PHY 7097 | Modern Astrophysics

Lecture X.

Black holes

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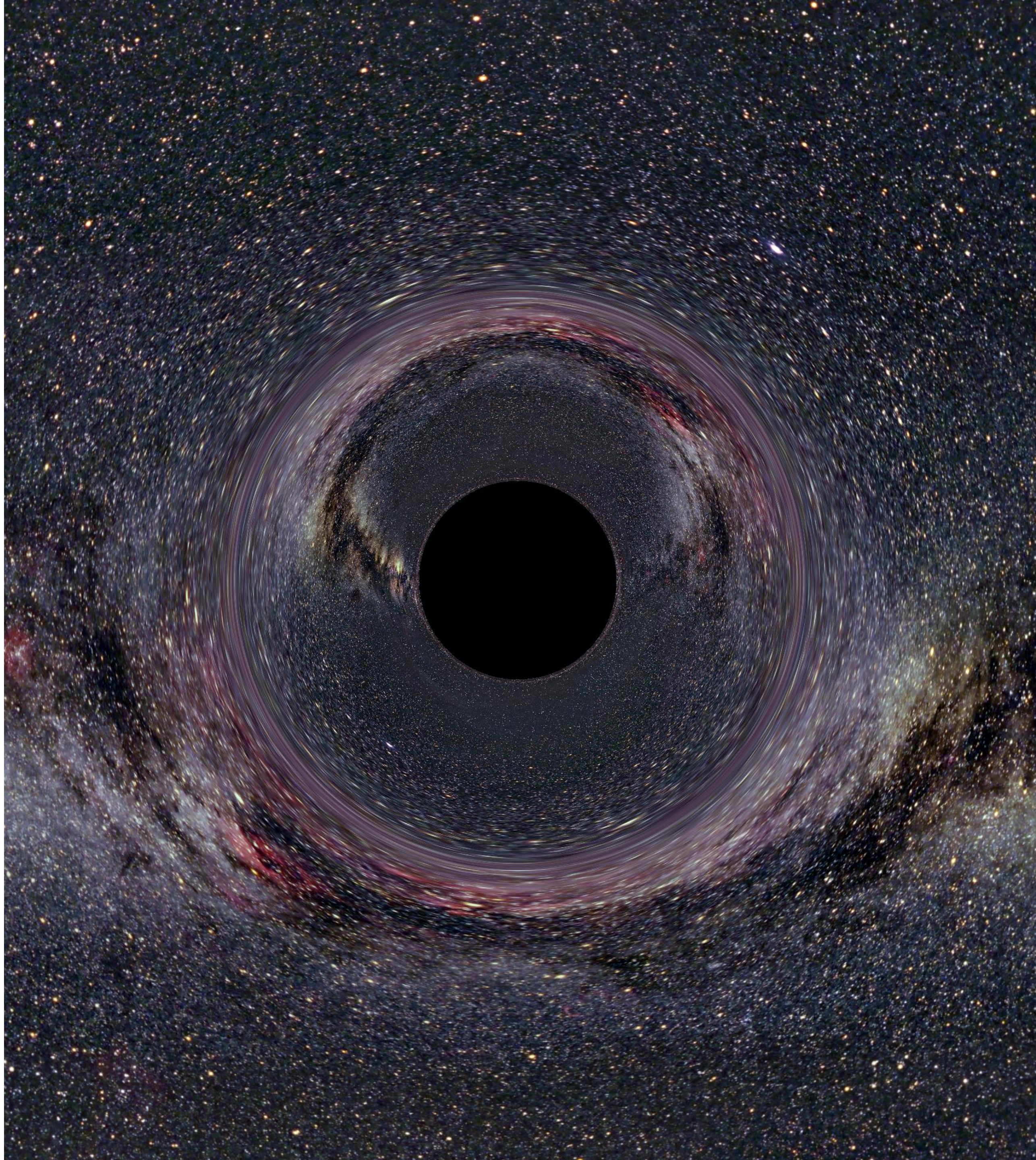
Spring 2020



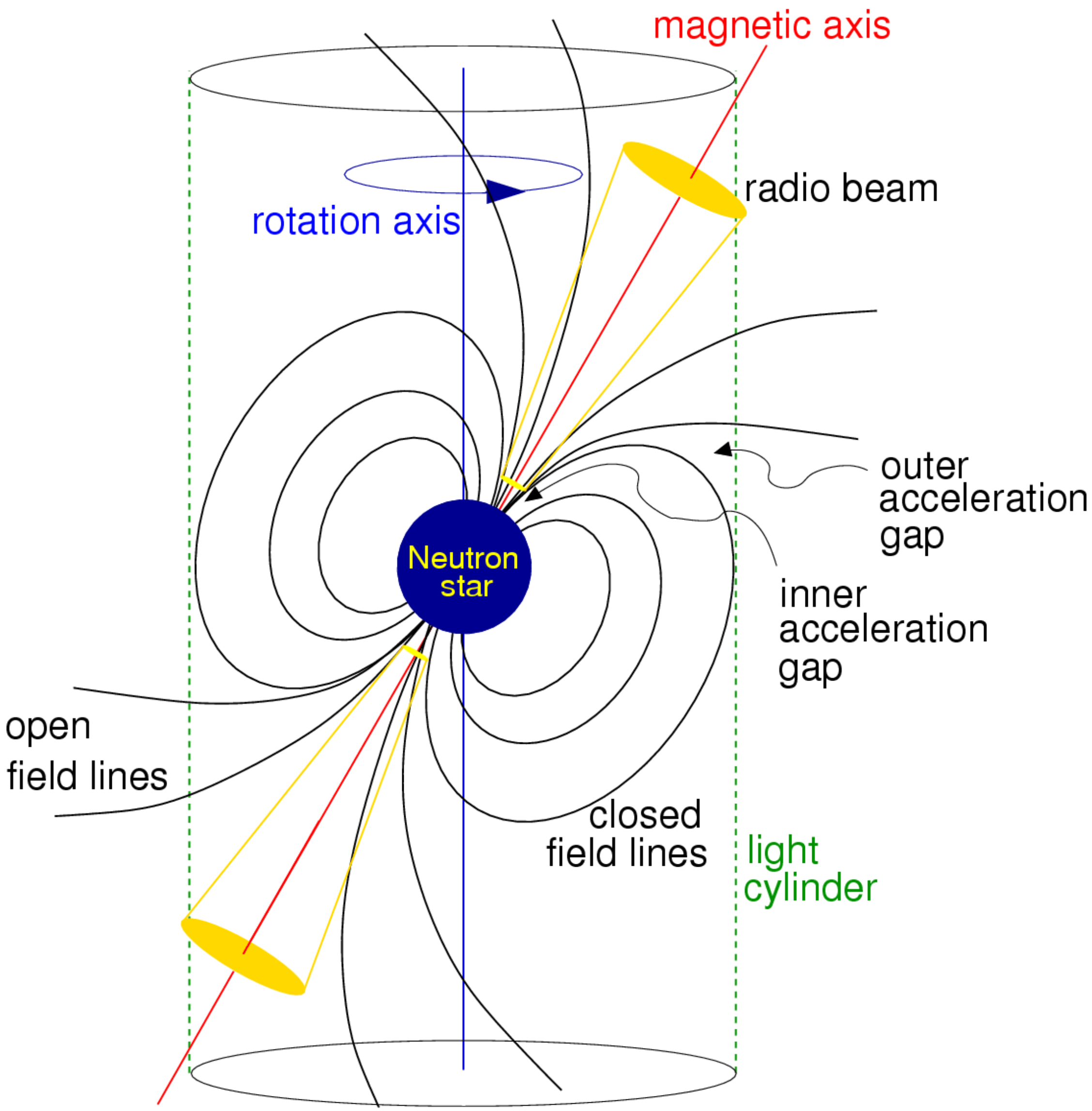
Pulsars

Very regular period

Formed in a supernova

After sufficient slowdown the radio pulsar mechanism is turned off.

Energy source:
- Rotation
- Accretion
- Magnetic fields



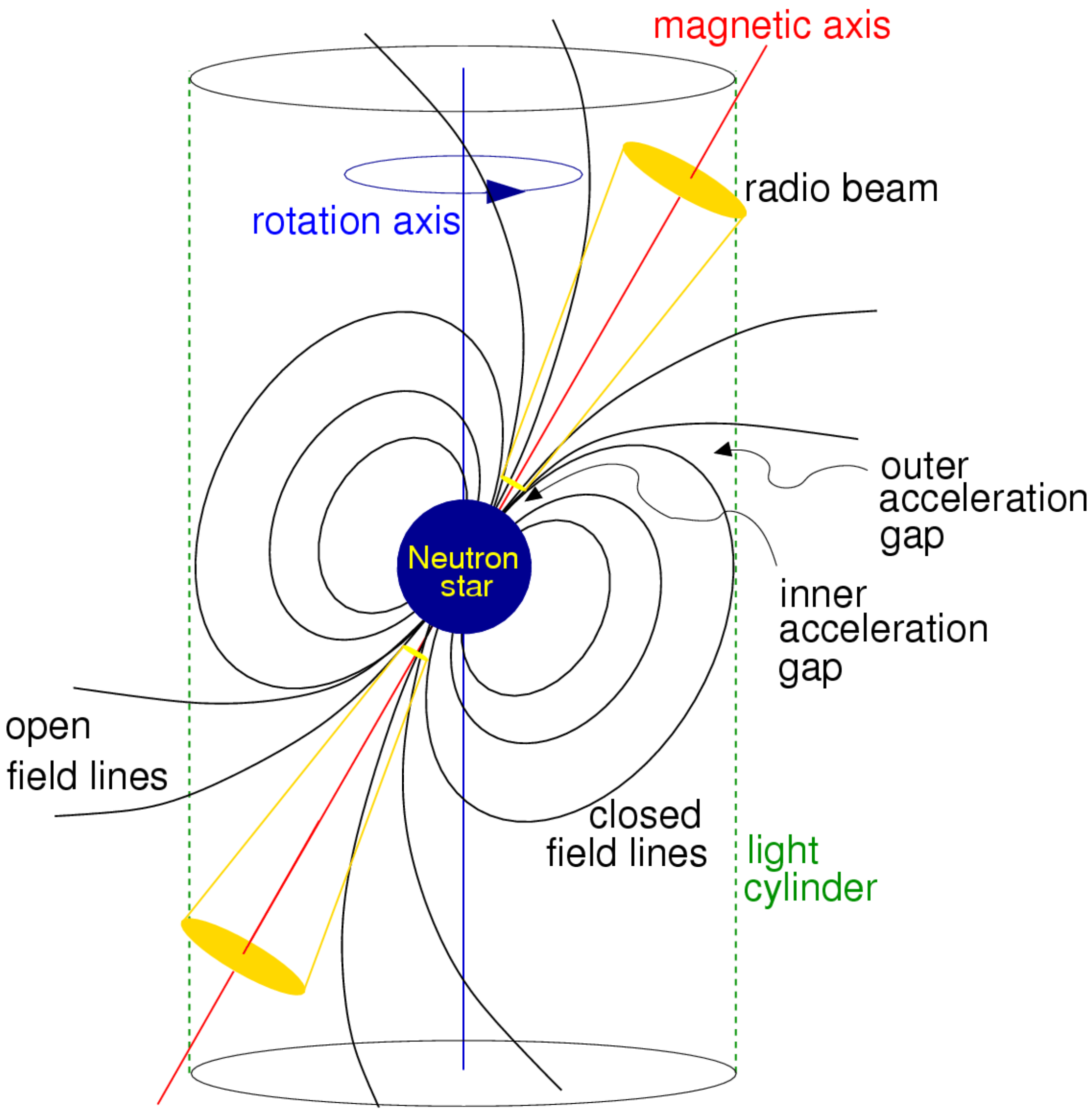
http://www.cv.nrao.edu

Pulsars

If the magnetic dipole is inclined from the rotation axis
→ Magnetic dipole radiation

