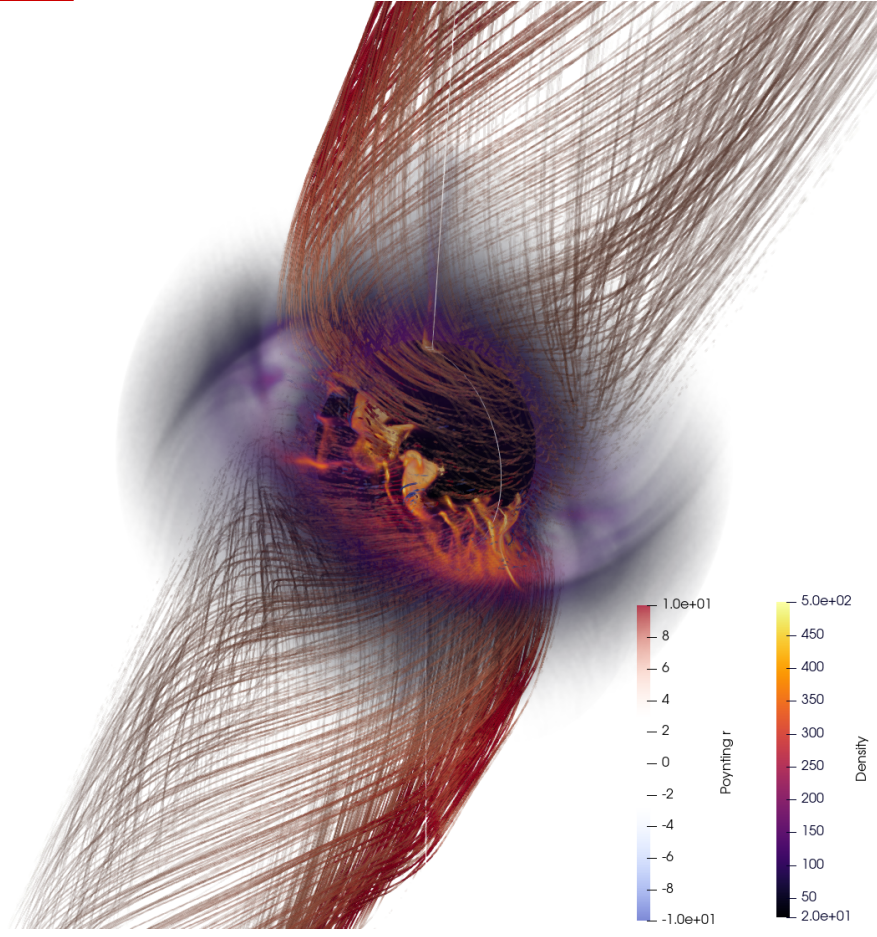
Particle-in-cell simulations of inclined black hole magnetospheres

Enzo Figueiredo

Supervisor: Benoît Cerutti

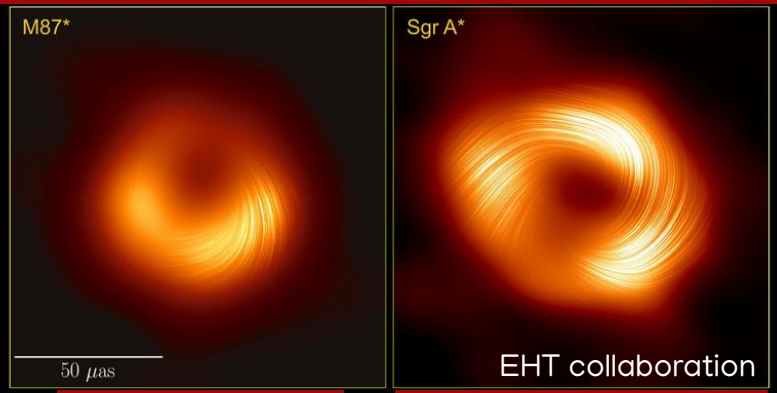


Université Grenoble Alpes
cnrs
erc European Research Council
GENCI Le calcul intensif au service de la connaissance
IPAG
SPAWN

Supermassive Black Holes and Jet Emission

Supermassive Black Holes and Jet Emission

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

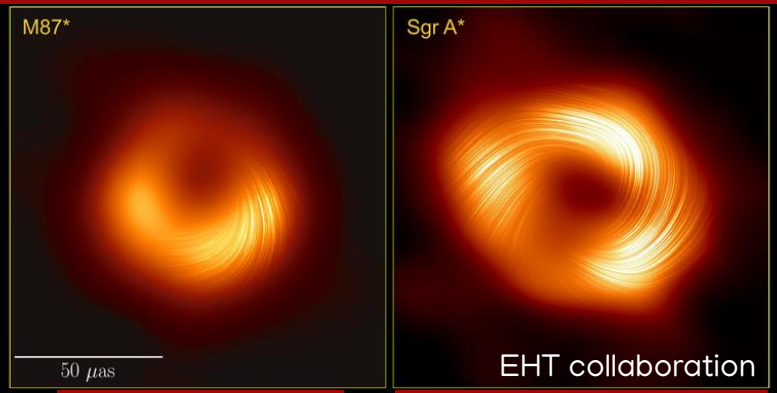


Strong jet

Weak/no jet?

Supermassive Black Holes and Jet Emission

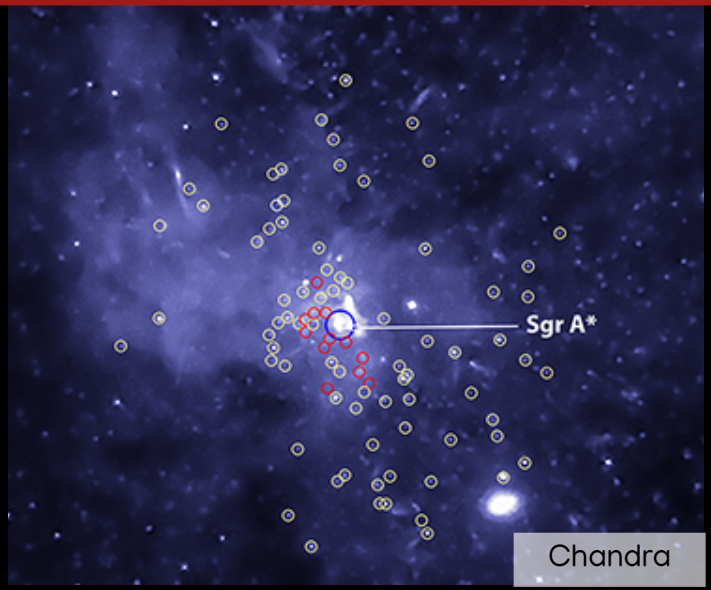
A few constraints on BH mass, matter density, magnetic field and jet power (BH spin?)



Strong jet

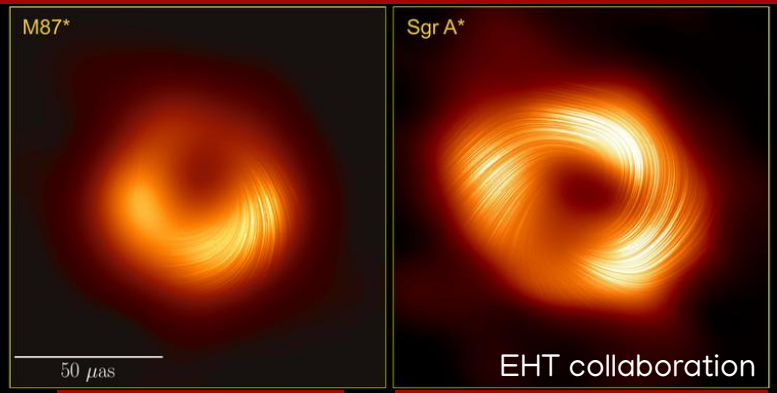
Weak/no jet?

Wind-fed accretion of Sgr A* in the Galactic Center?



Supermassive Black Holes and Jet Emission

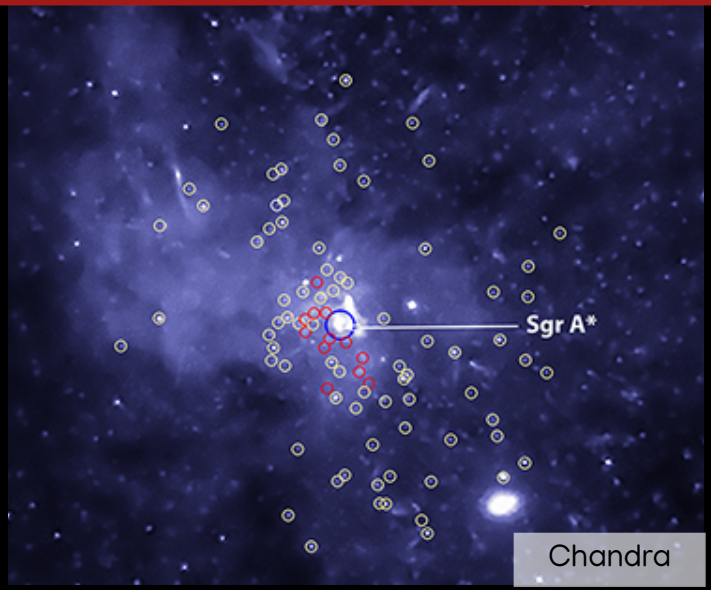
A few constraints on BH mass, matter density, magnetic field and jet power (BH spin?)



Strong jet

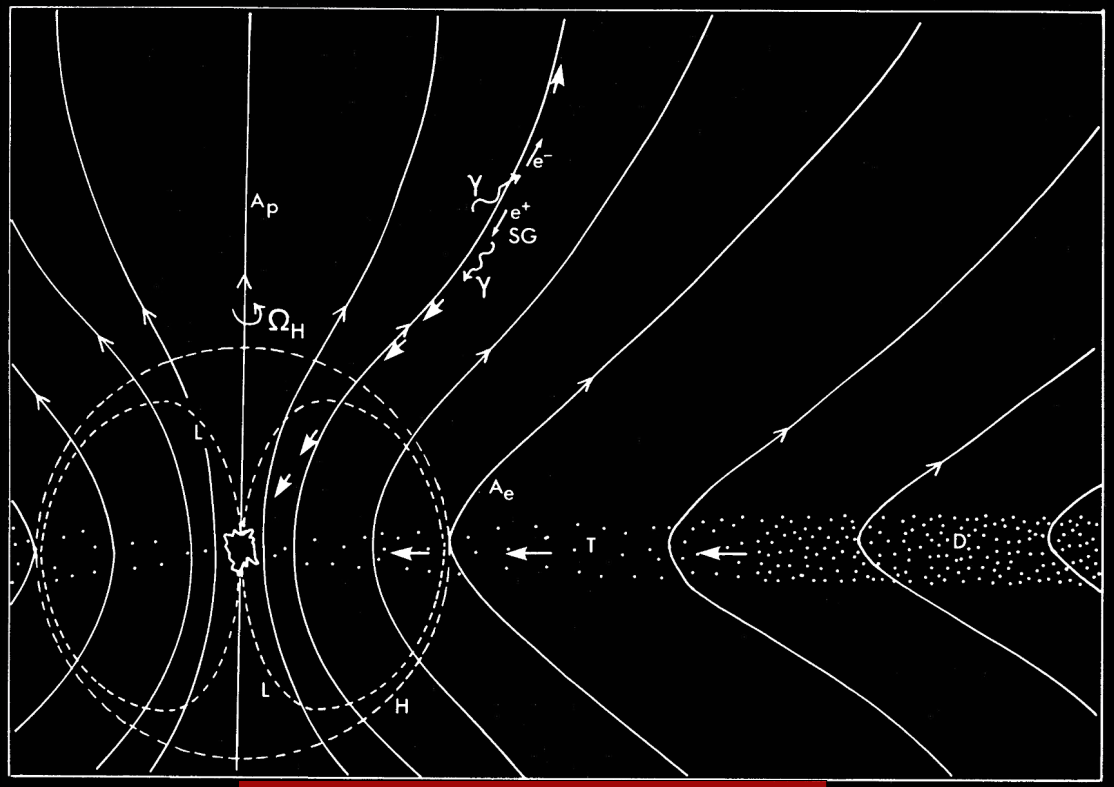
Weak/no jet?

Wind-fed accretion of Sgr A* in the Galactic Center?



Impact on the generation of a jet?

