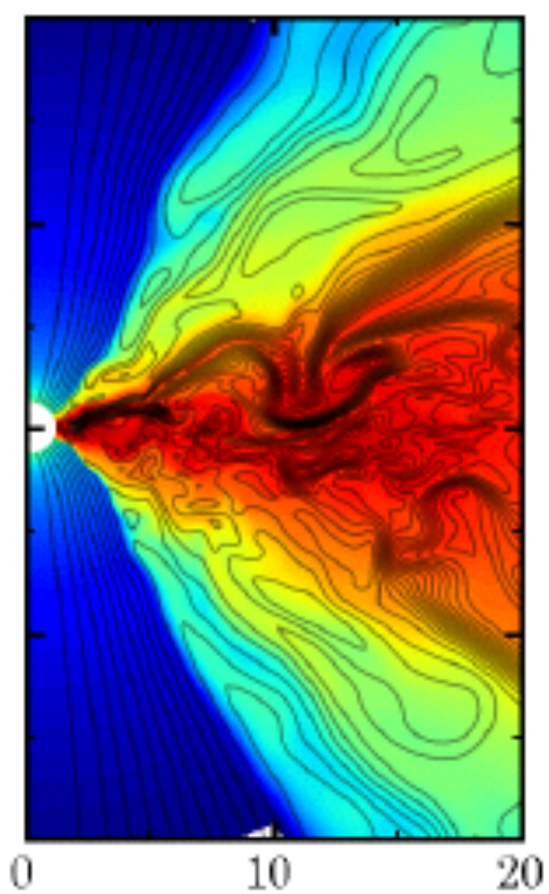
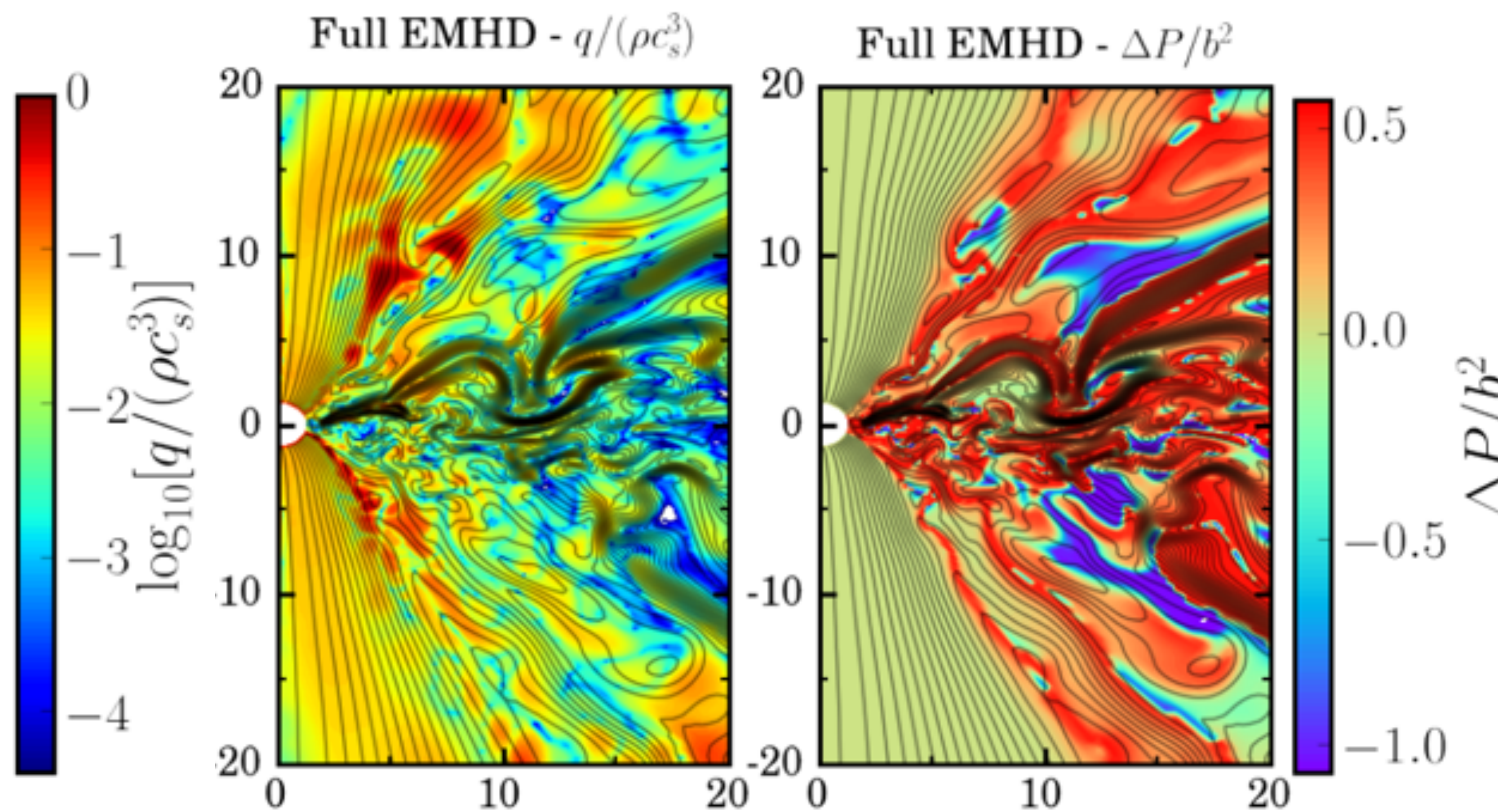
Evolution of accretion discs using an extended MHD model





