Particle Acceleration by Pressure Anisotropy-driven Instabilities in Weakly Collisional Accretion Flows

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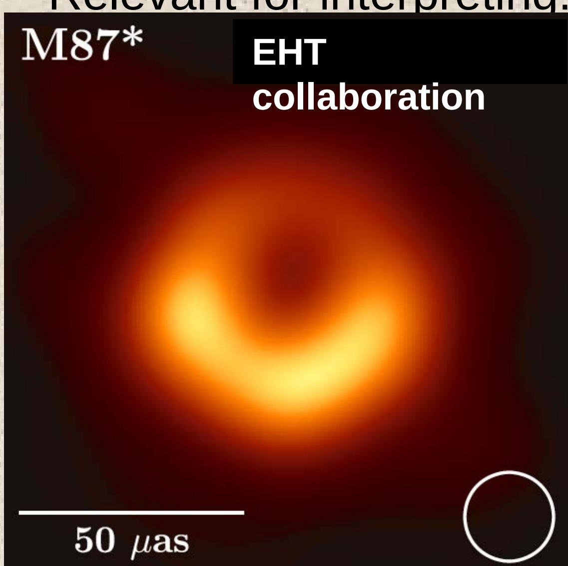
Motivation:

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

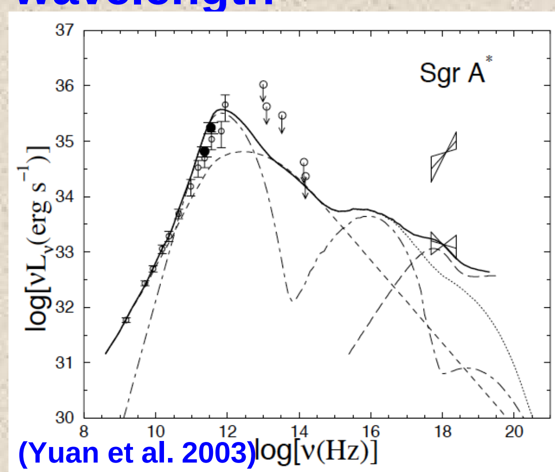
What do they have in common: $\tau_{coll} >> \tau_{accr}$
τ_{coll}: Coulomb collision time and τ_{accr}: Accretion time of the gas

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:



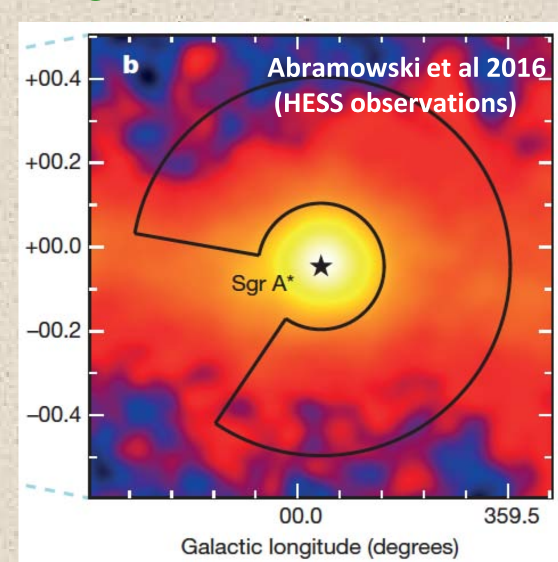
Sgr A* multi-wavelength



(Yuan et al. 2003)

Power-law tail with spectral $\alpha_s \sim 3.5$

Sgr A* a Pevatron?



Diffuse emission from inner ~100 pc.

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shocks, magnetic reconnection, stochastic acceleration by cascading MHD turbulence.

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where $v_{j,\perp}$ is the velocity of species *j* perpendicular to the magnetic field $\vec{B}$.

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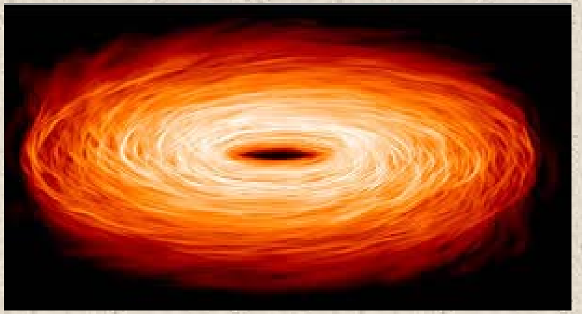

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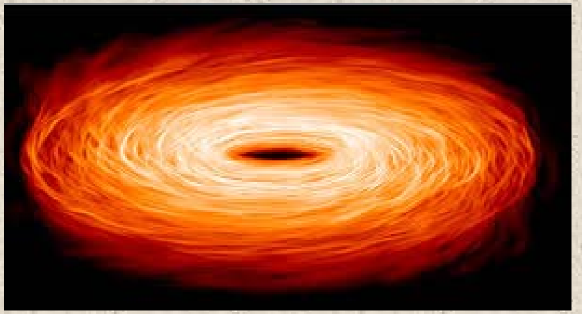

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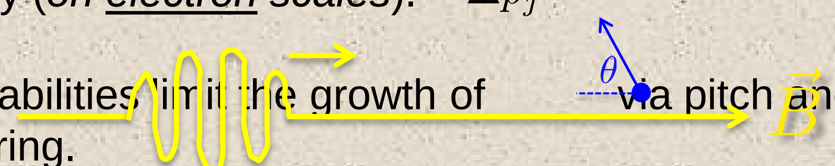

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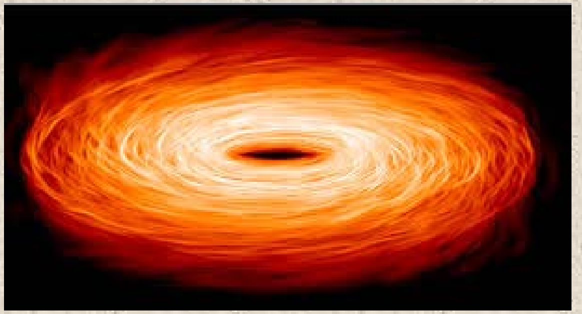

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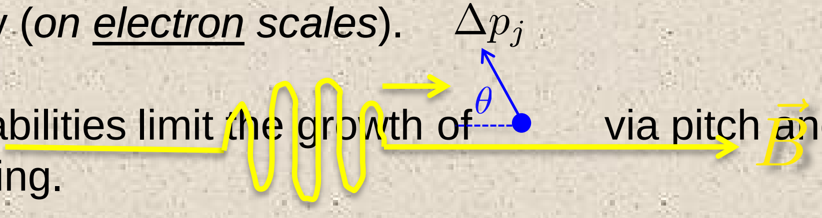

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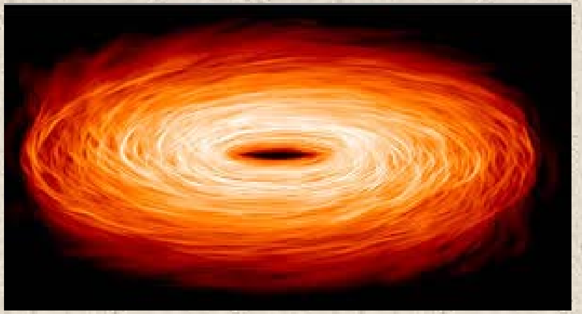

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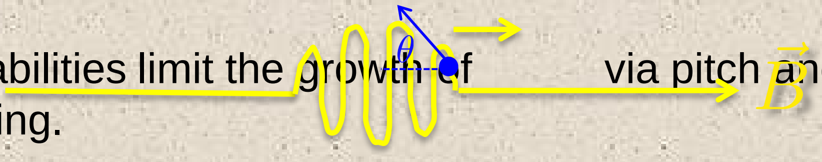

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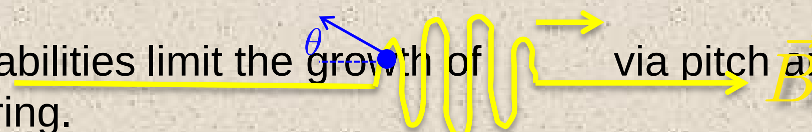

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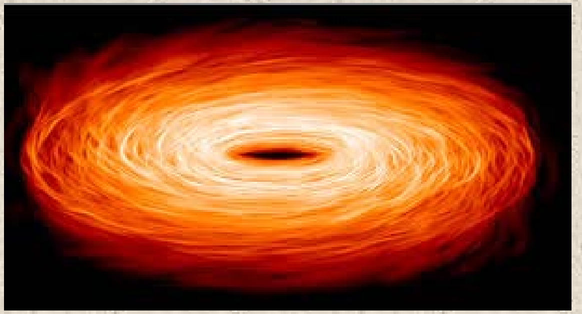

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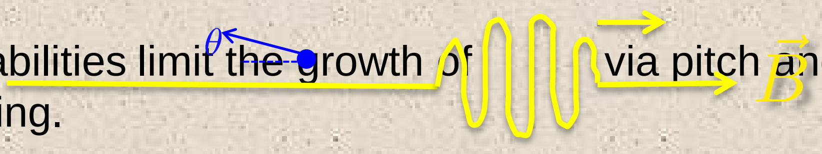

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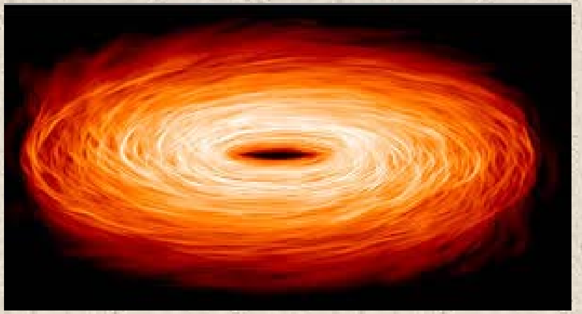

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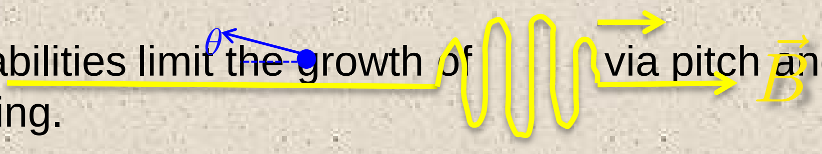

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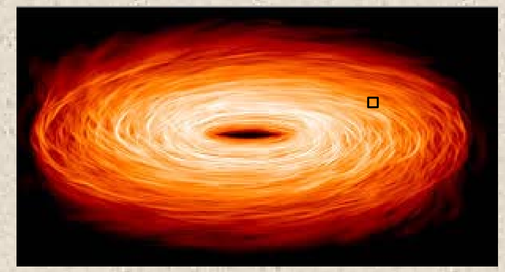

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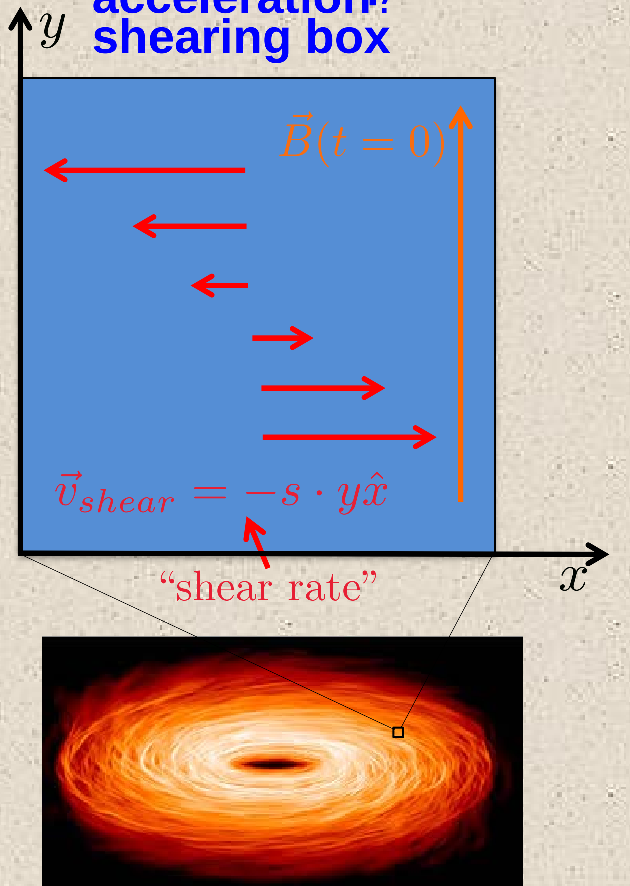

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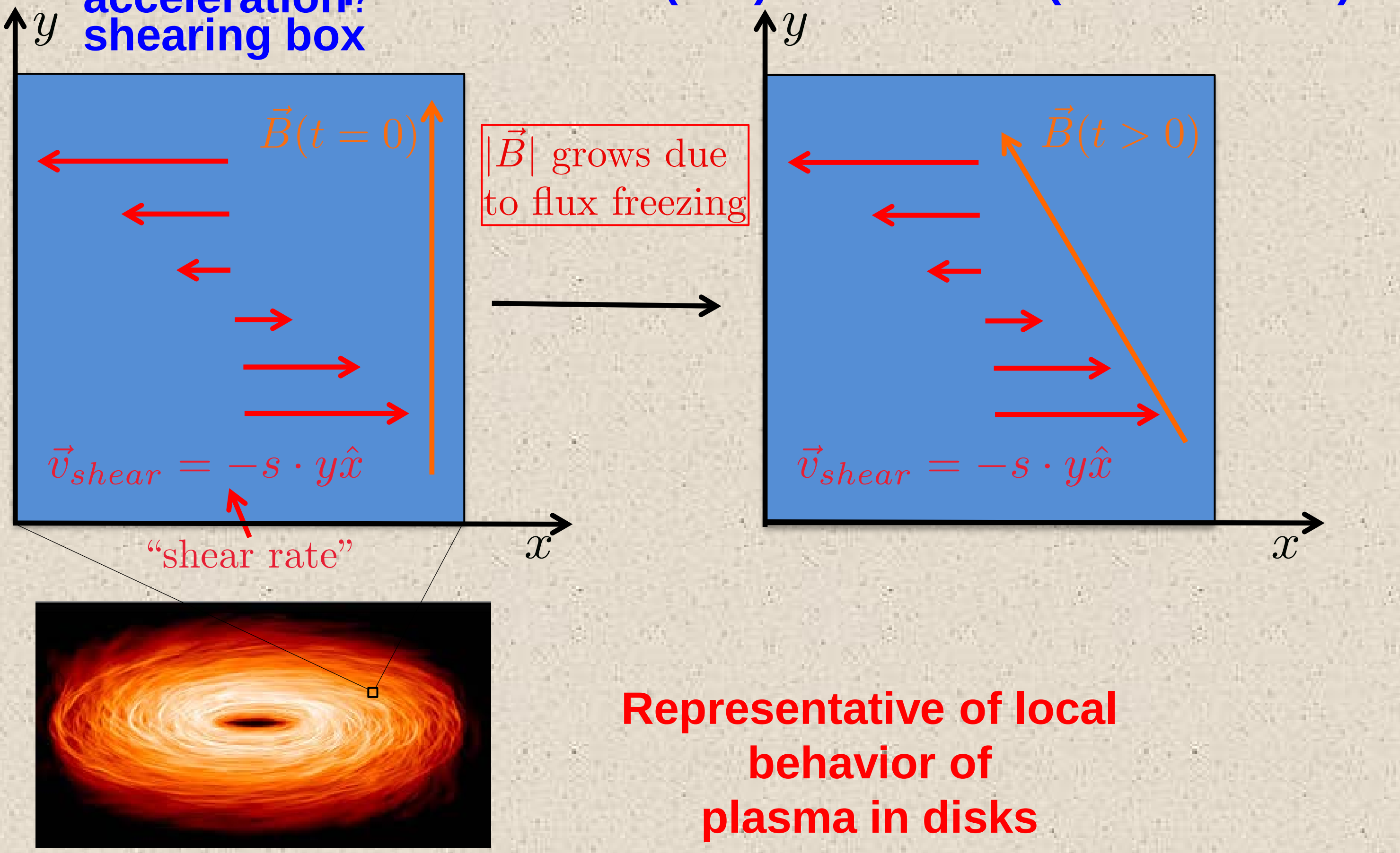

