Black Hole Jet Sheath as Comptonizing Corona

Part – I: *arXiv:2107.00263 (PIC: pair plasma)*

Part – II: *arXiv:2203.02856 (PIC: electron-ion plasma)*

Part – III: *arXiv:2310.04233 (PIC: guide field)*

Part – IV: arXiv:2411.10662 (GRRMHD: global picture)

Feeling the Pull and the Pulse of Relativistic Magnetospheres

Les Houches

11th April 2025

Navin Sridhar

With Lorenzo Sironi, Andrei Beloborodov, Sanya Gupta, and Bart Ripperda

Stanford University

SIMONS FOUNDATION

SCEECS


May 2019
Thank you!

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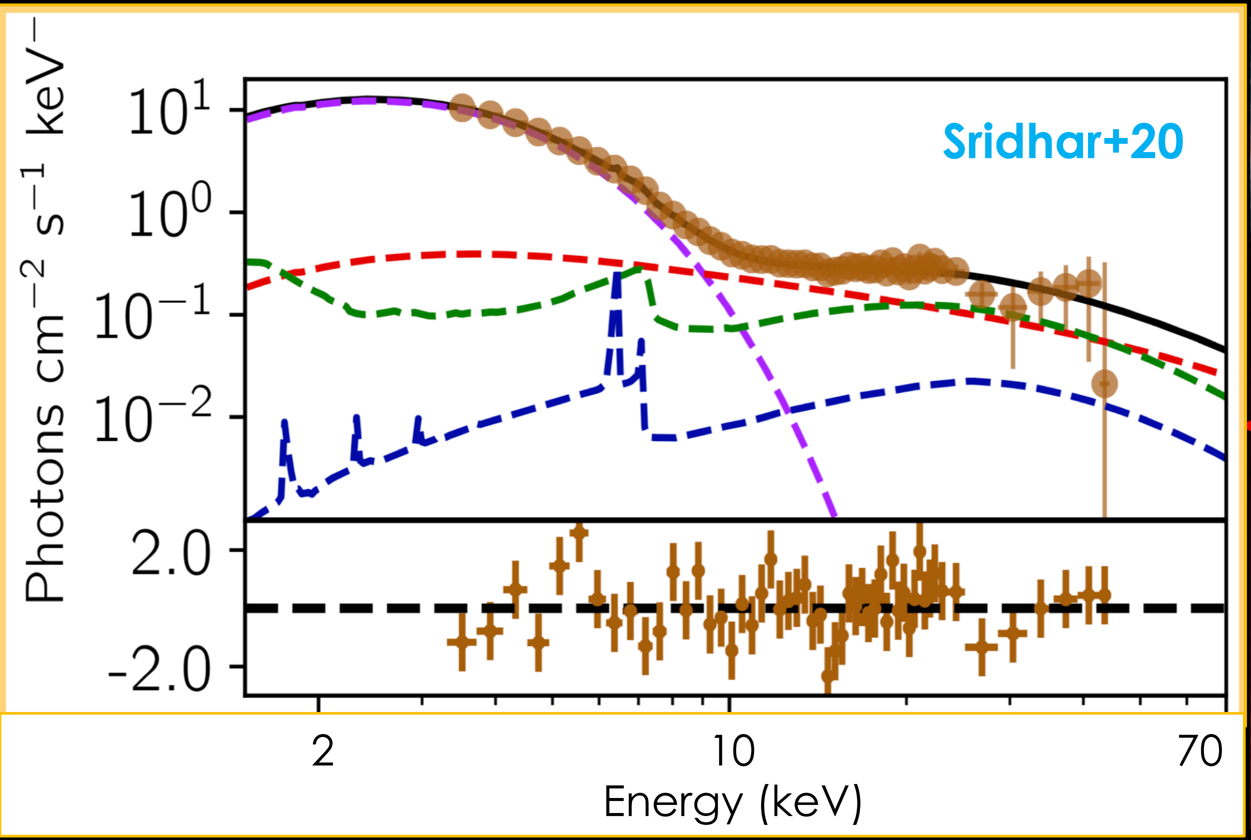
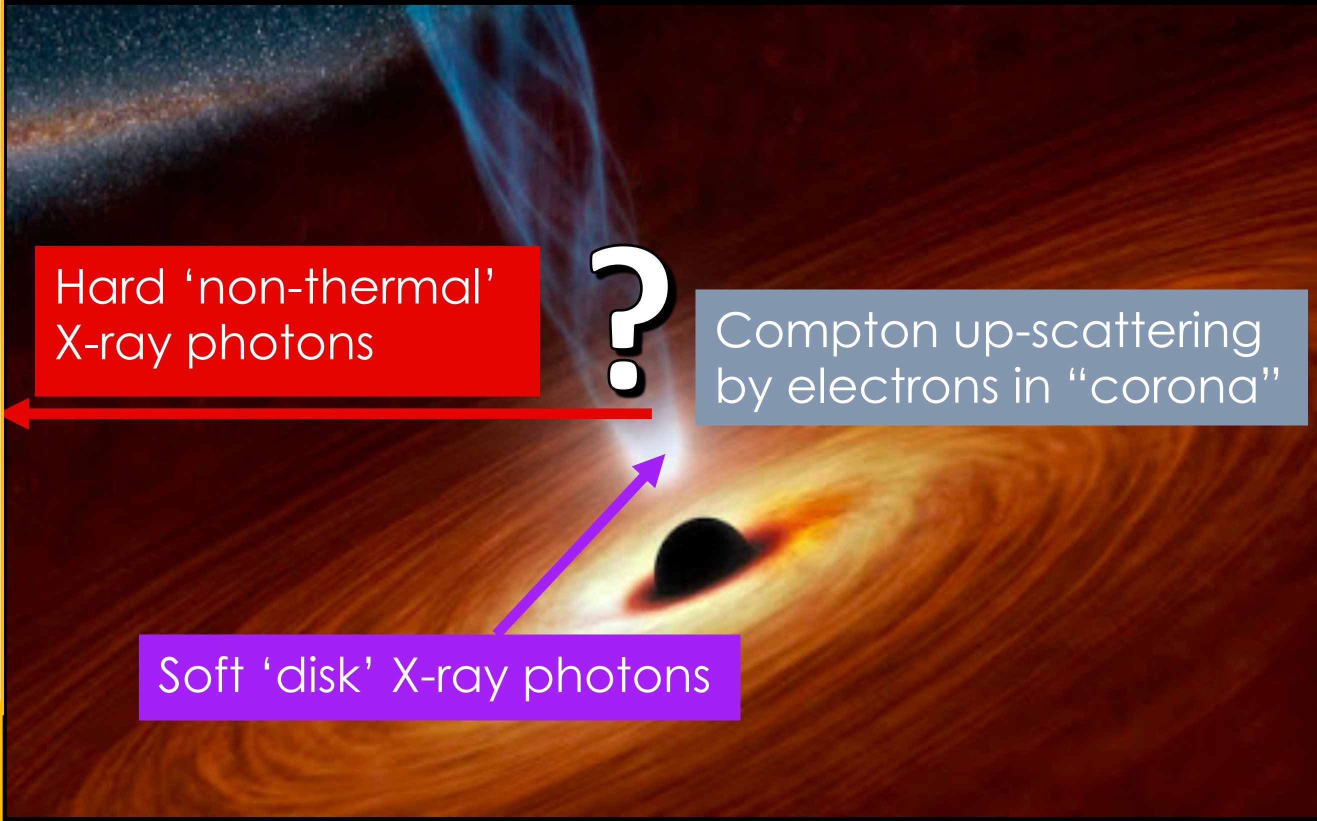
Conventional models and components





- Most models: Corona = hot electron cloud with a temperature kT_e~100 keV.
- But electrons get cooled down due to inverse-Compton (IC) scattering of soft photons.
- What keeps the corona energized?

Engine

- The underlying engine could be turbulence of **magnetic reconnection** (Beloborodov 2017).
  - I will discuss why heating by reconnection may not work.

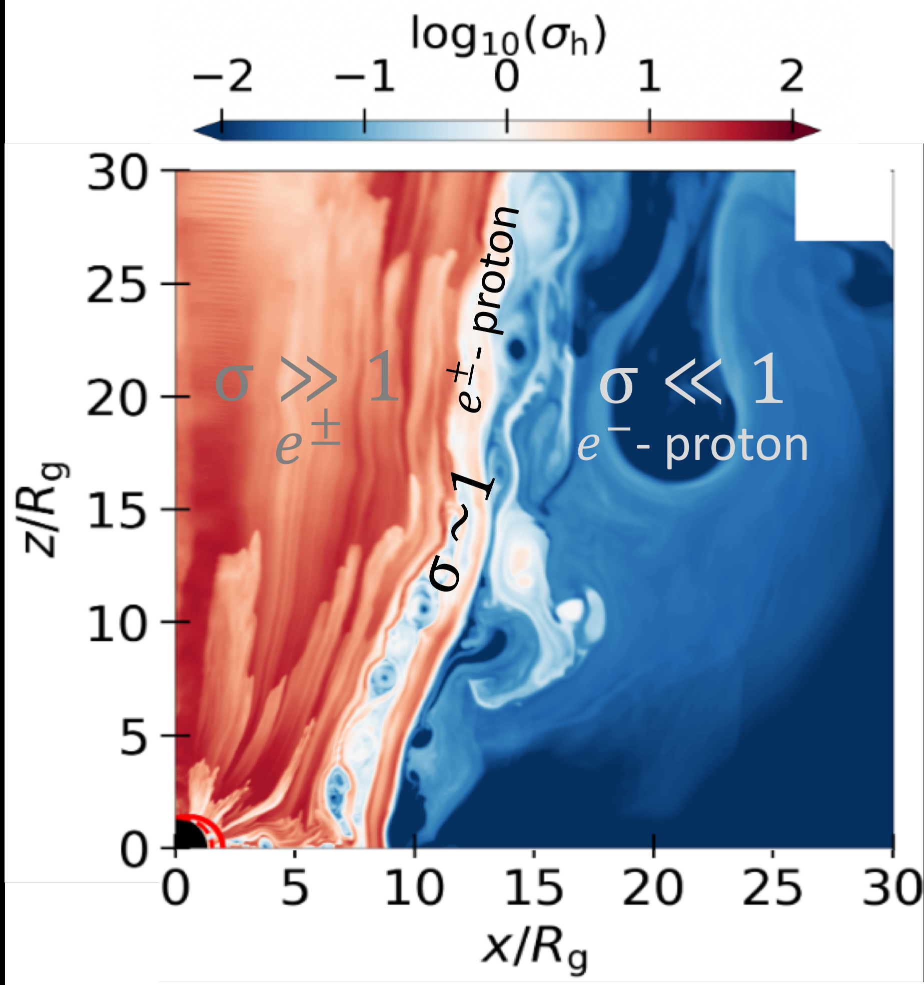
- PIC simulation parameters:
  - Composition: $e^{\pm}$, electron-ion corona
  - B-field: magnetization (σ), guide field strength (B_g/B_0).
  - Radiation: IC scattering off soft photon field (γ_{cr})

