BLACK HOLES AND PARTICLES AROUND

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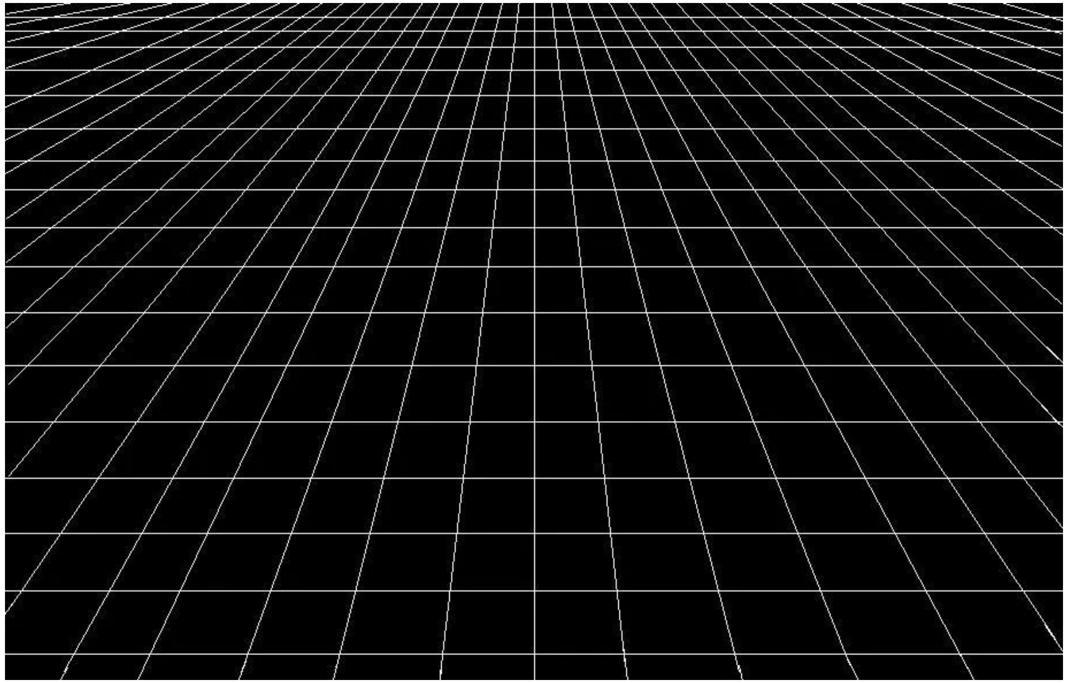
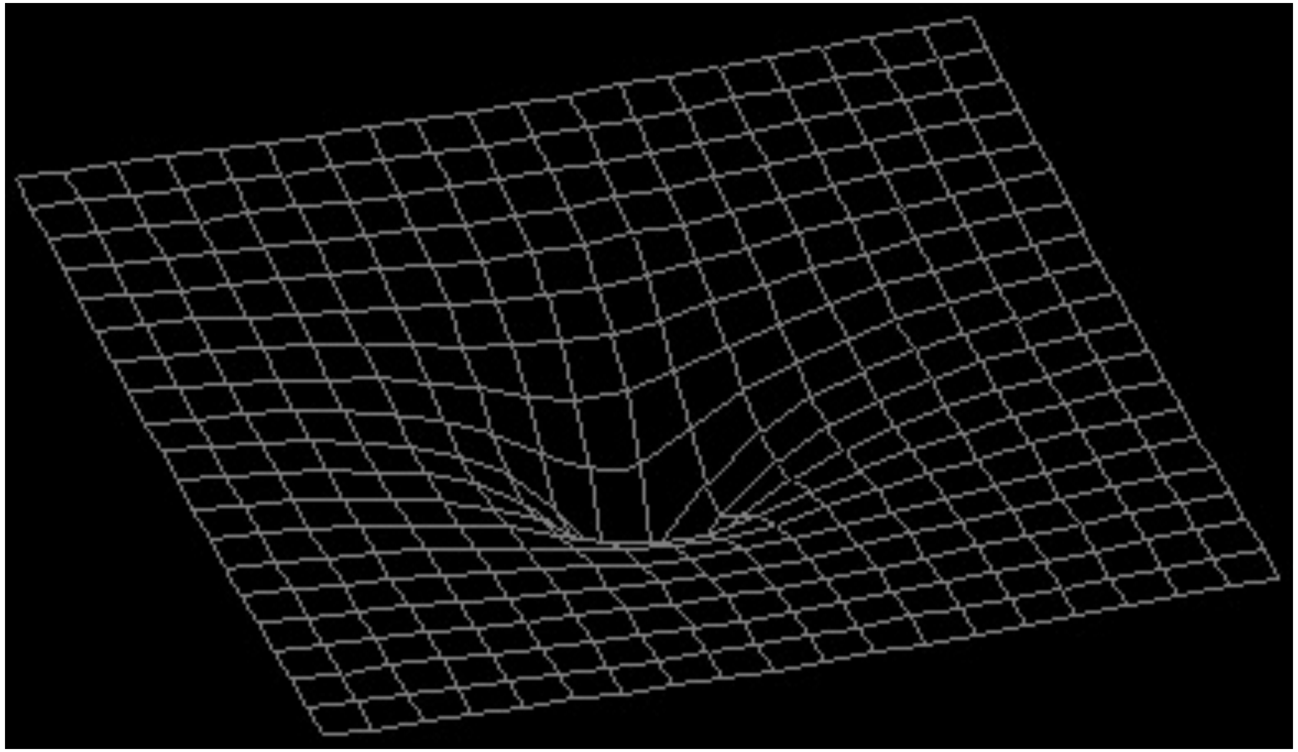
Sabancı University SIAM Seminar (May 9, 2023)



Flat space

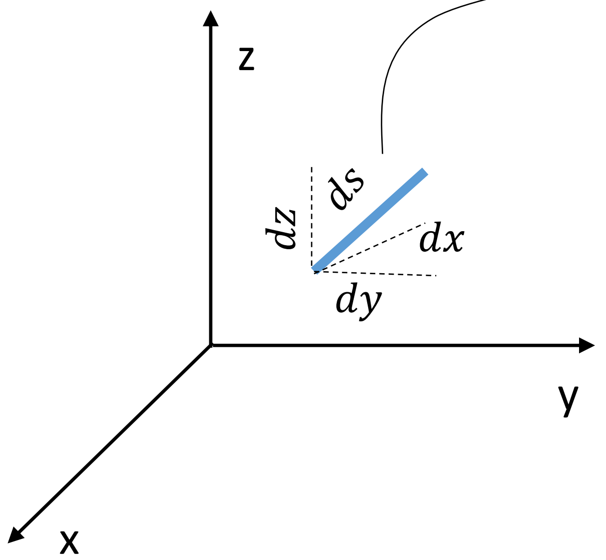


Curved space

E. Siegel, Forbes, 2018

FLAT SPACE

3D



two infinitesimally close events separated by a distance ds

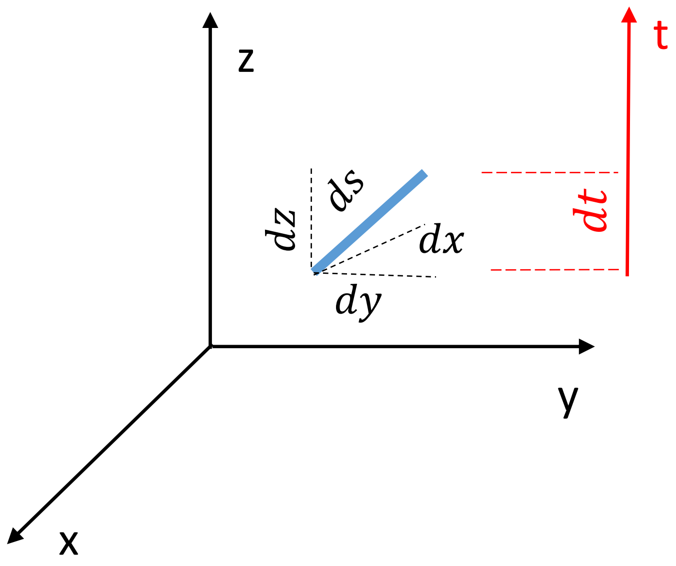
$$(ds)^2 = (dx)^2 + (dy)^2 + (dz)^2$$

space is flat

two events can have zero separation ($ds = 0$) if they coincide ($dx = 0$, $dy = 0$, $dz = 0$)

FLAT SPACETIME

4D



$$(ds)^2 = -(cdt)^2 + (dx)^2 + (dy)^2 + (dz)^2$$

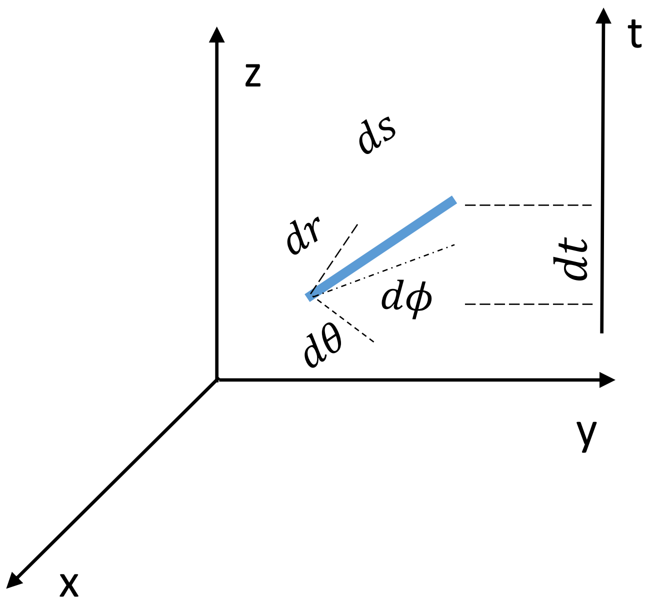
"minus" sign is needed for light to propagate

spacetime is flat

two events can have zero separation ($ds = 0$) even if they do not coincide ($dt \neq 0$, $dx \neq 0$, $dy \neq 0$, $dz \neq 0$)

FLAT SPACETIME

4D



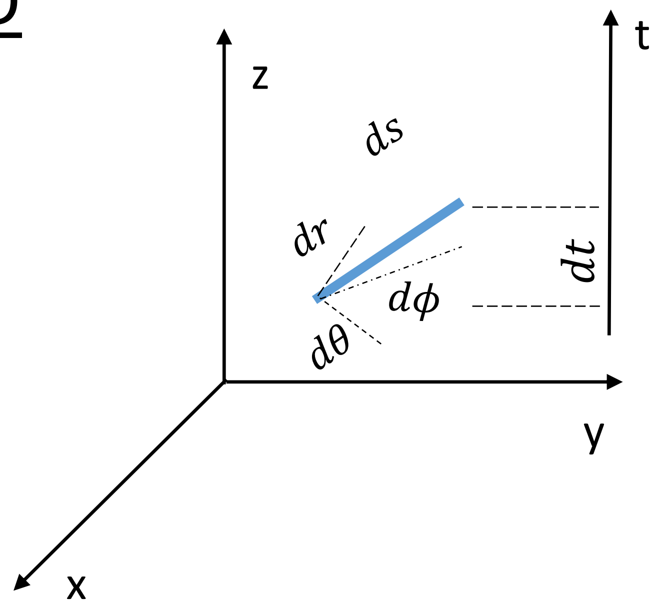
in spherical coordinates:

$$(ds)^2 = -(cdt)^2 + (dr)^2 + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

spacetime is flat
(coordinate change has no effect)

FLAT DILATED SPACETIME

4D



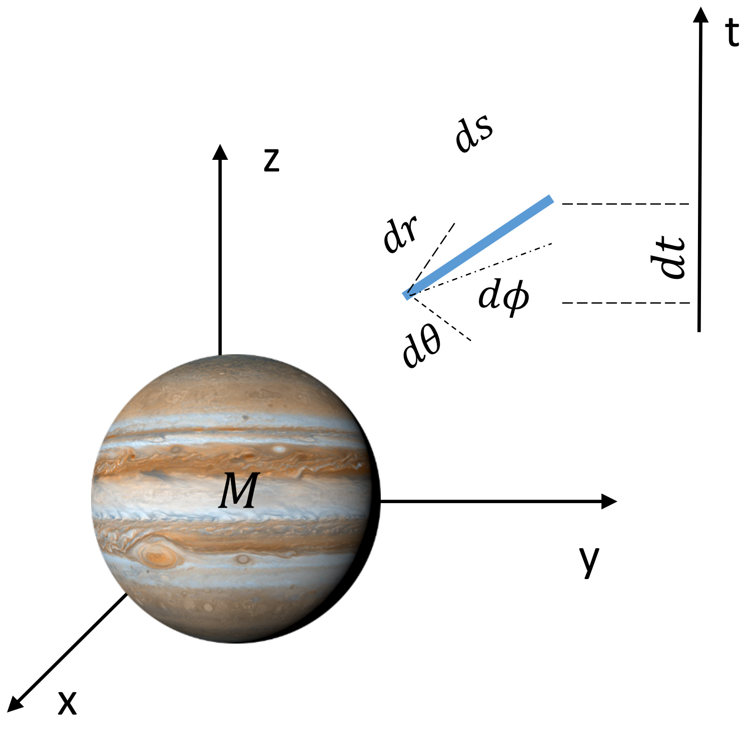
in an environment with intrinsic speed v_{int}:

$$(ds)^2 = -\left(1 - \frac{v_{int}^2}{c^2}\right)(cdt)^2 + \frac{(dr)^2}{1 - \frac{v_{int}^2}{c^2}} + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

dilated time

contracted distance

CURVED SPACETIME



(NASA-SSE, 2019)

in the presence of a body (Jupiter) of mass M, the escape speed v_{es} turns out to be the most natural intrinsic speed ($v_{int} = v_{es}$):

