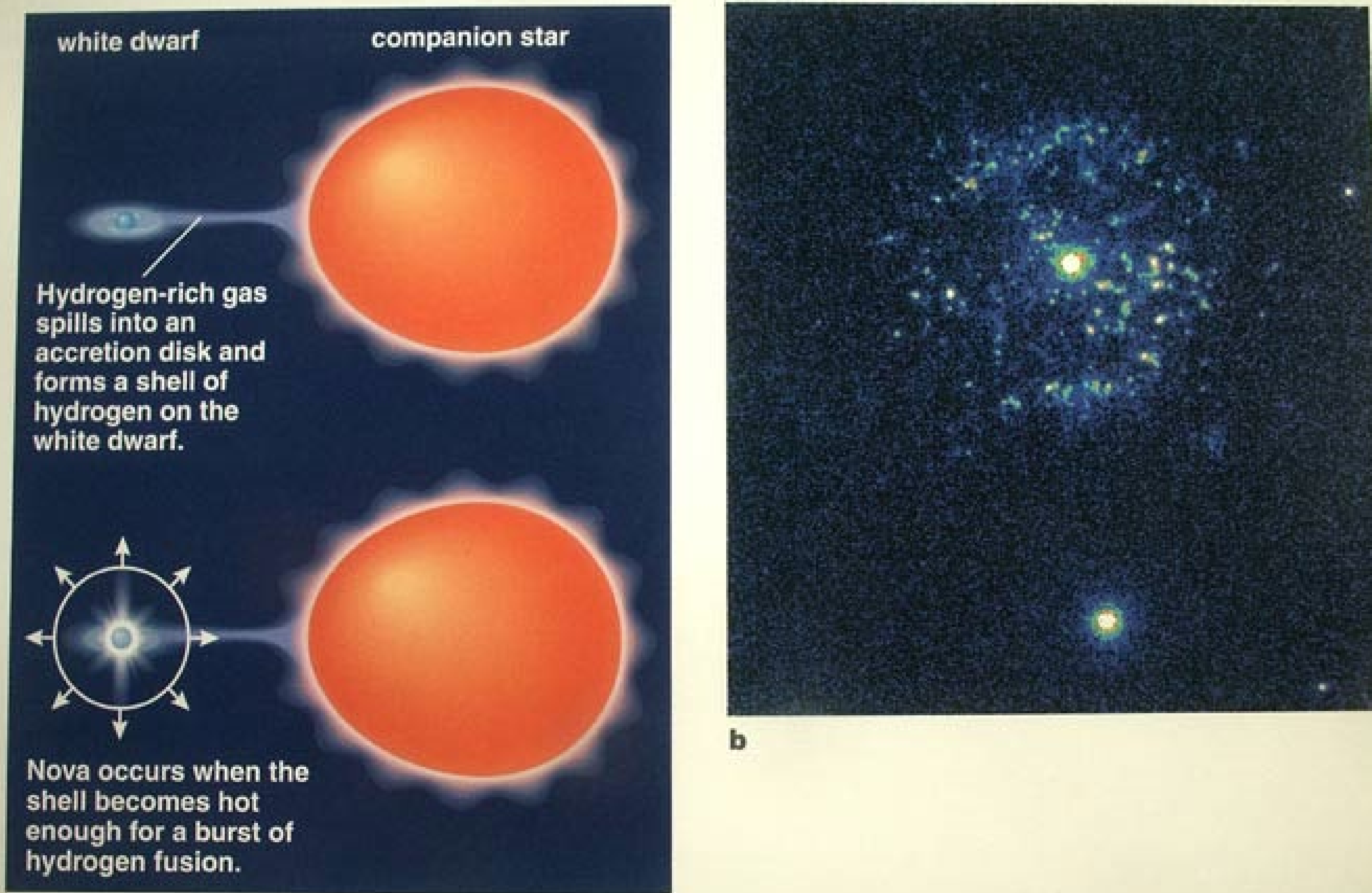




The Hot Carbon core was at least 180 Million K – far above the fusion temperature of hydrogen

- But the skin will likely be only a million K or less, since it's exposed to the cold of oute space, and radiates to it while the companion star is evolving
- But now, the material being dumped on it from the other star is from the outermost layer, which is unburned and so is mostly hydrogen!
- Danger! The hydrogen will be a blanket which heats up at the surface of the white dwarf, till it hits ~18 Million K and then the hydrogen all fuses to helium at once – a big NOVA explosion!
- **This is a NOVA (not a supernova)**

Figure 15.2 Nova mechanism



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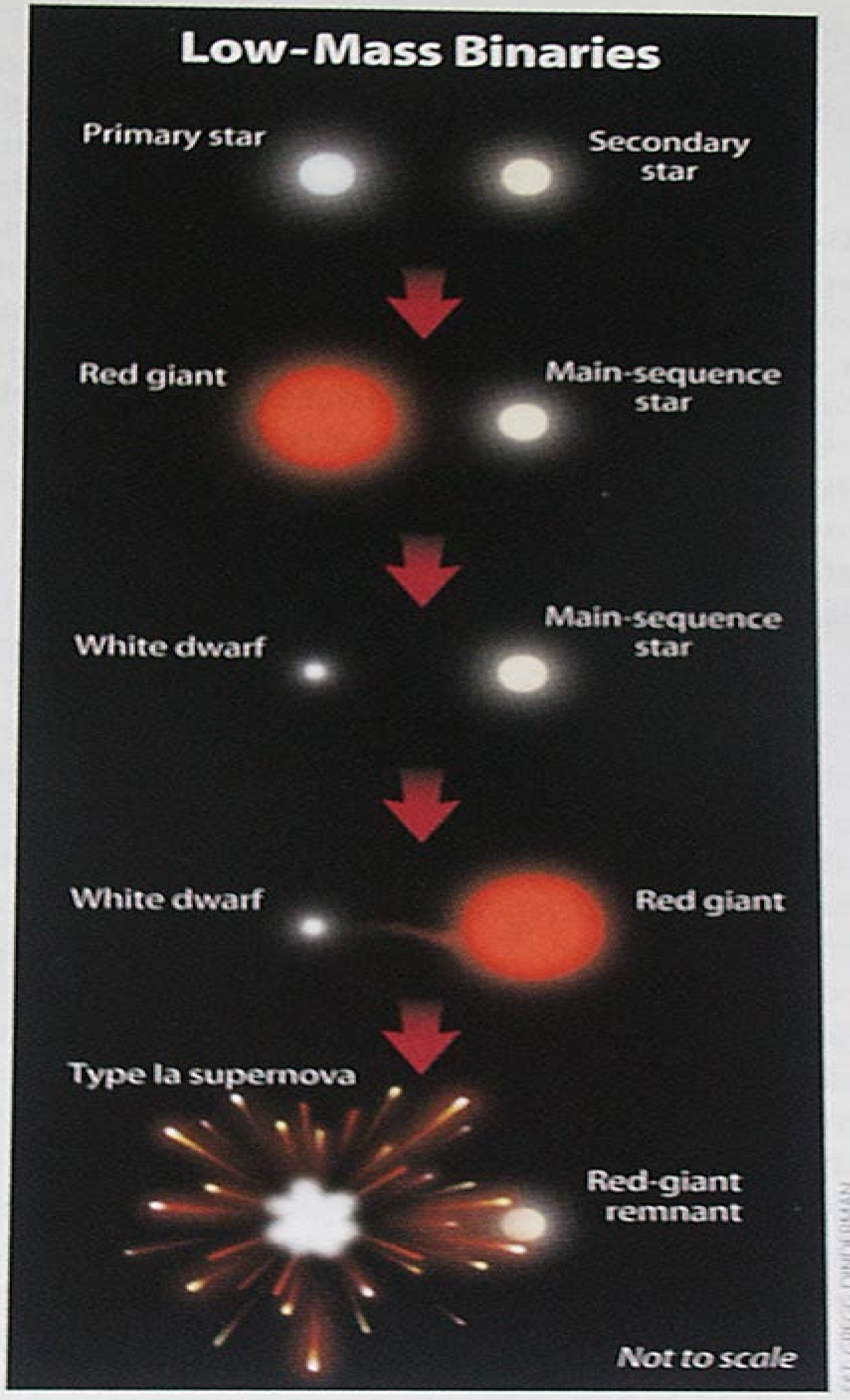
But with all this mass falling onto the white dwarf, there’s another possibility…

- … something more ominous… more terrifying… more…. *Scary!*
- You tell ME - What could that BE?!

Carbon Bomb Supernova (SN type Ia)

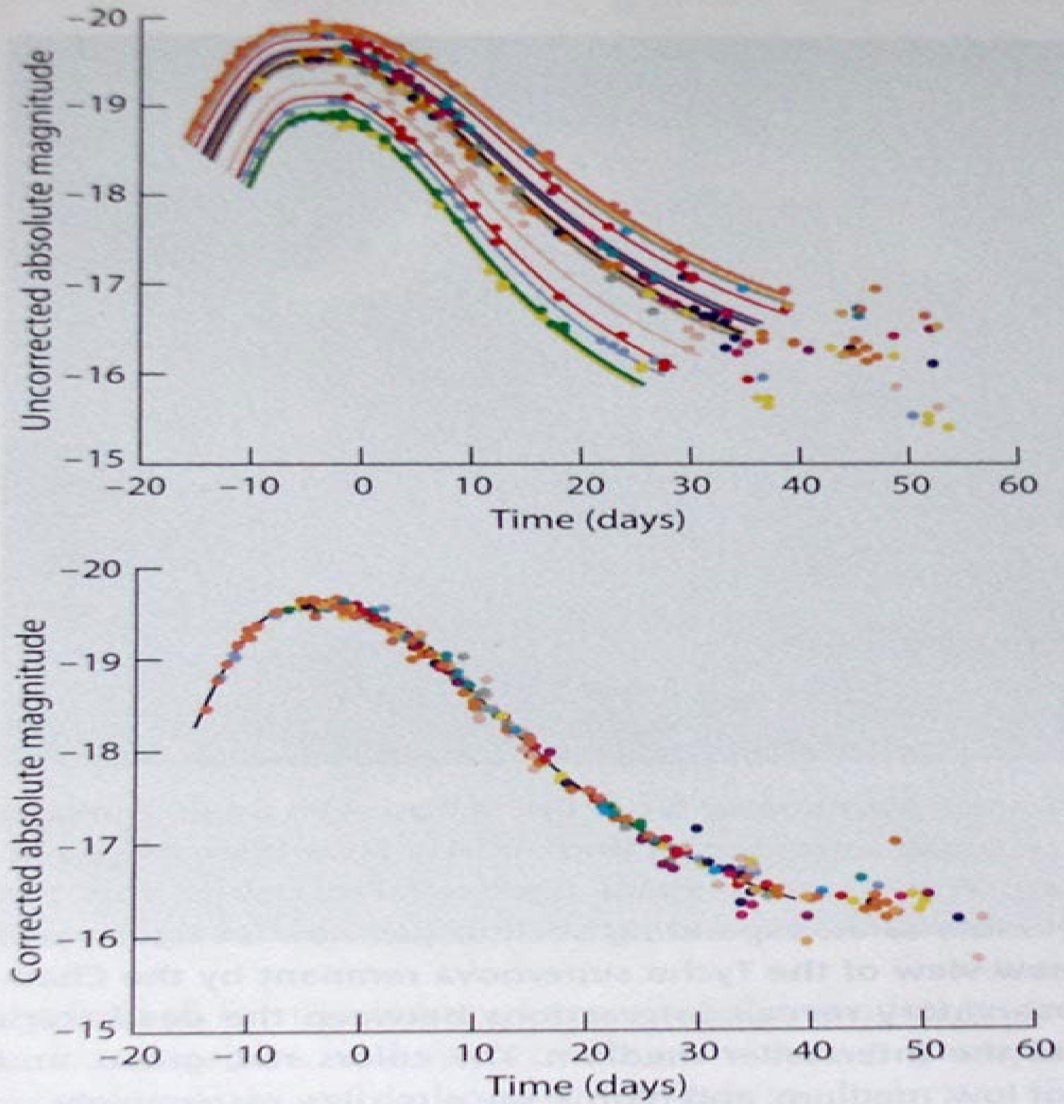
- If the white dwarf is close to the 1.4 solar mass upper limit that electron degeneracy can support…
- The added mass could push it past the limit before it gets hot enough to flash off
- Then, star collapses under the weight and because it is electron degenerate, energy created will not expand the star and shut off the fusion.
- So, entire star (carbon, mostly) undergoes fusion all at once. What a star normally takes millions to billions of years to burn, this star burns in an instant.
- You get a humongously **BIG Explosion!**

Supernova Type Ia – Sequence of events



Supernova! (SN Ia)

- These are even brighter than the SN II's, which come from massive stars.
- Very useful – SN Ia's are all the ~same event = 1.4 solar mass white dwarfs passing the Chandrasekhar Limit, collapsing initially, triggering carbon nuclear fusion all in a flash. So they turn out to be…
- GREAT **<u>“standard candles” – objects of known luminosity</u>**, on which we can then use simple math to determine their distance.
- So, any SN Ia (and its host galaxy), we can find its distance, even out to the edge of the observable universe, since they are so bright.
- ***Major*** observational effort today is going into discovering and charting the light curve of SN Ia's throughout the universe! They tell us the evolution of the Universe.



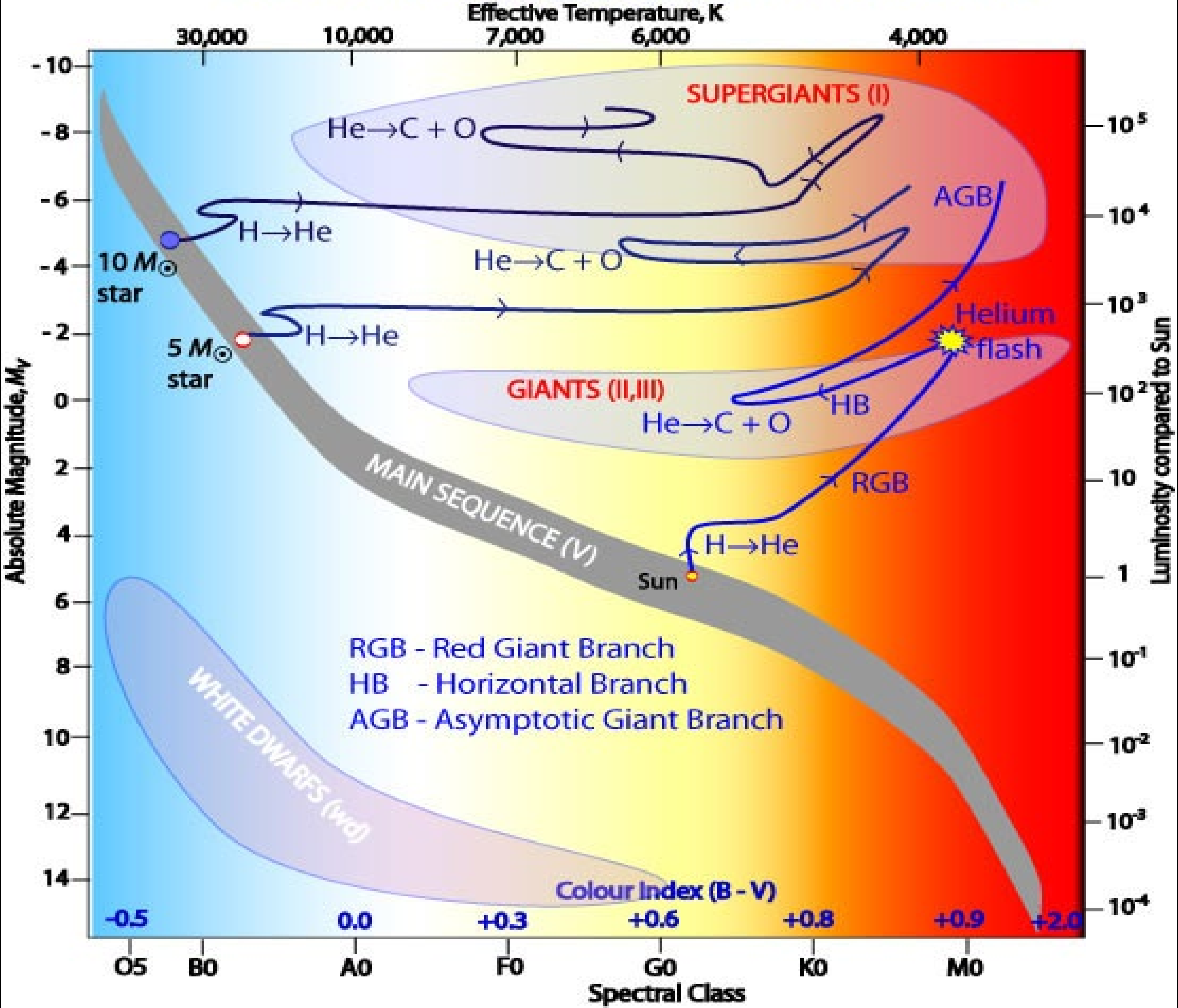
Top: These light curves show how Type Ia supernovae differ in their peak luminosities, with the most luminous being those that fade most slowly. *Bottom:* Correcting for the "brighter is broader" relationship makes a nearly universal template that will indicate whether newfound Type Ia's are under- or overluminous (and by how much). Courtesy the Supernova Cosmology Project.