$$\sigma_s = \frac{B^2}{4\pi n_0 m_s c^2} \;;\; \gamma_{cr} = \sqrt{\frac{3e\eta_{rec}B_0}{4\sigma_T U_{rad}\gamma_e}} \;;\; \tau_{cool} = \frac{\gamma_{cr}^2/(\eta_{rec}\sqrt{\sigma_s})}{L_x/(c/\omega_{pe})}$$

$\boldsymbol{\gamma_{cr}}$ (or $\boldsymbol{\gamma_{rad}}$): The particle Lorentz factor for which the decelerating IC power = accelerating power of reconnection electric field.

$\boldsymbol{\tau_{cool}}$: Ratio of IC cooling time and plasma advection time.

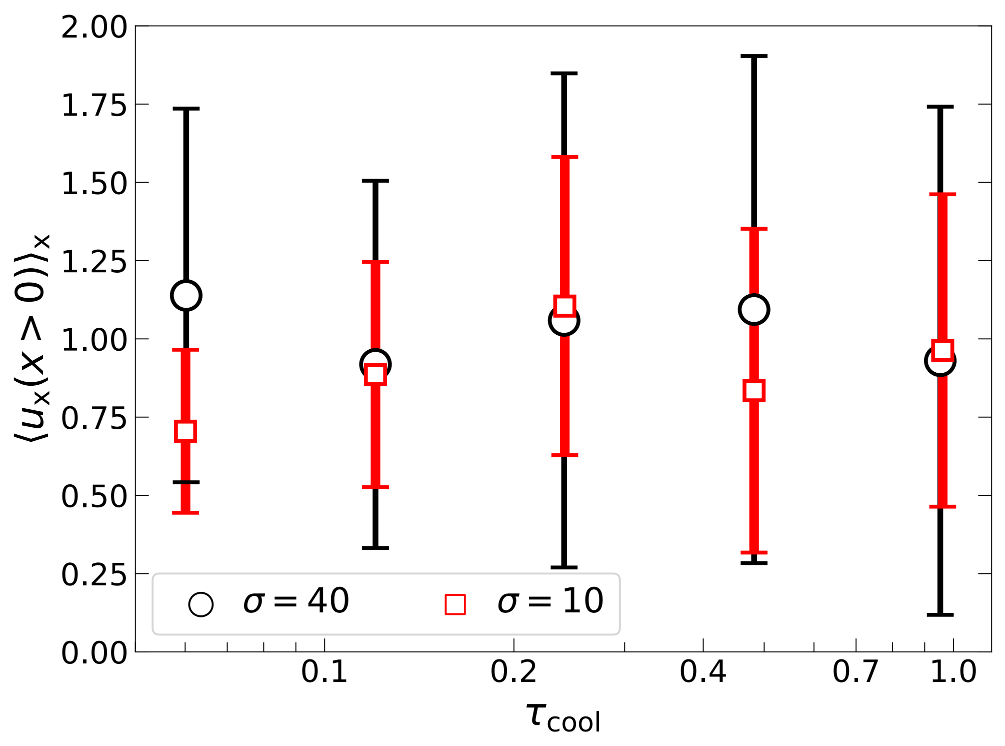
Higher γ_{cr} or τ_{cool} = lower IC cooling



Where is the corona?

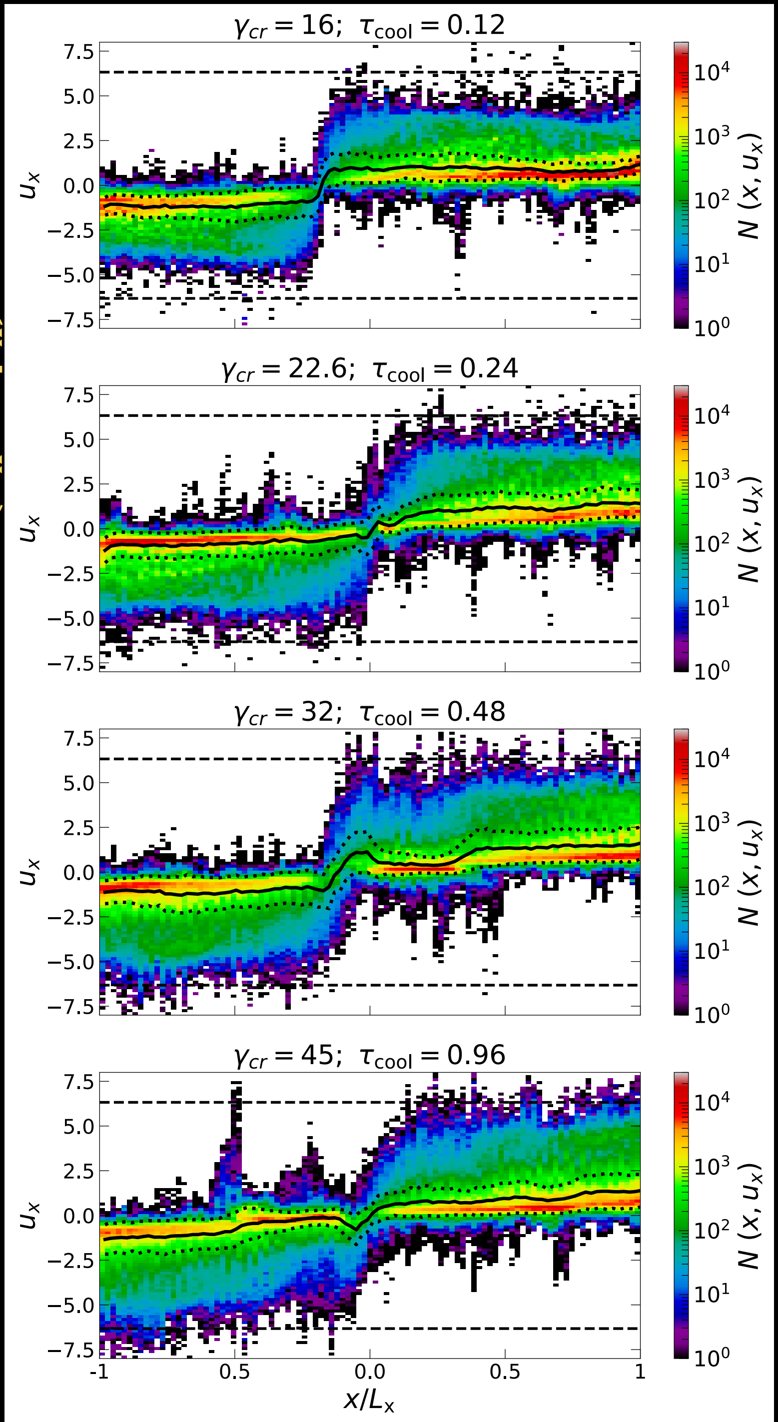
Bulk outflow motions

Dimensionless 4-momentum



← Stronger IC cooling

Bulk outflow momentum ($u_x = \Gamma\beta_x$)



← Stronger cooling

- Similar bulk outflow speed regardless of magnetization and IC-cooling strength.
- Motion more random for higher magnetization and low cooling.

Energies
Internal: $\langle \varepsilon_{\mathrm{int,\ e}} \rangle$, $\langle \varepsilon_{\mathrm{int,\ i}} \rangle$ and bulk: $\langle \Gamma \rangle - 1$

$\sigma_e = \left(\frac{m_i}{m_e}\right) \sigma_i$

$\sim 28 \times 3 = 84$

With stronger IC cooling:

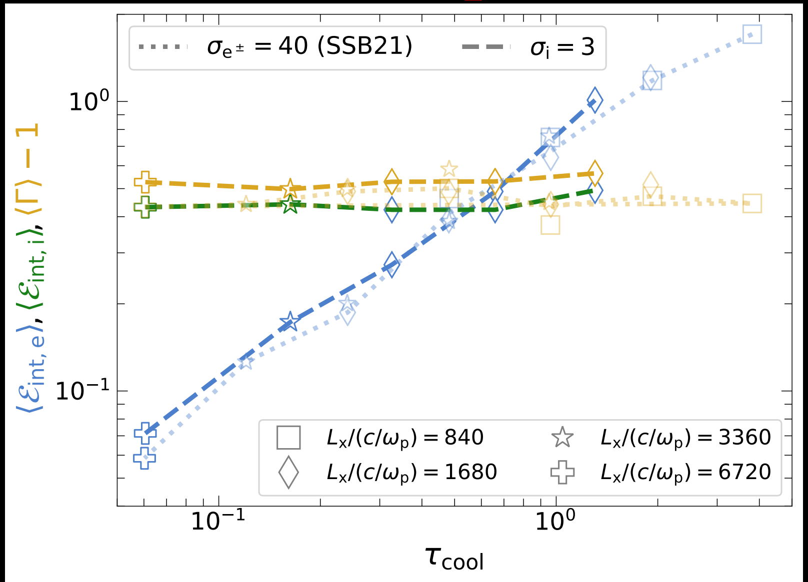
- ***Ions*** are not cooled down.
- ***Electrons*** are significantly cooled down.
    - Thermal Comptonization unfeasible.
- ***Bulk kinetic energy*** does not change.
    - Electron spectrum resembles a Maxwellian with $kT_e \sim 100$ keV.