- escape speed from the body:

$$\frac{1}{2}mv_{es}^2 = \frac{G_N M m}{r} \Longrightarrow v_{es}^2 = \frac{2G_N M}{r}$$

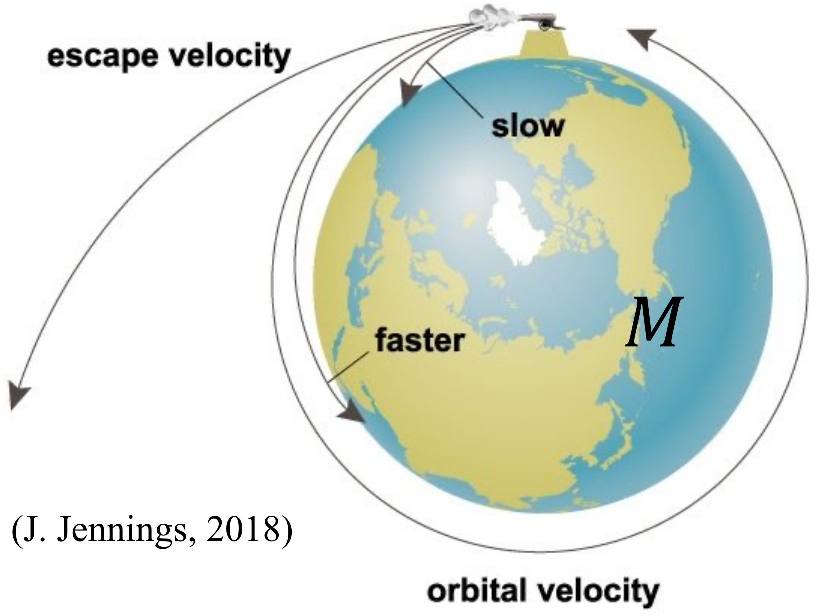
- distance between two points outside the body:

$$(ds)^2 = -\left(1 - \frac{v_{es}^2}{c^2}\right)(cdt)^2 + \frac{(dr)^2}{1 - \frac{v_{es}^2}{c^2}} + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

gravitational time dilation

gravitational space contraction

CURVED SPACETIME



(J. Jennings, 2018)

- Shwarzschild radius:

$$\frac{v_{es}^2}{c^2} = \frac{2G_N M}{rc^2} \equiv \frac{r_s}{r} \Longrightarrow r_s = \frac{2G_N M}{c^2}$$

- ds can be expressed in terms of Schwarzschild radius r_s:

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

- $r_s(\text{Sun}) = 3\text{ km}$
- $r_s(\text{Jupiter}) = 3\text{ m}$
- $r_s(\text{Earth}) = 10\text{ mm}$

EINSTEIN GRAVITY

- distance ds for the escape speed turns out to be the solution of the Einstein equations for gravity of a compact body of mass M :

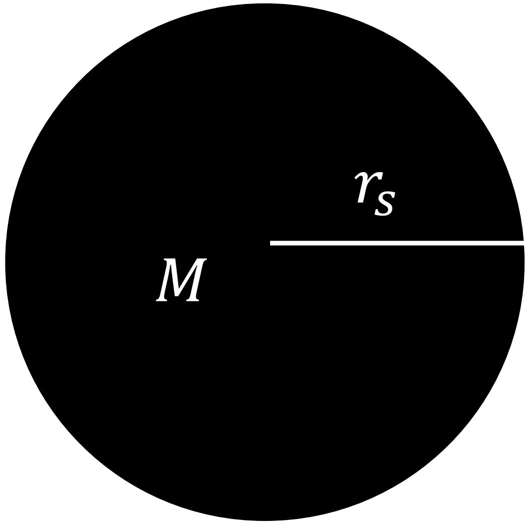
gravity theory	solution of Einstein equations
Einstein gravity action: $\int d(\mathrm{Vol})_4 \left(\frac{R}{16\pi G_N} - V_0\right)$	Schwarzschild solution (zero vacuum energy $V_0 = 0$) : $(ds)^2 = -\left(1 - \frac{r_s}{r}\right)(cdt)^2 + \frac{(dr)^2}{1-\frac{r_s}{r}} + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$

K. Schwarzschild, 1916 arXiv:physics/9905030

- true measure of curving is the Riemann curvature:

$$(\mathrm{Riemann\ curvature})^2 = \frac{12\, r_s^2}{r^6}$$

BLACK HOLE



- if the body M is too massive to require an escape speed bigger than the speed of light:

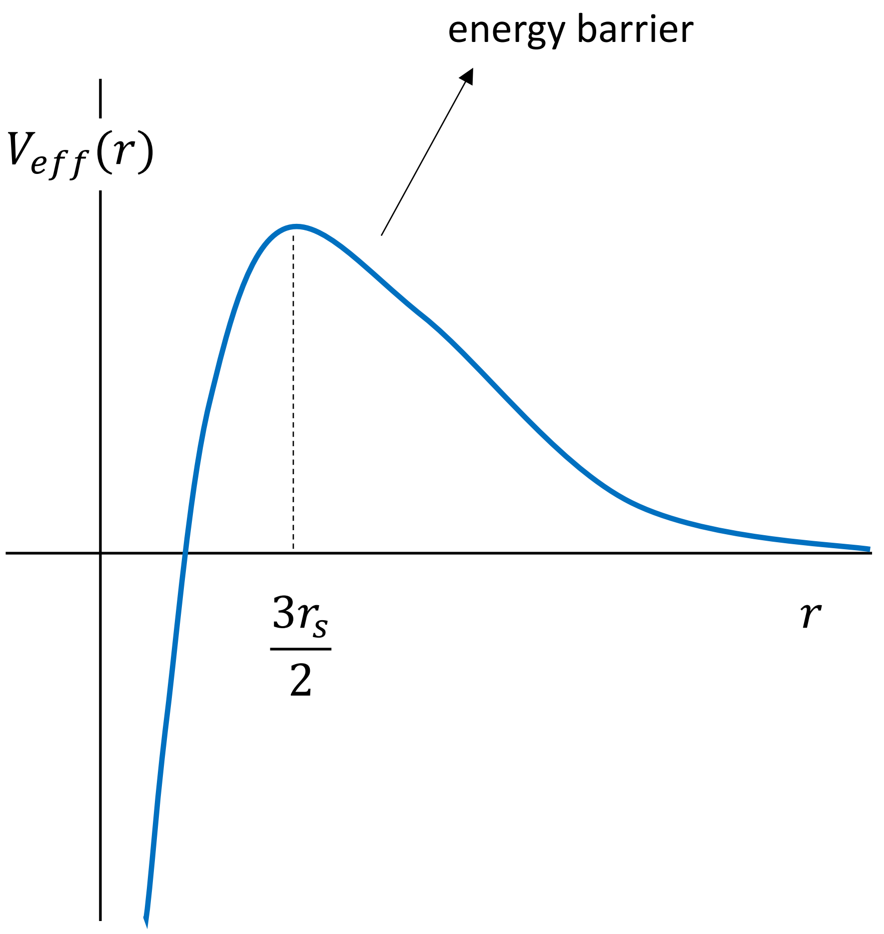
$$v_{es} > c$$

(or $r < r_s$) then a black hole forms:

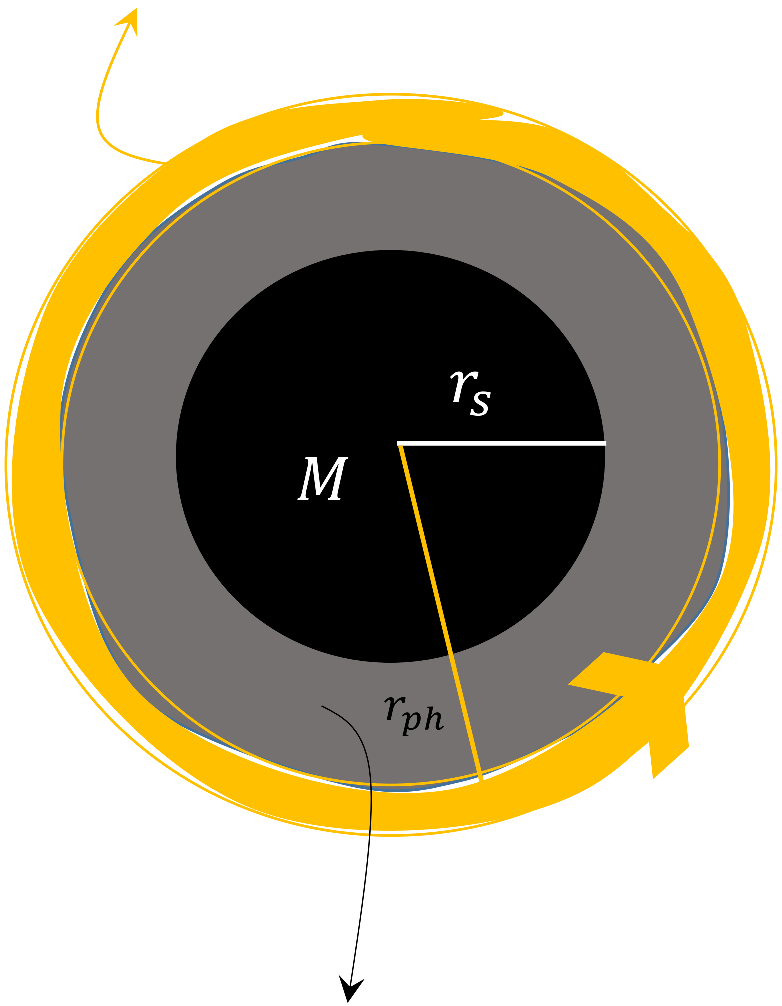
- $r = r_s \Rightarrow$ event horizon (the point of no return)
- $r = r_s \Rightarrow$ event horizon (infinite time dilation)
- $r < r_s \Rightarrow$ black hole interior (cannot be probed from outside)
- $r < r_s \Rightarrow$ black hole interior (effectively: time $\Leftrightarrow$ radial distance)

PHOTON MOTION AROUND BLACK HOLE

- Photon: $(ds)^2 = 0 \Longrightarrow \left(\frac{ds}{d\tau}\right)^2 = 0$
- Azimuthal plane ($\theta = \frac{\pi}{2}$): $-\left(1 - \frac{r_s}{r}\right) c^2\dot{t}^2 + \frac{\dot{r}^2}{1-\frac{r_s}{r}} + r^2\dot{\phi}^2 = 0$
- Energy is conserved: $\dot{t} = \frac{\epsilon}{1-\frac{r_s}{r}}$
- Ang. Mom. is conserved: $\dot{\phi} = \frac{\ell}{r^2}$
- Photon is a unit-mass particle: $\frac{\dot{r}^2}{2} + \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\epsilon}{2}$
- $V_{eff}(r) = \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\ell^2}{2r^2} - \frac{\ell r_s}{2r^3}$



PHOTON SPHERE



- photons orbiting in xy-plane ($r = r_{ph} =$ constant, $\theta = \frac{\pi}{2}$):

$$ds = 0 \implies \frac{d\phi}{dt} = \frac{c}{r_\gamma}\left(1 - \frac{r_s}{r_\gamma}\right)^{1/2}$$

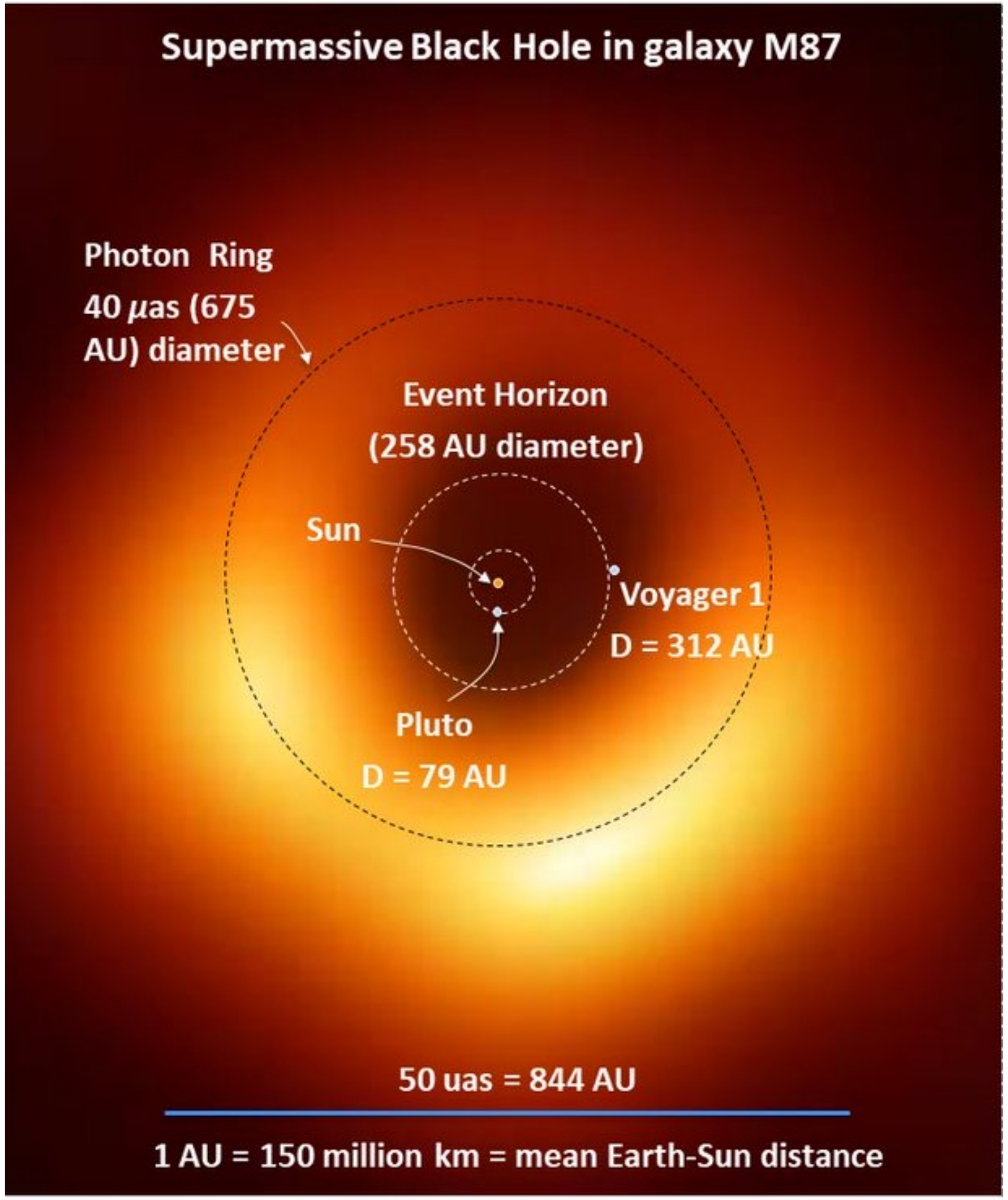
$$\text{EoM} \implies \frac{d\phi}{dt} = \frac{c}{r_\gamma}\left(\frac{r_s}{2r_\gamma}\right)^{1/2}$$

$$r_{ph} = \frac{3}{2} r_s$$

- photon radius $r = r_{ph}$ is the last stable orbit.

