Supermassive black holes

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Content of lectures

- Broad overview of theory and observations of *supermassive black holes in active galactic nuclei* (AGN)
- Focus on *basic physical concepts*
- Some coverage of galaxy-black hole coevolution

As grandes perguntas

Como as leis da física se comportam perto — e dentro — de um buraco negro?

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

Como buracos negros afetam o que está ao seu redor?

Eras da gravitação

Relatividade geral de Einstein: Gravidade é a curvatura do espaço

Leis da gravitação de Einstein

1. Geometria do espaço-tempo muda na presença de matéria

Equação de campo

2. Objetos se movem tal que sua passagem do tempo é maximizada

Equação de movimento
(equação da geodésica)

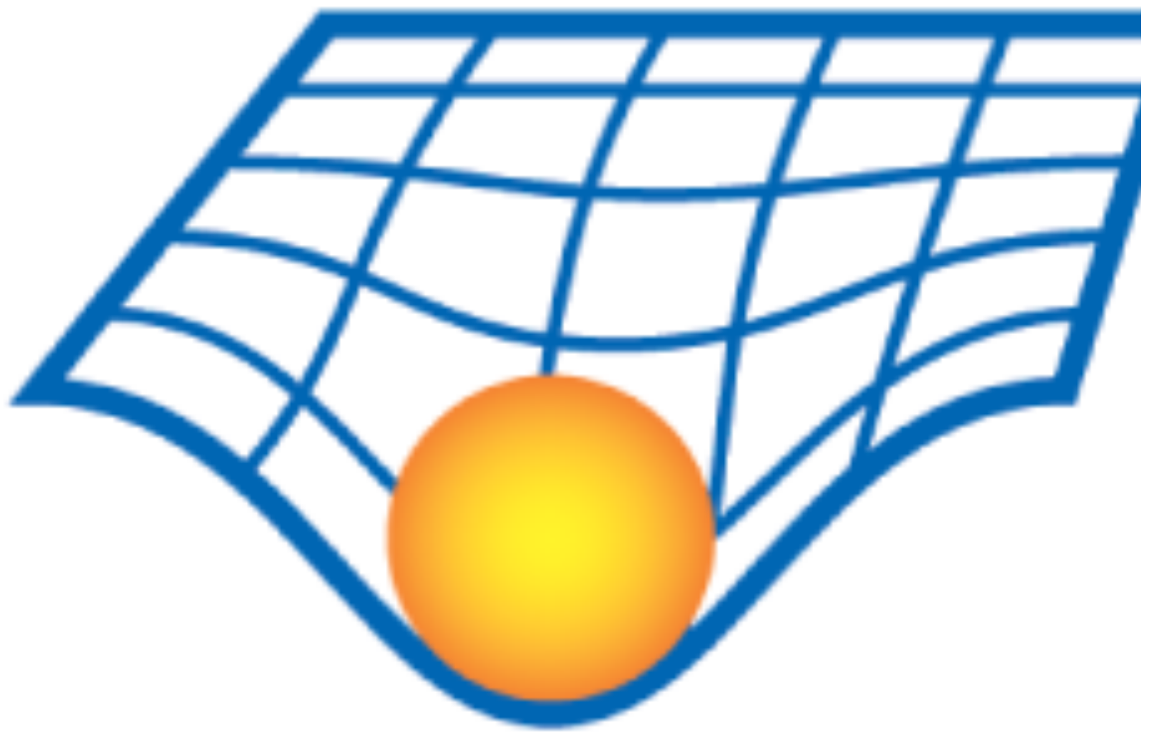
1ª lei da gravitação de Einstein

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

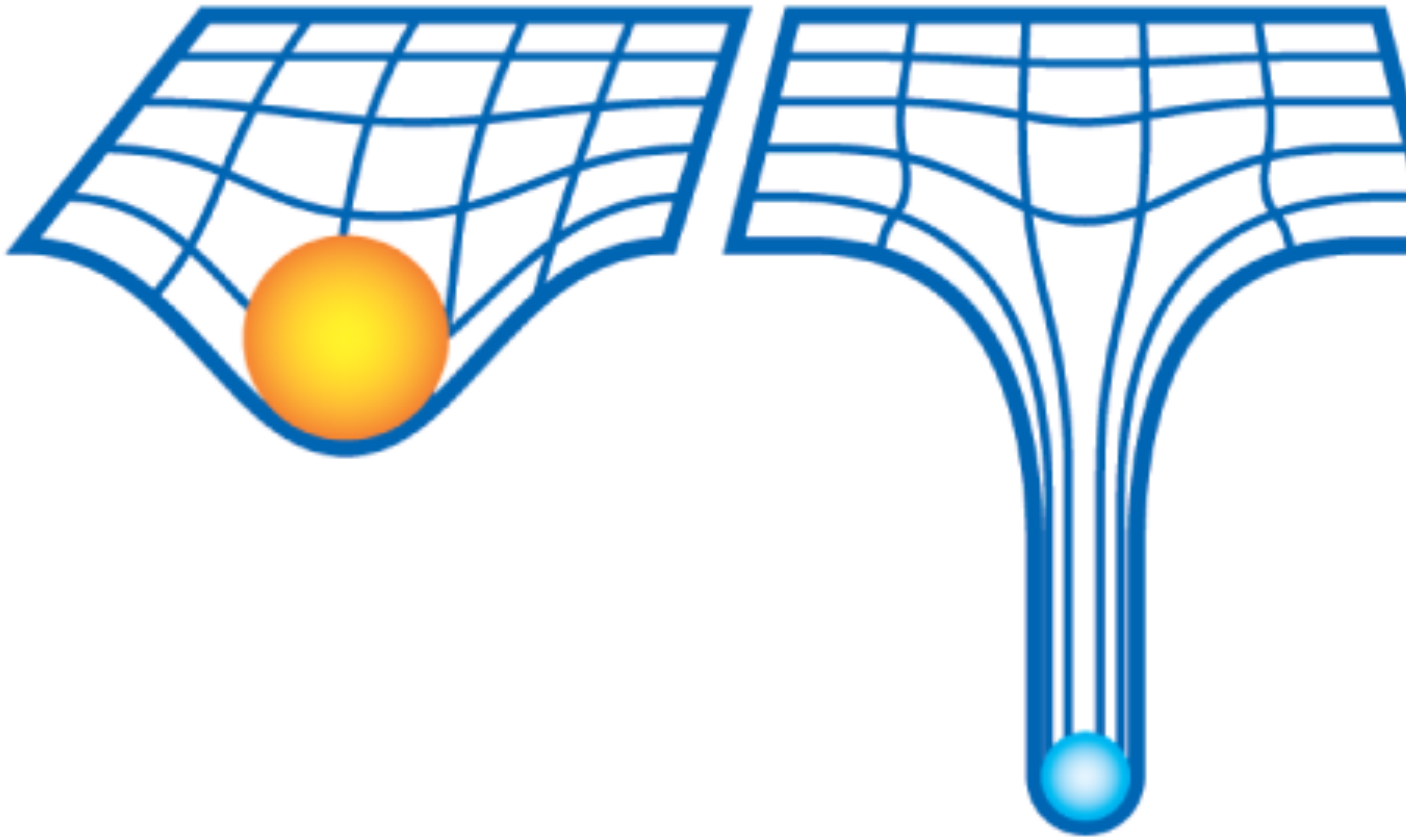
2ª lei da gravitação de Einstein

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

The Elegant Universe. Nova / PBS



James Provost



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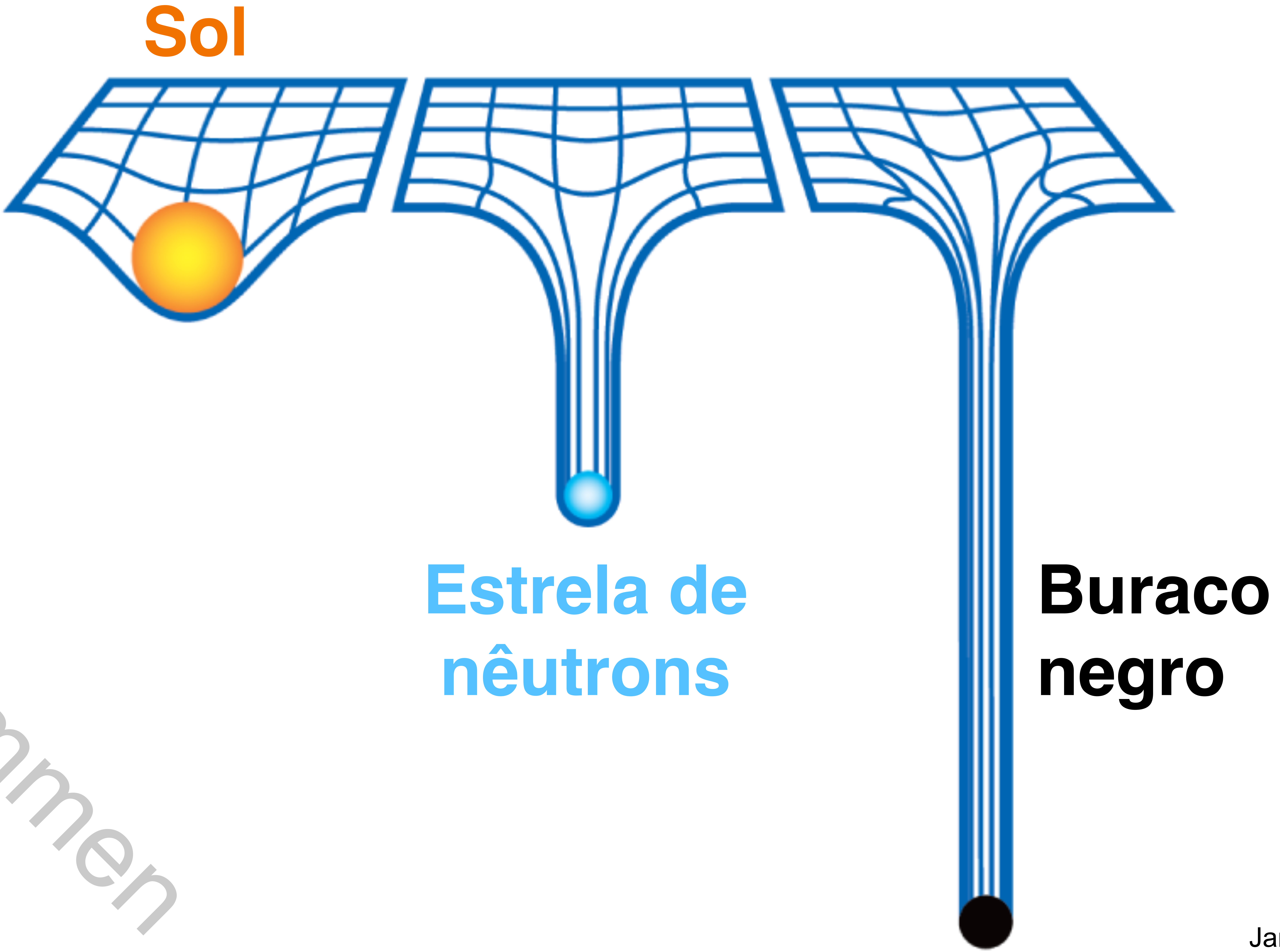


James Provost

O que é um buraco negro?

Astro massivo e compacto: gravidade tão forte que aprisiona tudo o que cai dentro dele

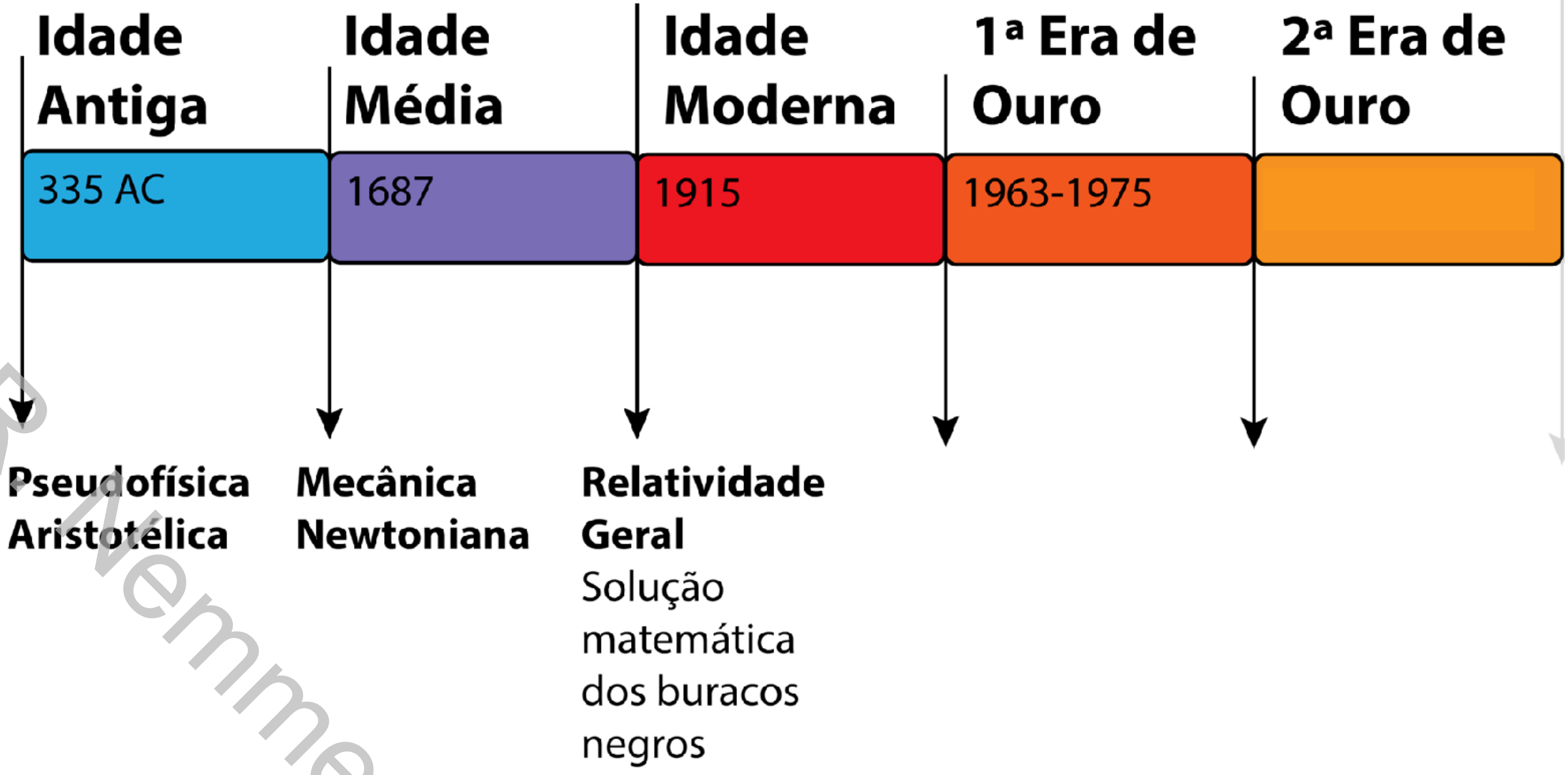
Uma vez dentro, nada escapa

Albert Einstein era cético em relação a buracos negros

Chega mais, deixa eu te contar uma coisa

Buracos negros não existem

Eras da gravitação



Eras da gravitação

Idade Antiga	Idade Média	Idade Moderna	1ª Era de Ouro	2ª Era de Ouro
335 AC	1687	1915	1963-1975	
Pseudofísica Aristotélica	**Mecânica Newtoniana**	**Relatividade Geral** Solução matemática dos buracos negros	**Renascimento Teórico** Buracos negros giram, vibram, são carecas e evaporam; termodinâmica; singularidades	

1a era de ouro: Renascimento teórico dos buracos negros

1963: Buracos negros giram — Kerr 1963

1964: Energia gravitacional extraível — Salpeter 1964; Zeldovich 1964

1965: Singularidades — Penrose 1965

1967: BNs carecas — Israel 1967; Carter 1971; Hawking 1972

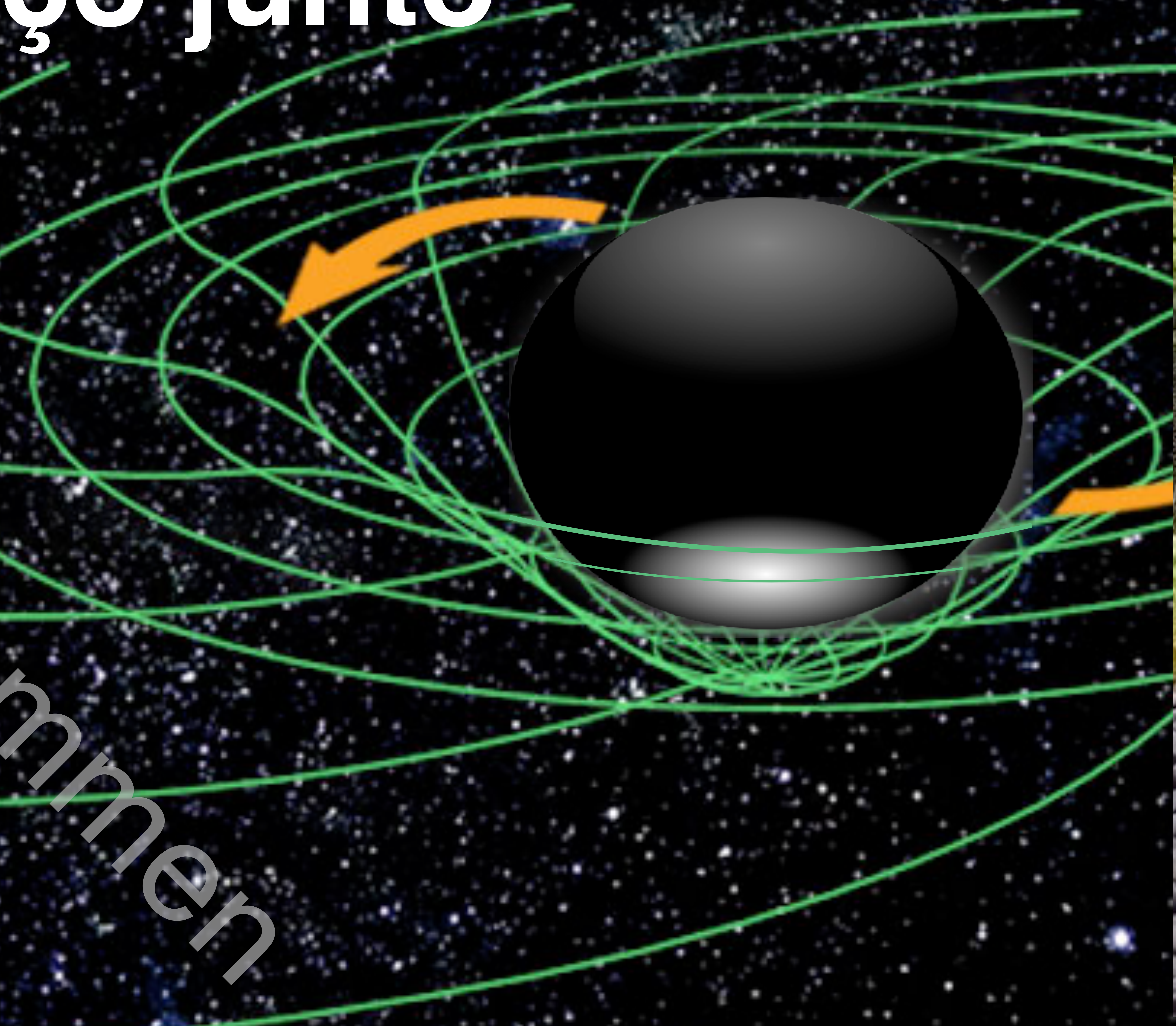
1969: Energia *rotacional* extraível — Penrose 1969

