Kinetic and Two-Temperature Plasma Physics of Black Hole X-ray Coronae

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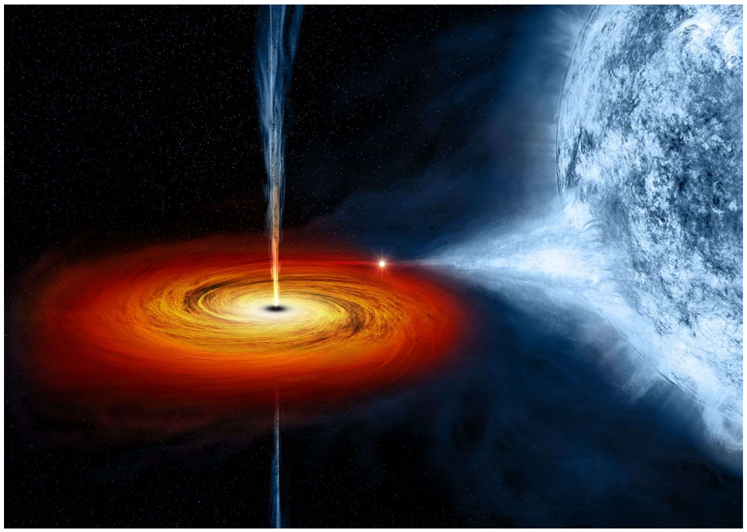
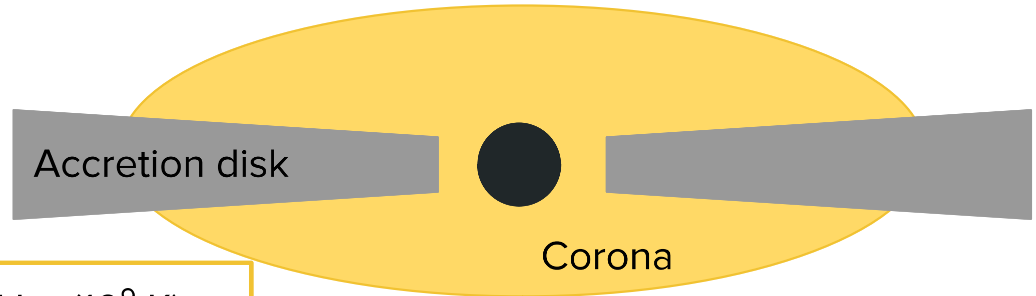
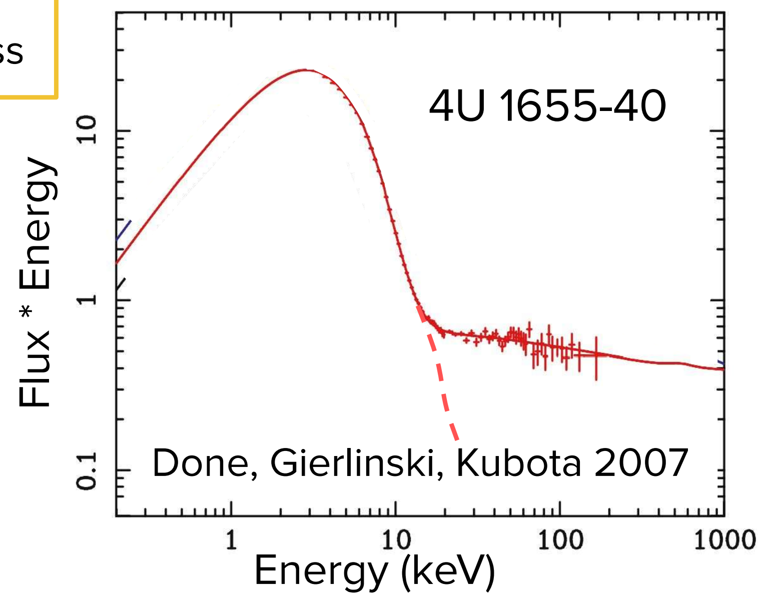
Accretion disks encapsulate a wide range of plasmas

