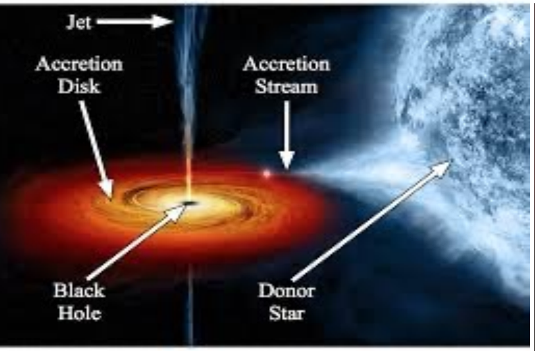
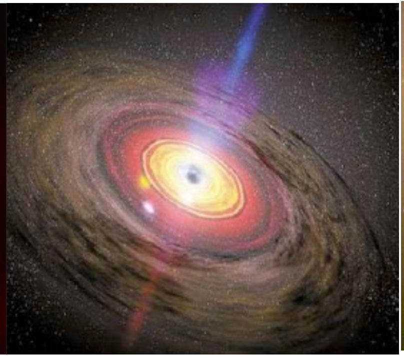
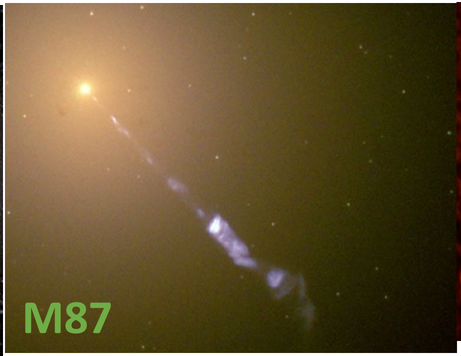
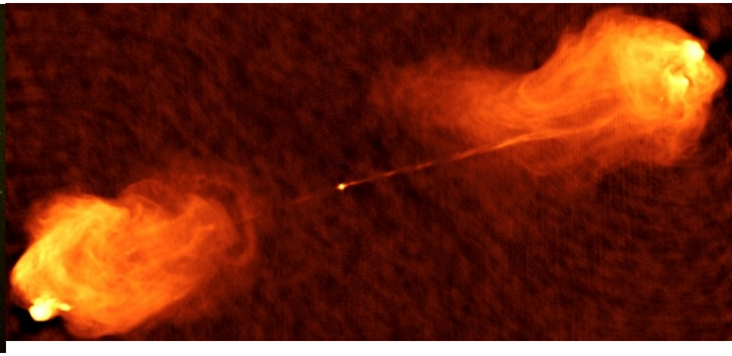




Plasma Physics of Accretion Flows

Dmitri Uzdensky (Univ. Colorado Boulder)

Thanks to:
G.Werner, M.Begelman, J.Dexter, N.Scepi, A.Chen, J.Mehlhaff, O.French

Supported by NSF, NASA

CDY Workshop on Black Hole Flares, Flatiron Inst., New York, November 13, 2023

OUTLINE

- Complexity and Diversity of Extreme Plasma Environments of Accreting Black Holes
- Focus of Flares --- Magnetic Reconnection:
  - Electron-Ion Heating Ratio
  - Nonthermal Particle Acceleration
- (Energy Scales in Radiative Relativistic Reconnection)
- (Sgr A* NIR/X-ray Flares)
- Conclusions

Structure of Accreting BH Systems

- Accreting BH system is a complex magnetized plasma machine with interacting moving parts:
  - Accretion disk/ RIAF
  - Corona/ Disk Wind
  - Magnetosphere
  - Jet
- Morphological structure governed by key geometrical surfaces, large-scale magnetic field topology, and key plasma parameters (e.g., plasma β).
- Different accretion & spectral states:
  - Standard (SS73) thin Disk + Corona
  - SANE RIAF
  - MAD RIAF

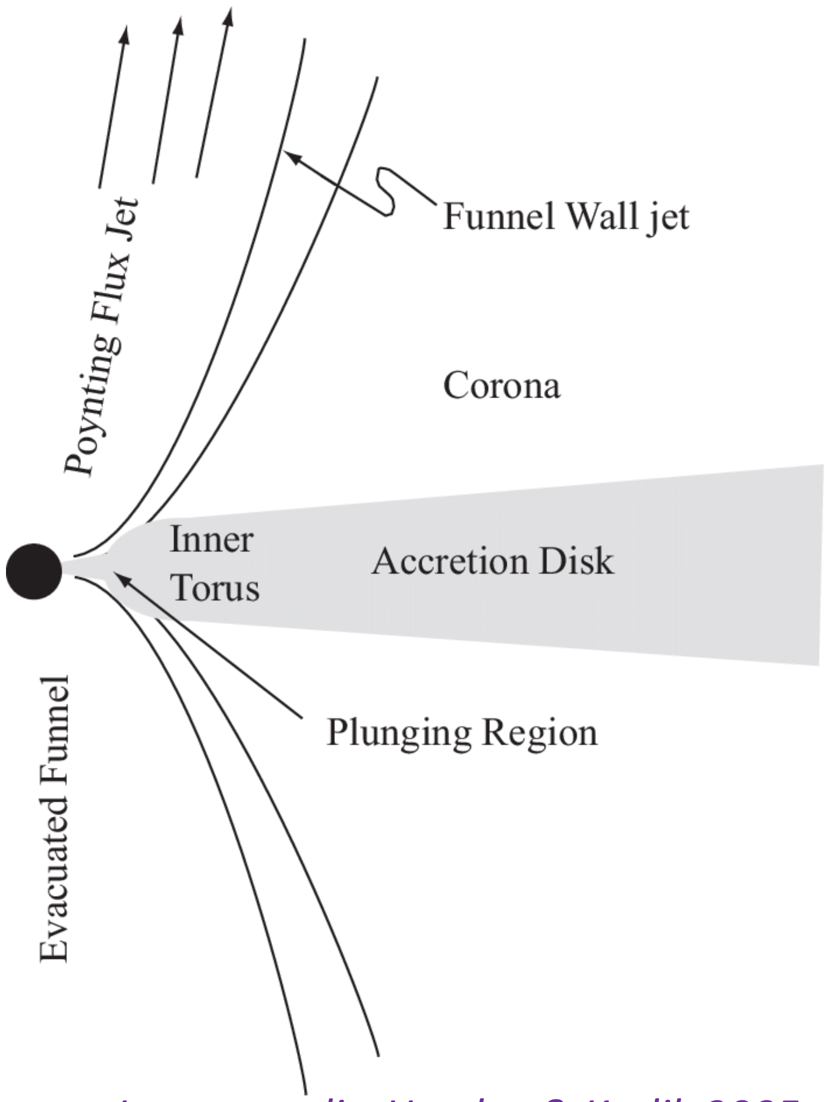


Image credit: Hawley & Krolik 2005

Components …

Each part of accreting BH system is a complex plasma environment consisting of several *Components*…