Theoretical Understanding of the Jet Emission

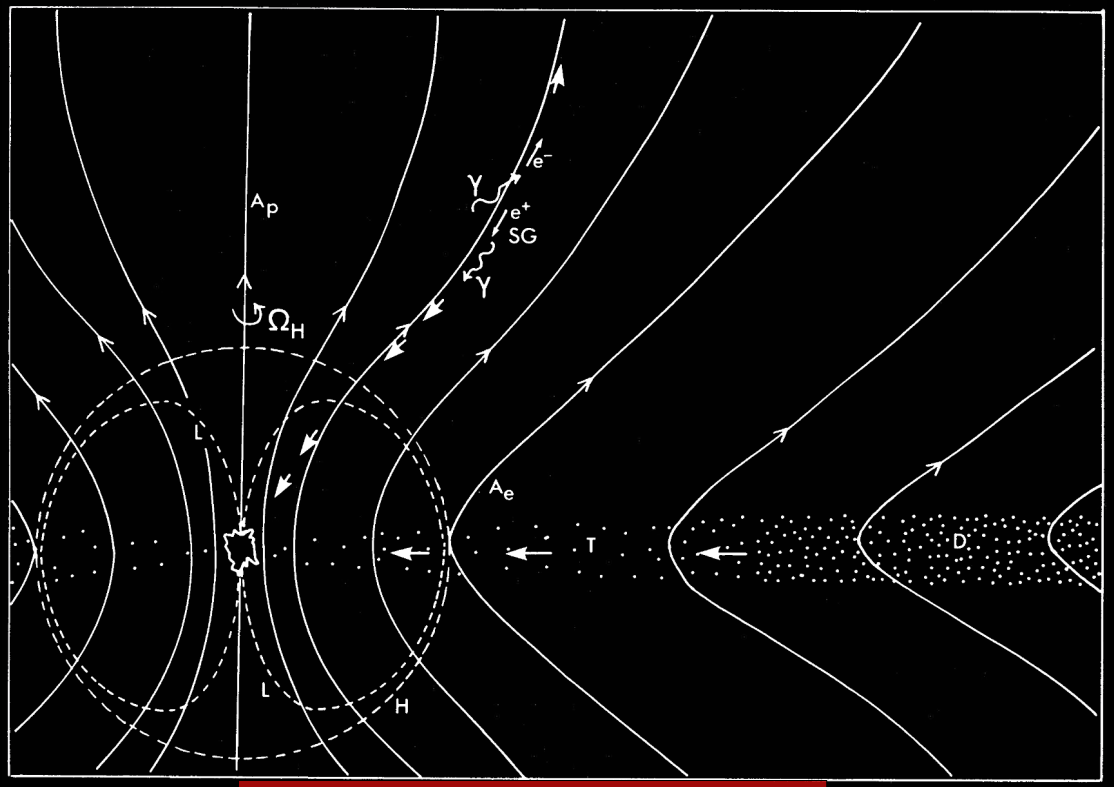


Blandford & Znajek, 1977

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



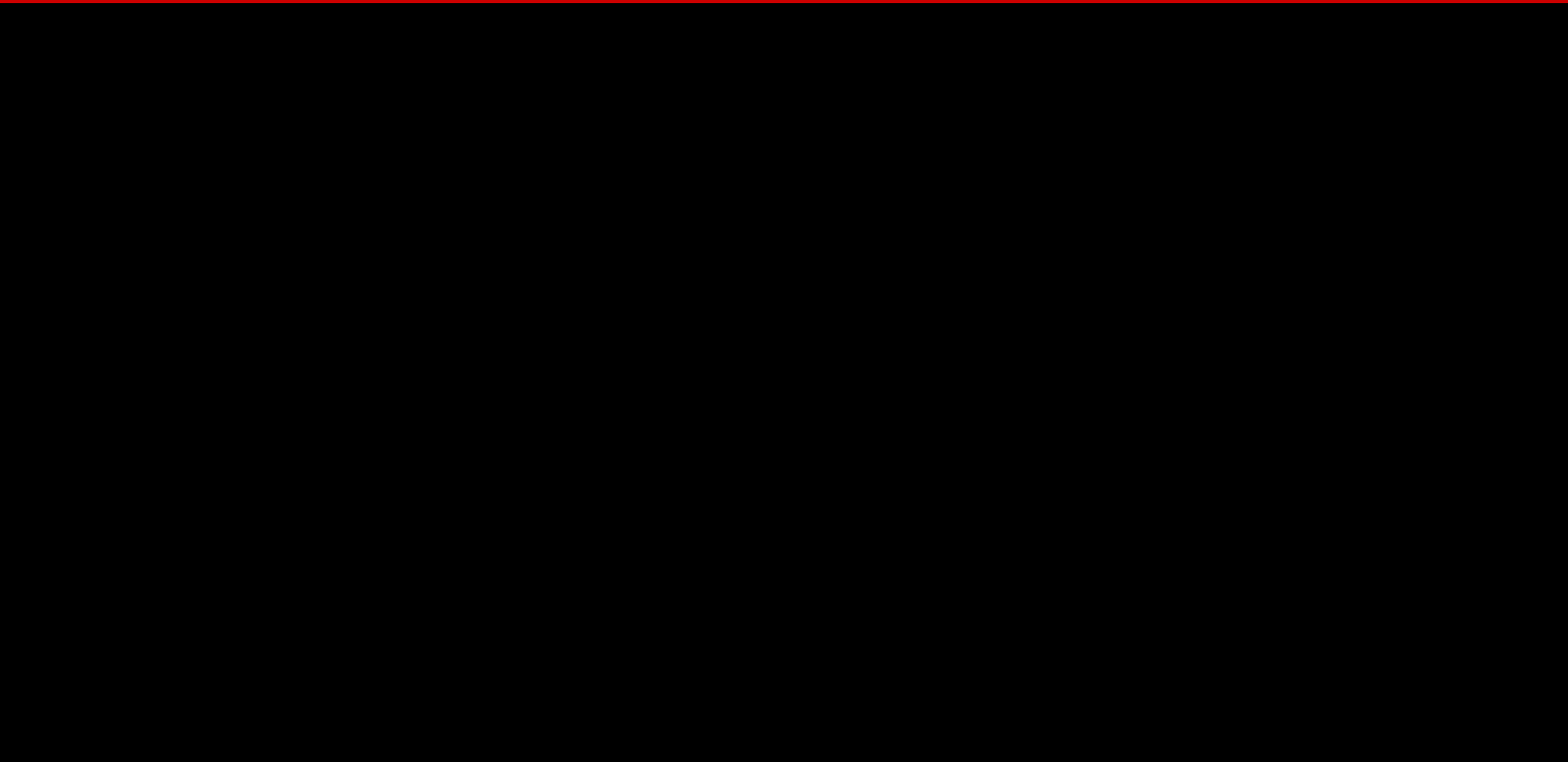
Blandford & Znajek, 1977

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

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

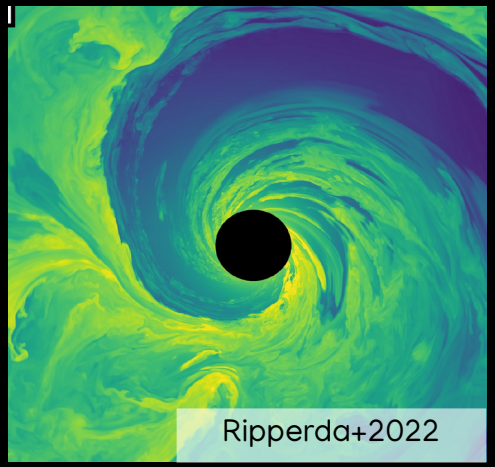
Does it work? With microphysics involved?
What if we loose axisymmetry?

Black Hole Accretion and Ejection Models



Black Hole Accretion and Ejection Models

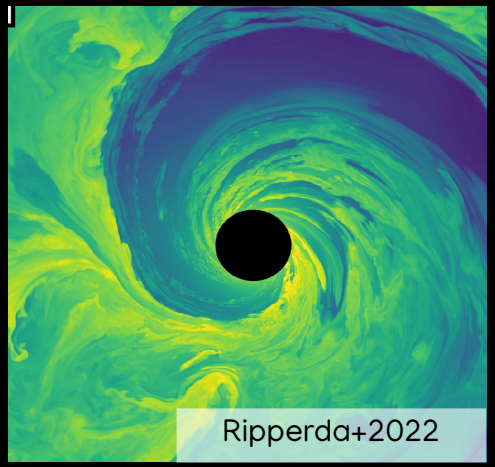
GRMHD



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

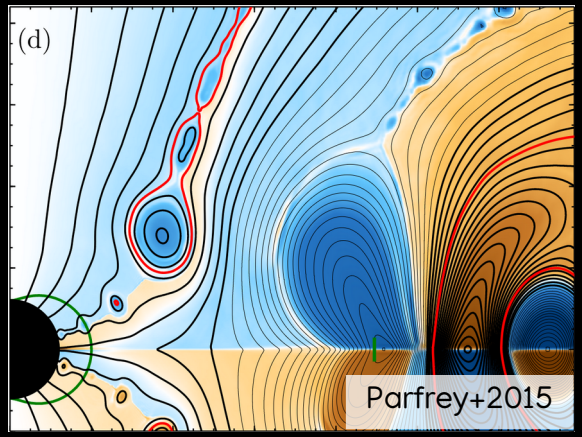
Black Hole Accretion and Ejection Models

GRMHD



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

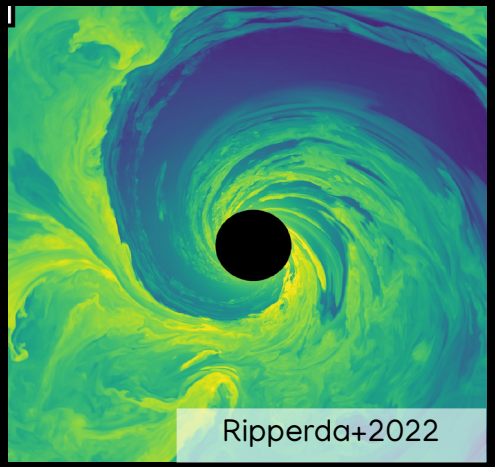
GR Force-Free Electrodynamics



- ✓ Large scales, highly magnetized plasma, cheap
- ✗ No microphysics, ideal, degenerate MHD

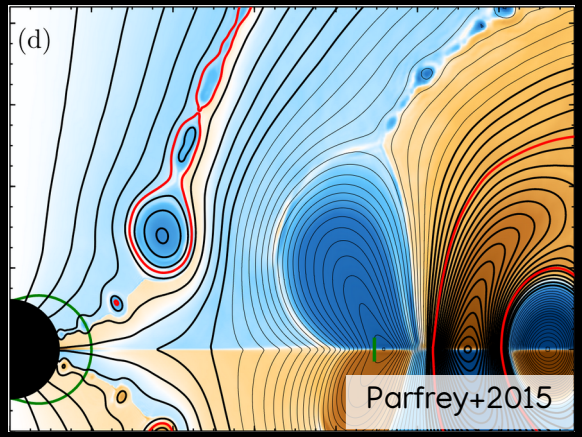
Black Hole Accretion and Ejection Models

GRMHD



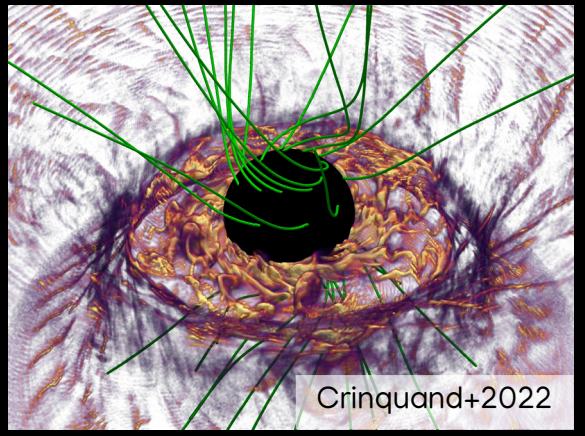
- ✓ Large scales, long term evolution
- ✗ No microphysics, mildly magnetized plasma

GR Force-Free Electrodynamics



- ✓ Large scales, highly magnetized plasma, cheap
- ✗ No microphysics, ideal, degenerate MHD

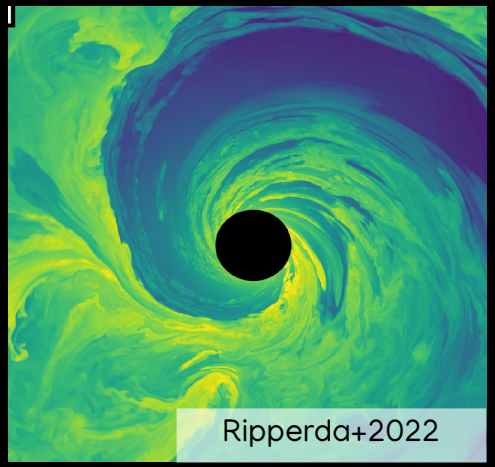
GR Particle-in-cell (PIC)



