Title: Black Hole Jet Sheath as a Candidate for the Comptonizing Corona

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Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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Abstract:

What powers the hard, non-thermal X-rays from accreting compact objects has been a longstanding mystery. In my talk, I will address the underlying question of what energizes the particles of the Comptonizing “corona” against the strong inverse Compton (IC) cooling losses with first-principle particle-in-cell simulations of magnetic reconnection subject to IC cooling in magnetically dominated electron-positron plasmas, and in mildly-magnetized electron-ion plasmas. I will also show---using results of global resistive GRMHD simulations of accreting black holes---that the black hole jet sheath is a site of efficient electromagnetic dissipation through processes such as magnetic reconnection and turbulence. The distribution of bulk motions of the radially outflowing plasma along the jet sheath also resembles a Maxwellian distribution with an effective bulk temperature of a few 100 keV, and this could be a candidate for the Comptonizing corona.

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)

Magnetic fields around Compact Objects Workshop
Perimeter Institute
26th March 2025

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

Stanford University

SIMONS FOUNDATION

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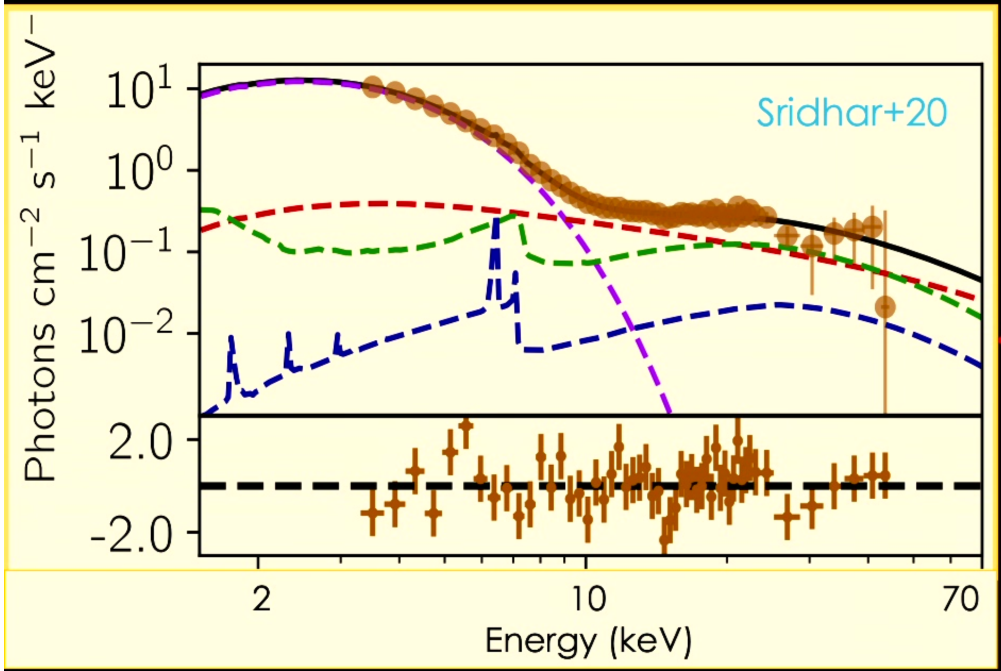
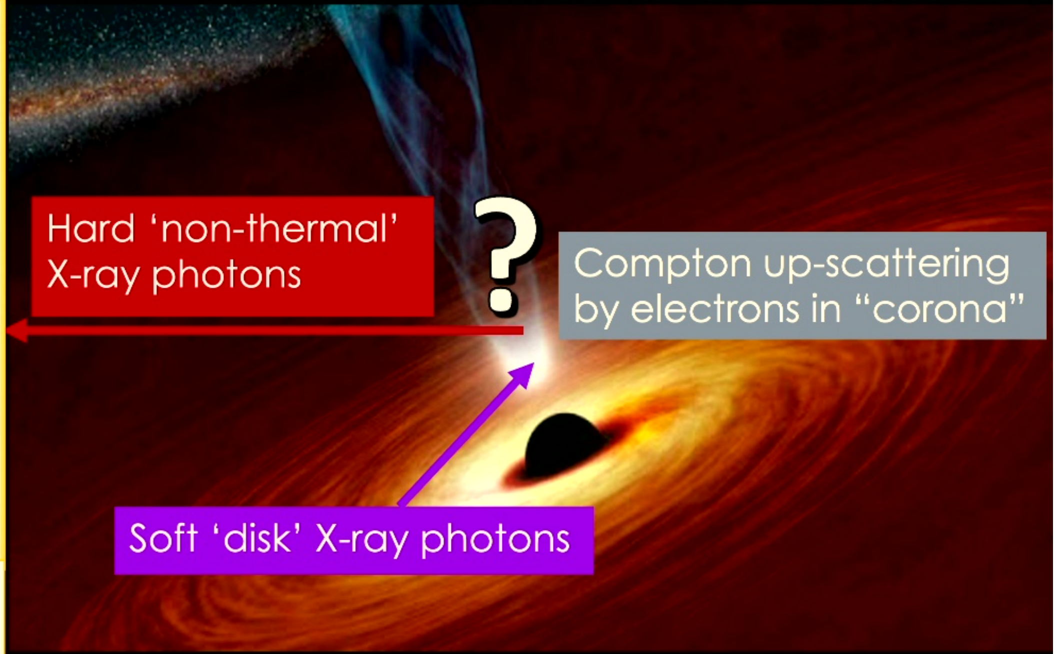
Conventional models and components