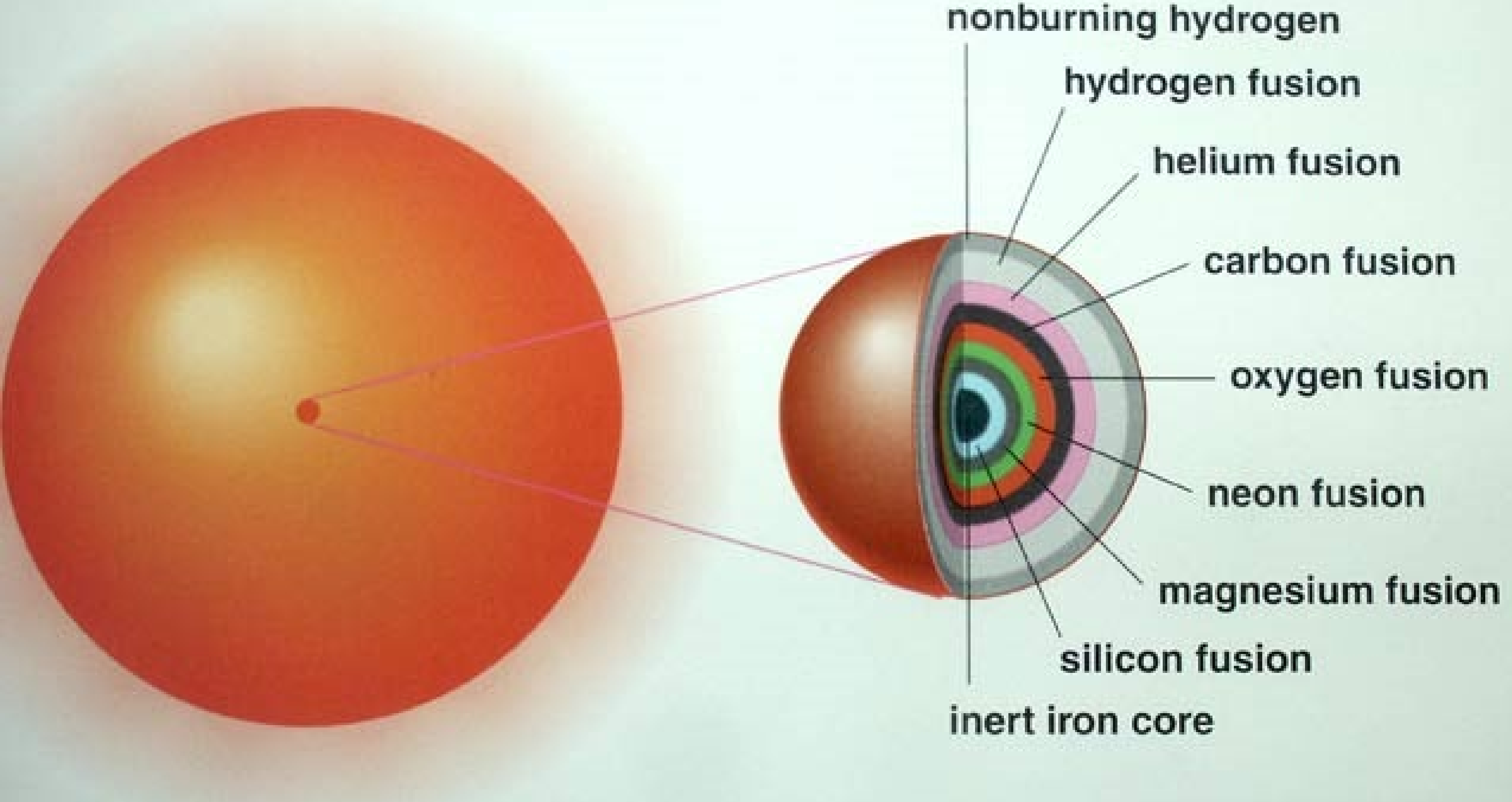
SN Ia light curves. More Luminous Ia's fade slower. After calibrating this out, we can put all SN Ia's on the same scale and they're good standard candles

Evolution of High Mass Stars – Short and Violent Lives

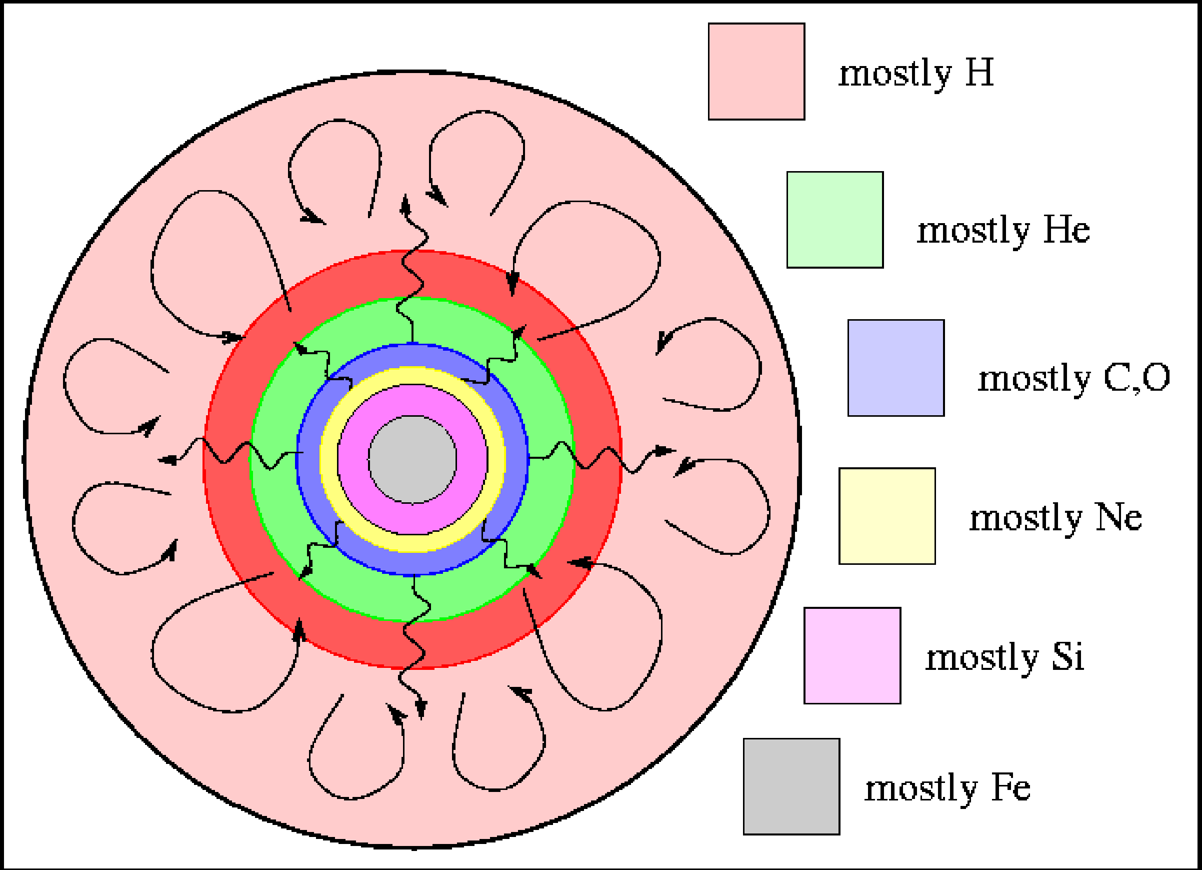
- Have enough mass to heat & compress core to fuse all the way up to ***iron***
- ***Iron*** – the most tightly bound of all nuclei; therefore…
- All fusion or fission involving iron will subtract heat from the star's core, not add to it.
- ***This can be a disaster for the star***

Evolutionary Tracks off the Main Sequence




nonburning hydrogen
hydrogen fusion
helium fusion
carbon fusion
oxygen fusion
neon fusion
magnesium fusion
silicon fusion
inert iron core

High mass star structure. Like layers of an onion, heavier and heavier nuclei are fused in the deeper, denser, hotter interior shells



Binding Energy per Nucleon for Periodic Table. Iron tightest of all. Neither fusion nor fission can extract energy from Iron. Note how shallow the curve gets for nuclei approaching Iron – little energy released by these fusion reactions to help hold up the star, so must burn through this fuel very fast. It's like trying to keep a house warm by just burning newspapers instead of oak logs (H-> is the oak logs of fusion!)

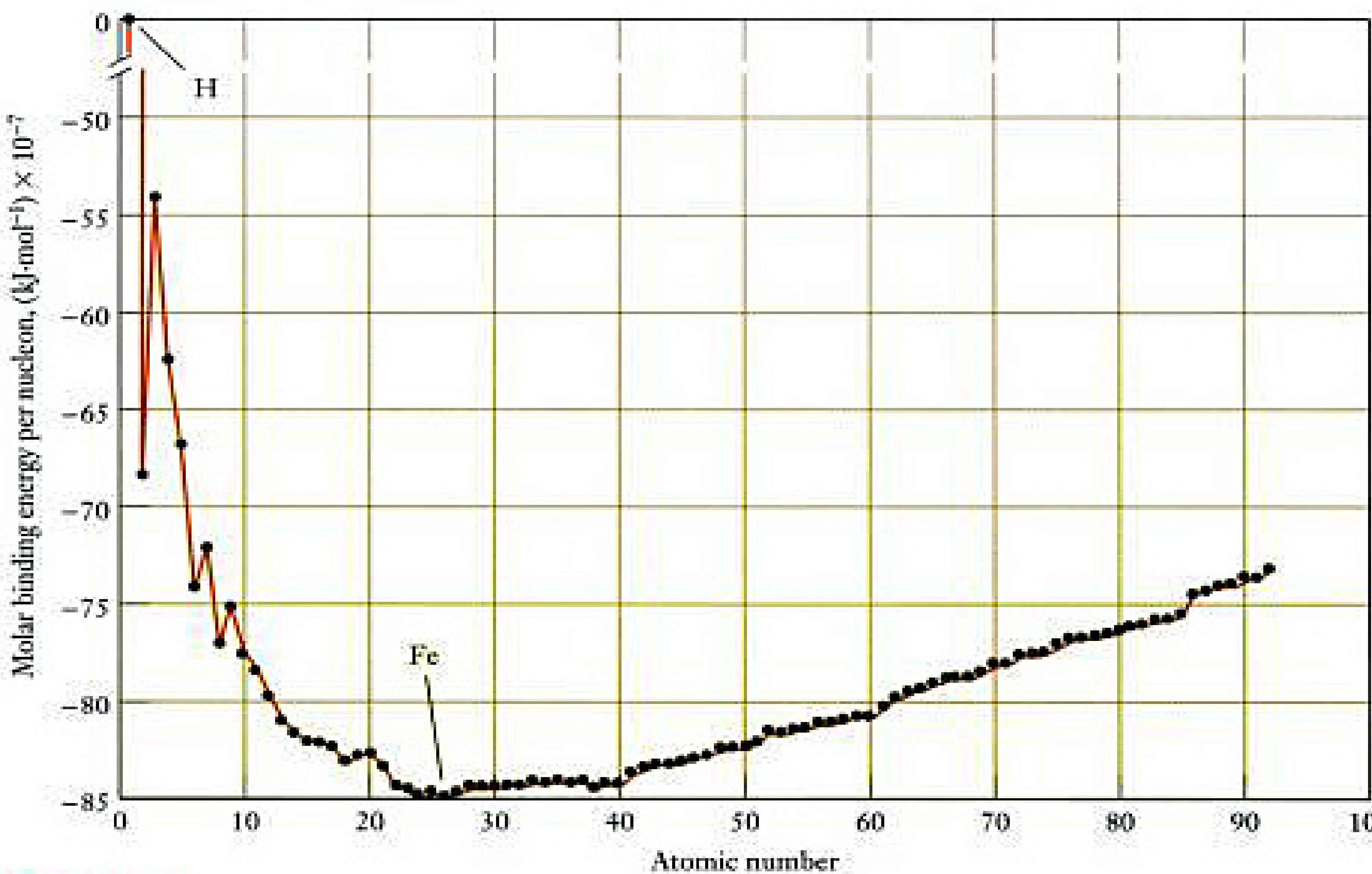


Figure 3.18.

Nuclear binding energy per nucleon. Zero energy on this plot is for hydrogen, $Z = 1$. The lowest energy, most stable nucleus is iron, $Z = 26$.

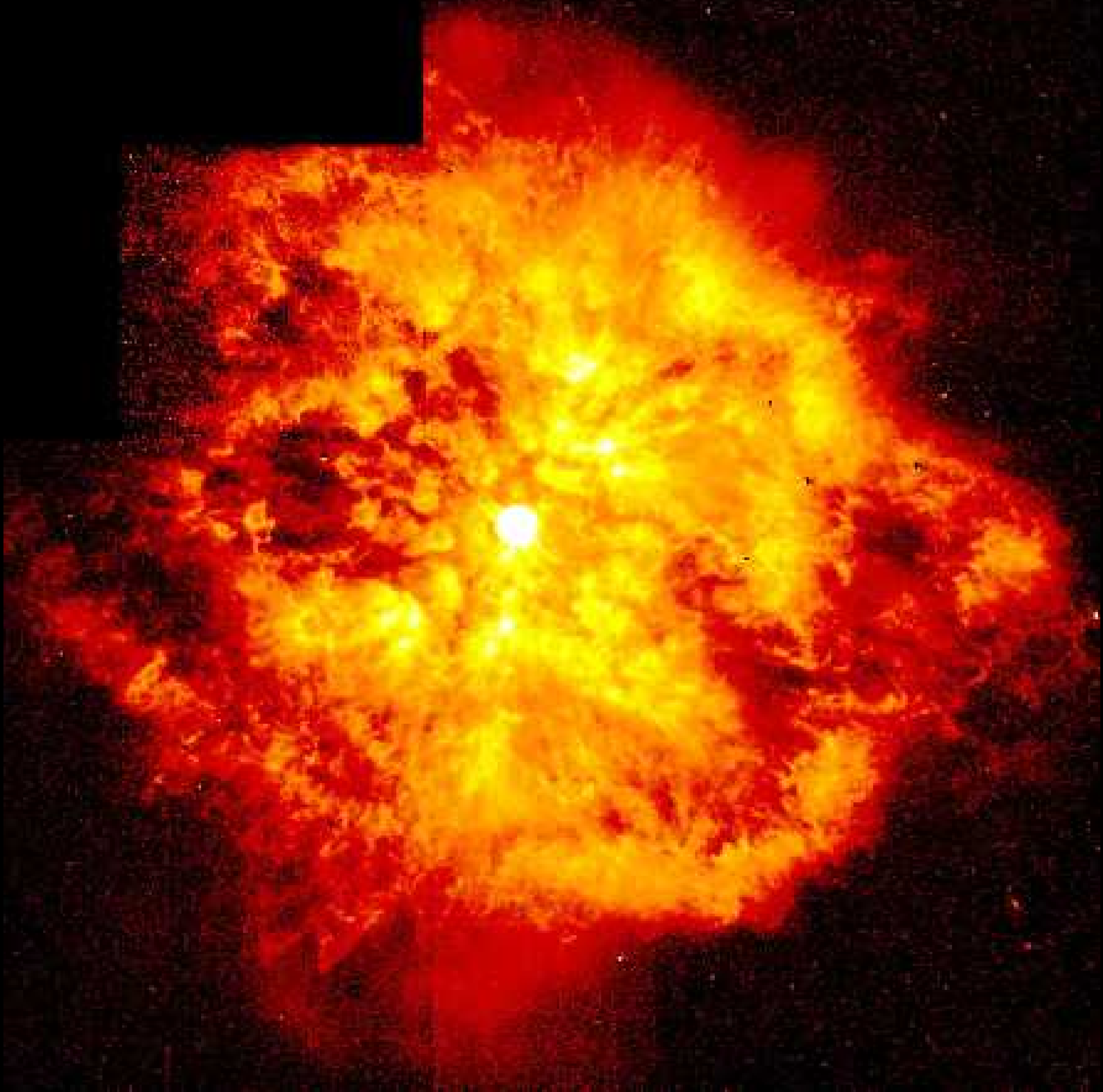
Nuclear Burning Goes Very Fast for Heavy Elements which provide Little Energy During Fusion

<u>Fuel lifetime for 20 solar-mass star</u>

- H fusion: 10 million years
- He fusion: 1 million years
- Carbon fusion: 300 years
- Neon fusion: 6 months
- Silicon into iron: 3 days!