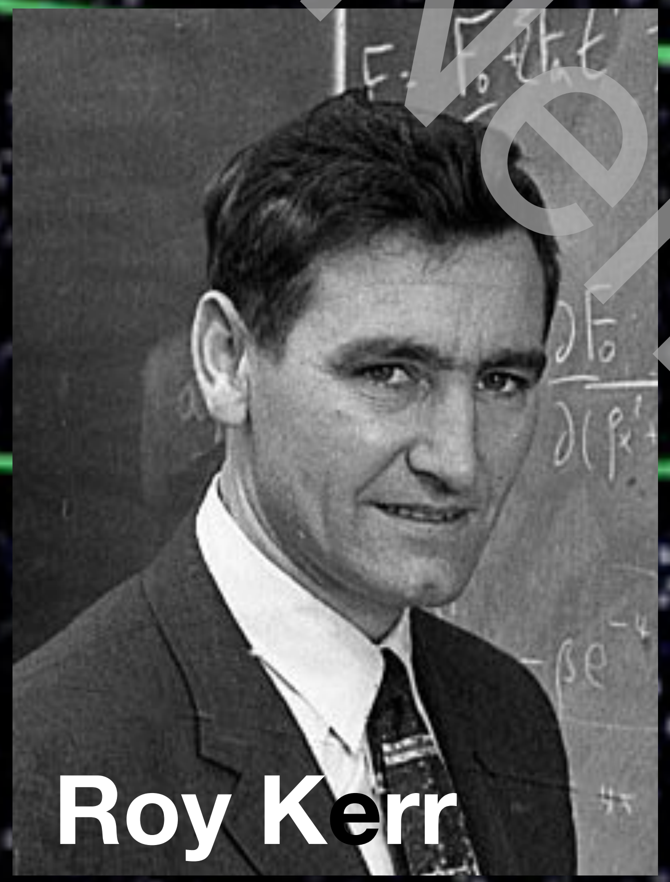
1971: BNs vibram — Press 1971; Teukolsky 1972

1973: Leis da termodinâmica — Bekenstein 1973; Bardeen+1973

1974: BNs evaporam — Hawking 1974

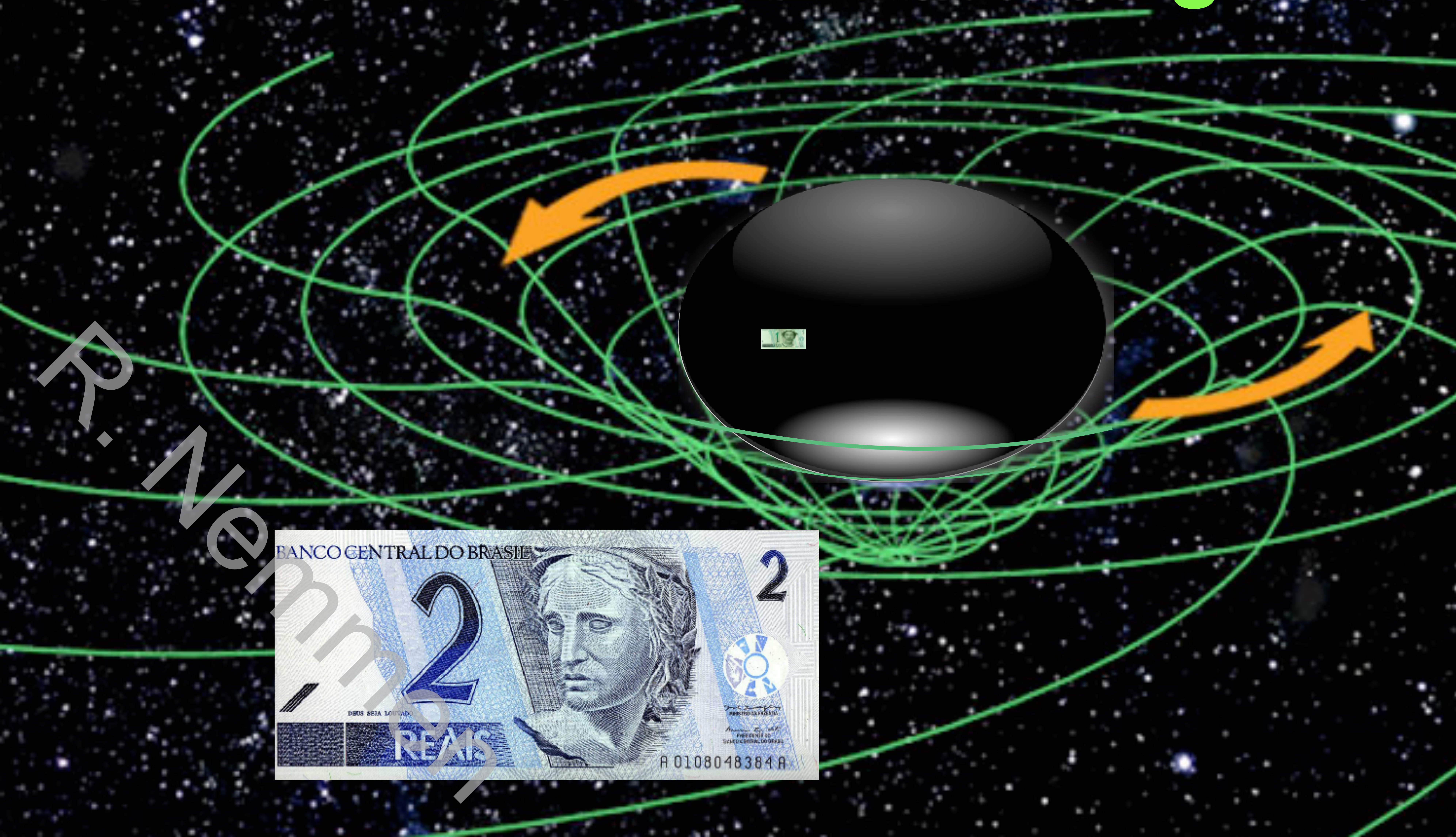
Buracos negros giram e arrastam o espaço junto

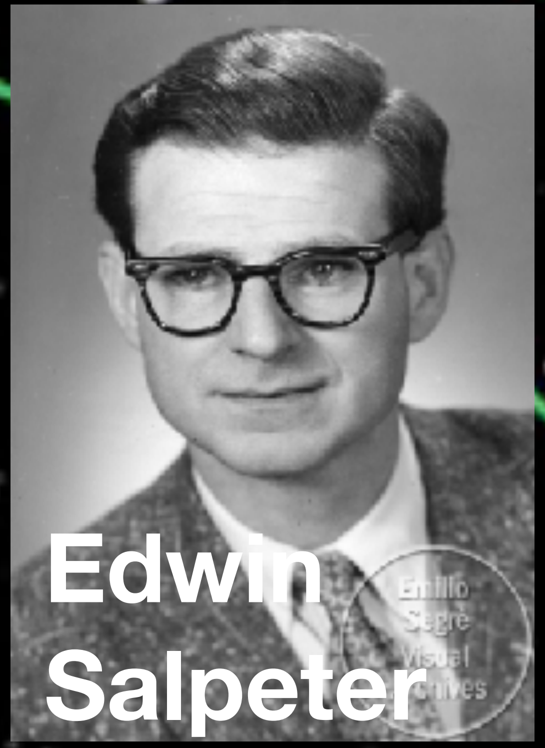


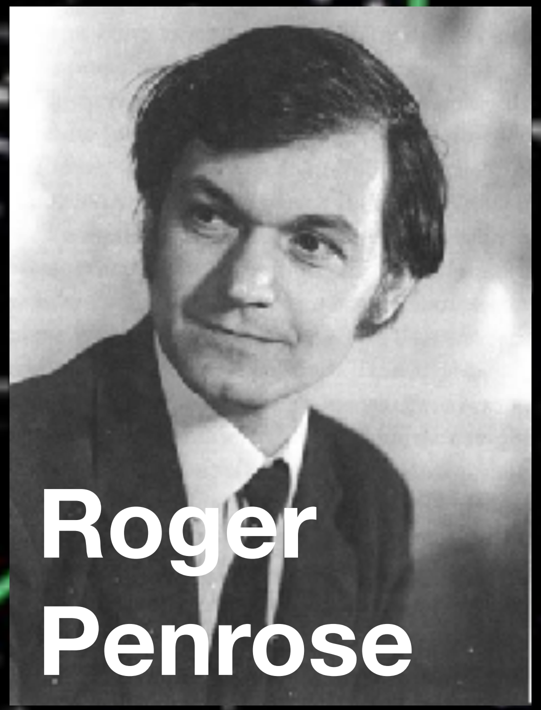


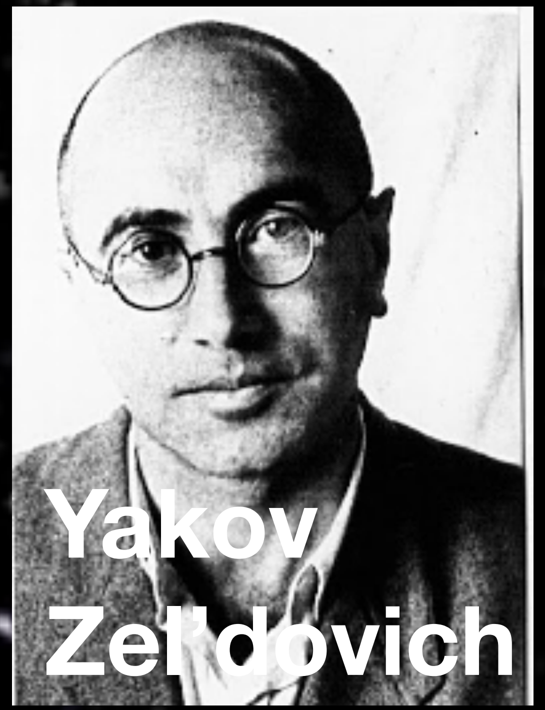
https://www.youtube.com/watch?v=9MHuhcFQsBg

Melhores usinas de energia do universo:
Mais de 6% de retorno energético







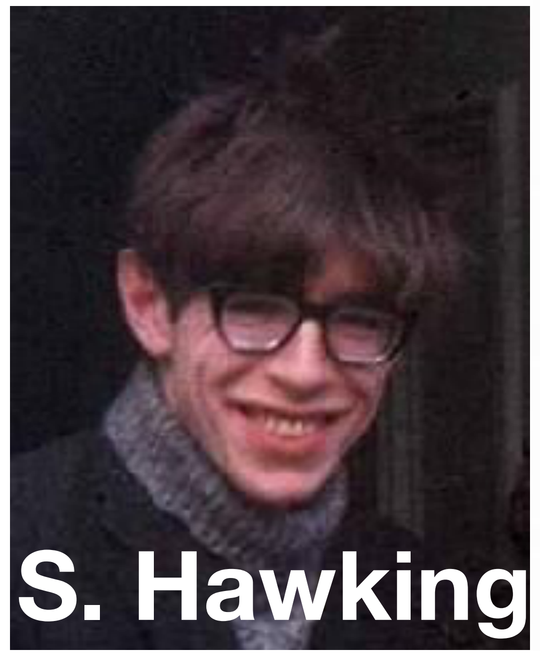


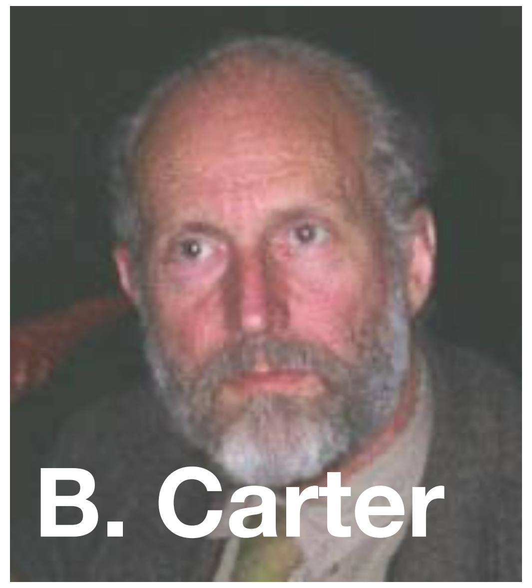
Buracos negros são carecas

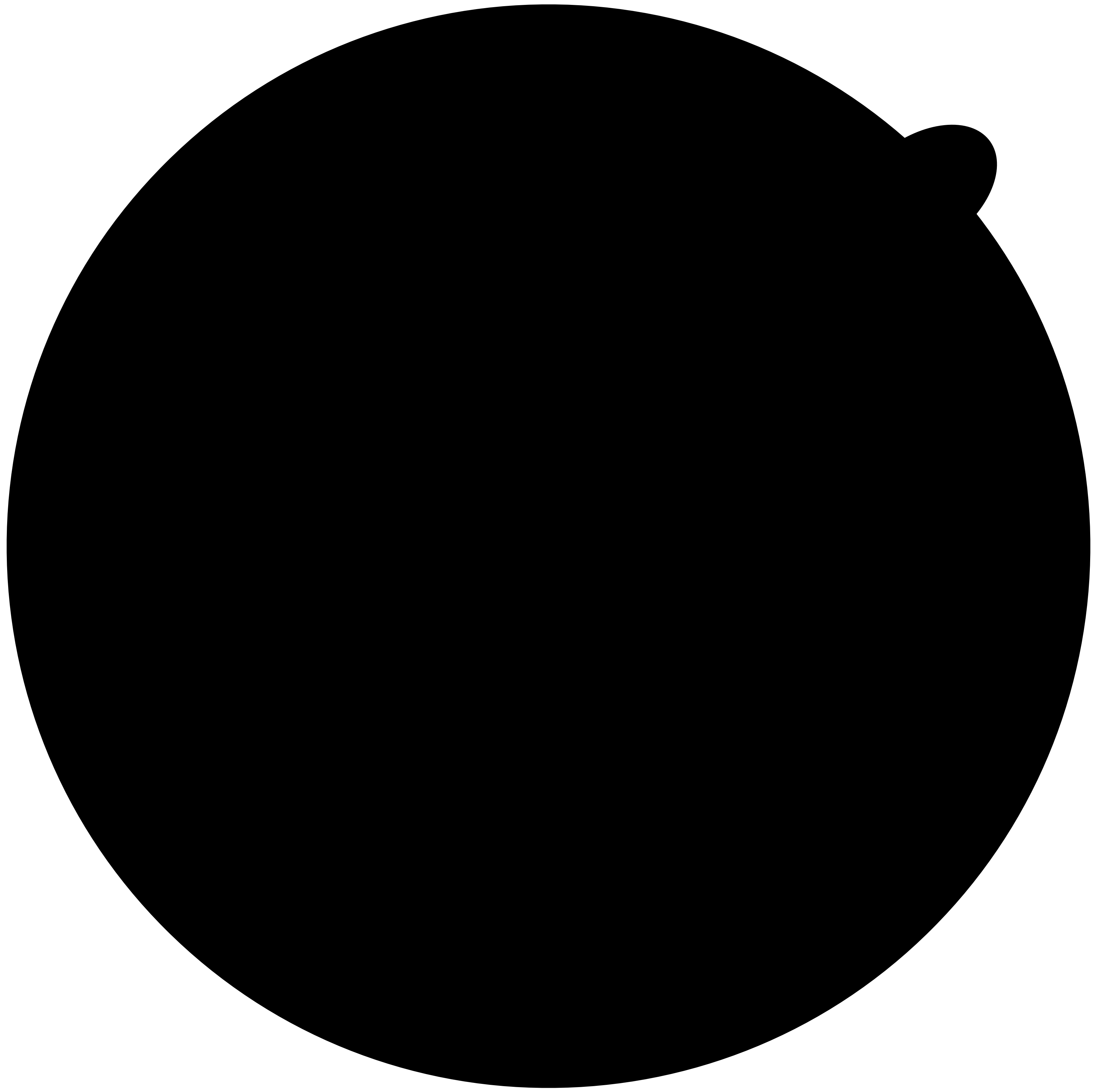
Um buraco negro é caracterizado por dois números e nada mais

