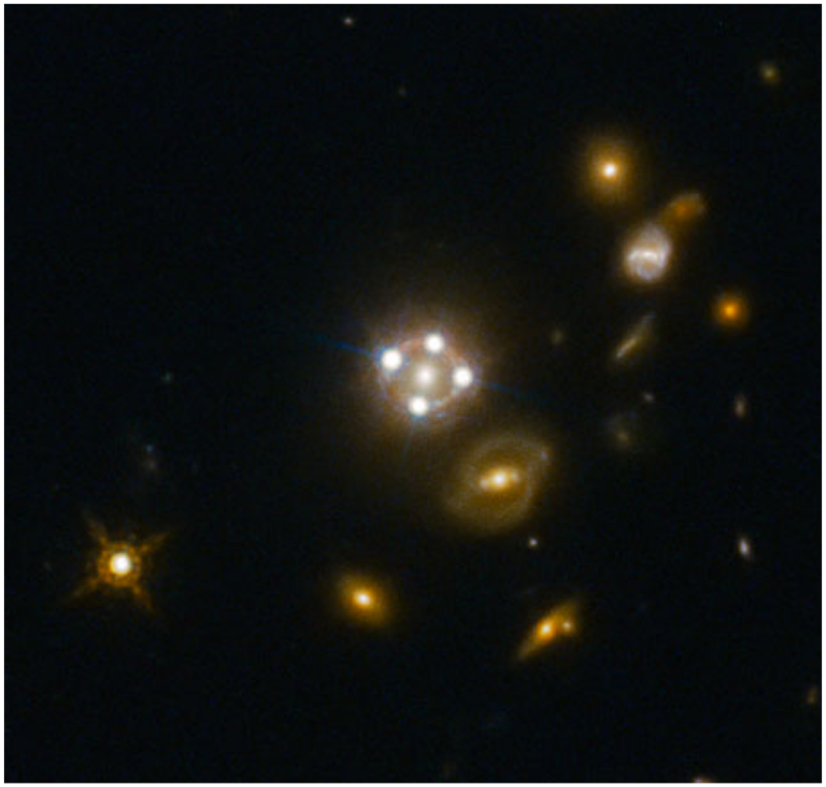
[11] Black Holes (3/1/18)

Upcoming Items

1. Midterm #1 next class!
2. Reviews in tomorrow's discussion, and Monday March 5, 6-8 PM, here. 100% driven by your questions!
3. Read Ch. 19.1 for next Thursday and do the self-study quizzes.
4. Homework #3 due **Tuesday March 13** (before the break!).

APOD 2/27/17



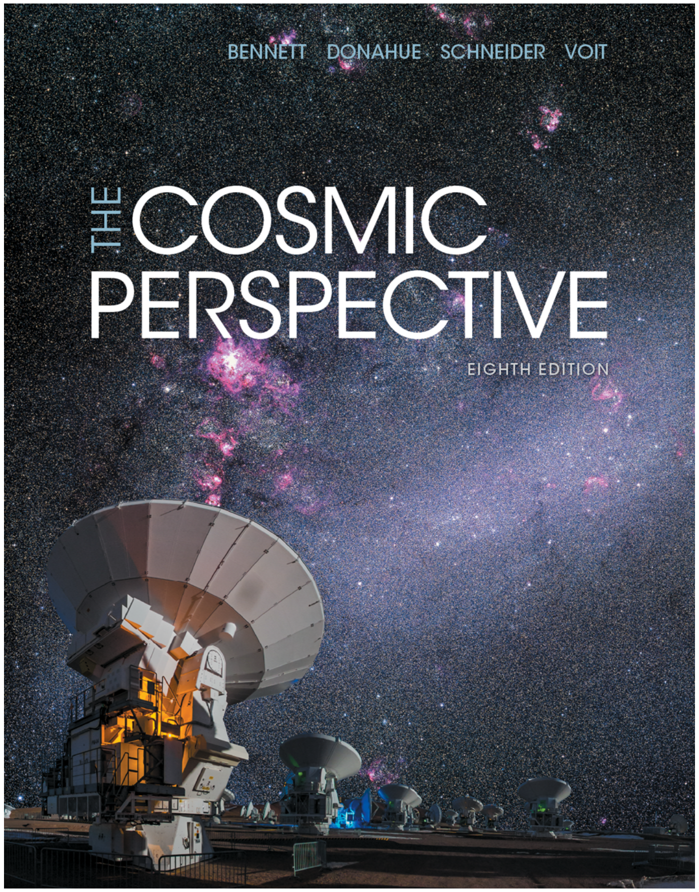
LEARNING GOALS

Ch. 18.3–18.4

For this class, you should be able to…

… *describe the circumstances that could lead to the formation of stellar-mass black holes, and provide evidence for their existence;*

… *explain what is meant by the term "event horizon" of a black hole, describe the physical effects in its vicinity, and find the Schwarzschild radius given the mass;*



Any astro questions?

In-Class Quiz

1. For a non-rotating, and therefore spherically symmetric, black hole, which of the following is true of orbits around it?

A. Elliptical orbits have precession of their pericenter.
B. The orbital plane precesses.
C. The orbits can extract energy from the black hole.
D. All circular orbits outside the horizon are stable.

