PHY 7097 | Modern Astrophysics

Lecture XII.

Black holes

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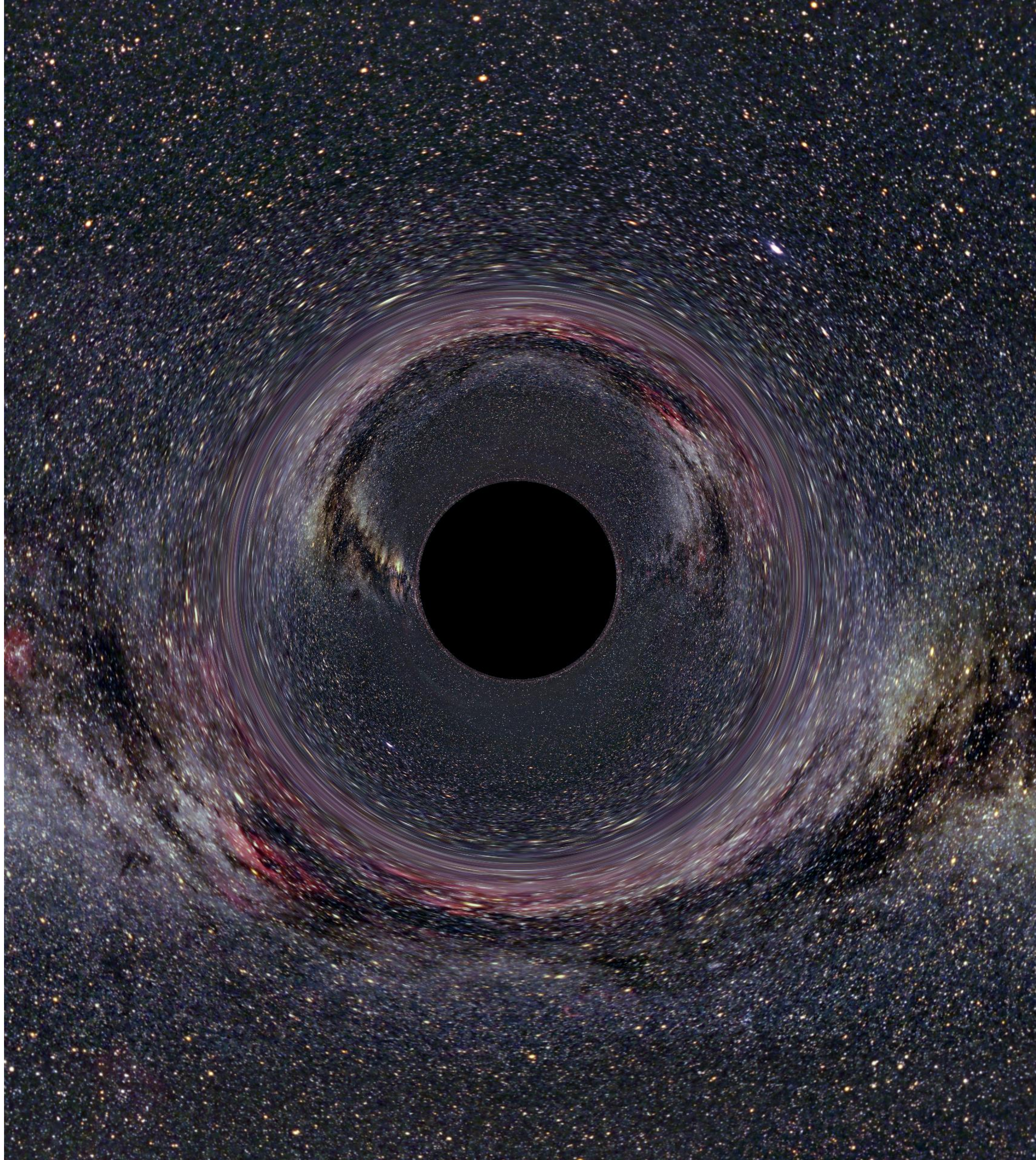
Spring 2020



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.

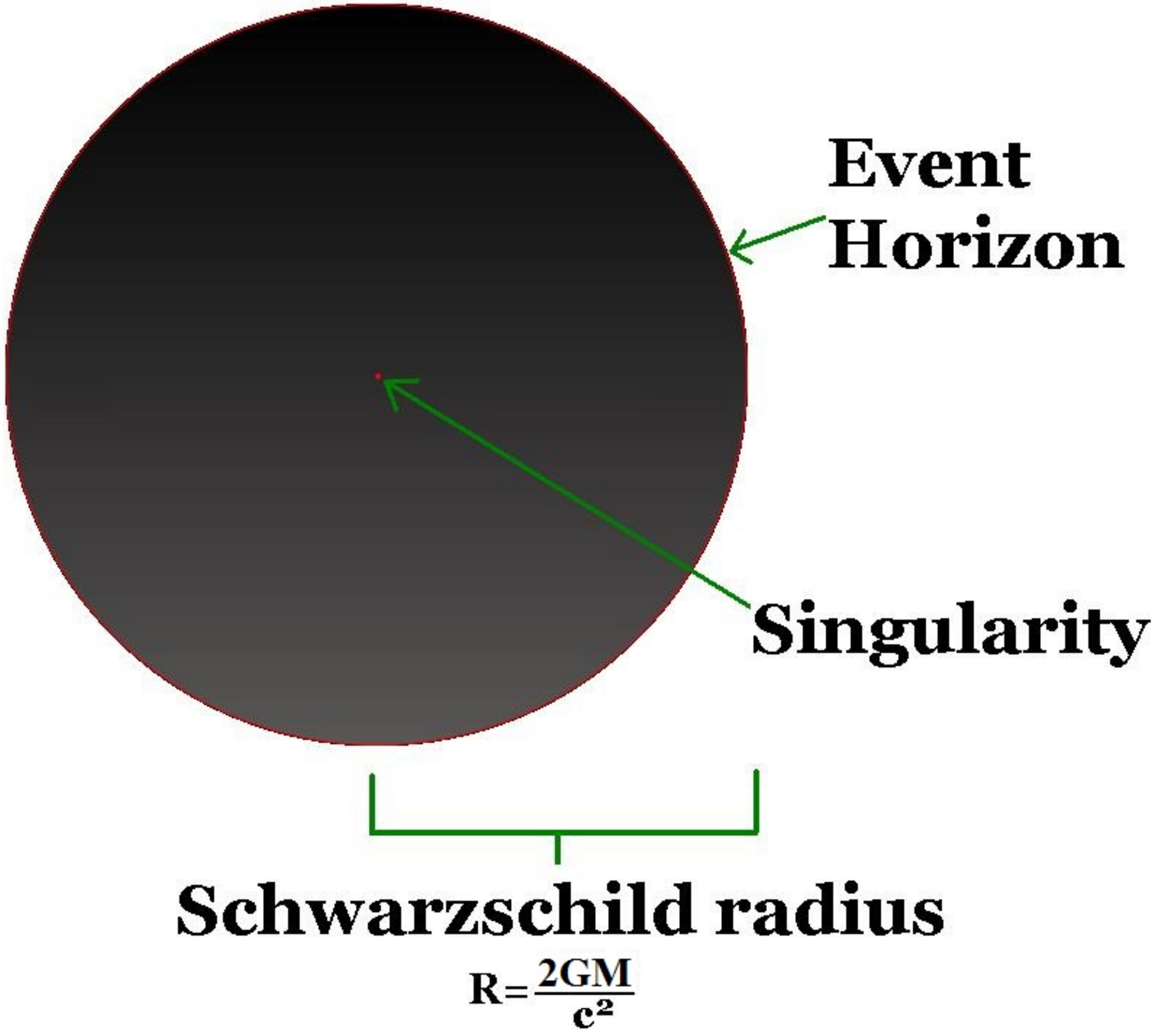
→ Loss of information upon infall.

