Plasma injection, sparks and HE emission in BH magnetospheres

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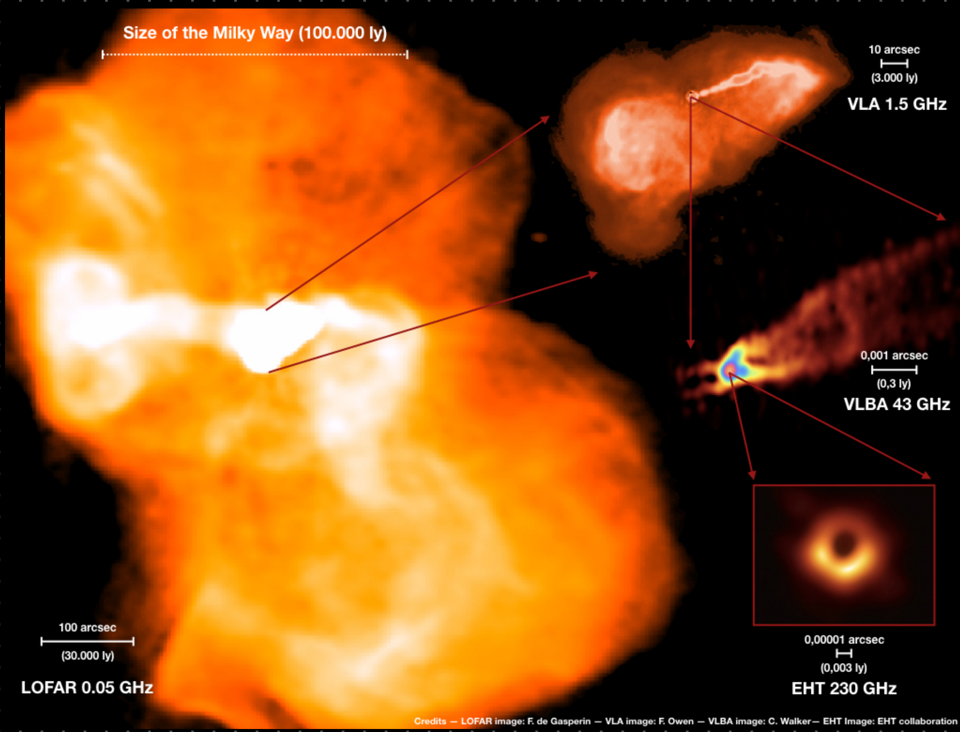
M87



GRMHD simulations

Tchekhovskoy + McKinney 12

Limitations of GRMHD simulations

- Can't handle well force-free regions, particularly in dissipative regions
- Artificial plasma injection (floor density)
- No microphysics
- Limited initial states
- No radiation processes
- Runtime, box size, resolution

Open quastions

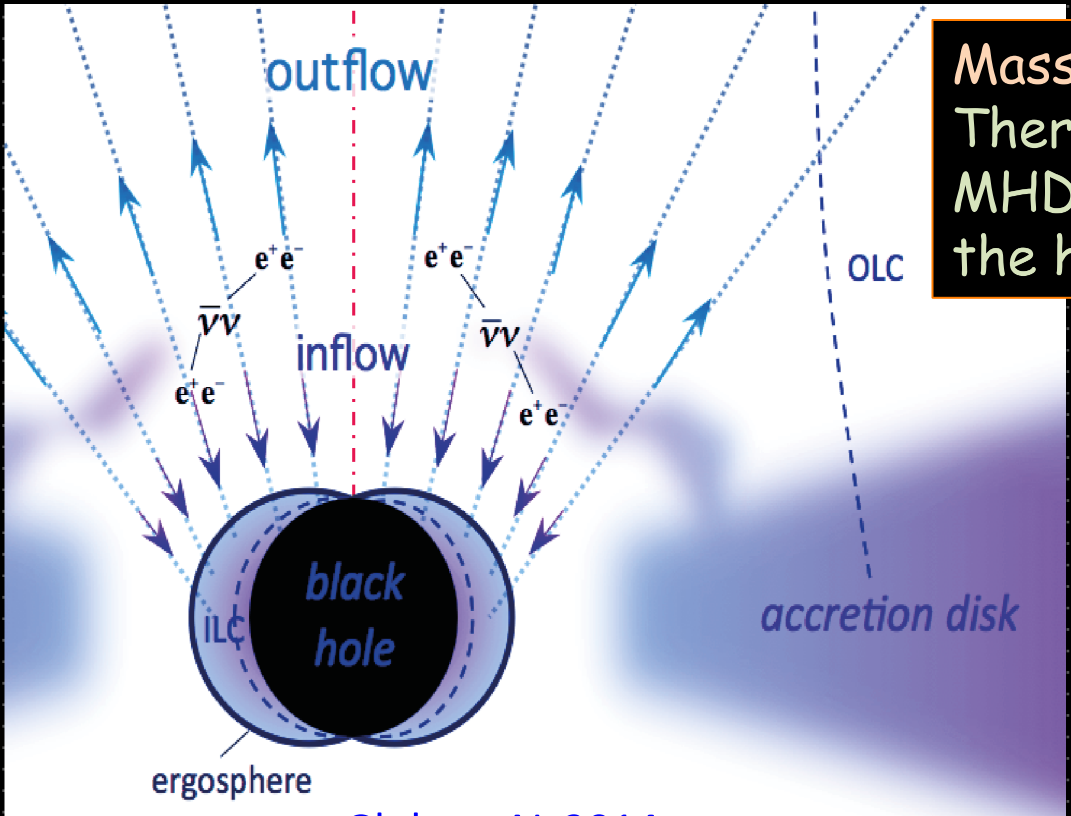
Formation of jets is reasonably well understood. But!

- What origin of plasma source in the magnetosphere? (external pp, spark gap, etc)
- What is the dissipation mechanism?

I. Plasma production and activation of BH outflows

Where plasma should be injected?

- plasma source between inner and outer Alfven surfaces
- escape time ≈ few r_g/c



Globus+AL 2014

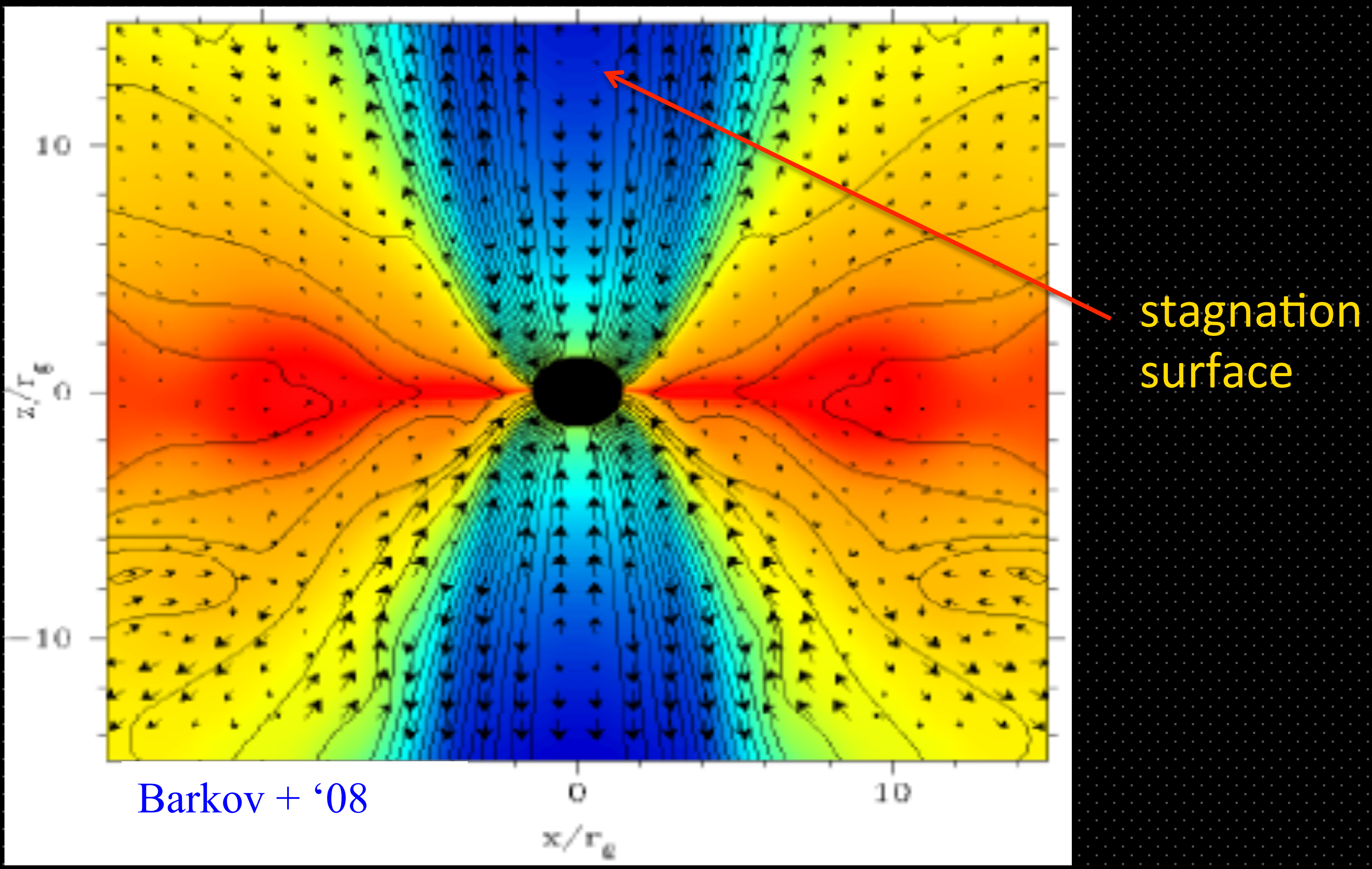
Mass flux not conserved !
There can be no continuous ideal MHD solution that extends from the horizon to infinity.

$\gamma\gamma \rightarrow e^{\pm}$ in AGNs

$\nu\nu \rightarrow e^{\pm}$ in GRBs

mass loading ?

A snapshot from a simulation showing streamlines.



How much plasma is needed?

Charge density needed to screen out E field:

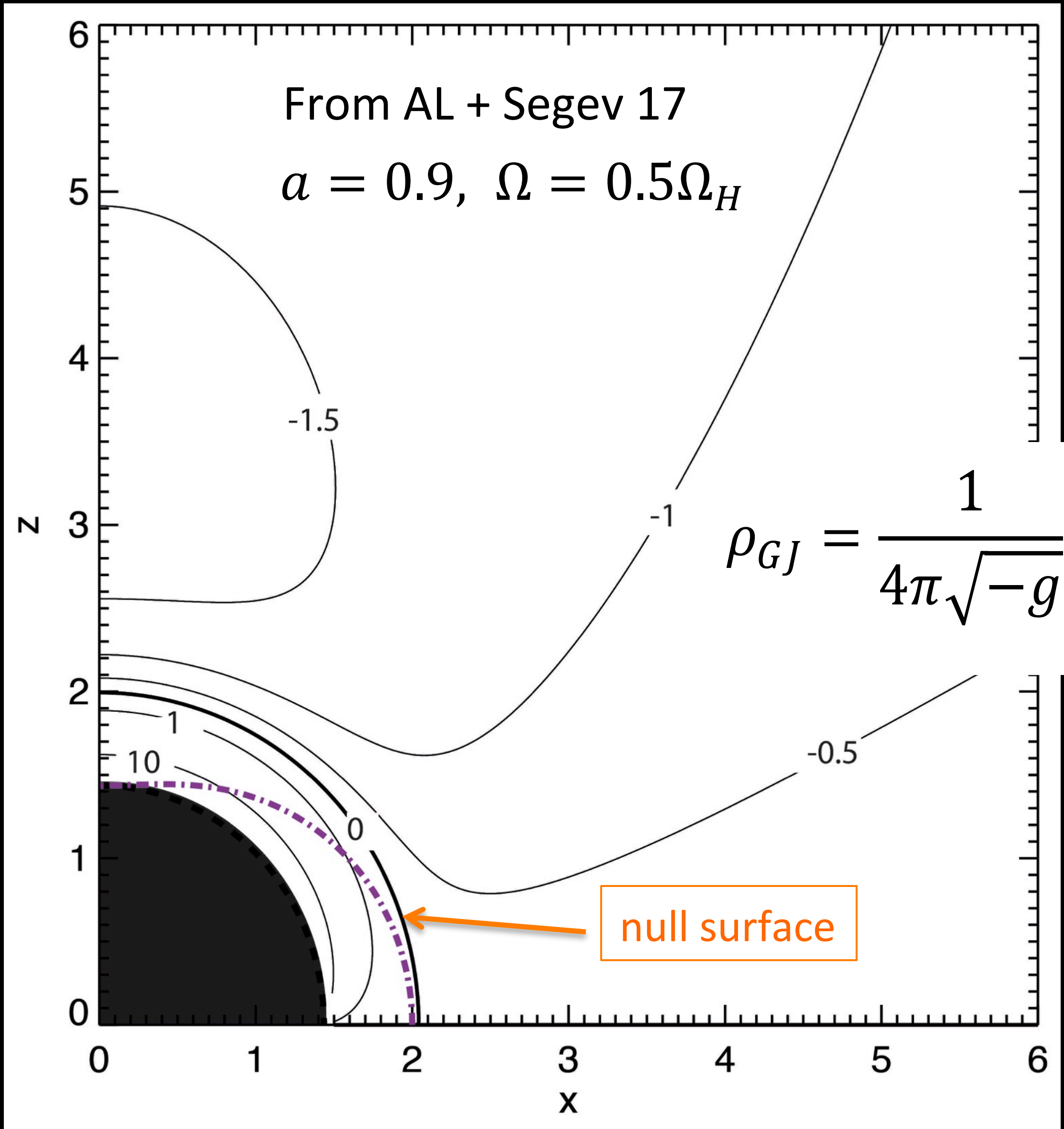
$$\vec{E}' = \gamma(\vec{E} + \vec{v}\times\vec{B}) = 0; \quad \vec{v} = \vec{\Omega}\times\vec{r}$$

