Radiative Penrose process:

energy gain by a single radiating charged particle in ergosphere of rotating black hole

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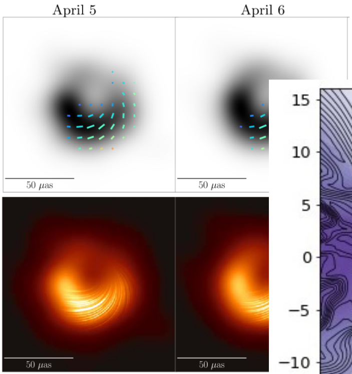
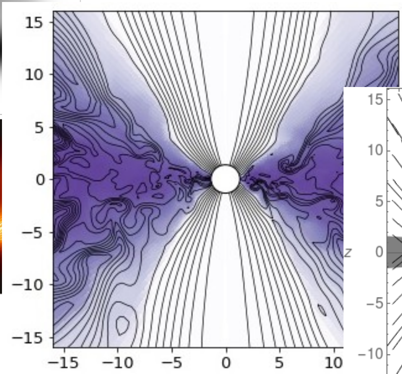
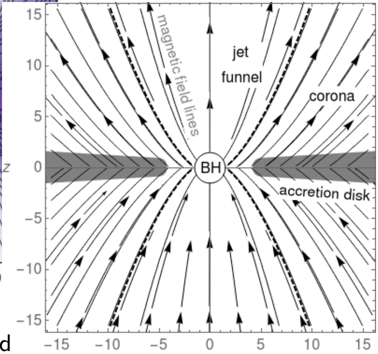
Black hole, accretion disk and electro**magnetic** field: observation ‖ numerical experiment ‖ analytical model





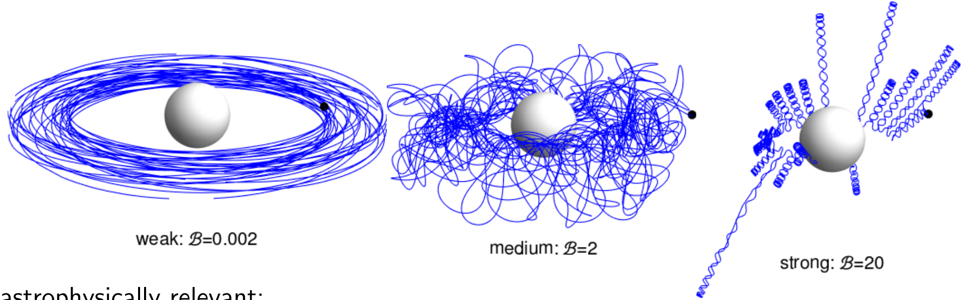


$B_{\rm M87} \sim 10$ Gs

from "Polarization of the Ring": 10.3847/2041-8213/abe71d

Magnetic field influence: weak $\mathcal{B} \ll 1$ $\|$ strong $\mathcal{B} \gg 1$

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} F^\mu{}_\nu u^\nu, \qquad \|F^\mu{}_\nu\| \sim \boxed{\mathcal{B} = \frac{qB}{2m}\frac{GM}{c^4}} \tag{1}$$



astrophysically relevant:

- weak $\mathcal{B} \ll 1$ case - small oscillations
- strong $\mathcal{B} \gg 1$ case - motion along magnetic field lines, Larmor radius

magnetic parameter $\mathcal{B}$ - relates gravitational and electromagnetic forces:

$\mathcal{B} \ll 1$ gravity wins $\|$ $\mathcal{B} \sim 1$ gr-elmag fight $\|$ $\mathcal{B} \gg 1$ elmag wins

Radiating charged particle dynamics in curved spacetime

radiation emitted by a charged particle leads to appearance of **radiation reaction force (RR)**

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} F^\mu{}_\nu u^\nu + \frac{q}{m} \mathcal{F}^\mu{}_\nu u^\nu, \tag{2}$$

