Electron heating and heat transport in collisionless accretion disks

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Outline

- When are accretion disks considered collisionless?
- Physical characterization of these disks: pressure anisotropies and kinetic plasma instabilities.
- Nonlinear studies of the kinetic plasma instabilities using particle-in-cell (PIC) plasma simulations.
- Importance for electron heating and heat transport
- Conclusions

When are accretion disks considered collisionless?

- If the accretion time is much shorter than the collision time between particles ($\tau_{accretion} << \tau_{collision}$), the disk can be considered collisionless This is expected to occur when $L << L_{Eddington}$.

- Most supermassive black holes at the center of nearby galaxies (e.g. Ho 2009)

- Some states of galactic X-ray binaries (low-hard state), and in some accreting neutron stars.

- And in Sgr A*, at the center of our galaxy

Physical characterization

- Particles tend to stay out of thermal equilibrium: $T_e << T_i$ (electrons cool faster and ions are main carriers of gravitational potential energy).

  Thus understanding heating (energy dissipation) and heat transport is crucial (e.g., for the Event Horizon Telescope).

- But kinetic plasma effects (that depend on the velocity distribution of particles) are expected to play a role in regulating these properties (somehow mimicking the effect of collisions).

- In particular, a key role is played by kinetic instabilities, caused by pressure anisotropies in the plasma.

- Pressure anisotropies are naturally expected due to the conservation of the magnetic moment of particles:

$$\mu = v_\perp^2/B$$

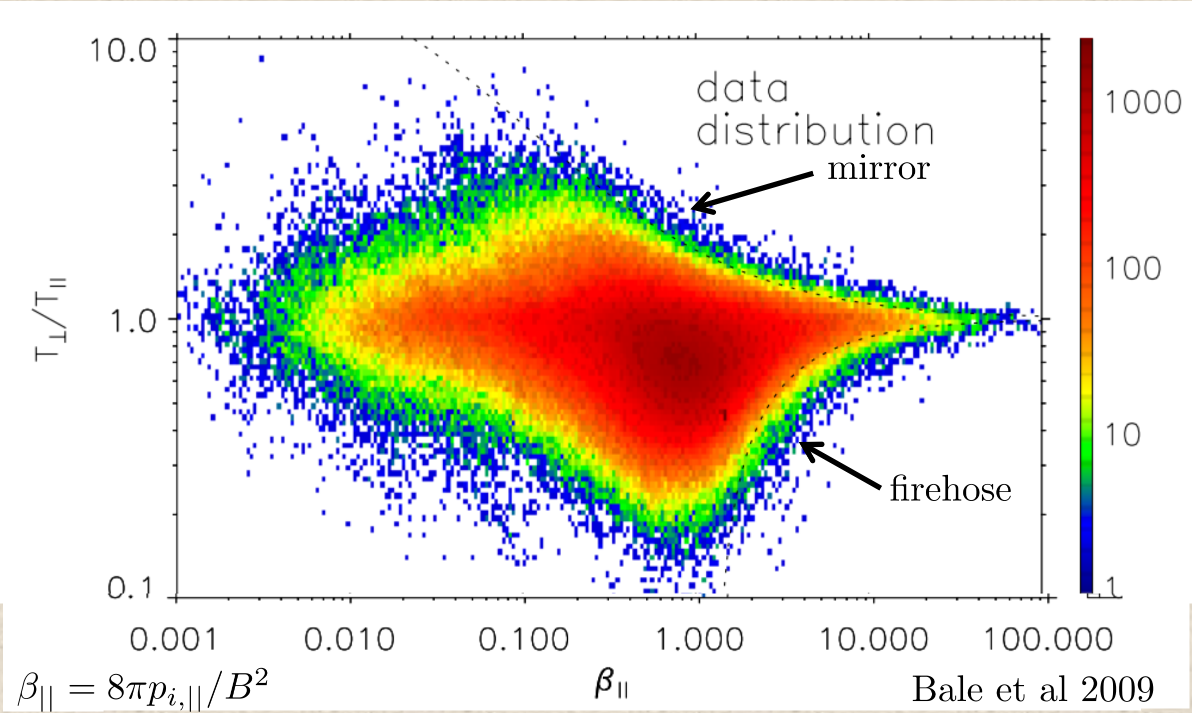
- Thus, if the magnetic field B grows, there will be a trend for

$$p_\perp > p_{||} \text{ (with respect to } \vec{B})$$

Physical characterization

Examples of kinetic instabilities: The mirror instability (for ions and $p_{i,\perp} > p_{i,||}$)
The firehose instability (for ions and $p_{i,\perp} < p_{i,||}$)
The whistler instability (for electrons and $p_{e,\perp} > p_{e,||}$)