Bulk motion of **cold electrons** even in a weakly magnetized electron-ion plasma ($\sigma_i \sim 3$) can participate in Comptonization.

More in upcoming talk by Valeriia.

Sridhar+21,23

(in units of mc^2)



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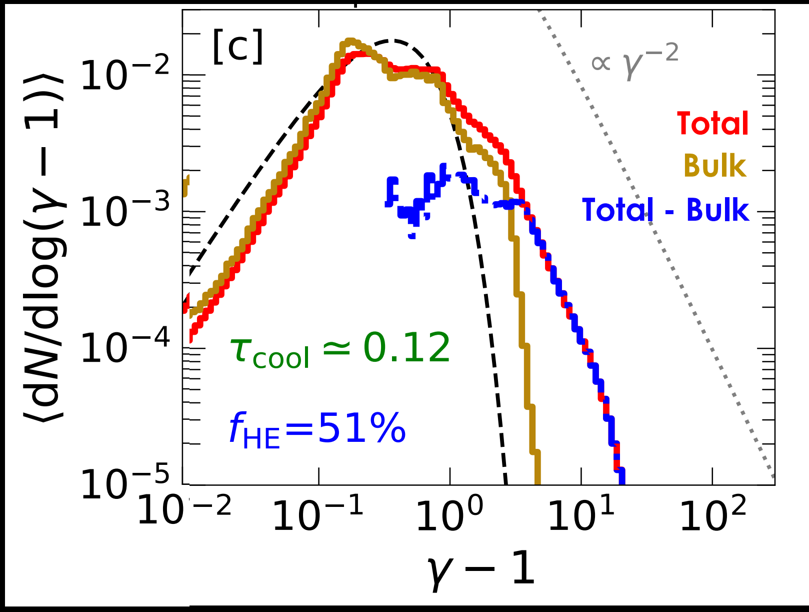
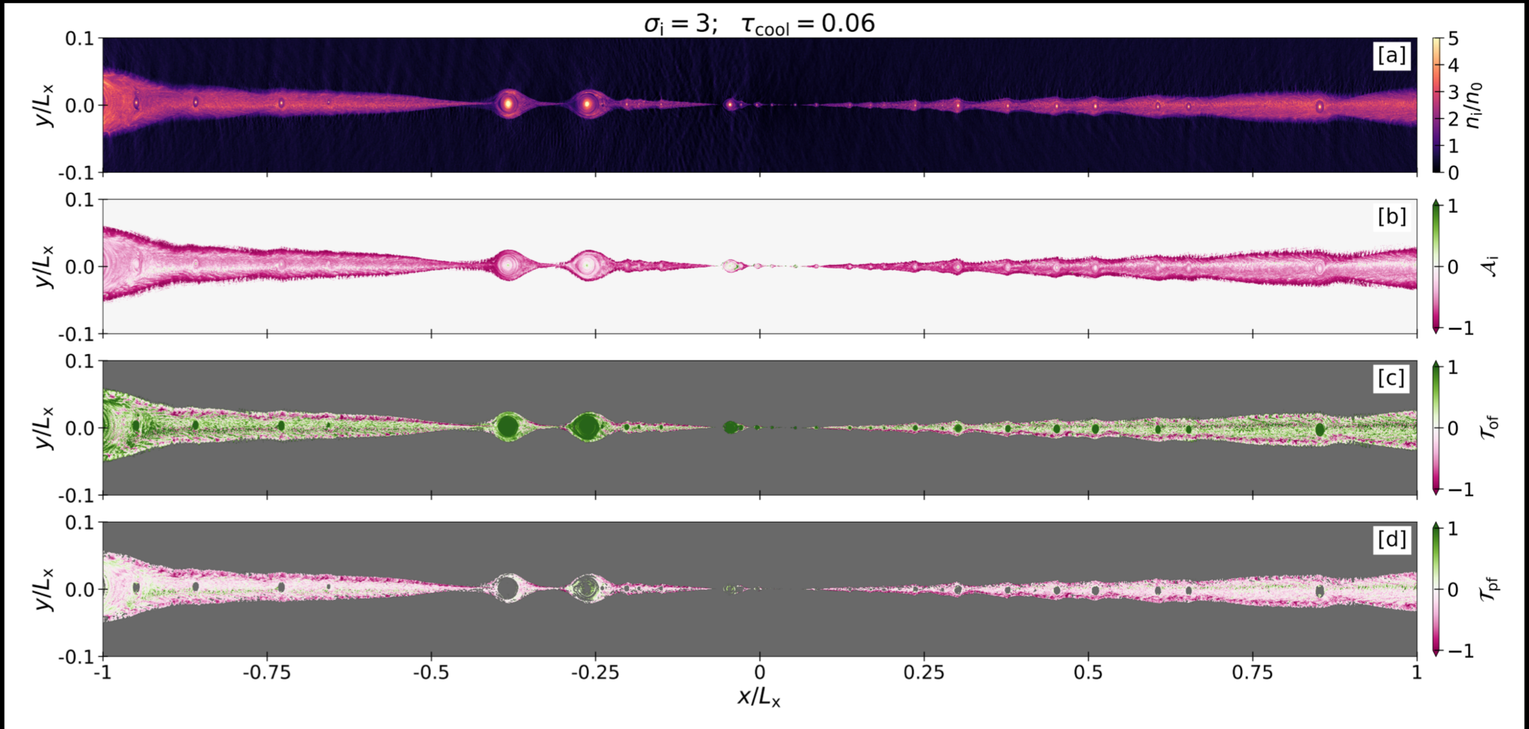


Sridhar+23
(see also Kunz+14)

Ion velocity-space instabilities

- Can hot ions transfer energy to cold electrons?
- Coulomb $t_{ei} > L_x/v_A$ for $\sigma > 1$



Particle density

Anisotropy parameter $\mathcal{A}_i = \frac{T_\perp^i}{T_\parallel^i} - 1$

Threshold to trigger oblique firehose instability: $\mathcal{T}_{of} = (\beta_\parallel + 0.11)\mathcal{A}_i + 1.4 < 0$

Threshold to trigger parallel firehose instability: $\mathcal{T}_{pf} = (\beta_\parallel - 0.59)^{0.53}\mathcal{A}_i + 0.47 < 0$

- Ion-cyclotron/mirror instabilities are non-operational throughout the layer (because $\mathcal{A}_i \ngtr 1$)
- **Inefficient transfer of thermal energy from ions to electrons—even via collisionless plasma instabilities (viz., firehose, ion-cyclotron).**

X-ray spectra

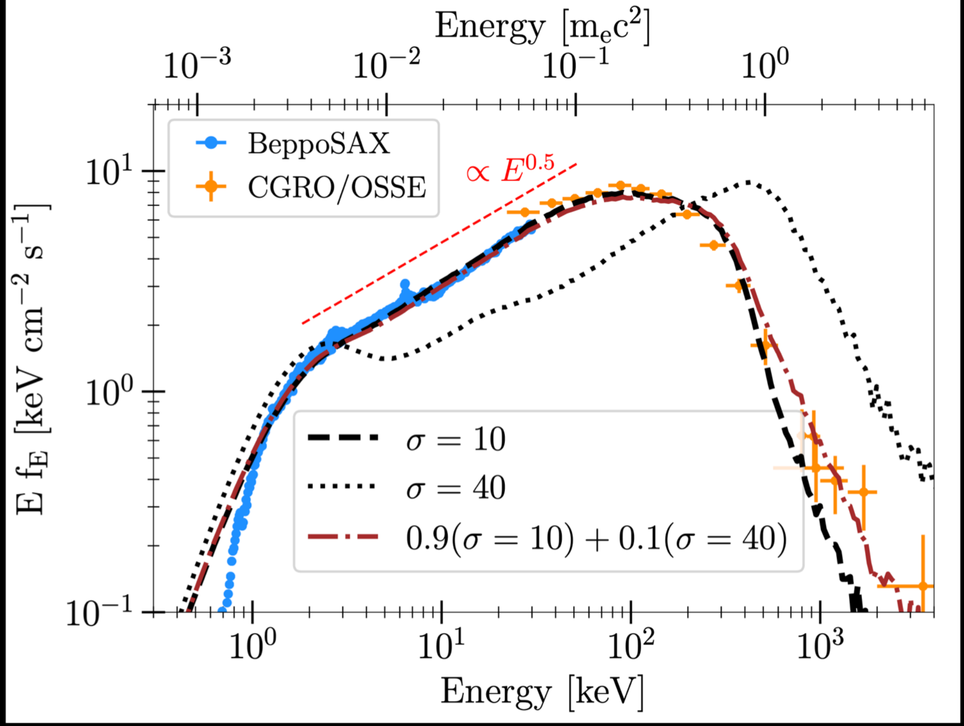
- Monte-Carlo simulation of photon propagation in the spatial-temporal structure of PIC simulations:

- <u>Assumptions:</u>
  - Soft photons with $T_s = 0.5$ keV
  - Thomson optical depth $\tau_T \sim 1.5$
  - $\gamma_{cr} = 16, \sigma = 1,3, \dots, 10,40$
    ($10^{6\sim8}$ G for stellar-mass BH XRBs)

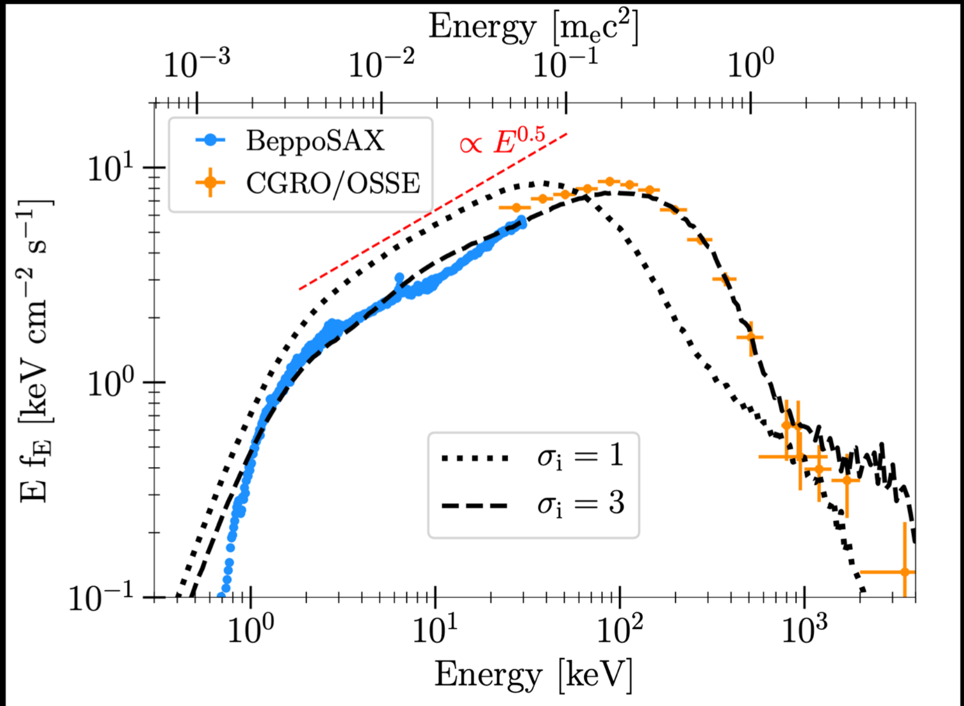
- Bulk Comptonization reproduces an "effective observed electron temperature" of $kT_e \sim 100$ keV.

$\sigma \sim 20$ for $e^{\pm}$ plasma and $\sigma \sim 3$ for e-ion plasma may provide best fit to observed spectra.