2. Which of the following is evidence for black holes?

A. On scales of kiloparsecs, our Galaxy has excess matter
B. Some X-ray binaries have optically dim >3 solar mass objects accreting from a companion
C. The expansion of the universe is accelerating
D. Some observed explosions can be explained by Hawking radiation

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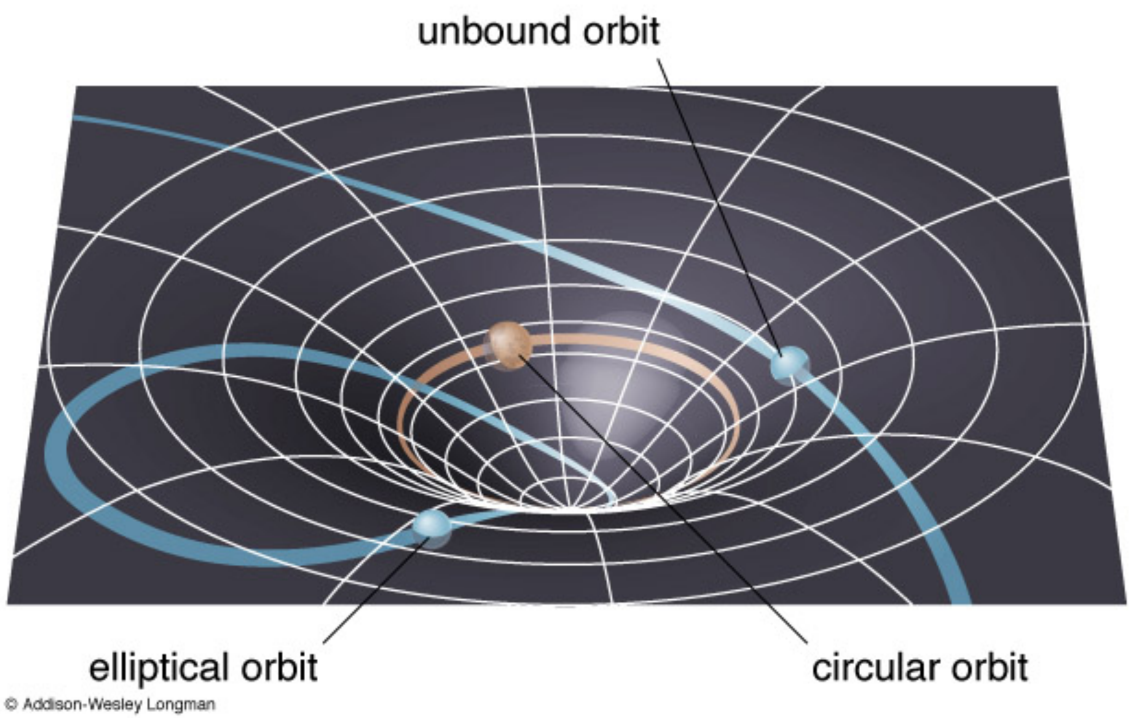
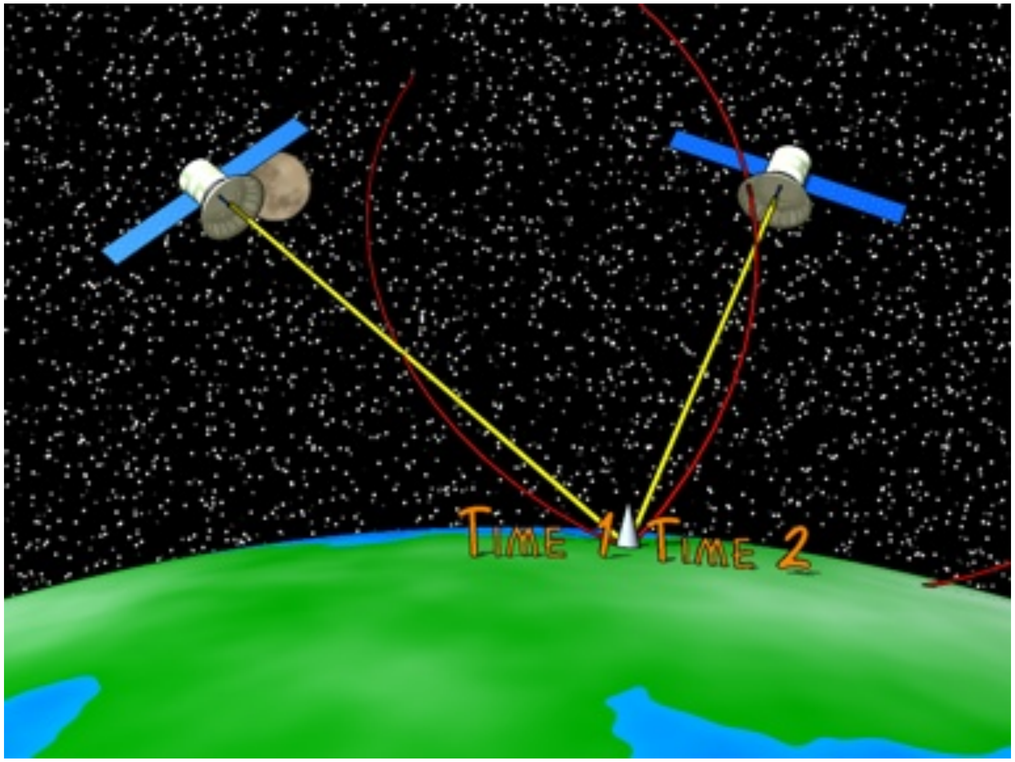
General Relativity



- Einstein's theory of gravity (1915)
- Free-fall is the "natural" state of motion
- Space+time (spacetime) is warped by gravity
- Reduces to Newton's laws in weak gravity

Practical Effects of GR?

