Stars

With special attention to Betelgeuse, and the Sun.

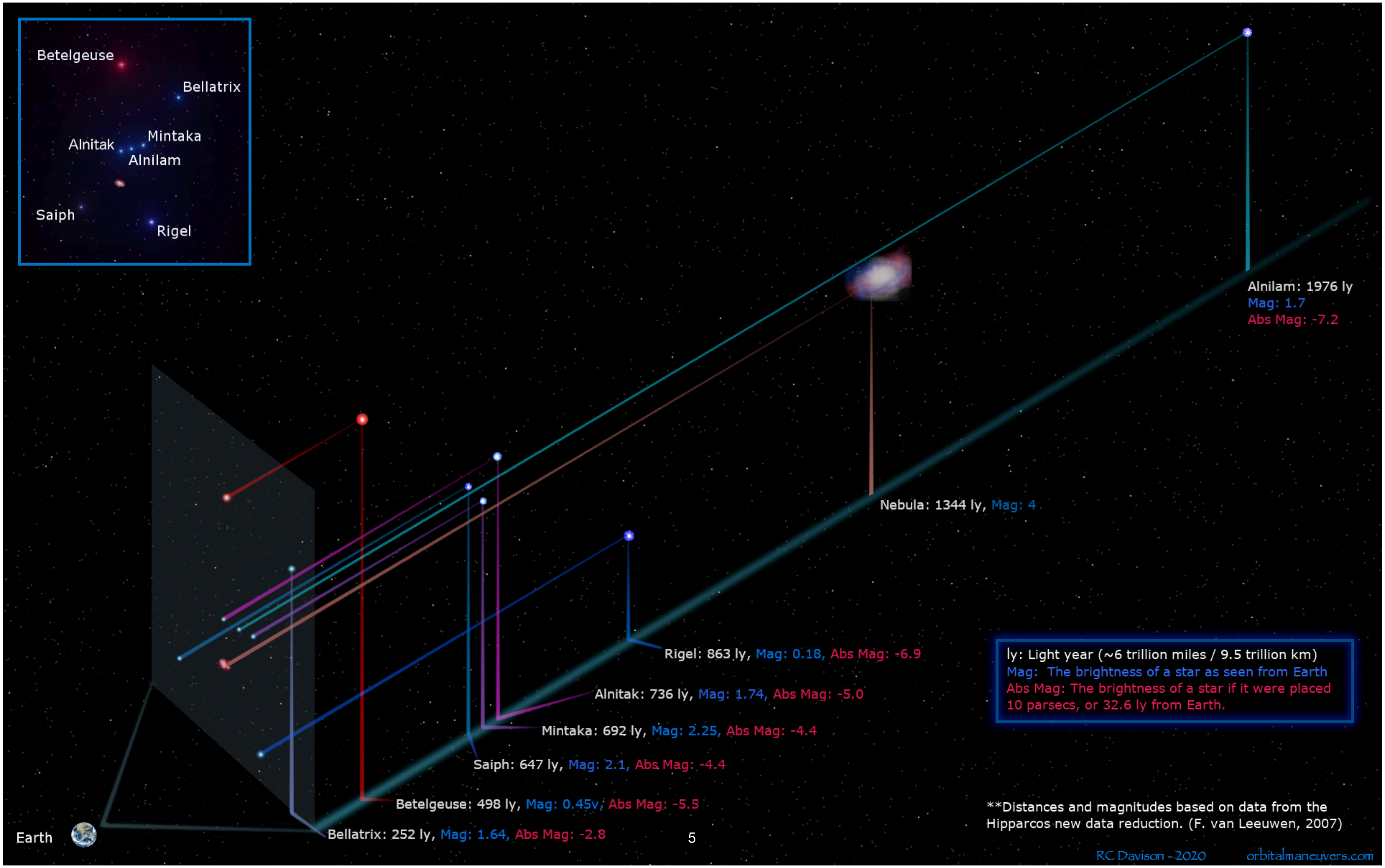
Richard J Edgar, Nov 4, 2020
What's New in Astronomy
Learners at Wind Crest

Sometimes when you stare into the void…

The void stares back at you.

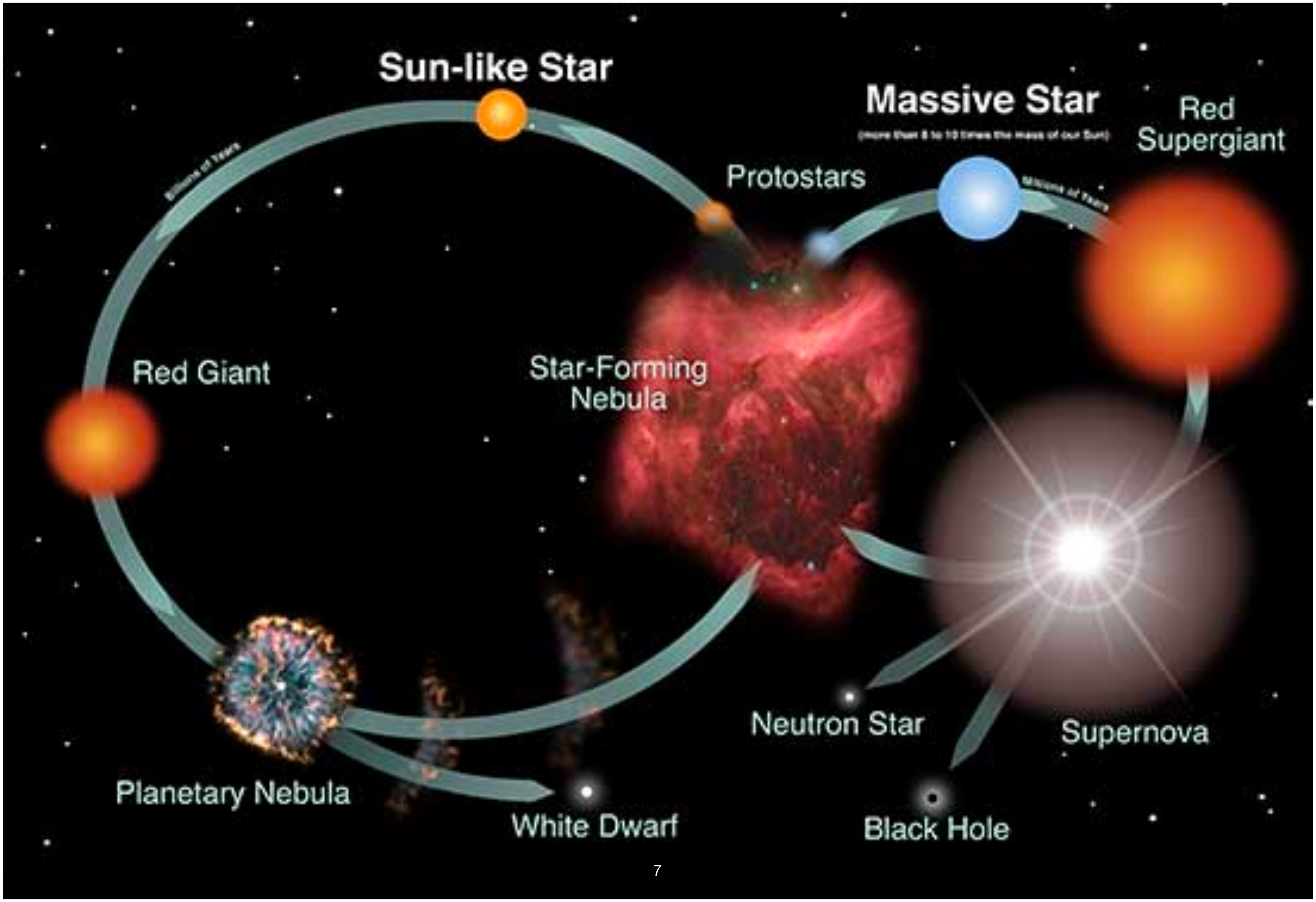
- Orion
- Right: naked eye, give or take.
- Left: Deep photograph from a dark site
- Betelgeuse is the orange star upper left

- Betelgeuse is (usually) the brightest star in the constellation Orion
- Orion rises around midnight now, and earlier as the winter goes on.
- Go out and look if you're up before dawn (or any time of the night around the new year). The pattern of stars is easy to recognize.
- Orion was a mythological hunter, and he's in the sky between his faithful dogs (Canis Major and Canis Minor) and a bull (Taurus).
- The stars we see are on the near side of a dark cloud of interstellar gas and dust, which is forming new generations of stars. The cloud is opaque in optical, but we can see into it in the infrared or x-ray wavelengths.
- Here is Orion in 3D, showing distances to the stars there:


Betelgeuse
Bellatrix
Alnitak
Mintaka
Alnilam
Saiph
Rigel
Alnilam: 1976 ly
Mag: 1.7
Abs Mag: -7.2
Nebula: 1344 ly, Mag: 4
Rigel: 863 ly, Mag: 0.18, Abs Mag: -6.9
Alnitak: 736 ly, Mag: 1.74, Abs Mag: -5.0
Mintaka: 692 ly, Mag: 2.25, Abs Mag: -4.4
Saiph: 647 ly, Mag: 2.1, Abs Mag: -4.4
Betelgeuse: 498 ly, Mag: 0.45v, Abs Mag: -5.5
Bellatrix: 252 ly, Mag: 1.64, Abs Mag: -2.8
Earth
ly: Light year (~6 trillion miles / 9.5 trillion km)
Mag: The brightness of a star as seen from Earth
Abs Mag: The brightness of a star if it were placed 10 parsecs, or 32.6 ly from Earth.
**Distances and magnitudes based on data from the Hipparcos new data reduction. (F. van Leeuwen, 2007)
RC Davison - 2020
orbitalmaneuvers.com

