Transport & Heating in Low-Luminosity Accretion Flows

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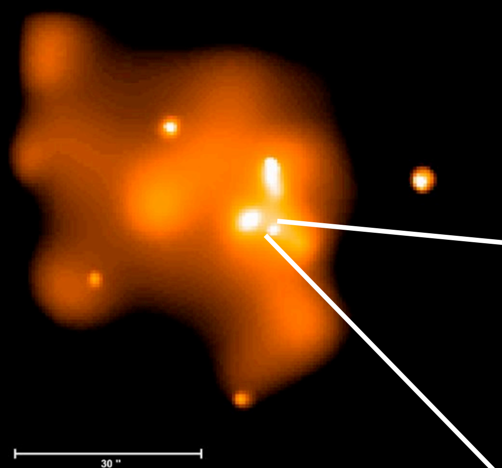
Low luminosity accretion flows

- 10^6-10^9 $M_\odot$ BHs at centers of galaxies
- most luminous objects, e.g., quasars, AGN
- low luminosity BHs in nearby galaxies; why this dichotomy? may be there is just not enough mass available?
- $L = \eta \dot{M} c^2$; $\eta \sim 0.1$ for thin disks
- $\eta \sim 10^{-(\text{a few})}$ for LLBHs (using $\dot{M}$ inferred from large scales)
- $\Rightarrow$ disk hot & thick; accretion energy not coupled to electrons
- low η or low $\dot{M}$ for low luminosity? requires detailed modeling

Sgr A*: Galactic center BH



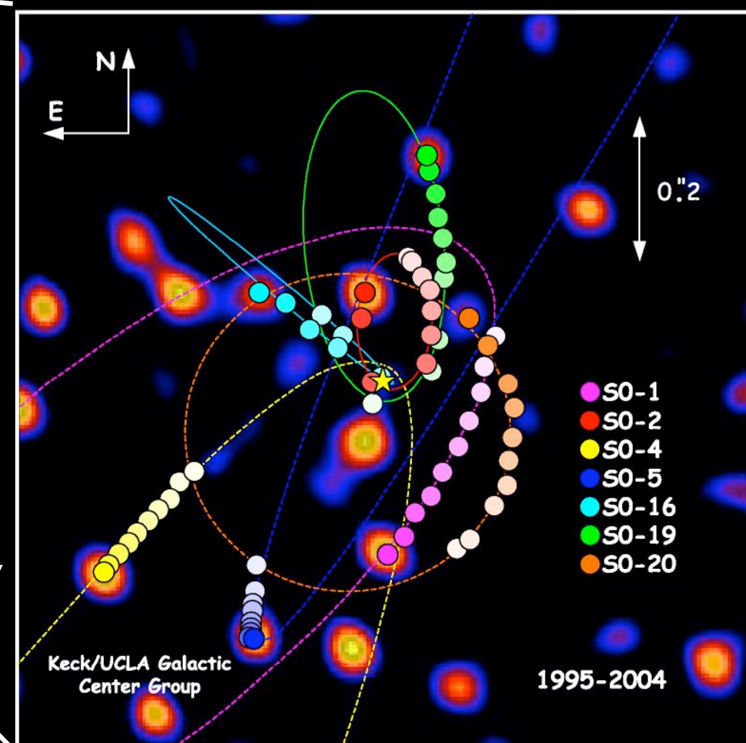
$4\times10^6\ M_\odot$ black hole

$\dot{M} \sim 10^{-5}\ M_\odot$ /yr by stellar outflows

$L_{obs} \sim 10^{36}$ erg/s $\sim 10^{-5} \times (0.1\ \dot{M}c^2)$, radio to X-ray

Why low luminosity? low $\dot{M}$ or radiative efficiency

outflows/convection can decrease $\dot{M}$

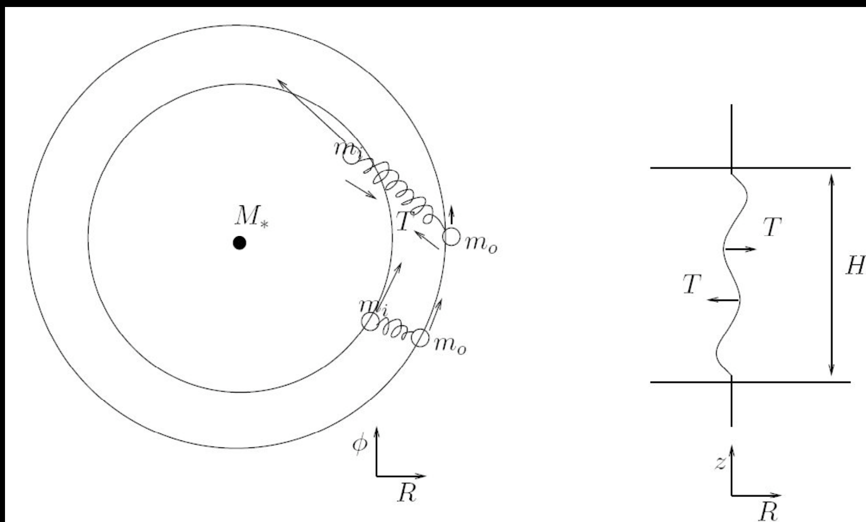


Bondi radius ~ 0.07 pc (2”), n~100/cc, T~1.2 keV

[Baganoff et al. 2003]

mfp ≈ r_{Bondi}, collisionless at smaller r; detailed transport calculations useful

