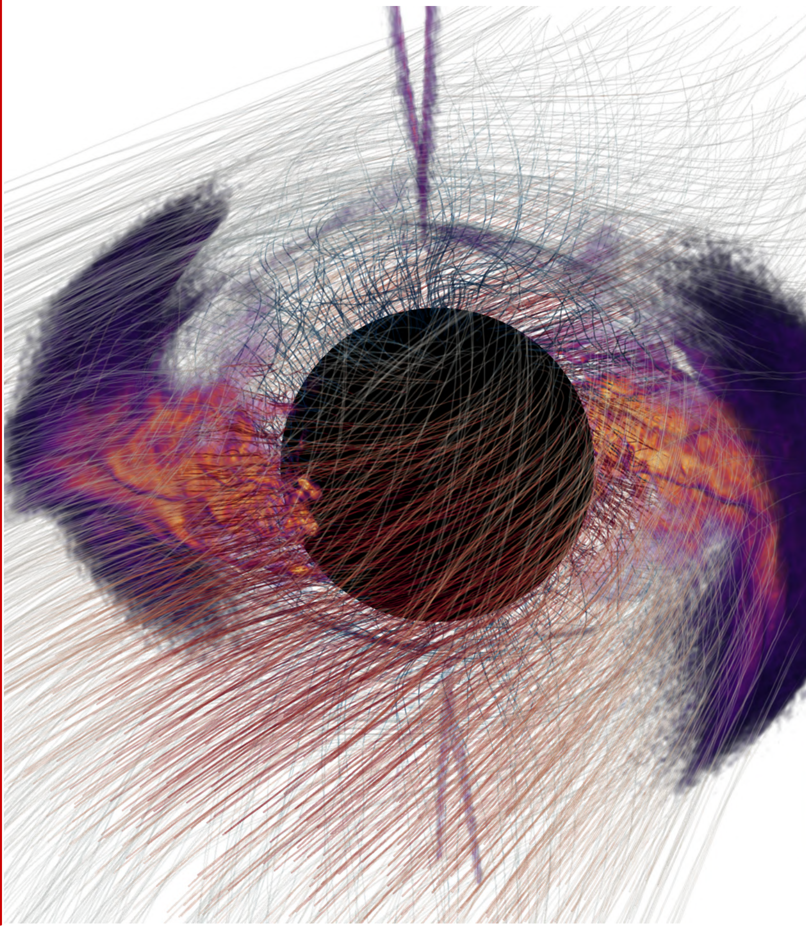
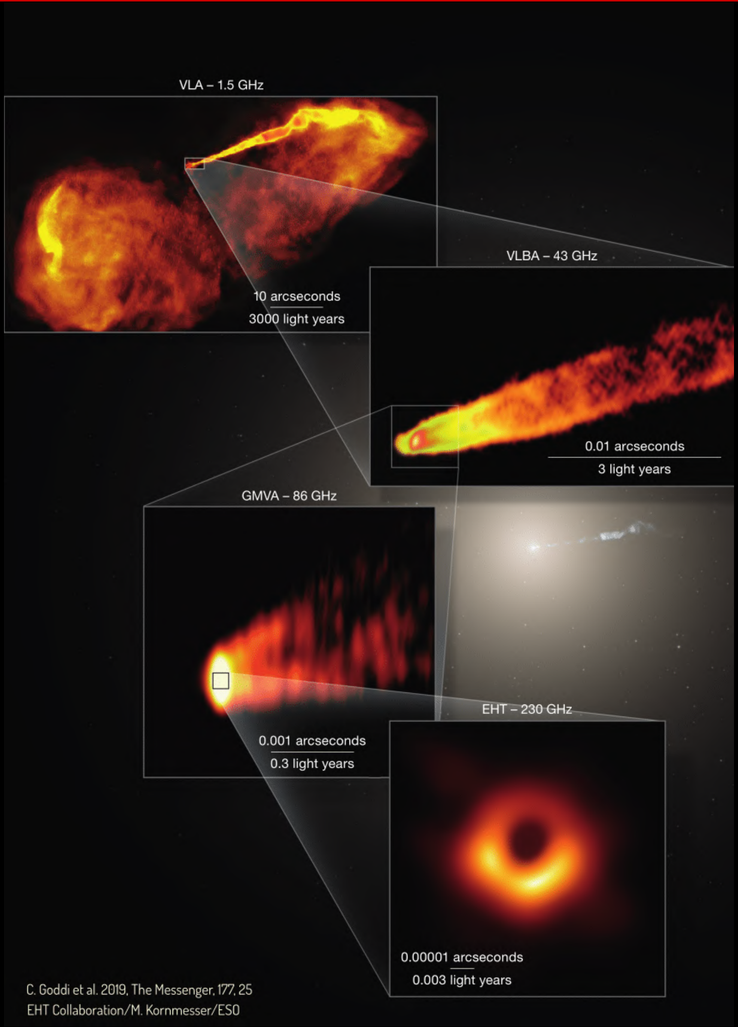
Investigating Black Hole Jets and Flares through Plasma Kinetic Simulations

Enzo Figueiredo (IPAG)

Benoît Cerutti, Kyle Parfrey



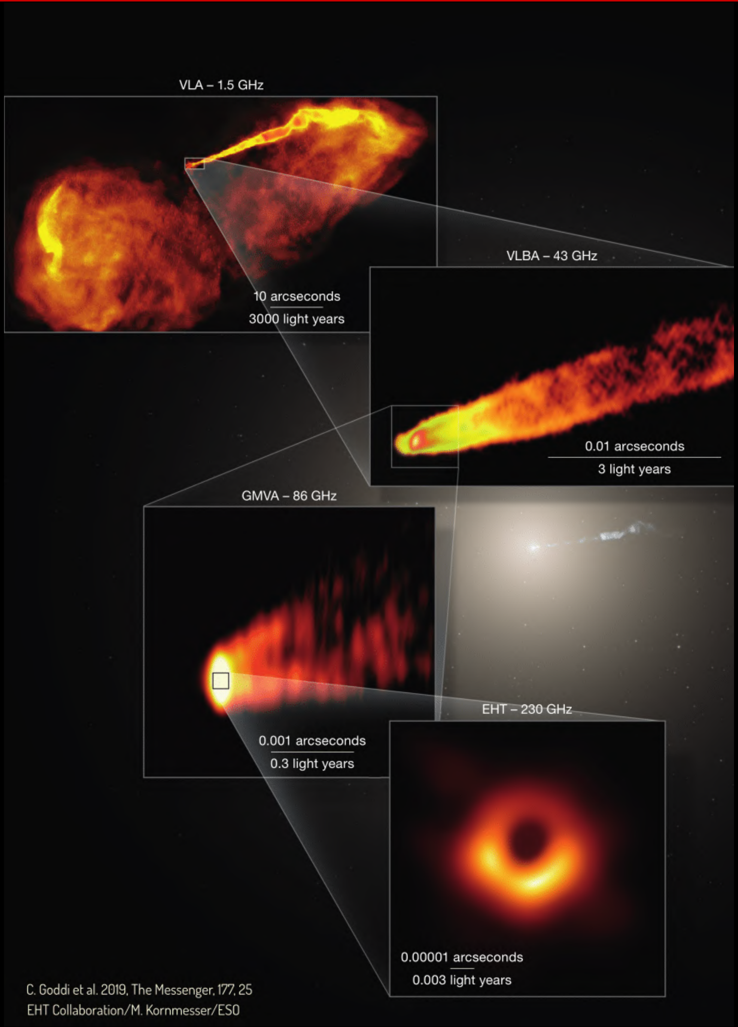
Black Holes and Jet Emission



Evidences for a connection between SMBH and galactic jets

Non thermal emission → Particle acceleration

Black Holes and Jet Emission



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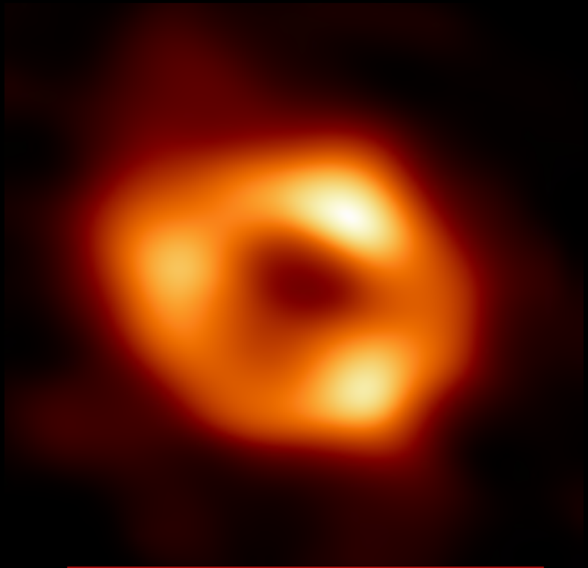
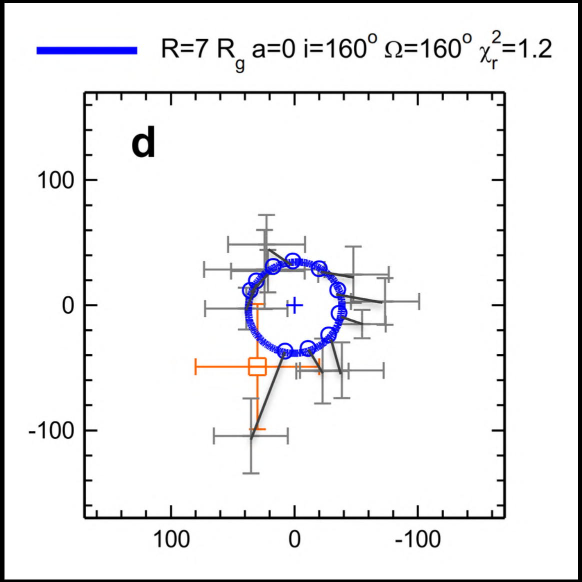
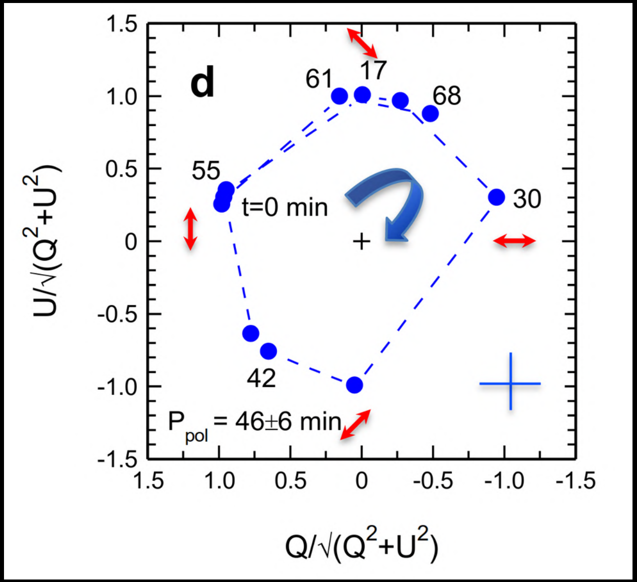


No jet? But flares!