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Einstein Fellows symposium - Oct 28th 2015

Slowly accreting disks around SMBHs

- Most disks around SMBH accrete well below the Eddington rate

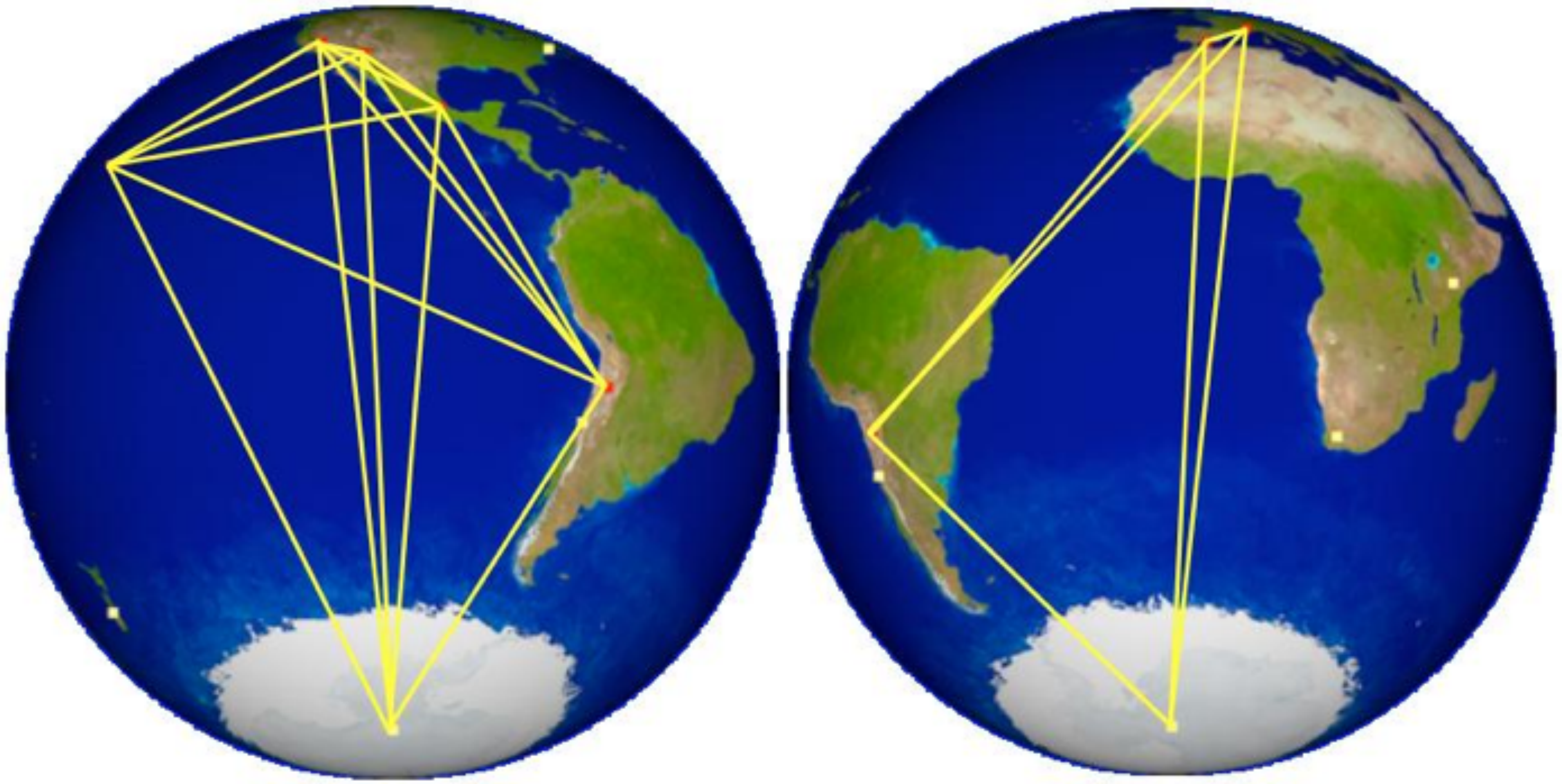
- Easiest BH to resolve are slowly accreting

  - SgrA* : $M \sim 4 \times 10^6 M_\odot$, $\dot{M} \sim 10^{-8} M_{\rm Edd}$, $d \sim 8\,{\rm pc}$

  - SMBH in M87 : $M \sim 4 \times 10^9 M_\odot$, $\dot{M} \sim 10^{-4} - 10^{-5} M_{\rm Edd}$, $d \sim 16\,{\rm Mpc}$

