PIC simulations of decaying turbulence: the role of reconnection (and other stuff…)

Enrico Camporeale
Applied Mathematics and Plasma Physics Group
Los Alamos National Laboratory

In collaboration with
David Burgess and Chris Haynes (Queen Mary University of London)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Queen Mary
University of London

Outline

- Solar wind simulations: explicit vs implicit
- Simulations: decaying turbulence
  - Methodology (implicit PIC)
  - Results
  - Comparison with linear theory
- Simulations: reconnection
- Non-modal linear theory
- 1 slide on gyrokinetics
- Linear coupling mediated by inhomogeneities
- Conclusions

Explicit vs Implicit

$$\frac{\partial f}{\partial t} = \mathbf{A} f$$

- Explicit

$$f^{n+1} = f^{n} + \Delta t \mathbf{A} f^{n}$$

- Easy and cheap
- Only conditionally stable: must solve fastest and shortest scale

- Implicit

$$f^{n+1} = f^{n} + \Delta t \mathbf{A} f^{n+1}$$

- More involved (inversion of a matrix) and expensive
- More stable !

Los Alamos NATIONAL LABORATORY EST. 1943

Simulation: how to model the solar wind

The overwhelming majority of PIC codes use an explicit algorithm, which is subject to stability constraints

Typical solar wind parameters: $T = 10$ eV, $n = 10$ cm^{-3}, $B = 6$ nT

$\lambda_d \sim 7$ m, $f_{pe} \sim 30$ kHz

$\rho_e / \lambda_d \sim 170 \rightarrow \rho_i / \lambda_d \sim \mathrm{Sqrt}(m_i/m_e) * 170 \sim 7200$

$\Delta x = 0.1\, \lambda_d$ → 1 ion gyroradius needs 72000 cells per dimension

→ 1 electron gyroradius needs 1700 cells per dimension

$\omega_{pe} / \Omega_{ce} \sim 170 \rightarrow \omega_{pe} / \Omega_{ci} \sim (m_i/m_e) * 170 = 310000$

$\Delta t\, \omega_{pe} = 0.1$ → 1 ion gyroperiod needs 3 millions timesteps

→ 1 electron gyroperiod needs 1700 timesteps

$c\, \Delta t/\Delta x \sim 1000$ → CFL condition not satisfied

A realistic PIC simulation of the solar wind is **practically impossible** with an explicit code, due to the large scales separation involved, both in time and space.

Explicit PIC simulations of solar wind MUST relax some physical parameters

The solution of Vlasov equation for a Maxwellian ion-electron plasma is determined by these parameters:

$\omega_{pe} / \Omega_{ce}$	ratio of plasma to gyro-frequency
T_e / T_i	temperature ratio
m_i / m_e	ion-to-electron mass ratio

Explicit PIC simulations have to compromise on some of these parameters, and CONJECTURE the validity of the results for realistic parameters

The Implicit PIC algorithm allows for more realistic simulations

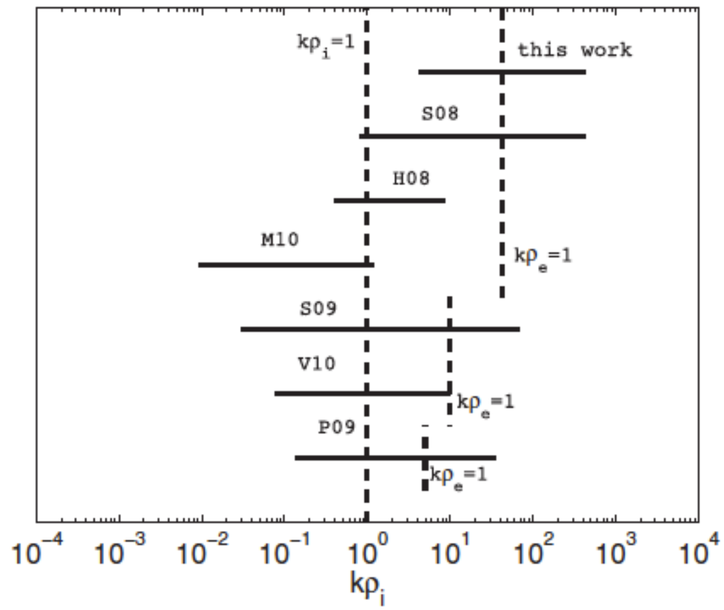
- In general, an Implicit PIC does not need to resolve the smallest time and spatial scales.
- It effectively averages over small scales, if the physical process is determined by larger scales
- Stability constraints are relaxed and become accuracy constraints

Comparison between this and previous works

Acronym	Reference	$k\rho_i$	ω_i/Ω_i	m_i/m_e	N_p	Type
...	This work	4.28–428.48	1650	1836	6400	2D-3V PIC
S08	Saito et al. (2008)	0.83–425	96	1836	64	2D-3V PIC
H08	Howes et al. (2008b)	0.4–8.4	...	1836	...	3D-2V Gyrokinetic
M10	Markovskii et al. (2010)	0.0095–1.21	192.3	...	1000	2D Hybrid
S09	Svidzinski et al. (2009)	0.03–66.7	15	100	>100	2D-3V PIC
V10	Valentini et al. (2010)	0.078–10.003	...	100	...	2D-3V Hybrid–Vlasov
P09	Parashar et al. (2009)	0.139–35.7	...	25	100	2D Hybrid

"this work" =

Camporeale & Burgess, ApJ (2011)



Los Alamos NATIONAL LABORATORY EST. 1943

Methodology of Camporeale & Burgess, ApJ (2011)

- Implicit moment method (Markidis, Camporeale, Burgess et al. 2009)
- 2D in space, 3D velocity
- Physical mass ratio, $\omega_{pi} / \Omega_{ci} \sim 1650$
- Plasma beta = 0.5
- Electron plasma frequency is resolved
- $\Delta x \sim 20\ \lambda_d$
- Courant condition: $c\ \Delta t / \Delta x \sim 9$ (saving factor wrt explicit = 80000)
- 6400 particles per cell
- The box includes wavevectors in the range $k\rho_e = 0.1\text{-}10$ (equivalent to $k\rho_i = 4.28 - 428$)

Open questions

Previous simulations have shown results that are difficult to unify in a single framework: different phenomena, different approach and numerical tools.

Q1) What is the scale at which the nonlinear cascade terminates ?

