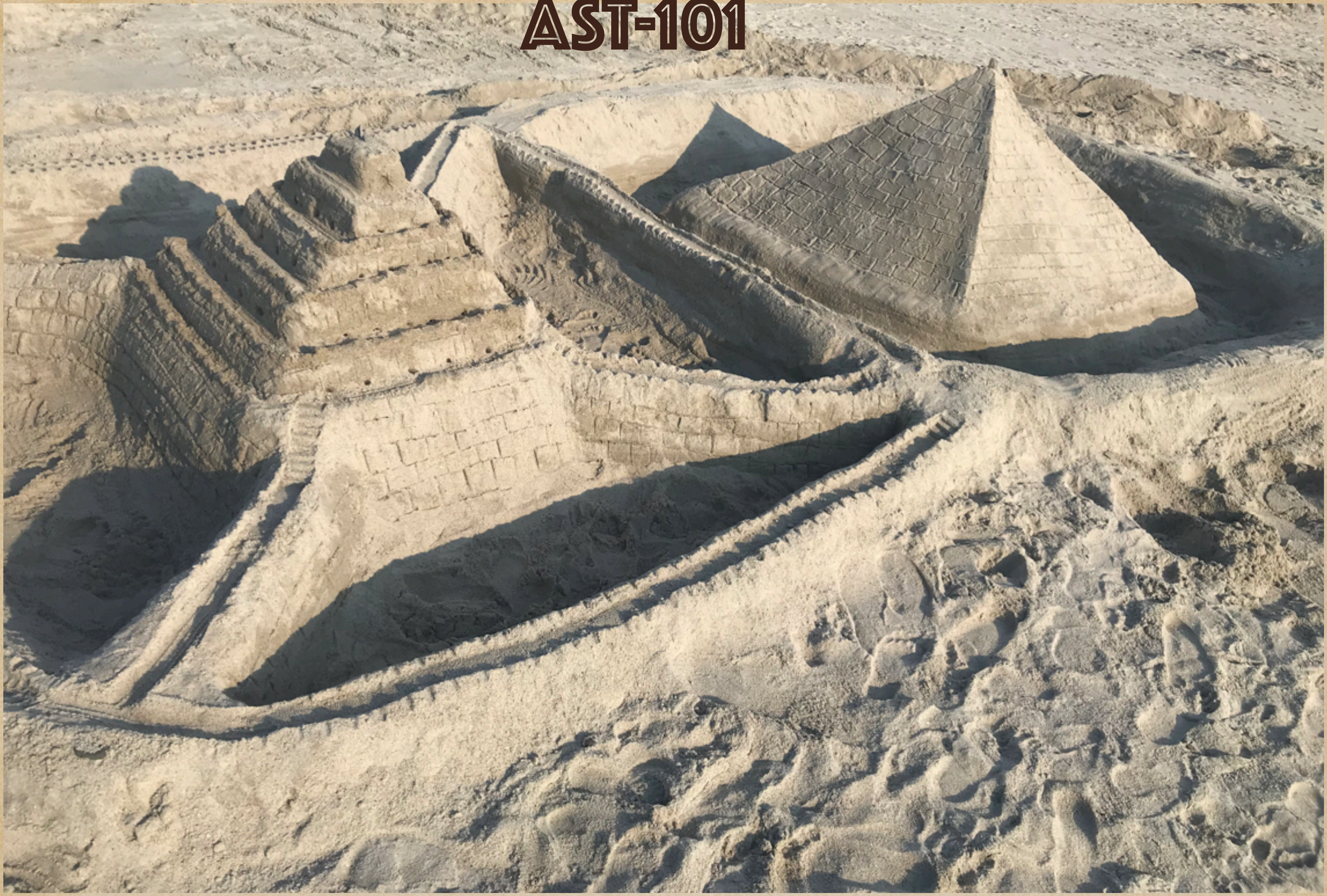


The stellar graveyard

Luis Anchordoqui

Sun's energy output

- pp cycle due to following sequence of fusion reactions:

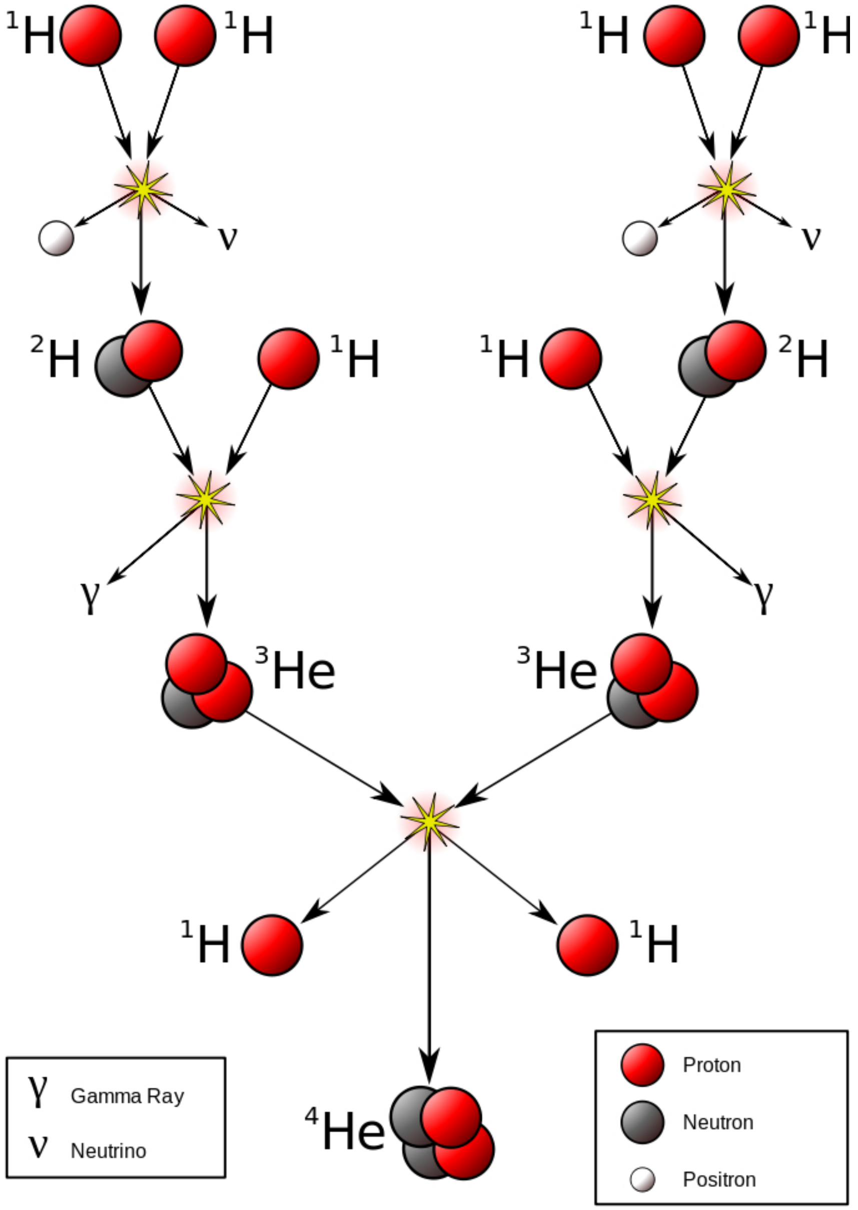
$$^1_1\mathrm{H} + ^1_1\mathrm{H} \rightarrow ^2_1\mathrm{H} + 2\,e^+ + 2\,\nu_e$$

$$^1_1\mathrm{H} + ^2_1\mathrm{H} \rightarrow ^3_2\mathrm{He} + \gamma$$

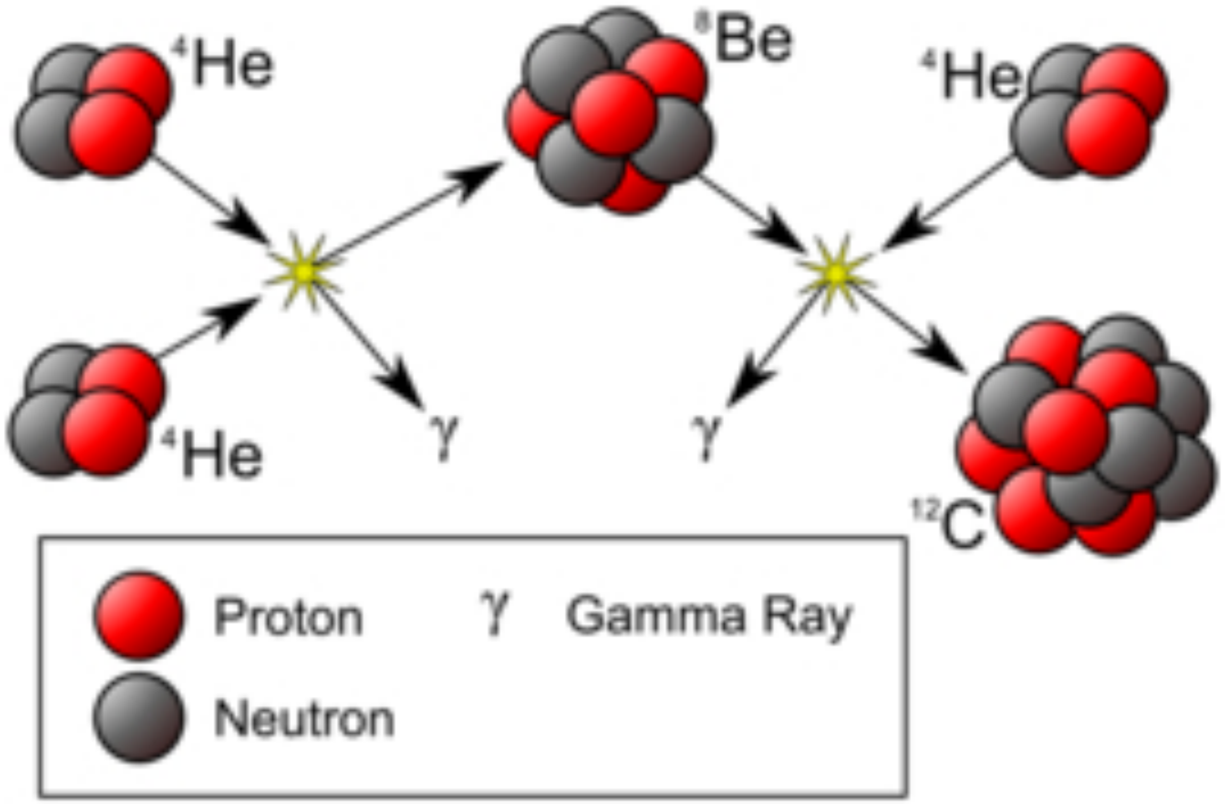
$$^3_2\mathrm{He} + ^3_2\mathrm{He} \rightarrow ^4_2\mathrm{He} + ^1_1\mathrm{H} + ^1_1\mathrm{H}$$

- Released energy ➢ mass difference between initial & final states
  ➢ carried off by outgoing particles
- Net effect $4\,^1_1\mathrm{H} \rightarrow ^4_2\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$
- Takes 2 of each of first 2 reactions to produce two $^3_2$He
- Deuterium formation has very low probability
  infrequency of reaction limits rate at which Sun produces energy

Nuclear Burning

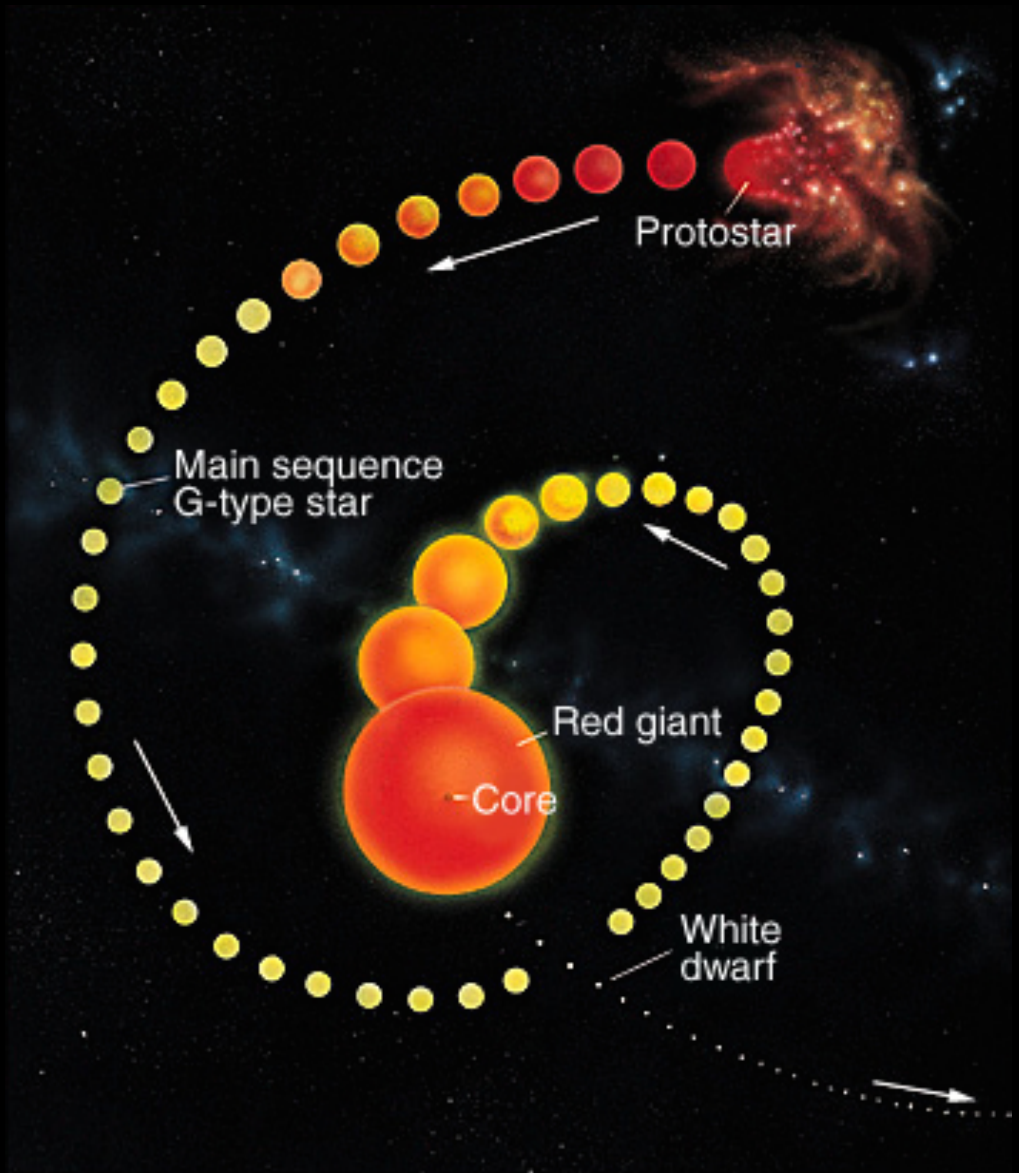


- If star is like our Sun or larger ☞ further fusion can occur
- As star's outer envelope expands ☞ core shrinks and heats up
- When the temperature reaches about 10^8 K
  helium nuclei reach each other and undergo fusion
- Reactions are



