Black Holes

"Not only does God definitely play dice, but He sometimes confuses us by throwing them where they can't be seen."

– Stephen W. Hawking

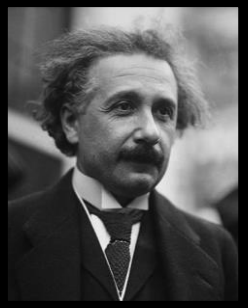
https://apod.nasa.gov/apod/ap141026.html
http://www.hawking.org.uk/does-god-play-dice.html

Black Holes…

- What are they?
- How are they born?
- What do they look like?
- How do they behave?
- How do they die?

- Sir Isaac Newton (1687):
  describes gravity in the *Principia*
  https://media1.britannica.com/eb-media/08/3008-004-F87BC031.jpg

- Rev. John Michell (1783):
  postulates star so massive light cannot escape
  (no image)

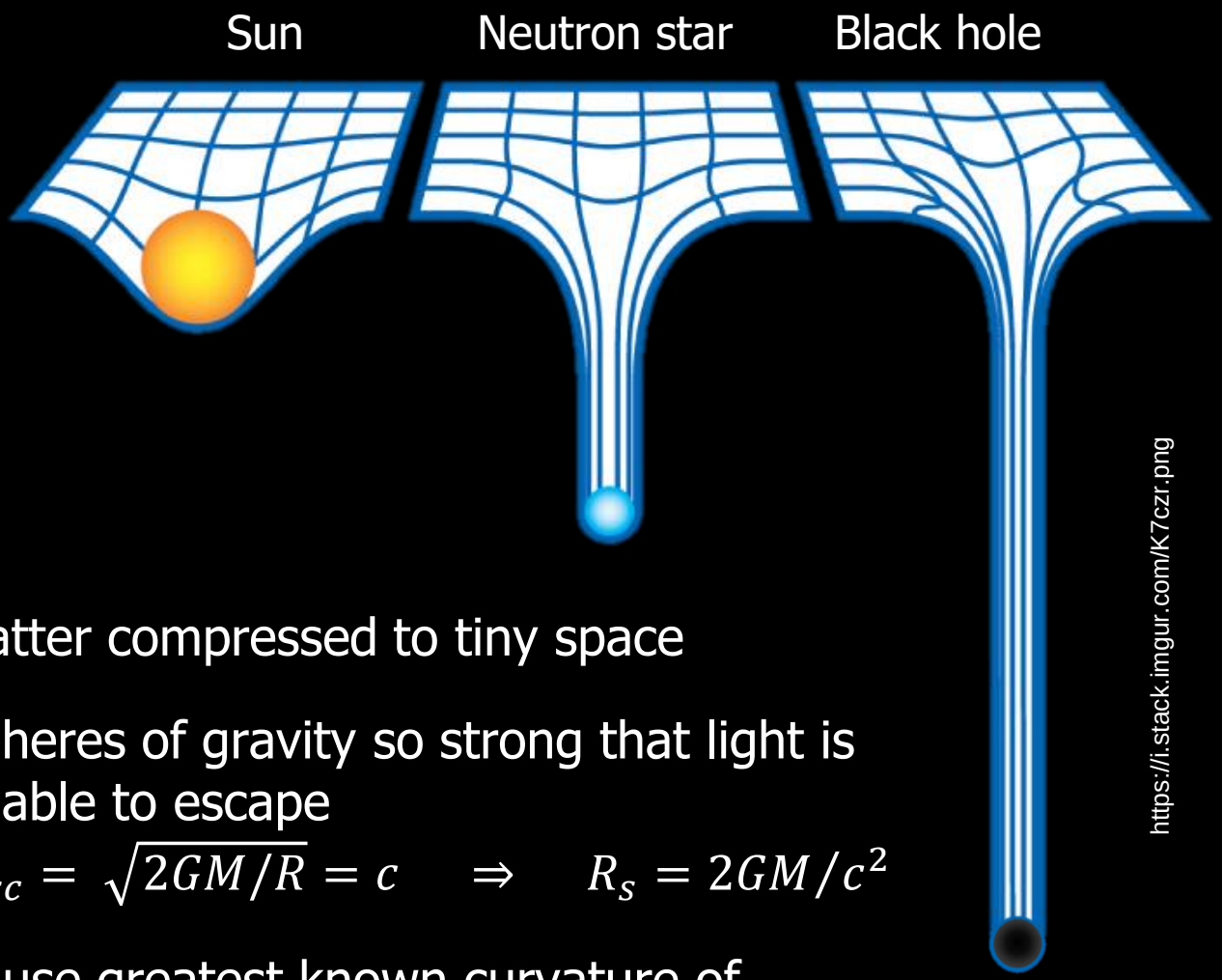


- Albert Einstein (1915):
  devises General Theory of Relativity, explains how massive objects distort spacetime
  https://media1.britannica.com/eb-media/59/23359-004-ADFA47C8.jpg

- Karl Schwarzschild (1916):
  finds first exact solution to $G_{\mu\nu} = 8\pi T_{\mu\nu}$ (Einstein Field Equations), shows escape velocity greater than speed of light is possible
  https://media1.britannica.com/eb-media/94/26394-004-1AF5988A.jpg

- John Wheeler (1964):
  uses the term "black hole" in a lecture
  https://media1.britannica.com/eb-media/25/164025-004-520BA505.jpg

What are they?