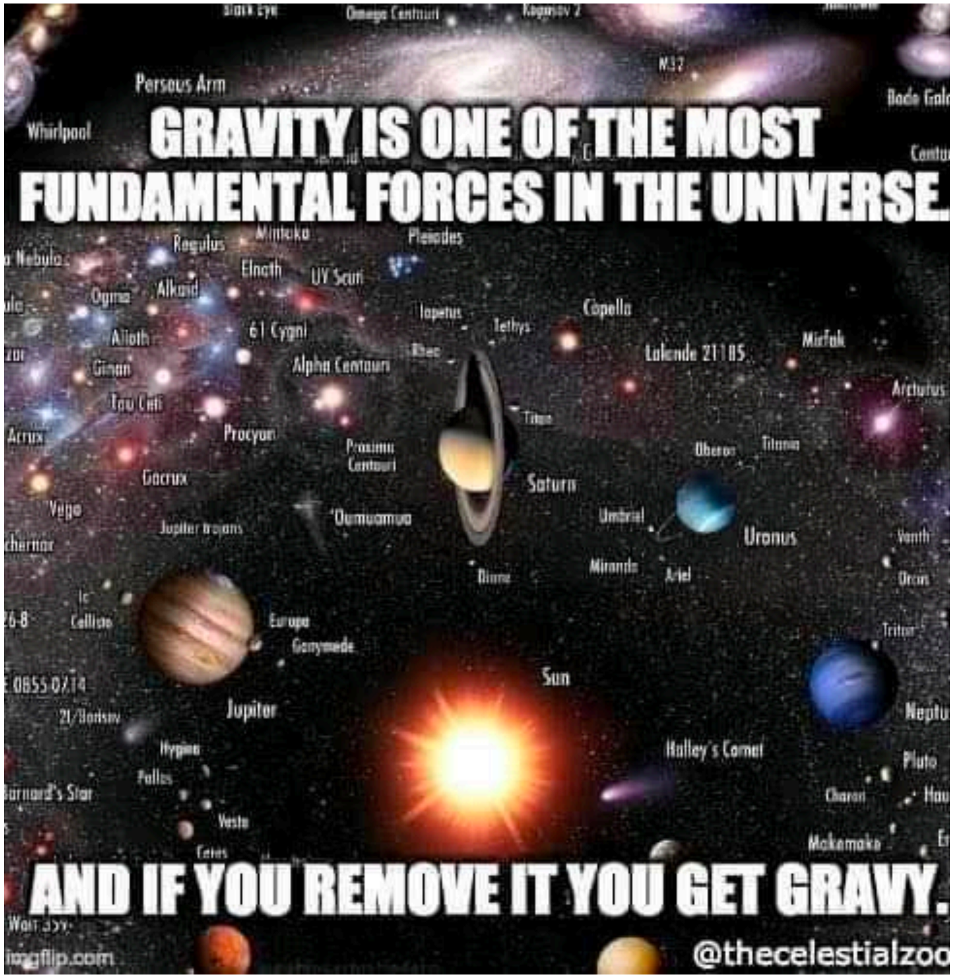
Orion, defocused

- Star images are typically overexposed.
- David Malin took a time exposure of Orion, with the camera fixed (to the earth), defocusing in steps as the earth rotates, smearing the stars into pie wedges.
- Note the variety of vivid colors.
- Betelgeuse is upper left; the Orion Nebula is the pink thing.


Sun-like Star
Massive Star
Red
Supergiant
Protostars
Red Giant
Star-Forming
Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole

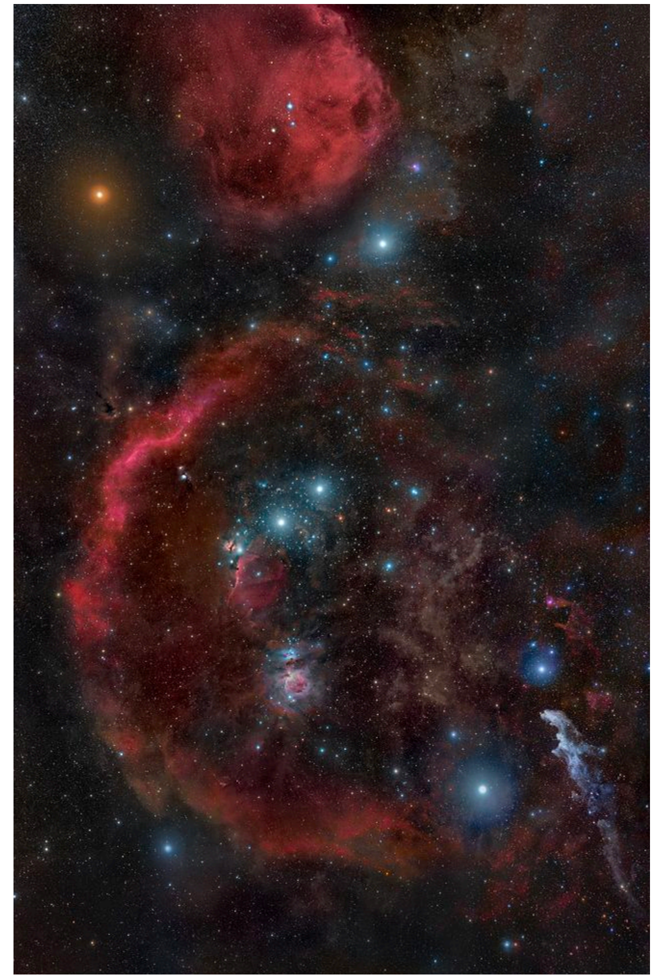
Life-cycle of stars

- Stars form when dark clouds collapse under their own gravity.
- What you get depends on how much mass ends up in the star. More mass, hotter stars, shorter lifetimes.
- The sun is in about the 70th percentile by mass of stars. Most stars are less massive, but some are more massive.
- A star is an epic battle between two forces:
    - Gravity, which compresses the star and makes the core hot. This fuses H into He in the core.
    - Escaping light (electromagnetic radiation) from the nuclear fusion in the core


GRAVITY IS ONE OF THE MOST FUNDAMENTAL FORCES IN THE UNIVERSE.
AND IF YOU REMOVE IT YOU GET GRAVY.
@thecelestialzoo
imgflip.com

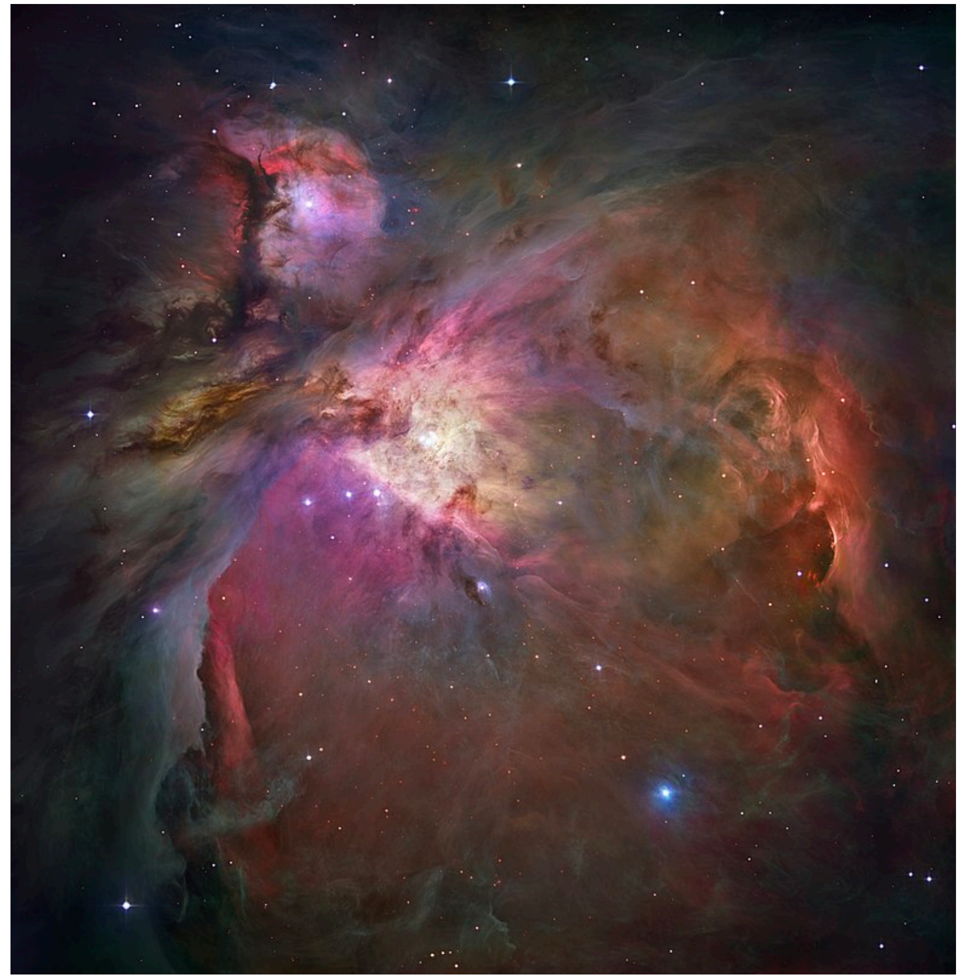
Orion shows ongoing star formation

- This is a very long exposure of Orion.
- Most of the stars are in front of a dark cloud
- Barnard's Loop (red semicircle) is an expanding shock driven by hot stars
- Betelgeuse is an aging star in the upper left
- The Orion Nebula is a star forming region breaking through the front surface of the cloud.



