Black hole magnetosphere

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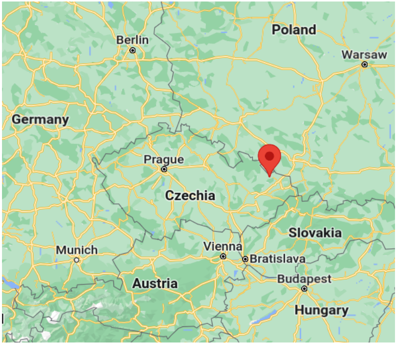
Institute of Physics at Silesian University in Opava

- Opava is located in Upper Silesia, Czech Republic; it has a population of 60 000.
- Institute of Physics: $\sim$ 50 people (Prof. Zdeněk Stuchlík, Roman Konoplya, ...)
- Research centres: Theoretical Physics and Astrophysics; Computational Physics and Data Processing; Educational Centre
- Black Hole Magnetosphere, GAČR standart project 23-07043S (2023-2025)
- Annual relativistic conference from November 10th to 14th `ragtime.physics.cz`



Motivation: Earth's magnetosphere / Van Allen radiation belts

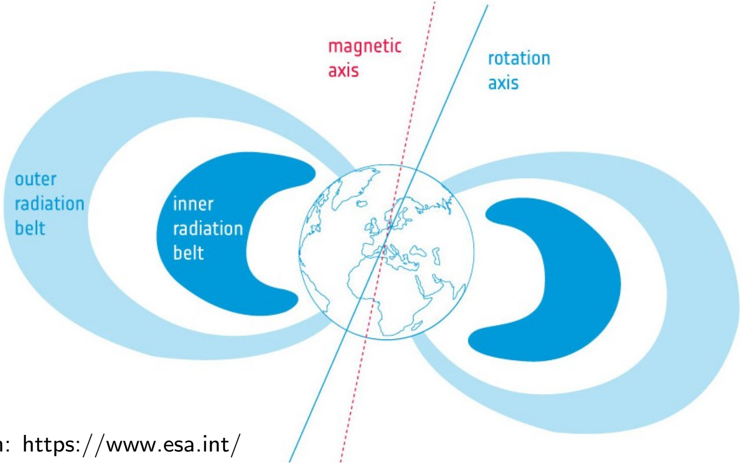
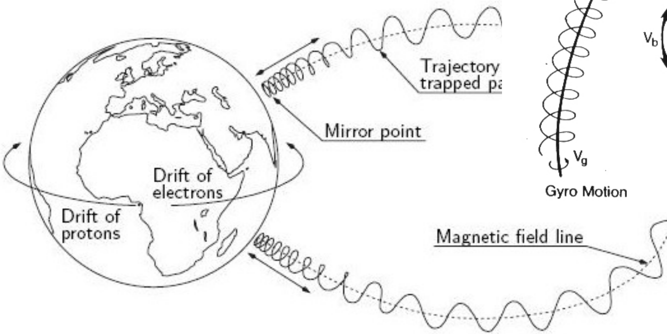
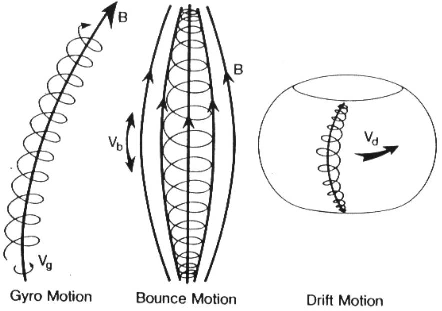


figure from: https://www.esa.int/

Radiation belts - high energy populations of trapped p^+ and e^-:
- inner belt: L-shell 1.2-2.0; 10^{-1} Gs
- outer belt: L-shell 3.0-8.0; 10^{-3} Gs