- 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

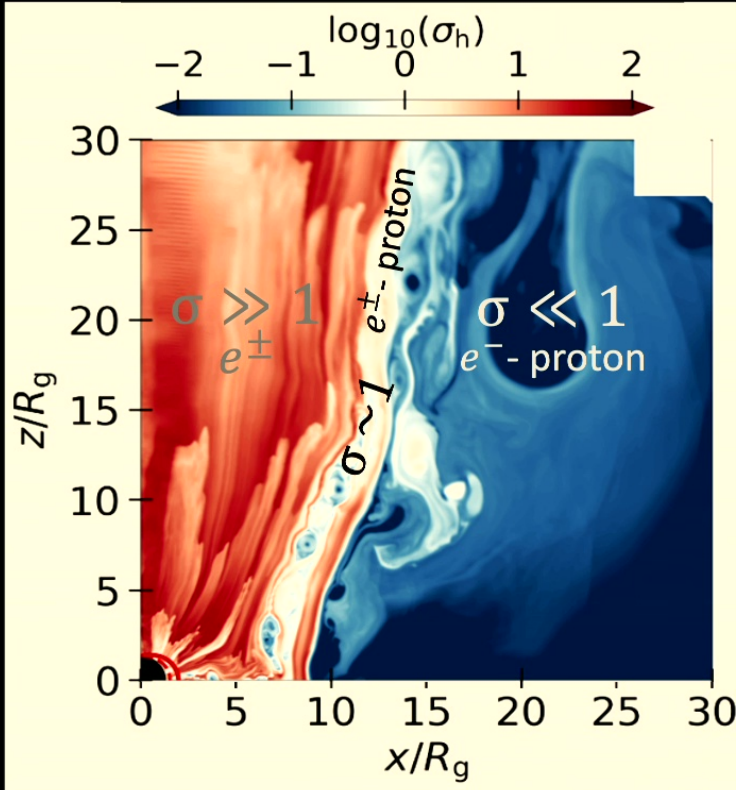
- The underlying engine could be **magnetic reconnection** or **turbulence**.
    - I will discuss why heating by reconnection may not work.

- 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?

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

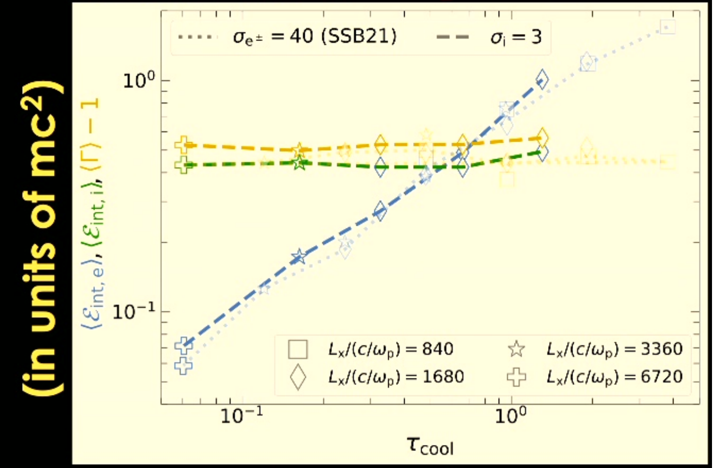
With stronger IC cooling:

- ***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~100 keV.

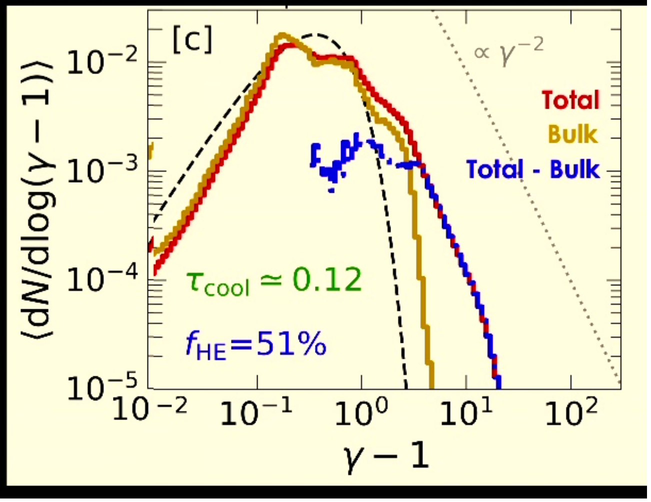
Bulk motion of **cold electrons** even in a weakly magnetized electron-ion plasma (σ_i~3) can participate in Comptonization.

Sridhar+21,23

$\sigma_e = \left(\frac{m_i}{m_e}\right)\sigma_i$ ~28×3 = 84



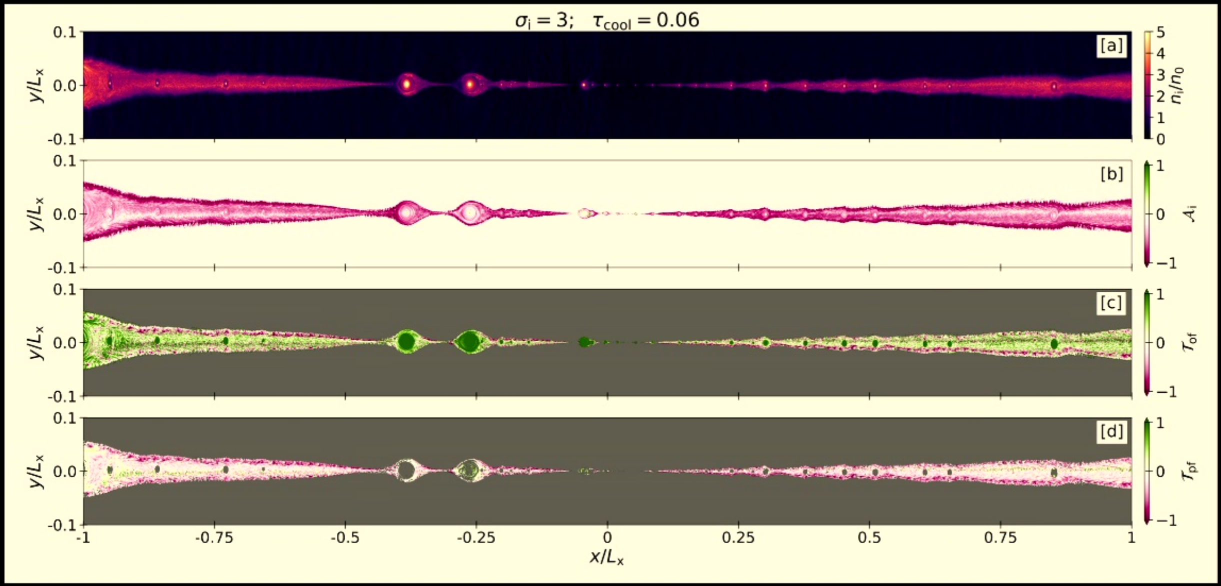
← Stronger IC cooling



Ion velocity-space instabilities

Sridhar+23
(see also Kunz+14)

