Particle acceleration by kinetic instabilities in accretion disks:

A particle-in-cell (PIC) simulation study

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CTA Symposium – Bologna, 2019

Motivation:

Low-luminosity accretion disks around **black holes:**
Examples: Sgr A* and M87.

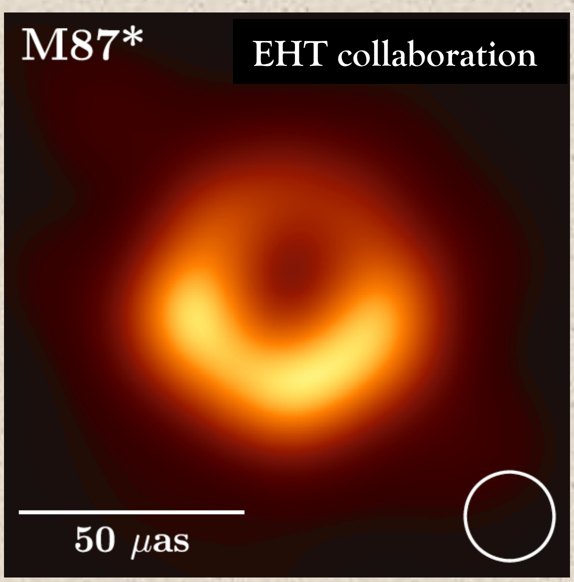
What do they have in common: $\boldsymbol{\tau_{coll} \gg \tau_{accr}}$

$\boldsymbol{\tau}_{coll}$: Coulomb collision time and $\boldsymbol{\tau}_{accr}$: Accretion time of the gas

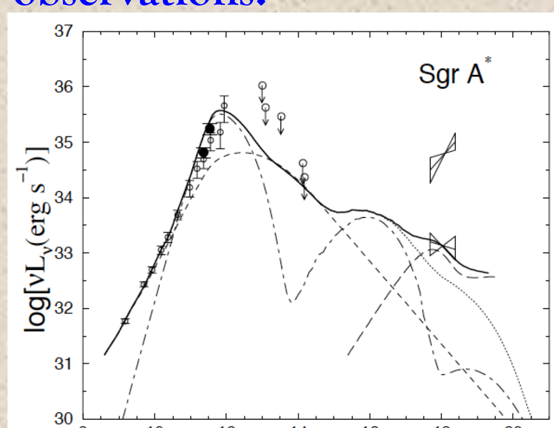
In this **weakly collisional plasmas**, there is **no obvious thermalization mechanism**.
Therefore the evolution of the energy distribution could involve **non-thermal acceleration.**

Relevant for interpreting:

High resolution imaging



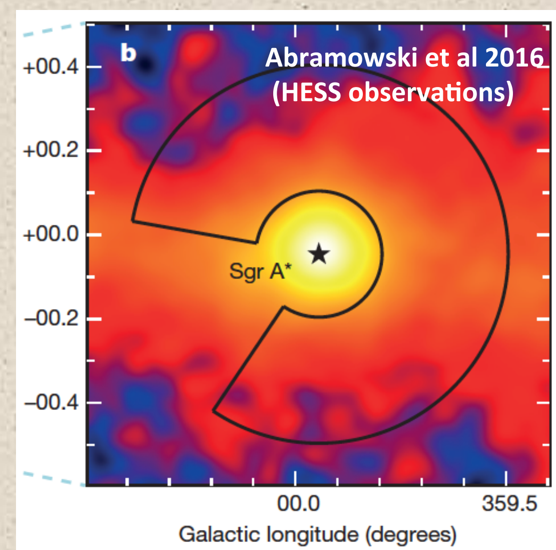
Sgr A* multi-wavelength observations.



(Yuan et al. 2003)

Power-law tail with spectral index $\alpha_s \sim 3.5$ in quiescent state

Sgr A* a Pevatron?



Diffuse emission from inner ~100 pc.

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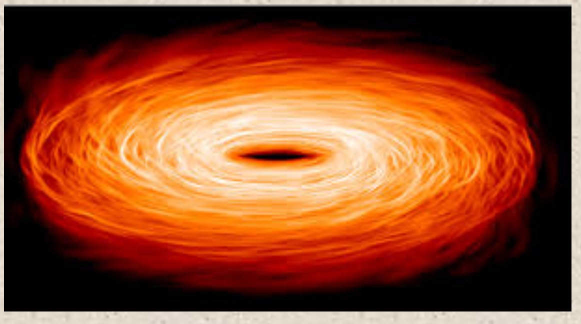

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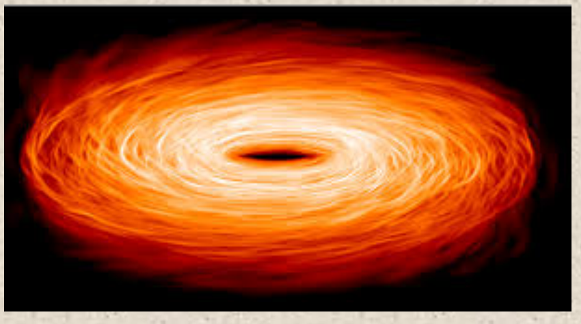

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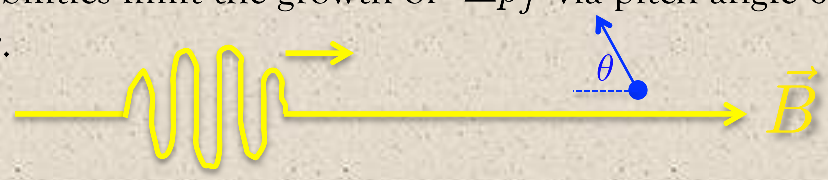

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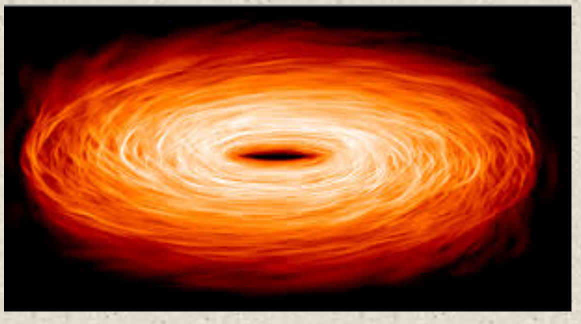

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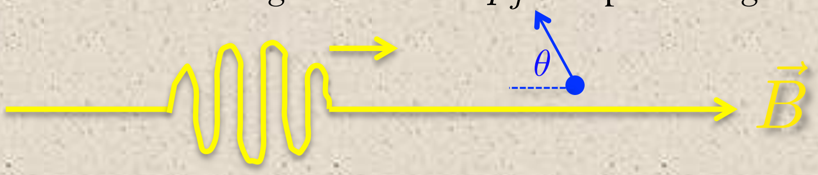

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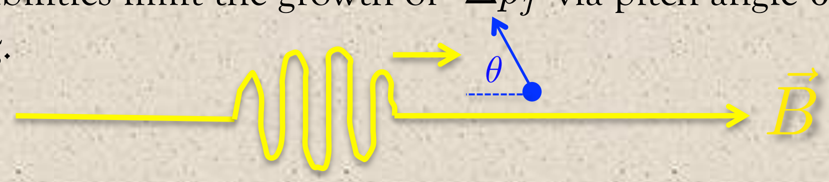

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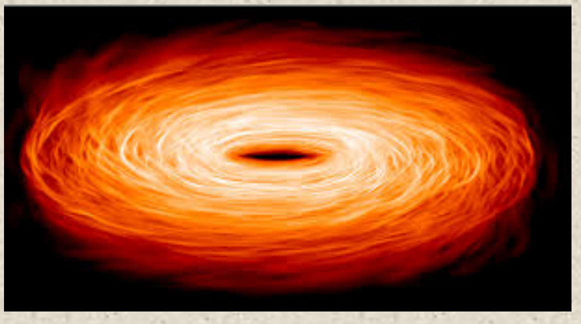

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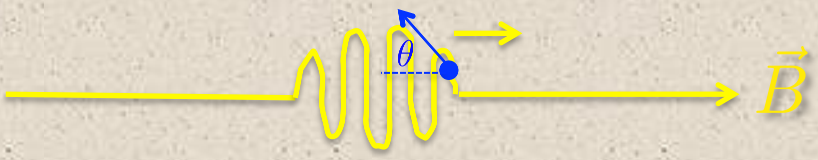

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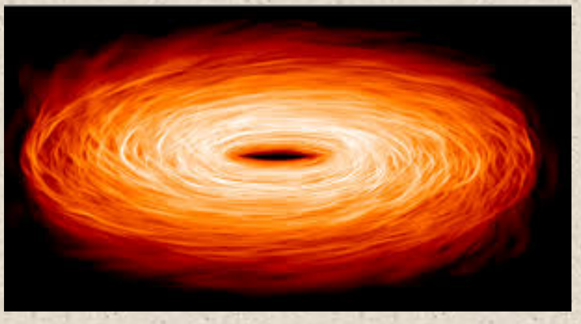

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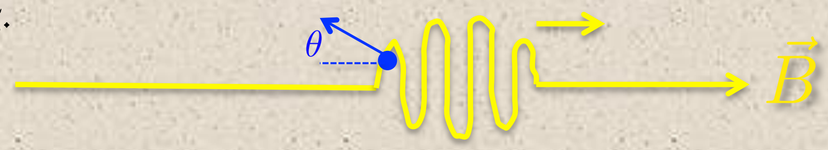

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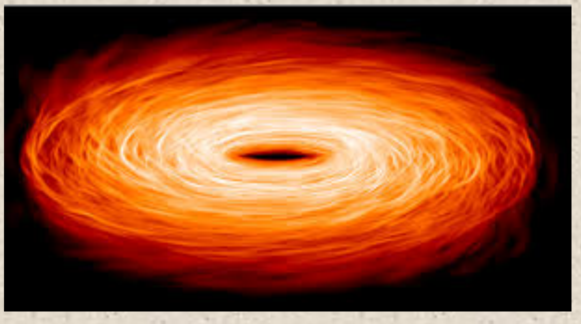

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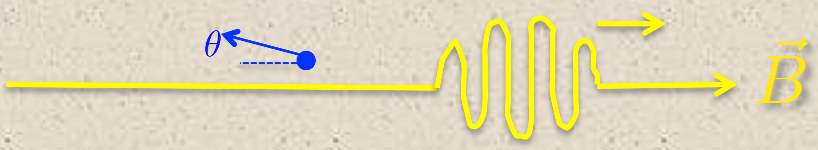

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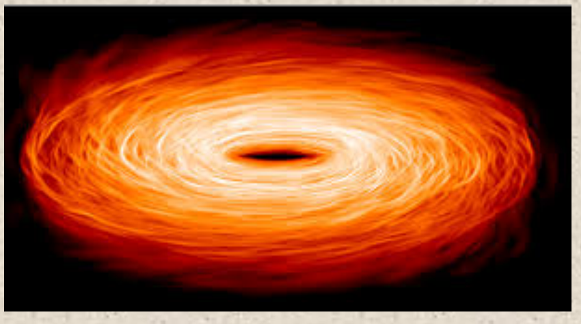

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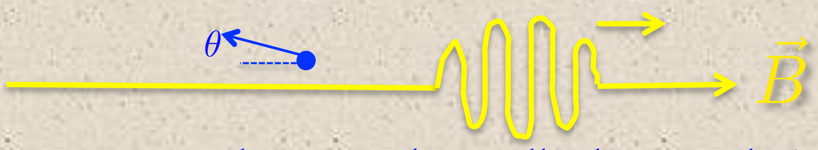

- **Can this scattering accelerate stochastically the particles?**

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2D particle-in-cell (PIC) simulations (TRISTAN-MP) in a shearing box

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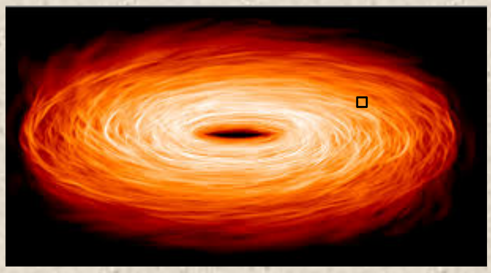

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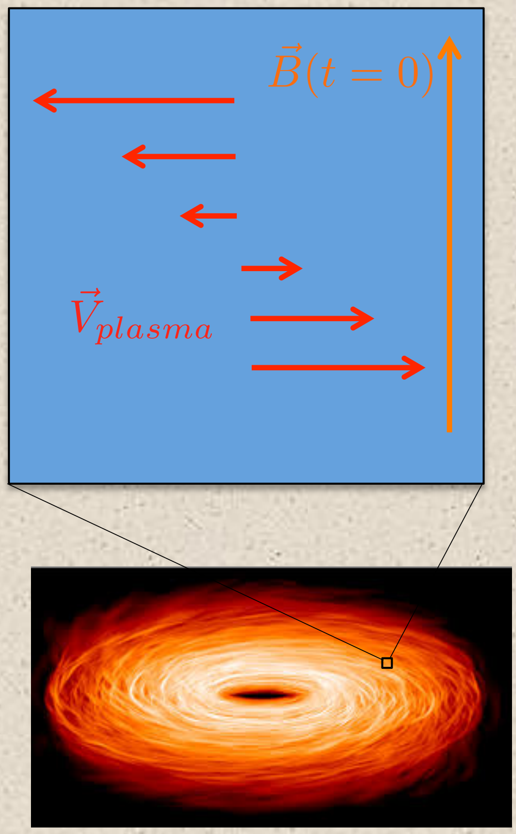