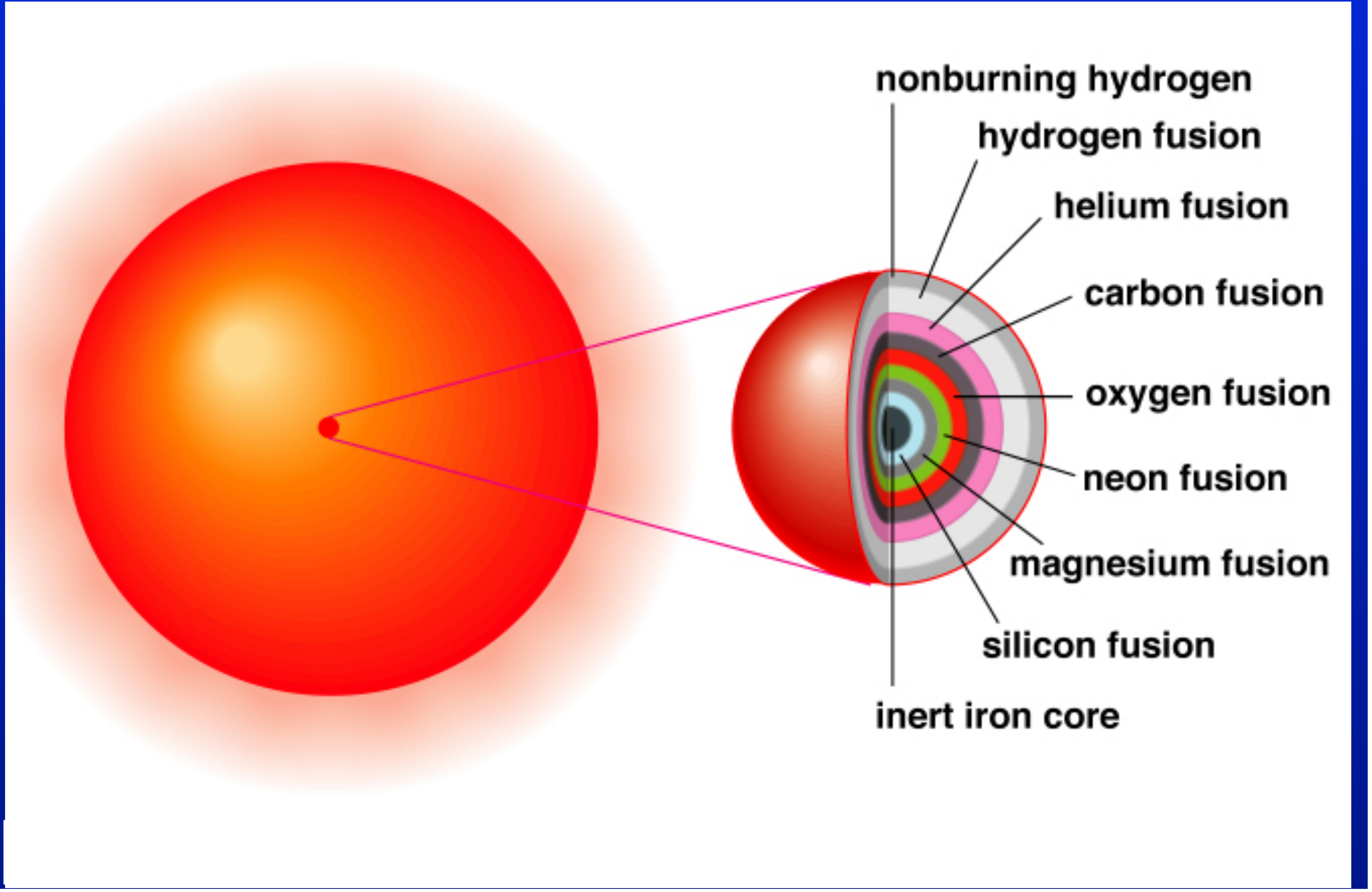
- Two reactions must occur in quick succession
  because ${}^{8}_{4}$Be is very unstable

Life cycle of the Sun



High-Mass Stars

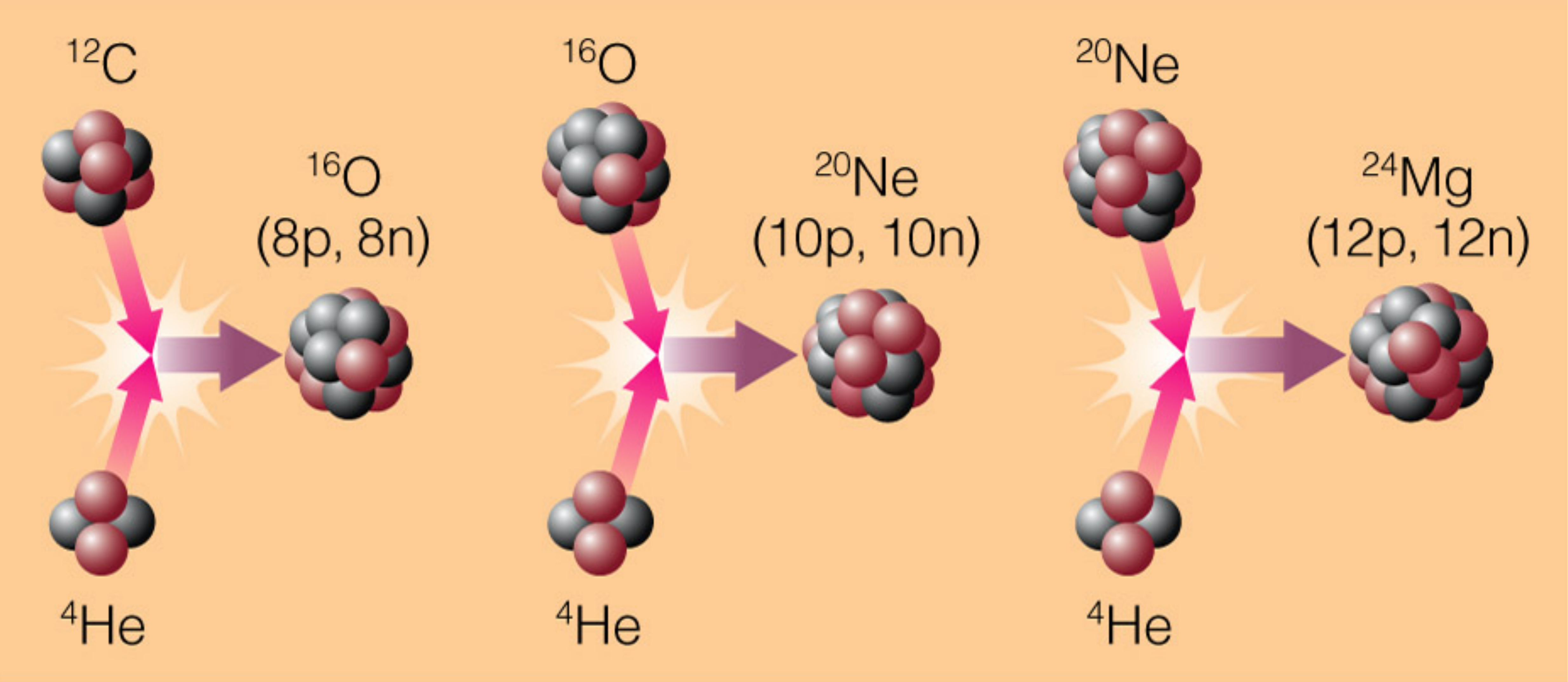
- Sequence of expansion/contraction repeats as higher and higher elements begin to fuse
- Each heavier element requires higher core temperatures to fuse



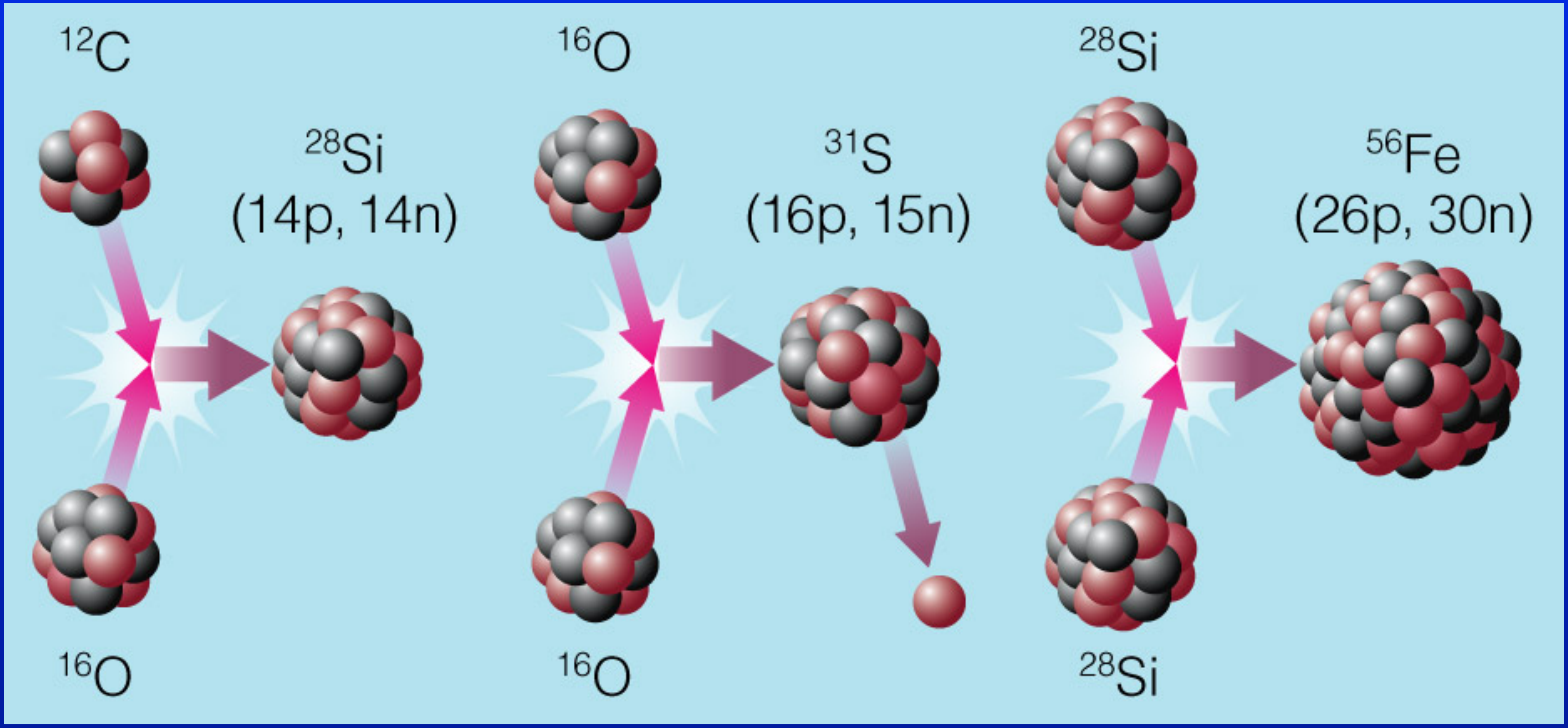
- Core structure keeps on building successive shell
  - Like an onion

- Lighter elements on the outside, heavier ones on the inside

- Most elements are formed via Helium Capture
  - A helium (2 protons) nucleus is absorbed, energy is released
- The elements are created going up the periodic table in steps of 2

