General relativity and black holes

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General relativity primer

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

$$M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12 \partial_\mu A_\nu \partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H -$$
$$\frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac14 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac43 s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1 - \frac83 s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac g2\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac g2\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 -$$

5

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

gluon (strong force)

W and Z bosons (weak force)

weak interactions + Higgs

Higgs ghosts

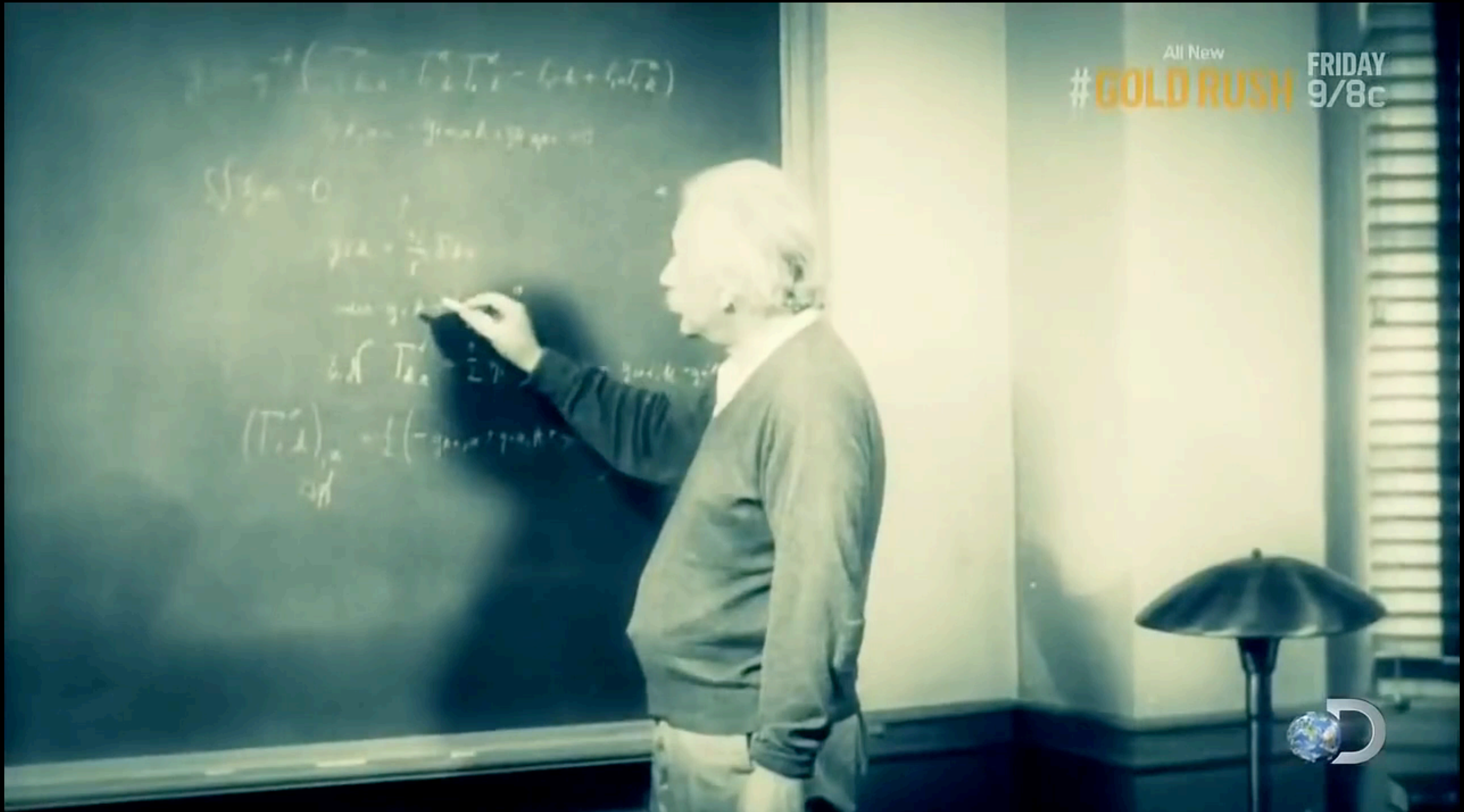
Faddeev-Popov ghosts

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

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

slides from black hole primer for undergrads

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

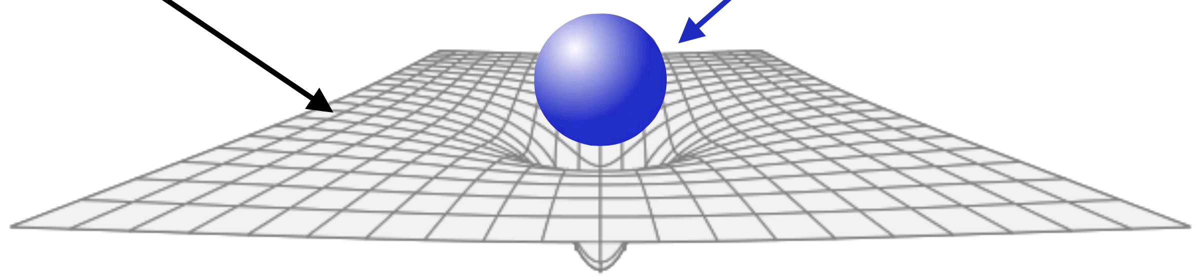
A general relativity primer

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

$\Rightarrow$ spacetime curvature = constant × matter-energy

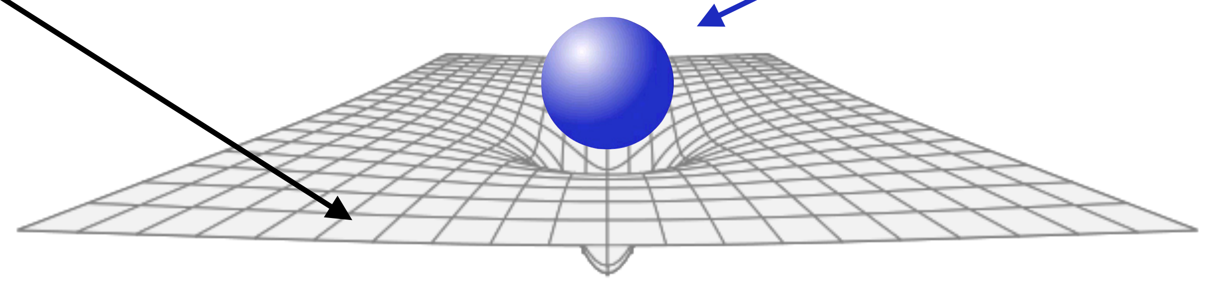


A general relativity primer

Einstein's field equation

$$\underbrace{R_{\mu\nu}}_{\text{Ricci curvature}} - \frac{1}{2}\underbrace{g_{\mu\nu}}_{\text{Metric}}\underbrace{R}_{\text{Ricci scalar}} = \frac{8\pi G}{c^4}\underbrace{T_{\mu\nu}}_{\text{Stress-energy}}$$

$\Rightarrow$ spacetime curvature = constant × matter-energy



Solution to field equation gives

$$\underbrace{g_{\mu\nu}}_{\text{Metric}} \qquad \underbrace{ds^2 = g_{\mu\nu}dx^\mu dx^\nu}_{\text{Line element}}$$

Newtonian analogue

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

For a free particle:

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

Geodesic equation

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

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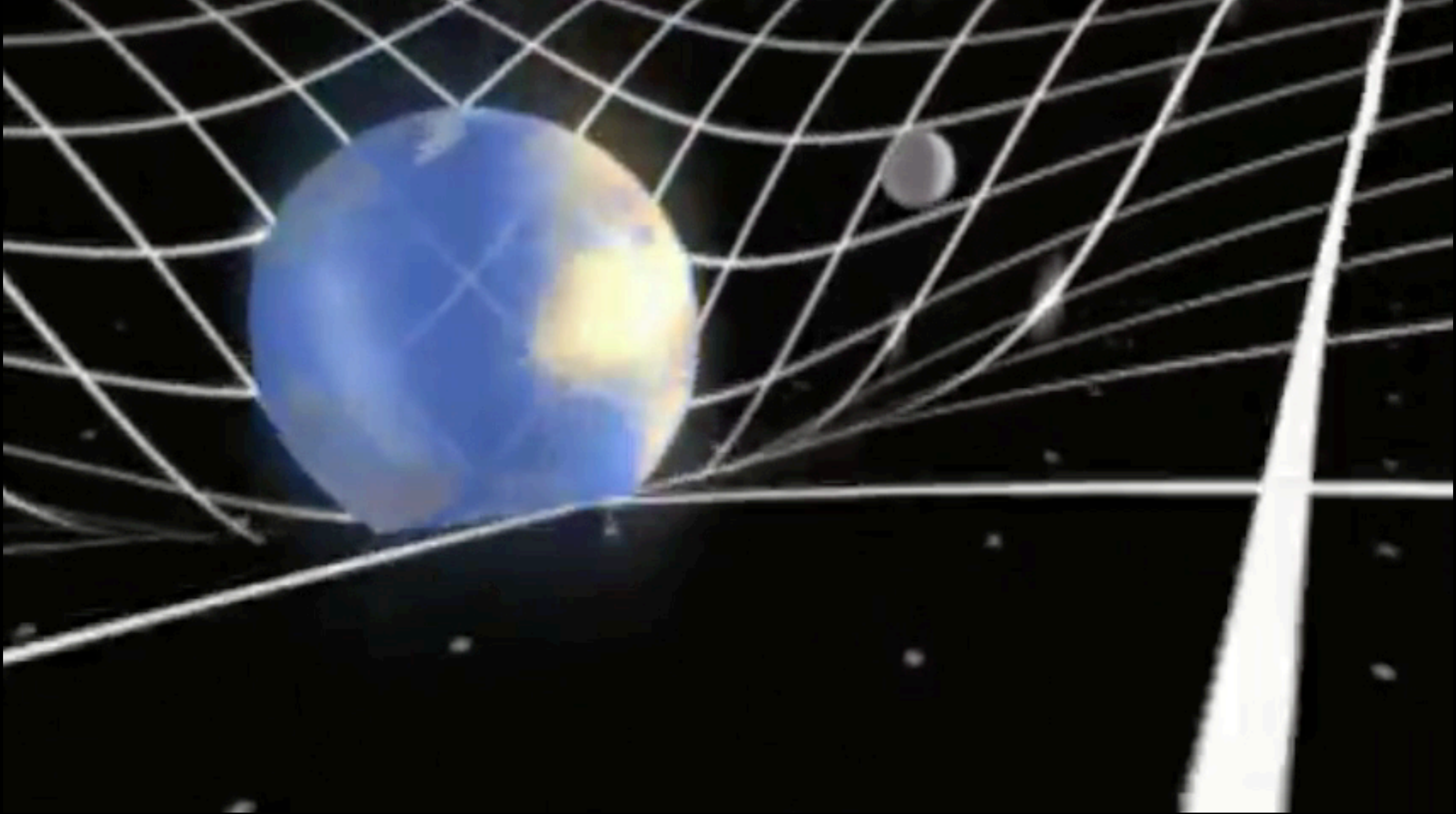

The Elegant Universe. Nova / PBS

A concise tutorial on general relativity

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General relativity primer

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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.

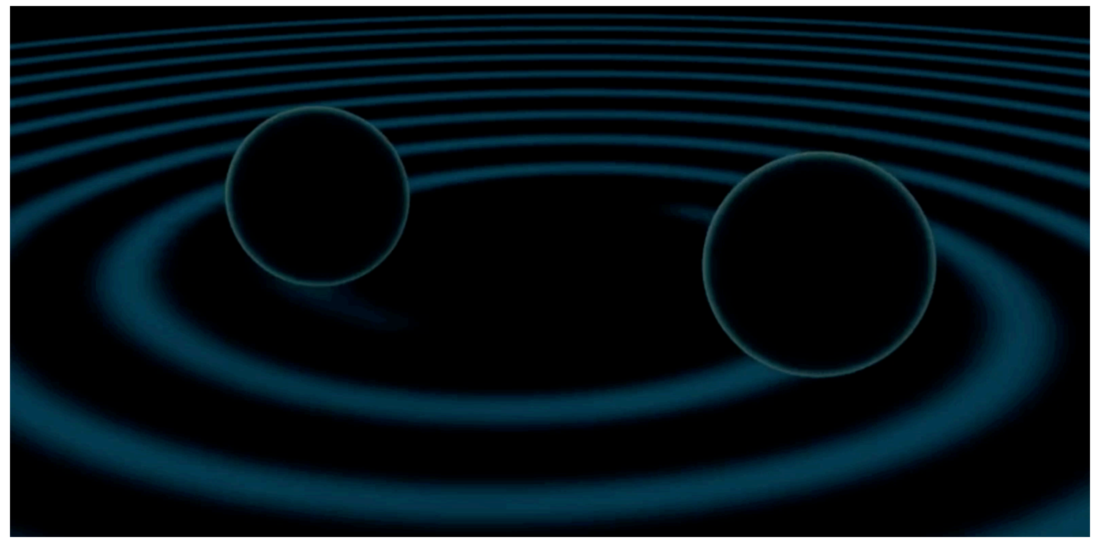
I assume that the reader comes to this article with two prerequisites: First, a familiarity is required with partial differential equations and their application in physics, as would certainly result from, say, a junior- or senior-level course in electrodynamics. Experience with partial differential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

General relativity is a classical theory

- All equations of motion are deterministic. No probabilities involved
- Once we specify the initial positions and velocities of particles, everything is determined!
- Evolving the gravitational field and matter dynamics for astrophysical situations can be challenging → 🖥️

$$\cancel{\Psi(x,t)}$$

$$x^\mu,\ v^\mu$$



from GR undergraduate course, introduction

Once initial conditions are given, the physical truth is perfectly determined

Some *important properties* of gravitational interaction

Gravity is unscreened: there are no negative gravitational charges. It is not possible to shield the gravitational field

Gravity is a long-range interaction. There is no characteristic length scale for gravitational interactions

Gravity is the weakest of fundamental interactions between elementary particles.