We can find the magnetic field strength of the NS from the spindown rate.

$$\left(\frac{B}{\text{Gauss}}\right) > 3.2 \times 10^{19} \left(\frac{P\dot{P}}{\text{s}}\right)^{1/2}$$



http://www.cv.nrao.edu/course/astr534/Pulsars.html

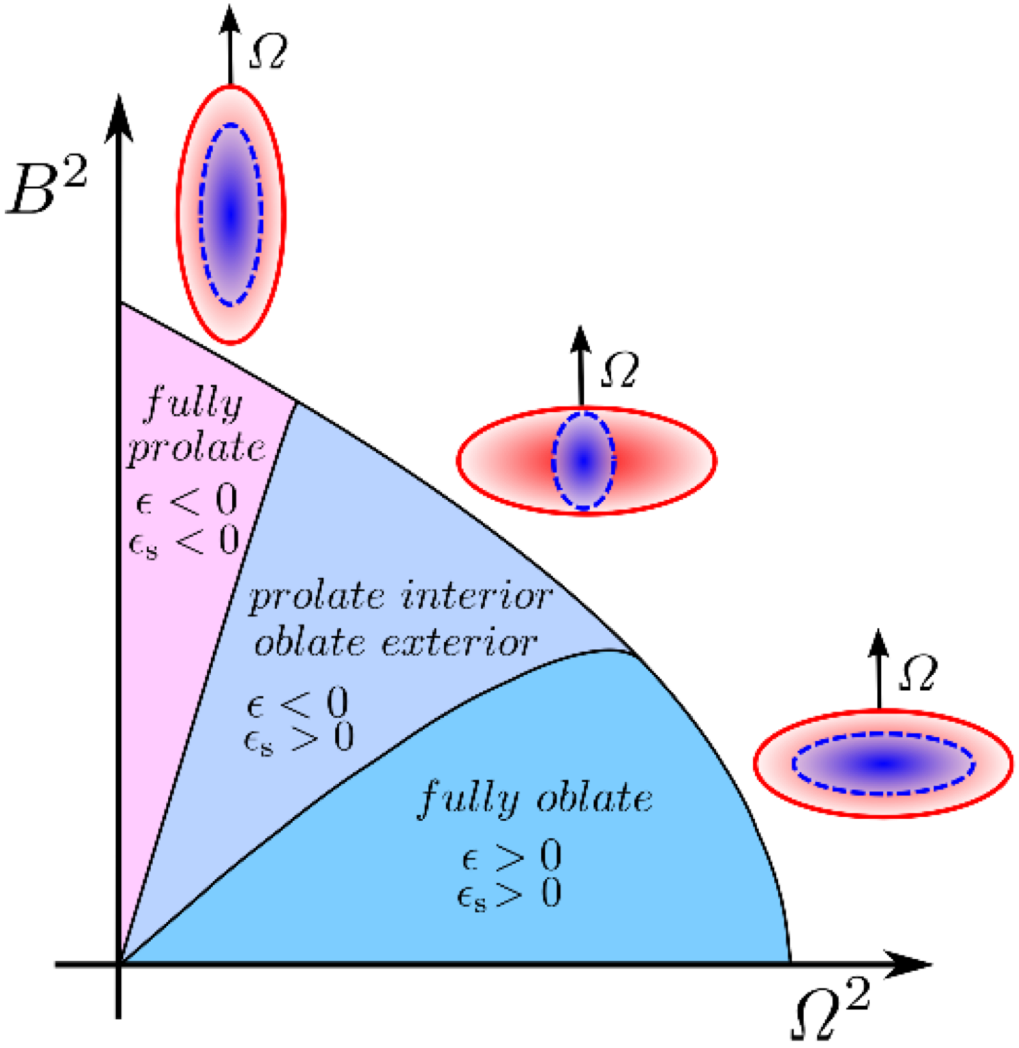
Magnetic deformation

If the magnetic dipole is inclined from the rotation axis
→ Magnetic dipole radiation

We can find the magnetic field strength of the NS from the spindown rate.

$$\epsilon = -\frac{3}{2}\varepsilon = \frac{1}{18}\frac{B^2R^4}{GM^2}$$
$$\approx 10^{-12}\left(\frac{R}{10\,\mathrm{km}}\right)^4\left(\frac{M}{1.4\,\mathrm{M}_\odot}\right)^{-2}\left(\frac{\bar{B}}{10^{12}G}\right)^2$$

Haskell+ 2002



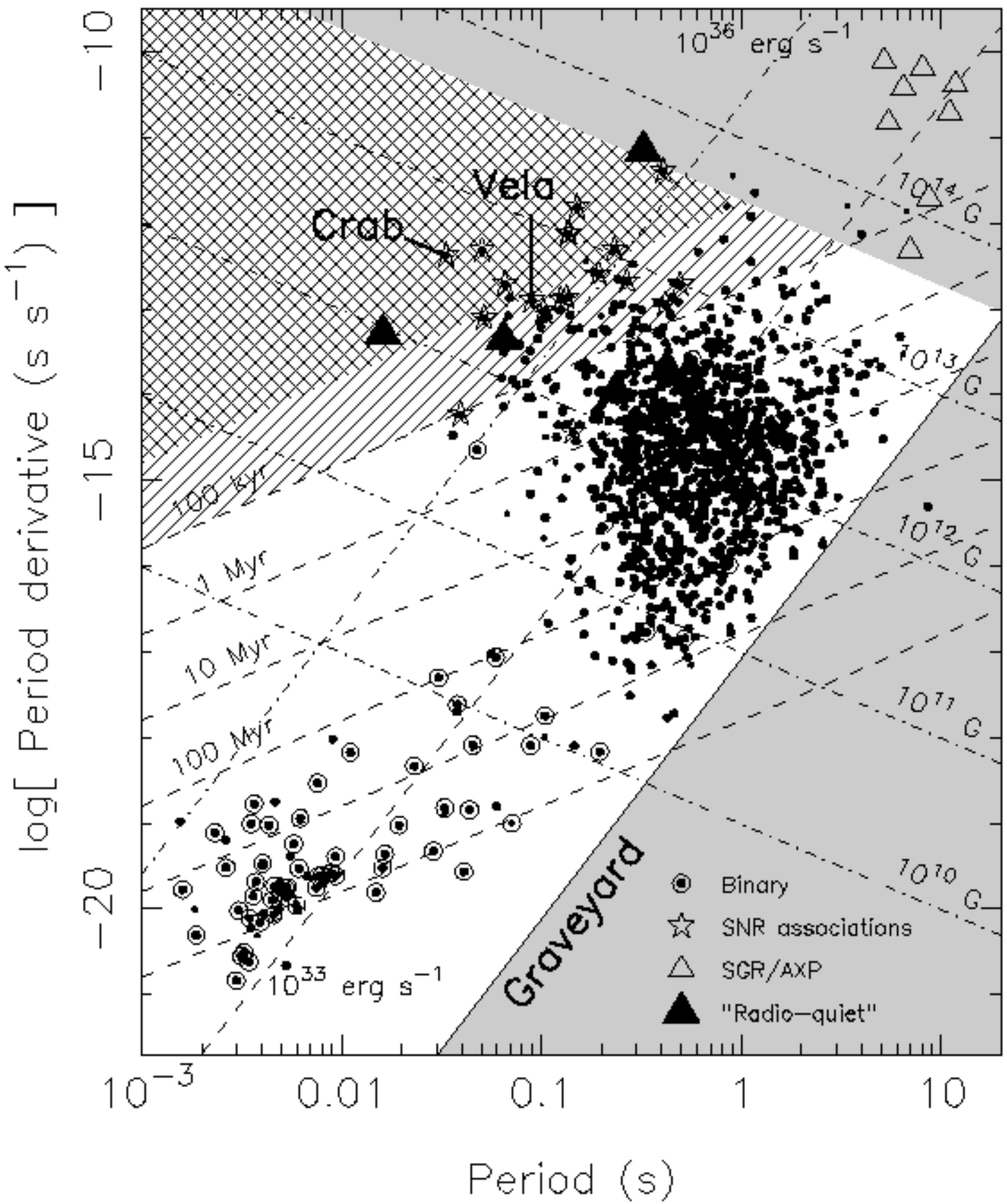
Fieben & Rezzolla 2014

Spin Down

Longer period typically means higher spindown rate.