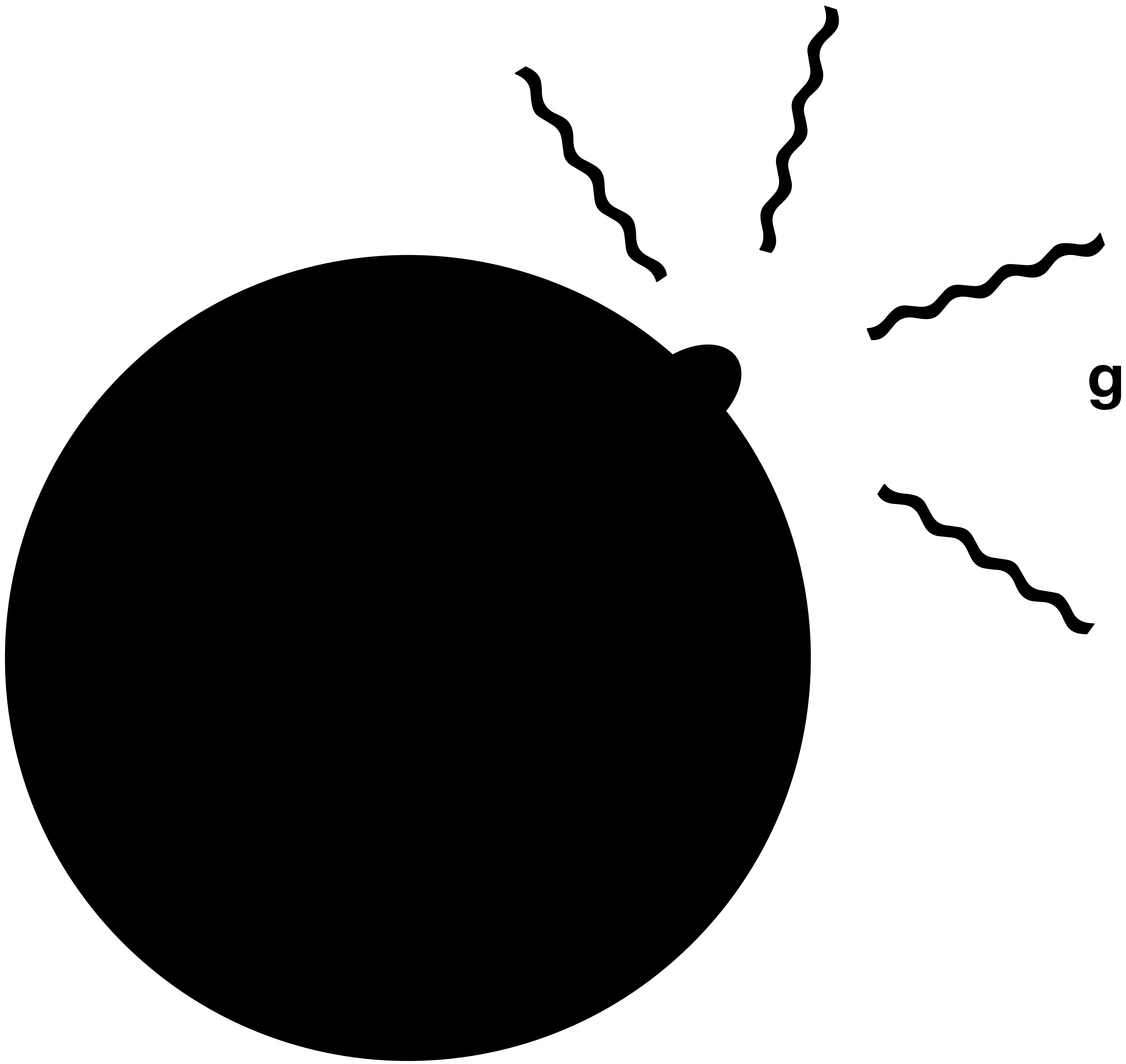
Mass M

Spin: momento angular a_*








ondas
gravitacionais

Buracos negros evaporam

Possuem temperatura, portanto emitem radiação e perdem massa

∴ BNs não são eternos

Credit: BBC

Lições: 1ª era de ouro

Buracos negros são:

1. Dinâmicos — Giram e vibram
2. Usinas de energia
3. Perecíveis — Evaporam e eventualmente desaparecerão

Dominada por avanços *teóricos*

Recap: Aula 1

- Breve história da gravitação
- Leis da gravitação de Einstein
  - Massa curva o espaço
  - Espaço curvo diz a partículas como se moverem
- 1ª era de ouro dos buracos negros
  - Principais resultados

References: theory

- *Physical processes in active galactic nuclei.* Blandford, R. in *Active galactic nuclei Saas-Fee lecture notes*
- *Black holes, white dwarfs and neutron stars.* Shapiro, S. L. & Teukolsky, S. A. (ch. 12, 14)

More details

- *Foundations of black hole accretion disk theory.* Fragile, C. & Abramowicz, M.
- *The Formation and Disruption of Black Hole Jets.* Contoupoulos, I. et al. (ch. 3, 6, 7)

References: observations

Active galactic nuclei. **Beckmann V. & Schrader, C.**

- ***An introduction to active galactic nuclei: Classification and unification*****. New Ast. Rev. Tadhunter, C.**
- ***Relativistic jets in active galactic nuclei.*** **ARAA. Blandford, R. arXiv:1812.06025**

- ***The Coevolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe.*** **ARAA. Heckman, T. & Best, P.**
- ***Observational Evidence of Active Galactic Nuclei Feedback.*** **ARAA. Fabian, A.**

What is an active galactic nuclei?

AGN

Presence of accreting, supermassive black hole at the center of a galaxy

What is an active galactic nuclei?

AGN

Presence of accreting, supermassive black hole at the center of a galaxy

Mass $M > 10^6 M_\odot$

Black hole feeding rate $\dot{M} > 10^{-3} \dot{M}_{\mathrm{Edd}}$

$(L > 10^{-5} L_{\mathrm{Edd}})$


R. Nemmen

Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow". The Event Horizon Telescope is hoping to see both the ring and the "shadow".

Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space. The GMVA will study how these jets form.

Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc

What physics is necessary?

What physics is necessary?

general relativistic MHD
(GRMHD)

however...

at low accretion rates:
general relativistic kinetic theory
(GRK)

What physics is necessary?

at $r > 100GM/c^2$ can use Newtonian approximations

- Will use mostly Newtonian treatment here
- Concepts more important than detailed calculations

Nature of AGNs: Accreting black holes

Gravitational energy source

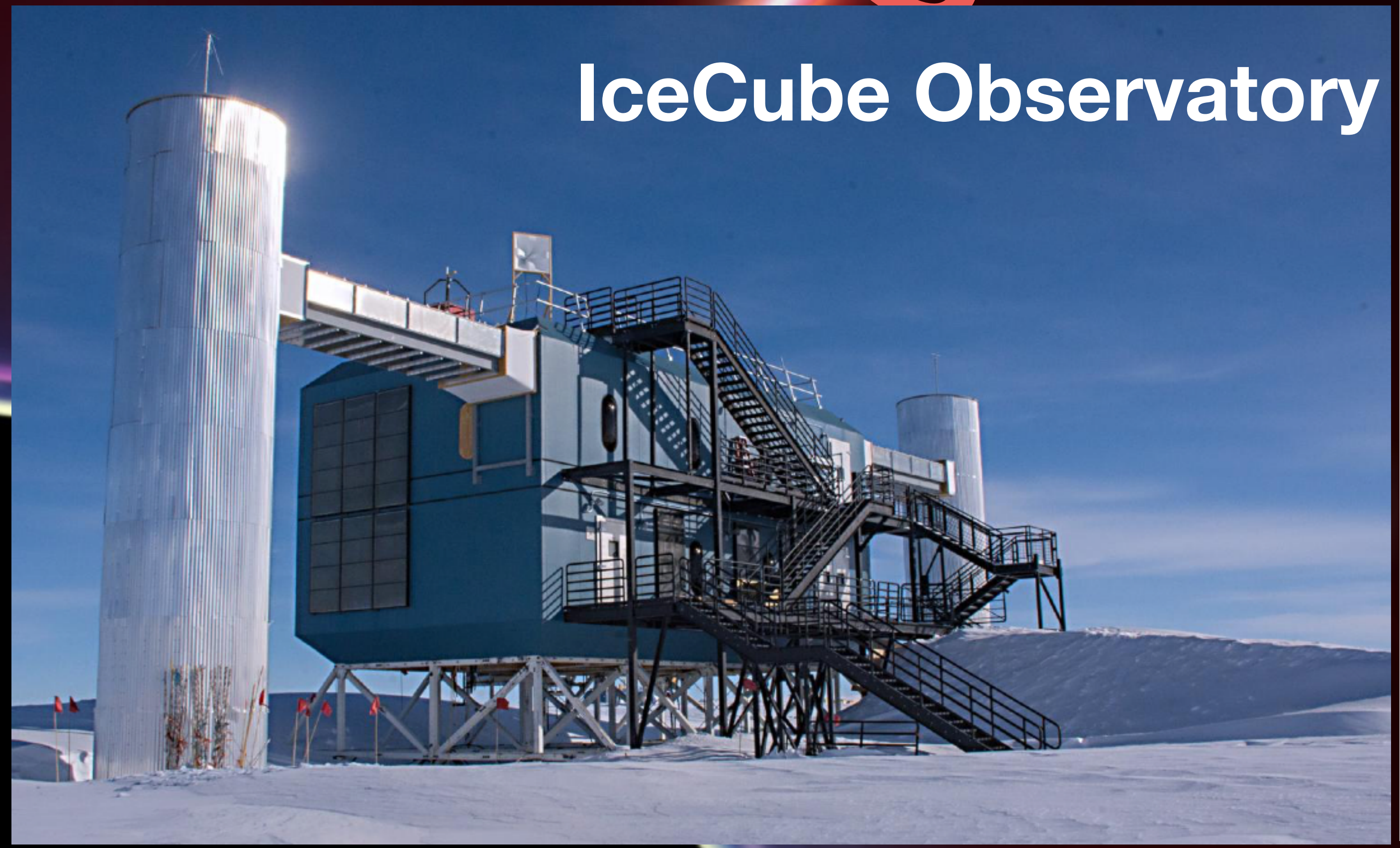
- enormous free energy
- can be extracted by particles/fields

AGNs: Powerful electromagnetic radiators, particle accelerators

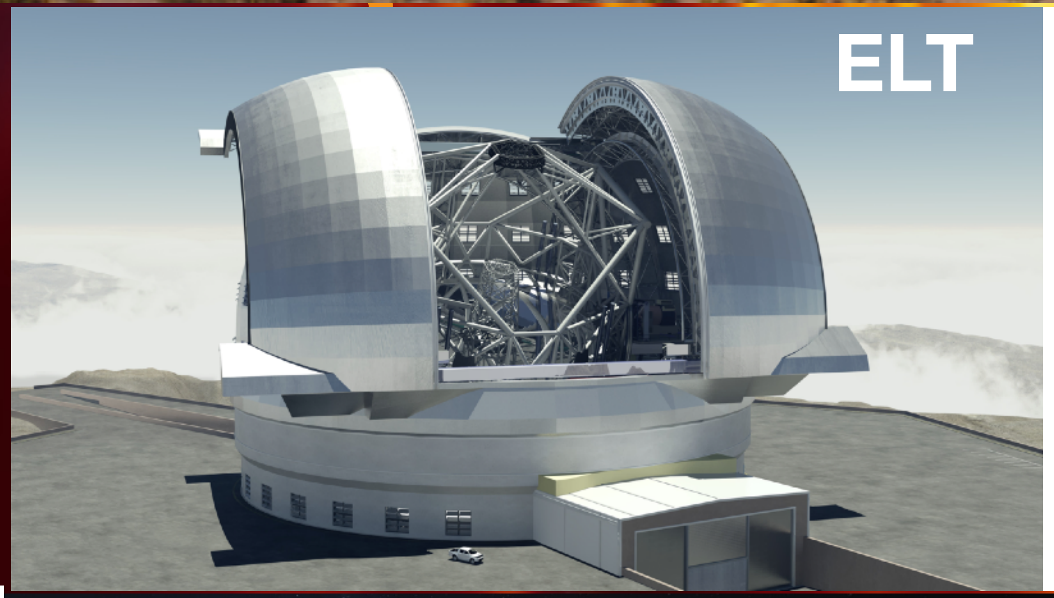
AGNs: Powerful EM radiators, particle accelerators

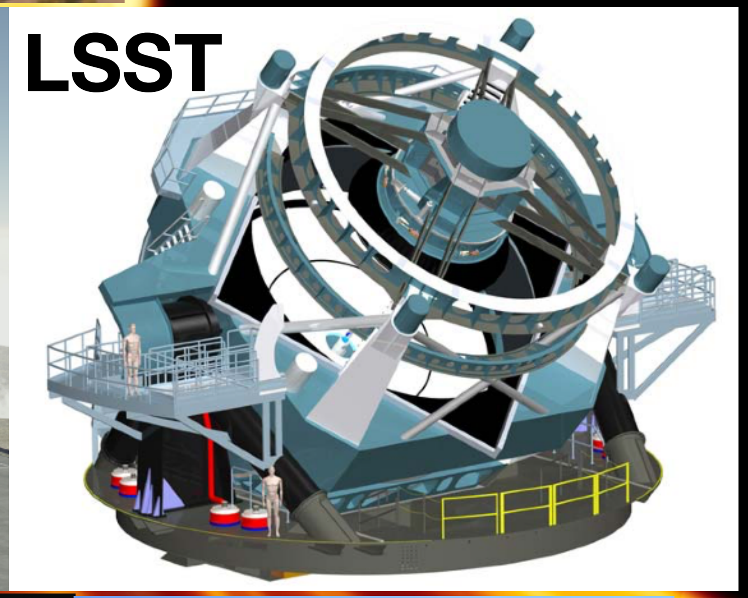
neutrinos, cosmic rays

Crucial for multi messenger astronomy



PIERRE AUGER OBSERVATORY





GWs

EM radiation:

radio, infrared, optical, X-rays, gamma-rays

Why are AGNs important?

- Laboratories to test general relativity, plasma physics
- Brightest persistent astronomical sources ∴cosmic background
- Affect large scale structure with their gas outflows and radiation
- Reionization sources during dark ages
- Crucial sources for multimessenger astronomy: photons, cosmic rays, neutrinos, GWs

Challenges

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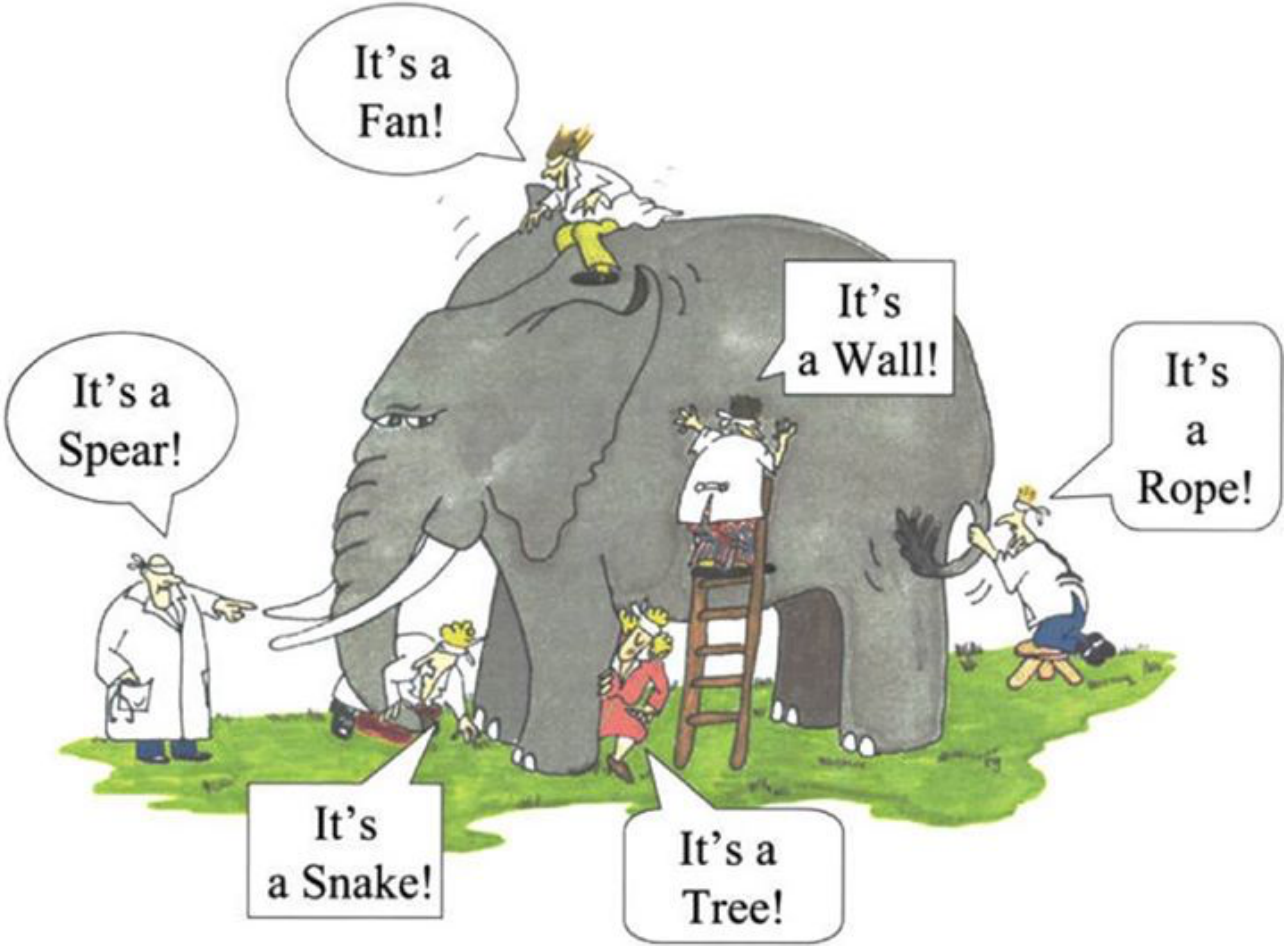
AGNs: multifaceted phenomenon (challenge #1)

