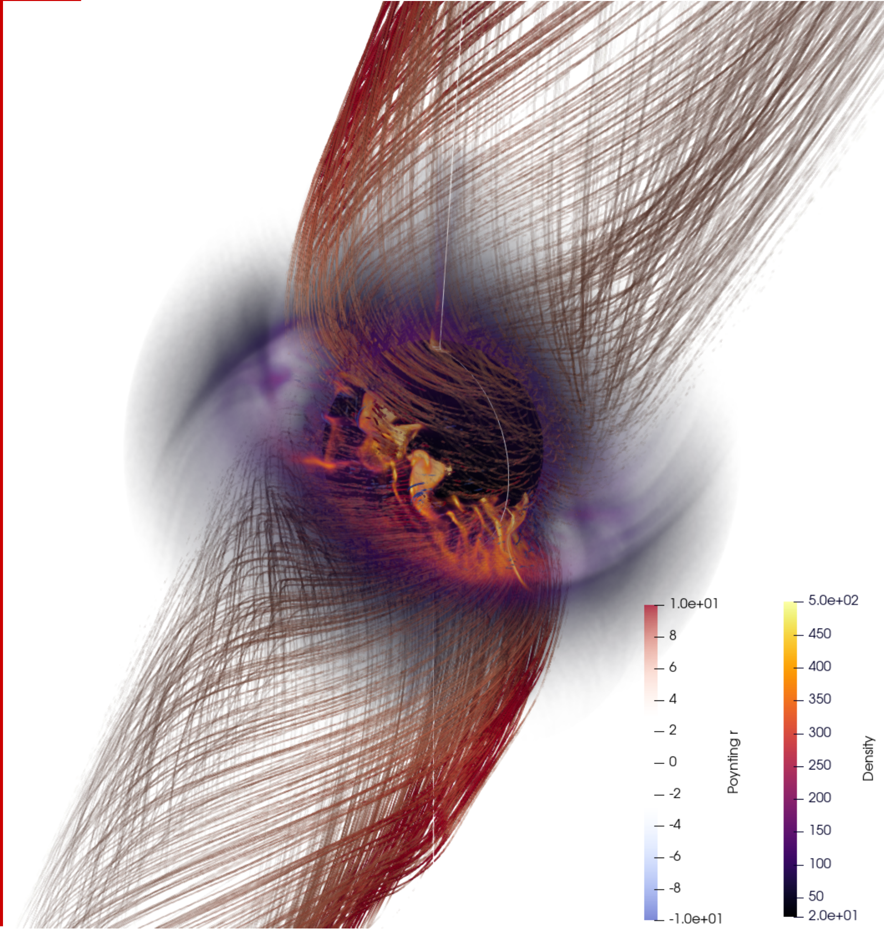
Particle-in-cell simulations of inclined black hole magnetospheres

Enzo Figueiredo

Supervisor: Benoît Cerutti



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erc European Research Council
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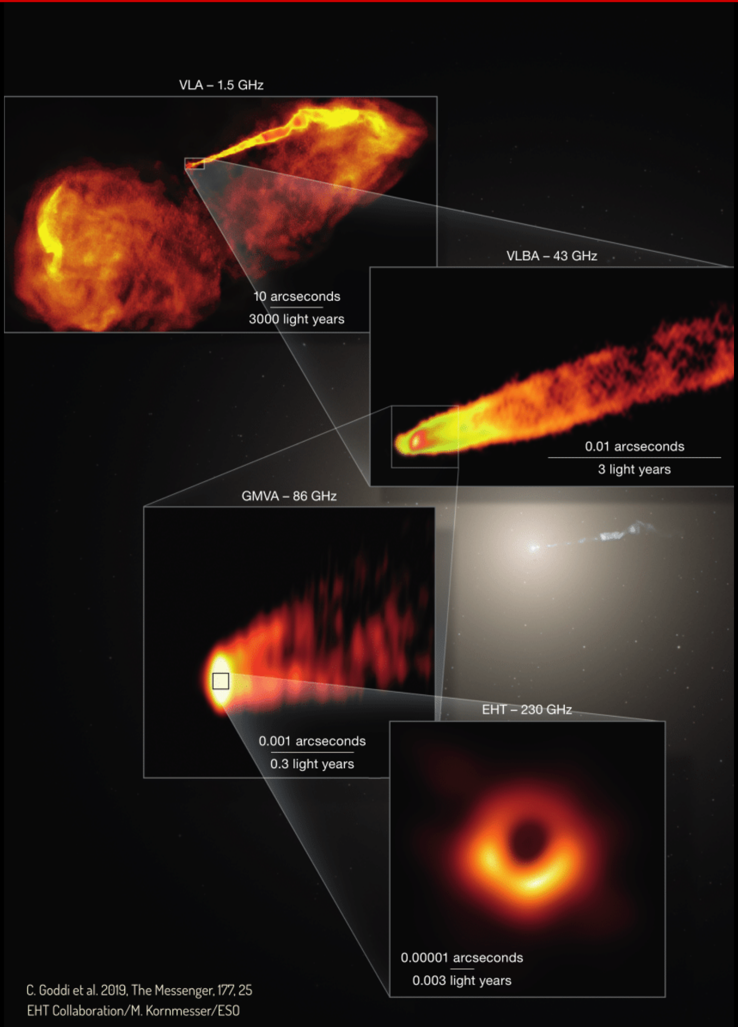
Supermassive Black Holes and Jet Emission

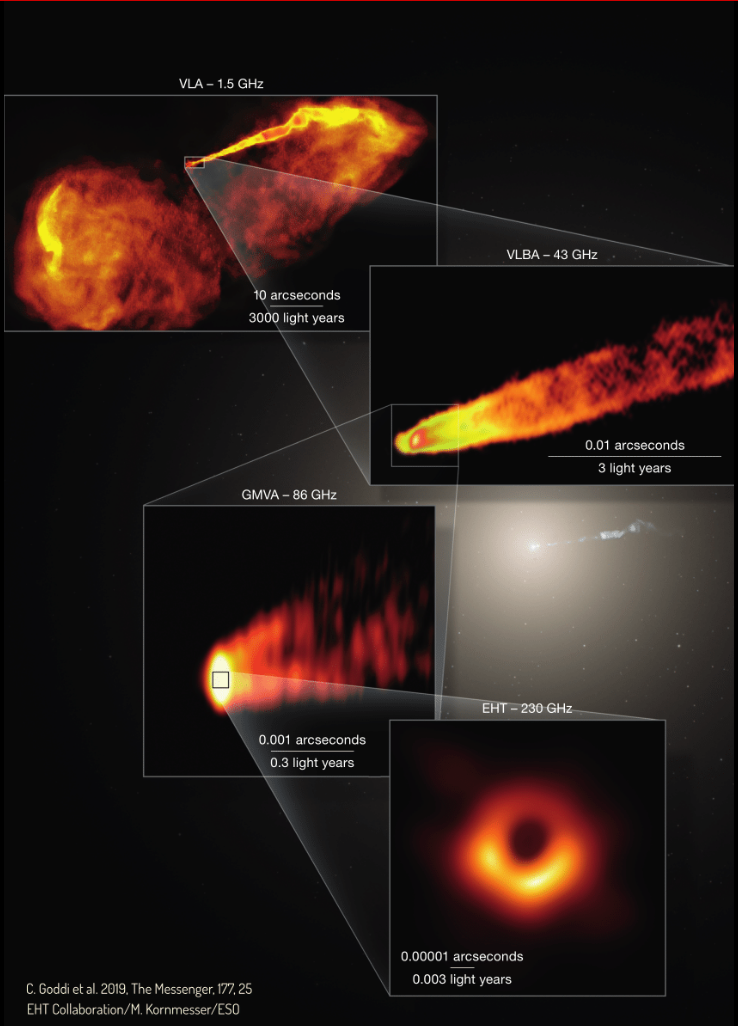


Evidences for a connection between SMBH and galactic jets

+

Non thermal emission

Supermassive Black Holes and Jet Emission

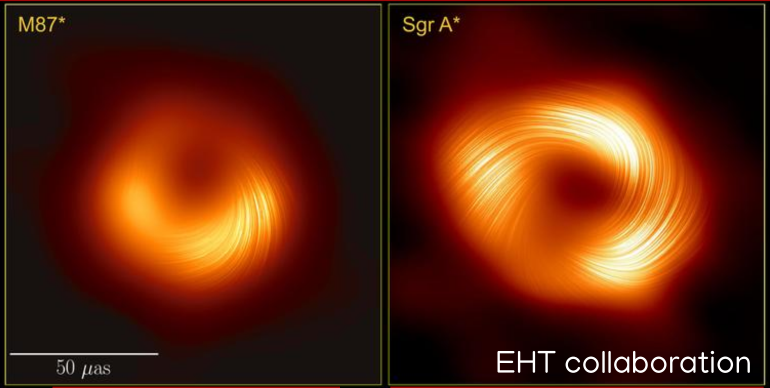


Evidences for a connection between SMBH and galactic jets

+

Non thermal emission

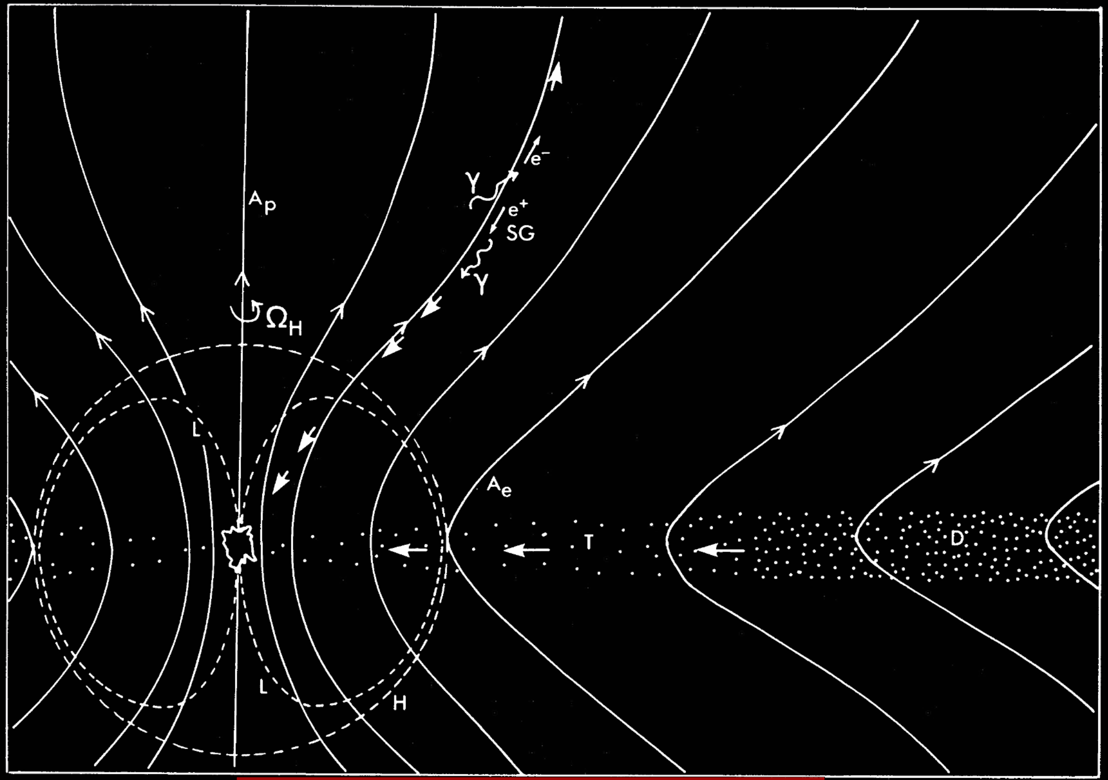
A few constraints on BH mass, matter density, magnetic field and jet power (BH spin ?)



Strong jet

Weak/no jet ?

