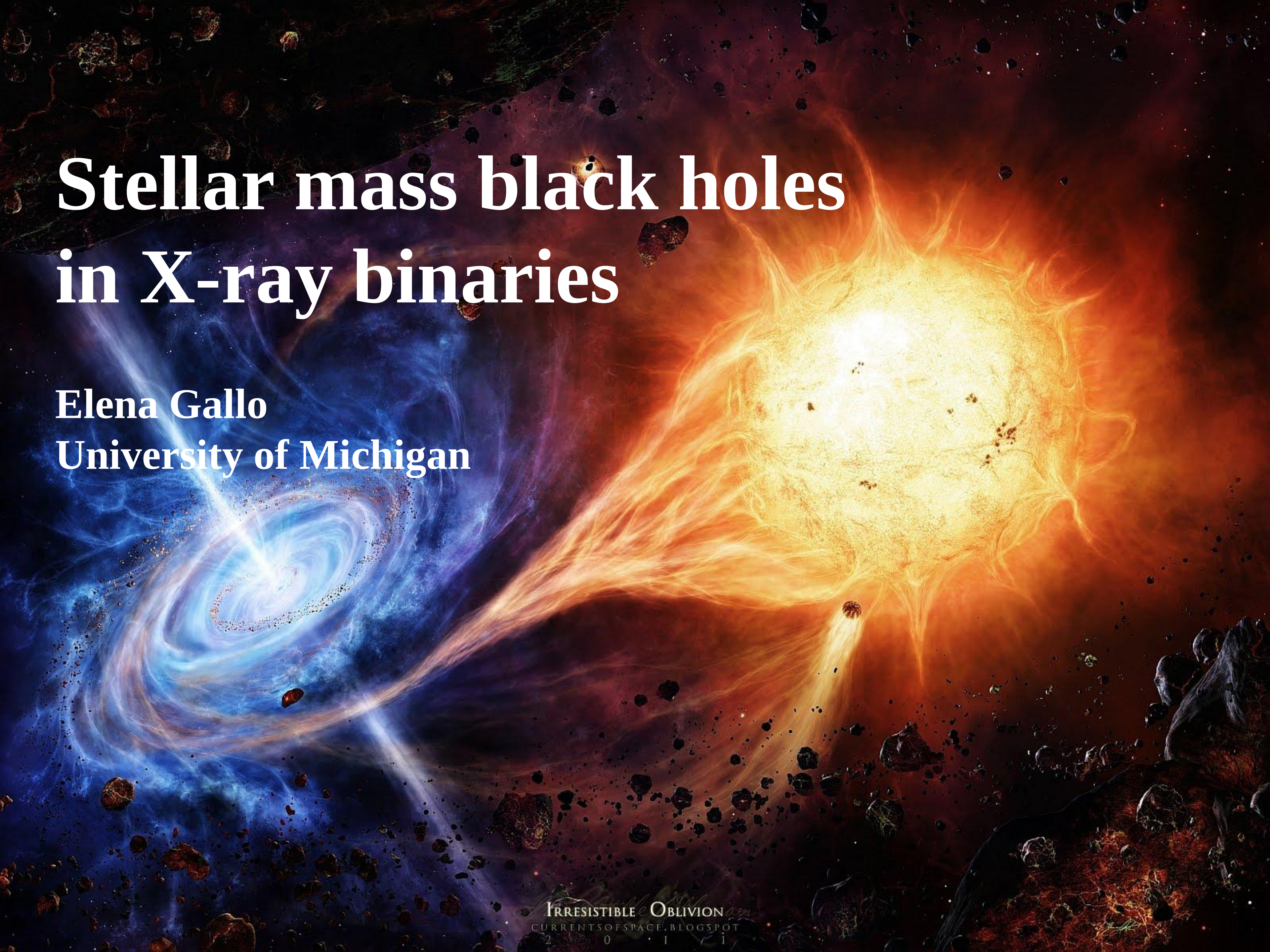
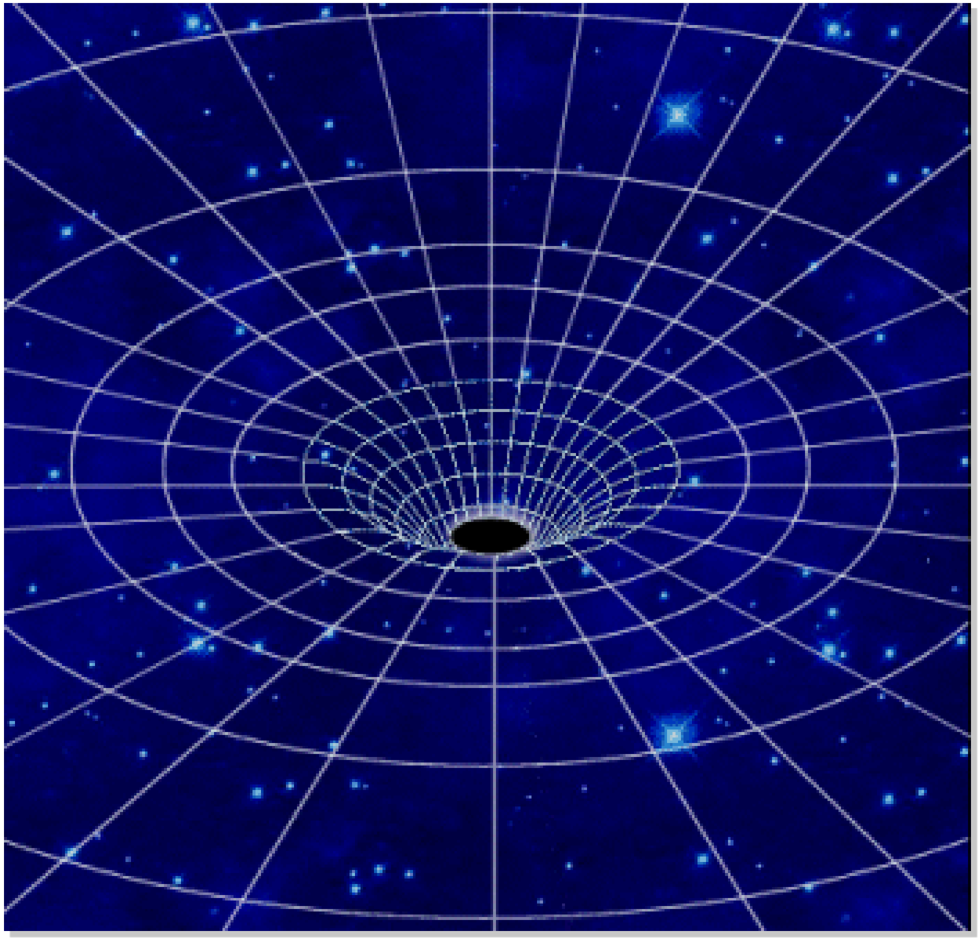
Stellar mass black holes in X-ray binaries

Elena Gallo
University of Michigan



Black Holes: Gravity Triumphant



A **black hole** is an object whose gravity is so powerful that **not even light can escape it.**

A Short History of Black Holes

- 1784 **John Michell**: Conjectures that there might be an object *compact* enough to have an escape velocity greater than the speed of light
- 1796 **Pierre Laplace**: Predicts the existence of such objects in space *"...[It] is therefore possible that the largest bodies in the universe may, through this cause, be invisible"*
- 1915 **Albert Einstein**: Publishes the General Theory of Relativity
- 1916 **Karl Schwarzschild**: Uses Einstein's theory to define (what today we call) a black hole.

A Short History of Black Holes

- 1964 **Jocelyn Bell**: Discovers pulsars.
- 1967 **John Wheeler**: First to coin the actual term black hole.
- 1970 **Stephen Hawking**: Defines modern theory of black holes, describes the final fate of black holes, i.e. evaporation via Hawking radiation.
- 1970s **X-ray Astronomy** & discovery of Cygnus X-1

The first good black hole candidate in the Sky. It has a companion star smaller than Earth but with a mass greater than that of a neutron star. The black hole and the star rotate around each other in a ‘X-ray binary’ system.

Event Horizon

The event horizon of a black hole is a **surface at which the escape velocity equals the speed of light.**

The event horizon is the point of no return: nothing can escape passed the horizon, not even light.