Electron-positron corona



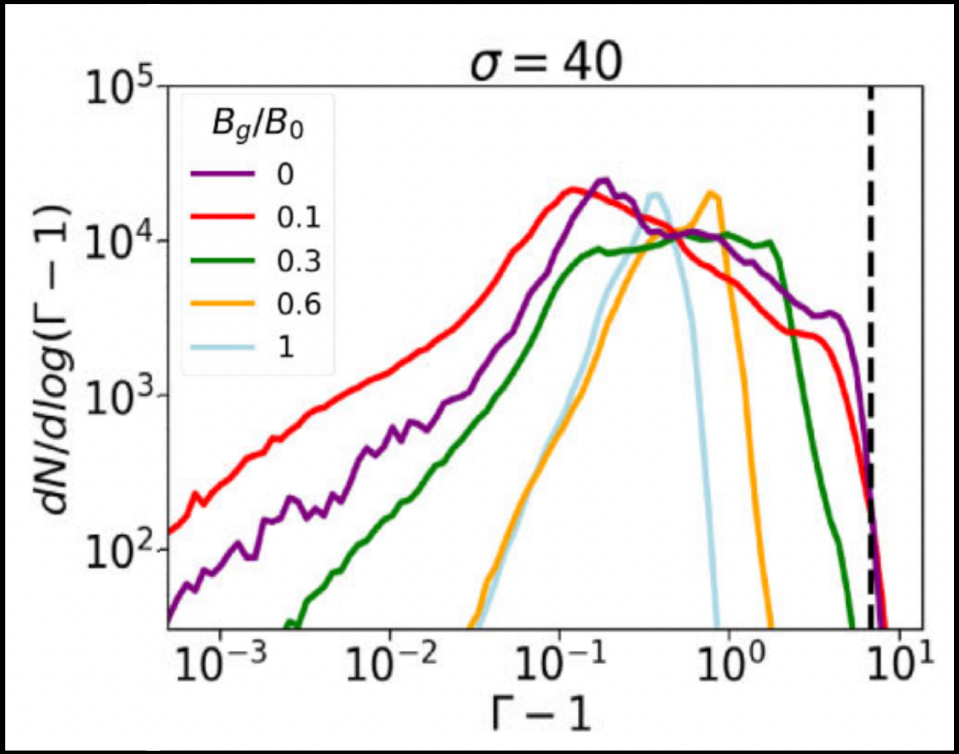
Electron-ion corona

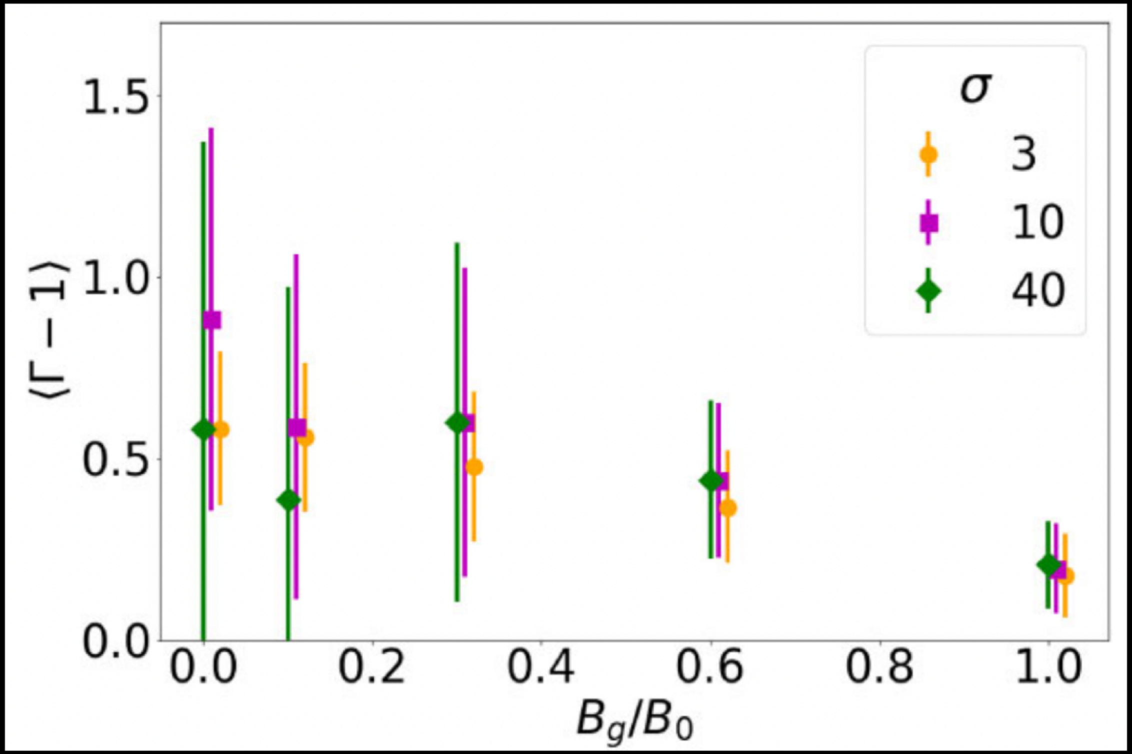


Effects of guide field

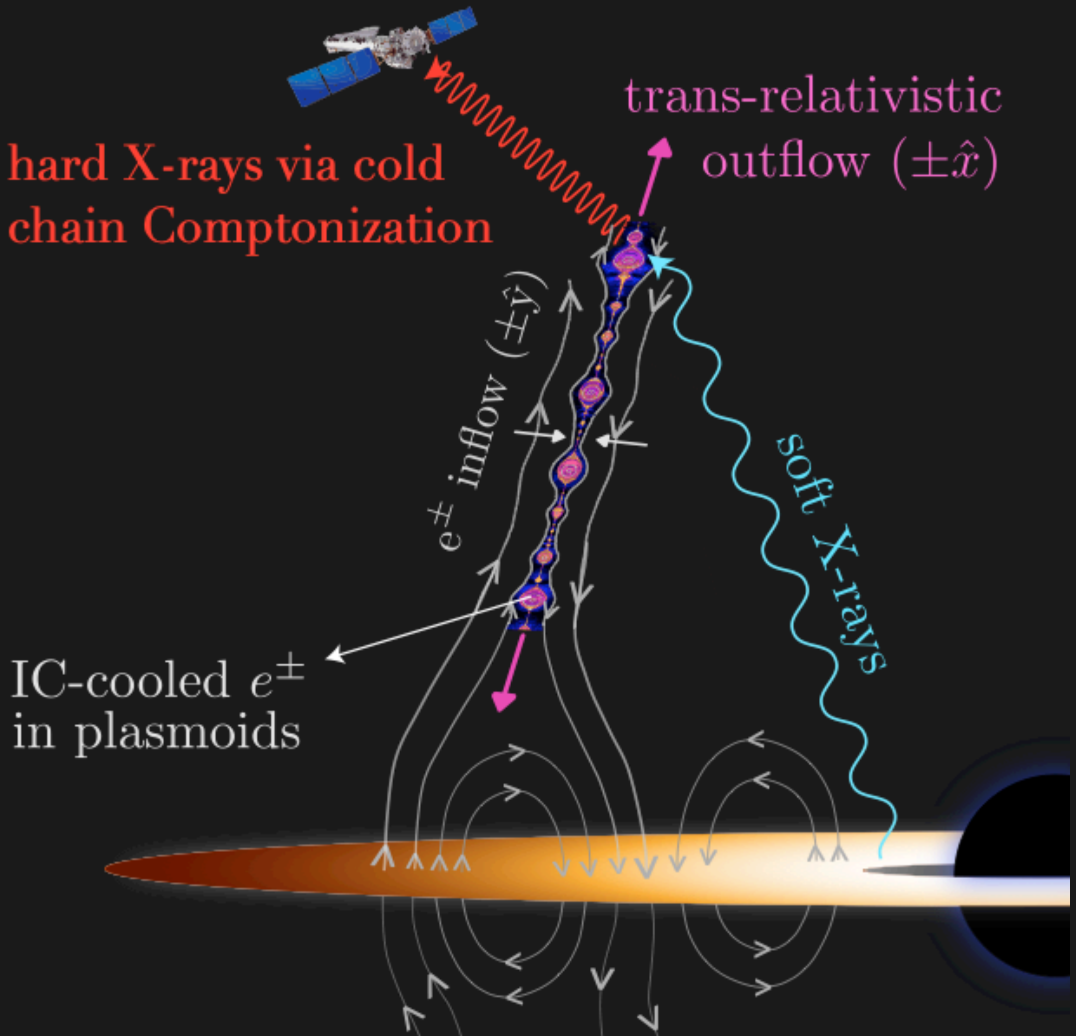
- Bulk outflow gets ordered (narrower bulk spectrum) for high B_g/B_0.
- Mean bulk energy is reduced for high B_g/B_0.
- Need **$B_g/B_0 \lesssim 0.3$** to produce 100 keV Maxwellian-like bulk spectrum.

Gupta, NS+24
Columbia undergrad





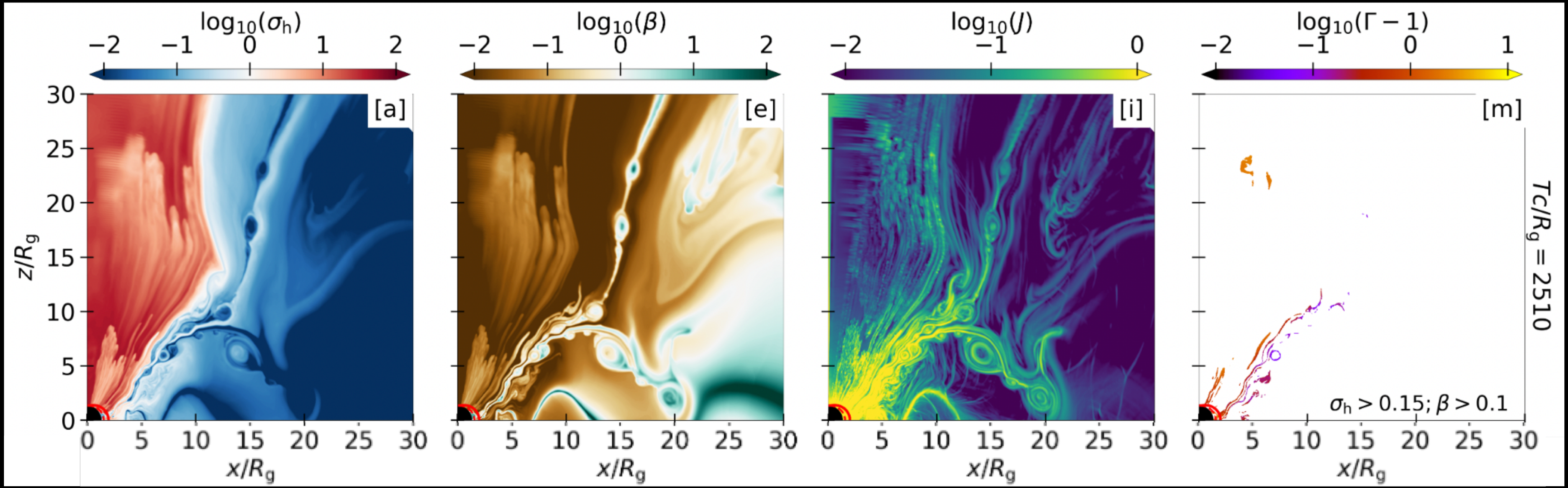
Global picture: sketch from 4 years ago…



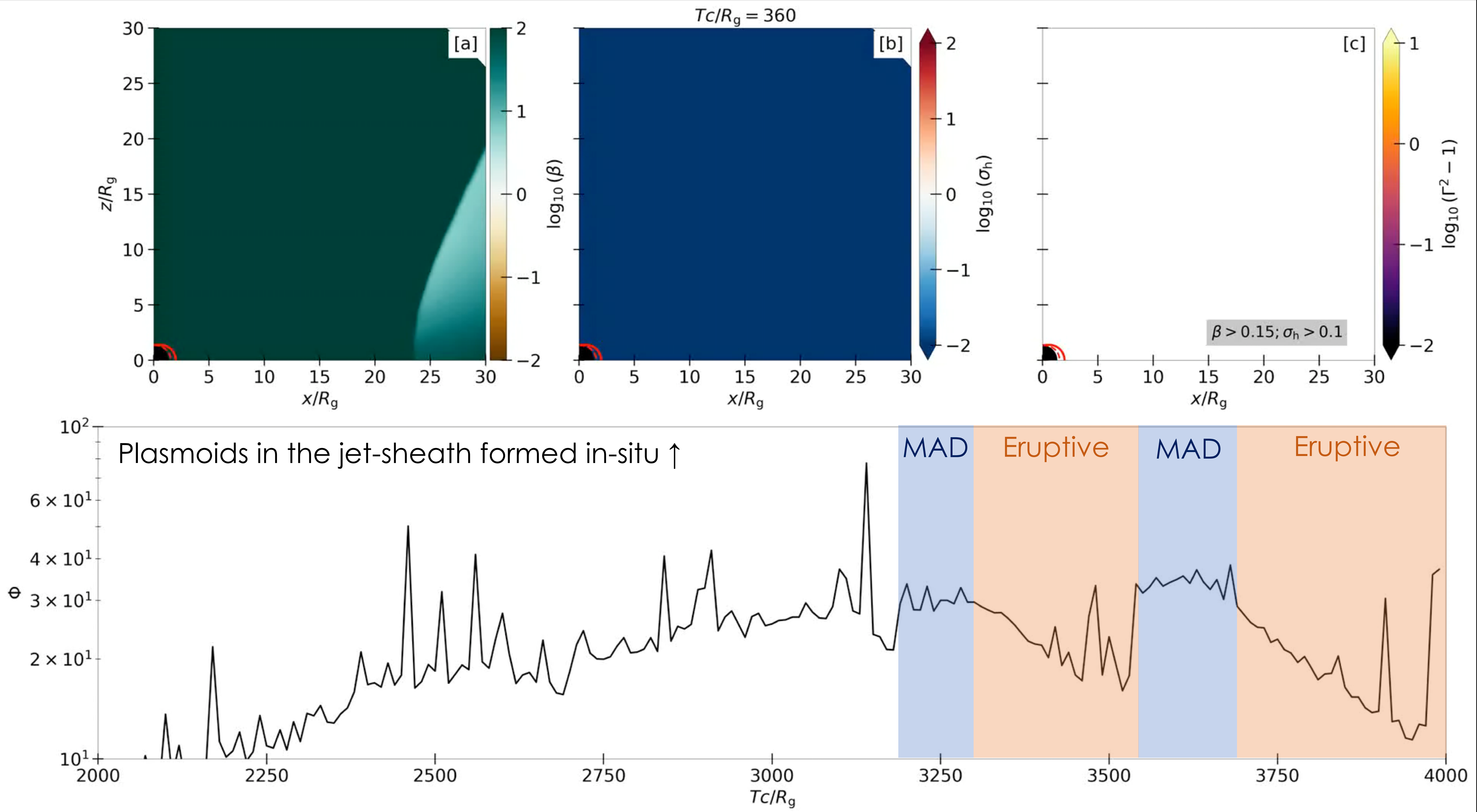
Sridhar+21

Global picture

- Resistive GRMHD simulations show instances of magnetic reconnection and Kelvin Helmholtz vortices occurring at the jet-disk wind boundary.