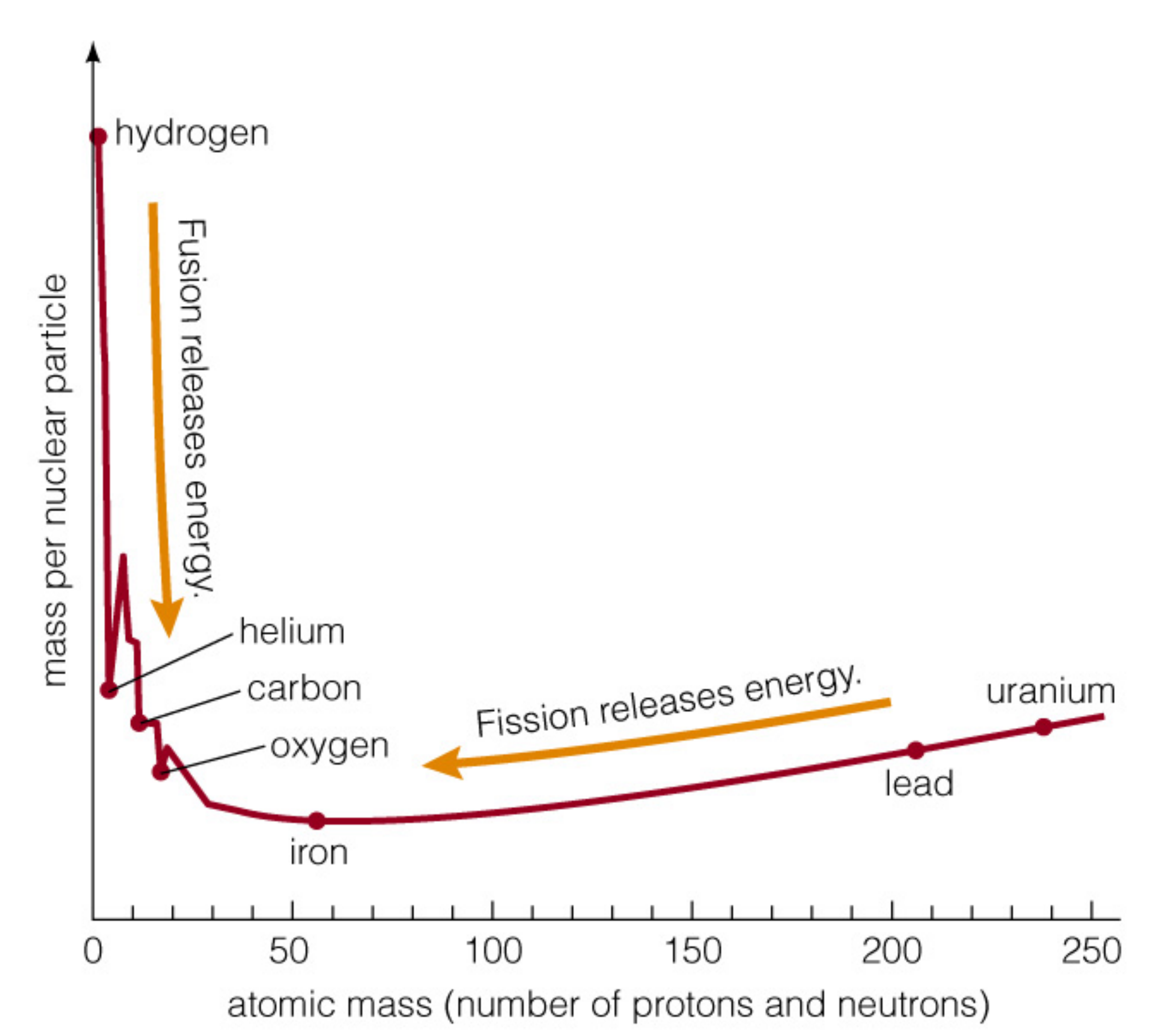


Other Reactions



HIGH mass stars keep creating elements up the periodic table UNTIL…. IRON (Fe, 26 protons)

- Iron does not release energy through fusion or fission
  - Remember: All energy created by the loss of mass from the fusion or the fission ($E=mc^2$)



There Is No Way Iron Can Produce Any Energy to Push Back Against the Crush of Gravity in the Star's Core

The star is DOOMED!!!

What is the heaviest element that can be created through fusion?

A. Carbon
B. Silicon
C. Iron
D. Uranium

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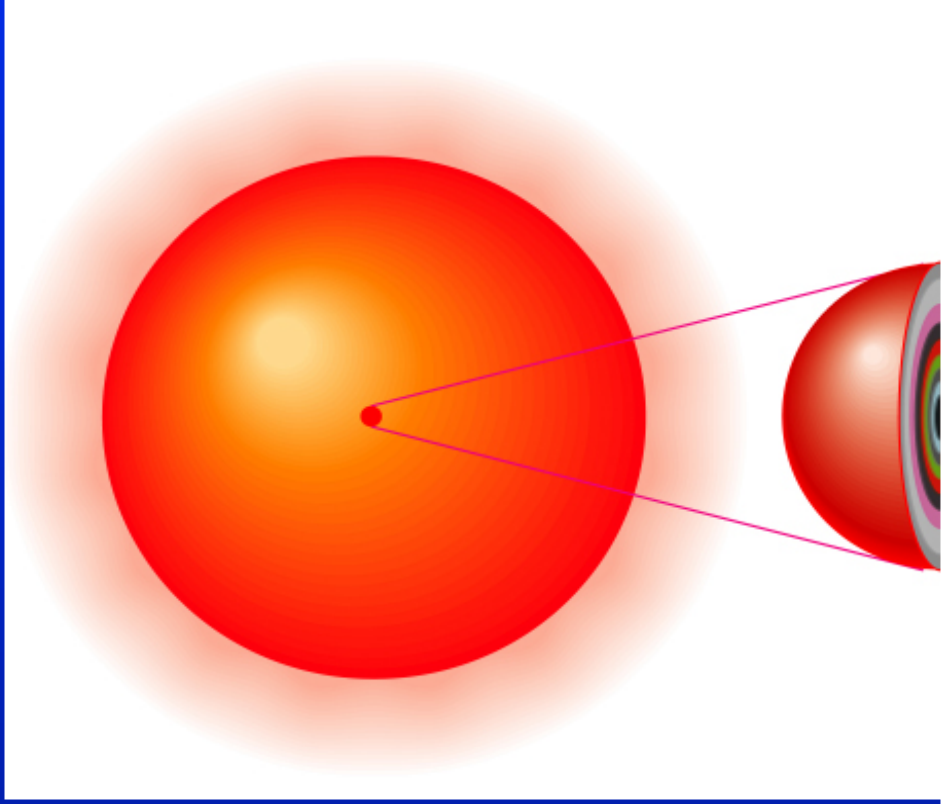
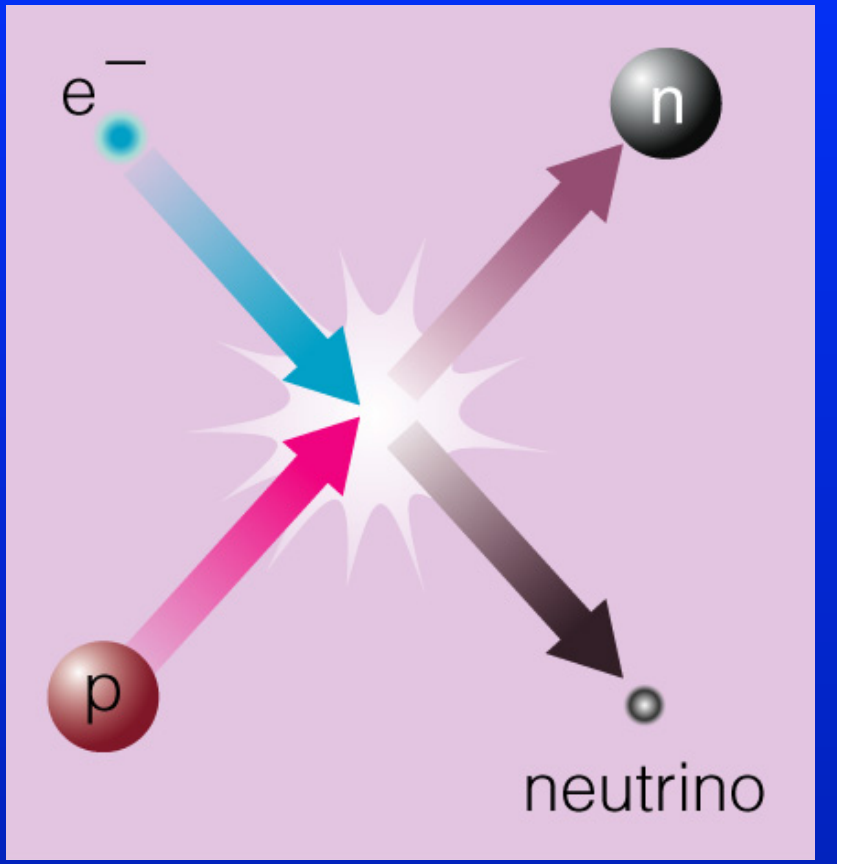
- The core of a high mass star accumulates iron as the layers above it fuse



- Without any outward pressure, the core once again starts to contract.
- Electron degeneracy pressure supports the core for awhile until the mass of iron gets too heavy (how heavy?)

- When mass is too large ($>1.4M_{sun}$), core collapses and iron atoms get compressed into pure neutrons

- protons + electrons → neutrons + neutrinos
  - This takes less than 0.01 seconds
    - Electron degeneracy pressure - *GONE!*
      - Core collapses completely



•Eventually *neutron degeneracy pressure* stops the collapse abruptly

•Infalling atmosphere impacts on the core.

Supernova!

- The lightweight atmosphere impacts on the heavy core and is "bounced" off in a huge explosion

- Plus huge energy release from neutrinos!

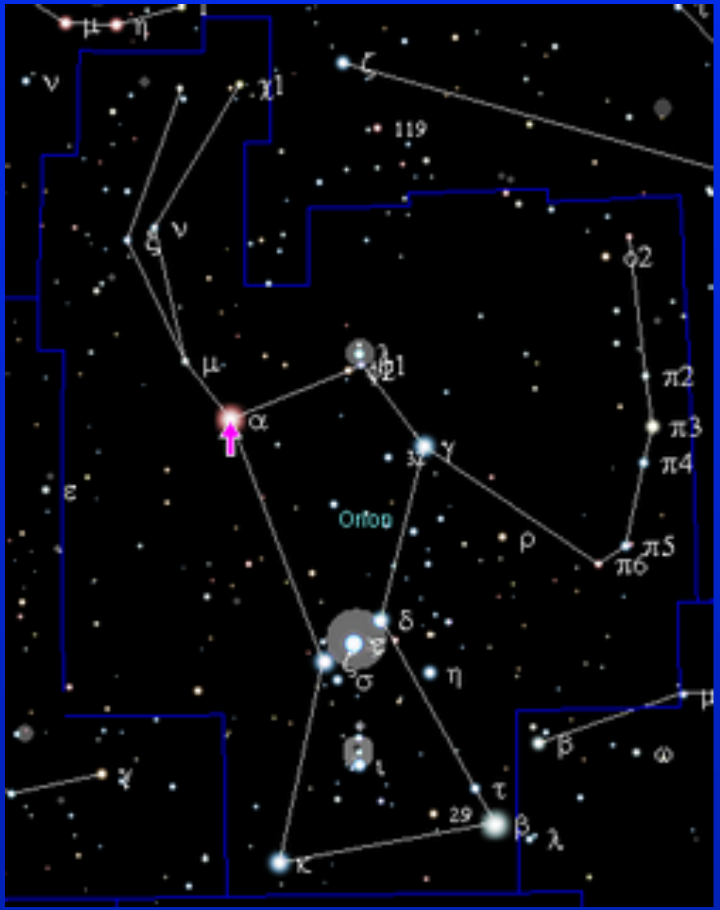
→ *The star's former surface zooms outward With a velocity of 10,000 km/s!*

"Massive Star SUPERNOVA"

- *Exploding remnant of massive star disperses heavy elements through the galaxy*
- *Inside may be a neutron star – a remnant core of pure neutrons!*

Crab Nebula (M1), first seen as SUPERNOVA on 4 July 1054 from China -- visible in daytime 6523 light years away

