PARTICLE PHYSICS WITH BLACK HOLES

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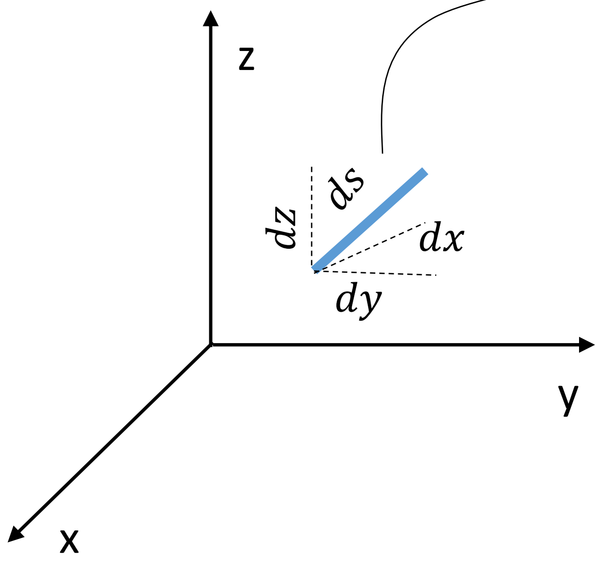
Boğaziçi Üniversitesi Fizik ve Astronomi Kulübü (April 29, 2023)

FLAT SPACE

3D



two events separated by a distance ds

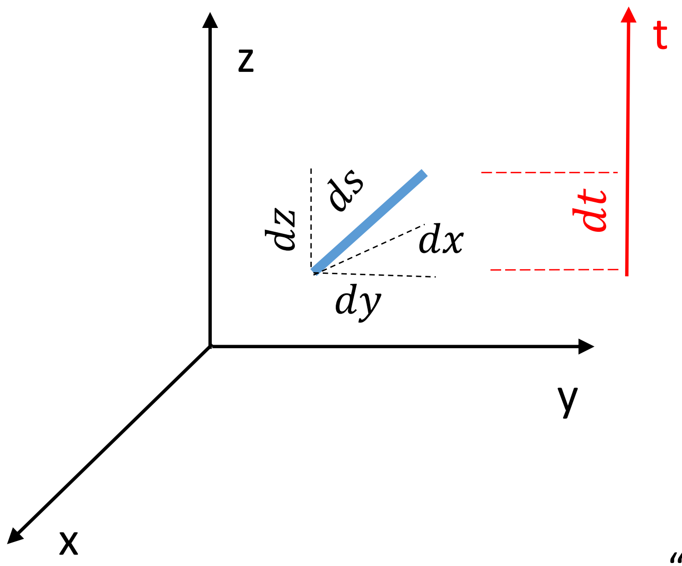
$$(ds)^2 = (dx)^2 + (dy)^2 + (dz)^2$$

space is flat

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

FLAT SPACETIME

4D



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

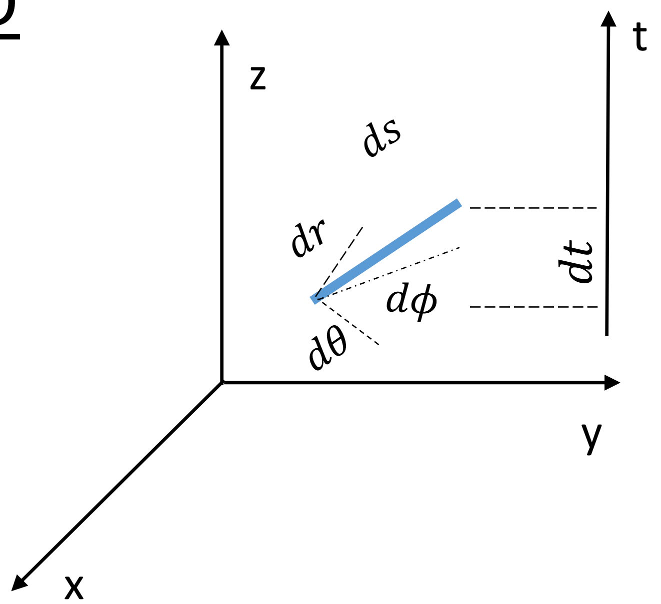
“minus” sign is needed for light to propagate

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



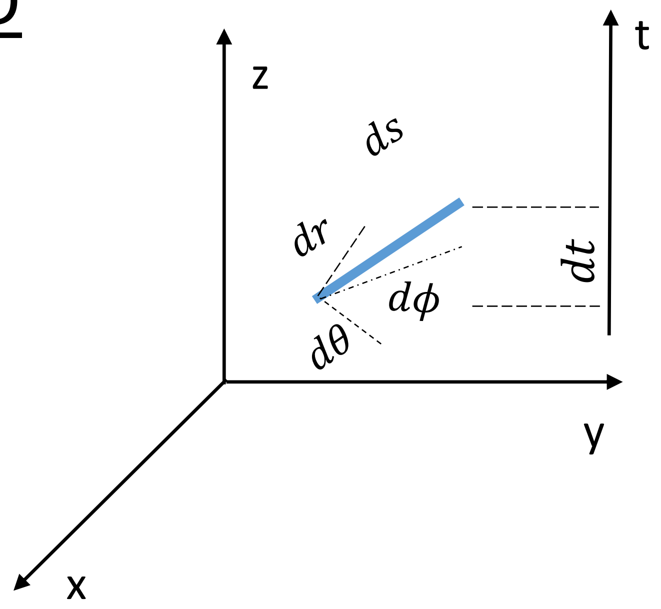
in spherical coordinates:

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

spacetime is flat
(coordinate change has no effect)

FLAT DILATED SPACETIME

4D



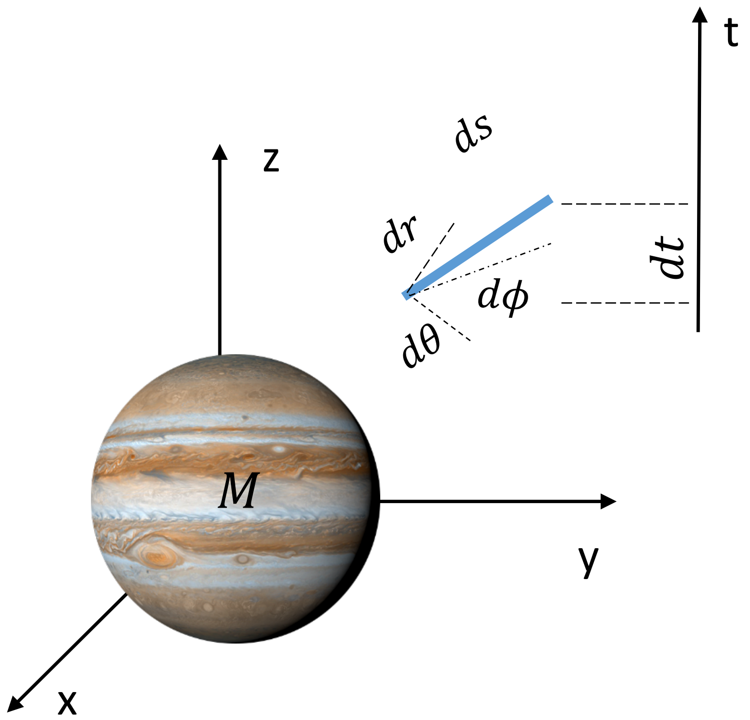
in an environment with intrinsic speed v_{int}:

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

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:

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

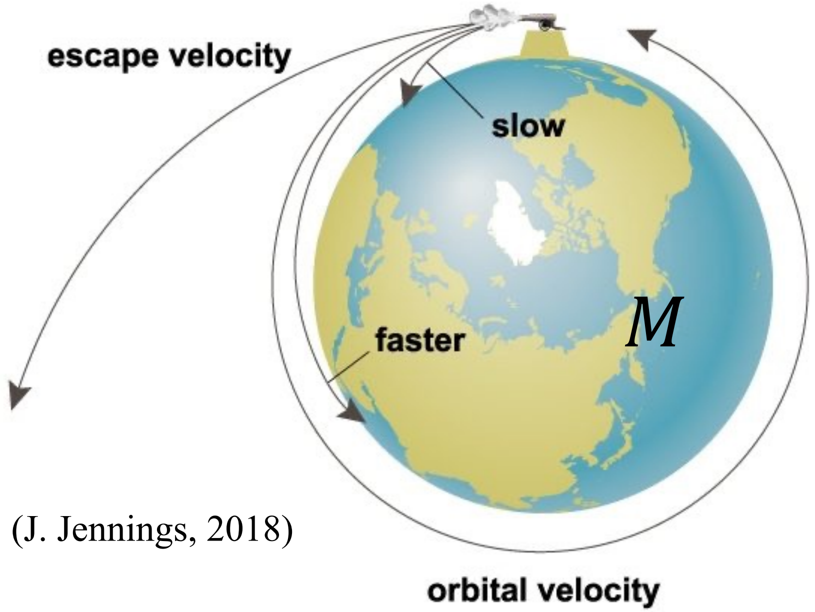
- distance between two points outside the body:

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

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:

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

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

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 :

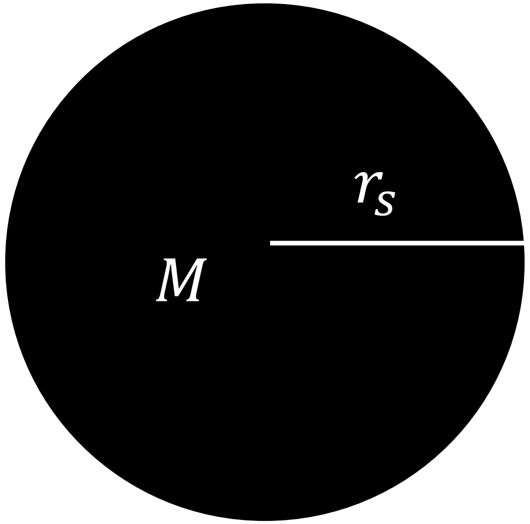
gravity theory	solution of Einstein equations
Einstein gravity action: $\int d(\mathrm{Vol})_4 \left(\frac{R}{16\pi G_N} - V_0\right)$	Schwarzschild solution (zero vacuum energy $V_0 = 0$) : $(ds)^2 = -\left(1 - \frac{r_s}{r}\right)(cdt)^2 + \frac{(dr)^2}{1-\frac{r_s}{r}} + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$

(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:

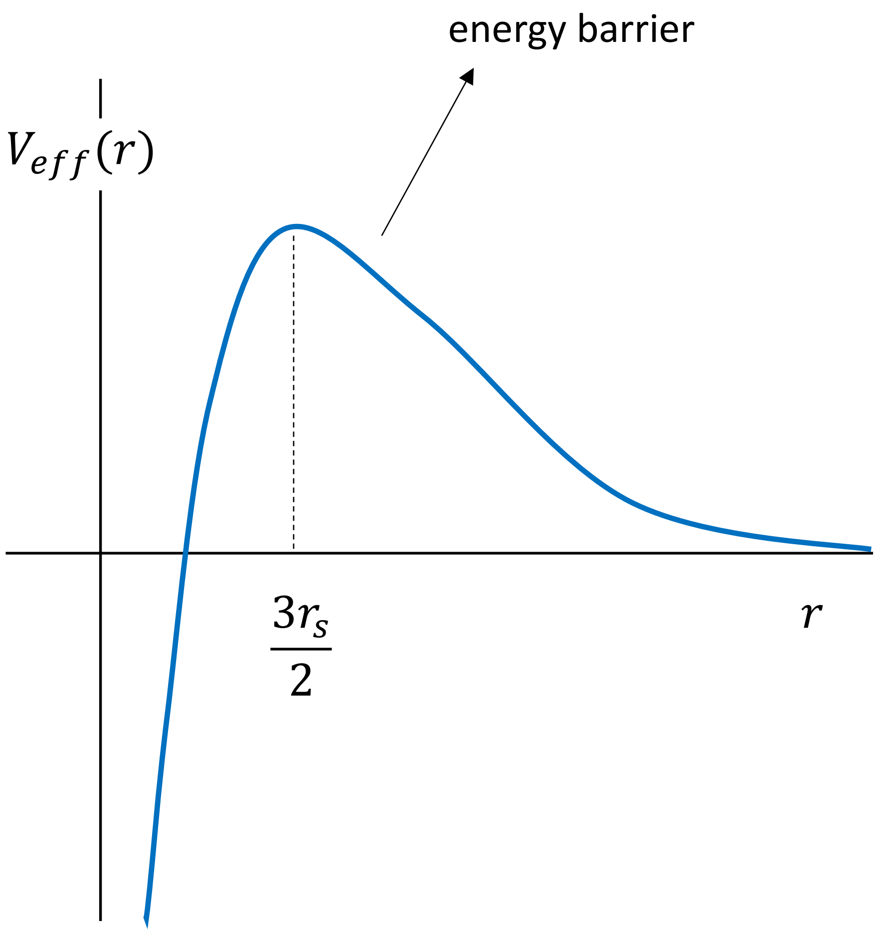
$$v_{es} > c$$

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

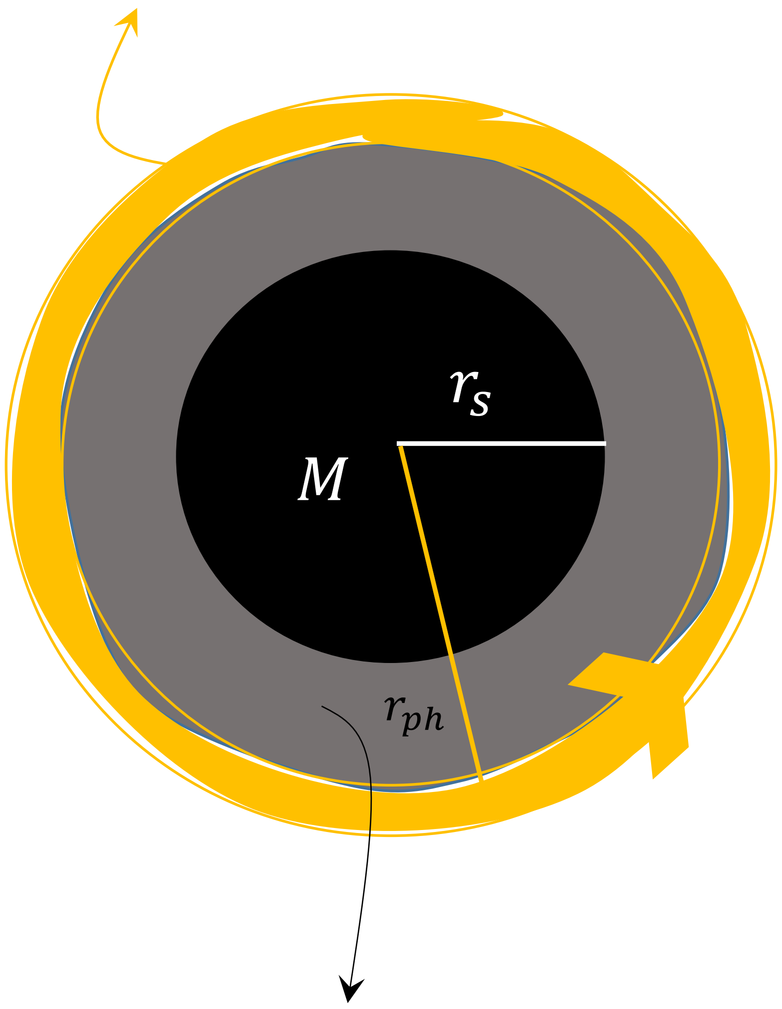
- $r = r_s \Rightarrow$ event horizon (the point of no return)
- $r = r_s \Rightarrow$ event horizon (infinite time dilation)
- $r < r_s \Rightarrow$ black hole interior (cannot be probed from outside)
- $r < r_s \Rightarrow$ black hole interior (effectively: time $\Leftrightarrow$ radial distance)

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, $\theta = \frac{\pi}{2}$):