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

Black Hole Accretion and Ejection Models

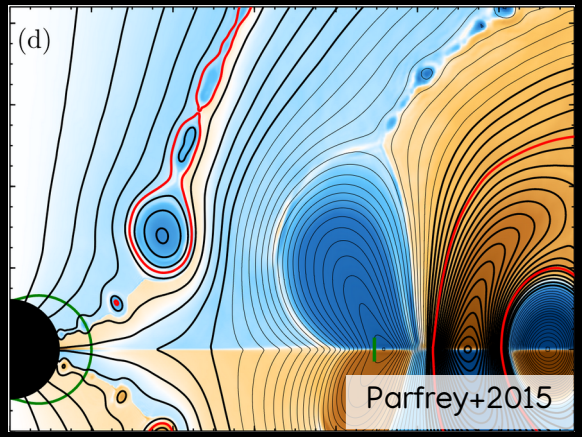
GRMHD



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

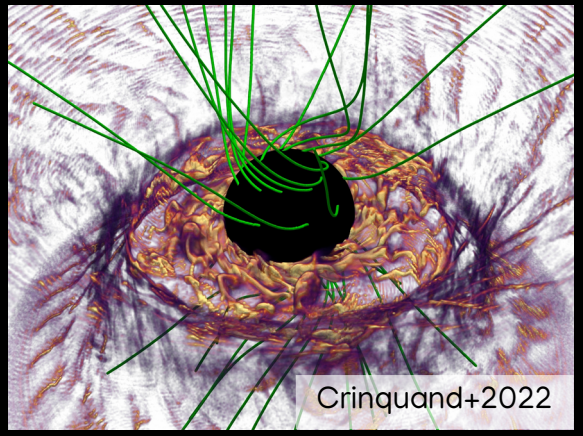
→ Disk accretion

GR Force-Free Electrodynamics



- ✓ Large scales, highly magnetized plasma, cheap
- ✗ No microphysics, ideal, degenerate MHD

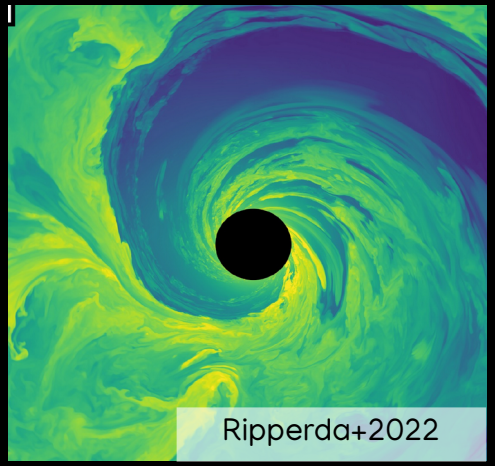
GR Particle-in-cell (PIC)



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

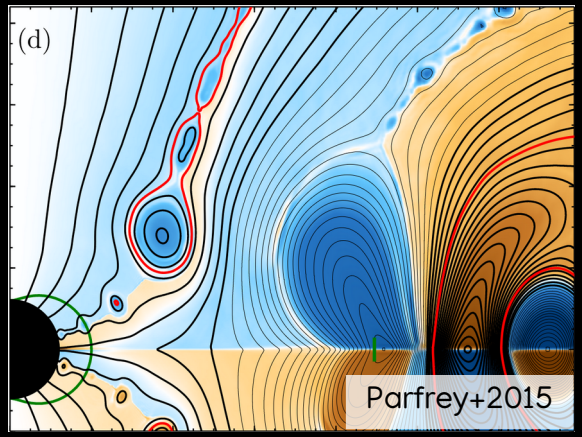
Black Hole Accretion and Ejection Models

GRMHD



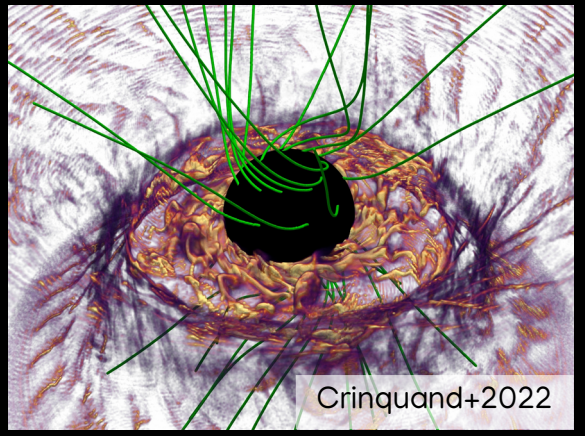
- ✓ Large scales, long term evolution
- ✗ No microphysics, mildly magnetized plasma

GR Force-Free Electrodynamics



- ✓ Large scales, highly magnetized plasma, cheap
- ✗ No microphysics, ideal, degenerate MHD

GR Particle-in-cell (PIC)



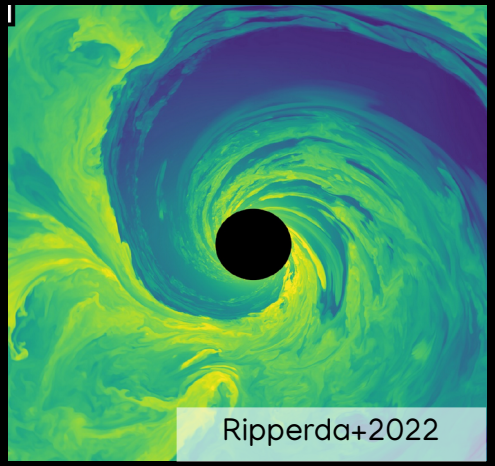
- ✓ Accurate modeling of plasma, particle acceleration
- ✗ Expensive, short scales

→ Disk accretion

→ Magnetospheric physics

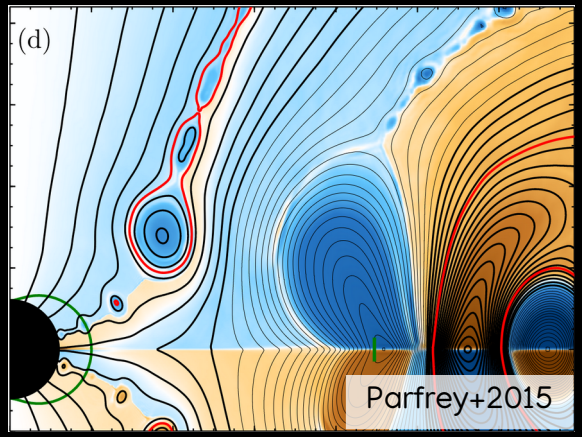
Black Hole Accretion and Ejection Models

GRMHD



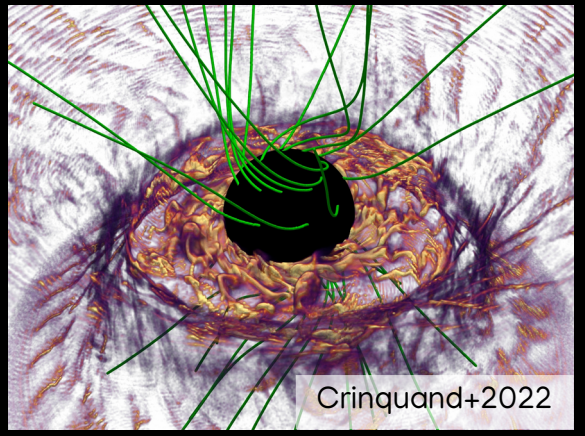
- ✓ Large scales, long term evolution
- ✗ No microphysics, mildly magnetized plasma

GR Force-Free Electrodynamics



- ✓ Large scales, highly magnetized plasma, cheap
- ✗ No microphysics, ideal, degenerate MHD

GR Particle-in-cell (PIC)



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

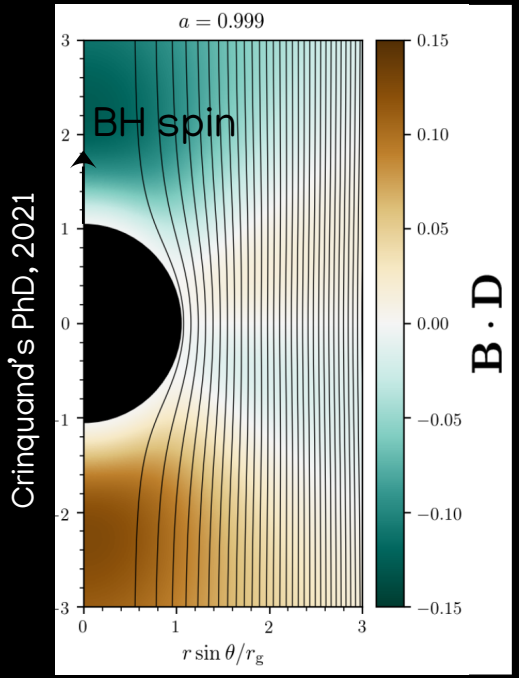
→ Disk accretion

→ Magnetospheric physics

BH Embedded in a Uniform Magnetic Field

In vacuum

a = 0.999



Crinquand's PhD, 2021

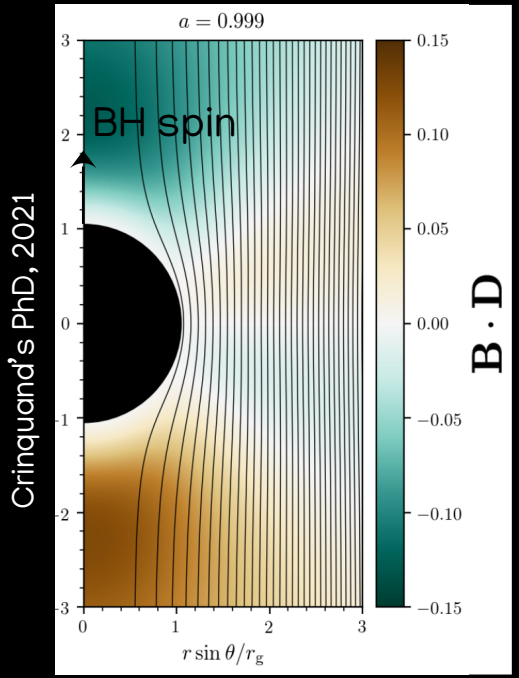
Wald (1974)

