Black Holes

Rodrigo Nemmen

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blackholegroup.org

@nemmen

We entered a new golden age of black hole (astro)physics

You **can be part of this!**

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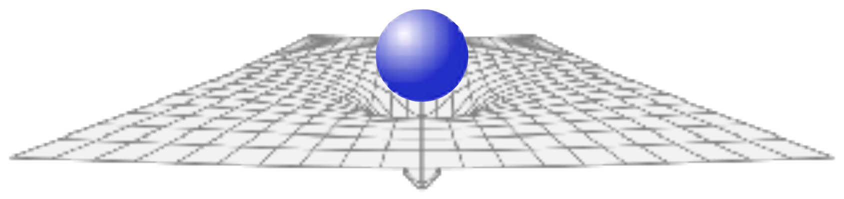
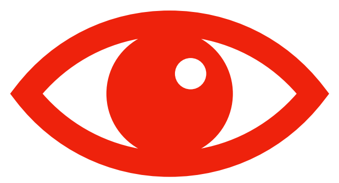
1. Gravity: General relativity

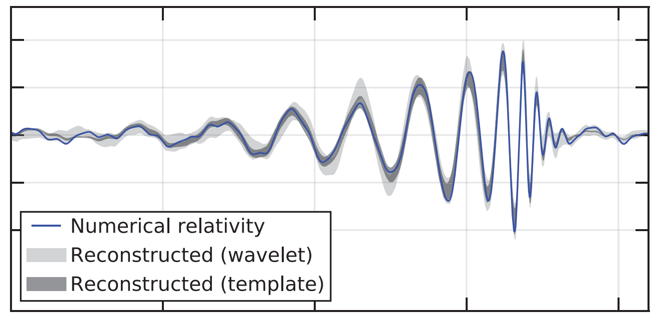


2. What is a black hole?

3. How to “see” a BH?

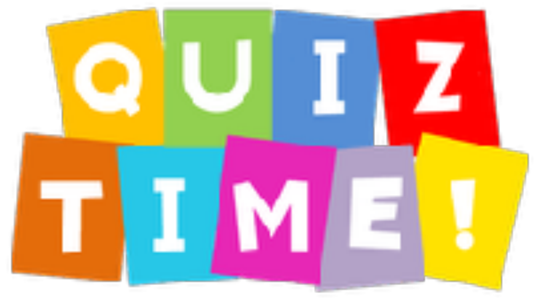


4. Gravitational waves



5. Summary

6. Quiz



Lagrangian for standard model of particle physics

http://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] +$$

4

$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

5

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

gluon (strong force)

W and Z bosons (weak force)

weak interactions + Higgs

Higgs ghosts

Faddeev-Popov ghosts

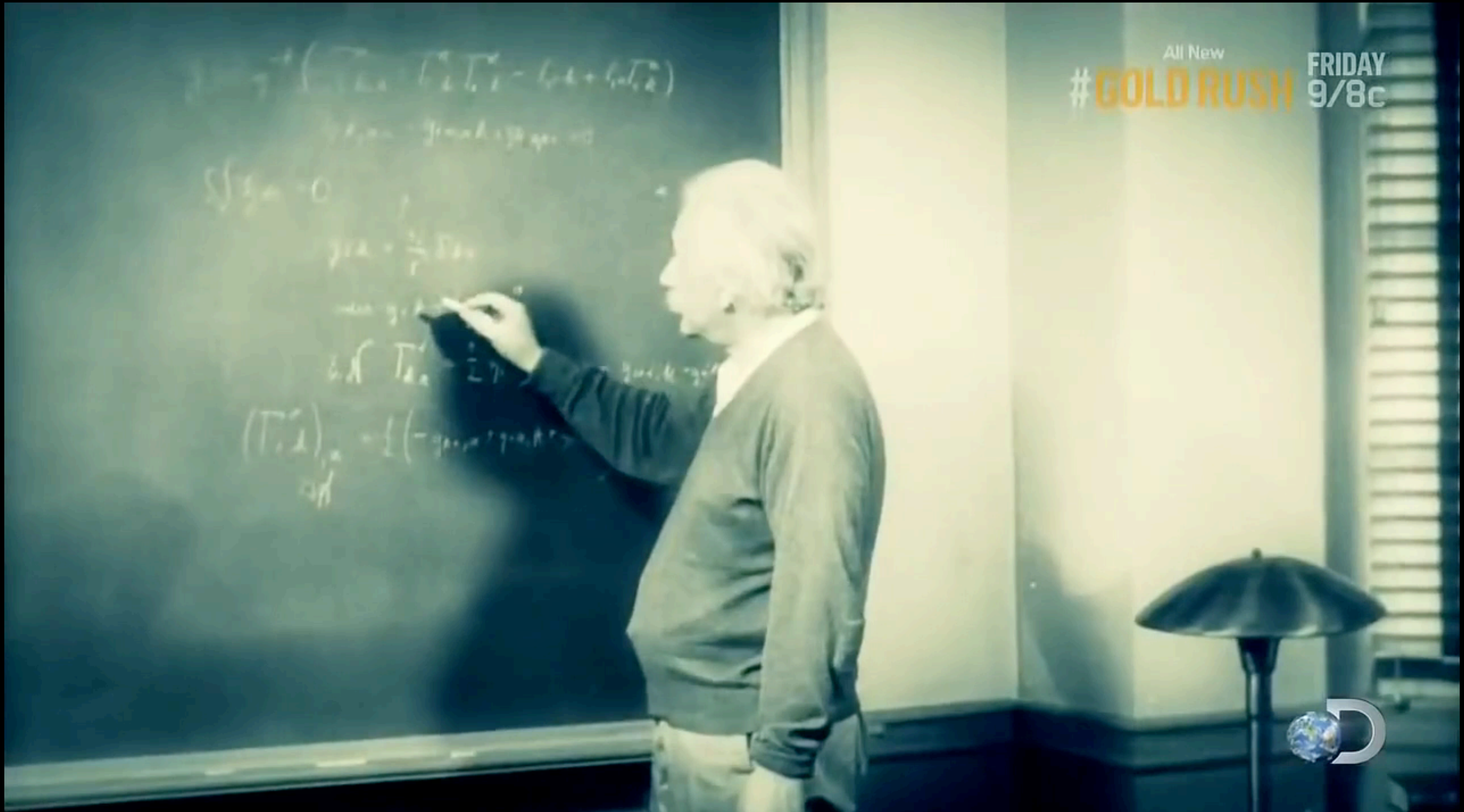
action

$$S = \int \mathscr{L}\sqrt{-g}\,\mathrm{d}^4x$$

Lagrange equations

$$\frac{\delta S}{\delta\phi} = \frac{\partial\mathscr{L}}{\partial\phi} - \partial_\mu\left(\frac{\partial\mathscr{L}}{\partial(\partial_\mu\phi)}\right) + \cdots = 0$$

Basic idea of general relativity:
GRAVITY = SPACETIME CURVATURE



A general relativity primer

Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Ricci curvature

Metric

Ricci scalar

Stress-energy

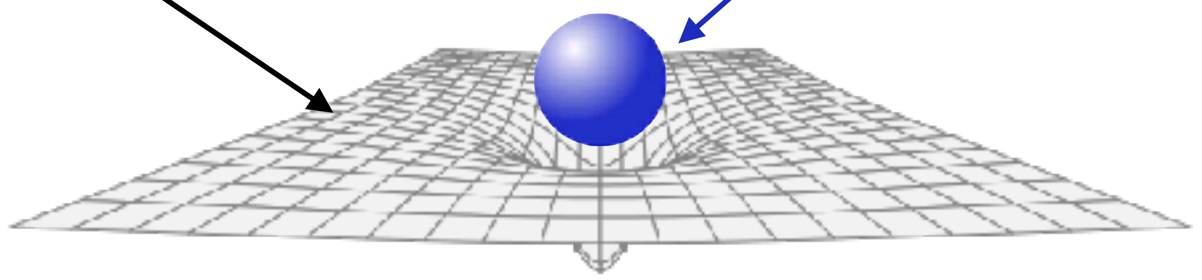
A general relativity primer

Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Ricci curvature · Metric · Ricci scalar · Stress-energy

⇒ spacetime curvature = constant × matter-energy



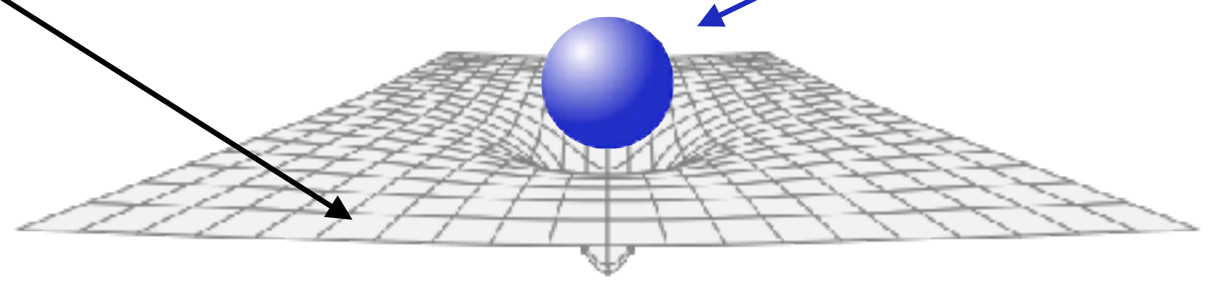
A general relativity primer

Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Ricci curvature — Metric — Ricci scalar — Stress-energy

⇒ spacetime curvature = constant × matter-energy



Solution to field equation gives

$g_{\mu\nu}$ — Metric

$ds^2 = g_{\mu\nu}dx^\mu dx^\nu$ — Line element

Newtonian analogue

$\nabla^2\phi = 4\pi G\rho$ — Poisson equation

For a free particle:

$$\delta S = 0 \rightarrow \frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0$$

Geodesic equation

Gravity visualized: https://www.youtube.com/watch?v=MTY1Kje0yLg&list

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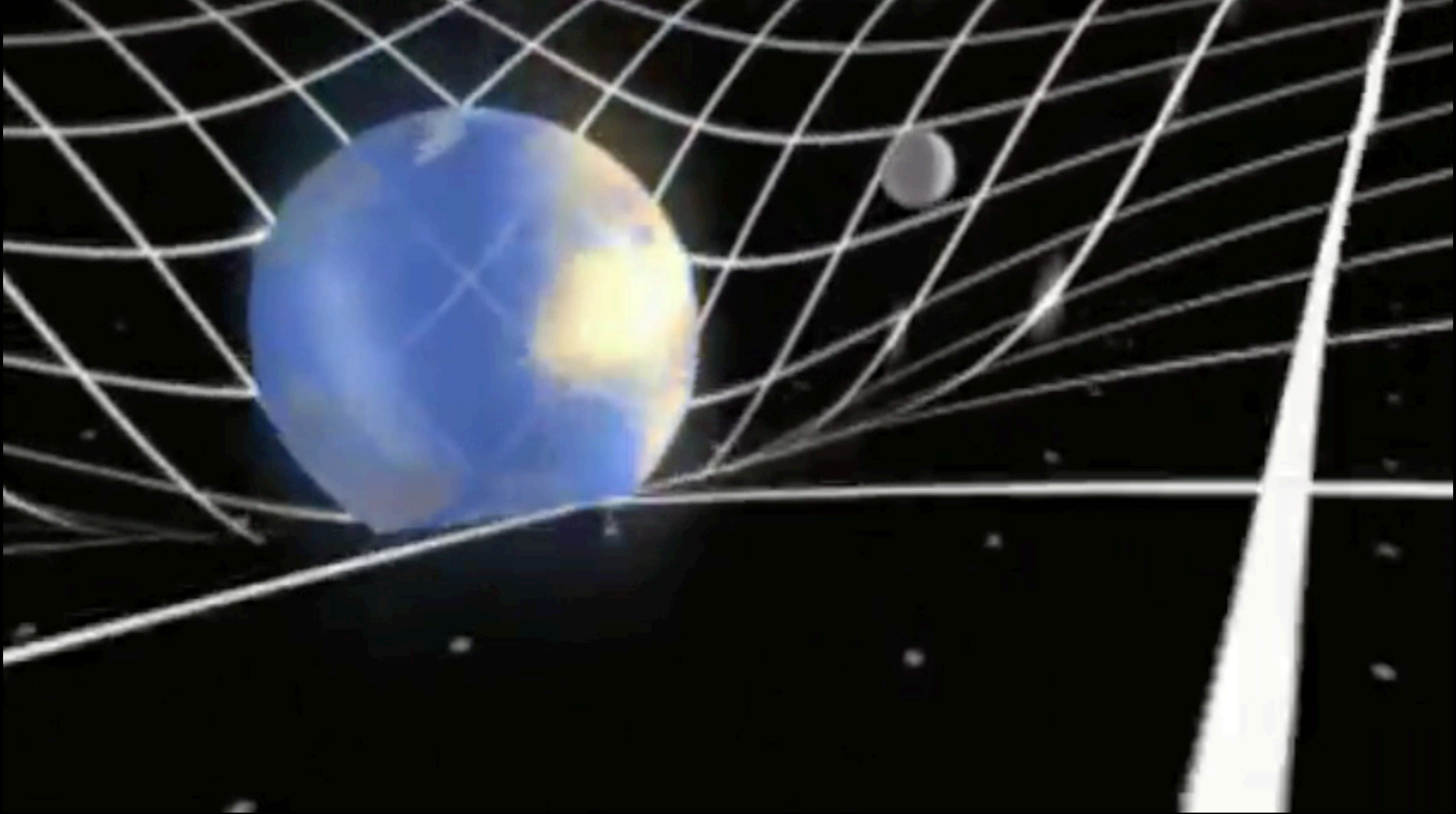

The Elegant Universe. Nova / PBS

A concise tutorial on general relativity

DOI: 10.1119/1.12853

General relativity primer

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(Received 14 July 1980; accepted for publication 2 December 1981)

In this tutorial article the physical ideas underlying general relativity theory are discussed and the basic mathematical techniques (tensor calculus, Riemann curvature) needed to describe them are developed. The general relativity field equations are presented and are used in several applications including a discussion of black holes.

I. INTRODUCTION

A. Purpose and outline

Special relativity theory (SRT) is a part of the intellectual toolbox of all physicists and a feature of the physicist's education even at the undergraduate level. The novel concepts of SRT, so shocking in 1905, hold no special terror now. The same, regrettably, cannot be said for the general relativity theory (GRT), Einstein's relativistic theory of gravity. The imagery of space-time curvature, and such exotica as black holes, give GRT such a recondite aura that it is too often regarded as hopelessly mystical, even by students and teachers who accept quantum mechanics as a perfectly reasonable description of the world. It is my goal in this article to show that this viewpoint on GRT is unjustified, that relativistic gravity is intuitively accessible and that space-time curvature is a natural conceptual basis for it. More specifically this article presents the mathematical and

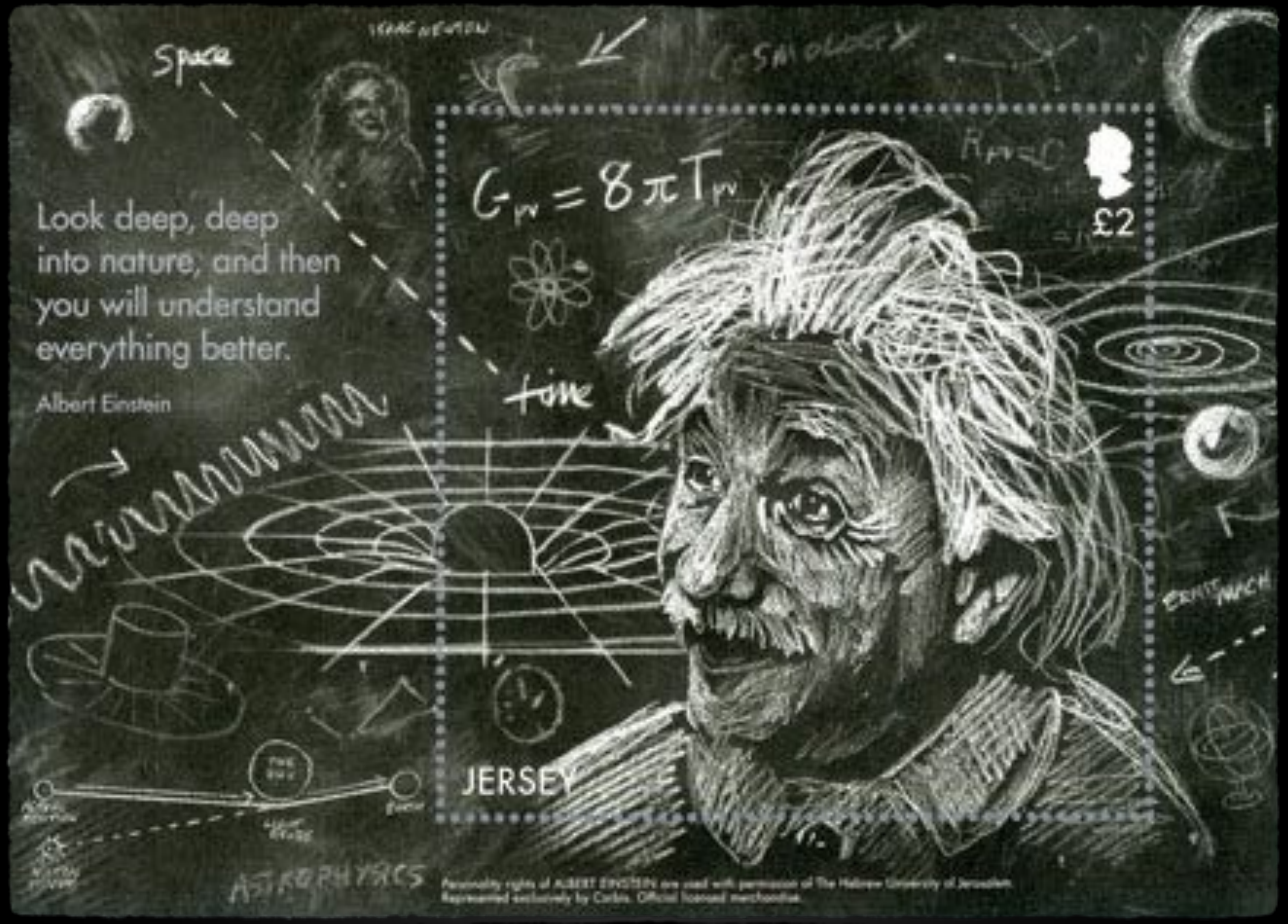
Clearly in a small article covering a large subject, sacrifices must be made. The most regrettable sacrifice will be the omission of all but a cursory discussion of the stress-energy tensor, the "source" of the gravitational field. Also omitted will be many mathematical details, some of them formal and elegant, some of them tricky and technical, some of them useful for reducing very difficult calculations to merely difficult ones. Missing too will be most of the applications of GRT to problems of current interest. A useful discussion is given, however, of that aspect of GRT that stimulates the most interest and confusion: black holes.

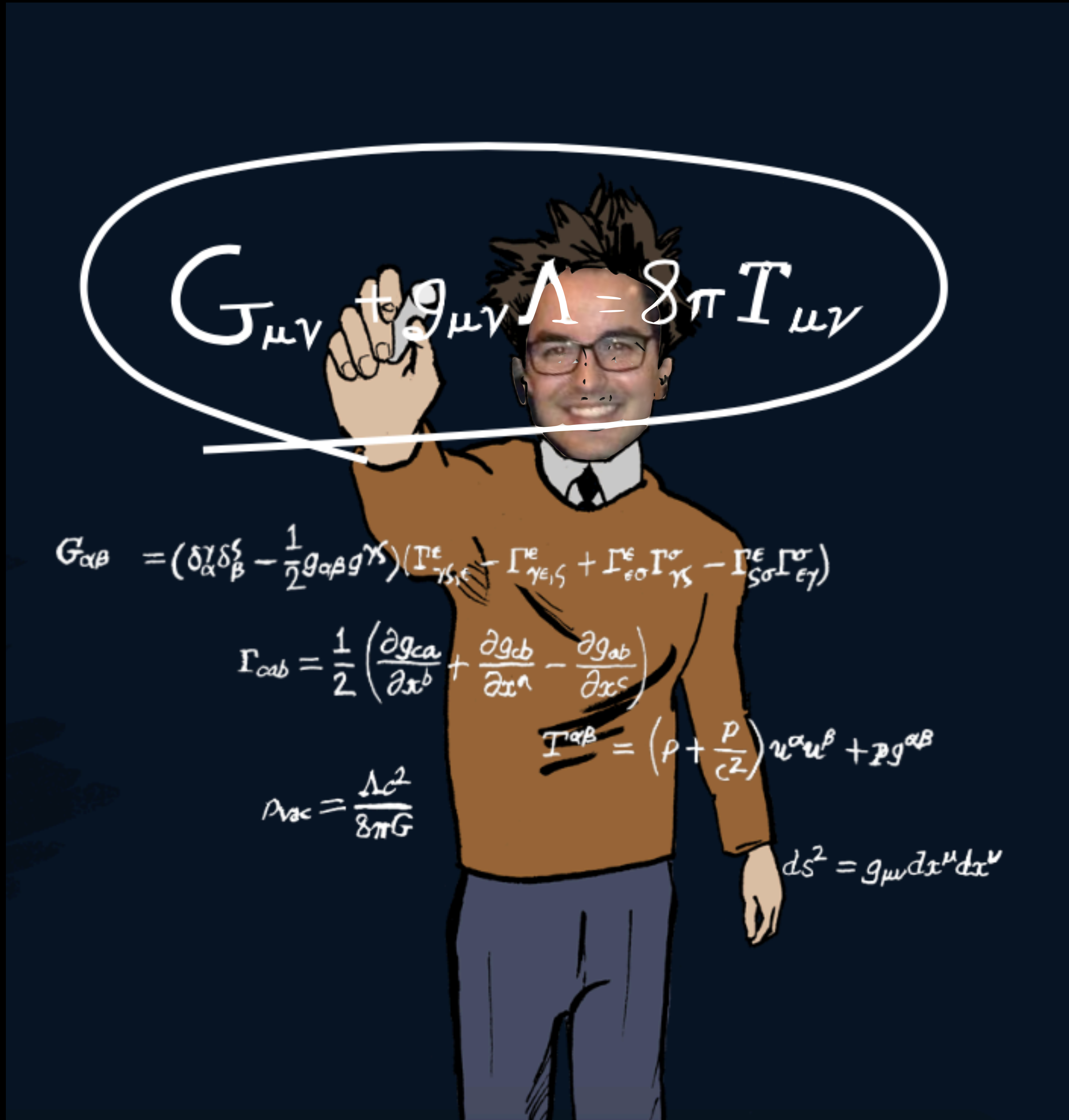
I assume that the reader comes to this article with two prerequisites: First, a familiarity is required with partial differential equations and their application in physics, as would certainly result from, say, a junior- or senior-level course in electrodynamics. Experience with partial differential equations will be necessary for an appreciation of the meaning of the GRT field equations; specific techniques

Nova disciplina graduação 2018/2

Relatividade geral e aplicações astrofísicas

AGA0319

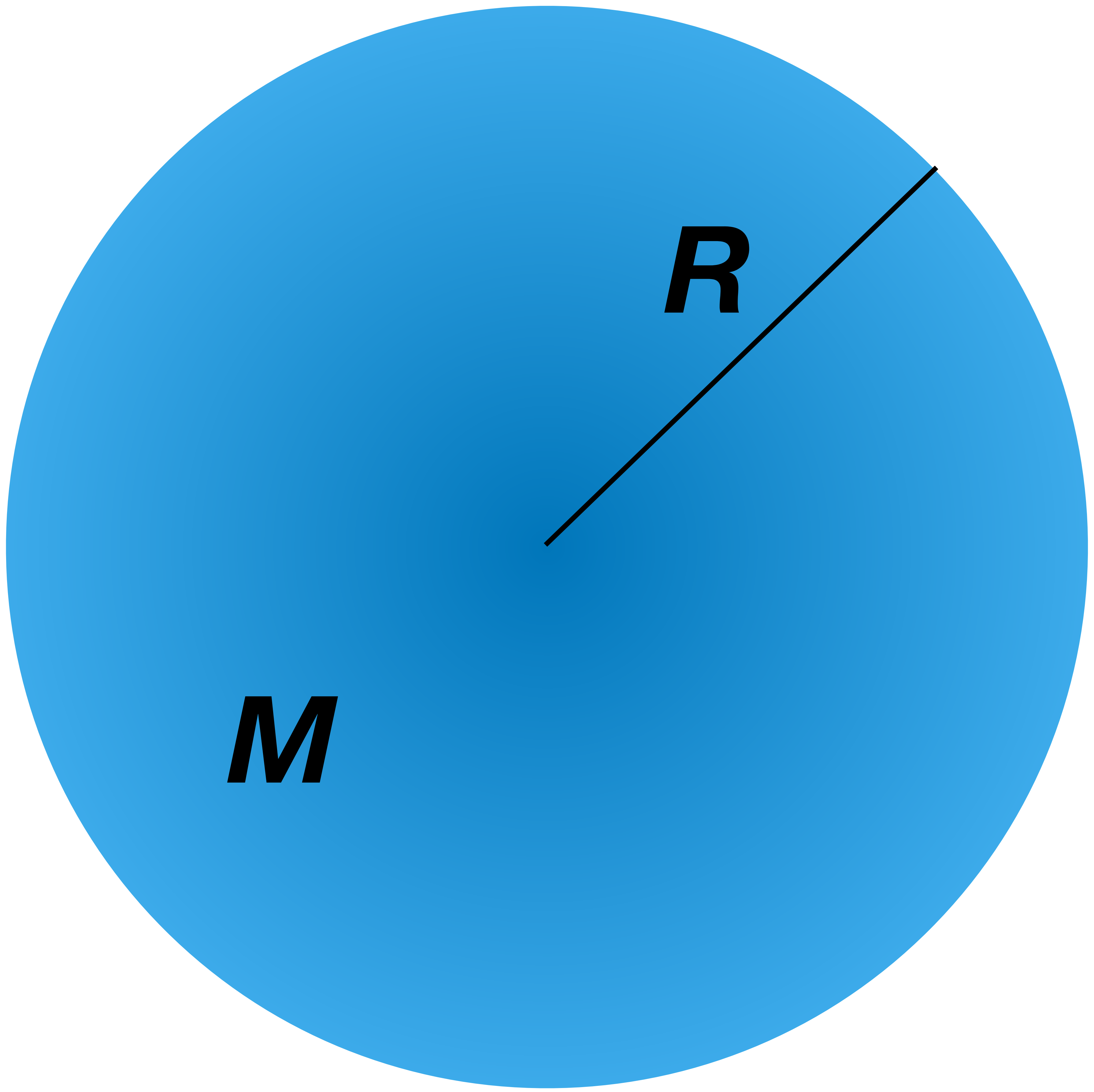




O que é um buraco negro?

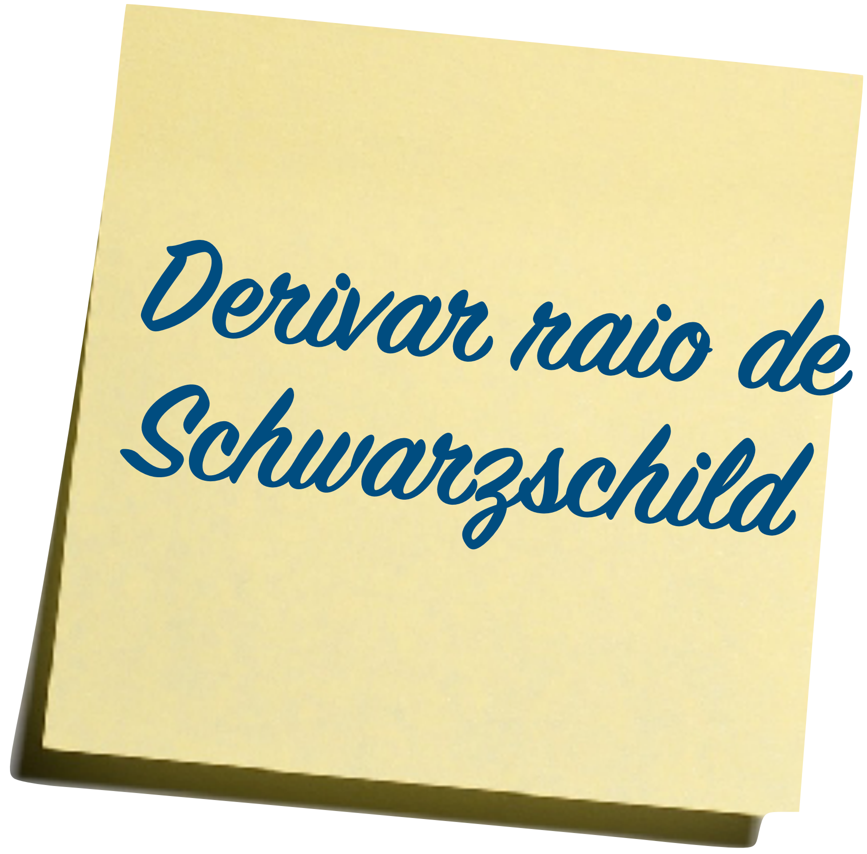
Definição: **Objeto com gravidade tão forte que nada consegue escapar, nem mesmo a luz**

Pergunta: Dada um objeto de massa *M*, qual o raio dentro do qual ele se torna um buraco negro?