Sagittarius A*: a not-so-quiet black hole

GRAVITY observations:

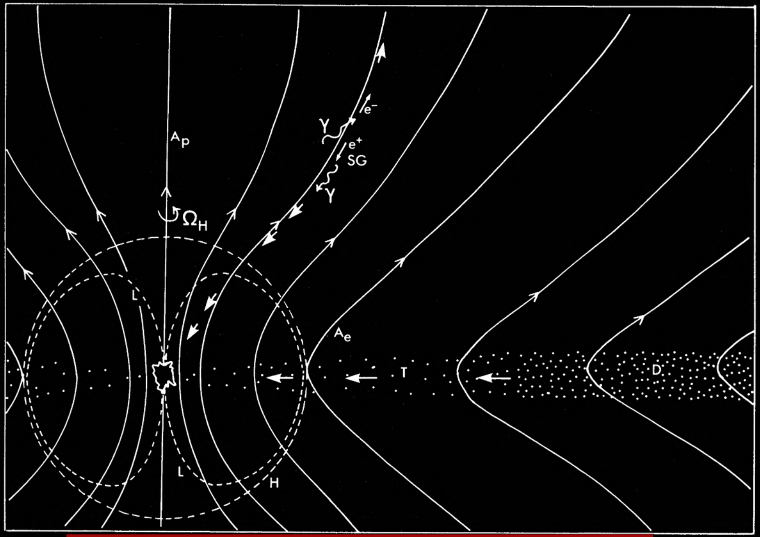




-Time-duration: 30-90 min
-Near-infrared + X-rays
Close to BH (6 r_g)

-Large-scale magnetic field (10-15 G)
-Orientation orthogonal to rotation axis

How to Make a Jet?



Blandford & Znajek, 1977

→ 2 ingredients: magnetic field and black hole spin (and plasma!)

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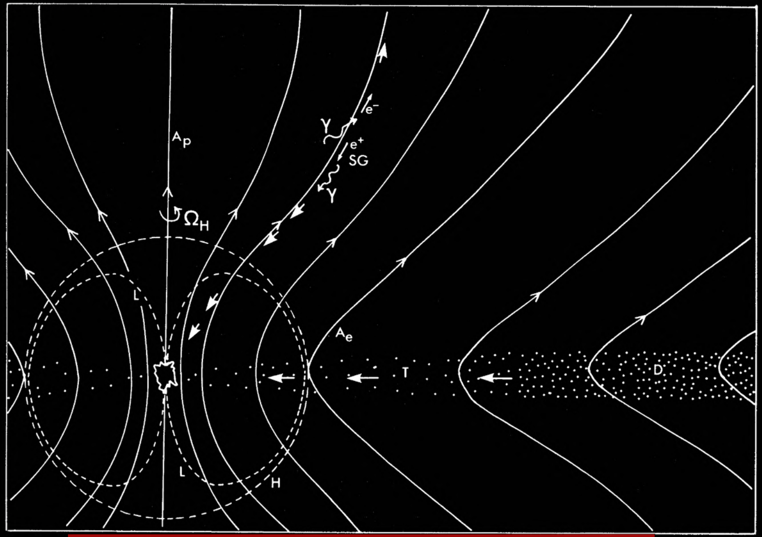

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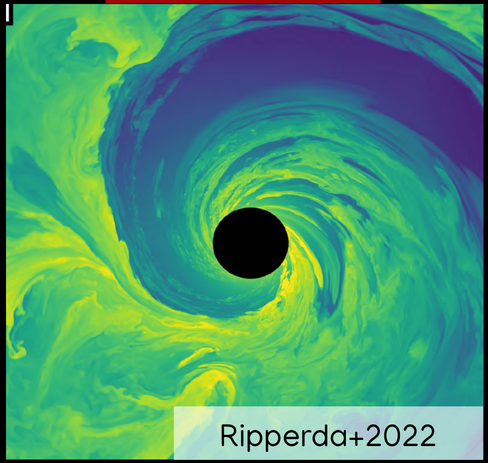
GRMHD



✓ Large scales, long term evolution

✗ No microphysics, difficult to handle particle acceleration

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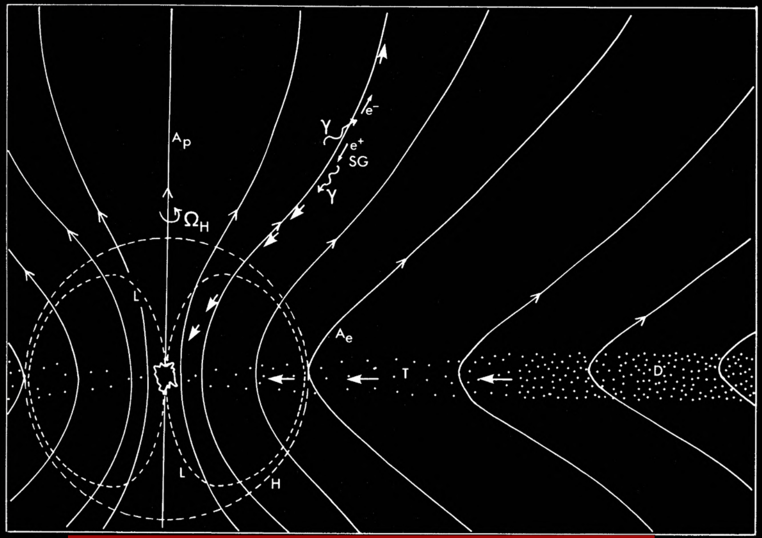

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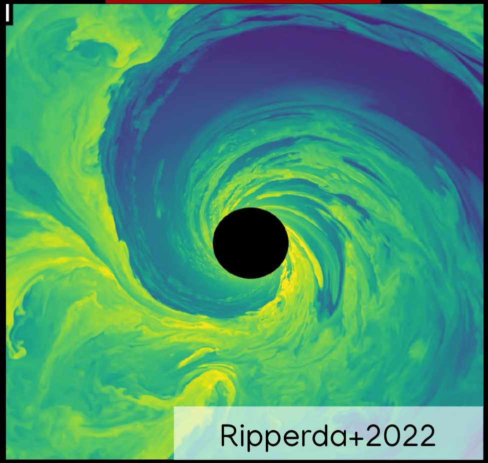

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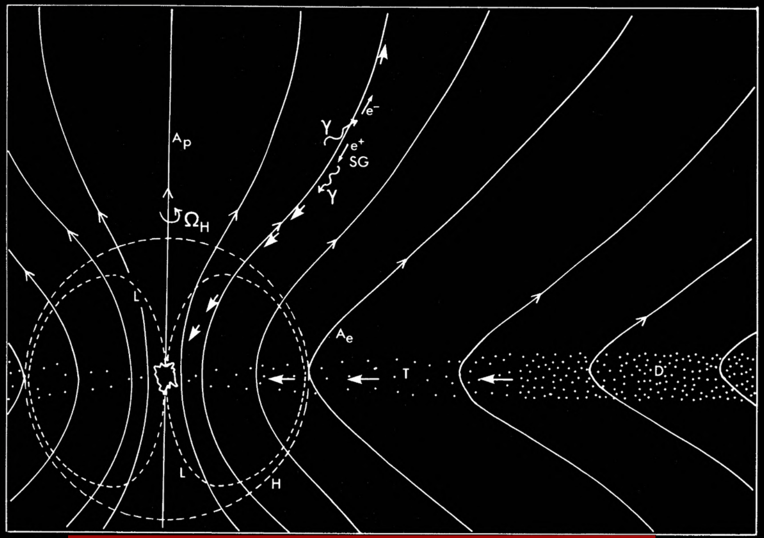

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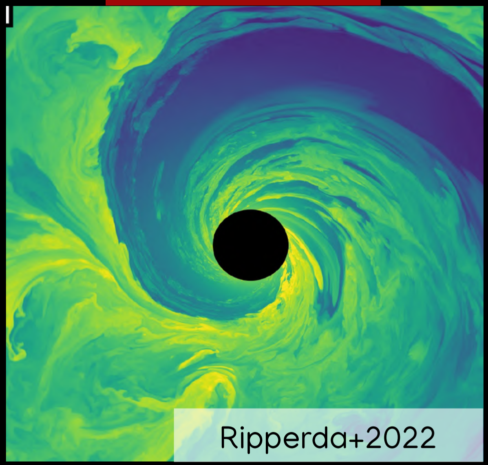


Ripperda+2022

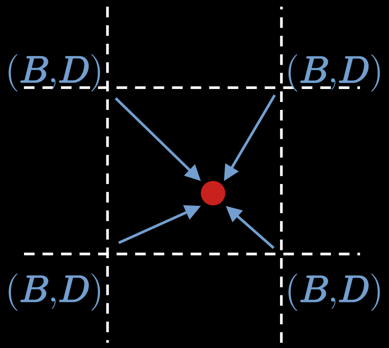
- ✓ Large scales, long term evolution
- ✗ No microphysics, difficult to handle particle acceleration

→ We want an approach that rather focuses on microphysics
→ PIC

GRZeltron: a GRPIC code (Parfrey+2019)

3+1 formalism (Komissarov, 2004)

Kerr metric, KS spherical coordinates



Field Interpolation

Particle Push

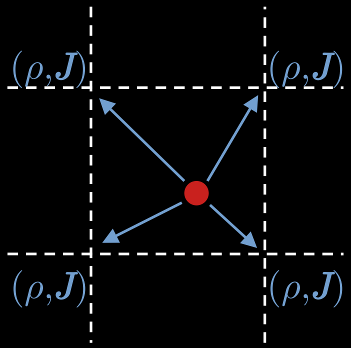
$$\dot{x}^i = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i$$

$$\dot{u}^i = \text{Lorentz + Metric}$$

Fields Evolution

$$\frac{\partial B}{\partial t} = -c\boldsymbol{\nabla} \times E$$

$$\frac{\partial D}{\partial t} = c\boldsymbol{\nabla} \times H - 4\pi\mathbf{J}$$