Eta Carina – Extreme massive star ready to go "Supernova"

Planetary Nebula Mz 3



The Death of High Mass Stars…

- The Chandrasekhar Limit – This is the limiting mass for an electron degenerate object. At this mass limit (1.4 solar masses for a bare electron degenerate spherical mass) the energy required to force electrons and protons together to become a neutron, is the same as the available energy due to gravitational attraction. Tipping this balance with more mass, initiates…
- $p^+ + e^- \rightarrow n$ + neutrino. The loss of the electron lowers the volume, allowing gravitational collapse, causing nuclear reactions involving Iron. This is major trouble -
- Nuclear reactions involving Iron, whether fusion or fission, will SUBTRACT pressure!
- So this nuclear burning causes further core collapse, which raises the density and accelerates the nuclear reactions even further.
- In 0.2 seconds (!) the core collapses completely down to nuclear density, fusing and fissioning Iron into both lighter and also heavier elements.
- Vast numbers of **neutrinos** produced, so vast that their pressure blows apart the star (or rather, that's a leading theory of how the star explodes)…

Supernova! (SN II)

- 99% of energy release, the gravitational potential E of the star, goes into neutrinos
- 1% goes into the explosion
- 0.01% goes into visible light. Still, the light is bright enough to equal the entire galaxy of 100 thousand million stars (Gah!)
- Some of the cosmic abundance of heavy elements (those heavier than Iron) are made by the r-process in SN II), although not near as much as was once thought

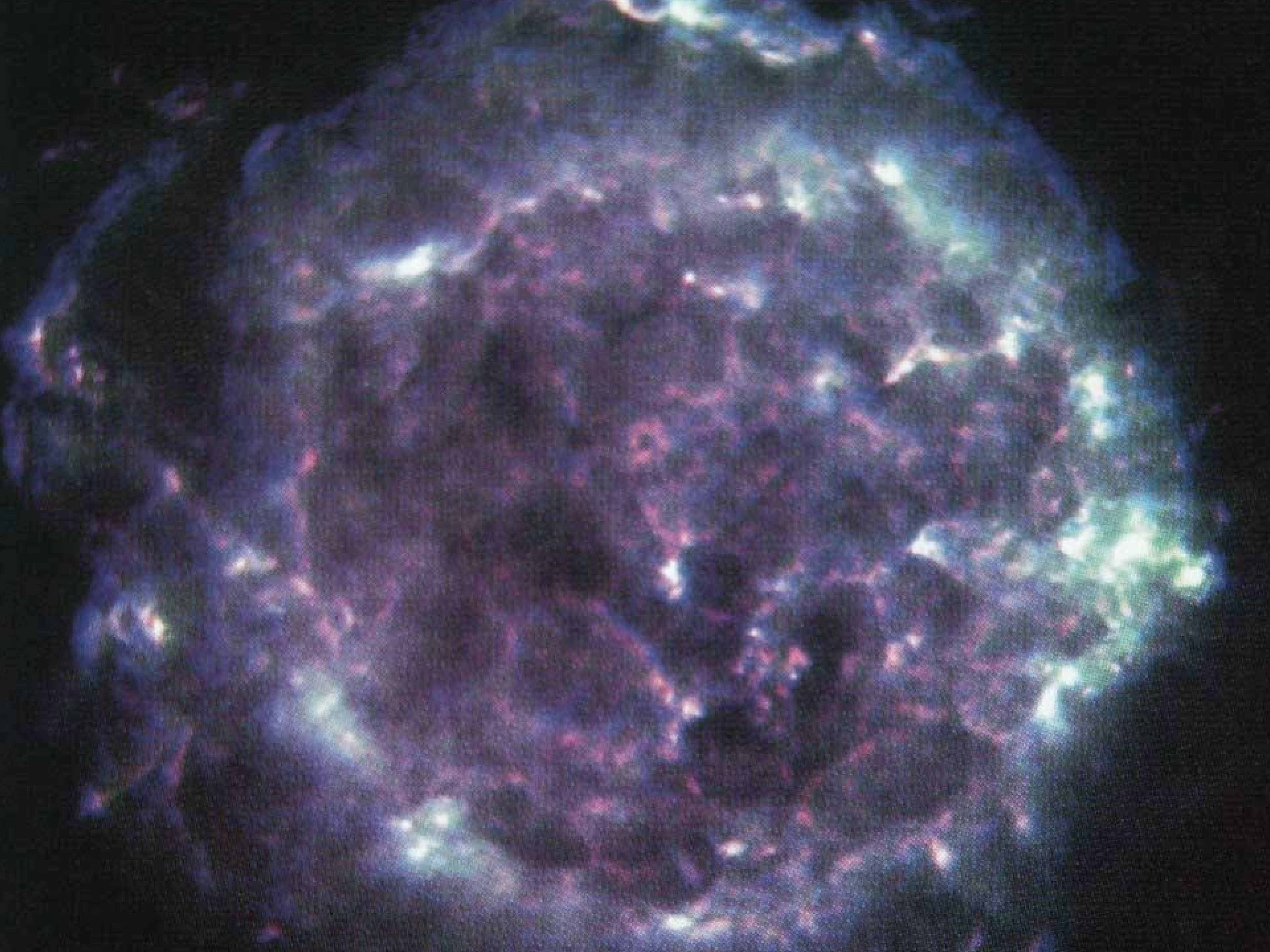
The r-Process and the Heavy End of the Periodic Table

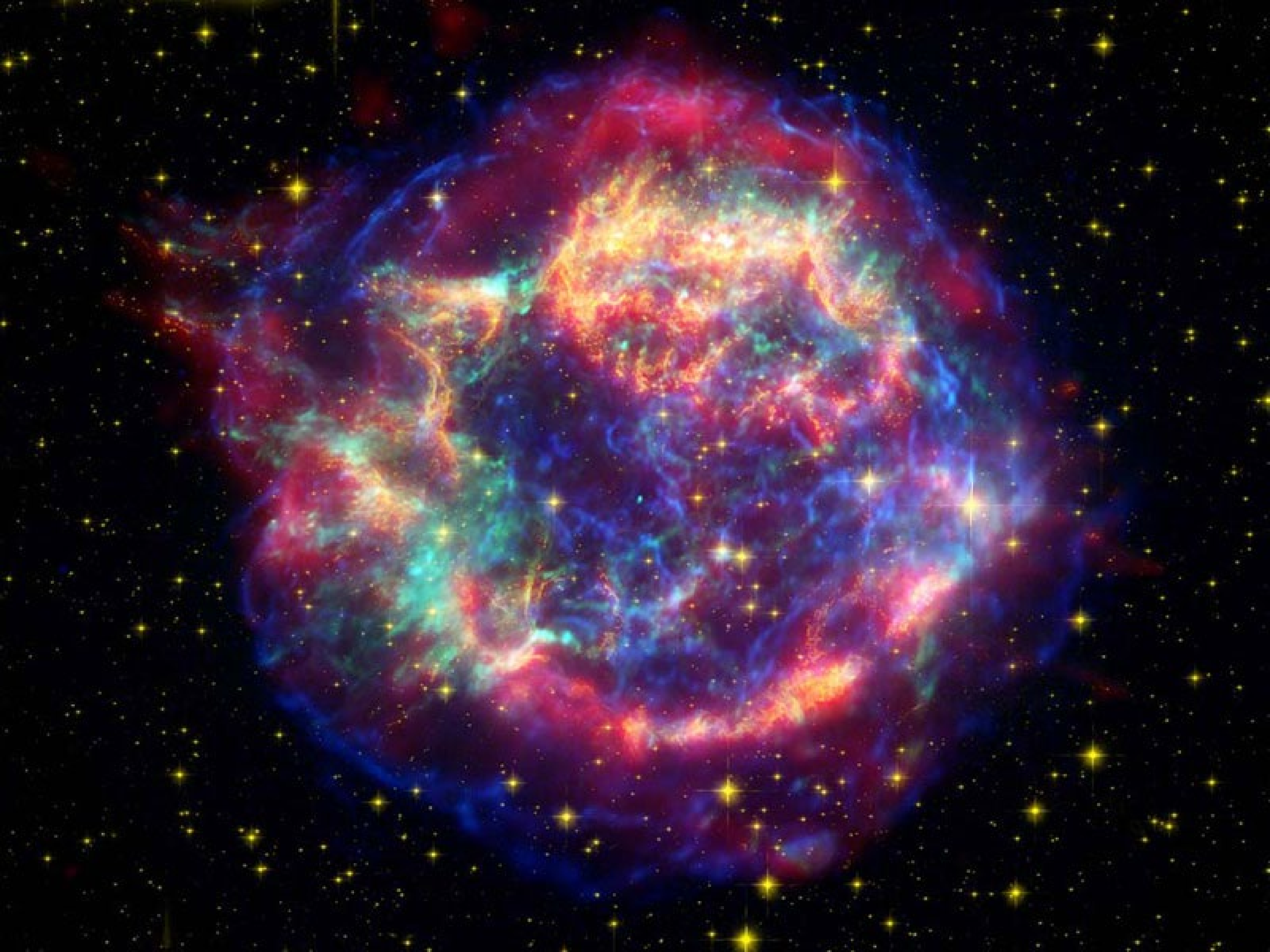
- "r- Process" = RAPID Process, for making very heavy elements. The neutrons slam onto nuclei too fast for them to radioactively decay
- It was once thought that neutrino-driven winds in SN II's drove out sufficient material in the explosion to account for the neutron-rich heaviest elements in the Universe.
- But better computers have, in the past ~10 years, told us that this can only account for a very small part of such elements
- Instead, a competing theory is now looking to be the answer – **the collision of neutron stars in a binary system**
- **Neutron stars are almost pure neutrons…**

Binaries are common, and higher mass binaries would be expected to produce binary neutron stars in the end.

- These binaries radiate **gravitational radiation**, according to Einstein, taking away angular momentum until the neutron stars smash into each other at near the speed of light
- The energy of the collision is sufficient for rapid nuclear fusion and nuclear reactions converting neutrons to protons, and the synthesis of the heaviest elements in the periodic table…Gold, Lead, Uranium, Platinum…!
- The are such massive nuclei they require lots of extra neutrons to provide the binding to hold them together against the protons' repulsion. Such neutrons are there in abundance in this collision
- Confirmation came with the discovery of radioactive-driven heated debris from a neutron star collision, in agreement with theoretical calculations which also show the synthesis of these elements.
- **All the Gold in the Universe came from Neutron Star collisions!**

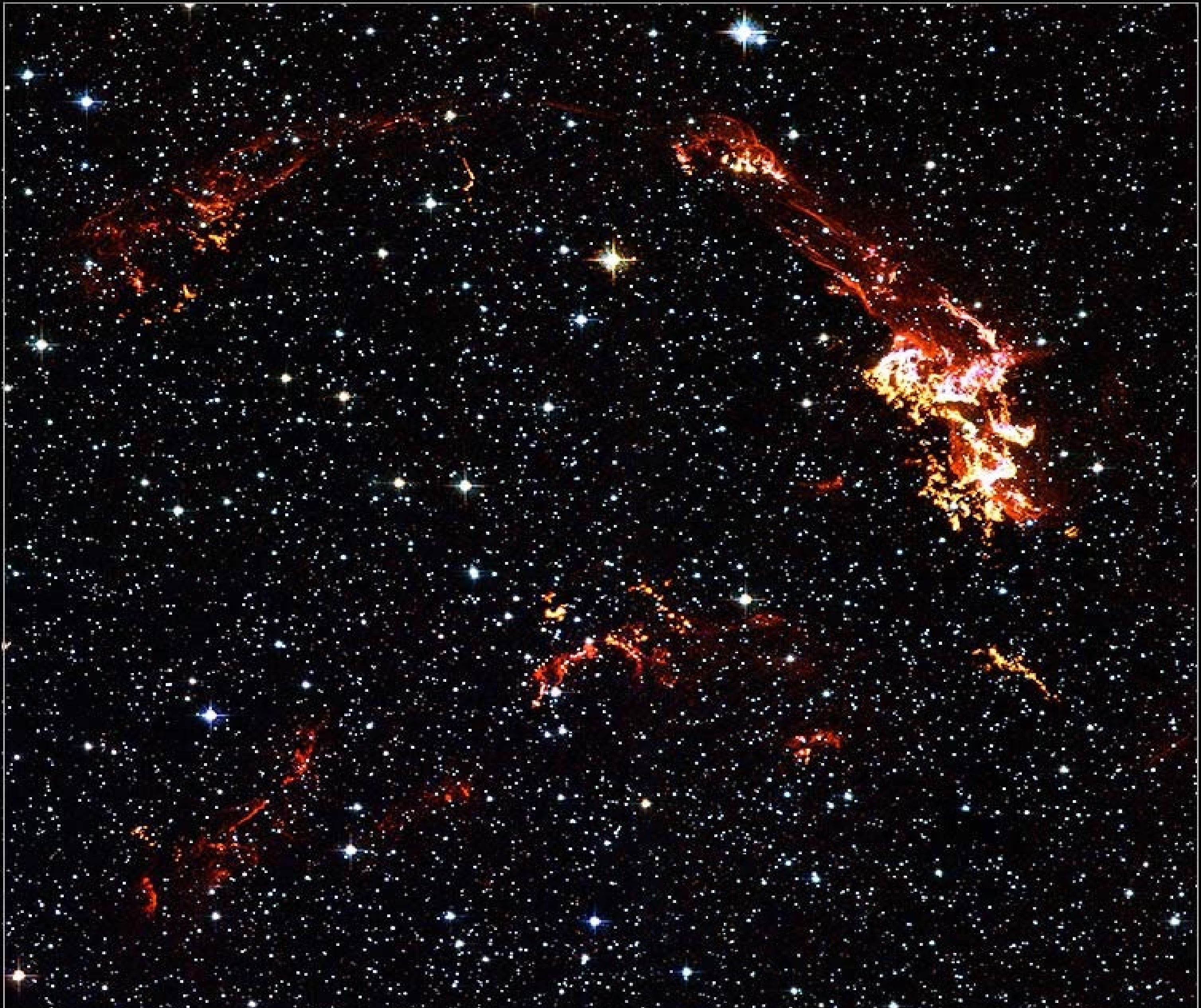
Let’s look at some ancient supernova remnants…





Supernova Remnant Cassiopeia A

Kepler's Supernova Remnant • SN 1604



Supernova Remnant LMC N 49

Supernova Remnant LMC N 63A

Hubble Heritage

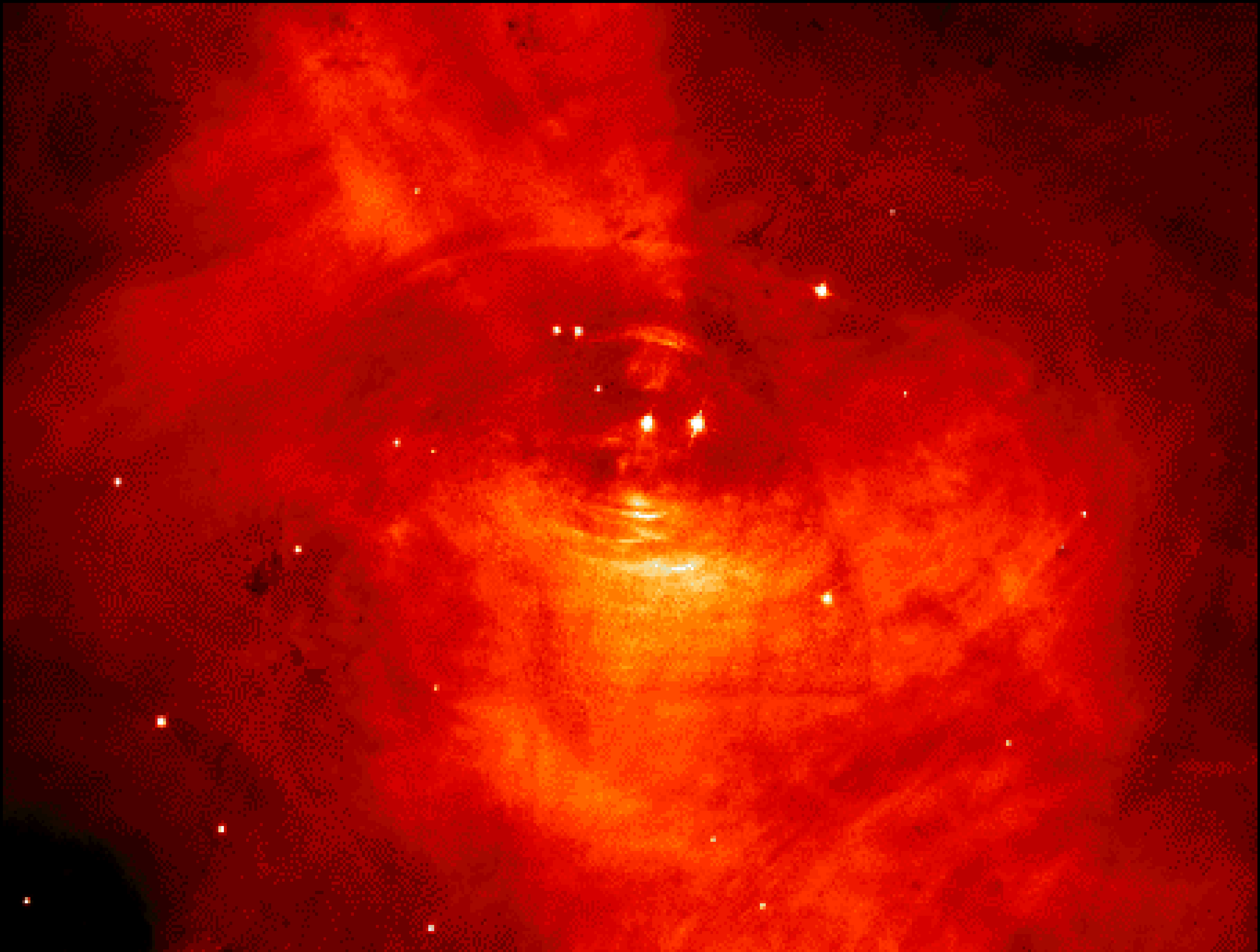
NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-15

