Symmergent Gravity Black Holes with Observational Constraints

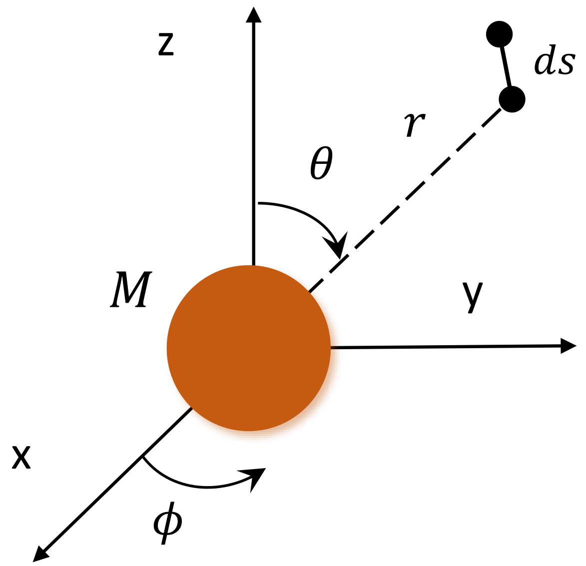
Durmuş Ali Demir

Sabancı Üniversitesi

Beyazıt YEAF Çalıştayı

İstanbul Üniversitesi – 03 Haziran 2023

GRAVITY: NEWTON'S VIEW



- A body of mass M creates the gravitational potential:

$$V(r) = -\frac{GM}{r}$$

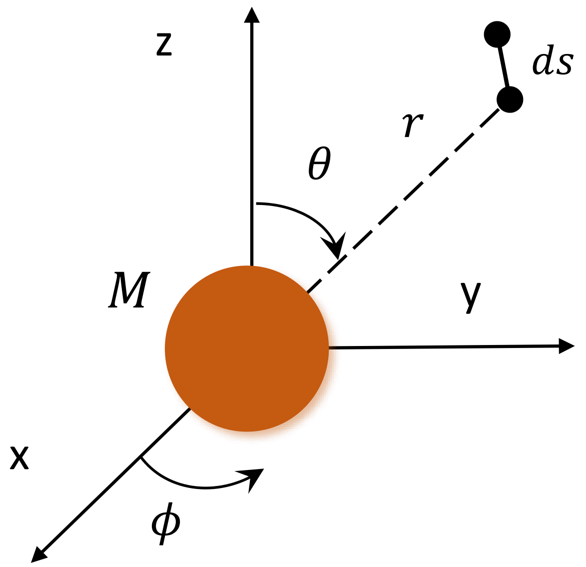
- Spacetime is flat:

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

- Gravity is a force like electricity.

- Newtonian gravity is not able to account for the perihelion advancement in Mercury's orbit.

GRAVITY: EINSTEIN'S VIEW



- Escape speed from a body of mass M:

$$\frac{v_{es}^2}{c^2} = \frac{2GM}{c^2 r} \equiv \frac{r_s}{r} \Longrightarrow r_s = \frac{2GM}{c^2}$$

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

- Spacetime is curved:

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

- Gravity is curving of spacetime.

- Einstein's approach is able to account for perihelion advancement in Mercury's orbit.

EINSTEIN'S GRAVITY

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:

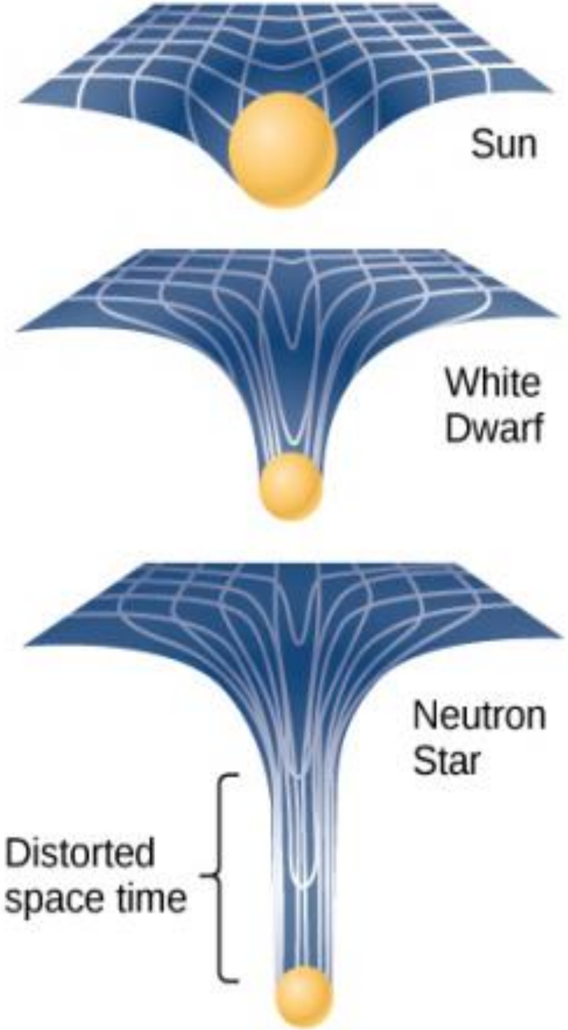
$$(\text{Riemann curvature})^2 = \frac{12\, r_s^2}{r^6}$$

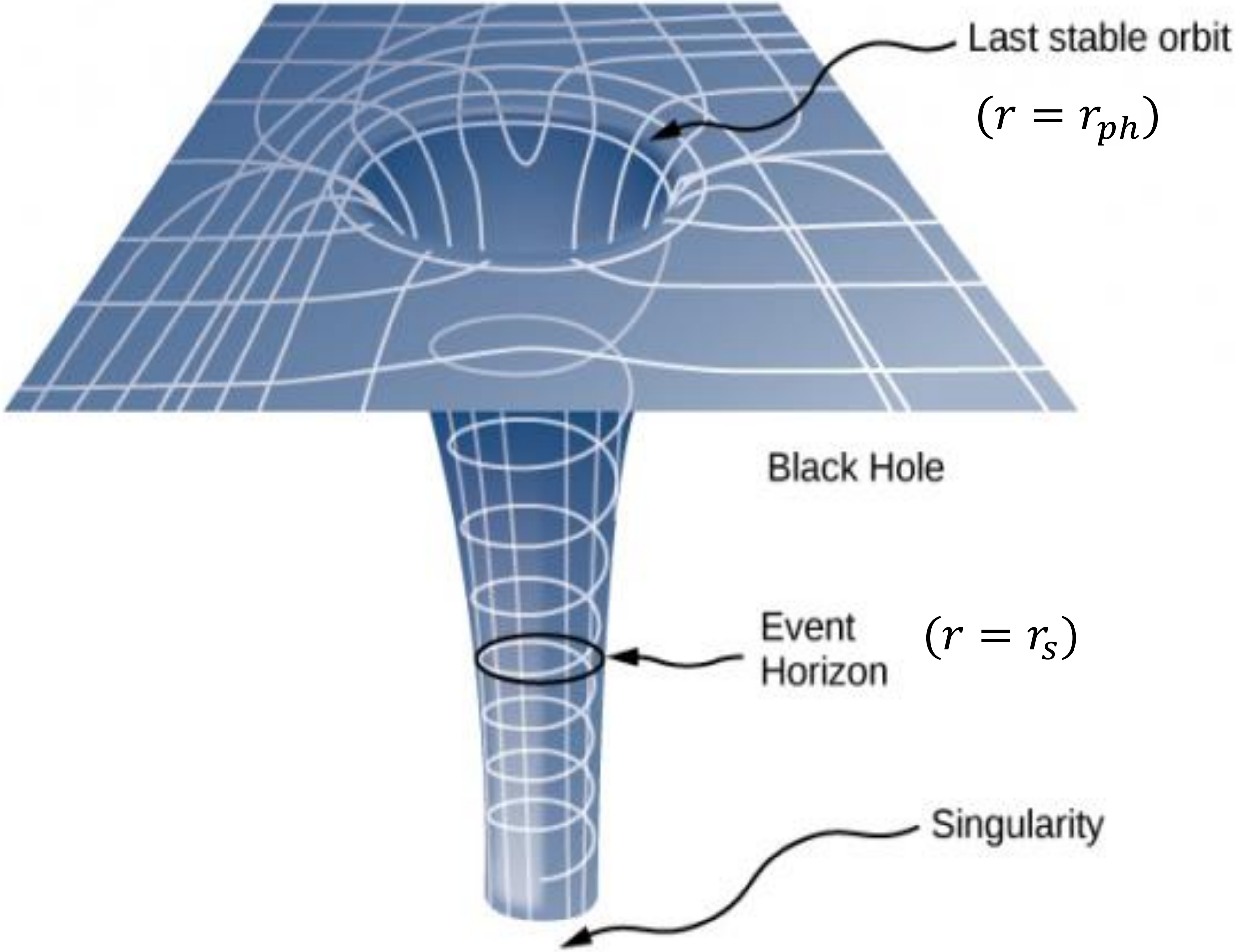
BLACK HOLE

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

$v_{es} > c$ or $r < r_s$

a black hole forms.

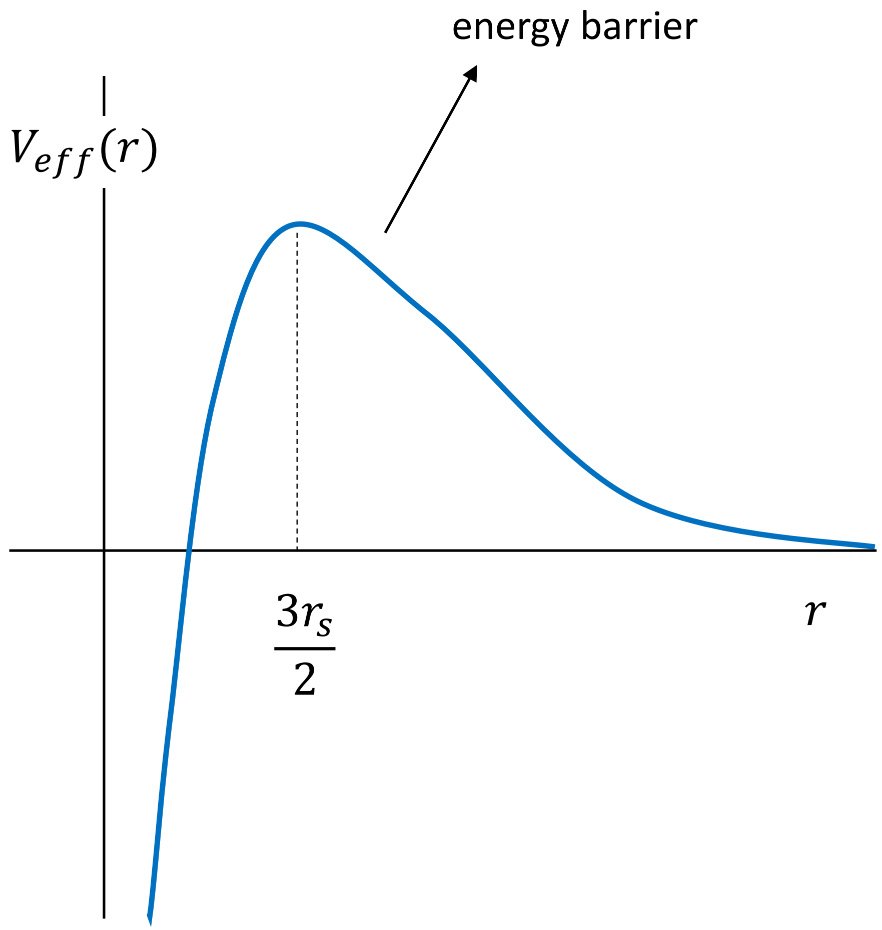




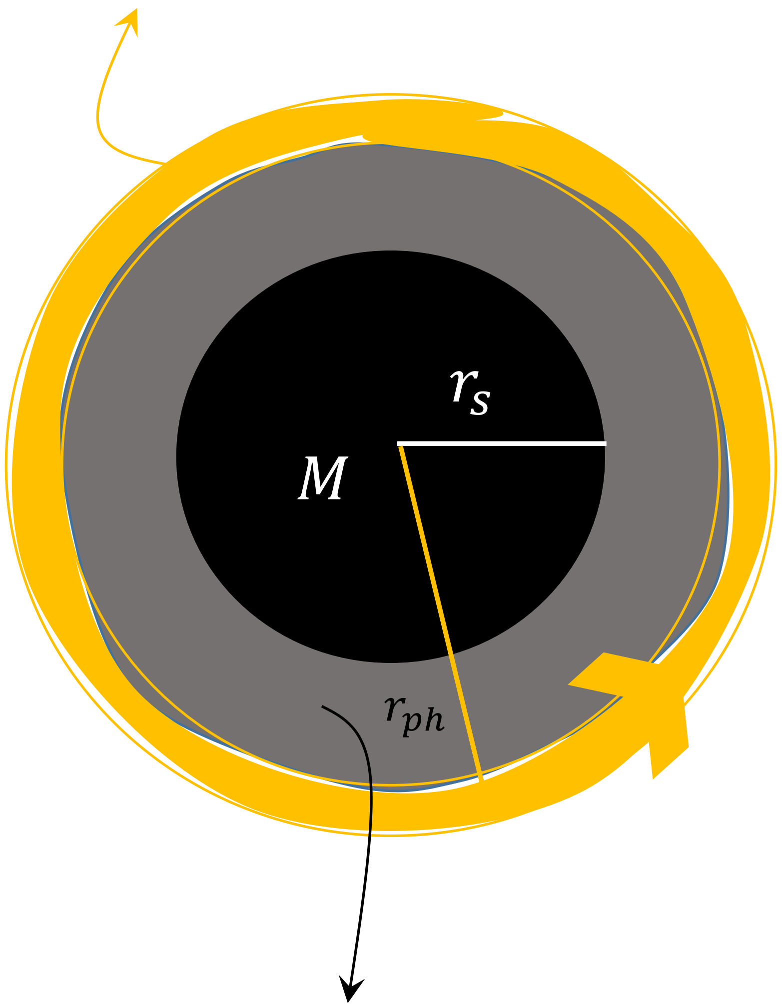
(nasa.gov)

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: $\dot{t} = \frac{E}{1-\frac{r_s}{r}}$
- Ang. Mom. is conserved: $\dot{\phi} = \frac{\ell}{r^2}$
- Photon is a unit-mass particle: $\frac{\dot{r}^2}{2} + \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{E}{2}$
- $V_{eff}(r) = \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\ell^2}{2r^2} - \frac{\ell r_s}{2r^3}$