- 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

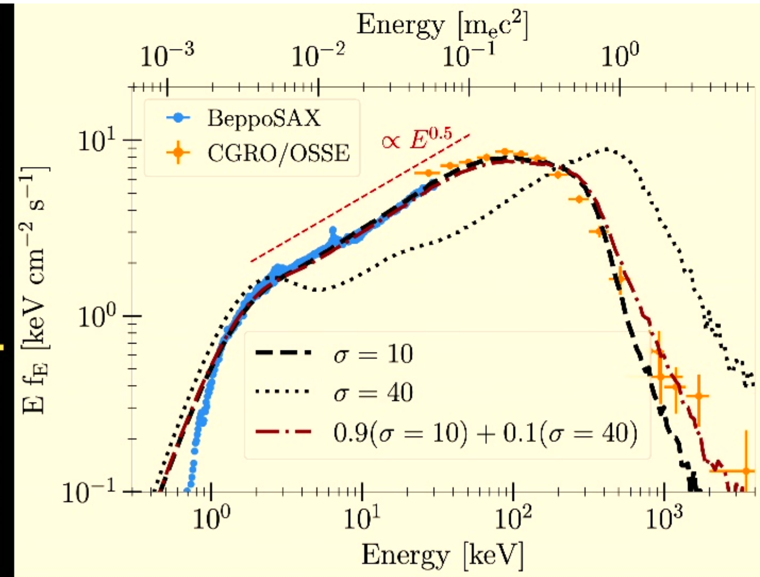
- Monte-Carlo simulation of photon propagation in the spatial-temporal structure of PIC simulations:

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

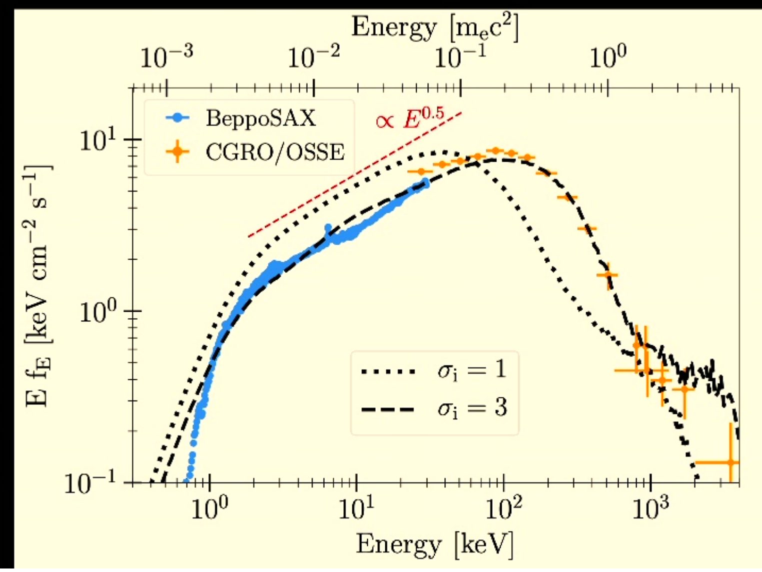
- Bulk Comptonization reproduces an "effective observed electron temperature" of $kT_e \sim 100$ keV.