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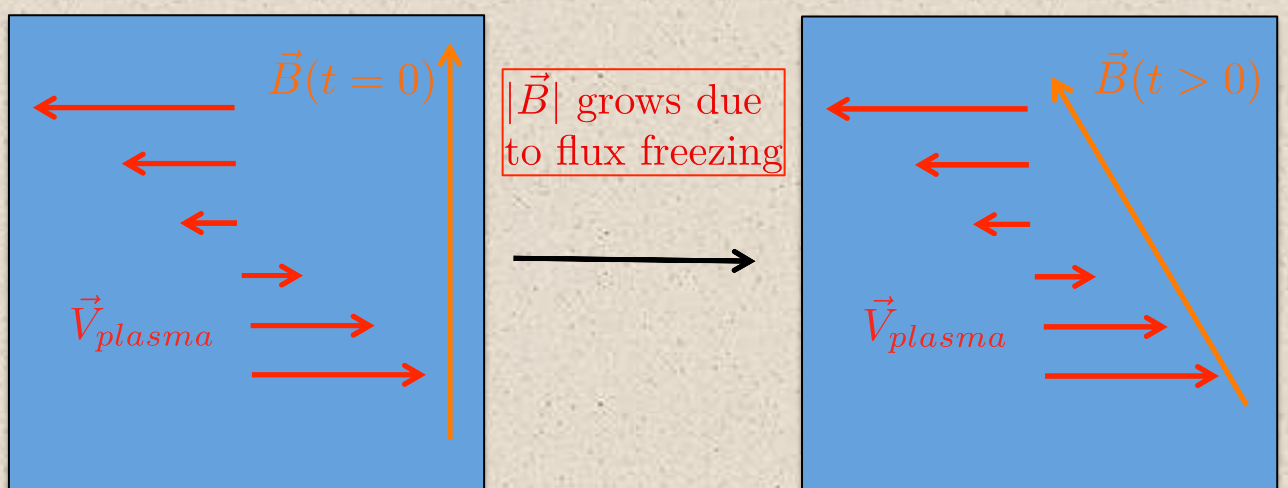

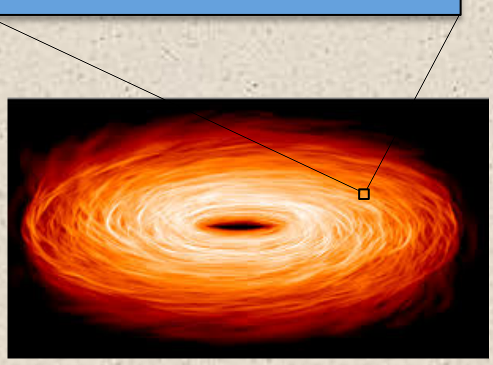

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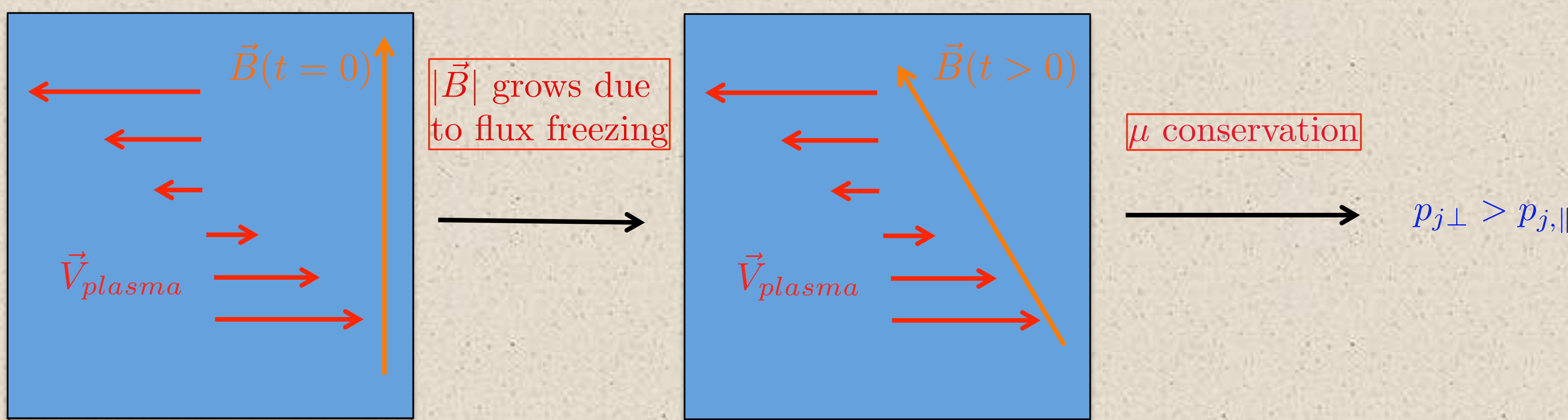

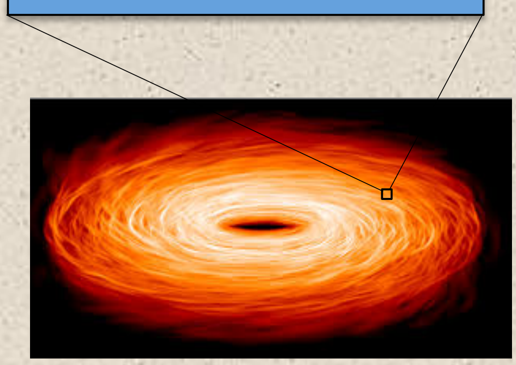

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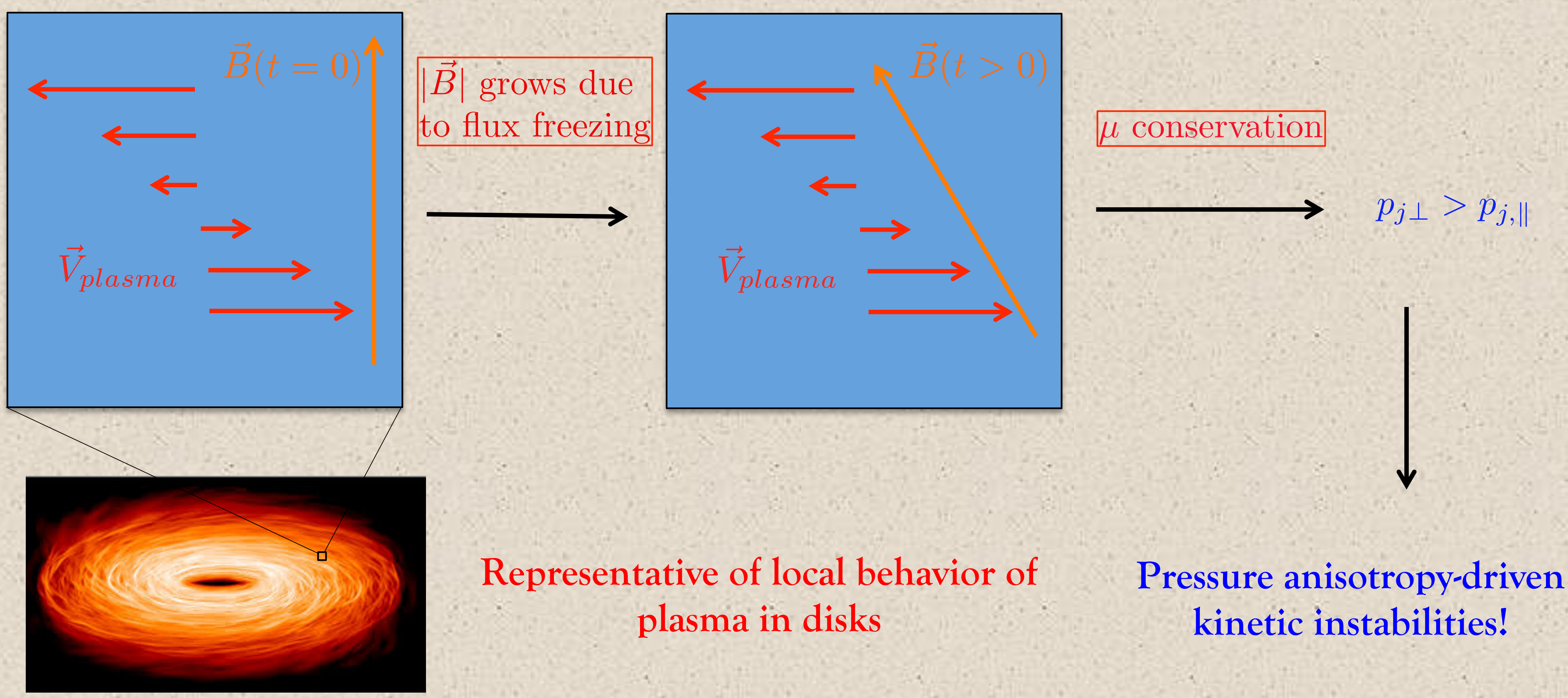


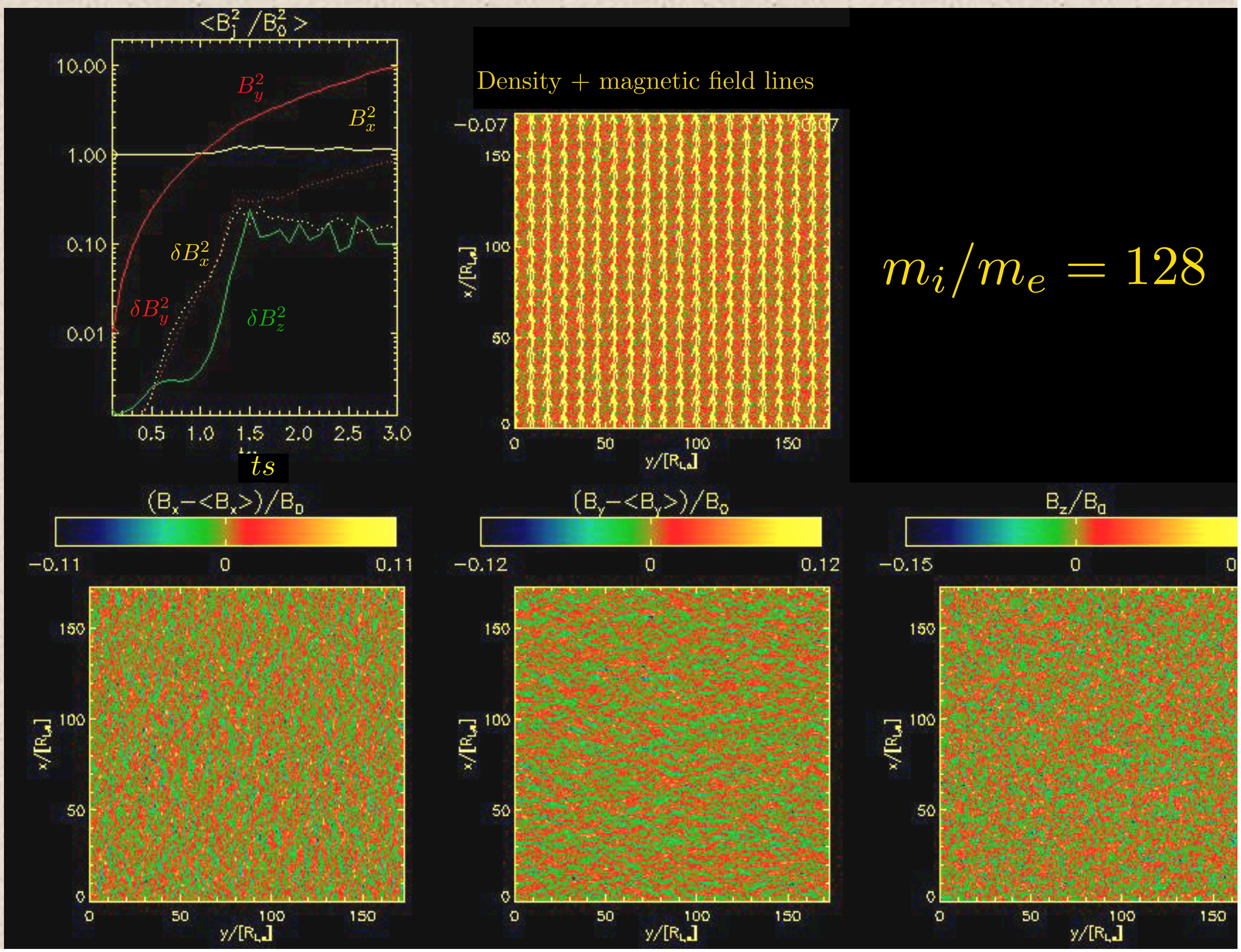
Example: Simulation with mi/me=128.

Ion-cyclotron and **mirror** instabilities on ion Larmor radius scales.

Whistler instability on electron Larmor radius scales.

