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First-principles Simulations of Black-hole* Plasmas: State of the Art and Recent Advances

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Les Houches Workshop, April 8 2025

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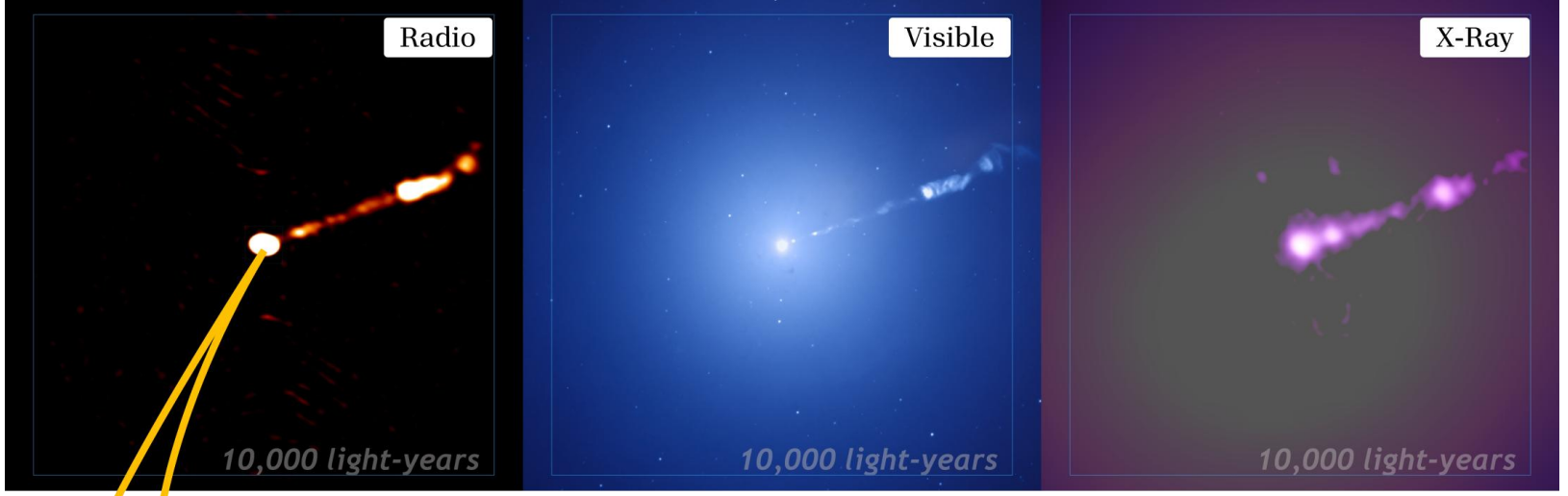
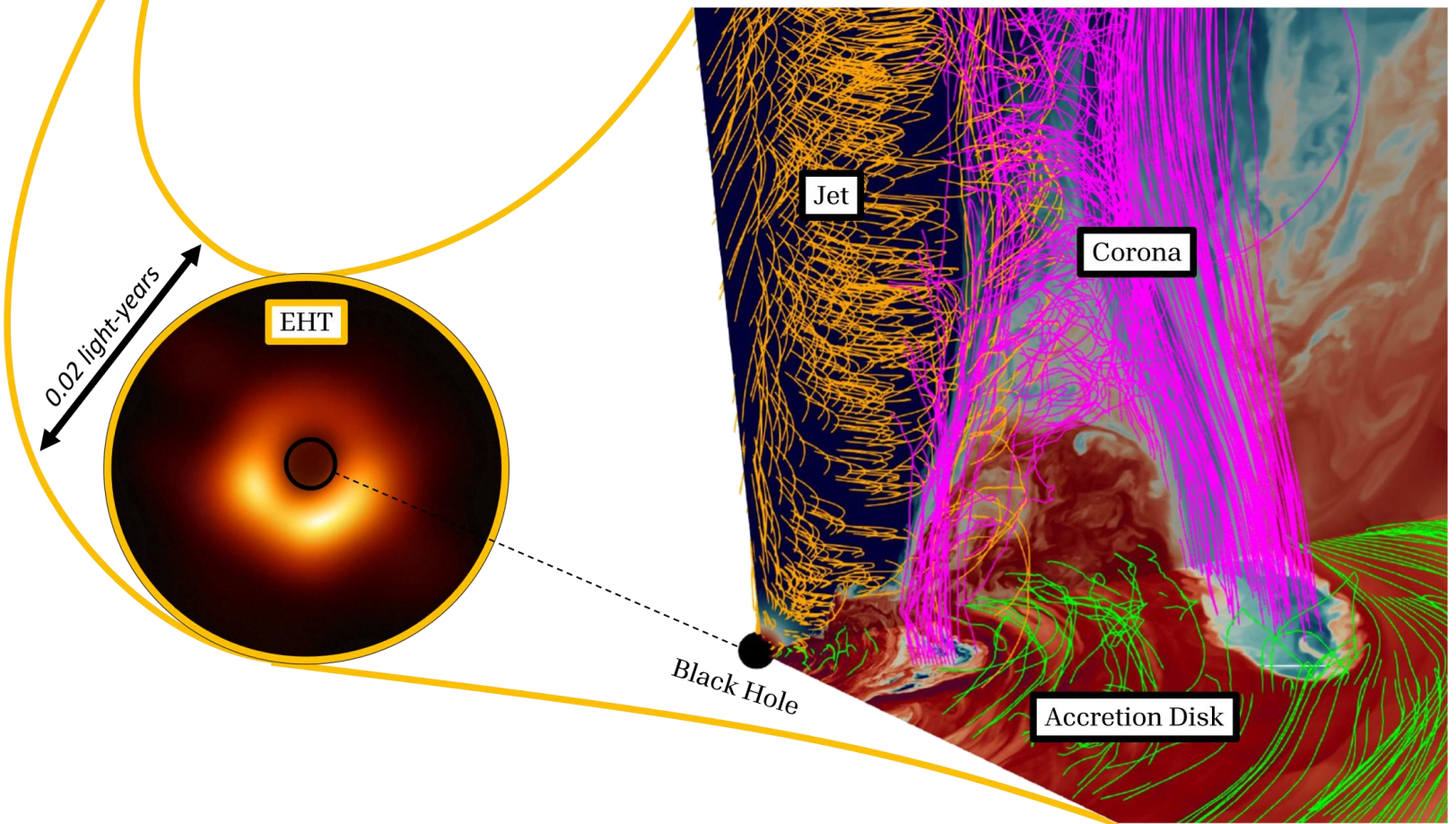
Astrophysical Plasmas: Recap



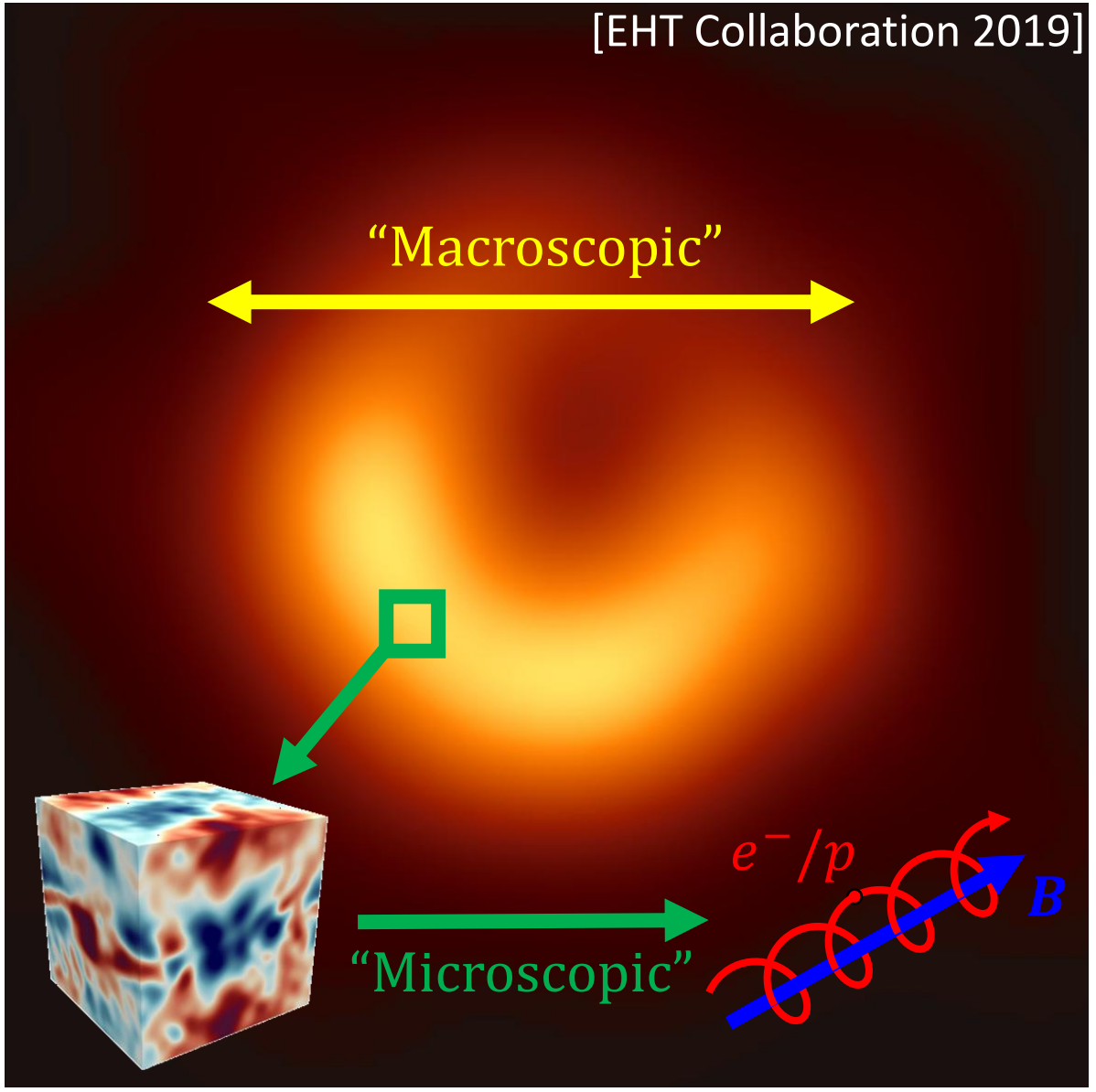


[Ripperda+2022]

Collisionless Plasmas Around Black Holes*

- Plenty of observations and theory models of AGNs (also EHT targets), XRBs, etc. point to important collisionless plasma processes

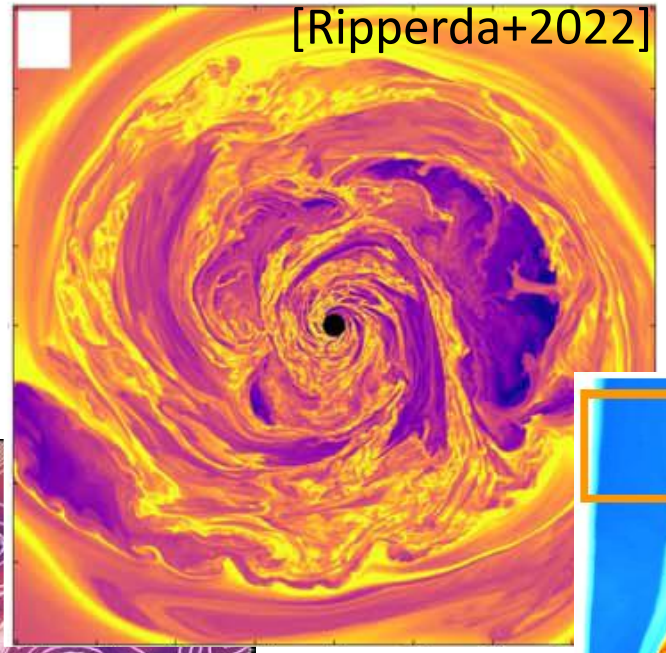
- *Black-hole* plasmas* are likely:
  - **Cross-scale: Globally structured, locally chaotic**
  - **Multispecies, multitemperature, nonthermal, …**
  - **Semirelativistic, ultrarelativistic, …**
  - **Emitting and interacting with radiation**
  - **…**
- Open questions:
  - What drives multiscale plasma dynamics? (e.g. accretion, turbulence, …)
  - What creates observable EM signals and variability?
  - How to accurately model plasma physics and radiation and connect with observations?