Disk Transport



Anisotropic

$$W_{r\phi} = -\left(1 - \frac{p_{\parallel} - p_{\perp}}{B^2}\right)\frac{B_r B_\phi}{4\pi} + \rho v_r \delta v_\phi$$

Maxwell Reynolds

molecular viscosity not sufficient, invoke turbulent viscosity

Hydrodynamic disks linearly stable, magnetic fields qualitatively different

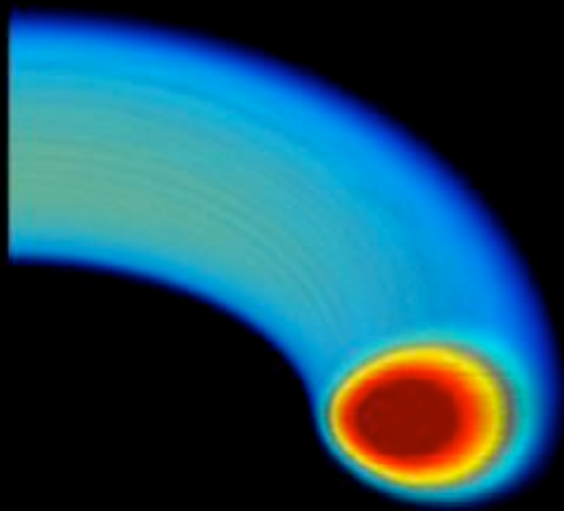
Source of turbulence is MRI when $d\Omega^2/d\ln r<0$; r-Φ correlations (due to shear) creates stress & causes transport

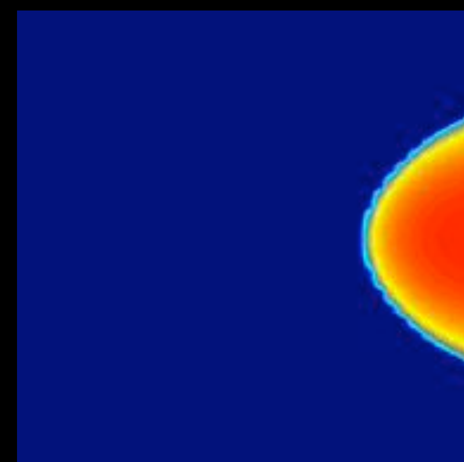
[Balbus & Hawley 1991]

Anisotropic viscous stress even if $B\rightarrow0$; mass falls in & angular momentum flows out

3-D MHD simulations

Movies by John Hawley





MHD simulations of MRI turbulence quite successful. Need to study it in collisionless regime applicable to Sgr A*

Drift Kinetic Equation

plasma is collisionless, hot w. H~r

Larmor radius << disk height

drift kinetic equation: moment of the Vlasov eq.

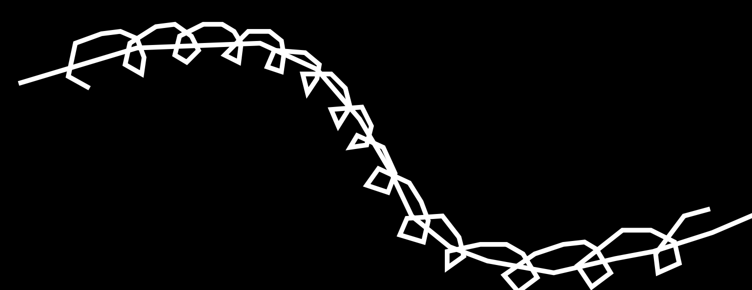
Table 1.2: Plasma parameters for Sgr A*

Parameter	$r = r_{acc}$ 2.2×10^{17} cm	$r = \sqrt{r_{acc} R_S}$ 4.2×10^{14} cm	$r = R_S$ 7.8×10^{11} cm
$\nu_{i,\mathrm{ADAF}}/\Omega_K \sim r^{3/2}$	11.4	9.4×10^{-4}	7.6×10^{-8}
$\nu_{i,\mathrm{CDAF}}/\Omega_K \sim r^{3/2+p}$	11.4	1.81×10^{-6}	2.62×10^{-13}
$\rho_{i,\mathrm{ADAF}}/H \sim r^{-1/4}$	2×10^{-11}	9.94×10^{-11}	4.59×10^{-10}
$\rho_{i,\mathrm{CDAF}}/H \sim r^{-1/4-p/2}$	2×10^{-11}	2.23×10^{-9}	2.48×10^{-7}

$$\frac{\partial f_{0s}}{\partial t} + (\mathbf{V}_E + v_\parallel \hat{\mathbf{b}}) \cdot \nabla f_{0s} + \left(-\hat{\mathbf{b}} \cdot \frac{D\mathbf{V}_E}{Dt} - \mu \hat{\mathbf{b}} \cdot \nabla B + \frac{1}{m_s}(q_s E_\parallel + F_{g\parallel}) \right) \frac{\partial f_{0s}}{\partial v_\parallel} = 0$$

$\mu = v_\perp^2/B \propto T_\perp/B$ is conserved; $V_E = c(E \times B)/B^2$

mfp >> disk height scales >> Larmor radius



Kinetic-MHD

Moments of the DKE

similar to MHD

pressure anisotropic wrt B

how $p_{||}$, $p_{\perp}$ evolve? next higher order moment $q_{||}$, $q_{\perp}$

closure problem; q=0 (CGL approx. may not be good)

