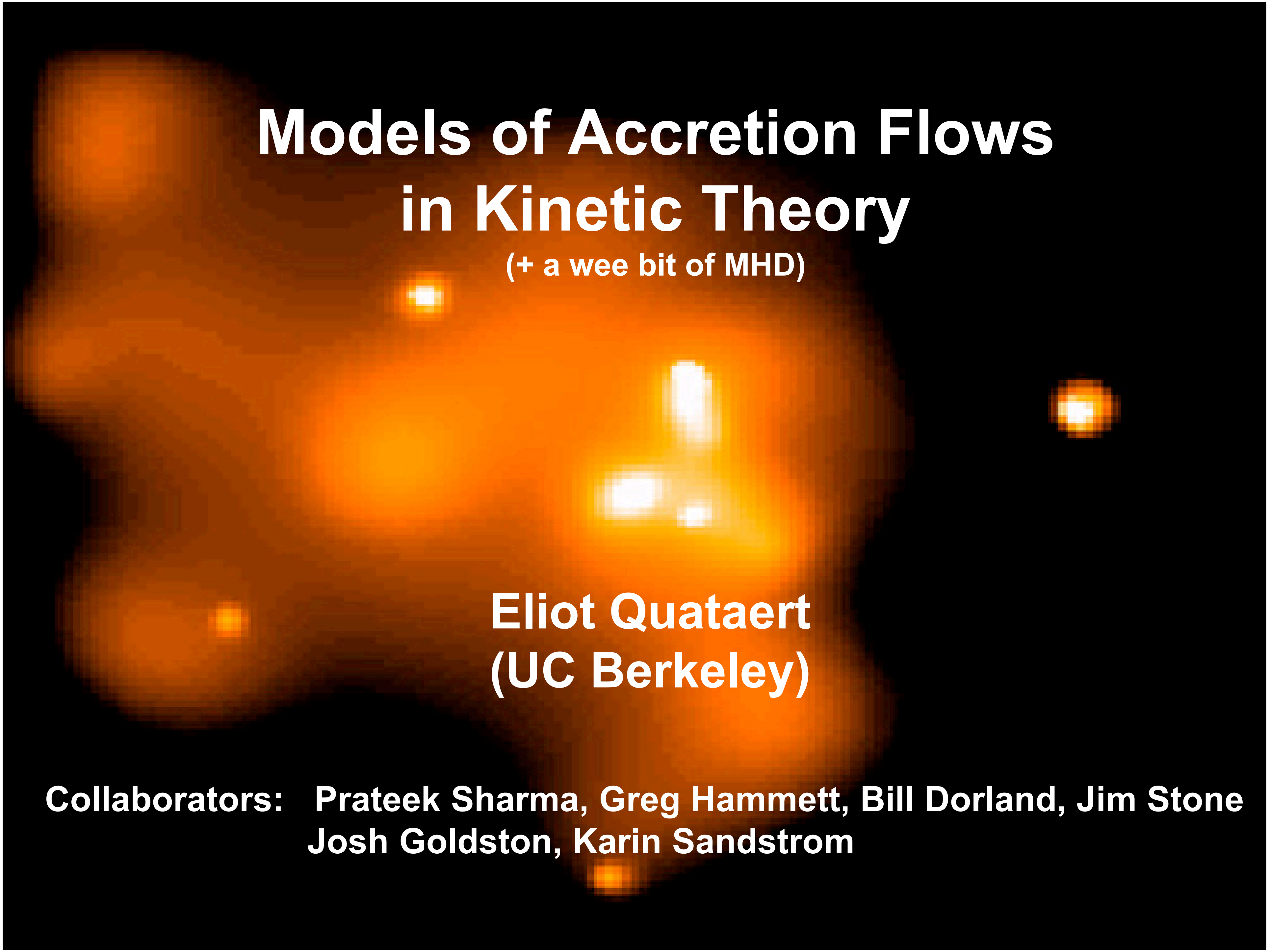

Models of Accretion Flows in Kinetic Theory

(+ a wee bit of MHD)