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

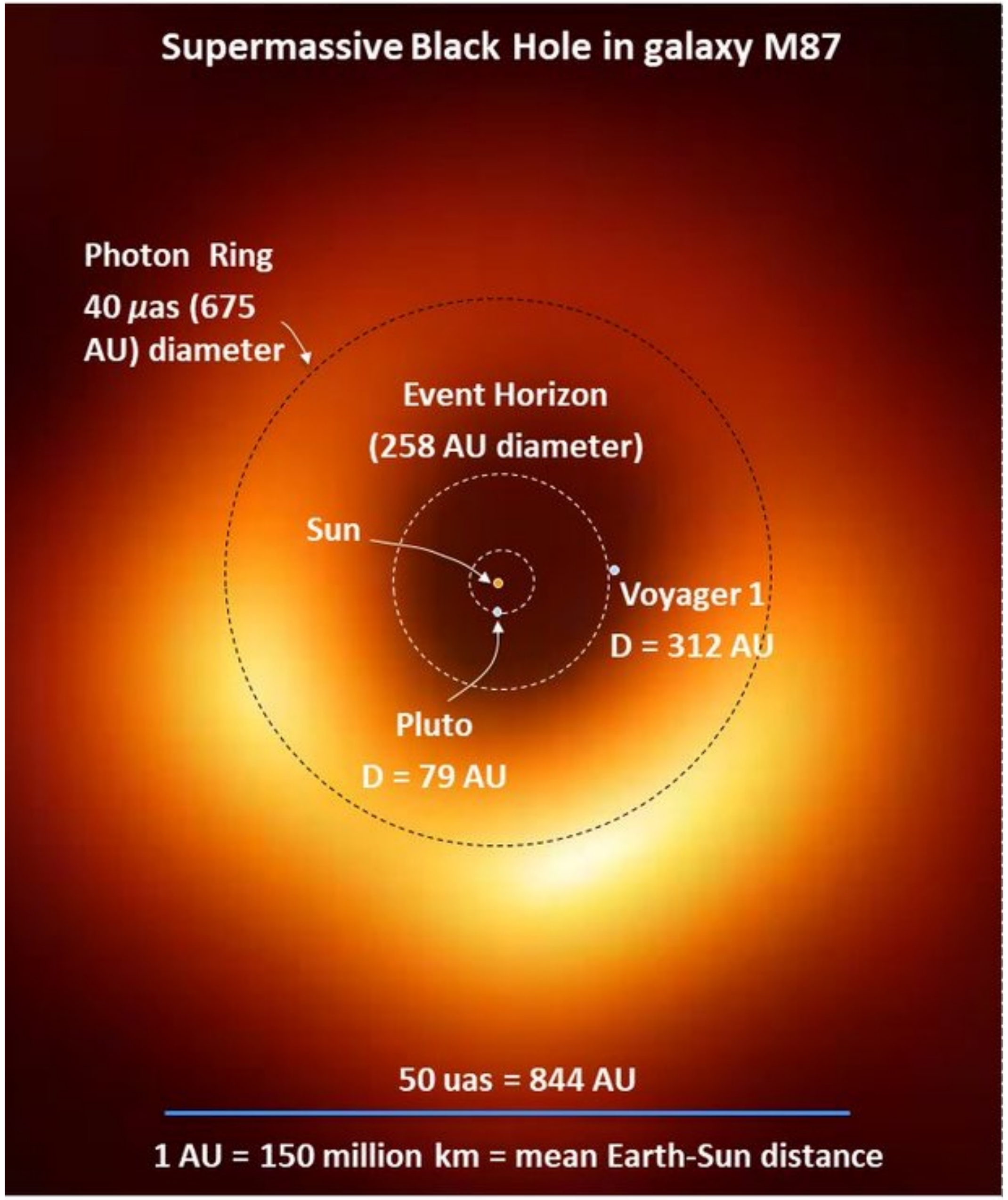
$$\text{EoM} \implies \frac{d\phi}{dt} = \frac{c}{r_\gamma}\left(\frac{r_s}{2r_\gamma}\right)^{1/2}$$

$$\left.\right\} \quad r_{ph} = \frac{3}{2} r_s$$

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

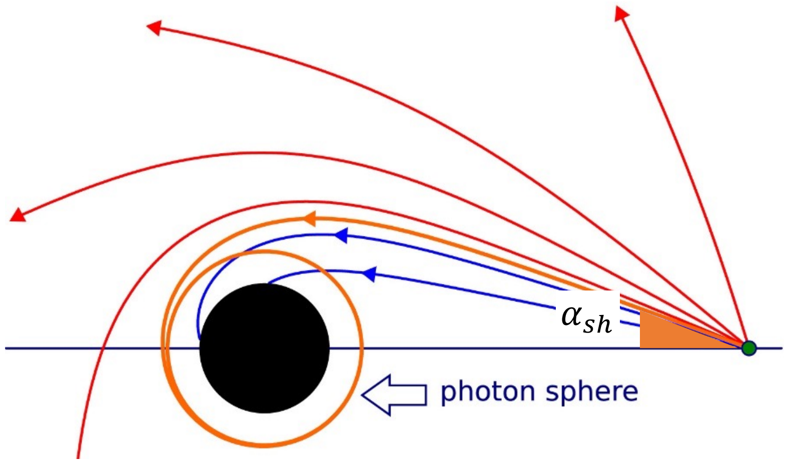
- photon radius $r = r_{ph}$ depends on the underlying gravity theory.

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!

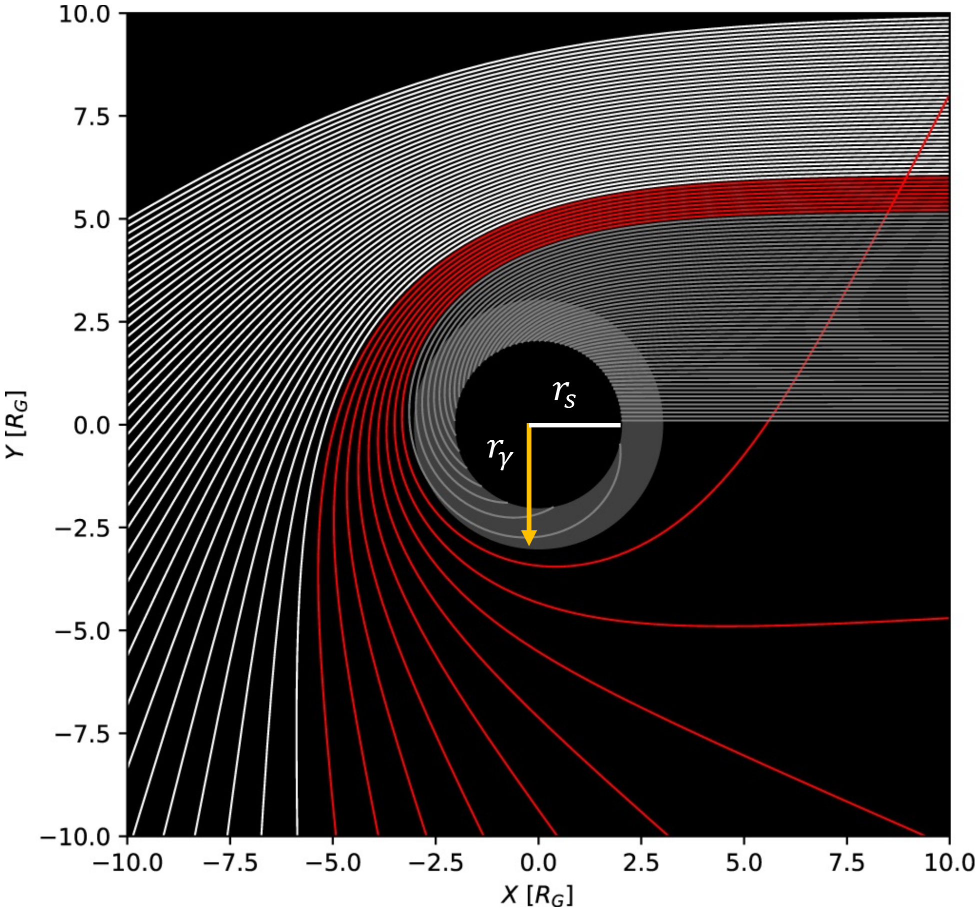
- consider a general spacetime:

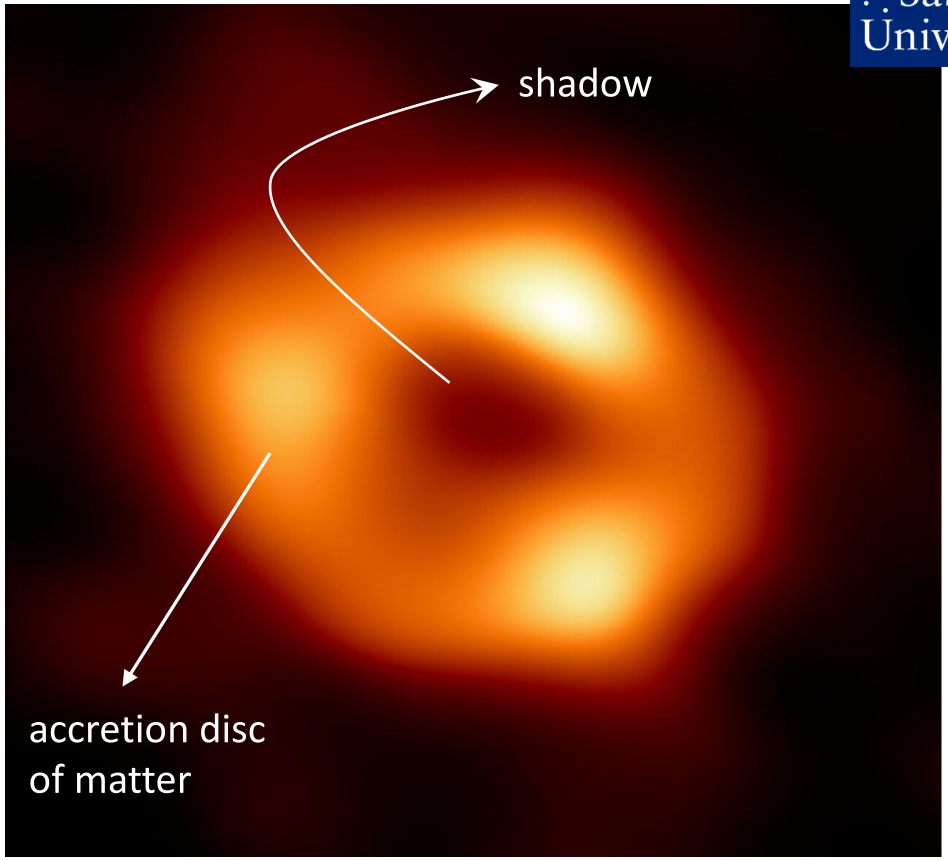
$$(ds)^2 = -A(r)(c\,dt)^2 + B(r)(dr)^2 + D(r)\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

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



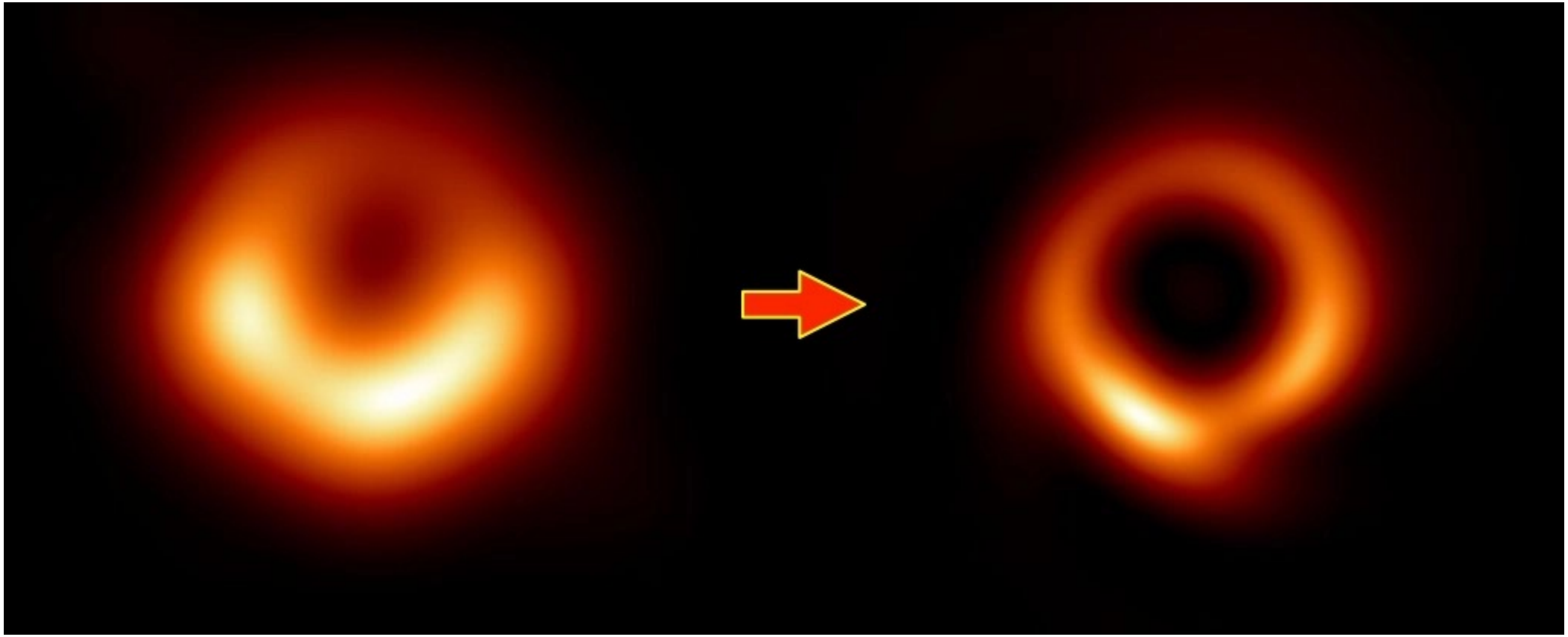


Shadow of a black hole

(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)

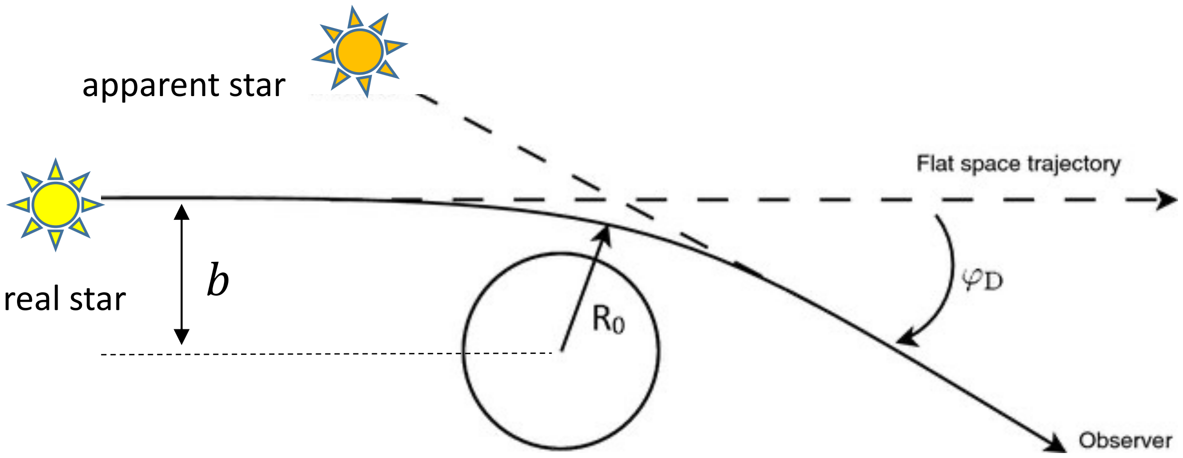
(EHT, 2019)

Shadow of M87* (AI)