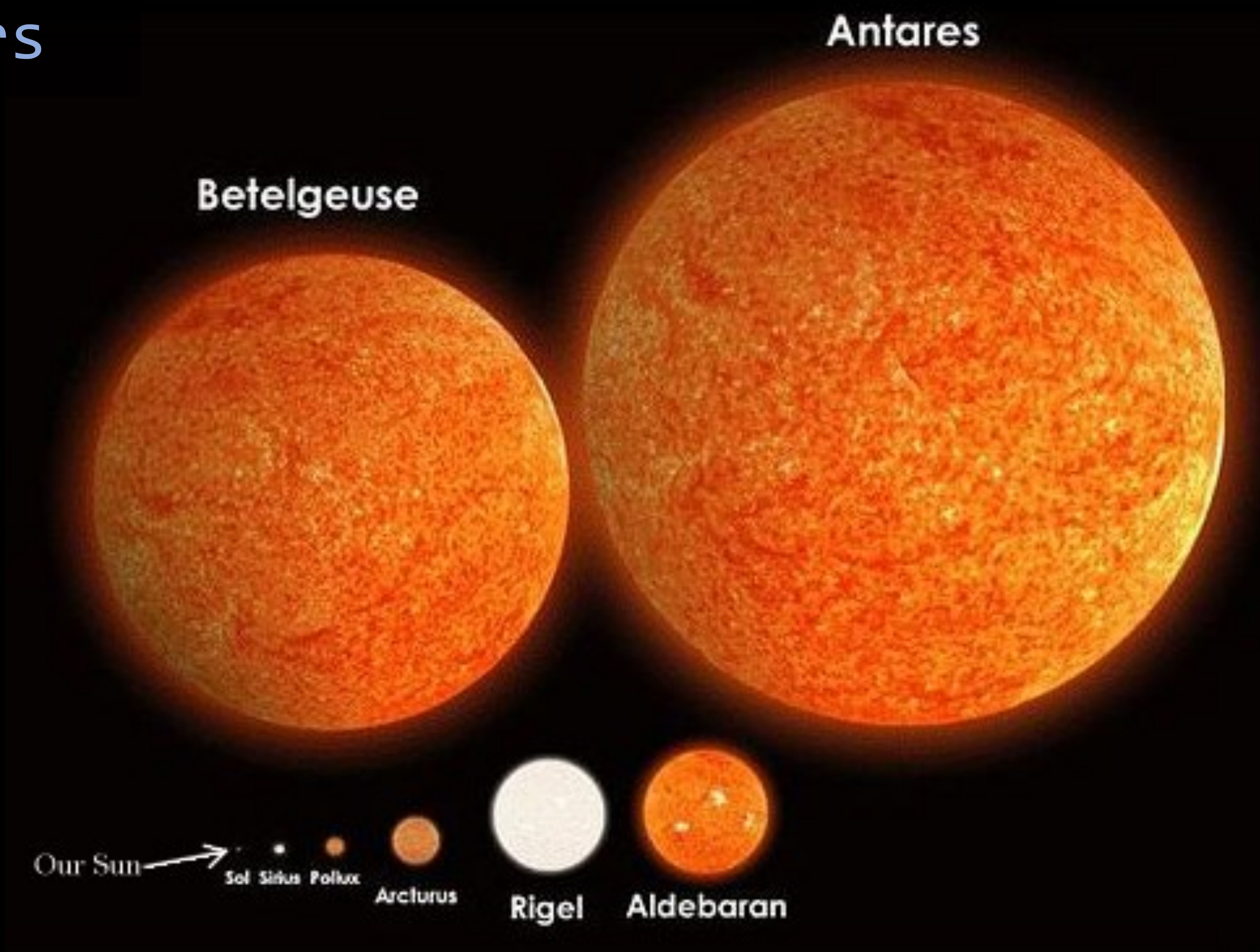
If luminosity ~ spin down power
→ <u>rotation powered</u>

Spindown rate and period gives us an estimate on the <u>characteristic age</u> of the pulsar.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

dark stars



John Michell
(1783)

Mitchell: Escape velocity for sufficiently massive+small stars would escape the speed of light.

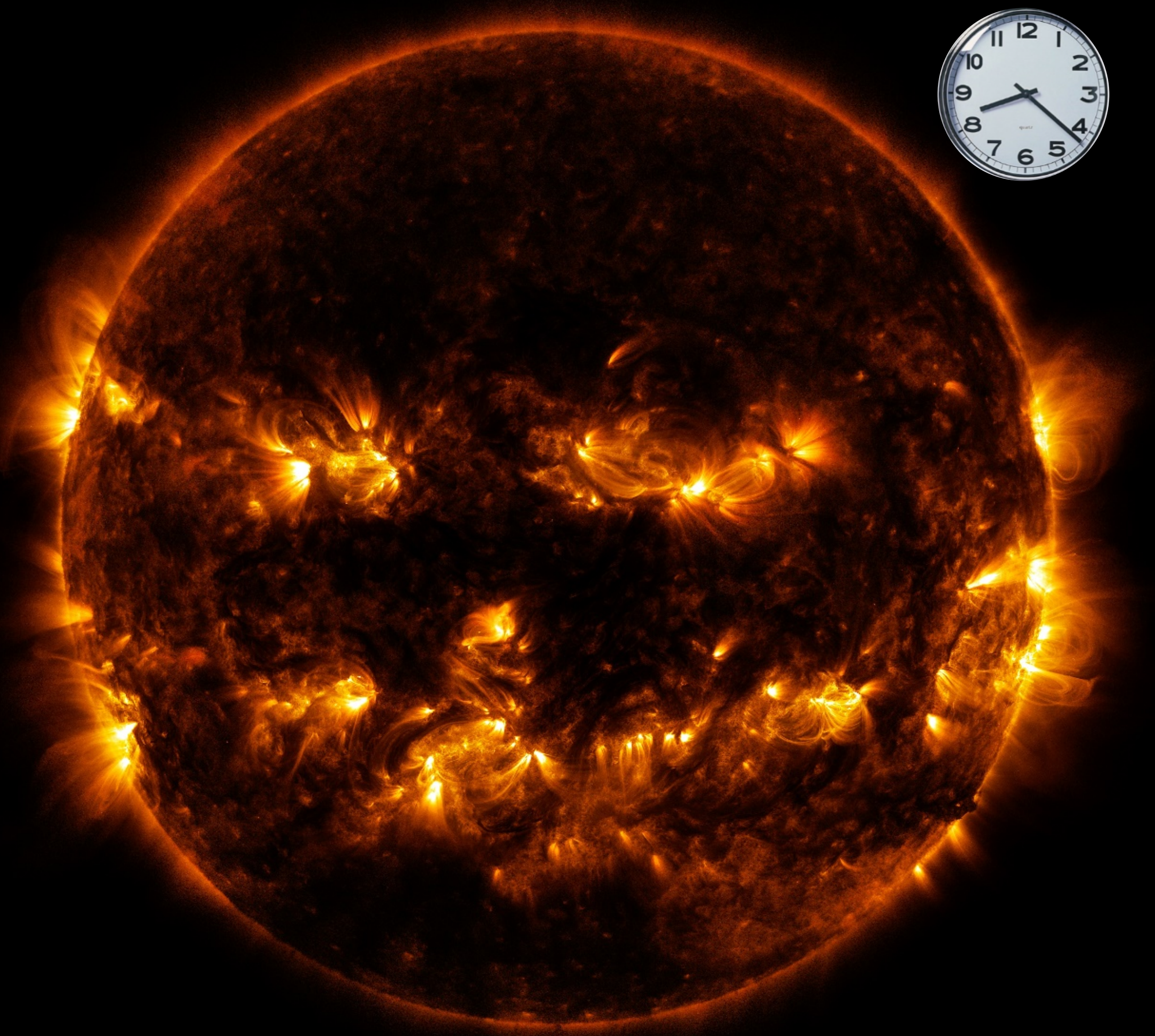
Eddington: showed that very large stars like Betelgeuse cannot possibly have the density of the Sun.

Escape velocity

At what radius would an object with the mass of the Sun become “dark?”
(assuming Newtonian gravity)

$$v_e = \sqrt{\frac{2GM}{r}}$$

“frozen stars”



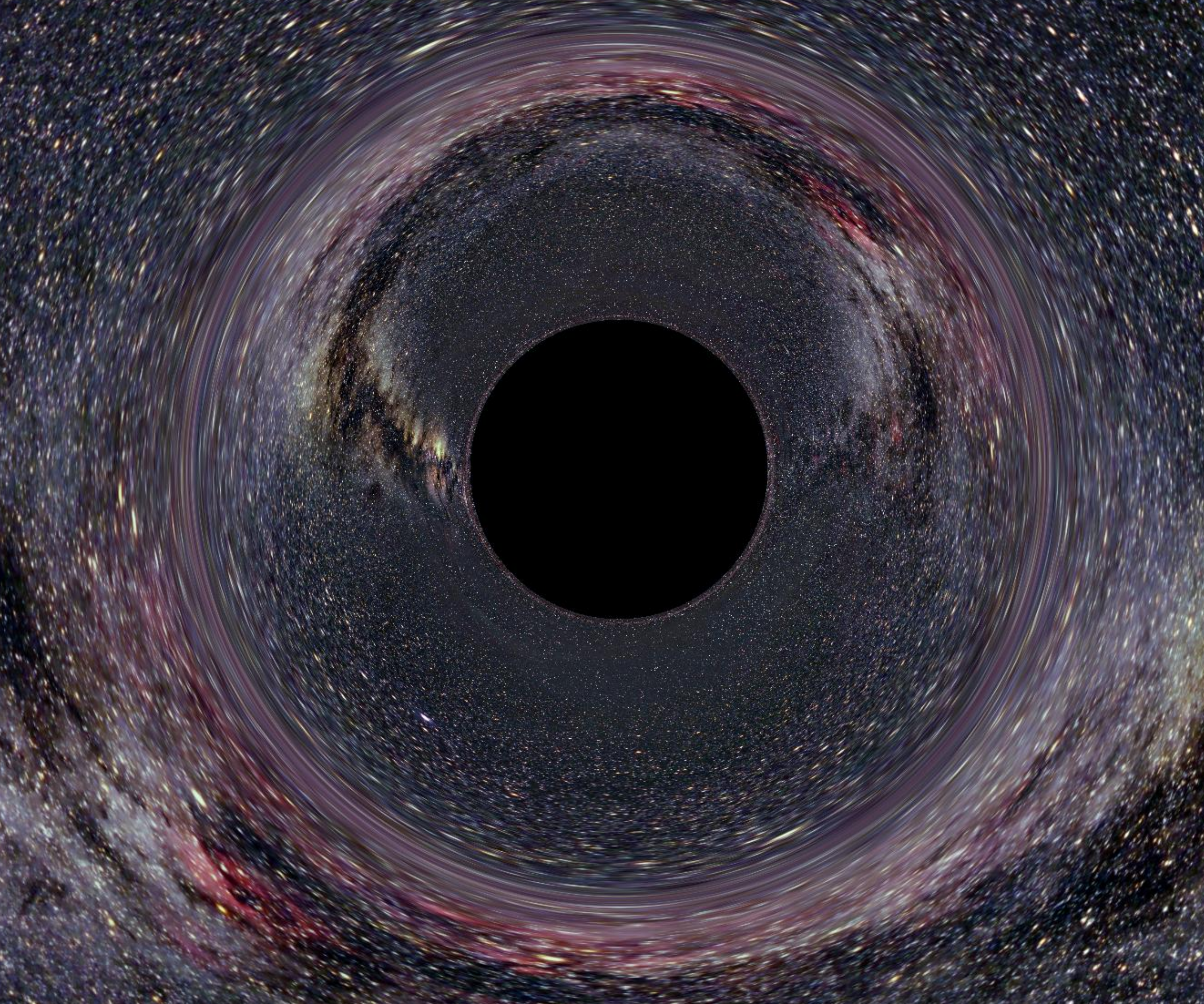
There is a mass limit above which gravitational collapse is inevitable. (Chandrasekhar 1931 for white dwarfs)

I think that there should be a law of Nature to prevent the star from behaving in this absurd way. (Eddington 1935)

…all stars heavier than 1SM, certainly possess regions in which the laws of quantum mechanics (and therefore quantum statistics) are violated.

There is a mass limit above which gravitational collapse is inevitable. (Tolman–Oppenheimer-Volkoff in 1939 for neutron stars)

→ Time would stop for the collapse at the Schwarzschild radius → frozen stars



1962 – discovery of compact X-ray sources.

1963 – discovery of quasars.

1963 - Kerr solution.

1965 - Newman solution.

1968 – discovery of pulsars.

1968 - Wheeler coins the name “black hole.”