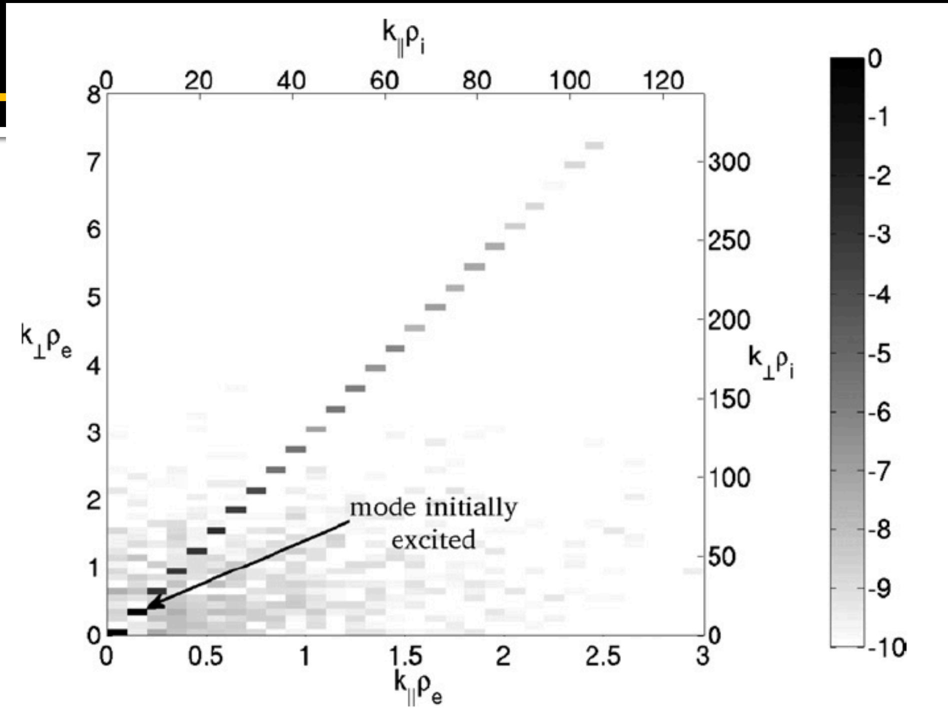
Q2) Which linear mode (if any) is predominant and responsible for the dissipation of turbulent fluctuations at small scales ?

Q3) Is the use of Vlasov linear theory justified in this context ?

Q4) Is the use of gyrokinetics justified at small scales ?

Q5) What about reconnection, small scale structures, etc … ?

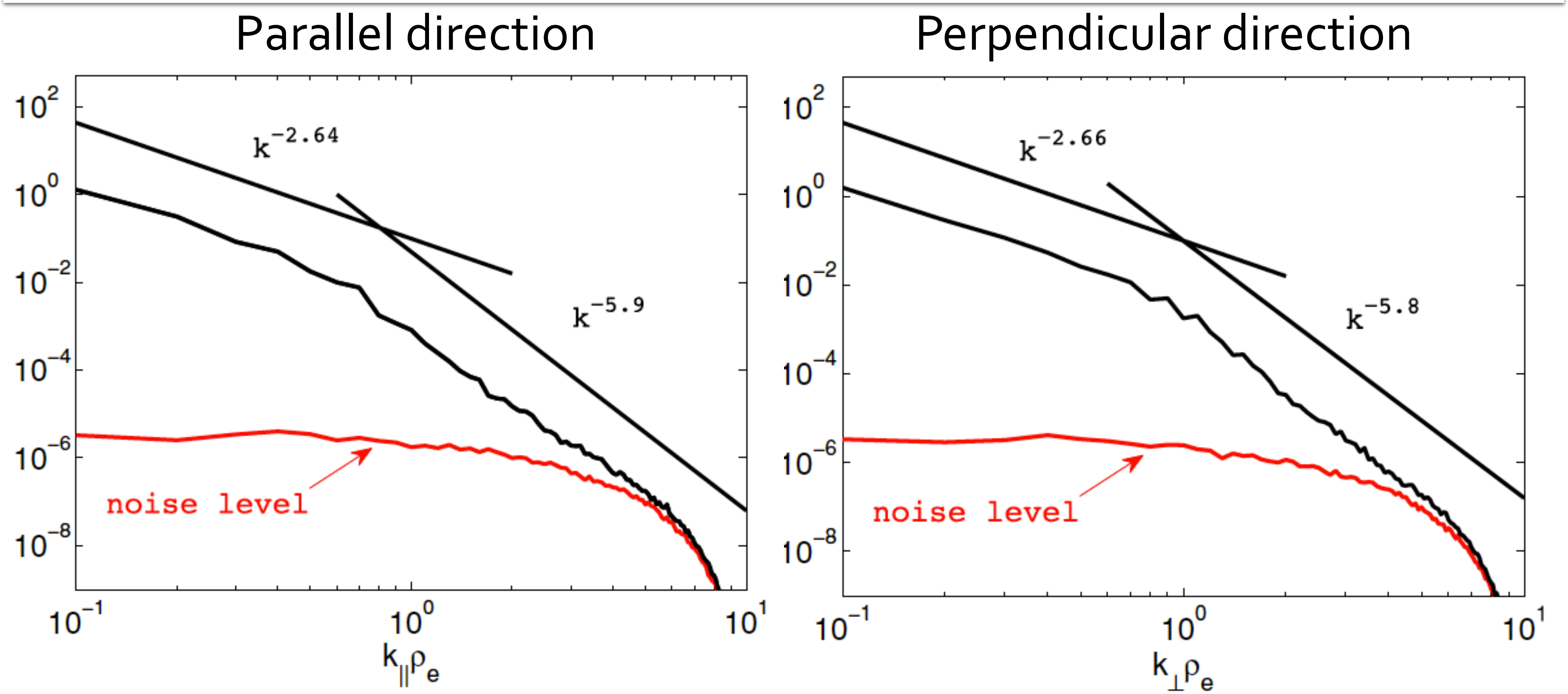
Results: single mode initialization



Q3) Is the use of Vlasov linear theory justified in this context ?