The horizon can be thought of as a spherical boundary, because the black hole gravity depends on the distance to its center. However, it is *not a physical surface.*

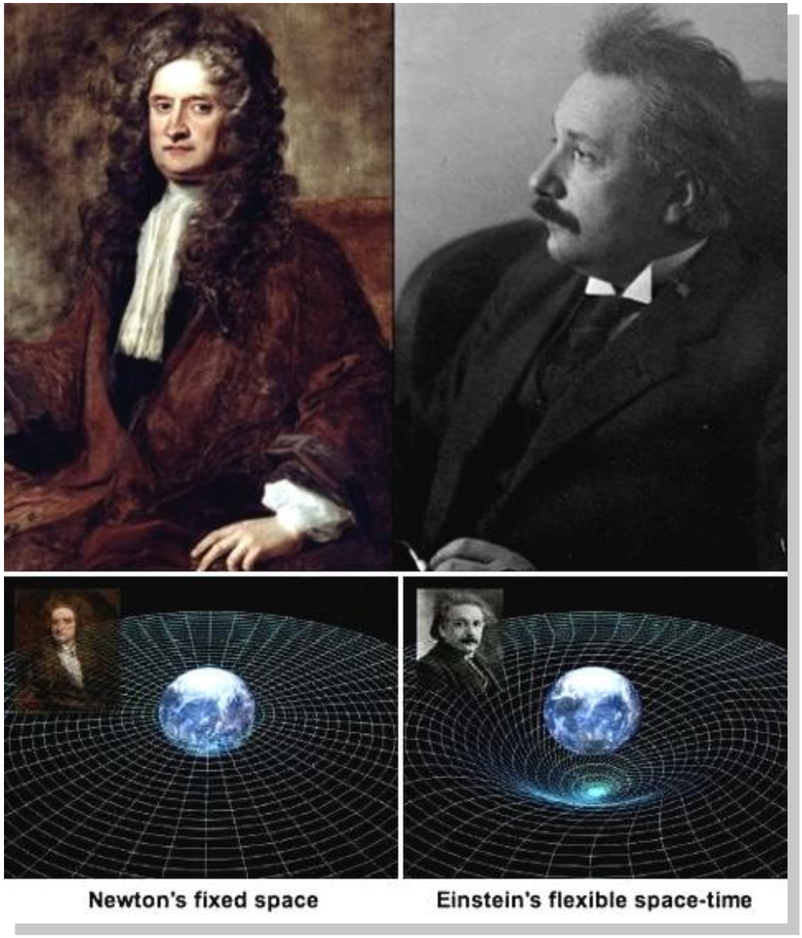
Spacetime

In the General Theory of Relativity, events are characterized by 4 coordinates in **spacetime** (3 spatial and one temporal).

The shape of spacetime is *curved* by the presence of mass

- **Mass tells space-time how to curve**
- **Space-time tells masses how to move**

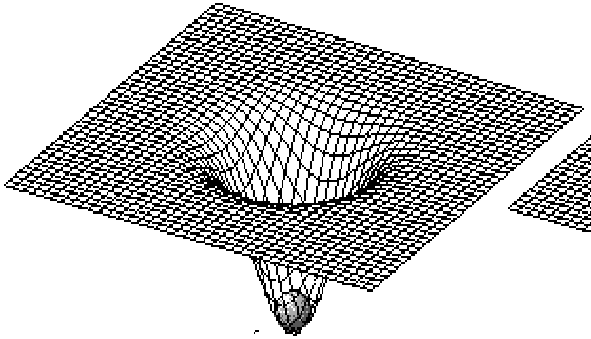
Spacetime curvature becomes stronger and stronger as we approach a black hole.



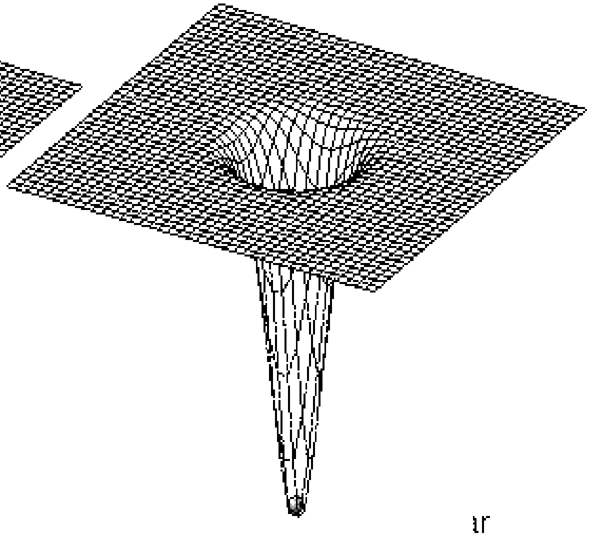
Spacetime Curvature I.

Steepness of the spacetime **curvature** determined by an object of mass M and radius R is set by the ratio (M/R)

The object **compactness (M/R)** determines the *steepness* of the curvature and the *depth* of the gravitational potential

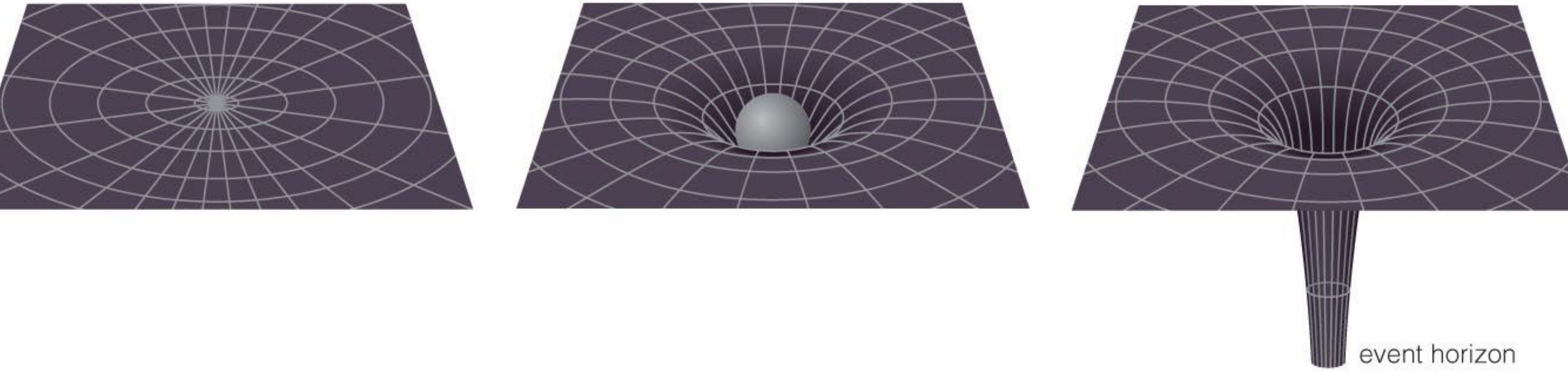


1.5 M_{Sun} **star**
R~6000 km



1.5 M_{Sun} **neutron star**
R~20 km

Spacetime Curvature II.

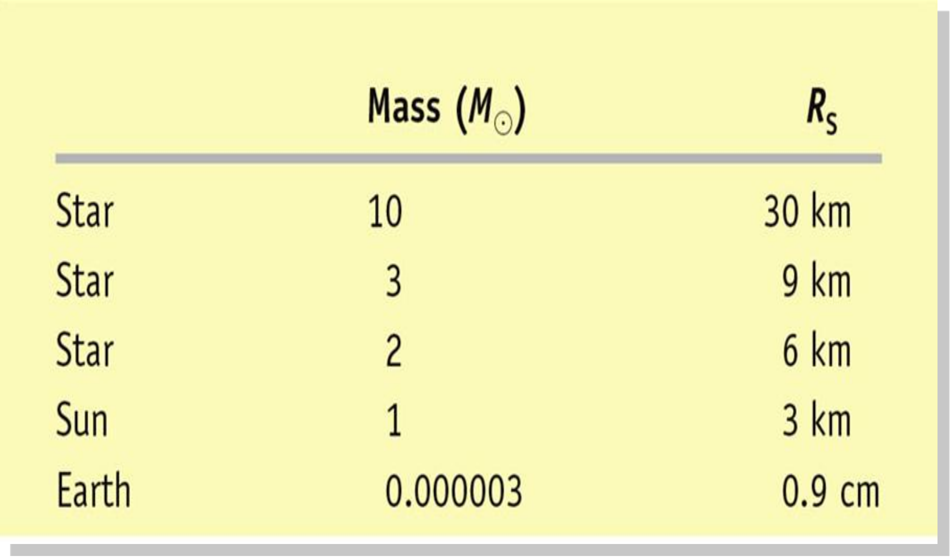


Spacetime curvature induced by a black hole is so extreme that a black hole can be thought of as a “bottomless pit” in the fabric of spacetime: a point of **infinite curvature**

The Size of a Black Hole

A black hole has no physical surface. Its “size” can be approximated as the **radius of the event horizon**, a.k.a. the Schwarzschild radius, R_S

- R_S of a black hole depends only on its mass
- More massive black holes have larger R_S



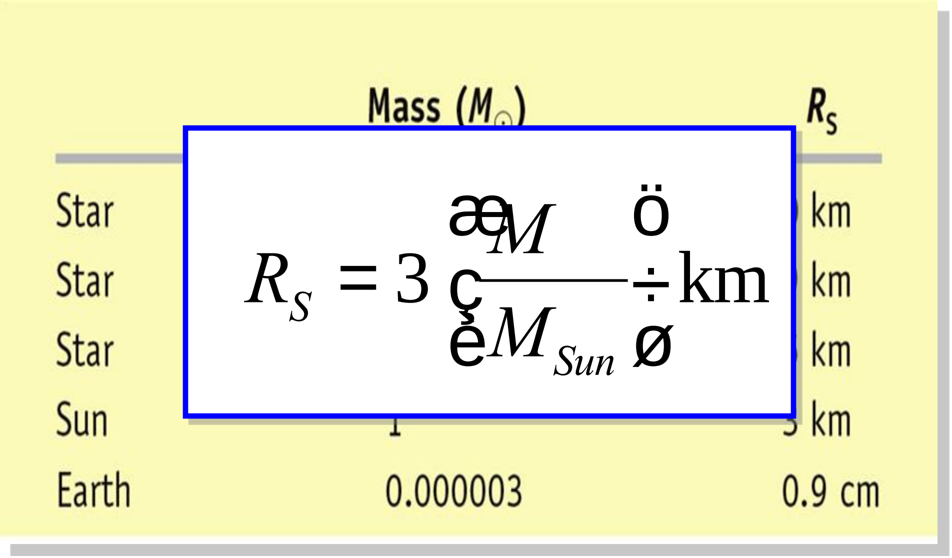
	Mass ($M_\odot$)	R_S
Star	10	30 km
Star	3	9 km
Star	2	6 km
Sun	1	3 km
Earth	0.000003	0.9 cm