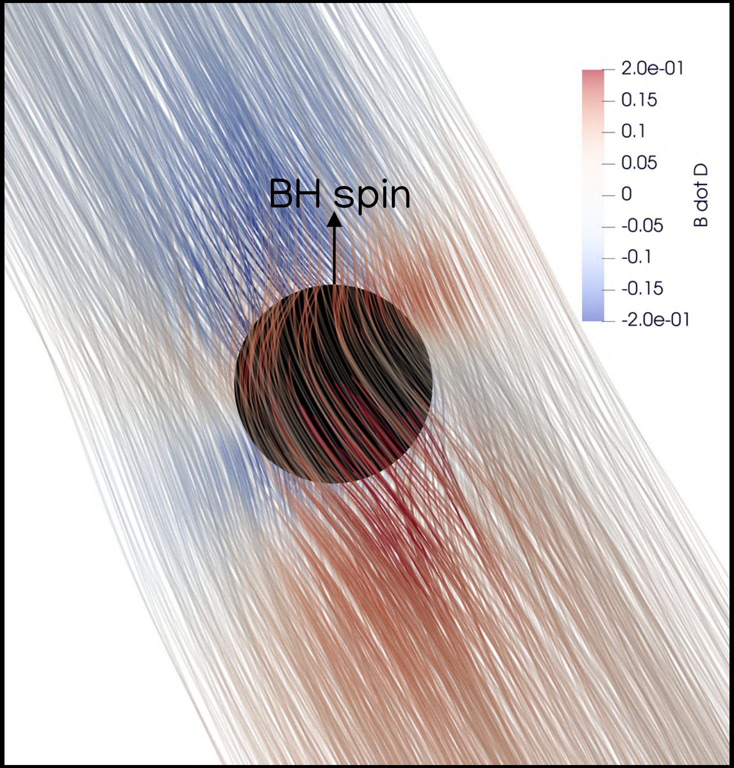


Charge/Current Deposition

- Full treatment of non ideal phenomena
- Can capture microphysics (e.g. QED processes)
- Acceleration of particles self consistently treated
- Straightforward radiative transfer

Inclined Black Hole Magnetsophere: Jet Emission

Vacuum initial state (a=0.99)



Bicak & Janis (1985)

Inclined Black Hole Magnetosphere: Jet Emission

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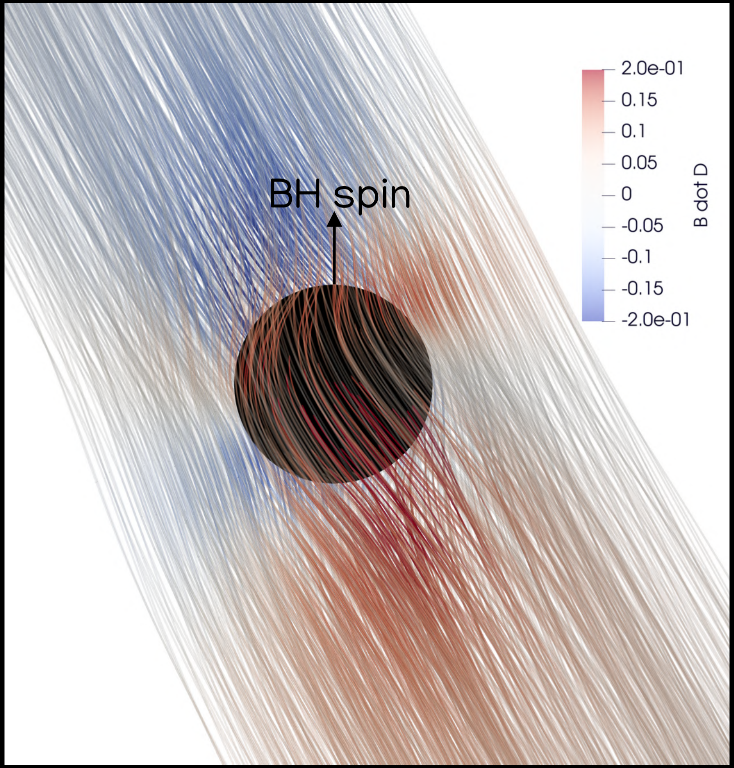


Bicak & Janis (1985)

Force-free like magnetosphere:

$$\sigma = \frac{B^2}{4\pi n m_e c^2} \gg 1$$

$$\kappa = \frac{n}{n_{GJ}} \gg 1 \quad n_{GJ} = \frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi e c}$$

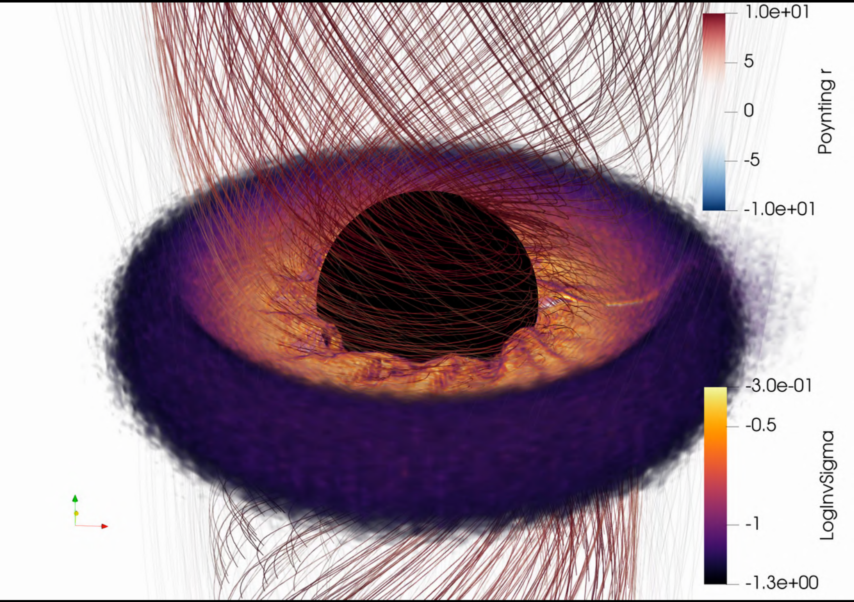
Ad hoc plasma injection

Injection if:

$$\sigma > \sigma_0$$

Overview of the simulations

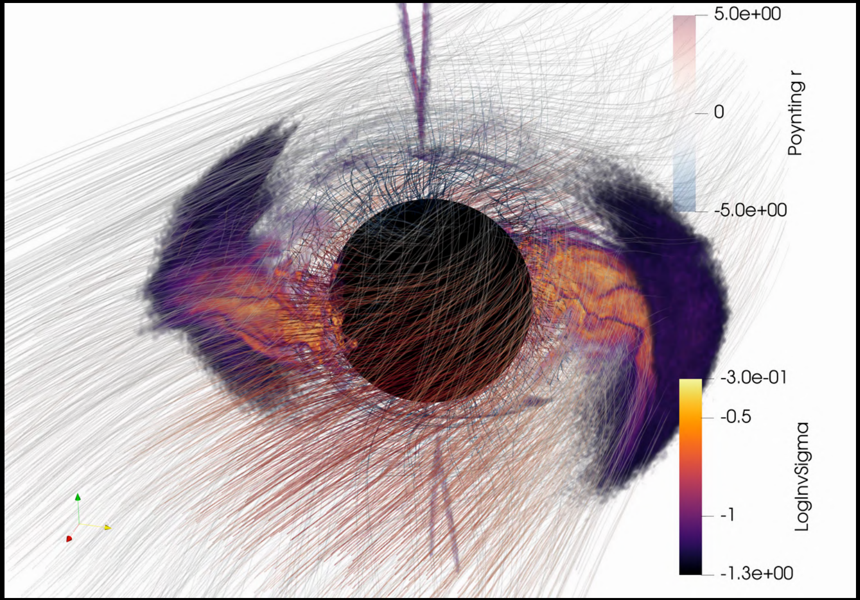
χ = 0°



$t \in [80, 84]\ t_g$

BH spin ↑

χ = 85°



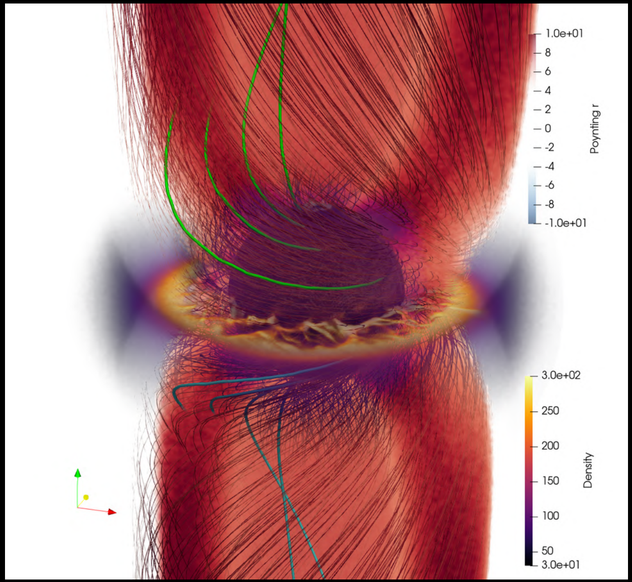
$t \in [52, 56]\ t_g$

→ The jet follows the large scale magnetic field orientation
→ A reconnecting current layer always forms

The Jet Structure Is Affected by the Inclination

BH spin

$\chi = 0°$



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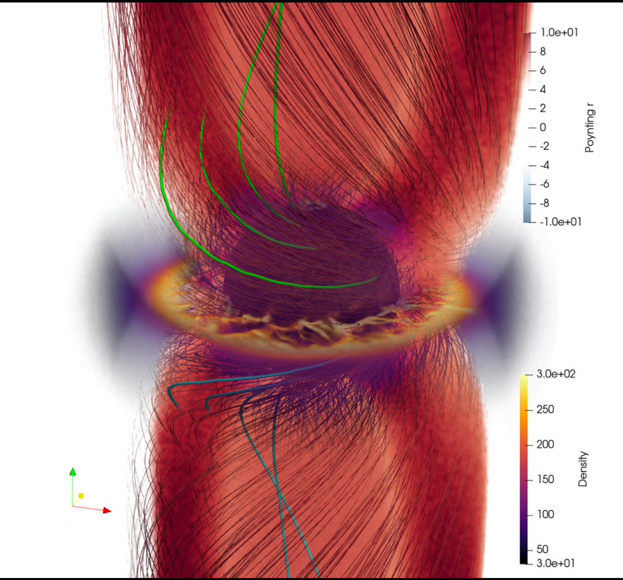
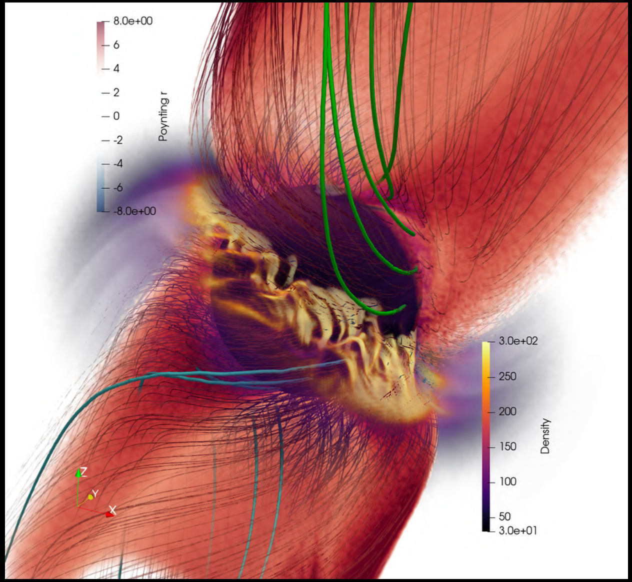
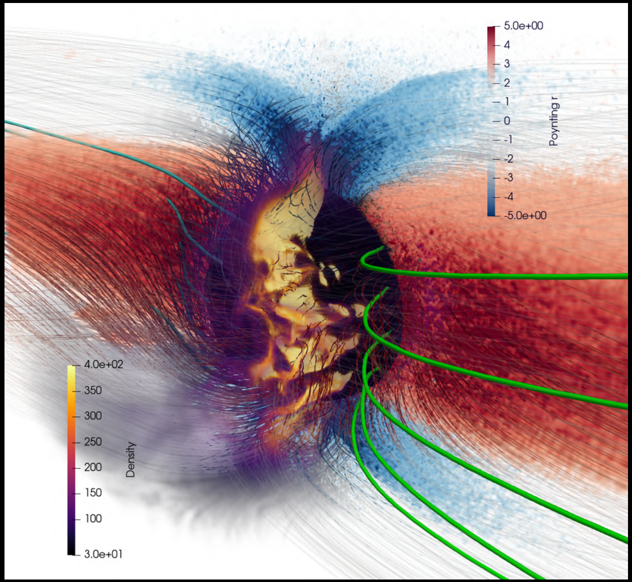


