Parabolic black hole magnetosphere and charged particle dynamic

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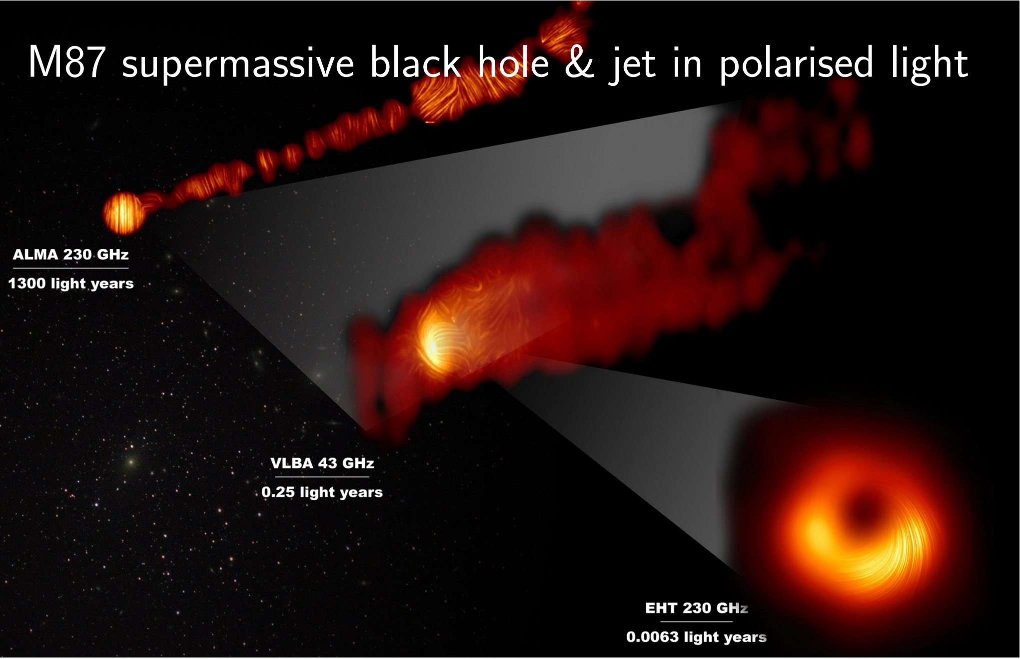
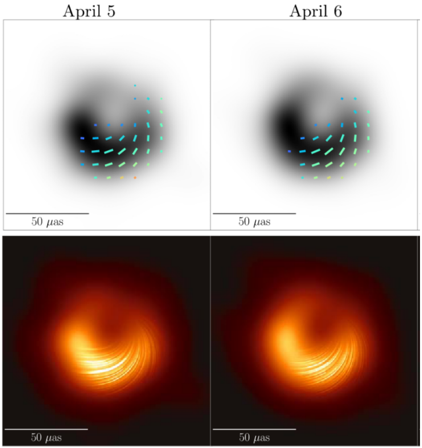
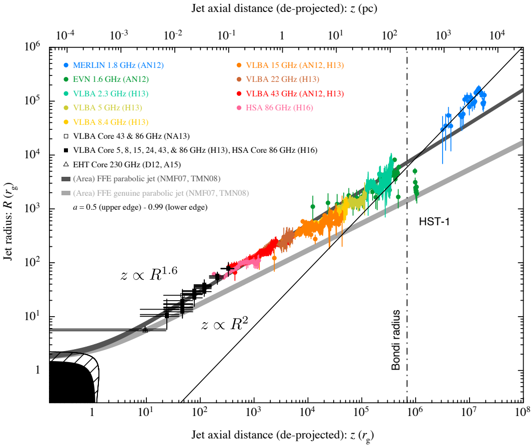
24nd RAGtime workshop 10-14 October 2022

M87 supermassive black hole & jet in polarised light







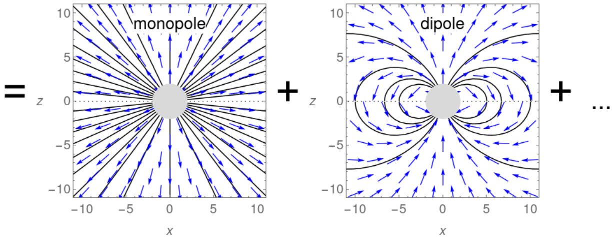
• The Event Horizon Telescope Collaboration: *First M87 Event Horizon Telescope Results. VII. Polarization of the Ring*, The Astrophysical Journal Letters on March 24 (2021) [arXiv:2105.01169]

