Charged particle dynamic in black hole magnetosphere

Habilitation lecture

Martin Kološ

Silesian University in Opava / 12.11.2025

Martin Kološ curriculum vitae

- 2013 PhD in Theoretical Physics and Astrophysics, SU Opava, String-loop dynamics... (Prof. Zdeněk Stuchlík)
- Web of Science: 47 publications, 1 568 Times Cited, 25 H-Index
- supervised defended bachelor/master/doctoral theses: 3/2/1
- Teaching: Deterministic chaos, Classical electrodynamic, Seminar on mat.methods
- PI in GAČR standard project 23-07043S Black Hole Magnetosphere (2023-2025)
- likes books (Jules Verne), bookshop antikopava.cz, Hrnčířská 13 Opava
- 3 kids, likes to dance swing, running...

Martin Kološ (room 214) **MindMap** (black holes+...)

Charged particle dynamic

- exploring various EM configurations
- radiation, EM spectrum, Radiative Penrose process
- particle acceleration, energy spectra
- spinning, magnetized,...

Arman Tursunov, Zdeněk Stuchlík, Misbah Shahzadi, David Kofroň, BakhtinurJuraev...

Data analysis

RQA, gravitational waves, QPOs

String Loop

vibrations, flux tube (FFE) connection, RingWorld stability

Magnetosphere

- Force-free electrodynamics, rotating split magnetic monopole (Pahlavon Yovqochev)
- particle-wave interactions
- neutron star (Jaroslav Vrba)

Numerical simulations

- GRMHD (HARM code, Dilshodbek Bardiev)
- GRPIC (GRZeltron, Farukh Abdulkhamidov)

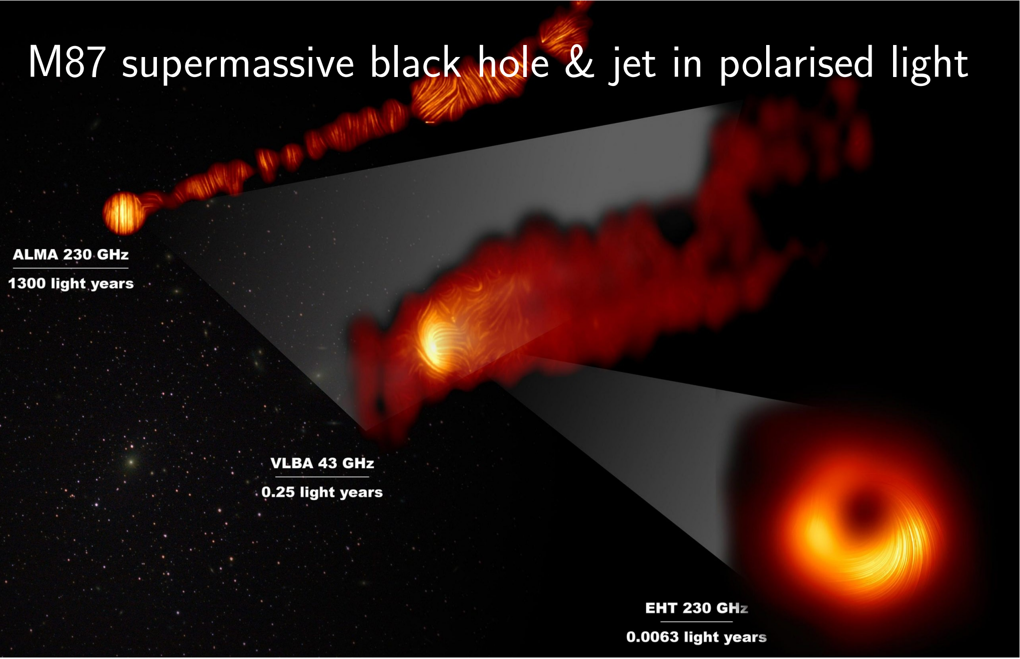
Chaos, QPOs & Resonances

3:2 resonances, nonlinear systems

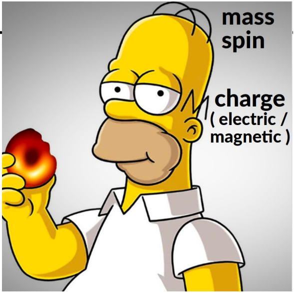
Black hole magnetosphere

- black hole - an extremely compact astronomical object whose gravity is so intense that nothing, not even light, can escape it.
- magnetosphere - a region of space surrounding an astronomical object in which charged particles are affected by that object's magnetic field