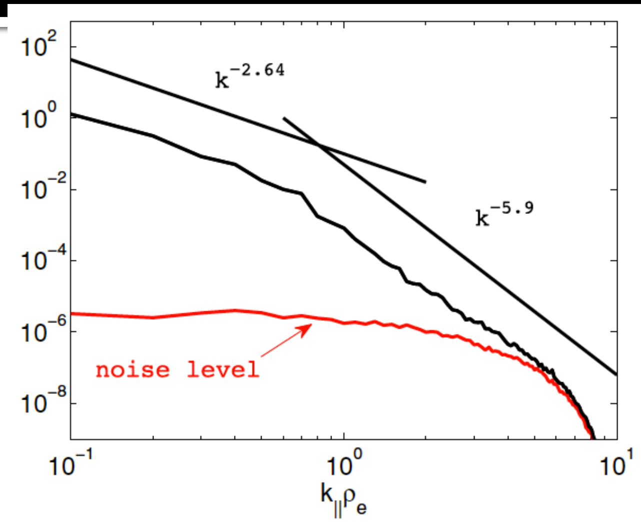
A3) Not sure. There is a fundamental contradiction in allowing a linear damping and a nonlinear cascade simultaneously. It is not clear at what scale the nonlinear terms become negligible. Moreover the traditional linear theory results might not apply because they assume that the plasma is a closed system in thermodynamical equilibrium.

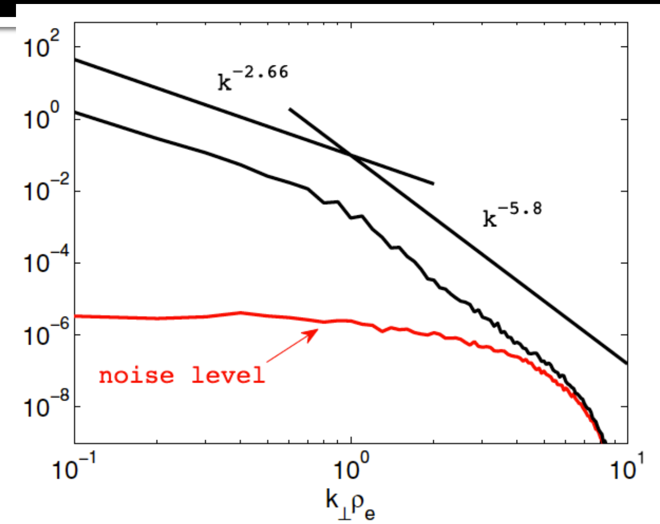
Results: magnetic power spectra $|\delta B|^2 / |B_o|^2$



An appreciable separation between the cascade and the noise ground requires number of particles per cell = 6400

Results: magnetic power spectra $|\delta B|^2 / |B_o|^2$





Q1) What is the scale at which the nonlinear cascade terminates ?

A1) Cascade proceeds up to $k\rho_e > 5$

No signs of exponential roll-over (in the region not effected from noise)

Los Alamos
NATIONAL LABORATORY
EST. 1943

Results: particle heating

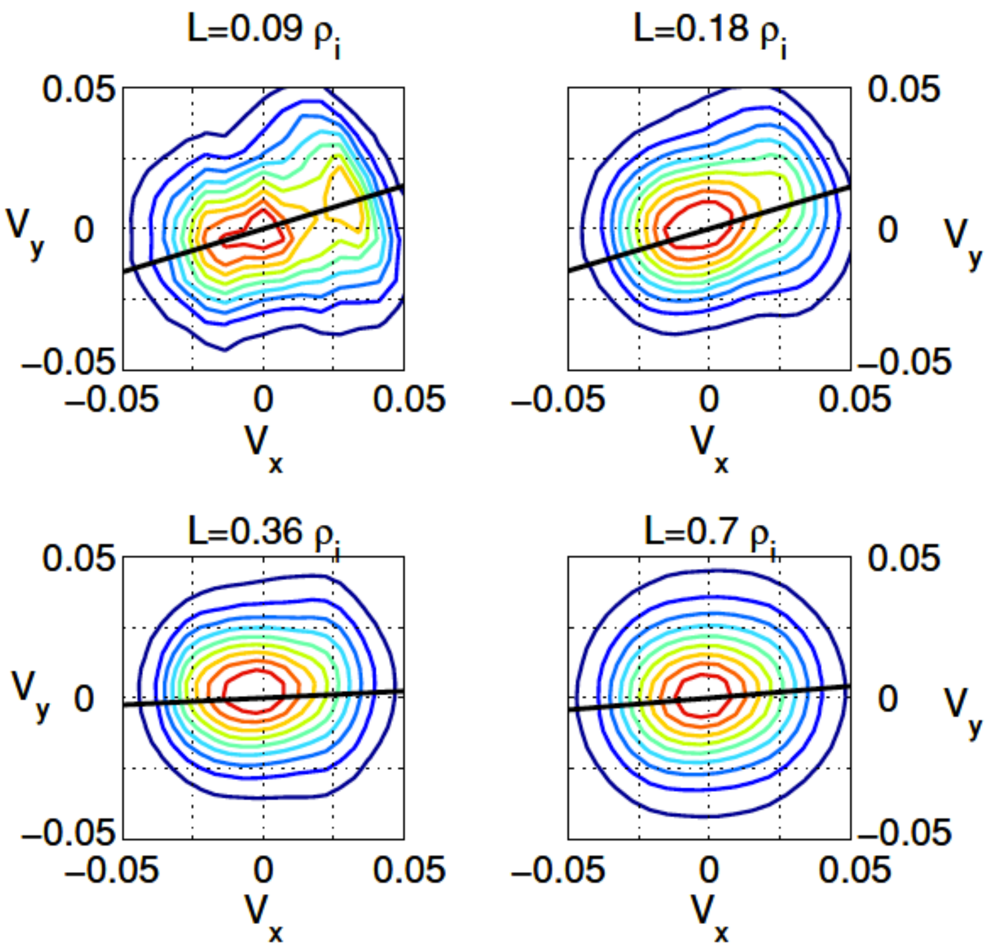
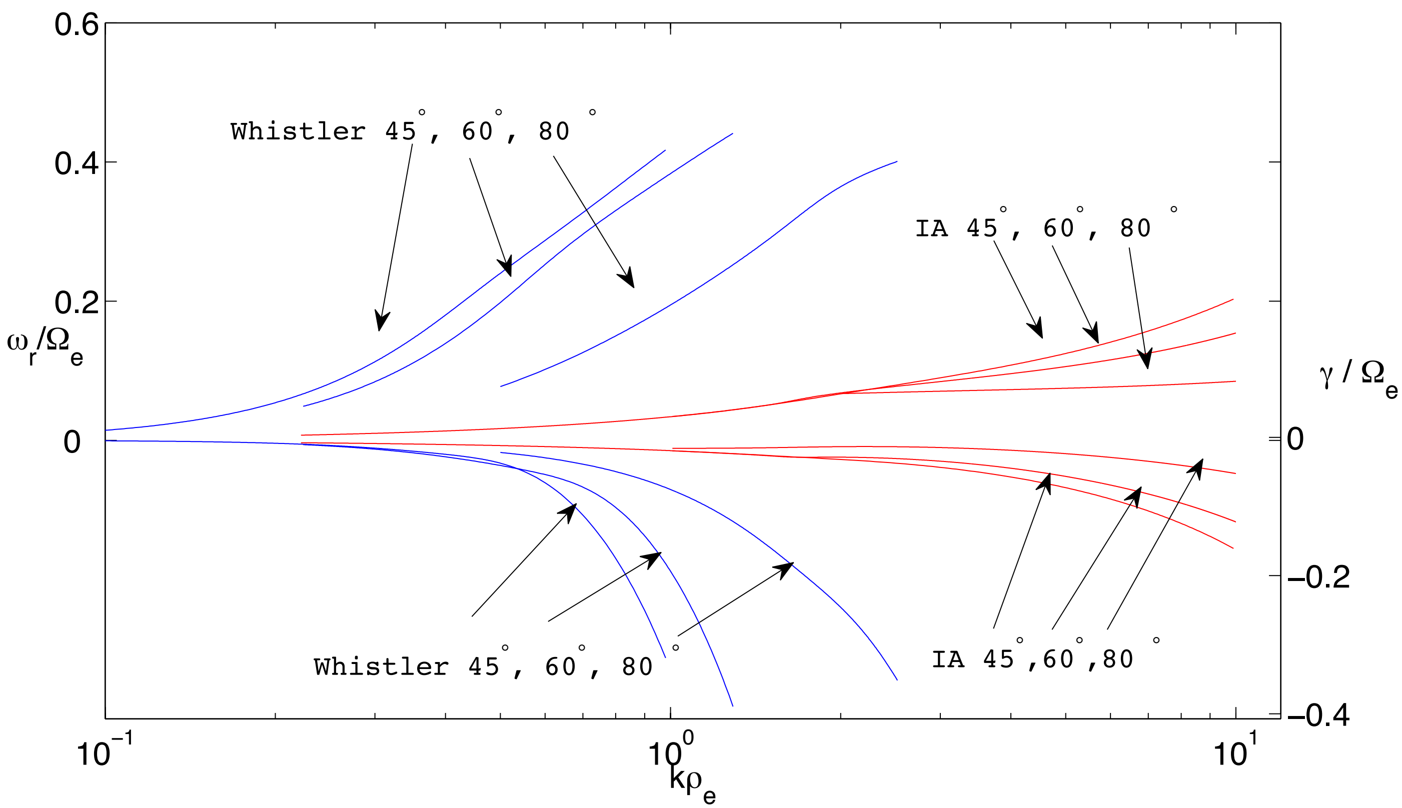