Depending on how you observe, AGNs look different

Appearance varies with EM energy band (radio to gamma-rays)



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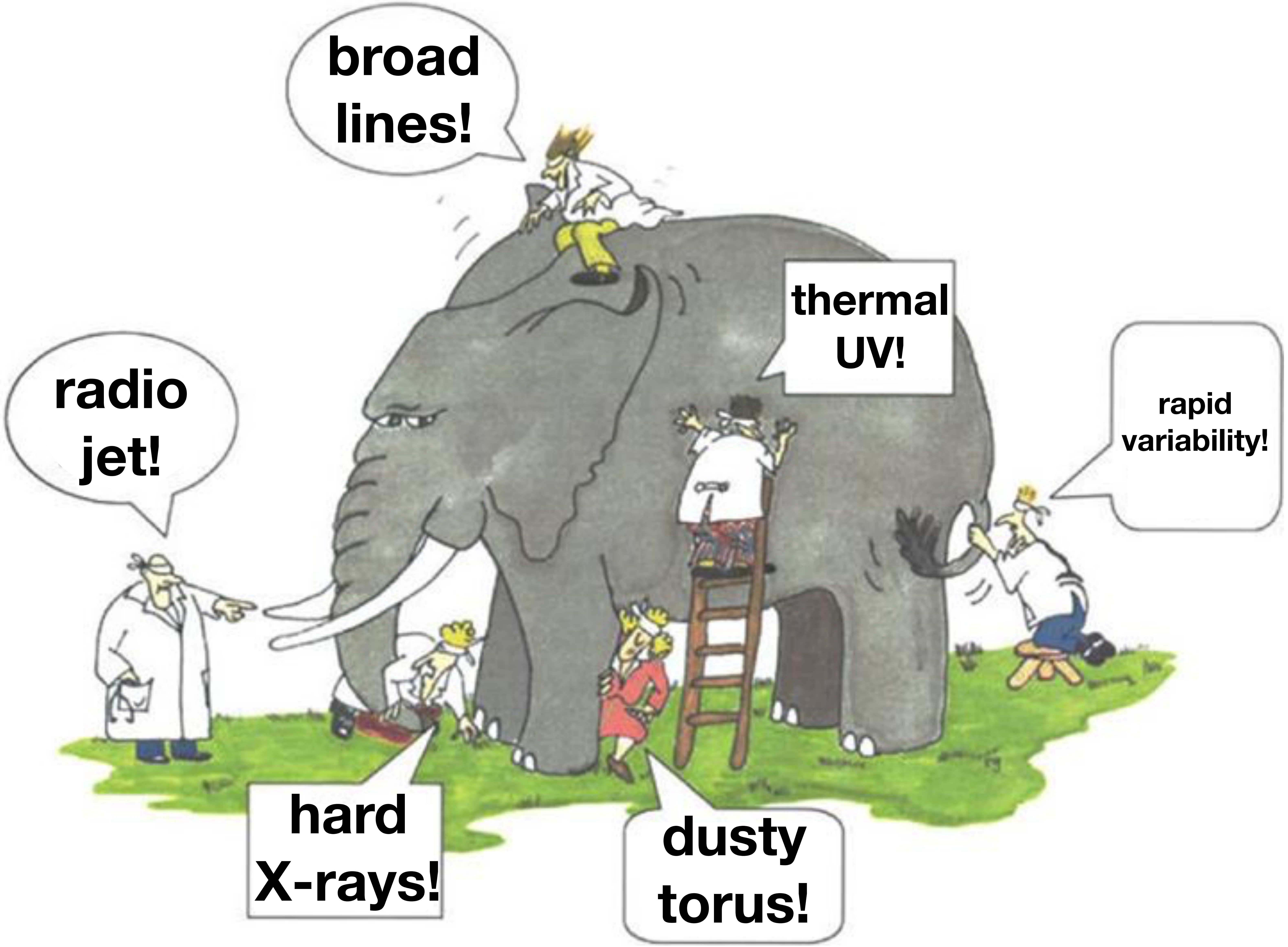
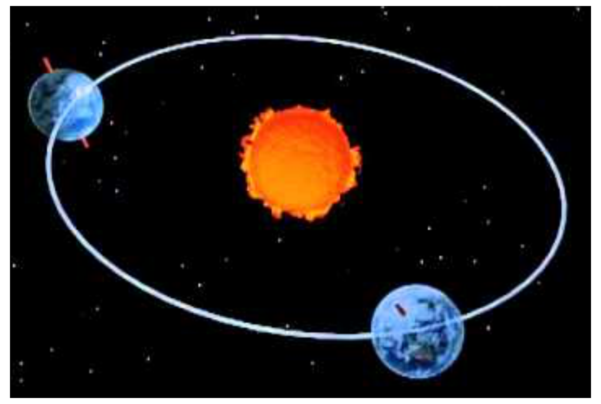


Quasar light curves imply $\Delta t_{var} < 1$ light-week

variability timescale

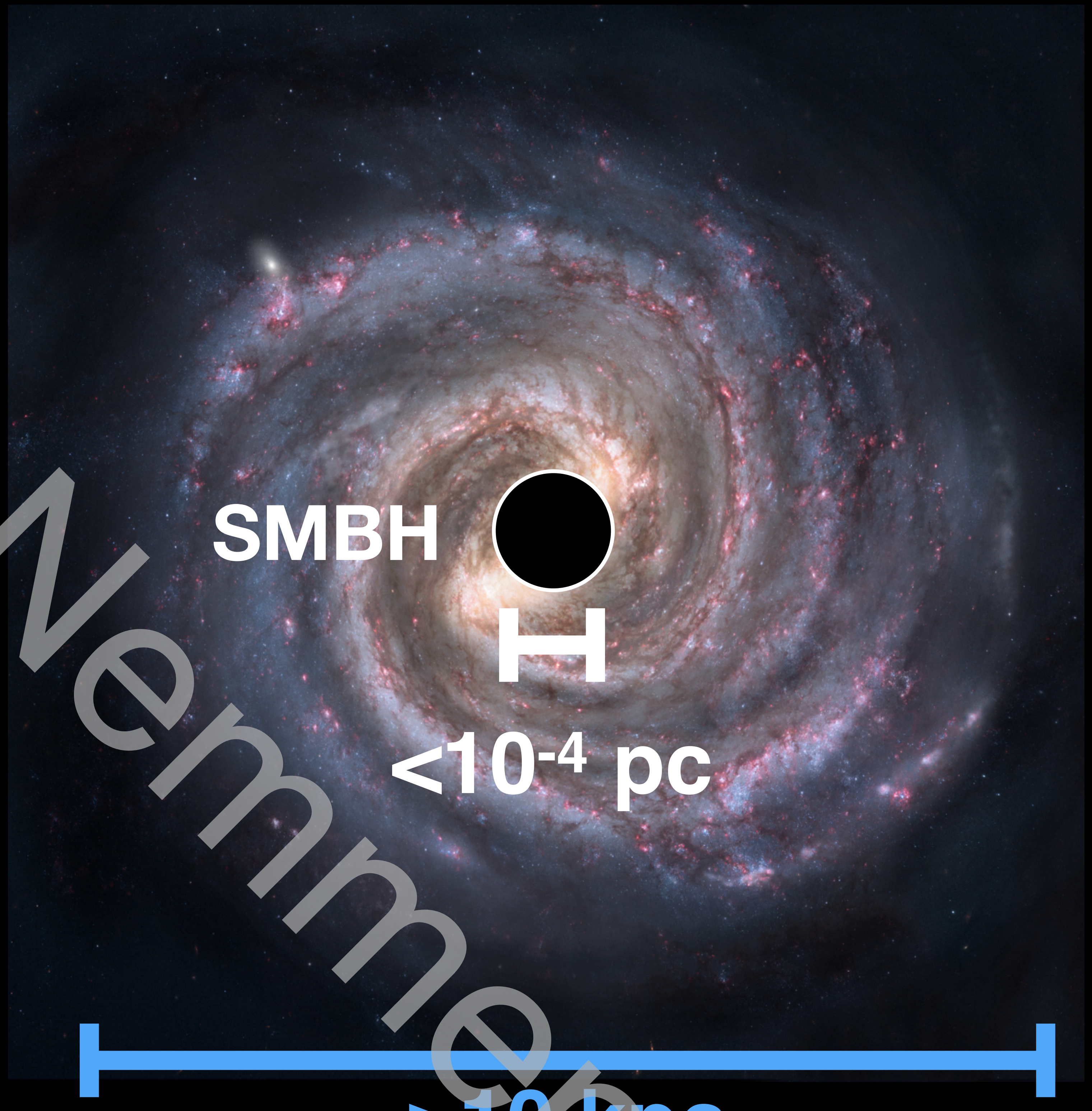
Size of system must satisfy size $< c\Delta t_{var}$ light-crossing radius

≈ 0.01 pc ~ 1000 AU



Supermassive black holes (SMBHs) are extremely small on the sky

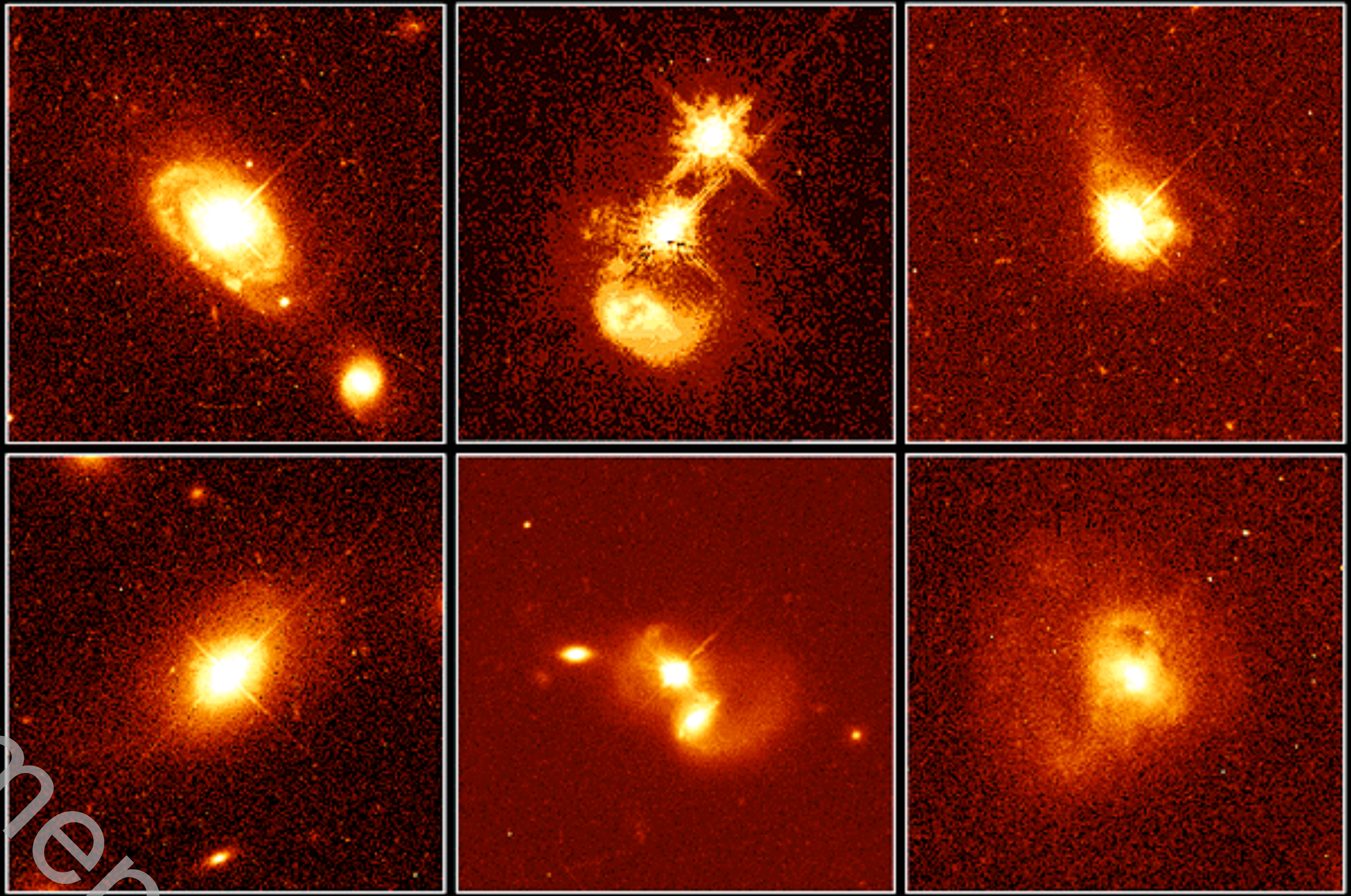
Very hard to observe (challenge #2)



$$\frac{\text{galaxy size}}{\text{event horizon size}} \sim 10^9$$

Grapefruit

AGNs easily outshine their host galaxies (challenge #3)



Hubble Space Telescope

Bahcall+1997

this image: z ~ 0.2
d_L ~ 1 Gpc

Four golden lessons

(1979 Nobel Prize, Physics)

Steven Weinberg

Scientist

Advice to students at the start of their scientific careers.

1. **Start doing research and pick up what you need as you go along** — No one knows everything, and you don't have to.
2. **Aim for the rough water** ("the mess"). — that's where the action is.
3. **Forgive yourself for wasting time**
4. **Learn the history of science** — or at least of your own field.

When I received my undergraduate degree — about a hundred years ago — th
seemed to me a vas
every part of which I
beginning any resear
could I do anythin
everything that had
Fortunately, in my fi
school, I had the goo
hands of senior physic
my anxious objection

work of many theoretical and experimental physicists has been able to sort it out, and put everything (well, almost everything) together in a beautiful theory known as

in order to understand why all attempts to detect effects of Earth's motion through the ether had failed. We now know that

ing most of your time not being
o being becalmed on the ocean of
knowledge.
, learn something about the history
, or at a minimum the history of your
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this is that the history may actually
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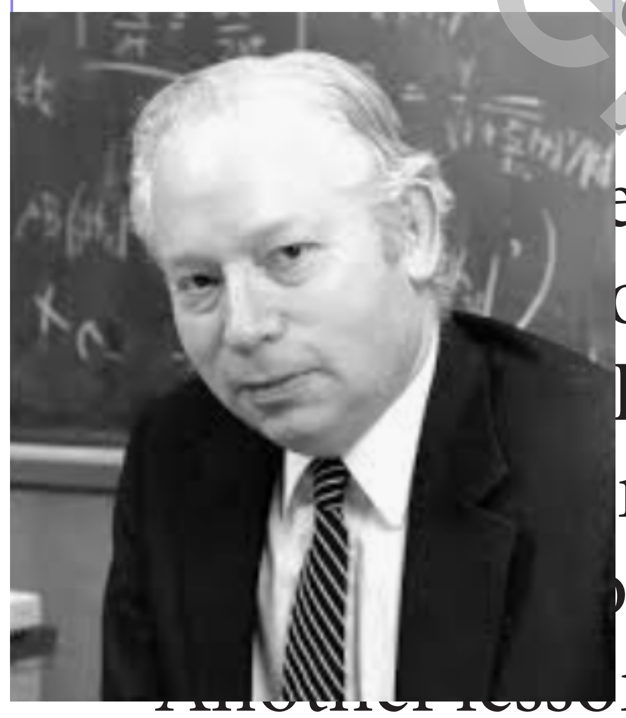
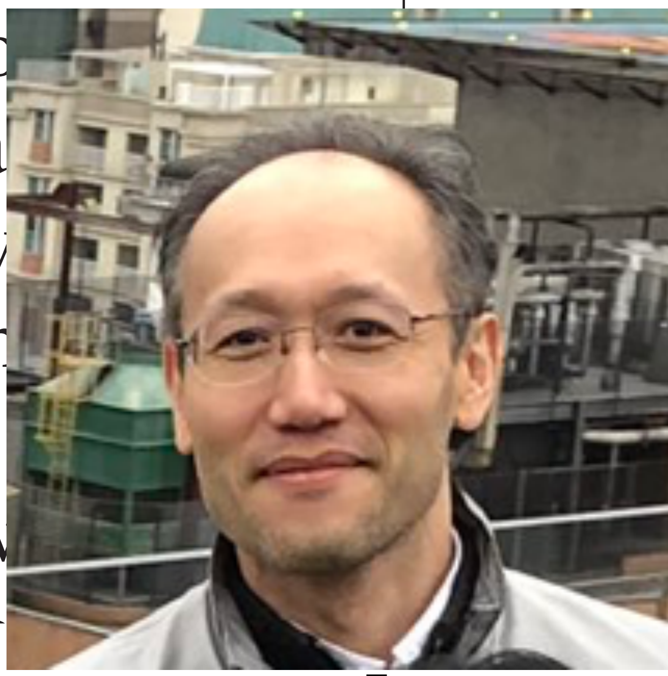




slide by Ken Nagamine

Recap: Aula 2

- **O que é um AGN**
- **Componentes: ⚫, acreção, jatos**
- **Desafios do estudo de AGNs**
  - Multifacetados
  - Minúsculo tamanho angular
  - Muito brilhantes!