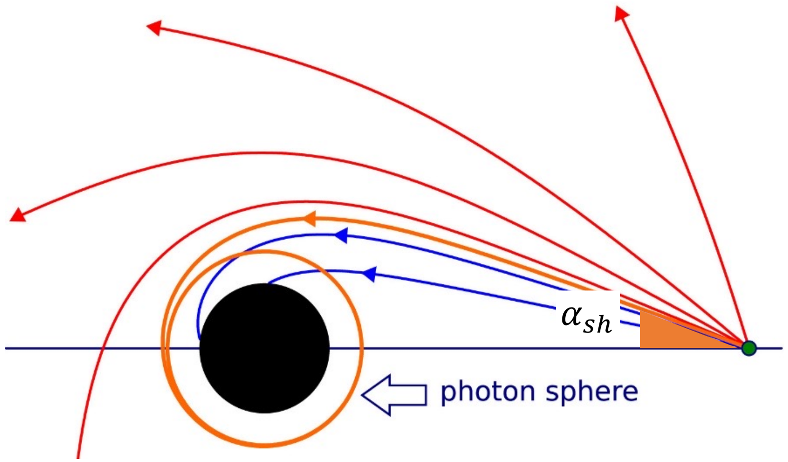
- photon radius $r = r_{ph}$ depends on the underlying gravity theory.

Mass (Solar Masses)	6.54 billion
Event Horizon diameter (AU)	258
Distance (Light Years)	55 million



fosstodon.org, 2022

BLACK HOLE SHADOW



Perlick and Tsupko 2022 *Phys Rep* **947** 1

- photons falling within the photon sphere fall into black hole – a large shadow!

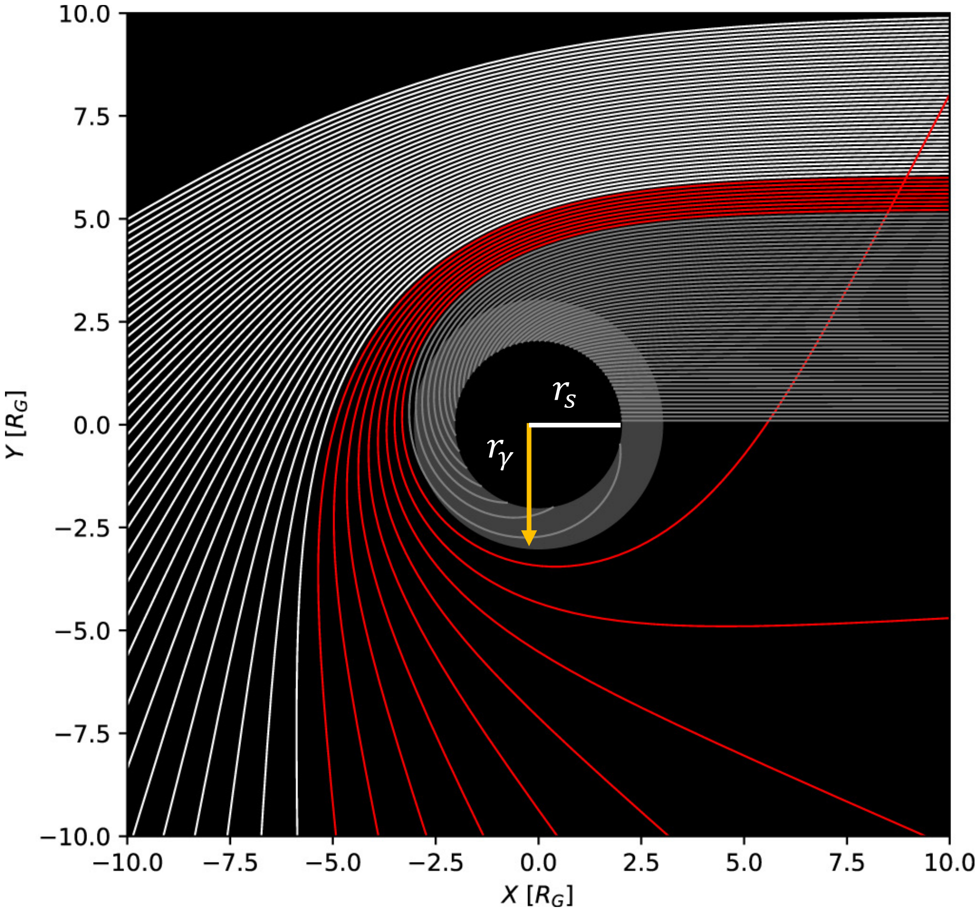
- consider a general spacetime:

$$(ds)^2 = -A(r)(c\,dt)^2 + B(r)(dr)^2 + D(r)\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

- shadow is characterized by "gravitational capture angle" ≡ shadow angle α_{sh}:

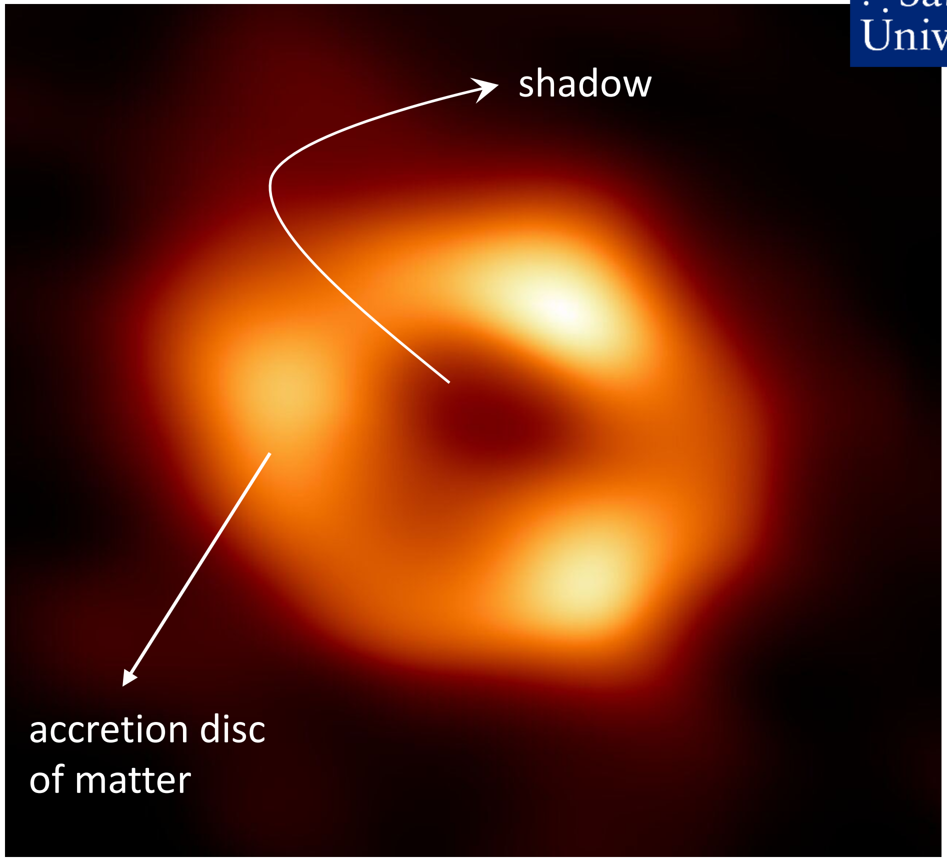
$$\sin^2\alpha_{sh} = \frac{D(r_{ph})}{A(r_{ph})}\frac{A(r_o)}{D(r_o)} \xrightarrow{\text{Schwarzschild}} \frac{r_{ph}^2}{1-\frac{r_s}{r_{ph}}} \times \frac{\left(1-\frac{r_s}{r_o}\right)}{r_o^2}$$

Distant observer: $\frac{27}{4}\frac{r_s^2}{r_o^2}$



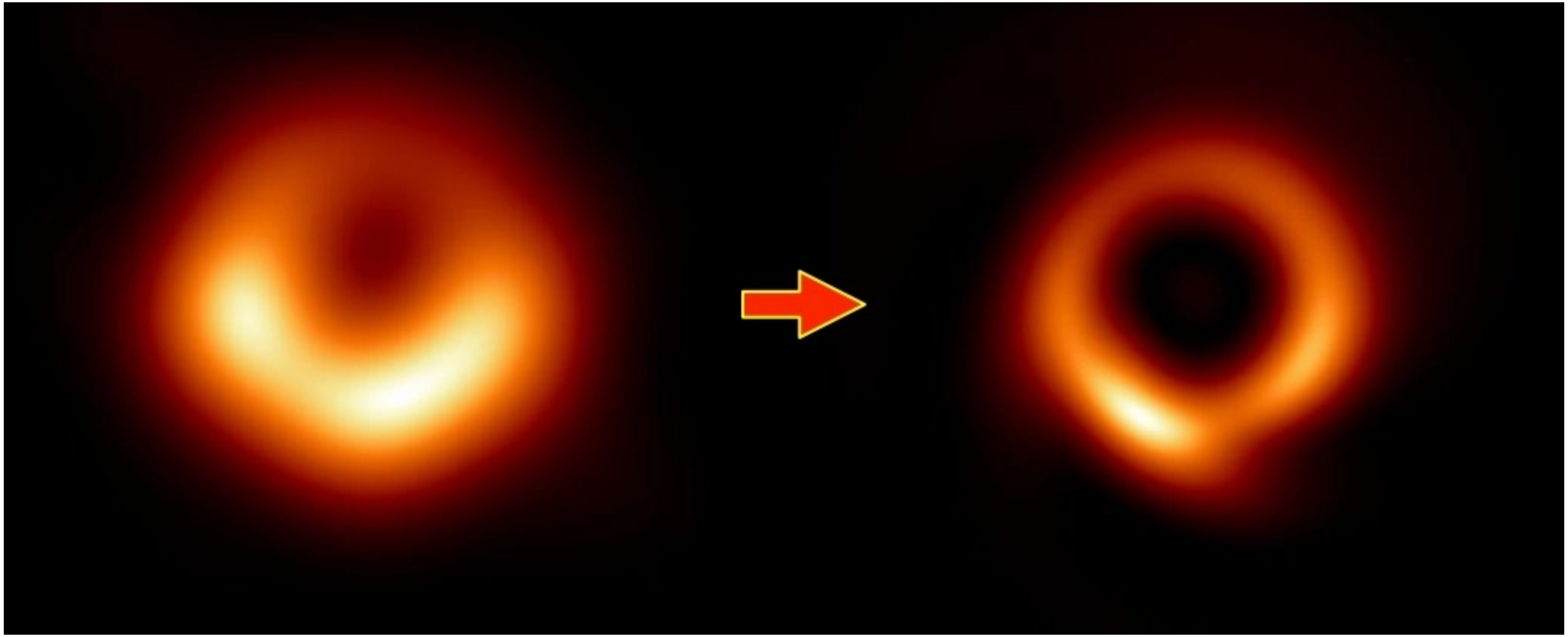
Shadow of a black hole

Thomas Bronzwaer and Heino Falcke 2021 *ApJ* **920** 155



Shadow of a black hole

EHT observation of Sgr. A* in 2019



Shadow of M87* (2019)

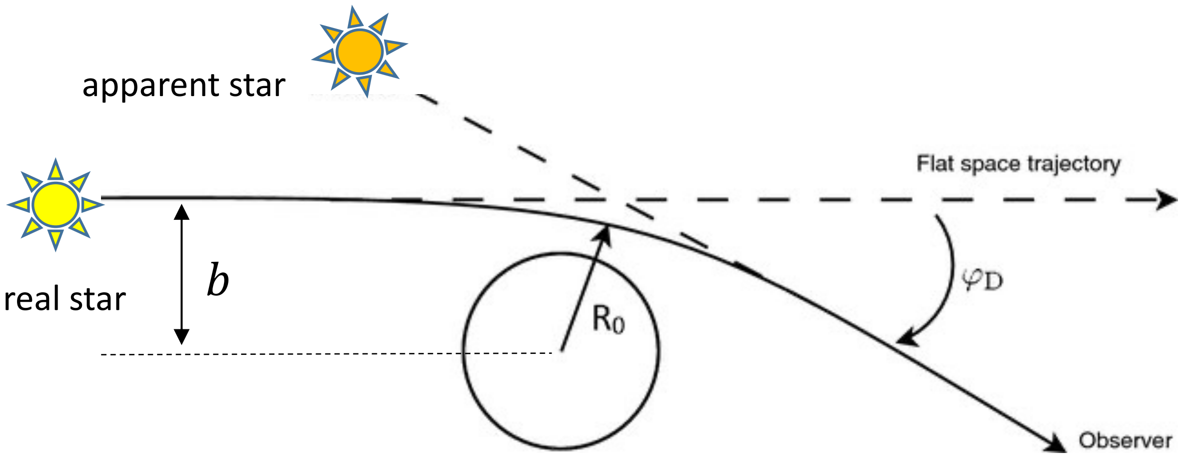
EHT observation of M87* in 2019

Shadow of M87* (AI)