Thin disk: Shakura & Sunyaev 1973





- Hot (10^9 K)
- Collisionless

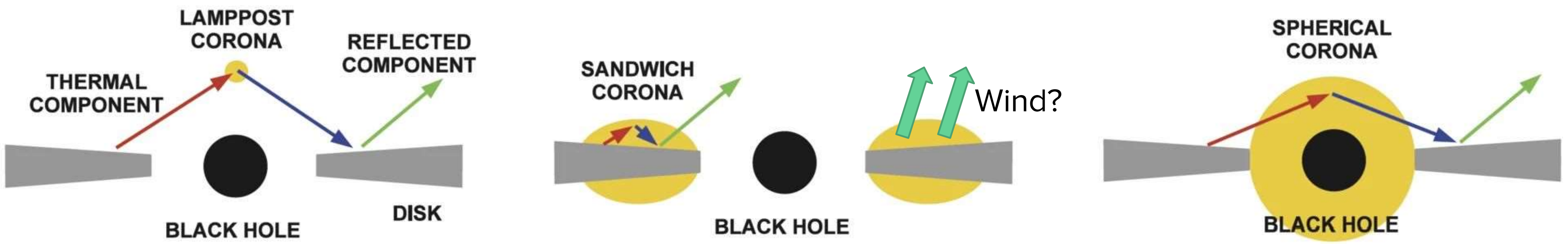


- High accretion rate: dense
- Collisional, high optical depth
- Radiates dissipation locally, as a blackbody
- Cold (10^7 K)

The Corona: some questions

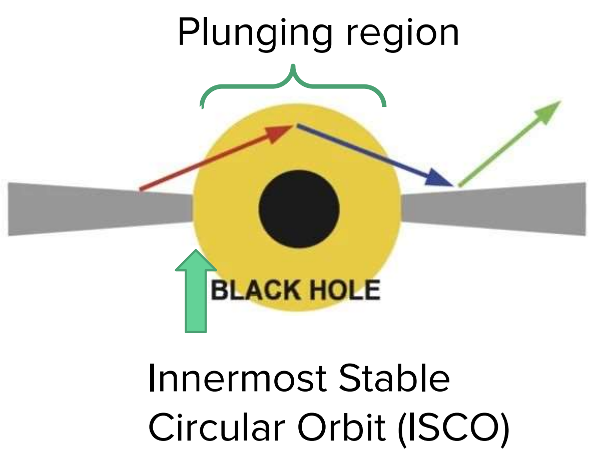
- Where is the corona? What is its geometry?
- What is the particle distribution in the corona?
- How does the corona affect dynamics in the accretion disk?

Ingredients: Coulomb collisions, nonthermal electrons, general relativity

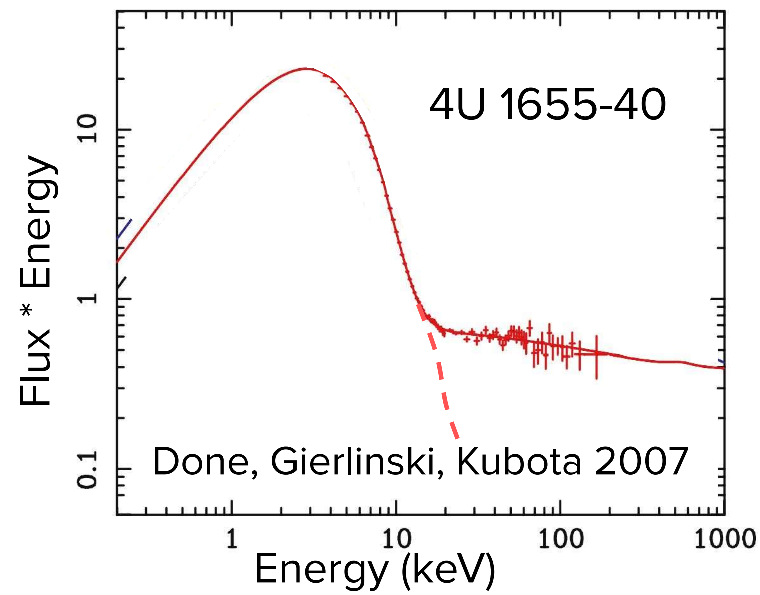


Geometry of the (Soft State) Corona

Creating an analytic model for the corona



Hankla, Scepi, Dexter 2022



Could nonthermal emission come from within the ISCO?