$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}}$$

velocidade de escape na superfície

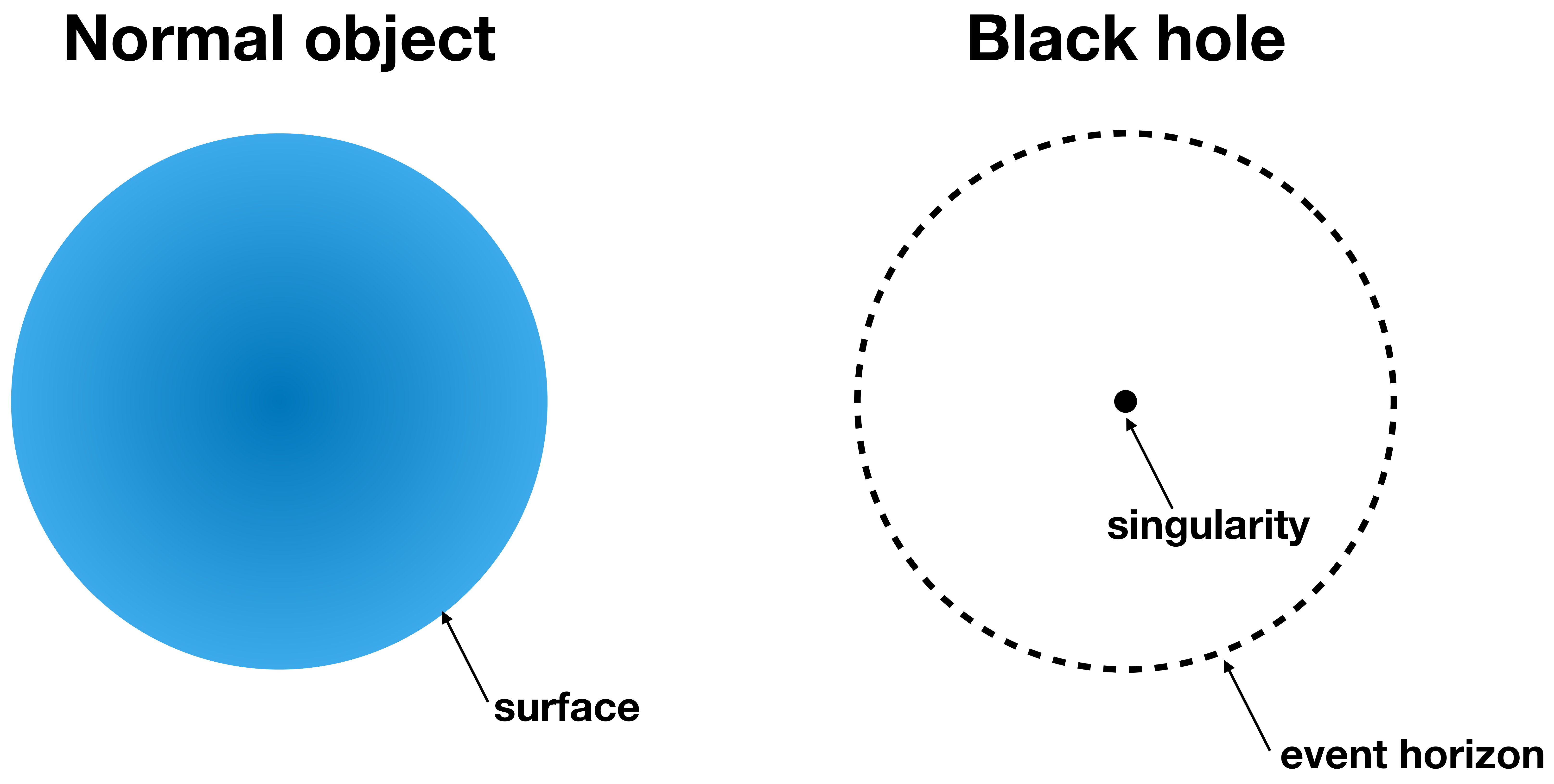


Raio de um buraco negro:

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

“raio de Schwarzschild”

What is a black hole? Remarkable prediction of general relativity



Event horizon: one-way membrane, matter/ energy can fall in, but nothing gets out

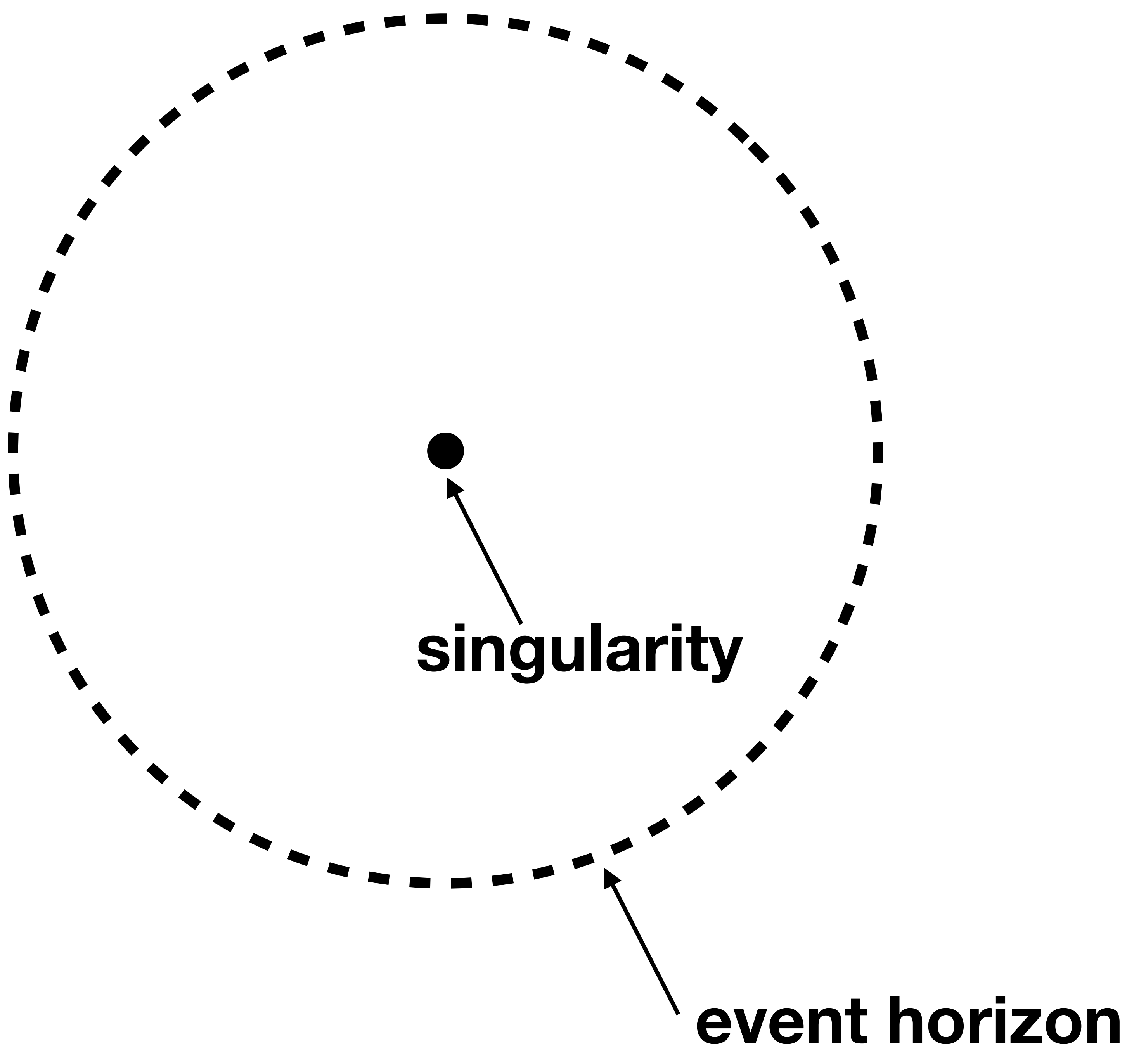
Region inside event horizon causally cut-off from outside

Radius of event horizon:

$$R_S = \frac{2GM}{c^2} = 2.95 \left(\frac{M}{M_\odot} \right) \text{ km}$$

Schwarzschild radius

Black hole



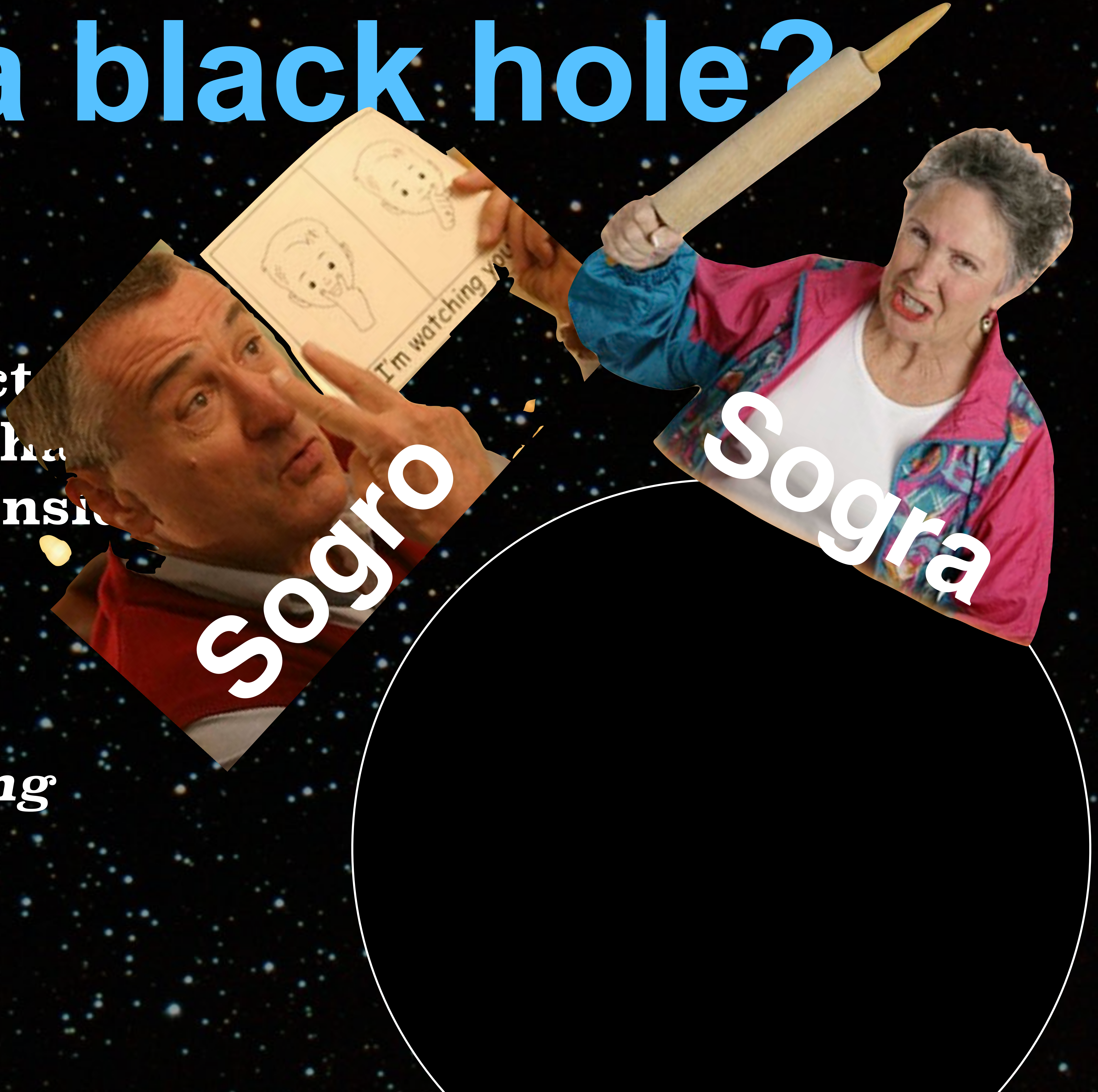
What is a black h

Massive, compact astronomical object: gravity so strong that it traps all that fall inside the event horizon

Once inside, nothing escapes

What is a black hole?

Massive, compact astronomical object gravity so strong th traps all that fall insi the event horizon



Once inside, nothing escapes

What is a black hole?

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What is a black hole?

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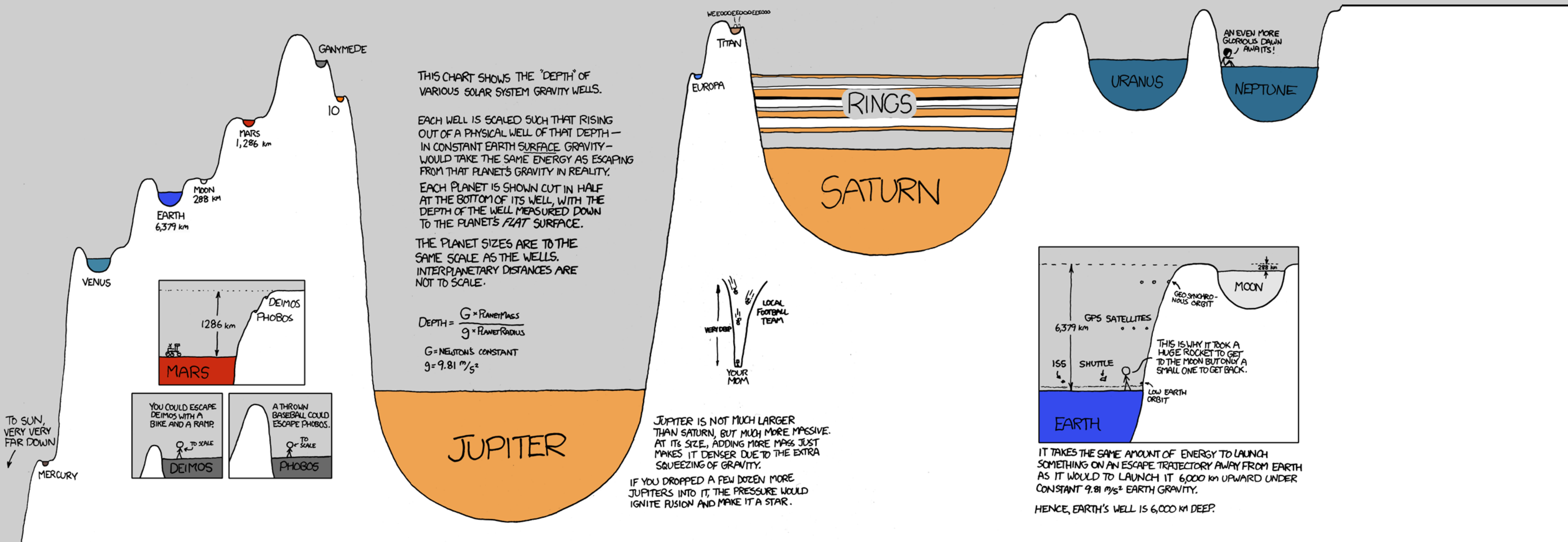
Once inside, nothing escapes

GRAVITY WELLS

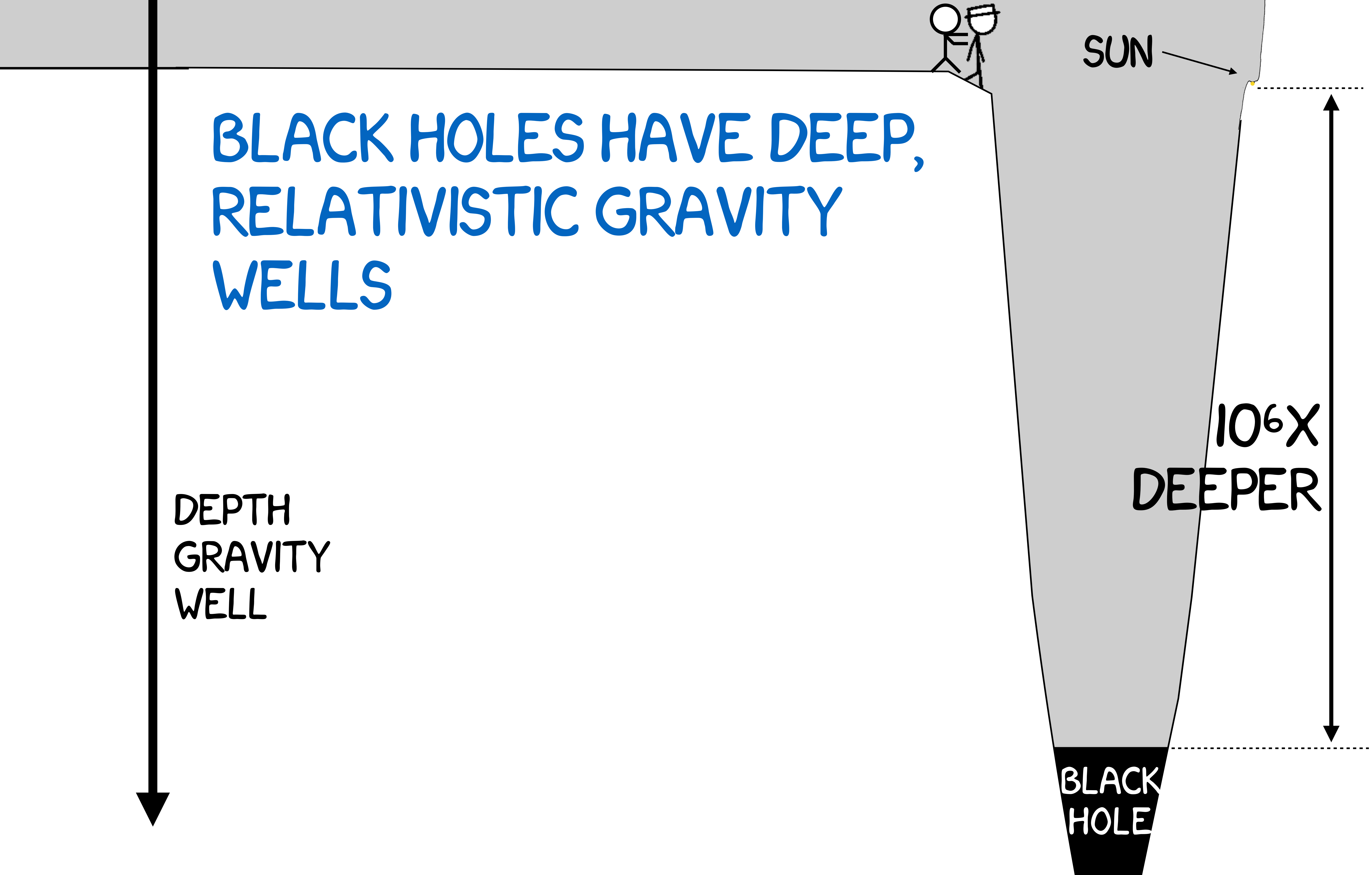
SCALED TO EARTH SURFACE GRAVITY

https://xkcd.com/681/




GRAVITY WELLS
SCALED TO EARTH SURFACE GRAVITY
THIS CHART SHOWS THE "DEPTH" OF VARIOUS SOLAR SYSTEM GRAVITY WELLS.
EACH WELL IS SCALED SUCH THAT RISING OUT OF A PHYSICAL WELL OF THAT DEPTH — IN CONSTANT EARTH SURFACE GRAVITY — WOULD TAKE THE SAME ENERGY AS ESCAPING FROM THAT PLANET'S GRAVITY IN REALITY.
EACH PLANET IS SHOWN CUT IN HALF AT THE BOTTOM OF ITS WELL, WITH THE DEPTH OF THE WELL MEASURED DOWN TO THE PLANET'S FLAT SURFACE.
THE PLANET SIZES ARE TO THE SAME SCALE AS THE WELLS. INTERPLANETARY DISTANCES ARE NOT TO SCALE.
DEPTH = G × PLANET MASS / g × PLANET RADIUS
G = NEWTON'S CONSTANT
g = 9.81 m/s²
TO SUN, FAR DOWN
MERCURY
VENUS
EARTH 6,379 KM
MOON 288 KM
MARS 1,286 km
GANYMEDE
IO
JUPITER
EUROPA
TITAN
WEEOOOEEOOOEEEOOO


DEPTH
GRAVITY
WELL
TO BLACK
HOLE, VERY
VERY FAR
DOWN
MERCURY
100X
DEEPER
SUN
RADII OF OBJECTS NOT TO SCALE


BLACK HOLES HAVE DEEP, RELATIVISTIC GRAVITY WELLS
SUN
10⁶X DEEPER
BLACK HOLE
DEPTH
GRAVITY
WELL

Classical vs quantum black holes

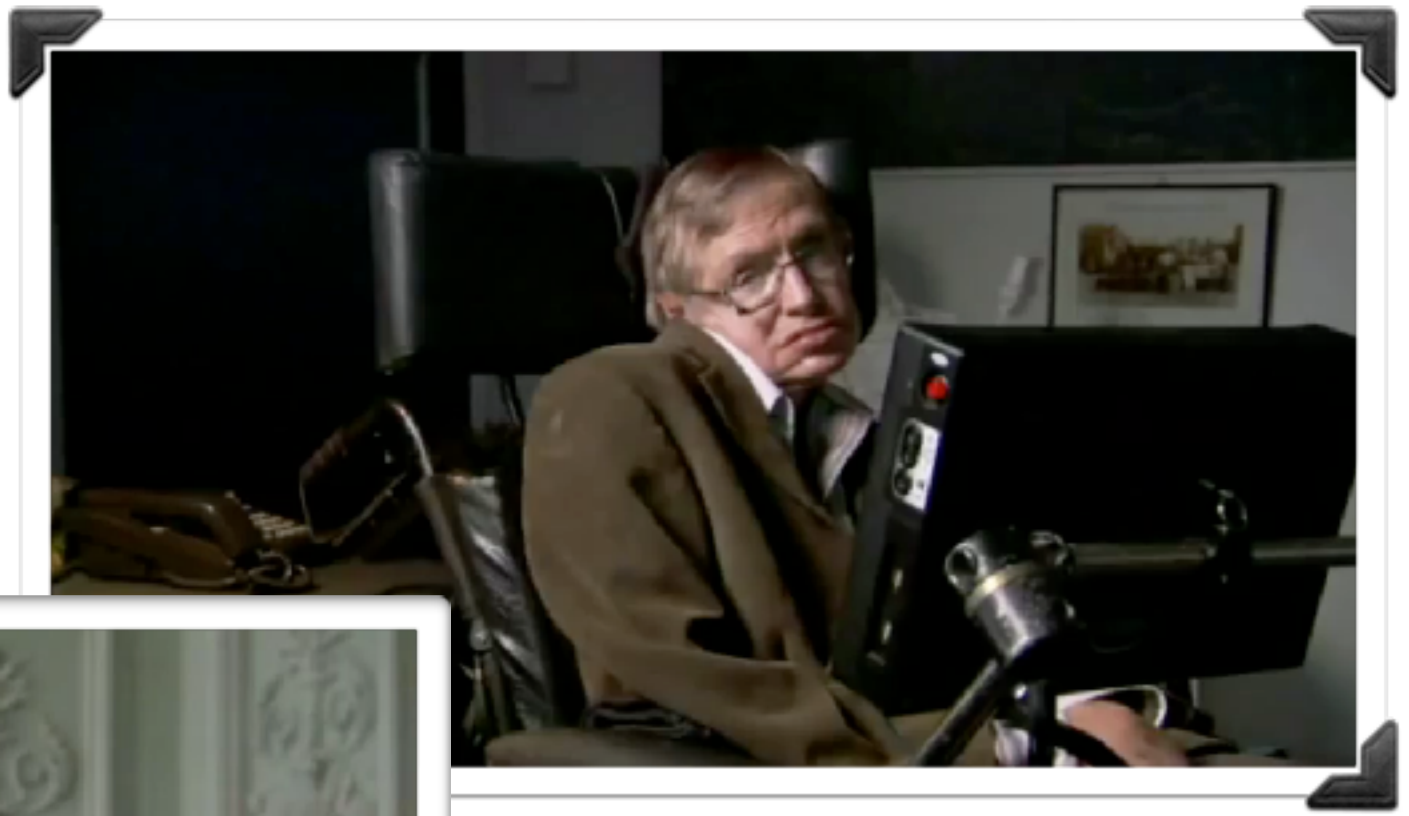
Black holes from general relativity are classical objects

Quantum BHs: need quantum gravity theory

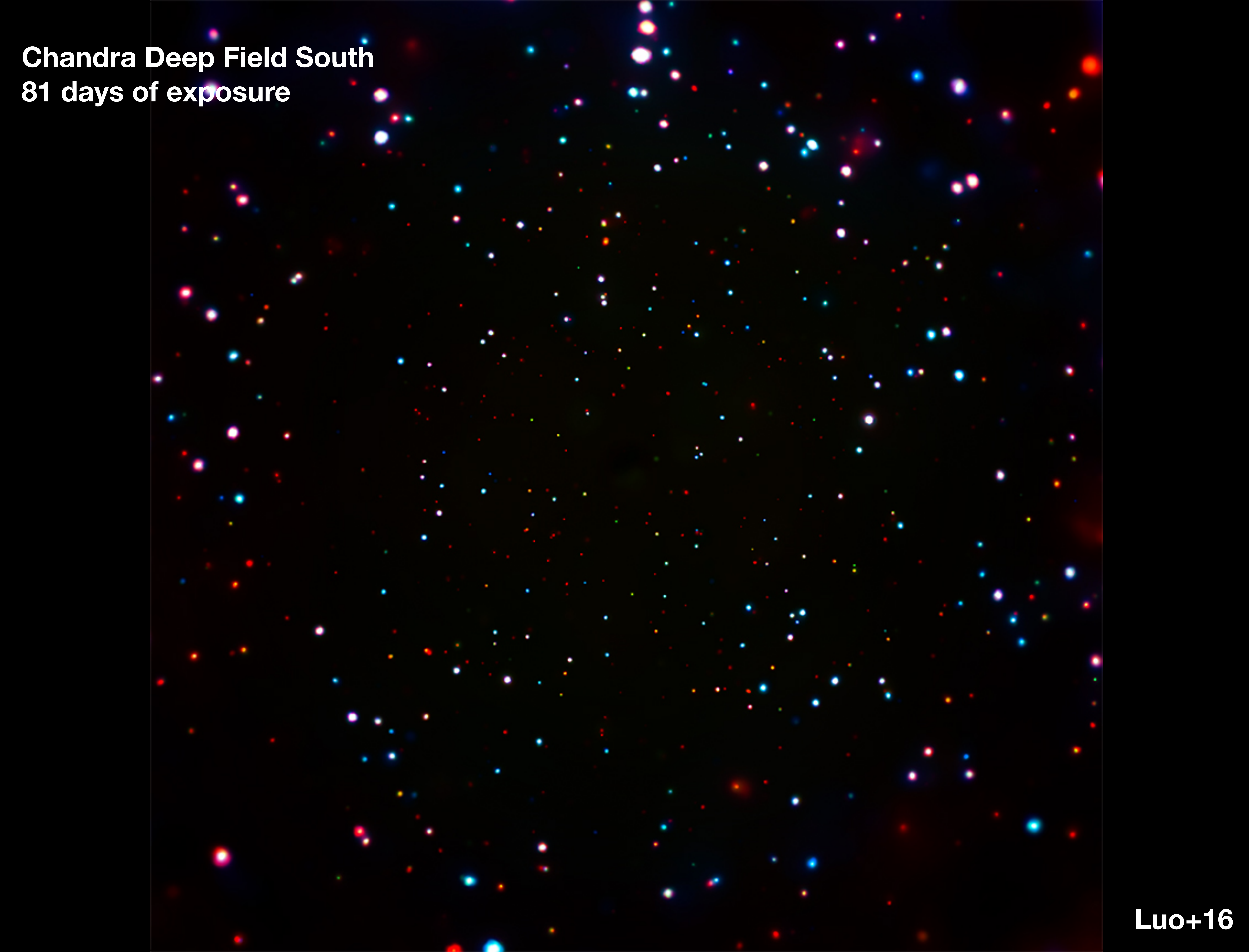
Quantum BHs have weird properties:

- **Hawking radiation**
- **Information paradox**

Will not talk about them



Credit: BBC


Chandra Deep Field South
81 days of exposure
Luo+16

How massive can a black hole be?

BHs with $M \gtrsim 3\, M_{sun}$ form naturally by gravitational collapse of massive stars

No other stable equilibrium available at these masses

<u>Open question:</u>
Do quantum BHs form naturally?