Historical perspective on AGNs

1783: Newtonian "dark stars" predicted — Michell 1783

1915: Einstein publishes his field equation — Einstein 1915

1916: black hole solution derived from GR — Schwarzschild 1916

1918: "curious straight ray" in galaxy M87, "connected with the nucleus by a thin line of matter"—jets discovered — Curtis 1918

1963: strong optical point source found at 3C 273 nucleus—quasars discovered — Schmidt+1963

Early 1990s: HST finds SMBHs at centers of nearby galaxies — Ford+1994; Harms+1994; Ferrarese & Ford 2004

Late 1990s: stellar orbits at Galactic Center—strongest BH case until 2015 (Sagittarius A*, $4\times10^{6}\ M_\odot$) — Genzel & Gillessen 2010

Historical perspective on AGNs

Late 1990s, early 2000s: *M-σ* relation—SMBHs and host galaxies are tightly connected — Magorrian+1998; Kormendy & Ho 2013

2000: SMBHs disturb thermodynamics of entire galaxy clusters — McNamara+2000; Fabian 2012

2003: Sloan Digital Sky Survey (SDSS) finds >100k AGNs — Abazajian+2003

2015: direct observation of gravitational waves from stellar-mass BHs — Abbott+2015

2018a: 1st multimessenger observation from AGNs (blazar TXS 0506+056) — IceCube, *Fermi* LAT Collaborations

2018b: GRAVITY resolves orbit at $r = 7M$ (Sgr A*) — Abuter+2018

2019: EHT images event horizon (M87*) — EHTC (new technologies)·(engineering)

= (new astronomical windows)

(new observations)×(grad students)

= paradigm change

General lessons from history

- Pace of discovery is accelerating
- Future: immense discovery space awaiting
- We entered 2nd golden age of black hole (astro)physics

Black hole physics

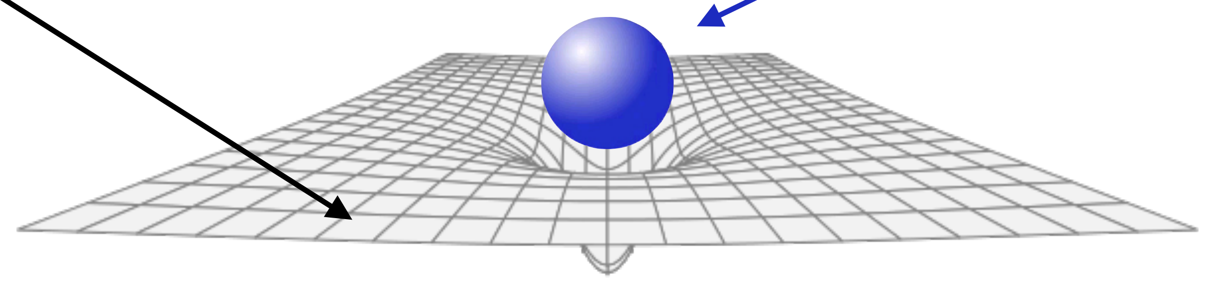
A general relativity primer

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



Solution to field equation gives

$g_{\mu\nu}$ — Metric

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

Newtonian analogue

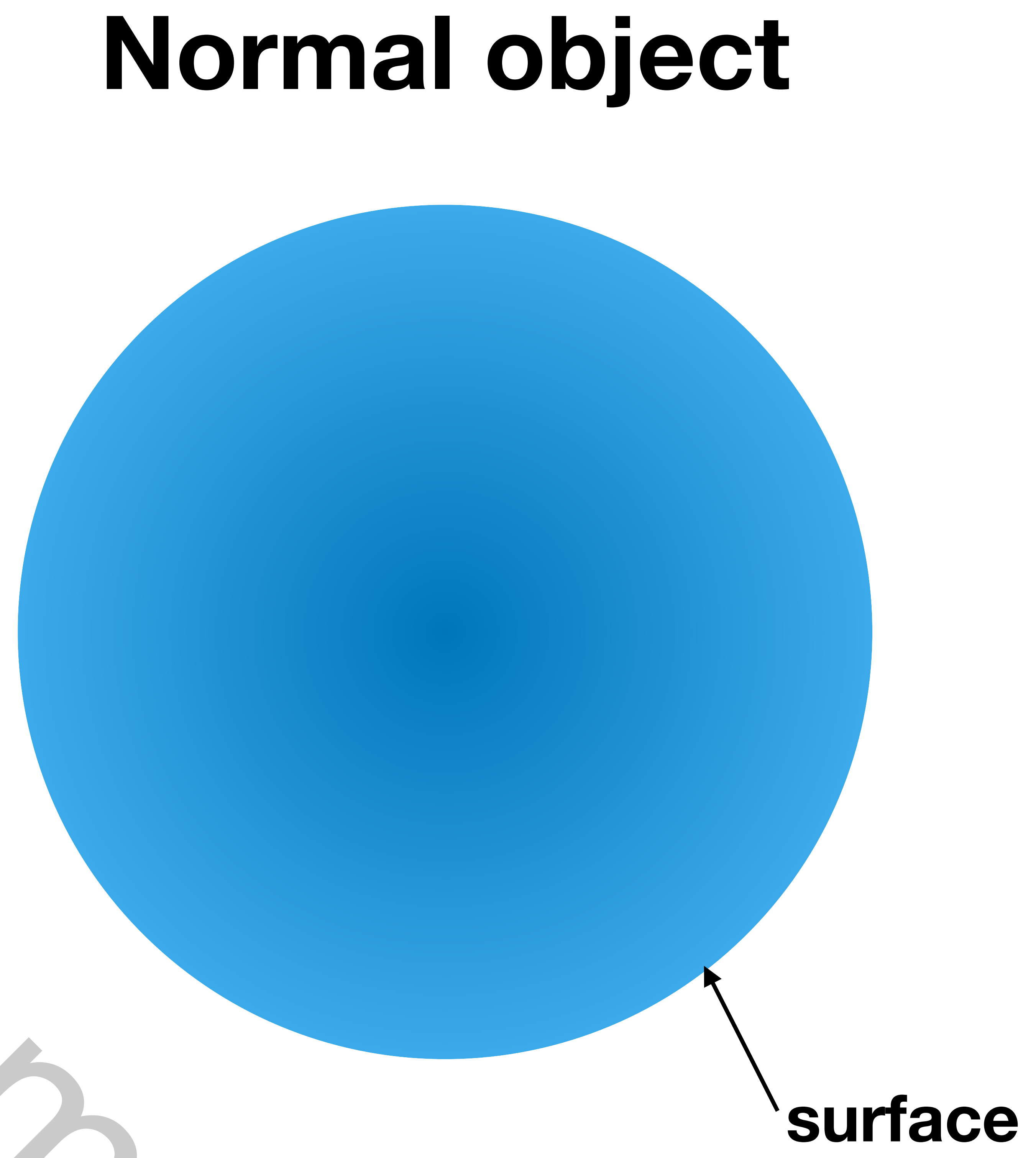
$\nabla^2 \phi = 4\pi G \rho$ — Poisson equation

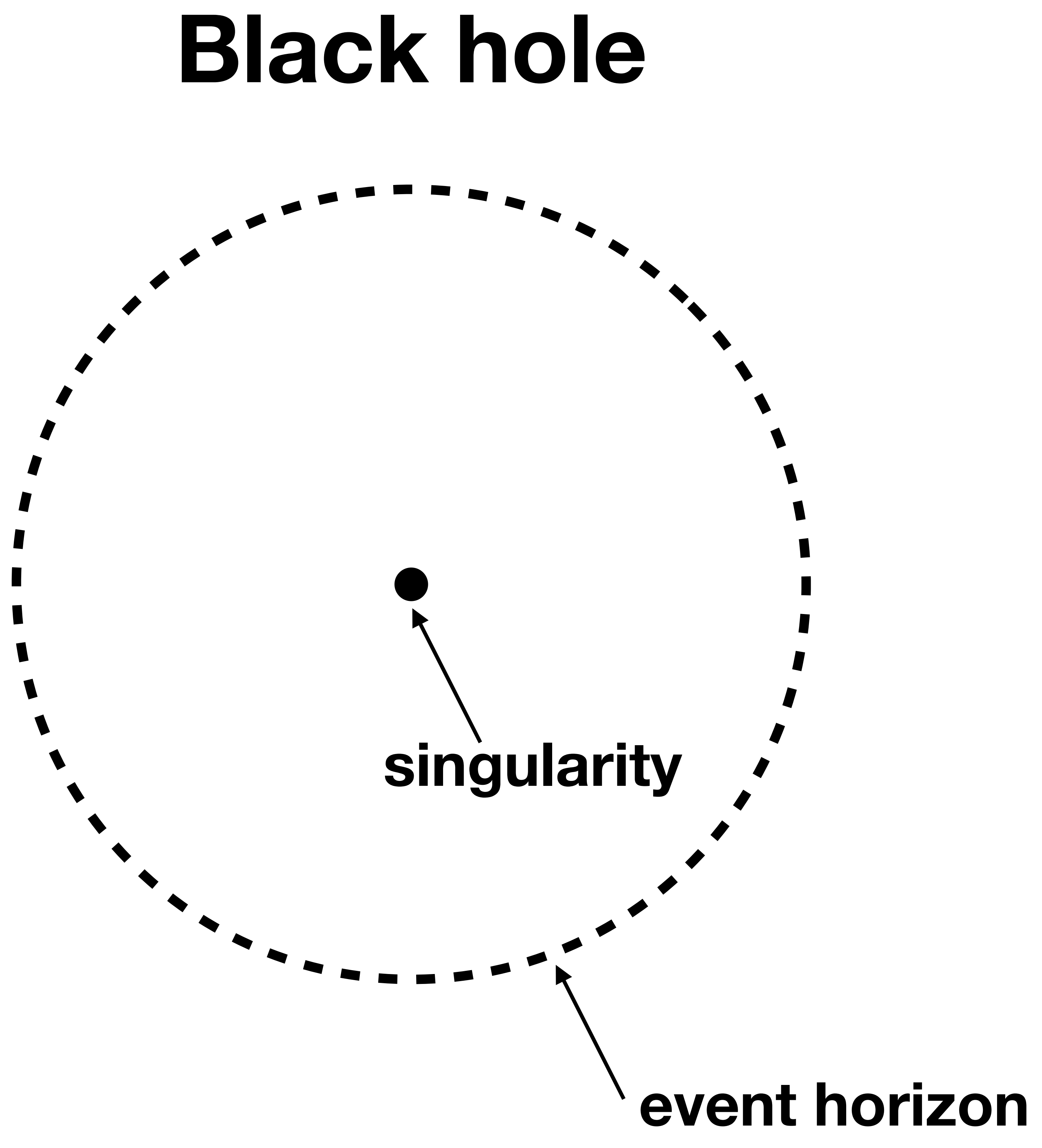
For a free particle:

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

Geodesic equation

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

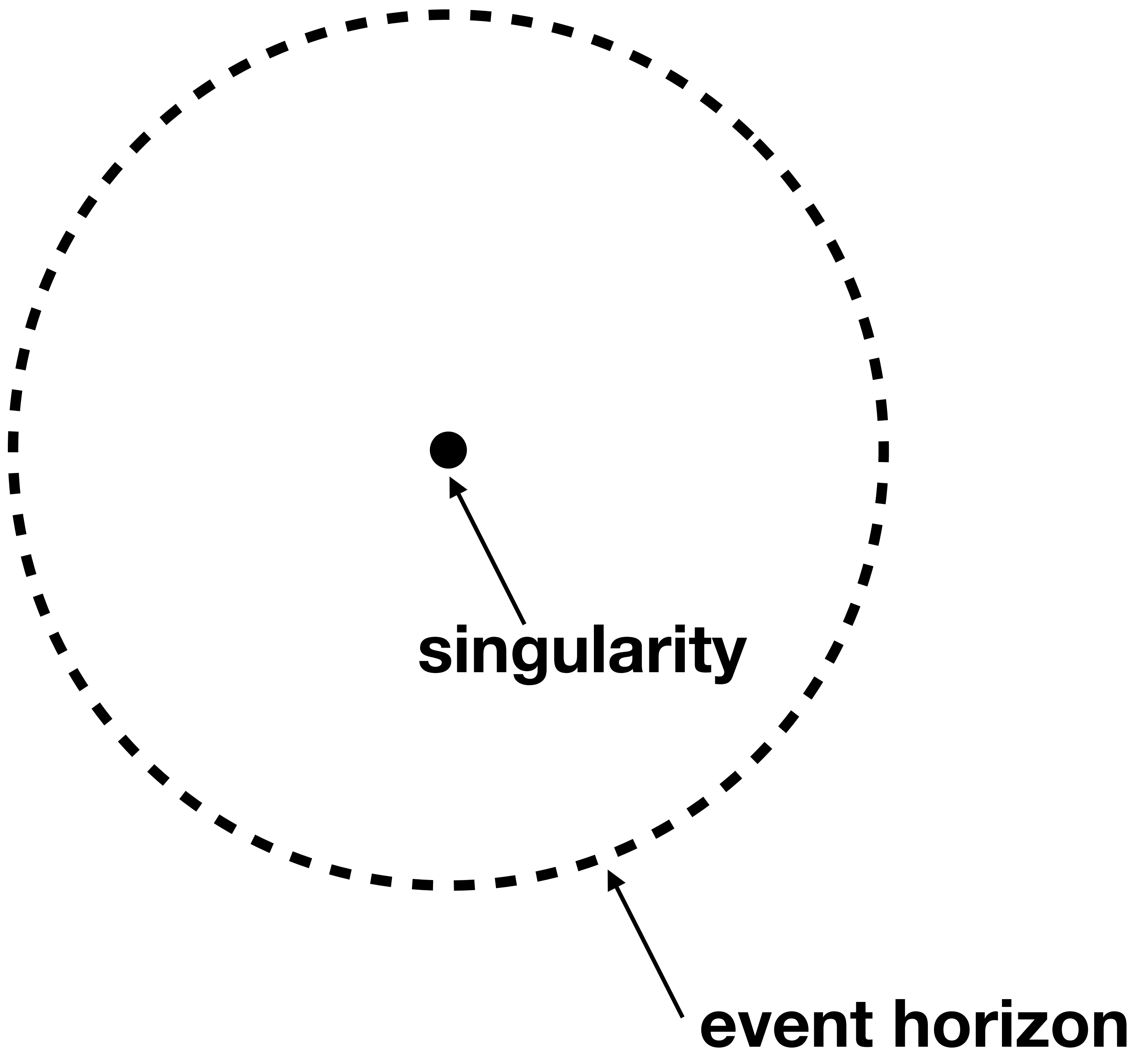
Radius of event horizon:

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

Schwarzschild radius

Gravitational radius: $R_g \equiv \frac{GM}{c^2}$ **Useful scale**

Black hole



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:

- $M_{min} = 3.3\ M_{Sun}$
- $M_{max} \sim 10^{10}\ M_{Sun}$

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

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

Boyer-Lindquist coords.

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

Main parameters for *astrophysical* BHs

Gravity	**units**
Mass M	($M_\odot = 2\times10^{33}$ g)
Spin a_*	(1 = max spin)

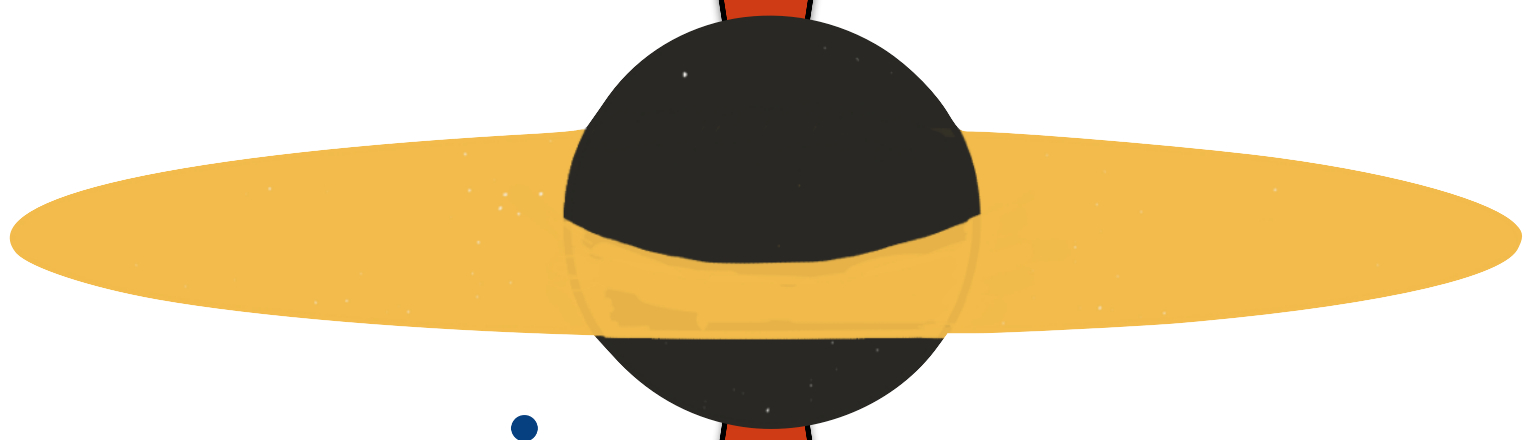
Accretion

Mass accretion rate $\dot{M}$ ($M_\odot$/yr or $\dot{M}_{\rm Edd}$)

Magnetic flux Φ

Predict

Energy output in all forms (erg/s or $L_{\rm Edd}$)



Main problem in BH astrophysics

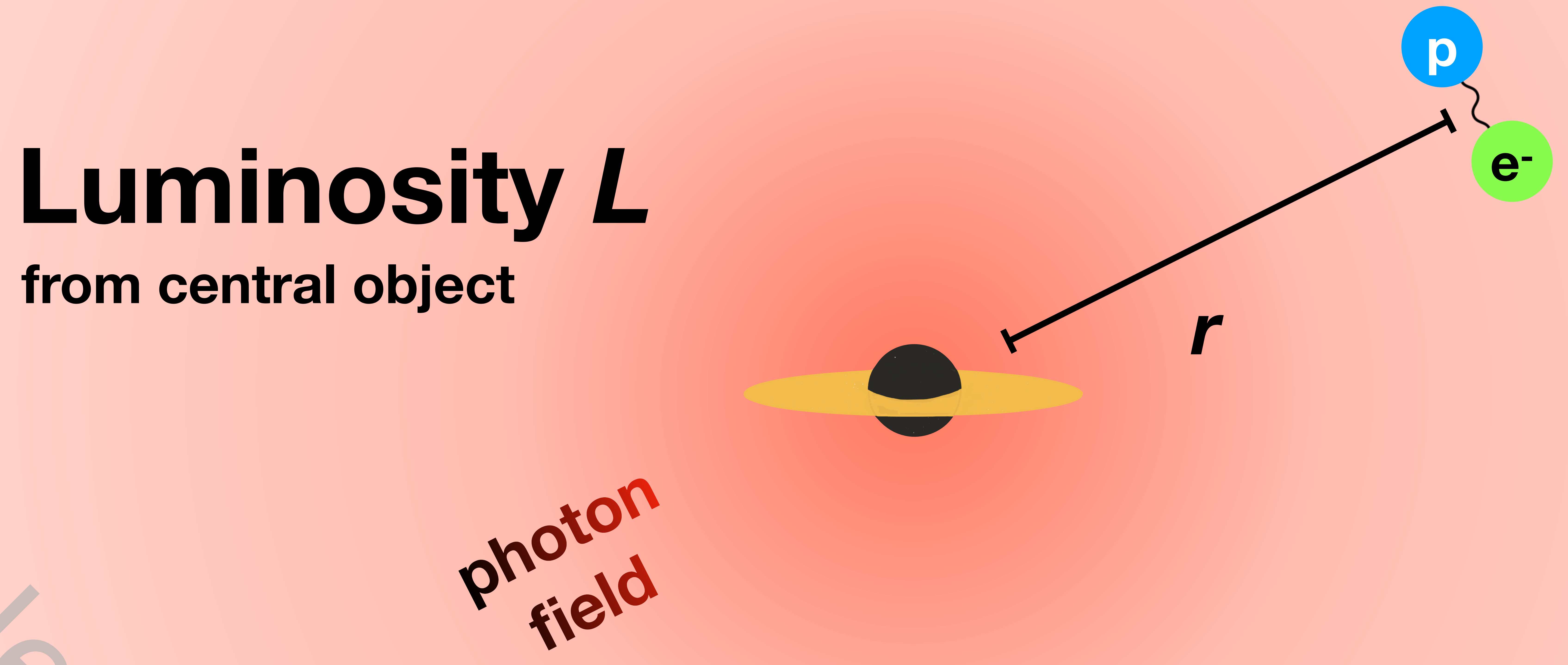
$$\mathrm{AGN}(t) = f(M, a_*, \dot{M})$$

Eddington luminosity L_{Edd}

Luminosity L

from central object

Eddington luminosity L_{Edd}



When is the radiation *strong enough to prevent accretion* of particles?