Thermal gas/plasma

Nonthermal particles (CRs)

Magnetic field

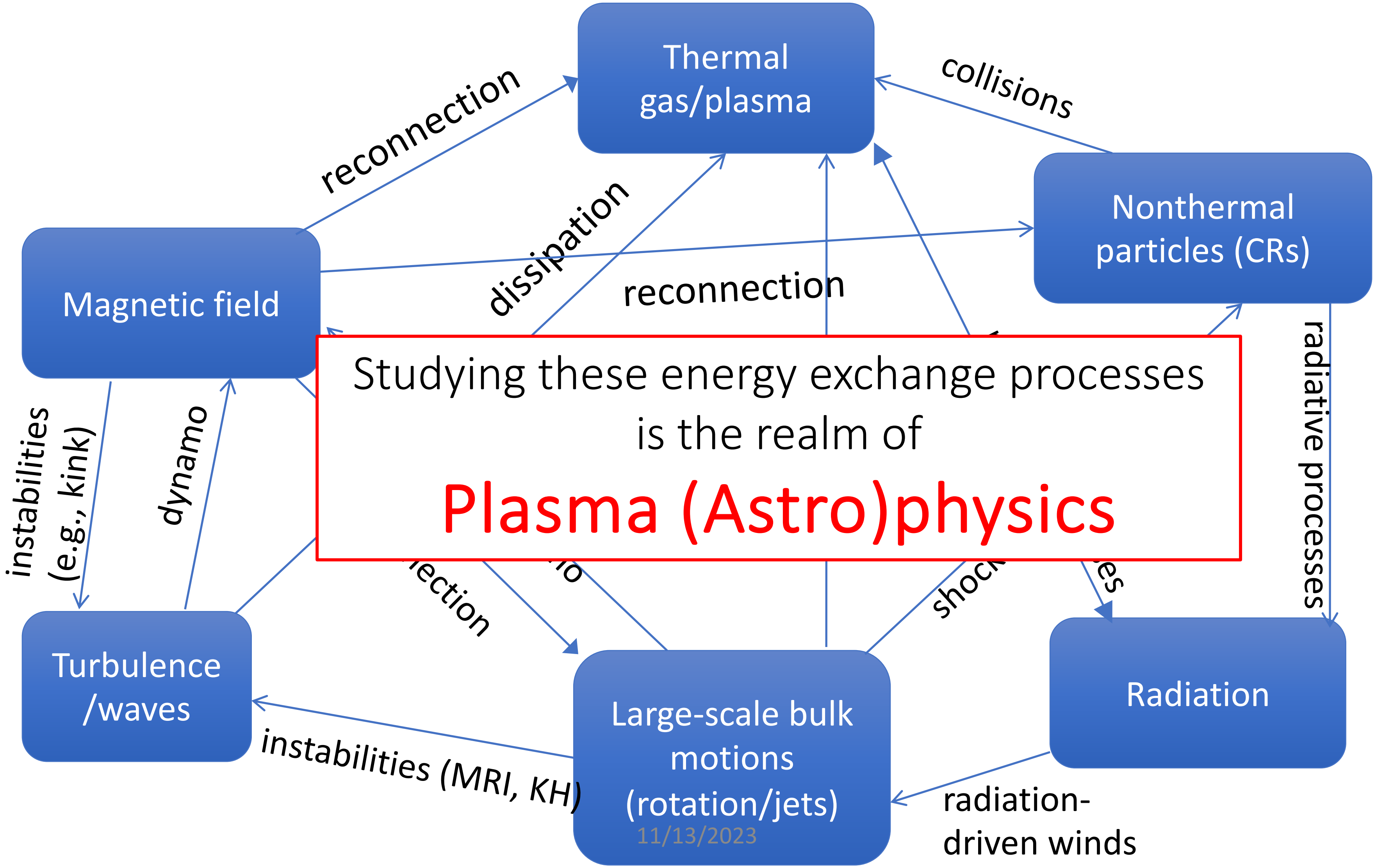
Turbulence /waves

Large-scale bulk motions (rotation/jets)

Radiation

... and Processes

Energy exchange between plasma components: plasma-physical ***processes*.**



Studying these energy exchange processes is the realm of

Plasma (Astro)physics

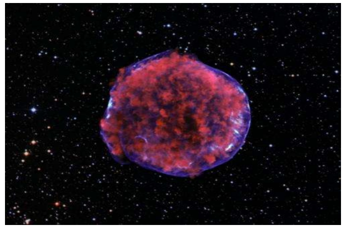
Flares: Rapid Energy-Release Events Powered by Dissipation Processes

AVAILABLE FREE ENERGY

Bulk Kinetic

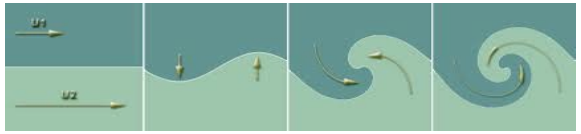
- longitudinal:

shocks: Weibel instability



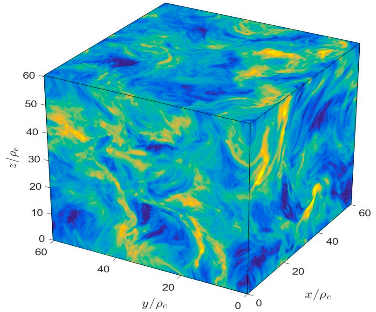
- transverse:

Kelvin-Helmholtz instability



STRUCTURE

TURBULENCE

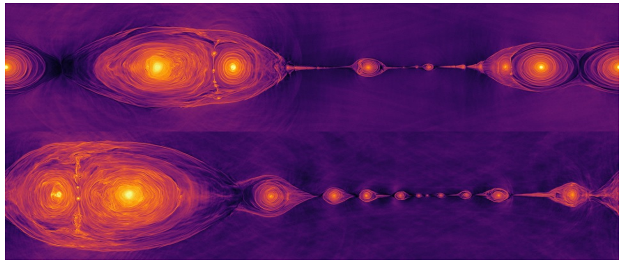


Magnetic (Poynting flux)

current sheets:

Tearing instability

Magnetic reconnection



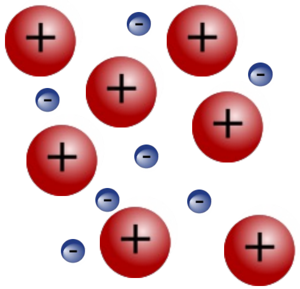
Complex nonlinear plasma processes excited by **linear instabilities.** Nonlinearly, they lead to **turbulence.**

- *Challenge to Plasma Astrophysics:* understand how these processes work under extreme physical conditions of BH environments.