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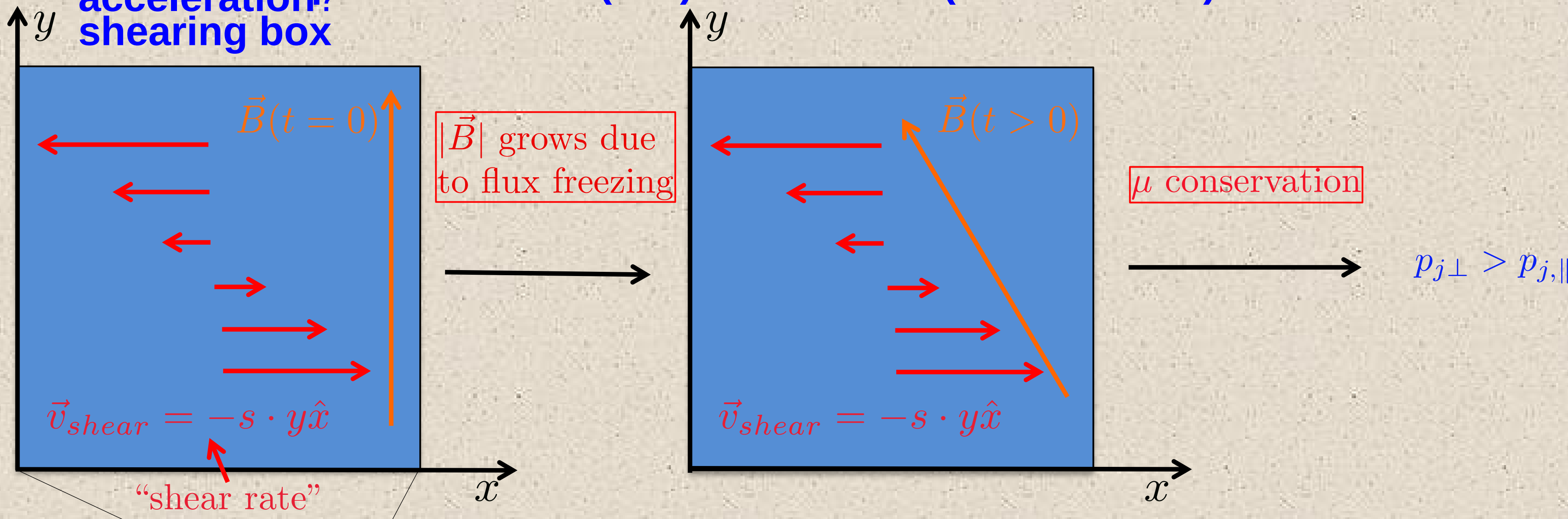

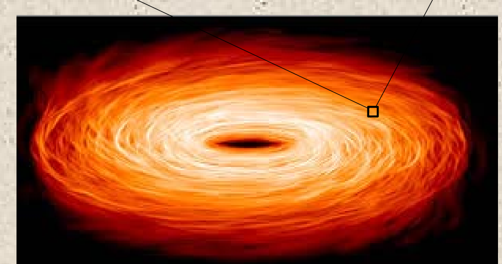

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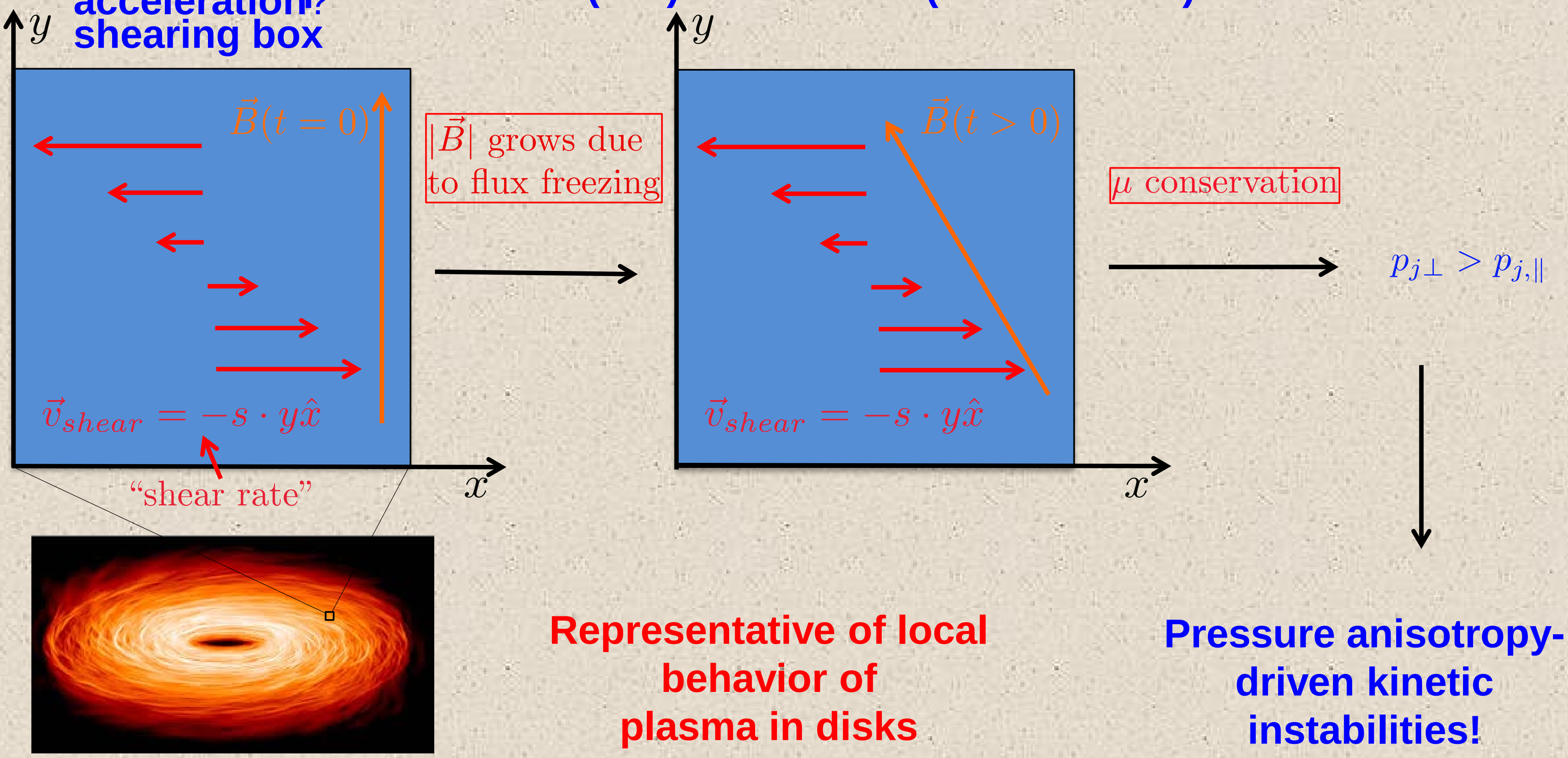

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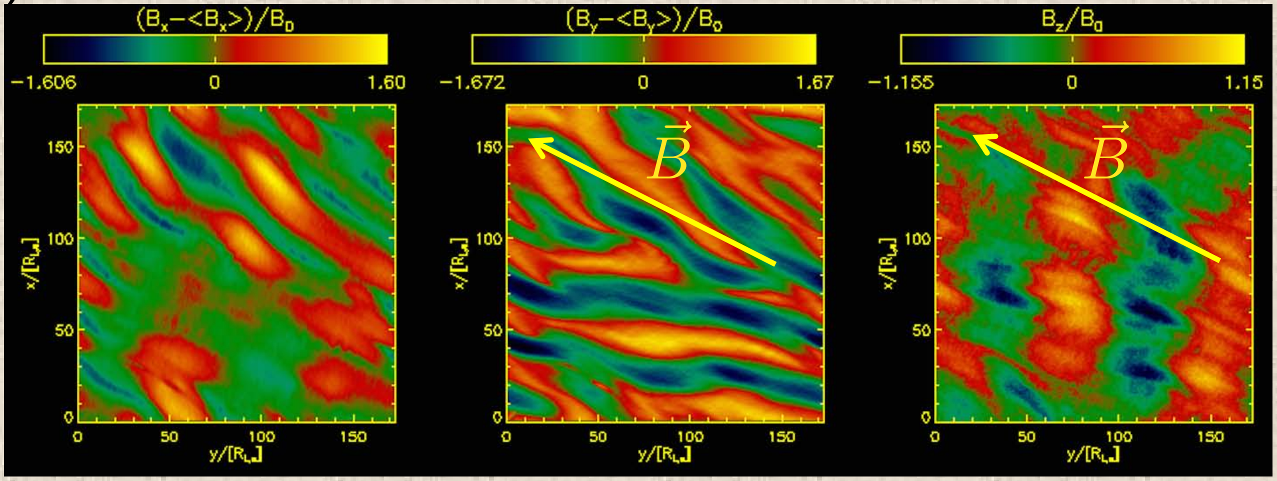
Pressure anisotropy-driven kinetic instabilities!

Example: run with **mi/me=128**.

Ion-cyclotron, **mirror**, and **whistler** instabilities are visible (Riquelme et al. 2016):



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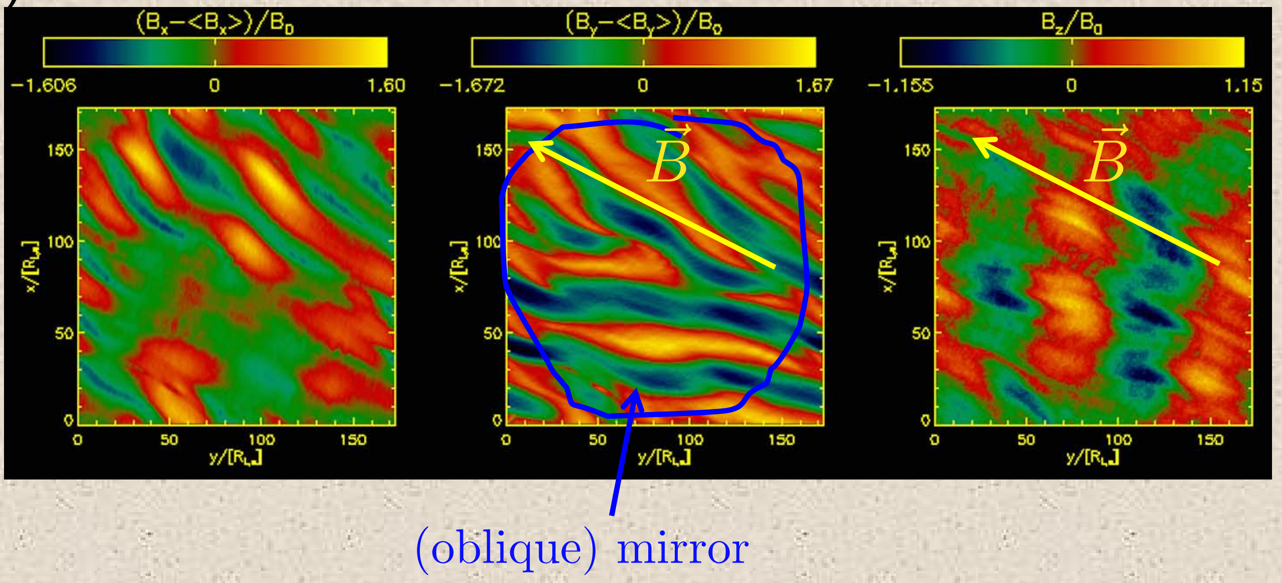

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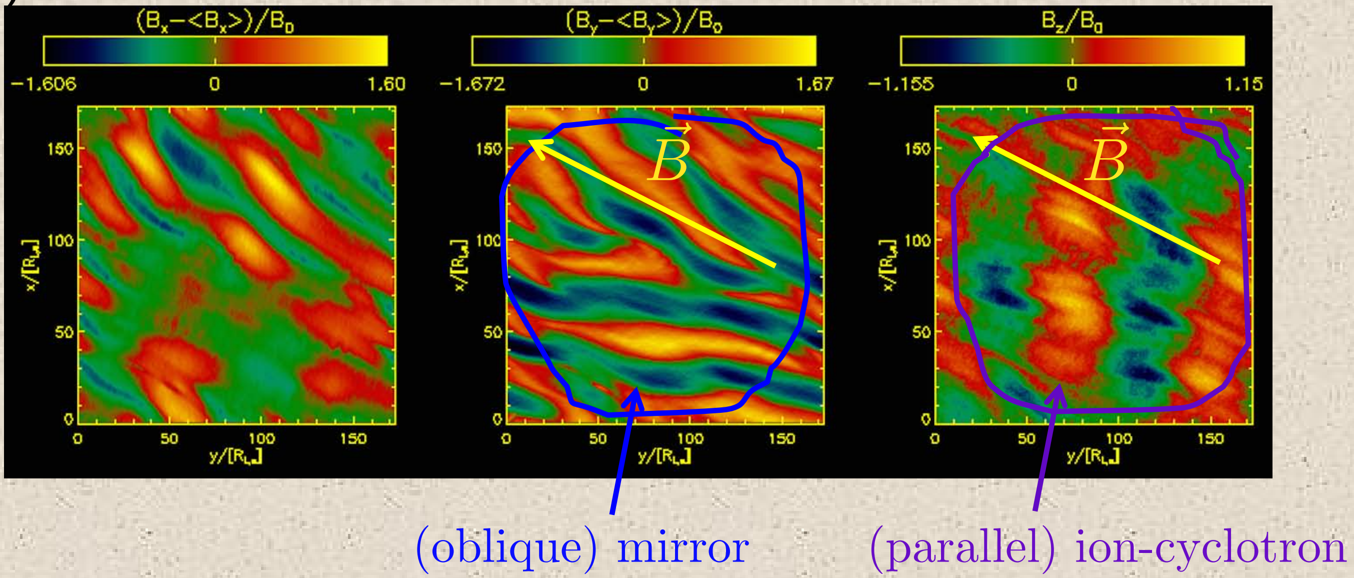

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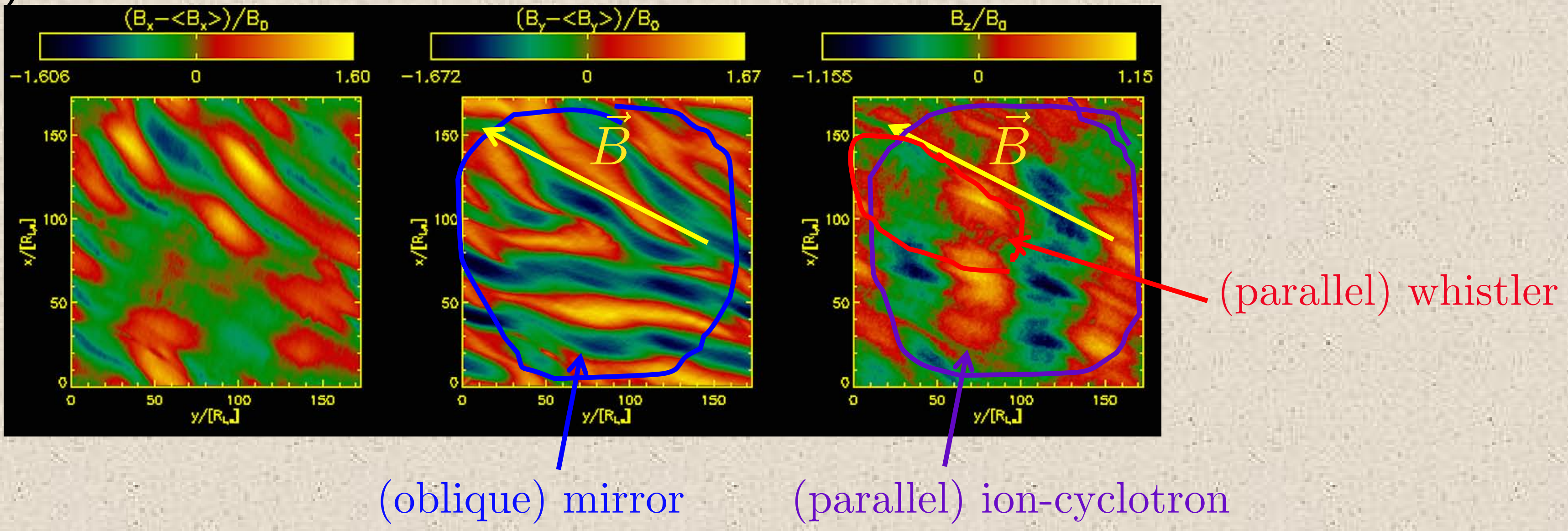