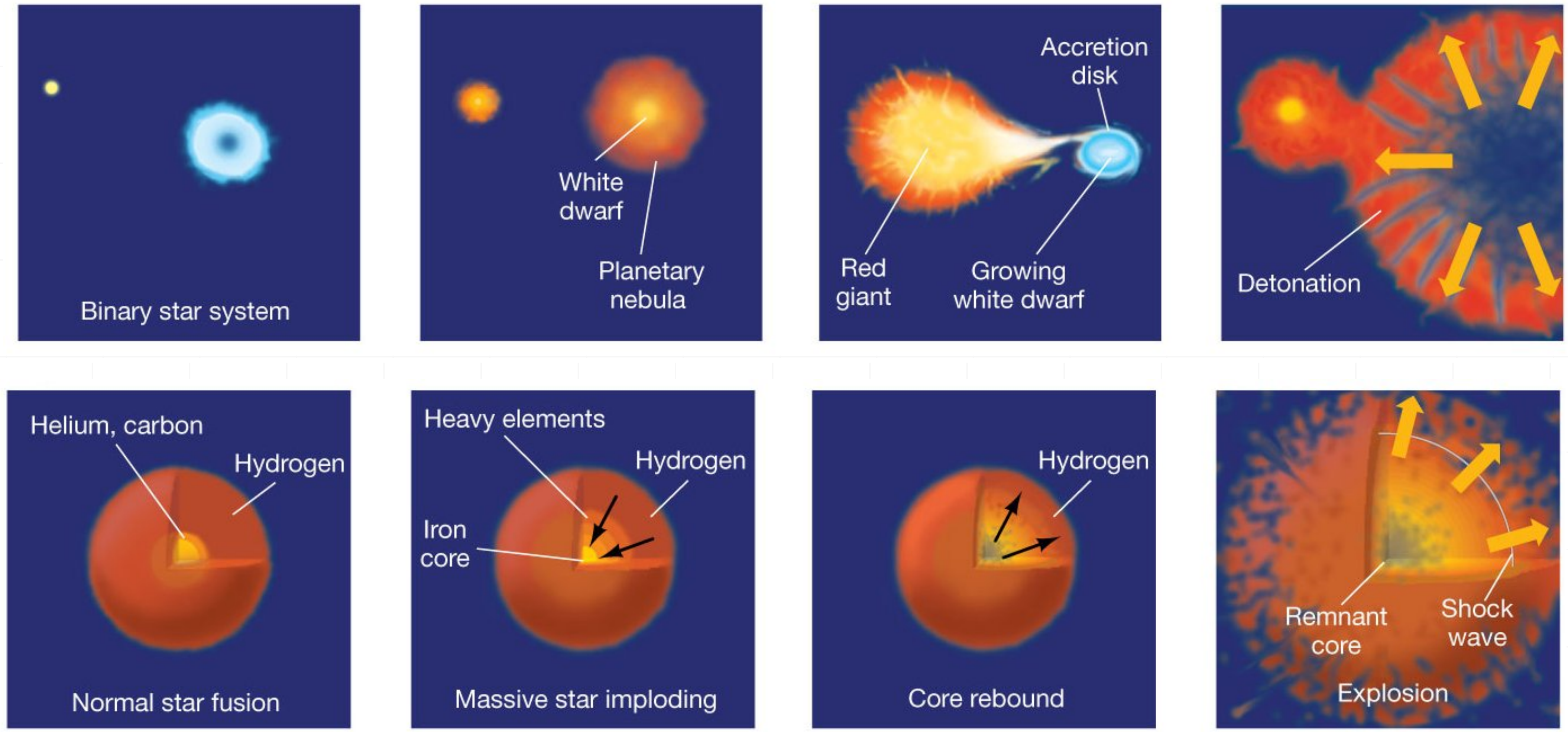
Betelgeuse (In Orion) Is Currently In Its Red Supergiant Phase



might be next…

only 1500 ly away.. would be very dramatic…

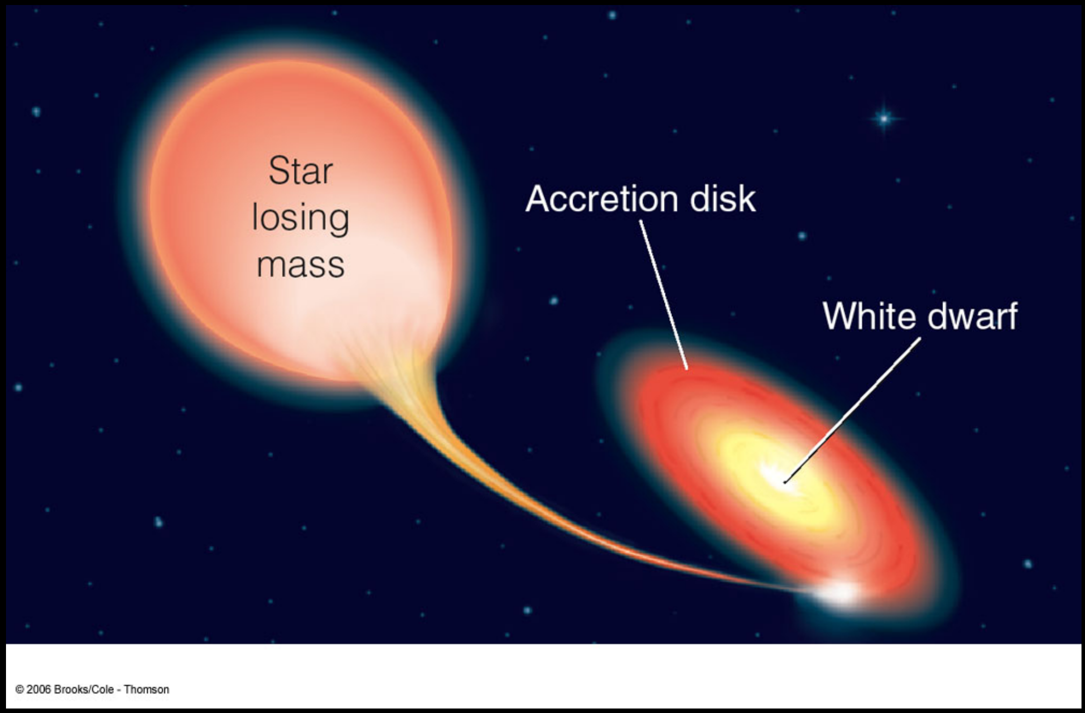
- Supernovae are massive explosions that take place at end of star's life cycle
- They can be triggered by one of two basic mechanisms:
  - I by sudden re-ignition of nuclear fusion in degenerate star
  - II by the sudden gravitational collapse of massive star's core



Accretion disks:

Because stars rotate, matter that leaves the star has angular momentum…

Conservation of angular momentum creates an accretion disk.



Tidal forces and friction cause two things to happen;

1. Heats the disk
2. Dissipates the angular momentum and allows the gas to fall to the star

If the accreting star happens to be a white dwarf…

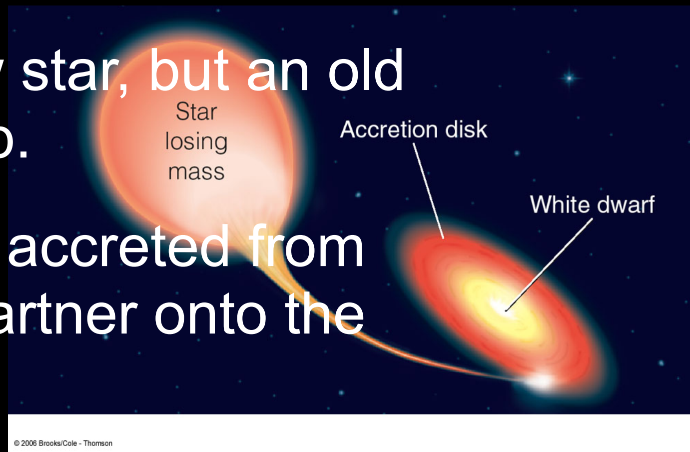
One of two things can happen…

Nova or supernova….

Novae:

A star that appears for a while and then fades away…

It's not a new star, but an old star flaring up.



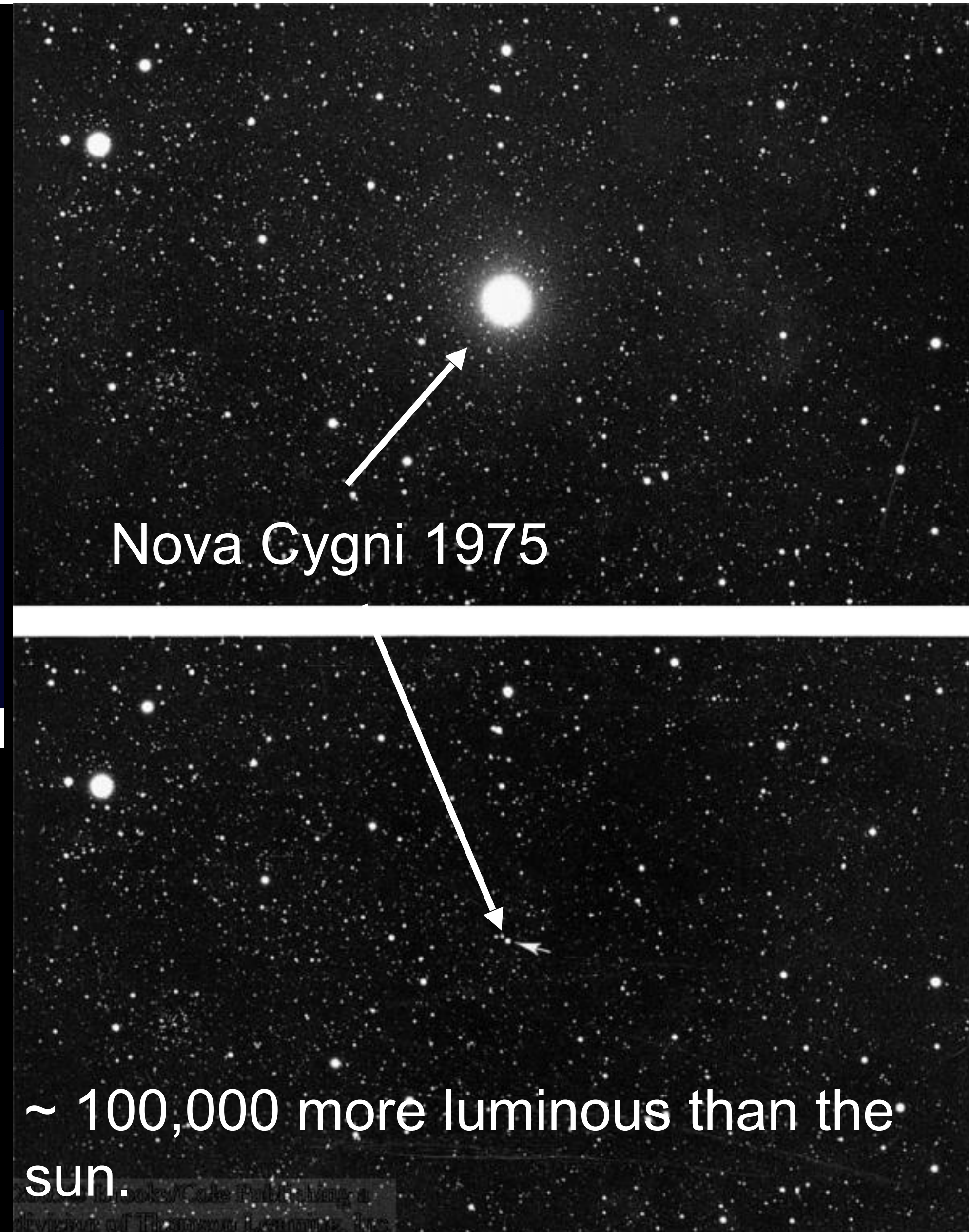
Hydrogen is accreted from the binary partner onto the white dwarf.

⇒ Very hot, dense layer of hydrogen accumulates on the white dwarf surface.

This layer grows denser and hotter until…

BAM!

Hydrogen fuses in a sudden explosion that blows the surface off the star.



Nova Cygni 1975

~ 100,000 more luminous than the sun.

Explosion lasts only minutes to hours, the brightness fades in ~ 1-3 months.

Where is fusion happening in a <u>white dwarf supernova</u>?

A. In the core, carbon is being fused into heavier elements.
B. On the surface, hydrogen is being fused into helium.
C. No fusion occurs in a white dwarf supernova, the light comes from the collapse (and bounce) of the star.

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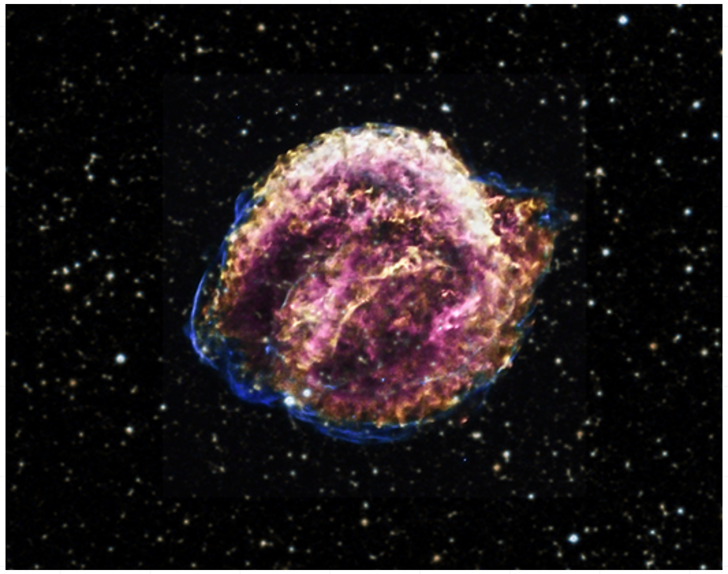
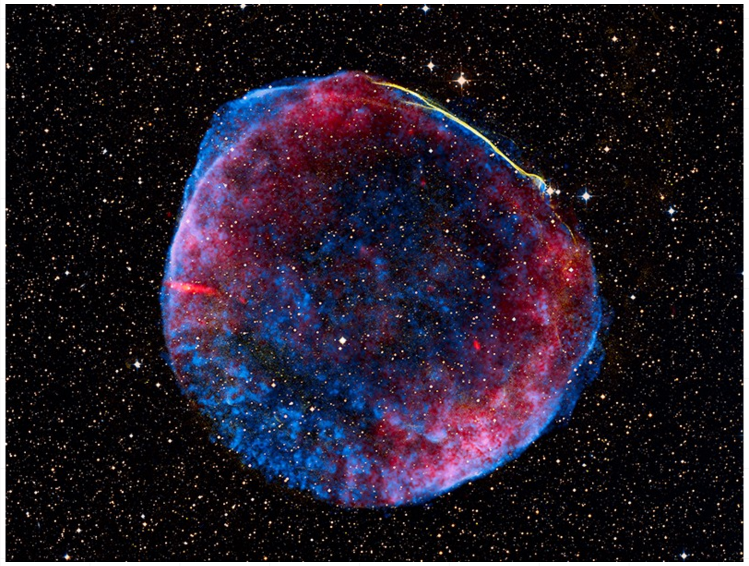
Pulsars