Traditional & Extreme Plasma Physics

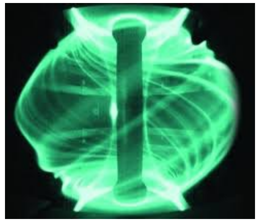
Traditional Plasmas

- Electrons and ions
- Non-relativistic
- Non-radiating

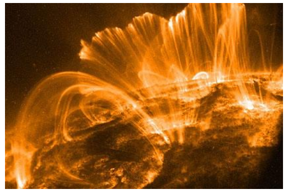


Applications:

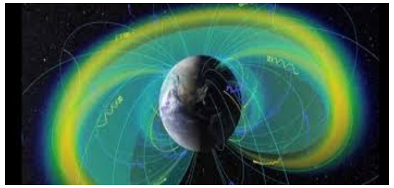
- Most lab plasmas



- Solar corona



- Earth's magnetosphere

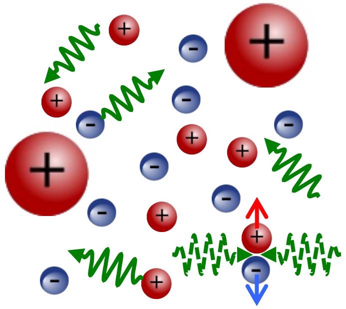


Based on 19th Century Physics!

Extreme Plasmas

"Exotic"* Physics:

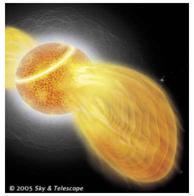
- e^-e^+ pairs (+ ions), photons
- Relativistic (Special & General)
- Radiation (cooling, drag, pressure)
- QED effects (e.g., pair creation)



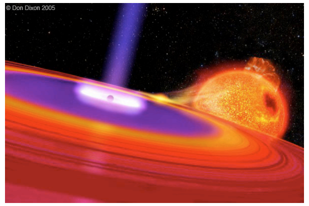
Applications:

Neutron Stars (NSs) & Black Holes (BH):

- Magnetospheres of pulsars, magnetars



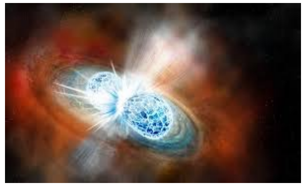
- BH accretion disks, coronae, jets



- Cosmic blasts (SNe, GRB)

- NS-NS mergers

- Early Universe



and soon…

- Laser-plasma lab experiments!

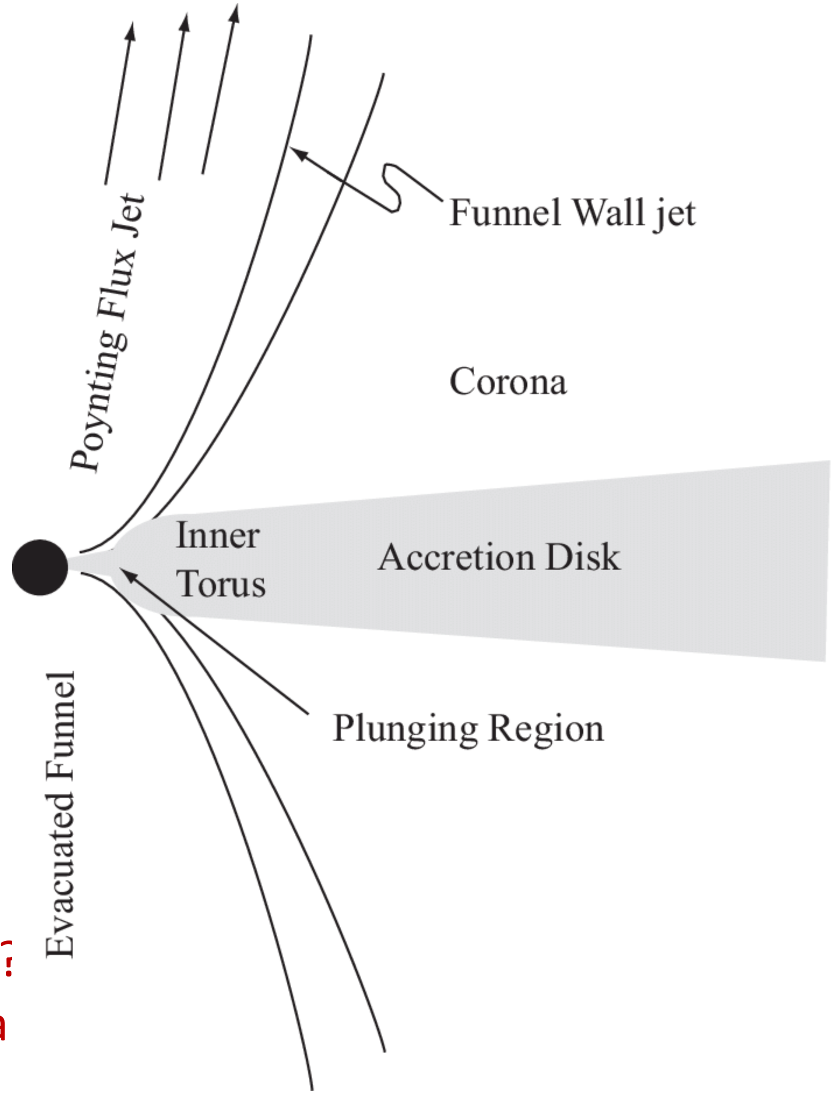
Based on 20th Century Physics!

Diversity of Plasma-Physical Regimes in BH Accretion Flows

- **Composition:**
  - Electron-ion (*ei*): SS73 disk, RIAF, corona
  - e^+e^- pairs: jet, magnetosphere
  - Mixed (*ei* + pairs): corona
- **Plasma beta:** $\beta = P_{pl} / P_{magn} = 8\pi P_{pl} / B^2$
  - High $\beta \simeq 10\text{-}10^3$: SS73 disk, RIAF (MRI-active)
  - Low $\beta \ll 1$: corona, jet, magnetosphere
- **Collisionality:** (binary Coulomb collisions)
  - Collisionless: $\tau_{\rm dyn} \ll \tau_{ee} \ll \tau_{ie}$
  - Semi-collisional: $\tau_{ee} \ll \tau_{\rm dyn} \ll \tau_{ie}$
  - Collisional: $\tau_{ee} \ll \tau_{ie} \ll \tau_{\rm dyn}$
- **Relativity:**
  - Non-relativistic: $v \ll c$
  - Trans-relativistic: $v \sim c$
  - Ultra-relativistic: $v \approx c$, $\gamma \gg 1$
- **Radiation:….**

But relativistic WHAT?

