# Lampposts and striped jets - numerical experiments

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# Magnetospheric dissipation and outflow formation: numerical experiments

1. Yuan, Blandford, Wilkins 2019
2. Yuan, Spitkovsky, Blandford, Wilkins 2019

Mechanism for lamppost formation

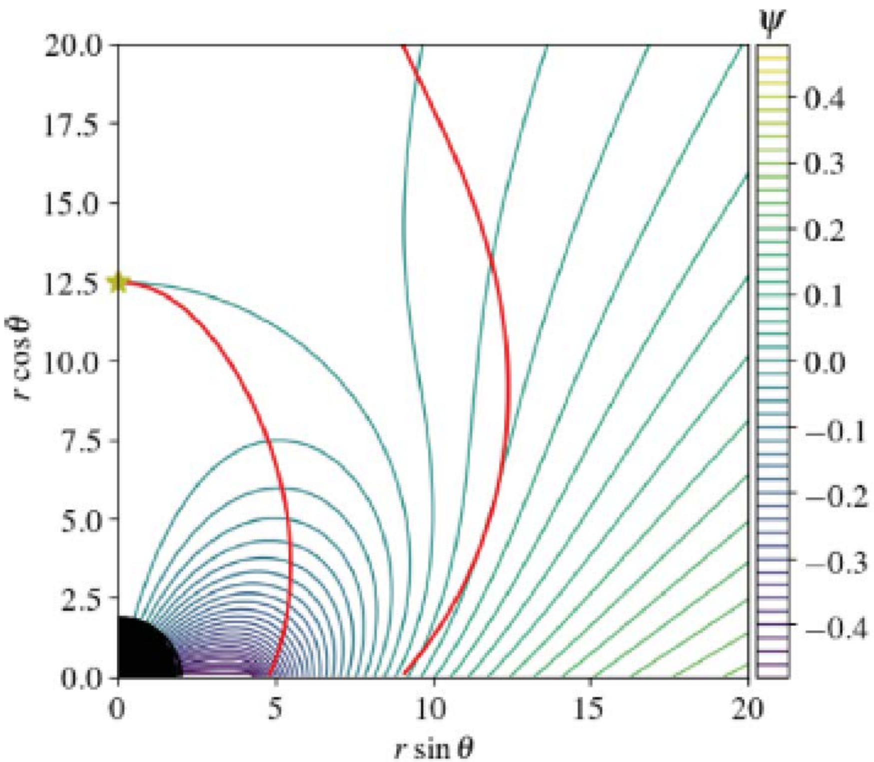
3. Parfrey, Giannois, Beloborodov 2015
4. Mahlmann, Levinson, Aloy 2020

Striped B-Z jets from small scale magnetic fields

# Yuan, Blandford, Wilkins 2019

2D axisymmetric solutions of small scale, disc-hole linking flux tubes. What happens in 3D?

2D axisymmetric GRFFE solution.

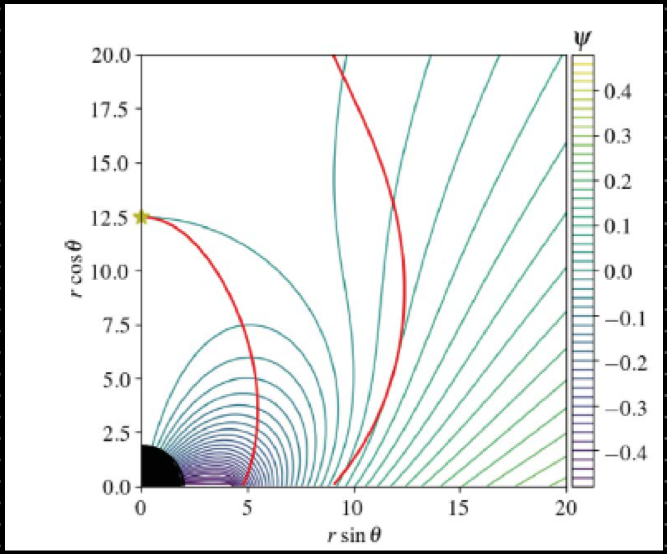



Yuan, Blandford, Wilkins 19 (pap 1)

Yuan, Spitkovsky, Blandford, Wilkins 2019

Dynamics in 3D:

Main result: small scale magnetic fields near BH can lead to dissipation on a few horizon scales under certain conditions



# Setup

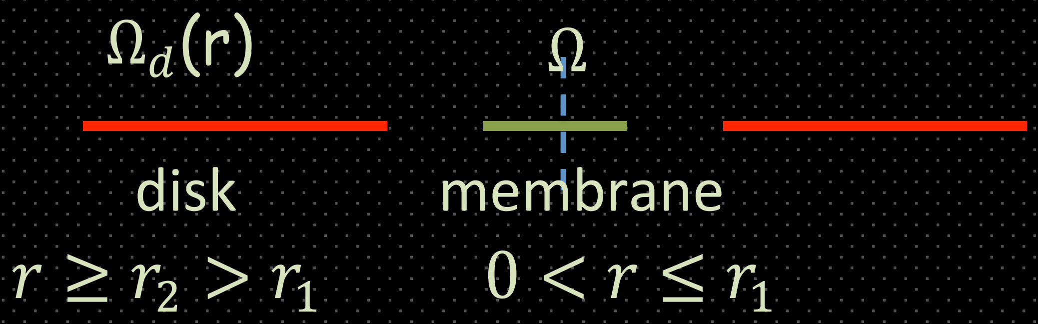
## 3D special relativistic FFE

- Inner membrane of radius $r_1$ representing the BH

  angular velocity: $\Omega = 0.9\, c/r_1$

- Perfectly conducting disk extending over $r > r_2 > r_1$

  angular velocity: $\Omega_d(r)$ , no accretion



# Boundary conditions

- Inner membrane is resistive

$$E_r = -\eta\frac{B_\varphi}{\gamma} - \frac{\Omega r}{c}B_z, \quad E_\varphi = \eta\gamma\left(B_r - \frac{\Omega r}{c}E_z\right),$$

$R = 4\pi\eta$ is the resistivity
$\eta = 0$: perfectly conducting star
$\eta = 1$: BH