M87 supermassive black hole & jet in polarised light



Black hole magnetosphere



A) Black hole alone - BH own EM field

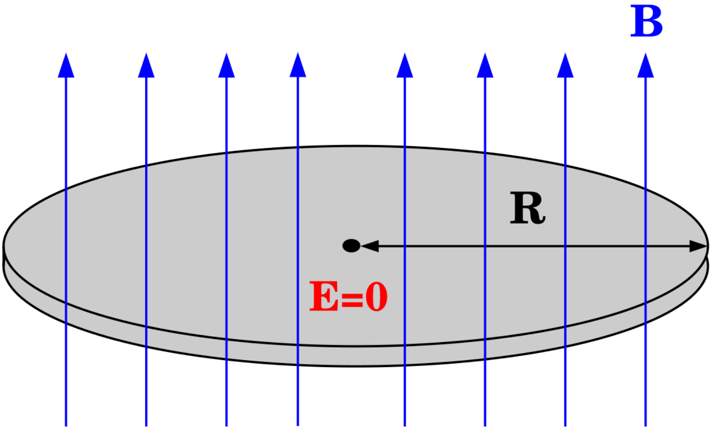
- no-hair theorem - black hole have only three hairs:
  mass, spin, **charge** (electric / magnetic)
  $\Longrightarrow$ monopole character of EM filed around BH
- $\nexists$ of magnetic monopole, but plasma accretion
  $\Longrightarrow$ BH will have **split monopole** magnetic field

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 - Faraday induction of electric field!

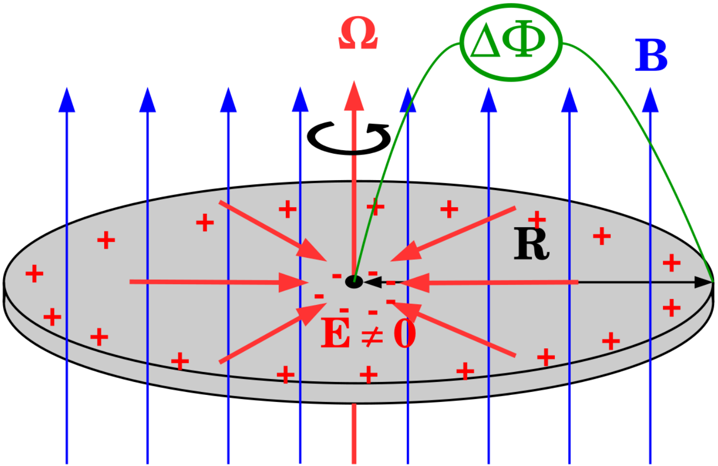
Faraday's disk analogy / electro&magnetic field



=> Electric field E=0

figures by Benoît Cerutti, more complex when conducting plasma is included

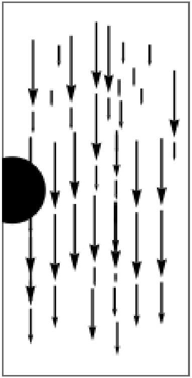
Faraday's disk analogy / electro&magnetic field



figures by Benoît Cerutti, more complex when conducting plasma is included

0) Vacuum Maxwell Equations

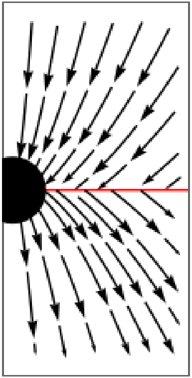
vacuum $J^\mu = 0$



Wald (1974)