Charged particle dynamic in Earth's magnetosphere



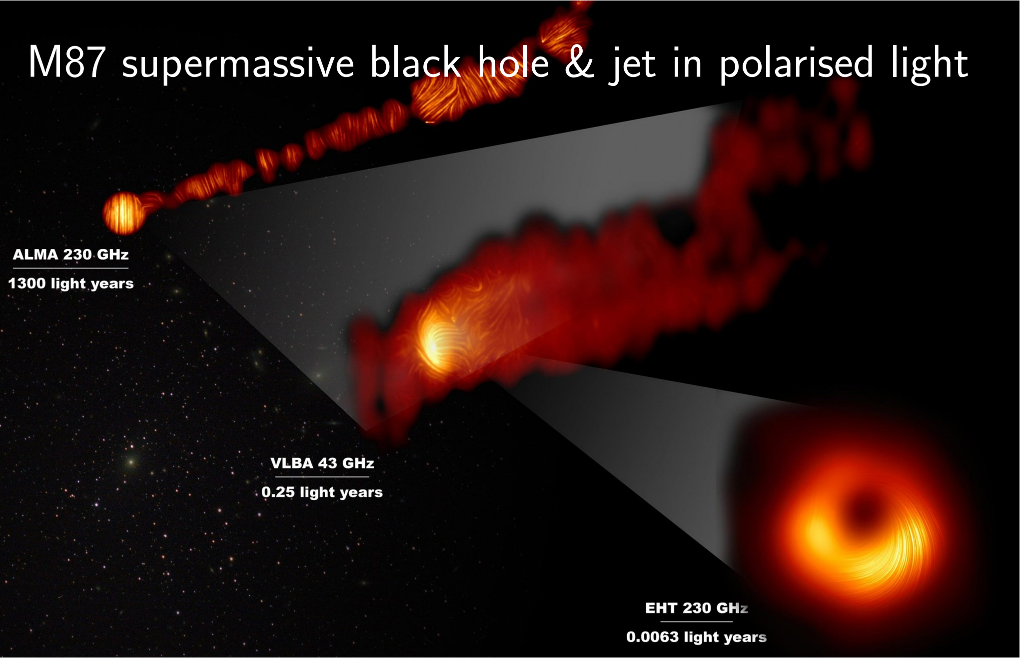


timescales for charged particle
e^-; 100 keV; $L = 4$; $\quad F_{\rm L}/F_{\rm G} = 10^{12}$

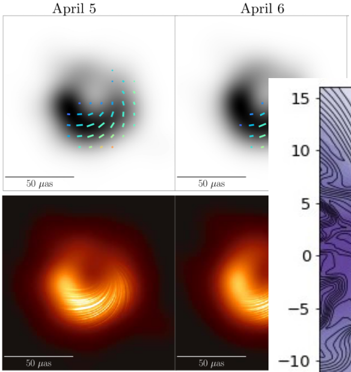
gyration	0.1 ms	$\sim 10^{-4}$ s
bounce	0.5 s	$\sim 10^{0}$ s
drift	2 h	$\sim 10^{4}$ s

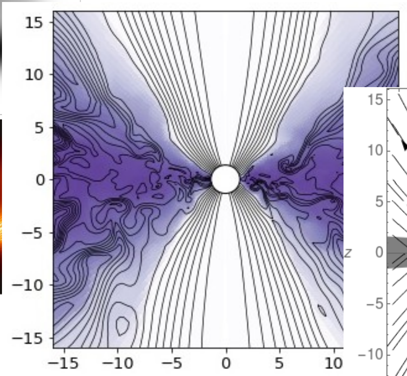
And now magnetic field around black holes!

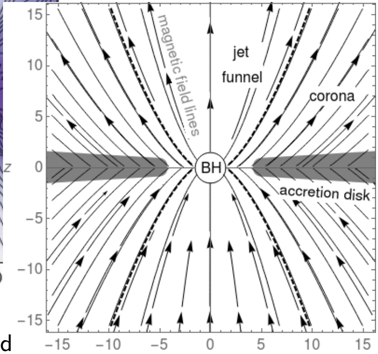
M87 supermassive black hole & jet in polarised light



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

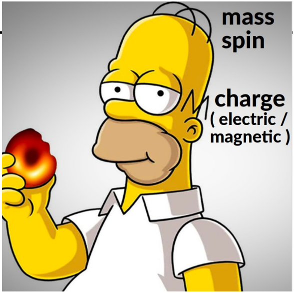






$B_{\mathrm{M87}} \sim 10$ Gs
from "Polarization of the Ring": 10.3847/2041-8213/abe71d

Black hole magnetosphere



A) Black hole alone - BH own EM field

- no-hair theorem - black hole have only three hairs:
  mass, spin, **charge** (electric / magnetic)
  $\Longrightarrow$ monopole character of EM filed around BH
- $\nexists$ of magnetic monopole, but plasma accretion
  $\Longrightarrow$ BH will have **split monopole** magnetic field

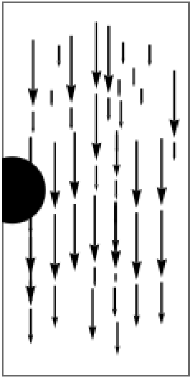
B) Black hole in plasma
electromagnetic field around BH generated by accretion disk

plasma is creating and reacting to magnetic field - much more complex problem

- observed synchrotron polarization: both toroidal B_ϕ and poloidal B_r, B_θ components are present
- solar mass BH $10\mathrm{M}_\odot$ up to 10^8 Gs / supermassive BH $10^9\mathrm{M}_\odot$ up to 10^4 Gs
- rotation (accretion disk or BH) in magnetic field - Farady induction of electic field!