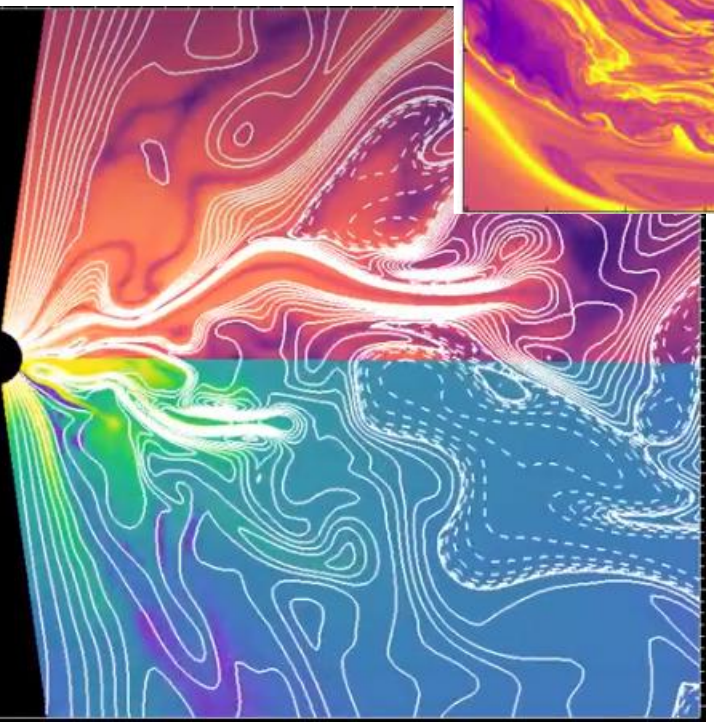
Simulations of Black-hole Plasmas: MHD

- Magnetohydrodynamics widely used for global and local simulations…

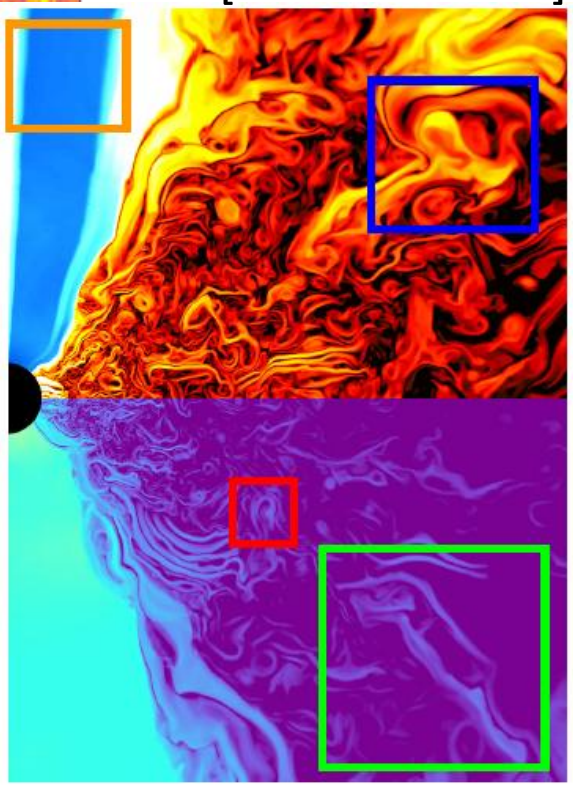
[Ripperda+2022]

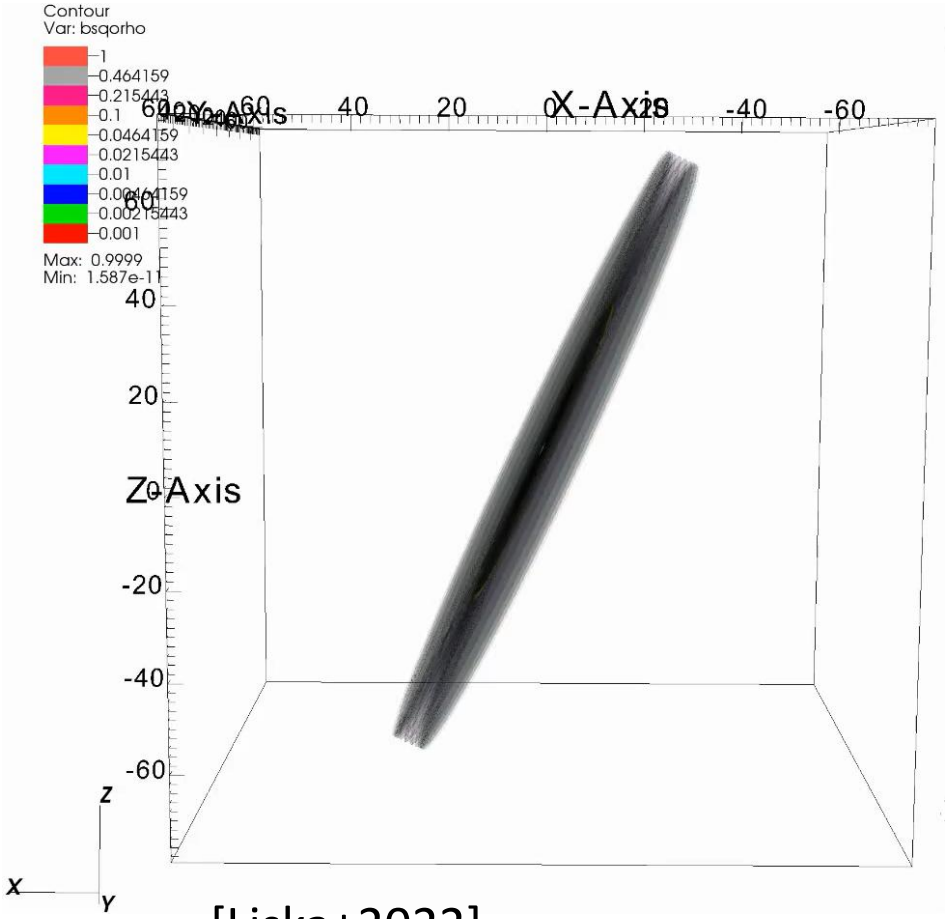


[Chael+2018]



[Bacchini+2019]



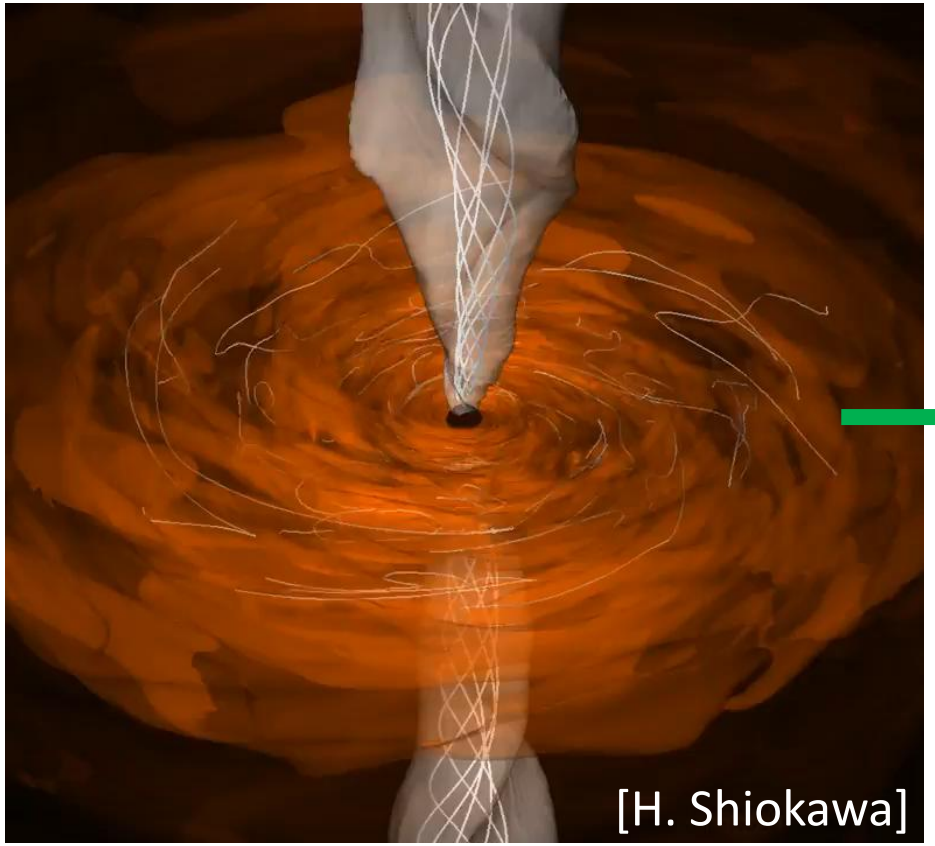


[Liska+2022]

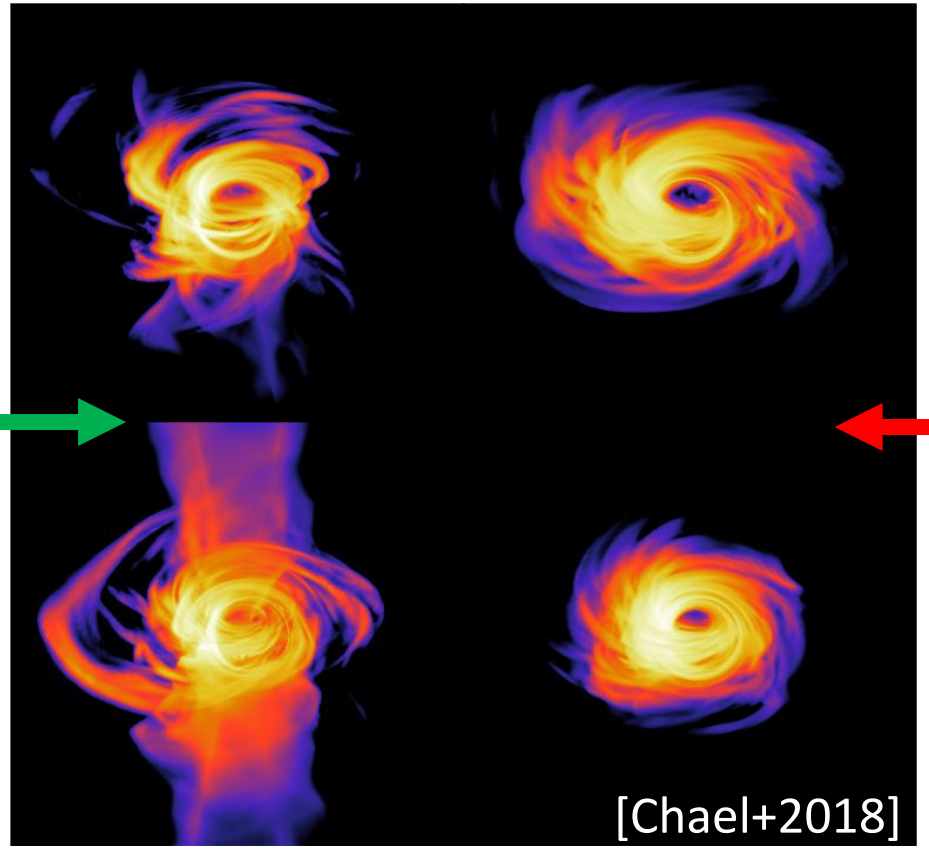
Simulations of Black-hole Plasmas: MHD + Subgrid

- Magnetohydrodynamics widely used for global and local simulations…
- …but radiation is emitted by (nonthermal) particles, and MHD doesn't know about them :(
- Hence MHD assumes *some* radiative processes, leaving ambiguities

Macroscopic model



Radiation maps



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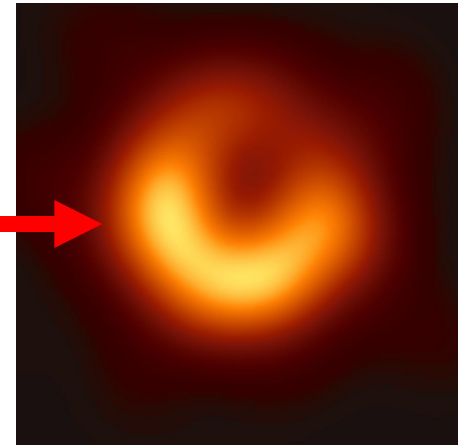
Observation



Simulations of Black-hole Plasmas: MHD + Subgrid

- Problem: MHD misses
  - Kinetic instabilities, scattering, transport
  - Nonideal effects
  - Extreme-regime dynamics (e.g. force-free limit)
  - Nonthermal effects
  - Radiation
  - Scales!