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

Electron-positron corona



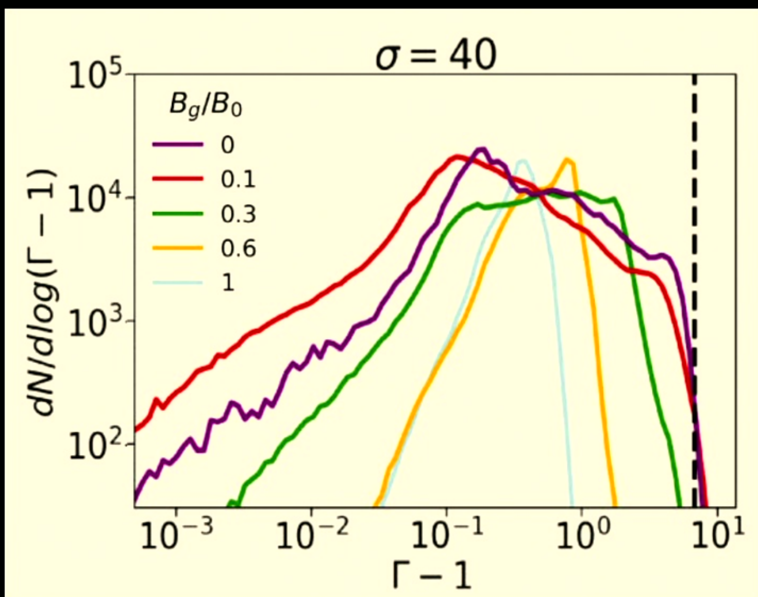
Electron-ion corona

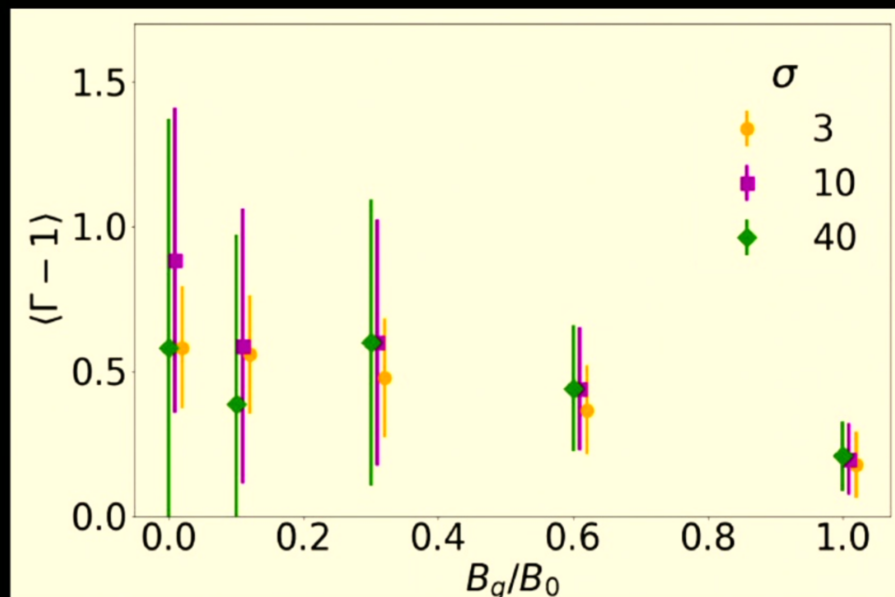


Effects of guide field

- 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.