Two populations of black holes

Supermassive

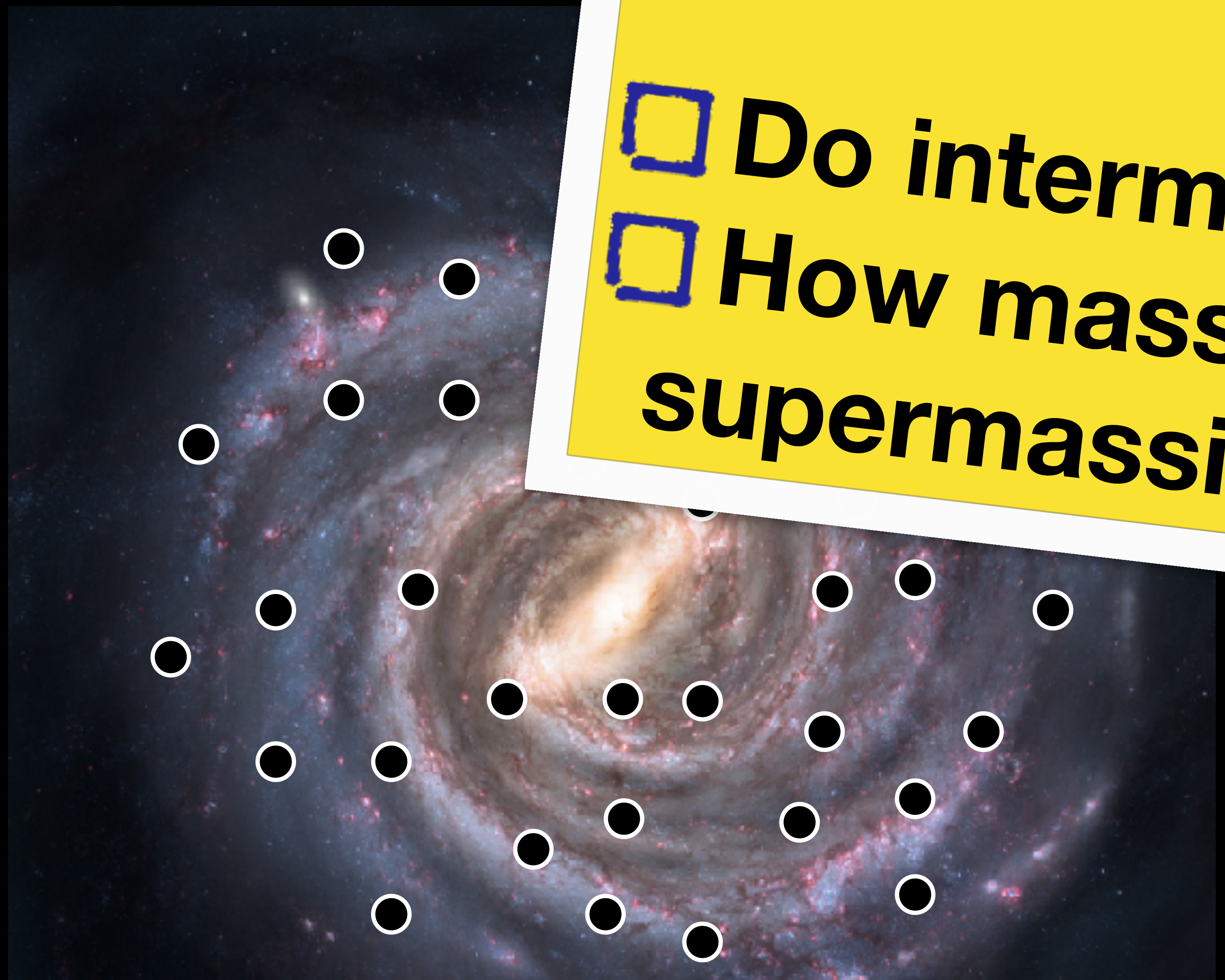
10^6-10^{10} solar masses

one in every galactic nucleus

Stellar

5-60 solar masses

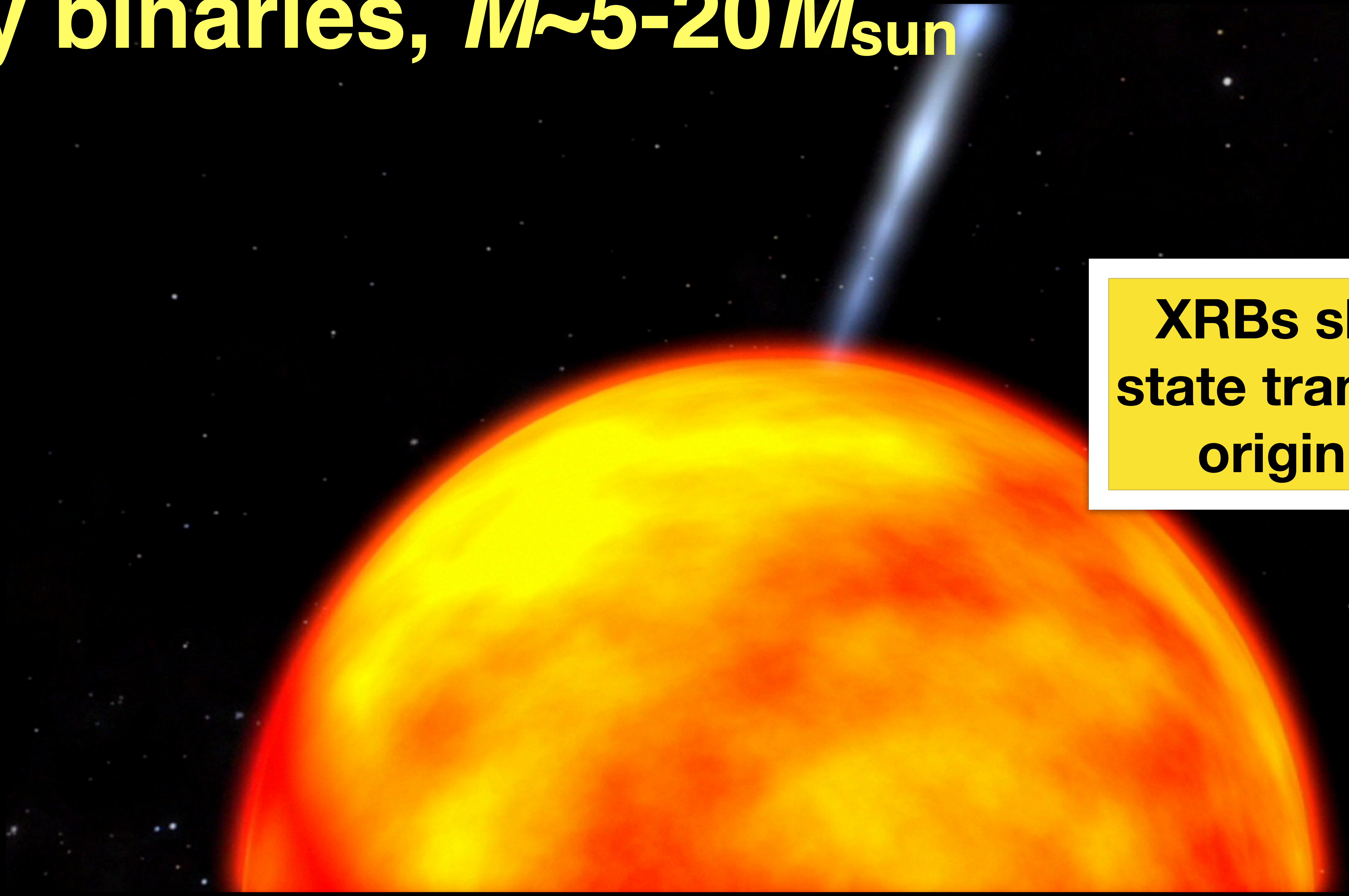
~10^7 per galaxy



Open question:

- ☐ **Do intermediate-mass BHs exist?**
- ☐ **How massive are the initial seeds of supermassive BHs?**

X-ray binaries, $M \sim 5\text{-}20\,M_{sun}$

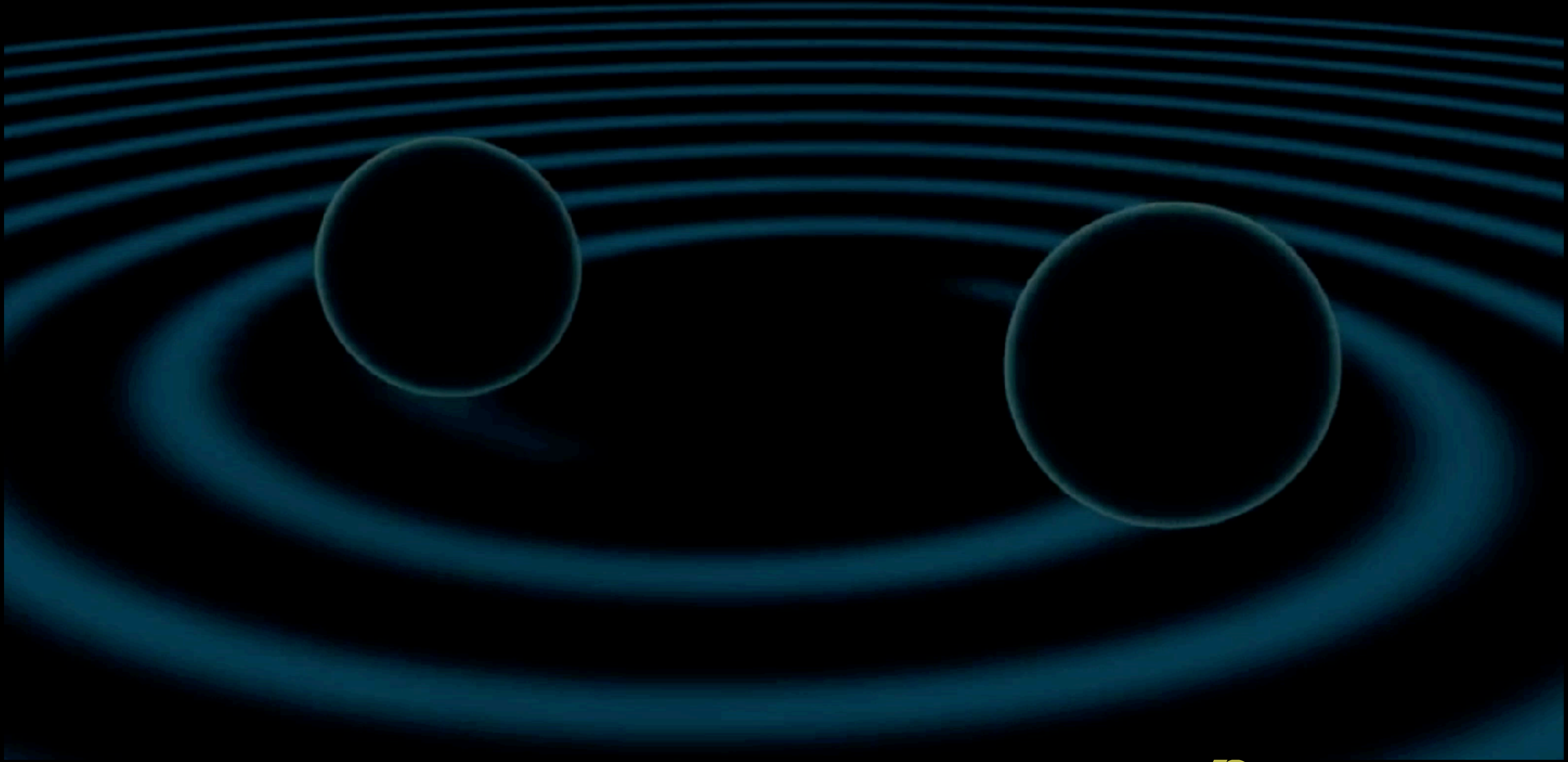


XRBs show dramatic state transitions, whose origin is unknown

10^7 XRBs per galaxy

Credit: NASA GSFC; Britannica

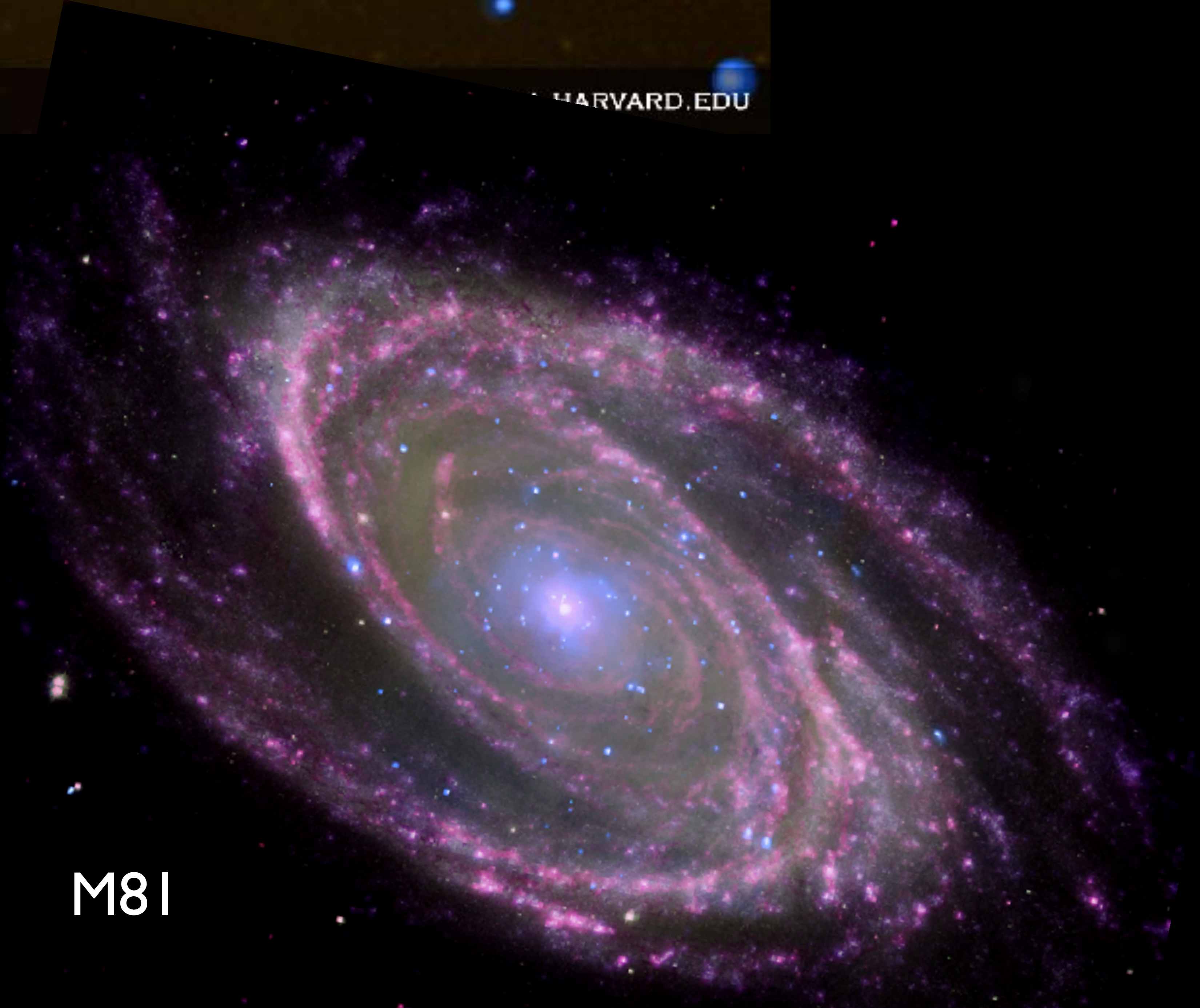
GW150914: M~20-60 M_{sun}

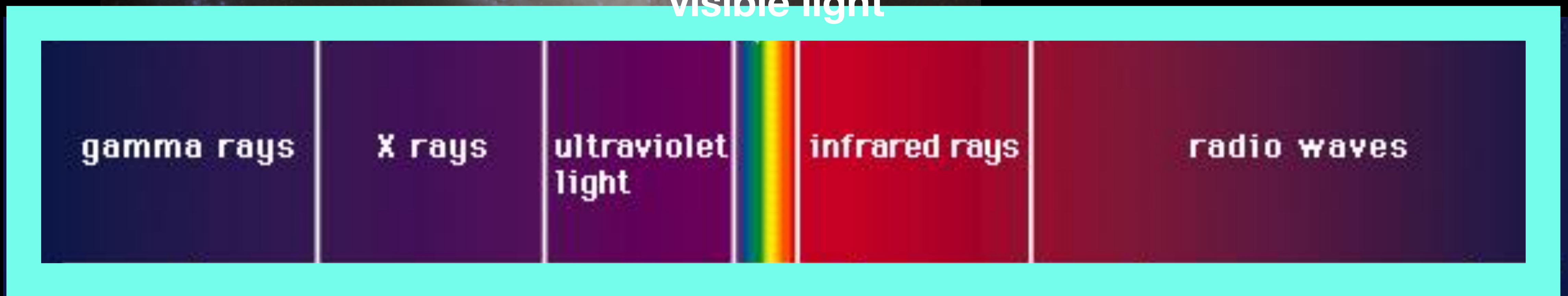


Credit: NASA GSFC; Britannica

Supermassive BHs have M~10^6-10^{10} M_{sun}, one in every galactic nuclei

Do dwarf galaxies host supermassive BHs?





Credit: NASA, HST, CXC

How do we know they are black holes?

Criteria used to identify astrophysical BHs

- Must be compact: radius < few R_s
- Must be massive: M > several M_{sun}, too massive to be a neutron star ($M_{ns,crit} \lesssim M_{sun}$)

These are strong reasons for BH candidates

It is possible to empirically prove the existence of event horizons

Prove that BHs have event horizons (soon: Event Horizon Telescope)

Black holes are the most perfect macroscopic objects in the universe

Made only of spacetime warpage

Mass *M*

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

Spin: angular momentum *J*

$$J = a\, GM^2/c$$

$$0 \leq |a| \leq 1$$

~~**Charge *Q***~~

A black hole has no-hair (no-hair theorem)

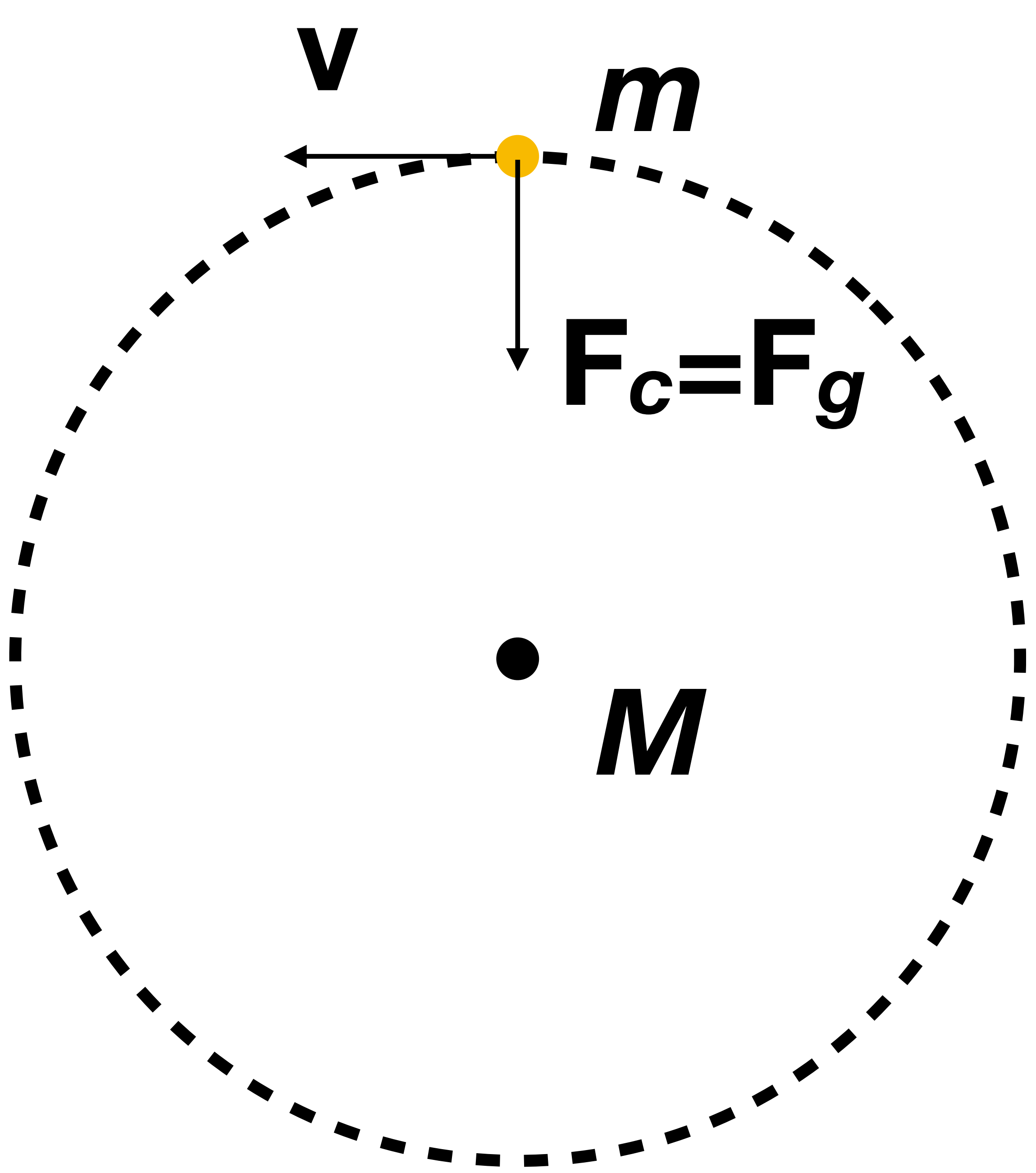
Measuring mass in astronomy

Best mass estimates are *dynamical*

Test particle in circular orbit

$$F_g = F_c \Rightarrow \frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$\Rightarrow \boxed{M = \frac{v^2 r}{G}}$$



Alternatively, Kepler's third law

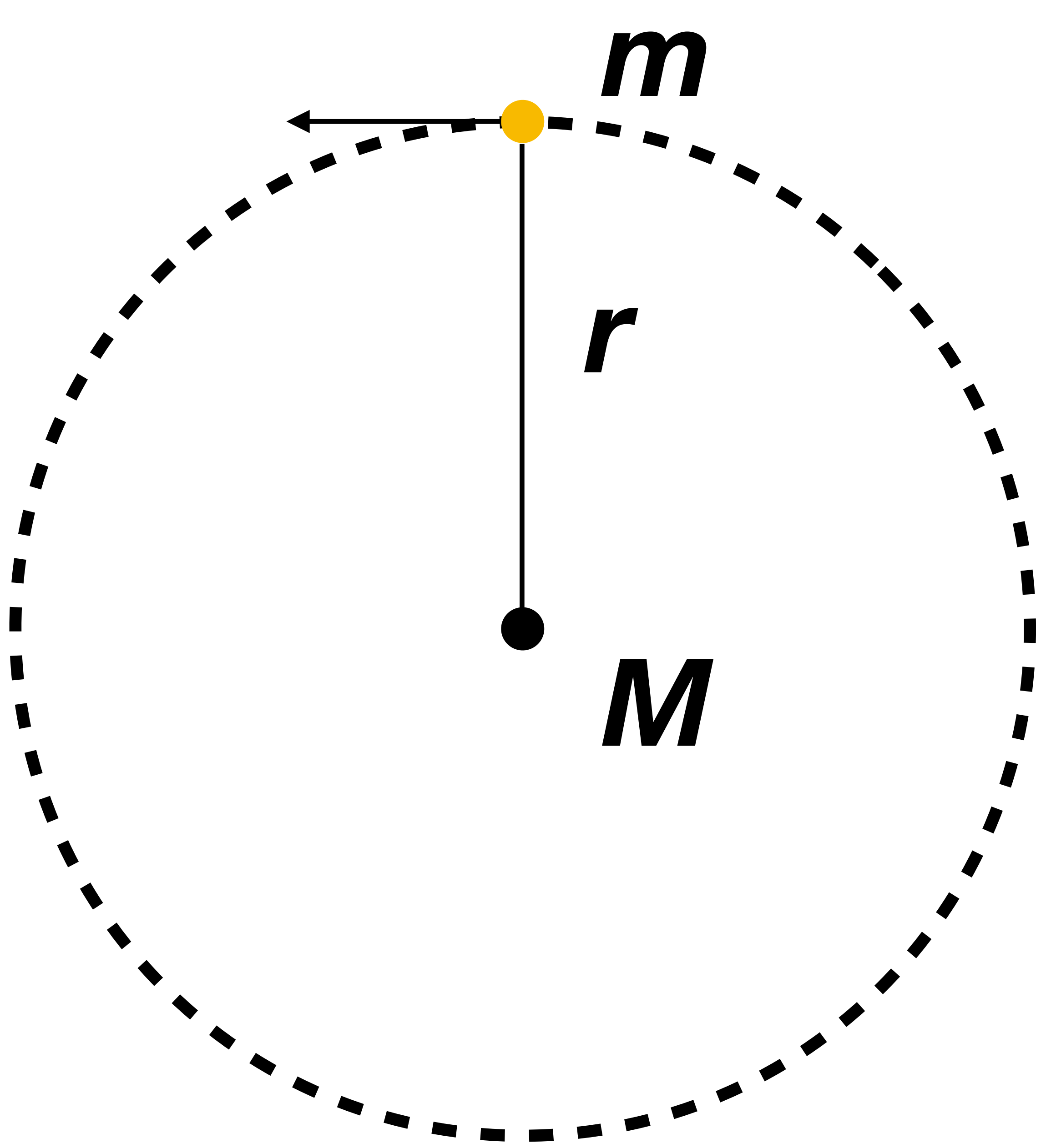
$$\frac{P^2}{r^3} = \frac{4\pi^2}{G(M+m)} \Rightarrow \boxed{M \approx \frac{4\pi^2 r^3}{GP^2}}$$

Exercise

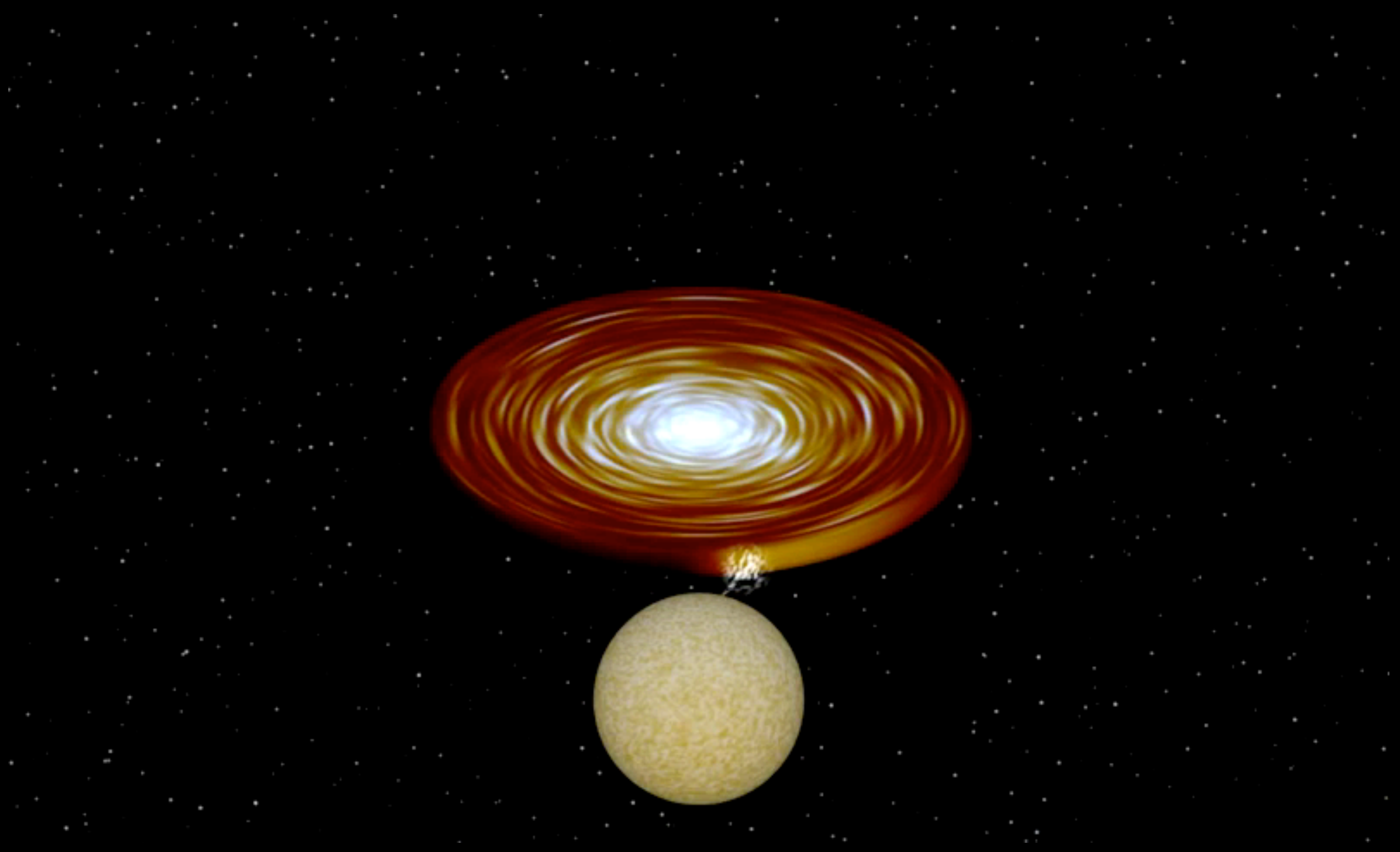
Suppose a star is measured in a circular orbit with *P*=15 years and *r*=1000 au. Compute *M*.