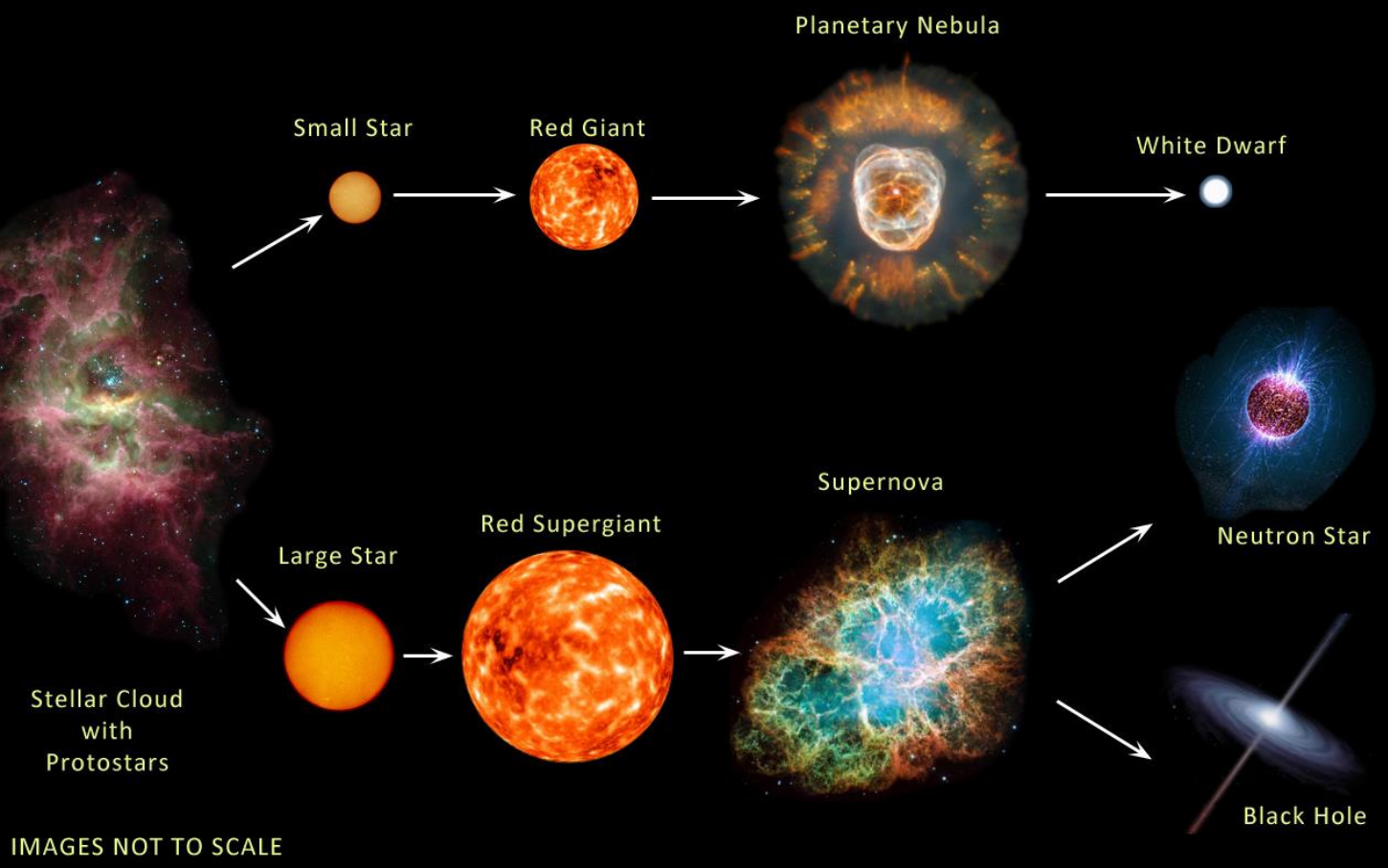
https://i.stack.imgur.com/K7czr.png

What are they?

- Matter compressed to tiny space
- Spheres of gravity so strong that light is unable to escape

  $V_{esc} = \sqrt{2GM/R} = c \quad \Rightarrow \quad R_s = 2GM/c^2$
- Cause greatest known curvature of spacetime
- Singularity at the center

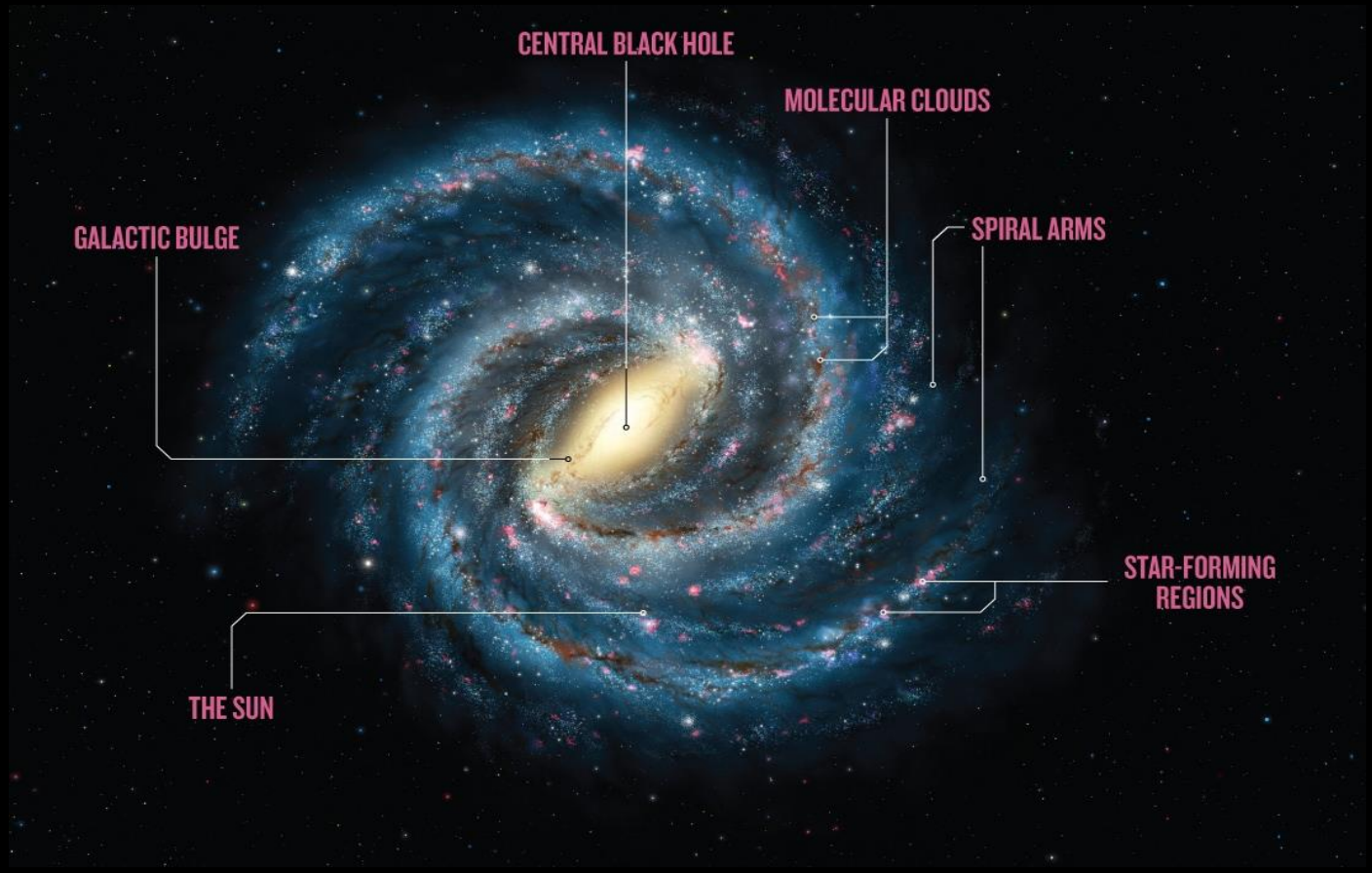
- Stellar:
  - massive star collapse
  - up to 20 times mass of sun *(recent developments)*



https://s3.amazonaws.com/user-media.venngage.com/488088-840398012017cbafeb377eaae4e5e9e9.jpg

How are they born?