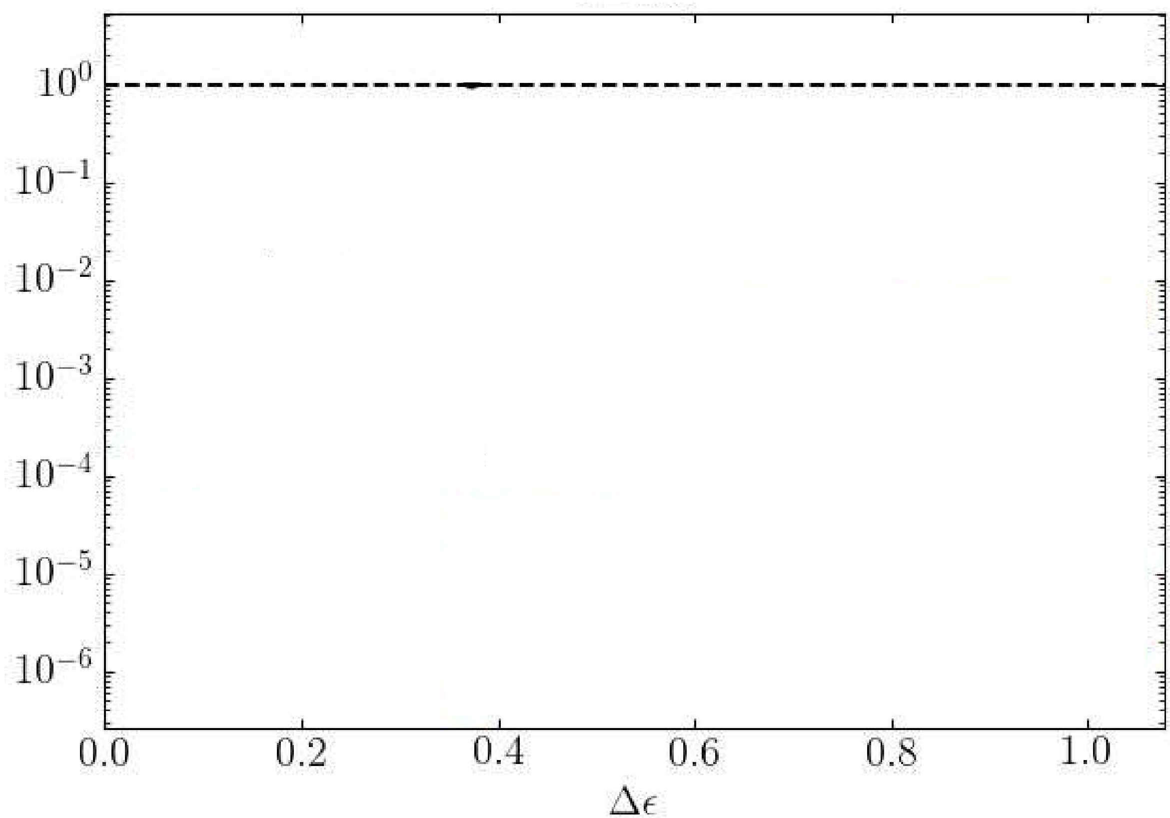
Physical Conditions in the Plunging Region

- Low density: $\dot{M} \propto \rho v_r$
- Strongly magnetized

$$\sigma_i \equiv \frac{B_0^2}{4\pi n_0 m_p c^2} \gtrsim 1$$

Is it collisionless? Consider:

- Electron-ion collision time
- Electron-electron collision time



Additional energy dissipated in plunging region

Increasing magnetization ➡

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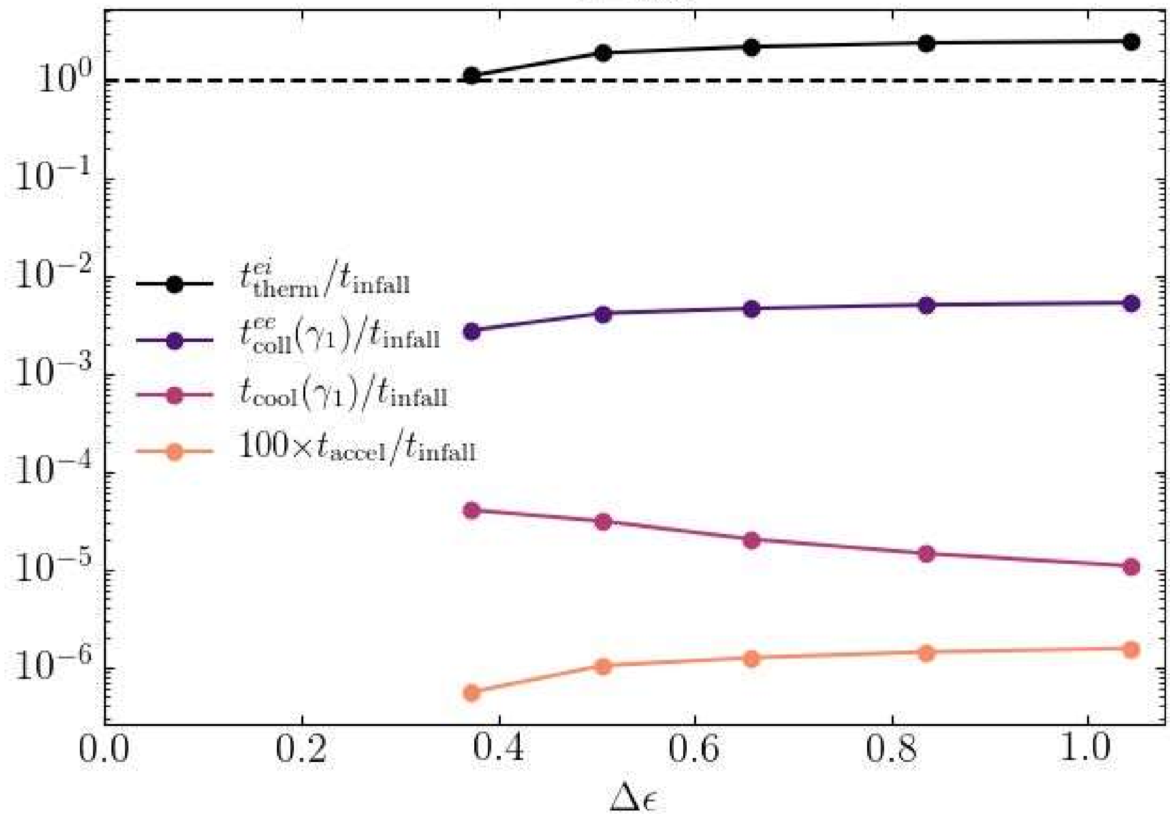
Other relevant timescales:

- Electron cooling time
- Electron acceleration time



Additional energy dissipated in plunging region

Increasing magnetization

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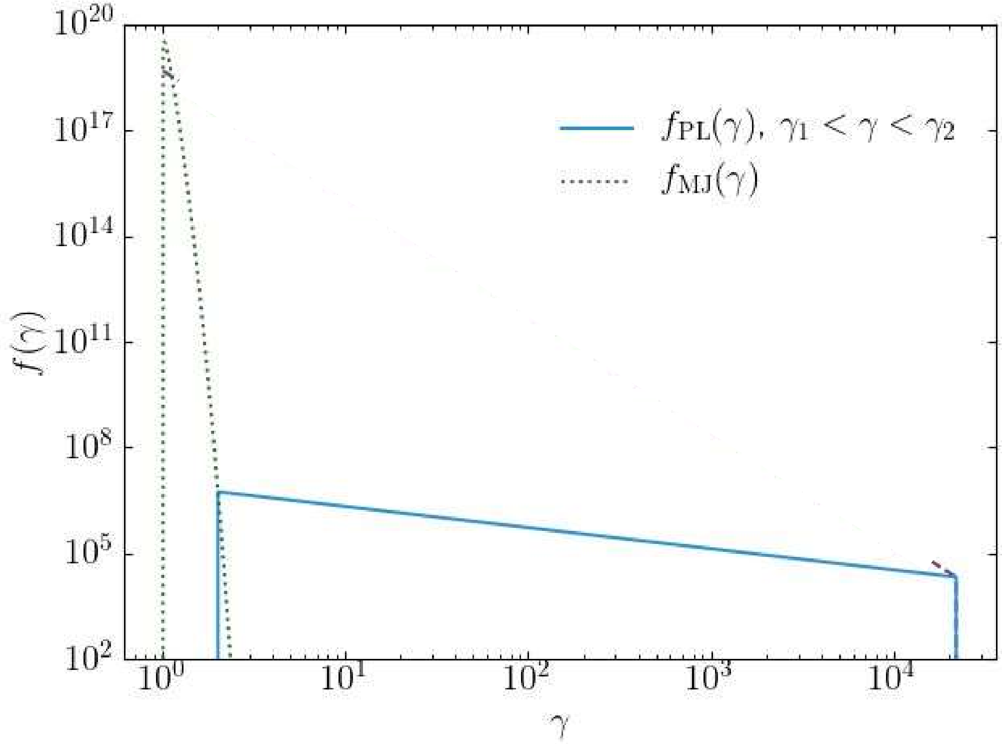
Building the electron distribution function in the plunging region

- Background analytic model
- Prescriptions from particle-in-cell simulations of reconnection (Werner+ 2018) for power-law index, high-energy cut-off
- Steady state: heating = cooling.
- Continuity of thermal/nonthermal population