$\chi = 30°$



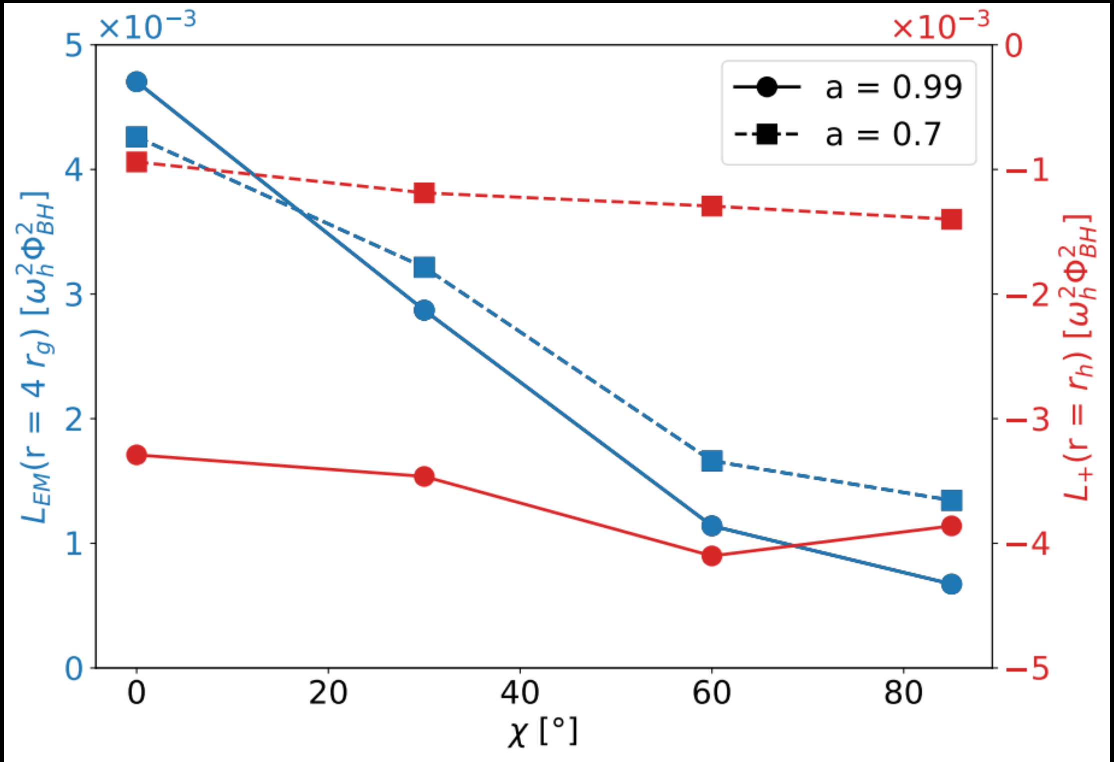
$\chi = 85°$



→ Inward EM flux at the polar regions for inclined magnetospheres

→ Outward EM flux rather comes from equatorial regions

The jet's power weakens, but not the particles'



$$L_{\rm EM}(r) = \iint \sqrt{\gamma} S^r \mathrm{d}\theta \mathrm{d}\phi$$

$$L_{\pm}(r) = \iint \sqrt{\gamma} \langle e^{\pm}_{\infty} v^r_{\pm} \rangle n_{\pm} \mathrm{d}\theta \mathrm{d}\phi$$

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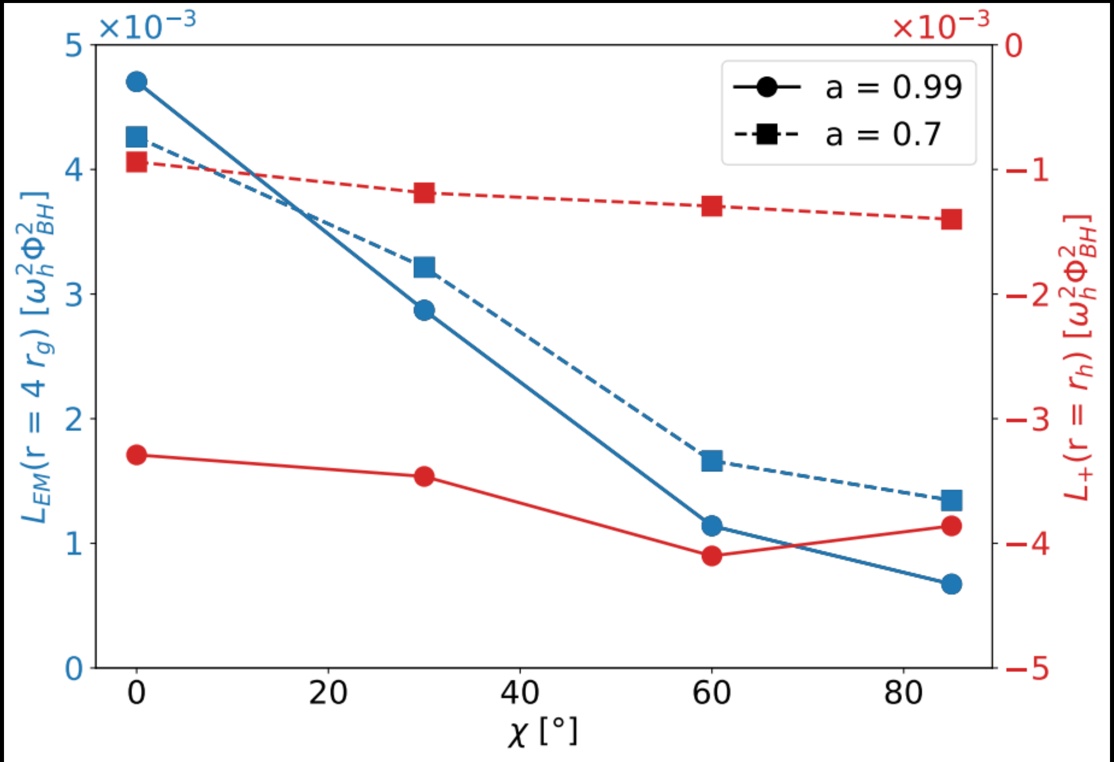

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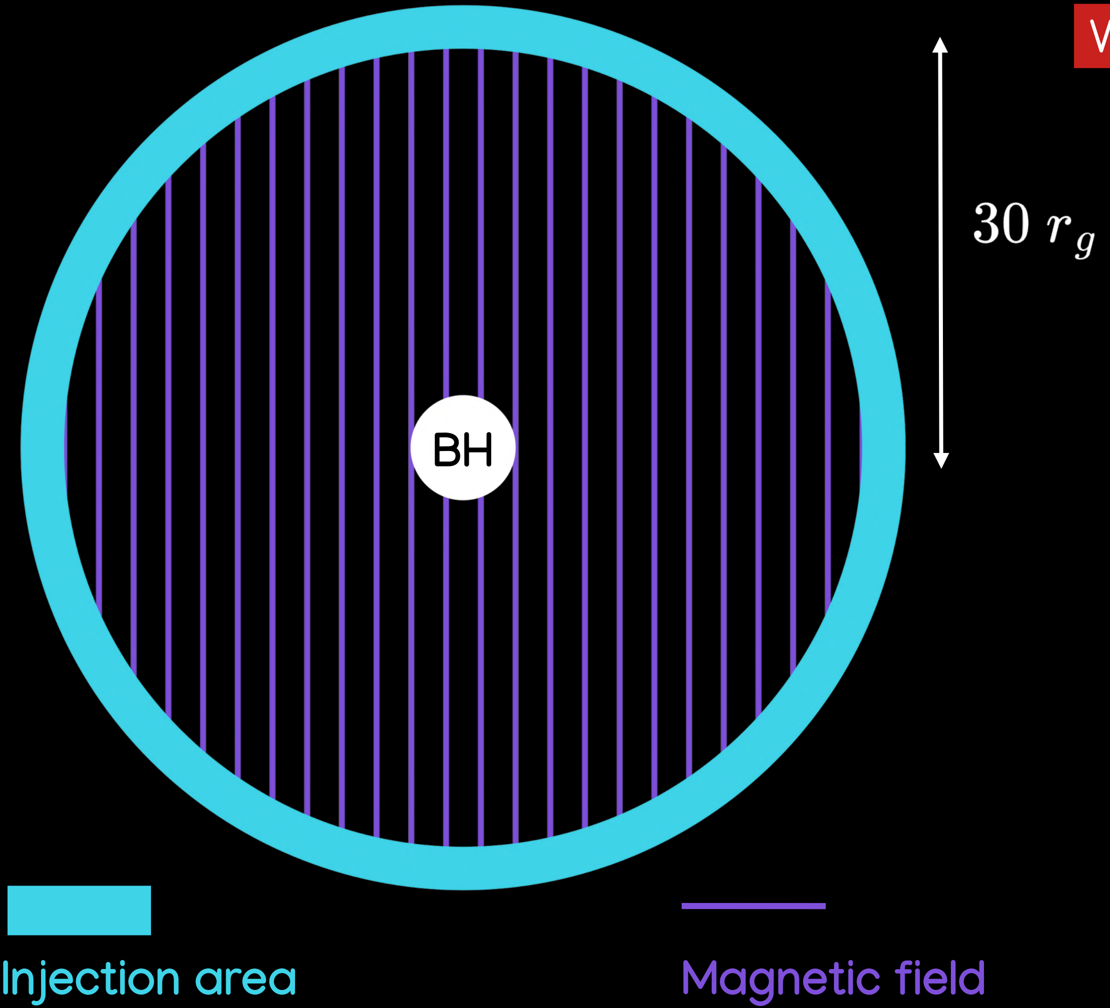
→ Dramatic weakening of the jet power for very inclined magnetospheres
→ Non correlated with particle energization

What if there is no spin?