$q \approx -n\nabla_{||}T/(k_{||}v_t+\upsilon)$
[Snyder et al. 1997]

heat carried by free-streaming particles

captures collisionless effects like Landau damping

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0,$$
$$\rho \frac{\partial \mathbf{V}}{\partial t} + \rho \left(\mathbf{V} \cdot \nabla\right) \mathbf{V} = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \nabla \cdot \mathbf{P} + \mathbf{F_g},$$
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}),$$
$$\mathbf{P} = p_\perp \mathbf{I} + \left(p_{\|} - p_\perp\right) \hat{\mathbf{b}}\hat{\mathbf{b}},$$

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

Anisotropic transport

Pressure anisotropy equivalent to anisotropic viscous stress, in addition to Reynolds & Maxwell stresses

$$\frac{\partial}{\partial t}(\rho V) + \nabla \bullet \left(\rho VV + \left(p_\perp + \frac{B^2}{8\pi} \right) I - \frac{BB}{4\pi} \left(1 - \frac{p_\parallel - p_\perp}{B^2} \right) \right) = 0$$

Large scale anisotropic viscous heating, small-scale resistive, viscous heating

$$\frac{\partial}{\partial t} e + \nabla \bullet (eV + q) = -p_\perp \nabla \bullet V - (p_\parallel - p_\perp) bb : \nabla V + \eta_R j^2 + \eta_V |\nabla V|^2$$

$$\delta p_{1s} = -\frac{p_{0s}}{\nu_s}(3\hat{\mathbf{b}} \cdot \nabla \mathbf{U} \cdot \hat{\mathbf{b}} - \nabla \cdot \mathbf{U})$$

$$\delta p = p_\parallel - p_\perp$$

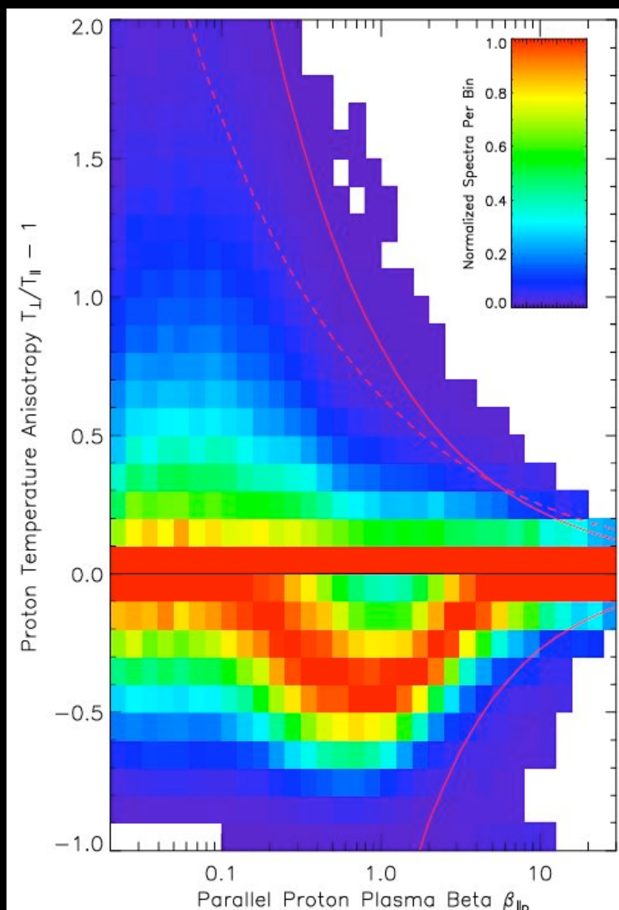
In Braginskii regime, $\upsilon \gg k v_t$, pressure anisotropy reduced by Coulomb collisions

For $\upsilon \ll k v_t$ anisotropy governed by μ invariance

Can anisotropy be arbitrarily large? No.