Sanya **Gupta+24**
Columbia undergrad

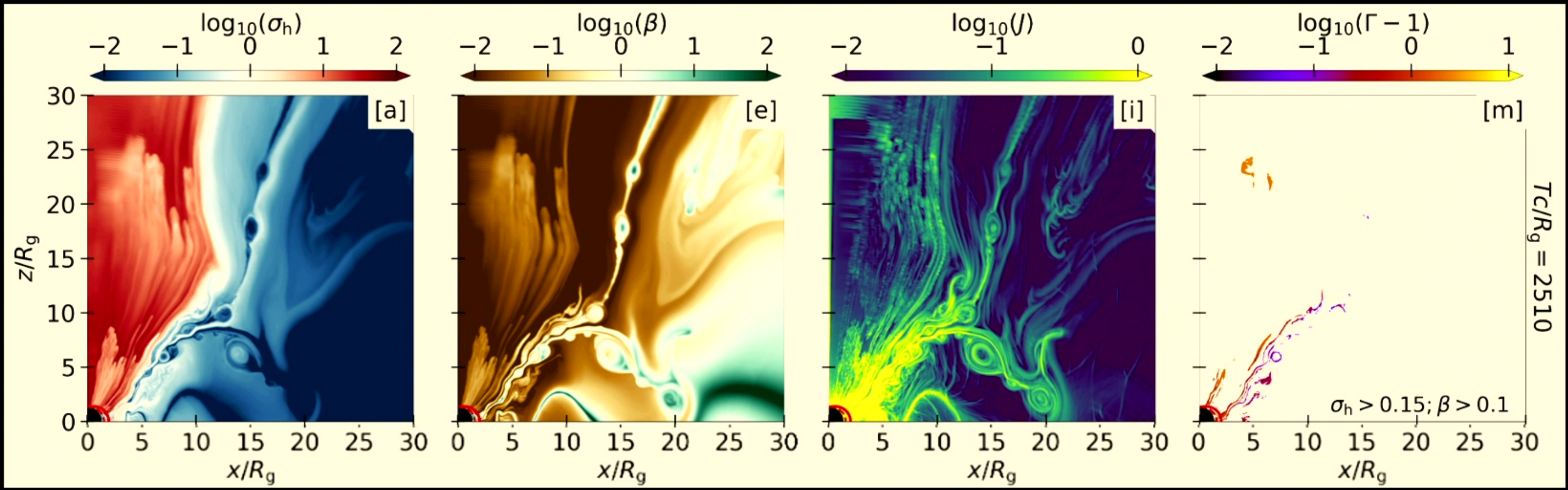




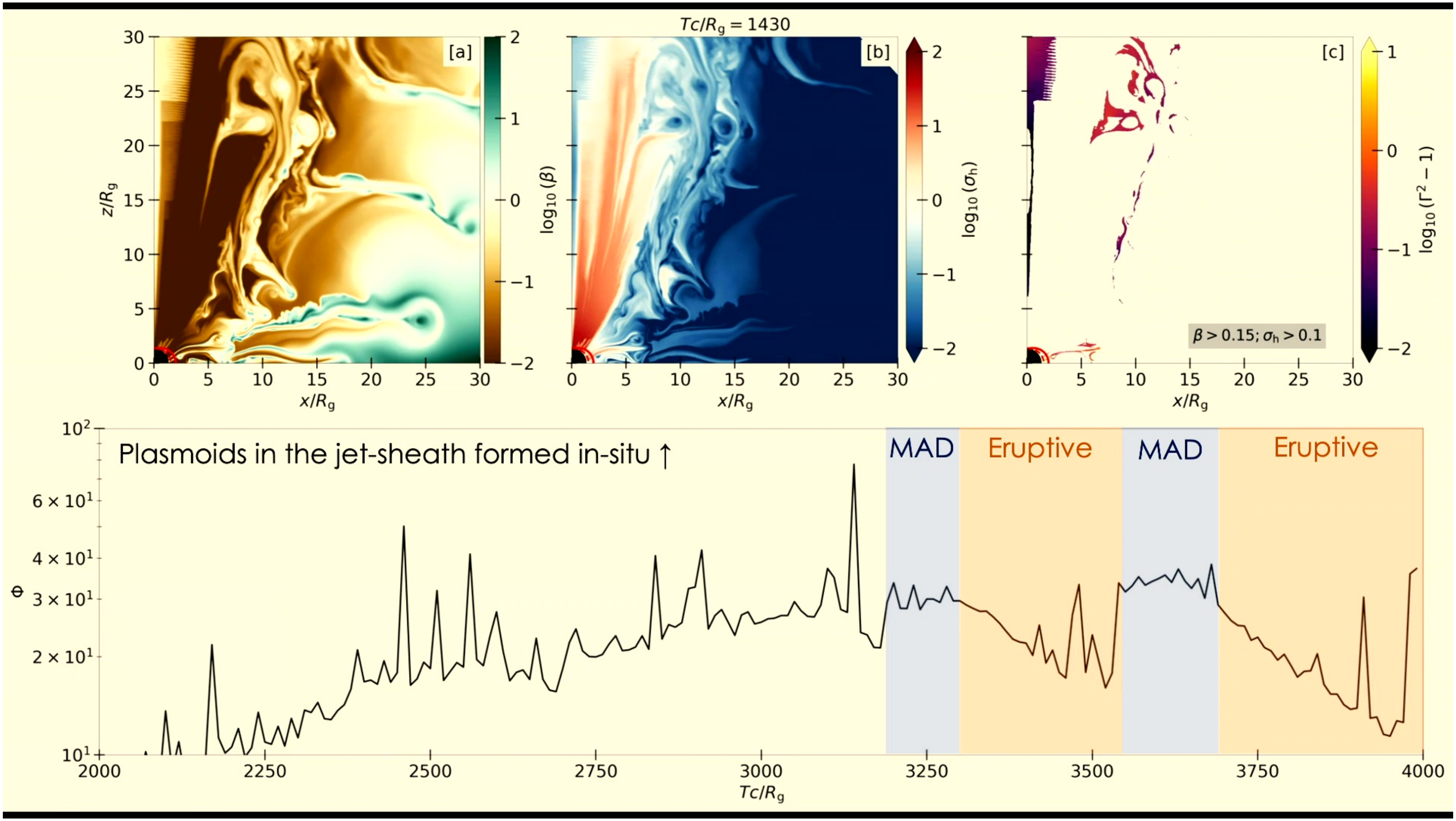
Sridhar+25

Global picture

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

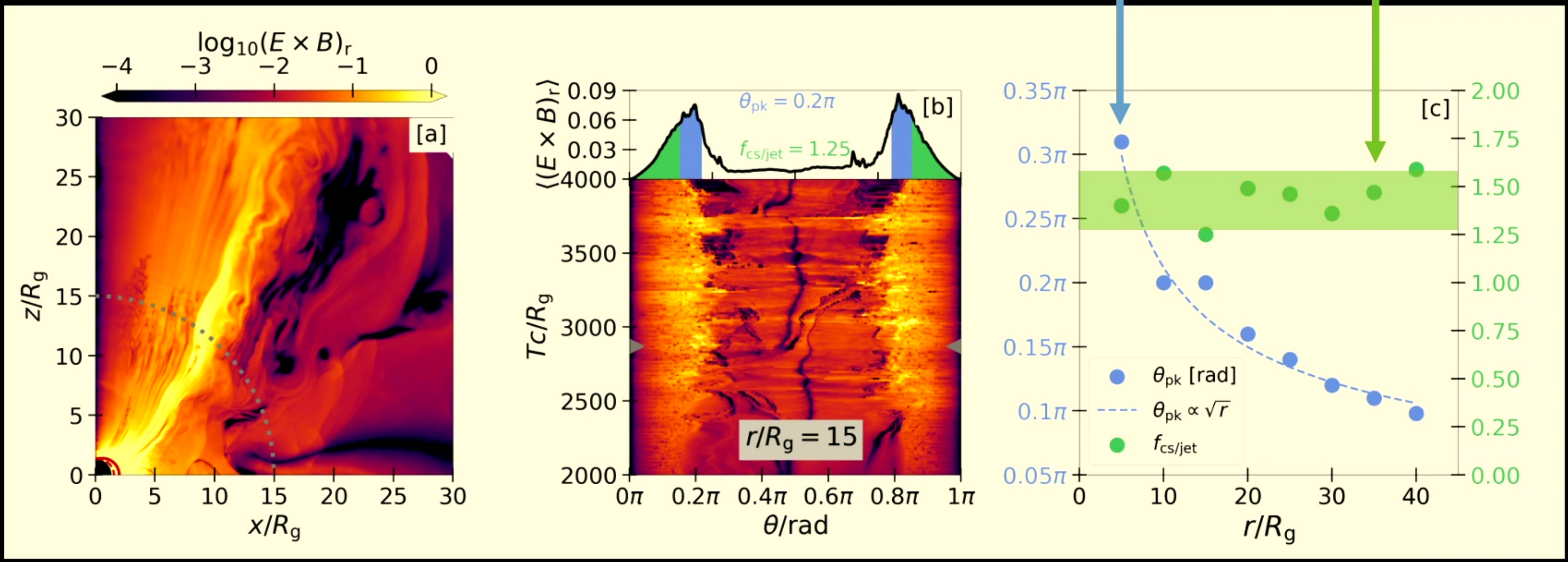


- Setup: Fishbone-Moncrief torus; a/M = 0.94; initial (poloidal) $\beta = 100$; floor $\sigma_{\max} = 100$, 6 levels of refinement, uniform resistivity $\eta = 5\times10^{-5}$ (Ripperda+20)



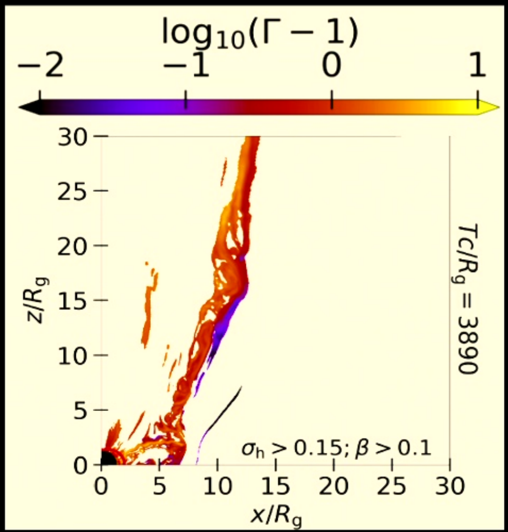
$Tc/R_g = 1430$
[a]
[b]
[c]
$\log_{10}(\beta)$
$\log_{10}(\sigma_h)$
$\log_{10}(\Gamma^2 - 1)$
$\beta > 0.15; \sigma_h > 0.1$
z/R_g
x/R_g
Plasmoids in the jet-sheath formed in-situ ↑
MAD
Eruptive
MAD
Eruptive
Φ
Tc/R_g