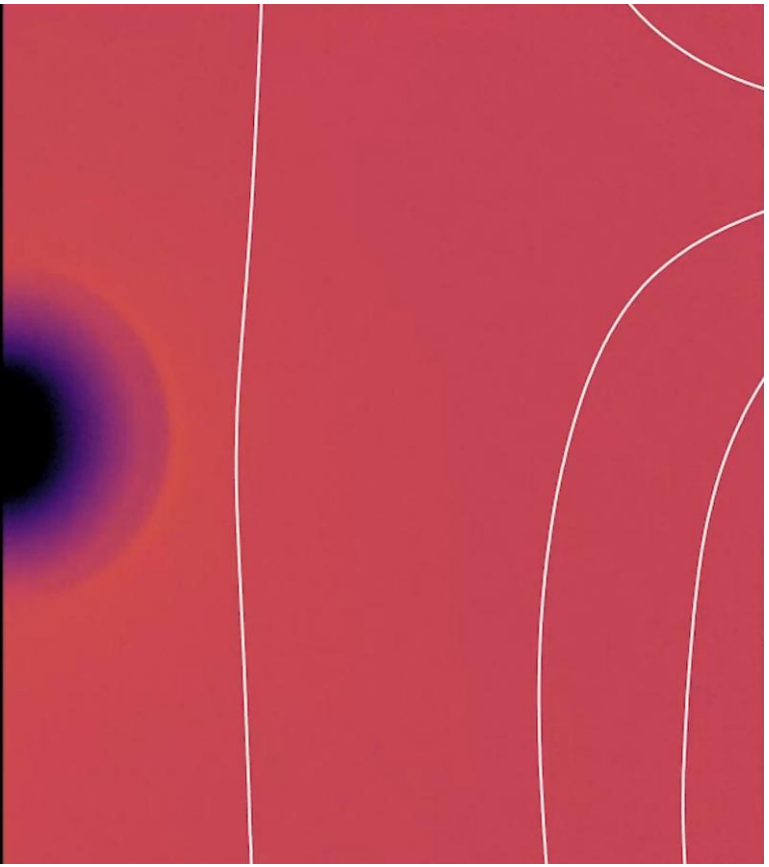
- Solution: Run kinetic (e.g. PIC) simulations and extract recipes to plug into MHD (e.g. EHT)

- New problem: high computing costs…

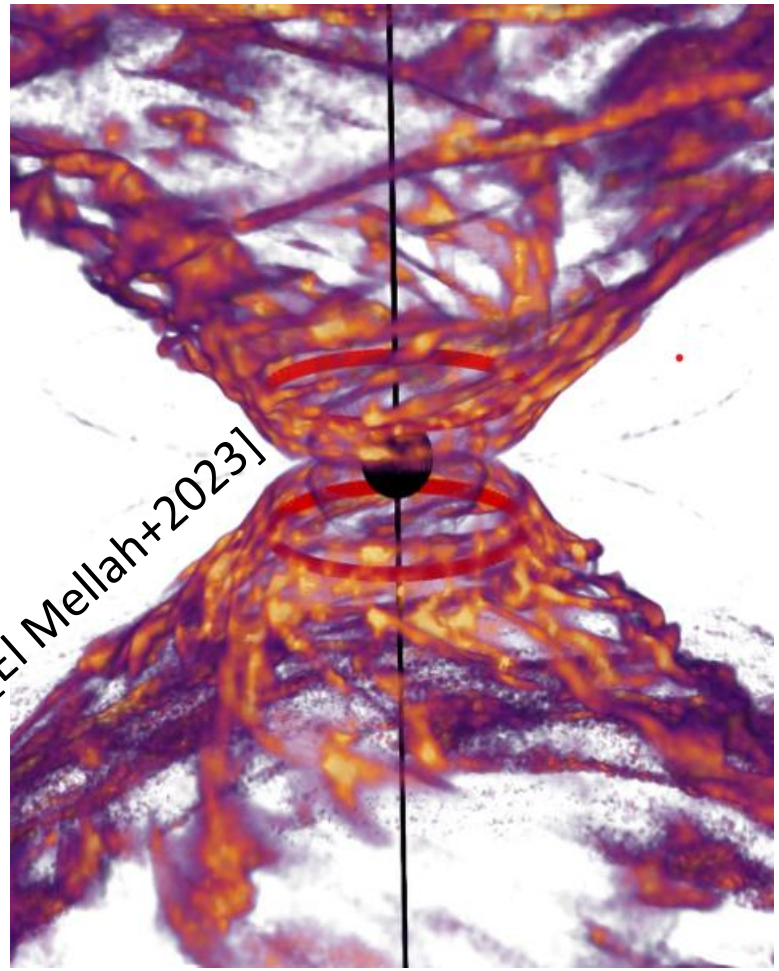
- …but fully kinetic simulations of black-hole plasmas are REALLY needed to remove ambiguities

Simulations of Black-hole Plasmas: PIC (Global)

- Parfrey, Crinquand, Bransgrove, El Mellah, Galishnikova, Torres, Vos, etc.:
  Multi-D general-relativistic collisionless plasma dynamics captured on global scales
- Scale separation too limited to study microscale processes in detail

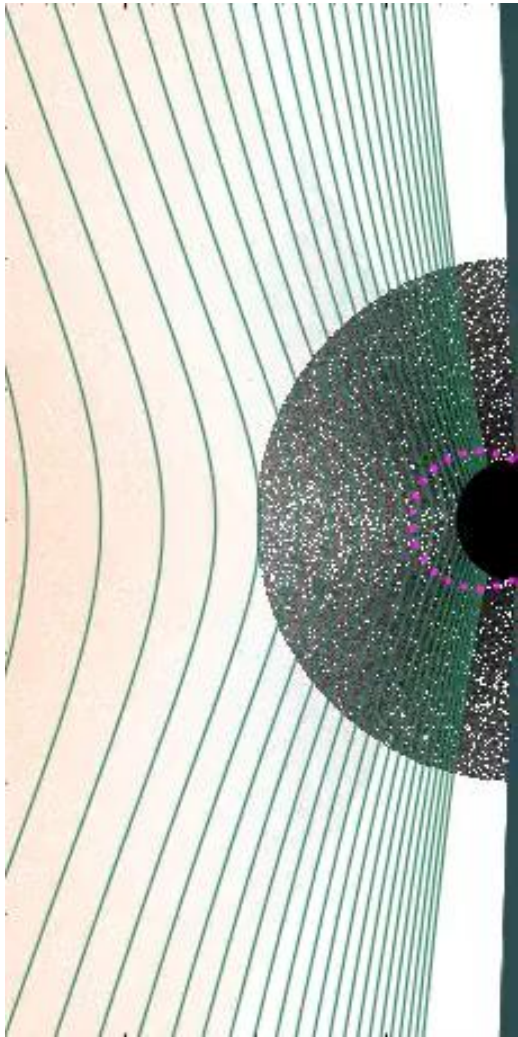


[Galishnikova+2023]



[El Mellah+2023]

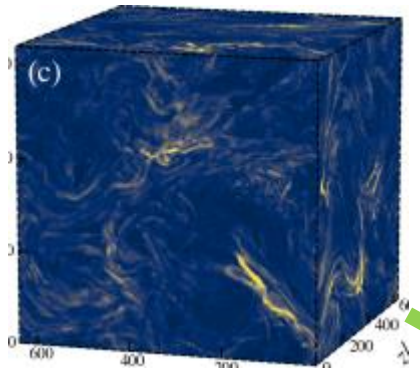
[Vos+2025]



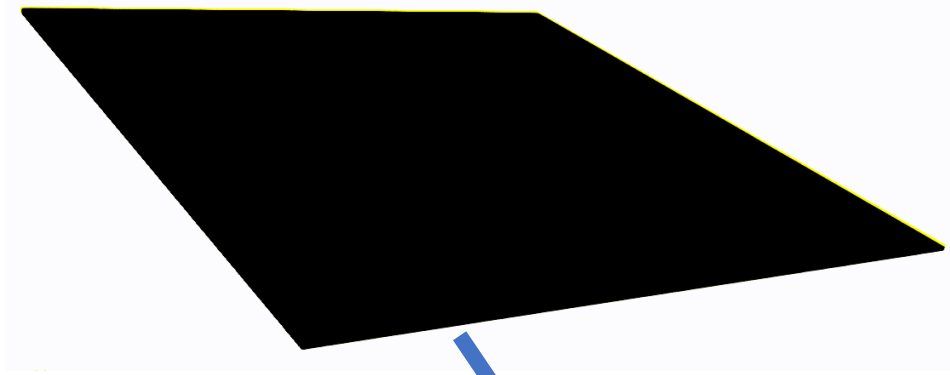
Simulations of Black-hole Plasmas: PIC (Local)

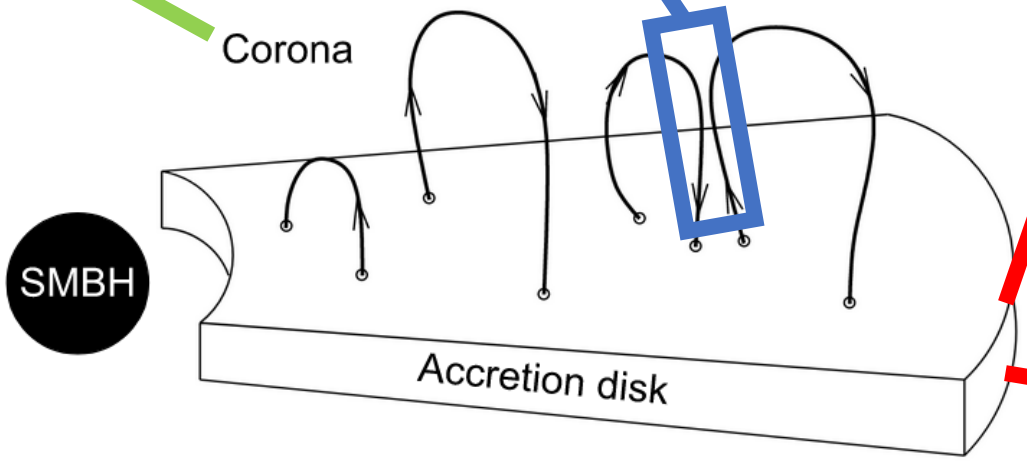
- Approach: Run localized PIC simulations and extrapolate

[Bacchini+ in prep., Granier+ in prep.]

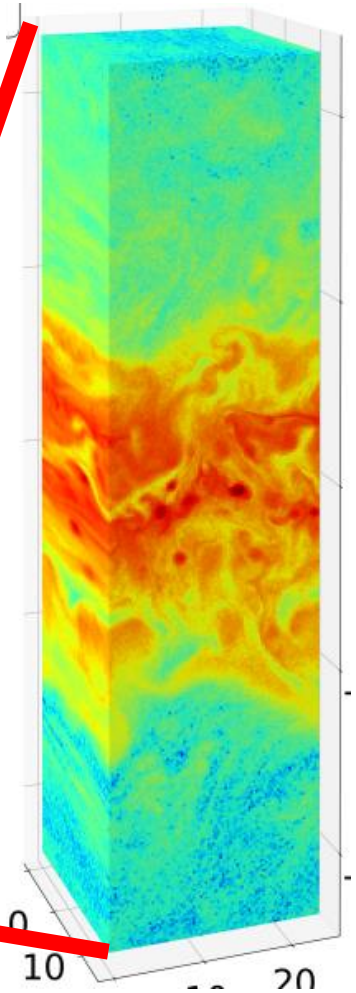


[Grošelj+2024]





[Uzdensky & Goodman 2008]



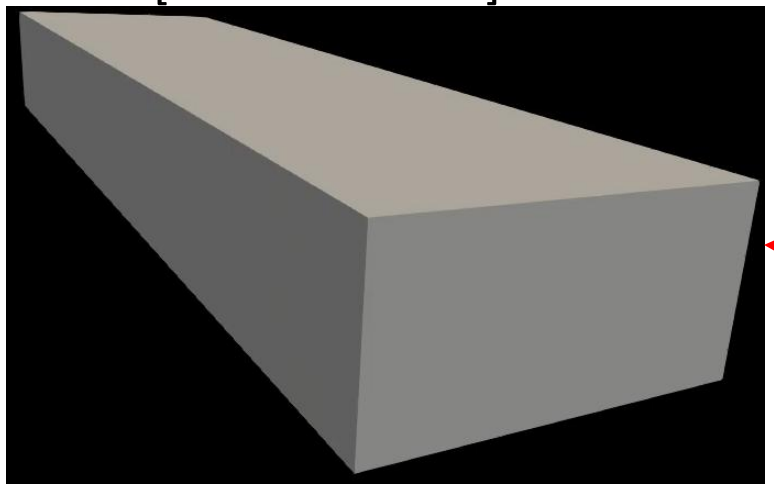
[Sandoval+2024]