1970’s – observation of X-ray binary Cygnus X-1.

No-hair theorem

A stable BH only has 3 independent physical properties:

1. mass
2. angular momentum
3. charge.

These properties are observable from outside.

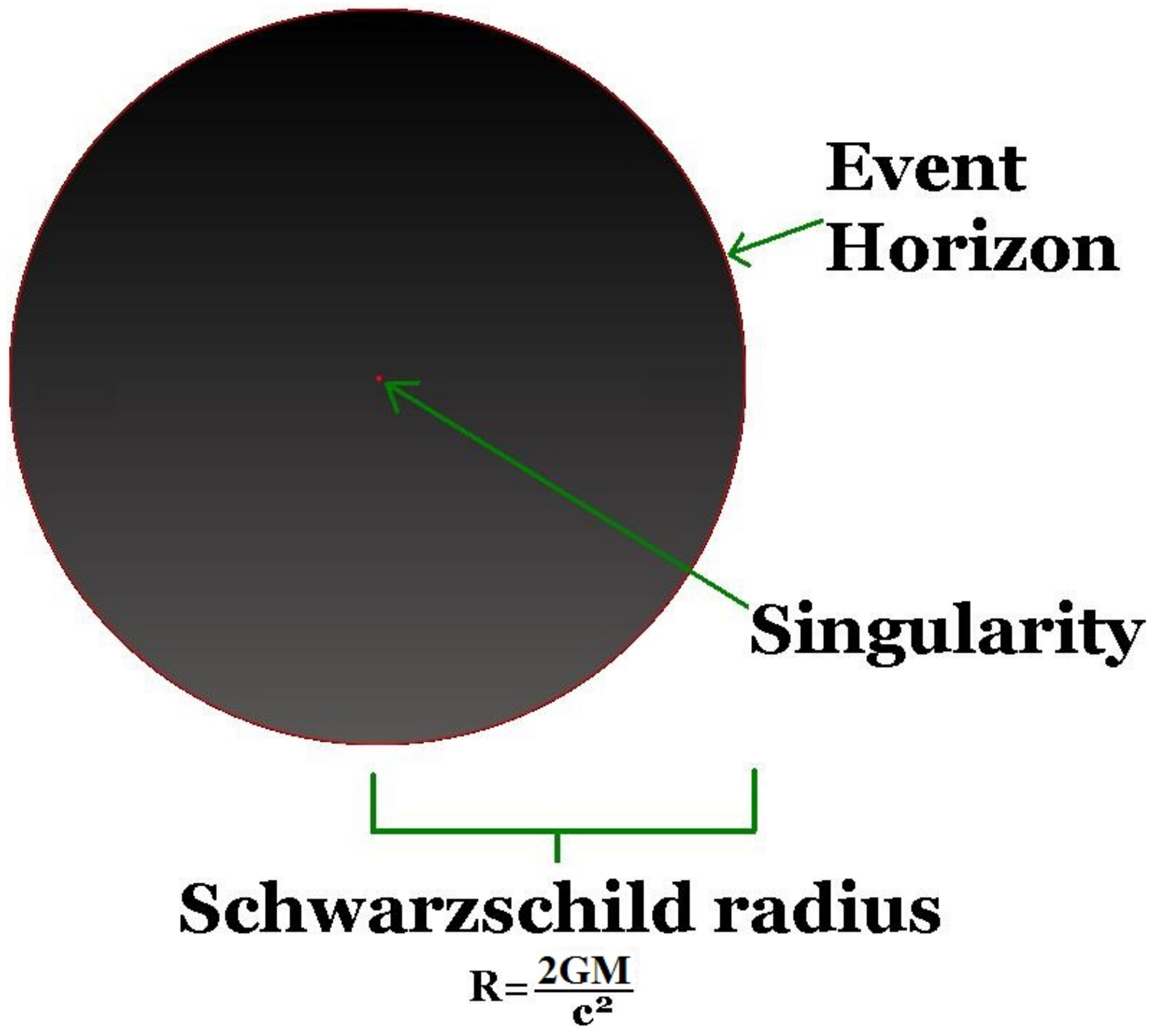
→ Loss of information upon infall.

Only mass → Schwarzschild BH
Mass + angular momentum → Kerr BH
Mass + charge → Reissner-Norström BH
Mass + angular mom. + charge → Kerr-Newman BH

Far from the horizon, the BH grav. field is identical to that of any other object with the same mass.

Limit on angular momentum and charge:

$$Q^2 + \left(\frac{J}{M}\right)^2 \leq M^2$$



(Wikipedia)

Innermost stable circular orbit (ISCO)

Schwarzschild BH:

$$r_{isco} = 3\, r_s = \frac{6\, GM}{c^2}$$

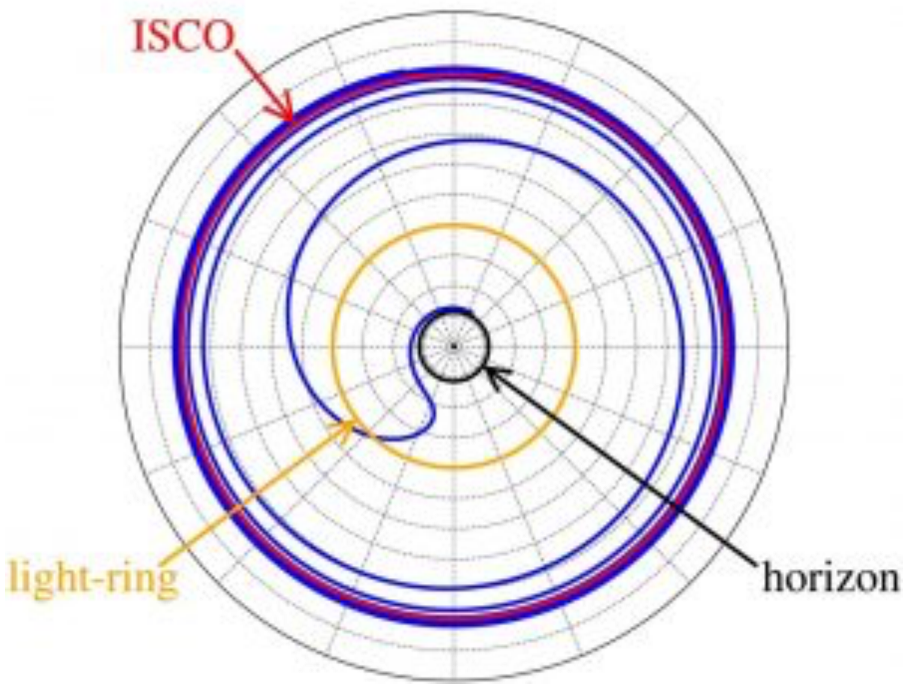
For photons (photon sphere):

$$r = \frac{3\, GM}{c^2}$$

Extreme Kerr BH (maximum spin):

$$r_{\mathrm{ISCO}} = 9M$$ *(counter-rotating)*

$$r_{\mathrm{ISCO}} = M$$ *(co-rotating)*



Surface area

No physical process can decrease the surface area of a BH (or multiple BHs)

Rotating BH (no charge):

$$A = 8\pi M(M + \sqrt{M^2 - J^2/M^2})$$

(→ 29% of initial mass can in principle be radiated away)

Reducing the angular momentum <u>increases</u> the surface area.

Merger of two (non-rotating BHs):

$$A \geq A_1 + A_2, \text{ or } M_f^2 \geq M_1^2 + M_2^2$$

(→ 29% of initial mass can in principle be radiated away)

Merger of two spinning black holes: up to almost <u>half</u> of mass can be extracted!

http://www.physics.umd.edu/grt/taj/776b/lectures.pdf

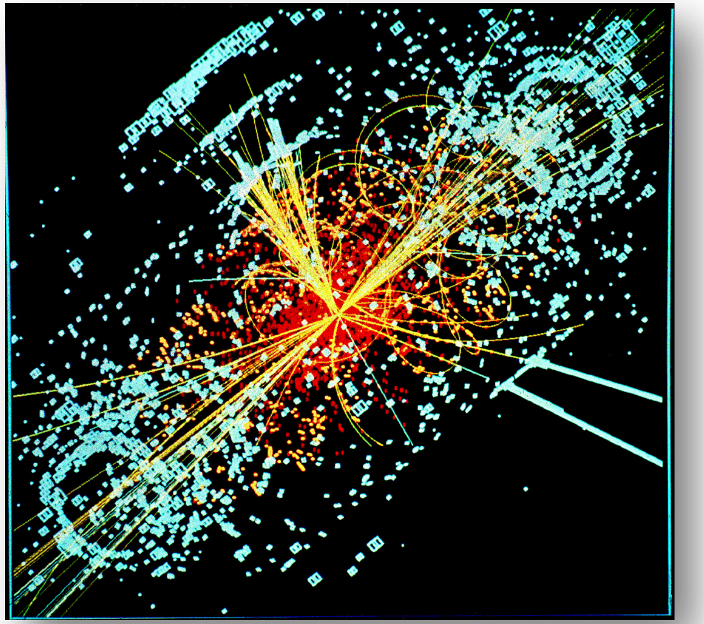
Formation mechanisms?

Micro-black holes

Schwarzschild radius: $R = 2GM/c^2$

Compton wavelength: $\lambda = h/Mc$

$$\left.\begin{array}{l} R = 2GM/c^2 \\ \lambda = h/Mc \end{array}\right\} M \geq Planck\ mass$$



In some extensions of present physics (e.g. string theory) gravity can increase faster at short distances → lower minimum BH mass

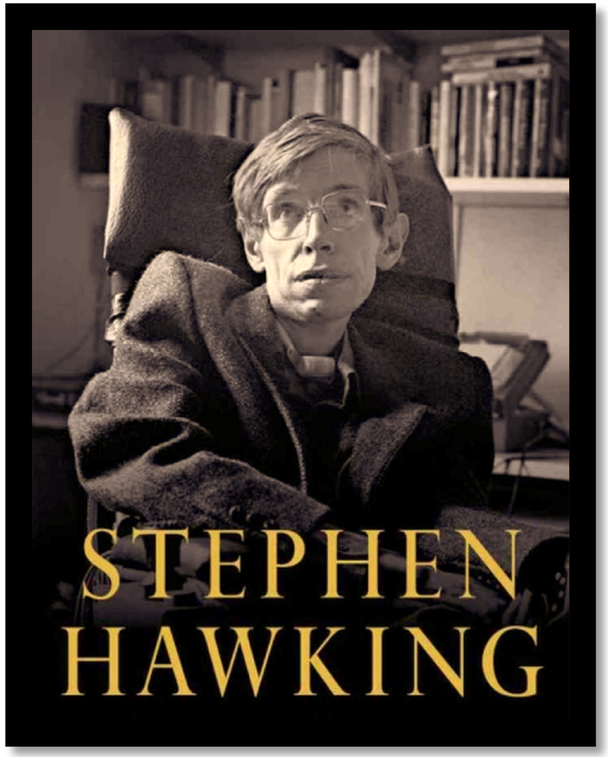
The Large Hadron Collider (LHC) and cosmic rays could produce BHs!