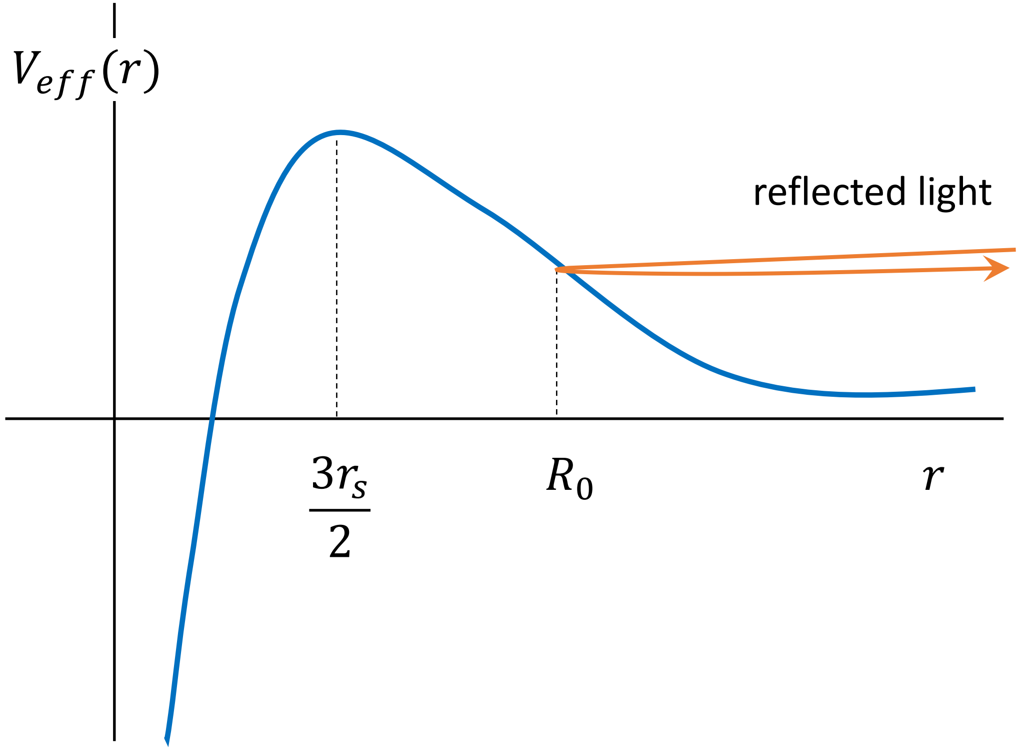
(PRIMO, 2023)

(Lia Medeiros et al 2023 ApJL 947 L7)

LIGHT BENDING BY BLACK HOLE



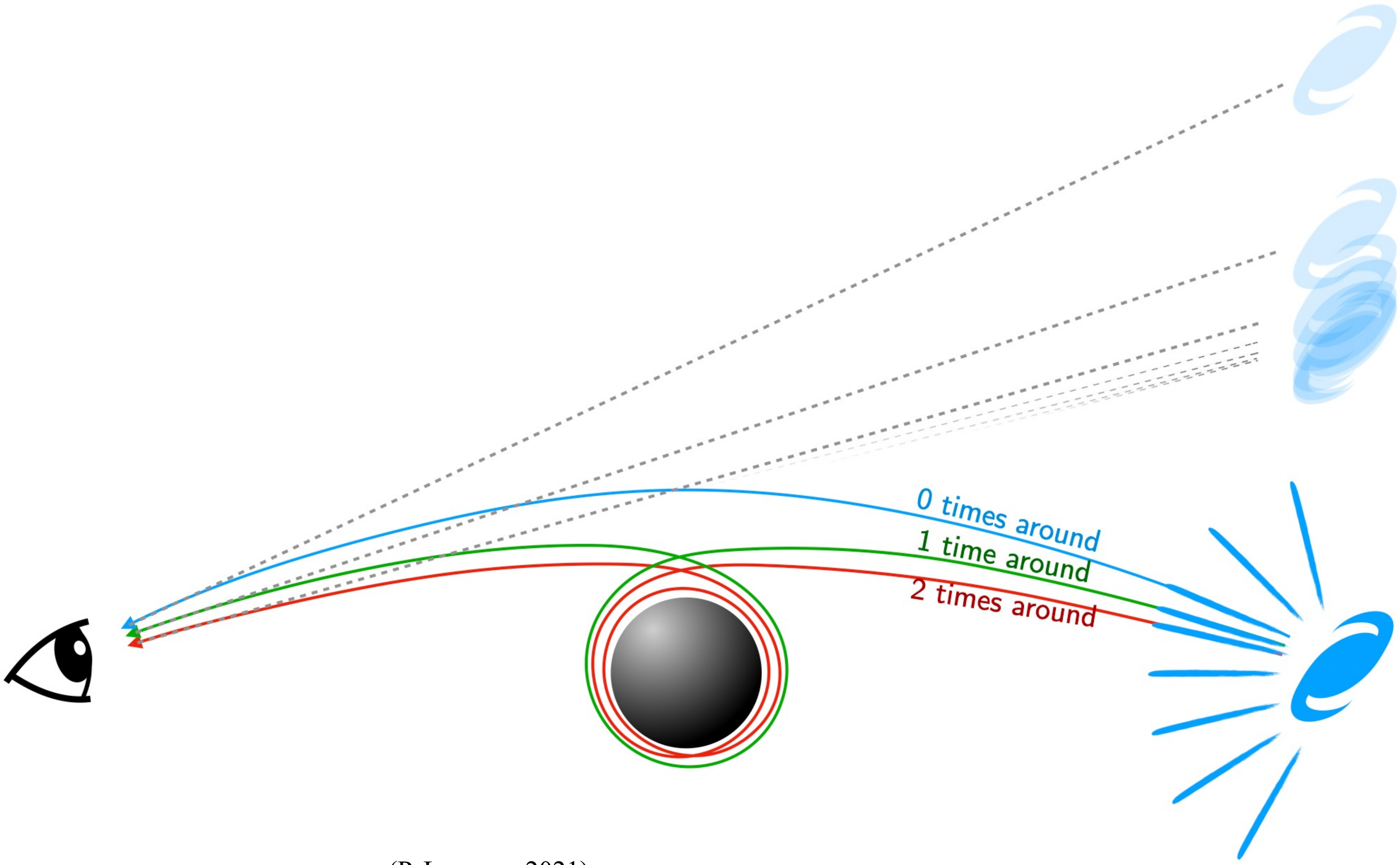
(Burger, D. et al 2018 Gen Relativ Gravit 50, 156)



- $\frac{dr}{d\tau} = \sqrt{\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{r_s}{r}\right)}$

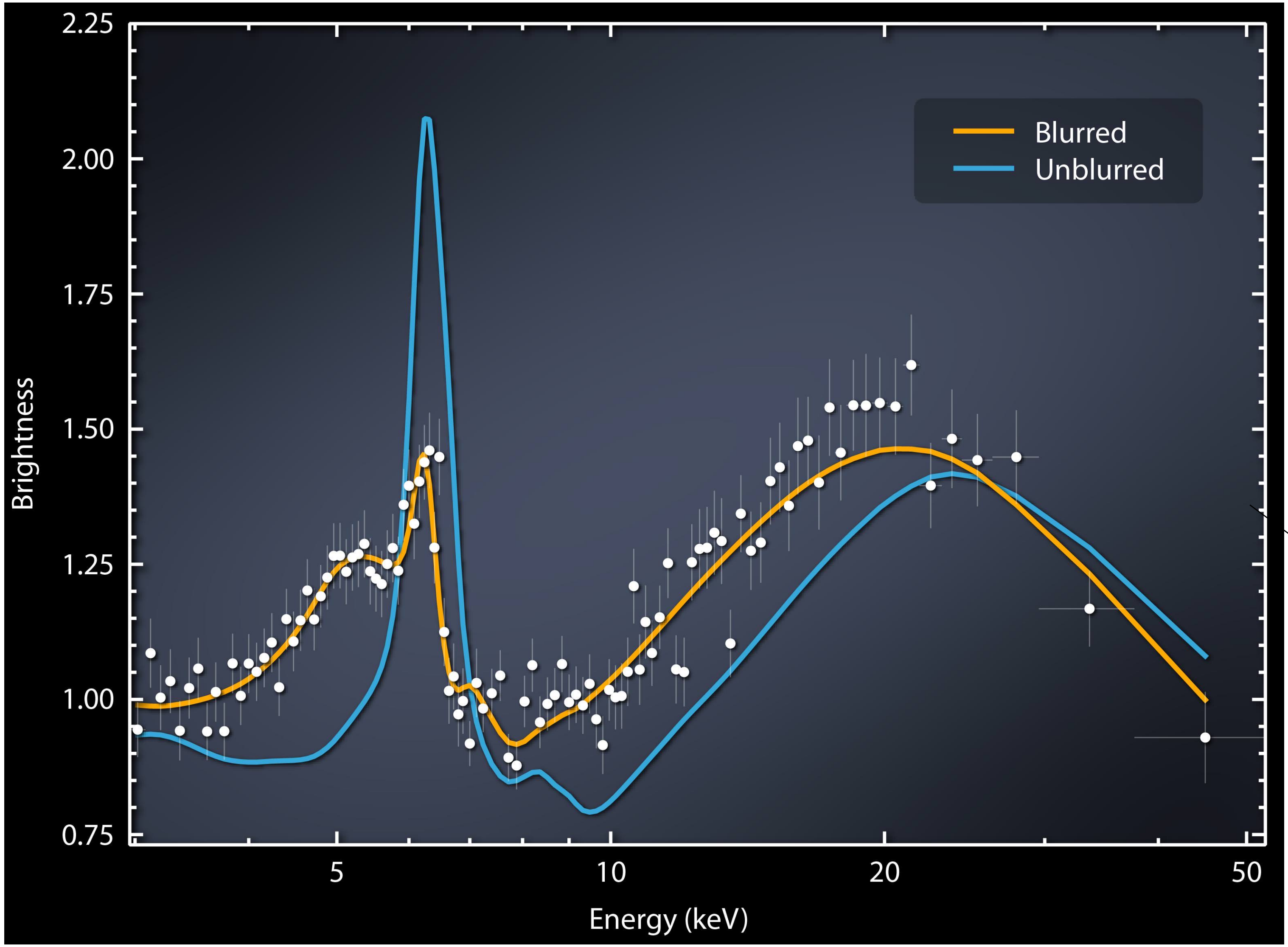
- $\frac{d\phi}{d\tau} = \frac{1}{r^2}$

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



(P. Laursen, 2021)

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



absorption of a corona by the (spinning) black hole Markarian (320 mil. lys)

(NASA-NuSTAR, 2014)

- effective potential seen by massless particle (photon):

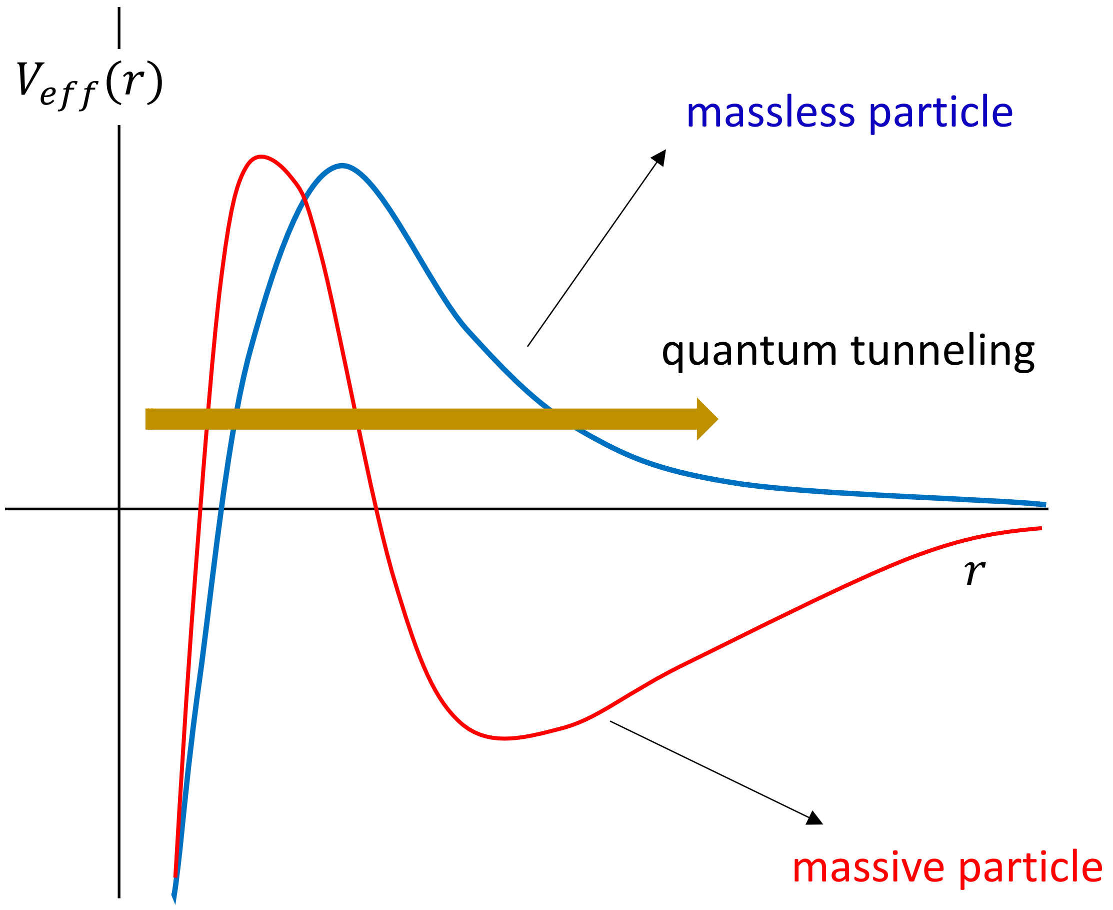
$$V_{eff}(r) = \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\ell^2}{2r^2} - \frac{\ell r_s}{2r^3}$$

- 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.