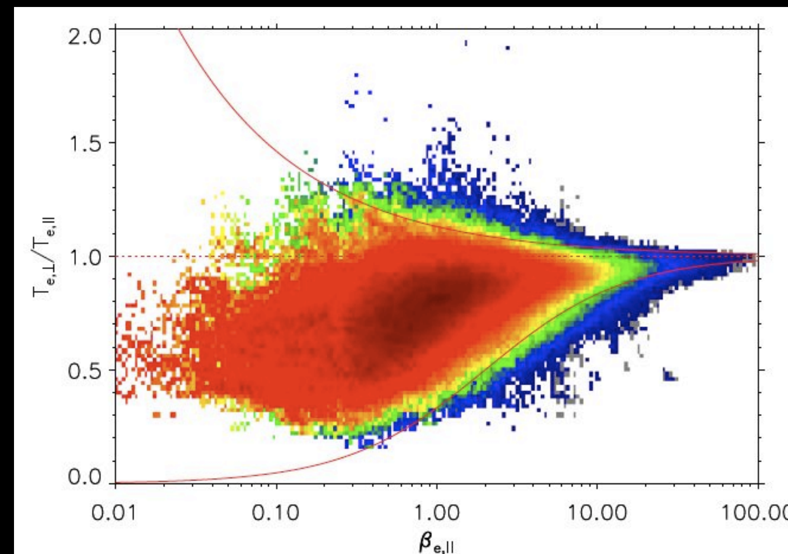
Δp limits

Protons; *[Kasper et al. 2003]*



$$\left|\frac{p_\perp}{p_\parallel}-1\right| \le \frac{S}{\beta^\alpha}$$

Electrons; *[S. Bale]*



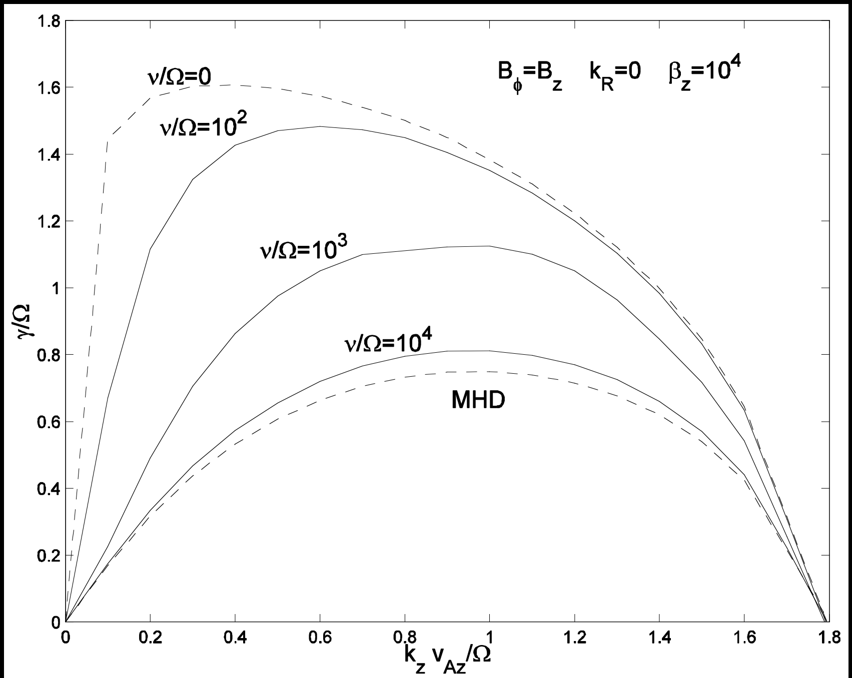
Pressure anisotropy reduced by Larmor-scale instabilities:

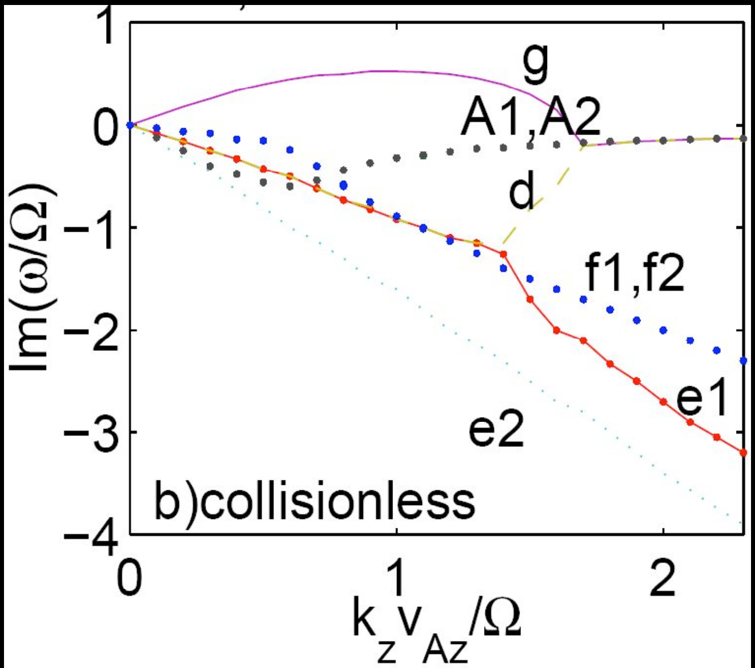
protons: ion-cyclotron, mirror ($p_\perp > p_{||}$)

electrons: electron-whistler ($p_\perp > p_{||}$)

firehose for ($p_\perp < p_{||}$)