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)

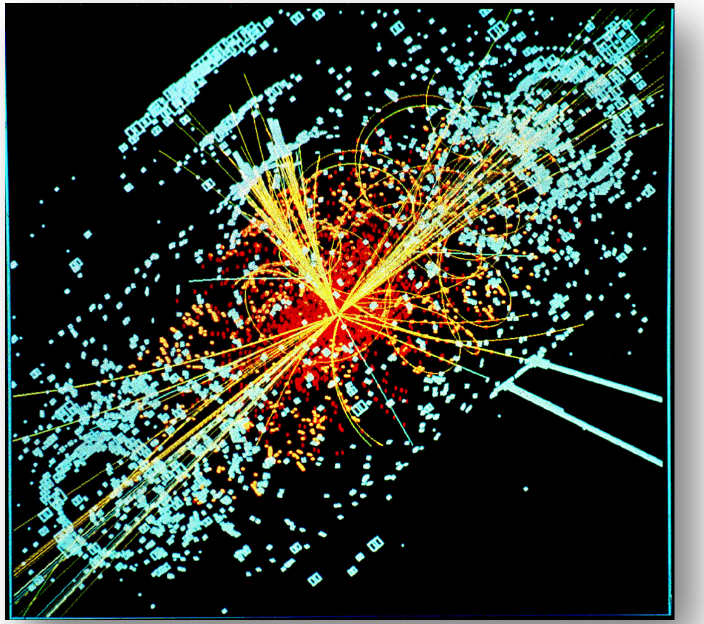
Formation mechanisms?

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!

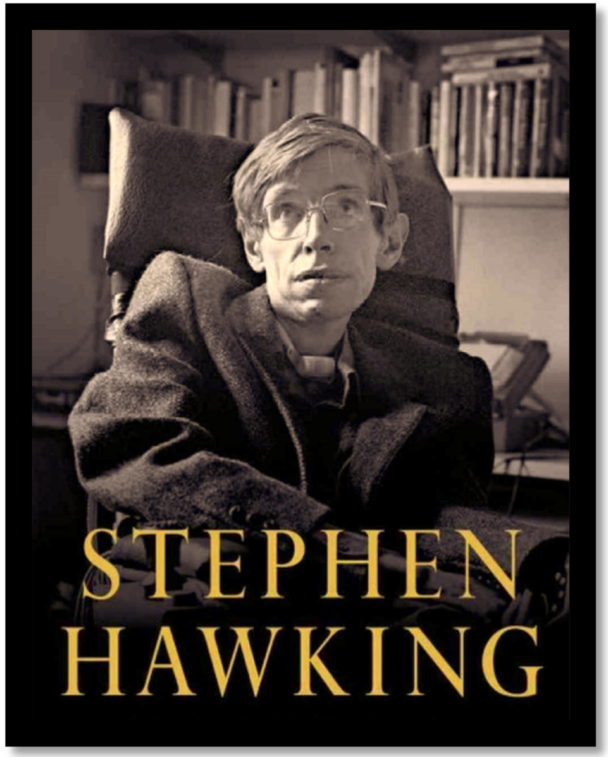
If such a small BH was created on Earth, would it be dangerous?

Hawking radiation

Black hole "temperature":

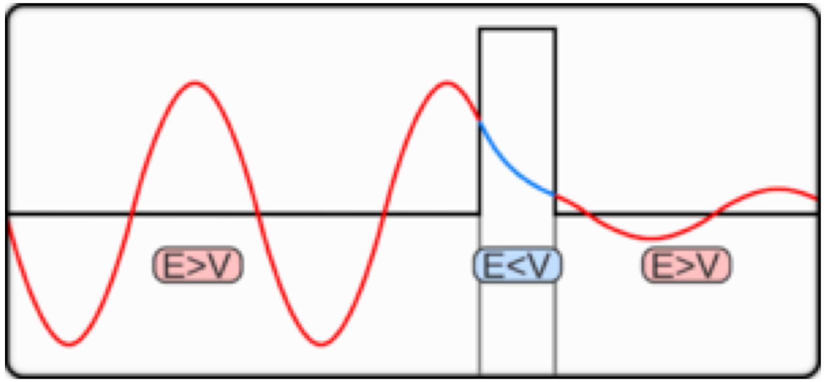
$$T = \frac{\hbar c^3}{8\pi G M k_{\mathrm{B}}} \qquad \left(\approx \frac{1.227 \times 10^{23}\ \mathrm{kg}}{M}\ \mathrm{K} = 6.169 \times 10^{-8}\ \mathrm{K} \times \frac{M_\odot}{M}\right)$$

Black hole will emit black body radiation at this temperature.