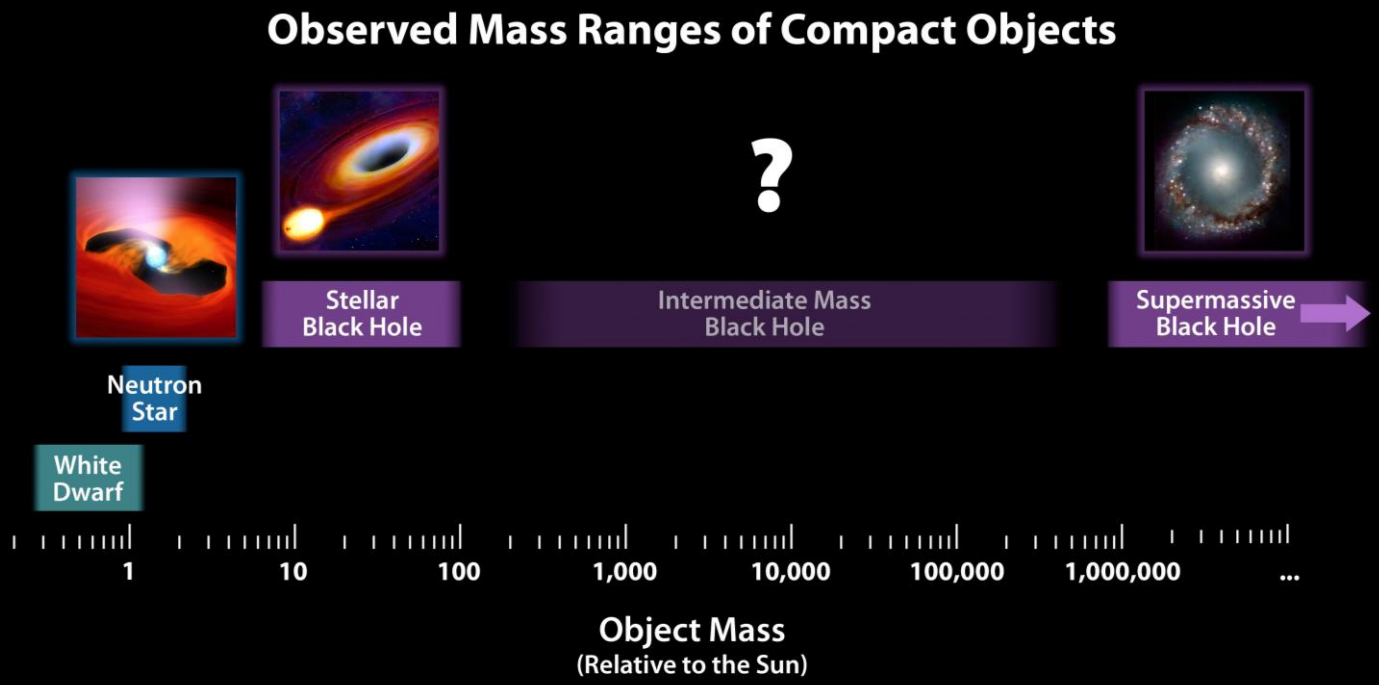
- Supermassive:
  - formed with galaxy
  - greater than 1,000,000 times mass of sun



https://theglobalscientist.files.wordpress.com/2015/01/fig1.jpg

How are they born?

- Intermediate (theoretical):
  - collisions within star cluster which then collapse
  - between stellar and supermassive
- Primordial/Miniature (theoretical):
  - created during Big Bang
  - small as an atom, mass of a mountain



https://www.nustar.caltech.edu/system/avm_image_sqls/binaries/62/jpg_original/nustar141008b.jpg?1412787614

How are they born?

- Solutions to Einstein's Field Equations

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Schwarzschild (1915)

$$ds^2 = -\left(1 - \frac{2m}{r}\right)dt^2 + \frac{dr^2}{1 - \frac{2m}{r}} + r^2 d\Omega_2^2$$

Reissner-Nordstrom (1916/1918)

$$ds^2 = -\left(1 - \frac{2m}{r} + \frac{Q^2}{r^2}\right)dt^2 + \frac{dr^2}{1 - \frac{2m}{r} + \frac{Q^2}{r^2}} + r^2 d\Omega^2$$

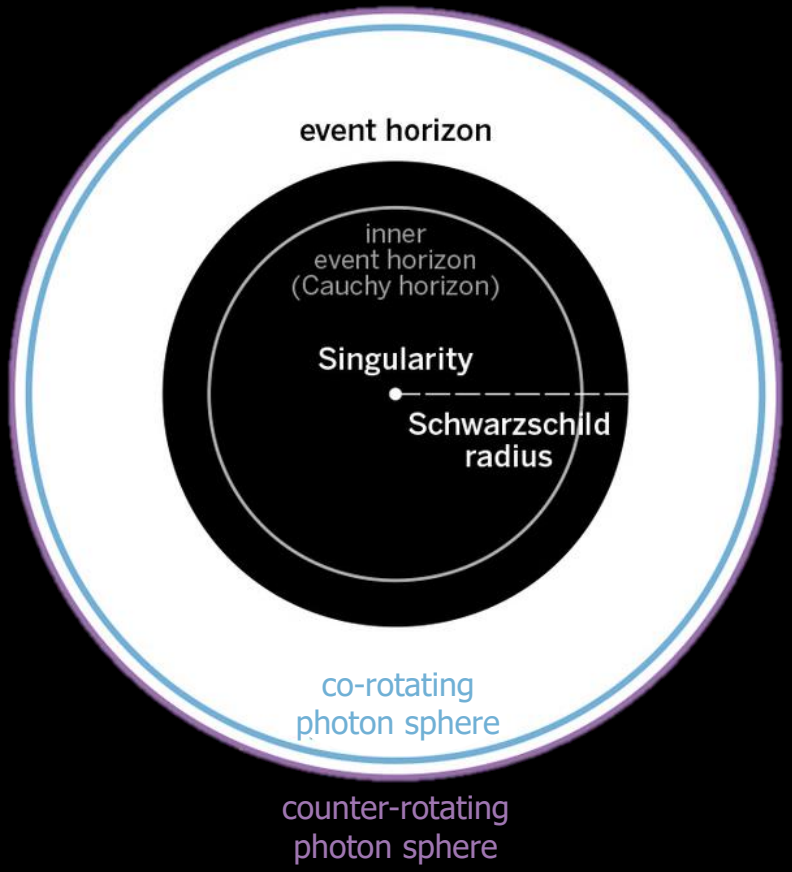
Kerr (1963) & Kerr-Newman (1965)

$$ds^2 = -\frac{\Delta}{\rho^2}(dt - a\sin^2\theta d\phi)^2$$

$$+ \frac{\sin^2\theta}{\rho^2}[(r^2 + a^2)d\phi - adt]^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2$$

How are they born?