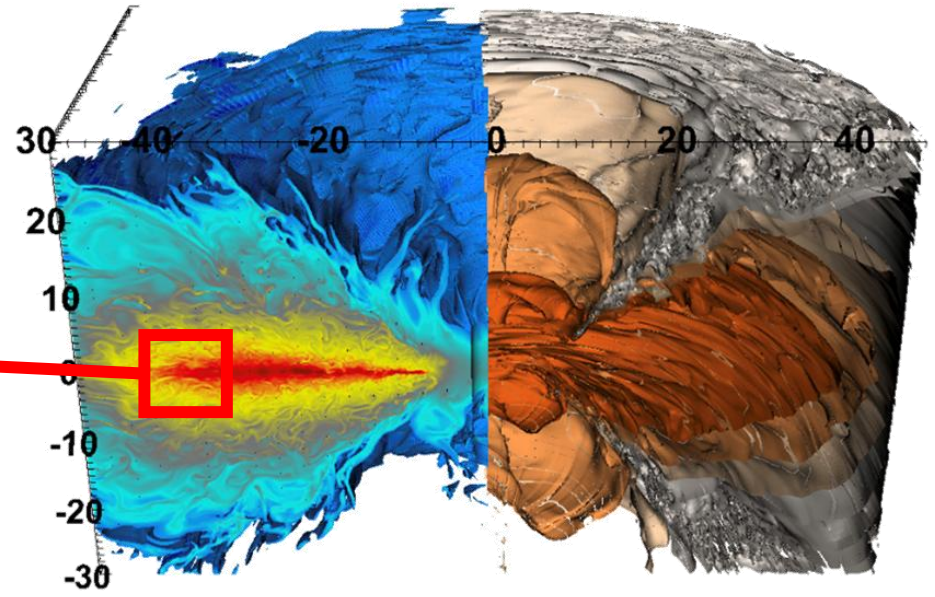
Localized PIC Simulations: The Disk

- Assuming disk emission from accelerated electrons:
- Popular radiation models for MHD → electron-ion energy partition (with radiating electrons):
  - Ad-hoc (empirical, e.g. EHT base approach)
  - From nonrelativistic "Reduced" MHD (Kawazura+2022)
  - From nonrelativistic gyrokinetics (Howes+2010, Kawazura+2019)
  - From relativistic collisionless ion-electron reconnection (Werner+2017)
  - From relativistic collisionless turbulence with ad-hoc drivers (Zhdankin+2019, Zhdankin 2021)
  - New & "more realistic": From relativistic collisionless-accretion simulations, global or local

→ Obtain: New heating prescription from first principles

[Bacchini+2024]



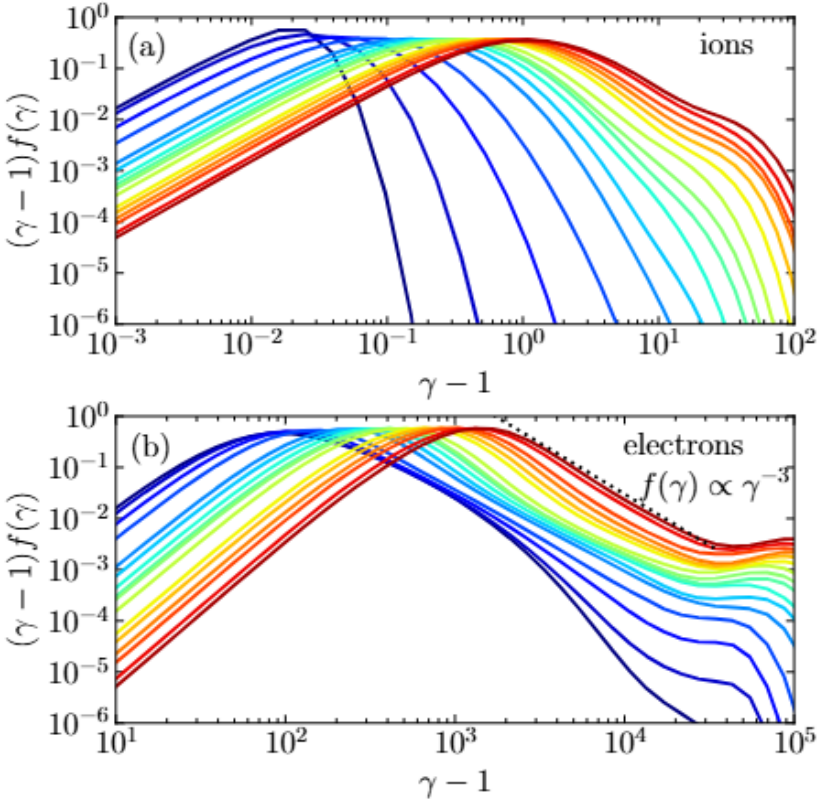


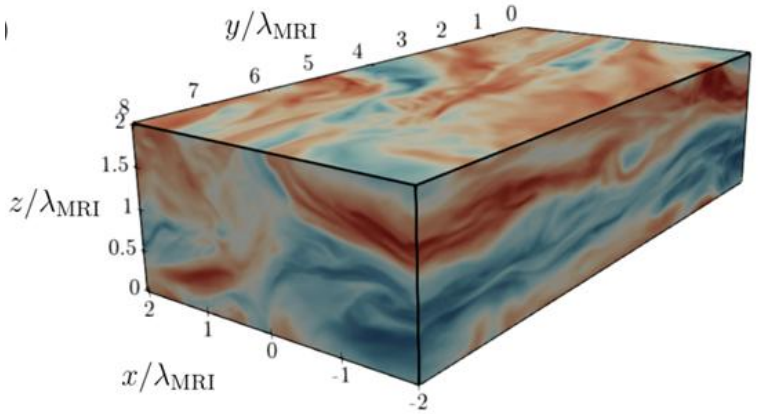
Localized PIC Simulations: MRI in the Disk

- New achievement with kinetic shearing box [Bacchini+2022, 2024]:
  - Semirelativistic ion-electron plasma → additional physical ingredient
  - Realistic mass ratio → additional scale separation
  - Removing effects of initial conditions → additional computational complexity

→ Nonthermal particle acceleration & new heating prescription from first principles

[Gorbunov+2025, ApJL]





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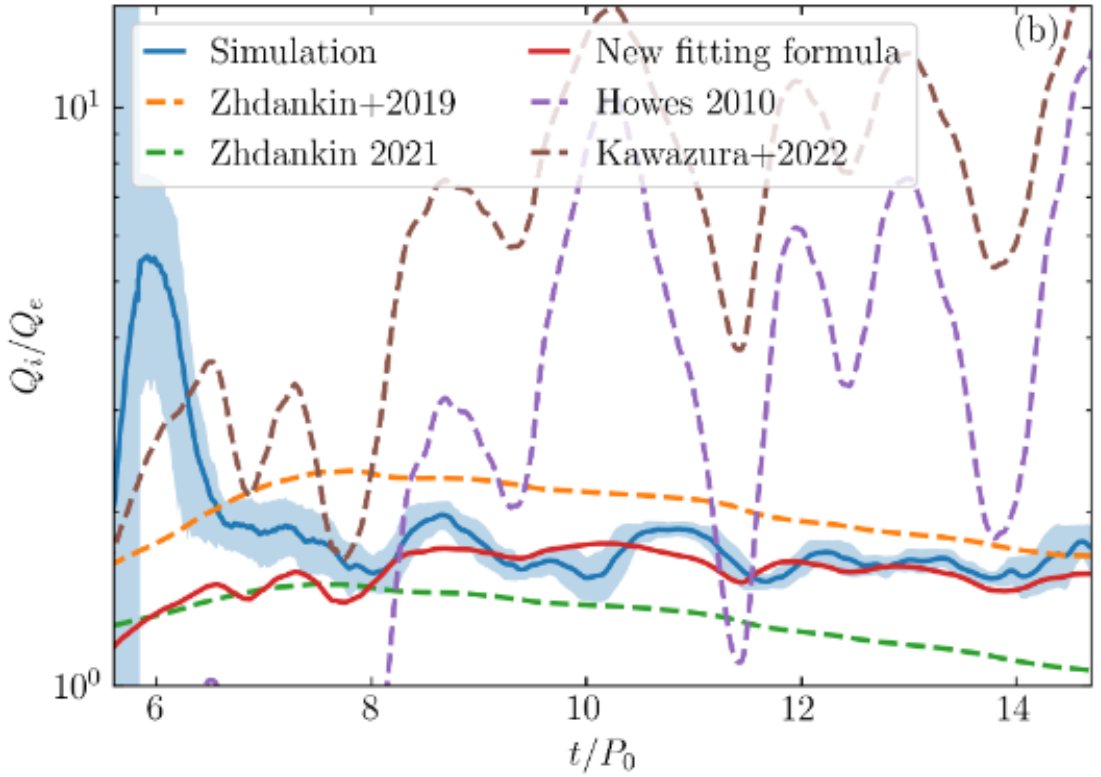

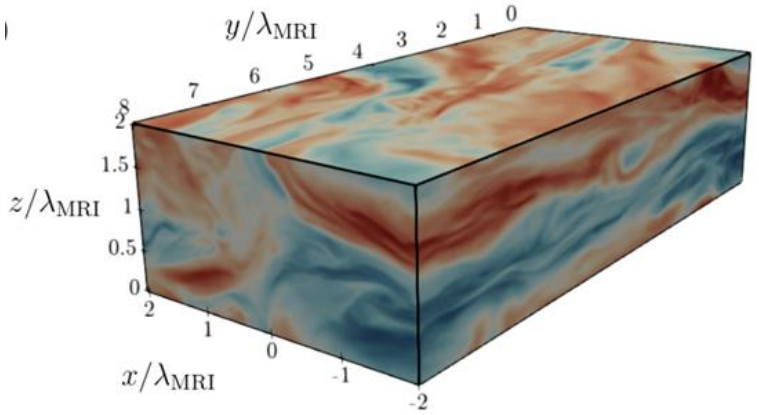

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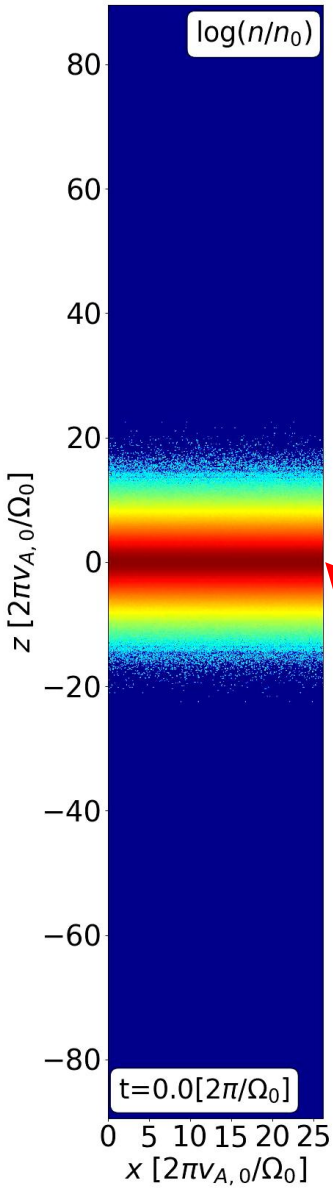
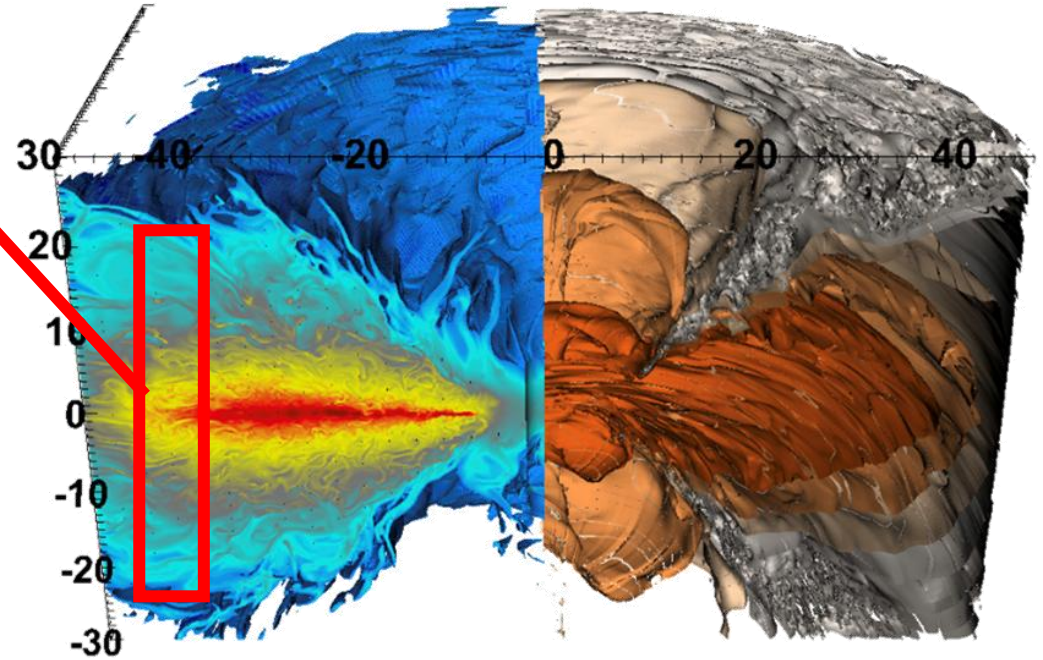