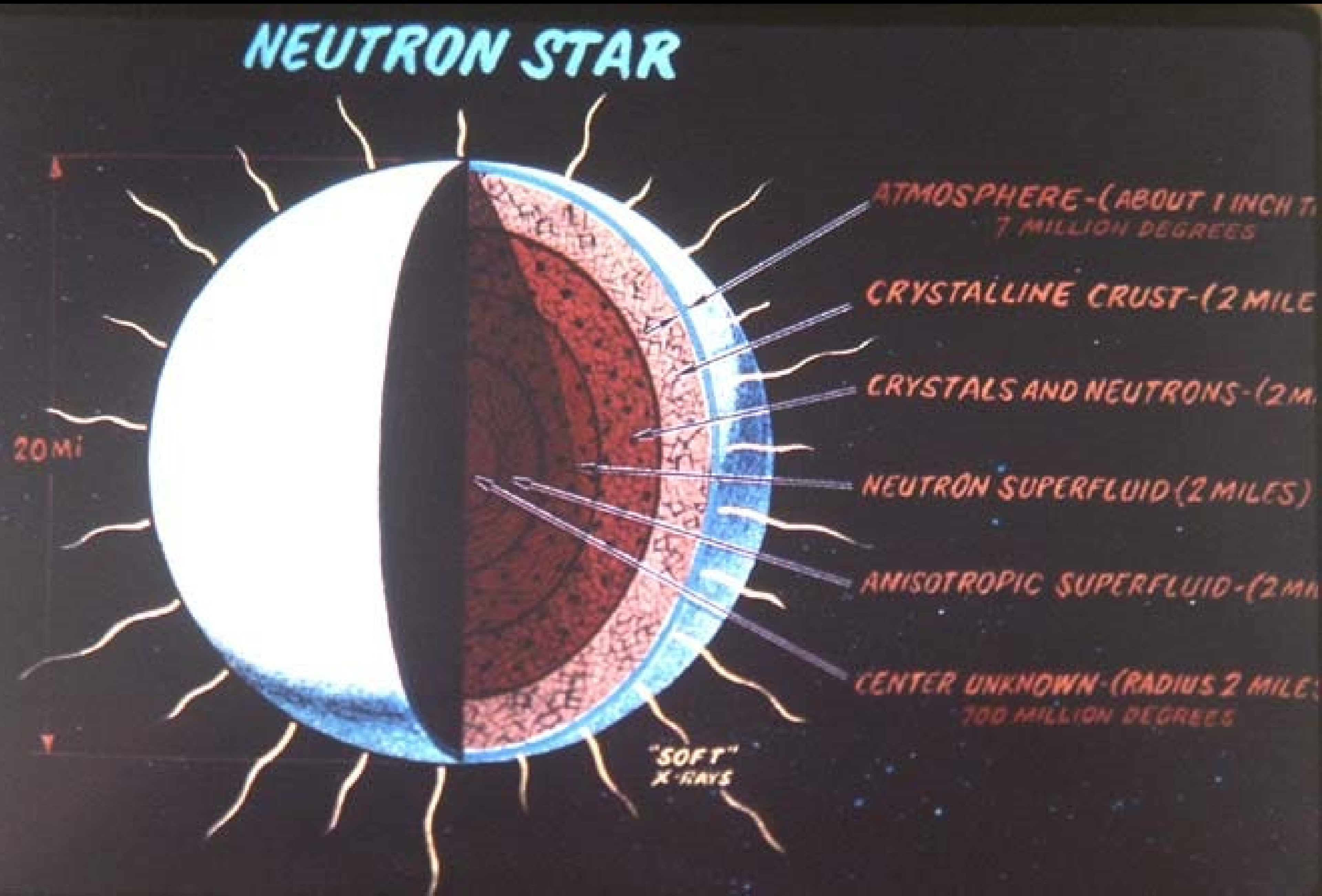
Pencil Nebula • NGC 2736

Veil Nebula (entire)

Part of the Veil Nebula

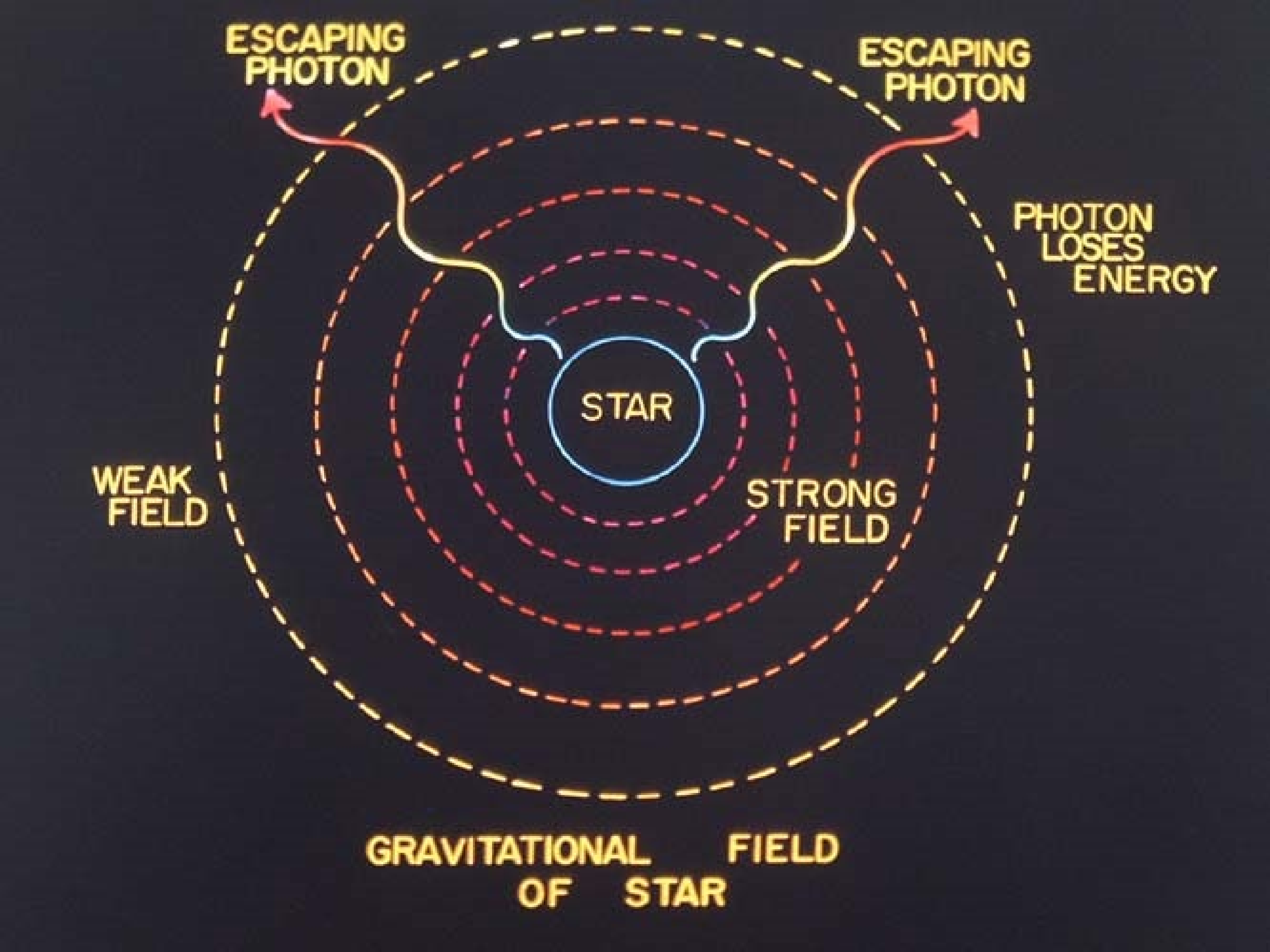
The Crab Nebula Pulsar (with HST)

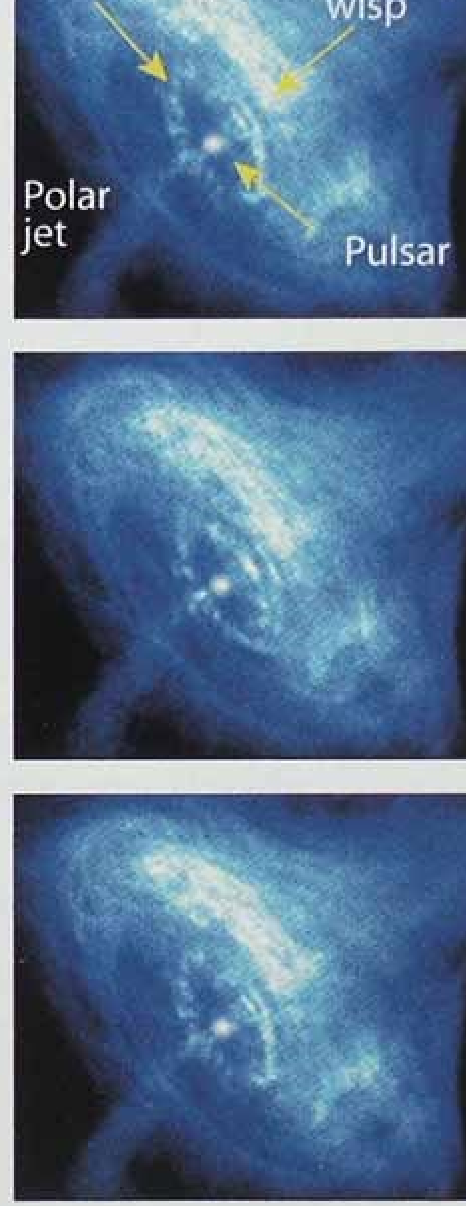



NEUTRON STAR
20 MI
ATMOSPHERE-(ABOUT 1 INCH
7 MILLION DEGREES
CRYSTALLINE CRUST-(2 MILE
CRYSTALS AND NEUTRONS-(2 M
NEUTRON SUPERFLUID (2 MILES)
ANISOTROPIC SUPERFLUID-(2 M
CENTER UNKNOWN-(RADIUS 2 MILES
700 MILLION DEGREES
"SOFT" X-RAYS

Neutron Stars

- Weight billions of tons per cubic inch
- The mass of the sun or bigger, and yet only the size of a city!
- Neutrons obey a quantum state exclusion principle like electrons do, and this is what holds up a neutron star against Gravity: Neutron Degeneracy Pressure
- But the warping of space is severe… a photon could lose a significant fration of it’s energy just climbing out of it’s gravity field
- Gravitational Redshift!

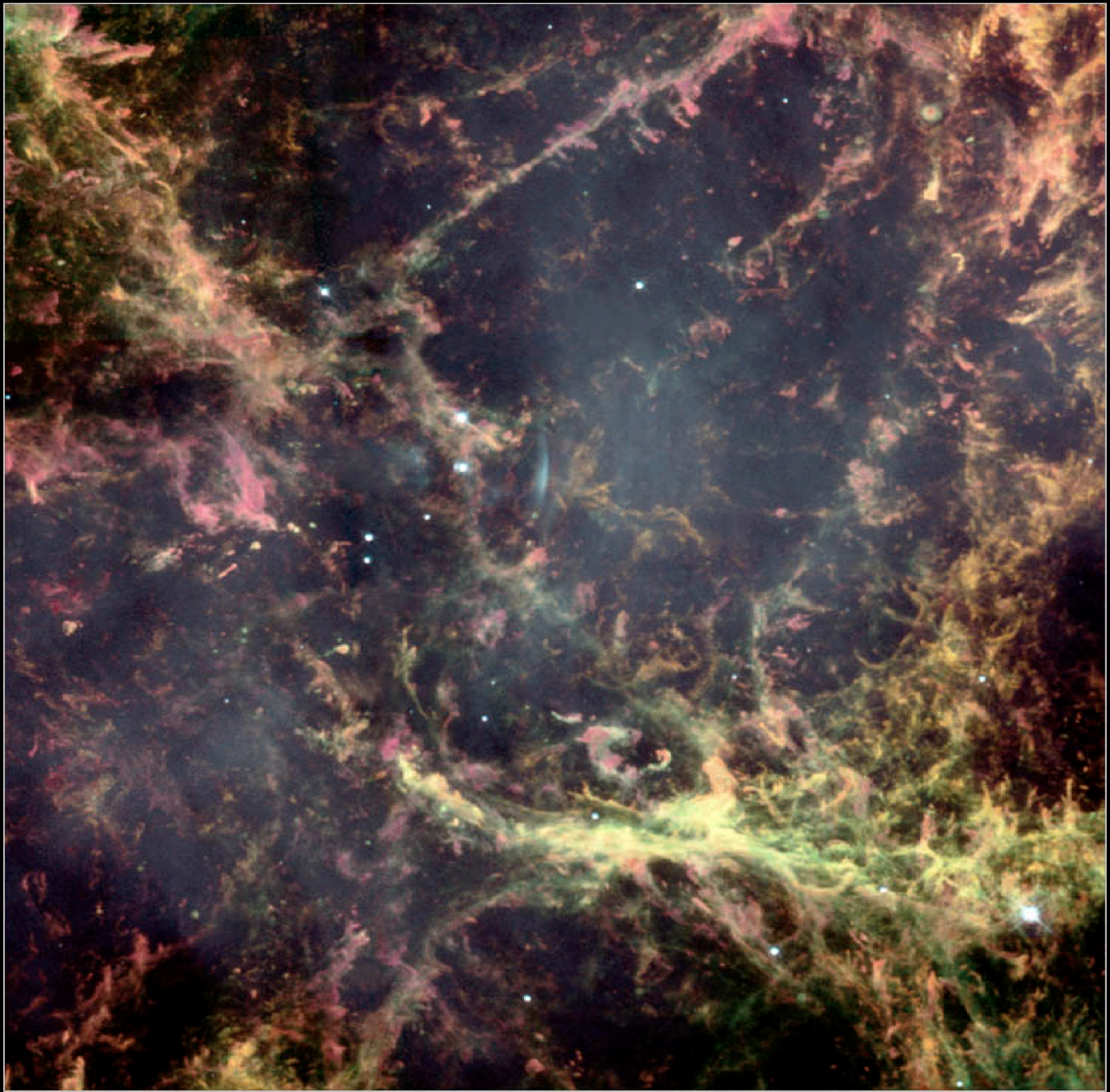

ESCAPING PHOTON
ESCAPING PHOTON
PHOTON LOSES ENERGY
STAR
WEAK FIELD
STRONG FIELD
GRAVITATIONAL FIELD OF STAR



J. JEFF HESTER ET AL. / NASA

Above: A composite X-ray and visible-light image of the Crab Nebula's inner region. X-rays are shown blue, visible light red. *Right:* X-ray frames taken weeks apart reveal a ripple or wisp of matter racing outward from the bright inner ring at half the speed of light. The full movie