If such a small BH was created on Earth, would it be dangerous?

Hawking radiation

Black hole "temperature":

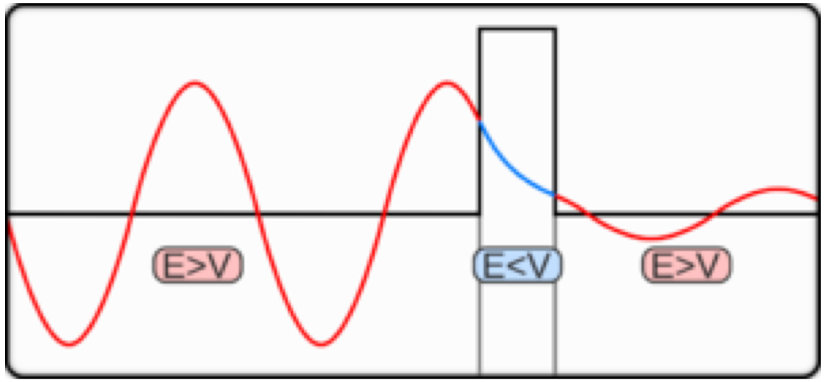
$$T = \frac{\hbar c^3}{8\pi G M k_{\mathrm{B}}} \qquad \left(\approx \frac{1.227 \times 10^{23}\ \mathrm{kg}}{M}\ \mathrm{K} = 6.169 \times 10^{-8}\ \mathrm{K} \times \frac{M_\odot}{M} \right)$$



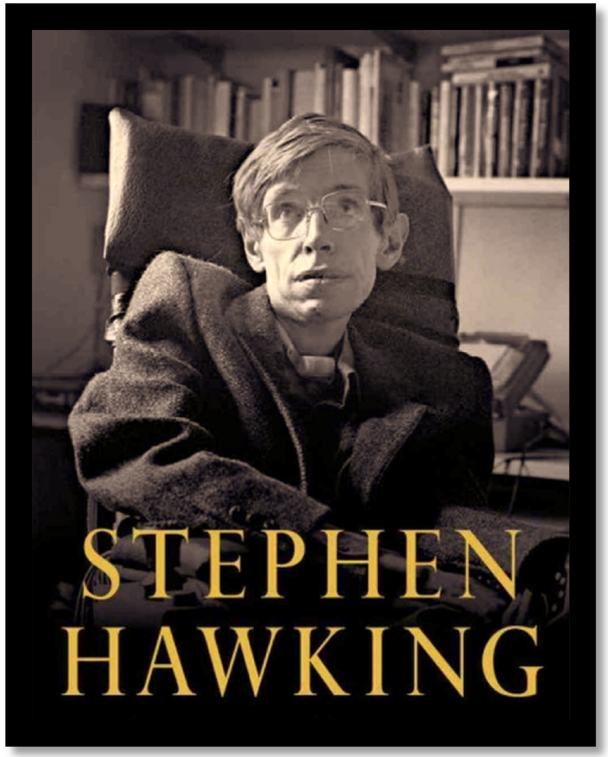
Black hole will emit black body radiation at this temperature.

Irrelevant for astrophysical BHs.

Relevant for BH masses below 10^{12} kg.



Hawking radiation



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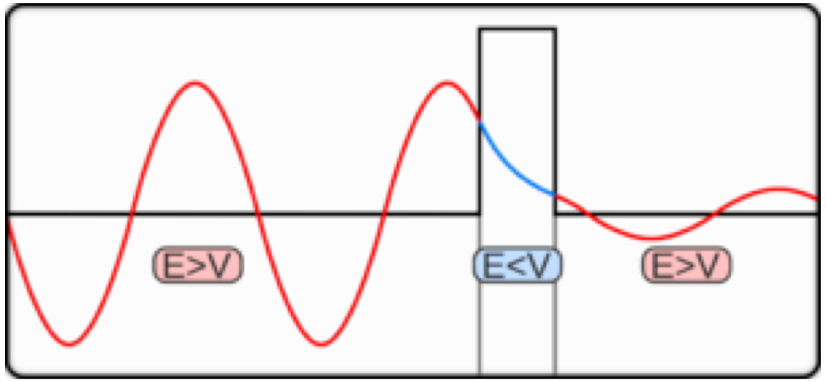


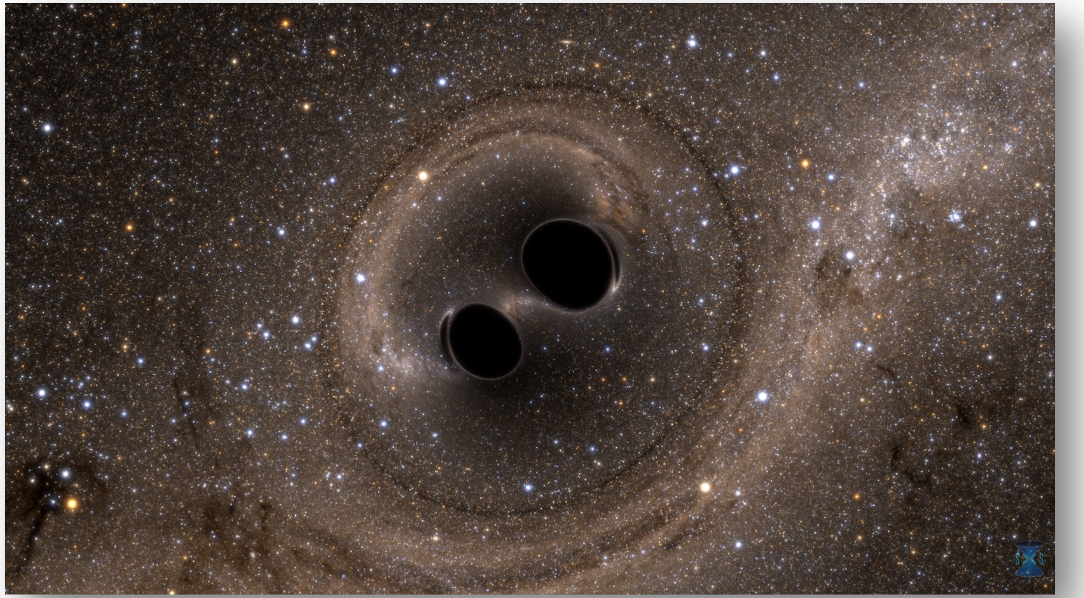
HW: What is the heaviest BH that, created on Earth, you would survive?

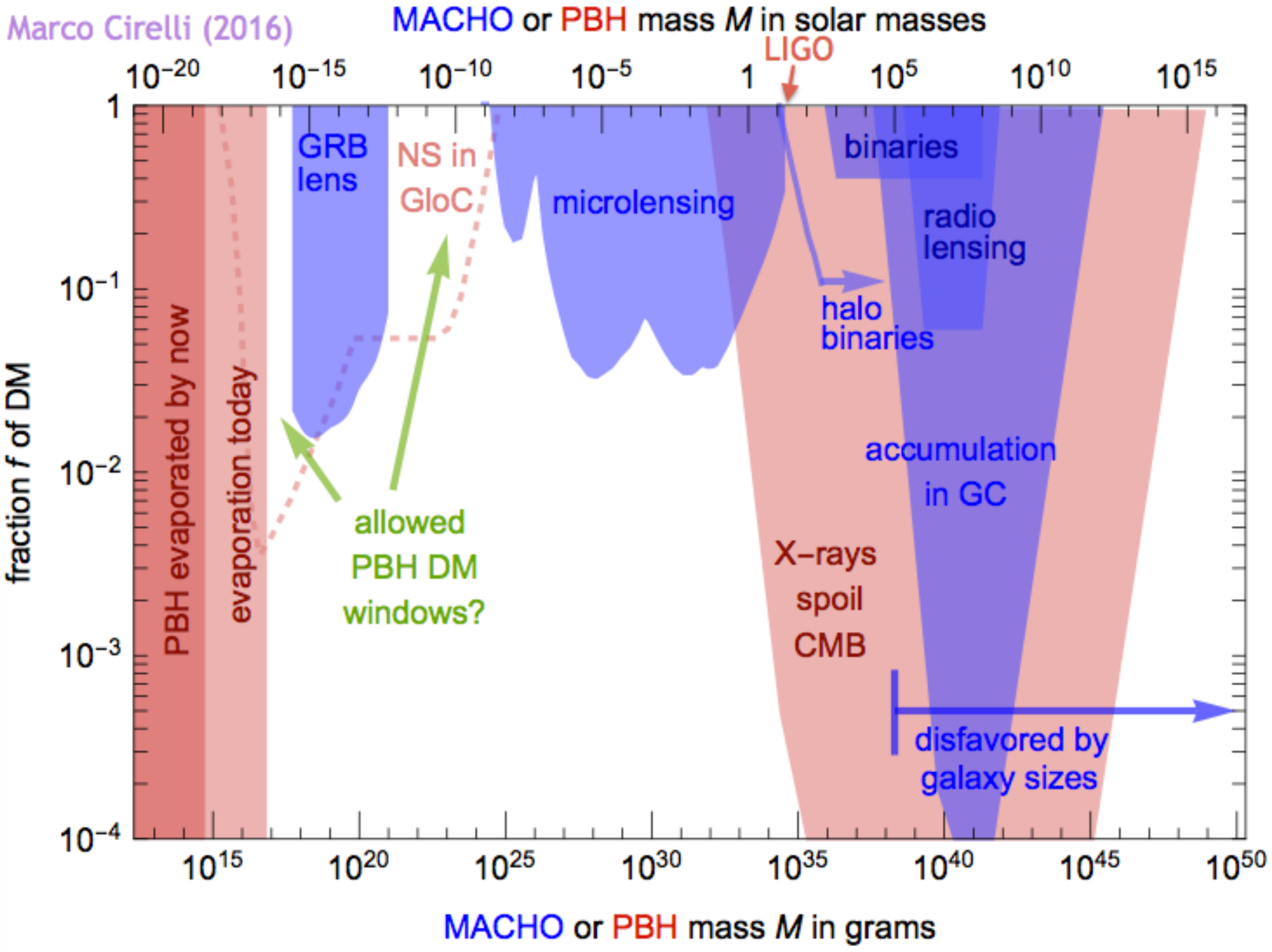
Primordial black holes

Large densities and density fluctuations soon after the big bang.

Mass distribution should be different from that of astrophysical black holes.