Collisionless MRI

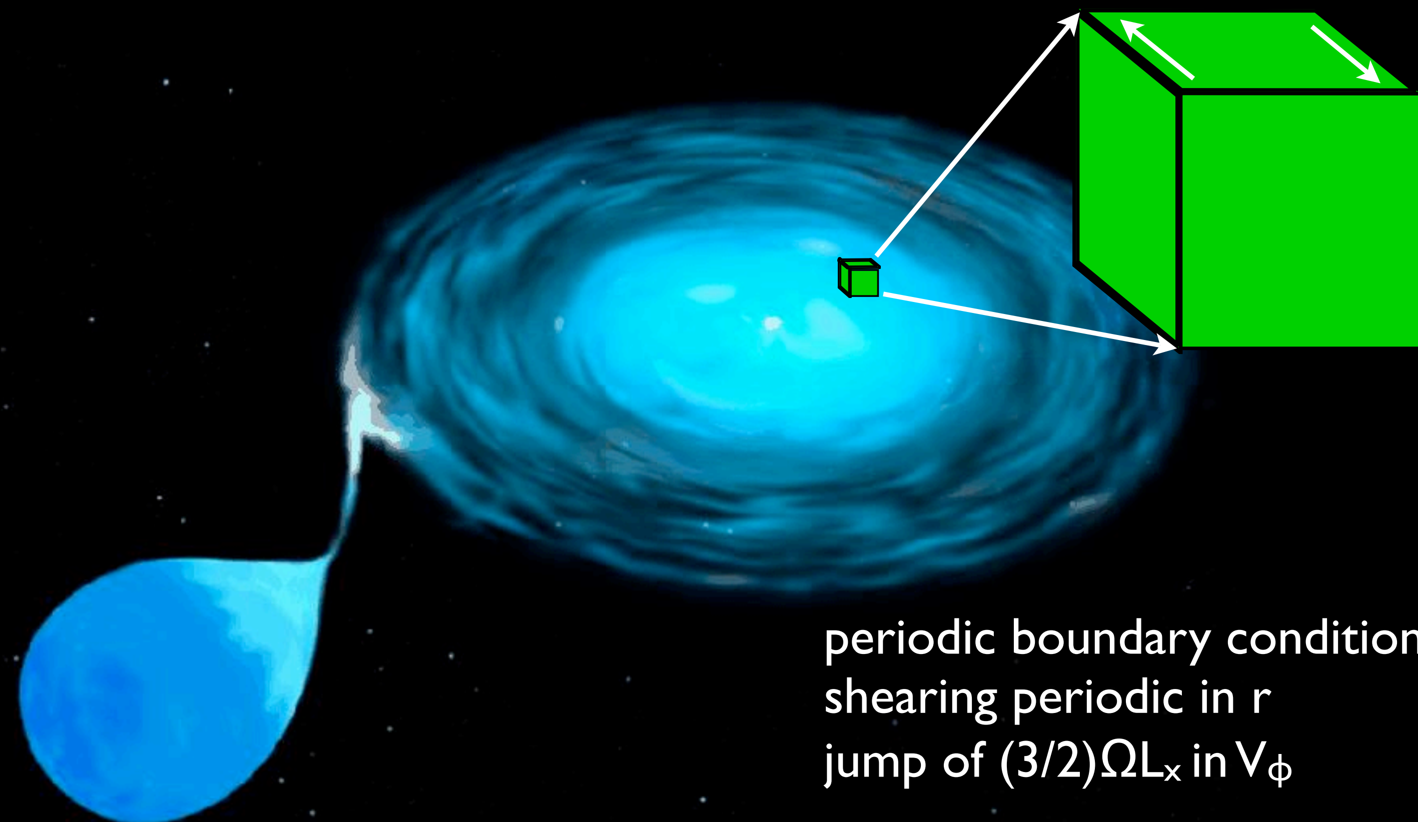




fastest growing mode twice faster than in MHD, at much larger scales

collisionless damping, large scale dissipation $dv_\parallel/dt = -\mu\nabla_\parallel B + eE_\parallel/m$
[Quataert et al. 2002; Sharma et al. 2003; Balbus 2004]

Shearing-box sims.

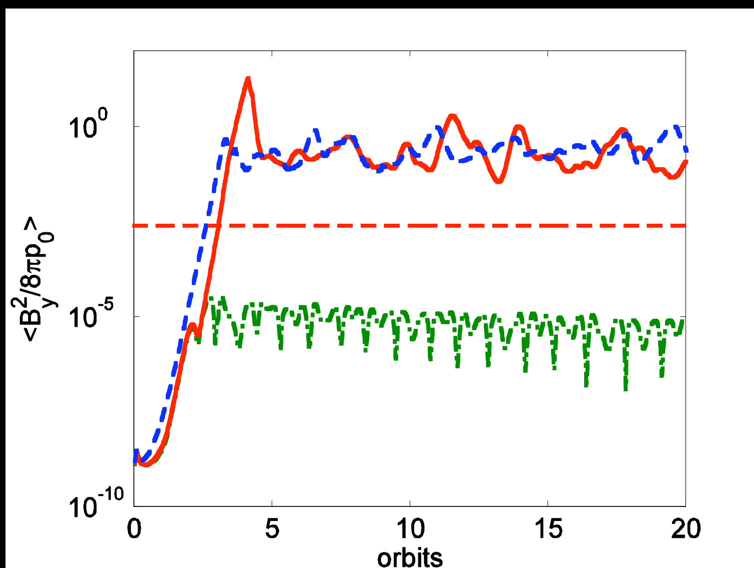


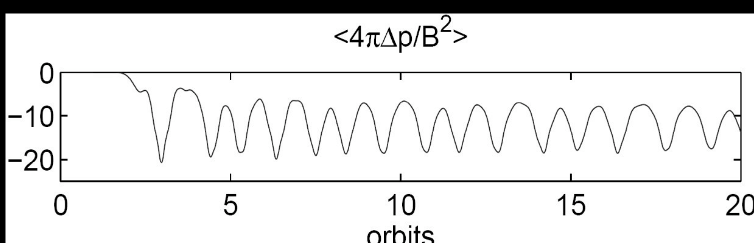
periodic boundary conditions in ϕ, z

shearing periodic in r

jump of $(3/2)\Omega L_x$ in V_ϕ

Δp due to MRI





$$B.\nabla B \longrightarrow \left(1 - \frac{(p_{\|} - p_{\perp})}{B^2}\right) B.\nabla B$$