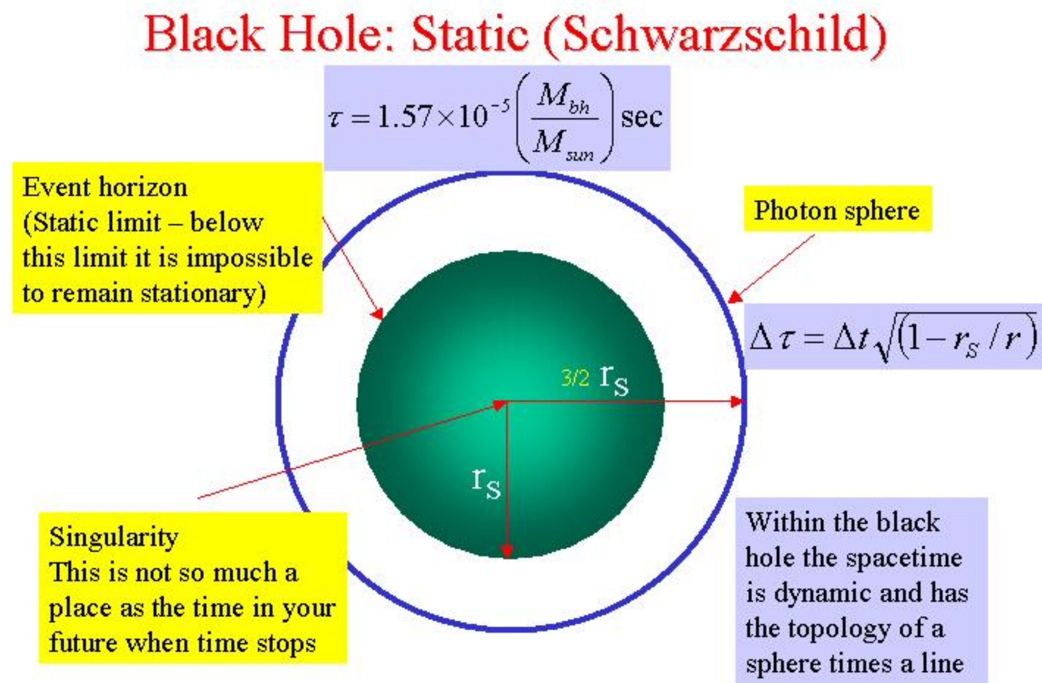
- Global positioning system (GPS)
- Must account for GR time dilation effect
- Otherwise, would drift rapidly out of alignment
- You never know the benefits of research!



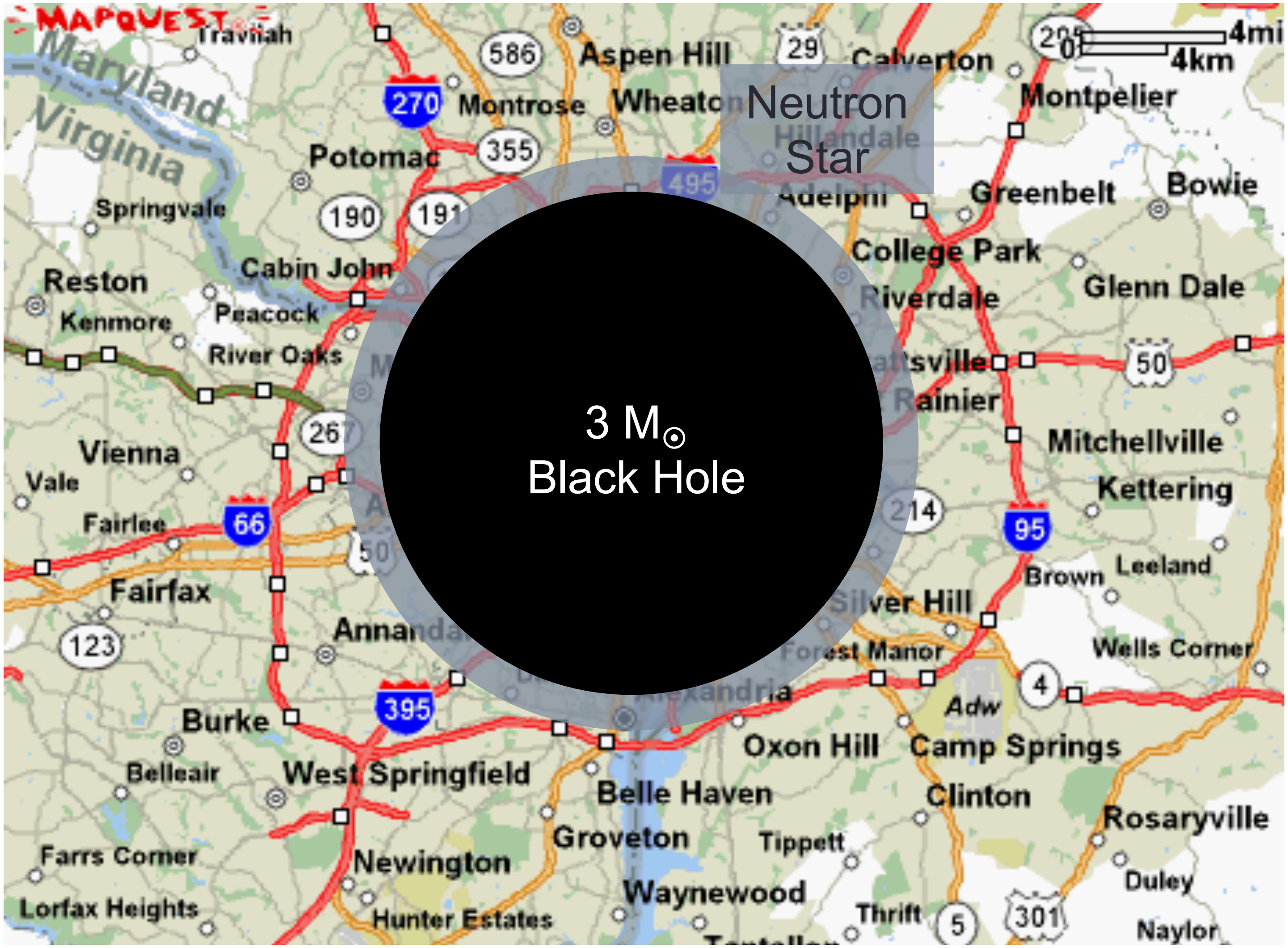
http://www.whylearnthat.co.uk/GPSPic.jpg

