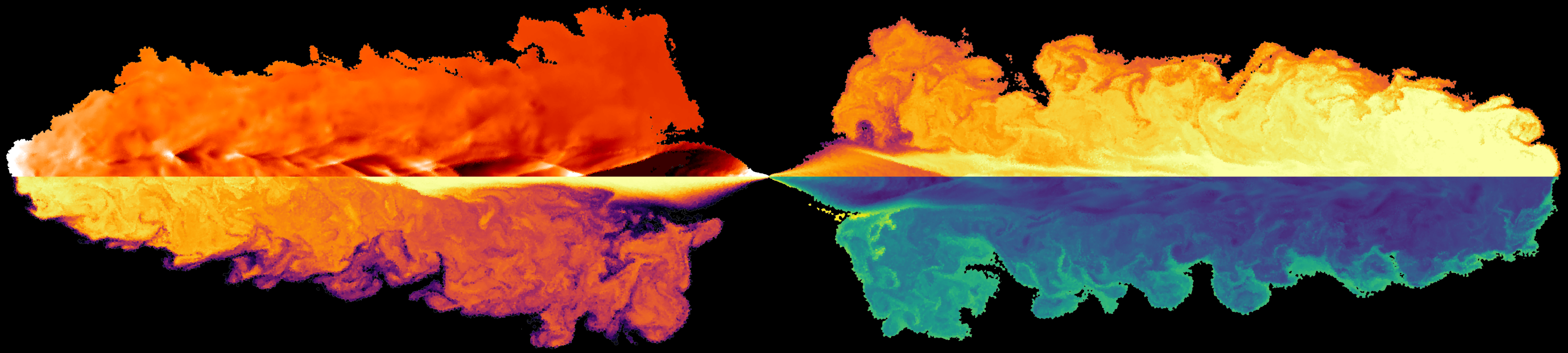

Blandford-Znajek jets in galaxy formation simulations

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Extragalctic jets on all scales - launching, propagation, termination; 18th June 2021

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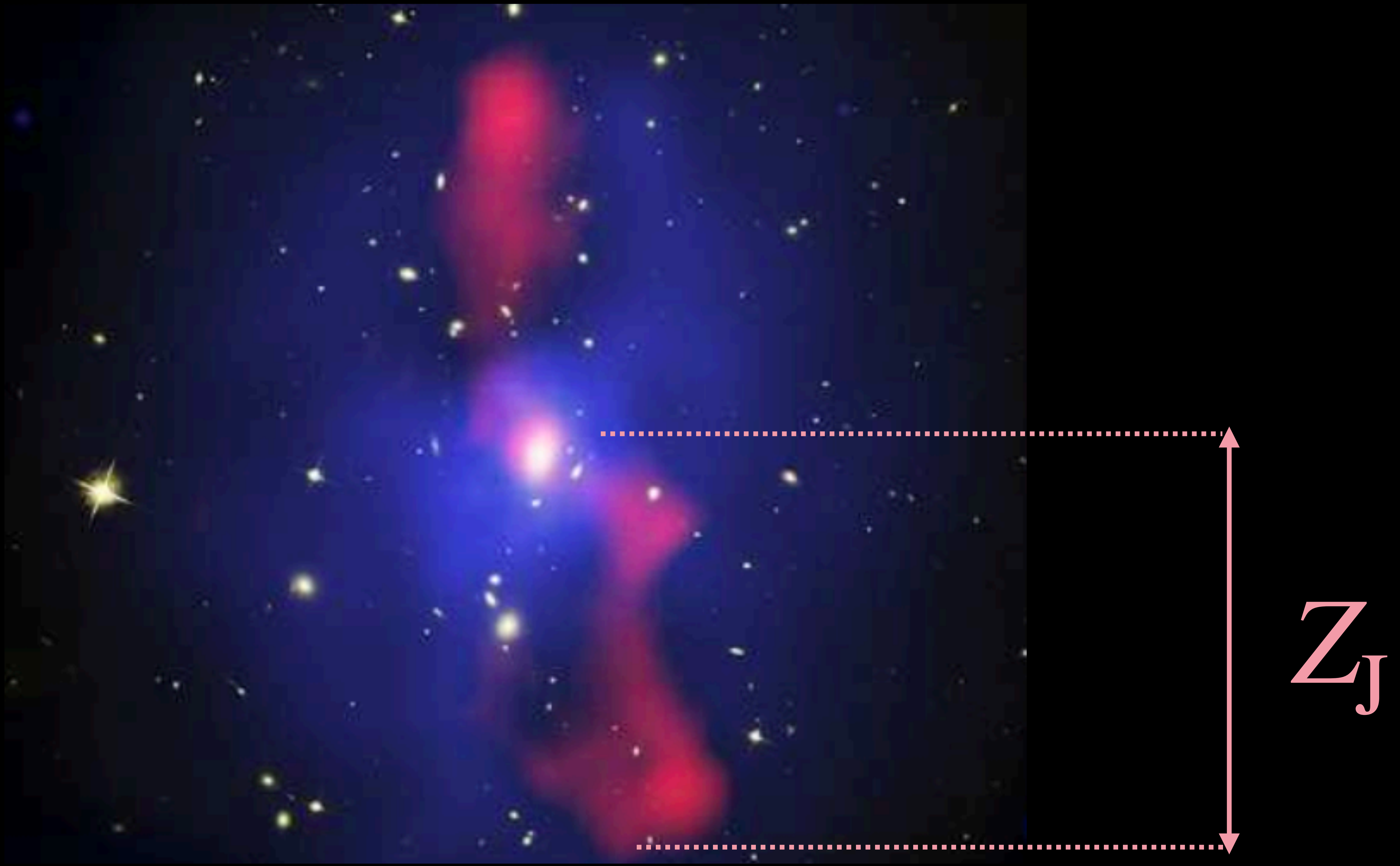
1. Motivation

Sub-grid modelling of jet launching in galaxy-scale simulations is necessary

The multi-scale nature of physical process often requires sub-grid modelling of micro-scale physics in galaxy scale simulations



McNamara & Nulsen (2007)

