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Black Hole Accretion: A (biased) Computational Perspective

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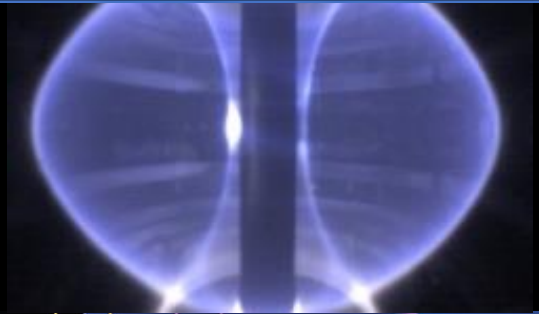
The regime of "relativistic plasmas"

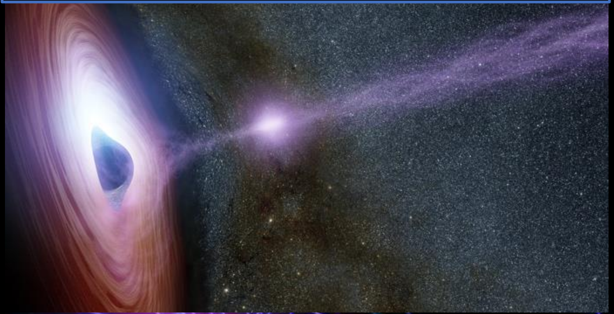
$$\sigma = \frac{B_0^2}{4\pi \rho c^2}$$

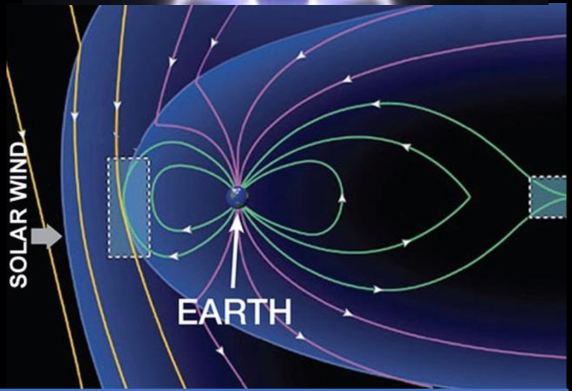
σ≪1 σ≫1

Tokamak

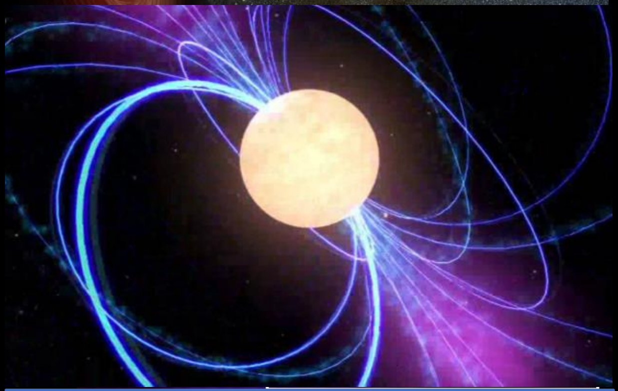


Black hole magnetosphere





Earth's magnetosphere



Neutron star magnetosphere

Credit: MAST/NASA/Goddard/CI Lab/JPL

Typical relativistic plasma conditions:

- Collisionless: $\lambda_{mfp} \gg r_{system}$
- Magnetized: $\sigma \geq 1$ $v_A = c\sqrt{\sigma/(\sigma+1)} \sim c$ $\gamma \gg 1$
- Scale separation: typical particle motion $r_L \ll r_{system}$

Large reservoir of magnetic energy and collisionless nature are ideal to accelerate plasma and power high-energy radiation

Magnetized plasma does not radiate – how to extract magnetic energy?

Difficult questions to answer:

- Magnetized and high-energy → special relativity
- Strong gravity → general relativity
- Collisionless pair plasma and ions → kinetic theory
- High energy emission → radiation and QED physics
- Nonlinear and large scale separation → extreme-resolution numerical solutions

Kinetic vs fluid (MHD) description of plasma

Captures all fundamental physics, can include radiation and QED → essential to explain non-thermal / high-energy radiation
Evolves particle distribution function in Vlasov equation (here given in flat spacetime):

$$\frac{Df(\boldsymbol{x},\boldsymbol{v})}{Dt} \equiv \frac{\partial f(\boldsymbol{x},\boldsymbol{v})}{\partial t} + \boldsymbol{v}\frac{\partial f(\boldsymbol{x},\boldsymbol{v})}{\partial x} + \frac{q}{m}\left[\boldsymbol{E}(\boldsymbol{x},\boldsymbol{t}) + \frac{\boldsymbol{v}}{c}\times \boldsymbol{B}(\boldsymbol{x},\boldsymbol{t})\right]\frac{\partial f(\boldsymbol{x},\boldsymbol{v})}{\partial \boldsymbol{v}} = 0$$

Evolves the electromagnetic fields (Maxwell's equations):

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho = 4\pi \sum_j q_j \int d^3v\, f_j$$

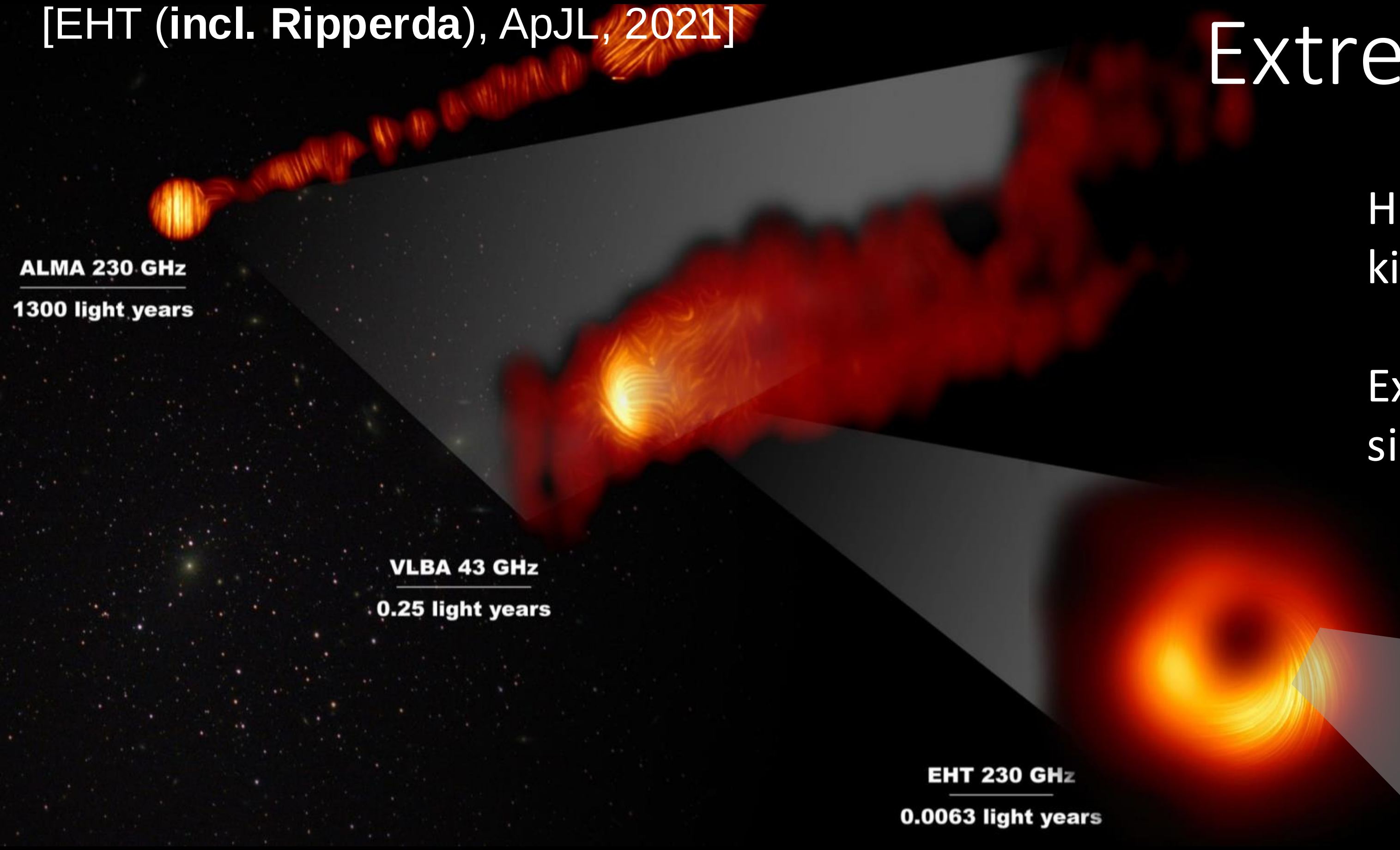
$$\frac{1}{c}\frac{\partial \boldsymbol{B}}{\boldsymbol{\partial t}} = -\nabla \times \boldsymbol{E}$$

$$\frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} = \nabla \times \boldsymbol{B} - \frac{4\pi}{c} j = \nabla \times \boldsymbol{B} - \frac{4\pi}{c}\sum_j q_j \int d^3v\, \boldsymbol{v} f_j$$

Typically, multi-dimensional non-linear many-body system: Need numerical solutions with particle-in-cell (PIC) method

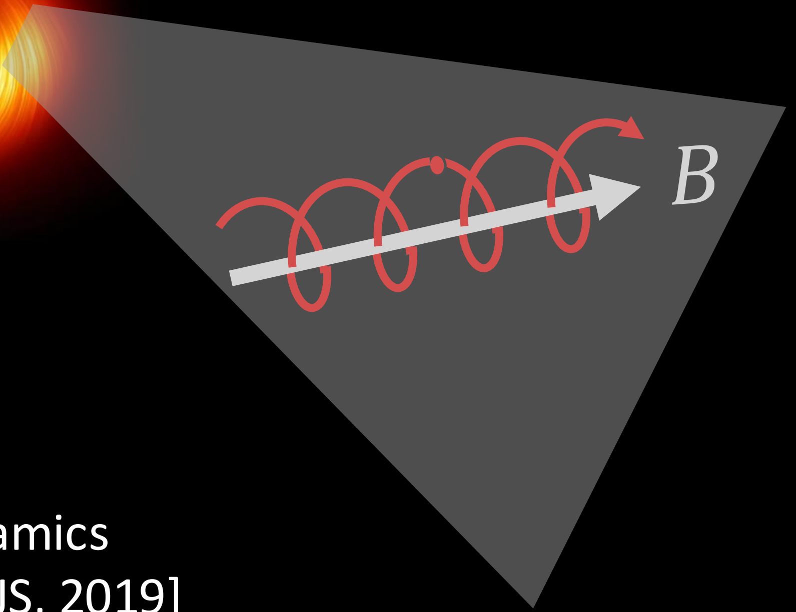
Extreme separation of scales

[EHT (**incl. Ripperda**), ApJL, 2021]



Hard to resolve plasma scales in global kinetic simulation

Extremely hard to do global kinetic simulations of black hole accretion disks



Global and plasma scales interact nonlinearly through instabilities, turbulence, dynamo, …

Magnetohydrodynamics is scale-free and captures global dynamics of accretion and jet launching [Porth et al (**incl. Ripperda**), ApJS, 2019]

$r_L \sim 10^{-11} r_{s(chwarzschild)}$

Kinetic vs fluid (MHD) description of plasma

Fluid approximation → taking moments reduces set of variables: mass density, velocity, energy, magnetic field

(general relativistic) magnetohydrodynamics (GRMHD):

Conservation laws (inviscid Navier-Stokes → Euler's equations)

$\nabla_\mu(nmu^\mu) = 0$ *Mass conservation*

$\nabla_\mu\left(T_f^{\mu\nu} + T_{EM}^{\mu\nu}\right) = 0$ *Energy-Momentum conservation*

Maxwell's equations

$\nabla_\nu F^{\mu\nu} = J^\mu$ *Gauss-Ampère law*

$\nabla_\mu {}^* F^{\mu\nu} = 0$ *Gauss-Faraday law*

Typically done: Ideal MHD approximation (infinite conductivity): Collisional and single temperature Maxwellian plasma

→ both assumptions are wrong in jet and accretion disk

- Plasma is a perfect conductor in ideal MHD: $\boldsymbol{E}' \equiv \boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B} = 0$ → No accelerating E-field
- We can solve (simpler) induction equation $\partial_t\left(\sqrt{\gamma}\, B^j\right) + \partial_i\left(\sqrt{\gamma}\left(v^i B^j - B^i v^j\right)\right) = 0$

Kinetic vs fluid (MHD) description of plasma

One can add a resistivity and evolve the electric field instead

Difficult because of stiff source term to Ampere's law to describe evolution of independent electric field

$$\frac{1}{\mathrm{c}}\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = \mathbf{0}$$

$$\frac{1}{\mathrm{c}}\frac{\partial \boldsymbol{E}}{\partial t} = \nabla \times \boldsymbol{B} - \frac{4\pi}{c} j = \nabla \times \boldsymbol{B} - \frac{4\pi}{c}\left(\rho \boldsymbol{v} + \frac{\Gamma}{\eta}[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}/\boldsymbol{c} - (\boldsymbol{E} \cdot \boldsymbol{v})\boldsymbol{v}/c^2]\right)$$

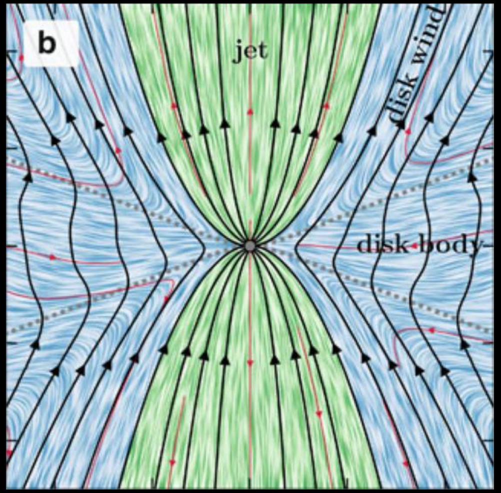
- Resistivity η is a proxy to capture dissipation (reconnection, turbulence) → requires high spatial and temporal resolution
- Implicit-Explicit (ImEx) time-stepping method allows to add more non-ideal physics [Most et al, PRD, 2021]

→ but still no particle acceleration

[Ripperda et al, ApJS, 2019]

Open source code: https://bhac.science

Force-Free magnetohydrodynamics



[Tchekhovskoy, A&SS, 2015]

