Blandford-Znajek monopole for Kerr magnetosphere

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Gravitational waves, black holes and fundamental physics

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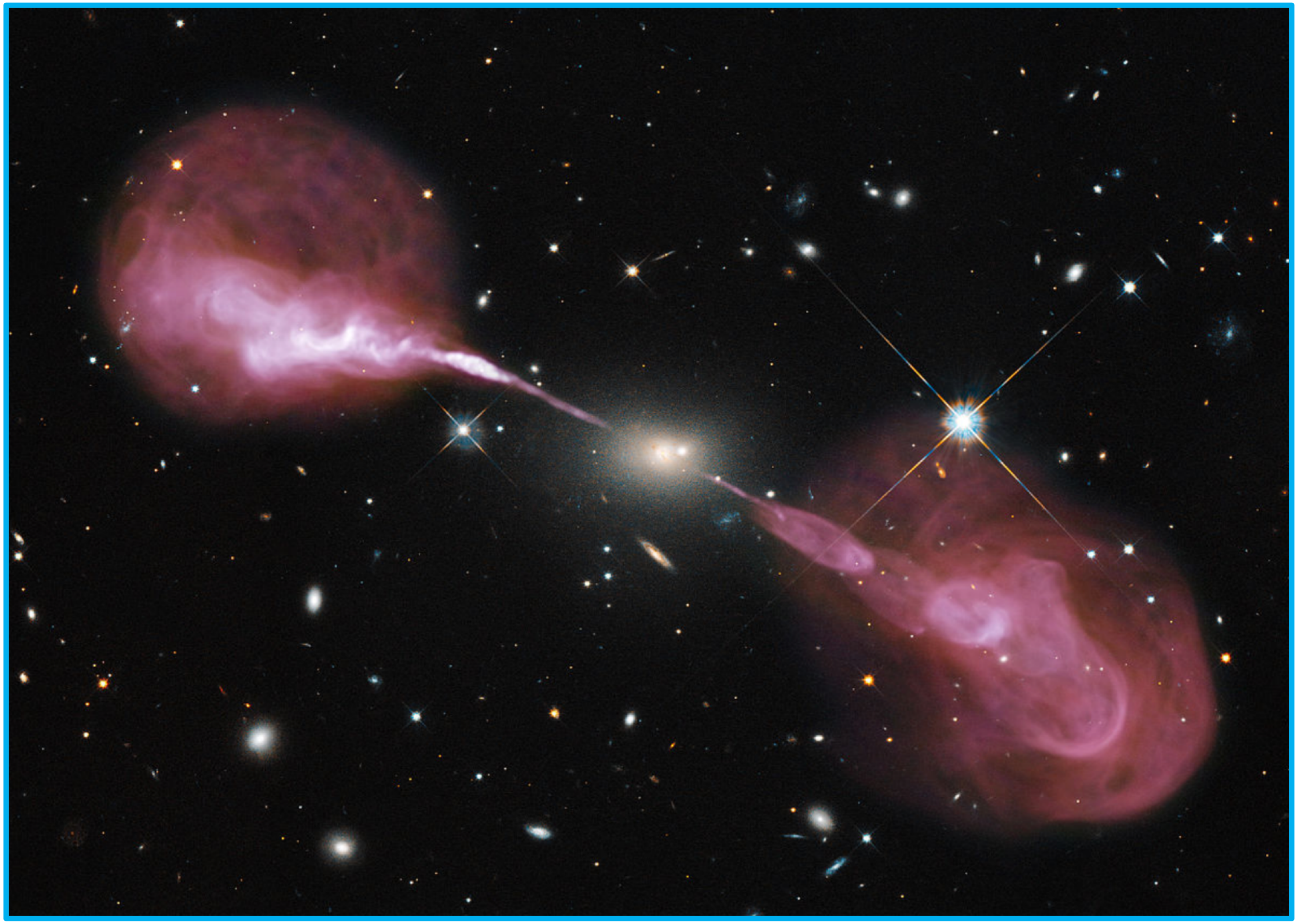
Talk mainly based on:

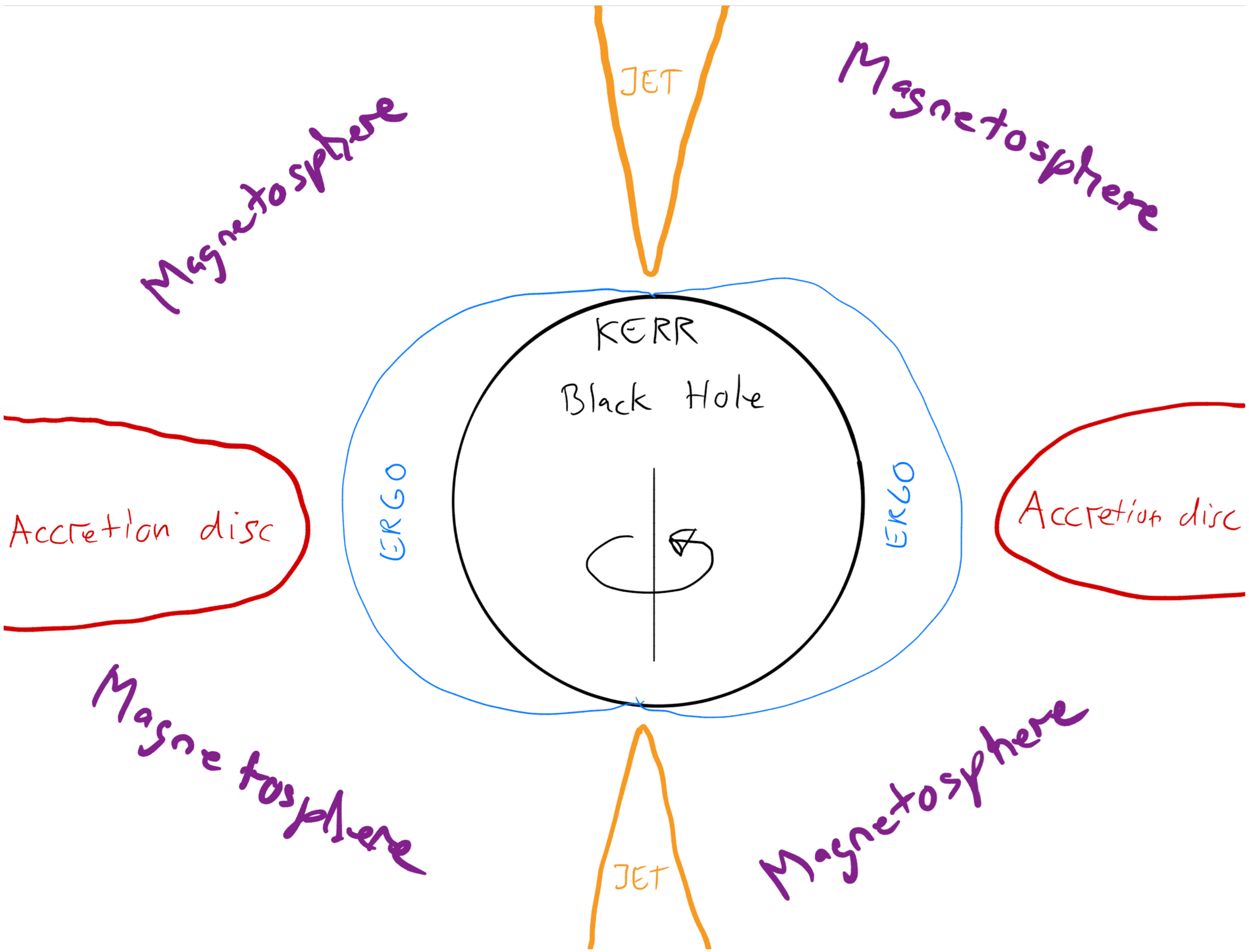
- **TH, Orselli and Grignani**, ArXiv:**1908.07227** [gr-qc].
- **TH, Orselli and Grignani**, Phys.Rev.D98 (2018) no.8, 084056 (ArXiv:**1804.05846** [gr-qc])

Astrophysical jets: Highly collimated and energetic jets of charged particles from compact objects, including black holes



Hercules A radio source in the 3C 348 elliptical galaxy. One can see jets emitted from the galactic nucleus.

What drives a jet that origins from a black hole?