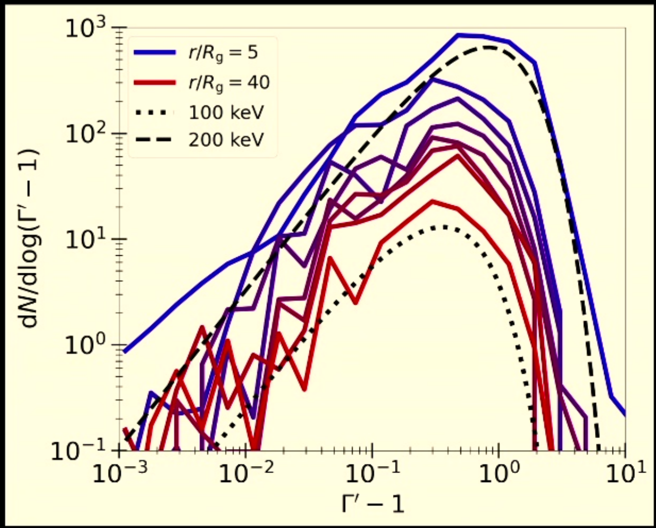
- The EM power at the BH jet sheath is ~ accretion power ≥ jet power.
- This region (if corona), would appear paraboloid*.

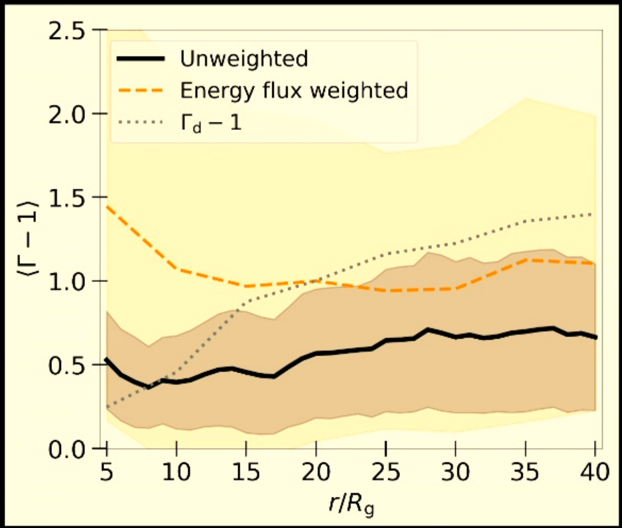


*Could be modified in the presence of radiative cooling in the simulations (c.f. Jim Stone's talk).

- 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: $\Gamma_\mathrm{d} = \sqrt{1 + \frac{B_\phi^2}{B_\mathrm{p}^2}} \approx \sqrt{1 + [\Omega r \sin(\theta_\mathrm{pk})]^2}$