Solve this to get L_{Edd}: $F_{\mathrm{rad}} = F_g$

$$P_{\mathrm{rad}} = \frac{F_{\mathrm{rad}}}{A_{\text{area}}} = \frac{F^{\text{flux}}}{c}$$

Solve this to get L_{Edd}: $F_{\rm rad} = F_g$

flux

radiation force on an electron

$$P_{\rm rad} = \frac{F_{\rm rad}}{A_{\rm area}} = \frac{F}{c} \Rightarrow F_{\rm rad} = \frac{FA}{c}$$

Solve this to get L_{Edd}: $F_{rad} = F_g$

flux

radiation force on an electron

$$P_{rad} = \frac{F_{rad}}{A_{\text{area}}} = \frac{F}{c} \Rightarrow F_{rad} = \frac{FA}{c} \Rightarrow F_{rad} = \frac{L}{4\pi r^2}\frac{\sigma_T}{c}$$

Solve this to get L_{Edd}: $F_{rad} = F_g$

flux; radiation force on an electron

$$P_{rad} = \frac{F_{rad}}{A_{\text{area}}} = \frac{F}{c} \Rightarrow F_{rad} = \frac{FA}{c} \Rightarrow F_{rad} = \frac{L}{4\pi r^2}\frac{\sigma_T}{c}$$

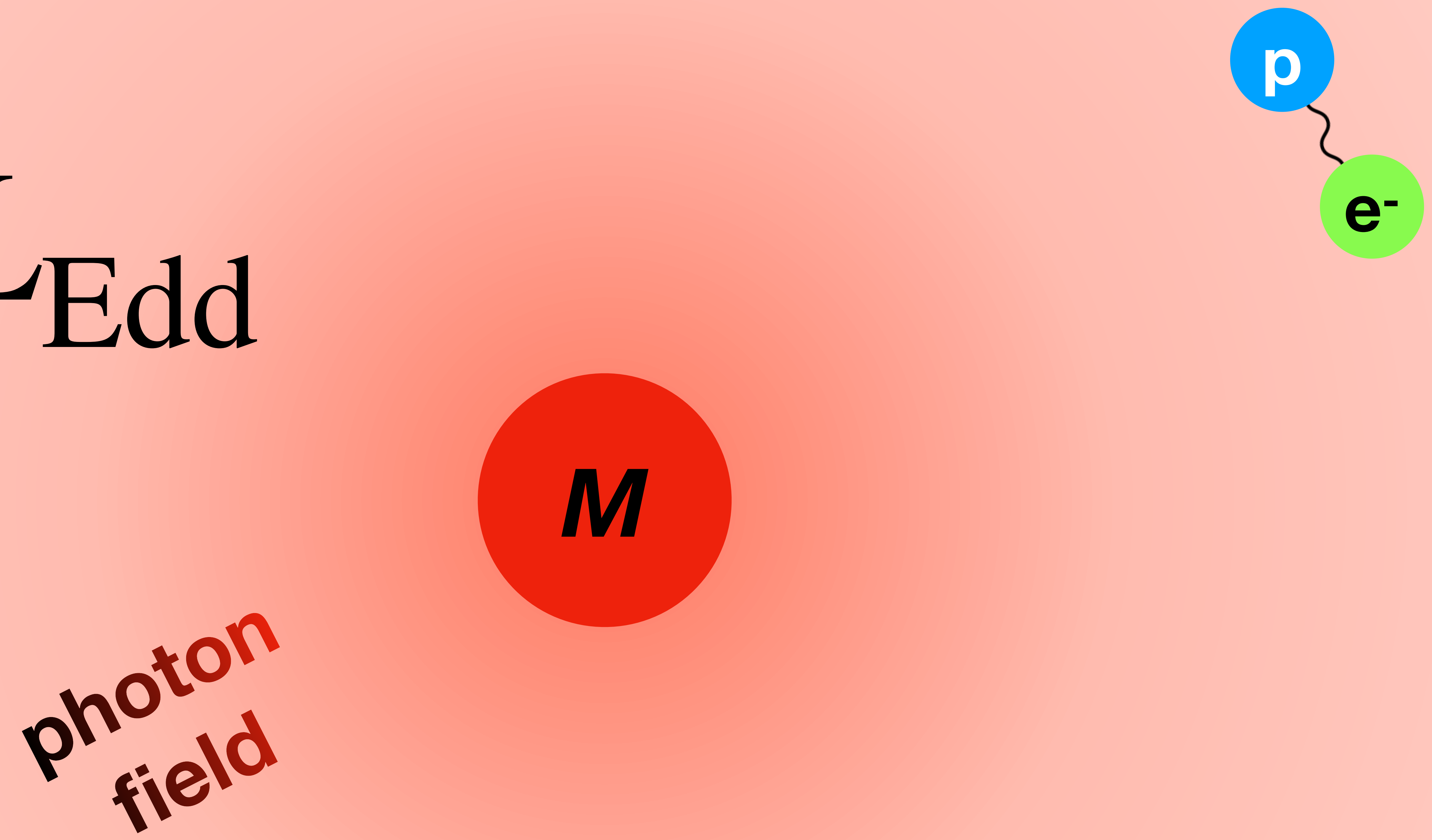
why?

$$F_g = \frac{GM(m_e + m_p)}{r^2} \approx \frac{GMm_p}{r^2}$$

$$L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T} = 1.3 \times 10^{38}\left(\frac{M}{M_\odot}\right) \text{ erg s}^{-1}$$

Eddington luminosity: importance

$$L > L_{\mathrm{Edd}}$$



Eddington luminosity: importance

Useful luminosity unit in BH astrophysics

A system radiating at $L > L_{Edd}$ can halt mass accretion due to strong radiation pressure

Roughly maximal luminosity that can be powered by accretion (if spherical symmetry)

Eddington accretion rate

- Assume an engine radiating at $L = L_{Edd}$
- If it were converting mass to radiative energy with efficiency η

Eddington accretion rate

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

Eddington accretion rate

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- If it were converting mass to radiative energy with efficiency η

$$L_{\rm Edd} = \eta \dot{M}_{\rm Edd} c^2 \Rightarrow \boxed{\dot{M}_{\rm Edd} \equiv \frac{L_{\rm Edd}}{\eta c^2}}$$

usually η = 0.1

Useful accretion rate unit in BH astrophysics

$$= 3 \left(\frac{0.1}{\eta}\right) \left(\frac{M}{10^8 M_\odot}\right) M_\odot \ {\rm yr}^{-1}$$

Eddington time t_{Edd}

also known as Salpeter time t_S

Assume BH accreting at Eddington rate

$$\dot{M} = \frac{dM}{dt} = \dot{M}_{\rm Edd} \Rightarrow \frac{dM}{dt} = \frac{M}{t_{\rm Edd}}$$

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Assume BH accreting at Eddington rate

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Useful timescale

$$t_{\rm Edd} \equiv \frac{\eta c \sigma_T}{4\pi G m_p} = 4 \times 10^7 \left(\frac{\eta}{0.1} \right) \text{ yr}$$

Useful websites and apps for grad students

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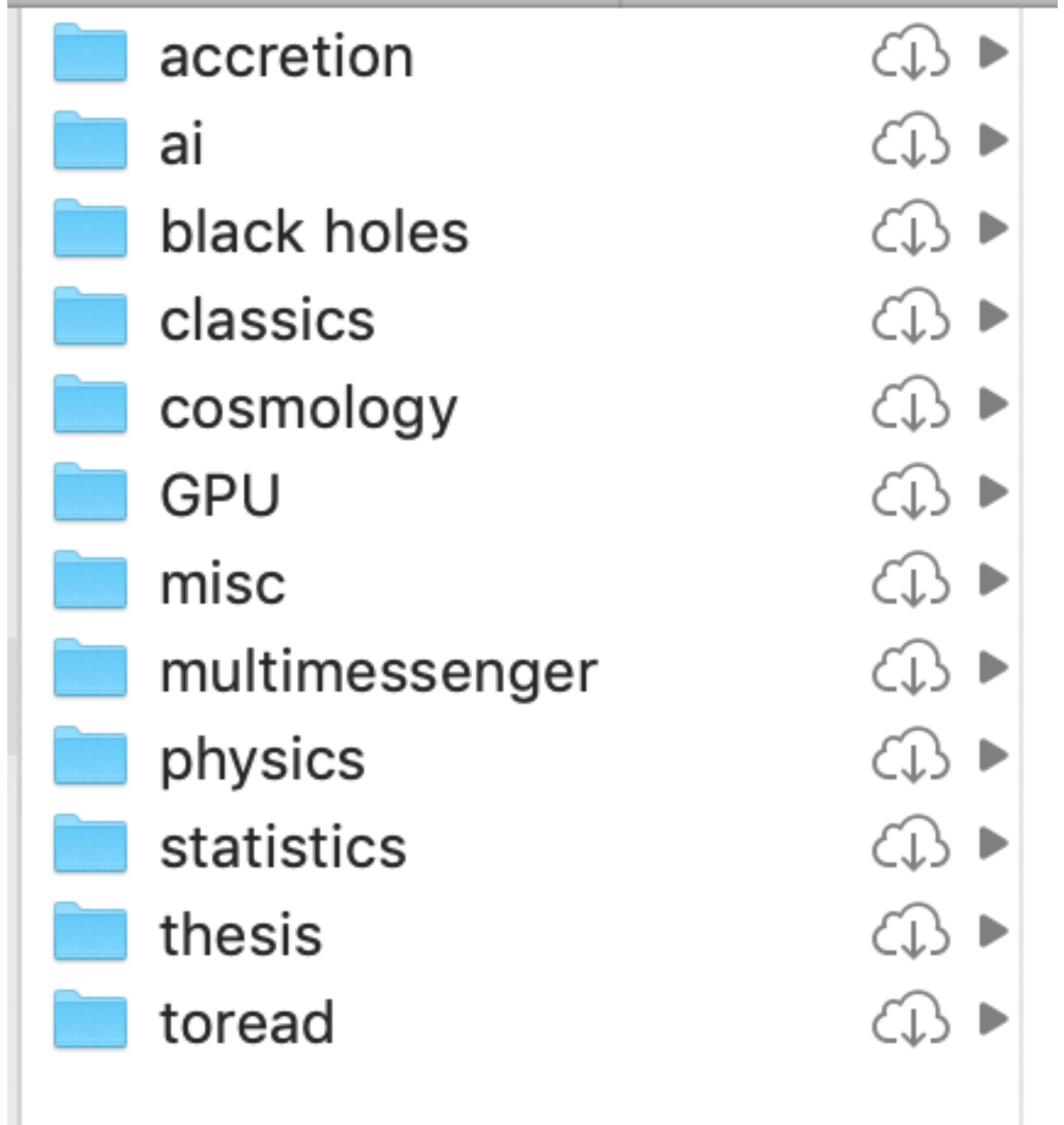
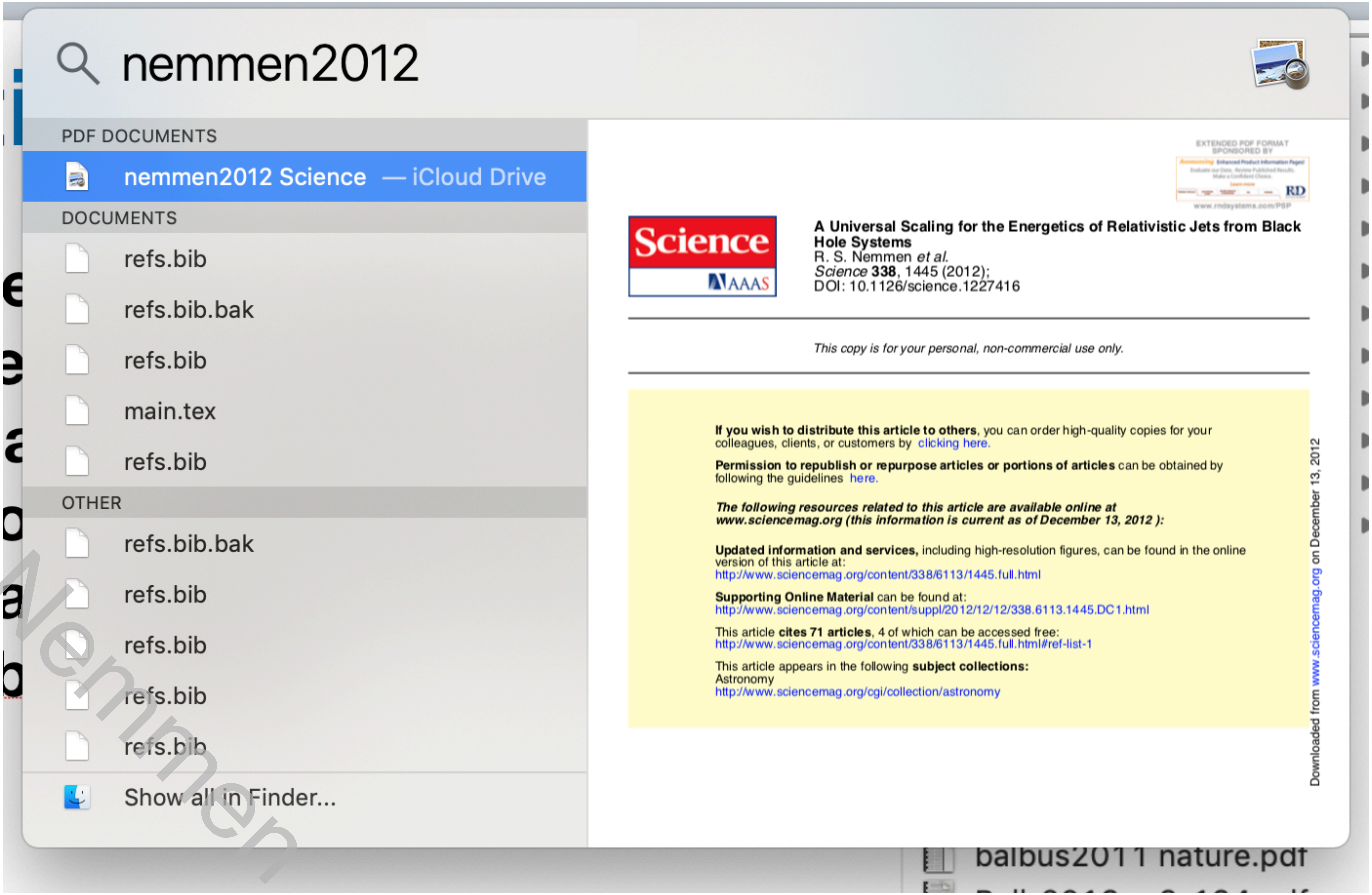
Pro tips

Organize papers using convention:

1. **Folders named after categories**
2. **Filename:** `<Last name of first author><publication year>`
3. **Use a desktop search app to find (spotlight, cerebro, albert)**