1) Force Free Electrodynamics

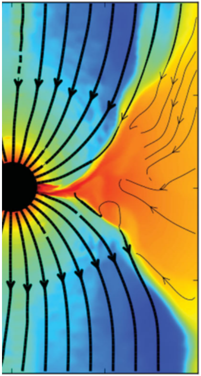
$B^2 \gg \rho c^2$



Blandford-Znajek (1977)

2) Magneto-hydrodynamics

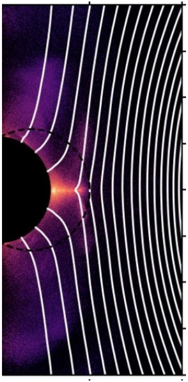
fluid description



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 four-potential for rotating Kerr BH

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

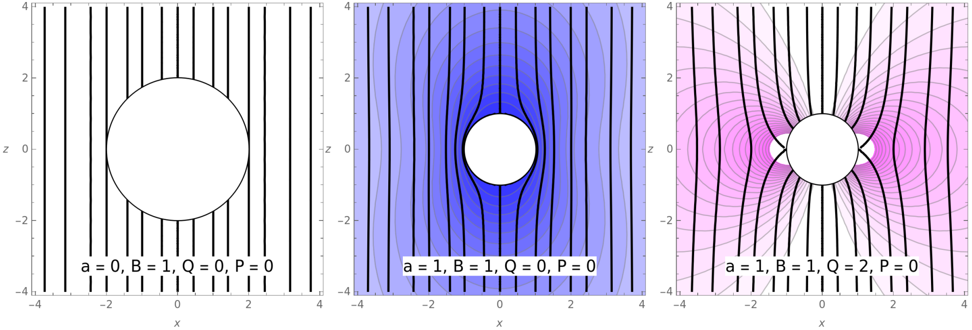
where Q is BH electric monopole charge

Vacuum Maxwell equations - Wald solution (1974)

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

$$\Delta\varphi = \varphi_{\rm H} - \varphi_{\infty} = \frac{Q - 2aMB}{2M}$$

A_t, $\vec{E}$ color (0 at ∞) $\parallel$ A_ϕ, $\vec{B}$ black lines



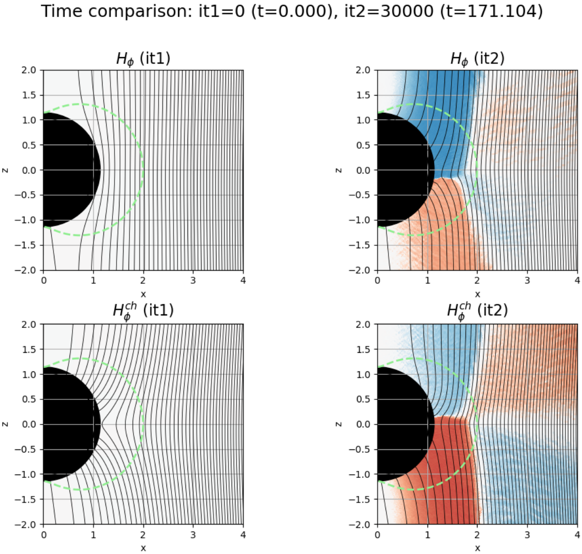
? It would be highly valuable to hear the candidate's extended perspective on the significance of this process in light of recent developments, such as the studies by Komissarov (MNRAS 521, 2022) and King&Pringle (ApJ Letters 918, 2021).

Induced Wald charge / GRPIC simulation (?) in preparation

black hole ($a = 0.99$) in uniform magnetic field, two initial configurations:

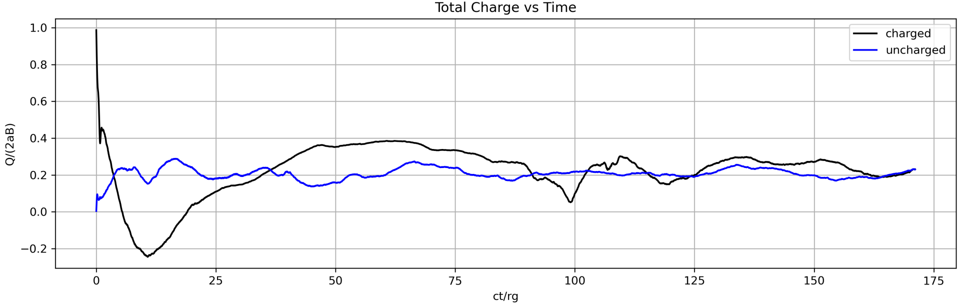
$Q = 0$ (upper row)
vs.
$Q = Q_{\rm W}$ (lower row)

simulations done by Farukh Abdulkhamidov using GRZeltron code (B.Cerutti+)



Induced Wald charge / GRPIC simulation (?) in preparation

black hole in uniform magnetic field, two initial configurations: $Q = 0$ vs. $Q = Q_{\mathrm{W}}$



- in GRPIC simulations $Q \sim 0.2\, Q_{\mathrm{W}}$ value has been reached for both cases
- energetic argument (without plasma / currents) $Q = 0.13\, Q_{\mathrm{W}}$ $(a \to 1)$
  • Li-Xin Li. Electromagnetic energy for a charged Kerr black hole in a uniform magnetic field. Phys. Rev. D, 61(8):084033 (2000)

Charged particle dynamic

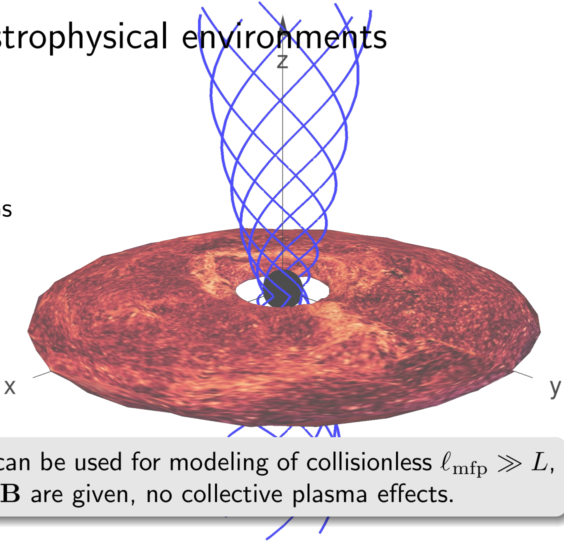
- The analysis of a single charged particle is a simple and elegant tool to explore the BH magnetosphere - only ODEs are solved.
  Plasma collective phenomena are neglected, not self-consistent scenario.
- Test particle dynamics can provide estimates of time scales for various astrophysical processes and are crucial in descriptions of fast processes like single-shot particle acceleration.

Plasma modeling across astrophysical environments

complete different conditions

* for different astro. objects
  - $10 M_\odot$ solar mass BH: 10^8 Gs
  - $10^9 \mathrm{M}_\odot$ supermassive BH: 10^4 Gs
  - planetary magnetosphere, star, neutron star, ...
* different parts of the object

accrection disk / corona / jet funnel

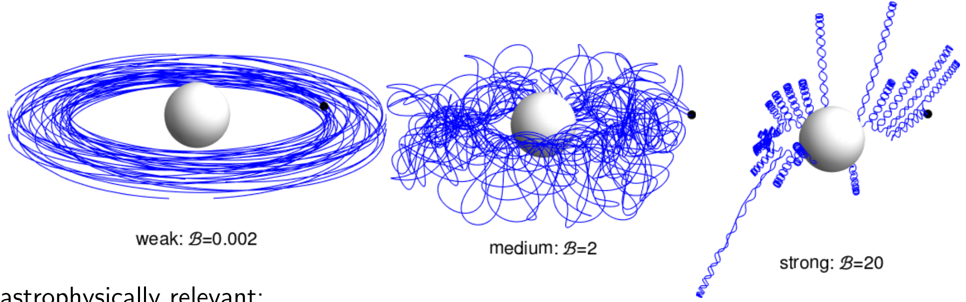


Single test charged particle dynamic can be used for modeling of collisionless $\ell_{\mathrm{mfp}} \gg L$, low density plasma $n \to 0$. Fields $\mathbf{E}, \mathbf{B}$ are given, no collective plasma effects.