These explain why gravity plays such a pivotal role in the universe

Gravity governs large scale structure formation in the universe

Phenomena for which general relativity is important

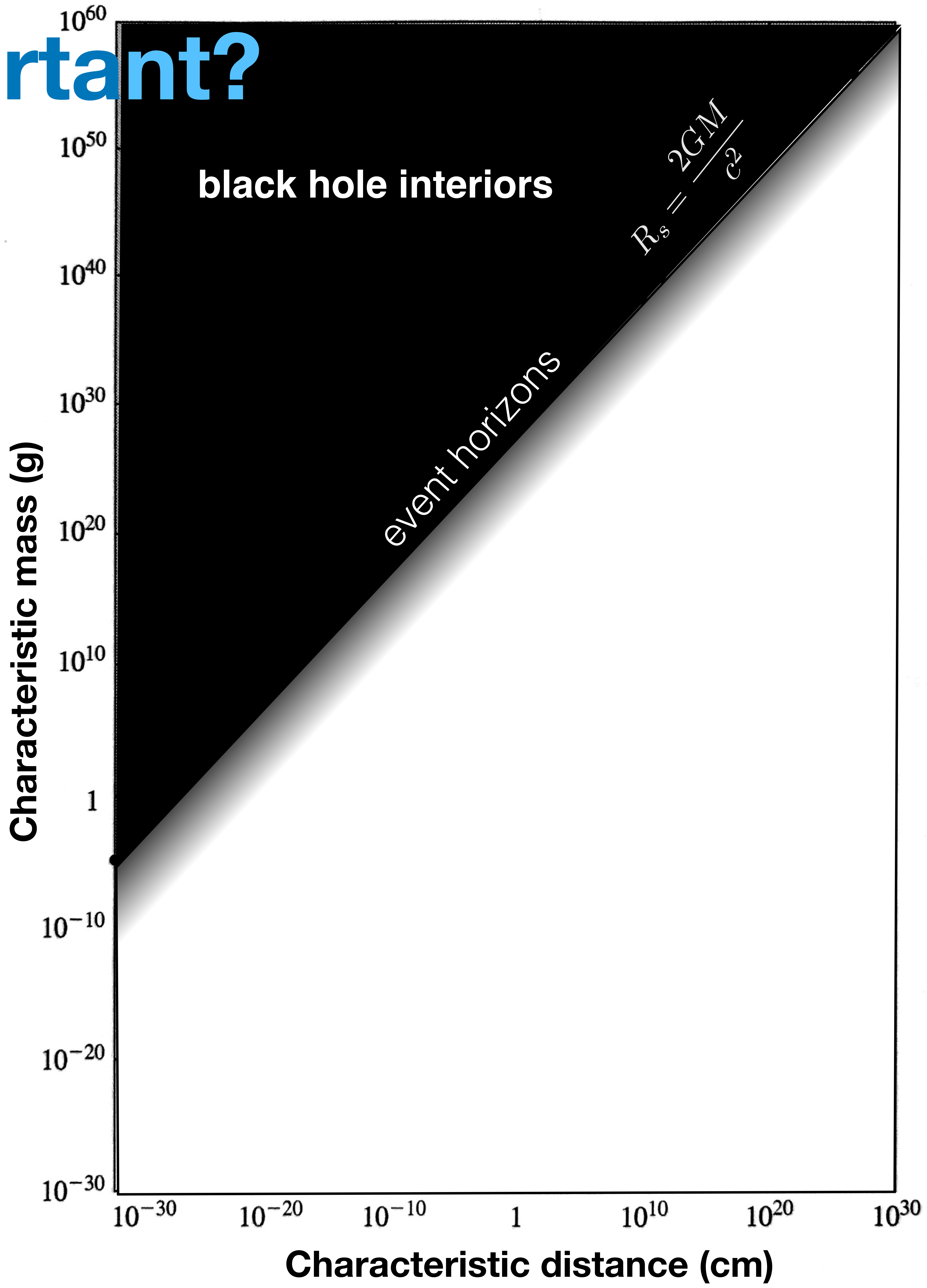
When is general relativity important?

vs. Newtonian gravity

Given object of mass *M* and size *R*

GR (general relativity) is important when

$$\frac{GM}{Rc^2} \to 1$$



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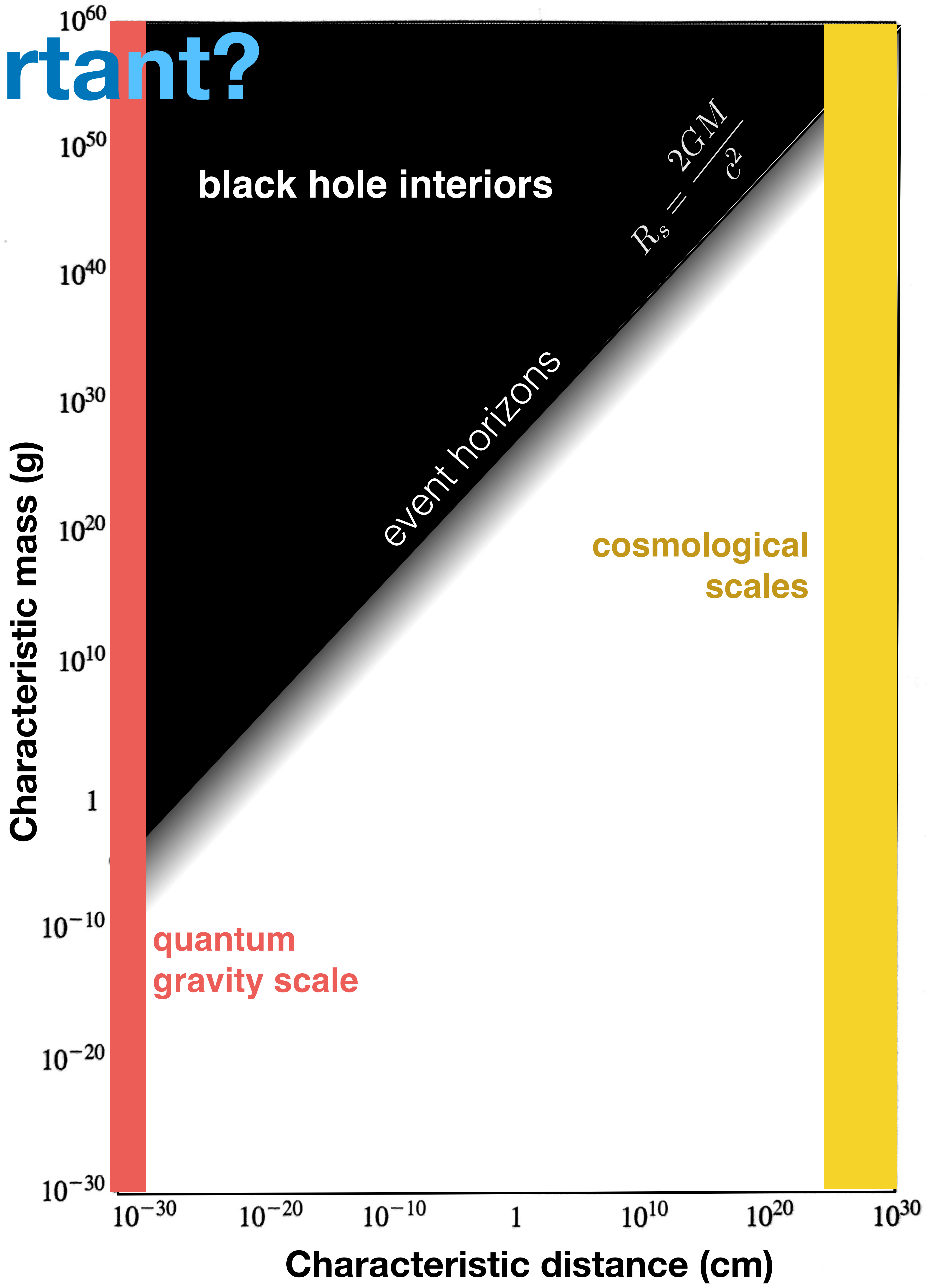

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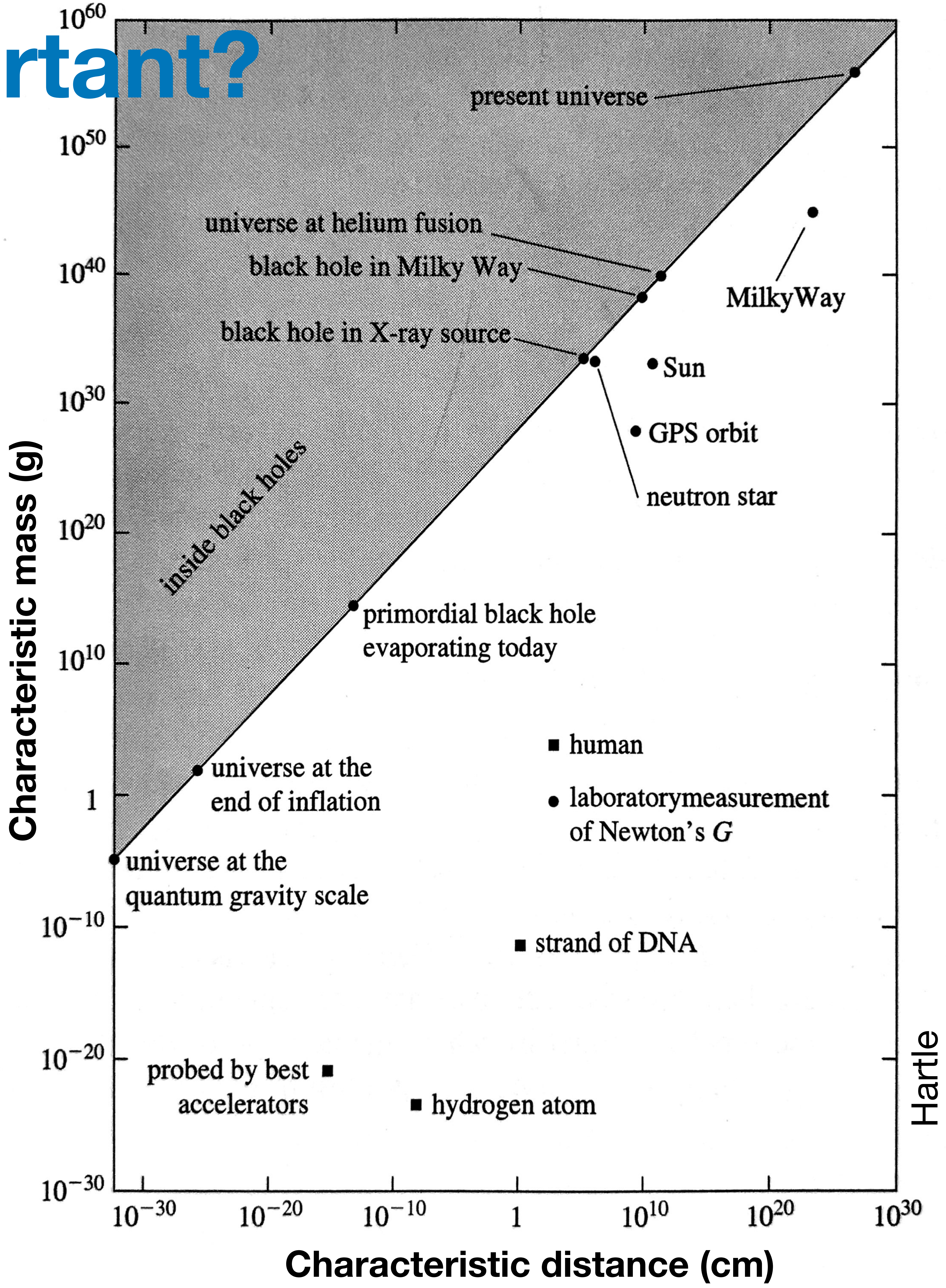

When is general relativity important?

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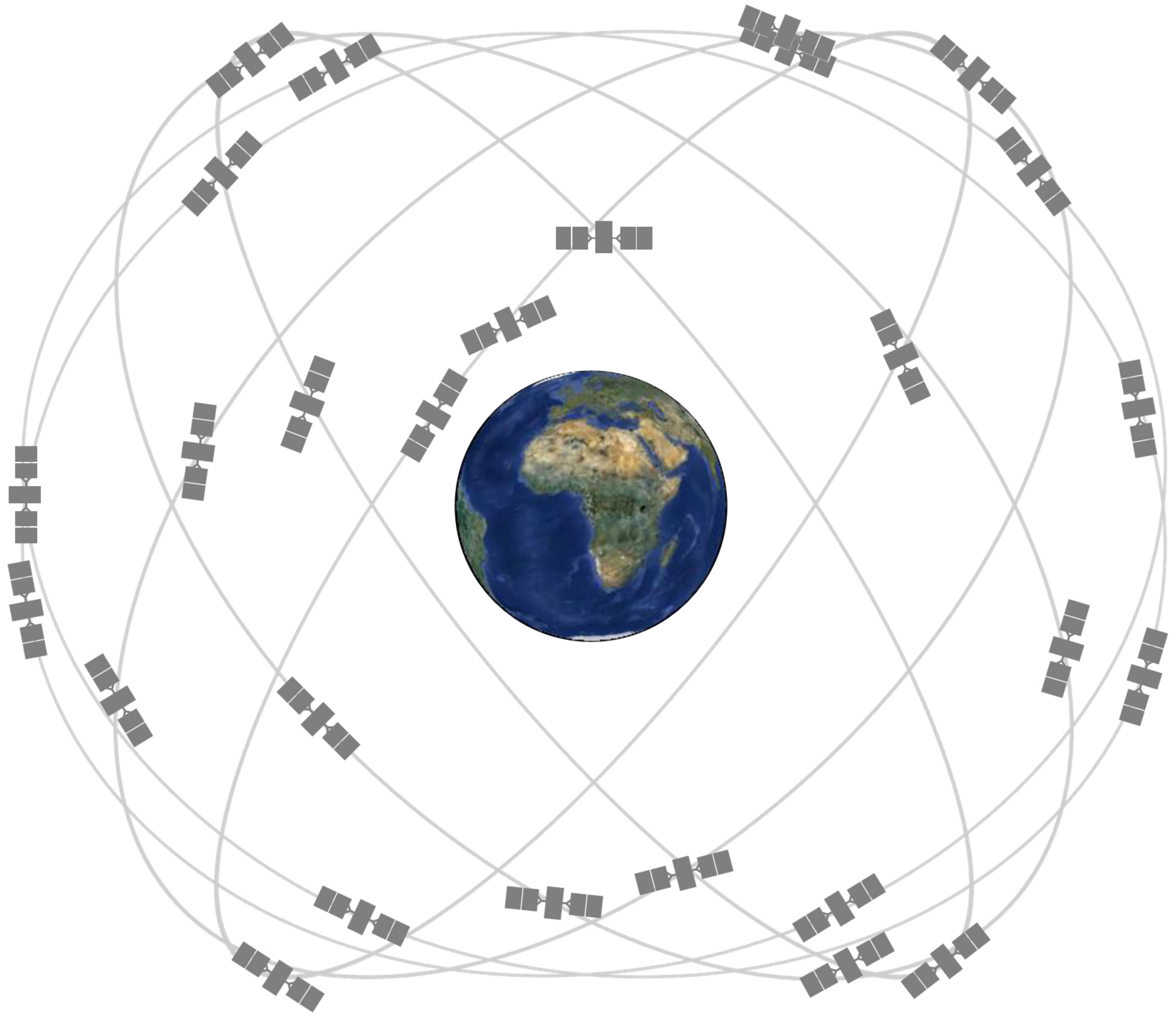