- Limit of negligible plasma inertia and pressure: $\sigma \rightarrow \infty$
- Applicable in black hole jets, where MHD (numerically) fails due to low density/high σ
- Corresponds to vanishing Lorentz force, $q\mathbf{E} + \mathbf{J} \times \mathbf{B} = 0$
- Implying ideal conditions $\mathbf{E} \cdot \mathbf{B} = \mathbf{0}$ and $E^2 < B^2$
- Solving Ampère's and Faraday's laws, as in resistive GRMHD
- Force-Free current closure damps non-ideal violations through resistivity

$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0$$

$$\partial_t \mathbf{E} - \nabla \times \mathbf{B} = \mathbf{J}$$

$$\mathbf{J} = \frac{q\mathbf{E} \times \mathrm{B}}{B^2} + \frac{1}{\eta}\left[(\mathbf{E} \cdot \mathbf{B})\frac{\mathbf{B}}{B^2} + \Theta(E^2 - B^2)\frac{\mathbf{E}}{B^2}\right]$$

(can be solved in full GR within resistive IMEX scheme)

[Ripperda et al, JPP, 2021]

Coupling: resistive MHD and force-free MHD

- MHD breaks if magnetization $\sigma \to \infty; \beta \to 0$
- FF breaks in sheets where $\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$ and $B^2 - E^2 < 0$
- We evolve both $\boldsymbol{E}$ and $\boldsymbol{B}$ for resistive MHD and FF-MHD

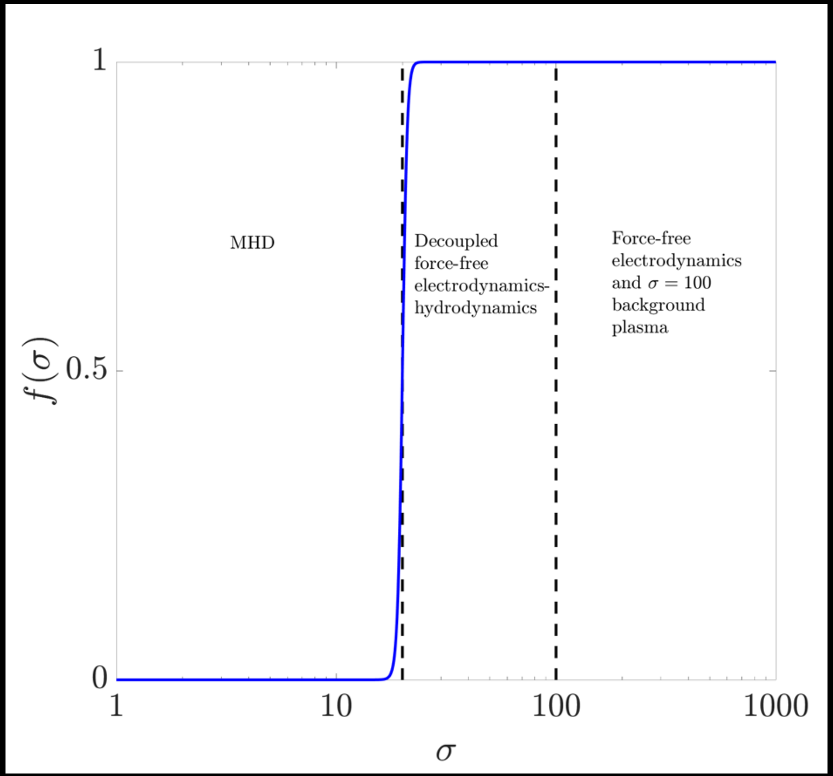
$$\partial_t \boldsymbol{B} + \nabla \times \boldsymbol{E} = 0$$
$$\partial_t \boldsymbol{E} - \nabla \times \boldsymbol{B} = -\boldsymbol{J}$$

+ hydrodynamics

- And couple via current density:

$$\boldsymbol{J} = (1 - f(\sigma))\, \boldsymbol{J_{MHD}} + f(\sigma)\boldsymbol{J_{FF}}$$
$$f(\sigma) = 0.5 + 0.5\tanh(\sigma - \sigma_{th})$$

- Coupling happens where $\boldsymbol{J_{MHD}} \sim \boldsymbol{J_{FF}}$ for threshold $\sigma > \sigma_{th}$



Resistive dissipation, highly magnetized regions, but still no particle acceleration!

[Ripperda, et al, in prep.; Grehan, Ghosal, Beattie, Ripperda et al, subm.]

Minghao Zou: High-school student!!

(Test) particles: Splitting gravitational, electromagnetic and radiative forces

For test particles, we can use that on small scales, spacetime is locally flat and Strang-split forces:

<u>Special Relativity</u> → <u>General Relativity</u>

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{u}}{\gamma} \quad \rightarrow \quad \frac{dx^\mu}{d\tau} = u^\mu$$

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{\mathbf{u}}{\gamma} \times \mathbf{B}\right) \quad \rightarrow \quad \frac{du_\mu}{d\tau} - \Gamma^\beta_{\mu\alpha} u_\beta u^\alpha = \frac{q}{m} F_{\mu\nu} u^\nu + \cdots$$

- Spacetime curvature (geodesic motion) → needs (quickly-converging) implicit step
- Lorentz force (external forces) → can be done in locally flat (orthonormal) frame with Boris push
- Resistive electric field can accelerate particles
- Locally flat step allows to include radiative losses, hadronic interactions, guiding center approximation

[Parfrey et al, PRL (2019), Bacchini, Ripperda, et al., ApJS (2021); Zou, Mbarek, Hakobyan, Ripperda, et al., PRD (2025)]

Coupling: the guiding center approximation

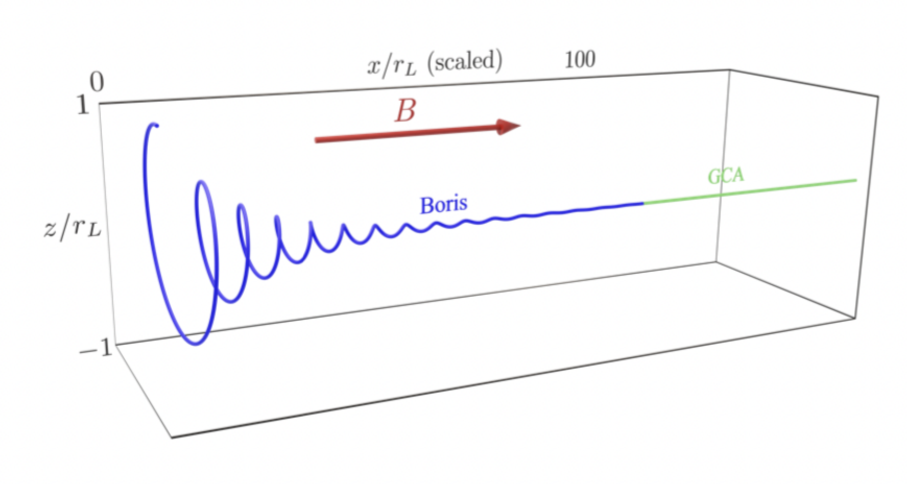
Remember:
$r_L \sim 10^{-11} r_S$ for M87*

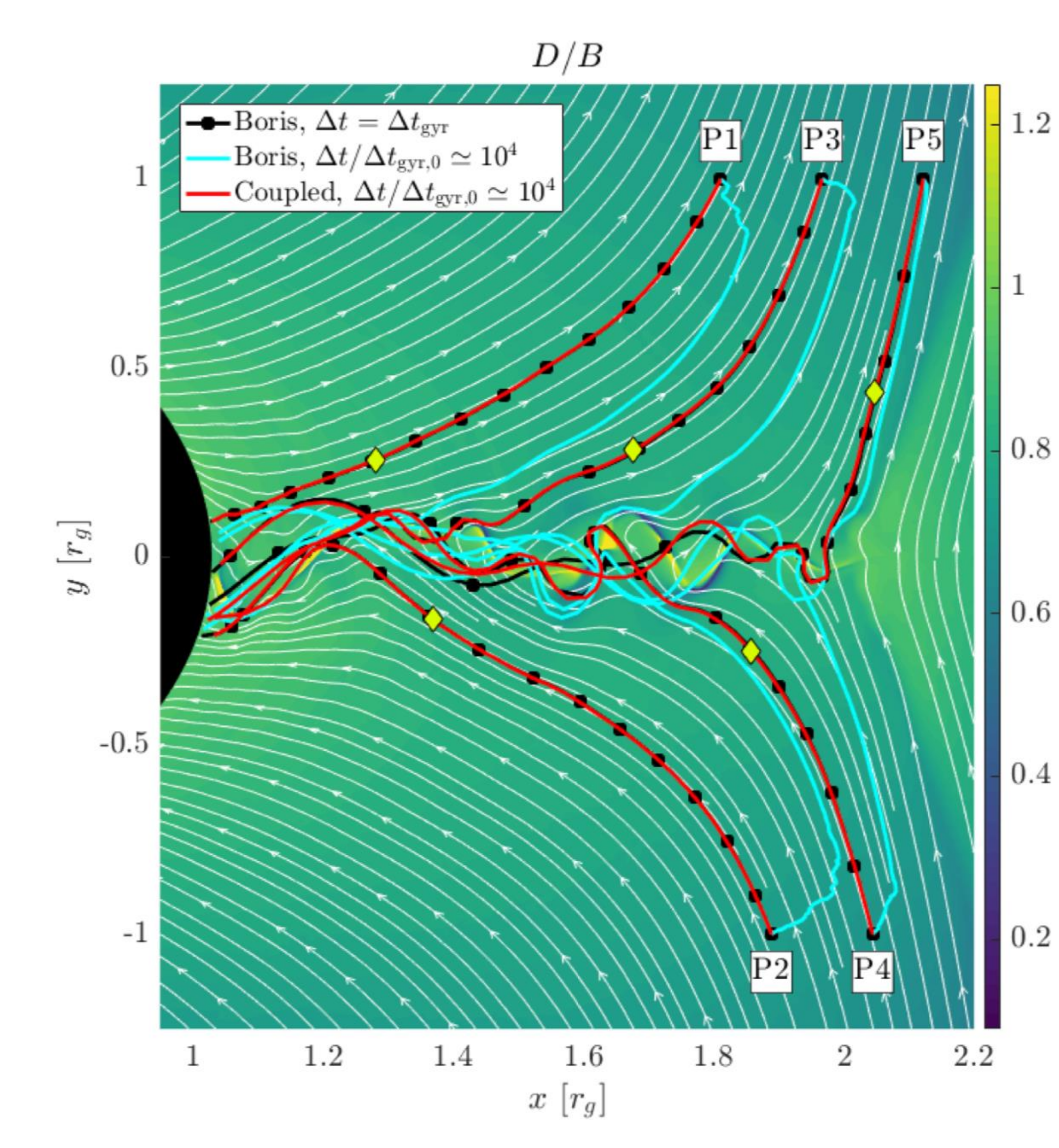
If Larmor radius is > cell size: Full equations of motion

If Larmor radius is < cell size: Guiding Center Approximation

Advantages:

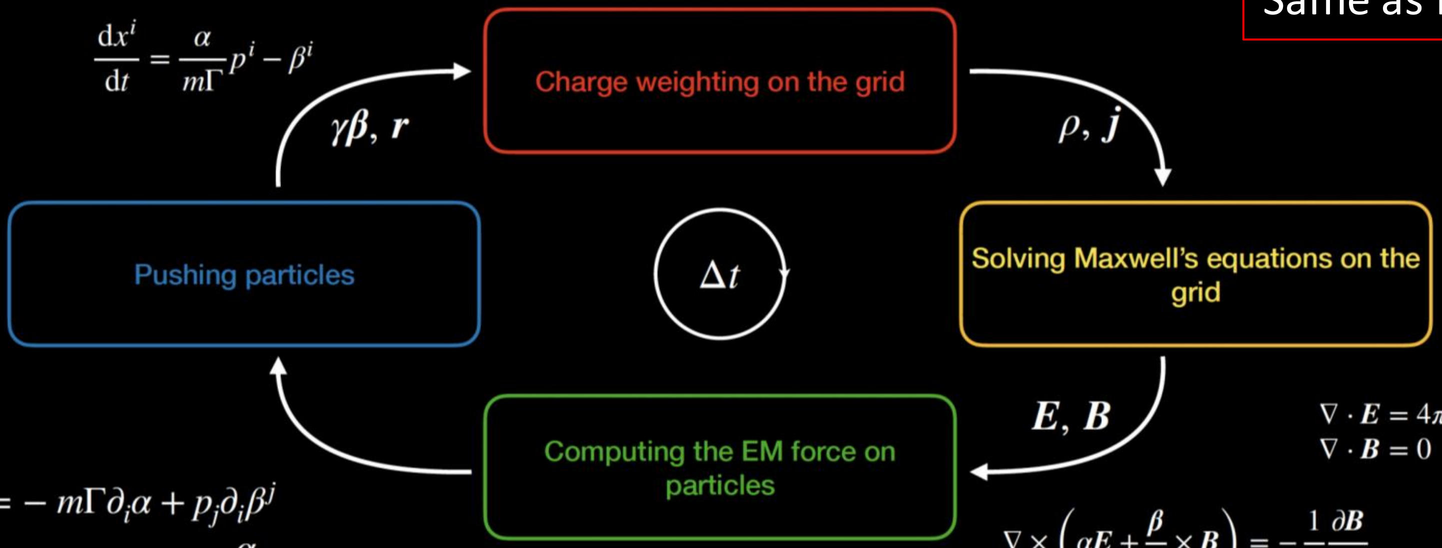
- More accurate particle dynamics in magnetized regions for affordable time steps
- Radiation drives particles to zeroth Landau level (Larmor radius goes to zero)





[Bacchini, Ripperda, et al., ApJS (2021); Zou, Mbarek, Hakobyan, Ripperda, et al., PRD (2025)]

General Relativistic Particle-In-Cell (GRPIC)



$$\frac{\mathrm{d}x^i}{\mathrm{d}t} = \frac{\alpha}{m\Gamma}p^i - \beta^i$$

$$\frac{\mathrm{d}p_i}{\mathrm{d}t} = -m\Gamma\partial_i\alpha + p_j\partial_i\beta^j - \frac{\alpha}{2\Gamma m}\partial_i\left(\gamma^{lm}\right)p_l p_m + q\left\{\alpha D_i + \epsilon_{ijk}(v^j + \beta^j)B^k\right\}$$

$$\nabla\cdot\boldsymbol{E} = 4\pi\rho$$
$$\nabla\cdot\boldsymbol{B} = 0$$

$$\nabla\times\left(\alpha\boldsymbol{E} + \frac{\boldsymbol{\beta}}{c}\times\boldsymbol{B}\right) = -\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t}$$

$$\nabla\times\left(\alpha\boldsymbol{B} - \frac{\boldsymbol{\beta}}{c}\times\boldsymbol{E}\right) = \frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} + \alpha\boldsymbol{j} - \rho\boldsymbol{\beta}$$

