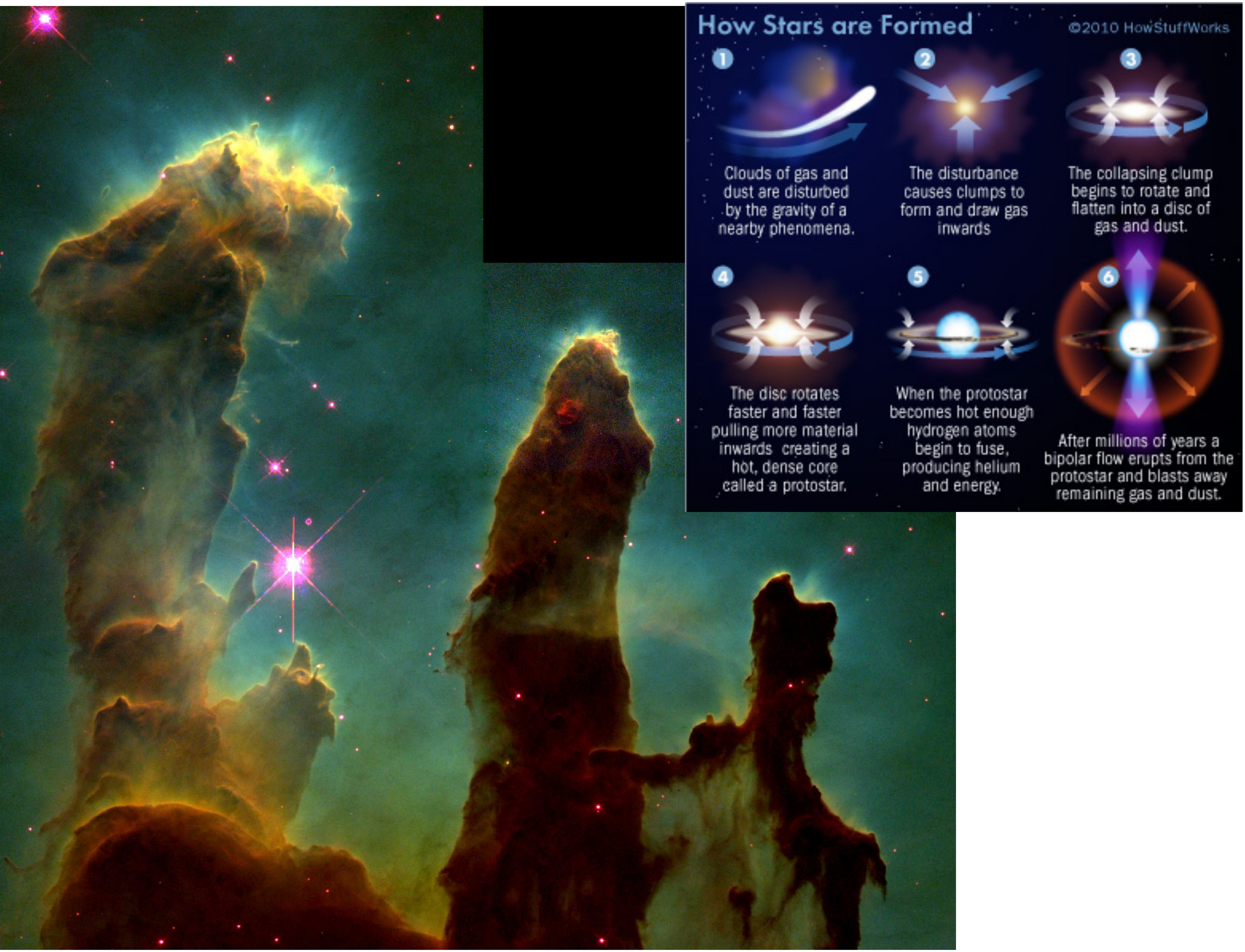
Stellar evolution, Einstein and extreme astrophysics!

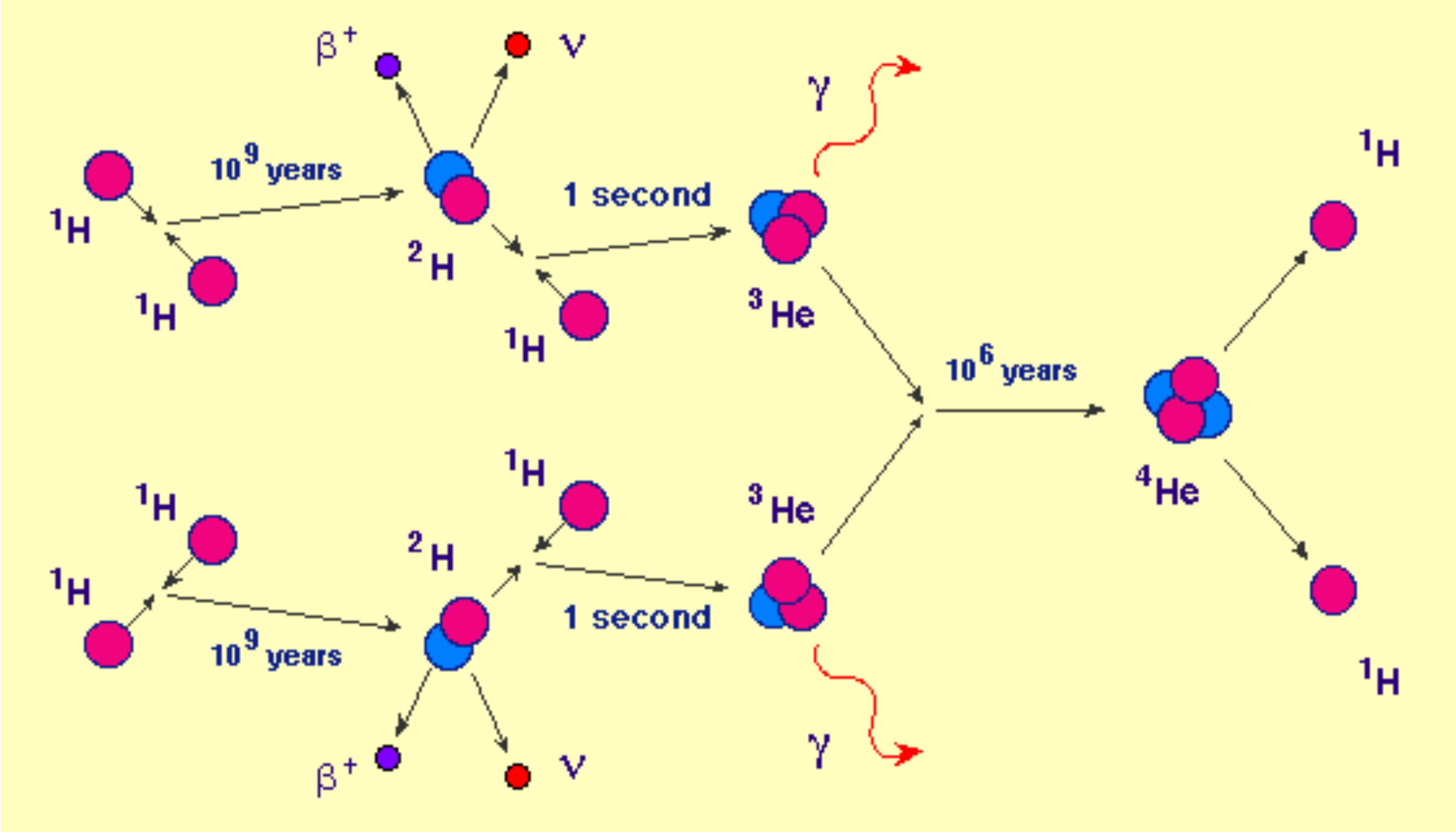
C&M Chaps 21 & 22 plus bits from chap 16, 17, 20



How Stars are Formed

1. Clouds of gas and dust are disturbed by the gravity of a nearby phenomena.
2. The disturbance causes clumps to form and draw gas inwards
3. The collapsing clump begins to rotate and flatten into a disc of gas and dust.
4. The disc rotates faster and faster pulling more material inwards creating a hot, dense core called a protostar.
5. When the protostar becomes hot enough hydrogen atoms begin to fuse, producing helium and energy.
6. After millions of years a bipolar flow erupts from the protostar and blasts away remaining gas and dust.

Energy production in stars through nuclear fusion: $E=mc^2$



Proton-proton chain (p-p chain). Net reaction converts 4H into 1 He.

Energy From Fusion Reactions

4 H nuclei = 6.693×10^{-27} kg

$\underline{\text{1 He nucleus} = 6.645 \times 10^{-27}\text{ kg}}$

difference = 0.048×10^{-27} kg

This difference in mass is called the mass defect. When nuclei undergo fusion, some of their mass is converted to energy. The same amount of energy is needed to break the nucleus apart. This energy is called the binding energy.

Mass defect can also be expressed as a fraction. E.g. here it is 0.007

The energy released from a single reaction from $E=mc^2$ is:

$0.048 \times 10^{-27} \times (3\times10^{8})^{2} = 0.43 \times 10^{-11}$ Joules.

Note that the units for this calculation are mass in kg, c in m/s and energy in Joules.

Example: How much energy is produced when the sun converts 500 g of mass into energy?

Using $E=mc^2$, energy = $0.5 \times (3\times10^8)^2 = 4.5 \times 10^{16}$ J.

How many megaton bombs is this equivalent to if a 1-megaton bomb produces 4×10^{15} J?

$4.5 \times 10^{16} / 4 \times 10^{15} = 11$ megaton bombs

Example: In a star, 100 kg of hydrogen is fused into helium. How much energy is liberated? How many kg of helium are produced?

Here, the easiest thing to do is use the mass defect, i.e. the fraction of mass that is turned into energy. We saw that for H and He, this is 0.007.

Using $E=mc^2$, $E = 0.007 \times 100 \times 300000000^2 = 6.3\text{x}10^{16}$ J.

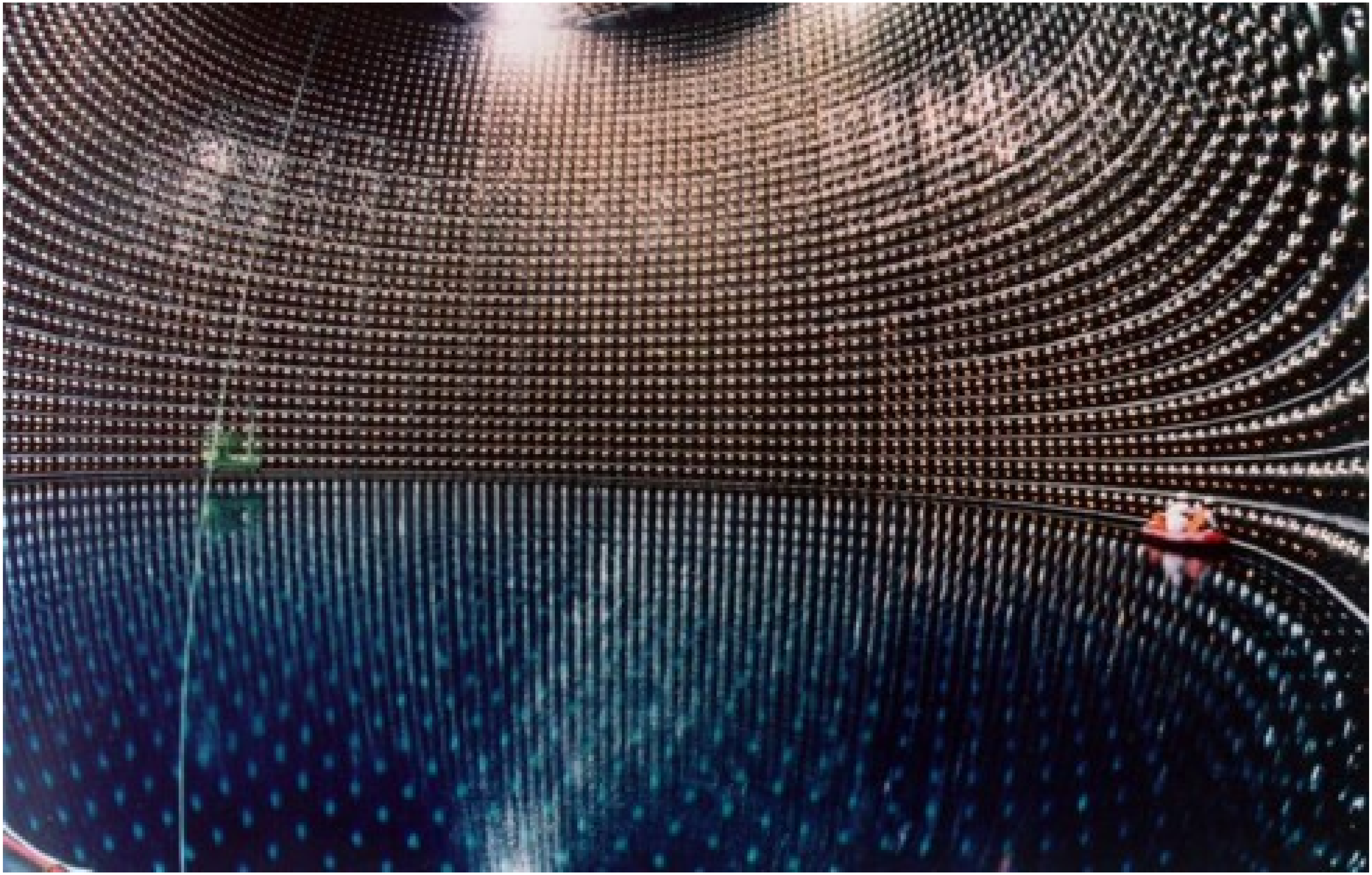
To calculate the amount of He produced, we again use the mass defect as a fraction. The mass defect tells us that 0.007 of the initial amount is converted to energy. That is 0.007 x 100 kg = 0.7 kg. This amount is therefore “missing”, so 100-0.7=99.3 kg of He are produced

Can test theory of energy production by counting the number of neutrinos coming from the sun.

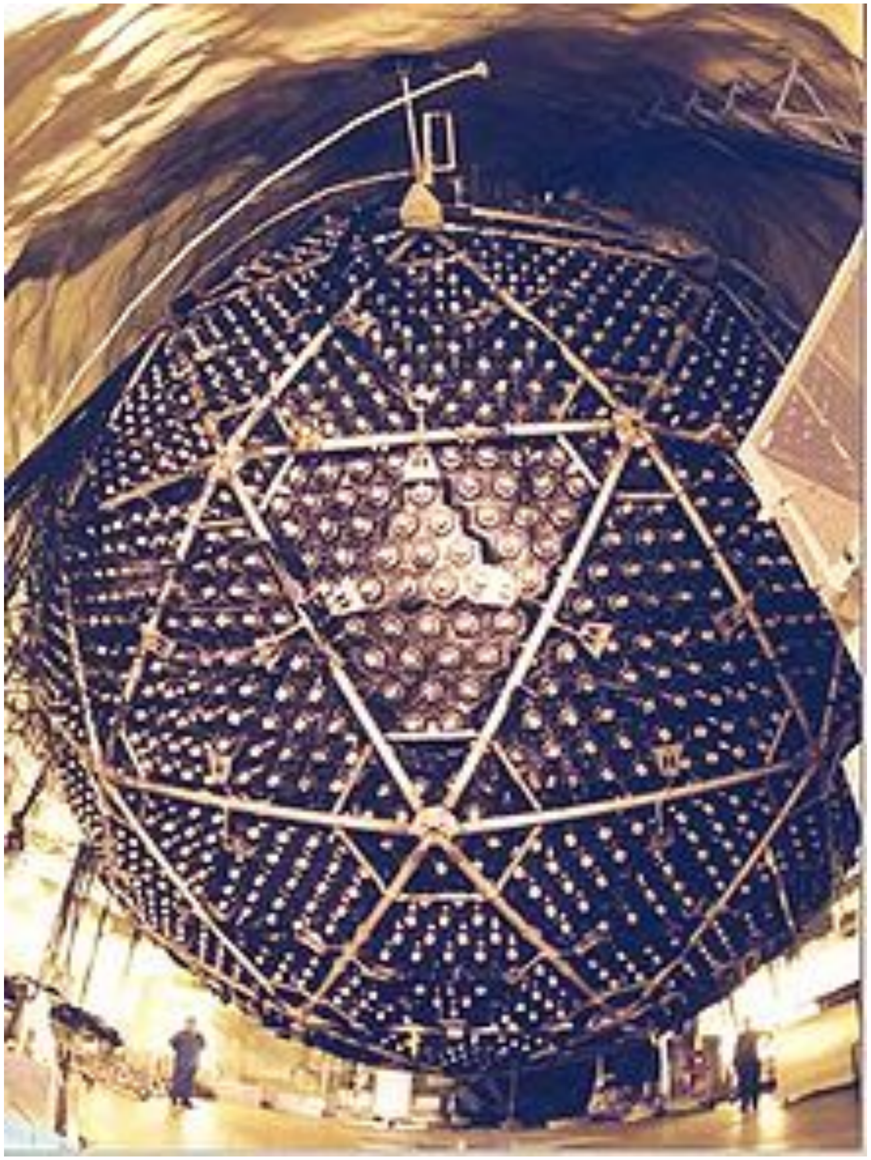
The solar neutrino problem

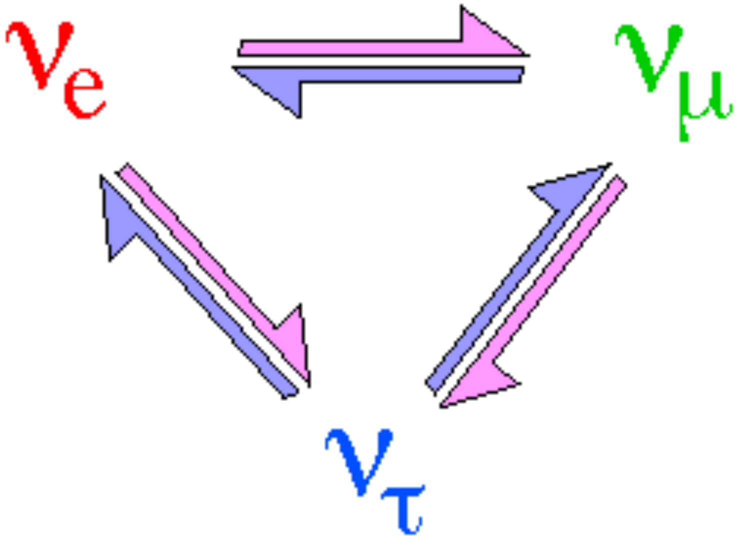
First neutrino observatory 1960s: Homestake goldmine, S. Dakota. Underground tank filled with cleaning fluid.

Cl + ν -> Ar (radioactive)



Super-Kamiokande neutrino observatory is filled with 50,000 tons of pure water.