pressure anisotropy ($p_\perp > p_{||}$) as B ↑

$\mu \propto \langle v_\perp^2 \rangle / B \propto p_\perp / B = \text{const.}$

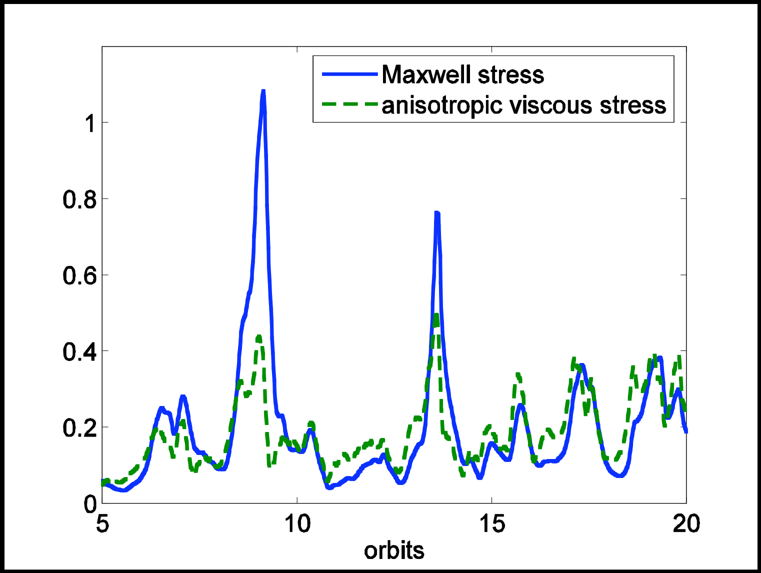
pressure anisotropy can stabilize MRI modes

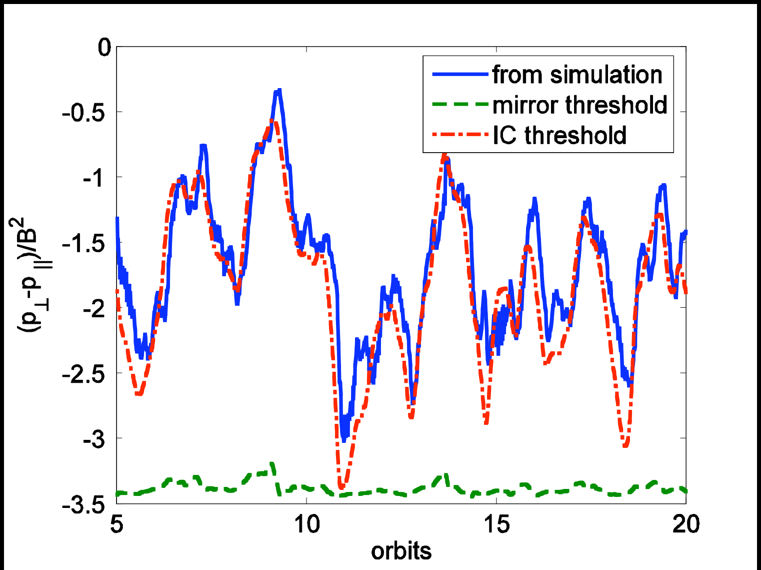
How large can pressure anisotropy become? Anisotropy driven instabilities: mirror, ion cyclotron, etc.

$\Delta p/p \approx O(1)/\beta$, $\beta = 8\pi p/B^2 \sim 1\text{-}100$

Microinstabilities => MHD like dynamics

Pressure anisotropy

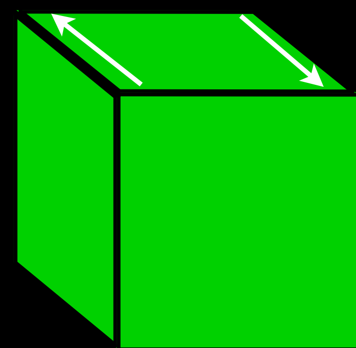




anisotropic stress ~ Maxwell stress (can dominate at β>>1)
anisotropic pressure => 'viscous' heating (due to anisotropic stress) at large scales

ion pressure anisotropy limited by IC instability threshold (with $\gamma/\Omega \sim 10^{-4}$)
Will electrons also be anisotropic? Yes, collision freq. is really tiny
electron pressure anisotropy reduced by electron whistler instability

Shearing-box energetics



work done by anisotropic viscous stress (~50% of energy added to SB)

↓

direct plasma heating at box-size scales

↓

viscous heating of electrons & ions

work done by Maxwell & Reynolds stresses

↓

converted to MHD motions (δV^2,δB^2)