Lorentz force is given by EM tenzor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$; radiation reaction force $\boxed{\frac{q}{m} \mathcal{F}^\mu{}_\nu u^\nu}$

$$\frac{2q^2}{3m}\left(\frac{D^2 u^\mu}{d\tau^2} + u^\mu u_\nu \frac{D^2 u^\nu}{d\tau^2}\right) + \frac{q^2}{3m}\left(R^\mu{}_\lambda u^\lambda + R^\nu{}_\lambda u_\nu u^\lambda u^\mu\right) + \frac{2q^2}{m} u_\nu \int D^{[\mu} G^{\nu]}_{+\lambda'}(z(\tau), z(\tau')) u^{\lambda'} d\tau'$$

$$= \frac{2q^2}{3m}\left(\frac{DF^\alpha{}_\beta}{dx^\mu} u^\beta u^\mu + \left(F^\alpha{}_\beta F^\beta{}_\mu + F_{\mu\nu} F^\nu{}_\sigma u^\sigma u^\alpha\right) u^\mu\right)$$

- 1st term $D^2 u^\mu / d\tau^2$ is problematic - high order derivative - can be substituted, particle acceleration mostly by Lorentz force (excellent for $\mathcal{B} > 1$), trick from Landau & Lifshitz
- 2nd term gone zero - Ricci tensor vanishes the vacuum metrics
- 3rd term - "tail" integral (non-local nature of RR) is negligible small (for $\mathcal{B} > 1$)

RR force act as damping - particle energy and ang. momenta are decreasing (not conserved)

• A. Tursunov, M. Kološ, Z. Stuchlík and D. V. Gal'tsov : *Radiation reaction of charged particles orbiting mag. Schw. BH*, The Astro. Journal 861 (1), 16 (2018) [arXiv:1803.09682]

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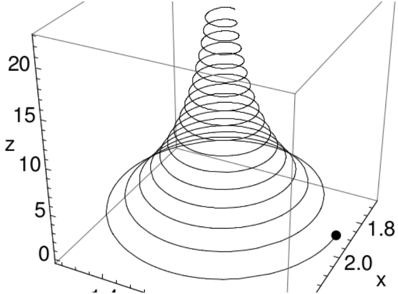
$$\begin{aligned}
\frac{du^x}{d\tau} &= \frac{qB}{m} u^y - \frac{2q^4 B^2}{3m^3} \left(1 + u_\perp^2\right) u^x, \\
\frac{du^y}{d\tau} &= -\frac{qB}{m} u^x - \frac{2q^4 B^2}{3m^3} \left(1 + u_\perp^2\right) u^y, \\
\frac{du^z}{d\tau} &= -\frac{2q^4 B^2}{3m^3} u_\perp^2 u^z, \\
\frac{du^t}{d\tau} &= -\frac{2q^4 B^2}{3m^3} u_\perp^2 u^t.
\end{aligned}$$