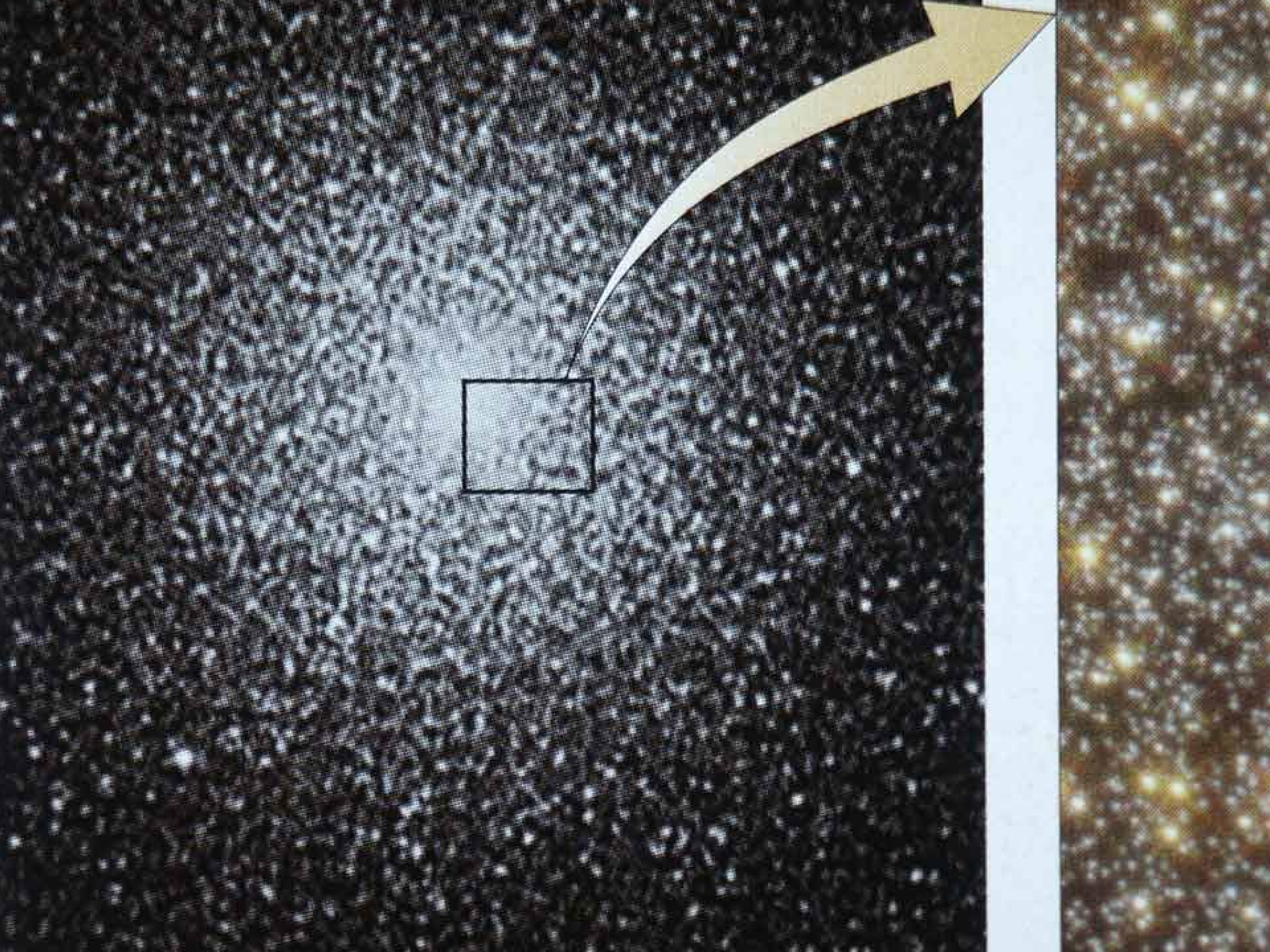
Crab Nebula

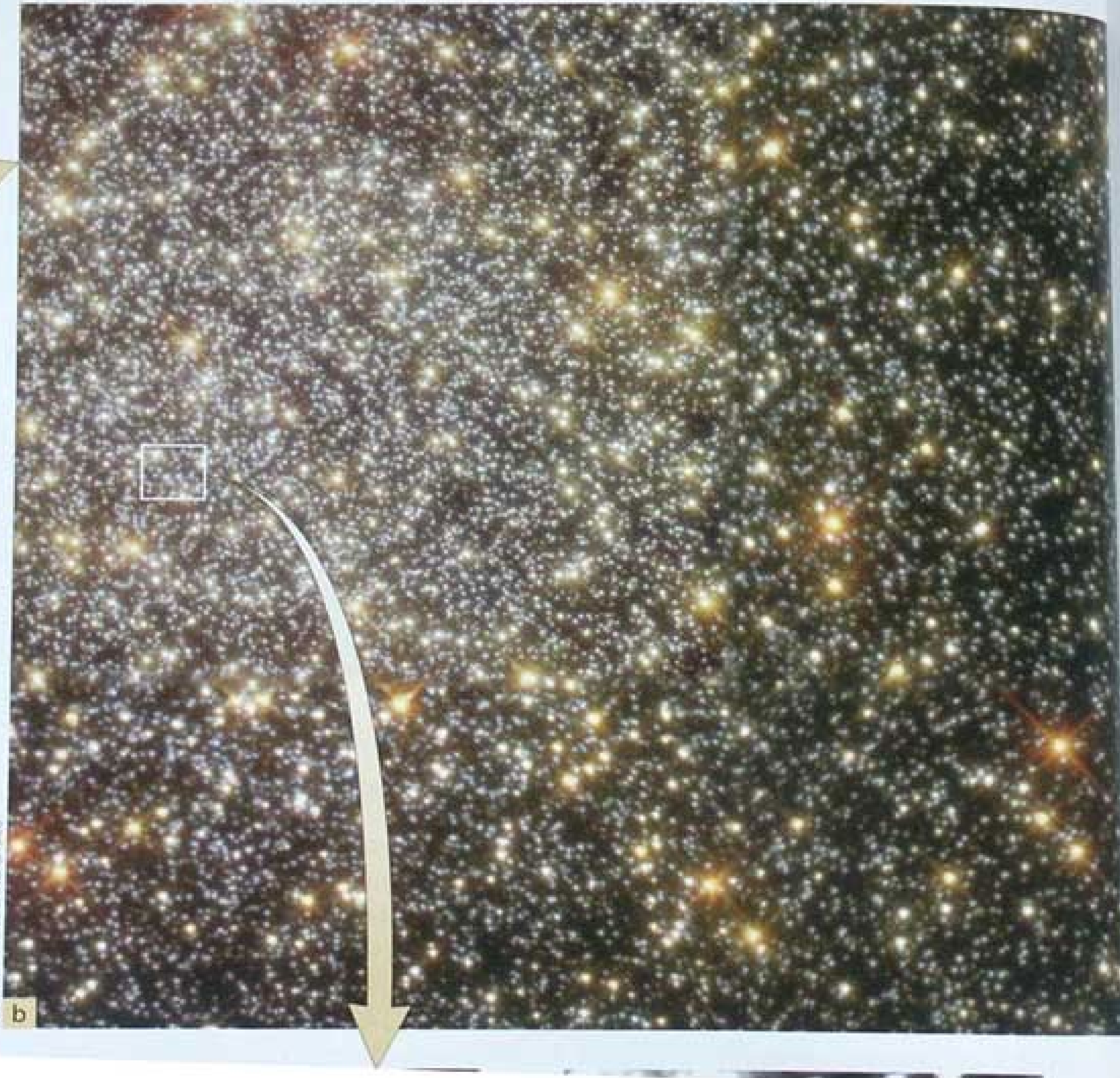


Pulsars Emit Synchrotron Radiation

- Caused by electrons spiraling around the field lines of a strong magnetic field
- Synchrotron radiation comes out mostly as radio waves.
- Running the radio pulses through a speaker makes for some interesting sounds…. Remember, pulsars spin dozens to hundreds of times per second!
- YouTube link "Pulsar Sounds"

Let's look at another Pulsar. This one is in the globular star cluster 47 Tucanae…





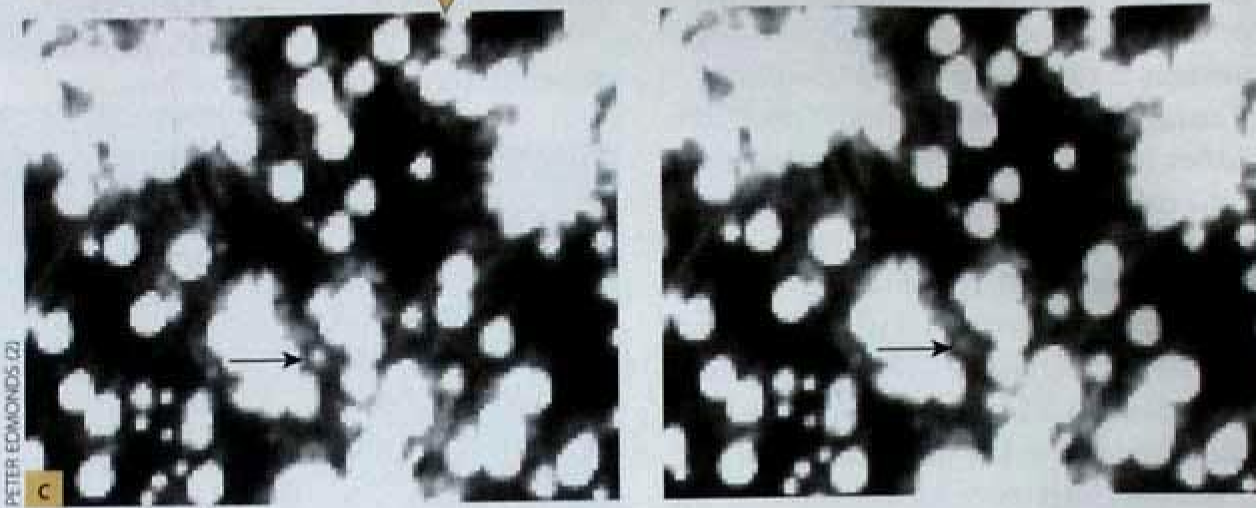
NASA / RON GILLILAND (STScI)

s a
ed

NSOLAion prize.

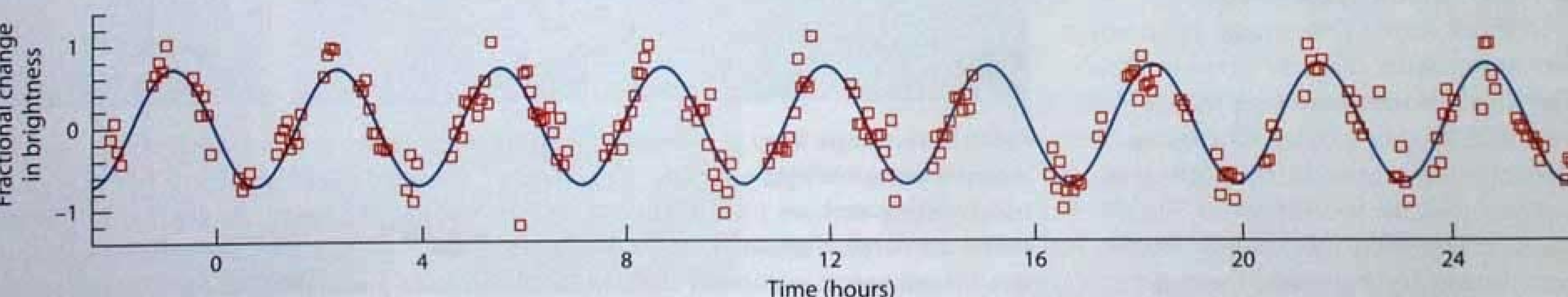
In 1999 the Hubble Space Telescope pent eight days staring at the bright, ar-southern globular cluster 47 Tucanae. ts goal: to monitor tens of thousands of he cluster's stars in hopes that transiting planets would periodically dim a few. Not one planet was discovered in the cluster (*S&T:* October 2000, page 23). But by combing the 1,289 archived Hubble imges and comparing them to observaions from the Parkes radio telescope and he Chandra X-ray Observatory, Peter D. Edmonds (Harvard-Smithsonian Center for Astrophysics) and four colleagues have found a binary system containing a millisecond pulsar and a main-sequence tar — "a freakish object among what are reakish objects anyway," in Edmonds's words.

Not only is the finding a first (no millisecond pulsar had previously been



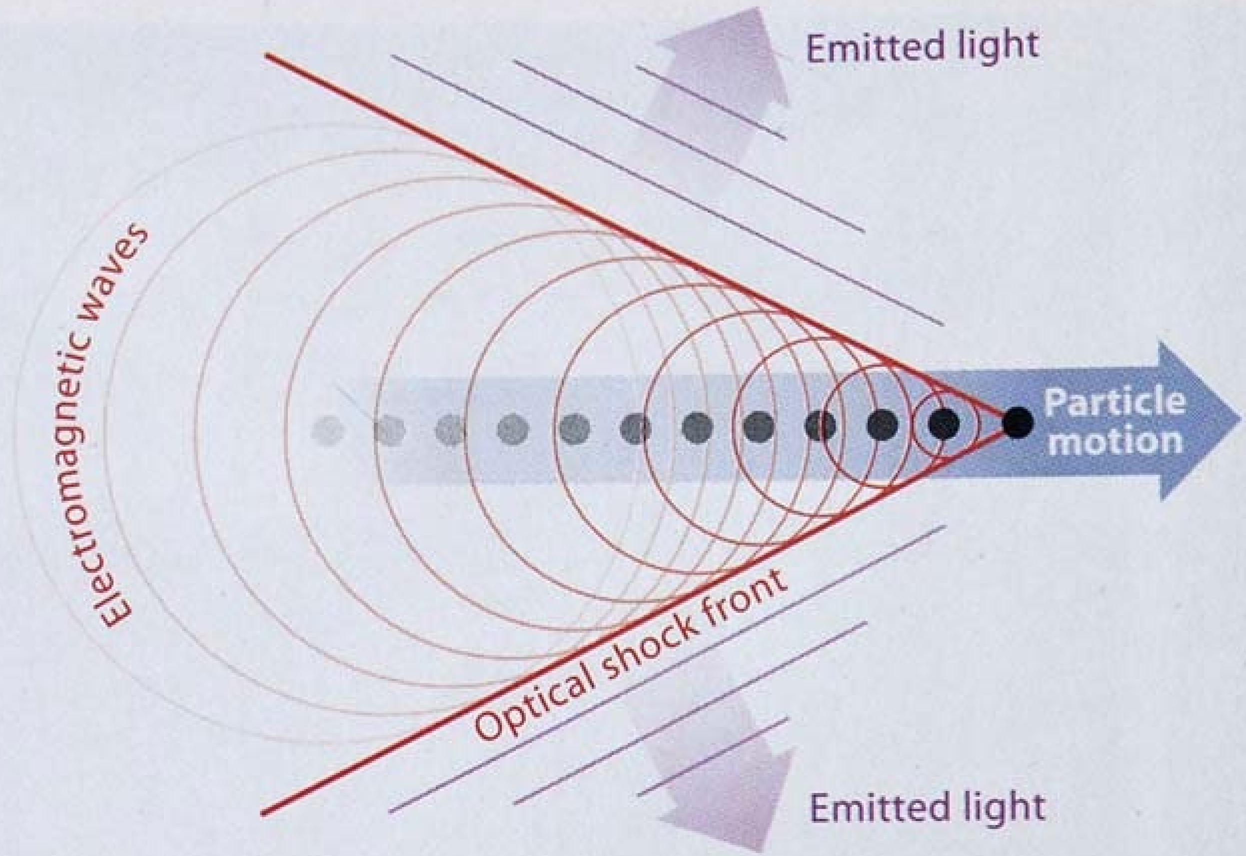
PETER EDMONDS (2)

Above: Zooming in toward an ill-fated star. [a] A ground-based photograph of the splendid 4th-magnitude globular cluster 47 Tucanae shows thousands of outlying stars but cannot match the Hubble Space Telescope's Wide Field and Planetary Camera 2 when it comes to singling out stars in the cluster's crowded core [b]. Two frames from Hubble's new Advanced Camera for Surveys [c] illustrate how one star brightens and dims more than threefold in the course of its three-hour orbit around an enigmatic pulsar (itself invisible even to Hubble). North is to the lower left. *Below:* As shown in this light curve from Hubble, the pulsar's companion star — a feeble 22nd magnitude on average — periodically brightens when its hotter, pulsar-facing side also faces Earth.

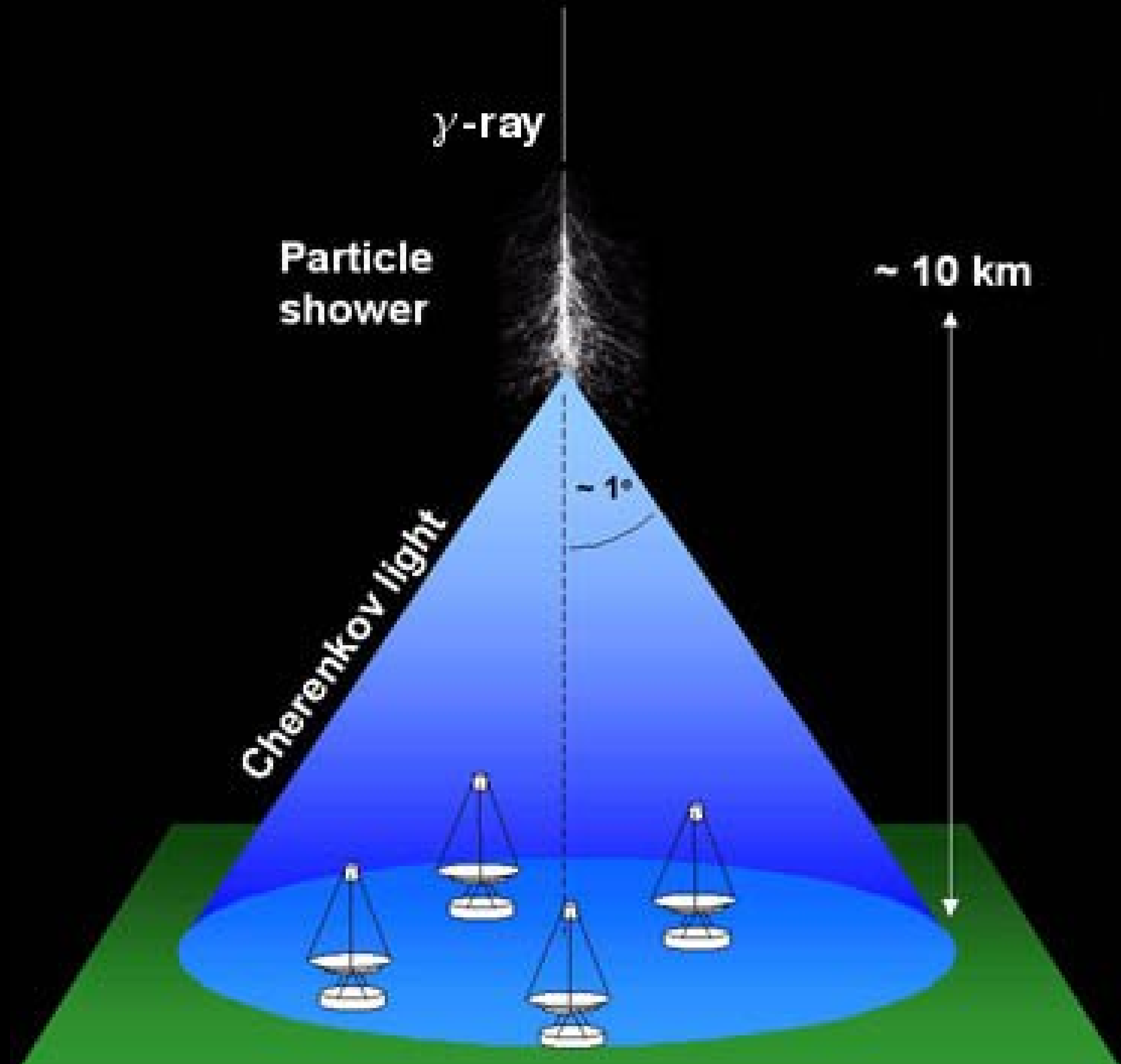


How to Detect Neutrinos?

