Radiating charged particle dynamics in black hole magnetosphere

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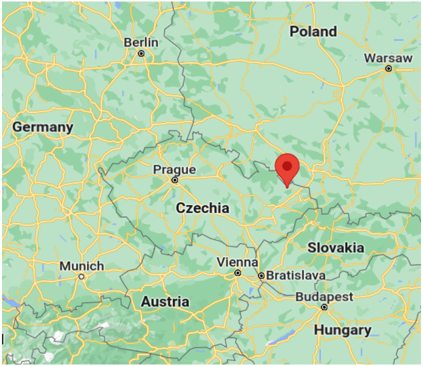
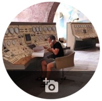
- Opava is located in Upper Silesia, Czech Republic; it has a population of 60 000.
- Institute of Physics: $\sim$ 50 people (Prof. Zdeněk Stuchlík, Roman Konoplya, ...)
- Research centres: Theoretical Physics and Astrophysics; Computational Physics and Data Processing; Educational Centre
- Annual relativistic conference in autumn – you are welcome!
  `https://ragtime.physics.cz/`





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Relativistic Astrophysics   Black holes   Dynamical systems

FOLLOWING

TITLE	CITED BY	YEAR
Influence of cosmic repulsion and magnetic fields on accretion disks rotating around Kerr black holes Z Stuchlík, M Kološ, J Kovář, P Slaný, A Tursunov Universe 6 (2), 26	195	2020
Quasi-harmonic oscillatory motion of charged particles around a Schwarzschild black hole immersed in a uniform magnetic field M Kološ, Z Stuchlík, A Tursunov Classical and Quantum Gravity 32 (16), 165009	170	2015
Acceleration of the charged particles due to chaotic scattering in the combined black hole gravitational field and asymptotically uniform magnetic field Z Stuchlík, M Kološ The European Physical Journal C 76, 1-21	166	2016
Circular orbits and related quasiharmonic oscillatory motion of charged particles around weakly magnetized rotating black holes A Tursunov, Z Stuchlík, M Kološ Physical Review D 93 (8), 084012	163	2016
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Models of quasi-periodic oscillations related to mass and spin of the GRO J1655-40 black hole	66	2016

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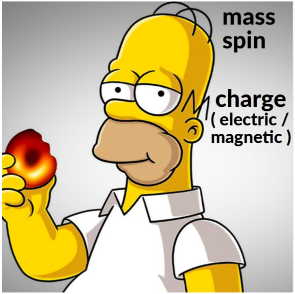
Black hole magnetosphere models

Why could it be useful to have a model for the BH magnetosphere?
So we can calculate:

- EM energy outflow (BH slowdown, Poynting flux, . . .)
- Charged particle dynamics (forces, timescales, frequencies, synchrotron spectrum, . . .)



A) Black hole alone – BH's own EM field

No-hair theorem – black holes have only three hairs:
mass, spin, **charge** (electric / magnetic)
$\Longrightarrow$ monopole character of the EM field close to the black hole

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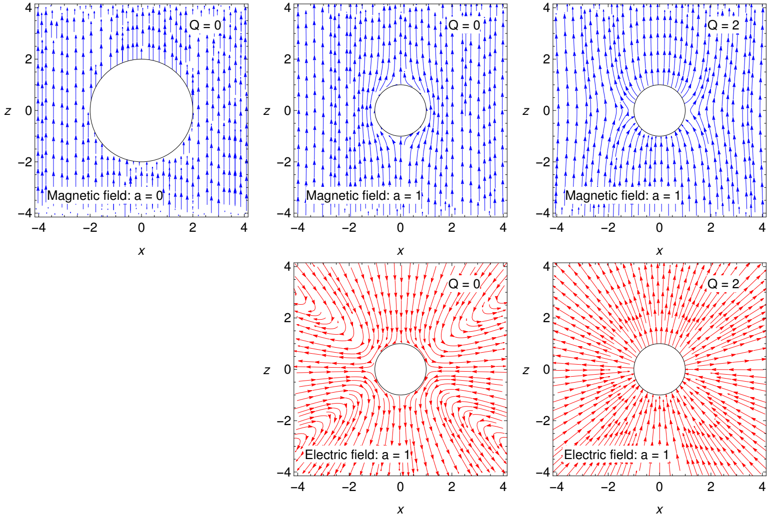
B) Black hole not alone
– electromagnetic field around the BH generated by moving plasma

