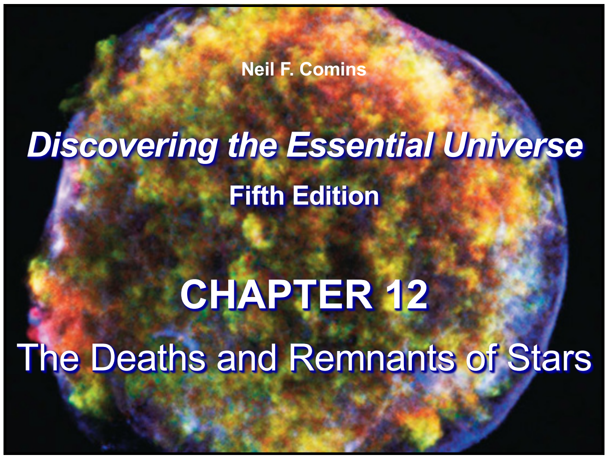


1

Evolution of low-mass stars M=0.08 to 0.4 M_{sol}

- Called red dwarfs
- All H is fused into He
- Convection
- Life time > trillion years
- Most common type of stars (85%)

4

Intermediate mass stars M=0.4 to 8 M_{sol}

- Our sun is an intermediate mass star
- 4H➔ He +γ+ν
- 3He➔ C +γ,
- C+He➔O +γ

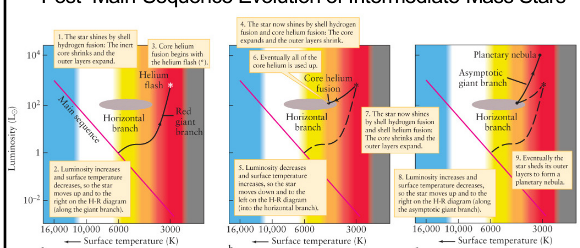
5

High-mass stars M=8 to ~50 M_{sol}

- Fusion till Fe is produced
- Core contraction, bounce, explosion as a supernova

6

Post–Main-Sequence Evolution of Intermediate-Mass Stars



(a) A typical evolutionary track on the H-R diagram as a star makes the transition from the main sequence to the giant phase. The asterisk (*) shows the helium flash occurring in a low-mass star. (b) After the helium flash, the star converts its helium core into carbon and oxygen. While doing so, its core re-expands, decreasing shell fusion. As a result, the star's outer layers recontract. (c) After the helium core is completely transformed into carbon and oxygen, the core recollapses, and the outer layers re-expand, powered up the asymptotic giant branch by hydrogen shell fusion and helium shell fusion.

7

Electron degeneracy pressure

- The He-rich core of a low-mass giant is supported by electron degeneracy pressure. It is based on the:
- Pauli exclusion principle: Two identical particles cannot exist at the same place at the same time
- Electron degenerate pressure does not change with temperature

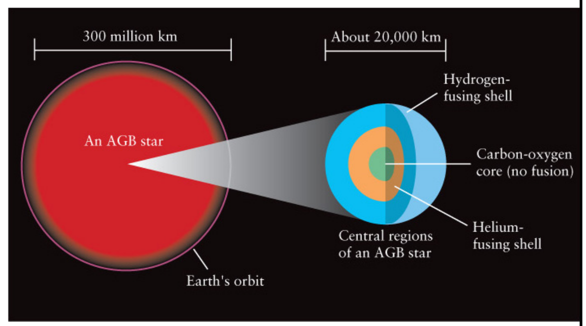
8

Helium flash

- Helium flash: He fusion at 100 Mill K.
- T increases but pressure constant.
- Fusion reactions on runaway for few hours.
- Luminosity increases enormously.
- When 350 Mill K is reached, He not degenerate anymore. Normal safety valve in place again.

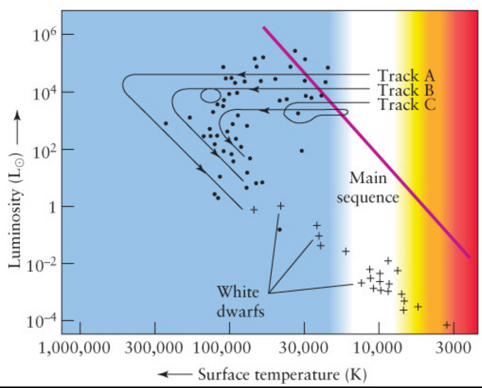
9

The Structure of an Old Intermediate-Mass Star



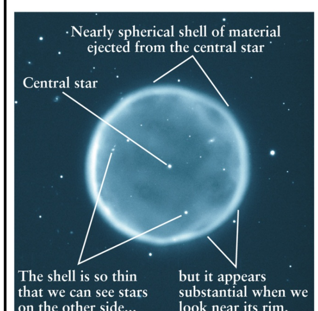
10

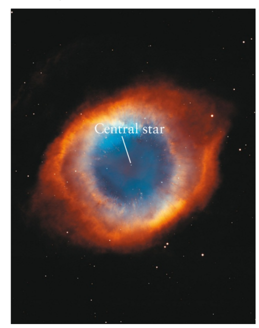
Evolution from Supergiants to White Dwarfs