Figure 11. Electron distribution functions in the (x, y)-plane, collected in four nested boxes of increasing size L. The solid line shows the direction of the mean magnetic field within each box. Velocities are normalized to the speed of light.

Los Alamos
NATIONAL LABORATORY
EST. 1943

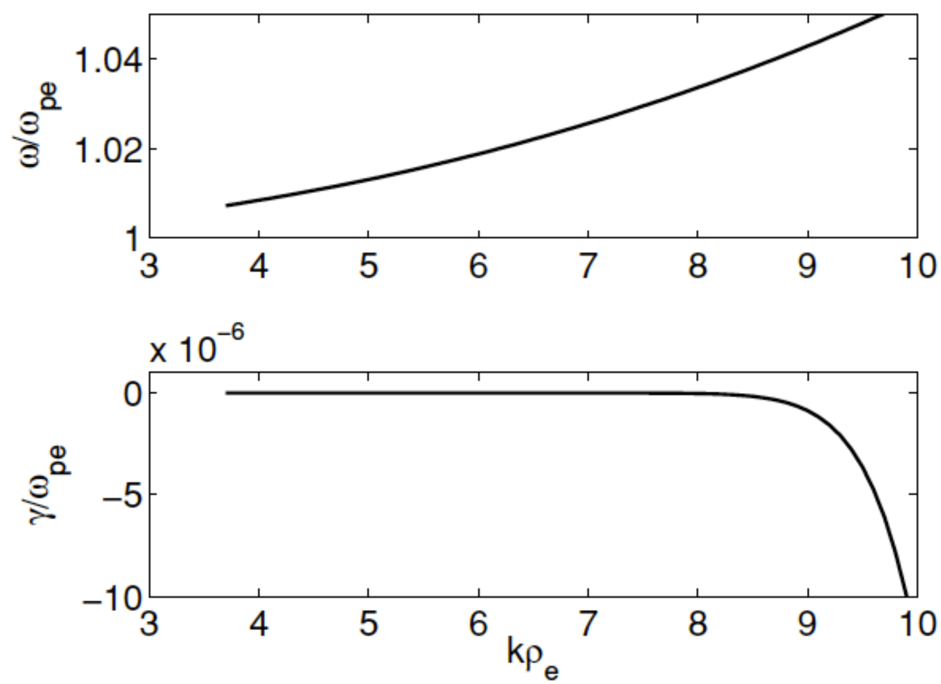
Linear theory

- Dispersion relation for whistler and ion-acoustic modes



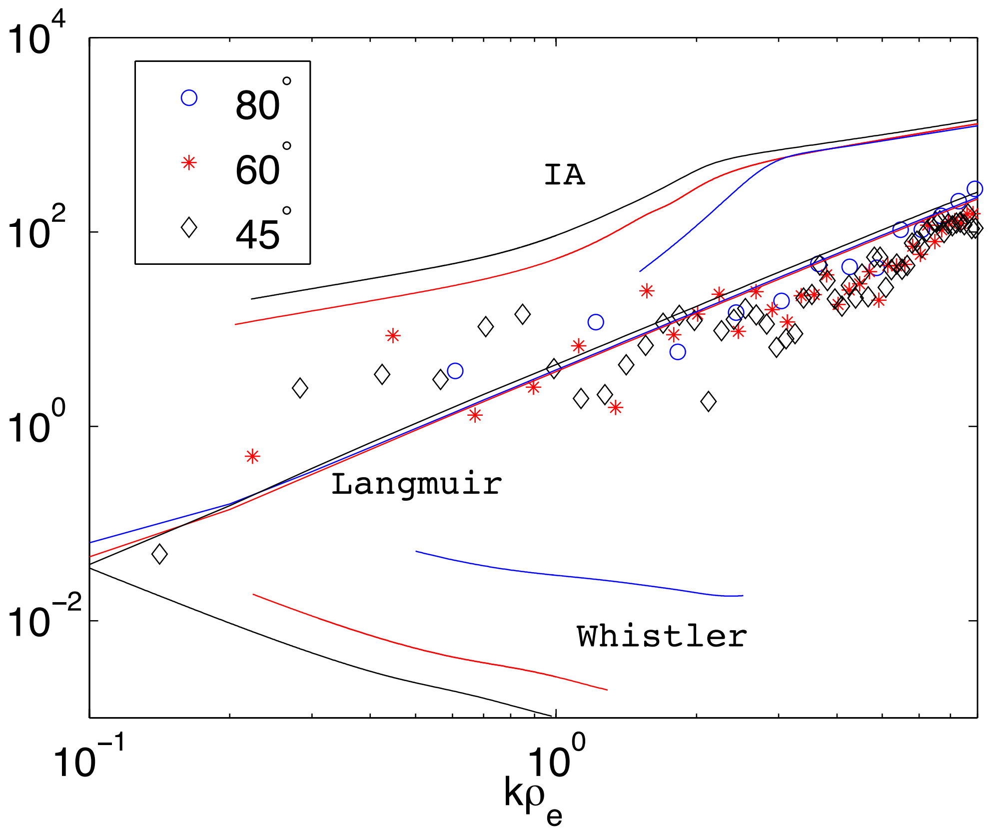
Linear theory

Dispersion relation for electrostatic Langmuir mode



Los Alamos
NATIONAL LABORATORY
EST. 1943

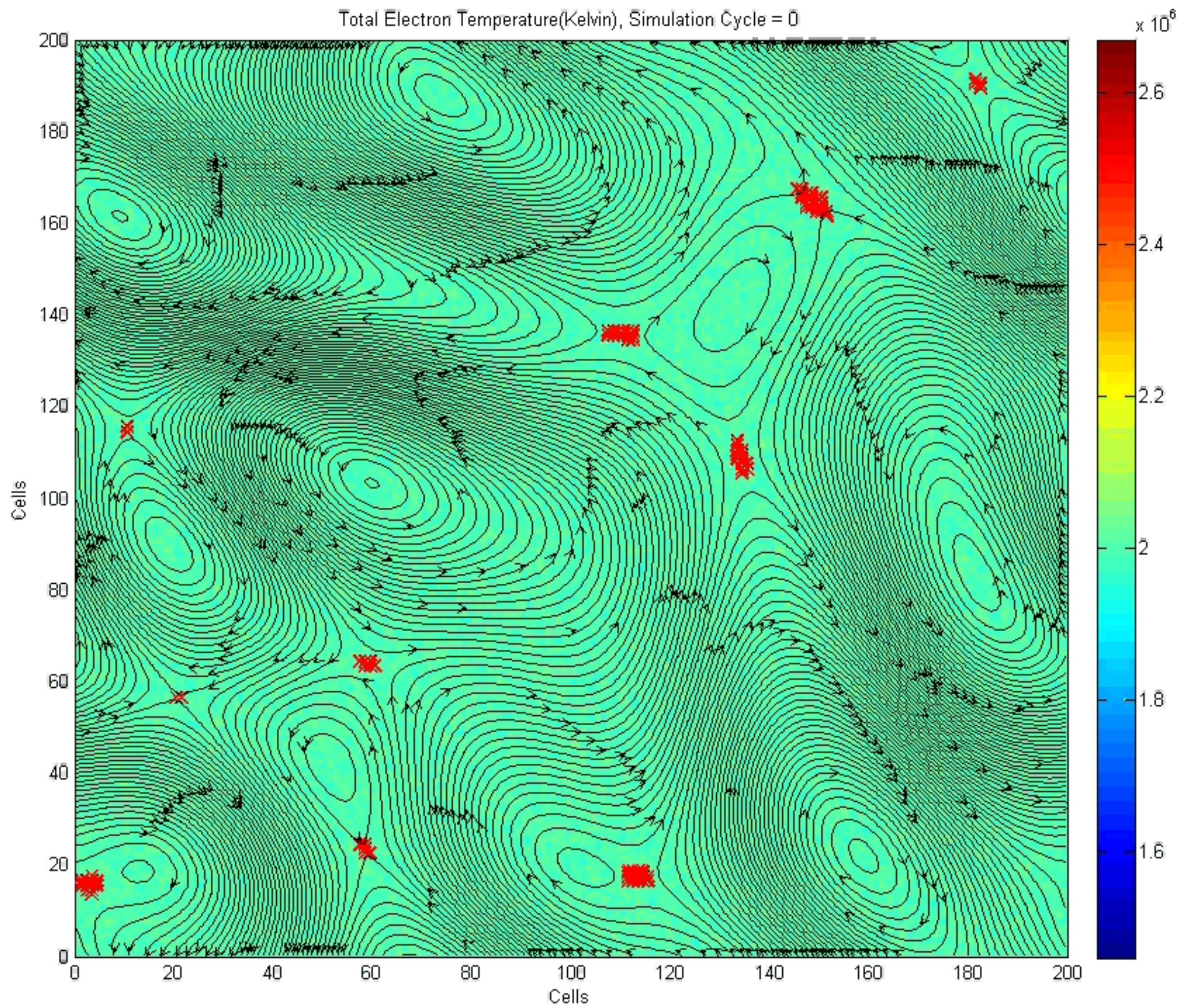
Comparison PIC-linear theory: electron compressibility



Q2) Which linear mode (if any) is predominant and responsible for the dissipation of turbulent fluctuations at small scales ?