(R) = radiation reaction force, photon emission, pair production mechanisms

Same as for test particles in GRMHD

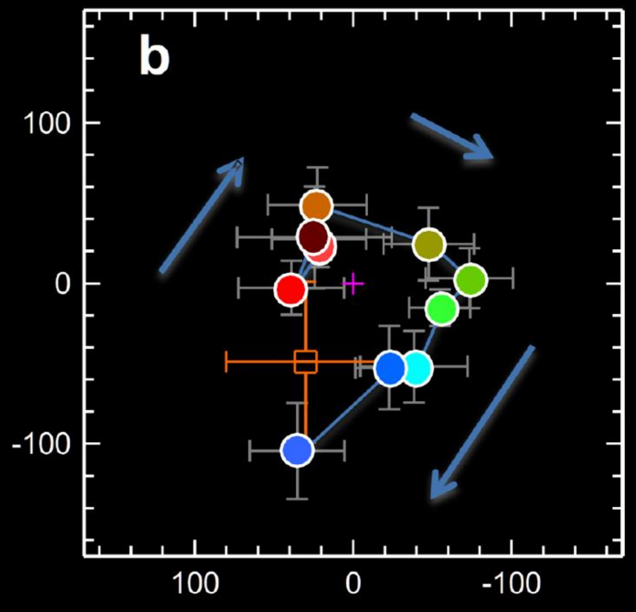
Solve particle equations of motion on a grid according to geodesic motion and Lorentz force

Particle's charge and current is source for Maxwell's equations (as opposed to Ohm's law)

[Parfrey et al, PRL (2019), Crinquand et al, PRL (2020); Bacchini, Ripperda et al., ApJS (2020); Zou, Hakobyan, Mbarek, Ripperda et al, PRD, (2025)]

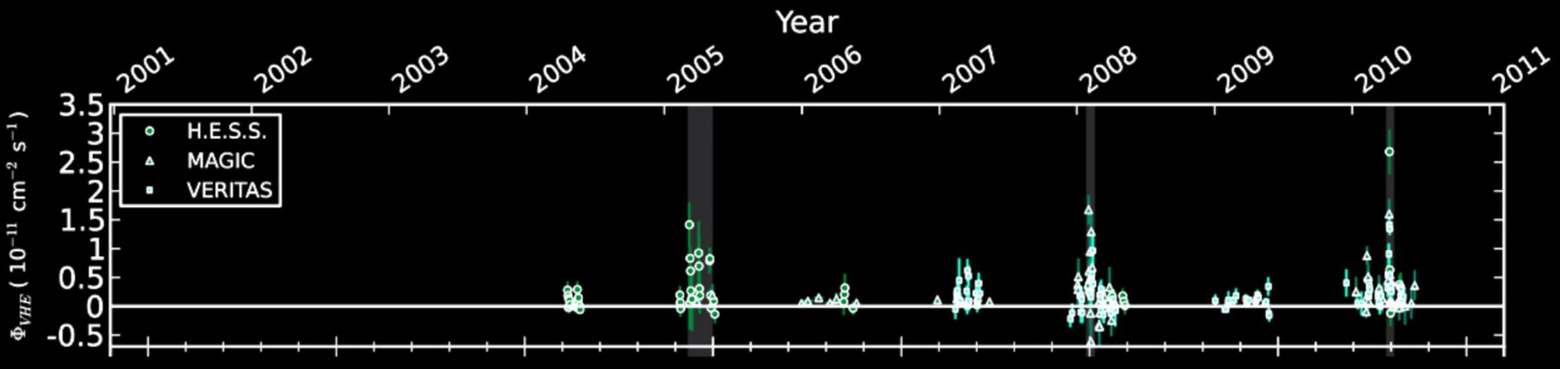
Canonical example: Sgr A* and M87*

[EHT collaboration (**incl. Ripperda**), ApJL, 2019]

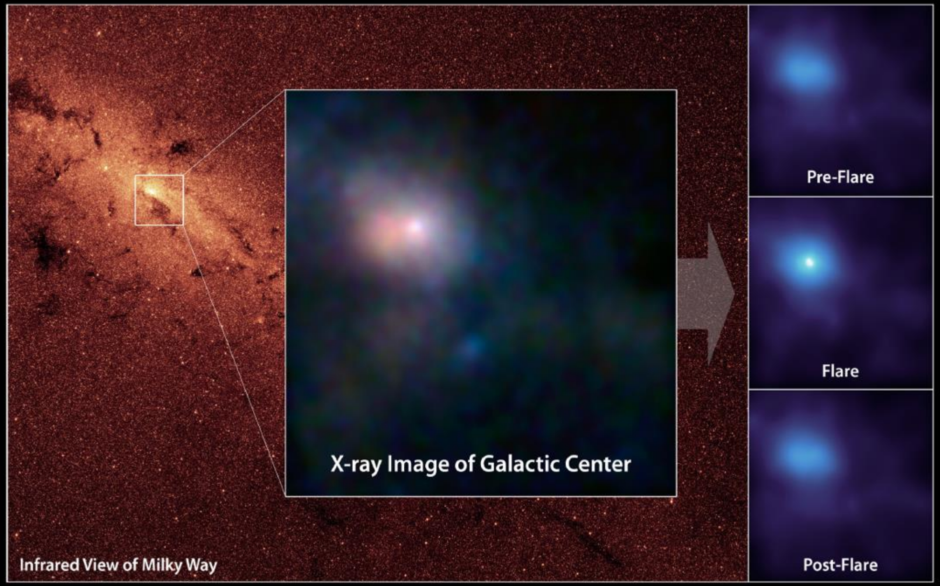


[GRAVITY collaboration, A&A, 2018]

- Conditions imply macroscopically collisionless, but strongly magnetized plasma
- Large-scale jet is observed for M87
- Multiwavelength flares (IR/X-ray for Sgr A*, X-ray/gamma-ray for M87) from near event horizon
- How can we combine MHD and PIC methods to study large and small scales



[Abramowski et al, ApJ, 2012]



How to accelerate plasma to power high-energy radiation?

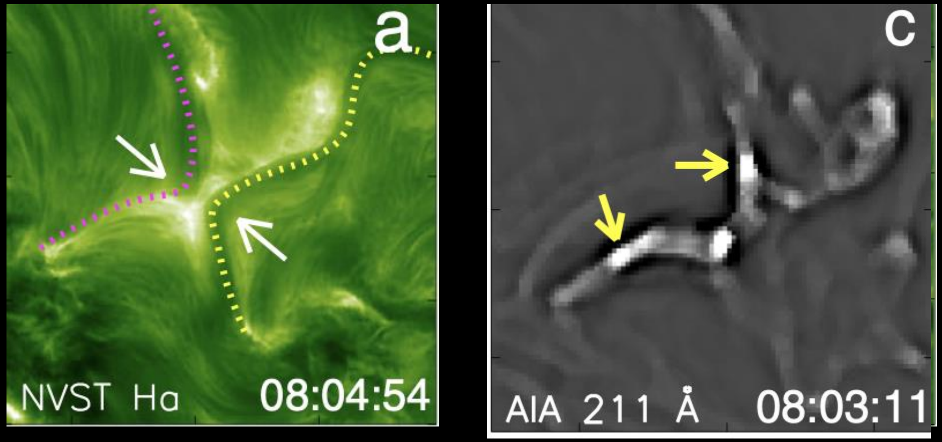
Often invoked flaring mechanism based on solar physics: magnetic reconnection

Large magnetic field reservoir accelerates and heats particles

“quick” reconnection rate of $\frac{v_{in}}{v_{out}} = 0.1$ can explain time scale of energy conversion powering flares

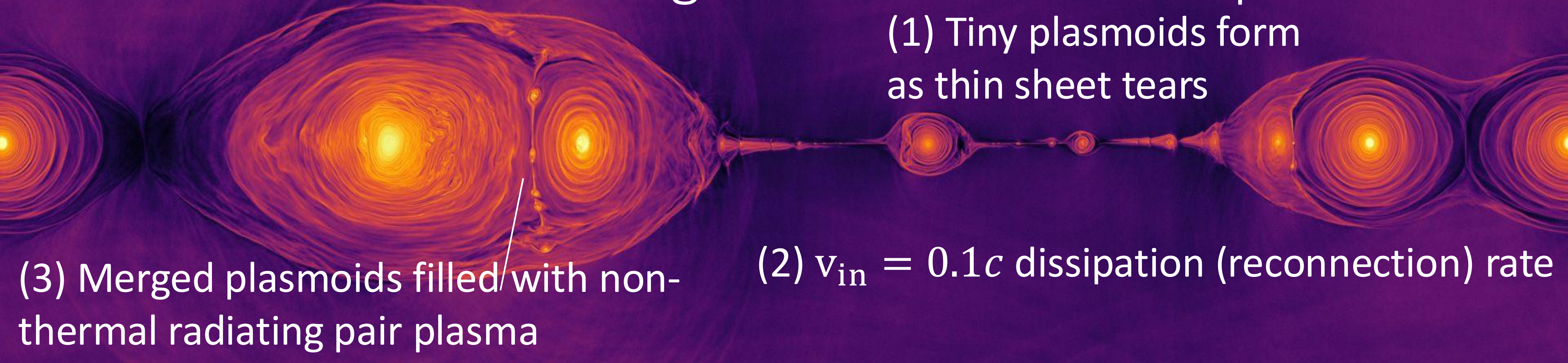
Does this happen under extreme plasma conditions near the event horizon?

Plasmoids!



[Yan et al, Nature, 2022]: Fast plasmoid-mediated reconnection in a solar flare

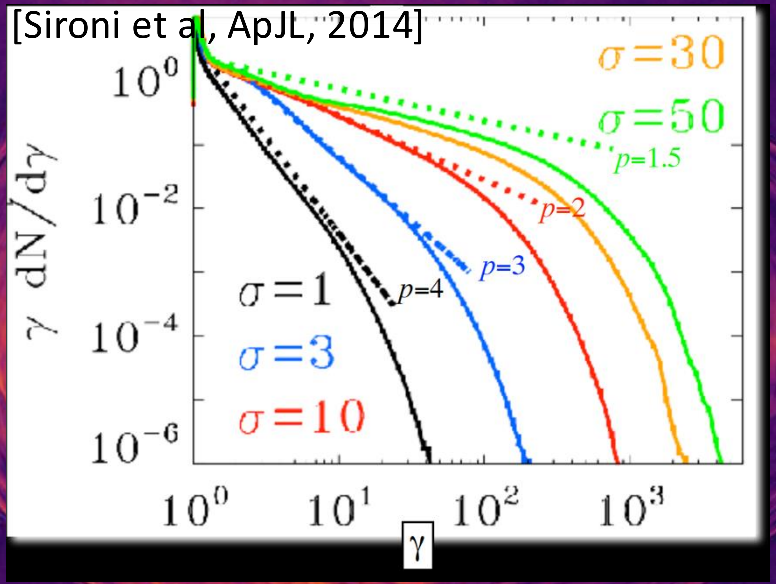
Reconnection in magnetized collisionless plasma

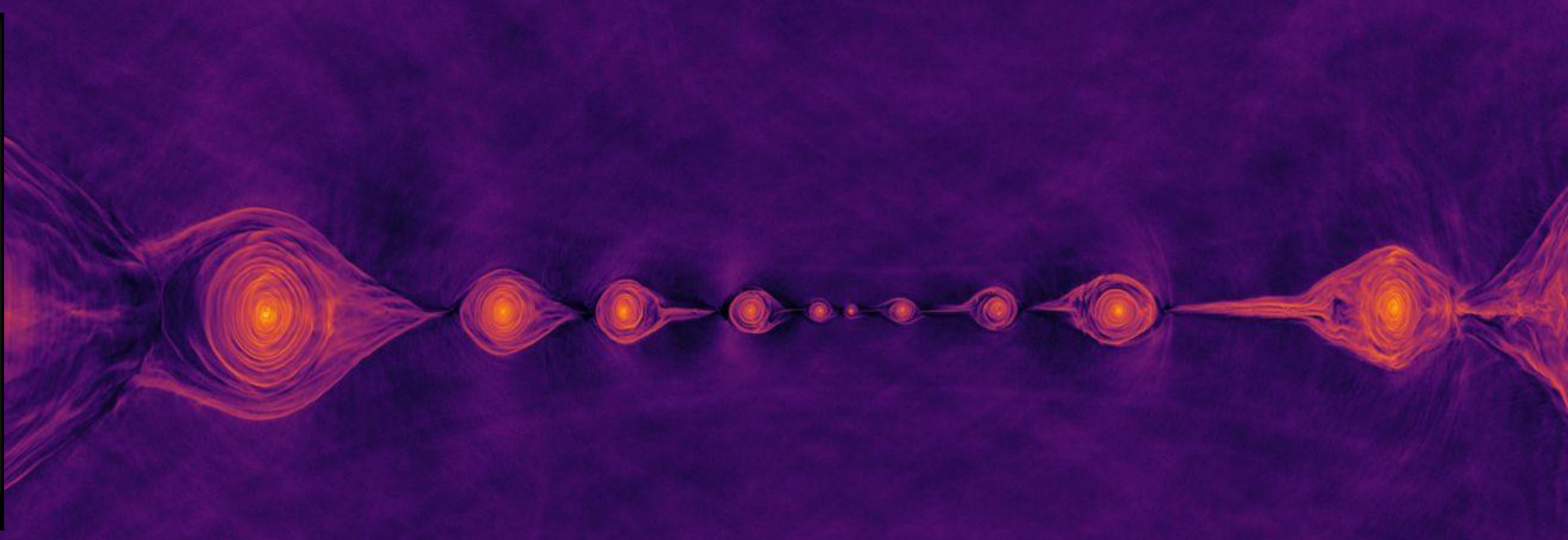


(1) Tiny plasmoids form as thin sheet tears

(2) $v_{in} = 0.1c$ dissipation (reconnection) rate

(3) Merged plasmoids filled with non-thermal radiating pair plasma





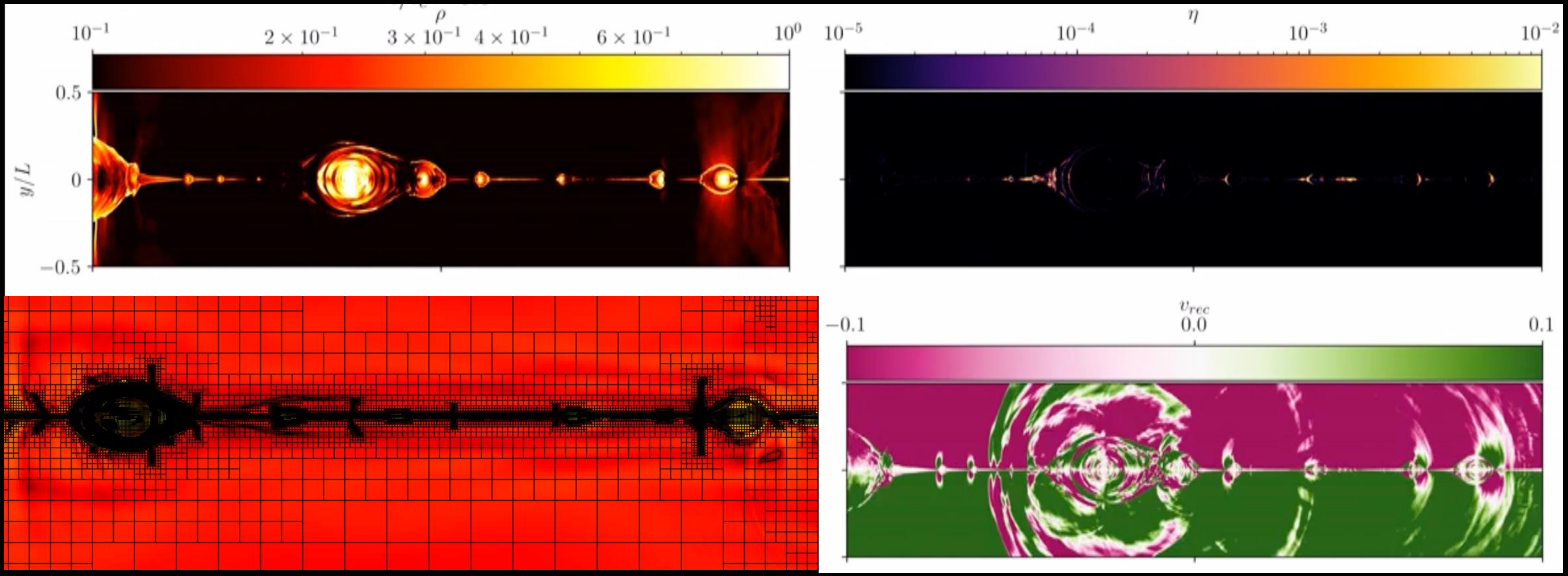
Kinetic (particle-in-cell) simulation: [Werner et al, MNRASL, 2019]