Black Holes

- John Michell, 1783: would the heaviest things be dark?
- Modern view based on general relativity
- Event horizon: point of no return
- Near BH, strong distortions of spacetime



Simplest big things in the universe!
But not large: R=3 km (M/M_{sun})



The event horizon of a 3 $M_\odot$ black hole is about the size of a small city, a bit smaller than a neutron star.

Caution

- We emphasize weird aspects of black holes
- But, far enough away, gravity is just the same as for any other mass.
- What would happen to Earth if the Sun magically became a solar mass BH?

Caution

- We emphasize weird aspects of black holes
- But, far enough away, gravity is just the same as for any other mass.
- What would happen to Earth if the Sun magically became a solar mass BH?
  Not much! Our orbit would be the same, although it would get mighty cold...

But Do Black Holes Exist?

- First idea was solution of Einstein's equations by Karl Schwarzschild in 1916
  From Russian front in WW I
- But do BH actually exist? How would we detect them?

Detecting Black Holes

- Problem: what goes down doesn't come back up
- Seems like they would be invisible...

"It's black, and it looks like a hole.
I'd say it's a black hole."

Group Q: Detecting Black Holes

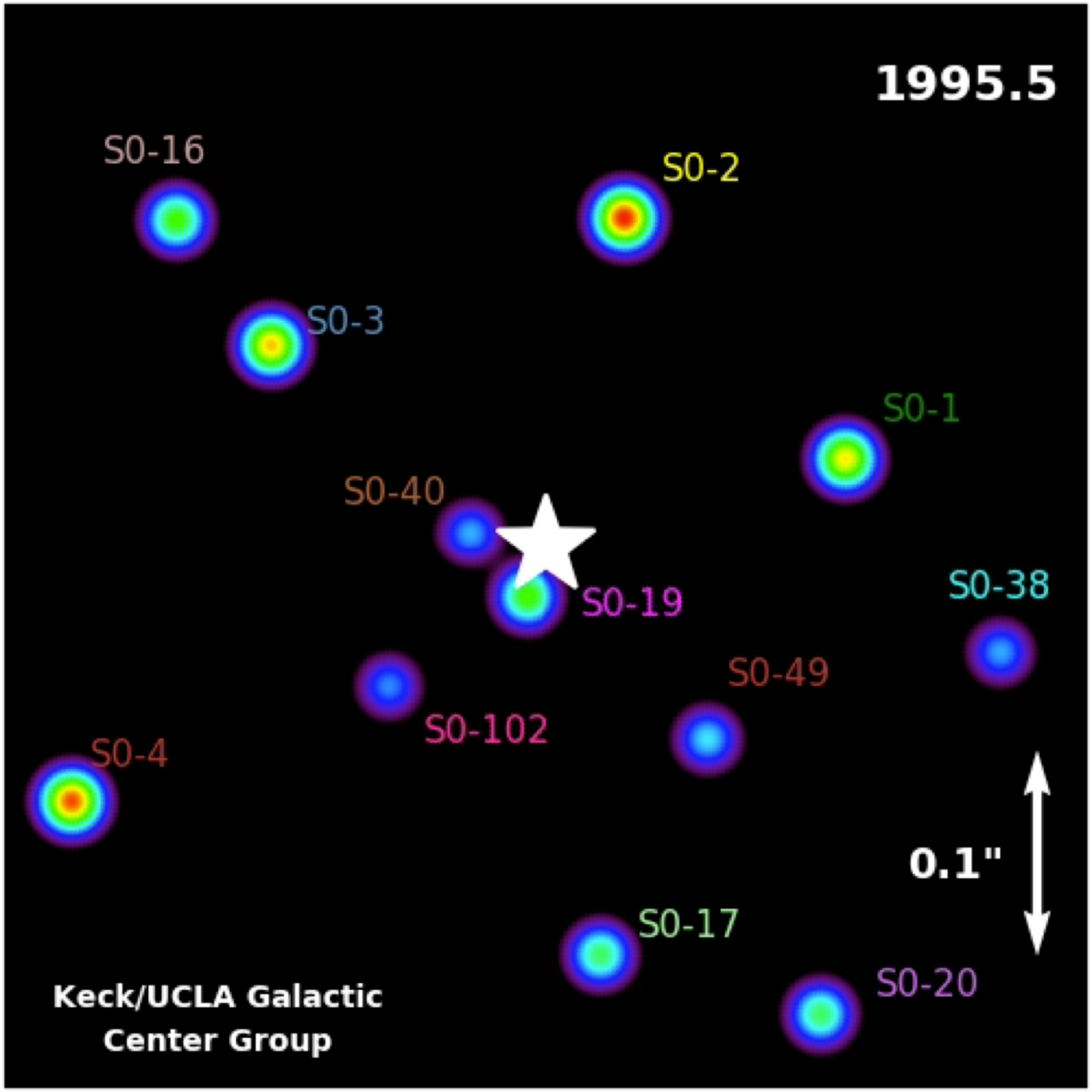
- In your groups, come up with as many ways as possible to detect black holes
- Really two questions:
  1. How could BH be detected?
  2. How could you be sure they are BH rather than something else?
- Good luck!

