# Electron Heating in (Hot) Accretion Flows

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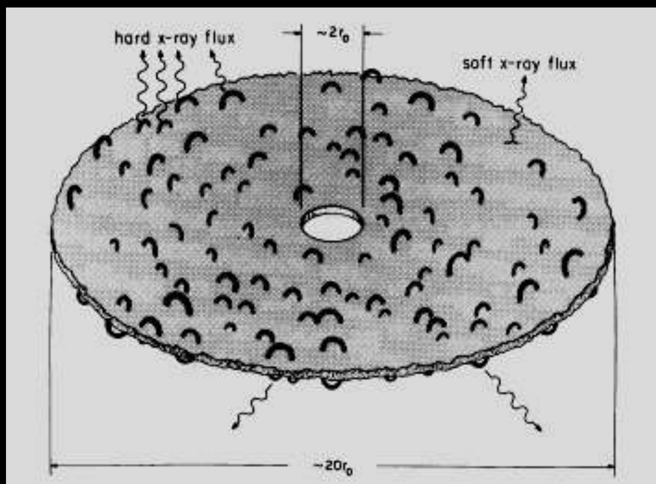
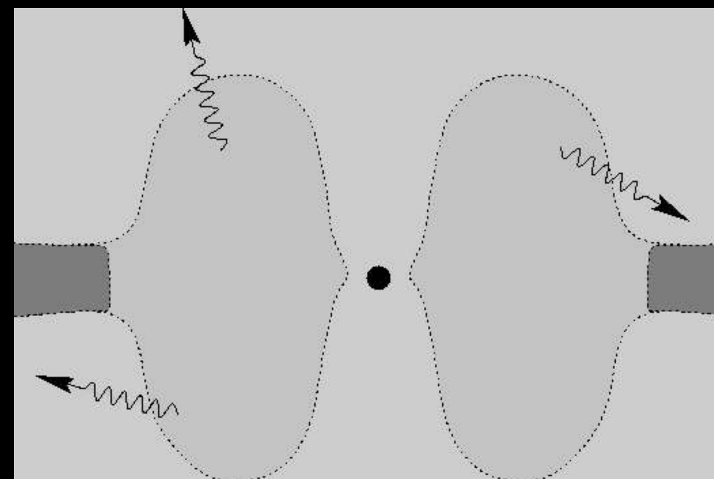
(work done in collaboration with Eliot Quataert, Greg Hammett, & Jim Stone)

# Outline

- Accretion in hot/cold disk regimes
- Hot accretion flows, e.g., Sgr A*
- Hot, dilute => collisionless
- Kinetic-MHD model for collisionless plasma
- Local shearing box sims. of collisionless MRI => $\alpha$, $q^+_e/q^+_i$
- Calculate $\eta$ (& $\dot{M}$) in 1-D models
- Conclusions & Future work

# Modes of Accretion



- Thin, dense (optically thick) disk *[S&S]*
- local BB: $GM\dot{M}/2r \approx 4\pi r^2 \sigma T^4$ ($T_e = T_i$)
- high/soft state

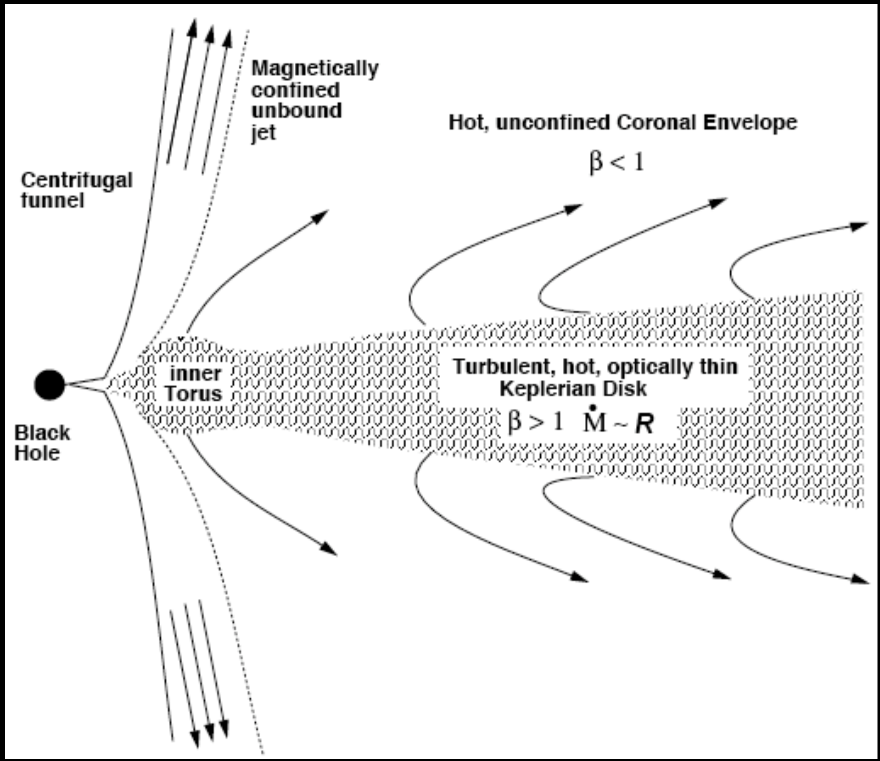
- Low density => no cooling => hot, thick (optically thin), collisionless disk *[RIAF, ADAF]*
- detailed electron heating/cooling ($T_e < T_i$) for radiation
- low/hard state