Selvi et al (incl Ripperda), ApJ (2023)
Moran et al (incl Ripperda), ApJL (2025)
Bugli et al, A&A (2025)

Relativistic reconnection in MHD



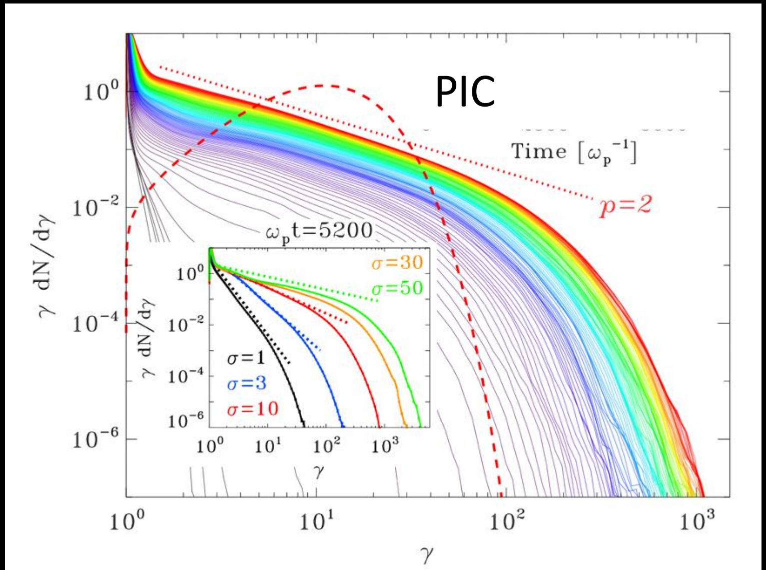
- Full PIC simulations for pair plasma show: X-points are charge-starved and $\left(\nabla \times \vec{B}\right)_z = J_z \sim q n_e c$
- Ohm's law $E_z = \eta J_z = \eta q\, n_e c$ → $\eta = \frac{E}{q n_e c} \sim \frac{m_e E}{q \rho c}$ → depends on resistive electric field and fluid density
- Reconnection through non-uniform resistivity as proxy for subgrid kinetic physics → 0.1c rate
- With adaptive mesh refinement we can capture small resistivity and resolve the dissipation
- Next: 3D [Berta, Ripperda, in prep.], add radiative cooling [Savelli, Ripperda, in prep.]: $\left(\frac{\gamma}{\gamma_{rad}}\right)^2 \rightarrow \left(\frac{T}{T_{rad}}\right)^2$



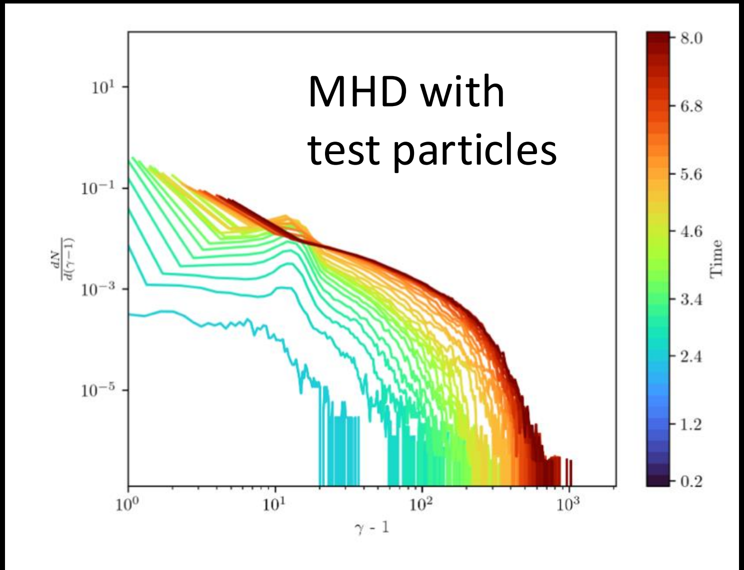
Test particles in reconnection

- Non-uniform resistivity results in realistic non-ideal electric fields
- Particles with $r_L \sim$ length scale of non-ideal field accelerate to high energy, similar to PIC results
- Test particles in resistive MHD quantitatively reproduce PIC results → promising for global resistive GRMHD simulations

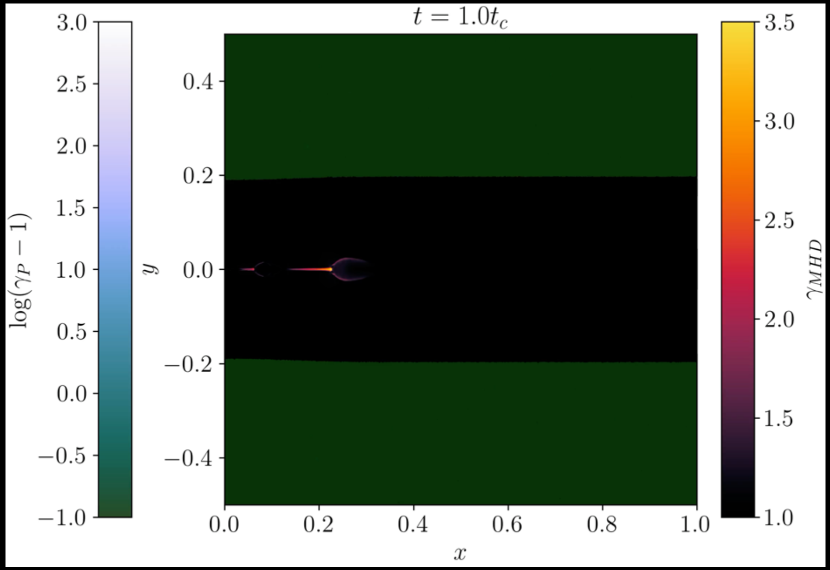
Next: study particle acceleration in black hole magnetospheres, jets, coronae



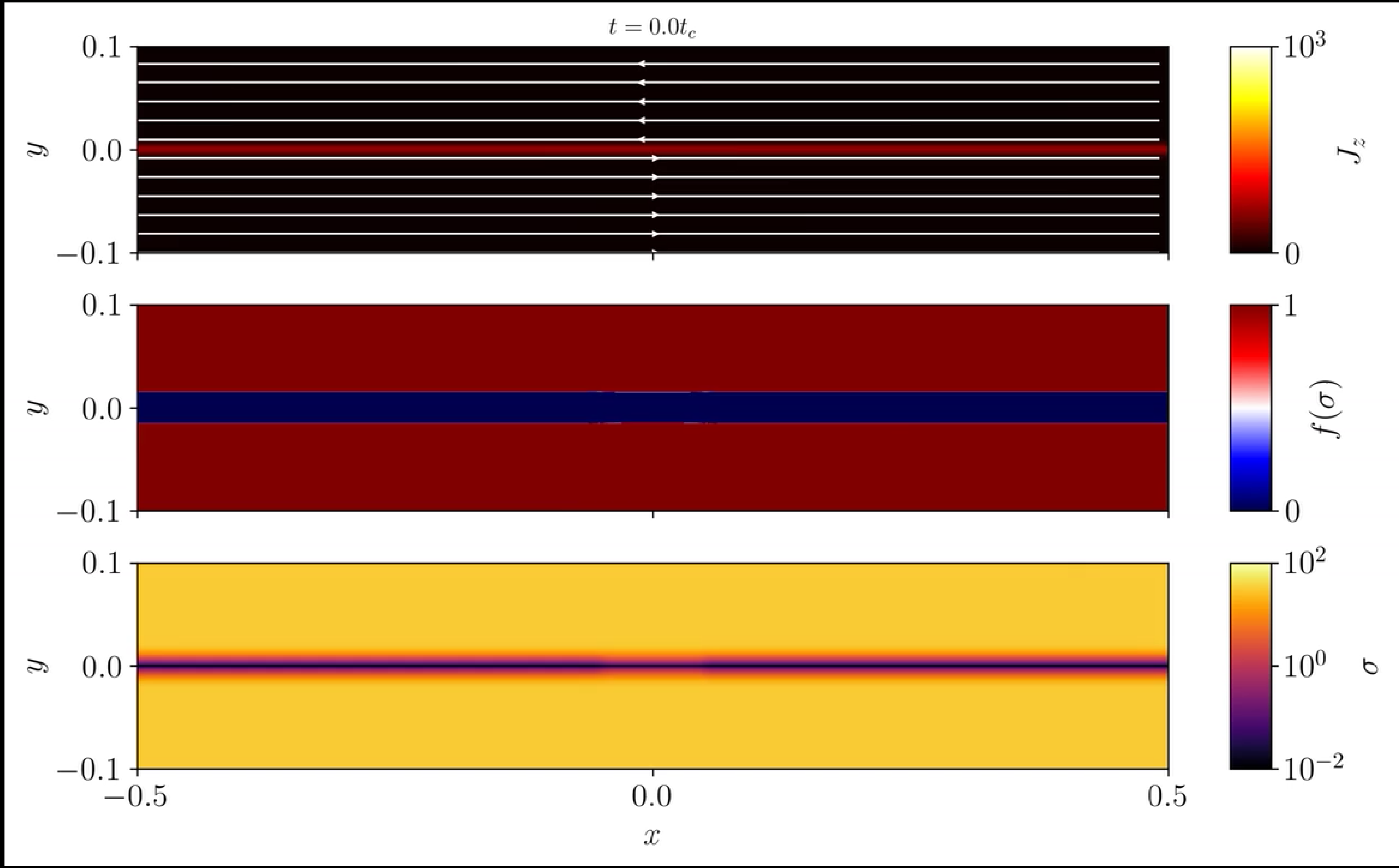
Sironi & Spitkovsky, ApJL (2014)



Ghosal, Ripperda, et al, in prep.



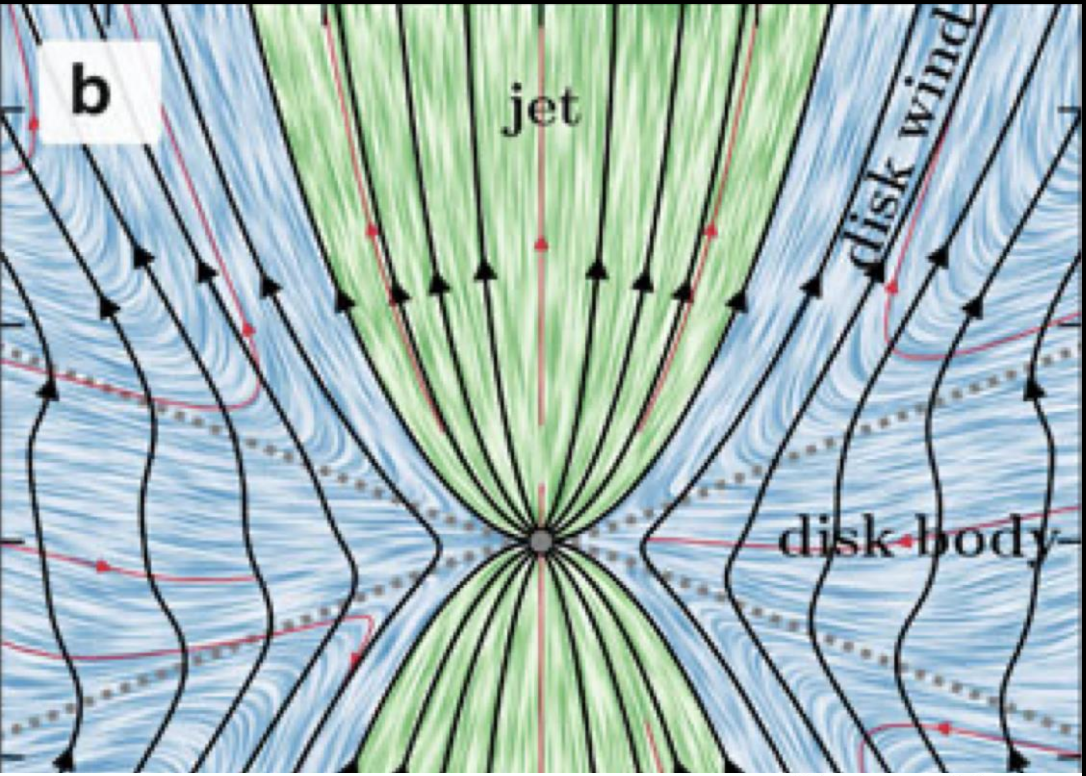
Force-free MHD Coupling: Current sheet

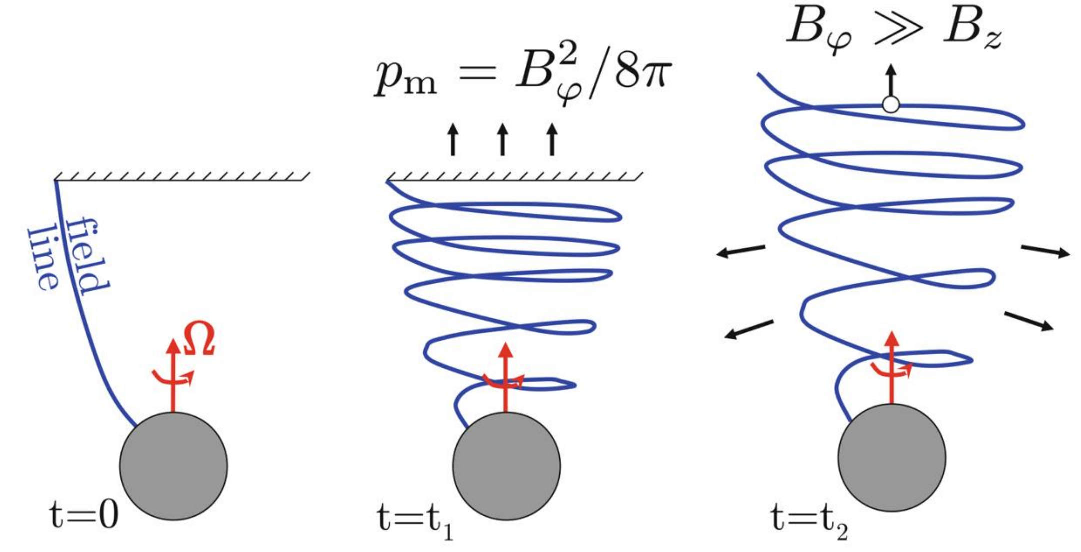


$$\boldsymbol{J} = (1 - f(\sigma))\, \boldsymbol{J_{MHD}} + f(\sigma) \boldsymbol{J_{FF}}$$
$$f(\sigma) = 0.5 + 0.5 \tanh(\sigma - \sigma_{th})$$

[Ripperda et al, in prep.]