With:

John Mehlhaff

Adrien Soudais

–Schwarzschild black hole

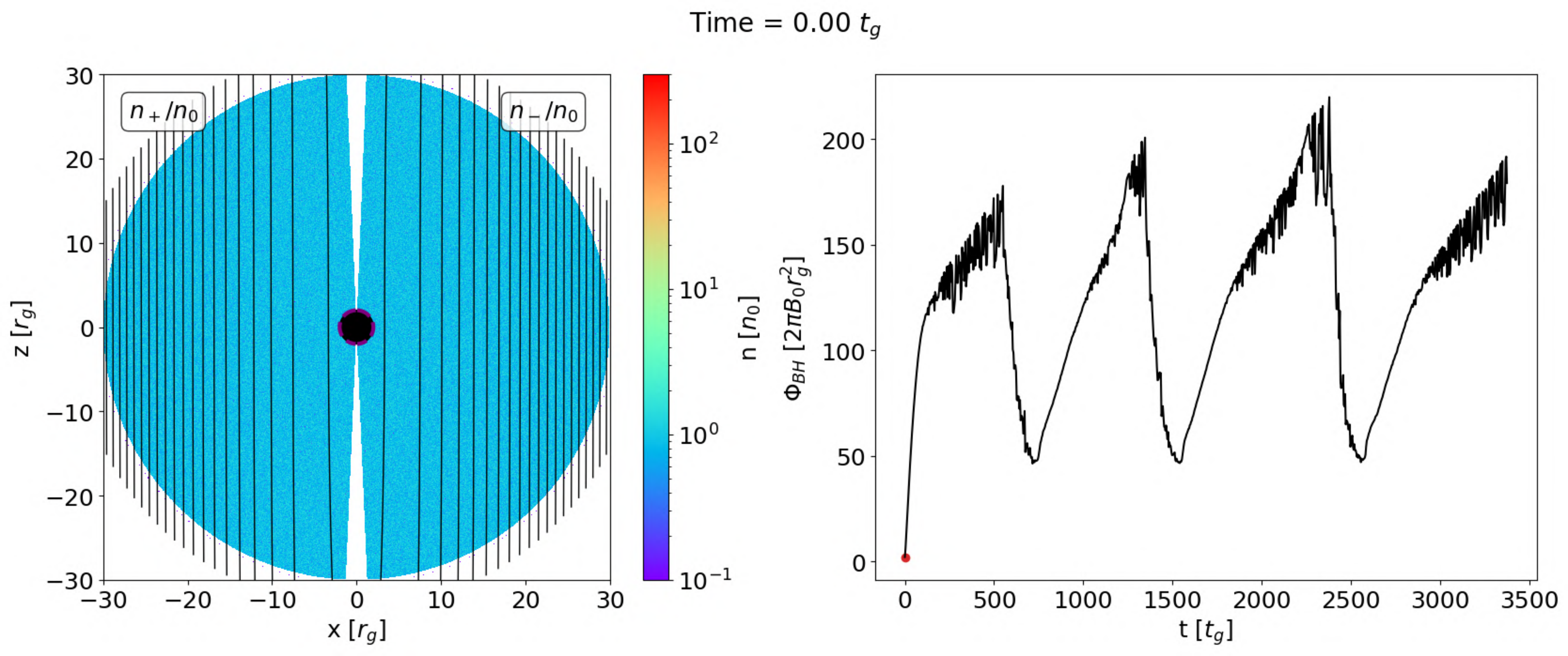
–Axisymmetric setup

–Plasma injected on the outer–edge of the box (free–fall)

–Pair plasma at “low” magnetization

$$\sigma_0 = \frac{B_0^2}{4\pi n_0 m_e c^2} = 0.1$$

Flux Eruptions in the Black Hole Surroundings



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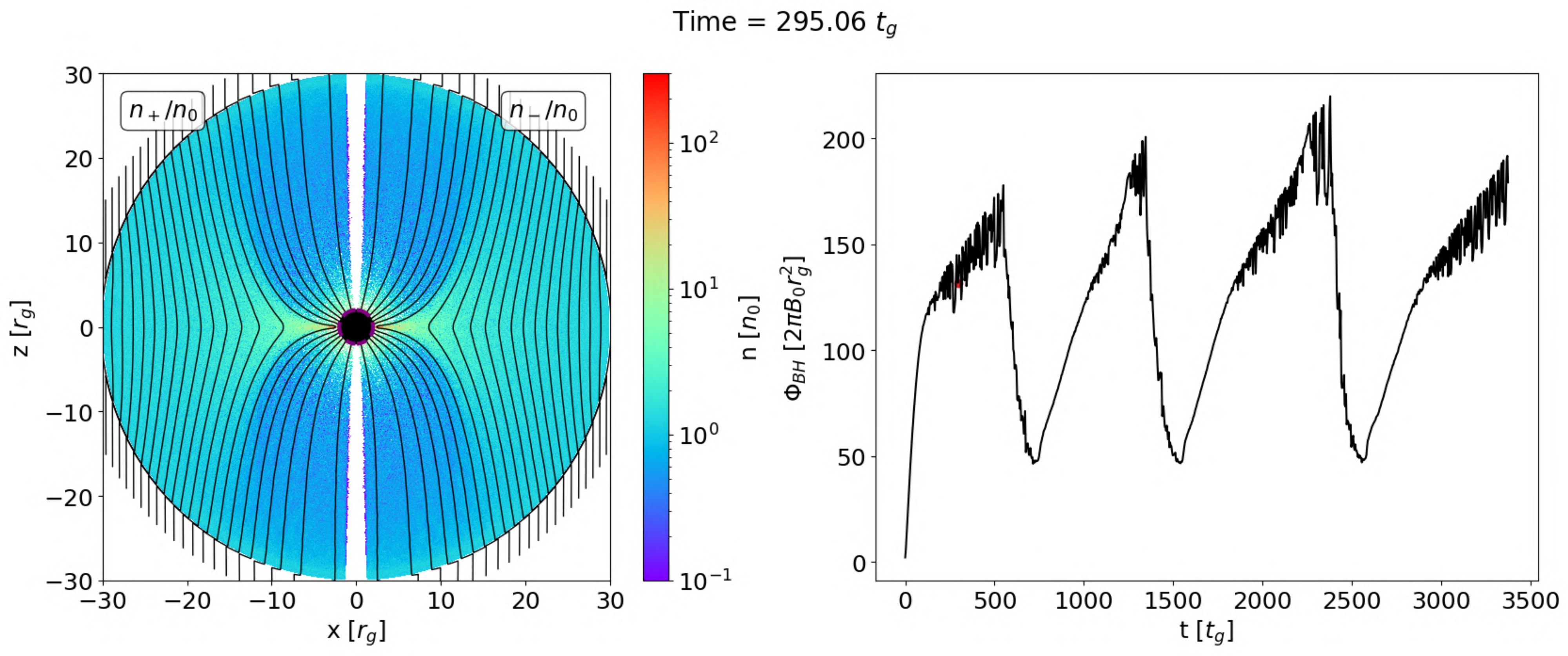

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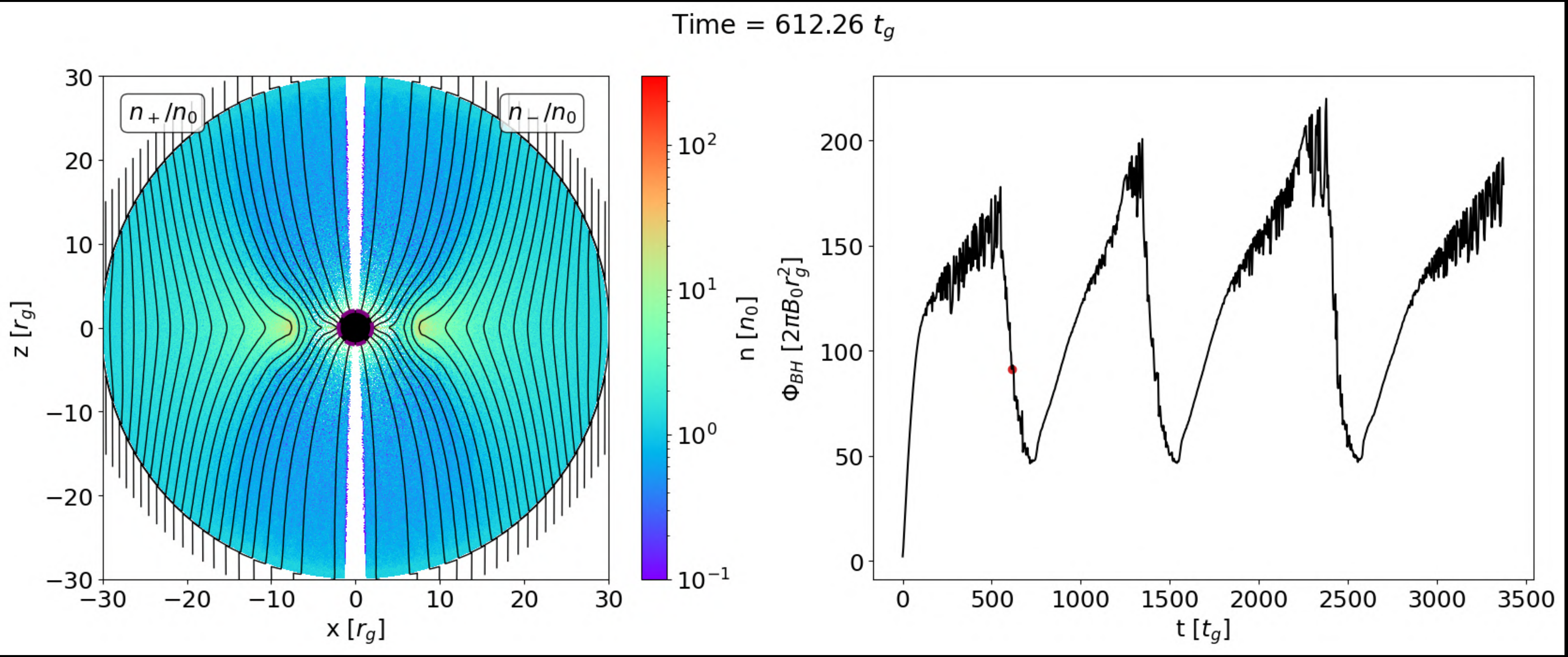