Frank Summers, STScI

How Do We Detect BH?

- By their effects on other things!
- Could see star (or stars) orbiting around something that we can't see
- Or, rapidly spiraling gas that is therefore hot
- Or other ways
- But do we actually see these things?

Stars at the Galactic Center



The Case of the Galactic Center

- ~4 million M_{sun} crammed into a volume less than the size of the Solar System out to Pluto
- That's impressive
- But in that volume there is room for a trillion suns!
- Okay, that would be too bright, but how could we tell if there were a few million white dwarfs or neutron stars; very dim?
- Need a more general argument...

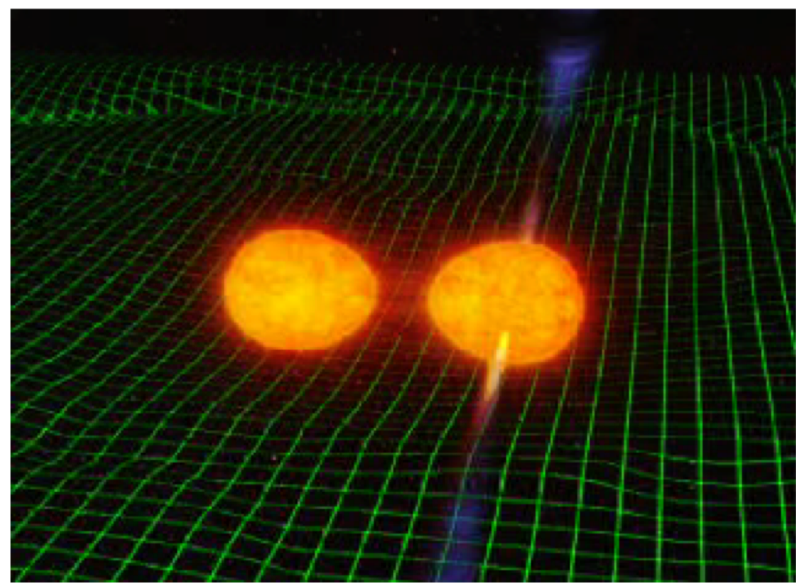
Black Hole Masses

- In principle, a black hole can be any mass, but we seem to find black holes in only two (maybe three) mass ranges:
  - Stellar-mass black holes.
    - Masses of a few–40 $M_{\odot}$.
    - Formed from death of massive stars.
  - Supermassive black holes.
    - Masses of 10^6–10^{10} $M_{\odot}$.
    - Found in centers of galaxies. Origin unknown, but almost certainly date back to formation of galaxy—more on these later!
  - Maybe: intermediate-mass black holes (still controversial!).
    - 100–10^4 $M_{\odot}$.
    - Evidence for existence of such black holes in centers of globular clusters and the outskirts of galaxies. Origin unknown.

Gravitational Waves

- Back to rubber sheet
- Moving objects produce ripples in spacetime
- Close binary black hole or neutron star are examples
- Very weak!
- How can we detect these?