0) Vacuum Maxwell Equations

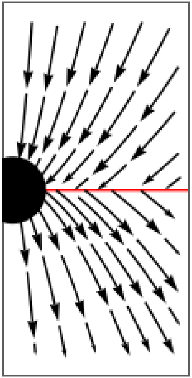
vacuum $J^\mu = 0$



Wald (1974)

1) Force Free Electrodynamics

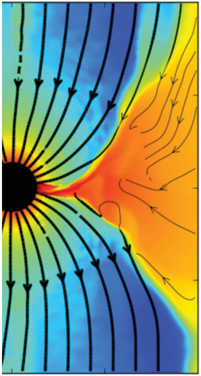
$B^2 \gg \rho c^2$



Blandford-Znajek (1977)

2) Magneto-hydrodynamics

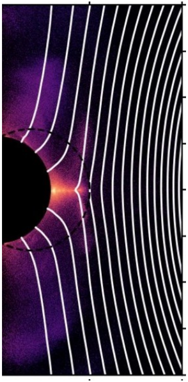
fluid description



Gammie+(2003) HARM code

3) Particle-In-Cell

charged particles



Cerutti+ (2020) GRZeltron

difficulty level $\Longrightarrow$

Vacuum Maxwell equations - Wald solution (1974)

A zero approximation to BH magnetosphere: Maxwell equations in the curved background

$$\nabla_{[\lambda} F_{\mu\nu]} = 0, \quad \nabla^{\mu} F_{\mu\nu} = \mu_0 J_{\nu},$$

where $F_{\mu\nu}$ is Faraday tensor which is related to EM four-potential A_α by

$$F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha .$$

For vacuum there in no EM charge or currents $J^\alpha = 0$.

Maxwell equations are linear and the princip of superposition will allow us to combine diferent solutions.

Example:
uniform magnetic field in Schwarzschild metric

$$A_\mu = \left(0,0,0,\tfrac{B}{2} r^2 \sin^2\theta\right)$$

$$\vec{B} = (B_x, B_y, B_z) = (0,0,B)$$

EM fourpotential for rotating Kerr BH

$$\begin{aligned} A_t &= \frac{B}{2}\left(g_{t\phi} + 2a g_{tt}\right) - \frac{Q}{2M} g_{tt}, \\ A_\phi &= \frac{B}{2}\left(g_{\phi\phi} + 2a g_{t\phi}\right) - \frac{Q}{2M} g_{t\phi}. \end{aligned}$$

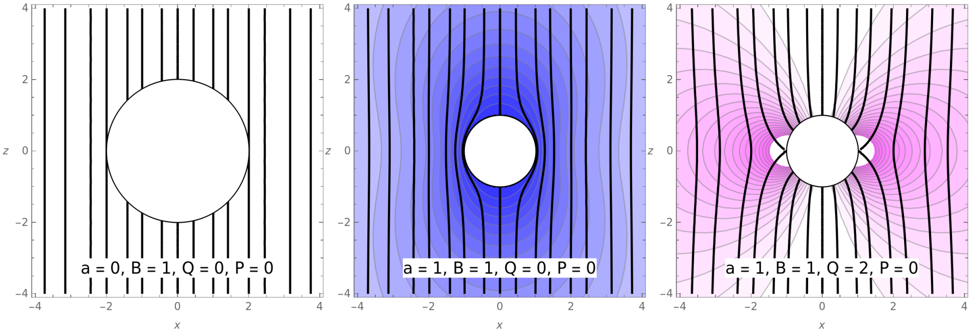
where Q is BH electric monopole charge

Vacuum Maxwell equations - Wald solution (1974)