Primordial BHs were suggested as Dark Matter, and the origin of some LIGO BBH mergers, e.g. GW150914 (Bird+ 2016)





Black hole mass distribution

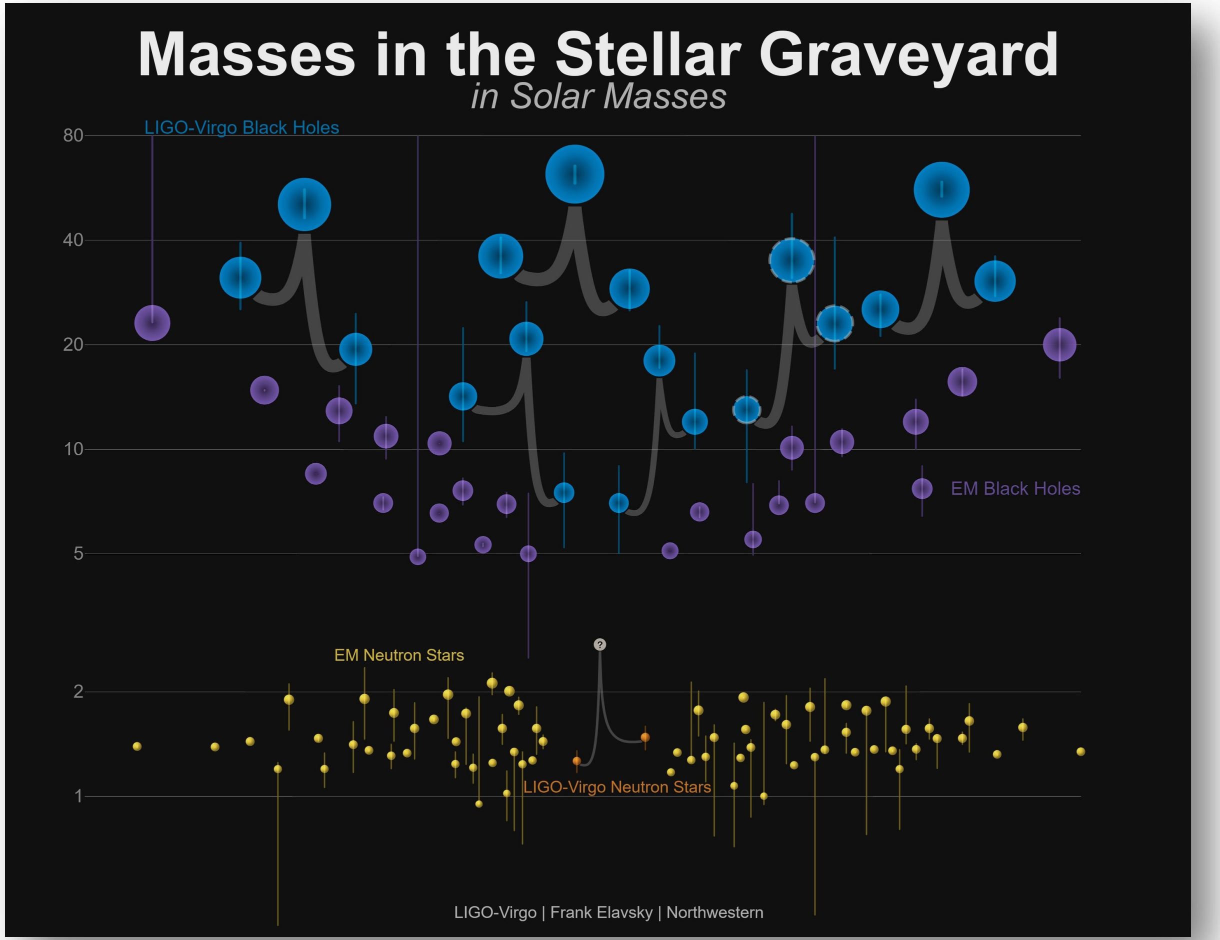
Three classes with different origin / evolution

- Stellar-mass (3 Msun – ~100 Msun)
- Intermediate-mass (~100 Msun – 10^5 Msun)
- Supermassive (10^5 Msun – 10^{11} Msun)

Stellar mass mass distribution:

- We don't know
- There seems to be a mass lower limit at 5 Msun
  → mass gap
- Best guess – Salpeter function (PDF ~ $M^{-2.3}$)

LIGO's detected BH mass distribution is consistent with Salpeter function up to a cutoff mass of ~ 50 Msun



Intermediate mass black holes

No confirmed observation.

Claims:
- Measurement of Doppler shift of stellar radiation in X-ray binaries.
- Super-Eddington radiation in X-ray binaries.
- Stellar dynamics in globular clusters.
- …

LIGO has limits on their abundance.

Origin:
- From stellar mass BHs through accretion
- Collision of multiple stars or stellar remnants in dense environments
- Primordial BHs
- Collapse of Pop III stars

Supermassive black holes

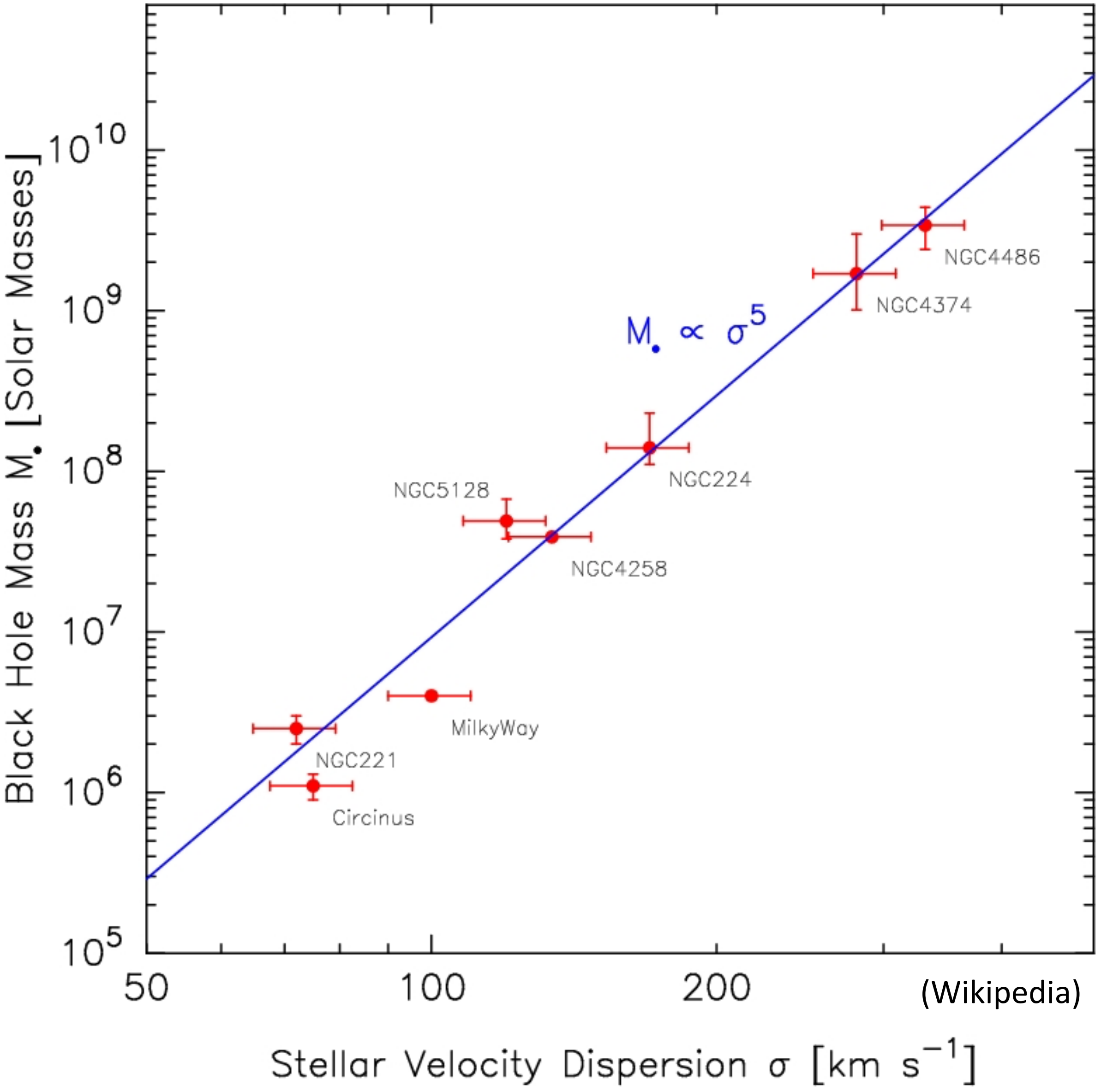
<u>Formation:</u> needs a seed
- Very massive star collapses
- Primordial black hole

But we don't know.

<u>Growth:</u>
- Accretion
- Merger with other black holes

But we don't really know.

They are fundamental components of galaxies:
- M-sigma relation.