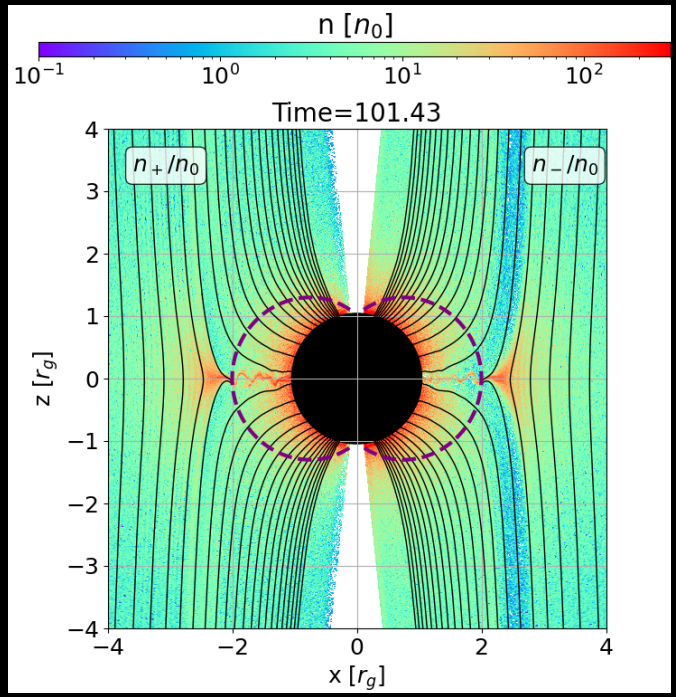
BH Embedded in a Uniform Magnetic Field

In vacuum

a = 0.999

With plasma injection



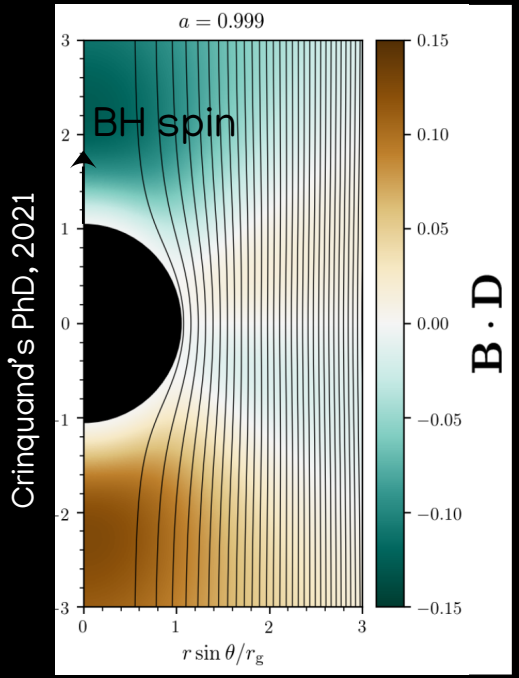


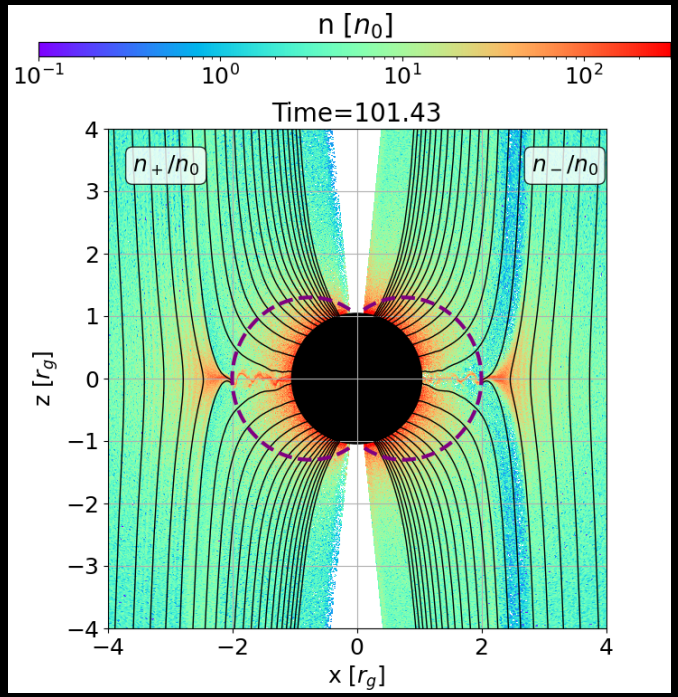
BH Embedded in a Uniform Magnetic Field

In vacuum

a = 0.999

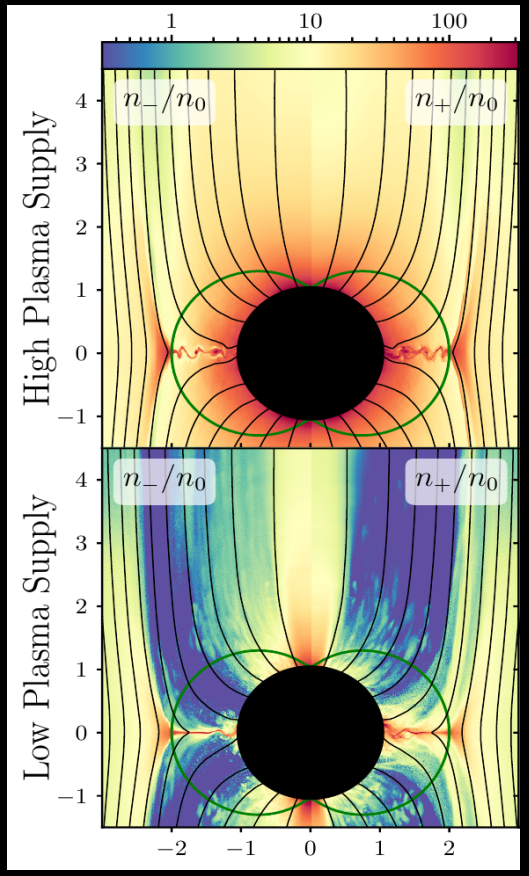
With plasma injection





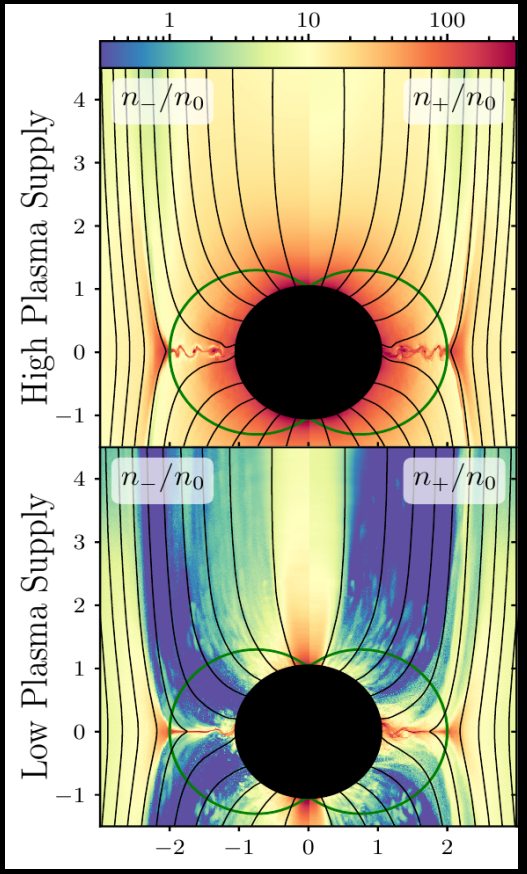
What happens if the magnetic field is inclined with respect to the BH spin ?

Magnetospheric Regime of Interest



Parfrey+2019

Magnetospheric Regime of Interest



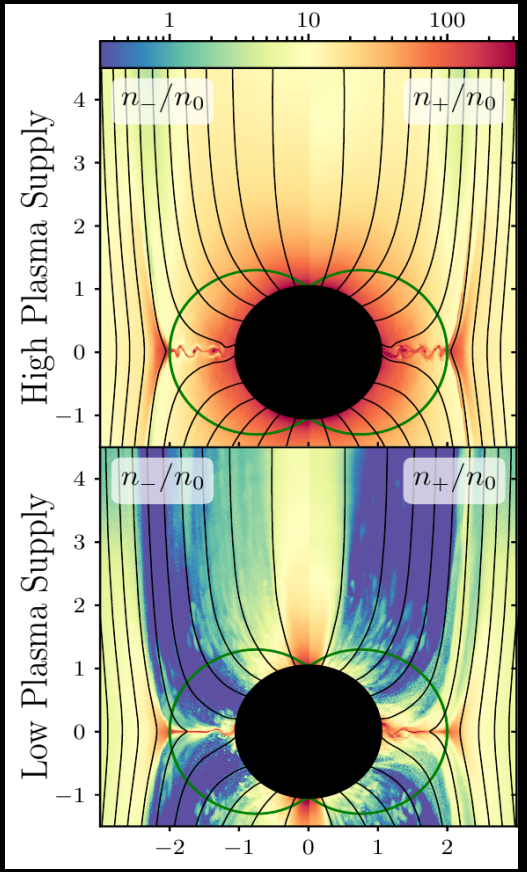
Parfrey+2019

→ Force-free like

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

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

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

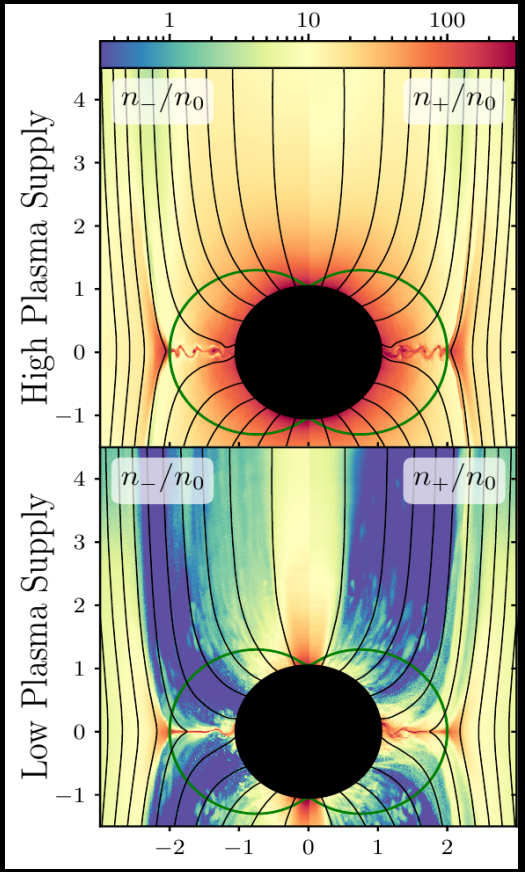
$$\kappa = \frac{n}{n_{GJ}} \gg 1 \quad n_{GJ} = \frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi e c}$$

→ Starved magnetosphere

– Charge separation

– Regions with an unscreened parallel electric field

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

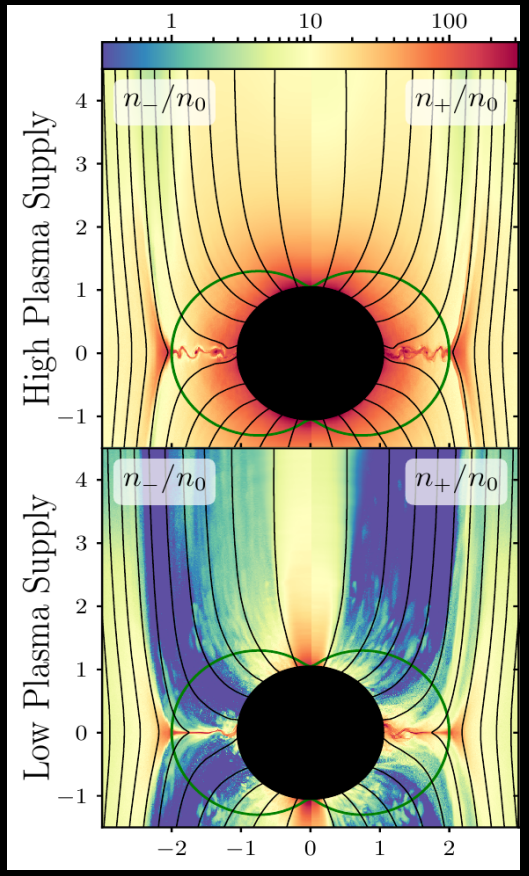
$$\kappa = \frac{n}{n_{GJ}} \gg 1 \quad n_{GJ} = \frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi e c}$$

→ Starved magnetosphere

– Charge separation

– Regions with an unscreened parallel electric field

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

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

→ Starved magnetosphere

– Charge separation

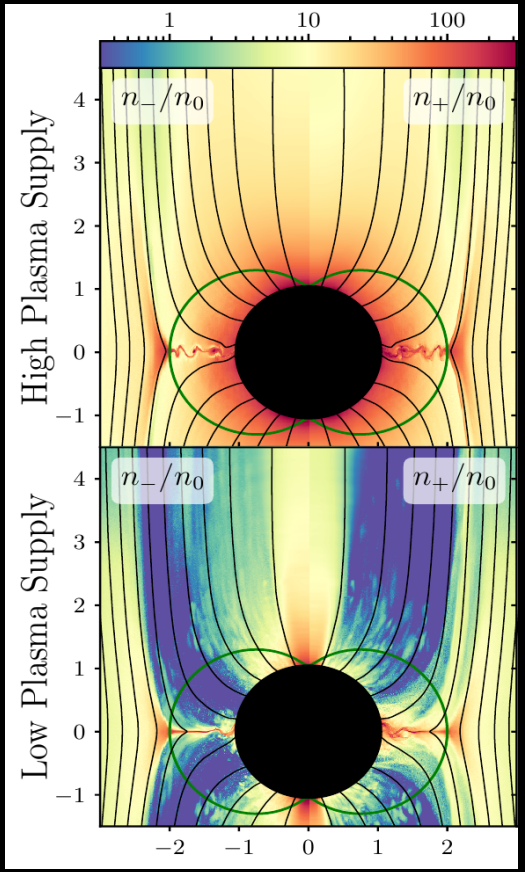
– Regions with an unscreened parallel electric field

Ad hoc injection

Injection if:

$$\sigma > \sigma_0$$

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

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

→ Starved magnetosphere

– Charge separation

– Regions with an unscreened parallel electric field

Ad hoc injection

Injection if:

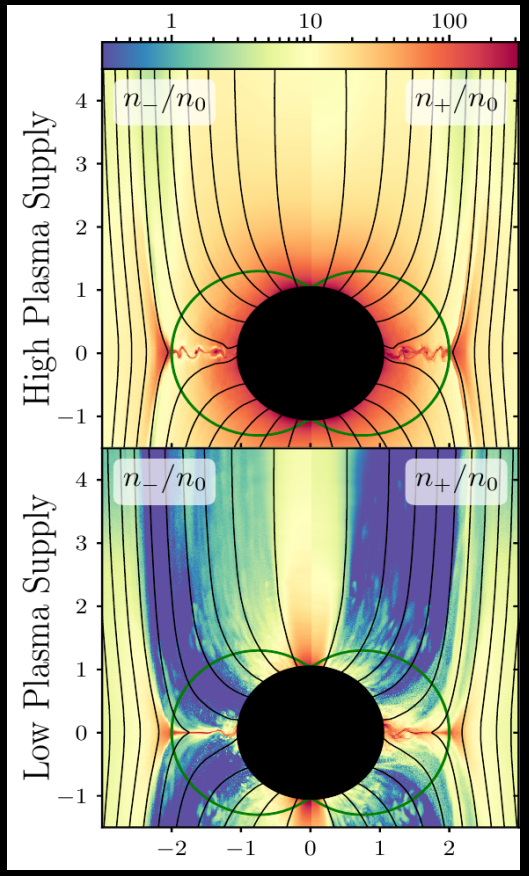
$$\sigma > \sigma_0$$

Scale separation

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

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

Magnetospheric Regime of Interest



Parfrey+2019

→ Force-free like

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

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

→ Starved magnetosphere

– Charge separation

– Regions with an unscreened parallel electric field

→ future work with more accurate pair production

Ad hoc injection

Injection if:

$$\sigma > \sigma_0$$

Scale separation

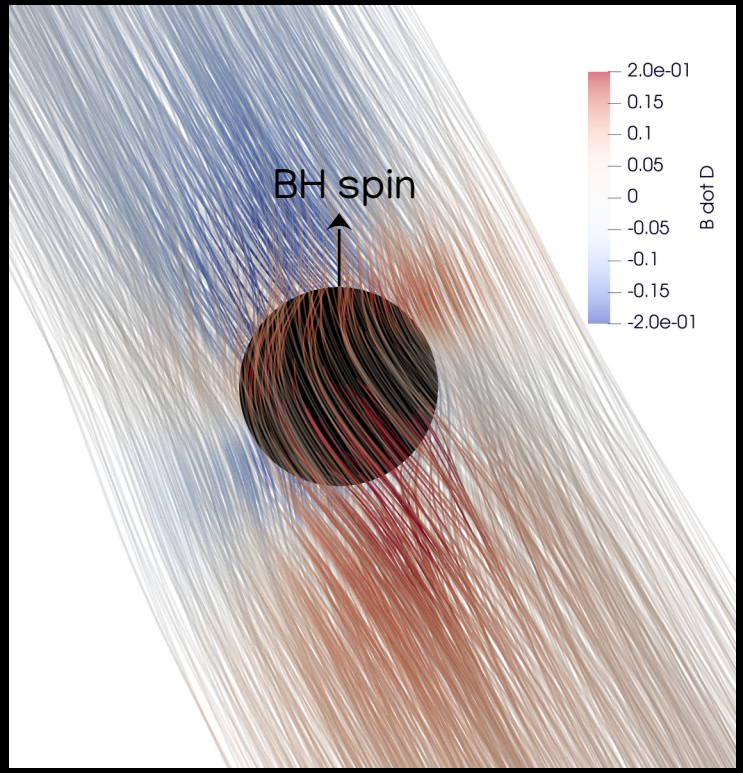
$$B_0 \propto \frac{r_g}{r_L}$$

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

Inclined Black Hole Magnetosphere

In vacuum

a = 0.99, χ=30°



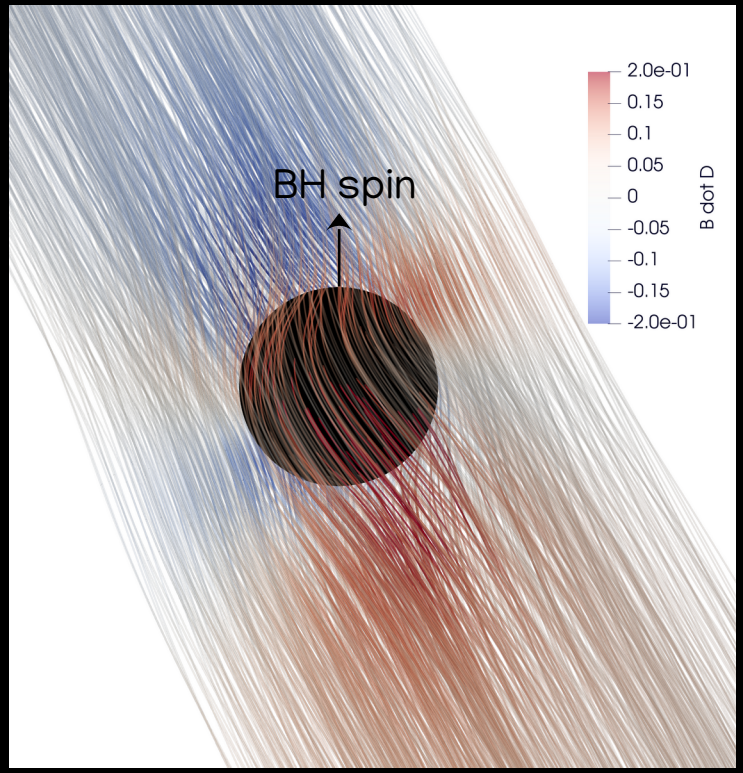
Bicak & Janis (1985)

Inclined Black Hole Magnetosphere

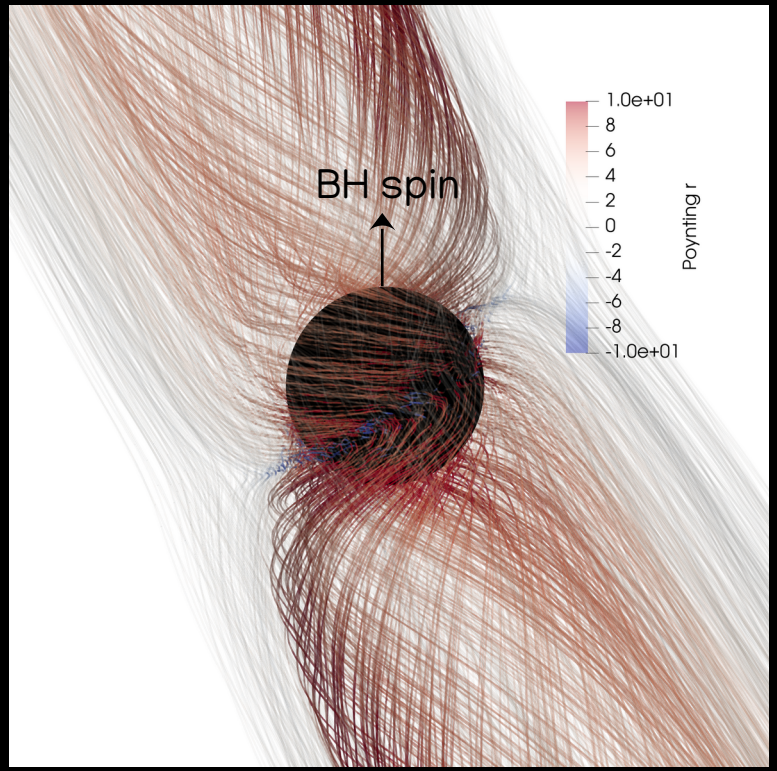
In vacuum

a = 0.99, χ=30°

With plasma injection



Bicak & Janis (1985)

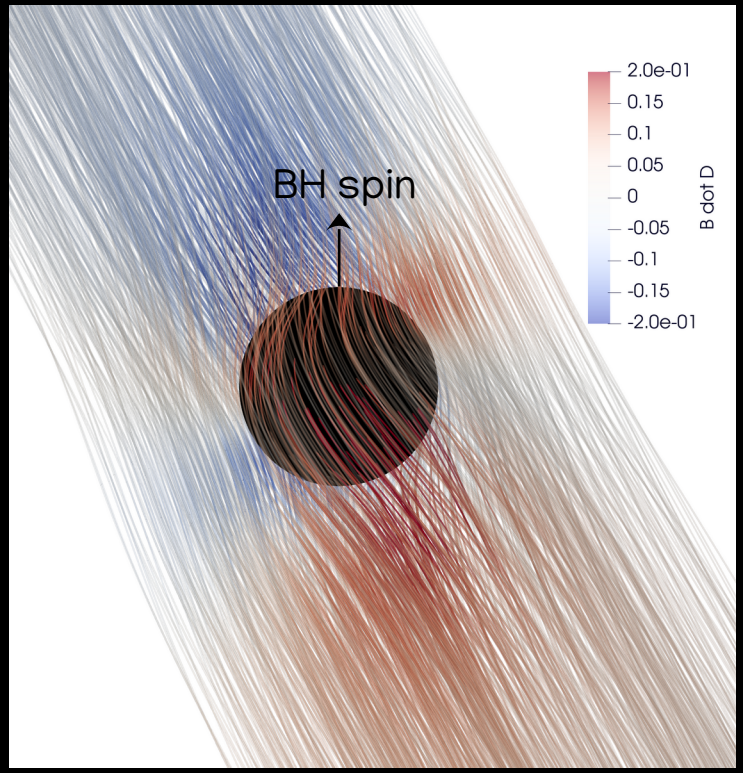


Inclined Black Hole Magnetosphere

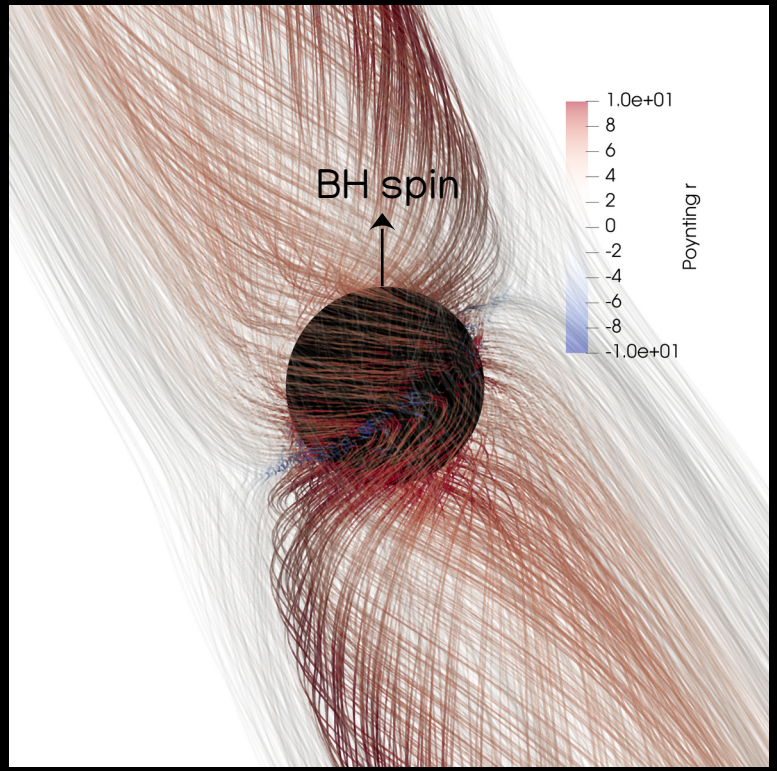
In vacuum

a = 0.99, χ=30°

With plasma injection



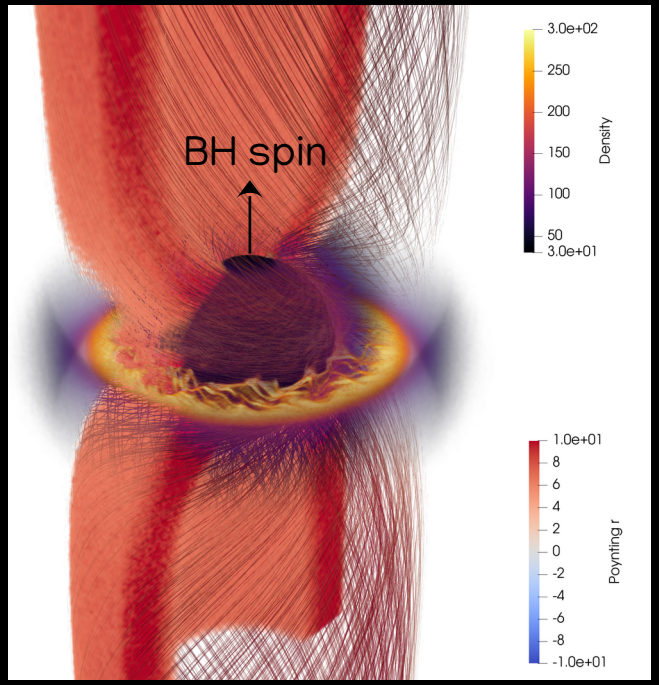
Bicak & Janis (1985)



> 15 millions CPU hours for 4 runs

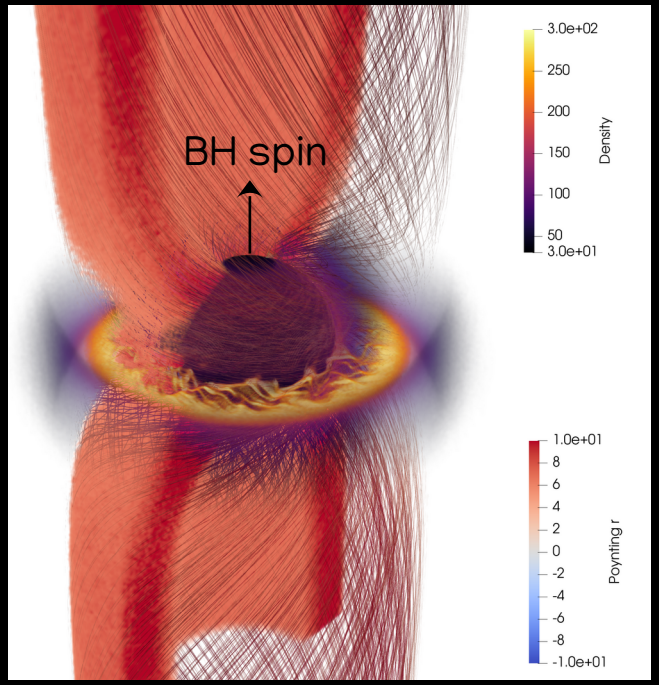
The Jet Structure Is Affected by the Inclination