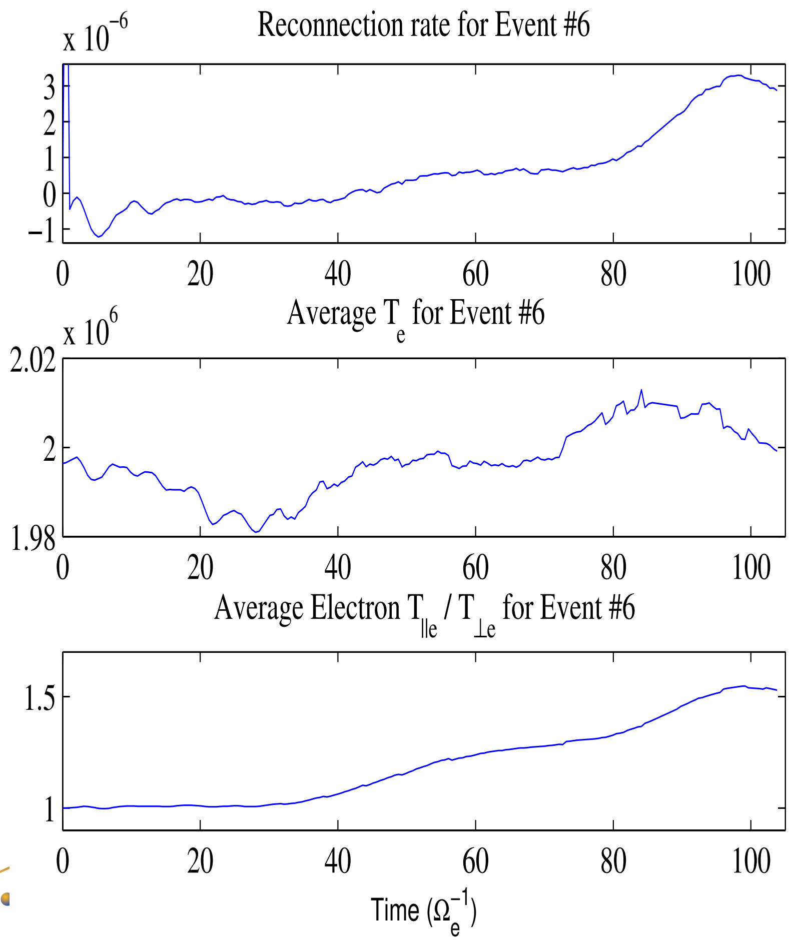
A2) In the regime investigated here (up to $k\rho_e \sim 8$) there is no clear evidence of one predominant mode.

An alternative route to dissipation: reconnection (work in progress)



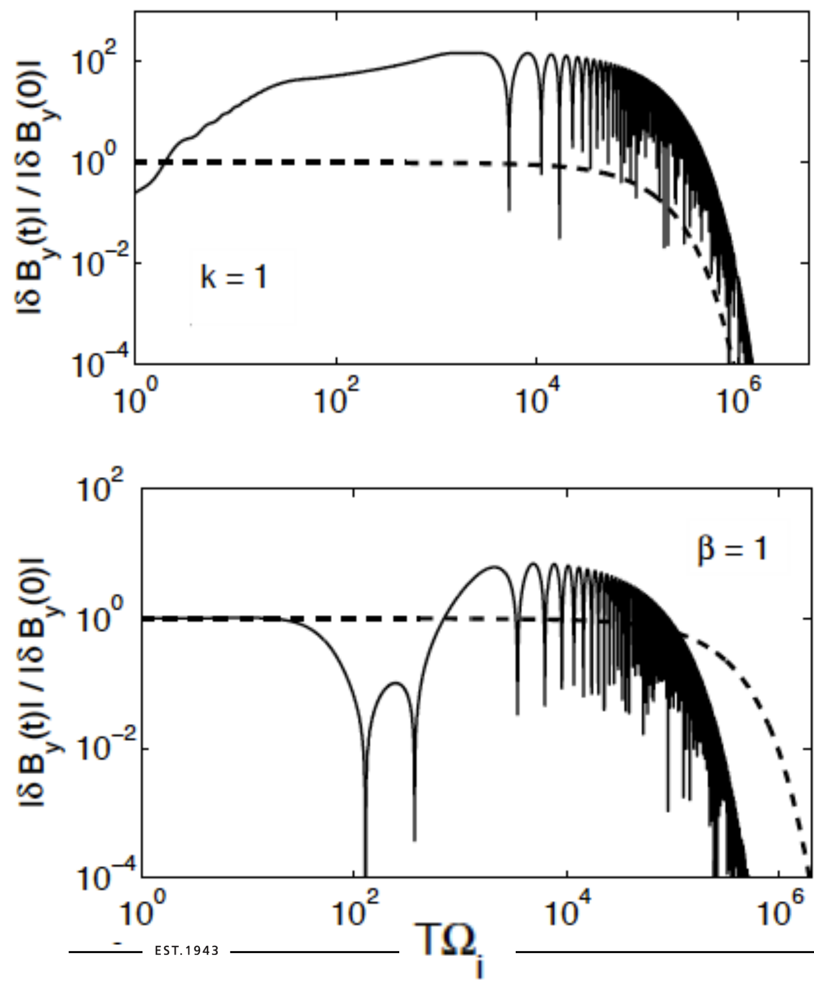
Los Ala
NATIONAL LAB
EST.1943

Reconnection and anisotropy



- In some cases a clear relationship between temperature anisotropy and reconnection rate
- Not generally true
- No clear signature on how reconnection influences turbulent cascade

Non-modal linear theory



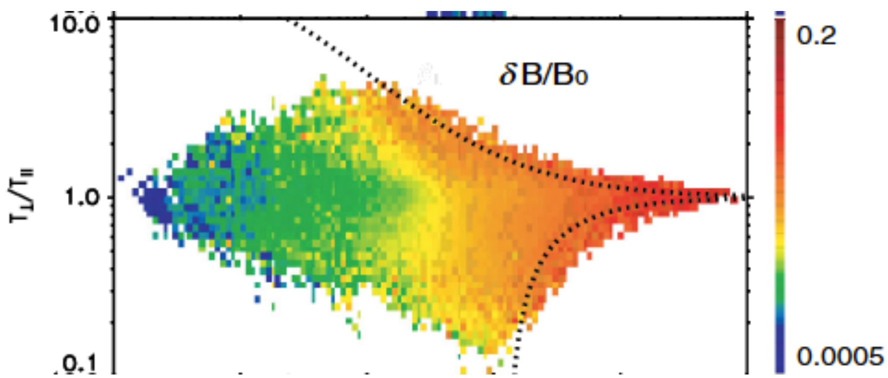
- In linear theory any perturbation damps according to the damping rate of the least damped modes only at large times

- Unless the perturbation picks only and exactly a single normal mode

- Transient growth are related to kinetic effects (they don't exist in ideal MHD)

Camporeale, Burgess, Passot, *POP* (2009)
Camporeale, Passot, Burgess, *ApJ* (2010)
Camporeale, *Space Science Rev* (2012)