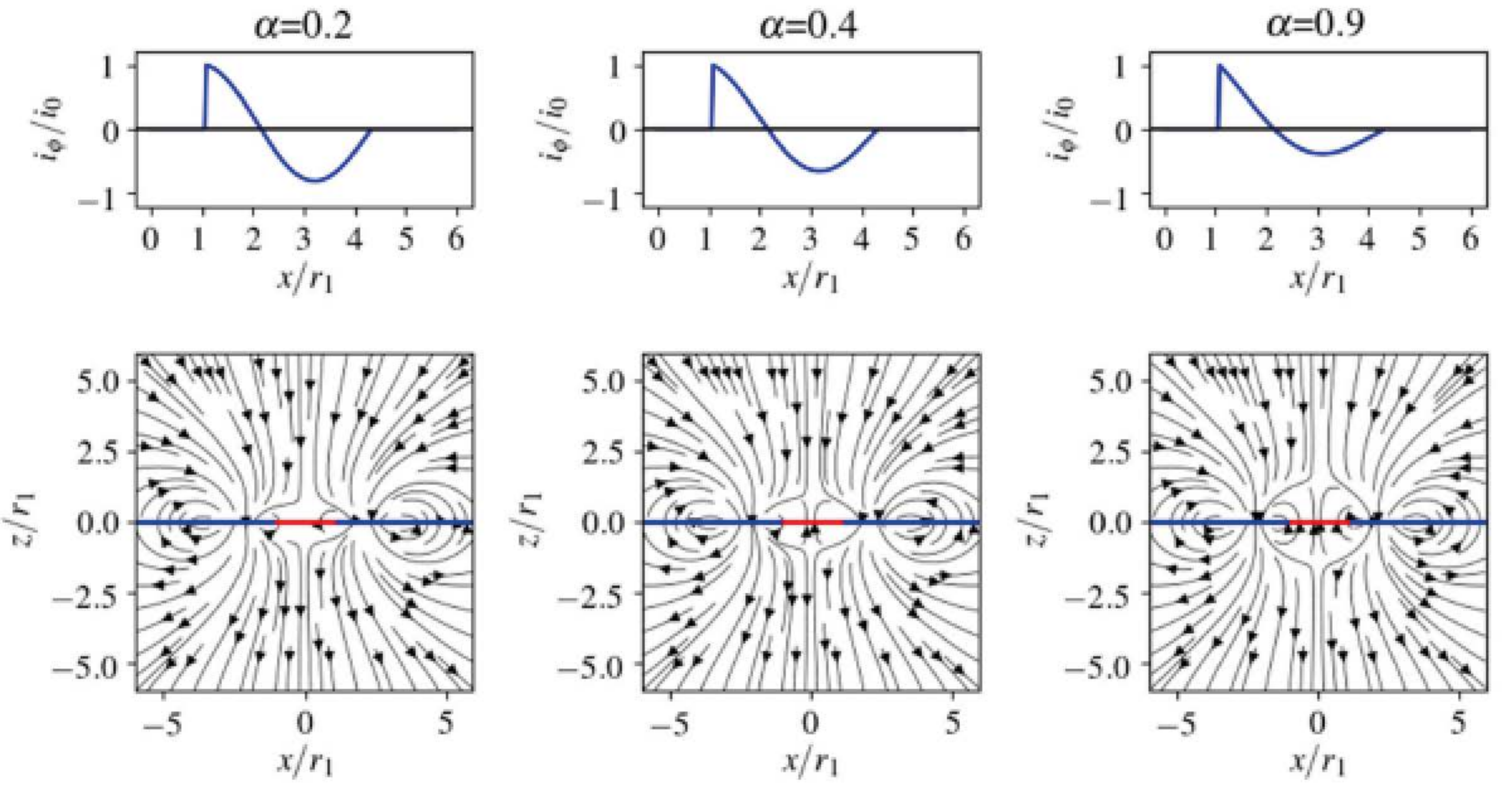
- Perfectly conducting disk

$$E_r = -\frac{\Omega_d(r)r}{c}B_z,$$

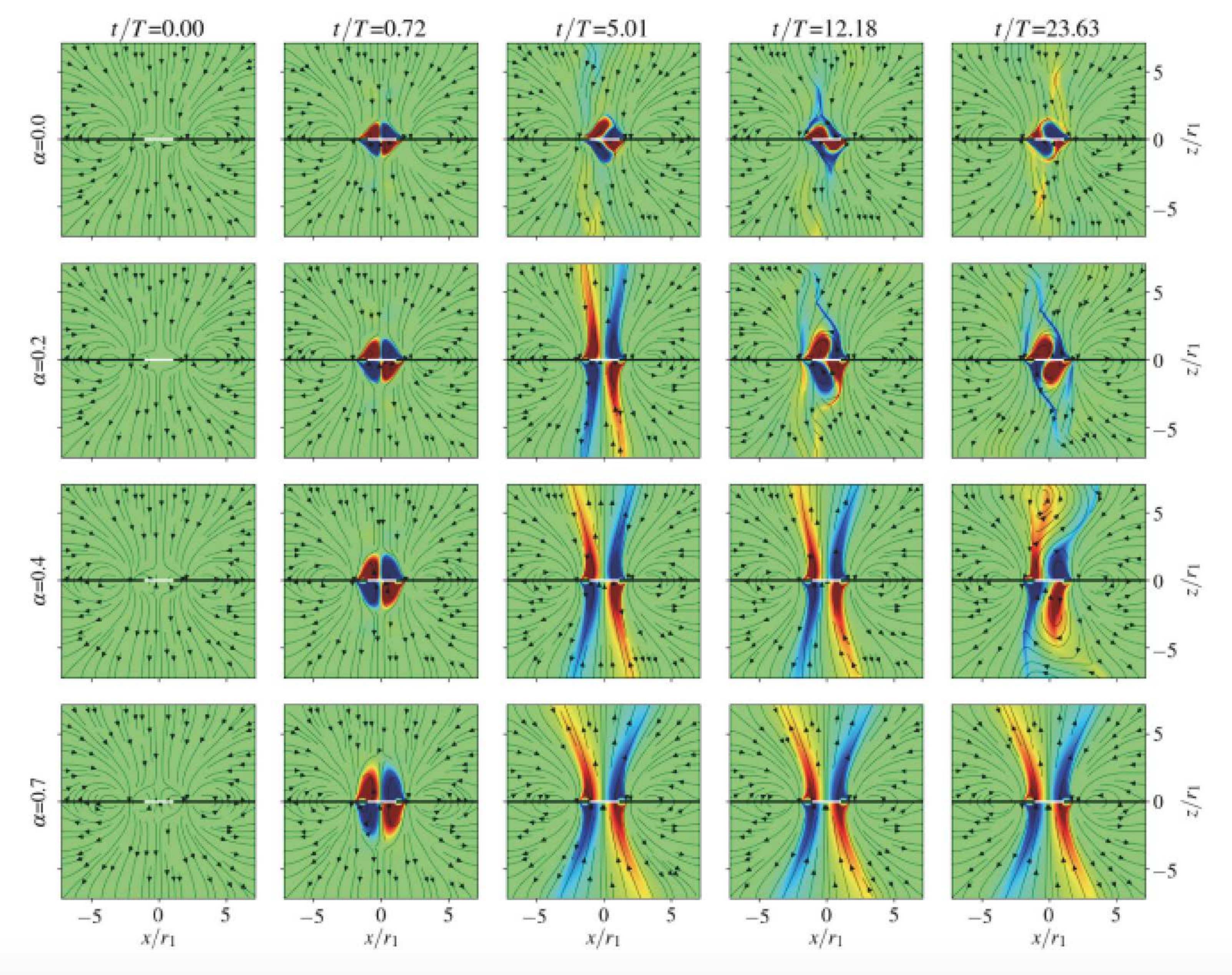
# Initial B field configuration

$$i_\phi = \begin{cases} i_0 \cos\left(\frac{2\pi}{r_0}(r - r_2)\right)\left(\frac{r_2}{r}\right)^\alpha, & r_2 \le r \le r_2 + \frac{3}{4}r_0, \\ 0, & \text{otherwise.} \end{cases}$$

$\alpha$ quantifies relative strength of inner and outer flux tubes

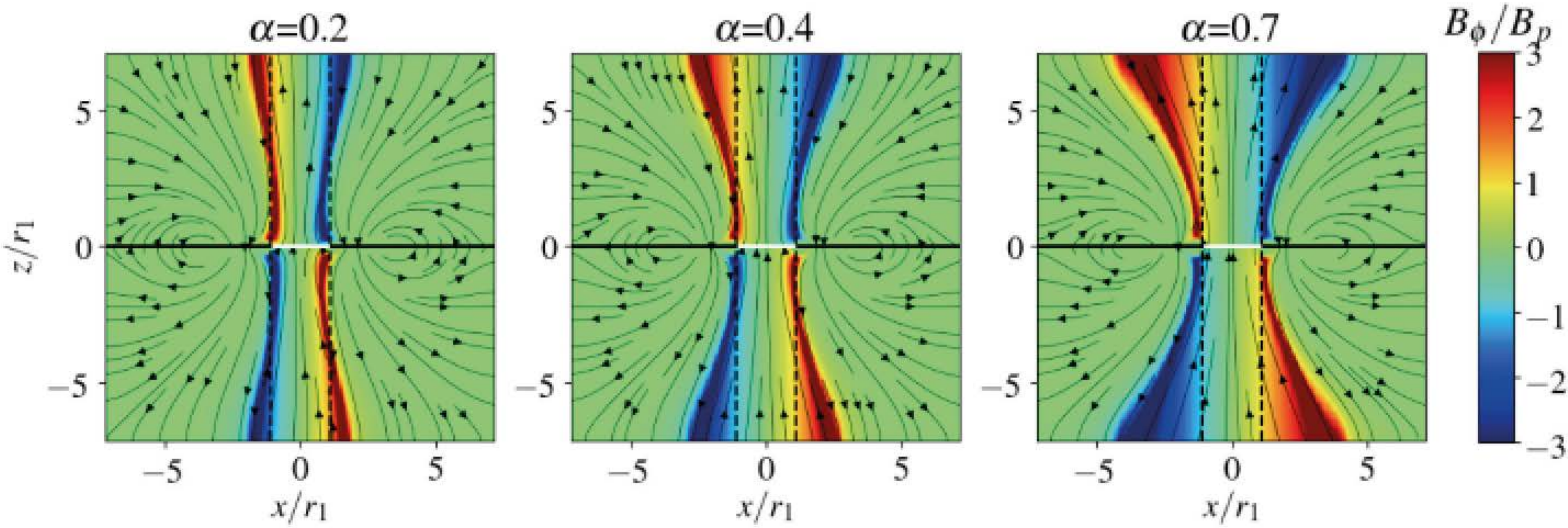


# evolution: $\Omega_d = \eta = 0$ (color shows $B_y$)



Small $\alpha$ : jet inside light cylinder → kink unstable

large $\alpha$ : jet outside light cylinder → stability



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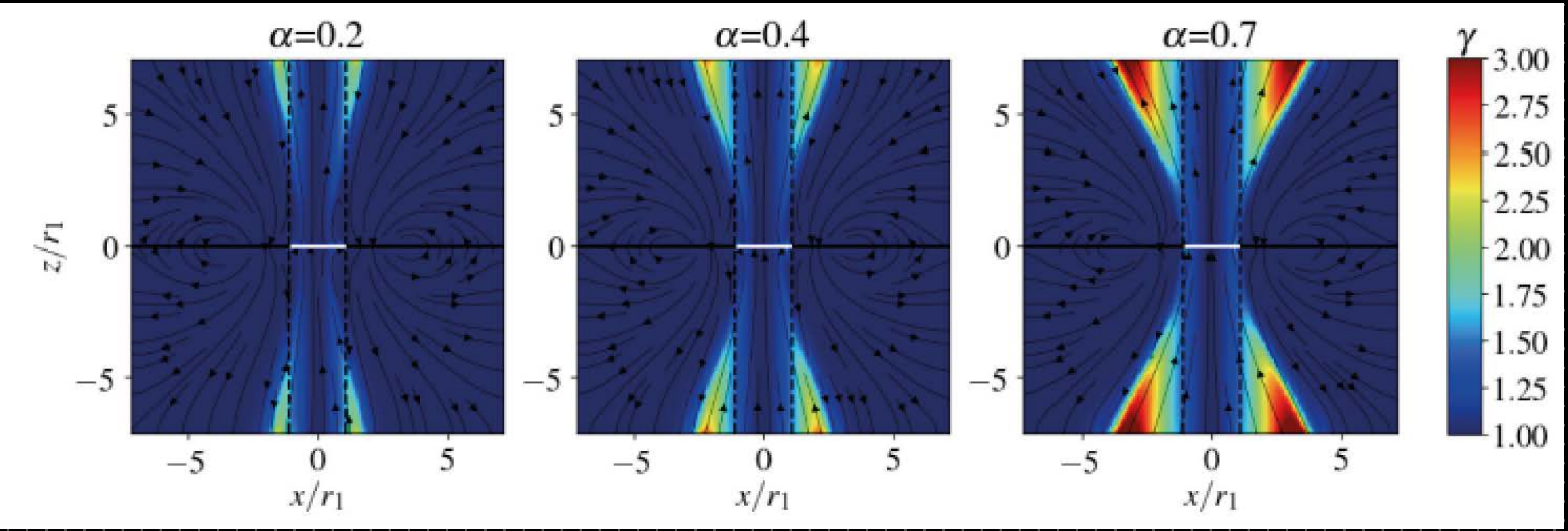
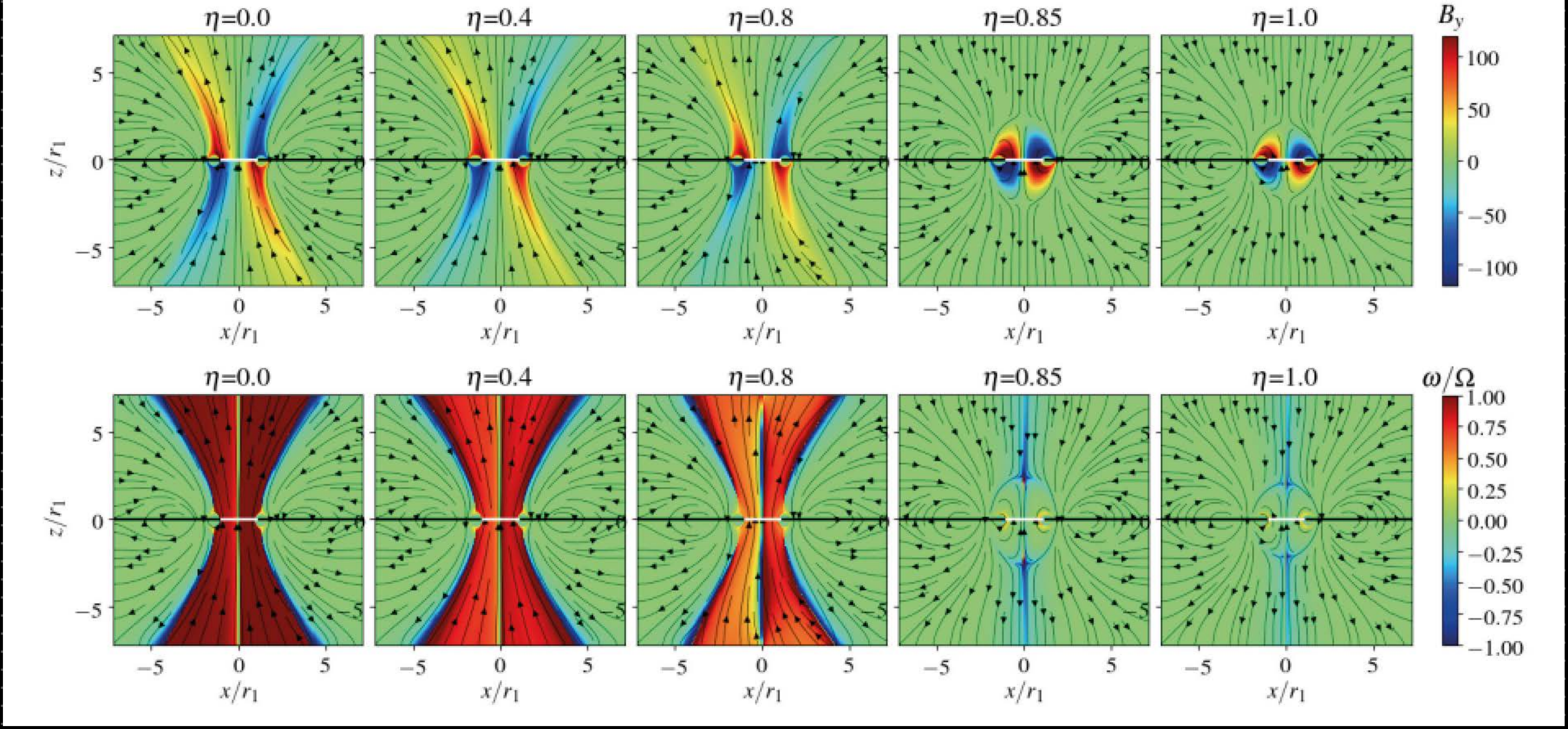