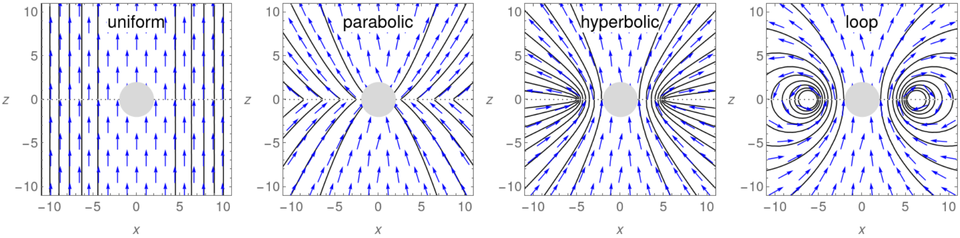
• M. Nakamura et al.: *Parabolic Jets from the Spinning Black Hole in M87*, The Astrophysical Journal, 868, 146, (2018) [arXiv:1810.09963]

Gravity & electro**magnetism** in curved spacetime

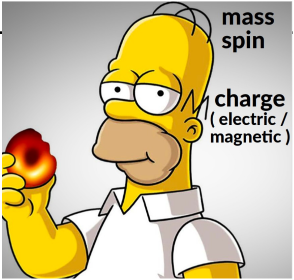
realistic astrophysical situations: magnetic field is test field only (if $\ll 10^{18}$ Gs ✓)
electromagnetic test field on Kerr background (this talk: Schwarzschild - no rotation)

Maxwell equations are linear
any mag.field can be given
(multipolar expansion)



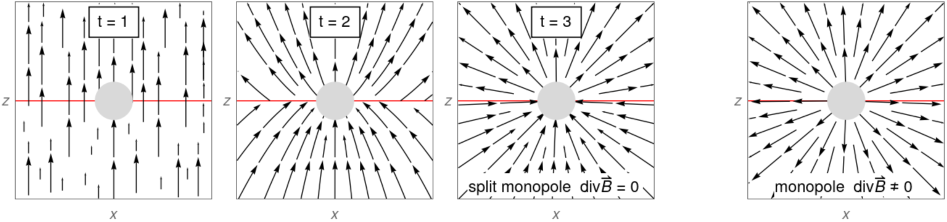


Black hole magnetosphere



A) Black hole alone - BH own EM field

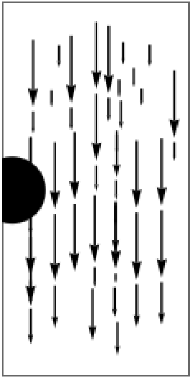
- no-hair theorem - black hole have only three hairs:
  mass, spin, **charge** (electric / magnetic)
  $\Longrightarrow$ monopole character of EM filed around BH
- $\nexists$ of magnetic monopole, but plasma accretion
  $\Longrightarrow$ BH will have **split monopole** magnetic field



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

0) Vacuum Maxwell Equations

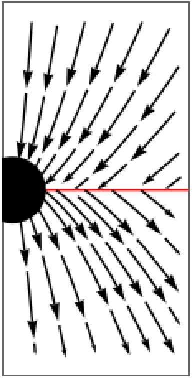
vacuum $J^\mu = 0$



Wald (1974)

1) Force Free Electrodynamics

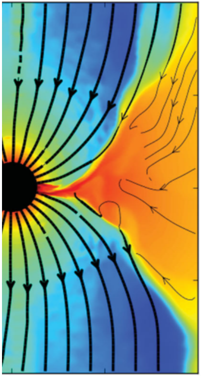
$B^2 \gg \rho c^2$



Blandford-Znajek (1977)

2) Magneto-hydrodynamics

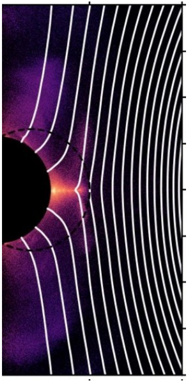
fluid description



Gammie+(2003)
HARM code

3) Particle-In-Cell

charged particles



Crinquand+(2020)
Hirotani+(2021)

difficulty level $\Longrightarrow$

Parabolic black hole magnetosphere (FFE heuristic solution)