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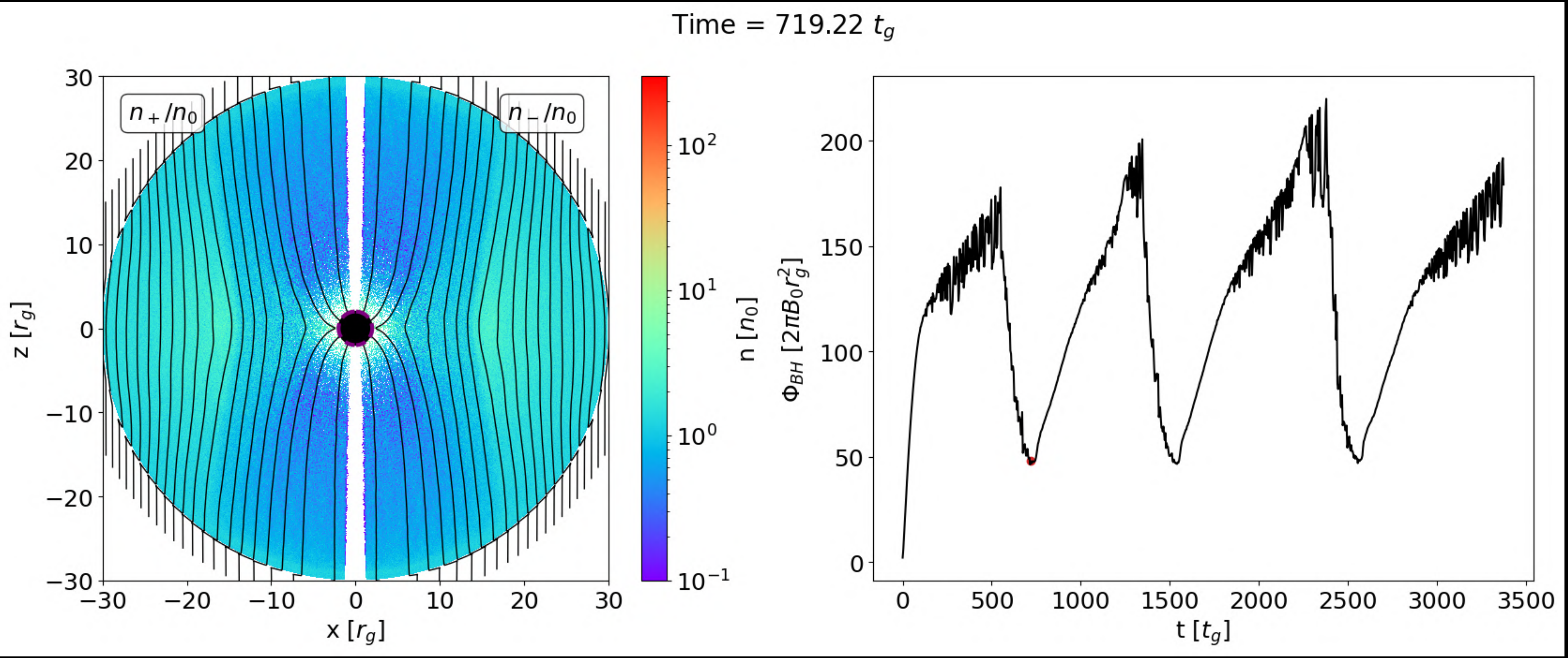
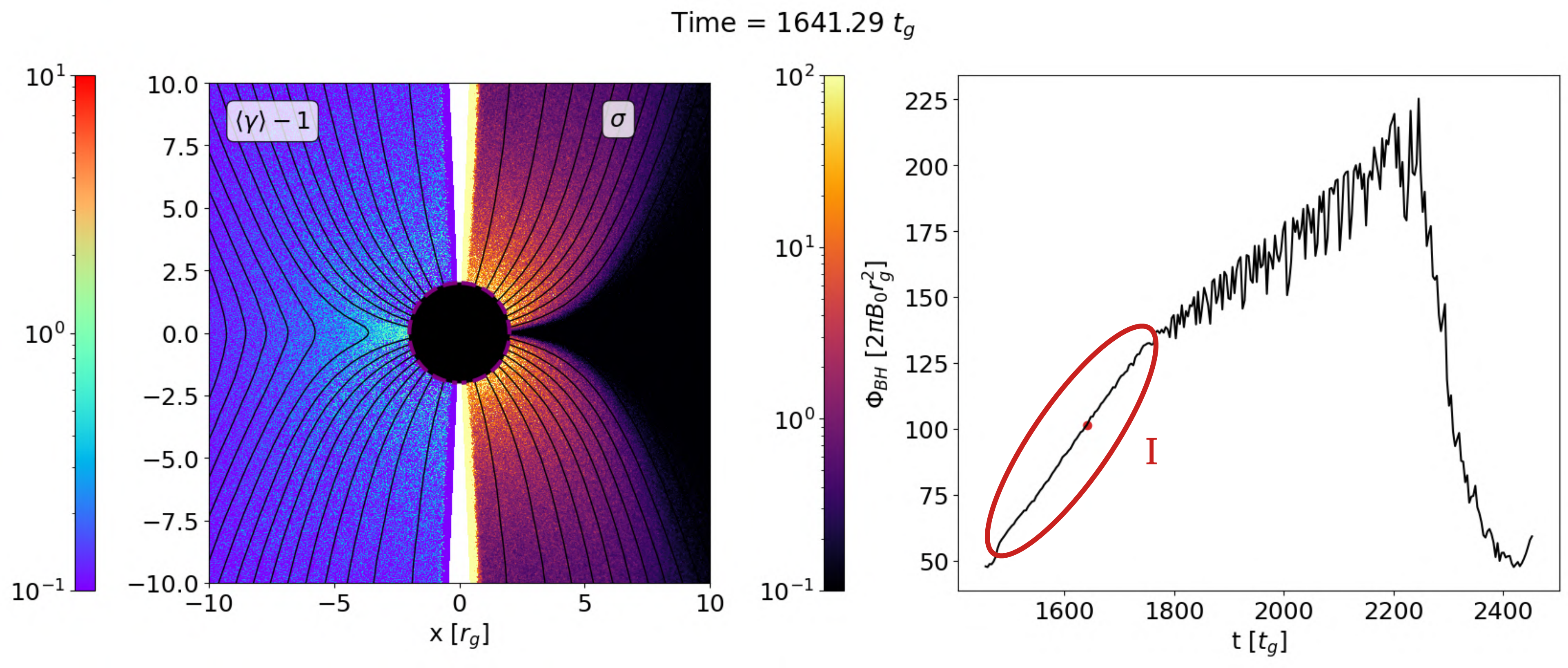


A mechanism in four phases



Ideal phase, free-fall of matter advecting magnetic flux

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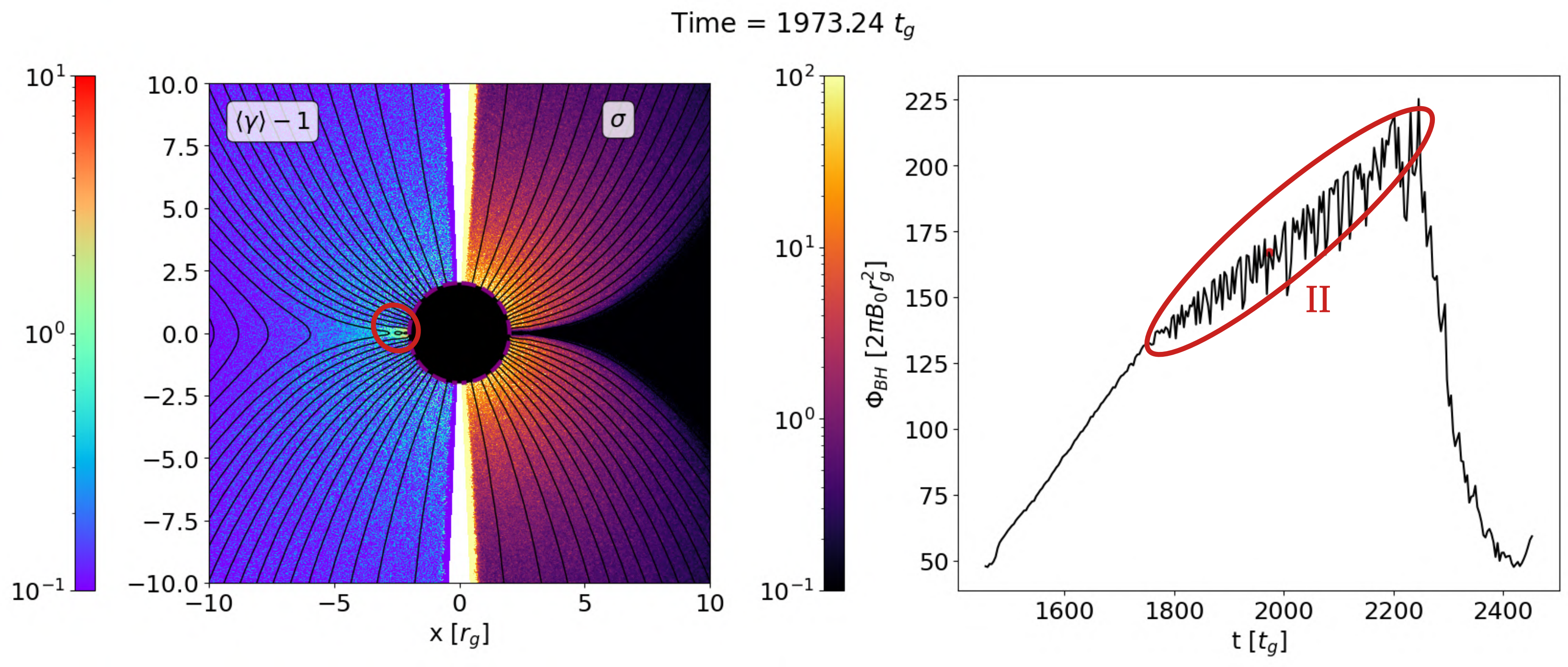
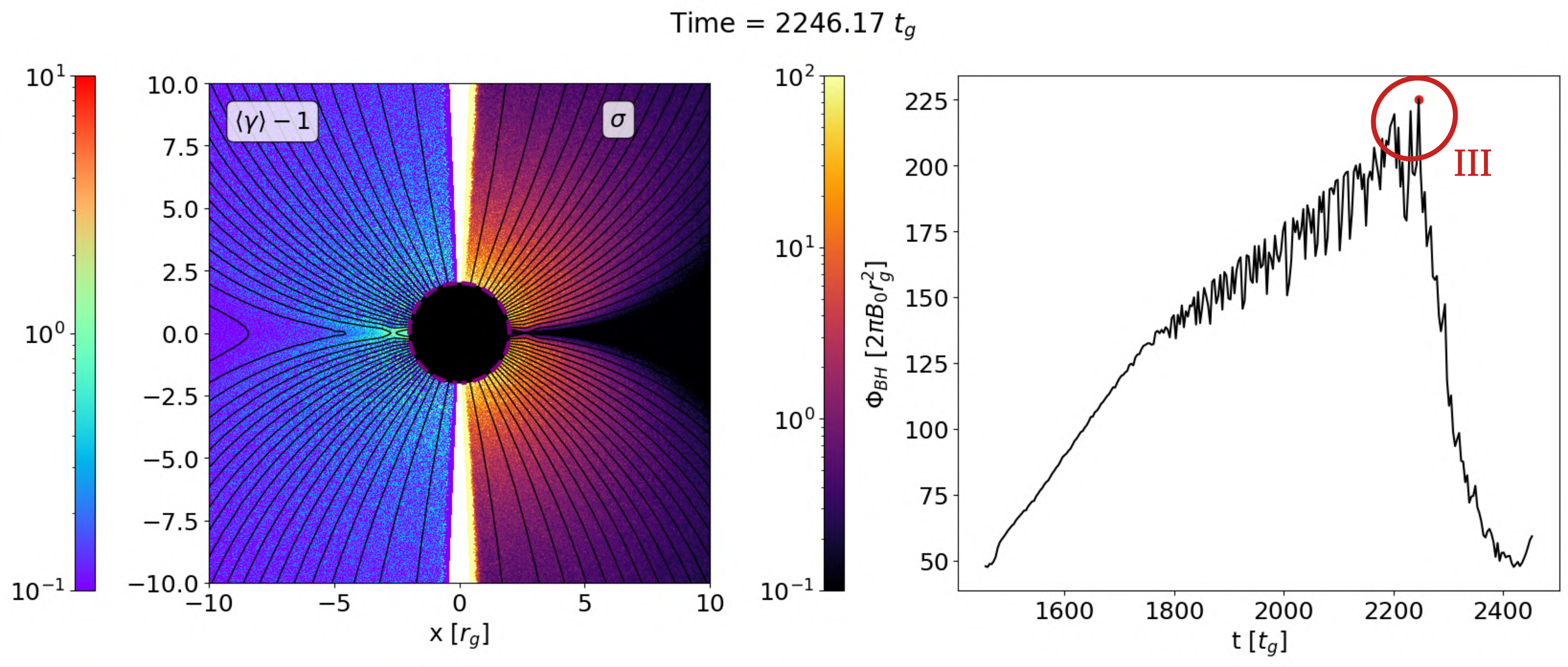