Solve equations iteratively at each radius

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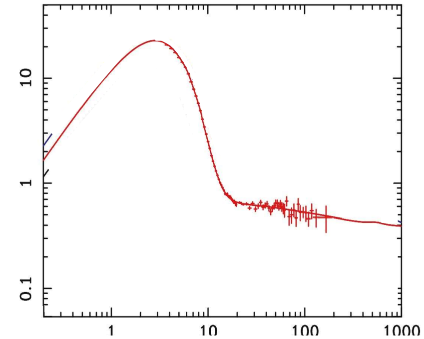
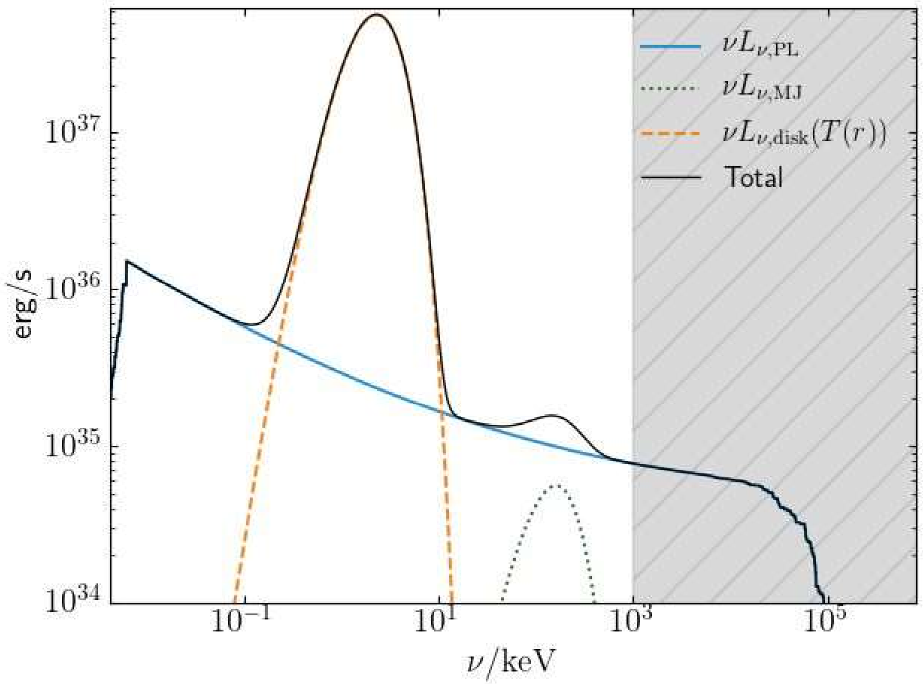
Model produces a visible hard power-law





- Observations show power-law p≳3, we find p=3 - 4
- Power-law cut-off past MeV

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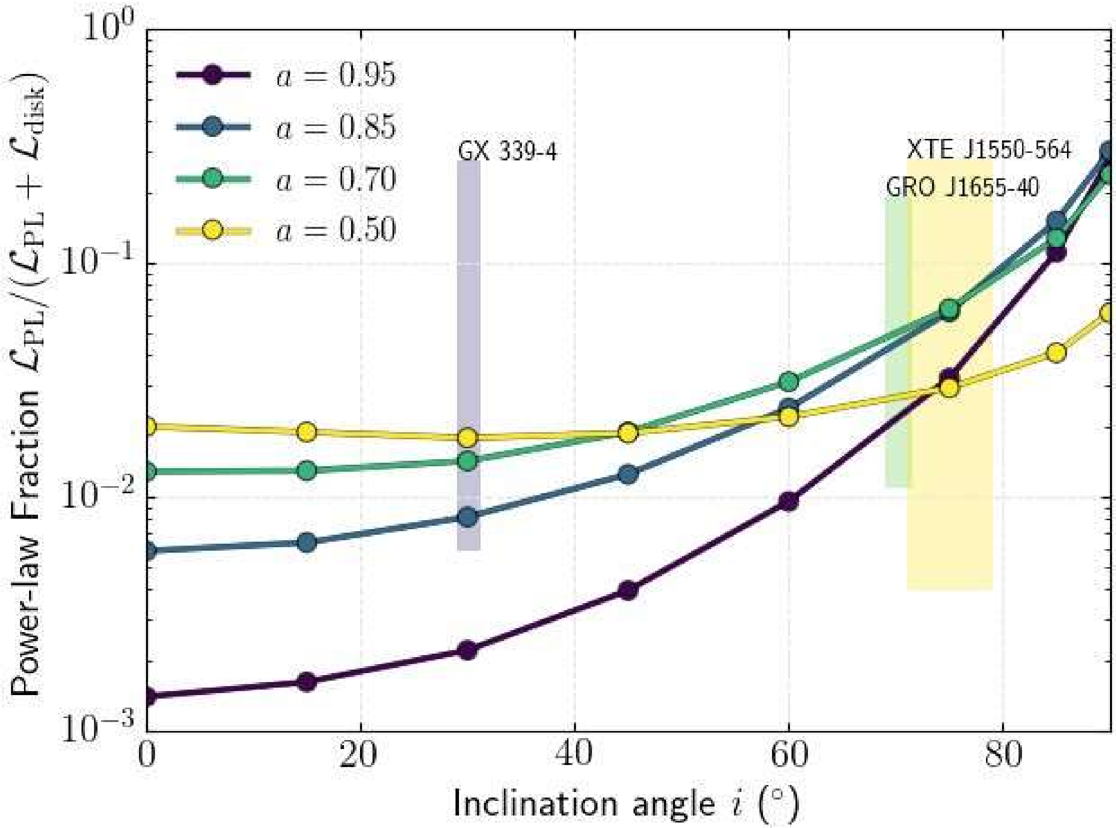
Model agrees with observational measurements