Notice: *Every object in the universe has a Schwarzschild radius* but, **only if their mass is contained within this limiting scale size do they become a black hole**

The Size of a Black Hole

A black hole has no physical surface. Its “size” can be approximated as the **radius of the event horizon**, a.k.a. the Schwarzschild radius, R_S

- R_S of a black hole depends only on its mass
- More massive black holes have larger R_S



	Mass ($M_\odot$)	R_S
Star		km
Star		km
Star		km
Sun	1	3 km
Earth	0.000003	0.9 cm

$$R_S = 3\left(\frac{M}{M_{Sun}}\right)\text{km}$$

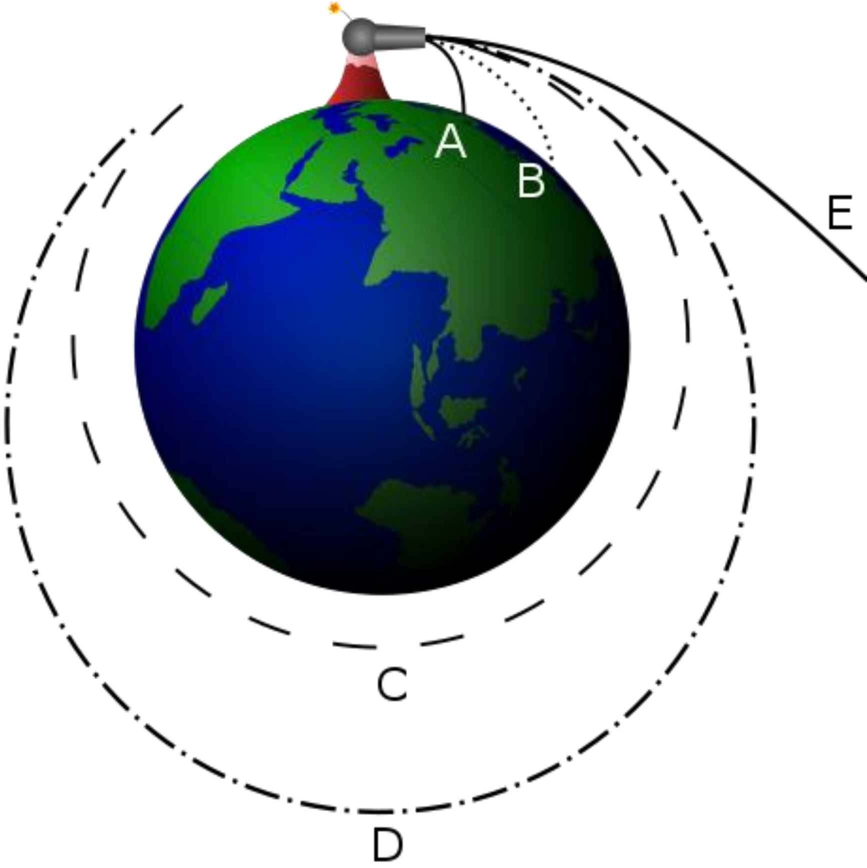
Notice: *Every object in the universe has a Schwarzschild radius* but, **only if their mass is contained within this limiting scale size do they become a black hole**

Escape Velocity

The speed needed to *break free* from a gravitational field

For an object of mass M and radius R, it is equal to:

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

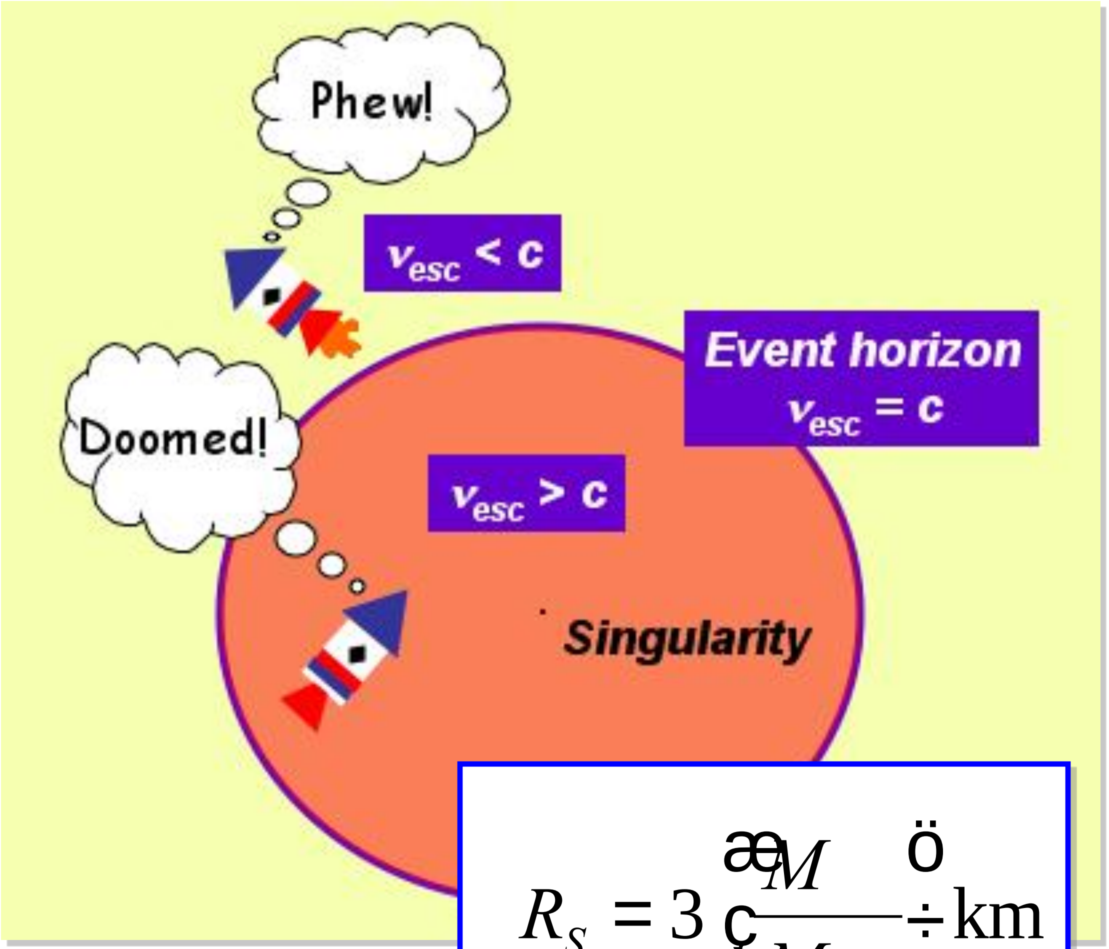


Escape Velocity & Schwarzschild Radius

i) $$v_{esc} = \sqrt{\frac{2GM}{R}}$$

ii) $$c = \sqrt{\frac{2GM}{R_S}}$$

iii) $$R_S = \frac{2GM}{c^2}$$



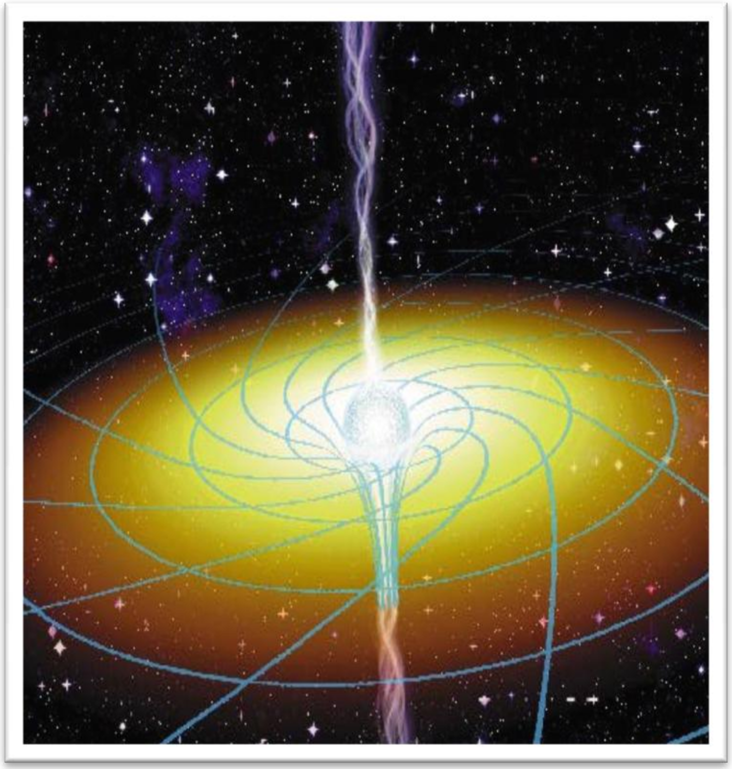
$$R_S = 3\left(\frac{M}{M_{Sun}}\right)\text{km}$$

Properties of a Black Hole

Black holes are completely defined by 3 quantities:

1. **Mass**
2. **Electric charge** (irrelevant in astrophysical contexts)
3. **Angular momentum**

- Spacetime is dragged along in the direction of the rotation, like a vortex
- **Frame-dragging** changes the shape of the horizon, as objects moving along with the hole resist falling in more easily than objects moving in the opposite direction