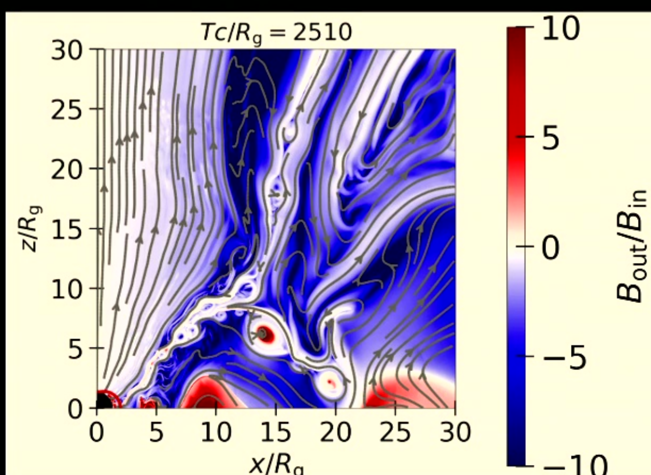


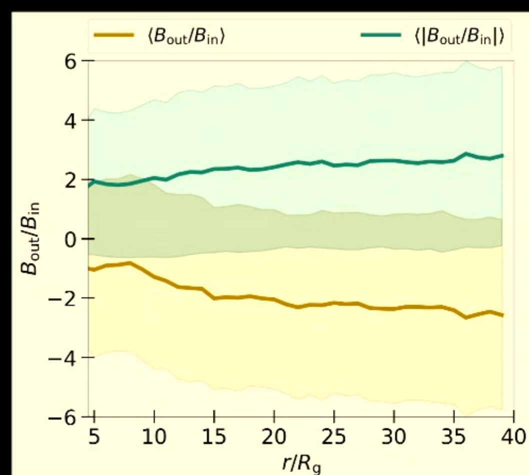


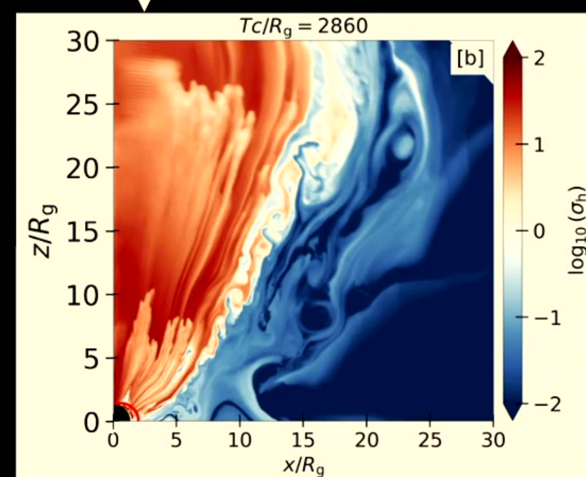


Azimuthal (~guide) field strength

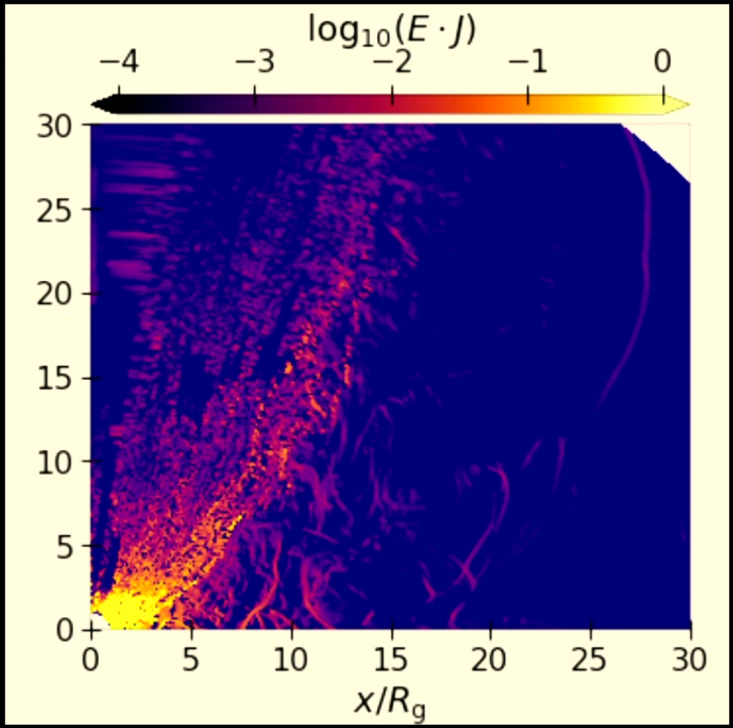
- -15 < B_g/B_0 < 15 in the sheath corona; $\langle|B_g/B_0|\rangle \sim 2$.
- Nonetheless, large dispersion in bulk motions (not seen in reconnection setup)
- Motions dictated by global dynamics incl. vortices and turbulence at the shear layer (see also Groselj+23, also Nattila+24).

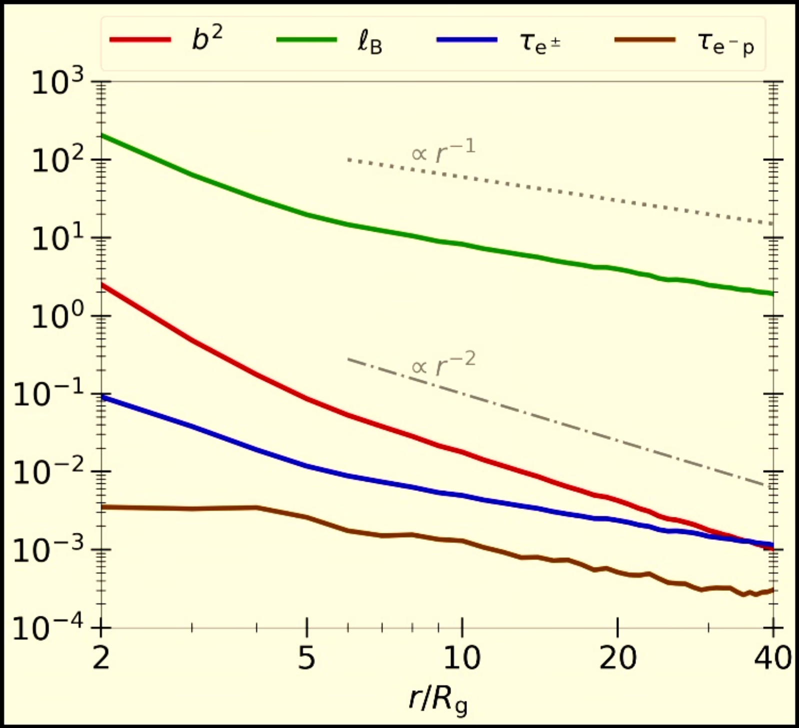






Site of Dissipation with e± optical depth~0.1*



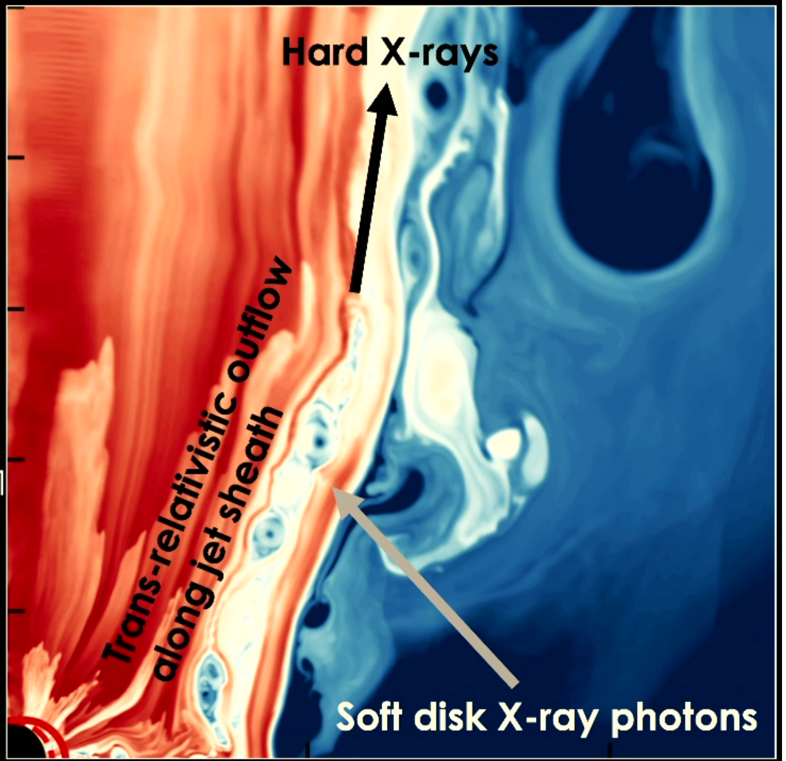


> ~20% of EM energy dissipated between 2-10 R_g.
> For Cyg X-1, that's ~10^{38} erg/s.