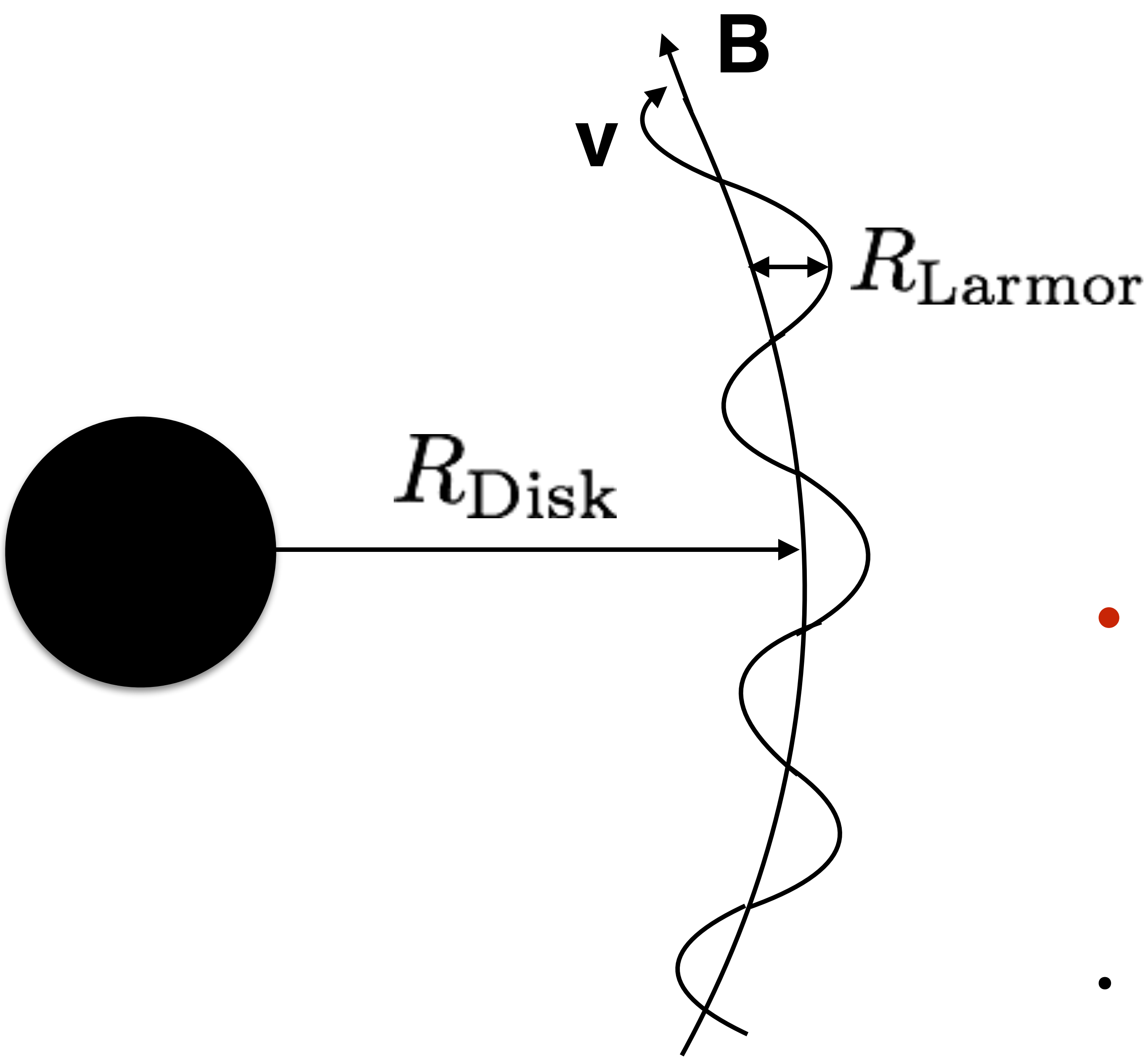
- Radiatively inefficient accretion disks: optically thin, geometrically thick, nearly collisionless plasmas

Event Horizon Telescope



- Array of ~mm wavelength telescopes, baseline the size of the earth
- Objective: resolve accretion flows to sub-Horizon resolution!

Important length scales



- For slowly accreting black holes:

$$R_{\mathrm{Larmor}} \ll R_{\mathrm{Disk}} \ll \lambda_{\mathrm{mfp}}$$

- Efficient transport of energy/momentum along magnetic field lines!