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R. Nemmen

Important lengths from now on, $G = c = 1$

r_{isco}: Innermost stable circular orbit

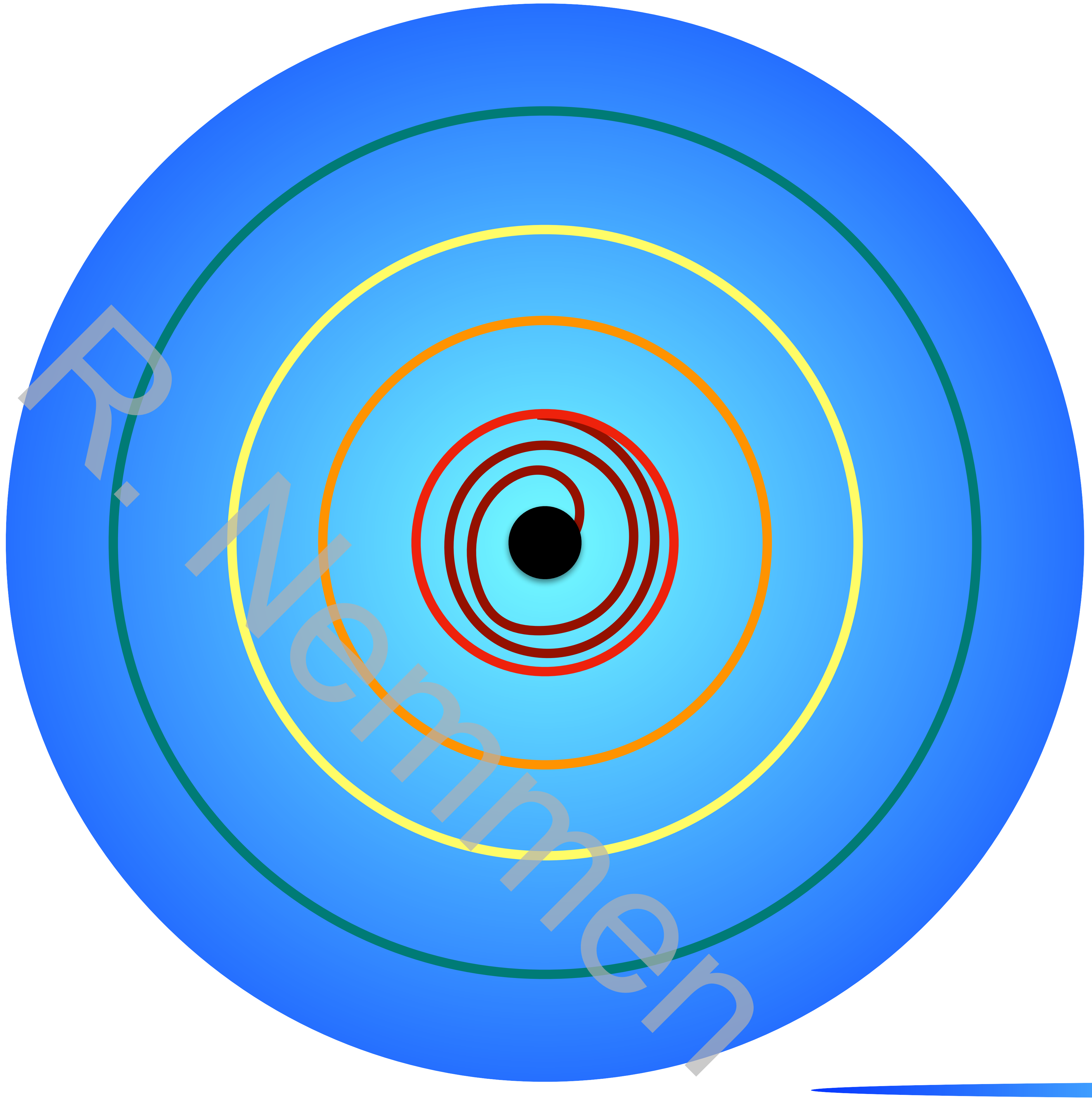
$$r_{\rm isco} = 6M \quad \text{for } a_* = 0$$

Effective potential for orbits around a Schwarzschild black hole

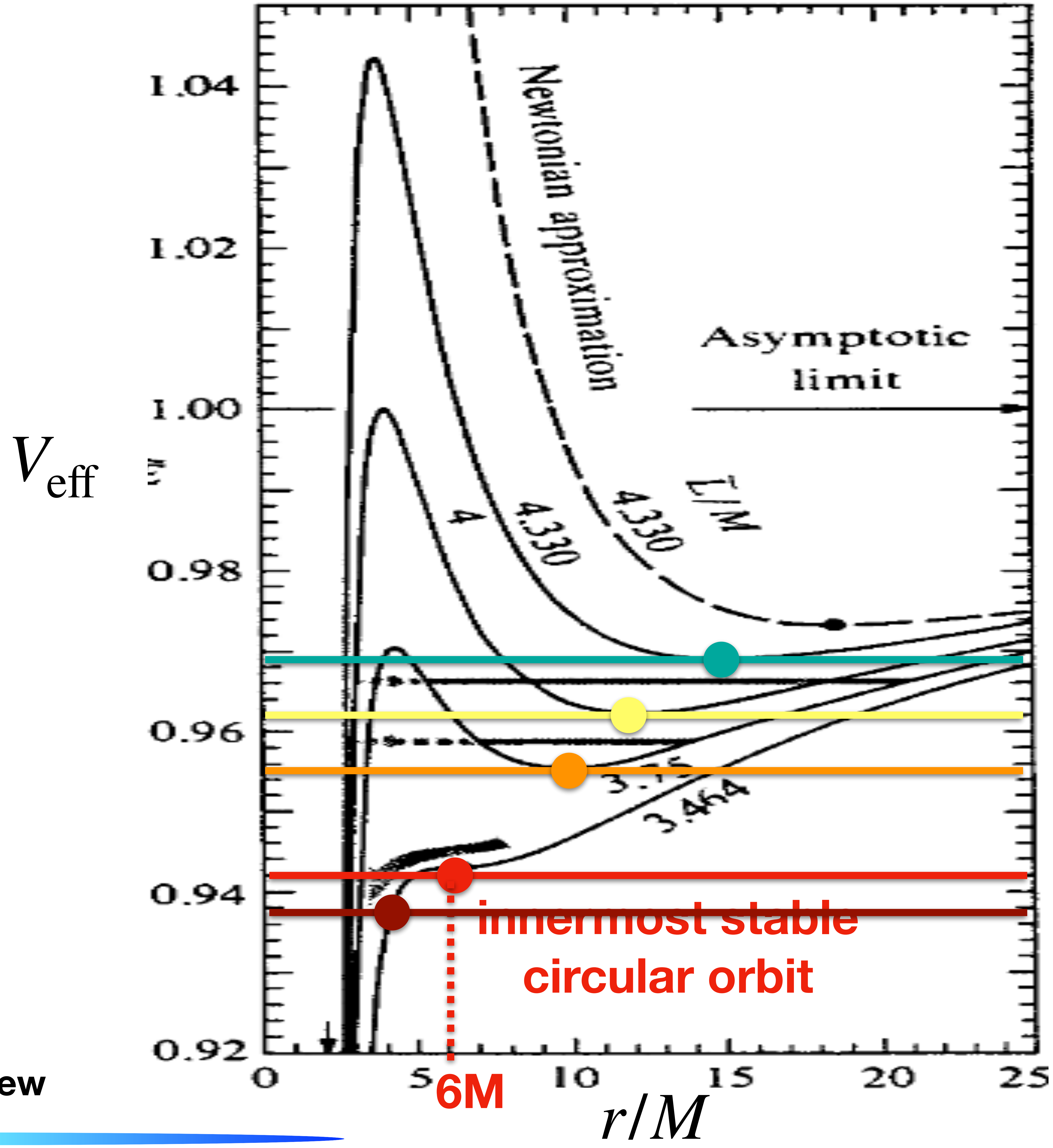
$$E = \frac{1}{2}\left(\frac{dr}{d\tau}\right)^2 + V_{\text{eff}}$$

effective potential

face-on view of accretion disk



edge-on view



Misner, Thorne & Wheeler

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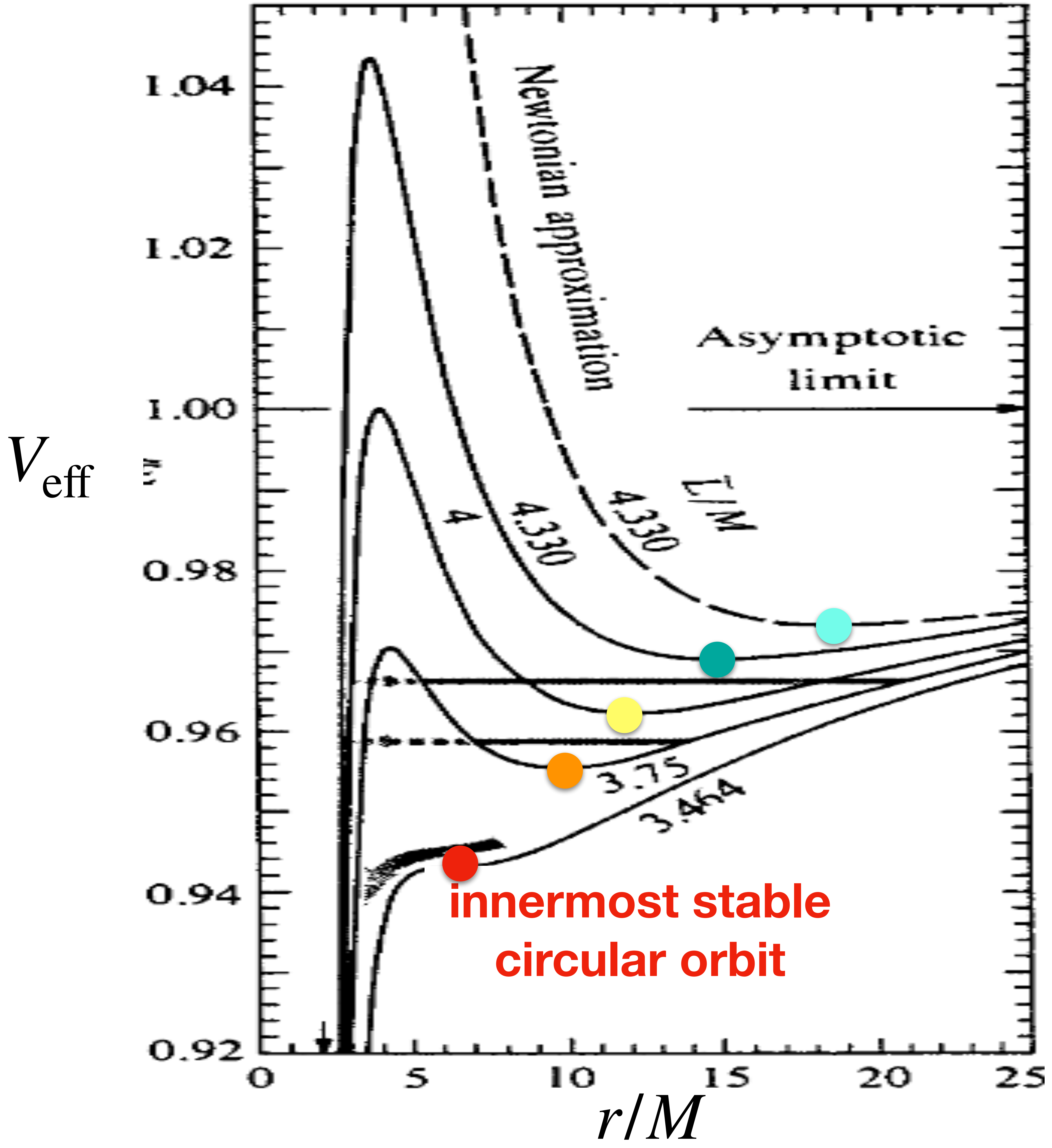


Misner, Thorne & Wheeler

Important radii

from now on, $G = c = 1$

r_{isco}: Innermost stable circular orbit

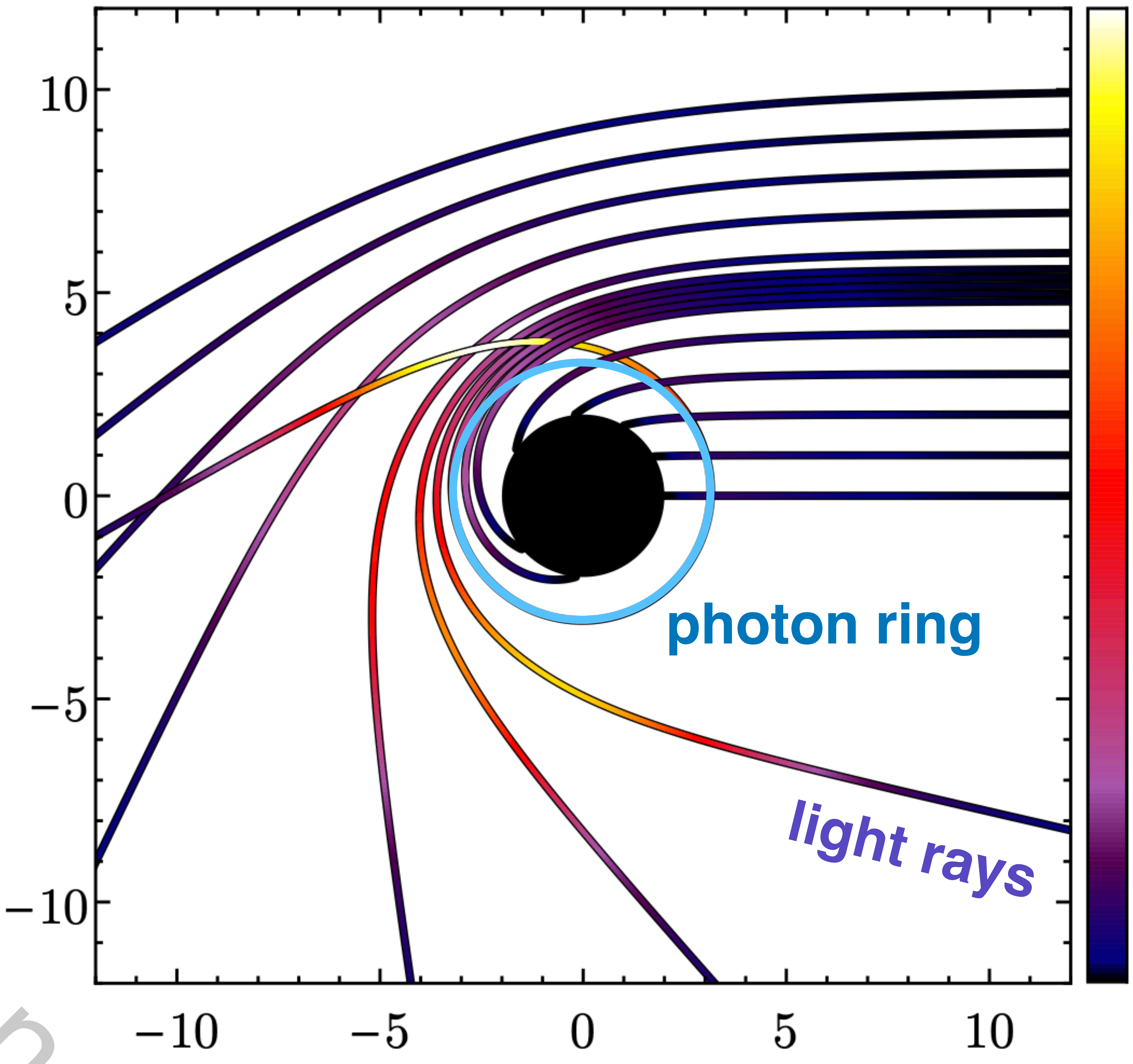
$$r_{\rm isco} = 6M \quad \text{for } a_* = 0$$