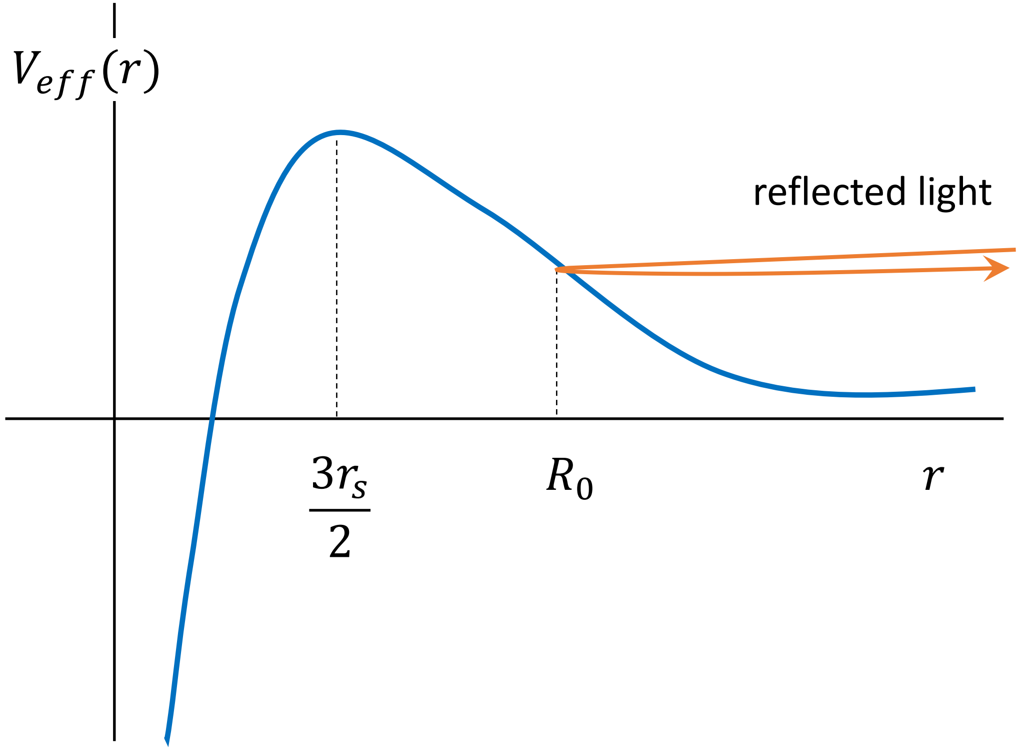
PRIMO, 2023

Lia Medeiros et al 2023 ApJL 947 L7

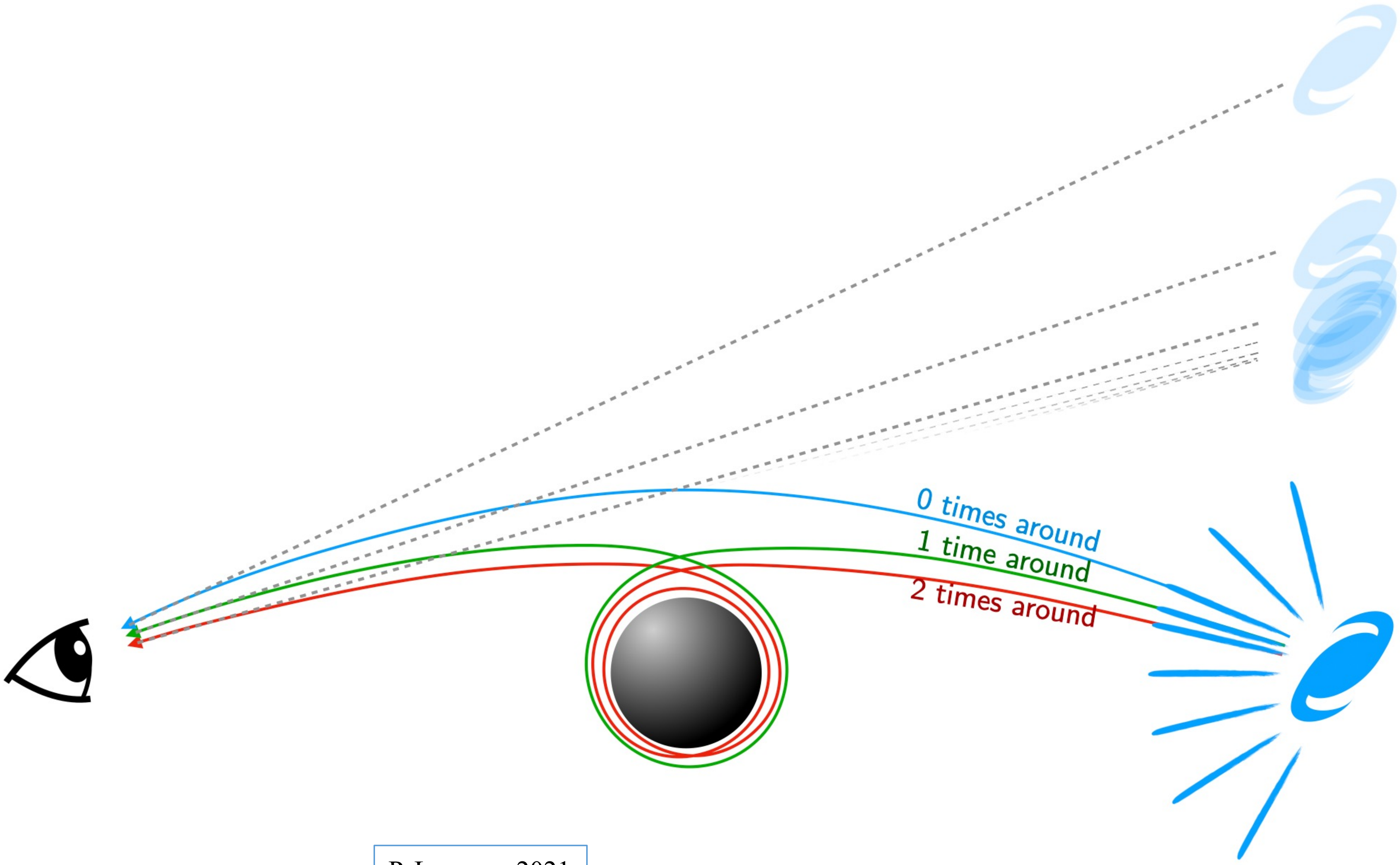
LIGHT BENDING BY BLACK HOLE



Burger, D. et al 2018 Gen Relativ Gravit 50, 156



- $\frac{dr}{d\tau} = \sqrt{\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{r_s}{r}\right)}$
- $\frac{d\phi}{d\tau} = \frac{1}{r^2}$
- $\varphi_D = 2\int_{R_0}^{\infty} \frac{dr}{r^2\left(\frac{1}{b^2}-\frac{1}{r^2}\left(1-\frac{r_s}{r}\right)\right)^{\frac{1}{2}}} \xrightarrow{\text{small } r_s} \frac{2r_s}{R_0}$



P. Laursen, 2021

bending of light leads to multiple images for objects behind (lensing effect)

- effective potential seen by massless particle (photon):

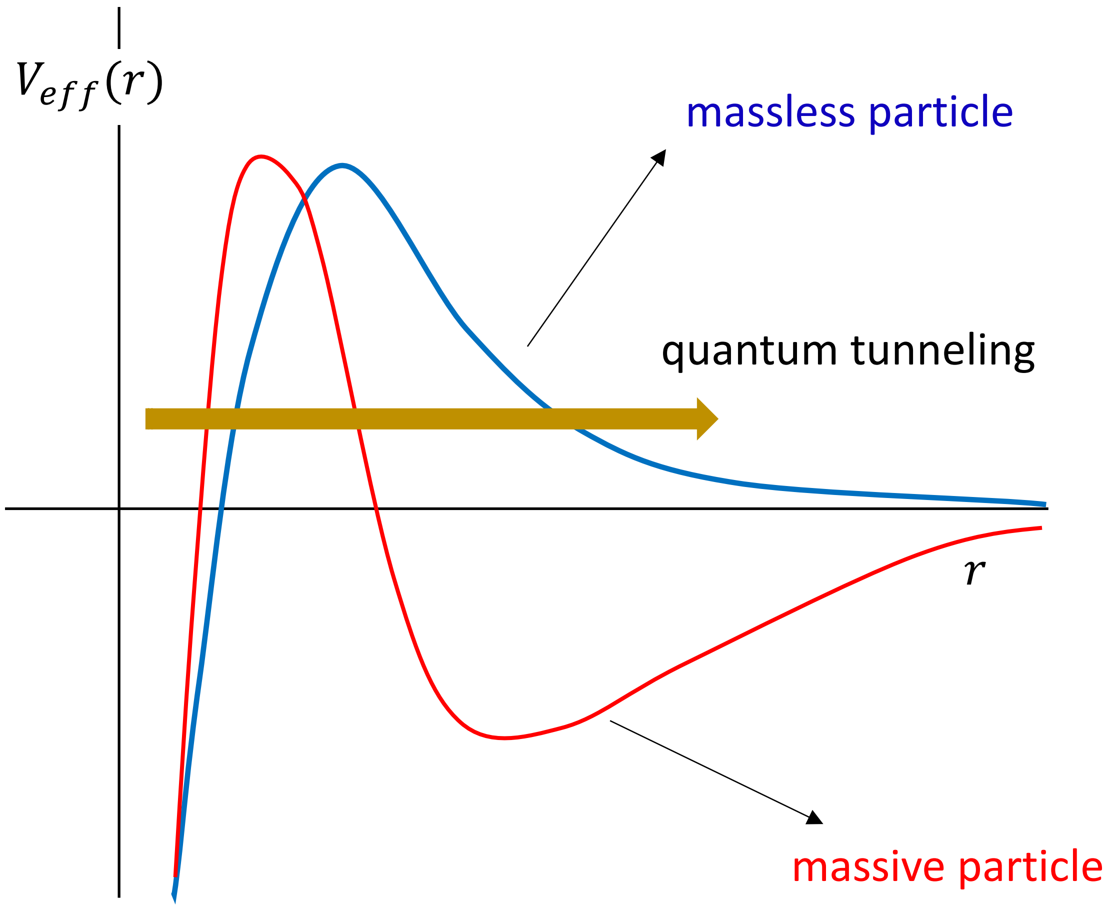
$$V_{eff}(r) = \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\ell^2}{2r^2} - \frac{\ell r_s}{2r^3}$$

- potential energy barrier for massless particles is formed by angular momentum ($1/r^2$) and Schwarzschild radius (r_s/r^3)

- potential energy barrier for massive particles involves in addition the Newtonian contribution ($1/r$)

- quantum particles that fell into the black hole can tunnel out through the barrier.

- tunneled particles appear as radiation – the Hawking radiation.



- Time it takes to traverse the barrier region:

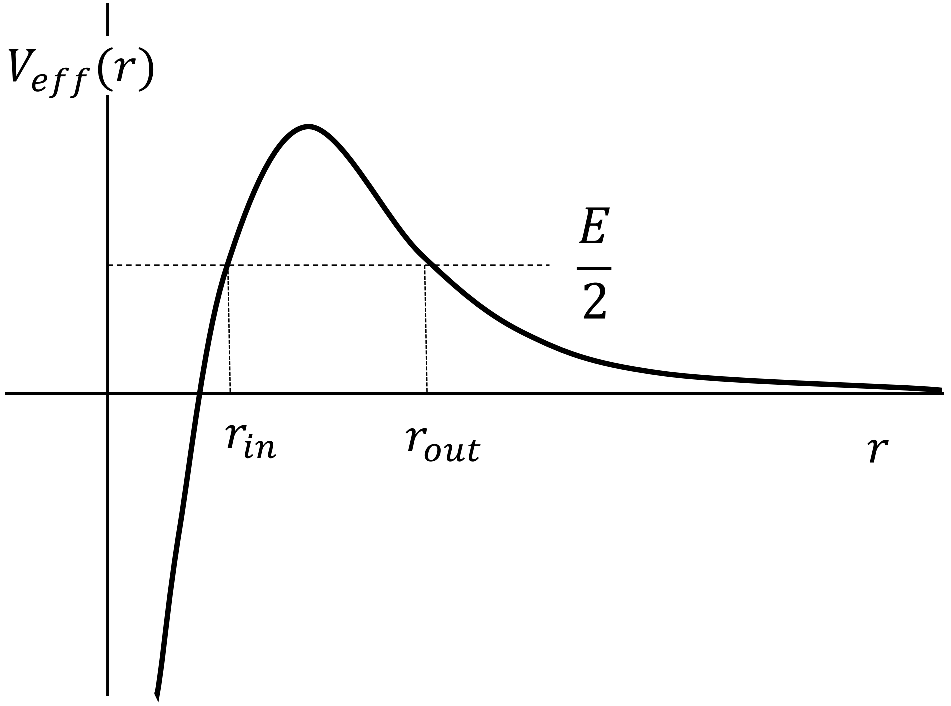
$$\Delta t = \pm \int_{r_{in}}^{r_{out}} \frac{dr}{\sqrt{E - 2\,V_{eff}(r)}} = \pm \int_{r_{in}}^{r_{out}} \frac{dr}{\sqrt{E - \frac{\ell^2}{r^2} + \frac{\ell r_s}{r^3}}} =$$

$$= \pm \frac{r_s^2}{\sqrt{2\ell^2 - 3\ell}} \int_{r_{in}}^{r_{out}} \frac{d\,\hat{r}}{\sqrt{\hat{r} - 1}}$$