In the solar wind:



$\beta_{||} = 8\pi p_{i,||}/B^2$

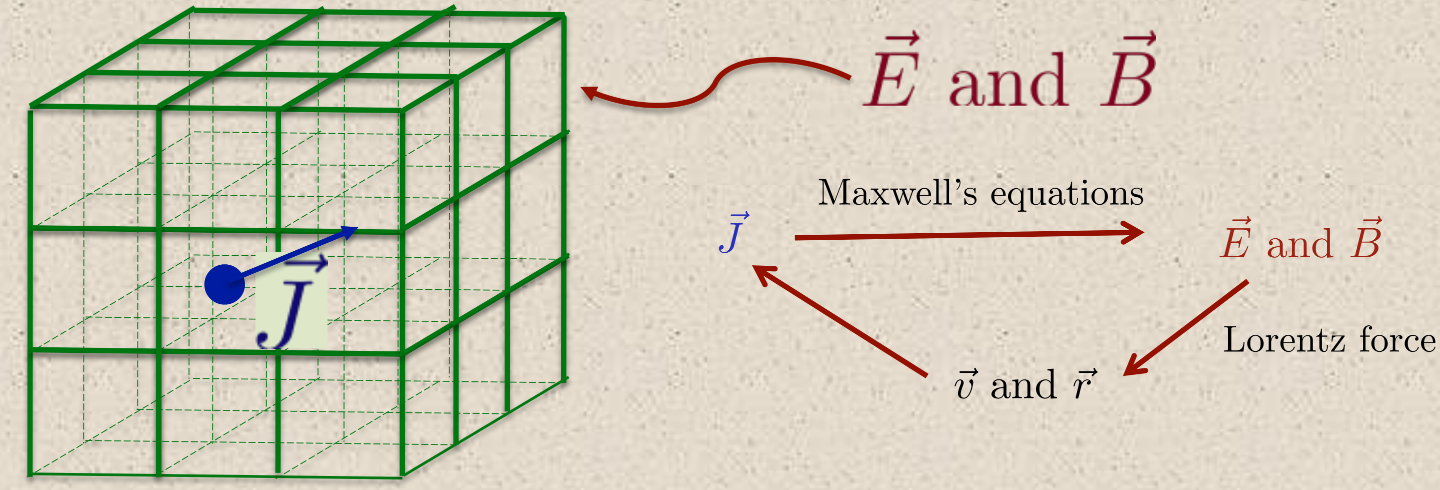
Bale et al 2009

Instabilities produce pitch-angle scattering that mimic the role of collisions. Therefore, they regulate processes like energy dissipation (heating) and the heat transport (mean free path) of particles.

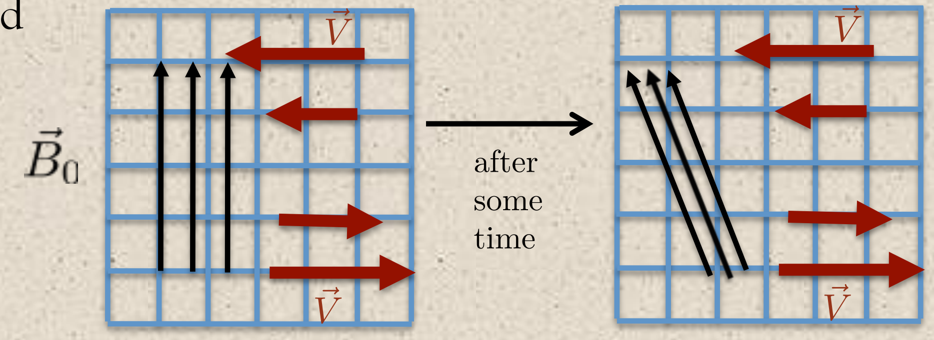
However, most previous studies apply to the linear regime → a nonlinear study (using simulations) is needed.

Nonlinear study using PIC

- We will use particle-in-cell (PIC) plasma simulations to study the nonlinear behavior of the kinetic instabilities, and to understand how they regulate particle heating and heat transport in the plasma.