PHOTON SPHERE



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

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

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

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

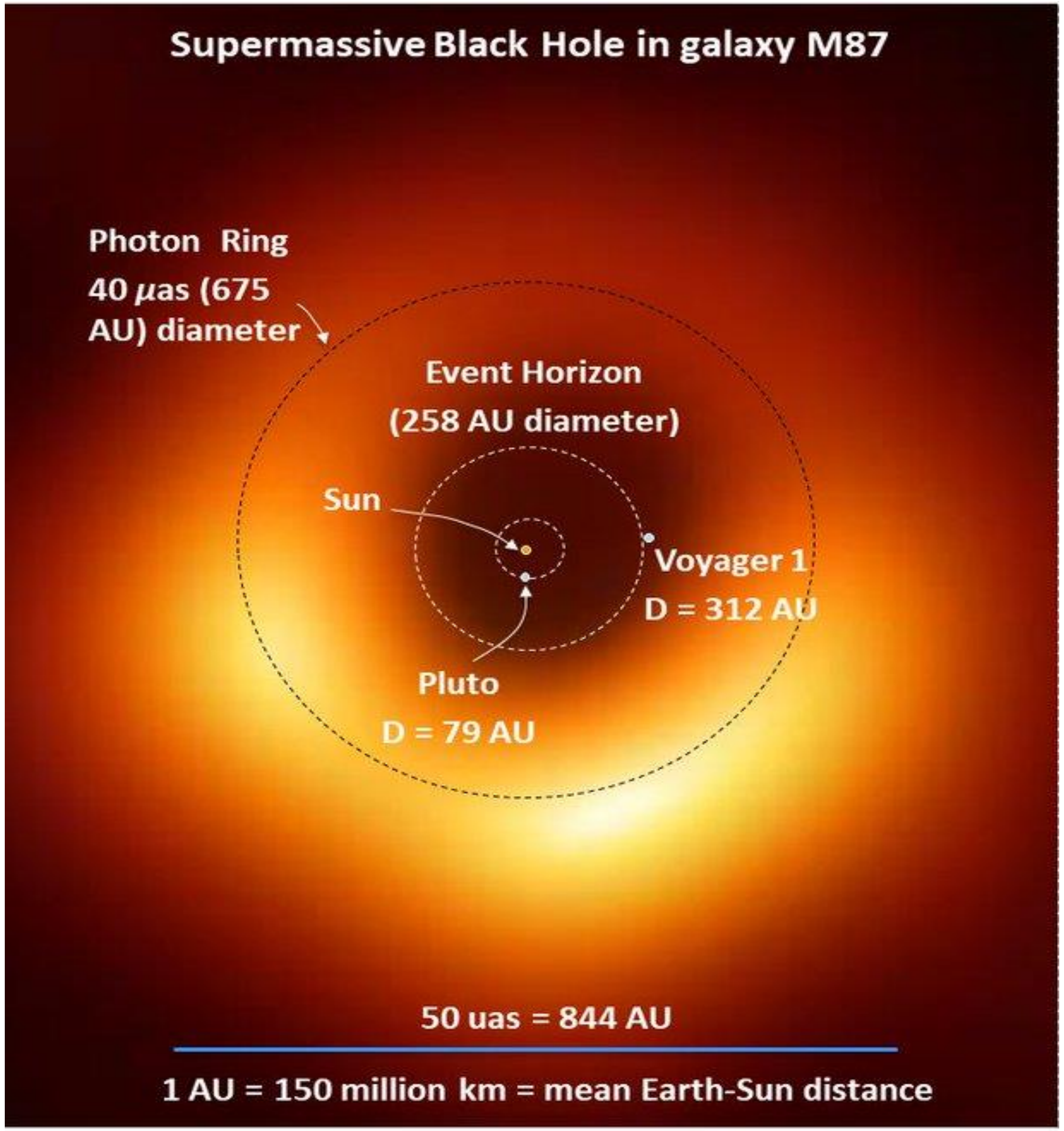
- photon radius $r = r_{ph}$ is the last stable orbit.

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

PHOTON SPHERE

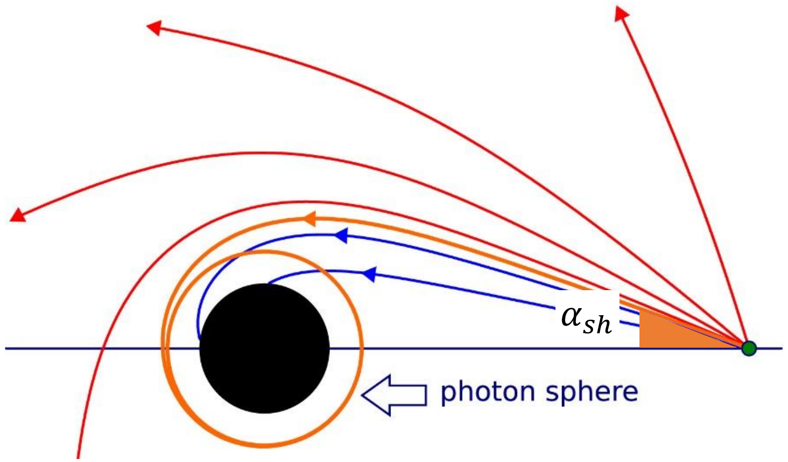
Mass (Solar Masses)	6.54 billion
Event Horizon diameter (AU)	258
Distance (Light Years)	55 million

(galaxy Messier 87 in the constellation Virgo)



(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:

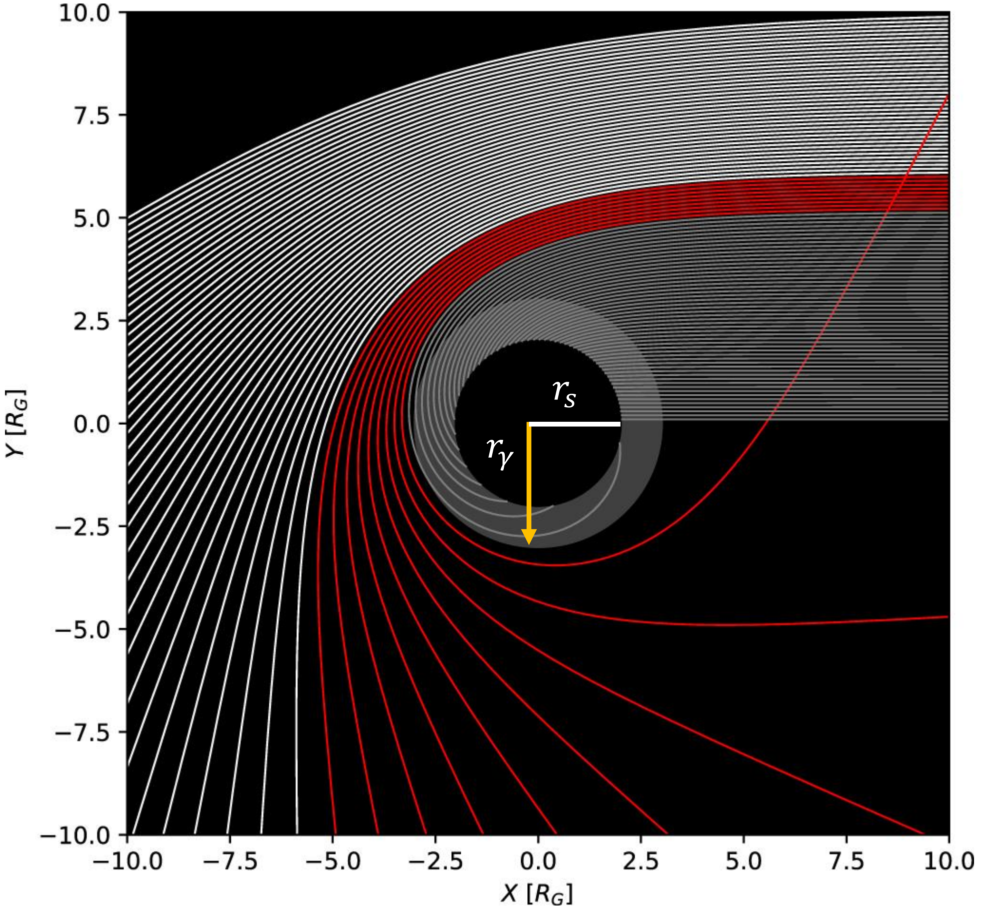
$$(ds)^2 = -A(r)(c\,dt)^2 + B(r)(dr)^2 + D(r)\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$$

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

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

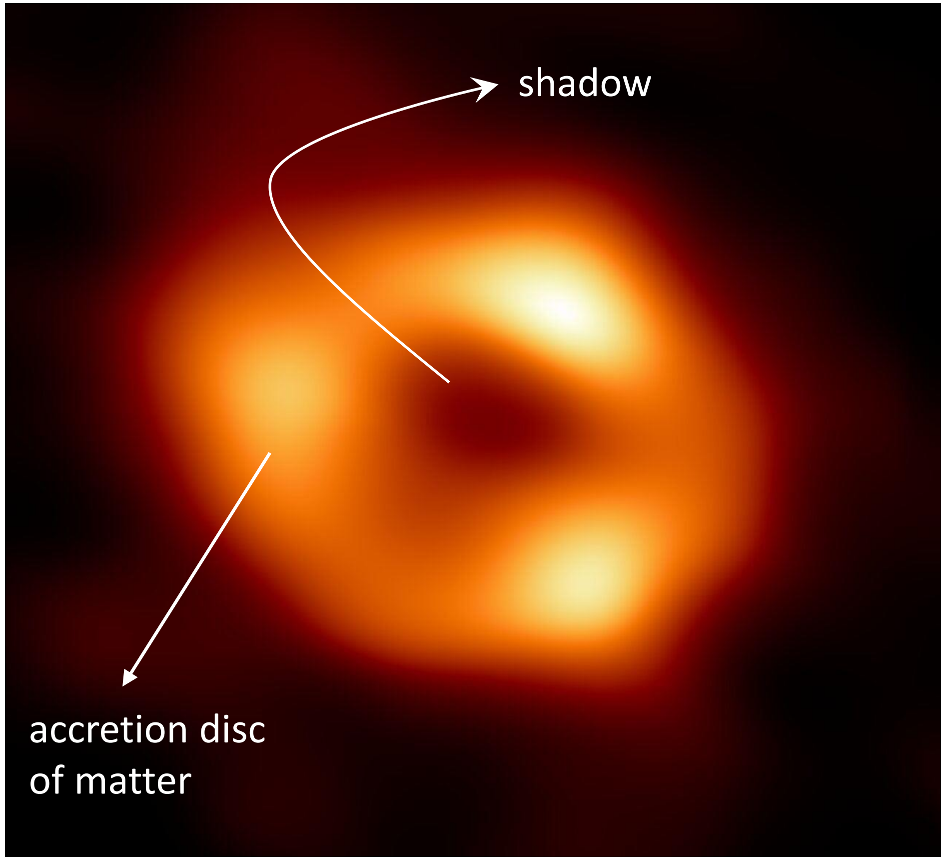
Distant observer: $\frac{27}{4}\frac{r_s^2}{r_o^2}$

BLACK HOLE SHADOW



Shadow of a black hole

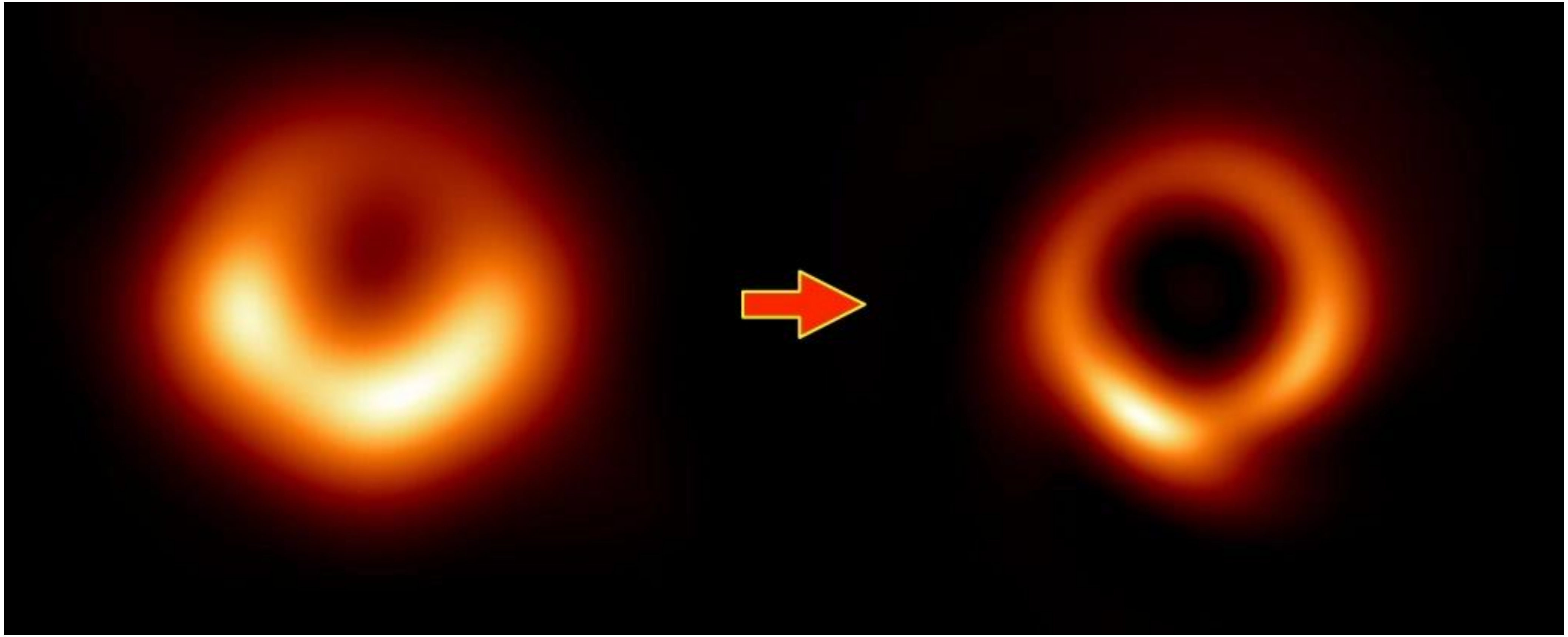
(Thomas Bronzwaer and Heino Falcke 2021 *ApJ* **920** 155)



Shadow of a black hole

(EHT observation of Sgr. A* in 2019)

BLACK HOLE SHADOW



Shadow of M87* (2019)

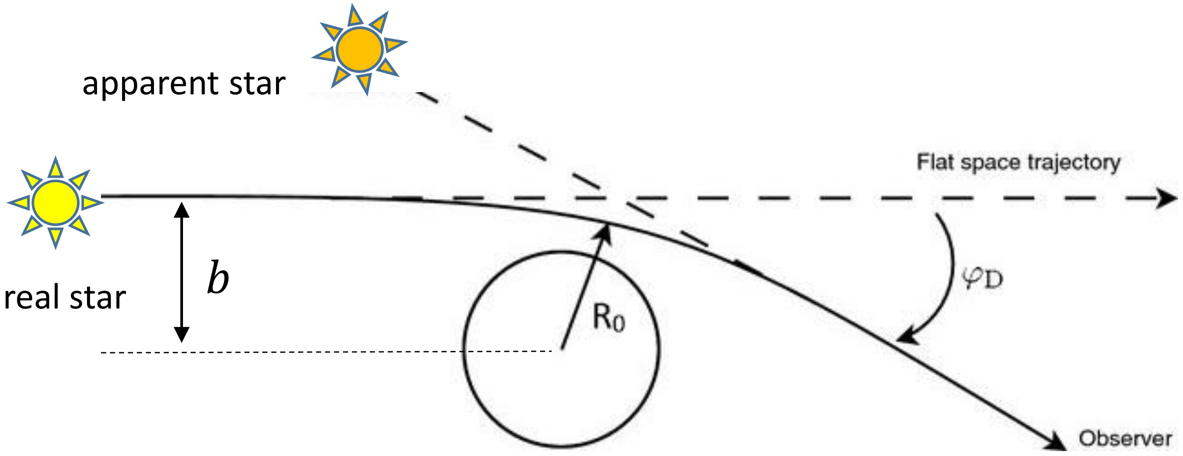
(EHT, 2019)

Shadow of M87* (AI)