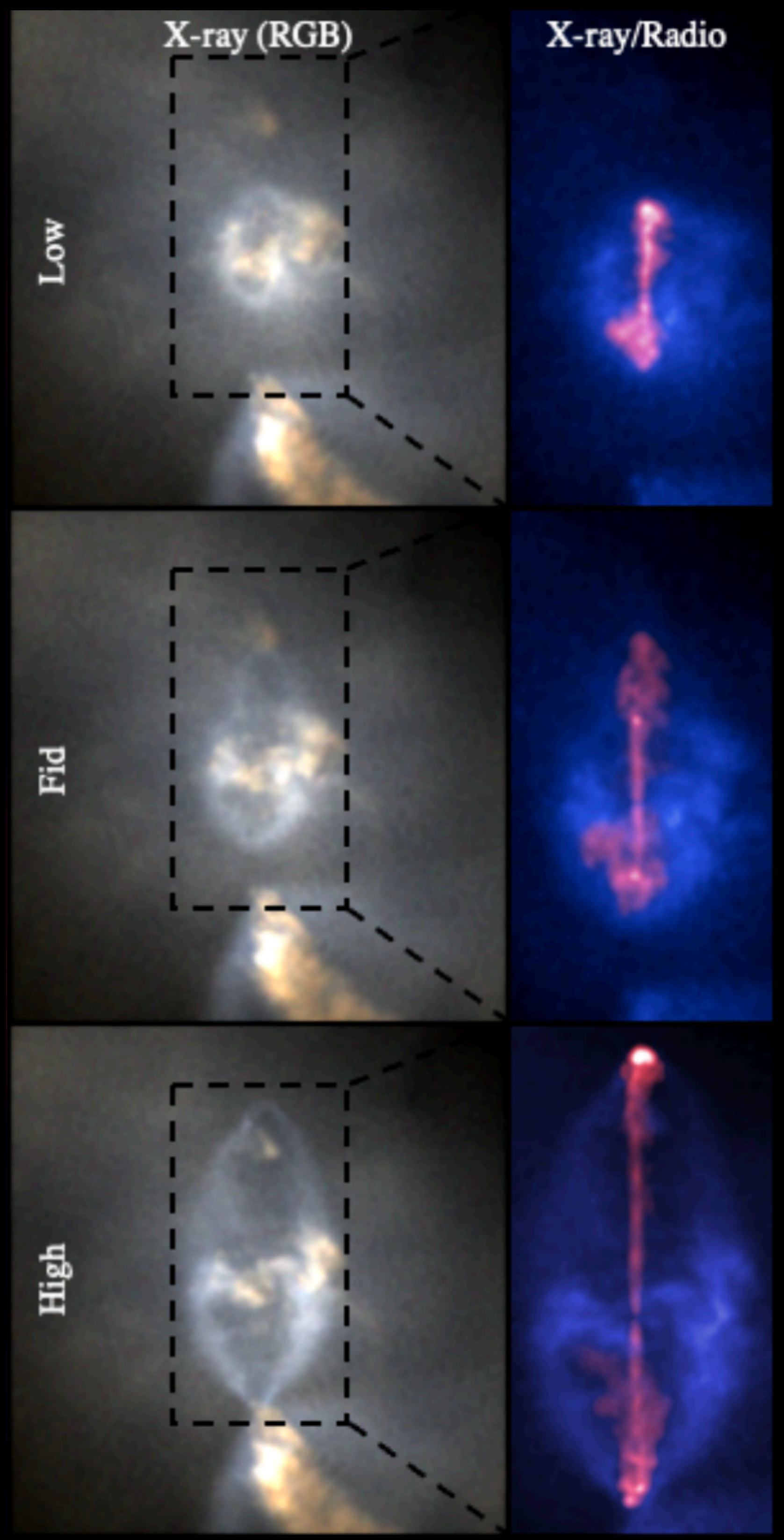
Jets are launched close to the BH horizon

and terminate on kpc scales

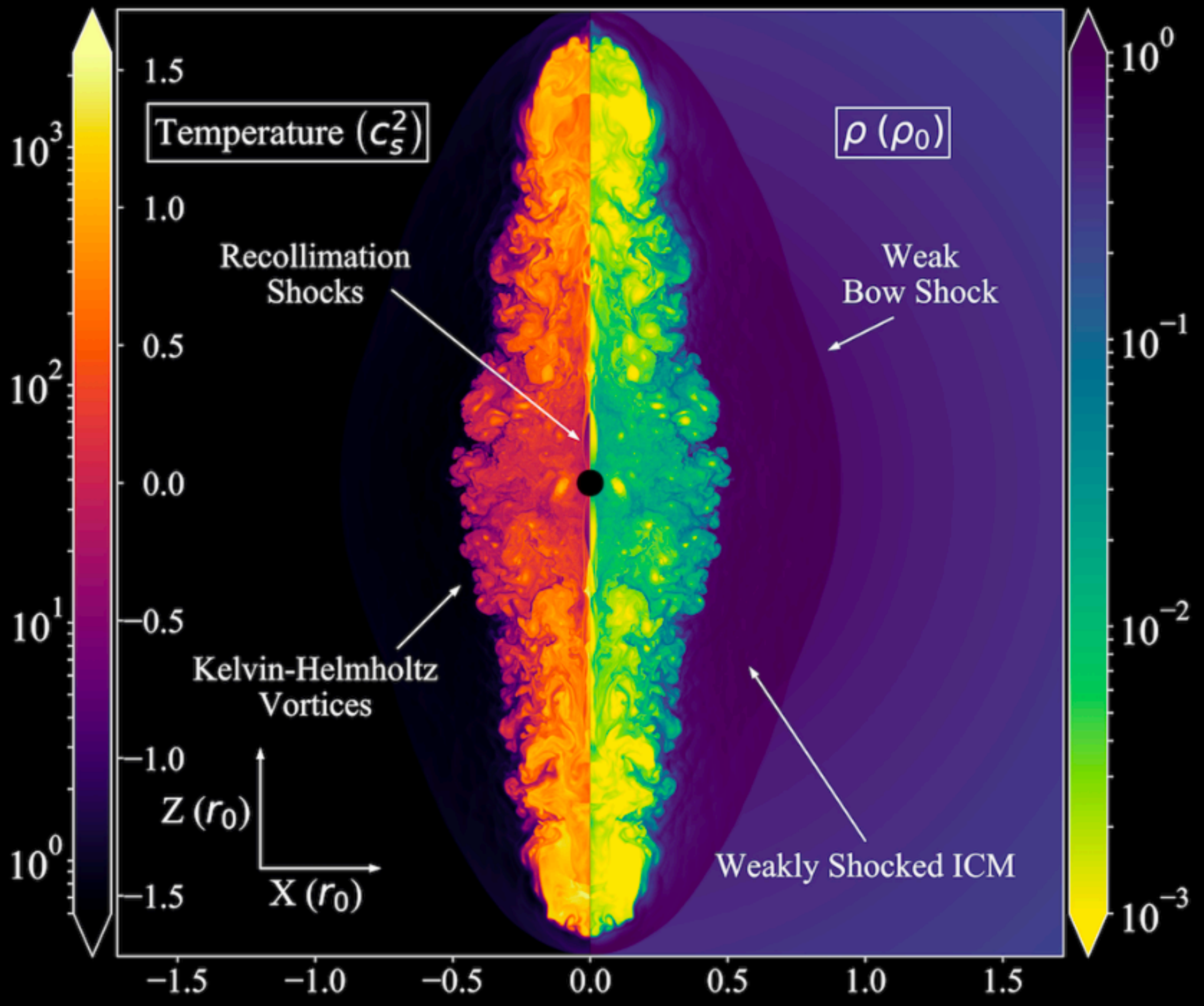
$$Z_{\rm J} \sim 10^9 \, R_{SZ}$$

a ‘perfect’ example of a multi-scale problem!