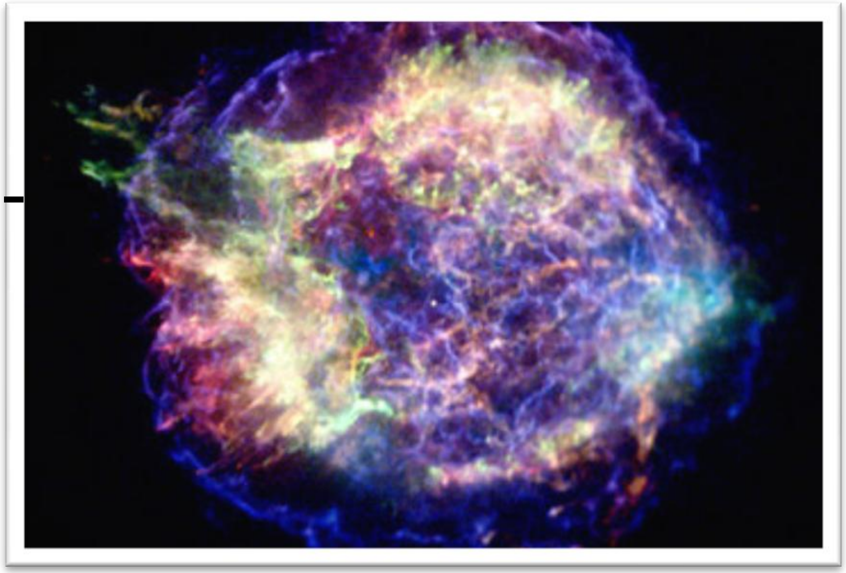


Stellar black hole formation

- Stars are held together against their own gravity by nuclear reactions in their cores (H => He=>..up to Fe)

- Beyond iron, the internal energy source is no longer available, and gravity crushes all the matter into a black hole

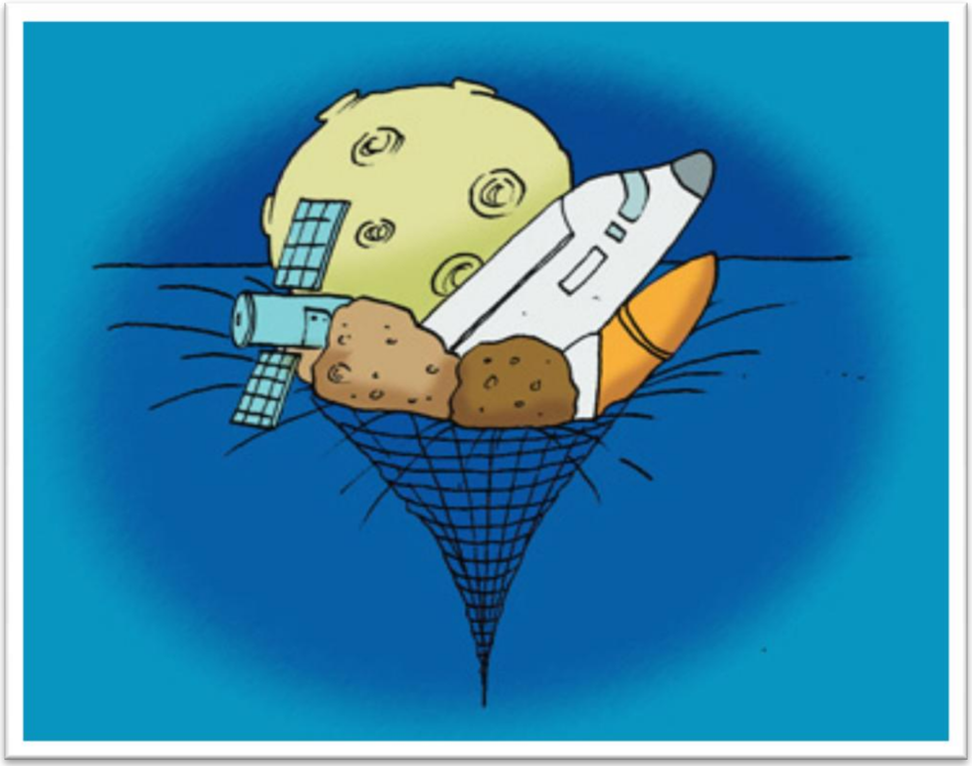
(The core of) a high mass star with initial mass higher than 20-30 solar masses will likely collapse into a black hole (the outer layers are ejected in a supernova).



What would it be like to visit a black hole?

Common misconception:
black holes suck everything!

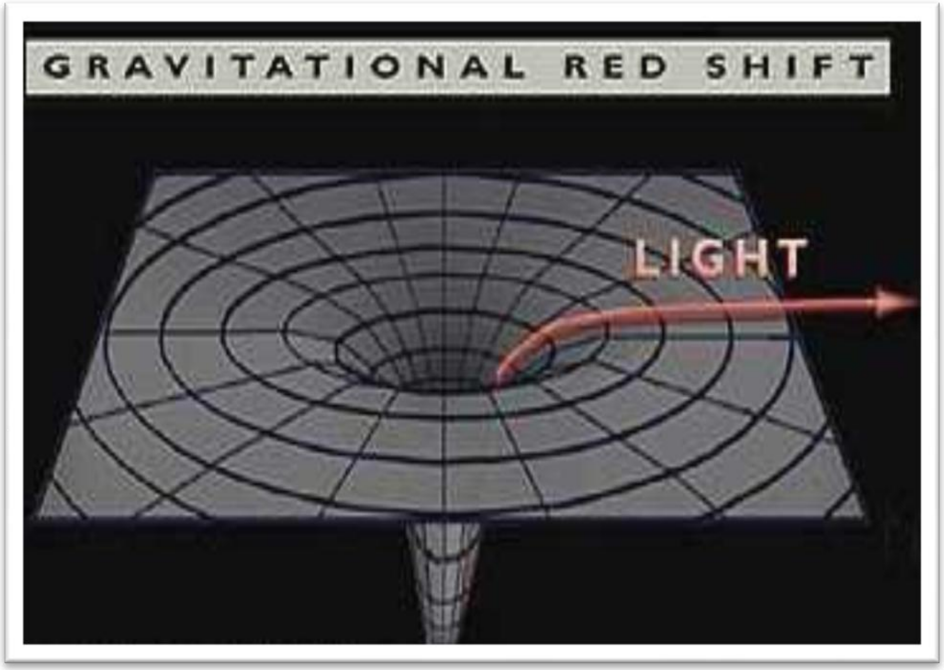
If the Sun became a black hole, its gravity would be different only near the event horizon.



Far from the event horizon, a 10 solar mass black hole has the same properties of a 10 solar mass star

Gravitational Red-shift

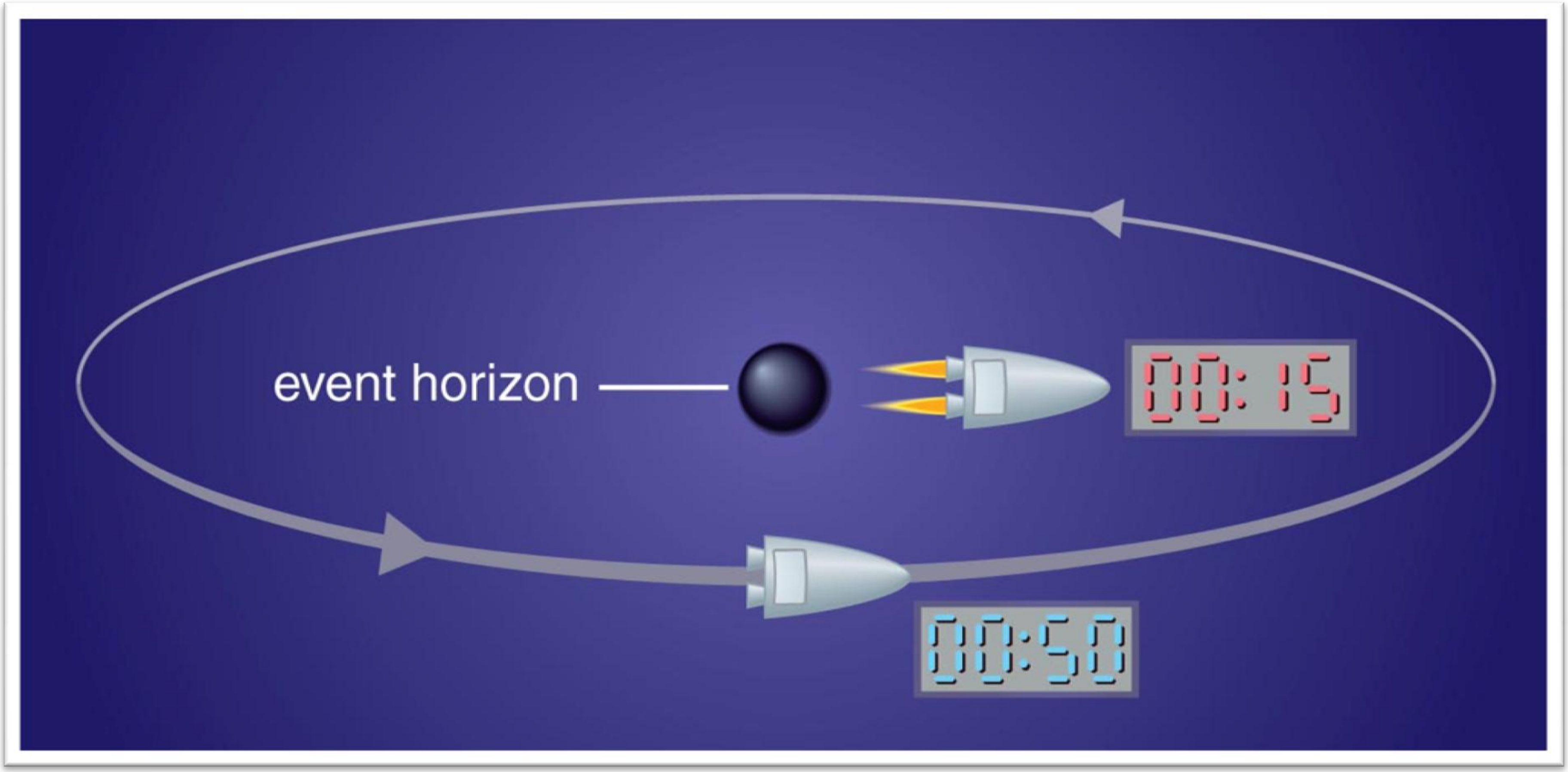
The wavelength of light emerging from a gravitational field will be shifted towards redder regions of the spectrum *(i.e. lower energies, lower frequencies)*



Think of a baseball hit high into the air, slowing as it climbs.