$$M \approx \frac{4\pi^2 r^3}{GP^2}$$

Kepler's third law

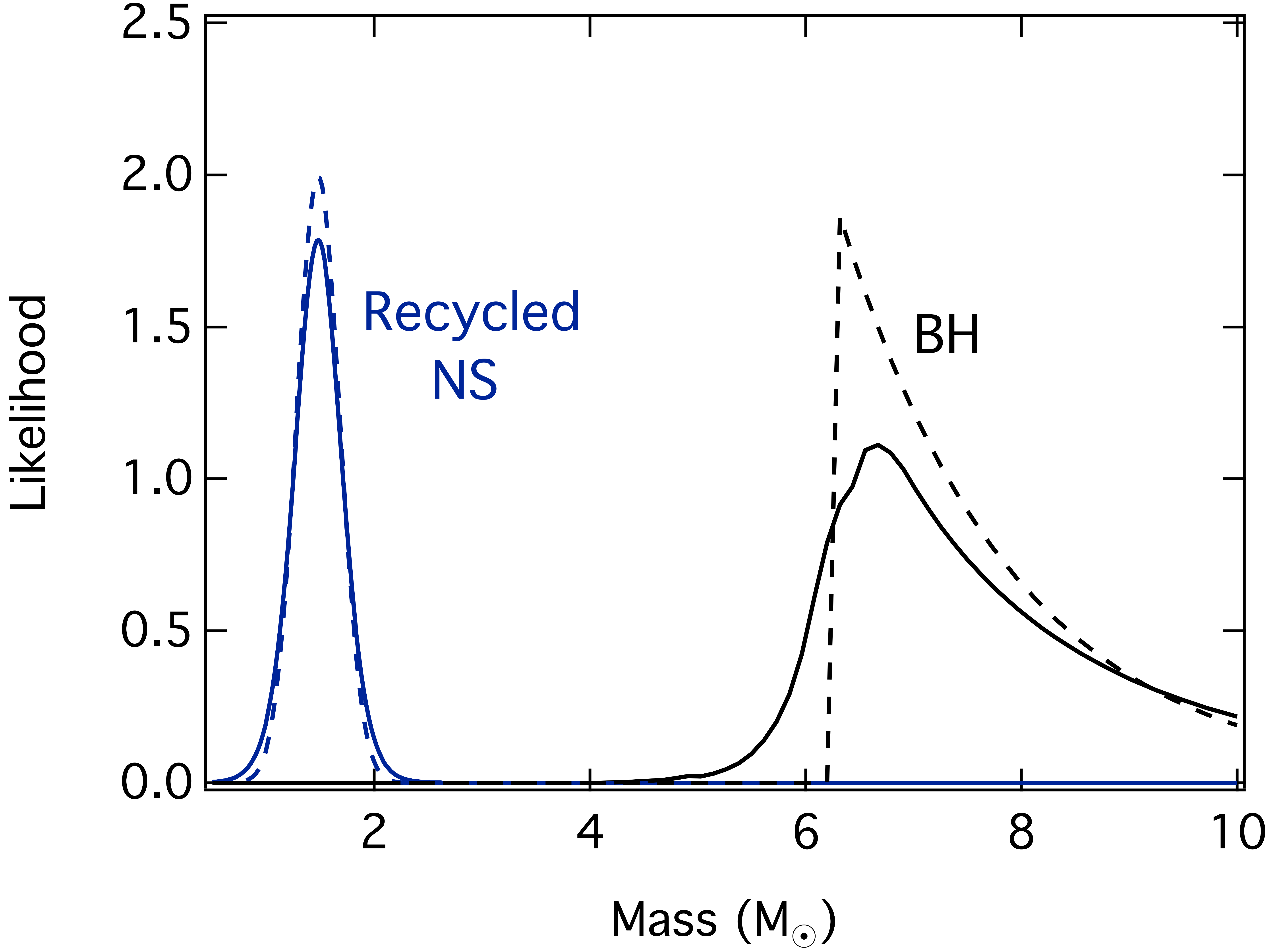


1 au = 1.5E11 m
G = 6.67E-11 N m^2/kg^2
M_{sun} = 2E30 kg



Credit: unknown

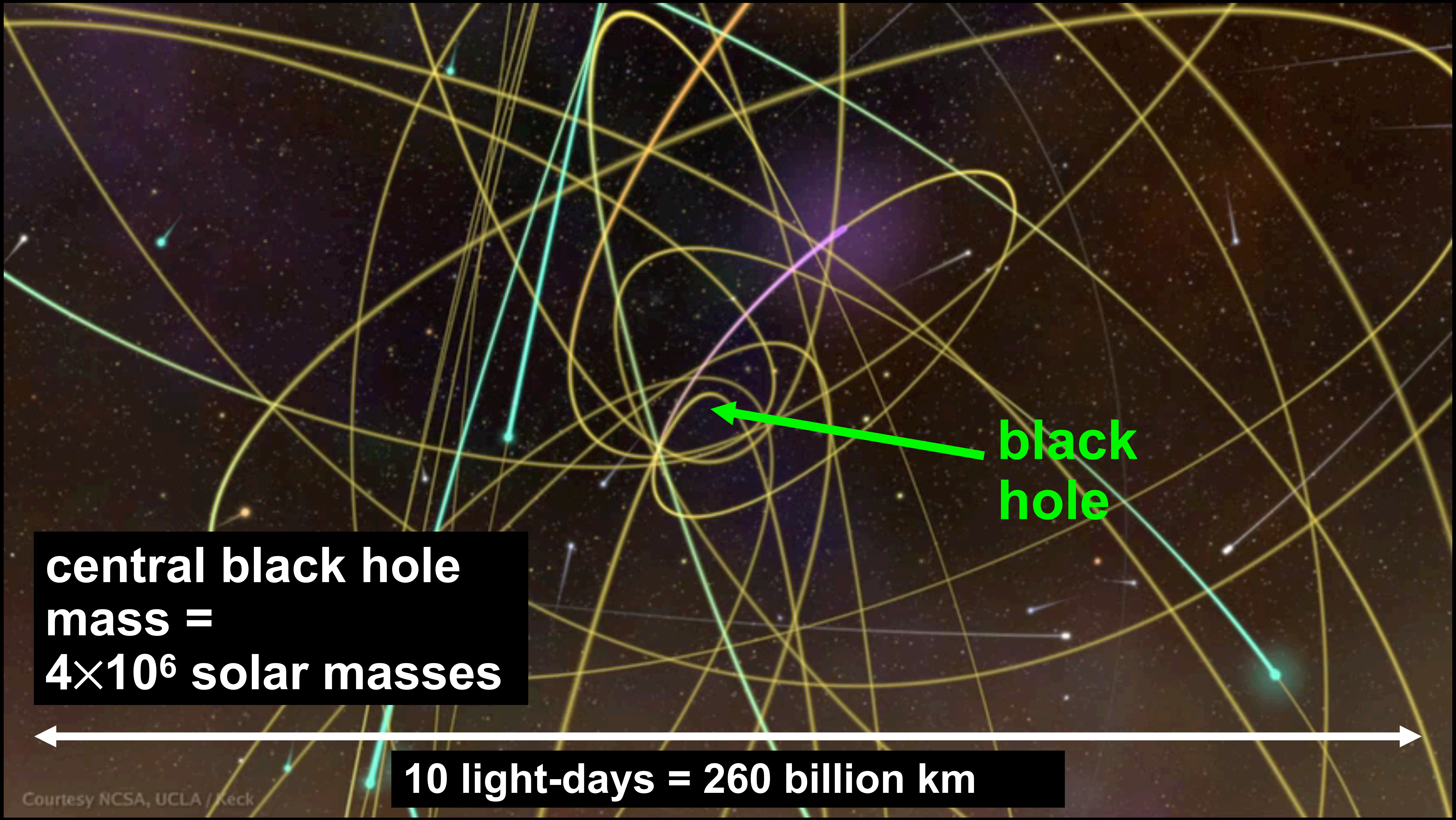
Distribution of masses of neutron stars and stellar mass black holes



Özel+12


Sagitário A*
Massa = 4×10^6 M_{Sun}
Sistema
Solar

Journey to Sagittarius A*: the supermassive black hole at the center of the Milky Way



Ghez, Schödel, Genzel et al.

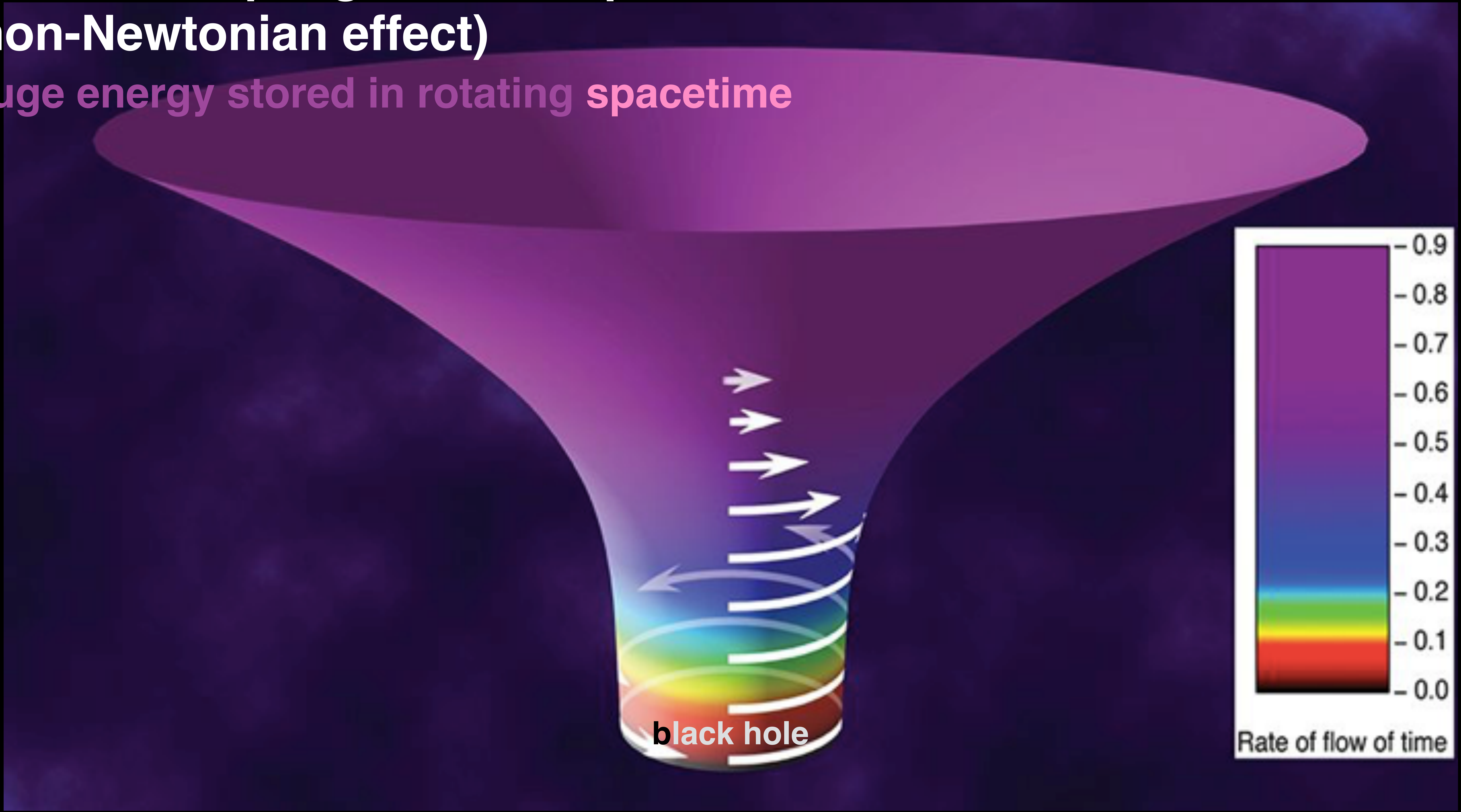
How to measure black hole spin?

$$J = \frac{aGM^2}{c}$$

$$0 \leq |a| \leq 1$$

Black hole spin generates spacetime whirlwind (non-Newtonian effect)

Huge energy stored in rotating spacetime



Credit: Thorne

How to reliably measure black hole spin?

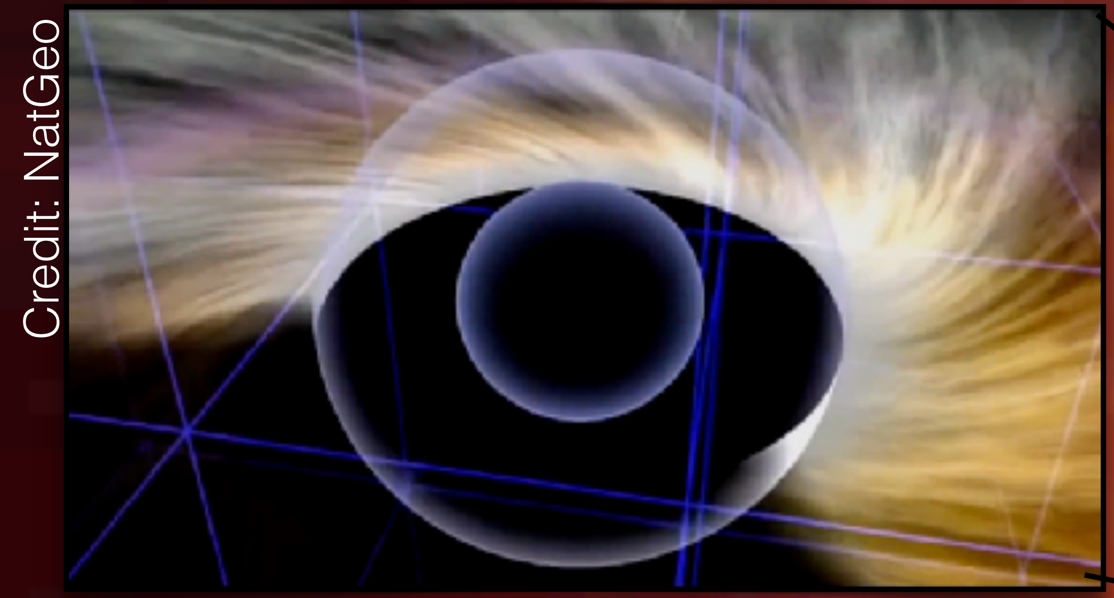
https://www.youtube.com/watch?v=9MHuhcFQsBg

How do we observe black holes?

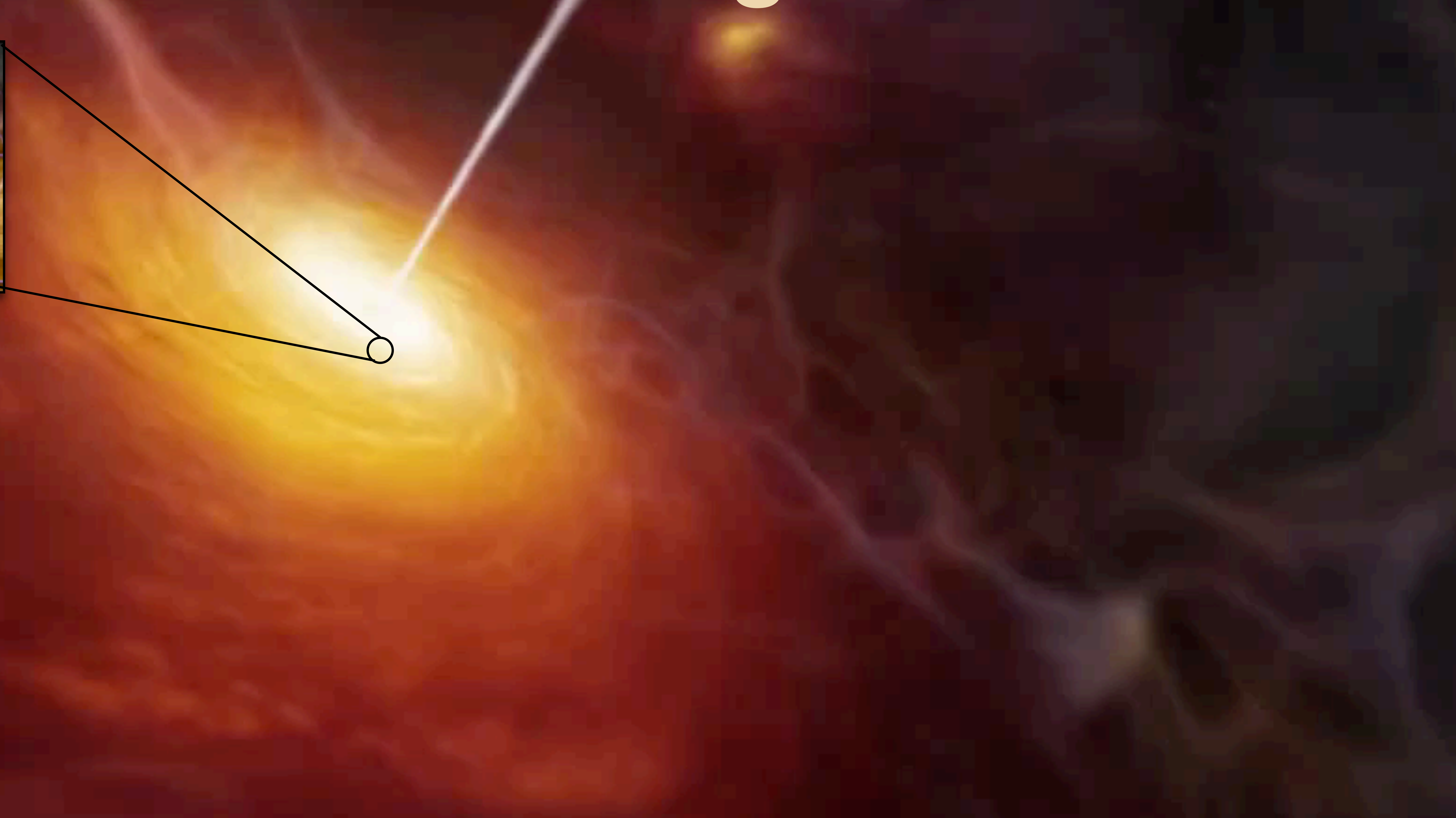

30
Just Jared


S.C. CORINTHIANS PAULISTA
1910

Black holes surrounded by accretion disks, release enormous amounts of light

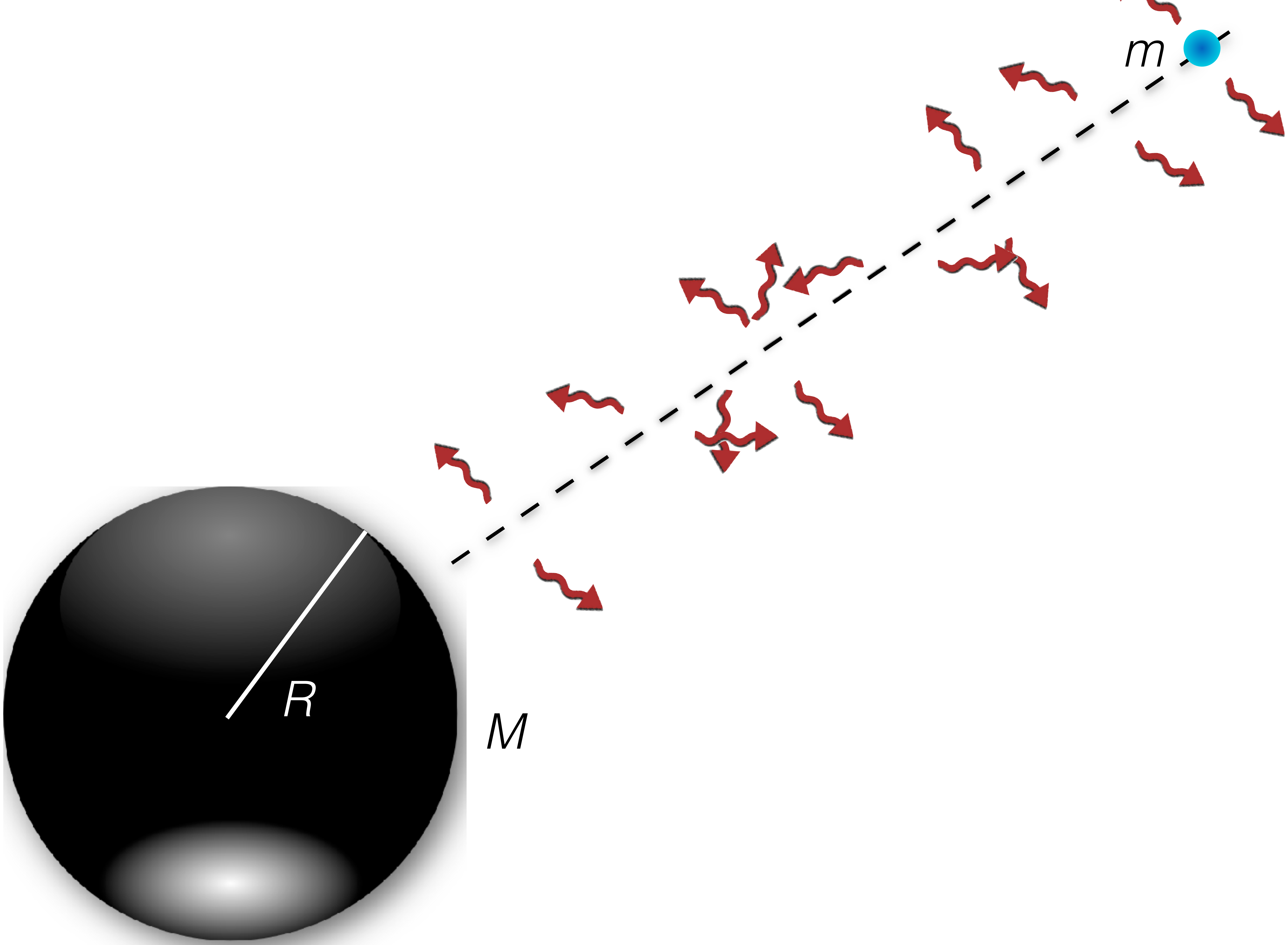


$v \rightarrow c$ **near the horizon**



How efficient is the release of light?

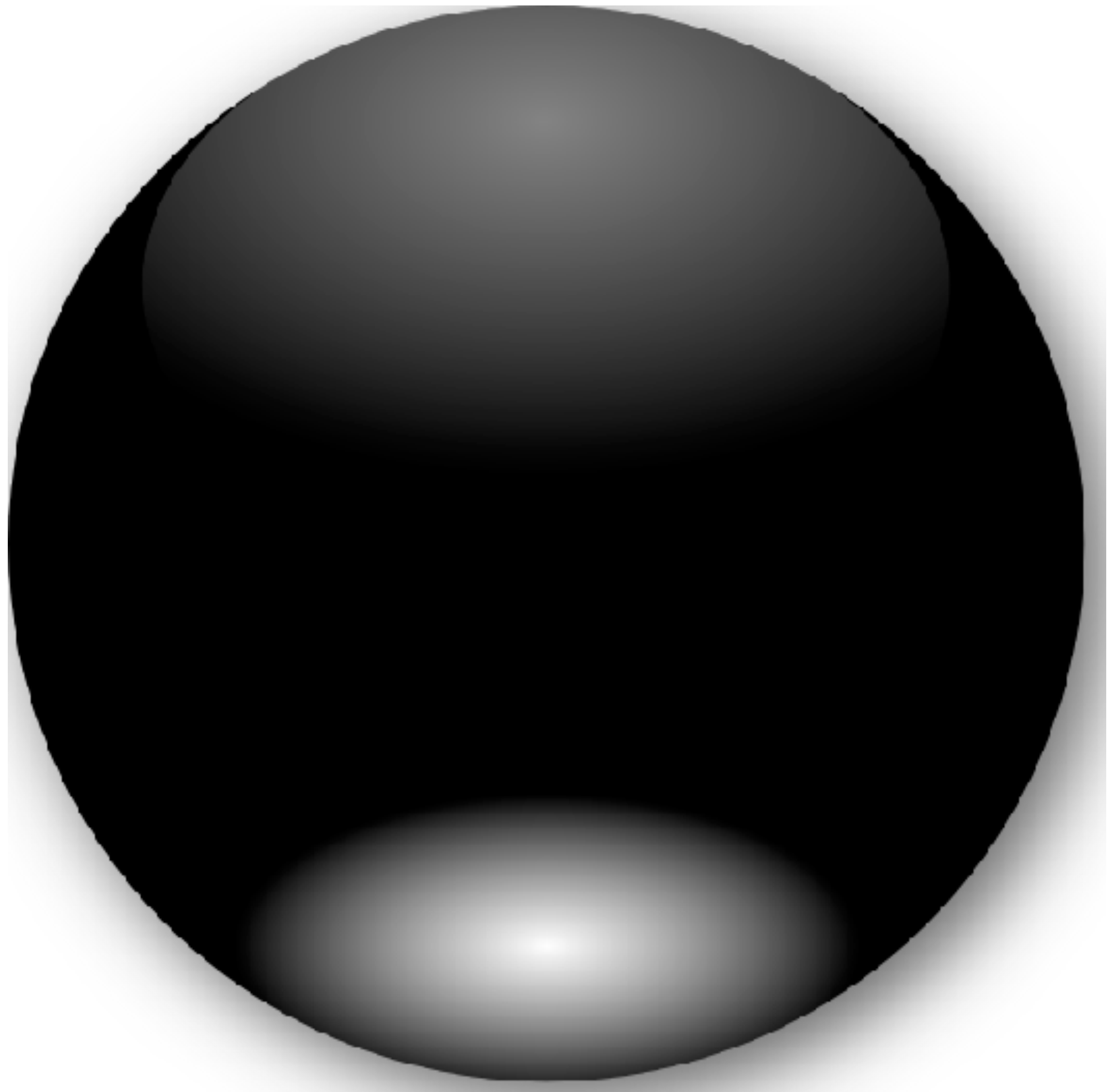
Credit: ESO


m
R
M

Energy released: $$U = \frac{GMm}{R}$$

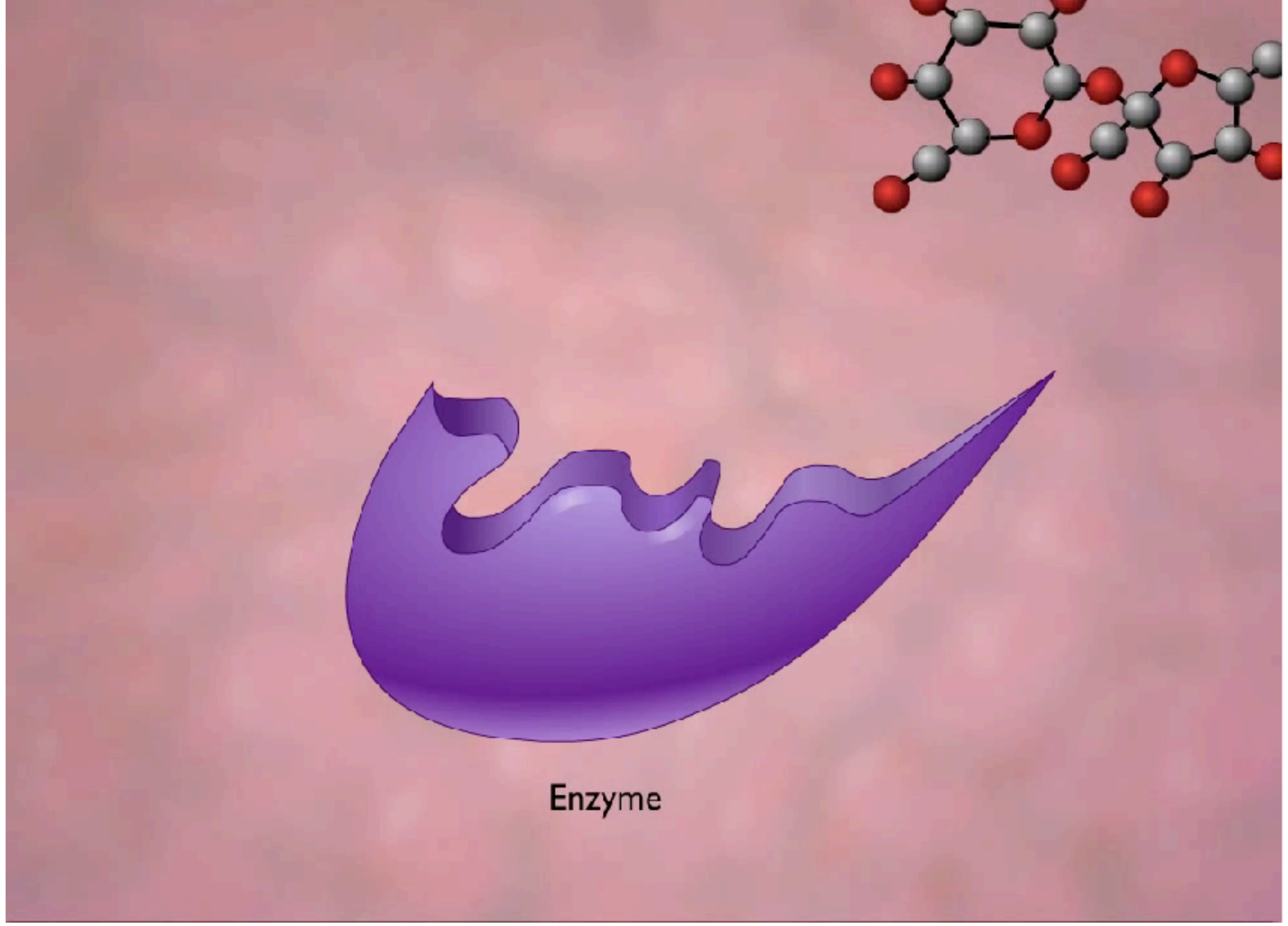
Luminosity: $$L = \dot{U} = \frac{GM\dot{m}}{R} \Rightarrow L = \eta \dot{m} c^2$$

Radiative efficiency: $$\boxed{\eta \propto M/R}$$



For black holes: $\eta \sim$ 10-40%

Sugar (sucrose) $C_{12}H_{22}O_{11}$



1g → 4 kcal= 16.2 kJ = 1e23 eV

$$\eta = \frac{E}{mc^2} = \frac{1.6 \times 10^{11} \text{erg}}{9 \times 10^{20} \text{erg}} = 2 \times 10^{-10}$$

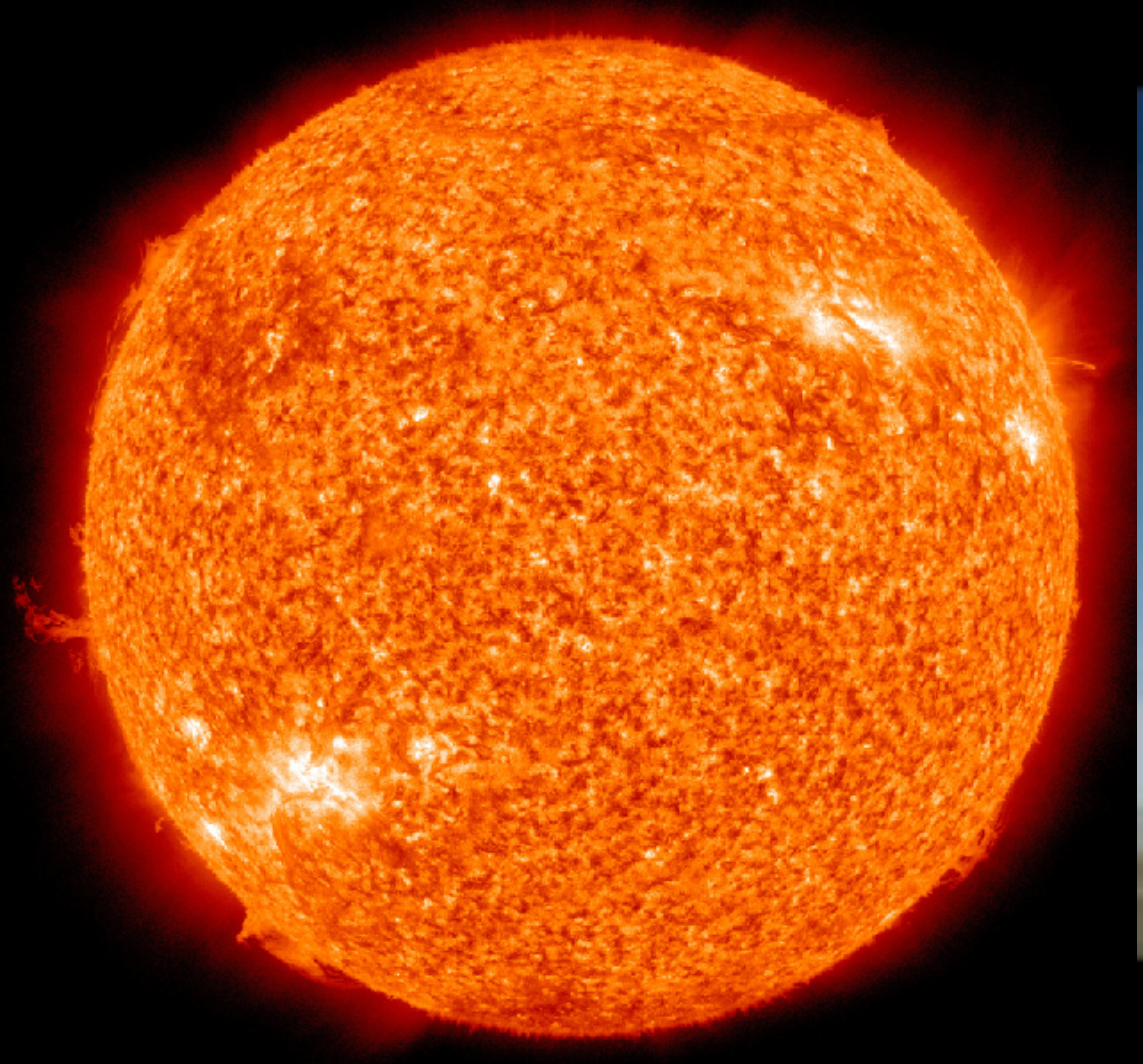
R. Nemmen

Itaipu Dam – 14 GW

$$\eta = \frac{mgh}{mc^2} = 10^{-14}\left(\frac{h}{100\ \mathrm{m}}\right)$$

$$\eta = \frac{mv^2}{2mc^2} \sim 10^{-14} \left(\frac{v}{200\ \mathrm{km/h}} \right)^2$$

Nuclear fusion



$$\eta = 0.008 \times 0.1 \sim 8 \times 10^{-4}$$

Black holes surrounded by accretion disks, release enormous amounts of light

Most efficient radiators in the universe

Radiative efficiency:

$$\eta_{\rm rad} = \frac{E_{\rm out}^{\rm rad}}{E_{\rm in}^{\rm gas}} = 10 - 40\%$$

100x more efficient than nuclear fusion!