↓

collisionless damping at large scales; nonlinear cascade to small scales

↓

dissipation at Larmor radius scales

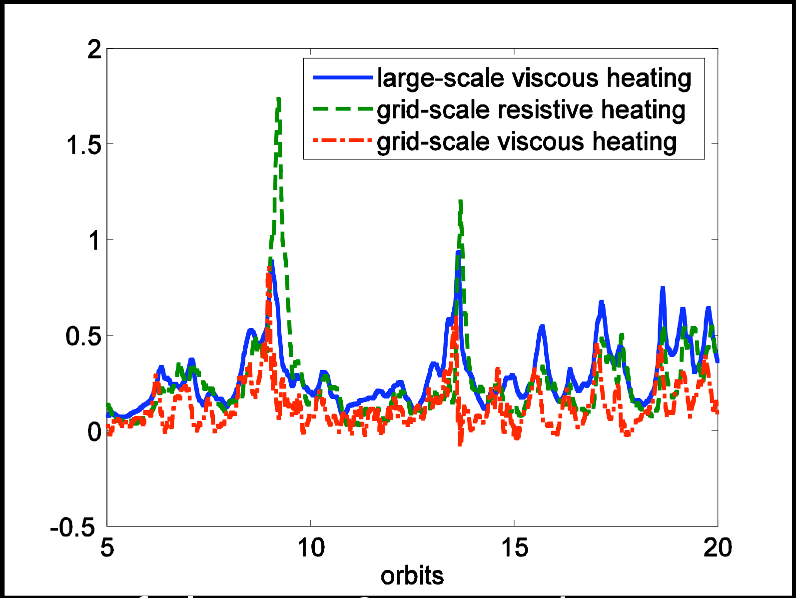
↓

resistive losses at plasma skin depth

$k^{-5/3}$

poorly understood

Electron heating



Ratio of electron & proton heating rates

In sims. anisotropic heating numerical losses => half the energy is captured as heating due to anisotropic pressure

Form of pressure anisotropy threshold from full kinetic theory for both electrons & ions:

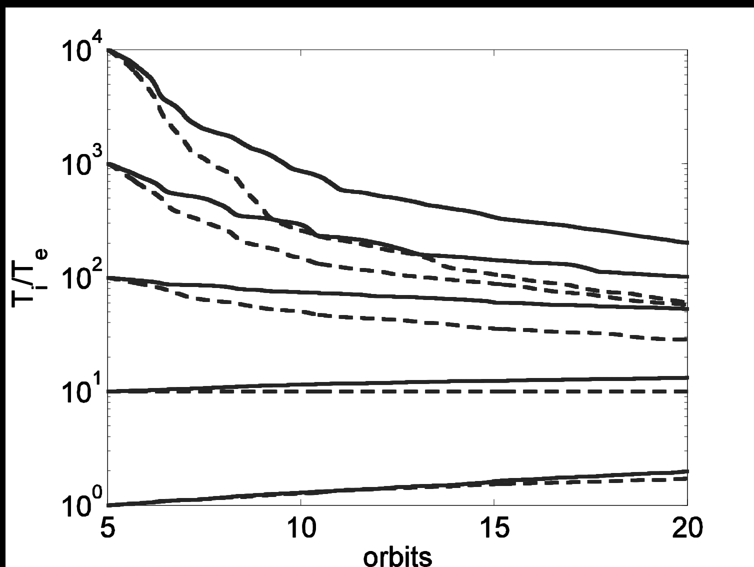
$$\frac{p_\perp}{p_\parallel} - 1 = \frac{S}{\beta^\alpha}$$

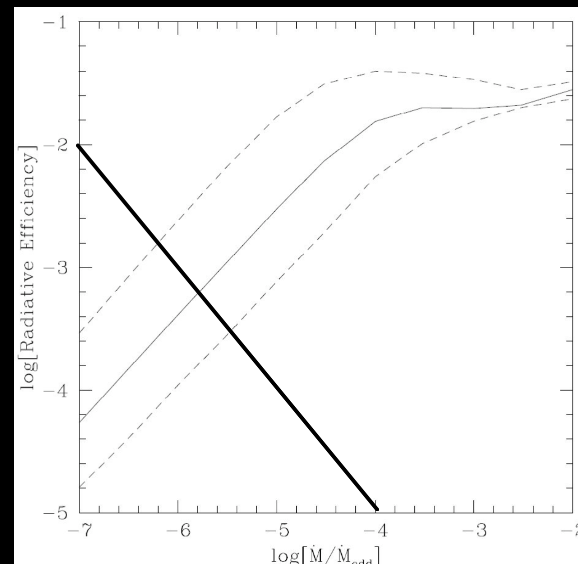
$\alpha \sim 0.5$, $S_e \sim 0.4\, S_i$ for ion cyclotron/electron whistler instabilities =>significant electron heating (compare with Braginskii where ions are heated preferentially)

$$\frac{q_e}{q_i} = \frac{\Delta p_e}{\Delta p_i} \sim \left(\frac{T_e}{T_i}\right)^{1/2}$$

Results depend on pitch angle scattering thresholds (which are fairly well-tested)