$r_L = v_\perp mc/qB$	Larmor radius	Radius of gyration around magnetic field lines
ℓ_{mfp}	Mean free path	Average distance between collisions
L	System scale	Characteristic gradient length of fields or density

Charged particle dynamic: weak $\mathcal{B} \ll 1$ || strong $\mathcal{B} \gg 1$

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

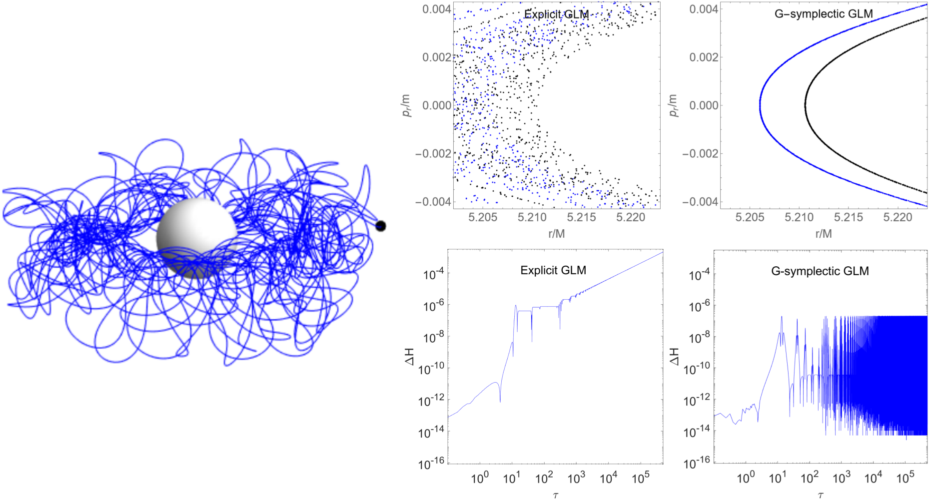


astrophysically relevant:

- 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:

Nonlinear ODE for trajectory - accuracy/stability/efficiency



? In figure 2.7 the plots of numerical errors in middle and right panels exhibit sharp constant upper and lower cut-offs for the oscillations. What is the reason behind this behavior?

Single charged particle dynamics → astrophysical applications

- Charged particle frequency and observed Quasi-Periodic Oscillations
  M. Kološ, Z. Stuchlík and A. Tursunov: *Quasi-harmonic oscillatory motion of charged particles around a Schwarzschild black hole immersed in a uniform magnetic field* CQQG 32 (16), 165009 182 (2015) [arXiv:1506.06799]
- Particle ionization process / accelerated particles as ultra-high-energy cosmic rays
  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) [arXiv:2004.07907]
- Full GR treatments of radiating charged particle dynamic
  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]

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Multi-messenger era: Black holes as cosmic rays source

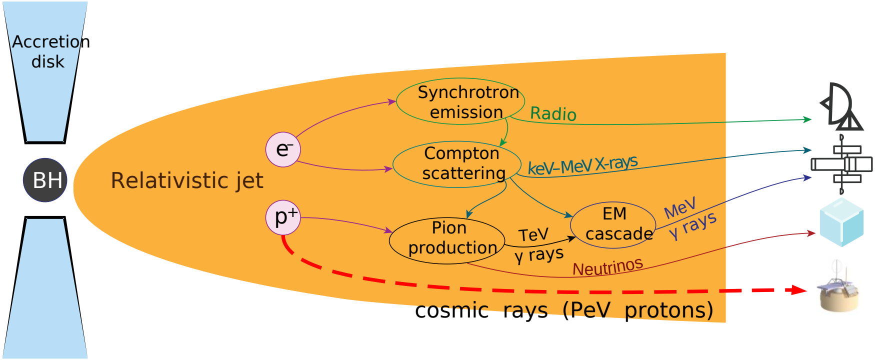


figure from:

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

+ my small update

Charged particle acceleration - magnetic Penrose process

- particle injection?
  neutral particle (1) → charged (2) + (3)

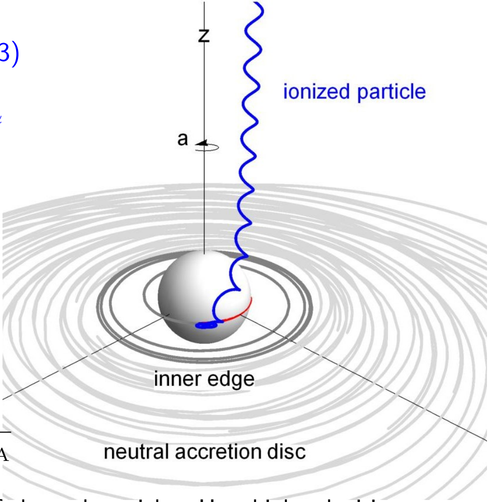
$$p_{\alpha(1)} = p_{\alpha(2)} + qA_\alpha + p_{\alpha(3)} - qA_\alpha$$

- 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 ↔ electric field
- max acceleraton (energy):

$$\mathcal{E} \sim \tilde{q}A_t = 5\times10^{15}\mathrm{eV}\cdot\frac{B}{10\mathrm{G}}\cdot\frac{M}{M_{\mathrm{SgrA}}}$$



(?) The figure 2.5 shows escaping trajectories of charged particles. How high velocities or energies can such escaping particles achieve asymptotically in realistic scenarios?

Inspiration: Earth's magnetosphere / Van Allen radiation belts

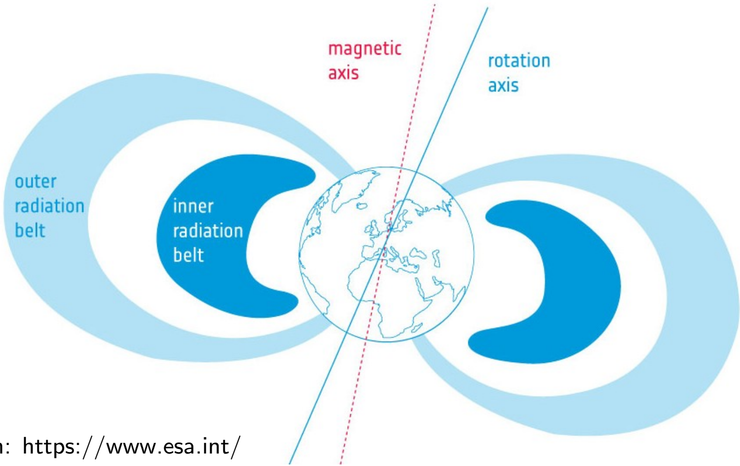
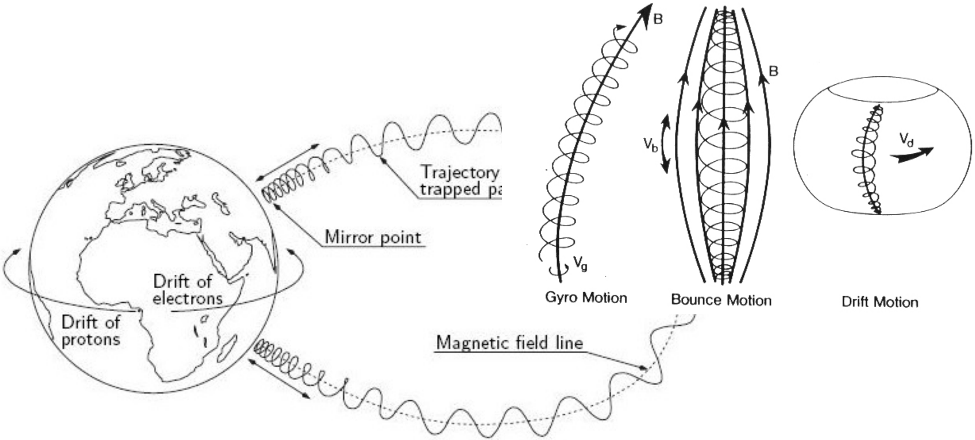


figure from: https://www.esa.int/

ⓘ In figure 3.9 the nature of motion of charged particles after ionization in the disk evidently leads to charge separation. Can one expect that this will have significant effect on the structure of the magnetic field in the vicinity of the disk?