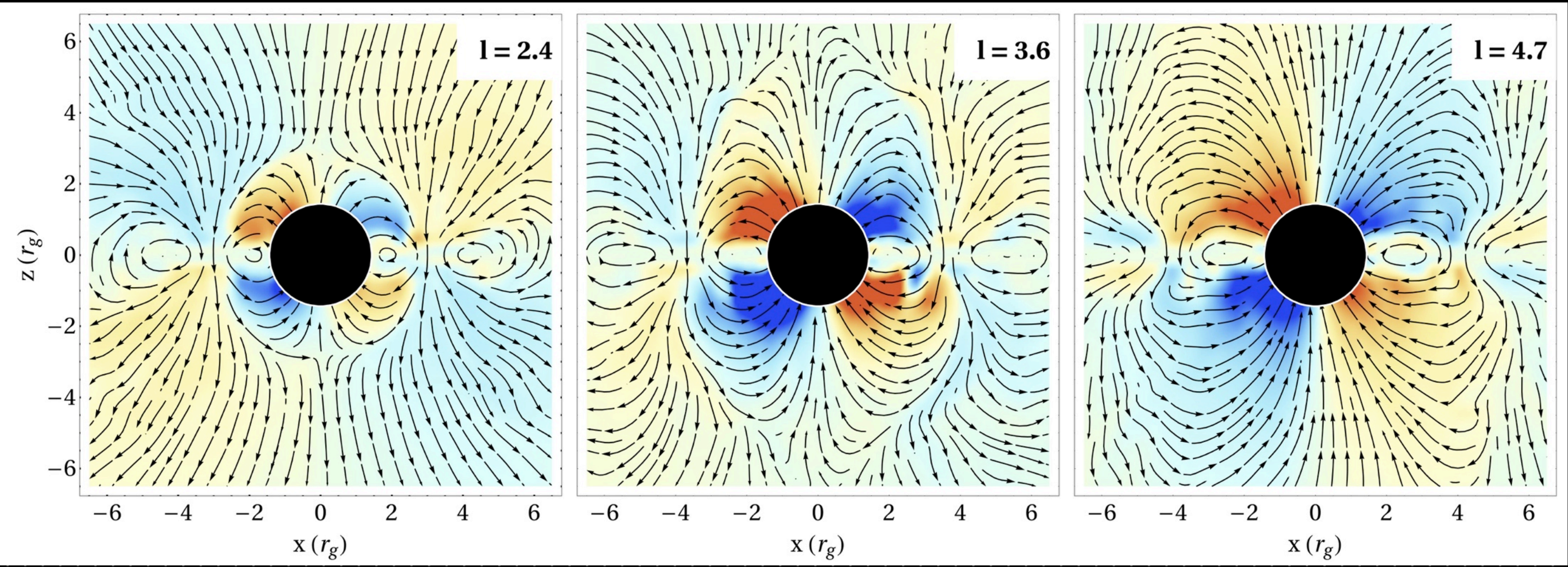

Lorentz factor

# Effect of resistivity

α=1

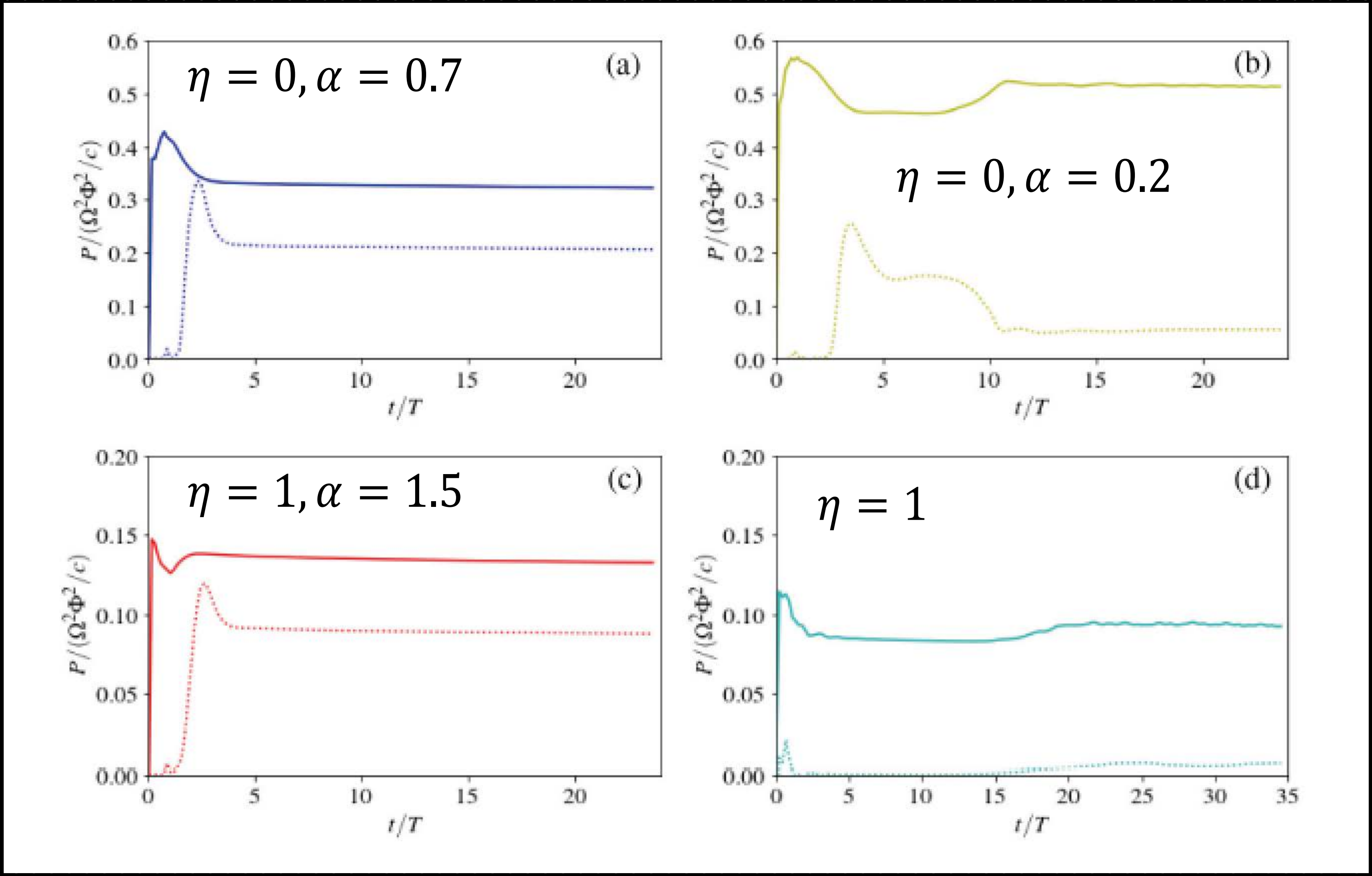


# Fully GR version (Mahlmann + 2020)



# Poynting flux

Solid lines: power from the membrane
dotted lines: power at a larger radius



# Summary of Yuan+19 results

- Inner loop relatively strong (large $\alpha$) → outflow
- Inner loop relatively weak (small $\alpha$) → dissipation by kink in the inner magnetosphere
- Inner loop very weak: stable, close configuration

# Mahlmann, Levinson, Aloy 2020

Motivation: How do magnetic jets dissipate their energy  at small scales?

# Dissipation of magnetized jets

Large scale (ordered) B fields:

efficient jet production (MAD, MCAF, etc.)

dissipation requires rapid growth of instabilities

Small scale B field:

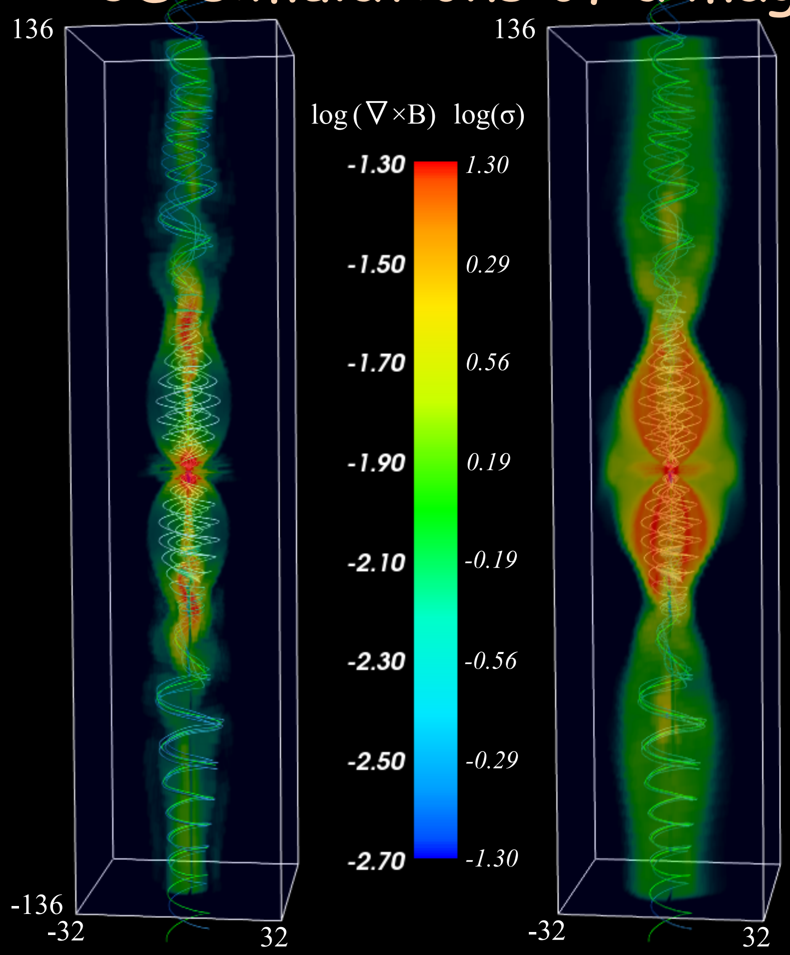
quasi-striped configuration (good for dissipation and loading)

Can relativistic jets form ?

# Dissipation of ordered field

## Small angle reconnection via CD kink inst.

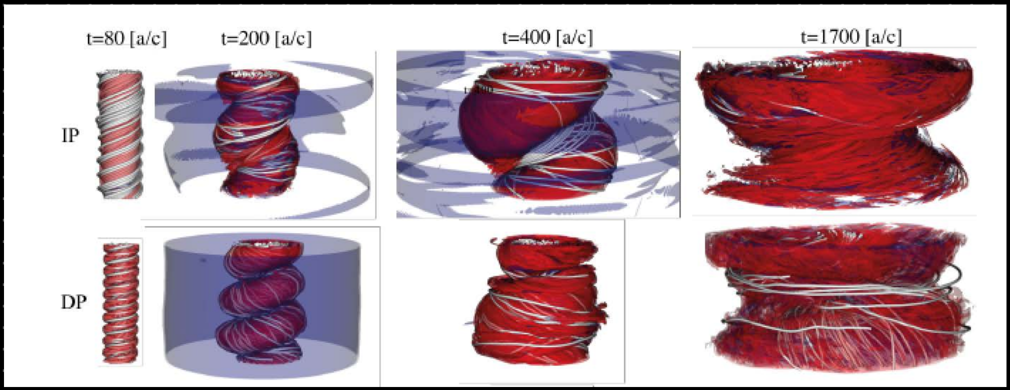
### 3D simulations of a magnetic jet propagating in a star