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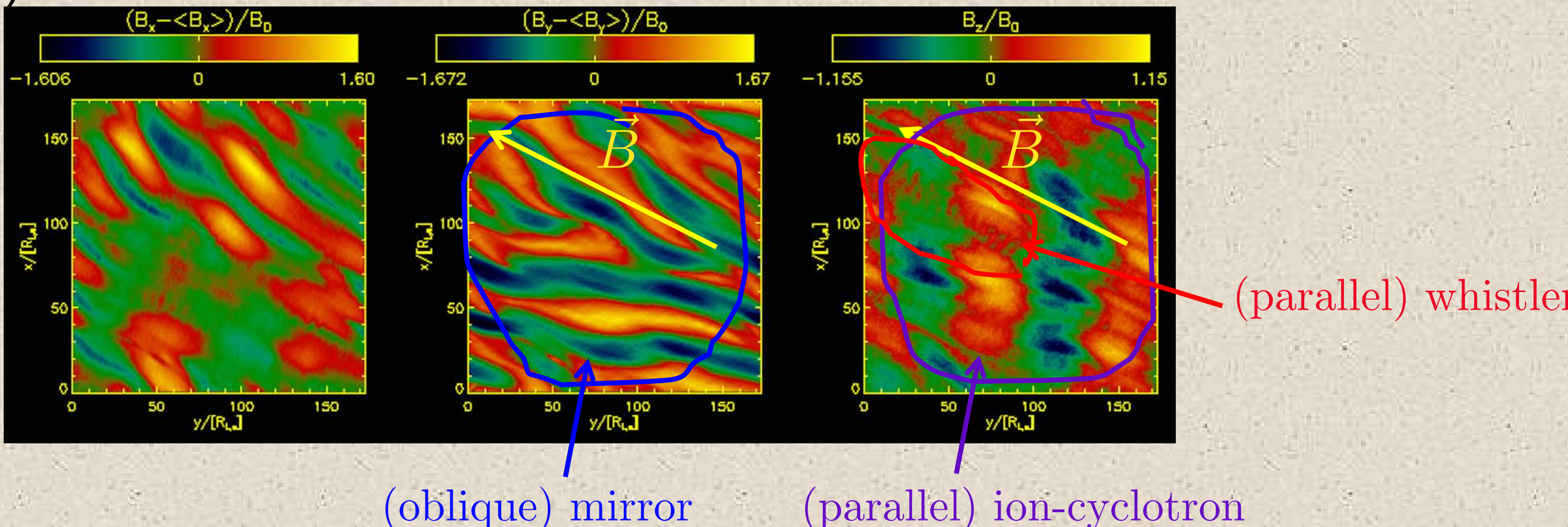

As long as $\beta_e \lesssim 10$ ($\beta_j \equiv 8\pi p_j/B^2$ is the ratio between the pressure of particles *j* and the magnetic pressure), the **electron anisotropy is dominated by the whistler instability**, with little influence of the ion-cyclotron and mirror instabilities.

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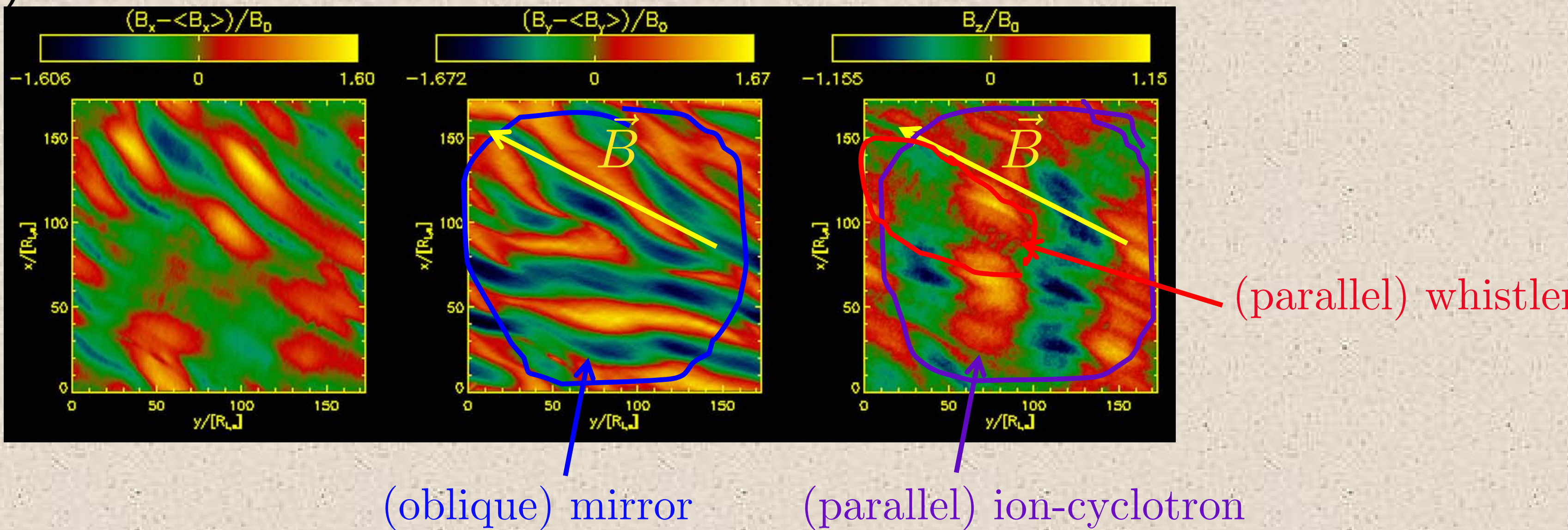

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=> As a first approach, we can neglect the ion physics and study the physics of the whistler instability assuming immobile ions (as if they had infinite mass).

Electron acceleration (Riquelme et al 2017):

We assume that ion-scale instabilities do not play any role. Thus we give ions infinite mass.

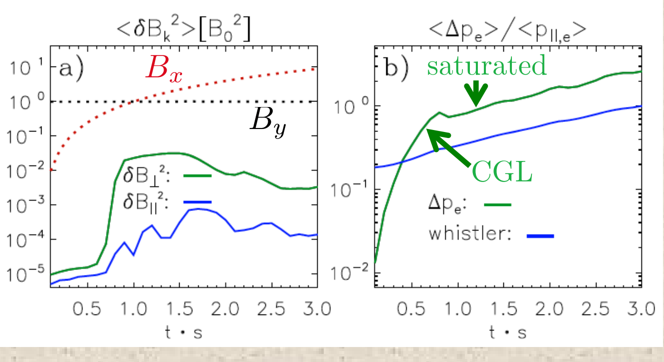
Example: case β_e^{init}=2, $k_B T_e/m_e c^2$=0.28.

$$t \cdot s \approx 0.7$$

At , there is the exponential growth of whistler m

saturate.

At the same time, the growth of pressure anisotropy also



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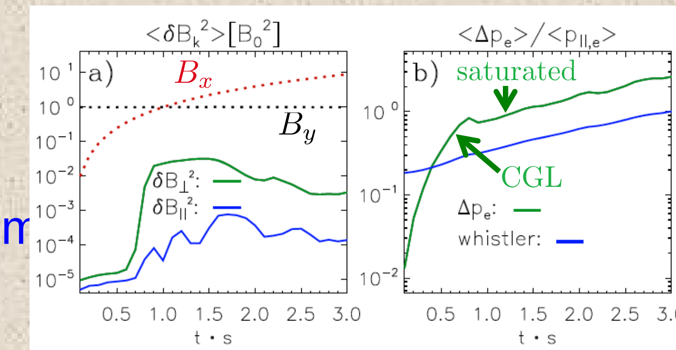

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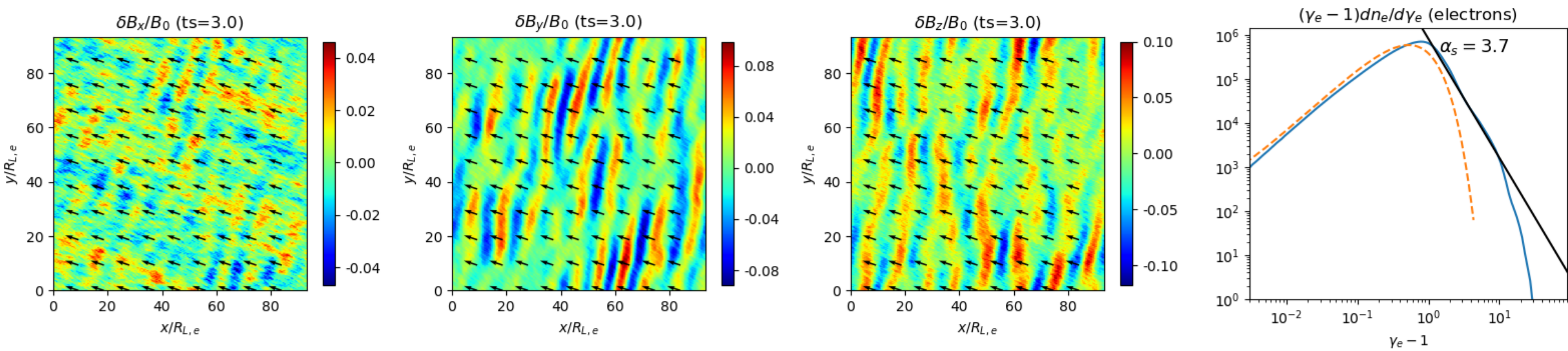


- After an amplification factor of ~3 ($s = 3$), the electron spectrum contains a non-thermal power-law tail of spectral index **α_s ~ 3.7**,

Close to the **α_s ~ 3.5** usually inferred from radio observations of the quiescent Sgr A*

(e.g., Yuan et al. 2003)

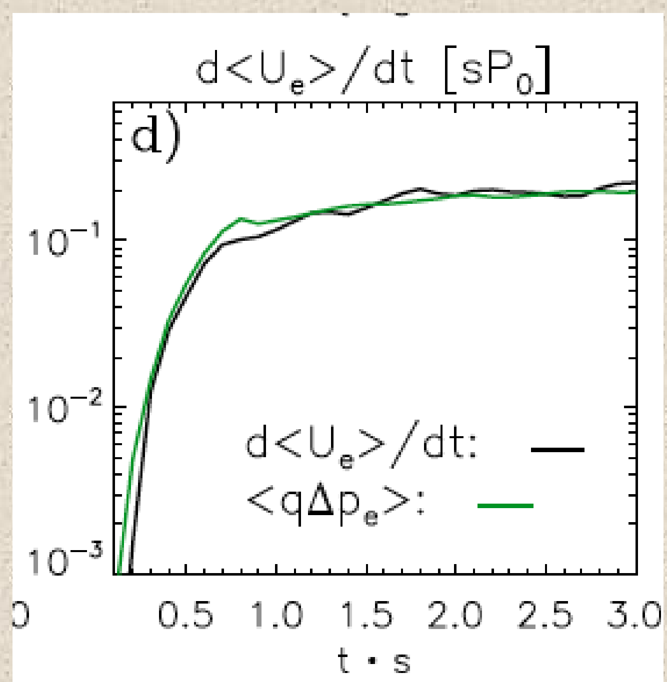
Electron acceleration:

But how does this electron energization work?

- **Anisotropic viscosity ("AV")**: it is possible to show that:

$$dU_j/dt = \Delta p_j q \quad \text{(Kulsrud et al 1983)}$$

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

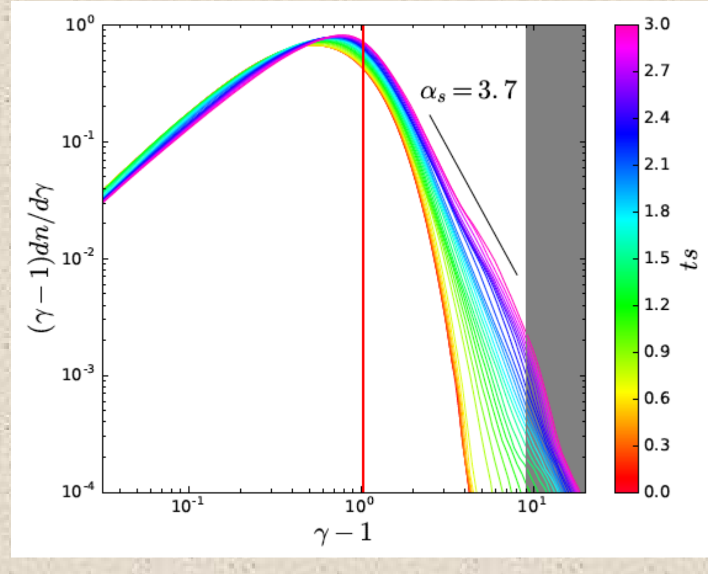


- The quantity $\langle q\Delta p_e \rangle$ accounts fairly well for the heating of the electrons.

Electron acceleration:

Spectrum evolution:

case $kT_e/m_ec^2=0.28$; $\beta_e=2$



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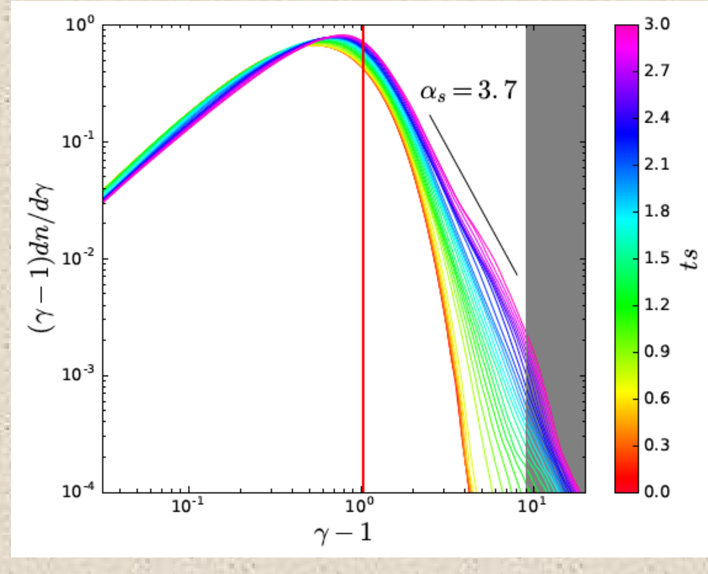
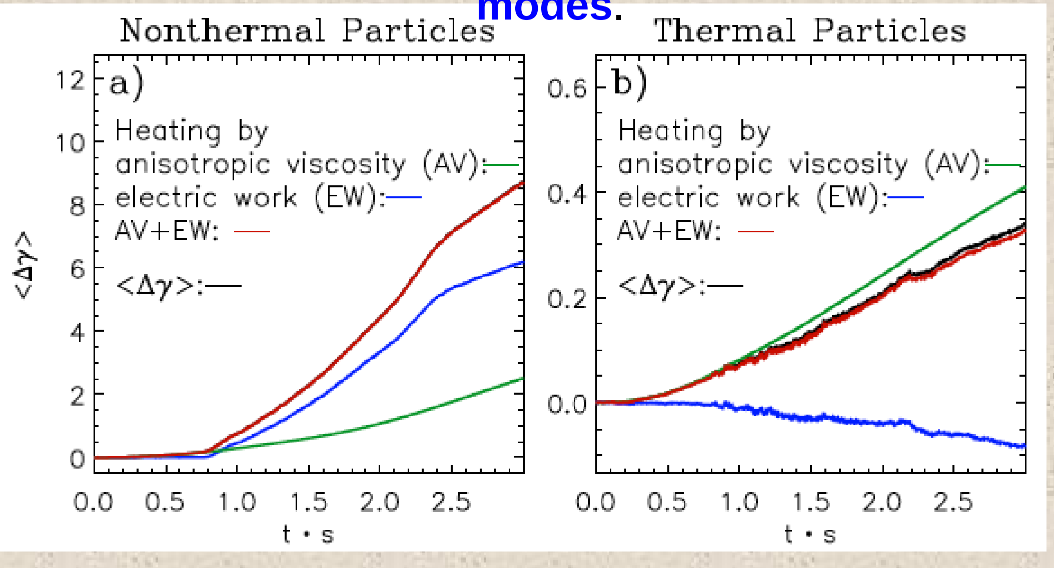