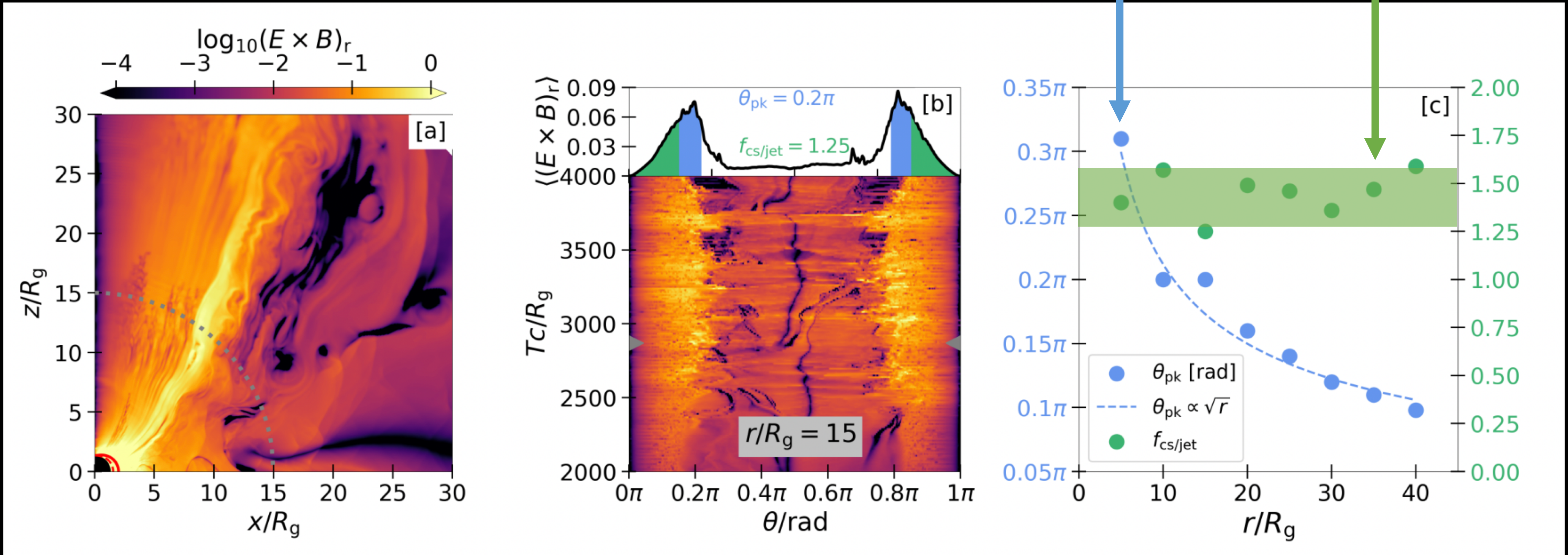


- Setup: Fishbone-Moncrief torus; a/M = 0.94; initial (poloidal) $\beta_5 = 100$; floor $\sigma_{max} = 100$, 6 levels of refinement, uniform resistivity $\eta = 5\times10^{-5}$ (Ripperda+20)



$Tc/R_g = 360$
[a]
[b]
[c]
z/R_g
x/R_g
$\log_{10}(\beta)$
$\log_{10}(\sigma_h)$
$\log_{10}(\Gamma^2 - 1)$
$\beta > 0.15; \sigma_h > 0.1$
Plasmoids in the jet-sheath formed in-situ ↑
MAD
Eruptive
MAD
Eruptive
Φ
Tc/R_g

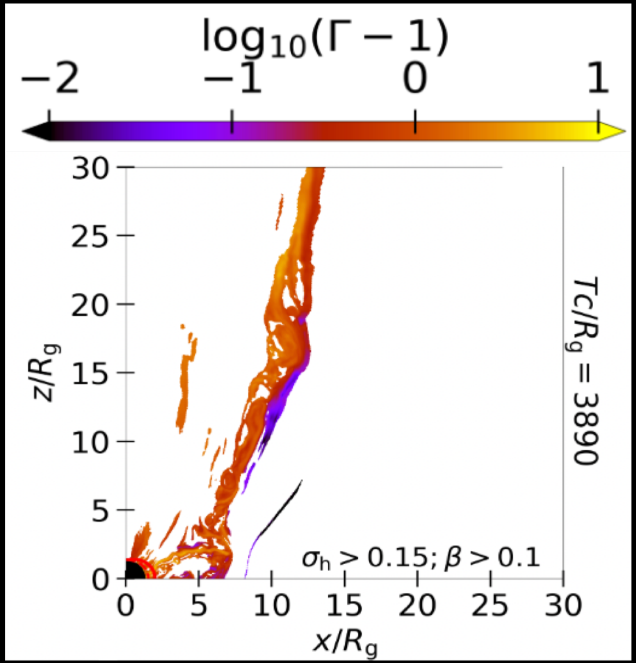
- The EM power at the BH jet sheath is ~ accretion power ≥ jet power.
- This region (if corona), would appear paraboloid.

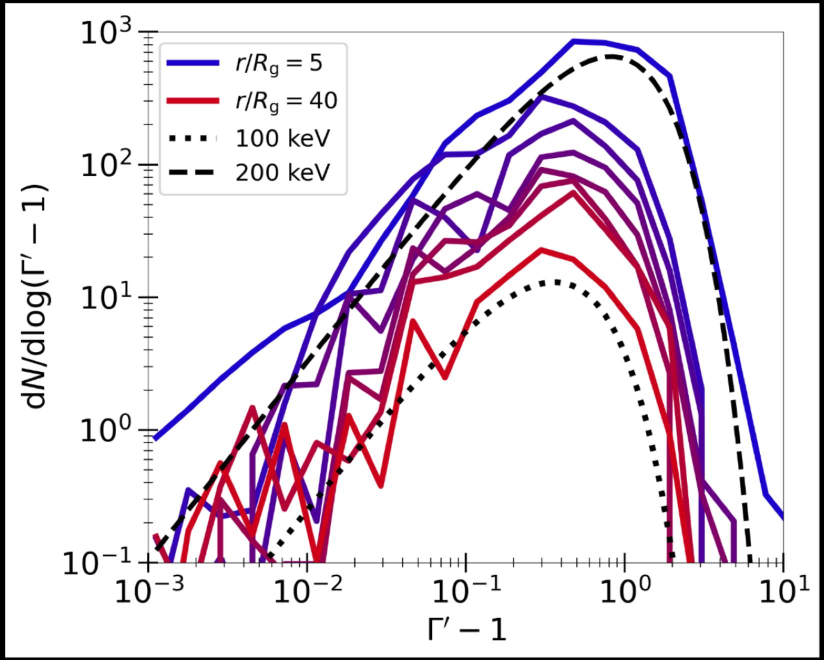


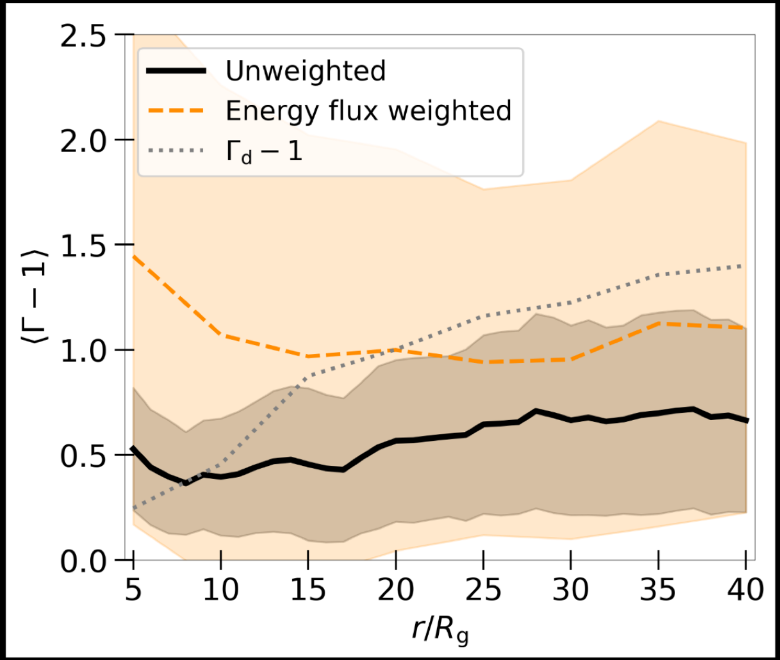
See also Moscibrodzka (2023)

- Bulk energy spectrum from the jet sheath 'corona' resembles a $O(100)$ keV Maxwellian.
  - *Recall the spectrum from PIC simulations.*

- $\langle \Gamma - 1 \rangle \sim 1.5$; comparable to ExB drift speeds: $\Gamma_{\rm d} = \sqrt{1 + \frac{B_\phi^2}{B_{\rm p}^2}} \approx \sqrt{1 + [\Omega r \sin(\theta_{\rm pk})]^2}$