11

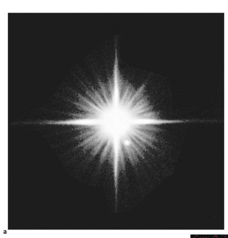
Some Shapes of Planetary Nebulae



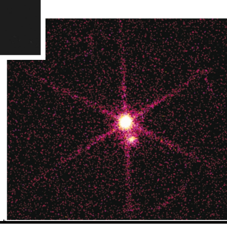


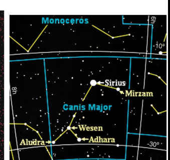
12

Sirius and Its White Dwarf Companion



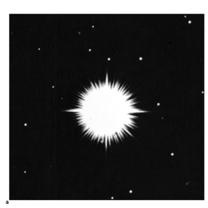
Since Sirius A (11,000 K) and Sirius B (30,000 K) are hot blackbodies, they are strong emitters of X rays.

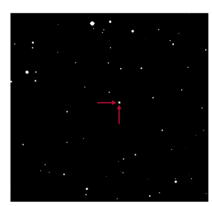




13

Nova Herculis 1934





These two pictures show a nova (a) shortly after peak brightness as a magnitude –3 star and (b) 2 months later, when it had faded to magnitude +12. Novae are named after the constellation and year in which they appear.

14

Two principally different kinds of SNe

- **Type Ia supernovae**

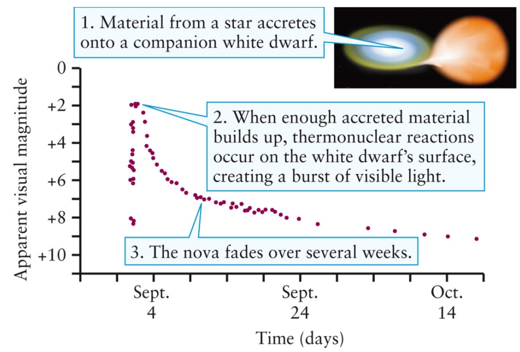
Thermonuclear detonation of a white dwarf (WD) in a binary system

1) WD accretes material from sun-like or giant companion, reaches Chandrasekhar M_{sol} and detonates

2) WD cannibalizes second WD and detonates

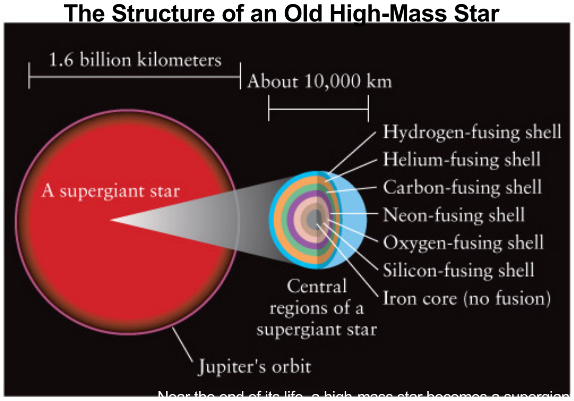
15

The Light Curve of a Nova



16

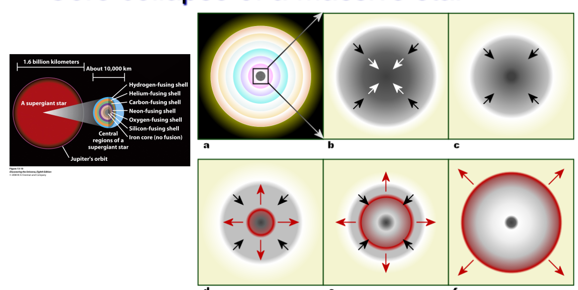
The Structure of an Old High-Mass Star



17

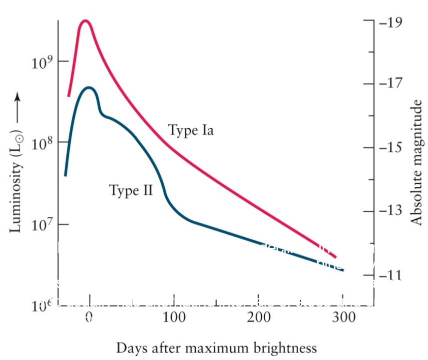
2) Type II supernovae and other types (core collapse of a massive star)

- **Core collapse of a massive star**



18

Supernova Light Curves



19

Mass Loss by a Supermassive Star

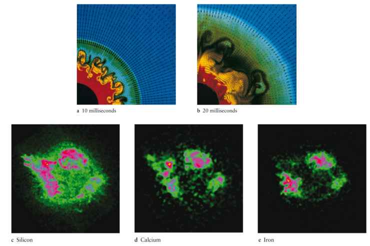
20

TABLE 11-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Central temperature (K)	Central density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	5×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	1×10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	0.2 second
Core bounce	2.3×10^{10}	4×10^{17}	milliseconds
Supernova explosion	about 10^9	varies	hours