Radiate across all eletromagnetic spectrum!

Credit: ESO

Back-of-the-envelope estimate of accretion disk luminosity

$L \sim 10^{10} L_{sun}$
$\sim 1\, M_{Earth}\, c^2$
every 3 hours

$$M = 10^8 M_\odot$$
BLACK HOLE MASS

$$m = 1 M_\odot$$
MASS SUPPLY TO BLACK HOLE

FREE-FALL TIMESCALE

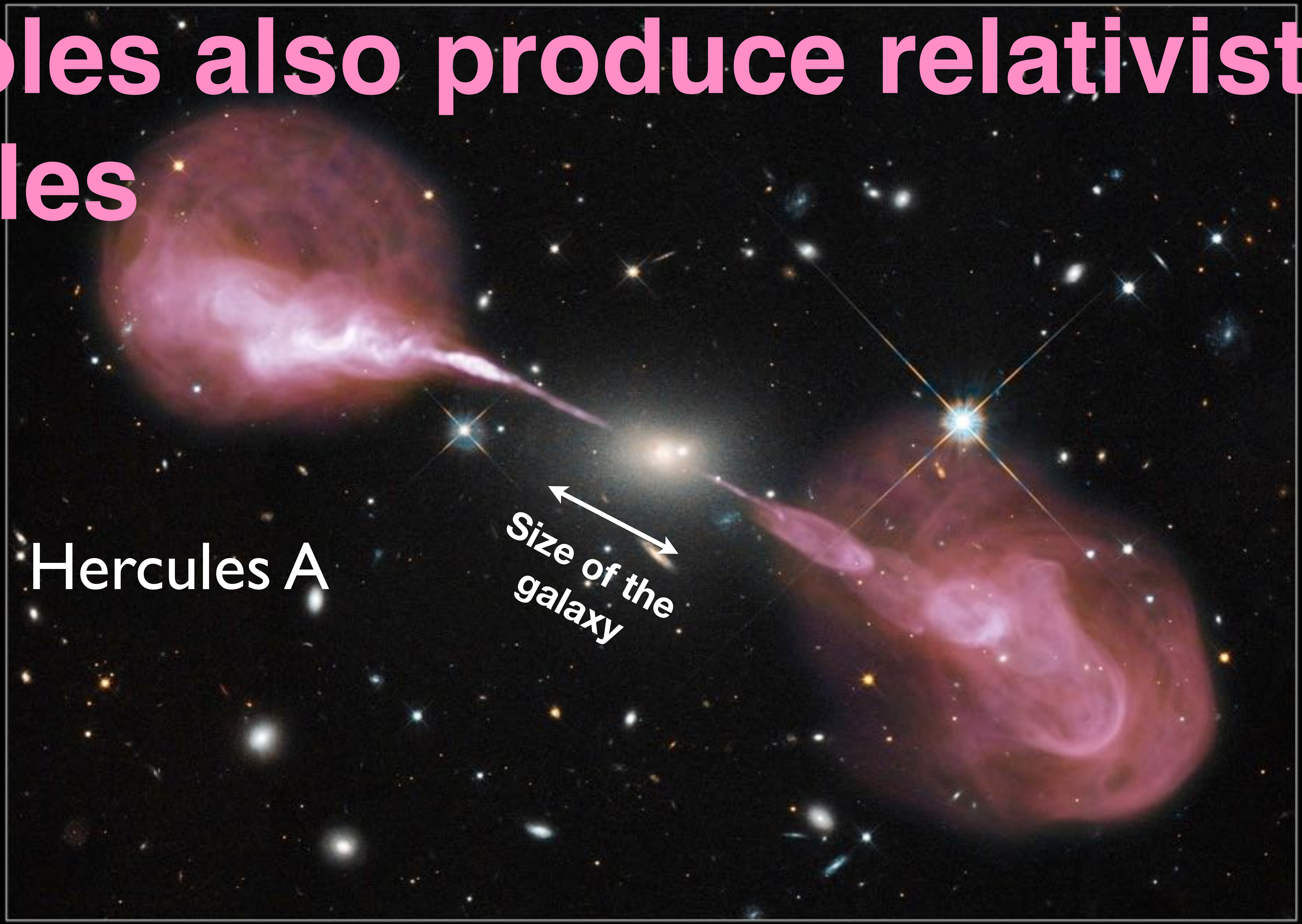
$$t_{\rm ff} = \sqrt{\frac{2r^3}{GM}}$$

$$\dot{m} \sim m / t_{\rm ff} = 10^{24}\ {\rm g\ s^{-1}}$$
MASS ACCRETION RATE

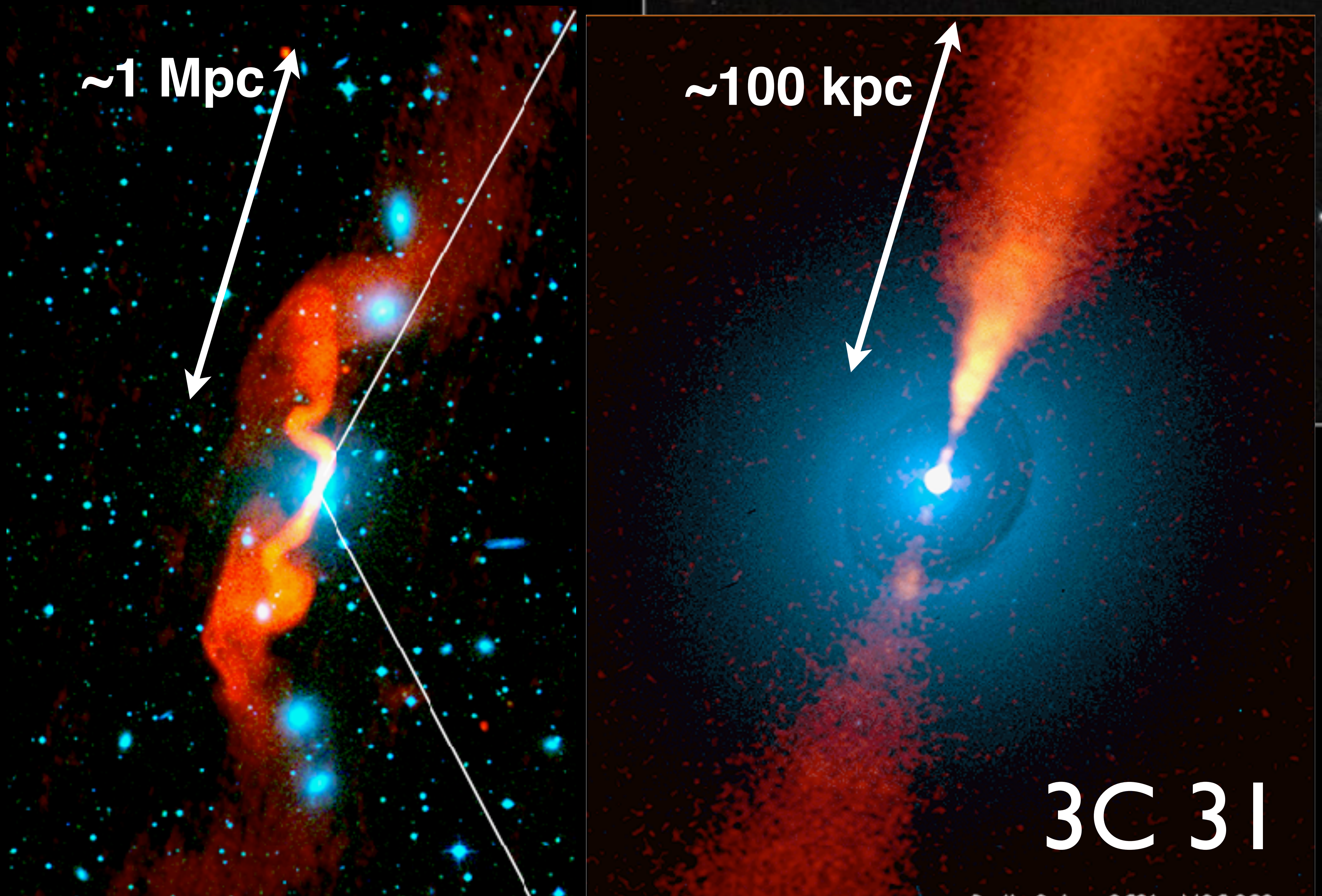
MASS OF ALL WATER ON EARTH

$$L \sim 0.1 \dot{m} c^2 \sim 10^{44}\ {\rm erg\ s^{-1}}$$
LUMINOSITY

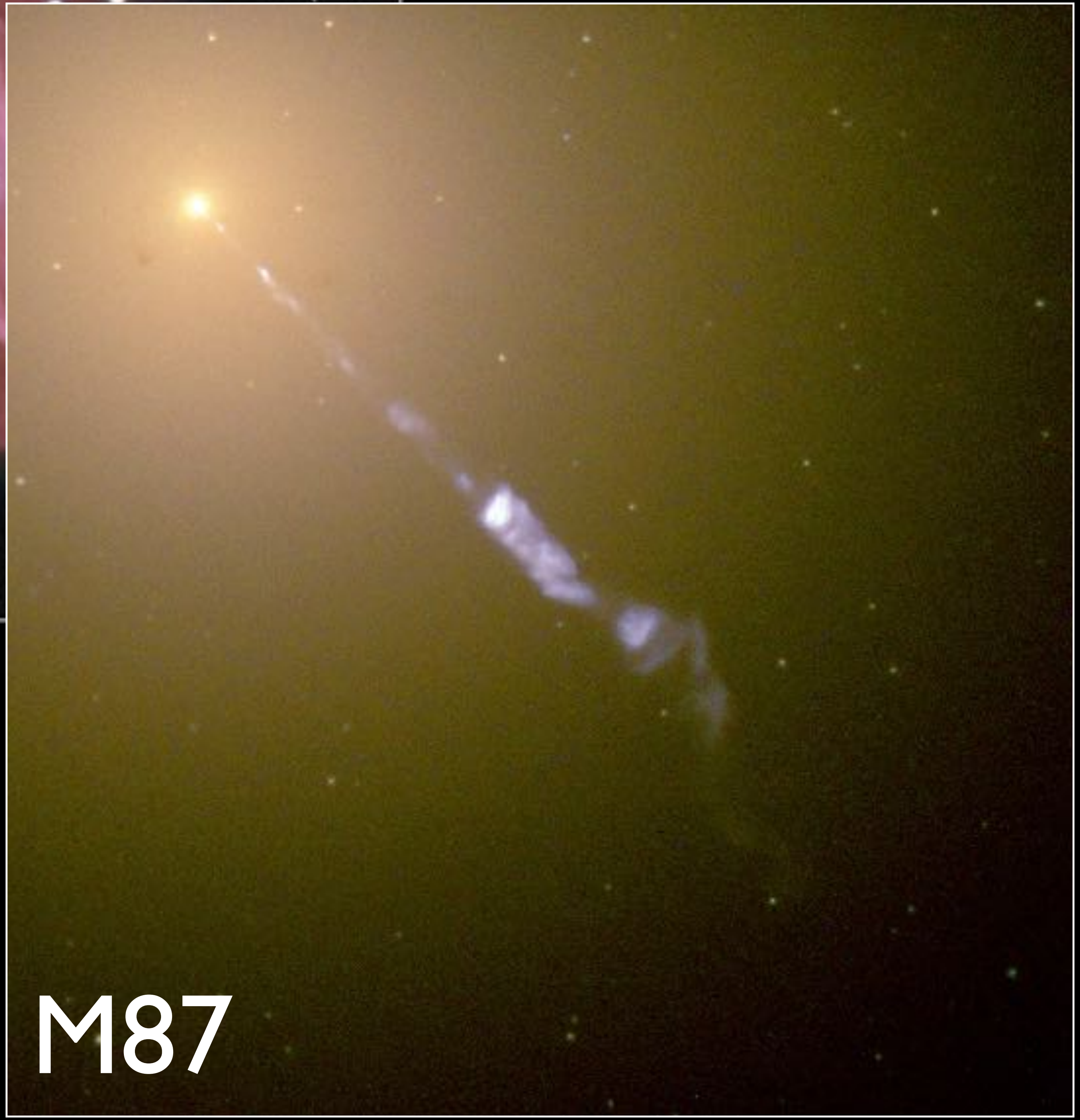
Black holes also produce relativistic jets of particles



Black holes also produce relativistic jets of particles



Cosmic particle accelerators!




~1 Mpc
~100 kpc
3C 31
Active galactic nuclei
Tidal disruption events
Gamma-ray bursts
~10-4 pc?
Black hole binaries (microquasars)
~1 pc
1E1740.7-2942
Swift
500 GRBs

```
if t>45’:
    goto slide 88
```

do not use `goto` **when coding!**

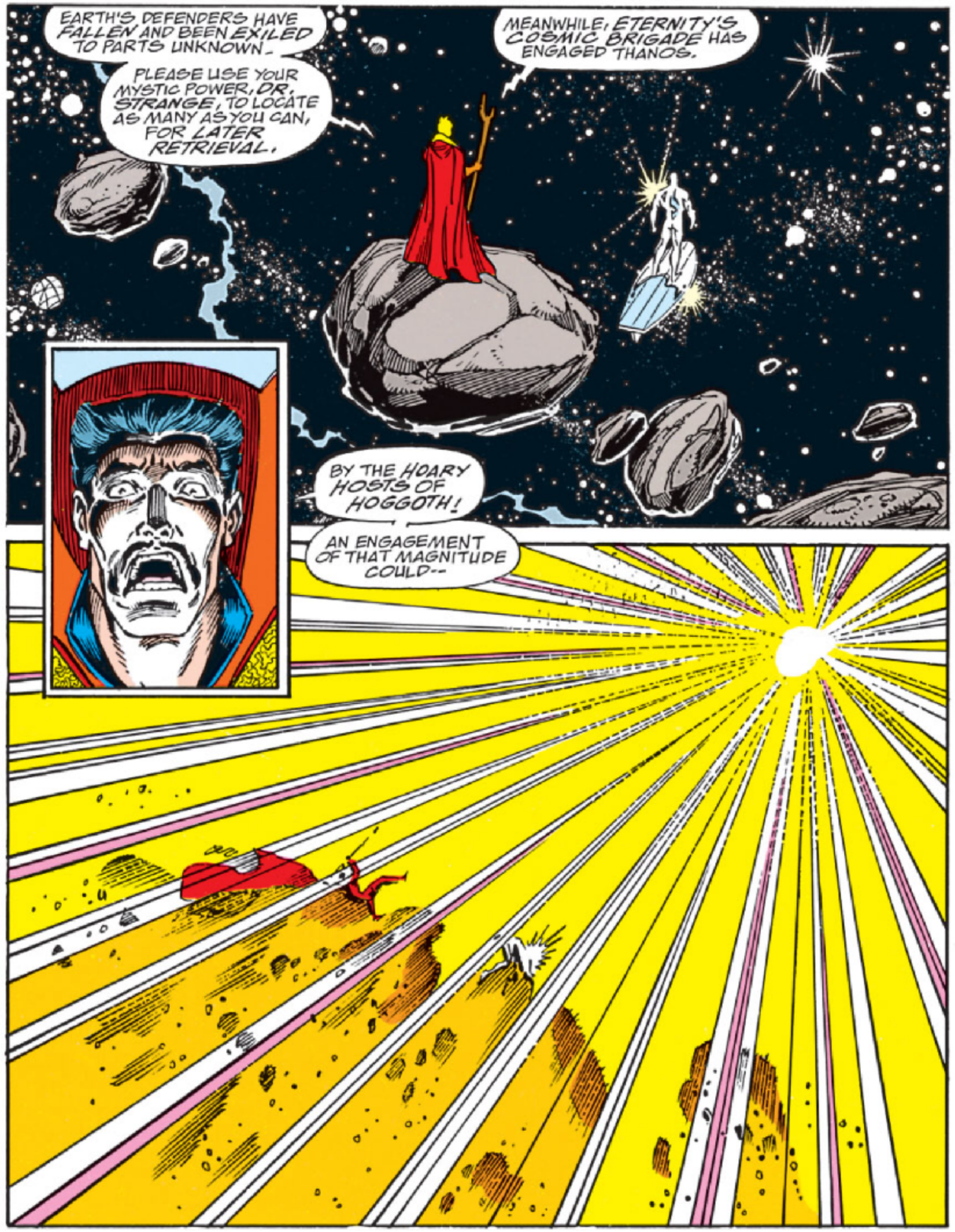
INTERROMPEMOS A PROGRAMAÇÃO

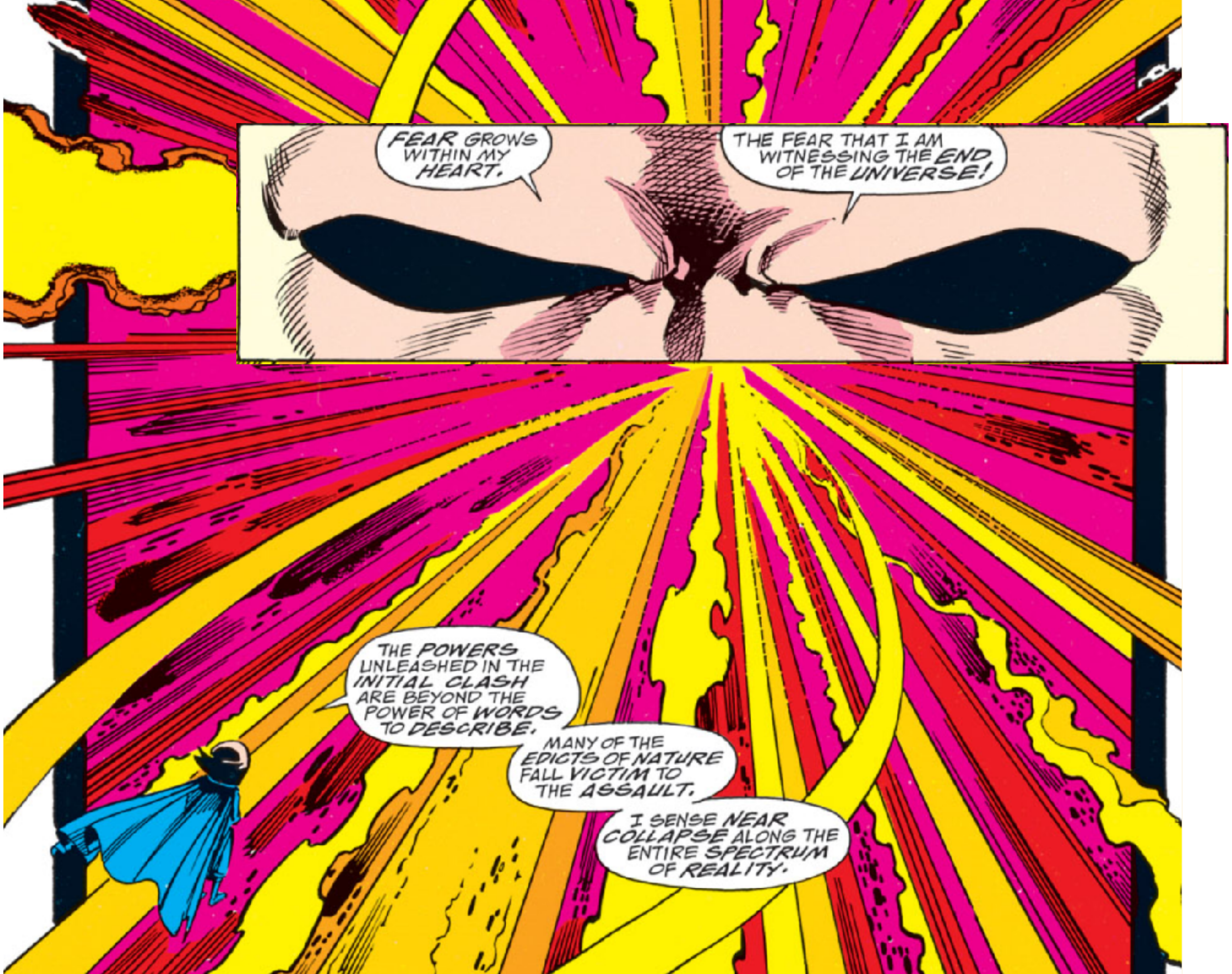
MOMENTO NERD


ROBERT DOWNEY JR.
CHRIS HEMSWORTH
MARK RUFFALO
CHRIS EVANS
SCARLETT JOHANSSON
BENEDICT CUMBERBATCH
DON CHEADLE
TOM HOLLAND
CHADWICK BOSEMAN
PAUL BETTANY
ELIZABETH OLSEN
ANTHONY MACKIE
SEBASTIAN STAN
DANAI GURIRA
LETITIA WRIGHT
DAVE BAUTISTA
ZOE SALDANA
WITH JOSH BROLIN AS THANOS
AND CHRIS PRATT
MARVEL STUDIOS
AVENGERS
INFINITY WAR


THE INFINITY GAUNTLET
MARVEL COMICS

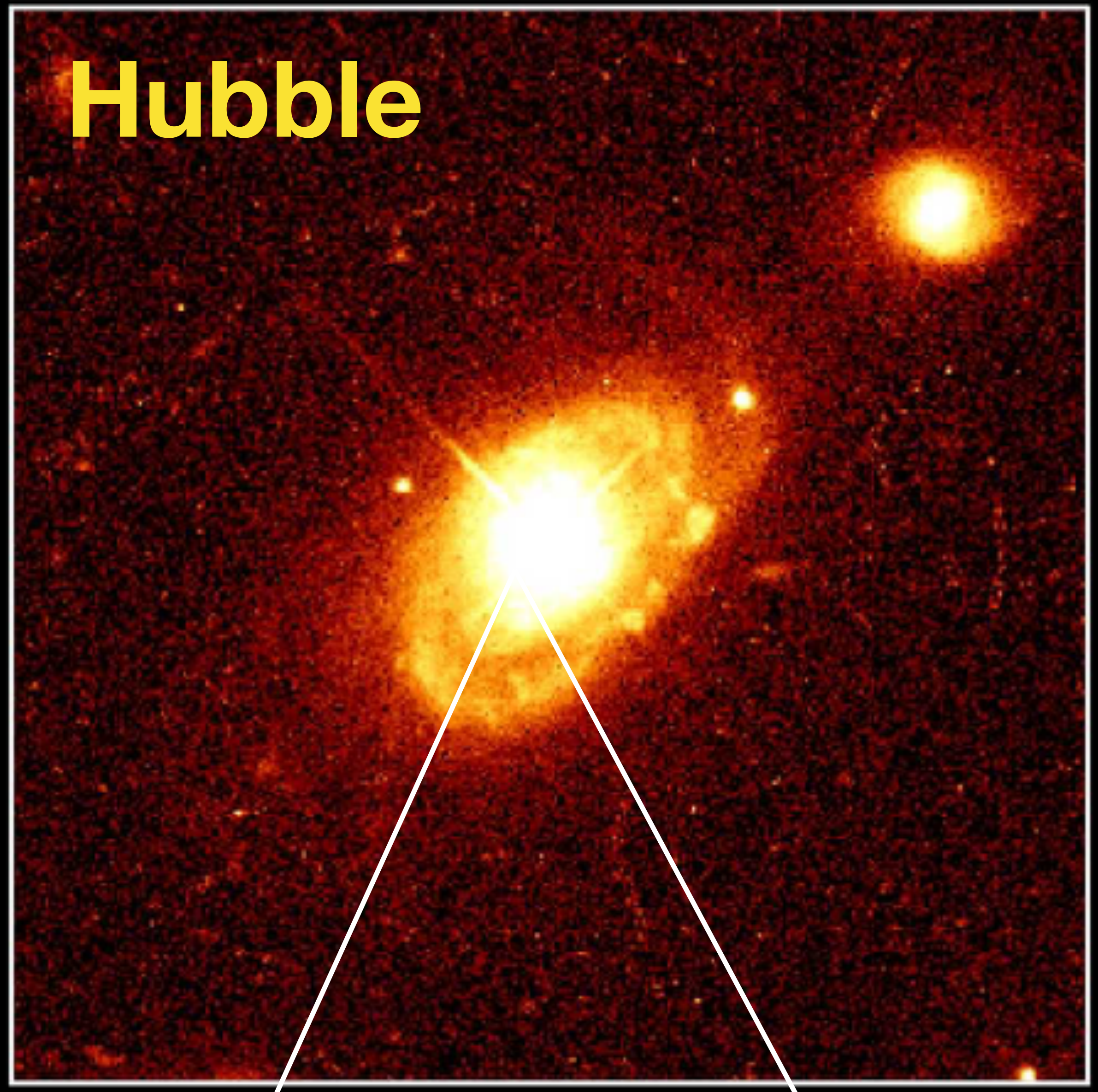

A CONTINGENT OF COSMIC ENTITIES CHALLENGES THANOS'S MIGHT. SUCH A CONFLICT MAY WELL PROVE MORE THAN THIS FRAGILE REALITY CAN BEAR.
THANOS OF TITAN...WE CALL UPON YOU TO SURRENDER THE INFINITY GEMS.
HONOR THIS REQUEST OR FACE POWER BEYOND YOUR WILDEST DREAMS.
ASTRAL CONFLAGRATION
I BELIEVE YOU WILL DISCOVER THE HORIZONS OF MY IMAGININGS FAR WIDER THAN YOU WOULD SUSPECT, LORD CHAOS.
YOU ADDRESS OMNIPOTENCE.
TREAD CAREFULLY.
JIM STARLIN WRITER
RON LIM PENCILS
JOSEF RUBINSTEIN INKS
LAUGHLIN & SCHEELE COLORS
JACK MORELLI LETTERS
CRAIG ANDERSON EDITOR
TOM DEFALCO CHIEF

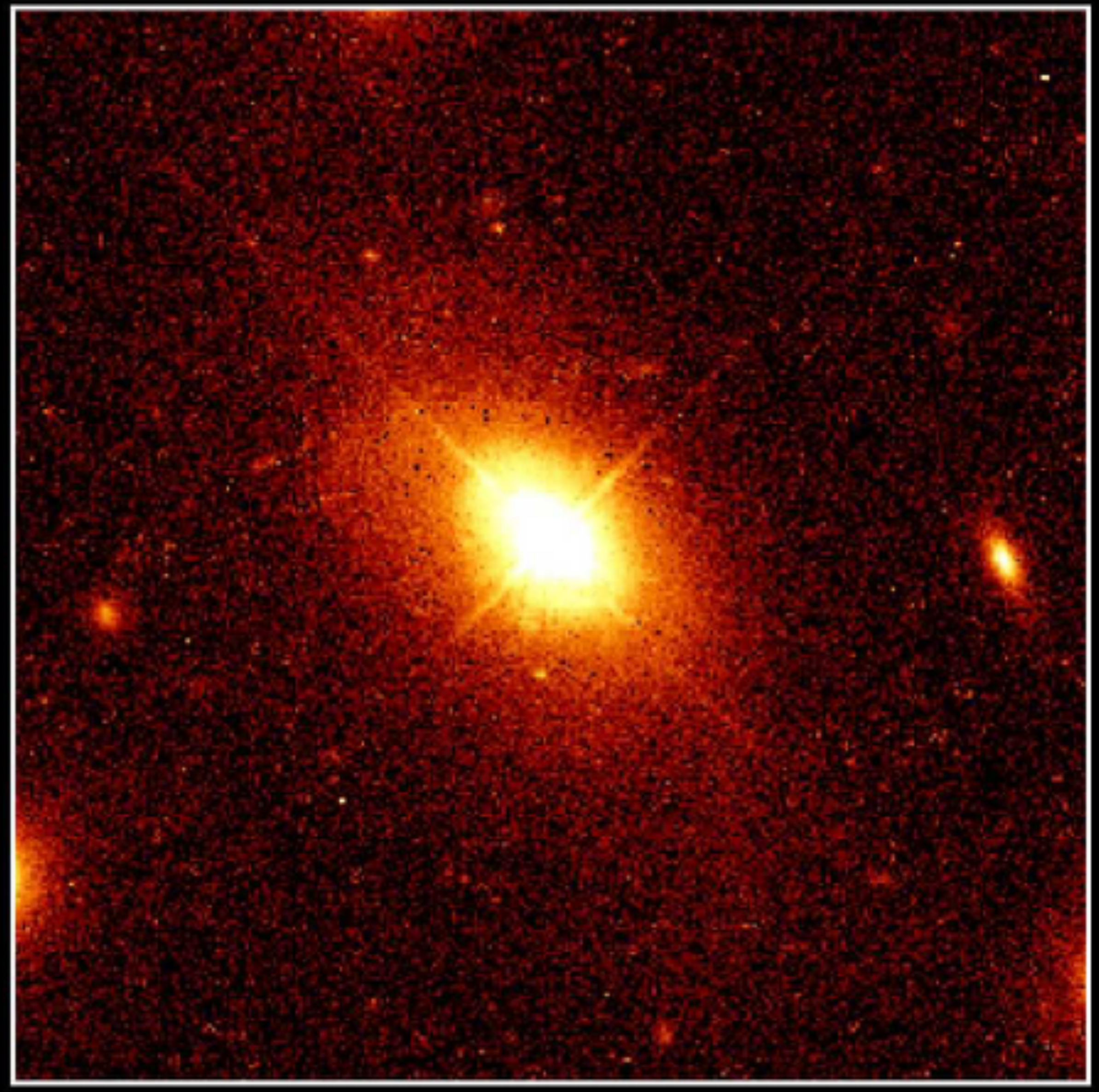

EARTH'S DEFENDERS HAVE FALLEN AND BEEN EXILED TO PARTS UNKNOWN.
PLEASE USE YOUR MYSTIC POWER, DR. STRANGE, TO LOCATE AS MANY AS YOU CAN, FOR LATER RETRIEVAL.
MEANWHILE, ETERNITY'S COSMIC BRIGADE HAS ENGAGED THANOS.
BY THE HOARY HOSTS OF HOGGOTH!
AN ENGAGEMENT OF THAT MAGNITUDE COULD--


FEAR GROWS WITHIN MY HEART.
THE FEAR THAT I AM WITNESSING THE END OF THE UNIVERSE!
THE POWERS UNLEASHED IN THE INITIAL CLASH ARE BEYOND THE POWER OF WORDS TO DESCRIBE.
MANY OF THE EDICTS OF NATURE FALL VICTIM TO THE ASSAULT.
I SENSE NEAR COLLAPSE ALONG THE ENTIRE SPECTRUM OF REALITY.

