Announcement: Quiz next Friday

(I may cancel class this Wednesday, unsure.)

What is the difference between the giant, horizontal, and asymptotic-giant branches? What is the Helium flash?

Why can't high-mass stars support themselves in hydrostatic equilibrium by fusing Iron?

What is the main sequence lifetime? Does it increase or decrease as mass increases?

What is the difference in outcomes for a star with $M < 4\ M_{sun}$, $4M_{sun} < M < 8\ M_{sun}$, $M > 8M_{sun}$?

What is the Chandrasekhar mass?

Why are there no stars with mass less than $\sim 0.1\ M_{sun}$

Black Holes

Astronomy 1101

Key Ideas:

Black Holes are totally collapsed objects

- gravity so strong not even light can escape
- predicted by General Relativity

Schwarzschild Radius/Event Horizon, Singularity.

Gravitational redshift, time dilation.

Find them by their Gravity, and light!

- X-ray Binary Stars

Black Holes Evaporate!

- Emit "Hawking Radiation"

Gravity's Final Victory

A star more massive than 20-30M_{sun} would leave behind a neutron star with $M > 2.2\ M_{sun}$:

- Neutron degeneracy pressure would fail, strong force fails, and nothing can stop gravitational collapse.

Core would collapse into a **singularity**, an object with

- Zero radius
- Infinite density: Density = Mass/Volume

Black Holes

The ultimate extreme object:

- Gravity so strong not even light escapes.
- Infalling matter gets shredded by powerful tides & crushed to infinite density.
- V_{esc} exceeds the speed of light

Black:

It neither emits nor reflects light.

Hole:

Nothing entering can ever escape.

Schwarzschild Radius

Light cannot escape from a Black Hole if it comes from a radius less than the *Schwarzschild Radius*:

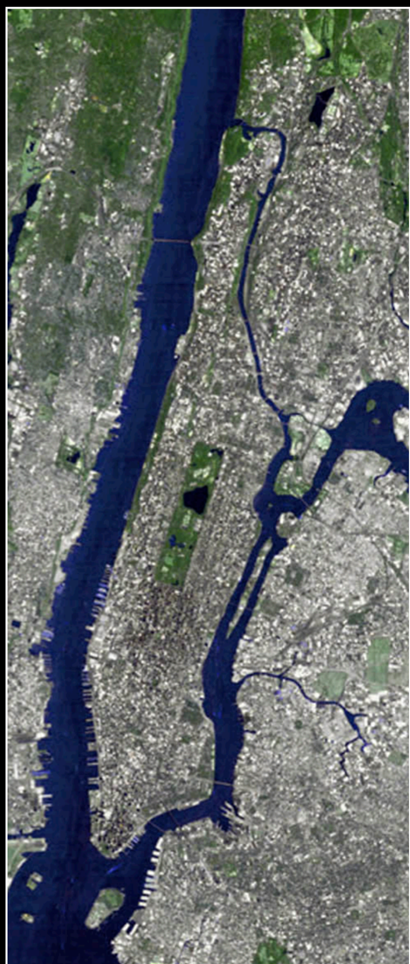
$$R_S = \frac{2GM}{c^2}$$

M = Mass of the Black Hole

For $M = 1\ M_{sun}$, $R_S \sim 3$ km

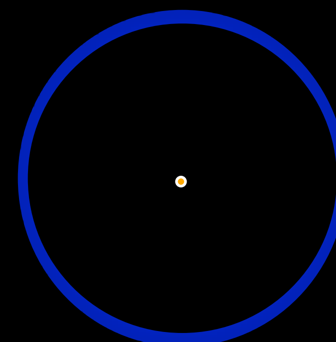
(Recall, for Neutron star: $M = 1\text{-}2\ M_{sun}$, $R \sim 10$ km)