Magnetic field expulsion (Meissner effect) for extreme Kerr

Induced electric field can't be screened (live MF) for any choice of Wald charge Q

$$\Delta\varphi = \varphi_{\mathrm{H}} - \varphi_{\infty} = \frac{Q - 2aMB}{2M} \qquad A_t,\ \vec{E} \text{ color } (0 \text{ at } \infty) \parallel A_\phi,\ \vec{B} \text{ black lines}$$



- Serguei S. Komissarov: Electrically-charged black holes and the Blandford-Znajek mechanism, MNRAS, 512/2 [arxiv.org/abs/2108.08161] (2022)

Force-free electrodynamics: Blandford-Znajek (1977)

Now plasma is taken into account, but MF energy density dominating over matter energy density $B^2 \gg \rho c^2$. Force-free condition: $F_{\mu\nu} J^\nu = 0, \quad J^\nu \neq 0$

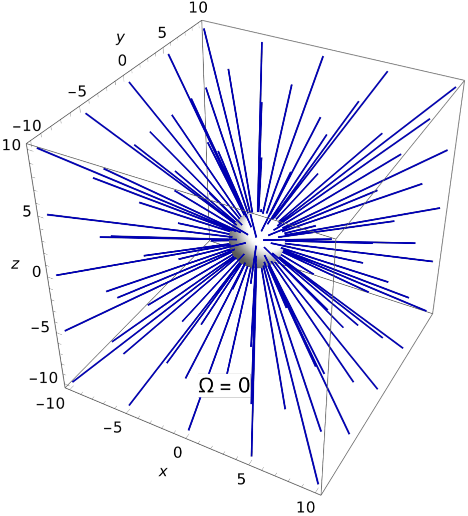
Maxwell equations are linear (superposition) but Force-free electrodynamics is not!

$$\nabla_{[\alpha} F_{\beta\gamma]} = 0, \quad F_{\alpha\beta} \nabla_\gamma F^{\beta\gamma} = 0$$

The Michel (1973) & BZ rotating monopole:

$$A_t = -\Omega B_0 r_0^2 (1 - \cos\theta),$$
$$A_r = 0,$$
$$A_\theta = -\Omega B_0 r_0^2 \sin\theta (2M \log(r - 2M) + r),$$
$$A_\phi = B_0 r_0^2 (1 - \cos\theta)$$

where B_0 is MF magnitude at radius r_0 and Ω is the mag. field line angular velocity



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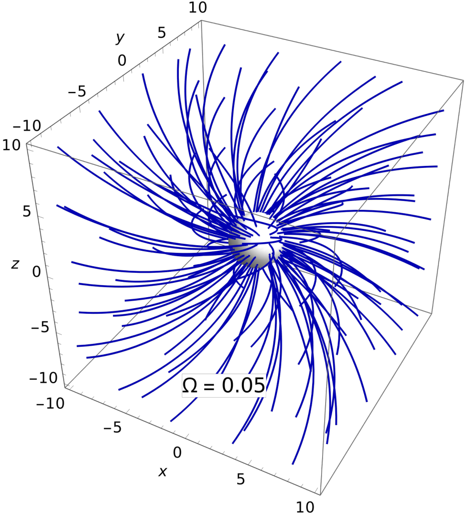


Multimessenger era: Black holes as cosmic rays source

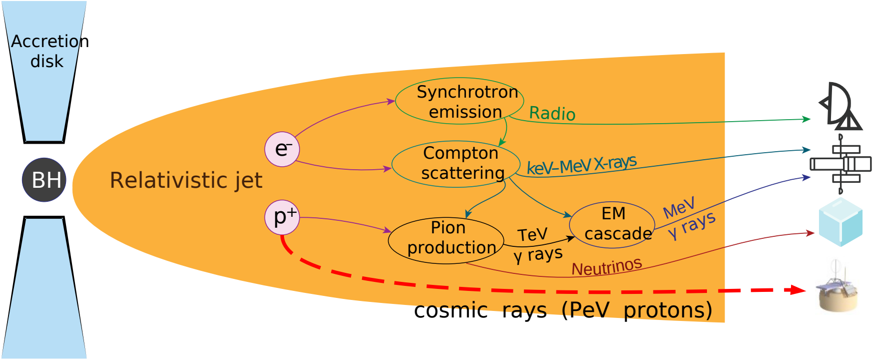


figure from:

- A.V.Plavin et al., The Astrophysical Journal, Volume 908, Issue 2, id.157 (2021)

+ my small update

How to accelerate charged particles?