- electrons or ions?
  Semirelativistic regime: ultra-relativistic *ens* but sub-relativistic ions
- bulk flow or thermal speed?
  Relativistically hot plasma vs. relativistic process

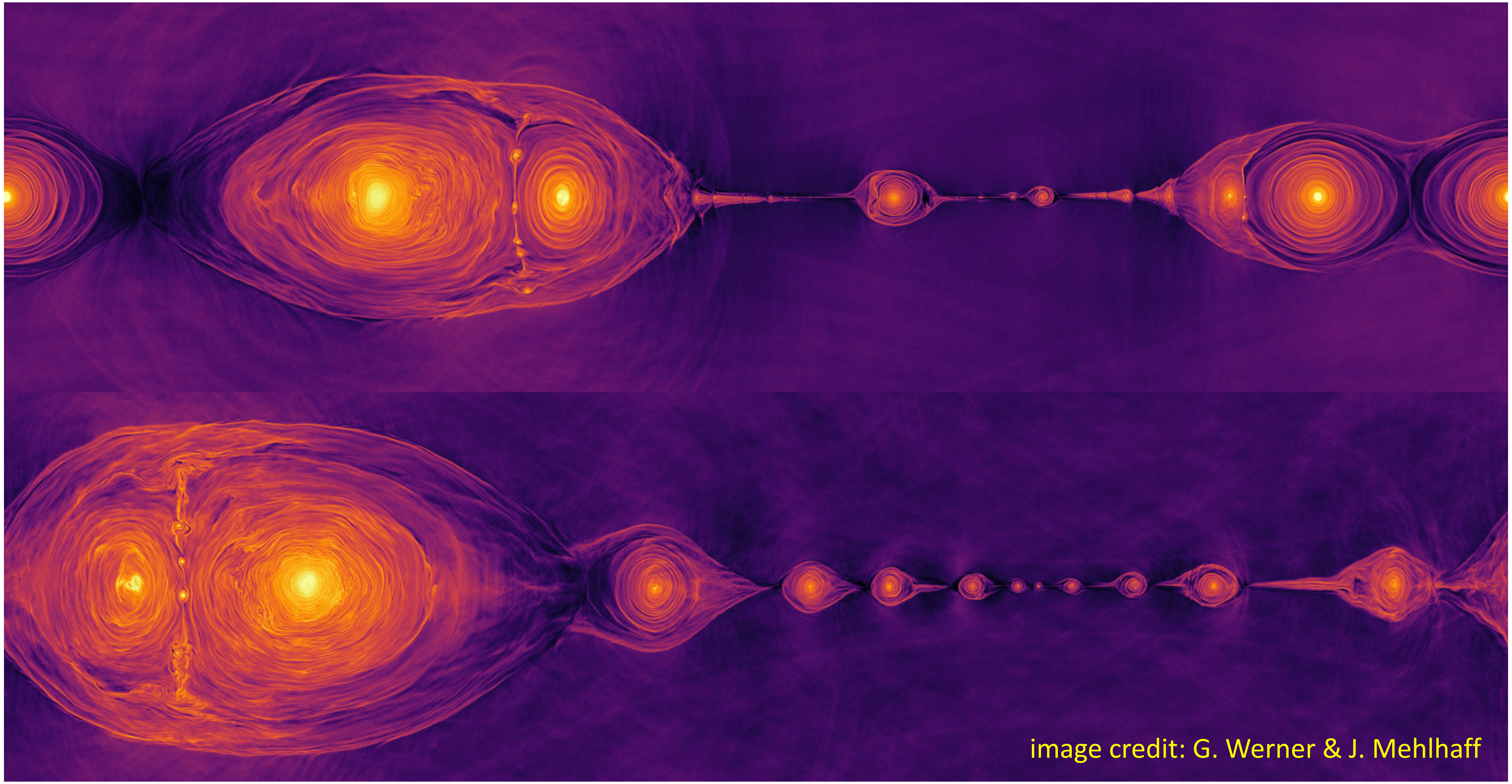


Macro- and Micro-scales, Plasma Descriptions, and Computational Approaches

- **MHD dynamics**: global system size L (macroscopic):
  - $L \sim R_g$ for BHs; disk scale-height for thin-disk MRI studies.
  - Computational approach: global 2D/3D GRMHD and local shearing-box MHD sims.
  - 1024^3 –grid sims can reach down down to $10^{-3}L$ (smaller with AMR) --- formally still macroscopic!
  - Advantages: large-scale system dynamics and structure.
  - Disadvantages: no electron-ion heating ratio, nonthermal particle acceleration, radiation.

- **Kinetic Physics**: kinetic plasma scales ℓ (microscopic):
  - $\ell \sim \lambda_D$, $d_{i,e}$, $\rho_{i,e}$ – local scales, governed by local plasma conditions (n,T,B), independent of L.
  - Related via dimensionless ratios: β, $\theta = T/mc^2$, m_i/m_e, Mach #, σ, (richness of kinetic plasma physics!)
  - Computational approach: 2D/3D particle-in-cell (PIC) sims
  - PIC sims have to resolve λ_D, can reach system sizes of $10^3\ \lambda_D$ --- formally still microscopic << L.
  - Advantages: can determine electron-ion heating ratio, nonthermal particle acceleration, radiation.
  - Disadvantages: local PIC sims need to be connected to large-scale MHD (e.g., via mesoscopic boxes); global PIC sims have small scale separation $L/\ell \sim$ 100-1000.