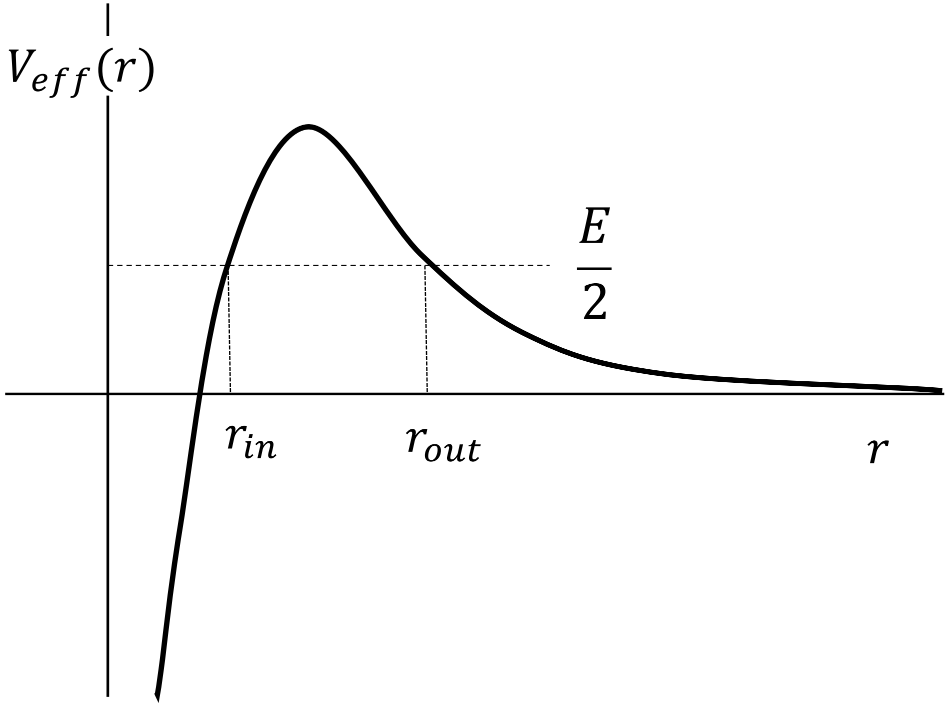


- Time it takes to traverse the barrier region:

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

$$= \int_{r_{in}}^{r_{out}} \frac{r^3 dr}{\sqrt{Er^6 - \ell^2 r^3 + r_s \ell r^2}} = 2\pi i \times \sum_{k} \mathrm{Res}_k$$

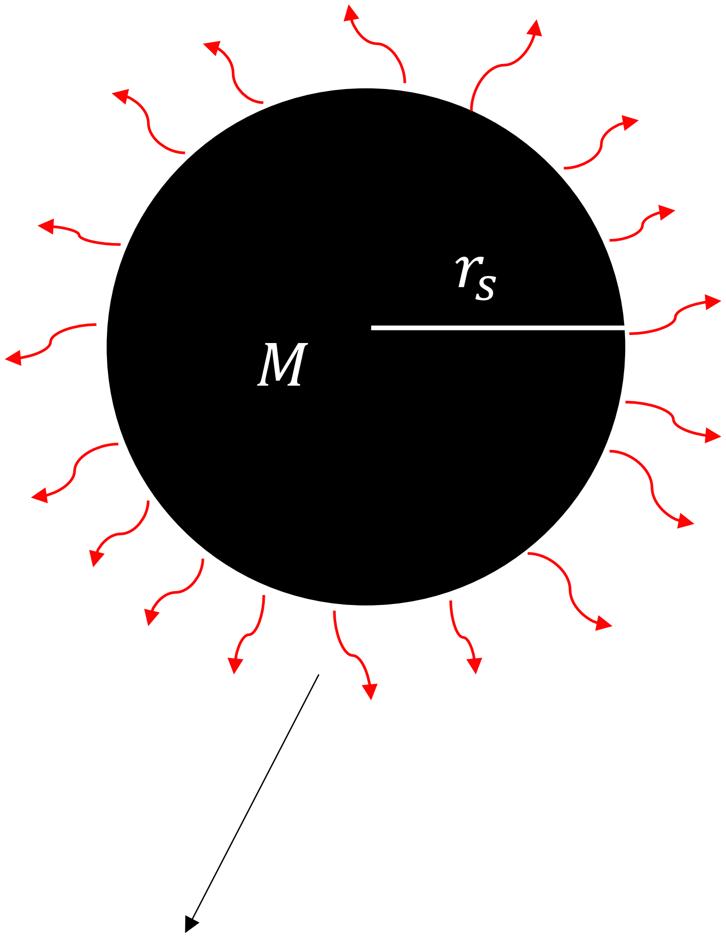
$$\xrightarrow{E\sim\ell\sim 1} 2\pi i \times (r_{out} - r_{in}) \simeq 2\pi i \times 2\, r_s$$



- Wavefunction: $\psi \propto e^{iE\Delta t} \simeq e^{-4\pi r_s E}$

- Black body spectrum: $T_H \simeq \frac{1}{4\pi r_s} \equiv \frac{\hbar c^3}{8\pi k_B G_N M}$

Hawking temperature



Hawking radiation

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 1976 PRD 13, 198)

QUANTUM TUNNELING AND HAWKING RADIATION

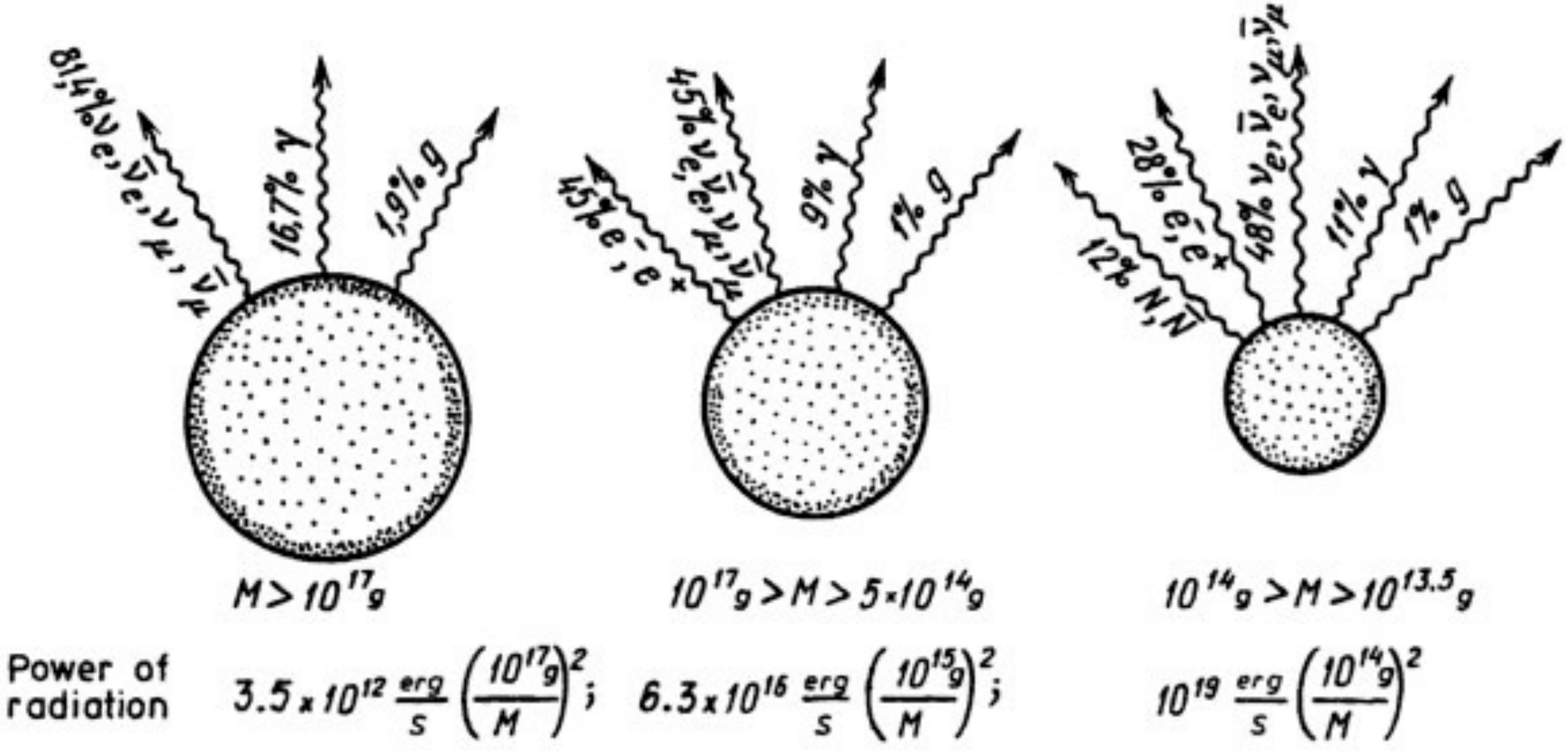


Figure 10.7: Quantum decay of a non-rotating black hole. The fractions of gravitons (g), photons (γ), neutrinos (ν) and other elementary particles are given in percent of the total number of particles emitted by black holes of different masses.

(Frolov and Novikov 1998 “Black hole physics” (Springer))

- Quantum field theories (QFTs) exist in flat spacetime and make sense with an ultraviolet (UV) cutoff scale.

- A gauge symmetry breaking cutoff can be:

  - either the mass of a vector particle (like Z boson or W boson masses)

  - or not the mass of a particle (like QCD scale or Newton's constant)

- A UV cutoff which is the mass of a vector boson respects translation symmetry and the gauge symmetries it breaks can be restored by introducing the Higgs field (Higgs mechanism).

- A UV cutoff which is not the mass of a particle breaks translation symmetry and the gauge symmetries it breaks can be restored by introducing affine curvature (Symmergence mechanism).

  - affine curvature leads to the usual curvature dynamically (holographically)

  - emergence of general relativity necessitates new particles beyond the new ones.

(DD, 2021 Gen Relativ Gravit 53, 22)

SYMMERGENT GRAVITY

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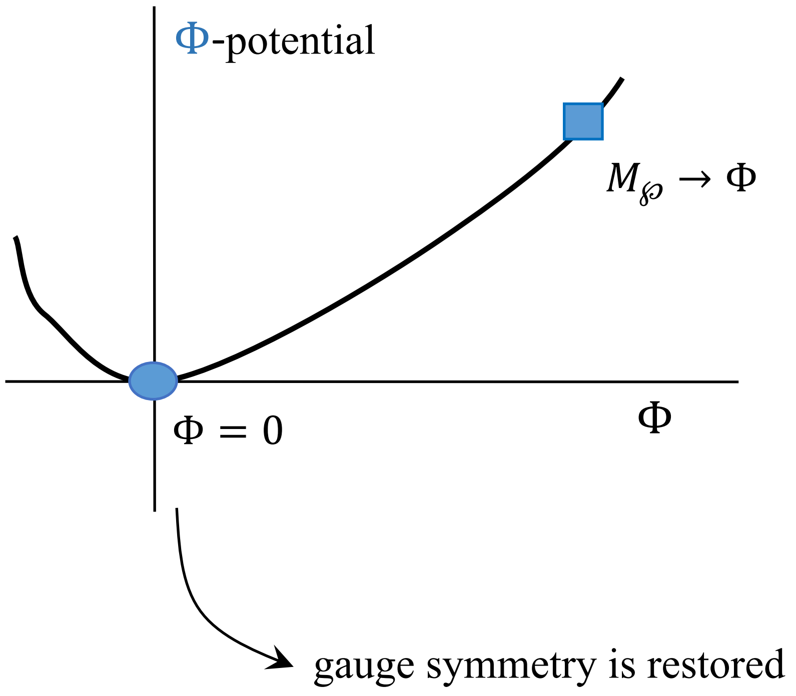
Translation-respecting UV Cutoff $M_\wp$

$M_\wp^2 \mathrm{Tr}[V_\mu \eta^{\mu\nu} V_\nu]$ → $\Phi^\dagger V_\mu \eta^{\mu\nu} V_\nu \Phi$ → $\eta^{\mu\nu}(D_\mu \Phi)^\dagger (D_\nu \Phi)$

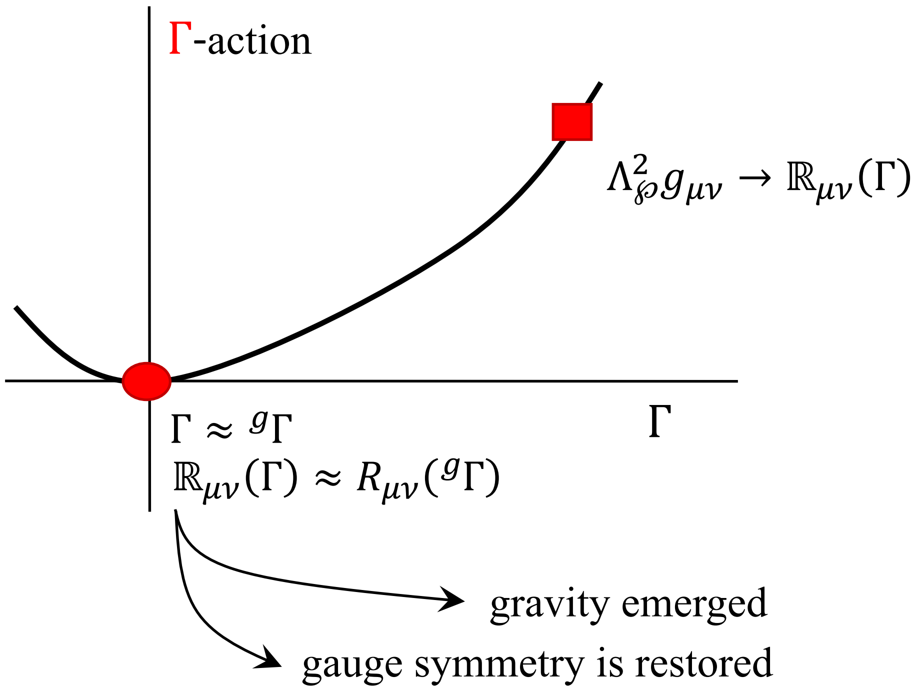
Translation-breaking UV Cutoff $\Lambda_\wp$

$\Lambda_\wp^2 V_\mu \eta^{\mu\nu} V_\nu$ → $V_\mu \mathbb{R}^{\mu\nu}(\bar{\Gamma}) V_\nu$ → $V_\mu\left(\mathbb{R}^{\mu\nu}(\Gamma) - R^{\mu\nu}({}^g\Gamma)\right)V_\nu$

Higgs mechanism:



Symmergence mechanism:



(DD, 2023 PRD, under review)

ASYMPTOTICALLY-FLAT SYMMERGENT BLACK HOLE

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gravity theory	solution of Einstein equations
Symmergent gravity: $\int d(\mathrm{Vol})_4 \left(\frac{R}{16\pi G_N} + \frac{1}{96\pi\gamma} R^2\right)$	$(ds)^2 = e^{\varphi(r)}\left(-\left(1-\frac{r_s}{r}\right)c^2(dt)^2 + \frac{(dr)^2}{1-\frac{r_s}{r}} + r^2\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)\right)$

$$\gamma = -\frac{64\pi}{3(n_B - n_F)}$$

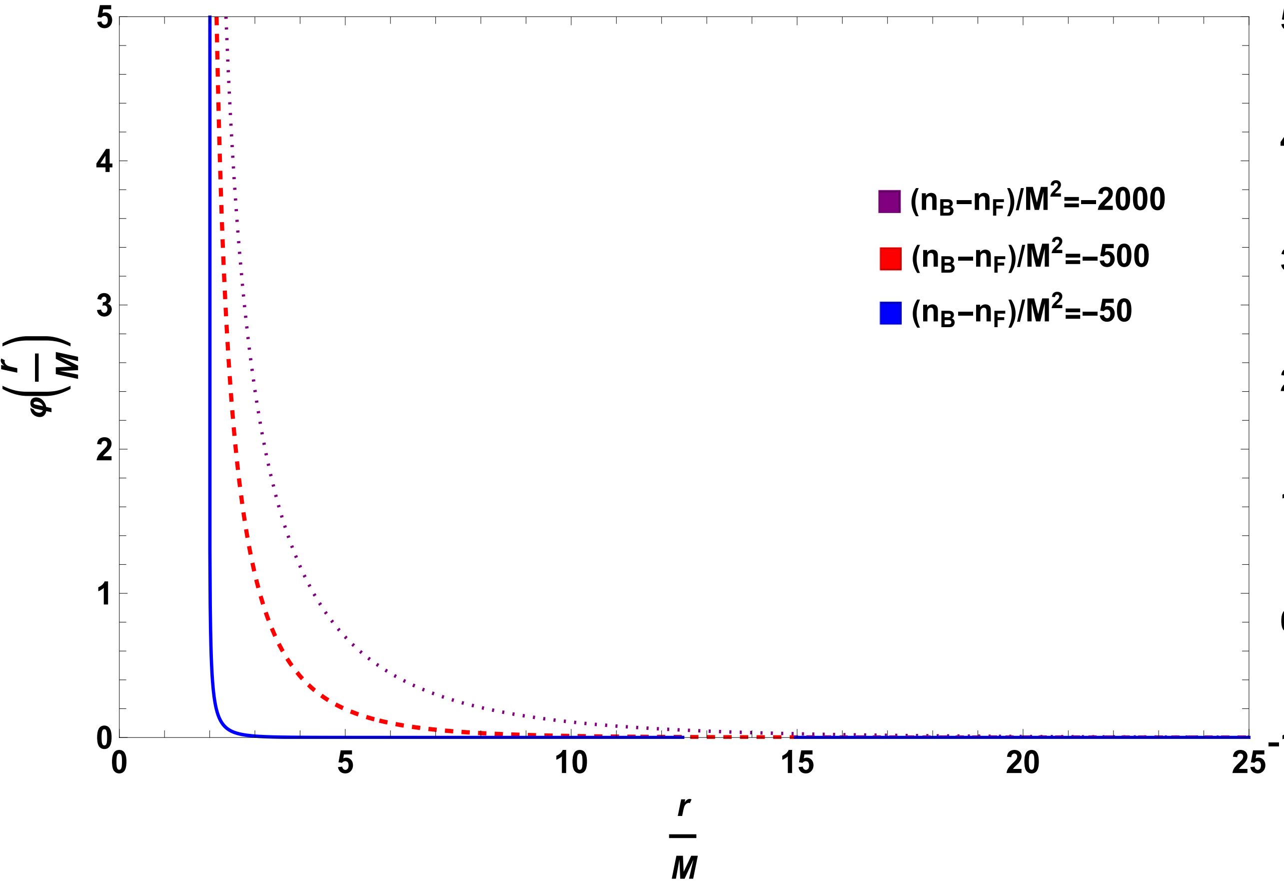
number difference between bosonic and fermionic degrees of freedom