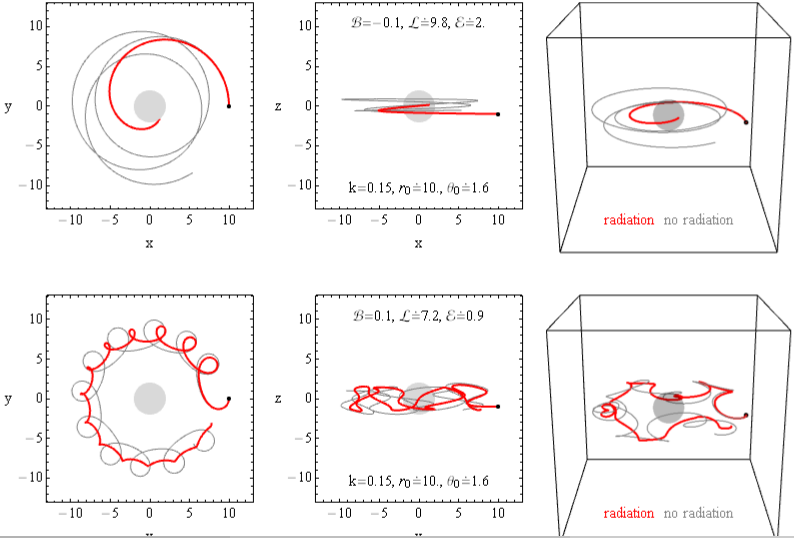


example for flat spacetime, uniform mag. field, $u_\perp^2 = (u^x)^2 + (u^y)^2$, RR has factor $q^4 B^2/m^3$, Lorentz force is relevant for any charged particle, radiation reaction mostly only for electrons.

• A. Tursunov, M. Kološ, Z. Stuchlík and D. V. Gal'tsov: *Radiation reaction of charged*

Charged particle motion around BH in uniform magnetic field

Particle is loosing energy and angular momentum, two cases $\mathcal{B} < 0$ (up), $\mathcal{B} > 0$ (low).



Rotating black hole ergosphere - photons with negative energy

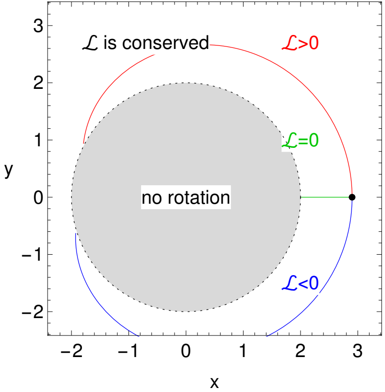
- BH ergosphere - g_{tt} changes sign from + to -

$$r_{\mathrm{H}} < r_{\mathrm{ergo}} < M + \sqrt{M^2 - a^2 \cos^2 \theta}.$$

In the ergosphere the energy of a test particle (photon) can become negative (related to ∞)

- angular momentum $\mathcal{L} = u_\phi$ and particle energy $\mathcal{E} = -u_t$ are constant of the motion
- Locally Non Rotating Frames $\mathcal{L} = u_\phi = 0$
- from ∞ contra-rotating (respect to LNRF) particles (photons) can have negative energies

$$-\mathcal{E} = u_t > 0, \quad \mathcal{L} = u_\phi < 0$$



Negative energy photons will be always captured by BH. Can moving charged particle in ergosphere radiate photons with negative energy? What will be consequences of negative photon emission on radiating charged particle dynamics?

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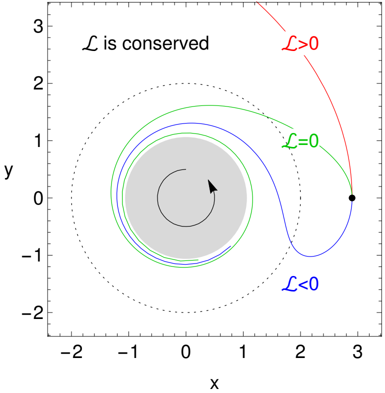