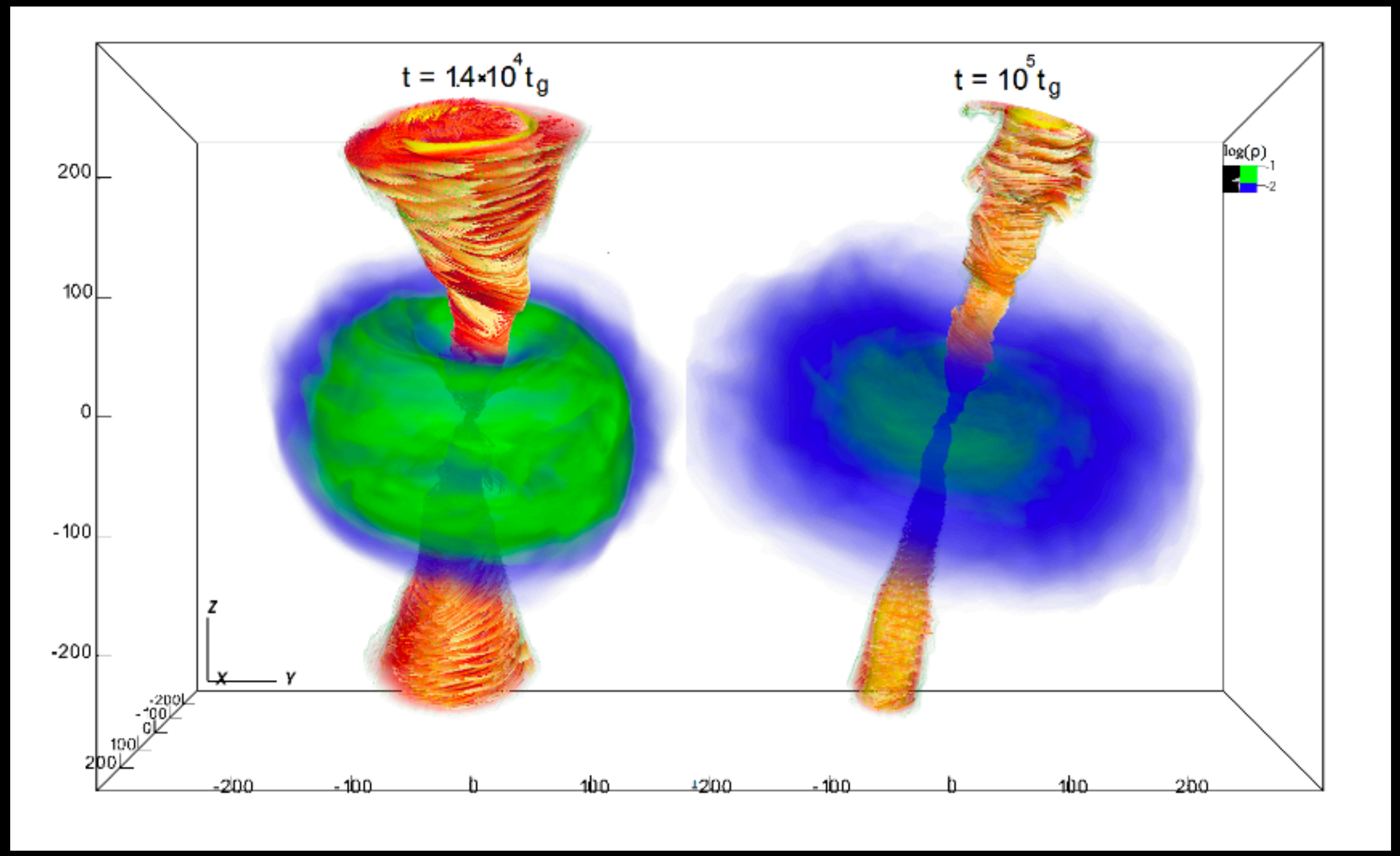
Simulations are vital for understanding AGN jet physics



Bourne & Sijacki (2021)



Bambic & Reynolds (2019)



Liska et al (2018)

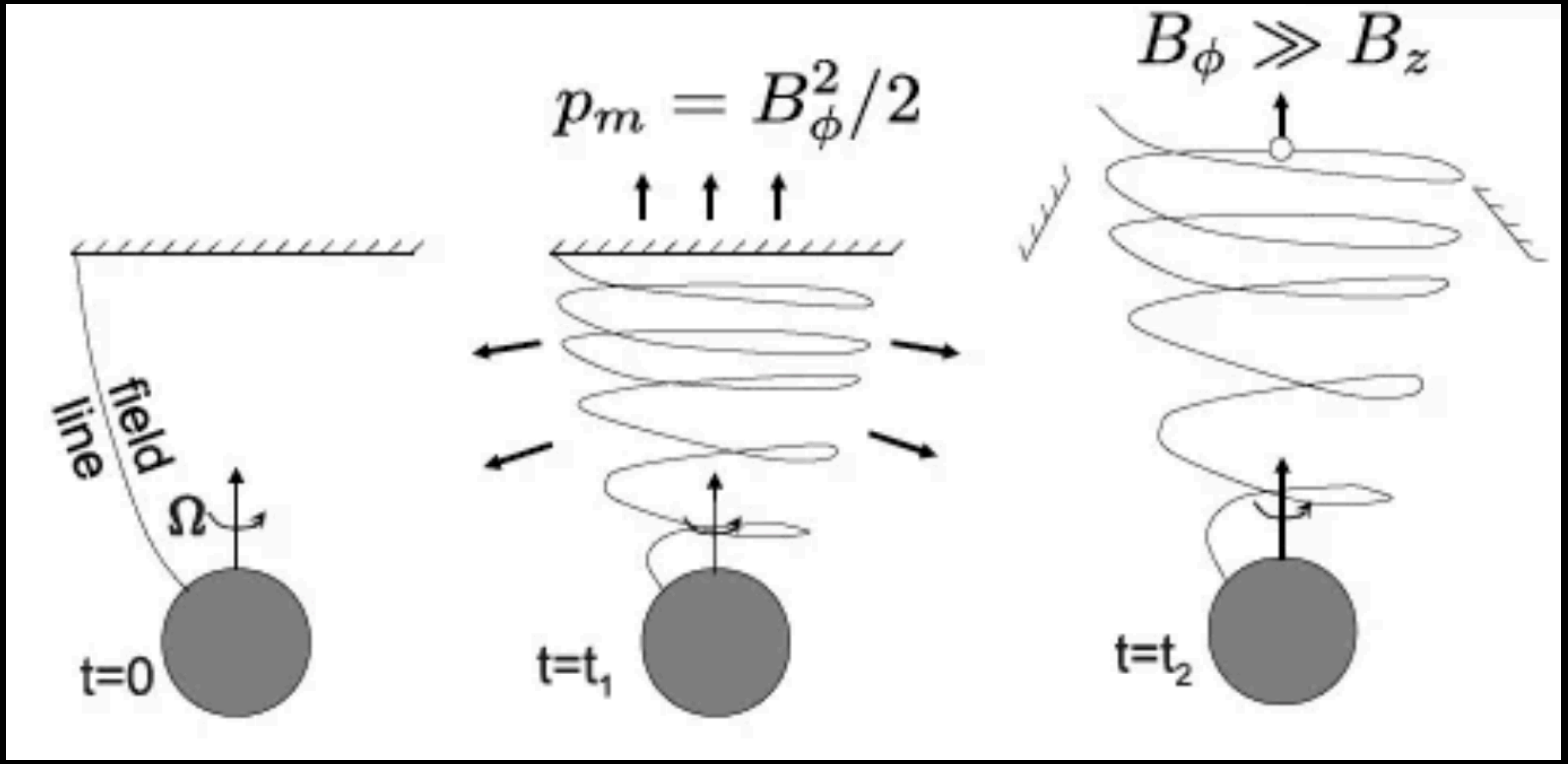
See also:

Weinberger et al. (2017)
Ehlert et al. (2018, 2020)
Li & Bryan (2014)
Yang & Reynolds (2016)

and many many more….

AGN jets can be launched by the Blandford-Znajek Mechanism

Tchekhovskoy et al. (2012)



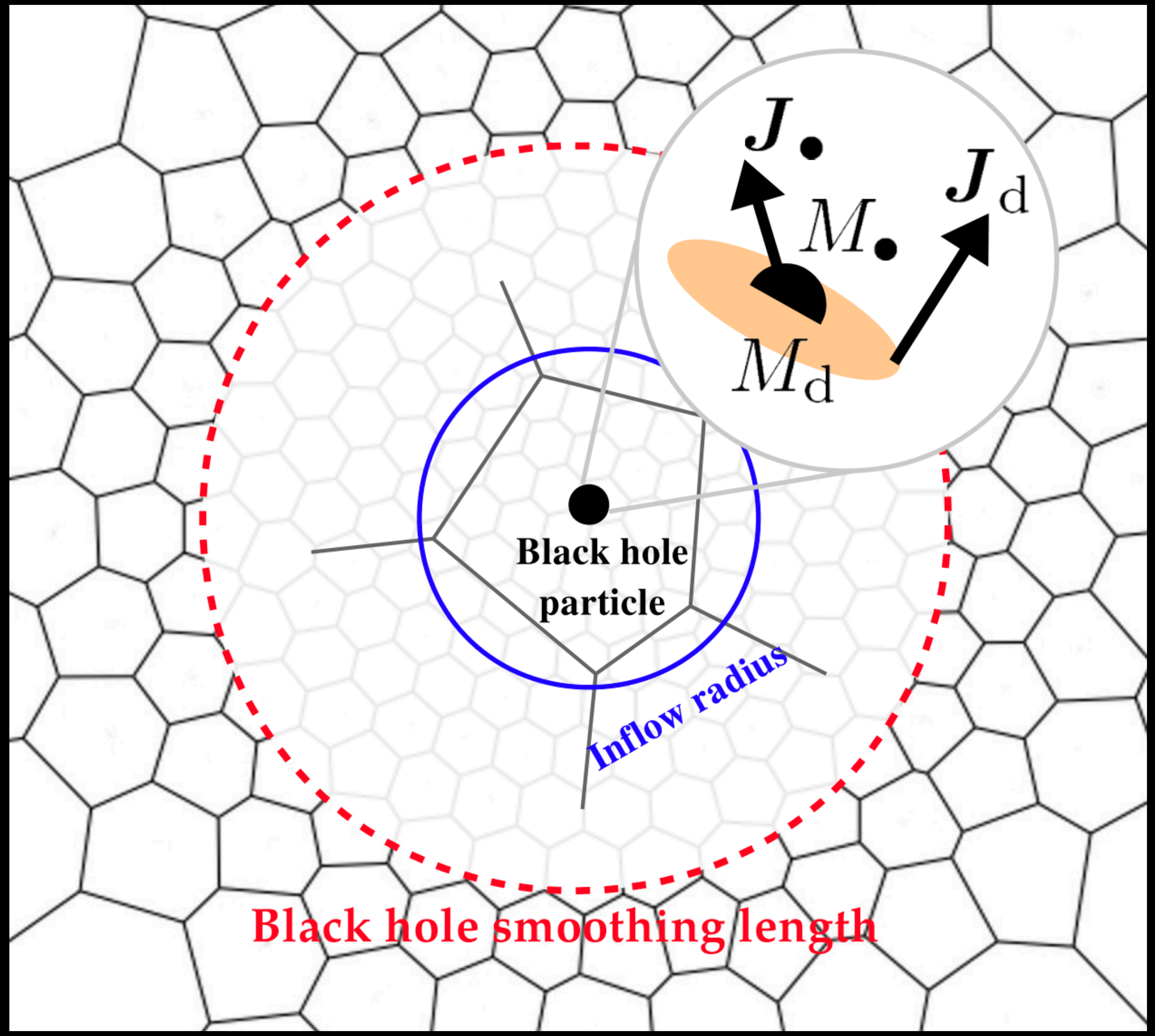
BZ jet power:

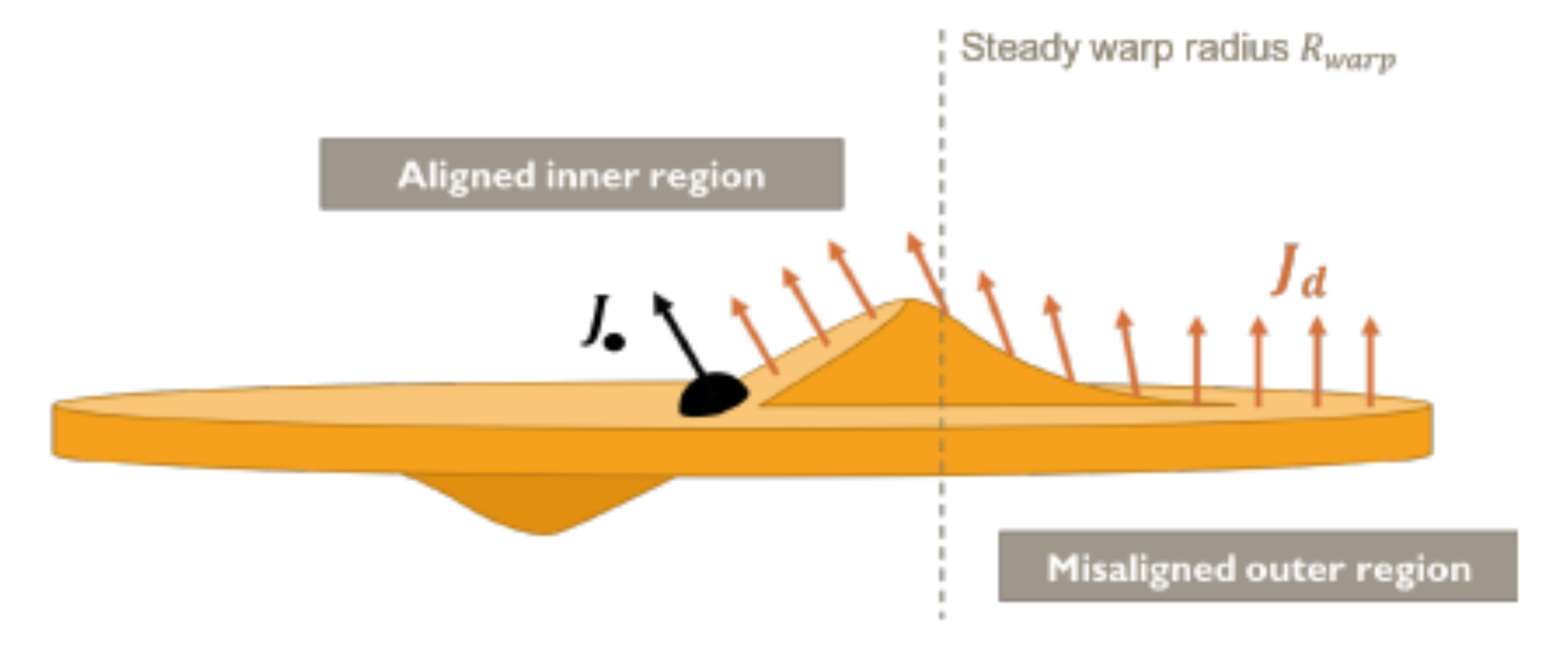
$$\dot{E}_{\rm BZ} = \epsilon_{\rm BZ}(a, \phi_{\rm BH})\, \dot{M}_{\rm BH,0}\, c^2$$

2. Our sub-grid, spin-driven, jet model

To calculate the jet power we need to accurately track the black hole spin

- Spherically symmetric Bondi won’t work here!
- We use an analytic, sub-grid, thin accretion disc





Fiacconi et al. (2018)

- A misaligned disc will warp
- This imposes mutual Bardeen-Petterson torques on the BH and disc

The equations governing our accretion and feedback model

black hole evolution

$$\dot{M}_{\rm BH} = \frac{1-\epsilon_{\rm r}-\epsilon_{\rm BZ}}{1+\eta_{\rm J}}\,\dot{M}$$

$$\boldsymbol{j}_{\rm BH} = \frac{(L_{\rm ISCO}-L_{\rm BZ})}{1+\eta_{\rm J}}\,\dot{M}\,\boldsymbol{j}_{\rm BH} - J_{\rm BH}\left[\frac{\sin(\pi/7)}{\tau_{\rm GM}}(\boldsymbol{j}_{\rm BH}\times\boldsymbol{j}_{\rm d}) + \frac{\cos(\pi/7)}{\tau_{\rm GM}}(\boldsymbol{j}_{\rm BH}\times(\boldsymbol{j}_{\rm BH}\times\boldsymbol{j}_{\rm d}))\right]$$

α-disc evolution

$$\dot{M}_{\rm d} = \dot{M}_{\rm in} - \dot{M}$$

$$\boldsymbol{j}_{\rm d} = \dot{M}_{\rm in}\,\boldsymbol{L}_{\rm in} - \dot{M}\,L_{\rm ISCO}\,\boldsymbol{j}_{\rm BH} + J_{\rm BH}\left[\frac{\sin(\pi/7)}{\tau_{\rm GM}}(\boldsymbol{j}_{\rm BH}\times\boldsymbol{j}_{\rm d}) + \frac{\cos(\pi/7)}{\tau_{\rm GM}}(\boldsymbol{j}_{\rm BH}\times(\boldsymbol{j}_{\rm BH}\times\boldsymbol{j}_{\rm d}))\right]$$

jet launching

$$\dot{E}_{\rm J} = \frac{\epsilon_{\rm BZ}}{1+\eta_{\rm J}}\,\dot{M}c^2 \qquad \dot{M}_{\rm J} = \frac{\eta_{\rm J}}{1+\eta_{\rm J}}\,\dot{M}$$

jet direction || $\boldsymbol{j}_{\rm BH}$

(2021) Talbot et. al.

A more accessible summary of ~~The equations governing~~ our accretion and feedback model

Mass evolution:

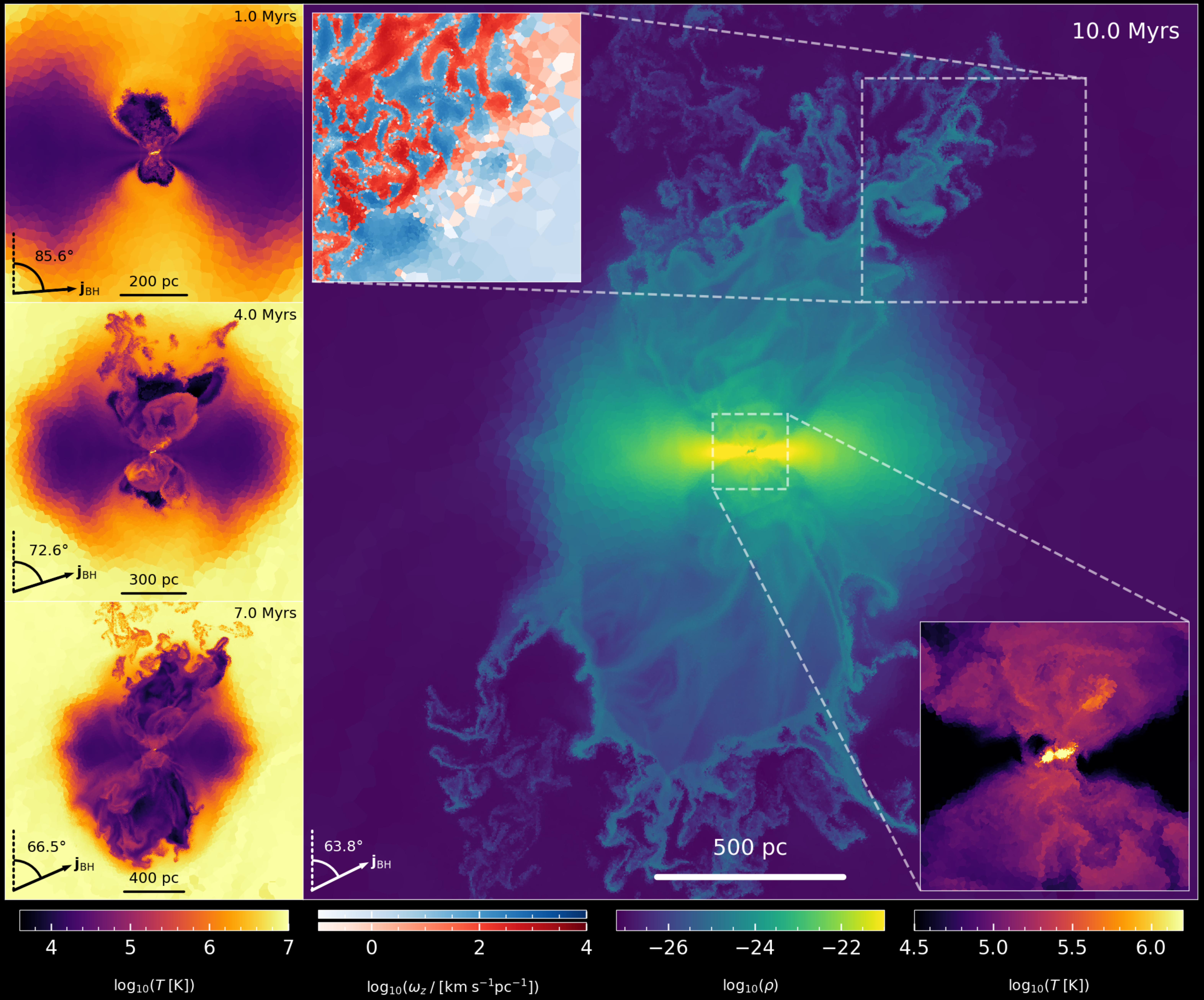
Black hole	**Disc**
+ Accretion from disc	- Accretion onto the BH
- Launching of the jet	+ Inflow from surroundings

