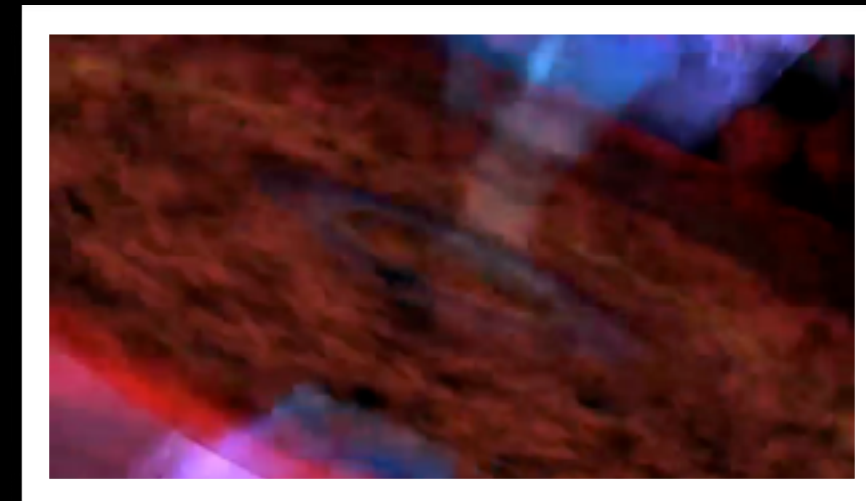


Research Overview: Black Holes

Hung-Yi Pu (卜宏毅)
July 3rd 2026



Near the
Black Hole



Why black hole matters
(to the Universe)?

Laboratory of Extreme physics!

(General) relativistic regime:

$$r \sim \frac{GM}{c^2}$$

(Special) relativistic regime:

$$\begin{aligned} v &\sim c \\ E_k &\gtrsim mc^2 \\ kT &\gtrsim mc^2 \end{aligned}$$

$$1/c$$

G

Classical world

h

$$c \rightarrow \infty, G \rightarrow 0, h \rightarrow 0$$

Black hole entropy

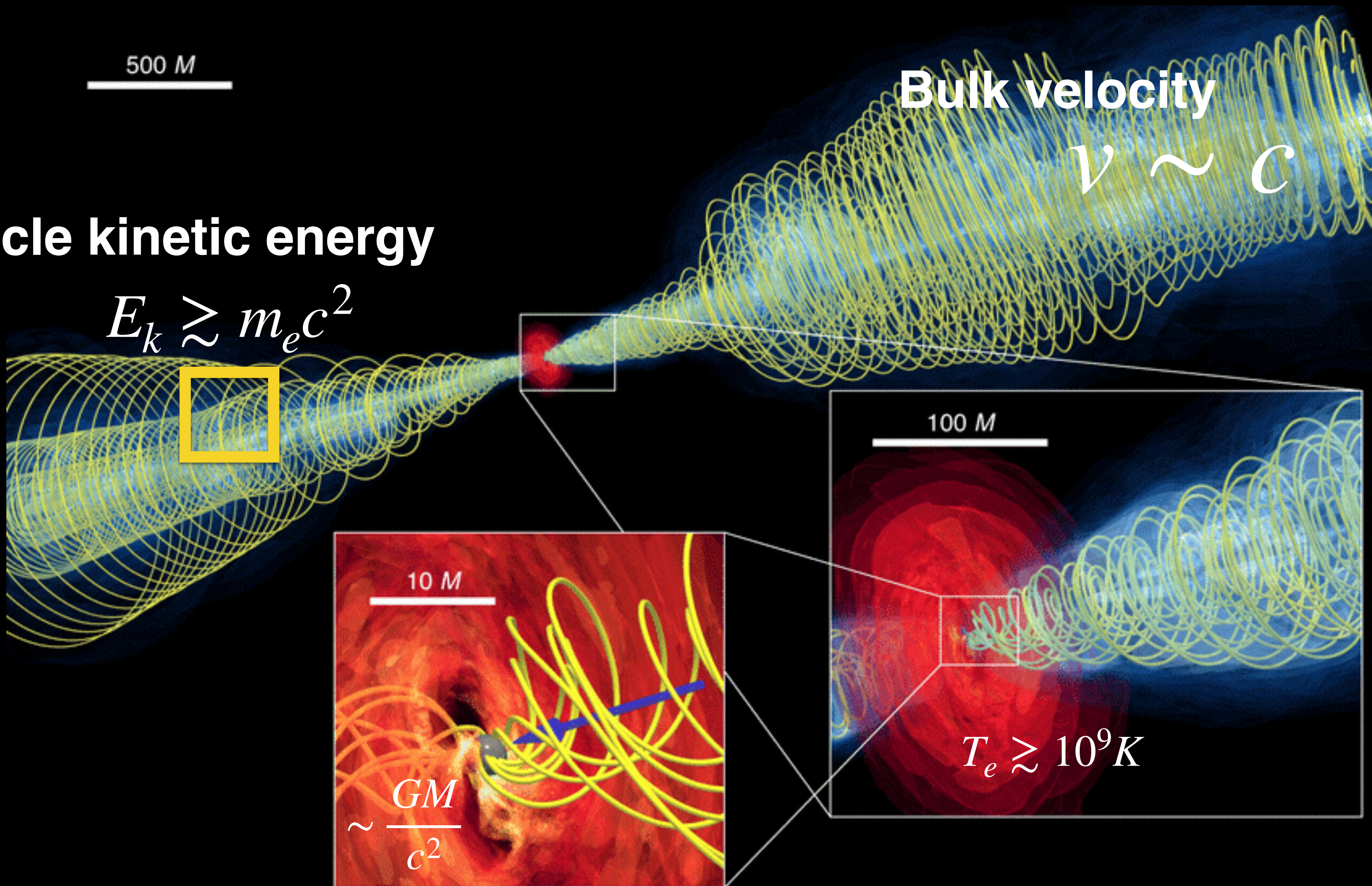
$$S = \frac{kc^3 A}{4G\hbar}$$

Particle kinetic energy

$$E_k \gtrsim m_e c^2$$

Bulk velocity

$$v \sim c$$



The big picture (astrophysics)

- predicted by **general relativity**
- tested by modern observations
- powered by **accretion**
- capable of launching **jets** and **high-energy particles**
- important agents in **galaxy evolution**

a brief history for BH astrophysics

- 1905 special relativity (SR)
- 1915 general relativity (GR)
- 1916 black hole (BH) solution
- 1960s BH astrophysics
- 2016 GW150914
- 2019 M87* BH shadow image

Outline

- Relativity 101
- What is a black hole?
- Key physical parameters for a black hole system
- Types of astrophysical black holes
- Black holes as multi-messenger engines
- AGN and galaxy convolution

Relativity 101:

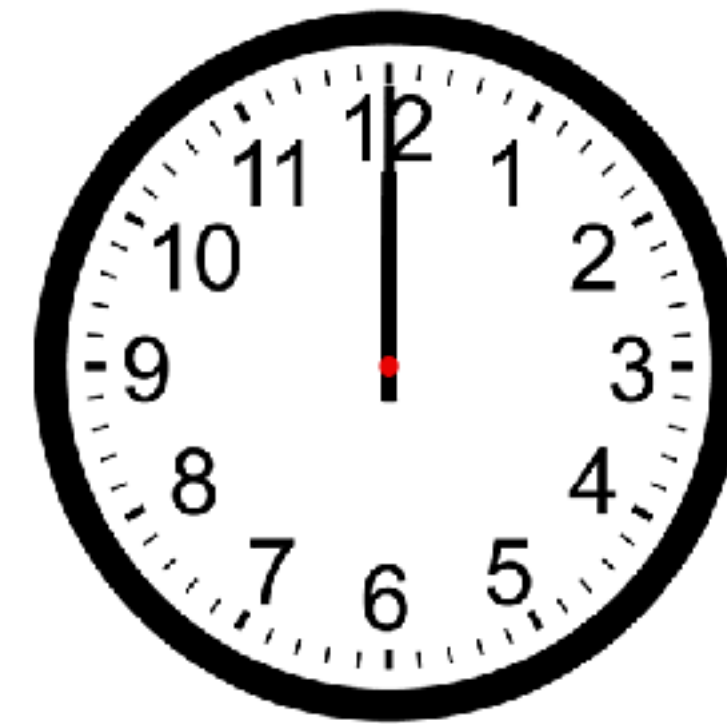
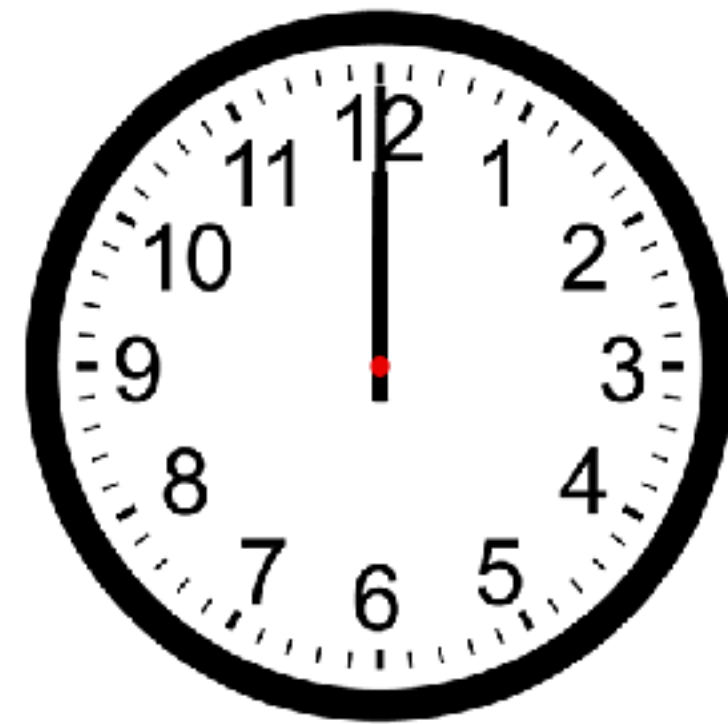
Space, time, mass, electric field,
magnetic field .. are all relative!

Galileo/Newton : “time is...”



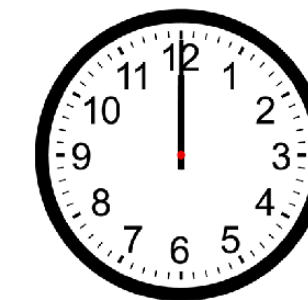
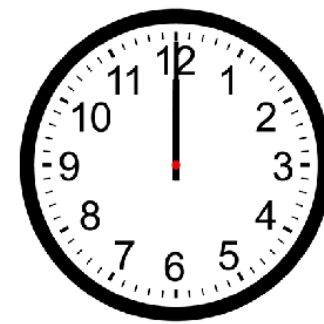
Absolute!

Relativity : “time is ...”

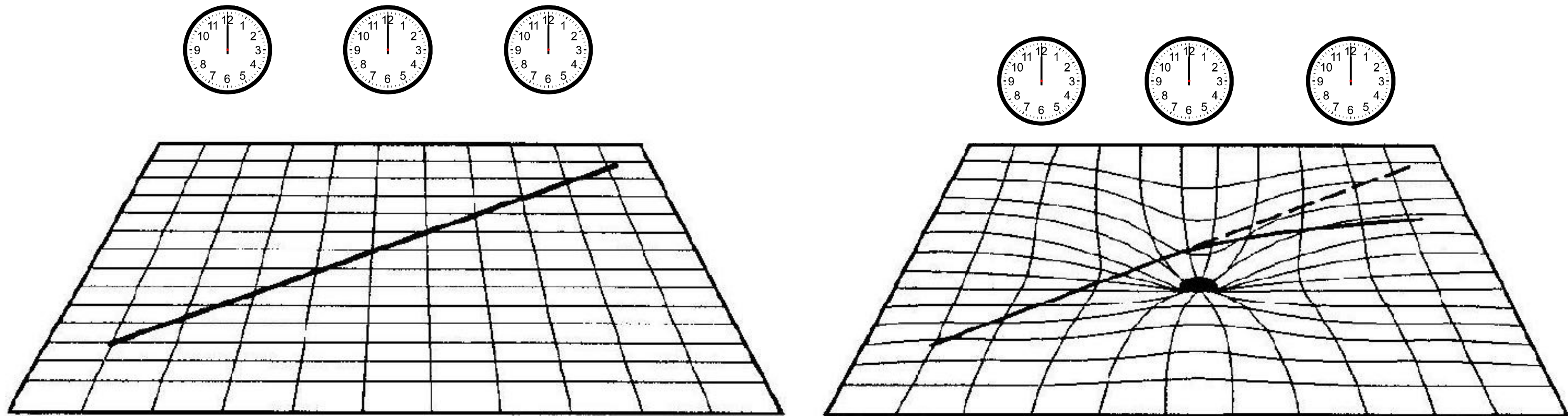


Flexible!

Running clock ticks slower...



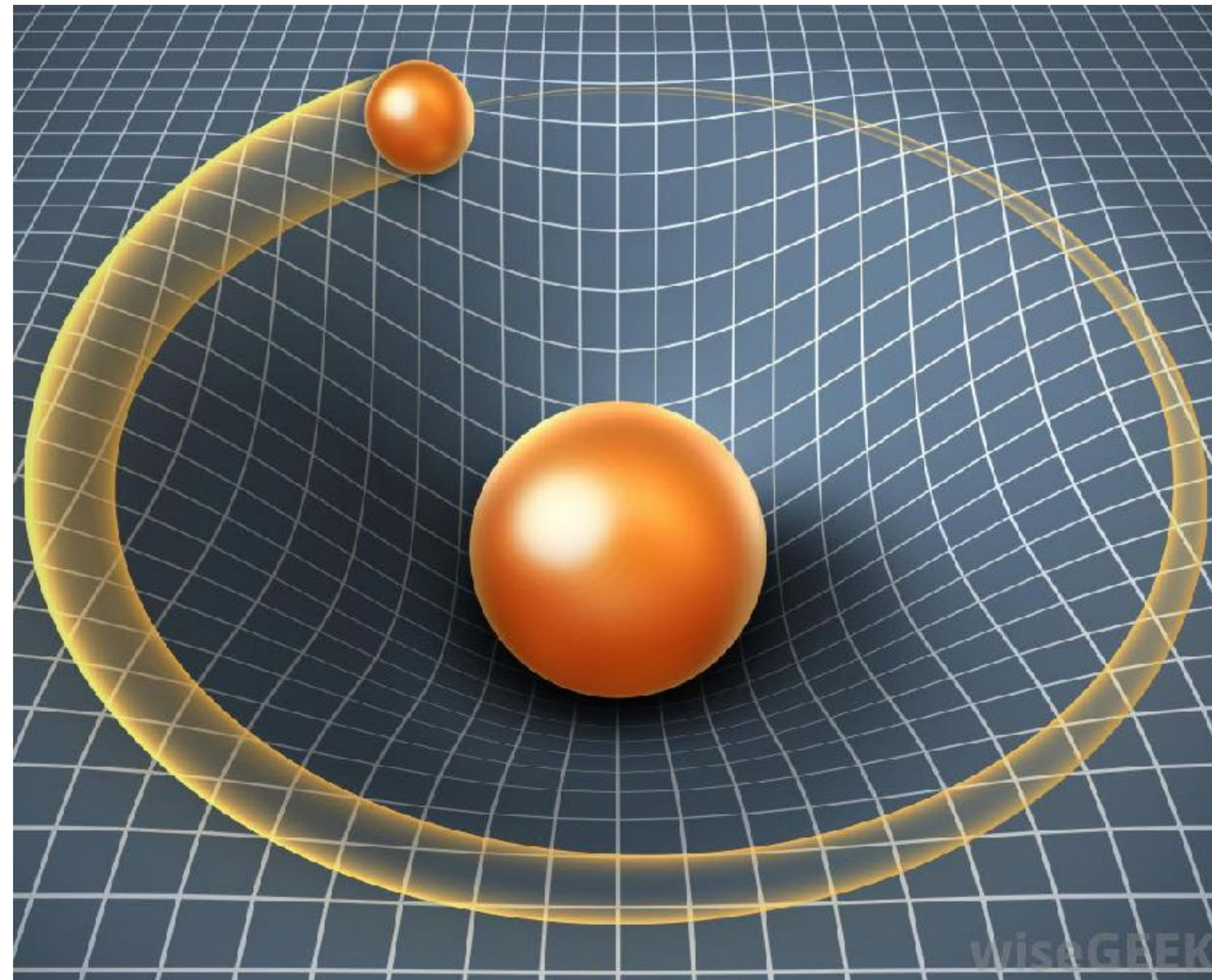
The clock closer to the mass ticks slower...



*The space is also flexible: “spacetime fabric”.

The geometry of such spacetime fabric is mathematically describe by the “spacetime metric”

John Wheeler:
“ Matter tell space how to curve,
Space tell matter how to move”



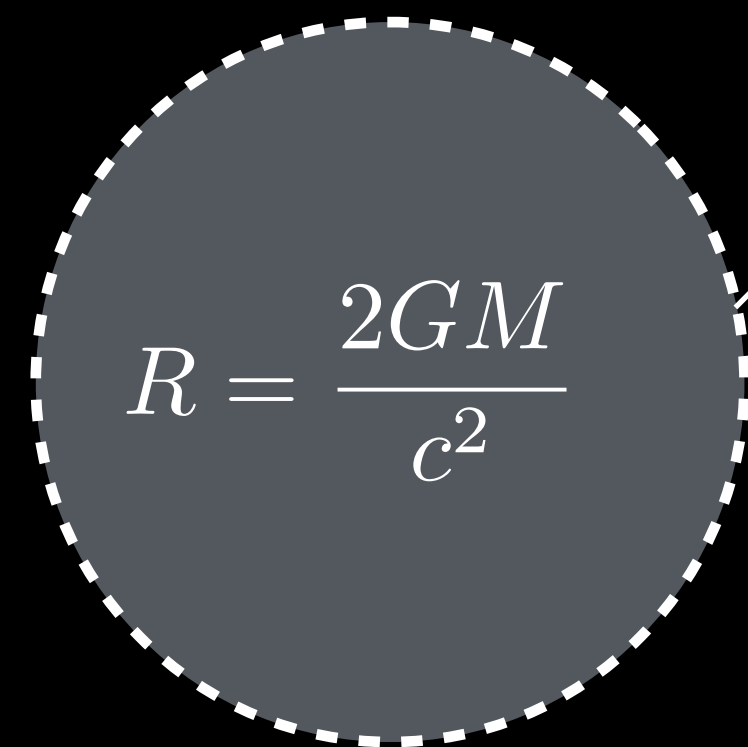
What is a black hole?

Spacetime structure
& astronomical object

black hole: spacetime structure

Non-rotating BH:

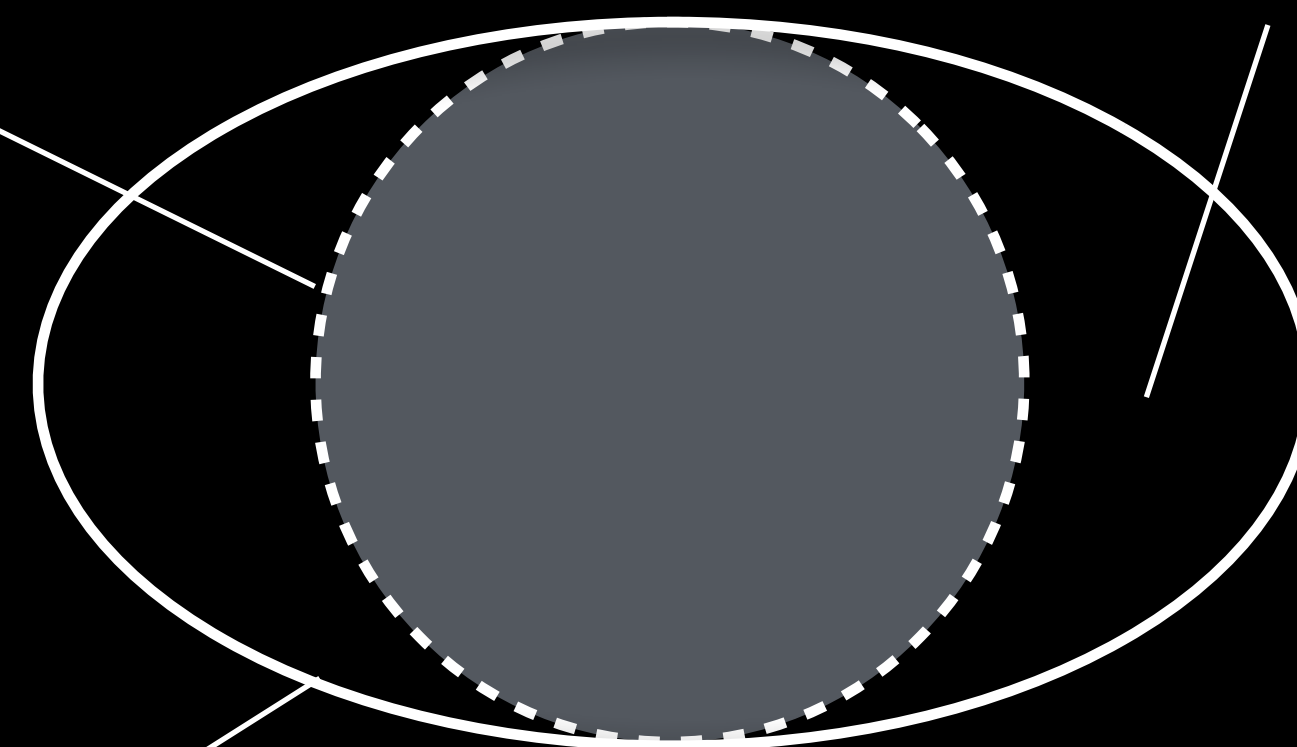
described by **Schwarzschild geometry (1916)**



event horizon

Rotating BH:

described by **Kerr geometry (1963)**

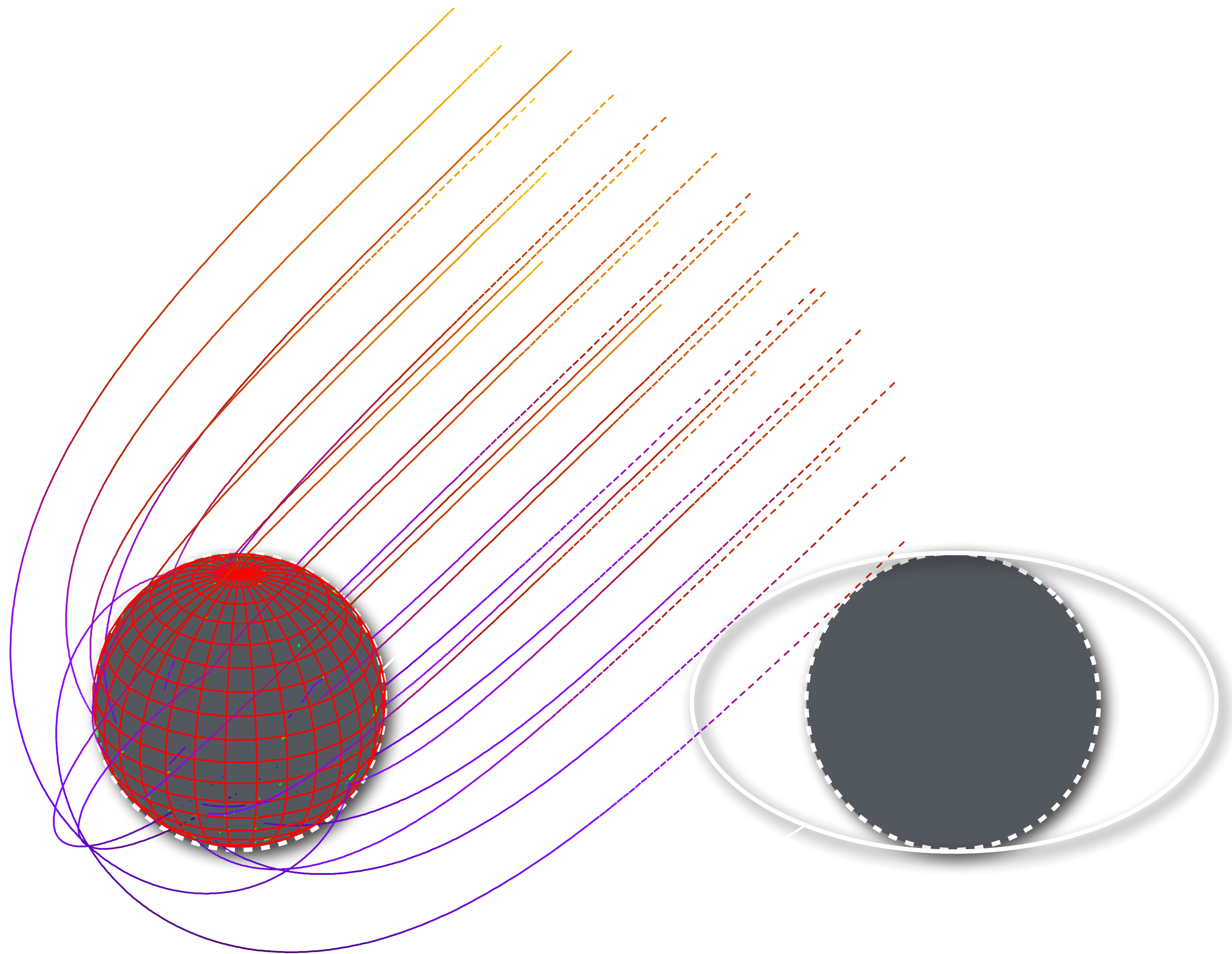


ergosphere

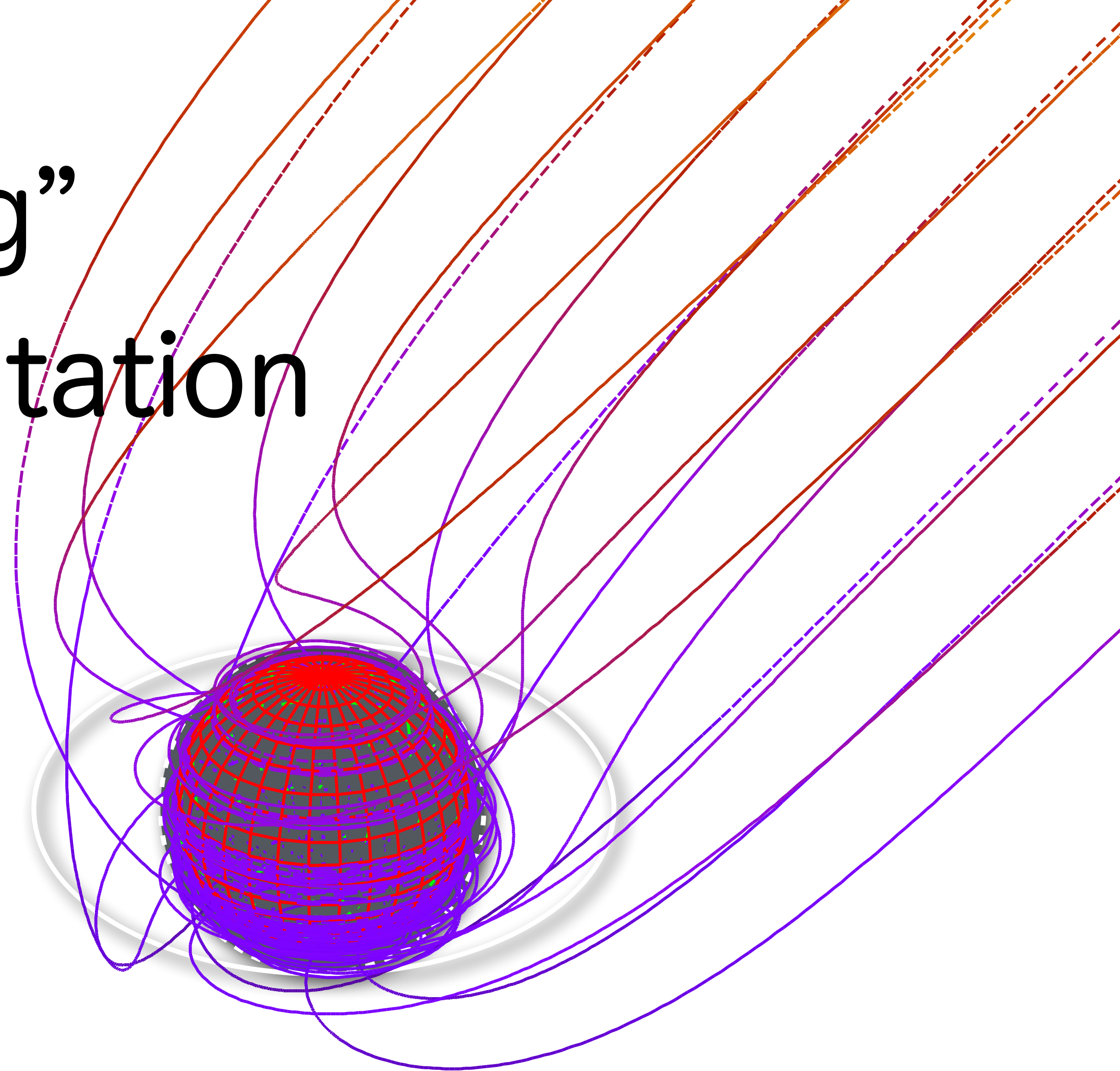
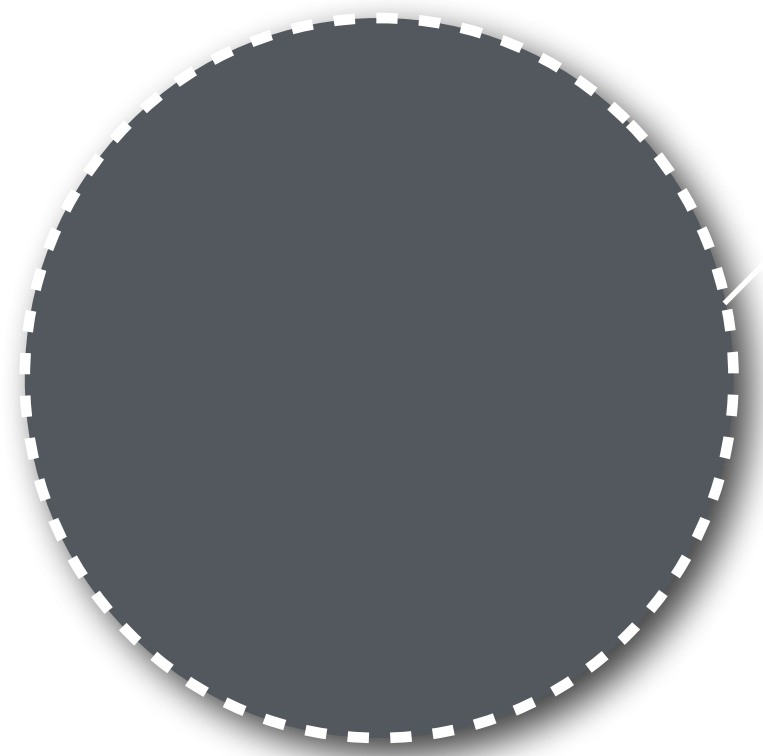
static limit