John Rowe Animation



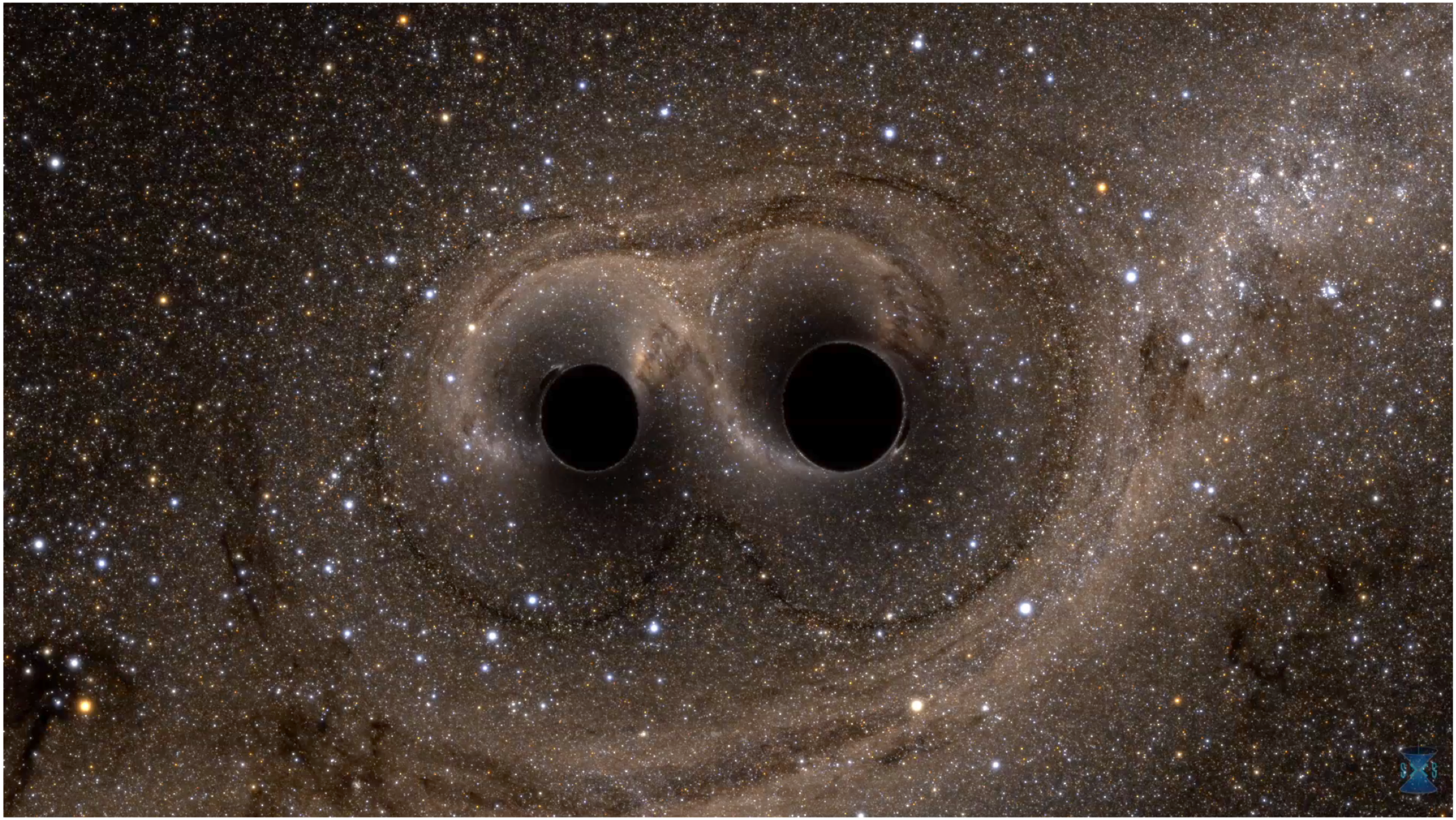
Gravitational Wave Detectors

LIGO

Laser
Interferometer
Gravitational-wave
Observatory

Part in 10^{22} precision
Like measuring distance to a star with an error equal to width of a hair!