(expand at $r = r_s$)
($E = \ell(\ell - 1)/r_s^2$)

$$= \pm \frac{r_s^2}{\sqrt{2\ell^2 - 3\ell}} \times \pi i \simeq \pm \pi i r_s$$

(residue theorem)
($\ell \simeq r_s$)



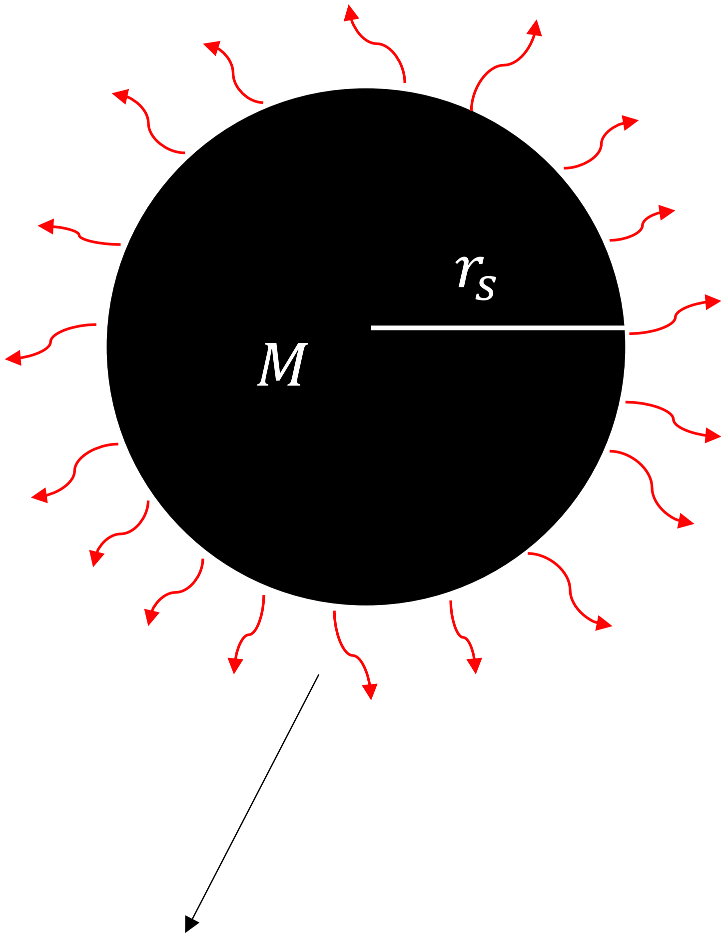
- Wavefunction: $\psi \propto e^{iE\Delta t} \simeq e^{\pm \pi r_s E}$

$\rho_{em} \simeq e^{-2\pi r_s E}$

$\rho_{ab} \simeq e^{+2\pi r_s E}$

- Net emission rate = $\frac{\rho_{em}}{\rho_{ab}} = e^{-4\pi r_s E} \Longrightarrow T_H \simeq \frac{1}{4\pi k_B r_s} \equiv \frac{\hbar c^3}{8\pi k_B G_N M}$

Hawking temperature



Emitted power (photons only):

$$P = \frac{\hbar c^6}{15360\pi G_N^2 M^2}$$

Evaporation time (photons only):

$$t_{\text{eva}} = \frac{5120\,\pi G_N^2 M^3}{\hbar c^4} \approx 10^{67}\ \text{years} \times \left(\frac{M}{M_{\text{Sun}}}\right)^3$$

D. N. Page, Phys. Rev. D 1976

QUANTUM TUNNELING AND HAWKING RADIATION

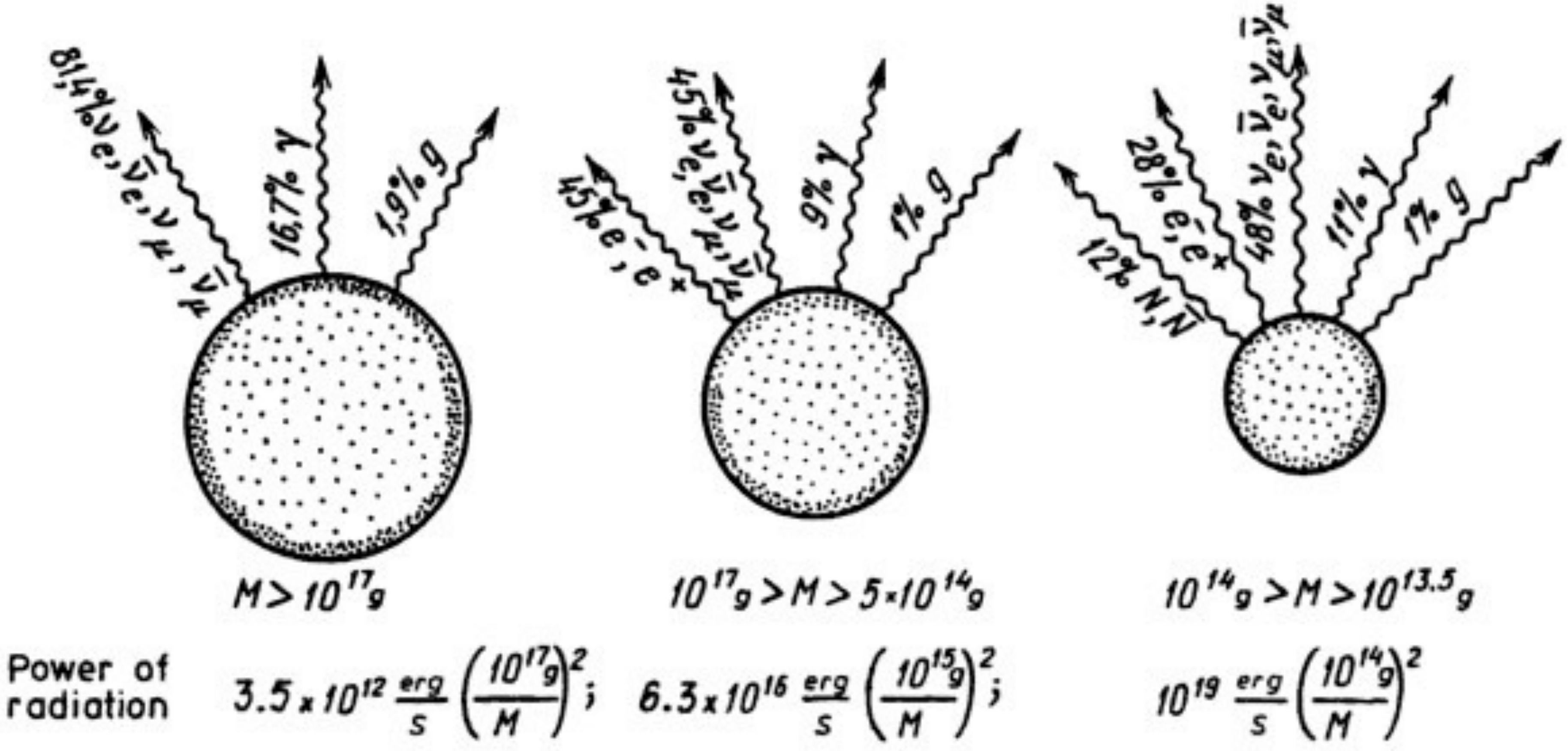


Figure 10.7: Quantum decay of a non-rotating black hole. The fractions of gravitons (g), photons (γ), neutrinos (ν) and other elementary particles are given in percent of the total number of particles emitted by black holes of different masses.

Frolov and Novikov 1998 "Black hole physics" (Springer)

In classical physics: Black holes must have zero temperature and zero entropy!

In quantum physics: Black holes must have nonzero temperature and nonzero entropy!

First law of thermodynamics: $\Delta E = \Delta Q = T_{BH}\, \Delta S_{BH}$

$$S_{BH} = \frac{k_B c^3 A}{4\hbar G_N}$$

$$T_{BH} = T_H = \frac{\hbar c^3}{8\pi k_B G_N M}$$

J. Bekenstein, Lett. Nuovo Cimento, 1972

CHARGE CONSERVATION BY HIGGS PARTICLE

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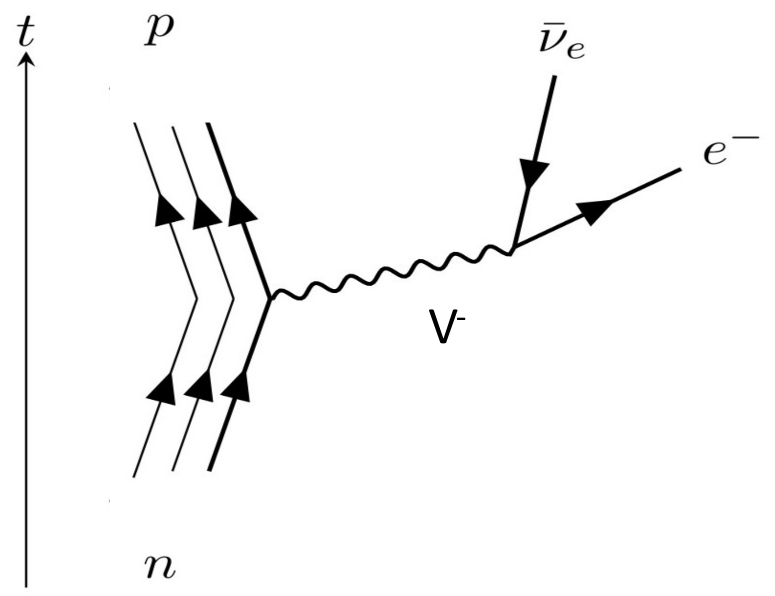
- To ensure conservation of electric charge, photon interactions remain unchanged under the shift (S is an arbitrary scalar): $\gamma \rightarrow \gamma + \partial S$

- Uranium disassociates via the decay of neutrons into protons, electrons and neutrinos.

- The decay is mediated by a massive and charged photon V.

- The mass breaks $\mathrm{V} \rightarrow V + \partial S$ symmetry and charge conservation breaks down.

- To restore charge conservation one replaces mass by some scalar field: $M_V^2 \rightarrow \phi^2$



the god particle
(Higgs particle)

P. Anderson, 1962; P. Higgs, 1964; S. Weinbegr, 1967; Abdus Salam, 1968

CHARGE CONSERVATION BY CURVATURE

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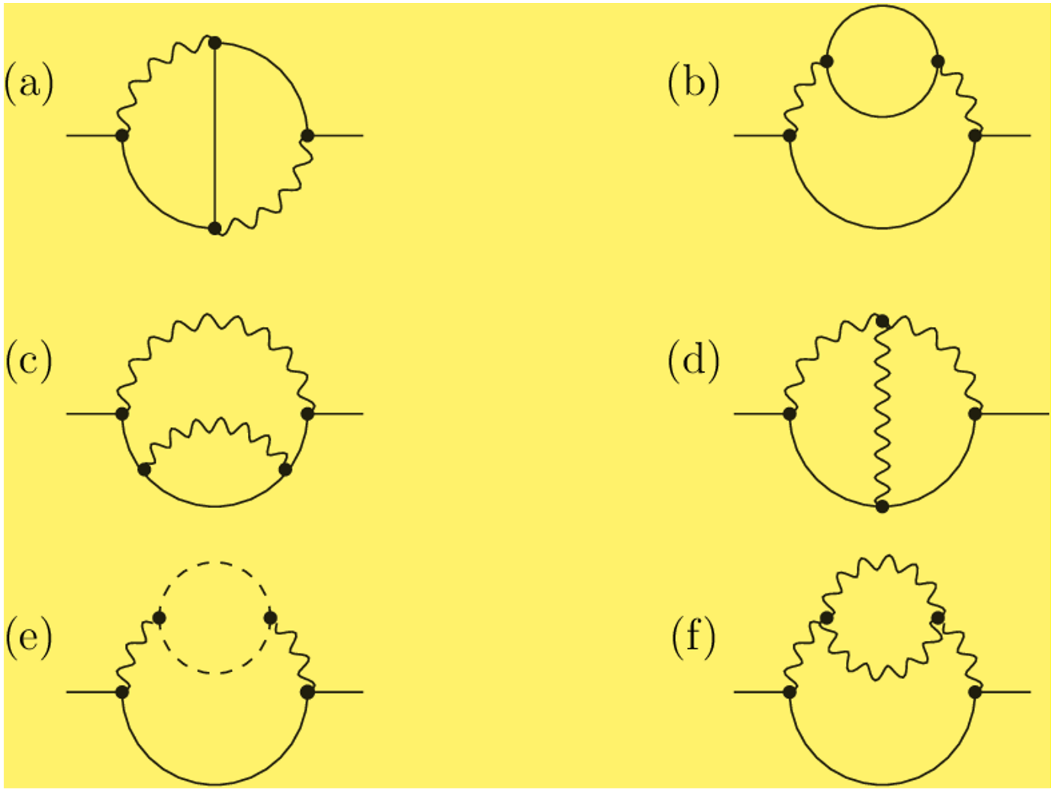
- Quantum fields can be understood only by a UV cutoff Λ_{UV}.
- The cutoff Λ_{UV} breaks translation symmetry.
- Quantum loops generate masses in proportion to Λ_{UV}.
- Photon acquires mass in proportion to Λ_{UV}.
- Photon mass breaks $\gamma \to \gamma + \partial S$ symmetry and electric charge conservation breaks down.
- To restore electric charge conservation one replaces the cutoff by curvature: $\Lambda_{UV}^2 \to R$

$\because$ curvature breaks translation symmetry

symmetry-restoring emergent gravity: symmergent gravity



DD, Adv. High En. Phys., 2019
DD, Gen. Relativity Gravit., 2021
DD, C. Karahan, O. Sargın, 2023
DD, Phys. Rev. D, 2023

SYMMERGENT GRAVITY

- Symmergent gravity is new topic.
- It can be tested at particle colliders like CERN-LHC.
- It can bring explanations for elusive particles like dark matter.
- It can be tested at strong gravity domains like black holes and early Universe.