$$-1 < a^* = (J/M_{\text{BH}}c)/M_{\text{BH}} < 1$$

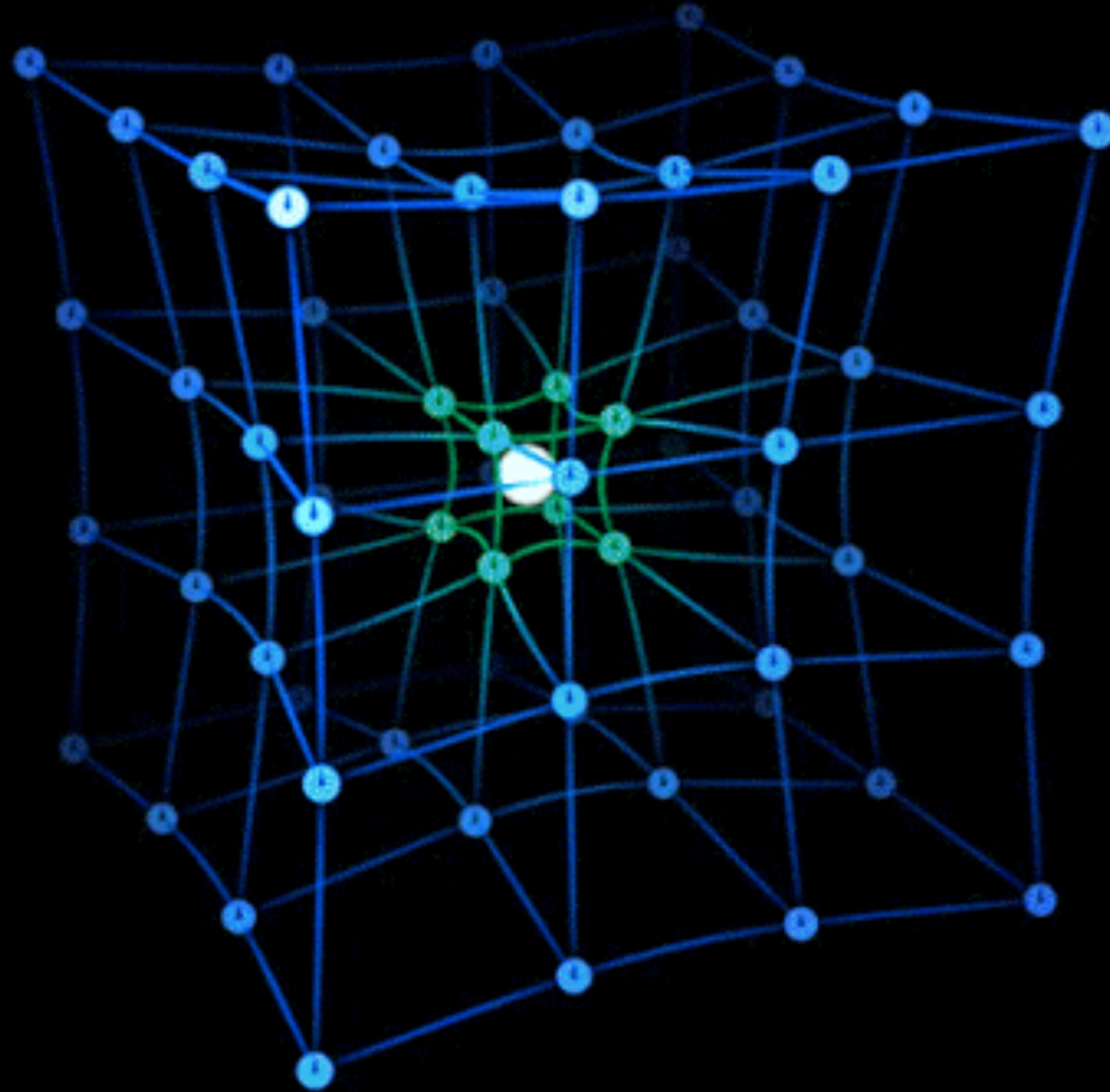
Kerr hypothesis: “astronomical black holes are described by the Kerr metric”

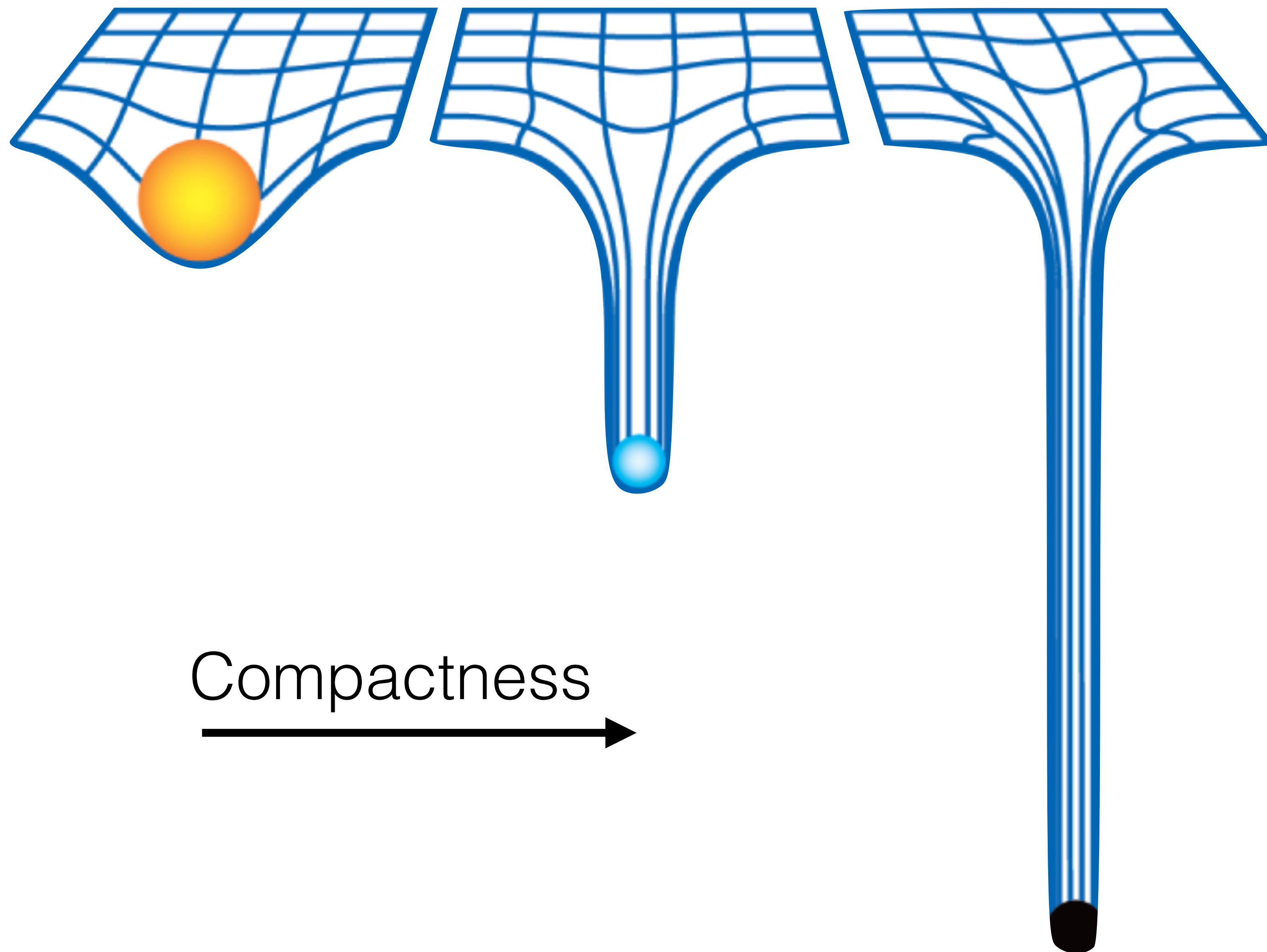


“frame dragging”
due to spacetime rotation



spacetime around a spherical mass

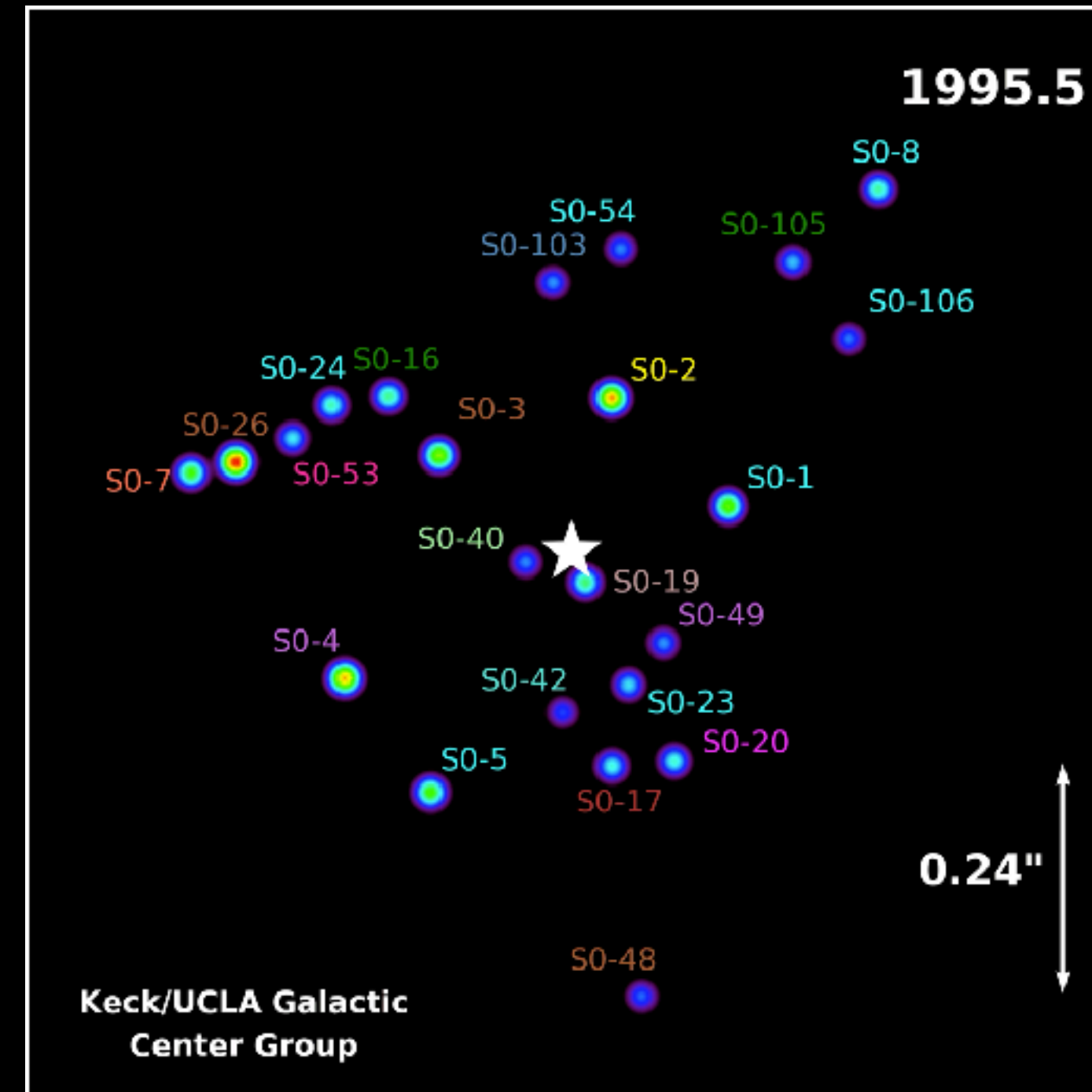




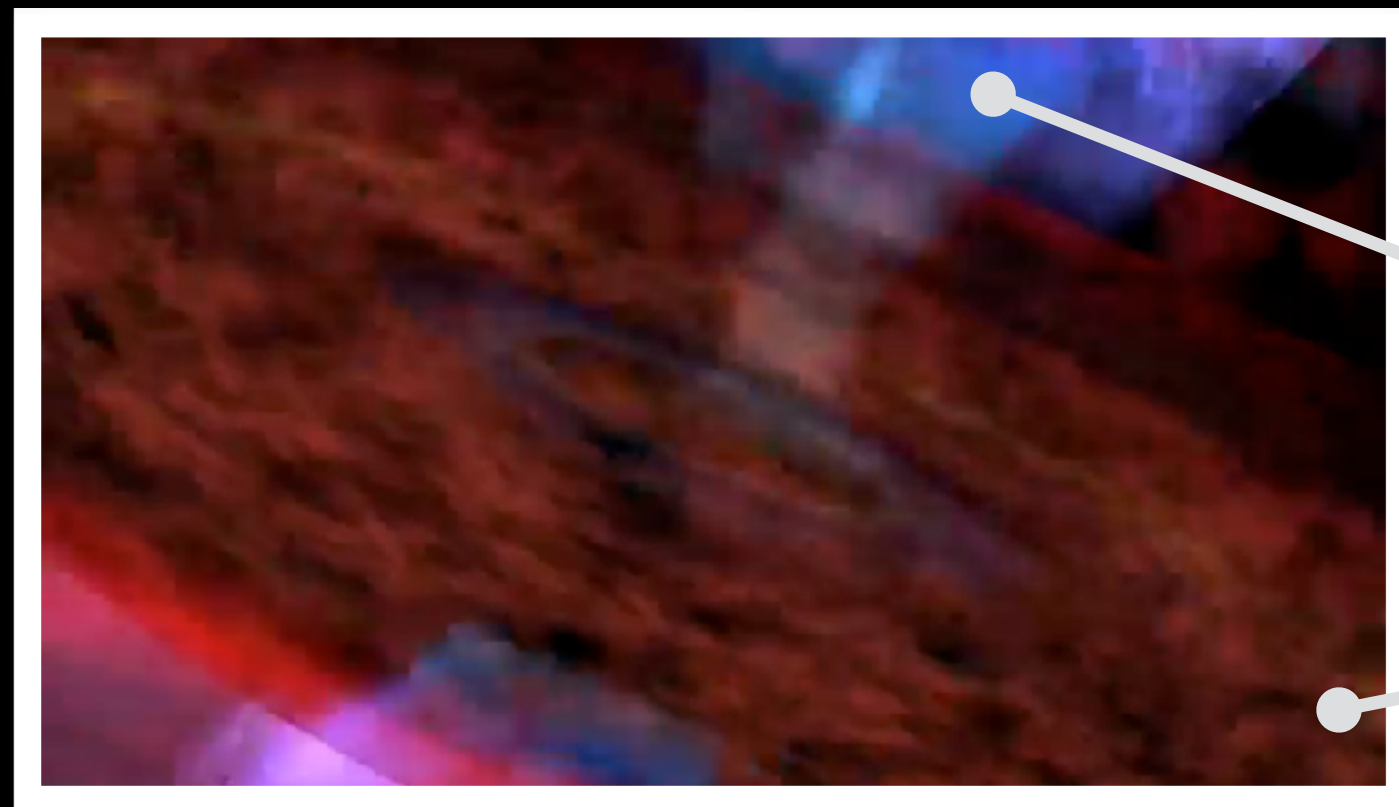
*radius of BH with one solar mass = 3km

Compactness

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



Black hole + accretion = powerful power factory



Jet

Accretion

$$\Delta E \approx \frac{GMm}{R} = 0.5mc^2$$

Key parameters:
Black hole spin, mass, and
accretion rate

Black hole mass

$$r_g = \frac{GM}{c^2} = 14.77 \frac{M_{BH}}{10M_{\odot}} \text{ km}$$

$$t_g = \frac{GM}{c^3} = 49.23 \frac{M_{BH}}{10M_{\odot}} \mu\text{s}$$

$$r_{Sch} = \frac{2GM}{c^2} \sim 30 \frac{M_{BH}}{10M_{\odot}} \text{ km}$$

Black hole mass

$$L_{Edd} = 1.3 \times 10^{39} \frac{M_{BH}}{M_{\odot}} \text{ erg/s}$$

Eddington luminosity:

maximum luminosity at which outward radiation pressure balances inward gravity.

The more massive, the (potentially) more powerful!

Black hole mass

$$L_{Edd} = 1.3 \times 10^{39} \frac{M_{BH}}{M_{\odot}} \text{ erg/s}$$

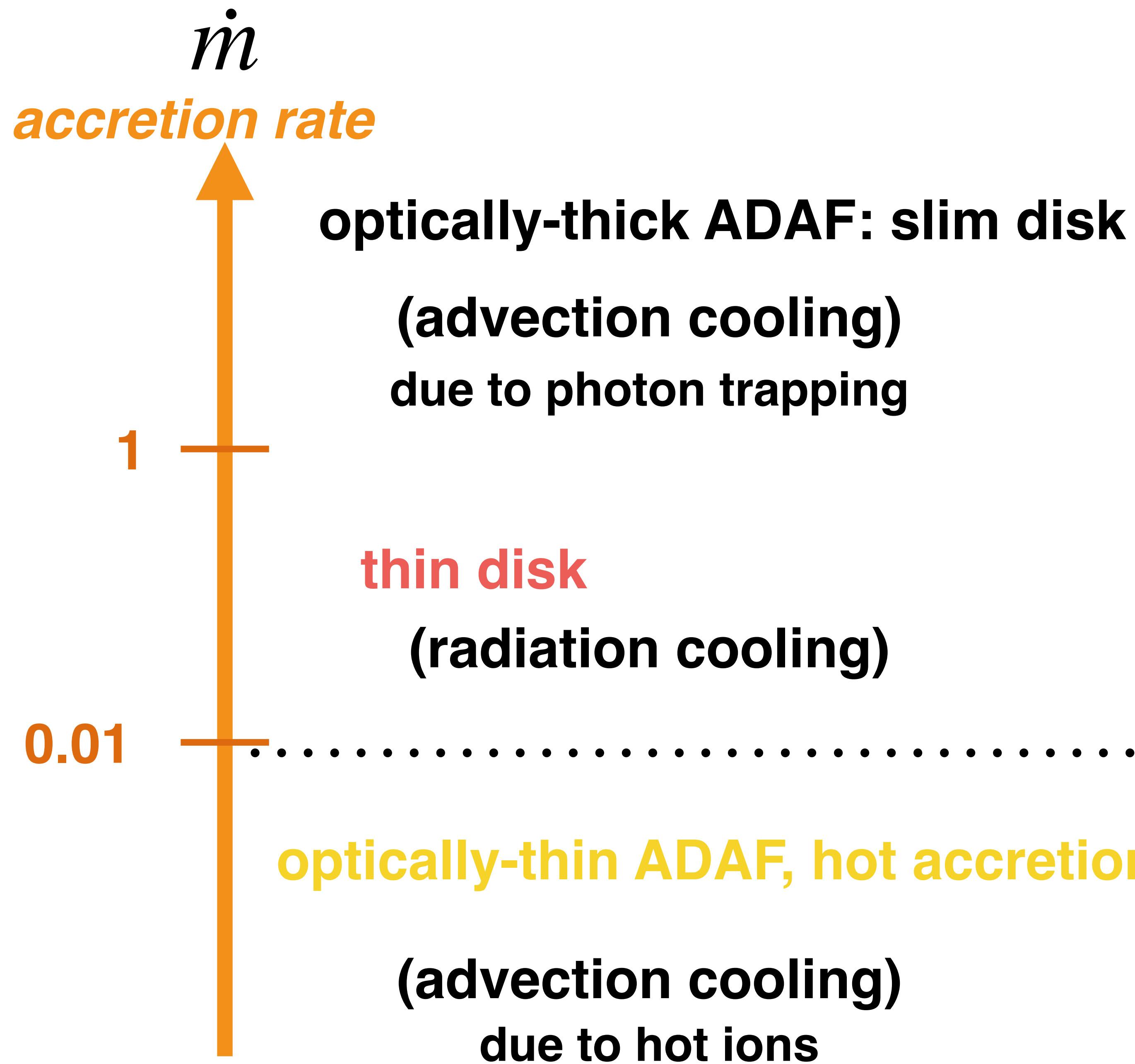
$$L = \eta \dot{M} c^2$$

Eddington accretion rate:

$$L_{Edd} = \eta \dot{M}_{Edd} c^2$$

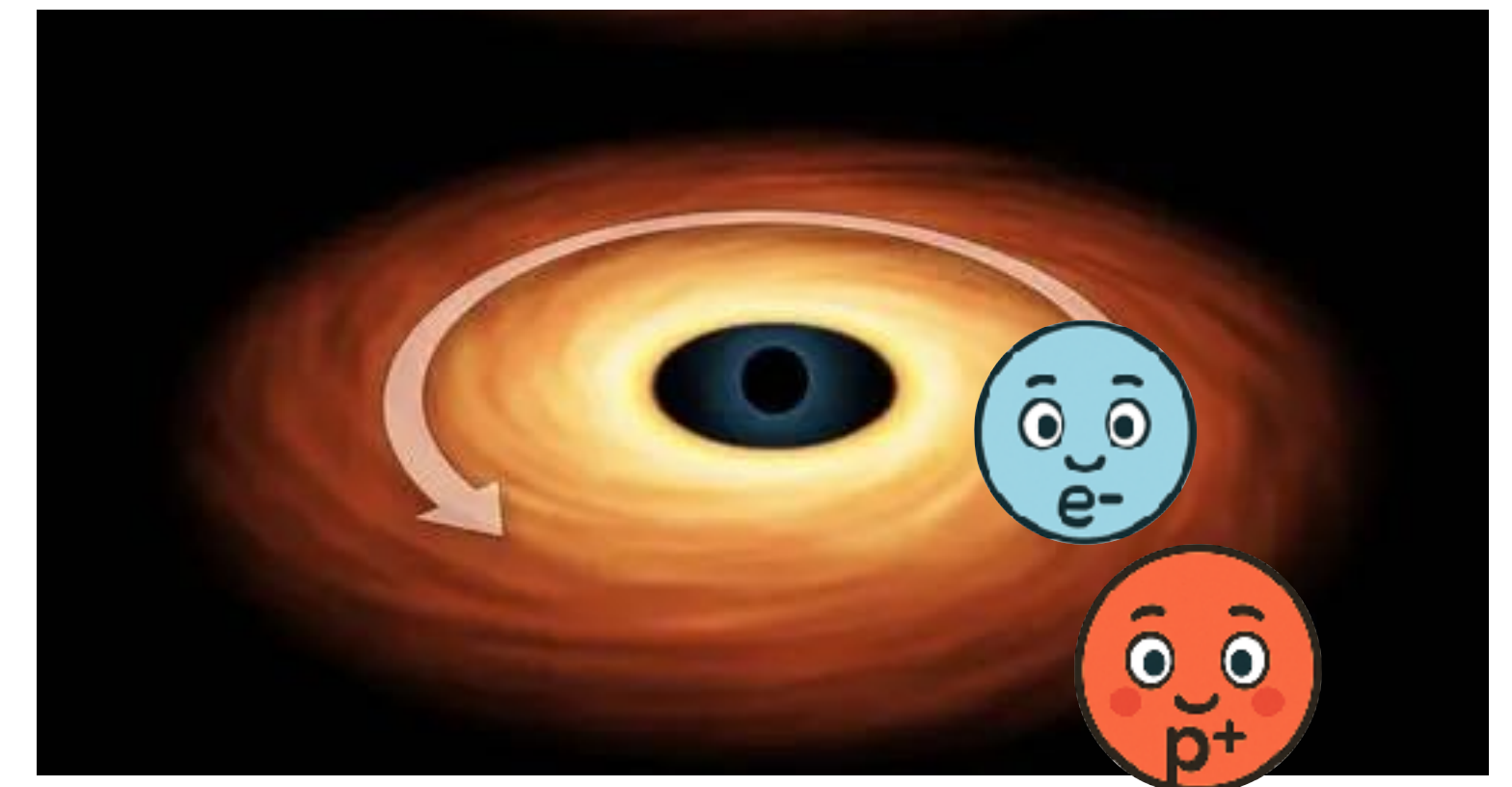
$$\dot{m} = \frac{\dot{M}}{\dot{M}_{Edd}}$$

Black hole accretion type is function of Eddington accretion rate

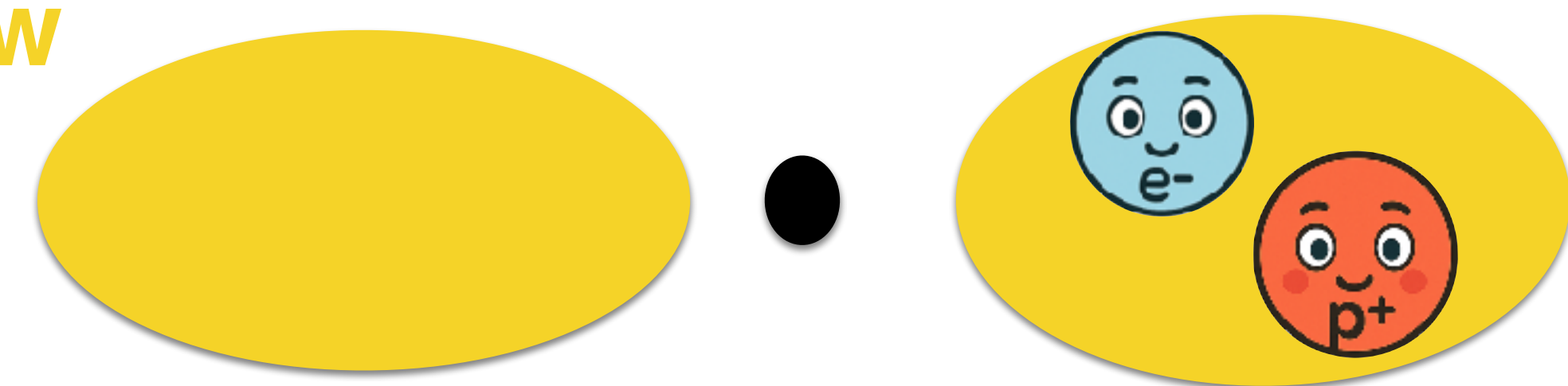


$$Q_{adv,i} = (1 - \delta_e)Q_{vis}^+ - Q_{ie}$$

$$Q_{adv,e} = \delta_e Q_{vis}^+ + Q_{ie} - Q_{rad}^-$$



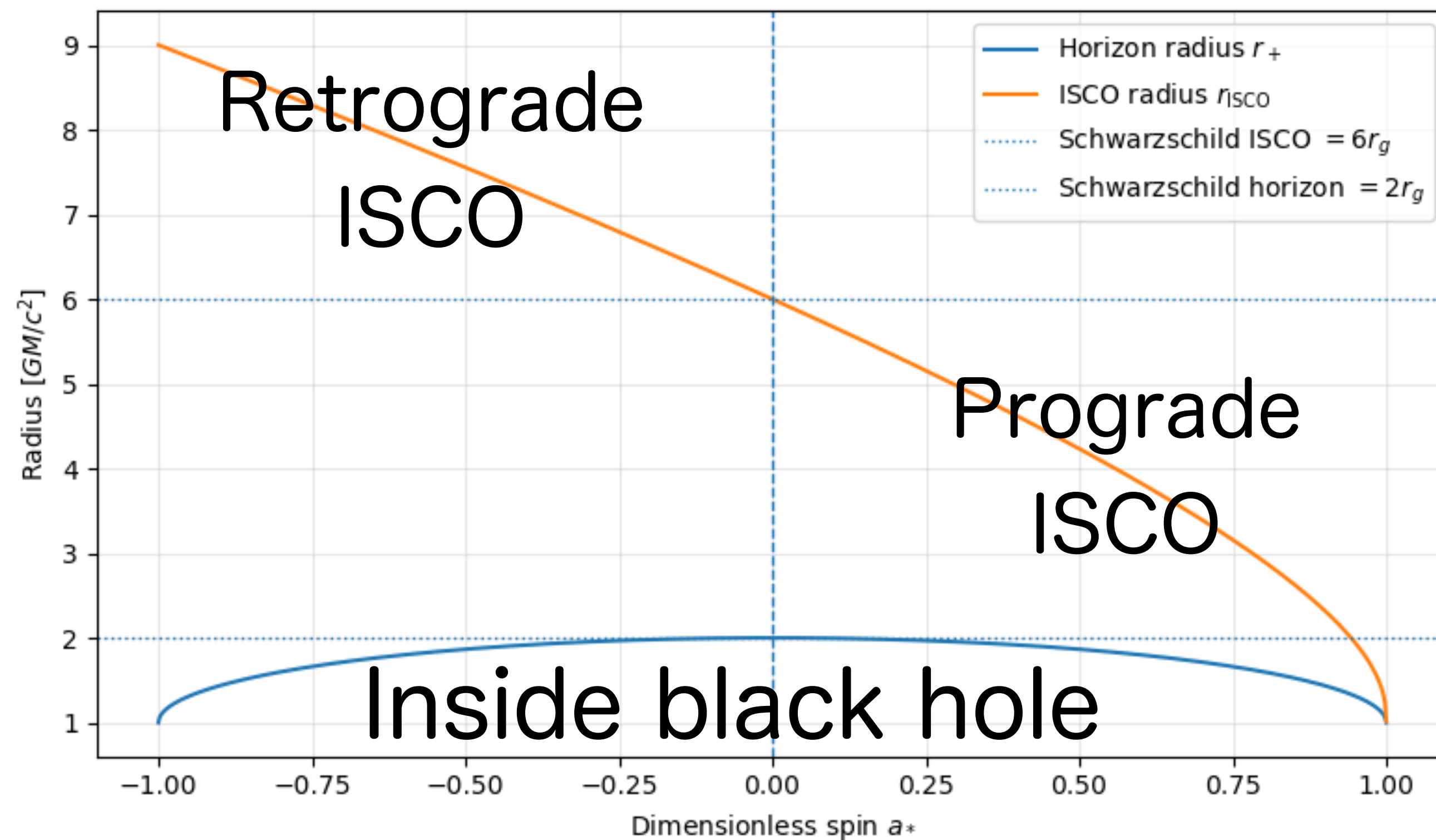
$$T_i \approx T_e \text{ (large } Q_{ie})$$