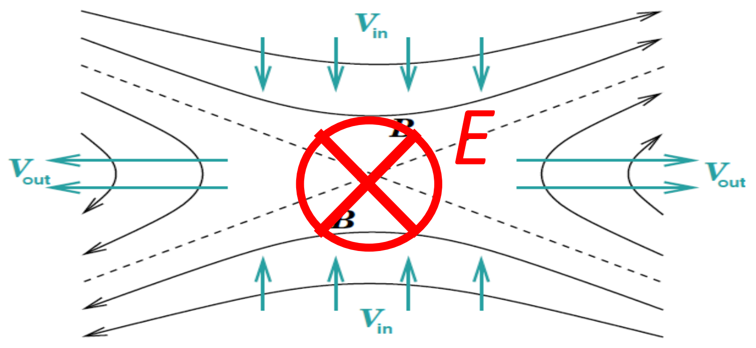
Relativistic Magnetic Reconnection

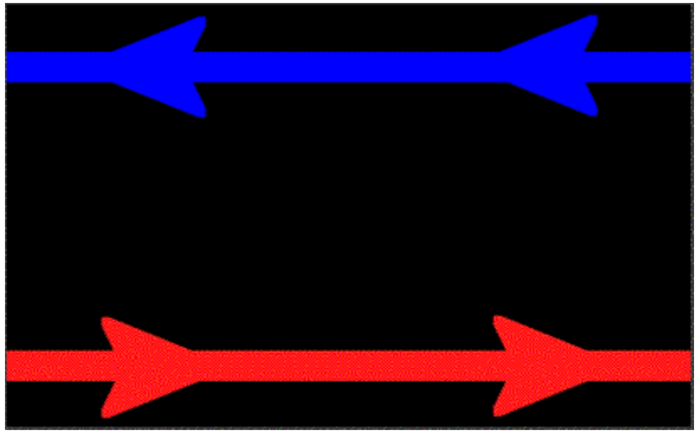


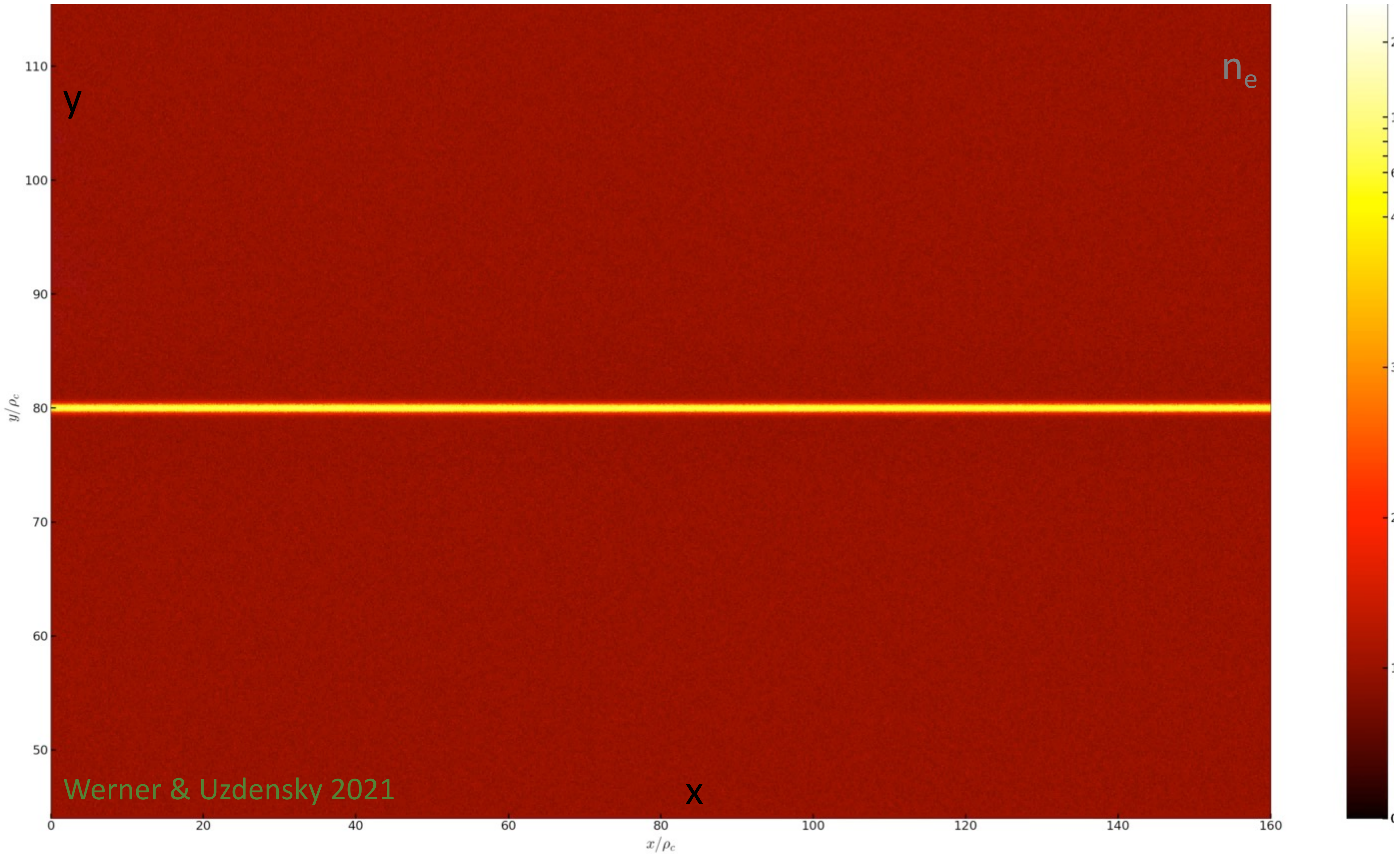
Introduction: Magnetic Reconnection

- **<u>Magnetic reconnection</u>** is a rapid rearrangement of magnetic field topology, breaking ideal-MHD.

- Reconnection results in a violent <u>release of magnetic energy</u> and its conversion to:
  - electron and ion heating
  - bulk flow kinetic energy
  - non-thermal particle acceleration
  - **radiation**





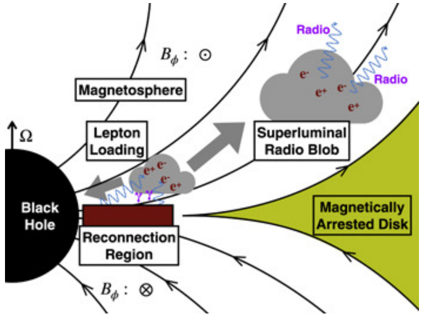


110
100
90
80
70
60
50
y/ρ_c
y
n_e
Werner & Uzdensky 2021
x
0
20
40
60
80
100
120
140
160
x/ρ_c

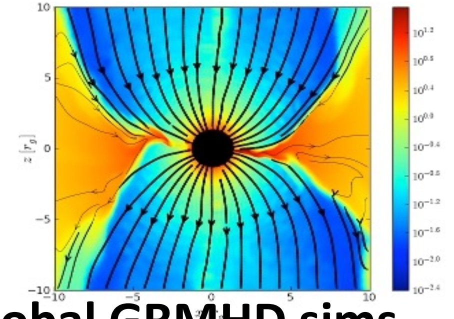
Reconnection in Accreting Black Hole Environments (Disks/RIAFs/Magnetospheres/Coronae/Jets)

Black-hole accretion disks, flows, coronae, magnetospheres are highly dynamic, complex magnetized plasma environments, so reconnection is generally expected.

- E.g.: *Equatorial current sheet* in MAD plunging region/ergosphere:

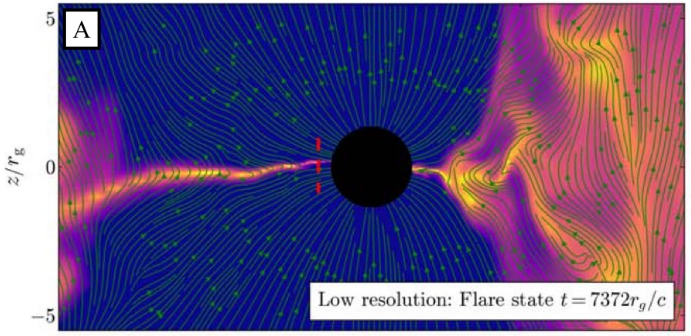


(image: Kimura+ '22)