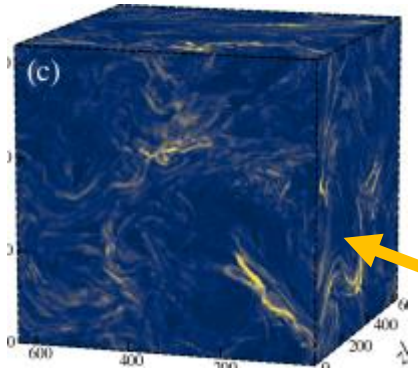
- Additional ingredient: Density stratification
- Yields self-consistent corona formation
- MRI substantially modified → Impact on kinetic processes

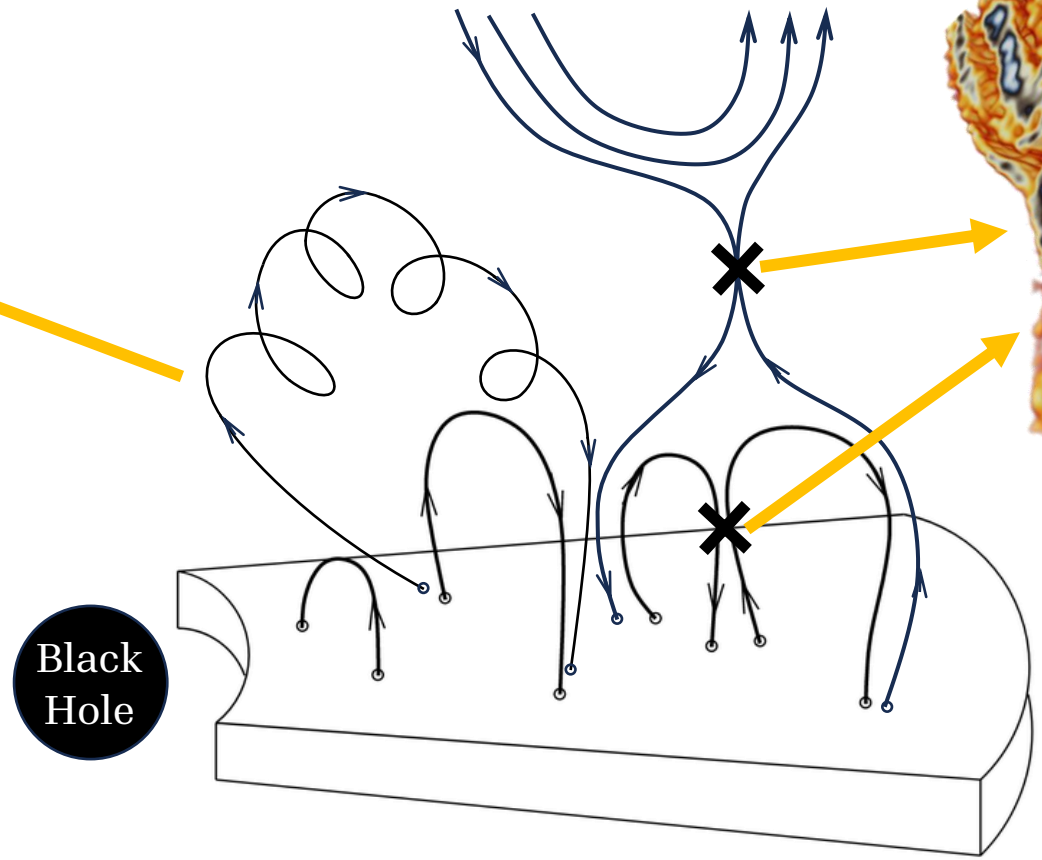


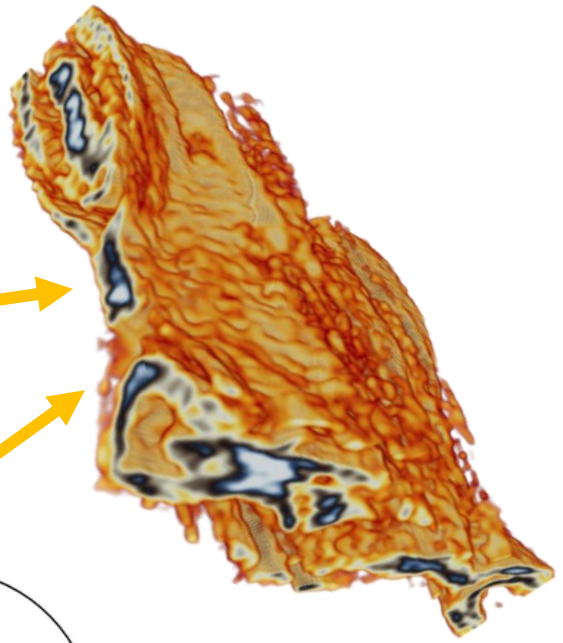
[Sandoval+2024]

Localized PIC Simulations: The Corona

- Very high coronal magnetization → large-scale magnetic-energy release
- Particle acceleration to extremely high energies could explain TeV flares
- Need very large system sizes, ion-electron plasma, realistic mass ratio, radiation, …





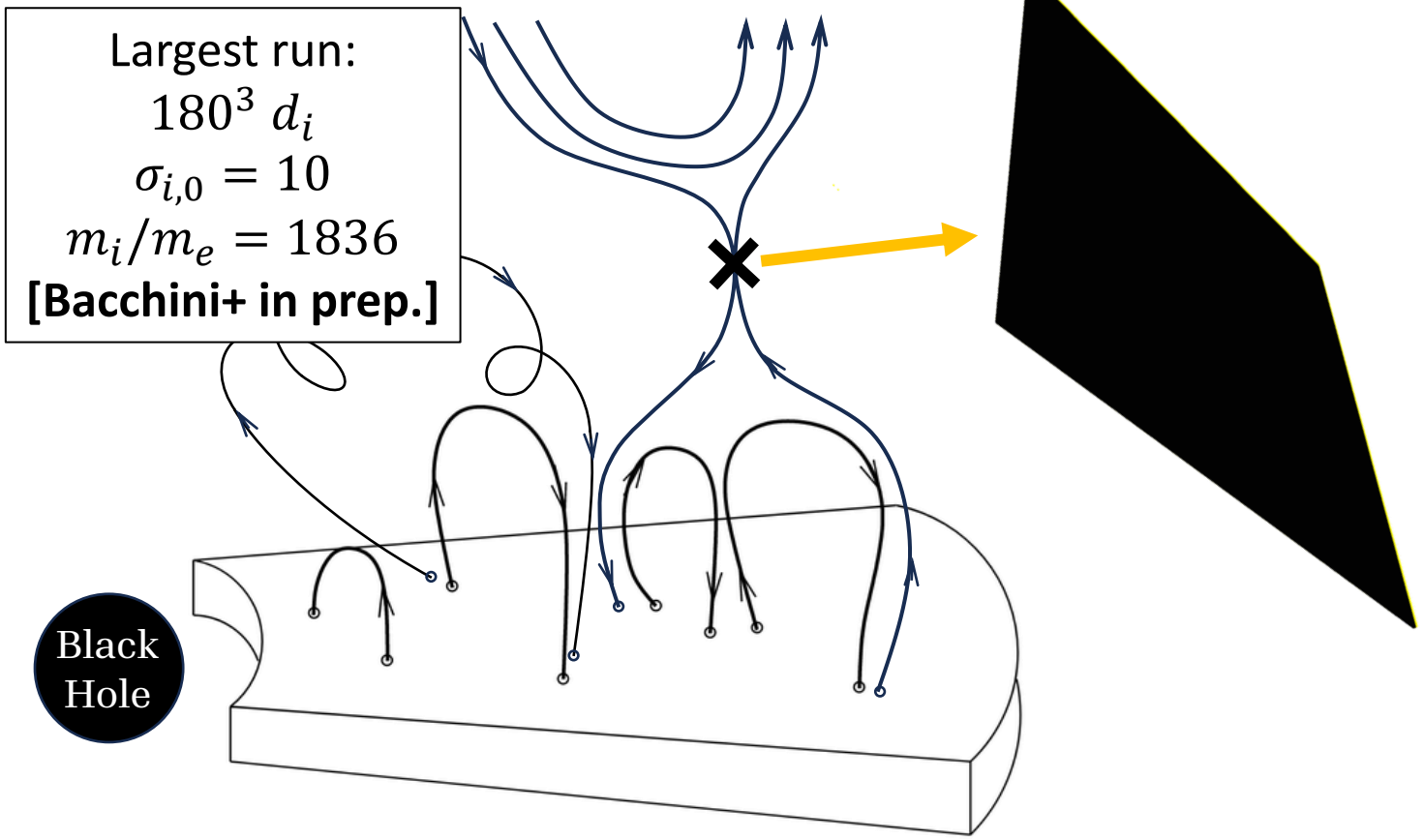


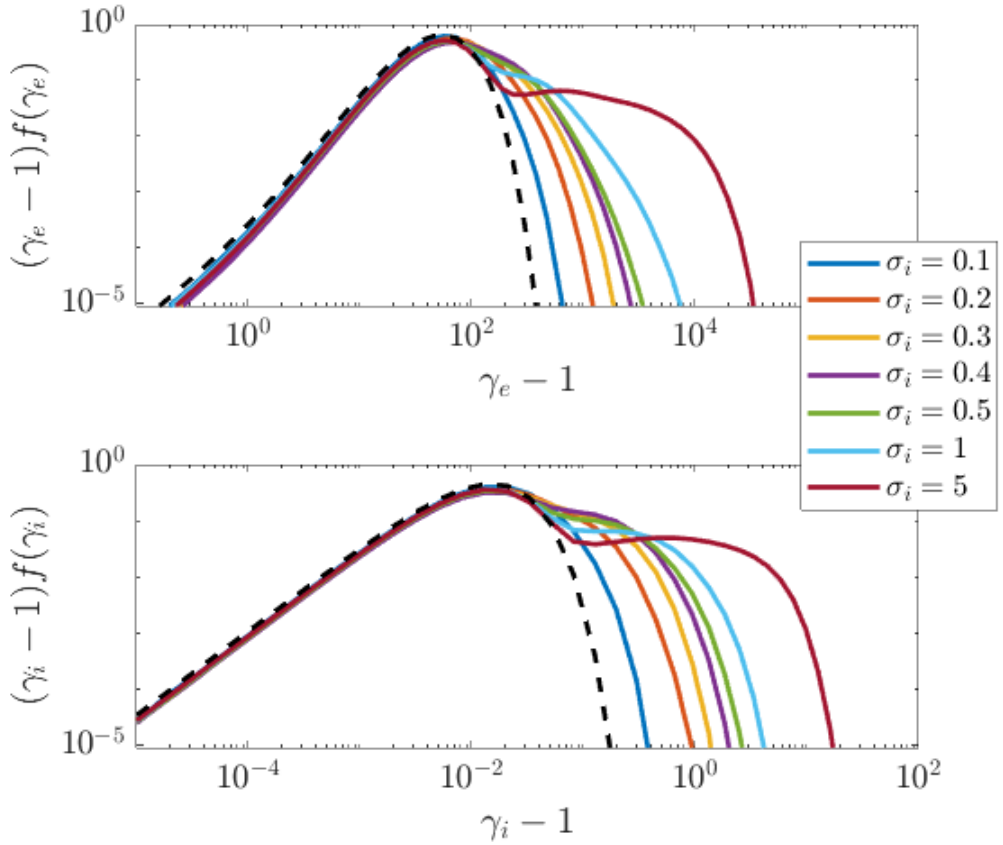
Localized PIC Simulations: Coronal Reconnection

- Very high coronal magnetization → large-scale magnetic-energy release
- Particle acceleration to extremely high energies could explain TeV flares
- Need very large system sizes, ion-electron plasma, realistic mass ratio, radiation → **RelSIM**

[Bacchini 2023]

Largest run:
$180^3\ d_i$
$\sigma_{i,0} = 10$
$m_i/m_e = 1836$
[Bacchini+ in prep.]