$\chi = 0°$

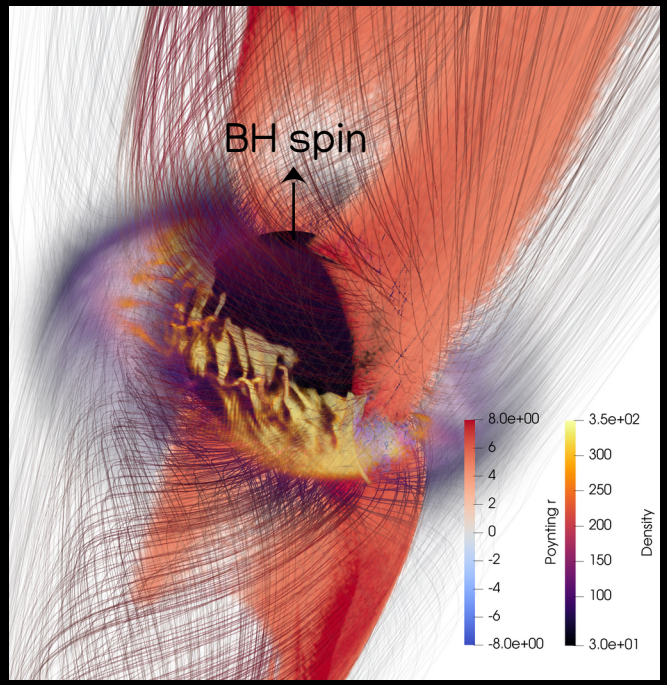


The Jet Structure Is Affected by the Inclination

$\chi = 0°$

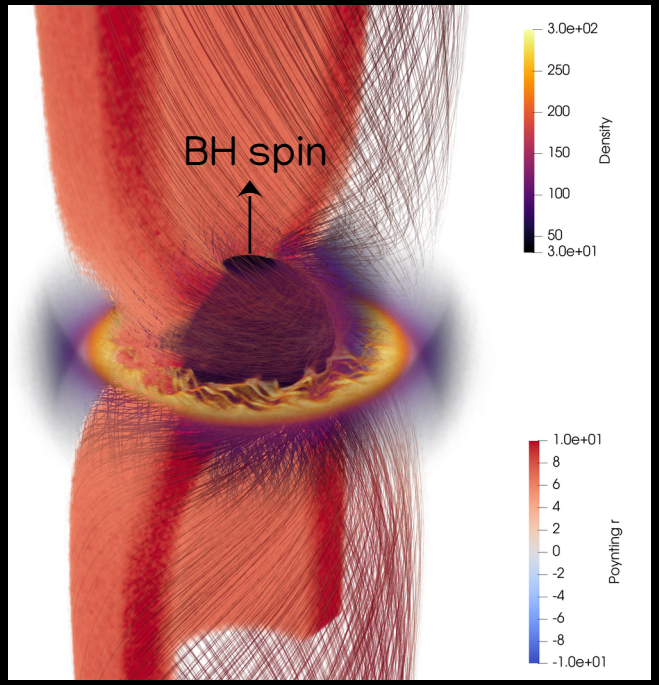


$\chi = 30°$

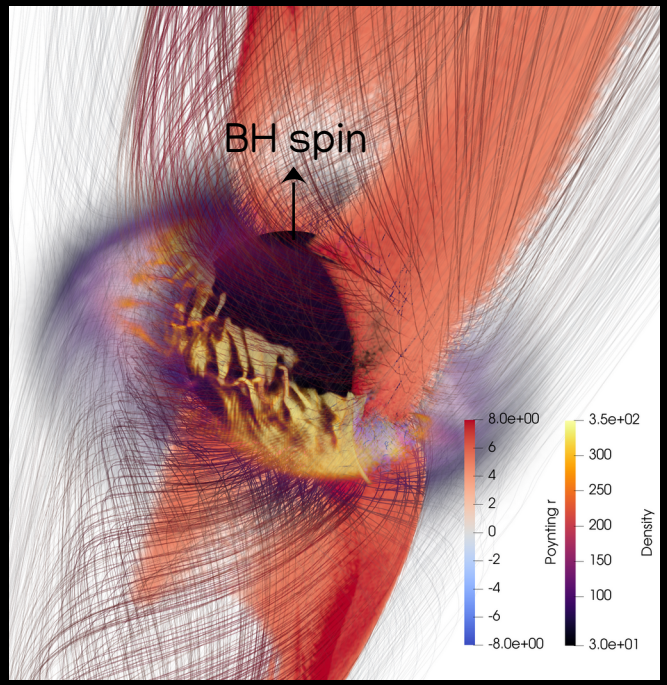


The Jet Structure Is Affected by the Inclination

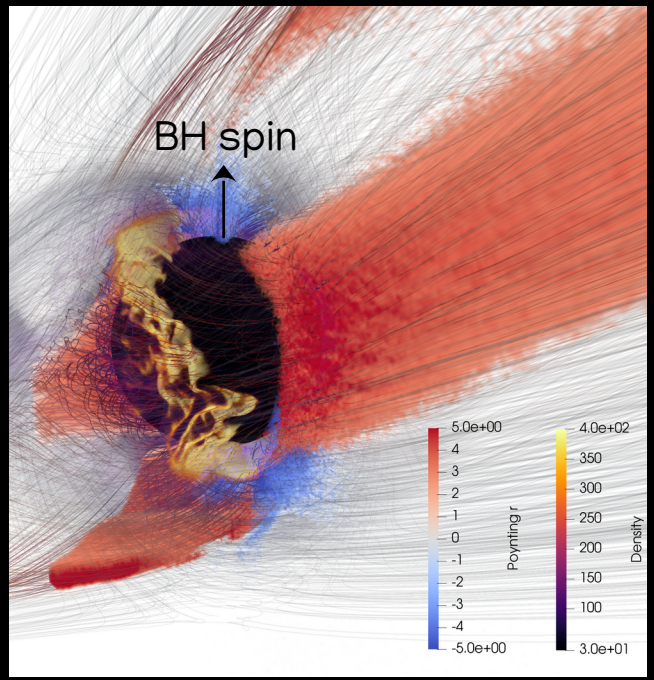
$\chi = 0°$



$\chi = 30°$

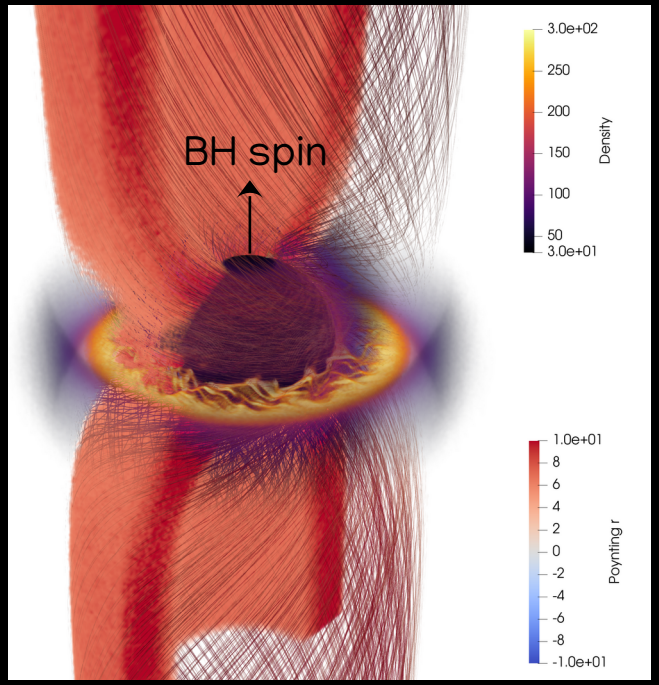


$\chi = 60°$

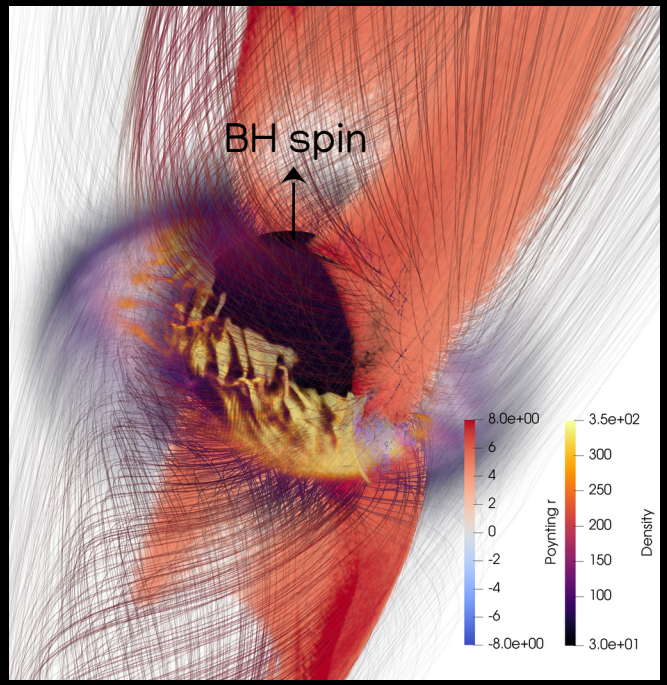


The Jet Structure Is Affected by the Inclination

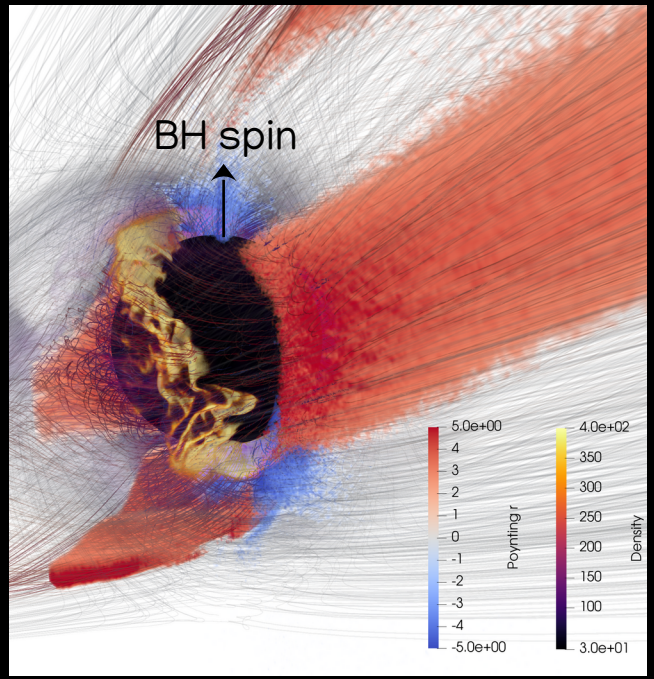
$\chi = 0°$



$\chi = 30°$



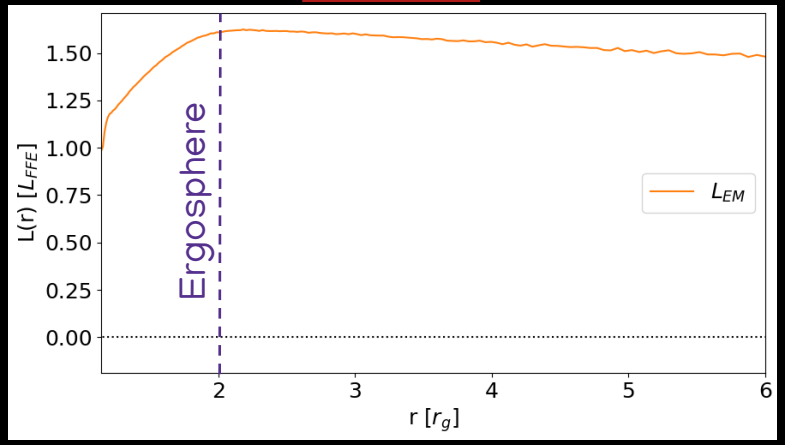
$\chi = 60°$



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

Electromagnetic Energy Flux

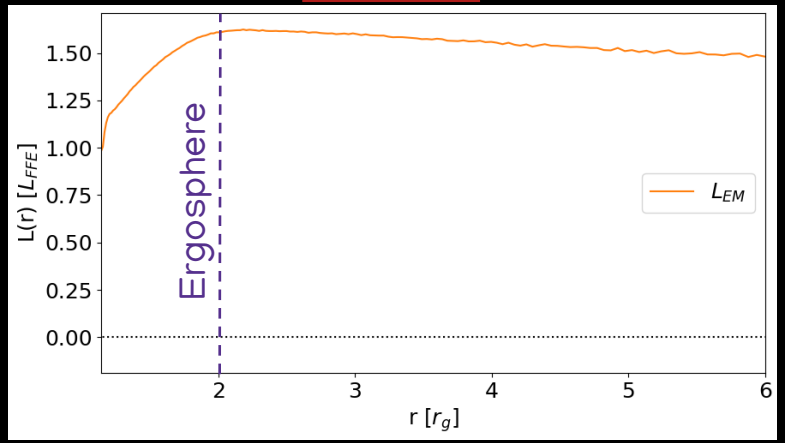
$\chi = 0°$



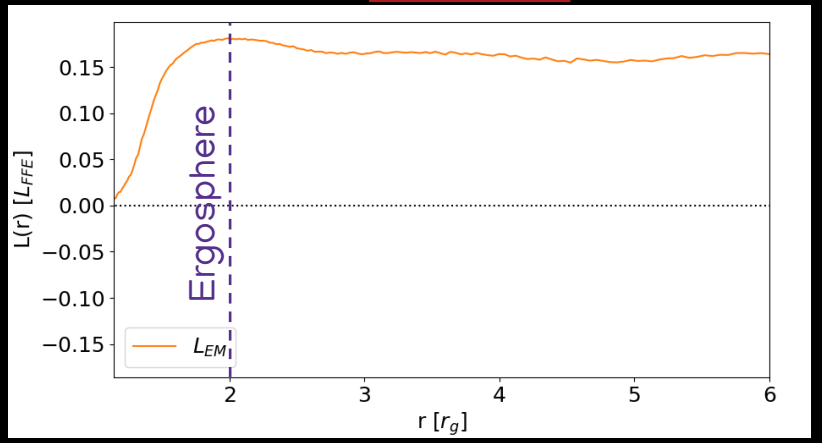
$$L_{\mathrm{EM}} = \iint \Pi^r \sqrt{\gamma} \mathrm{d}\Omega$$