Setup captures the **saturated, non-linear** state of the instabilities

(shear velocity that amplifies the field)



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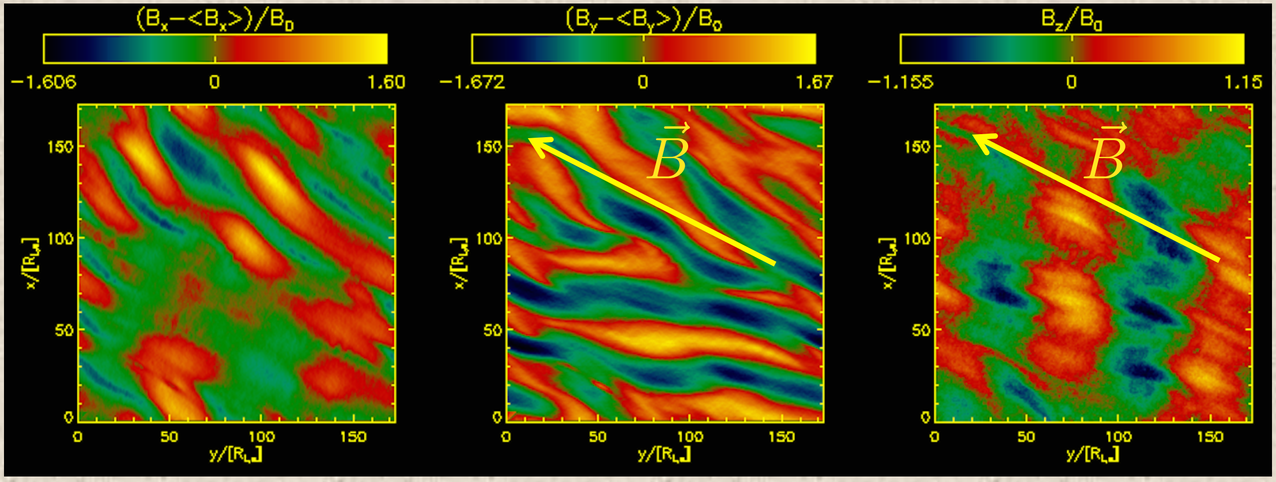

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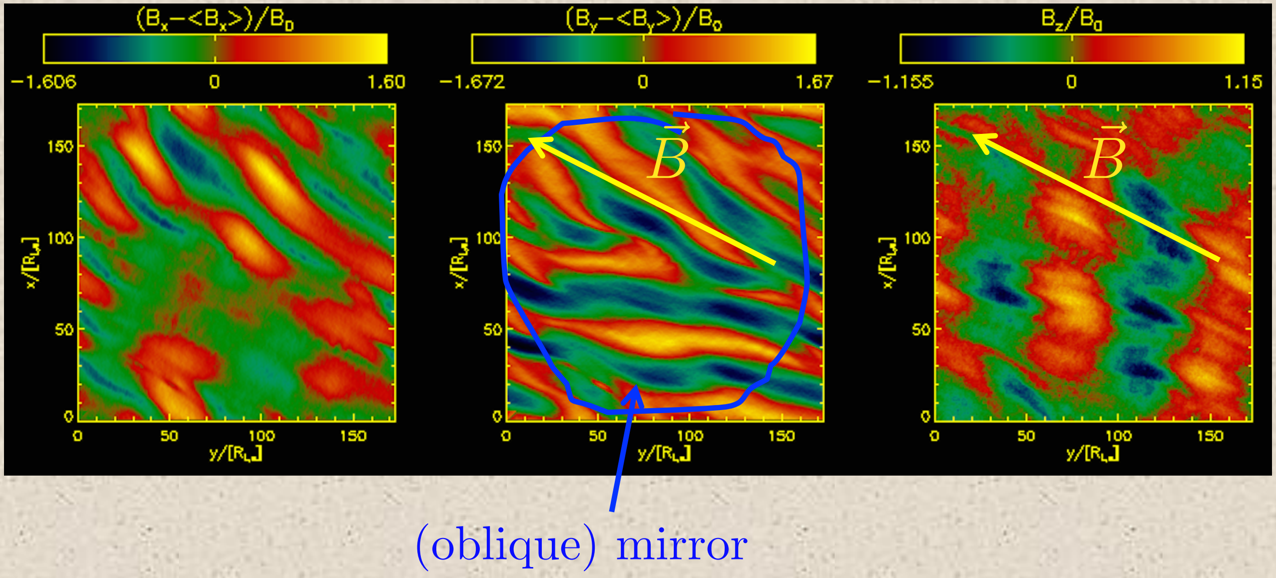

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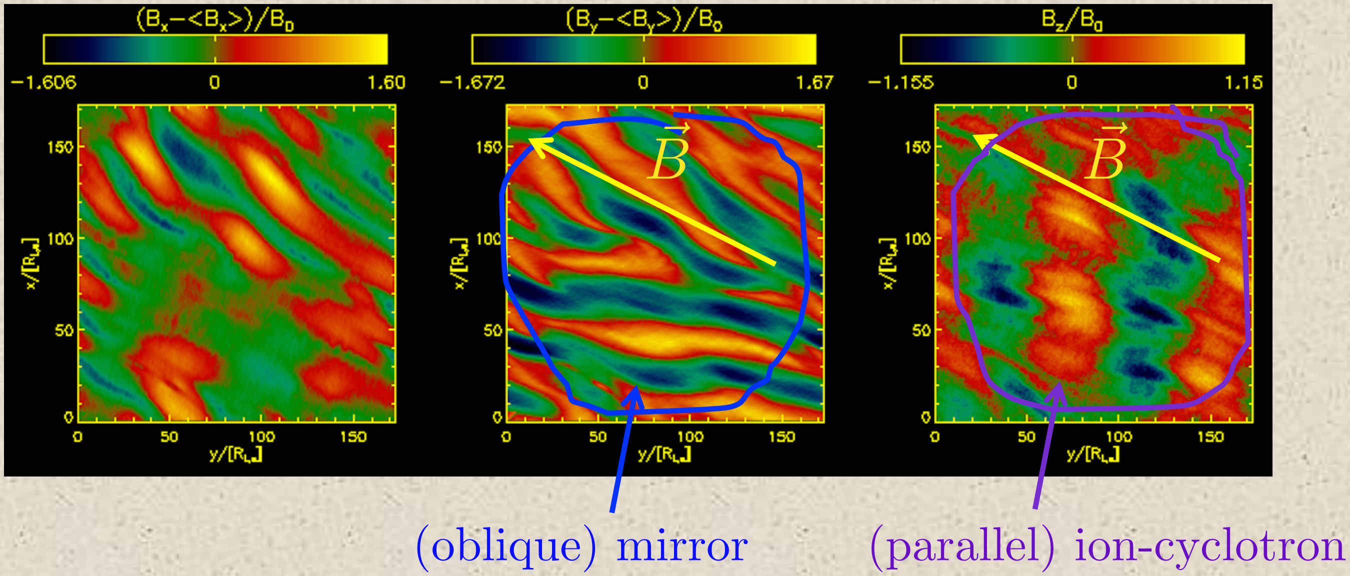

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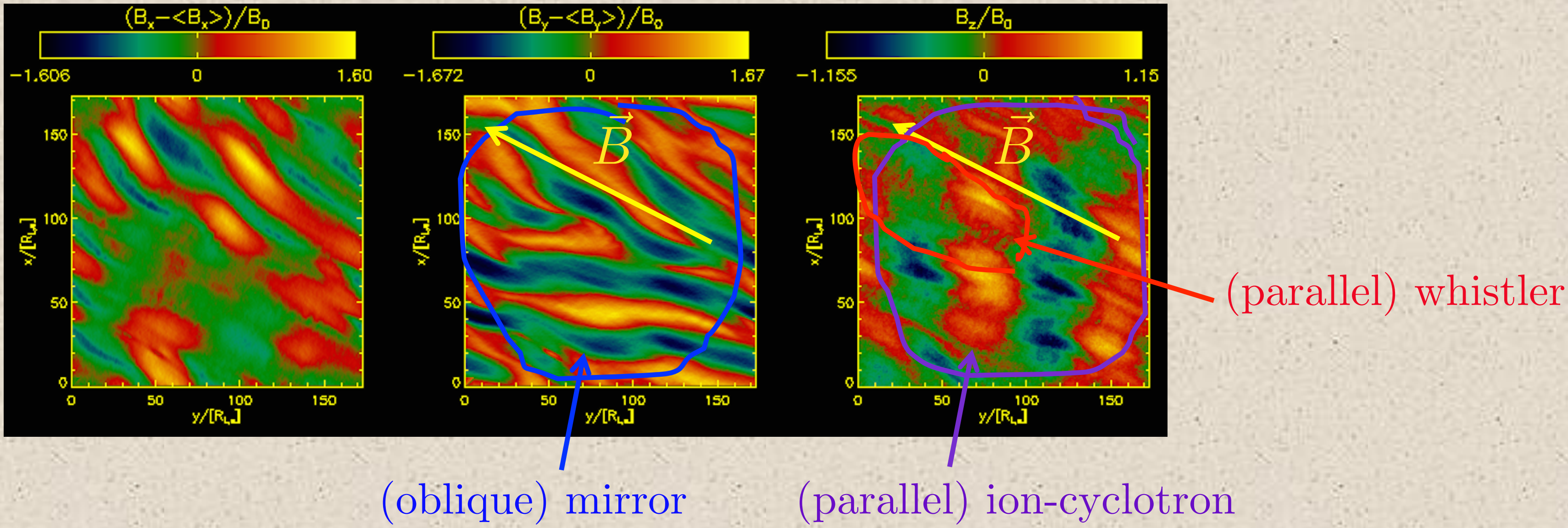

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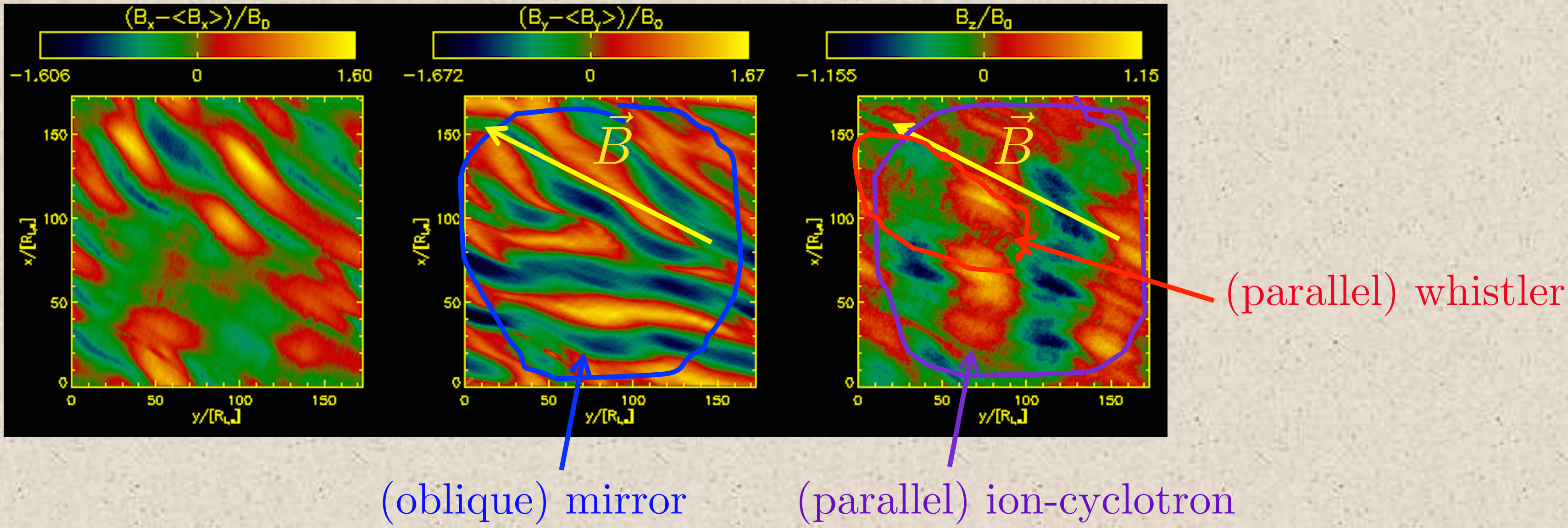

As long as $\beta_e \lesssim 10$ ($\beta_j \equiv 8\pi p_j/B^2$ is the ratio between the pressure of particles *j* and the magnetic pressure), the **electron anisotropy is dominated by the whistler instability alone**, with no influence of the ion-cyclotron and mirror instabilities.