$$\rho_e = \frac{\nabla\cdot\vec{E}}{4\pi} = -\frac{\nabla\cdot(\vec{v}\times\vec{B})}{4\pi} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi} \equiv \rho_{GJ}$$

Plasma density must satisfy: $\boldsymbol{n > \rho_{GJ}/e}$

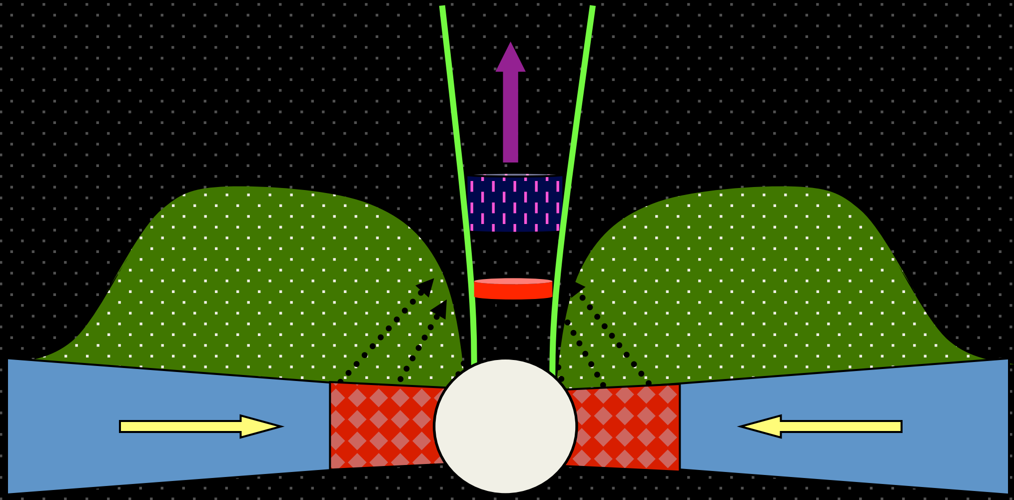
Otherwise the magnetospere becomes charge starved, $\vec{\boldsymbol{E}} \cdot \vec{\boldsymbol{B}} \neq \boldsymbol{0}$

GJ density in Kerr geometry



$$\rho_{GJ} = \frac{1}{4\pi\sqrt{-g}}\partial_\mu\left[\frac{\sqrt{-g}\,g^{\mu\nu}}{\alpha^2}(\omega-\Omega)F_{\nu\varphi}\right]$$

How to produce the required charge density?



- Protons from RIAF ?
- Protons from n decay ?
- $e^{\pm}$ from $\gamma\gamma$ annihilation ?
- Other source ?

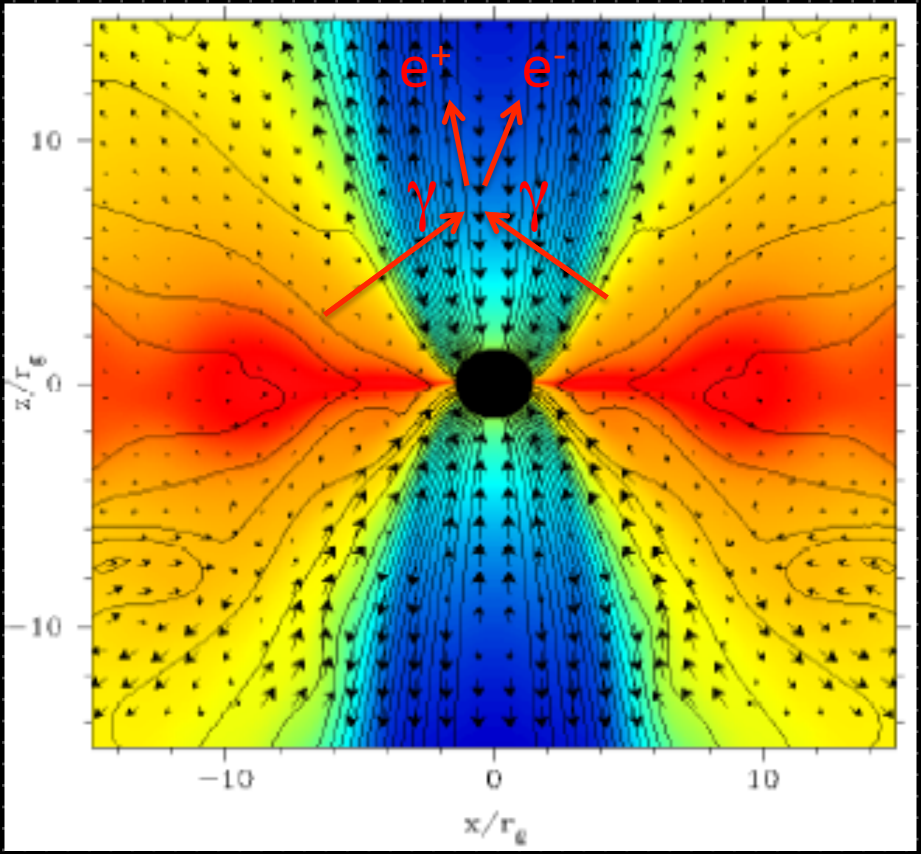
➢ Protons have to cross magnetic field lines. Diffusion length over accretion time extremely small.

➢ instabilities or field reversals. But intermittent spark gaps may still form.

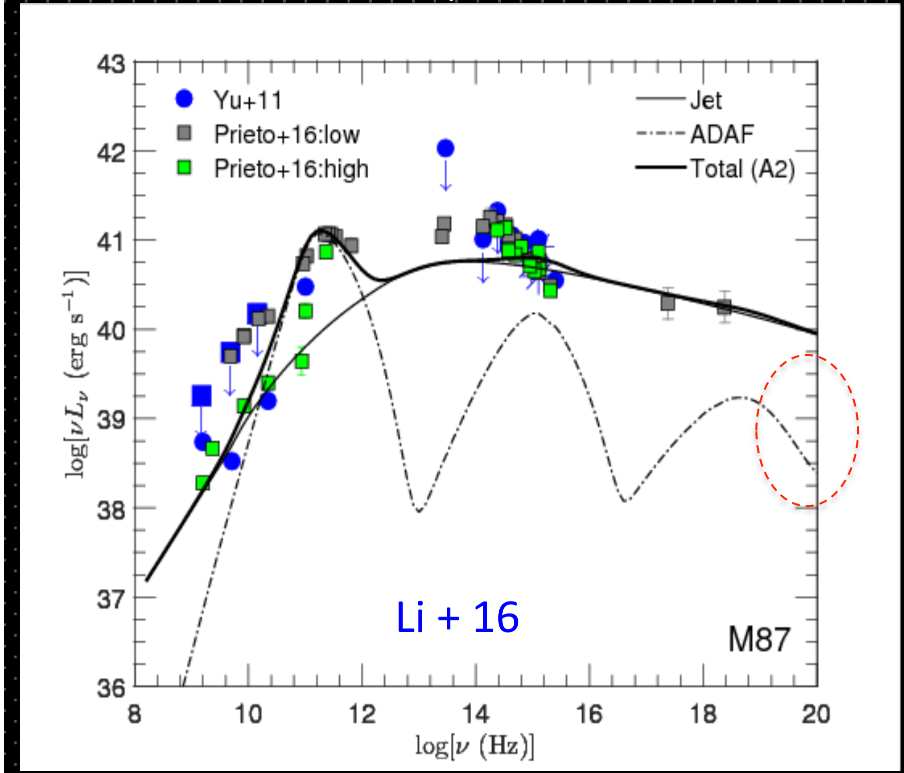
Direct pair injection by $\gamma\gamma \rightarrow e^+ e^-$

Requires emission of MeV photons:

- Low accretion rates: from hot accretion flow
- High accretion rate: from corona ?