Neutron Star vs. Black Hole



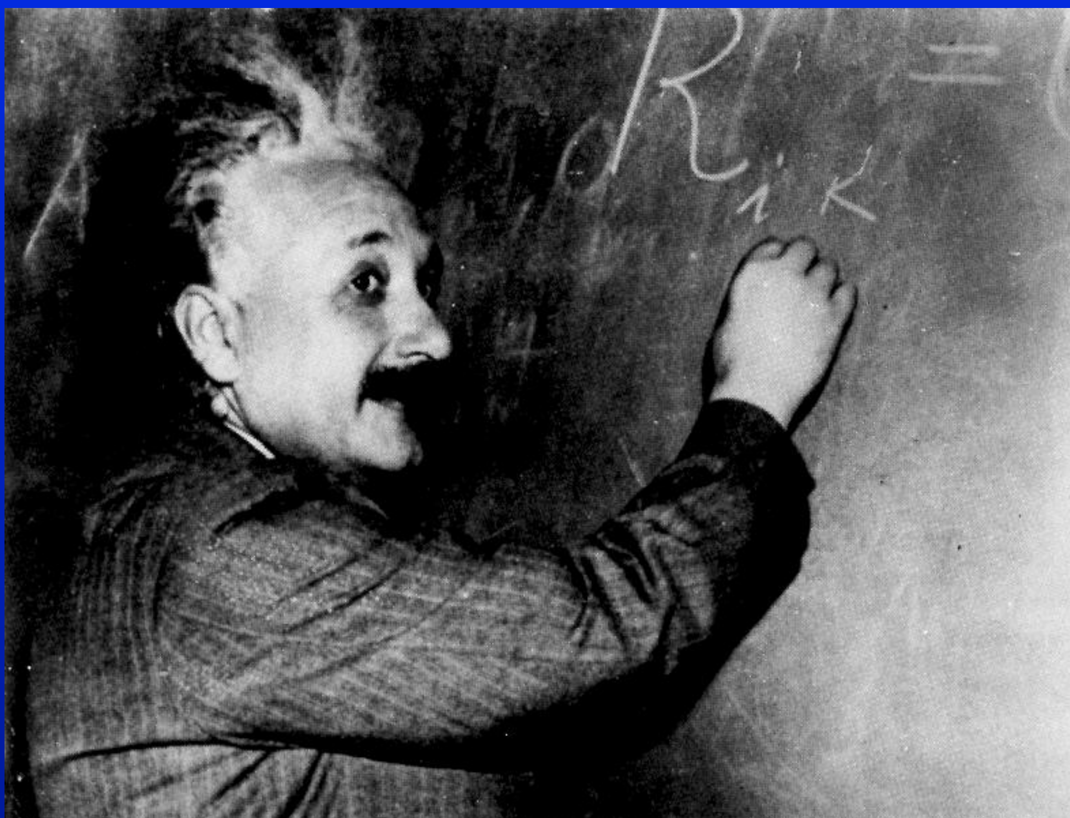
Manhattan

Neutron Star
$M=1.5\ M_{sun}$
$R=10$ km



Black Hole
$M=1.5\ M_{sun}$
$R_S=4.5$ km

1915: General Relativity, Einstein's Theory of Gravity
1916: Schwarzschild's Discovery of BHs in GR
BHs only understood & accepted in the 1960s
(Term "Black Hole" coined by John Wheeler in 1967)



Albert Einstein

Karl Schwarzschild

R_S defines the ***Event Horizon***:

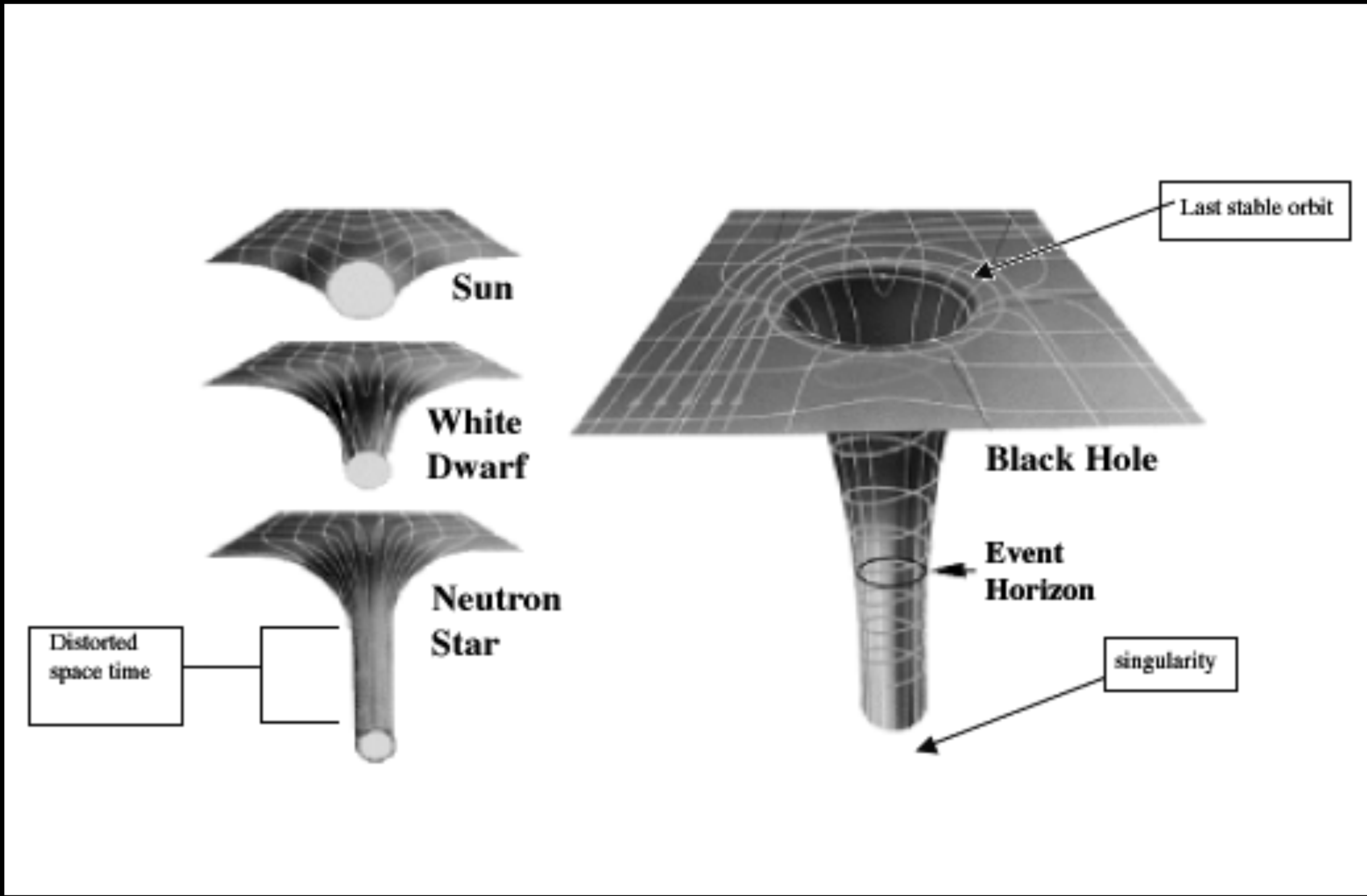
Events that happen inside R_S are invisible to the outside Universe.