# Accretion Luminosity

- Standard model: $L=\eta \dot{M} c^2$, $\eta$(BH spin)
- $\eta \sim 0.1$ for thin disks
- For Sgr A*, $L_{obs} << 0.1 \dot{M}_{Bondi} c^2$ => $\eta << 1$ or/and $\dot{M} << \dot{M}_{Bondi}$?? observational degeneracy
- $\eta$(electron heating/cooling) in RIAFs

# Electron Heating

- $e^-$s lighter => radiate (from radio to X-rays)
- thin disk steady BB vs. thick disk non-BB
- $\beta$<1 corona/jet => $e^-$ acc., X-ray by IC, radio from jet
- thermal $e^-$ heating in thick disks due to MRI turbulence (this talk); well posed idealized problem
- $e^-$ acc. in corona much more difficult to understand!




*[from Balbus 2003]*

# Sgr A*

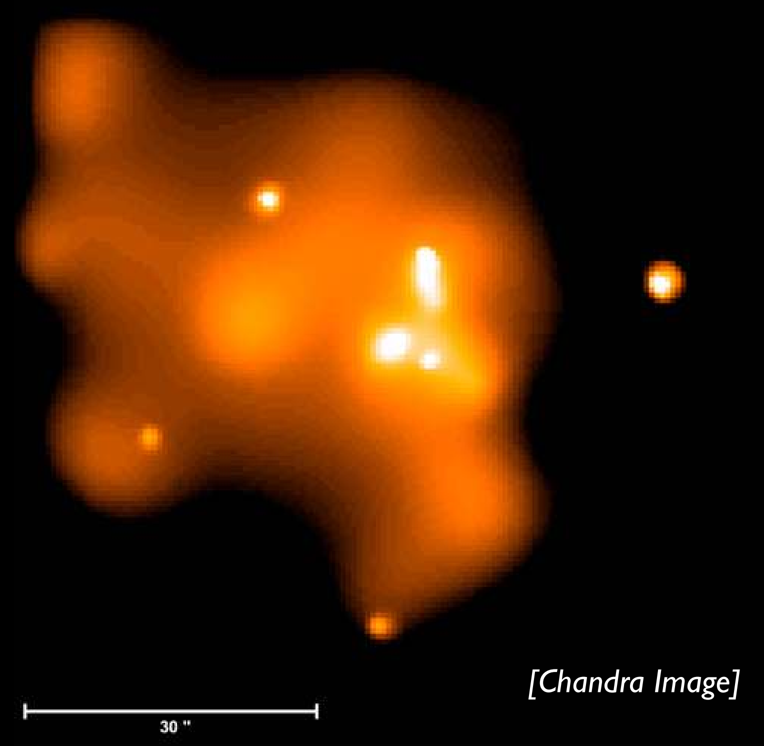
$4 \times 10^6\ M_\odot$ black hole

$r_{Bondi}$~0.1 pc (2"), n~100 $cm^{-3}$, T~1.2 keV
*[Baganoff et al. 2003]*

$\dot{M}_{Bondi}$~$10^{-5}\ M_\odot$ /yr fed by colliding massive stellar outflows

$L_{obs}$~$10^{36}$ erg/s ~$10^{-5}$ x (0.1 $\dot{M}_{Bondi}c^2$)

mfp ($\propto T^2/n$) ~ $r_{Bondi}$ => collisionless at small r, where most energy is released