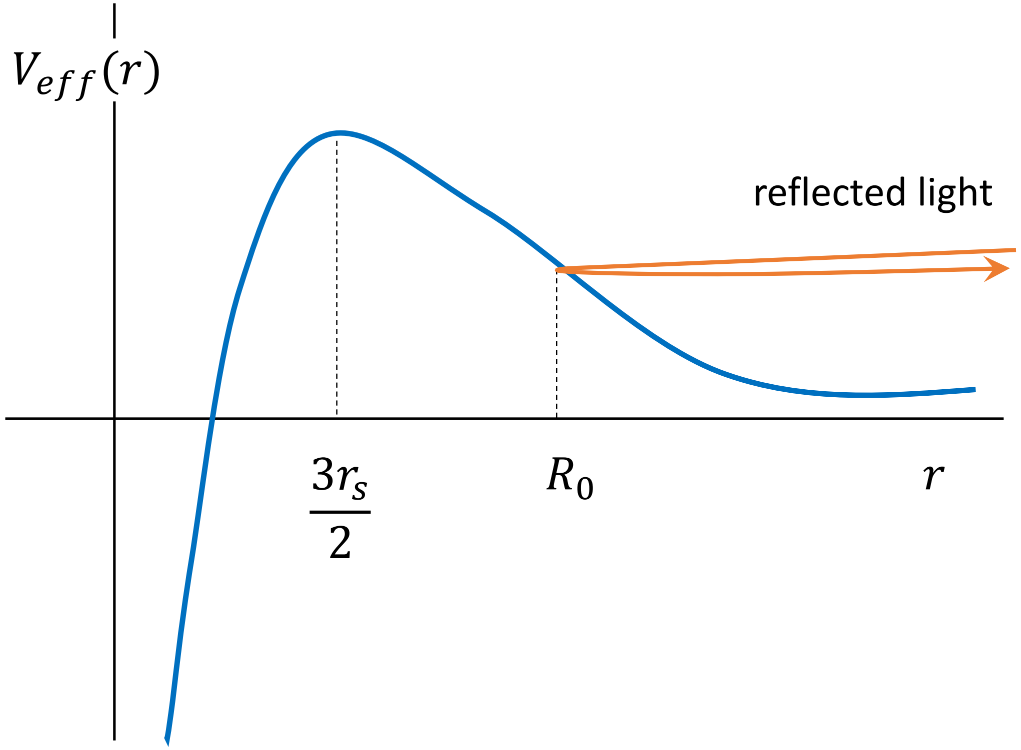
(PRIMO, 2023)

(Lia Medeiros et al 2023 ApJL 947 L7)

LIGHT BENDING BY BLACK HOLE



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

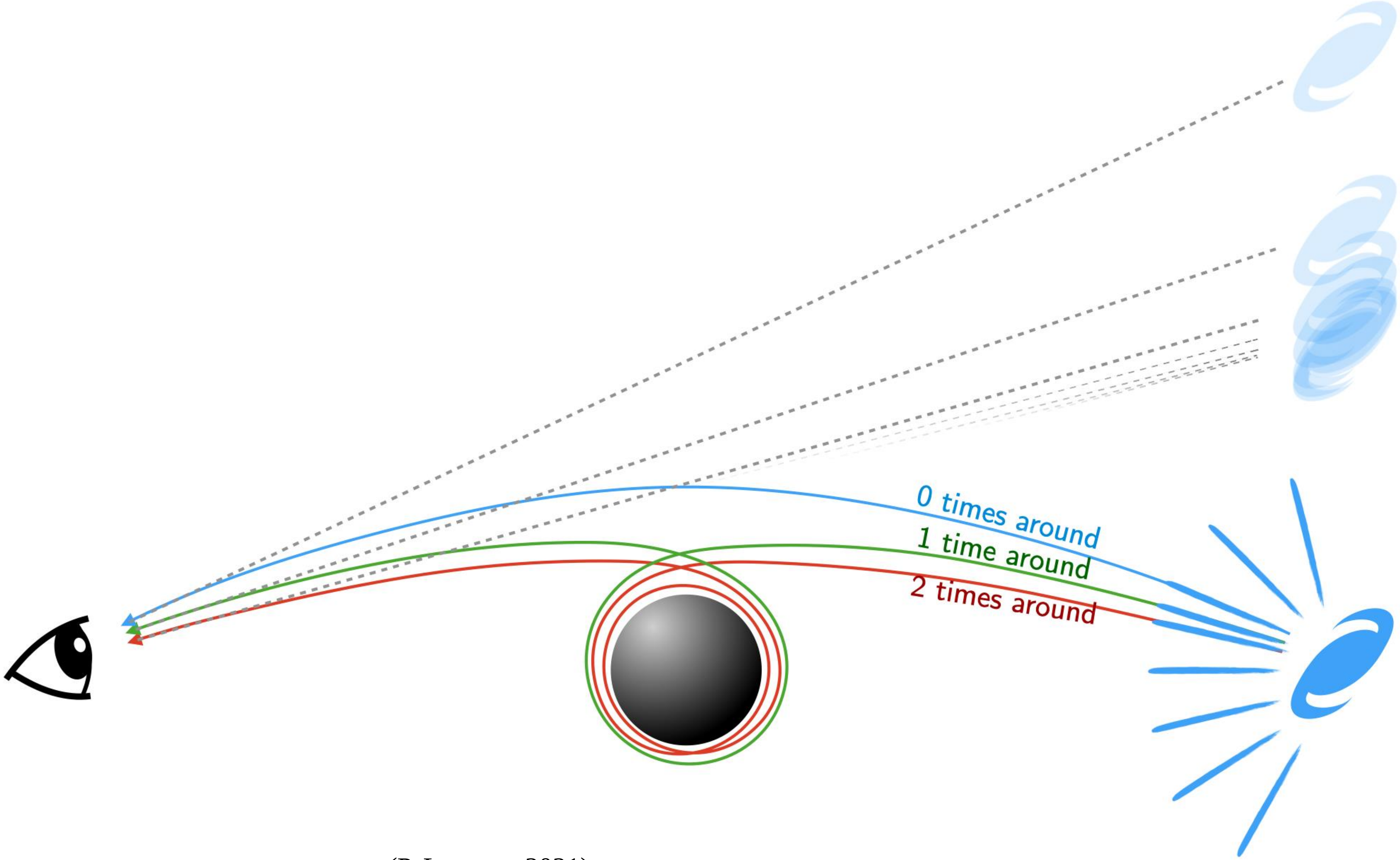


- $\frac{dr}{d\tau} = \sqrt{\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{r_s}{r}\right)}$

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

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

LIGHT BENDING BY BLACK HOLE



(P. Laursen, 2021)

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

QUANTUM TUNNELING AND HAWKING RADIATION

- effective potential seen by massless particle (photon):

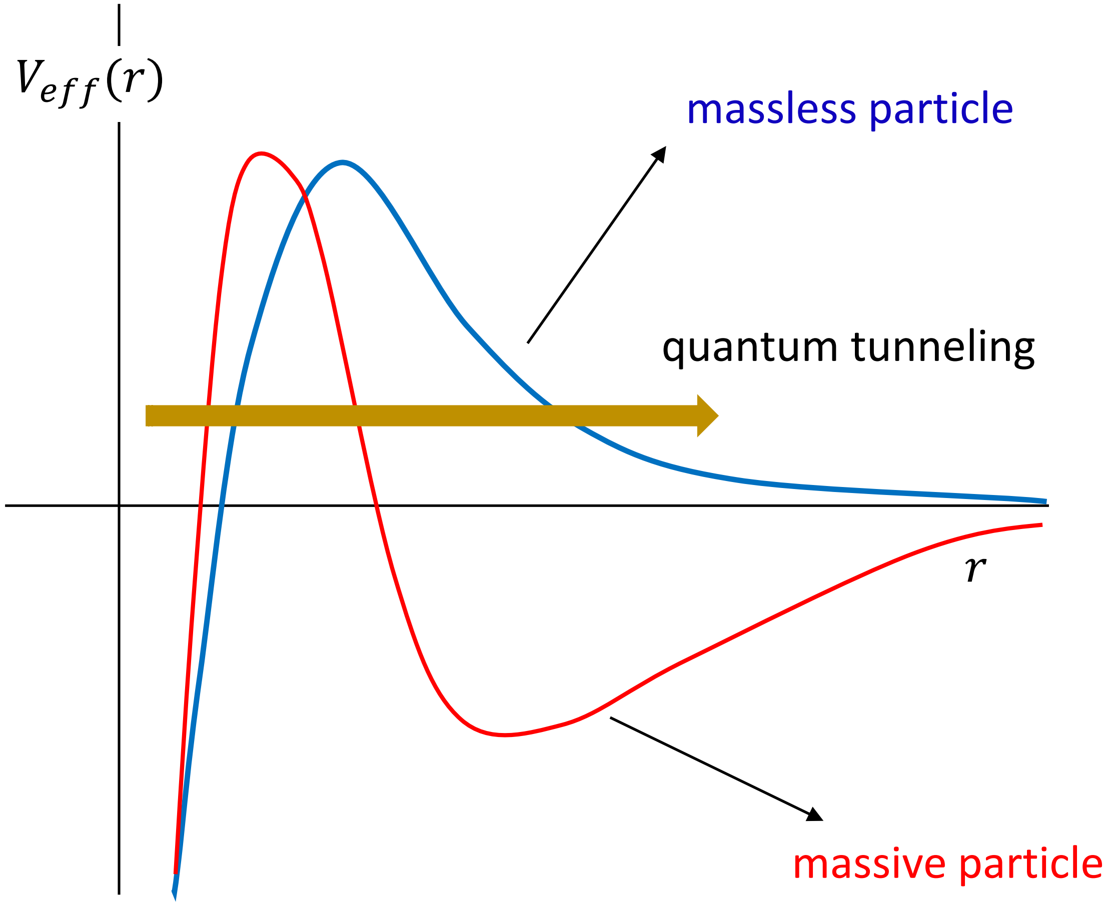
$$V_{eff}(r) = \frac{\ell^2}{2r^2}\left(1 - \frac{r_s}{r}\right) = \frac{\ell^2}{2r^2} - \frac{\ell r_s}{2r^3}$$

- 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:

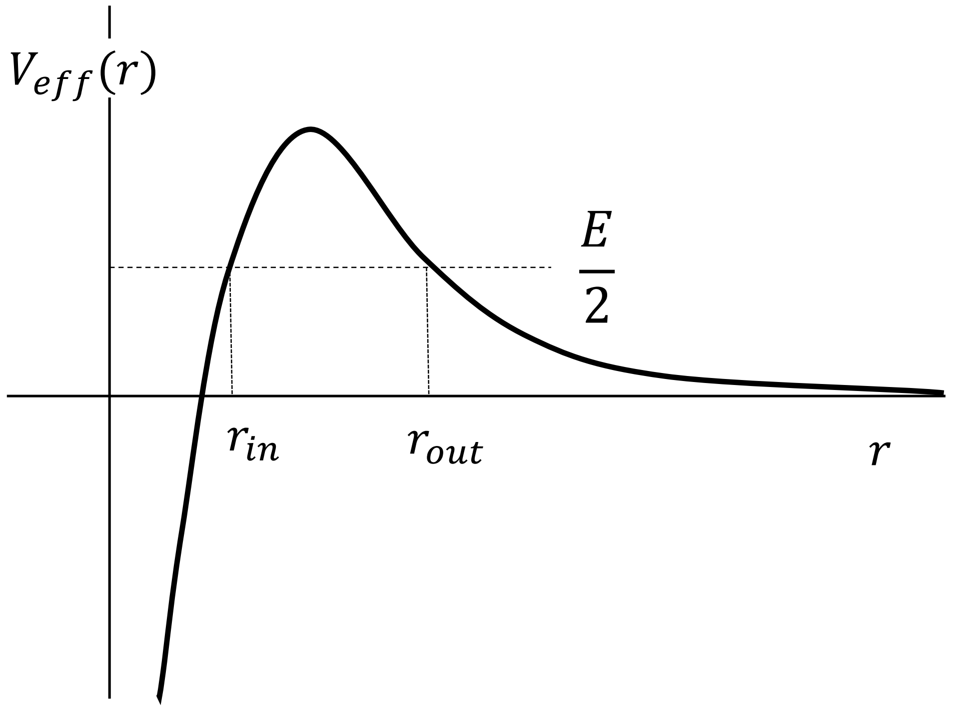
$$\Delta t = \pm \int_{r_{in}}^{r_{out}} \frac{dr}{\sqrt{E - 2\,V_{eff}(r)}} = \pm \int_{r_{in}}^{r_{out}} \frac{dr}{\sqrt{E - \frac{\ell^2}{r^2} + \frac{\ell r_s}{r^3}}} =$$

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

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

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

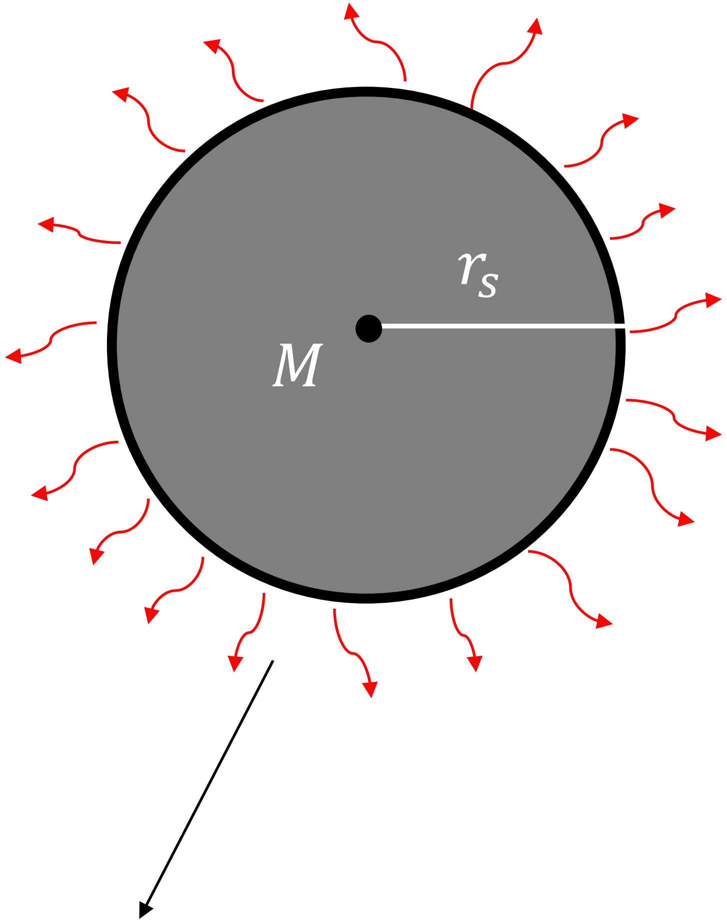
(residue theorem)
($\ell \simeq r_s$)



- Wavefunction: $\psi \propto e^{iE\Delta t} \simeq e^{\pm \pi r_s E}$ → $\rho_{em} \simeq e^{-2\pi r_s E}$, $\rho_{ab} \simeq e^{+2\pi r_s E}$

- Black body spectrum (a rough prediction): $T \simeq \frac{1}{4\pi r_s} \equiv \frac{\hbar c^3}{8\pi k_B G_N M}$ → Hawking temperature

QUANTUM TUNNELING AND HAWKING RADIATION



Hawking radiation

Emitted power (photons only):

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

Evaporation time (photons only):

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

(D. N. Page 1976 PRD 13, 198)