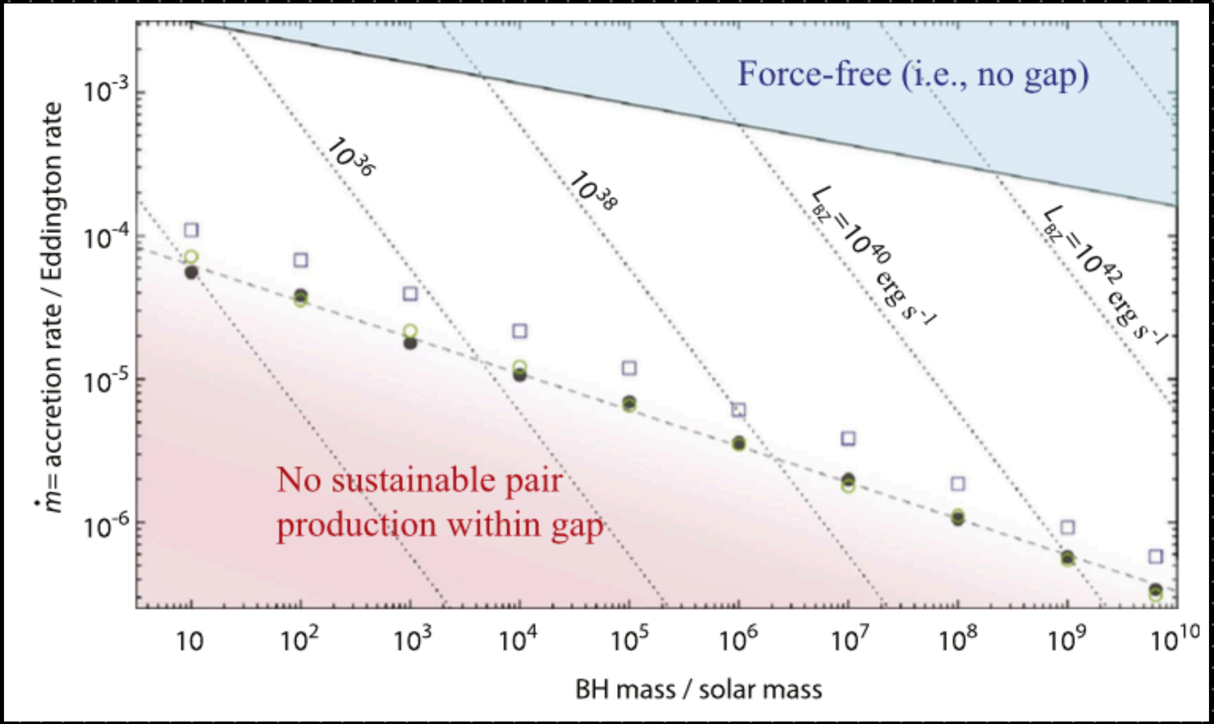


Example: M87



Direct pair injection

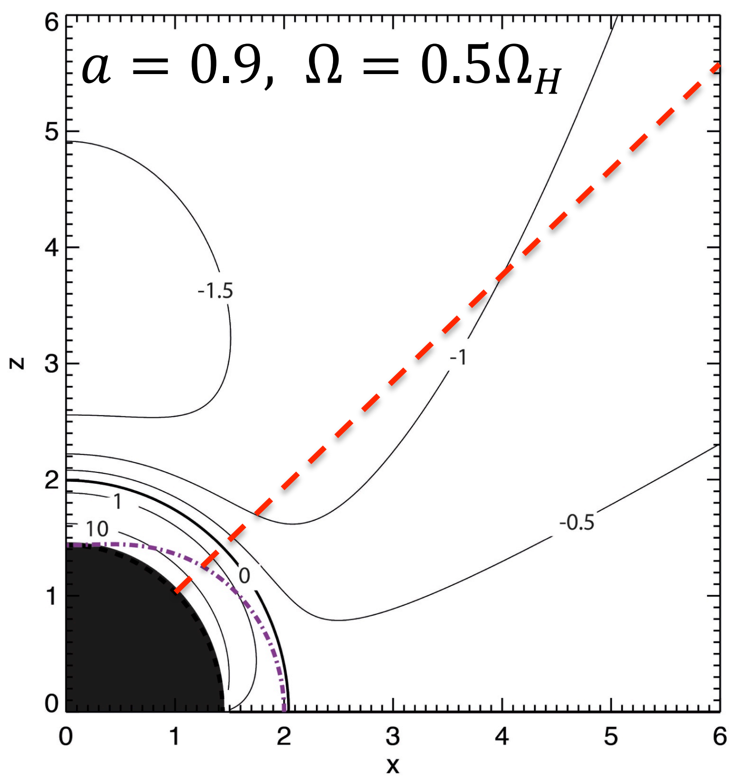
- Low accretion rates (RIAF): AC may be hot enough to produce gamma-rays above threshold (Levinson +Rieger 11, Hirotani + 16)

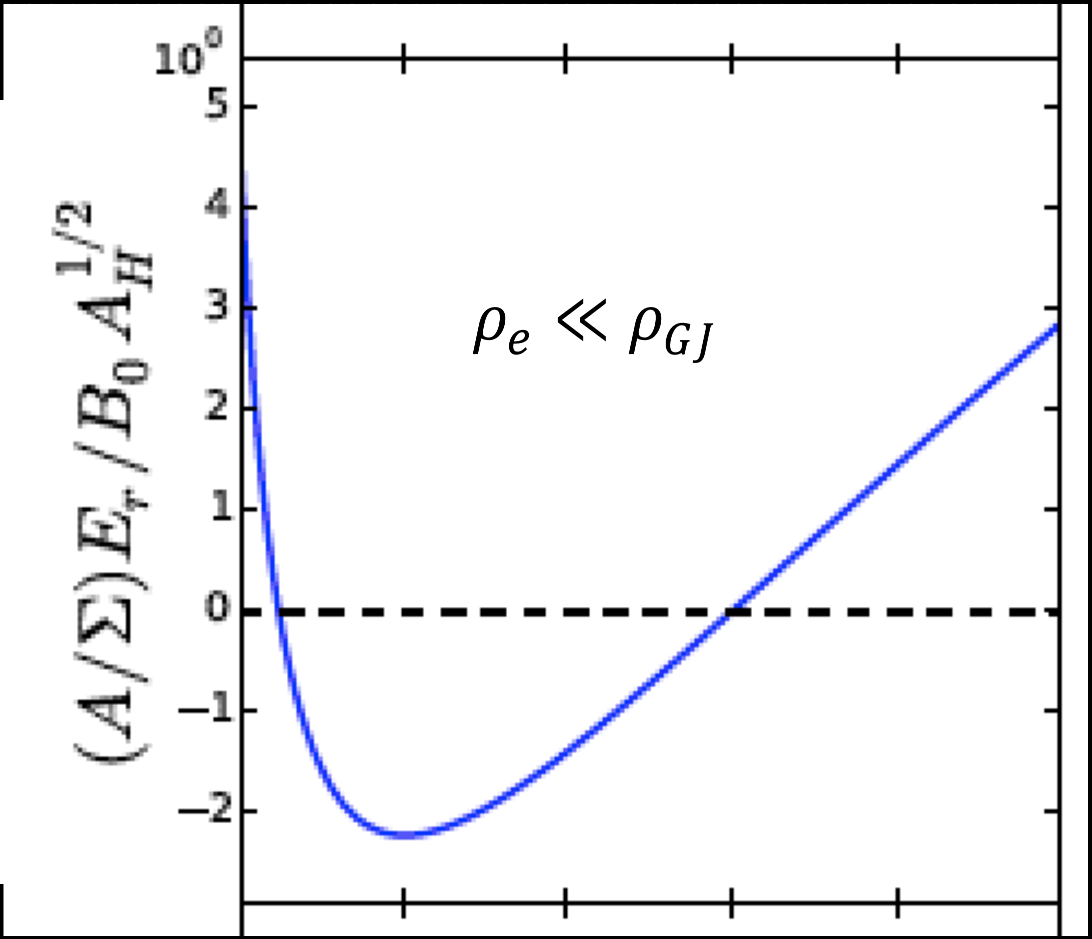


Conditions for gap formation (From Hirotani+ 16)

Starvation

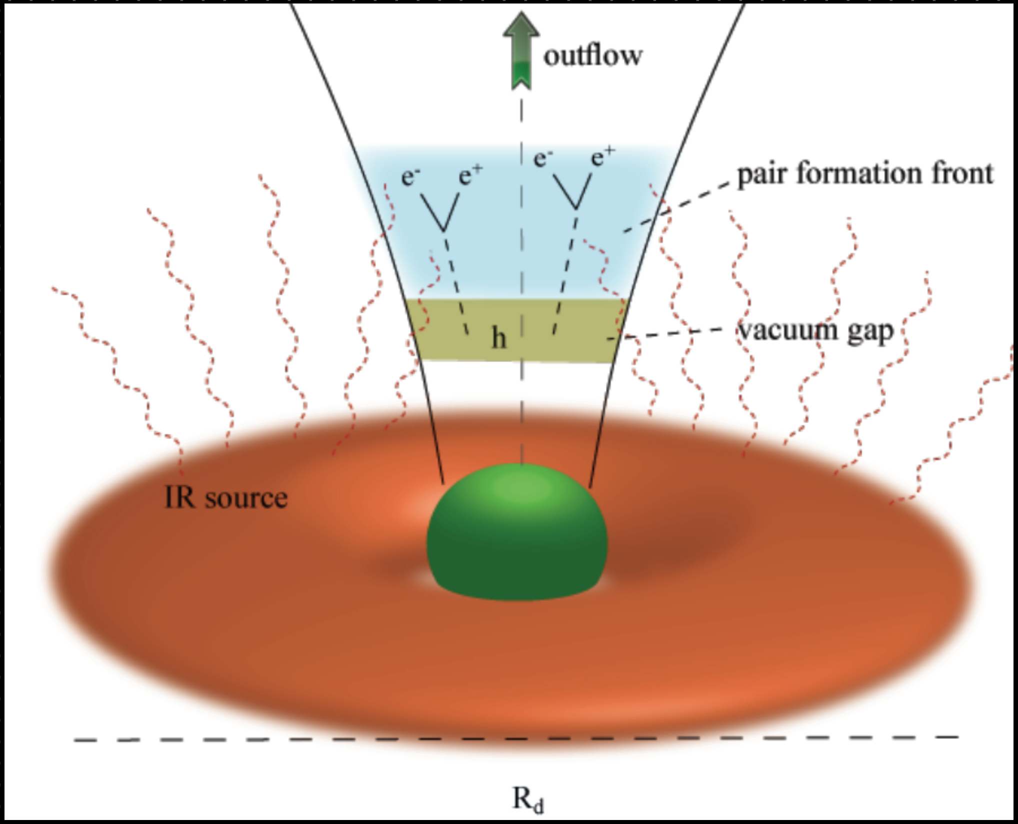
Electric flux along a starved fieldline





Activation of a spark gap

AL 00; Neronov + '07, AL + Rieger '11, Broderick + 15; Hirotani+ 16, 17



- activated when $n < n_{GJ}$. Expected in M87 when accretion rate < 10^{-4} Edd.
- must be intermittent (Segev+AL 17).
- particle acceleration to VHE by potential drop.

Challenges

Analysis of gap dynamics requires GRPIC simulations

Multi-scale problem:

Global : $> 10 r_g$

Radiation (Thomson length): $\lambda = r_g/\tau$

Plasma (skin depth): $l = \frac{c}{\omega_{pe}} < \sqrt{\frac{\langle\gamma_e\rangle m_e c^3}{4\pi e^2 n_{GJ}}} \sim 10^{-7}\sqrt{\langle\gamma_e\rangle}\, r_g$

Possible in 1D for local gaps.

Needs rescaling in global 2D sim.

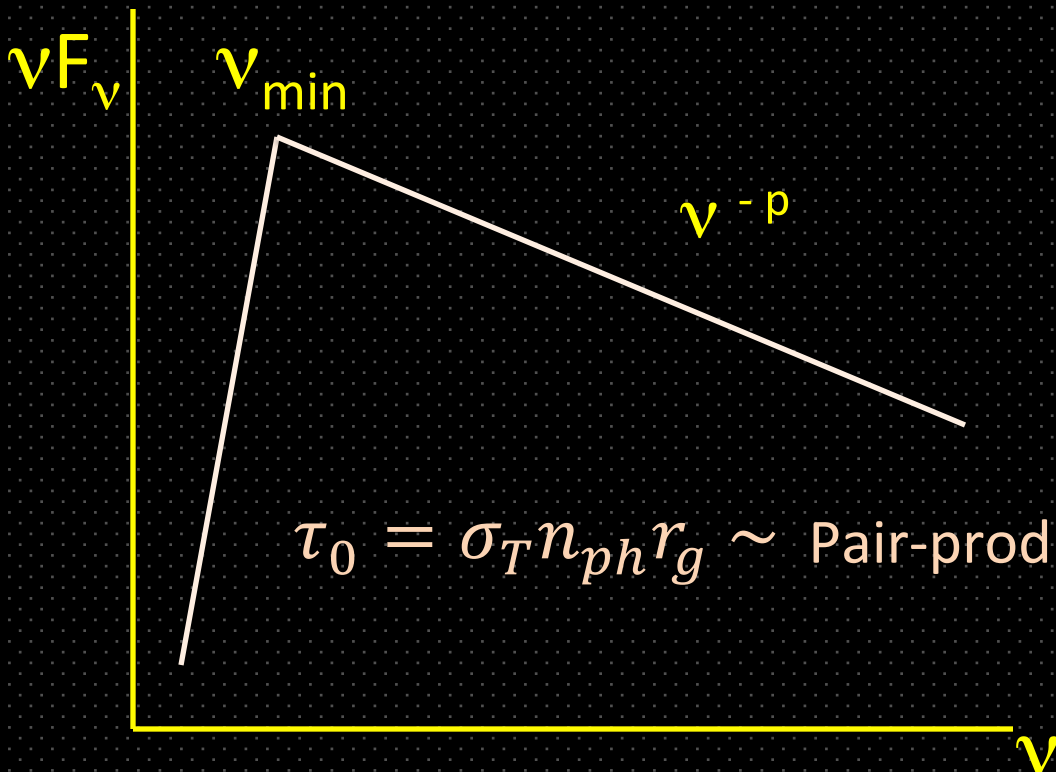
GRPIC Simulations

With Benoit Cerutti and his Zeltron code
More recent work by S. Kisaka & K. Toma
Global 2D: Perfray+19, Crinquand + 20

- Fully GR (in Kerr geometry)
- Inverse Compton and pair production are treated using Monte-Carlo approach.
- Curvature emission + feedback included
- Resolves skin depth in 1D