What do we know about magnetic field around black holes





Theoretical picture [Blandford, Znajek, MNRAS, 1977]

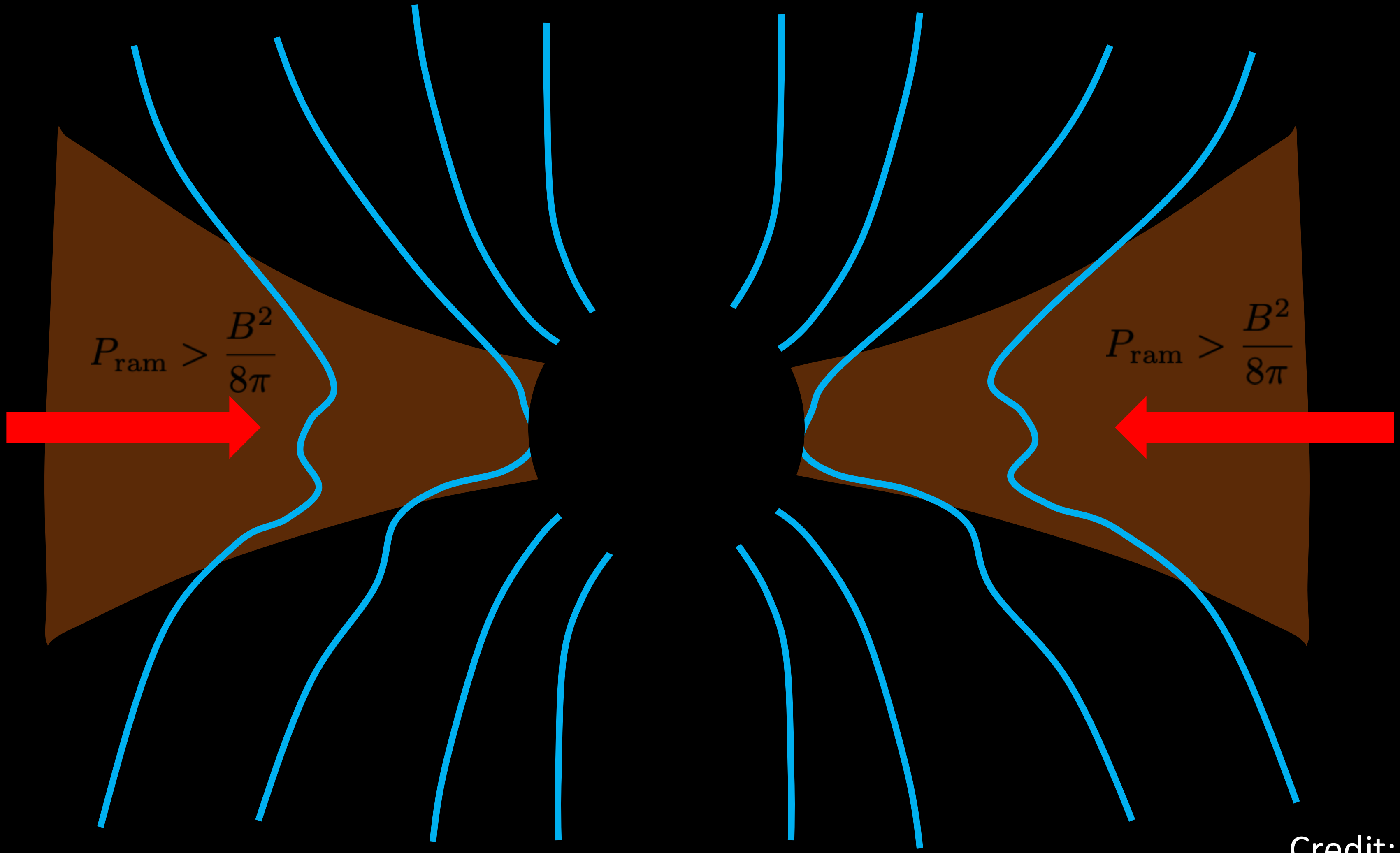
Infalling magnetic field co-rotates with black hole to produce outward Poynting flux → jet

GRMHD simulations of infalling weakly magnetized gas reproduce magnetic field dynamics of the BZ picture [Tchekhovskoy, A&SS, 2015]

Do we see any magnetic reconnection? → need high-resolution

What do we know about magnetic fields near the horizon

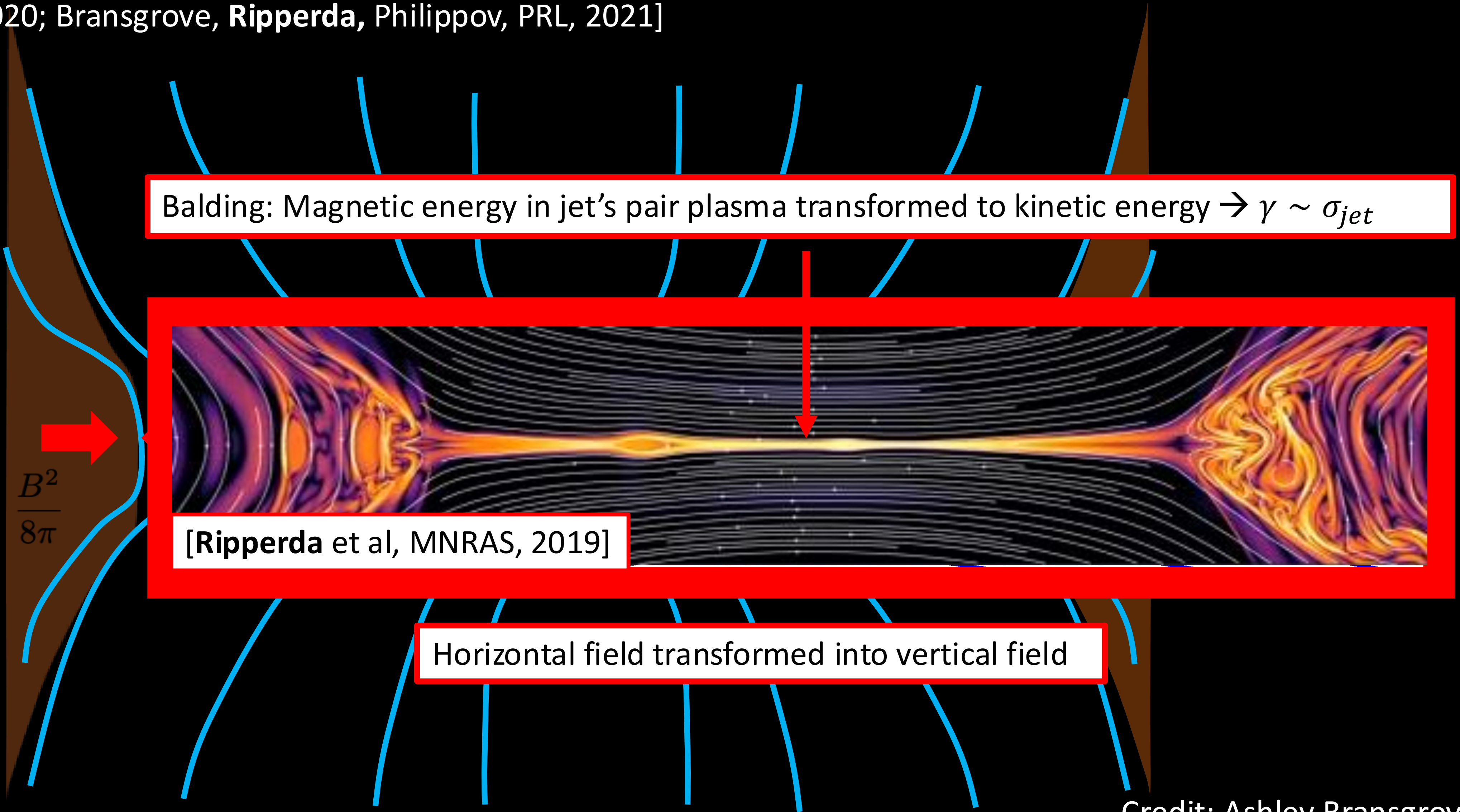
Accretion cycle of magnetically arrested state starts with infalling cold weakly magnetized gas