B amplification is achieved by mimicking a shear motion in the plasma (characteristic of incompressible MHD turbulence or instabilities like the MRI).



This set up makes

$$p_{j,\perp} > p_{j,||}$$

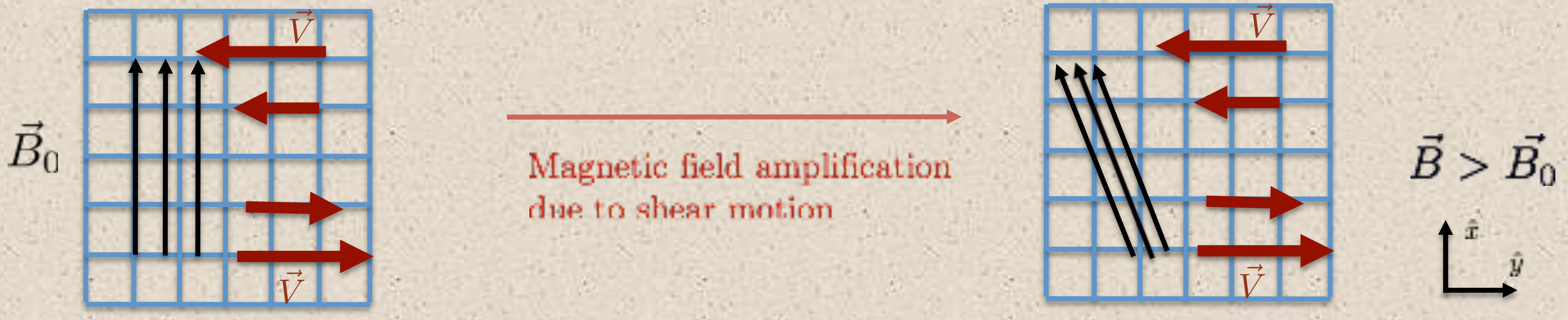
due to conservation of

$$\mu_j = v_{j,\perp}^2/B$$

with *j*=*i*,*e*.

(simultaneously)