$$T_i \gg T_e \text{ (small } Q_{ie})$$

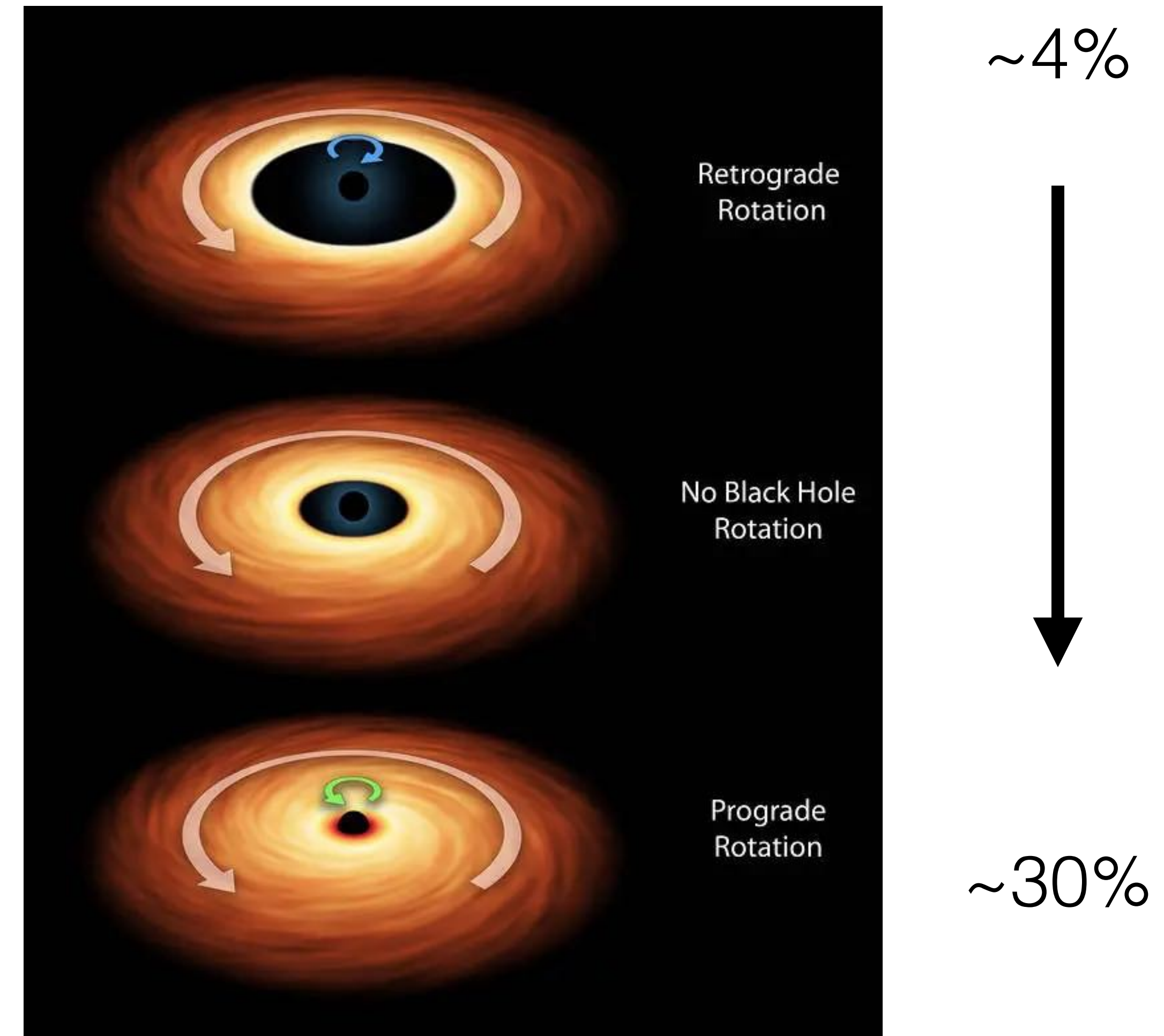
Black hole spin

$$-1 < a_* < 1$$



Radiative efficiency:

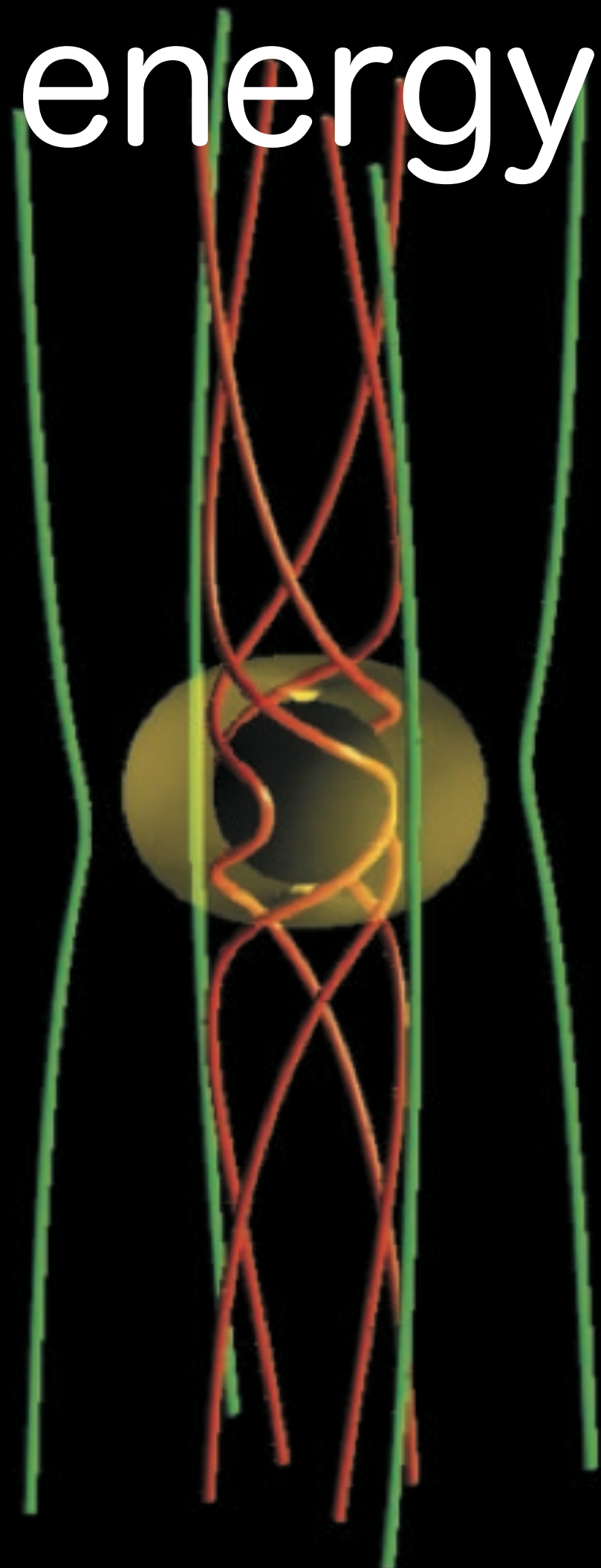
$$\frac{E_\infty - E_{ISCO}}{E_\infty} \approx 1 - E_{ISCO}(\text{in unit of } mc^2)$$



*ISCO: innermost stable circular orbit

extraction of BH rotational energy by magnetic fields

Penrose71,
Blanford&Znajek+04,
Takahashi+90

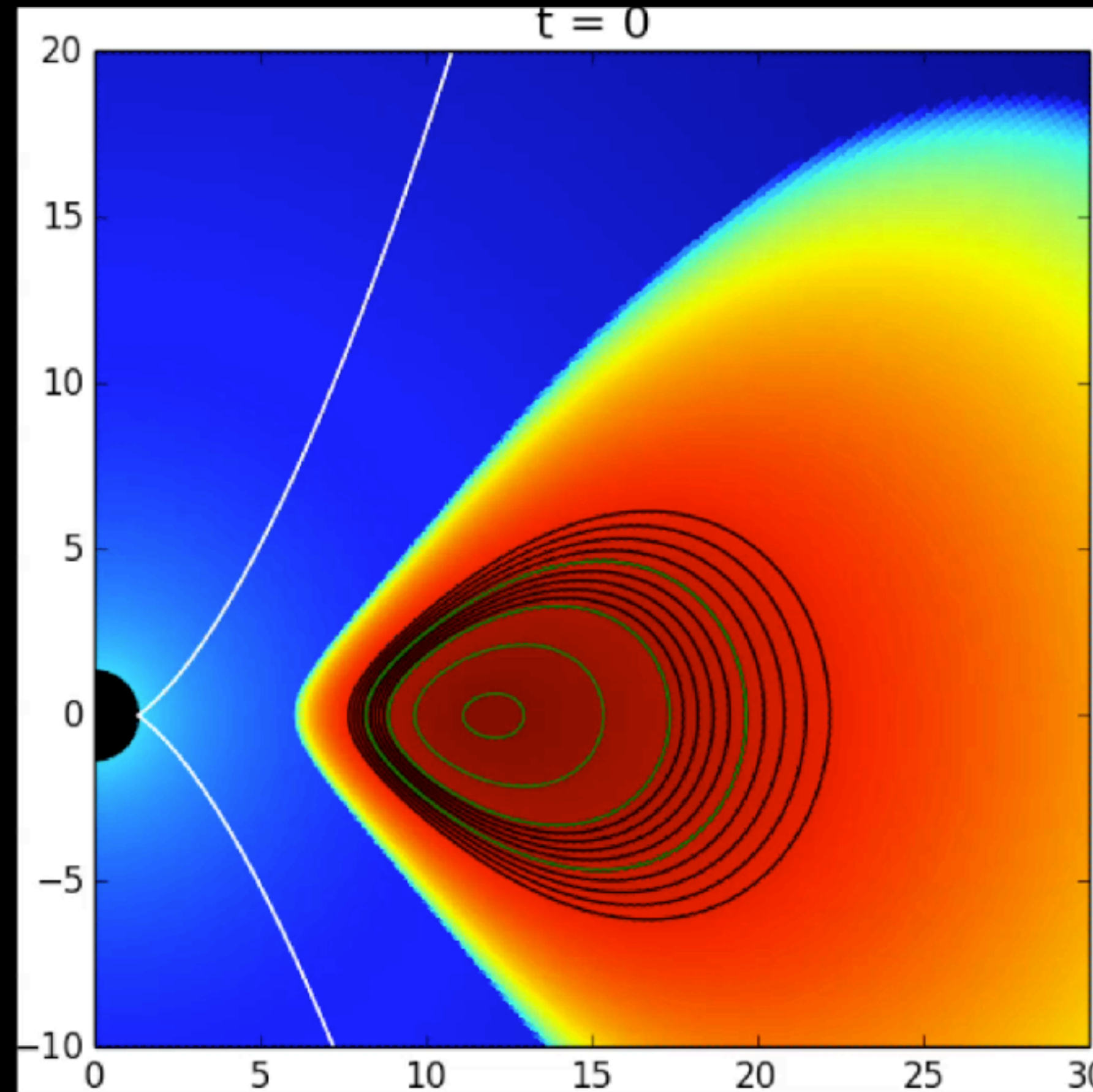
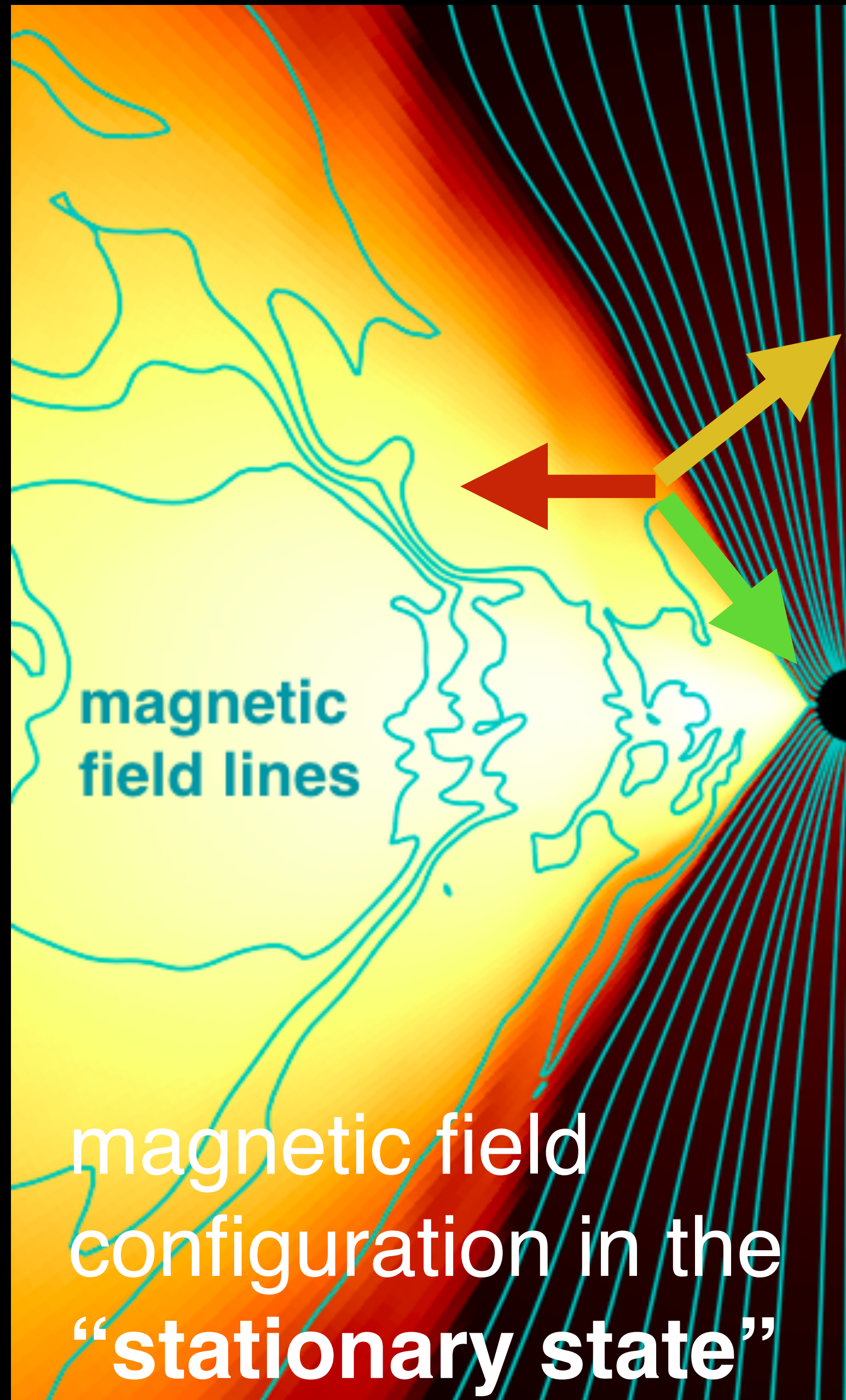


Semenov+04, Koide+02

few plasma (nearly vacuum)



General Relativistic MagnetoHydroDynamics simulation



more plasma $\rightarrow$ accretion flow

magnetic field

strong

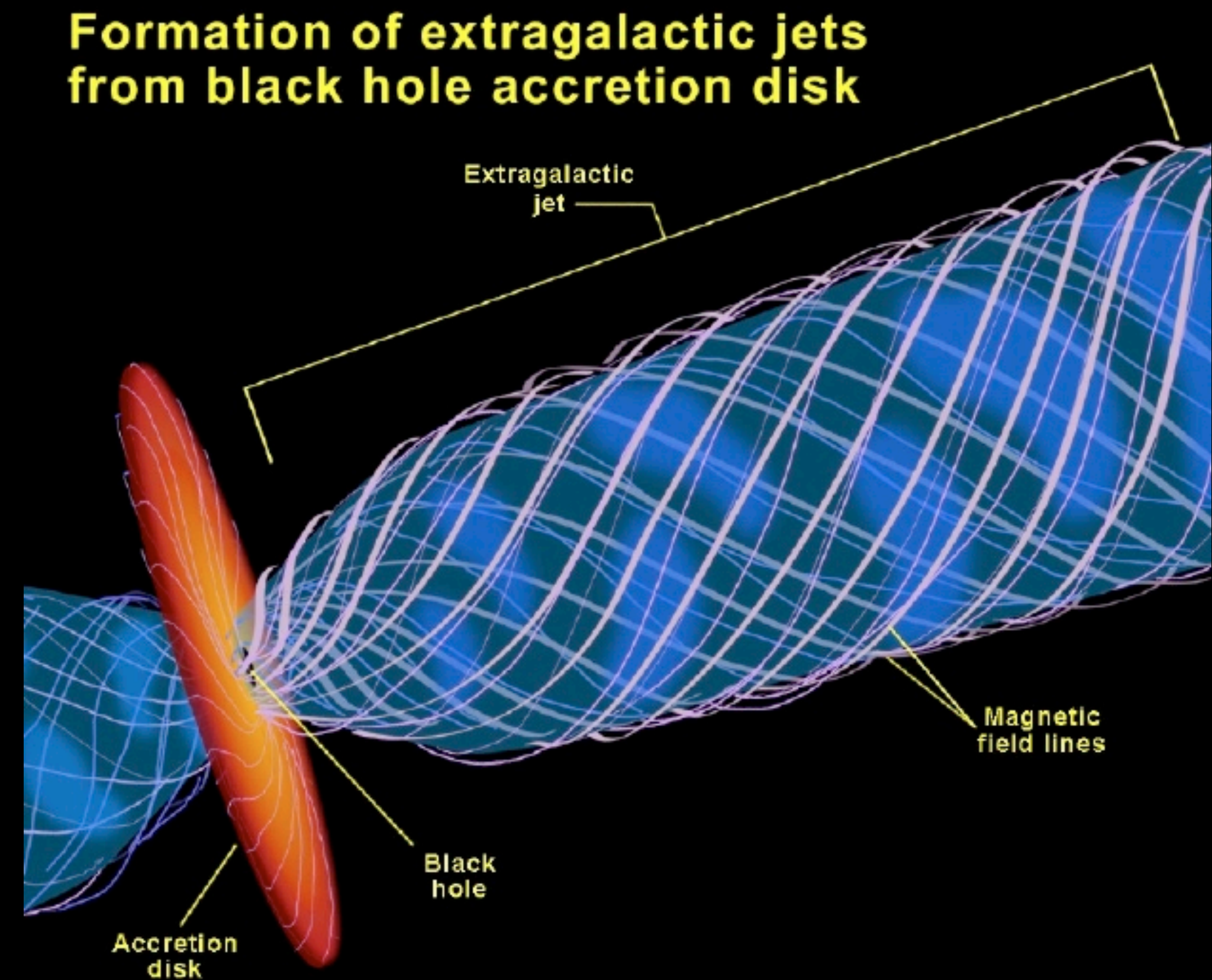
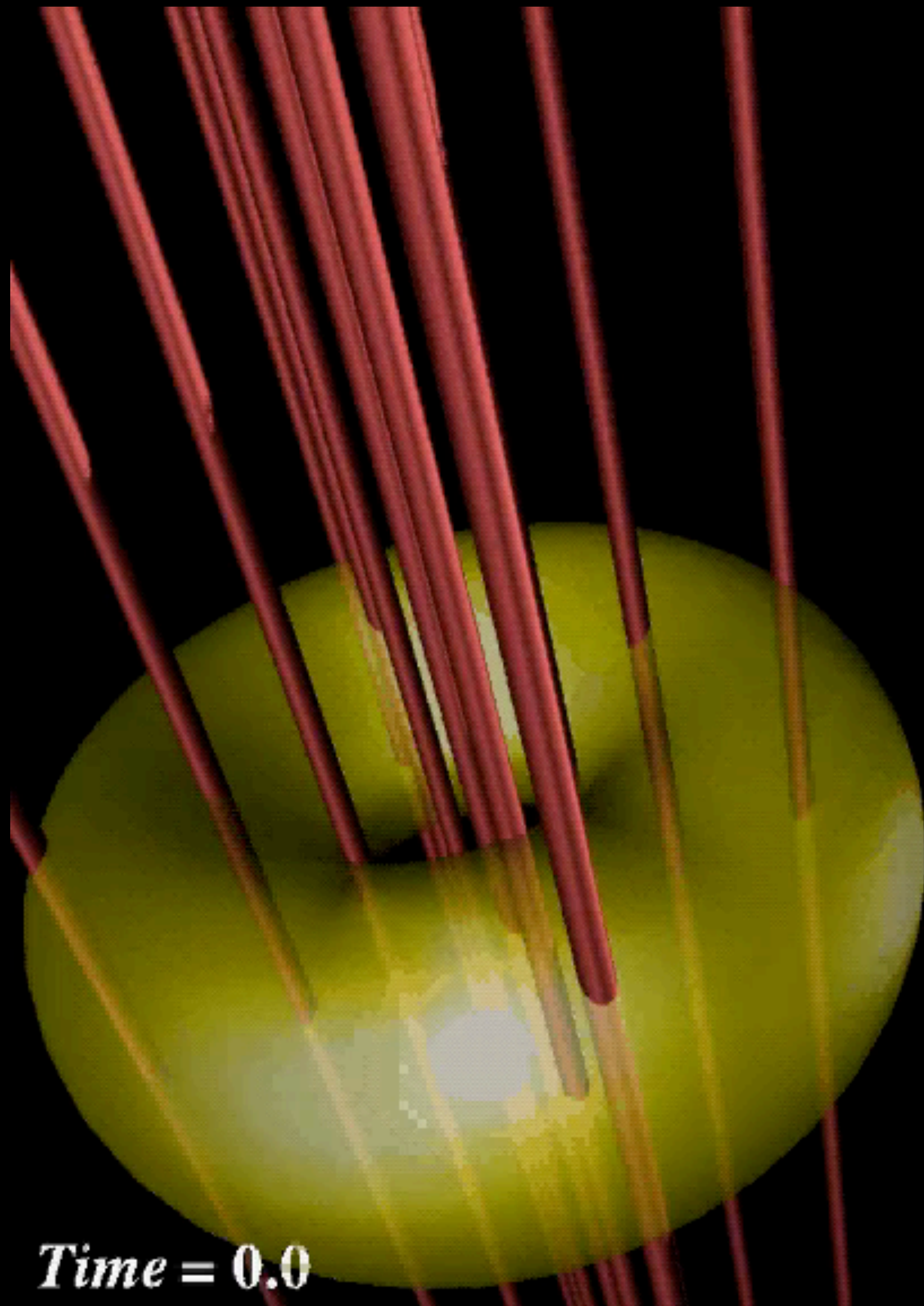
weak