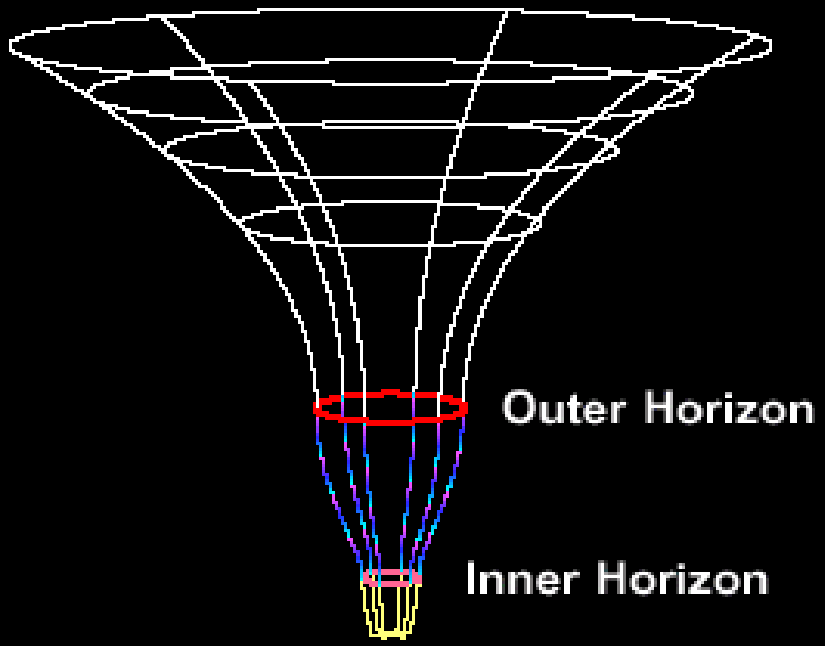
- Schwarzschild (1915)
  - no rotation, no charge (ideal case)
  - Schwarzschild radius: $r = 2GM/c^2$
  - sphere becomes black hole when its radius = r
  - singularity at $r = 0$



https://img.huffingtonpost.com/asset/592c8f3a1600002500ddd5c1.jpg?ops=scalefit_820_noupscale

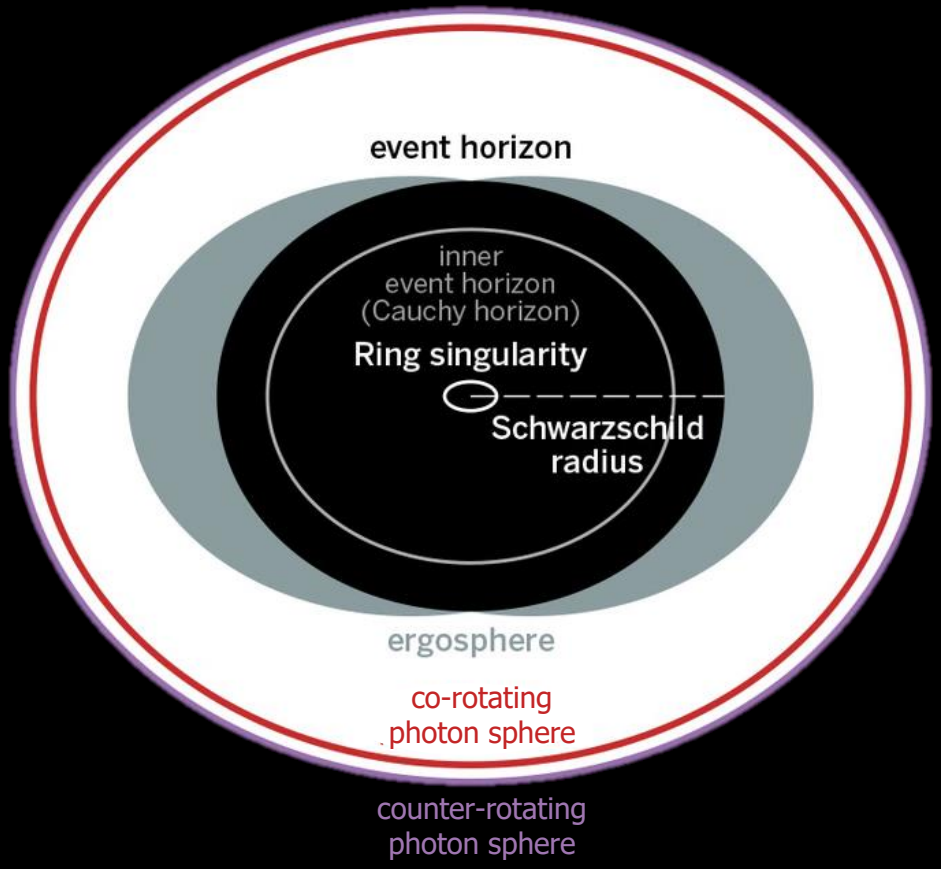
How are they born?

- Reissner-Nordström (1916/1918)
  - no rotation, has charge
  - if charge is less than mass, then goes to a regular black hole, but with two horizons
  - astrophysically irrelevant: a charged black hole in space would attract charged particles and neutralize



http://casa.colorado.edu/~ajsh/geomrnbig_gif.html

- Kerr (1963)
  - rotates, no charge
  - singularity is a ring, not a point
  - special ergosphere region outside the horizon
  - spin (range from 0 to 1): $a = J/(G\,M^2/c)$



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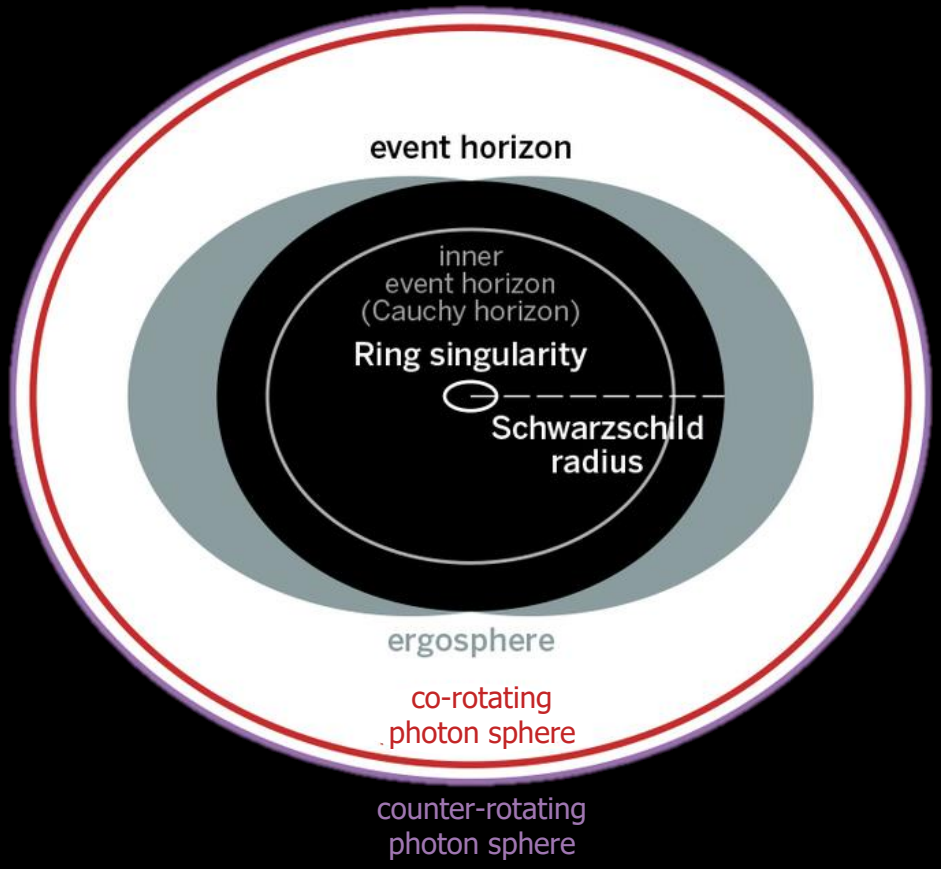
How are they born?