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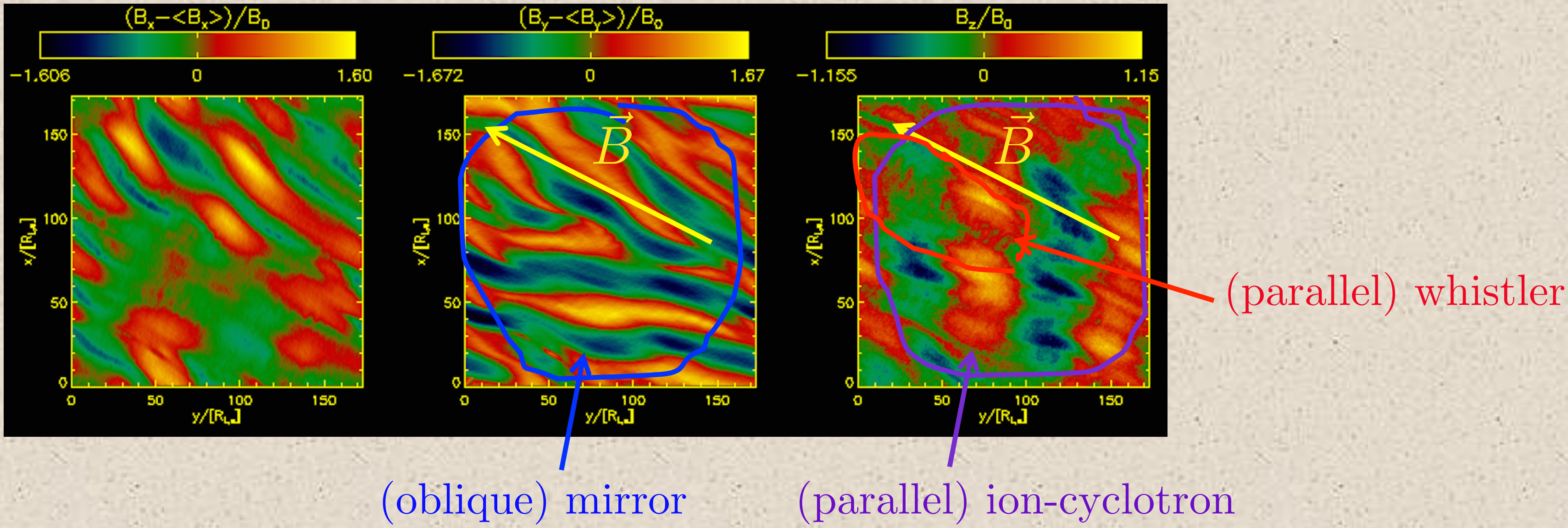

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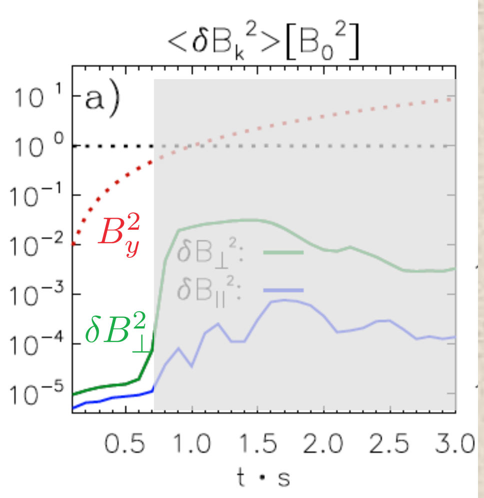
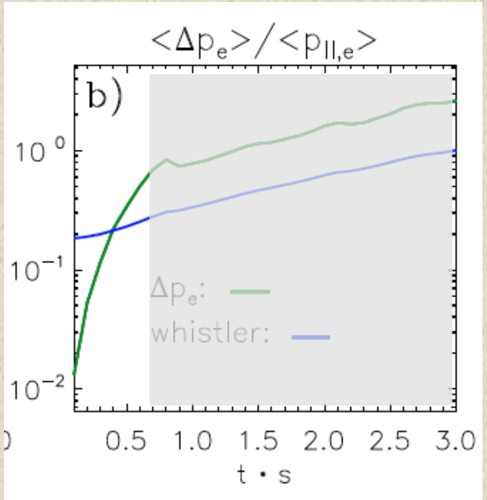
=> if $\beta_e \lesssim 10$ we can neglect the ion physics and study the physics of the whistler instability assuming immobile ions (as if they had infinite mass)

Simulations with infinite mass ions (Riquelme et al 2017)

These simulations only capture the electron dynamics. Example: $\beta_e = 2$, $k_B T_e = 0.28 m_e c^2$.





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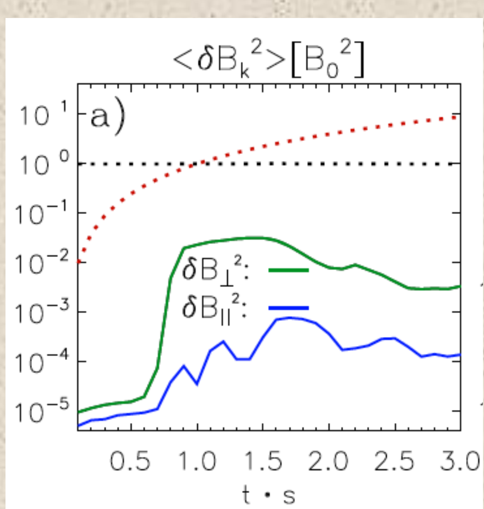

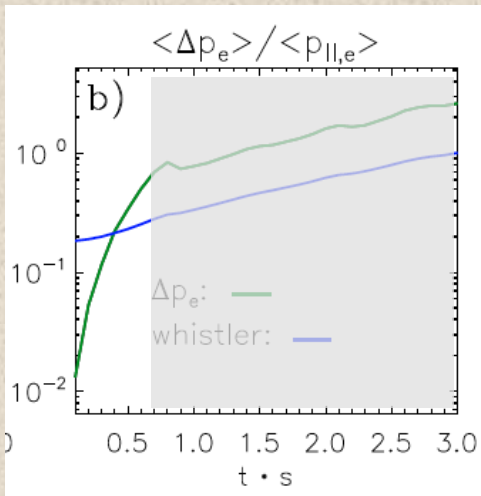

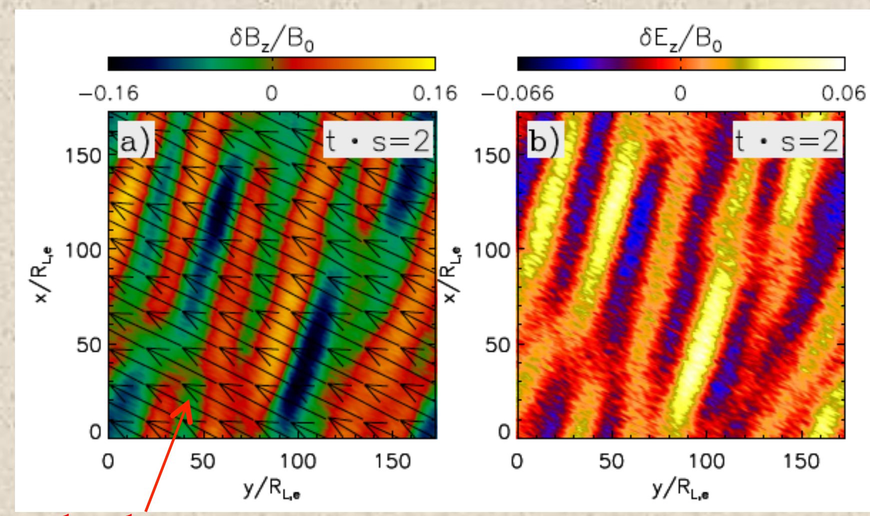

whistler waves

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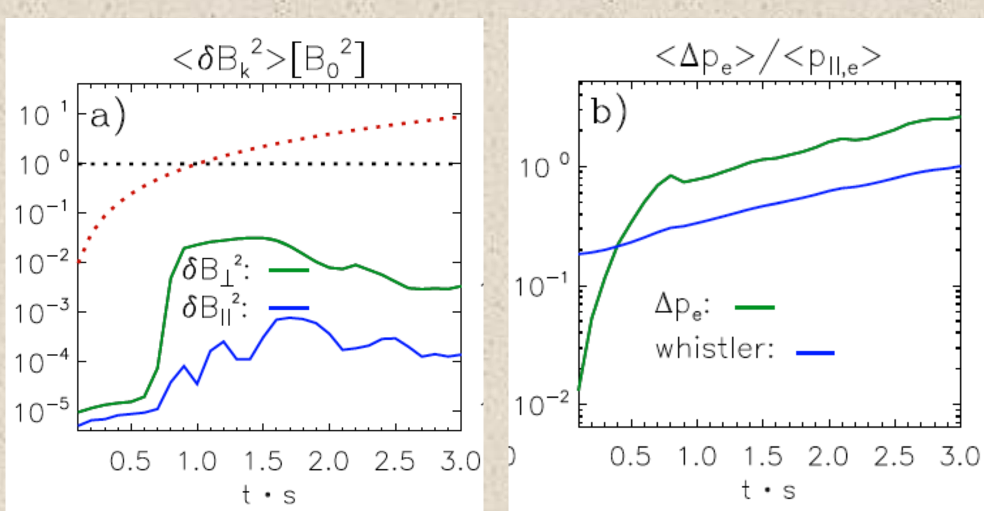

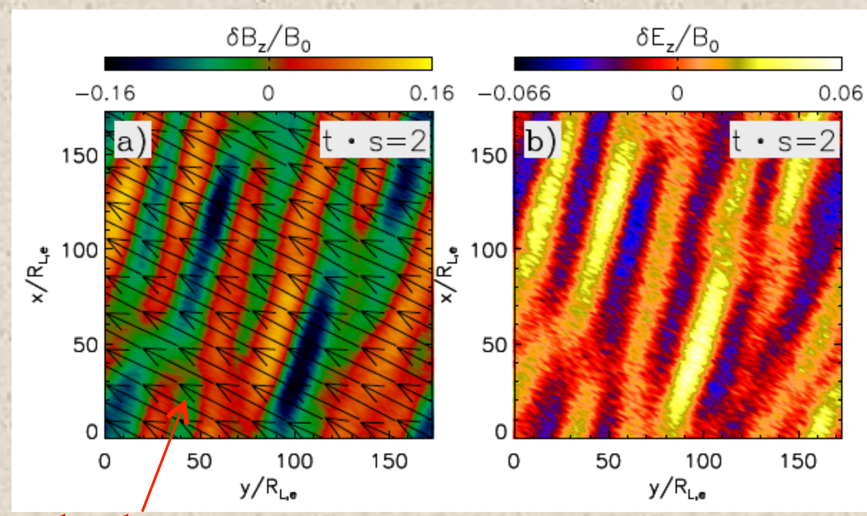

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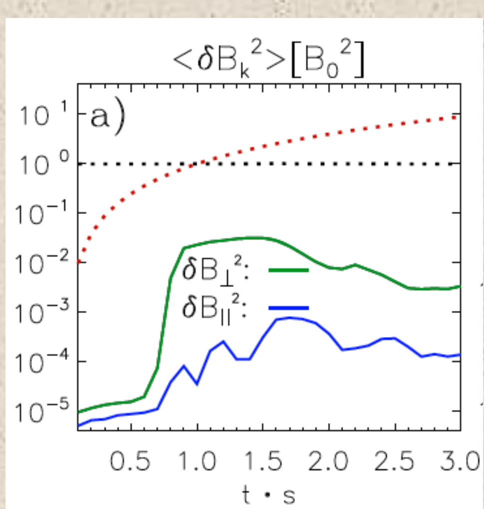
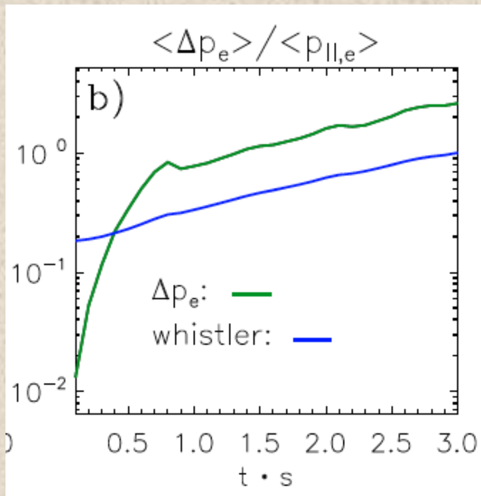
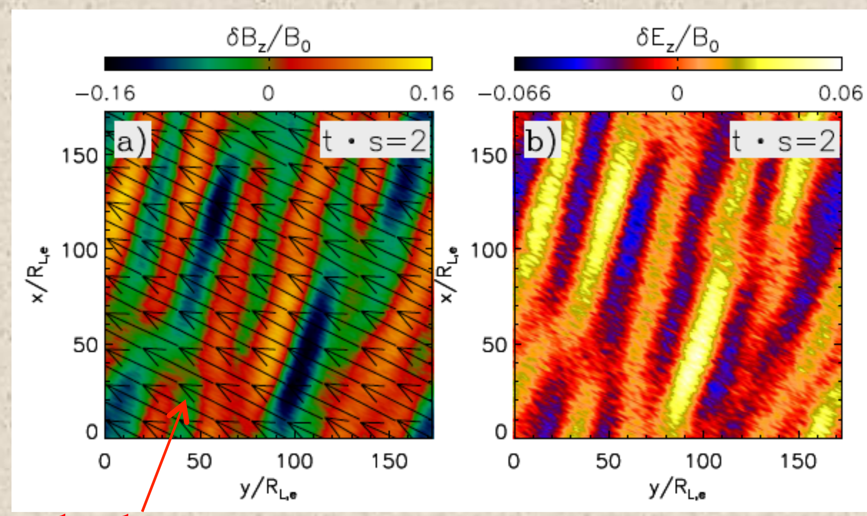
- The anisotropy produces exponential growth and saturation of the whistler modes.
- After that, the anisotropy evolves in a quasi- stationary way.

Simulations with infinite mass ions (Riquelme et al 2017)

These simulations only capture the electron dynamics. Example: $\beta_e = 2,\ k_B T_e = 0.28 m_e c^2$.