*[Chandra Image]*

# Drift Kinetic Equation

plasma is collisionless, hot, H~r

$\rho_{i,e} << H\sim r << \lambda_{mfp}$

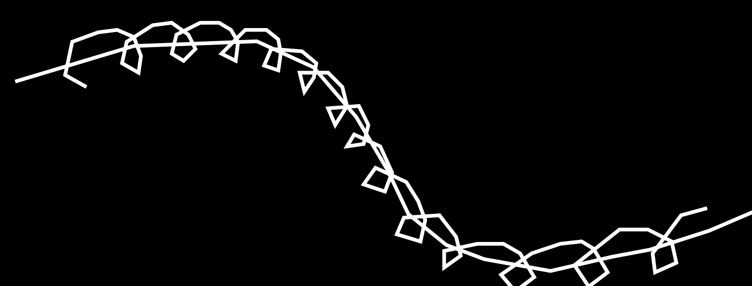
drift kinetic equation: approx. for Vlasov eq. if $k\rho_i<<1$, $\omega<<\Omega_i$, averaging over fast gyromotion =>

Table 1.2: Plasma parameters for Sgr A*

| Parameter | $r = r_{acc}$ $2.2\times10^{17}$ cm | $r=\sqrt{r_{acc}R_S}$ $4.2\times10^{14}$ cm | $r = R_S$ $7.8\times10^{11}$ cm |
|---|---|---|---|
| $\nu_{i,\mathrm{ADAF}}/\Omega_K \sim r^{3/2}$ | 11.4 | $9.4\times10^{-4}$ | $7.6\times10^{-8}$ |
| $\nu_{i,\mathrm{CDAF}}/\Omega_K \sim r^{3/2+p}$ | 11.4 | $1.81\times10^{-6}$ | $2.62\times10^{-13}$ |
| $\rho_{i,\mathrm{ADAF}}/H \sim r^{-1/4}$ | $2\times10^{-11}$ | $9.94\times10^{-11}$ | $4.59\times10^{-10}$ |
| $\rho_{i,\mathrm{CDAF}}/H \sim r^{-1/4-p/2}$ | $2\times10^{-11}$ | $2.23\times10^{-9}$ | $2.48\times10^{-7}$ |

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

$f(x,v_{||},\mu)$ in 5-D phase space!
$V_E=c(E\times B)/B^2$; $\mu = v_\perp^2/B \propto T_\perp/B$ is conserved



# Kinetic-MHD

moment eqs. similar to MHD

pressure anisotropic wrt B

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

closure problem

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

$q \approx -n v_t^2 \nabla_{||} T / (k_{||} v_t + \upsilon)$ *[Snyder et al. 1997]*