- **Not an ideal fluid!!**

Anisotropic distribution function of charged particles:

$$f(x^\mu, p^\mu) \rightarrow f(x, t, p_\perp, p_{||})$$

Beyond ideal fluid theory

- Local simulations predict *effective* collision rate from wave-particle interactions
- Motivates description of plasma as *weakly collisional* fluid

$$f(x^\mu, p^\mu) = f_{\rm ideal}(\rho, T) + \epsilon f_1(x, t, p_\perp, p_{||}) + \epsilon^2 f_2(x, t, p_\perp, p_{||})$$

Extended MHD model

see M. Chandra et al, ApJ 810,162

(1) Modified stress-energy tensor

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + q^\mu u^\nu + q^\nu u^\mu + \Pi^{\mu\nu}$$

(2) Evolved heat flux along B

$$q^\mu = q\hat{b}^\mu$$

(3) Evolved pressure anisotropy

$$\Pi^{\mu\nu} = -\Delta P\left(\hat{b}^\mu\hat{b}^\nu - \frac{1}{3}h^{\mu\nu}\right)$$

$$P_\parallel = P - \tfrac{2}{3}\Delta P \qquad P_\perp = P + \tfrac{1}{3}\Delta P$$

(4) Equations for non-ideal pieces (causality, 2nd law)

$$\nabla_\mu(\tilde{q}u^\mu) = -\frac{\tilde{q}-\tilde{q}_0}{\tau_R} + \frac{\tilde{q}}{2}\nabla_\mu u^\mu, \qquad \tilde{q} = q\left(\frac{\tau_R}{\chi\rho\Theta^2}\right)^{1/2}$$

$$\nabla_\mu(\Delta\tilde{P}u^\mu) = -\frac{\Delta\tilde{P}-\Delta\tilde{P}_0}{\tau_R} + \frac{\Delta\tilde{P}}{2}\nabla_\mu u^\mu \qquad \Delta\tilde{P} = \Delta P\left(\frac{\tau_R}{\nu\rho\Theta}\right)^{1/2}$$

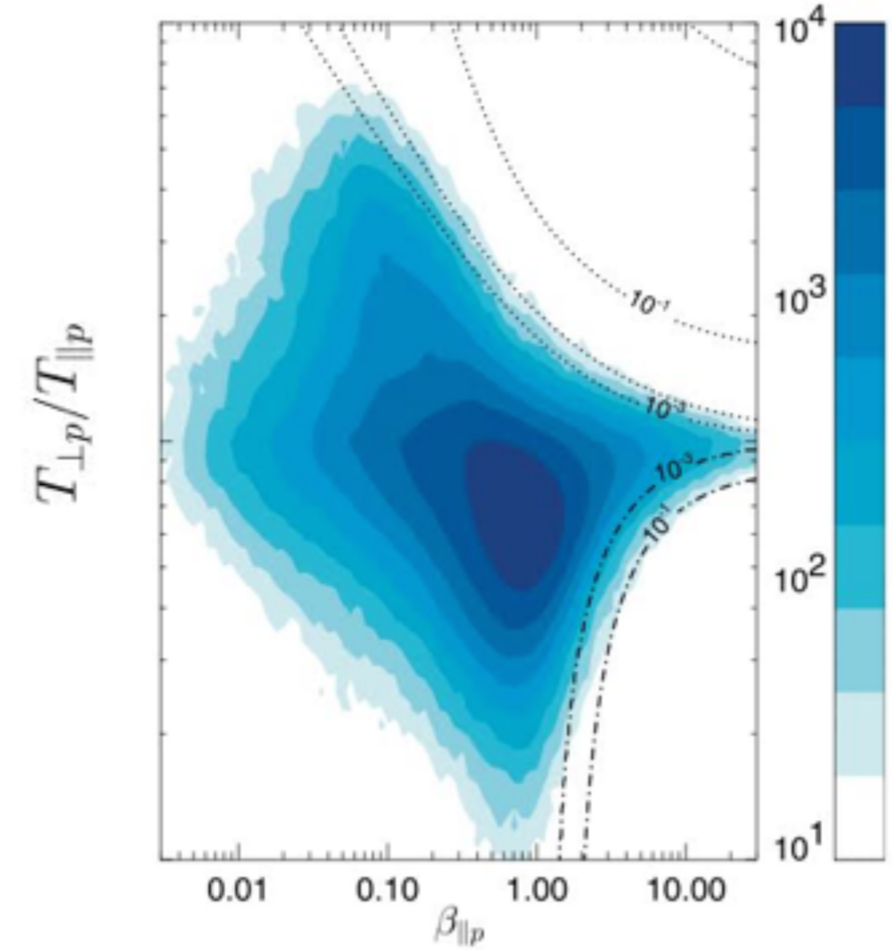
(5) Equilibrium values (2nd law, Braginskii)

$$q_0 = -\rho\chi\hat{b}^\mu(\nabla_\mu\Theta + \Theta u^\nu\nabla_\nu u_\mu) \qquad \Delta P_0 = 3\rho\nu\left(\hat{b}^\mu\hat{b}^\nu\nabla_\mu u_\nu - \frac{1}{3}\nabla_\mu u^\mu\right)$$

Beyond ideal fluid theory

- Model has 3 free parameters
  - Damping timescale ~ collision timescale τ_R
  - Kinematic viscosity $\nu = \psi c_s^2 \tau_R$
  - Conductive diffusivity $\chi = \phi c_s^2 \tau_R$
- What is the collision timescale?
  - Estimate: ~ orbital timescale
  - BUT: ion pressure anisotropy may saturate due to velocity-space instabilities (mirror, firehose, ion cyclotron), for $|\Delta P| \sim b^2$
  - At saturation, effective collision rate increases / non-ideal effects saturate