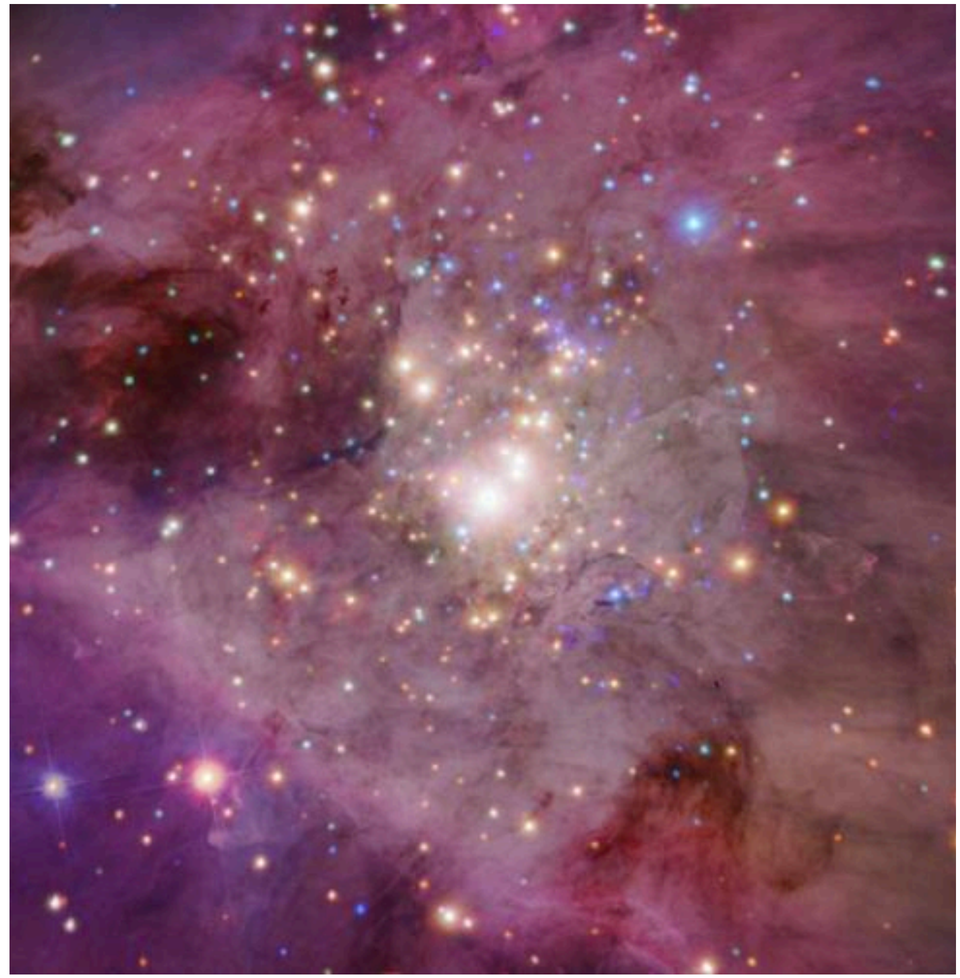
Orion Nebula

- Hot stars formed in the dark cloud.
- Their light and winds are blowing a hole in the front of the cloud.
- We're looking into a bowl-shaped divot with the hot young stars lighting it up.
- New generations of stars are forming, still embedded in the dark cloud behind the nebula.
- Distance 1500 light years



Orion Nebula in x-rays

- The wispy stuff is from Hubble, seen in visible light.
- The blue & orange points are young stars forming within the dark cloud, mostly behind the optical nebula.
- Every young star is an x-ray source
- The x-rays they emit can be seen through the cloud.



- A star is a ball of gas. Since gravity is trying to compress it, the temperature, density, and pressure of the gas are much higher in the core than at the surface.

- The “photosphere” of the Sun (the surface you see) has a temperature of about 5800 K. The core has a temperature of about a million K.

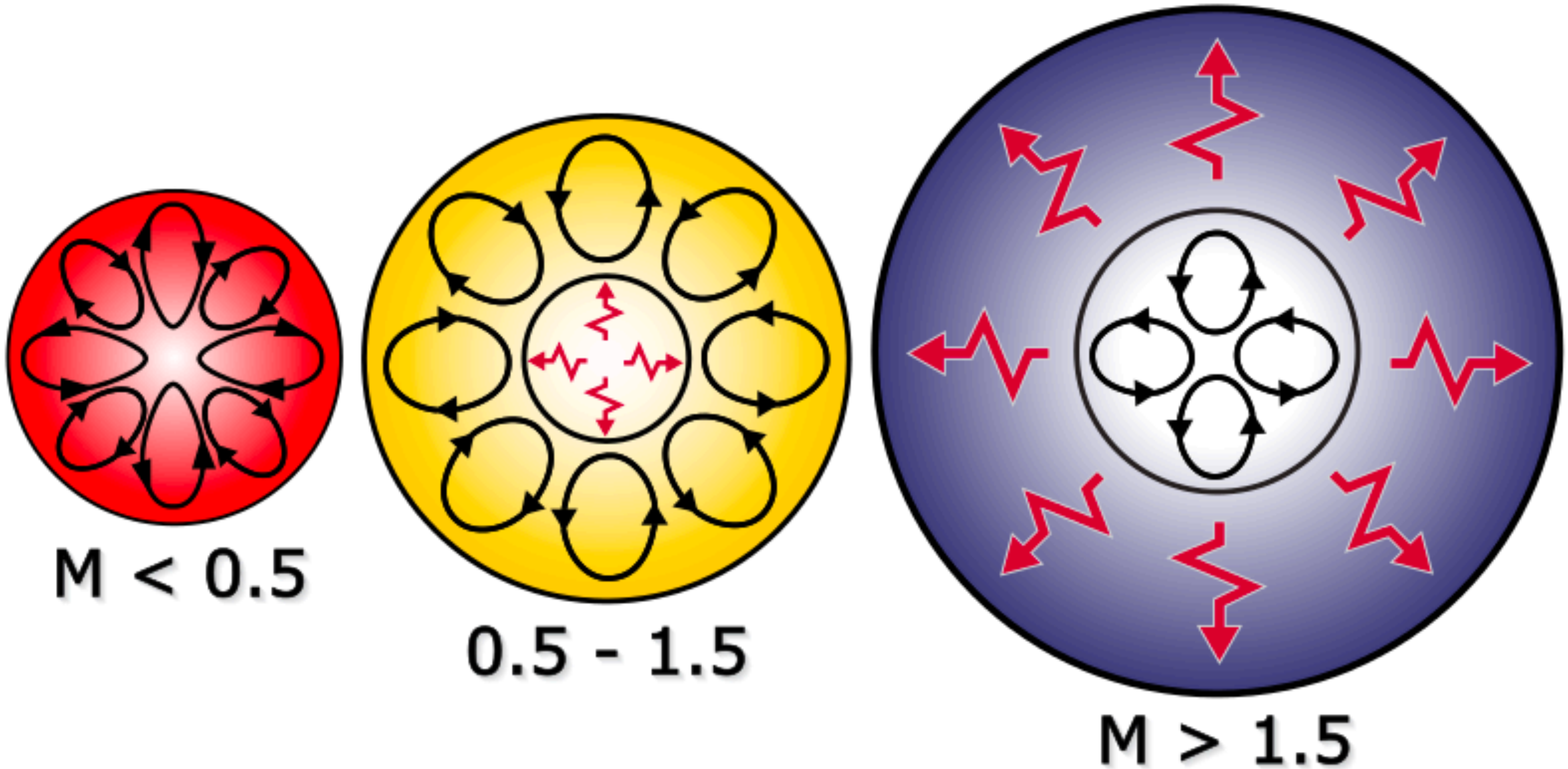
- About 90% of the atoms in the universe are hydrogen (one proton, one electron). Most of the rest are helium (2 neutrons, 2 protons, 2 electrons). Around a part in a thousand are everything else.

- At temps of around a million K, protons have enough energy to come very close together. They repel each other (like charges repel) at larger distances, but the Strong Nuclear Force has limited range and can bind them together.

- The net nuclear fusion reaction is 4p -> He + 2 positrons (e^+), 2 neutrinos and some energy.

- This reaction releases a lot of energy, as gamma rays and kinetic energy (i.e. heat).
- The gamma ray photons diffuse upwards through the star, providing some pressure support.
- Hydrogen fusion is pretty stable, and stars can burn mostly unchanged for millions to billions of years.
- The fuel source is finite, however, and eventually runs out.
- The lifetime of hydrogen-burning stars varies as the cube of the mass, with small stars living much longer.
- The sun is middle aged at about 4.5 billion years; it's expected to last 10-12 billion years.
- Betelgeuse has a mass of 16-18 solar masses, and is about 8 Myr old. It has run out of hydrogen to fuse in its core.

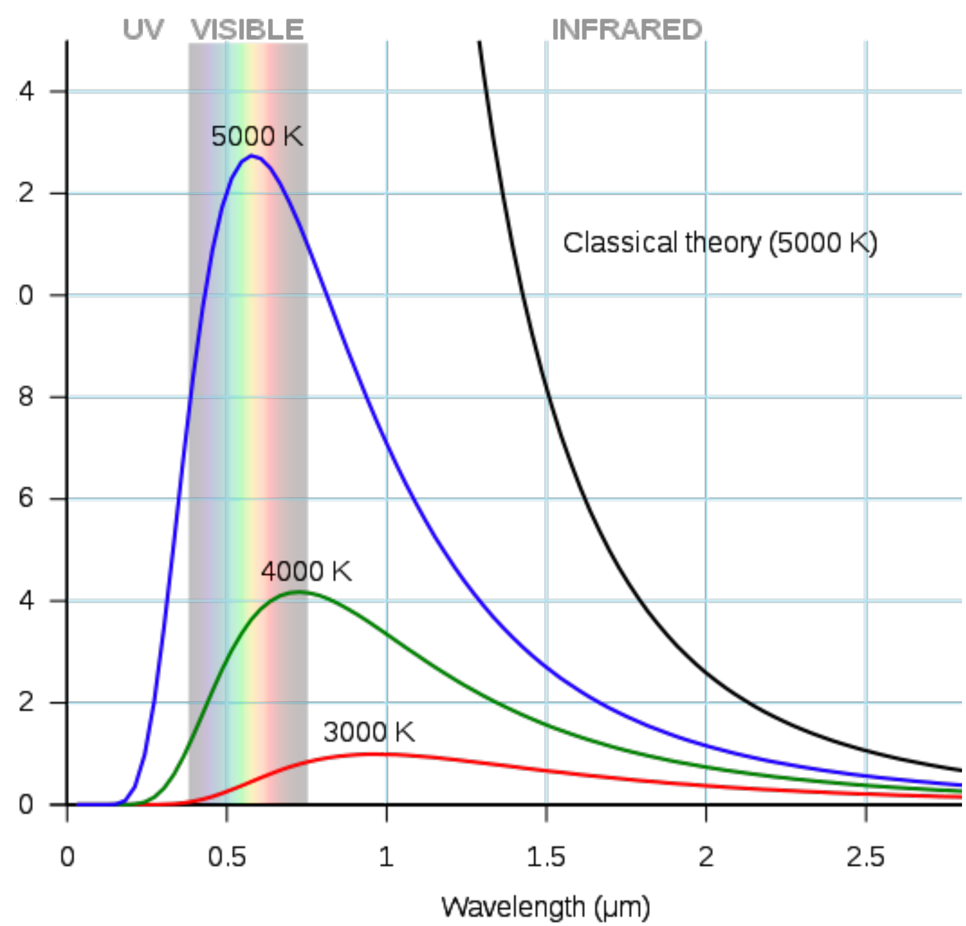
- Some stars have convective cores, so must burn all the H in the core.
- The sun does not; it'll burn H only in the hottest part.