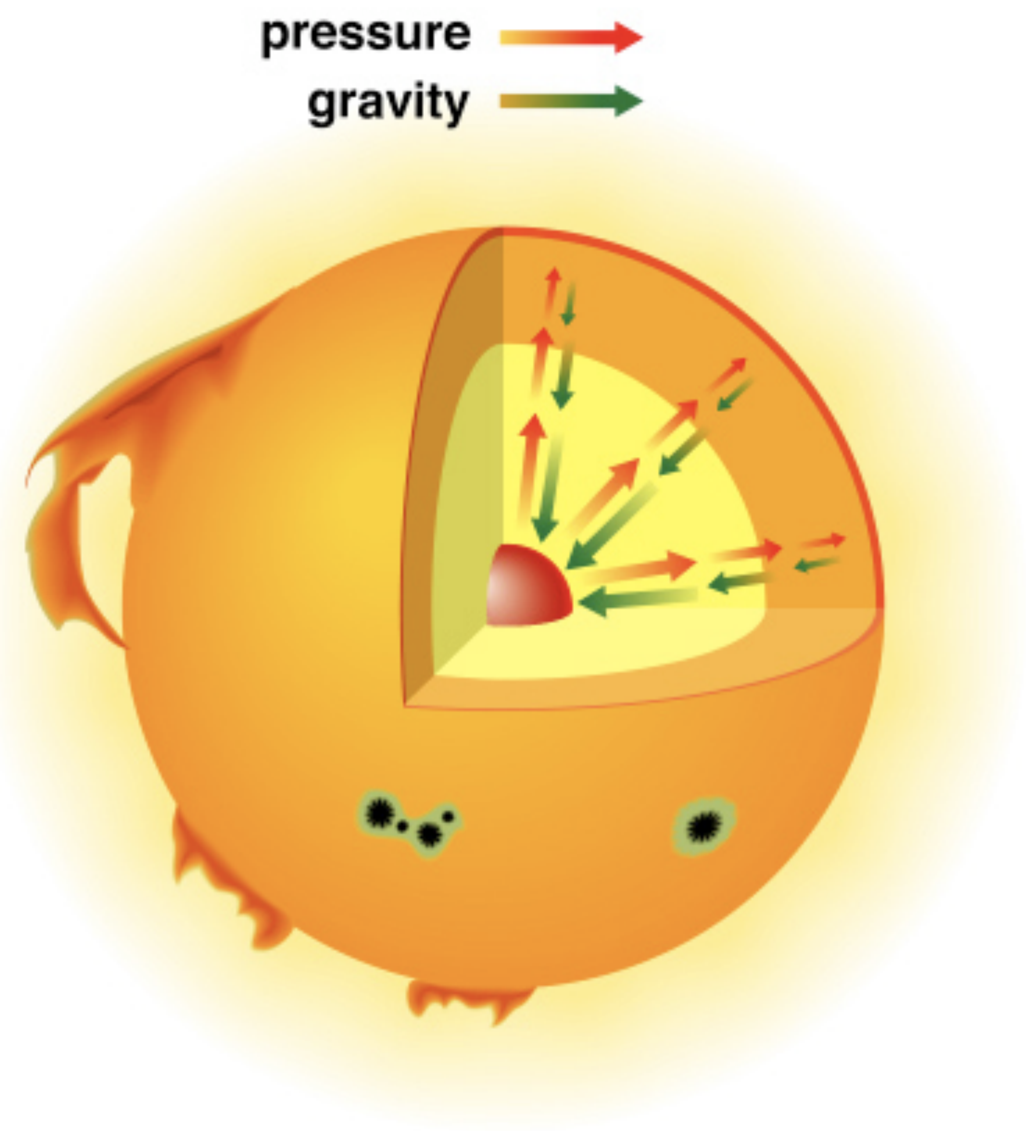




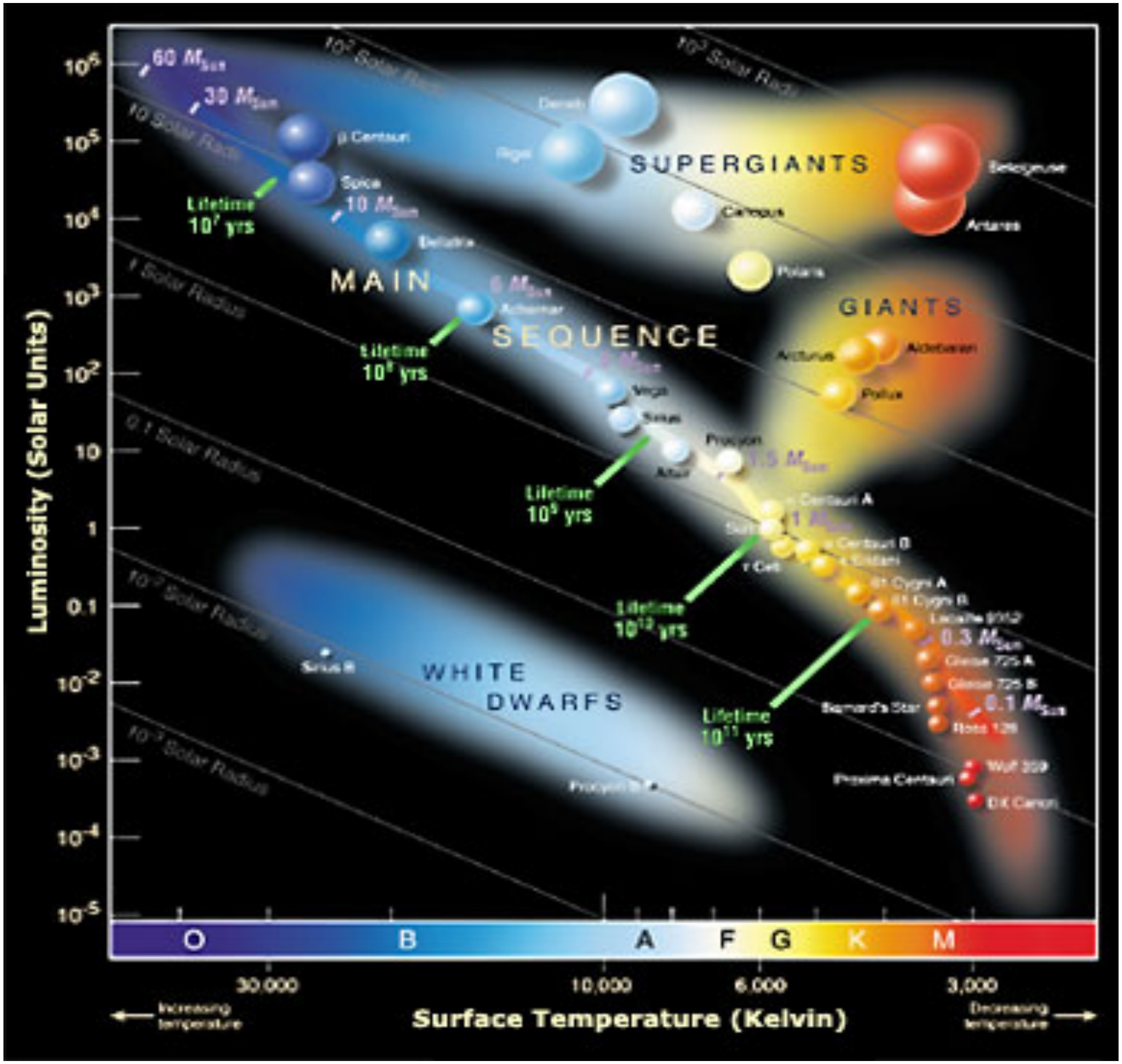
Sudbury neutrino observatory, Ontario. Filled with heavy water. Sensitive to all three types of neutrino.

2015 Nobel prize in physics to Canadian Arthur McDonald (Queens)

Hydrostatic equilibrium keeps stars in balance whilst they have effective fusion.



Most important property is stellar mass. Governs lifetime, colours, sizes…



At what wavelengths can we observe different stars?

We can use Wien's law to calculate the wavelength at which stars of different masses (temperatures) will emit most of their energy.

Recall Wien's law: $\lambda_{max}(\mathrm{nm}) = 2.9 \times 10^6 \ / \ T(\mathrm{K})$

Example

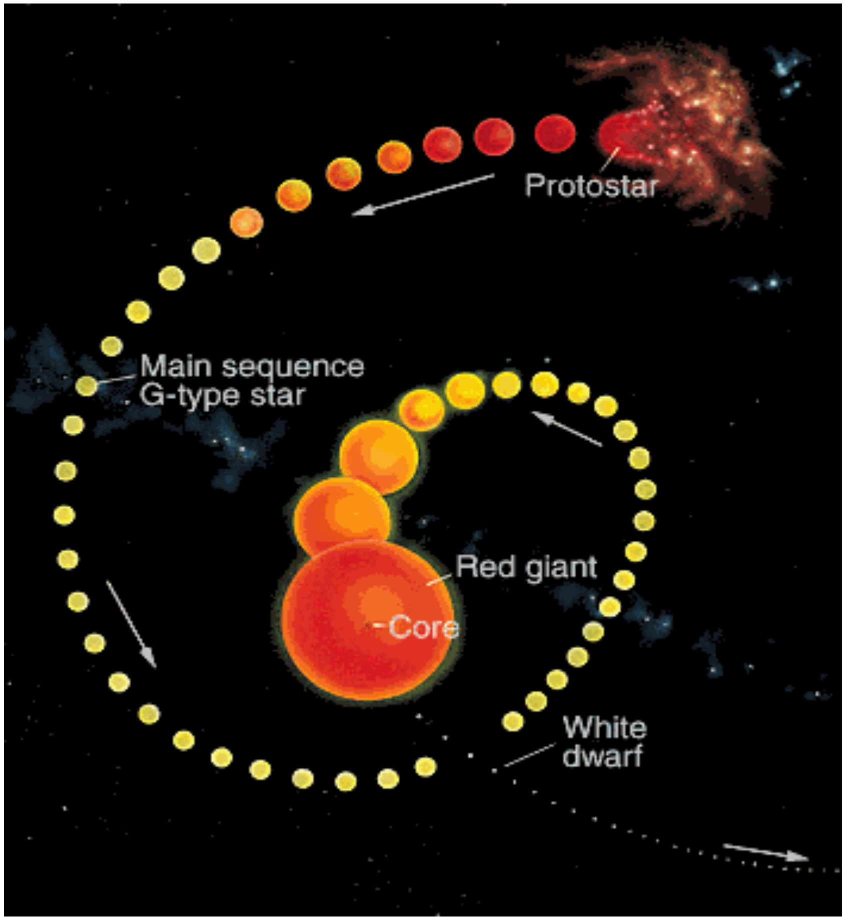
An IR survey centred at 2700 nm finds a large number of brown dwarfs. What can we infer about their temperature?

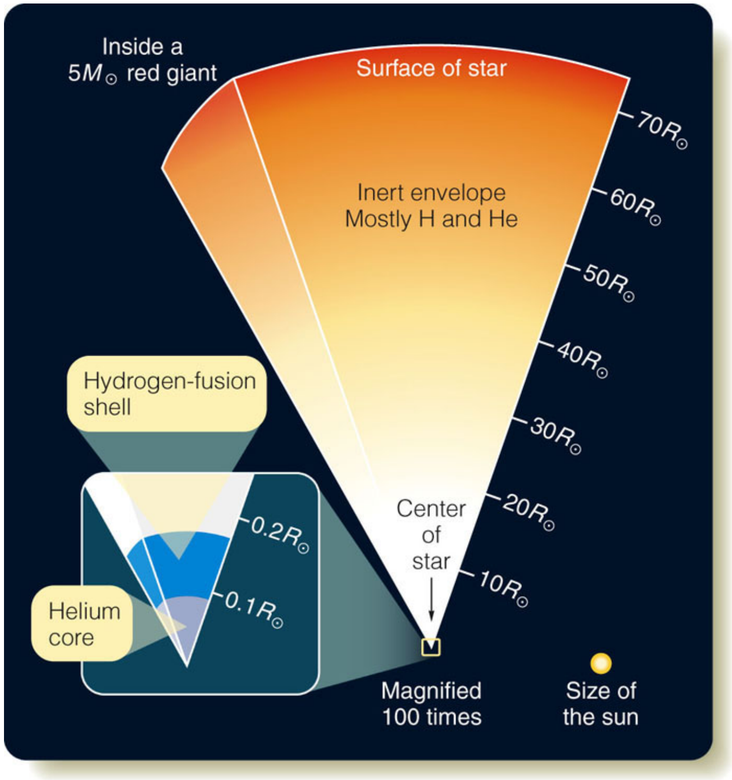
Using Wien's law, $T = 2.9 \times 10^6 / 2700 = 1074$ K

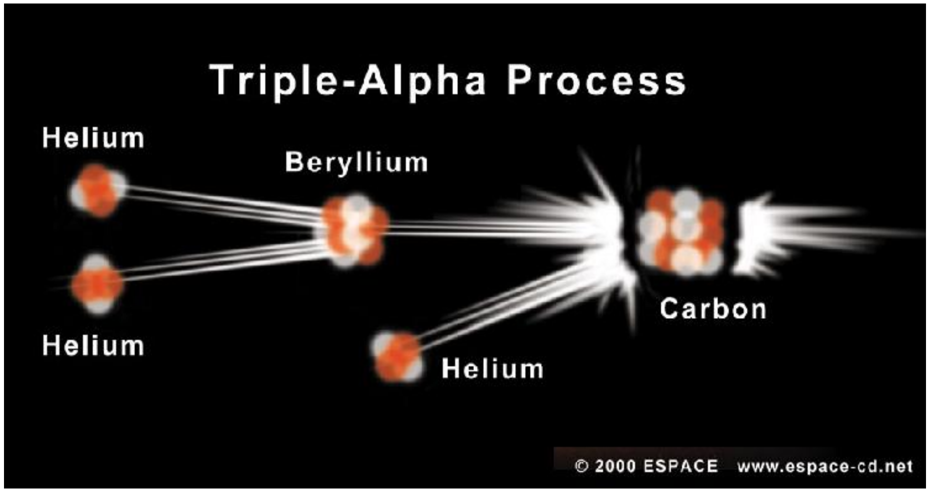
Methane molecules are destroyed at temperatures above about 1500 K. What is the minimum wavelength at which we should pre-select objects that might contain methane?

wavelength = 2.9e6/1500 = 1933 nm. This is in the near infrared.

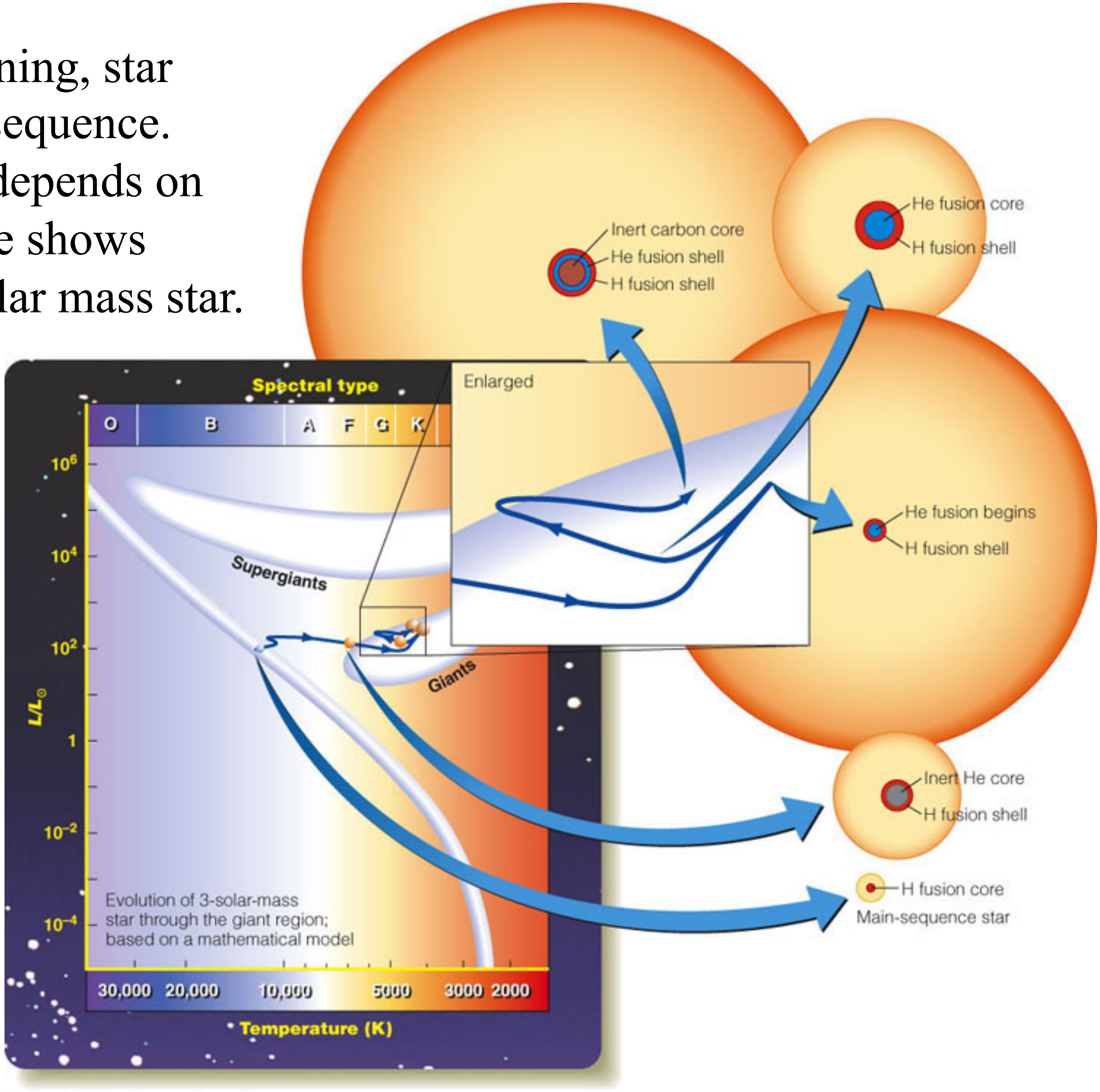
Post-main sequence evolution: formation of the red giant.







After core H-burning, star moves off main sequence. Exact evolution depends on mass. This figure shows evolution of 3 solar mass star.



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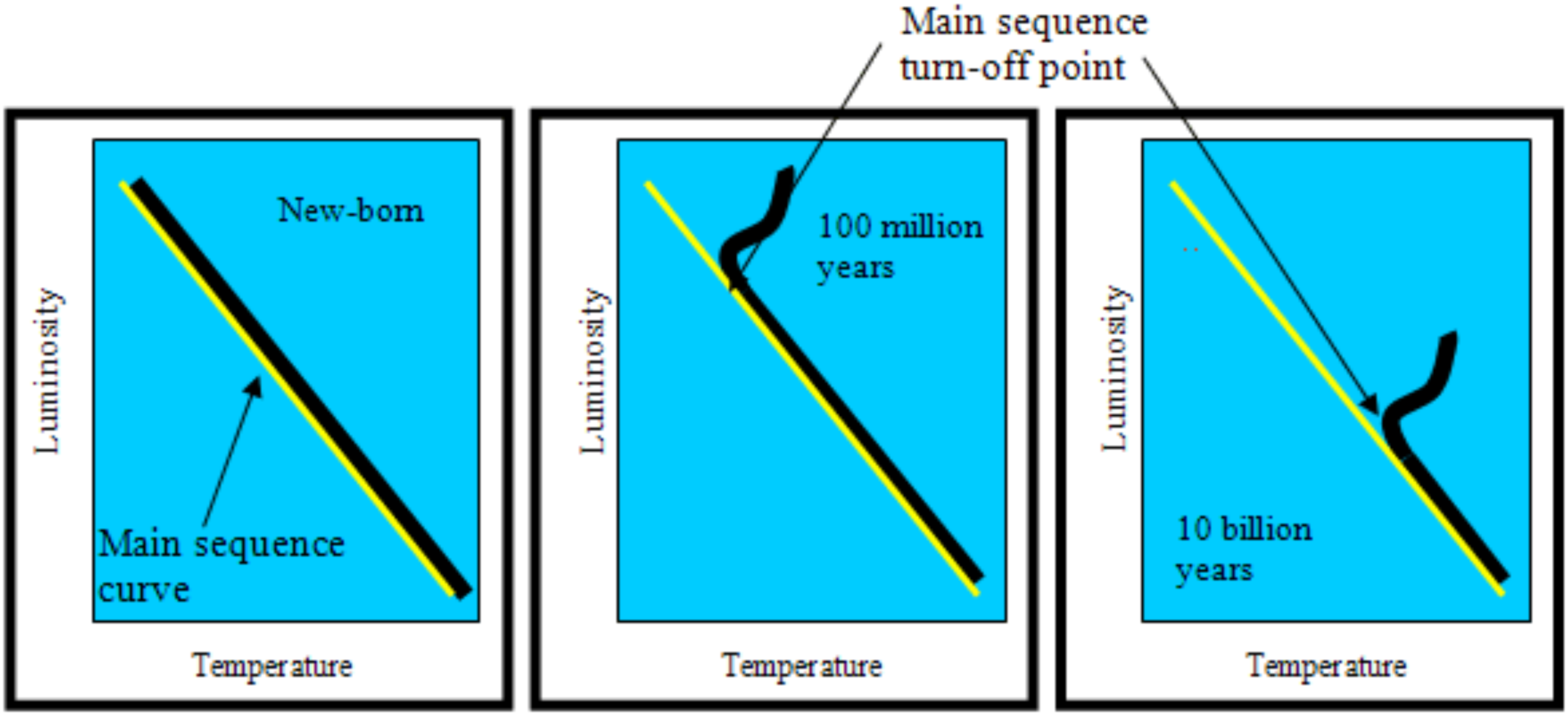
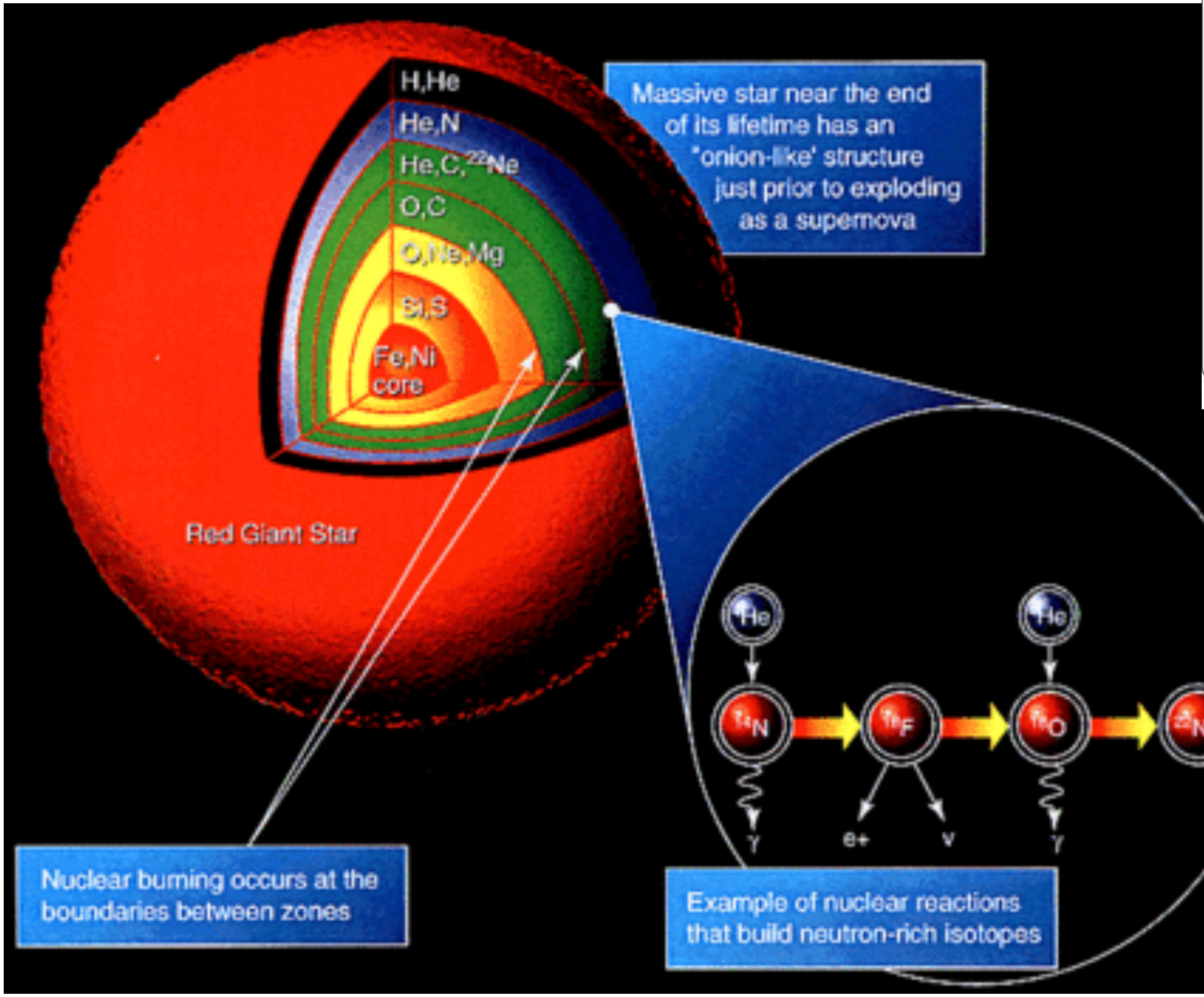
Measuring the main sequence “turn-off” allows us to age date stellar populations