From the referee report:

"… This paper is still difficult because its point of view is novel. However, that is to be expected for novel ideas."

DD, Phys. Rev. D, 2023

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE

gravity theory	solution of Einstein equations
Symmergent gravity action: $\int d(\mathrm{Vol})_4 \left(\frac{R}{16\pi G_N} - V_0 + \frac{c_O}{16}R^2 - \frac{1-a}{(8\pi G_N)^2 c_O}\right)$	Schwarzschild-dS/AdS solution ($V_0 = 0$): $(ds)^2 = h(r)(cdt)^2 + \frac{(dr)^2}{h(r)} + r^2\left((d\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$

loop-induced quadratic curvature constant:

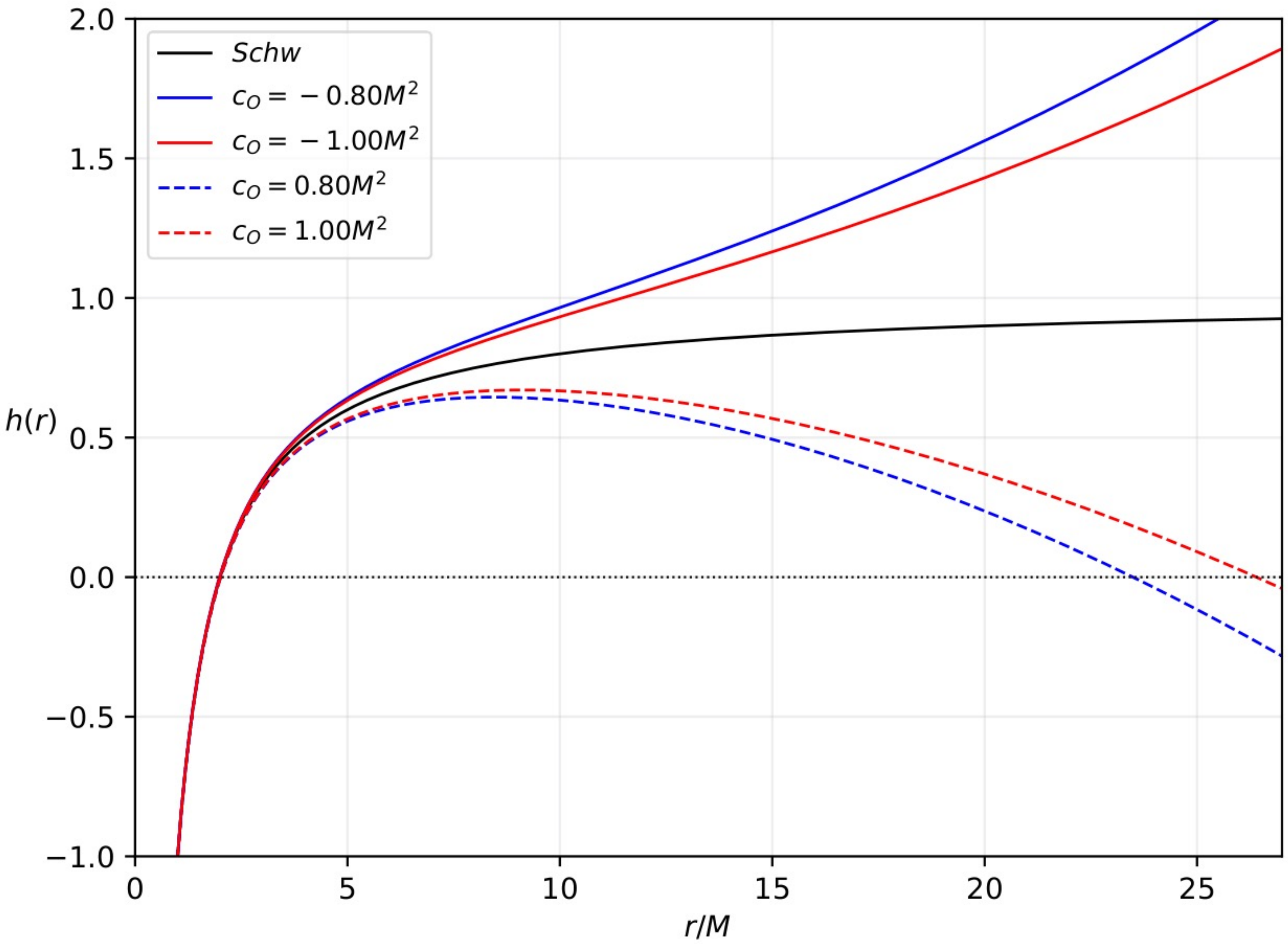
$c_O = \frac{n_B - n_F}{248\pi^2}$

a: an $O(1)$ constant parametrizing the symmergent vacuum energy

$$h(r) = -\left(1 - \frac{r_s}{r} - \frac{(1-a)r^2}{24\pi G_N c_O}\right)$$

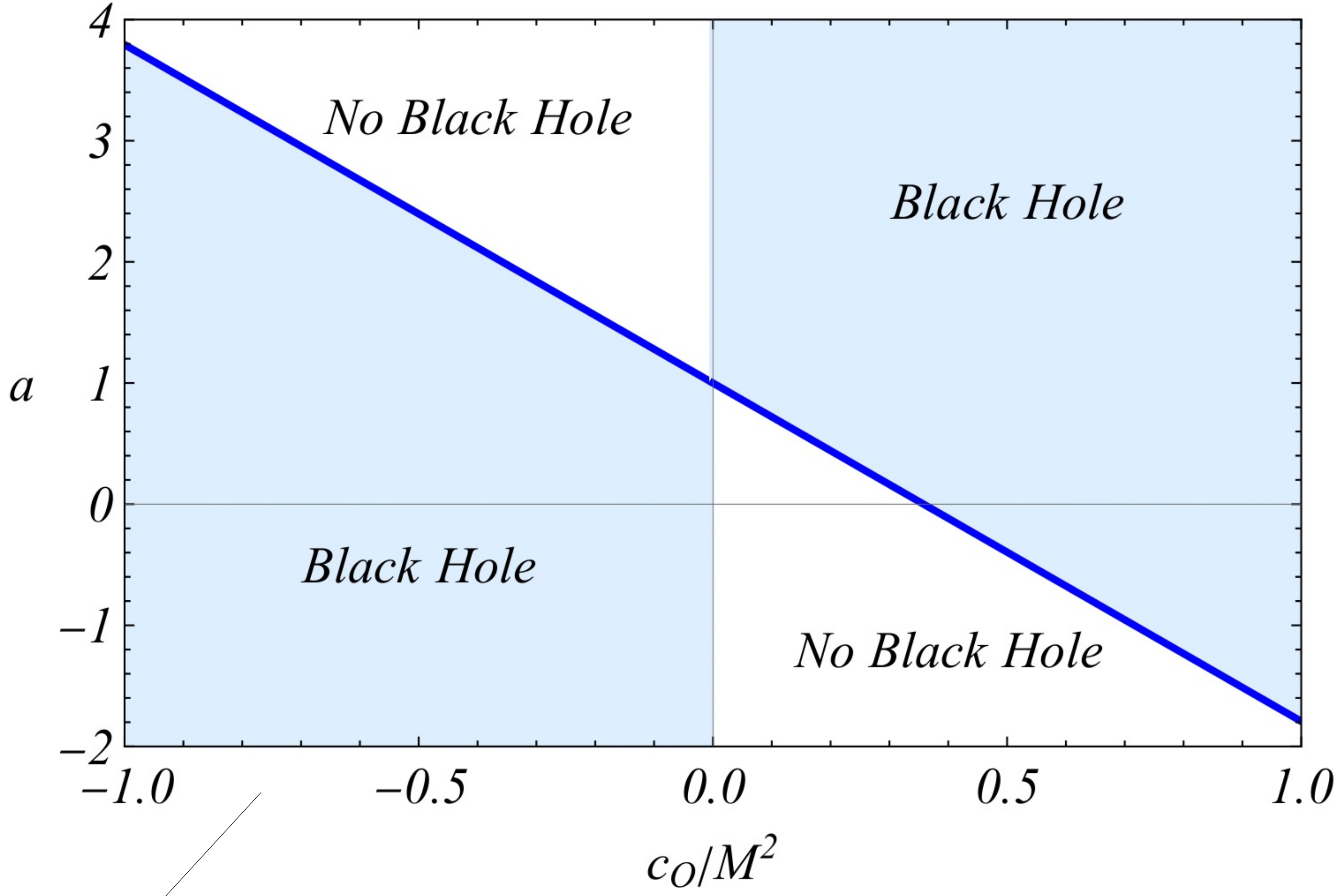
İ. Çimdiker, A. Övgün, DD, Phys. Dark Univ., 2021

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021

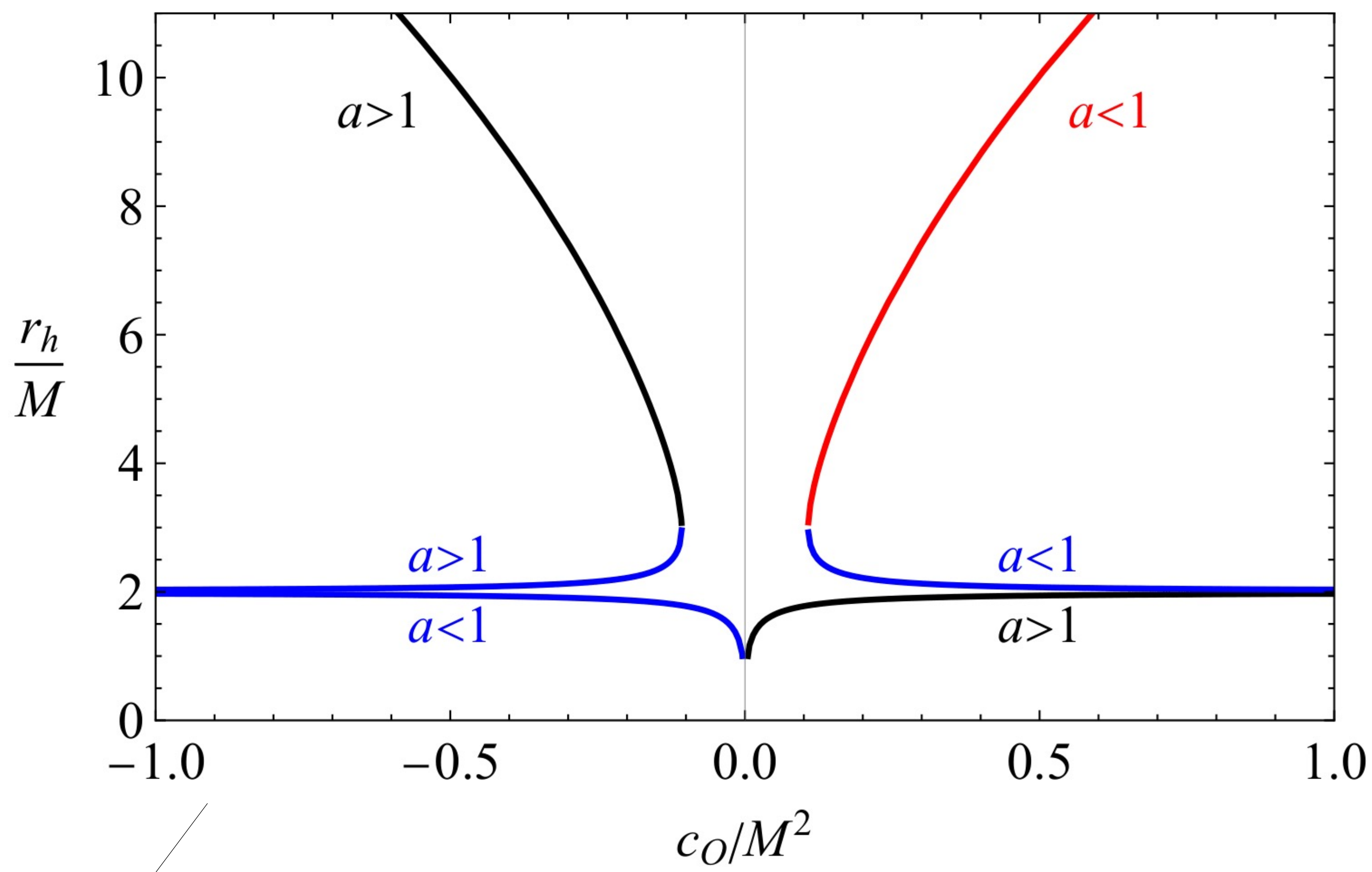
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