- Crudely speaking, stellar spectra are “blackbodies” so the colors depend on the surface temperatures.

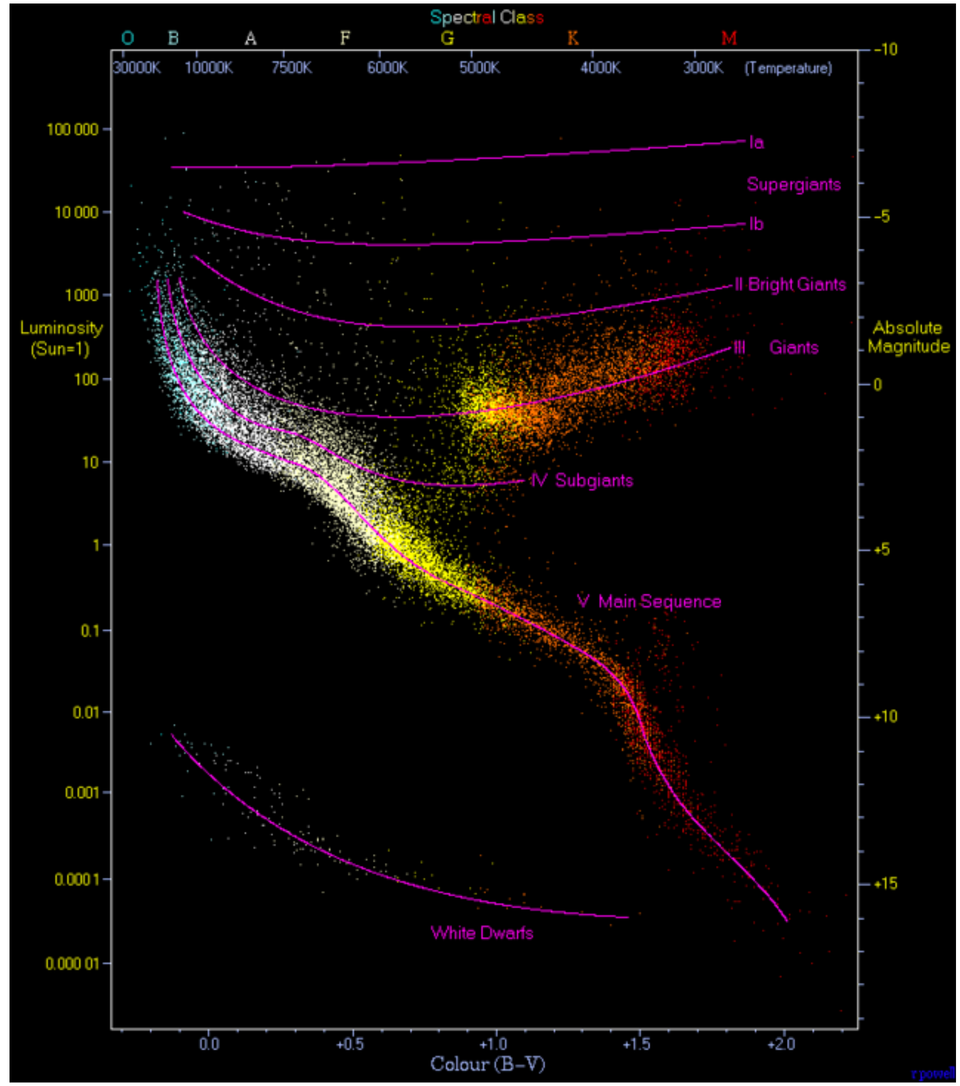
- Cooler stars are redder, hotter stars are bluer.

- Measuring the colors (temperatures) and brightnesses of a bunch of stars tells us something about how they behave.



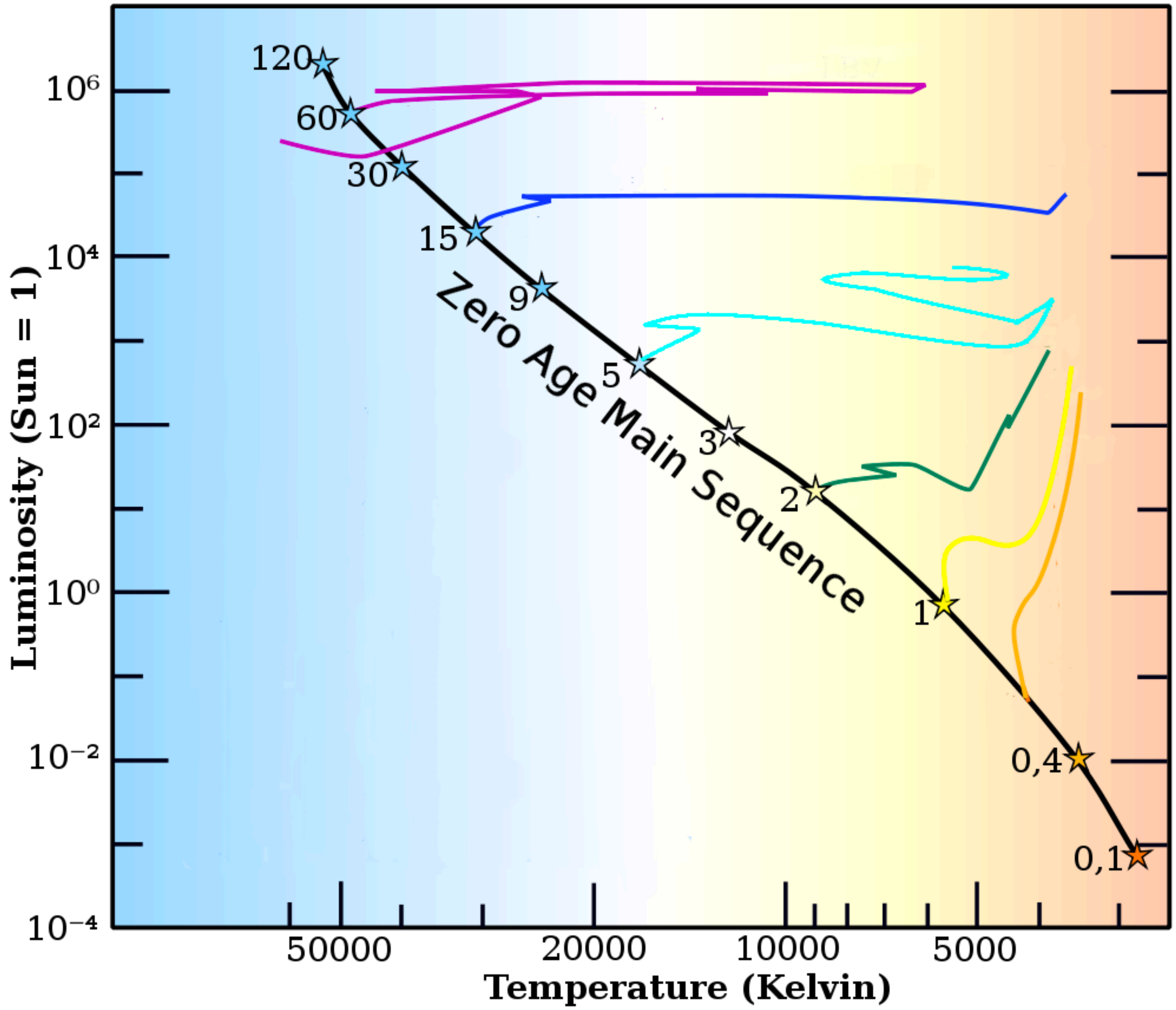
The Hertzprung-Russel (HR) Diagram

- Color (blue to red) across the bottom (so temperature runs cool to hot right to left)
- Brightness up and down, with brighter stars at the top.
- Nearly all stars fall on the “main sequence”
- Sun in yellow zone; Betelgeuse extreme upper right.