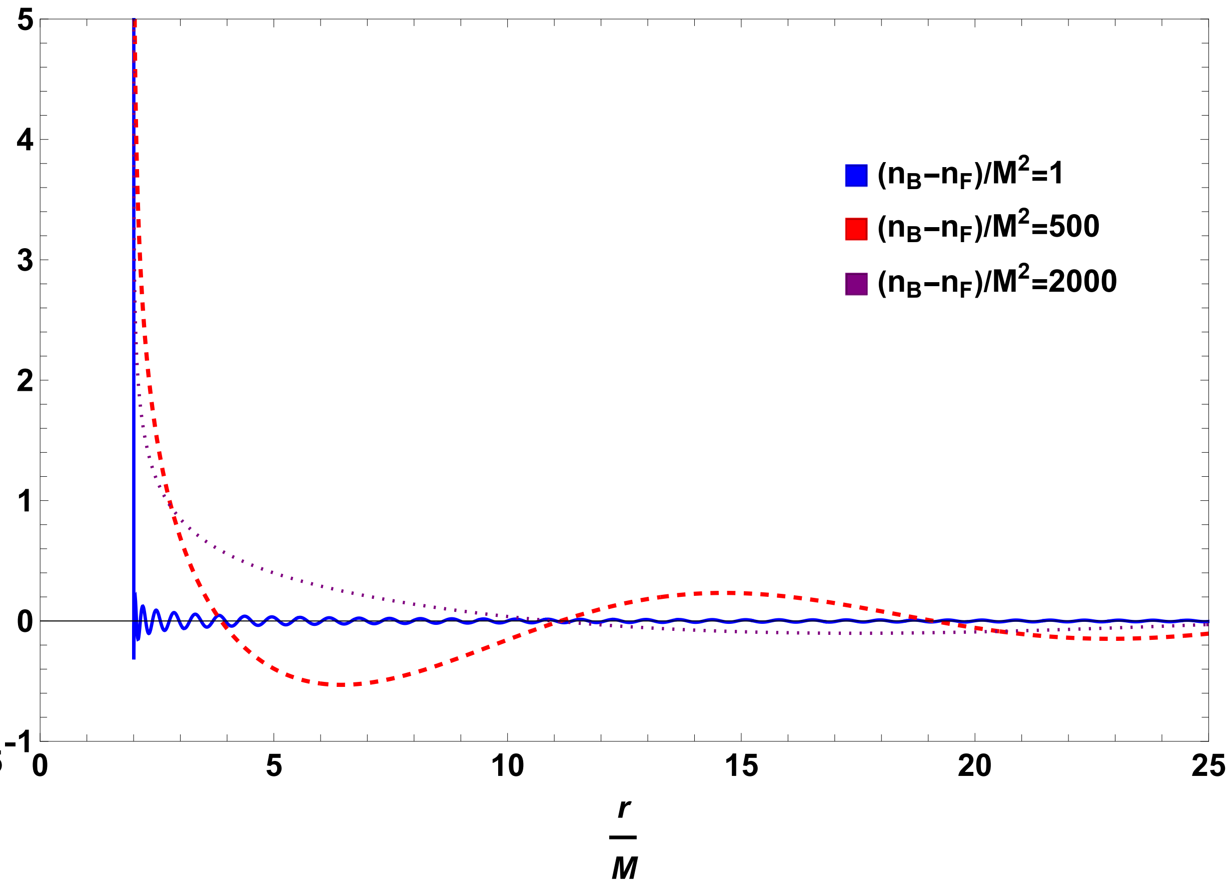
$$\frac{d}{dr}\left((r^2 - r r_s)\frac{d\varphi(r)}{dr}\right) = -\gamma r^2 \varphi(r)$$

Schwarzschild solution

(H. K. Nguyen, 2022 arXiv:2211.07380)
(B. Puliçe, R. Pantig, A. Övgün, DD, work in progress)

ASYMPTOTICALLY-FLAT SYMMERGENT BLACK HOLE





- The conformal factor $\varphi(r)$ diverges at the Schwarzschild event horizon $r = r_s \equiv 2M$ and gets diminished exponentially (power-law periodically) at large r for $n_B - n_F < 0$ ($n_B - n_F < 0$).

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

ASYMPTOTICALLY-FLAT SYMMERGENT BLACK HOLE

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it is convenient to write the symmergent metric as:

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

time-dilation potential:

$$A(r) = e^{\varphi(r)}(1 - \frac{r_s}{r})$$

space-contraction potential:

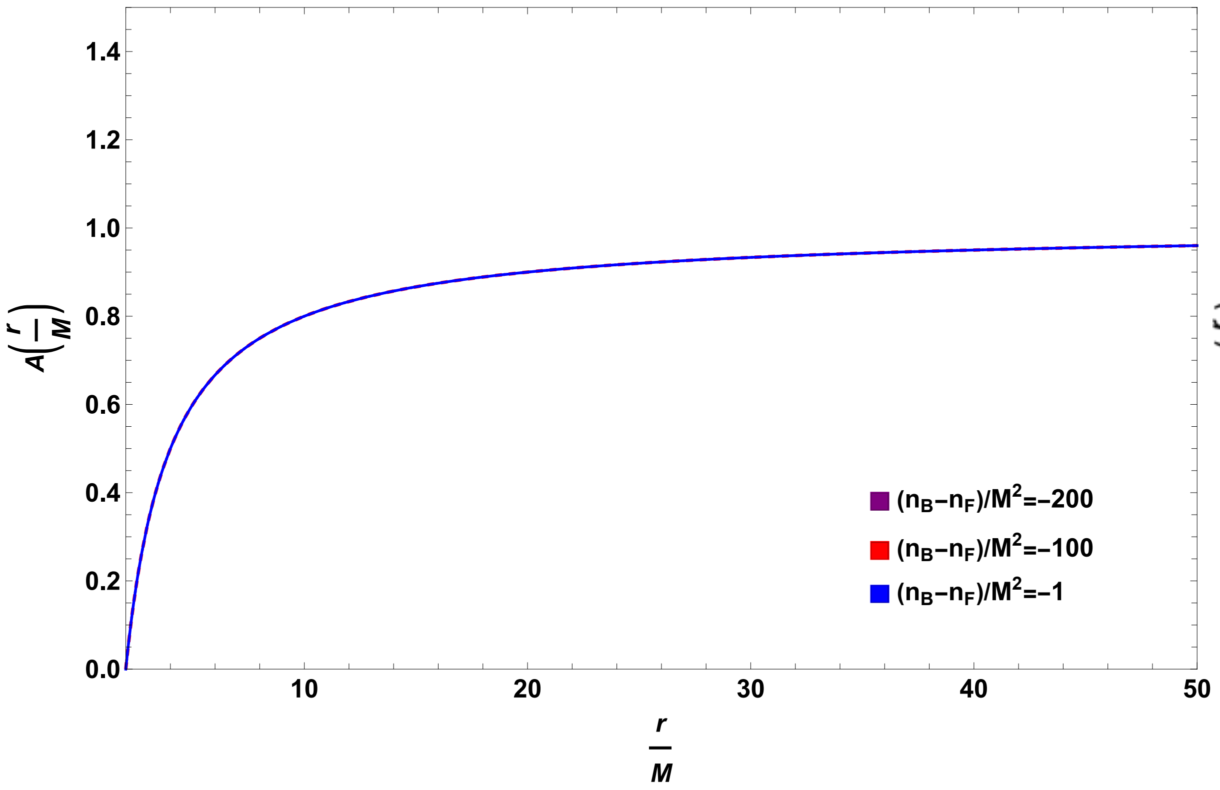
$$B(r) = e^{-\varphi(r)}(1 - \frac{r_s}{r})$$

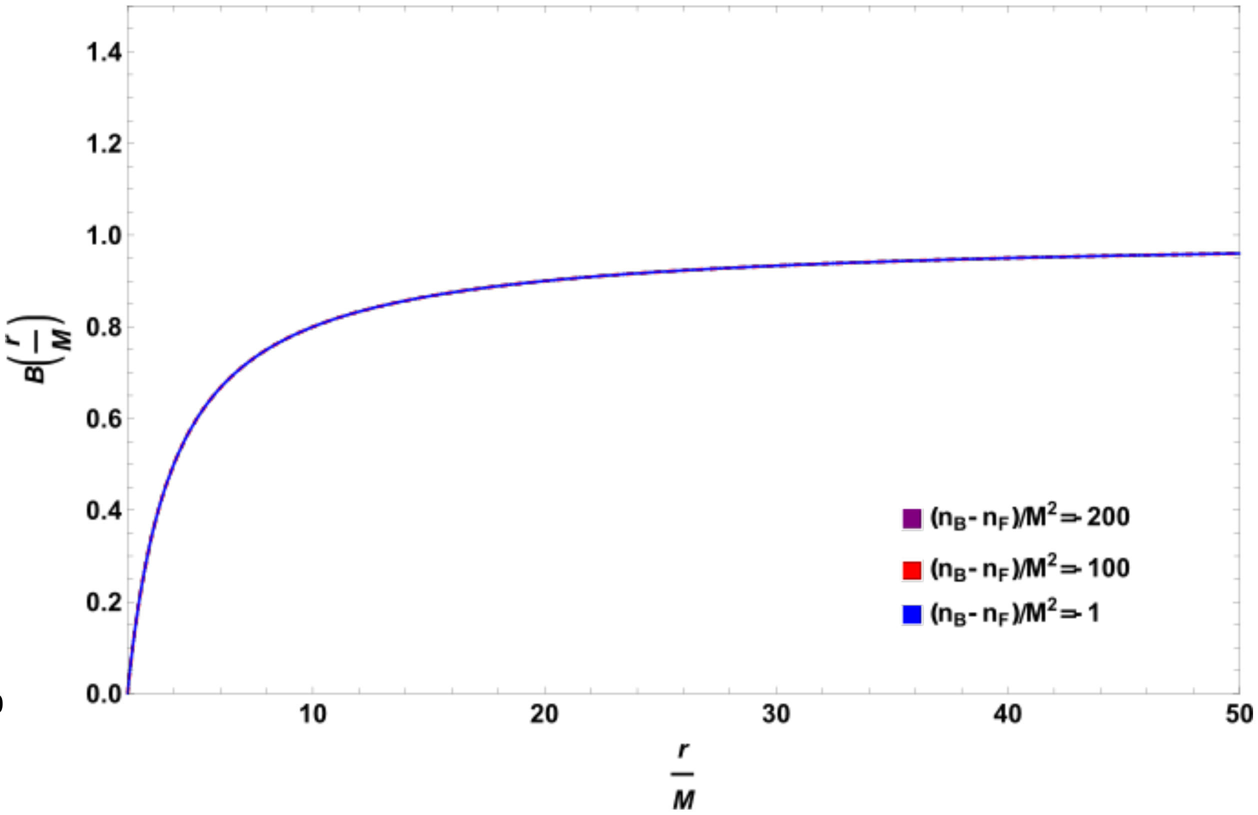
angular potential:

$$C(r) = e^{\varphi(r)}r^2$$

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

ASYMPTOTICALLY-FLAT SYMMERGENT BLACK HOLE

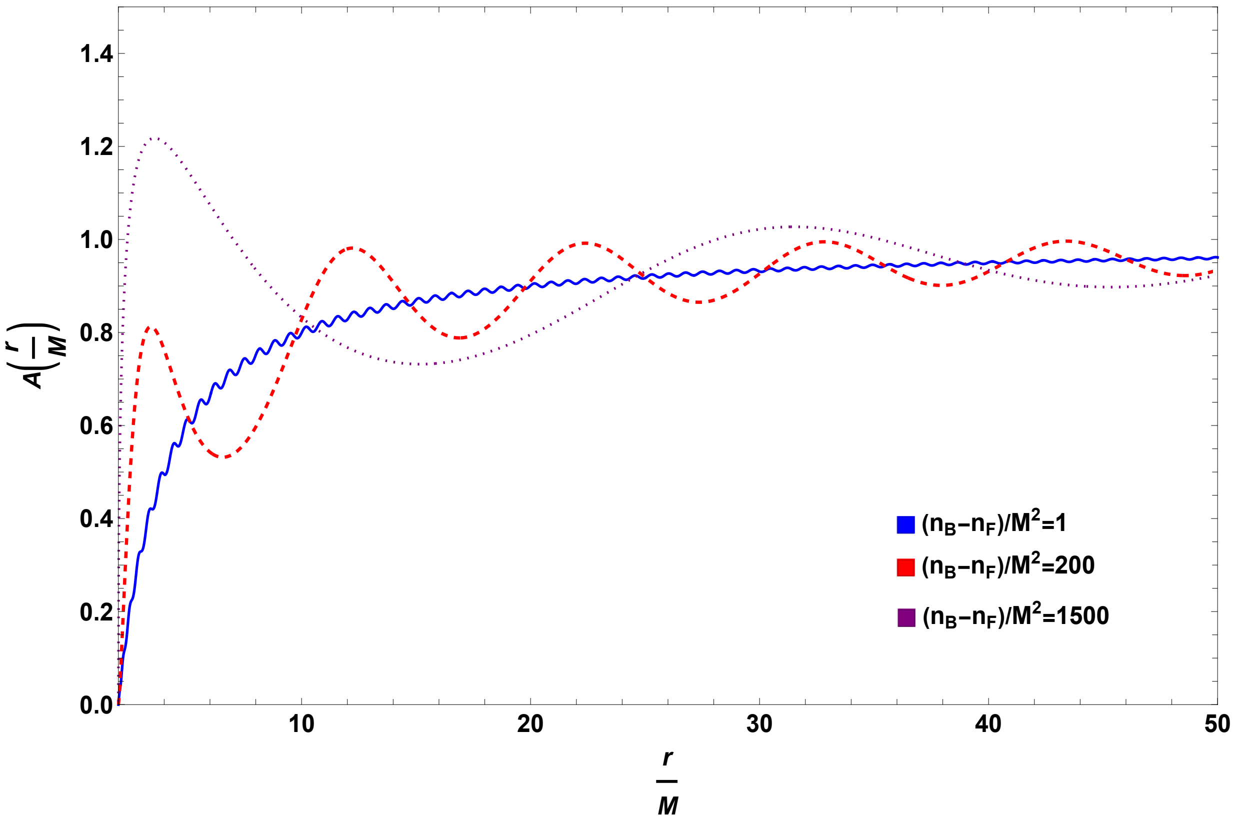


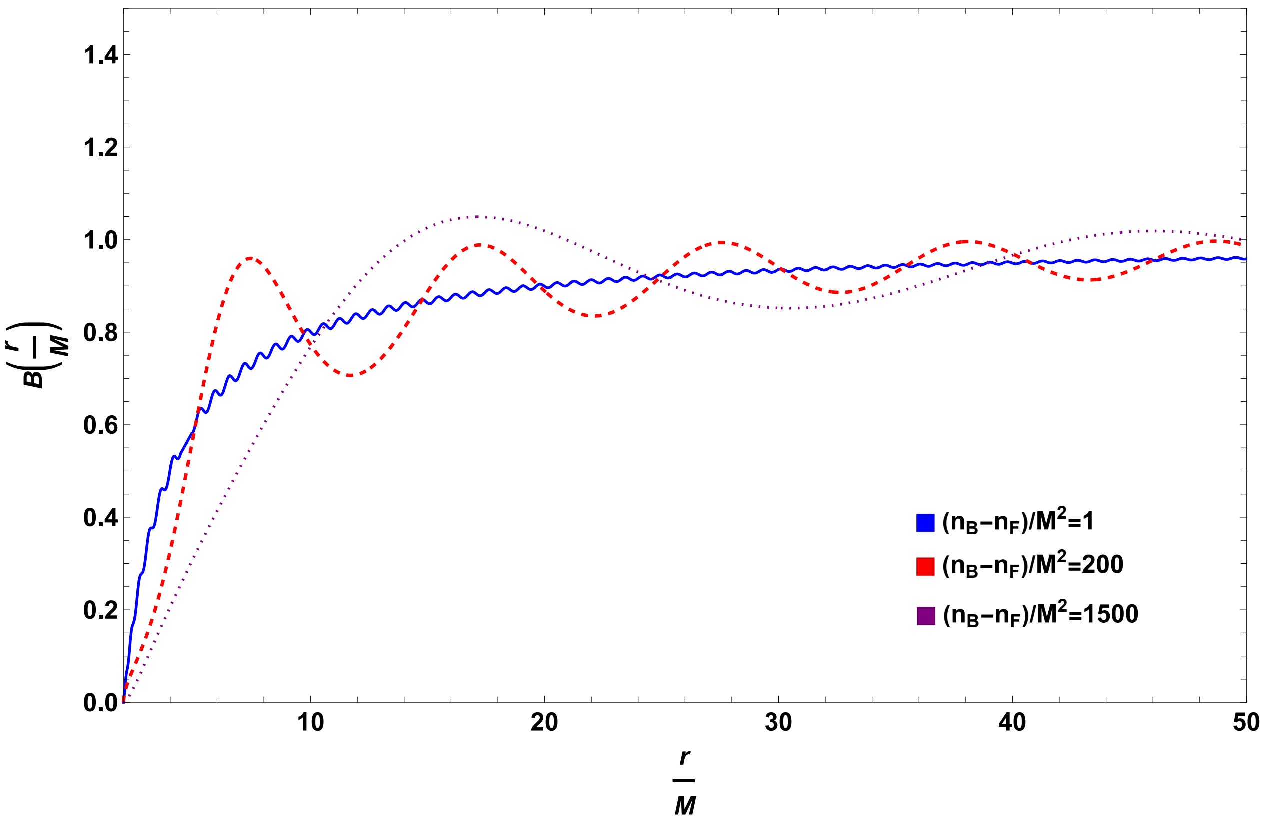


- The metric potentials $A(r)$ and $B(r)$ approach to the flat spacetime limit of $A(r) = B(r) = 1$ at large r for $n_B - n_F < 0$. The approach is exponential and different $n_B - n_F$ values are hard to distinguish observationally.