Acceleration mechanism

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



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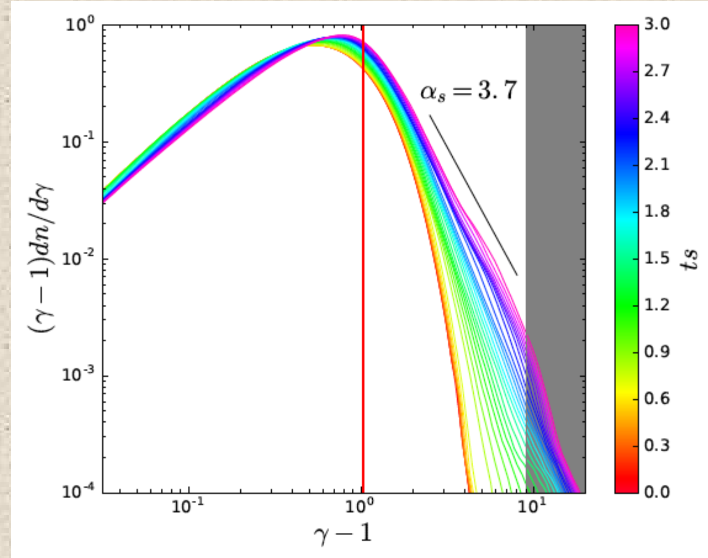

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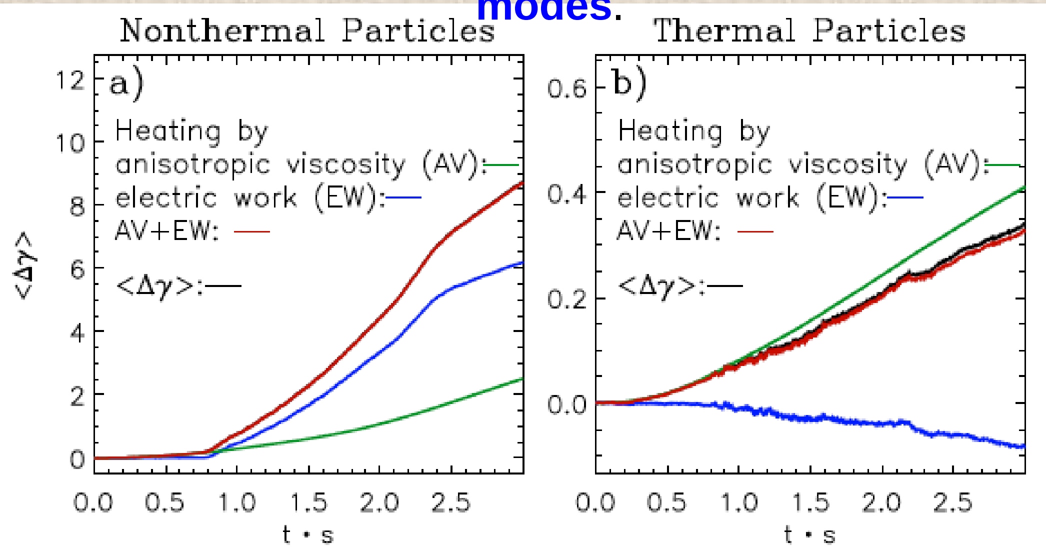
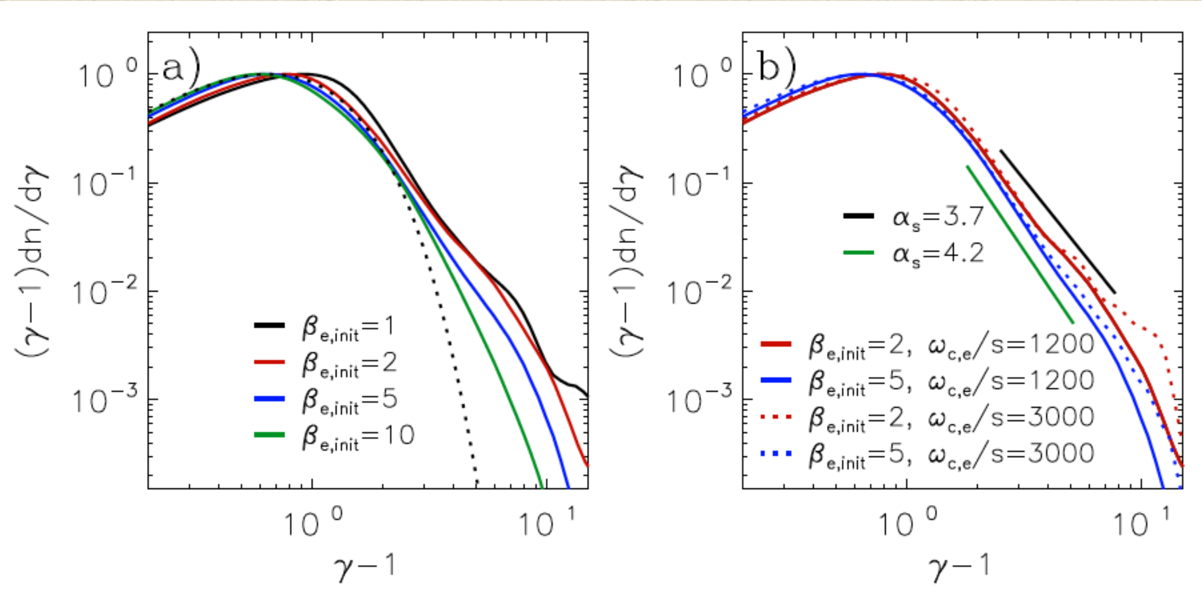


- The thermal electrons **give energy** to the whistler waves.
- The non-thermal electrons **receive energy** from the waves.

Electron acceleration: Dependence on plasma parameters

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



kT_e/m_ec^2=0.28

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

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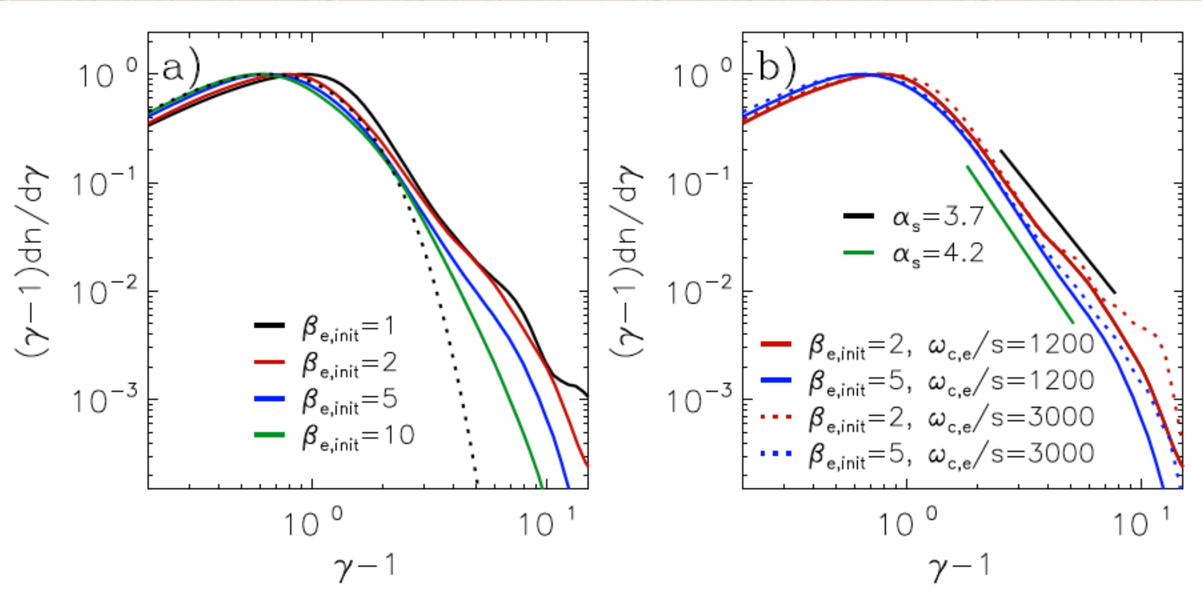

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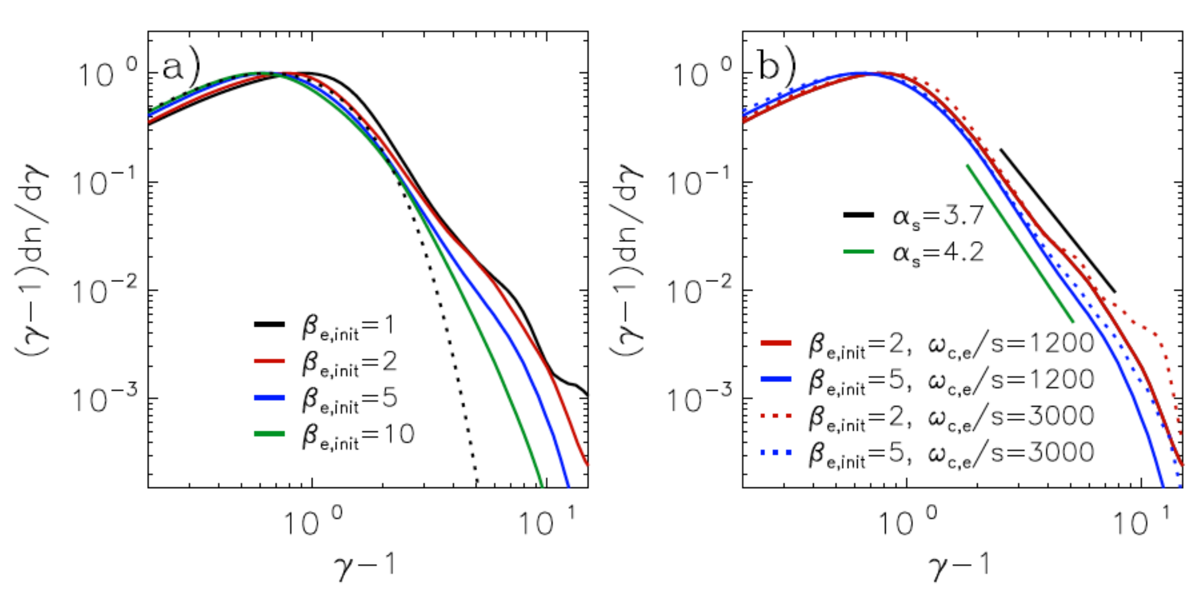

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$\omega_{c,e}$: cyclotron frequency of the electrons
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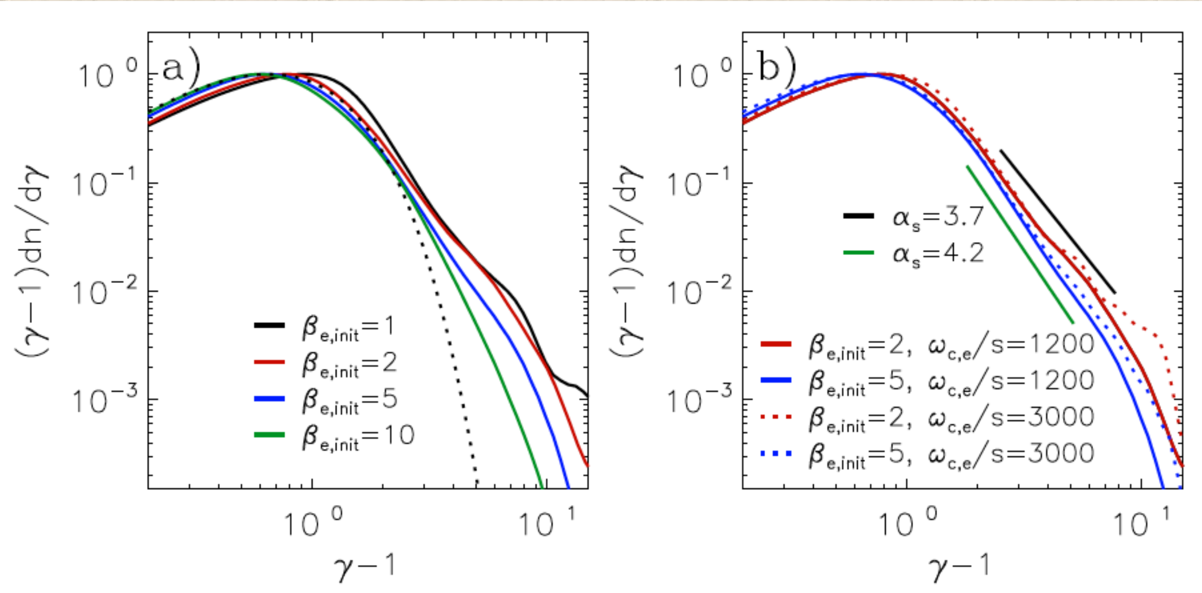

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- However, for a fixed value of $\beta_{e,init}$ the electrons can have different temperatures **kT_e/m_ec^2**.

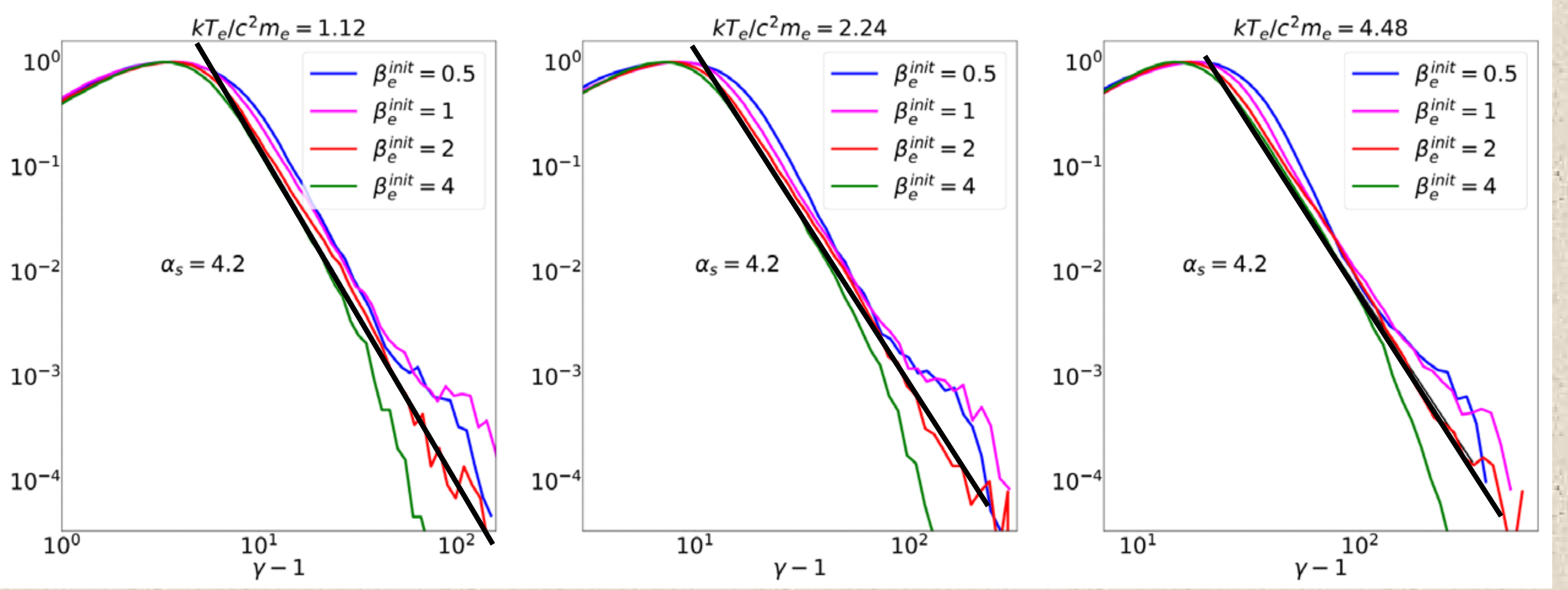
We are currently studying this dependence