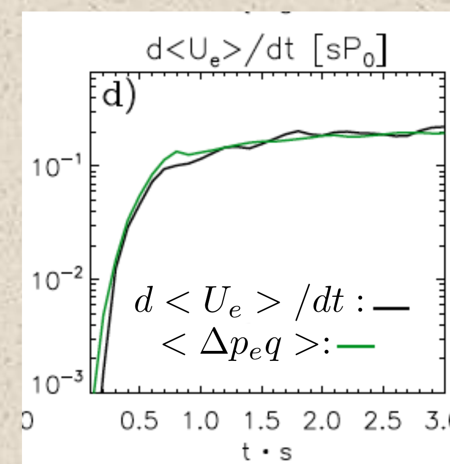






whistler waves

- Initially there is growth of the background field that gives rise to the growth of electron pressure anisotropy.
- The anisotropy produces exponential growth and saturation of the whistler modes.
- After that, the anisotropy evolves in a quasi- stationary way.
- The anisotropy also gives rise to **anisotropic viscosity ("AV")**, that heats the plasma. It is possible to show that:



$$dU_j/dt = \Delta p_j q$$

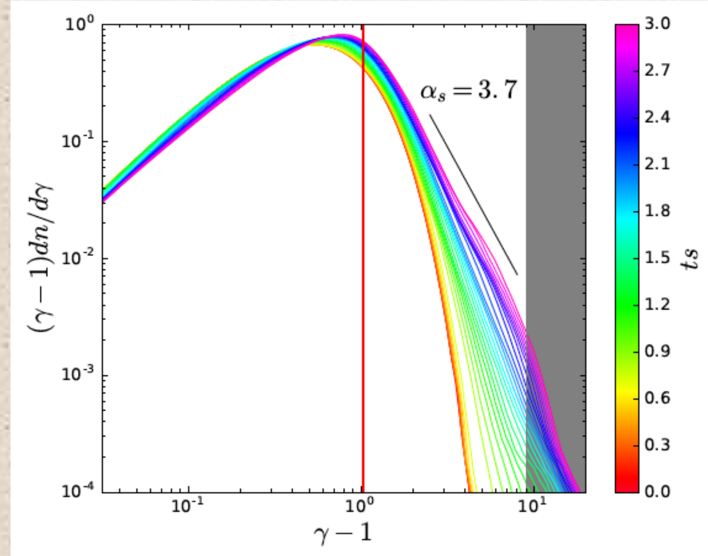
(Kulsrud et al 1983)

where U_j is the internal energy of species *j*, and "*q*" is the growth rate of the magnetic field.

Electron acceleration:

Spectrum evolution:

case kT_e/m_ec^2=0.28; β_e=2



- By the end of the simulation ($t \cdot s = 3$, equivalent to a magnetic amplification factor of ~3) the energy spectrum of the electrons contains a non-thermal tail that can be approximated as a power-law of spectral index $\boldsymbol{\alpha_s \sim 3.7}$,

interestingly close to the $\boldsymbol{\alpha_s \sim 3.5}$ inferred from radio observations (e.g., Yuan et al. 2003)

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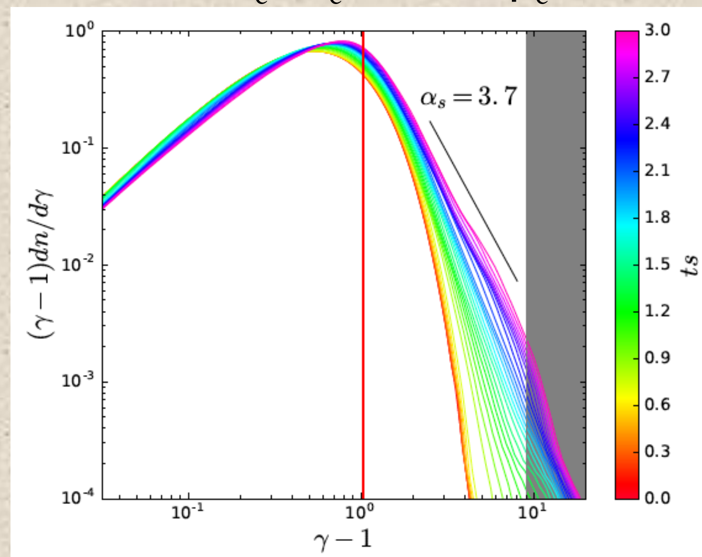

But how is the acceleration produced?

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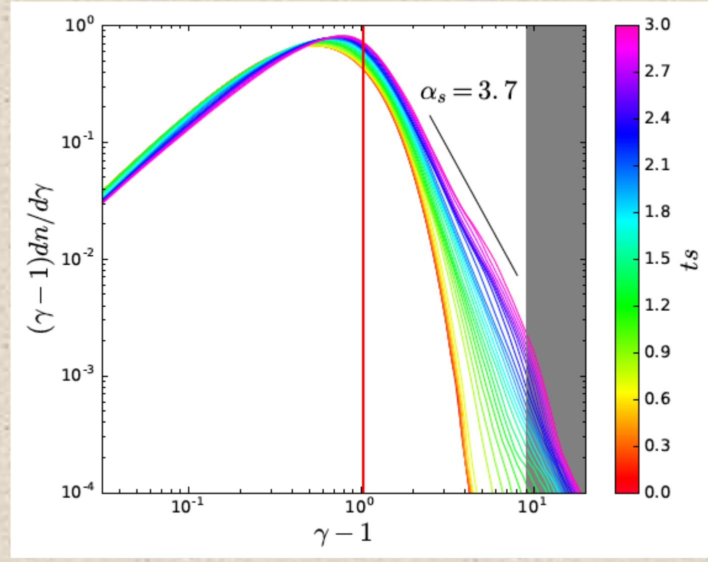
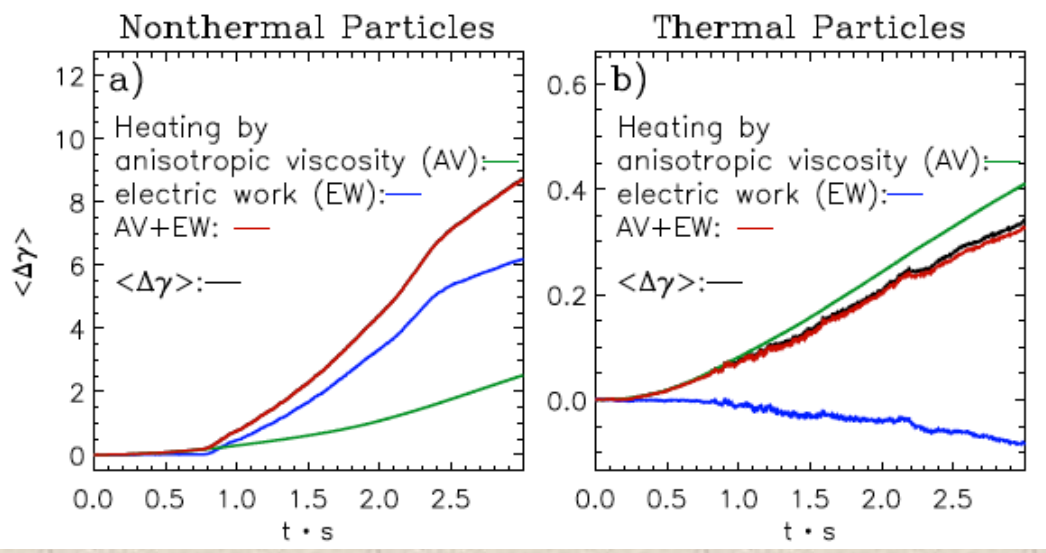


Acceleration mechanism

Energy gains due to anisotropic viscosity and **work done by the electric field of the whistler modes**.



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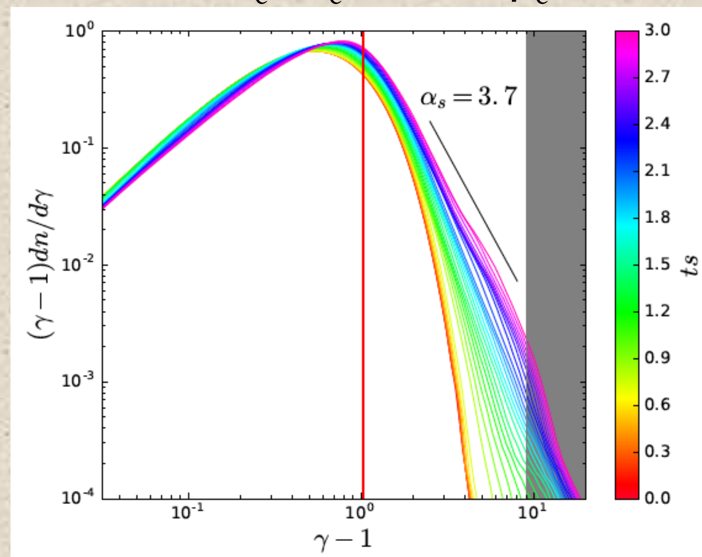

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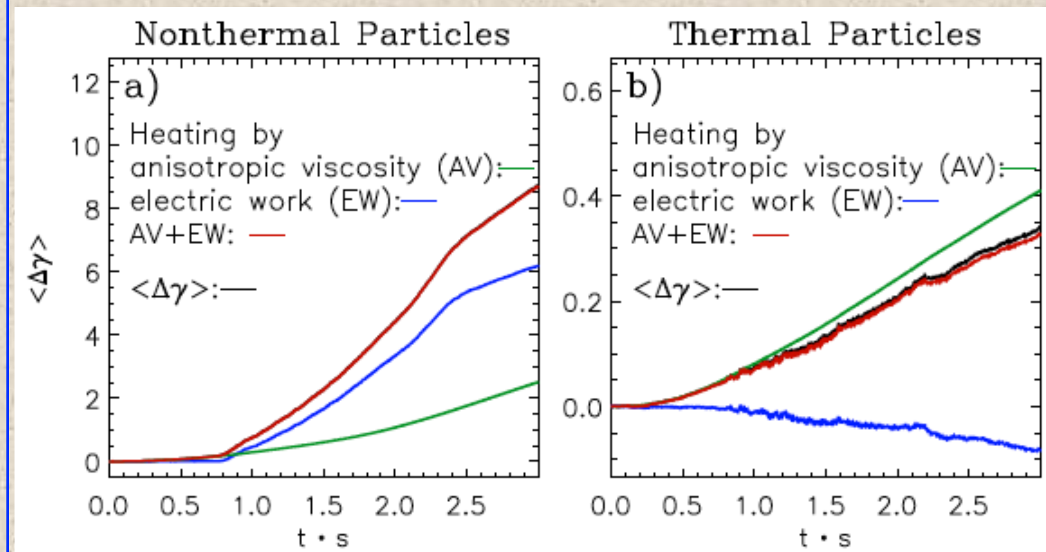

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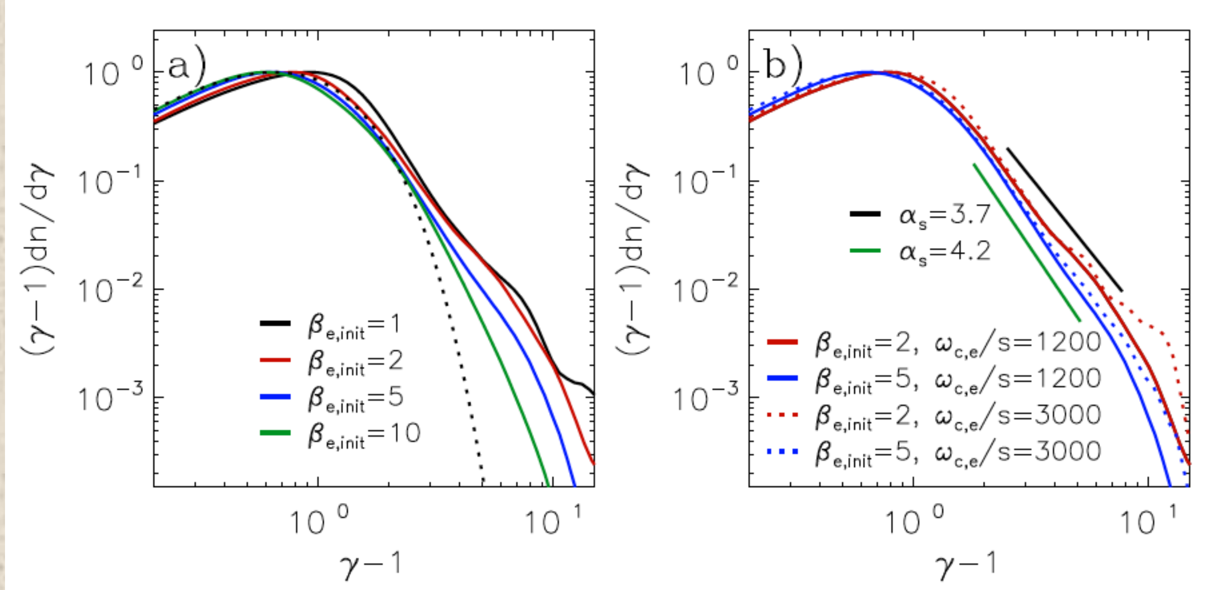
  interestingly close to the $\boldsymbol{\alpha_s}$ **~ 3.5** inferred from radio observations (e.g., Yuan et al. 2003)

- The thermal electrons **give energy** to the whistler waves.