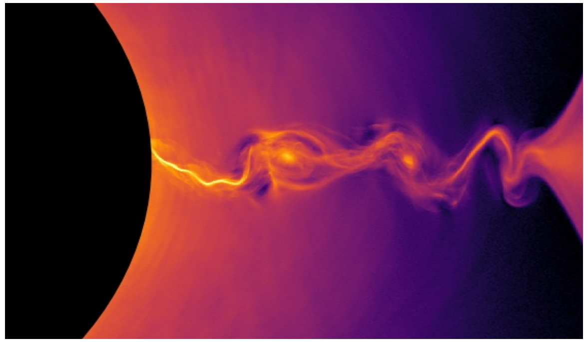
Global GRMHD sims

(McKinney+ '12, Chatterjee+ '21, Dexter+ '21)



Global resistive GRMHD sims

(Ripperda+ '22)

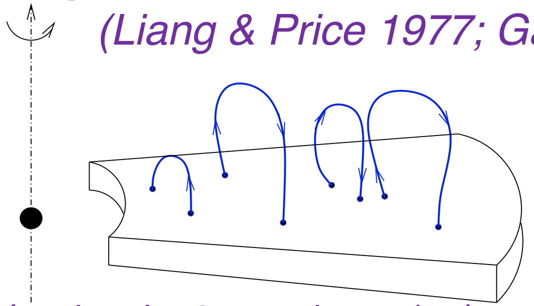


Global rad. GR-PIC sims

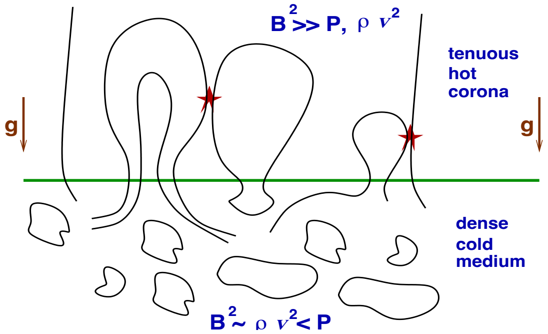
(Parfrey+'19, Crinquand+'20)

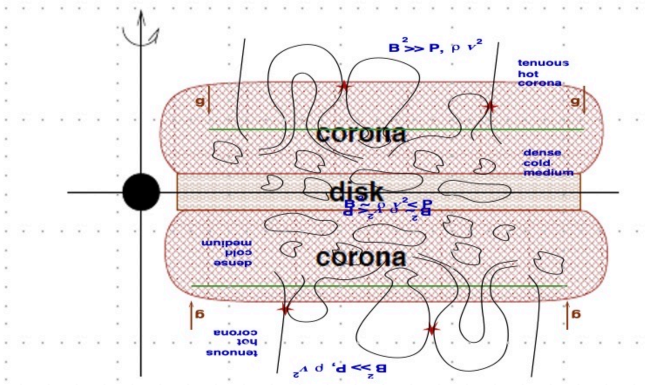
- E.g.: Accretion Disk Corona (ADC): sandwich model; analogy with solar corona

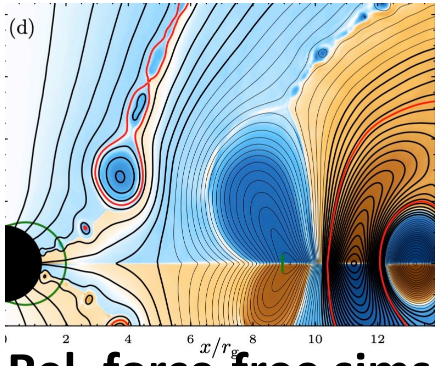
(Liang & Price 1977; Galeev, Rosner, & Vaiana 1979)



(Uzdensky & Goodman '08)







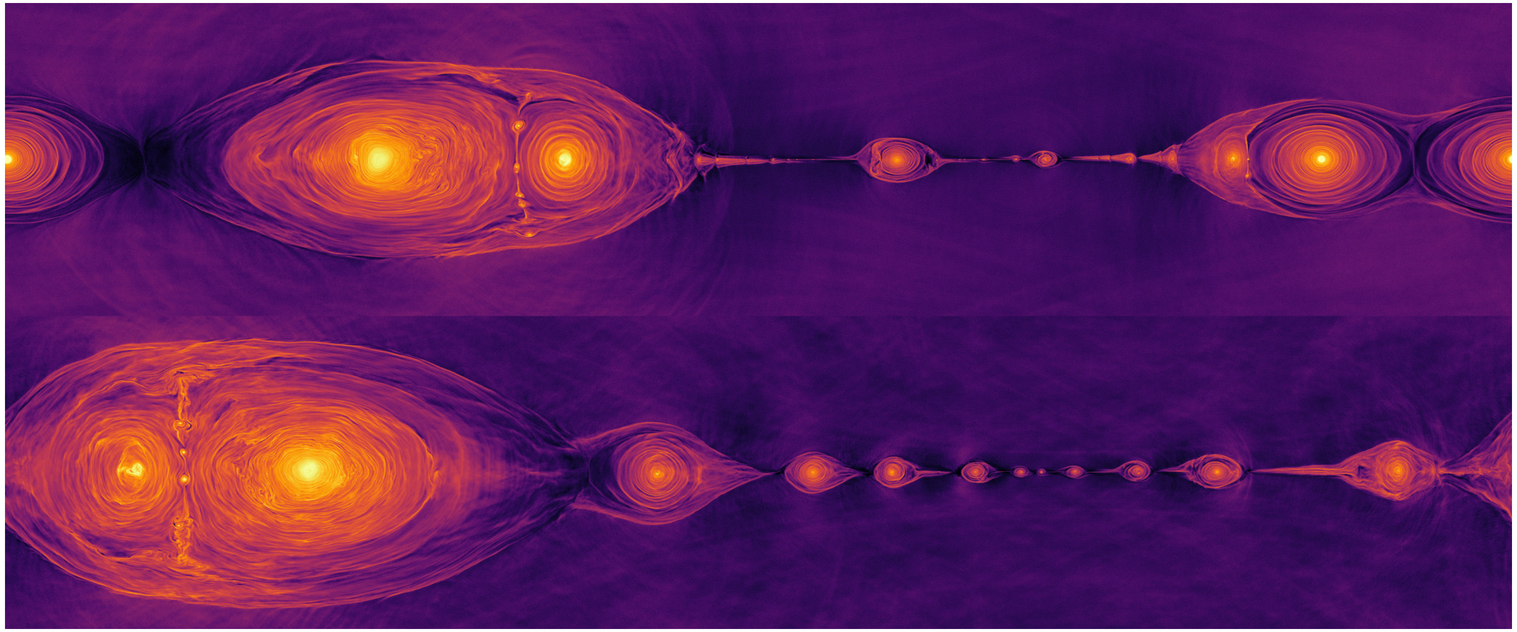
Rel. force-free sims

(Parfrey+'15)

Electron-Ion Heating Ratio Q_e/Q_i in Magnetic Reconnection in Collisionless Semi-Relativistic Electron-Ion Plasmas (2D & 3D PIC Simulations)

Ions dominate dynamics and energetics, but electrons produce all the light we see!