BH without rotation - only $A_\phi \neq 0$

split parabolic solution

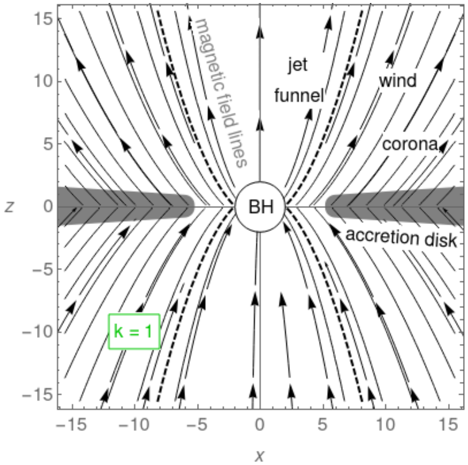
$$A_\phi \sim r^k(1 - |\cos\theta|)$$

mag. field supported by accretion disk
field lines declination $k \in [0, 1.25]$

$k = 1$ Blandford—Znajek paraboloidal model

$k = 0$ split monopole solution

$k = 3/4$ observed BH mag. field in jet funnel, see Nakamura (2018)



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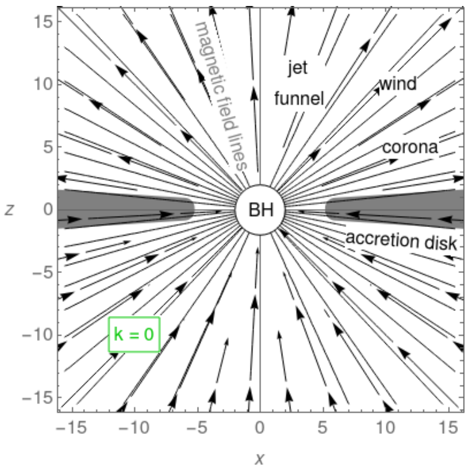

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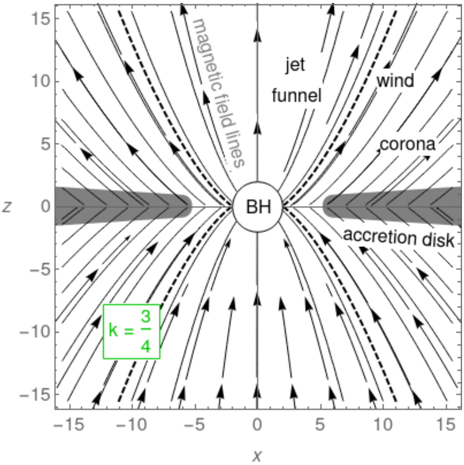
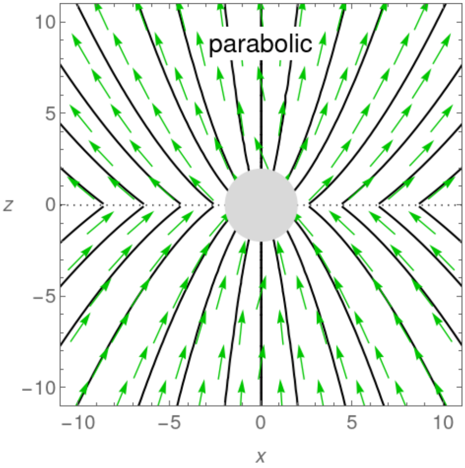


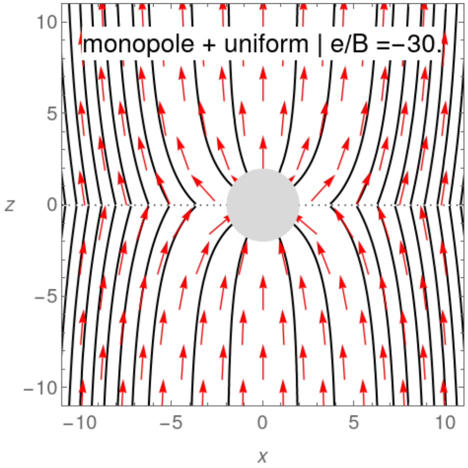
- M. Nakamura et al., *Parabolic Jets from the Spinning Black Hole in M87*, The Astrophysical Journal, 868, 146, (2018) [arXiv:1810.09963] parabolic (FFE heuristic solution)

$$A_\phi = B\, r^k (1 - |\cos\theta|)$$



monopole + uniform (Maxwell sol.)

$$A_\phi = B\, r^2 \sin\theta + e\,|\cos\theta|$$



parabolic (FFE heuristic solution)