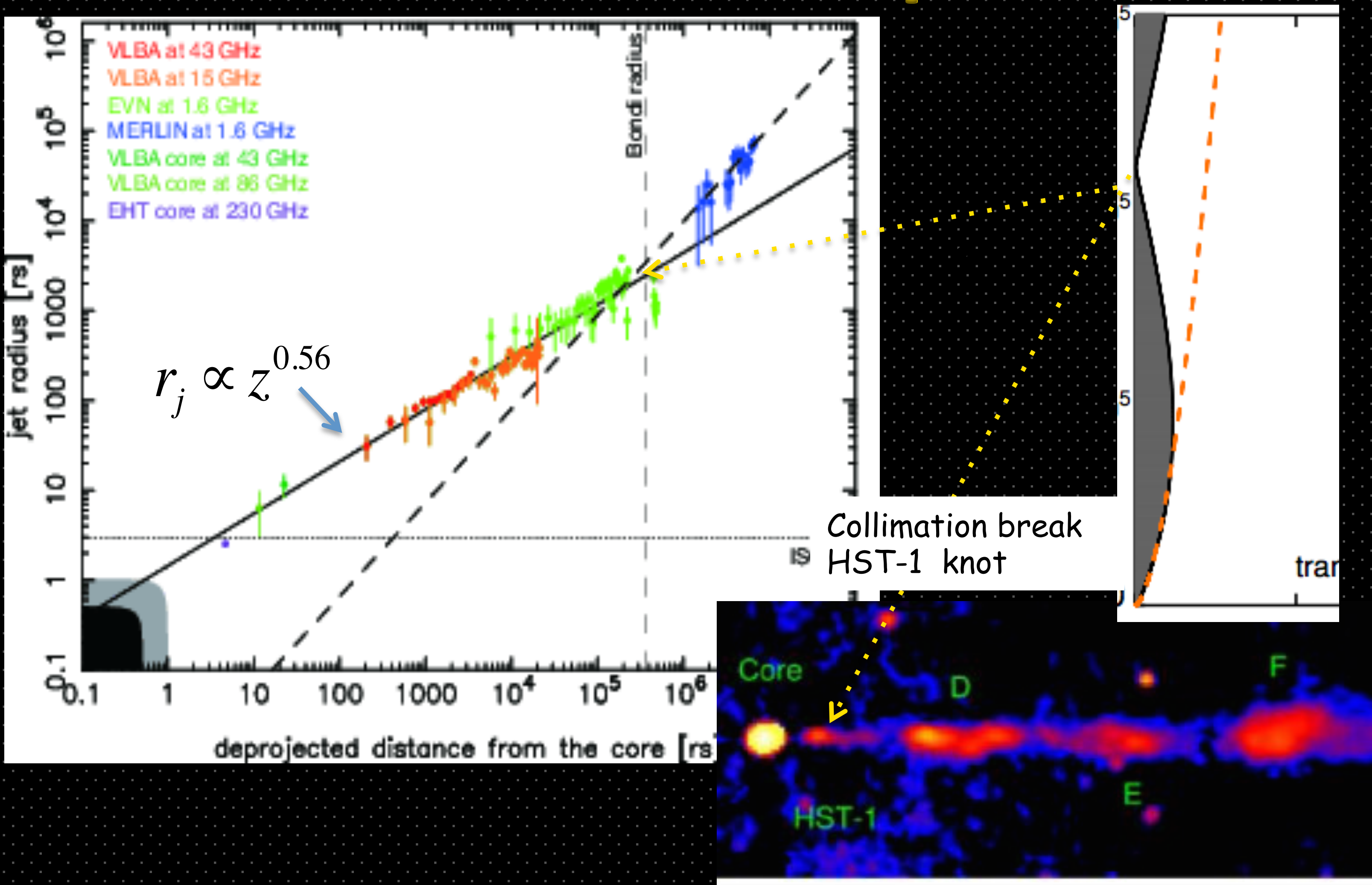

Bromberg + Tchekhovskoy '16

kink instability requires strong collimation. Develops fastest in a collimation nozzle (Mizuno+12, Bromberg+19, Davelaar+19)

CD kink experiment (Bromberg +19)

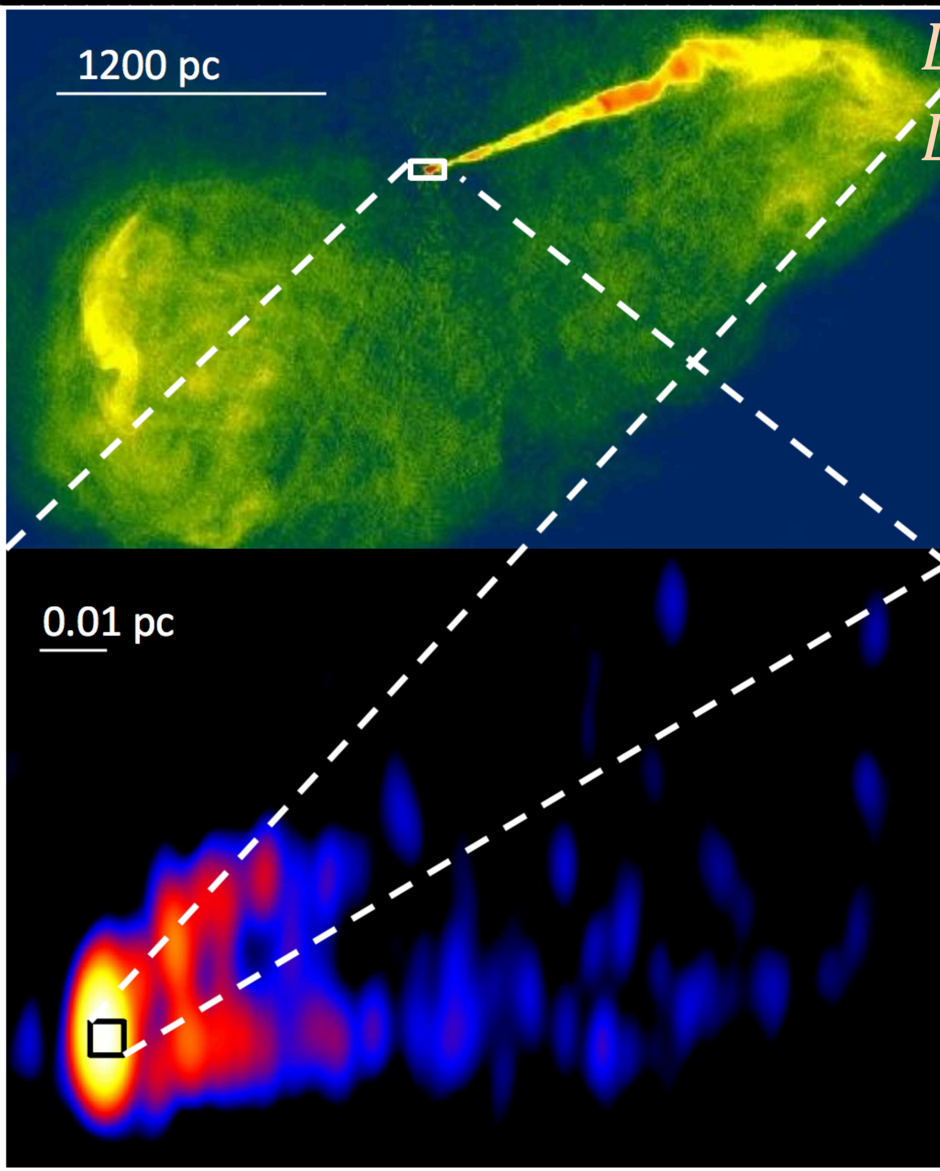


# M87 - collimation profile



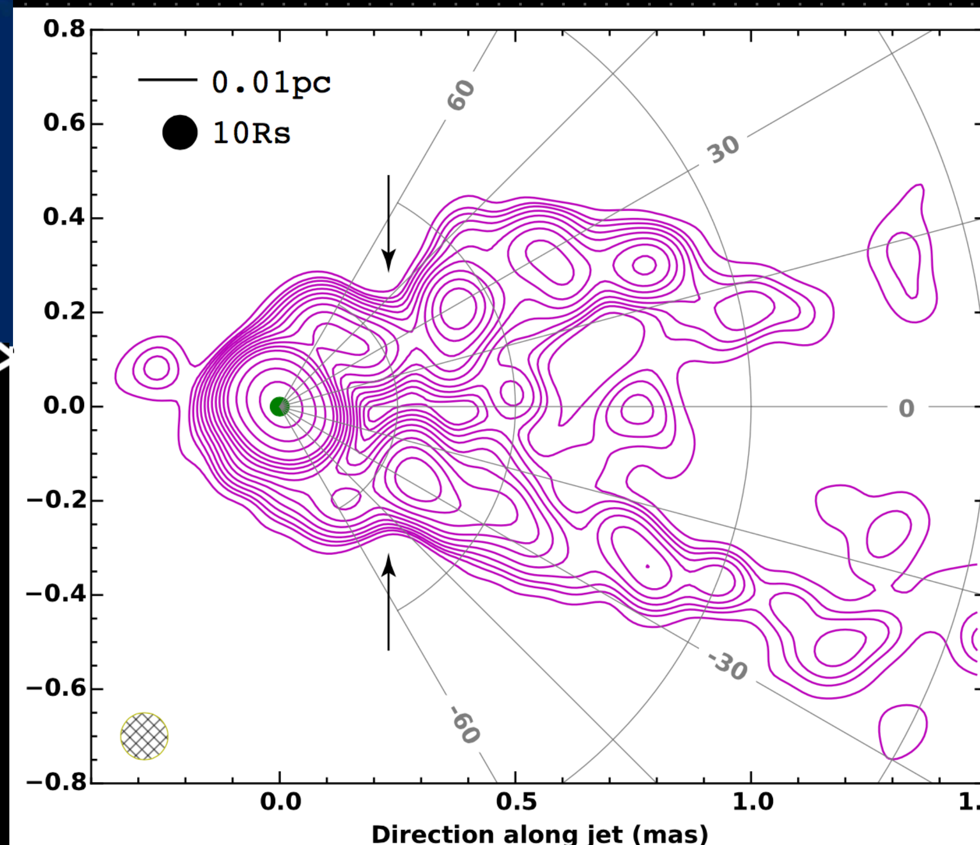

Jet is stable below the collimation break

# M87




$L_j \approx 10^{44}$ erg $s^{-1}$ (on kpc scales)