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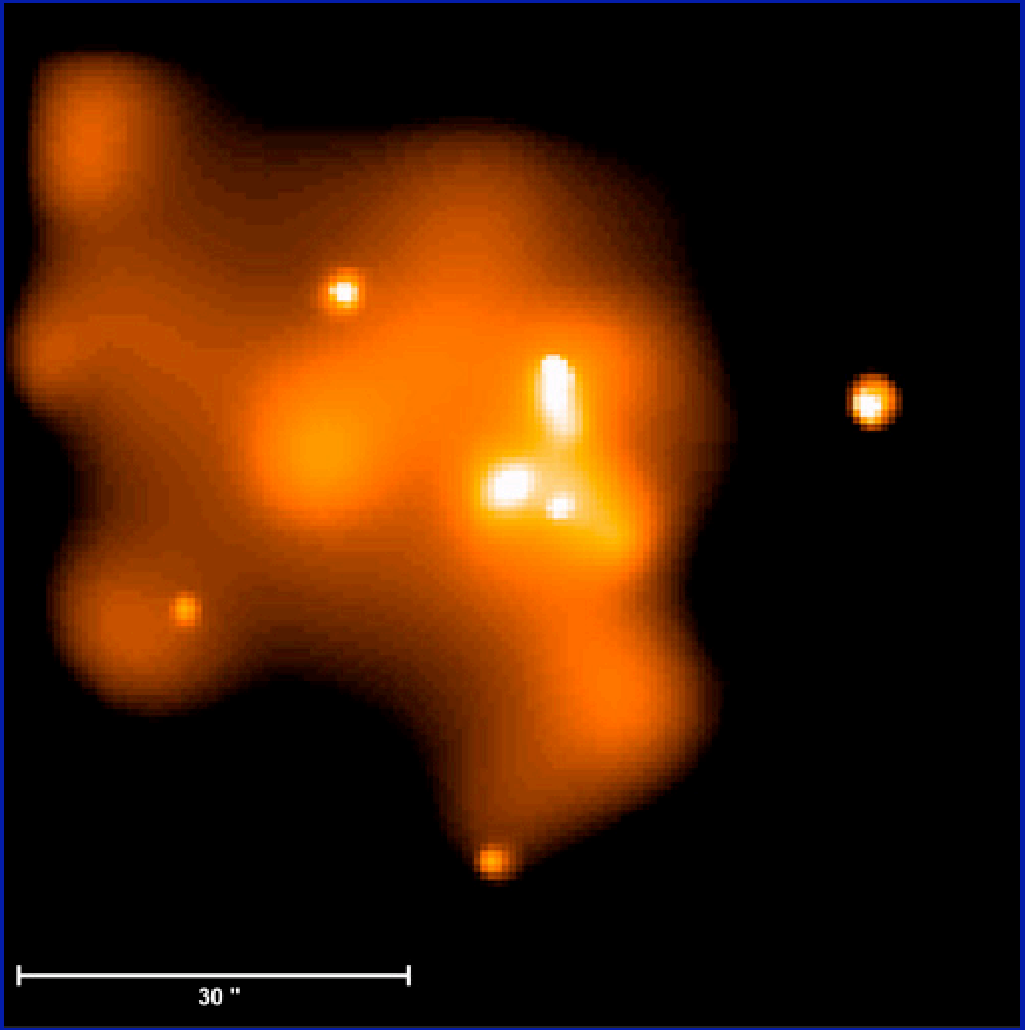
Collaborators: Prateek Sharma, Greg Hammett, Bill Dorland, Jim Stone
Josh Goldston, Karin Sandstrom

The (In)Applicability of MHD?