Theoretical Understanding of the Jet Emission

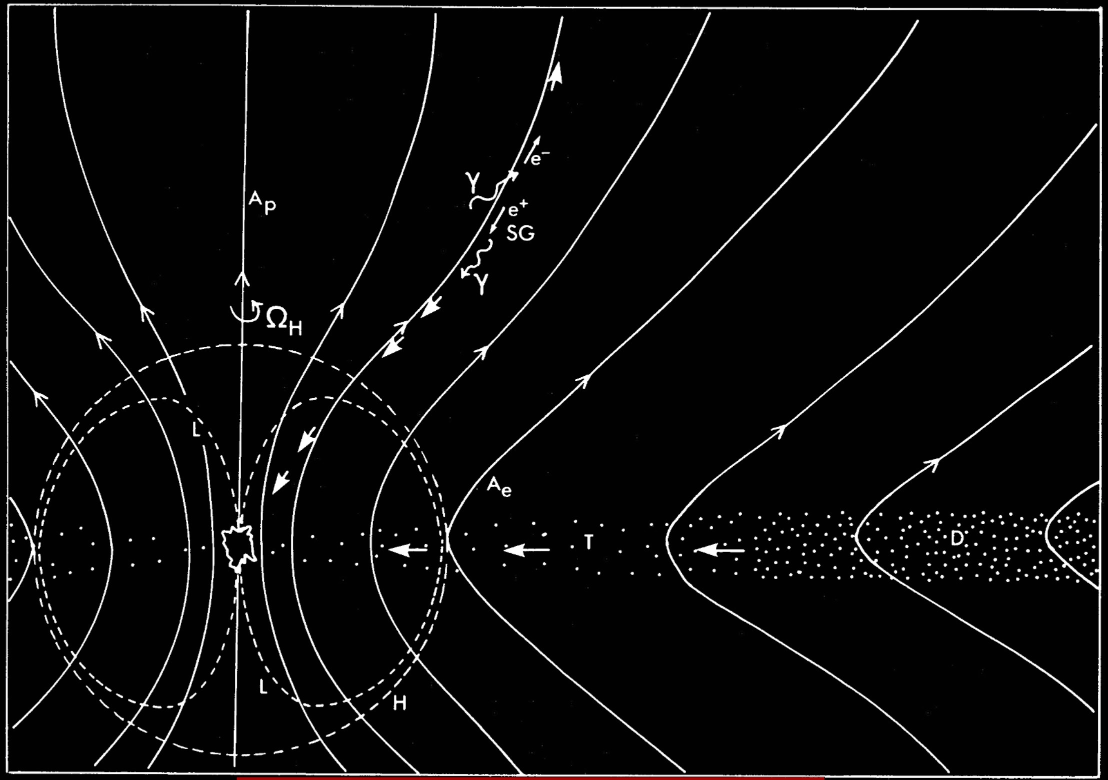


Blandford & Znajek, 1977

Accretion of magnetized plasma, together with pair creation mechanisms, powers a highly magnetized jet

$$L_{BZ} = \frac{1}{96} a^2 B_0^2, \ a \ll 1$$

Theoretical Understanding of the Jet Emission



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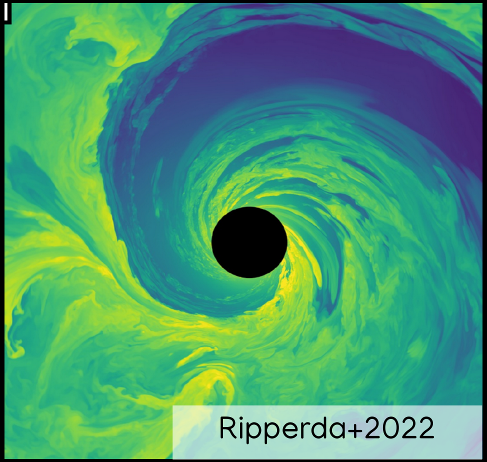
Does it work? With microphysics involved?
What if we loose axisymmetry?

Black Hole Accretion and Ejection Models

Black Hole Accretion and Ejection Models

GRMHD



- ✓ Large scales, long term evolution
- ✗ No microphysics, mildly magnetized plasma

Black Hole Accretion and Ejection Models

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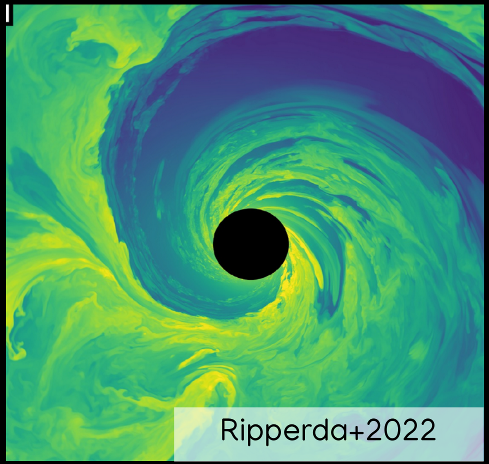

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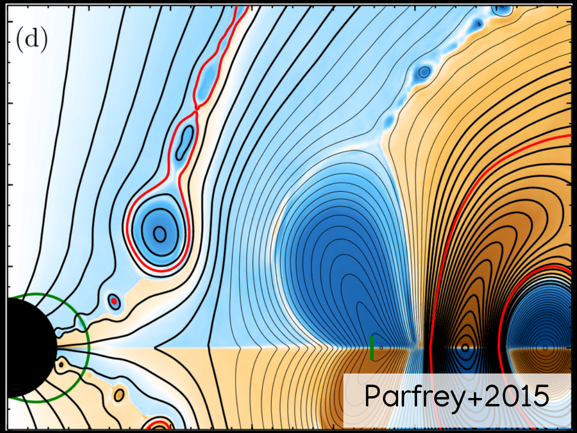
GR Force-Free Electrodynamics



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Black Hole Accretion and Ejection Models

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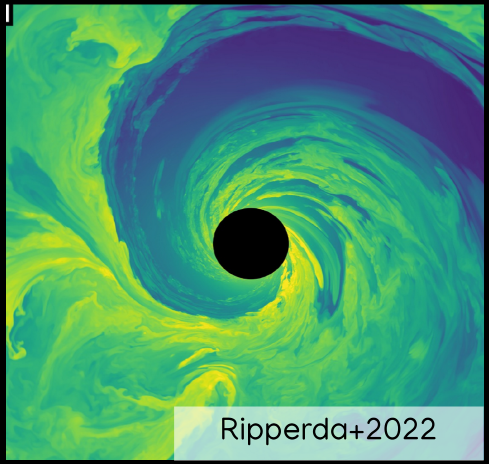

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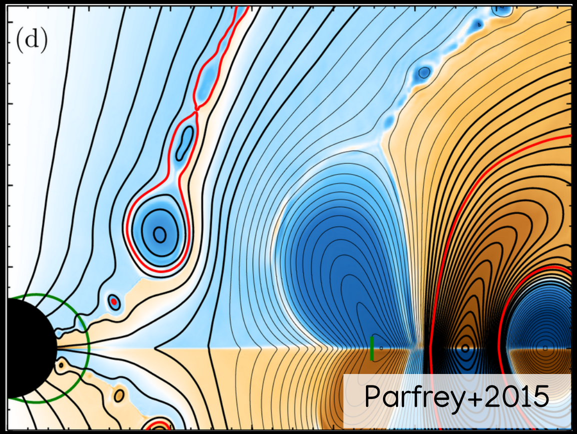

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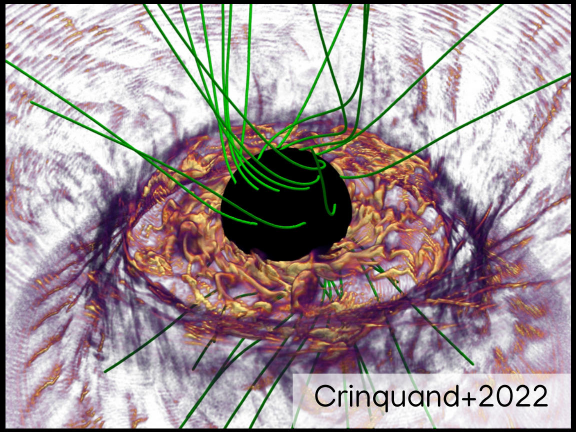
GR Particle-in-cell (PIC)



- ✓ Accurate modeling of plasma, particle acceleration
- ✗ Expensive, short scales

Black Hole Accretion and Ejection Models

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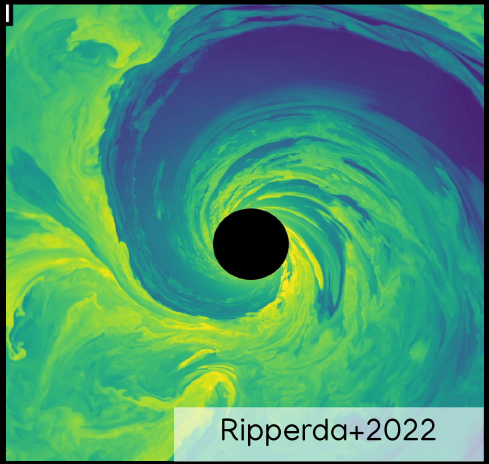

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→ Disk accretion

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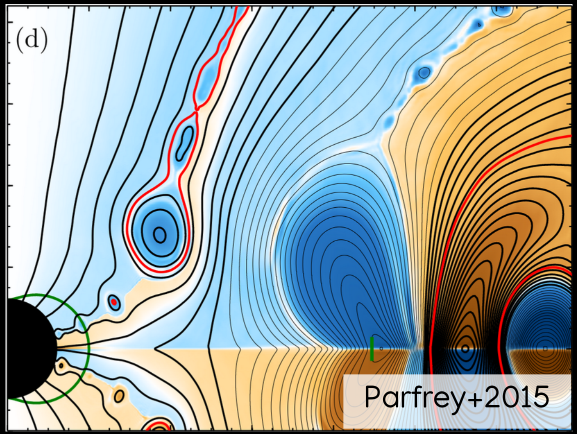

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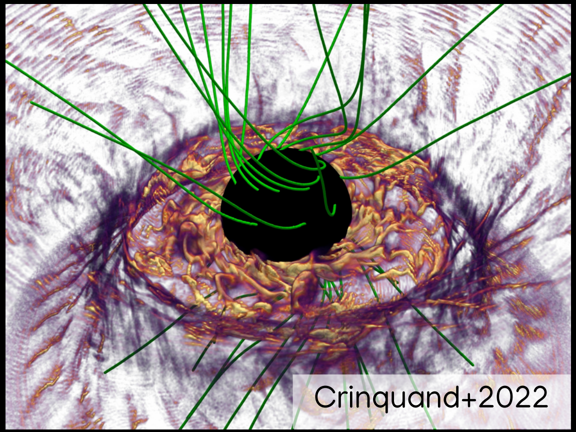

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Black Hole Accretion and Ejection Models

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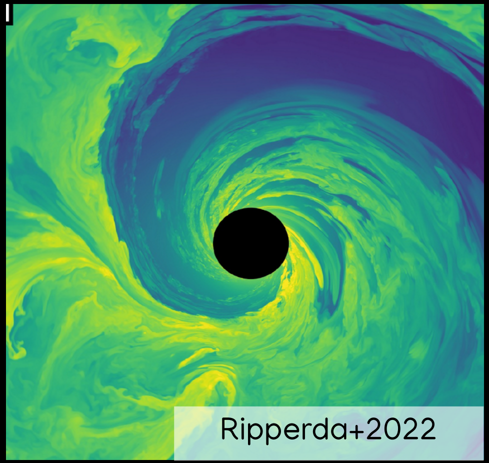

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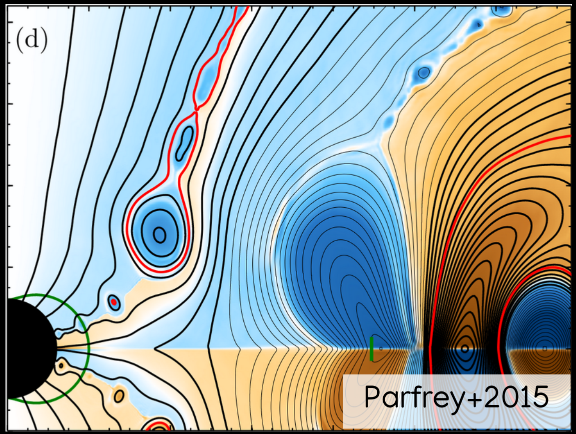