Irrelevant for astrophysical BHs.

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



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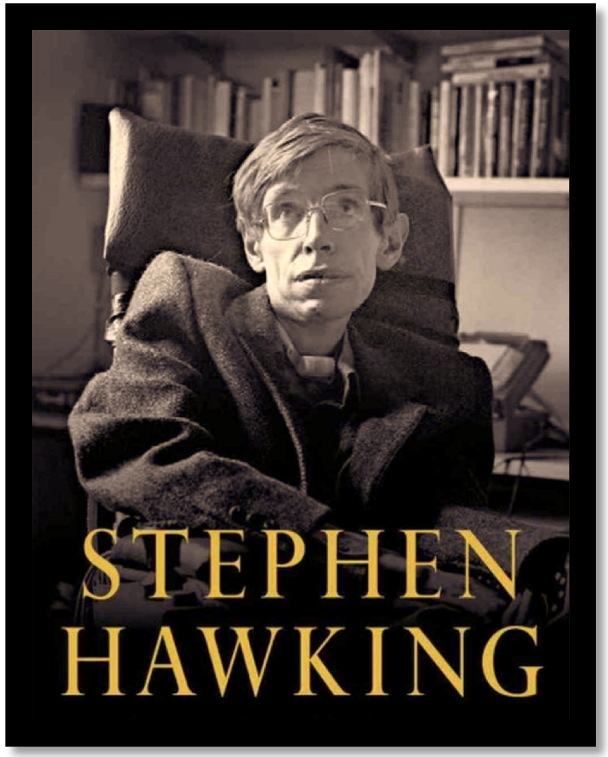

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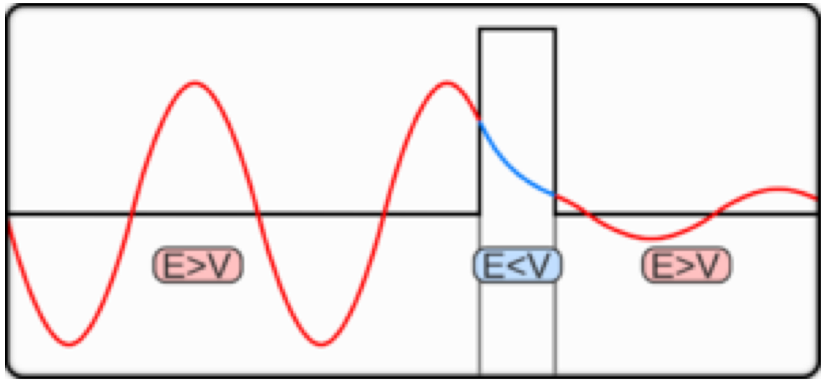


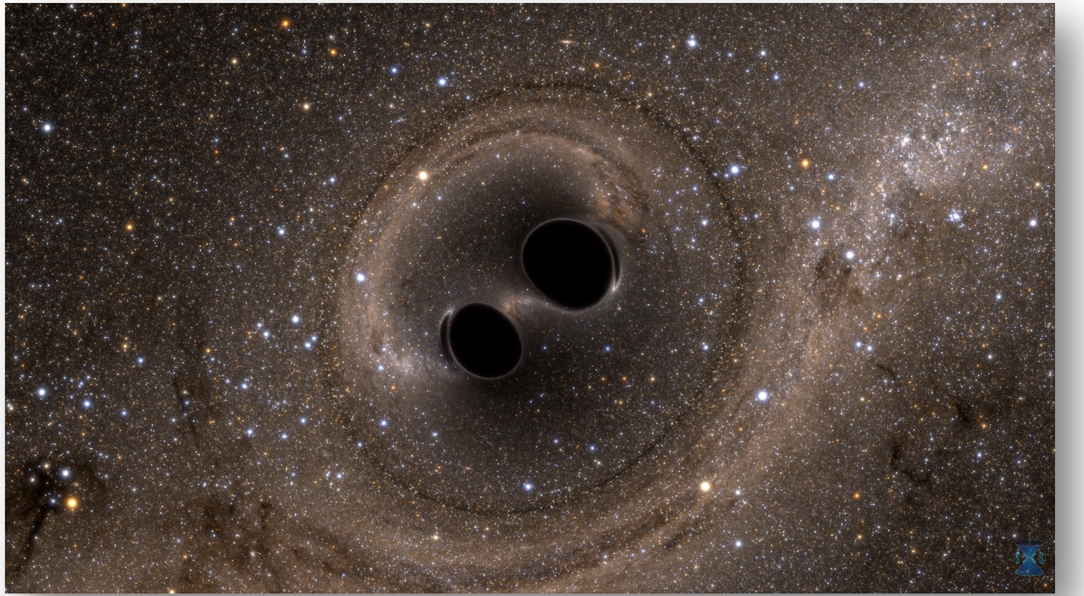
HW: What is the heaviest BH that, created on Earth, you would survive?