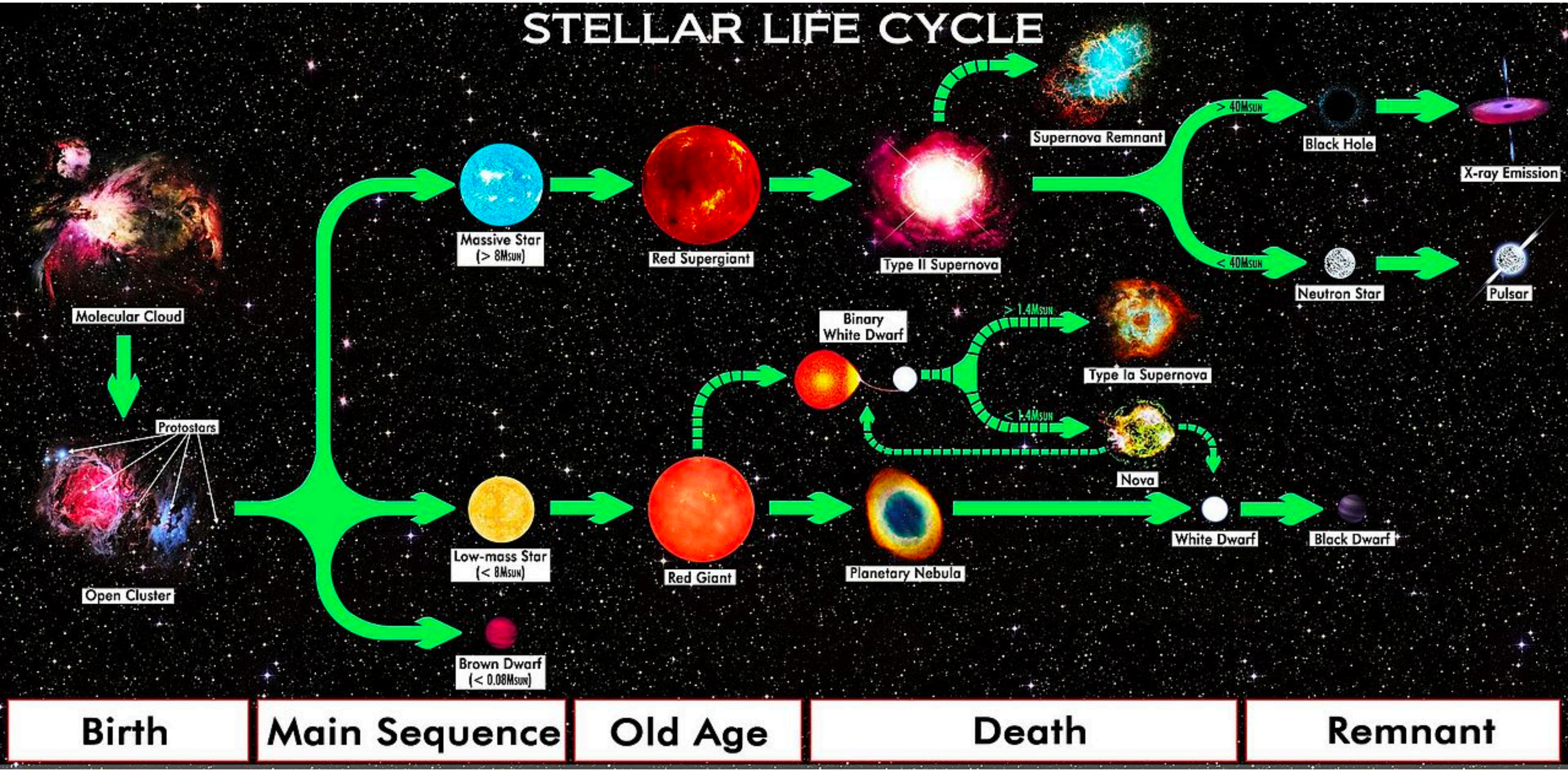


HR Diagram

- Stars stay put for most of the H burning lifetime
- Slowly get brighter and redder
- When core H is gone, they get dramatically brighter and redder, and larger.
- “Red Giant” stars.

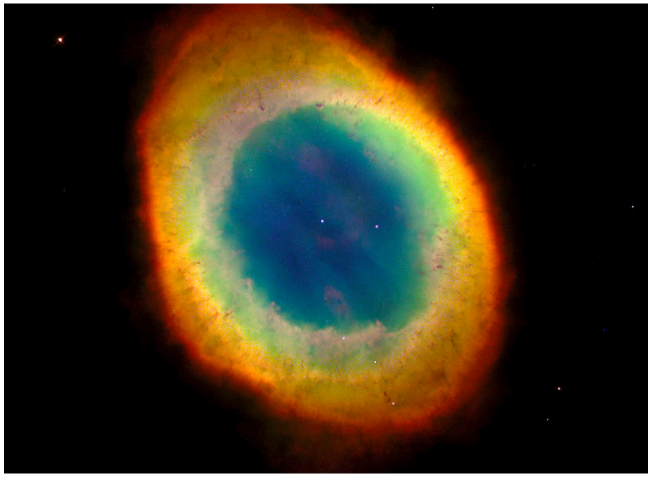


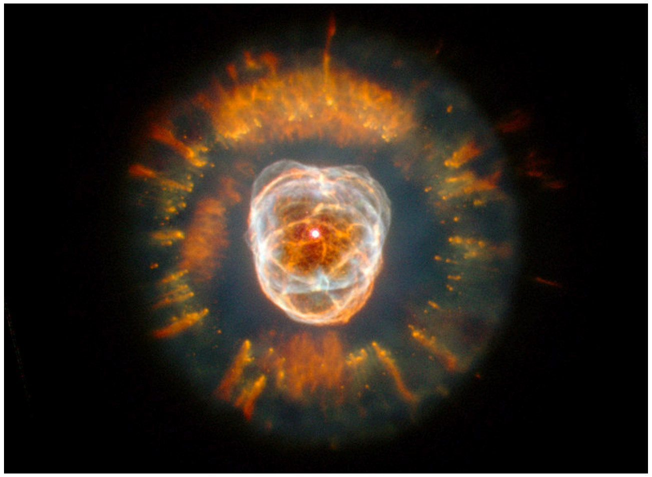
- When core H runs out, the core begins to shrink due to gravity.
- This makes it hotter and denser, and for a while the rest of the H can fuse.
- When the inner core is essentially pure He, it shrinks quite a lot, gets hotter and denser, until finally it’s hot enough to fuse 3 He nuclei into Carbon.
- All the extra radiation coming from the core fluffs up the envelope of the star, so the visible surface expands and becomes cooler (and redder).
- Betelgeuse is in this phase now.
- Fusing He goes much faster than fusing H did. And when the He is gone, fusing C, O, Ne, etc. go even faster, until…
- Iron. After you get iron-group elements no further nuclear energy is available, and gravity, finally, wins.



STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star
(> 8Msun)
Low-mass Star
(< 8Msun)
Brown Dwarf
(< 0.08Msun)
Red Supergiant
Red Giant
Binary
White Dwarf
Type II Supernova
Supernova Remnant
Planetary Nebula
> 1.4Msun
< 1.4Msun
Type Ia Supernova
Nova
> 40Msun
< 40Msun
Black Hole
X-ray Emission
Neutron Star
Pulsar
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

- What happens next depends on the mass of the star.
- Low-mass stars have lifetimes longer than the current age of the universe… Nobody knows what happens next.
- Sunlike stars' cores contract until the electrons won't compress any more, gently puff off the surface layers of the star, expose the very hot core, which cools to a white dwarf star (mass ~ 1 M-sun, size like the earth). The hot core lights up the nebula made from the stellar envelope to make a "Planetary Nebula."
- Cores of stars over 8 M-sun collapse dramatically, exploding the stars as Supernovae.
- But first some really pretty pictures of deceased sunlike stars.