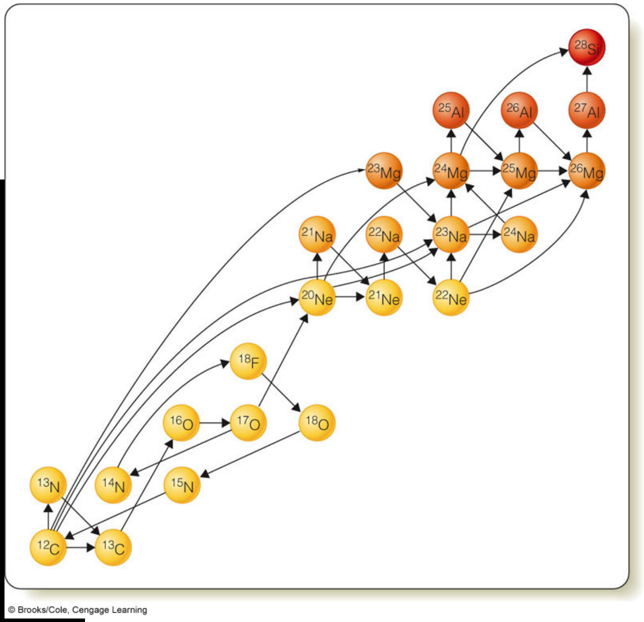
We are all stardust!



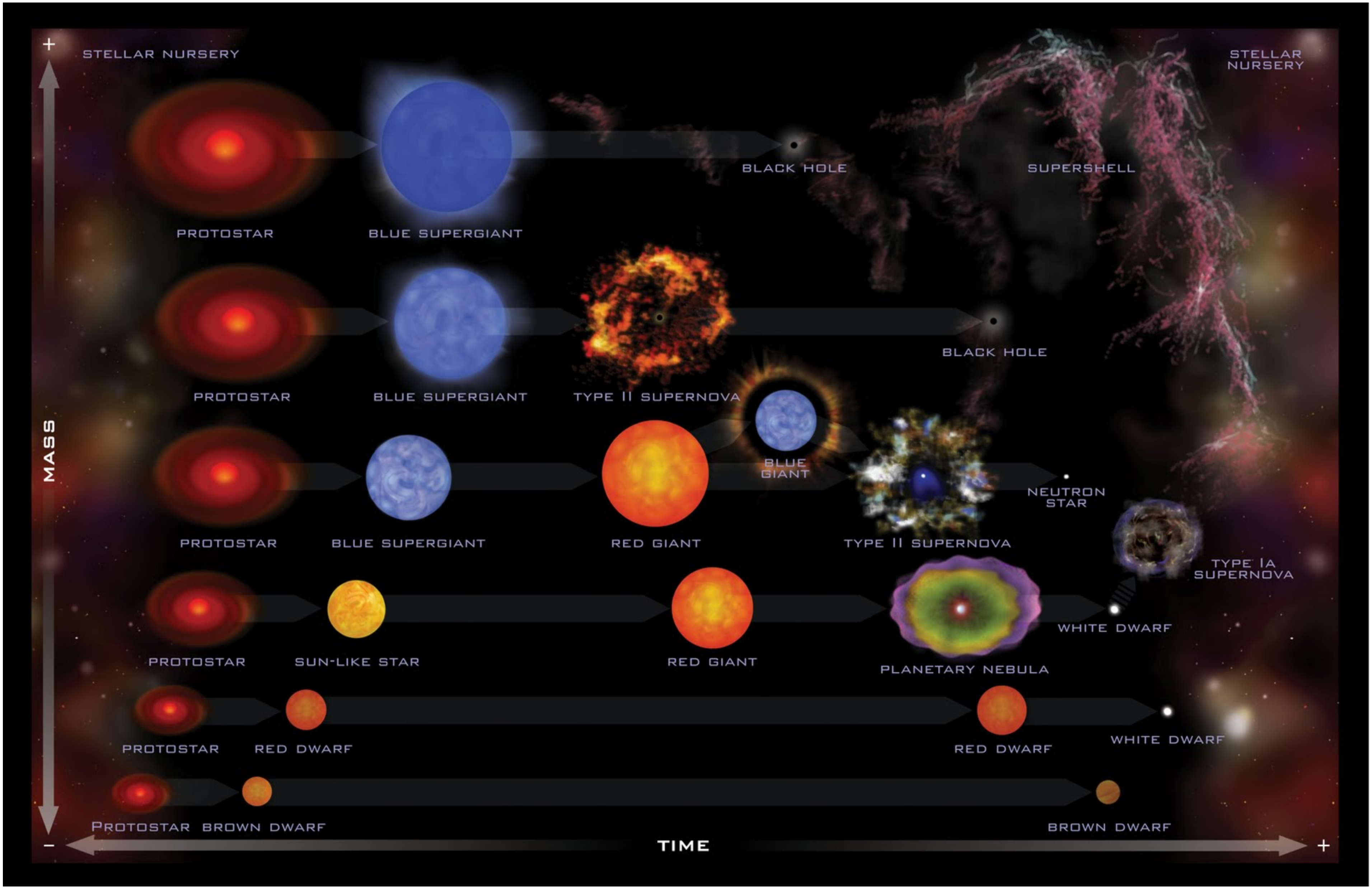
Massive star near the end of its lifetime has an 'onion-like' structure just prior to exploding as a supernova

Nuclear burning occurs at the boundaries between zones

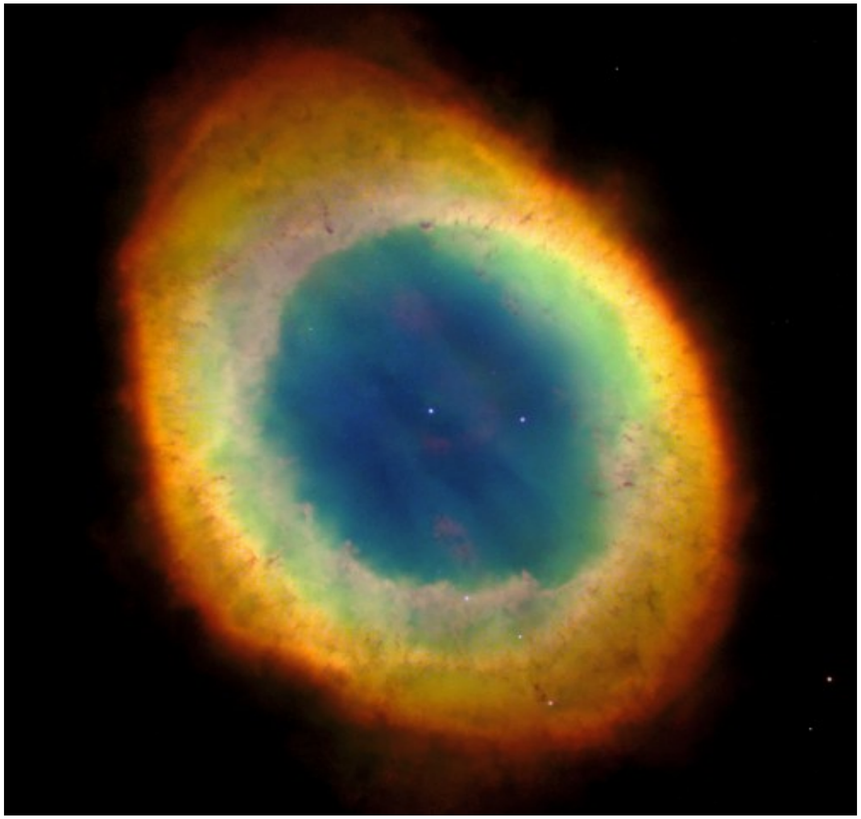
Example of nuclear reactions that build neutron-rich isotopes

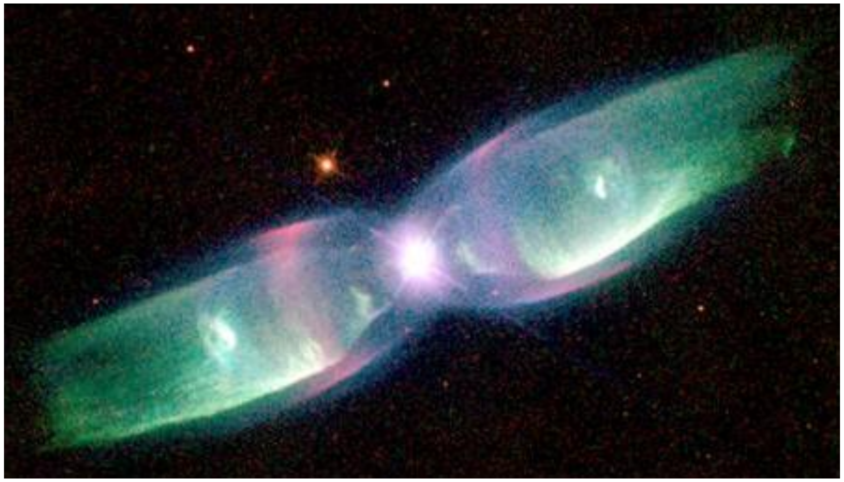


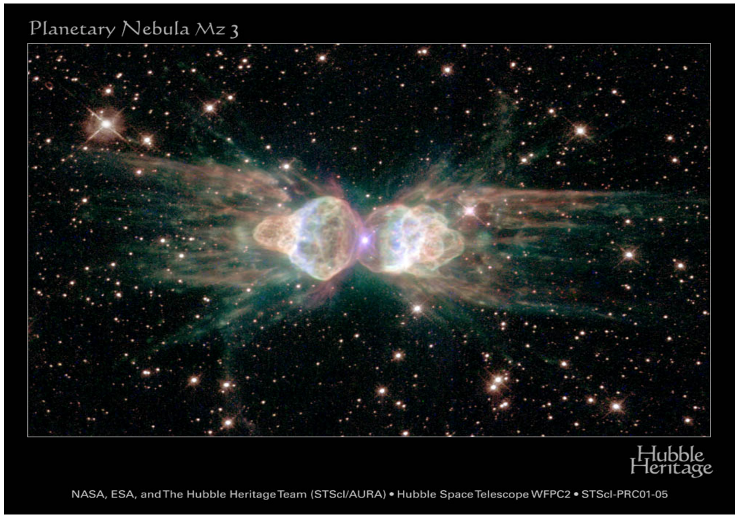
What happens next depends on the star’s mass…..



The death of sun-like stars. Planetary nebula.







NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-05

Example:

In a spectrum of the ring nebula (whose diameter is 1.7 lightyears), we find that the Balmer H alpha line is shifted from its rest wavelength of 656.3 nm by 0.04 nm. How old is the nebula?

1). Calculate the radius of the nebula. radius=diameter/2. So the radius is 0.85 lightyears.

2) Calculate the expansion velocity. To do this, we use the shift in wavelength of the emission line which is caused by the Doppler shift.

$$\frac{\text{velocity}}{\text{speed of light}} = \frac{\text{change in wavelength}}{\text{original wavelength}}$$

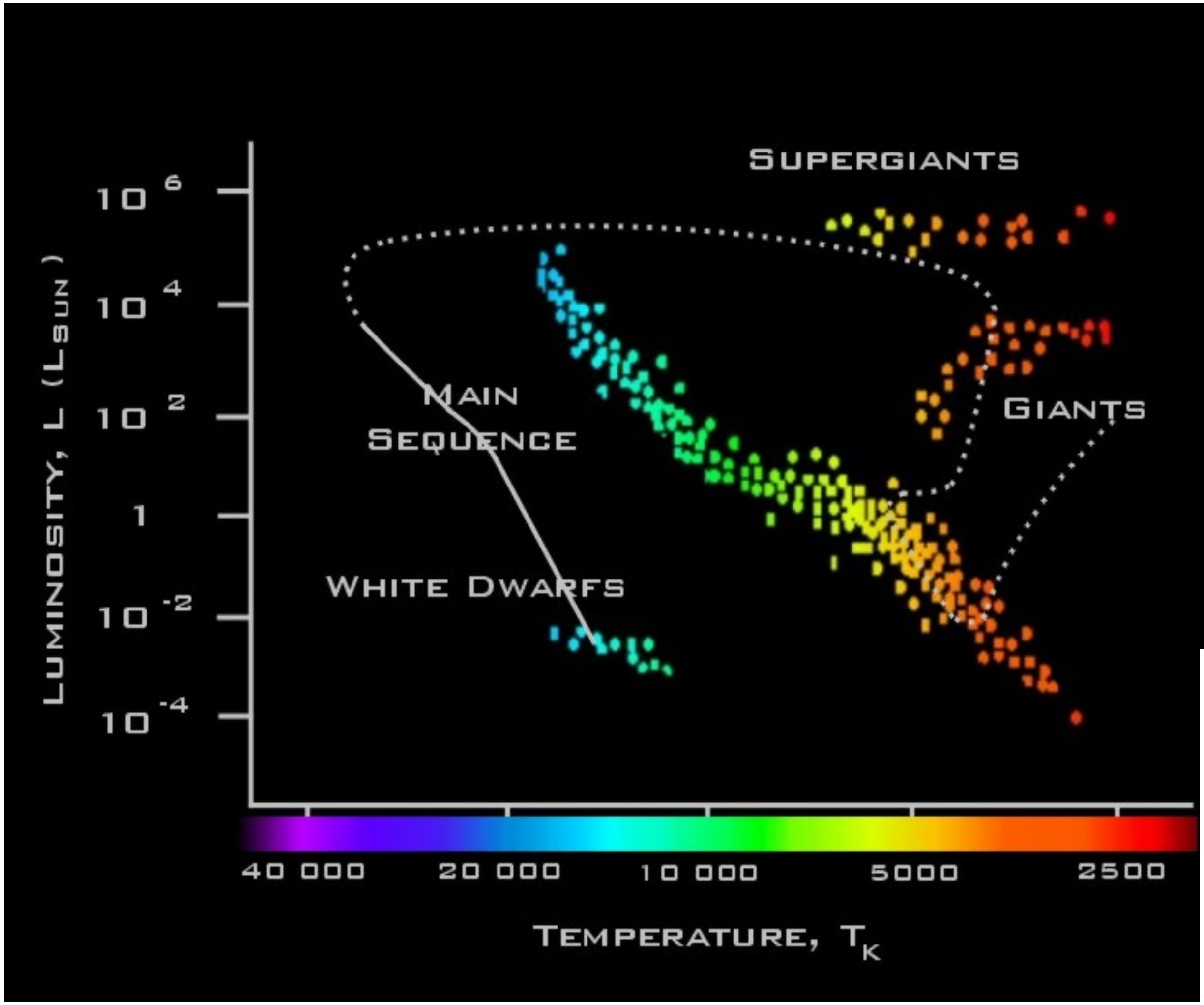
So, velocity = (0.04/656.3) x 300,000 = 18 km/s

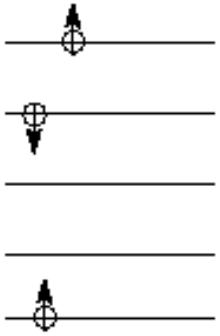
3) Finally, to get the time required for the bubble to grow, we use time=distance/velocity. However, we first have to convert the distance (0.85 lightyears) into km. 1 ly = $9.5x10^{12}$ km, so 0.85 lyrs = $8x10^{12}$ km.

$$\text{time} = 8x10^{12} / 18 = 4.4x10^{11} \text{ seconds}$$

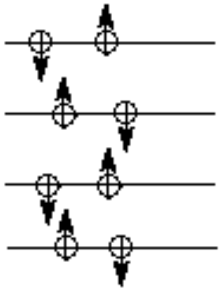
So the age of the nebula is about $4x10^{11}$ seconds, or about 14,000 years.

White dwarfs and degenerate matter



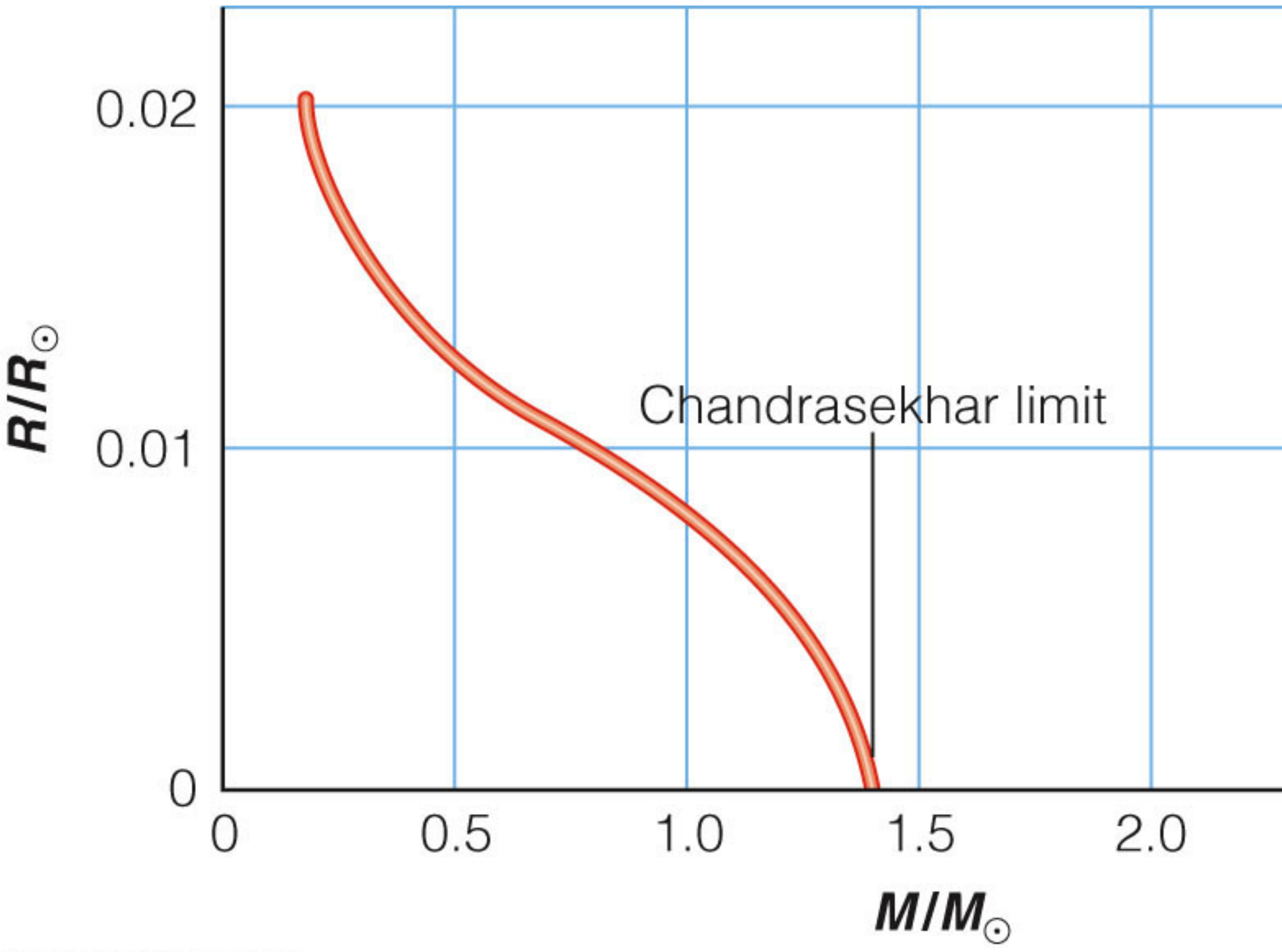


Regular gas: many unfilled energy levels. Particles free to move about and change energy levels.