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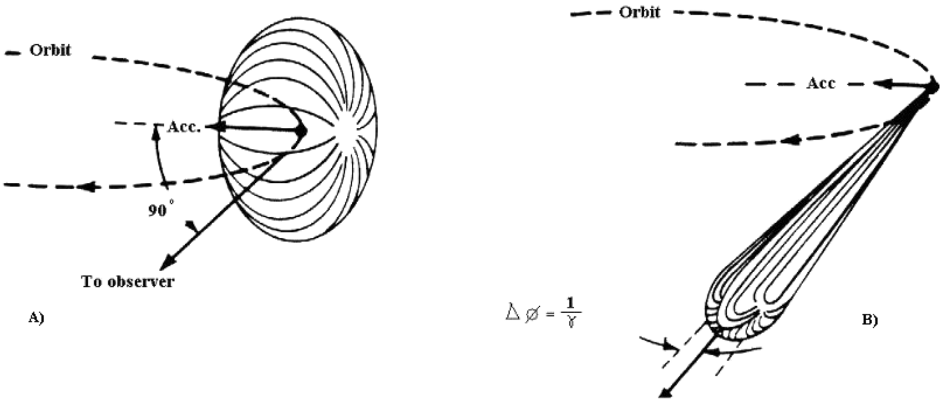
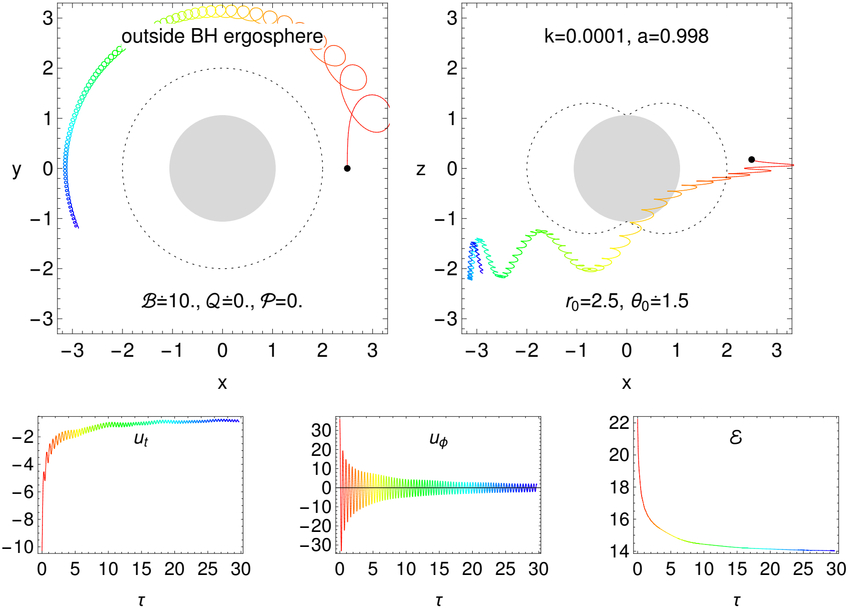
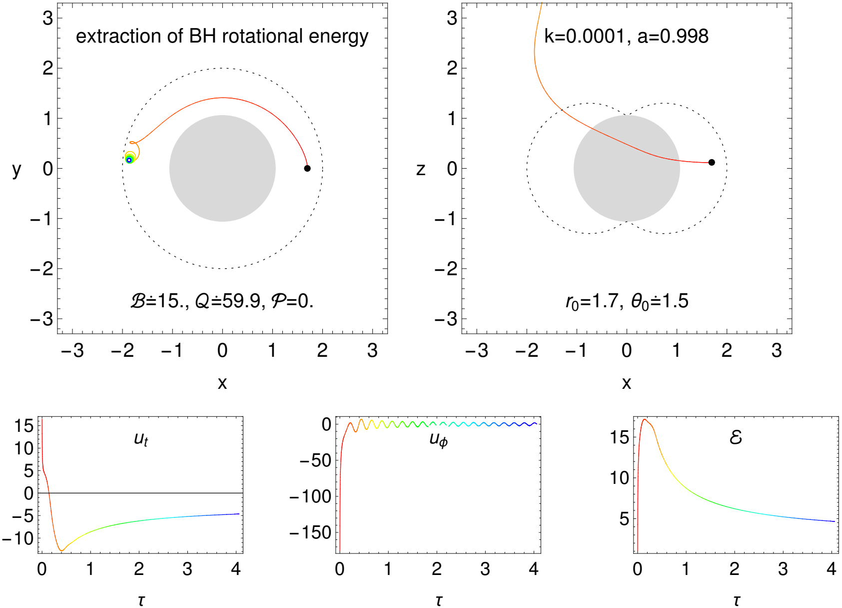
Emitted synchrotron radiation - photons with negative energy