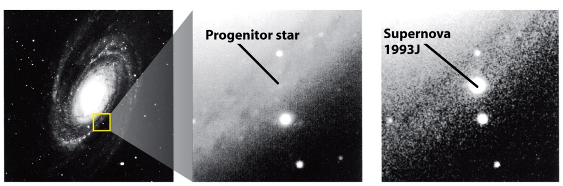
21

Supernovae Proceed Irregularly



Images (a) and (b) are computer simulations showing the chaotic flow of gas deep inside the star as it begins to explode as a supernova. This uneven flow helps account for the globs of iron and other heavy elements emitted from deep inside, as well as the lopsided distribution of all elements in the supernova remnant, as shown in (c), (d), and (e). These three pictures are X-ray images of supernova remnant Cassiopeia A taken by *Chandra* at different wavelengths.

22



(a) Spiral galaxy M81 (b) Before the explosion (c) After the explosion

Figure 20-16
Universe, Eighth Edition

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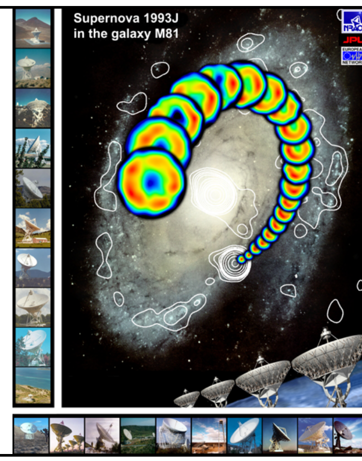
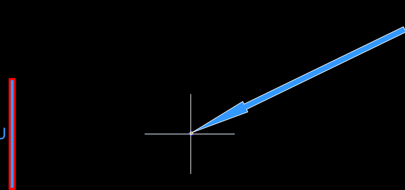


24

Movie of SN1993J



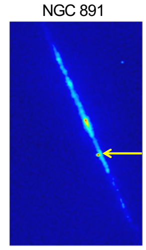
from t = 50d (r=200 AU) to t = 22 yr (r=40,000 AU)

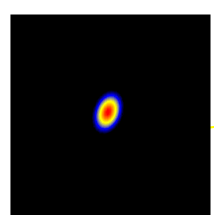
Free download: www.yorku.ca/bartel

25

Evolution of SN1986J

NGC 891





Youngest Neutron Star or Black Hole with 200 L_{Crab}?

Or dense shell condensation?

1 mas

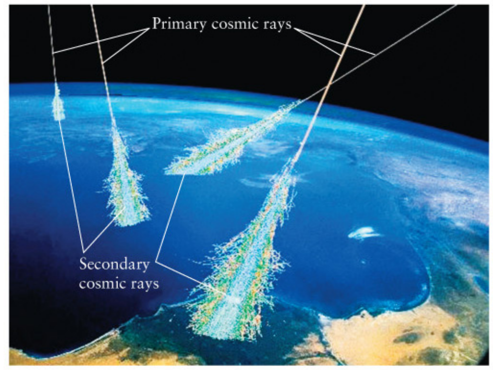
from t = 3 yr to t = 25 yr

26

The Gum Nebula

27

Cosmic Ray Shower



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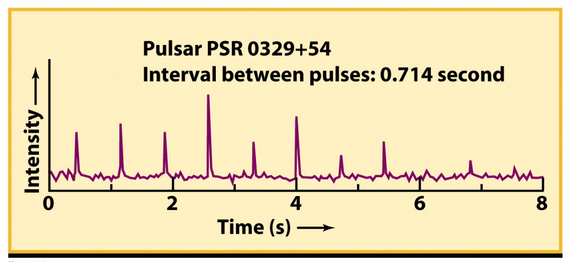


Figure 21-2
Universe, Eighth Edition

30

Why a pulsar must be a neutron star

- Radius of neutron star: 10 km
- Circumference of neutron star: ~60 km
- Fastest rotation from pulse period: 700/s
- Surface rotation speed: 42,000 km/s
- Escape velocity from WD: 1,500 km/s
- Escape velocity from NS: 150,000 km/s
- Everything less compact than a NS would disintegrate

31

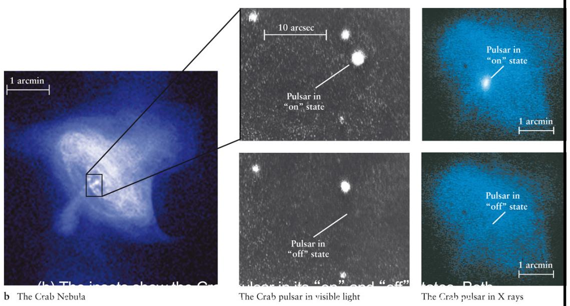
Escape velocity

- The velocity that must be acquired by a body to just escape, i.e., to have zero total energy, is called the *escape velocity*. By setting $E_k + E_p = 0$, we find:

$$v^2_{escape} = 2\,G\,m\,/\,r$$

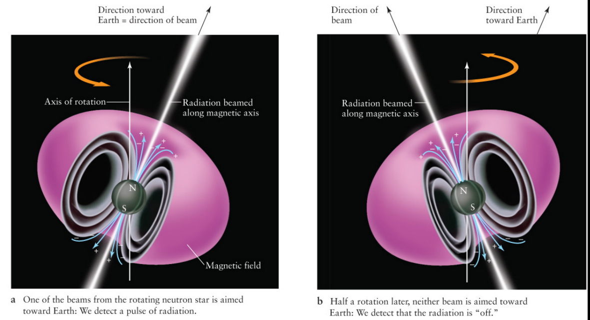
32

The Crab Nebula and Pulsar



33

A Rotating, Magnetized Neutron Star



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The relativity theories

- Special relativity (1905)
- General relativity (1916)

35

Einstein in school (~ 1892)

36

Bern with clock tower

37

38


Einstein at the Swiss Patent Office

39

1905 - Miraculous Year
"A storm broke loose in my mind"

- Einstein wrote three fundamental papers.

➡ The 1st paper claimed that light must sometimes behave like a stream of particles with discrete energies, "quanta."

➡ The 2nd paper offered an experimental test for the theory of heat. Atoms do exist!

➡ The 3rd paper addressed a central puzzle for physicists of the day – the connection between electromagnetic theory and ordinary motion – and solved it using the "principle of relativity."

40

Special Relativity

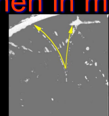
- 1905
- The laws of physics are the same for all inertial observers
- c=constant

➡ Clocks slow down when in motion

➡ Objects contract when in motion

➡ $E=mc^2$

➡ Spacetime



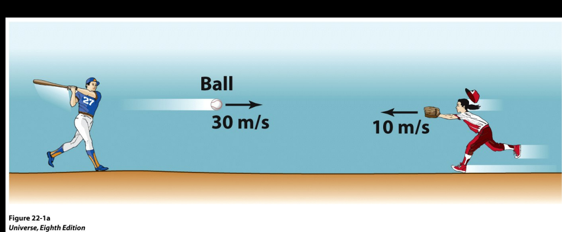
41

Einstein's list of conditions to his wife Mileva
before they separated in 1914

Mileva with Eduard and Hans Albert 1914

"You make sure ... that I receive my three meals regularly in my room.
You are neither to expect intimacy nor to reproach me in any way."

42



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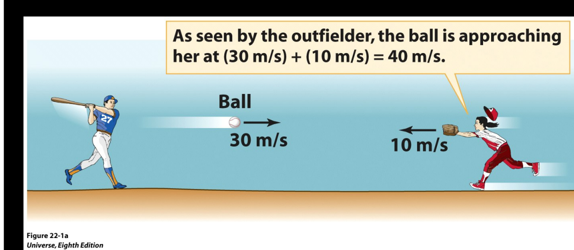

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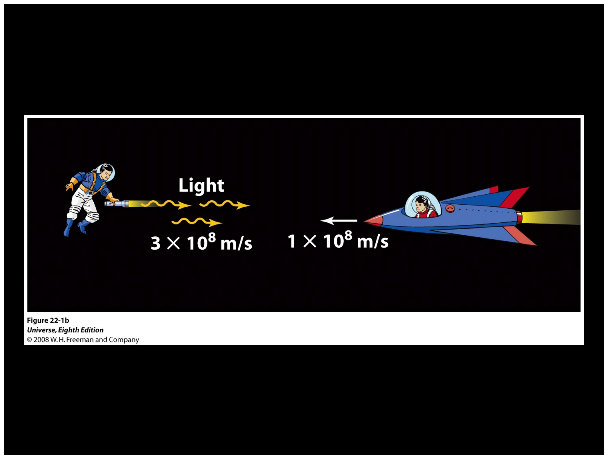

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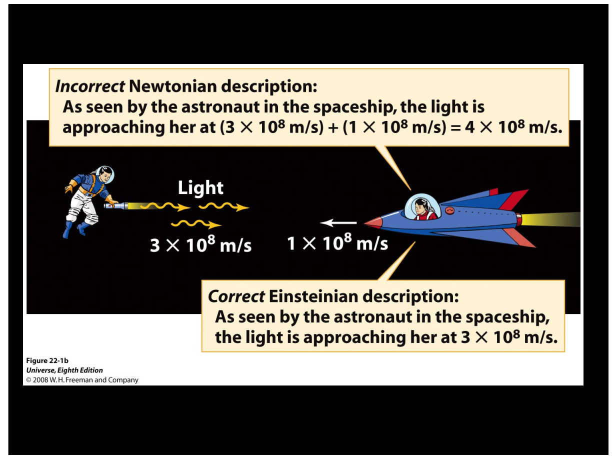