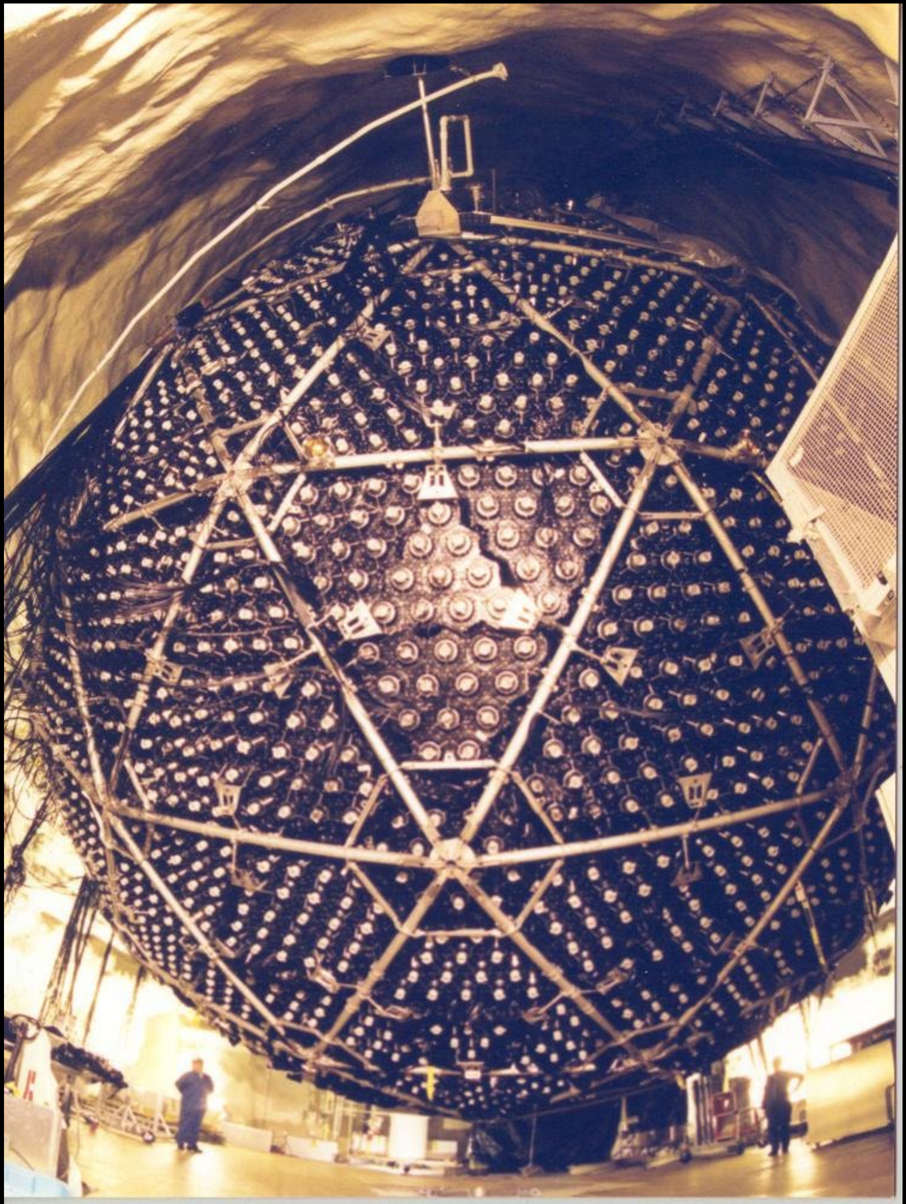
- Like, neutrinos from supernova explosions
- …or neutrinos from the sun (the strongest source because it's so close)
- - once in a great while a neutrino will hit an electron and deposit its energy, accelerating the electron to almost the (vacuum) speed of light. This rapid acceleration causes the electron to give of photons of light = Cerenkov radiation.
- Cerenkov radiation is given off when a charge moves faster than the local speed of light (remember, only the speed of light in a vacuum is an absolute Einsteinian limit! Light moves slower in a dense medium, such as air or water for example). It's something like a "sonic boom" as applied to light

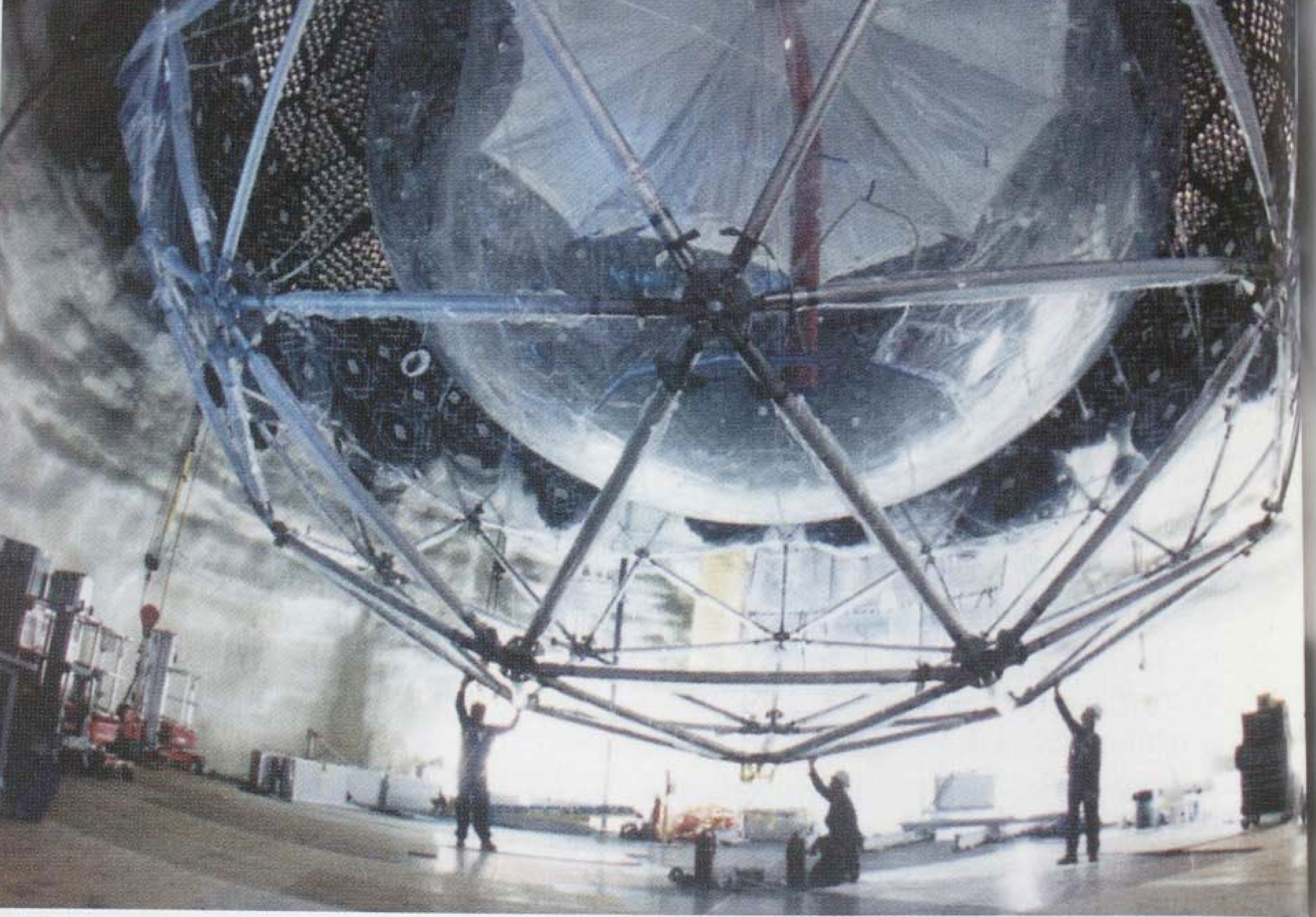


Cherenkov radiation can be thought of as an optical shock wave. Like a sonic boom, it occurs when a charged particle exceeds the speed of light in the substance through which it travels. Secondary particles from cosmic-ray-induced air showers can create Cherenkov radiation in our atmosphere and in water tanks on the ground; the radiation can be monitored for clues to a cosmic ray's energy and trajectory. *Sky & Telescope* diagram by Gregg Dinderman.


γ-ray
Particle shower
~ 10 km
~ 1°
Cherenkov light

The Sudbury Neutrino Observatory – a giant sphere of water. Neutrinos hit electrons in the water, causing Cerenkov Radiation detected by photometric detectors. SN 1987a neutrino emission detected here – proving type II supernovae produce neutron stars, for the first time



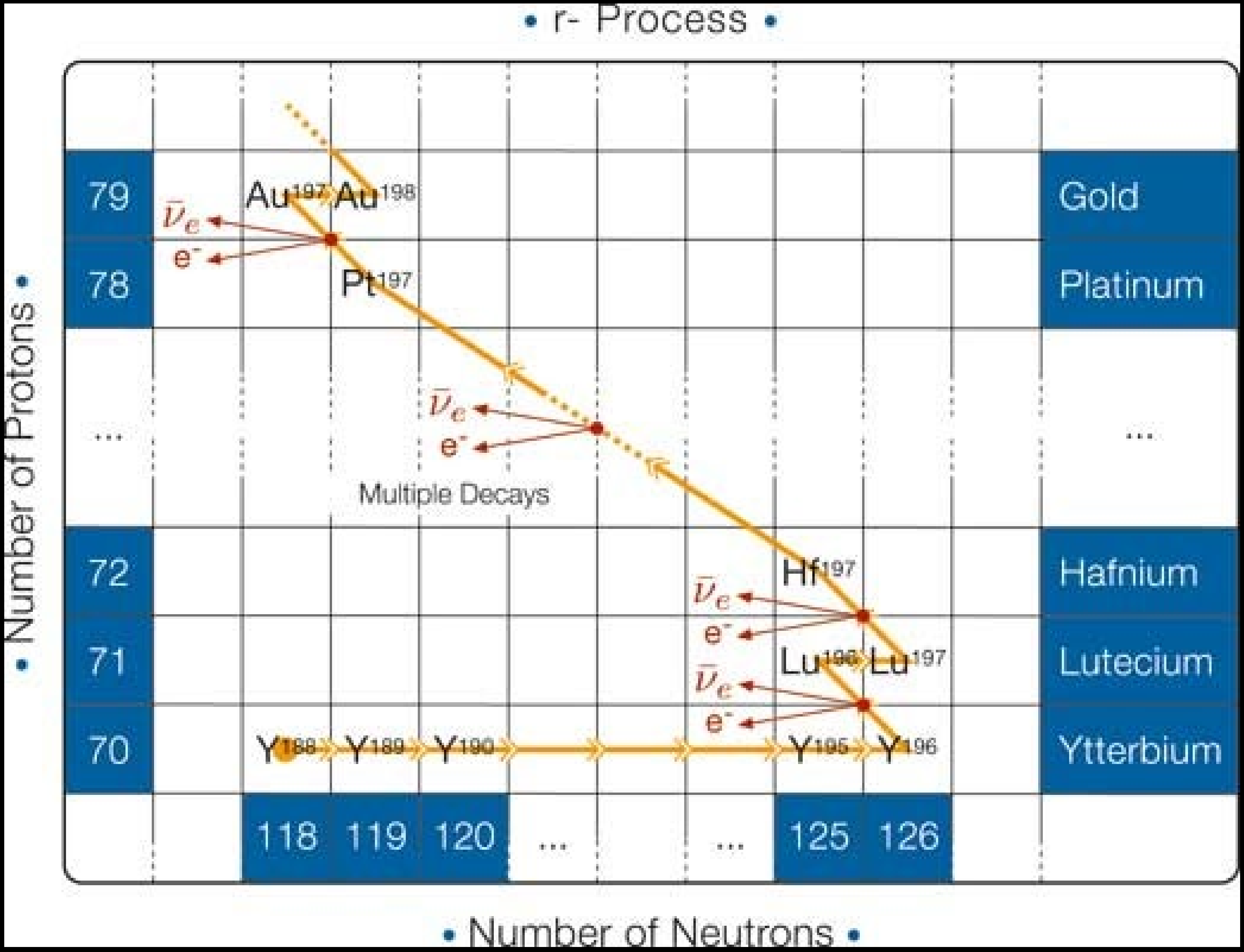


hown while under construction 2 kilometers underground in a Canadian nickel mine, the

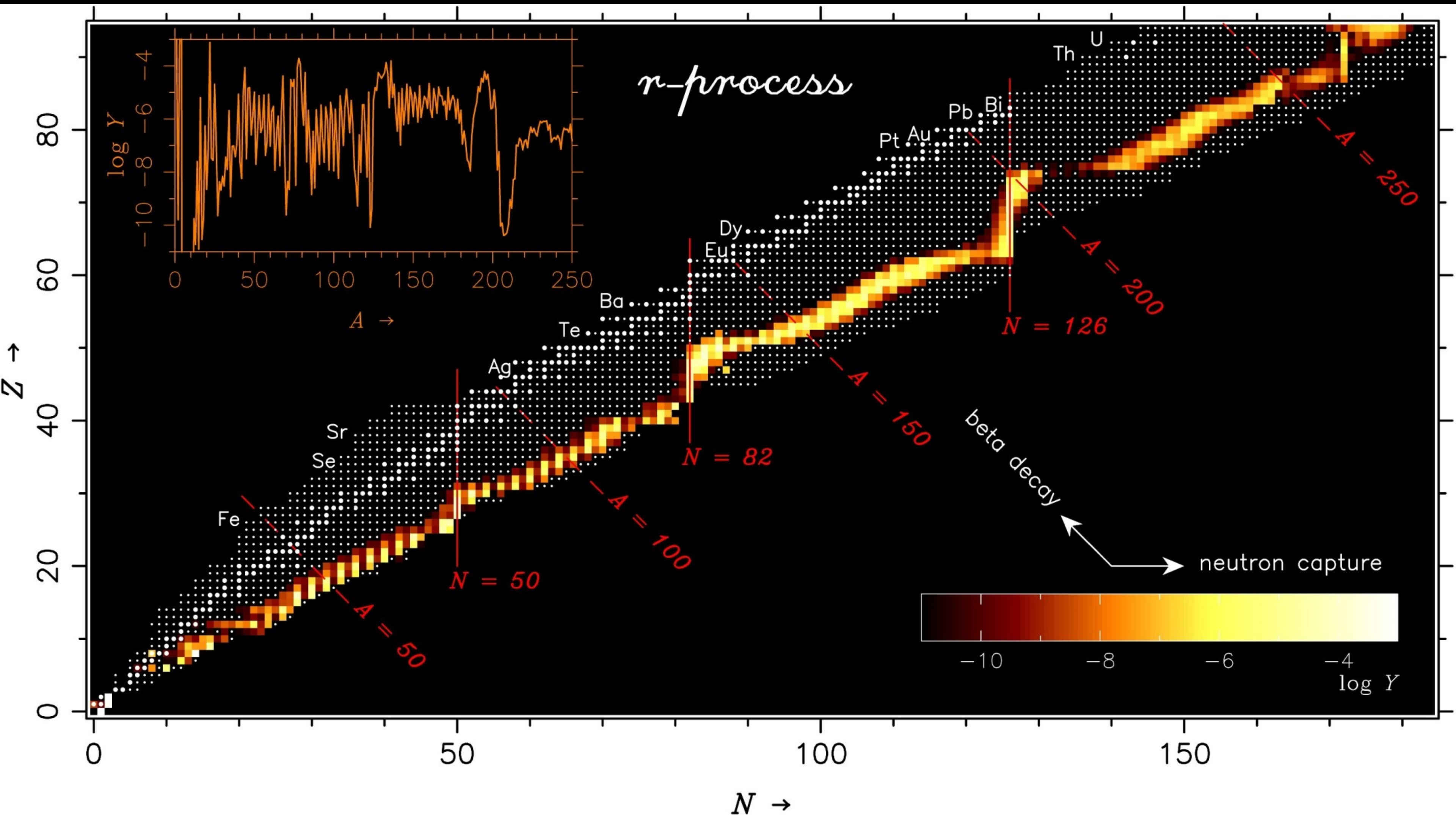
The Cosmic Abundances of the Chemical Elements