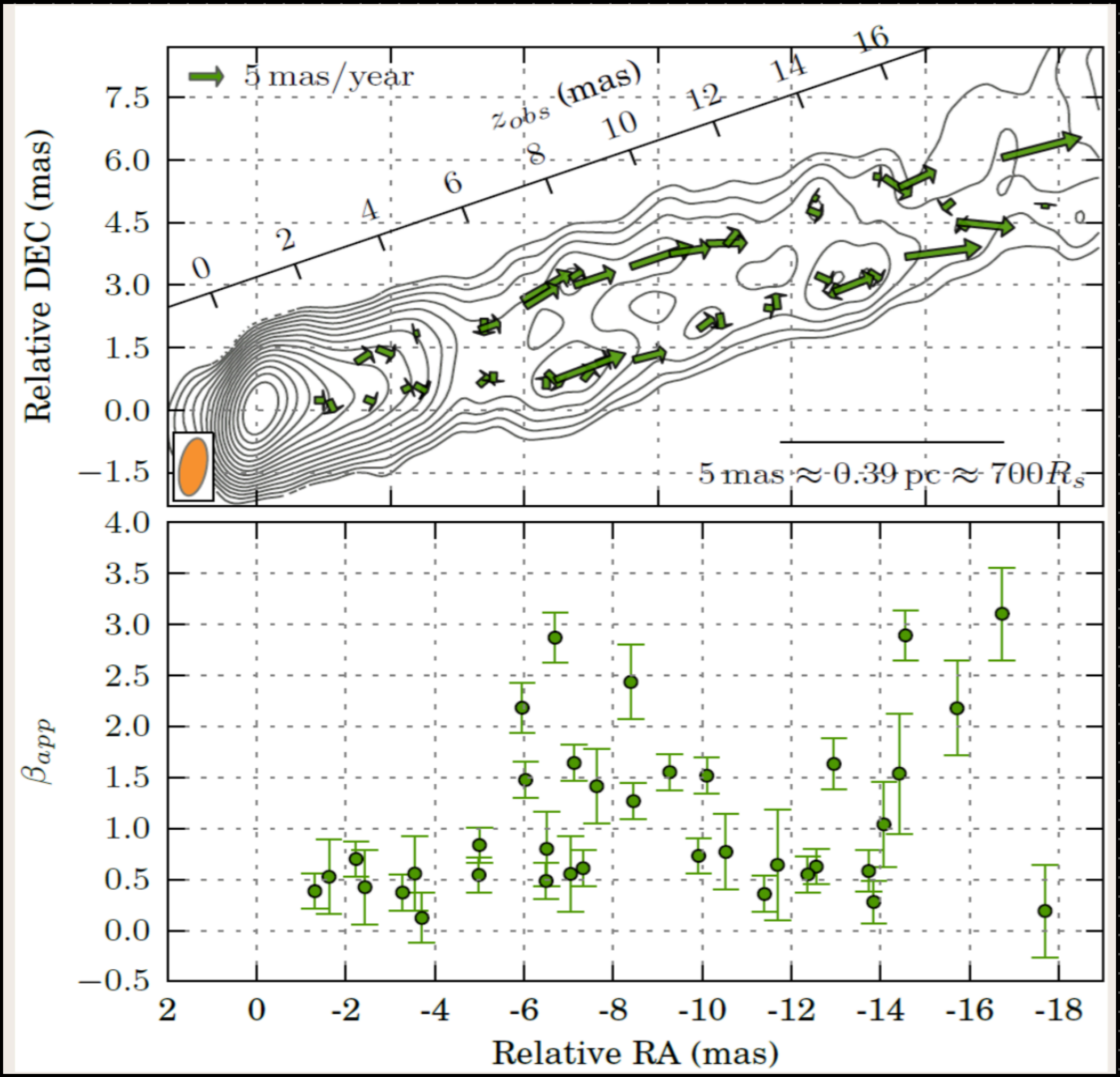
$L_{Bol} \approx 10^{42}$ erg $s^{-1}$




Hada + 2016

# Stratified flow

Mertens + 16



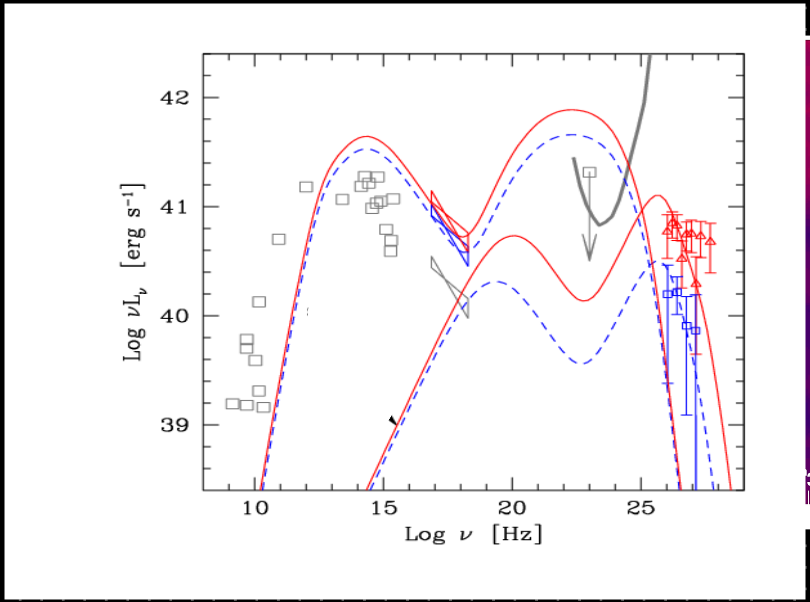
# M87- TeV emission

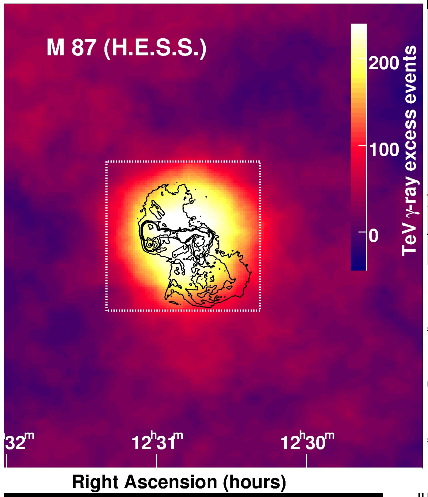
Strong flares observed in 2005, 2008, 2010

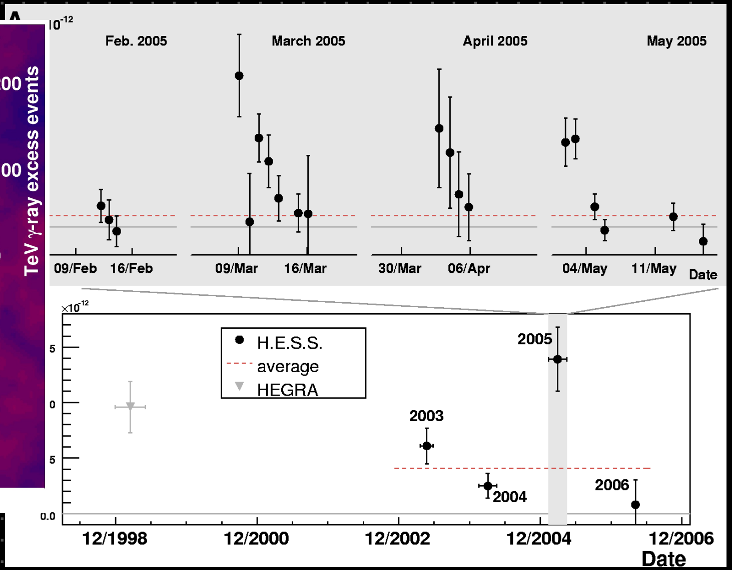
$L_j \approx 10^{43}\ \text{erg}\ s^{-1}, \quad L_\gamma \approx 10^{41}\ \text{erg}\ s^{-1}$

Variability time ≈ 1 day ~ $r_s$

TeV emission from inner region or a remote, small region?

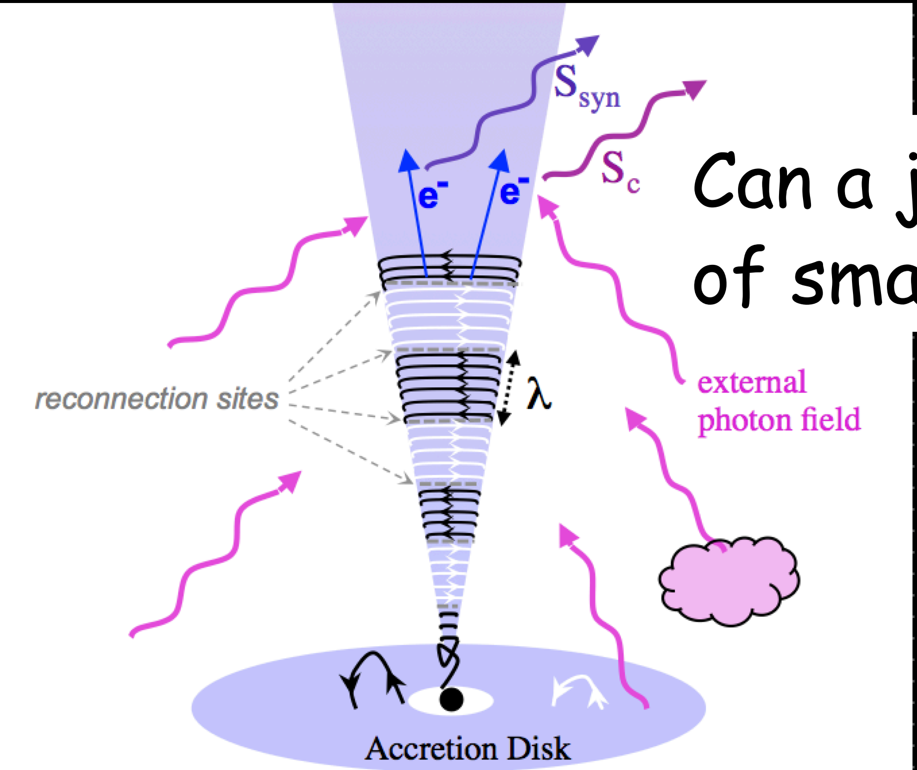


# quasi-striped jet

Reconnection of non-symmetric component



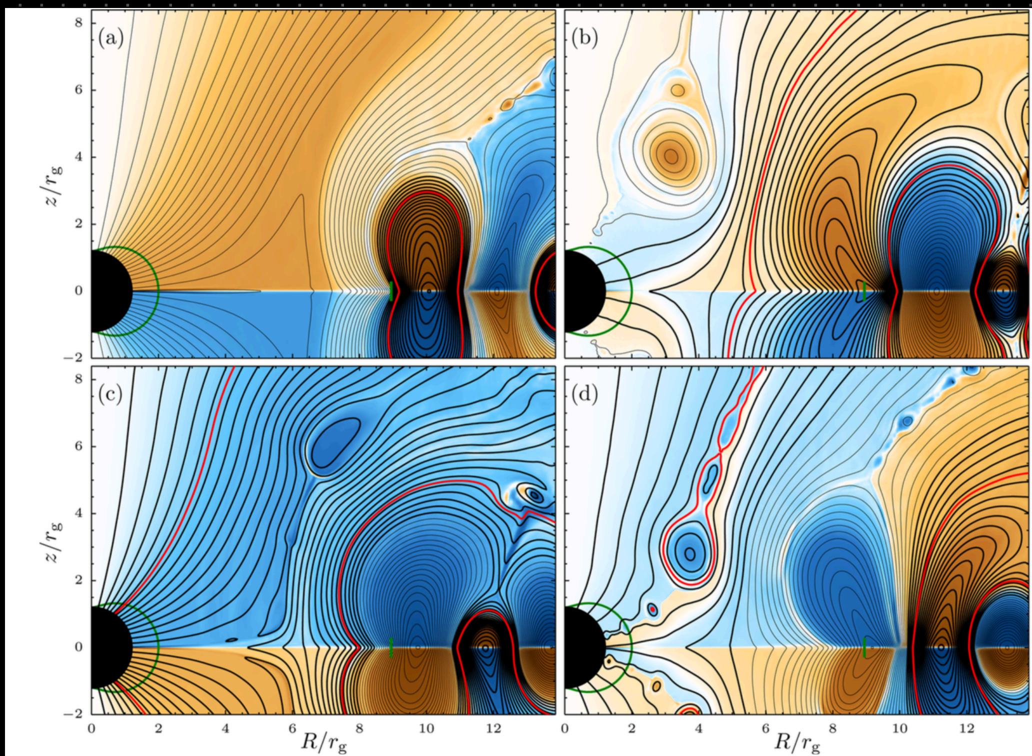

Can a jet form upon advection of small scale field?

Romanova + Lovelace 92
AL + Van Putten 97
Drenkhahn + Spruit '02
AL+Globus '16

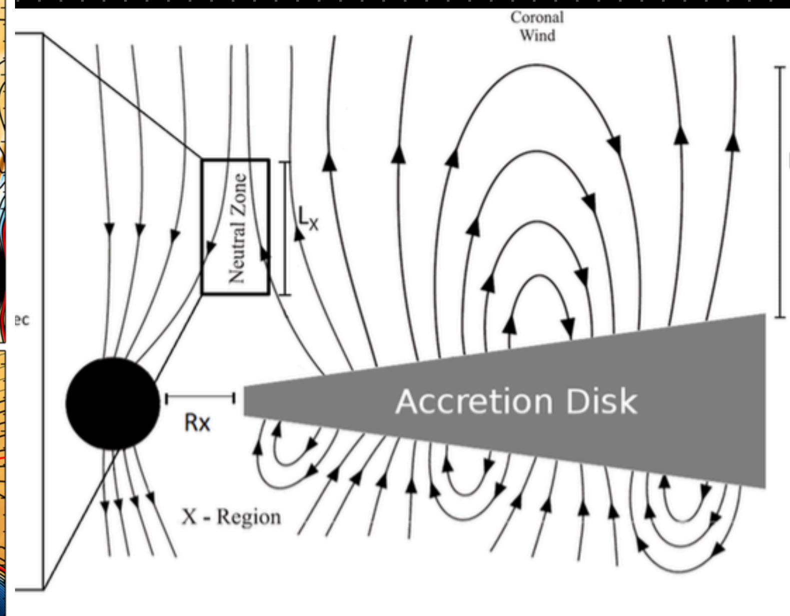
# Accretion of magnetic loops

Spruit, uzdenski, goodman

Reconnection can lead to electron acceleration in the jet + sheath. Potential site of VHE emission.