Quasars: $L \sim 10^{45}$ erg/s

distance = 5 billion ly



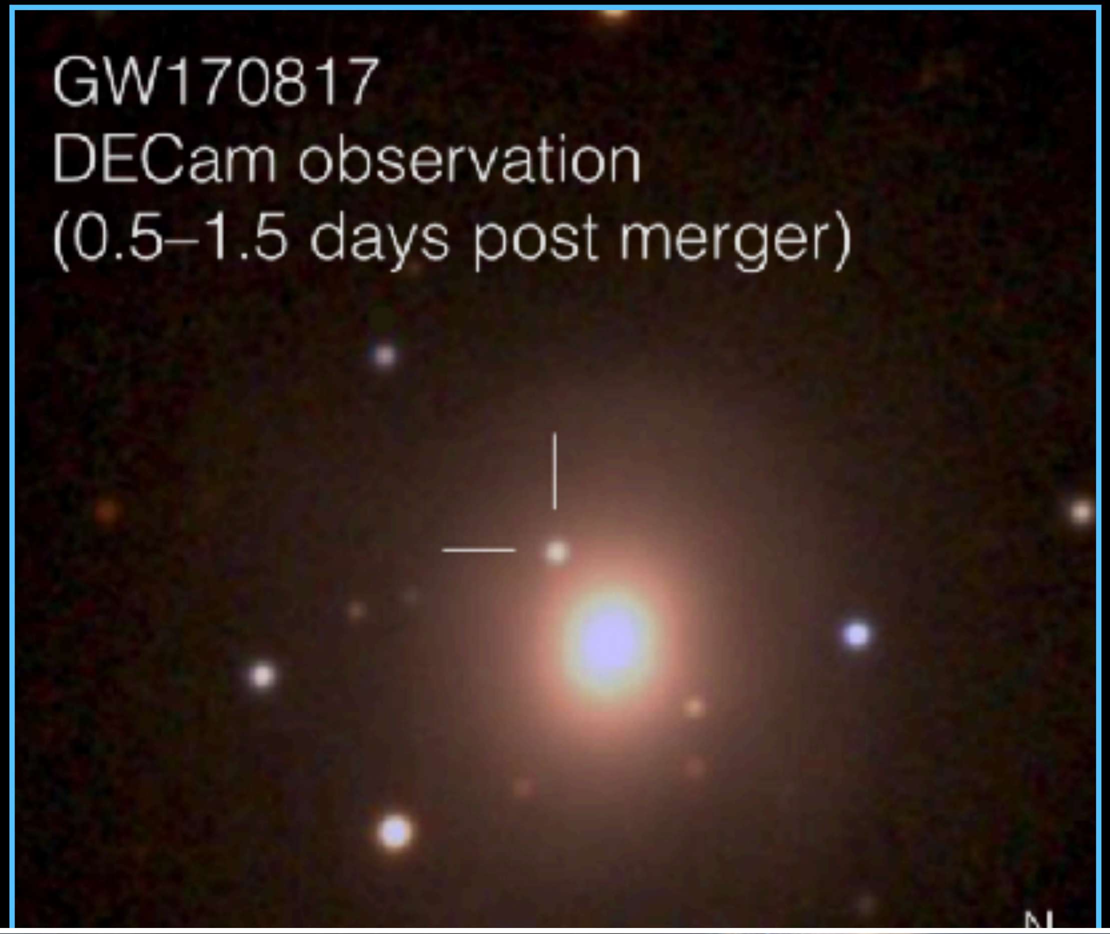


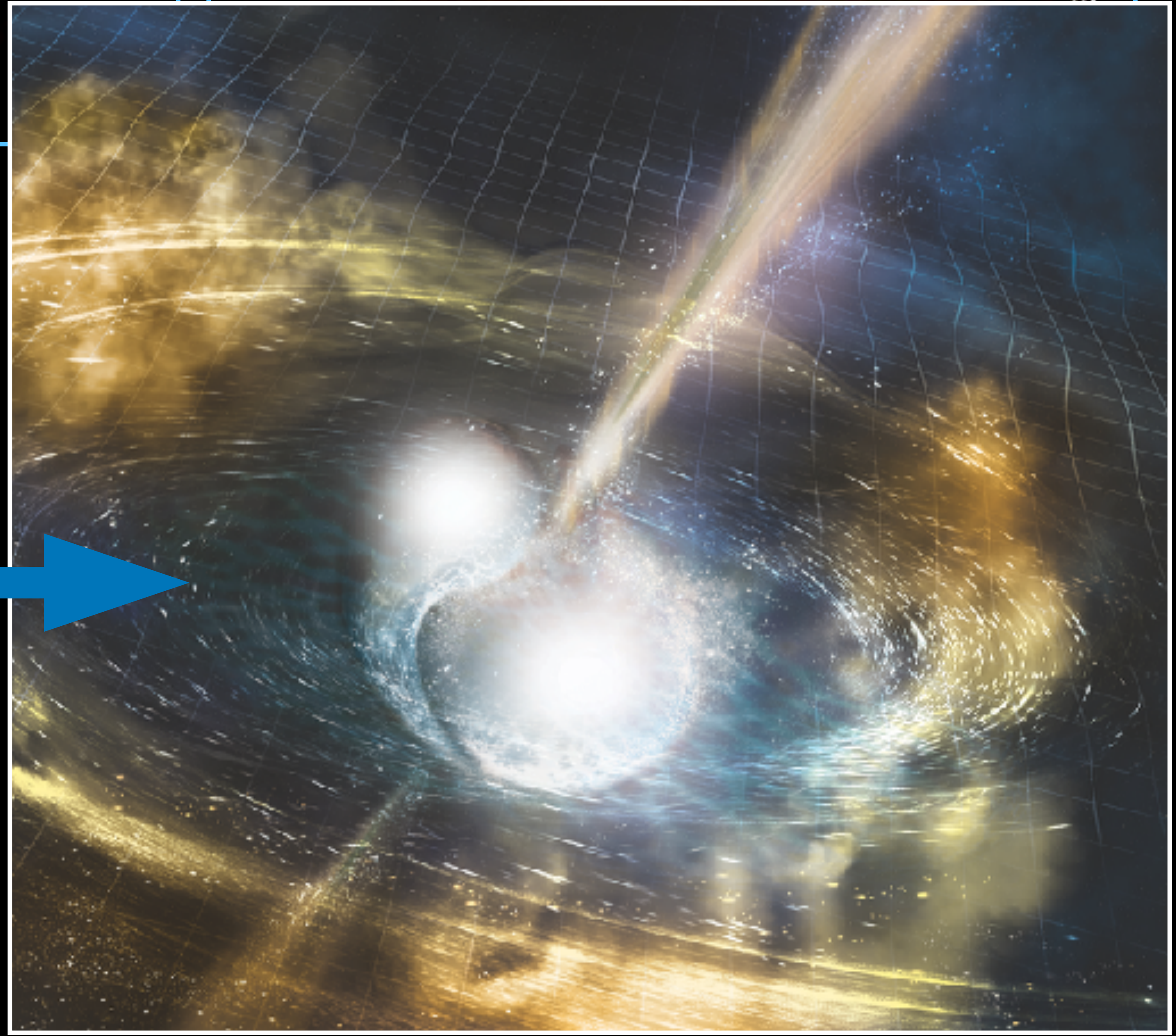
Bahcall+1997

Collision of neutron stars:

converted 5% of $M_{sun}c^2$ into GWs and light

distance = 130 million ly





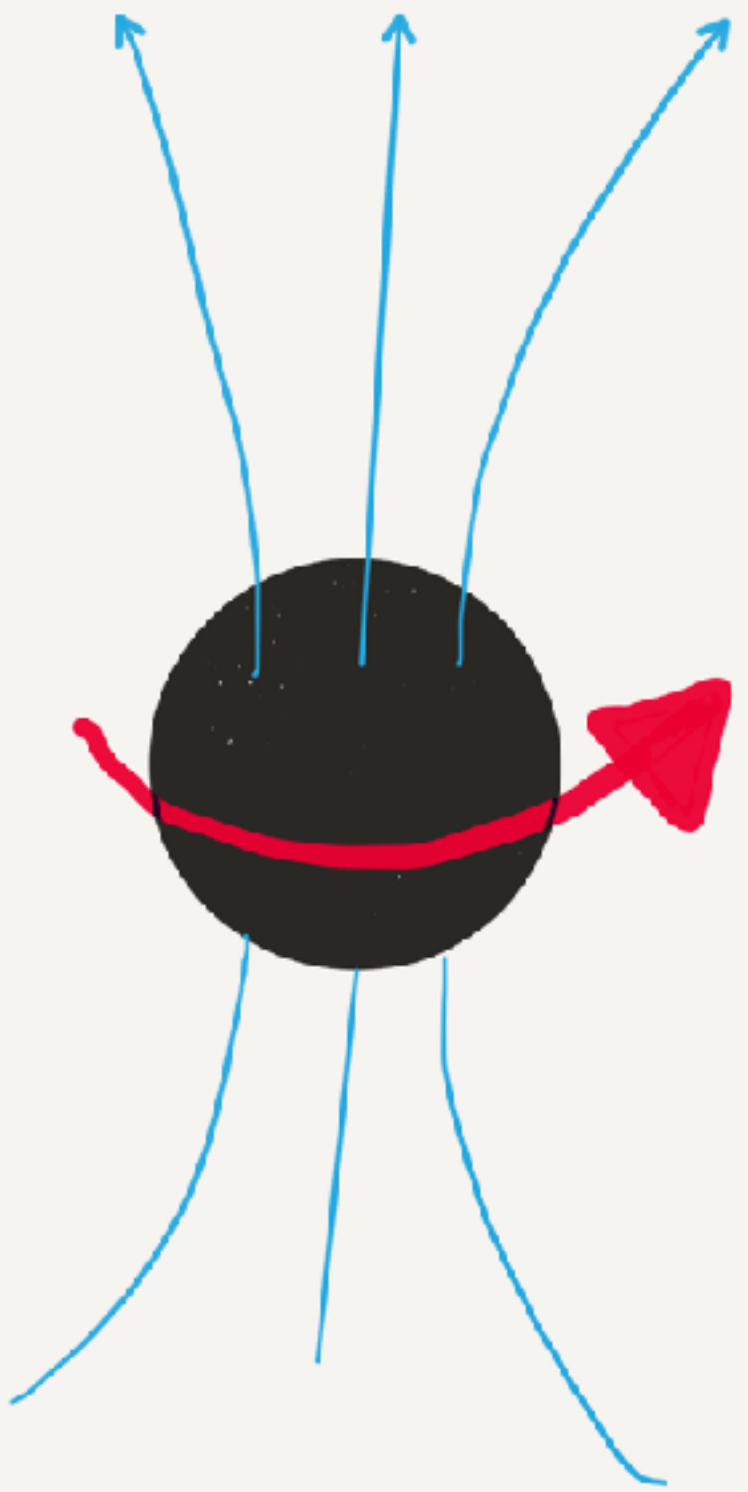
LIGO

How are relativistic jets produced by black holes?

Conjecture: from spinning black holes

Growing evidence that this is correct

- [x] Theory/simulations
- [ ] Observations (?)



Penrose process: Spinning black hole has free energy that can be extracted

Penrose 1969

Rotational energy of spacetime (frame dragging)

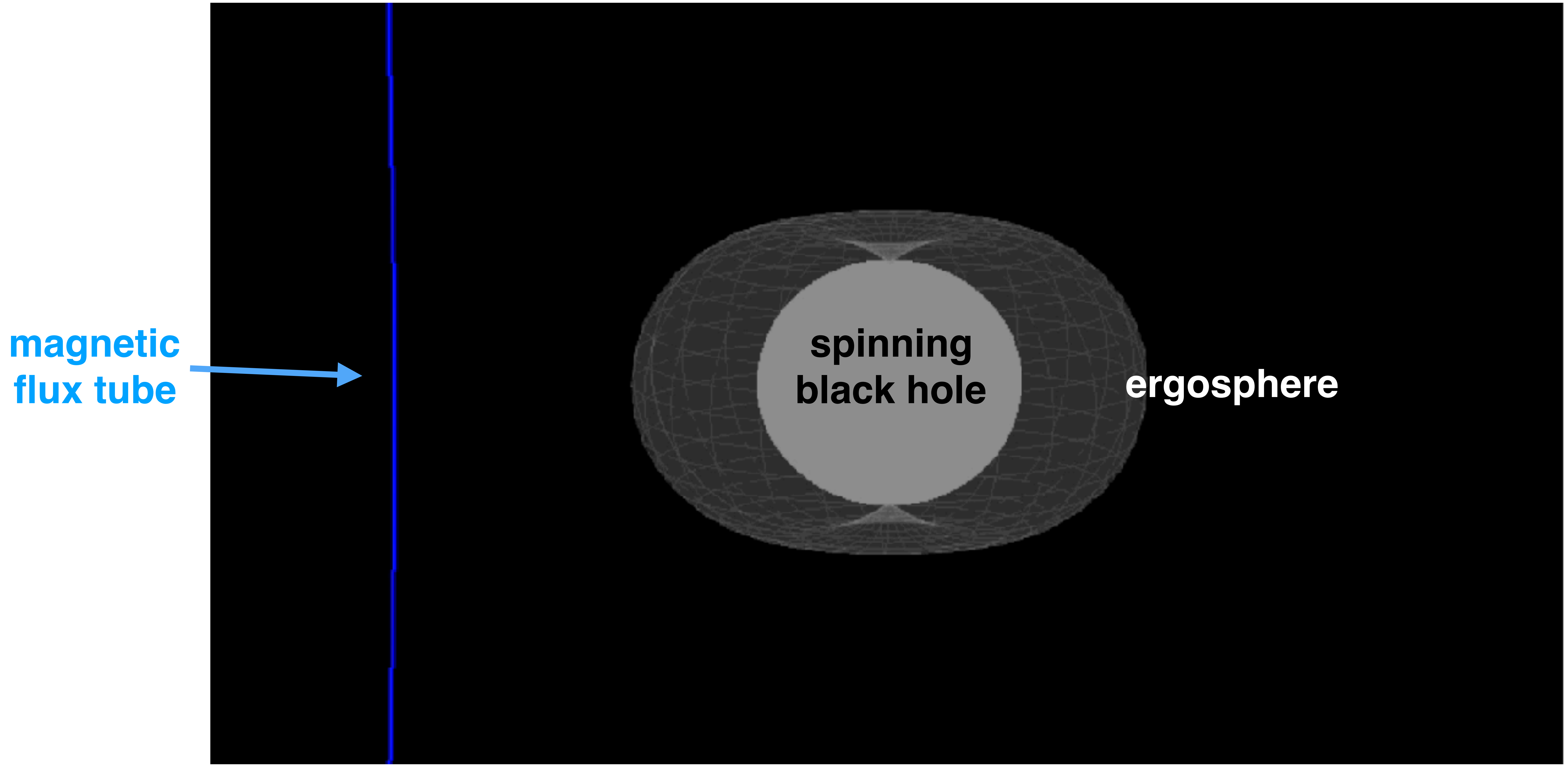
Thought experiment by Penrose that demonstrates the principle, probably not important in astrophysics

But *magnetized* accretion disks is promising

Ruffini & Wilson 1975; Blandford & Znajek 1977

https://www.youtube.com/watch?v=9MHuhcFQsBg

Toy model for jet production from black hole: rotation + accretion + $\vec{B}$



Blandford-Znajek mechanism:

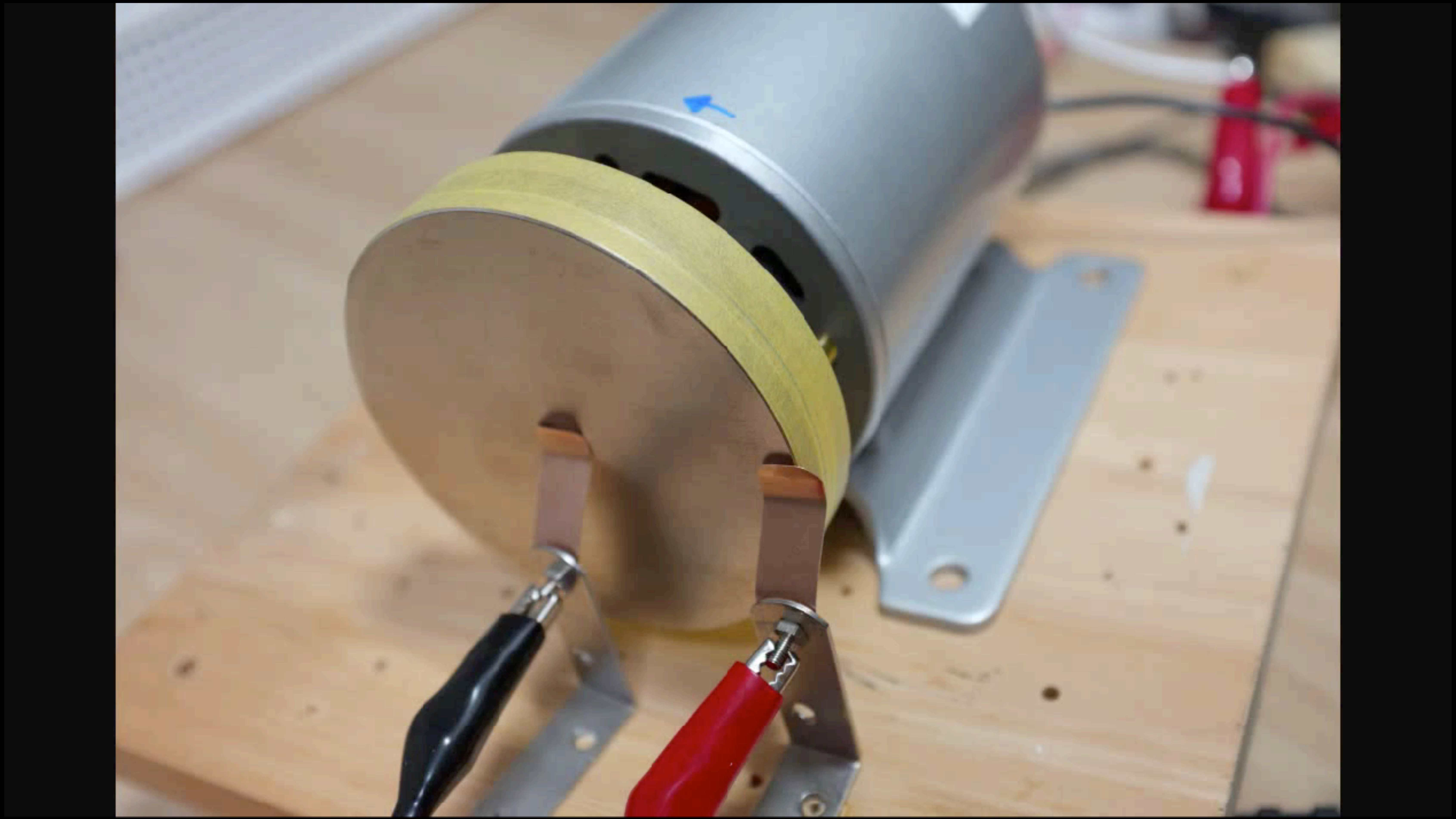
$$\text{Jet power} \propto \left(\frac{a\Phi_h}{M}\right)^2 \sim a^2 \dot{M} c^2$$

spin

magnetic flux

Blandford & Znajek 77; Komissarov+; Nemmen+07; Tchekhovskoy+

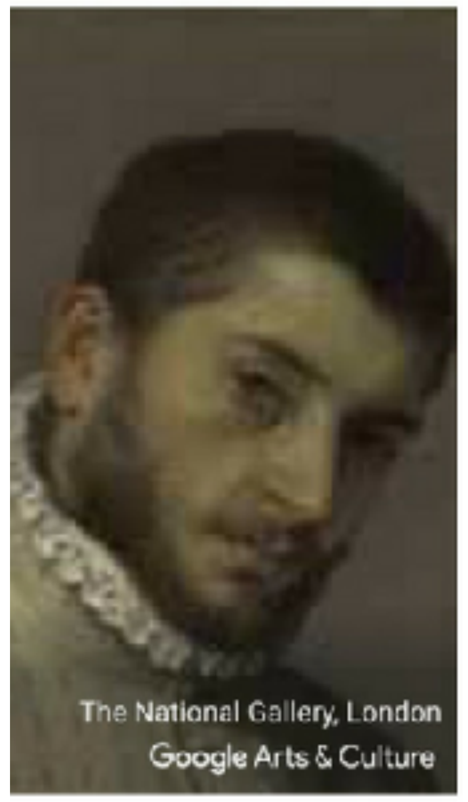
How to make a black hole jet at home: Homopolar generator



Kudos to Alice Harding (NASA GSFC)

https://www.youtube.com/watch?v=R173dLlktsw

55% match
The Tailor ('Il Tagliapanni')
Giovanni Battista Moroni



57% match
The Watcher
Frank Weston Benson

58% match
OFF Crimes of minds C215
C215

56% match
Pyotr Ilyich Tchaikovsky portrait a...

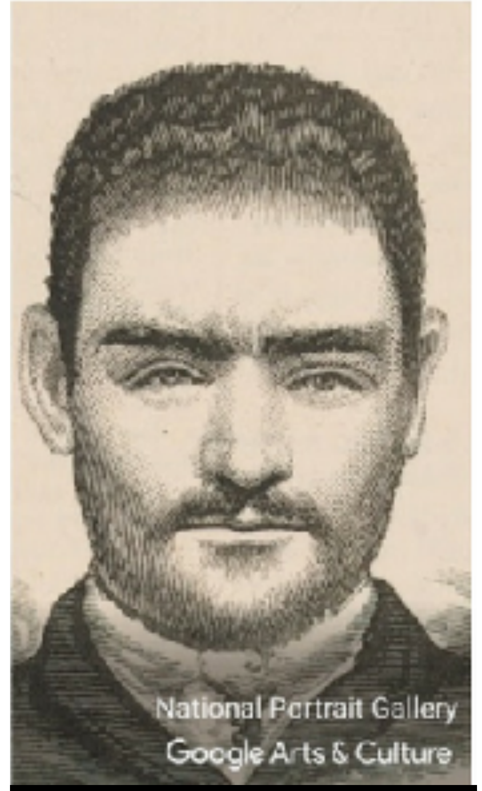
51% match
The Three Musicians
Diego Velázquez

black hole group

iag usp

58% match
Ritratto di Andrea Maffei in divisa...
Carlo Bellosio

55% match
The Bushranger Tragedy (from Th...
an unknown artist



64% match
Canção sentimental
Berthe Worms

56% match
No. 4
Durdy Bayramov

Made with Google Arts & Culture app

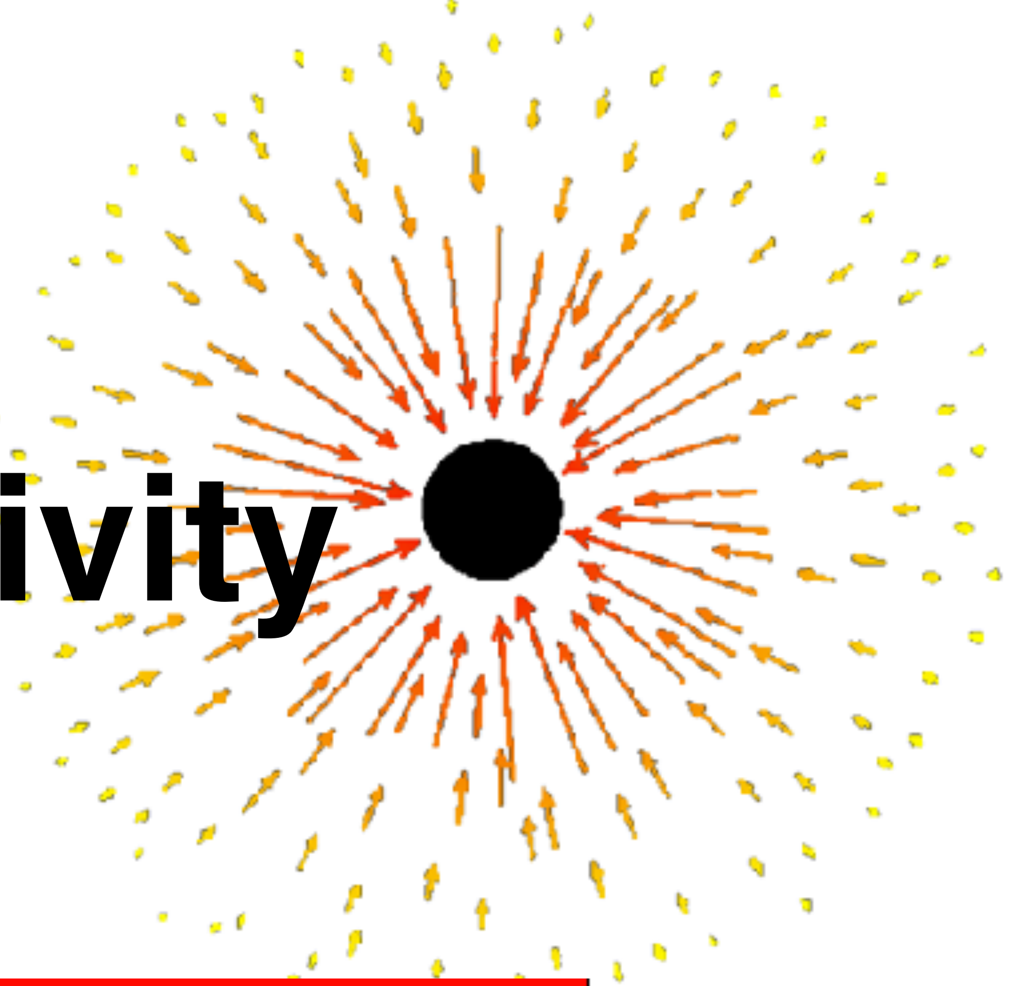
black hole group

iag usp

https://blackholegroup.org

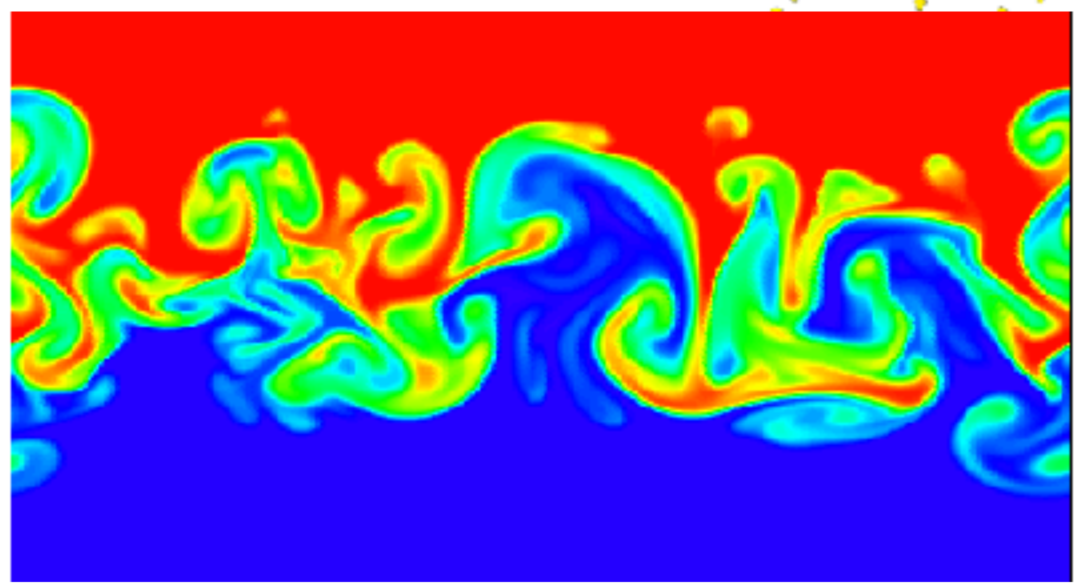
Virtual laboratory of numerical relativistic astrophysics

"Weather forecast for black holes"

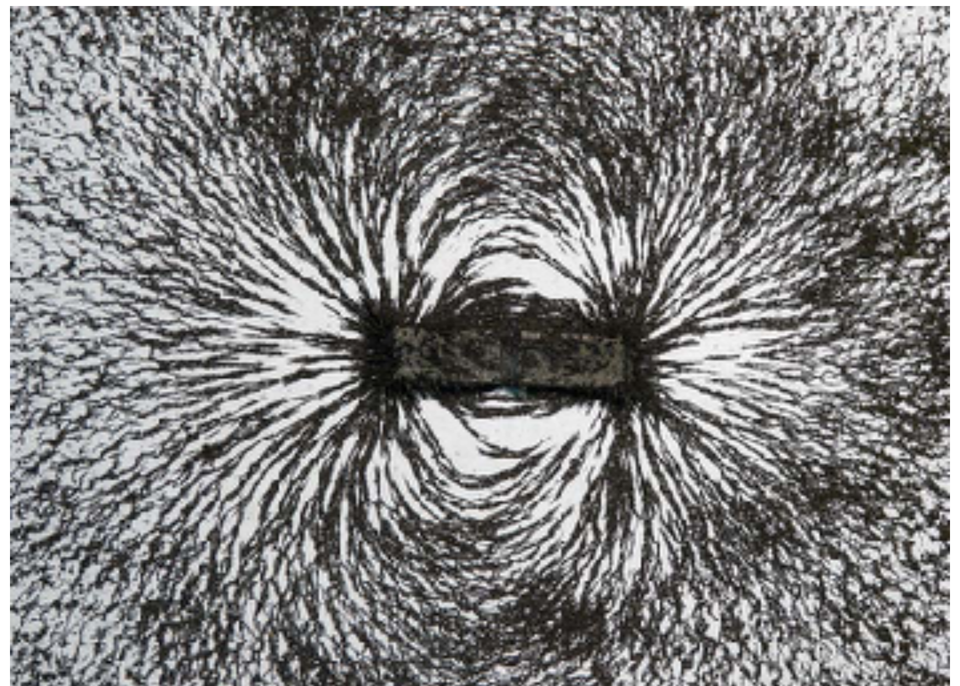


Gravity: general relativity

Gas (plasma)