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

ASYMPTOTICALLY-FLAT SYMMERGENT BLACK HOLE





- The metric potentials $A(r)$ and $B(r)$ approach to the flat spacetime limit of $A(r) = B(r) = 1$ at large r for $n_B - n_F > 0$. The approach is power-law/ periodic and different $n_B - n_F$ values are easier to distinguish observationally.

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

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE

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

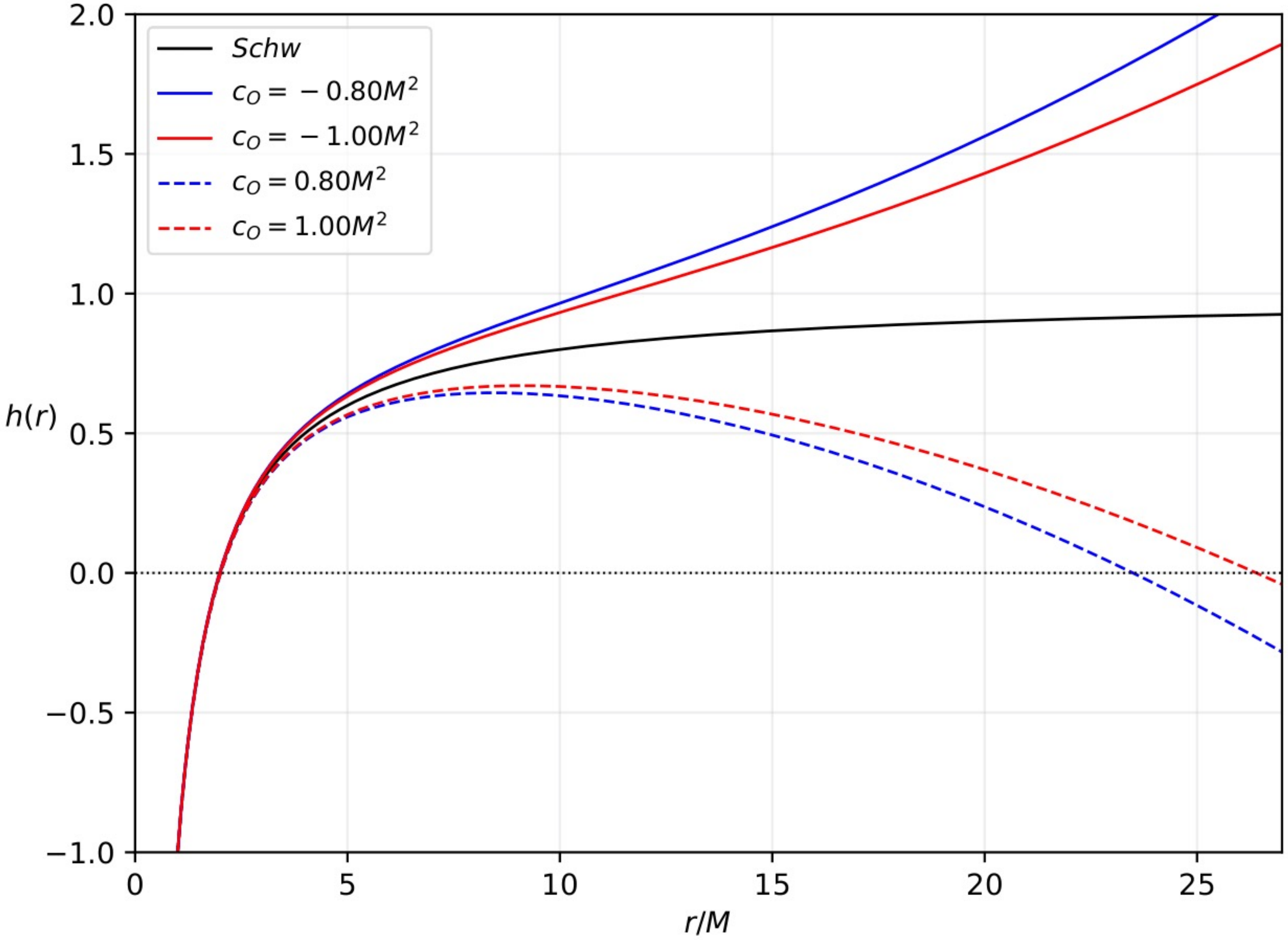
loop-induced quadratic curvature constant:
$c_O = \frac{n_B - n_F}{248\pi^2}$

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

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

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

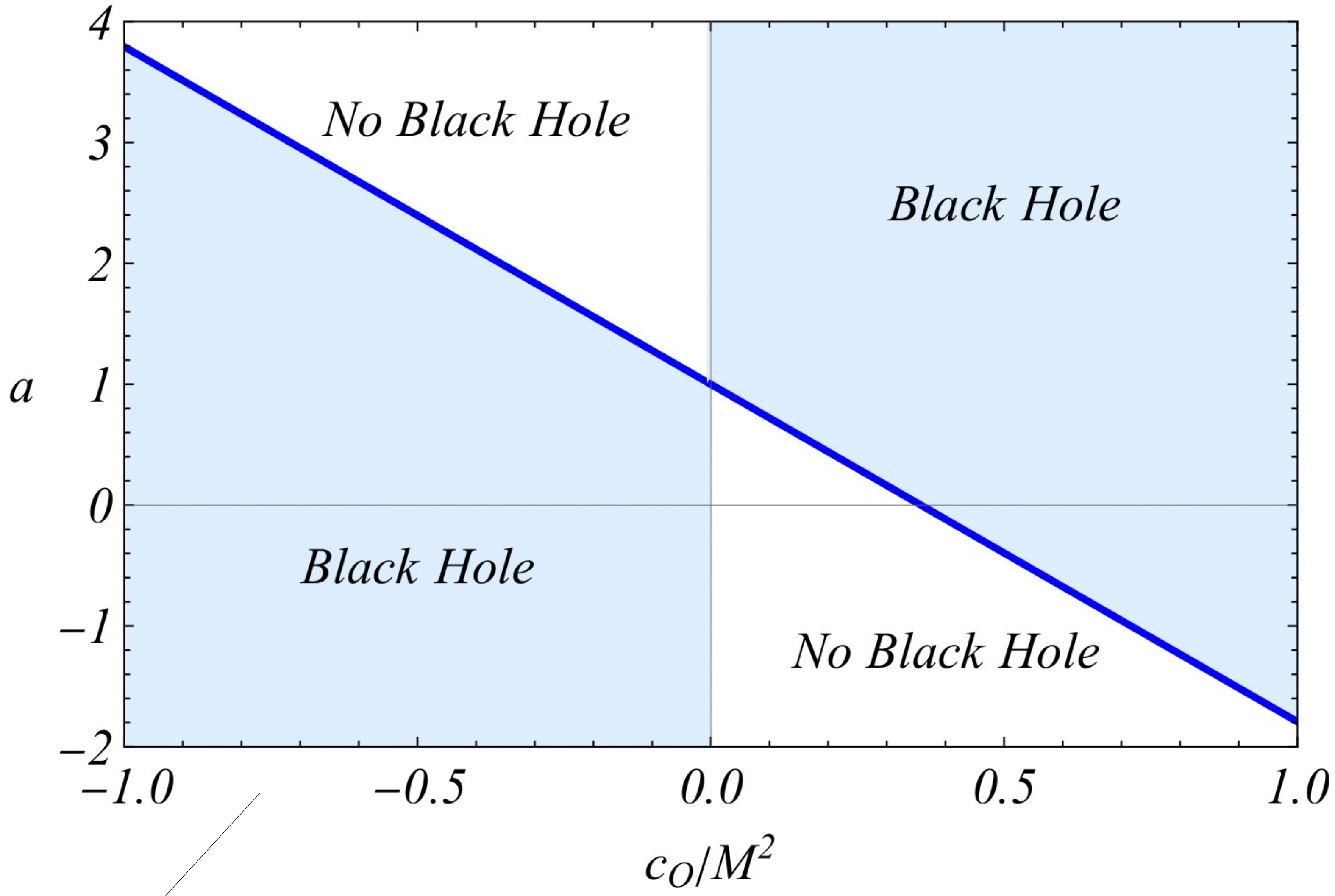
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



(J. Raimbayev et al 2206.06599 (Annals of Physics)

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE

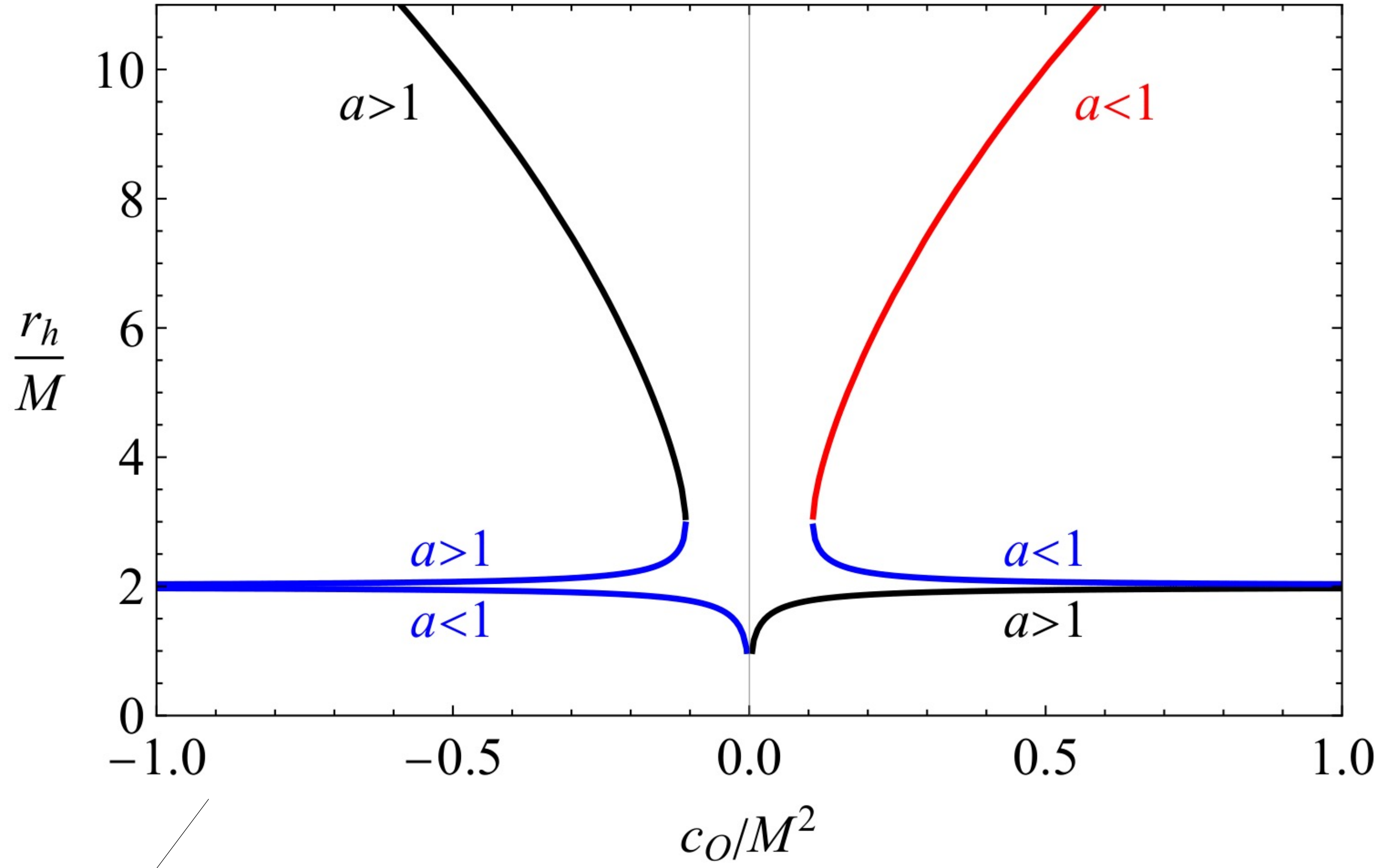


the regions in $a - c_O$ plane admitting BH solutions

(J. Raimbayev et al 2206.06599 (Annals of Physics))

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



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

(J. Raimbayev et al 2206.06599 (Annals of Physics)