QUANTUM TUNNELING AND HAWKING RADIATION

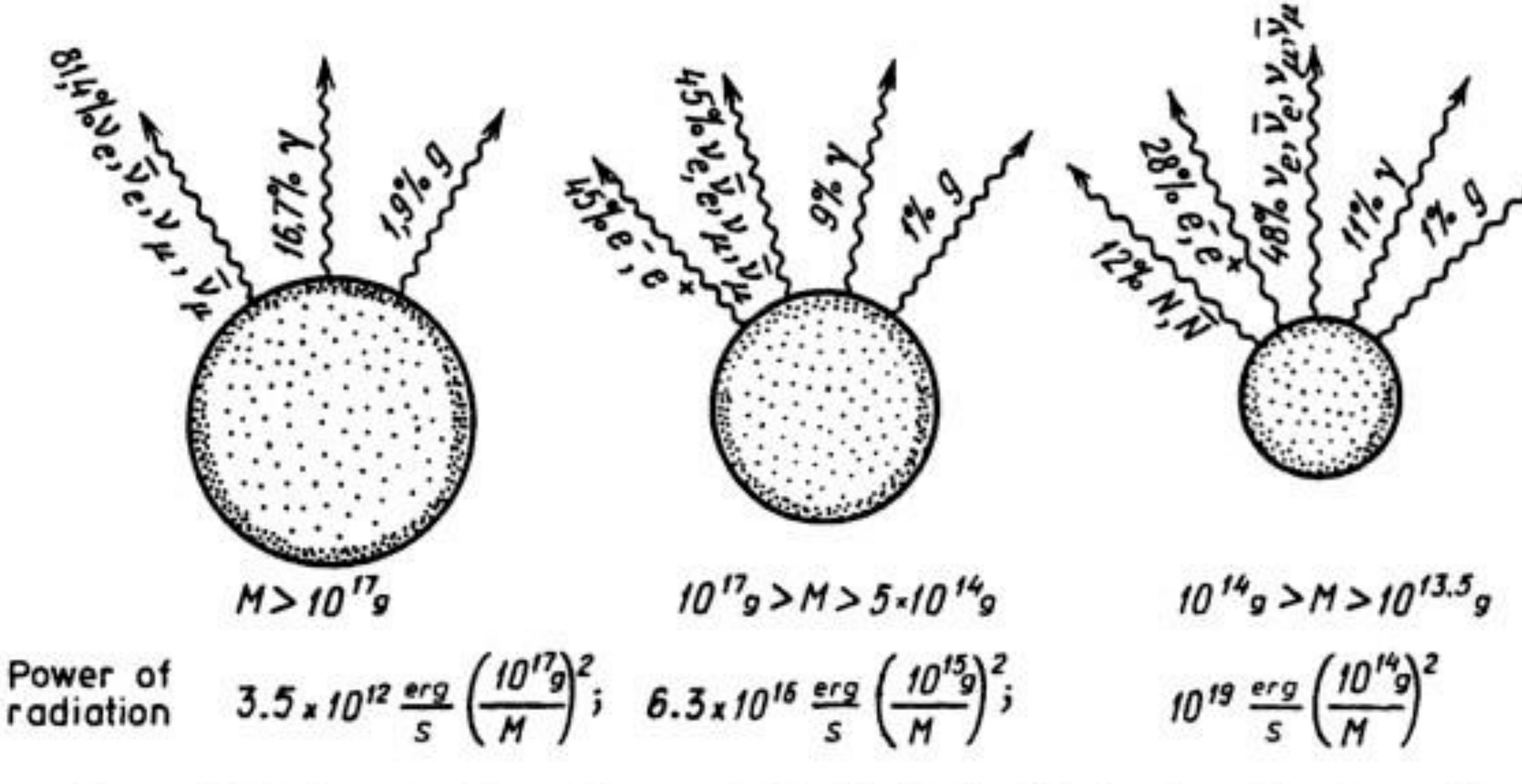


Figure 10.7: Quantum decay of a non-rotating black hole. The fractions of gravitons (g), photons (γ), neutrinos (ν) and other elementary particles are given in percent of the total number of particles emitted by black holes of different masses.

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

SYMMERGENT GRAVITY

Poincare-conserving UV cutoff $M_{\wp}$:

tree-level mass term = $M_{\wp}^2 \mathrm{tr}[V_\mu V^\mu]$

$M_{\wp}^2$ ⟹ "spurion S"
(Poincare-conserving)

$\mathrm{tr}[S^\dagger V_\mu V^\mu S]$

"spurion S" ⟹ "Higgs ϕ "

$\mathrm{tr}[(D_\mu \phi)^\dagger D^\mu \phi]$

P. Anderson, Phys. Rev. Phys. **130**, 439 (1962)
F.Englert & R. Brout, Phys. Rev. Lett. **13,** 321 (1964)
P. Higgs, Phys. Rev. Lett. **13,** 508 (1964)

Poincare-breaking UV cutoff $\Lambda_{\wp}$:

loop-level mass term= $\Lambda_{\wp}^2 \mathrm{tr}[V_\mu V^\mu]$

$\Lambda_{\wp}^2$ ⟹ "spurion Σ"
(Poincare-breaking)

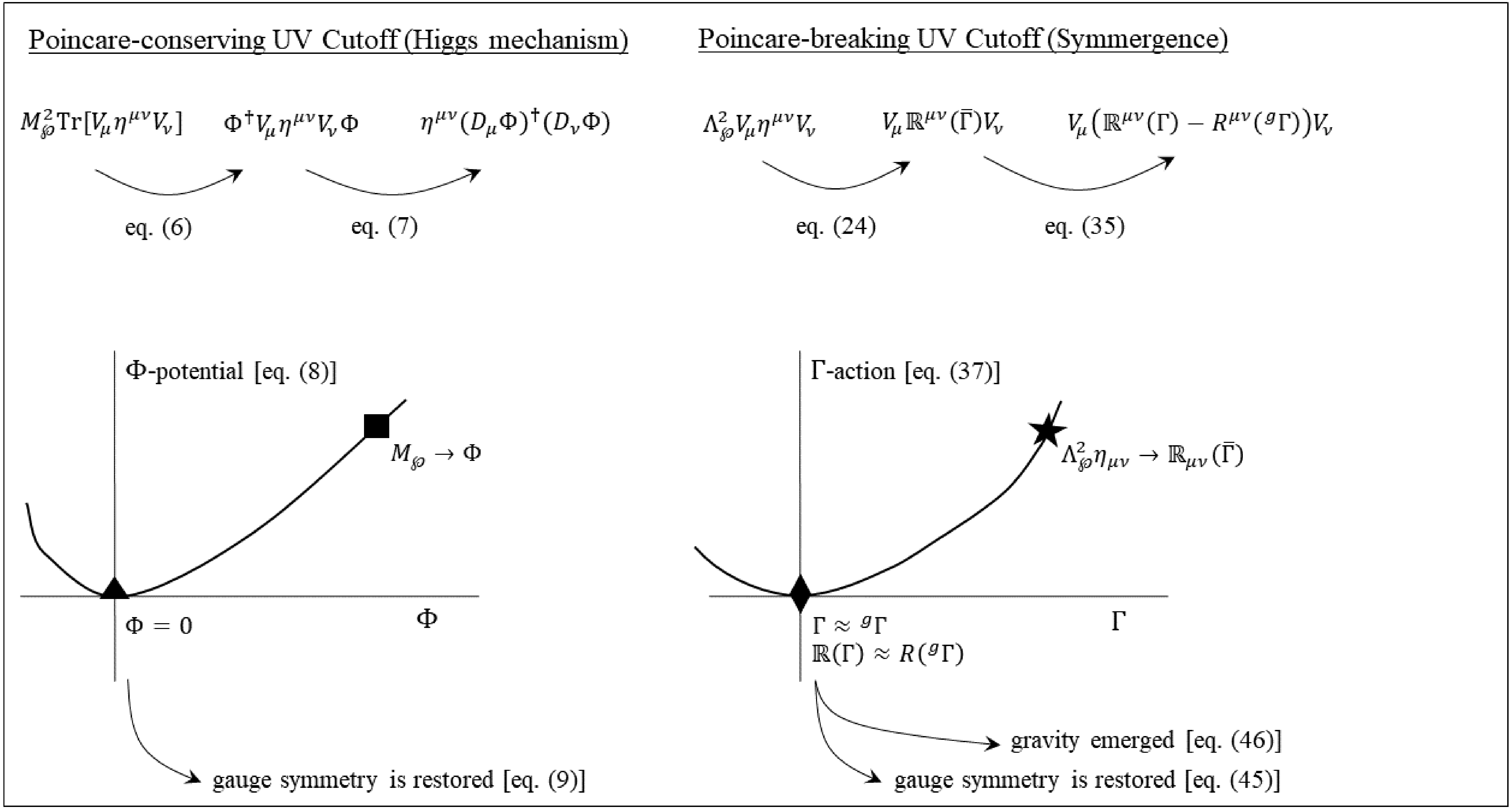
$\mathrm{tr}[\, V^\mu \Sigma_{\mu\nu} V^\nu]$

"spurion Σ" ⟹ "affine curvature $\mathbb{R}$"

$\mathrm{tr}[\, V^\mu \mathbb{R}_{\mu\nu} V^\nu]$

DD, Phys. Rev. D 107, 105014 (2023)
DD, Gen Relativ Gravit 53, 22 (2021)
DD, Adv. High En. Phys. 4652048 (2019)
DD, Adv. High En. Phys. 6727805 (2016)

SYMMERGENT GRAVITY



DD, Phys. Rev. D 107, 105014 (2023)

SYMMERGENT GRAVITY

$$S_{QFT+GR} = S\,(g,\psi\,) + \delta S(g,\psi) + \int d^4x\,\sqrt{-g}\,\left\{-\frac{R(g)}{16\pi G_N} - \frac{c_O}{16}R(g)^2 - \frac{c_\phi}{4}R(g)\phi^\dagger\phi + \mathcal{O}(G_N)\right\}$$

QFT with

- dimensional-regularization in curved background geometry,
- loop corrections computed in the flat spacetime QFT

$R + R^2$ gravity with

- non-minimal coupling to scalars,
- loop-induced coefficients originating from the flat spacetime QFT.

symmetry-restoring emergent gravity = "symmergent gravity"

DD, Phys. Rev. D 107, 105014 (2023)
DD, Gen Relativ Gravit 53, 22 (2021)

SYMMERGENT BLACK HOLES

$$S_{sgr} = \int d^4x \sqrt{-g} \left\{ -\frac{R(g)}{16\pi G_N} - \frac{c_O}{16} R(g)^2 - V_{tot} \right\}$$

$$G_N^{-1} = 8\pi \, \mathrm{str}[M^2]$$

$$c_O = \frac{n_b - n_f}{128\pi^2}$$

$$V_{tot} = V_{tree} + \delta V$$

$$\delta V = \frac{1}{64\pi^2} \mathrm{str}[M^4]$$

$$\delta V = \frac{m_0^4}{64\pi^2} \left(n_b - n_f \right) = \frac{1}{24\pi G_N^2 c_O}$$

(if bosons and fermions had equal masses m_0)

$$\delta V = \frac{(1 - \hat{\alpha})}{24\pi G_N^2 c_O}$$

(one possible parametrization)

J. Rayimbaev *et al.*, Annals of Physics 454, 169335 (2023)
R. Pantig, A. Övgün, DD, Eur. Phys. J. C83, 250 (2023)

SYMMERGENT BLACK HOLES

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} - 2\pi G_N c_O \left(R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu} + \Box g_{\mu\nu} - \nabla_\mu \nabla_\nu \right) R - 8\pi G_N V_{tot} = 0$$

- One class of solutions corresponds to constant scalar curvature ($R = R_0 = -8\pi G_N V_{tot}$)
  - dS solution ($V_{tot} > 0$ or $n_B > n_F$)
  - AdS solution ($V_{tot} < 0$ or $n_B < n_F$)
  - c_O disappears from asymptotically-flat zero-R solution

W. Nelson, Phys. Rev. D 82, 104026 (2010)
H. Lü *et al*. Phys. Rev. Lett. 114, 171601 (2015)

- Another class corresponds to corresponds to variable scalar curvature ($R \neq \text{constant}$)
  - There exist asymptotically-flat solutions explicitly involving c_O

H. Buchdahl, Nuovo Cim. 23, 141 (1962)
H. Nguyen, Phys. Rev. D 107, 104009 (2023)
B. Puliçe, R. Pantig, A. Övgün, DD, work in progress (2023)

gravity theory ($V_{tot} = 0$)	static spherically-symmetric solutions
Symmergent gravity action: $\int d^4x \sqrt{-g}\left(-\frac{R}{16\pi G_N} - \frac{c_O}{16}R^2\right)$	Buchdahl-Nguyen solution: $(ds)^2 = A(r)\,(dt)^2 - \frac{(dr)^2}{B(r)} - C(r)\left((d\,\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$

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

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

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

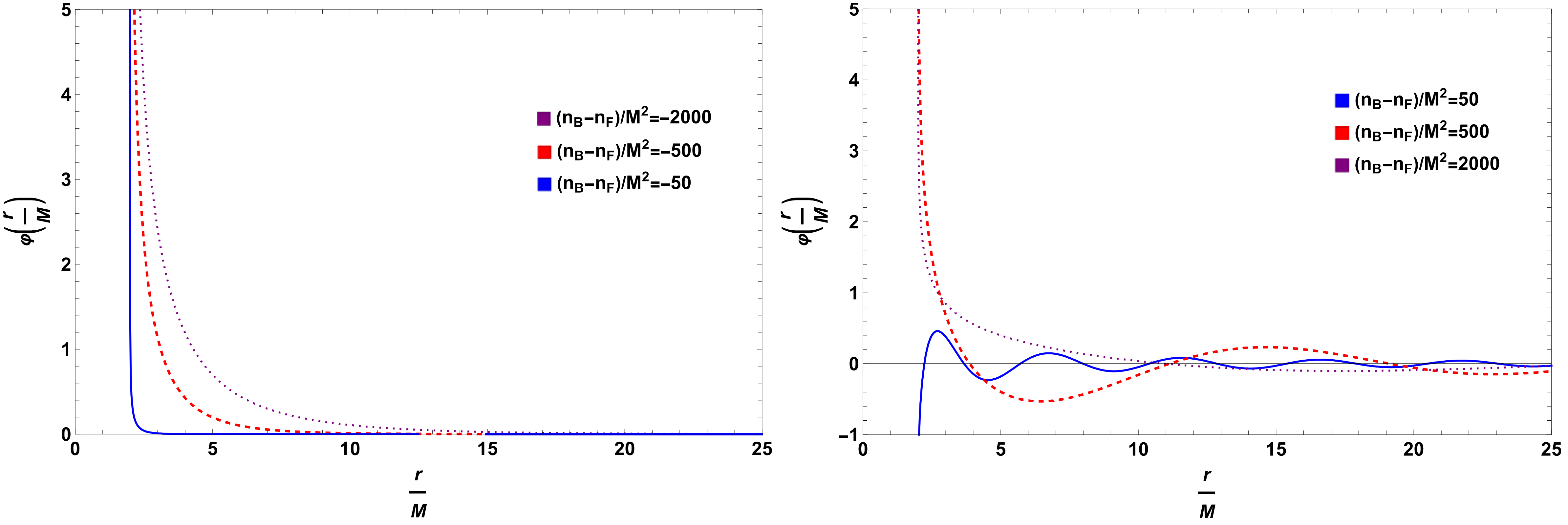
$$\frac{d}{dr}\left((r^2 - r r_s)\frac{d\varphi(r)}{dr}\right) = -\gamma r^2 \varphi(r)$$

$$\gamma = -\frac{1}{6\pi c_O} = -\frac{64\pi}{3(n_b - n_f)}$$

H. Buchdahl, Nuovo Cim. 23, 141 (1962)
H. Nguyen, Phys. Rev. D 107, 104009 (2023)
B. Puliçe, R. Pantig, A. Övgün, DD, work in progress (2023)