Einstein's theory says that as a photon fights its way out of a gravitational field, it loses energy and its color reddens

Gravitational Time Dilation



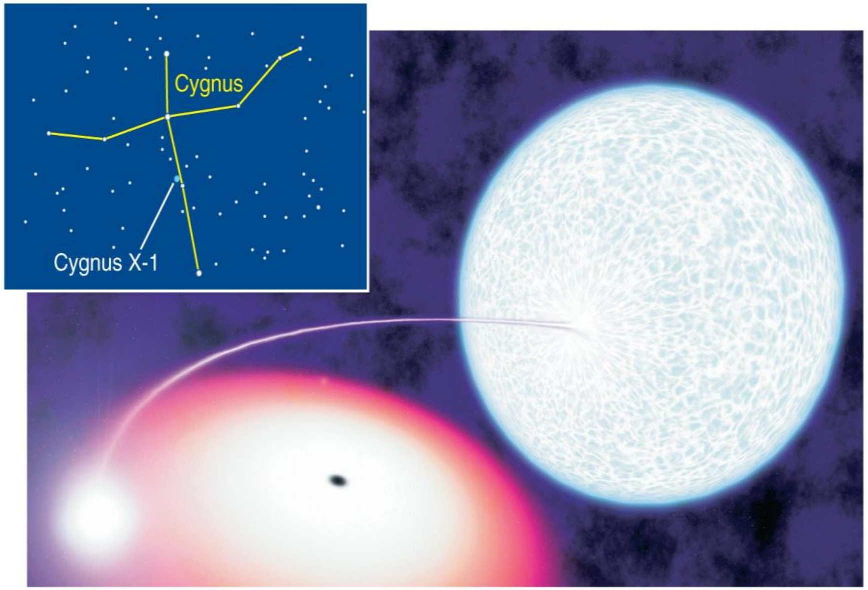
Time runs more slowly as the force of gravity increases

Do black holes really exist?

- Black holes don’t shine.. However, gas falling towards a black hole can become extremely hot – million of degrees – thus shining in the X-ray band

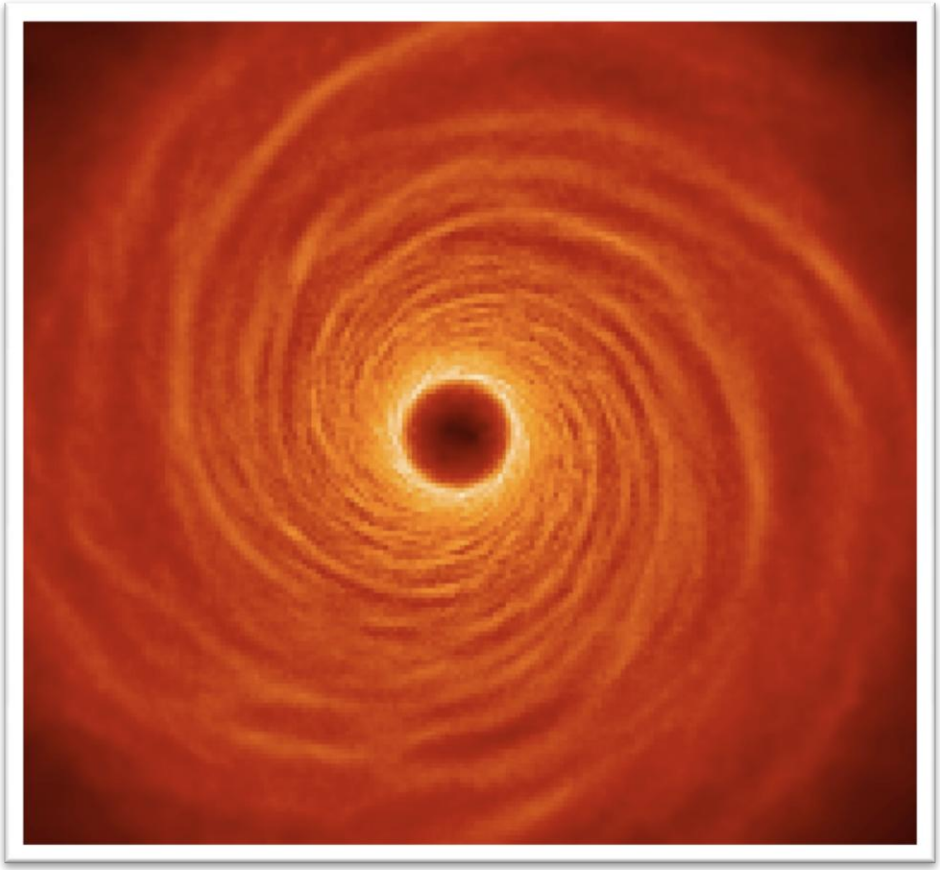
- The process becomes very efficient if the black hole is ‘fueled’ by a companion star in **black hole X-ray binary**

- A well studied black hole is in the Cygnus constellation: Cygnus X-1



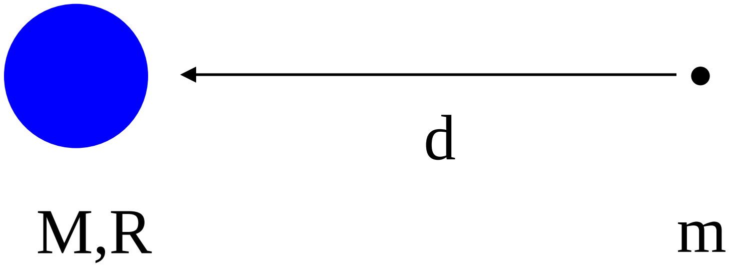
Accretion disks

- Matter from the star outer envelope falls onto the black hole and forms a disk
- **Gravitational potential energy of the in-falling matter is converted into heat and radiation extremely efficiently**
- This process is 100s times more efficient than fusion in the sun



Black Holes: Gravity Triumphant

- Let us consider a mass *m* which falls into the gravitational potential of an object of mass M and radius R (the ‘accretor’)
  - $F_{grav} = GMm/d^2$
  - $E_{grav} = \mathbf{- GMm/d}$



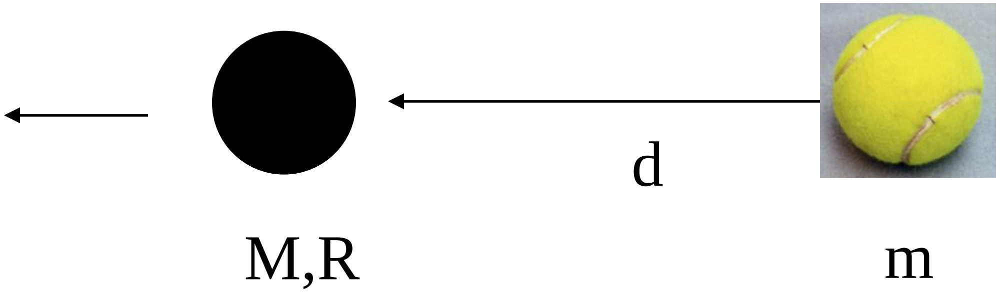
- As *m* falls, its gravitational potential energy decreases (i.e. becomes more negative)
- The amount of dissipated gravitational potential energy is

$$\mathbf{dE_{grav}} = [-GMm/d]_{d=\infty} - (-GMm/d)_{d=R} = \mathbf{GMm/R}$$

- The more compact the accretor is (i.e. the higher M/R) the more gravitational potential energy gets dissipated