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

The Chandrasekhar Limit



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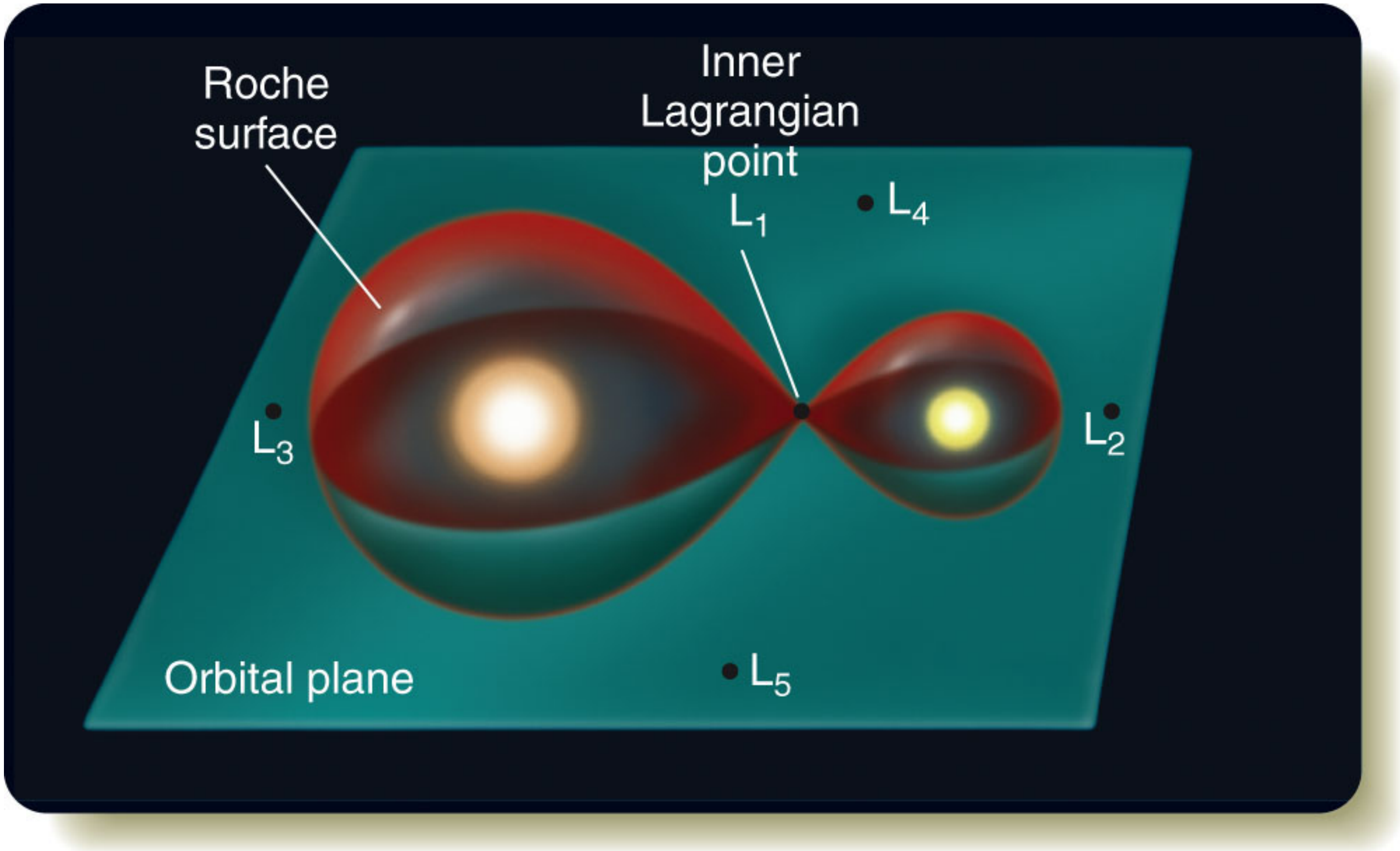

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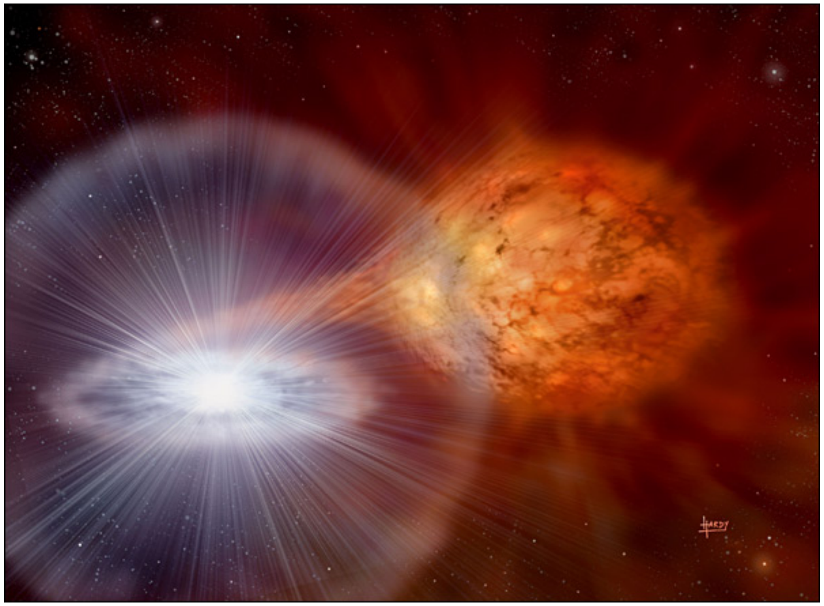
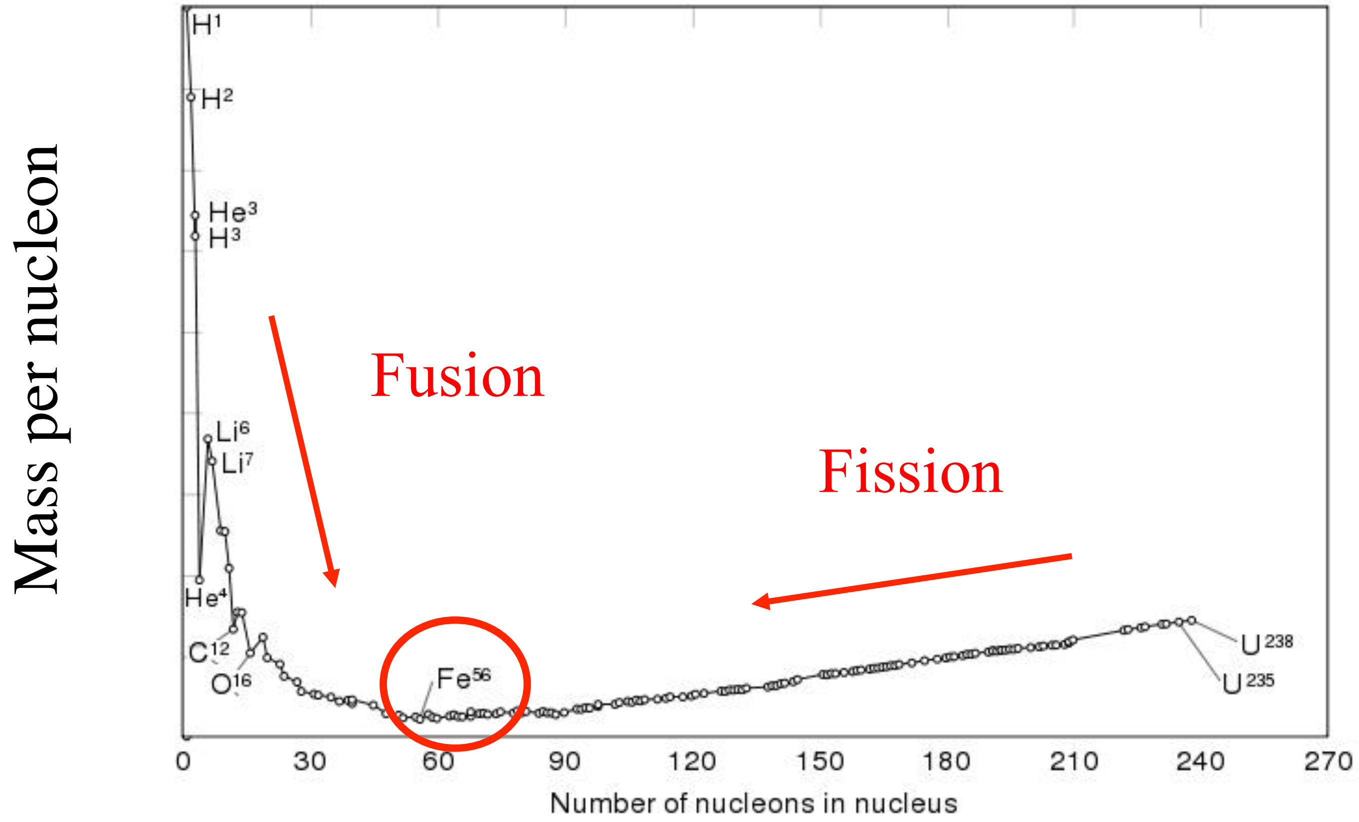


Formation of a Type Ia supernova:

Type Ia SN do not have H in their spectra and leave no remnant.

The death of the most massive stars.

When the light elements fuse, the “average” mass of a nucleon decreases. That lost mass has been converted to energy. Similarly, energy released in fission.

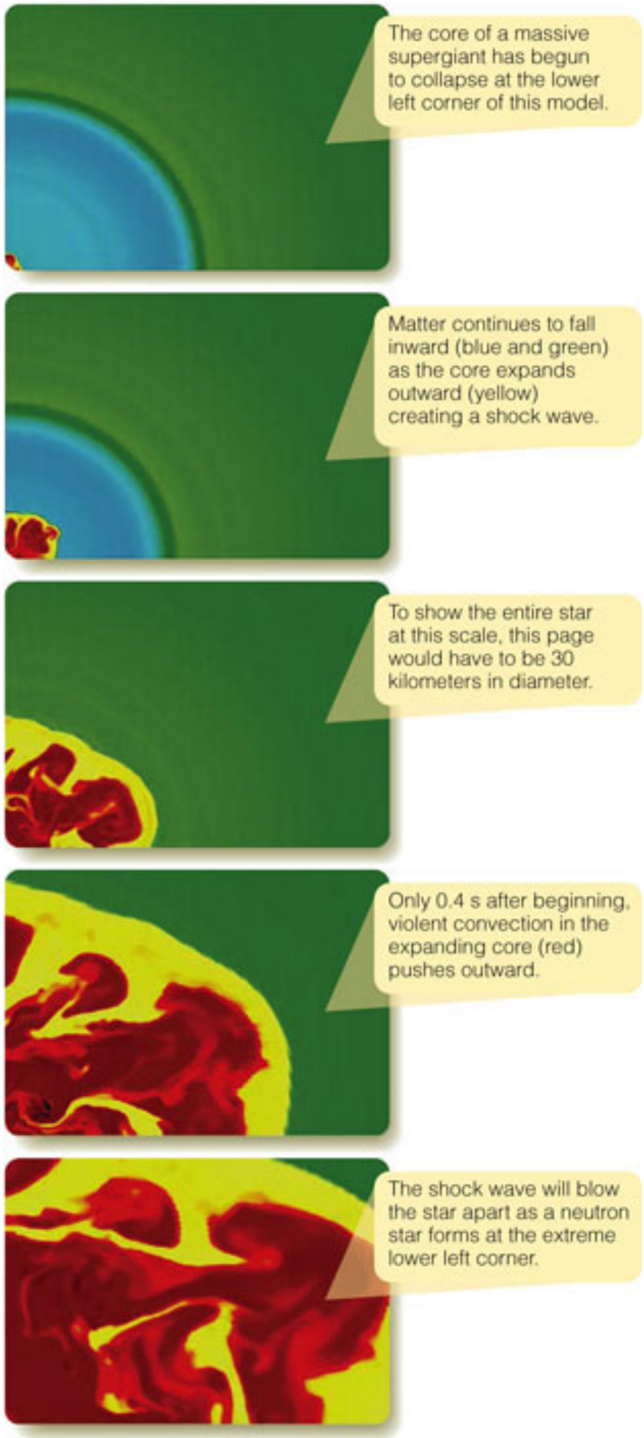


Iron lies at the trough of this curve, so there is no nuclear process (fission or fusion) that can create energy from iron.

Formation of a Type II SN:

Strong H lines observable in the spectrum.

The Exploding Core of a Supernova



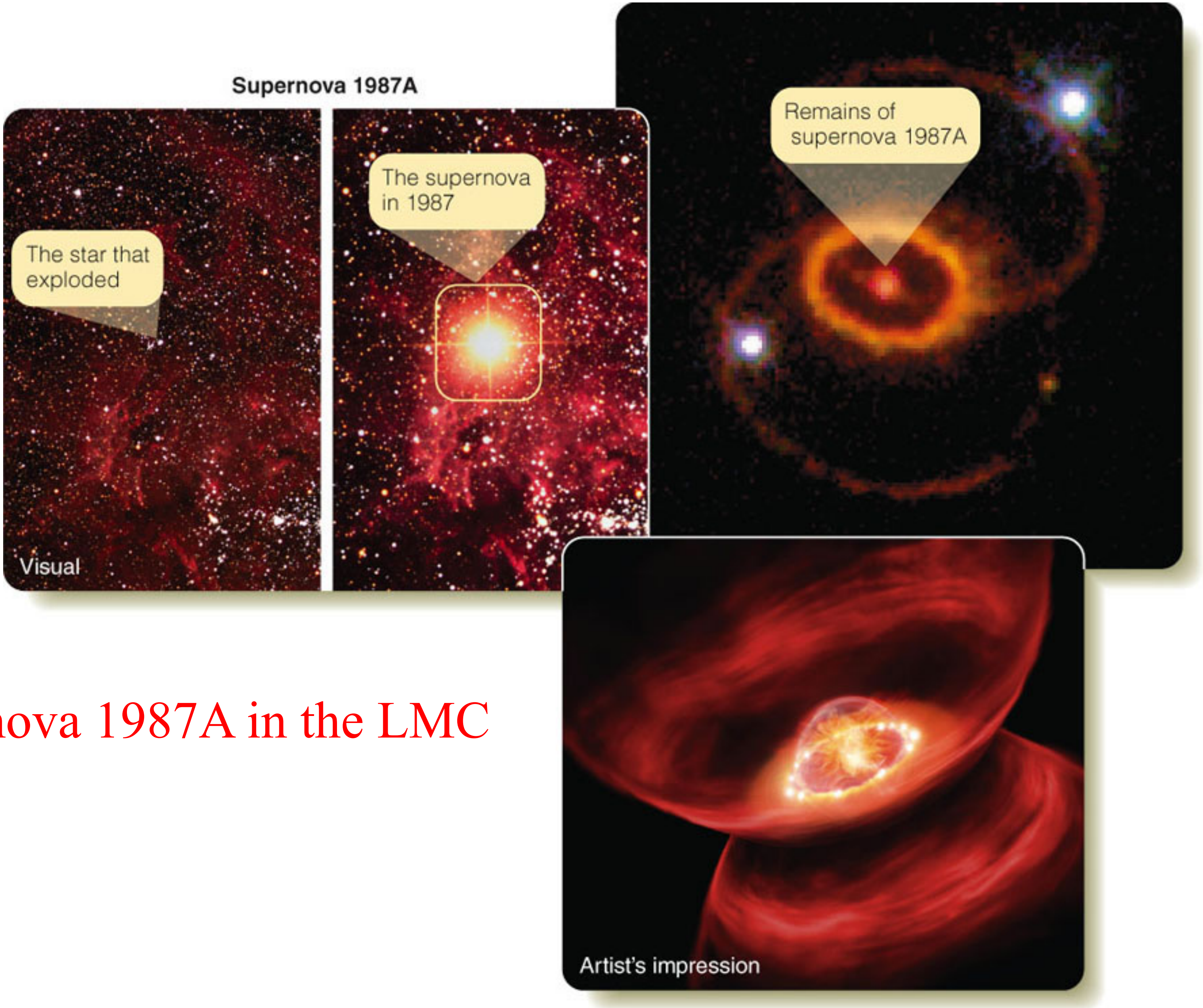
The core of a massive supergiant has begun to collapse at the lower left corner of this model.

Matter continues to fall inward (blue and green) as the core expands outward (yellow) creating a shock wave.

To show the entire star at this scale, this page would have to be 30 kilometers in diameter.

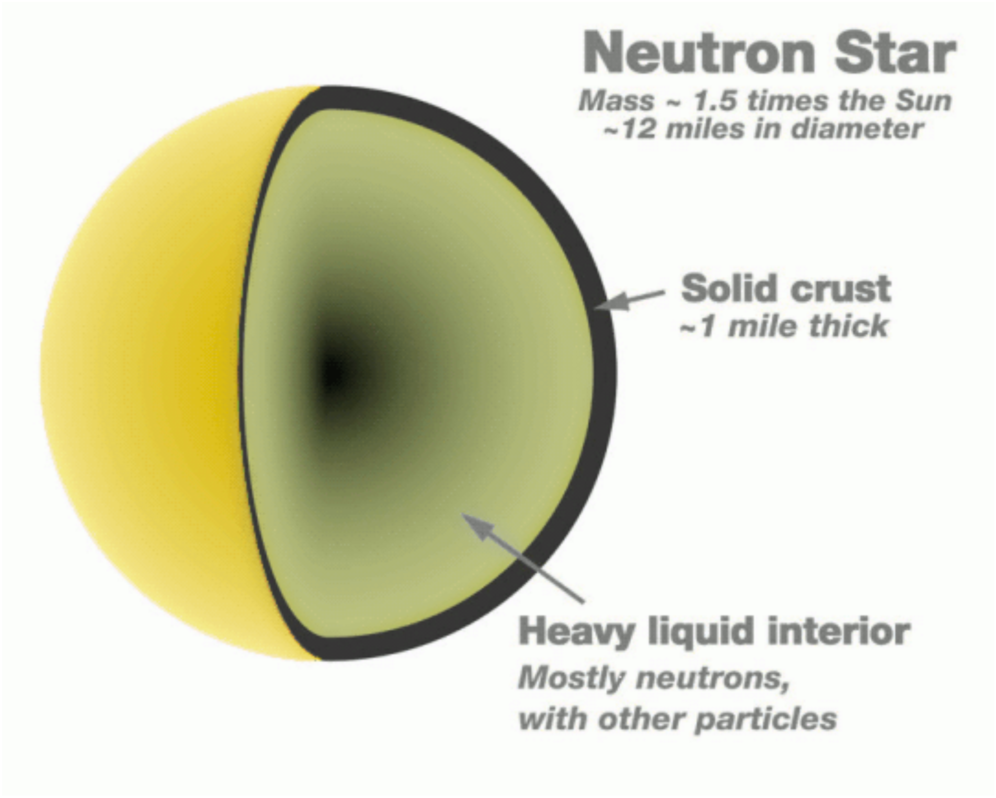
Only 0.4 s after beginning, violent convection in the expanding core (red) pushes outward.

The shock wave will blow the star apart as a neutron star forms at the extreme lower left corner.