ASYMTOTICALLY-FLAT SYMMERGENT BLACK HOLES

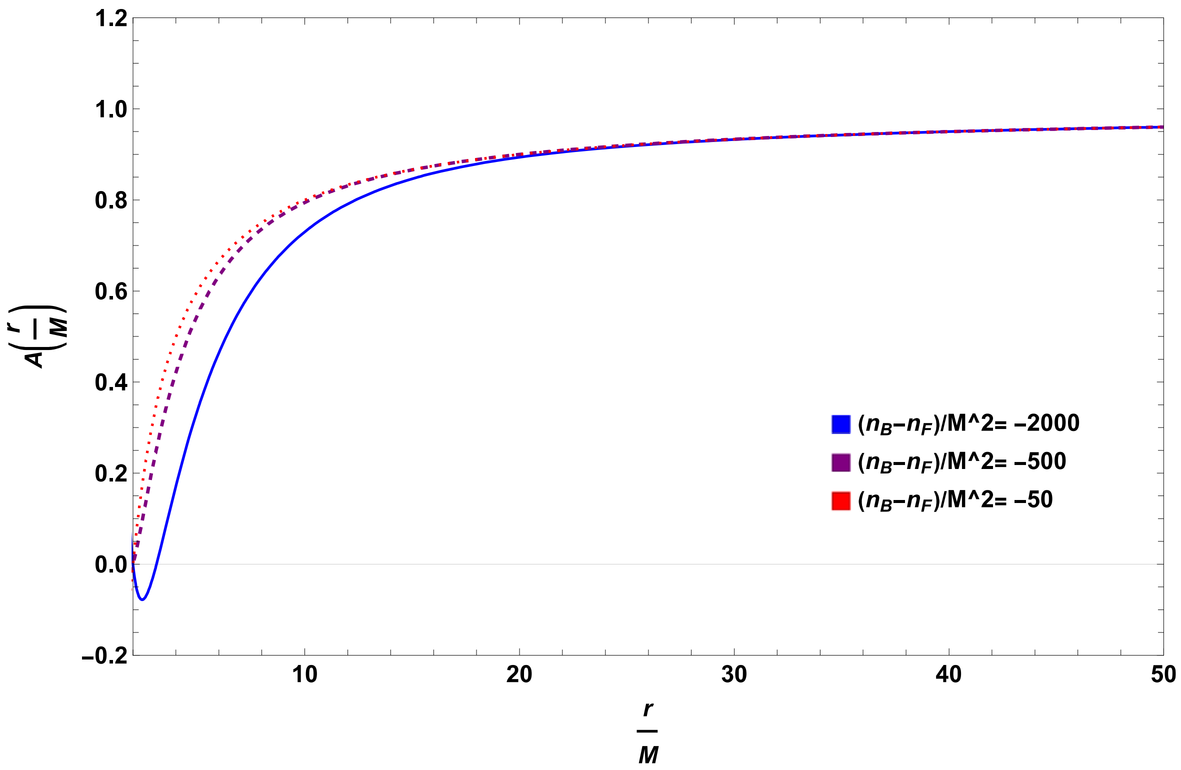
Sabancı Üniversitesi

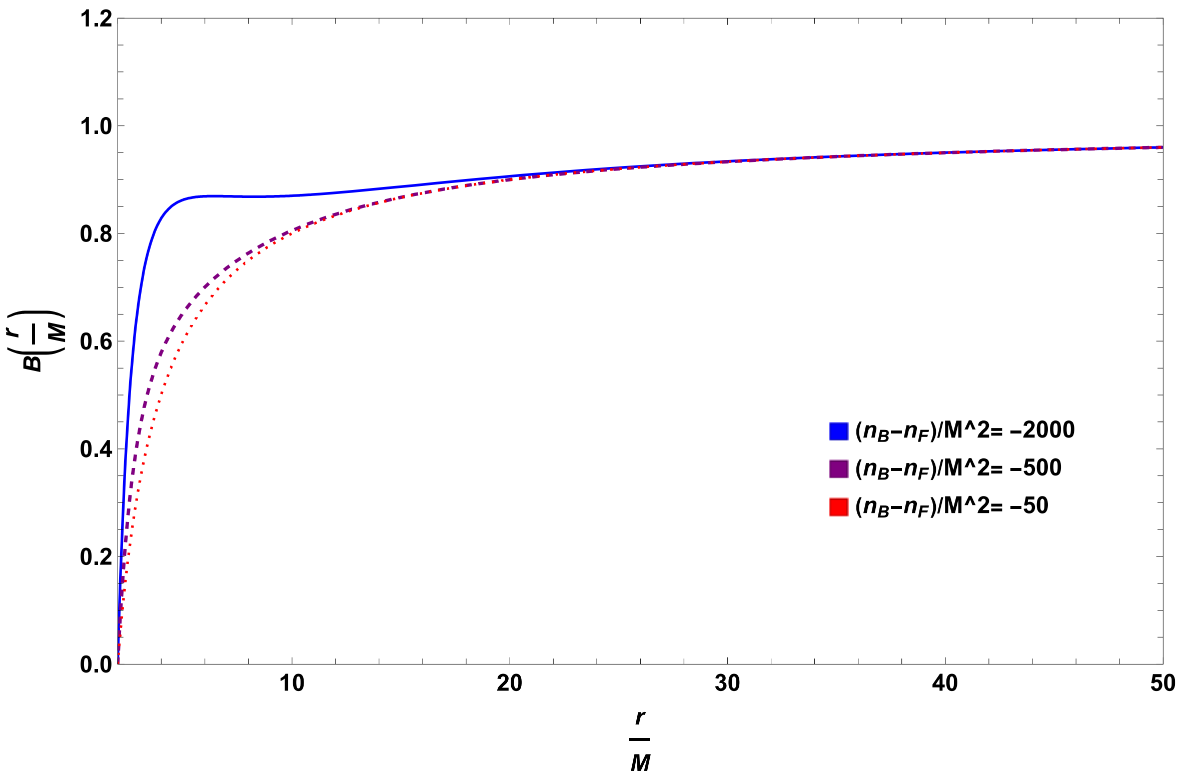


- **Conformal factor** $\varphi(r)$ diverges at the Schwarzschild horizon $r = r_s \equiv 2M$ and gets suppressed exponentially (sinusoidally) at large r for $n_B - n_F < 0$ $(n_B - n_F < 0)$.

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

ASYMTOTICALLY-FLAT SYMMERGENT BLACK HOLES

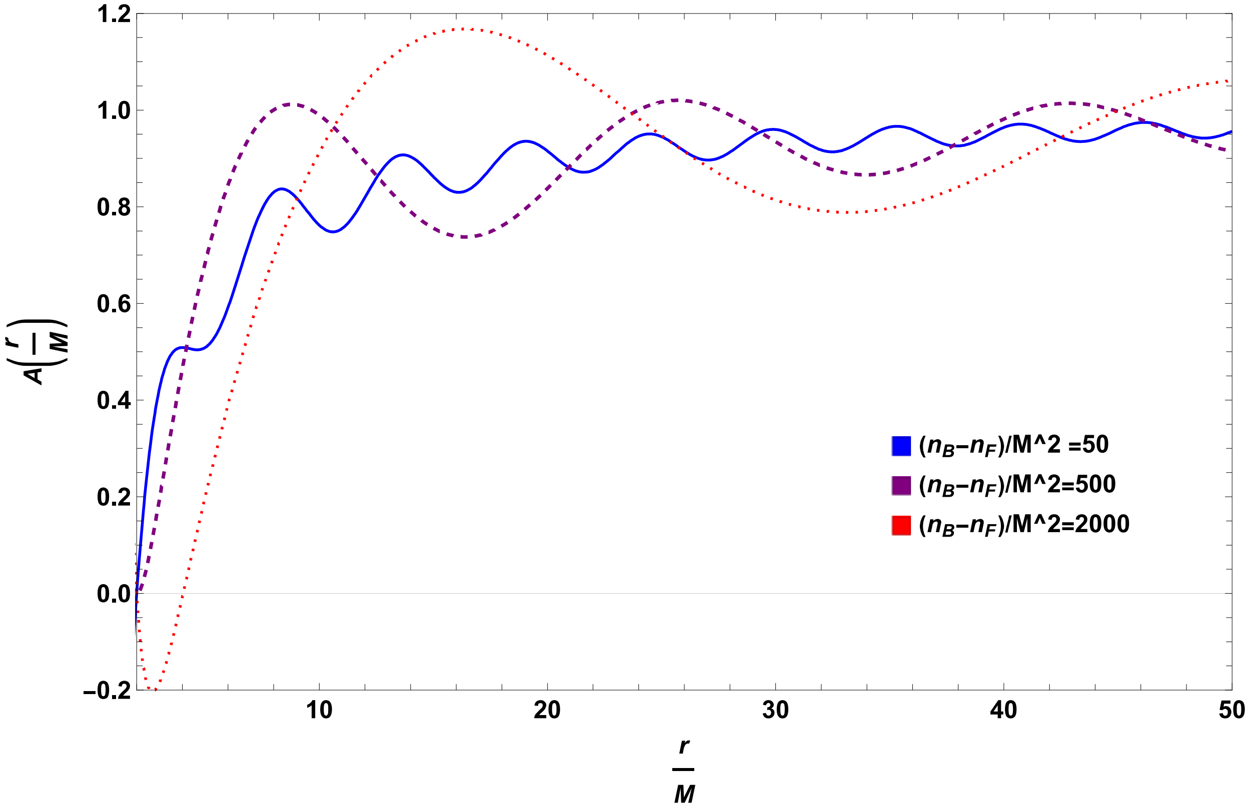


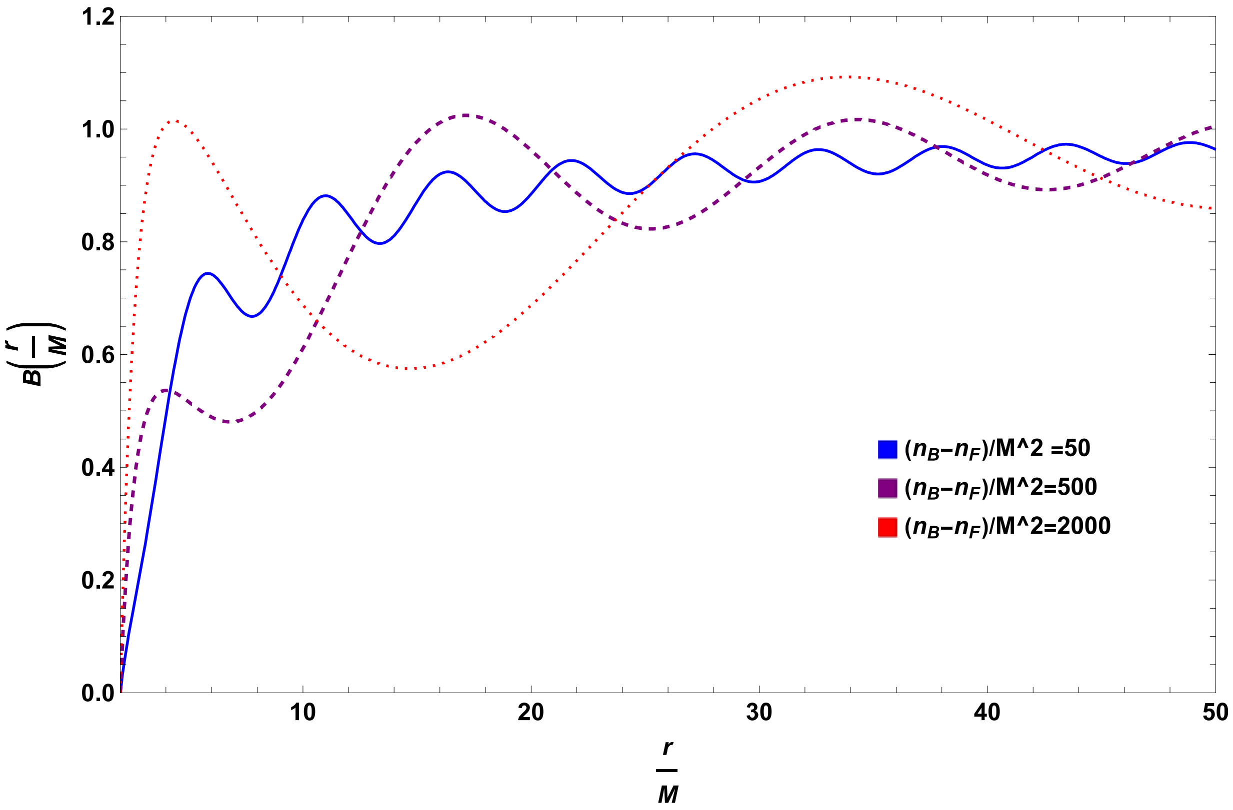


- Metric potentials $A(r)$ and $B(r)$ approach to the flat spacetime limit of $A(r) = B(r) = 1$ at large r. The approach is exponential and different $n_B - n_F < 0$ values are hard to distinguish observationally.

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

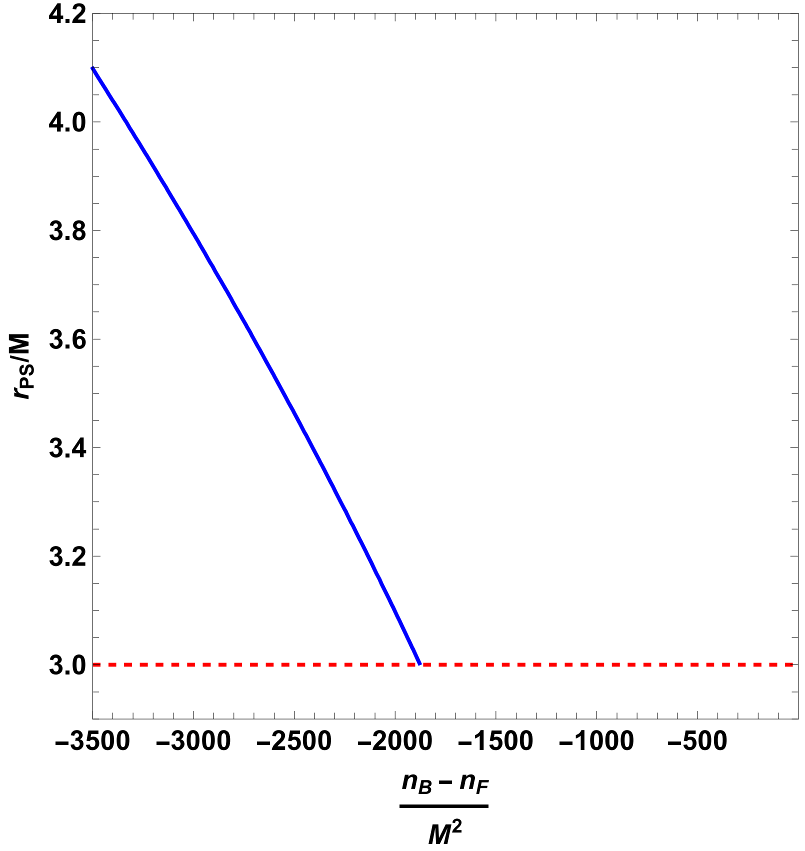
ASYMTOTICALLY-FLAT SYMMERGENT BLACK HOLES

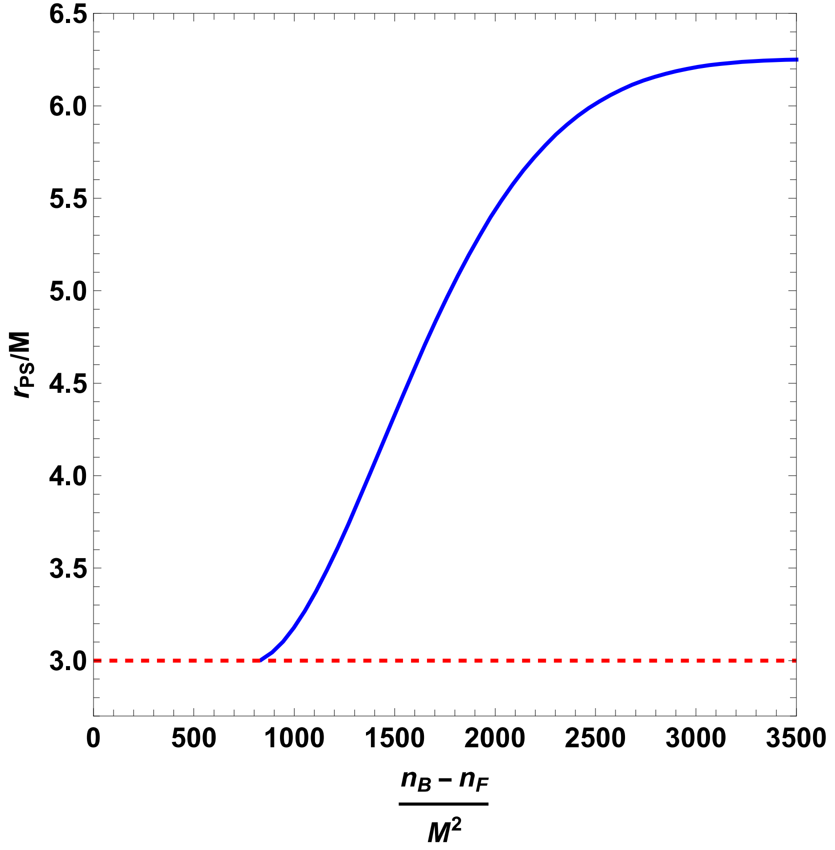




- Metric potentials $A(r)$ and $B(r)$ approach to the flat spacetime limit of $A(r) = B(r) = 1$ at large r. The approach is sinusoidal and gradual and different $n_B - n_F > 0$ values could be distinguished observationally.