2D simulations by Parfrey + ‘15




Kadowaki, de Gouveia Dal Pino + ‘15

Van Putten + AL ’03

# Mahlmann, Levinson, Aloy 2020

## Fully 3D GRFFE

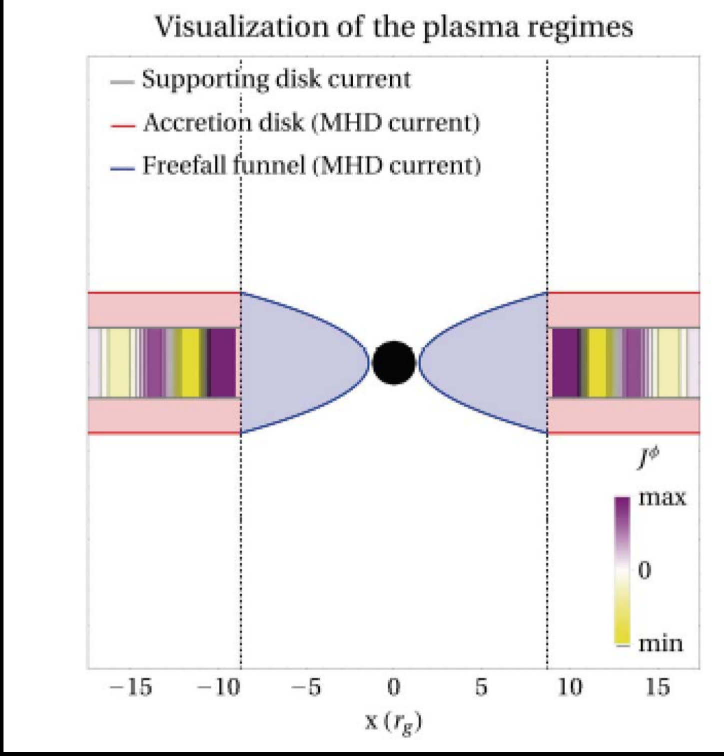
- Resistive disk extending from ISCO

  Keplerian angular velocity

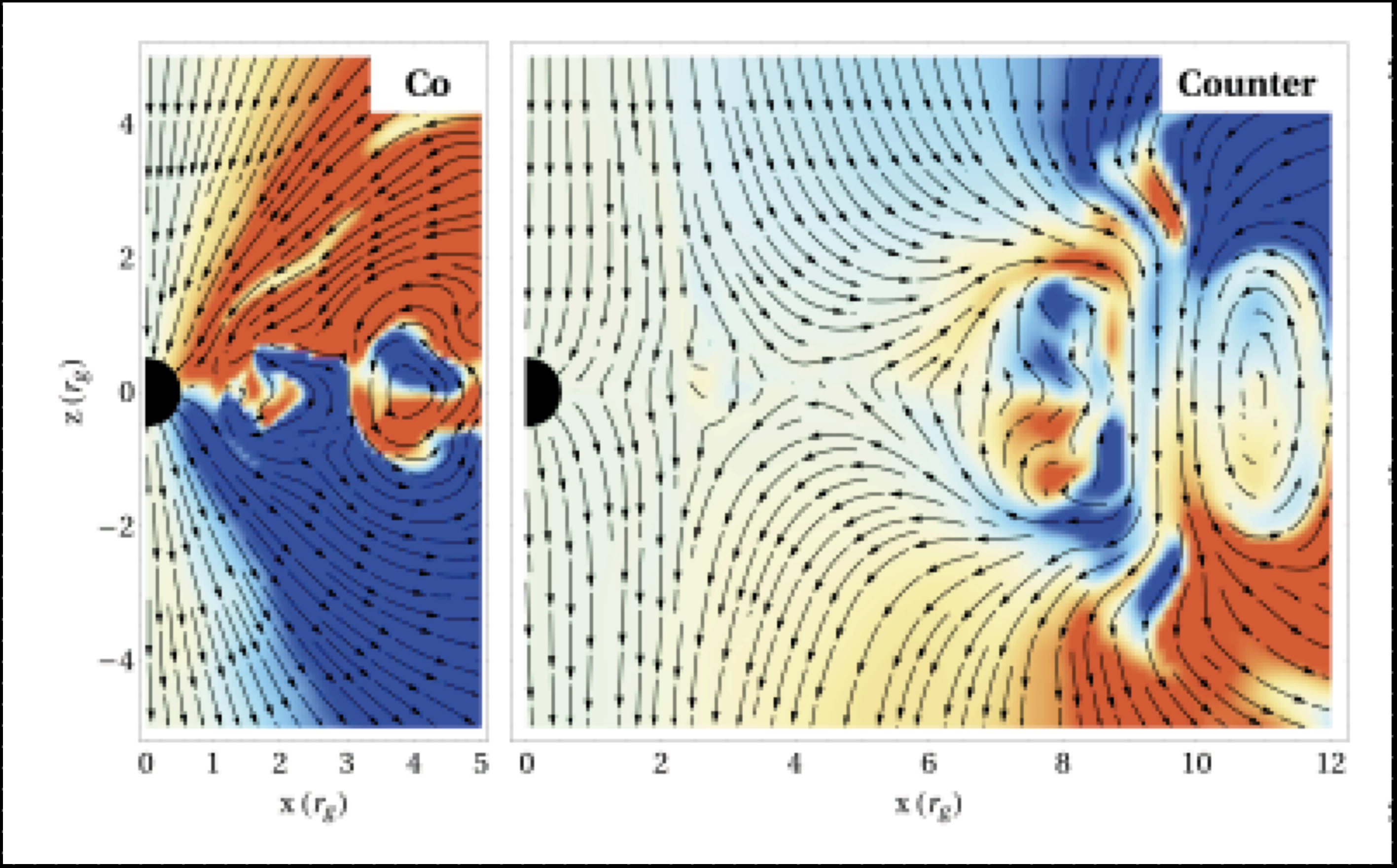
  prescribed radial velocity (accretion)

$$J^{\phi}_{\text{disk}}\,(r_c, t) = J_0 \times \cos\left(\pi \frac{r_c - r_{\text{ISCO}} + t v_0}{l}\right) \times \frac{\alpha}{\sqrt{g}\sqrt{g_{rr}\, g_{\phi\phi}}}$$