Things that get inside R_S can never leave the black hole.

The "Point of No Return" for a Black Hole.

But, R_S is not the "singularity".

Space (and time) is curved and warped by gravity.



How does gravity make things fall.

Gravity around Black Holes

Far away from a black hole:

- Gravity is the *same* as for a star of the same mass.
- If the Sun became a black hole, the planets would all orbit *the same as before*.

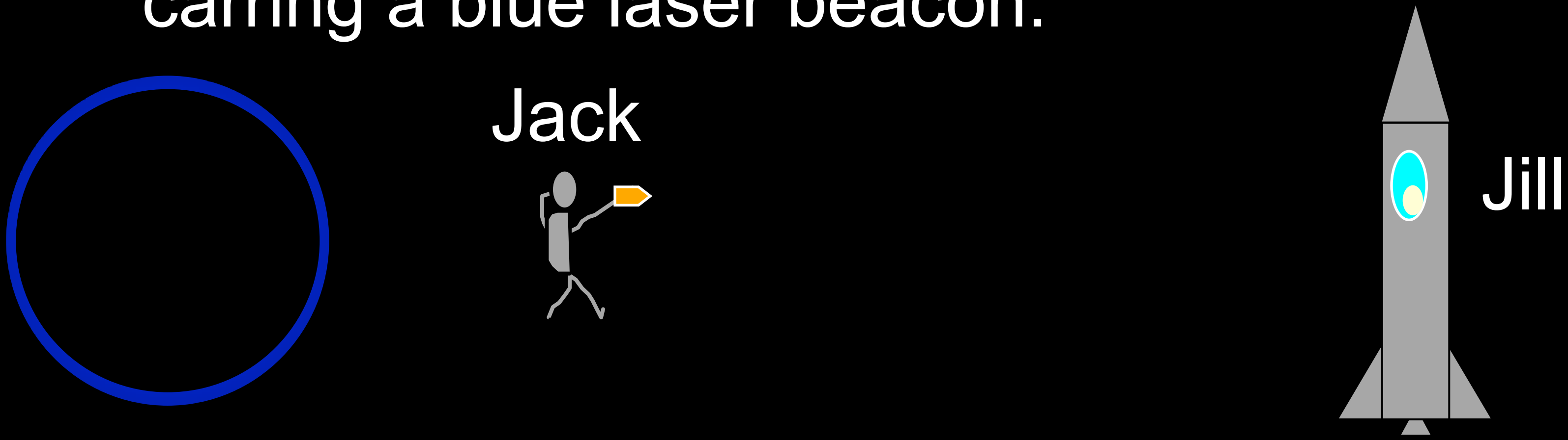
Close to a black hole:

- $R < 3\ R_S$, no stable orbits – all matter sucked in.
- At $R = 1.5\ R_S$, photons orbit in a circle!
- At $R = R_S$, event horizon.
- At $R = 0$, singularity.

Journey to a Black Hole: A Thought Experiment

Two observers: Jack & Jill

- Jack, in a spacesuit, is falling into a black hole, carring a blue laser beacon.