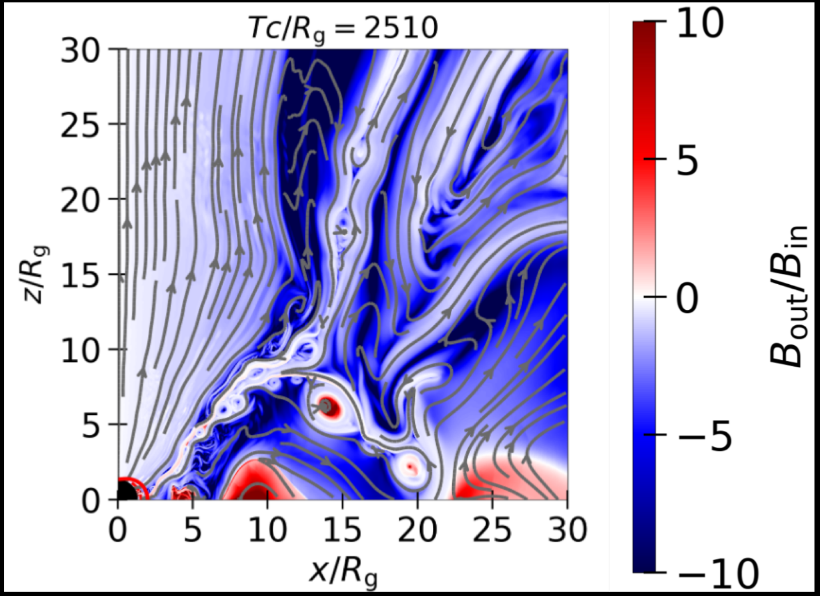


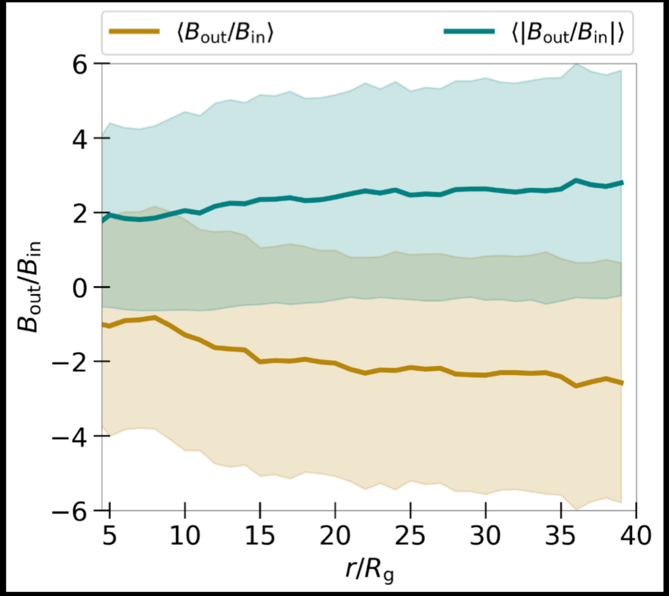


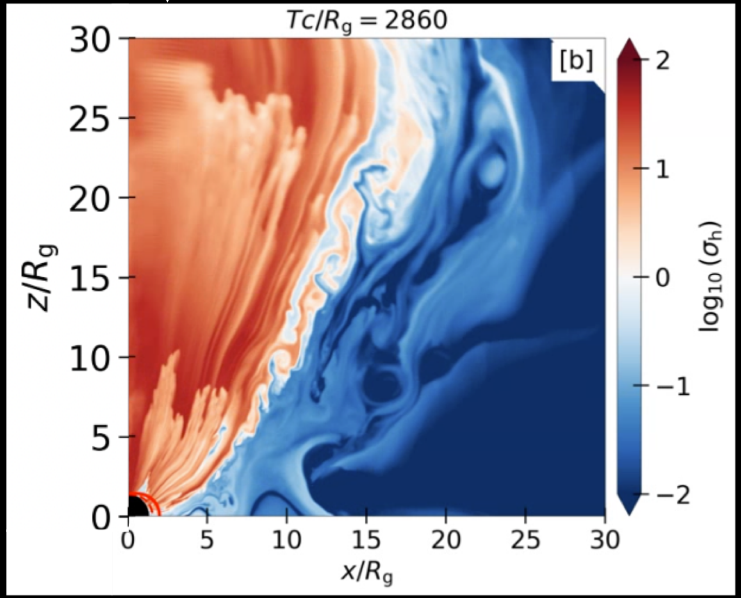


Azimuthal (~guide) field strength

- -15 < B_g/B_0 < 15 in the sheath corona; $\langle |B_g/B_0| \rangle \sim 2$.
- Nonetheless, large dispersion in bulk motions (not seen in local reconnection setup)
- Motions dictated by global dynamics incl. vortices and turbulence at the shear layer*.