Inspiration: Earth's magnetosphere / Van Allen radiation belts



? In figure 3.9 the nature of motion of charged particles after ionization in the disk evidently leads to charge separation. Can one expect that this will have significant effect on the structure of the magnetic field in the vicinity of the disk?

Radiating particle in curved background - full GR formalism

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

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

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

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

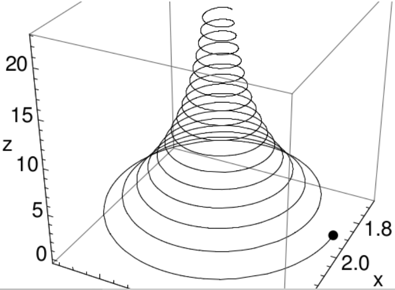
flat spacetime:

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

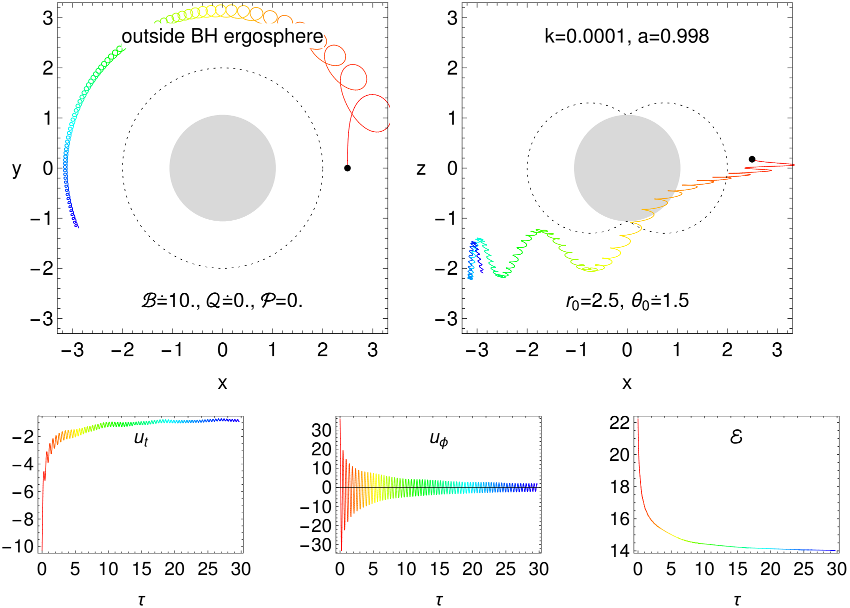
$$\frac{du^y}{d\tau} = -\frac{qB}{m} u^x - \frac{2q^4 B^2}{3m^3}\left(1 + u_\perp^2\right) u^y,$$