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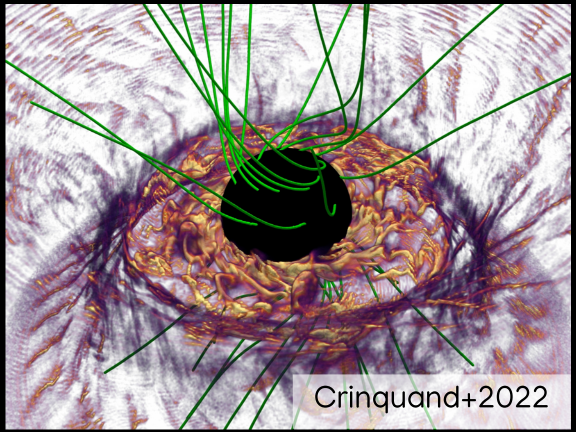

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→ Magnetospheric physics

Black Hole Accretion and Ejection Models

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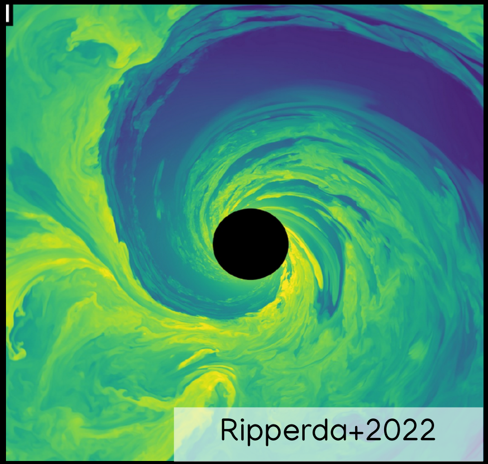

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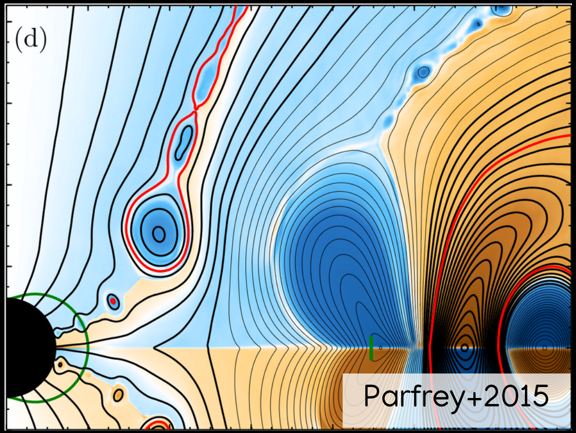

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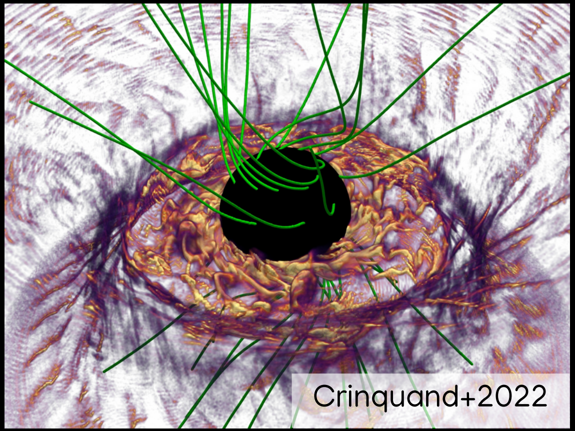

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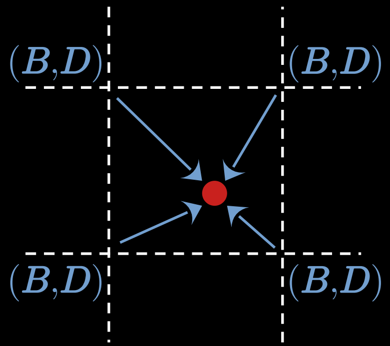
→ Disk accretion

→ Magnetospheric physics

GRZeltron: a GRPIC code (Parfrey+2019)

3+1 formalism (Komissarov, 2004)

Kerr metric, KS spherical coordinates



Field Interpolation

Particle Push

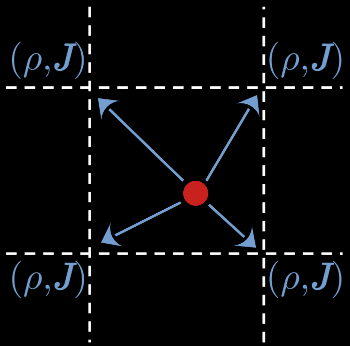
$$\dot{x}^i = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i$$

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

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

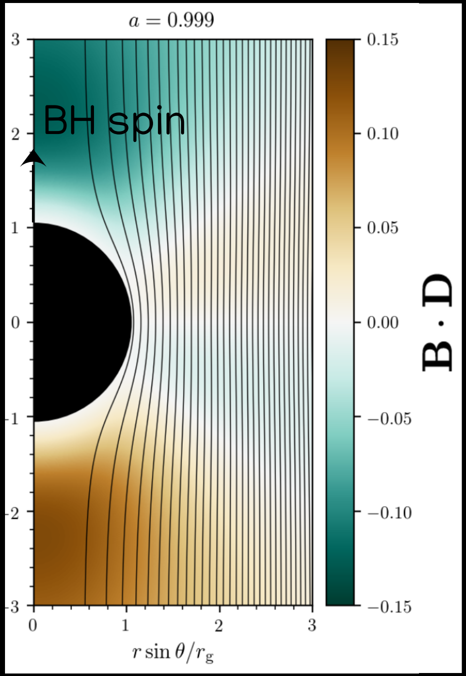
- Full treatment of non ideal phenomena
- Can capture microphysics (e.g. QED processes)
- Acceleration of particles self consistently treated

BH Embedded in a Uniform Magnetic Field

In vacuum

a = 0.999

Crinquand's PhD, 2021



Wald (1974)

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With plasma injection

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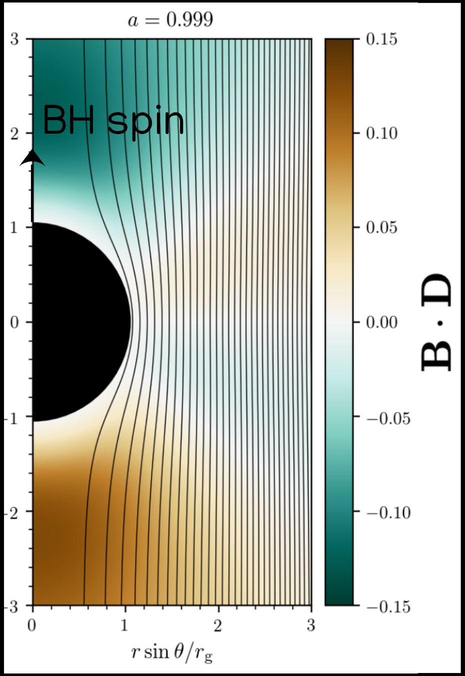
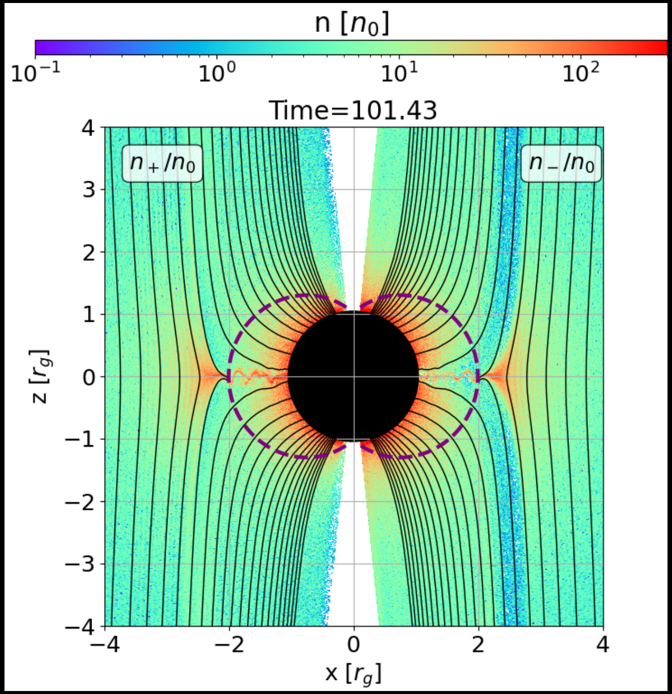


Wald (1974)



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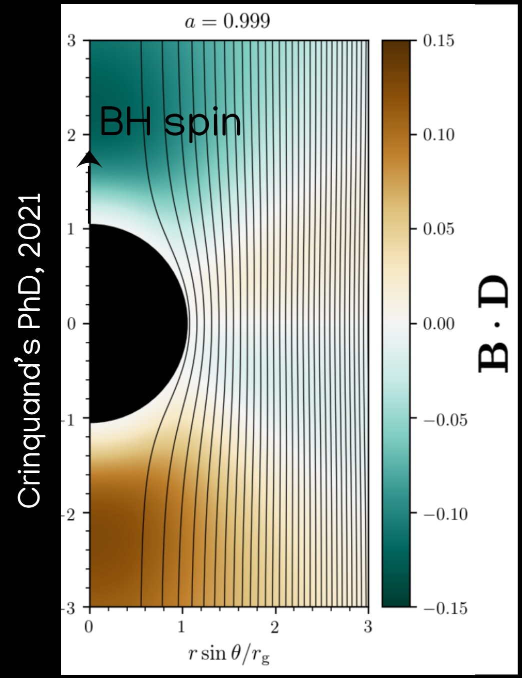

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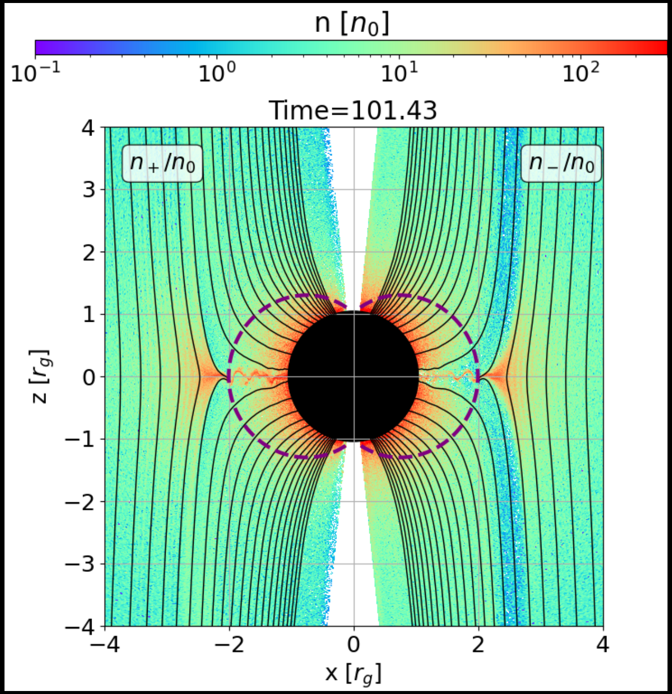
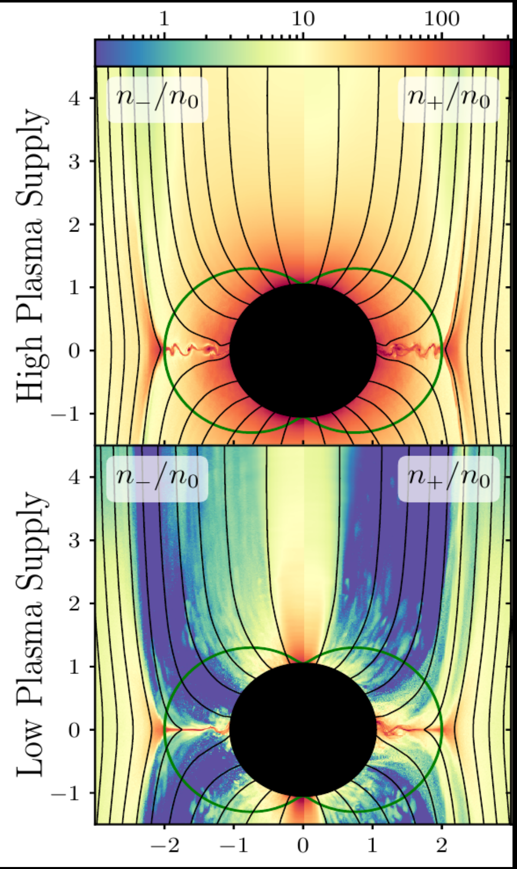