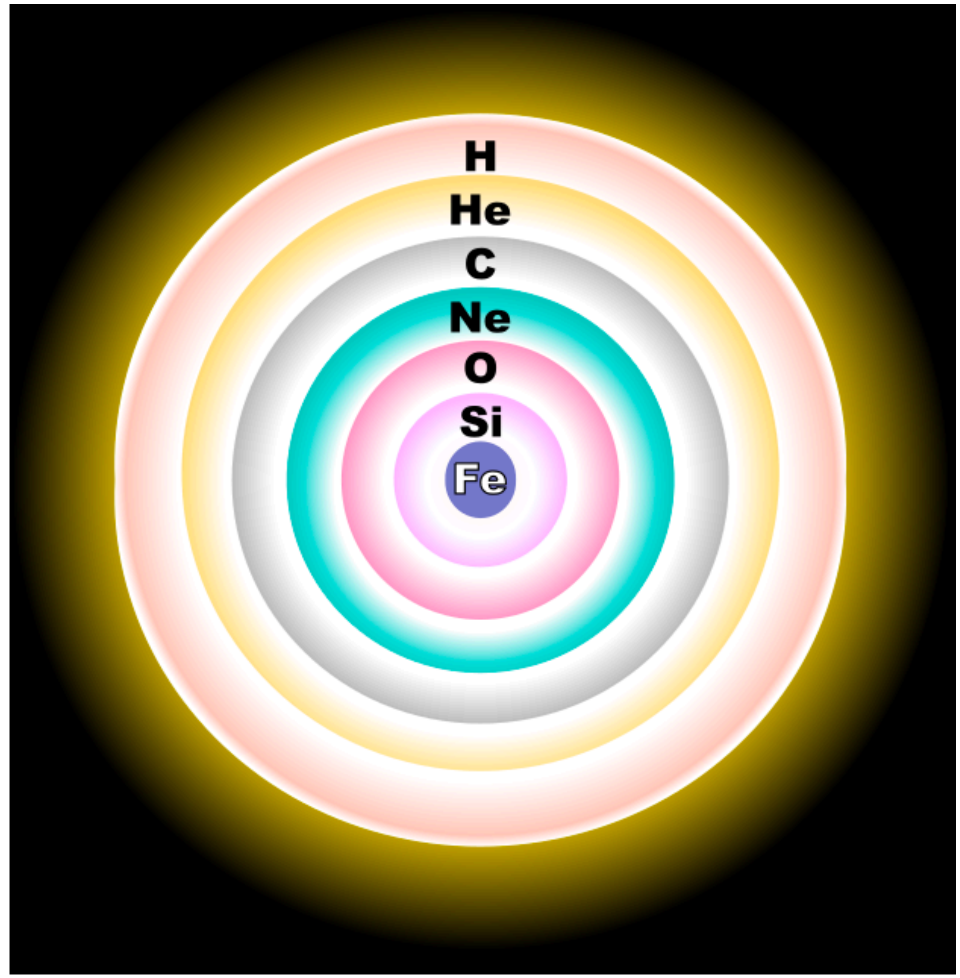




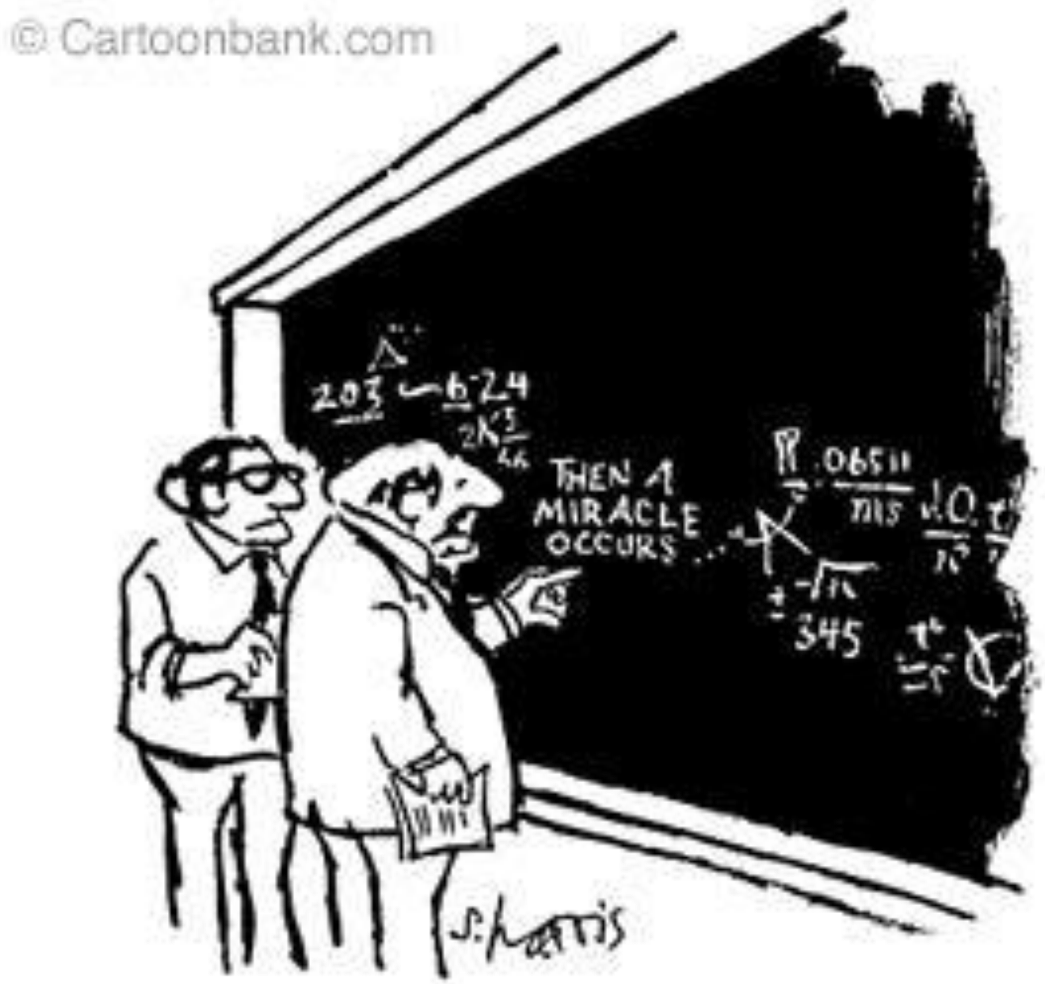
- The gas in the planetary nebula is returned to the galaxy at large to make into new generations of stars and planets.
- Since (almost) all nuclei heavier than He are formed in stars, this is where we came from. Carl Sagan: “We are star-stuff.”
- The white dwarf has no further energy source, so it cools until it’s no longer bright enough to see.
- White dwarfs made of C and O in close binary systems can get enough mass from the companion star to reactivate the fusion reaction and detonate the star. This is called a “type 1A supernova.” They seem to be all about the same brightness and can be used as distance indicators in faraway galaxies.

Massive Stars

- The core of a massive star develops an onion-skin structure (not to scale).
- When the Fe core can't produce any more energy, gravity wins and it collapses.
- Temps are high enough to squeeze electrons into protons and make neutrons, and neutrinos (which escape), further draining the energy from the core.
- The white dwarf phase is skipped.

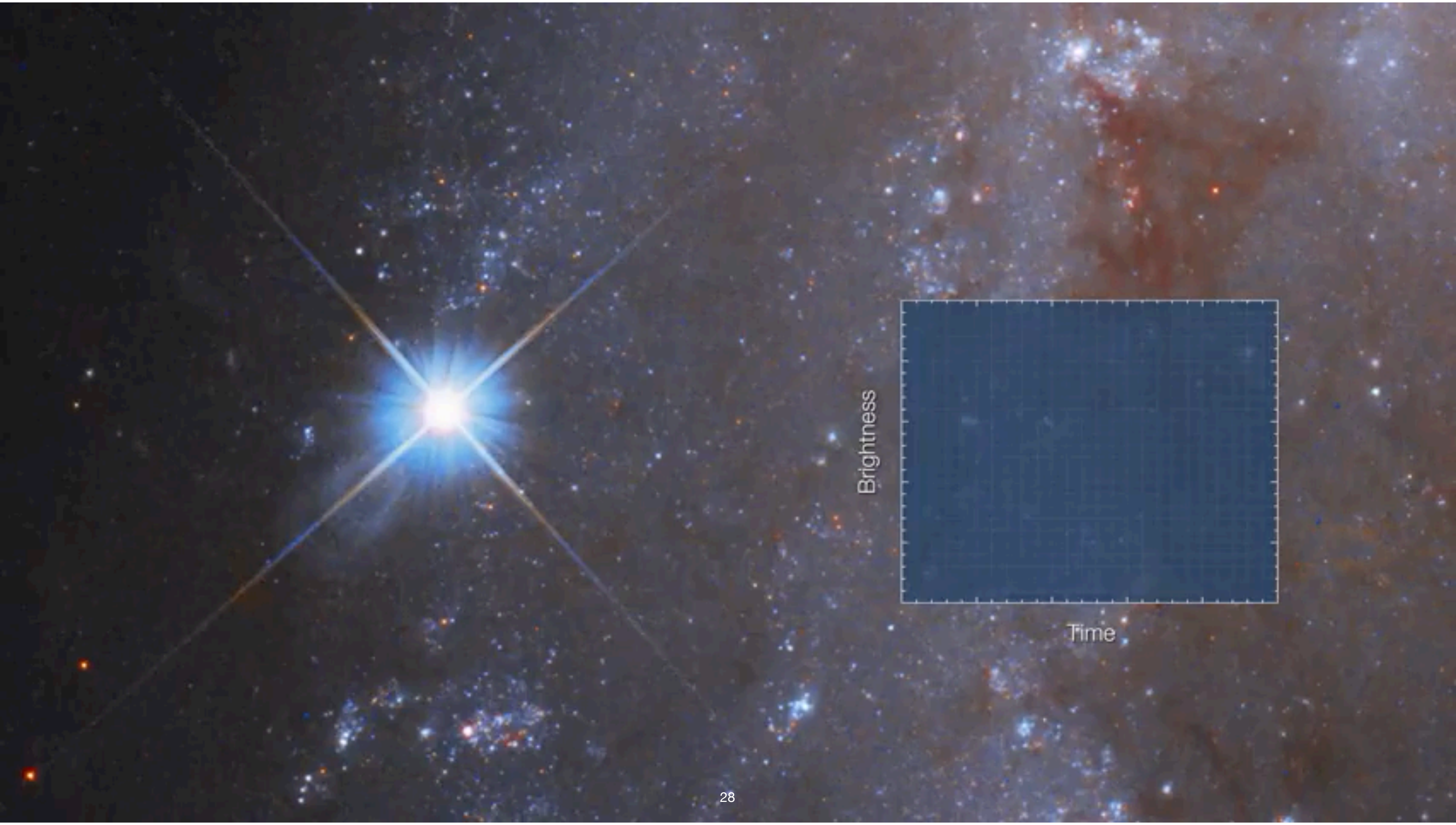


- The core of the massive star is collapsing.
- When it reaches the density of an atomic nucleus (or a bit more), the neutrons strongly resist further compression, forming a “neutron star”. Mass up to about 2 M-sun, size about 10 km (city sized). Often rotating very rapidly, with very strong magnetic fields.
- Somewhere in here, in a manner poorly understood…

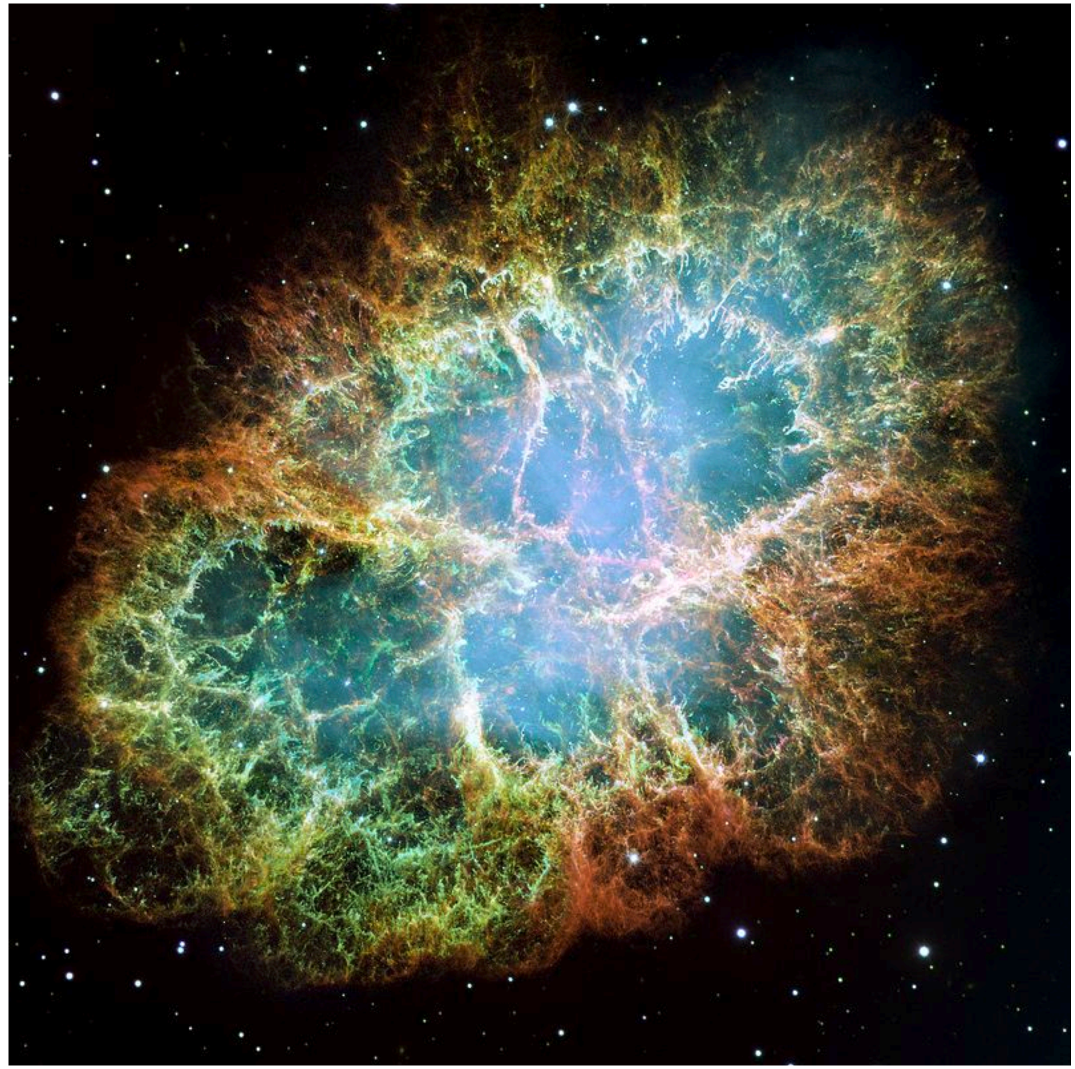


"I think you should be more explicit here in step two."