Input

- Global magnetospheric curret (in 1D)
- External radiation field

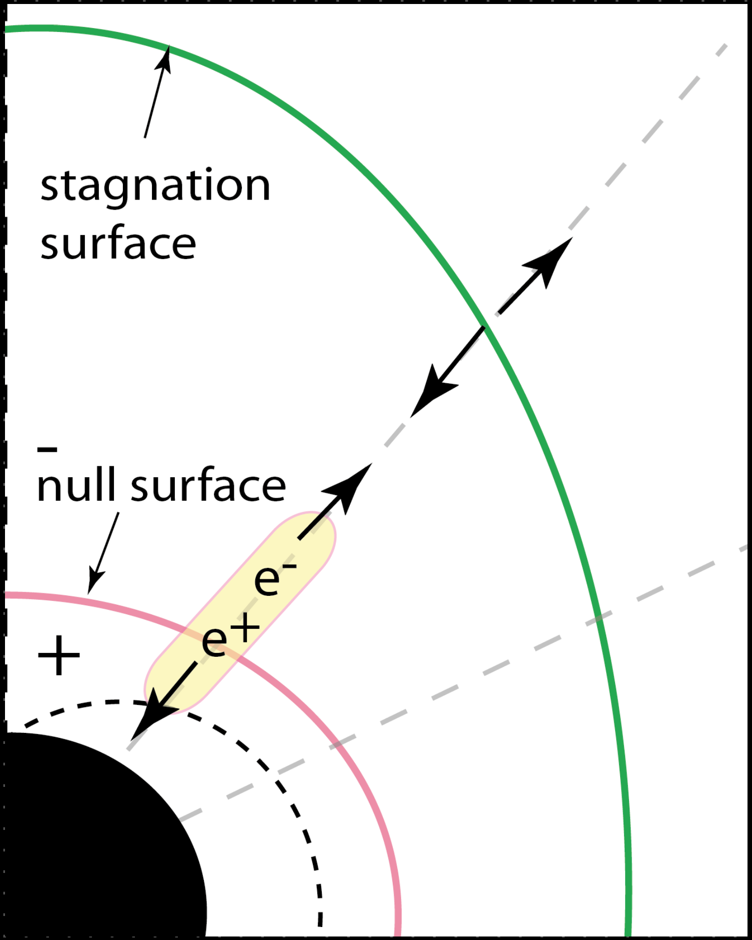


$\tau_0 = \sigma_T n_{ph} r_g \sim$ Pair-production opacity across gap

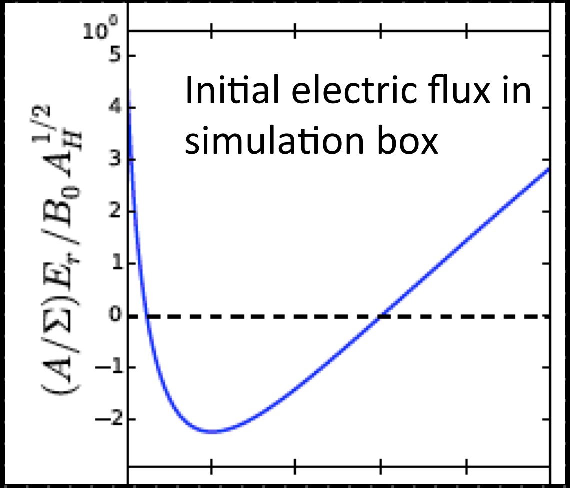
1D models

AL + Cerutti 18, Chen+19,Kisaka+20

Global structure



- Solves GRPIC equations along a particular field line
- Magnetospheric current is a given parameter



Example

$\tau_0 = \sigma_T n_{ph} r_g \sim$ Pair-production opacity across gap

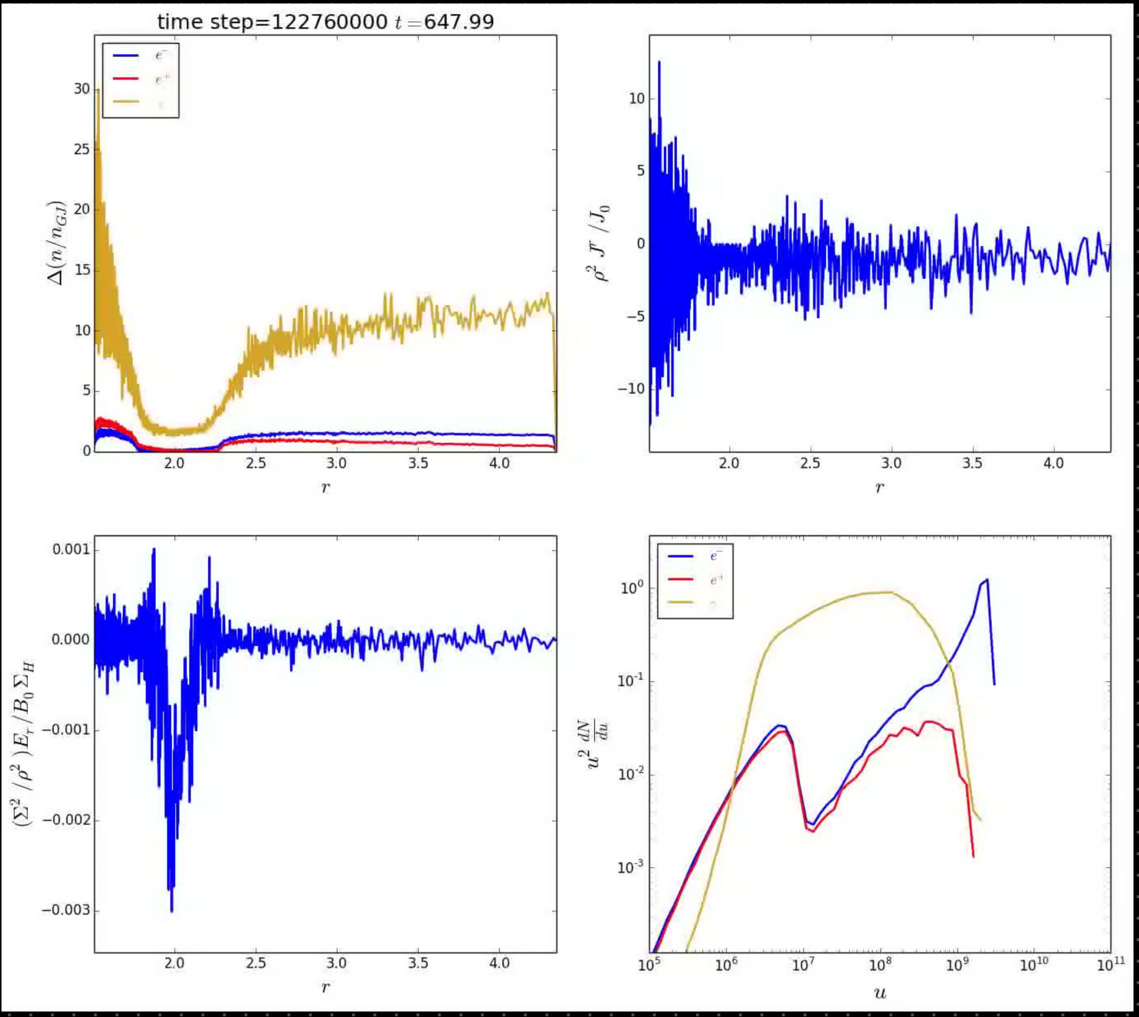
$$\tau_0 = 10\,, \varepsilon_{min} = 10^{-8}, p = 2$$

Radiation reaction limit

Gap oscillations

Kisaka+ 20

$\tau_0 = 100$

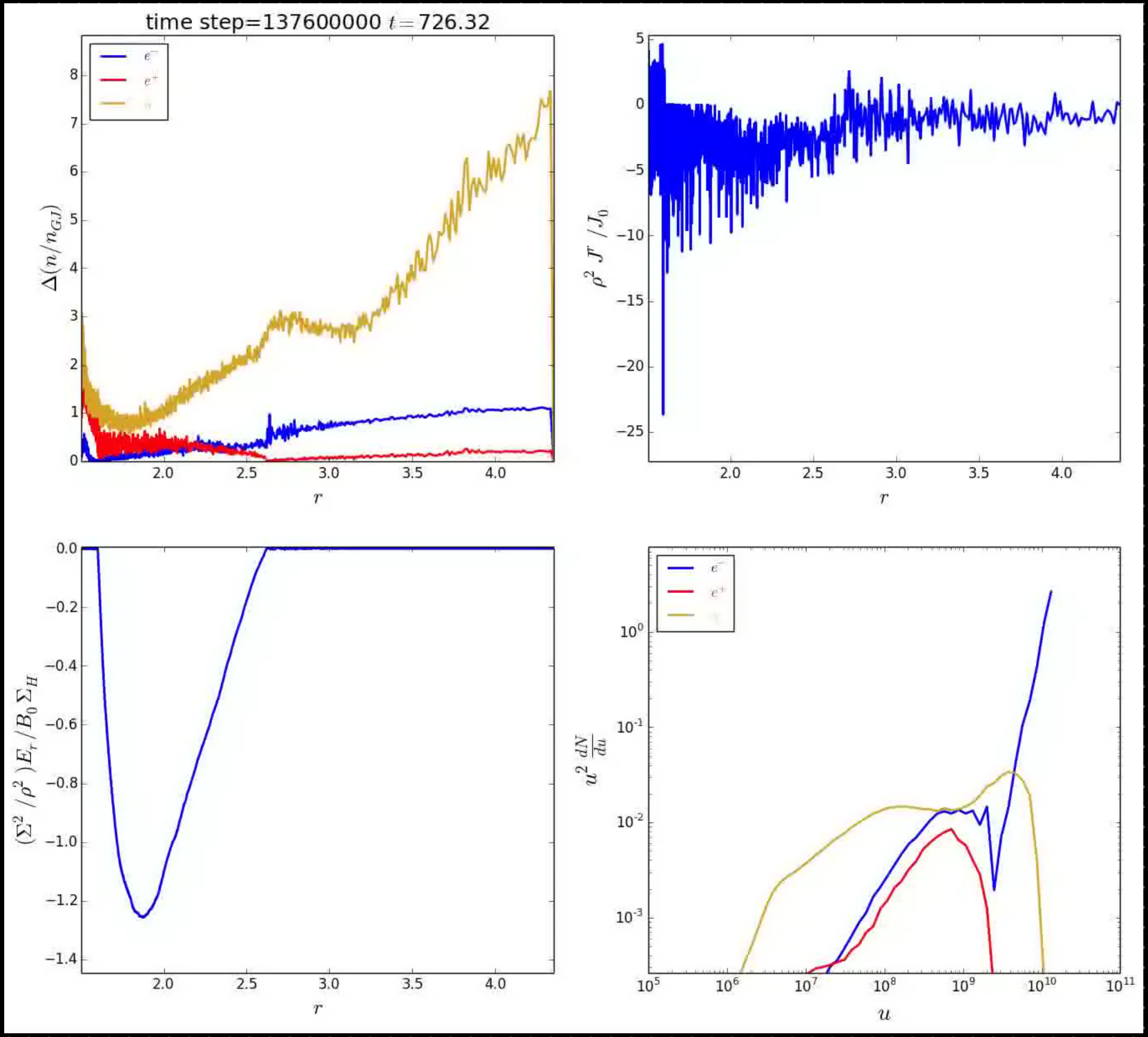


Gap dynamics depends on global magnetospheric current!