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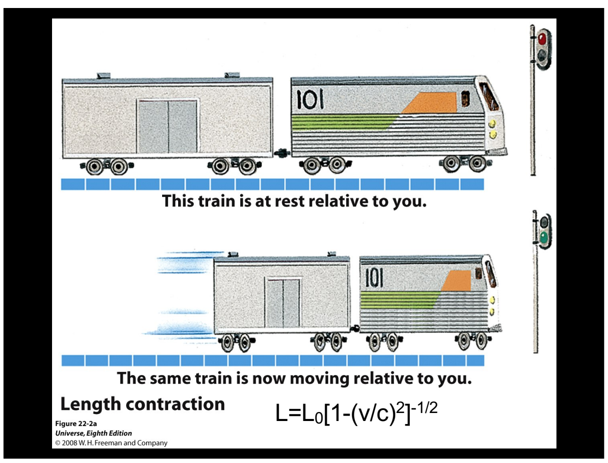

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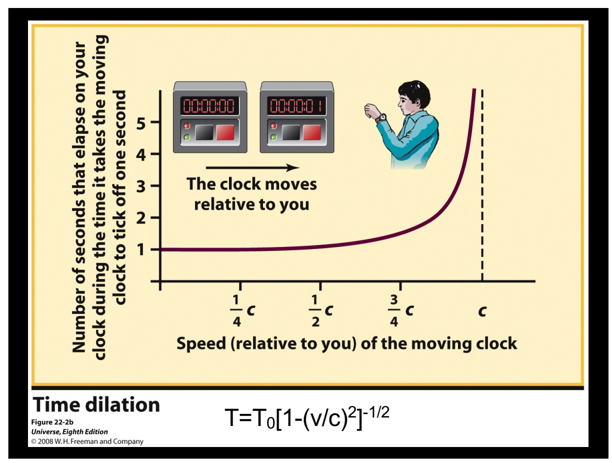

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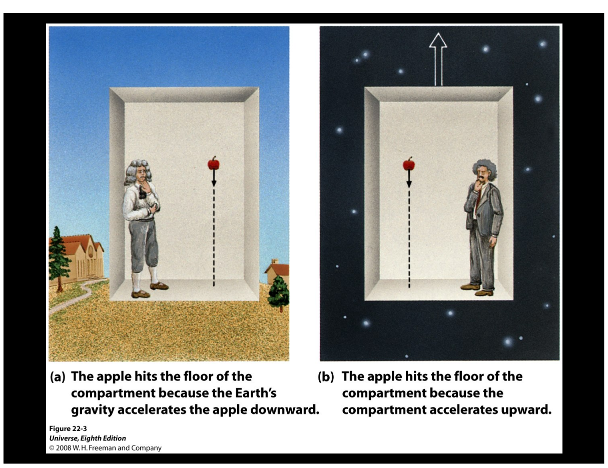

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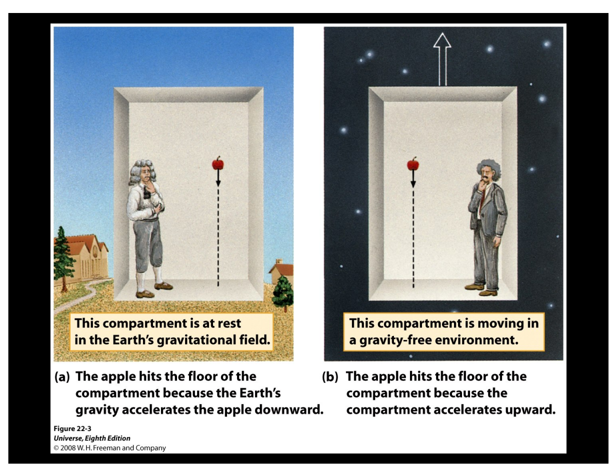

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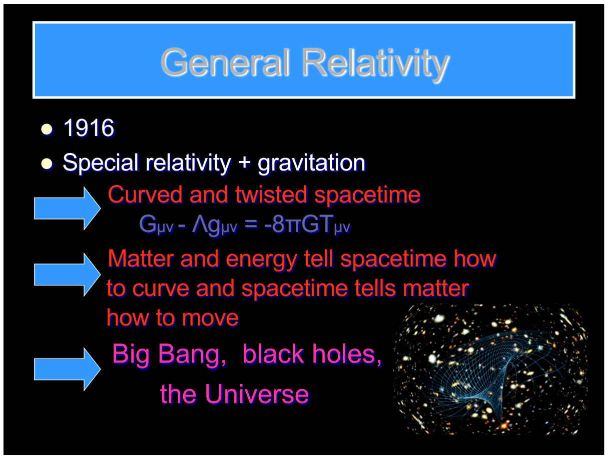