- … the star blows the envelope away in a Type II Supernova.
- Many of the nuclei synthesized over the lifetime of the star are scattered into space, where they can be made into future generations of stars and planets.
- Additional nucleosynthesis occurs during the explosion itself.
- Perhaps the neutrons can resist further collapse, and a neutron star will appear.
- If not, a black hole forms and (we think…) everything collapses to a mathematical point (“singularity”).
- The supernova can be as bright as the rest of the galaxy combined, for a few weeks. Here’s one in galaxy NGC 2525, fading.


Brightness
Time

- The Crab Nebula is the remnant of a supernova observed by the Chinese in 1054
- The colored filaments are ejecta from the star, observed in optical with Hubble.
- The blue glow is x-rays from high-energy electrons spun up in the magnetic field of the neutron star.
- The neutron star spins 33 times a second and flashes like a lighthouse. “Pulsar”

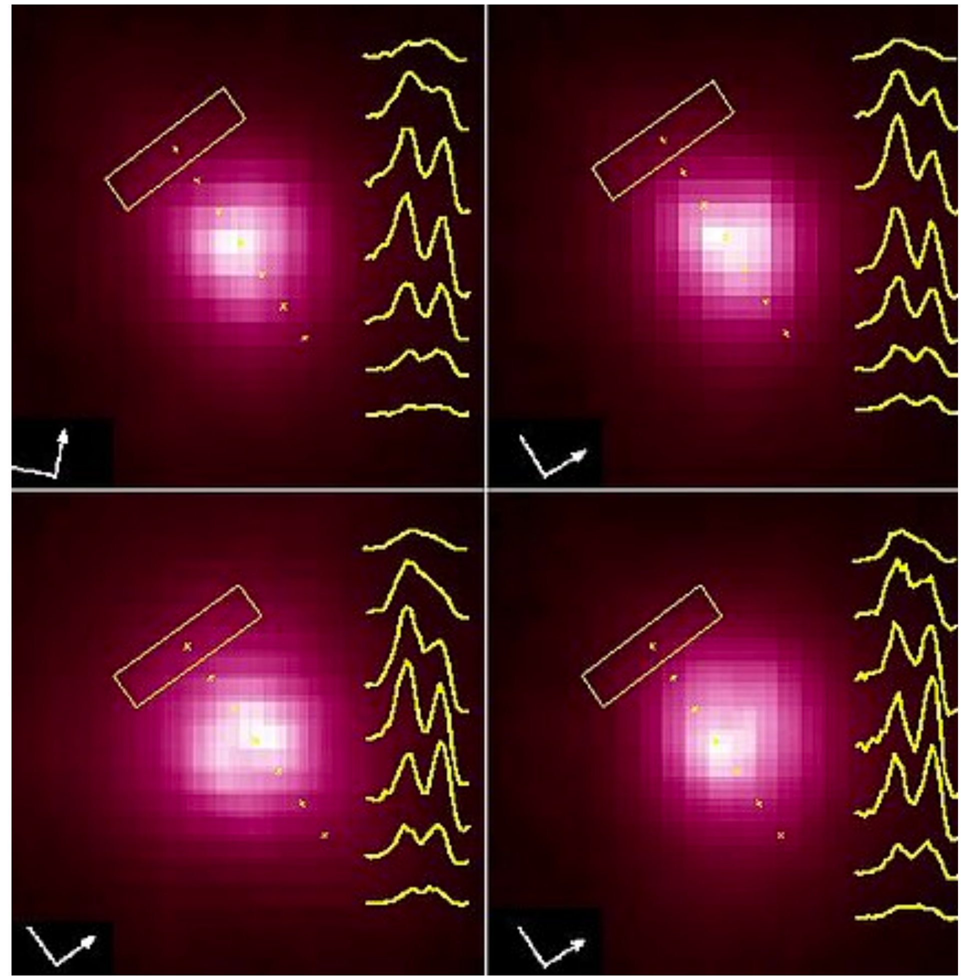


Cassiopeia A Supernova Remnant

- A Chandra X-ray Observatory image of the remnant of the supernova Cassiopeia A (“Cas A”) from the 1680s.
- Colors represent different elements in the ejecta
- Blue is the blast wave
- White dot is the neutron star (it doesn’t pulse).

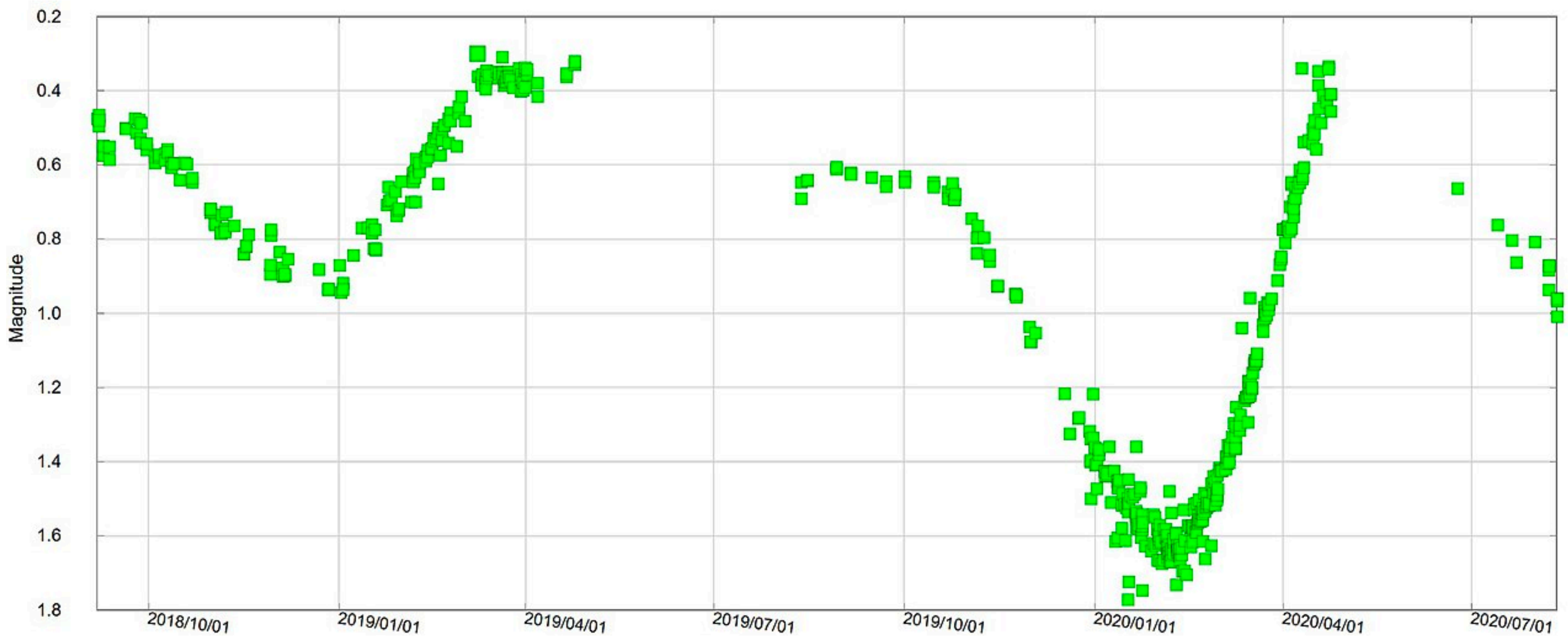
Back to Betelgeuse

- Betelgeuse is a Red Supergiant.
- It’s bigger than the earth’s orbit.
- It’s beginning to fuse He->C in its core. When that’s done, kerblooey. Real Soon Now (perhaps 100,000 years).
- It’s big enough and close enough to image the disk of the star.
- It pulsates in irregular ways.



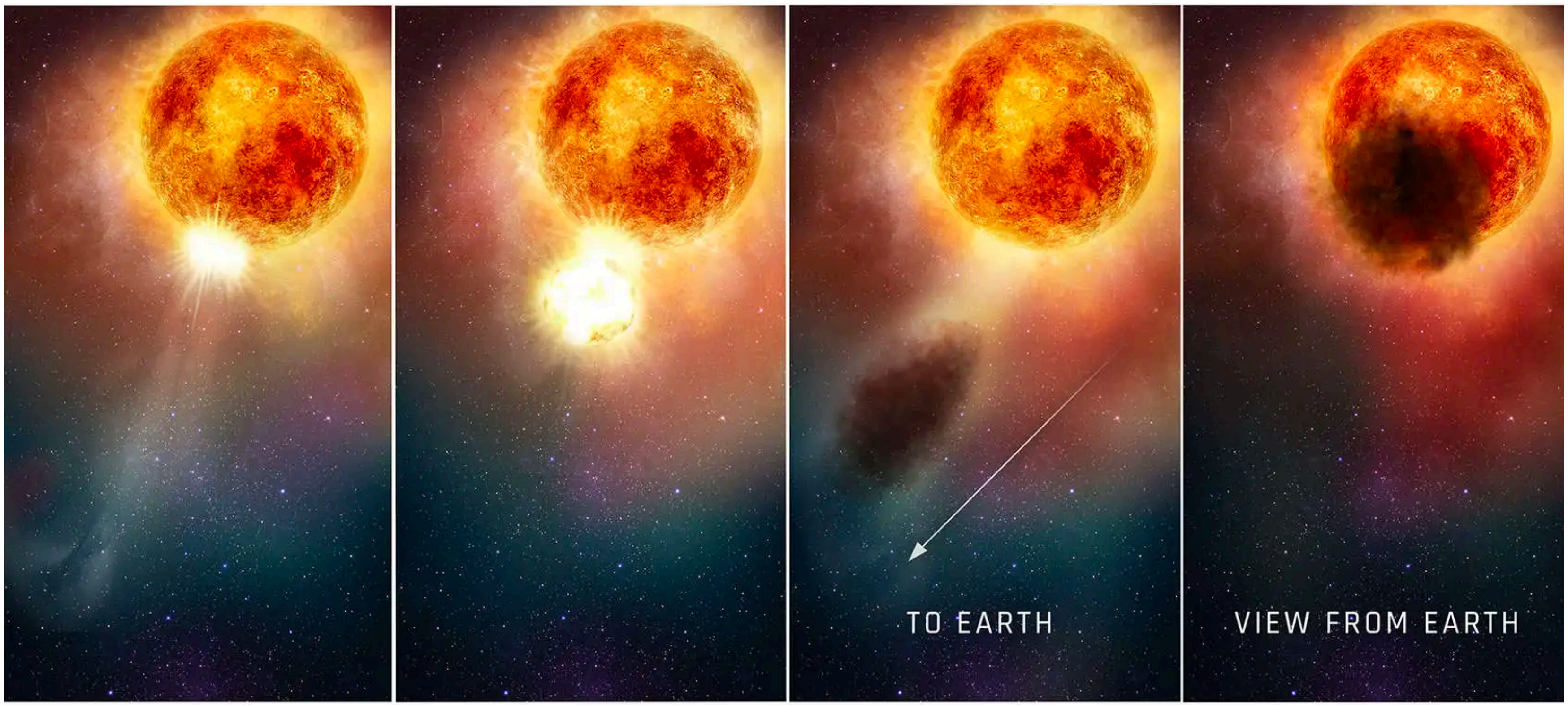
- In 2019 Betelgeuse faded by about 70%. A portent of a coming explosion?