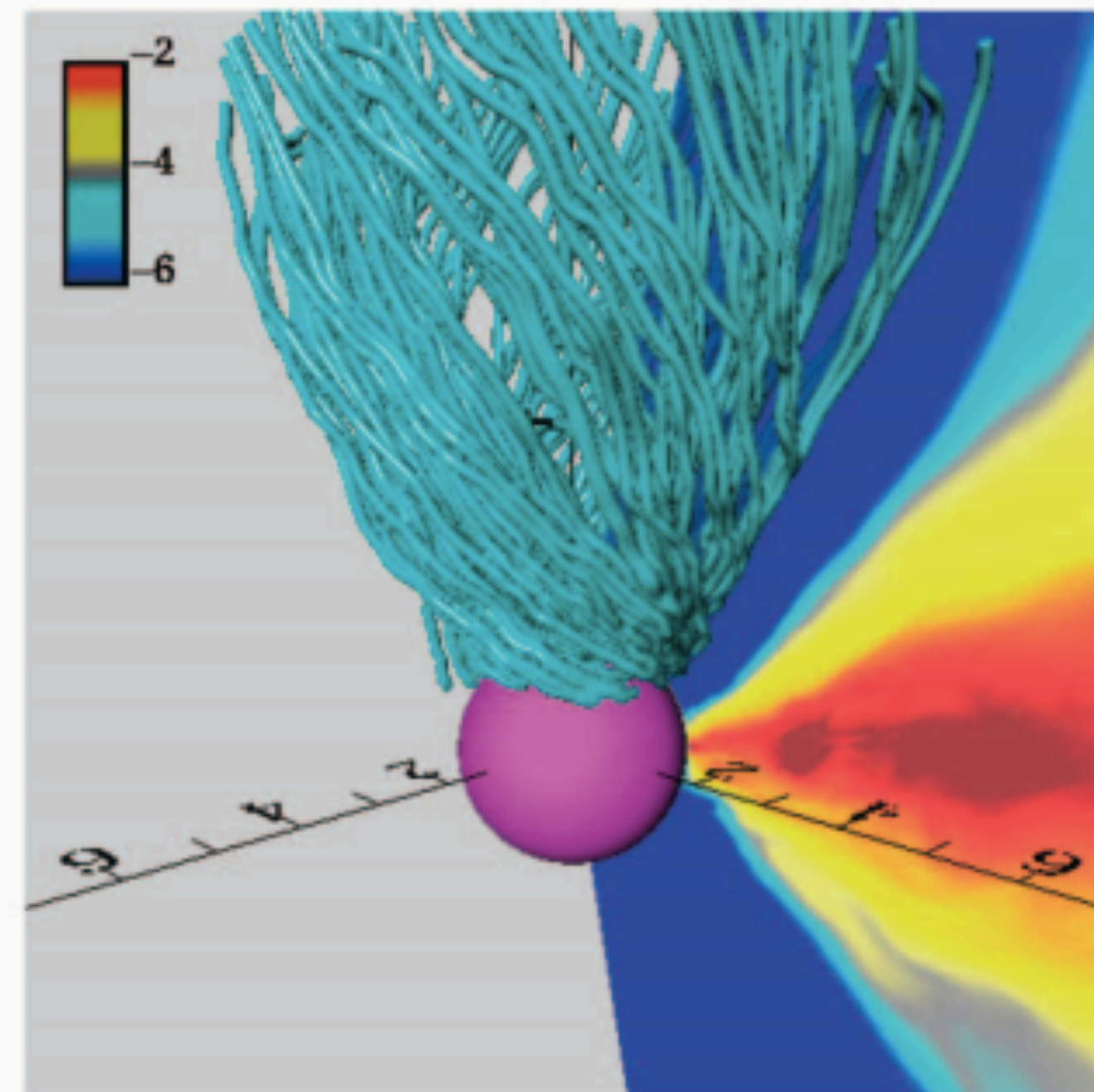
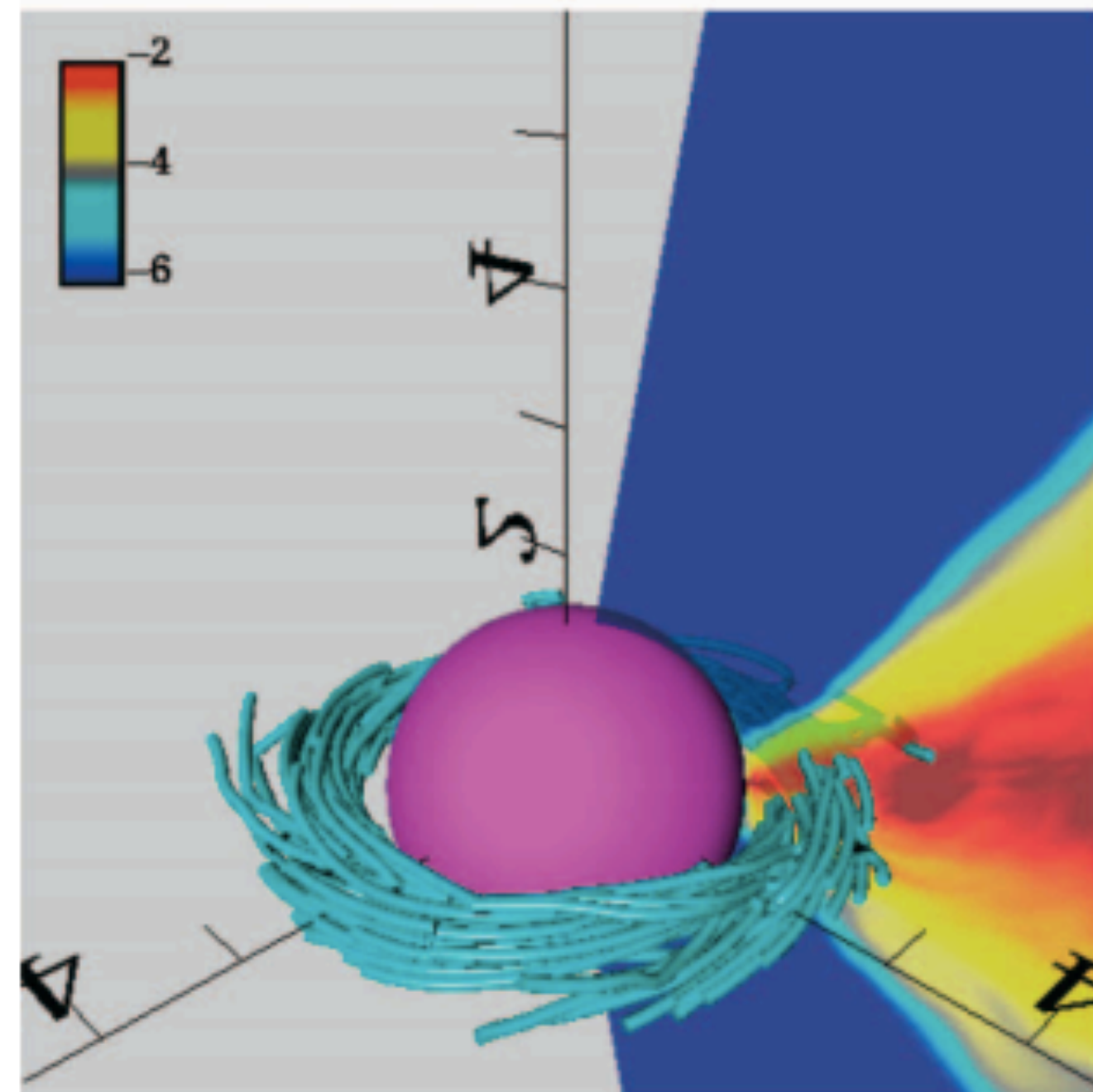
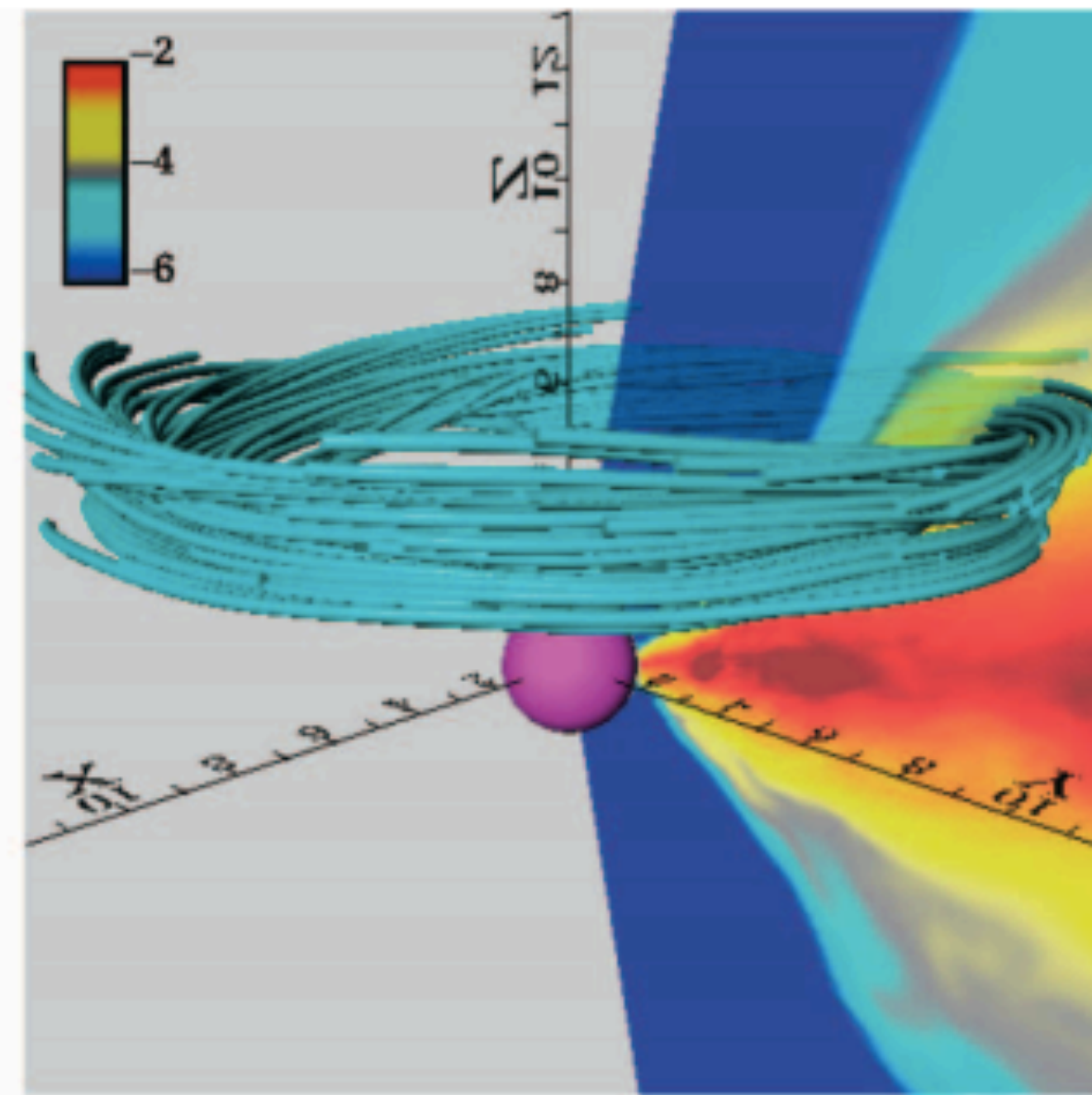
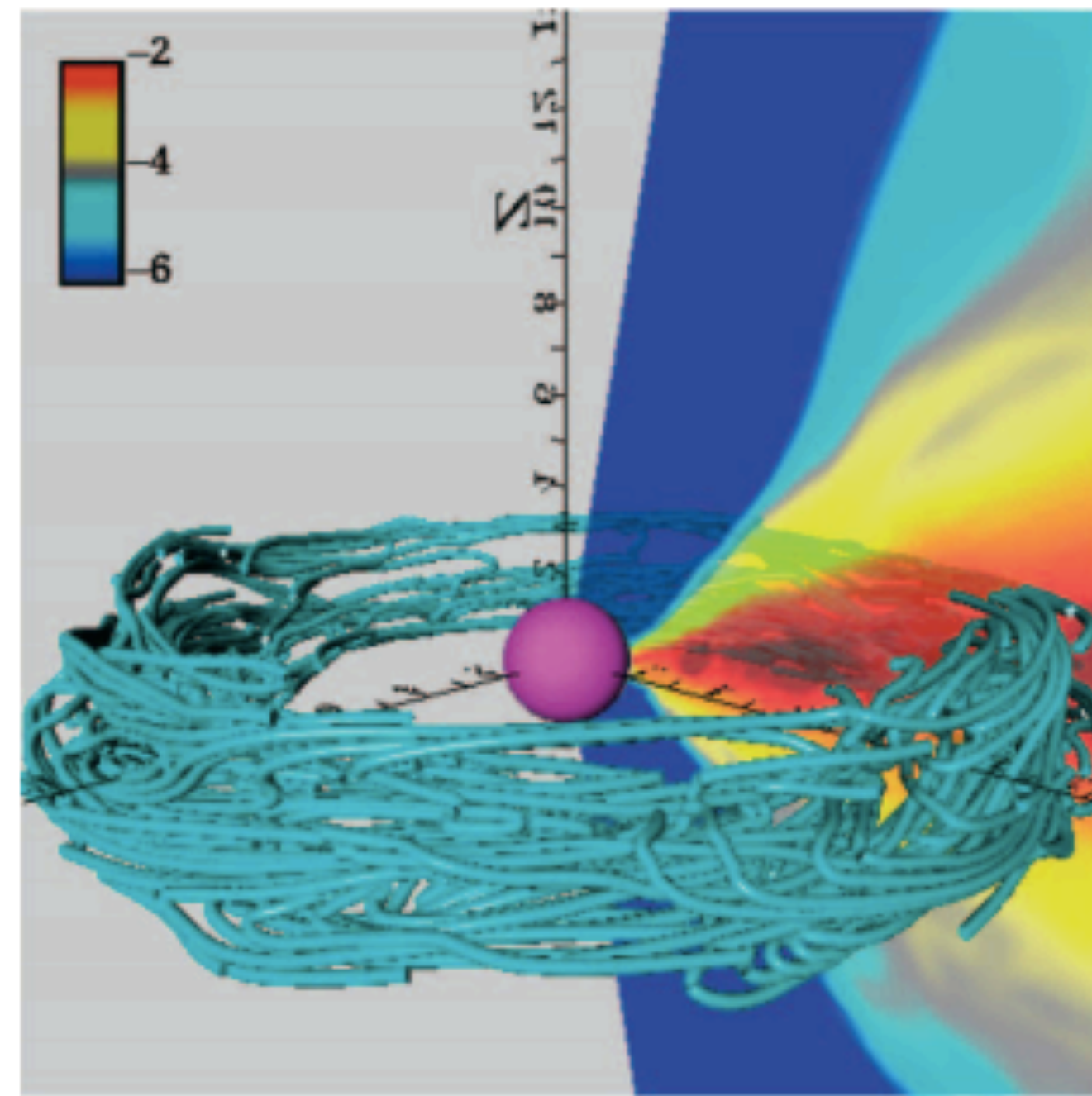
braking

Magneto-
Rotational
Instability

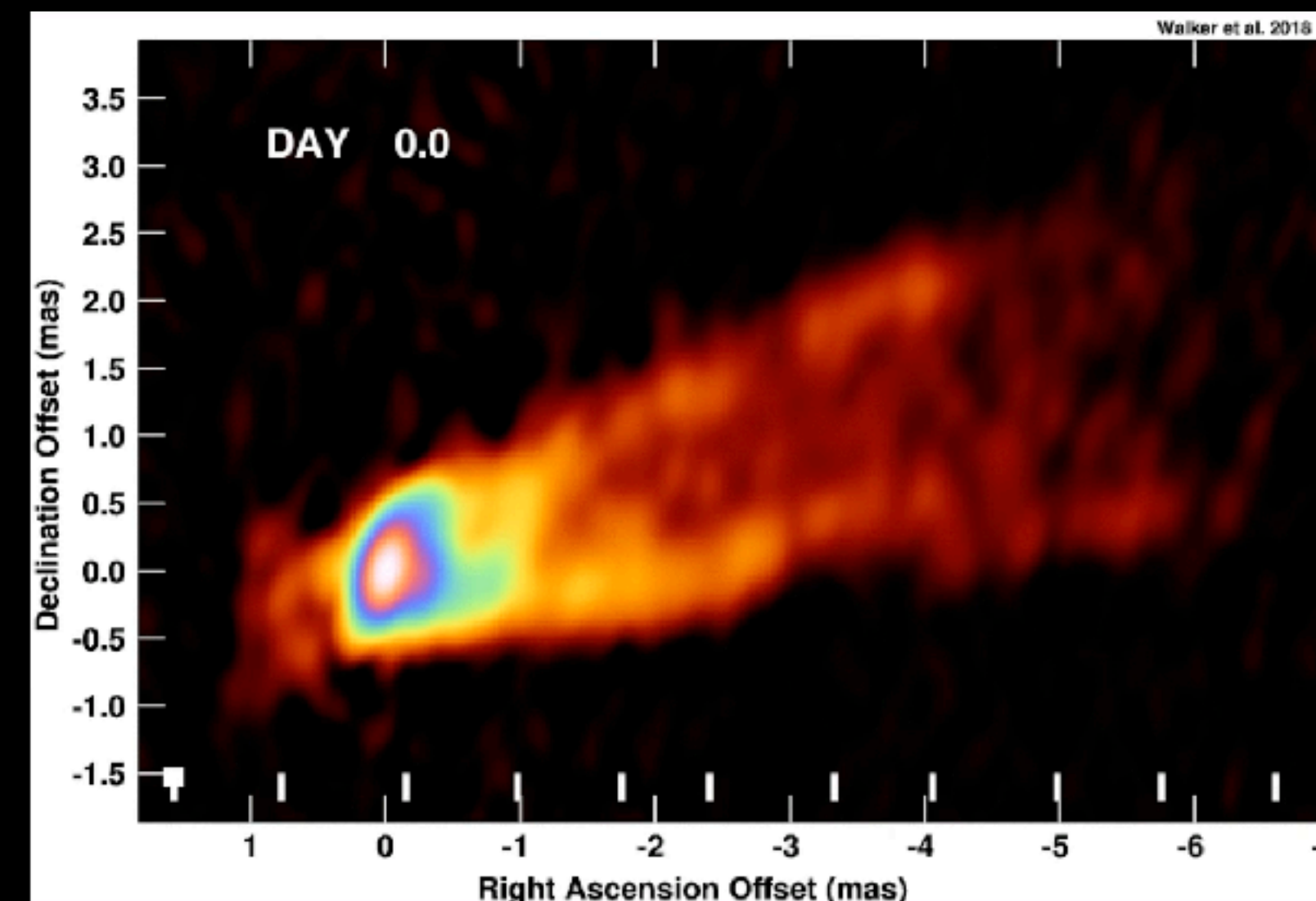
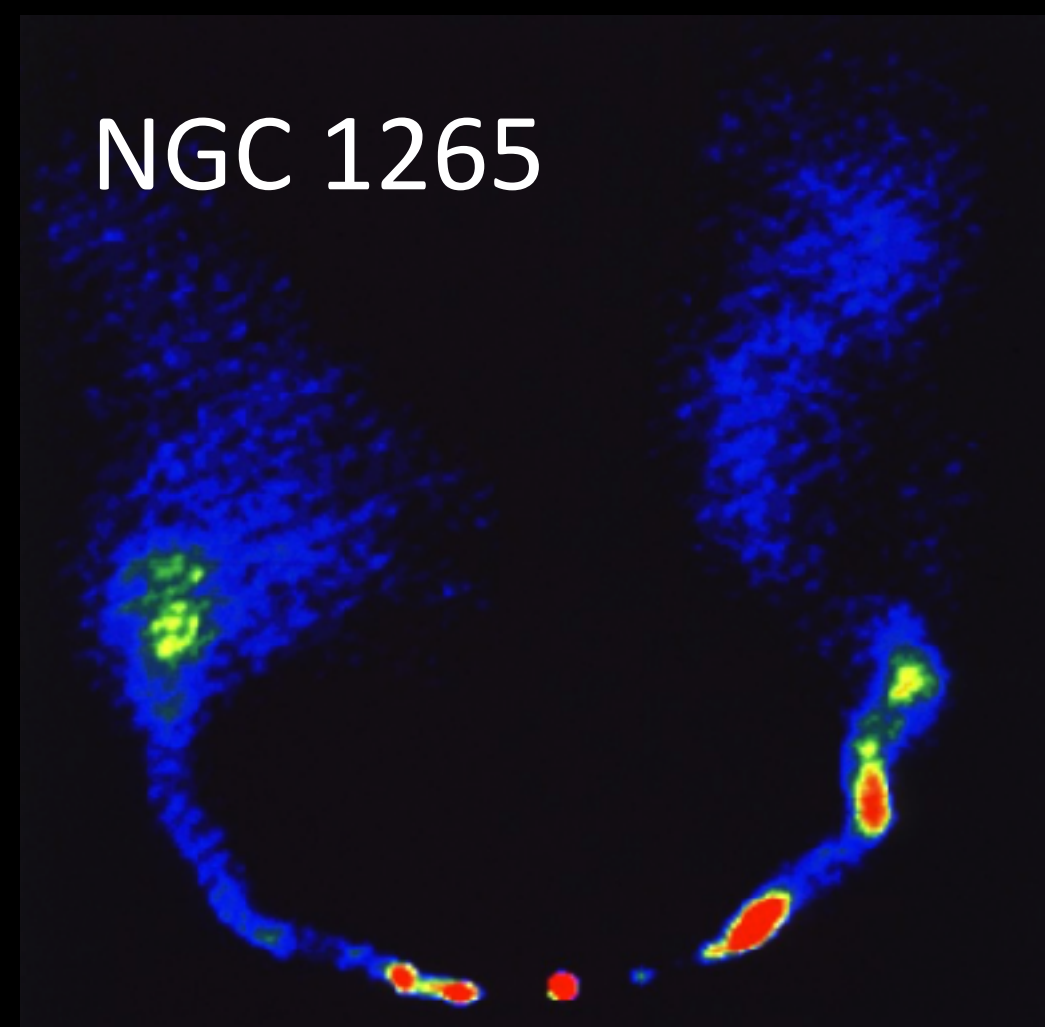
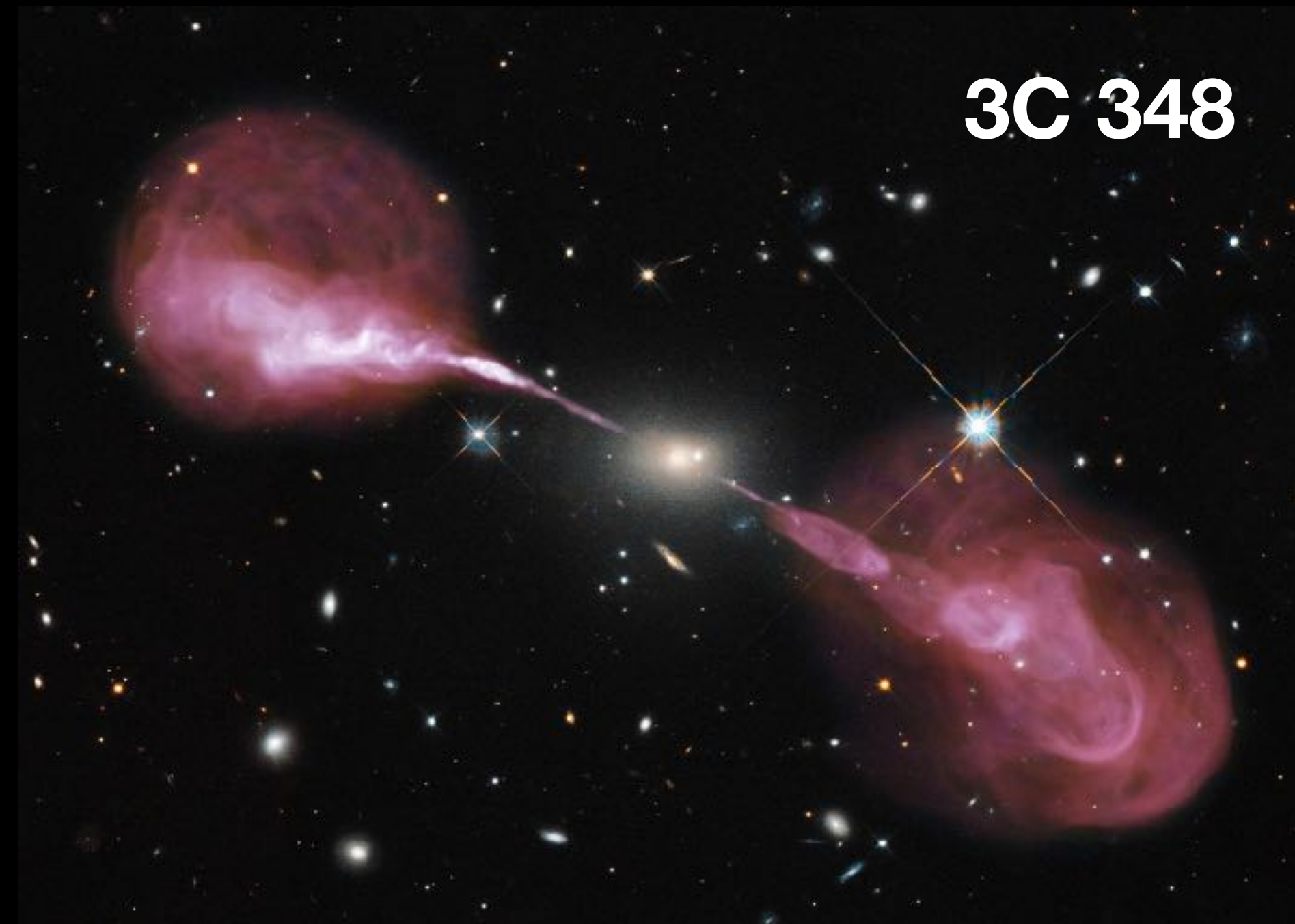
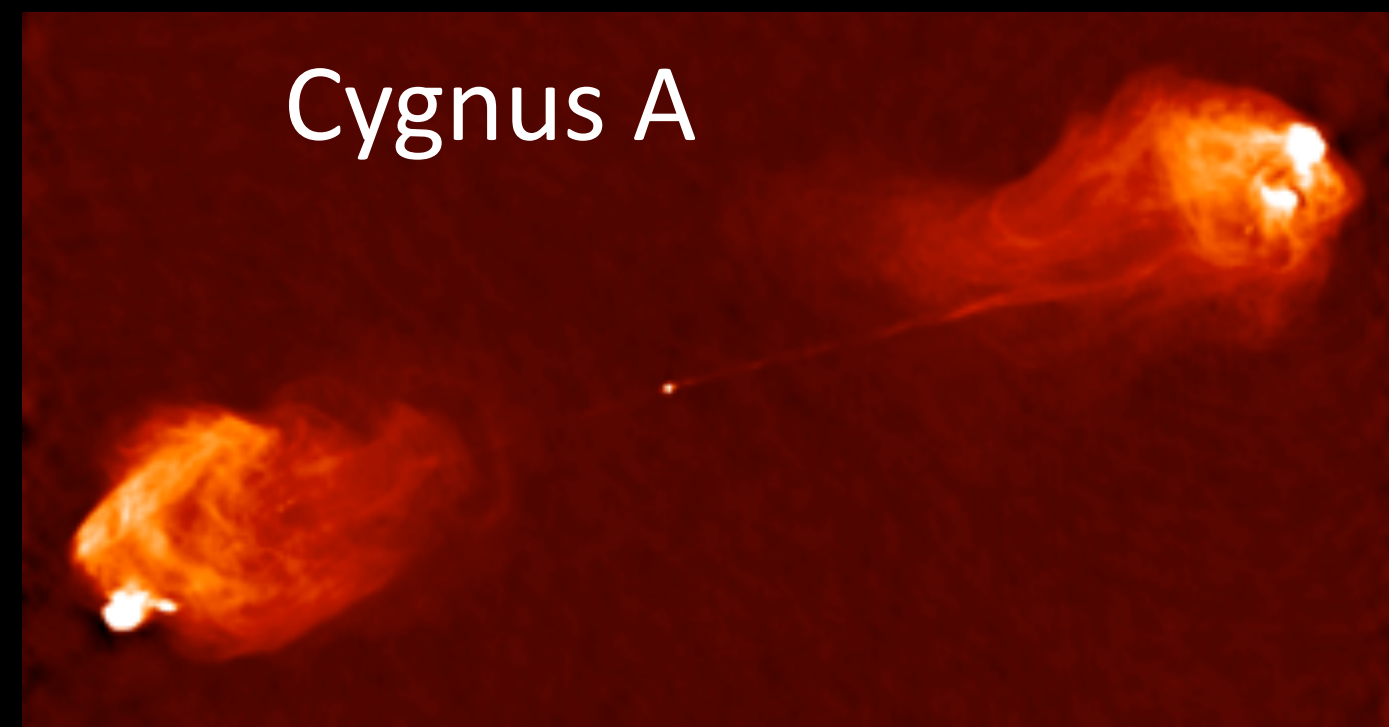
(Bulbus & Hawley 91)