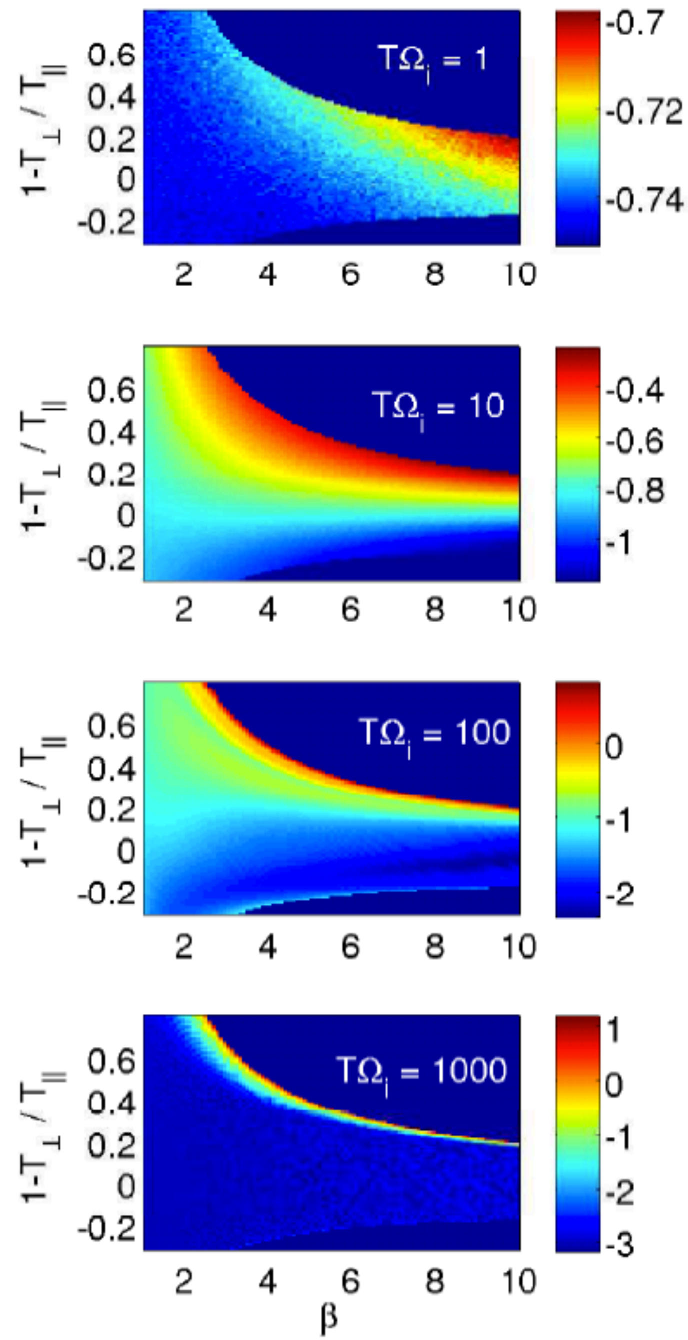
Non-modal linear theory



Bale et al (2009)

Magnetic fluctuations.
Average on 10000 random initial perturbation.

"All" perturbations grow transiently !



Gyrokinetics throws away ‘almost’ all the interesting physics (at small scales) !