- Fraction of luminosity in the power law
- Observational values between 10^{-3} and 10^{-1}



Takeaway: nonthermal electrons in the plunging region reproduce observational trends

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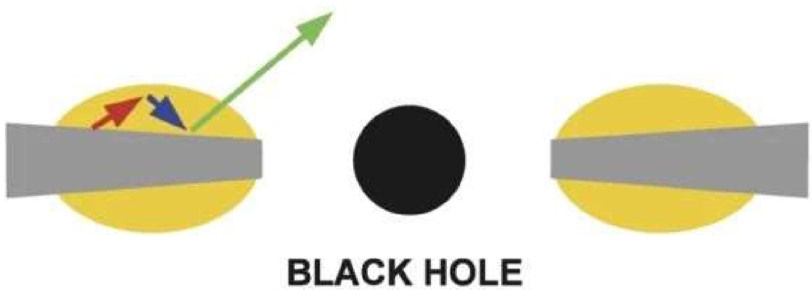
Particle Acceleration in the Corona

Studying the collisionless corona with first principles numerical simulations



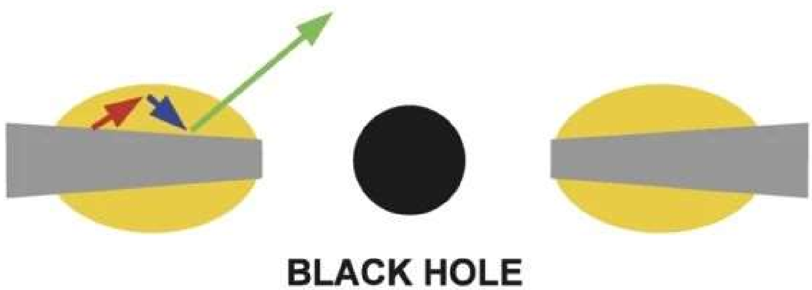
Magnetization
Magnetized: $\rho \ll L$

Collisionality
Collisionless: $\lambda_{\rm mfp} \gg L$

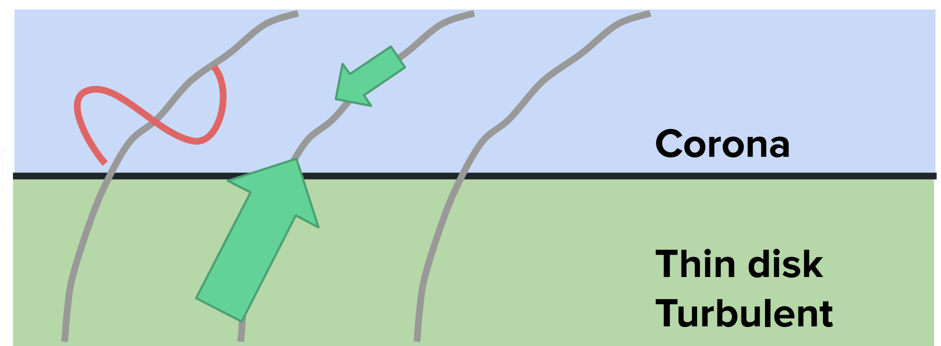
Can particles be efficiently accelerated when injected energy is asymmetric?