Launching of black hole jet



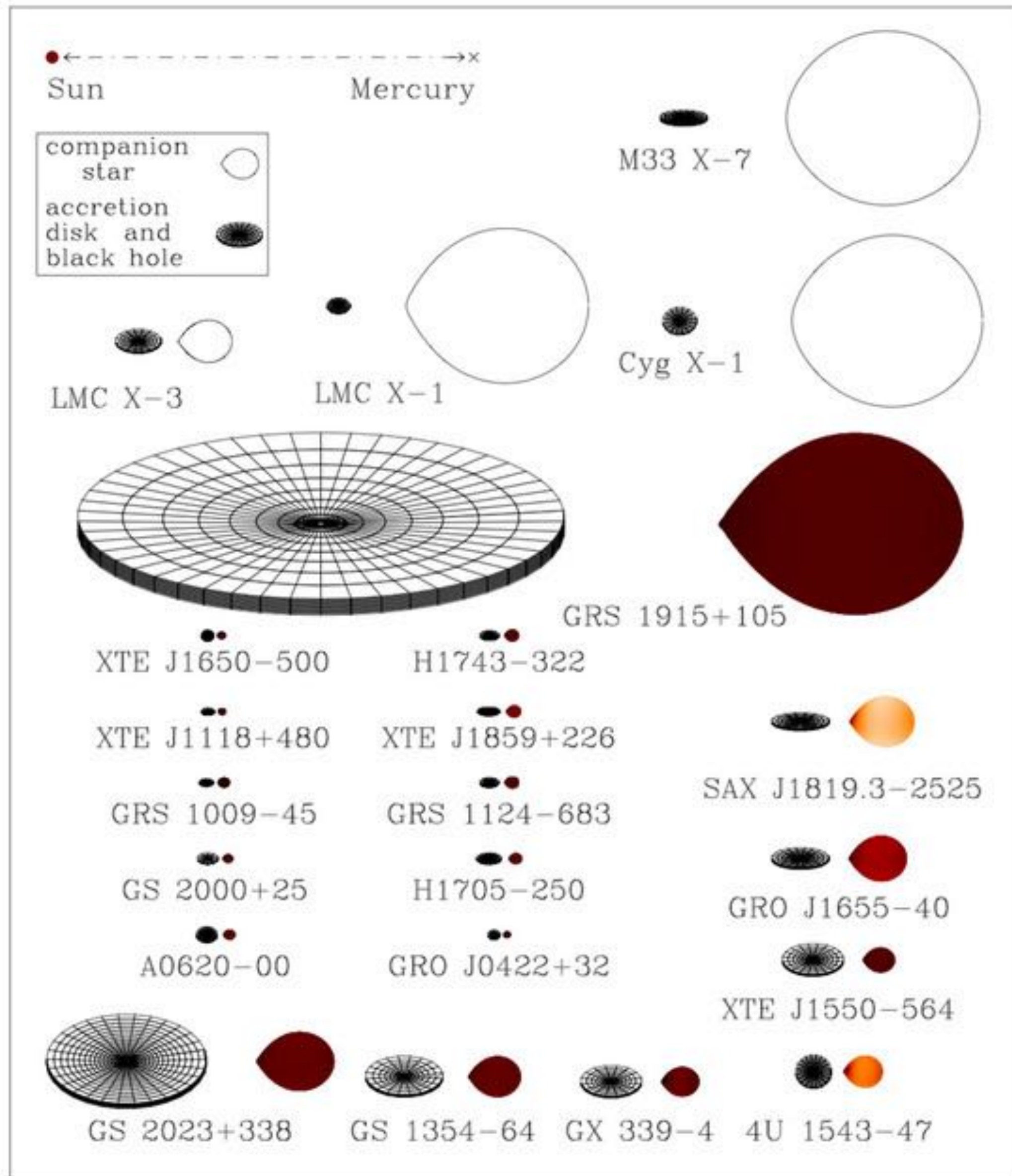


Hirose & Krolik
2003, 2004,
2005a, 2005b



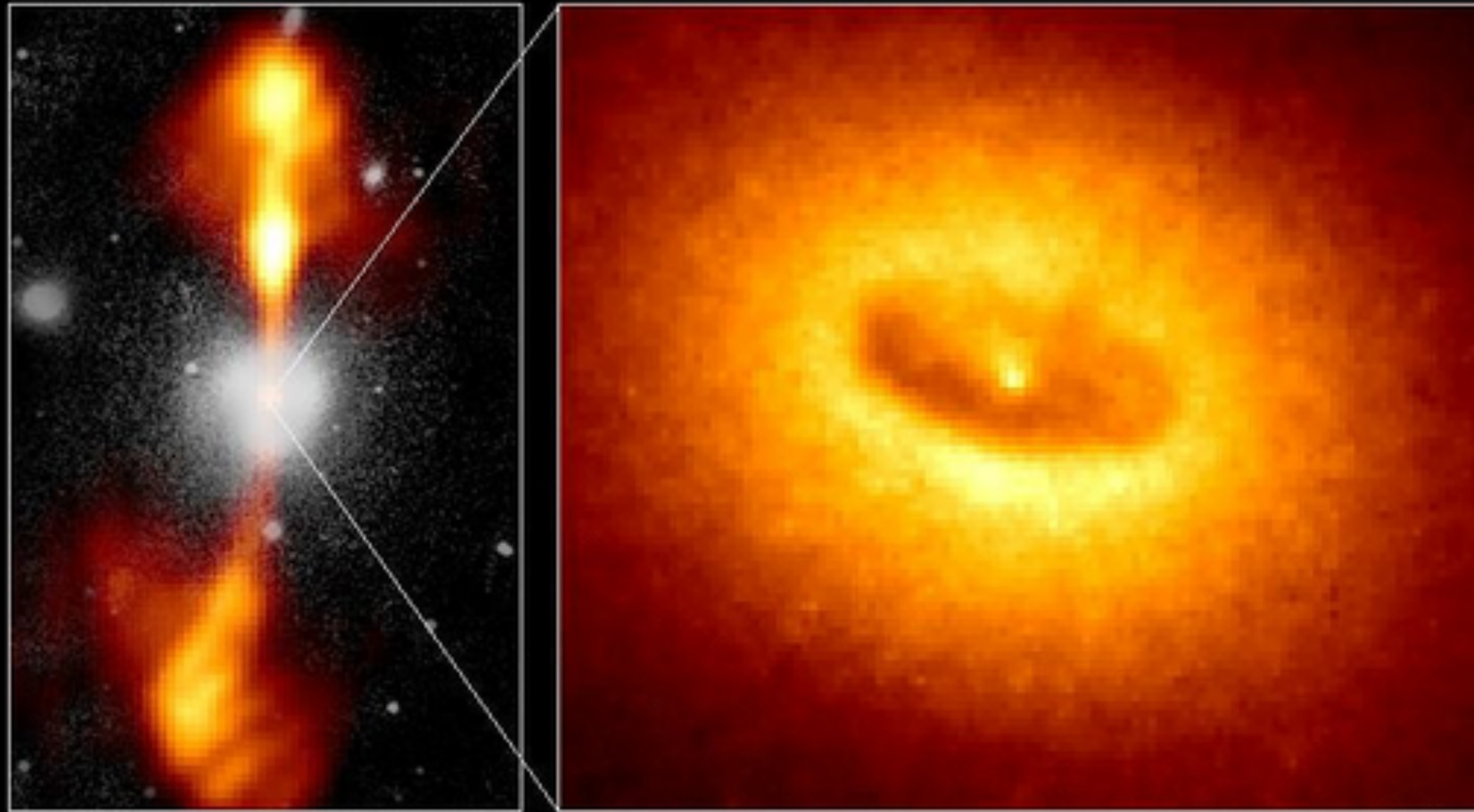
Types of black holes

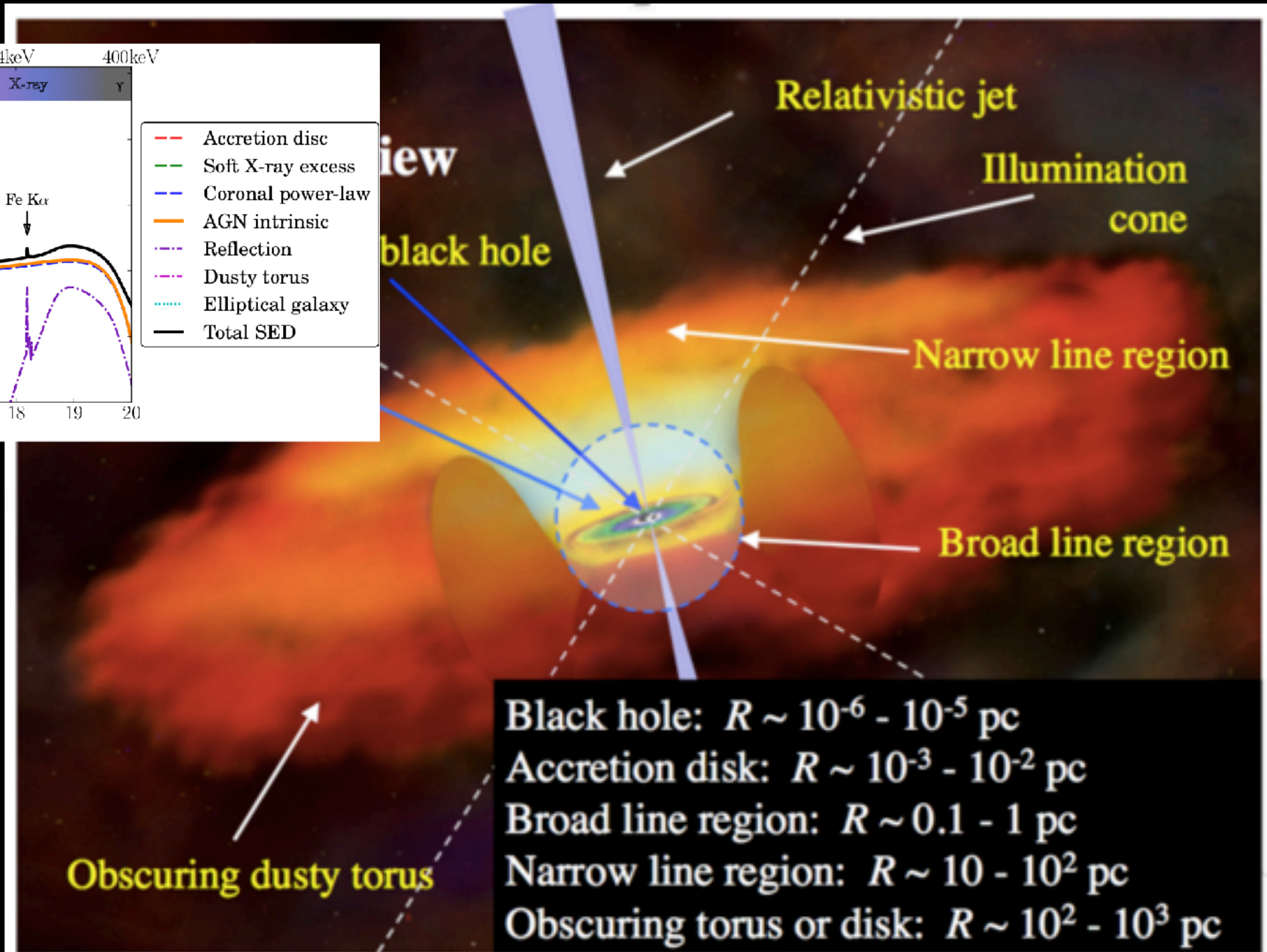
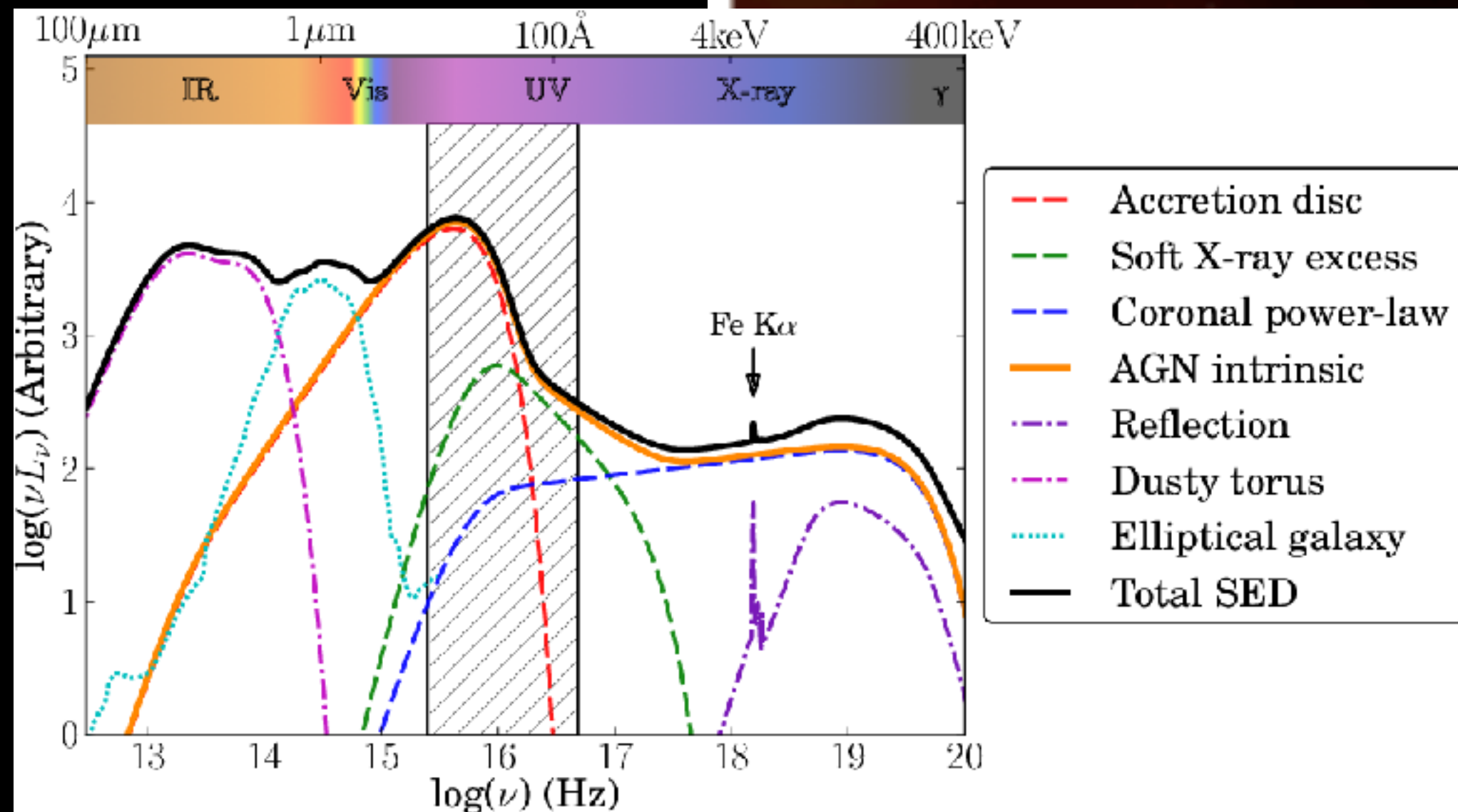
Stellar mass black holes in black hole binaries



Credit: J. Orosz

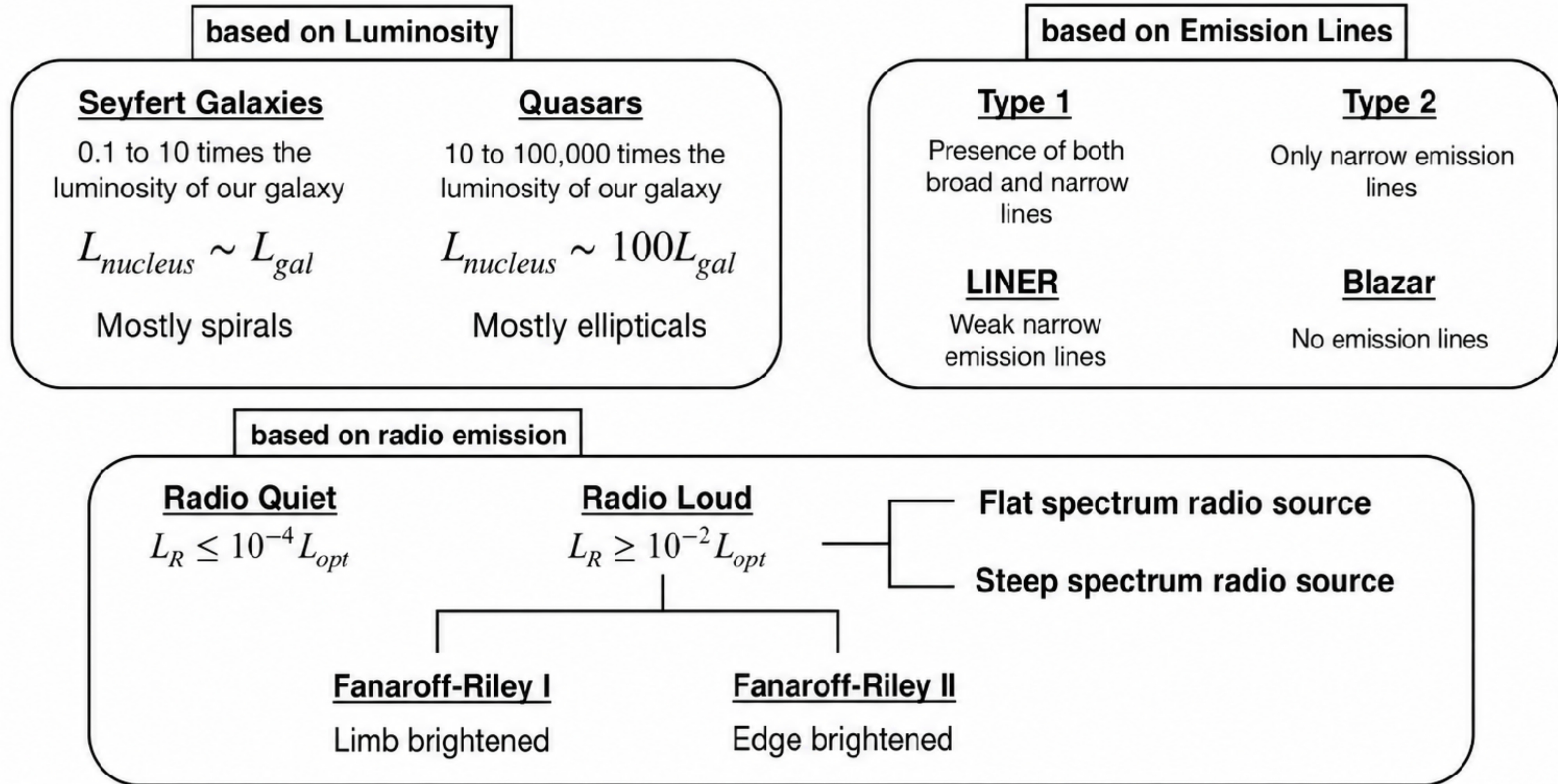
NGC 4261: an example of super massive black hole (SMBH)





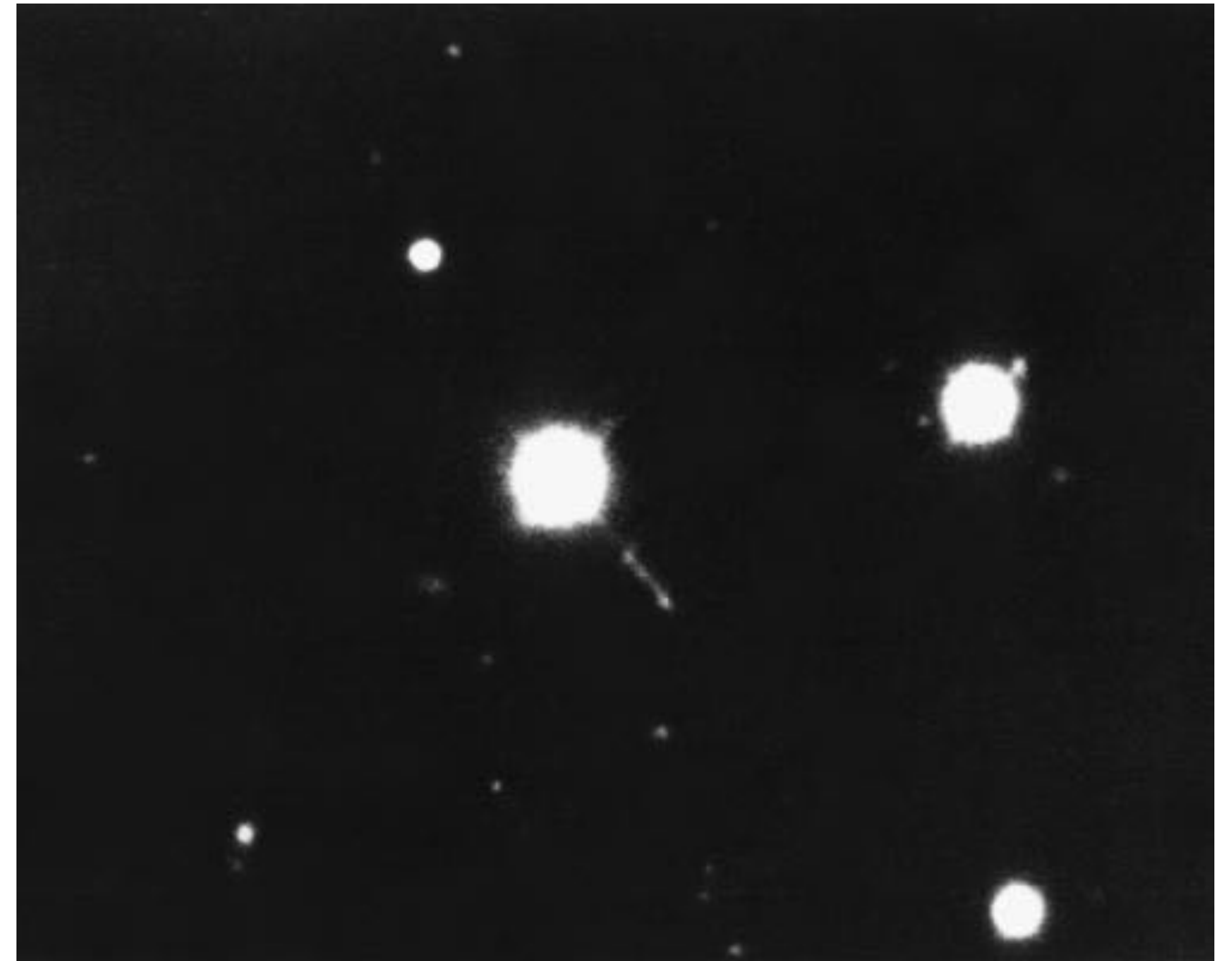
Credit: astrobite

Active Galactic Nuclei (AGN) family

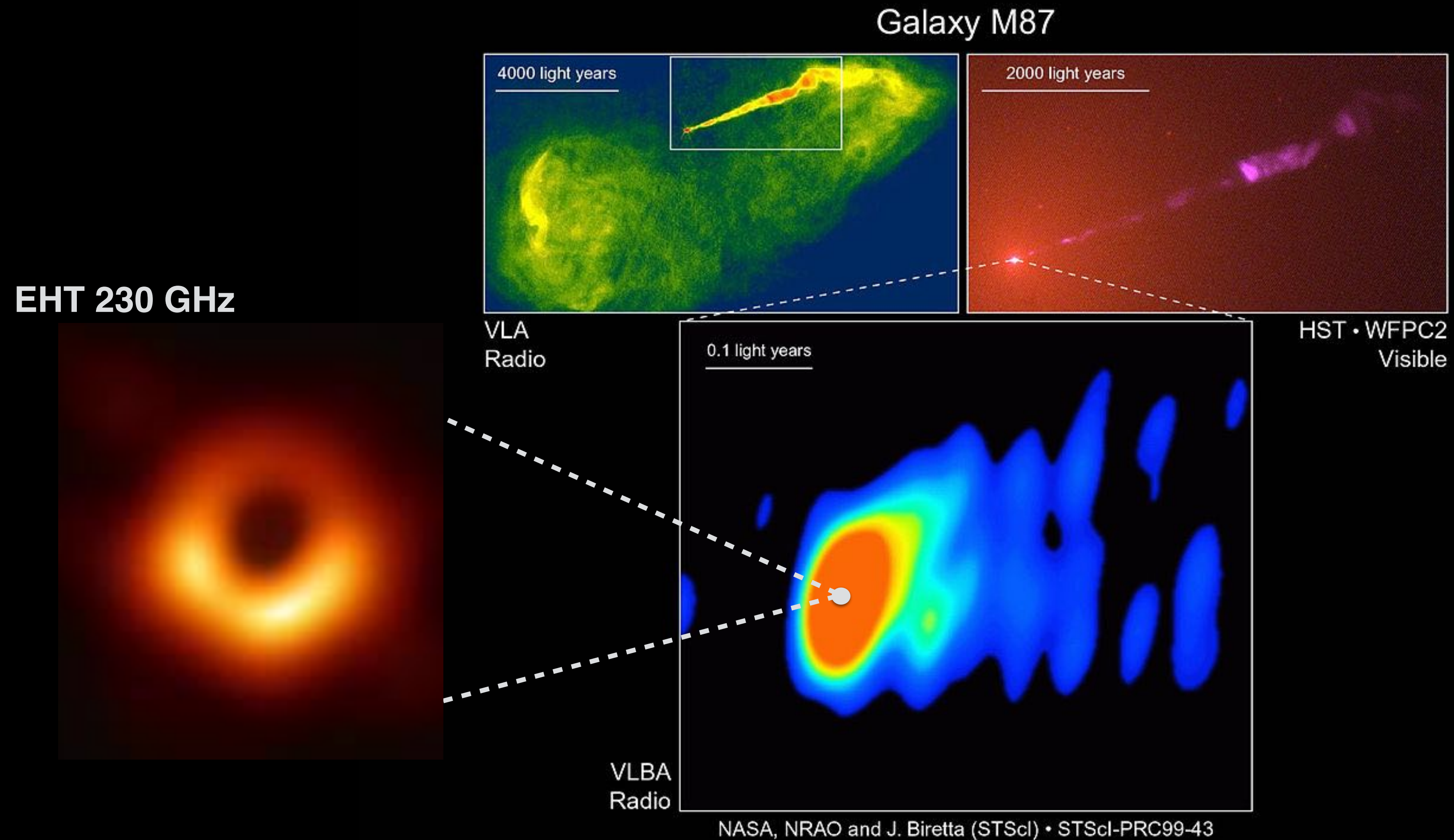


First quasar (1963)

- Quasi-stellar radio source
- 3c 273
- The same year Roy Kerr found the Kerr solution

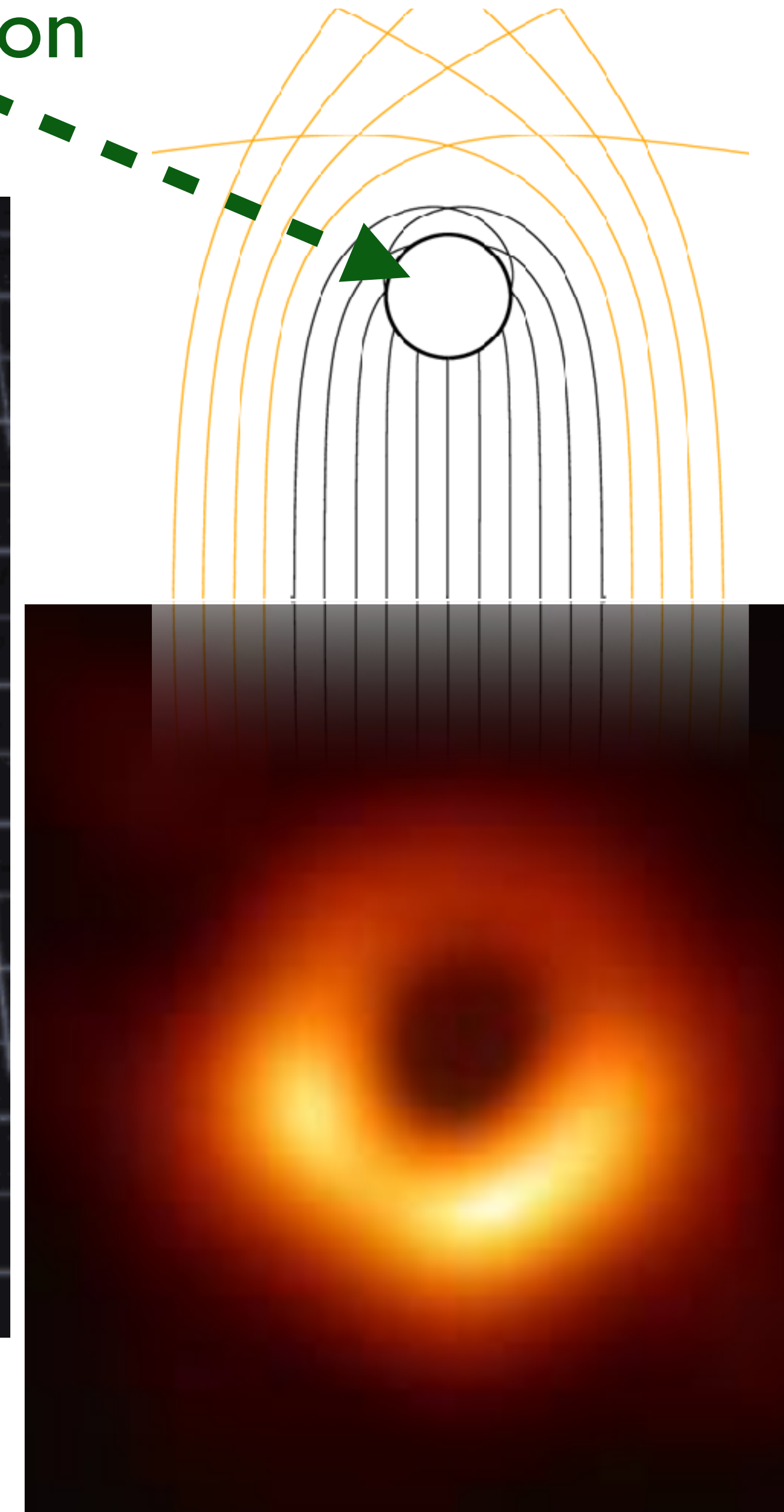
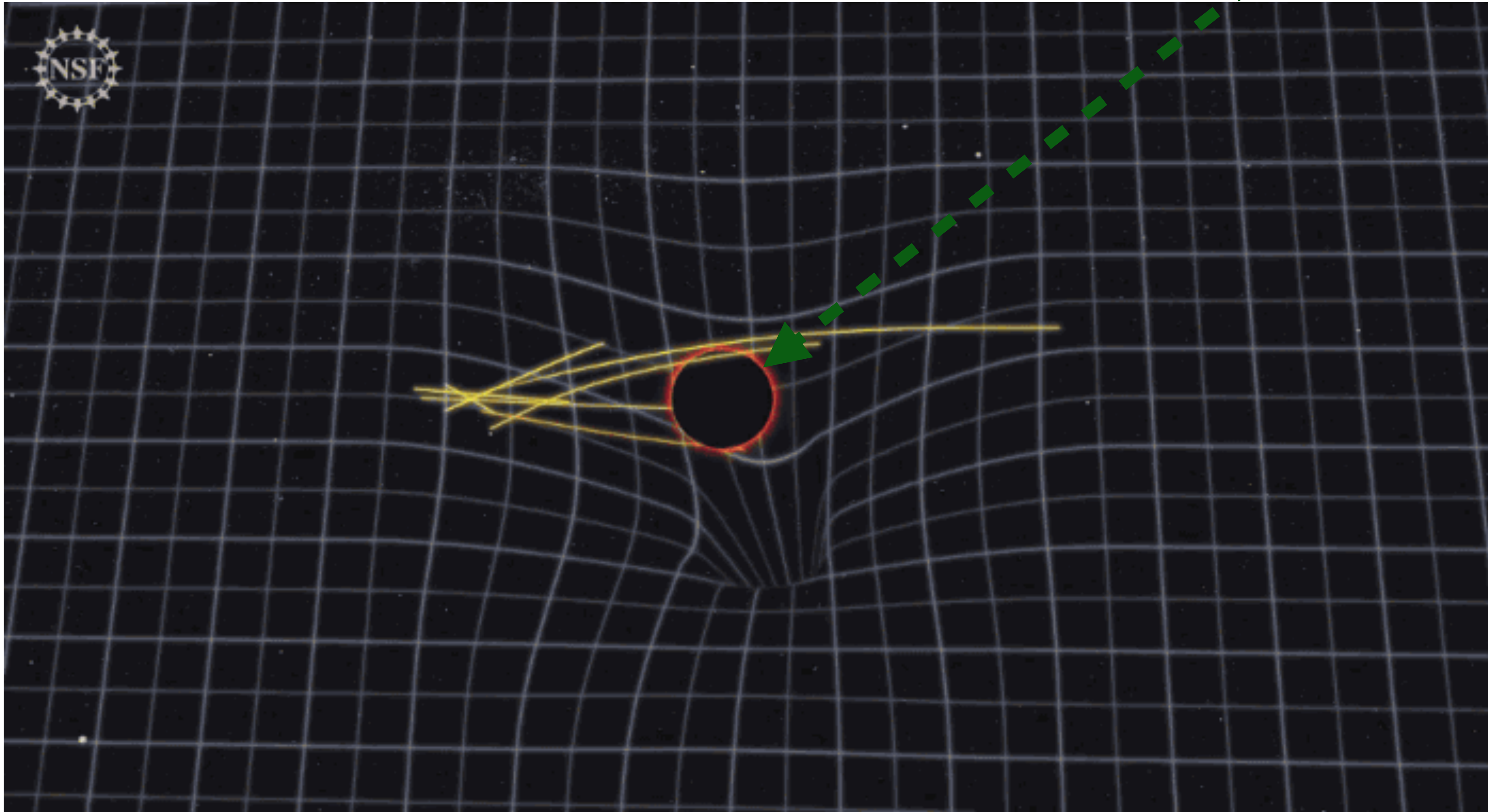


M87*: a SMBH we can resolve!