Observed Plasma

(~ 1" ~ R_{Bondi} ~ 10^5 R_S)

T ~ few keV   n ~ 100 cm^{-3}

e-p thermalization time ~ **2000 yrs**

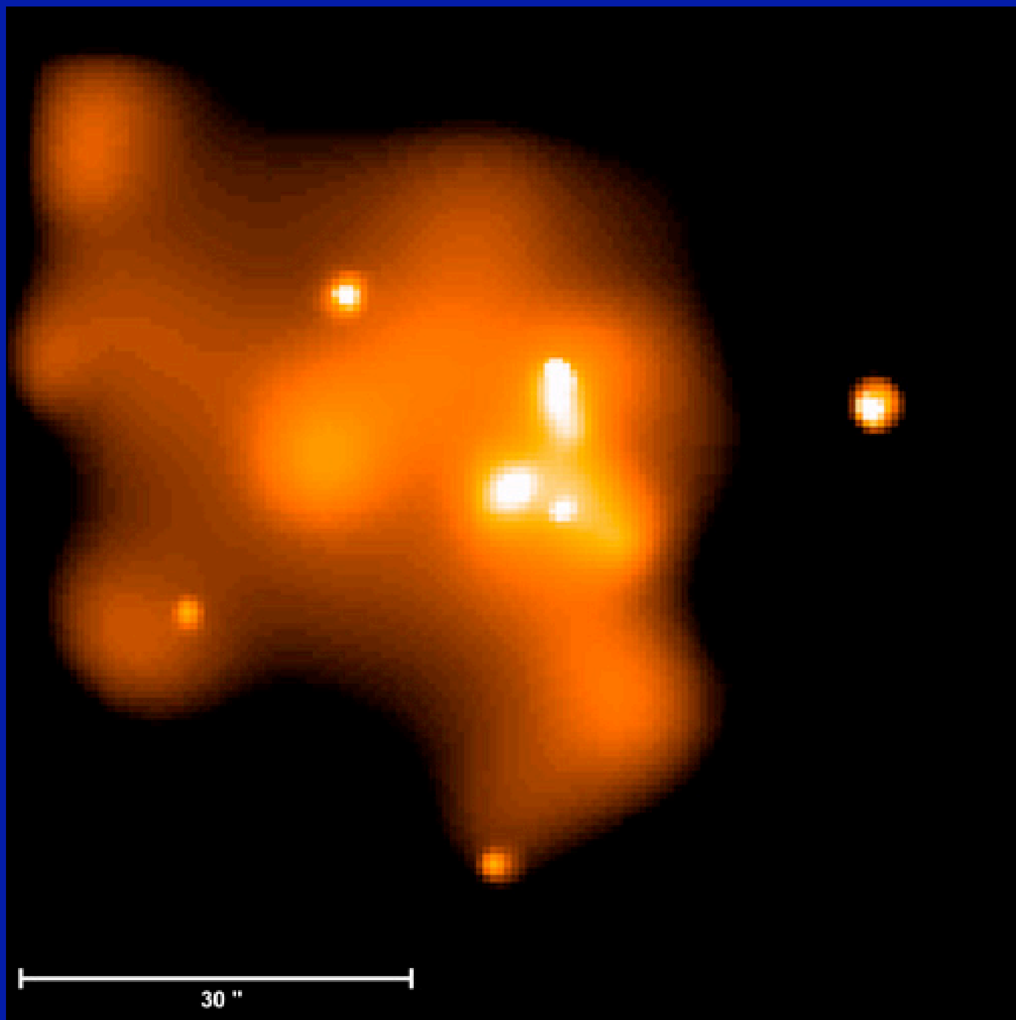
>>

inflow time ~ R_{Bondi}/c_s ~ **100 yrs**

$\Longrightarrow$

$T_{electron}$ measured by X-rays
need not equal T_{proton}
(complicates inference of R_{Bondi})

The (In)Applicability of MHD?