Angular momentum evolution:

Black hole	**Disc**
Accretion from disc	Accretion onto the BH
Launching of the jet	Inflow from surroundings
Bardeen-Petterson torques	Bardeen-Petterson torques

3. Model validation

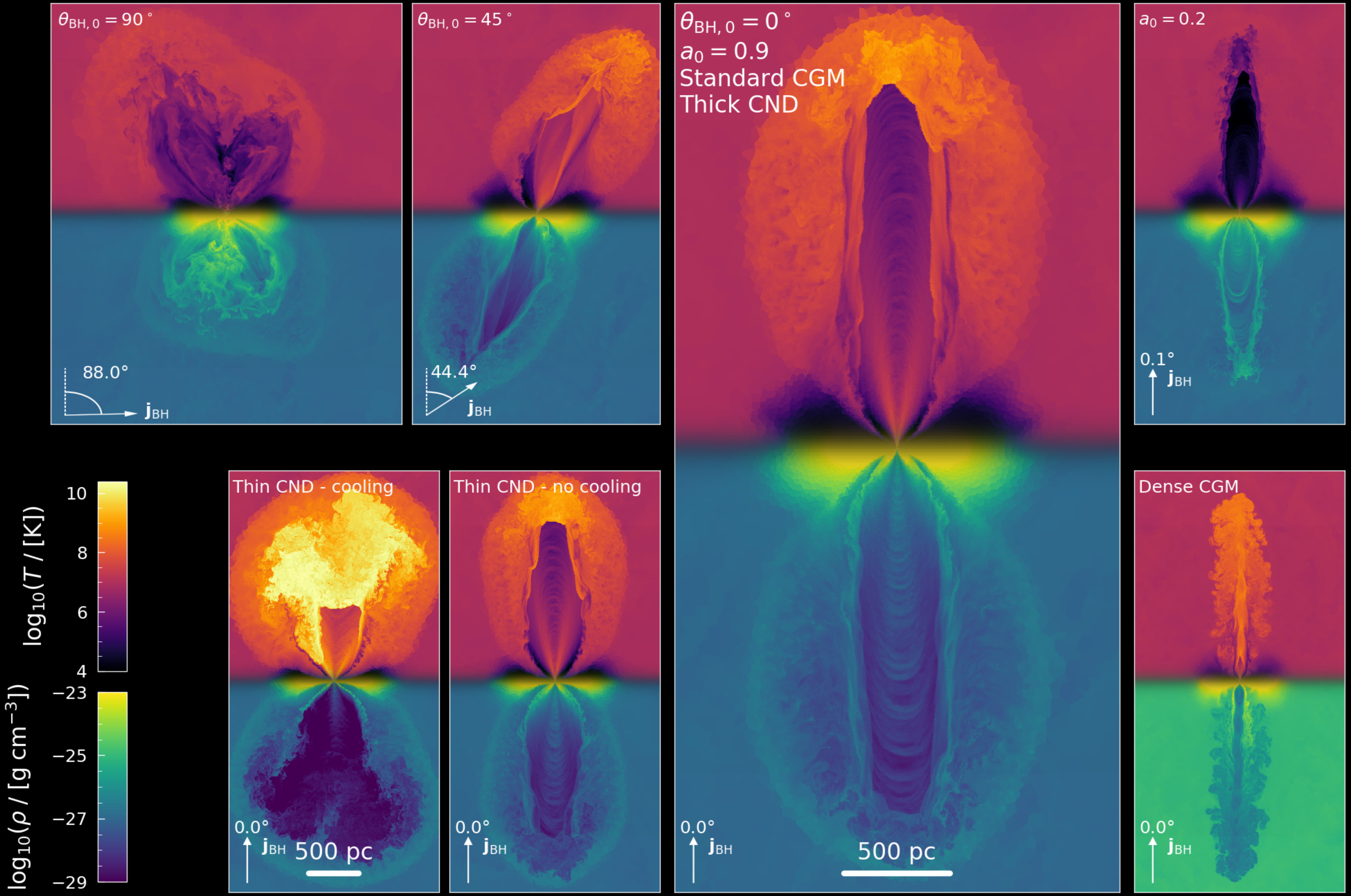
(2021) Talbot et. al.



- The morphology of jets whose power and direction are determined self-consistently differs from those of jets with fixed power and direction
- Jets launched into the circumnuclear disc drive turbulent, multi-phase, quasi-bipolar outflows
- Misaligned black holes undergo significant Bardeen-Petterson torquing
- These jets are torqued out of the circumnuclear disc, driving outflowing shells of disc material that collide and shock

The outflow properties are very sensitive to:

- Black hole spin magnitude
- Black hole spin direction
- Gas availability
- Properties of the ambient medium



(2021) Talbot et. al., in prep.