Electromagnetic Energy Flux

$\chi = 0°$



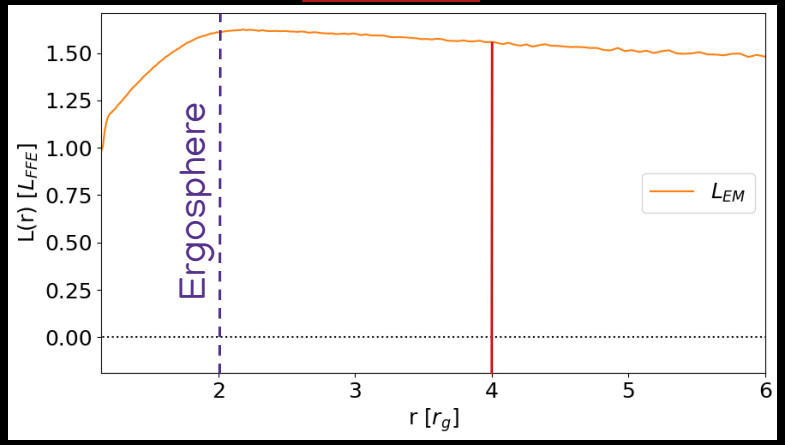
$\chi = 85°$



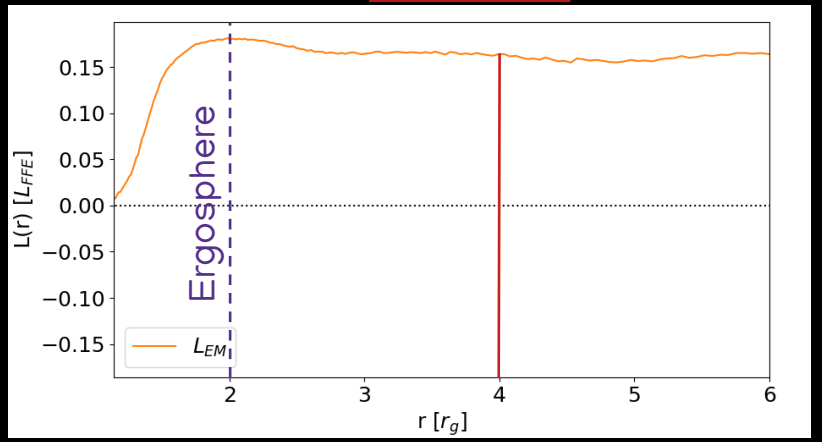
$$L_{\mathrm{EM}} = \iint \Pi^r \sqrt{\gamma} \mathrm{d}\Omega$$