$$\frac{du^z}{d\tau} = -\frac{2q^4 B^2}{3m^3} u_\perp^2 u^z,$$

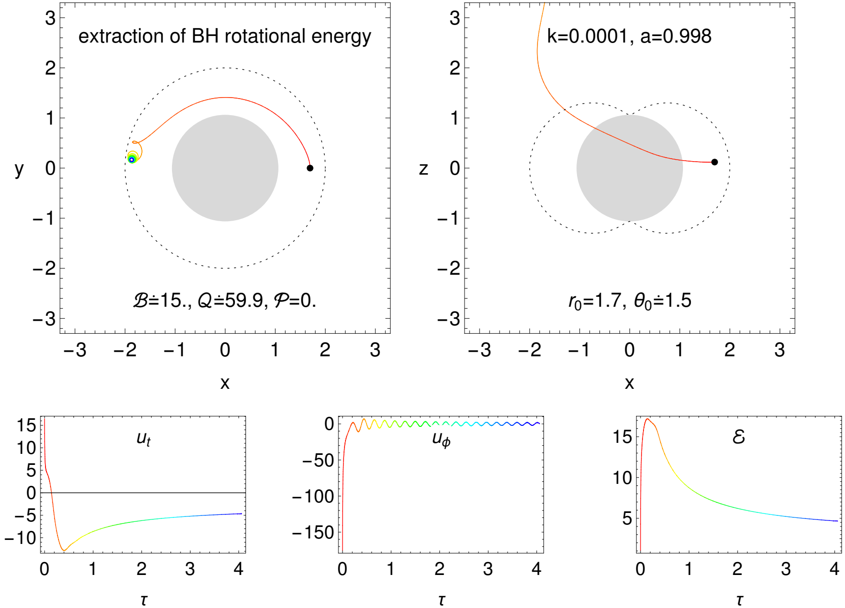
$$\frac{du^t}{d\tau} = -\frac{2q^4 B^2}{3m^3} u_\perp^2 u^t, \qquad u_\perp^2 = (u^x)^2 + (u^y)^2$$



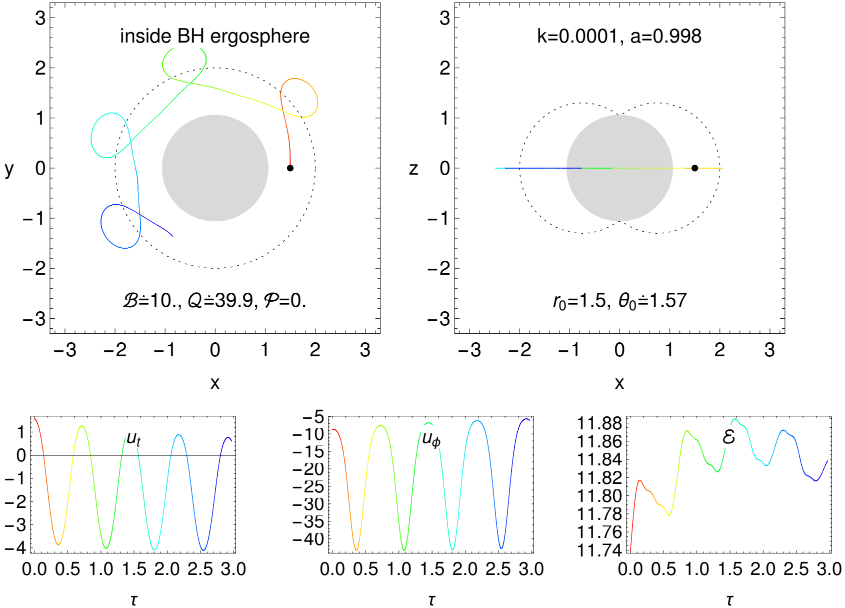
Charged particle radiation - losing energy (& ang. mometum)



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

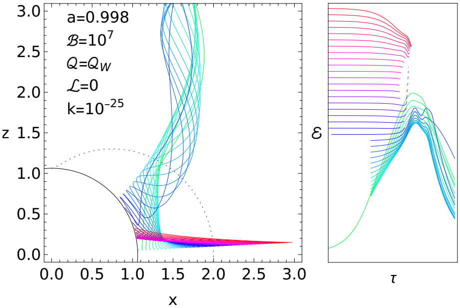


Energy gain in BH ergosphere - **Radiative Penrose process**



Radiative Penrose process - astrophysical relevance (?)

- rotating BH ergosphere - photons with negative energy relative to ∞
- conditions for emitting negative energy photons: $u_\phi < 0$, $u_t > 0$
- RPP for particles with low γ factor - "weak" synchrotron emission?
- GRPIC codes have $\gamma \gg 1$ limit - now full Radiation Reaction term



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"?

? Are the conditions for radiative Penrose process described in section 3.6 realistic or does one need to assume low probability situation for combined system of particle and emitted radiation?

BH magnetosphere: 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; → 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 evidence?

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