See talk by Shota Kisaka

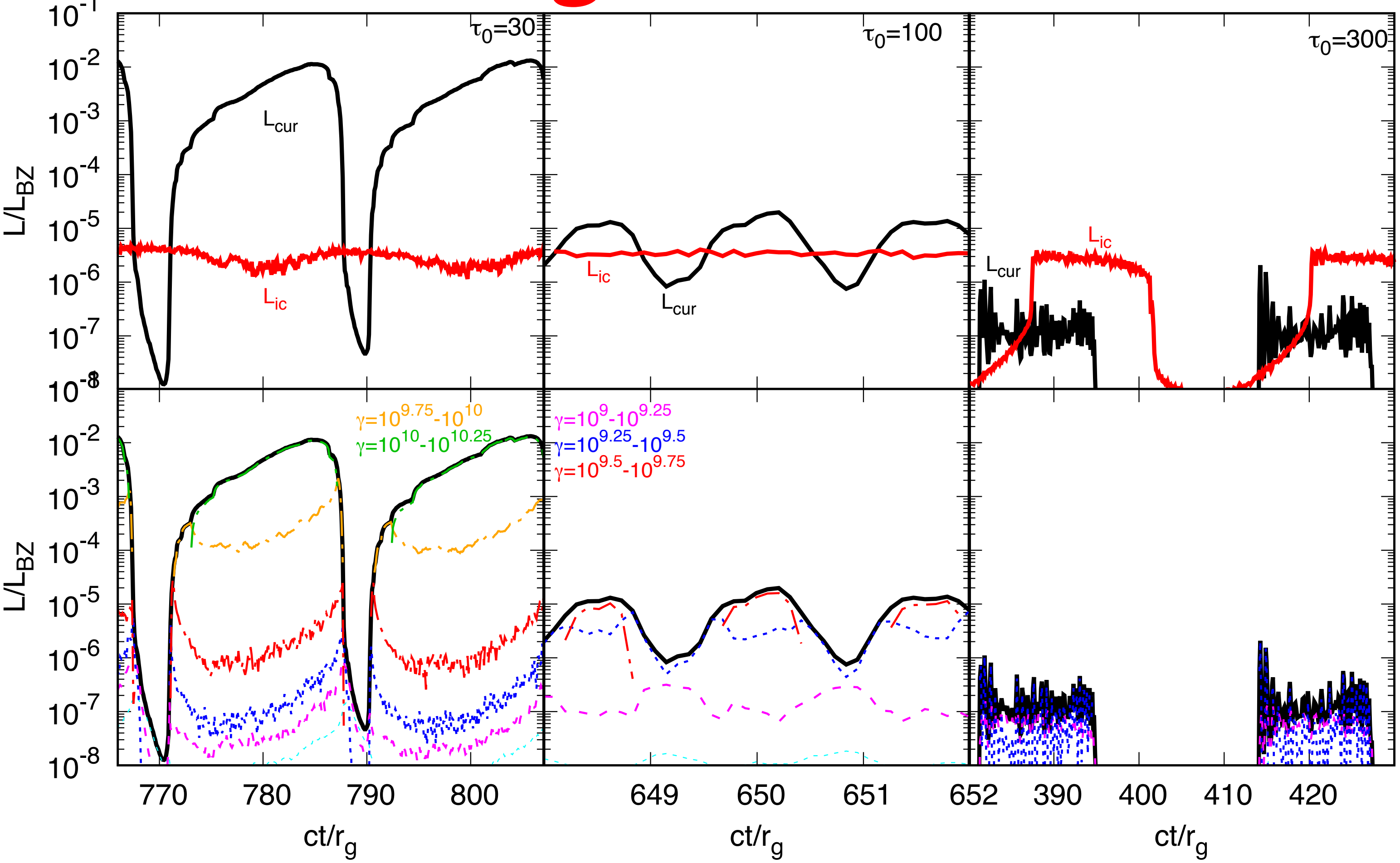
Kisaka+ 20

$\tau_0 = 30$



TeV emission §

Light curve



Characteristic energy of curvature radiation $\epsilon_{\rm cur} \sim 10^6 \gamma_{10}^3$

Global 2D GRPIC experiments: Challenges

- System is rescaled to resolve skin depth
- Artificial pair creation
- No radiation

Plasma (skin depth):

$$l = \frac{c}{\omega_{pe}} < 10^{-7}\sqrt{\langle \gamma_e \rangle}\, r_g$$

(Parfrey+19)

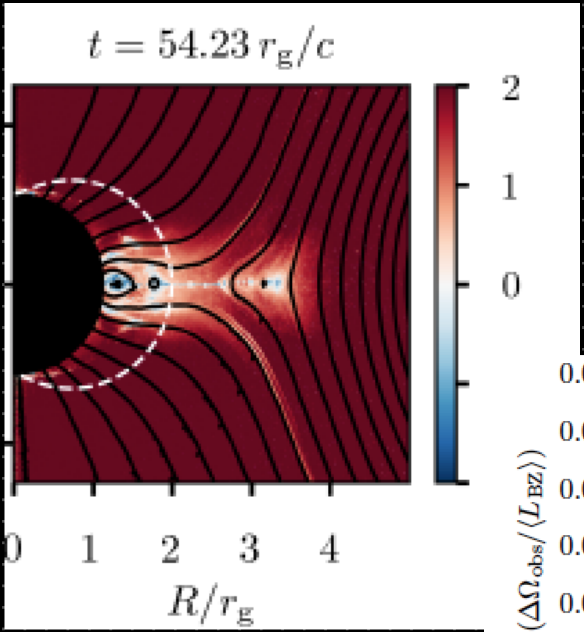
2D PIC with radiation

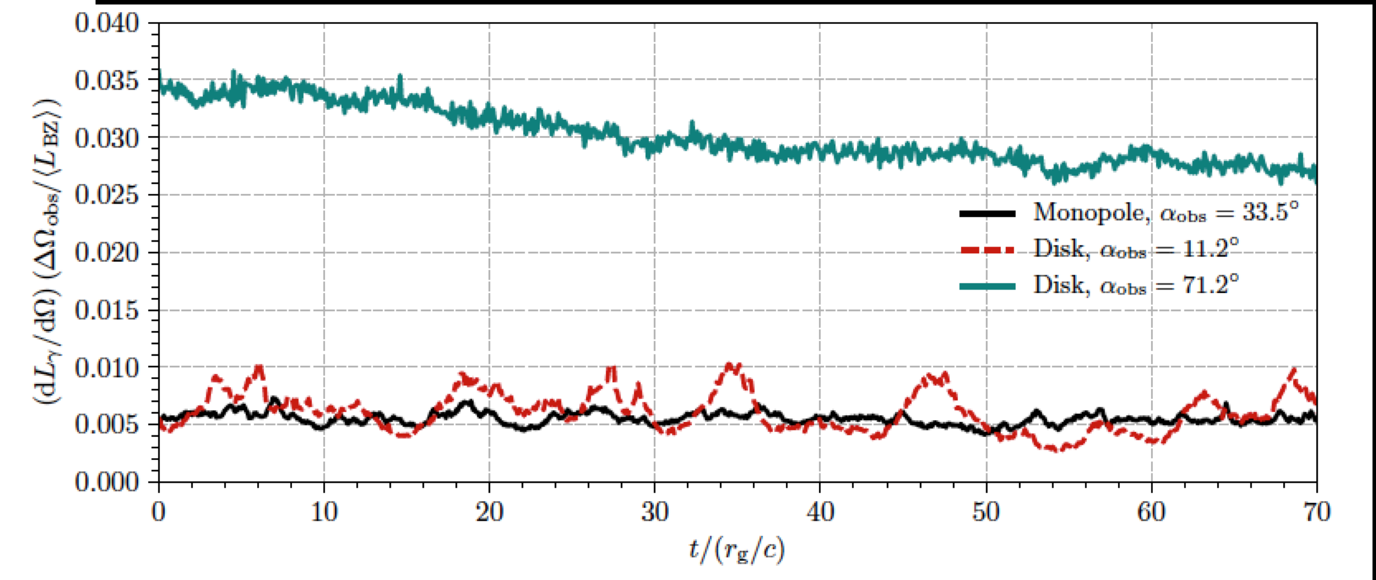
Radiation: $\lambda = r_g/\tau$

Plasma (skin depth):

$$l = \frac{c}{\omega_{pe}} < 10^{-7}\sqrt{\langle\gamma_e\rangle}\, r_g$$

Crinquand + 20





Conclusions

- spark gaps may form if survival time of coherent magnetic domains exceeds a few dynamical times. May be the production sites of variable VHE emission.
- gaps are inherently intermittent, or cyclic.
- strong TeV flares can be produced if gap is restored
- Future, global GRPIC sims, may shade more light, but need careful rescaling.

II. Dissipation of magnetized jets

Large scale (ordered) B fields:

efficient jet production (MAD, MCAF, etc.)
but stable! dissipation requires rapid growth of instabilities

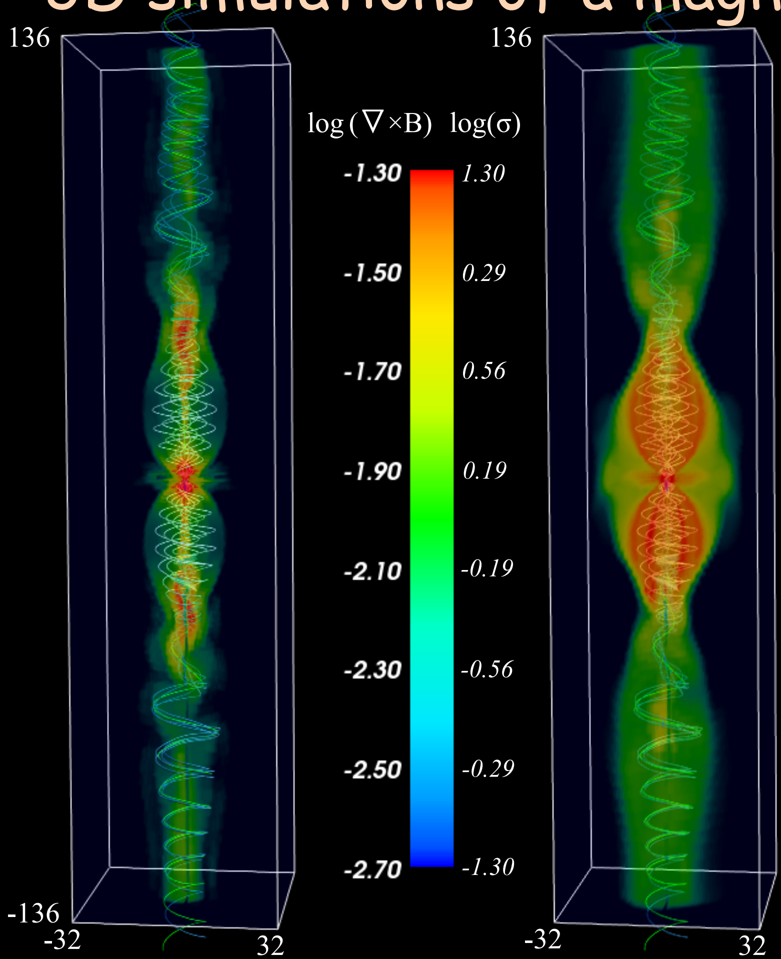
Small scale B field:

quasi-striped configuration (good for dissipation and loading)
Smaller efficiency

Dissipation of ordered field

Small angle reconnection via CD kink inst.

3D simulations of a magnetic jet propagating in a star



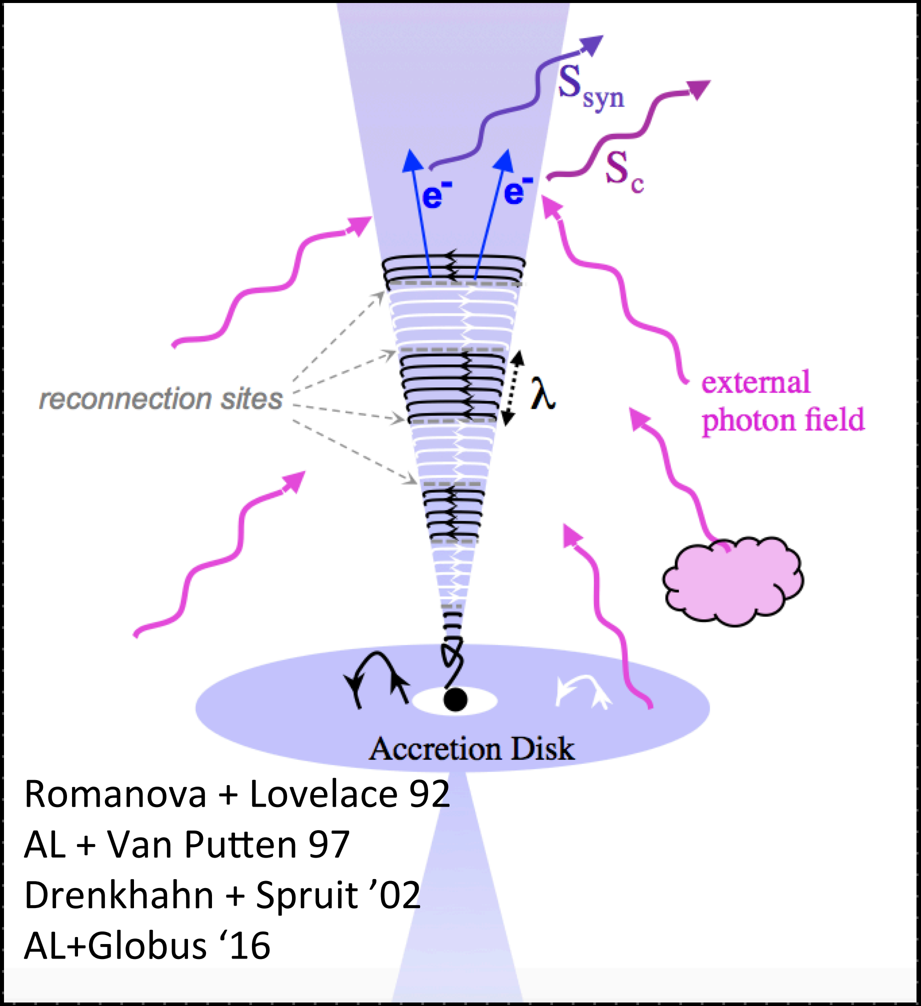
Bromberg + Tchekhovskoy '16

kink instability requires strong collimation. Develops fastest in a collimation nozzle.