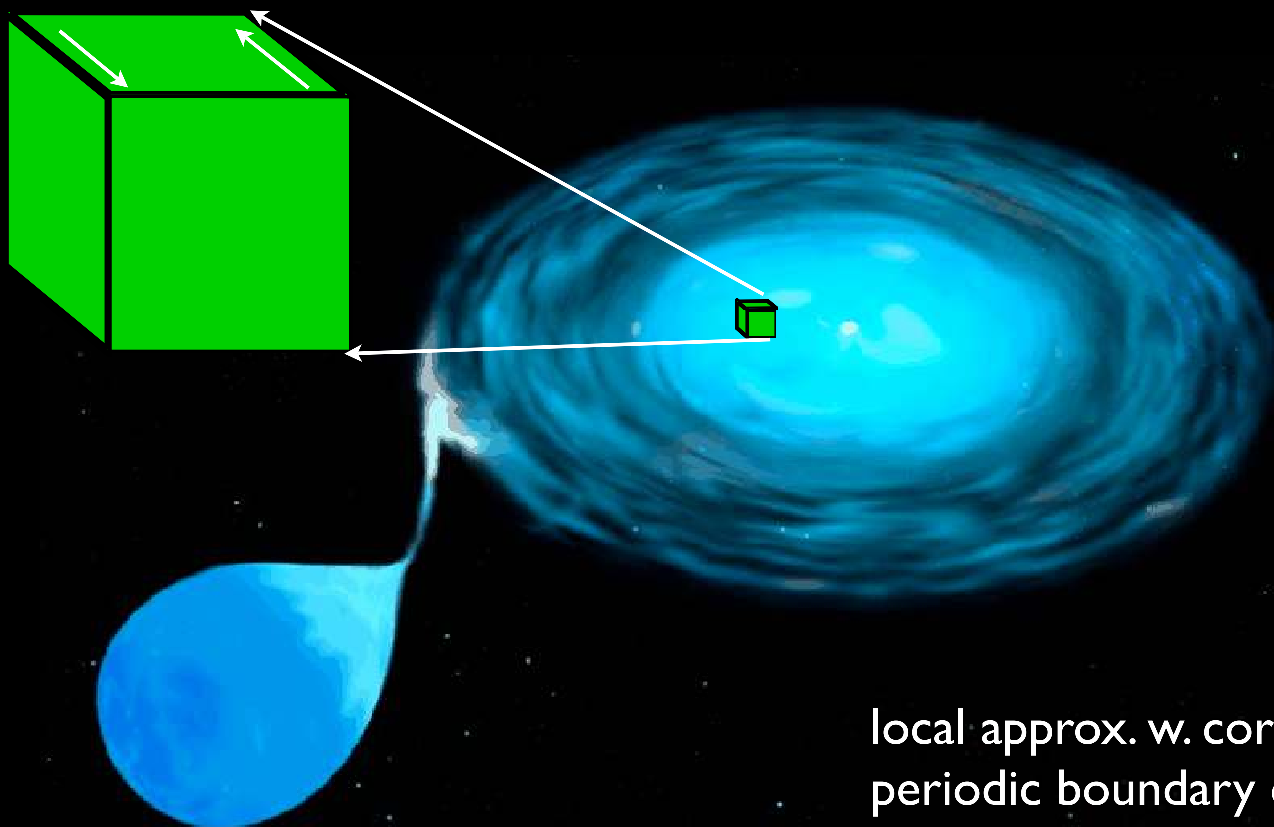
like saturated conduction *[McKee & Cowie]*
free-streaming particles carry heat

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

includes collisionless effects like Landau damping

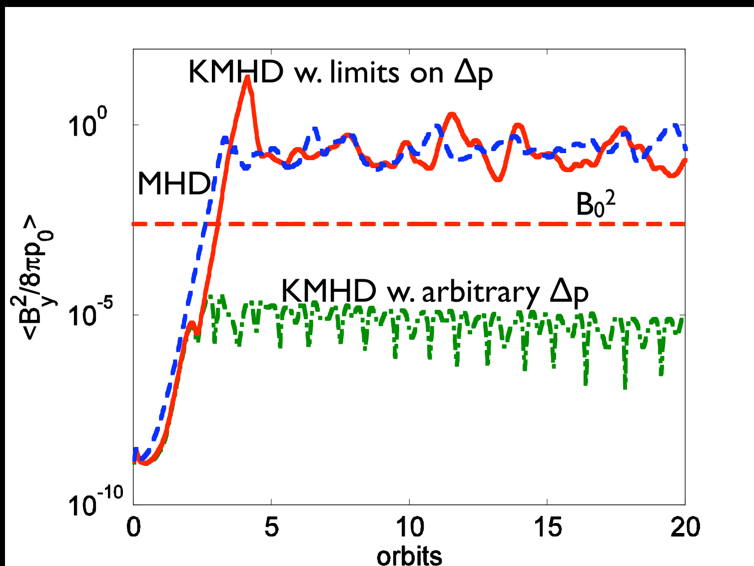
=> as B ↑, $p_\perp$ ↑ & $p_{||}$ ↓; $\Delta p$ natural

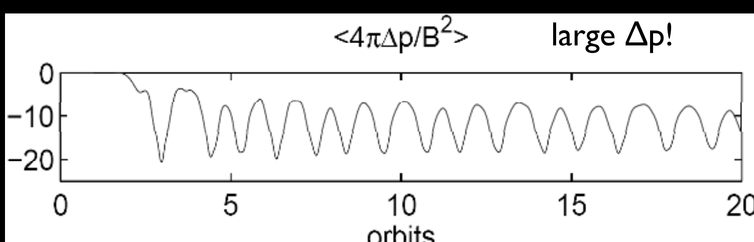
# Shearing-box sims.



local approx. w. coriolis/tidal forces
periodic boundary conditions in $\phi$, z
shearing periodic in r
jump of $(3/2)\Omega L_x$ in $V_\phi$
sims. w. a net vertical flux!