- The non-thermal electrons **receive energy** from the waves.

Electron acceleration: Dependence on plasma parameters

Dependence on $\beta_{e,init}$ Dependence on $\omega_{c,e}/s$



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$(\beta_{e,init} \equiv p_e/8\pi B^2)$

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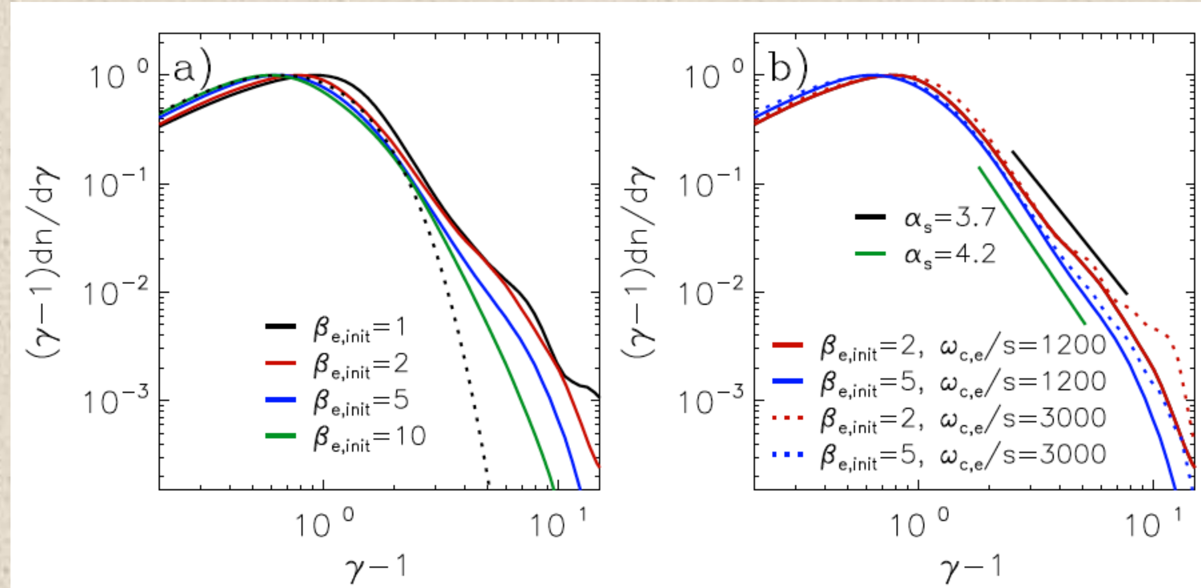

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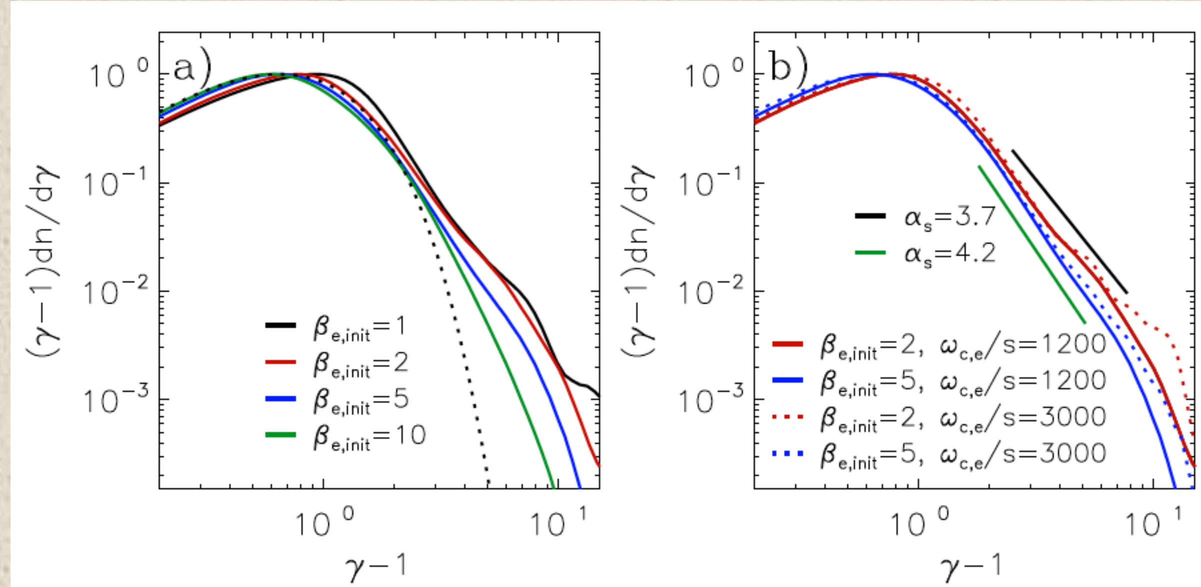

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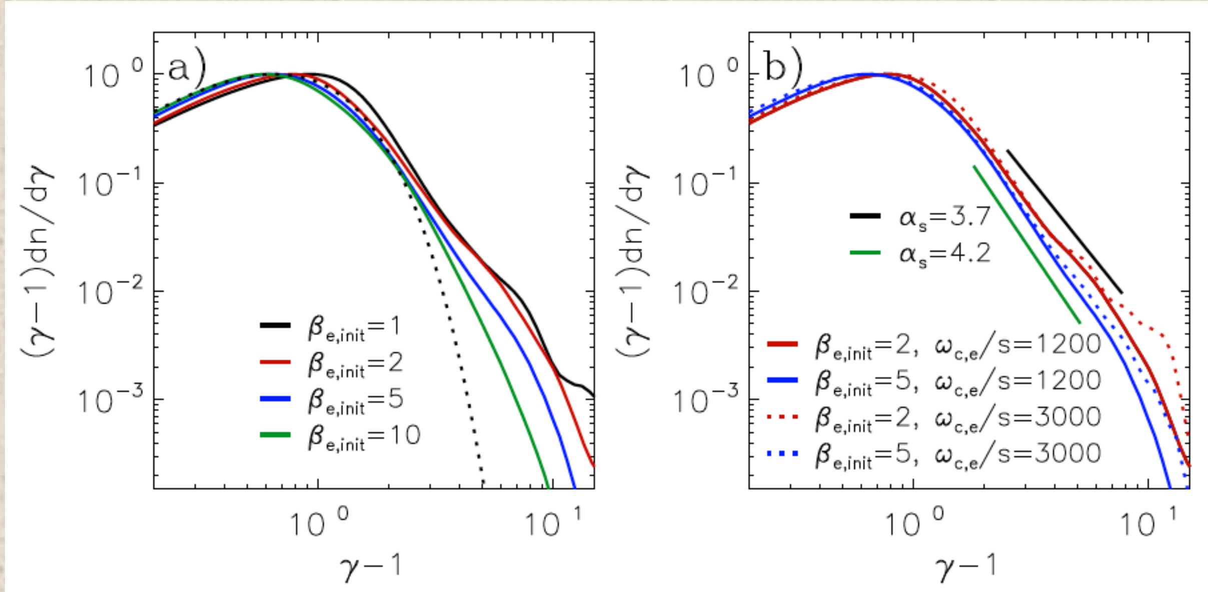

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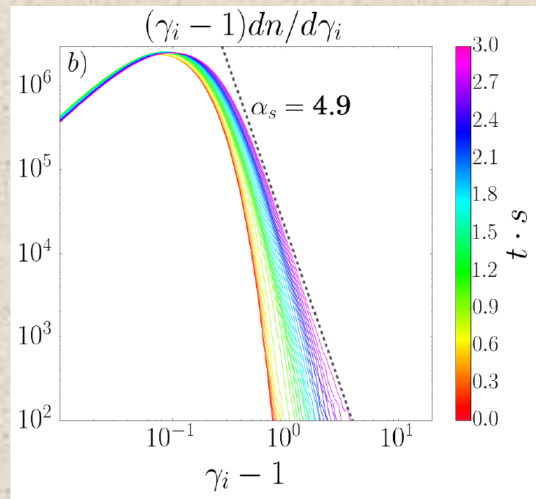
- However, for a fixed value of $\beta_{e,init}$ the electrons can have different temperatures **kT_e/m_ec^2**.
We are currently studying this dependence

Can **ions** also be accelerated stochastically?

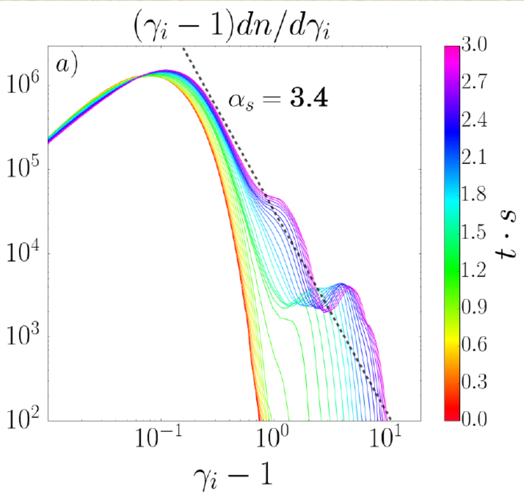
2) **Ion Acceleration:** spectra in different β_i regimes

Thus, this change to a IC-dominated regime should produce a change in the resulting spectra of the ions:

$\beta_i = 2$



$\beta_i = 0.5$



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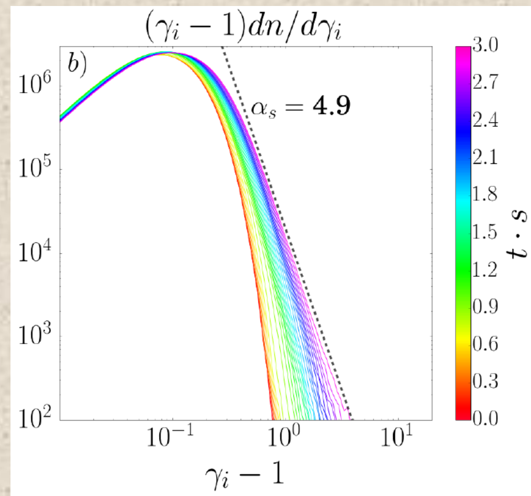

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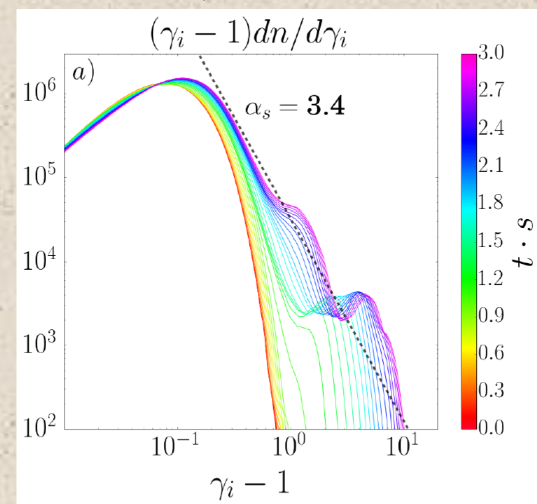

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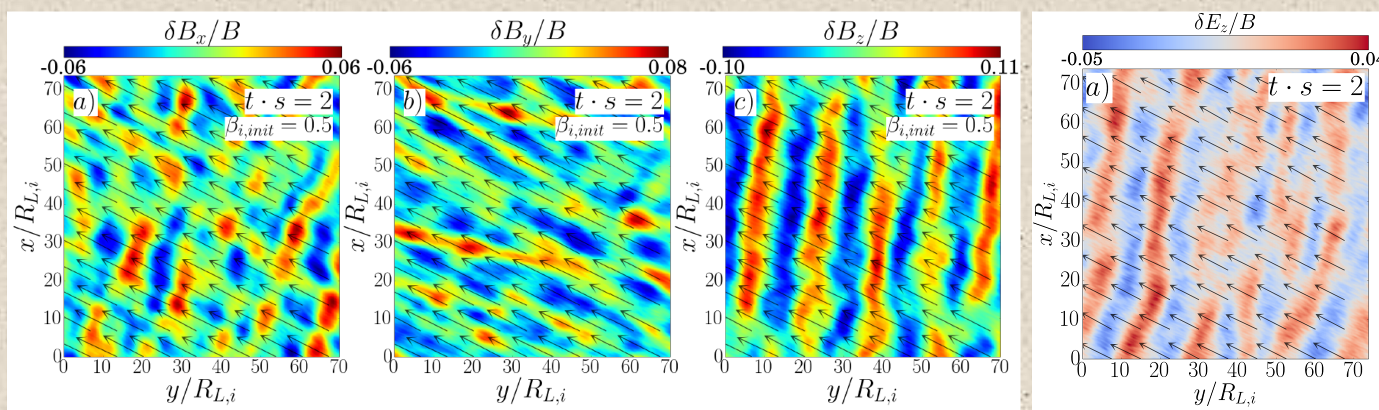
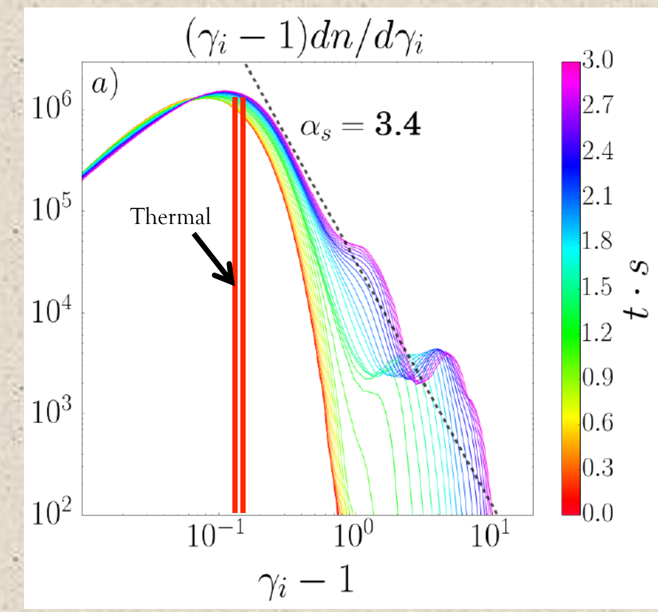