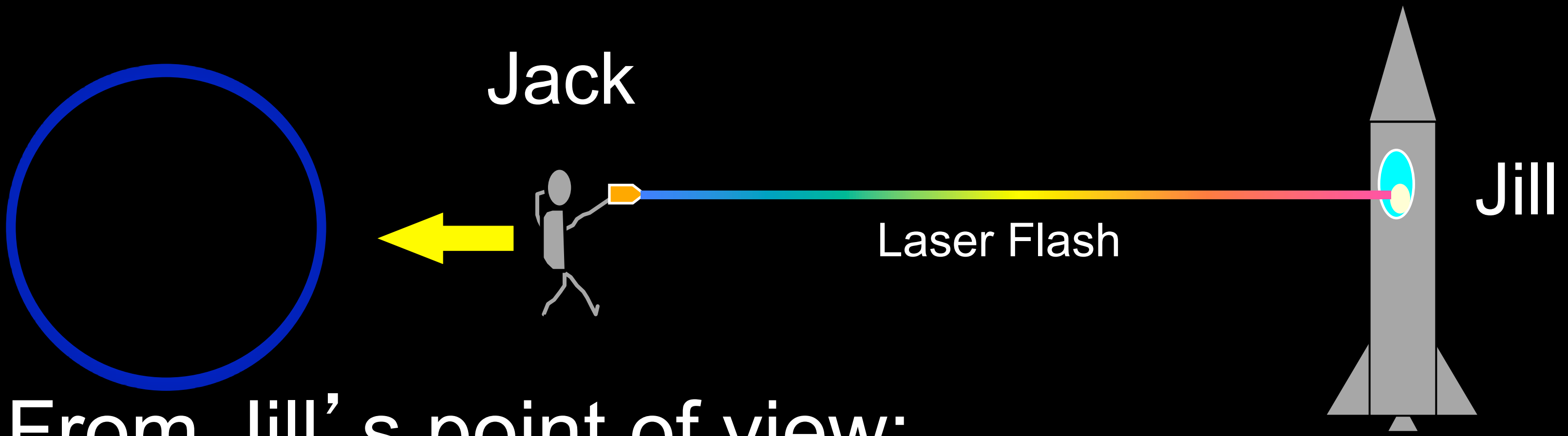


- Jill is orbiting the black hole in a starship at a safe distance in a stable circular orbit.

He Said, She Said

From Jack's point of view:

- Sees the ship getting further away.
- Flashes his blue laser once a second by his watch



From Jill's point of view:

- Each flash takes longer to arrive, and is
- Redder and fainter than the one before it.

Near the Event Horizon...

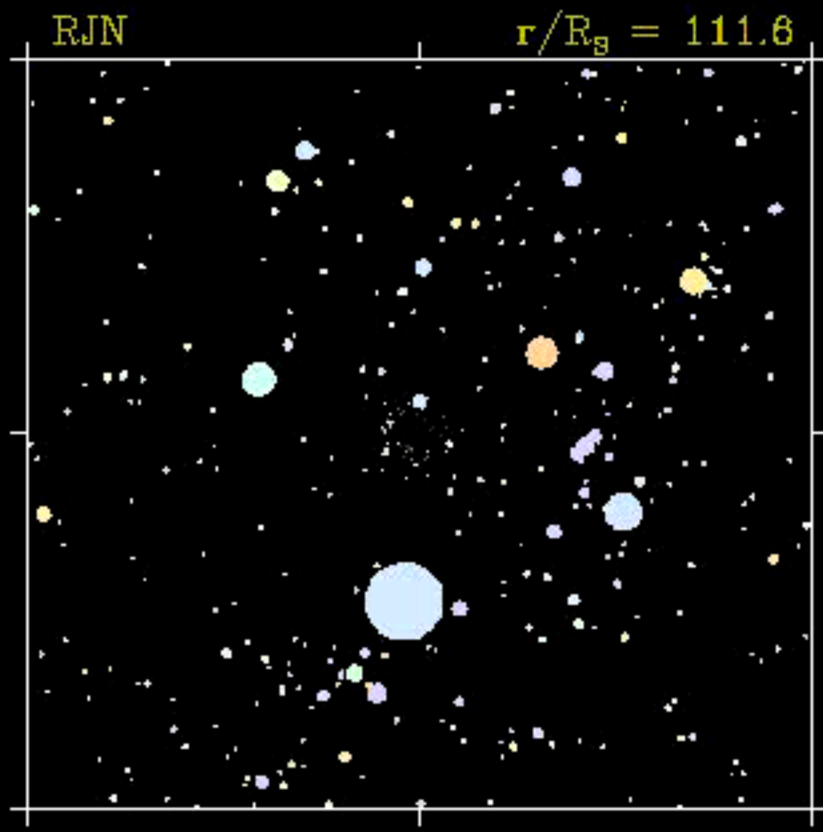
Jack Sees:

- His blue laser flash every second by his watch
- The outside world looks distorted