# 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 stabilize resolved MRI modes when Δp arbitrary

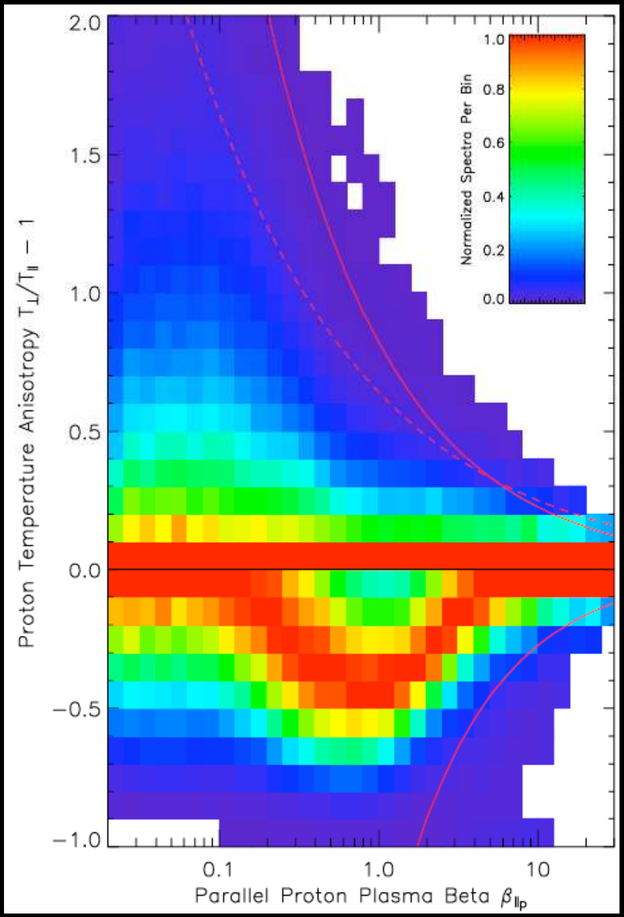
How large can pressure anisotropy become? Anisotropy driven instabilities: mirror, ion cyclotron, etc.

$|\Delta p/p| \simeq 0.5/\beta^{1/2}$ , $\beta = 8\pi p/B^2 \sim 10\text{-}100$

Microinstabilities => MHD like dynamics

# Δp limits

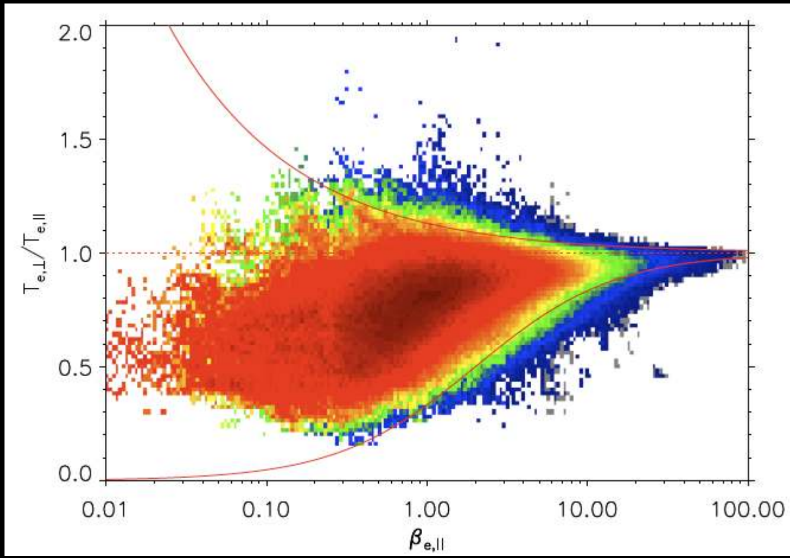
Protons; *[Kasper et al. 2003]*




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

S≈0.5, α≈0.5 for relevant instabilities

Electrons; *[S. Bale]*




Pressure anisotropy reduced by Larmor-scale instabilities (not captured by DKE); thus subgrid models for instabilities:

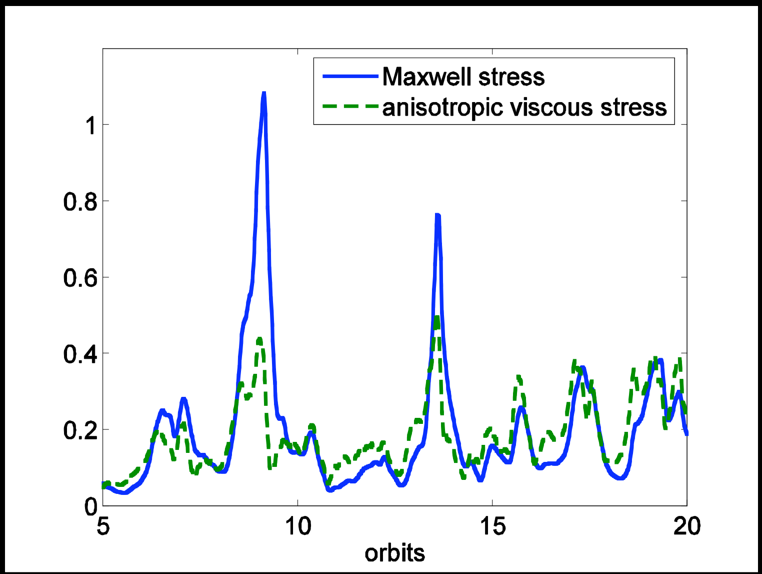
protons: ion-cyclotron, mirror ($p_\perp > p_\parallel$)

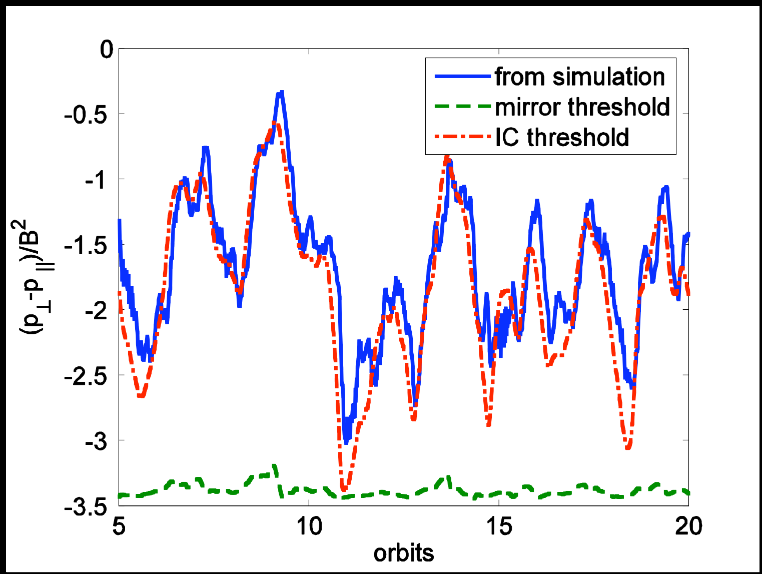
electrons: electron-whistler ($p_\perp > p_\parallel$)

firehose for ($p_\perp < p_\parallel$)

agree with kinetic PIC simulations *[Gary et al.]*

# Stress due to Δp




anisotropic stress [$\Delta p b_r b_\varphi$] ~ Maxwell stress [$-B_r B_\varphi/4\pi$]

$\alpha \approx 0.5$; quite large!

anisotropic pressure => 'viscous' heating ($T_{r\varphi} d\Omega/d\ln r$ due to anisotropic stress) at large scales => this goes directly into internal energy!

ion pressure anisotropy limited by IC instability threshold

Will electrons also be anisotropic? Yes, collision freq. is really tiny

electron pressure anisotropy reduced by electron whistler instability

# Transport/heating by Δp

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

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

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

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

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

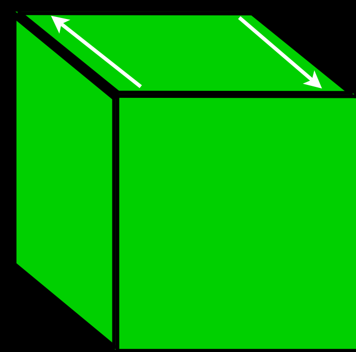
In collisional regime ($\upsilon$>>k$v_t$), Δp reduced by Coulomb collisions

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

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

Δp reduced by scattering by small scale instabilities

# 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

↓

$k^{-5/3}$

converted to MHD motions ($\delta V^2, \delta B^2$)