Electron acceleration: Dependence on plasma parameters

Dependence on $k_B T_e/m_e c^2$ -> relativistic electrons regime (work in progress):

Electron acceleration: Dependence on plasma parameters

Dependence on k_BT_e/m_ec^2 -> relativistic electrons regime (work in pr



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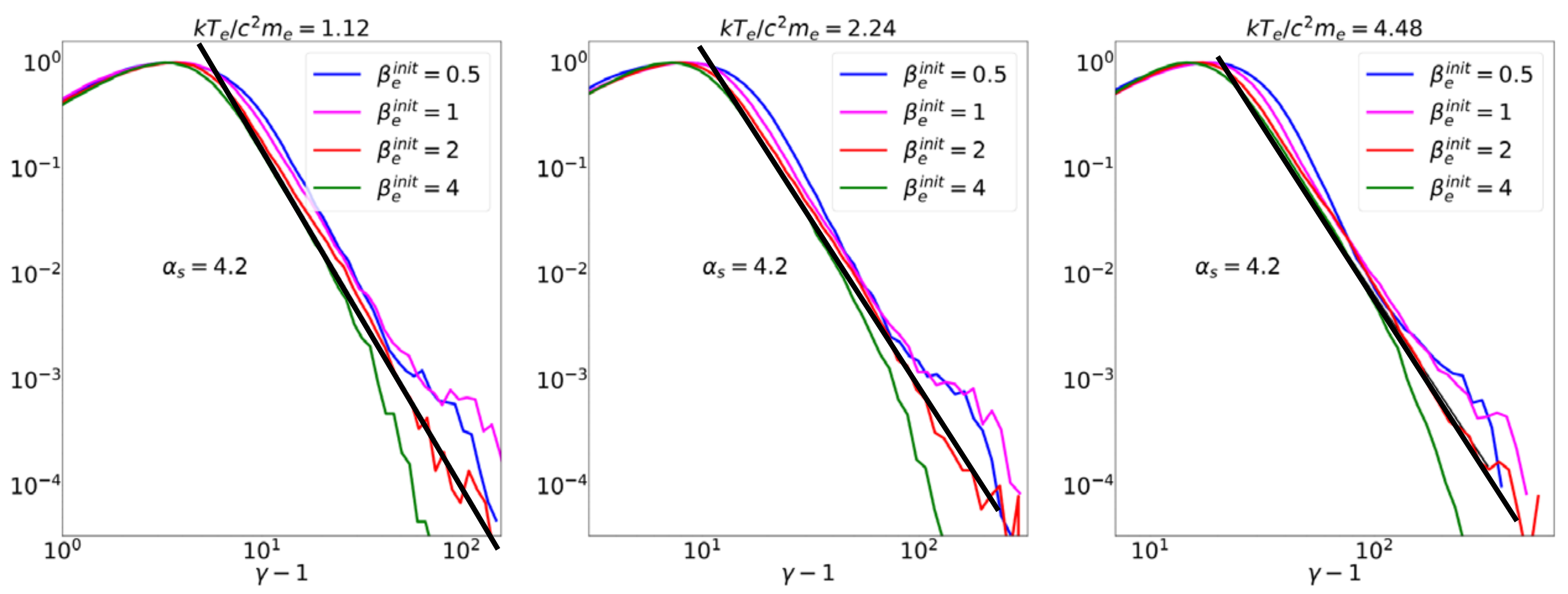

We see essentially the same dependence on β_e^{init}:

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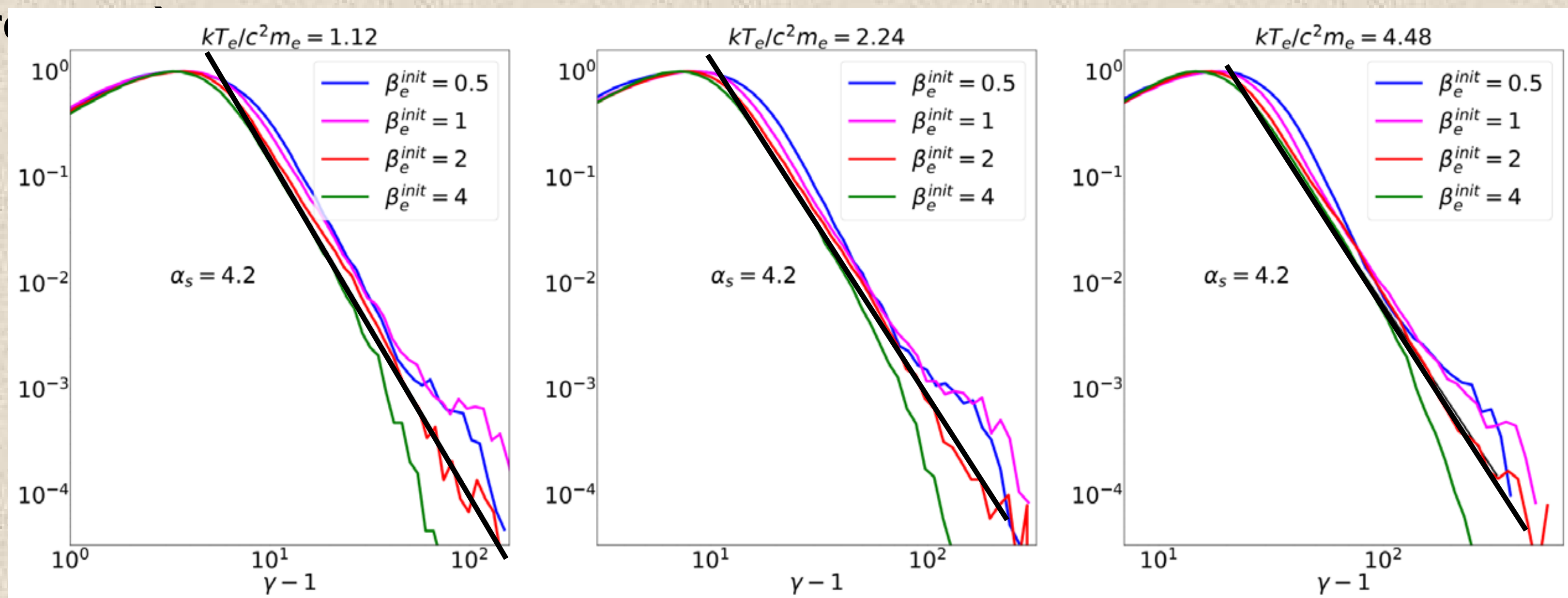
Electron acceleration: Dependence on plasma parameters

Dependence on k_BT_e/m_ec^2 -> relativistic electrons regime (work in pr



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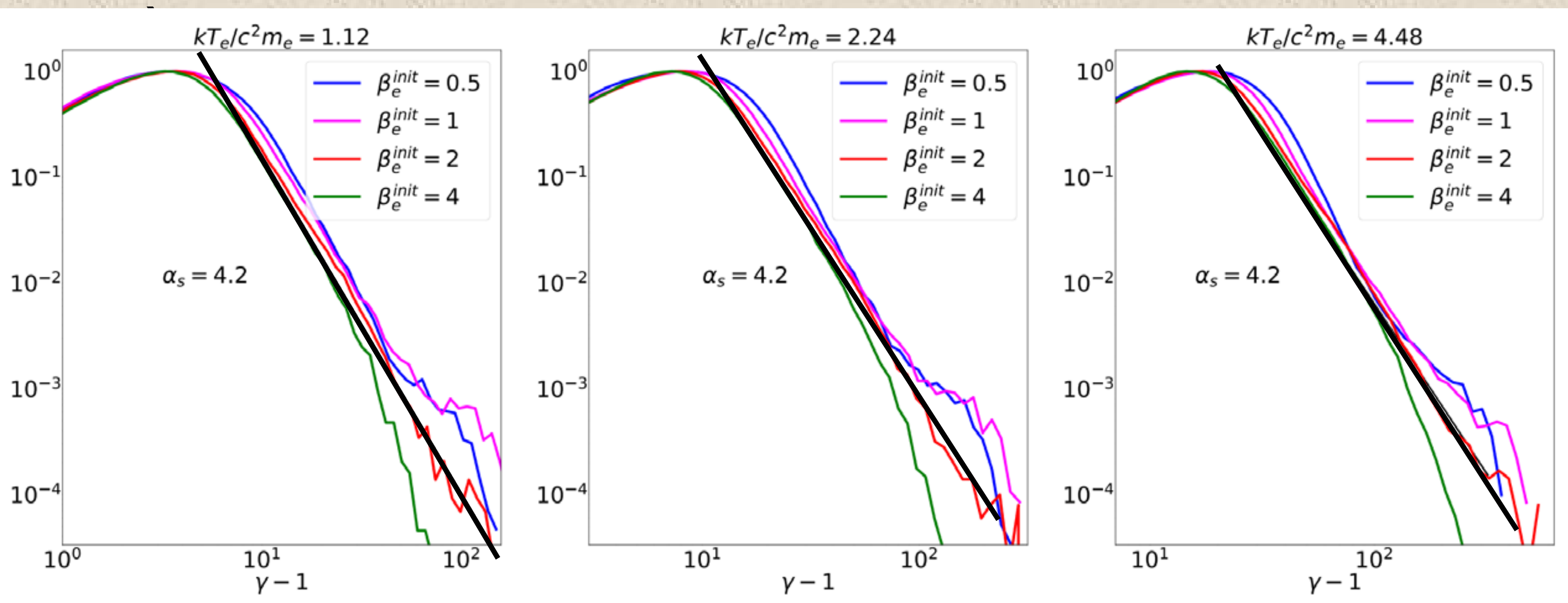

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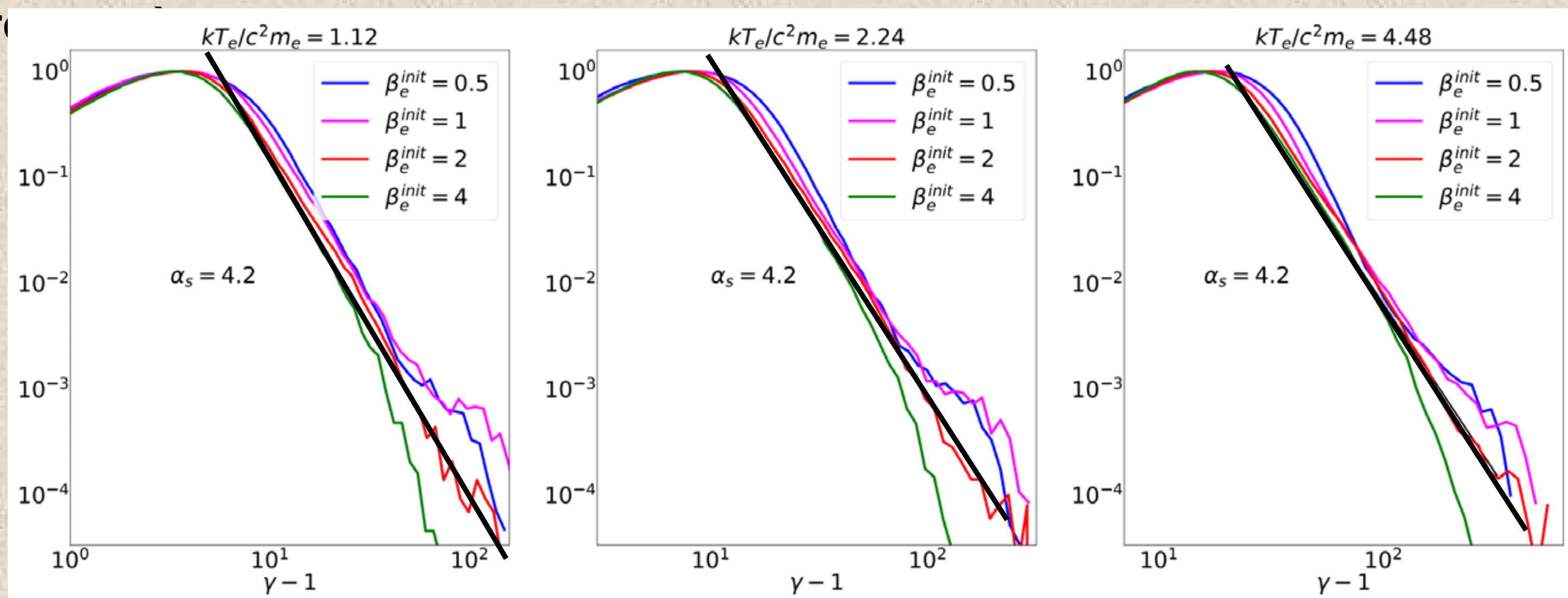

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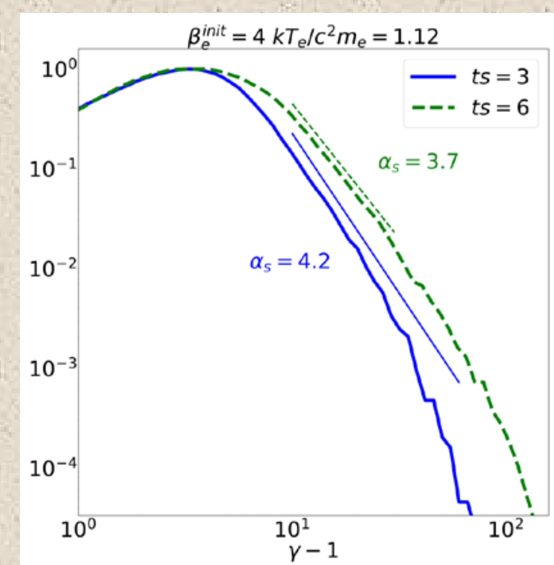
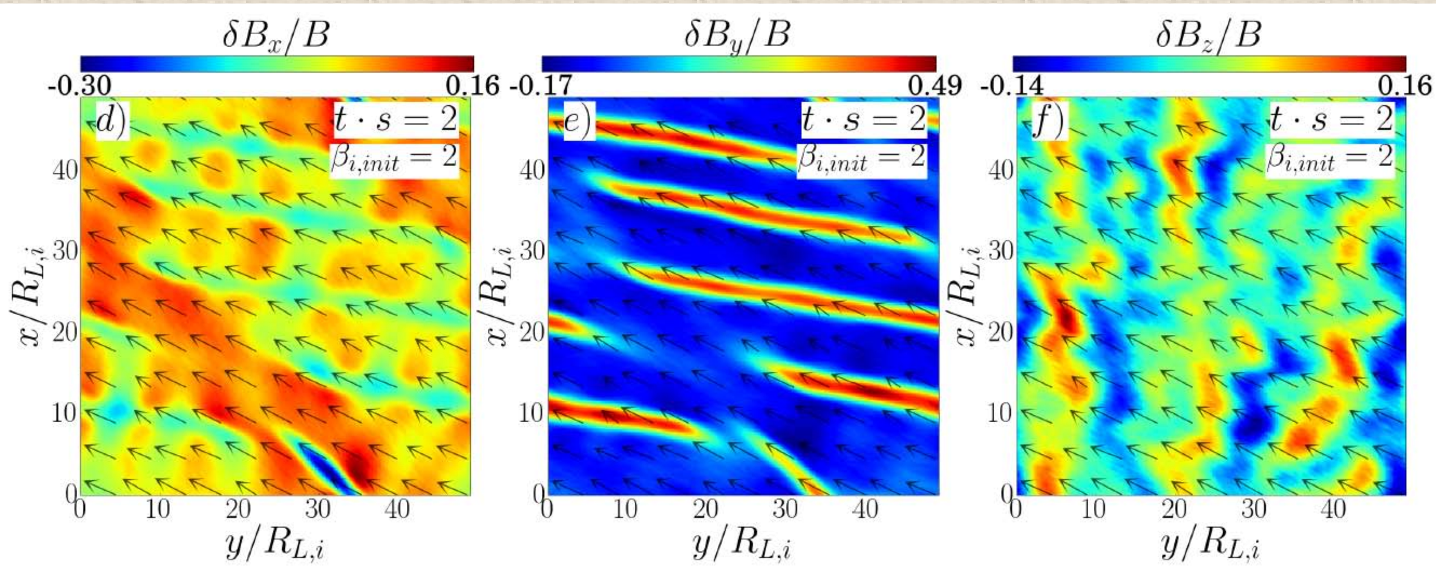
- Although once the $k_BT_e/m_ec^2 \gtrsim 1$ regime is reached, there is not further decrease in the acceleration efficiency as k_BT_e/m_ec^2 grows.
- Interestingly, if B is amplified by a factor larger than ~3, a power-law with index~3.7 is recovered.