Blandford-Znajek mechanism (1977):

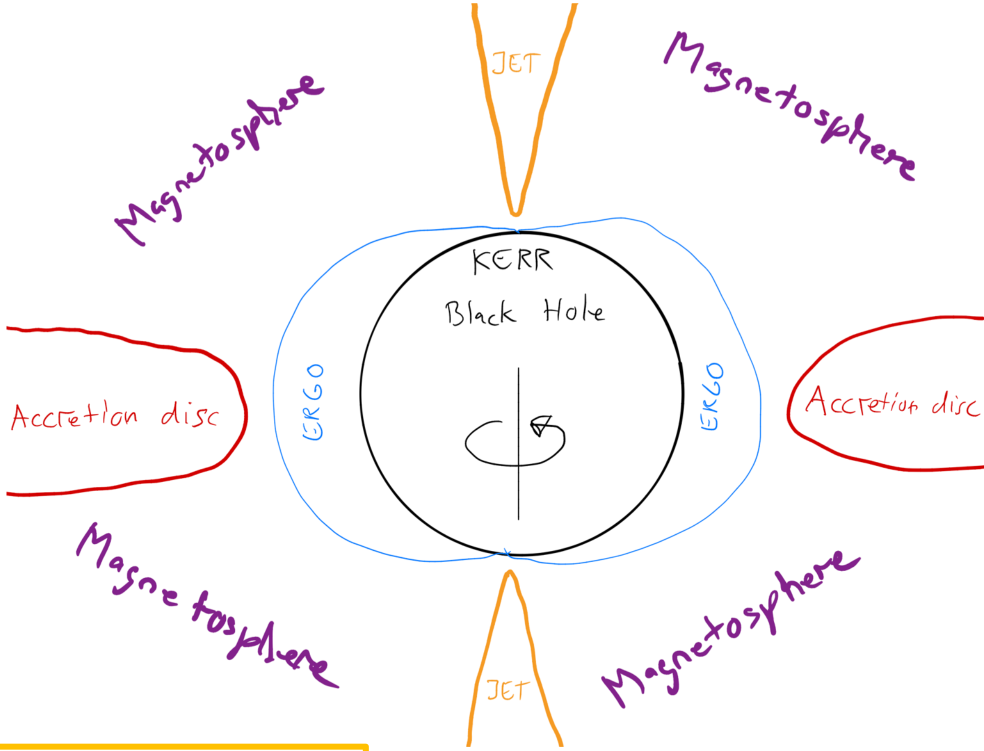
Rotation energy of BH → Magnetosphere → Acceleration of charged particles

Can one make an analytical model of astrophysical jets from black holes?

Magnetosphere outside accretion disc:

Magnetic field >> plasma

Described to good approximation
by force-free electrodynamics



$$\nabla_{[\mu}F_{\nu\rho]} = 0 \ , \qquad F_{\mu\nu}\nabla_\rho F^{\rho\nu} = 0$$

Maxwell's equations + Conservation of energy-momentum of EM-field

Should be magnetically dominated: $F^2 > 0$

Can one make an analytical model of astrophysical jets from black holes?

No known analytical solution of force-free electrodynamics in the background of the Kerr black hole (magnetically dominated)!

One of the most successful analytical model is perturbative:

Blandford-Znajek split-monopole (1977)

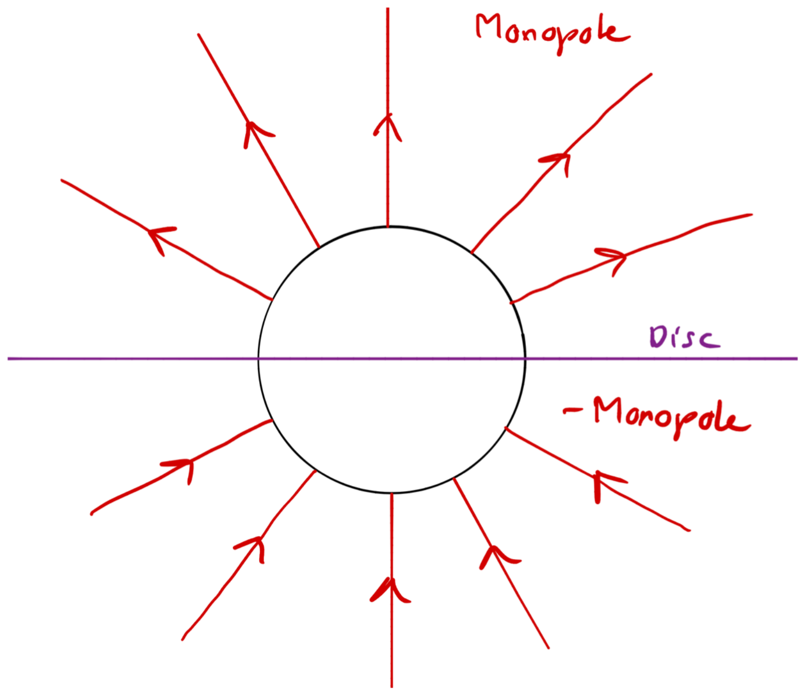
1) Start with static magnetic monopole in background of Schwarzschild BH
2) Perturb monopole solution in small angular momentum J (Kerr background)
3) Make it into a split-monopole solution