Determining electron heating fraction is thus critical for connecting theoretical/numerical (GRMHD) models of BH accretion flows to observations.



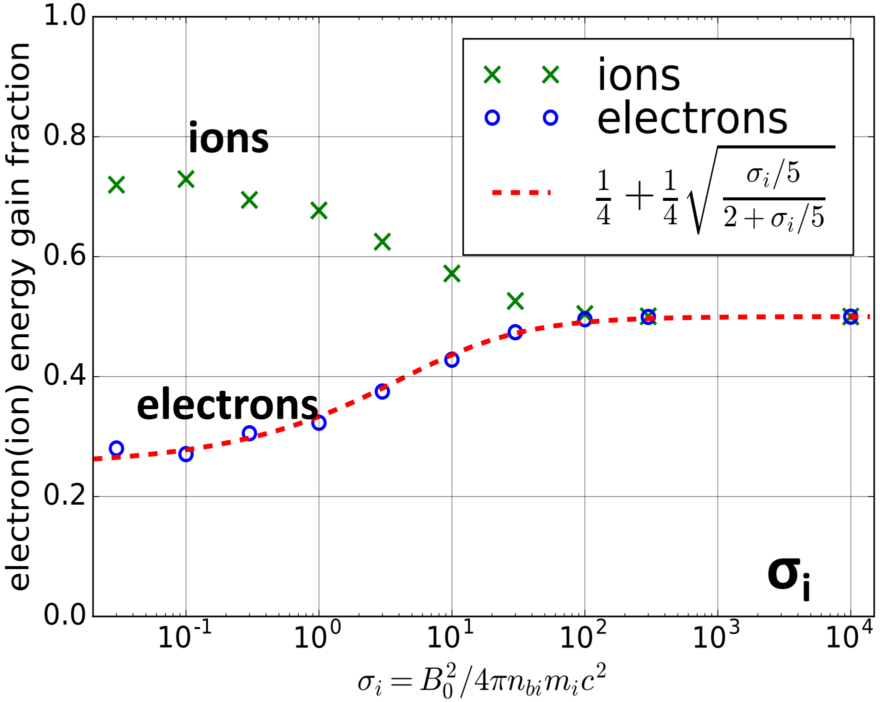
[Werner et al. 2018 (2D); Werner & Uzdensky 2023 (3D)

See also in 2D: Melzani et al. 2024, Rowan et al. 2017, Sridhar et al. 2023]

Semi-Relativistic *e-i* Reconnection: 2D PIC Sims, B_g=0

Werner et al. 2018

Energy partitioning between electrons and ions

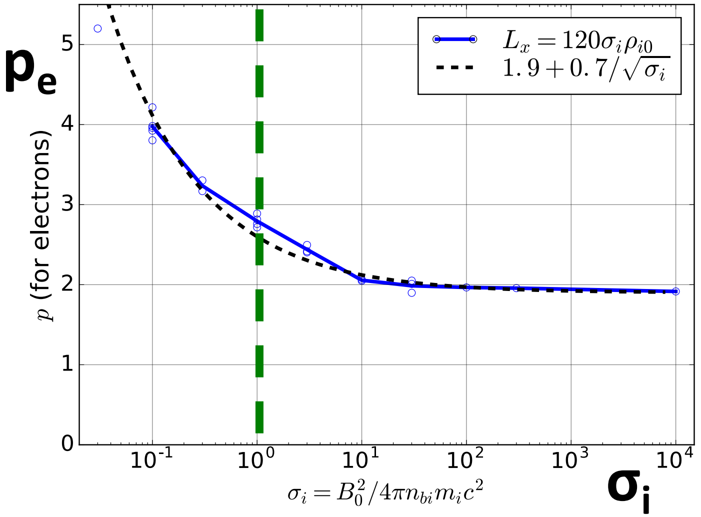


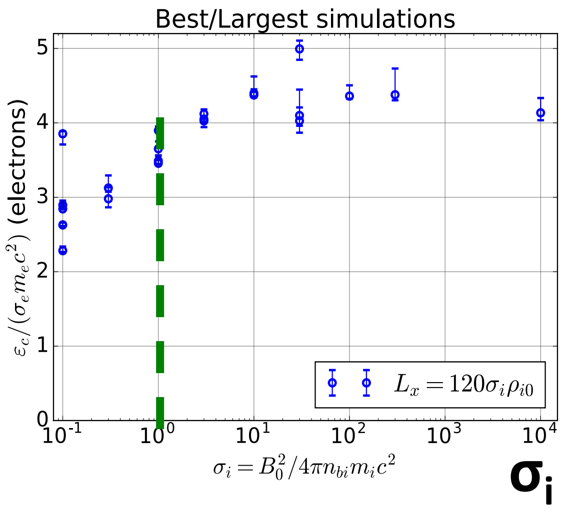
In semi-relativistic B_g=0 case ions gain 3 times more energy than electrons.

(*Werner et al. 2018; c.f*. Rowan et al. 2017, 2019)

Nonthermal Particle Acceleration:

Electron power-law index *p* and cutoff γ_c:





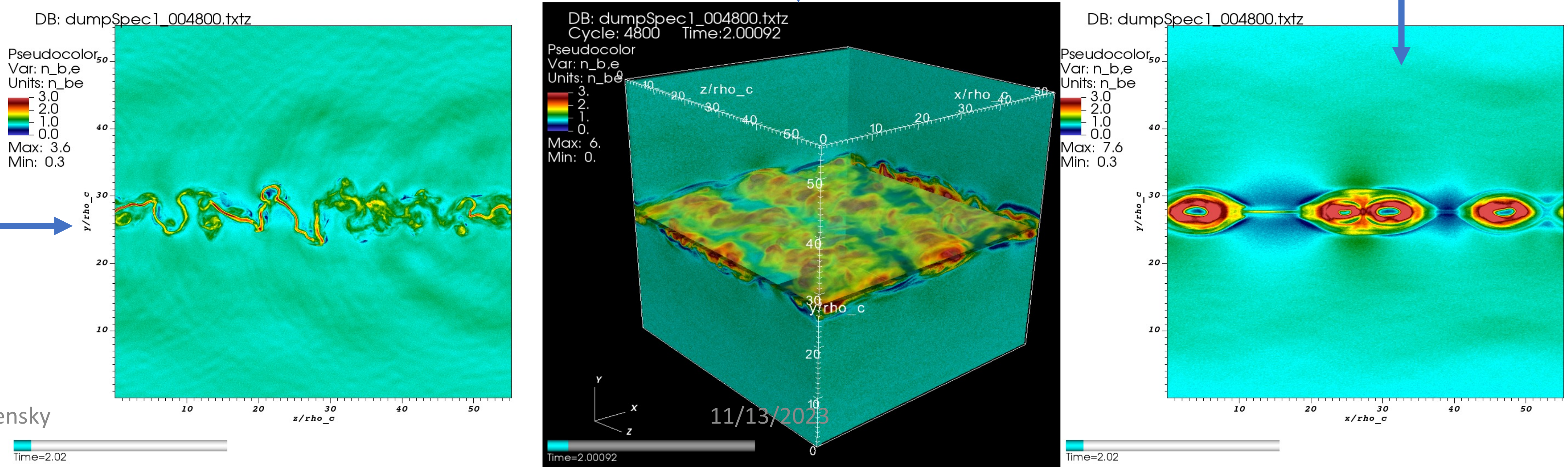
(*Werner et al. 2018; c.f*. Ball et al. 2018)