- Field advection inside ergosphere
- BH spin: a=0.9



# Initial state



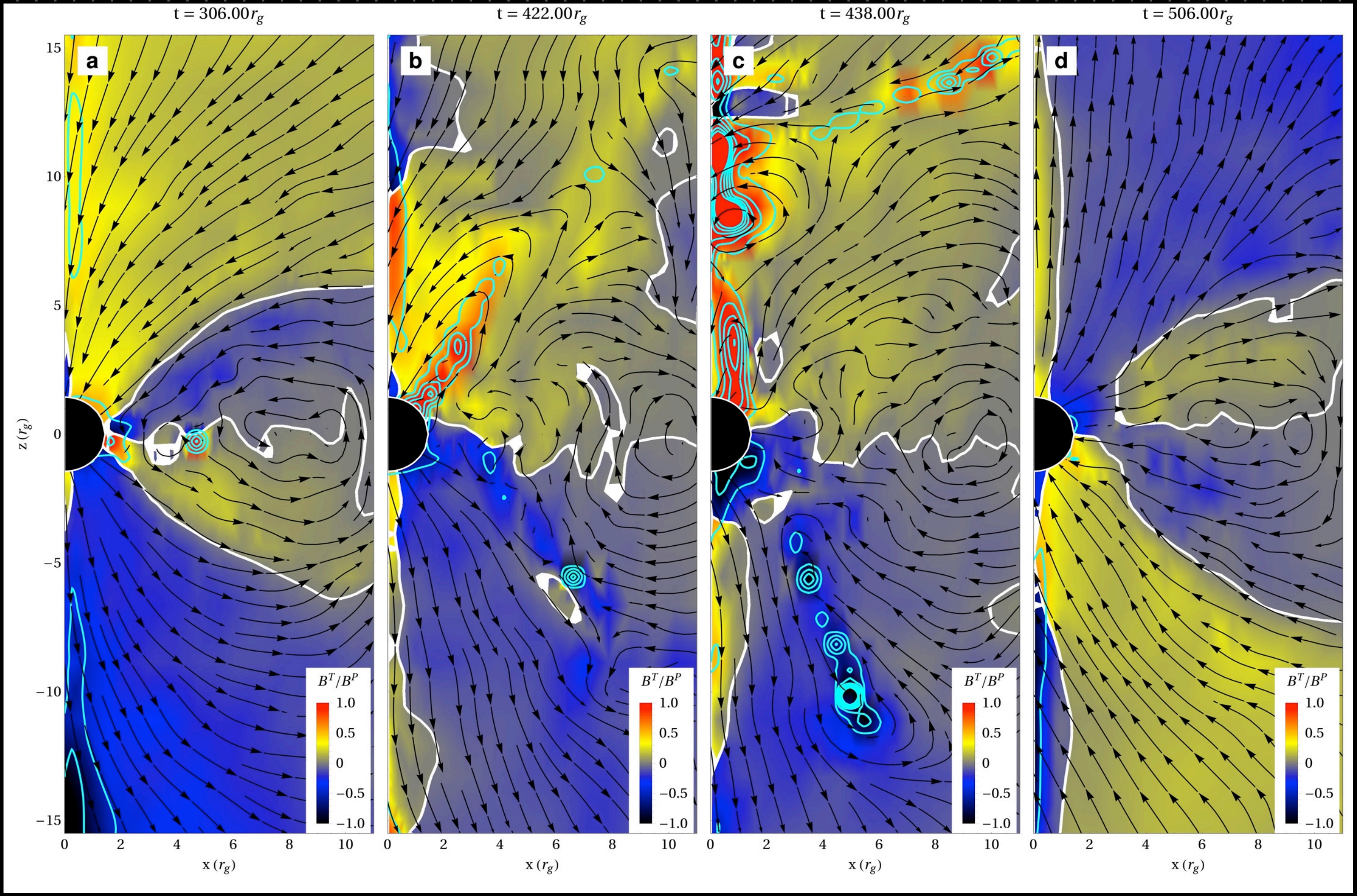
# Dynamical evolution

# Counter-rotating disk

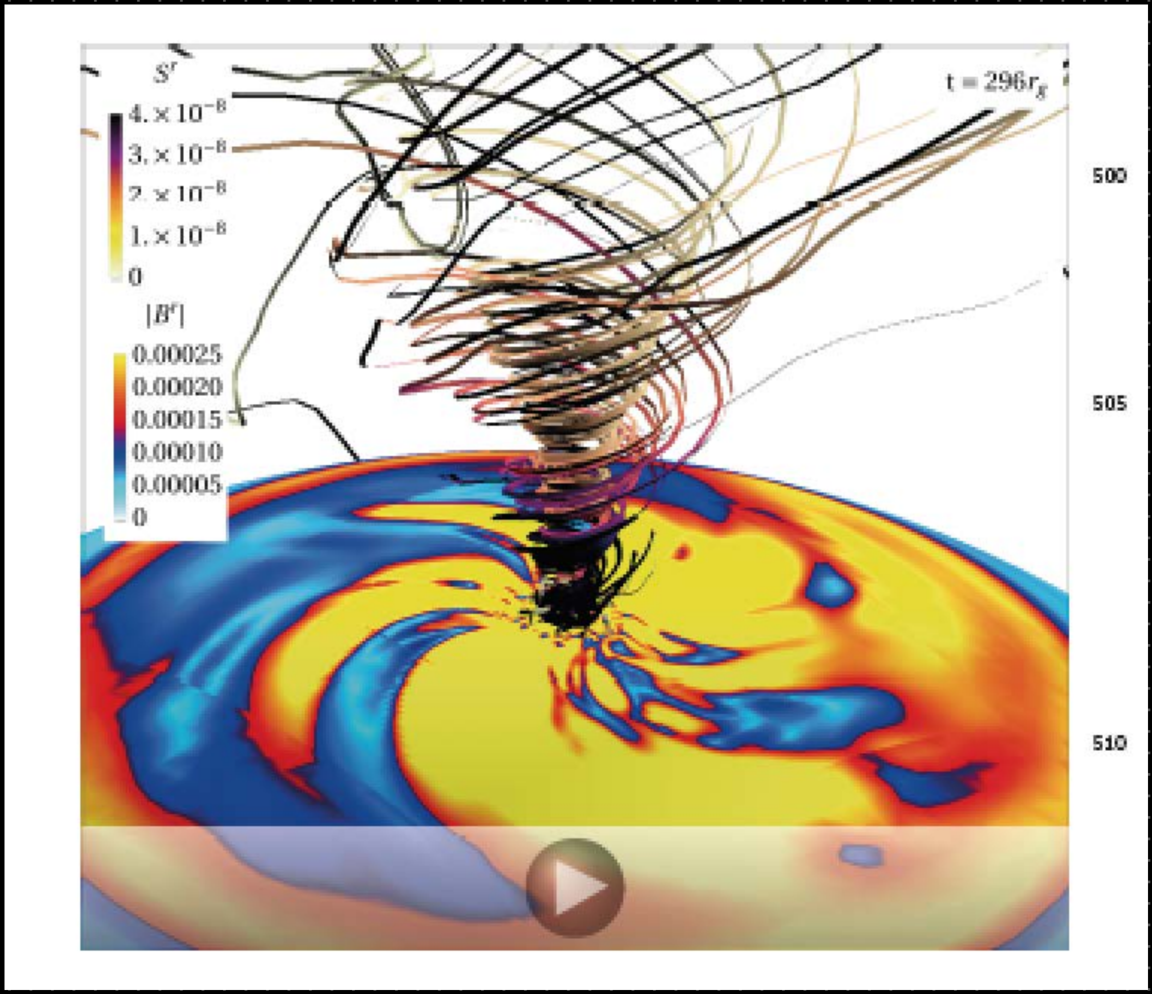
Efficient extraction

Dissipation & turbulence

Efficient extraction



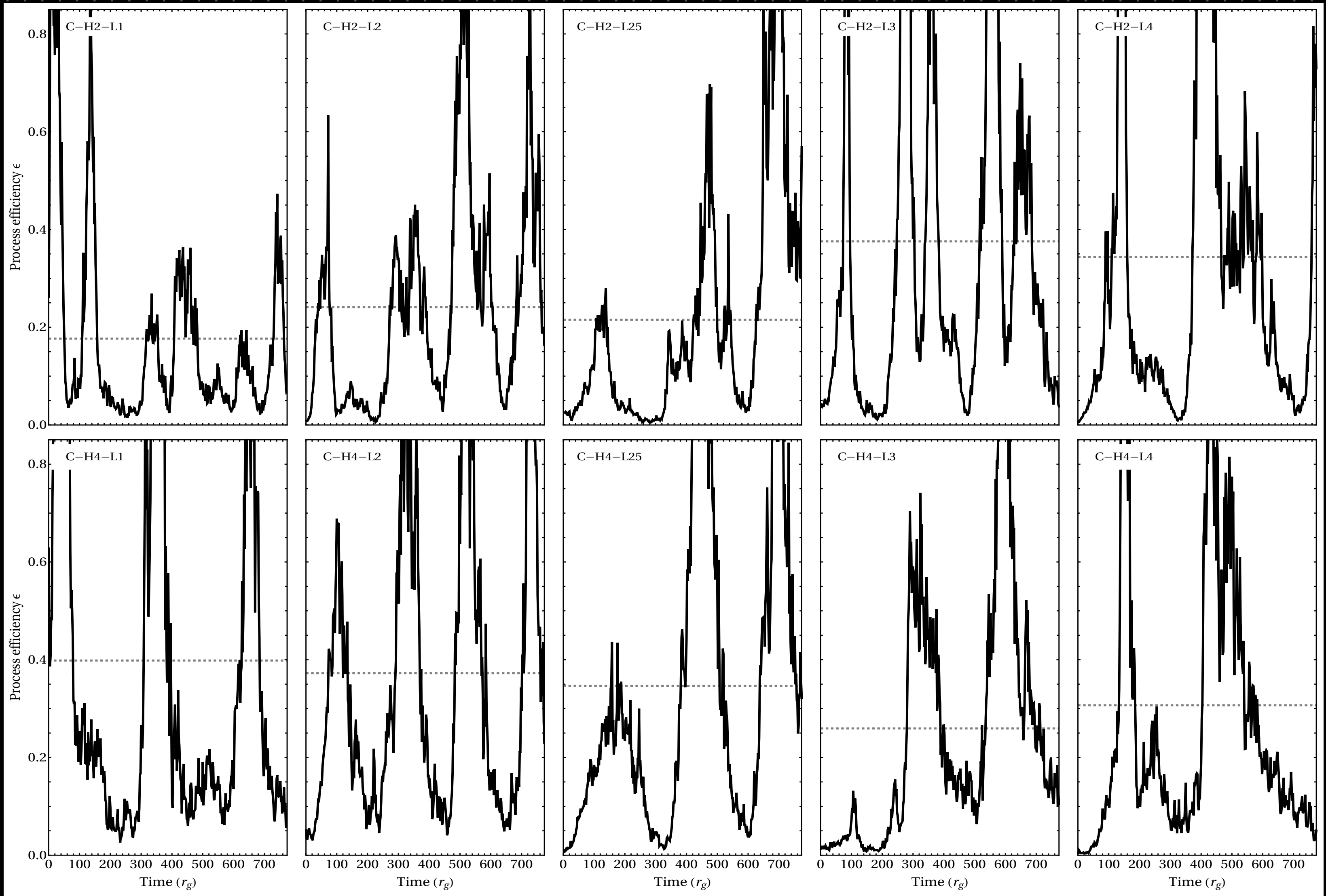
# 3D impression of accretion of one flux tube



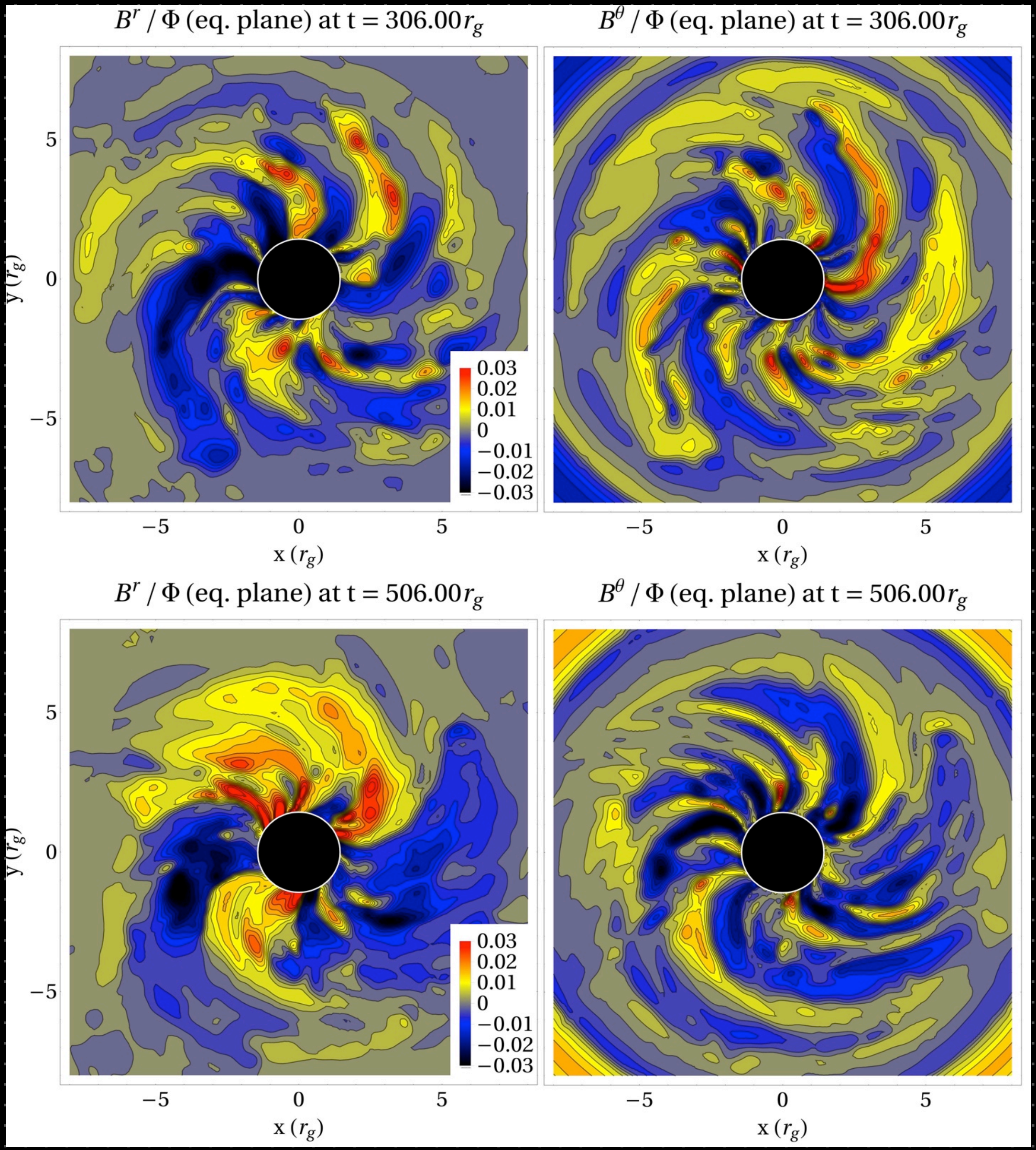

Colored ribbons represent outgoing Poynting flux

# Emergent power from BH: counter-rotating disk

Each panel corresponds to a different model (different loop size and height)