Estimated Conditions Near the BH

$T_p \sim 10^{12}$ K
$T_e \sim 10^{11}$ K
$n \sim 10^6$ cm^{-3}

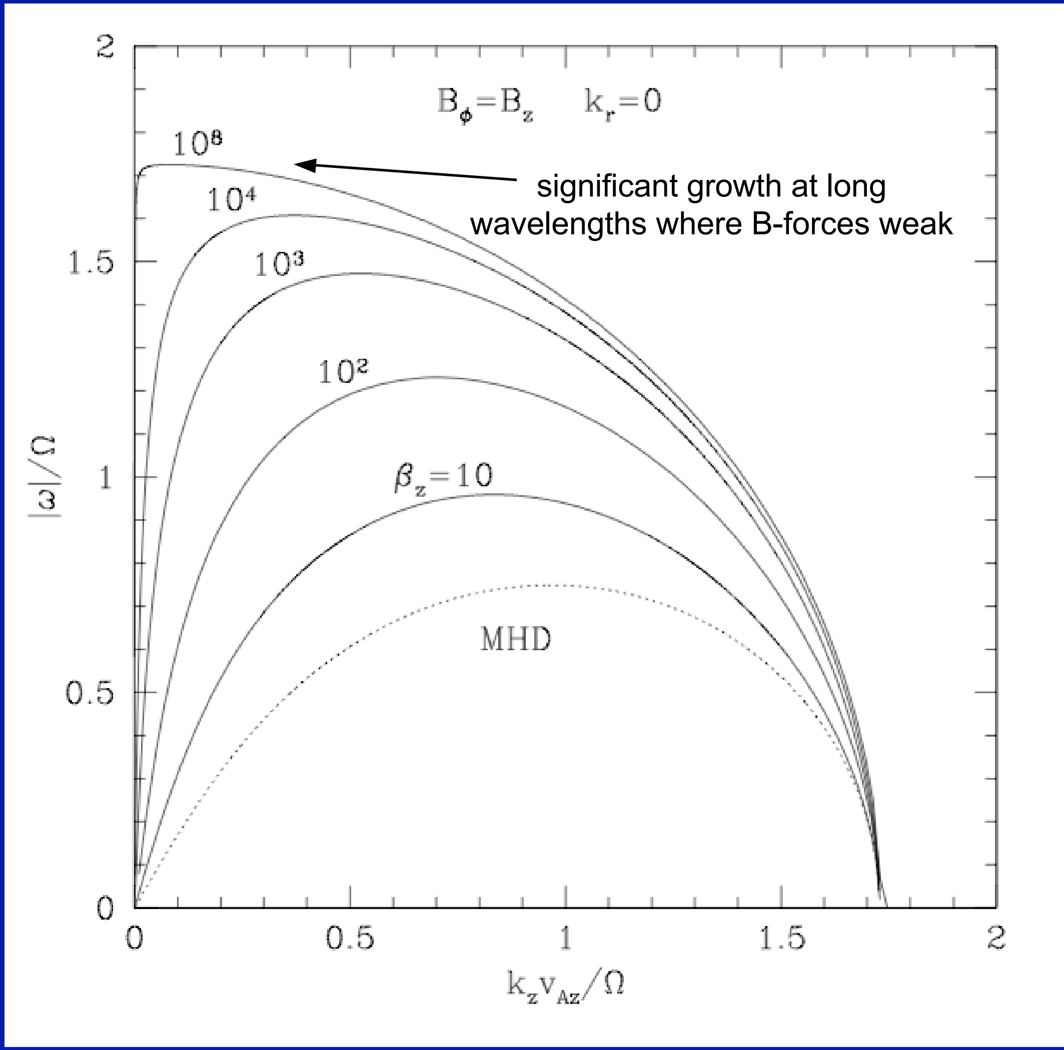
proton mfp ~ kpc >>> R_S

$\Rightarrow$

We need to understand accretion of a magnetized collisionless plasma

⇣

The MRI in a Collisionless Plasma



Quataert, Dorland, Hammett 2002; also Sharma et al. 2003; Balbus 2004

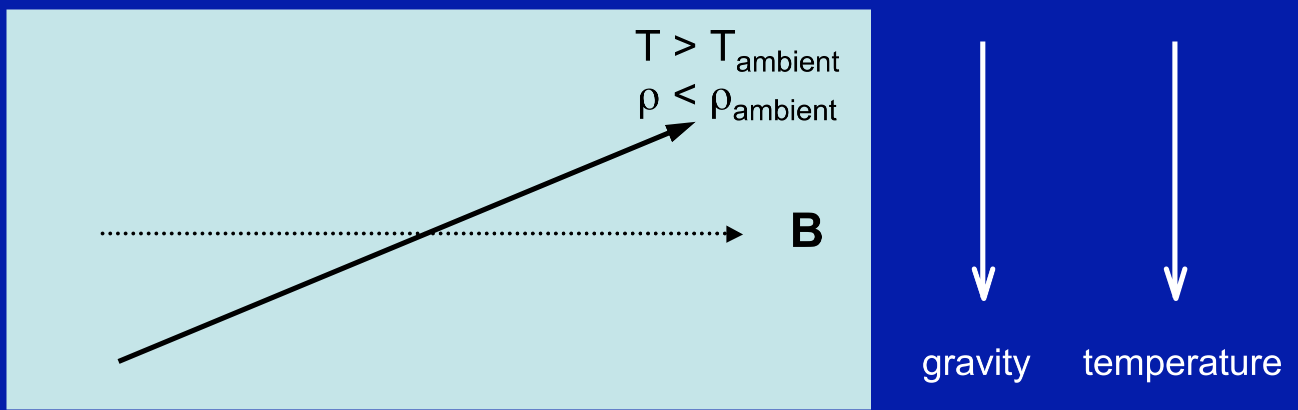
angular momentum transport
via anisotropic pressure (viscosity!)
in addition to magnetic stresses

Collisionless Convection

(Balbus 2000; Karin Sandstrom & EQ 200N)

- Convection (Buoyancy) May be Dynamically Impt in Hot, Thick Disks

- Schwarzschild Criterion for Instability in Hydro & MHD (β >> 1): **ds/dr < 0**



$t_{conduction} < t_{buoyancy} \Rightarrow \quad \nabla_{||} T \approx 0$ (temp constant along field lines)

"Convection" if **dT/dr < 0**

Hydro & MHD Simulations Do Not Capture the Correct Physics of Dynamical Instabilities in Hot Collisionless RIAFs (neither MRI nor Convection)

Goal: Kinetic Simulations

Kinetic-MHD

(e.g., Kulsrud 1983)

- Large-scale Dynamics of collisionless plasmas: expand Vlasov equation retaining "slow timescale" & "large lengthscale" assumptions of MHD
- Particles efficiently transport heat and momentum along field-lines

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0,$$

$$\rho \frac{\partial \mathbf{V}}{\partial t} + \rho \left(\mathbf{V} \cdot \nabla \right) \mathbf{V} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \nabla \cdot \mathbf{P} + \mathbf{F_g},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{V} \times \mathbf{B} \right),$$

$$\mathbf{P} = p_\perp \mathbf{I} + \left(p_\| - p_\perp \right) \hat{\mathbf{b}}\hat{\mathbf{b}},$$

Evolution of the Pressure Tensor

$$\rho B \frac{d}{dt}\left(\frac{p_\perp}{\rho B}\right) = -\nabla\cdot(\hat{\mathbf{b}} q_\perp) - q_\perp \nabla\cdot\hat{\mathbf{b}}$$