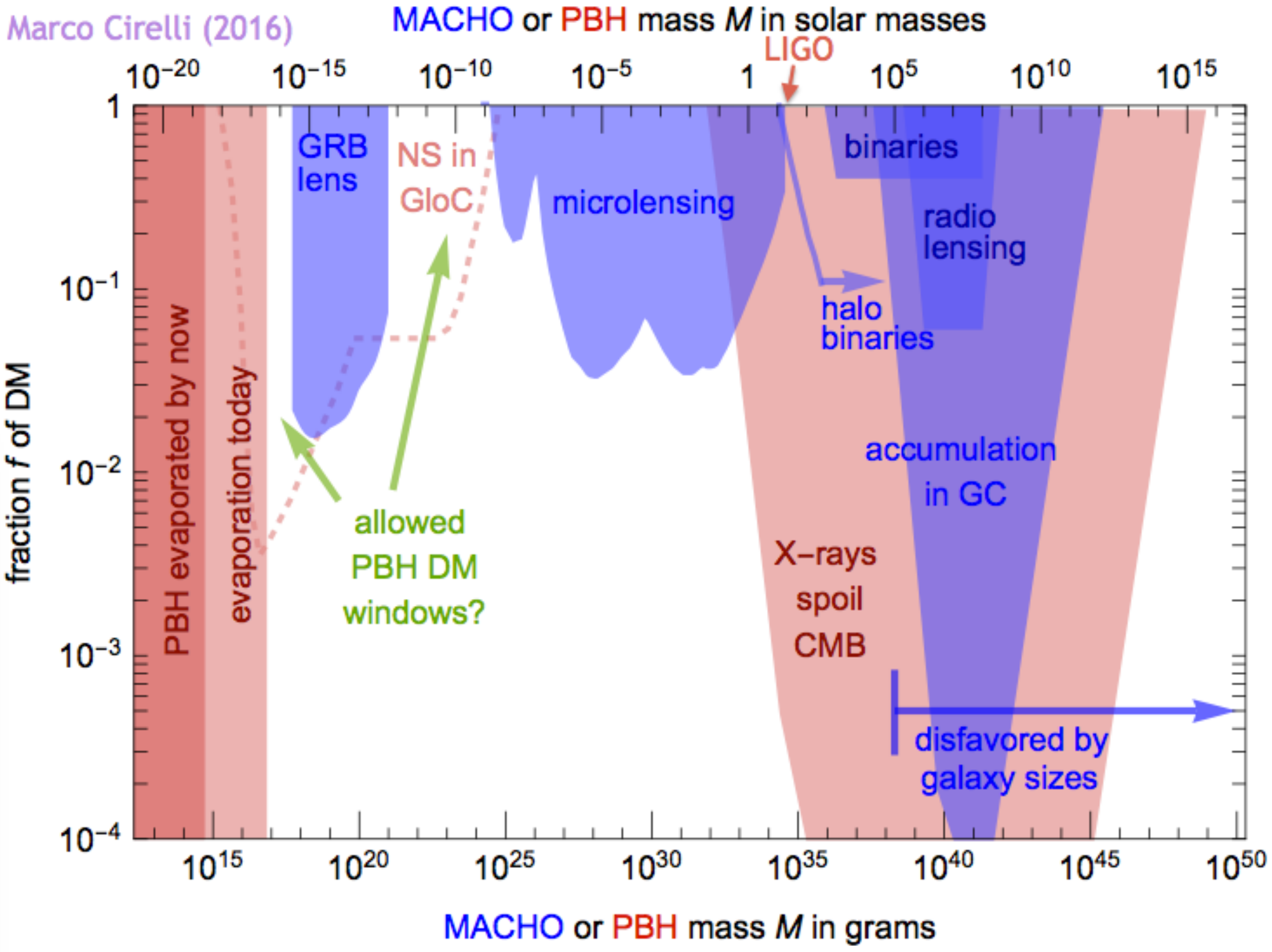
Primordial black holes

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

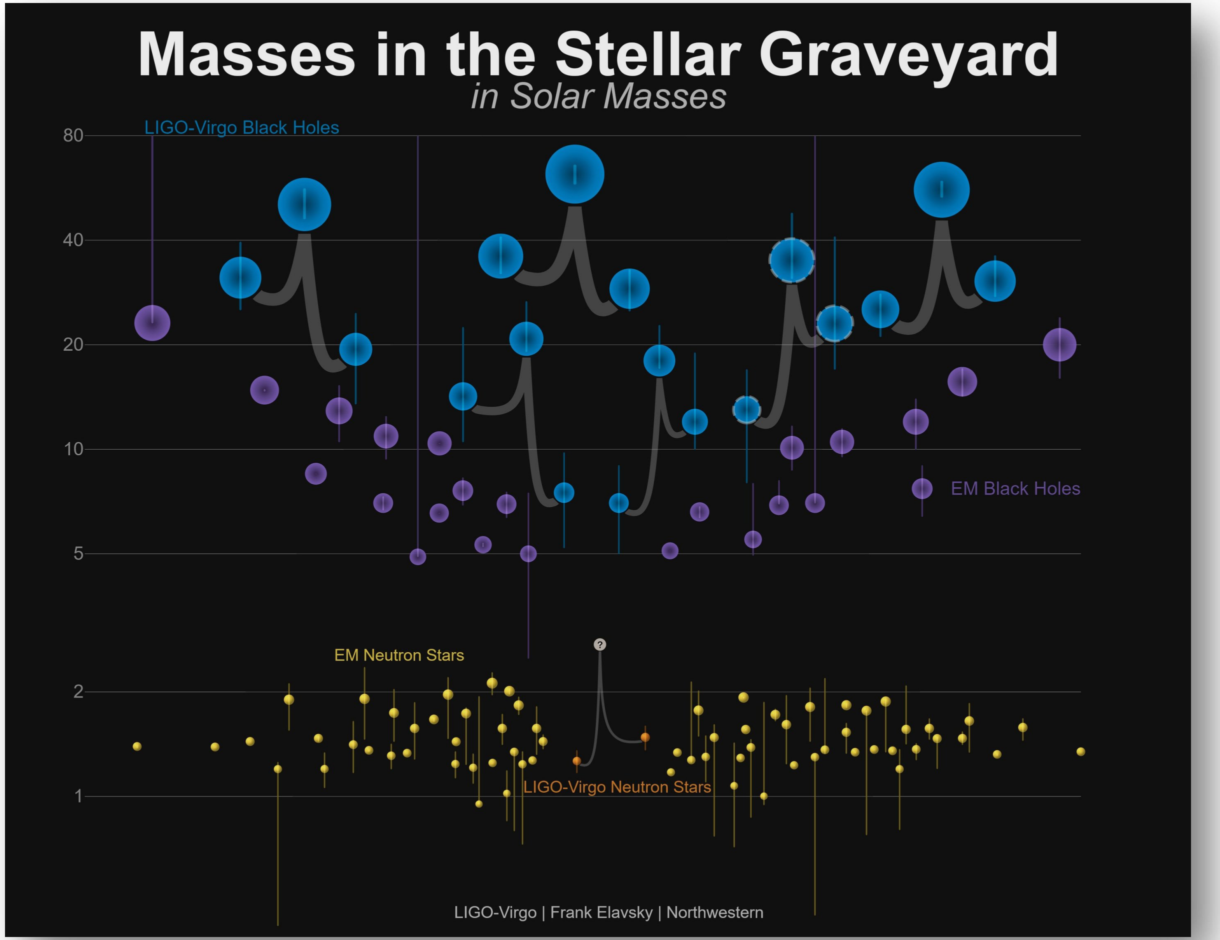
Three classes with different origin / evolution