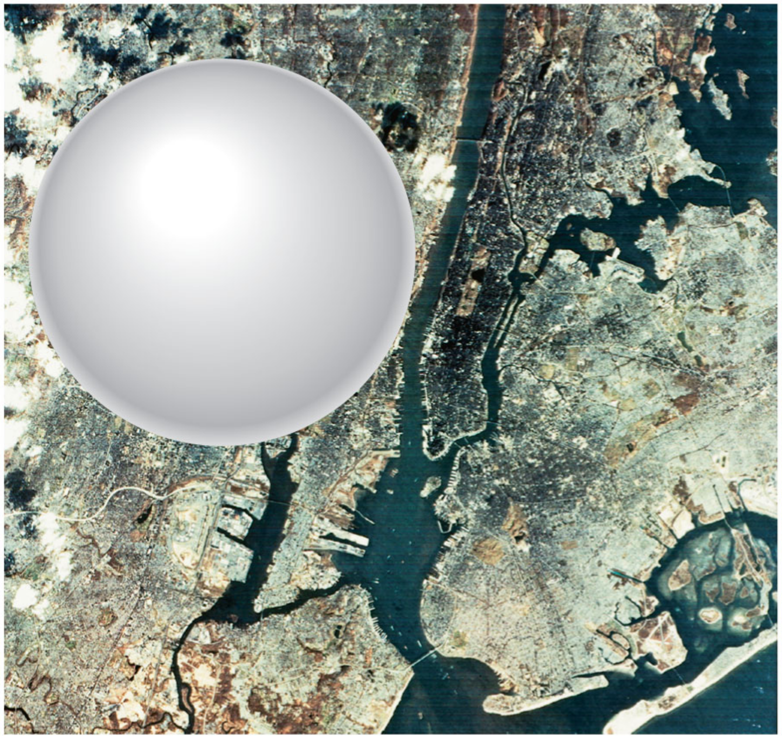


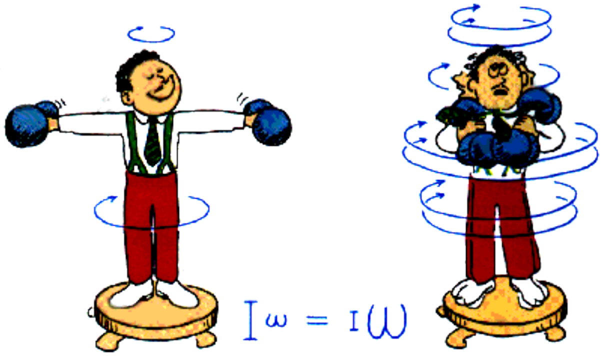
Supernova 1987A in the LMC

Post-SN for a massive star: neutron stars

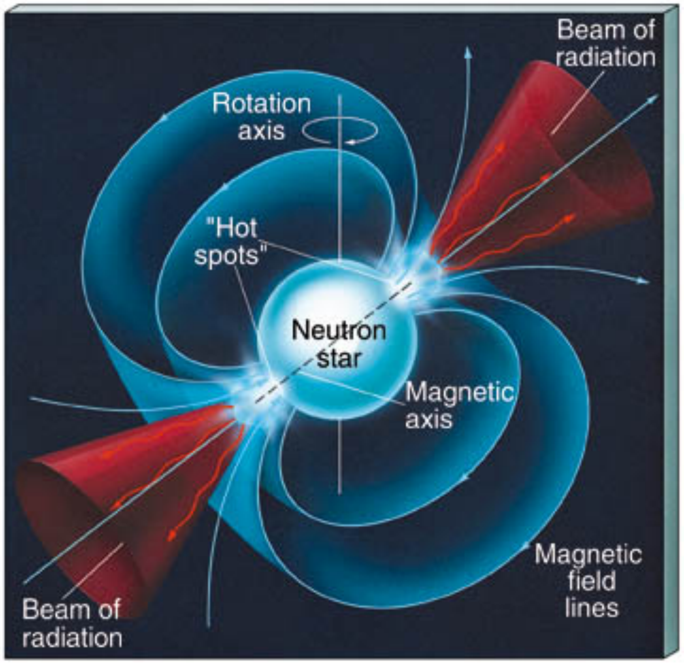


Remnant of SN no longer supported by thermal pressure of nuclear reactions, but by degeneracy pressure from either electrons (case of the white dwarf) or neutrons (neutron star).



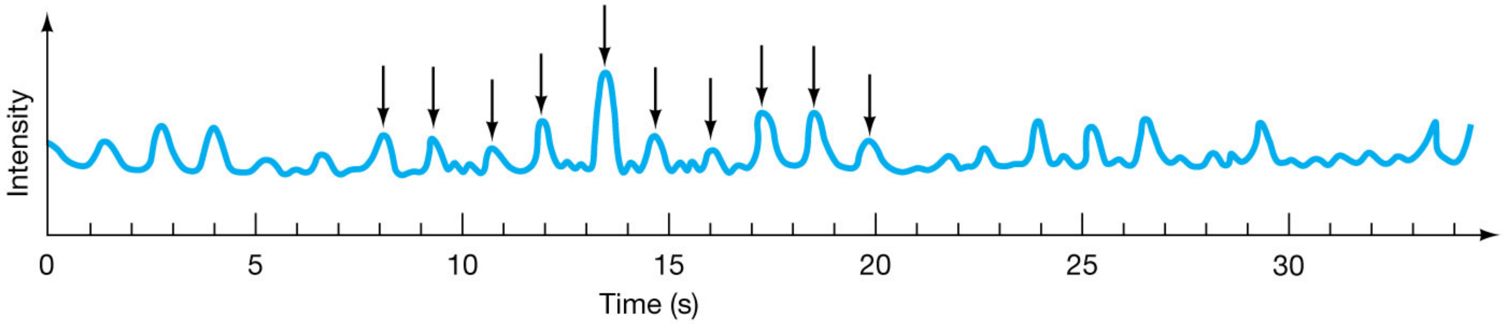


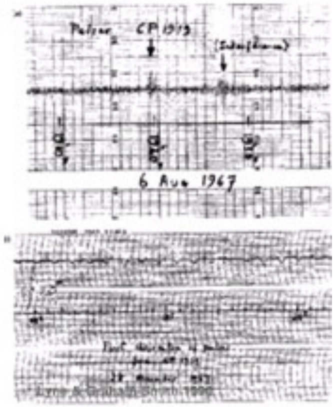
Conservation of angular momentum ($L=I\omega \propto mr^2\,\omega$) "shrinking" of stellar core into a neutron star increases its velocity -> fast spin.



Example: Sphere of radius 1m rotates at 1 revolution/min. How fast does it rotate if it contracts by factor 10?

$$M_i\,\omega_i\,r_i^2 = M_f\,\omega_f\,r_f^2$$
$$M \times 1 \times 1 = M \times \omega_f \times (0.1)^2$$
$$\omega_f = 100 \text{ rev/min.}$$





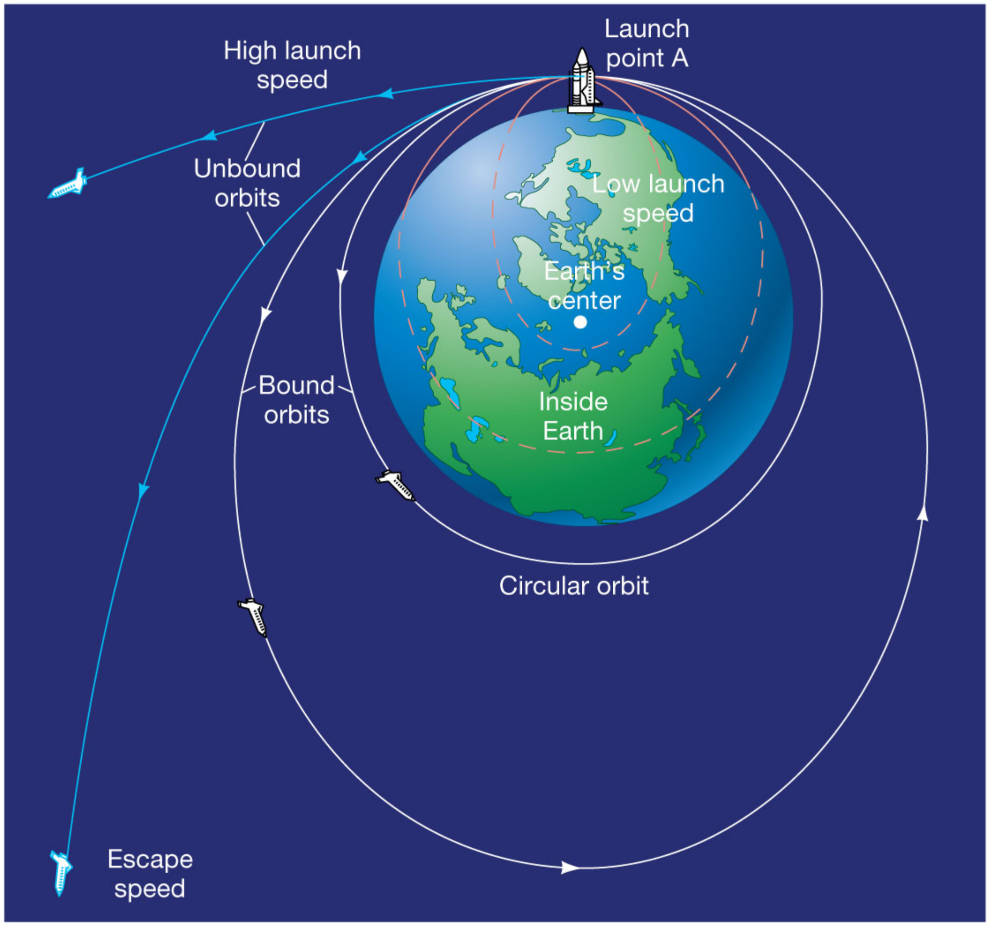
Periodic radio pulses found by graduate student Jocelyn Bell using antenna in Cambridge.

Discovery of pulsars, led to Nobel prize for Anthony Hewish in 1974.

TABLE 22.1 Properties of Stellar Remnants

Remnant	Typical mass (solar masses)	Typical radius (km)	Typical density (kg/m^3)	Support	Context (section)
brown dwarf	less than 0.08	70,000	10^5	electron degeneracy	H fusion never started (19.3)
white dwarf	less than 1.4	10,000	10^9	electron degeneracy	stellar core after fusion stops at C/O (20.3)
black dwarf	less than 1.4	10,000	10^9	electron degeneracy	"cold" white dwarf (20.3)
neutron star	1.4–3 (approx.)	10	10^{18}	neutron degeneracy	remnant of a core collapse supernova (22.1)
black hole	more than 3	10	infinite at the center	none	remnant of a core collapse supernova with massive progenitor (22.5)

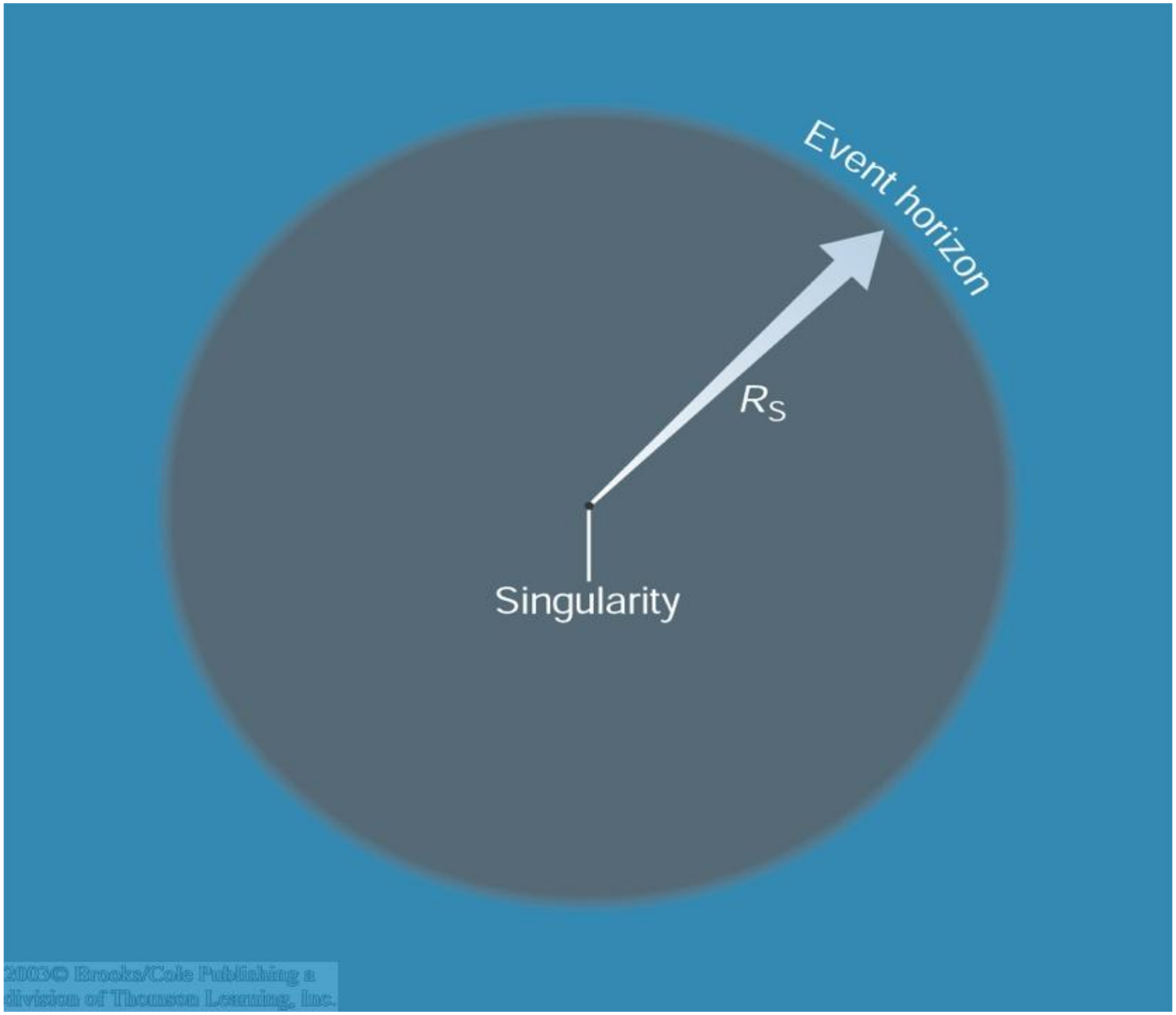
Making a black hole: at the highest densities, the escape velocity exceeds the speed of light. So if remnant's mass exceeds limit for neutron degeneracy, becomes a black hole.



$$V^2_{esc} = 2\ GM / R$$

Re-arranging the eqn for escape velocity gives the size that a mass must shrink to in order that light can not escape, the Schwarzschild radius:

$R_s = 2\ GM / \ c^2$



Example: What is the Schwarzschild radius of a 1 solar mass black hole?

$R_s = 2\ GM / \ c^2$

$2 \times 6.67 \times 10^{-11} \times 1.99 \times 10^{30} / (3 \times 10^8)^2 = 2.9 \times 10^3\ \text{m} = 2.9\ \text{km}$

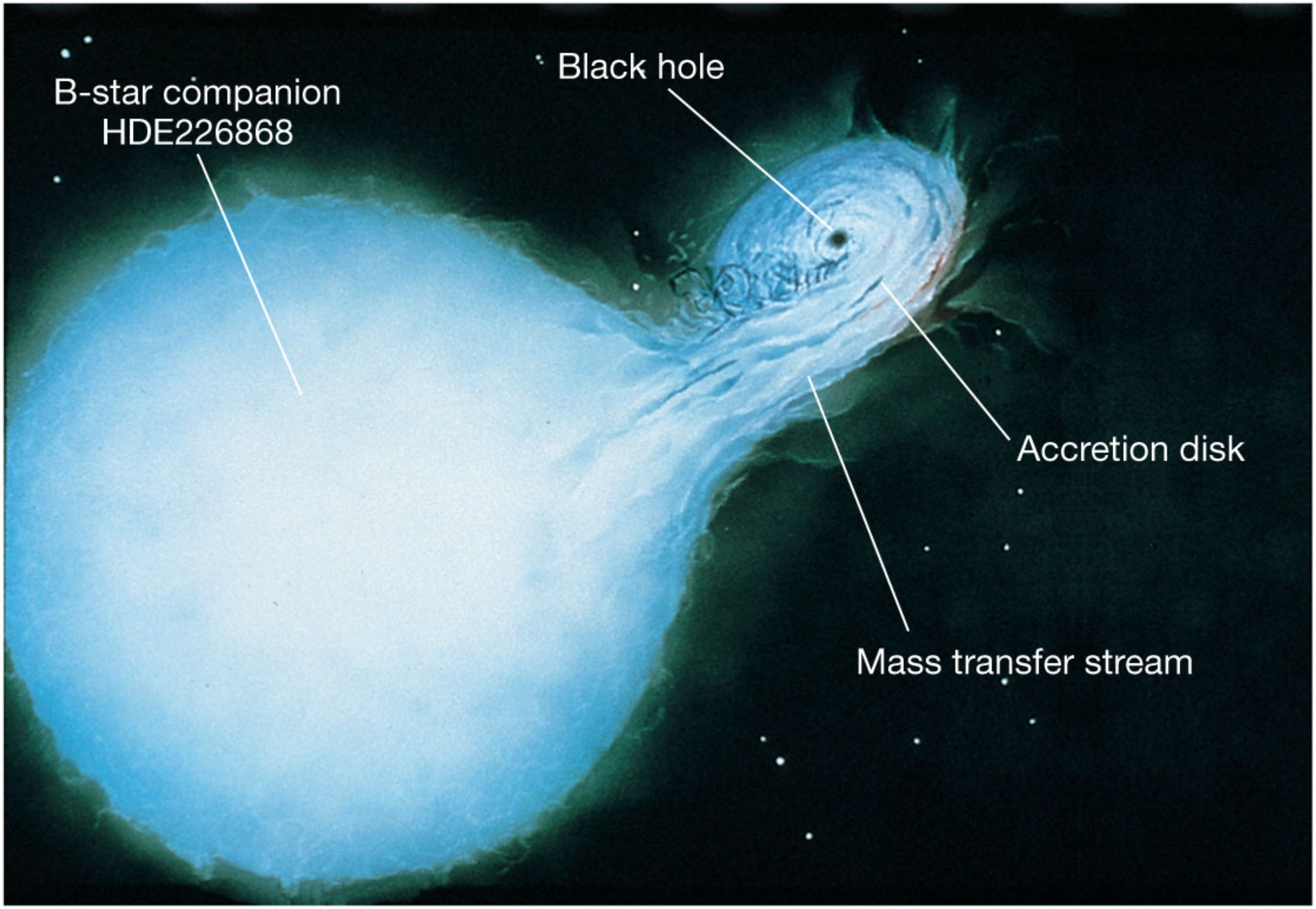
This is also the size the sun would have to shrink to to become a BH.

Example: What size would the Earth have to shrink to in order to become a black hole?

$R_s = 2\ GM / \ c^2$

$2 \times 6.67 \times 10^{-11} \times 6 \times 10^{24} / (3 \times 10^8)^2 = 0.009\ \text{m} = 0.9\ \text{cm}$

How to find a (stellar mass) black hole?

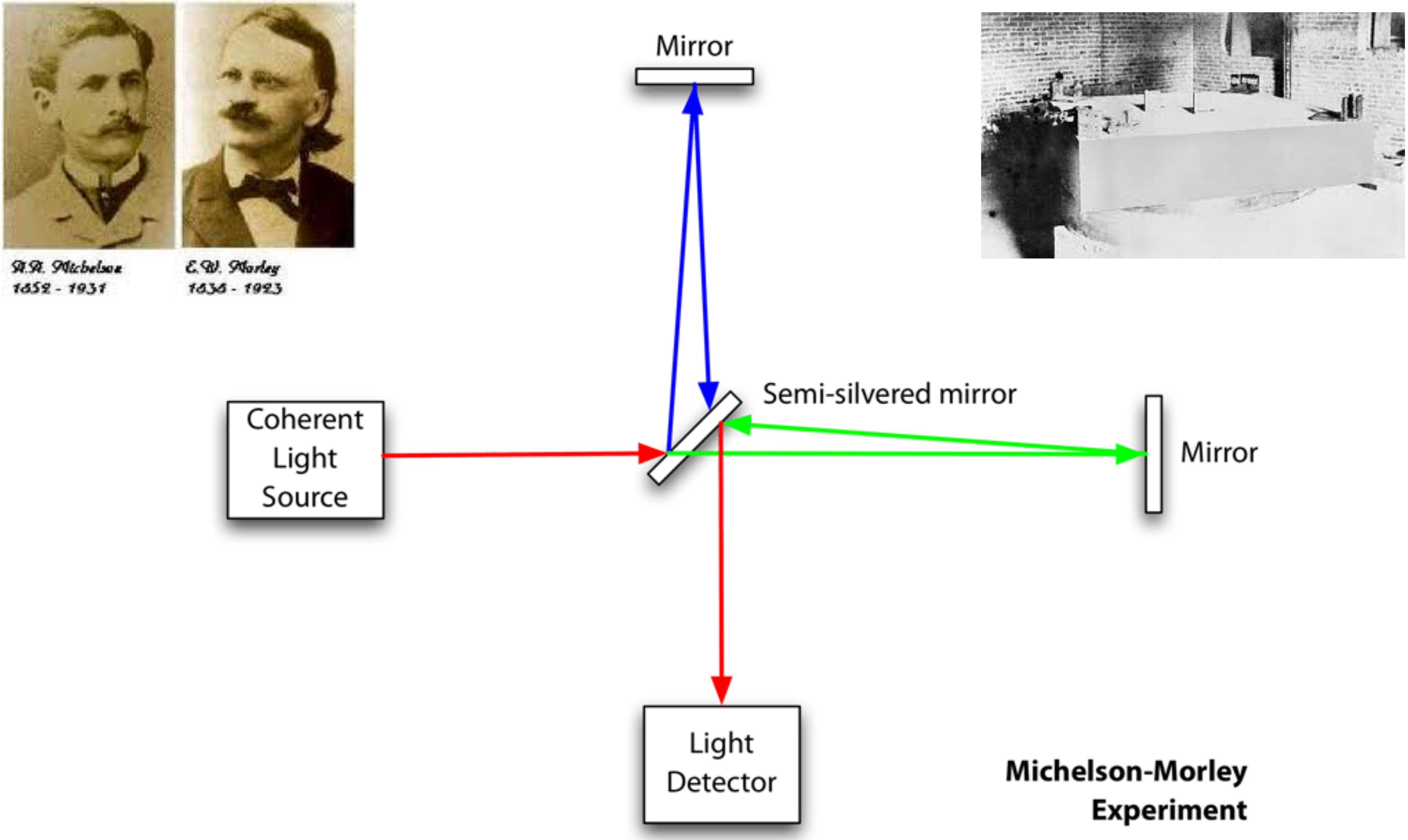


In order to really understand black holes, we need to know a little bit about Einstein's theories of relativity.