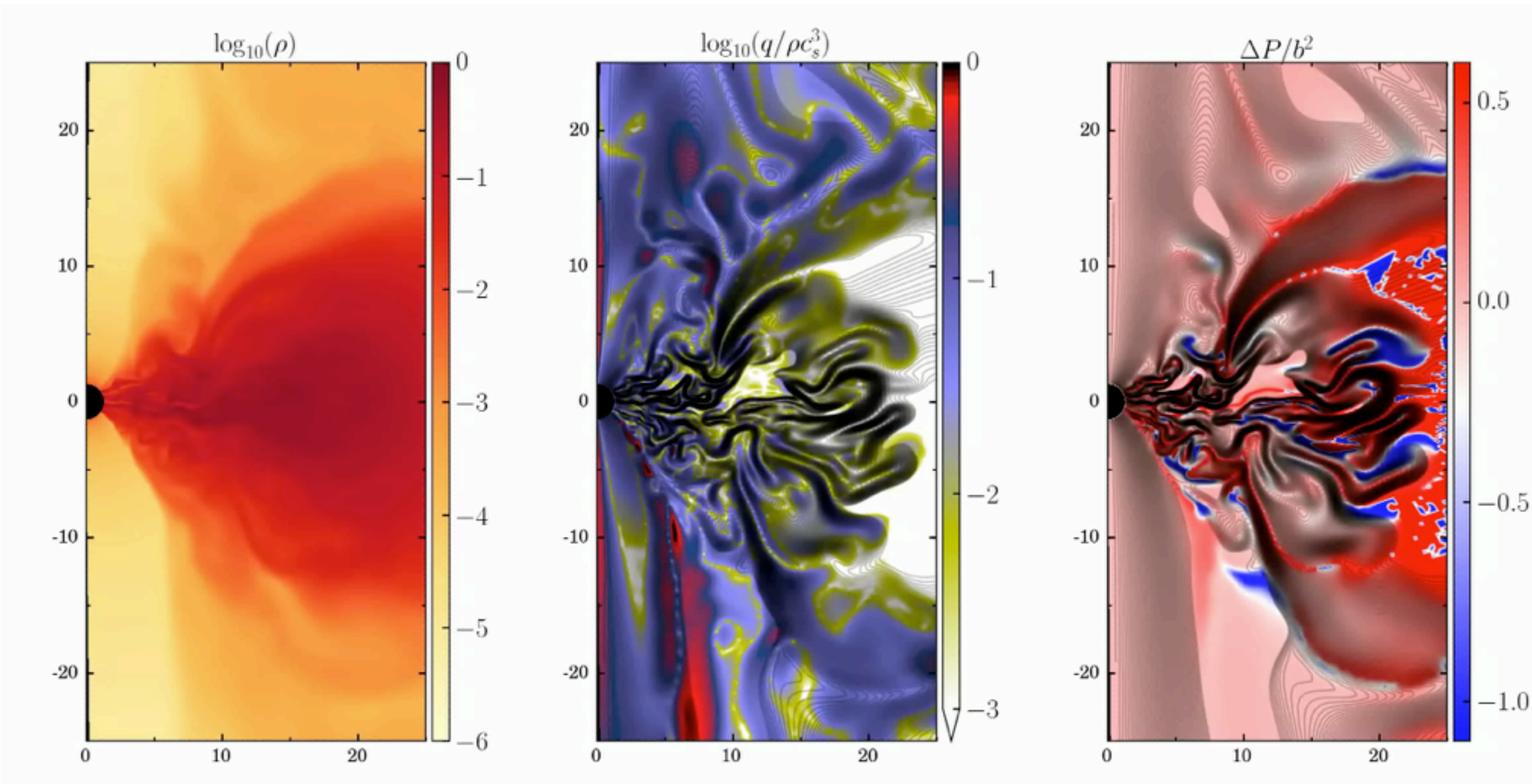
Solar Wind Hellinger et al 2006



A new code: grim

- Why do we need a new code?
  - Stiff sources for heat flux / pressure anisotropy
  - With ideal part in conservative form, time/spatial derivatives of evolved variables in sources!
- grim (**M. Chandra**, F. Foucart, C. Gammie, in prep)
  - Implicit treatment of sources, explicit treatment of fluxes
  - Inversion uses automated jacobian assembly (PETSc)
  - Flexible code for non-ideal MHD
  - http://afd-illinois.github.io/grim/