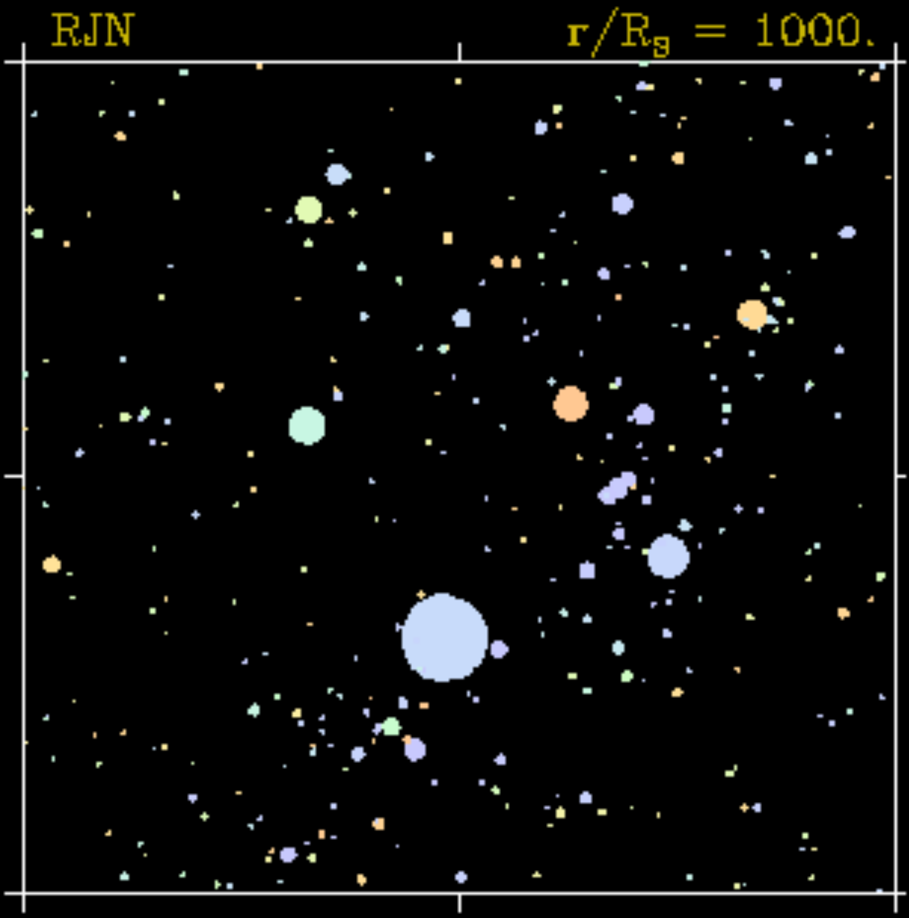
Jill Sees:

- Jack's laser flashes come ~1 hour apart
  Time Dilation (Time slows down).
- Flashes are redshifted to radio wavelengths
  Gravitational Redshift (a bit like Dopple shift, but not)
- Flashes are getting fainter with each flash

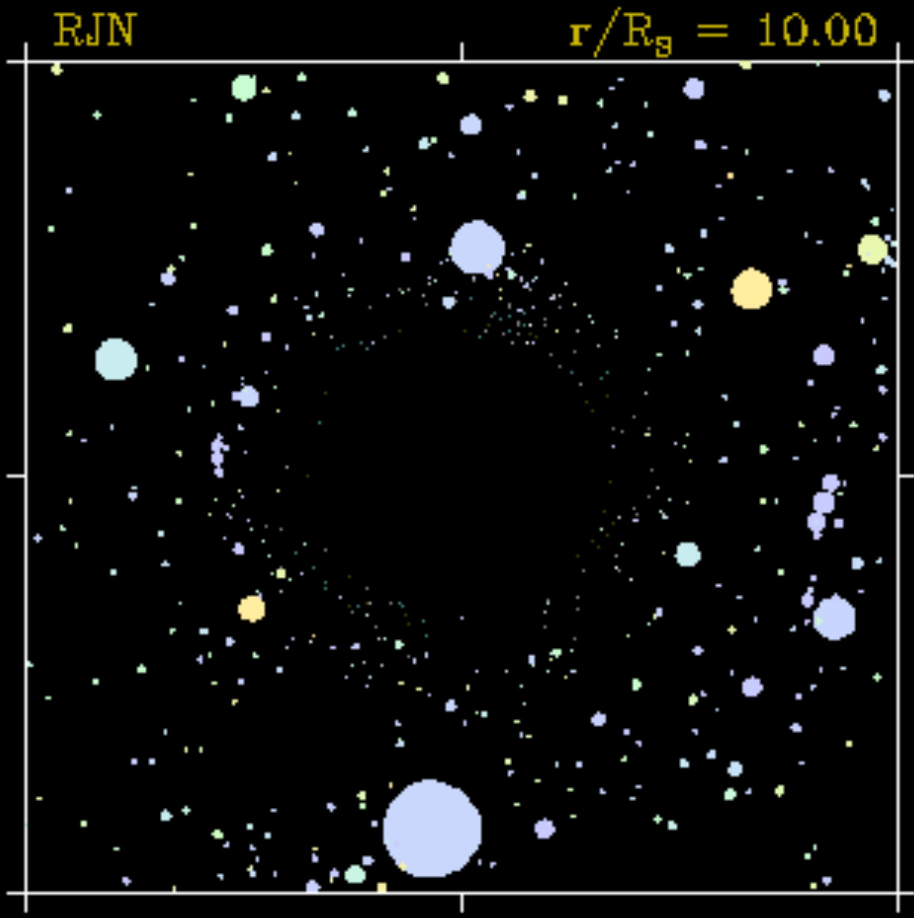
Light is bent/deflected by a strong gravitational field.