- Kerr-Newman (1965)
  - rotates, has charge
  - same matrix as Kerr solution
  - also astrophysically irrelevant (at this time)



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How are they born?

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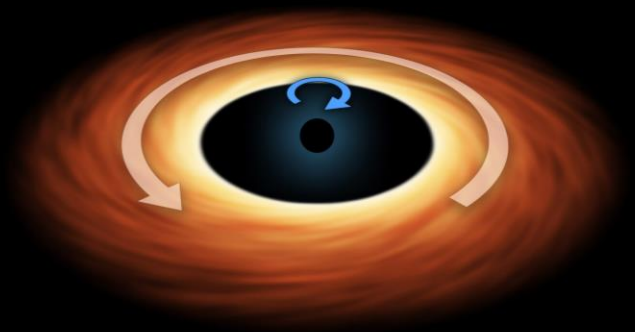
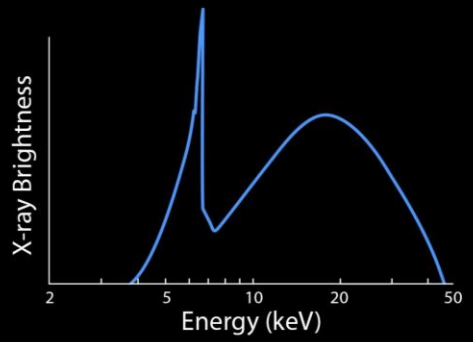
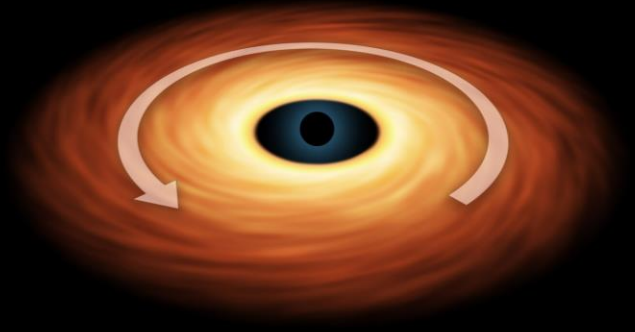
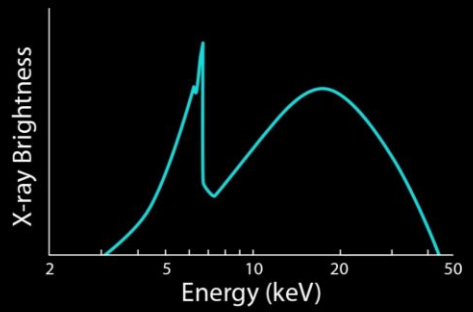


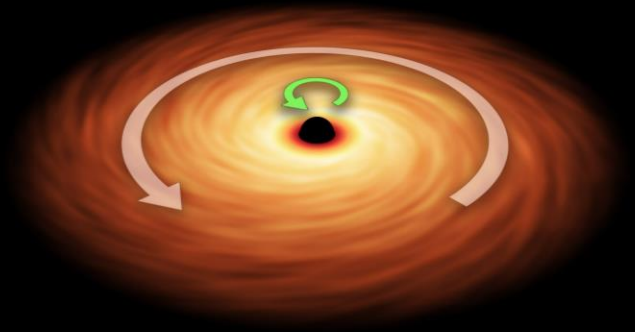
Retrograde Rotation



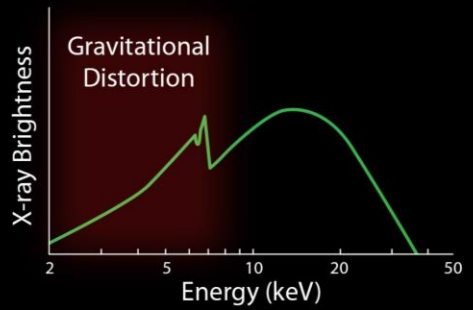


No Black Hole Rotation



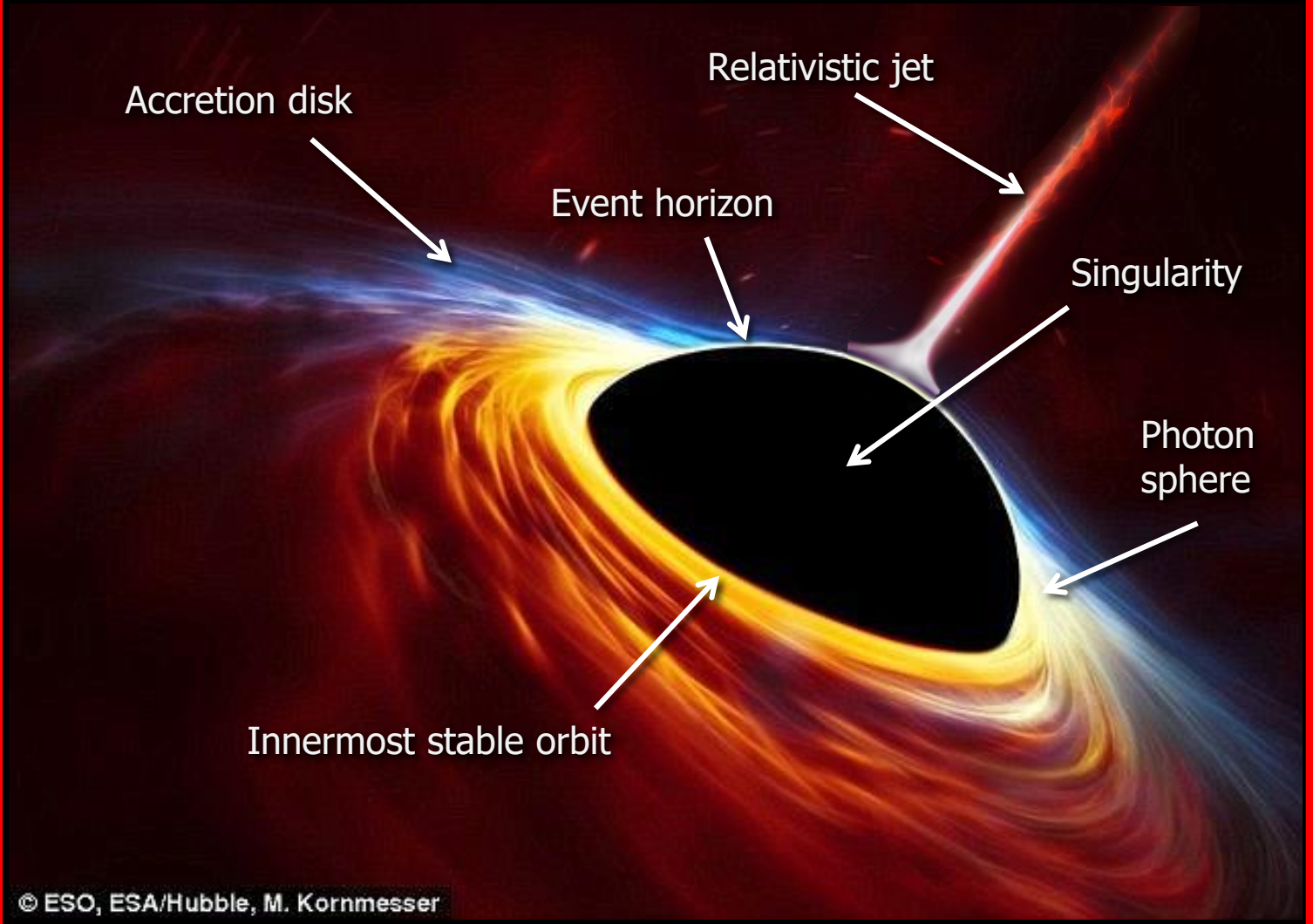


Prograde Rotation



https://www.nasa.gov/mission_pages/nustar/multimedia/pia16696.html

What do they look like?