the regions in $a - c_O$ plane admitting BH solutions

J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021

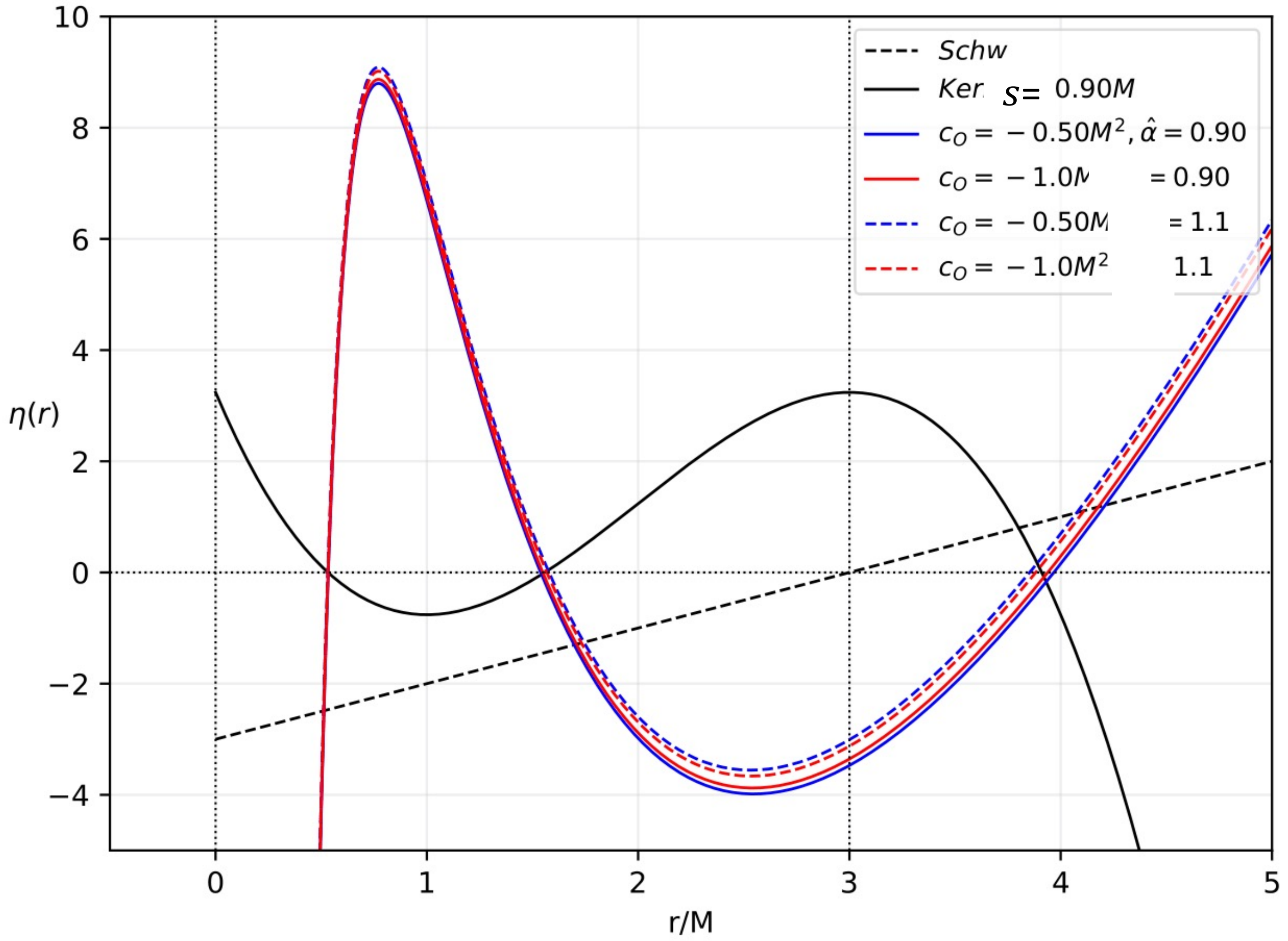
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



event horizon: $r_h = 2\ M$ is the Schwarzschild radius

J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021

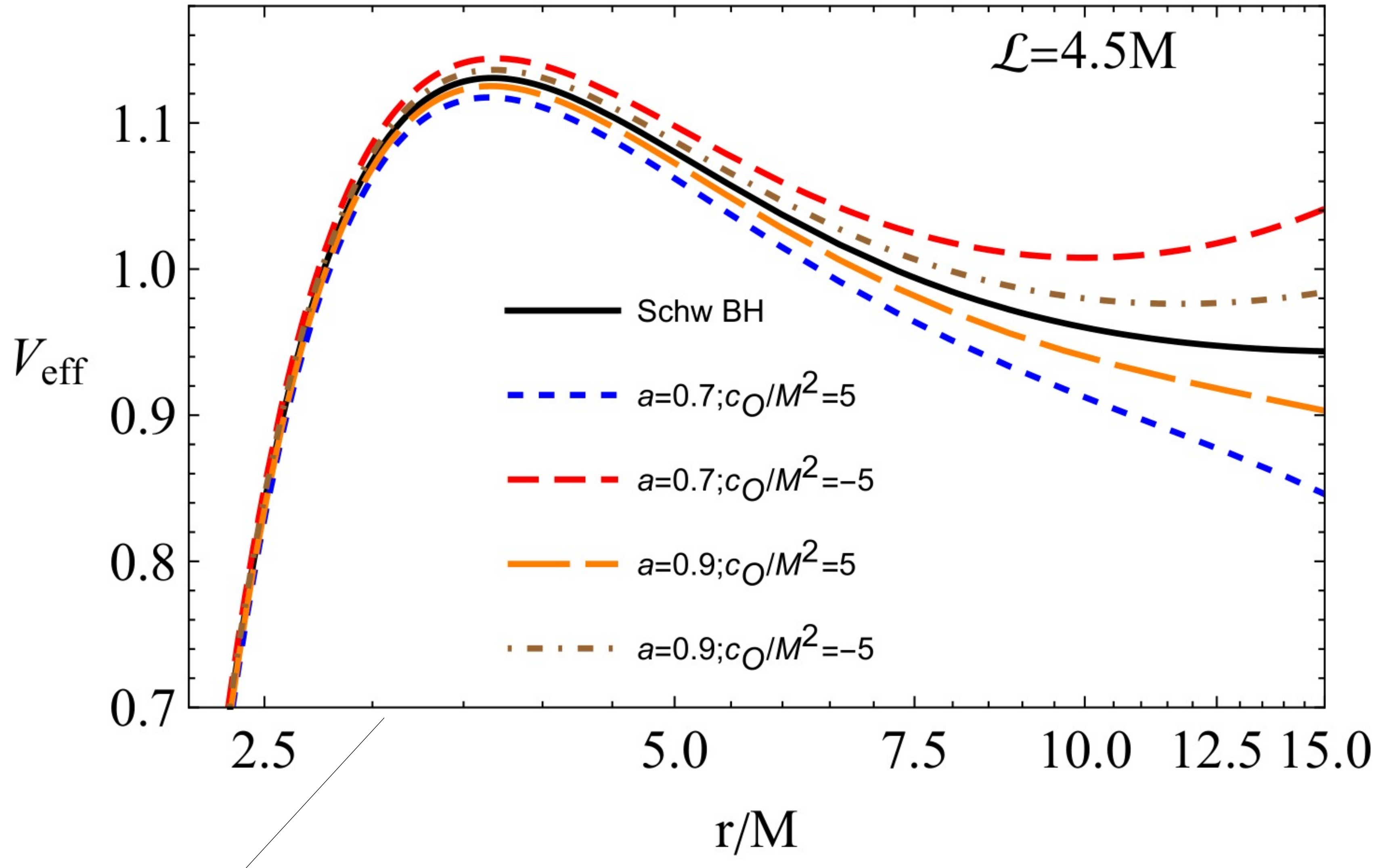
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



Photon sphere radius for a rotating symmergent black hole of angular momentum number s)

R. Pantig, A. Övgün, DD, Eur. Phys. J. C., 2023

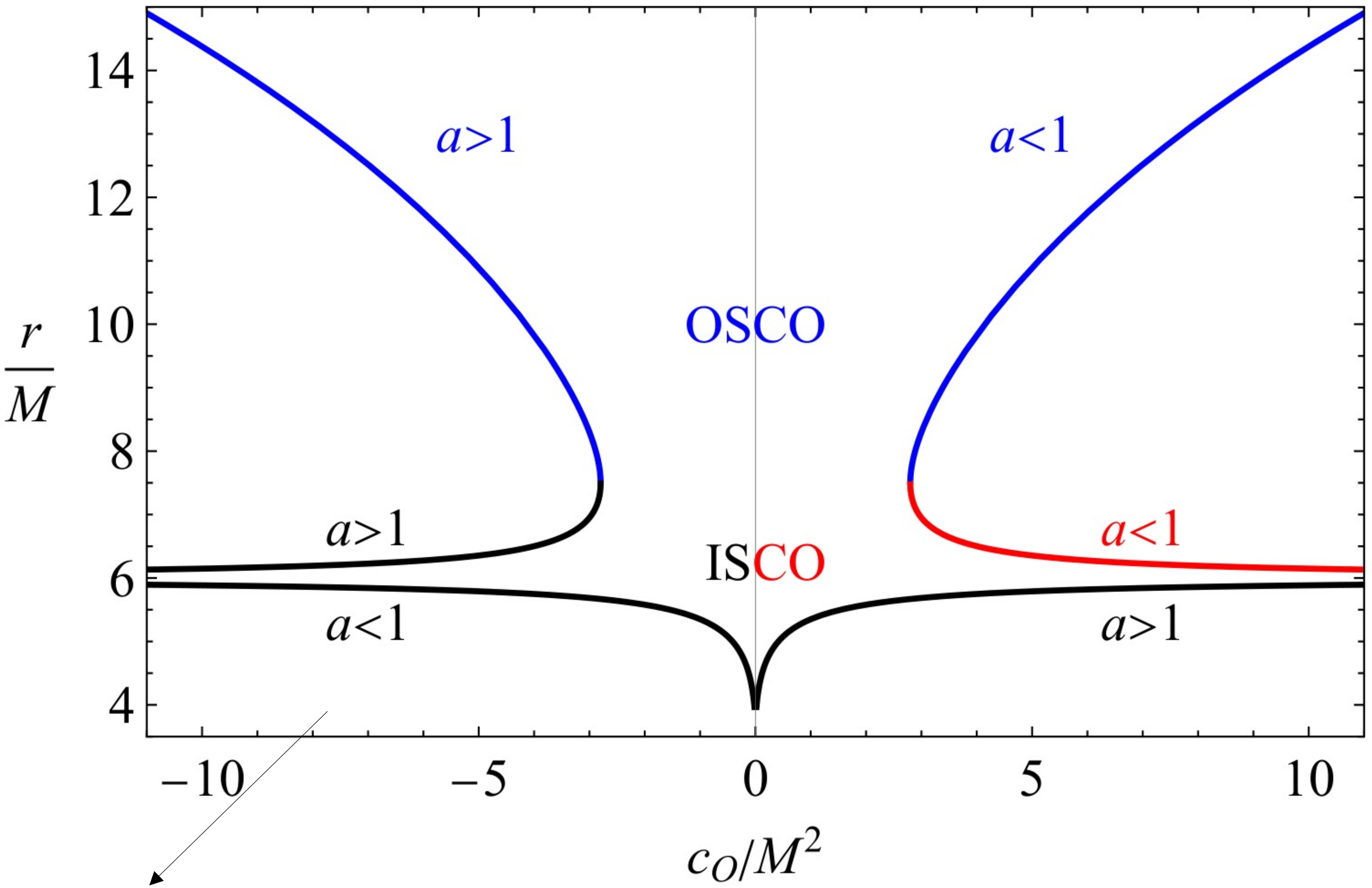
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