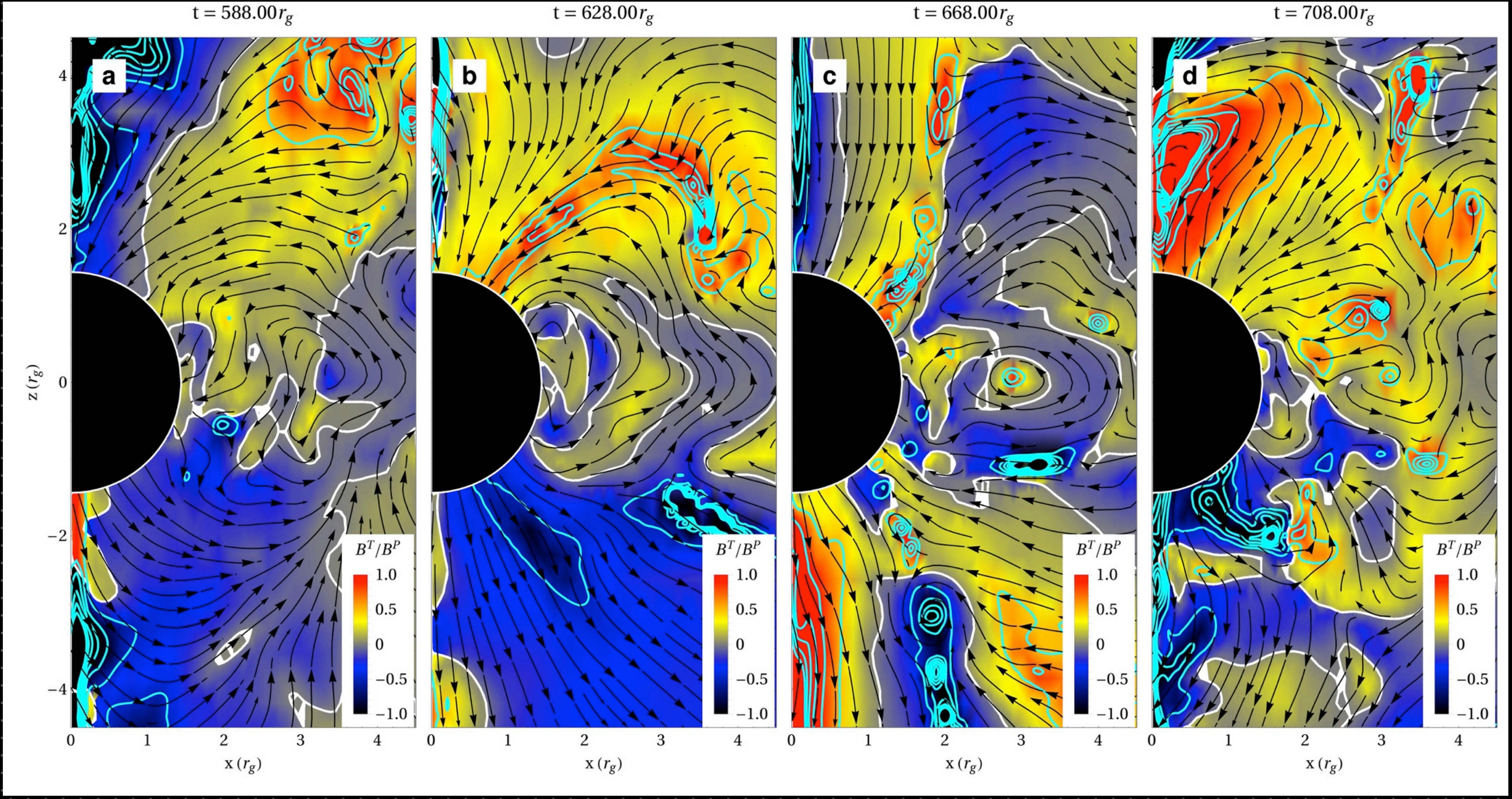
# Poloidal field components on eq plane



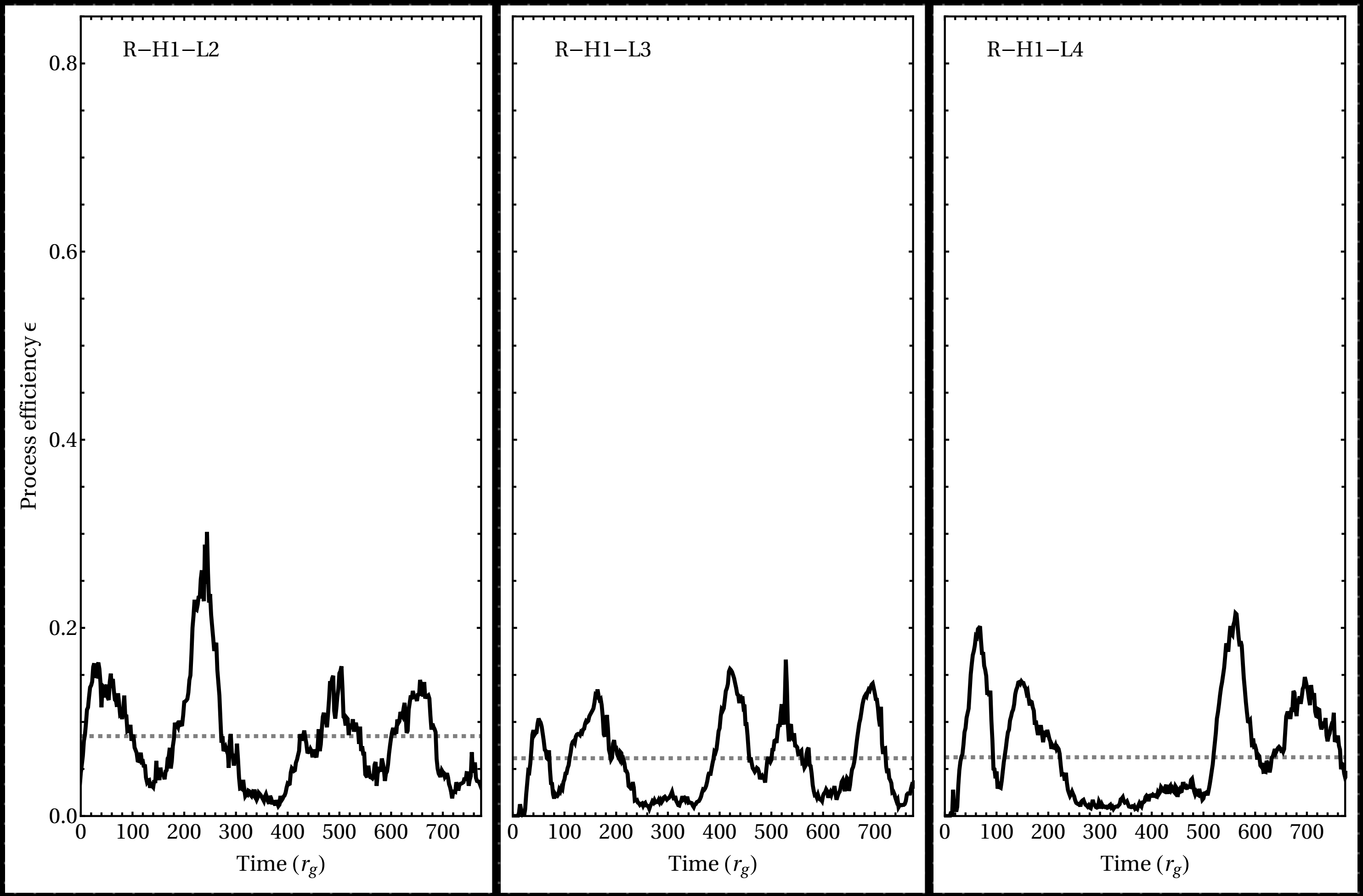

Development of 3D structures during advection of magnetic field

# Co-rotating disk

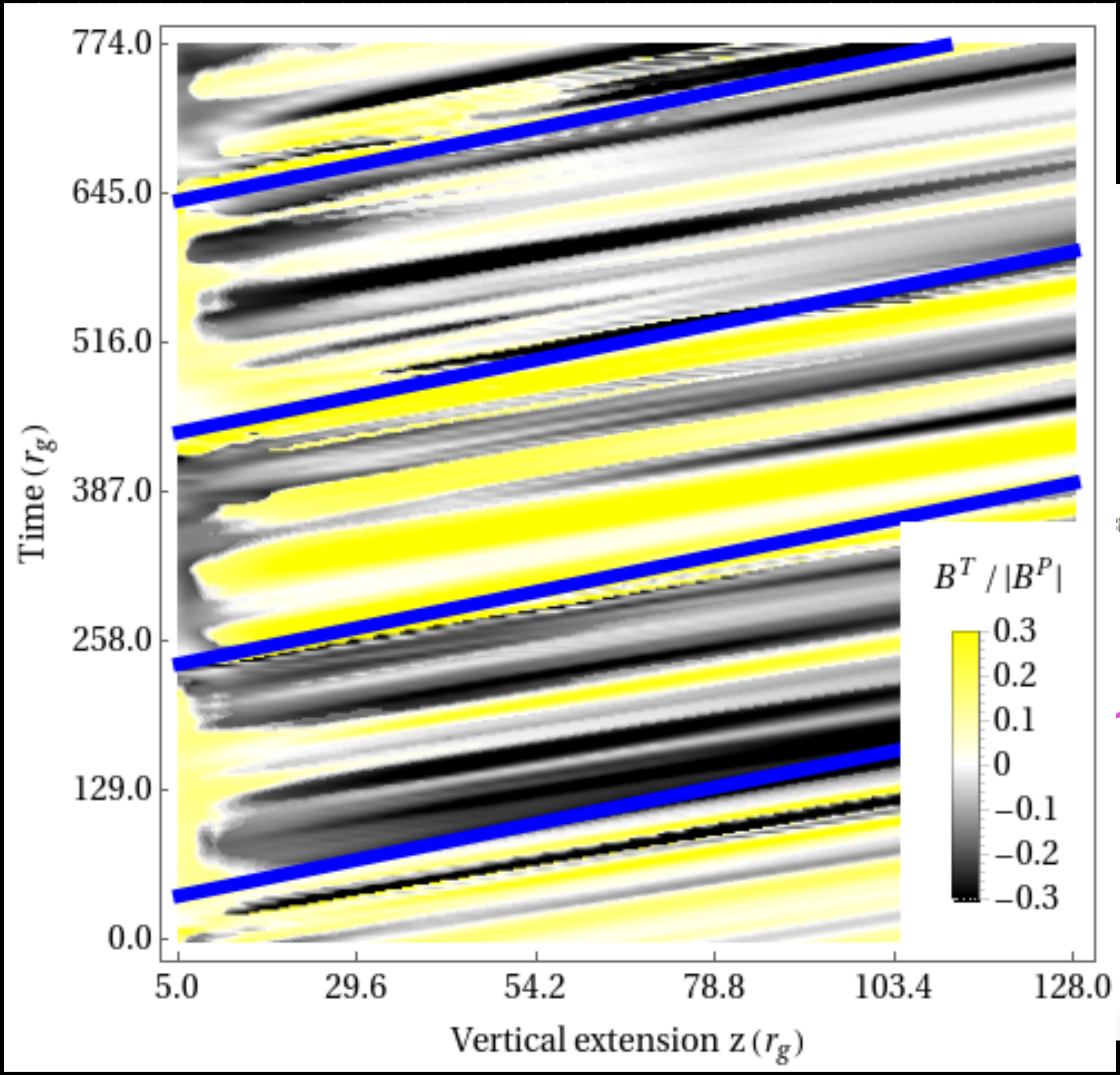
Closed inner loop
Opening up
Jet launching
Turbulent rearrangement

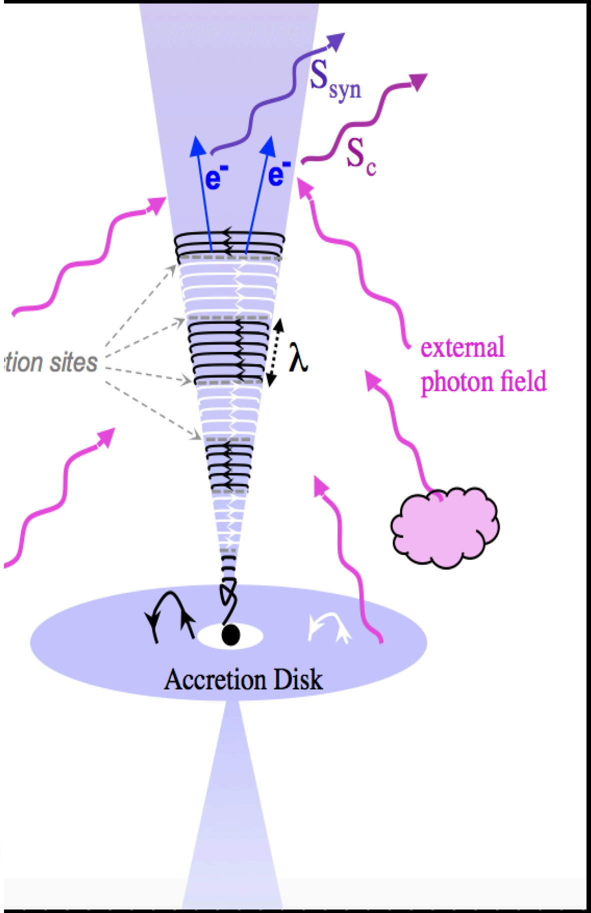


# Emergent power: corotating disk



# Emergence of a striped jet



# Summary

- Small scale dipolar field can lead to substantial BZ outflows
- Larger power for counter-rotating disk (but needs more study)
- Enhanced dissipation in current sheets due to interaction of consecutive loops (jet sheath).
- Striped relativistic jet in polar region (good for dissipation)

Comparison with GRMHD simulations is underway