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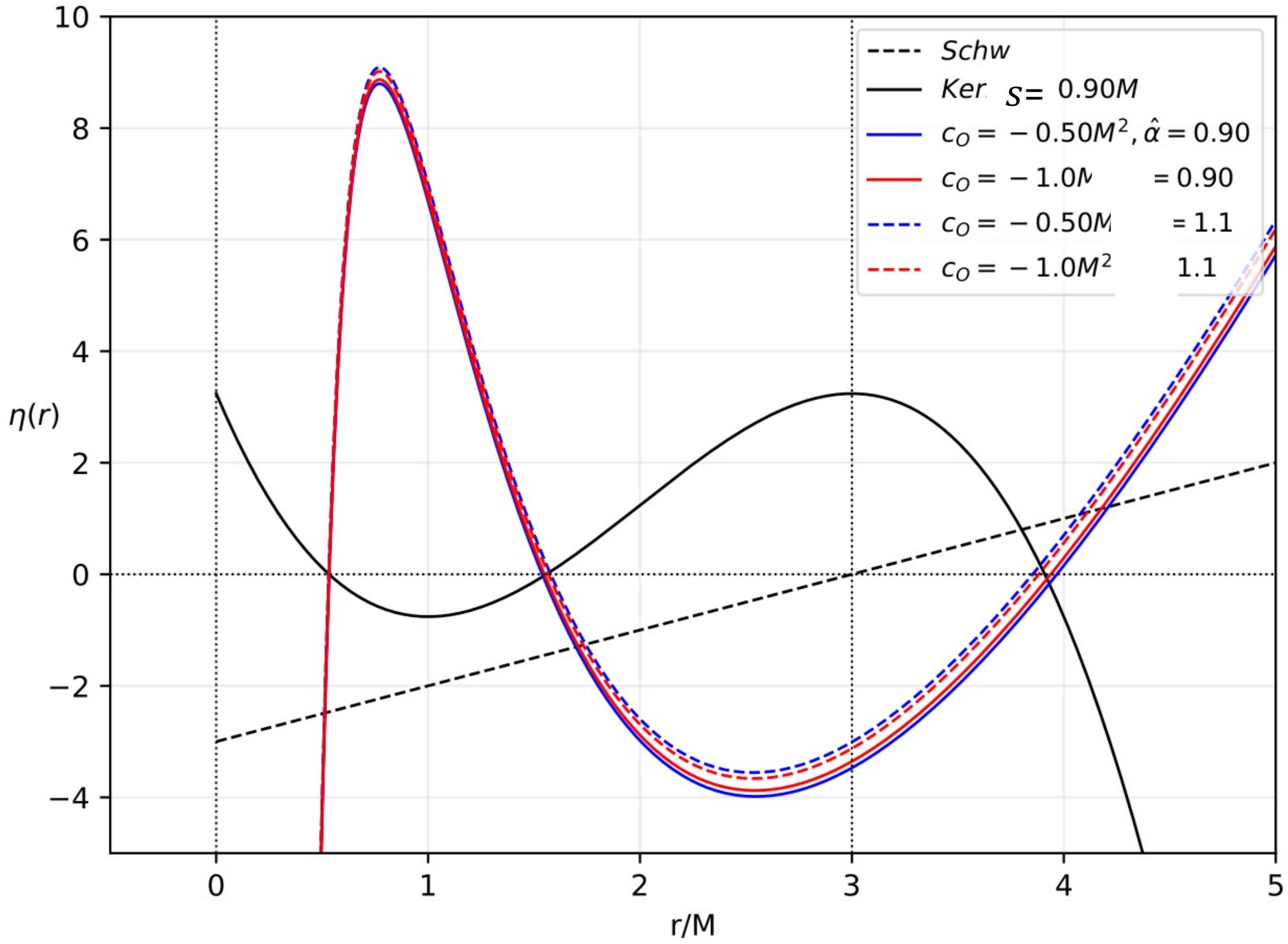
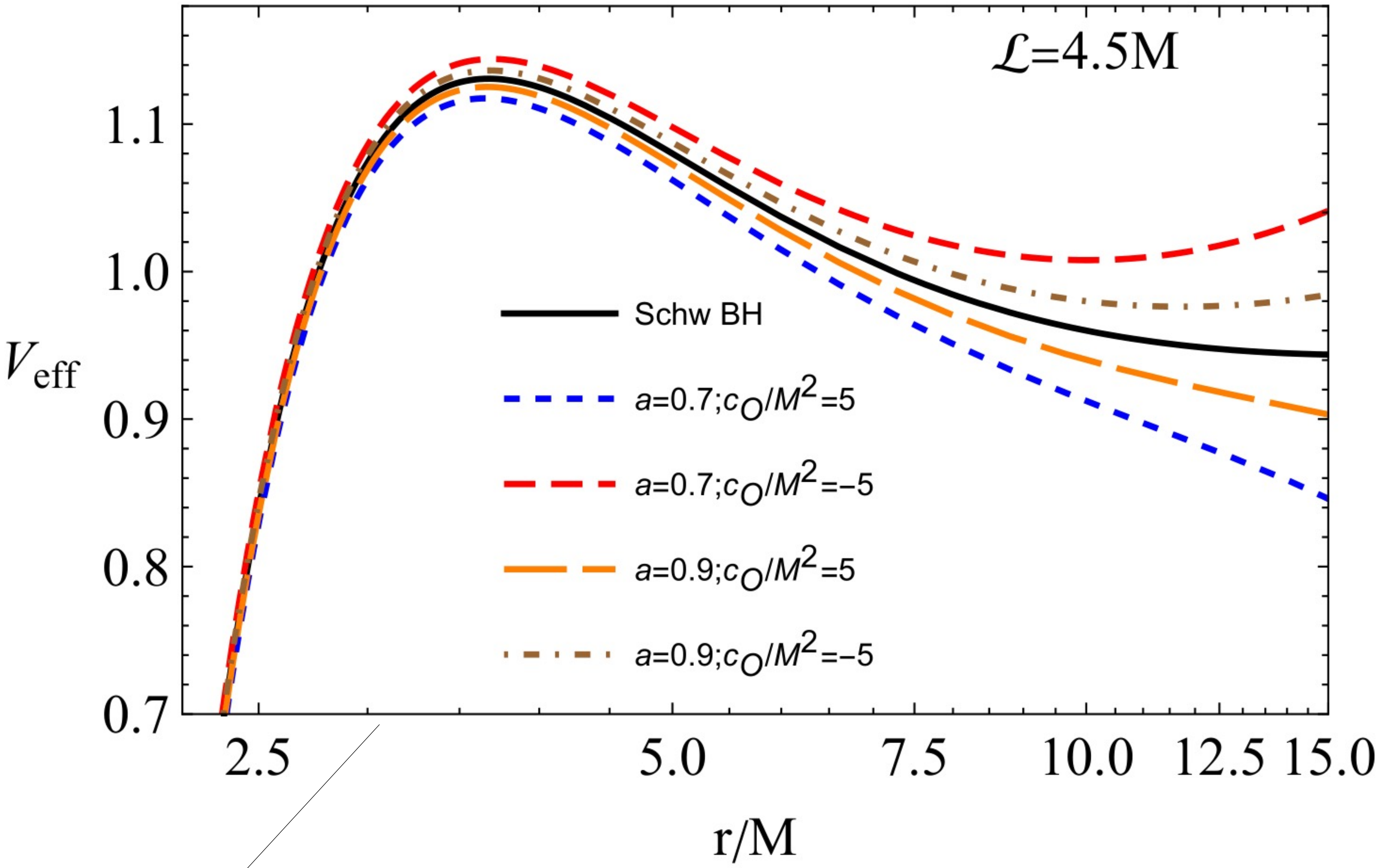


Photon sphere radius for a rotating symmergent black hole of angular momentum number s)

(R. Pantig, A. Ögün, DD, Eur. Phys. J. C 83 (2023) 250)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



effective potential for $\ell = 4.5\ M$

(J. Raimbayev et al 2206.06599 (Annals of Physics)

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

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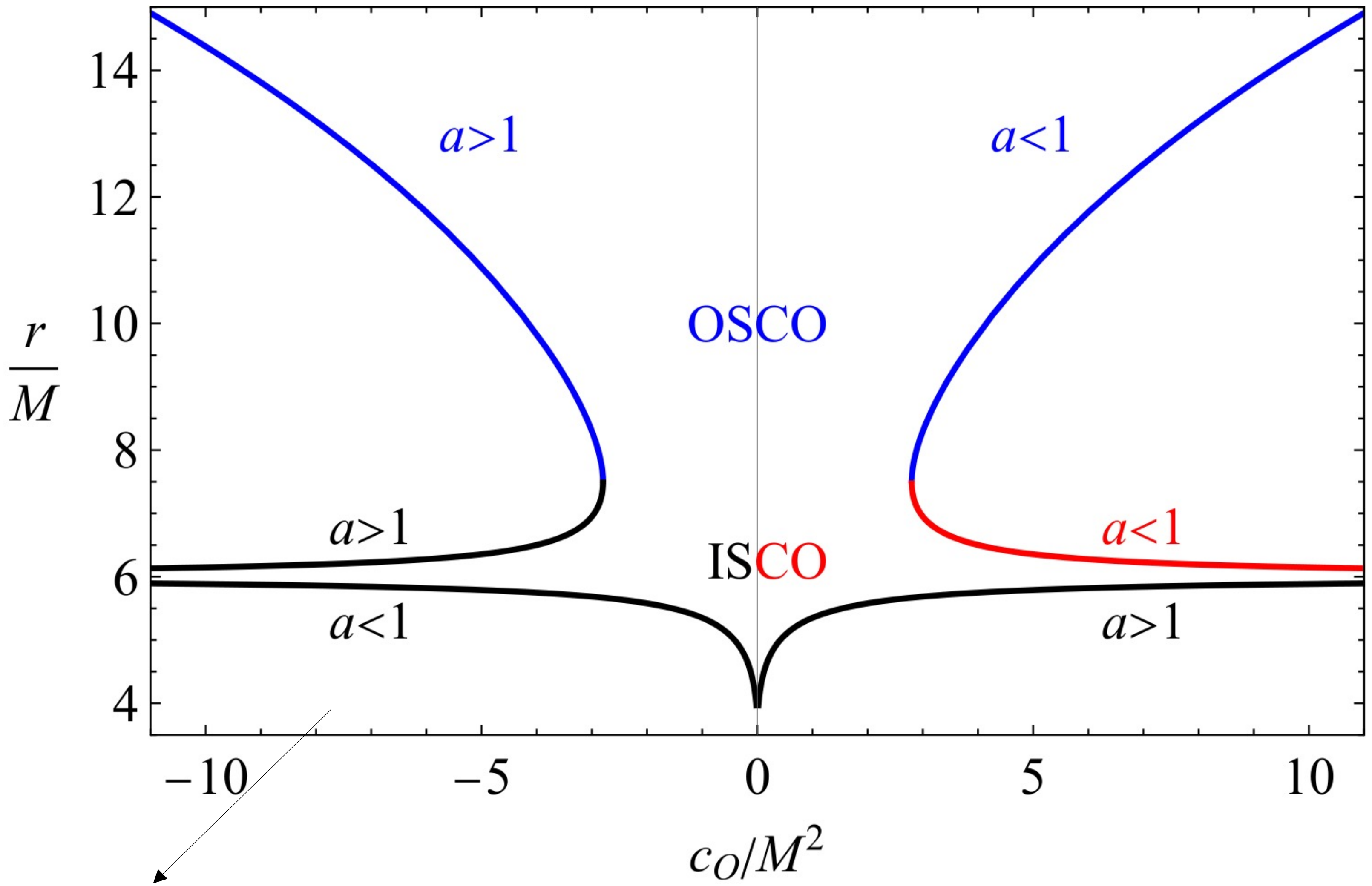
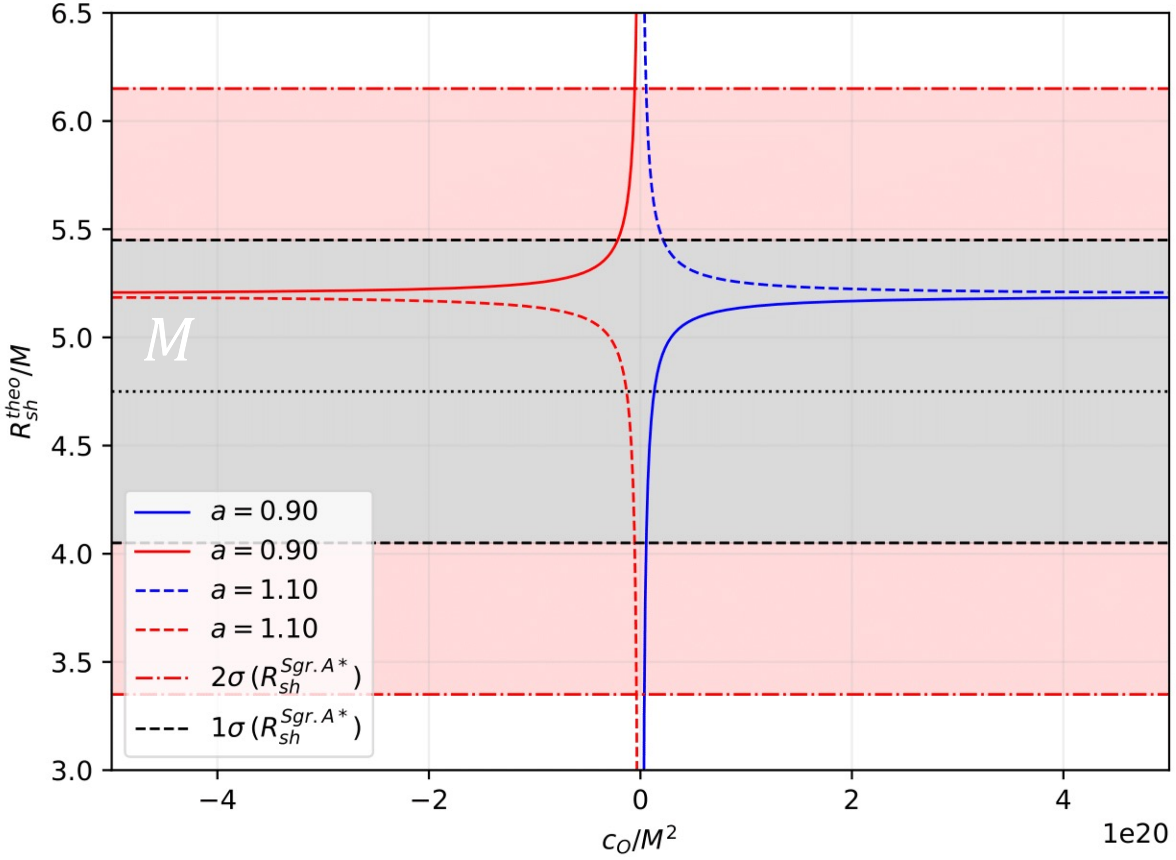


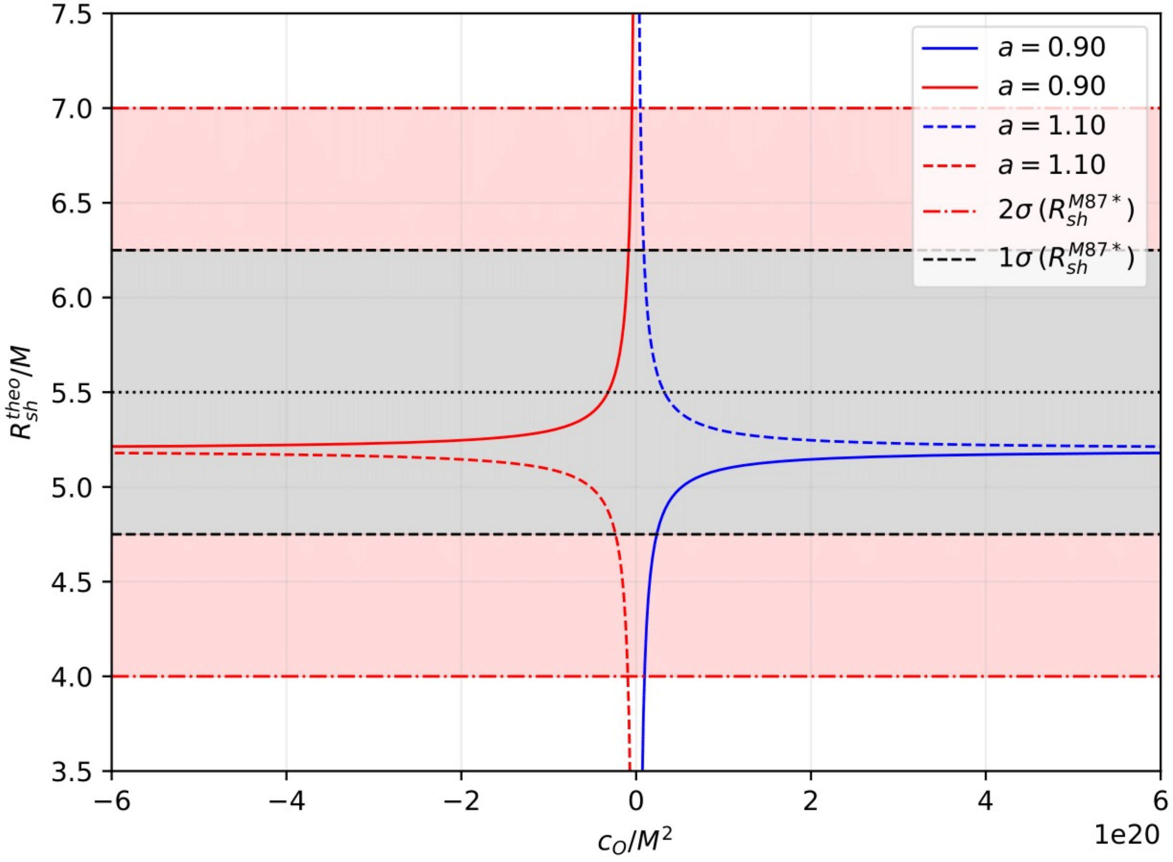
innermost (ISCO) and outermost (OSCO) stable circular orbits