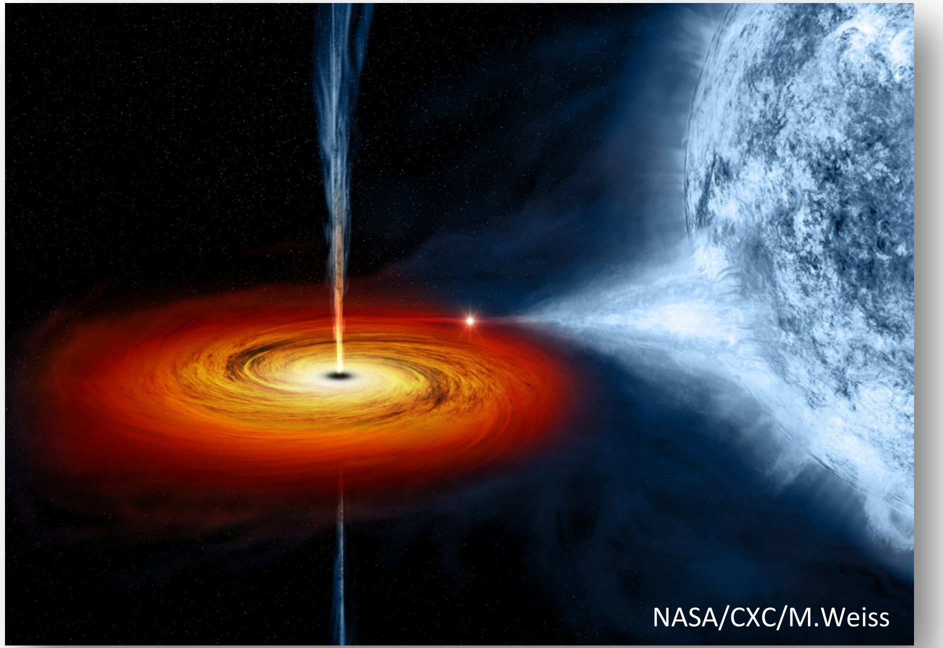


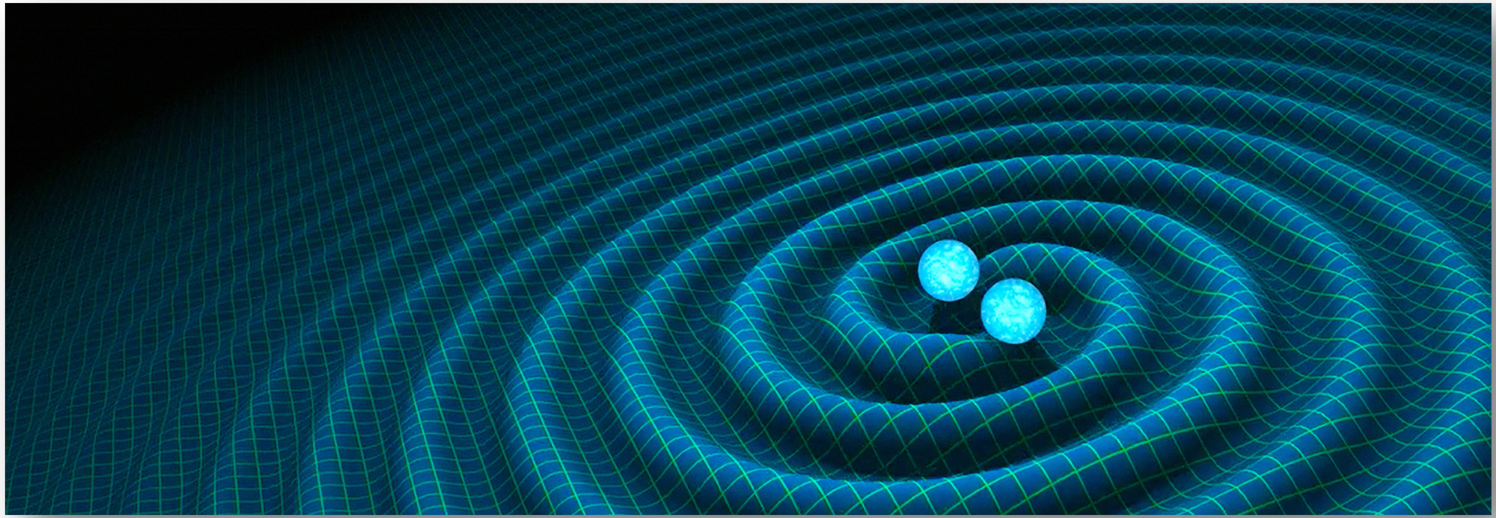
(Wikipedia)

Observations

Hawking radiation is undetectable.

- Gravitational waves!
- Motion of stars orbiting Sagittarius A*
- Accretion of matter
- Gravitational lensing (not yet observed)

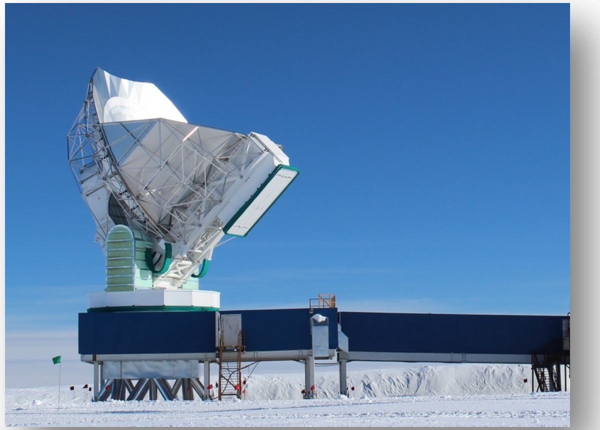

NASA/CXC/M.Weiss

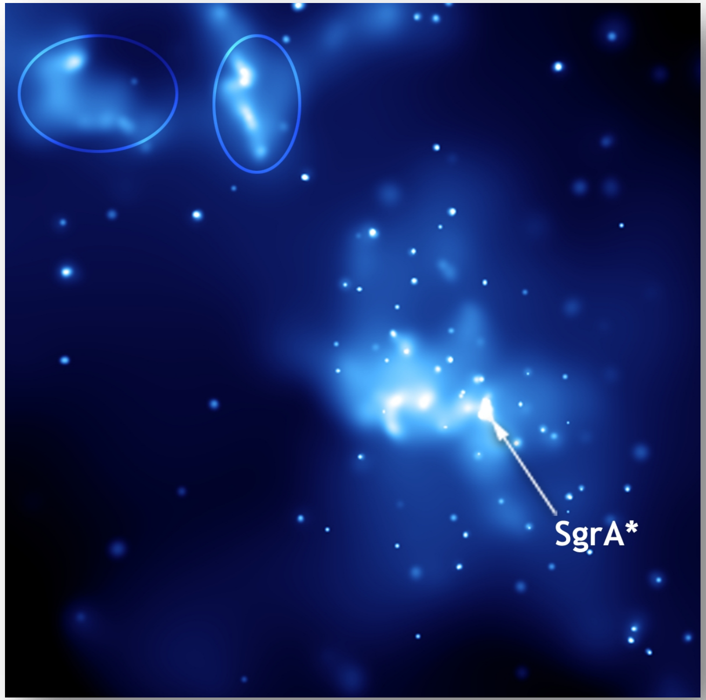


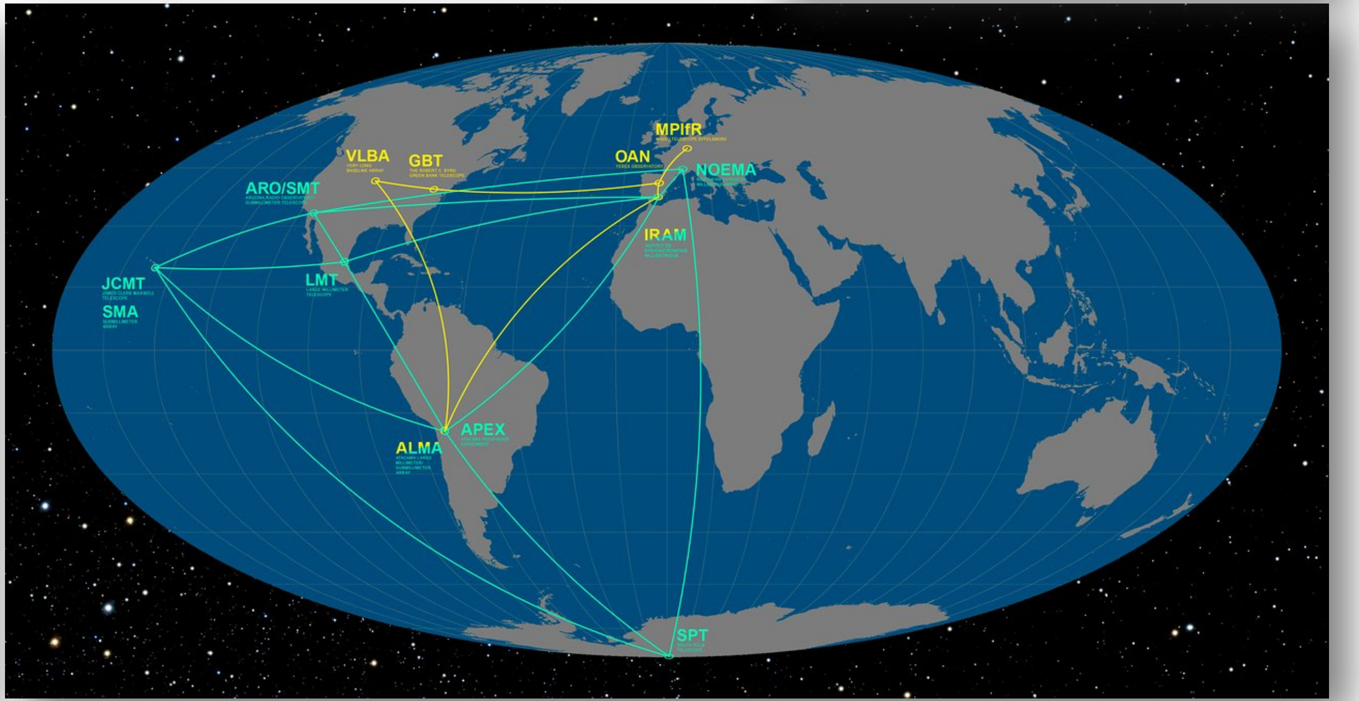

REUTERS/NASA/JPL-Caltech/Handout

Event Horizon Telescope

- Network of radio telescopes.
- Interferometry
- Observe the immediate environment of the SMBH in the Milky Way (Sagittarius A*); and maybe others.
- Can resolve distance on the order of the Schwarzschild radius.
- Results expected soon…







Collisionless spherical accretion

- Collisionless gas
- Uniform dist. (spherically symmetric inflow)
- Approximation.

Loss cone – particles that get within the loss cone are accreted.

Defined w.r.t. min. angular momentum! (not radius)

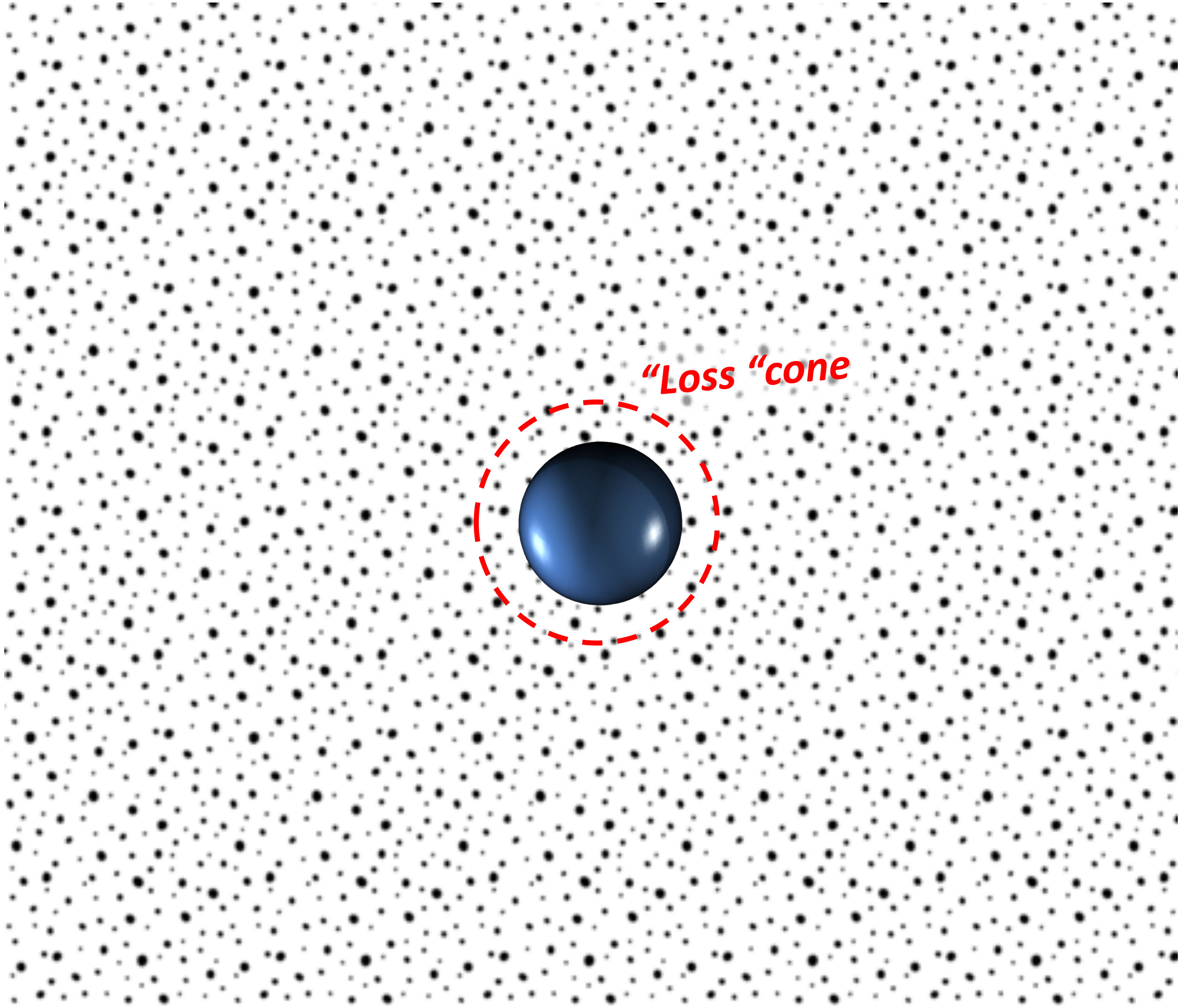
$$J_{\min}(E) \equiv \left[2\left(E + \frac{GM}{R}\right)\right]^{1/2} R \quad \text{(NR particles; Newtonian star)}$$