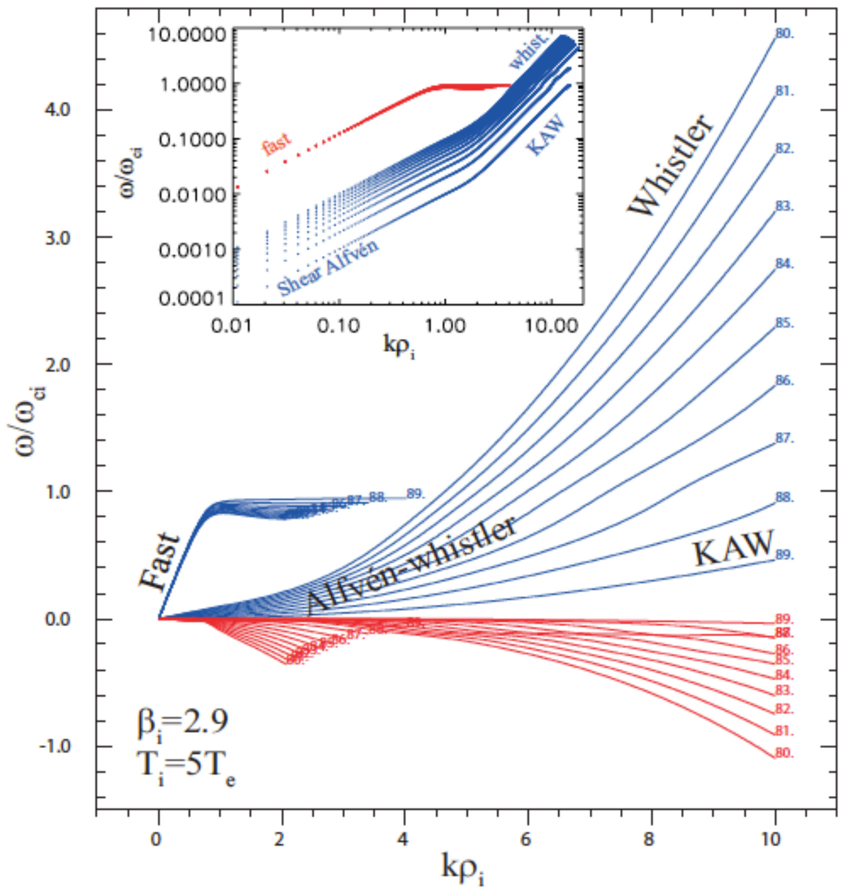
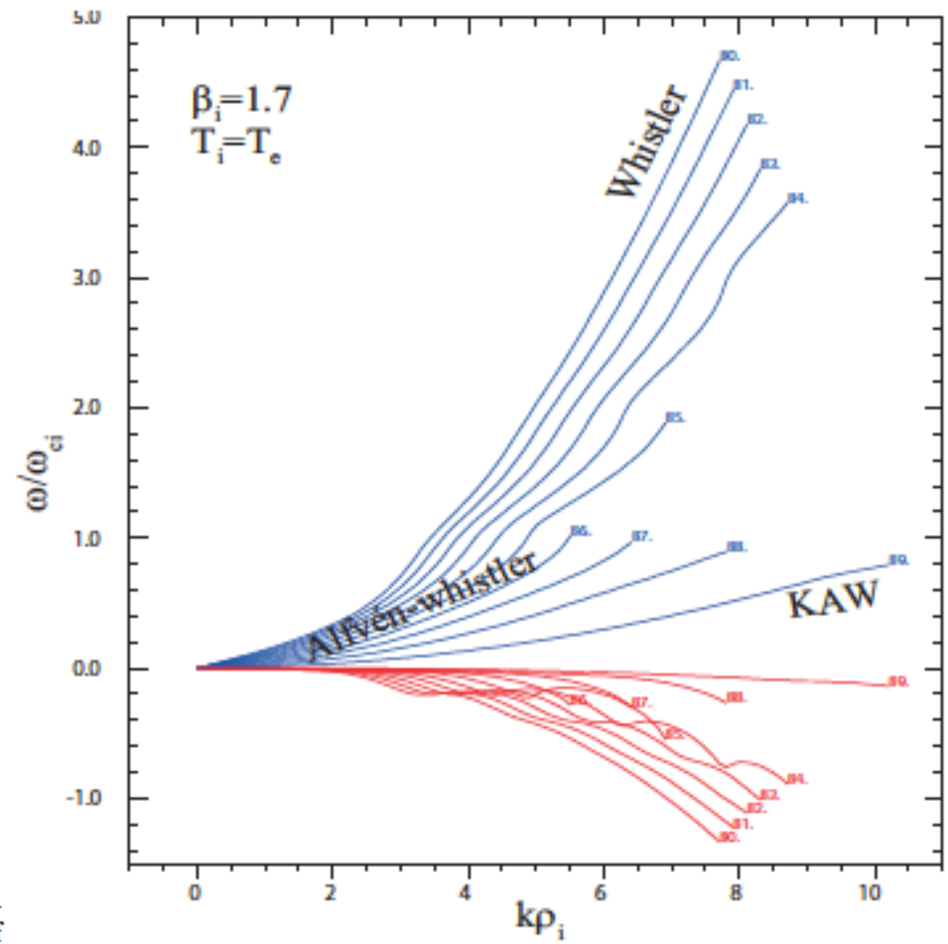
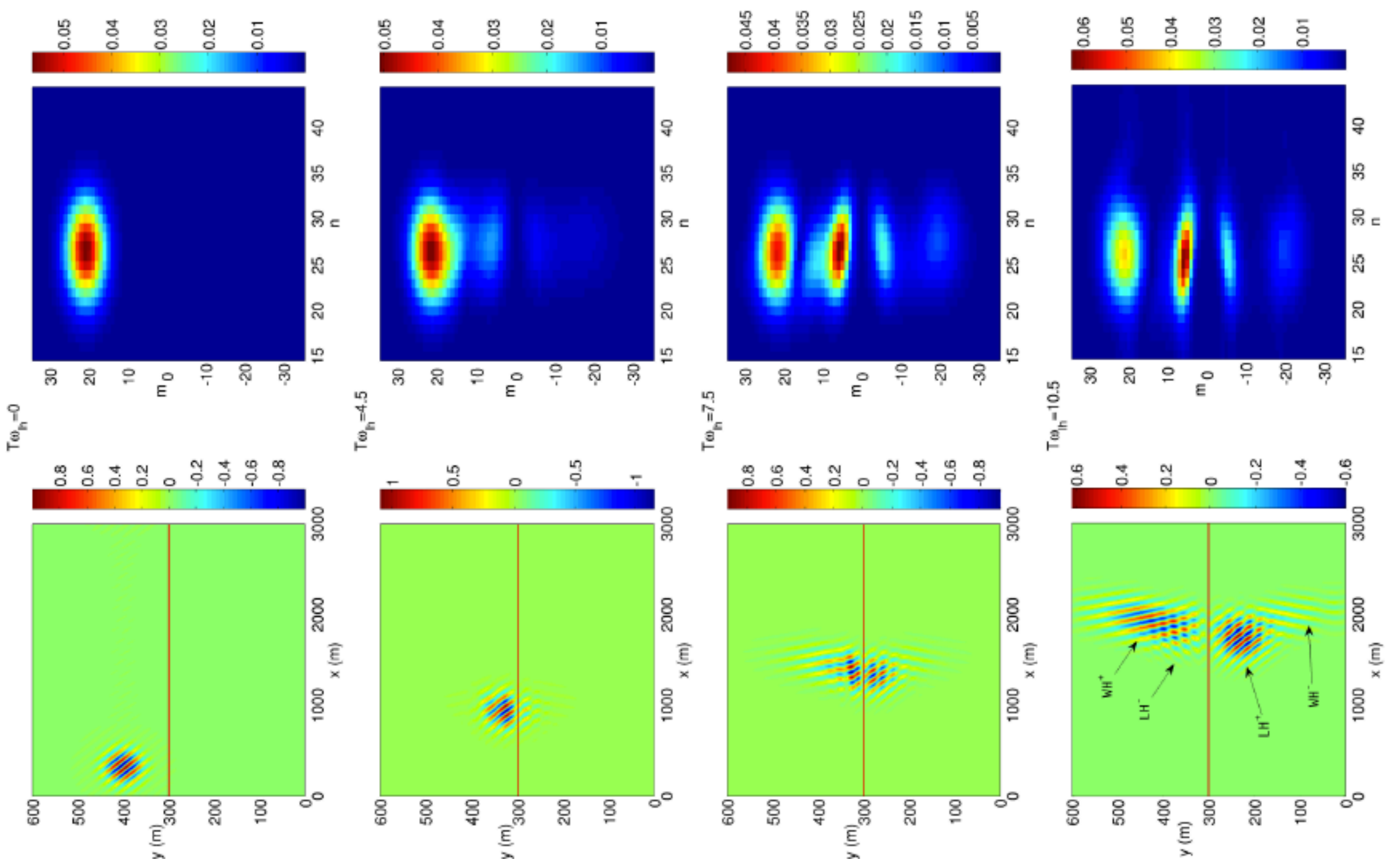


FIG. 3.— Linear solutions of the Maxwell-Vlasov equations: dispersion relations (blue) and damping rates (red) for the angles of propagation $80^\circ \le \theta_{\mathbf{kB}} \le 89^\circ$. The insert is a log-log plot of the same dispersion relations to show the connection between low and high frequency modes.



Linear coupling mediated by structures



Conclusions and future work

- 2D PIC simulations show no sign of a roll-over of the cascade up to $k\rho_e \sim 8$. The dissipation must be investigated at smaller scales
- The appearance of nonthermal features in the electron distribution function depends on the box length in which the particles are sampled.
- There is no clear evidence of a predominant linear mode
- No clear evidence of reconnection influencing turbulence
- The implicit PIC code is currently the only computational tool able to simulate the solar wind with realistic parameters (but only in 2D)
- Linear theory and gyrokinetics 'seem' to work, but they shouldn't. Why ?
- Role of structure: linear coupling (see Camporeale, Delzanno and Colestock, JGR (2012))