Accumulation of magnetic flux regulated by magnetic reconnection

A mechanism in four phases



An X point forms farther from the event horizon!

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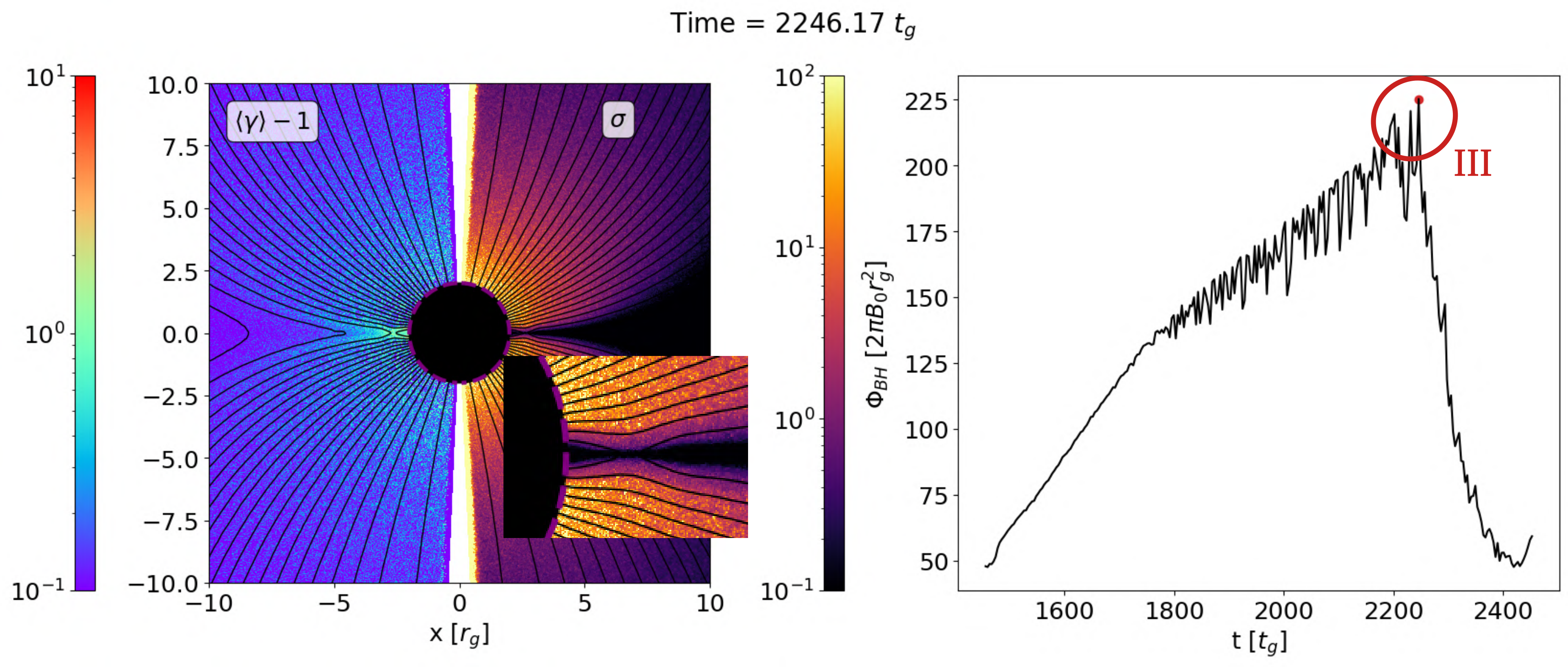

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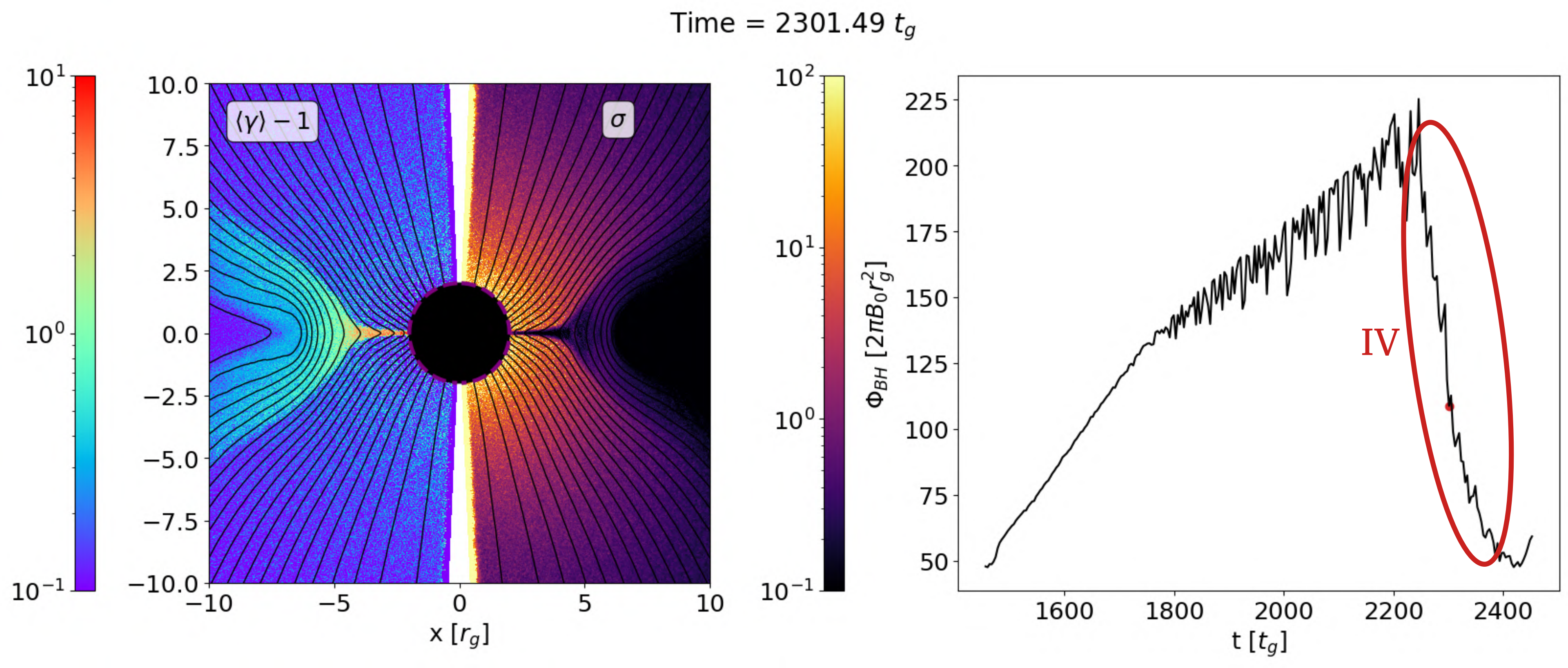
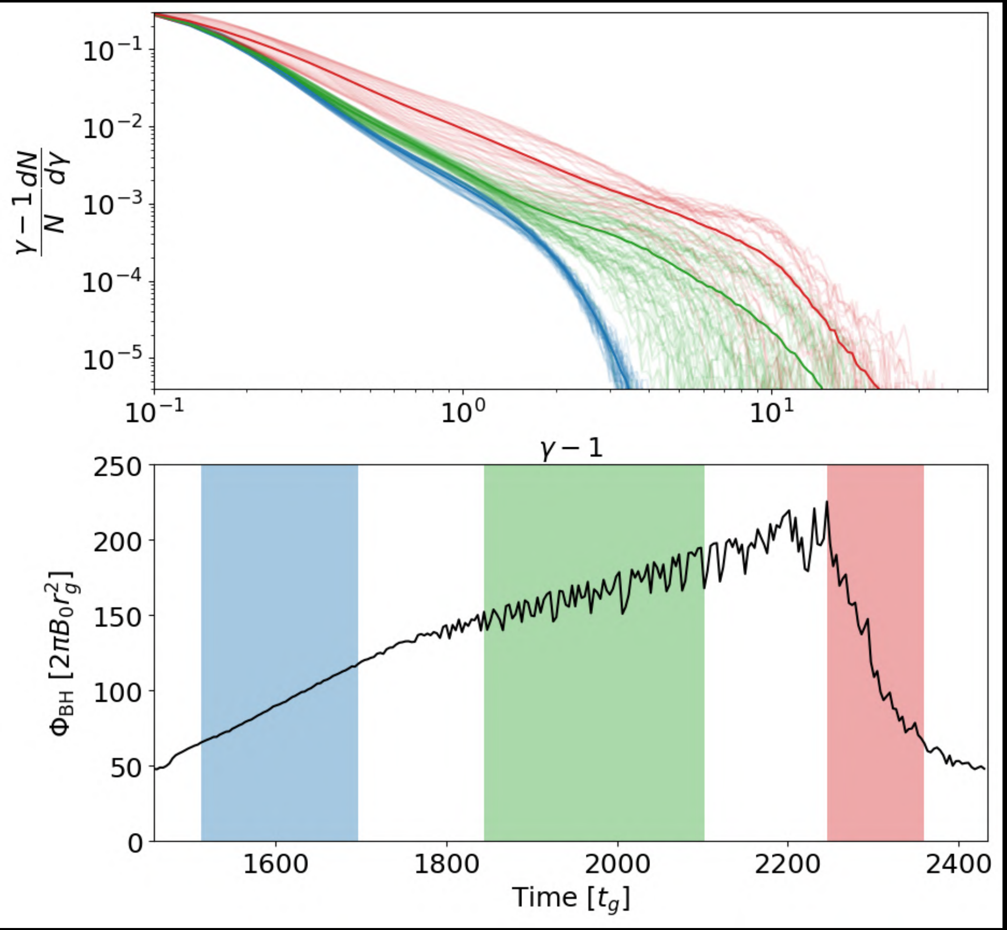