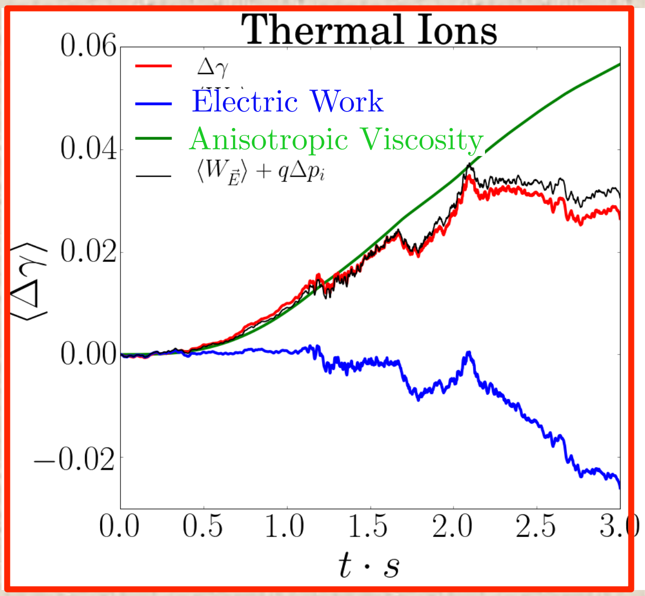
- In the IC-dominated, β_i=0.5 case there is a high energy tail that can be modeled as a **power-law plus two bumps.**

- The origin of the tail can be investigated by analyzing the way the particles in different parts of the tail gain their energy (similarly to what we did with electrons).

2) Ion Acceleration: physics of the acceleration

$\beta_i = 0.5$





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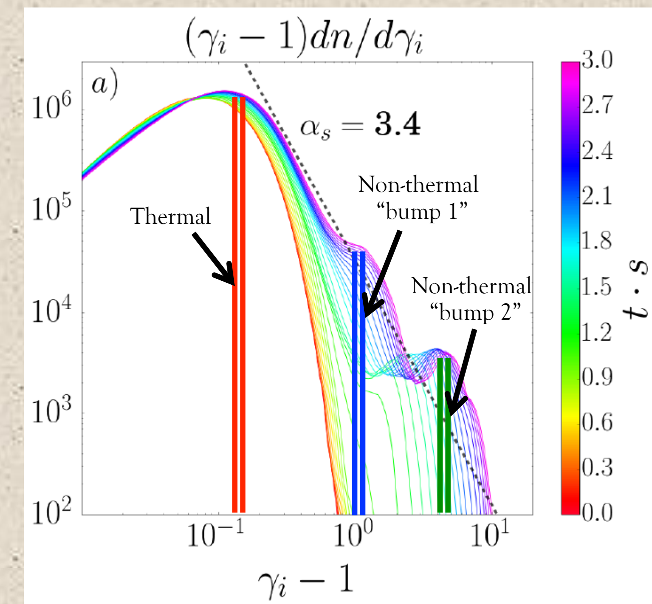
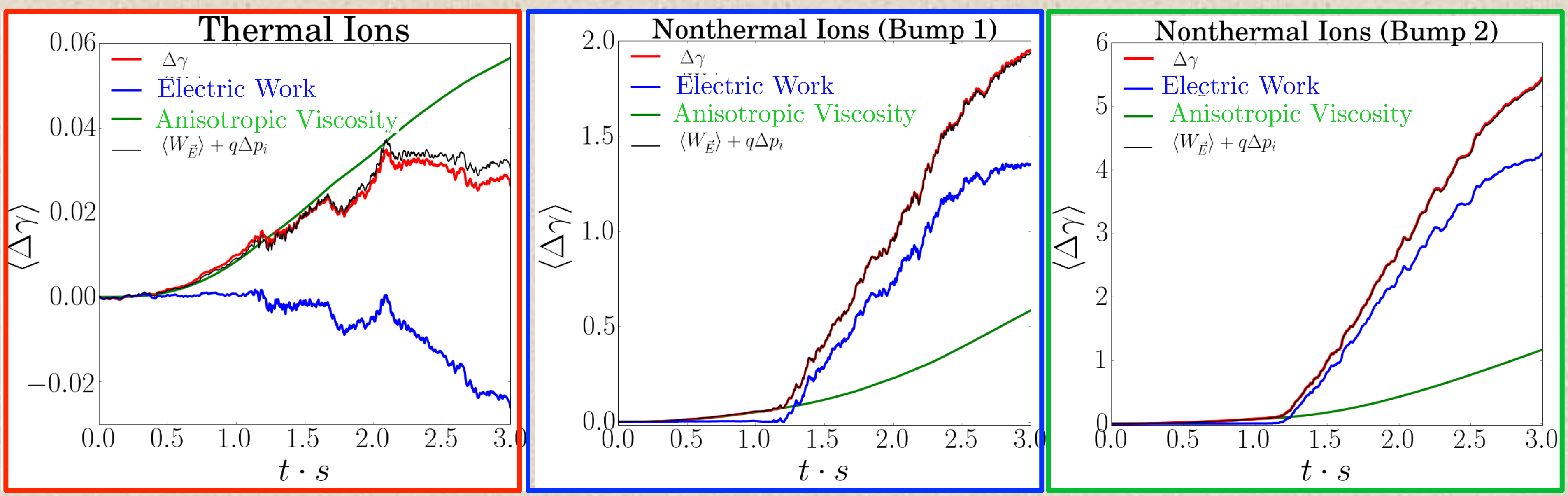
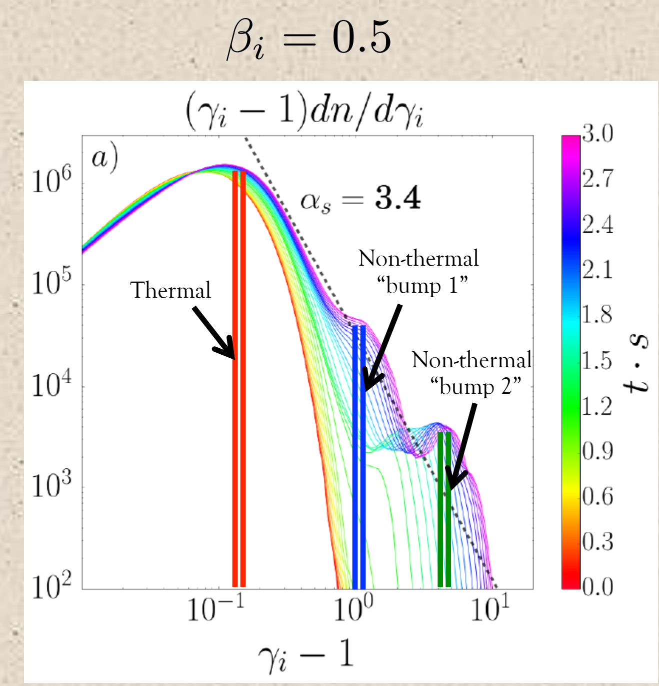
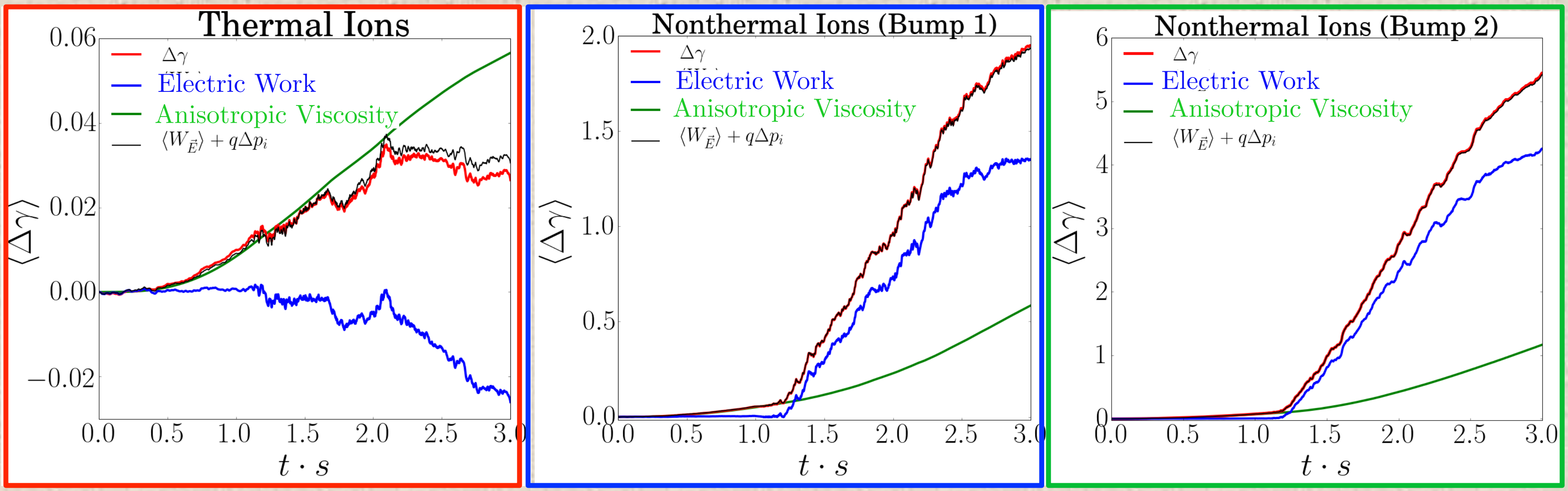




2) Ion Acceleration: physics of the acceleration

- The electric field of the IC modes transfers energy from the thermal to the non-thermal ions.



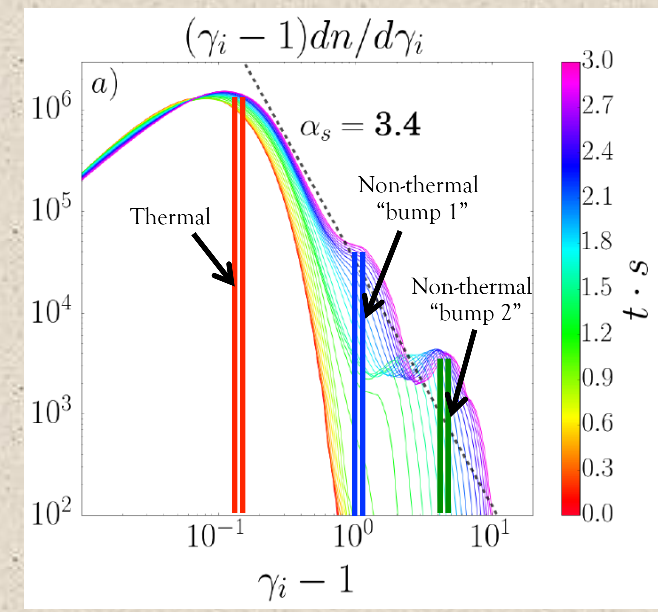


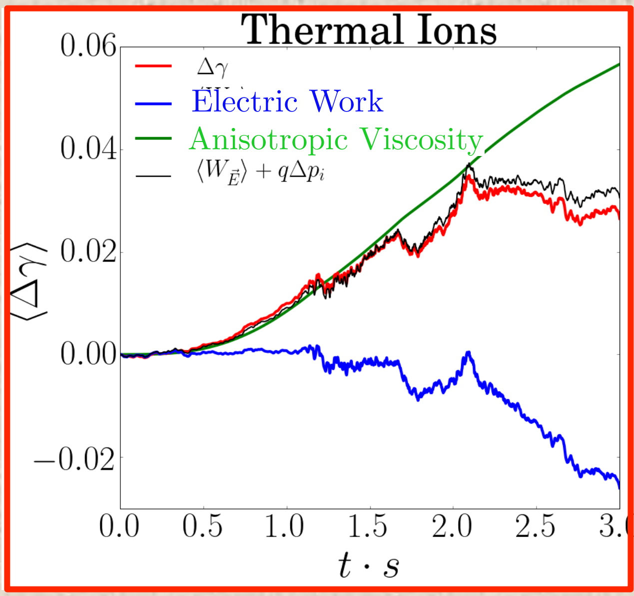
2) **Ion Acceleration:** physics of the acceleration

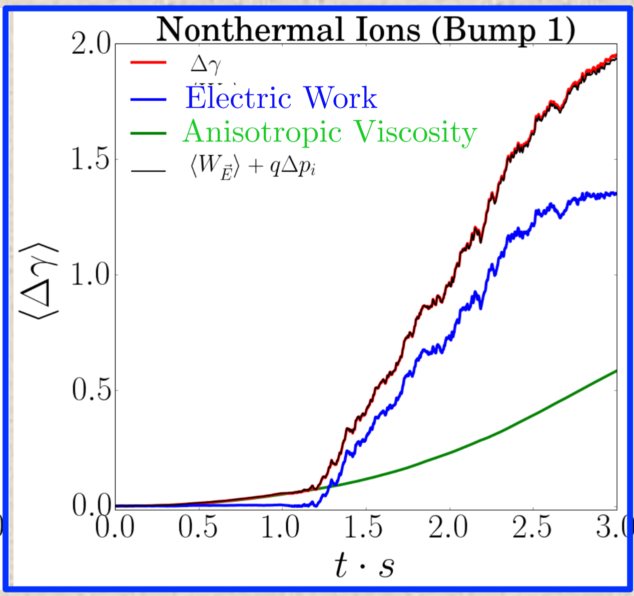
- The electric field of the **IC modes transfers energy from the thermal to the non-thermal ions**.