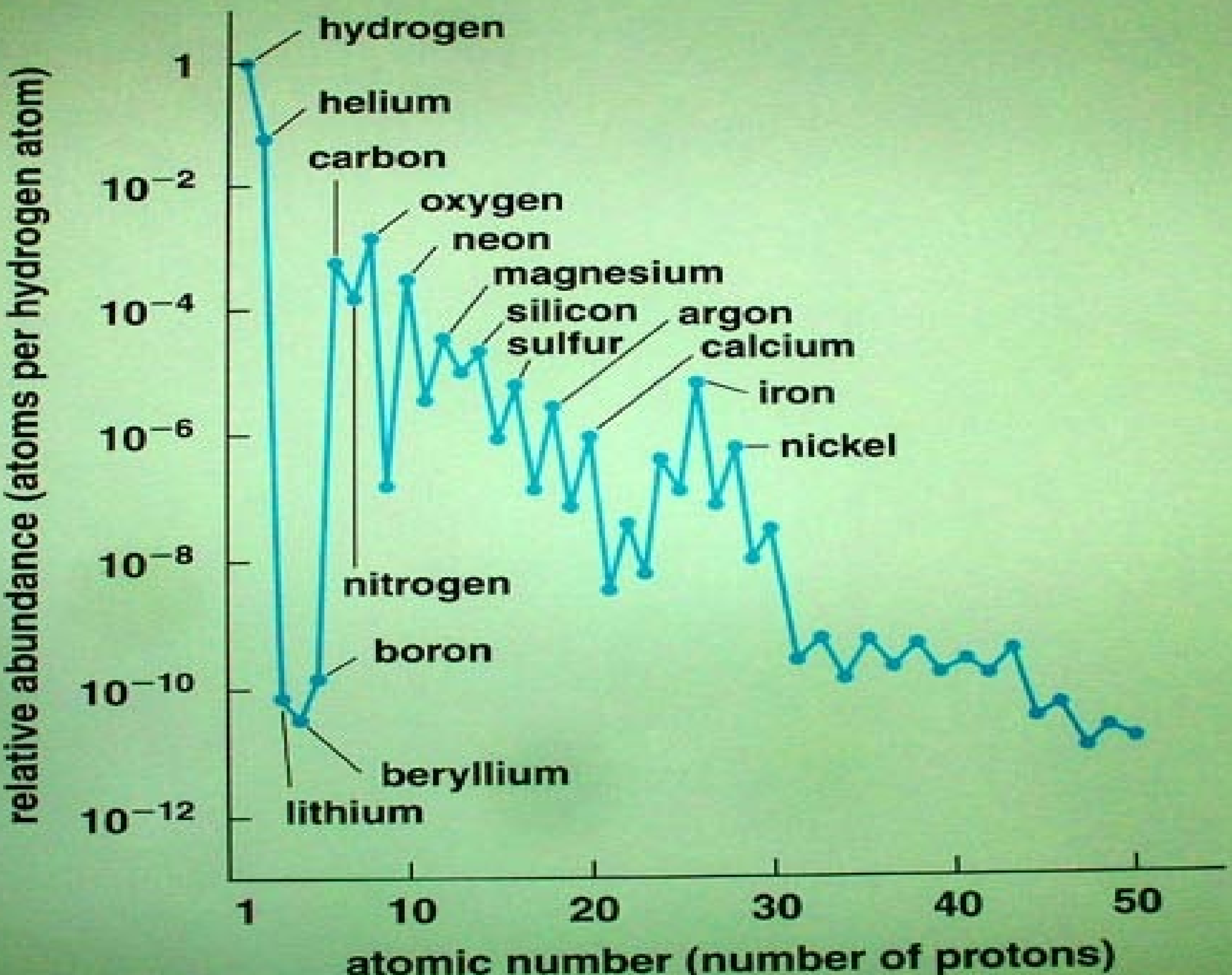
- Due to nuclear fusion in the cores of stars
- …to supernova explosions
- …and to binary neutron star collisions
- Remember – Supernova explosions are the only place in the universe where neutron stars are created, and if in a binary system, that binary neutron star system will eventually merge, and the explosion of that collision will produce very neutron-rich ***heavy elements.***
- This is the "r-process" which happens within seconds
- ***All the isotopes which are neutron rich and beyond Iron in the periodic table (e.g. gold, silver, uranium, platinum…) are created mostly in the collisions of neutron stars.***
- ***Slow neutron capture in the cores of certain massive stars makes trans-iron elements which are not neutron-rich. This is the "s-process", taking centuries.***

r-process for Producing Gold, in colliding Neutron Stars

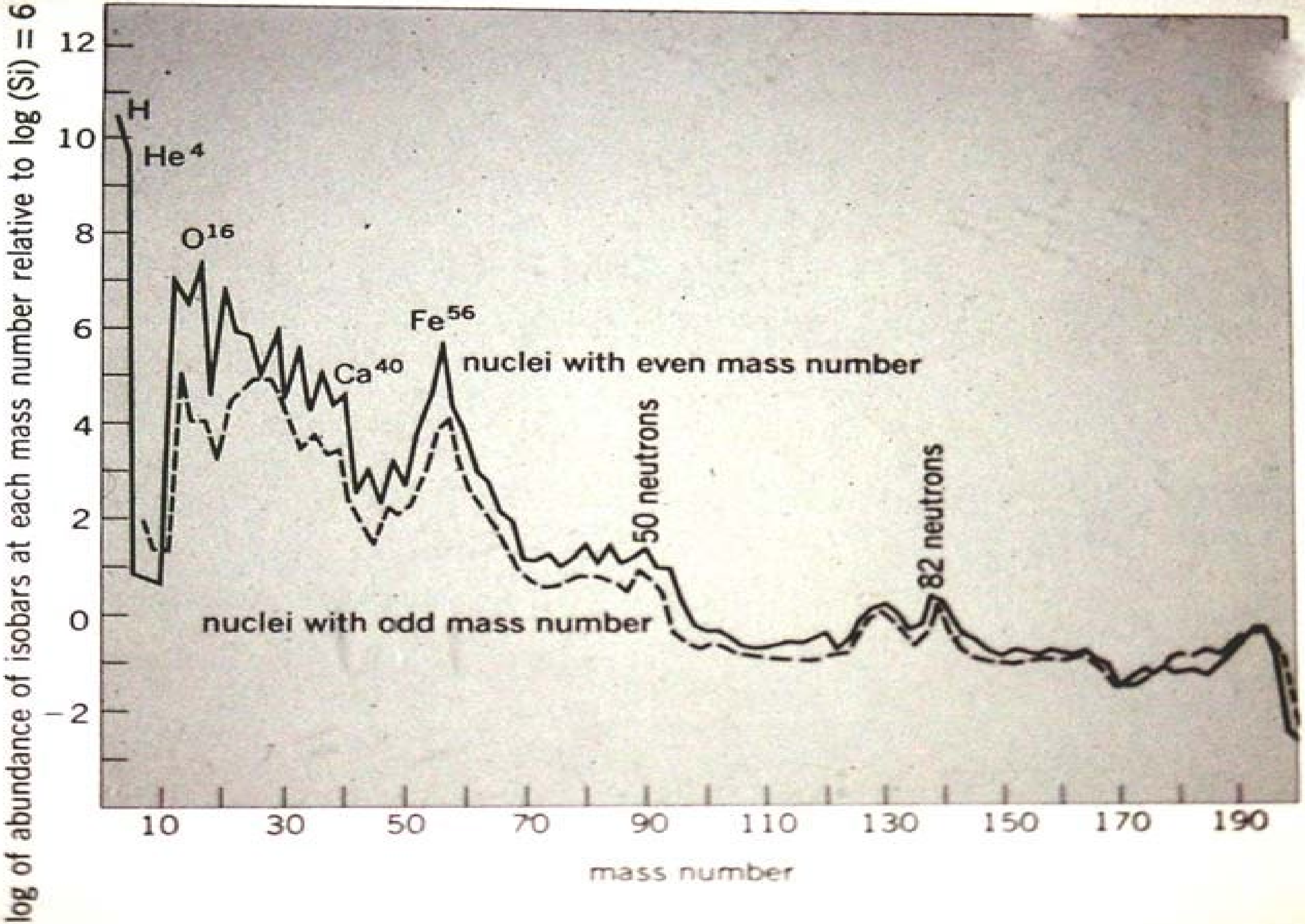


R-Process Elements within the Wider Band of ~Stable Elements. They're the Neutron-Rich Elements





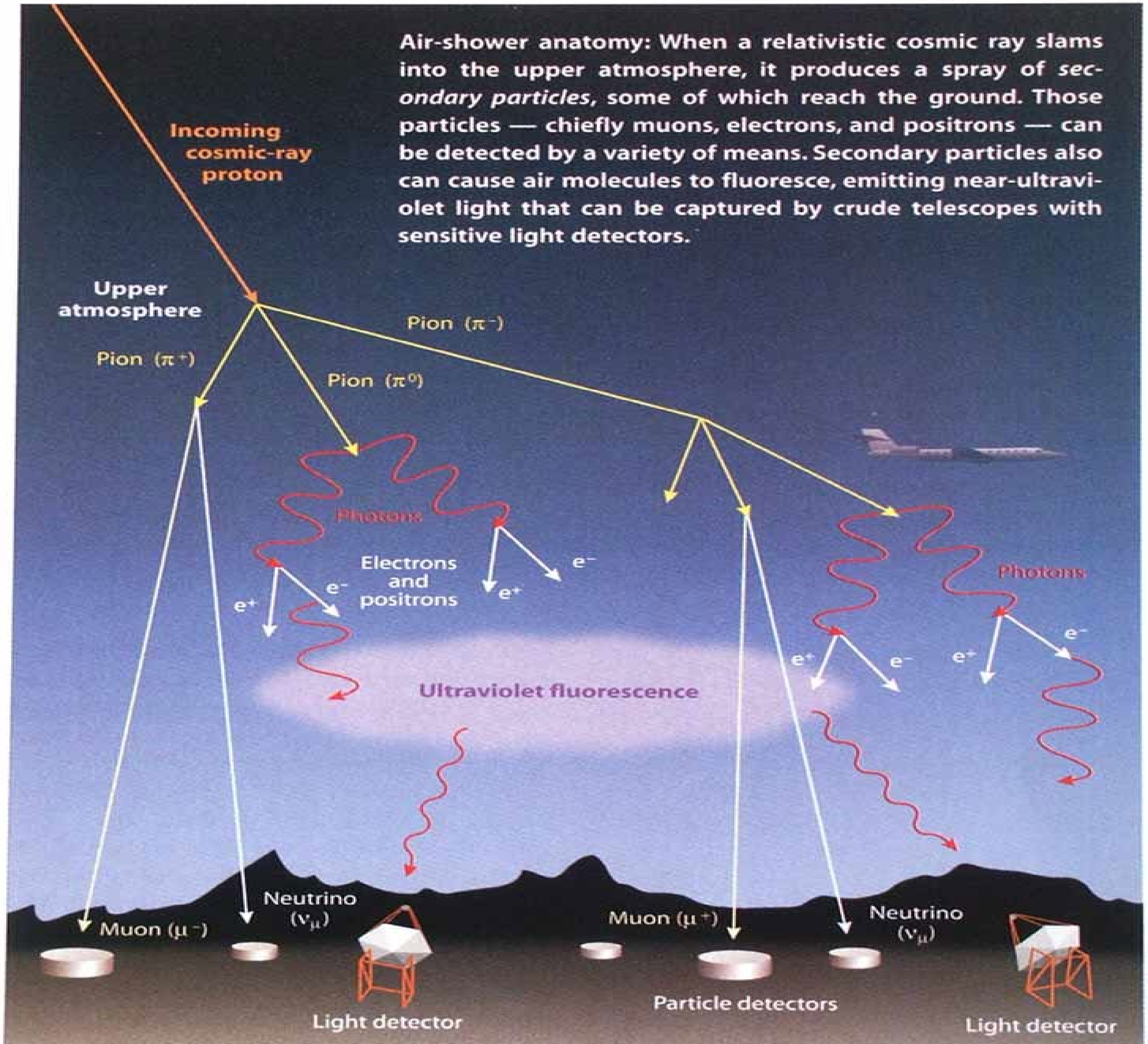
hydrogen
helium
carbon
oxygen
neon
magnesium
silicon
sulfur
argon
calcium
iron
nickel
nitrogen
boron
beryllium
lithium
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
relative abundance (atoms per hydrogen atom)
1
10
20
30
40
50
atomic number (number of protons)



Plot of abundances of isobars by mass number. *(After H. E. Suess and H. C. Urey)*

Cosmic Rays…

- The blast of a supernova explosion sends out elementary particles at near the speed of light.
- These get further accelerated by galactic magnetic fields to become orders of magnitude more energetic still.
- When they impact Earth, they smash into our atmosphere and create cosmic ray air showers



Air-shower anatomy: When a relativistic cosmic ray slams into the upper atmosphere, it produces a spray of *secondary particles*, some of which reach the ground. Those particles — chiefly muons, electrons, and positrons — can be detected by a variety of means. Secondary particles also can cause air molecules to fluoresce, emitting near-ultraviolet light that can be captured by crude telescopes with sensitive light detectors.

S&T ILLUSTRATION

Interesting Cosmic Ray Factoids

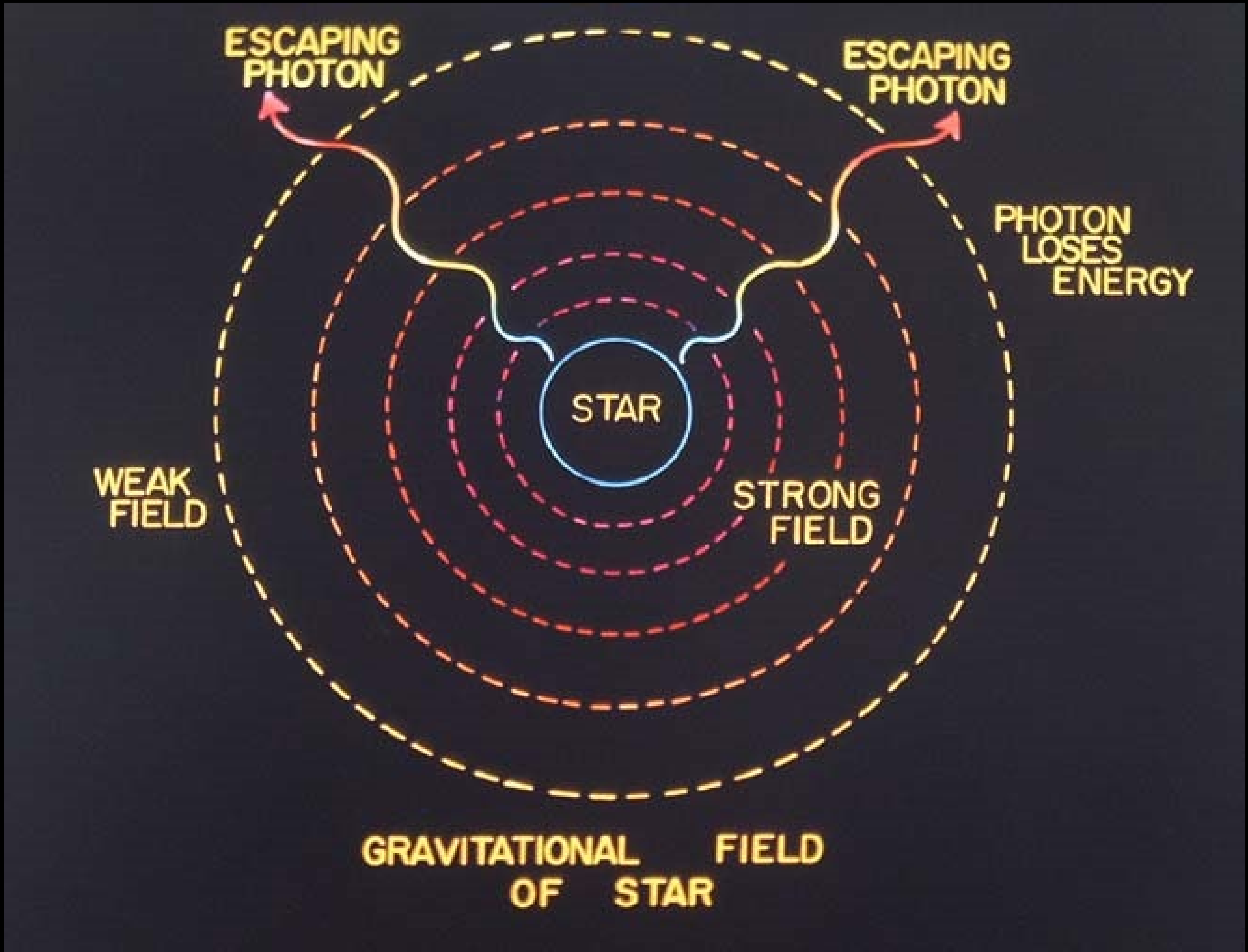
- Air showers are composed of "secondaries" – the pieces of the original atmosphere atoms hit (protons, neutrons, electrons) as well as many more particles created by the fact $E=mc^2$ and so new massive particles can be created out of available energy. Pions, kaons, lambdas, muons (most of what arrives at sea level are muons), and many more particles you don't hear about much because they decay rapidly in ordinary circumstances…
- Radioactive carbon-14 is also created (in trace amounts) by cosmic ray collisions producing free neutrons acting on ordinary nitrogen in our atmosphere. This C^{14} has a half-life of 5,730 years and is incorporated like other carbon into living tissue and is a very useful "clock" for age-dating recent fossils. Use the ratio of C^{14}/C^{12} ratio in air as a starting point in your plant sample, and measure the ratio incorporated in your sample, and it will show lower C^{14}/C^{12} due to radioactive decay, telling you how long ago it incorporated atmospheric carbon.
- Cosmic rays are a significant (~5-10%) source of genetic mutations. Our atmosphere protects us from most primaries, although we still get hit by secondaries which are quite powerful. Their health effects, however, are complex and poorly understood at present.