Light is bent/deflected by a strong gravitational field.

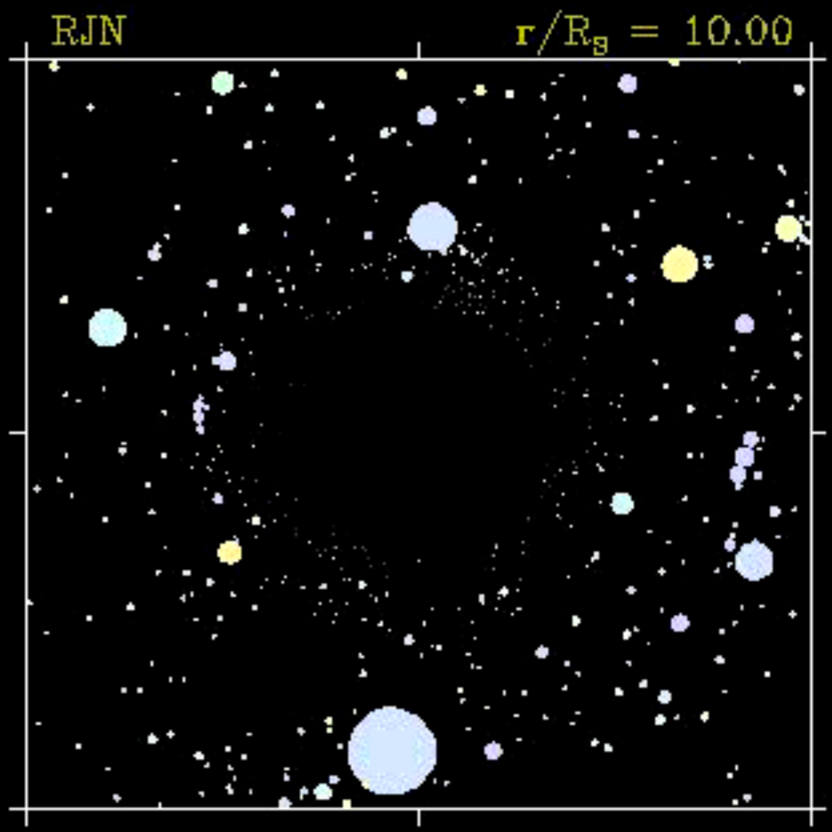


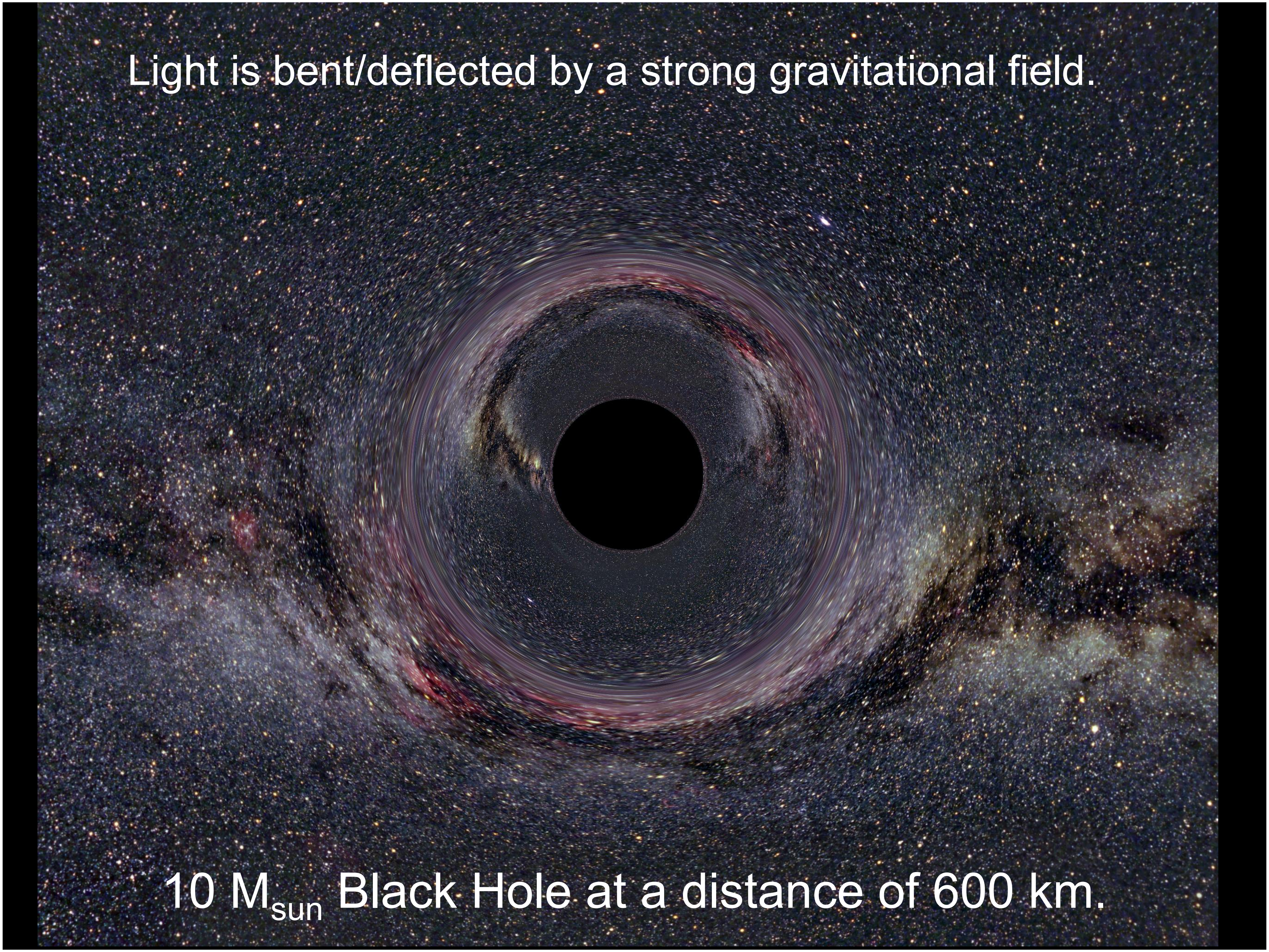
Jill's View from far away



Jack's view from $10R_S$

Circling a Black Hole.




Light is bent/deflected by a strong gravitational field.
10 M_{sun} Black Hole at a distance of 600 km.

Down the hole...

Jill Sees:

- Sees one last laser flash after a long delay
- Flash is faint and at long radio wavelengths
- She never sees another flash from Jack…

Jack Sees:

- Universe warped as he crosses the Event Horizon
- Gets shredded by strong tides near the singularity and crushed to infinite density.