Nonlinear study using PIC



Magnetic field amplification
due to shear motion

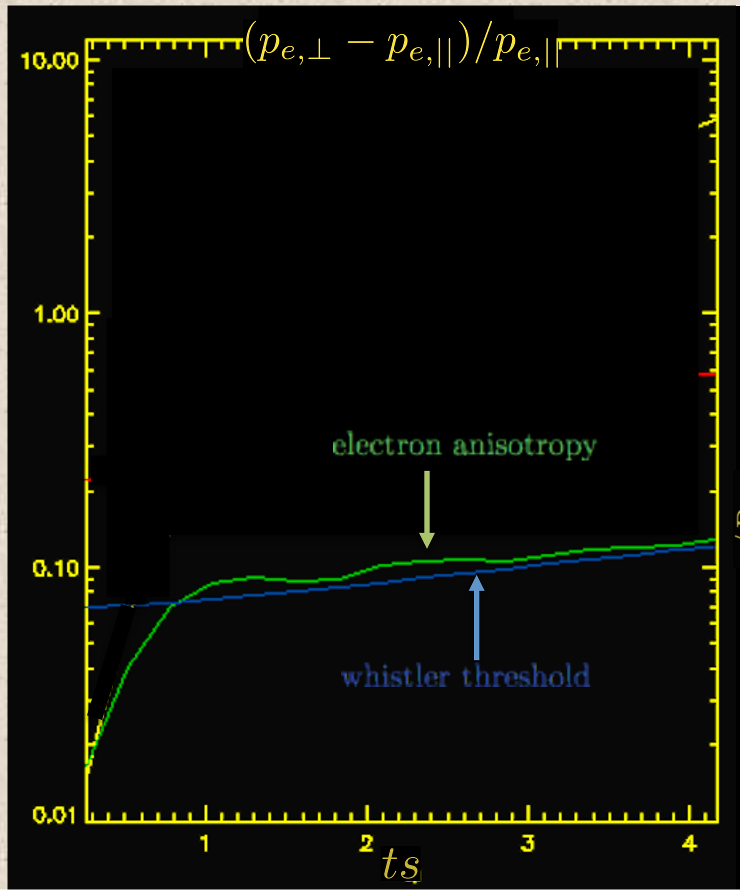
Whistler instability

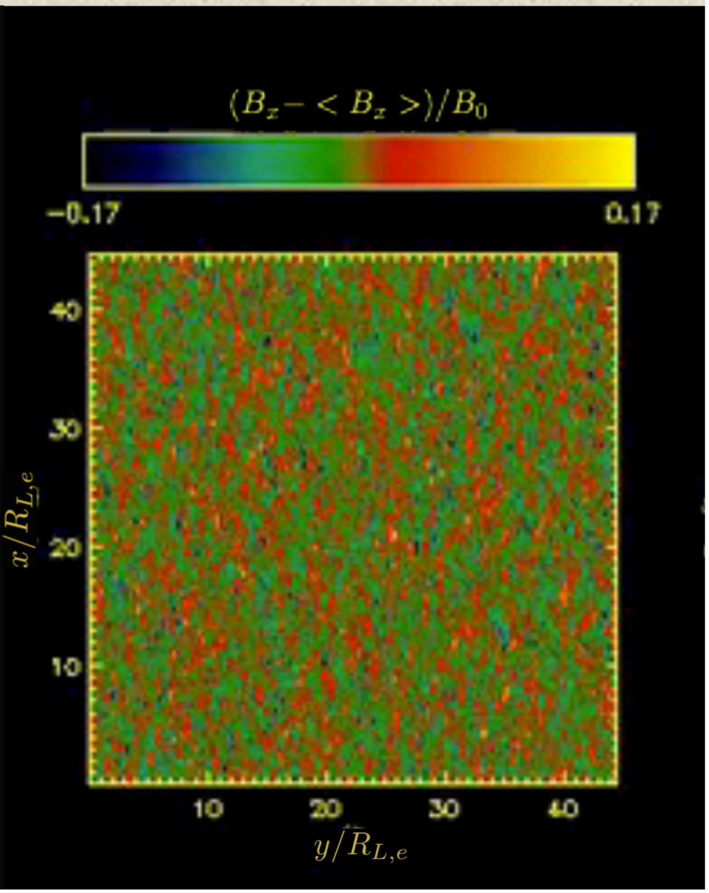
$kR_{L,e} \sim 1,\ \vec{k}||\vec{B}_0$

$m_i/m_e = \infty$

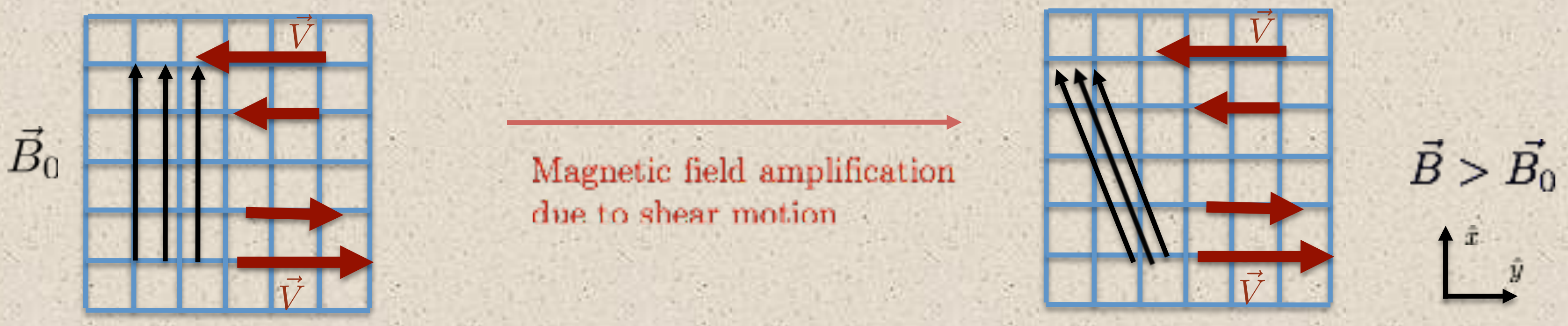
(only electron-scale
instabilities allowed)

Electron anisotropy is consistent with linear threshold for the whistler instability