*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.**



Questions/comments welcome at nsridhar@stanford.edu

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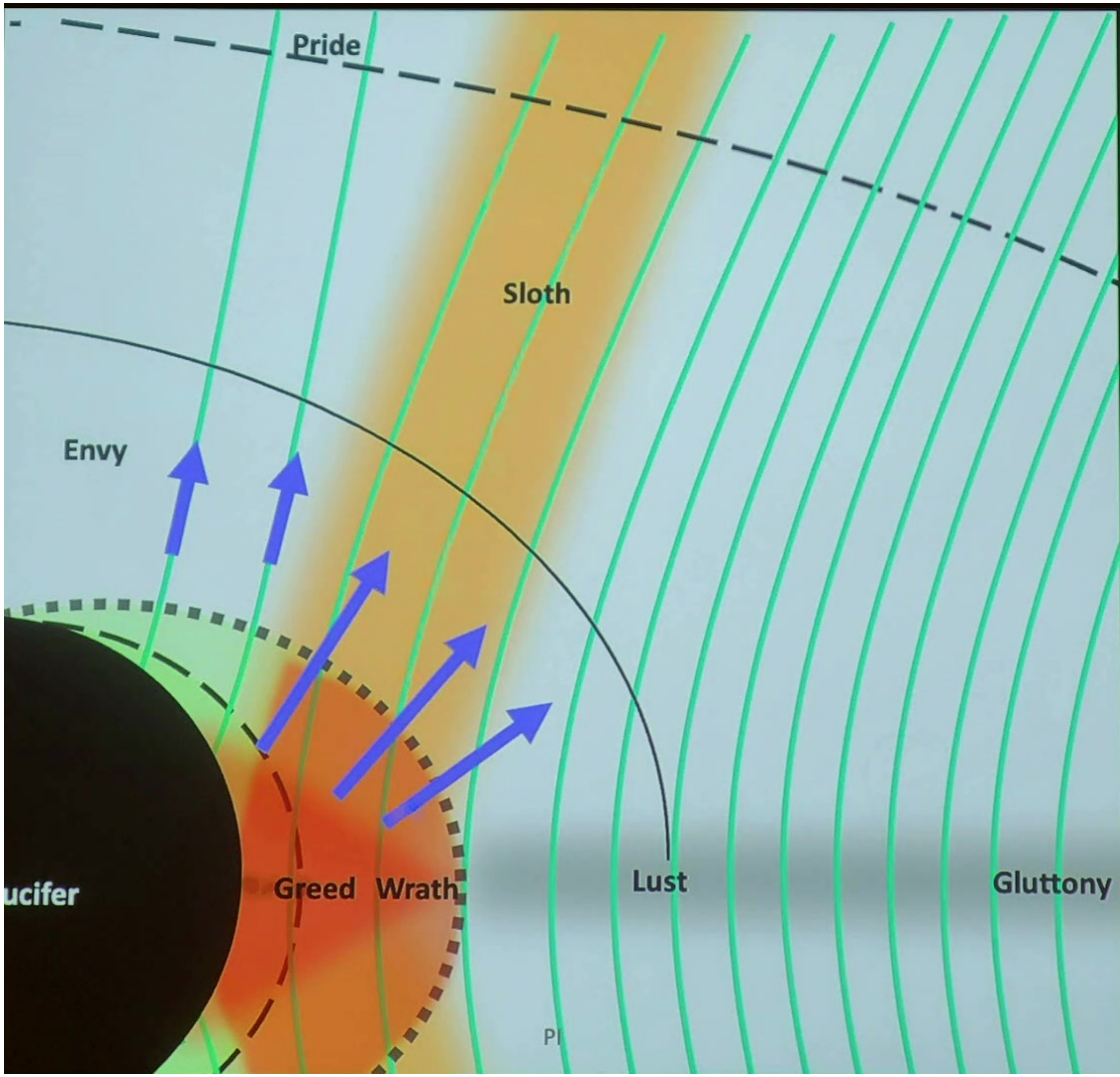

Take away

- The jet sheath is an extremely active, energetic, and hard-working region capable of being the Corona.
- Anything but Sloth!

Take away

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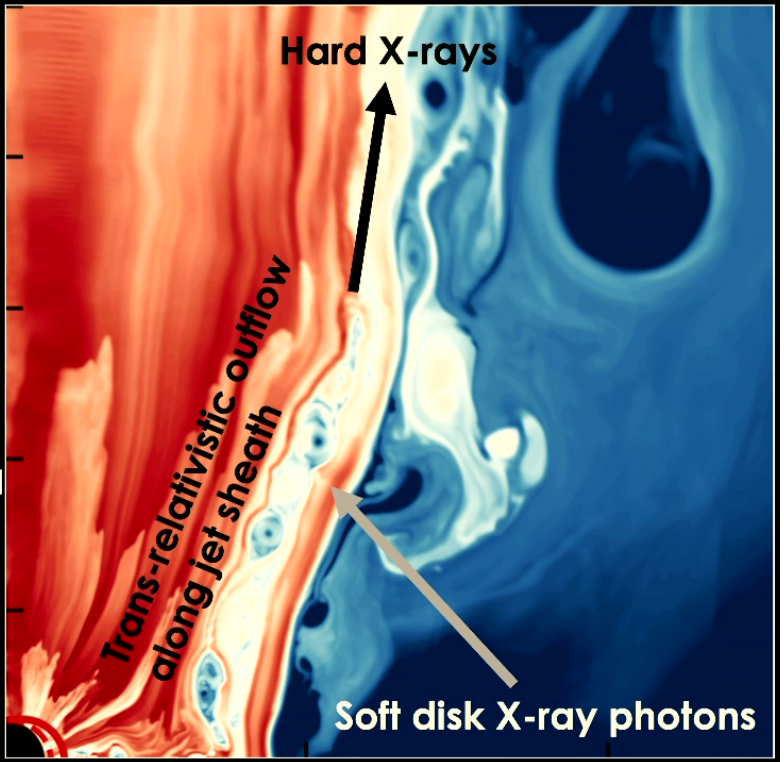

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