Black hole shadow

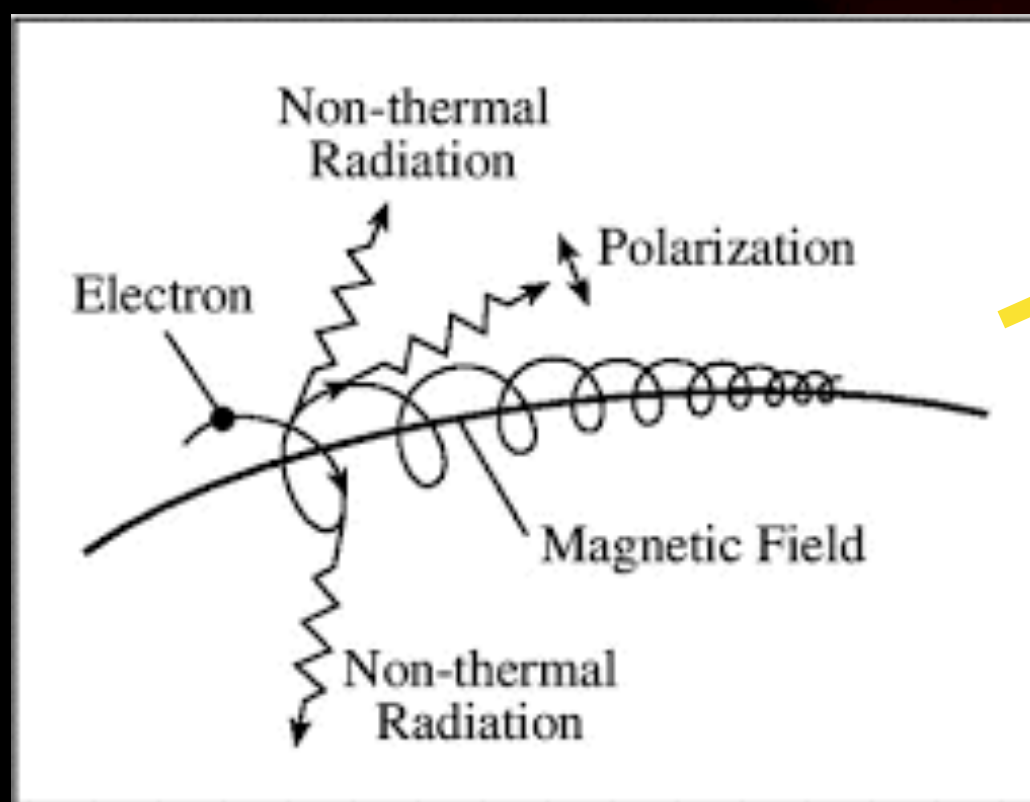
Event horizon



Credit: NSF https://www.nsf.gov/news/news_images.jsp?cntn_id=298276&org=NSF

影片來源: 美國國家科學基金會

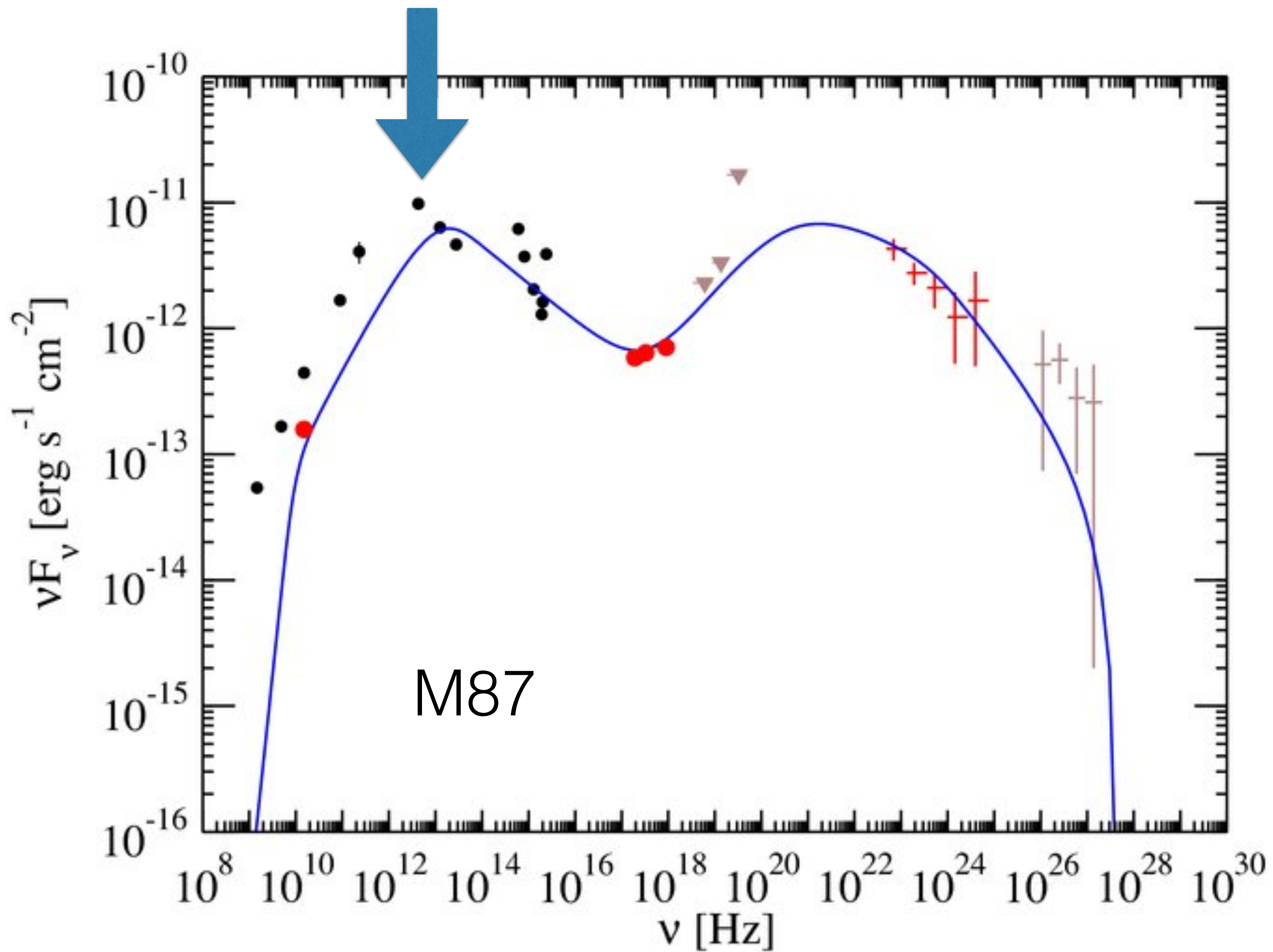
$\nu = 1.0 \times 10^{10} \text{ Hz}$
 $\lambda = 3.0 \times 10^1 \text{ mm}$



credit: C.-K. Chan

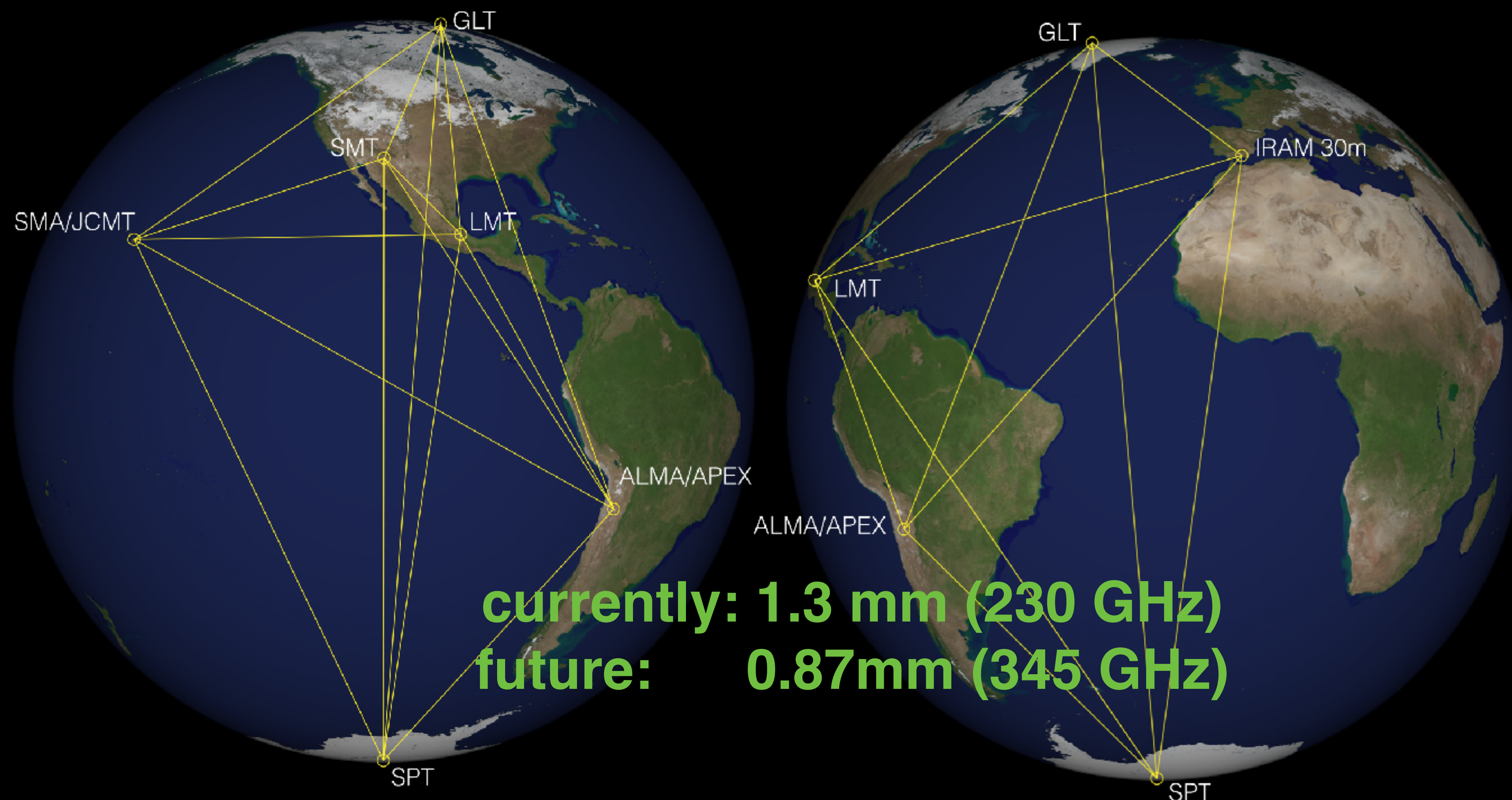
$$\text{Resolution} \propto \lambda / B$$

B = size of the telescope





Event Horizon Telescope



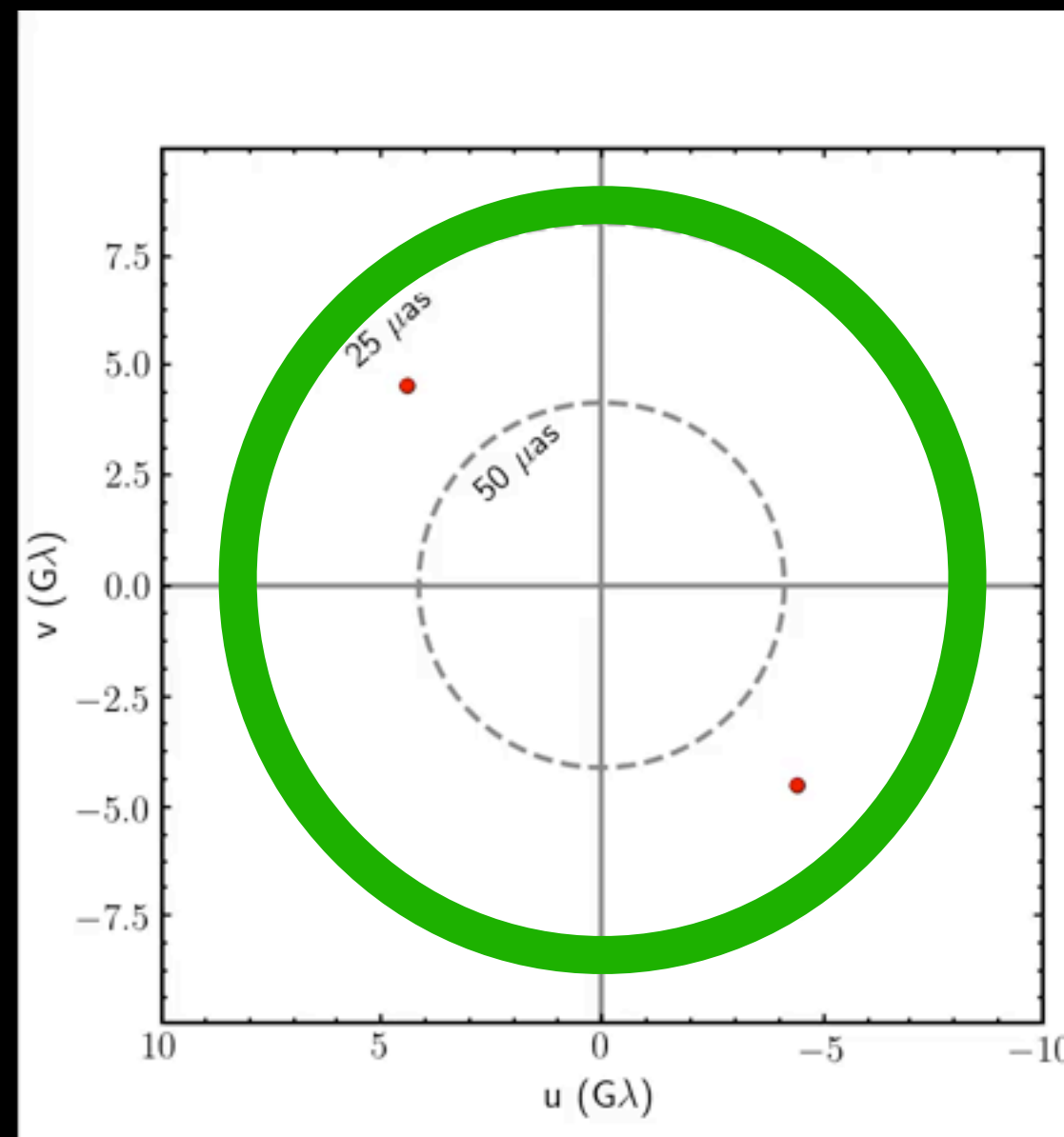
VLBI (Very Long Baseline Interferometry)

credit: Daniel Palumbo and Maciek Wielgus (Harvard)

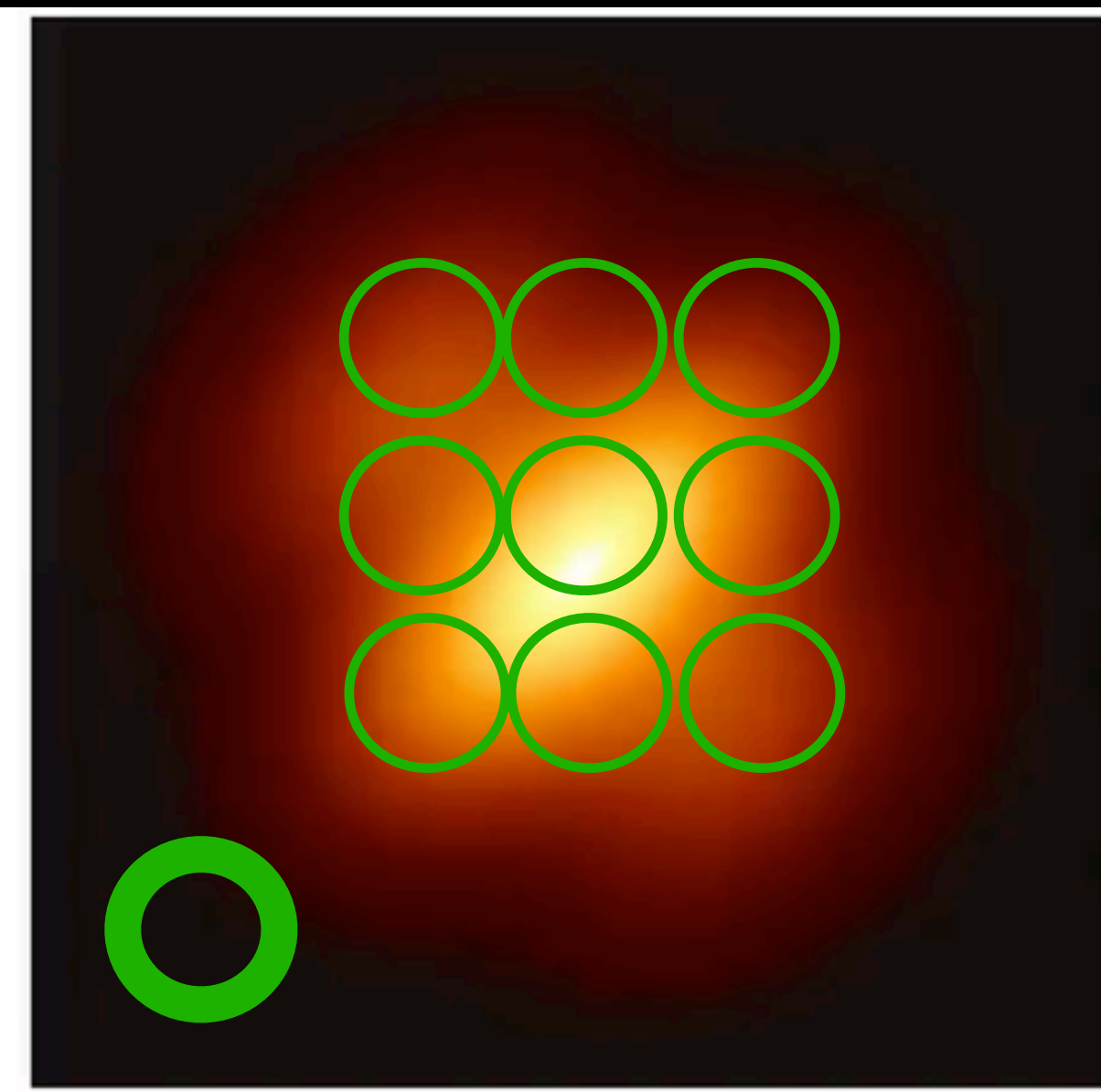
Baseline



From the source to the
earth



Form the earth to the
source



Data Analysis



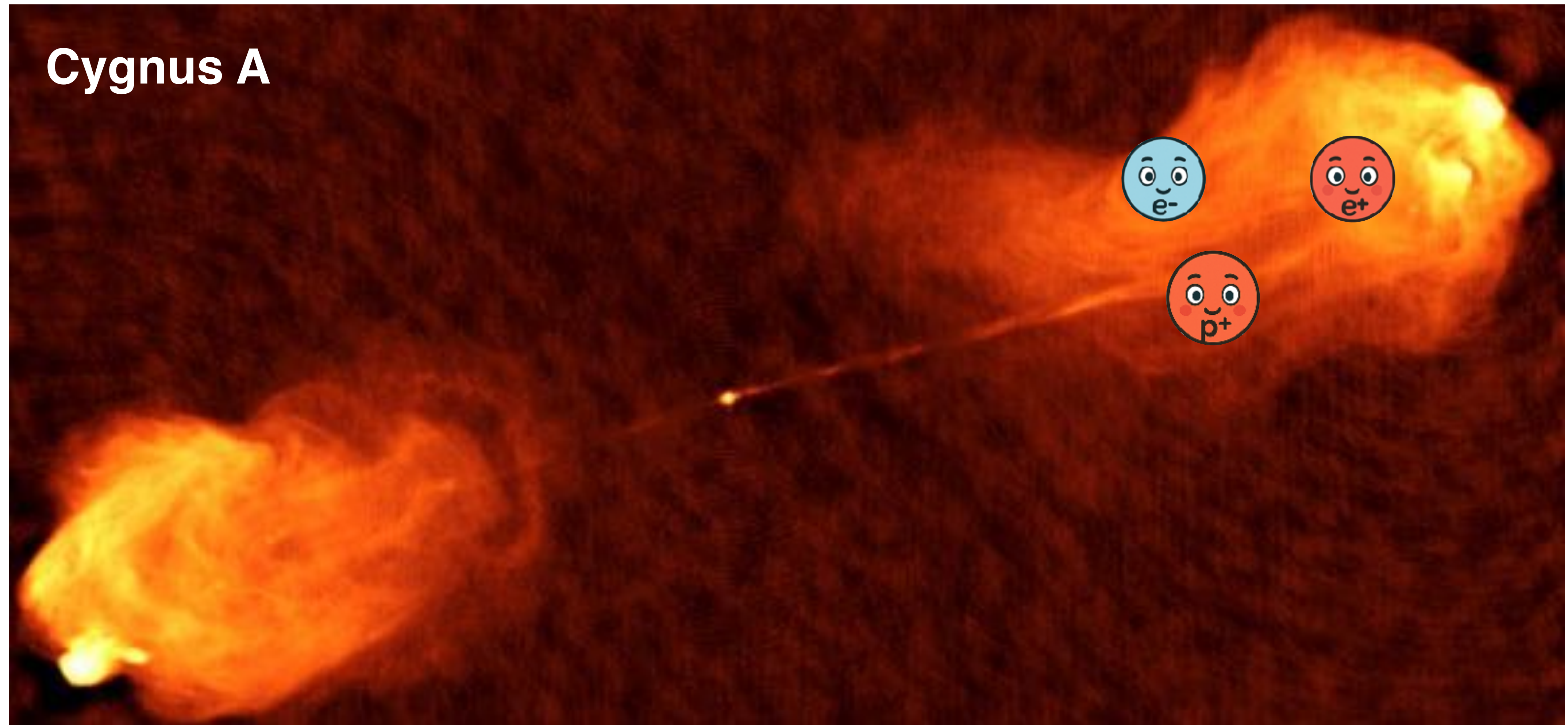
Chandra Deep Field South

>5000 SMBH systems in
this X-ray image!

Credit: NASA/CXC/Penn State/B.Luo et al.

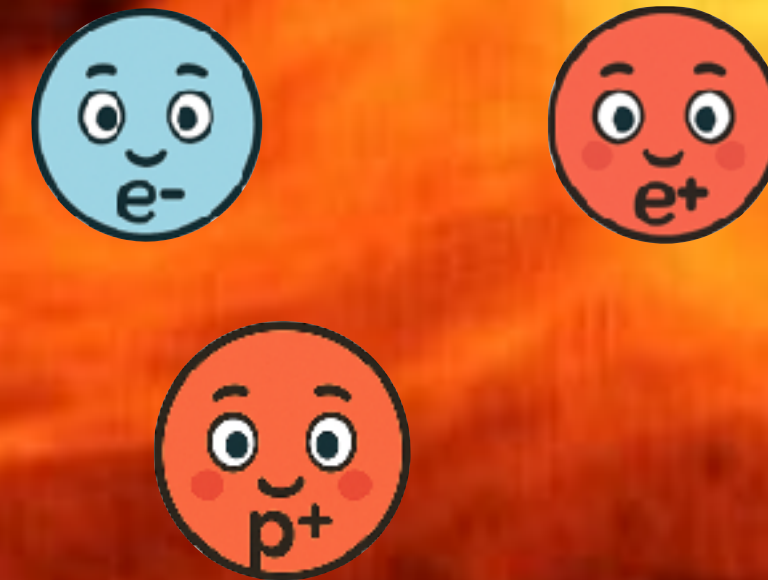
Black Hoel as
multi-messenger engines

Electromagnetic wave



Cosmic ray

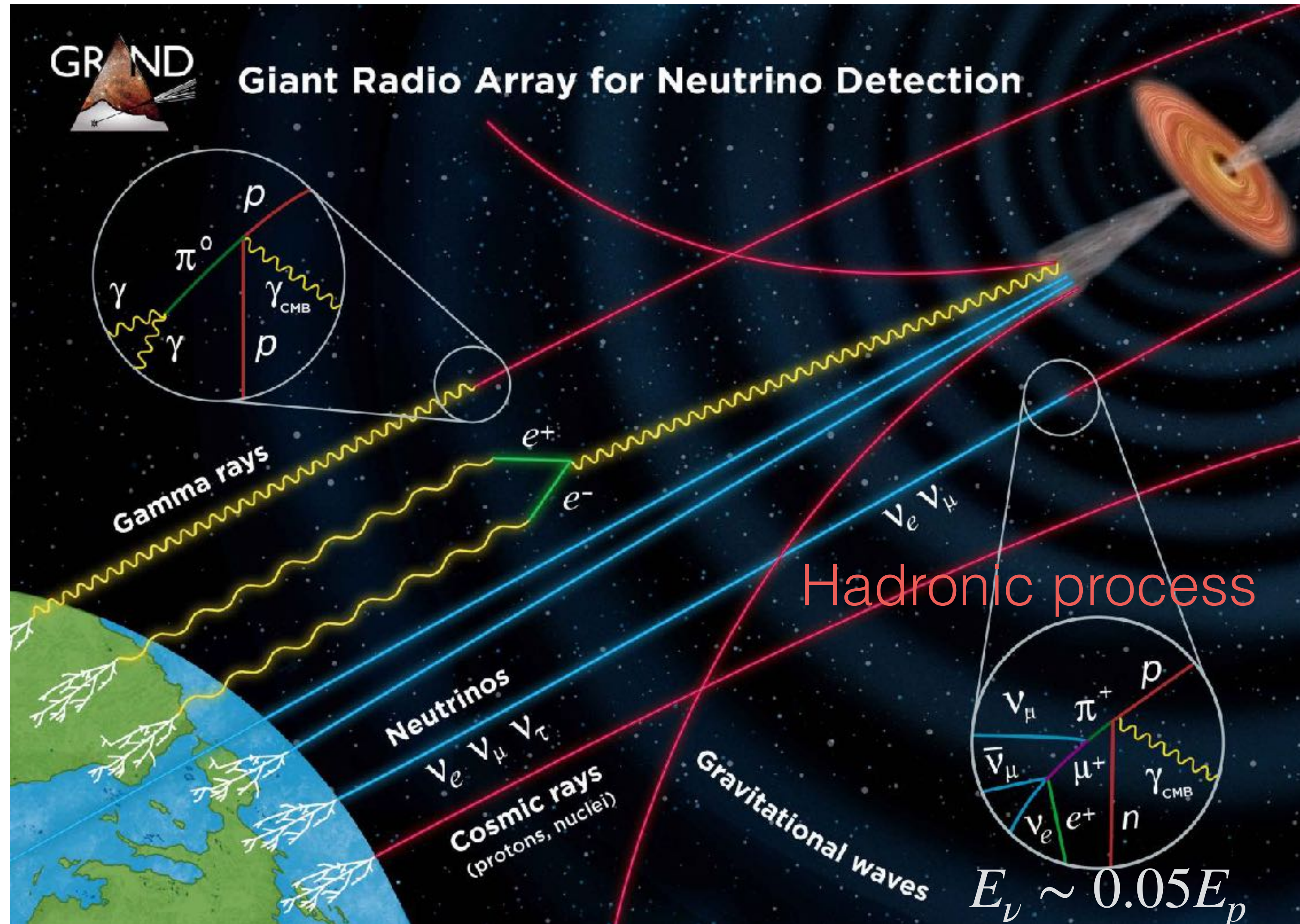
Cygnus A



Particle acceleration (shock, magnetic reconnection etc.) → cosmic ray

$$\text{GeV} < E_p < \text{PeV}$$

Neutrino



TXS 0506+05

Event:

IceCube-170922A

Fermi-LAT gamma-ray flare

→ IceCube neutrino detection

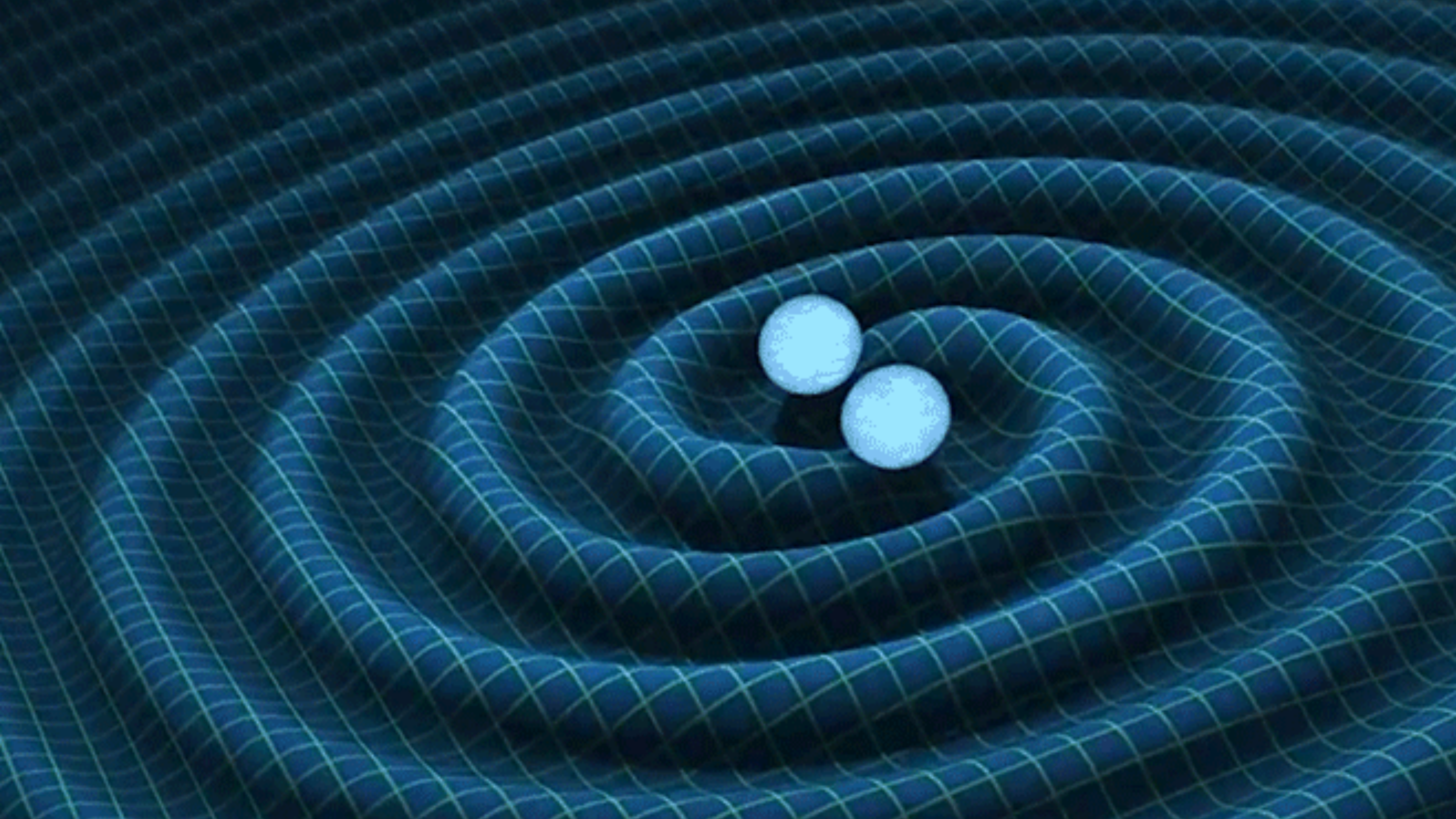
$E_\nu \sim 0.3 \text{ PeV}$

→ multi-wavelength follow-up

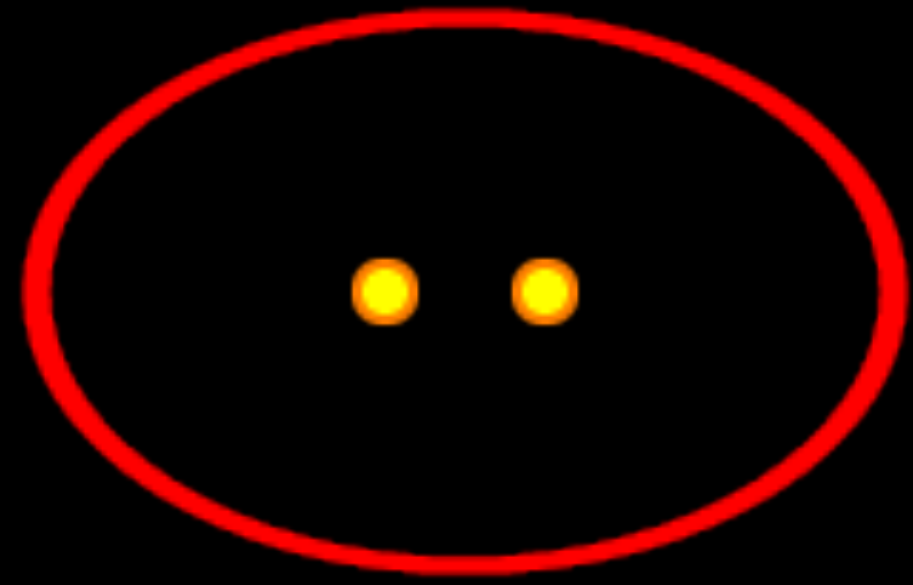


Gravitational wave

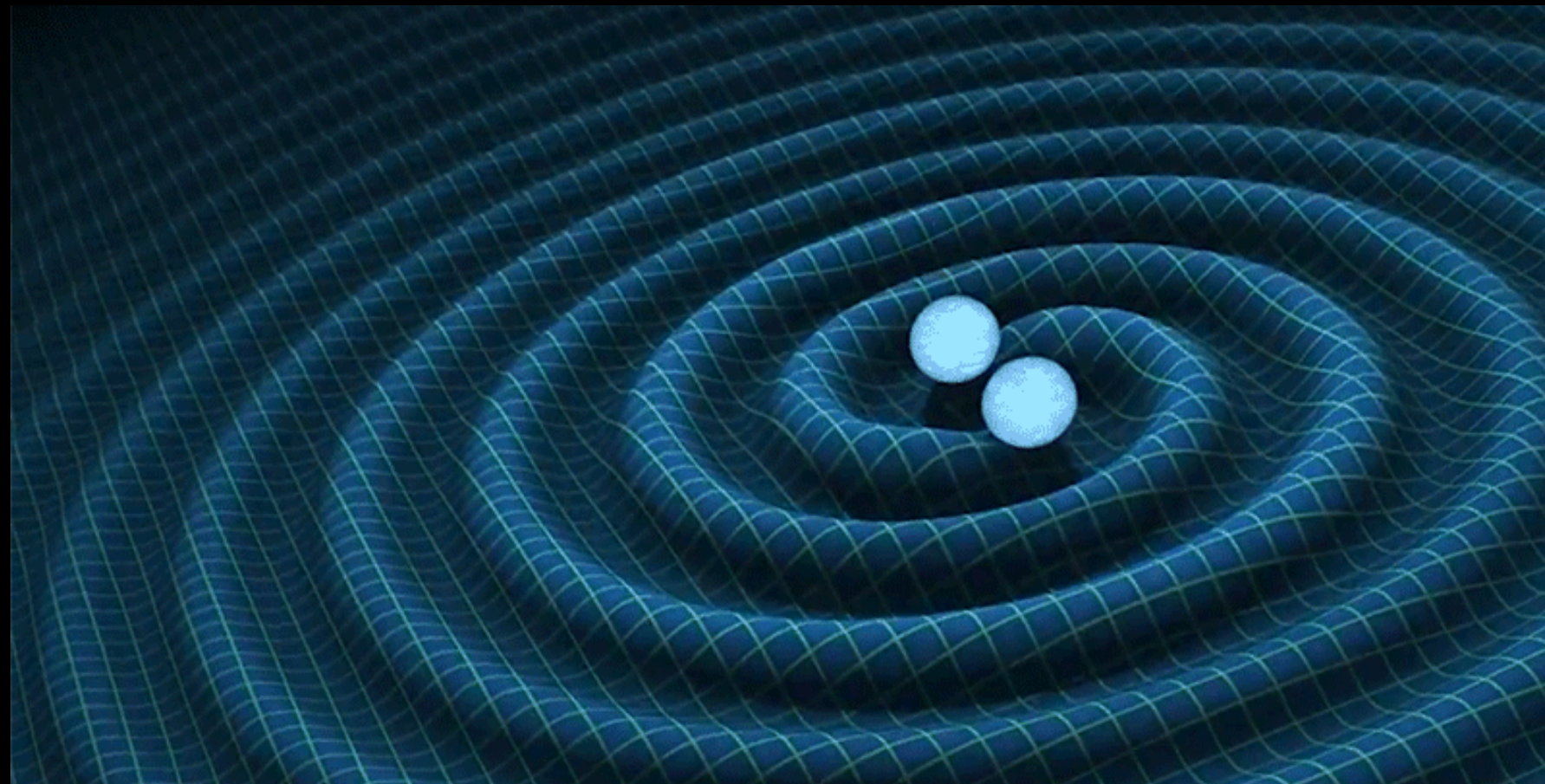




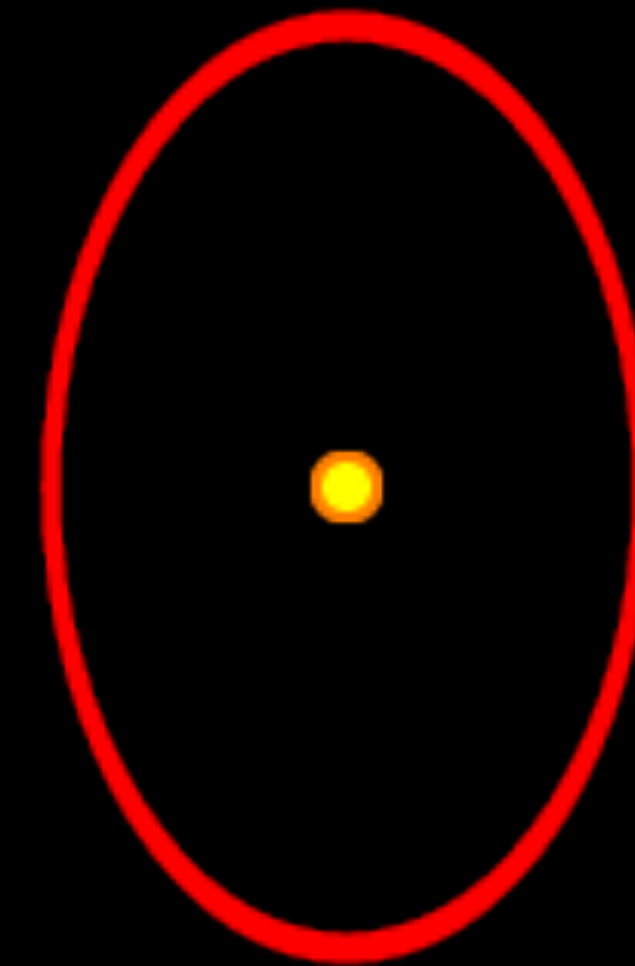
Polarization of GW



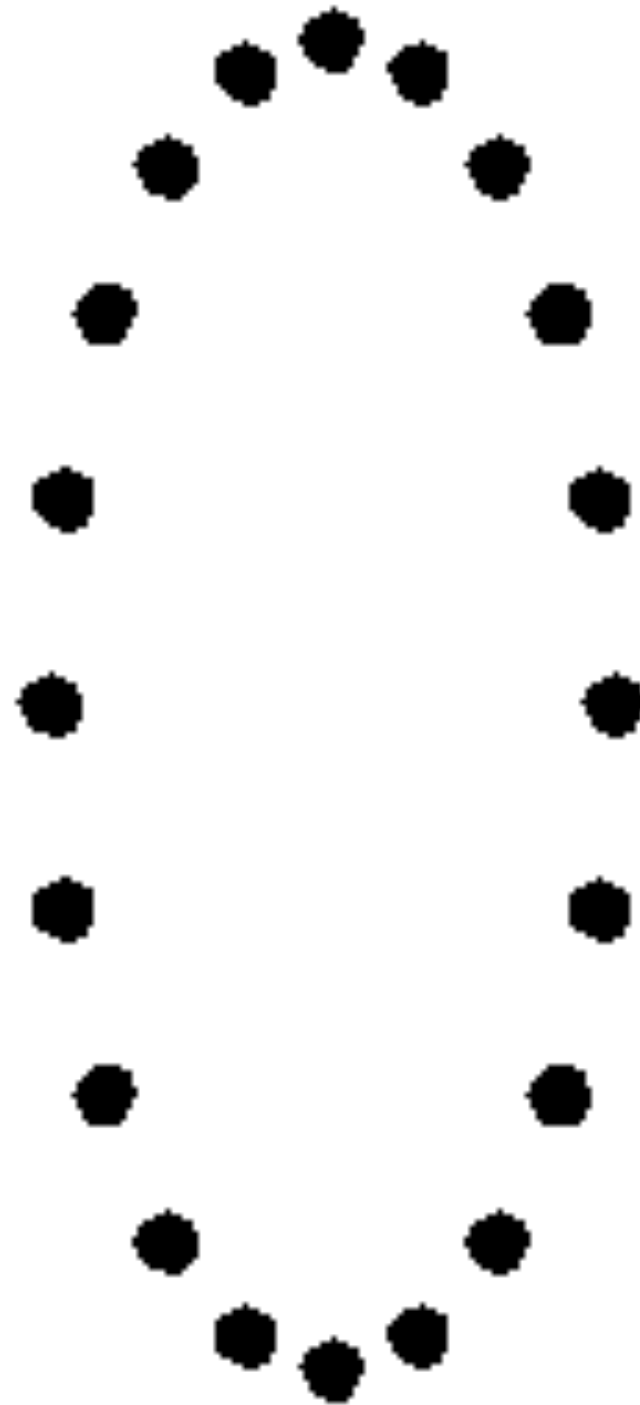
Face on
observation



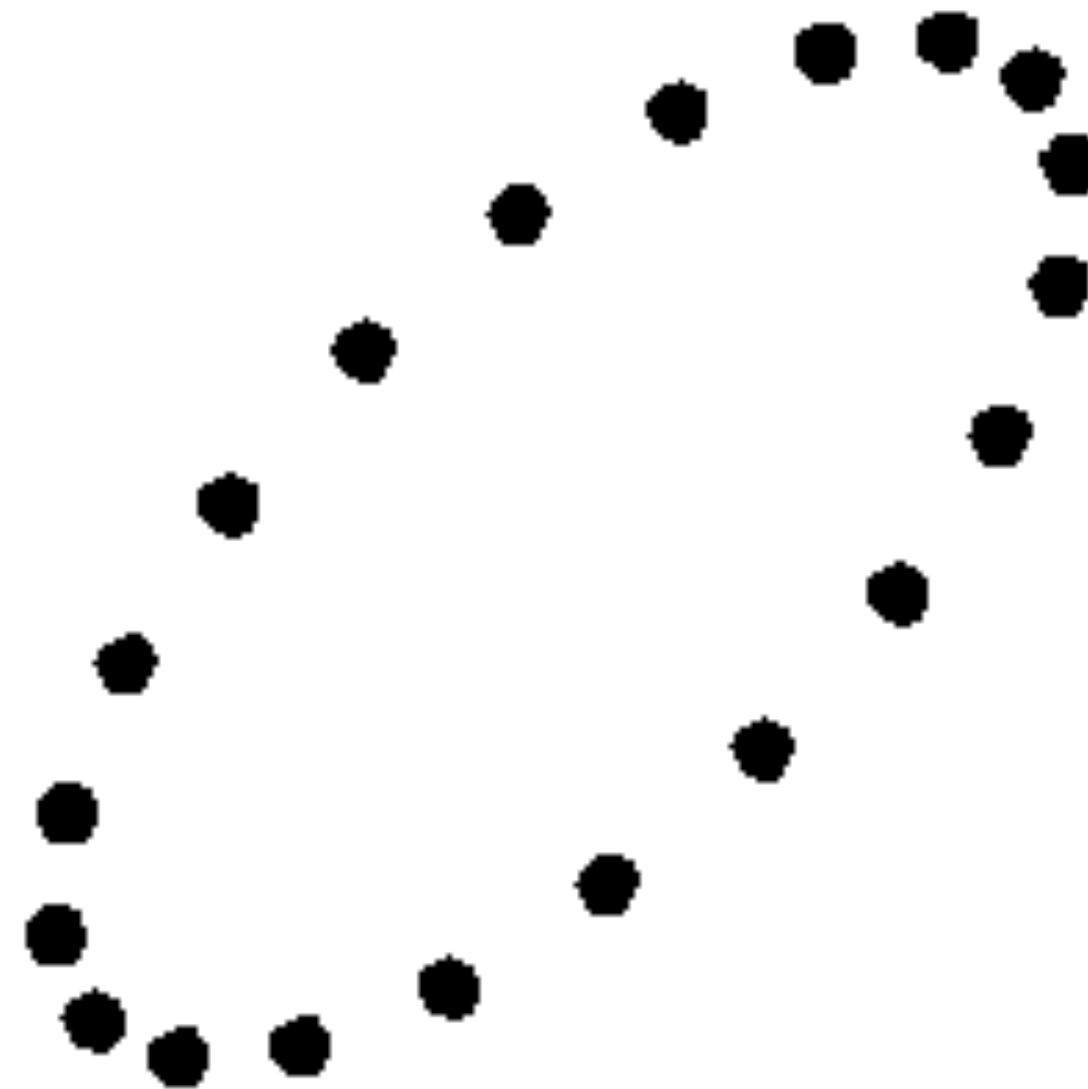
Edge on
observation



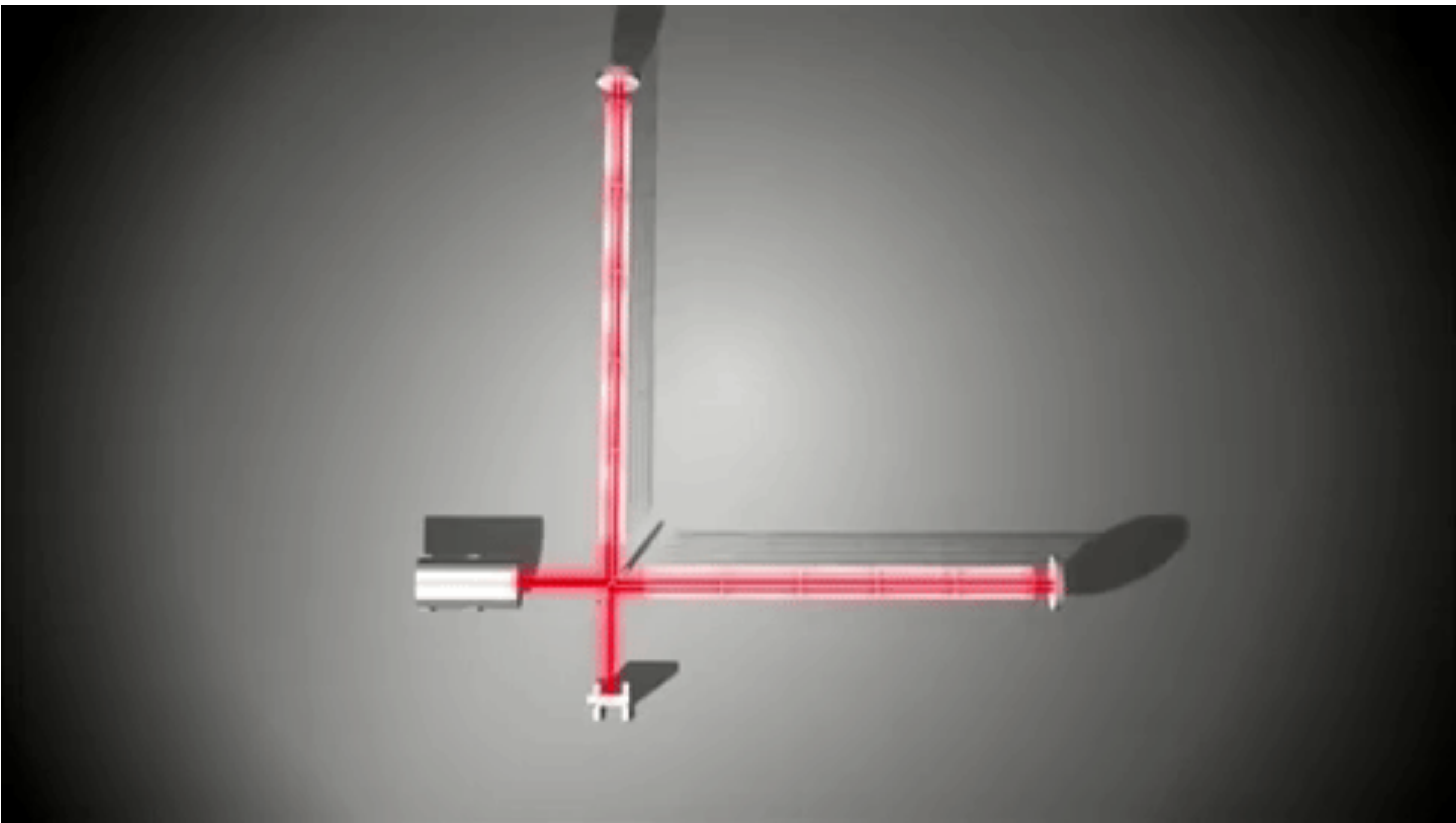
Two modes of GW



+ mode



X mode



GW150914

First observed GW signal

Lasts for 0.2 s

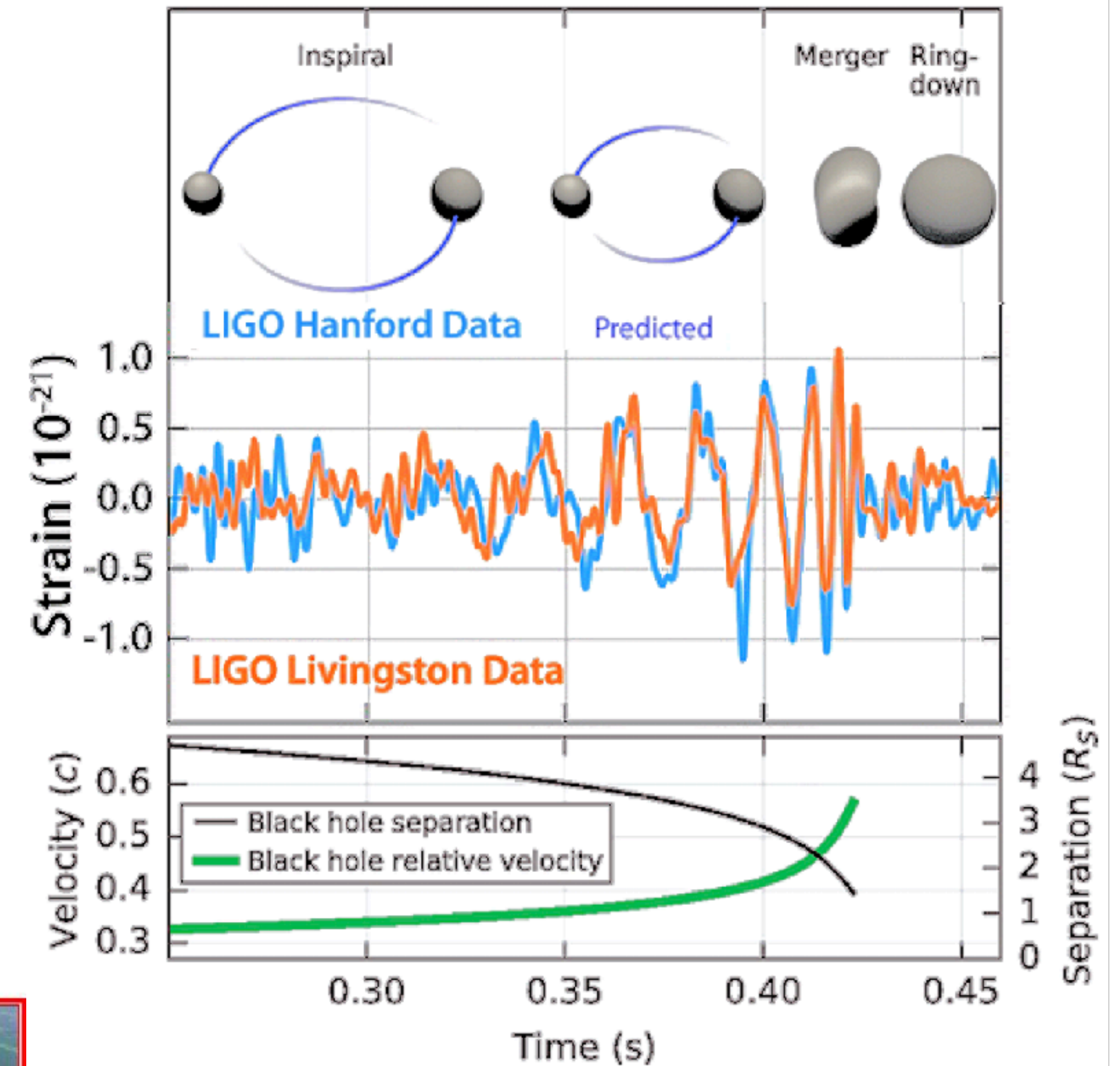
Signal frequency 35 Hz – 250 Hz

Distance: 410 Mpc

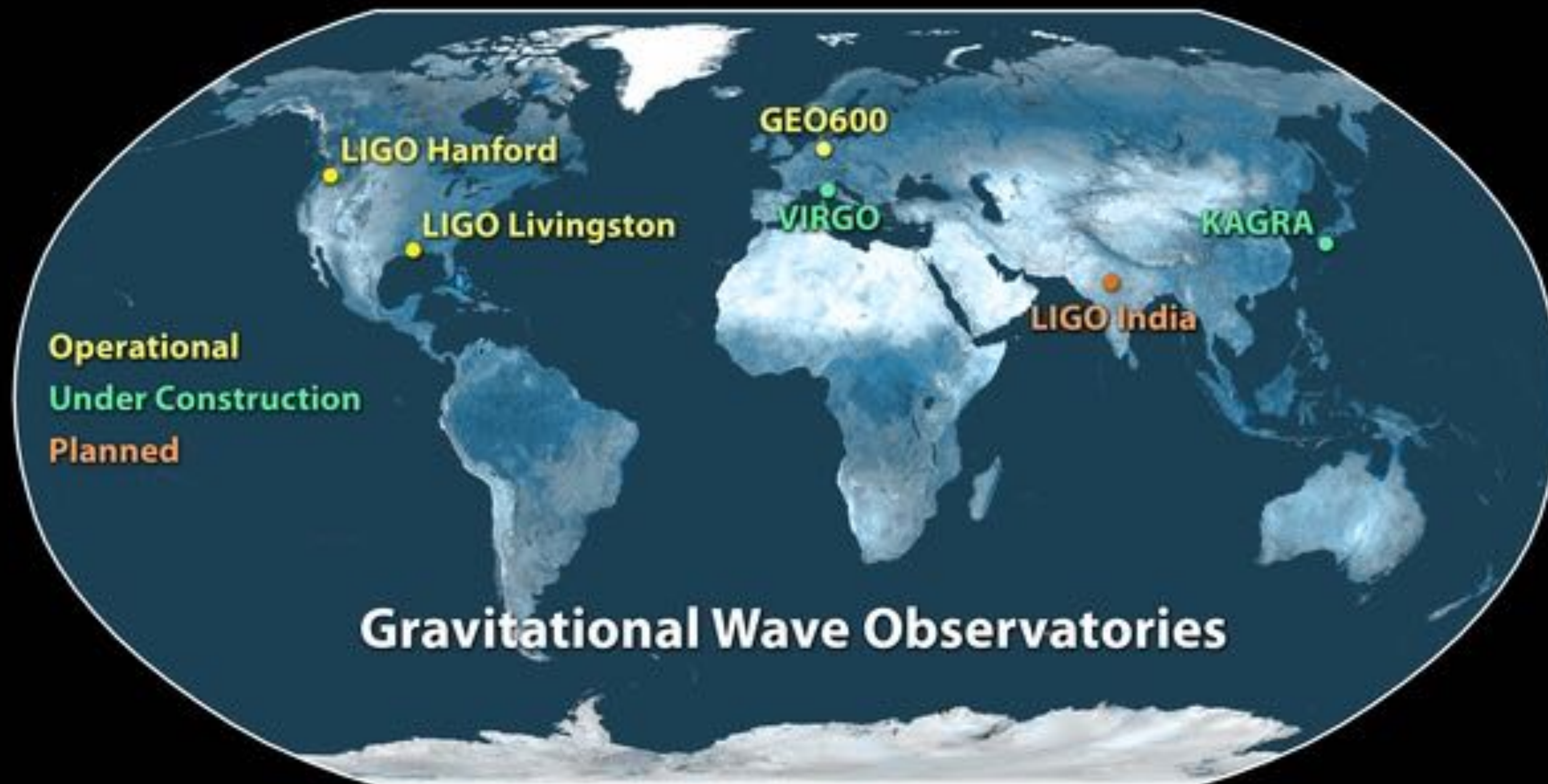
Before collision: 36 + 29 solar mass

After collision: 62 solar mass

LIGO

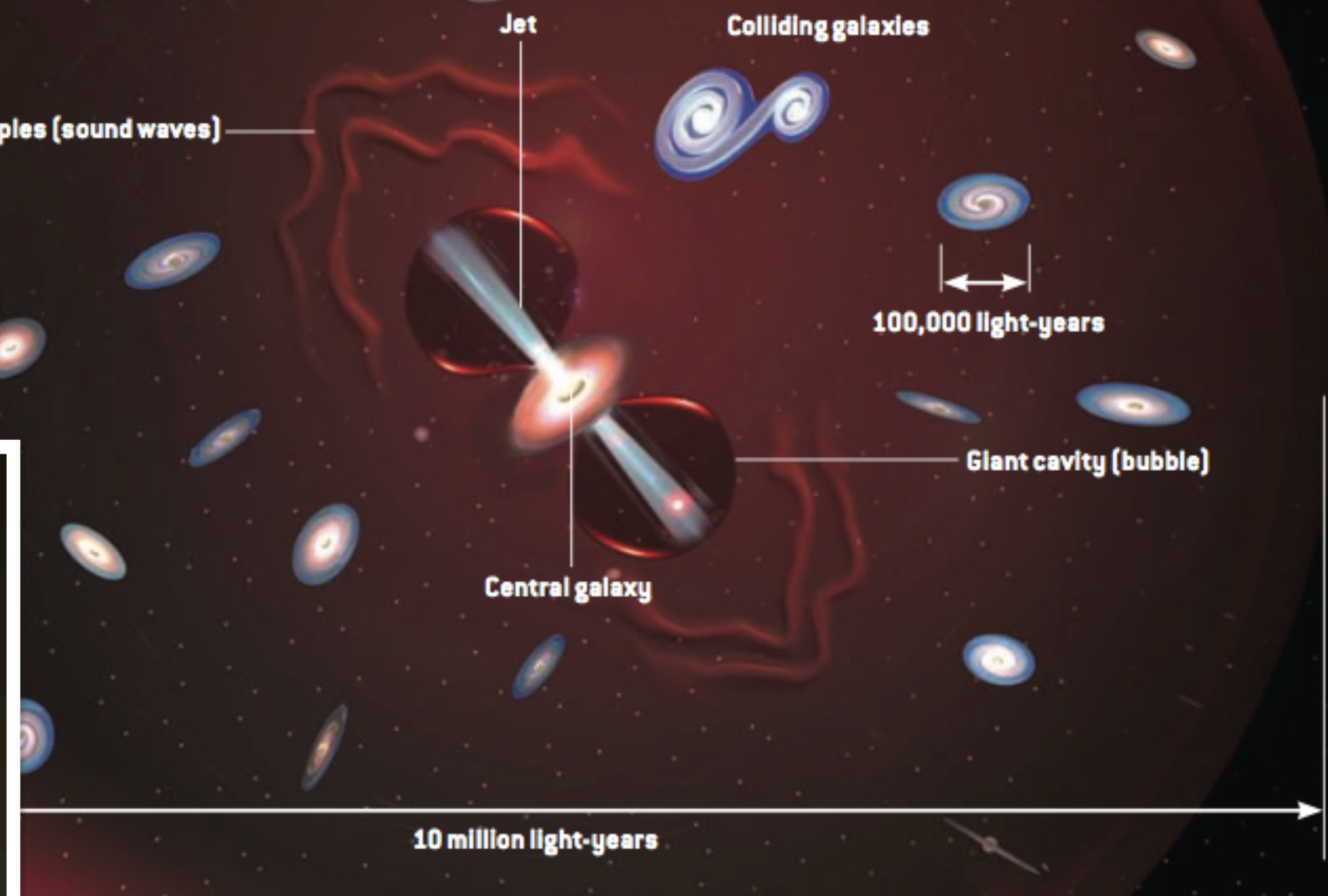


A few hundreds of detections so far



AGN and galaxy coevolution

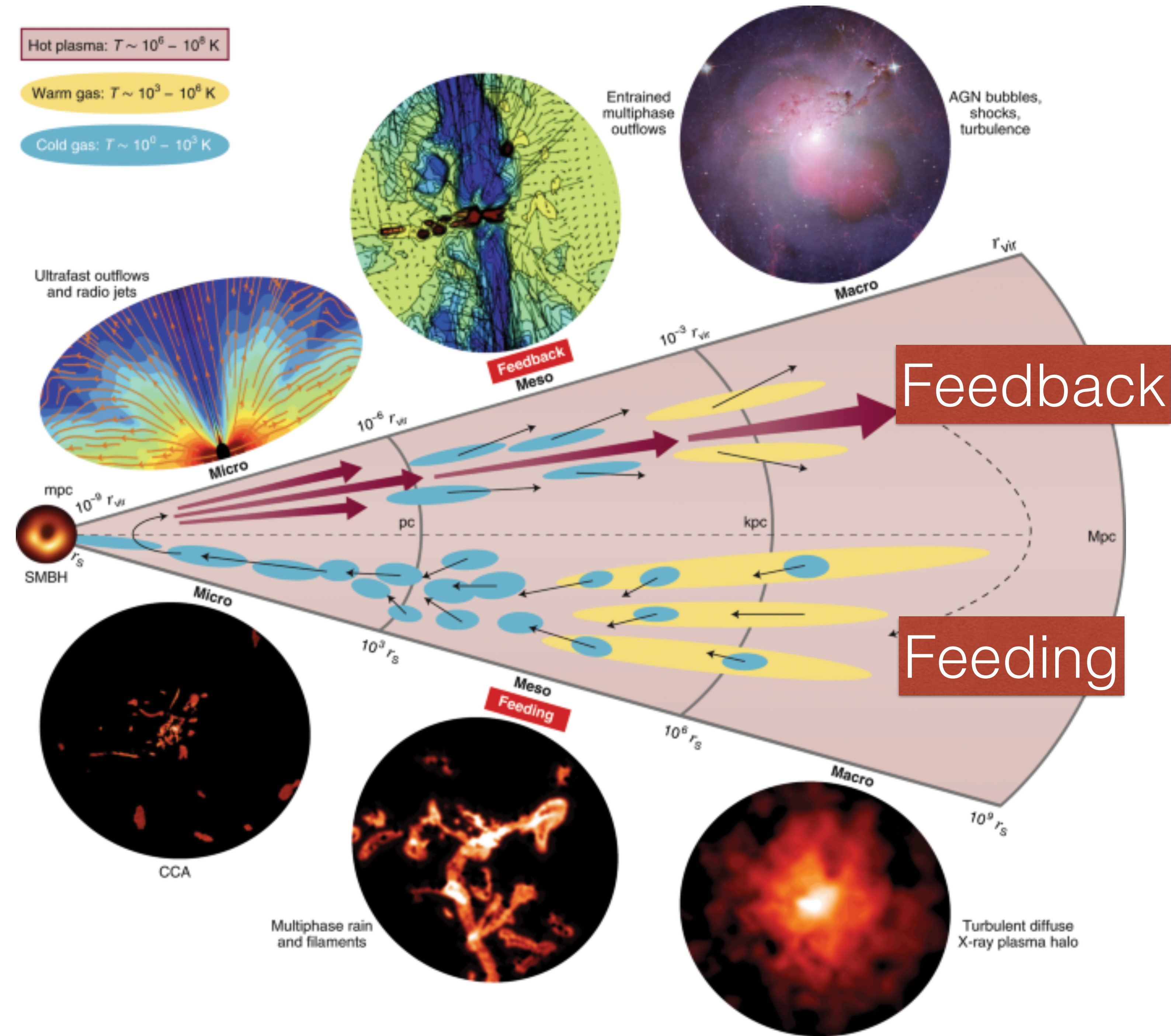
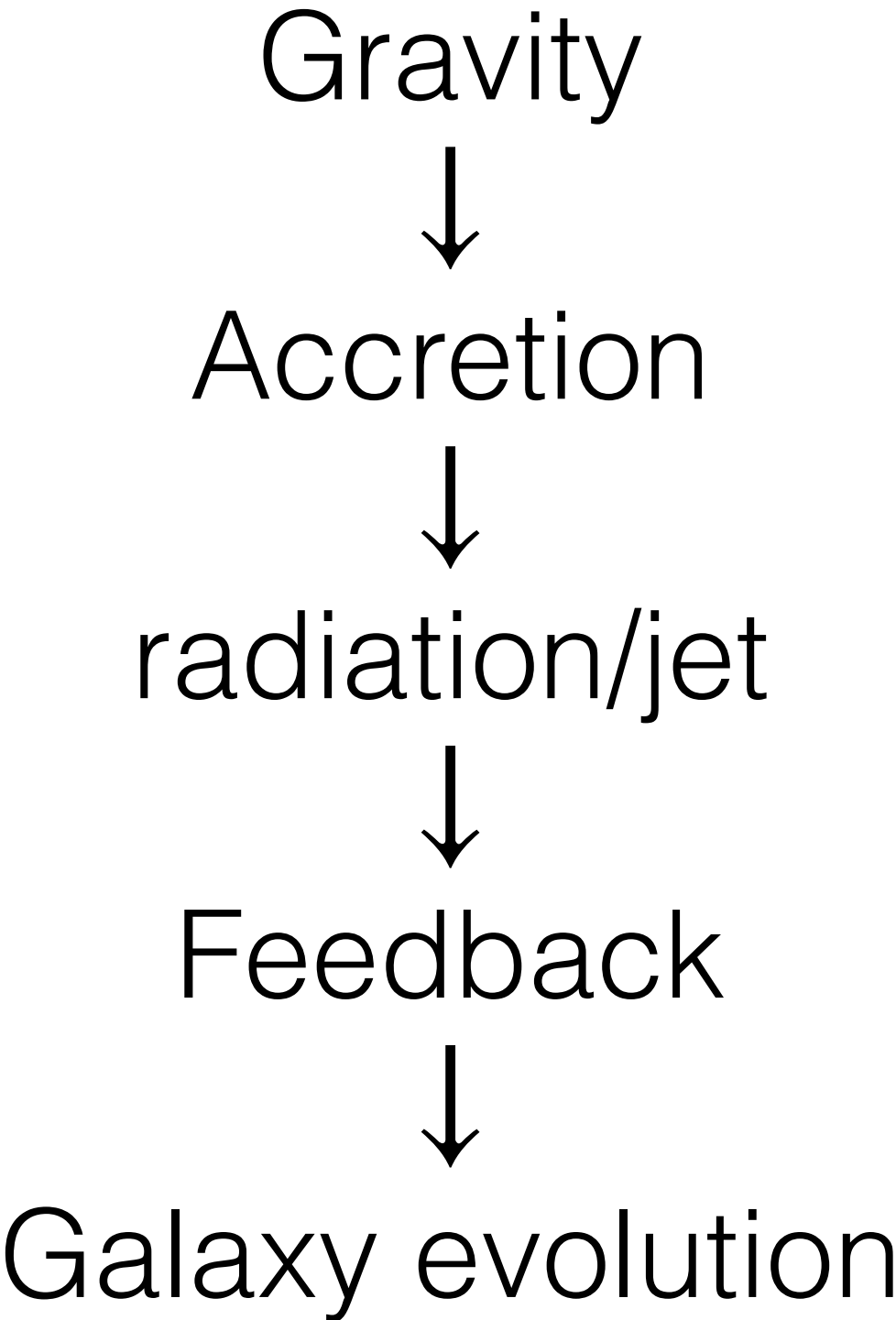
Radio/Jet mode

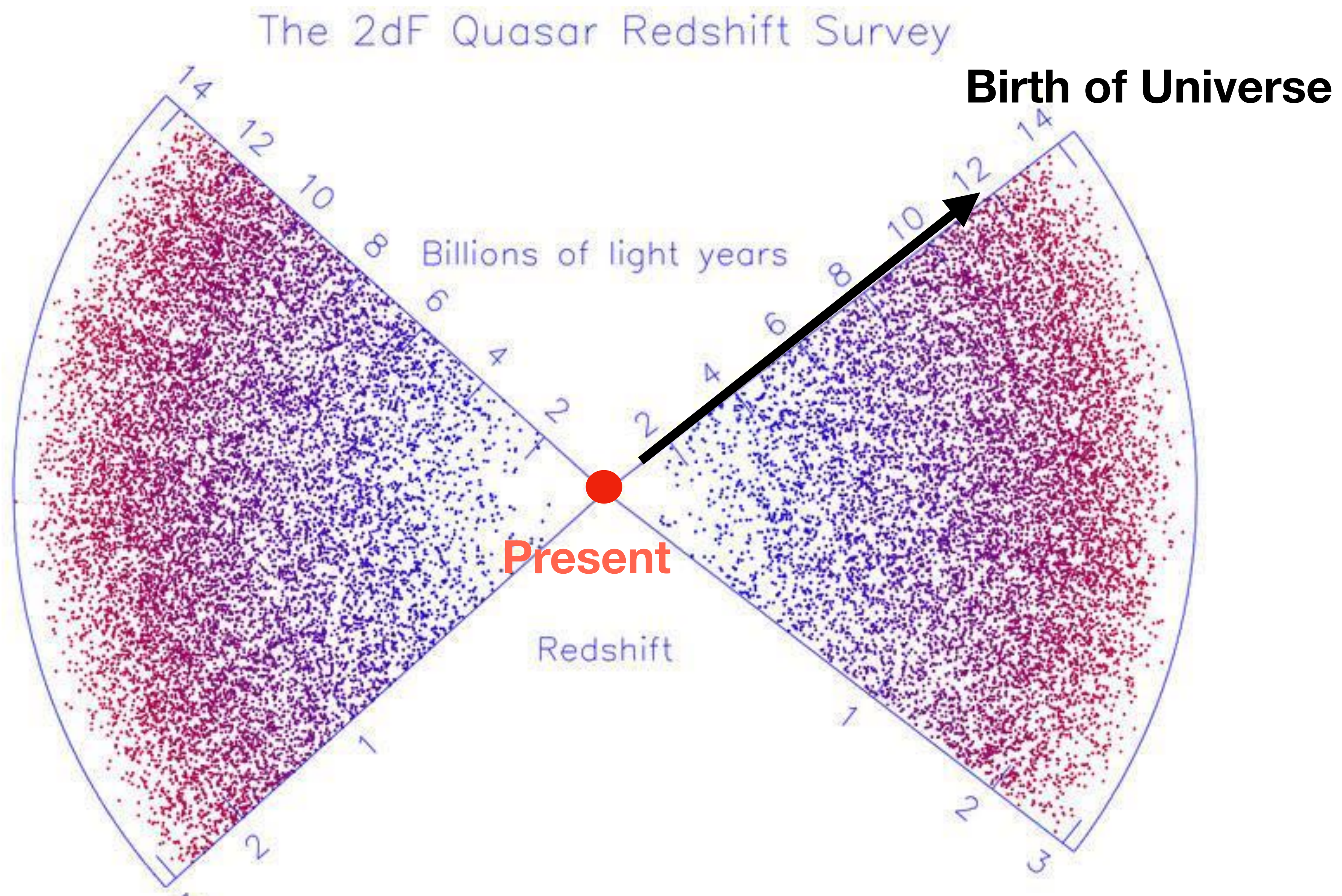


Quasar/Radiative mode



Black hole ecosystem:

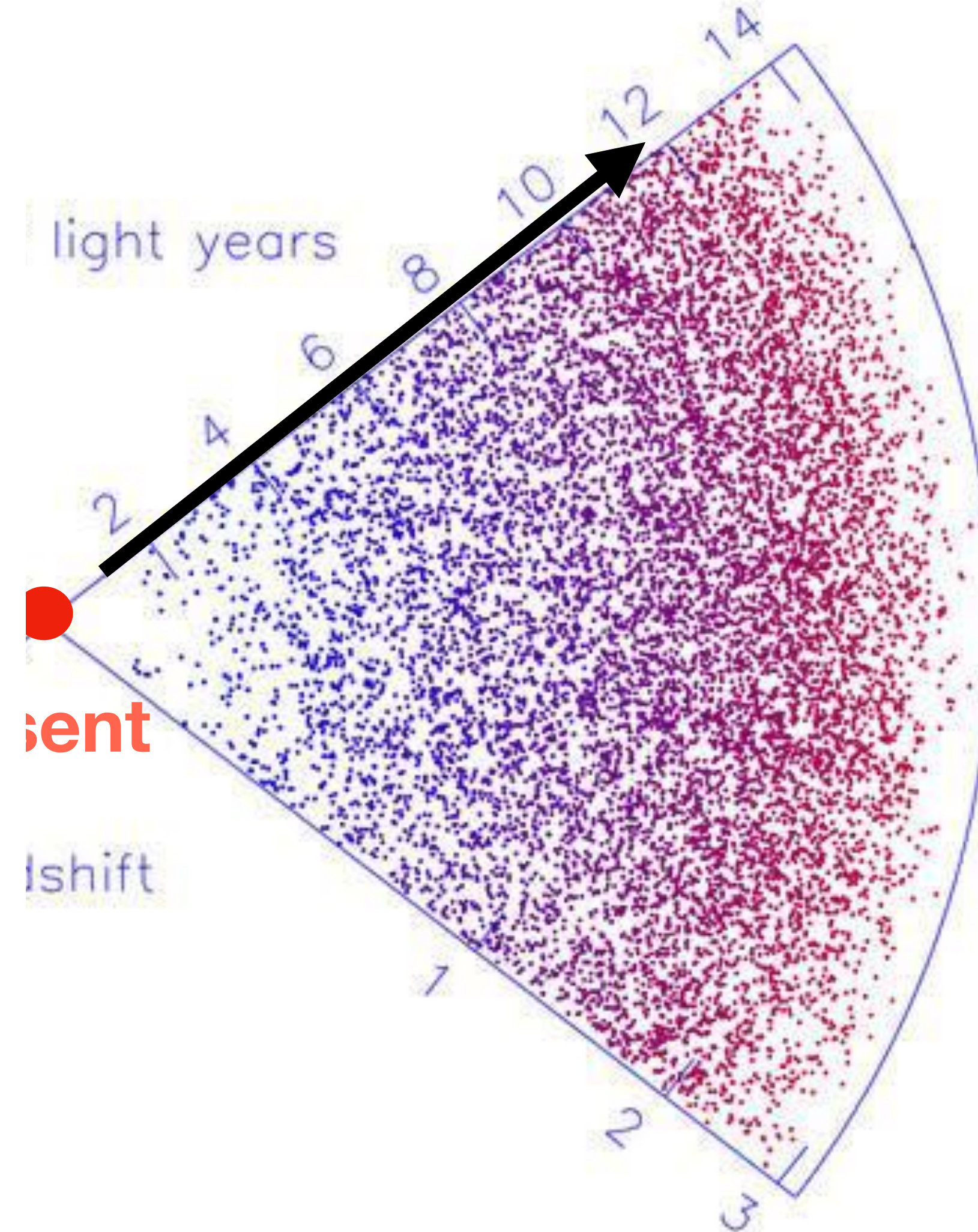
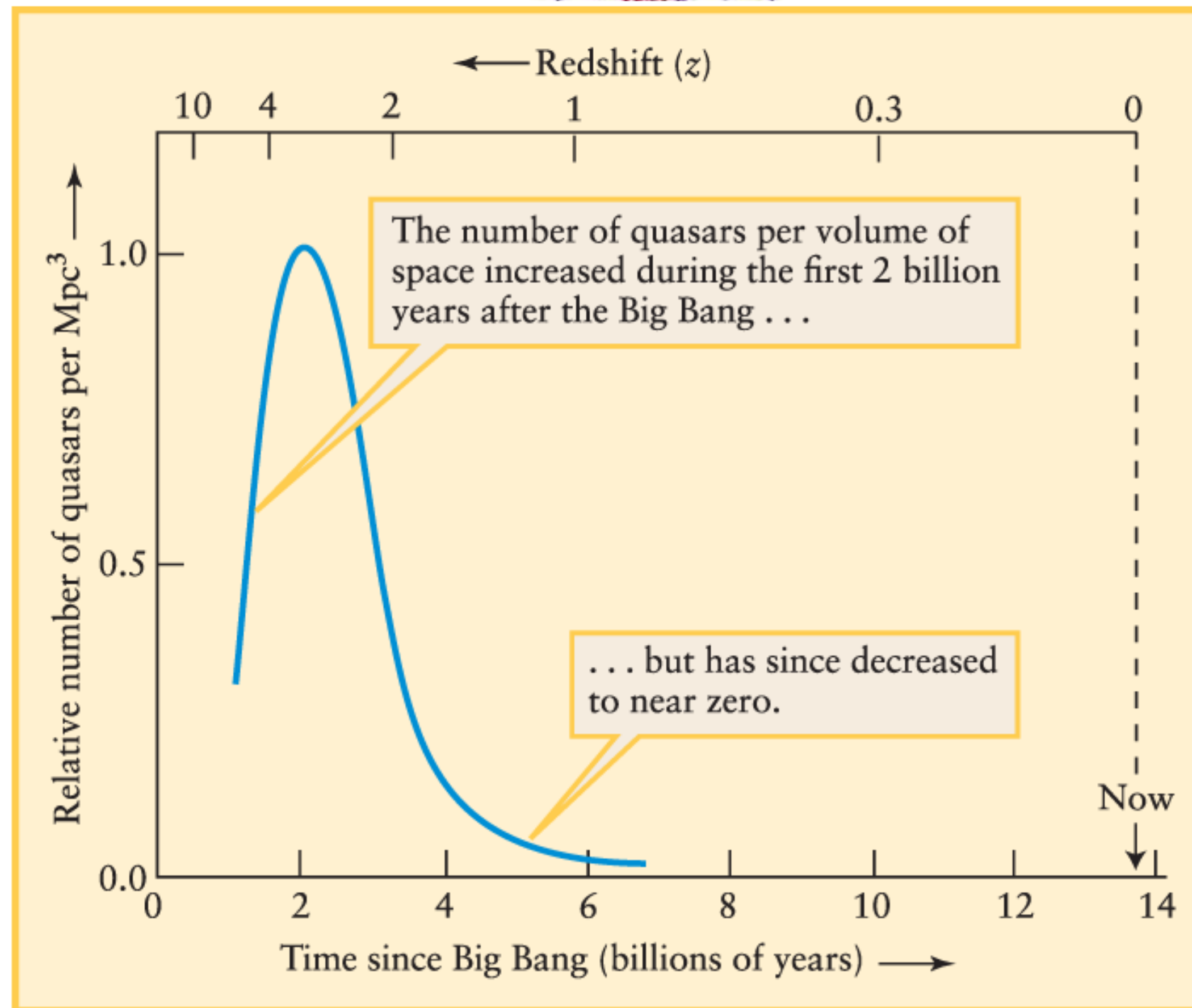




Credit: Two-degree-Field Galaxy Redshift Survey Team

The 2dF Quasar Redshift Survey

Birth of Universe



Geller et al., *Universe*, 11e, © 2019 W. H. Freeman and Company