150 t_g (50 min), only mediated by the reconnection rate: $\frac{\mathrm{d}\Phi_{\mathrm{BH}}}{\mathrm{d}t} \propto \beta_{\mathrm{rec}}\Phi_{\mathrm{BH}}$

Strong Particle Acceleration at the Eruptions



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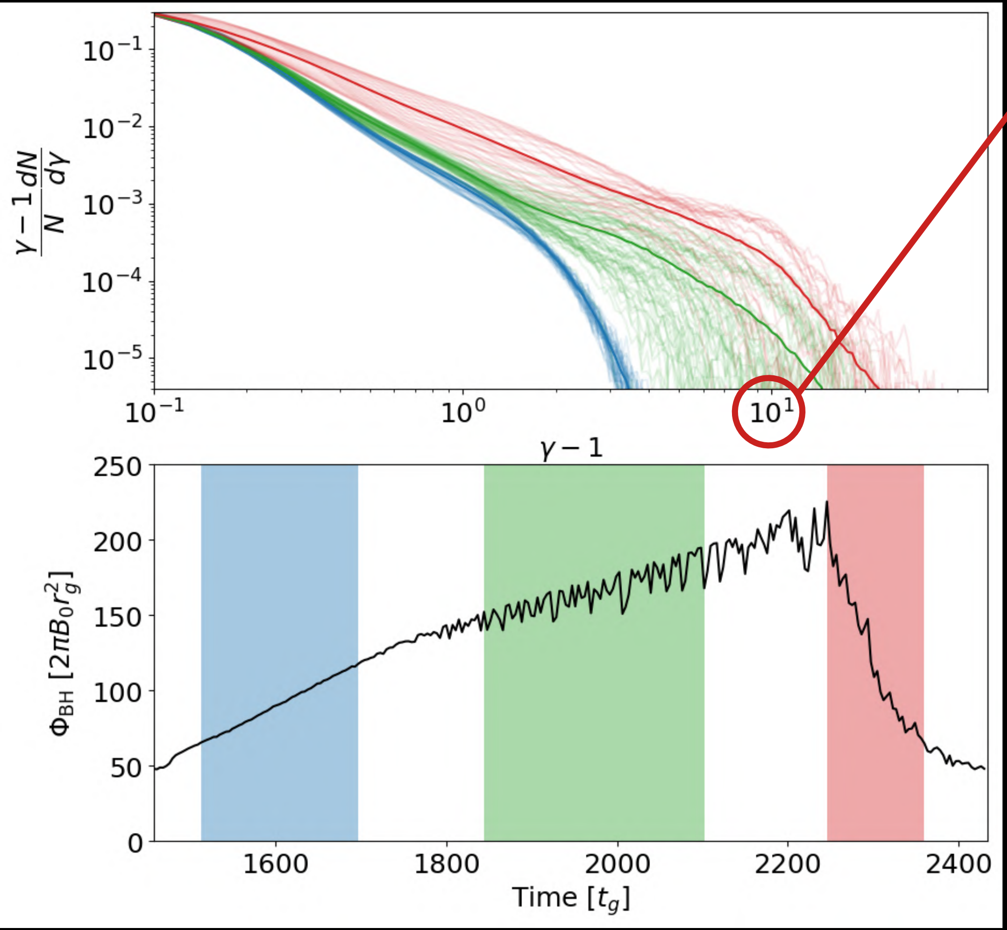

$\sim \sigma$, as predicted by reconnection theory!

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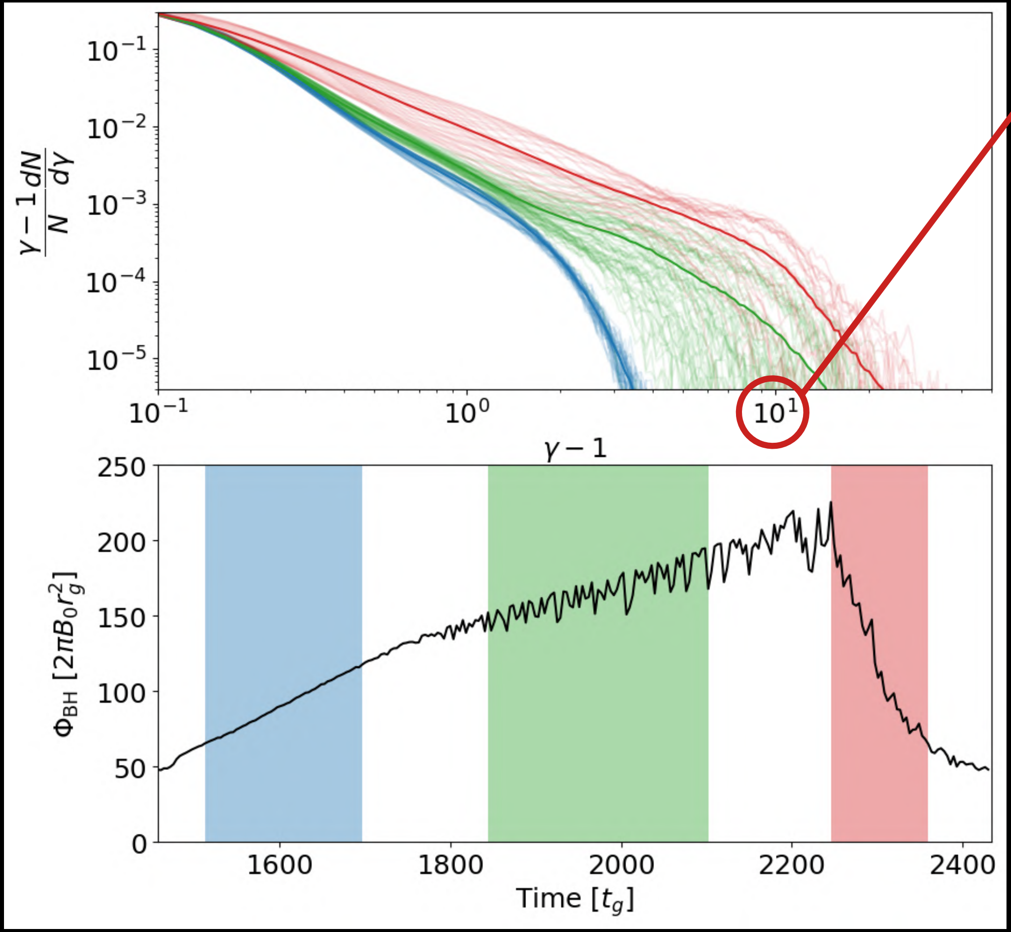


$\sim \sigma$, as predicted by reconnection theory!

And with realistic mass ions?

–Same magnetic energy reservoir but different mass → higher Lorentz factor for the lightest species

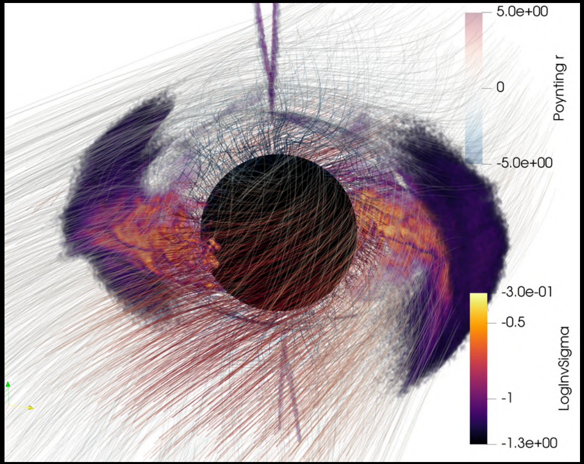
$$\langle \gamma_e \rangle \sim 10^4$$

Close to what is needed for X-rays! (assuming synchrotron emission)

Conclusions

–A black hole can be highly spinning without generating a strong jet

–Magnetic reconnection would still remain an efficient particle accelerator



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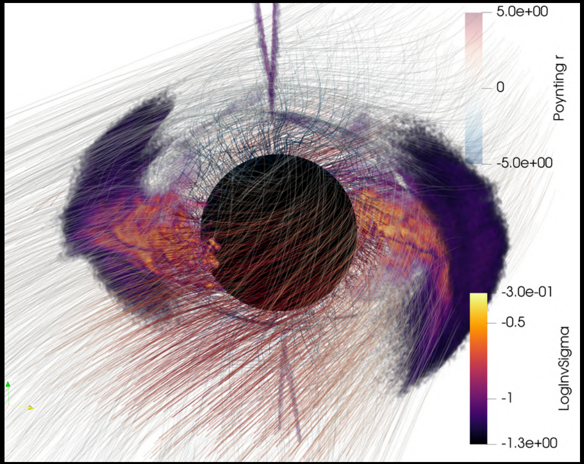

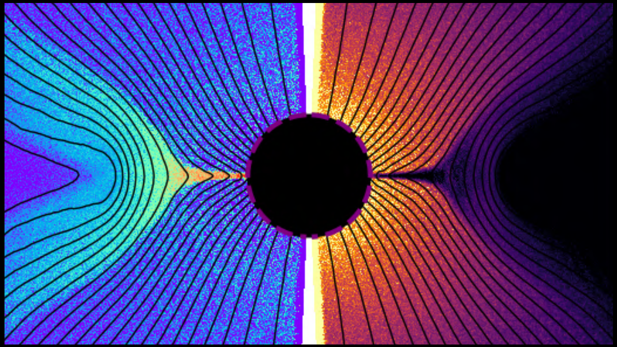

–A simple setup can capture flaring activity of a black hole magnetosphere from first principles

–The universality of magnetic reconnection appears to have a central role to explain the eruptions timescales