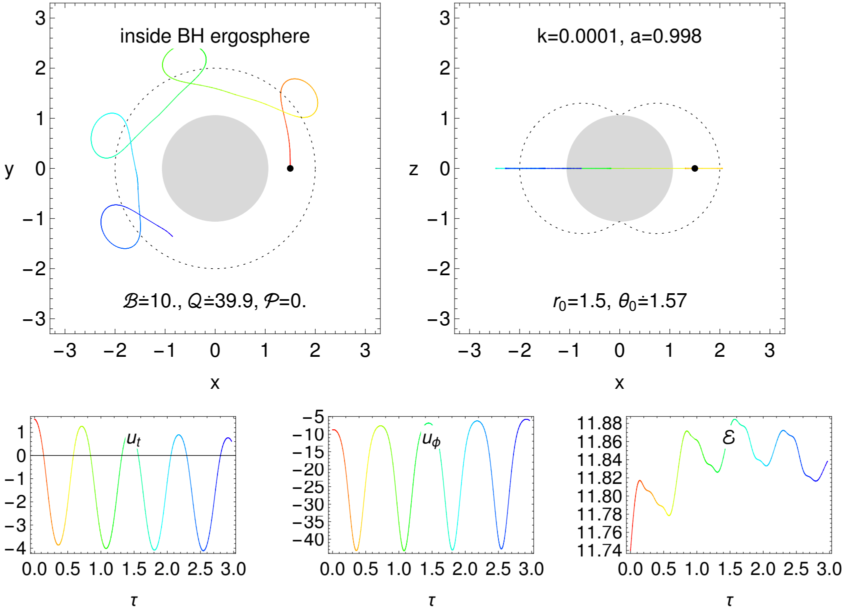


When the electron velocity approaches the speed of light, the emission pattern is sharply collimated forward - photon emission will slow down the radiating electron.

`https://en.wikipedia.org/wiki/Synchrotron_radiation`


outside BH ergosphere
$\mathcal{B} \doteq 10., \mathcal{Q} \doteq 0., \mathcal{P}=0.$
k=0.0001, a=0.998
$r_0=2.5, \theta_0 \doteq 1.5$
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ


extraction of BH rotational energy
k=0.0001, a=0.998
$\mathcal{B}$≐15., $\mathcal{Q}$≐59.9, $\mathcal{P}$=0.
r_0=1.7, θ_0≐1.5
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ


inside BH ergosphere
$\mathcal{B}$≐10., $\mathcal{Q}$≐39.9, $\mathcal{P}$=0.
k=0.0001, a=0.998
r_0=1.5, θ_0≐1.57
x
y
z
u_t
u_ϕ
$\mathcal{E}$
τ

Radiative Penrose process (RPP): summary & consequences

- Radiating charged particle in rotating BH ergosphere emits photons with negative energy if $u_t > 0, u_\phi < 0 \rightarrow$ radiating charged particle will be gaining energy.
- Photons with negative energy (and angular momenta) are always captured by the BH $\rightarrow$ BH spin down $+$ extraction of BH rotation energy
- Radiative Penrose process
  $=$ energy gain by a single radiating charged particle in ergosphere of rotating black hole.
  RPP energy gain is increased with BH rotation and EM field strength.
- Cubic dependence on the particle mass - for electrons only (protons if B is huge).
- Charged particle energy gain by RPP only in BH ergosphere implies: decrease of expected radiation in the ergosphere, but increase of the radiating energy above the ergosphere $+$ existence of floating orbit $\rightarrow$ we expect increase of synchrotron emission just above the static limit (ergosphere edge). Will there be polarized ring at static limit?

Thank you for your attention

codes and more info: `https://github.com/XyhwX` `martin.kolos@physics.slu.cz`

• M. Kološ, A. Tursunov and Z. Stuchlík: *Radiative Penrose process: Energy Gain by a Single Radiating Charged Particle...*, Phys. Rev. D 103, 024021 (2021) [arXiv:2010.09481]