Electromagnetic fields



Required physics: Fluid dynamics + electrodynamics

Fluid dynamics conservation equations

Mass

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0$$

Momentum

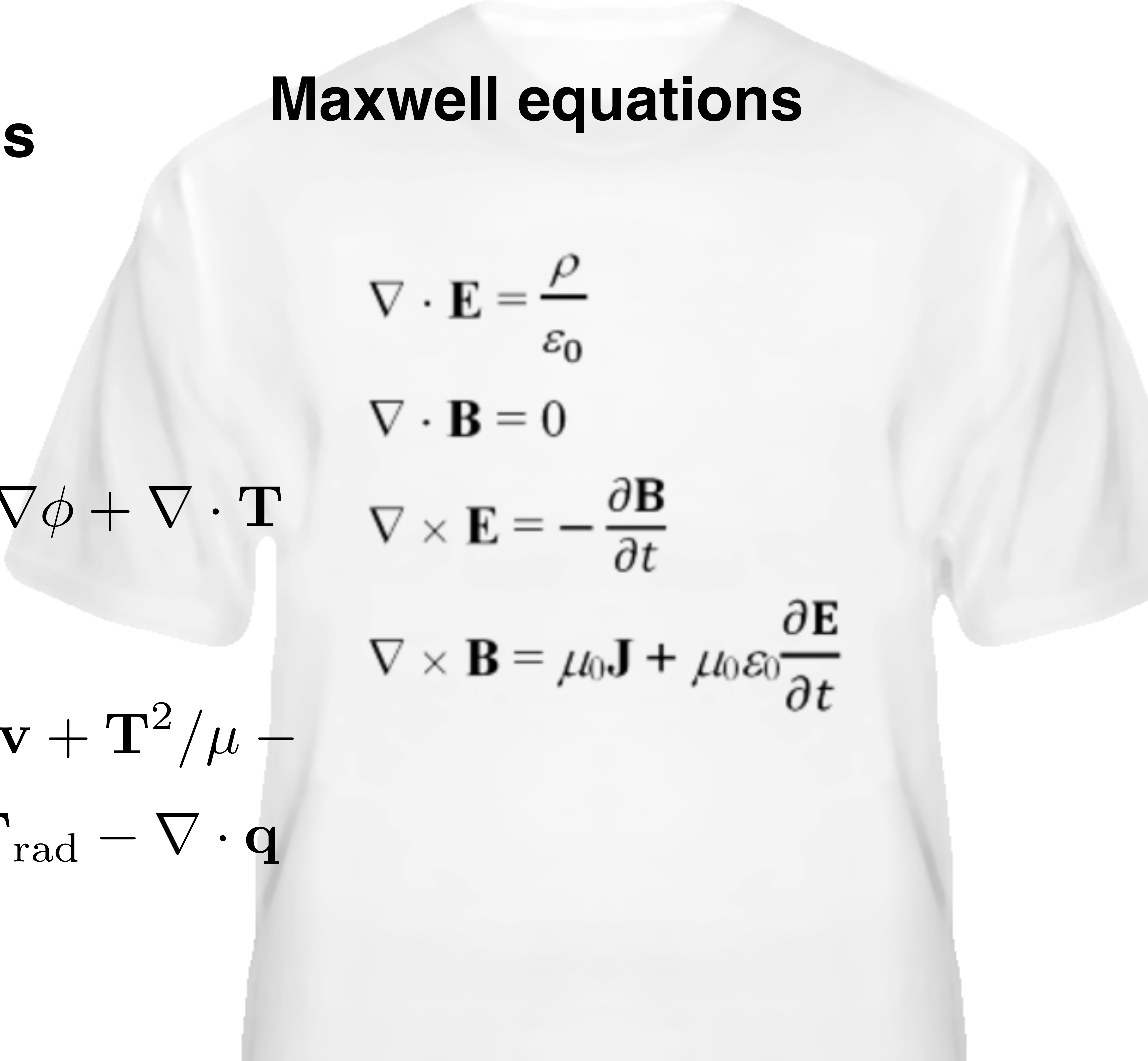
$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p - \rho \nabla \phi + \nabla \cdot \mathbf{T}$$

Energy

$$\rho \frac{D(e/\rho)}{Dt} = -p\nabla \cdot \mathbf{v} + \mathbf{T}^2/\mu - - \nabla \cdot \mathbf{F}_{\mathrm{rad}} - \nabla \cdot \mathbf{q}$$

Plus: ⁕ equation of state

Maxwell equations



Equations of general relativistic magnetohydrodynamics

Conservation of

Particle number $$\nabla_\nu(\rho u^\nu) = 0$$

Energy-momentum $$\nabla_\nu T^{\mu\nu} = 0$$

Maxwell equations

$$\nabla_\nu * F^{\mu\nu} = 0$$

$$\nabla_\nu F^{\mu\nu} = -J^\mu$$

Plus:
- equation of state
- ideal MHD condition
- Kerr metric

$$p = (\Gamma - 1)\rho\epsilon$$

$$F^{\mu\nu}u_\nu = 0$$

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j +$$

$$T^{\mu\nu}_{\text{fluid}} = (\rho + u + p)u^\mu u^\nu + pg^{\mu\nu} \qquad T^{\mu\nu}_{\text{EM}} = F^{\mu\alpha}F^\nu_\alpha - \frac{1}{4}g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}$$

Global, general relativistic MHD (GRMHD) simulations of gas around spinning BHs

HARM code + MPI + 3D = **HARMPI**

Gammie+03; Tchekhovskoy

3D computational mesh

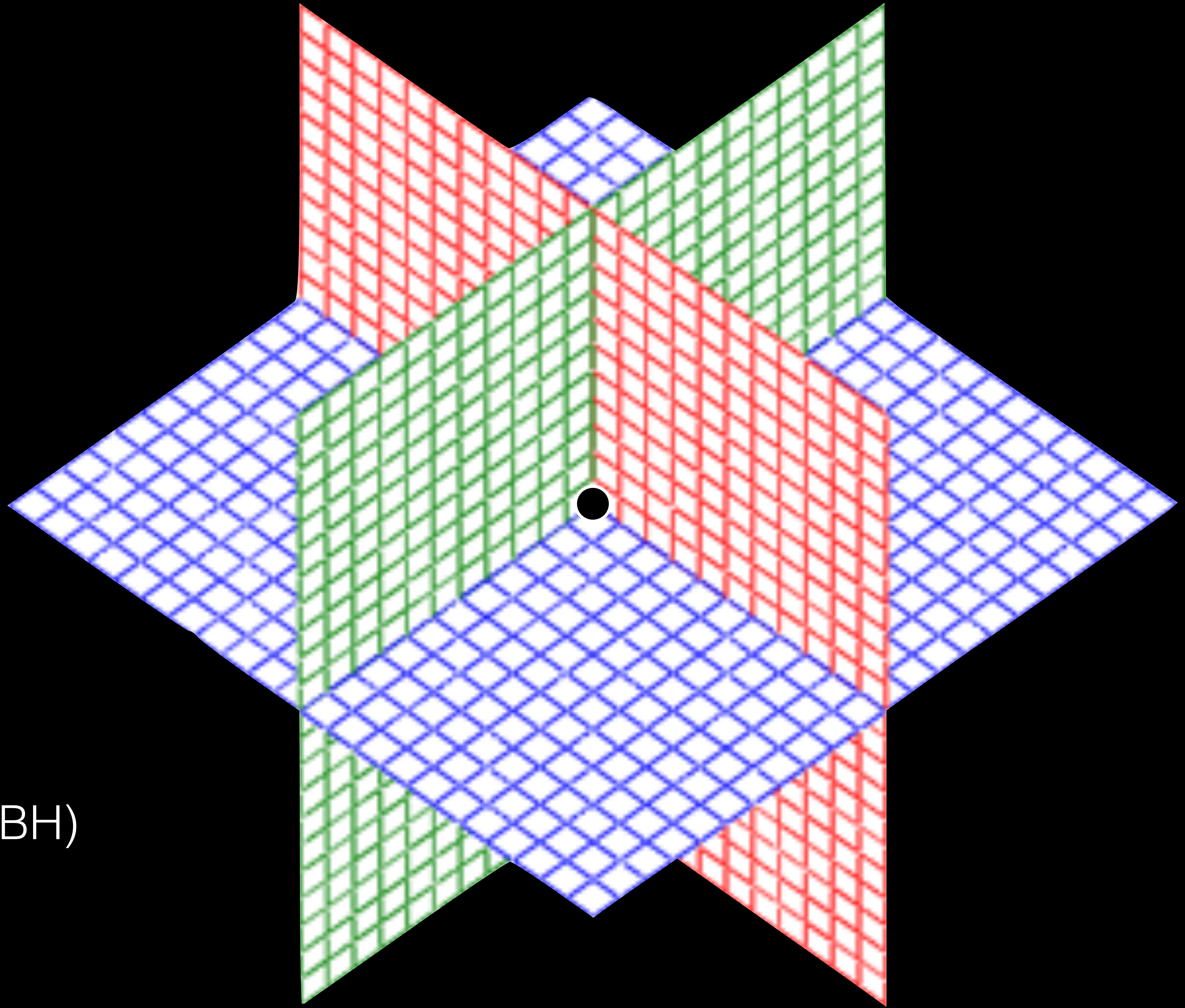
256 x 256 x 64

r θ ϕ

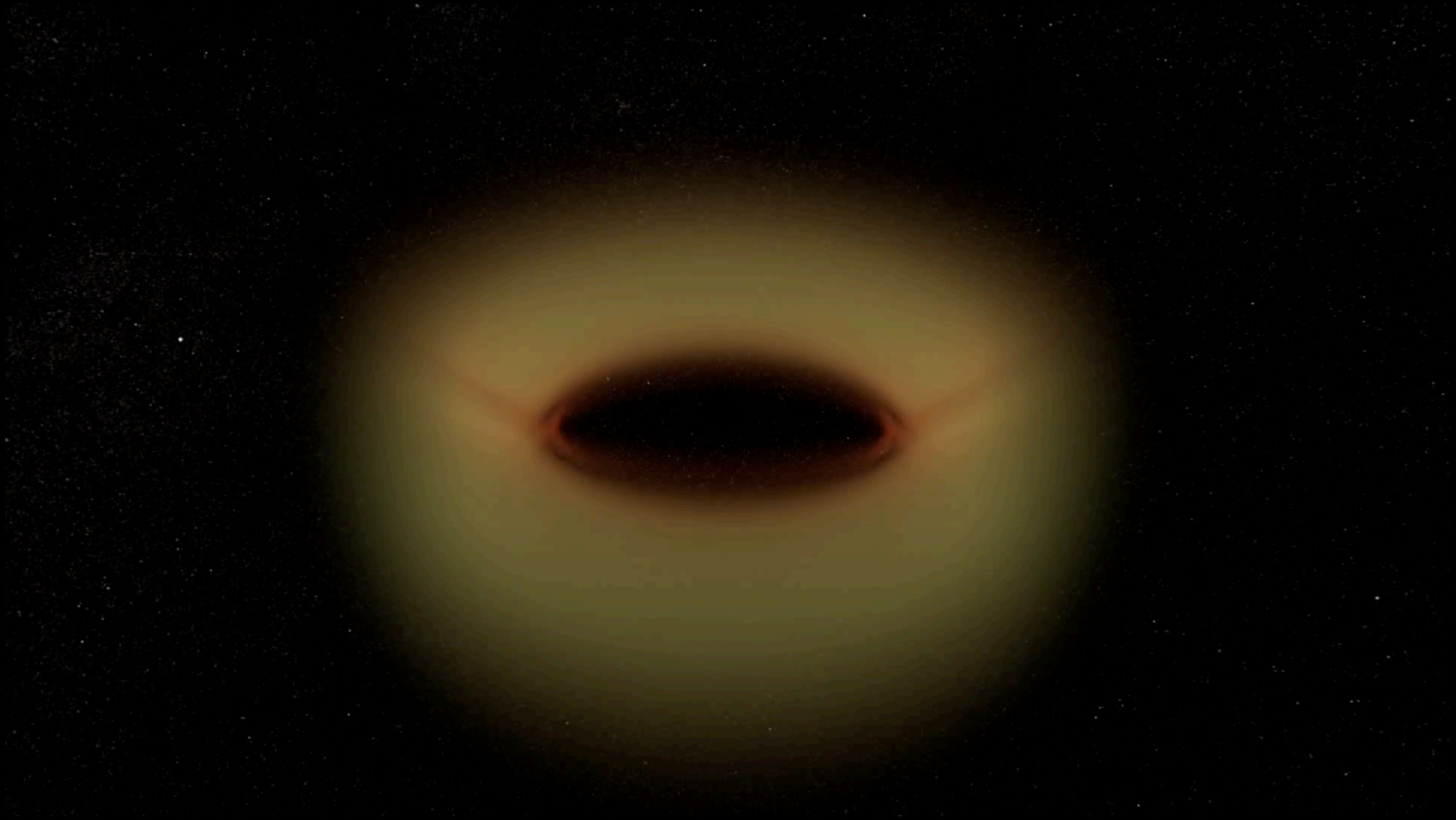
4×10^6 resolution elements

Need to evolve to $t > 15000\ M$

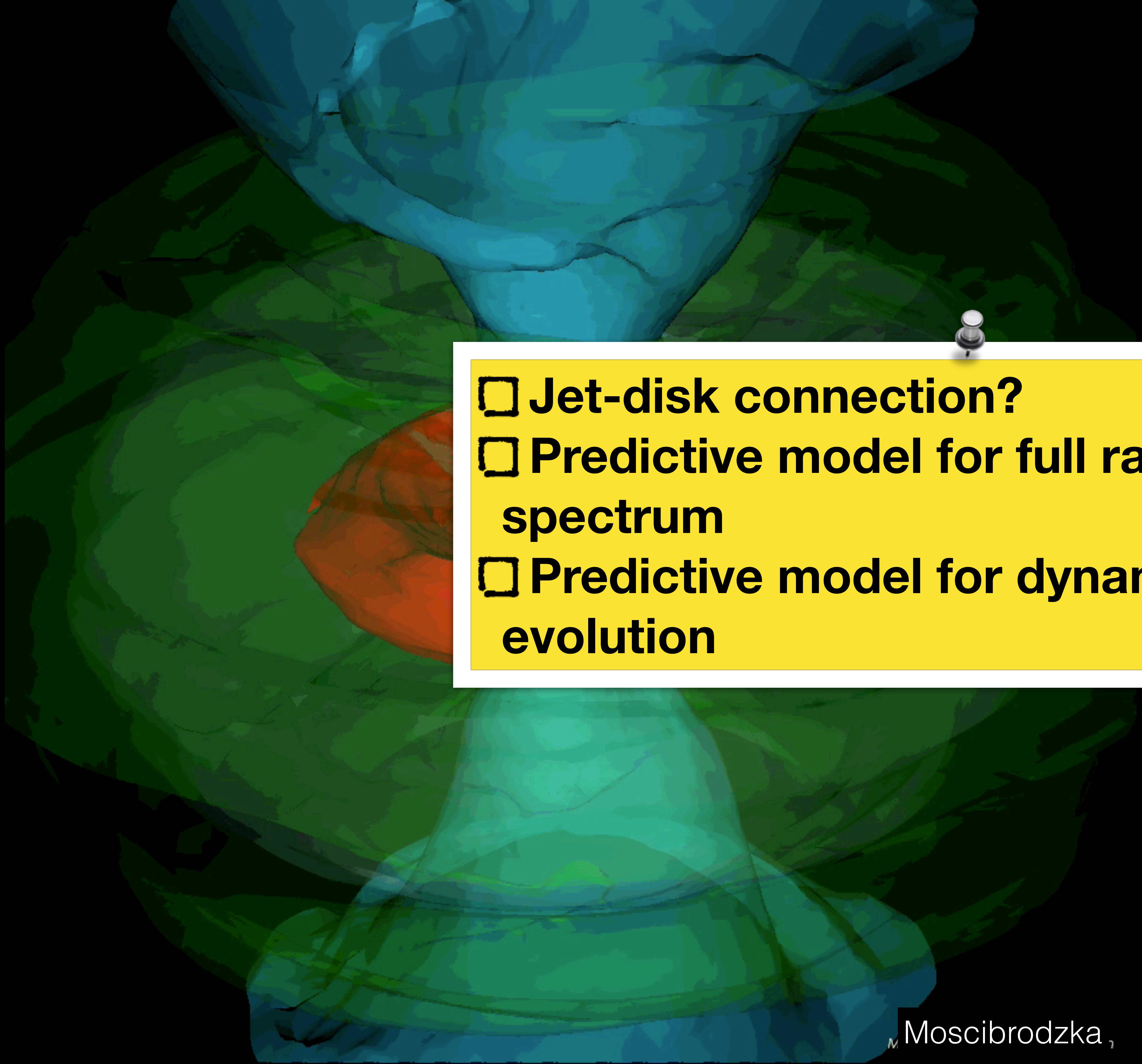
(4 yrs for a 10^9 BH)



Black hole weather forecast



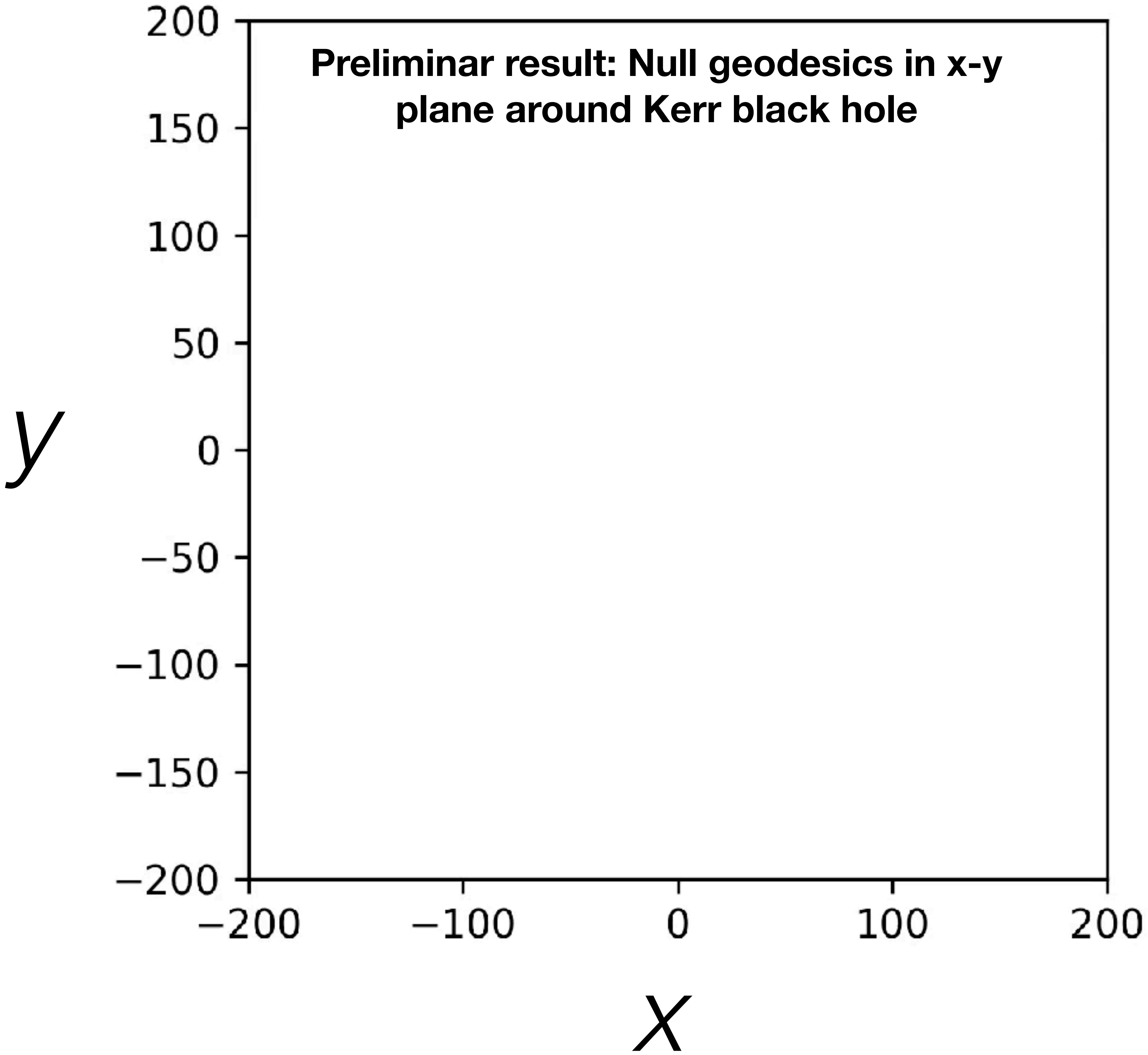
McKinney et al. 2013, *Science*



- ❑ Jet-disk connection?
- ❑ Predictive model for full radiation spectrum
- ❑ Predictive model for dynamical evolution

We are starting to treat the radiation from these systems

Work in progress

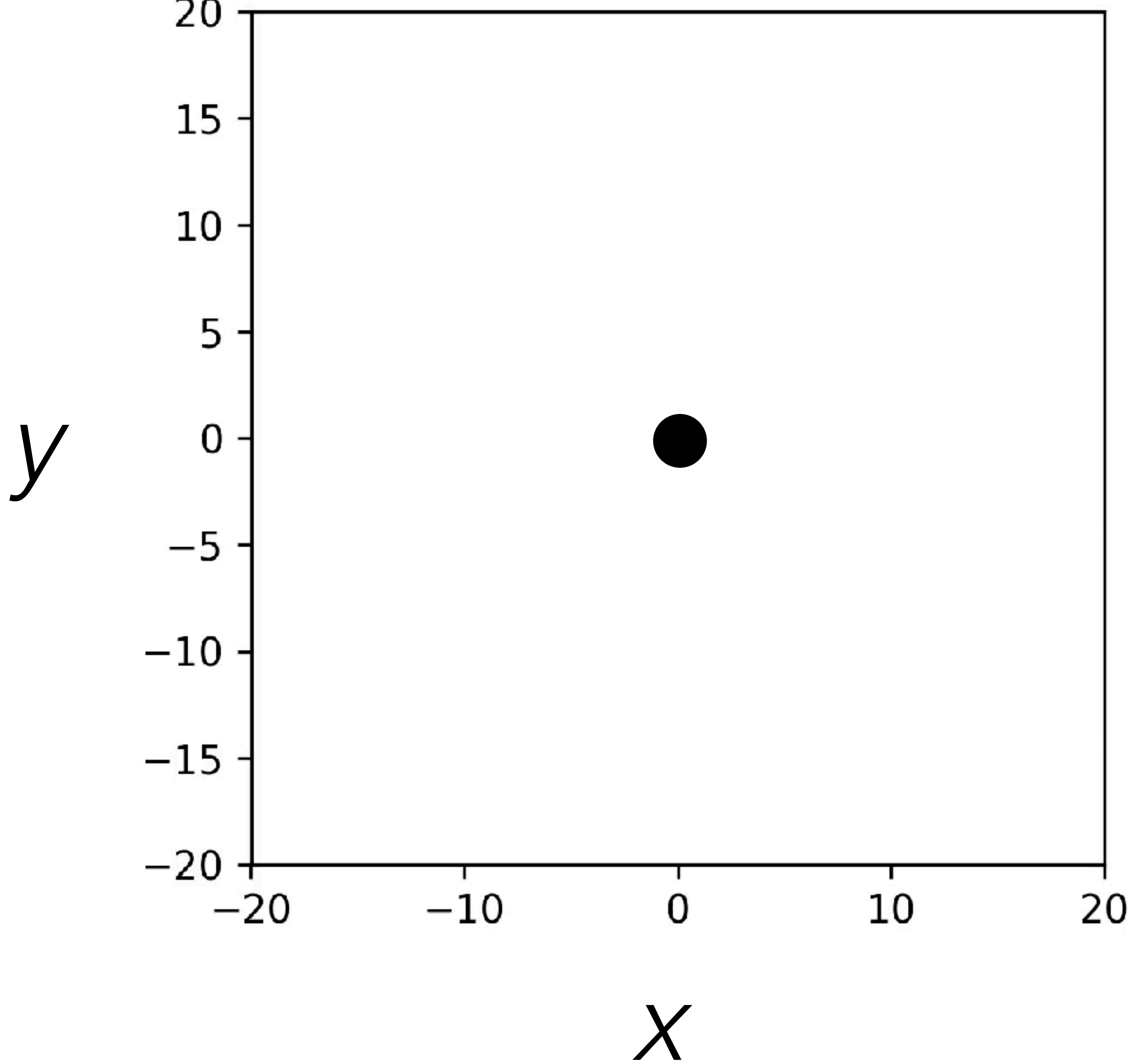



PHD, GUSTAVO SOARES

Units of GM/c^2

Preliminar result: Null geodesics in x-y plane around Kerr black hole

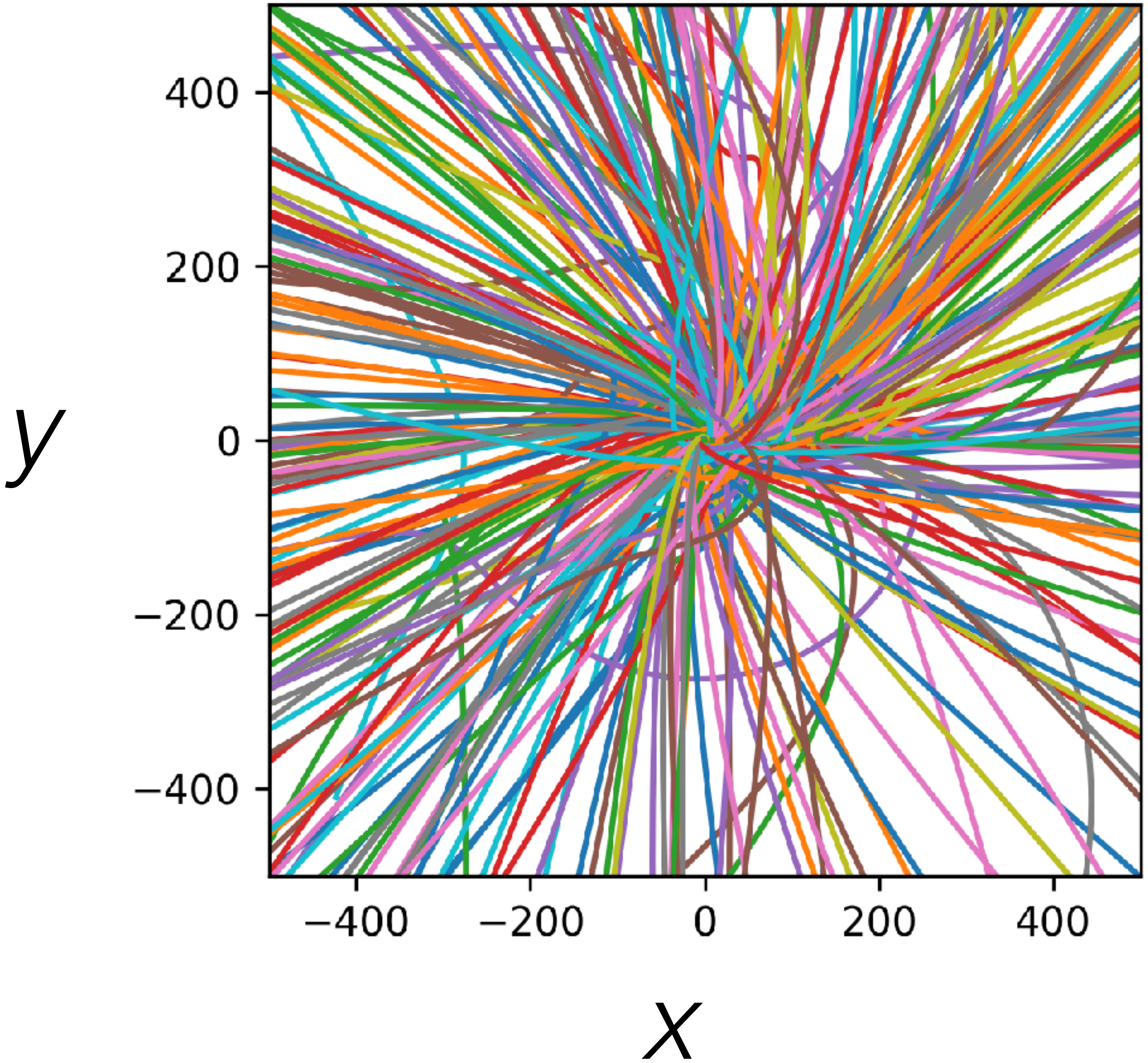
Work in progress



Units of GM/c^2

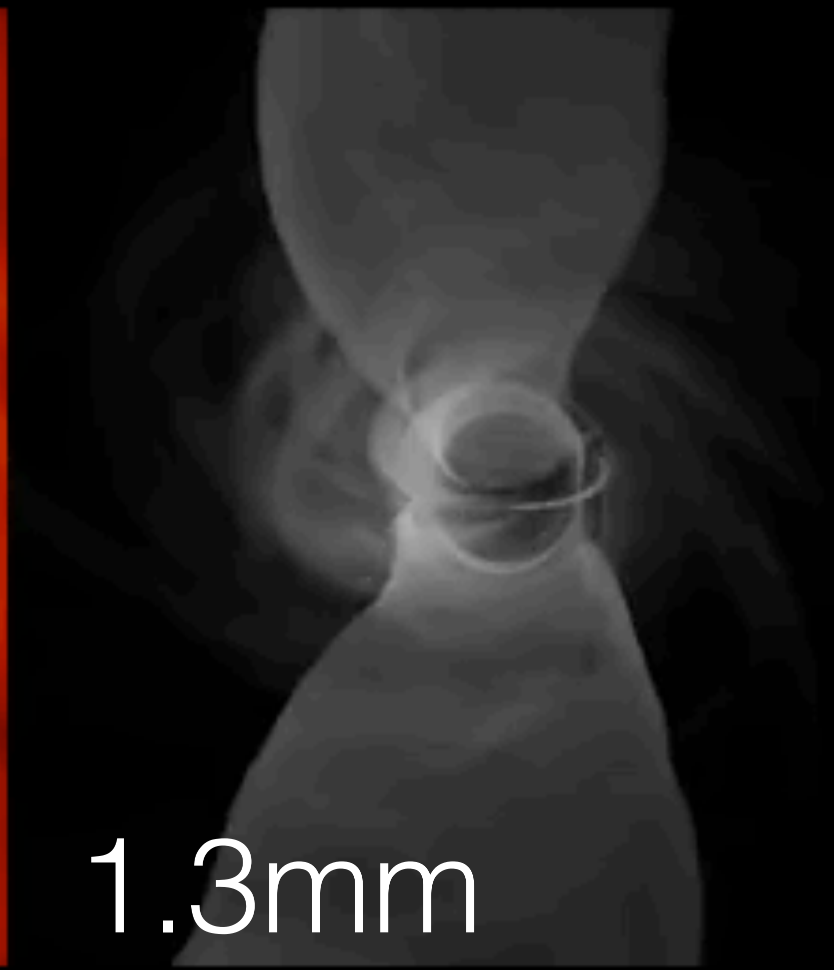
Preliminar result: Null geodesics in x-y plane around Kerr black hole