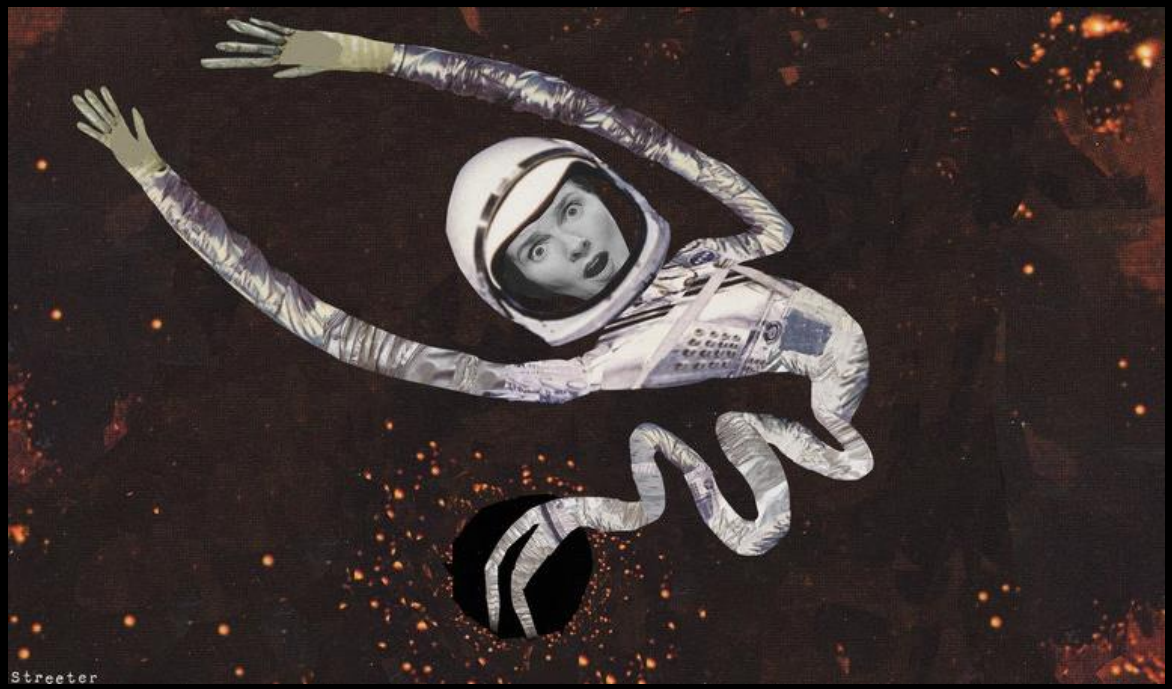
https://www.eso.org/public/archives/static/outreach/alma_first_picture_black_hole/black_holes_infographic-v2.jpg
http://i.dailymail.co.uk/i/pix/2017/03/27/15/3EAE6ECE00000578-4346886-An_artist_s_depiction_of_a_rapidly_spinning_supermassive_black_h-a-25_1490623530981.jpg

- Event horizon
  - grows while black hole forming, capturing matter
  - marked by light rays which neither escape nor fall in
- Apparent horizon
  - light rays directed away from star
  - surface neither contracting nor expanding
- If event horizon stops expanding, then both horizons coincide

http://archive.ncsa.illinois.edu/Cyberia/NumRel/Images/horizon.gif

How do they behave?

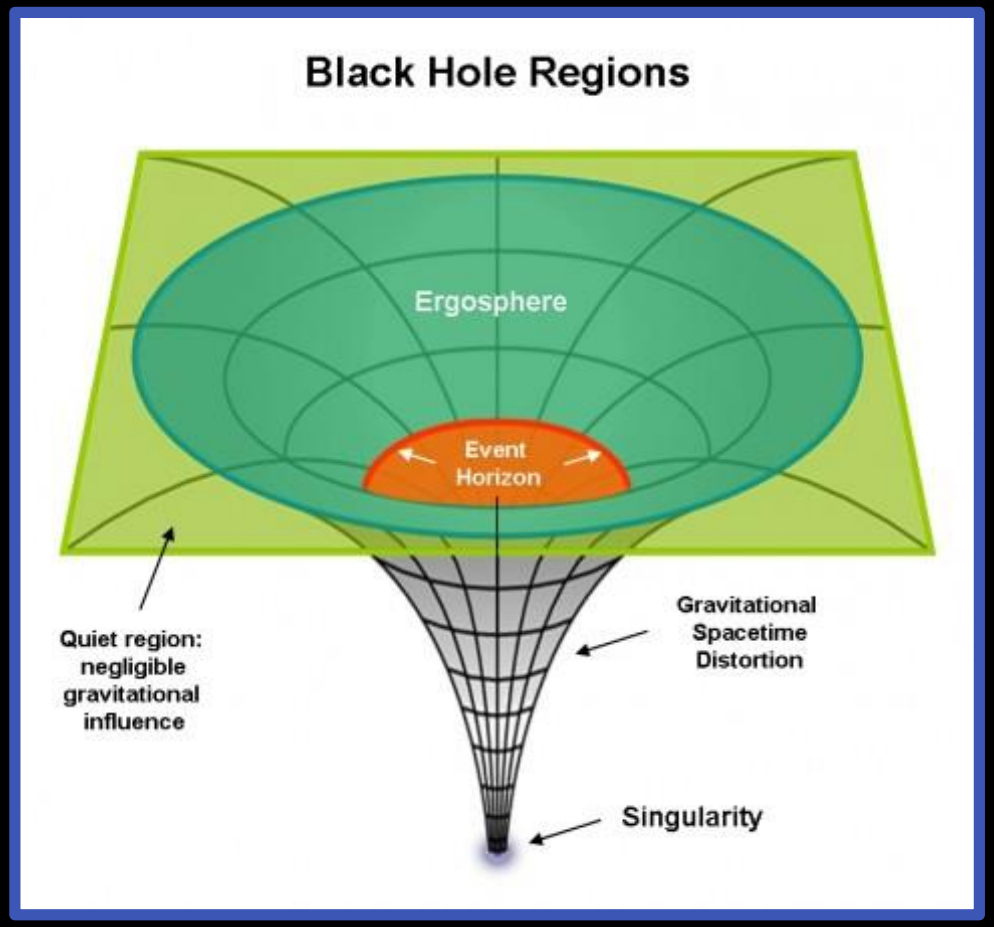
- To outside observer:
  - falling object's clock ticks slower
  - object's radiation appears redshifted
- To the falling object:
  - outside observer's clock ticks faster
  - radiation from outside appears blueshifted



media.npr.org/assets/img/2013/12/24/blackhole1a_wide-7ee72dbf78e99e35e09cf719b0596343796579fe-s800-c85.jpeg

How do they behave?