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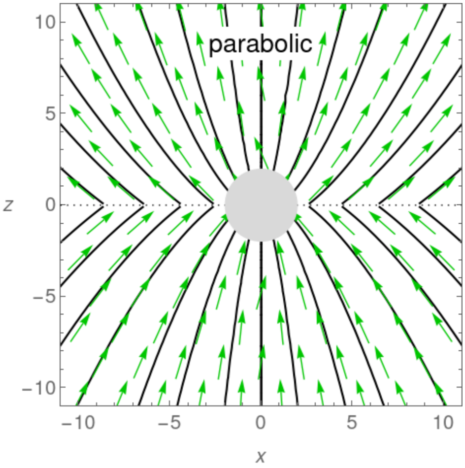

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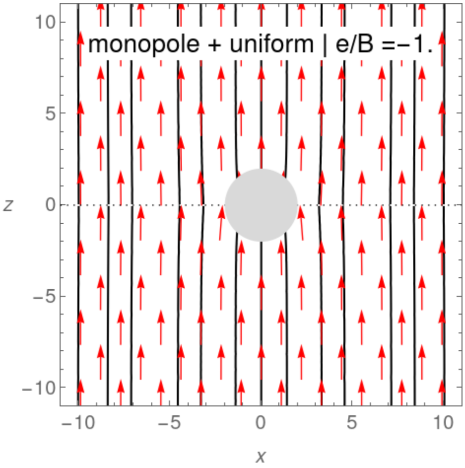


Charged test particle dynamic examine BH magnetosphere

Lorentz equation: gravity and magnetic field

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta} u^\alpha u^\beta = \frac{q}{m} g^{\mu\rho} F_{\rho\sigma} u^\sigma \quad + \ldots \tag{1}$$

$u^\mu = dx^\mu/d\tau$ particle four-velocity, $\Gamma^\mu_{\alpha\beta}$ Christoffel symbols for BH metric, $F_{\mu\nu}$ is tensor of electromagnetic field constructed from EM four-potential A_ν

$$\Gamma^\mu_{\alpha\beta} = \frac{1}{2} g^{\mu\gamma} \left(g_{\gamma\alpha,\beta} + g_{\gamma\beta,\alpha} - g_{\alpha\beta,\gamma} \right); \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{2}$$

gravity ~ 1 Lorentz force up to $\sim 10^{11}$? another forces ?

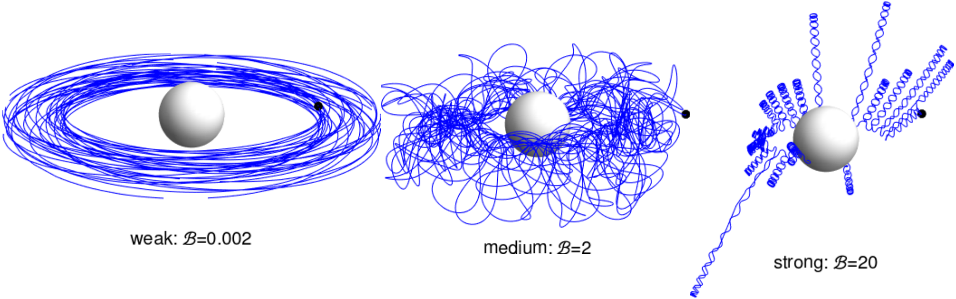
- symmetries $\rightarrow$ conserved quantities: energy E and angular momentum L

$$-E/m = \pi_t = g_{tt} u^t + g_{t\phi} u^\phi + \tilde{q} A_t, \quad L/m = \pi_\phi = g_{\phi\phi} u^\phi + g_{\phi t} u^t + \tilde{q} A_\phi$$

test charged particle is moving in 2D effective potential $V_{\text{eff}}(r,\theta)$

code in Mathematica for charged particle motion: github.com/XyhwX/particle

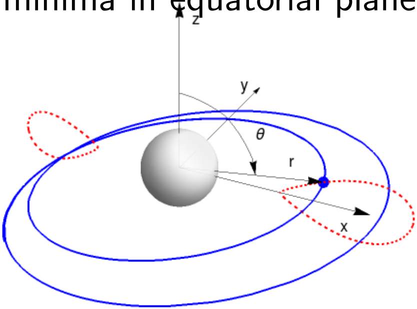
Magnetic field influence: weak $\mathcal{B} \ll 1$ || strong $\mathcal{B} \gg 1$