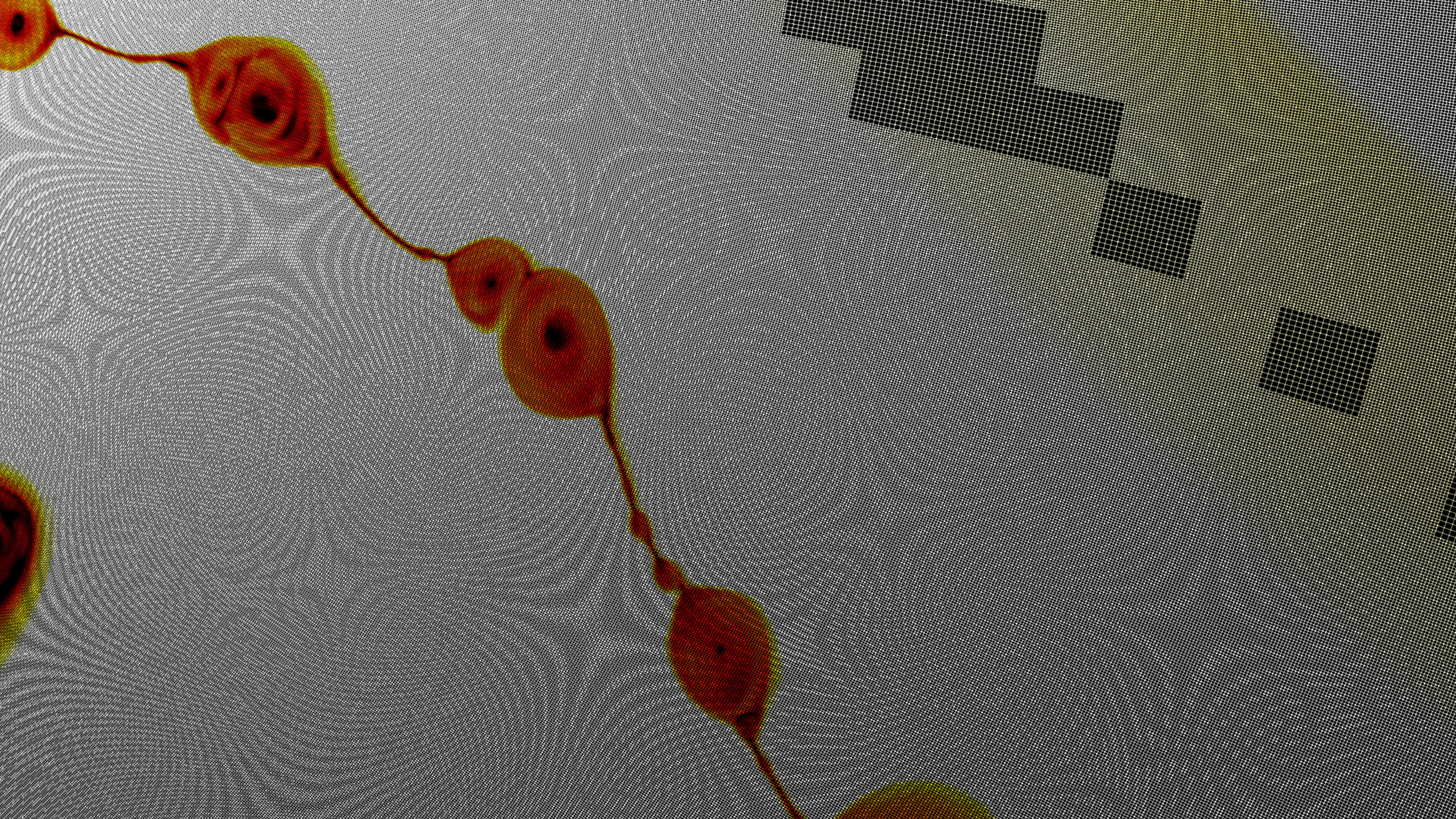
Credit: Ashley Bransgrove

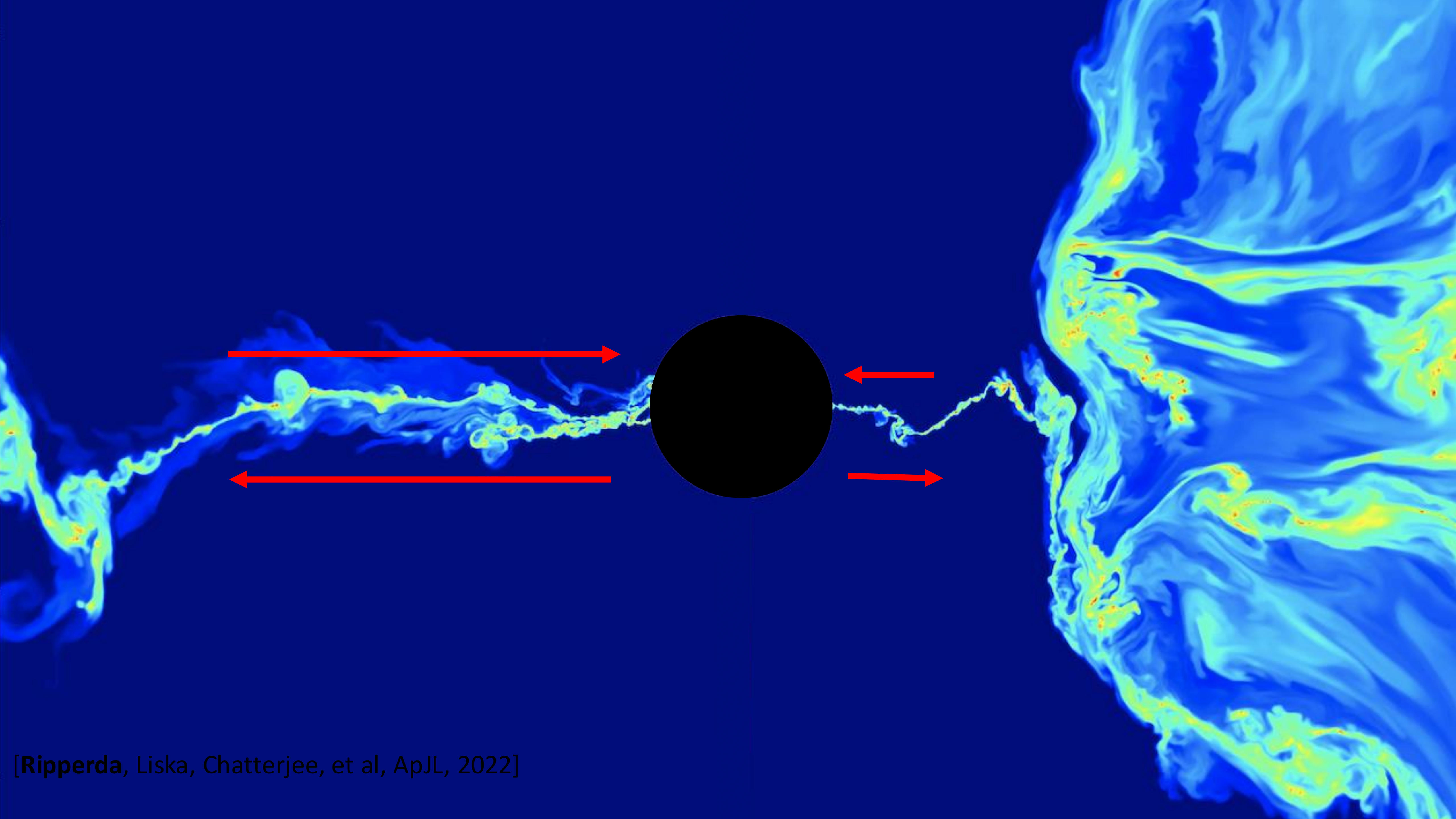
What do we know about magnetic fields near the horizon

Idea: Episodically flux builds up to maximum $p_{gas} \sim B^2/8\pi$, then magnetic reconnection expels magnetic field to power flare [**Ripperda** et al, ApJ, 2020; Bransgrove, **Ripperda,** Philippov, PRL, 2021]



Credit: Ashley Bransgrove



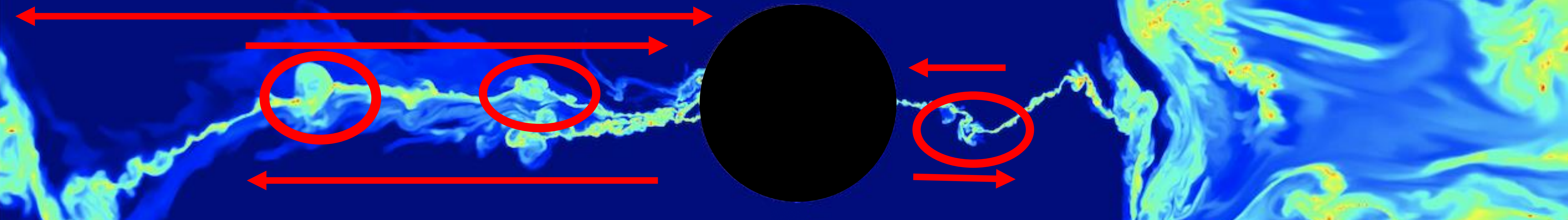


[**Ripperda**, Liska, Chatterjee, et al, ApJL, 2022]

Largest 3D GRMHD simulation ever zooms into Event Horizon

Take-away from 3D GRMHD:

- Transient non-axisymmetric macroscopic reconnection layer and ejected disk in accretion duty cycles
- Jet’s reconnected magnetic energy can power a very high energy flare
- Reconnection is essential in accretion duty cycle to redistribute magnetic flux!



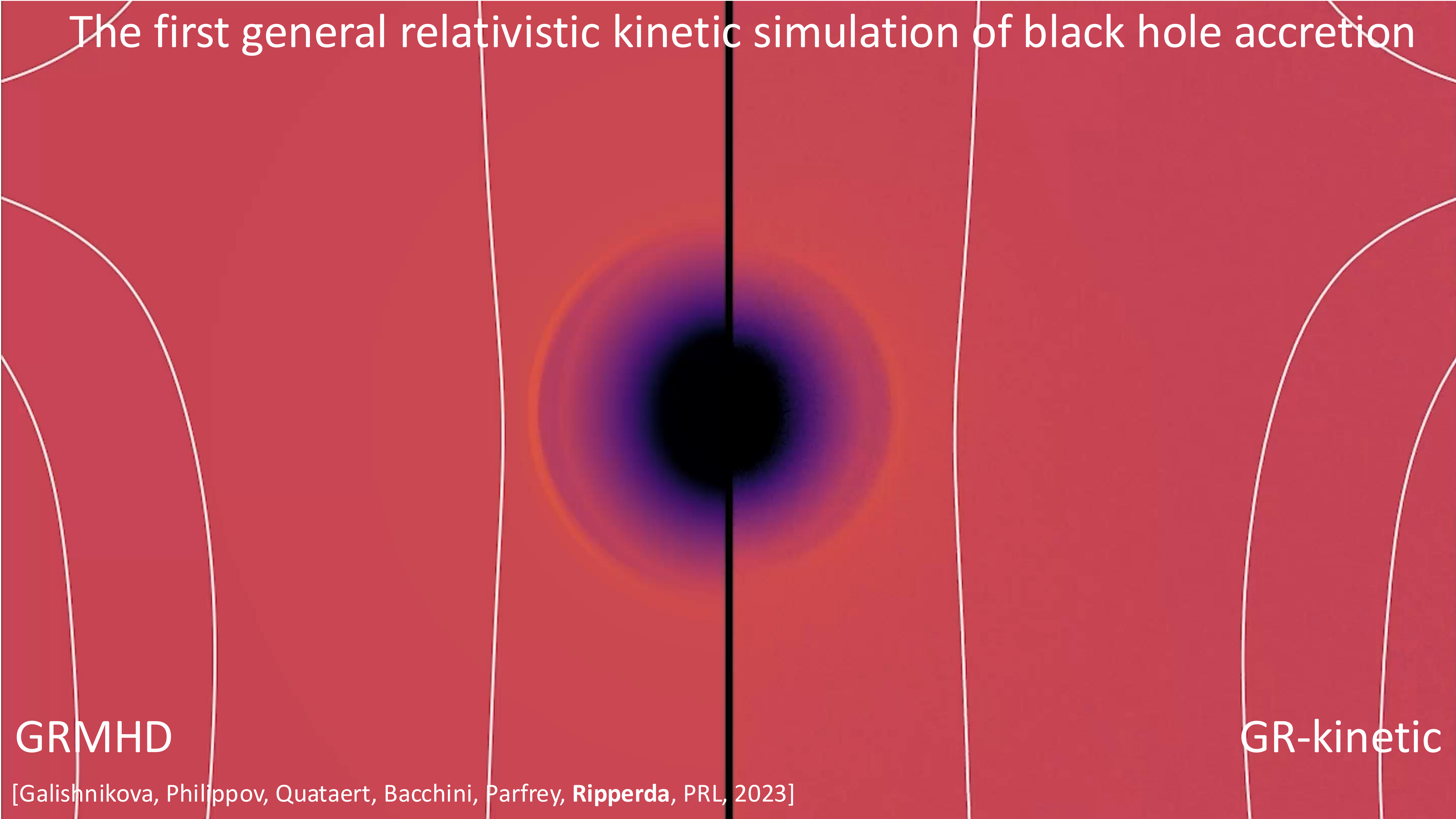
- Resolving fast reconnection requires $\geq 5000 \times 2500 \times 2500$ cells
- $> 10 \times 10 \times 10$ larger than our EHT simulations → 2.1×10^6 GPU hours on 6000 GPU’s
- Only possible with GPU-accelerated H-AMR code! [Liska et al, arXiv:1912.10192]

Details of flare depend on collisionless kinetic plasma dynamics:

- particle acceleration, radiation, pair creation

[**Ripperda,** Liska, Chatterjee, et al, ApJL, 2022]

The first general relativistic kinetic simulation of black hole accretion

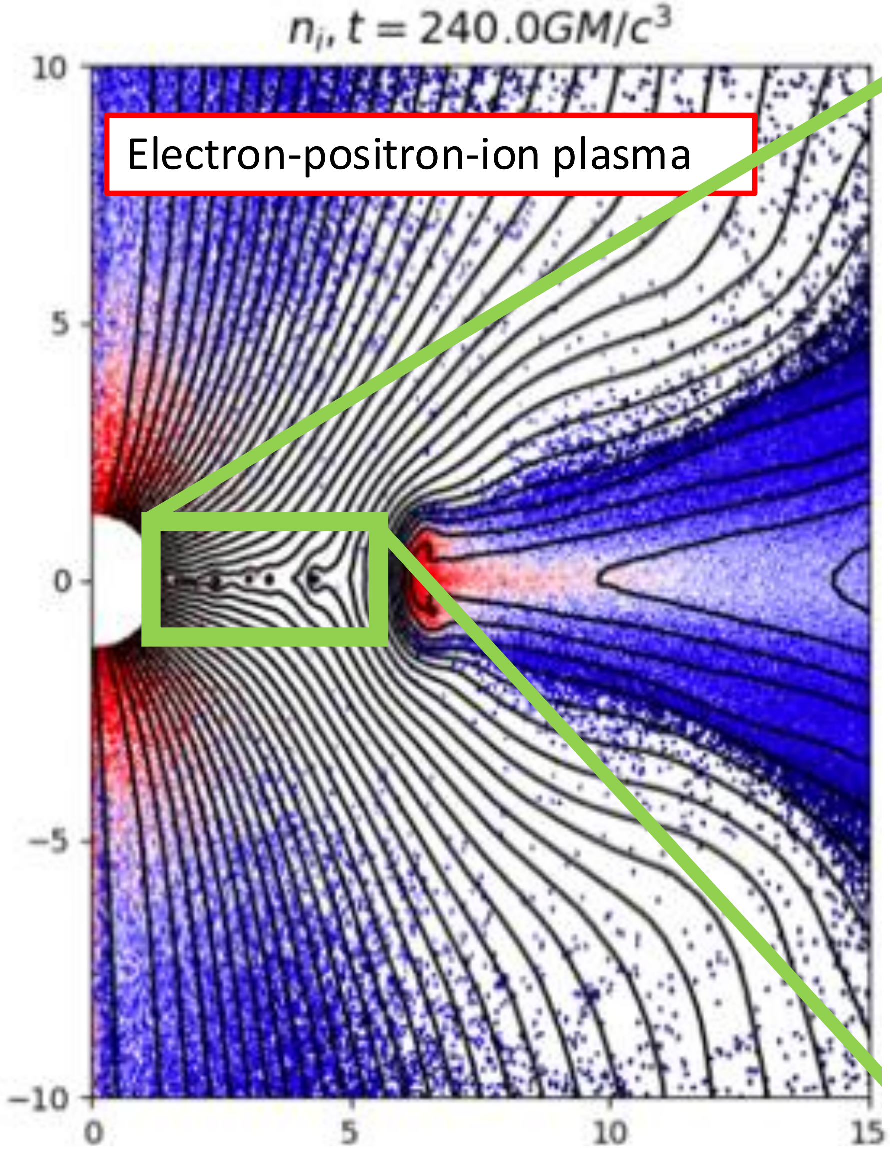


[Galishnikova, Philippov, Quataert, Bacchini, Parfrey, **Ripperda**, PRL, 2023]

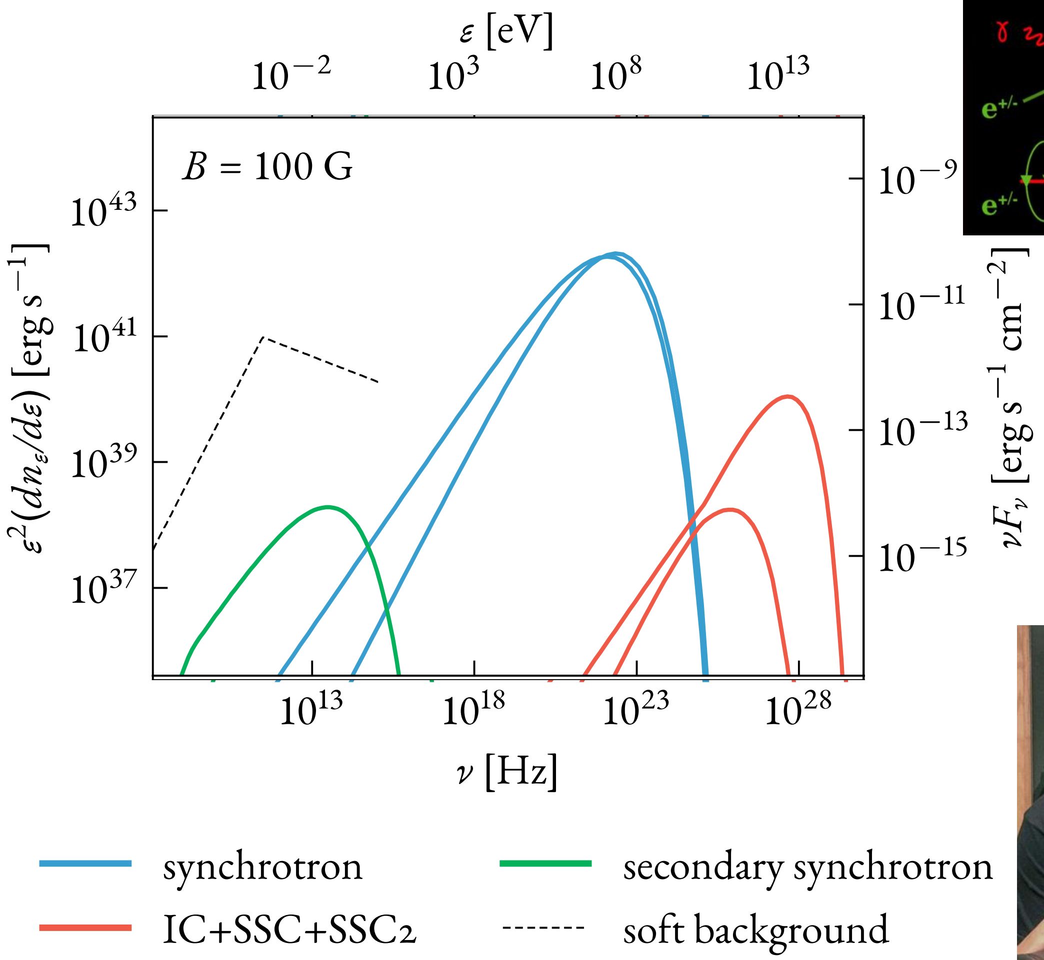
M87 flares with all physics: GR, radiation, QED, and kinetic physics at the horizon