Nonlinear study using PIC



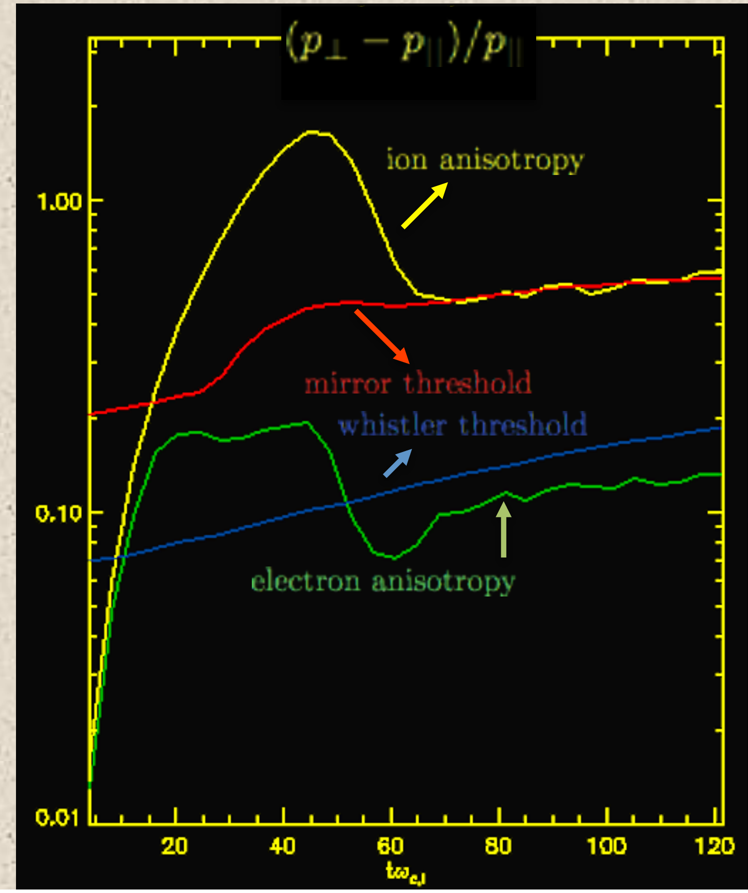
Magnetic field amplification due to shear motion

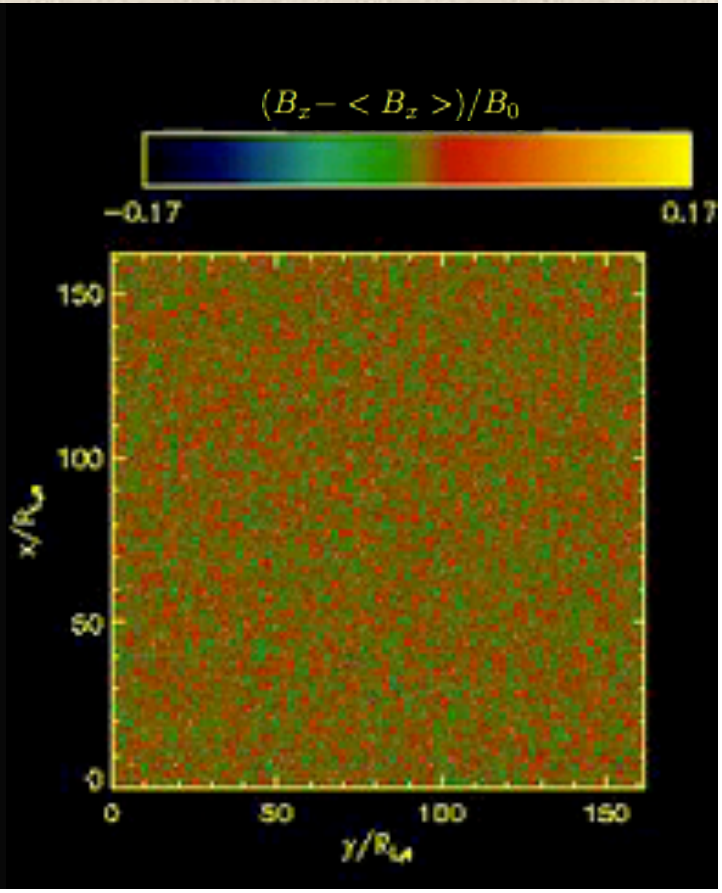
Mirror instability & **whistler instability**

Mirror: oblique modes with $kR_{L,i} \sim 1$

$m_i/m_e = 128$
(Ion and electron scale instabilities are allowed)

Due to the mirrors, the electron anisotropies are a factor ~2 smaller than the linear whistler threshold