But even then, saturates at equipartition.

quasi-striped jet

Reconnection of non-symmetric component



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

Dissipation on scales:

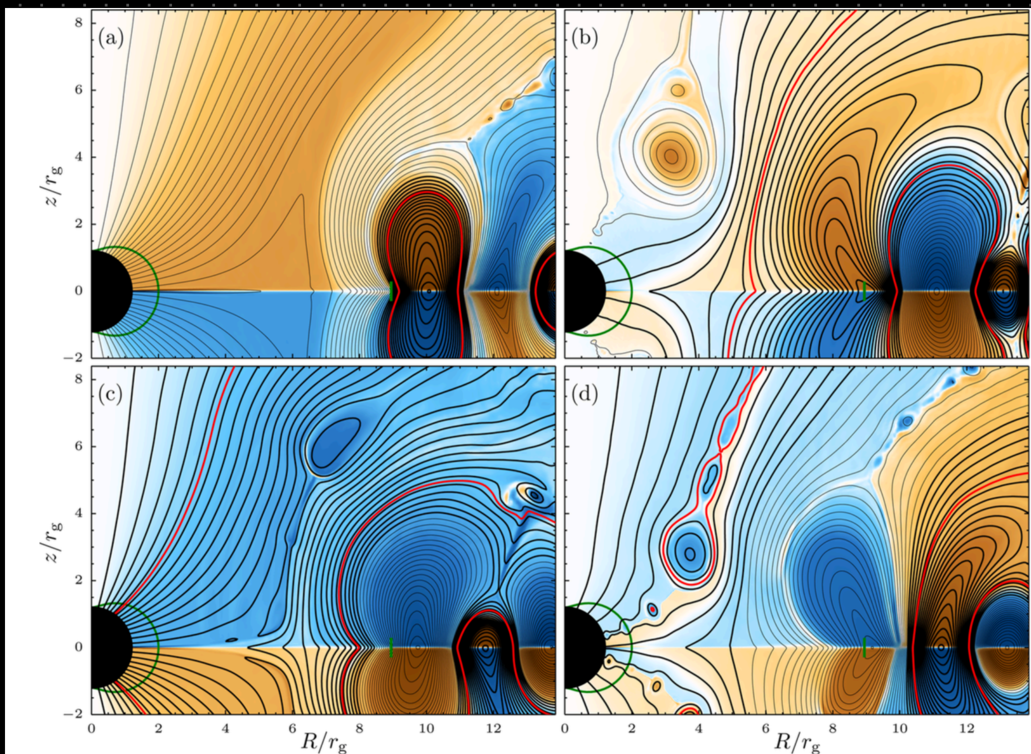
$$r_{diss} \sim \lambda \Gamma_0^2 \beta_{rec}^{-1} \gg r_g$$

Difficult to account for extreme flares (but see next)

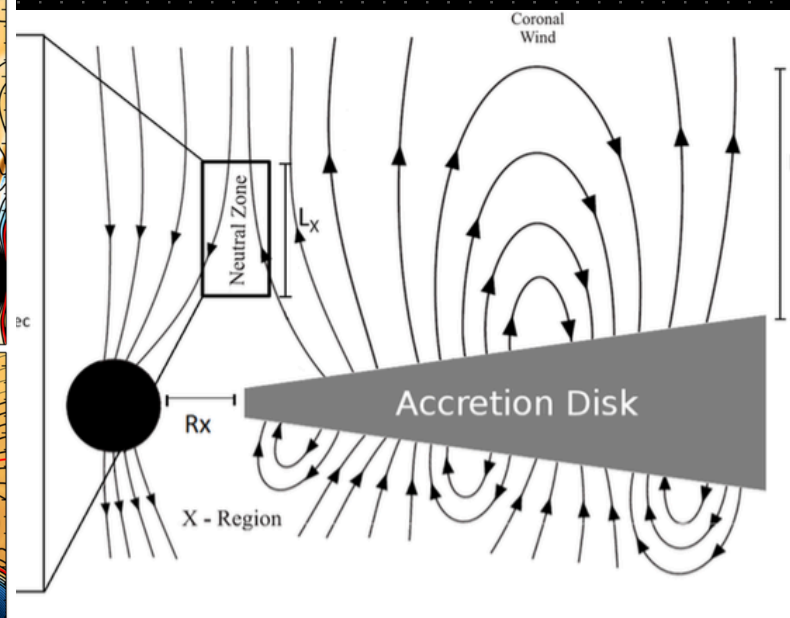
Accretion of flux loops

Spruit, uzdenski, goodman

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



2D Simulations by Parfrey + '15



Van Putten + AL '03

Kadowaki, de Gouveia Dal Pino + '15

Fully 3D GRFFE

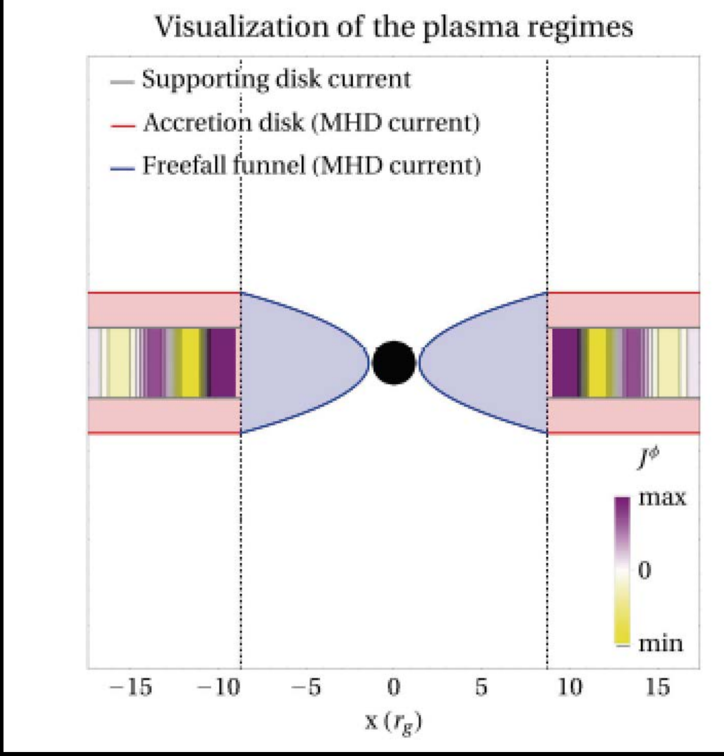
Mahlmann, AL, Aloy 2020

- Resistive disk extending from ISCO

  Keplerian angular velocity

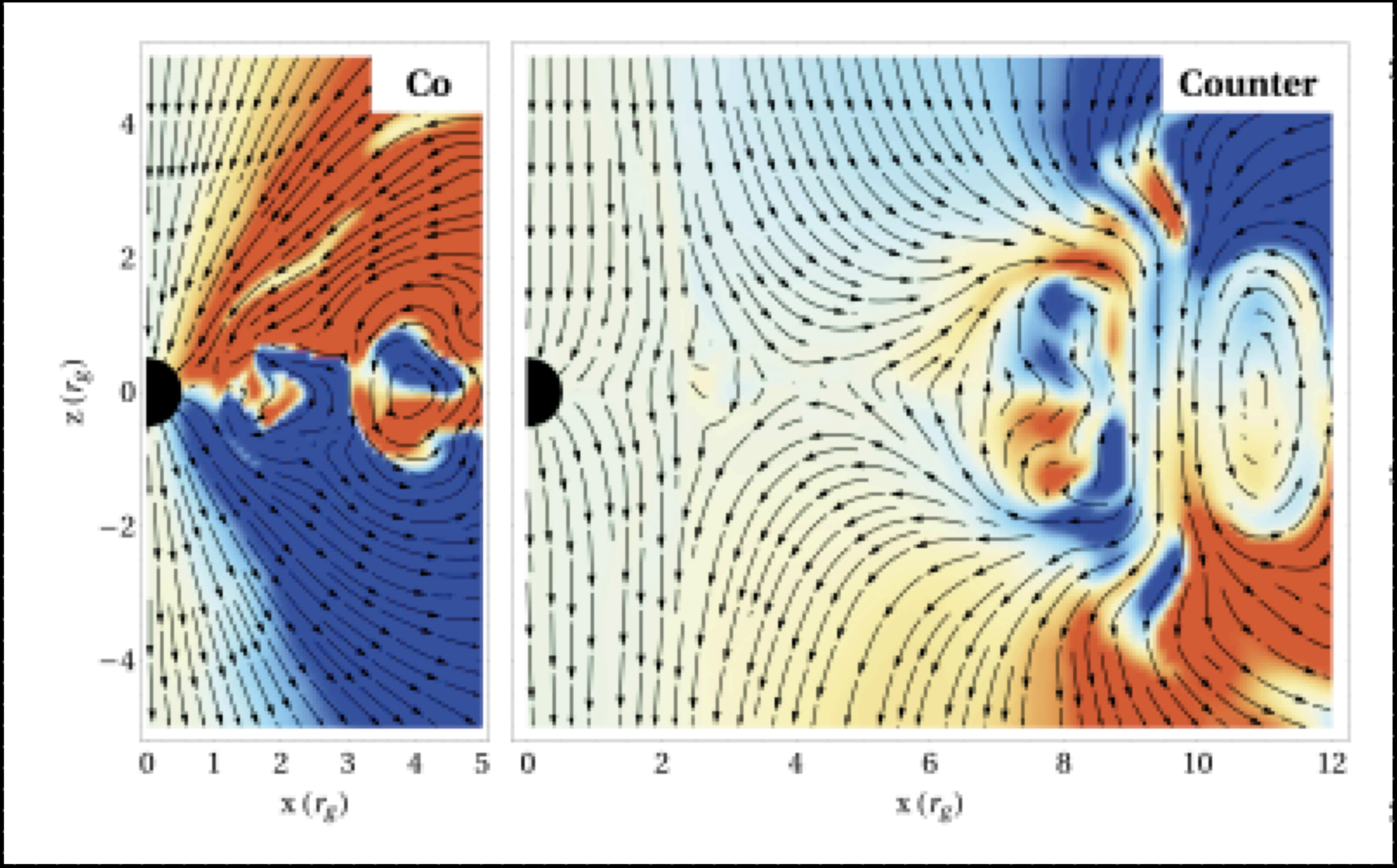
  prescribed radial velocity (accretion)