Hankla, Zhdankin, Werner, Uzdensky, Begelman 2022

Accretion Disks Inject Energy **Asymmetrically** Into the Corona



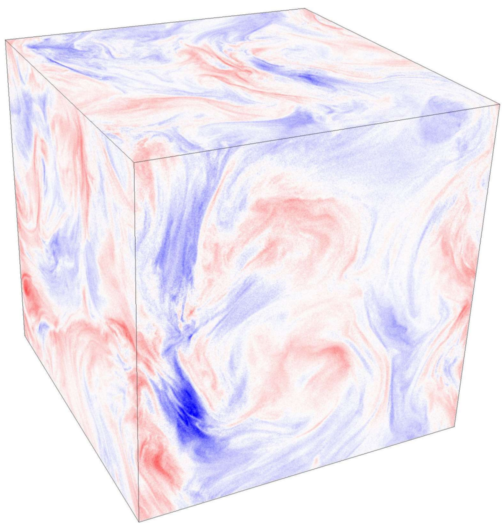
Imbalanced
turbulence



Previous studies:
balanced turbulence
(symmetric energy injection)

Studying collisionless imbalanced turbulence with Particle-in-Cell (PIC) simulations

- Needed to study collisionless plasmas
- Solve Maxwell equations, push particles with Lorentz force
- Drive with external current that generates Alfvén waves



- Electron-positron pair plasma
- Periodic boundary conditions
- Background magnetic field