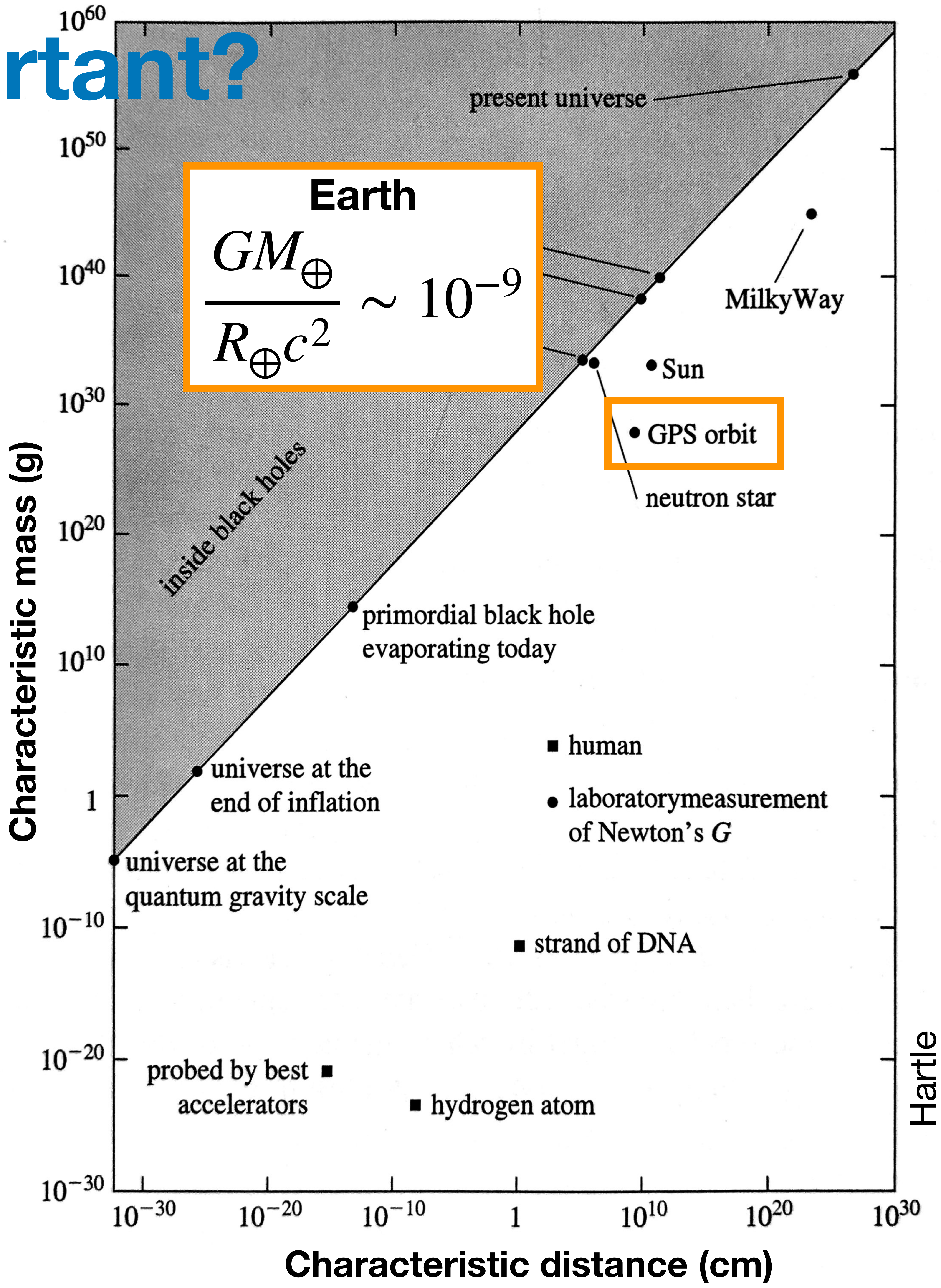

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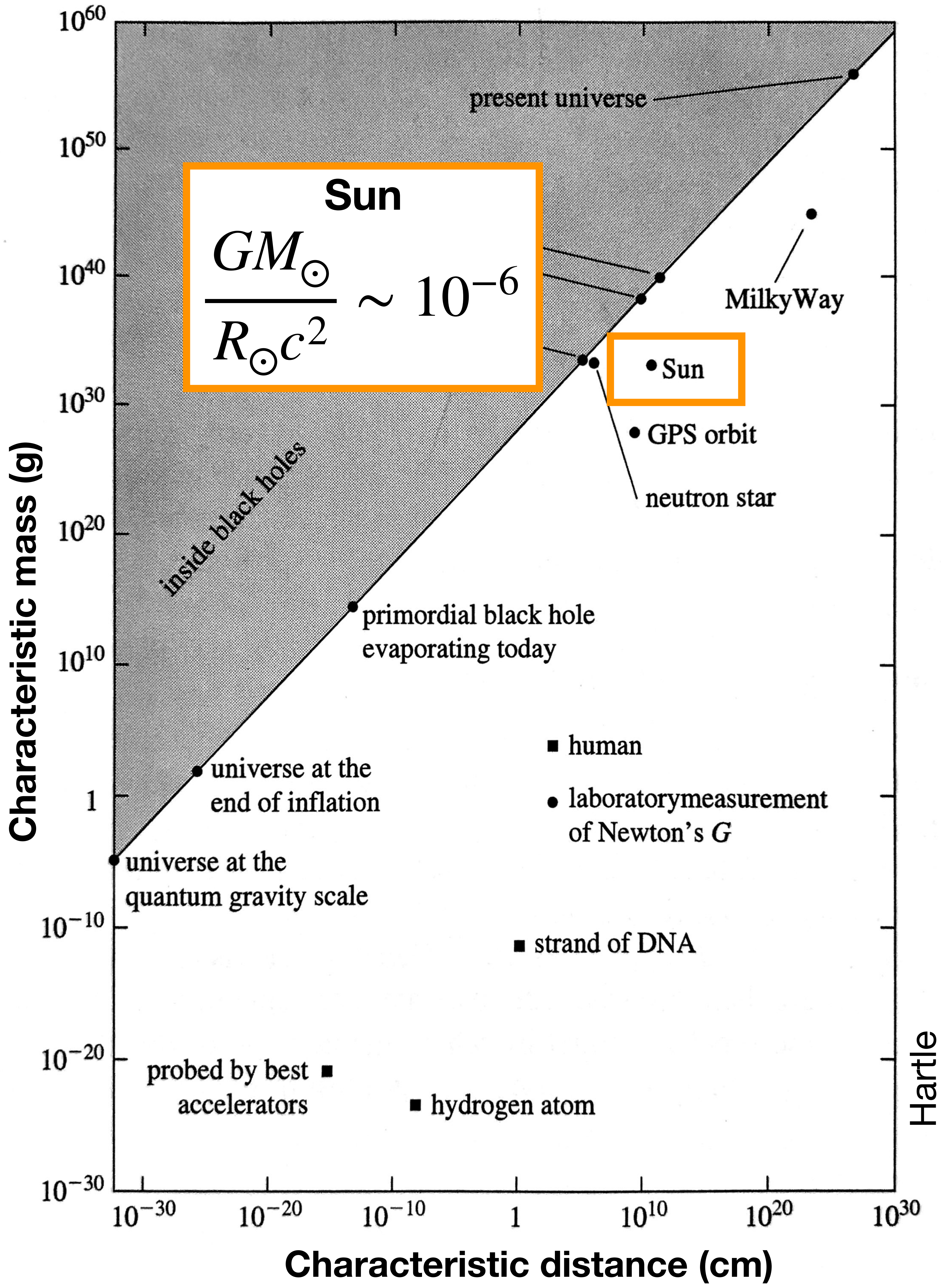
Solar System

Precession of perihelion of Mercury

Bending of path of light rays passing near the Sun



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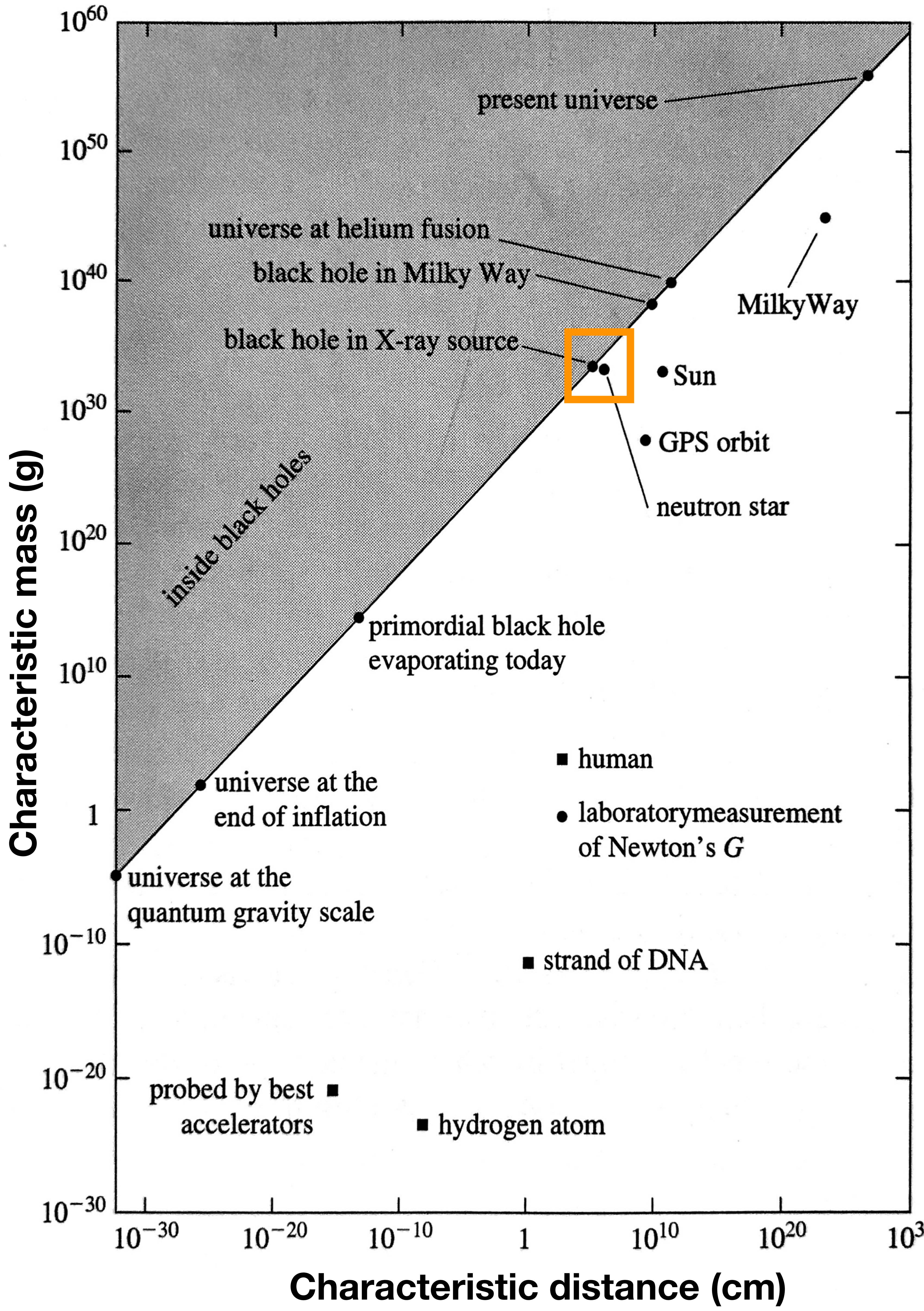
Neutron stars

$M \lesssim 3M_\odot$ **(maximum mass)**

radius ~ 10 km

$$\boxed{\frac{GM}{Rc^2} \sim 0.1}$$

Credit: NASA's Goddard Space Flight Center/CI Lab



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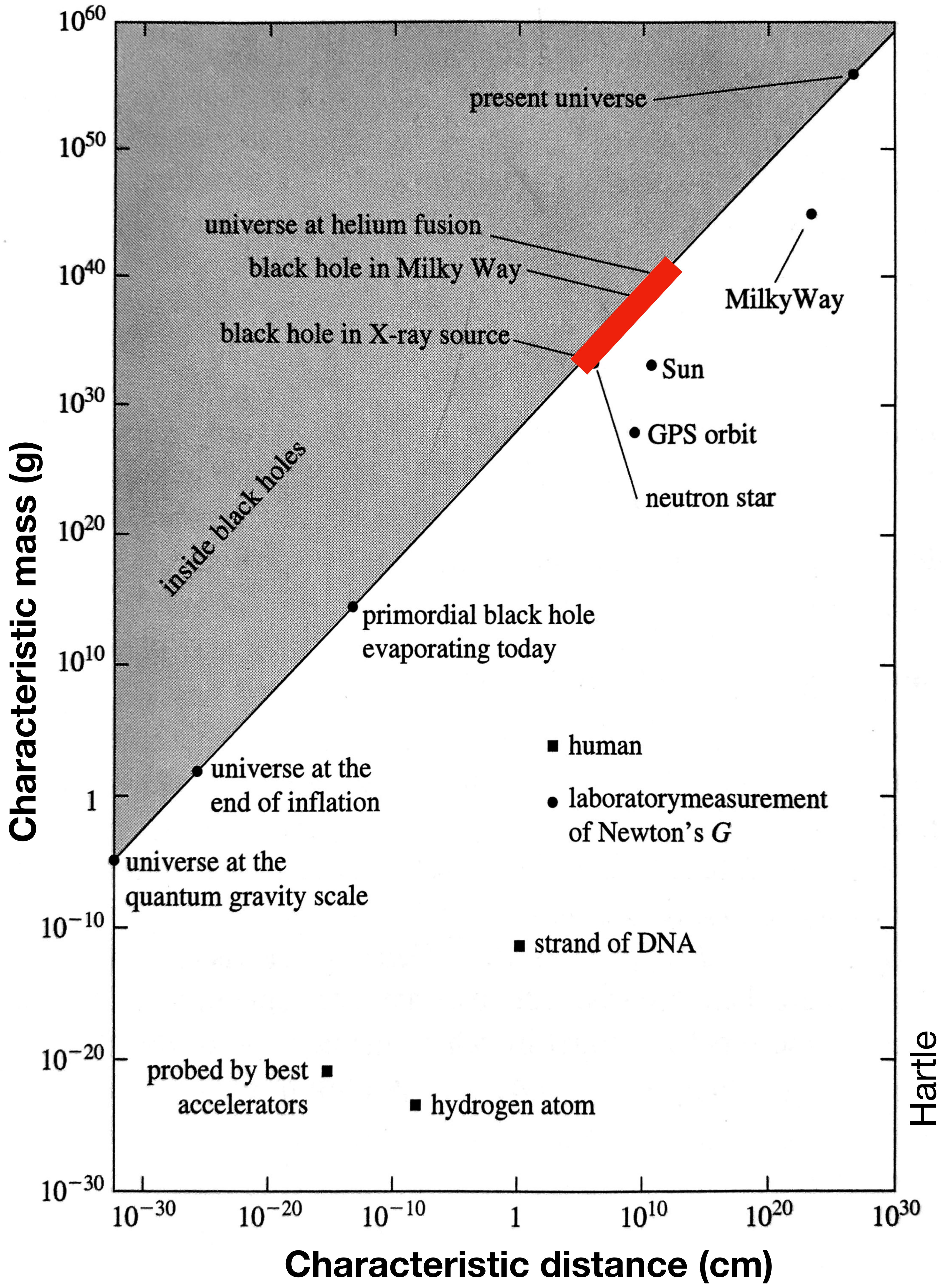
Black holes