- 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

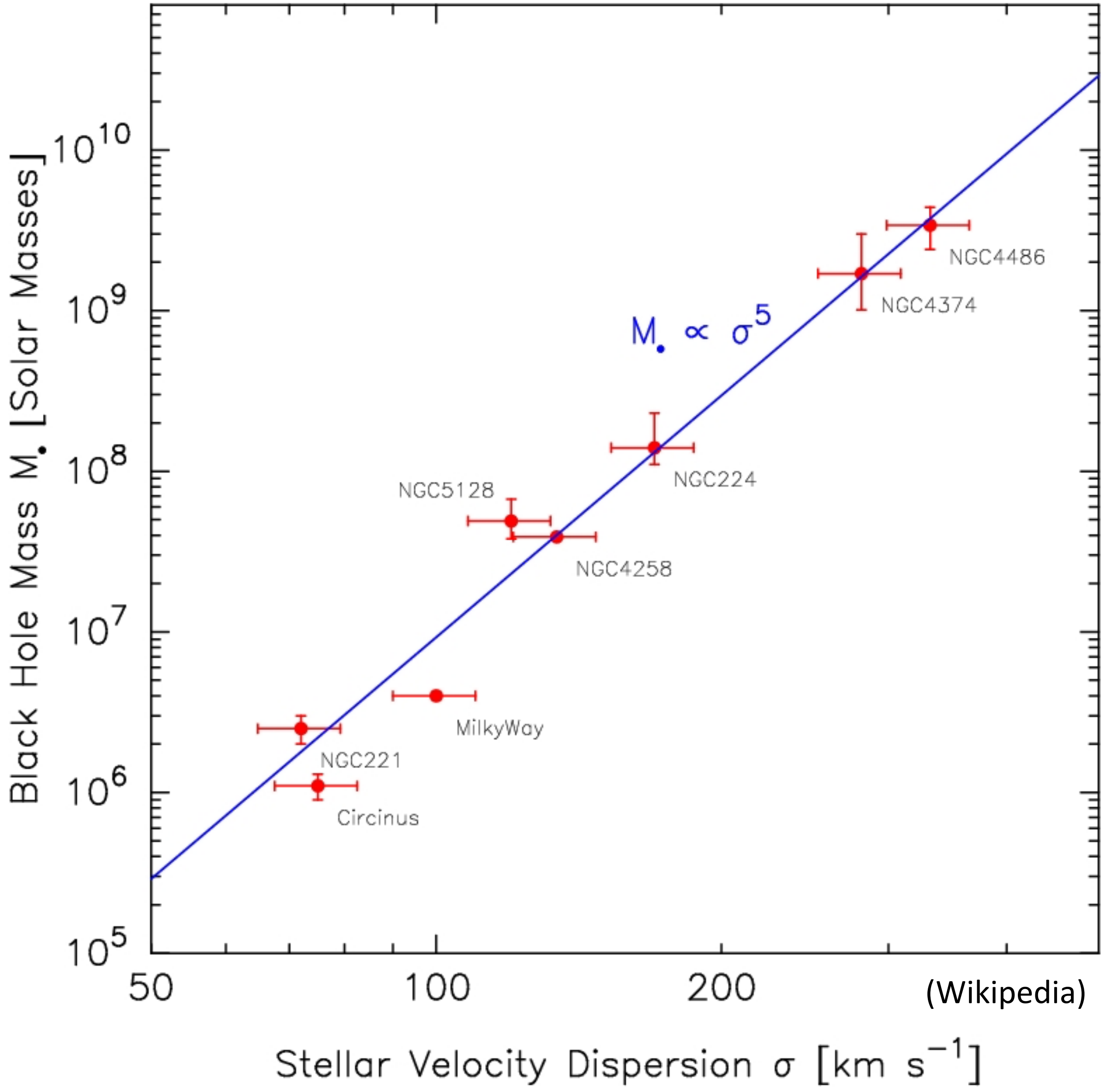
<u>Formation:</u> needs a seed
- Very massive star collapses
- Primordial black hole

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.

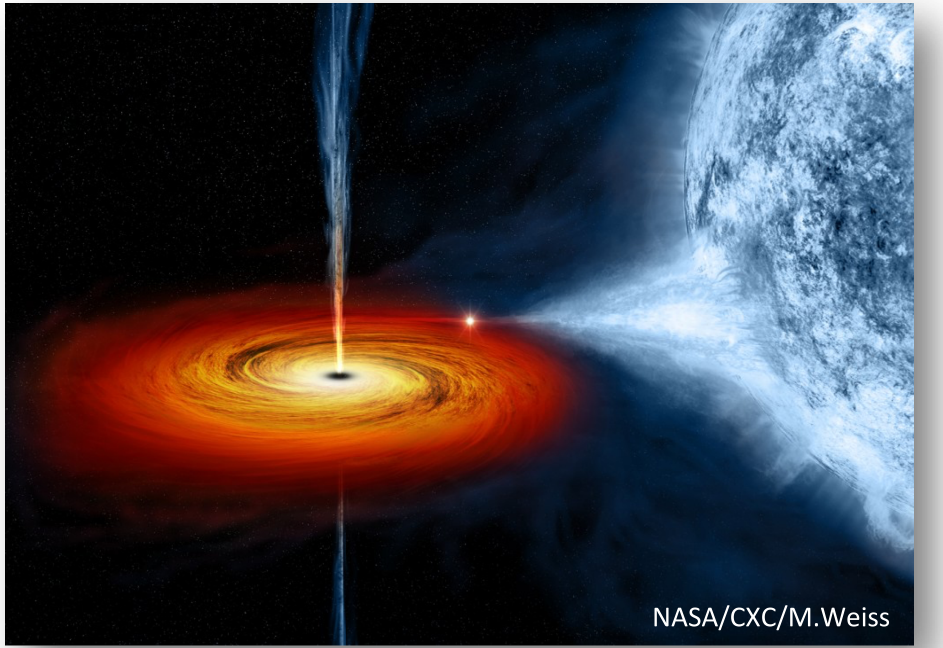


(Wikipedia)