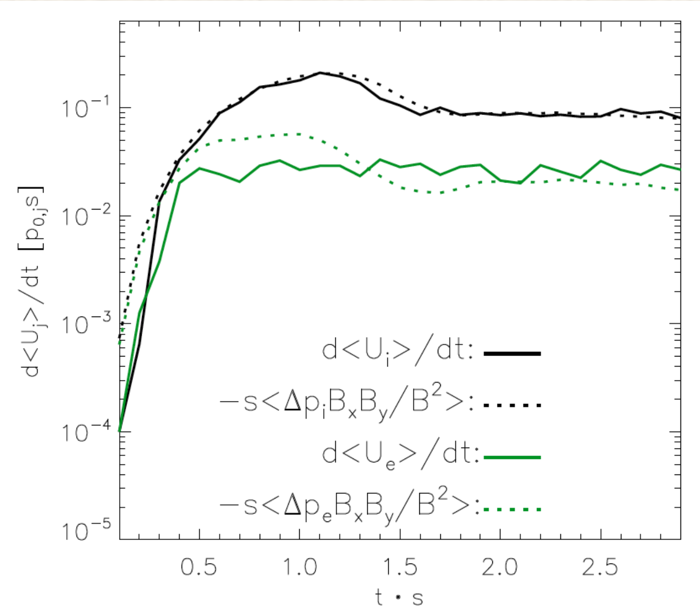


Importance for heating and heat transport

Checking anisotropic viscosity directly from the simulations:

$$\frac{\partial E_j}{\partial t} = (p_{j,\perp} - p_{j,||})\hat{b}_i\hat{b}_j\partial_i V_j \qquad \hat{b}_i = B_i/B$$

$\vec{V}$: mean velocity of the plasma



(Riquelme et al 2015 - in prep.)

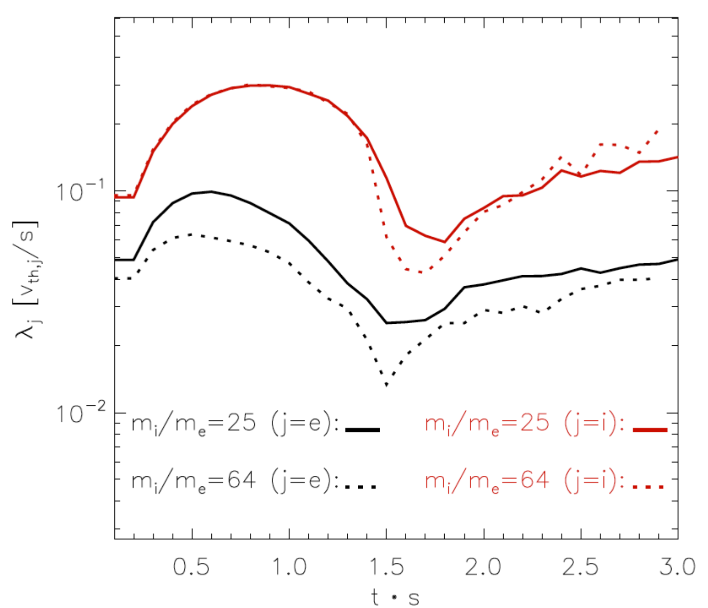
Simulation with $m_i/m_e = 25$ and taking $\vec{V} = -\hat{y}sx$ (s : shear rate)

This heating is relevant in collisionless accretion disks considering the expectation: $T_e \ll T_i$ (electrons cool faster and ions are the main carriers of the gravitational potential energy)

(The viscous heating is complementary to other electron heating mechanisms (like reconnection or wave-particle interactions - see, e.g., Sironi et al 2015))

Importance for heating and heat transport

Measuring the mean free path, λ_j, of the particles:



(Riquelme et al 2015 - in prep.)

$$\lambda_j \approx 0.3\frac{v_{th,j}}{s}\frac{(p_{j,\perp} - p_{j,||})}{p_{j,||}}$$

s is the shear rate in the plasma ($\vec{V} = -\hat{y}sx$).
And $v_{th,j}$ is the thermal velocity of species j.

Conclusions

- Collisionless accretion disks are common (e.g., Sgr A*)
- The temperature ratio between electrons and ions is an open question ($T_e \ll T_i$).
- We explored the role of electron- and ion-scale instabilities driven by pressure anisotropies in the heating of electrons and on heat transport using PIC simulations.
- We found that electron heating by the anisotropic viscosity is quite robust, and it is determined by the combined actions of the whistler and the mirror instabilities.
- The heat transport was quantified by the mean free path of the electrons, which also depends on the electron anisotropy (regulated by the whistler and mirror instabilities)