↓

collisionless damping at large scales; nonlinear cascade to small scales

↓

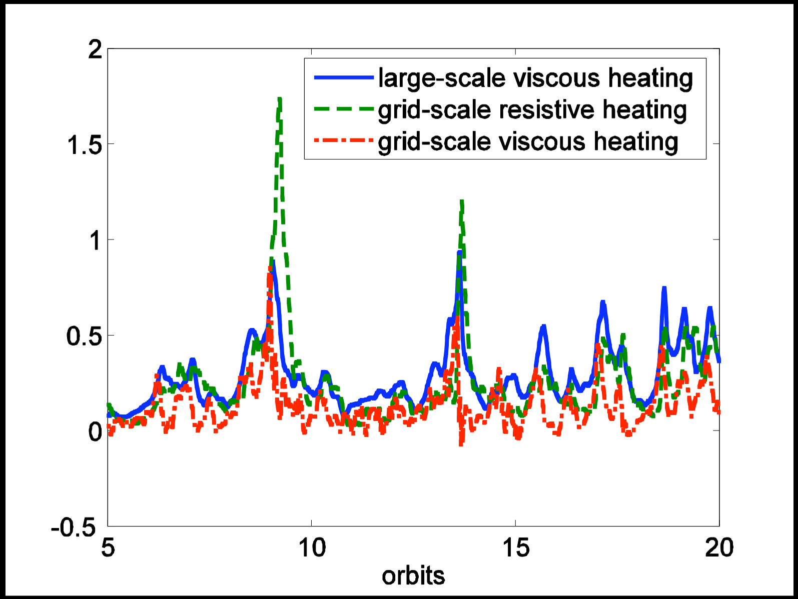
dissipation at Larmor radius scales

↓

resistive losses at plasma skin depth

poorly understood; appears in simulations as grid scale dissipation; $e^-$s or ion heating?? non-thermal particles??

# Electron heating




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:

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

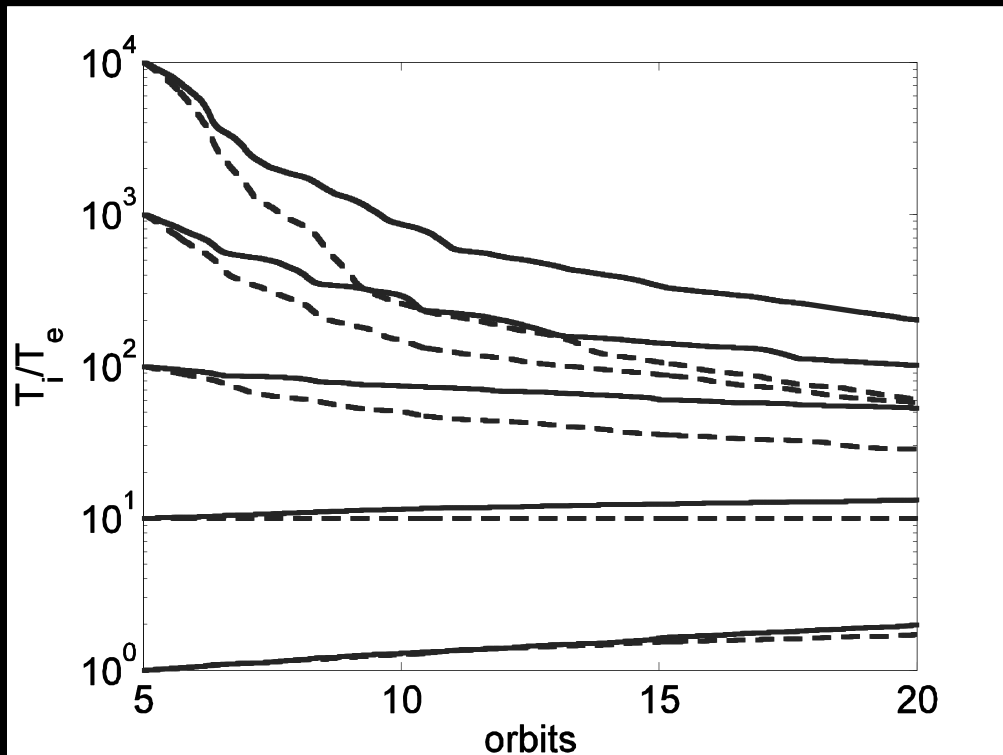
Ratio of electron & proton heating rates ($q_e/q_i$, a key qty. in ADAF models)