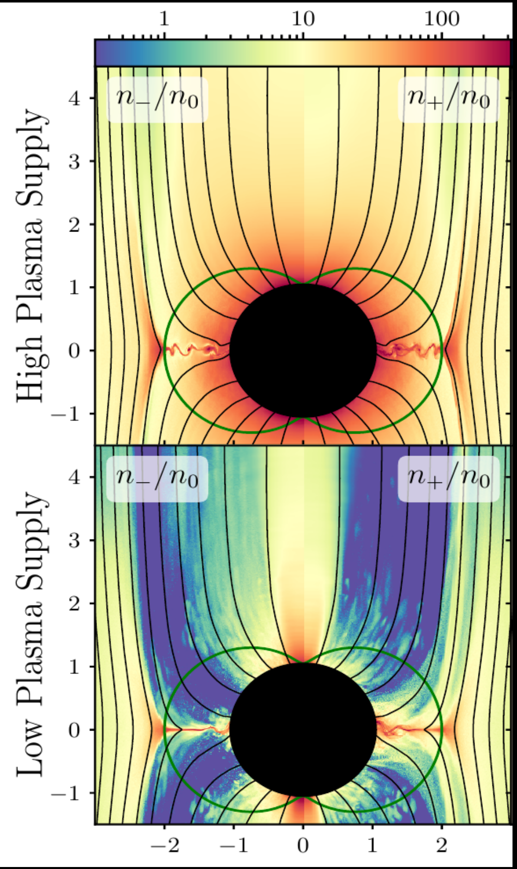
What happens if the magnetic field is inclined with respect to the BH spin ?

Magnetospheric Regime of Interest



Parfrey+2019

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

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

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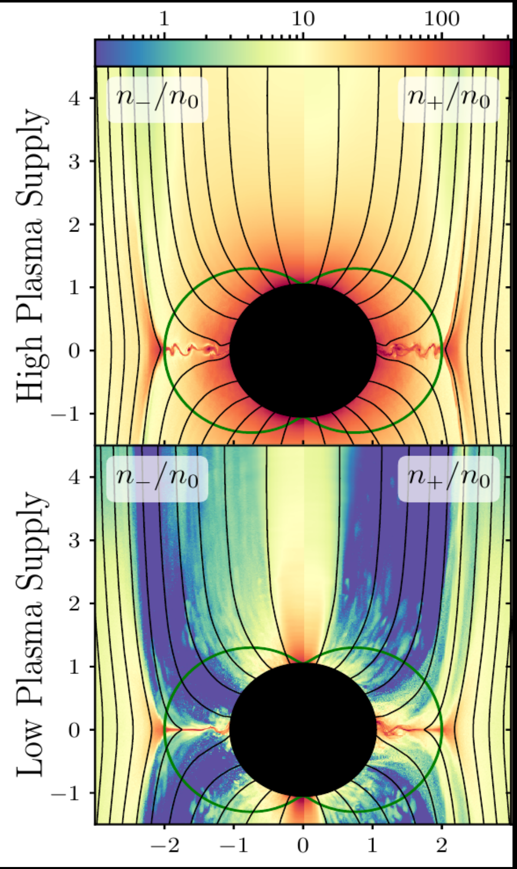

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→ Starved magnetosphere

– Charge separation

– Regions with an unscreened parallel electric field

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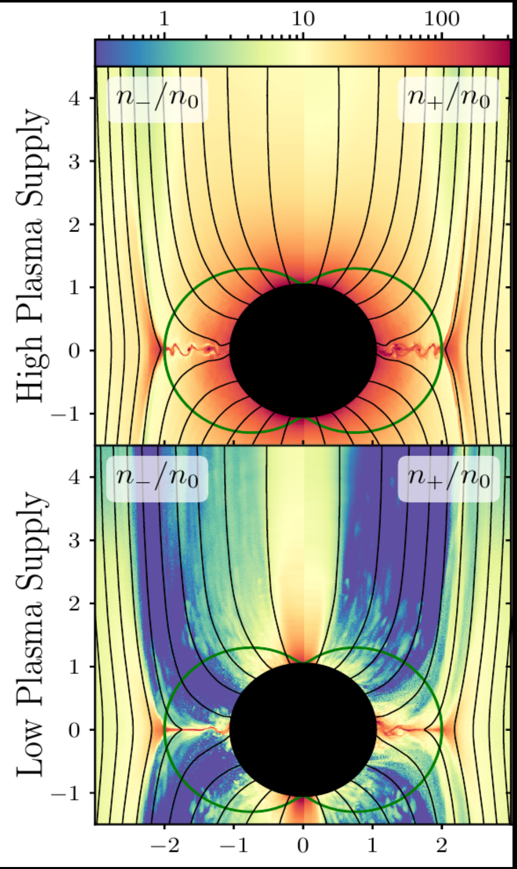

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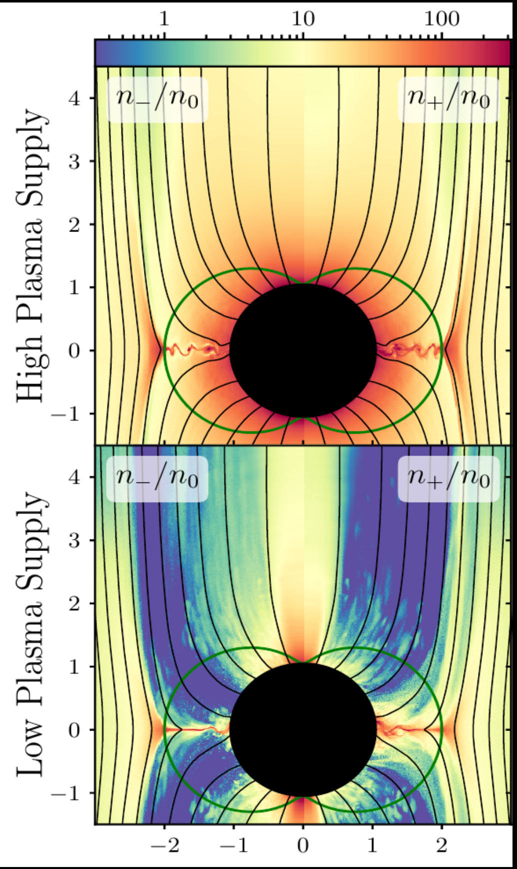

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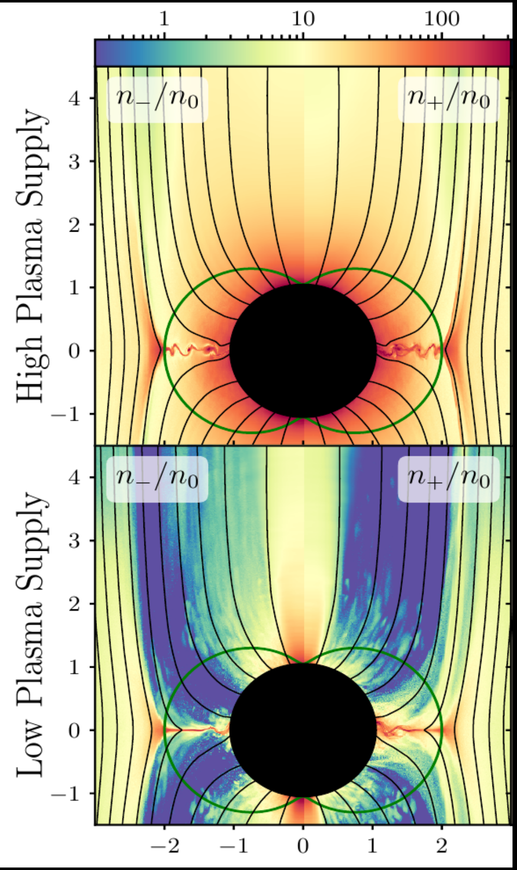
Ad hoc injection

Injection if:

$$\sigma > \sigma_0$$

Magnetospheric Regime of Interest



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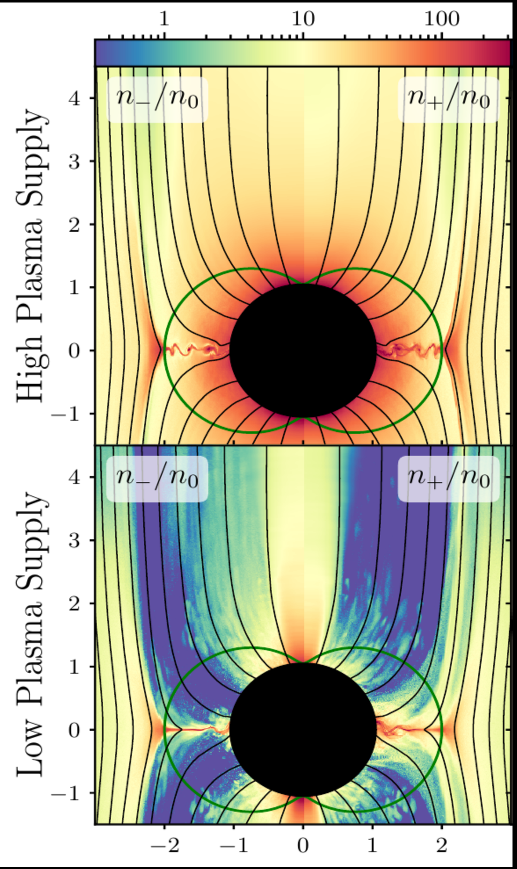
Scale separation

$$B_0 \propto \frac{r_g}{r_L}$$

Our simulations → 500
For Sg A* → 10^{10}

Magnetospheric Regime of Interest



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→ Starved magnetosphere

- Charge separation

- Regions with an unscreened parallel electric field

→ future work with more accurate pair production

Ad hoc injection

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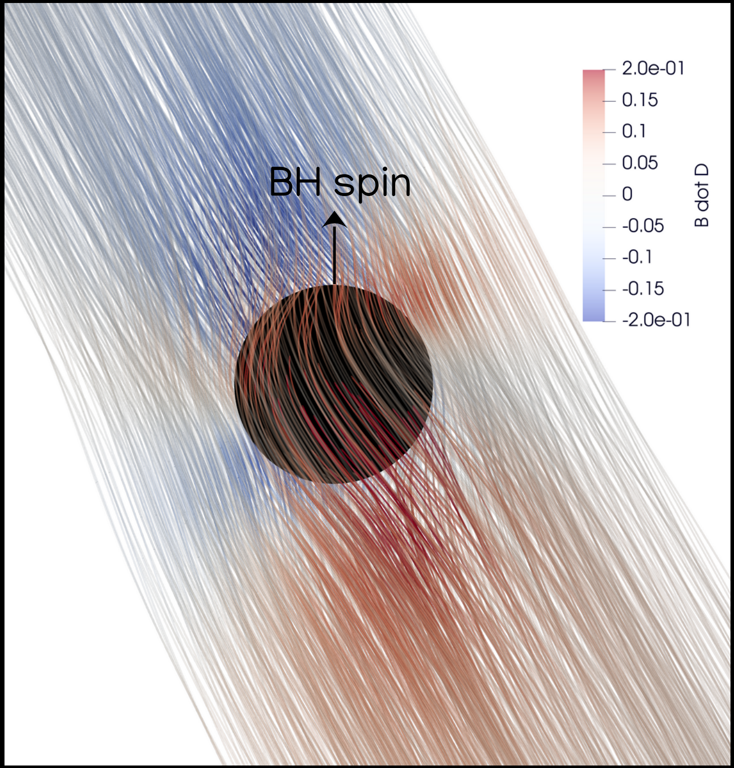
$$B_0 \propto \frac{r_g}{r_L}$$