SN1604 (Kepler)



SNR-0509-67.5 (LMC)

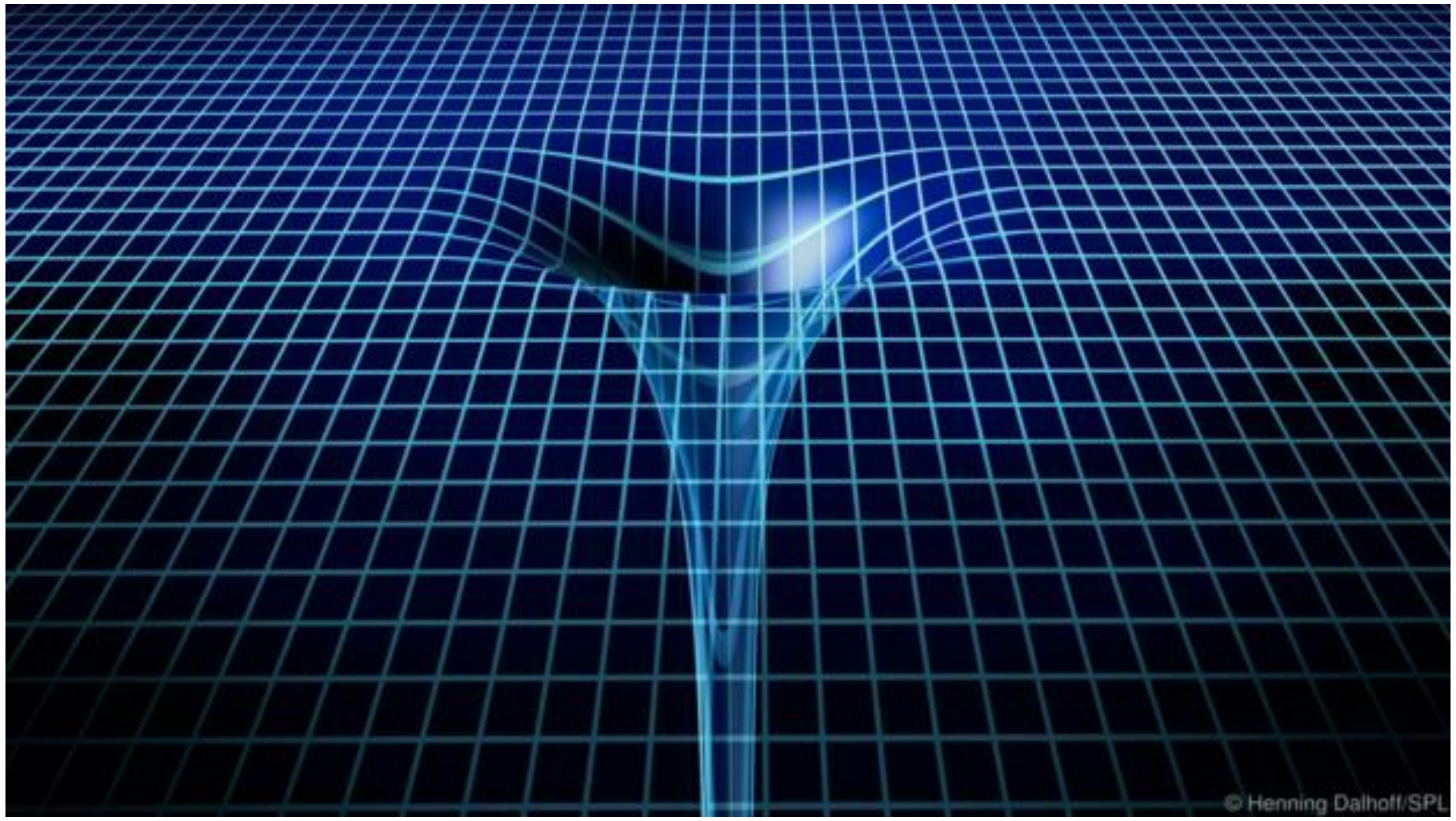
SN1006



- Core of collapsed star contracts until all nuclei are touching
- Forces are so great that all the nuclei disintegrate into their constituents (neutrons and protons)
- Protons combine with electrons to leave dense core of neutrons (star is about as large as Boston)
- Newly born neutron star (or pulsar) ☞ rotates madly about its axis emitting energy at a billion times rate of Sun

Black Holes

- If neutron star mass $> 3M_\odot$ ☞ star further contracts under gravity
- As density increases
  paths of light rays emitted from star are bent
  and eventually wrapped irrevocably around star
- This is called a black hole ☞ because no light escapes "the star"



The ultimate fate of a massive star

Core burns to Fe, leading to a core collapse

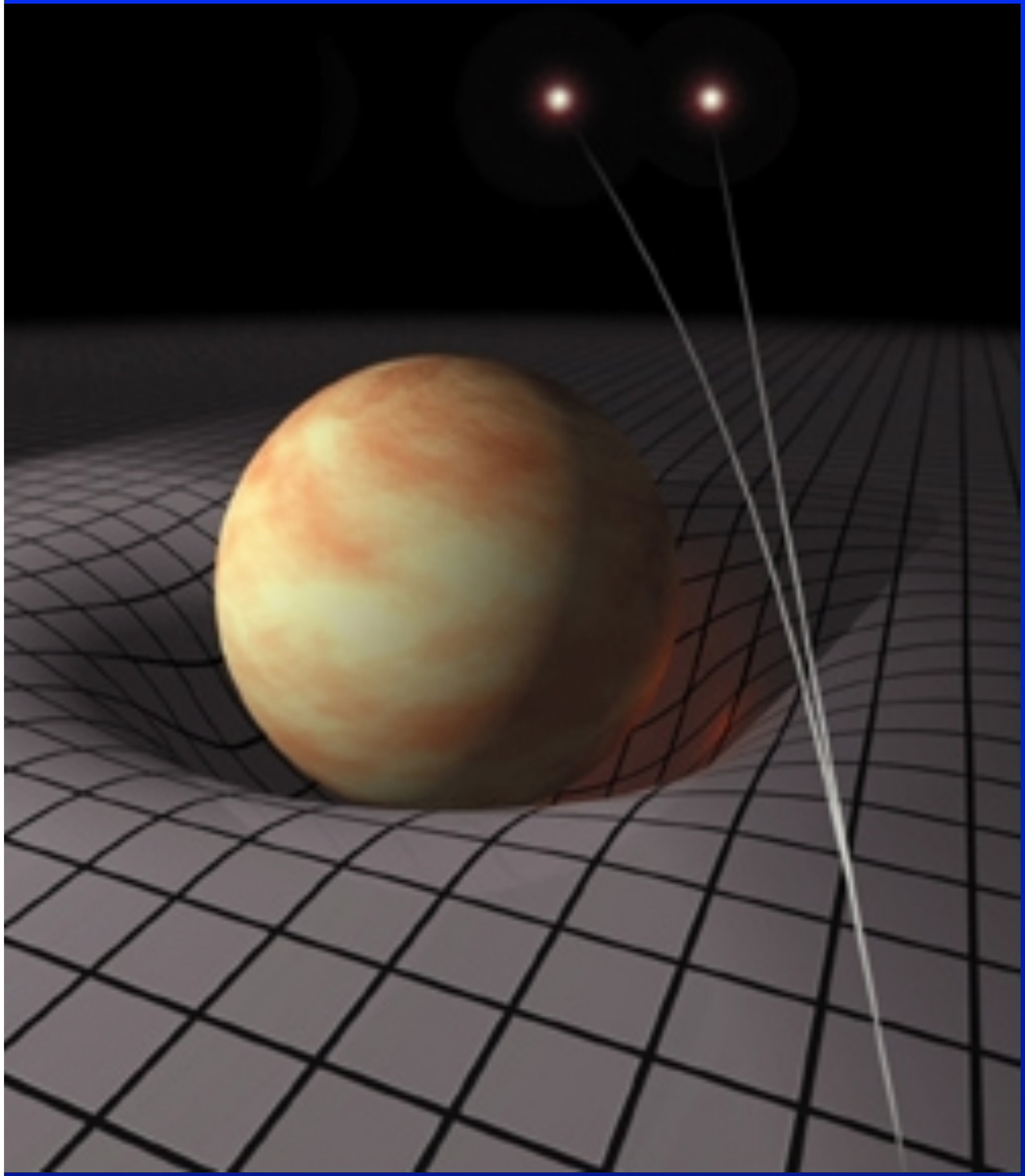
SUPERNOVA

What happens to the Fe core?

Neutron Star - for star masses $< 3M_\odot$

Black Hole - for star masses $> 3M_\odot$

GENERAL RELATIVITY: (in a nutshell)



Masses tell spacetime how to curve.

Spacetime, with its curvature, tells masses how to move.

Light also gets bent!!

Effects of strong gravity on light

can act like lens

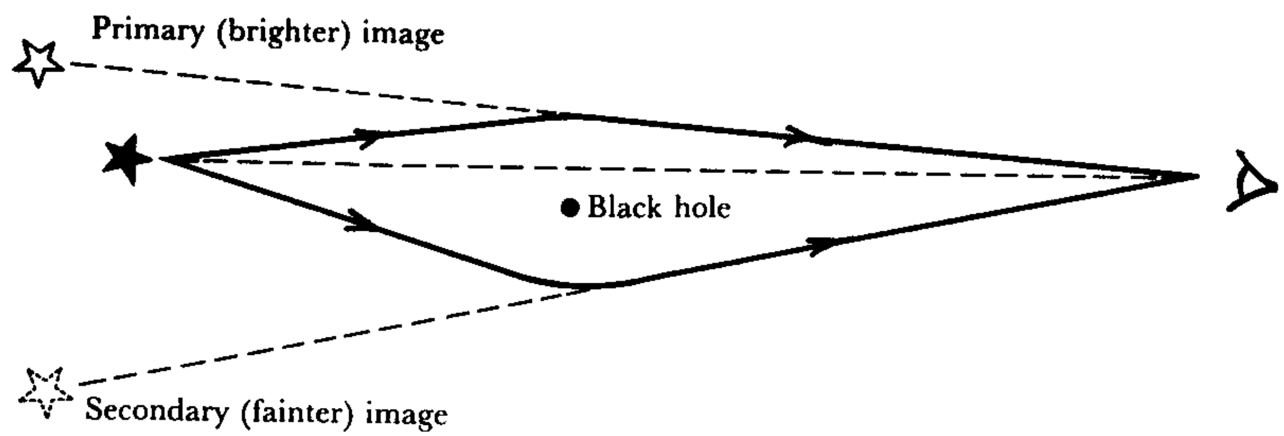
can redshift light

EFFECTS OF GRAVITY ON LIGHT

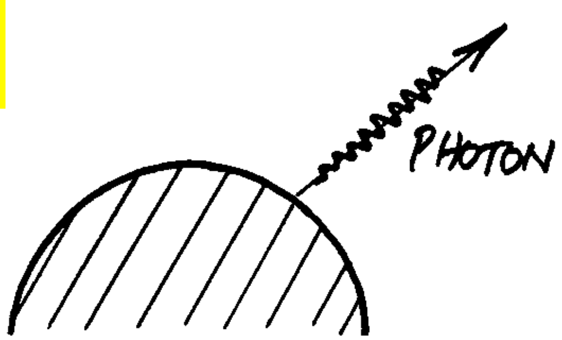
. . . COURTESY OF EINSTEIN

1. STRONG GRAVITY CAN BEND LIGHT:

USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY ⇒ GRAVITATIONAL LENSES!



2. LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED: "GRAVITATIONAL REDSHIFT"

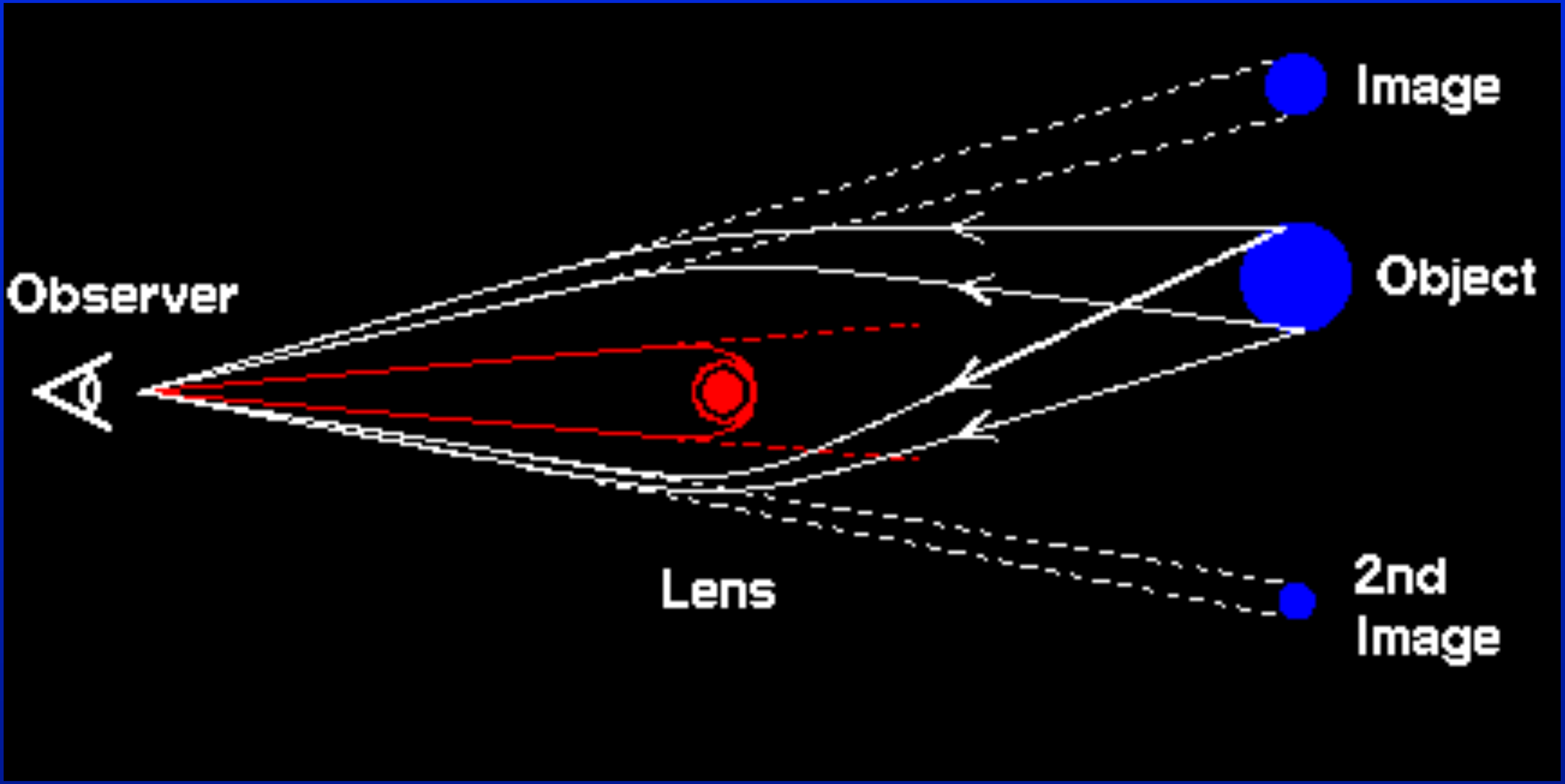


PHOTONS LOSE ENERGY FIGHTING GRAVITY

REDDER PHOTONS

≡ LOWER FREQUENCY

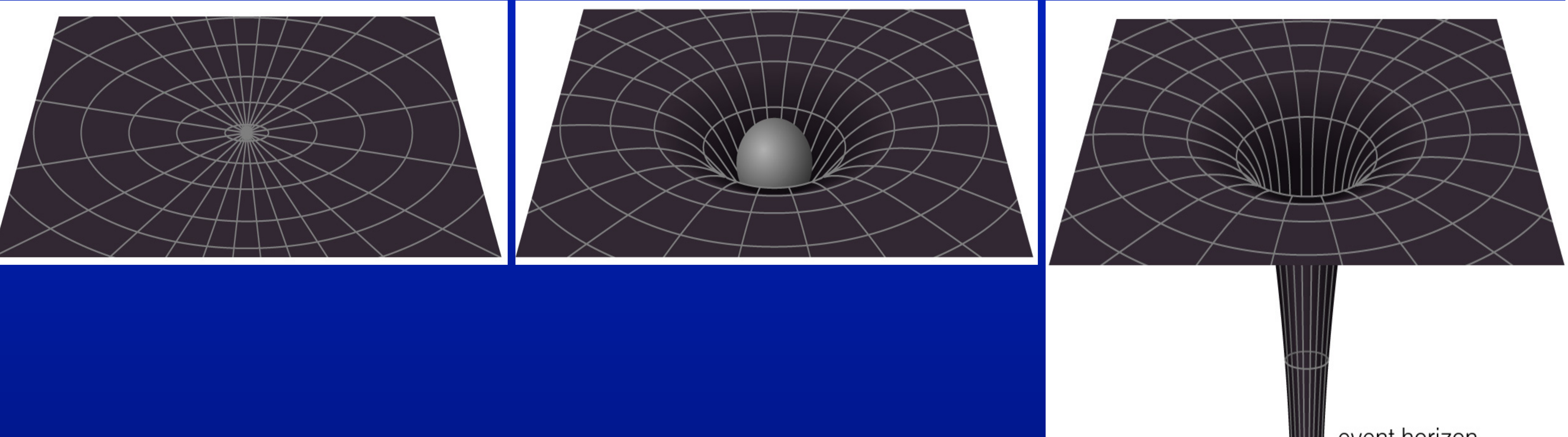
Gravitational lensing: schematic diagram



Black Holes

Solutions to the Einstein's equations of General Relativity, describing how spacetime curves around bodies of a certain size and mass.

For a given size, the larger the mass, the larger the curvature of spacetime.



Black Hole: object whose escape velocity is faster than the speed of light---> can't escape!!

- Event horizon (Schwarzschild radius) is the point at which escape velocity equals _*speed of light*_

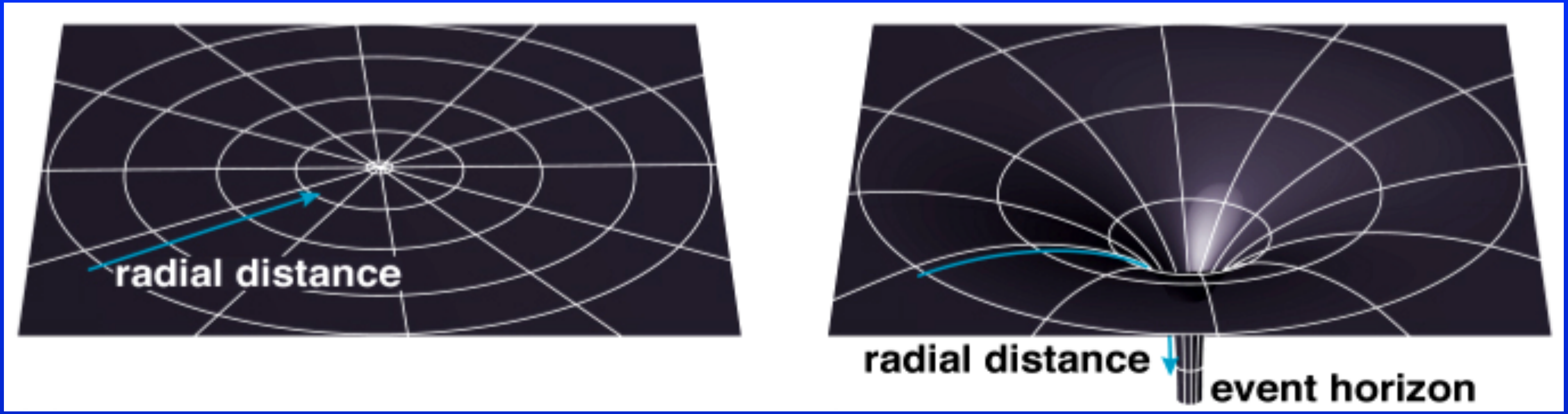
  ~ 3 km for each solar mass in the BH

- Inside this radius not even light can escape
  - can fall in but never get out

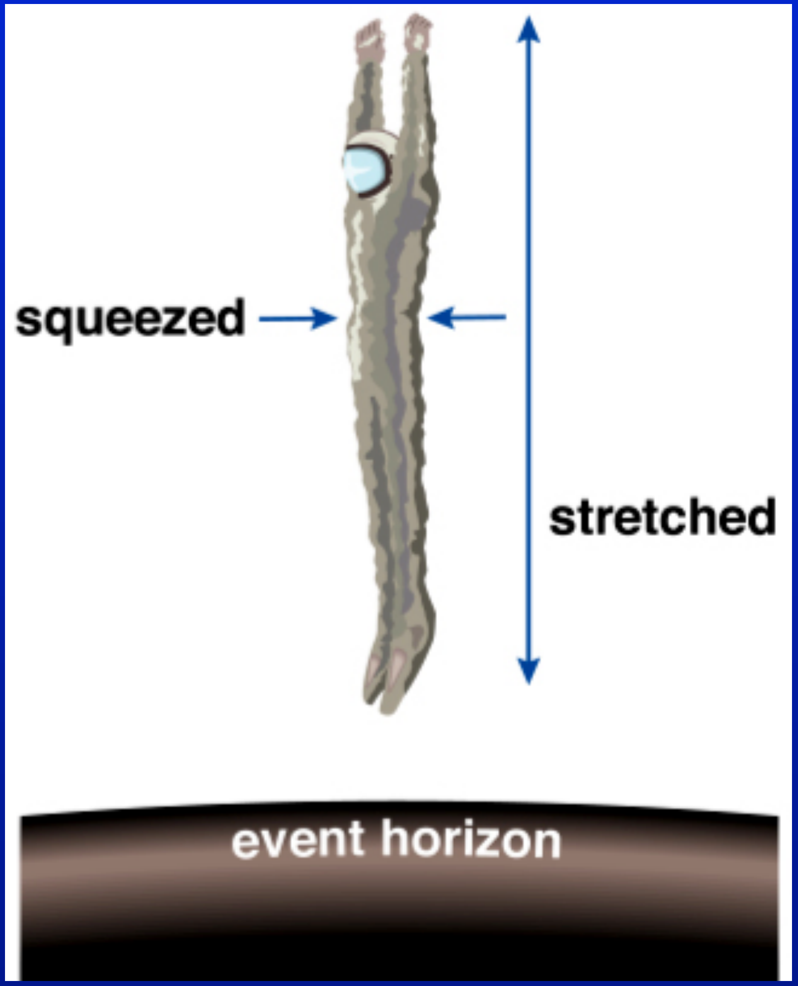
- We can't see any light coming from inside → BLACK hole

- *NO hard surface!!*
  - Event horizon is a *"theoretical"* point of no return

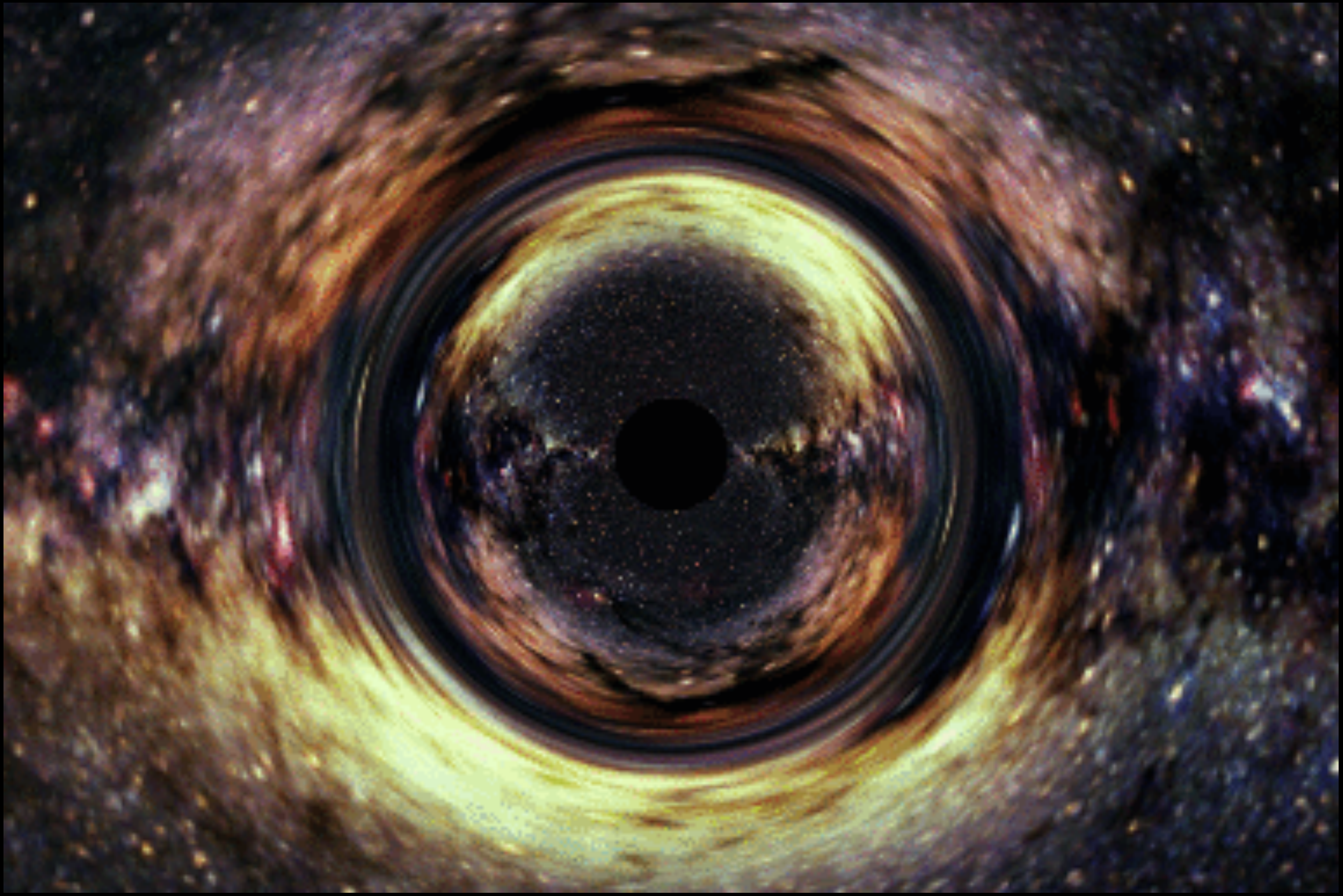
Warping of Space by Gravity



- *Gravity imposes curvature on space*
  - light's path through space will be "bent by gravity"
  - within the event horizon, it cannot climb out of the hole
- *As matter approaches event horizon…*
  - tidal forces are tremendous
  - object would be "spaghettified"



Can we detect BLACK HOLES ?