$$M \gtrsim 3M_\odot$$

$$\boxed{\frac{GM}{Rc^2} = 0.5}$$



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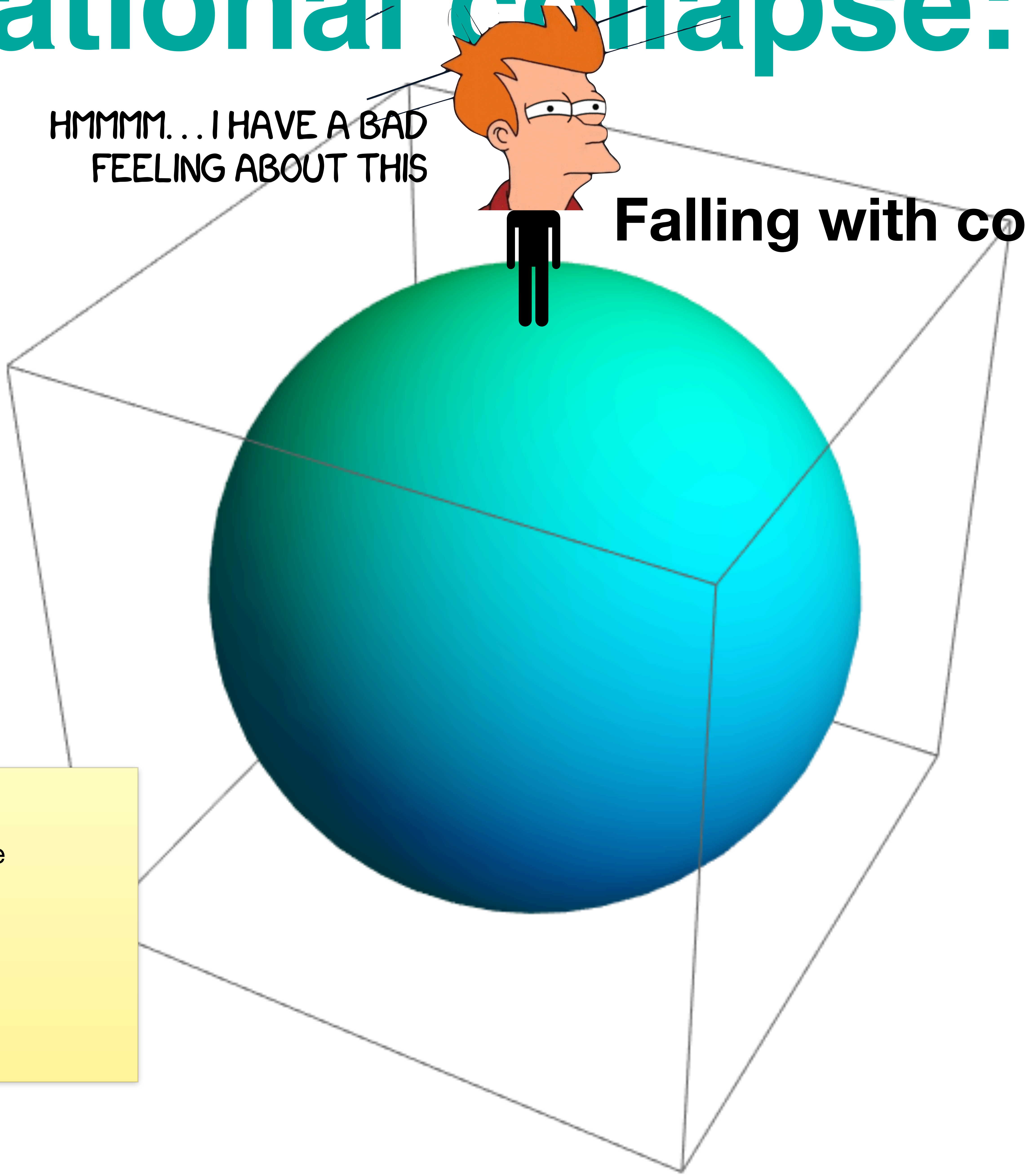
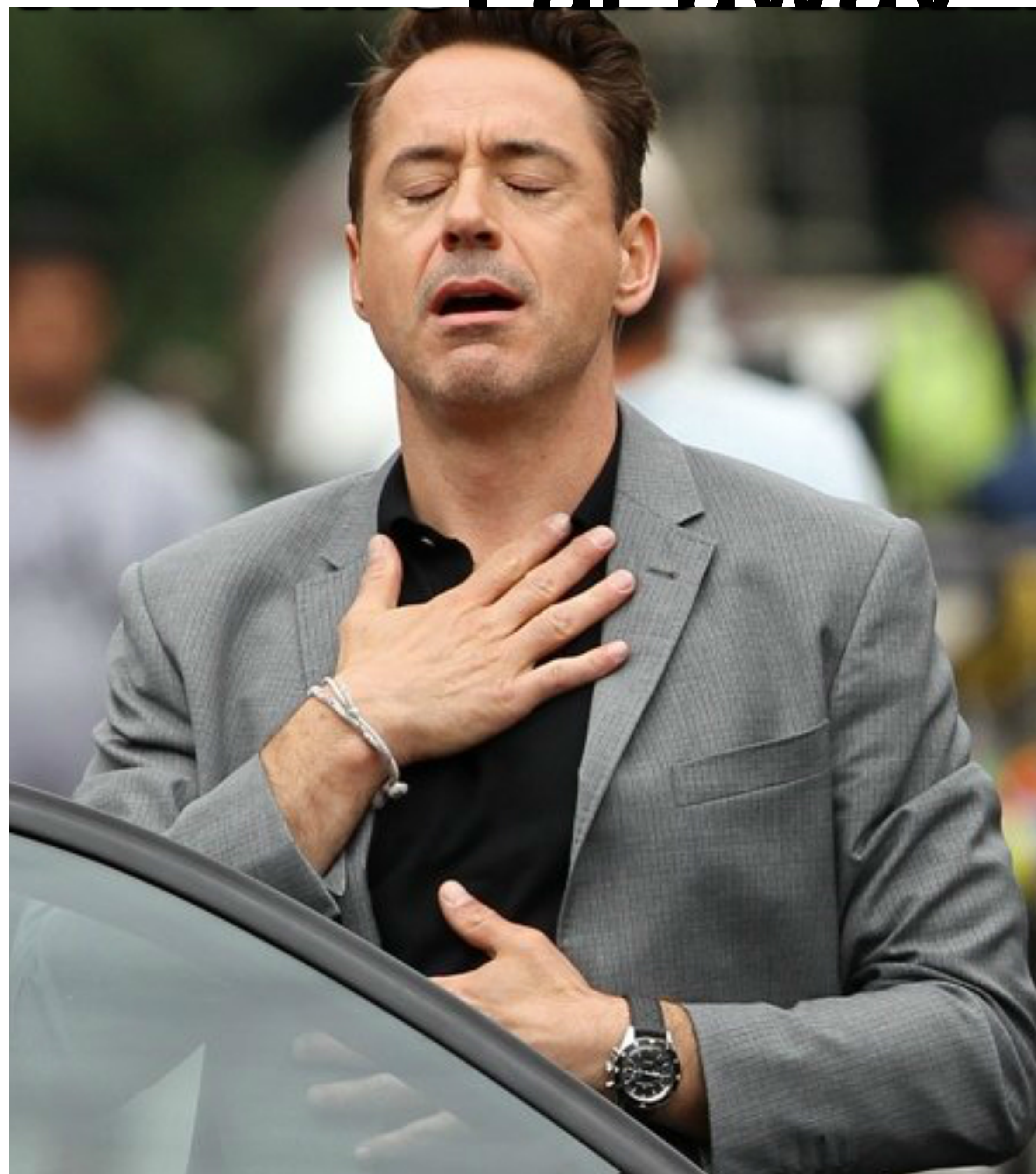
Analysis of gravitational collapse leading to a BH

Gravitational collapse: Two views



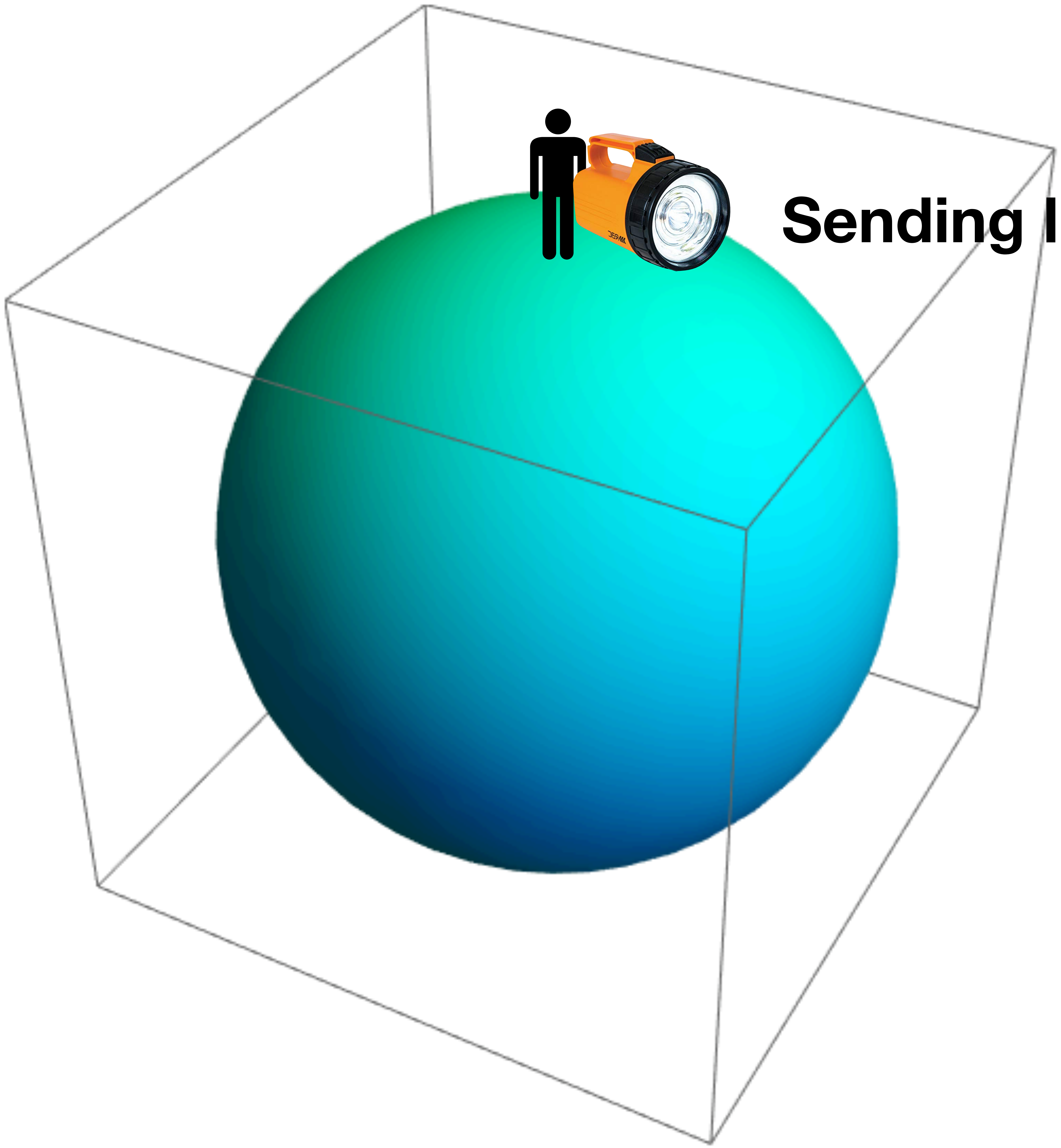
Falling with collapsing star

Far away



slides from GR undergraduate course, black holes

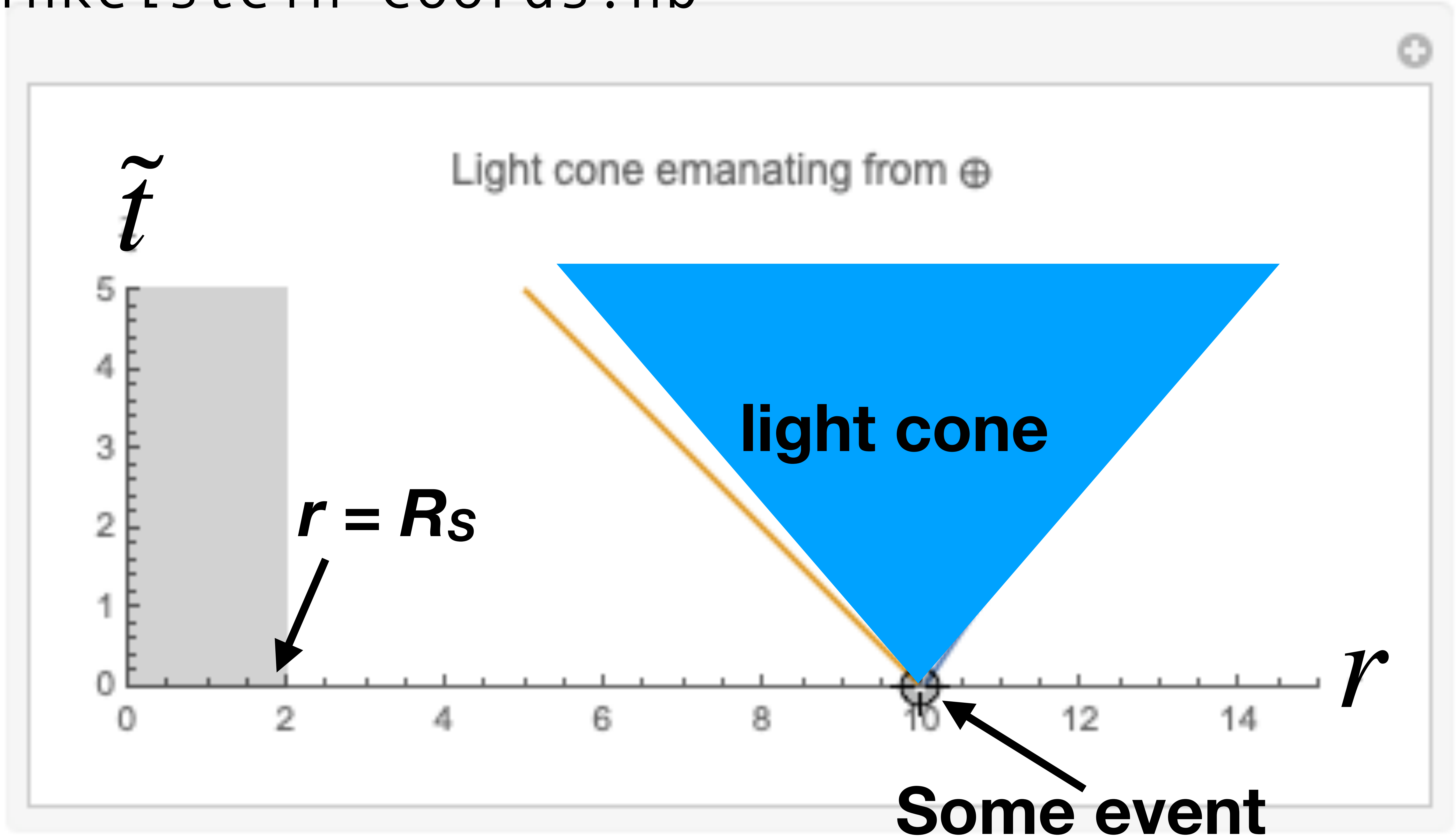
Gravitational collapse: View from inside