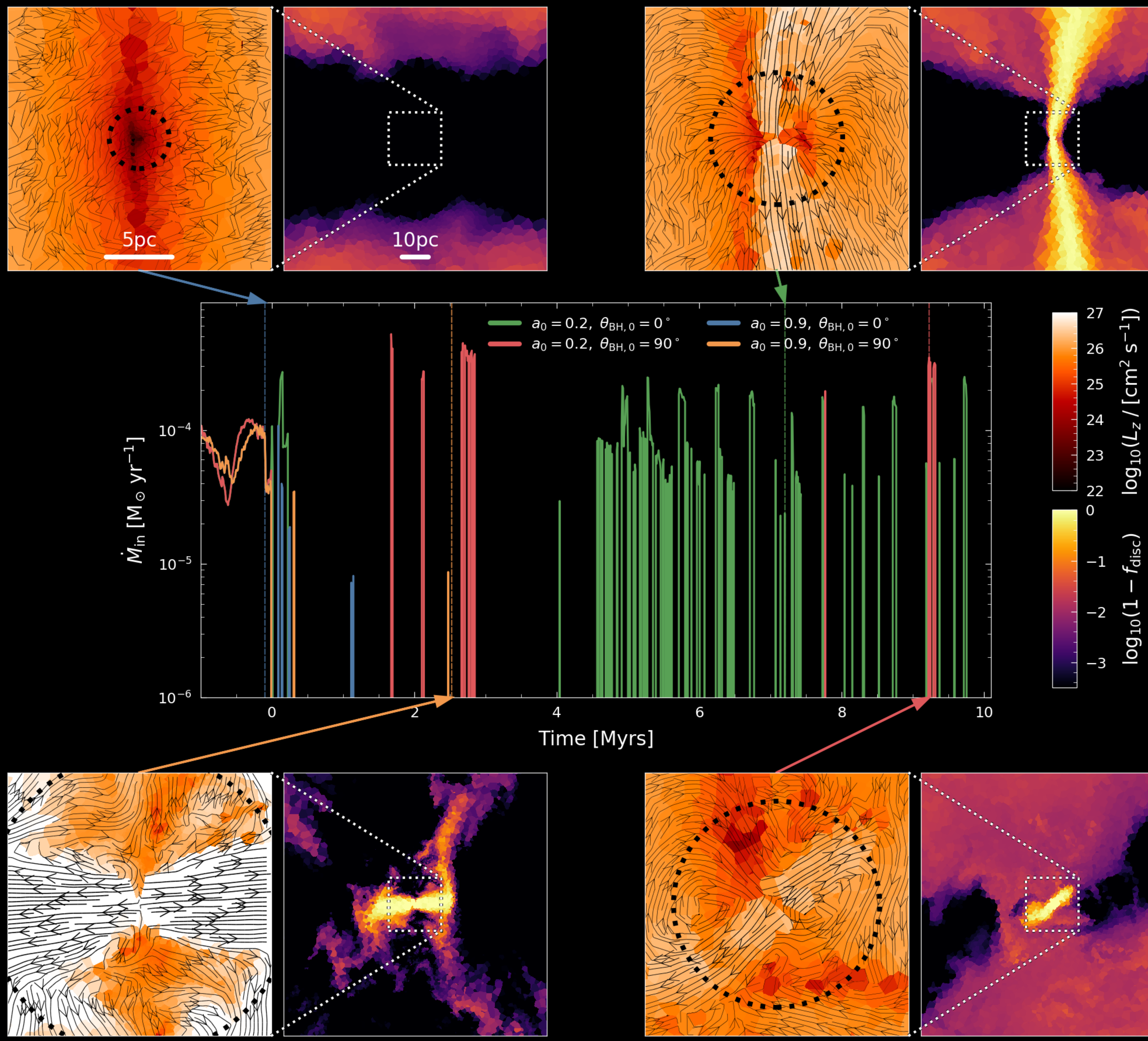
$$\theta_{BH} = \cos^{-1}(j_{BH} \cdot \hat{z})$$

- Gas accretion before the jet turns on is coherent and axisymmetric

- After the jet turns on it is bursty and more chaotic

- Backflows draw in gas from the disc to feed the black hole

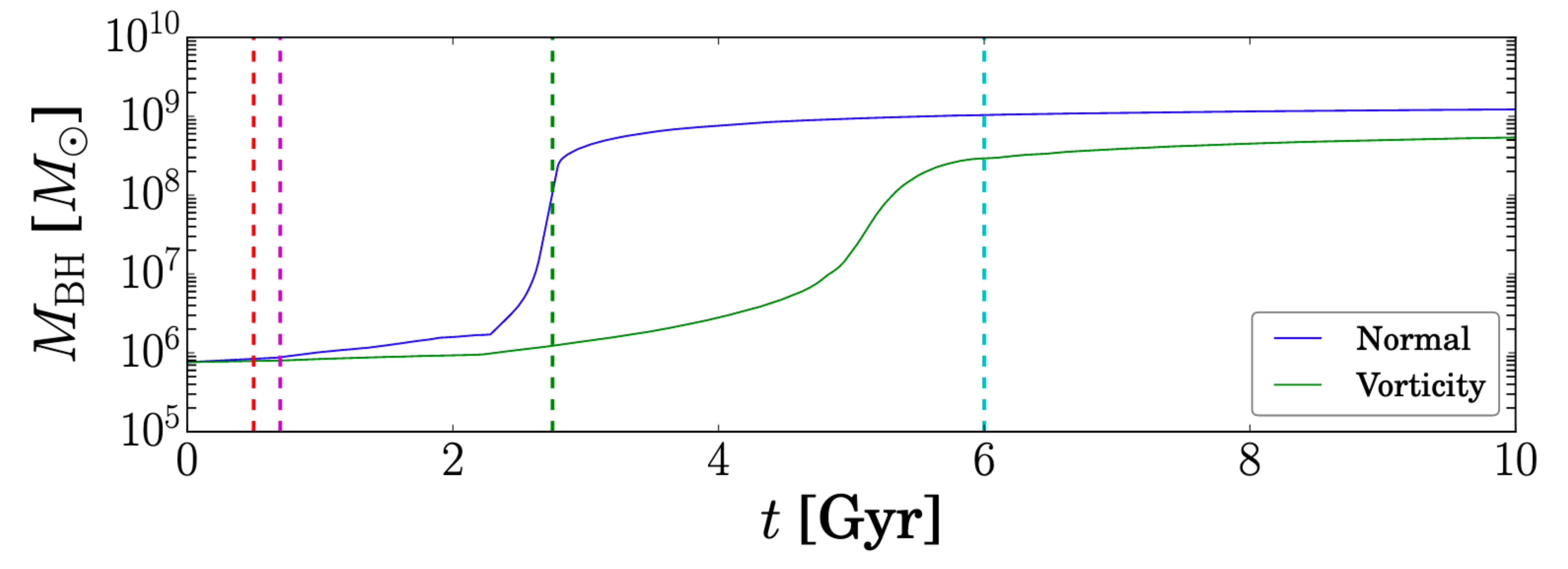
- The jet power (i.e. black hole spin) is naturally self-regulated by the accretion flow - gas inflows are surpassed for longer



(2021) Talbot et. al., in prep.