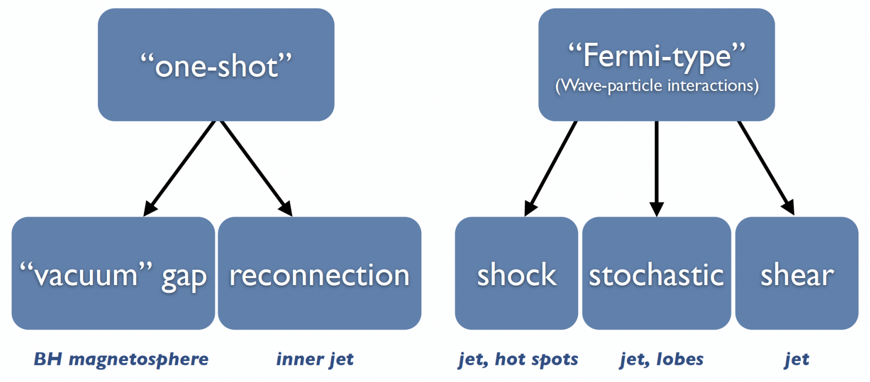
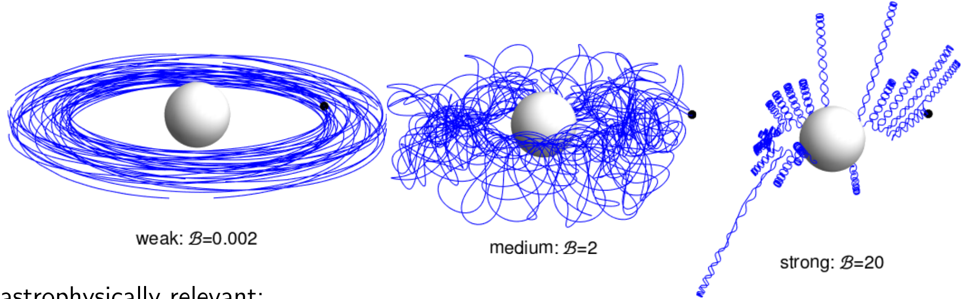


figure from:

- Frank M. Rieger: Active Galactic Nuclei as Potential Sources of Ultra-High Energy Cosmic Rays, Universe, Volume 8, Issue 11, id.607 (2022)

Charged particle dynamic: 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:

Charged particle acceleration - magnetic Penrose process

- particle injection?
  neutral particle (1) $\rightarrow$ charged (2) + (3)

$$p_{\alpha(1)} = p_{\alpha(2)} + qA_{\alpha} + p_{\alpha(3)} - qA_{\alpha}$$

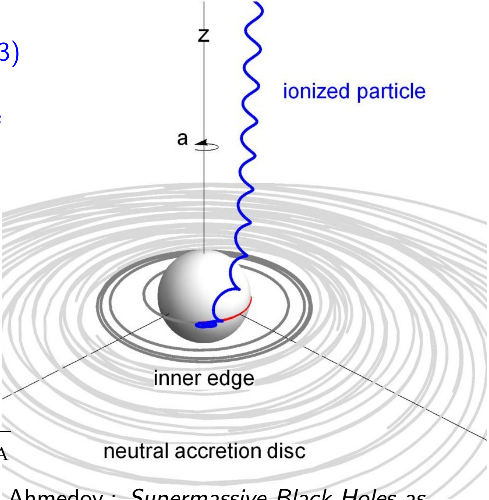
- to shift the particle energy we need A_t

$$E/m = -g_{t\alpha}u^{\alpha} + (q/m)A_t$$

  we need BH / accretion disk rotation
  to change magnetic $\leftrightarrow$ electric field