- Atoms break down into constituents, then nuclei, then protons & neutrons, then …

Jill’s Conclusions:

The powerful gravity of a black hole warps space and time around it:

1. Time appears to stand still at the event horizon as seen by a distant observer.
2. Time flows as it always does as seen by an infalling astronaut. *Time Dilation*
3. Light emerging from near the black hole is *Gravitationally Redshifted* to longer (redder) wavelengths

Seeing what cannot be seen…

Q: If black holes are black, how can we see them?

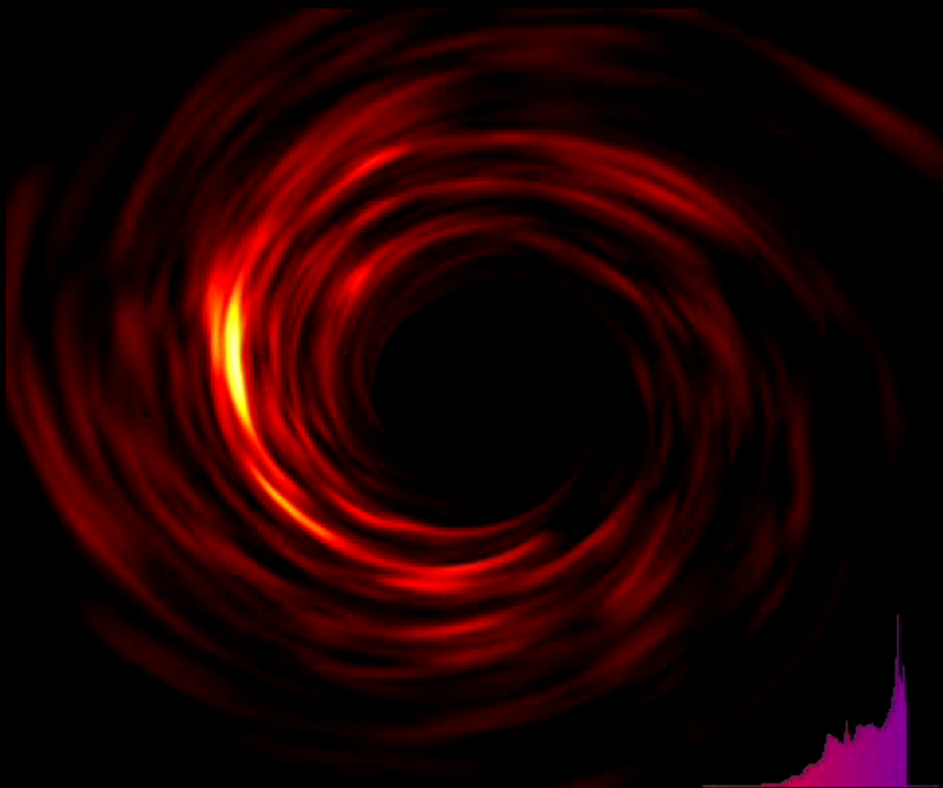
A: By the effects of their gravity on their surroundings:

- We see stars orbiting around an unseen but very massive object.
- X-rays emitted by gas superheated as it falls into the black hole. A significant fraction of the rest mass energy ($E=mc^2$) is radiated.

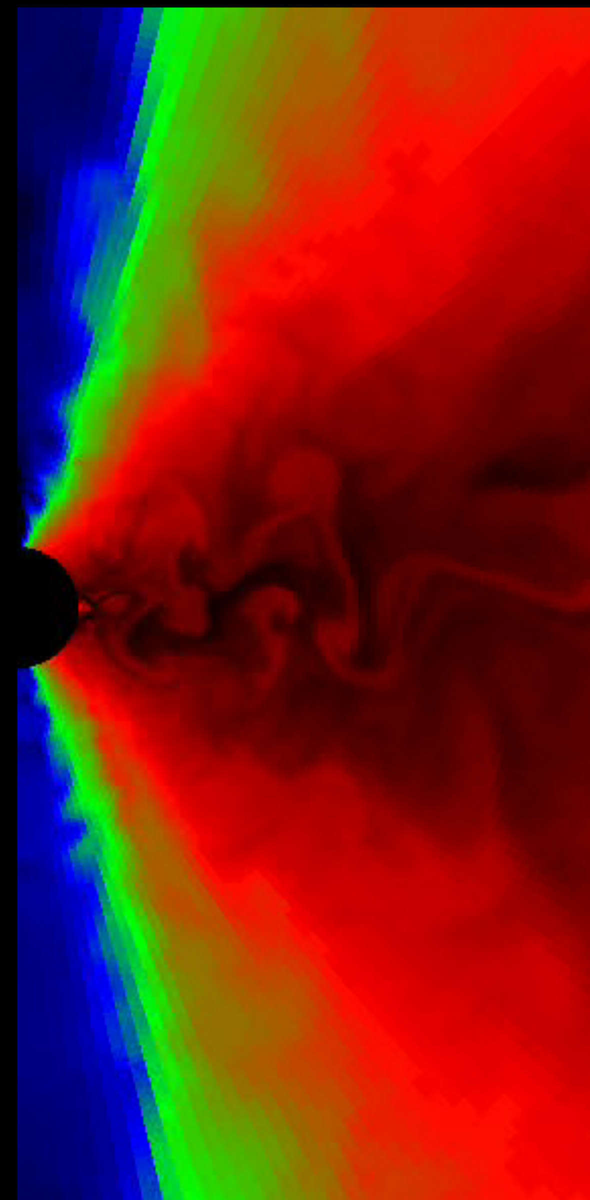
  How? "Friction"

Matter glows because it becomes very hot as it "accretes" onto the black hole.

Matter "falls" in to the black hole via an "accretion disk."



Armitage & Reynolds



Stone

X-Ray Binaries

Bright, variable X-ray sources identified by X-ray satellites:

- Binary with only one set of spectral lines – the companion is invisible.
- Gas from the visible star is dumped on the companion, disk forms, heats up, and emits X-rays.

Estimate the mass of the unseen companion from the orbit.

- Black hole candidates will have $M > 3\ M_{sun}$

Artist’s Conception of an X-Ray Binary

Black Hole Candidates

X-ray binaries with unseen companions of mass > 3 M_{sun}, too big for a Neutron Star.

Currently ~20 confirmed black hole candidates:

- First was Cygnus X-1: 7 – 13 M_{sun}
- Largest is GRS1915+105: 10 – 18 M_{sun}
- Most are in the range of 4 – 10 M_{sun}

Estimated to be ~1 billion stellar-mass black holes in our Galaxy alone.

Black Holes are not totally Black!

"Classical" General Relativity says:

- Black Holes are totally black.
- Can only grow in mass and size
- Last forever (nothing gets out once inside)

But,

General Relativity does not include the effects of Quantum Mechanics.

Evaporating Black Holes

Black Holes evaporate very slowly by emitting Hawking Radiation:

- Very cold thermal radiation (T~10 nK)
- Bigger black holes are colder (evaporate slowly)

Takes a very long time…

- 5 M_{sun} black hole takes ~10^{73} years.
- ~10^{63} times the present age of the Universe.

Not important today for massive BHs. But, a BH the mass of **me** would evaporate in ~10^{-10} s.