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

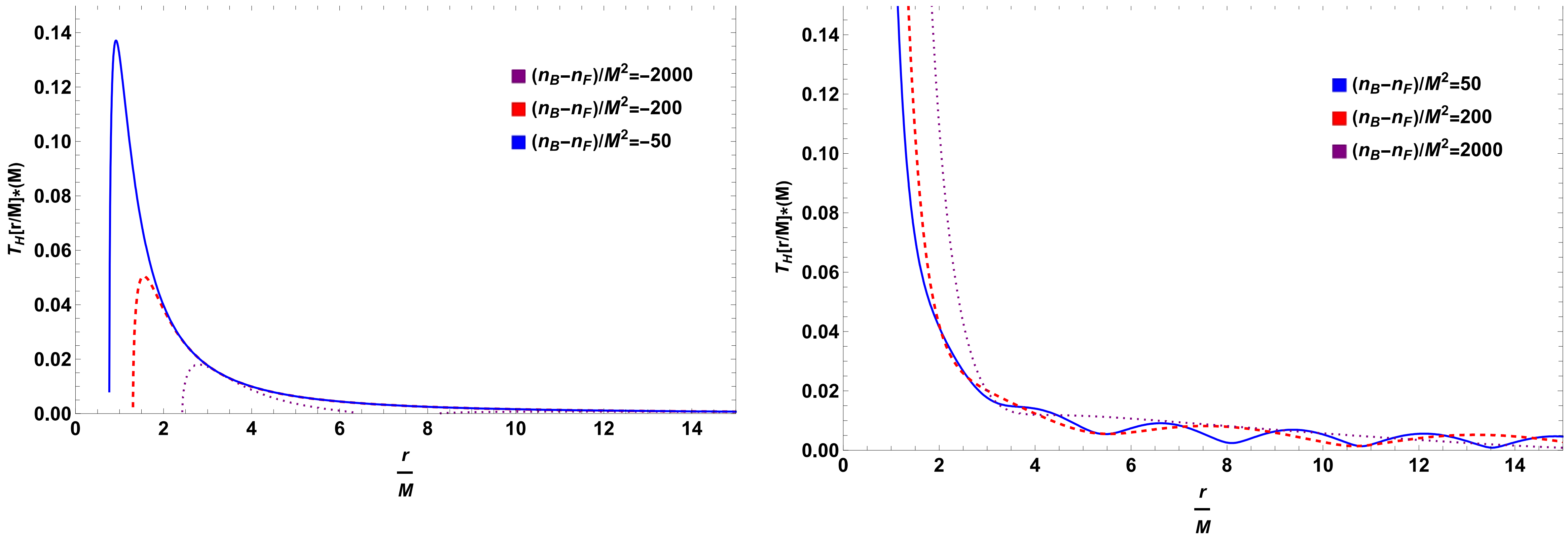




- Photonsphere radius r_{PS} for $n_B - n_F < 0$ (left) and $n_B - n_F > 0$ (right).

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

ASYMTOTICALLY-FLAT SYMMERGENT BLACK HOLES



- Hawking temperature as a function of the radial coordinate r for $n_B - n_F < 0$ (left) and $n_B - n_F > 0$ (right).

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

gravity theory ($V_{tree} = 0$)	static spherically-symmetric solutions
Symmergent gravity action: $\int d^4x \sqrt{-g}\left(-\frac{R}{16\pi G_N} - \frac{c_O}{16}R^2 - \frac{1-\hat{\alpha}}{(8\pi G_N)^2 c_O}\right)$	Schwarzschild-dS/AdS solution: $(ds)^2 = h(r)(cdt)^2 - \frac{(dr)^2}{h(r)} - r^2\left((d\theta)^2 + \sin^2\theta\,(d\phi)^2\right)$

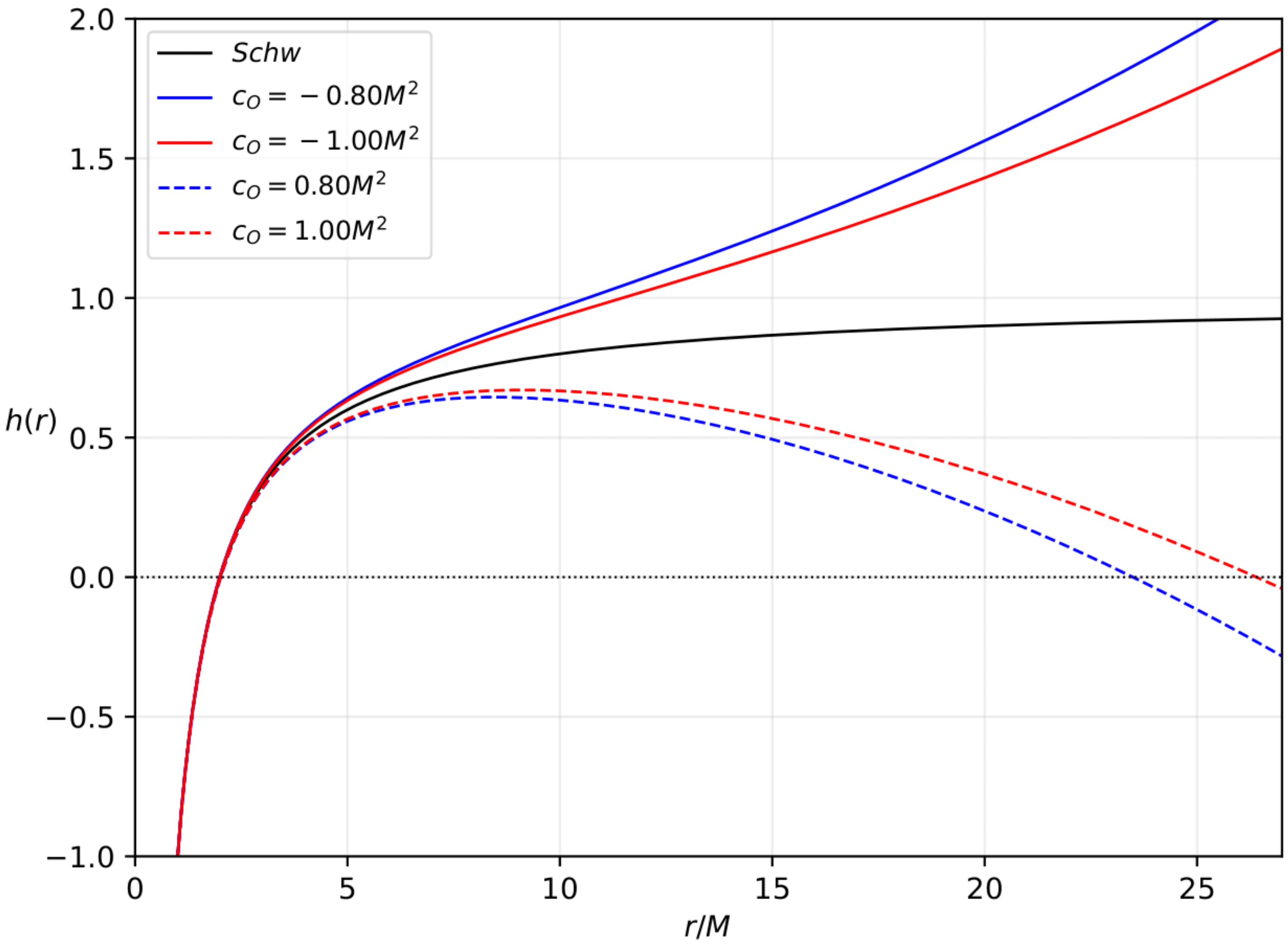
$$c_O = \frac{n_b - n_f}{248\pi^2}$$

$\hat{\alpha}$ = a constant parametrizing symmergent vacuum energy

$$h(r) = 1 - \frac{r_s}{r} - \frac{(1-\hat{\alpha})r^2}{24\pi G_N c_O}$$

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

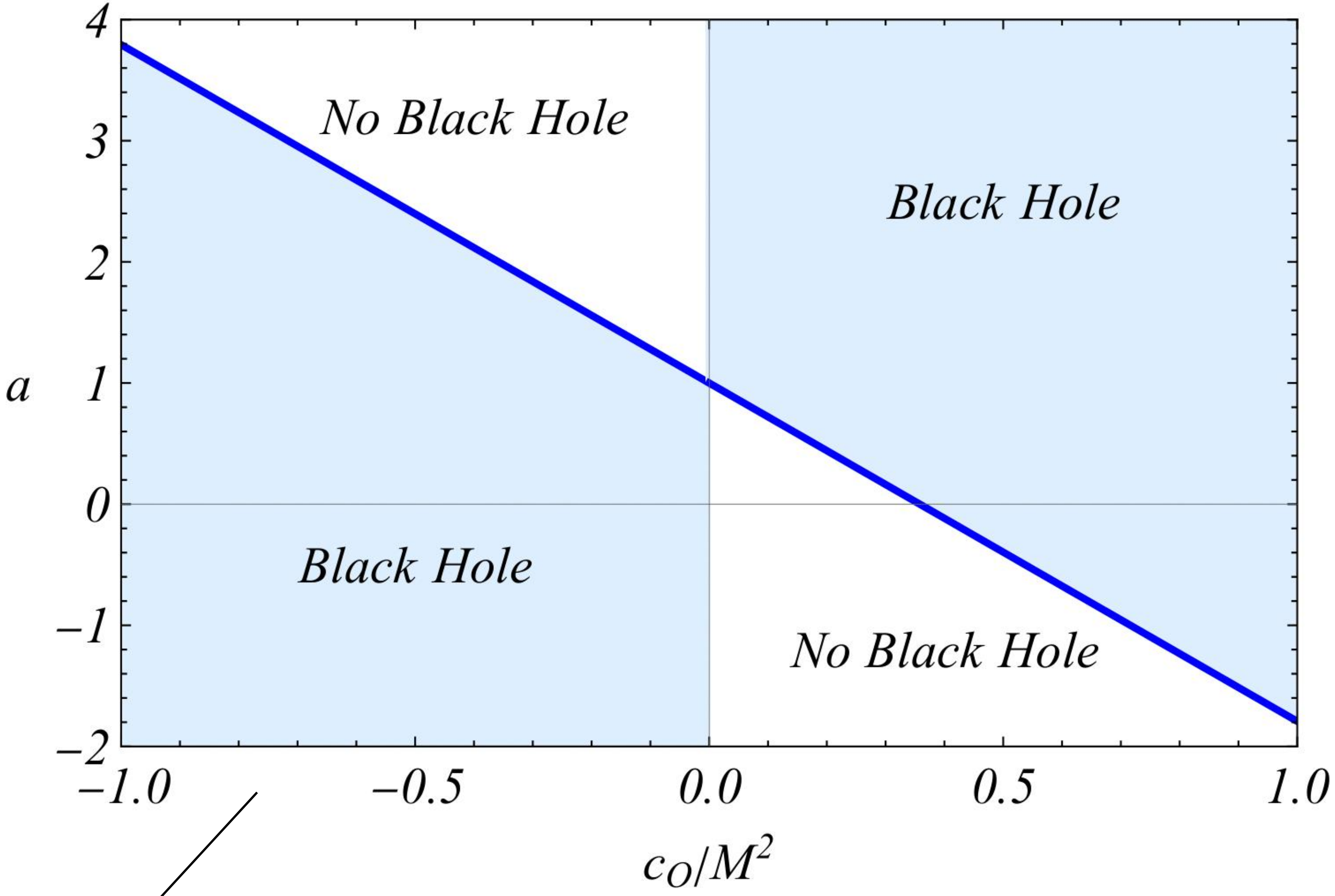
SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE



(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)

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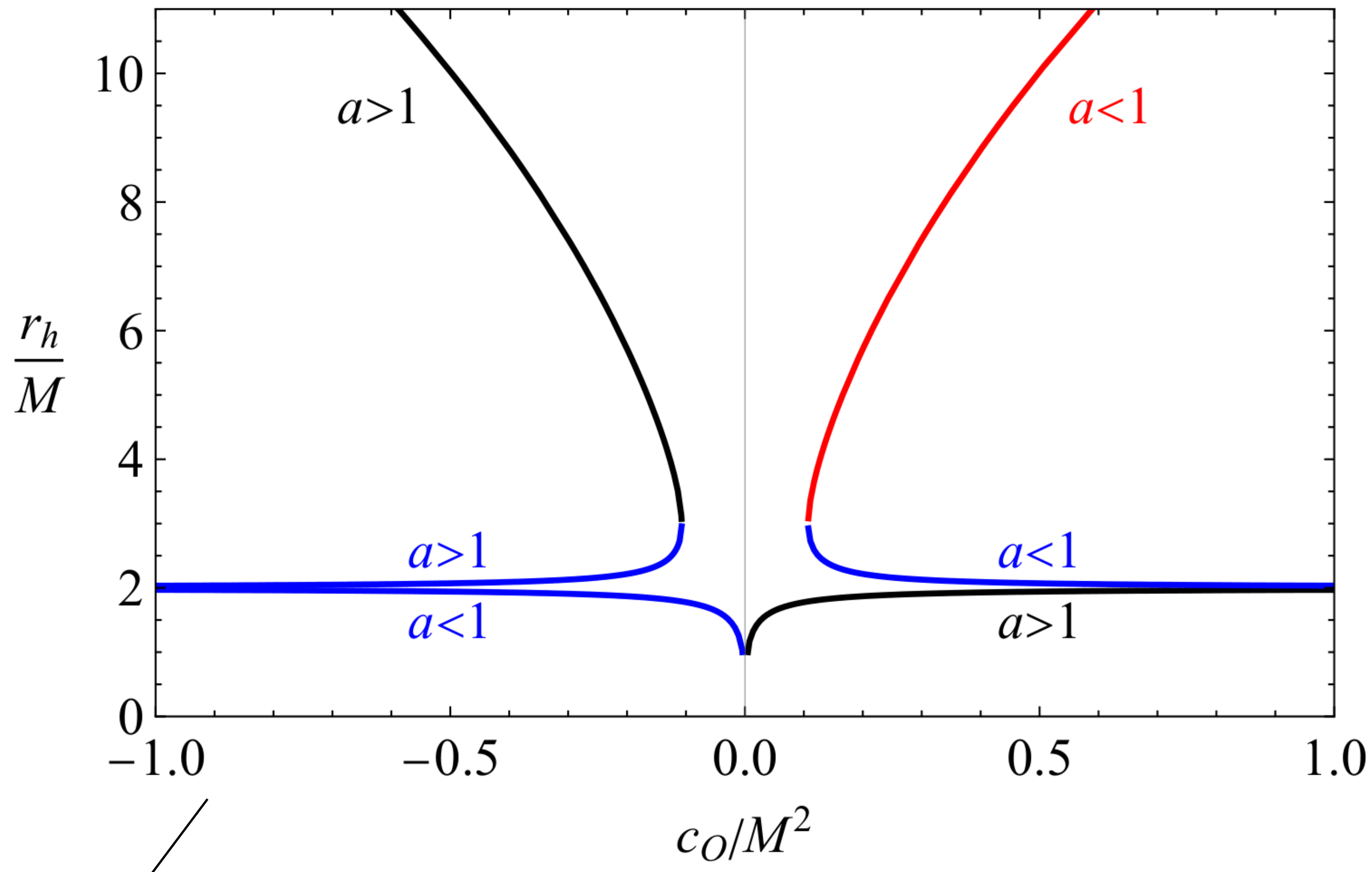