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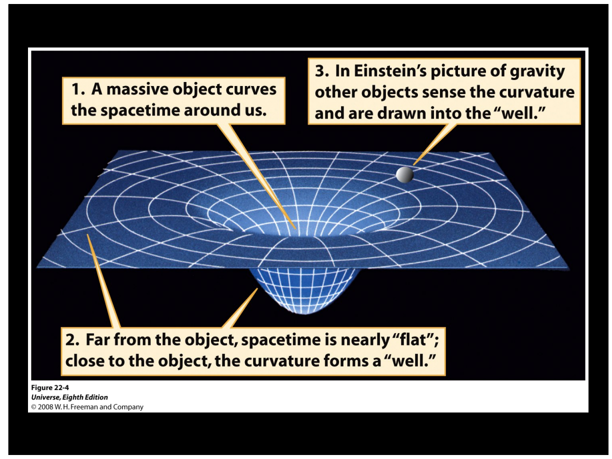

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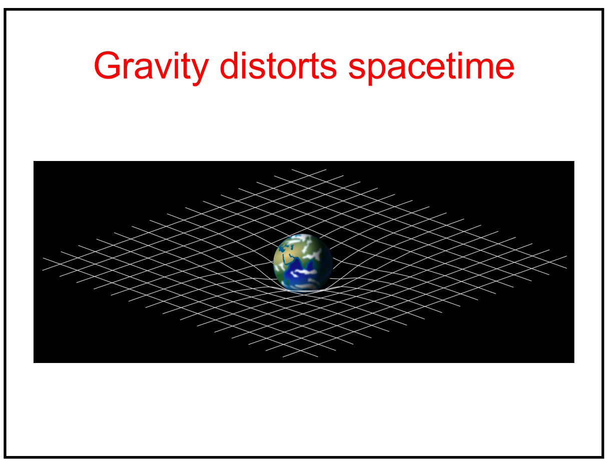

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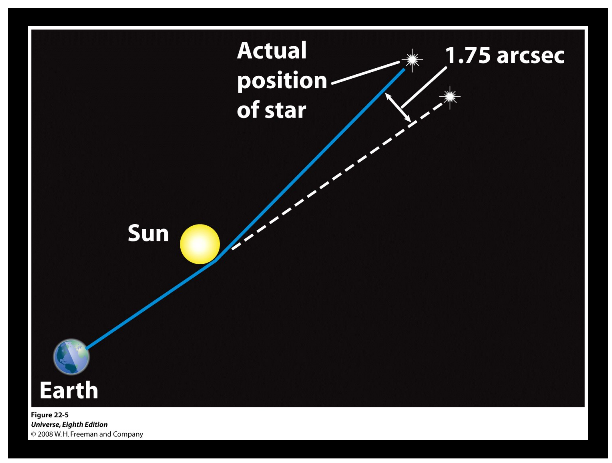

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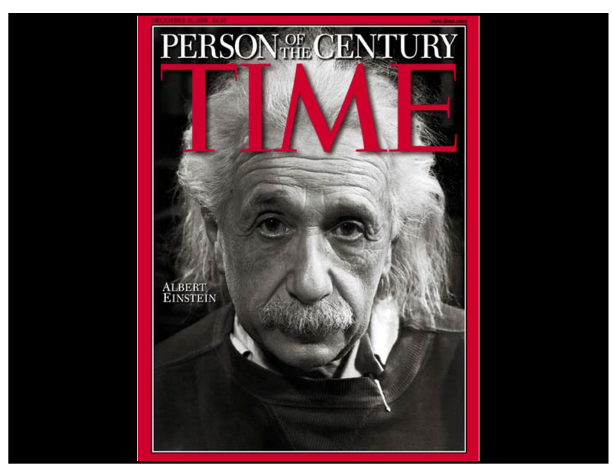

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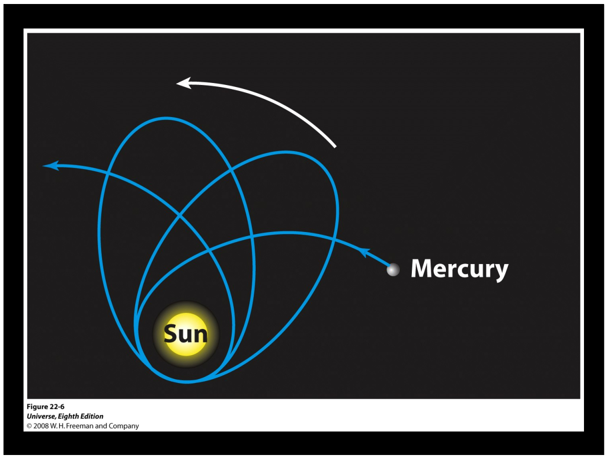

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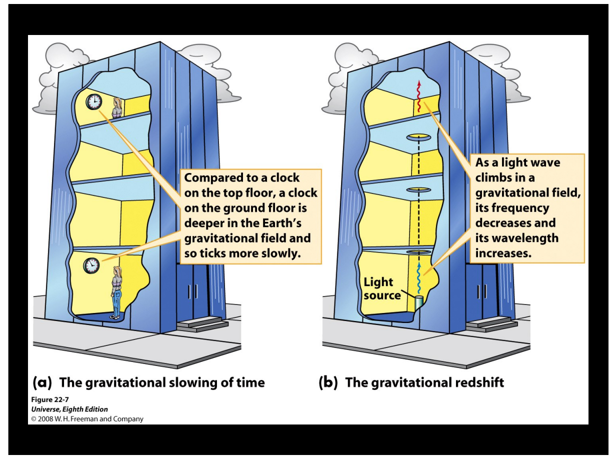