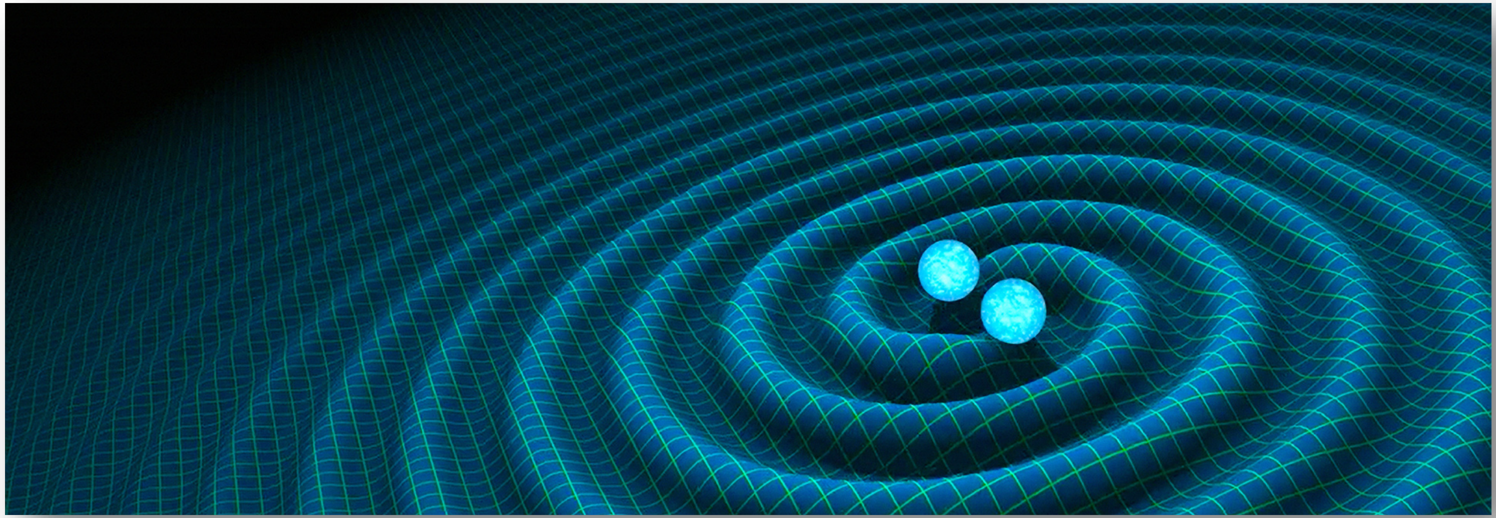
Observations

Hawking radiation is undetectable.