3. Galaxy mergers

- Assess the impact of the merger torques on the jet directions both before and the black holes coalesce
- Investigate how the **α**-disc and jet alter the ‘cannonical’ prediction of BH growth in a major merger

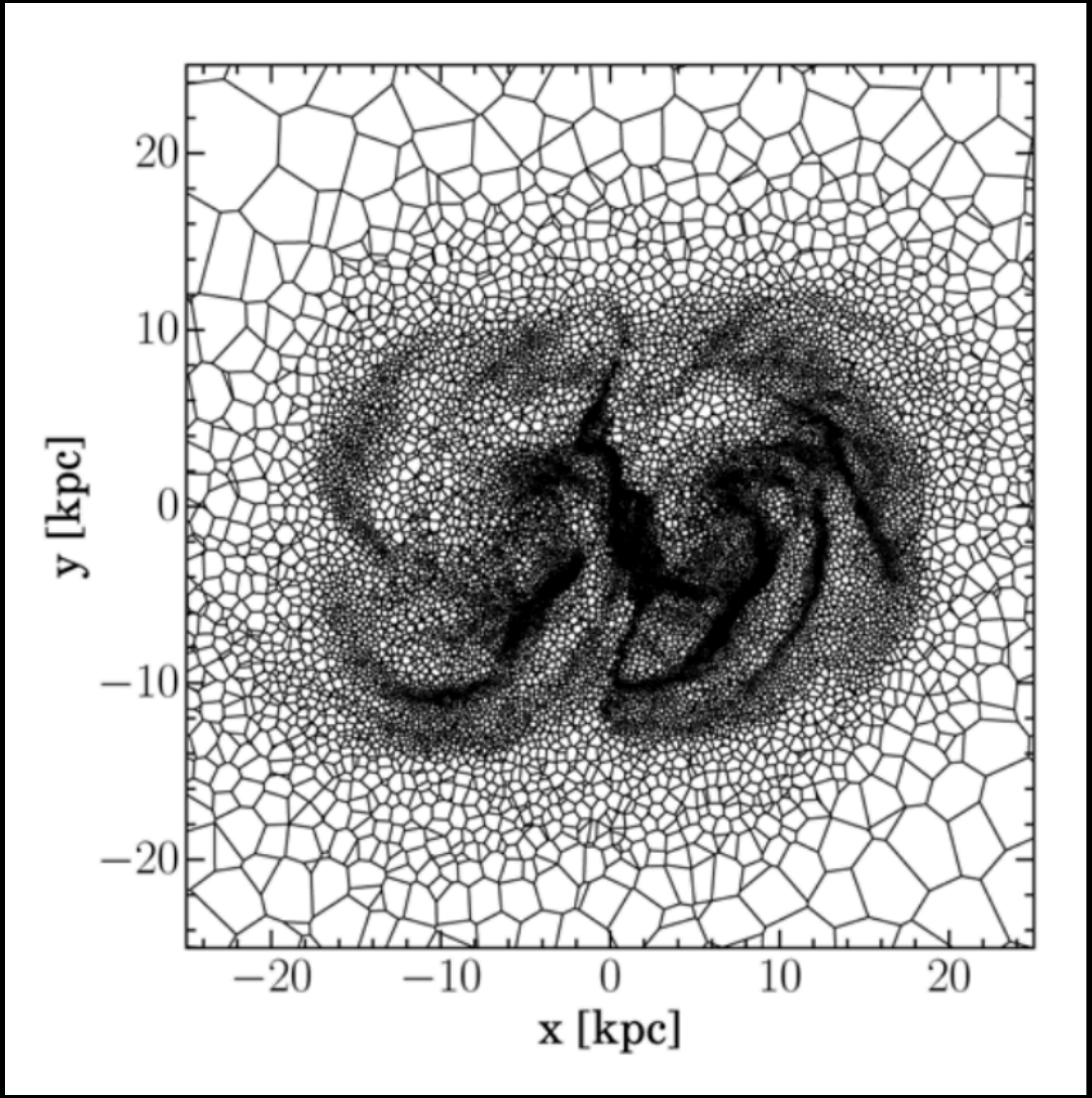


Curtis & Sijacki (2016)

Halo parameters

M_{200c}	$10^{12}\,h^{-1}\mathrm{M}_\odot$
$M_{\rm bulge}$	$8\times10^9\,h^{-1}\mathrm{M}_\odot$
$M_{\rm BH}$	$10^{6-7}\,h^{-1}\mathrm{M}_\odot$
$f_{\rm gas}$	0.6

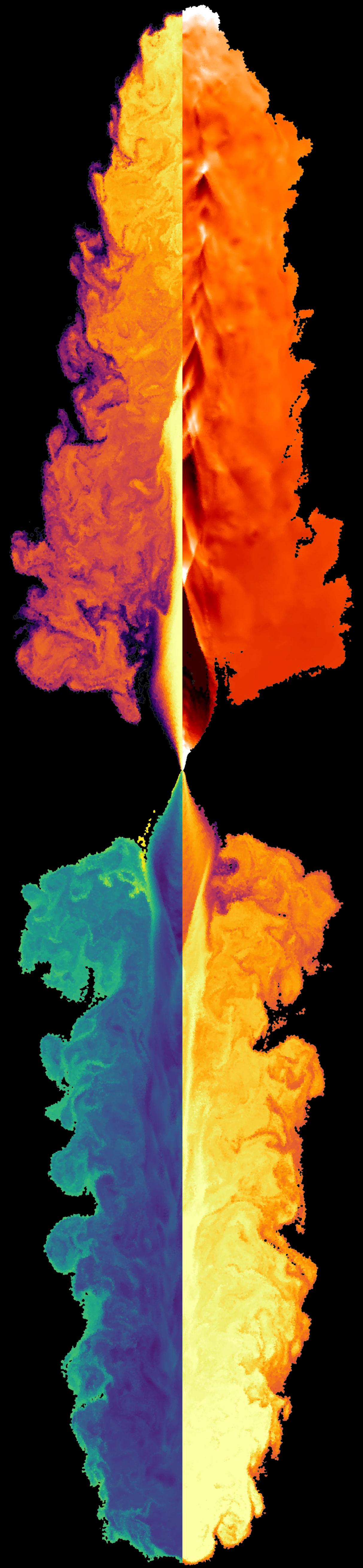
- Investigate how efficient gas fuelling impacts the mass accretion rate through the α-discs and the resulting jet powers
- Investigate how the flow patterns in the vicinity of the black holes depend on the mass ratio, black hole spins, gas fractions….
- … and how these flows respond to the jet launching
- Provide predictions for the X-ray emission, counterpart to the merger



Curtis & Sijacki (2016)

Summary

- We have developed a new, self-consistent sub-grid model for black hole accretion through a (warped) α-disc and feedback in the form of a kinetic Blandford-Znajek jet.
- We verified our model by carrying out idealised simulations of the central regions of a typical Seyfert galaxy
- We found that the outflow morphologies are highly dependent on the jet power and direction and so self-consistent determination of these quantities is crucial!
- We're now applying our jet model to merger scenarios and, ultimately, we aim to provide constraints on the link between electromagnetic observations and GW signals that would result if the AGN coalesce



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