(J. Raimbayev et al 2206.06599 (Annals of Physics))

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



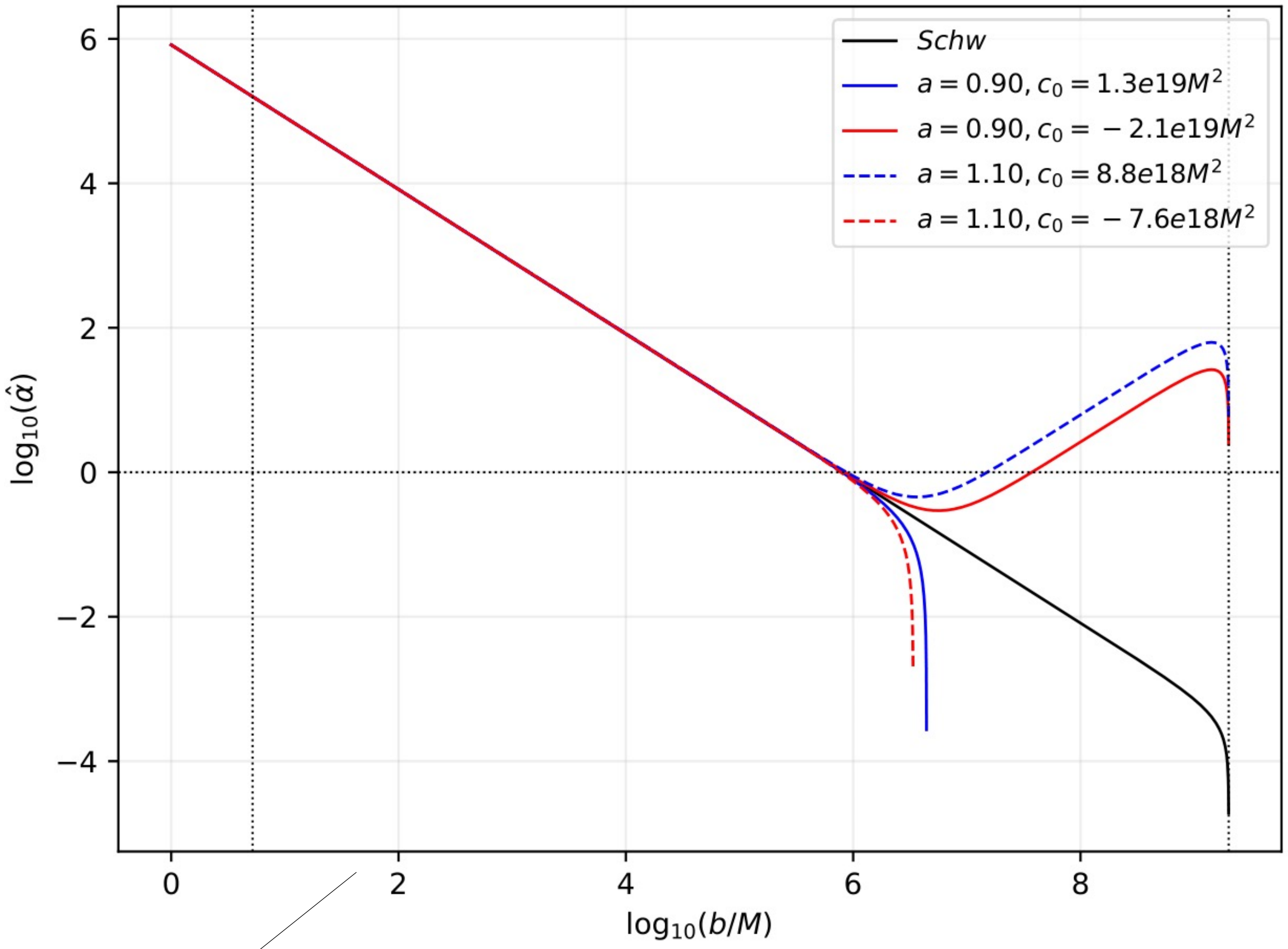


bounds on model parameters form shadow radii of Sgr.A* (left) and M87* (right)

(J. Raimbayev et al 2206.06599 (Annals of Physics)

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)

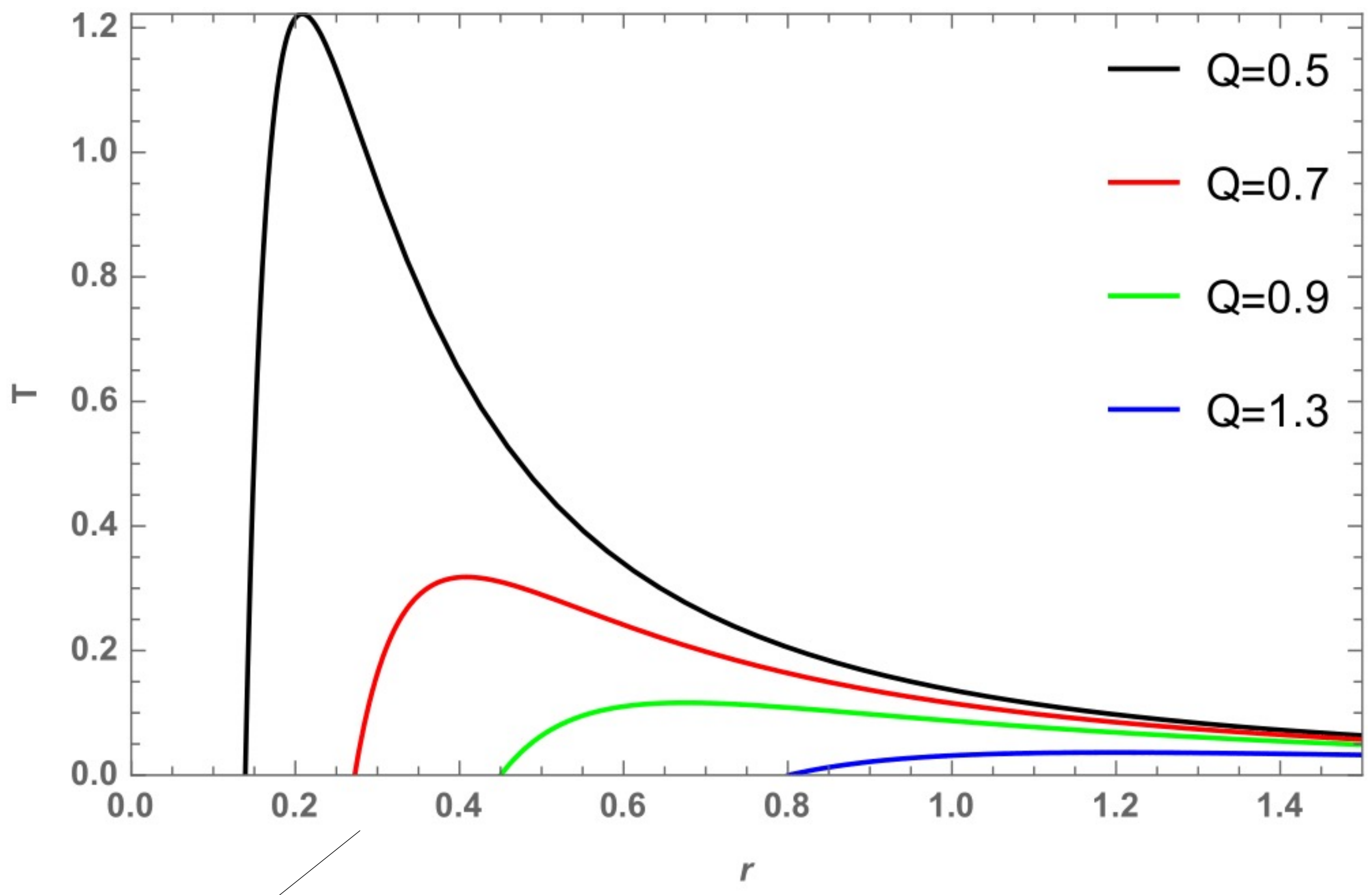
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



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

(J. Raimbayev et al 2206.06599 (Annals of Physics)

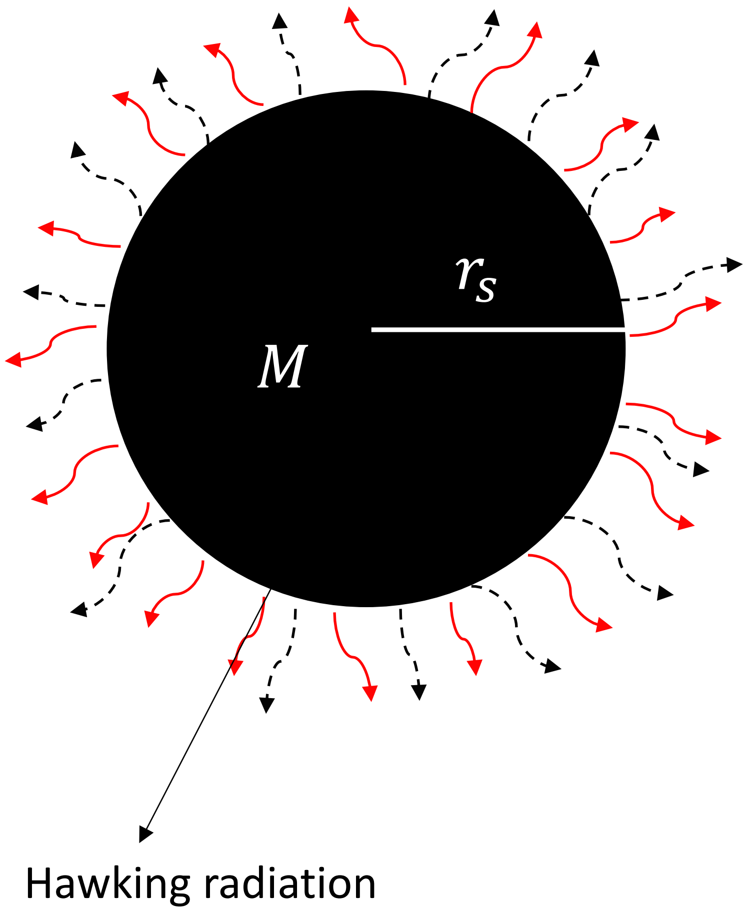
(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)



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

(B. Puliçe, R. Pantig, A. Ögün, DD, under review CQG)

SYMMERGENT BLACK HOLE

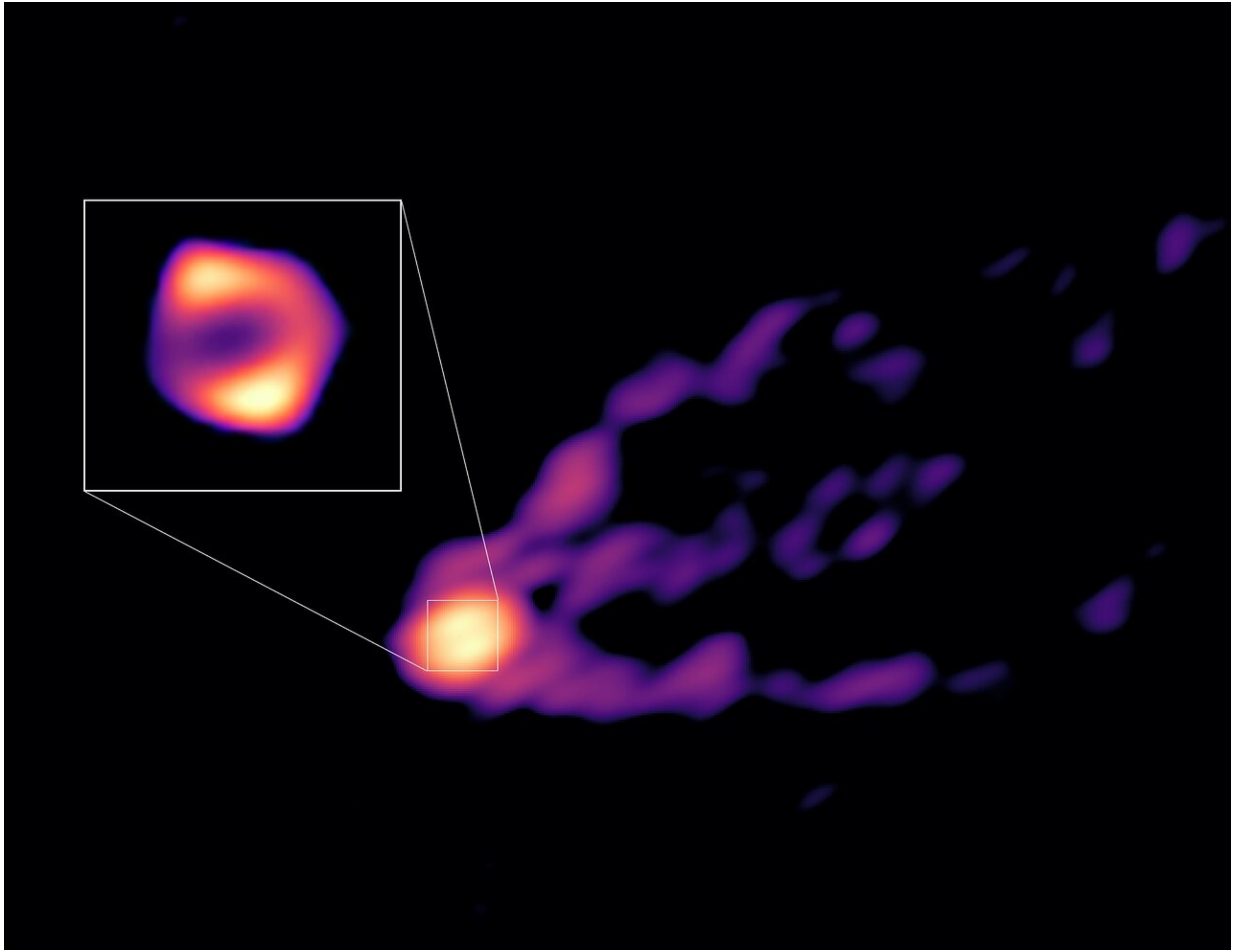


Hawking radiation from photon, electron etc. :

Hawking radiation from new dark fields:

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

THANK YOU !



Accretion Disk around and Shadow of M87*

(R S Lu et al 2023 Nature 616, 686–690)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE

Sgr. A*	observed R_{sh}	1σ		2σ	
dS type	mean	lower	upper	lower	upper
$c_0 > 0, a = 0.90$	1.3x10[19]	5.6x10[18]	-	3.8x10[18]	-
$c_0 < 0, a = 1.10$	-1.3x10[19]	-5.6x10[18]	-	-3.8x10[18]	-
AdS type	mean	lower	upper	lower	upper
$c_0 > 0, a = 1.10$	-	-	2.1x10[19]	-	5.4x10[18]
$c_0 < 0, a = 0.90$	-	-	-2.1x10[19]	-	-5.4x10[18]
M87*	observed R_{sh}	1σ		2σ	
dS type	mean	lower	upper	lower	upper
$c_0 > 0, a = 0.90$	-	2.4x10[19]	-	9.5x10[18]	-
$c_0 < 0, a = 1.10$	-	-2.4x10[19]	-	-9.5x10[18]	-
AdS type	mean	lower	upper	lower	upper
$c_0 > 0, a = 1.10$	3.2x10[19]	-	8.7x10[18]	-	4.8x10[18]
$c_0 < 0, a = 0.90$	-3.2x10[19]	-	-8.7x10[18]	-	-4.8x10[18]

bounds on model parameters form
shadow radii of M87* and Sgr.A*

(J. Raimbayev et al 2206.06599 (Annals of Physics)

(I. Çimdiker, A. Övgün, DD, Phys.Dark Univ. 34 (2021) 100900)