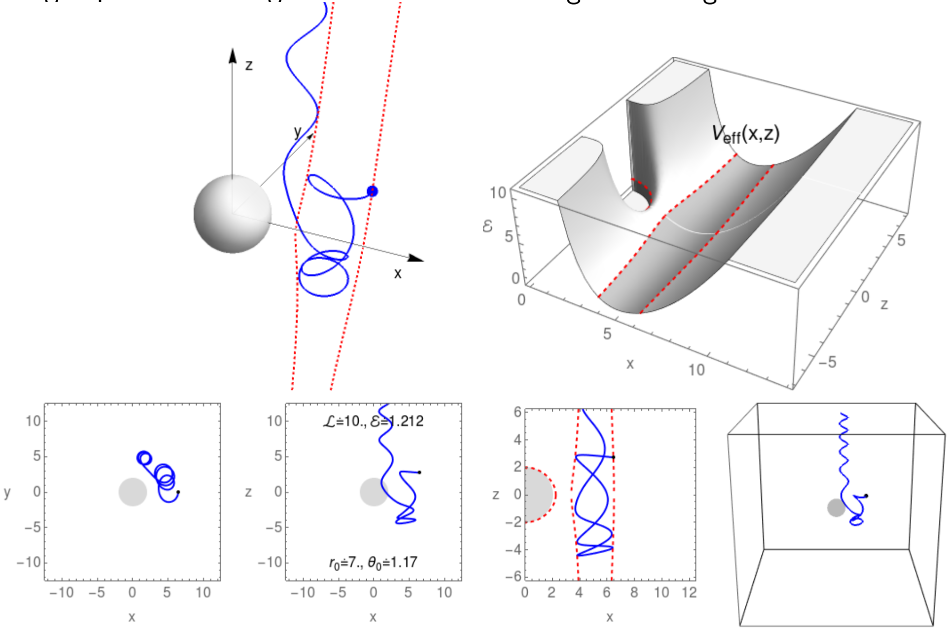
0) Vacuum Maxwell Equations	1) Force-Free Electrodynamics	2) Magnetohydrodynamics	3) Kinetic Approach: Particle-In-Cell
vacuum $J^\mu = 0$	$B^2 \gg \rho c^2$	fluid description	charged particles

BH magnetosphre model: 0) vacuum Maxwell equations - Wald solution (1974)

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



Charged particle moving in combined electromagnetic and gravitational fields



Full GR formalism for radiating charged particle dynamics in curved background

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

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

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

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

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

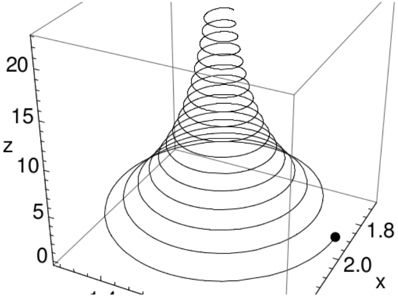
- 1st term $D^2 u^\mu / d\tau^2$ is problematic - high order derivative - can be substituted, particle acceleration mostly by Lorentz force (excellent for $\mathcal{B} > 1$), trick from Landau & Lifshitz
- 2nd term gone zero - Ricci tensor vanishes the vacuum metrics
- 3rd term - "tail" integral (non-local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

Flat spacetime EQM:

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

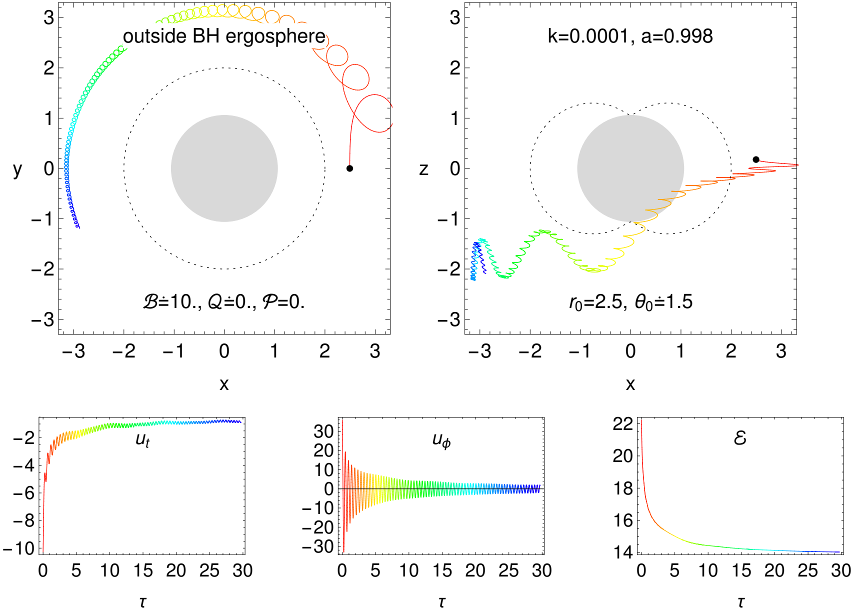


example for flat spacetime, uniform mag. field, $u_\perp^2 = (u^x)^2 + (u^y)^2$

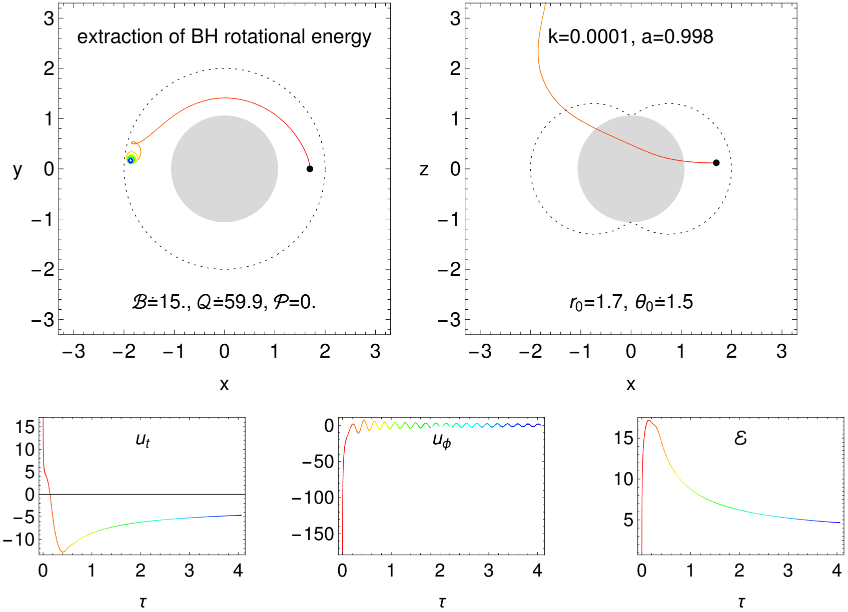
vs. **Kerr ergosphere** - Radiative Penrose process

- In the rotating black hole ergosphere, a photon's energy can be negative (relative to ∞)
- A particle with angular momentum $\mathcal{L} = u_\phi < 0$ and energy $-\mathcal{E} = u_t > 0$ can emit these negative-energy photons; negative energy photons are captured by the black hole)
- Radiating charged particle in ergosphere is gaining energy* (*not always, sometimes)

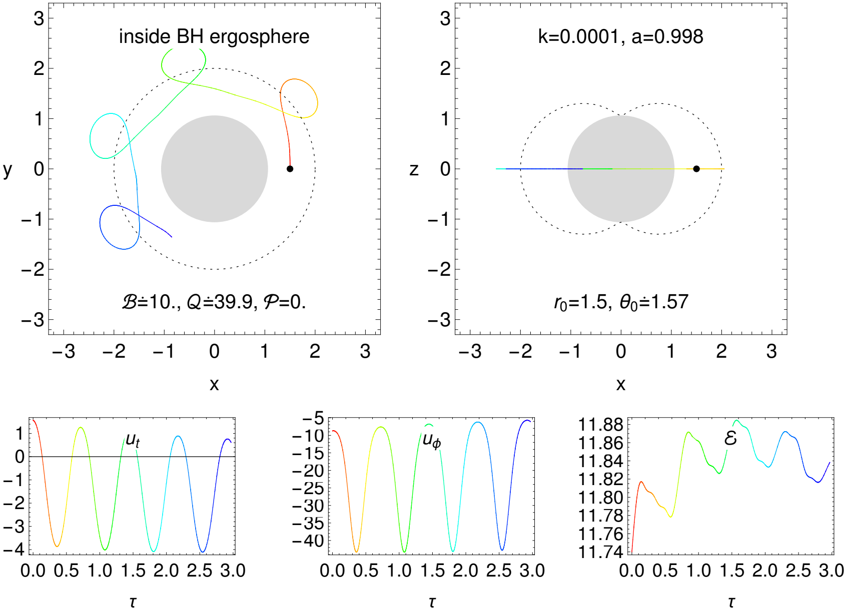
• M. Kološ, A. Tursunov and Z. Stuchlík: *Radiative Penrose process: Energy Gain by a Single Radiating Charged Particle...*, Phys. Rev. D 103, 024021 (2021) [arXiv:2010.09481]



Particle is losing energy (and angular momenta) due to radiation reaction - this is common -



Particle is **gaining** energy in ergosphere due to radiation reaction – **Radiative Penrose process**



repetitive **RPP** - extracting energy inside ergosphere; depositing energy γ outside ergosphere

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). Only ODEs are solved for particle dynamics instead of complex systems of partial differential equations, such as those in GRMHD. Test particle dynamics can provide estimates of time scales for various astrophysical processes and are crucial for describing fast processes like single-shot particle acceleration.
  - Plasma collective dynamics (particle-to-particle interactions) are missing.

- **Radiative Penrose process (RPP)**
  = energy gain by a single radiating charged particle in the ergosphere of a rotating BH;
  RPP implies: a decrease in expected radiation within the ergosphere, but an increase in the radiated energy above the ergosphere, plus the existence of a **floating orbit** $\rightarrow$ we expect an increase in **synchrotron emission** just above the ergosphere edge.
  Will next-generation Event Horizon Telescope see polarized "ergospheric ring"?

- Our current plans:
  - Improve the particle-in-cell code (kinetic methods) with fully general relativistic radiation reaction.
  - Will this full GR treatment of RR provide unique observational signatures of General Relativity in polarized synchrotron radiation?

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