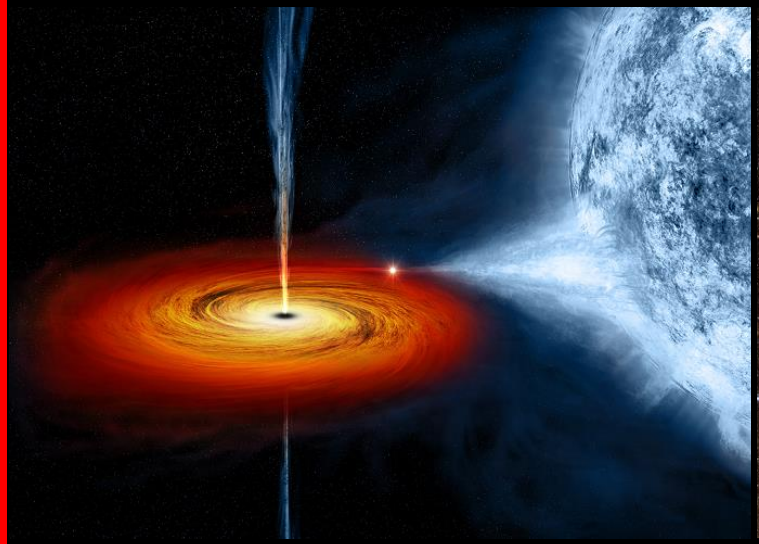
- Singularity (theoretical)
  - matter falls to point of zero volume
  - density of matter at center becomes infinite
  - existence suggests theory is incomplete

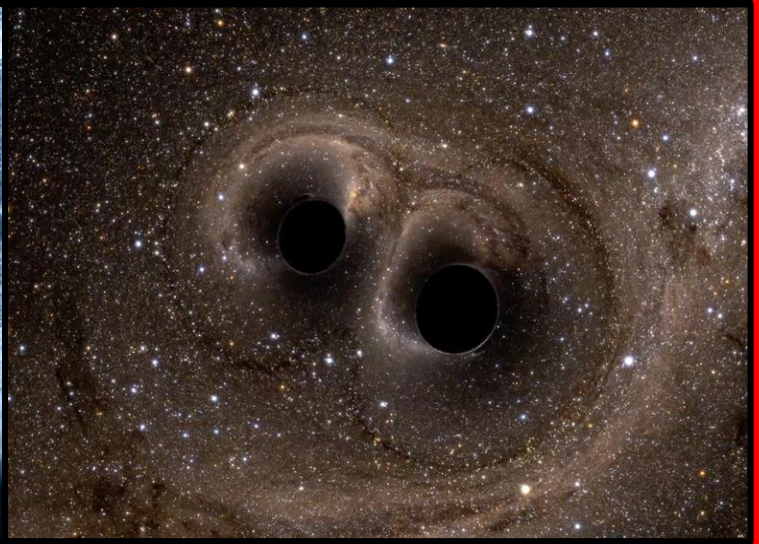


https://van.physics.illinois.edu/website/pictures/18721/Black-Hole-Regions-2_866px-475x444.jpg

How do they behave?

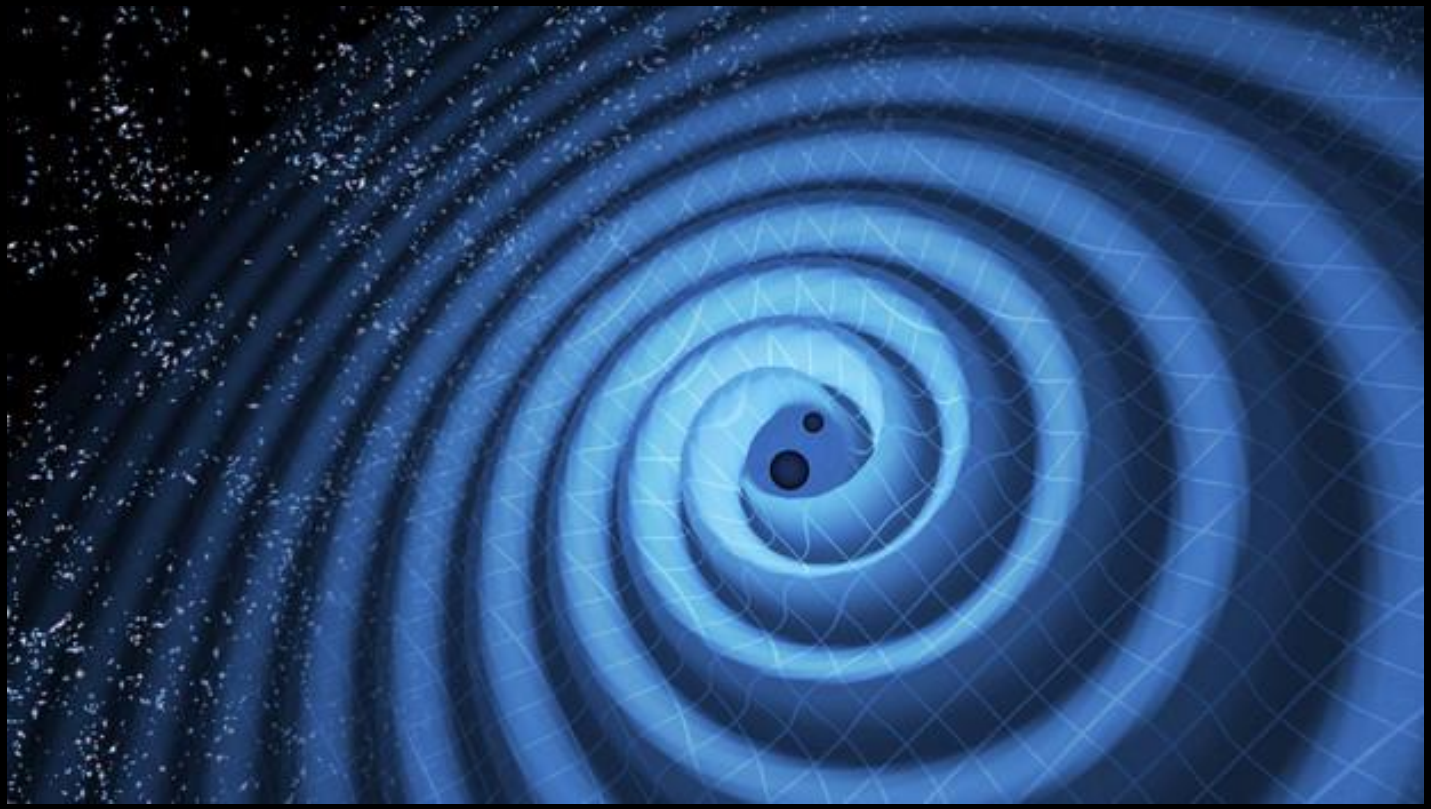
- Obeys laws of physics (at least externally)
  - if a black hole with mass of the sun replaced the sun, solar system movement would stay the same
  - does not wander about looking for matter
- Captures objects that get too close
  - Accretion disk: matter and light pulled from a star
  - Binary black hole: another black hole gets drawn in





https://www.nasa.gov/sites/default/files/cygx1_ill.jpg
https://www.ligo.caltech.edu/system/video_items/images/32/medium/ligo20160211v3_Tn.jpg?1455162048