Black Holes: Gravity Triumphant

300 x



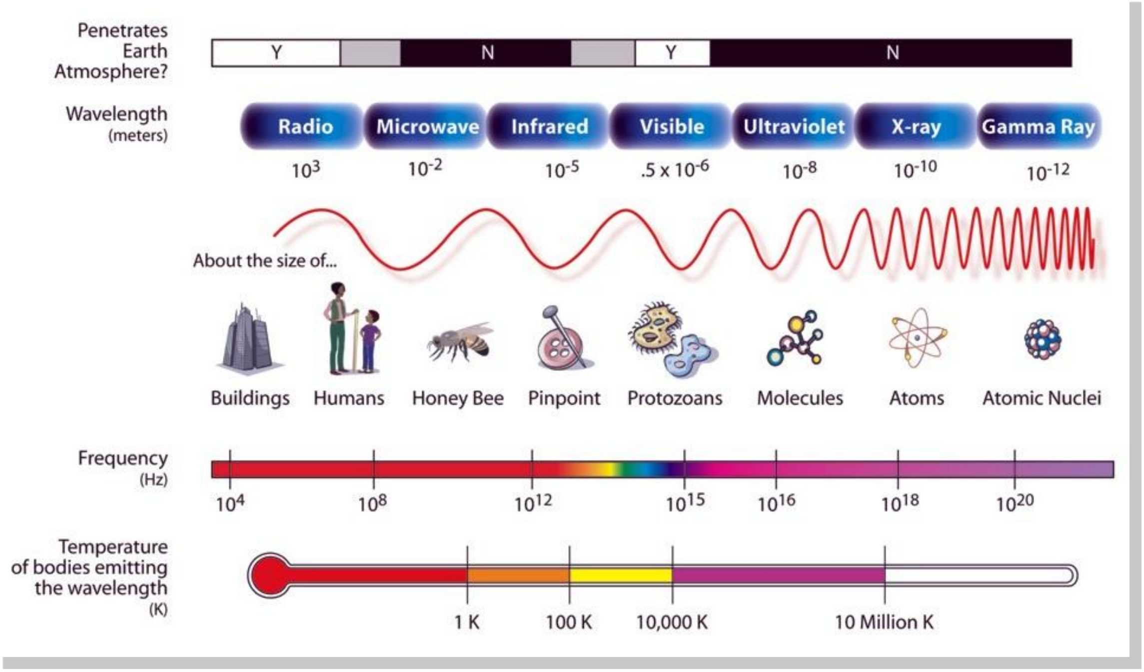
- The amount of dissipated gravitational potential energy is

$$\mathbf{dE_{grav}} = [-GMm/d]_{d=\infty} - (-GMm/d)_{d=R} = \mathbf{GMm/R}$$

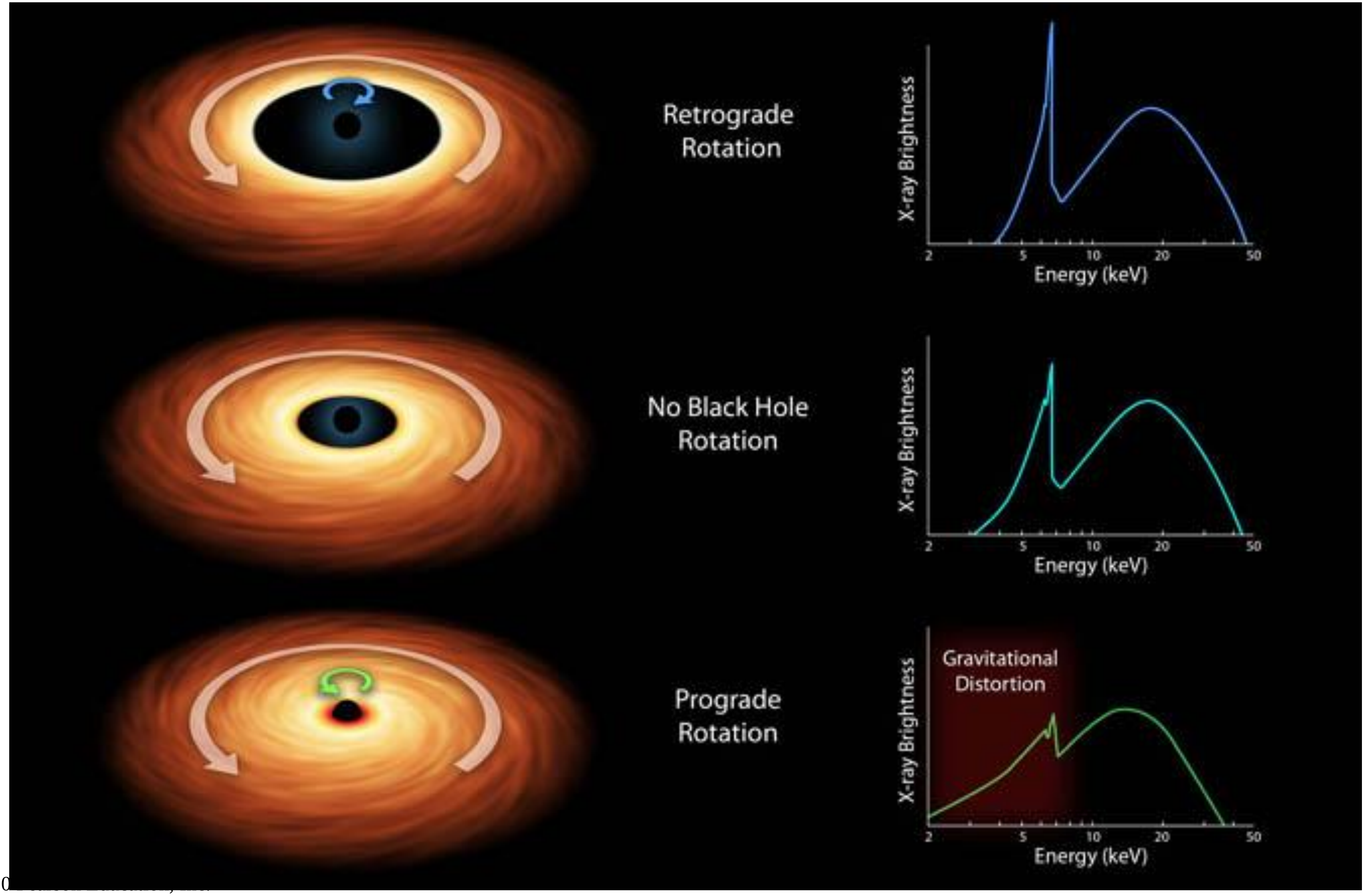
- The more compact the accretor is (i.e. the higher M/R) the more gravitational potential energy gets dissipated

Black Holes and X-ray Astronomy

- Accretion disk temperatures get higher closer to the black hole (i.e. as gas sinks deeper into its gravitational potential)
- Close to the horizon, the gas temperature reaches millions of degrees K and therefore the disk emits in the X-ray band
- Since X-ray do not penetrate the Earth atmosphere, X-ray astronomy is done with space telescopes