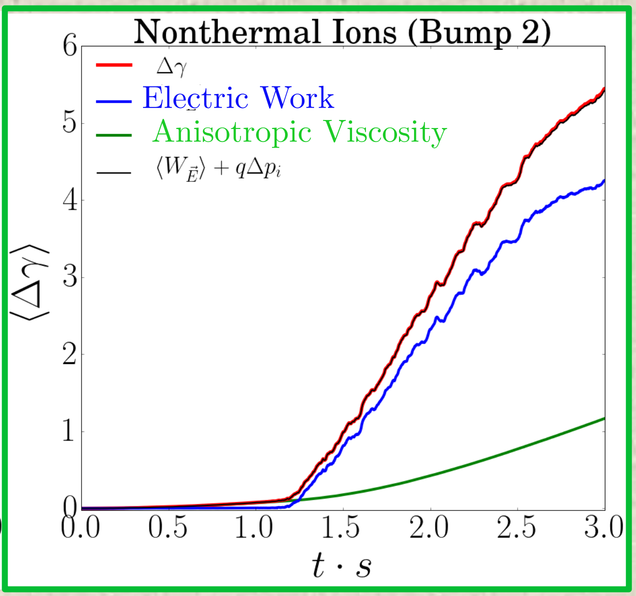
- However, these results correspond to **m_i/m_e=10 with $\omega_{c,i}/s$=800**. We need to push both parameters towards more realistic values. (At ~10 Schwarzschild radii in Sgr A*, $\omega_{c,i}/s \sim 10^8$ [e.g., Ponti et al 2017]).

$\beta_i = 0.5$



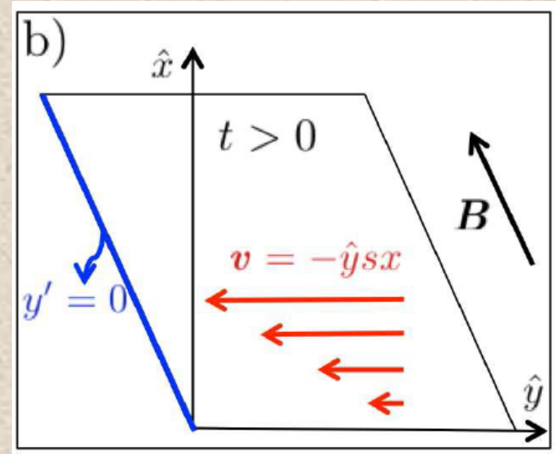






2) Ion Acceleration:

Pushing m_i/m_e and ω_{ci}/s using 1D simulations.



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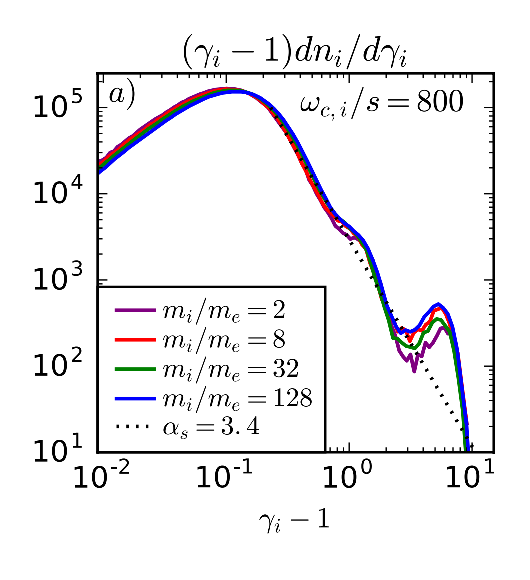

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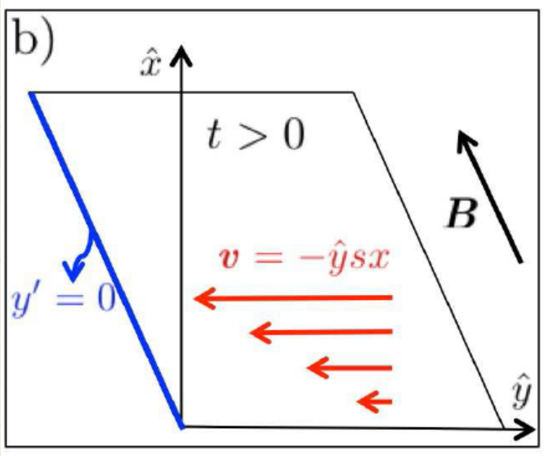

- There is practically **no difference** between the ion spectra for **different m_i/m_e**.

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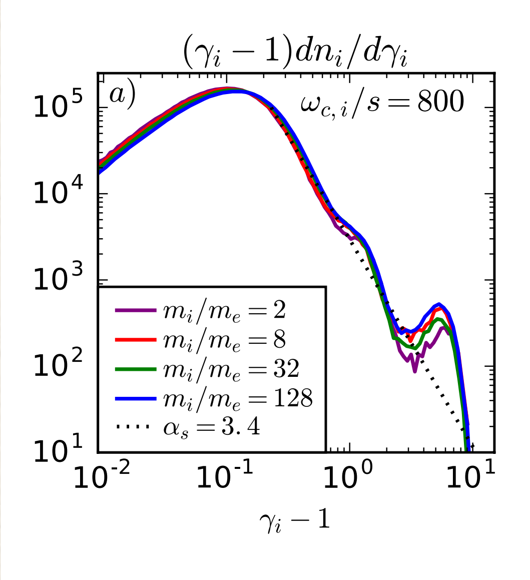

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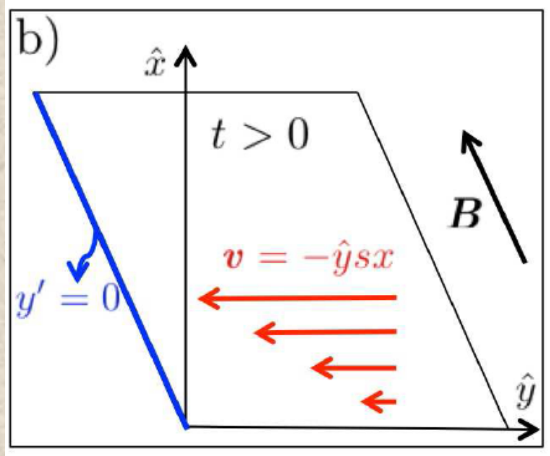

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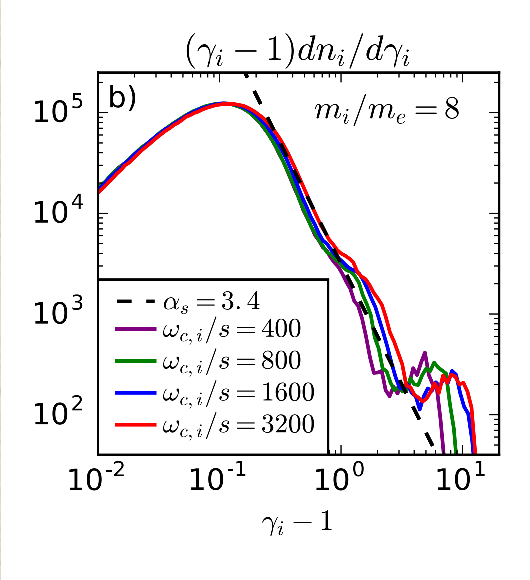
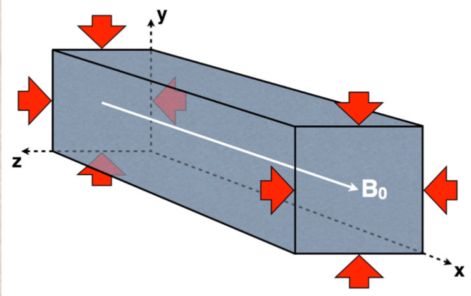


- Also **little difference** when increasing magnetization
- Although some trend to make the **spectra slightly harder for larger ω_{ci}/s.**
- Another interesting and final test:

  What happens if the IC modes are driven by **plasma compression instead of shearing?**

2) Ion Acceleration: Testing the process using compressing box

Setup of Sironi et al 2015



$$B = B_0(1 + qt)^2$$

Case with
- β_i=0.5,
- kT_i/m_ic^2=0.05,
- m_i/m_e=8 and 16
- $\omega_{c,i}/s$=1600 and 3200

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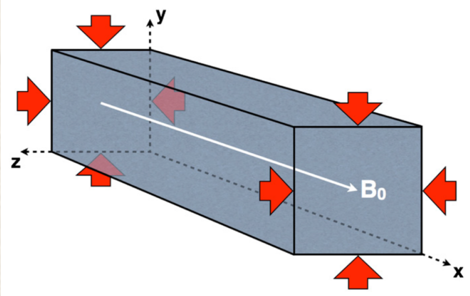

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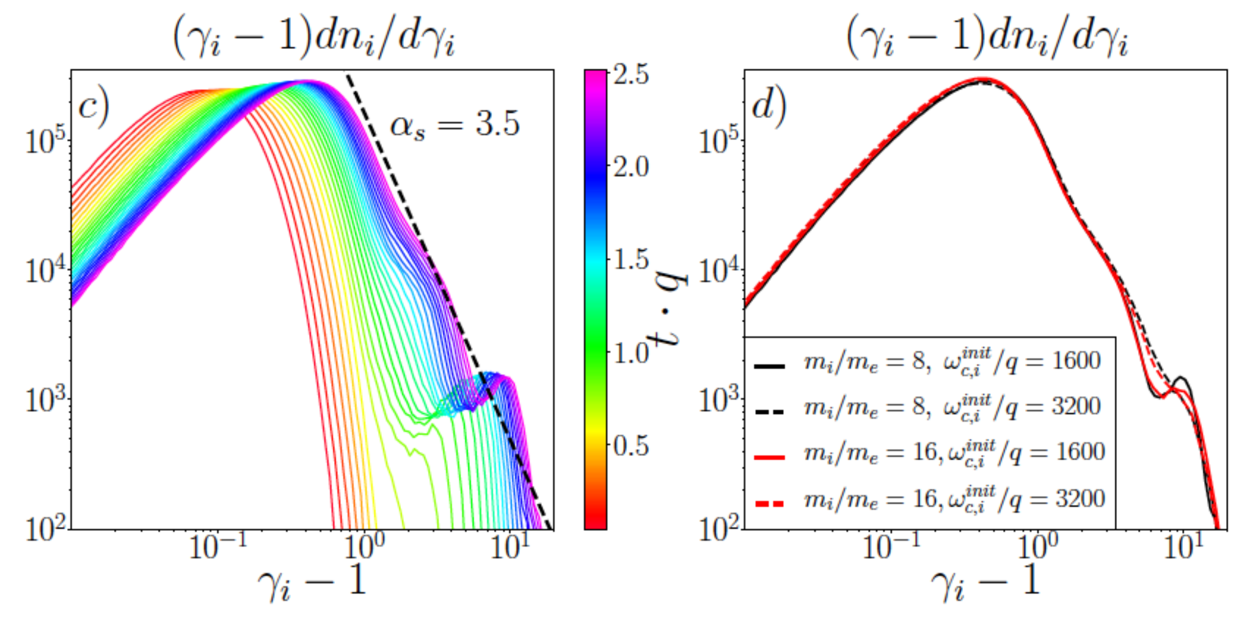

- Essentially **no difference between mi/me=8 and 16**.
- **Little difference between $w_{c,i}/s$=1600 and 3200** (a bit harder when $w_{c,i}/s$=3200).
- The amplification mechanism **(shear or compression) does not matter!**

Conclusions

- **Pressure anisotropy-driven, kinetic instabilities** can **accelerate ions and electrons stochastically** in low-luminosity (weakly collisional) accretion disks.

- For two specific cases with initial $\beta_j \sim 1$ ($j =$i and e)**, and after the magnetic field is amplified by a factor of ~3**, these spectra can be approximately modeled by

  i) **Case of electrons:** a power-law of **index ~3.7**, which is close to what radio observations suggest for Sgr A* (e.g., Yuan et al. 2003). **[Riquelme et al 2017]**

  ii) **Case of ions:** a power-law of **index ~3.4 + two bumps**. Largest Lorentz factor ~10. **[Ley et al 2019]**

- Open Questions:

  i) How does this process depend on the **plasma parameters**: kT_j/m_jc^2 and ω_{cj}/ω_{pj} (j=i and e)?

  ii) **Long(er) term evolution**: what happens if these processes occur many times due to turbulence?

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