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



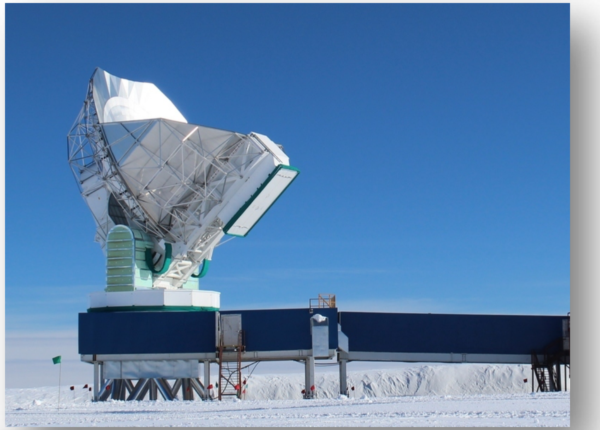
NASA/CXC/M.Weiss

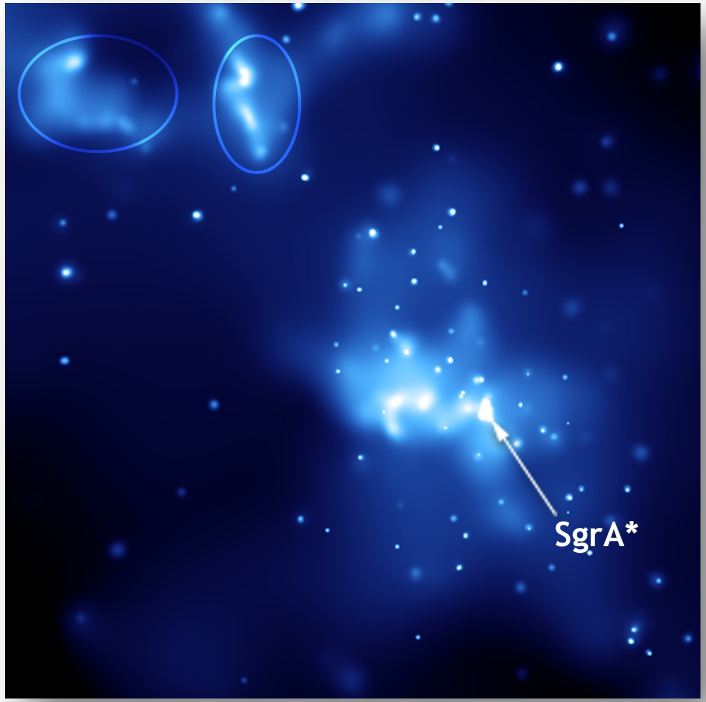


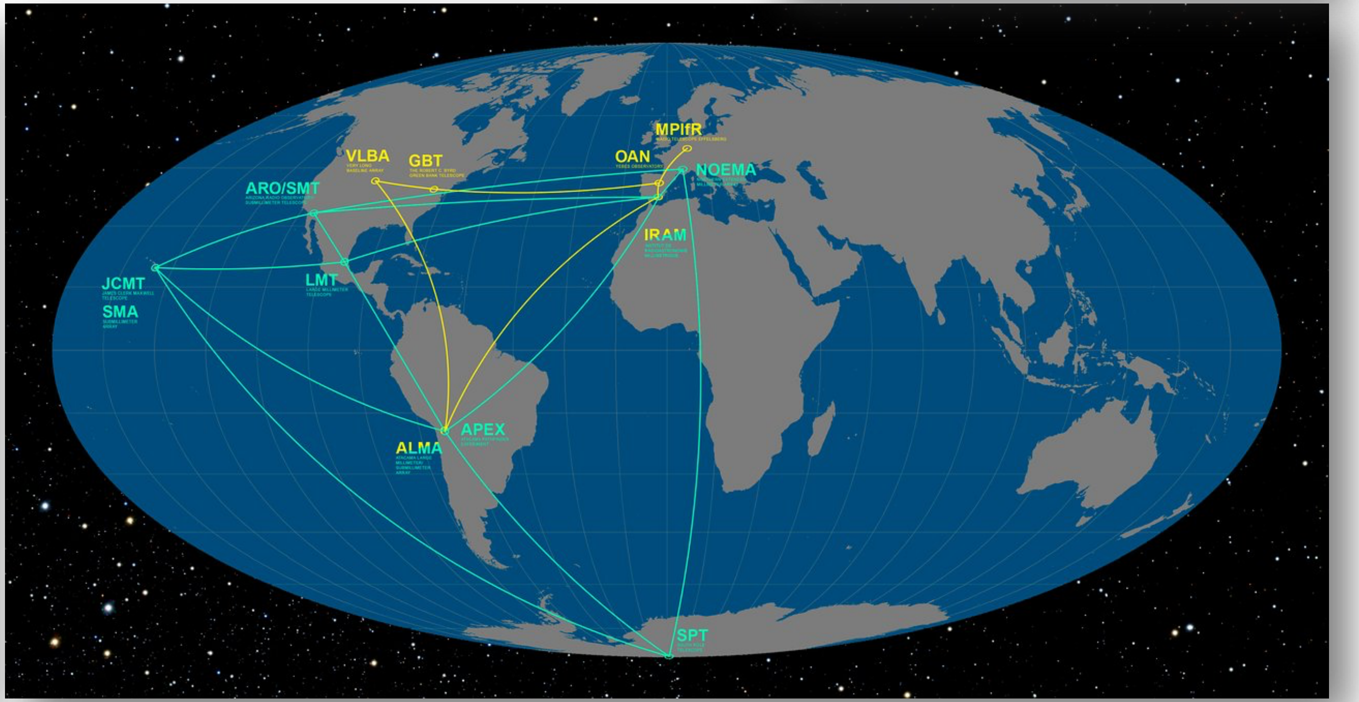
REUTERS/NASA/JPL-Caltech/Handout

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)

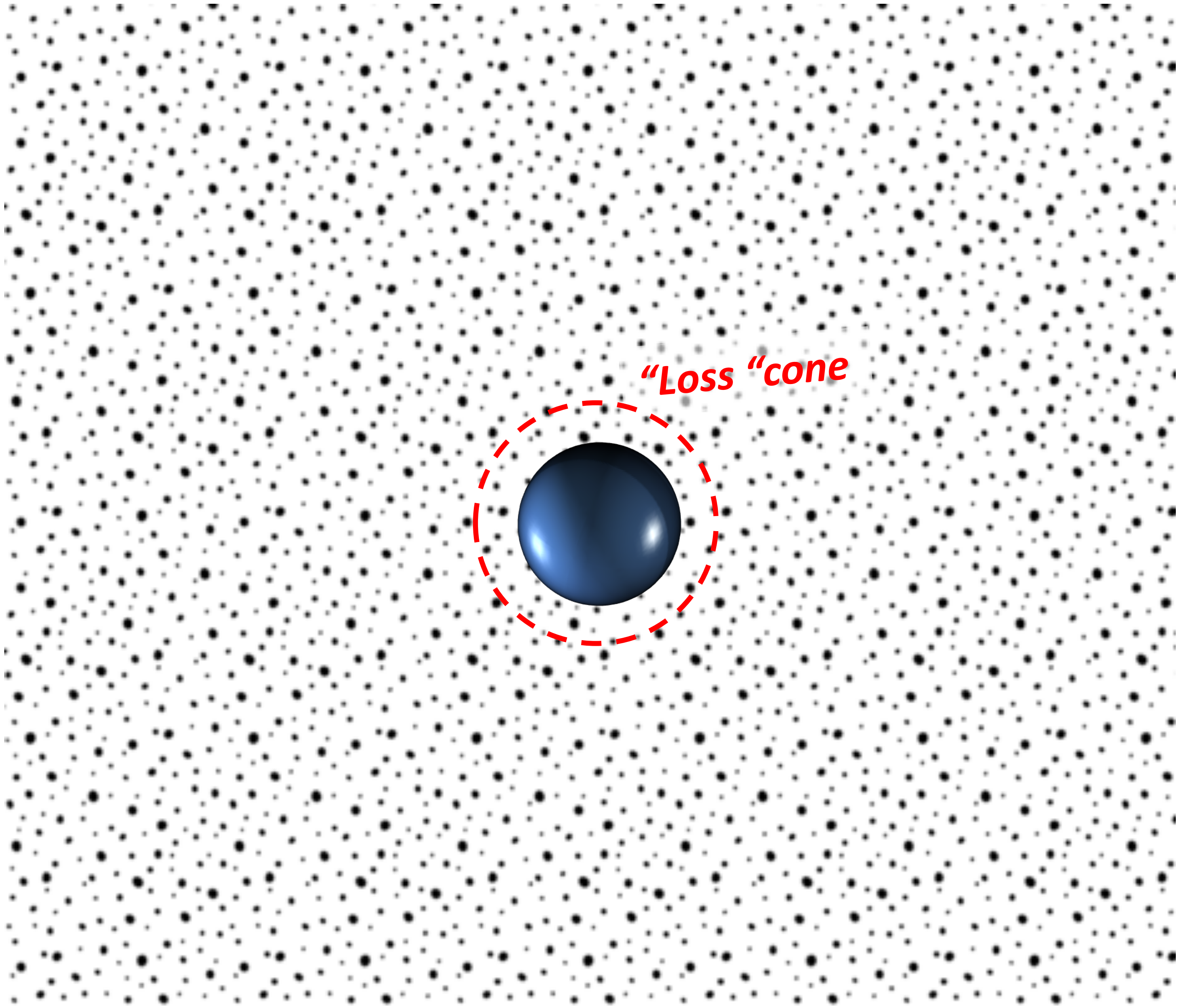
$$J_{\min}(E) \equiv \left[2\left(E + \frac{GM}{R}\right)\right]^{1/2} R \quad \text{(NR particles; Newtonian star)}$$

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

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

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

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.:

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

Bondi accretion:

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

Bondi-Hoyle-Lyttleton accretion:

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

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

Shapiro & Teukolsky (14.3)

Where does spherical accretion occur?