Black Holes in Binaries

CYGNUS – X 1 *Black hole*

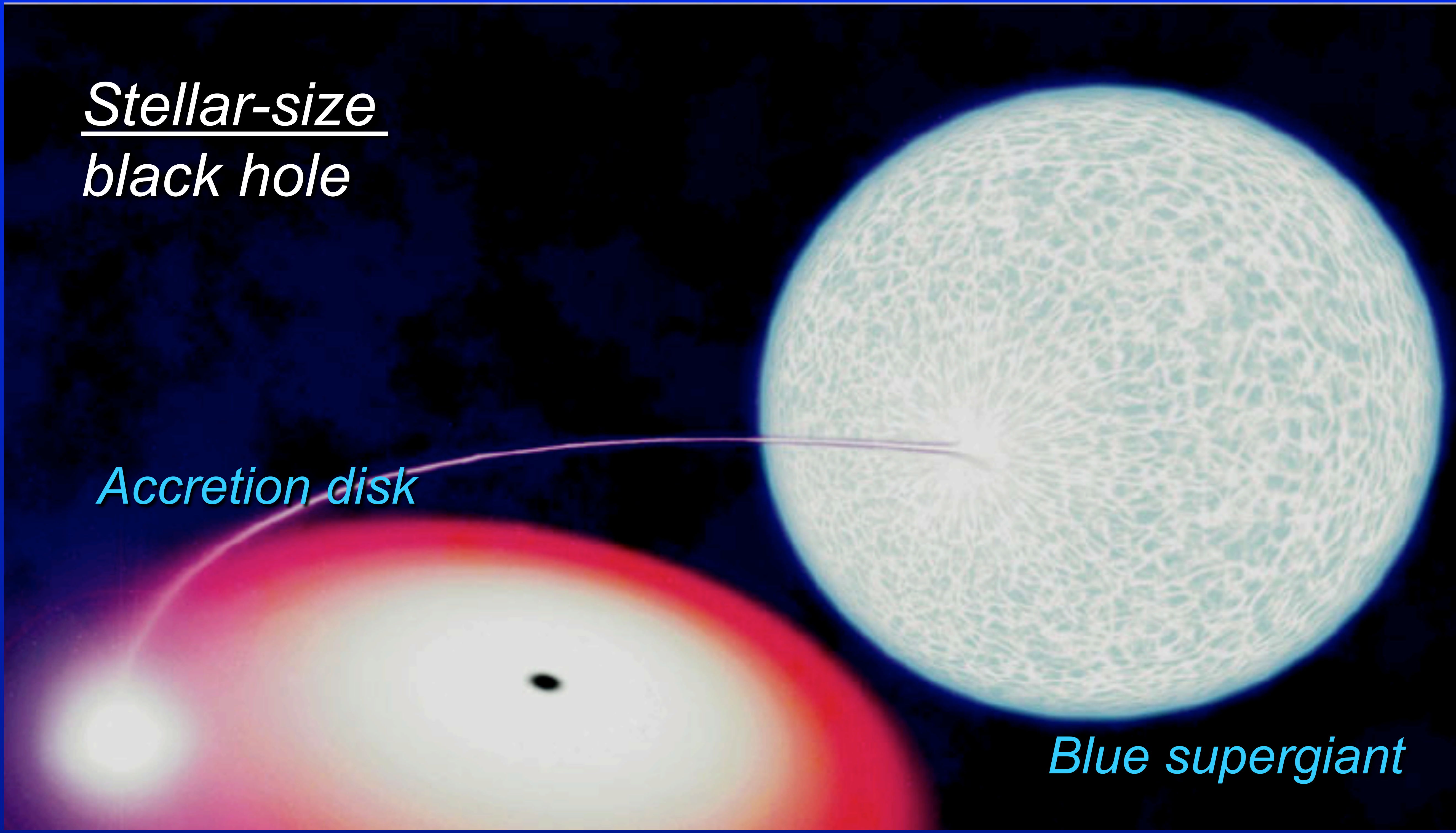
Black Holes in Binaries → 'X-ray Binary'

- We can detect the *effects* of black holes on nearby matter (stars, gas, etc.)
- Astronomers look for compact "X-ray binaries"

Criteria:

1. "Invisible" star in binary system is *too massive* to be white dwarf or neutron star
   - Mass > 3 M_{Sun}
2. *Too small in radius* to be a normal star

Cygnus X-1: Blue supergiant (strong winds) pours H + He onto accretion disk of black hole



What is a Black Hole?

A. A black star
B. A concentration of mass with a gravitational field so strong that not even light can escape its grip
C. A white dwarf painted in black
D. The compact remnant of a low-mass star

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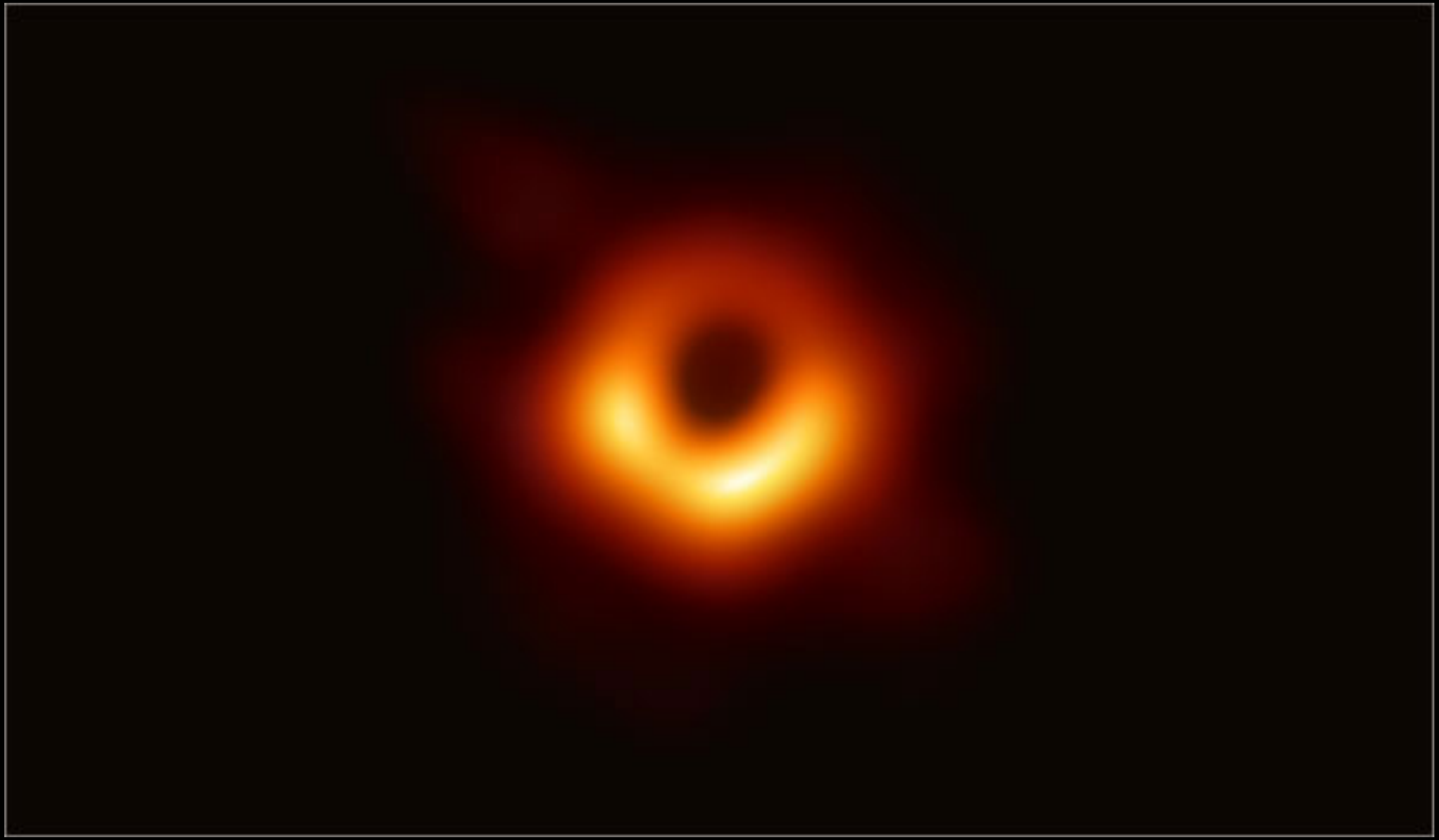
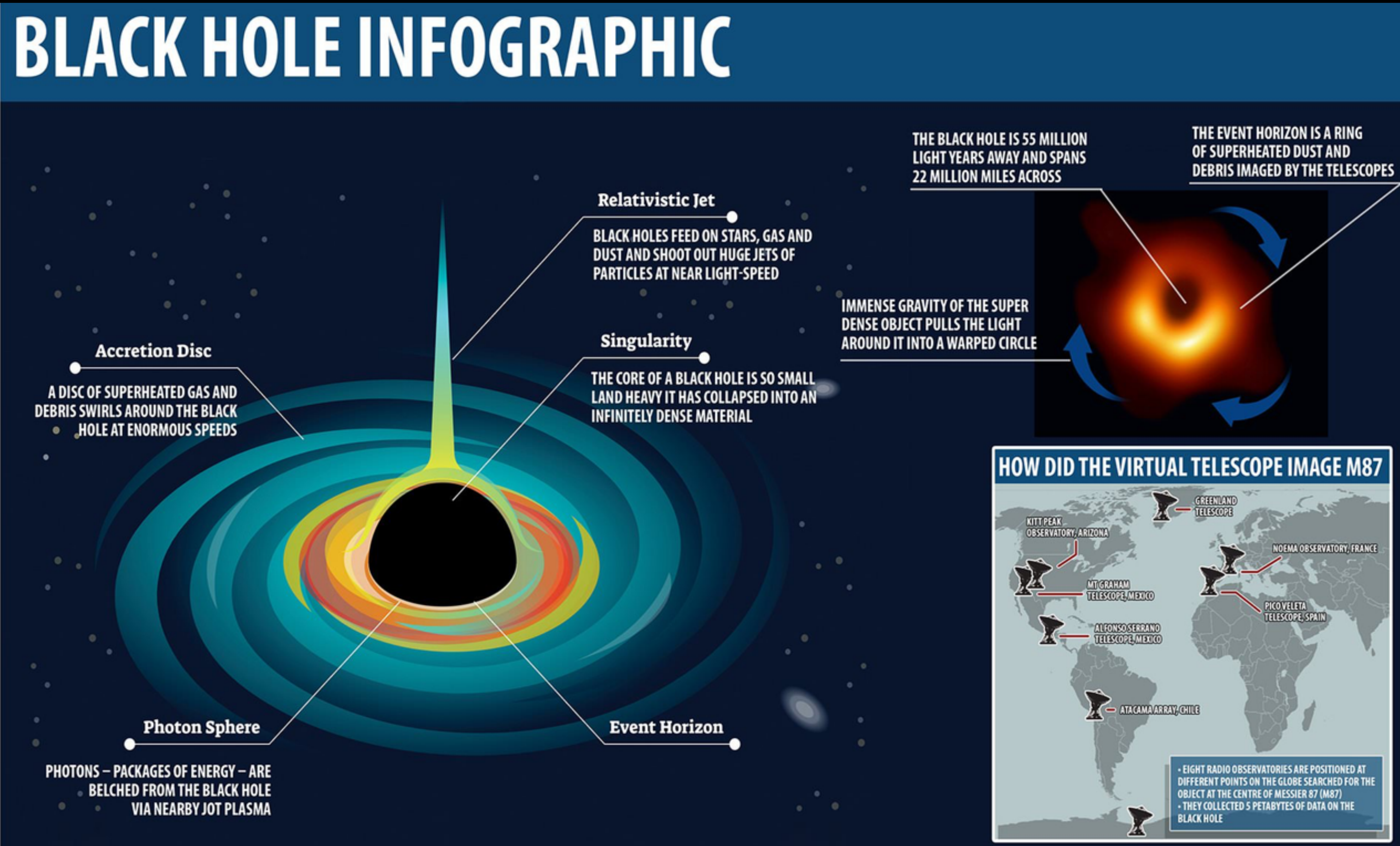
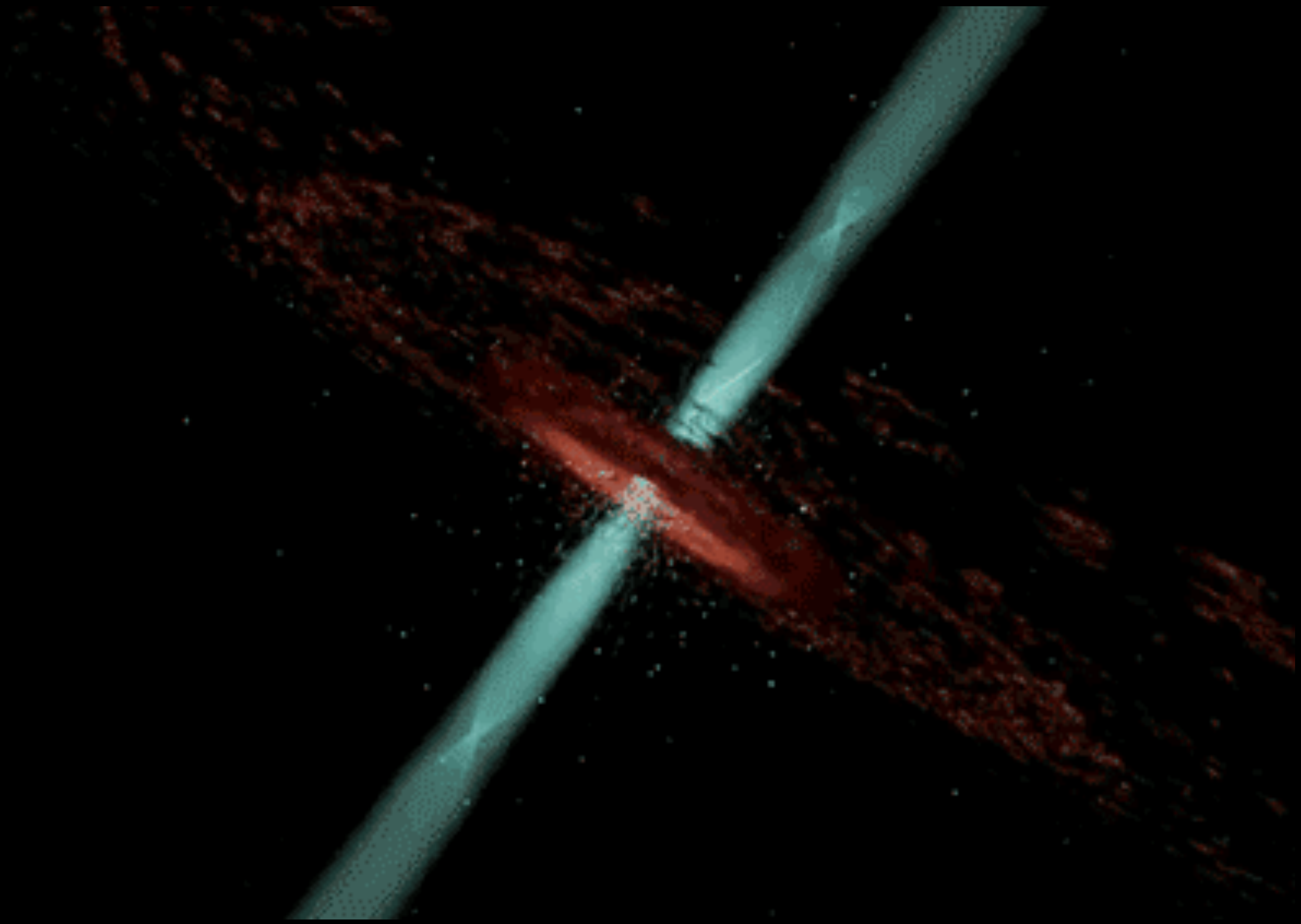
The Very First Image Of A Black Hole