EMHD disk evolution



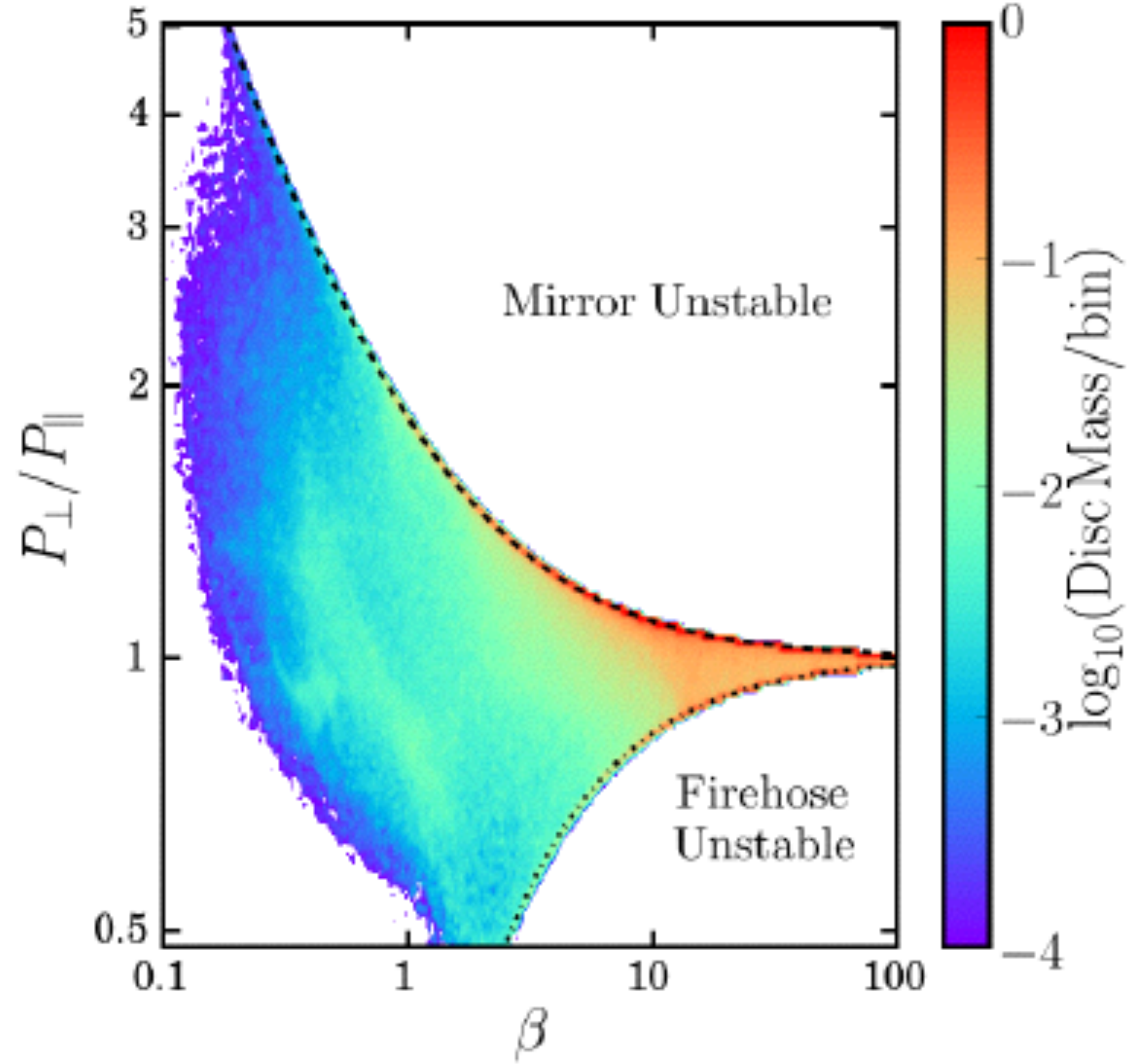
Density

Heat flux

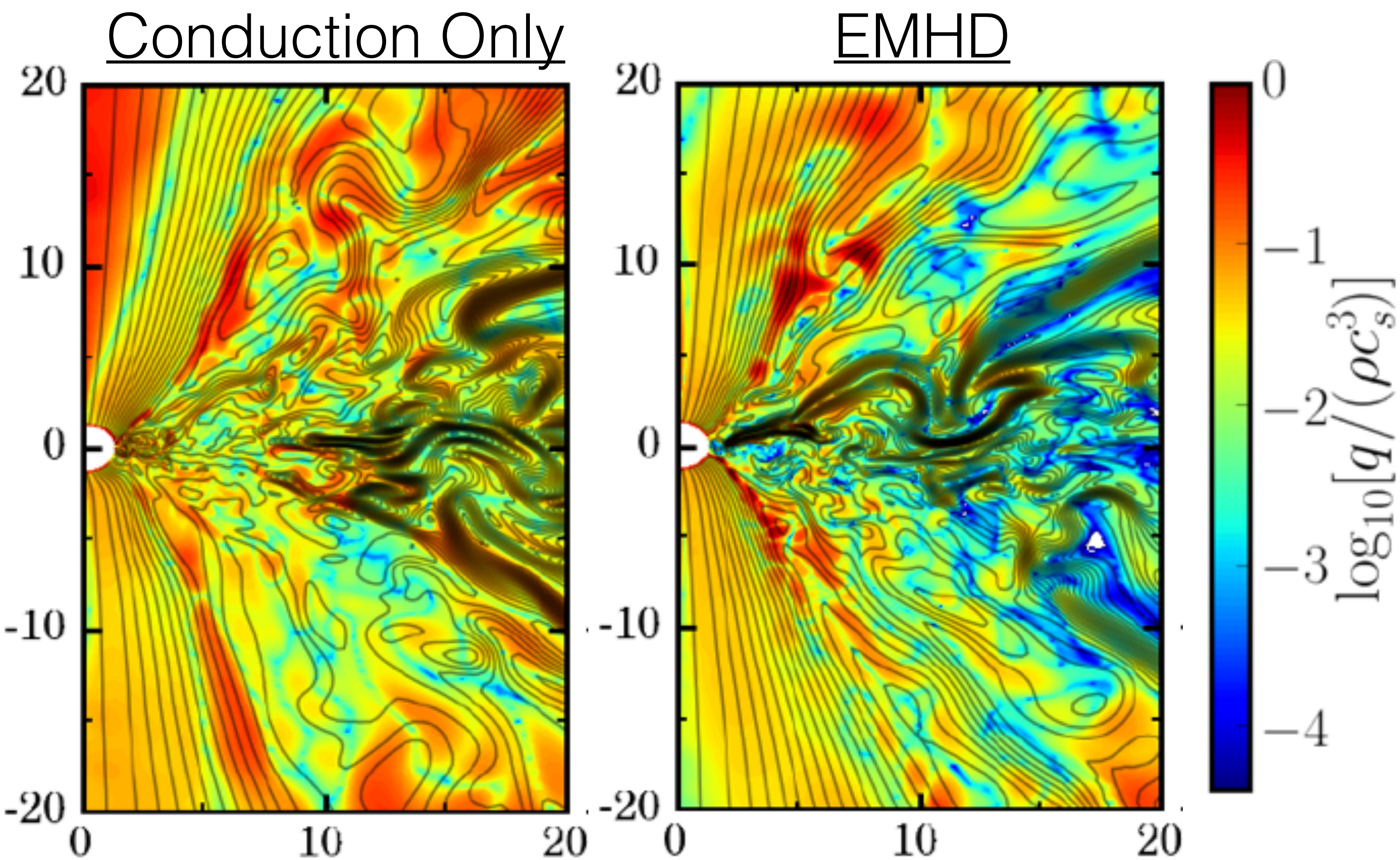
Pressure anisotropy

Pressure anisotropy

- >50% of the mass at mirror saturation
- Agrees with theoretical expectation for Keplerian shear flow, outflows
- Shows importance of saturation limit
- In corona: what about the ion cyclotron instability?