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

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

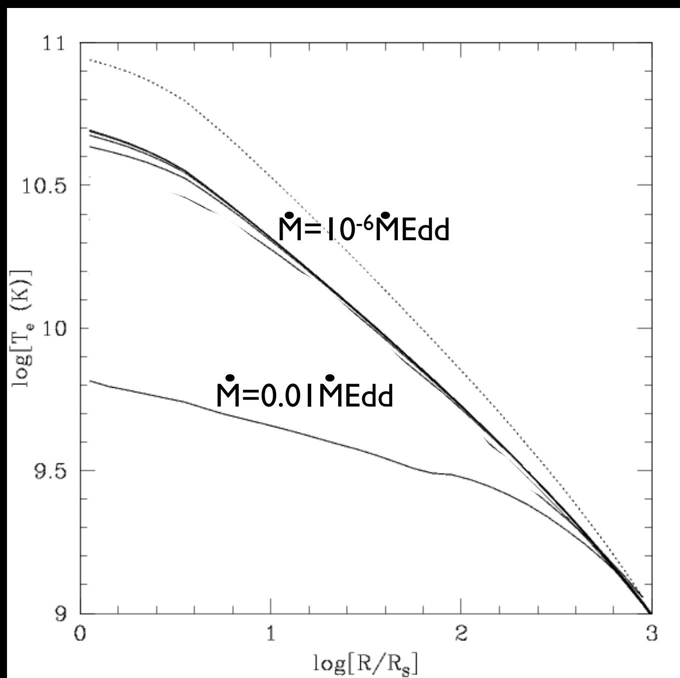
Results depend on pitch angle scattering thresholds (which are well-tested in the Solar Wind)

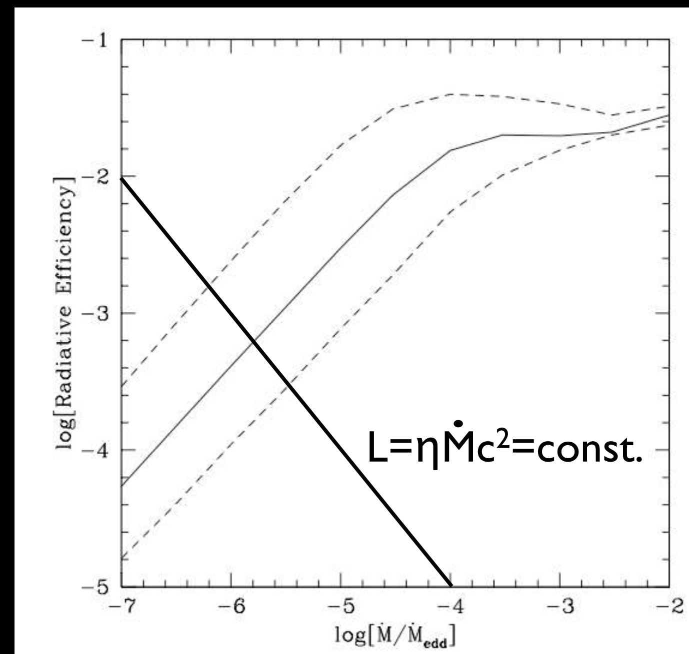
# Electron Temperature




Even if electrons are cold initially, viscous heating will eventually give $T_e/T_i \sim 1/$(few 10s) [synchrotron cooling of $e^-$s not included in sims]

# Putting SB in 1-D model




measured electron temperature ~ $3\times10^{10}$ at ~ 24 $r_S$ *[Bower et al. 2004]*

Electrons quite radiatively efficient w. $\eta\sim10^{-3}$ & $\dot{M}\sim10^{-7}M_\odot$/yr

consistent with Faraday RM observations which give $\dot{M} \ll \dot{M}_{Bondi}$ *[Bower, Marrone, et al.]* & with global MHD sims.

# Conclusions

- pressure anisotropy natural as $\mu$ conserved
- scattering due to microinstabilities
- anisotropic stress ≈ Maxwell stress
- significant $e^-$ heating => hot $e^-$s ($\eta \sim 10^{-5}$ ruled out)
- $\dot{M} \ll \dot{M}_{Bondi}$ for low luminosity; consistent with rotation measure toward Sgr A*

# Future Work

- Global simulations w. anisotropic pressure & thermal conduction
- 2-species treatment for $e^-$s and ions; mildly relativistic EOS for $e^-$s; simple radiation model
- Diagnosis of energy flow; phenomenological models of flaring
- Direct comparison w. observations (e.g. T[r])
- Non-thermal acc. still unresolved!

The End