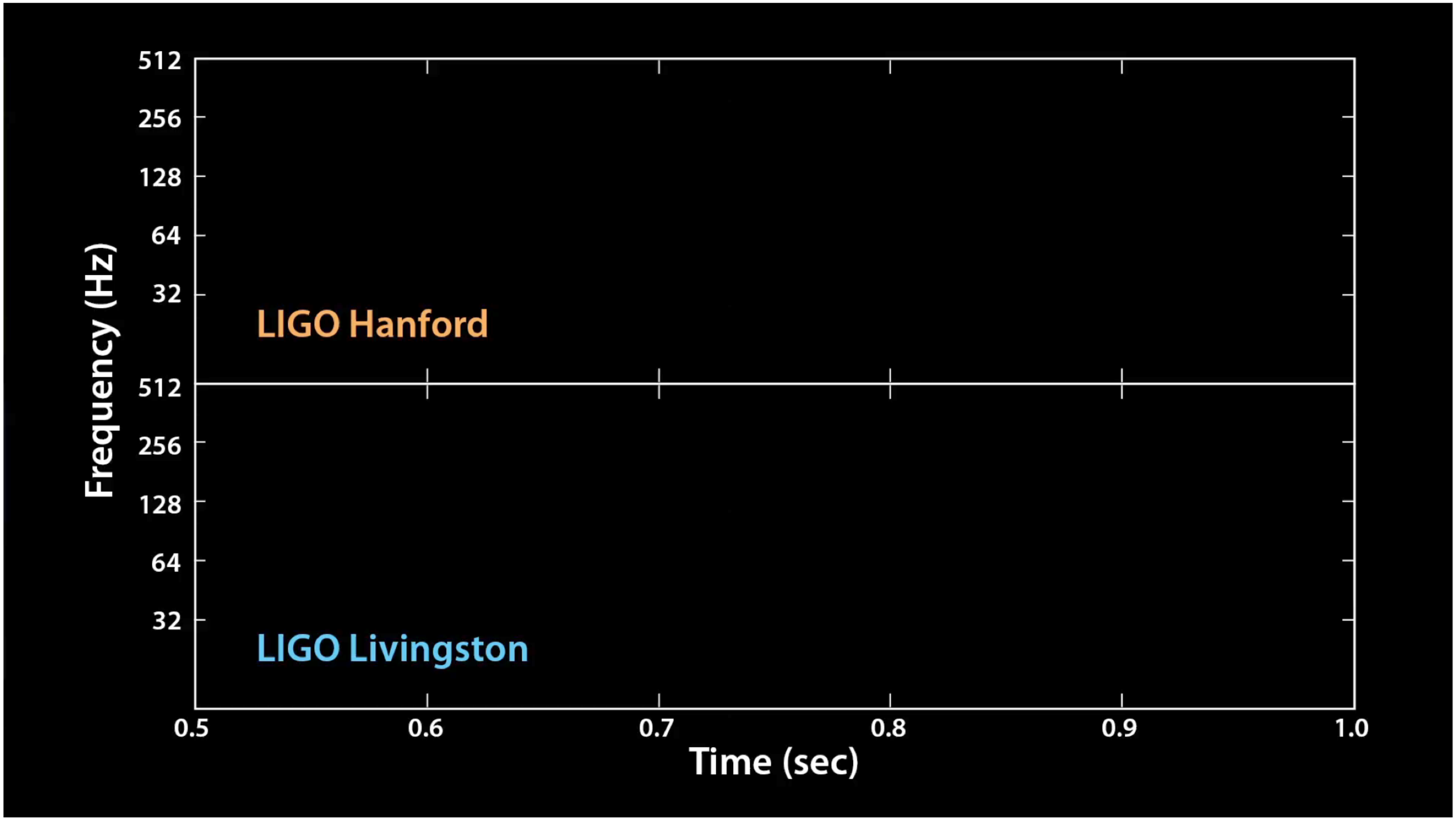
September 14, 2015

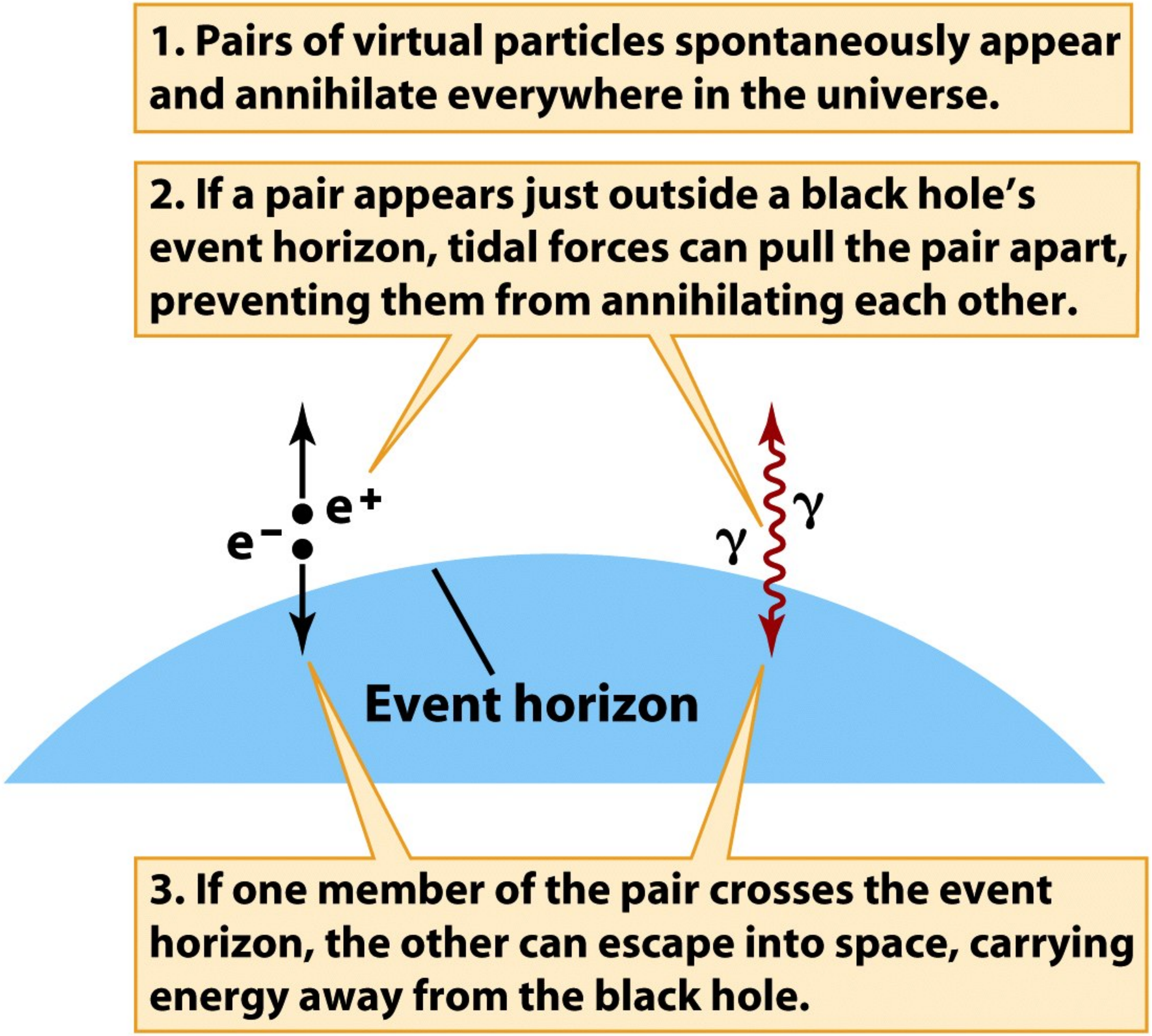


General Perspectives

- Limited set of deep-space messengers
  Photons, ν, CR; now GW added!
- Can now see very energetic but previously invisible events
  During merger, GW150914 produced ~50x as much energy as all stars in the visible universe combined over that time!
- These weren’t minor events we were missing...