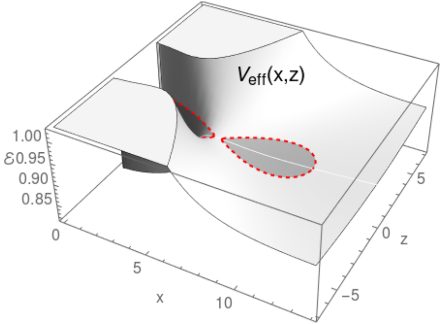


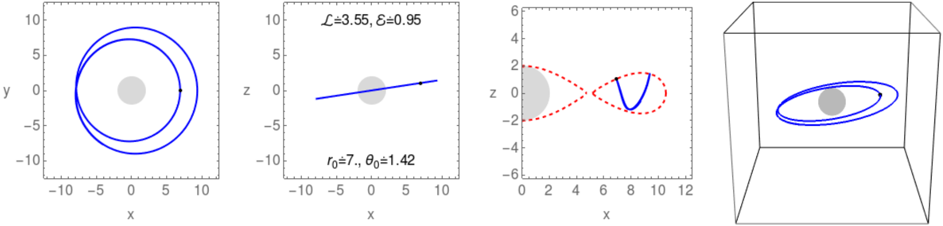
- astrophysically relevant:
  weak $\mathcal{B} \ll 1$ case - small oscillations
  strong $\mathcal{B} \gg 1$ case - motion along magnetic field lines

- Lorentz force: $\mathcal{B} < 0$ attractive || $\mathcal{B} > 0$ repulsive
- $\mathcal{B} \sim 1$ Lorentz force is comparable to gravity - the richest case

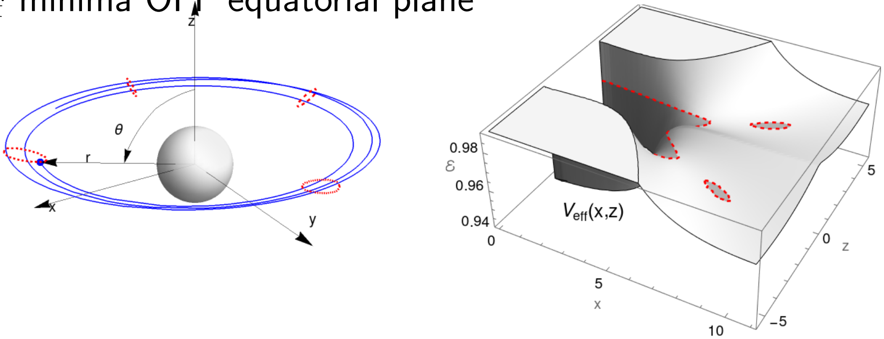
$V_{\rm eff}$ minima in equatorial plane