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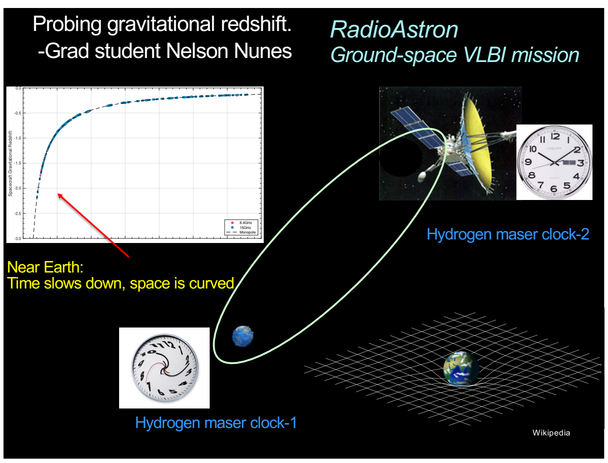

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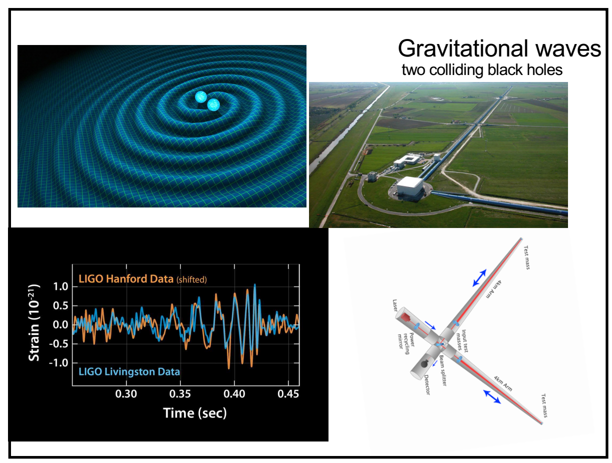

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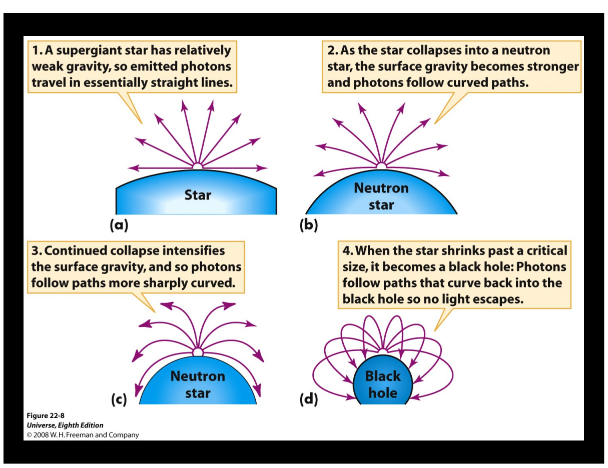

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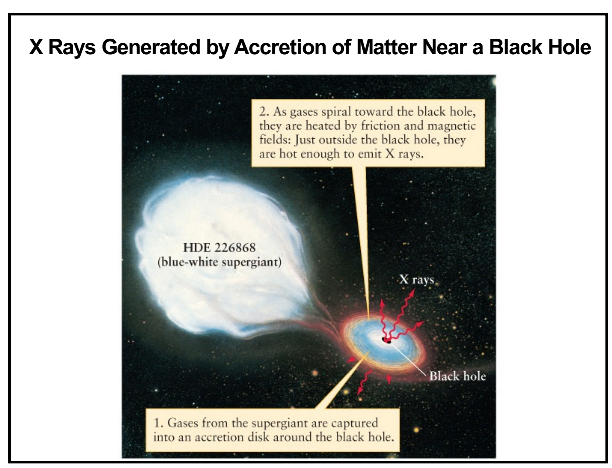

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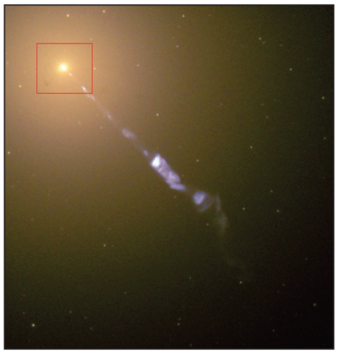
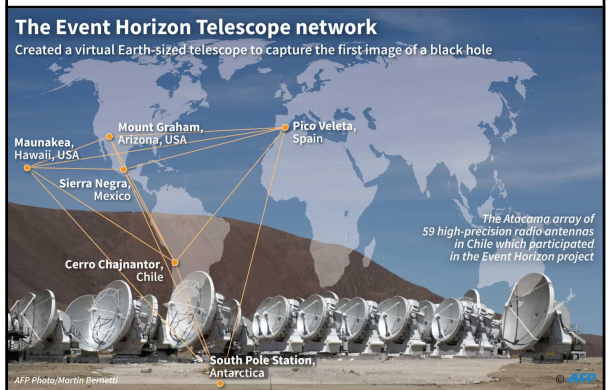
Supermassive Black Hole in the galaxy M87



The bright region in the center of galaxy M87 has stars and gas held in tight orbits by a black hole. M87's bright nucleus (center of the region in the white box) is only about the size of the solar system but it pulls on the nearby stars with so much force that astronomers calculate that it is a 6-billion-solar-mass black hole. One of the bright jets of gas shooting out perpendicular to the black hole's accretion disk is also visible.