Our simulations → 500
For Sg A* → 10^{10}

Inclined Black Hole Magnetosphere

In vacuum

$a = 0.99, \chi=30^{\circ}$



Bicak & Janis (1985)

Inclined Black Hole Magnetosphere

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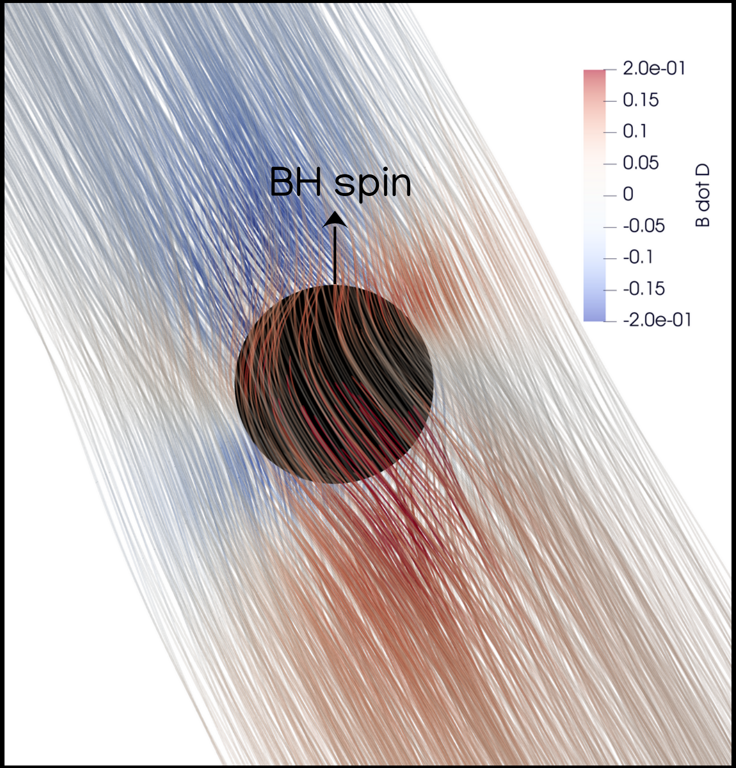
With plasma injection



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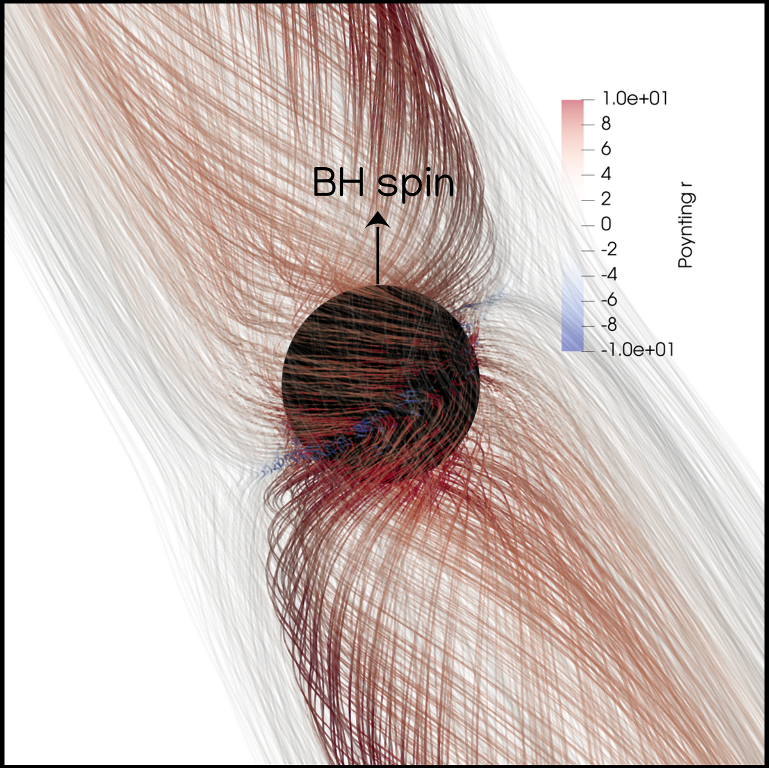

Inclined Black Hole Magnetosphere

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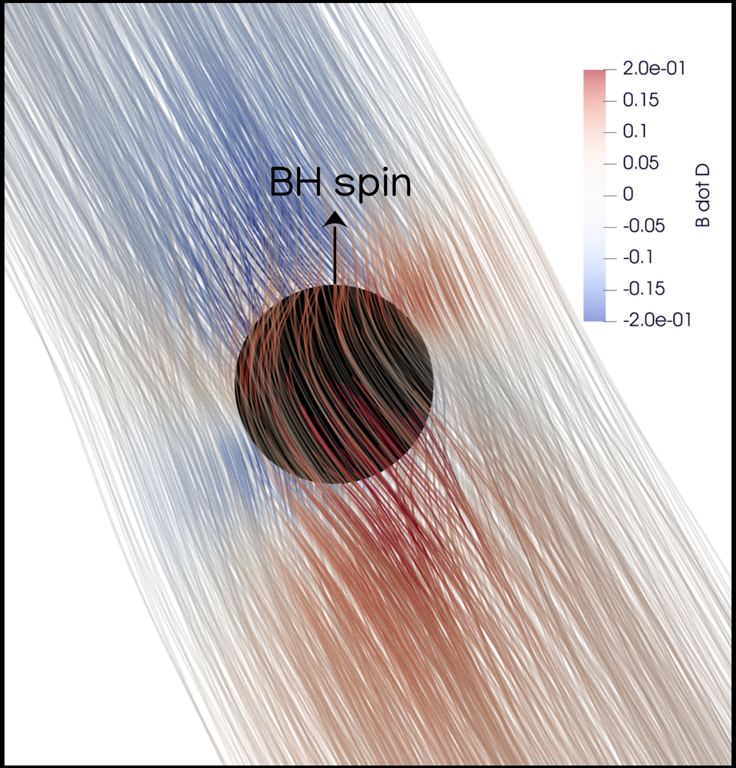

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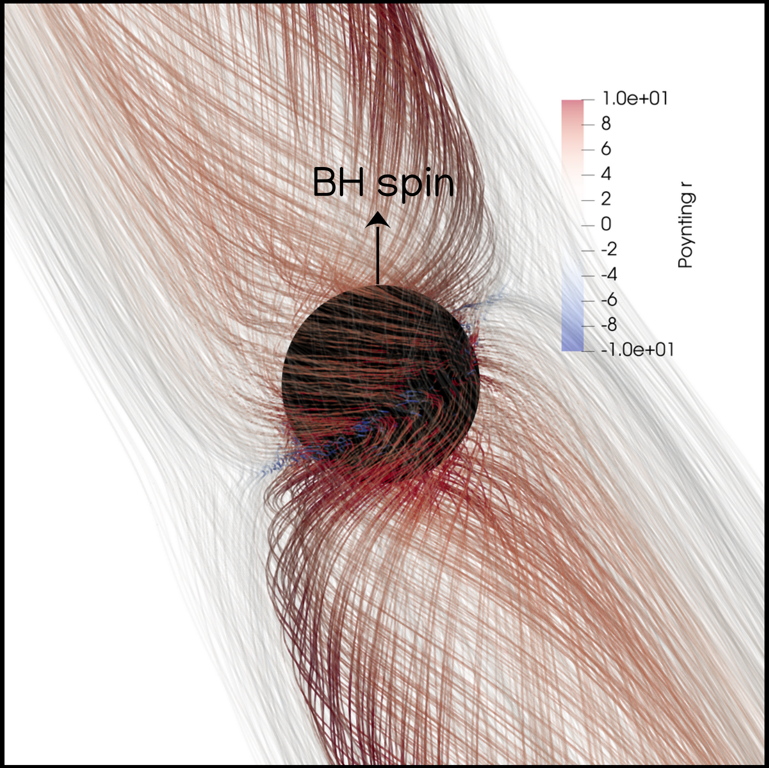
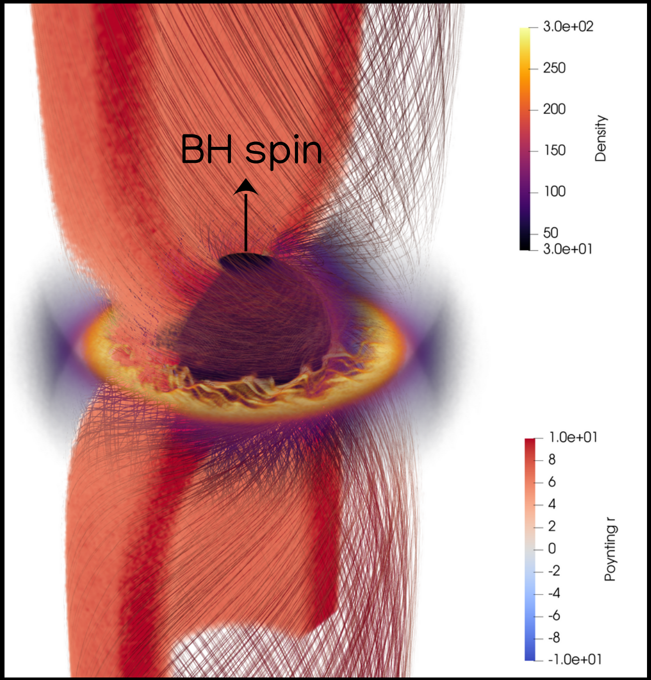


> 15 millions CPU hours for 4 runs

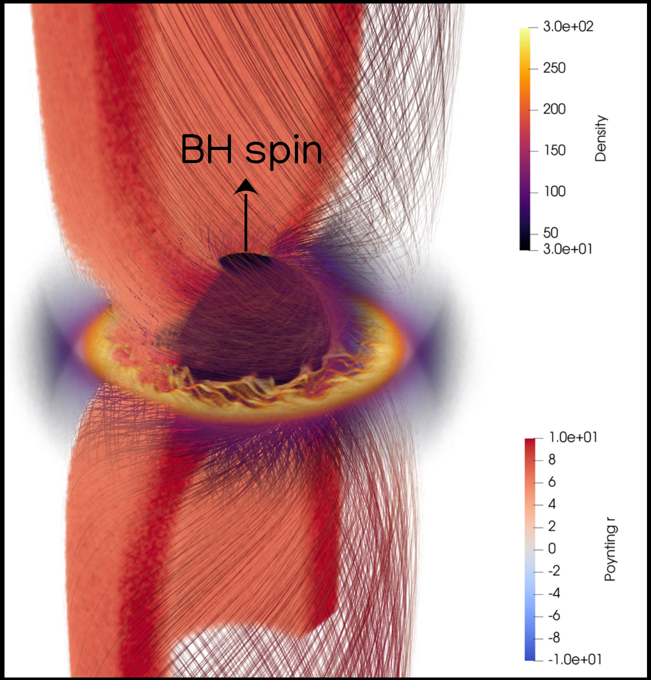
The Jet Structure Is Affected by the Inclination