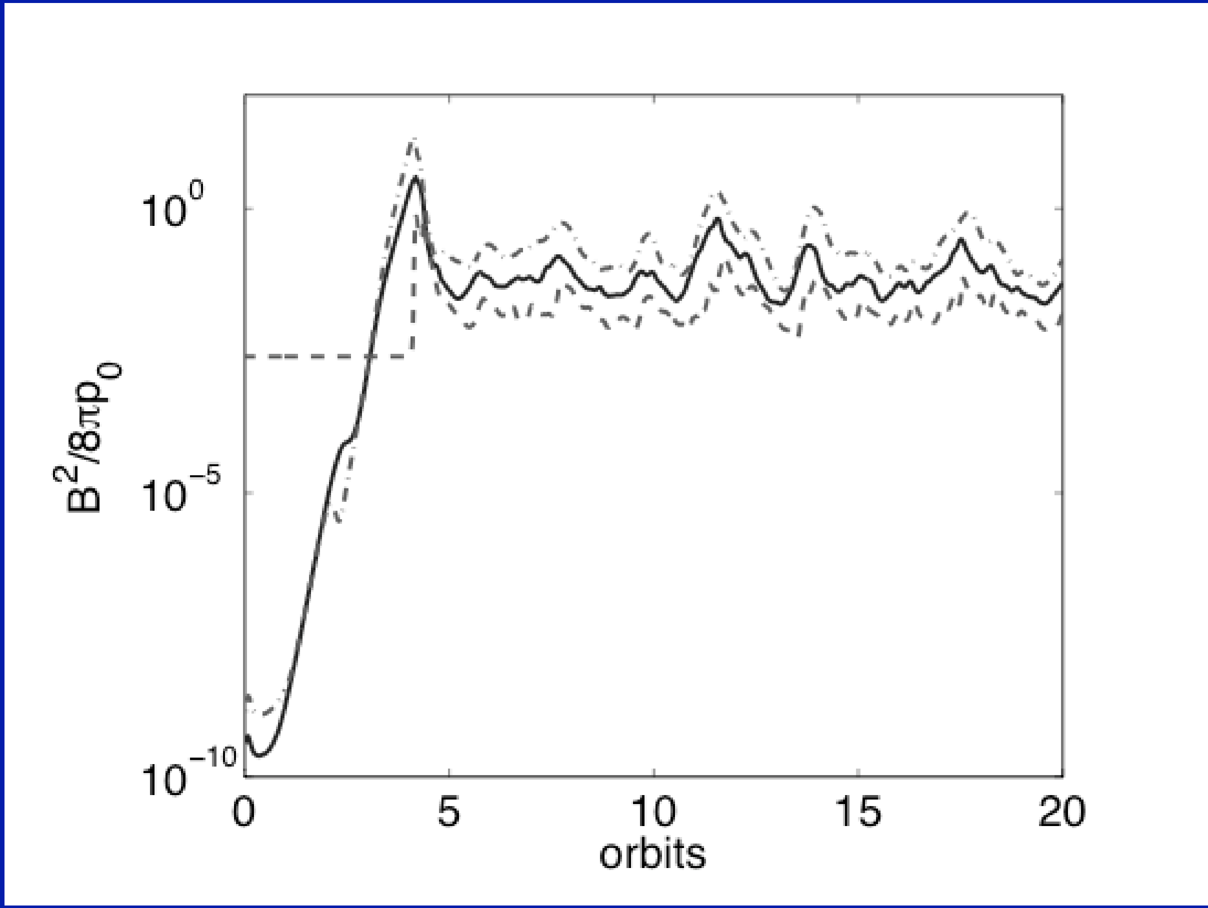
$$\frac{\rho^3}{B^2}\frac{d}{dt}\left(\frac{p_{||} B^2}{\rho^3}\right) = -\nabla\cdot(\hat{\mathbf{b}} q_{||}) + 2 q_\perp \nabla\cdot\hat{\mathbf{b}},$$

adiabatic invariance of $\mu \sim mv^2_\perp/B \sim T_\perp/B$

$$q \approx \frac{n v_{th}}{|k_{||}|}\nabla_{||} T$$

Closure Models (Approximations) for the Heat Flux (temp gradients along fields wiped out on ~ a crossing time)