Sending light rays at regular intervals

Light rays in Schwarzschild spacetime

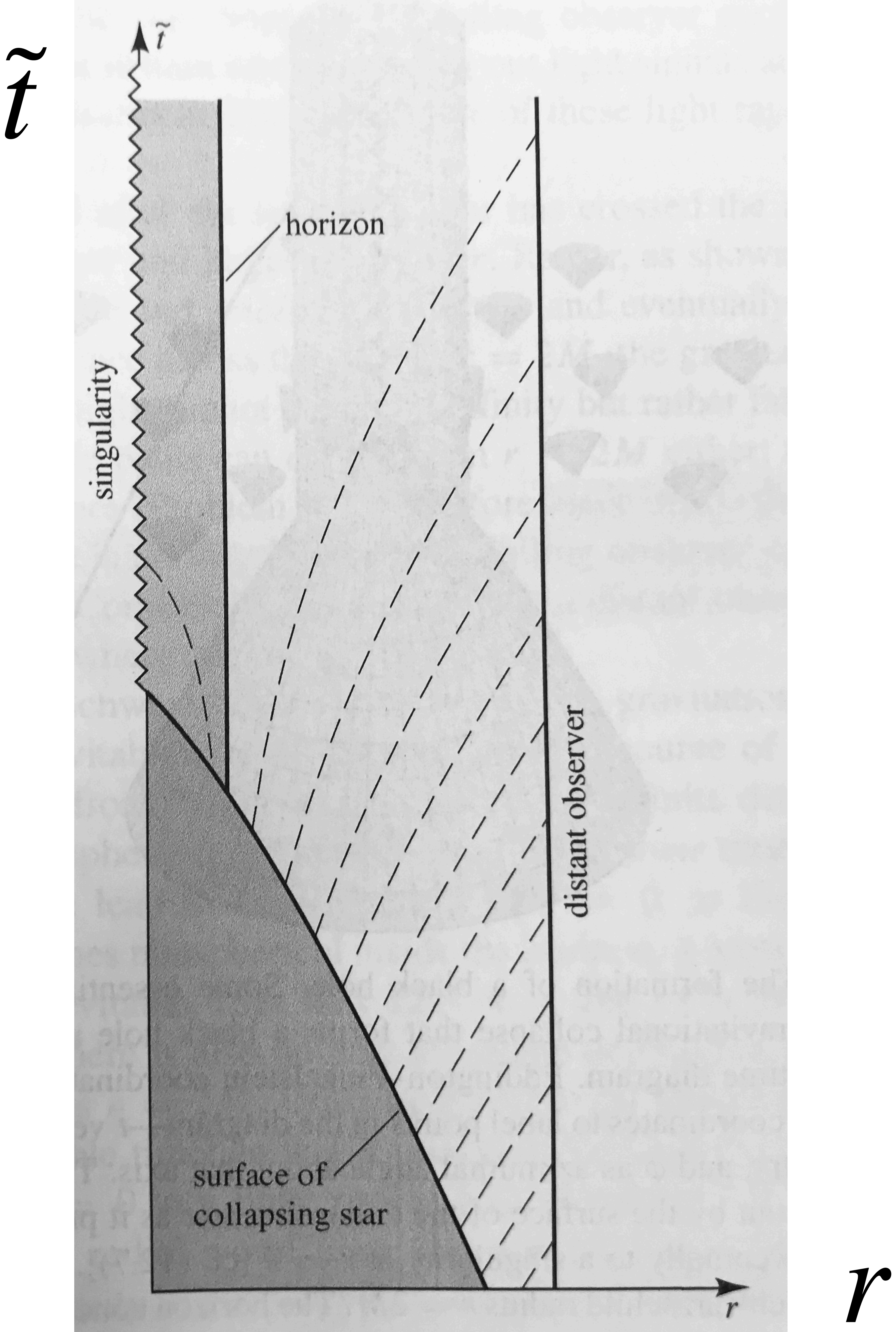
GOTO Mathematica: `light-rays near black holes, Eddington-Finkelstein coords.nb`



Schwarzschild radius

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

Spacetime diagram of gravitational collapse



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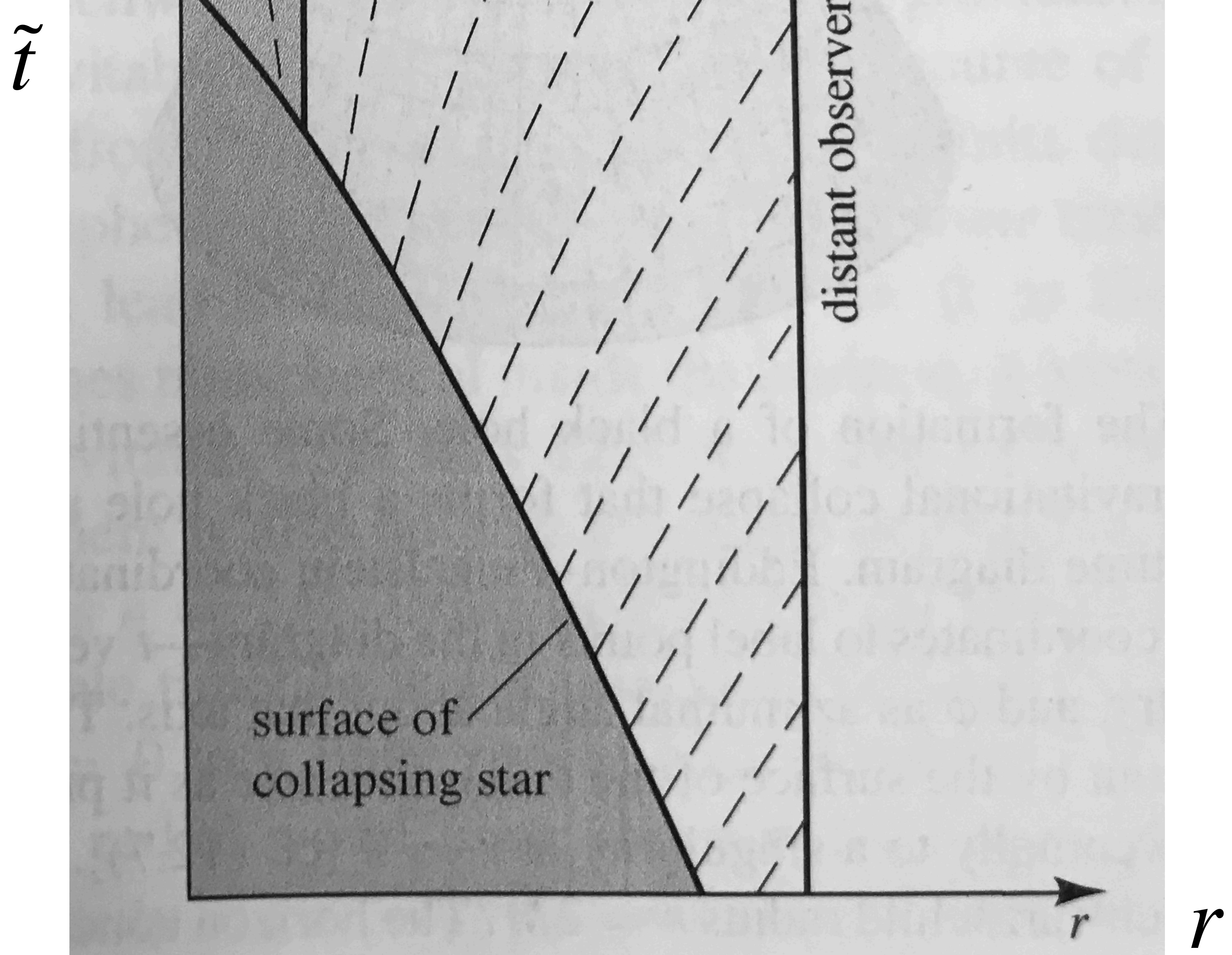
View from inside



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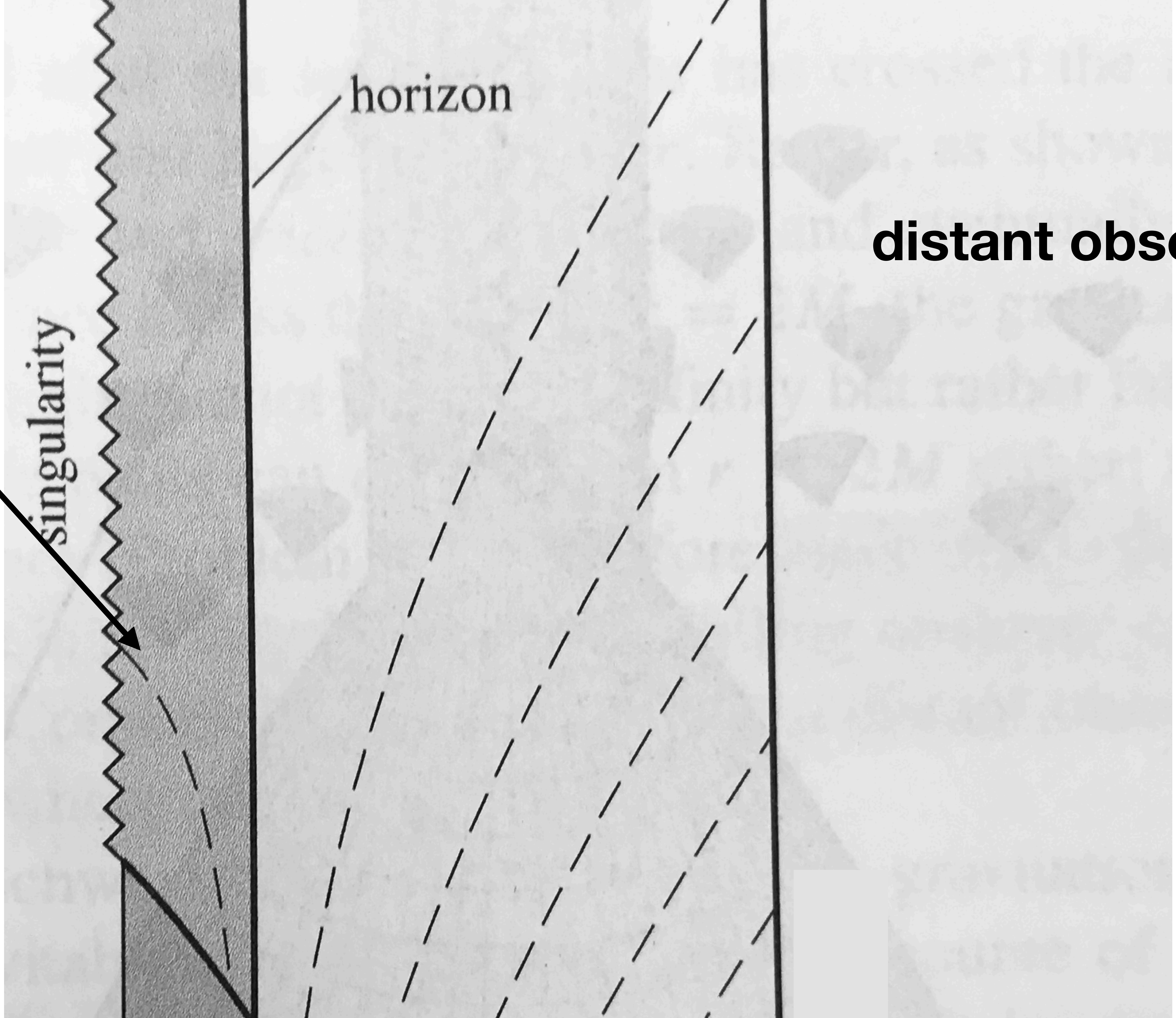
$\tilde{t}$