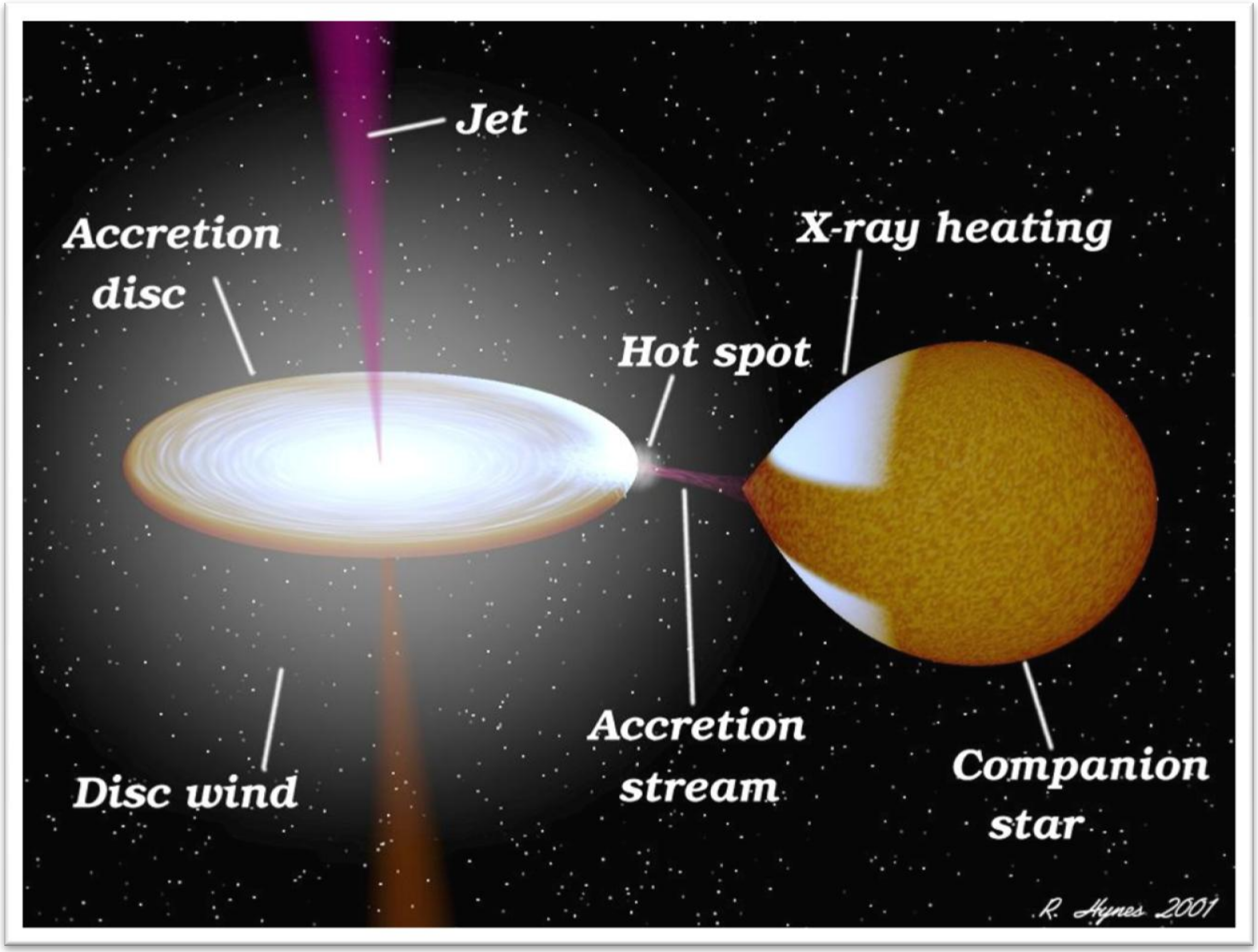
Measuring the spin of black holes



E.M. Radiation from Black Hole X-ray Binaries

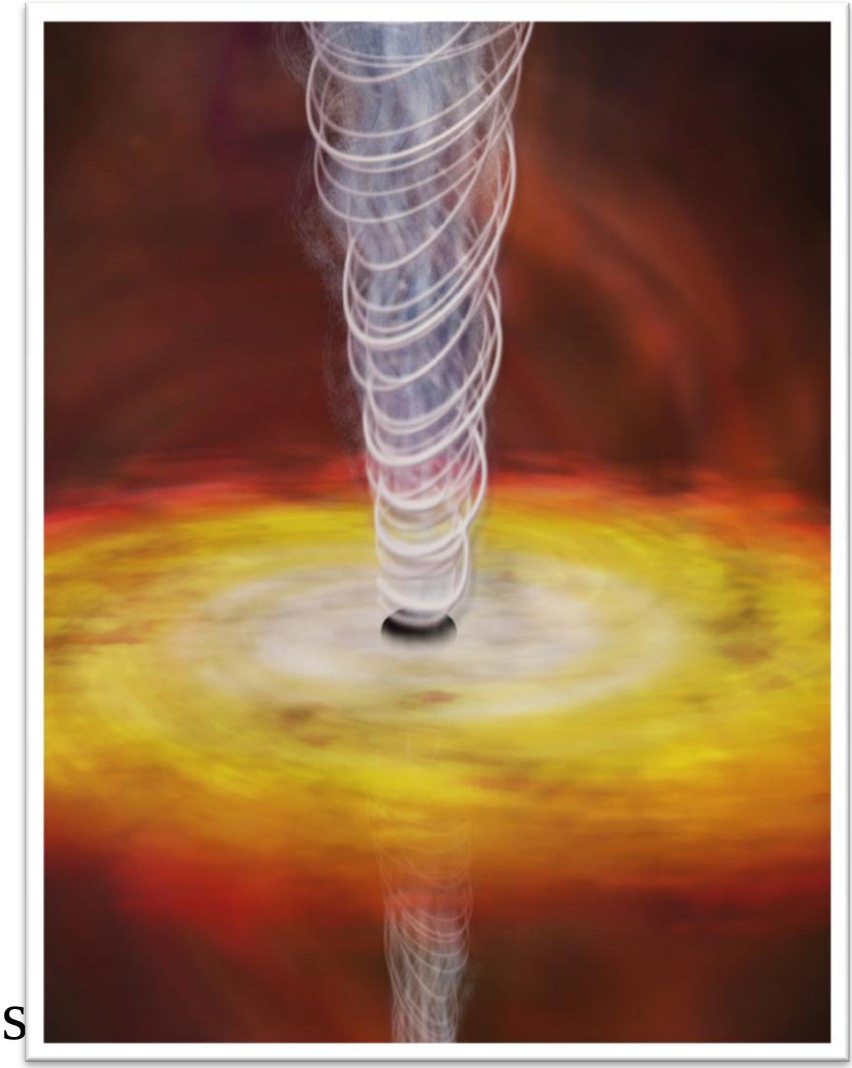
Black hole X-ray binaries emit radiation across the entire electromagnetic spectrum:

- Radio: from relativistic jets
- IR-optical-UV: from the companion star the outer disk
- X-rays: from the inner disk
- Gamma-rays: ?



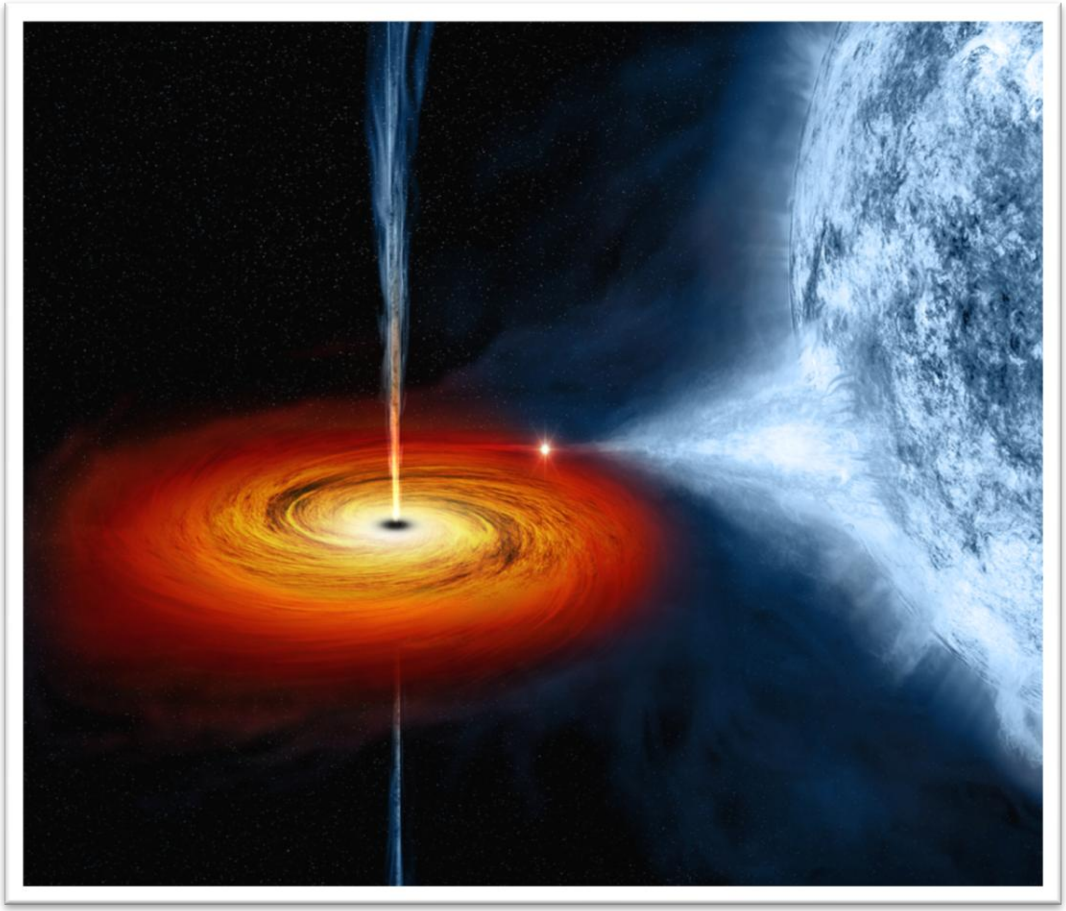
Relativistic jets

- Black holes are able to turn part of that matter around and eject it outward along highly collimated bipolar streams, a.k.a. relativistic jets
- Jets emit mainly in the radio band due the ‘synchrotron’ emission (same as in particle accelerators on Earth)
- Synchrotron radiation requires
  - high magnetic fields and
  - relativistic (v close to c) particles



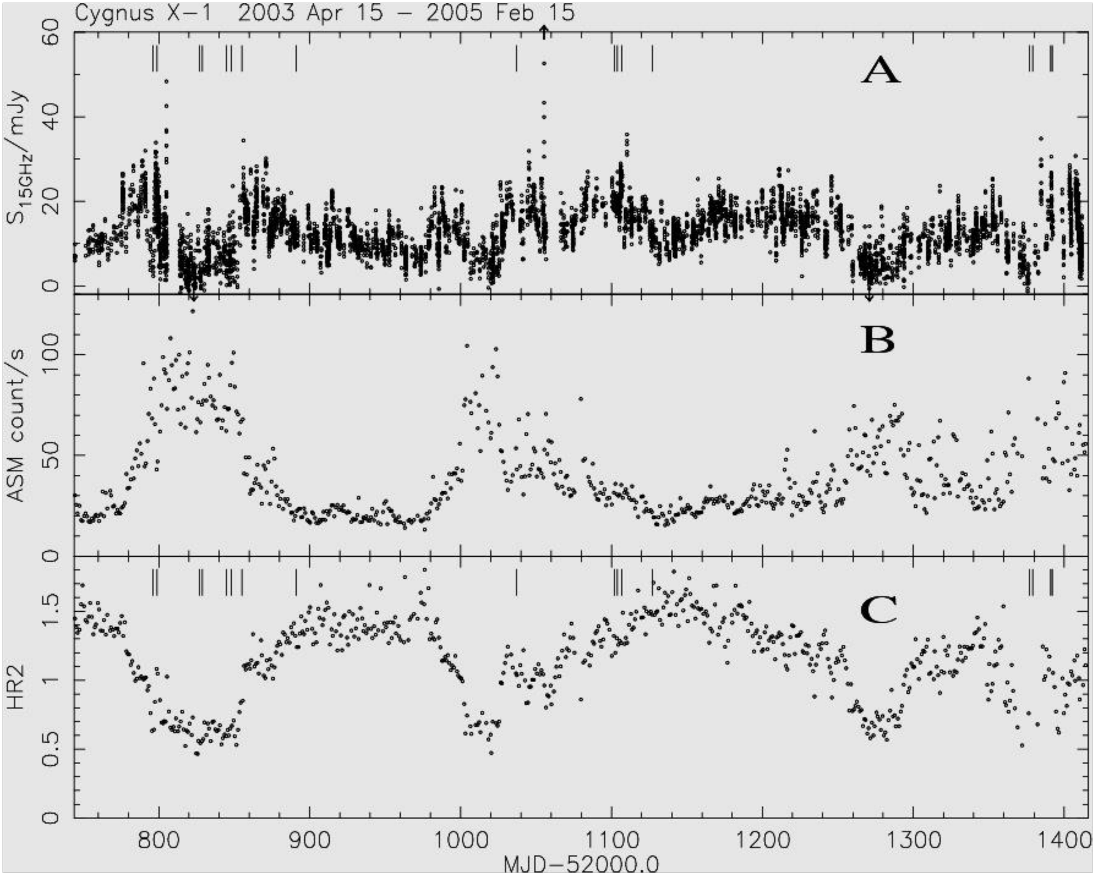
Case study: Cygnus X-1

- 15 solar mass black hole orbiting a giant companion star
- Distance: 2 kpc (~6000 lyr)
- Orbital distance: 0.2 A.U.
- Orbital period: 5.6 days
- Discovered as a bright X-ray source in 1964 with suborbital rockets carrying Geiger counters