Can **ions** be accelerated as well?

2) **Ion Acceleration:** more than one instability

In the case of ions, under typical conditions, there is **not a single electromagnetic mode** regulating the anisotropy:



Simulation with

β_i=2, m_i/m_e=2

Depending on the δB component, one can see different modes:

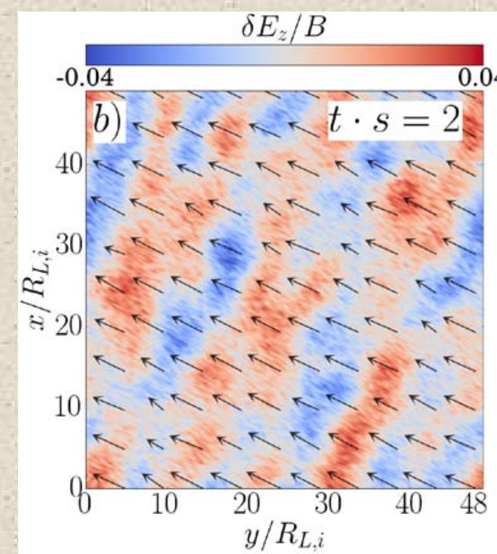
Mirror:
oblique modes

Ion-cyclotron (IC):
quasi-parallel mode

- The dominance of the mirror and **IC modes** is **important if we are interested in ion acceleration**. This is because only the IC modes have finite phase velocity (mirror modes are "purely growing").

- This can be seen by looking at the **electric field**, which is **correlated with the IC modes** only

- However, there is the theoretical expectation that the **IC instability should dominate for** β_i <~1 (if



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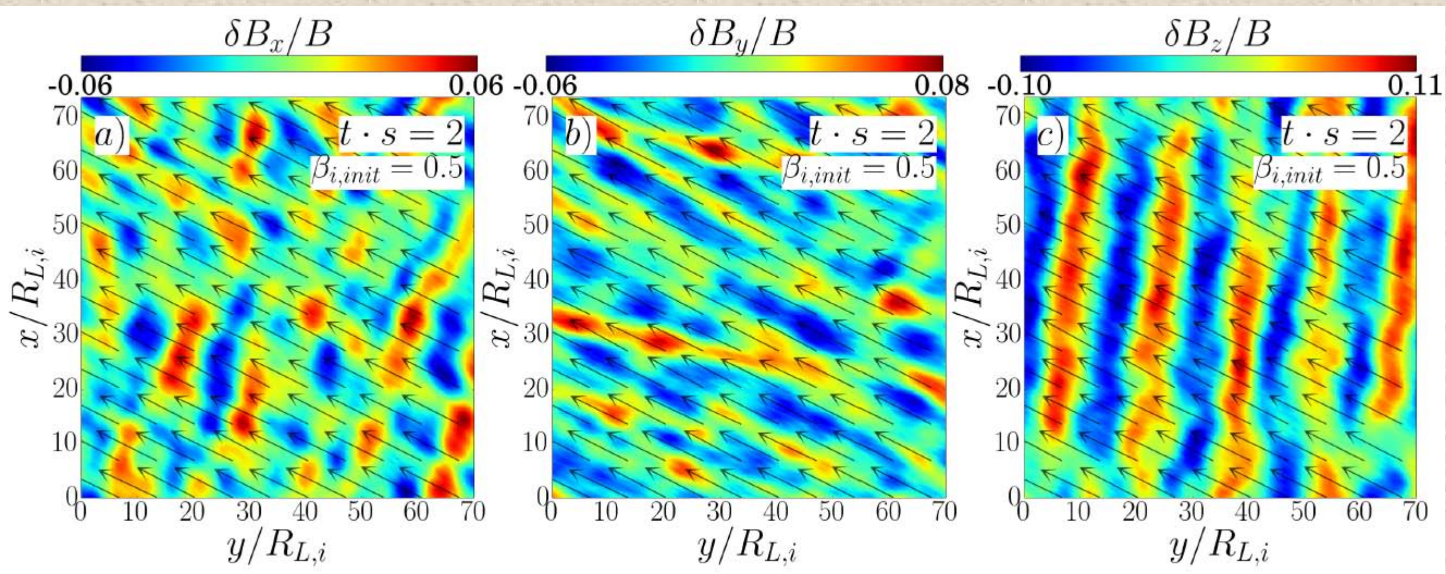

Simulation with $\boldsymbol{\beta_i=0.5}$, $m_i/m_e=2$
Depending on the δB component, one can see different modes:

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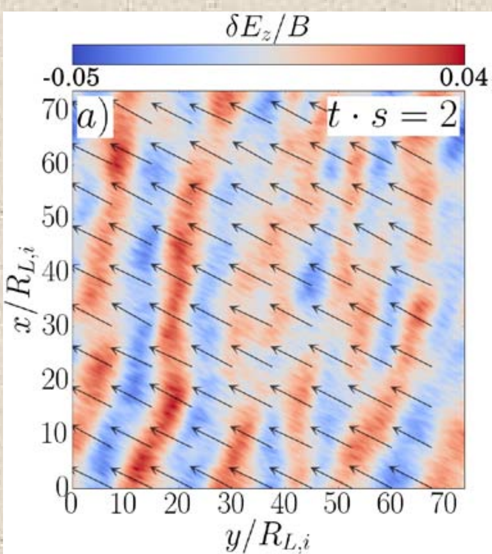
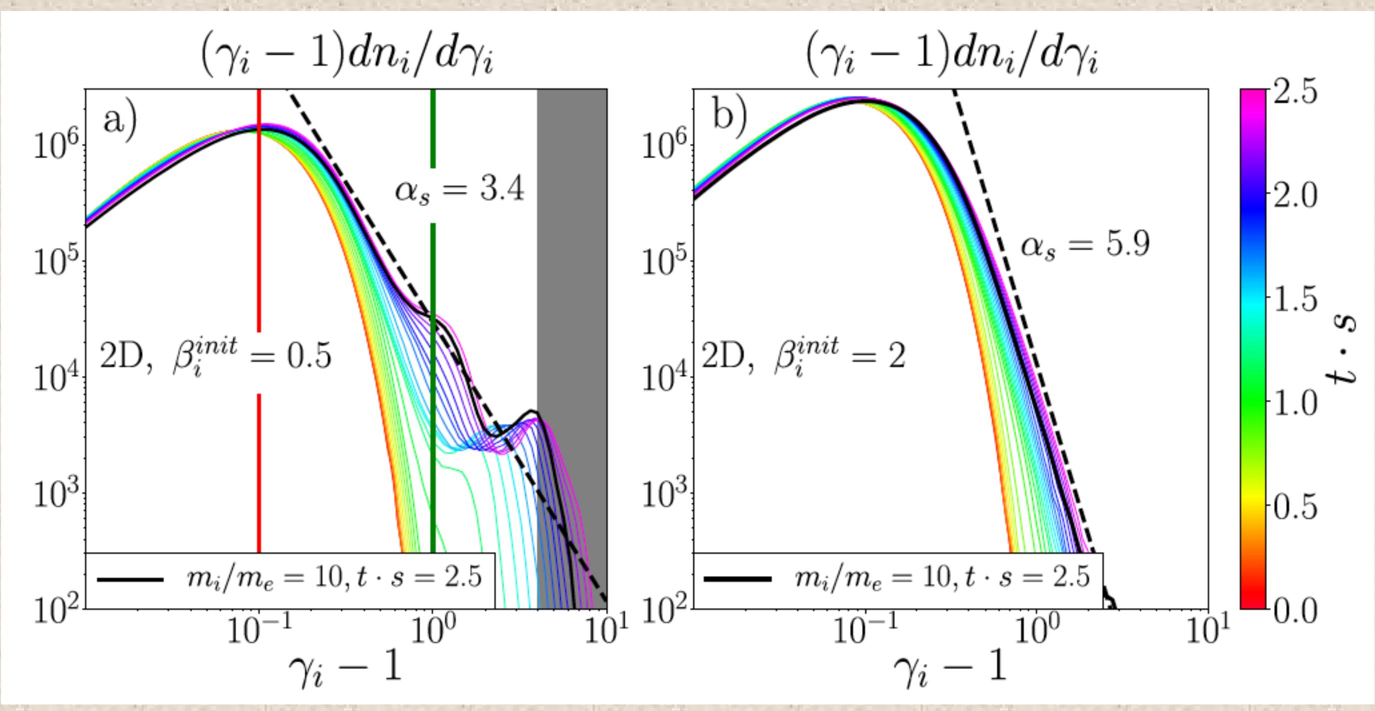


2) Ion Acceleration:

Case: β_i^{init}=0.5, kT_i/m_ic^2=0.05, ω_{ci}/s=800, m_i/m_e=2

When the IC instability dominates (β_i^{init}=0.5), ions show a “bumpy” power-law tail with α_s~3.4.

2) Ion Acceleration: spectra in different β_i regimes



- **kT_i/m_ic^2=0.05**
- **ω_{ci}/s=800**
- **m_i/m_e=2 and 10**

(Ley, MR, et al 2019)

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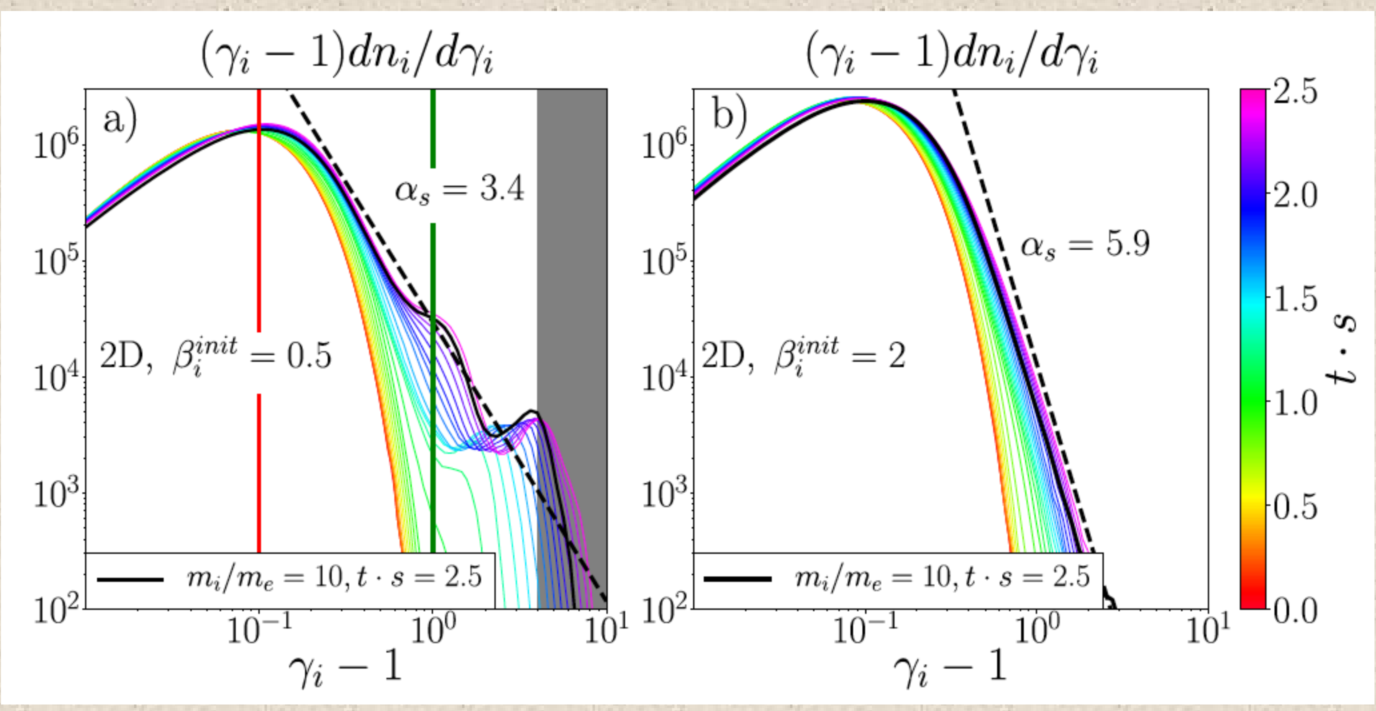

- $kT_i/m_ic^2=0.05$
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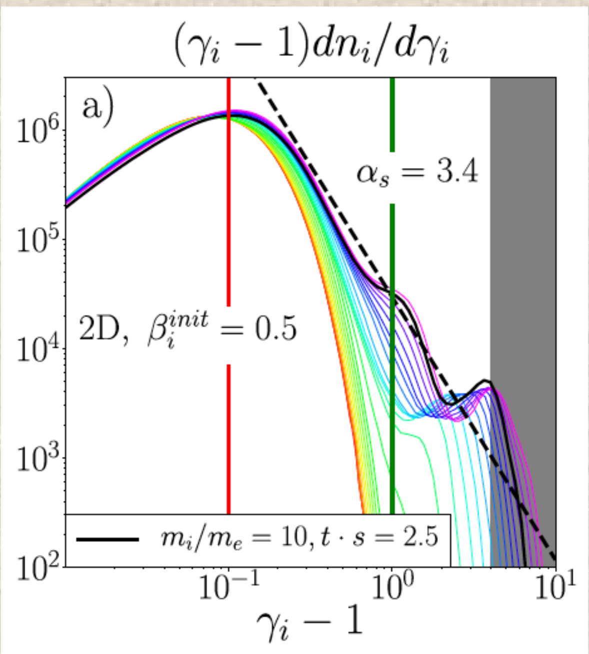
- **m_i/m_e=2 and 10**

(Ley, MR, et al 2019)

- 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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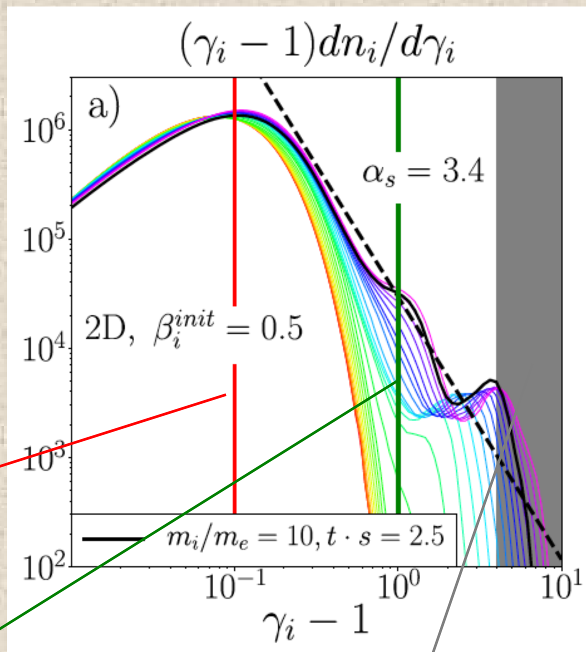