distant observer

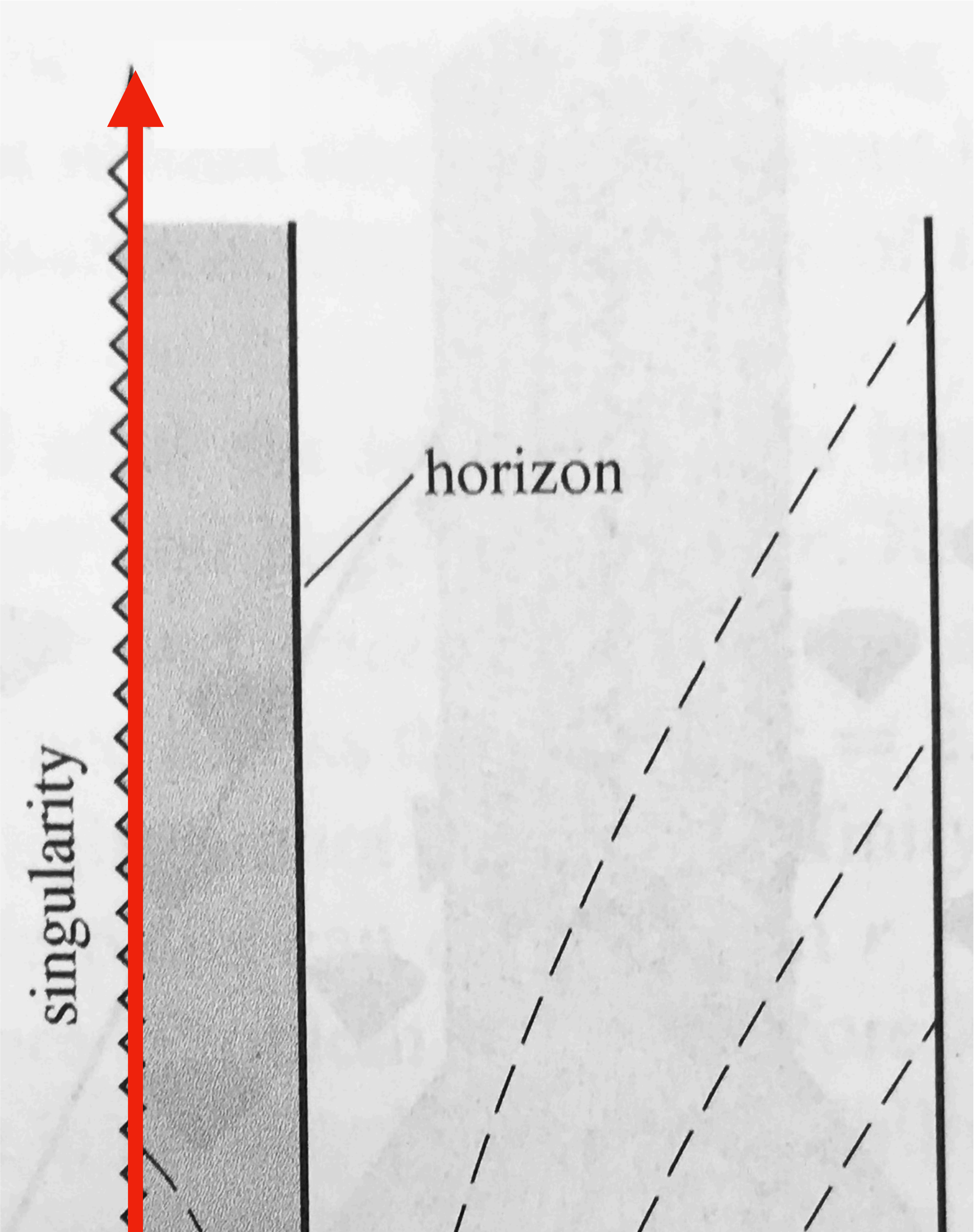
once inside r_S=2M, falling observer cannot communicate with distant one anymore

Collapse to singularity at r=0 is inevitable

r

Hartle

$\tilde{t}$



PAREI AQUI...

distant observer

Singularity hidden from observers outside black hole

r

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View from *inside*: Conclusion

Death crushed at singularity (r=0)

In a finite proper time

View from *outside*: Conclusion

Distant observer sees gravitational collapse:

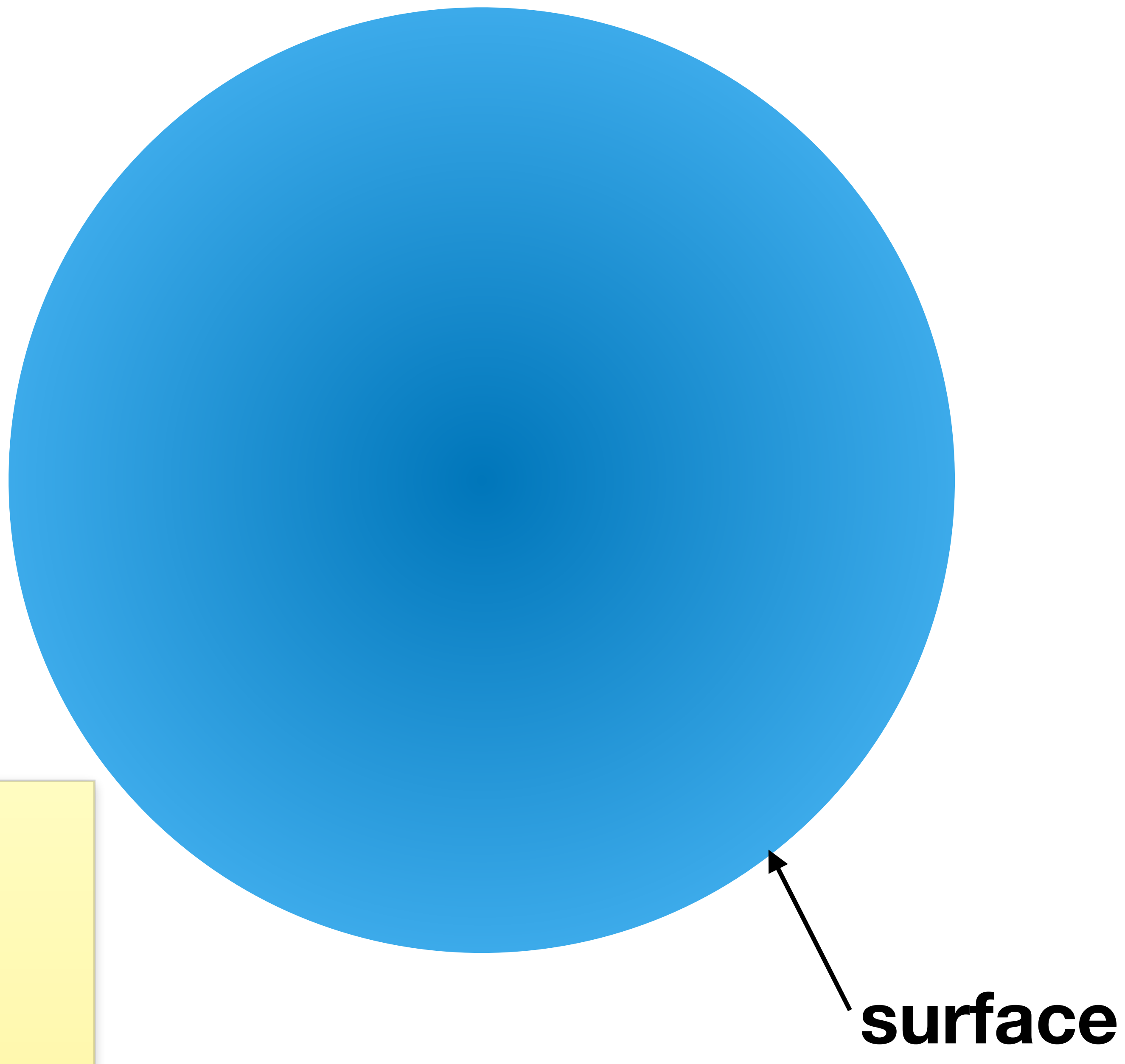
- slow down
- get redshifted
- darken

All records of star's history and its properties will be erased from the exterior geometry

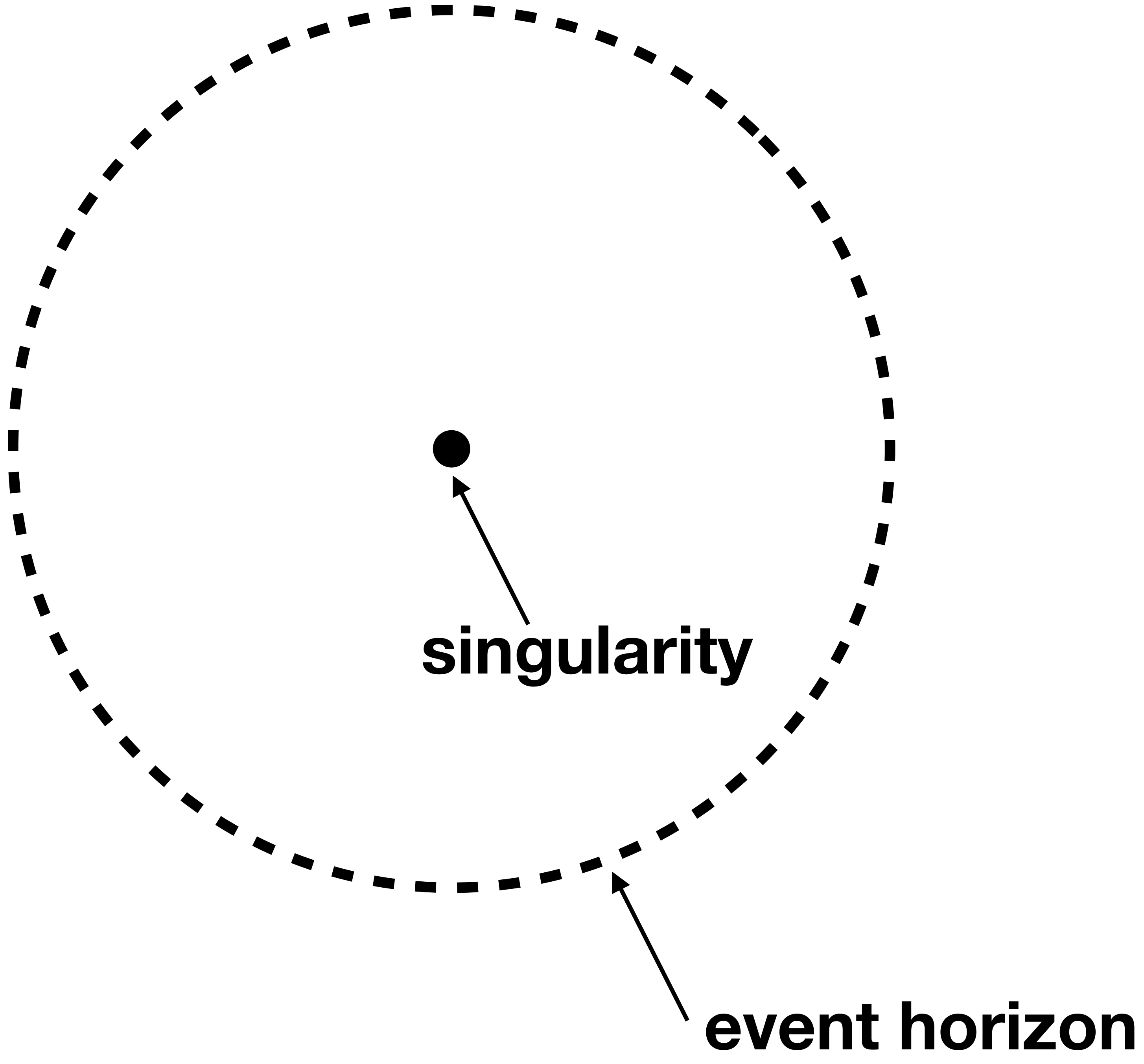
Reduced to one number: mass *M* (Schwarzschild spacetime)

What is a black hole? Remarkable prediction of general relativity

Normal object



Black hole



from black hole primer for undergrads

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

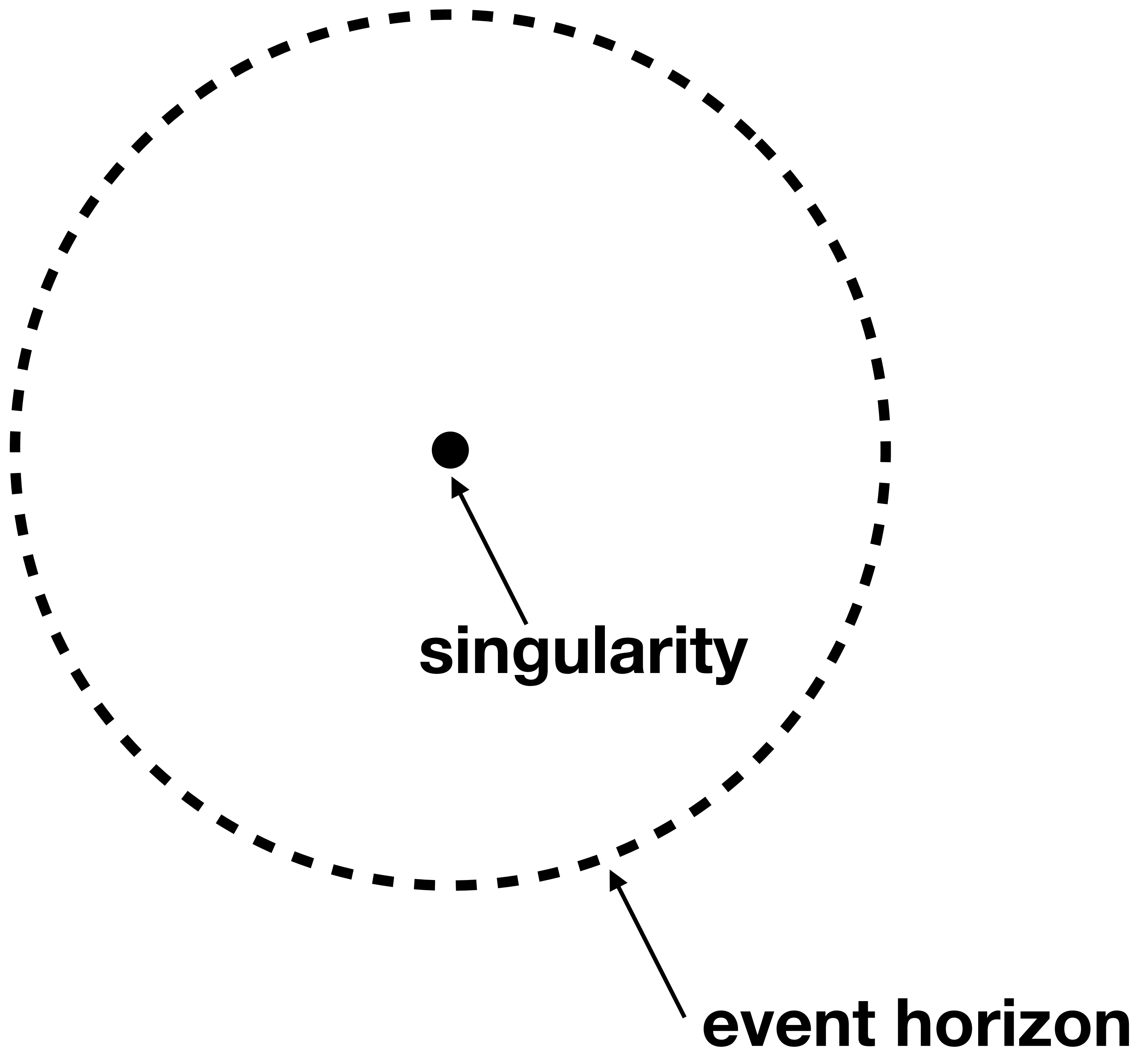
Region inside event horizon causally cut-off from outside

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 everything that falls inside the event horizon

Once inside, nothing escapes

What is a black hole?