H-noAGN
 $z=2.5$

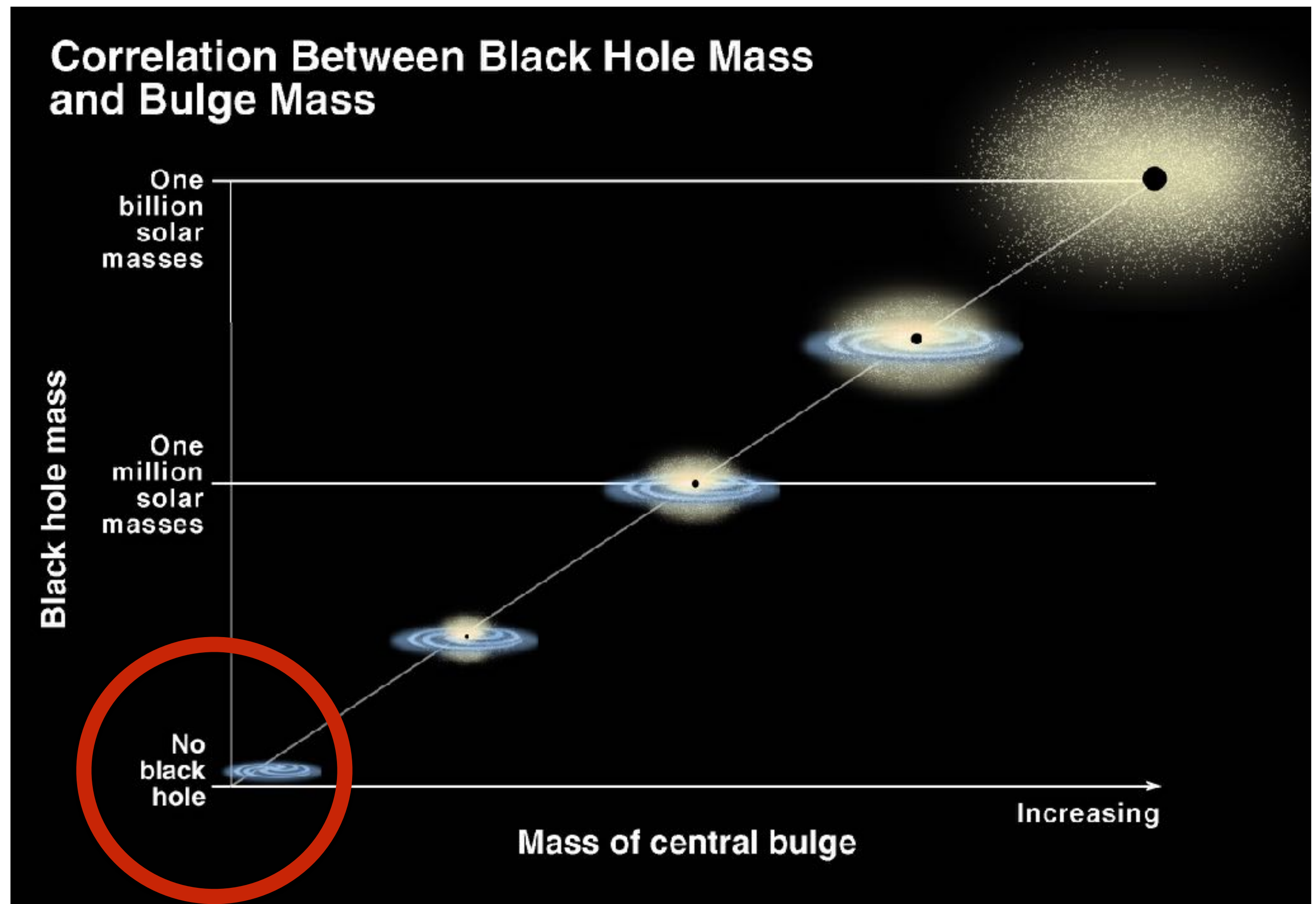
H-AGN
 $z=2.5$

Credit: Horizon-AGN. Horizon-noAGN simulation

$M_{BH} - M_{bulge}$ relation

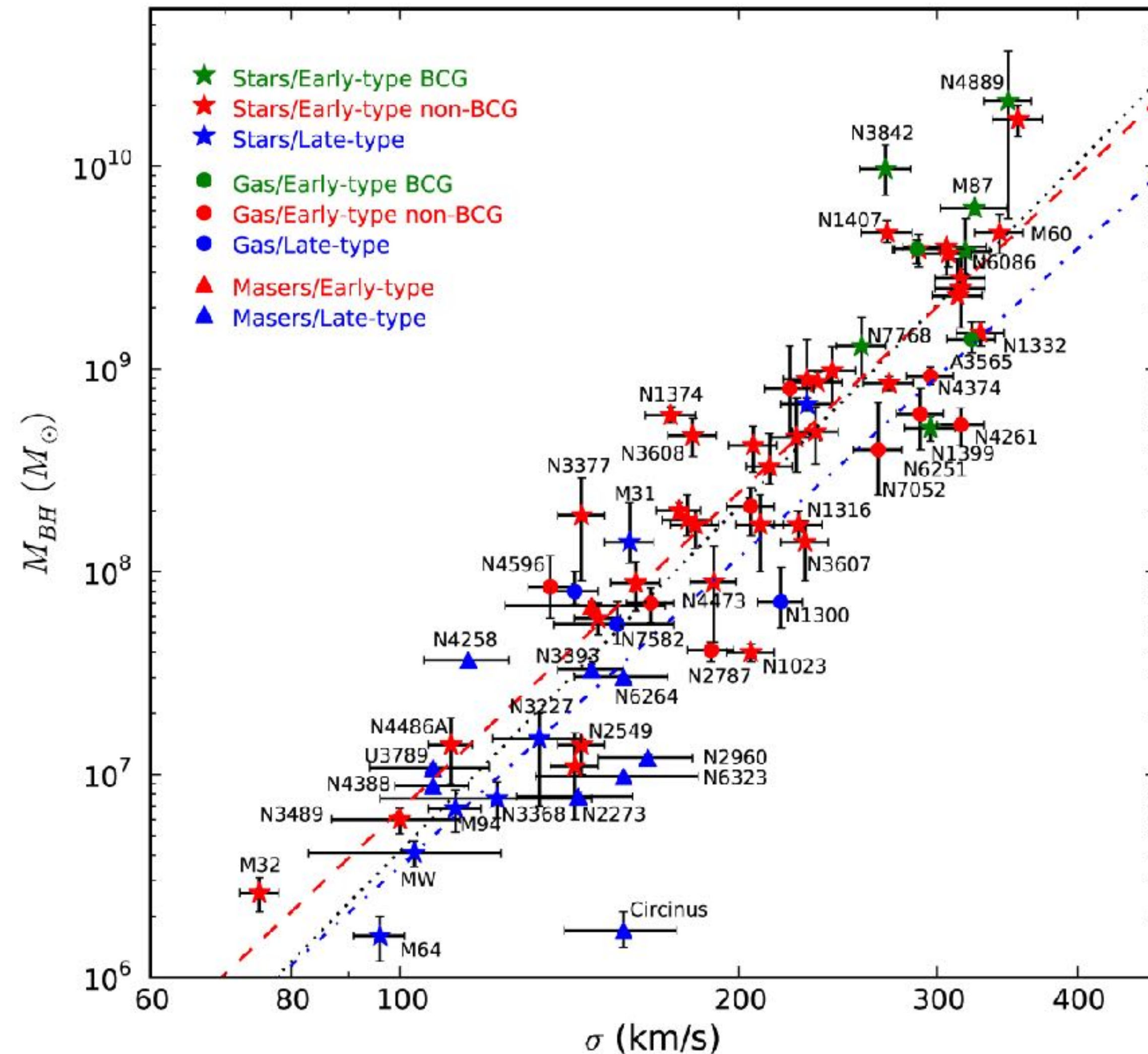
$$M_{BH} \approx 0.0013 M_{bulge}$$

Not necessary!



$M_{BH} - \sigma$ (stellar velocity dispersion) relation

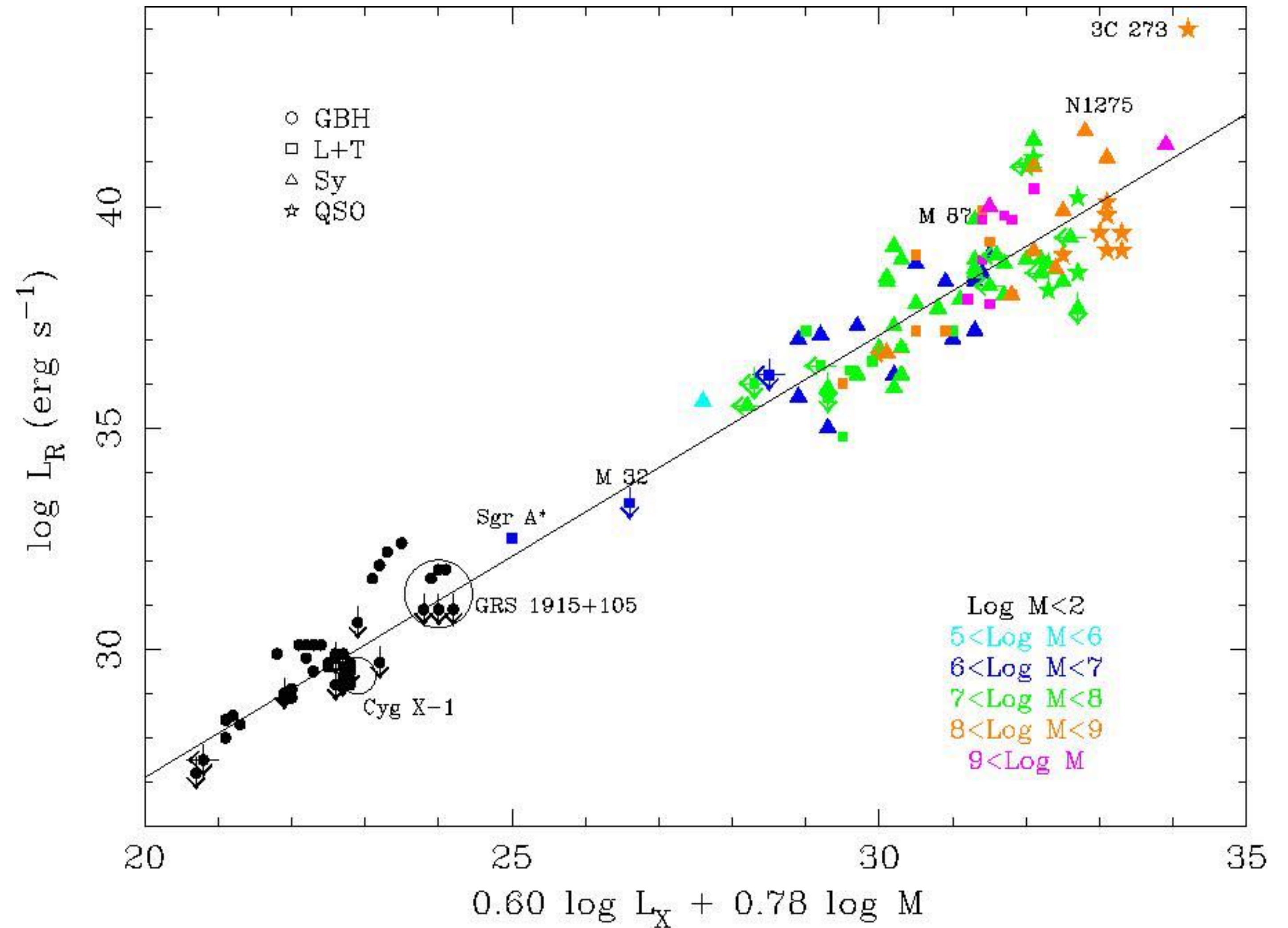
$$M_{BH} \propto \sigma_{\text{bulge}}^{\alpha}$$
$$\alpha \sim 4 - 5$$



Fundamental plane

radio luminosity
→ compact jet

X-ray luminosity
→ inner hot flow / corona



Summary

- Relativity 101
- What is a black hole?
- Key physical parameters for a black hole system
- Types of astrophysical black holes
- Black holes as multi-messenger engines
- AGN and galaxy convolution

The big picture (astrophysics)

- predicted by **general relativity**
- tested by modern observations
- powered by **accretion**
- capable of launching **jets** and **high-energy particles**
- important agents in **galaxy evolution**

Some open questions

- Are astrophysical black holes exactly Kerr black holes?
(Now is the golden age of black hole astrophysics)
- How are relativistic jets launched and powered?
- What is the plasma physics of black-hole accretion flows?
- How do supermassive black holes form and grow so early?
- How exactly do black holes affect galaxy evolution through feedback?