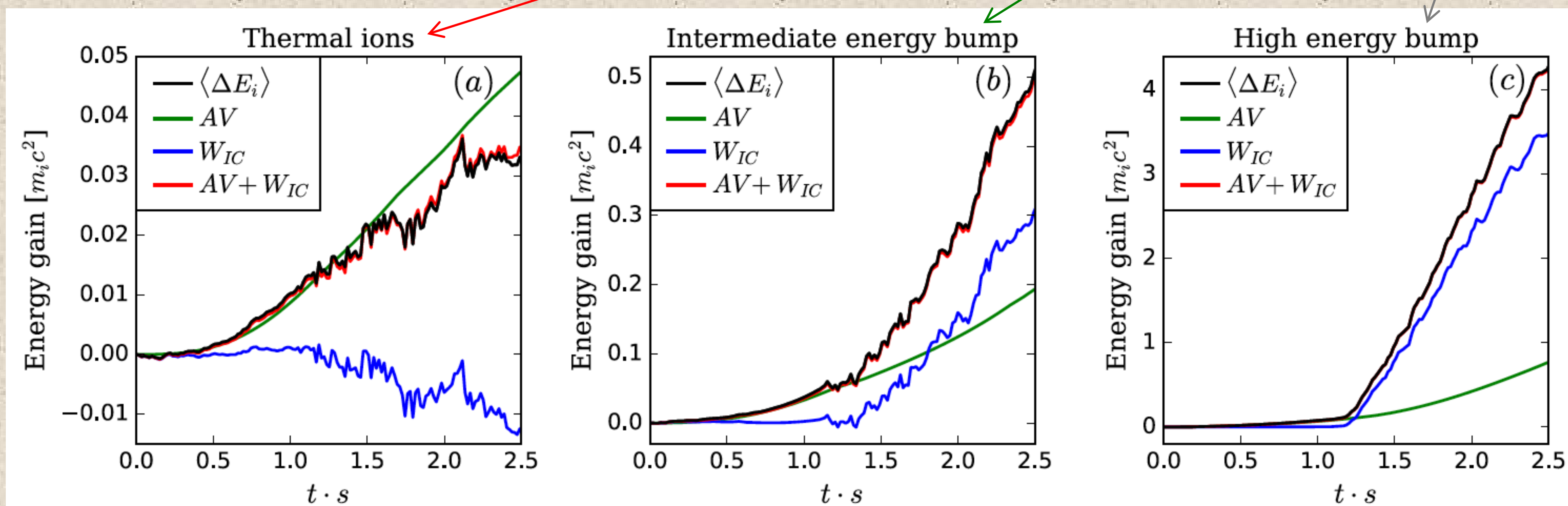

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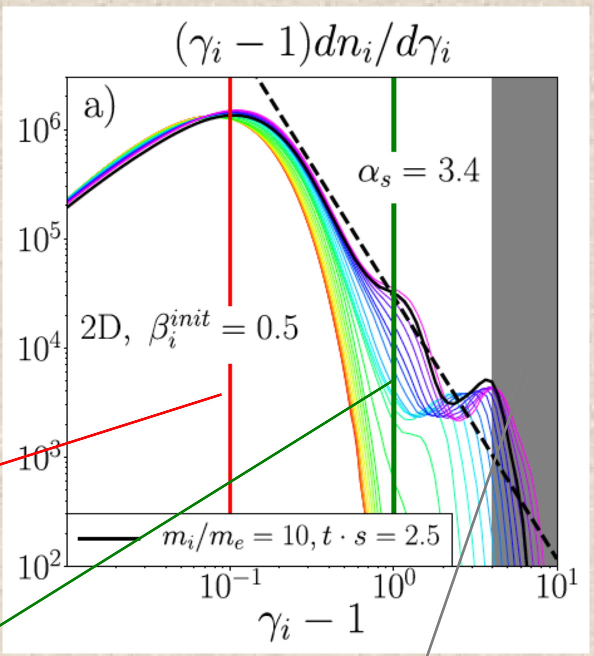

- The electric field of the **IC modes transfers energy from the thermal to the non-thermal ions**, similarly to what whistler waves do it with the electrons.

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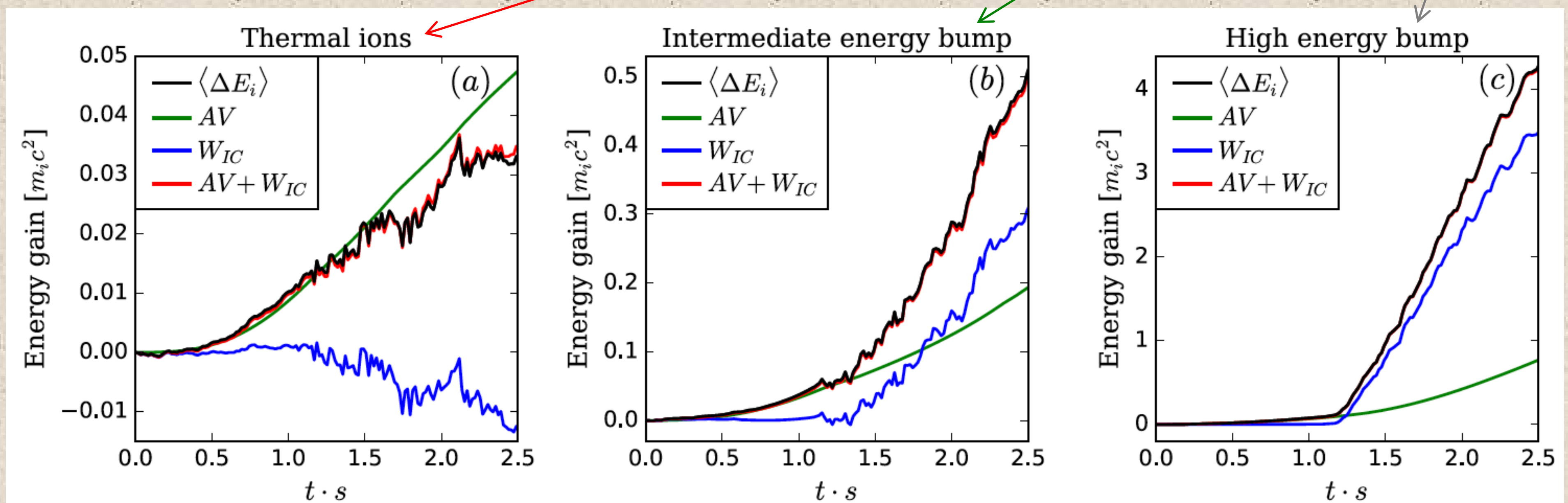
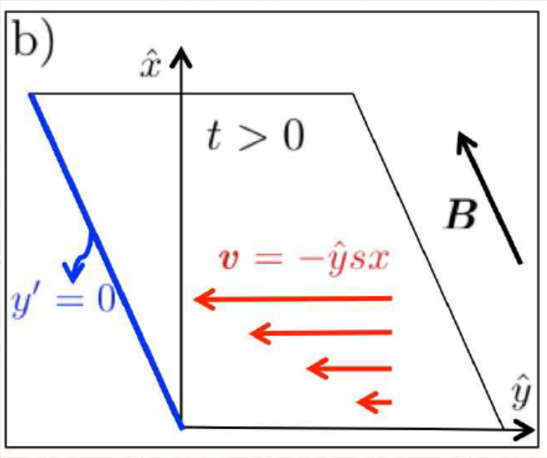


2) Ion Acceleration:

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



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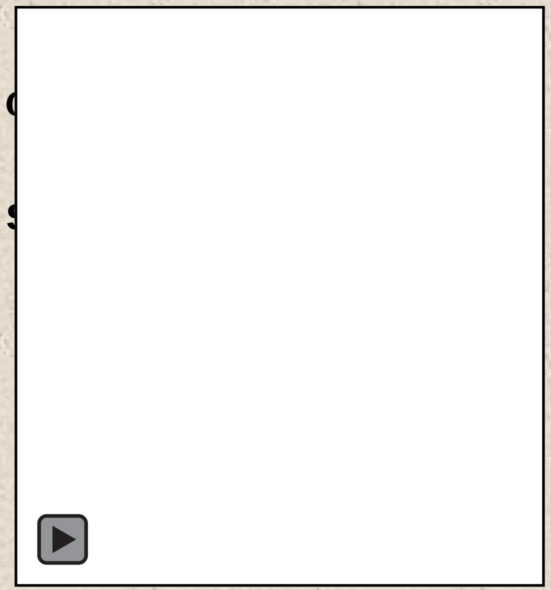
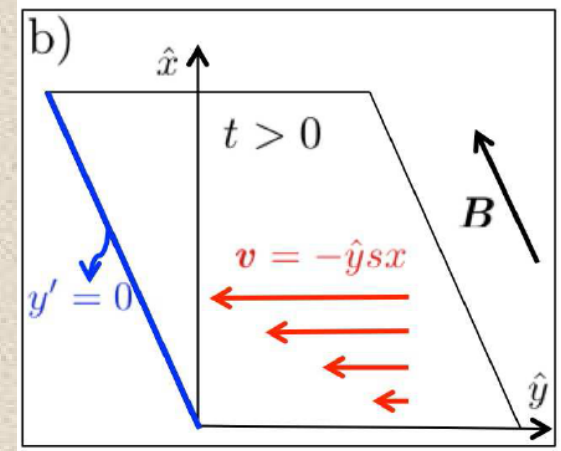


Pushing m_i/m_e and

using 1D



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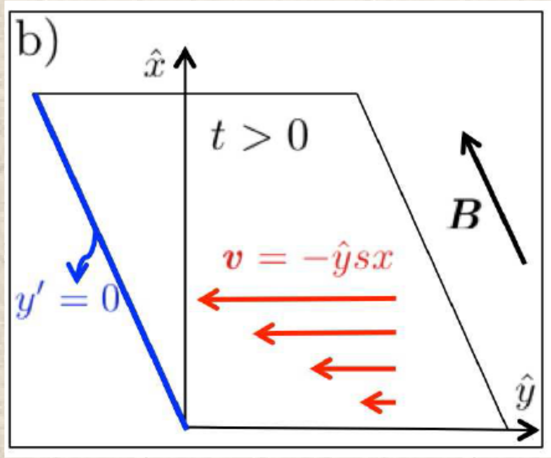

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- Also **little difference** when increasing magnetization

- Although some trend to make the **spectra slightly harder for larger ω_{ci}/s.**

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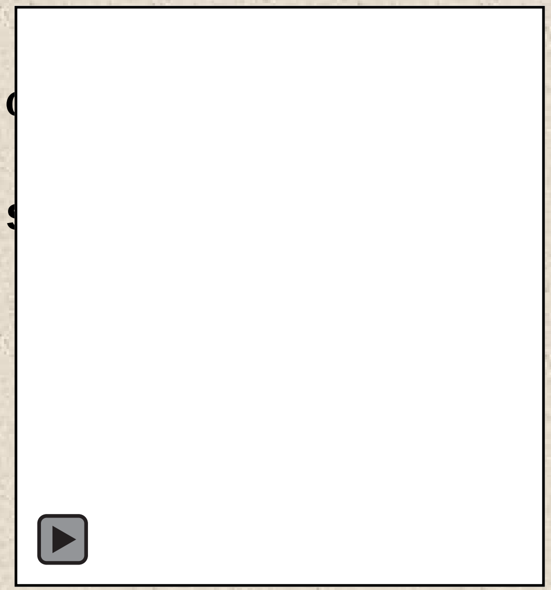

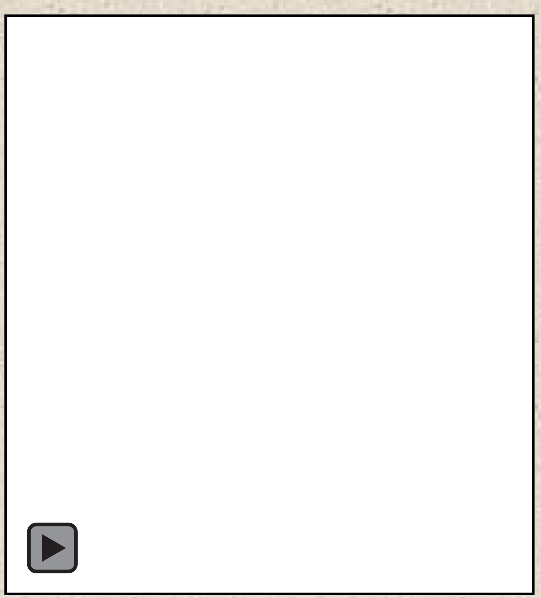

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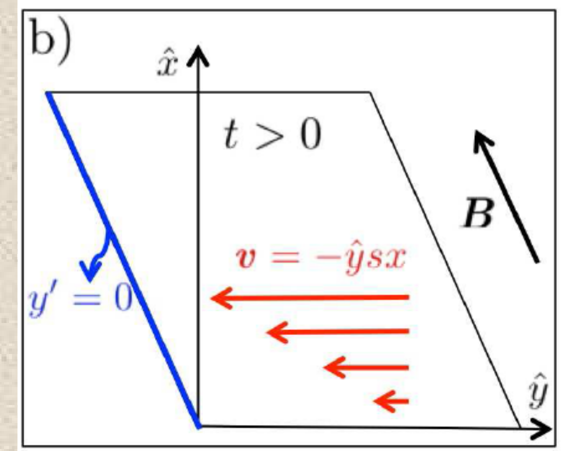

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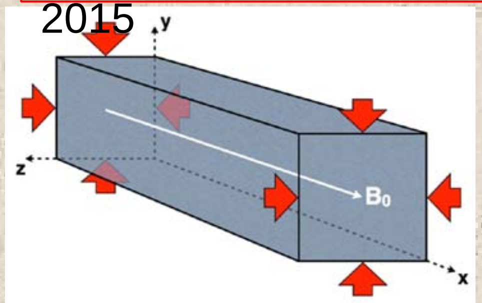
- Another interesting test:

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

2) Ion Acceleration: Testing the process using compressing box

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

Setup of Sironi et al 2015



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

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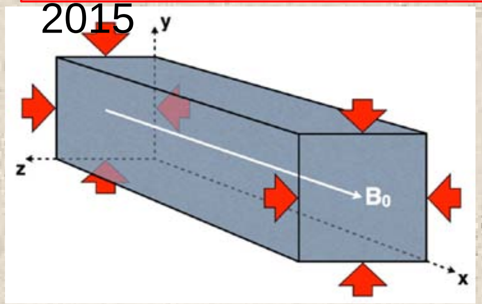

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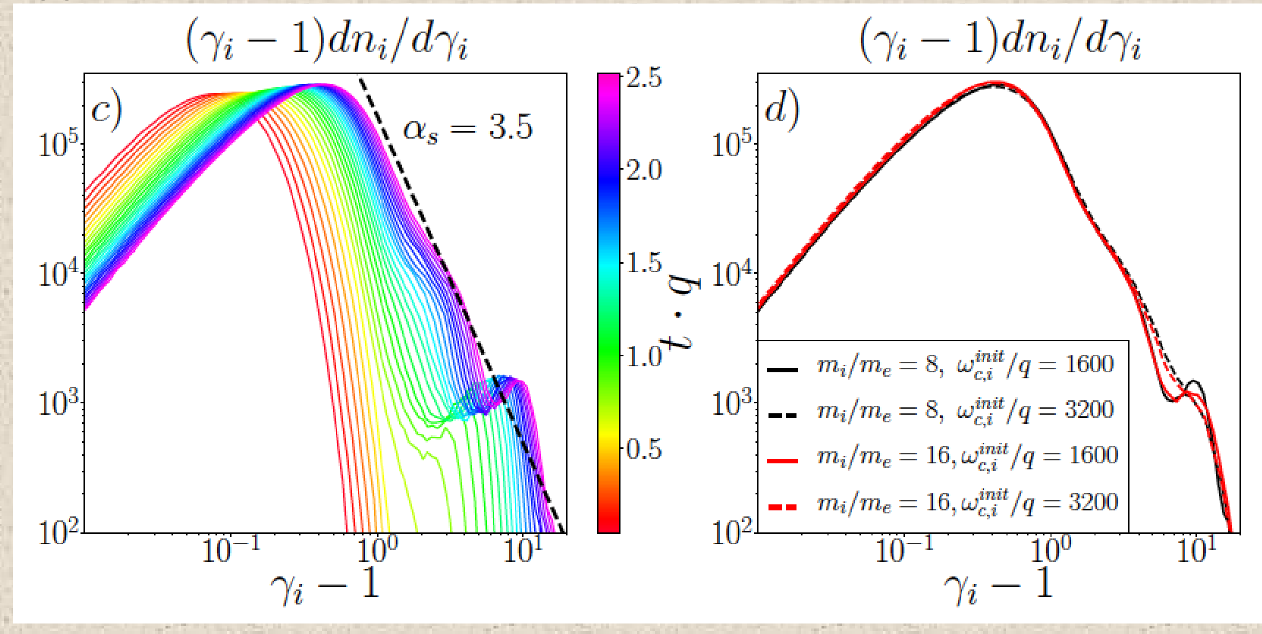

- Essentially **no difference between mi/me=8 and 16**.