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



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

Initial state



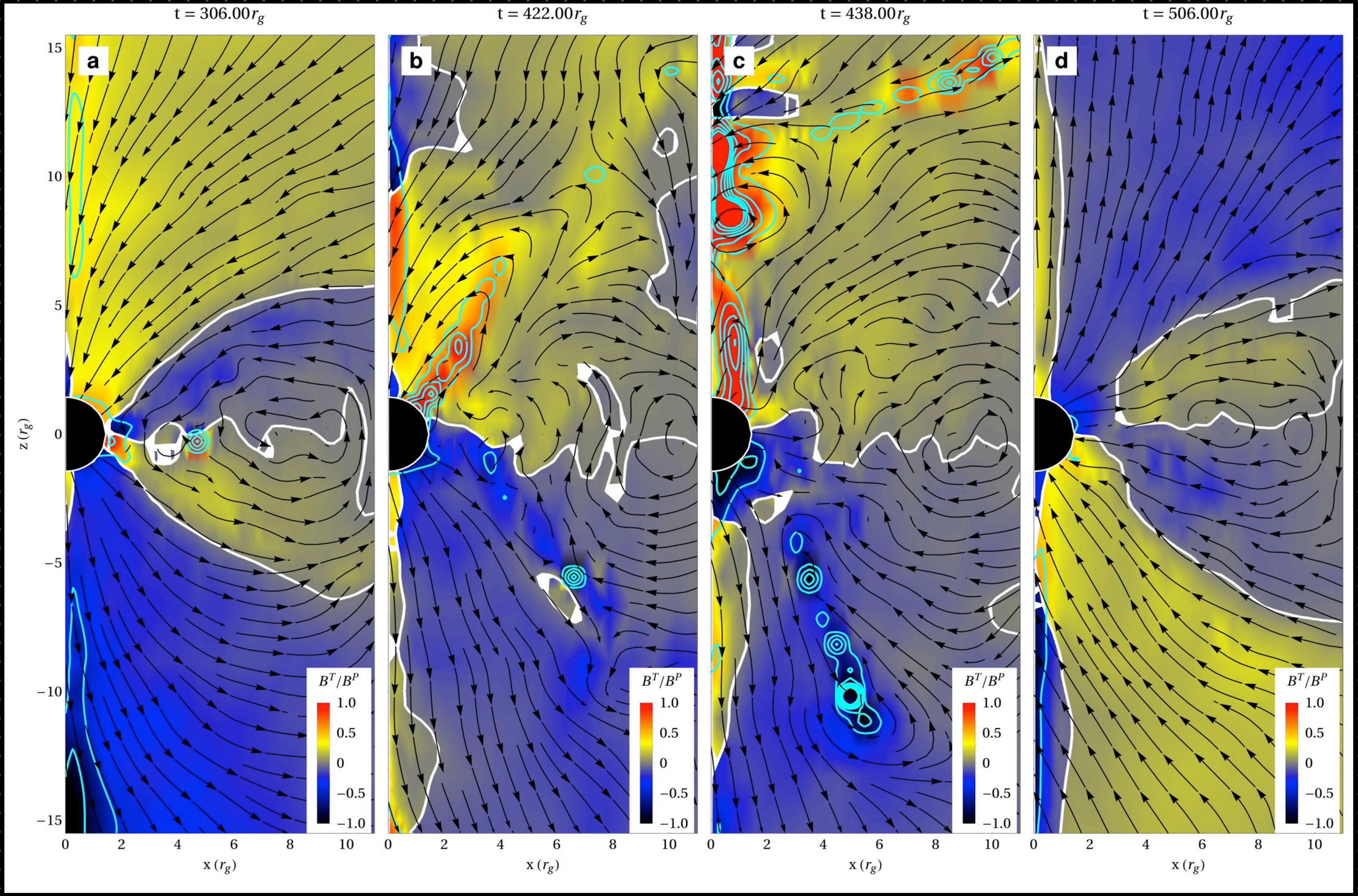
Dynamical evolution

Counter-rotating disk

Efficient extraction

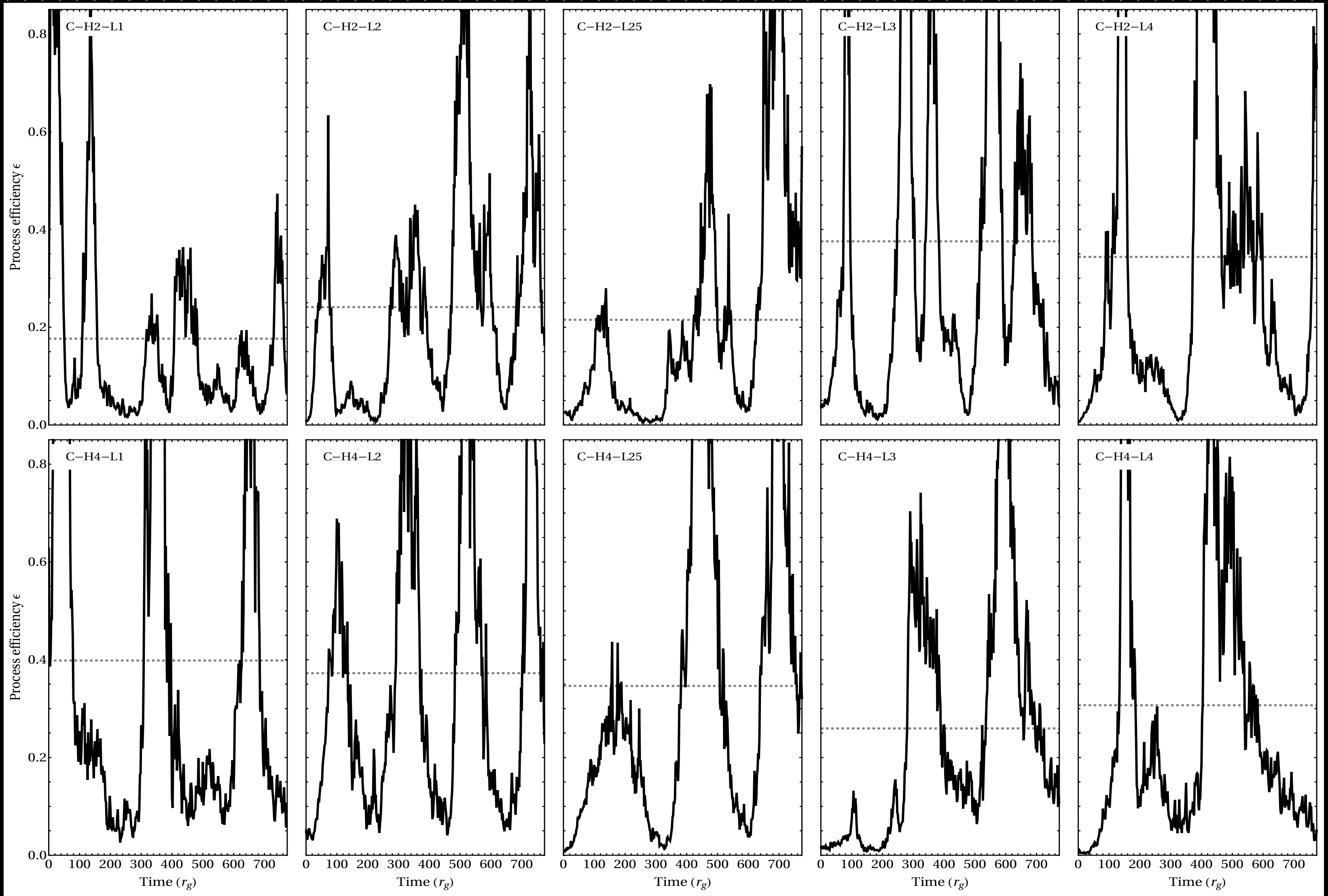
Dissipation & turbulence

Efficient extraction

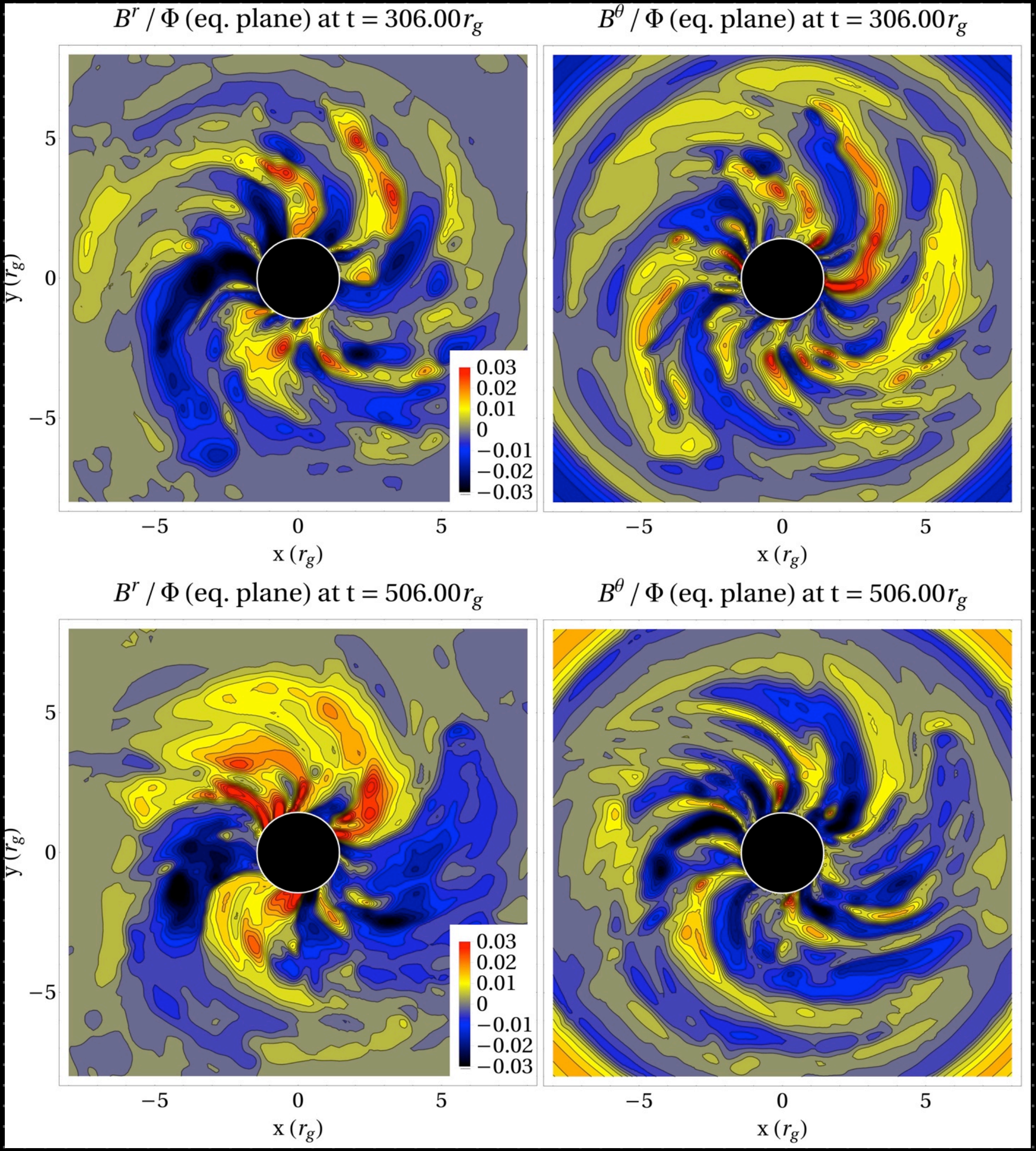


Emergent power from BH: counter-rotating disk

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