63



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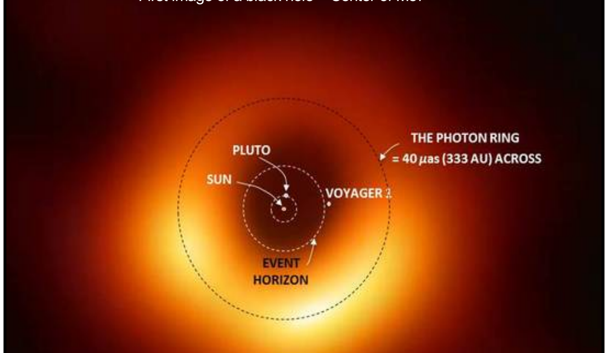
First image of a black hole – Center of M87

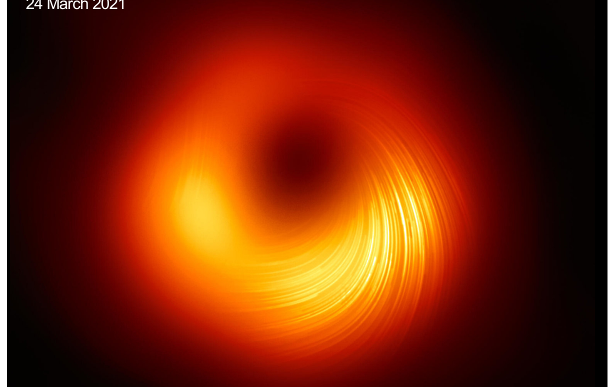


Radius of the event horizon:
$R_s = \frac{2GM}{c^2}$ M: mass of black hole
(Schwarzschild radius)

Eventhorizontelescope.org

65

Magnetic field orientation around the black hole event horizon
24 March 2021



EHT collaboration

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Wikipedia

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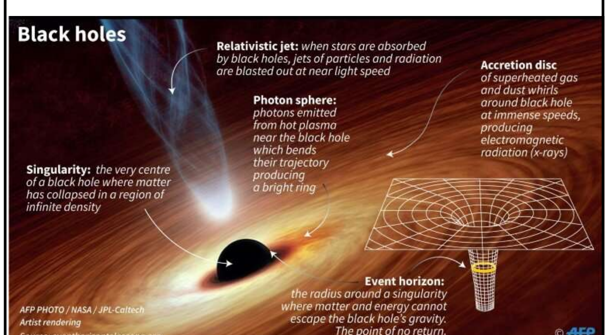

Eventhorizontelescope.org

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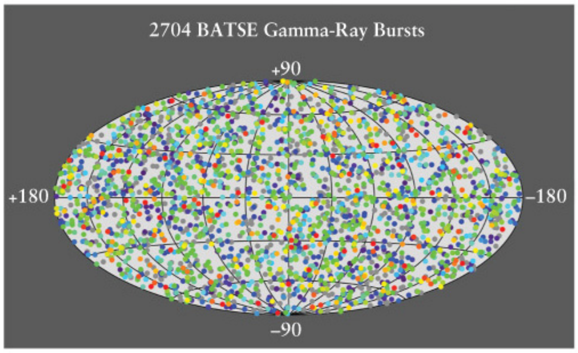
The Most Powerful Known Gamma Ray Bursts



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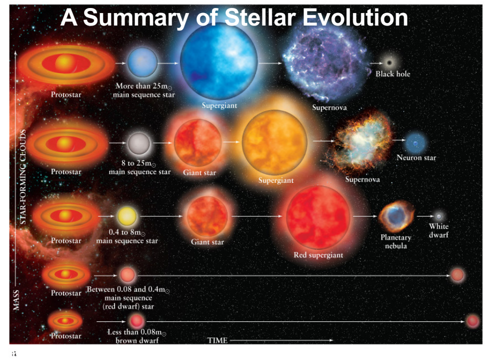

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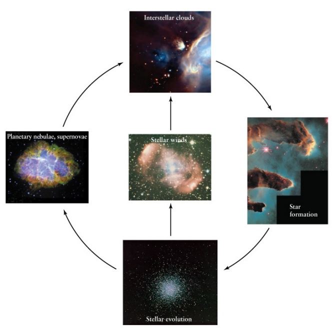

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