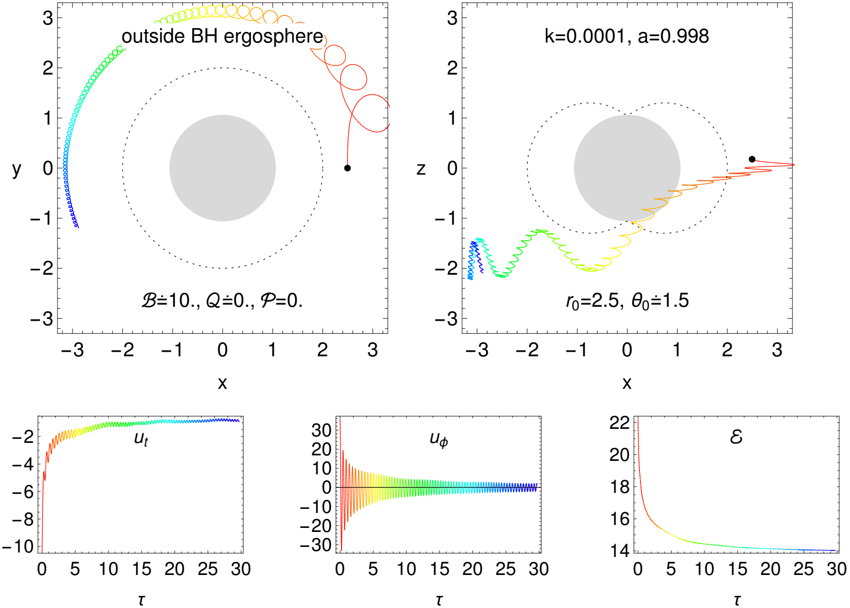
- max acceleraton (energy):

$$\mathcal{E} \sim \tilde{q}A_t = 5{\times}10^{15}\mathrm{eV} \cdot \frac{B}{10\mathrm{G}} \cdot \frac{M}{M_{\mathrm{SgrA}}}$$

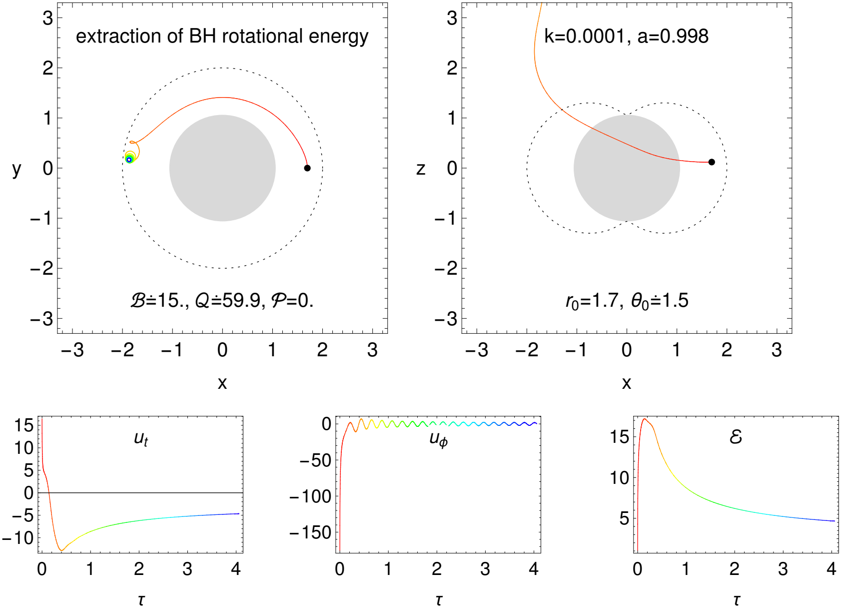


• A.Tursunov,Z.Stuchlík,M.Kološ,N.Dadhich,B. Ahmedov,: *Supermassive Black Holes as Possible Sources of Ultrahigh-energy Cosmic Rays*, The Astrophysical Journal, Volume 895, Issue 1, id.14, 11 pp. (2020)

Charged particle radiation - losing energy (& ang. mometum)



Energy gain in BH ergosphere - **Radiative Penrose process**



Summary & Our Plans for the Future

- Black hole magnetosphere = plasma + large-scale magnetic field
  + Single charged test particle dynamics can reveal the forces acting within the system (equilibrium positions); can describing fast processes like single-shot particle acceleration.
  - Plasma collective dynamics (particle-to-particle interactions) are missing.

- Magnetic Penrose process: Supermassive BH can accelerate charged particles to Ultra High Energies (cosmic rays); Sgr A* as a PeVatron

- Radiative Penrose process (RPP): energy gain by a single radiating charged particle in the ergosphere of a rotating BH; $\rightarrow$ increase in **synchrotron emission** just above the ergosphere. Could ngEHT see polarized "ergospheric ring"?

- Our current plans:
  - Explore BH magnetosphere analytic models using force-free electrodynamics.
  - Testing various problems (stability, BH charge,...) with GR particle-in-cell code.
  - EM (synchrotron) spectrum produced by charged particle radiation. Will this full GR treatment provide unique observational signature? RPP observational evedence?

Codes / info: `https://github.com/XyhwX` `martin.kolos@physics.slu.cz`