Radiative efficiency



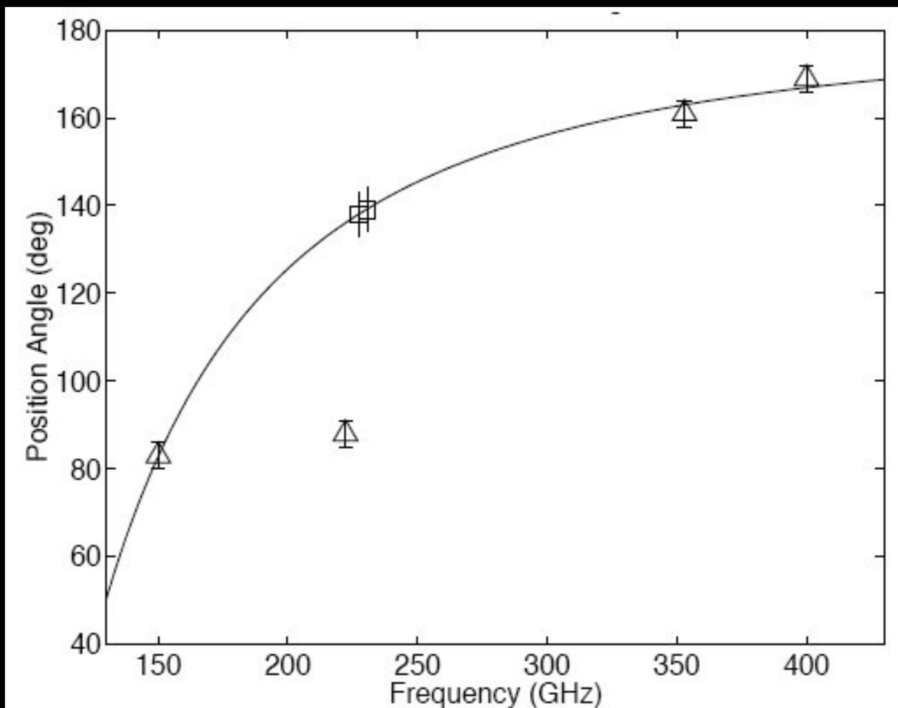


Even if electrons are cold initially, viscous heating will eventually give T_e/T_i~few tens (neglecting synchrotron cooling of electrons)

measured electron temperature ~ $3x10^{10}$ at ~ 24 r_S *[Bower et al. 2004]*

Electrons somewhat radiatively efficient w. η~10^{-3} & $\dot{M}$~$10^{-7}M_\odot$/yr consistent with Faraday RM observations

RM observations



[Bower et al. 2003]

Constrains accretion flow:

Faraday rotation measurements

polarization angle rotated in a non-relativistic plasma

$\theta=\theta_0+RM\lambda^2$, $RM \sim nB_{||}r$

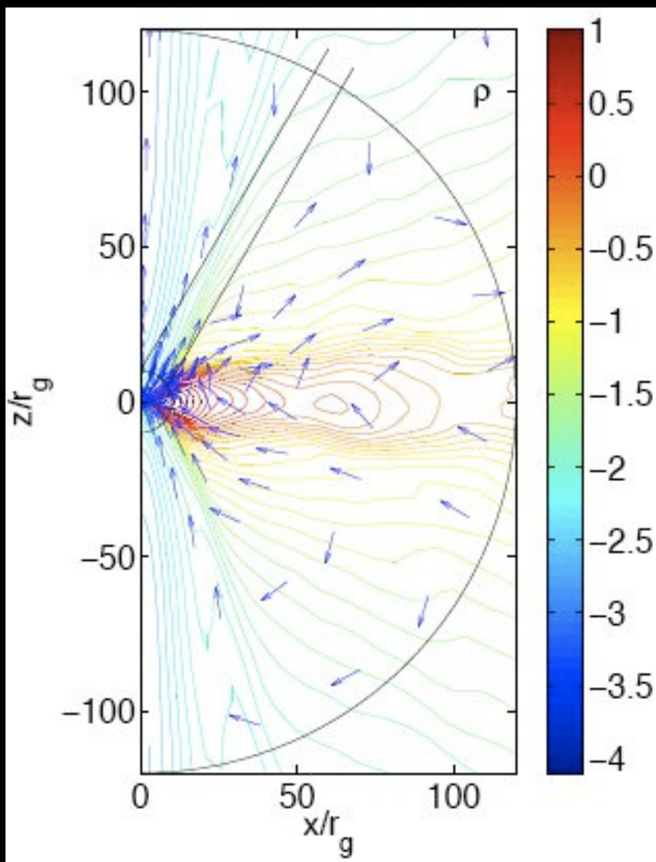
RM=-6x10^5 rad/m^2 stable over 8 years!

too small compared to Bondi estimate

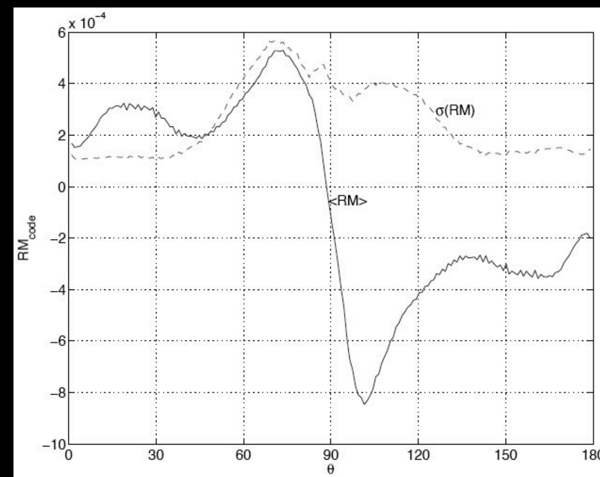
=> $\dot{M}_{in} << \dot{M}_{Bondi}$

all available mass is not accreted; outflows reduce accretion rate

RM simulations



[Sharma et al. 2007]



begin with rotating, magnetized, torus

MRI turbulence => torus accretes to form a quasi-steady Keplerian disk

equatorial viewing angles are variable, unlike polar

we may be looking through the poles! (if there is a large scale field), or

RM is dominated by larger radii

Conclusions

- pressure anisotropy natural as μ conserved
- scattering due to microinstabilities
- anisotropic stress ≈ Maxwell stress
- significant e^- heating => radiative (ADAF w. $\eta \sim 10^{-5}$ ruled out)
- $\dot{M} \ll \dot{M}_{Bondi}$ for low luminosity
- consistent with RM observations & RM sims
- steady RM if viewing through poles