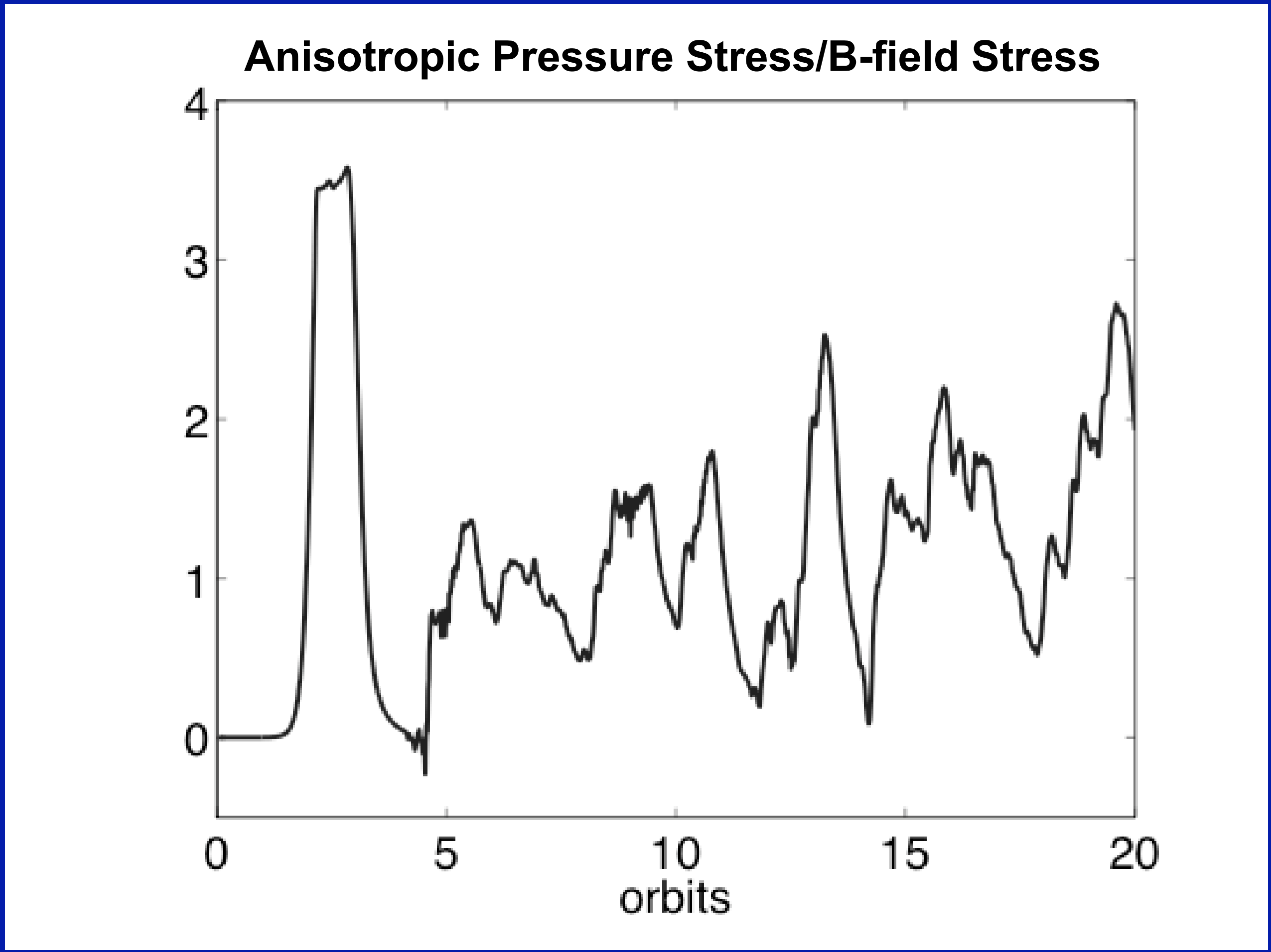
Local Simulations of the Kinetic MRI



Sharma et al. in prep

Non-linear Evolution Depends Critically On Isotropization Of Pressure Tensor via small-scale Kinetic Instabilities