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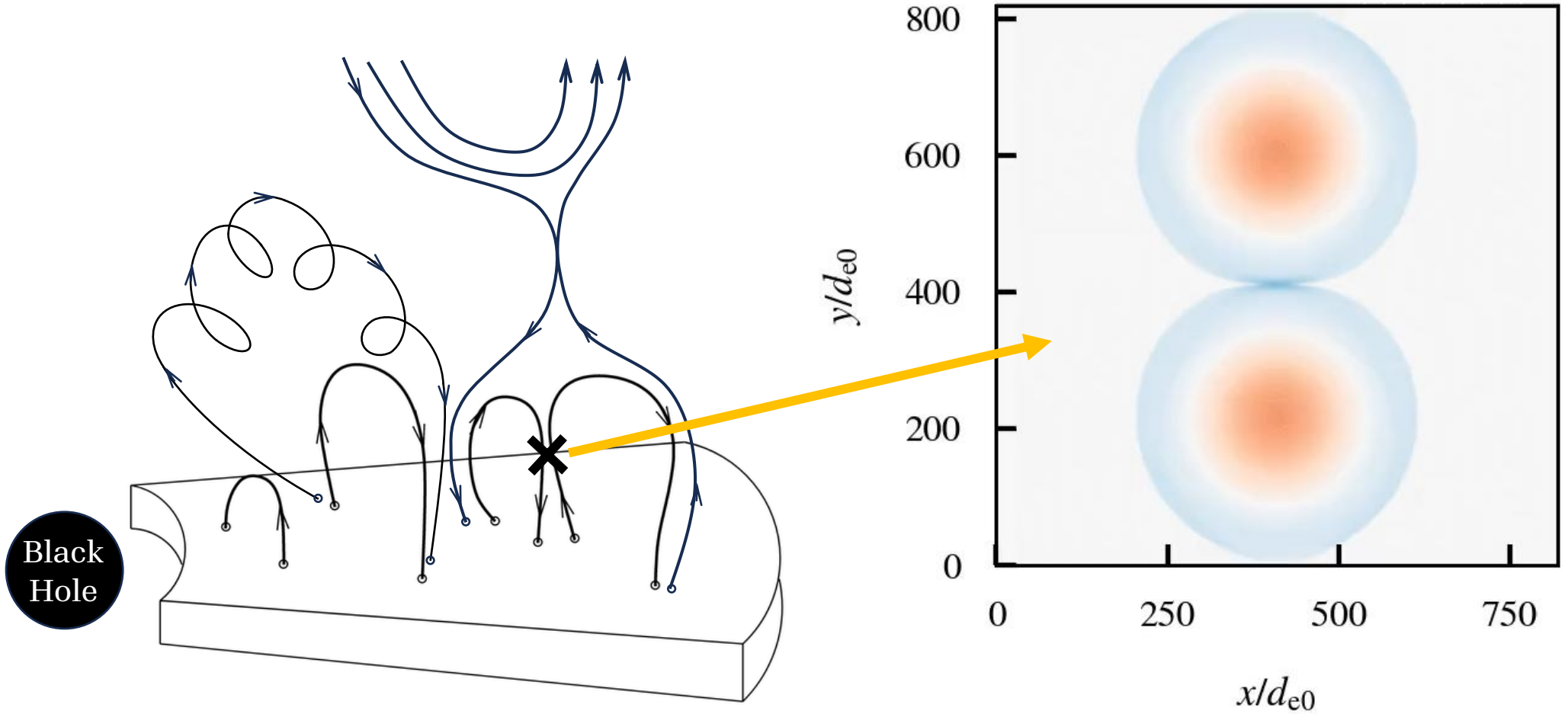

[Granier+ in prep.]

Localized PIC Simulations: Coronal Turbulence

- Very high coronal magnetization → large-scale magnetic-energy release
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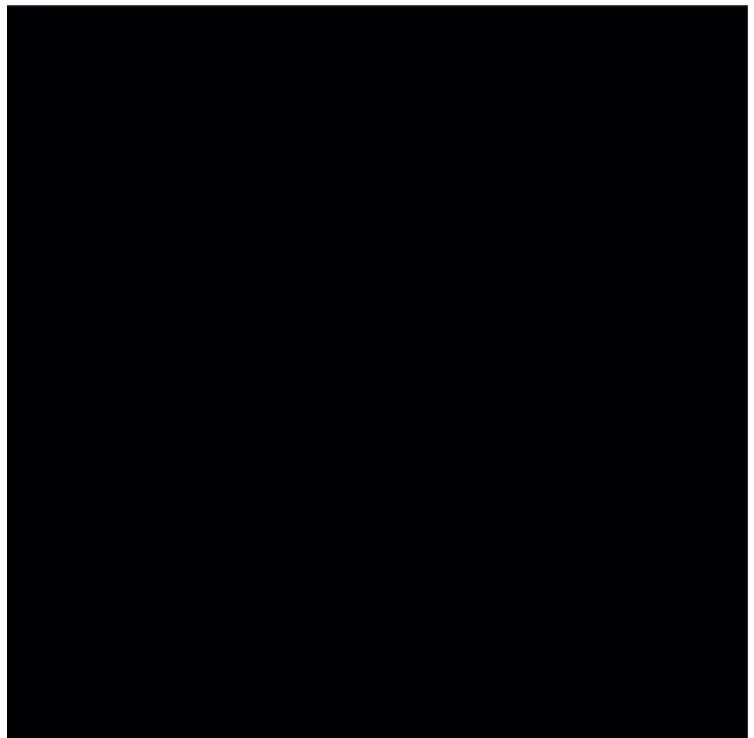
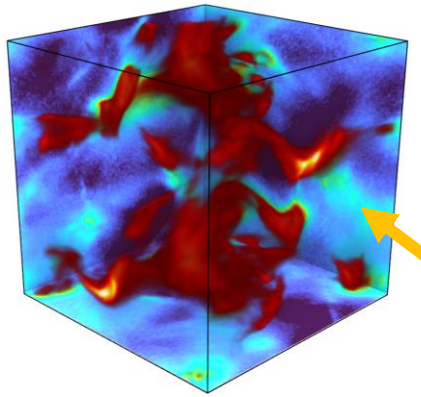
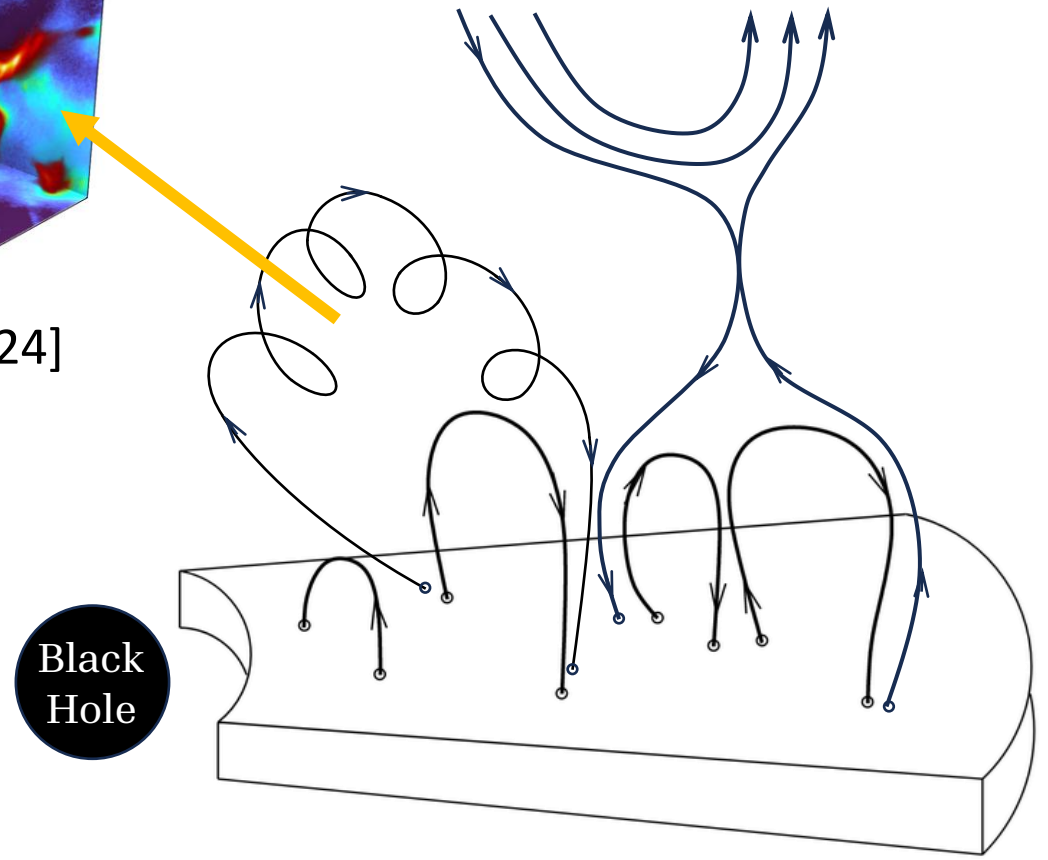
[Grošelj+ in prep.]

T_i





[Grošelj+2024]



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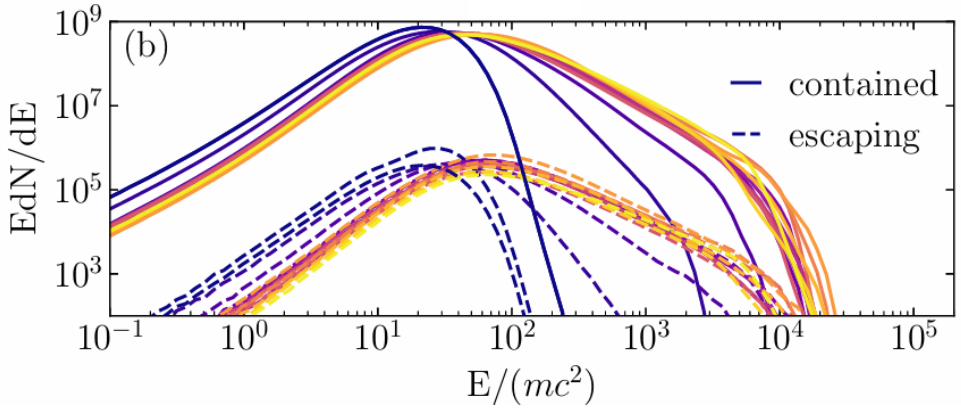
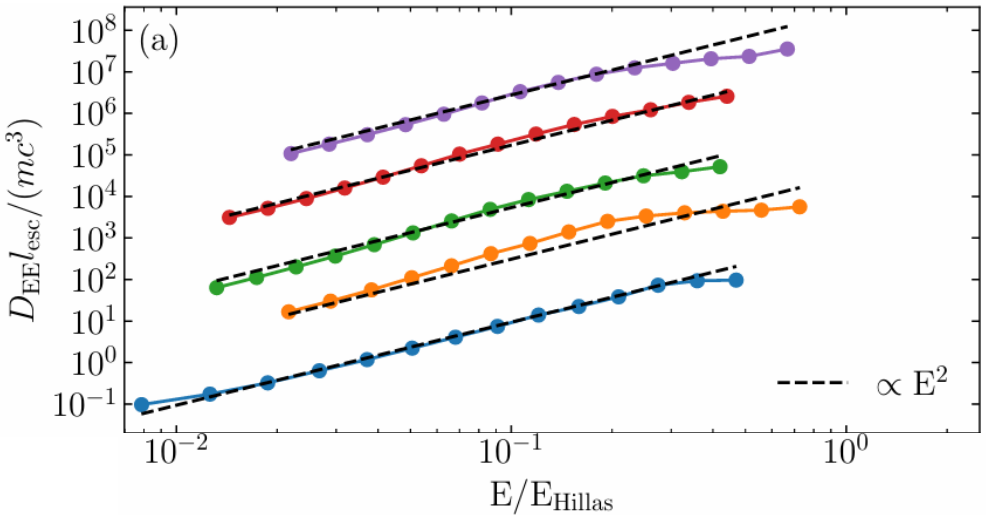
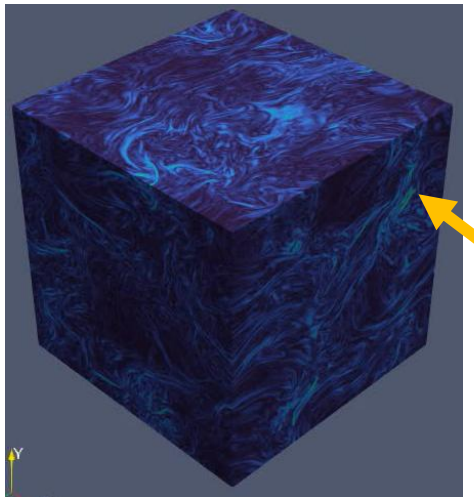
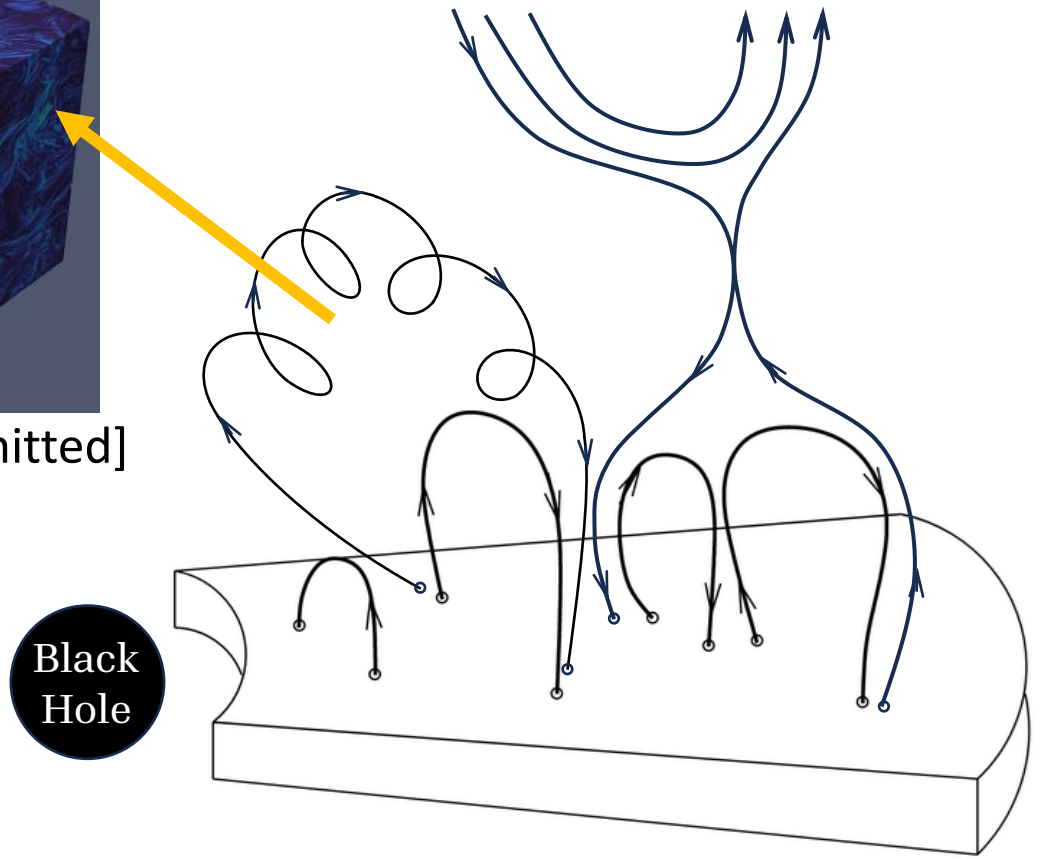