Einstein's theory of special relativity: tells us about motion at near light speed

Einstein's theory of general relativity: tells us about gravity near large masses

A constant speed of light: The Michelson Morley Experiment (1887)



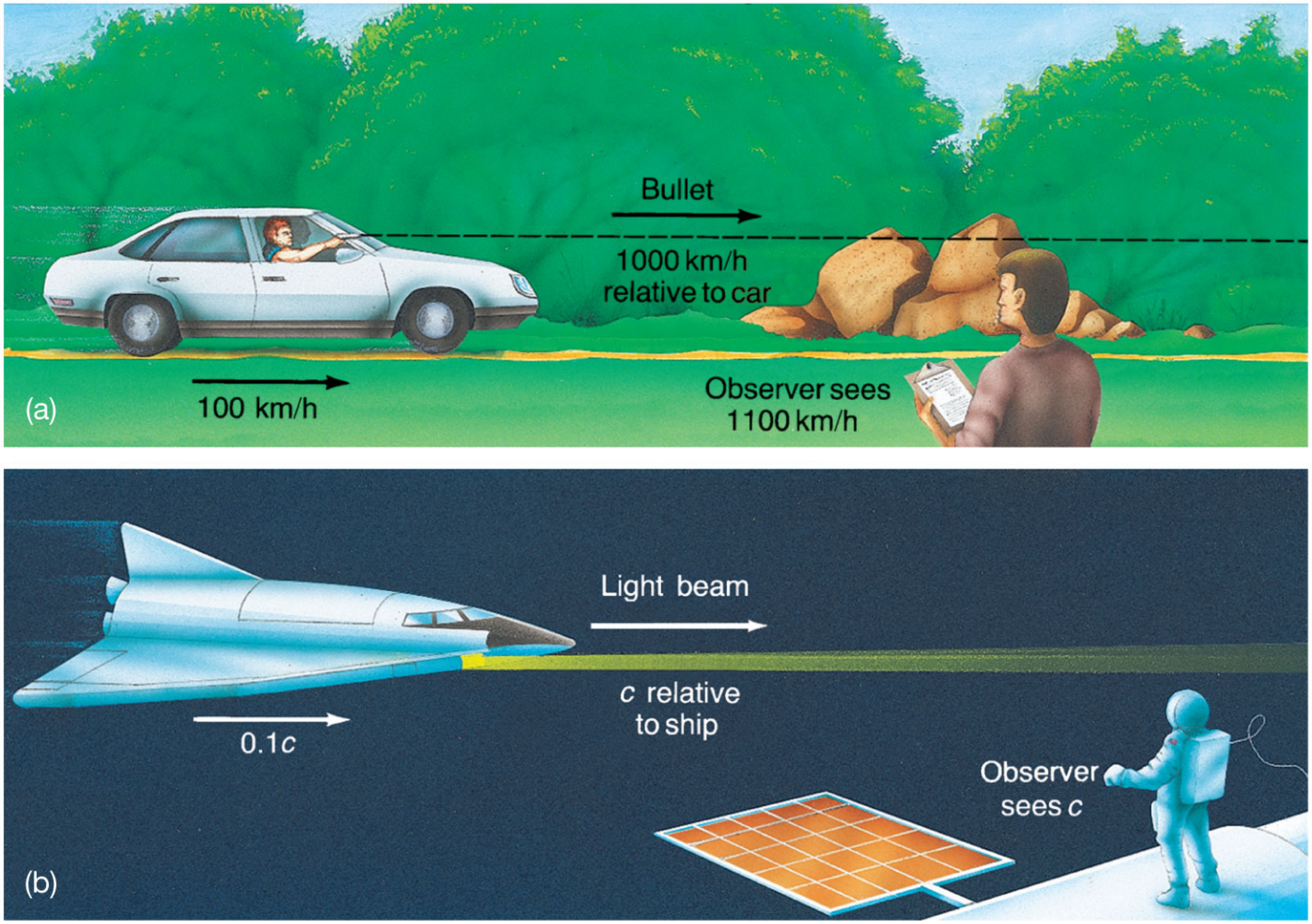
A.A. Michelson
1852 - 1931

E.W. Morley
1838 - 1923

Michelson-Morley Experiment

Light beams sent in different directions did not interfere, so they had not been slowed due to relative motion in the putative ether.

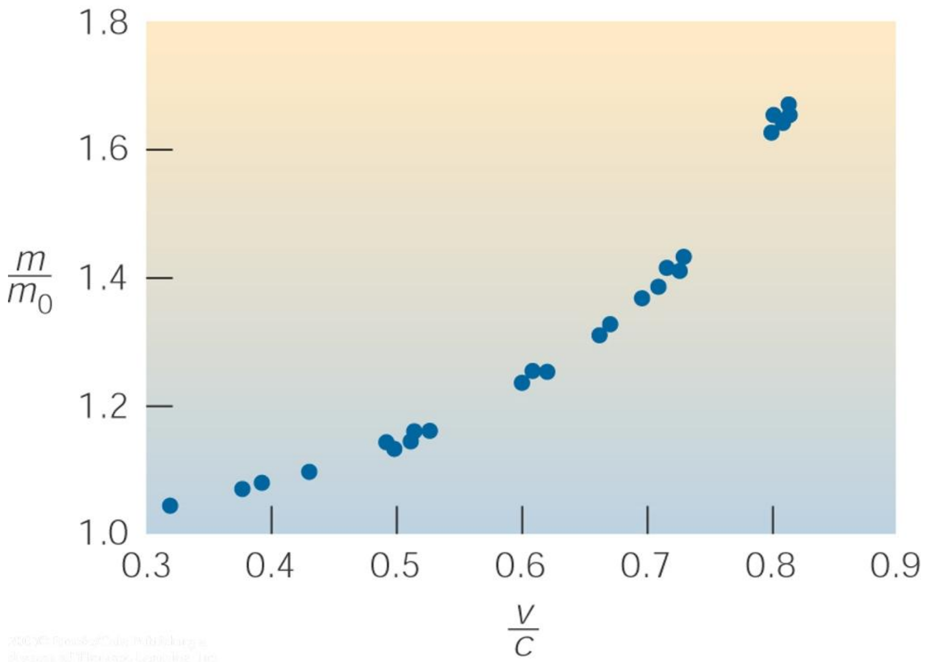
Unlike everyday objects, light has a fixed speed, regardless of the speed of its source, or observer.



1905: Einstein publishes special theory of relativity that extends the laws of physics to the “relativistic” regime where velocities approach c.

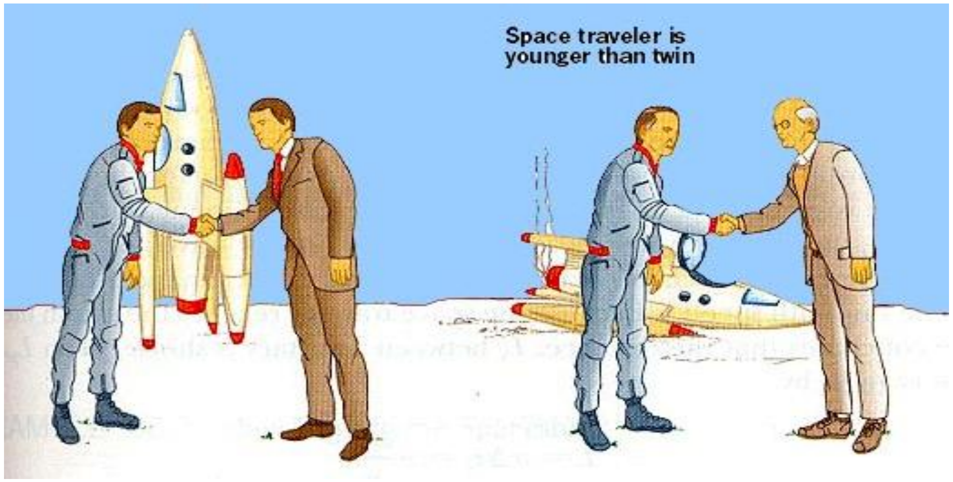
Some Weird Predictions of Special Relativity

The faster an object moves....



1) The heavier it becomes

2) The slower time travels



3) The shorter things become

Why time seems to travel more slowly…

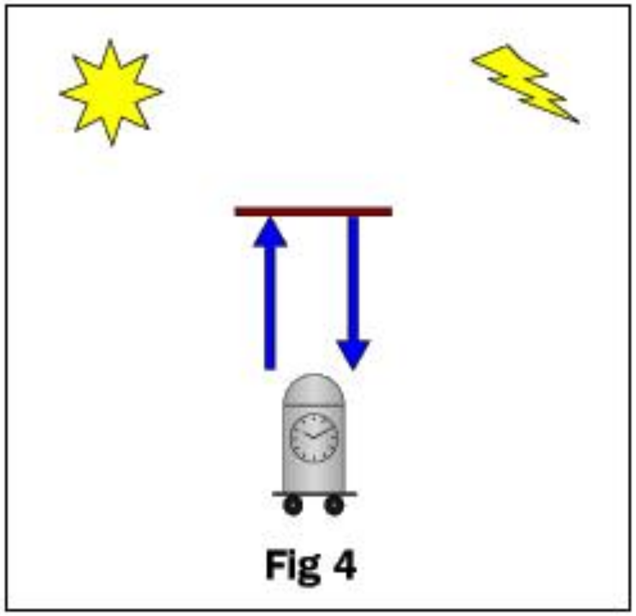


Fig 4

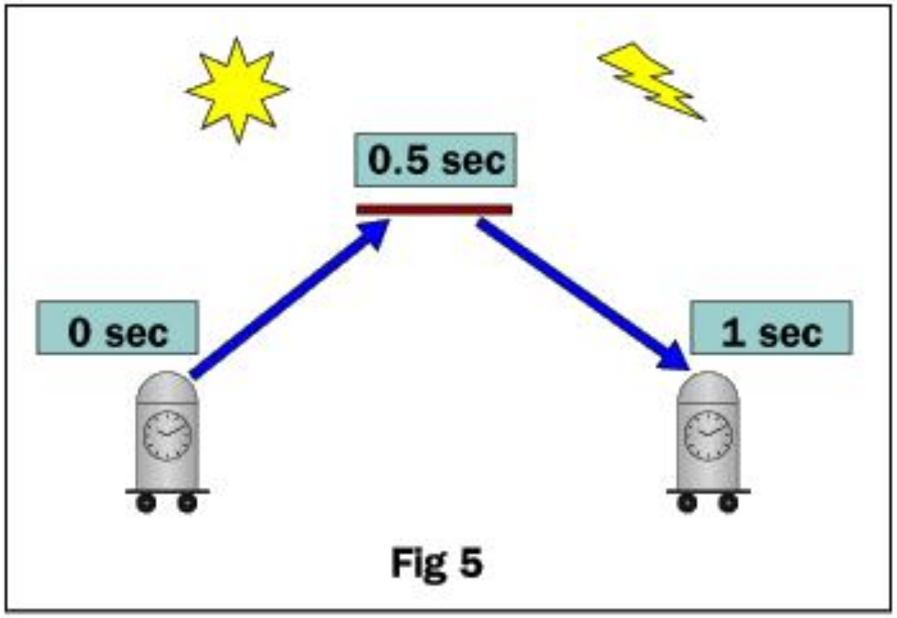
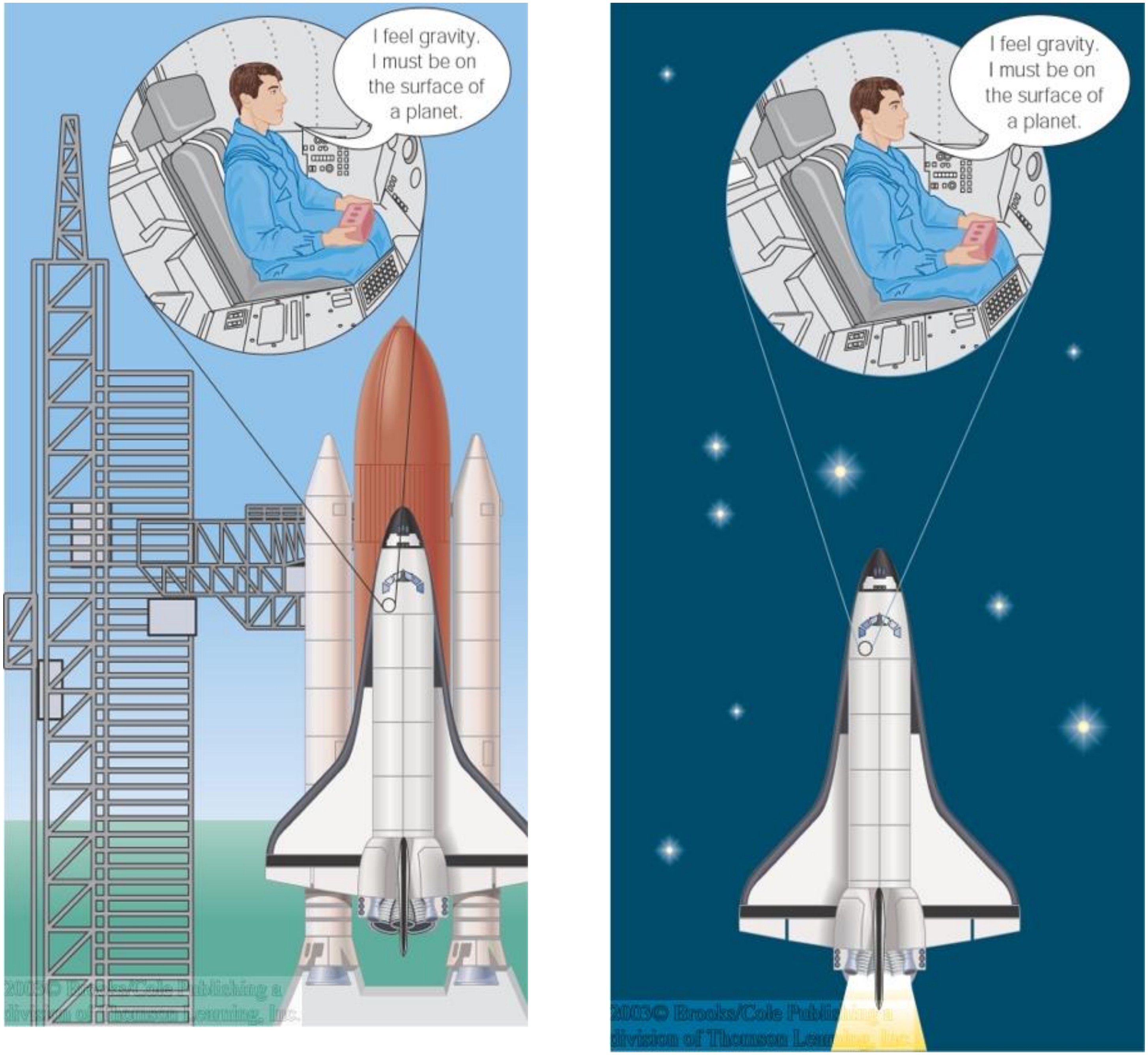
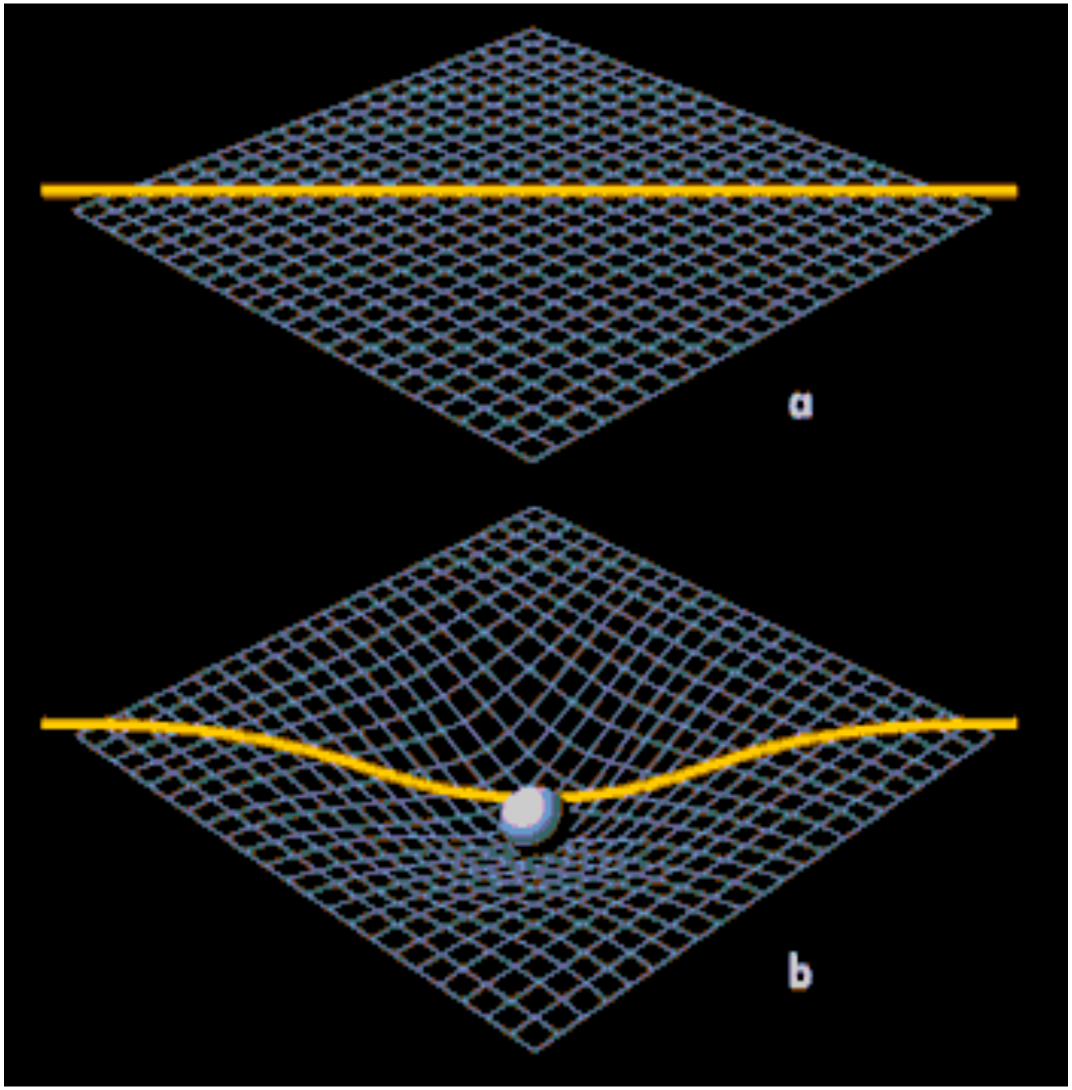


Fig 5

The General Theory of Relativity - the equivalence principle

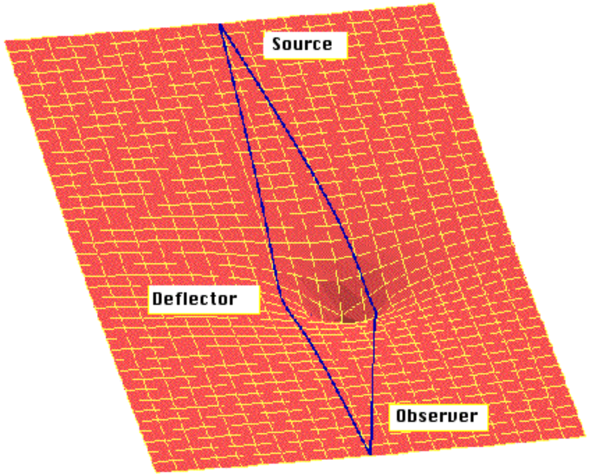


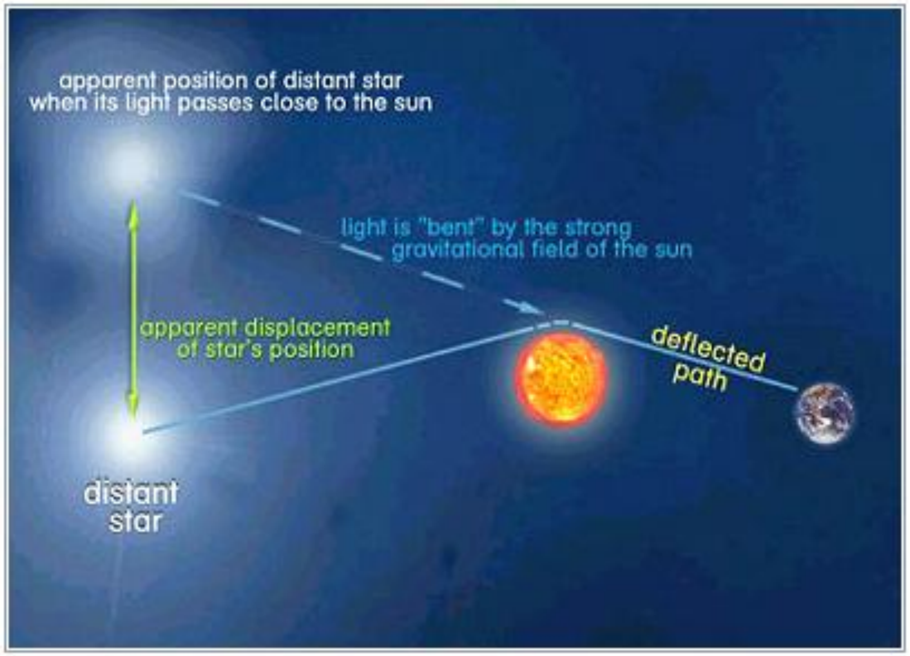
Mass tells space-time how to curve, and the curvature tells mass how to move and accelerate.