Perturbation parameter: $\alpha = \frac{J}{GM^2}$

Zeroth order α^0: Static

First order α^1:
Background still Schwarzschild
Rotation of magnetosphere: Michel solution

Second order α^2:
Metric corrected
First non-trivial correction to magnetosphere



TH, Orselli and Grignani 2018

Problem with Blandford-Znajek split-monopole:

Tanabe and Nagataki went to order α^4 in perturbation theory (2008)

Solution in terms of ψ = magnetic flux through loop around rotation axis

$$\psi = \psi_{(0)} + \alpha^2 \psi_{(2)} + \alpha^4 \psi_{(4)} + \mathcal{O}(\alpha^6)$$

They found at order α^4: $\psi_{(4)} \sim r^2$ (Tanabe and Nagataki 2008)

⇒ **The perturbation in α blows up for large r**

How is this possible?

0th order: $\mathcal{L}\psi_{(0)} = 0$

2nd order: $\mathcal{L}\psi_{(2)} = S_2$

4th order: $\mathcal{L}\psi_{(4)} = S_4$

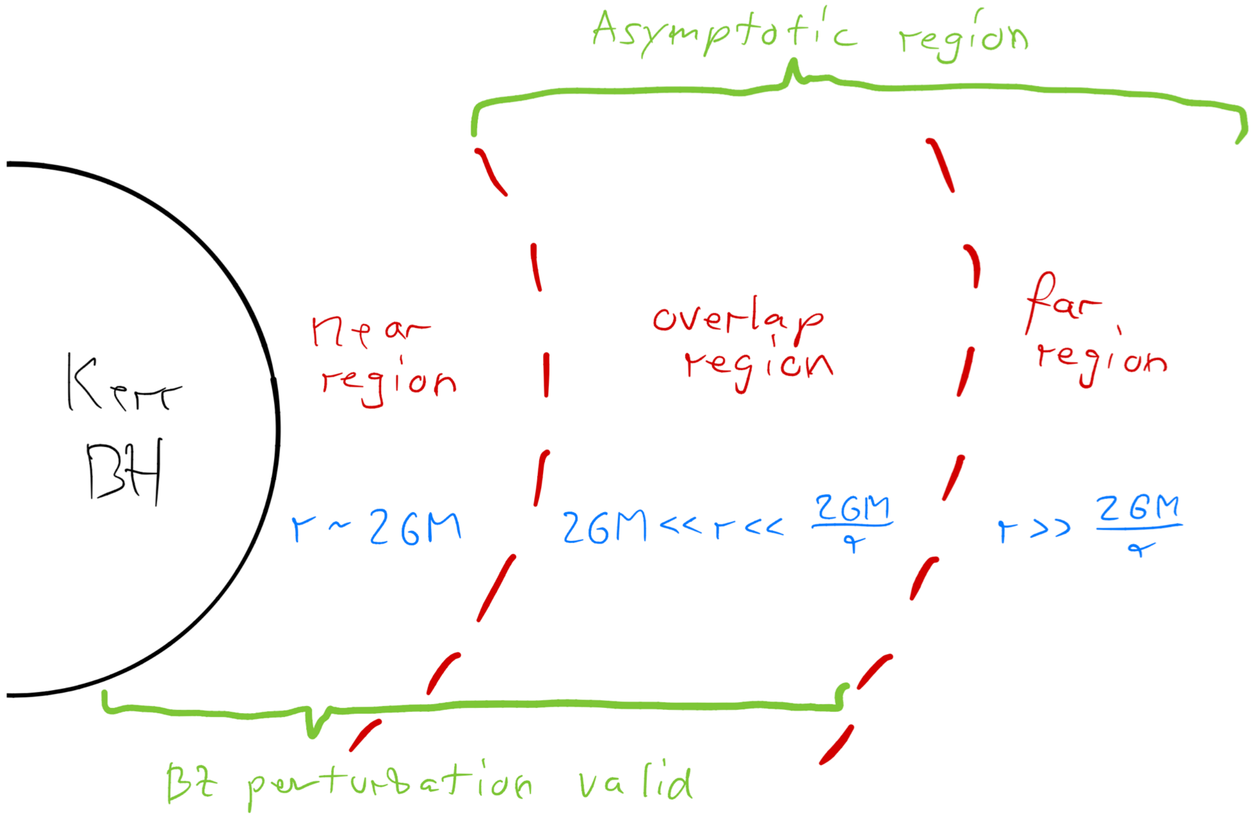
with $$\mathcal{L} = \frac{1}{\sin\theta}\partial_r \left(1 - \frac{2GM}{r}\right)\partial_r + \frac{1}{r^2}\partial_\theta \frac{1}{\sin\theta}\partial_\theta$$