Massive, compact astronomical objec
gravity so strong th
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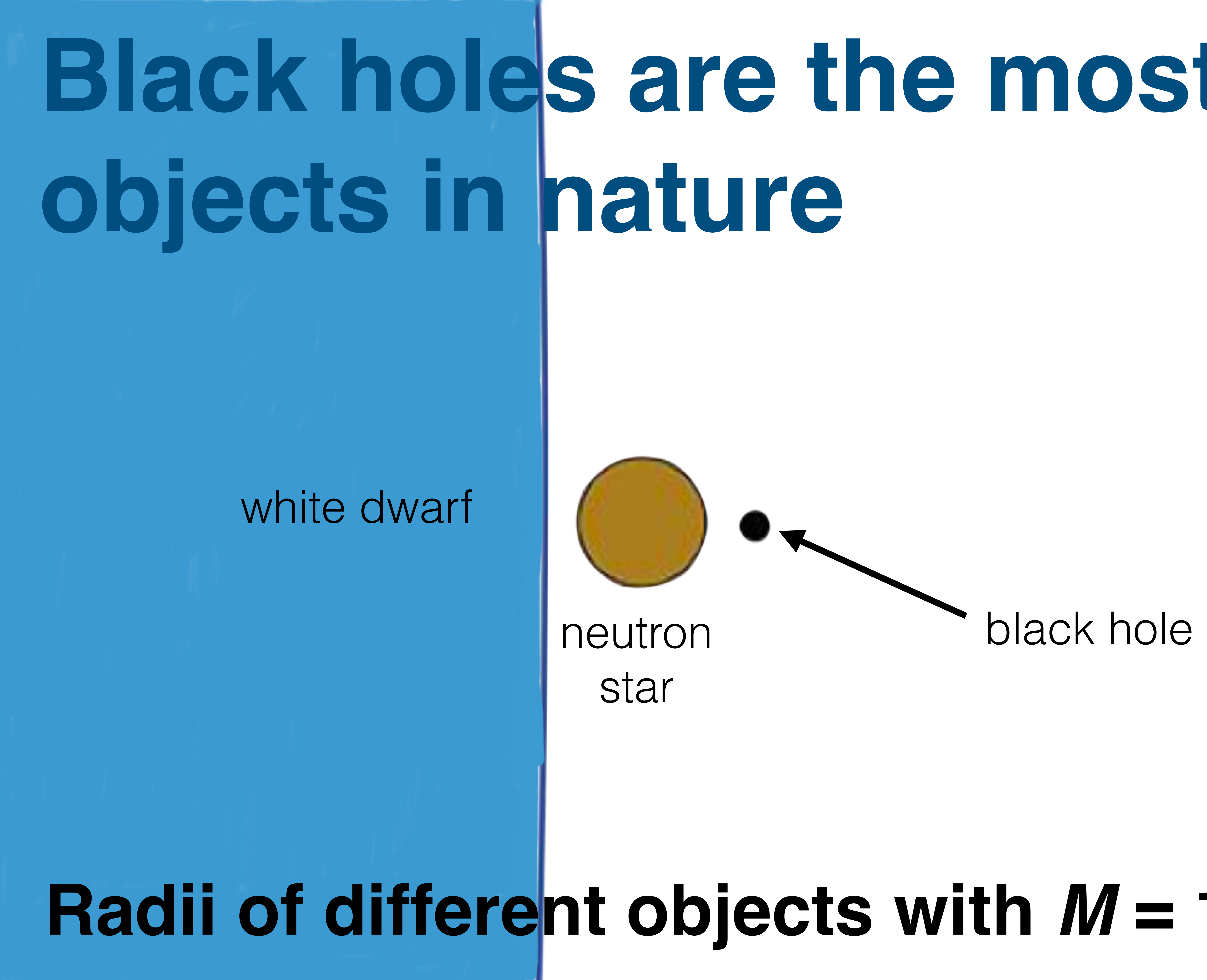
Black holes are the most compact objects in nature



Radii of different objects with $M = 1.2\ M_{Sun}$

Thorne

Generic features of gravitational collapse

Formation of spacetime singularity:

- unavoidable once star crosses r=2M (singularity theorems)
- point where theory breaks down

Formation of event horizon:

- singularities inside event horizon, hidden from external observers
- *Cosmic censorship conjecture*: singularities always hidden inside event horizon even for nonspherical collapse

Area increase:

- if mass falls in a black hole, its area will increase
- analogous to entropy in thermodynamic → laws of black hole thermodynamics

Growth of black holes

If particles fall into the black hole

- ***M* increases**
- **Schwarzschild radius $r_S = 2M$ increases**
- **surface area increases**

Growth of black holes

If particles fall into the black hole

- **M increases**
- **Schwarzschild radius $r_S = 2M$ increases**
- **surface area increases**

There is no limit to how big a BH can grow. From astrophysics:

- **$M_{min} = 3.6\ M_{Sun}$**
- **$M_{max} \sim 10^{10}\ M_{Sun}$**

A black hole has no hair

All black hole solutions of Einstein's equation completely characterized by only three externally observable classical parameters:

Mass *M*

Spin: angular momentum *J*

Charge *Q*

$$J \equiv a\frac{GM^2}{c}$$

$$-1 \leq a \leq 1$$ spin parameter

No-hair theorem

All other information ("hair"=metaphor) disappears behind the event horizon, therefore permanently inaccessible to external observers

Types of black holes

Mass M	Schwarzschild spacetime
Spin a	Kerr spacetime
Charge Q	Reissner–Nordström spacetime

Schwarzschild black hole

- Simplest black hole
- Spherically symmetric spacetime
- Relatively "easy" to handle analytically

Schwarzschild geometry in Schwarzschild coordinates

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

Kerr black hole

Conservation of angular momentum leads to spinning black holes
Rotational energy deforms spacetime → Kerr spacetime

Kerr metric considerably more complex than Schwarzschild

$$ds^2 = -\left(1 - \frac{2Mr}{\rho^2}\right) dt^2 - \frac{4Mar\sin^2\theta}{\rho^2} d\phi dt + \frac{\rho^2}{\Delta} dr^2 + \rho^2 d\theta^2$$

Boyer-Lindquist coords.

$$+\left(r^2 + a^2 + \frac{2Mra^2\sin^2\theta}{\rho^2}\right)\sin^2\theta d\phi^2$$

$$a \equiv J/M, \quad \rho^2 \equiv r^2 + a^2\cos^2\theta, \quad \Delta \equiv r^2 - 2Mr + a^2$$

A Kerr black hole is spinning

Spin

$$j \equiv \frac{J}{J_{\max}} = \frac{a}{M} \qquad J_{\max} = \frac{GM^2}{c}$$

angular velocity

$$\Omega_H = \frac{jc}{2r_H}$$

Period

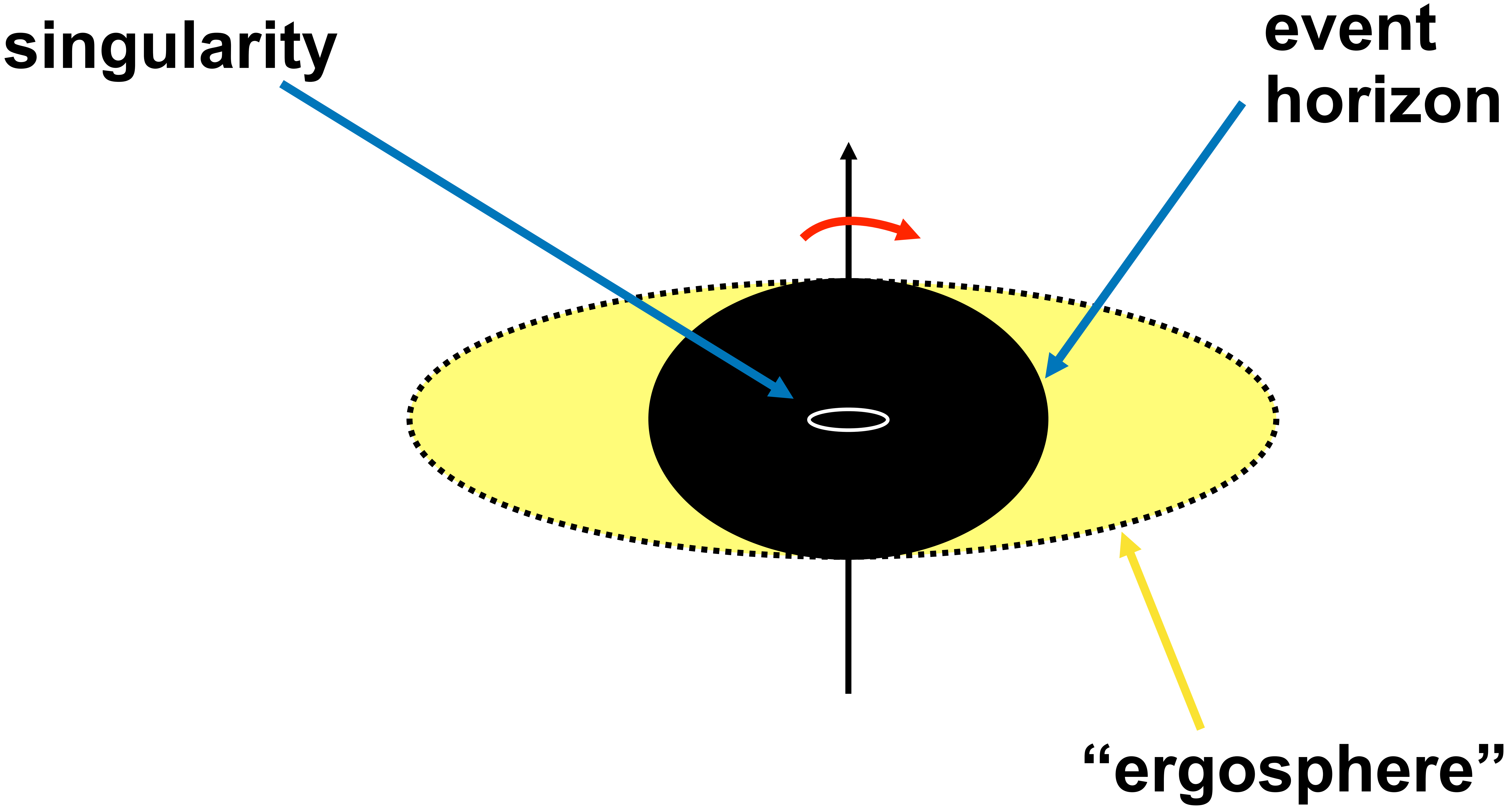
$$P_H = \frac{2\pi}{\Omega_H} = \frac{4\pi r_H}{jc}$$

Velocity

$$v_H = \frac{4\pi r_H}{P_H} = jc$$

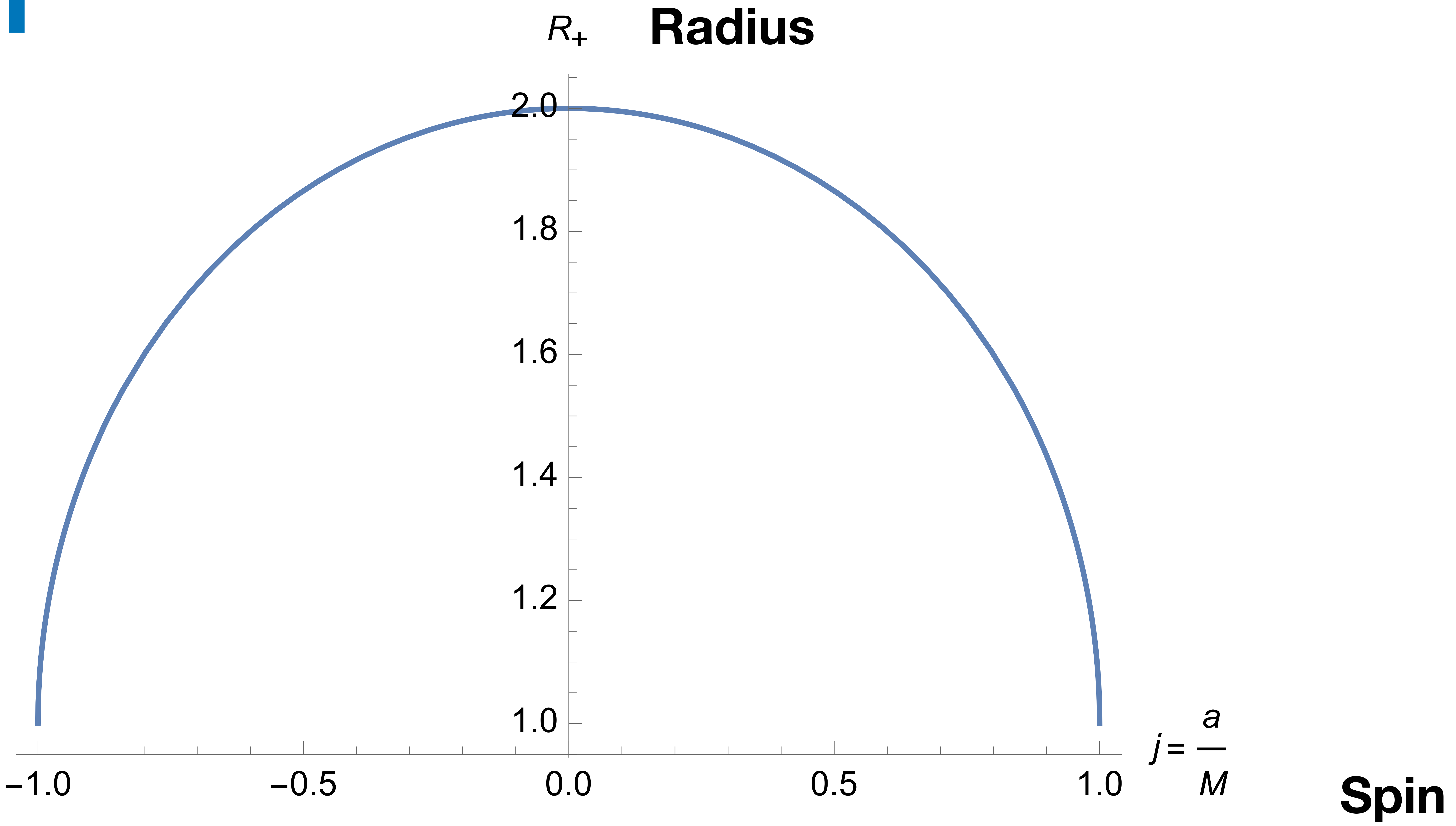
$$j = 1 \quad \Rightarrow \quad v_H = c$$

Structure of a Kerr black hole



Event horizon radius decreases with spin: $$R_H = \frac{GM}{c^2}$$ for a/M = 1 (maximal spin)