$\chi = 0^{\circ}$

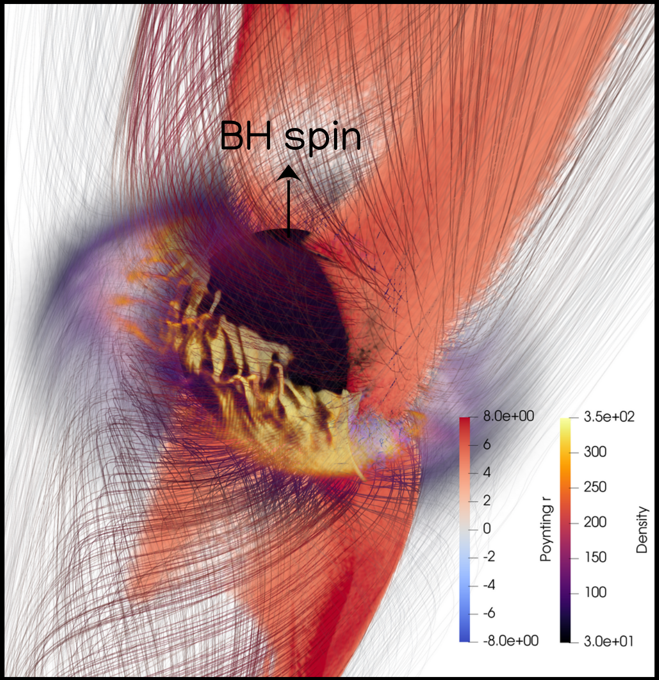


The Jet Structure Is Affected by the Inclination

$\chi = 0°$

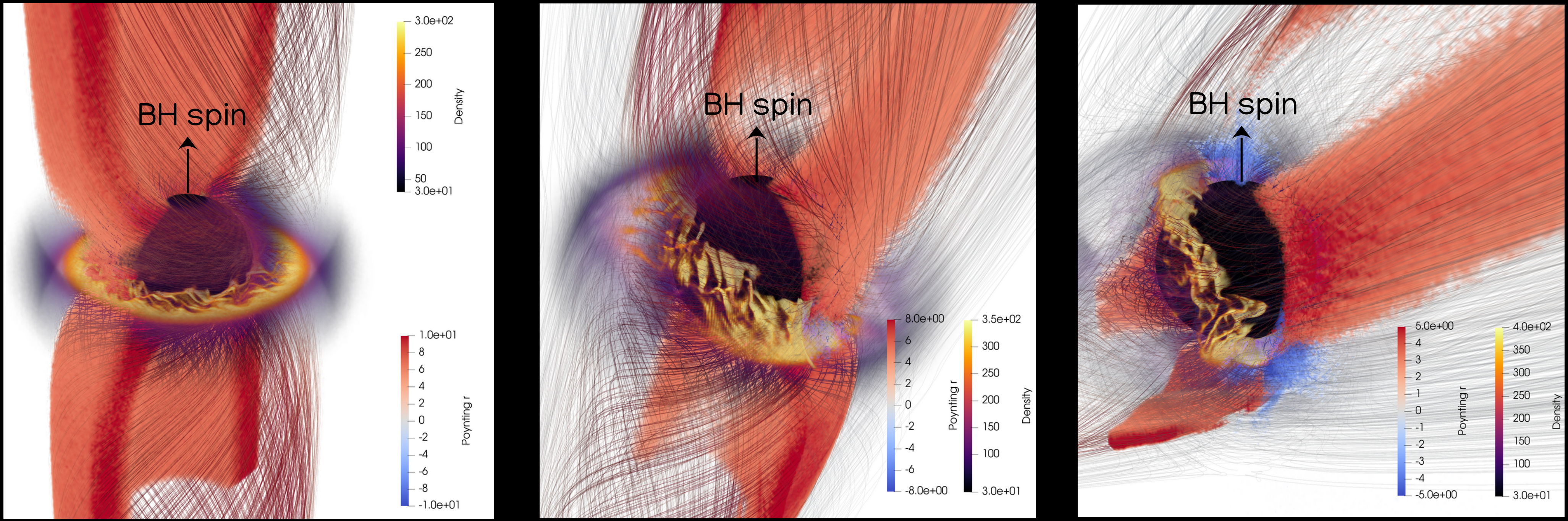


$\chi = 30°$



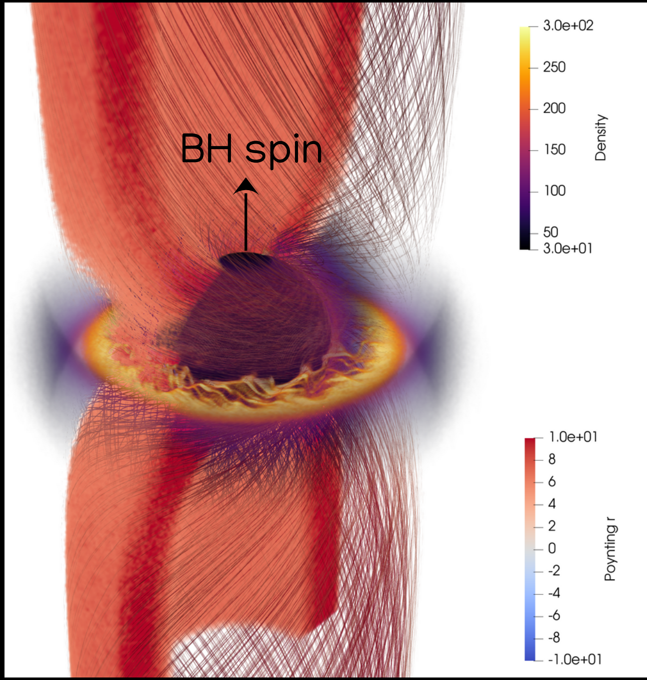
The Jet Structure Is Affected by the Inclination

$\chi = 0°$ | $\chi = 30°$ | $\chi = 60°$

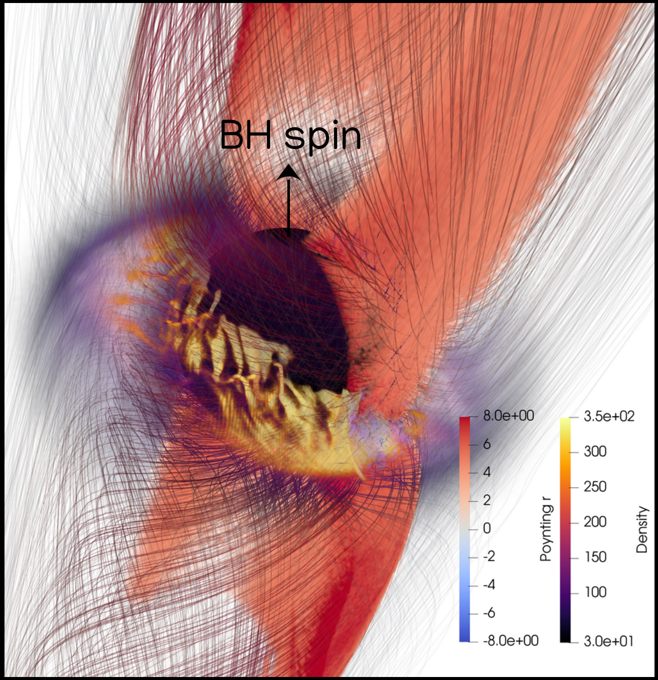


The Jet Structure Is Affected by the Inclination

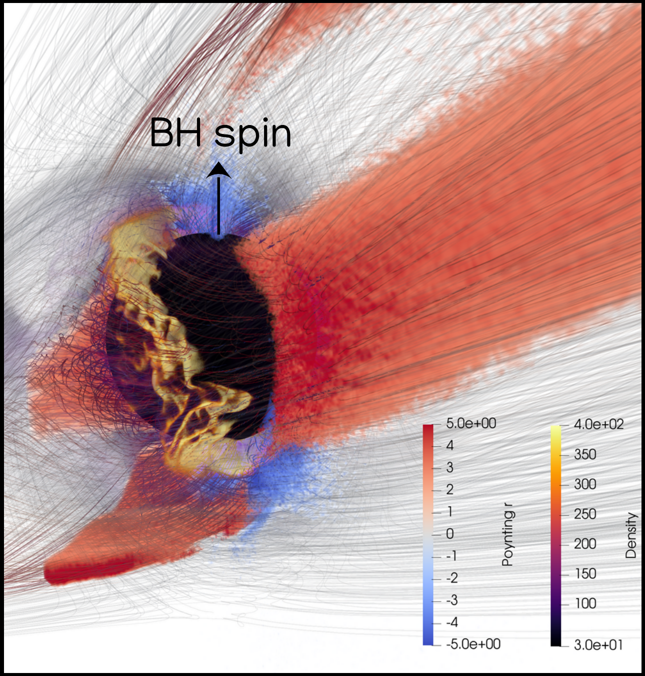
$\chi = 0^\circ$



$\chi = 30^\circ$



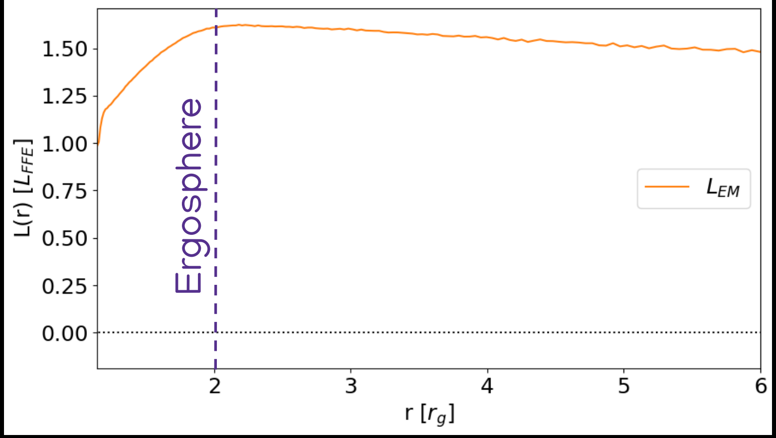
$\chi = 60^\circ$



→ Development of inward Poynting flux close to the separatrix
→ Outward EM flux rather comes from equatorial region of space-time

Electromagnetic Energy Flux

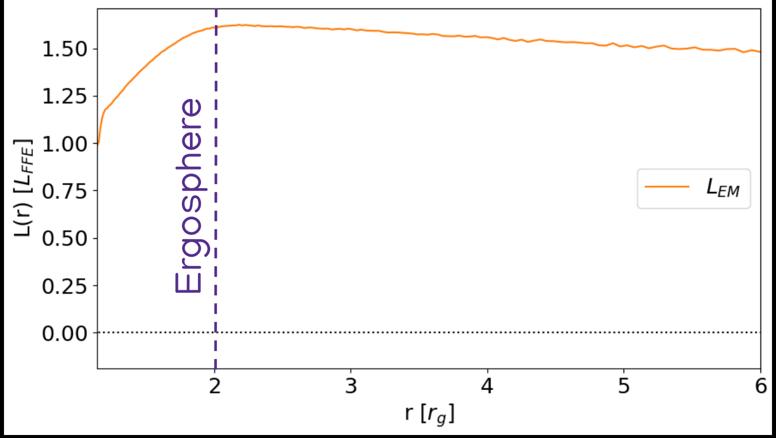
$\chi = 0^\circ$



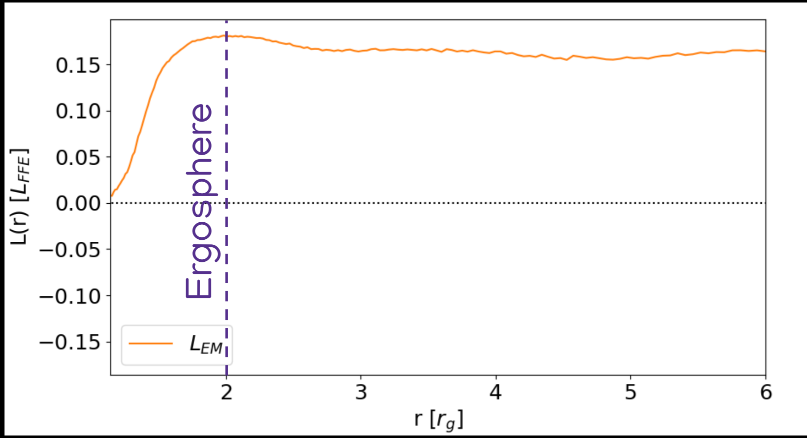
$$L_{\rm EM} = \iint \Pi^r \sqrt{\gamma} {\rm d}\Omega$$