Event Horizon Telescope




BLACK HOLE INFOGRAPHIC
Relativistic Jet
BLACK HOLES FEED ON STARS, GAS AND DUST AND SHOOT OUT HUGE JETS OF PARTICLES AT NEAR LIGHT-SPEED
Accretion Disc
A DISC OF SUPERHEATED GAS AND DEBRIS SWIRLS AROUND THE BLACK HOLE AT ENORMOUS SPEEDS
Singularity
THE CORE OF A BLACK HOLE IS SO SMALL LAND HEAVY IT HAS COLLAPSED INTO AN INFINITELY DENSE MATERIAL
Photon Sphere
PHOTONS – PACKAGES OF ENERGY – ARE BELCHED FROM THE BLACK HOLE VIA NEARBY JOT PLASMA
Event Horizon
THE BLACK HOLE IS 55 MILLION LIGHT YEARS AWAY AND SPANS 22 MILLION MILES ACROSS
THE EVENT HORIZON IS A RING OF SUPERHEATED DUST AND DEBRIS IMAGED BY THE TELESCOPES
IMMENSE GRAVITY OF THE SUPER DENSE OBJECT PULLS THE LIGHT AROUND IT INTO A WARPED CIRCLE
HOW DID THE VIRTUAL TELESCOPE IMAGE M87
GREENLAND TELESCOPE
KITT PEAK OBSERVATORY, ARIZONA
NOEMA OBSERVATORY, FRANCE
MT GRAHAM TELESCOPE, MEXICO
PICO VELETA TELESCOPE, SPAIN
ALFONSO SERRANO TELESCOPE, MEXICO
ATACAMA ARRAY, CHILE
• EIGHT RADIO OBSERVATORIES ARE POSITIONED AT DIFFERENT POINTS ON THE GLOBE SEARCHED FOR THE OBJECT AT THE CENTRE OF MESSIER 87 (M87)
• THEY COLLECTED 5 PETABYTES OF DATA ON THE BLACK HOLE



GAMMA-RAY BURSTS:

witnessing the birth of a new Black Hole in the Universe

How it all started…..

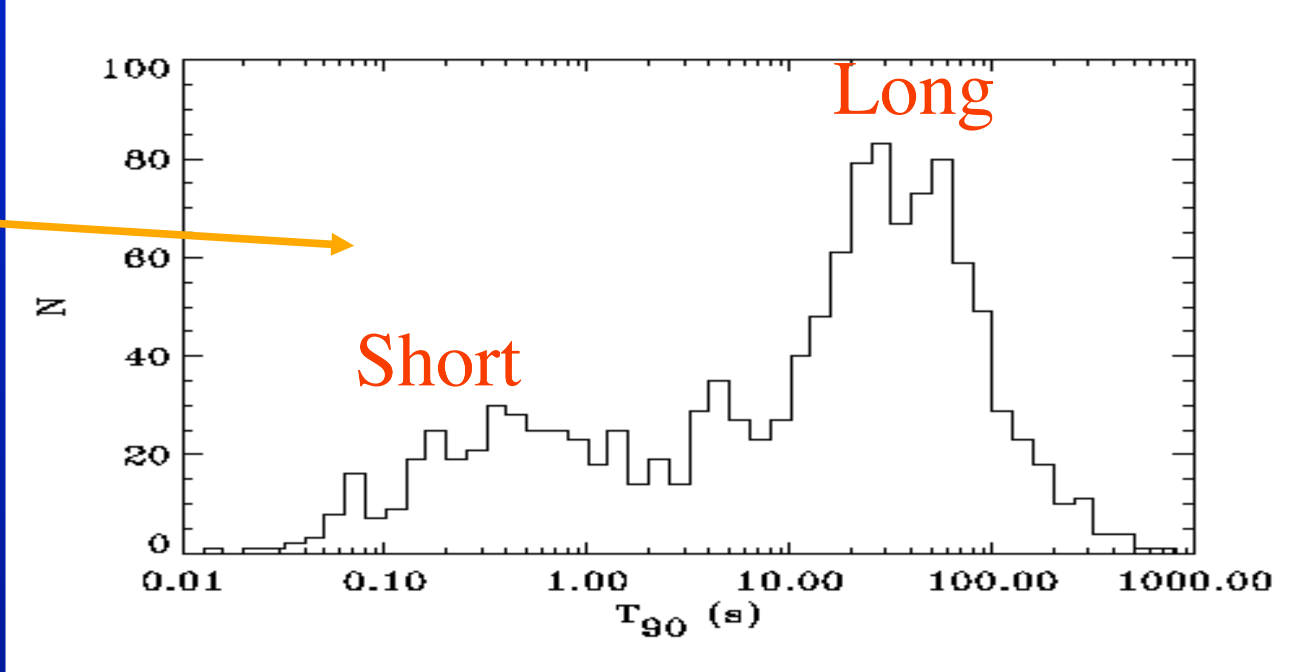
mid 1960s: VELA satellite

… looking for signs of nuclear tests…

Most GRB data gathered by BATSE in the 1990s

Main properties of GRBs:

- Rates: about 1 per day
- Durations: from tens of milliseconds to several hundreds of seconds, with bimodal distribution



- Highly variable

March 2003:
a “special”, very energetic supernova (HYPERNOVA) is found coincident with the position of the (long) GRB

Long GRBs are produced by the collapse of a massive star into a Black Hole!!

High star rotation likely needed

Several pieces of evidence seem to indicate that…

[Image from http://www.laeff.esa.es/BOOTES/esp/grb/grb4.htm]

…*Short* Gamma-Ray bursts are likely the result of a merger of two compact objects (i.e. NS-NS, NS-BH)

Should we be afraid of GRBs?

A powerful GRB in our Galaxy can wipe out life within a distance of several hundred light years….

But not very likely to happen..

What is a Gamma-Ray Burst?

A. An energetic burst of gamma rays from the center of the Milky Way.

B. An energetic burst of gamma rays from the birth of black holes and collisions of neutron stars

C. The sign that a new star is born.

D. A burst of gamma-rays with duration between 1000 seconds and 1 day

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What is the likely origin of a <u>long-</u> duration Gamma-Ray Burst?

A. The merger of two neutron stars.
B. The collapse of a massive, rapidly rotating star.
C. The collapse of a low-mass star.
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a) hydrogen is fused to helium on the white dwarf surface
b) an isolated white dwarf fuses the carbon in its core

2.) How is a White Dwarf Supernova produced?
a) electron degeneracy pressure is overcome by gravity and a core of neutrons is formed
b) accretion from binary companion allows mass to exceed 1.4 Msun

3.) What can make a long gamma-ray burst?
a) the collapse of a massive rotating star into a black hole
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4.) What is a pulsar?
a) accreting white dwarf b) rotating neutron star

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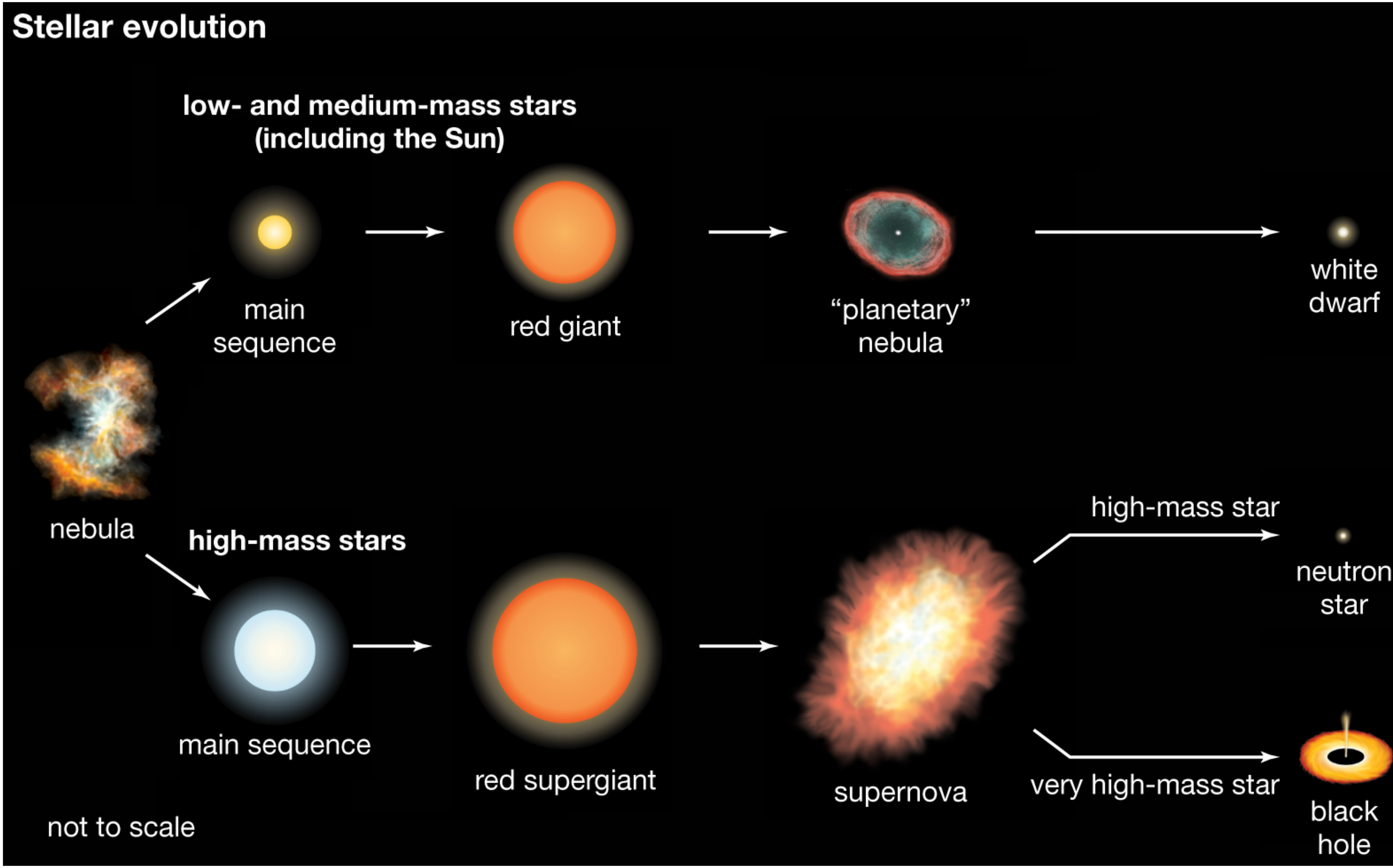
The Stellar Graveyard

What's In The Stellar Graveyard?

- Lower mass stars $(M < 1.4 M_\odot)$ → white dwarfs
  - Gravity vs. electron degeneracy pressure
- High mass stars $(1.4 M_\odot < M < 3 M_\odot)$ → neutron stars
  - Gravity vs. neutron degeneracy pressure
- **Even more massive stars** $(M > 3 M_\odot)$ → **black holes**
  - **Gravity wins**



- ✧ Star form when gaseous (mostly ^{1}H) clouds contract due to pull of gravity
- ✧ Energy releasy in ^{1}H fusion reactions produces outward pressure to halt inward gravitational contraction