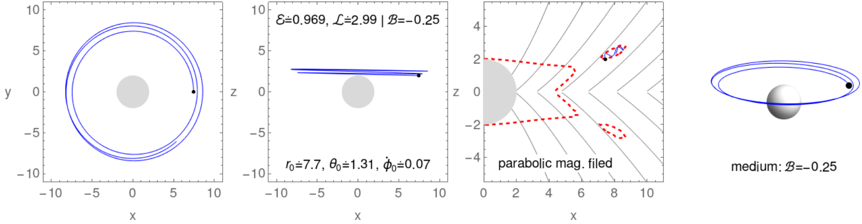




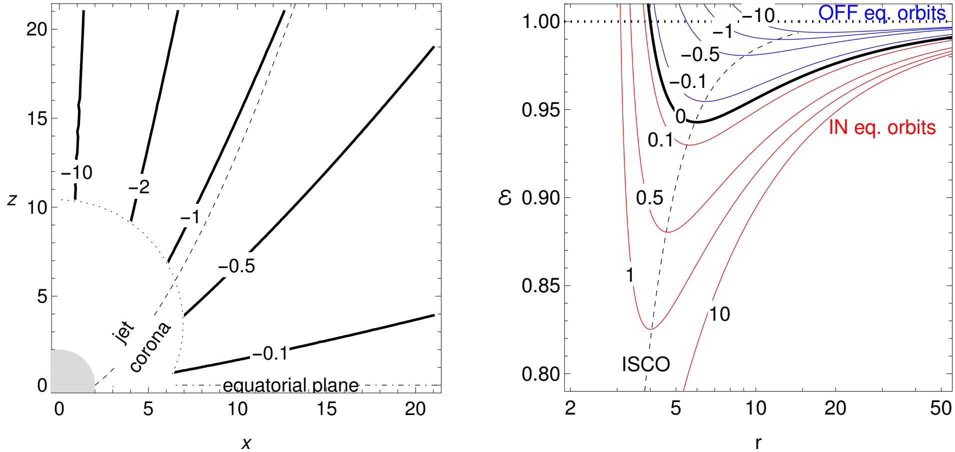


$V_{\rm eff}$ minima OFF equatorial plane



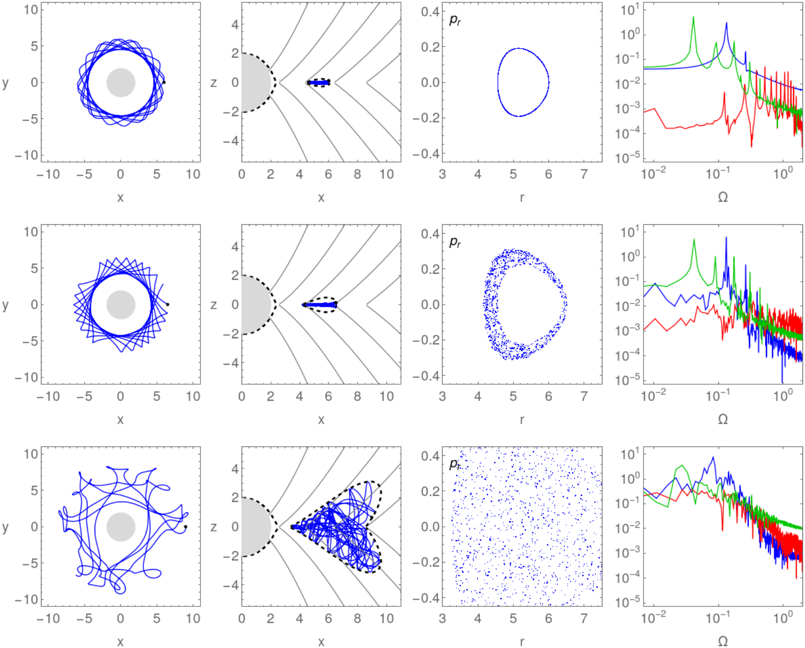


Can charged particles accumulate in off equatorial minima?

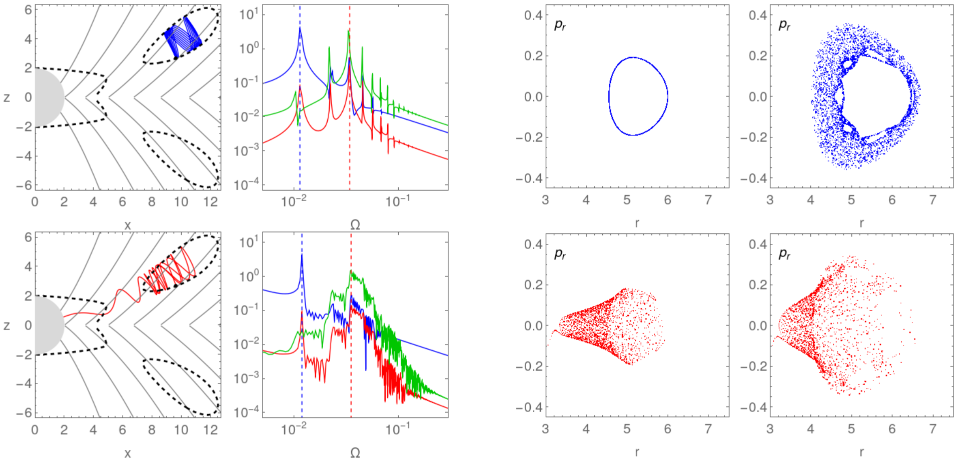


- Magnetic field parameter $\mathcal{B} < 0$ determine the off equatorial plane position.
- For $\mathcal{B} < -1$ located in "empty" jet region.
- Off eq. orbit binding energy is low - no room to accumulate charged particles?

here comes the CHAOS



Radiation reaction = dumping force: spectrum & Poincaré sec.



Influence of dumping force on power spectrum: oscillatory peaks are smear out.
Points Poincaré section points attracted to black hole.

Summary, conclusions & future work

- magnetic field can strongly influence charged particle dynamic around BH
- off equatorial orbit existence - chan charged particle accumulate there?
- influence of damping radiation reaction force - trajectory appear more chaotic

- charged test particle dynamic is a tool to examine BH magnetosphere
- GRMHD/PIC simulation vs. one particle - new GR effects close to the BH

- we are now working on electromagnetic spectra emitted by particle (full GR)

Thank you for your attention.