Electromagnetic Energy Flux

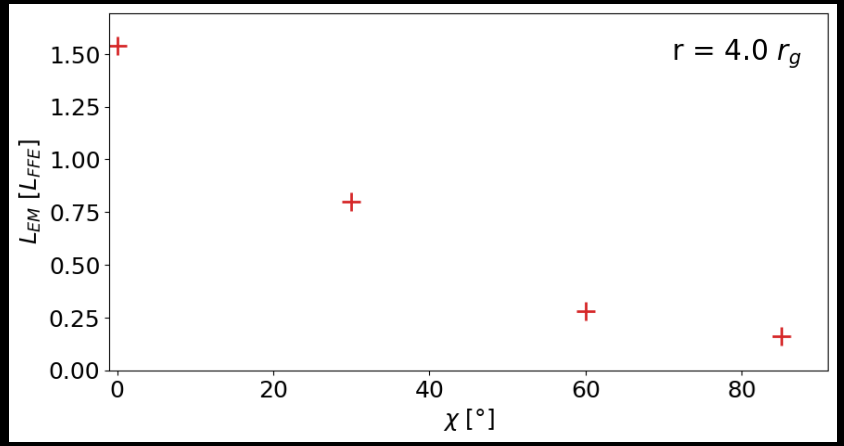
$\chi = 0°$



$\chi = 85°$

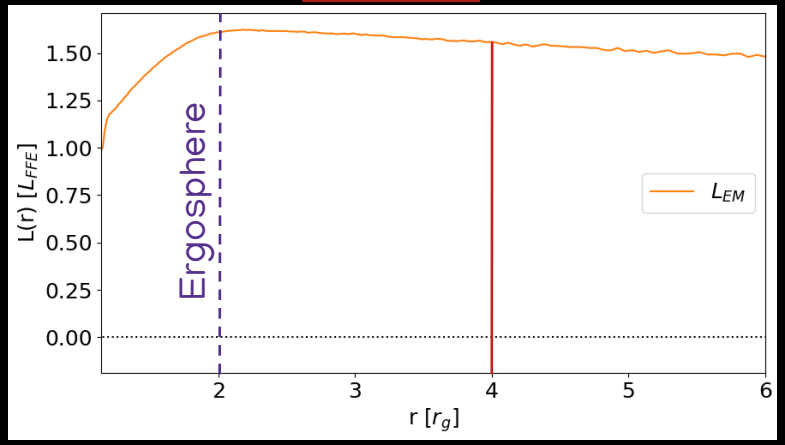


$$L_{\mathrm{EM}} = \iint \Pi^r \sqrt{\gamma} \mathrm{d}\Omega$$

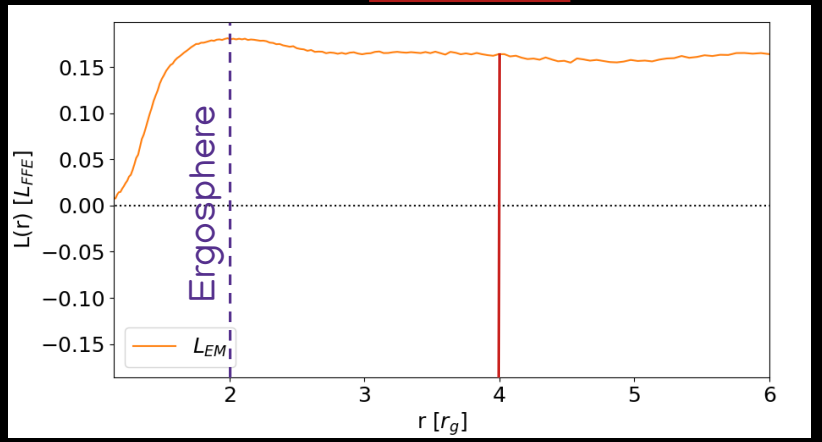


Electromagnetic Energy Flux

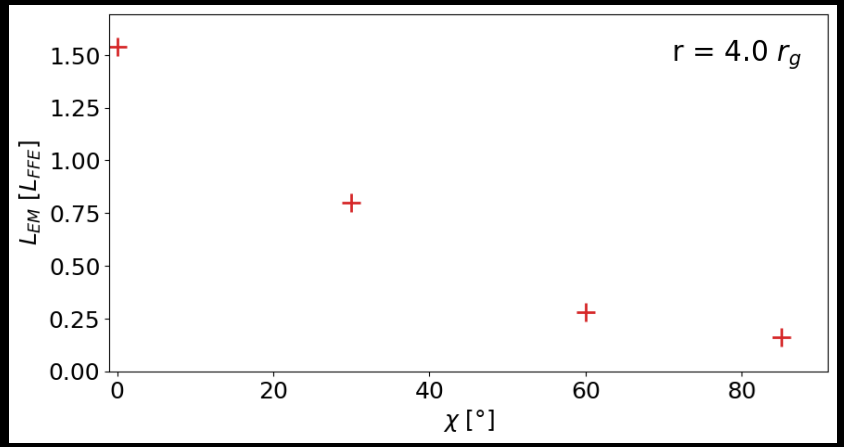
$\chi = 0°$



$\chi = 85°$

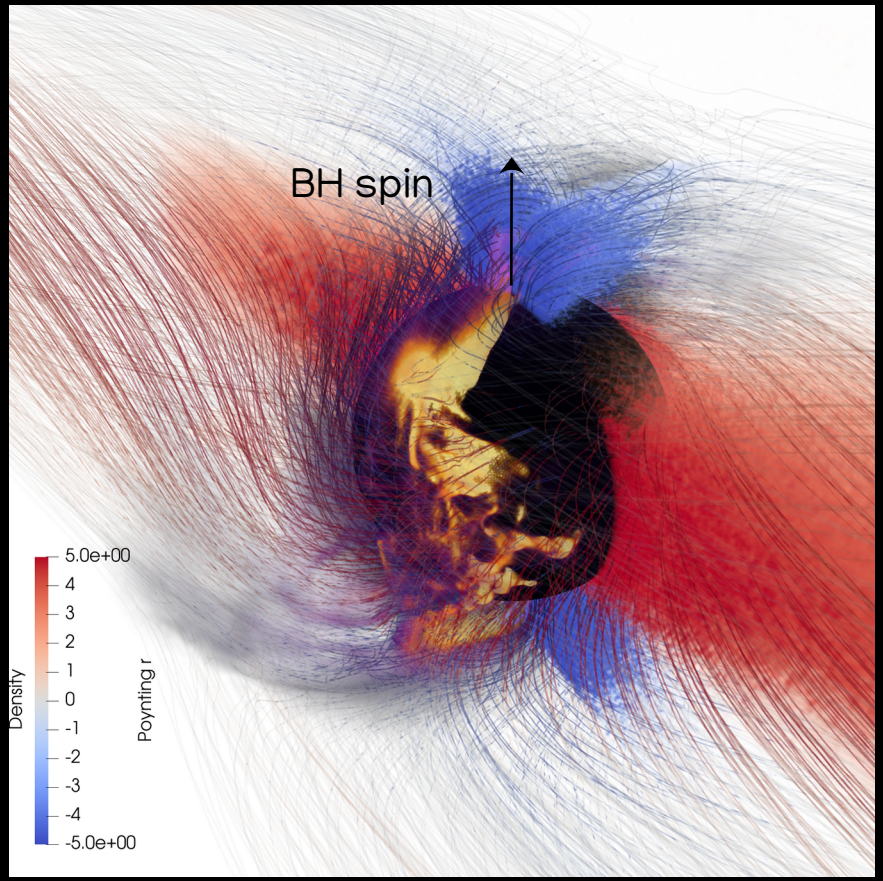


$$L_{\mathrm{EM}} = \iint \Pi^r \sqrt{\gamma} \mathrm{d}\Omega$$

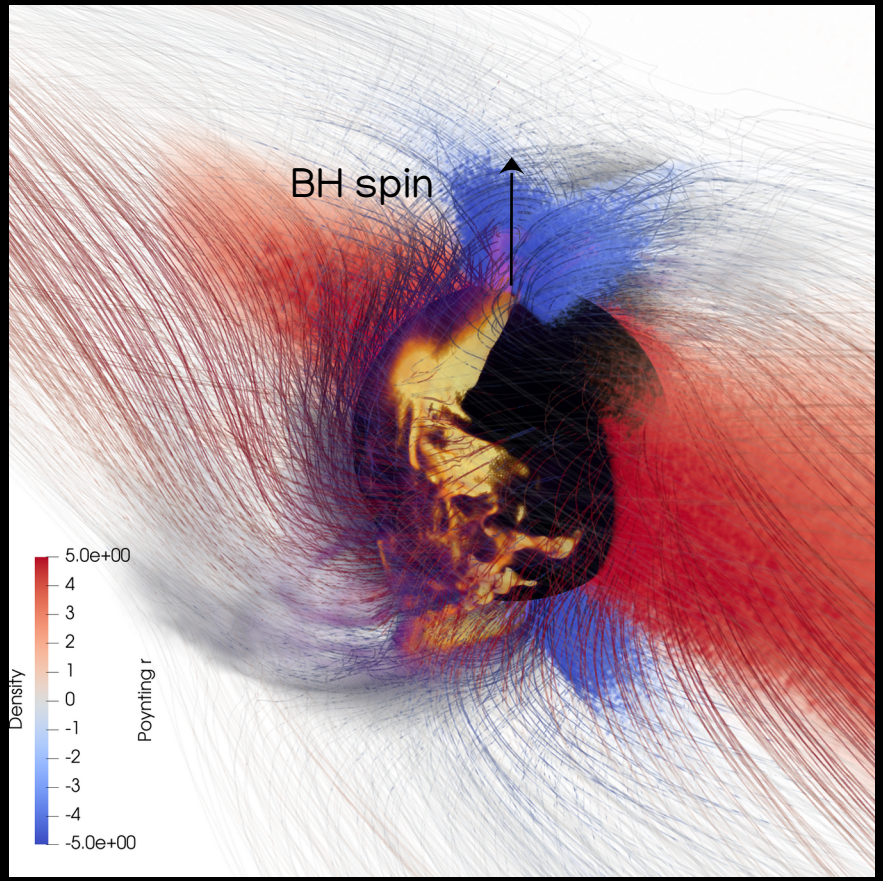


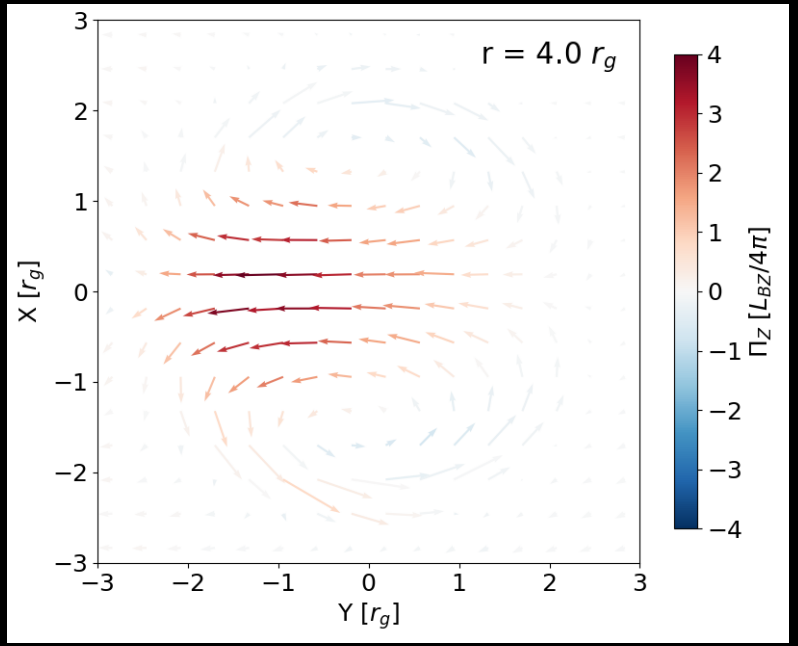
→ Dramatic weakening of the jet power for very inclined magnetospheres

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

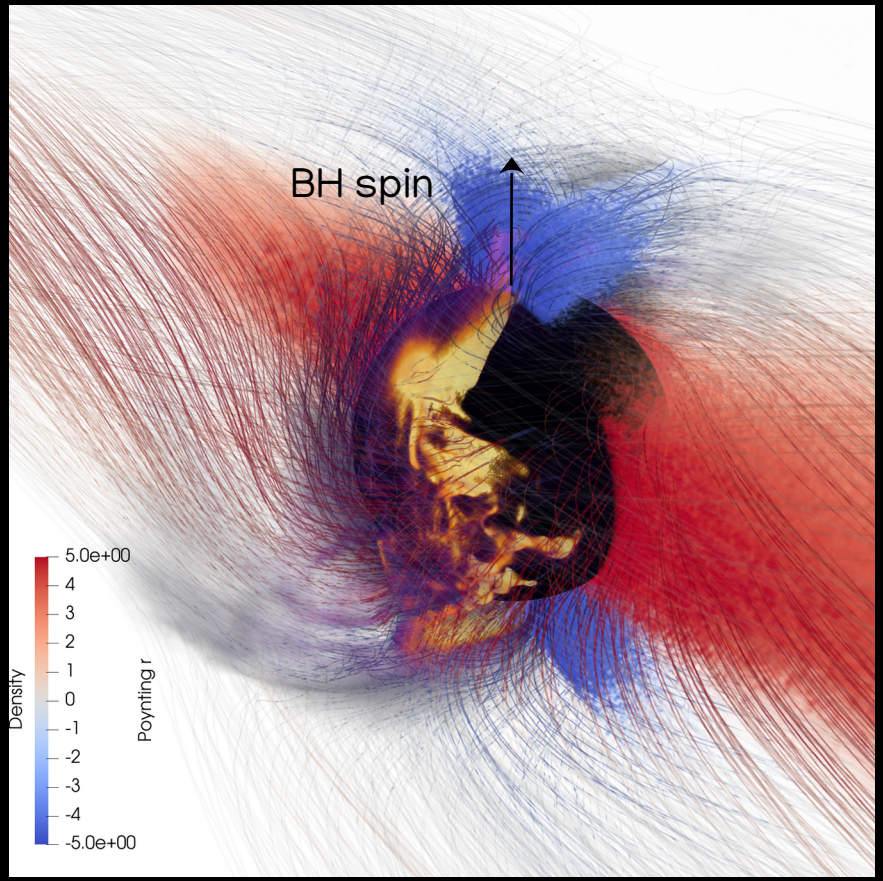


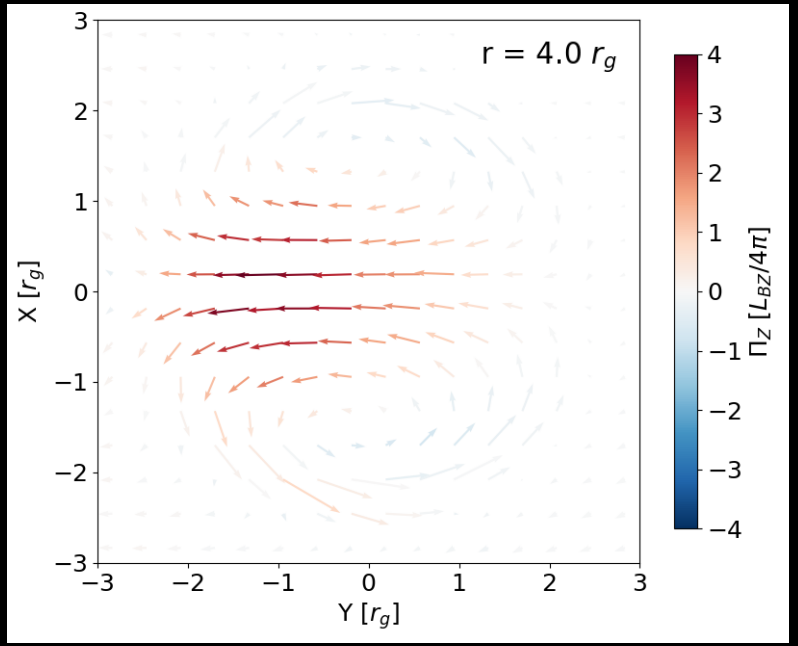
The Case of the Orthogonal Magnetosphere (χ = 85°)





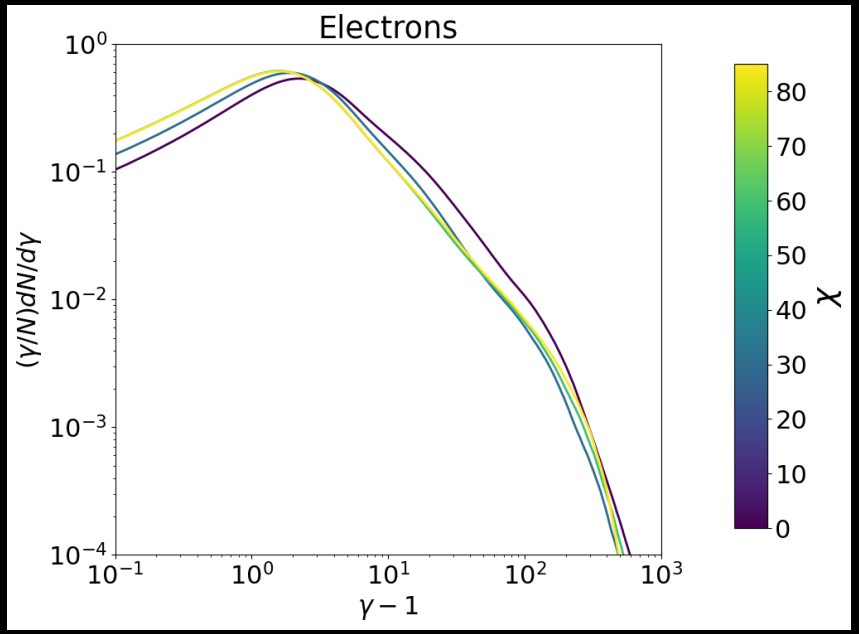
The Case of the Orthogonal Magnetosphere (χ = 85°)



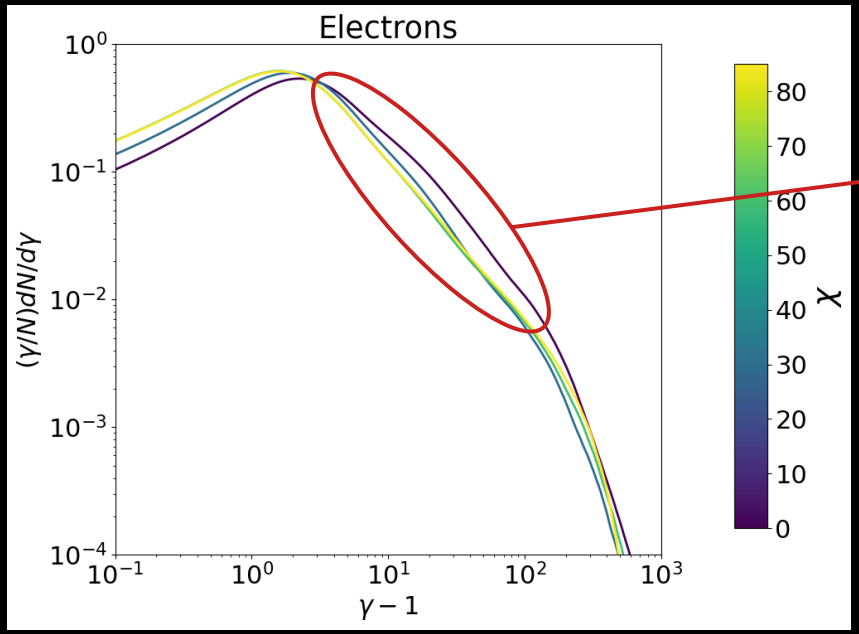


→ Inward Poynting flux compensates EM energy extraction on the event horizon
→ Very interesting jet structure

Particle Energization

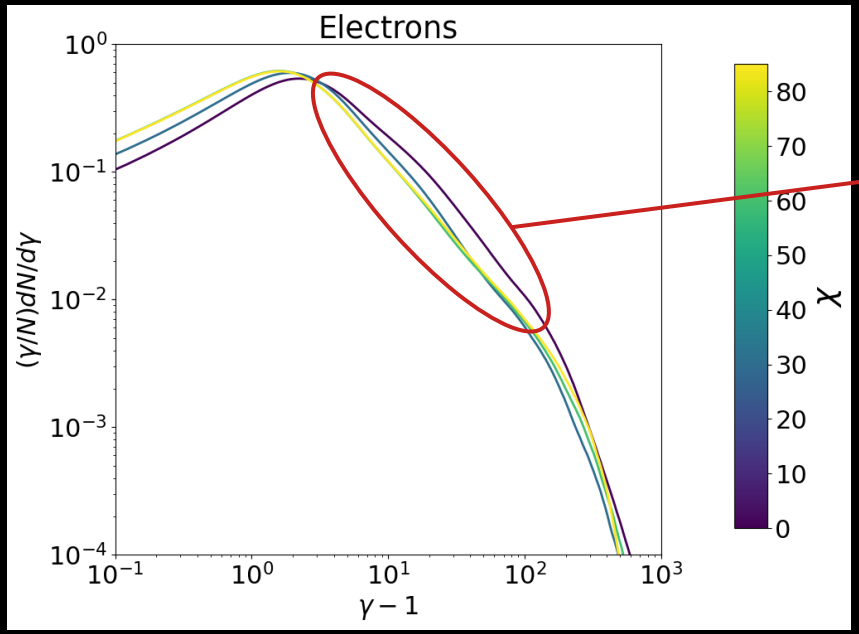


Particle Energization



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 (Sgr A*, …), NS–BH binaries, …

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