event horizon: $r_h = 2\,M$ is the Schwarzschild radius

(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

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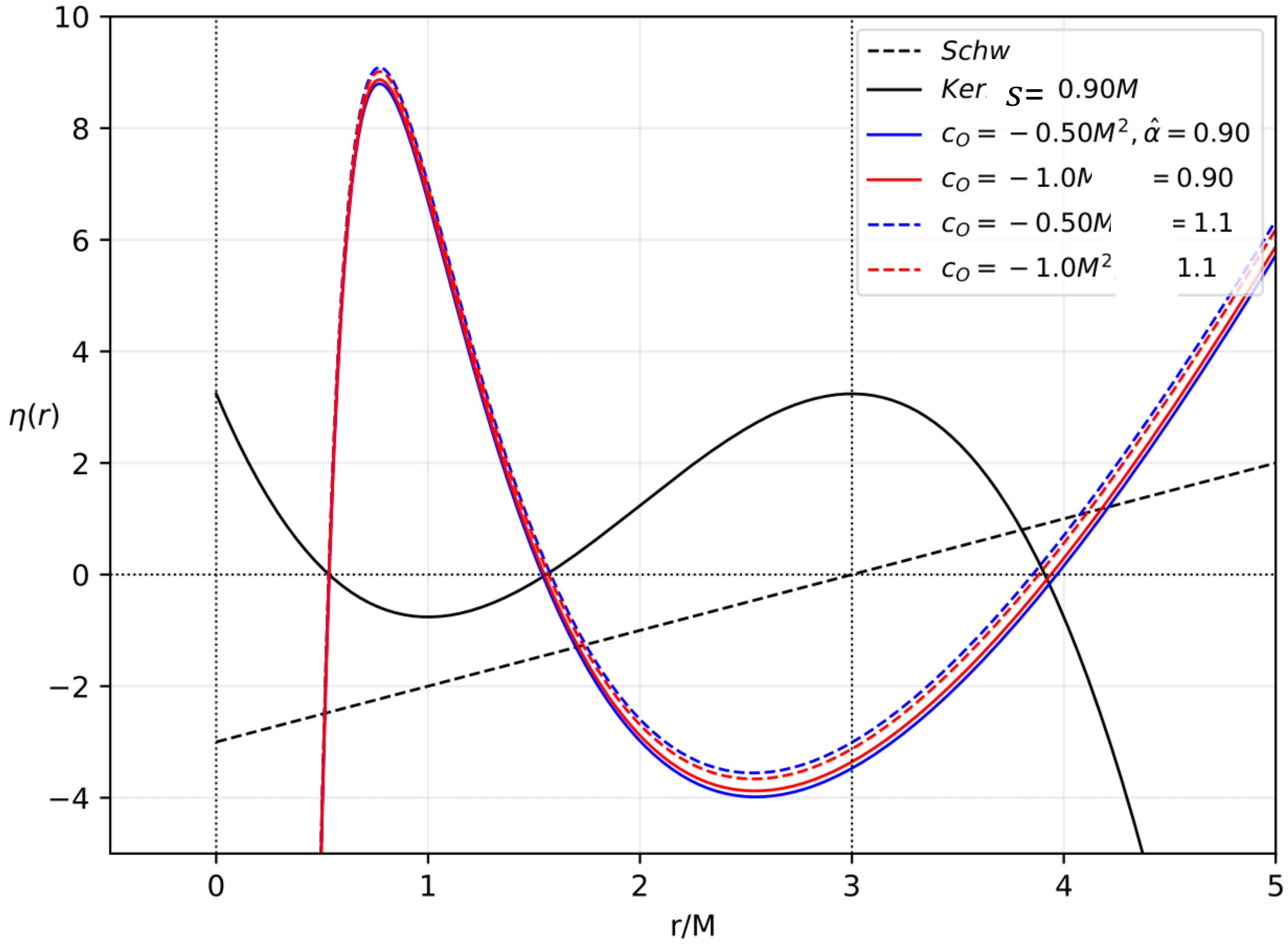
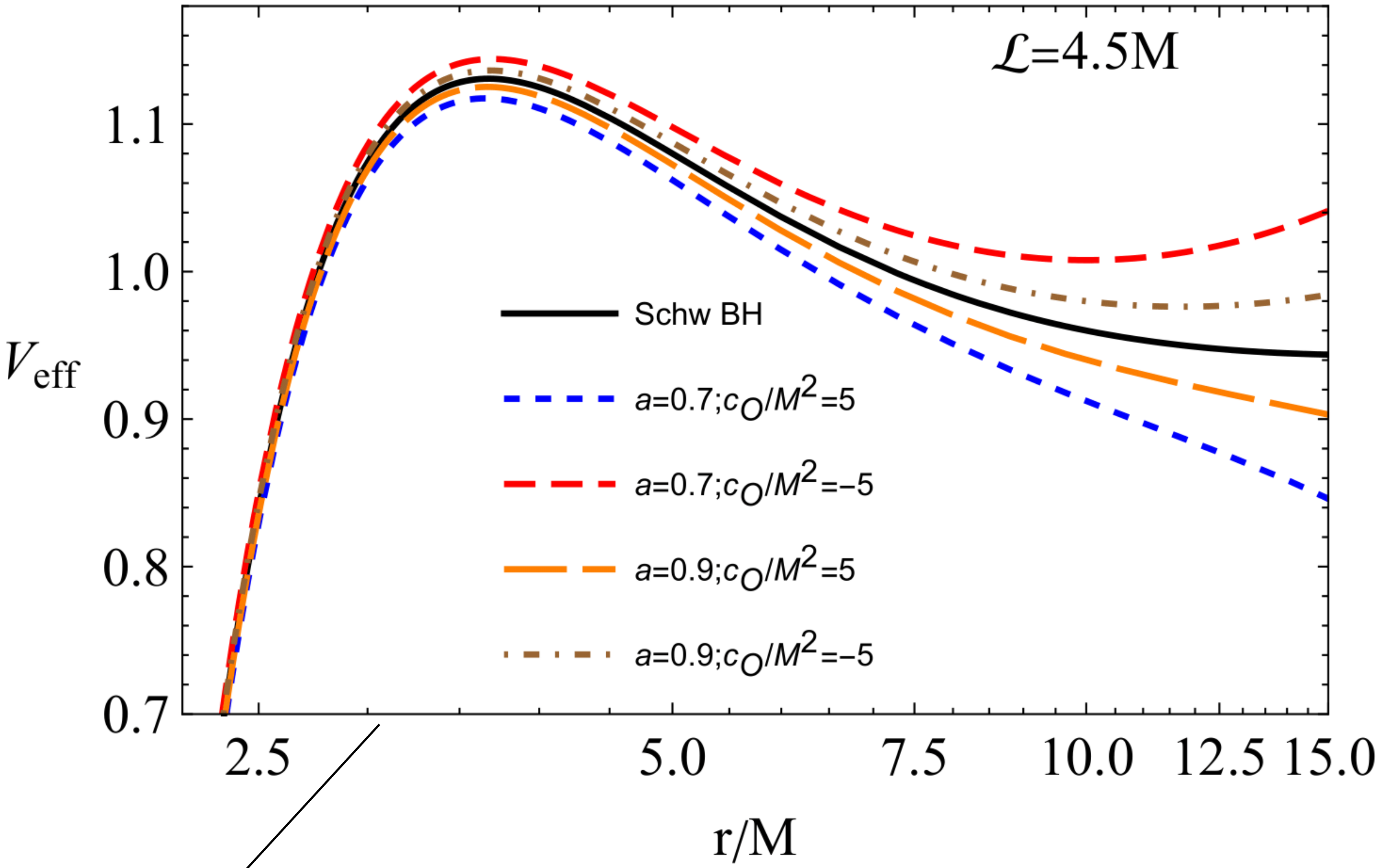


Photon sphere radius for a rotating symmergent black hole of angular momentum number s)

(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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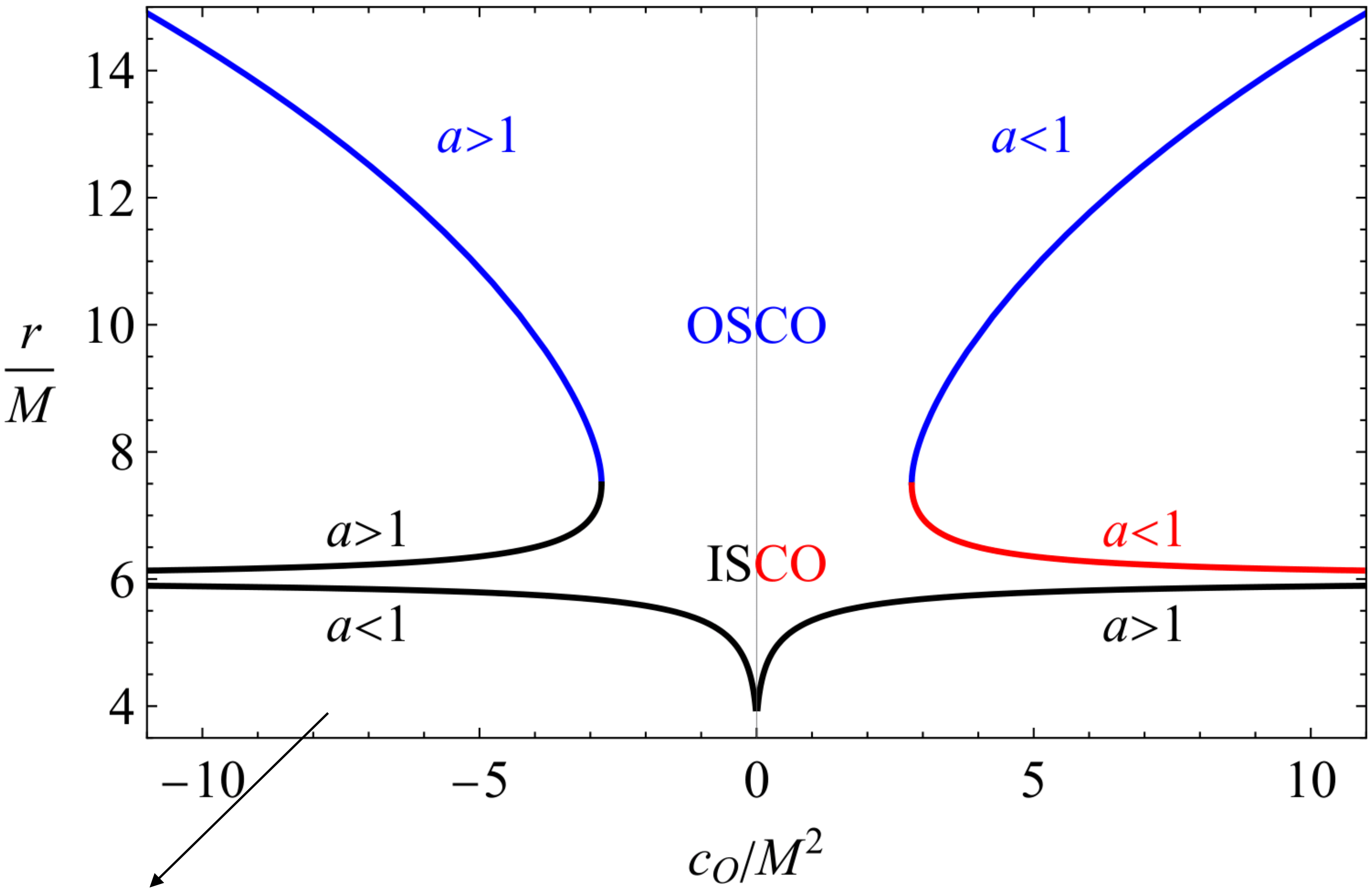
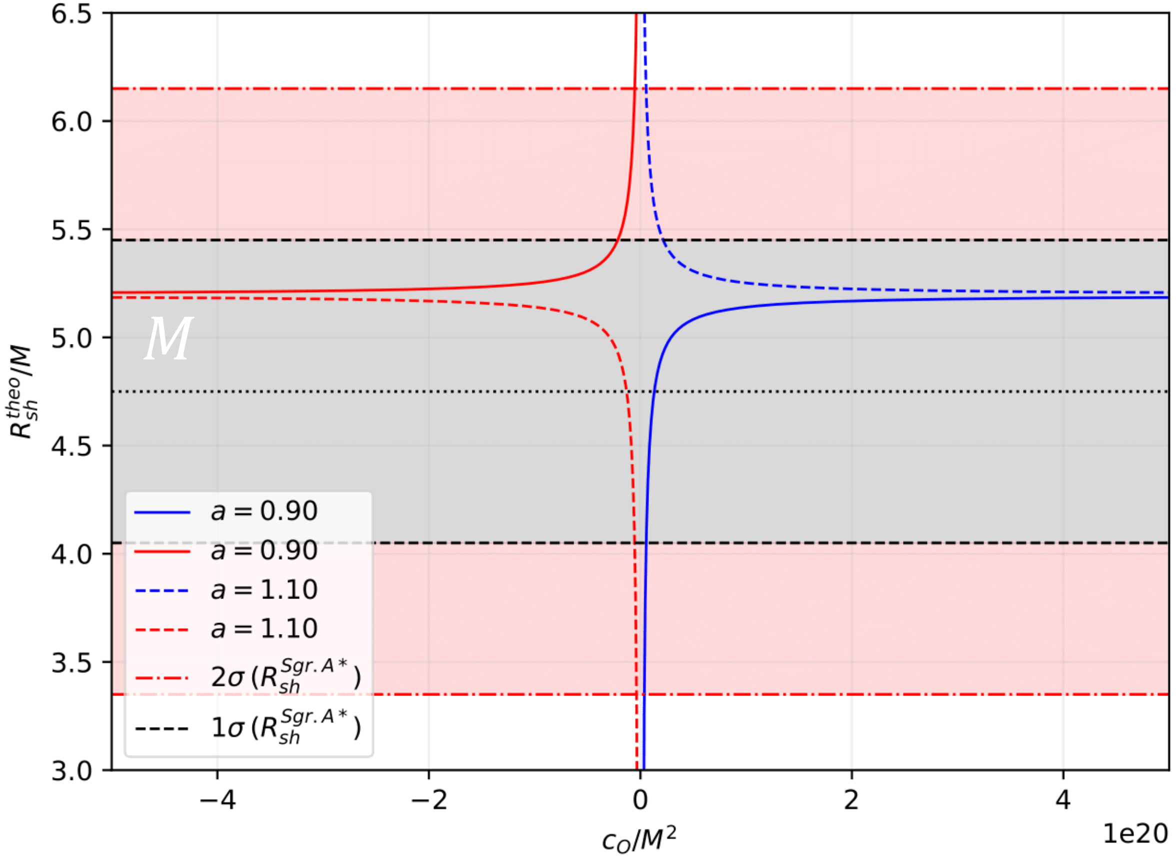