Listening to Gravitational Waves




1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.
2. If a pair appears just outside a black hole's event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.
e+
e−
γ
γ
Event horizon
3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.

Black Hole Evaporation

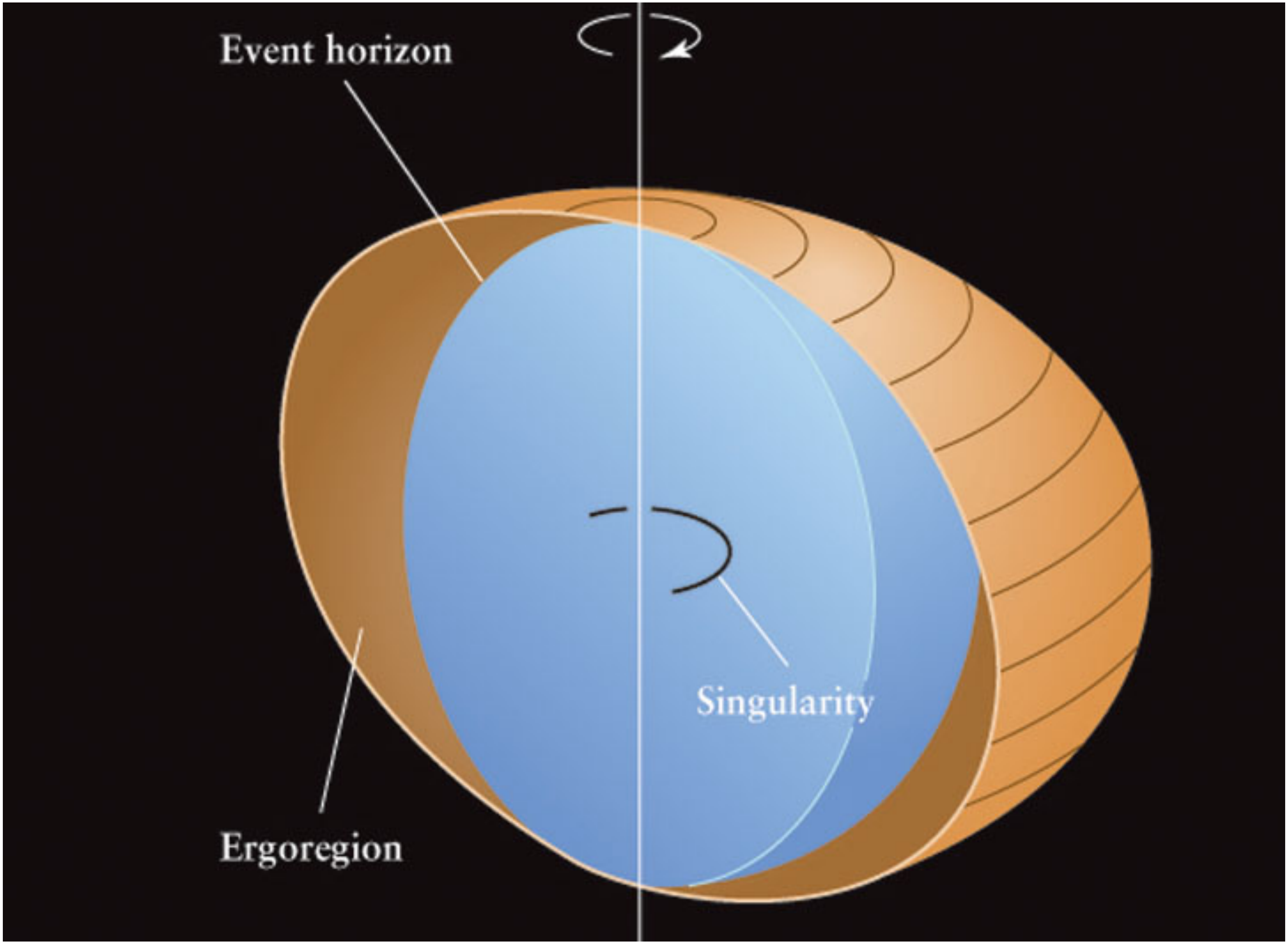
- Hawking showed that quantum effects cause black holes to behave like black bodies with temperature

$$T = \frac{hc^3}{16\pi^2 GMk_B}.$$

- So, over time, they radiate away their energy and hence grow smaller. Time: ~10^{70} years $(M/10\ M_{sun})^3$!!!
- Larger black holes are much "cooler" and evaporate much more slowly… so slow the process is generally irrelevant.
- It *does* matter for microscopic black holes that may be created, e.g., at the LHC… they would probably never even make it out!

Spinning Black Holes

- Spacetime is twisted by rotation… objects close to black hole are "dragged" into rotation with it (frame-dragging).
- Within ***ergoregion***, it becomes impossible to stand still… you have to revolve in same sense as black hole rotates.
- It turns out that the ergoregion is where the rotational energy of the black hole is stored.
- Nature can tap this energy store: can energize accretion disk or power jets.


Event horizon
Singularity
Ergoregion