r_c: photon capture radius

also called photon sphere or photon ring

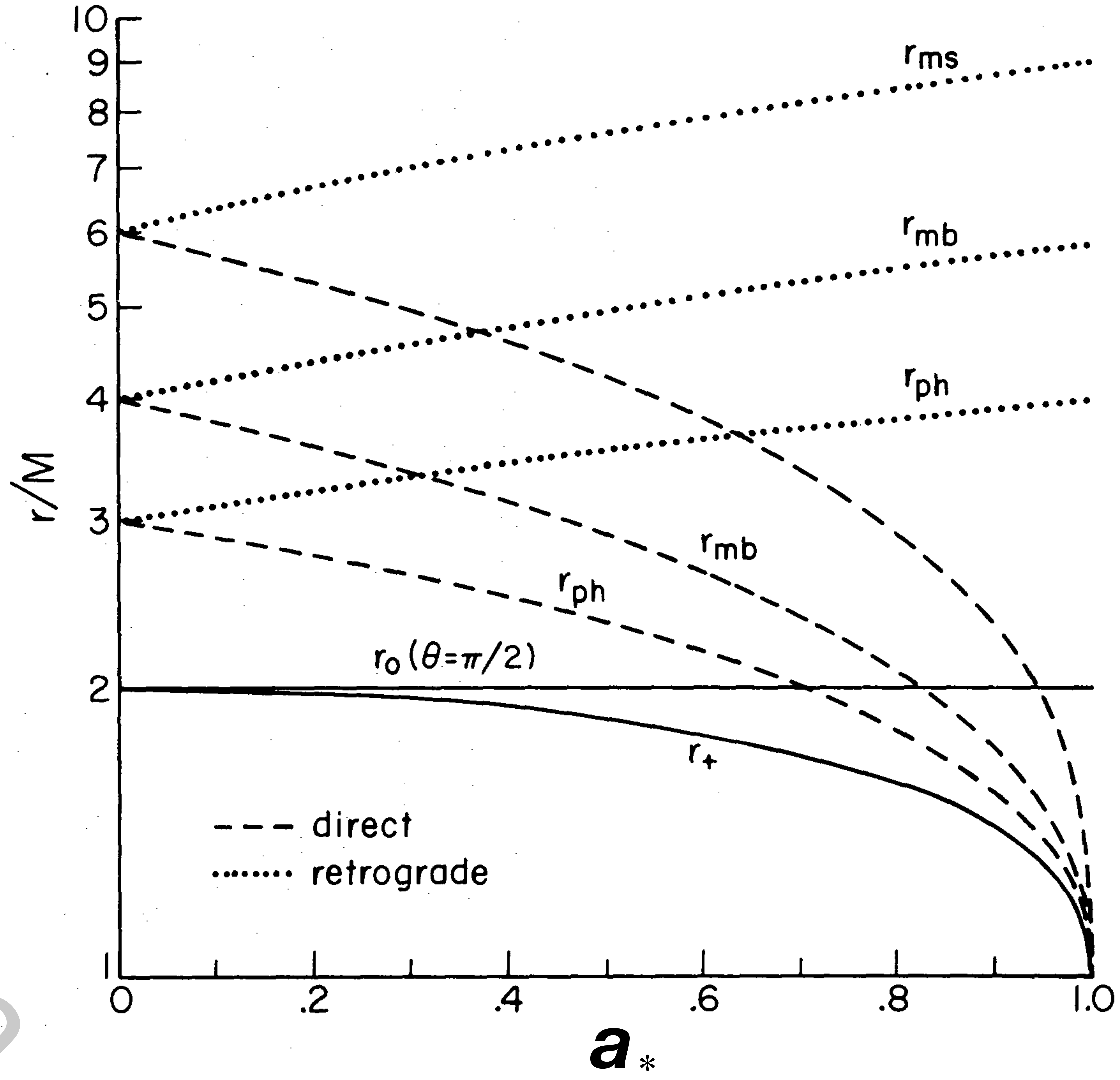
$$r_c = 3M \quad \text{for } a_* = 0$$

apparent radius $\sqrt{27}M$ seen from ∞



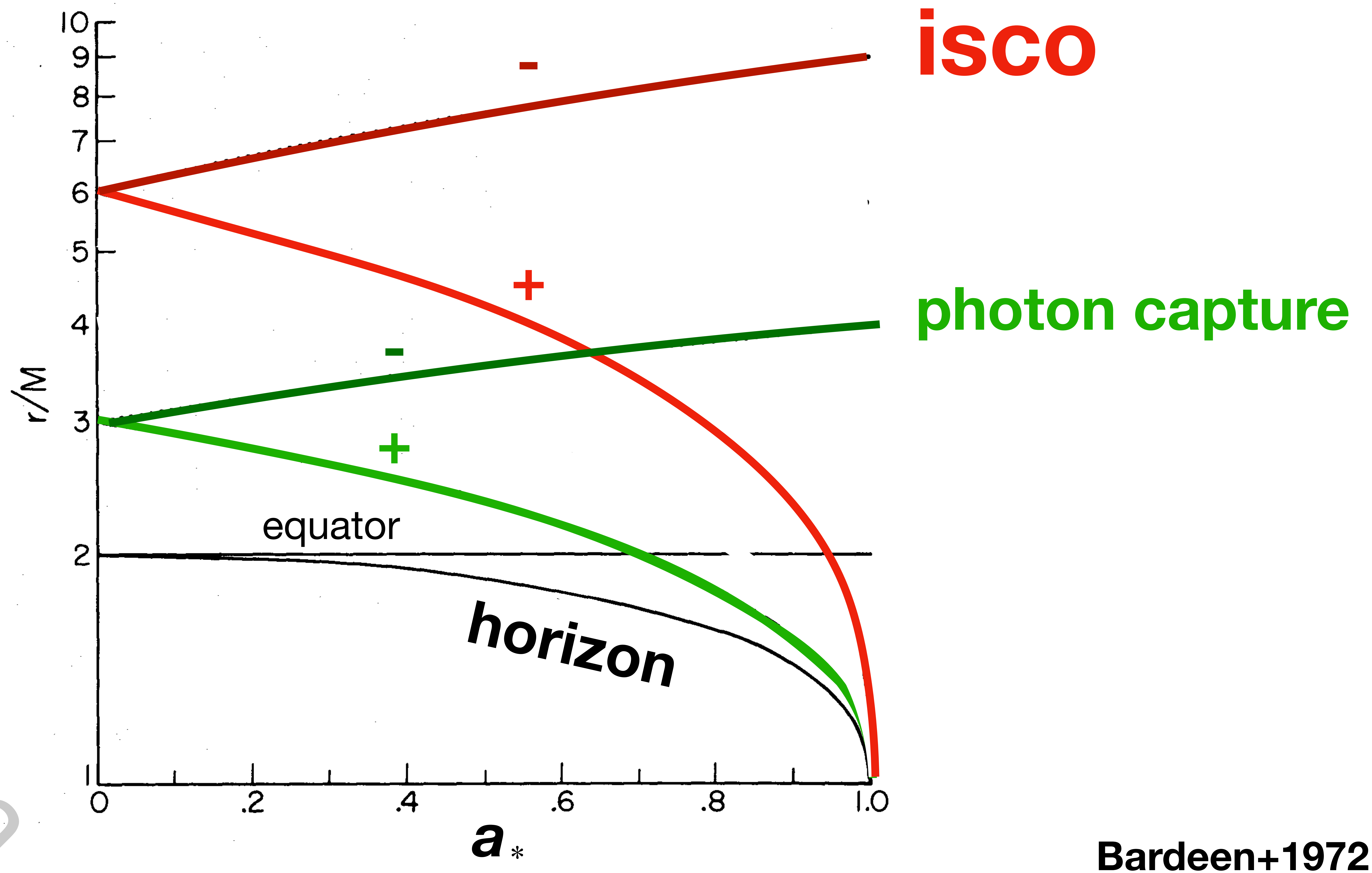
Narayan, Johnson & Gammie 2019

Dependence of radii on BH spin



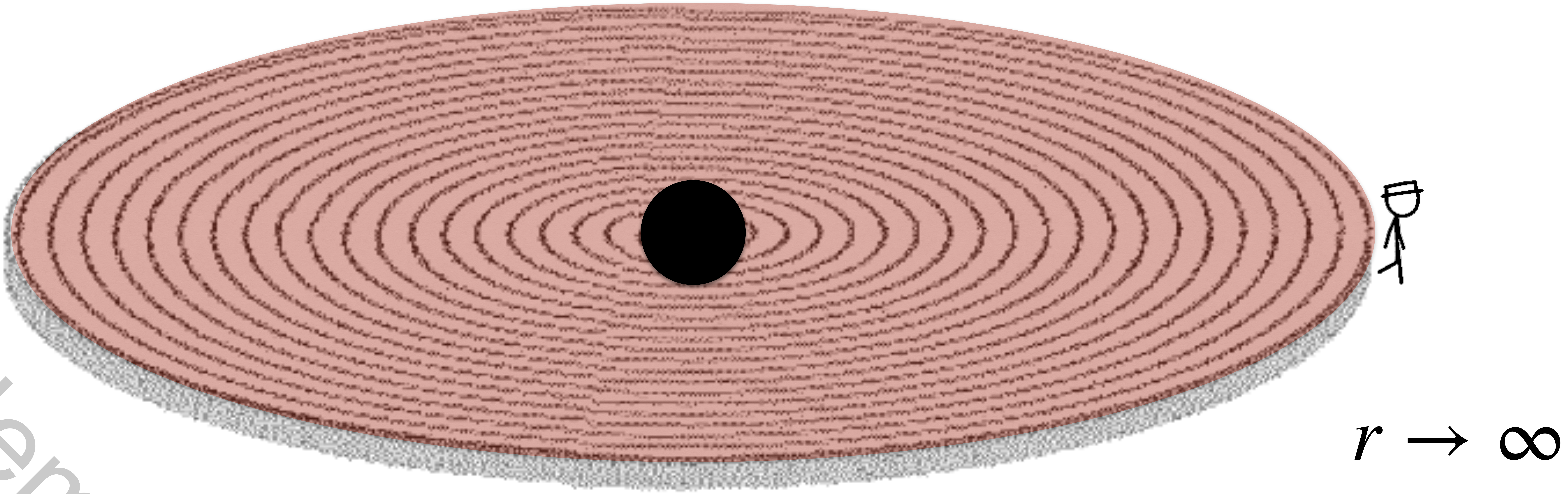
Bardeen+1972

Dependence of radii on BH spin



Bardeen+1972

Efficiency of release of free energy from BH accretion disks



How much orbital energy lost by particle when it disappears behind event horizon?

1st order estimate of L_{acc}

How much orbital energy lost by *one* particle?

$$E_{\rm acc} = U(r \to \infty) - U(r_{\rm surface}) = \frac{GMm}{r_{\rm surface}}$$

gravitational potential energy

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gravitational potential energy

Energy lost by *continuous inflow* of particles?

$$\dot{m} = \frac{dm}{dt} \qquad \frac{dE_{\rm acc}}{dt} = \frac{GM\dot{m}}{r_{\rm surface}} \Rightarrow L = \frac{GM\dot{m}}{r_{\rm surface}}$$

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Luminosity released from accretion

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

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Luminosity released from accretion

$$L = \eta \dot{m} c^2 \Rightarrow \eta = \frac{L}{\dot{m}c^2} = \frac{GM}{r_{surface}c^2}$$

maximized for compact objects

For a Schwarzschild BH $\eta = 0.5$ incorrect Newtonian value

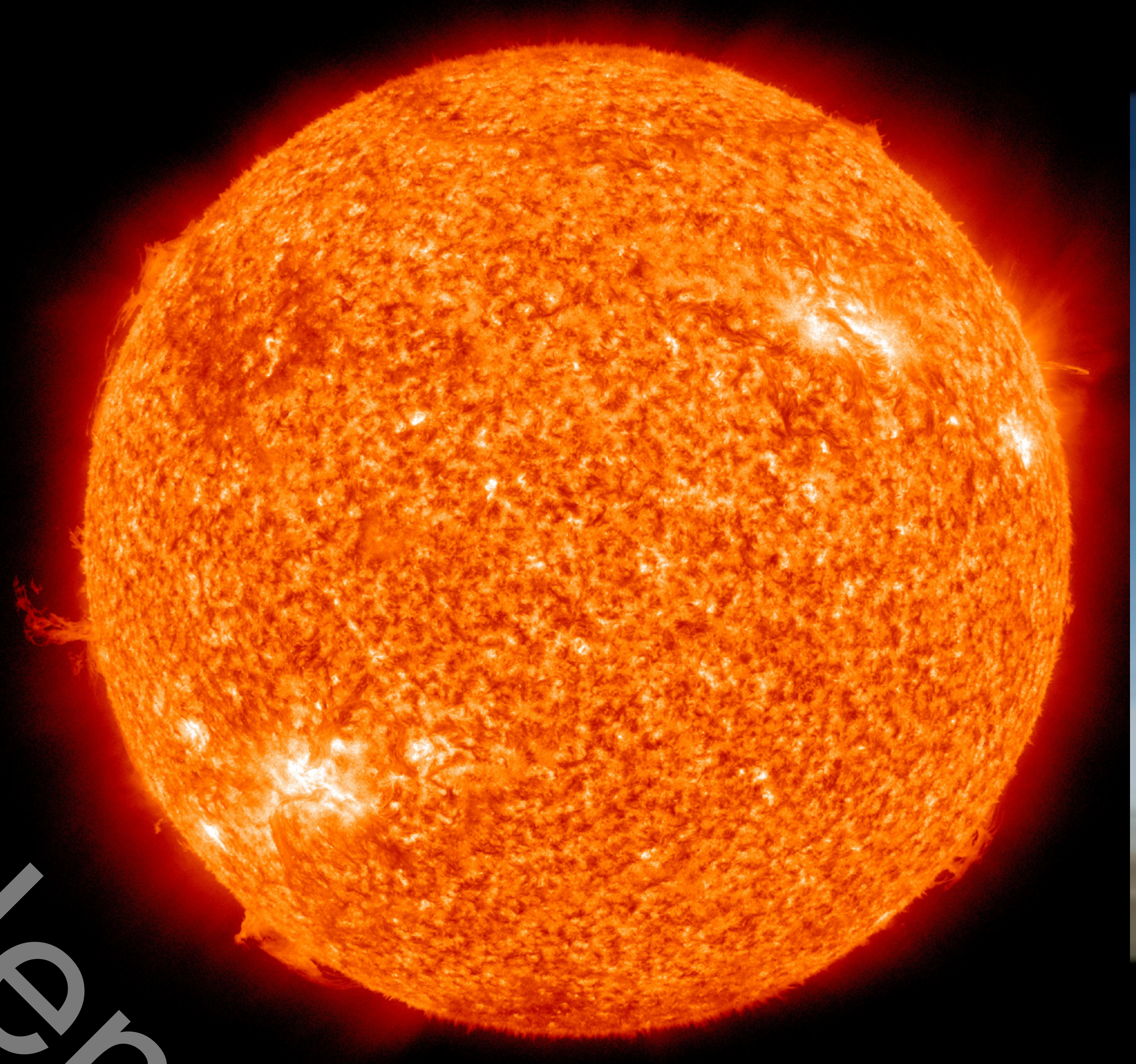
Correct GR result $\eta = V_{\text{eff}}(\infty) - V_{\text{eff}}(6M)$

$$= -V_{\text{eff}}(6M) = \frac{1}{18} = \boxed{0.06}$$

Itaipu Dam – 14 GW

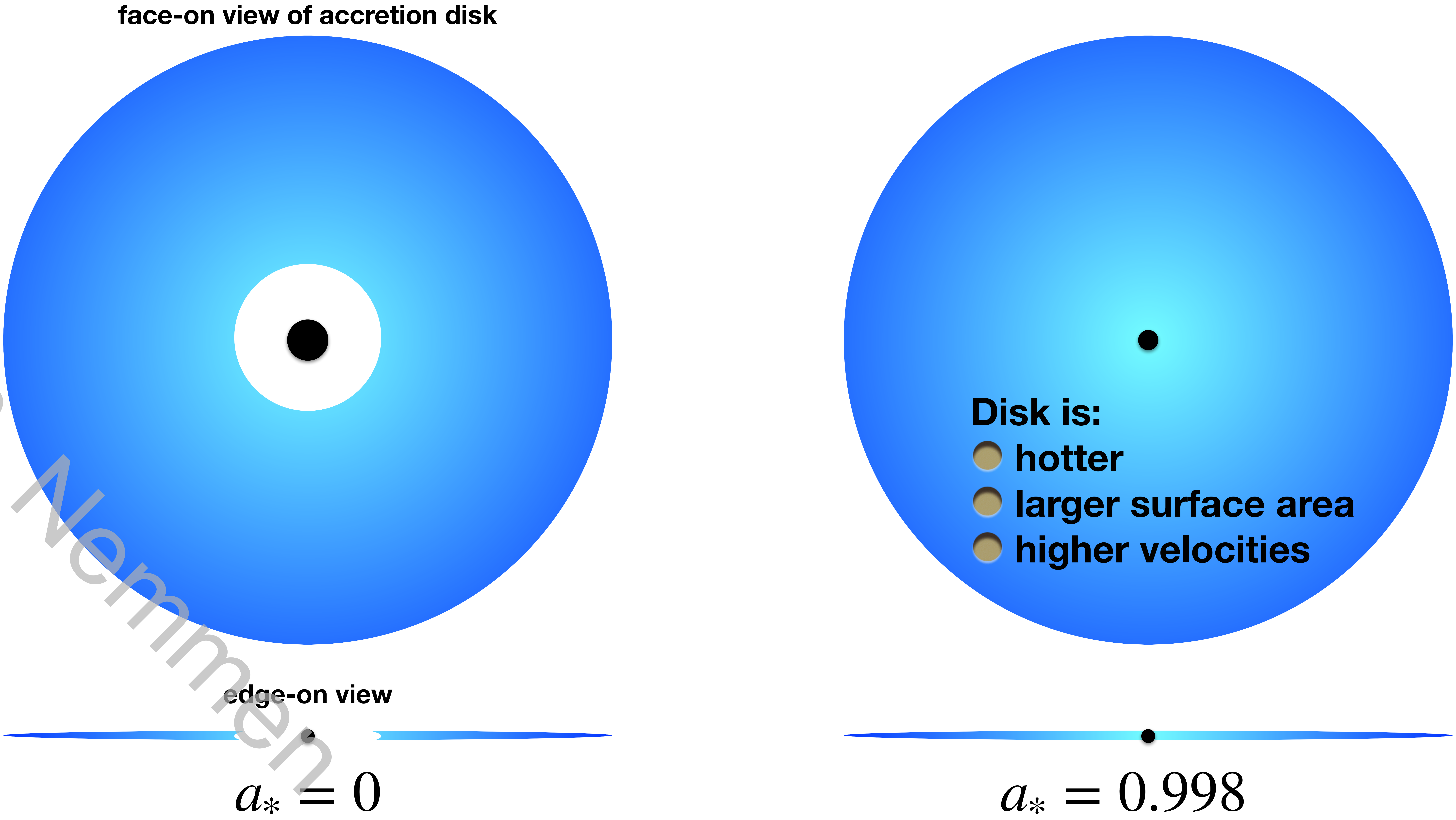
$$\eta = \frac{mgh}{mc^2} = 10^{-14} \left(\frac{h}{100 \text{ m}} \right)$$

Nuclear fusion



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

ISCO radius depends on the BH spin



Blandford 1990

Black hole spin leaves imprint on accretion disk

Faster, hotter, brighter

but gravitational redshift

BLACK HOLE PHYSICS SUMMARY

Black holes

- ✦ Mass-energy falls in, but nothing gets out
- ✦ Only three numbers: **mass *M*, spin** a_* **and ~~charge~~**
- ✦ For astrophysics: **accretion rate** $\dot{M}$ also important
- ✦ Mass range: $3.6M_\odot < M \lesssim 10^{11} M_\odot$

Black hole accretion

- ✦ Accretion converts gravitational potential energy into other forms (e.g. light)
- ✦ BHs maximize energy release efficiency: η up to 40% (for max spin)

Main lenghts

- ✦ ISCO: Innermost stable circular orbit, $r = 6M$
- ✦ Photon capture: $r = 3M$ ($\sqrt{27}M$) seen from far away
- ✦ Sphere of influence: $r \sim 10^6 M$

Main scales

- ✦ Luminosity: $L_{\rm Edd} = 1.3 \times 10^{38} \left(M/M_\odot\right) \text{ erg s}^{-1}$
- ✦ Mass accretion rate: $\dot{M}_{\rm Edd} \equiv L_{\rm Edd}/(0.1c^2)$
- ✦ Growth timescale: $t_{\rm Edd} \equiv 4 \times 10^7 (\eta/0.1) \text{ yr}$