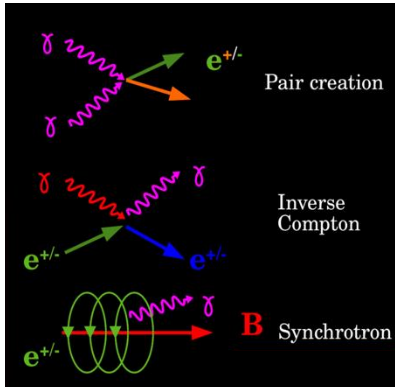
First collisionless accretion in GRPIC

First PIC simulation with fully dynamic IC, synchrotron and pair production



power-law electrons/positrons are considered $f_{e\pm} \propto \gamma^{-p} e^{-\gamma/\gamma_c}$
with $\gamma_c \sim$ 1-10 · 10^7, and $1 < p < 1.5$

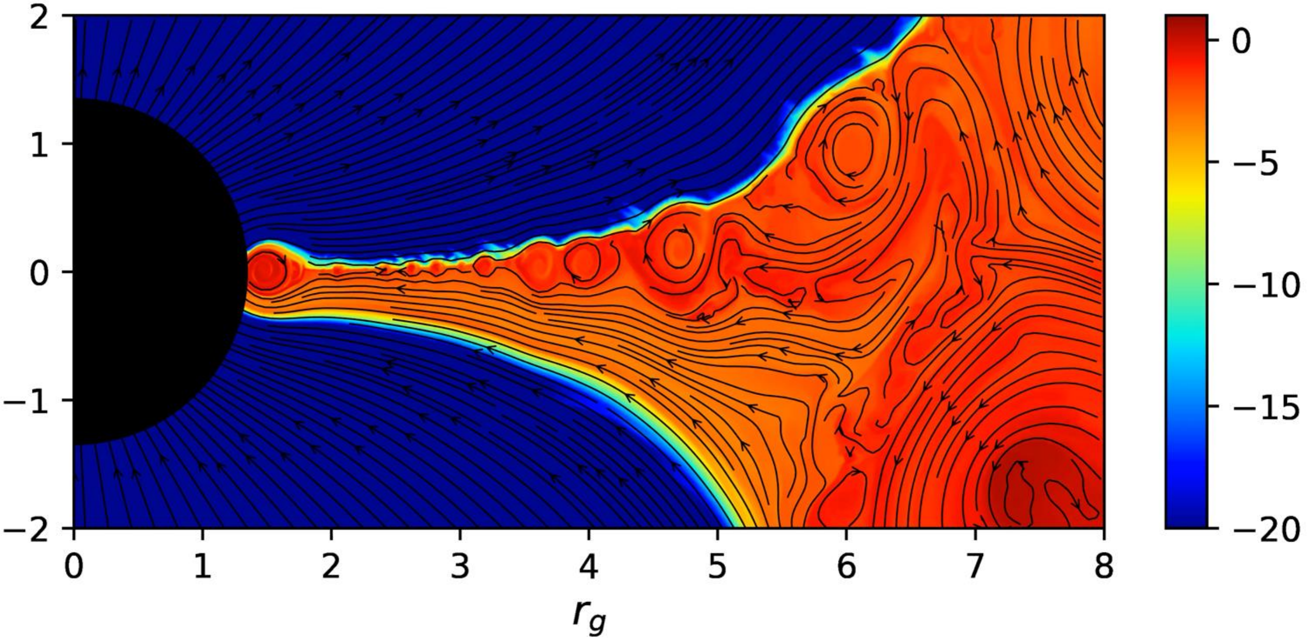




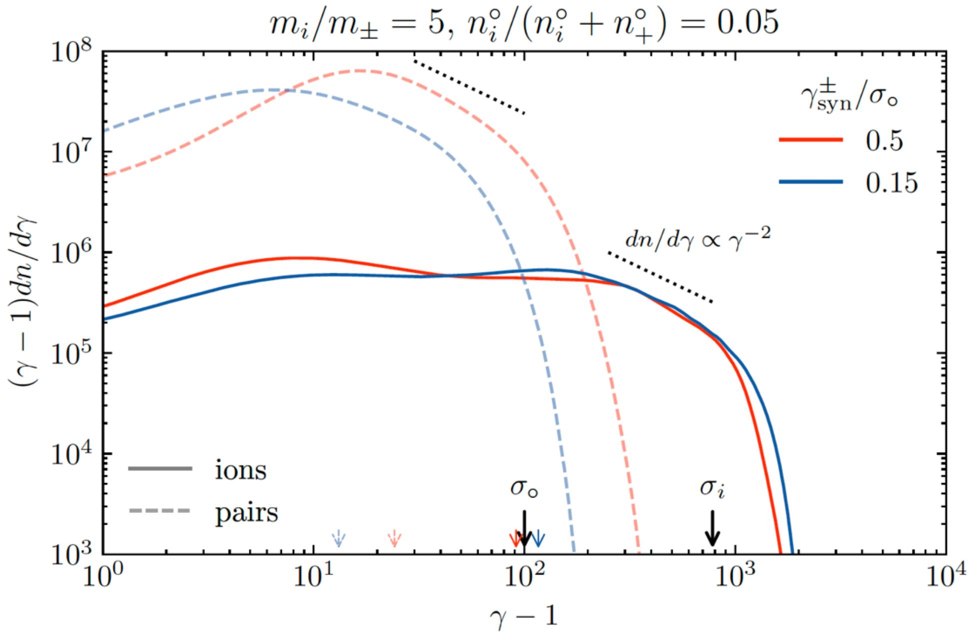
[Galishnikova, Philippov, Quataert, Bacchini, Parfrey, **Ripperda**, PRL, 2023]

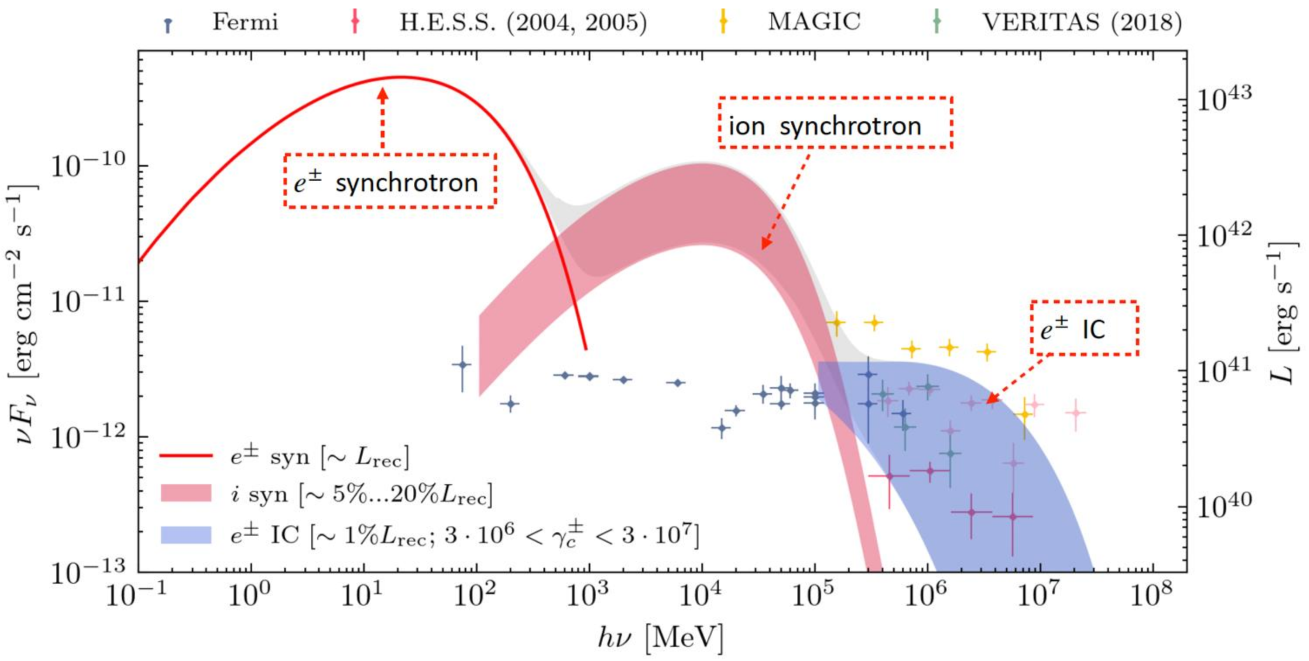
[Hakobyan, **Ripperda**, Philippov, ApJL, 2023]

Prediction: Accelerated protons could power GeV flare from M87



- We evolve a tracer to measure protons from disk ending up in reconnection layer
- We use PIC simulation including radiative interactions for proton acceleration



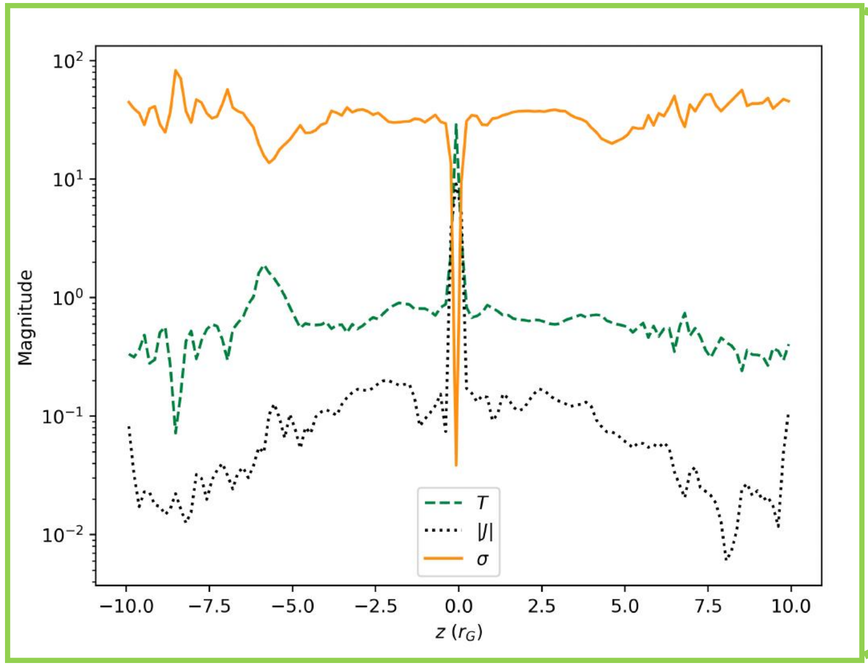


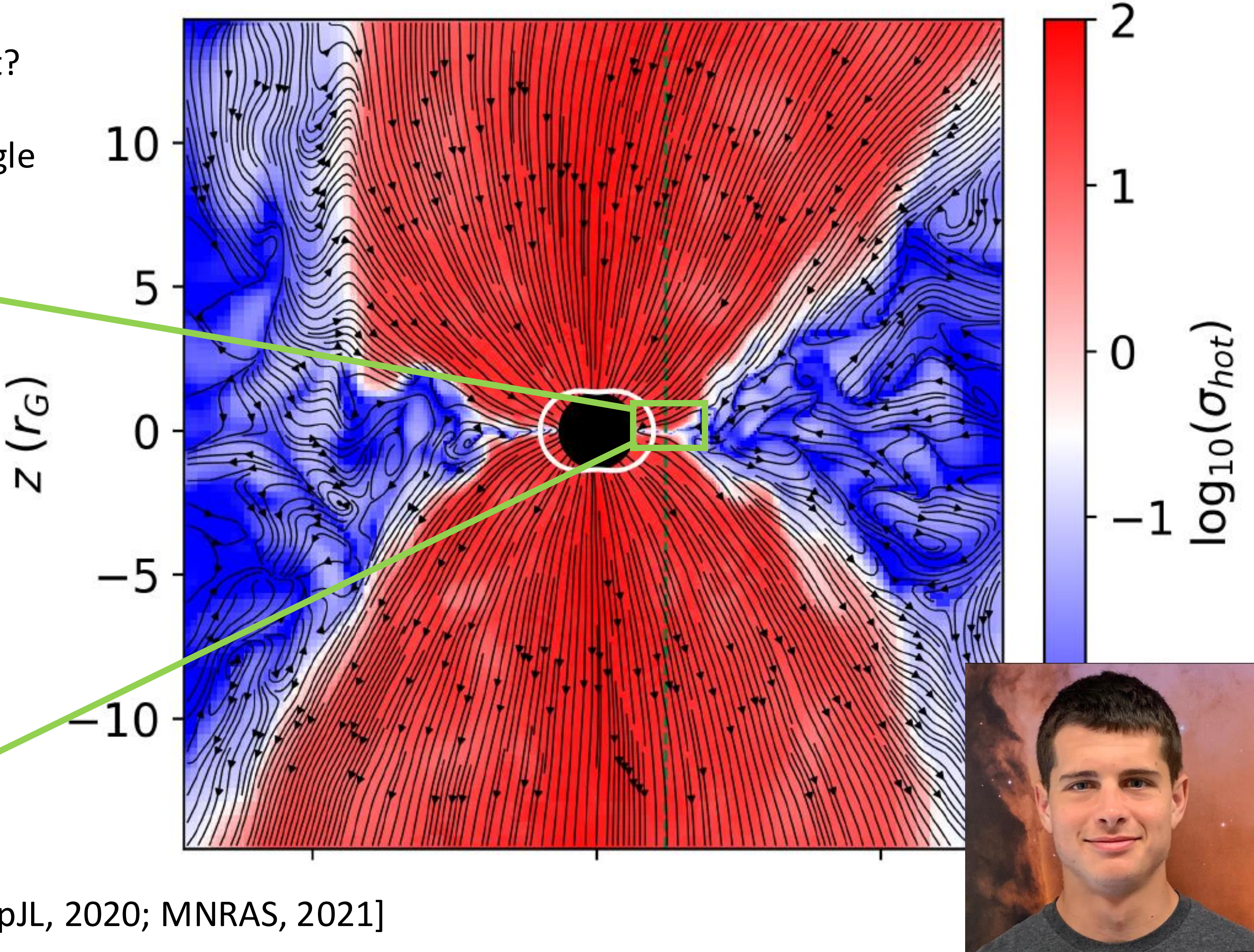
[Algaba et al (incl Ripperda), A&A (2024); Chow et al (incl Ripperda), in prep; Hakobyan et al (incl Ripperda), in prep.]