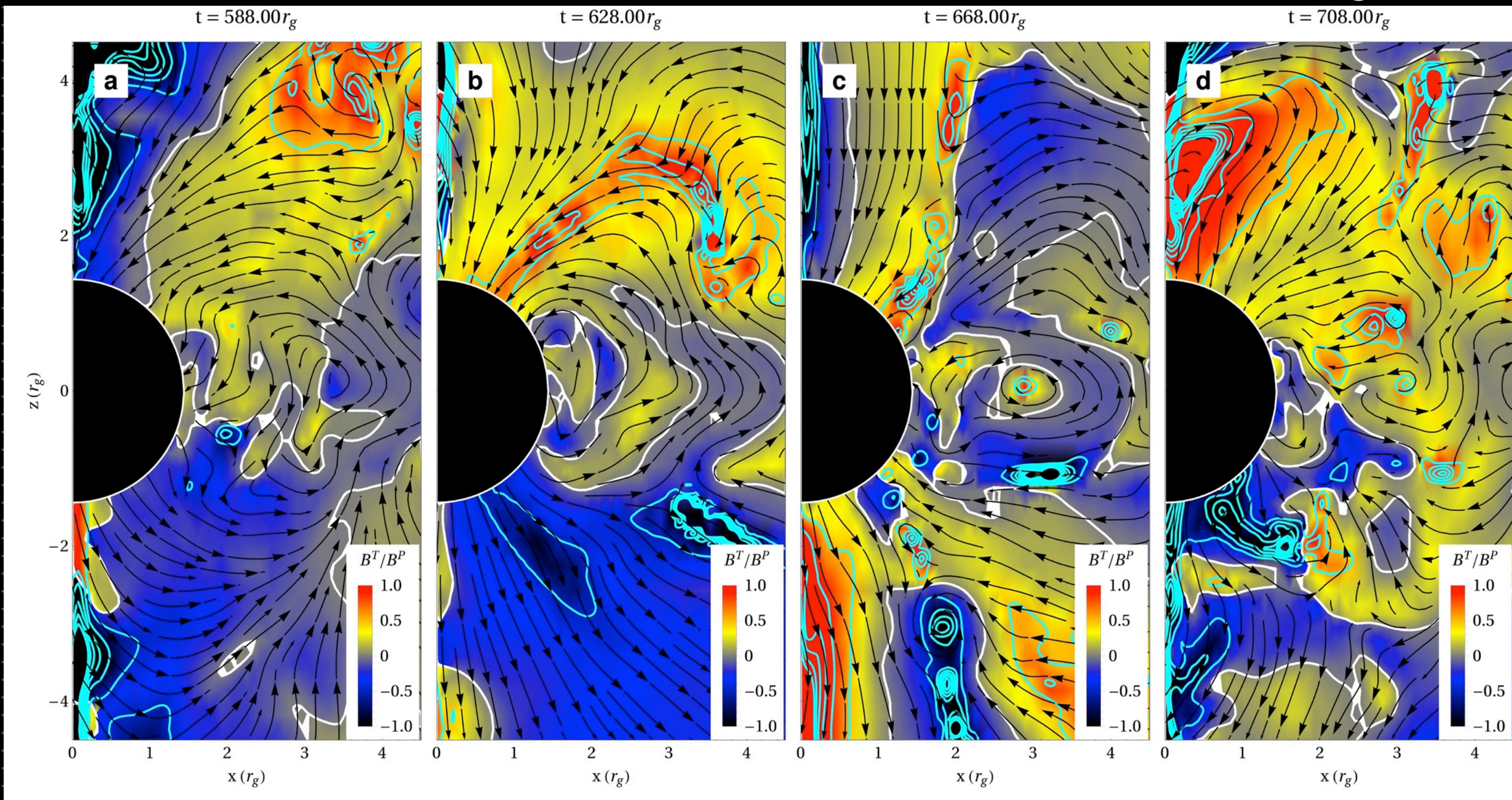
Co-rotating disk

Closed inner loop

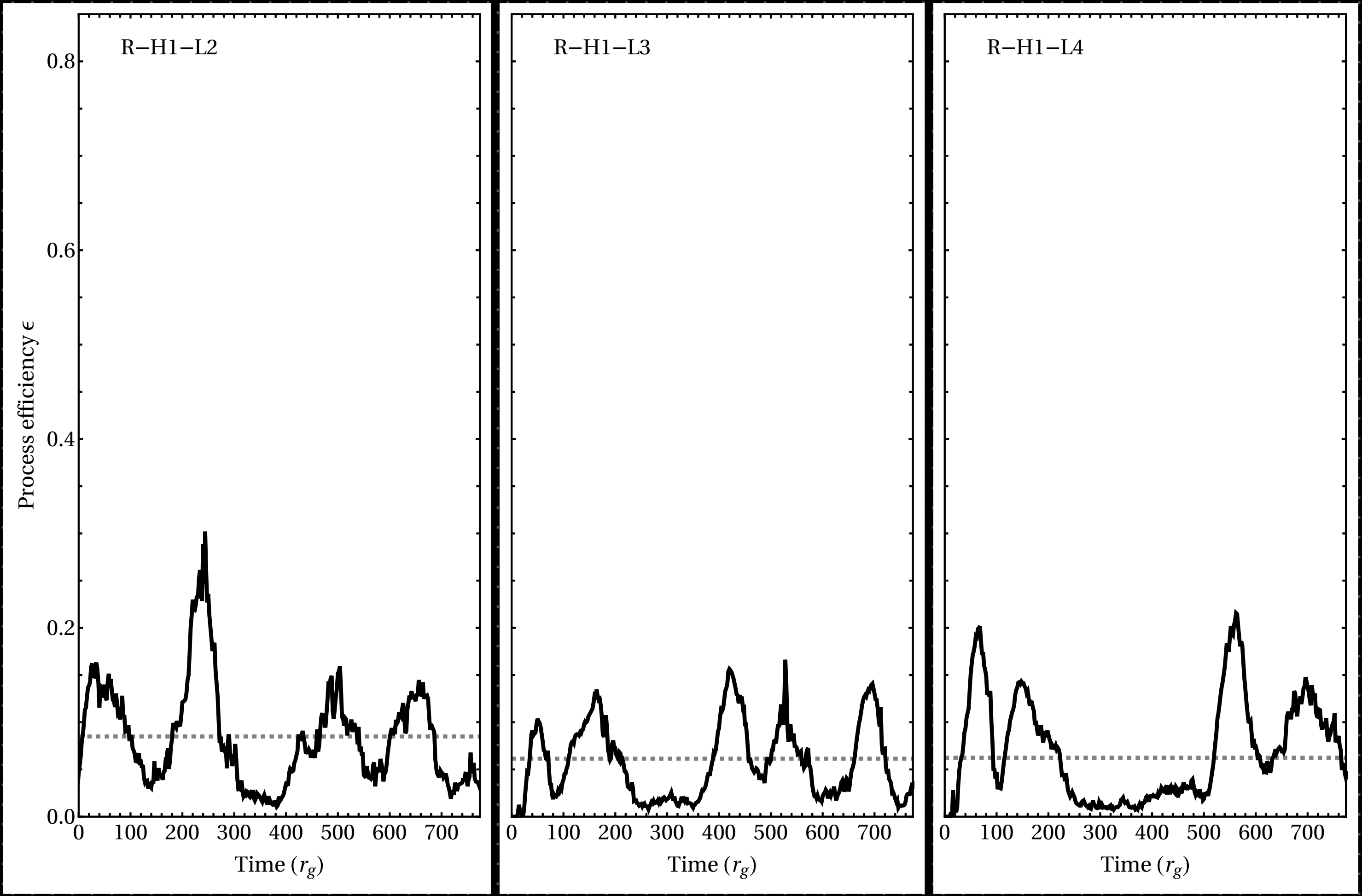
Opening up

Jet launching

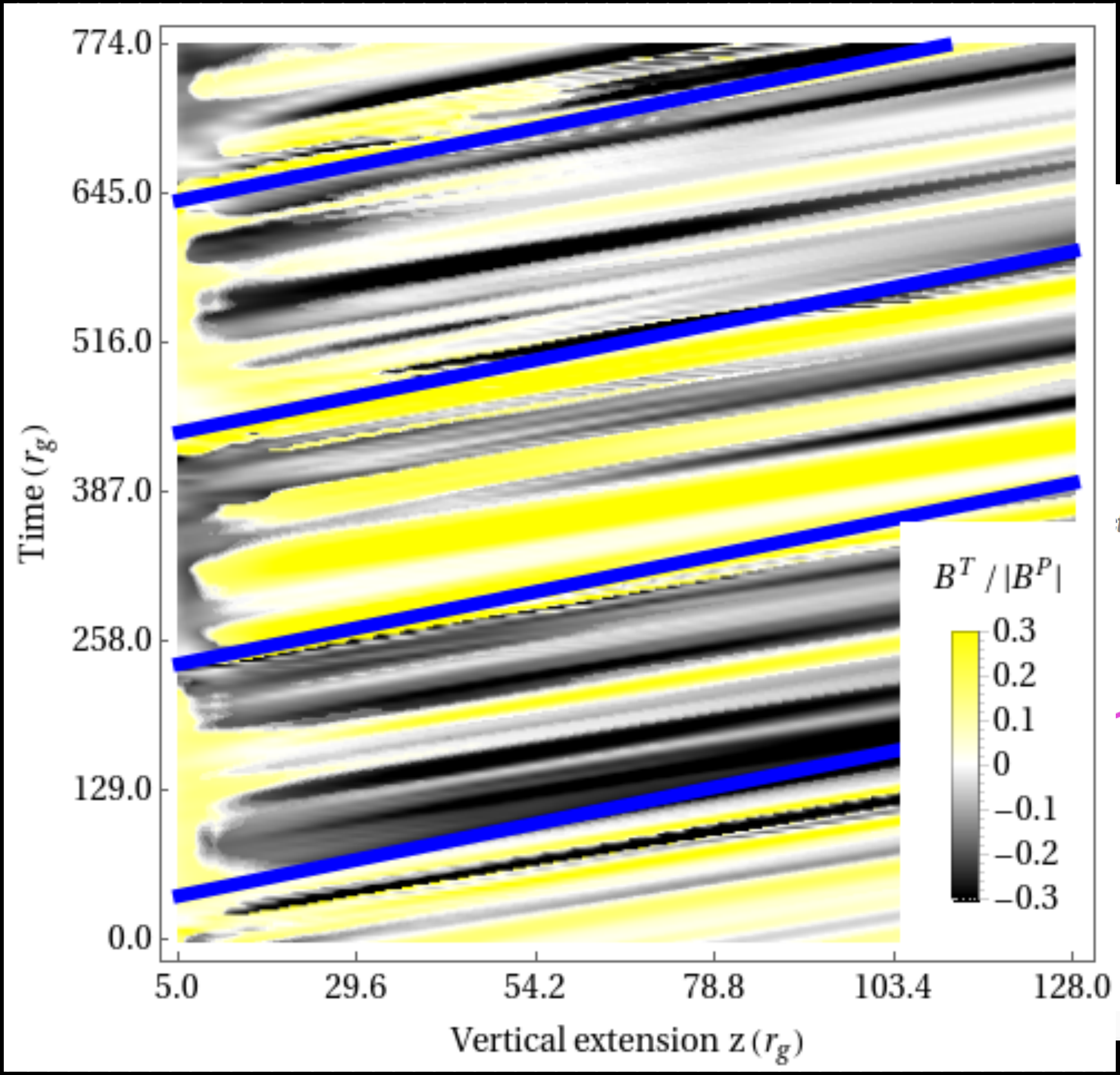
Turbulent rearrangement

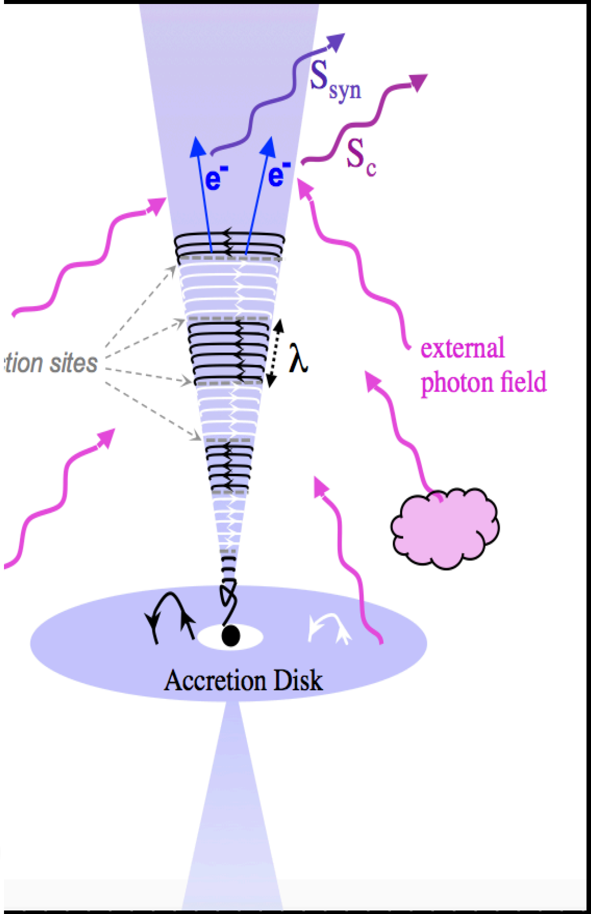


Emergent power: corotating disk



Emergence of a striped jet





GRMHD simulations of loop accretion

Chasinka, Bromberg, AL in preparation
Preliminary results

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