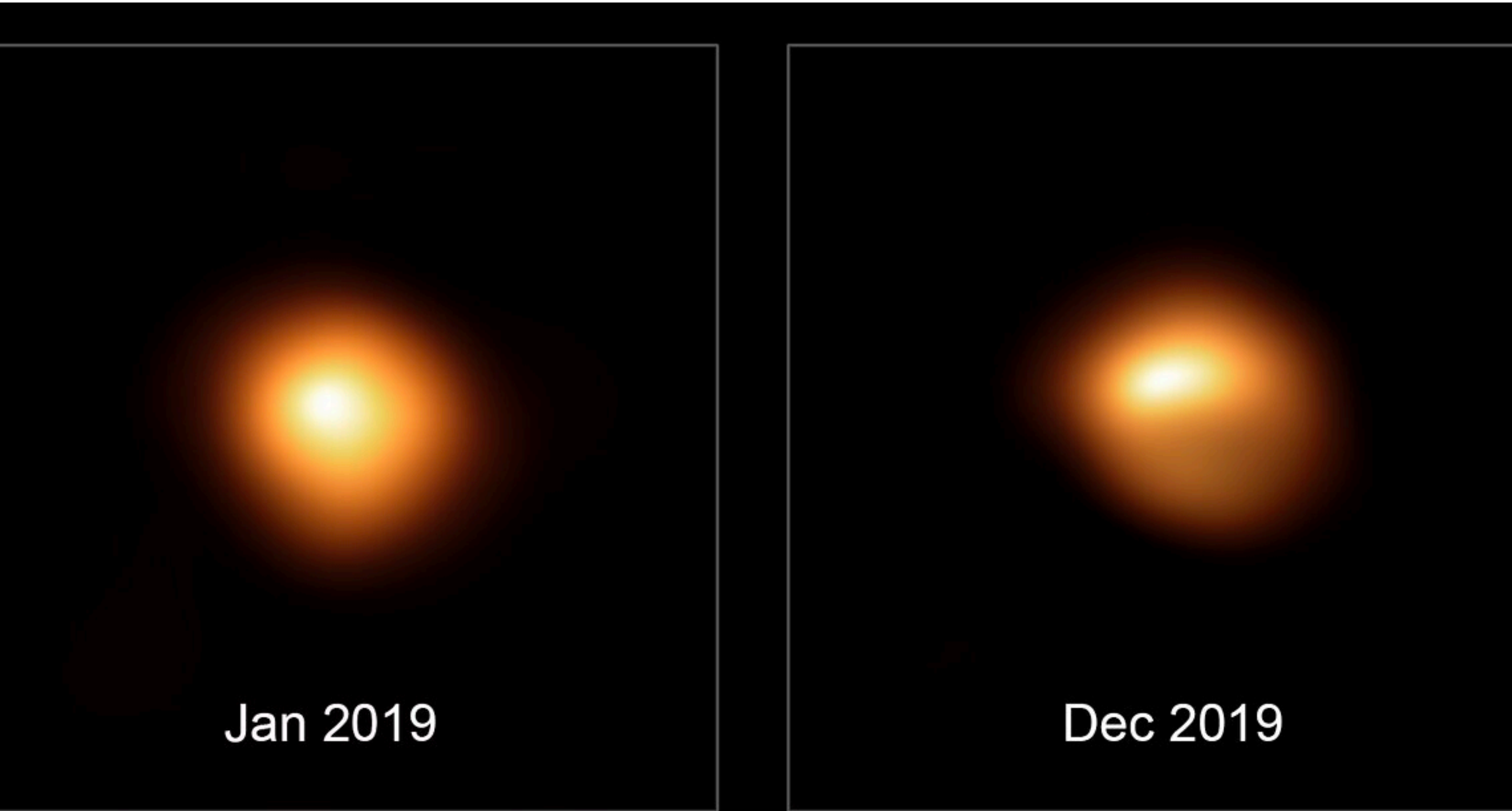
- Probably just dust in the wind.



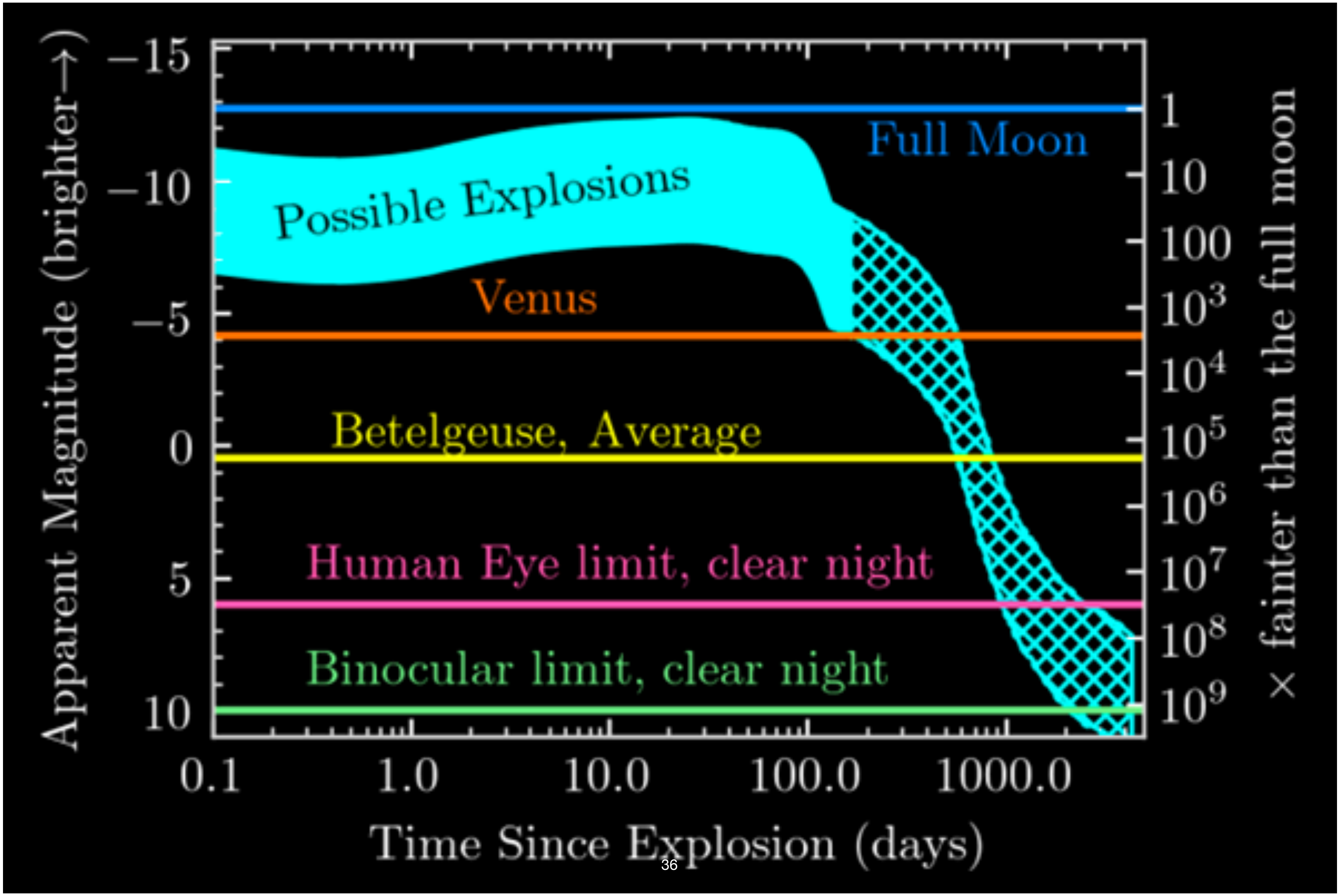
Artist's conception

Blob of gas ejected, formed into dust, and hid part of the star's surface for a few months.




Jan 2019
Dec 2019

- This activity is probably on the high side of normal for Betelgeuse
- The time for core disruptions to diffuse to the surface is many years
- So there probably won't be any warning when it does finally go supernova.
- Recent attempts to fit the normal variations suggest Betelgeuse has only just entered the He->C burning phase, so don't hold your breath waiting. This is called "asteroseismology" and allows some insight into the stellar interior from the variations observed on the surface.
- At 500-700 light years away, a supernova wouldn't hurt us.
- It would, however, be bright… about like the half-moon, for a month. And very obvious in the night sky (and visible in daytime as well).
- ~ Million neutrinos might be detected before the optical brightening.


Apparent Magnitude (brighter→)
−15
−10
−5
0
5
10
Full Moon
Possible Explosions
Venus
Betelgeuse, Average
Human Eye limit, clear night
Binocular limit, clear night
1
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
× fainter than the full moon
0.1
1.0
10.0
100.0
1000.0
Time Since Explosion (days)

SN 1987A

- The most recent nearby supernova was in 1987
- It's in the Large Cloud of Magellan (LMC), a satellite galaxy of the Milky Way.
- A dozen neutrinos were detected from the core collapse.
- Naked-eye object from 170k ly
- The progenitor turns out to have been a blue supergiant star…