Angular Momentum Transport



Sharma et al. in prep

Anisotropic Stress ~ Maxwell Stress

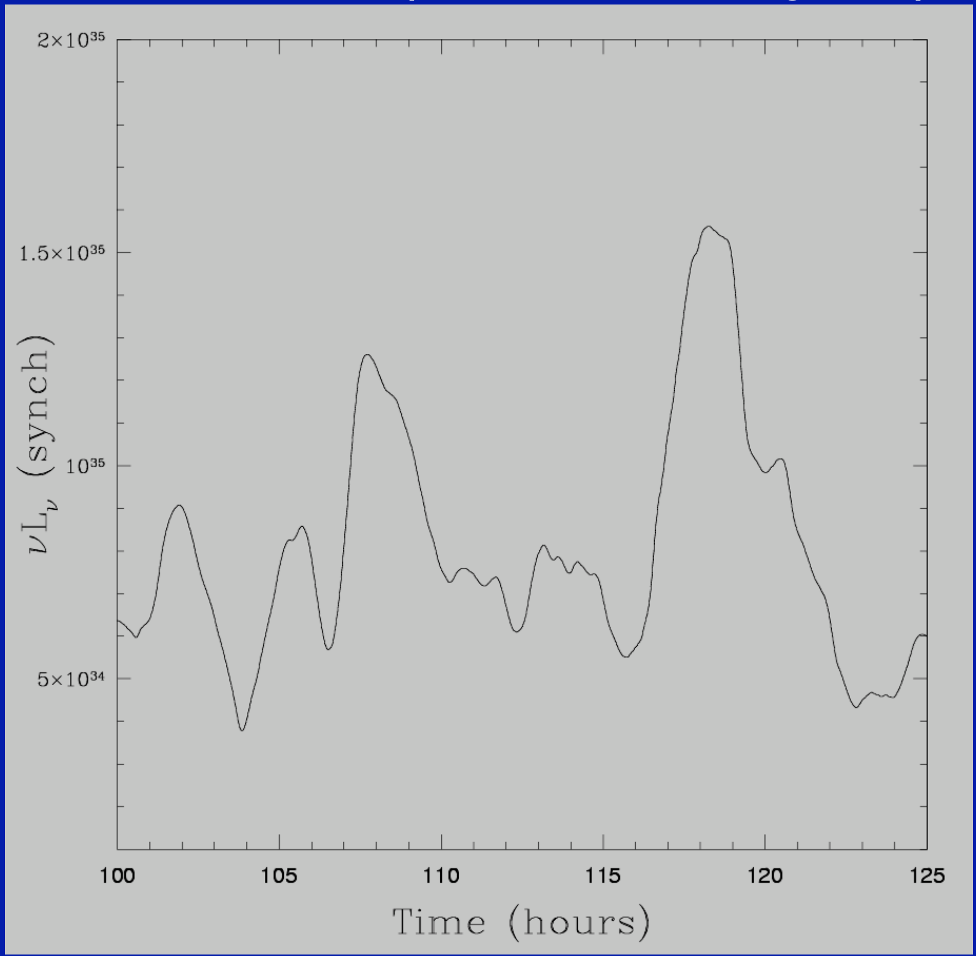
Local Rate of Angular Momentum Transport Enhanced (by factor ~ 2)

Global Dynamics In Collisionless Limit Remains to Be Explored

Connecting Simulations
To Observations

Synchrotron Emission in Global MHD Sims of RIAFs

1mm/300 GHz (thermal; optically thin)



Goldston, Quataert, & Igumenschev 2005

At high (optically thin) frequencies, factors of ~ few-5 variability on ~ hour timescales (~ orbital period near BH)

How Quantitative Can we Be?

- IR & X-ray ‘Flaring’ Depends on e- DF: **Plasma Physics Weather?**
- Electron Heating & Acceleration Remain Poorly Understood
- electron conduction time << inflow time, electron cooling time
- $\Rightarrow$ conduction strongly influences T_e & thus the radiation we see
- (maybe submm better bec. ~ thermal population of e^{-}s?)

Summary

- Accretion Flow onto Sgr A* is Collisionless: mfp/$R_s \sim 10^9$!
- Instabilities that Determine Accretion Flow Dynamics Qualitatively Different in Collisionless Plasmas (MRI, Convection)
- Local Simulations of Kinetic MRI Similar to MHD with Enhanced Transport due to Anisotropic Pressure Stresses
- Radiation from MHD Simulations Similar to Observations of SgrA*
  - Caution Required Re. Quantitative Comparisons (Electron DF?)