Case study: Cygnus X-1

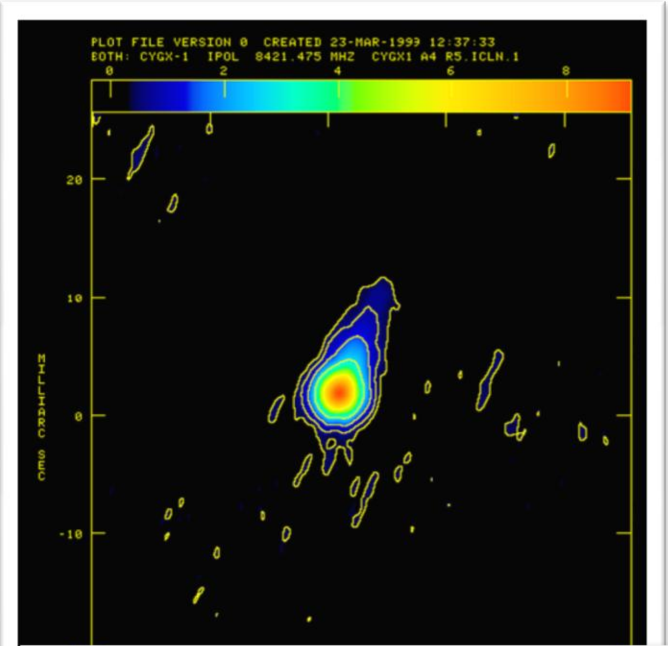
- 15 solar mass black hole orbiting a giant companion star
- Distance: 2 kpc (~6000 lyr)
- Orbital distance: 0.2 A.U.
- Orbital period: 5.6 days
- Discovered as a bright X-ray source in 1964 with suborbital rockets carrying Geiger counters

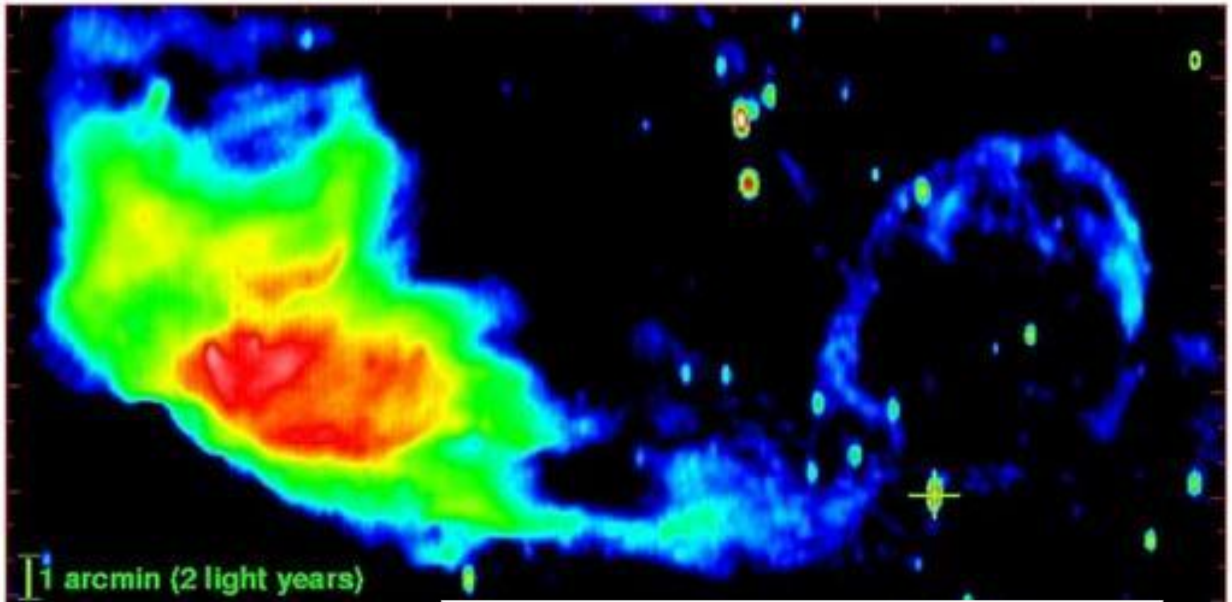


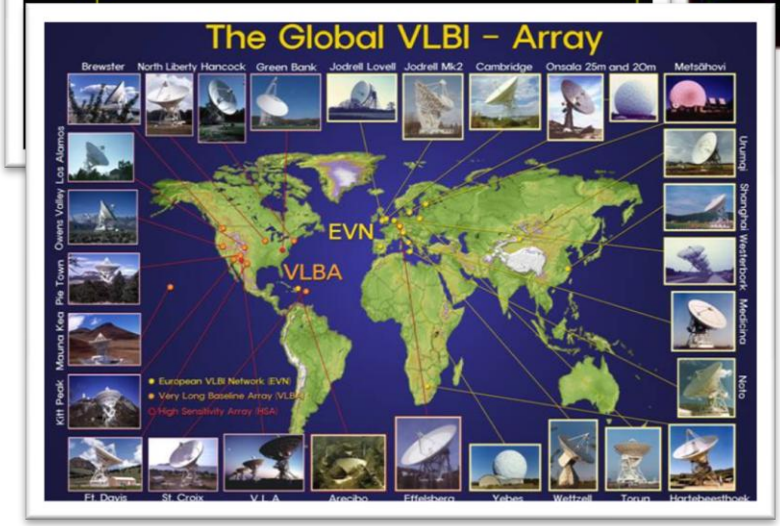
Case study: Cygnus X-1

optical wave-lengths

Case study: Cygnus X-1

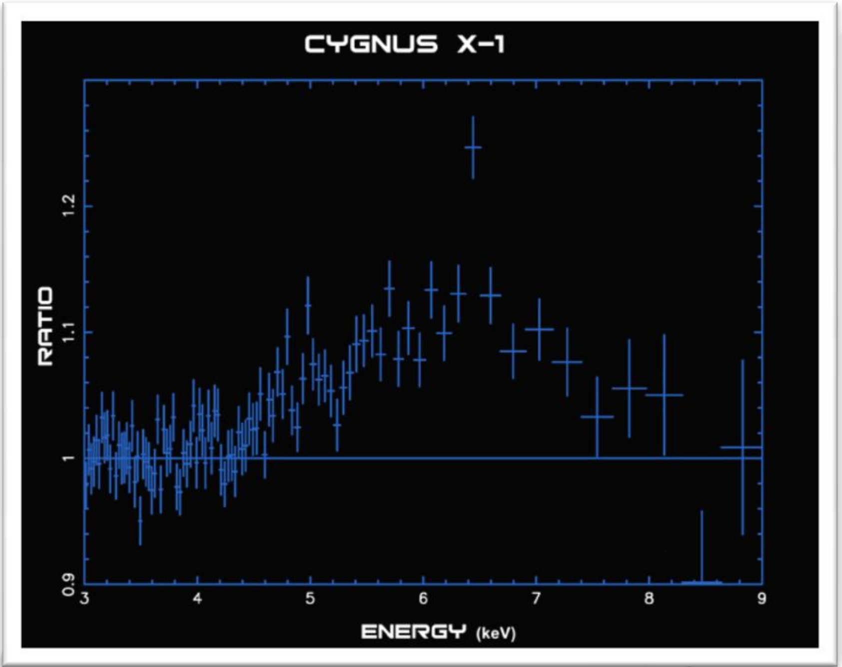




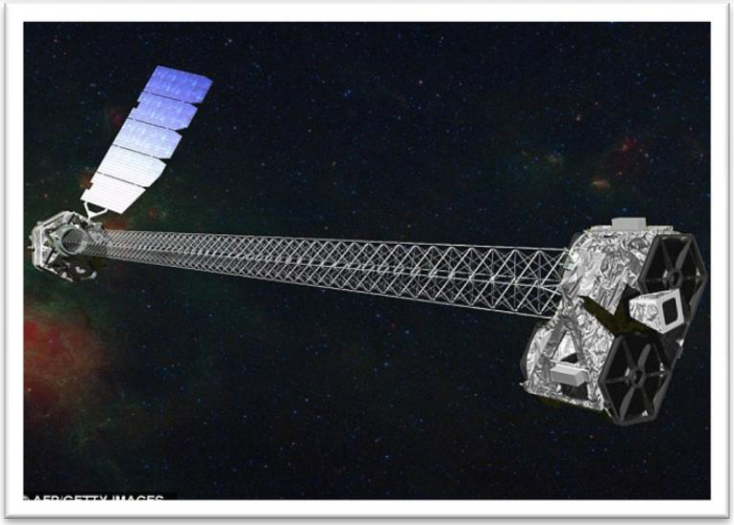


radio wave-lengths

Case study: Cygnus X-1



X-ray wavelengths



© AFP/GETTY IMAGES