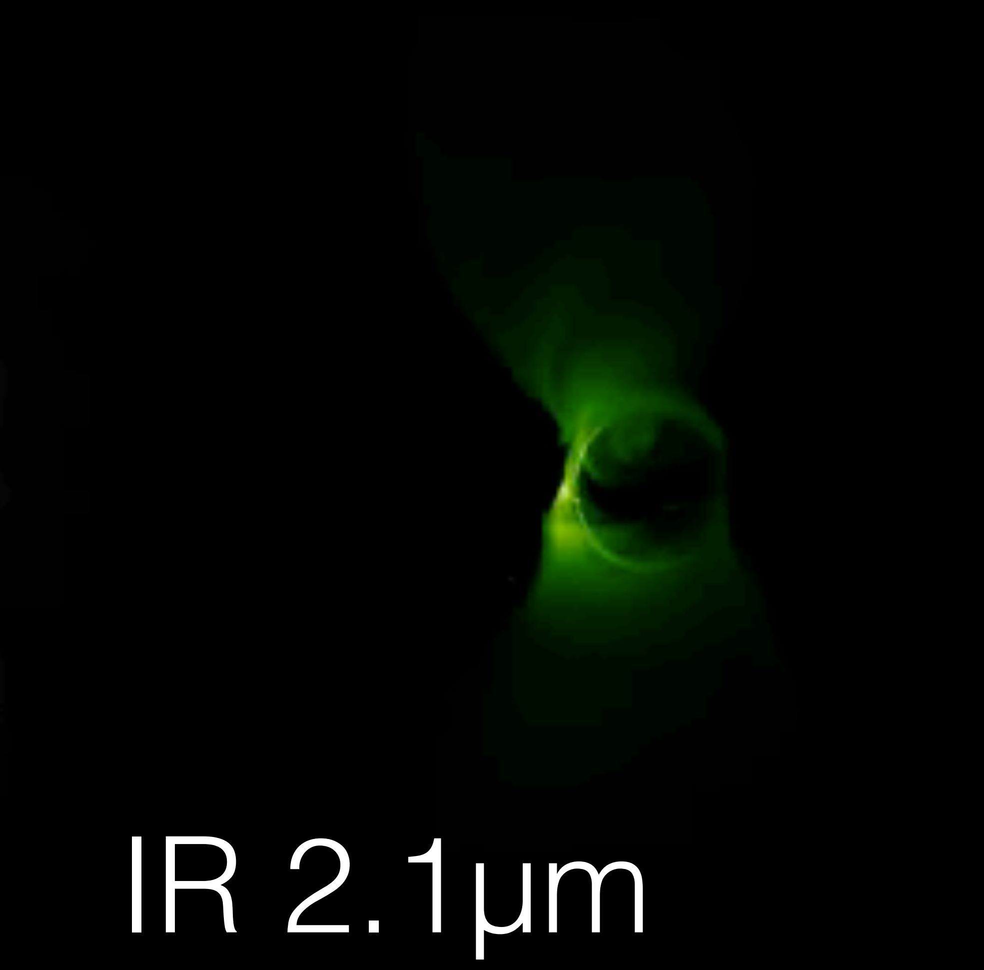
Work in progress

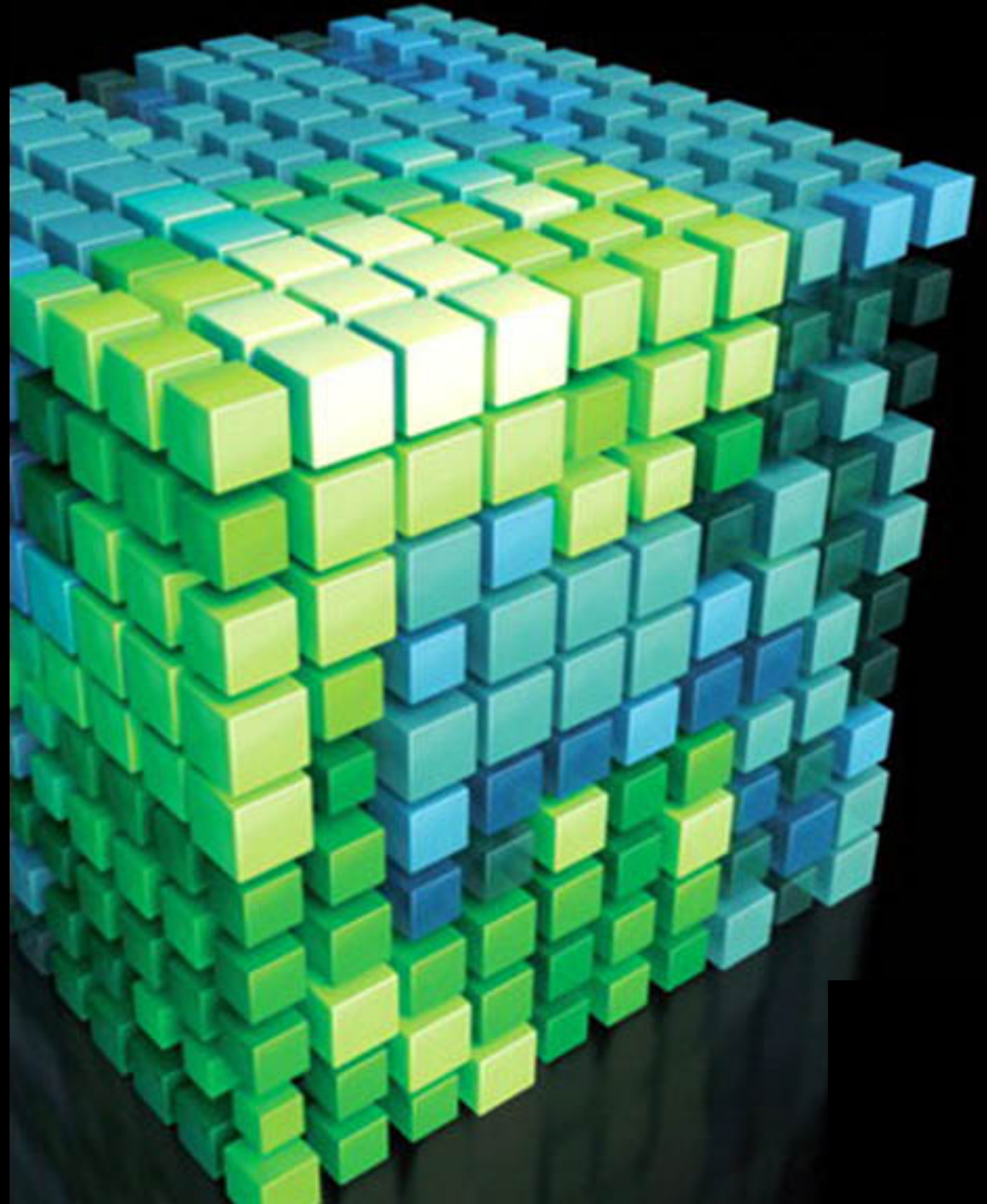


Units of GM/c^2

Future: Radiative transfer and GPU-accelerated ra tracing in BH spacetimes





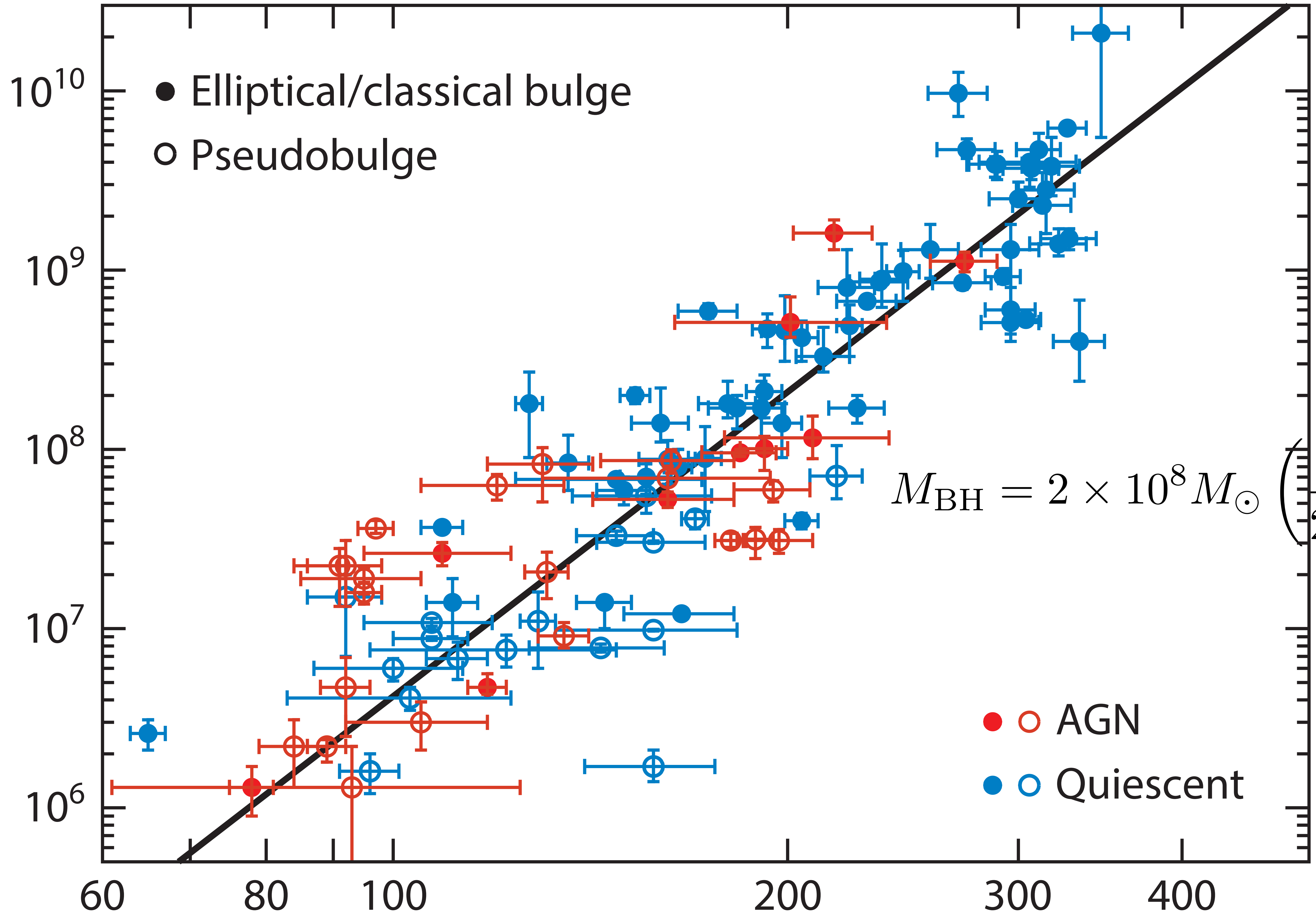


Chan+15a,b ApJ

Remarkable connection between central black holes and host galaxies: the *M-σ* relation

Fundamental link between BH growth and galaxy evolution

mass central black hole



$$M_{\rm BH} = 2 \times 10^{8} M_{\odot} \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right)^{5.6}$$

host galaxy propriety: σ_{bulge} (km/s)

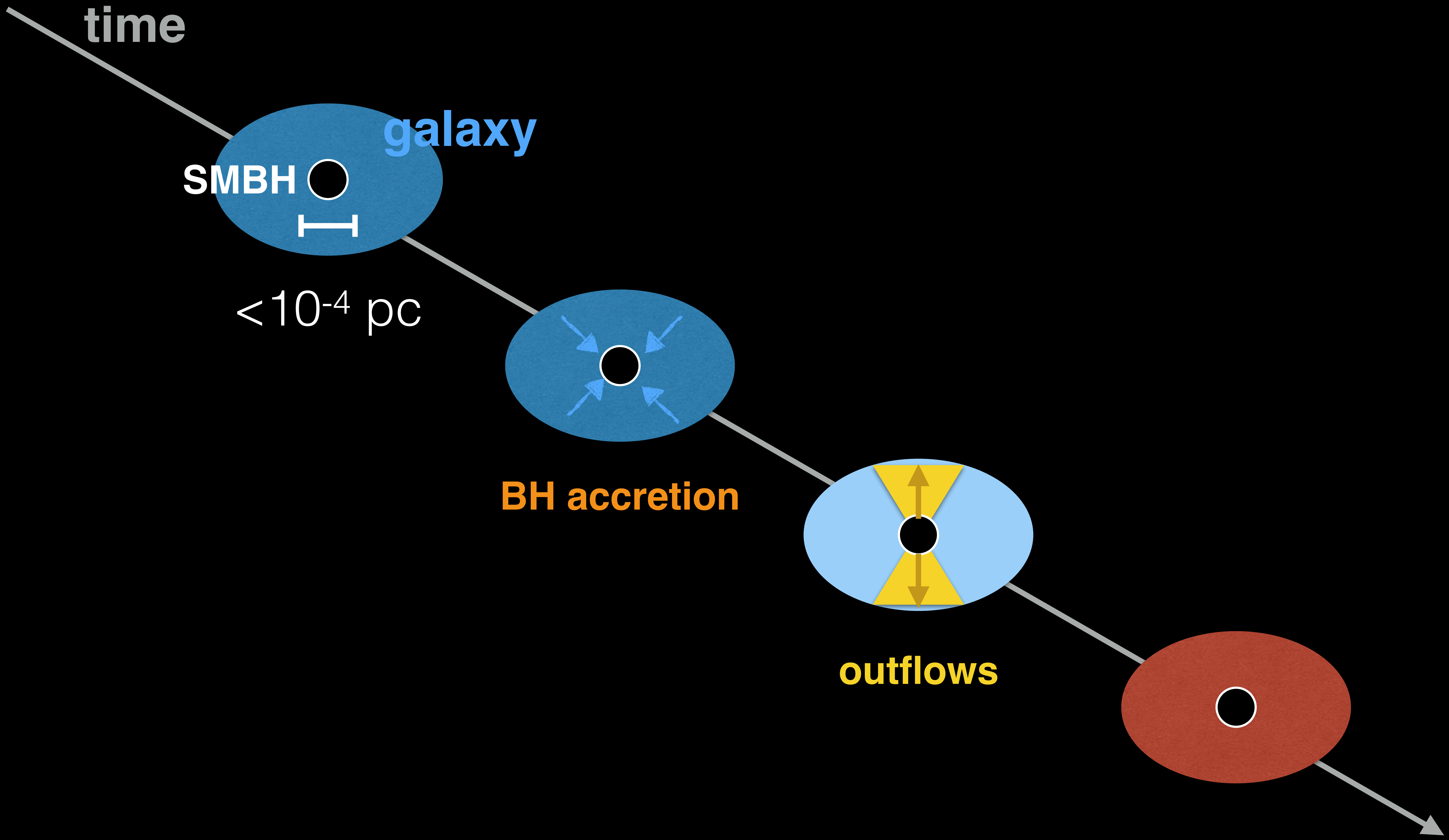
Woo+13; McConnell & Ma 13; Heckman & Best ARA&A 14

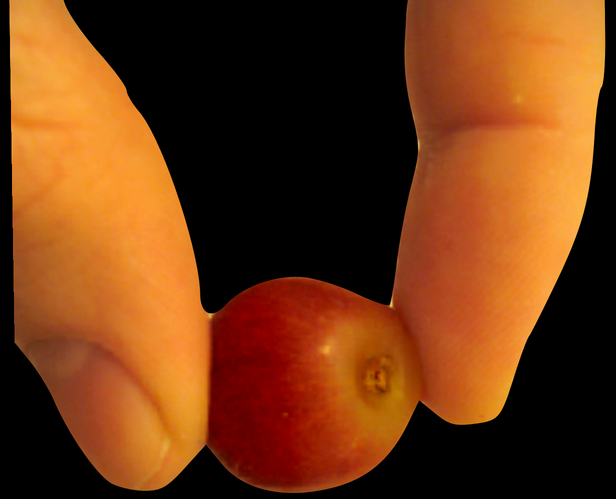
Why are black holes and host galaxies connected?

SMBH

Grapefruit

Energy release from supermassive BHs impact large scale structure formation ("AGN feedback")

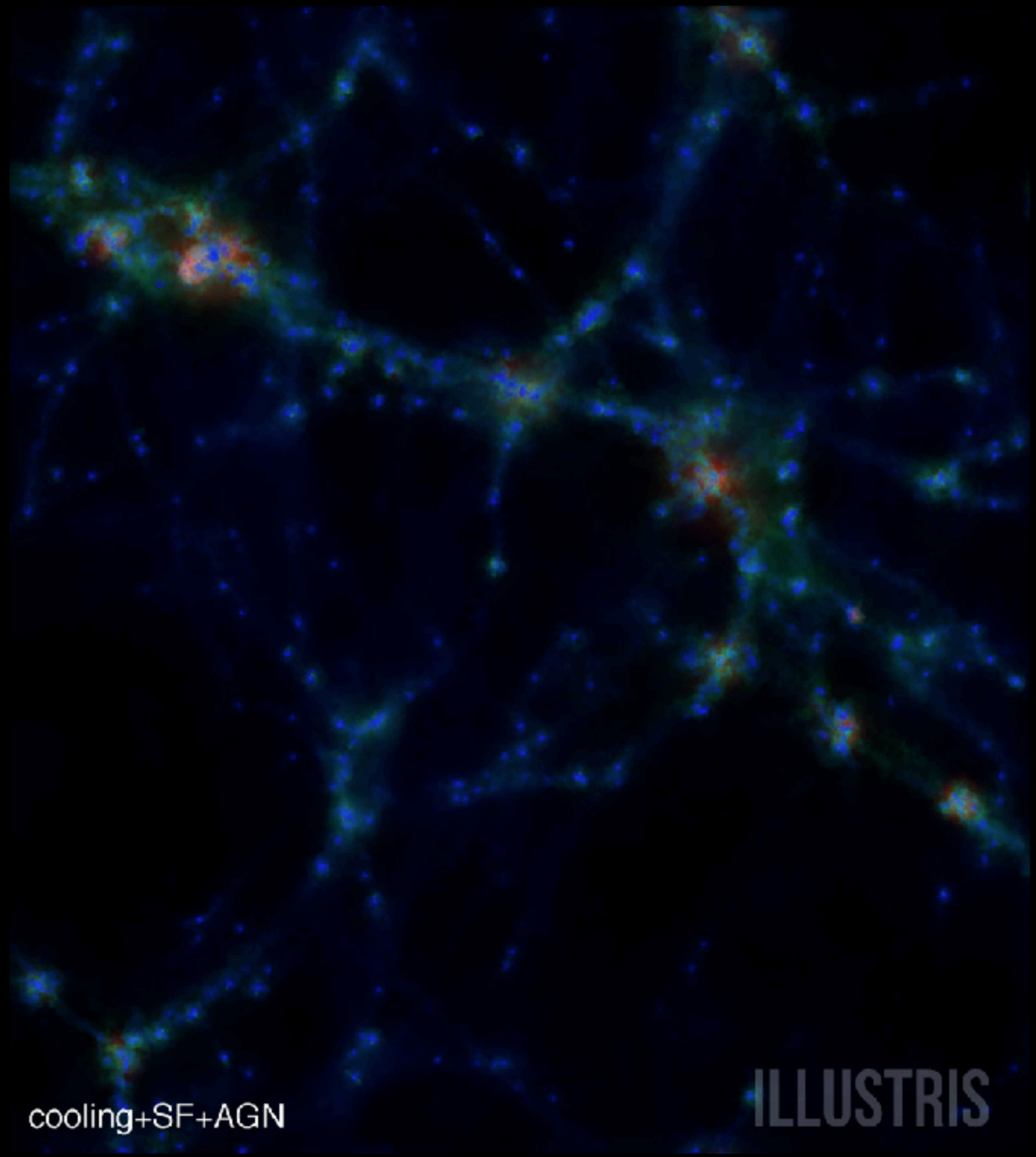




- [ ] How do supermassive black holes affect their host galaxies?
- [ ] What is their cosmological evolution?

Energy release from supermassive BHs impact large scale structure formation ("AGN feedback")

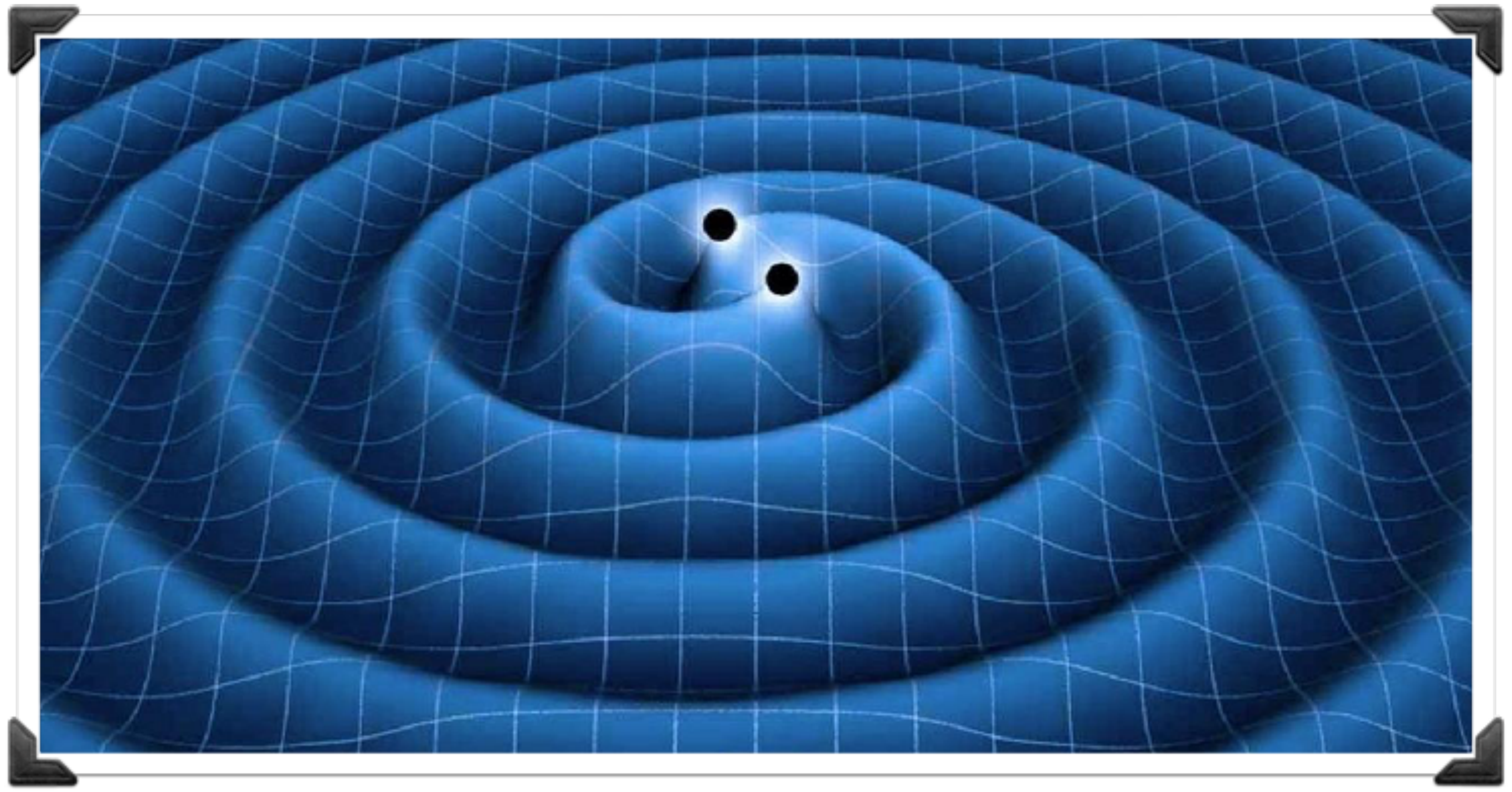
10 Mpc



"BH explosions" in the simulation

Fabian 12 ARAA; Tombesi+15 Nature;
Cheung+16 Nature; Vogelsberger+14 Nature

Gravitational waves



open GWs for undergrads.key

Attaining the impossible: first image of an event horizon just around the corner

PI: S. Doeleman (MIT/Haystack)
idéia original: H. Falcke (Radboud)

Goal of Event Horizon Telescope

Credit: Warner, Paramount

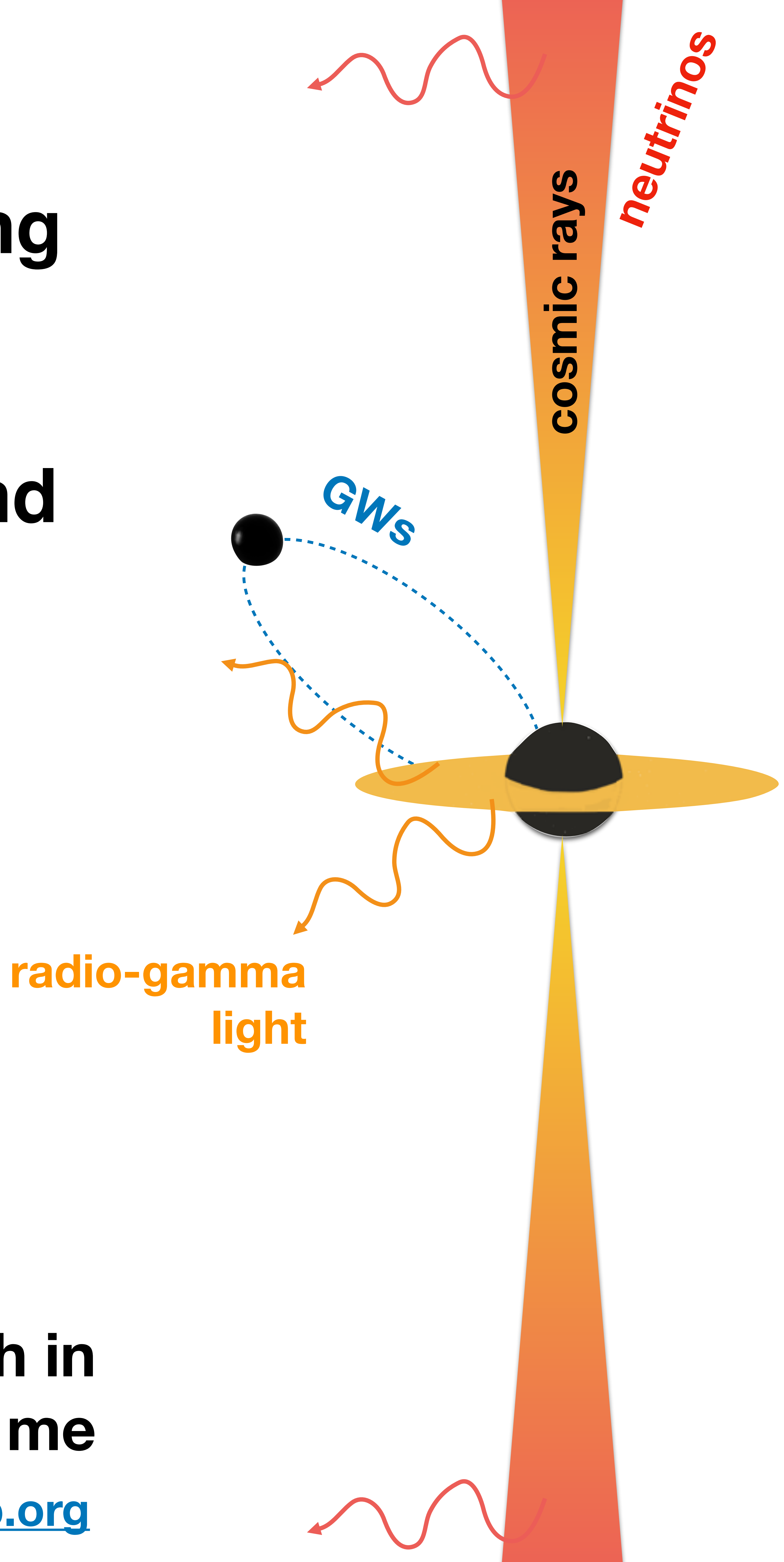
Summary: Black holes

- Black holes: collapsed objects from which nothing can escape (once inside)
- Astrophysical labs of general relativity, fluid dynamics and electrodynamics that can't be found on Earth

☆ Brightest systems in the universe
☆ Important for galaxy formation/evolution

☆ Cosmic particle accelerators
☆ Sources of gravitational waves

Soon: first image of a black hole



If interested in doing research in these topics, please talk to me

blackholegroup.org

Quiz time!

https://kahoot.com/

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