[Gorbunov+ submitted]



Summary

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- Localized PIC simulations of BH plasmas* can contribute to MHD global modeling and connect with observations

Bacchini+2022 ApJ, 2024 PRL
Grošelj+2024 PRL
Sandoval+2024 MNRAS
Gorbunov+2025 ApJL, 2025 submitted
Granier+ in prep.

- Large 3D multispecies simulations are necessary
  → extract microphysical recipes for
  - Nonthermal particle acceleration
  - Electron/ion energy partition
  - Turbulent angular-momentum transport
  - …

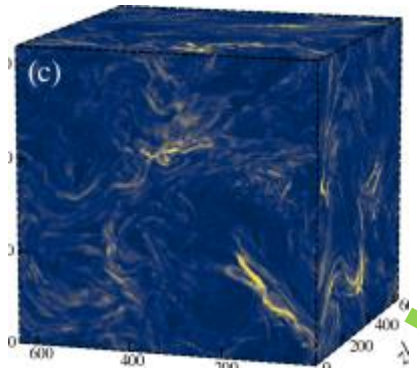
- More physical ingredients needed eventually (radiation, gravity, …)

- Streamline different simulations, codes, and numerical methods to connect separate parts of BH magnetospheres

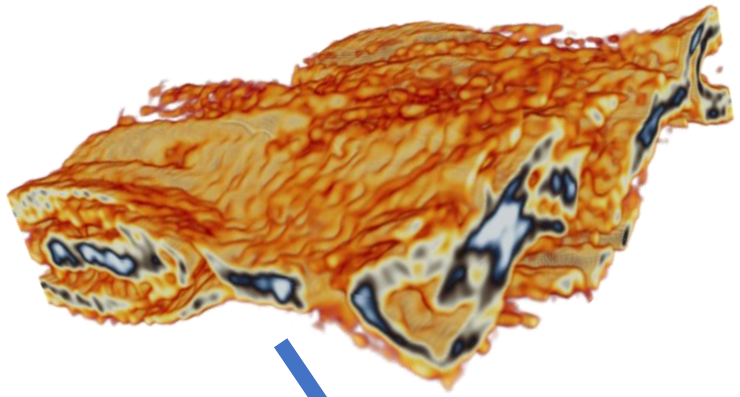
Outlook: Connecting Disk and Corona

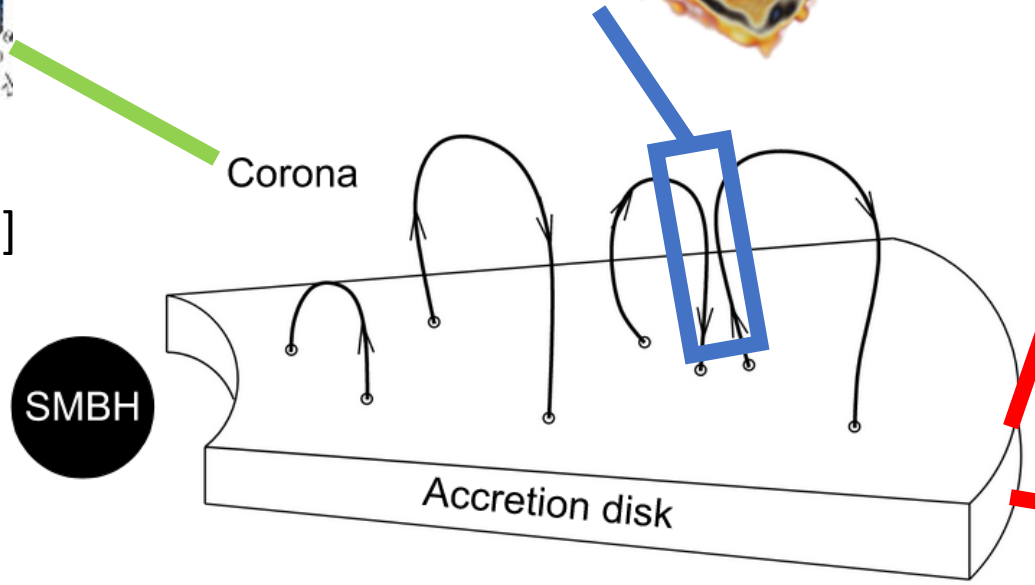
- Streamlining different codes and local simulations could yield better models overall

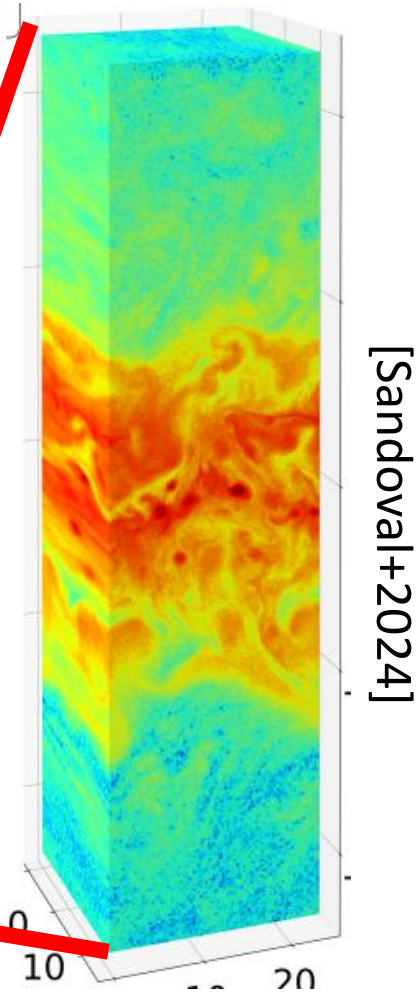
[Bacchini+ in prep., Granier+ in prep.]



[Grošelj+2024, Grošelj+ in prep.]