effective potential for $\ell = 4.5\ M$

J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



innermost (ISCO) and outermost (OSCO) stable circular orbits

J. Raimbayev et al, Annals of Physics, 2023
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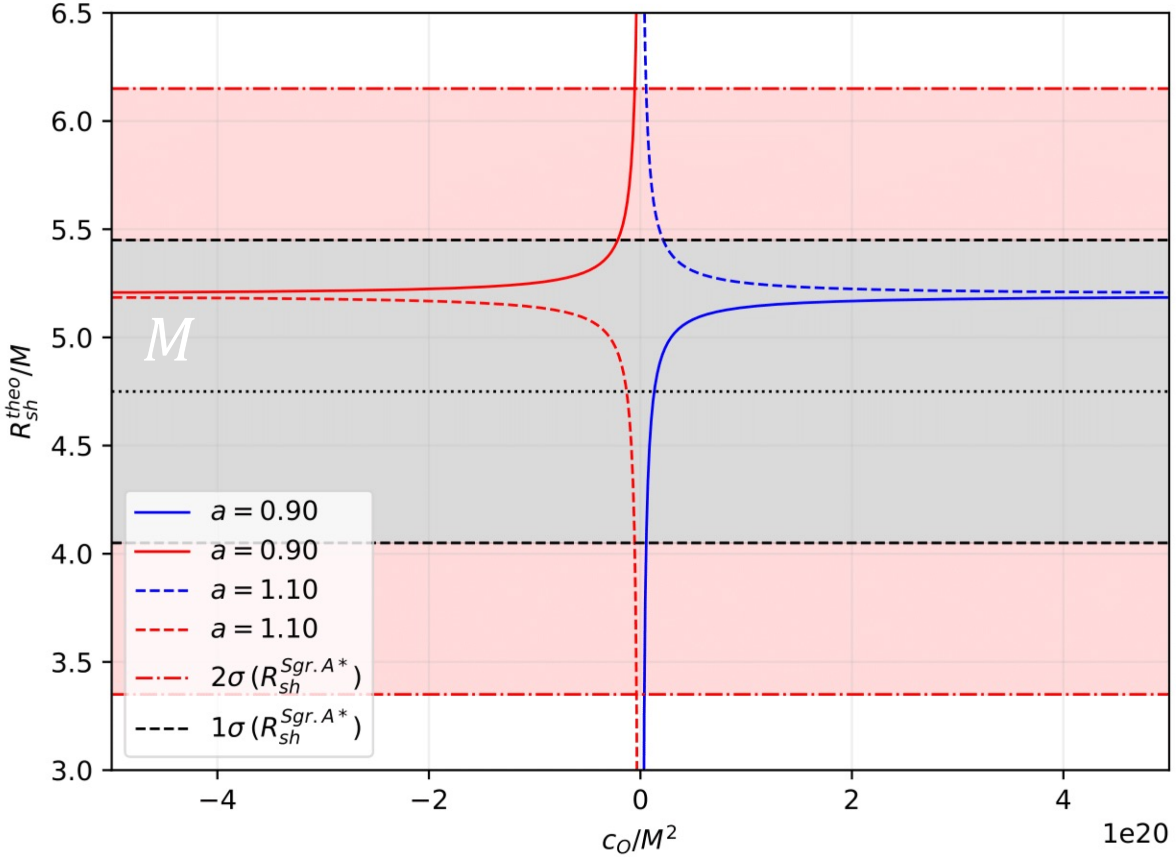
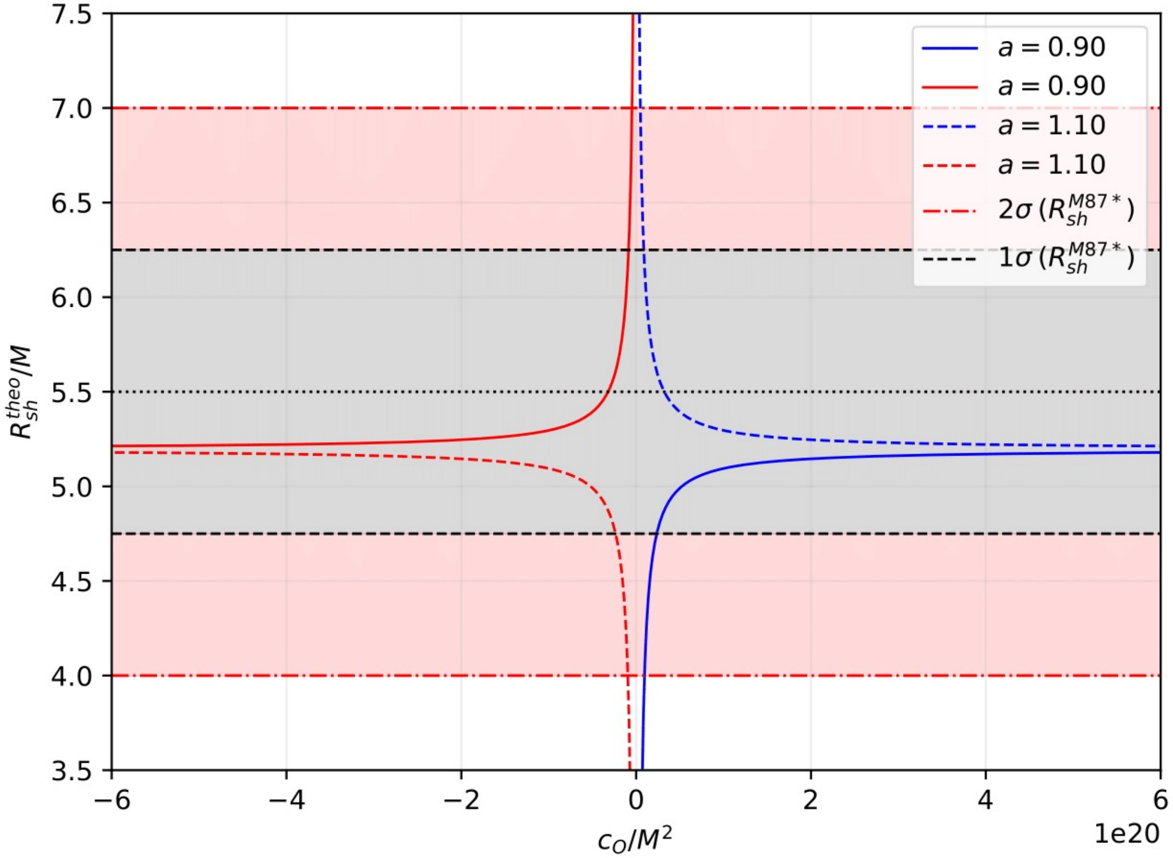
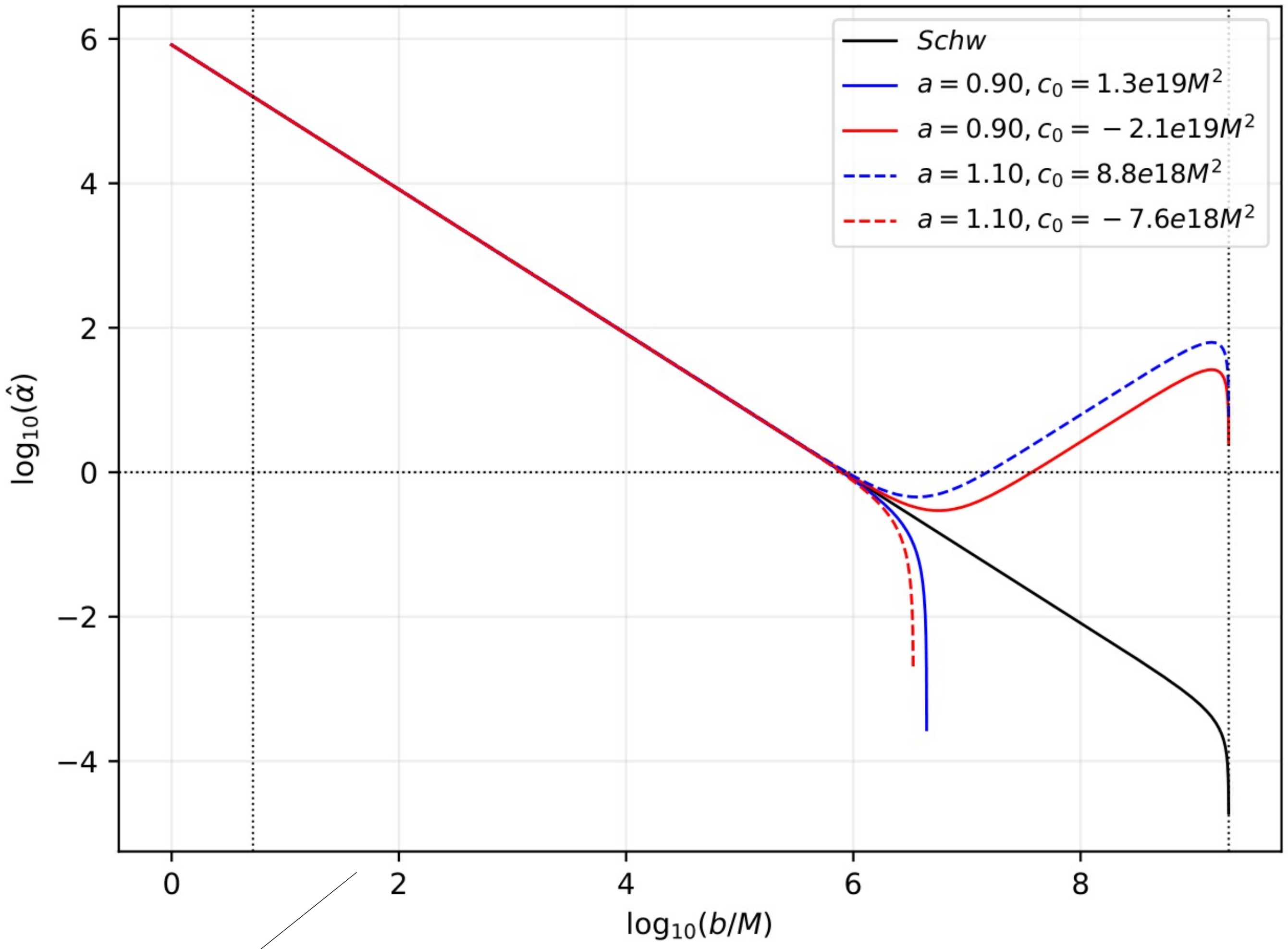




bounds on model parameters form shadow radii of Sgr.A* (left) and M87* (right)

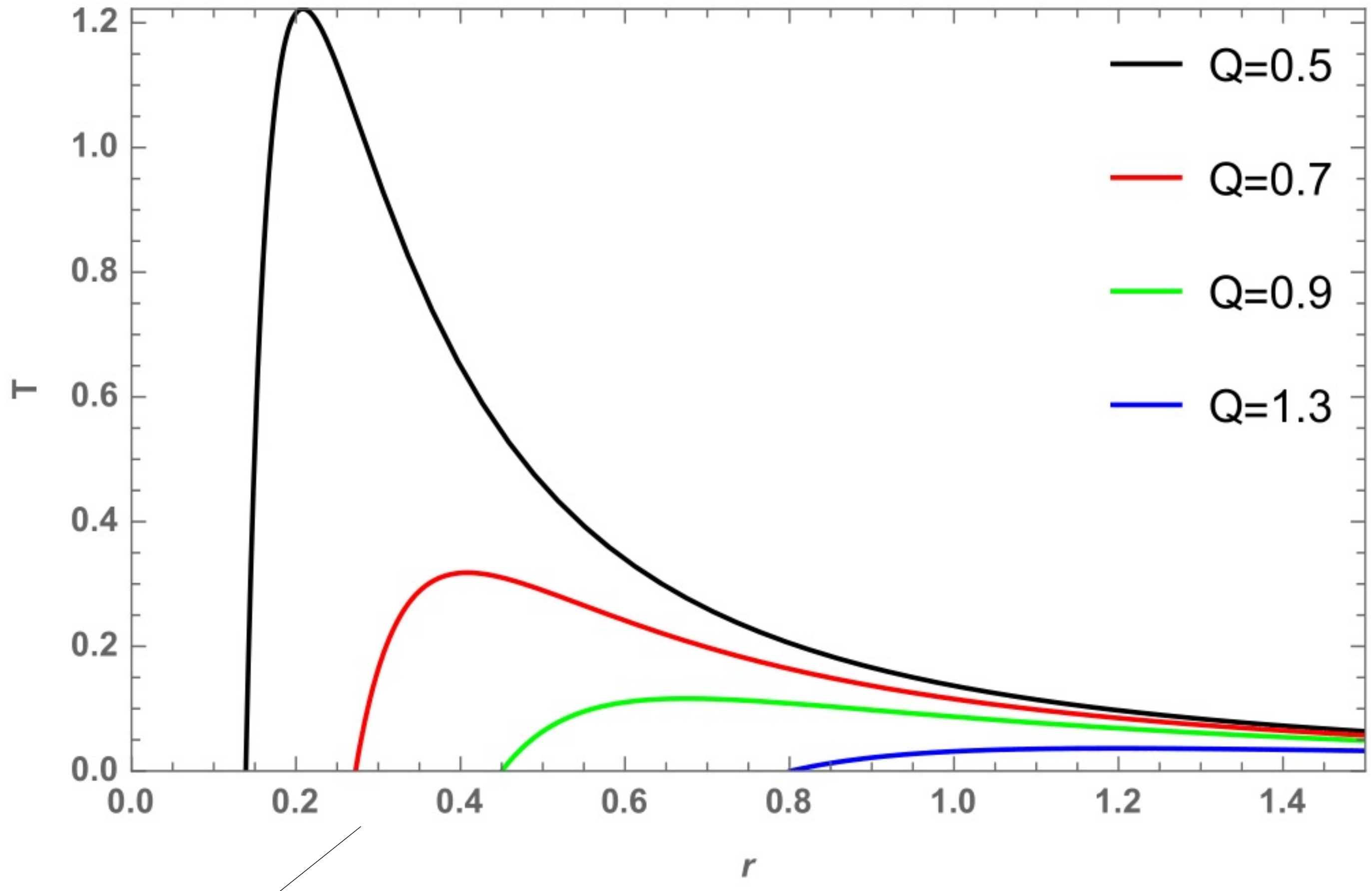
J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



bending angle (μas) for a nearby source ($r_o/20$) and an observer with impact parameter b.

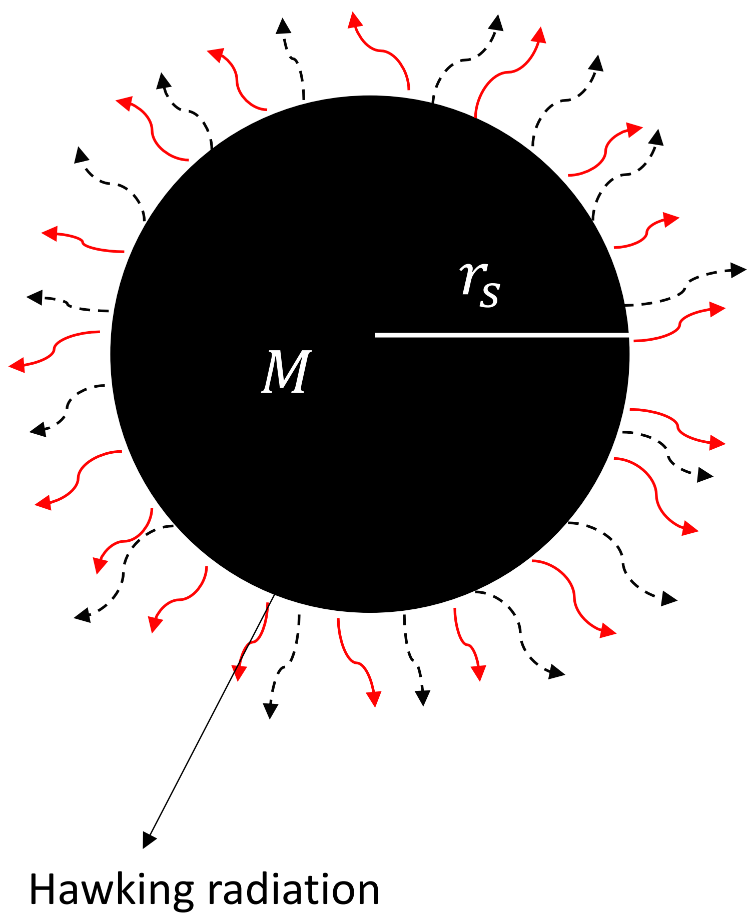
J. Raimbayev et al, Annals of Physics, 2023
İ. Çimdiker, A. Övgün, DD, Phys.Dark Univ., 2021



Hawking temperature ($r_s = 1$) for a charged symmergent black hole ($c_O = 0.9$ and $a = 0.5$) .

B. Puliçe, R. Pantig, A. Övgün, DD, Class. Quan. Grav. (under review), 2023

SYMMERGENT BLACK HOLE



Hawking radiation from photon, electron etc. :

Hawking radiation from new dark fields:

Black hole temperature and evaporation rate change if symmergent particles are included!

B. Puliçe, R. Pantig, A. Övgün, DD, work in progress, 2023

THANK YOU!