3 Possible Ends of a Star, Depending on the Mass M of the end state

- **If M < 1.4 M_{sun} => White Dwarf**
- **If 1.4x M_{sun} < M < 2 M_{sun} => Neutron star**
- **If M > 2 M_{sun} => Black Hole!**

Less than 1.4 M_{sun} and you can be supported by electron degeneracy. Between 1.4 and 2 M_{sun}, you can be supported by neutron degeneracy. More than 2M_{sun} and nothing can support you – ultimate collapse w/o end – a Black Hole

For a Black Hole, the "Gravitational Redshift" would be 100% - All of the Photon's Energy is redshifted away

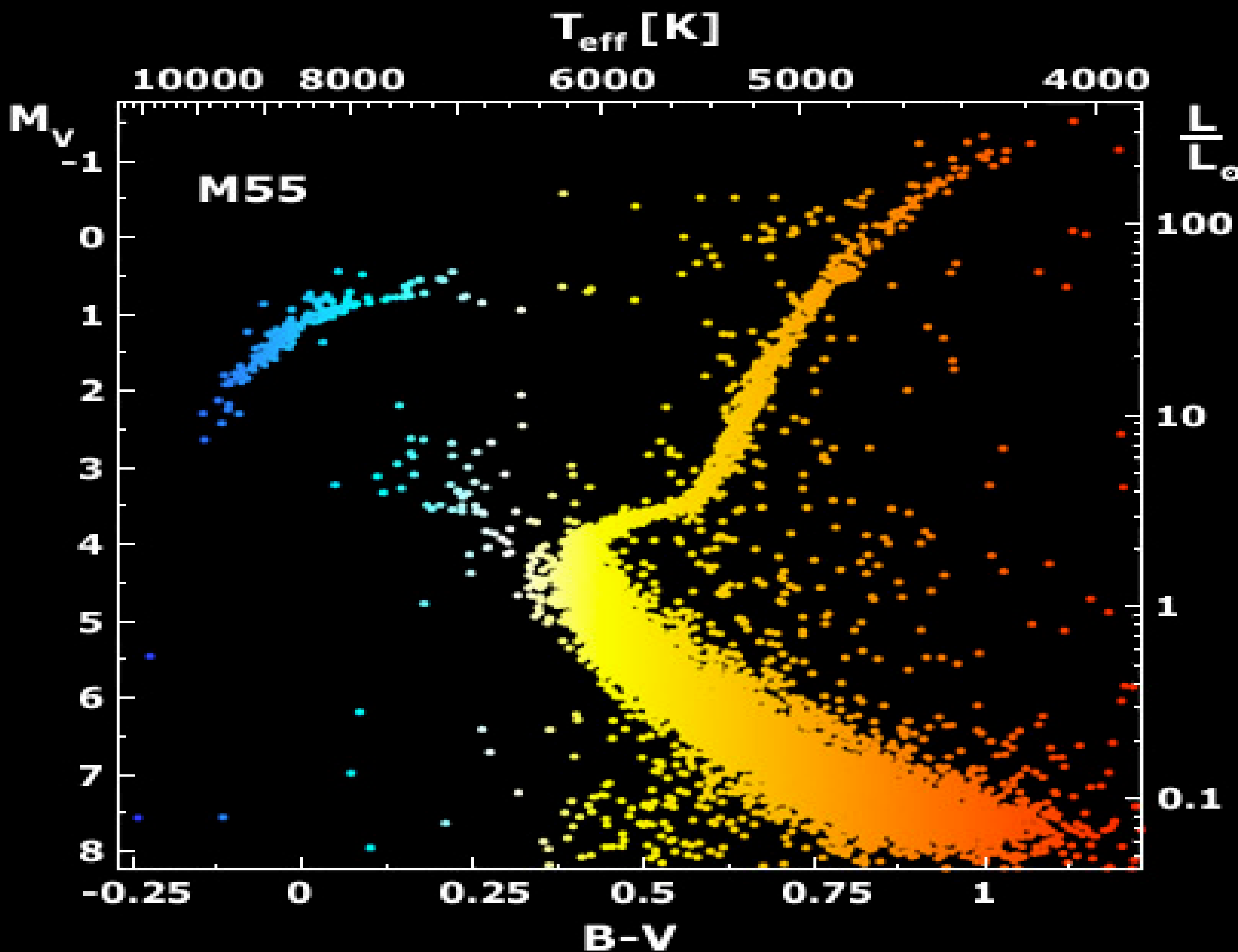


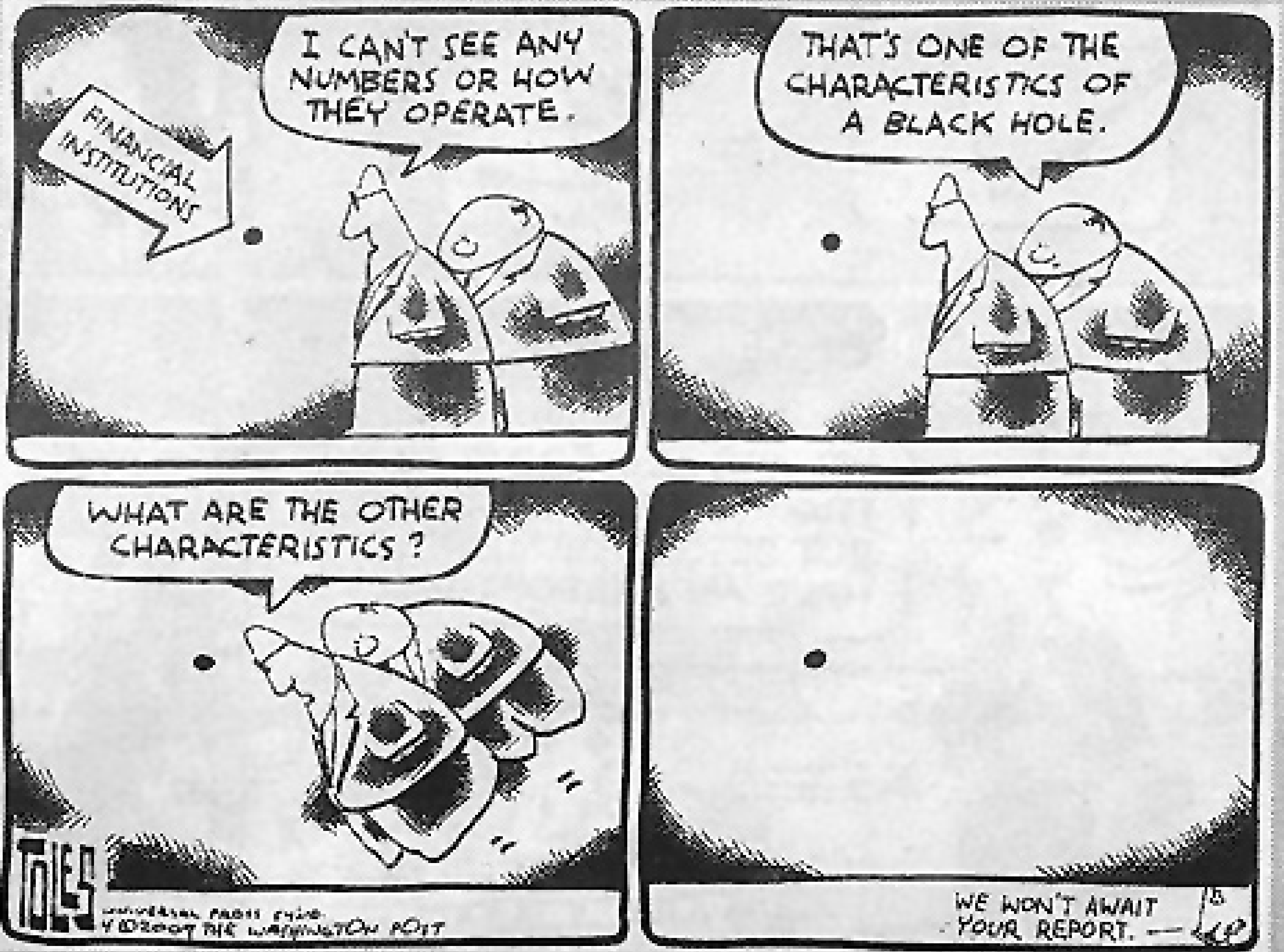
A Black Hole, against a starry background. Gravity bends light around the BH, creating the crowded ring of light

The Event Horizon of a Black Hole

- Looking from the outside, the event horizon is the radius within which no light can escape and it is permanently cut off from our Universe
- The **Escape Velocity at the Event Horizon is the speed of light**, and inside the Event Horizon the escape velocity is GREATER than the speed of light – so nothing can escape.

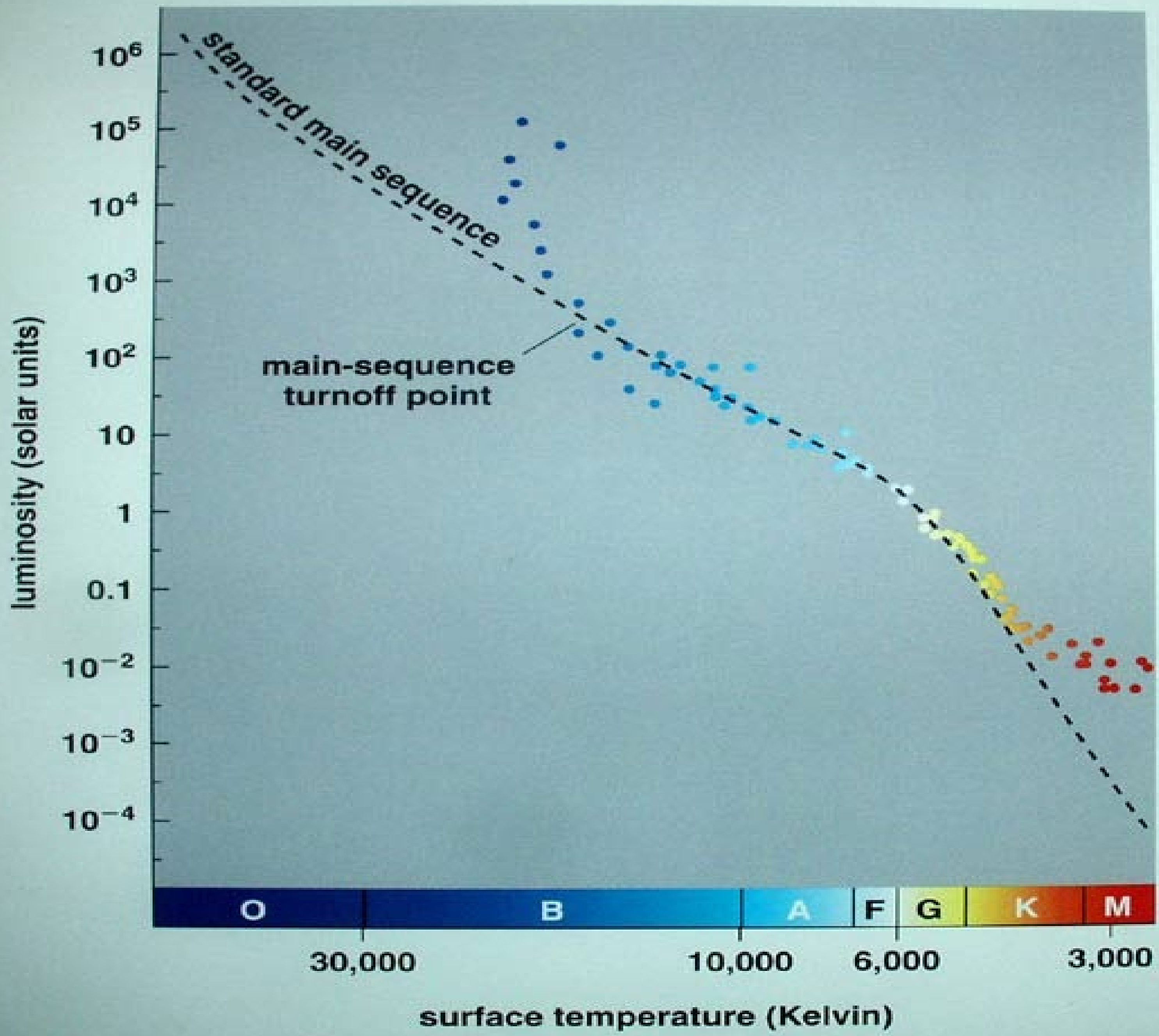
Globular Cluster HR Diagram – 13 Billion Year Old Cluster!




FINANCIAL INSTITUTIONS
I CAN'T SEE ANY NUMBERS OR HOW THEY OPERATE.
THAT'S ONE OF THE CHARACTERISTICS OF A BLACK HOLE.
WHAT ARE THE OTHER CHARACTERISTICS?
TOLES
WE WON'T AWAIT YOUR REPORT.

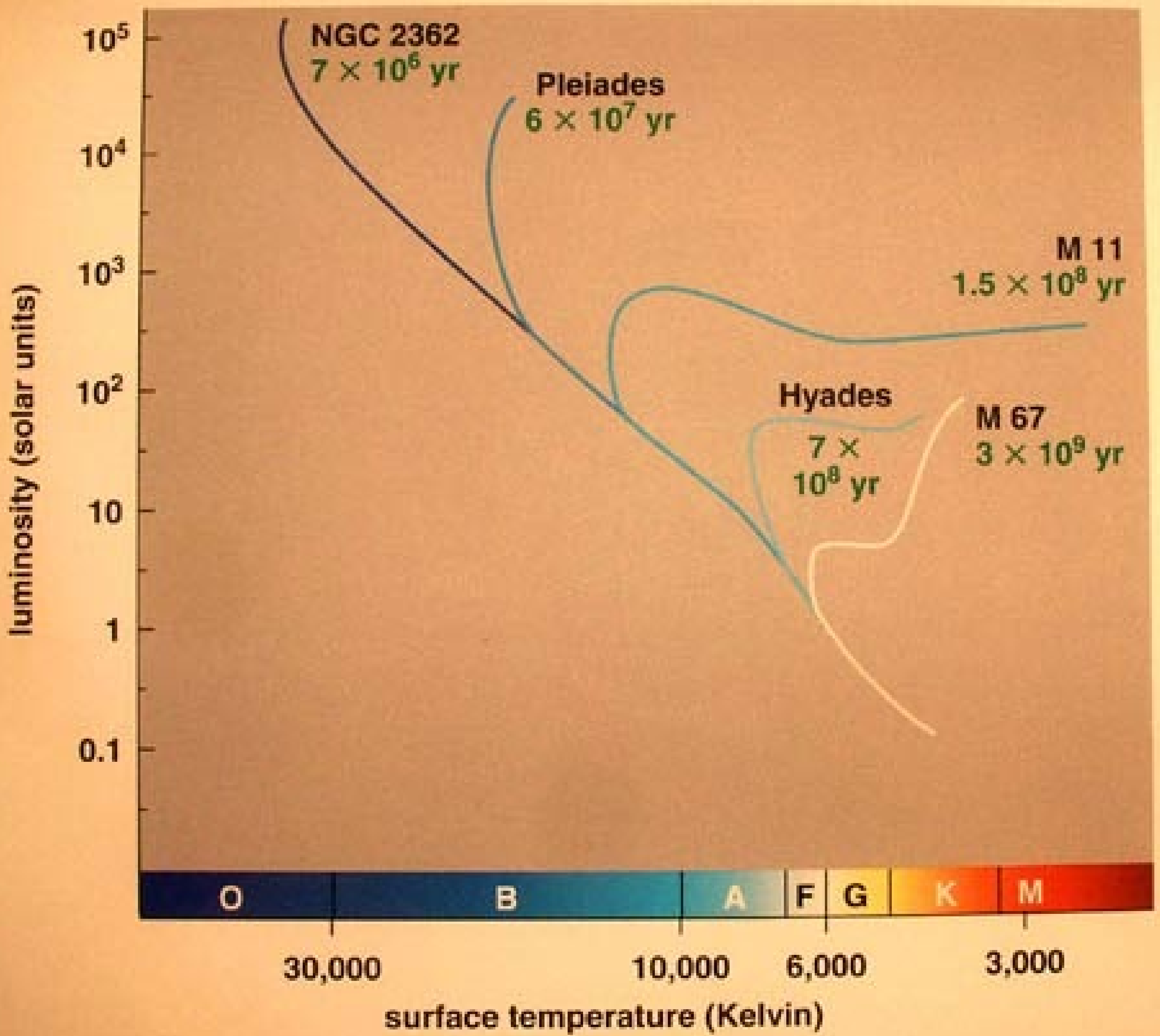
Putting This Together: How Star Cluster HR Diagrams Evolve

- The high mass stars plop down onto the Main Sequence quickly, evolve off quickly and die
- Meanwhile the lowest mass stars are so slow they haven’t even finished collapsing enough to initiate fusion!


standard main sequence
main-sequence
turnoff point
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

So, We Can Date the Age of a Star Cluster!

- This is usually very tough for an individual star – they age so slowly and gracefully when on the Main Sequence…
- They're like we all would like to be – come to full flower quickly, then not age on their surface at all, till very near the End
- For Star Clusters, we can see where the turn-off of the Main Sequence is, look at our stellar computer models to see how old a star of that mass is, and that must be the age of the cluster.



NGC 2362
7 × 10^6 yr
Pleiades
6 × 10^7 yr
M 11
1.5 × 10^8 yr
Hyades
7 × 10^8 yr
M 67
3 × 10^9 yr
luminosity (solar units)
10^5
10^4
10^3
10^2
10
1
0.1
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

Key Points – Chap 17, 18: Stellar Evolution

- Low mass stars burn H-He and then die as white dwarfs, but Universe not old enough for any to have done this yet
- Medium mass stars die as planetary nebulae and then white dwarfs
- Carbon stars: dredge carbon from the core to the surface, stellar winds blow it out, cools, becomes graphite grains which redden the light before it arrives to us. Very red stars, and a key source of carbon in the formation of new stars and planets
- High mass stars die as Type II supernovae as iron core collapses if weight higher than 1.4 solar masses
- Most elements heavier than iron were made in supernova explosions
- Gold, platinum, and some other heavies were made only in **neutron star collisions**
- Close binaries produce mass tranfer onto white dwarf, leading to a nova. Or a Type Ia ("carbon bomb") supernova, leaving no remnant
- Neutron stars: mass of the sun, size of a city
- **Pulsars**, rapidly spinning neutron stars with matter falling onto magnetic poles, sending beams of light out, which rapidly sweep around since magnetic axis and rotation axis are rarely the same. You see flashes of light many times per second.
- Gravitational redshift: light spends energy and reddens as it tries to climb out of a strong gravity field, like neutron stars or white dwarfs.
- Black holes: at the event horizon, the escape velocity is the speed of light, so nothing inside the event horizon can ever escape it.
- White dwarfs cool to become diamond, due to high pressure
- Iron: tighest bound element, all fusion and fission subtract energy from the star. Energy is produced by fusion from lighter elements, and by fission from heavier elements.