$$J_{\min}(E) = \frac{4GM}{c} \quad \text{(NR particles; black hole)}$$

$$\dot{M}(E>0) = m\dot{N}(E>0)$$

$$= \begin{cases} 2\pi GM^2 \rho_\infty v_\infty^{-1} \dfrac{R}{M}\left(1 + \dfrac{v_\infty^2 R}{2MG}\right) \\ \qquad \text{(NR particles; Newtonian star),} \\ 16\pi (GM)^2 \rho_\infty v_\infty^{-1} c^{-2} \\ \qquad \text{(NR particles; black hole),} \end{cases}$$

Shapiro & Teukolsky (14.2)



Hydrodynamic spherical accretion onto a black hole

- Interactions between gas molecules are important
- Collisions and/or macroscopically weak magnetic fields

O(1) constant

$$\dot{M} = 4\pi\lambda_s (GM)^2 \rho_\infty a_\infty^{-1} c^{-2} \frac{c^2}{a_\infty^2}$$

sound speed

(c.f. collisionless gas $16\pi (GM)^2 \rho_\infty v_\infty^{-1} c^{-2}$)

~10^9 higher than in the collisionless case!

More details: Edgar 2004 (https://arxiv.org/abs/astro-ph/0406166)

Shapiro & Teukolsky (14.3)

Hydrodynamic spherical accretion onto a black hole

Bondi radius --- defiones **effective area** of accretion, where the black hole's escape velocity is the same as the thermal velocity of the gas.:

$$r_{\mathrm{B}} = \frac{2GM}{c_\infty^2}$$

Bondi accretion:

$$\dot{M}_{\mathrm{BH}} = \frac{4\pi G^2 M^2 \rho_\infty}{c_\infty^3}$$

Bondi-Hoyle-Lyttleton accretion:

$$\dot{M}_{\mathrm{BH}} = \frac{4\pi G^2 M^2 \rho_\infty}{(c_\infty^2 + v_\infty^2)^{3/2}}$$

More details: Edgar 2004 (https://arxiv.org/abs/astro-ph/0406166)

Shapiro & Teukolsky (14.3)

Where does spherical accretion occur?

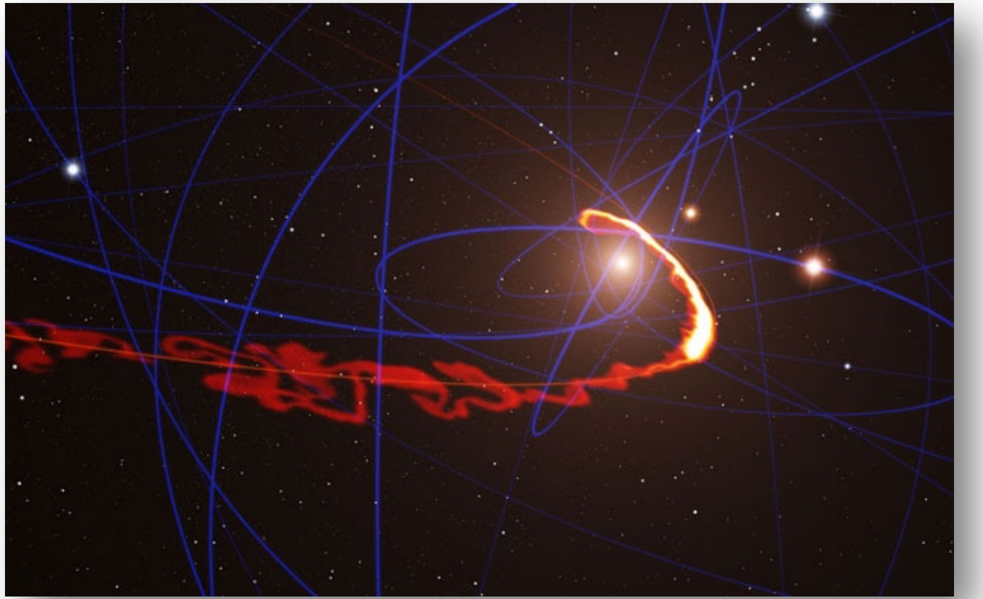
It is rare --- typically there is angular momentum.

- Planet formation from protoplanetary disk
- Accretion of interstellar gas onto a solar-mass BH

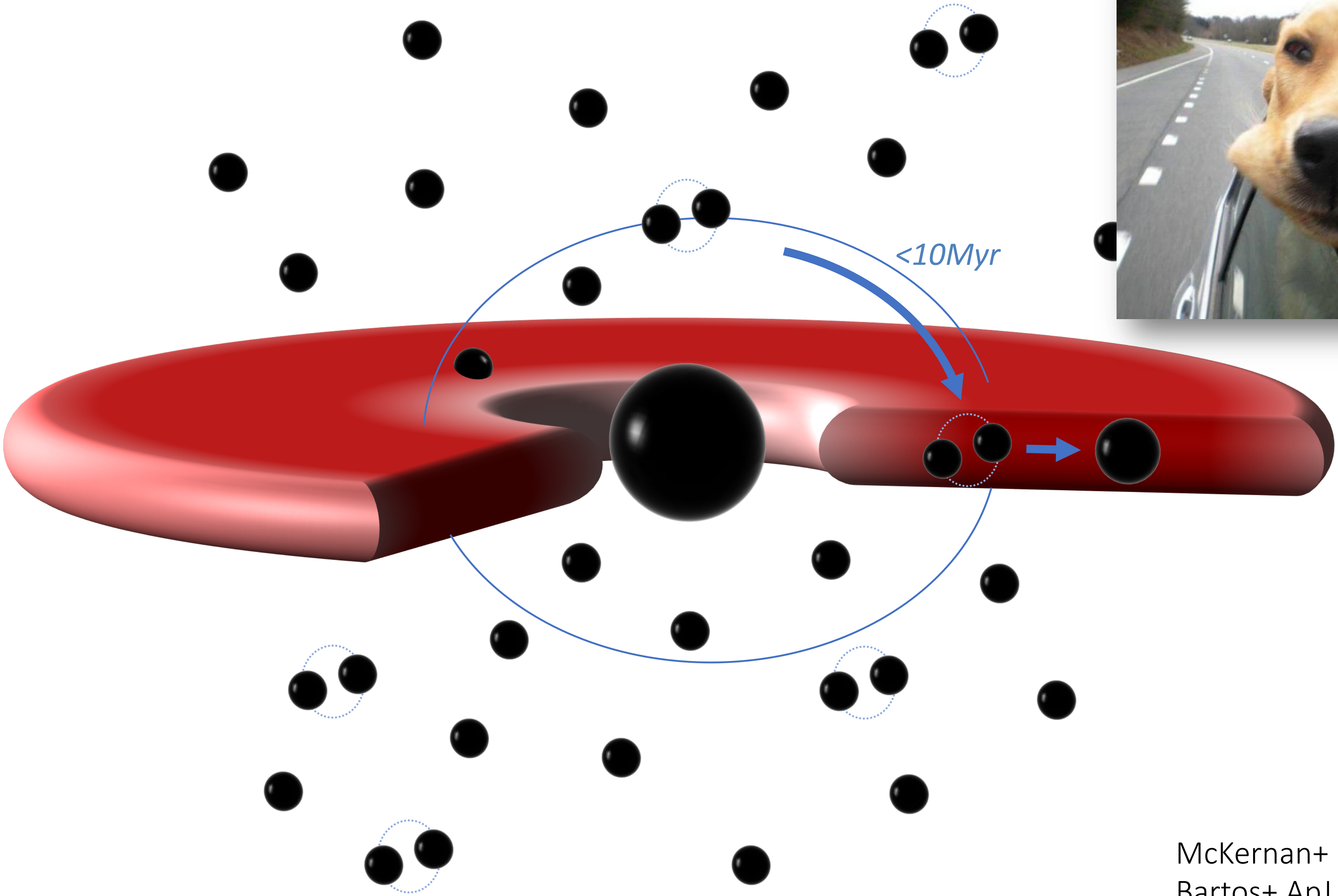
$$\dot{M} = 8.77 \times 10^{-16} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{\rho_\infty}{10^{-24}\ \mathrm{g\ cm^{-3}}} \right) \left(\frac{a_\infty}{10\ \mathrm{km\ s^{-1}}} \right)^{-3} M_\odot\ \mathrm{yr}^{-1}$$

Shapiro & Teukolsky (14.3)

- Black hole + gas cloud encounter



Nature



McKernan+ MNRAS 2012
Bartos+ ApJ 2017

Radiation from spherical accretion

- Gas heats up as it falls in → radiates (mainly thermal Bremsstrahlung radiation)
- Most emission will come from the innermost part of the accretion where the gas is hottest.

$$L_{\mathrm{ff}} = 1.2 \times 10^{21} \left(\frac{n_\infty}{1\ \mathrm{cm}^{-3}} \right)^2 \left(\frac{T_\infty}{10^4\ \mathrm{K}} \right)^{-3} \left(\frac{M}{M_\odot} \right)^3 \mathrm{erg\ s}^{-1}$$

- Mostly hard X-rays and gamma rays (up to ~10 MeV) for 1 solar mass BHs.
- Bigger BH → **softer** spectrum
- Very low efficiency for BHs! (Spherical accretion on to NSs can have 10% efficiency!)

$$\varepsilon = \frac{L_{\mathrm{ff}}}{\dot{M} c^2} \sim 6 \times 10^{-11} \left(\frac{n_\infty}{1\ \mathrm{cm}^{-3}} \right) \left(\frac{T_\infty}{10^4\ \mathrm{K}} \right)^{-3/2} \left(\frac{M}{M_\odot} \right)$$

Shapiro & Teukolsky (14.4)