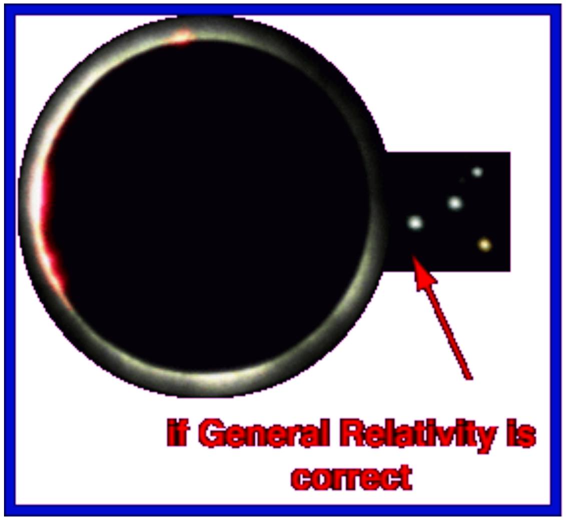


The 3 Tests of General Relativity

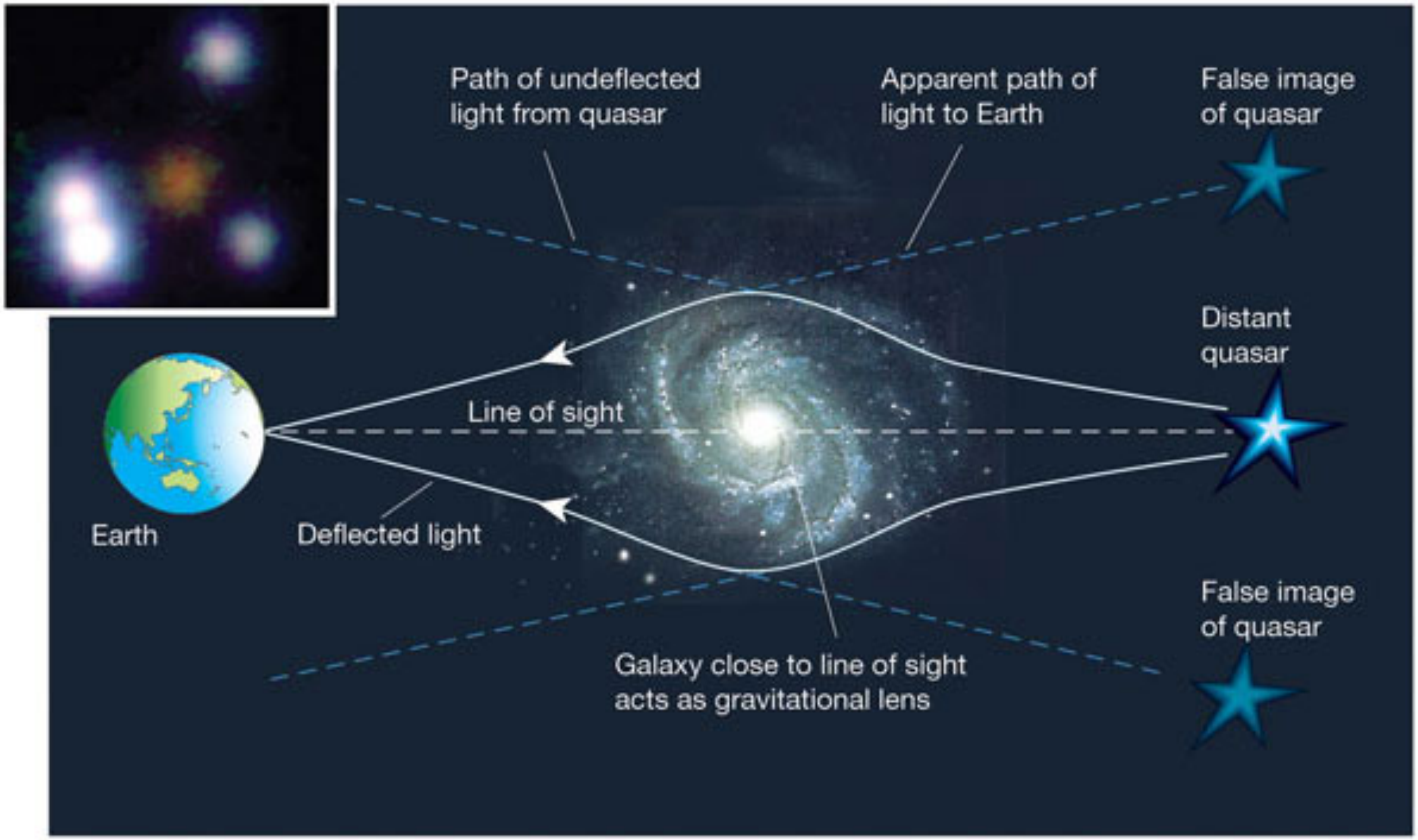
1) Bending of starlight: gravitational lensing.



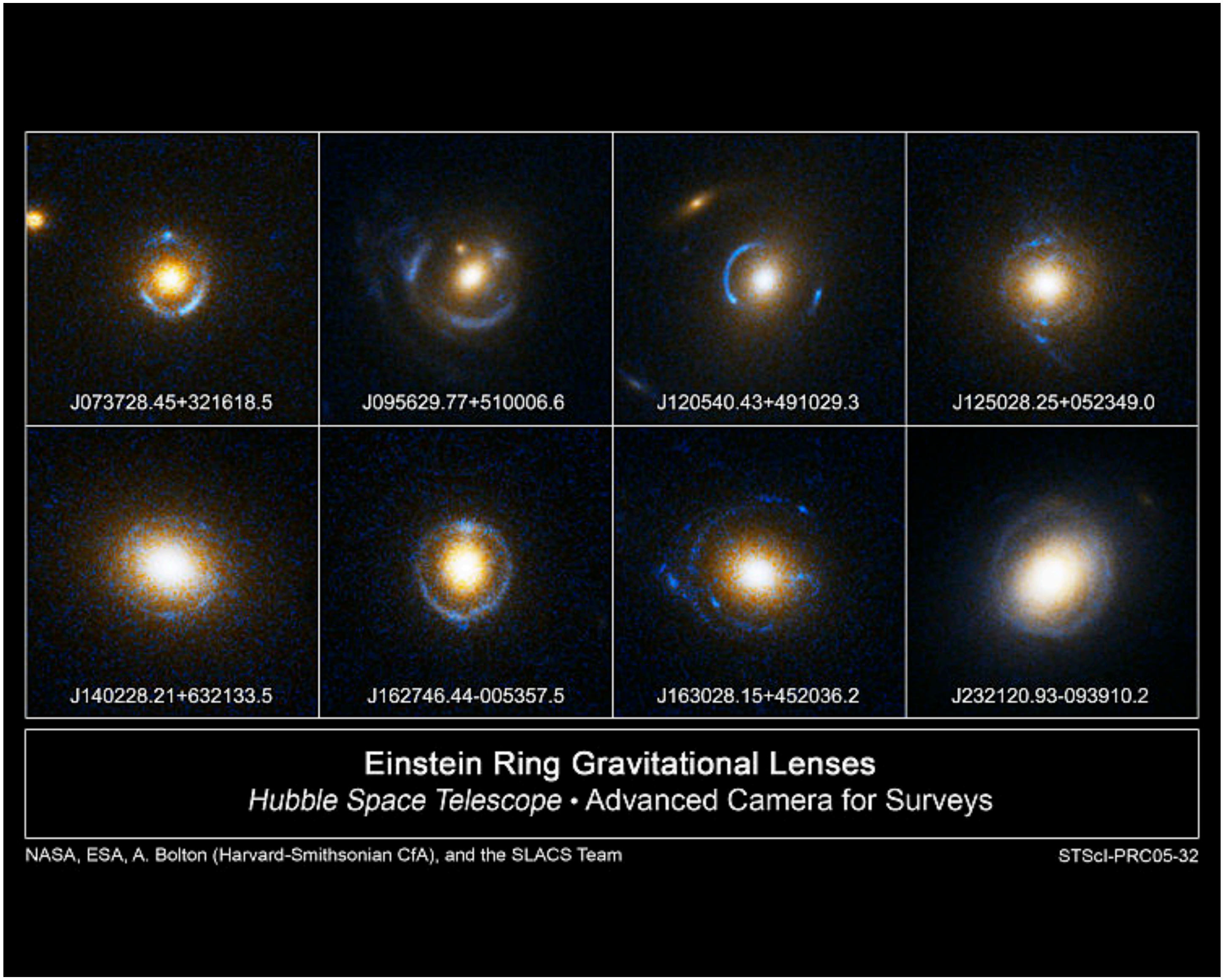




More spectacular….
Lensing of a distant quasar/galaxy by an intervening galaxy



Einstein rings occur when the background object is well aligned with the foreground lens. Misalignments lead to multiple images.



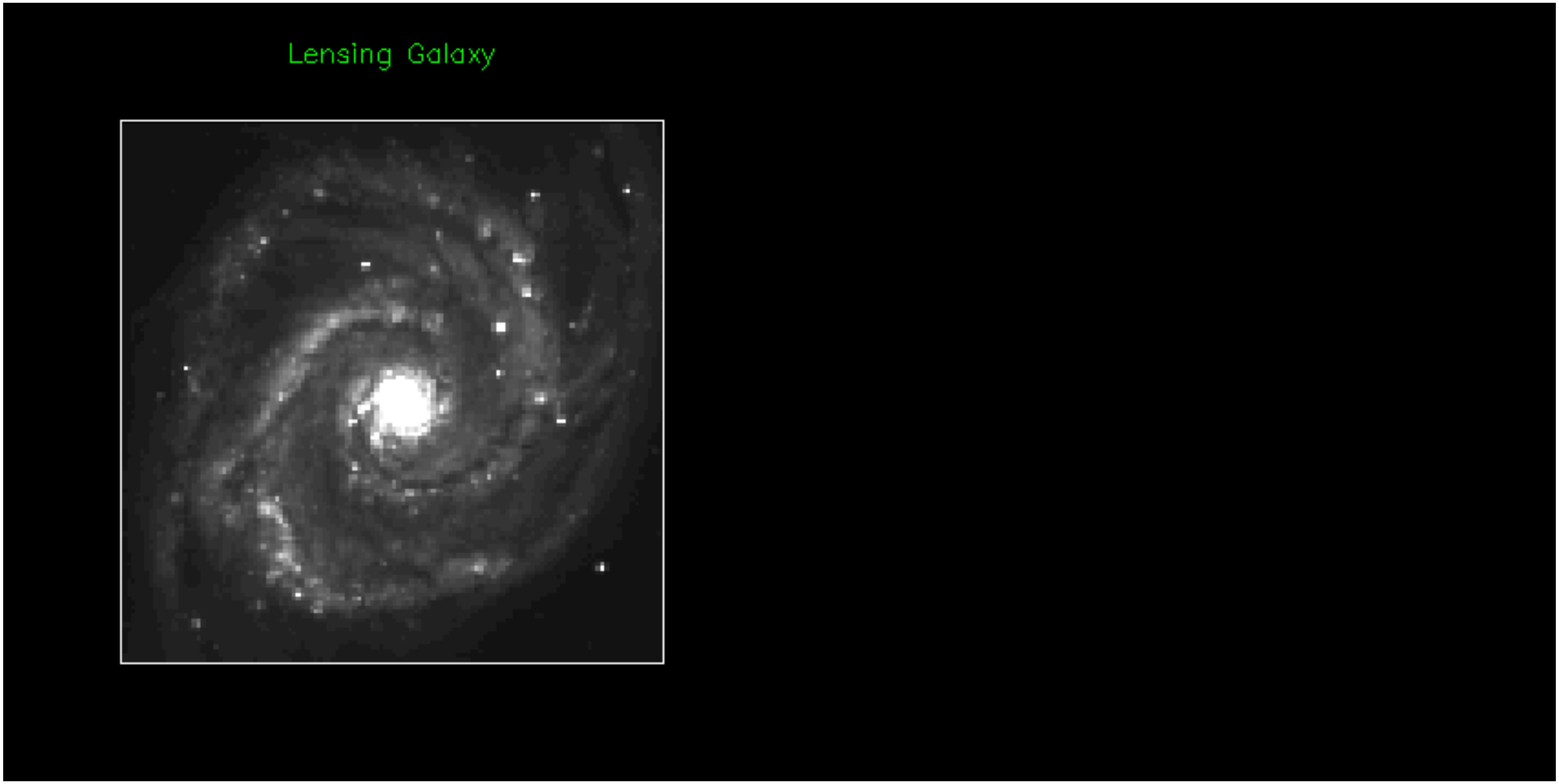
Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

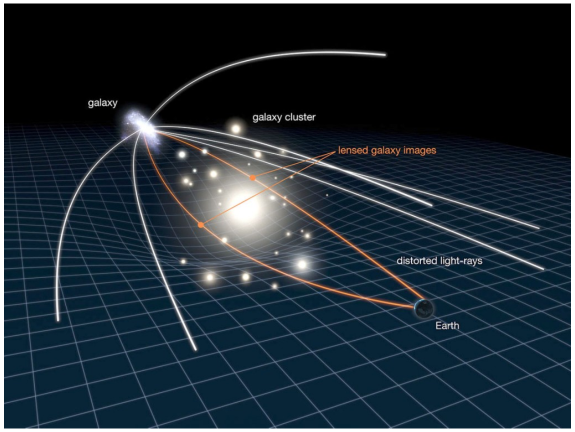
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

Animation (artificially) dims the visible light from the galaxy and then shows how a background object would be gravitationally lensed at different positions behind the galaxy.



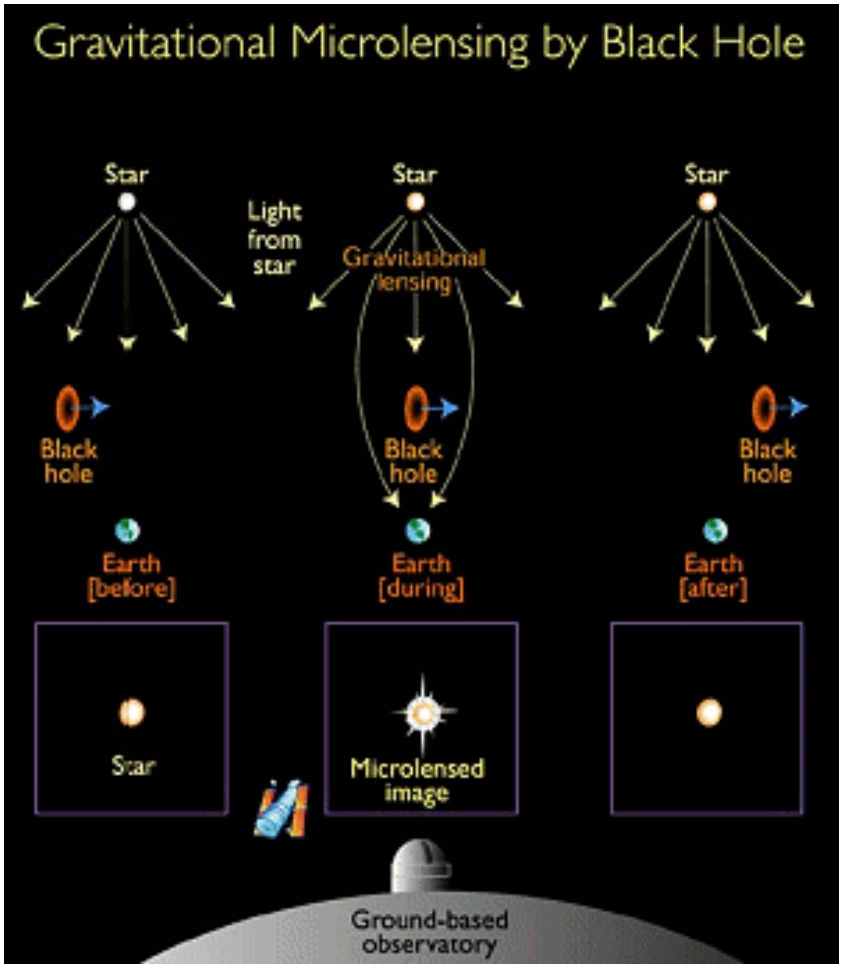
Even more spectacular….
Lensing by a massive cluster



Multiple images of background galaxies:

Gravitational lensing: some modern applications.

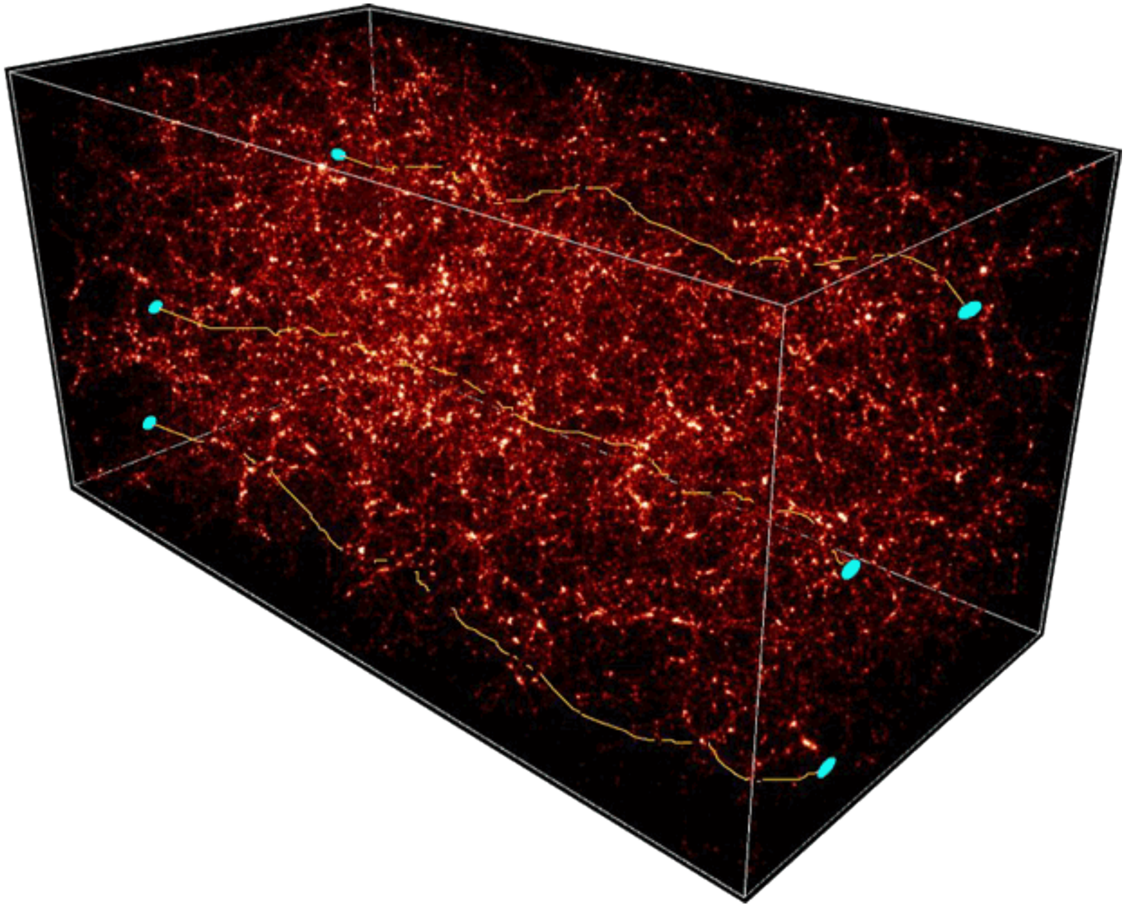
Microlensing: transient events due to stellar mass objects in Galactic halo.