Electromagnetic Energy Flux

$\chi = 0°$



$\chi = 85°$



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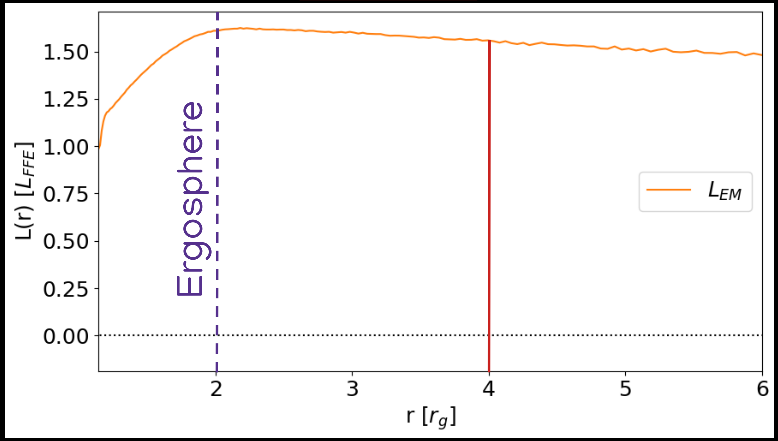

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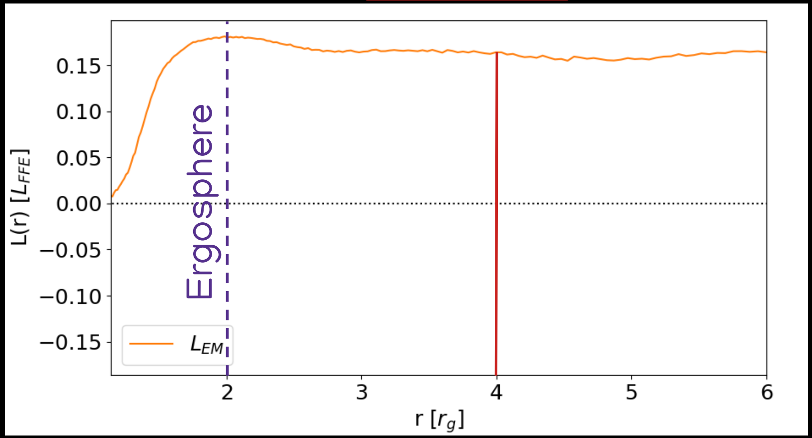

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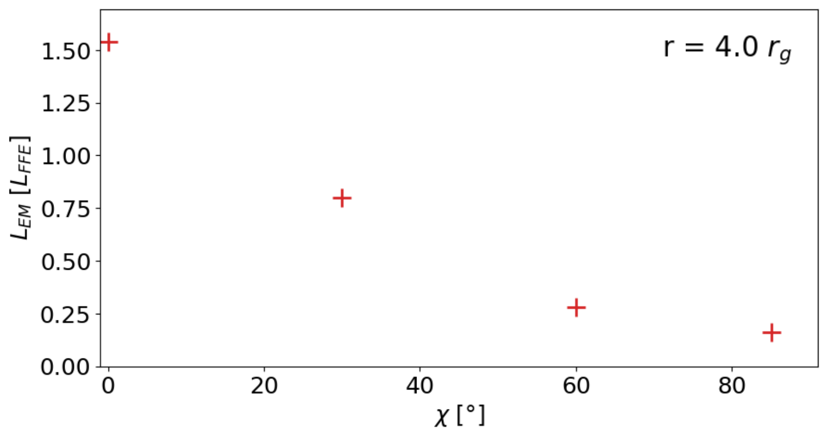
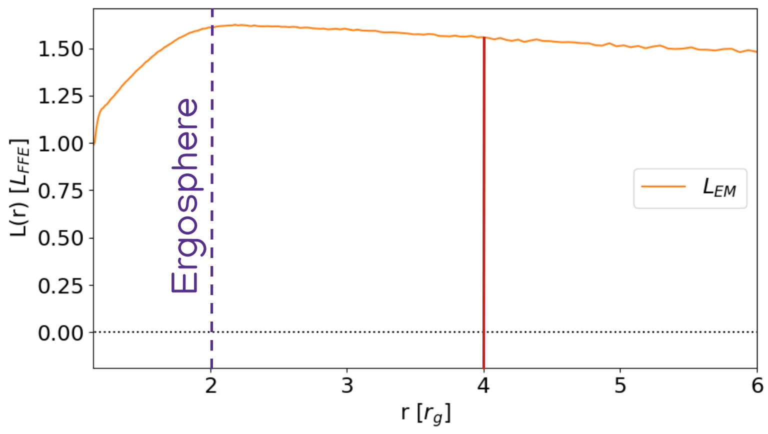
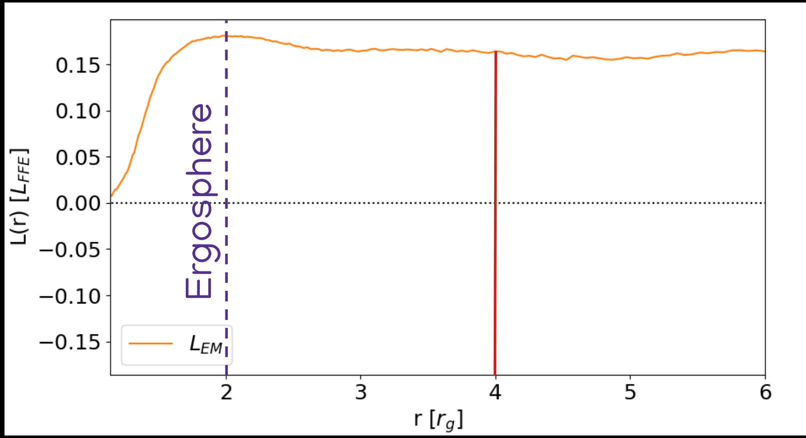


Electromagnetic Energy Flux

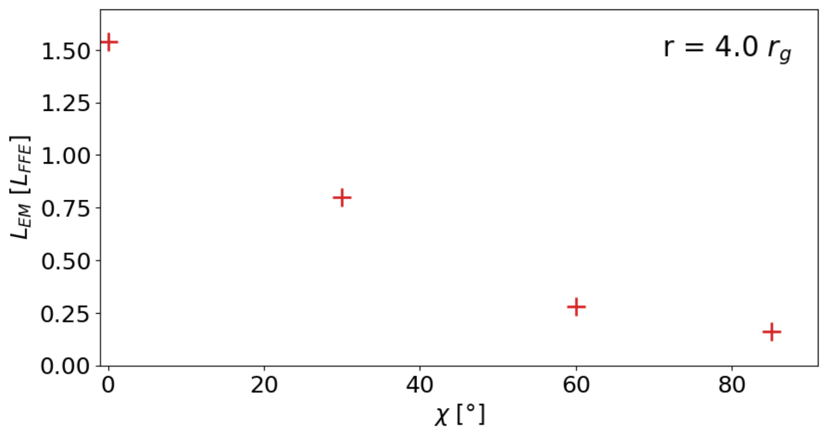
χ = 0°



χ = 85°

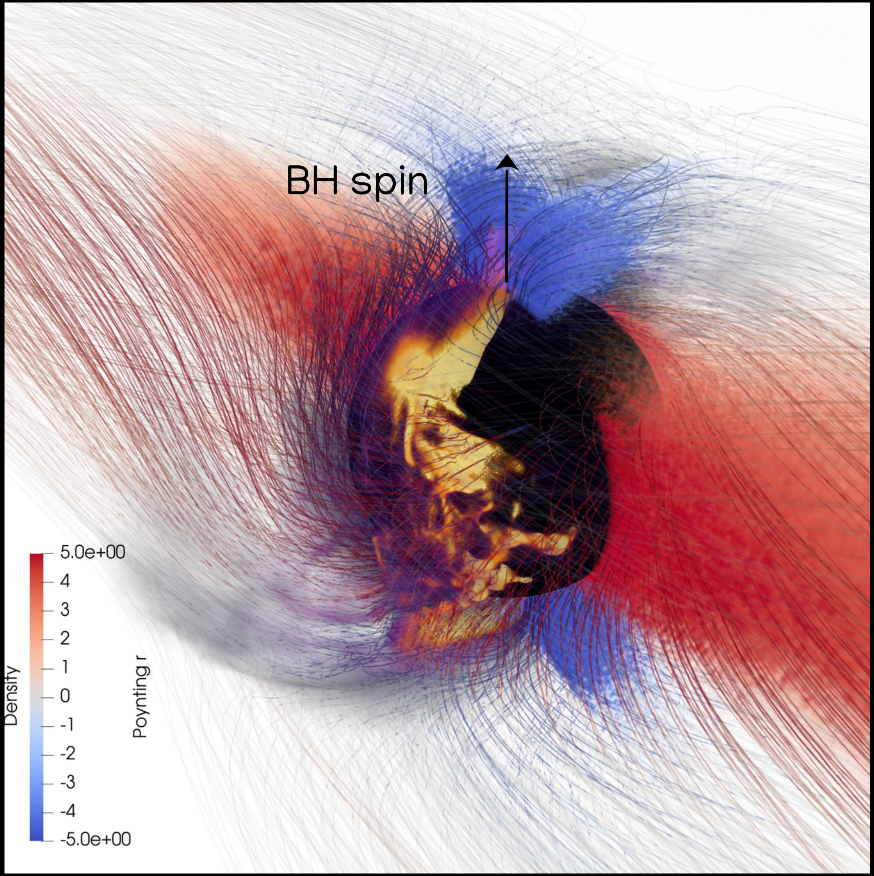


$$L_{\mathrm{EM}} = \iint \Pi^r \sqrt{\gamma} \mathrm{d}\Omega$$

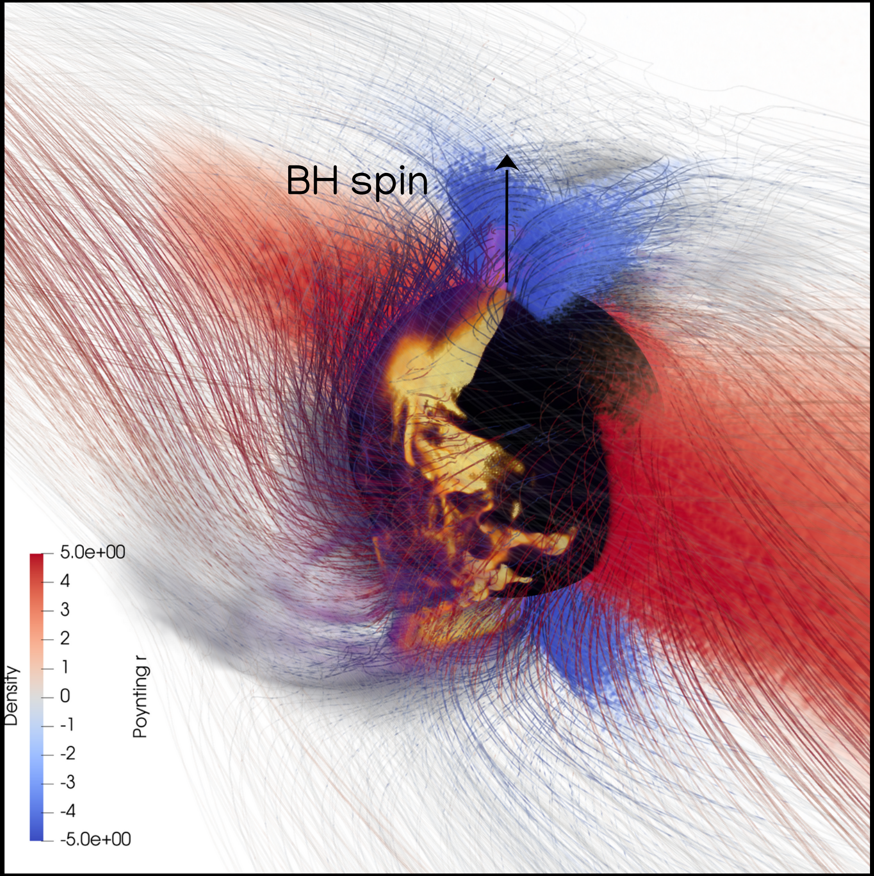


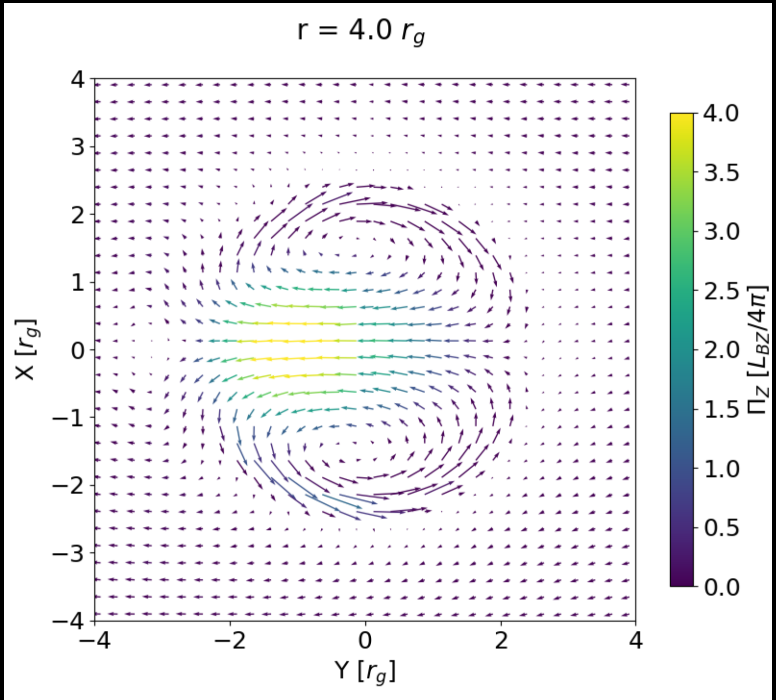
→ Dramatic weakening of the jet power for very inclined magnetospheres