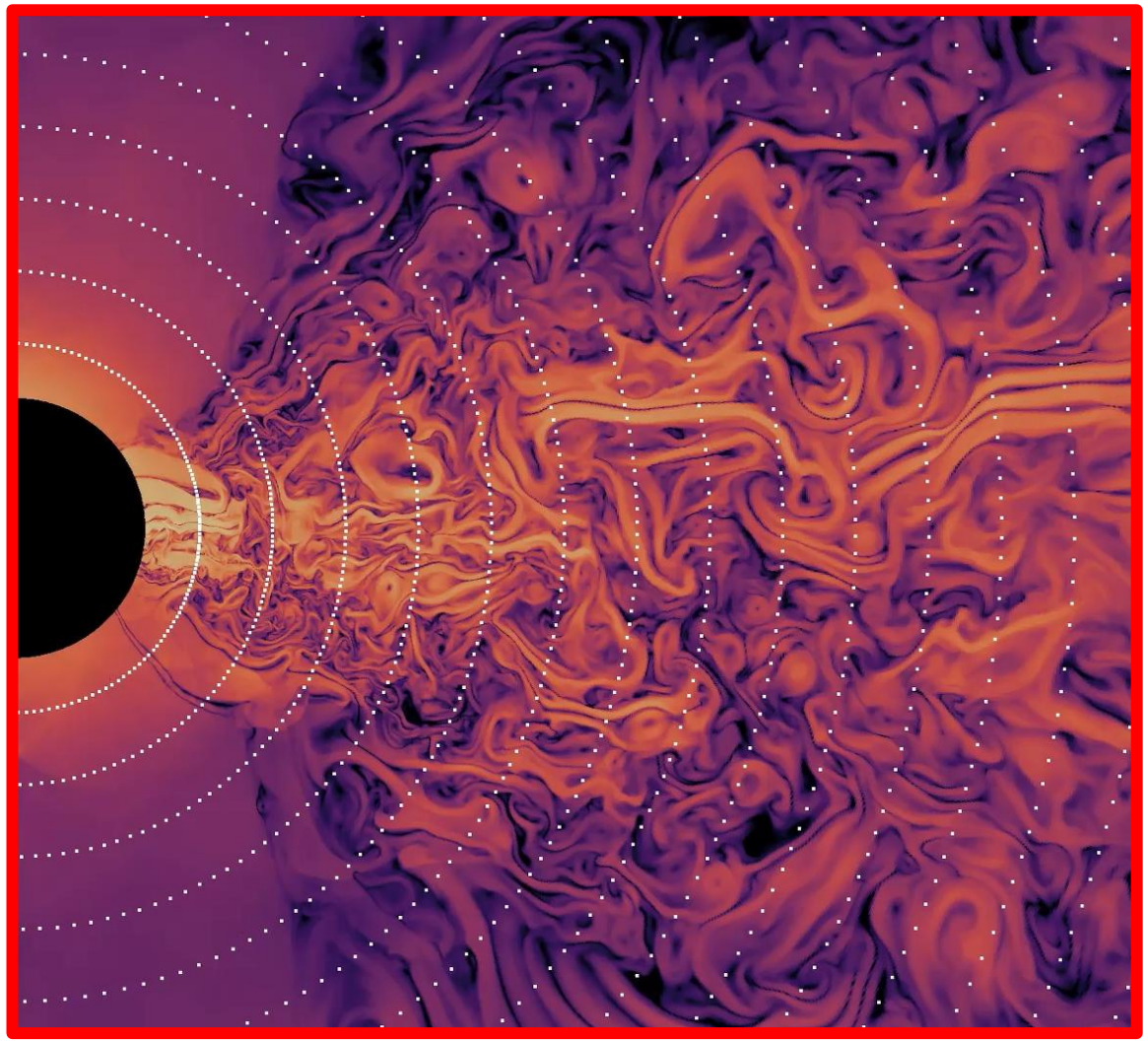




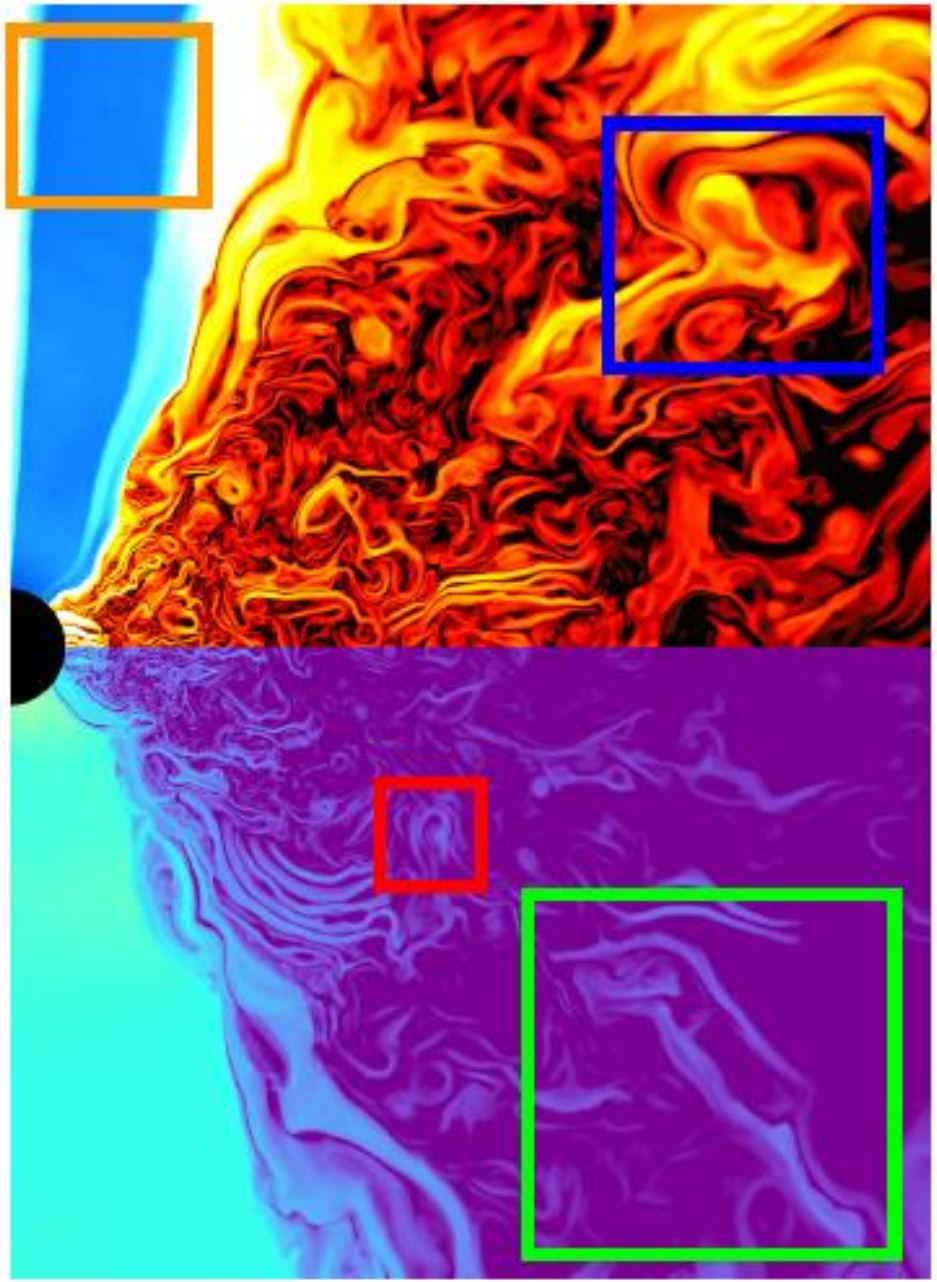
[Sandoval+2024]

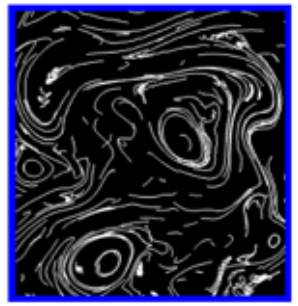
Outlook: Hybrid Numerical Methods

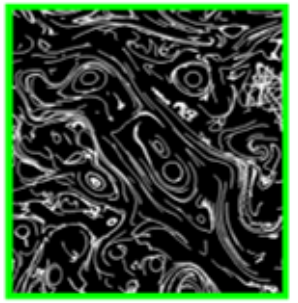
- MHD + particles (one-way coupling)



[Bacchini+2018, 2019]







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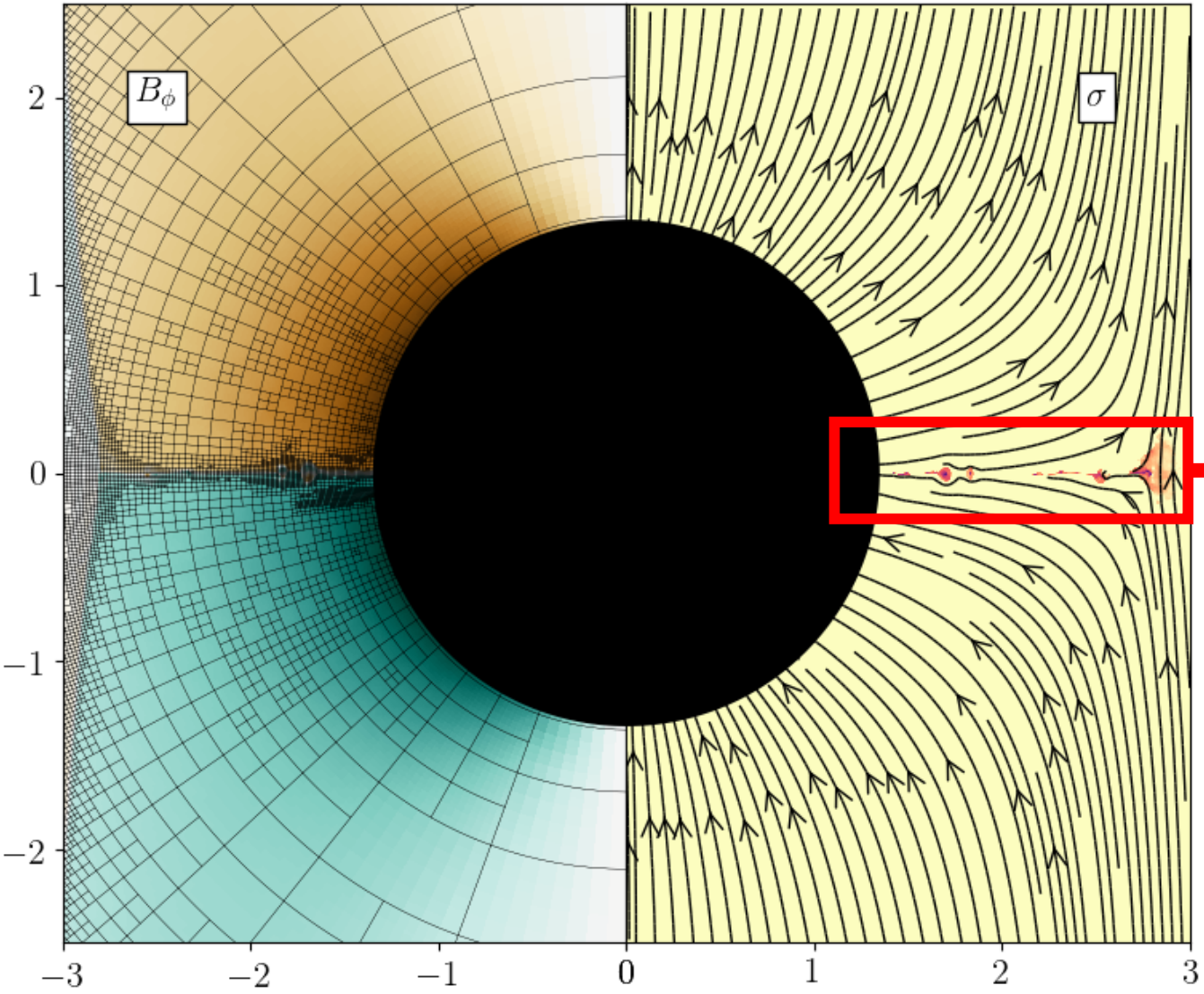
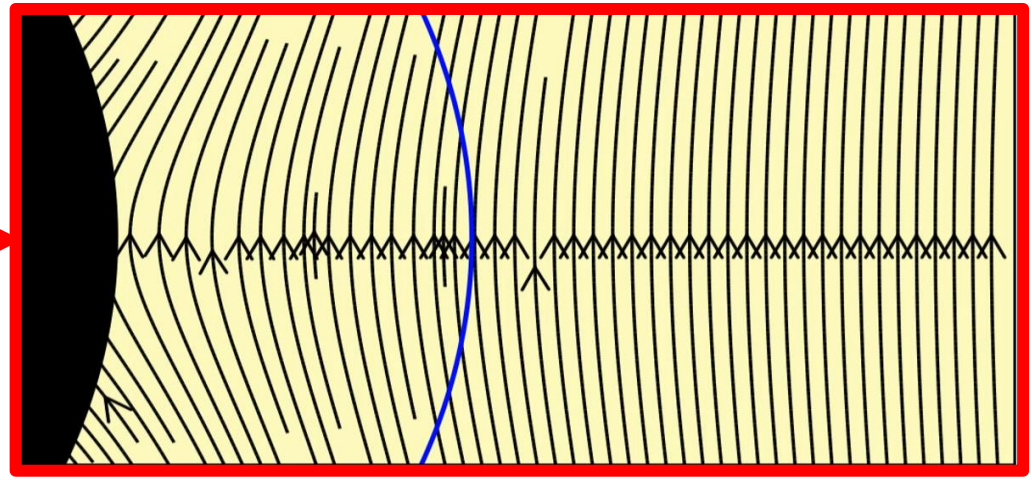
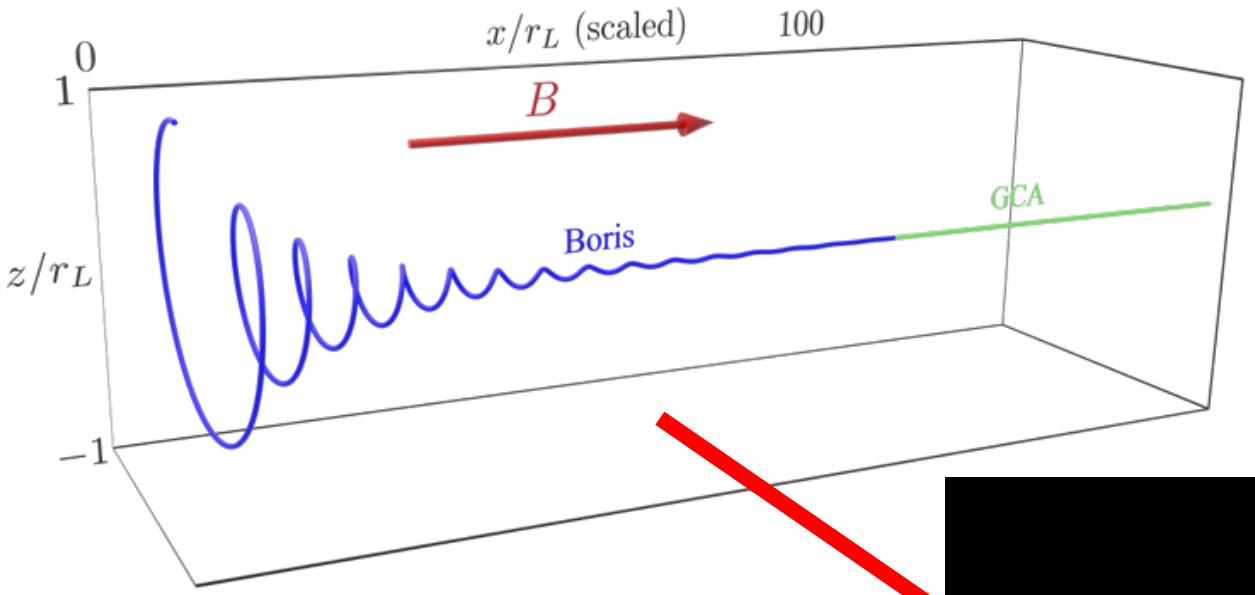


- MHD + Force-free
  (see also: PIC + Force-free, Soudais+2024)



[Grehan+ in prep., Ripperda+ in prep.]

Outlook: Hybrid Numerical Methods



- Boris + GCA (+ radiation)
  → Larger scale separation in PIC

[Bacchini+2020; Hakobyan+2023; Zou+2025, accepted]