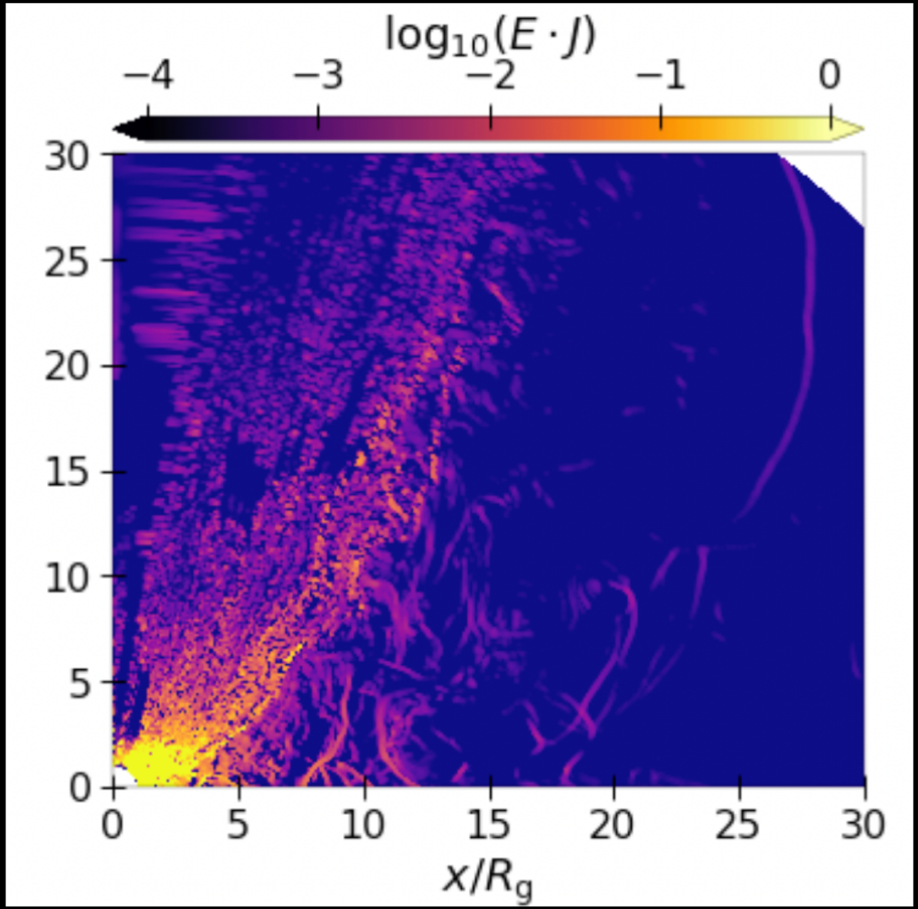


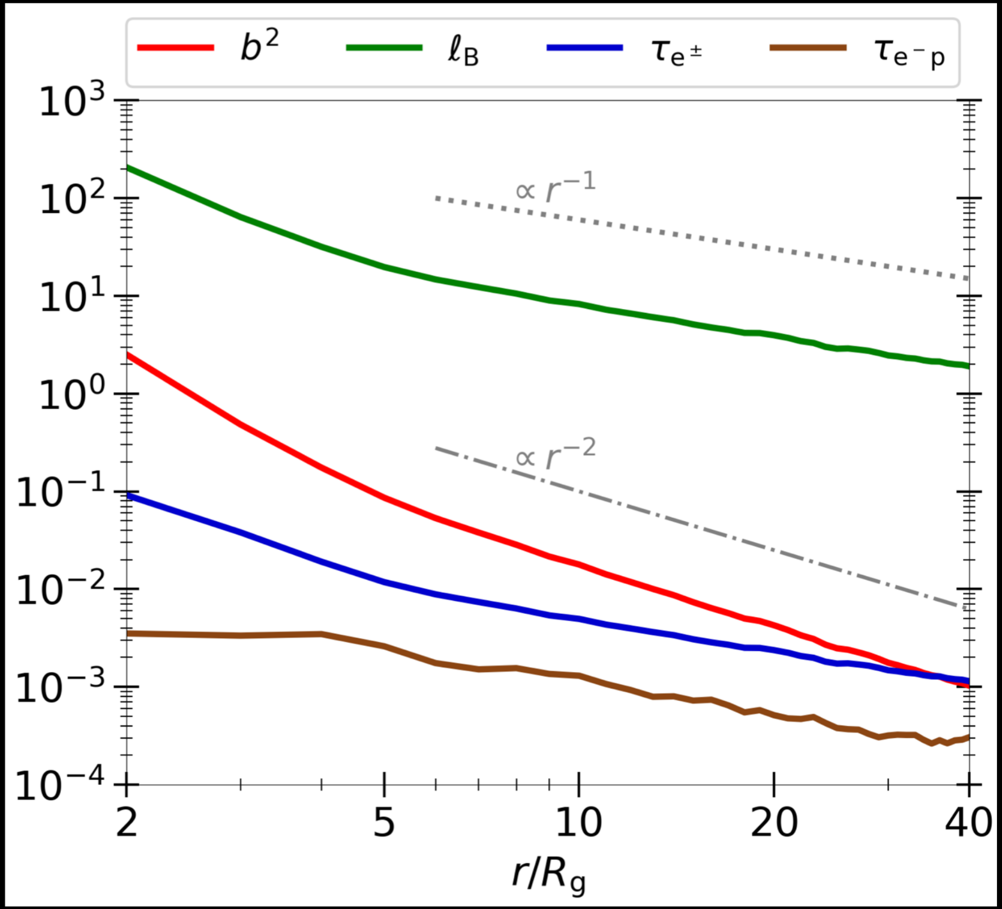




*c.f. Groselj+23, Nattila+24

Site of Dissipation with $e^{\pm}$ optical depth~0.1*



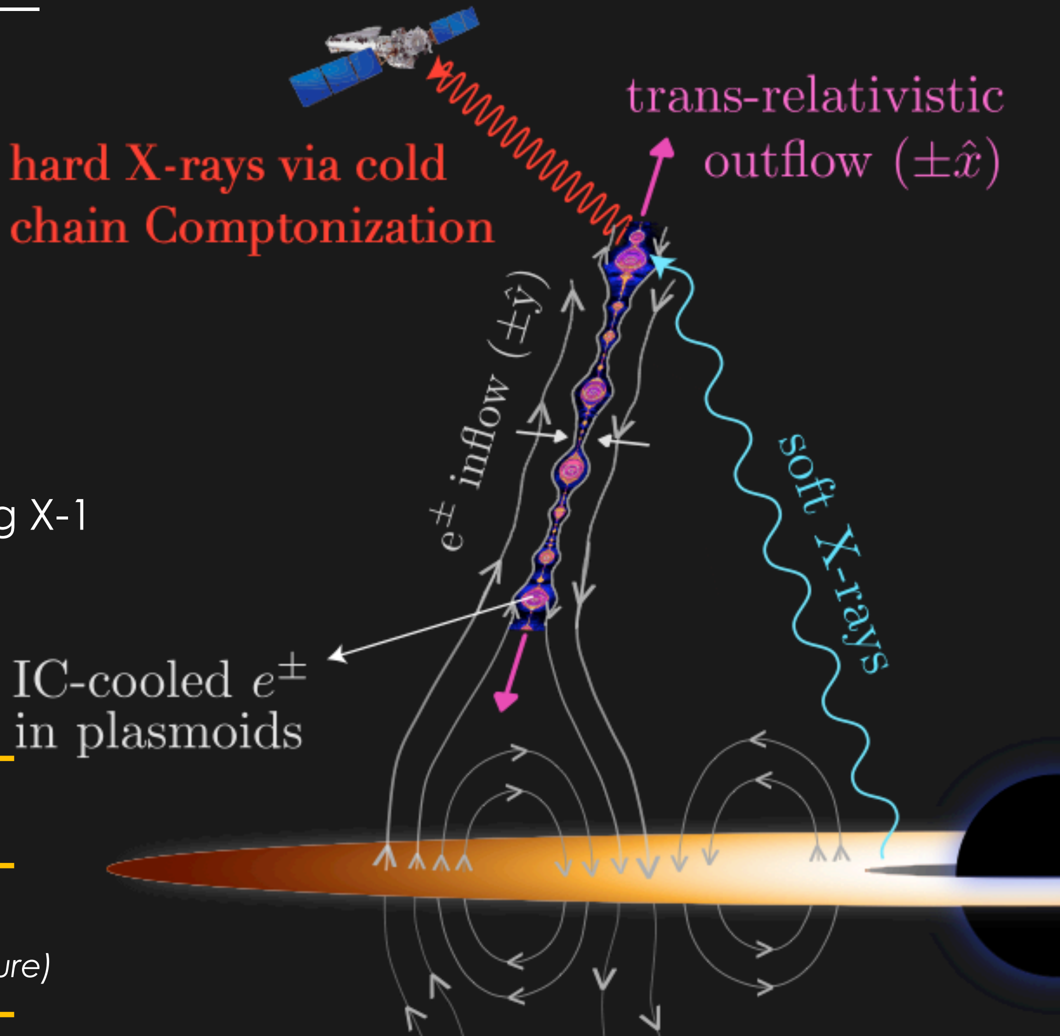


> ~20% of EM energy dissipated between 2-10 R_g.
> For Cyg X-1, that's ~10^{38} erg/s.

*For Cyg X-1 parameters; will change with more physics.

Take away

- For large soft photon flux, electrons are cooled to non-relativistic temperatures for all σ.
  - Thermal Comptonization unfeasible.
- Their bulk flows however, remain trans-relativistic.
  - Particles' energy spectrum—dominated by bulk motions—resembles a ~100 keV Maxwellian distribution.
- The jet sheath is a site of magnetic dissipation.
  - Reconnects, forms plasmoids in-situ; ~20% EM power dissipated at 2-10 Rg.
- EM power flowing is ~ accretion power.
  - Sufficient to power the seen nonthermal X-ray emission from Cyg X-1
- Trans-relativistic bulk motions with τ~0.1.
  - **The corona might be in the jet sheath.**



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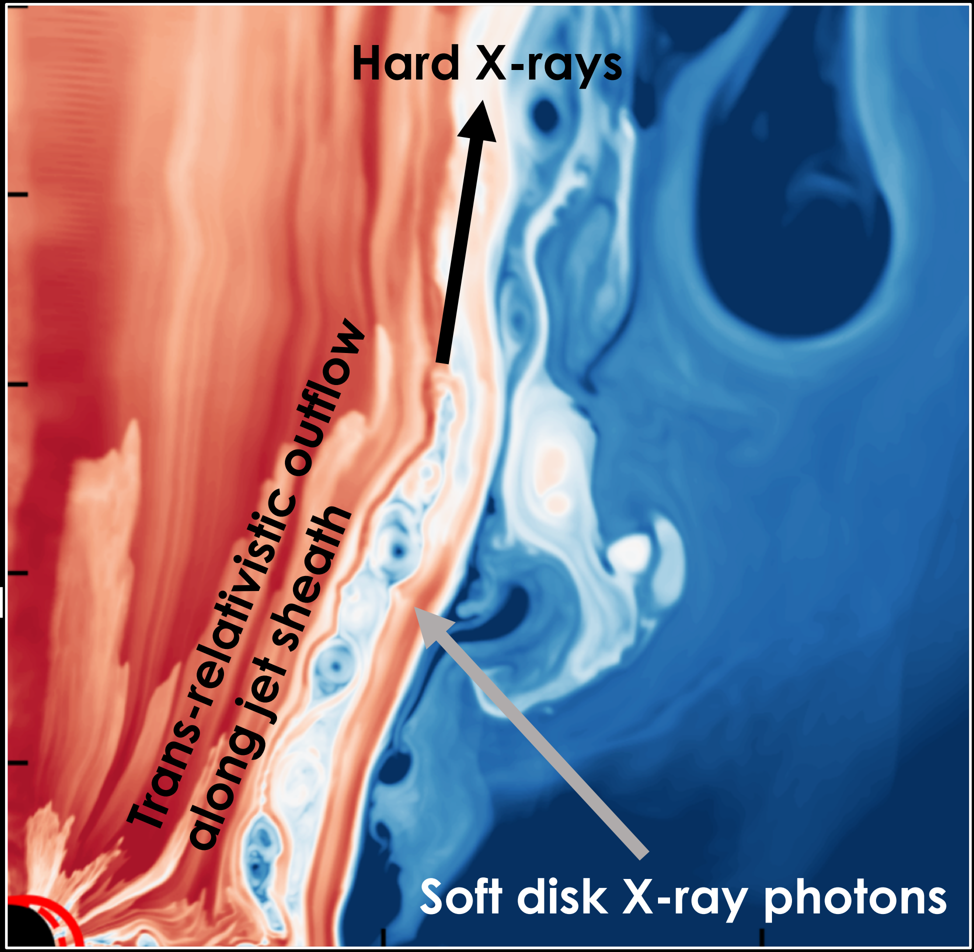

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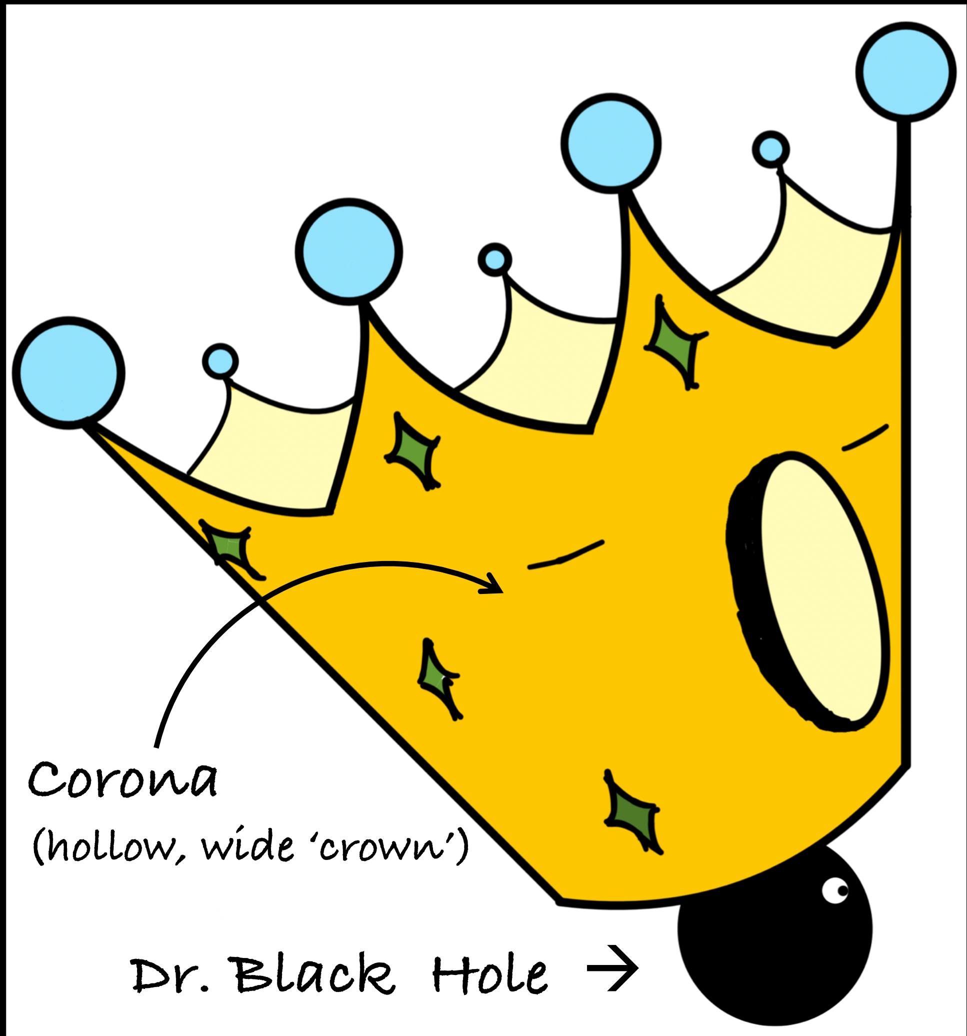

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