The Case of the Orthogonal Magnetosphere (χ = 85°)

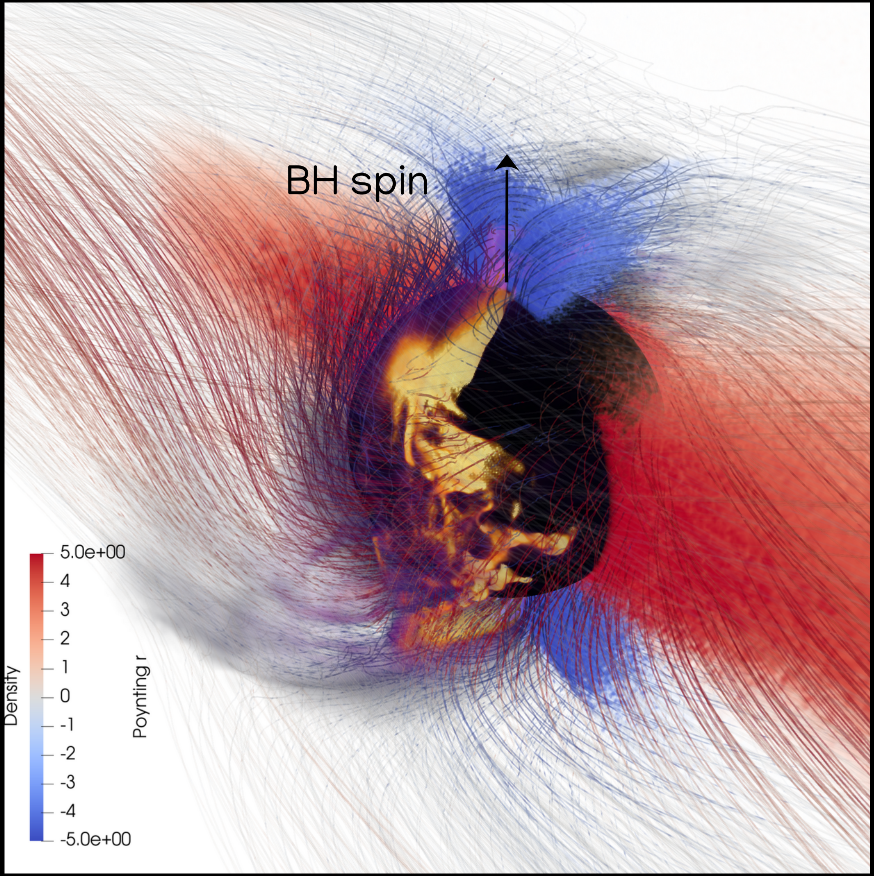


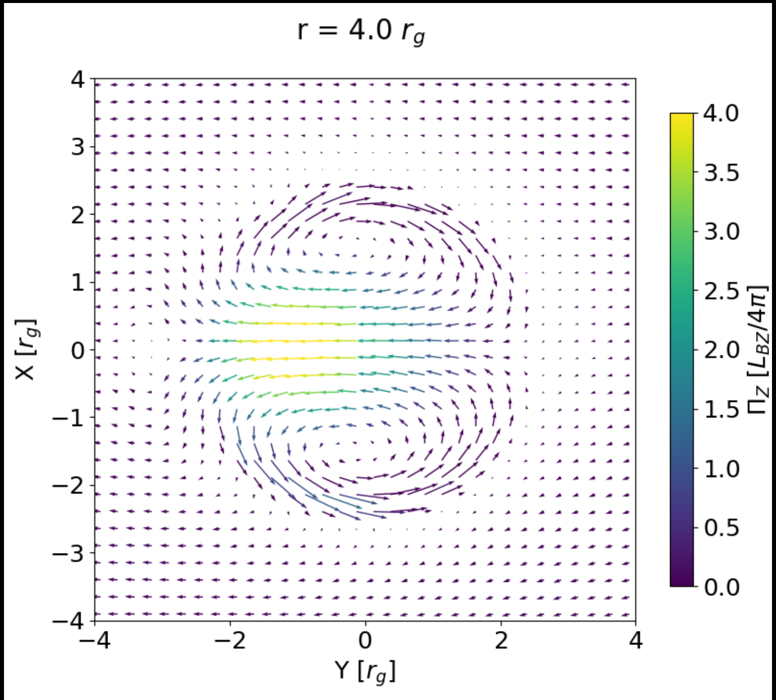
The Case of the Orthogonal Magnetosphere (χ = 85°)





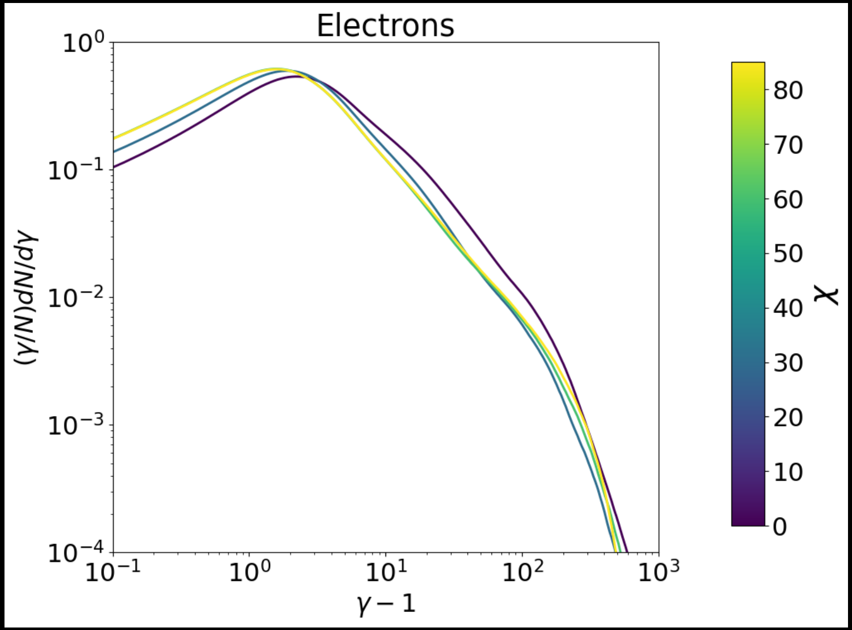
The Case of the Orthogonal Magnetosphere ($\chi = 85°$)



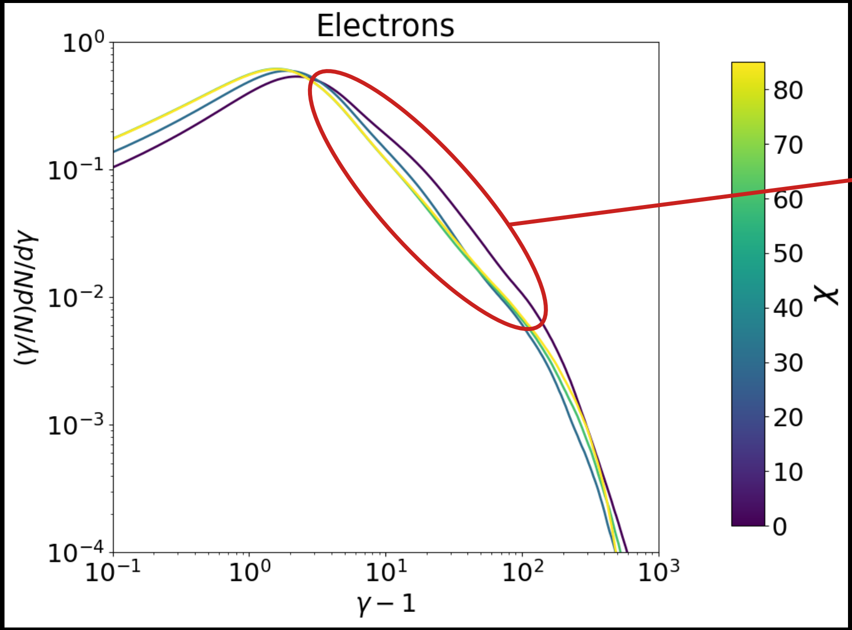


→ Inward Poynting flux compensates EM energy extraction on the event horizon
→ Very interesting jet structure

Particle Energization

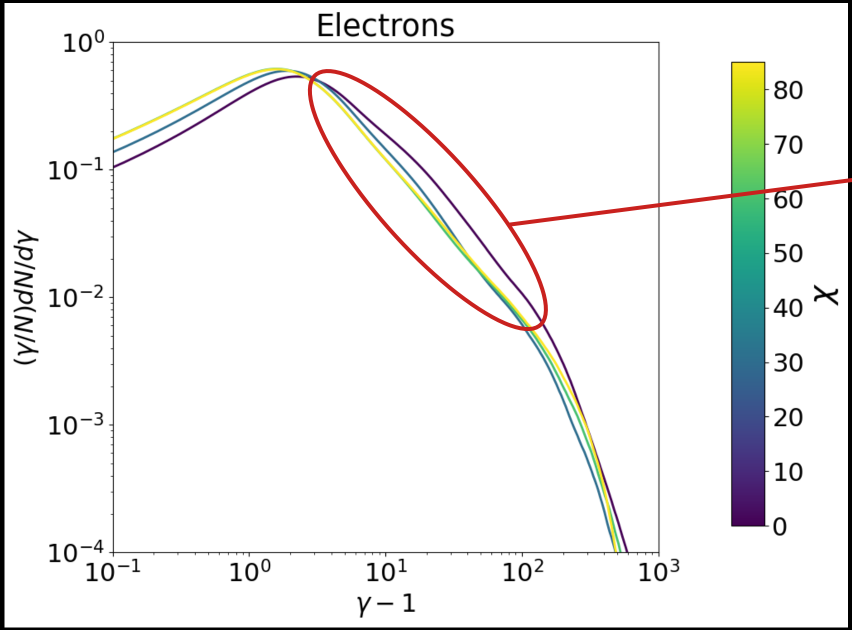


Particle Energization



Magnetic reconnection in the current layer

Particle Energization



Magnetic reconnection in the current layer

→ More features should appear with a more physical pair injection

Conclusions

– The jet always follows the magnetic direction

– Inclination has a strong impact on the jet's shape and power

– As the current layer always develop, magnetic reconnection provides efficient particle acceleration for all inclinations

Conclusions

– The jet always follows the magnetic direction

– Inclination has a strong impact on the jet’s shape and power

– As the current layer always develop, magnetic reconnection provides efficient particle acceleration for all inclinations

– More analysis required to understand the physics involved here

– Crucial step into understanding of a wide range of phenomena:
wind accretion (Sg A*, …), NS–BH binaries, …

– Future work will involve more realistic pair production
→ starved magnetospheres, lightcurves, polarization, …