What is the magnetic structure of the accretion flow of Sgr A*?

Starting from unmagnetized wind-fed accretion, a magnetically arrested low-angular-momentum near-spherical accretion forms

- Supported by observations [EHT (incl. Ripperda, ApJL, 2022)]
- Jet destroyed by kink instability? → Sgr A* jet?
- Does it always go MAD?
- Balding happens but sometimes under an angle

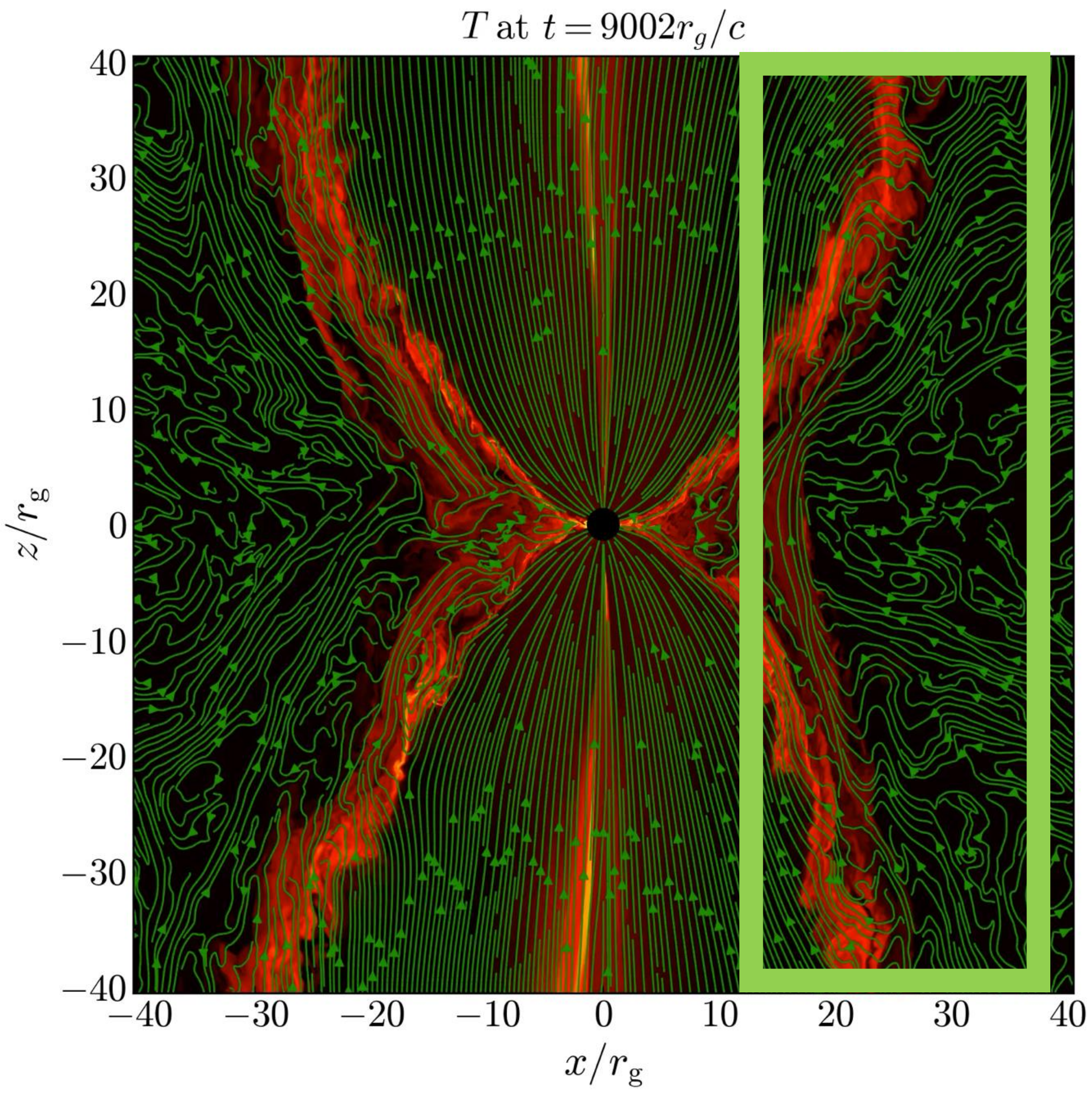


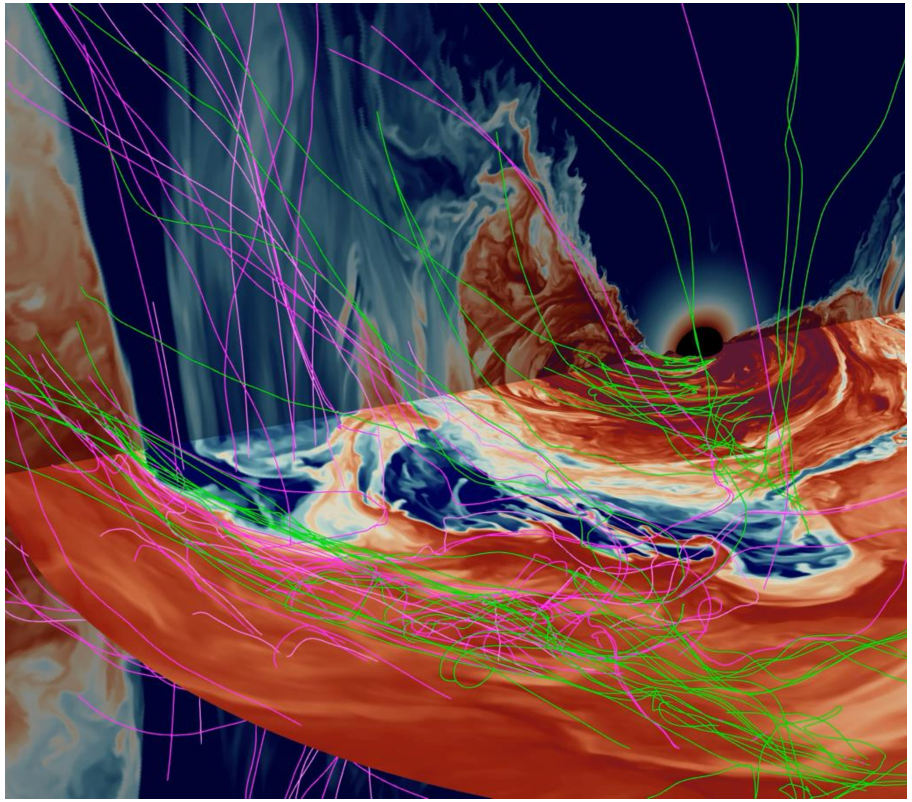


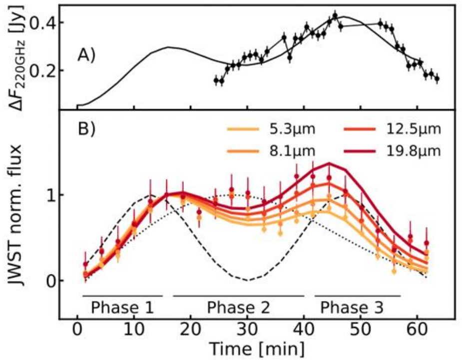
[Ressler et al, ApJL, 2020; MNRAS, 2021]

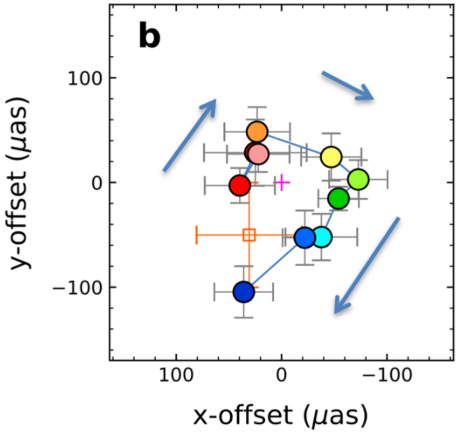
Can we model Sgr A*'s orbiting flares?

von Fellenberg et al (incl Ripperda), ApJL (2025)









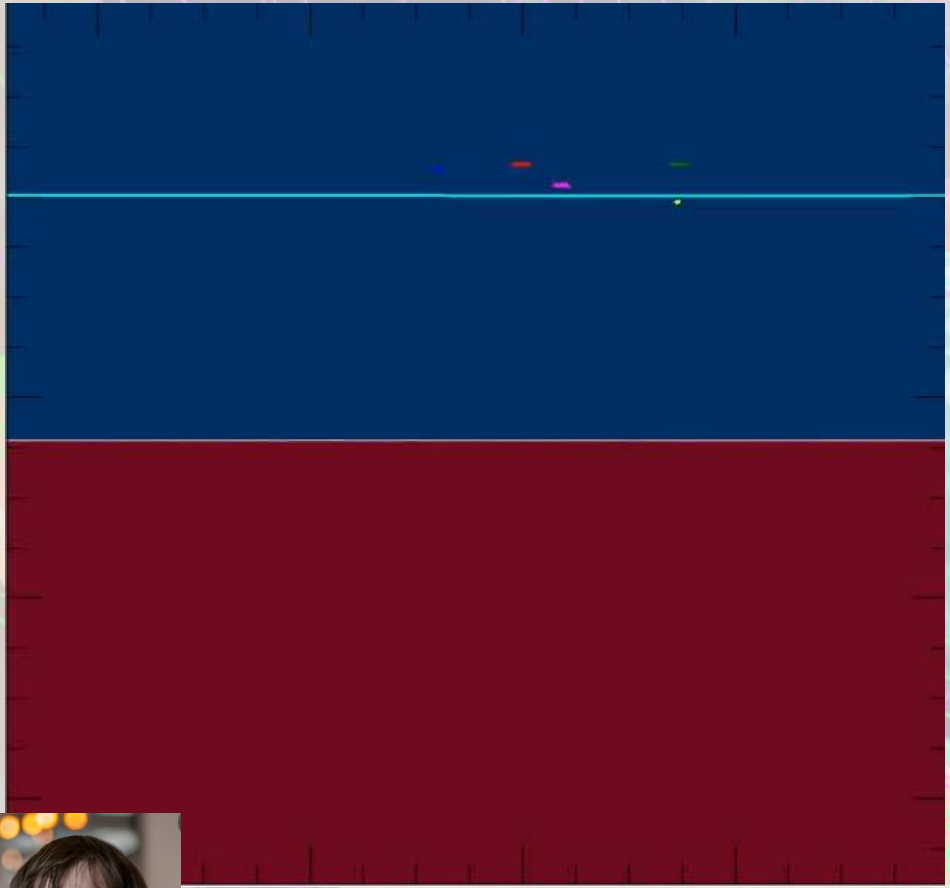
[GRAVITY, A&A, 2018]:

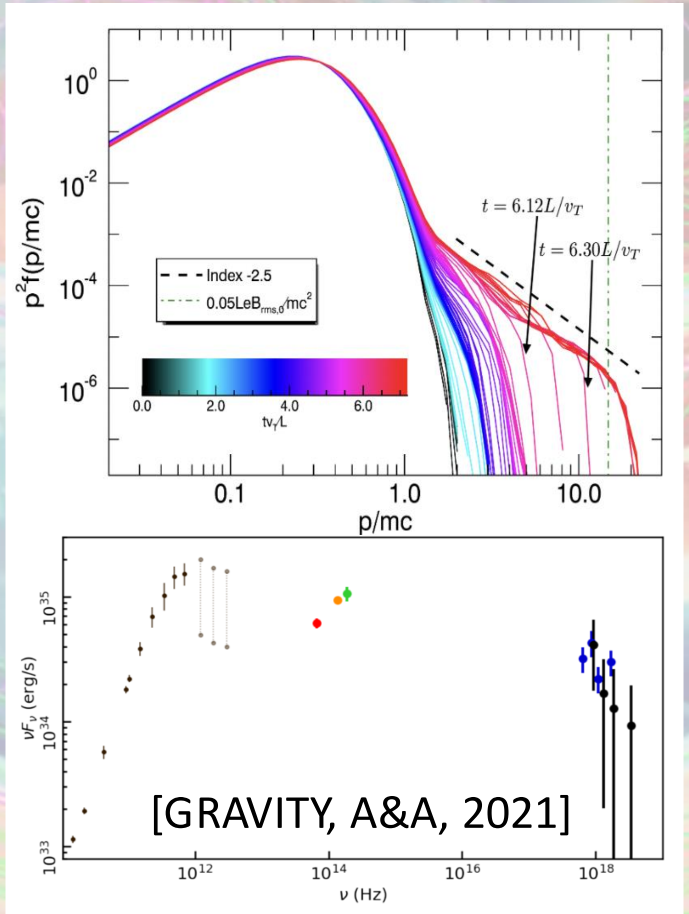
Reconnection expels orbiting hot spot with vertical field confining pair plasma
Rayleigh-Taylor instability develops on low-density hot spot → powers flare?

[Gail, Ripperda, et al, in prep]

Can Rayleigh-Taylor instabilities power the observed NIR flare?

Black hole





Power law index power-law index from RTI-induced reconnection:

$$\alpha \approx -2.5$$

synchrotron spectrum with

$$\alpha = 3 - 2\beta$$

matching spectral slope of flare luminosity [GRAVITY, A&A, 2021]:

$$\nu F_\nu \propto \nu^\beta$$

with $0 \leq \beta \leq 0.5$

10.00

1.00

[Zhdankin, **Ripperda**, Philippov, PRR (2023)]

3D: [Ressler, Skoutnev, Buck, Ripperda et al, in prep.]

Ambient accretion flow

Conclusions

- The future of multimessenger and plasma-astrophysics is bright with exciting new missions: ngEHT, BHEX, JWST, XRISM, AXIS, IXPE, LHAASO, IceCube, KM3NeT, DSA-2000, LISA, NANOGrav

- Solving puzzles of black holes requires (computational) plasma physics and astrophysics
- GPU-accelerated GRMHD codes can resolve essential scales in 3D
- Non-ideal MHD (resistivity, test particles, radiation, …) allows to solve questions not doable with PIC or ideal MHD
- Novel numerical methods are needed to include essential physics