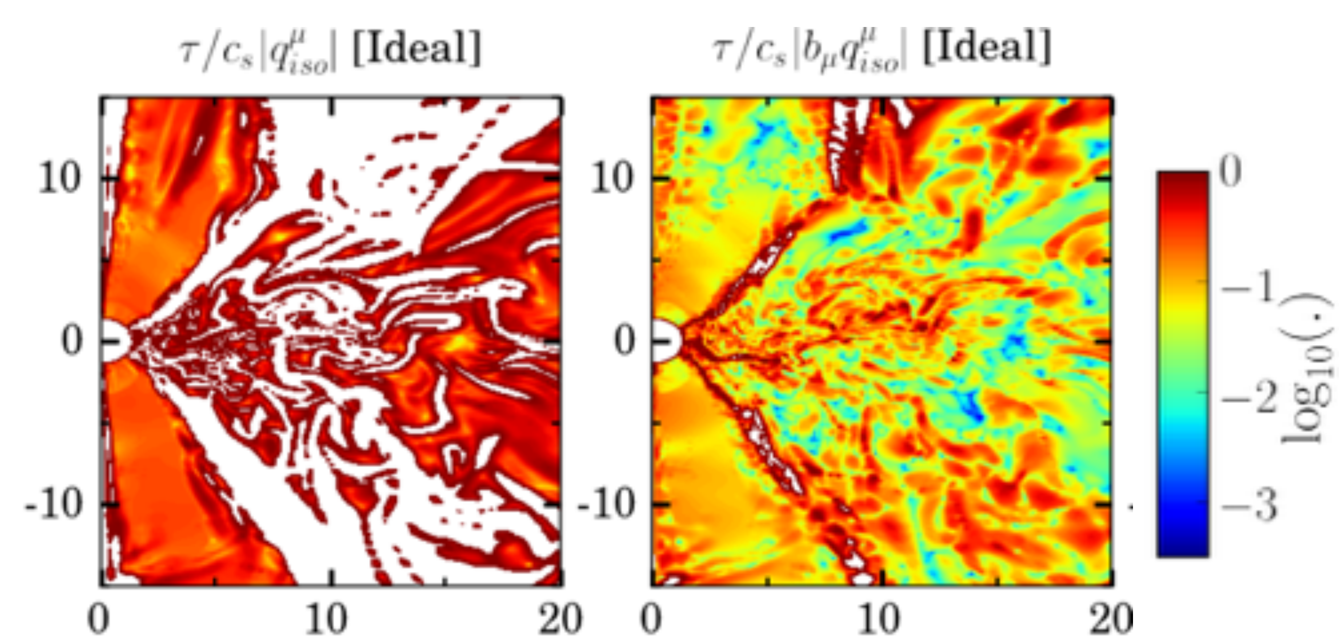
Heat flux



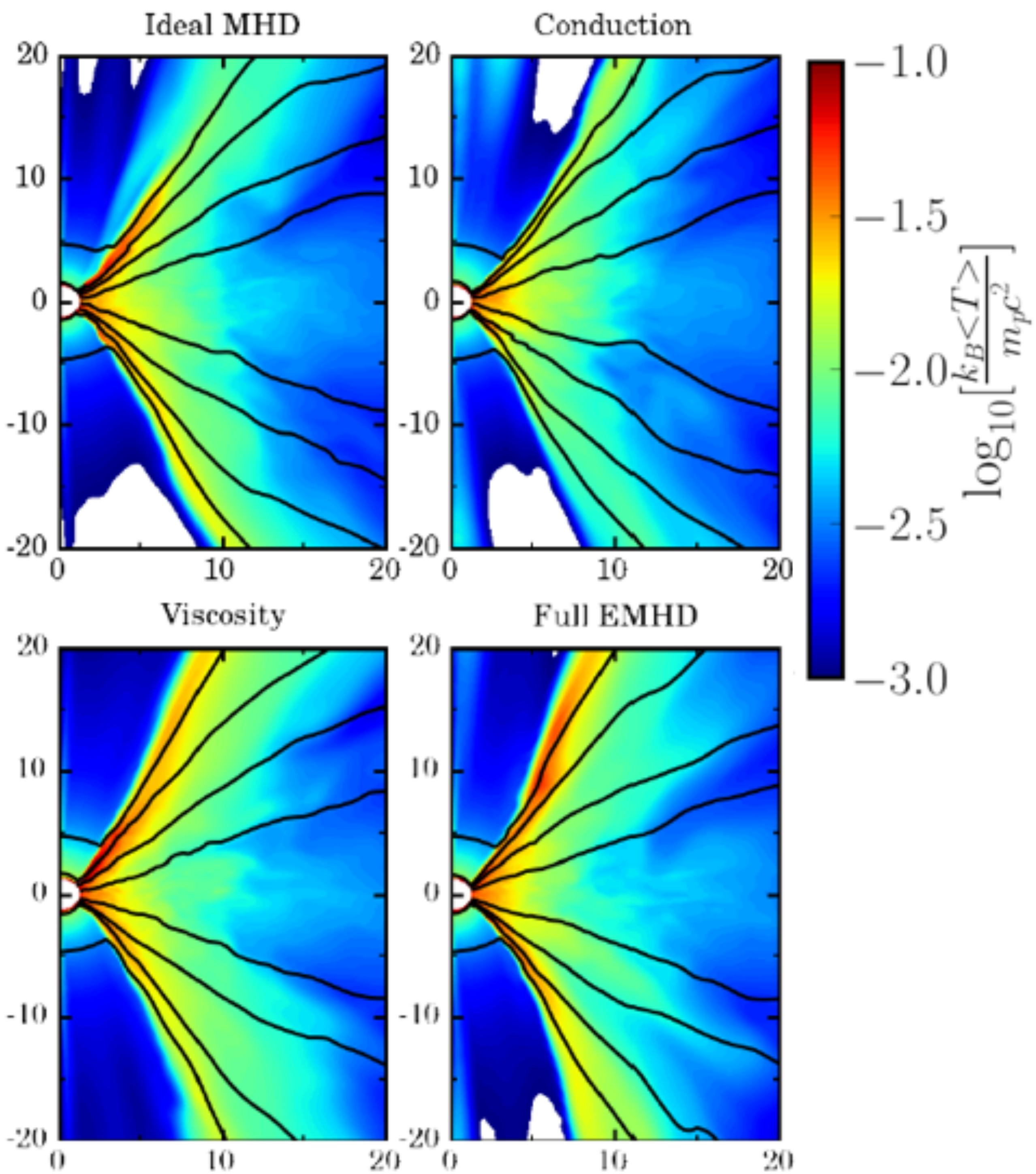
Heat flux
<< Saturation

(1) Temperature gradients are not along **B**

(2) Mirror instability increases collisionality, decreases q



Coronal heating and outflows



- Pressure anisotropy increases heating of corona
- Conduction has only mild effect
- BUT: temperature is not a converged result in 2D!!!
- Need hi-res 3D simulations!
- For radiation, the important parameter is the *electron* temperature…

Conclusions

- Many accretion disks around SMBH are poorly modeled by ideal MHD
- First global 2D simulations including non-ideal effects, imply O(1) impact on outflows/inflows
- Non-ideal effects could significantly affect heating of corona, radiative properties of the disk
  - Need 3D simulations, electron thermodynamics (e.g. Sasha's talk) to get reliable models