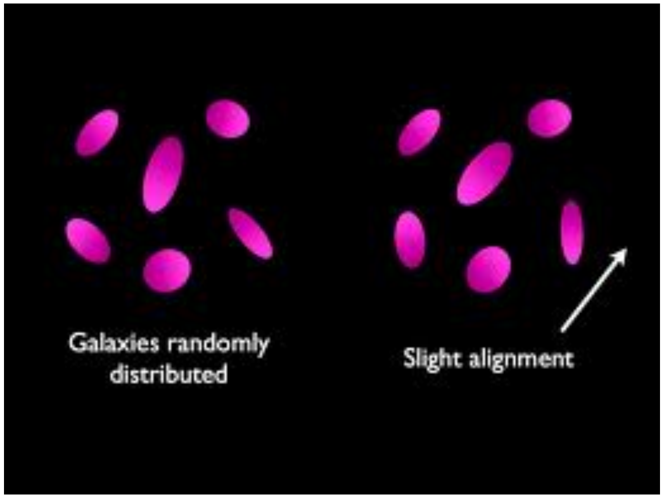


Microlensing helped to rule out dark stellar and sub-stellar mass objects (MACHOs: Massive Compact Halo Object) as significant sources of dark matter in the Milky Way

Gravitational lensing: some modern applications.

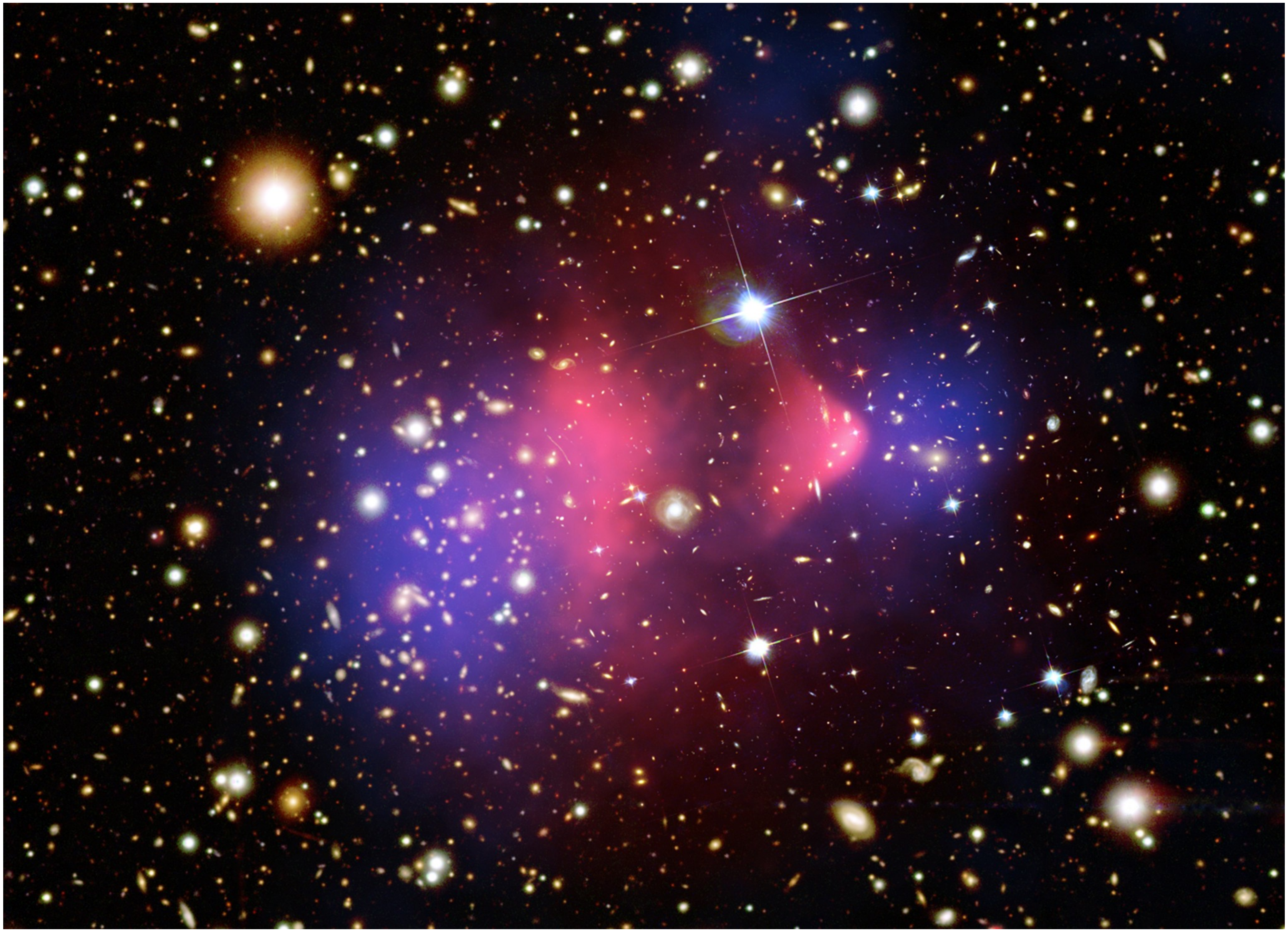
Weak gravitational lensing: measuring dark matter and energy.



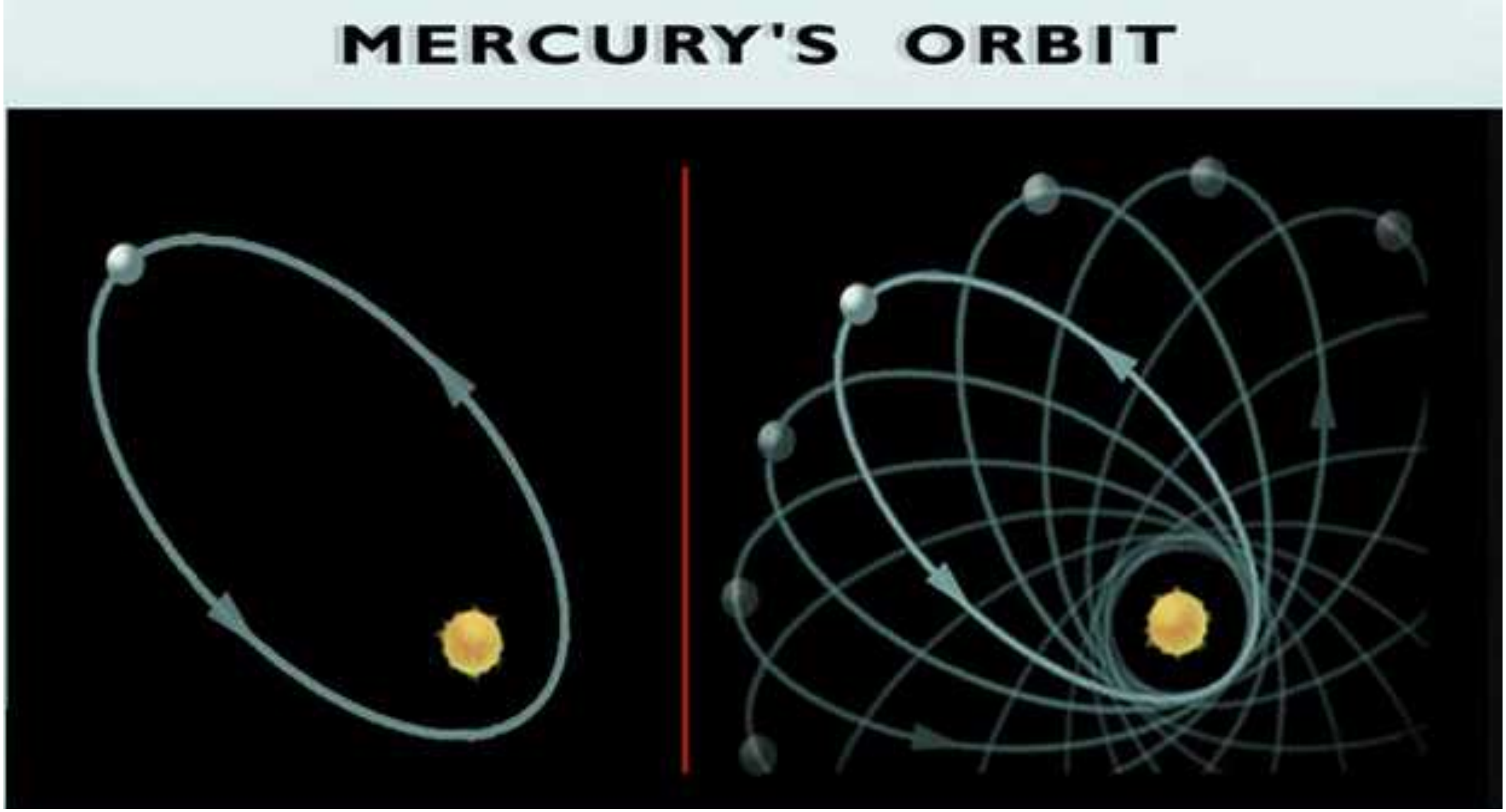


Gravitational lensing: some modern applications.

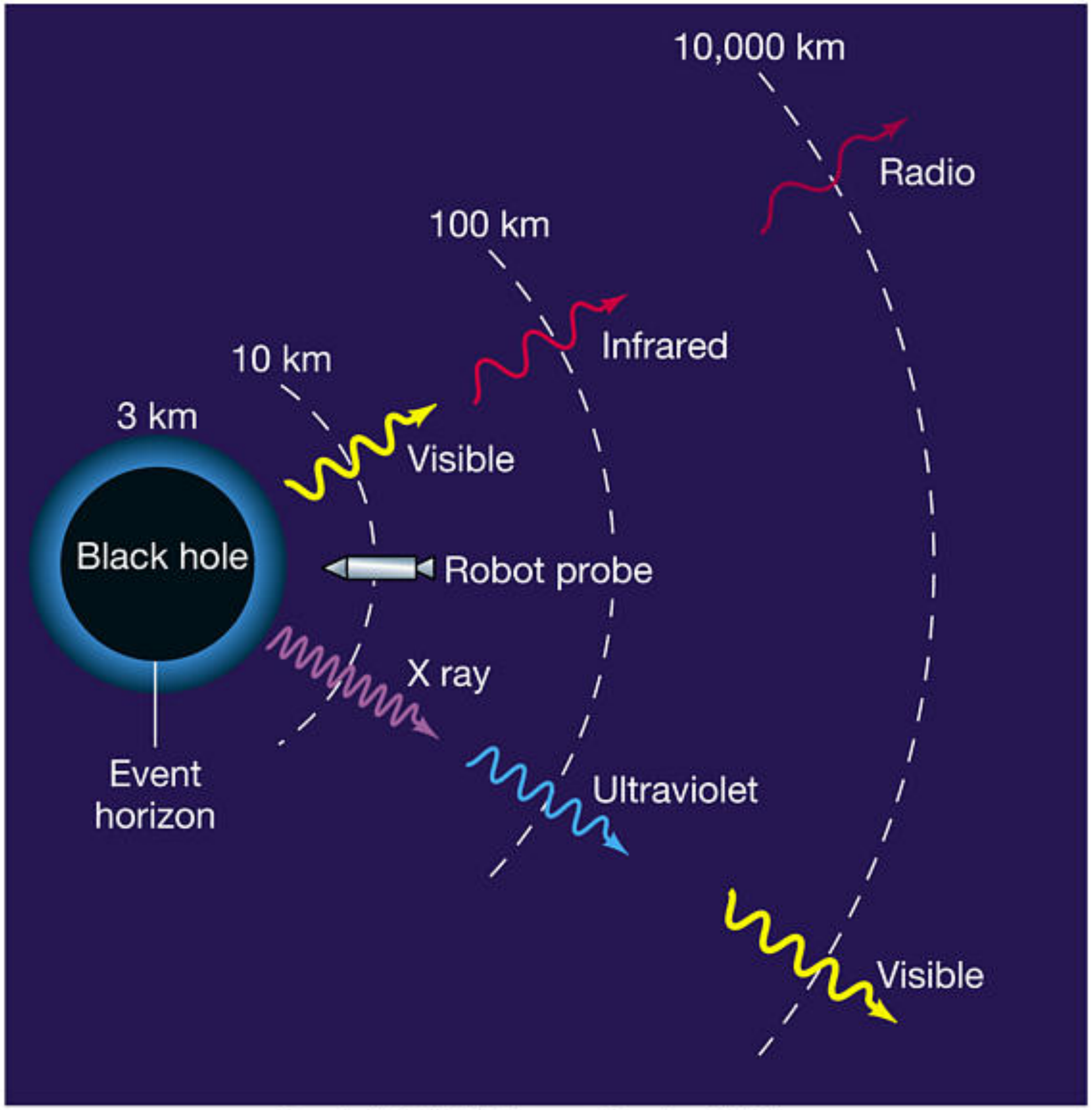
Bullet cluster: two galaxy clusters in collision and evidence of dark matter

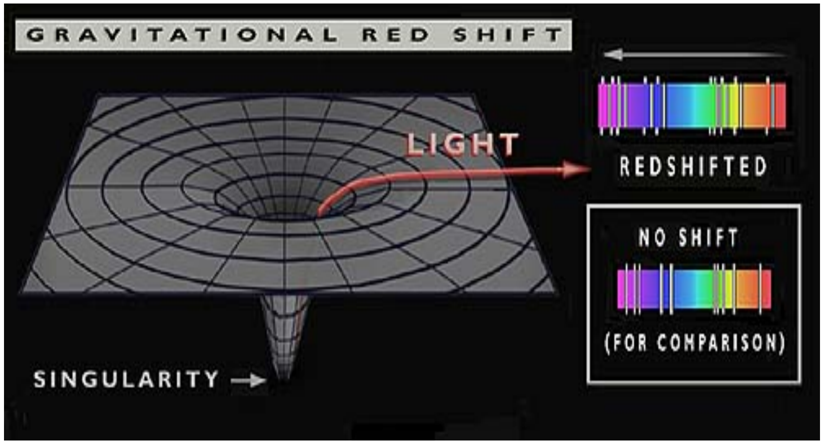


2) The precession of the perihelion of Mercury. That is, the drifting of Mercury's closest approach to the sun.



3) Gravitational redshift. Do not confuse this with cosmological redshift!!

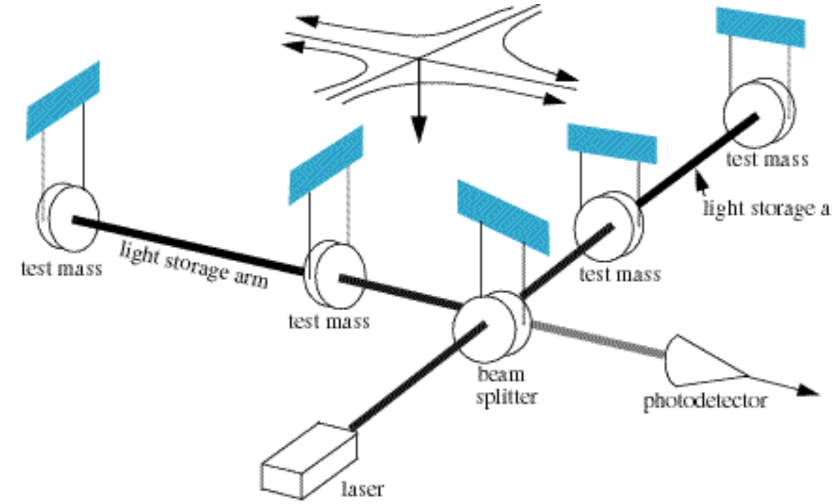


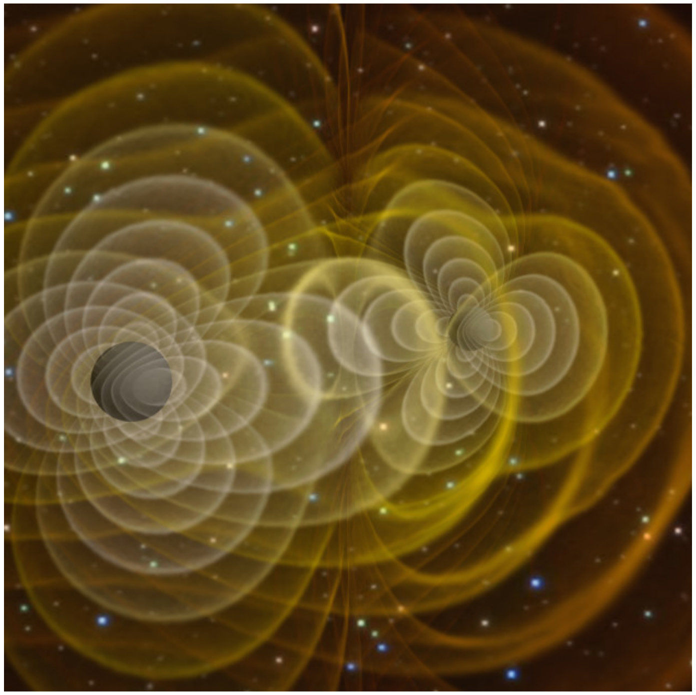


Towards a complete understanding of gravity: gravity wave detectors

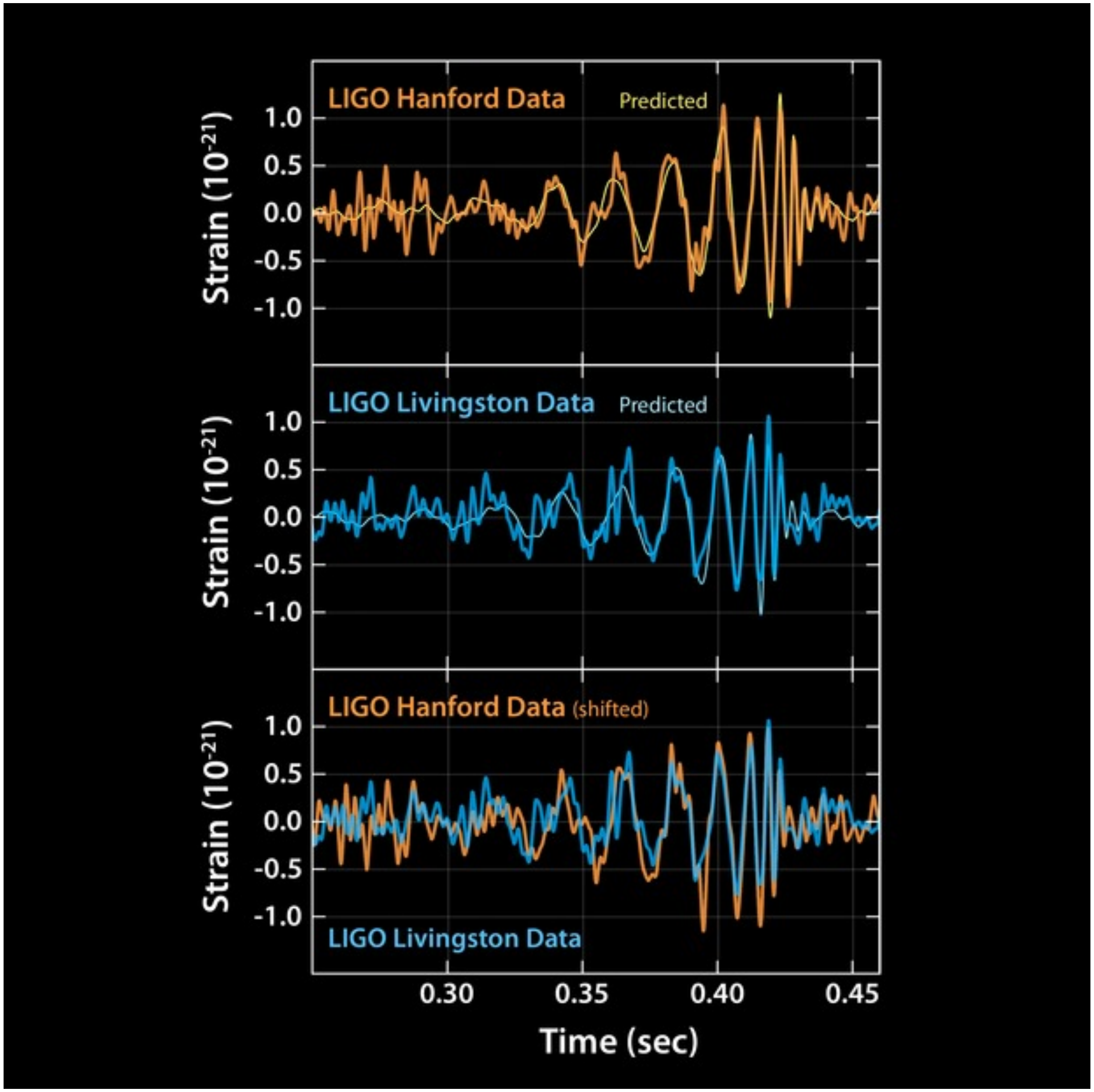
The LIGO Hanford Observatory in Washington State (left); and the LIGO Livingston Observatory (right) in Louisiana.

Laser Interferometric Gravity Wave Observatory (LIGO), twin observatories for triangulation/ confirmation.





Feb 11 2016: LIGO detection of black hole merger.



Black holes weighed in at 29 and 36 solar masses.