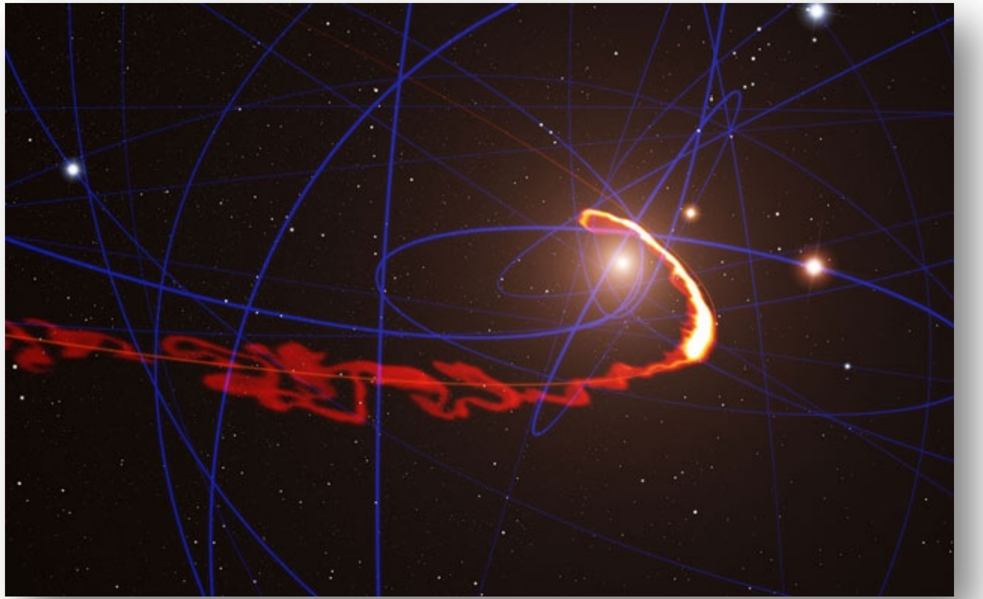
It is rare --- typically there is angular momentum.

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

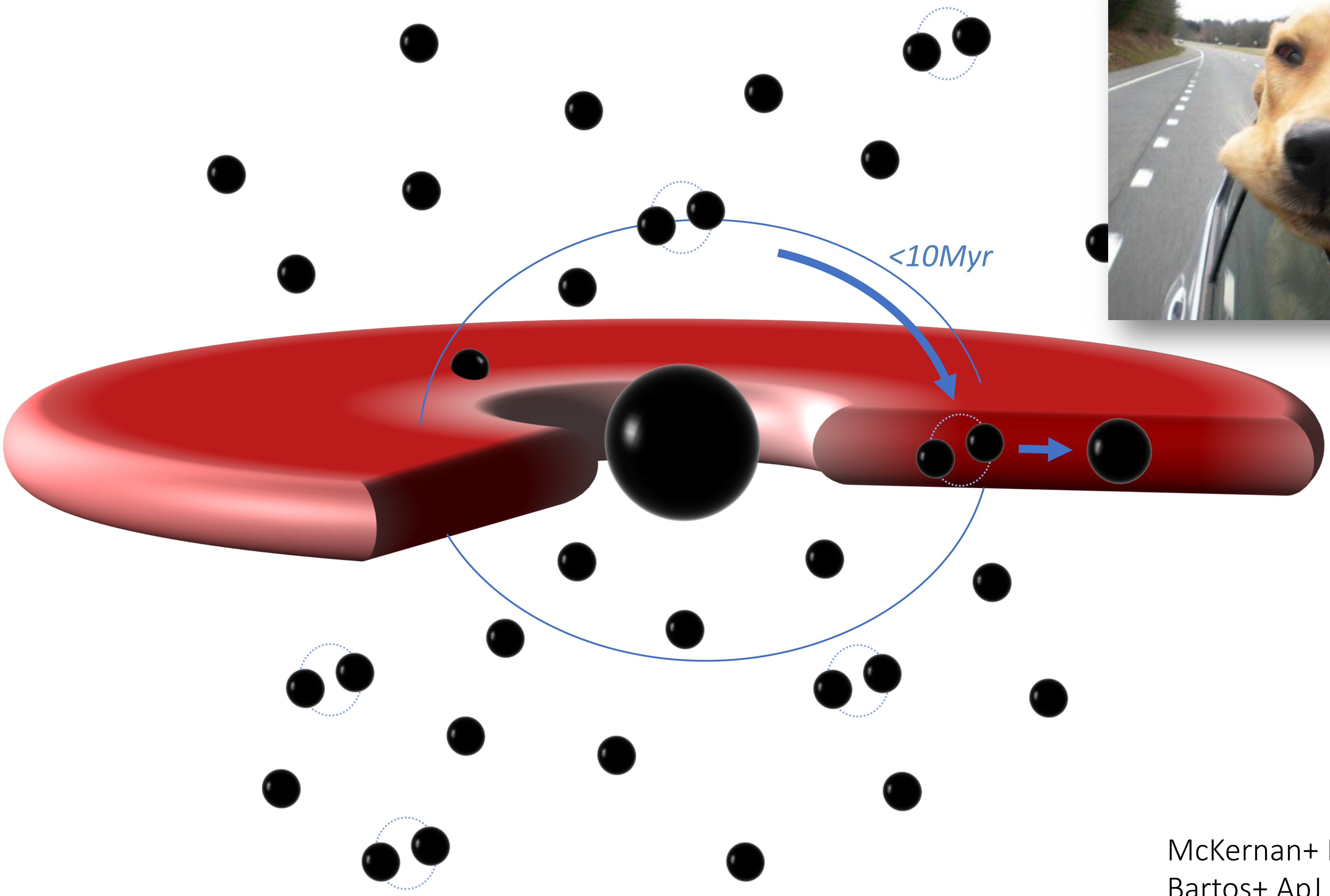
$$\dot{M} = 8.77 \times 10^{-16} \left(\frac{M}{M_\odot} \right)^2 \left(\frac{\rho_\infty}{10^{-24}\ \mathrm{g\ cm^{-3}}} \right) \left(\frac{a_\infty}{10\ \mathrm{km\ s^{-1}}} \right)^{-3} M_\odot\ \mathrm{yr}^{-1}$$

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)