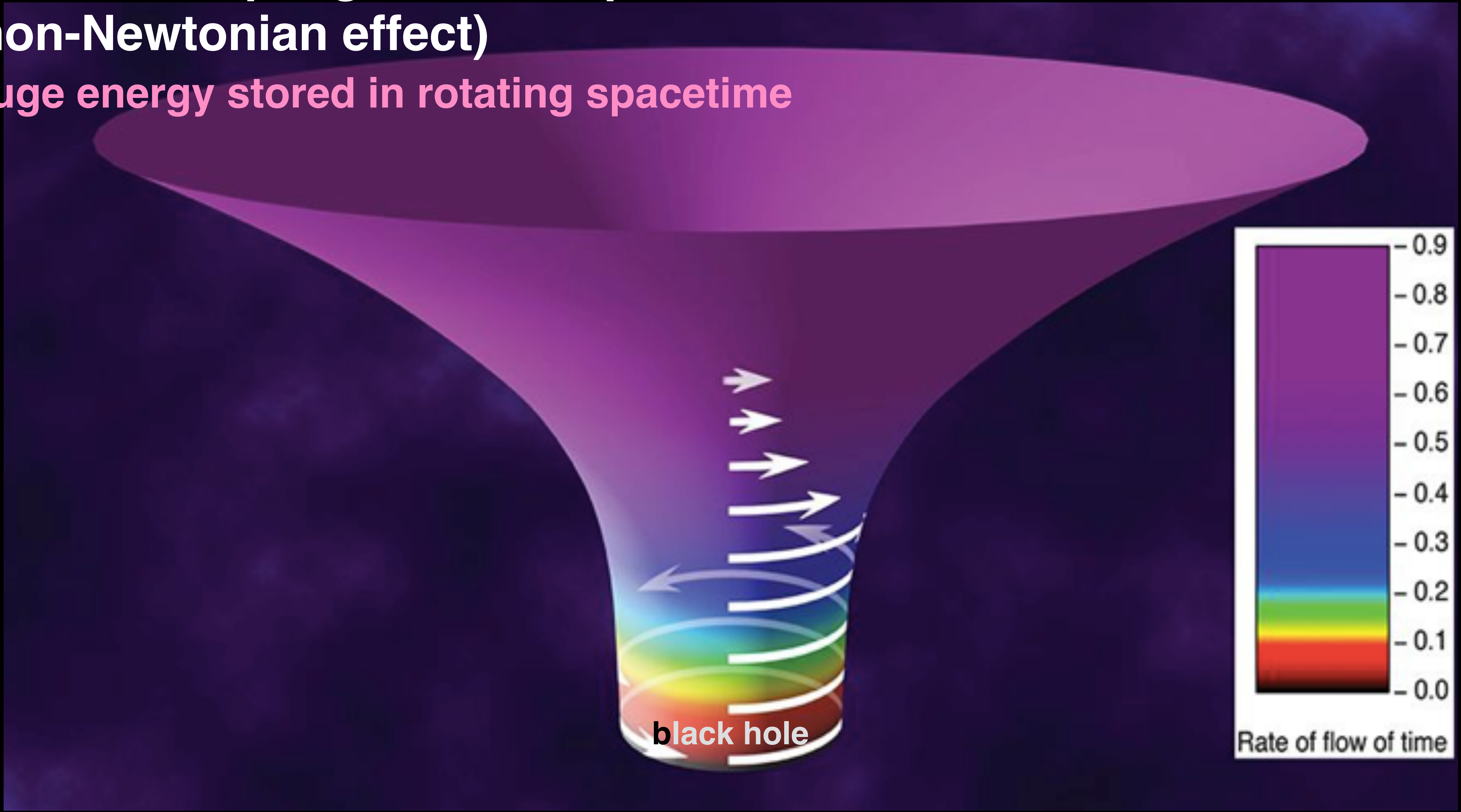
Event horizon radius as a function of spin



Spacetime around a Kerr black hole

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

Huge energy stored in rotating spacetime

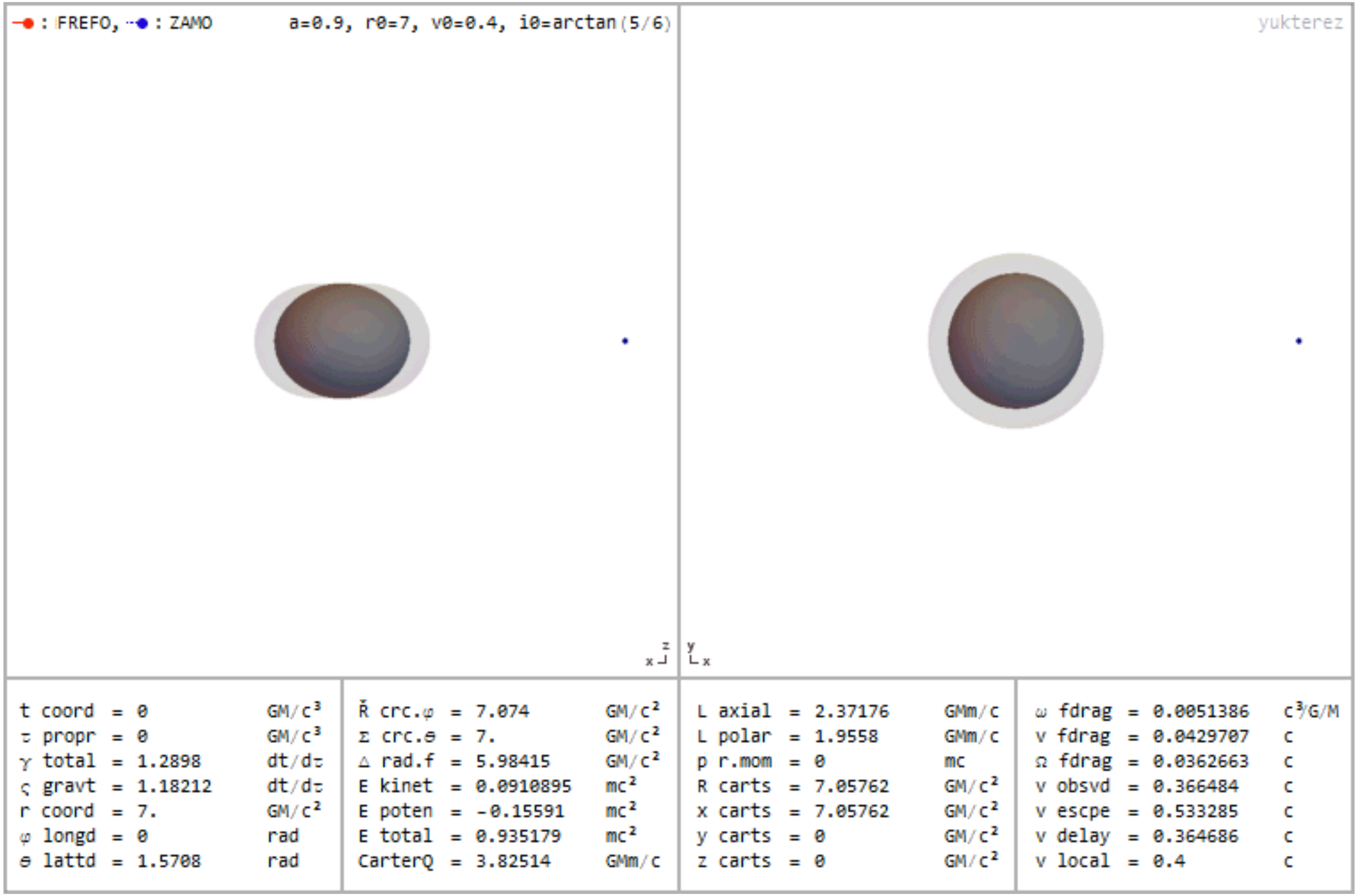


Credit: Thorne

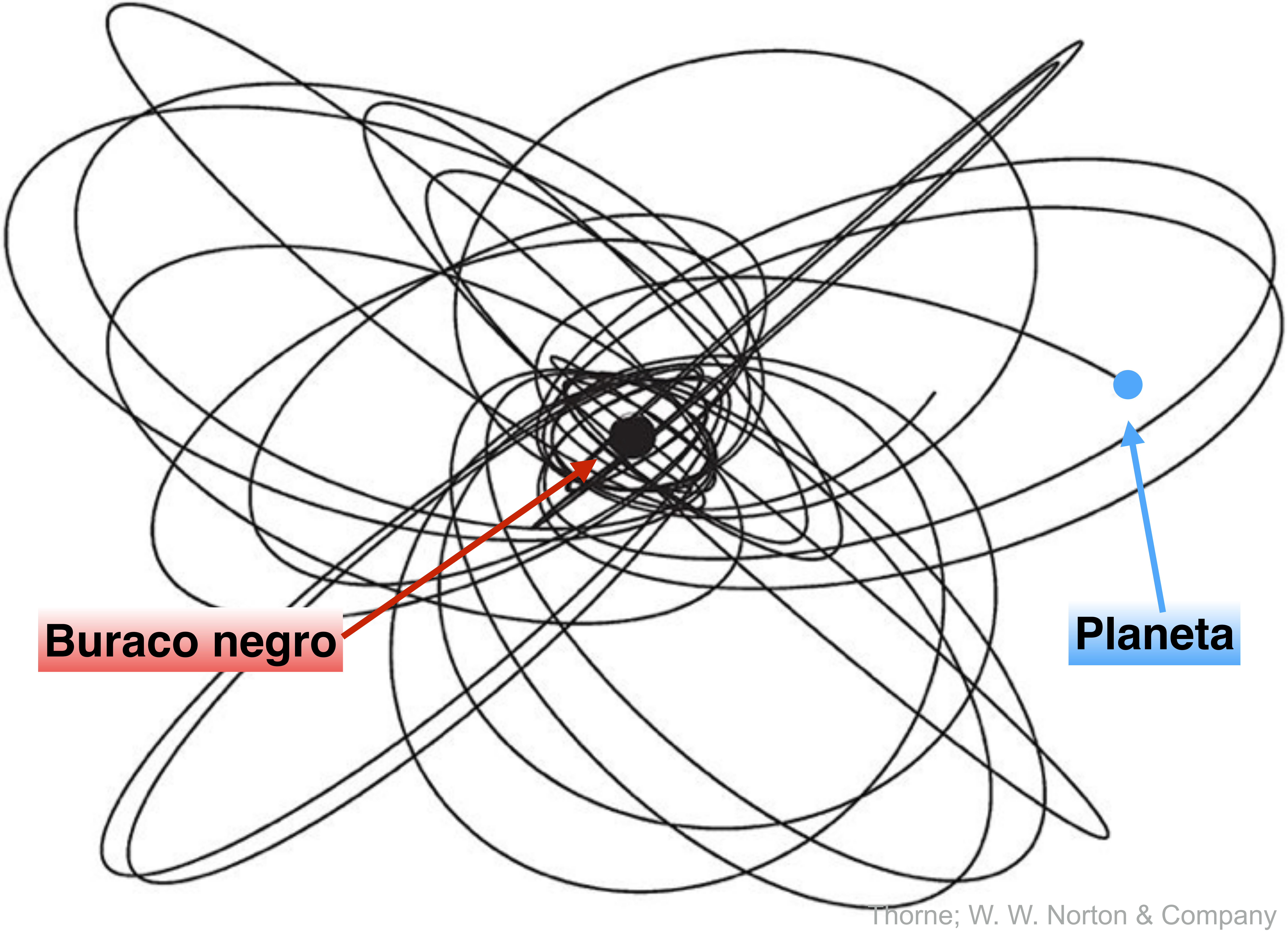
Frame-dragging effect

Penrose effect:
rotational energy can be extracted (more about this in next lecture)

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



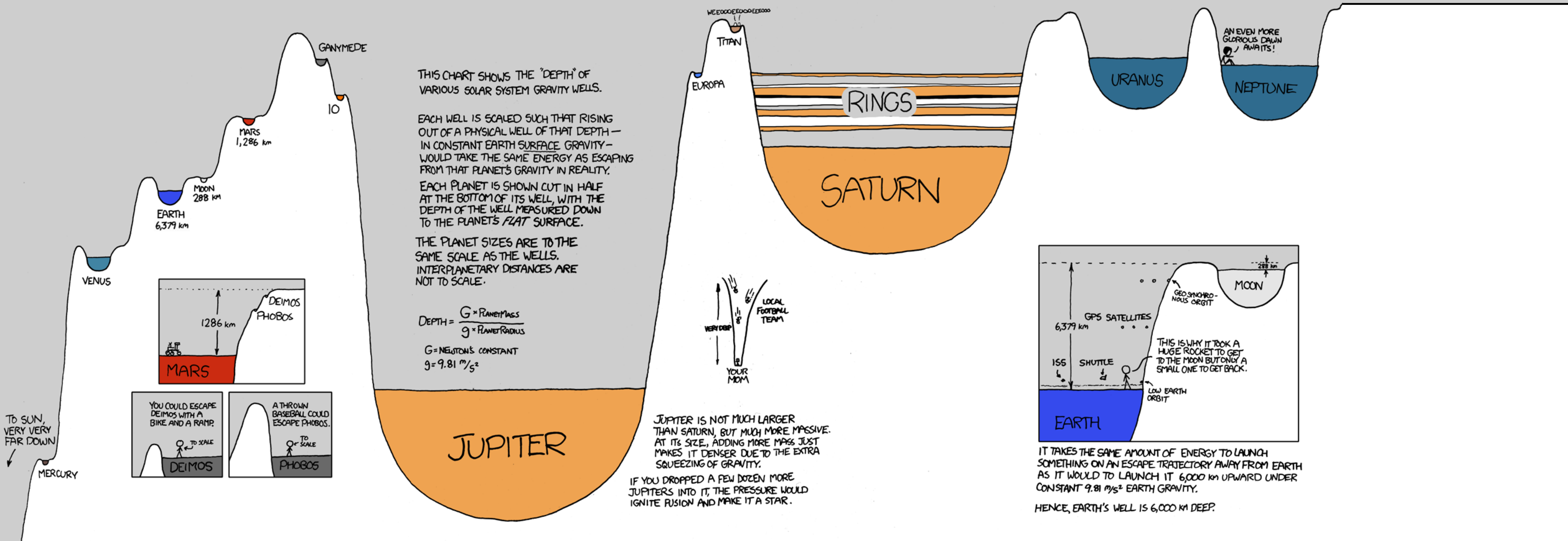
https://en.wikipedia.org/wiki/File:Orbit_um_ein_rotierendes_schwarzes_Loch_(Animation).gif#file


Buraco negro
Planeta
Thorne; W. W. Norton & Company

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 = $\frac{G \times \text{PlanetMass}}{g \times \text{PlanetRadius}}$
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
10^6X DEEPER
DEPTH
GRAVITY
WELL
BLACK
HOLE

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

QUIZ TIME!

https://kahoot.it/

black hole group

iag usp

Next: Accretion flows

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