Problem: Perturbation eqs. only valid for: $$\frac{2GM}{r} \gg \alpha$$

This requires: $$r \ll \frac{2GM}{\alpha}$$ ⇒ Perturbation eqs. invalid for r → ∞

TH, Orselli and Grignani 2018

We tried to fix problem using Matched Asymptotic Expansions (MAE) technique



However, even at order α^2 one cannot match BZ expansion with the expansion in asymptotic region

⇒ The analytical construction of the BZ monopole breaks down at first non-trivial order!

Force-free electrodynamics near rotation axis:

TH, Orselli and Grignani 2019

We consider force-free electrodynamics near rotation axis of Kerr BH

Enables us to prove no-go theorem:

Assumptions:

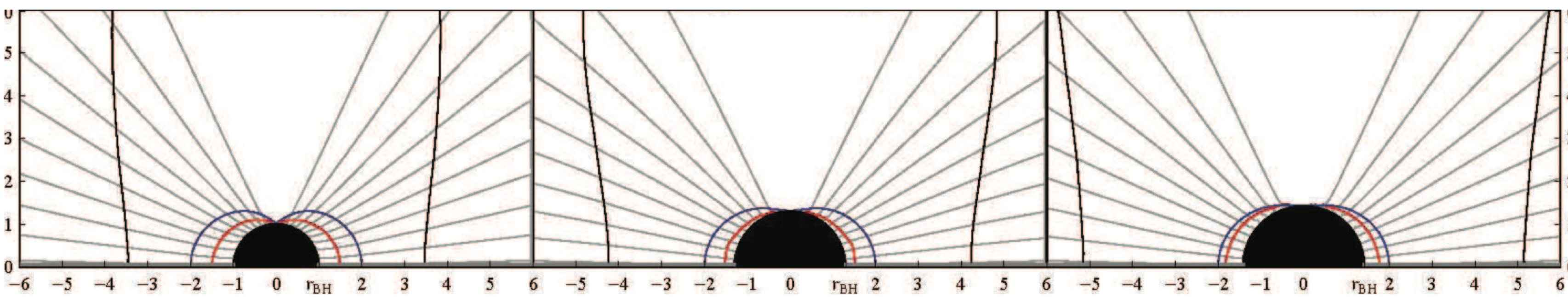
1) Regularity at horizon
2) Smoothness at inner and outer light surfaces
3) Monopole-like asymptotic behavior
4) Regularity at rotation axis
5) $\theta \to 0$ and $r \to \infty$ limits commute

⇒ Not possible to find solution that connects in the $\alpha \to 0$ limit to a static monopole-like solutions in the background of Schwarzschild BH

Conclusions:

How can our analytical results be reconciled with numerics?

α = 0.9999 α = 0.95 α = 0.9



From Nathanail and Contopoulos 2014

Can one make a new type of perturbative monopole solution by breaking assumptions?

Could one start with extremal Kerr solution instead?

→ Force-free electrodynamics in NHEK region

Lupsasca, Rodriguez and Strominger 2014. Lupsasca and Rodriguez 2015.
Gralla, Lupsasca and Strominger 2016. Compère and Oliveri 2016