New! Semi-Relativistic *e-i* Reconnection: 3D PIC Sims

Werner & Uzdensky 2023 (in prep)

Current sheets in semirelativistic plasma suffer multiple competing instabilities

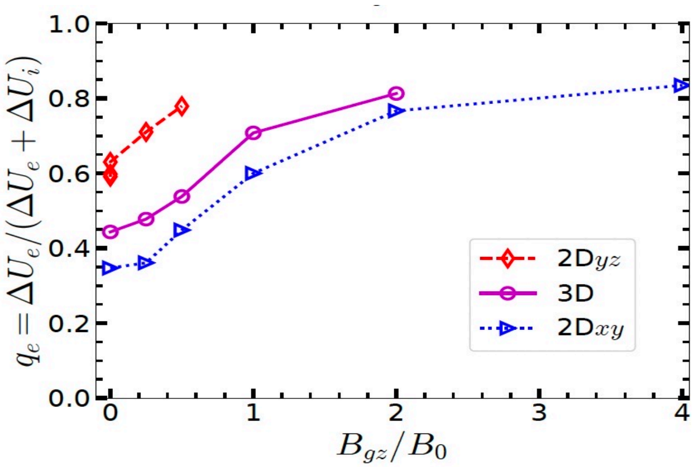
- magnetic reconnection (tearing, coalescence) -- can be studied in 2D
- drift kink instability (DKI) – can be studied in 2D
- flux rope kink instability (MHD kink) – requires 3D



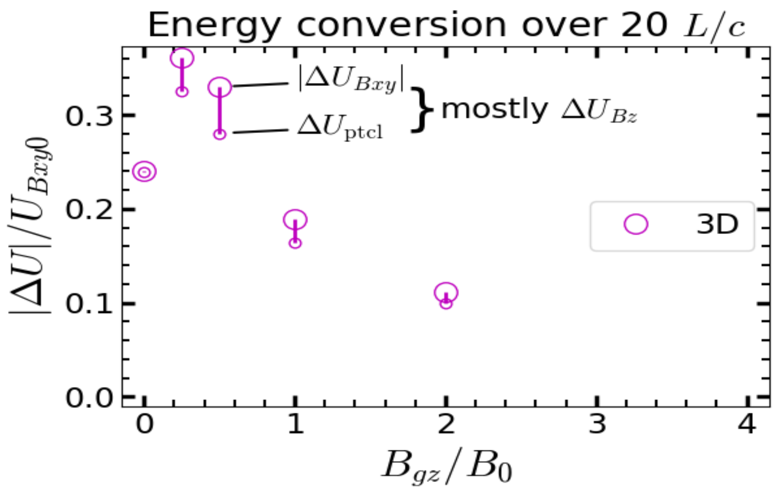
New! Semi-Relativistic *e-i* Reconnection: 3D PIC Sims

Werner & Uzdensky 2023 (in prep)

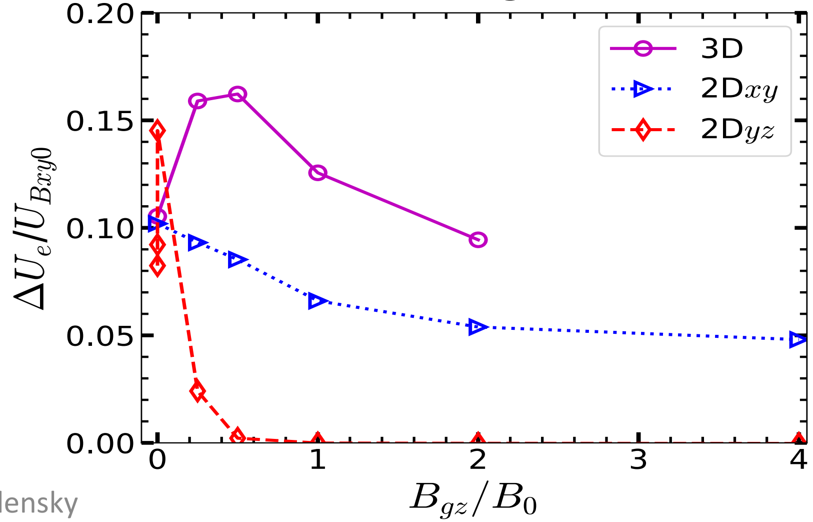
Electron/Ion Energization Ratio



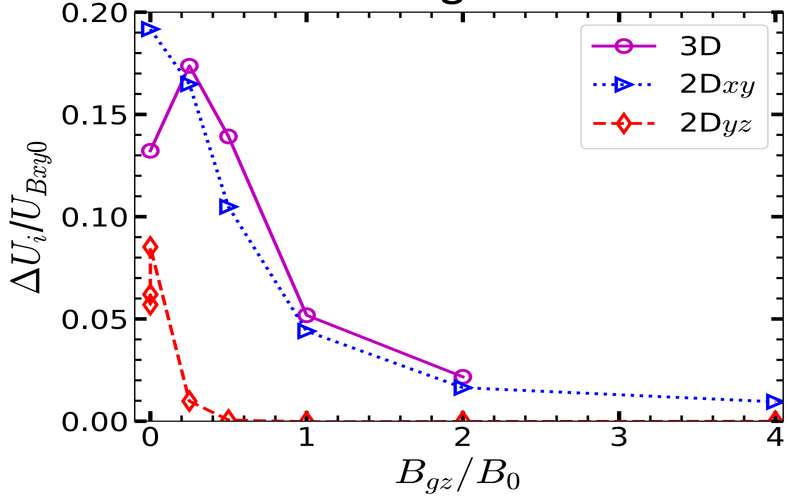
Overall Magnetic Energy Release



Electron Energization



Ion Energization



(Werner & DAU 2023; c.f. Rowan+ 2019 in 2D)

Summary

- Accreting Black Holes are a great natural laboratory (aka a theorist's playground) for studying extreme plasma physics.
- Great variety of physical regimes, but all on a well-defined underlying BH metric.
- Numerical GRMHD models are an excellent tool to explore overall fluid dynamics and magnetic field structure.
- But connecting these models to observations (EM radiation) requires kinetic plasma physics (beyond MHD): electron heating fraction Q_e, NTPA.
- (radiative) PIC simulations probe this physics from first principles, yielding prescriptions for Q_e, p_e, etc.

THANK YOU!