- **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) doesn't matter!**

2) Ion Acceleration: the effect of $k_B T_i/m_i c^2$ and T_e/T_i (work in progress)

Previous studies show that the IC instability can dominate even for $\beta_i^{init} > 1$ if $T_e/T_i \ll 1$ (e.g., Sironi et al 2015) -> relevant for low-luminosity accretion flows

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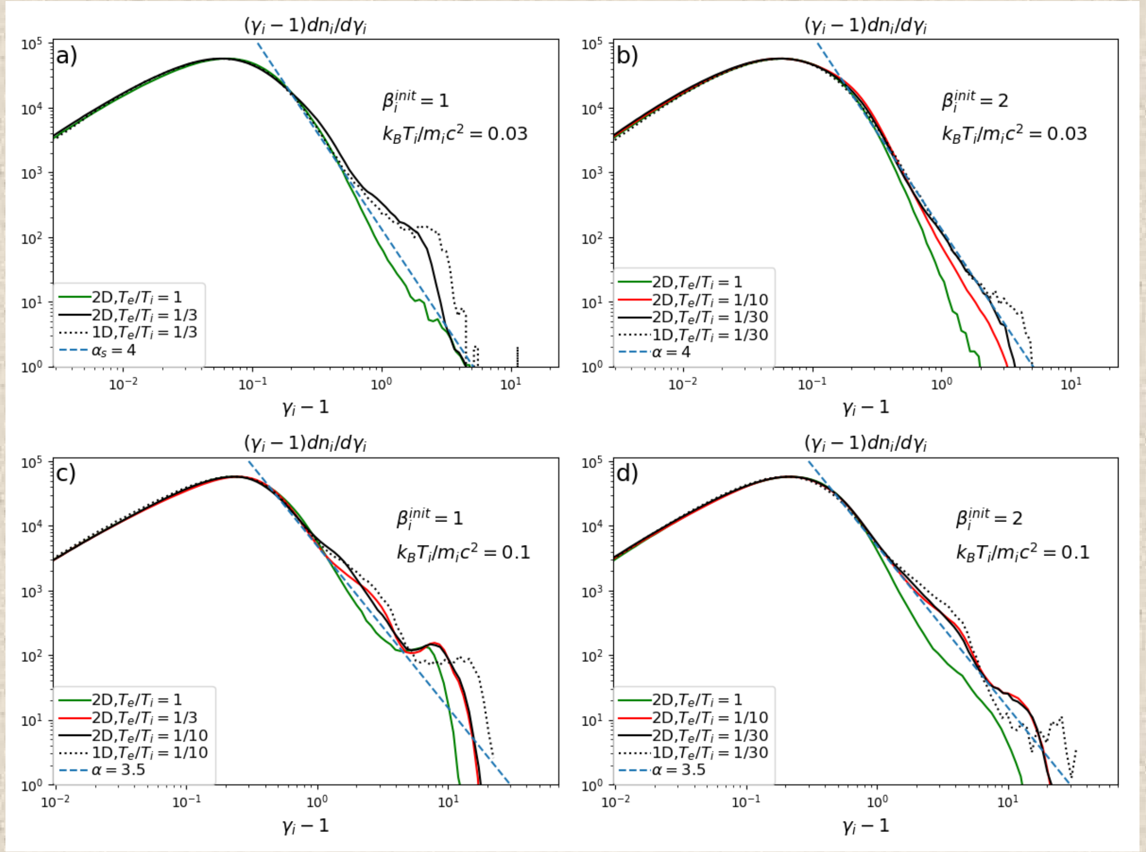

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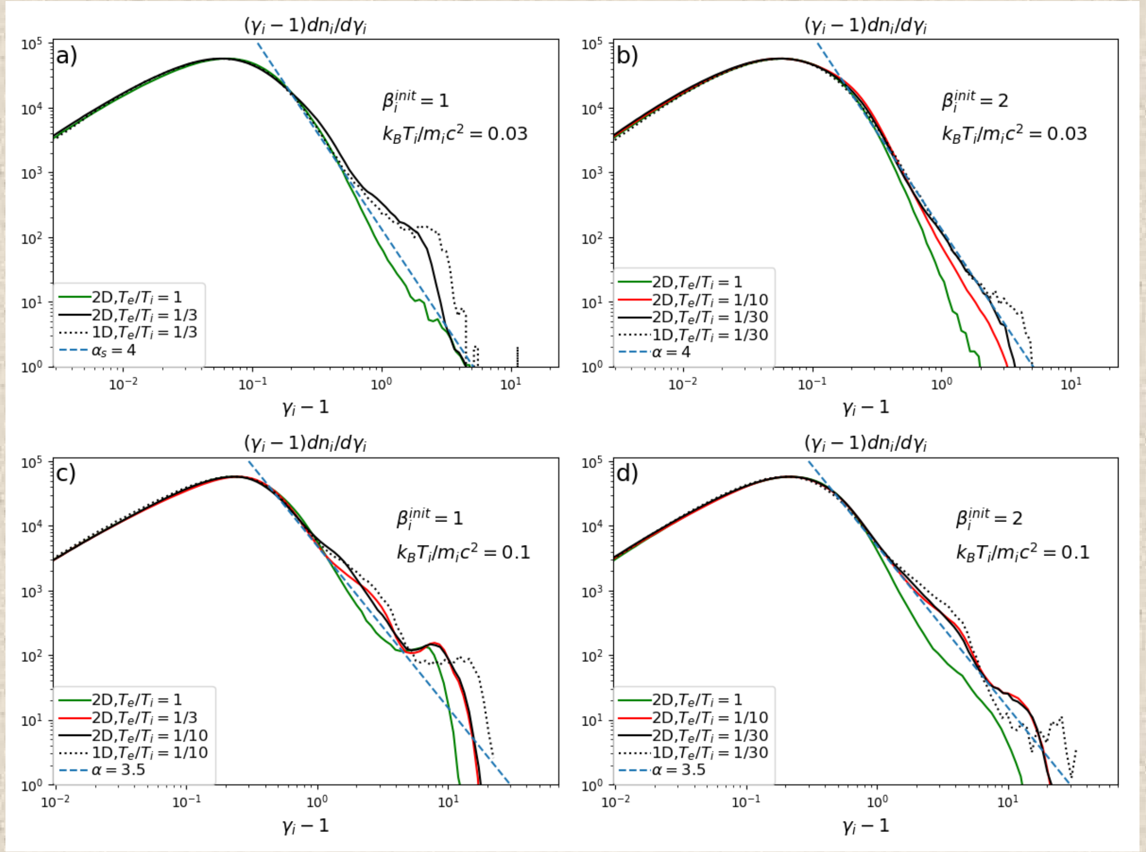
- For low enough T_e/T_i the dominance of the IC modes and corresponding acceleration is "reactivated".
- However, acceleration is less efficient as $k_B T_i/m_i c^2$ decreases.



Acceleration by “non-thermal” anisotropic viscosity

(work in progress; in collaboration with Ellen Zweibel and Francisco Ley)

We know that $dU_j/dt = \Delta p_j q$ (anisotropic viscosity).

However, this energyzation is **reversible** unless there is pitch-angle scattering that breaks adiabaticity.

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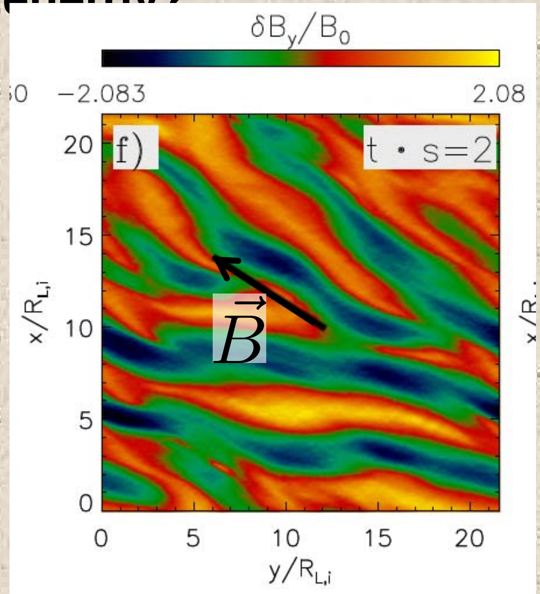
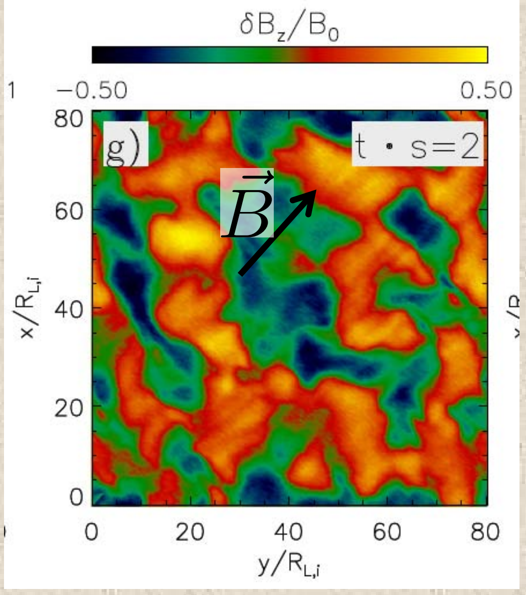


Mirror modes
(increasing magnetic field)



Firehose modes
(increasing magnetic field)

In both cases, the fluctuations occur on length scales comparable with ion Larmor radius.
(as also obtained by Kunz et al 2014)

Acceleration by “non-thermal” anisotropic viscosity

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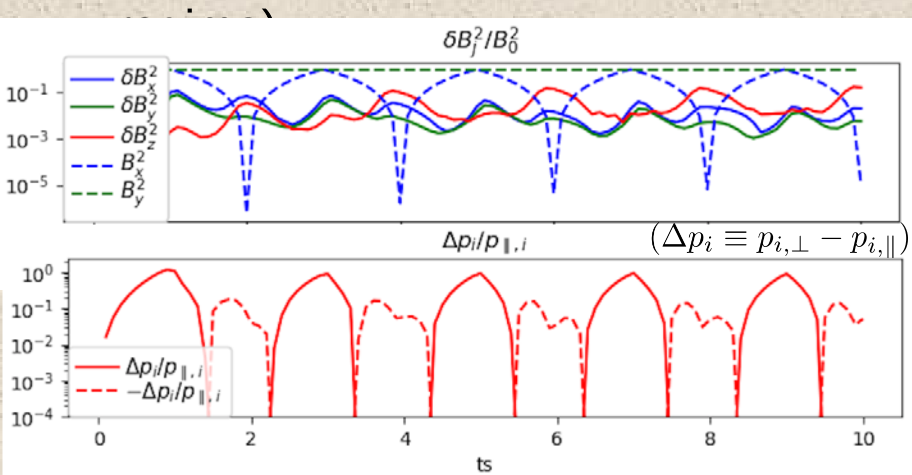
“Proof of Concept”: m_i/m_e=1, $k_B T_i/m_i c^2$=0.1, β_i^{init}=10, **δB/B=1**
(intended to be representative of MRI-type turbulence in sub-relativistic regime)



When B_x grows, Δp_i>0 and δB dominated by their in-plane components (**mirror**).

When B_x decreases, Δp_i<0 and δB dominated by their out-of-plane components (**firehose**).

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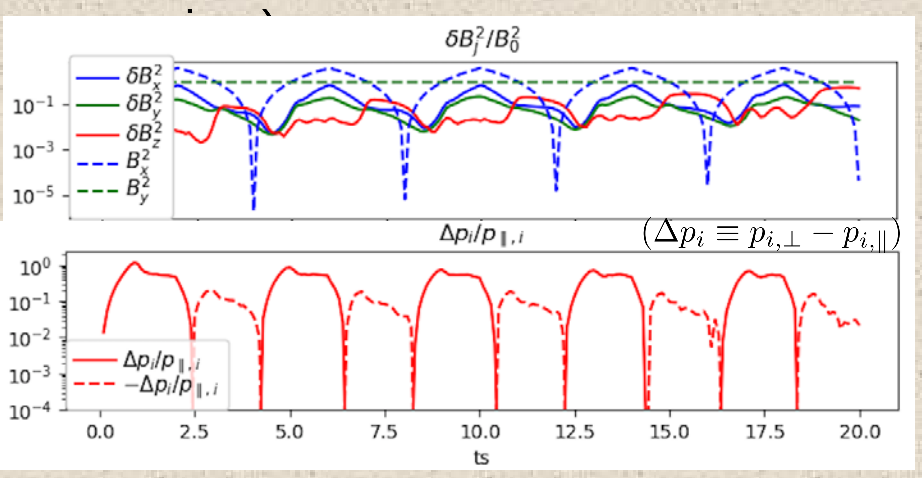

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Conclusions

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  i) **In the case of electrons:** a power-law of α_s**~3.7**, which is close to what multi-wavelength observations suggest for Sgr A* (e.g., Yuan et al. 2003, Ball et al. 2016).

  ii) **In the case of ions:** a power-law of α_s **~3.4 + two bumps** can be produced .

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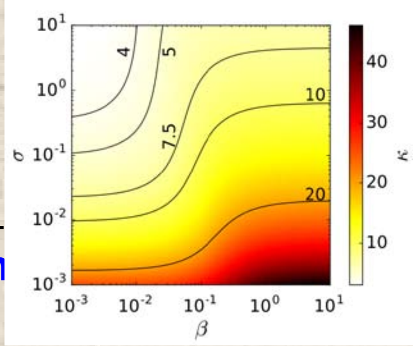
  iii) Most efficient where **reconnection** is not so efficient.



$(\alpha_s = \kappa - 1)$

(Davelaar et al. 2019, from Ball et al 2018)

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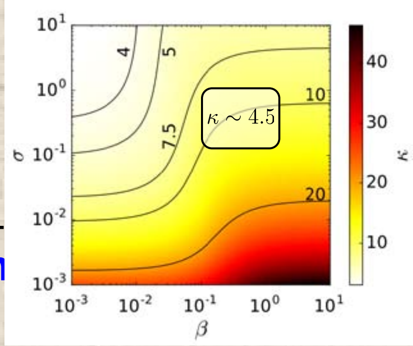

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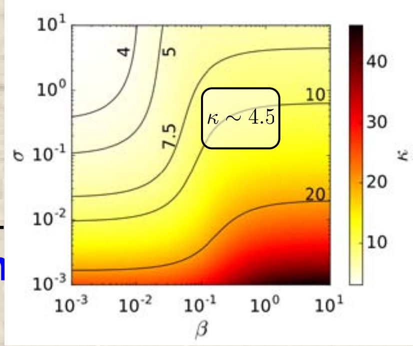

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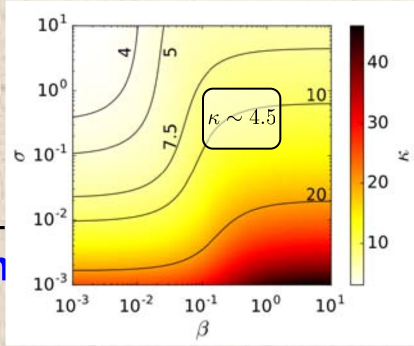

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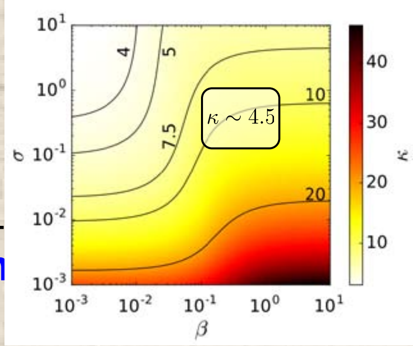

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