$$\mathbf{B_0} = B_0 \hat{z}$$

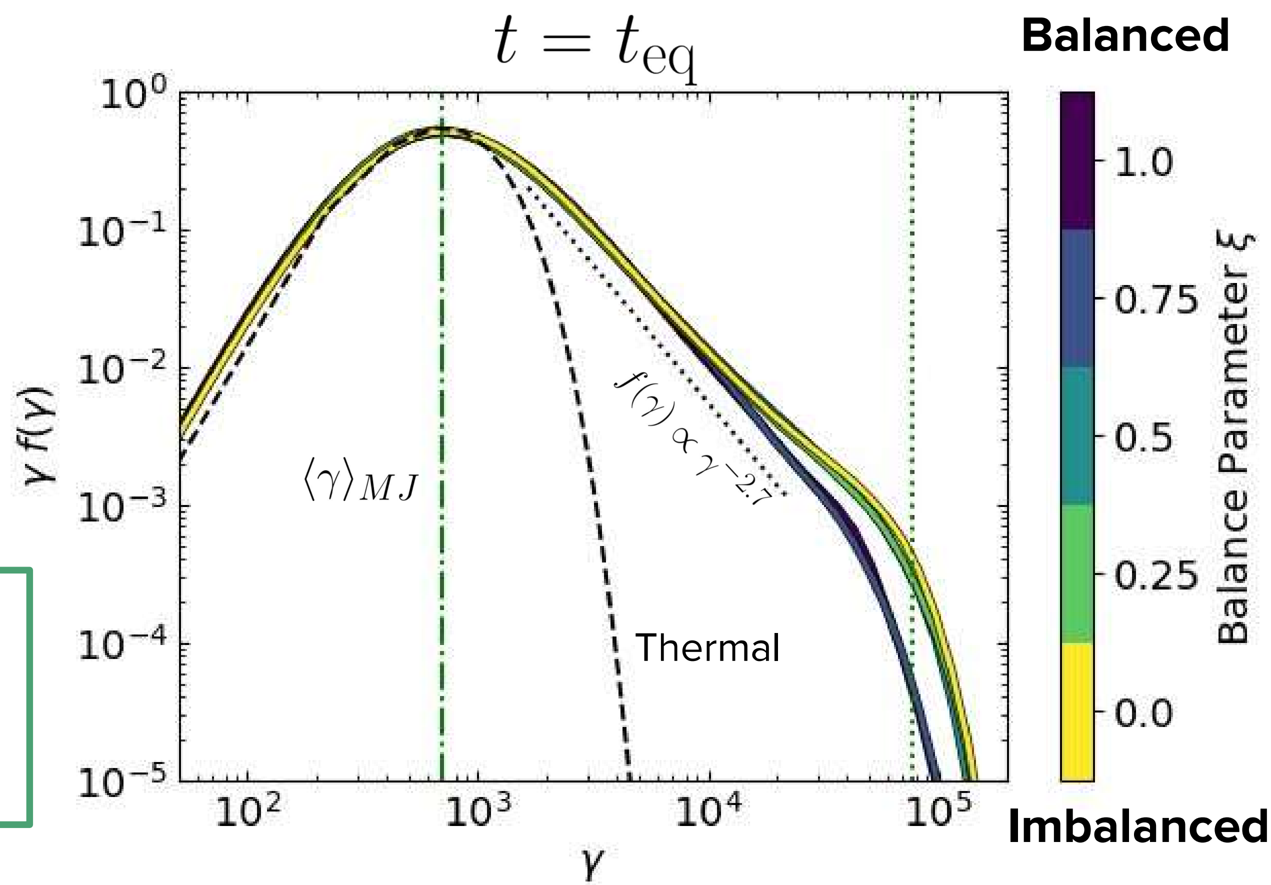
- Maxwell-Juettner distribution

$$T_{e0} = 100mc^2 \qquad \bar{\gamma} = 300$$

Imbalanced Turbulence Can Efficiently Accelerate Particles

Equivalent times (same injected energy): **t=20 L/c** for most imbalanced, **t=8 L/c** for balanced

Imbalanced case takes more than twice as long to accelerate



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Imbalanced Driving Can Launch A Net Flow

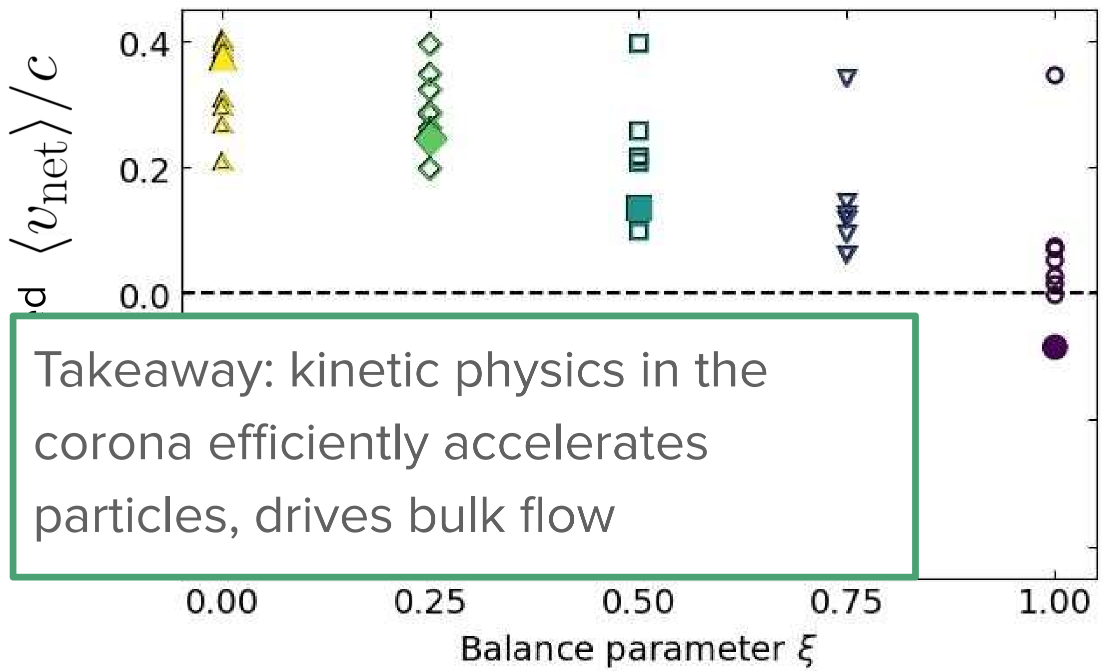
Hankla et al. 2022a

$$\epsilon \mathcal{P}_{\mathrm{EM},z} = \mathcal{P}_{\mathrm{plasma},z}$$

- Simple estimate: Alfvén wave momentum converts into plasma momentum

$$\Gamma_{\mathrm{net}} v_{\mathrm{net}} = \frac{4}{3}\epsilon\ \sigma\ v_{A0}$$

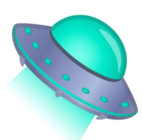
$$\sigma \propto \langle \delta B^2 \rangle$$



Takeaway: kinetic physics in the corona efficiently accelerates particles, drives bulk flow

Imbalanced ⟷ Balanced

- Plasma can attain saturated net bulk velocity $\approx 0.4c$



  - Consistent with $\epsilon \approx 0.5$
  - About 7% of injected energy
  - UltraFast Outflows (UFOs)!

Summary & Outlook

Questions?

Kinetic and two-temperature physics improves disk/corona models.

- Nonthermal particles can arise in the corona and affect observed radiation
- Including Coulomb collisions can change disk structure