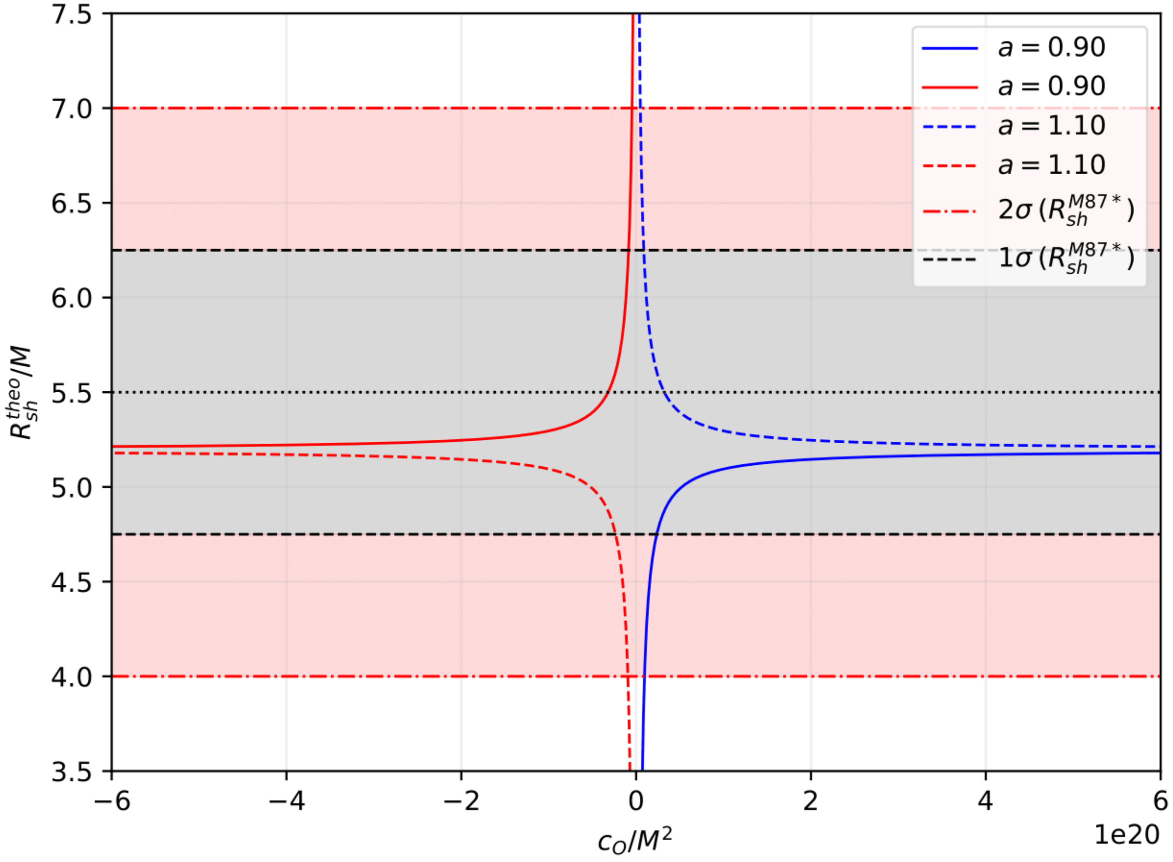
innermost (ISCO) and outermost (OSCO) stable circular orbits

(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



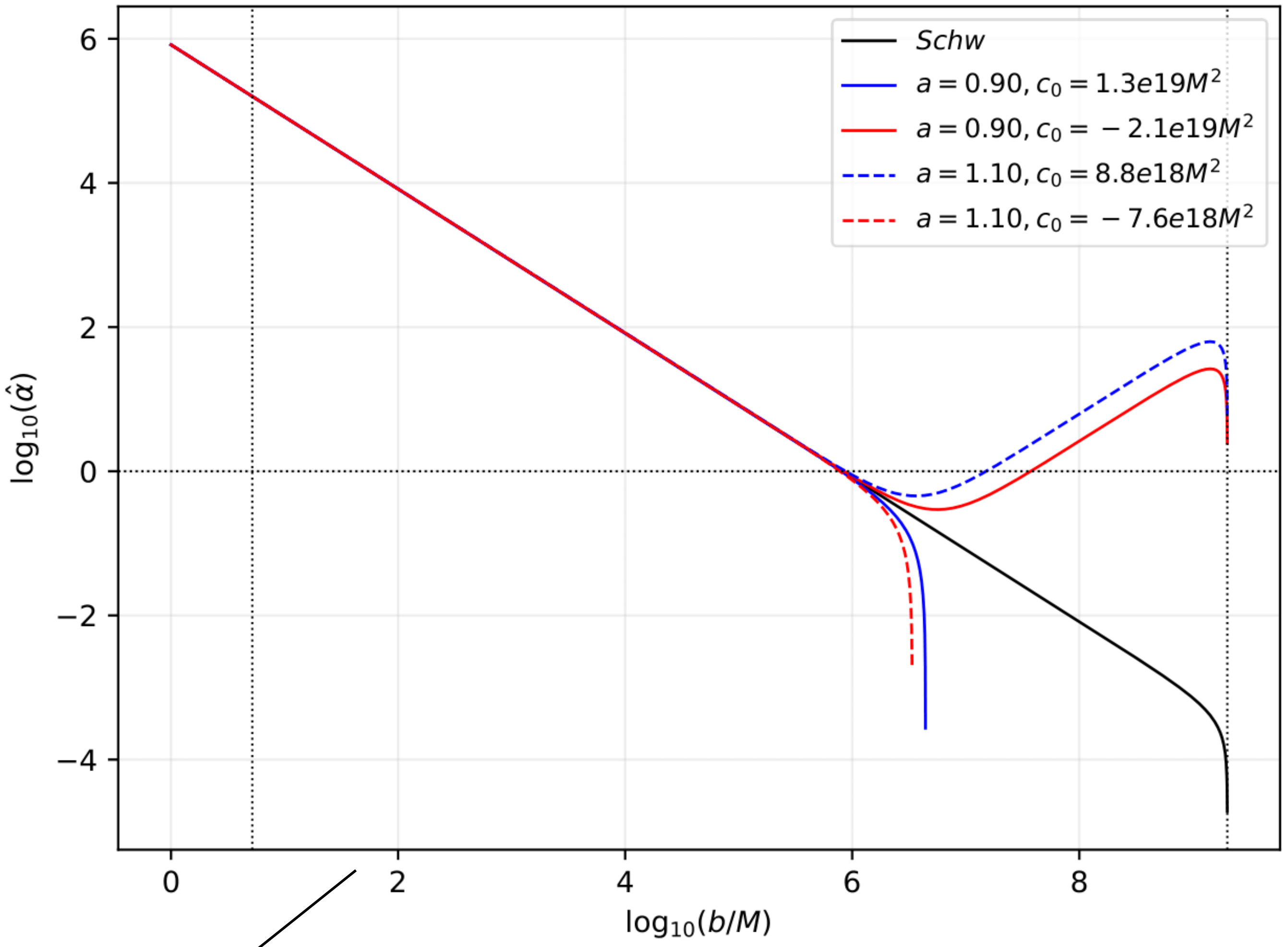


bounds on model parameters form shadow radii of Sgr.A* (left) and M87* (right)

(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)

SCHWARZSCHILD-dS/AdS SYMMERGENT BLACK HOLE

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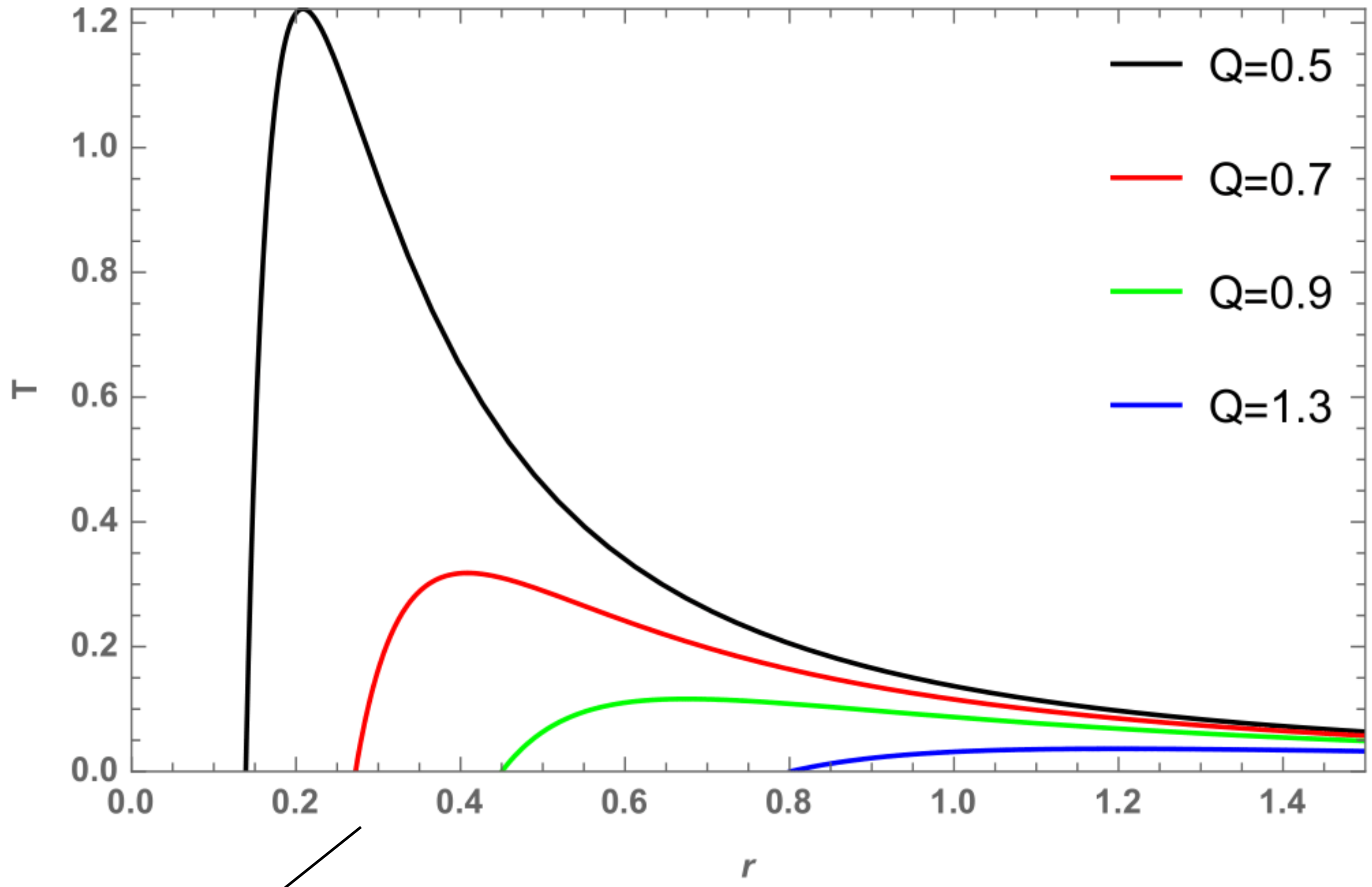
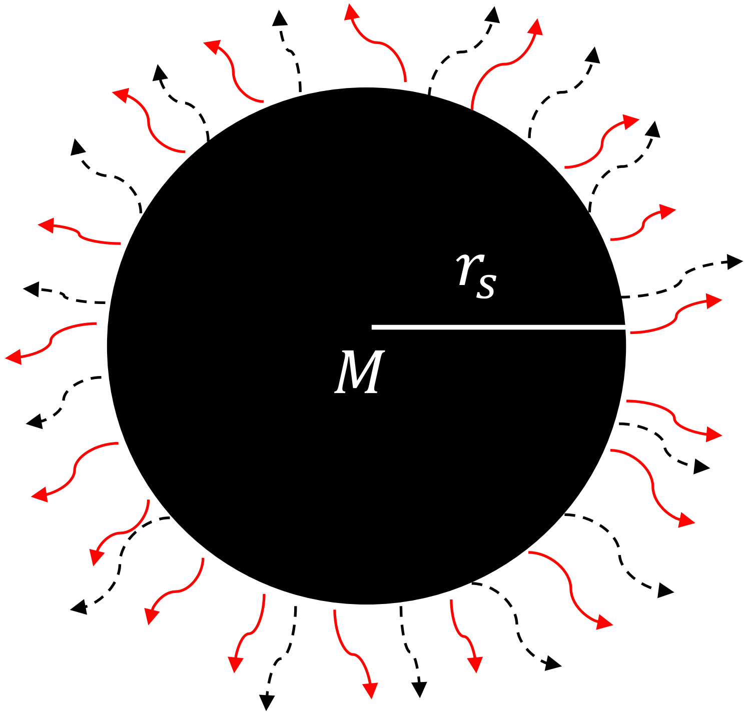
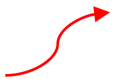


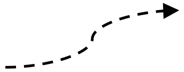
Hawking temperature ($r_s = 1$) for a charged symmergent black hole ($c_O = 0.9$ and $a = 0.5$) .

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

BLACK HOLE EVAPORATION IN SYMMERGENT GRAVITY



Hawking radiation from photon, neutrino etc. : 

Hawking radiation from new dark fields: 

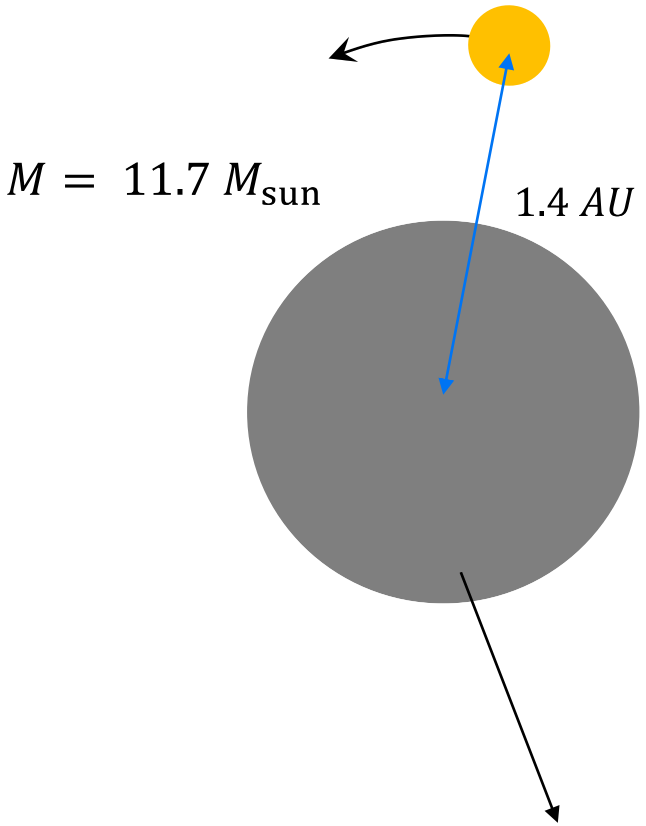
Black hole temperature and evaporation rate change if symmergent particles are included!

Hawking radiation=$\{\gamma, \nu\}$ + {light symmergent particles}

D. Gogoi, A. Övgün, DD, work in progress (2023)

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

DARK STARS IN SYMMERGENT GRAVITY



GAIA: A sun-like star is orbiting about a dark object.

Calculations: The dark object is less likely to be a black hole.

Analyses: The dark object is likely to be a dark star.

dark stars and even dark galaxies
are expected in symmergent gravity

A. Vallenari *et al*. [GAIA] Ast. Astrophys. (2022)

A. Pombo & I. Saltas (2023)

S. Das, S. Chattopadhyay, A. Övgün, DD (2023)

Thank you.