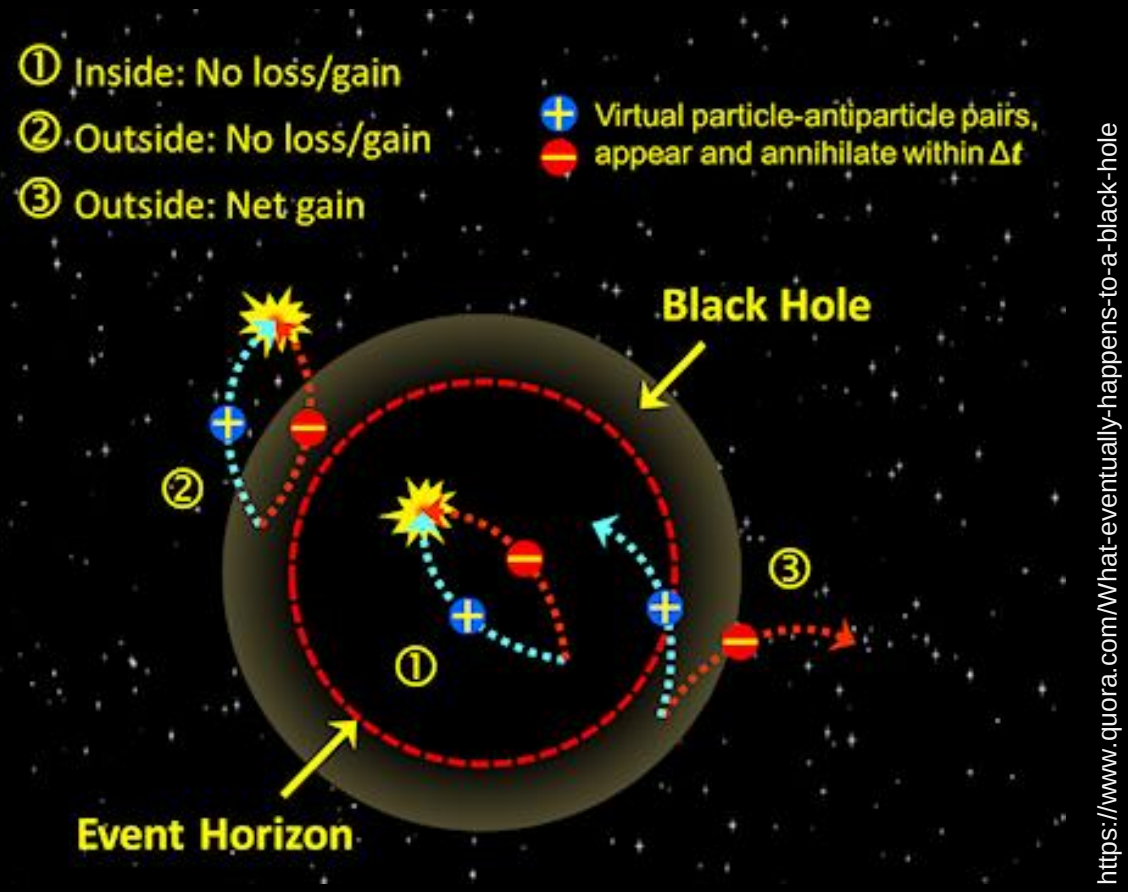
- Gravitational Waves
  - method for a black hole to lose energy
  - predicted by general relativity, 1915 (Einstein)
  - first observed September 14, 2015 (LIGO & Virgo)
  - causes objects to spiral inwards towards each other



https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/58/page/Gravity_Waves_StillImage.jpg?1465865066

How do they die?

- Hawking Radiation (theoretical)
  - method for a black hole to lose matter
  - predicted by Stephen Hawking (1974)
  - quantum mechanics allows tunneling
  - potential issue with the calculation



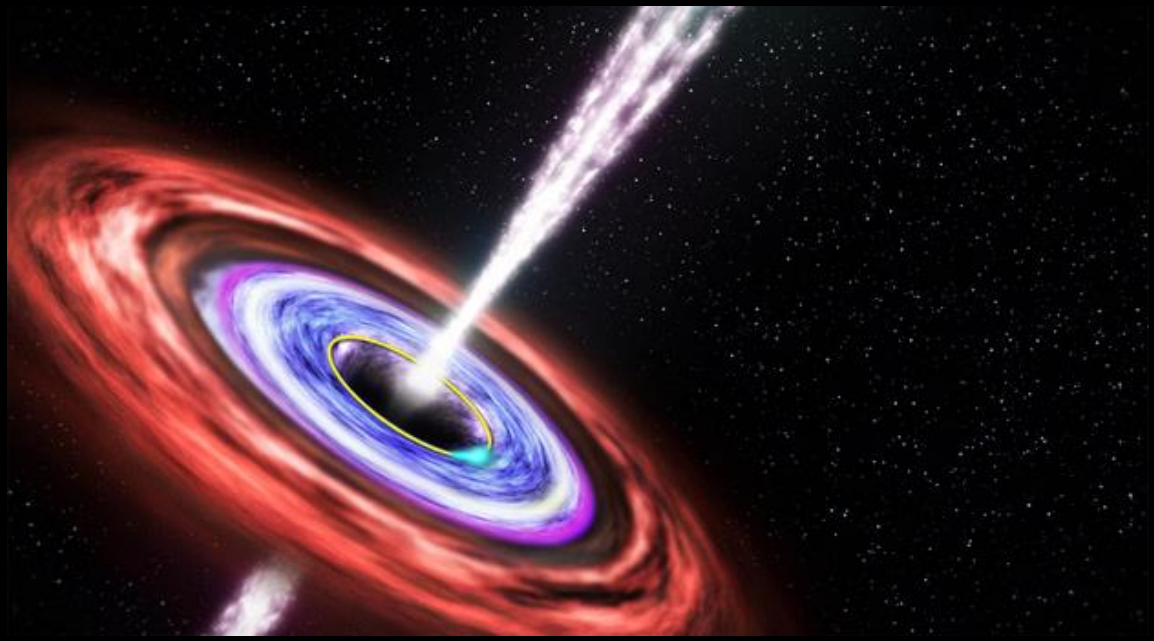
https://www.quora.com/What-eventually-happens-to-a-black-hole

How do they die?

Black Holes…

From their birth to a seemingly inevitable death, they are still one of the greatest mysteries in our universe.

Is information preserved past an event horizon, or can it be lost forever?



http://sci.esa.int/science-e-media/img/d0/XMM-Newton_SwJ1644_QPO_625.jpg

Summary

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Dr. Jodi Cooley

PHYS 3305 Classmates (Spring 2017)

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