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GTP Workshop on LES and MHD Turbulence

Session 2: Anisotropy and Kinetic Effects

May 20 – 23, 2013

NCAR, Boulder, Colorado, USA

Key questions to address

- What happens at the kinetic tail of the MHD cascade?
  - Ex 1: Heating of the solar corona and solar wind acceleration
  - Ex 2: Radiation from (hot) black hole accretion flows
  - Note: Combines *anisotropy* and *kinetic effects*!

- Option 1: „Collisionless“ damping of (quasi-)linear waves
  - Efficiency of Landau damping in a turbulent environment?
  - Significant deviations from Maxwellian distribution functions?

- Option 2: Particle acceleration (formation of current sheets)
  - Magnetic reconnection in a turbulent environment?
  - Role of strong guide field?

Promising advances in kinetic simulation

macrophysics
(collisional)

inextricably
linked

microphysics
(collisionless)

3D magneto-
hydrodynamics

current workhorse of
plasma astrophysics

promising initial
results, calling
for more work

5D gyrokinetics

long considered
too costly, but
now becoming
more accessible

6D kinetics

computational effort

Thanks to the continuous advance in supercomputing power, „serious“ kinetic turbulence simulations have become feasible

Recently, strongly growing interest and activity in this area

From magneto-hydrodynamics to kinetics

Charged plasma particles undergo mostly small-angle (distant) Coulomb collisions.

Hot and/or dilute plasmas are almost collisionless.
Here, MHD is not applicable; one must use a kinetic description!

Vlasov (collisionless Boltzmann) equations (α=species label)

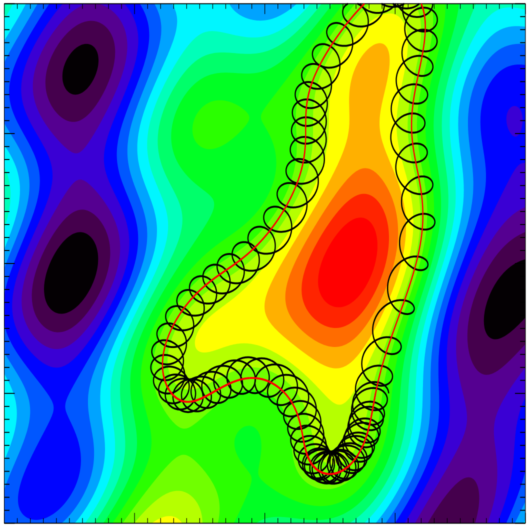
$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla f_\alpha + \frac{q_\alpha}{m_\alpha}\left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right] \cdot \nabla_v f_\alpha = 0$$

$f_\alpha = f_\alpha(\mathbf{x}, \mathbf{v}, t)$ ...from Liouville equation via BBGKY hierarchy

…plus Maxwell's equations (w/o displacement current)

From kinetics to gyrokinetics

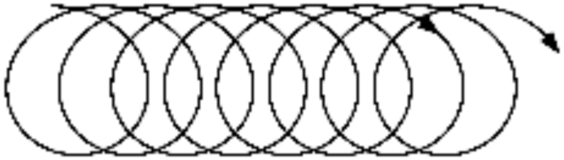
Tail of the MHD cascade is gyrokinetic!



Large magnetic field (points into the plane), causing **strong anisotropy**

Electrostatic potential fluctuations (color-coded)

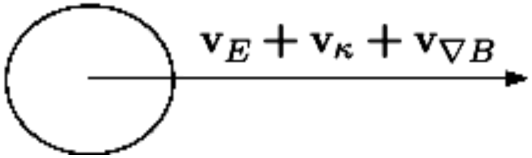
Particle orbit = fast gyromotion + slow (ExB) drift



Basic idea of gyrokinetics:

Remove the fast gyromotion $\omega \ll \Omega$

Introduce charged rings as quasiparticles; go from particle to **gyrocenter coordinates**



Brizard & Hahm, Rev. Mod. Phys. **79**, 421 (2007)

The nonlinear gyrokinetic equations

$$f = f(\mathbf{X}, v_\|, \mu; t)$$

Advection/Conservation equation

$$\boxed{\frac{\partial f}{\partial t} + \dot{\mathbf{X}} \cdot \frac{\partial f}{\partial \mathbf{X}} + \dot{v}_\| \frac{\partial f}{\partial v_\|} = 0}$$

X = gyrocenter position
v_{II} = parallel velocity
μ = magnetic moment

$$\dot{\mathbf{X}} = v_\| \mathbf{b} + \frac{B}{B^*_\|}\left(\frac{v_\|}{B}\bar{\mathbf{B}}_{1\perp} + \mathbf{v}_\perp\right)$$

$$\mathbf{v}_\perp \equiv \frac{c}{B^2}\bar{\mathbf{E}}_1 \times \mathbf{B} + \frac{\mu}{m\Omega}\mathbf{b}\times\nabla(B + \bar{B}_{1\|}) + \frac{v_\|^2}{\Omega}(\nabla\times\mathbf{b})_\perp$$

$$\dot{v}_\| = \frac{\dot{\mathbf{X}}}{m v_\|} \cdot \left(e\bar{\mathbf{E}}_1 - \mu\nabla(B + \bar{B}_{1\|})\right)$$

Appropriate field equations

$$\frac{n_1}{n_0} = \frac{\bar{n}_1}{n_0} - \left(1 - \|I_0^2\|\right)\frac{e\phi_1}{T} + \|x I_0 I_1\|\frac{B_{1\|}}{B}$$

$$\nabla_\perp^2 A_{1\|} = -\frac{4\pi}{c}\sum \bar{J}_{1\|}$$

$$\frac{B_{1\|}}{B} = -\sum \epsilon_\beta\left(\frac{\bar{p}_{1\perp}}{n_0 T} + \|x I_1 I_0\|\frac{e\phi_1}{T} + \|x^2 I_1^2\|\frac{B_{1\|}}{B}\right)$$

GENE code (grid-based, CFD-like, >260 kcores): http://gene.rzg.mpg.de

Entropy-like quadratic ideal invariant

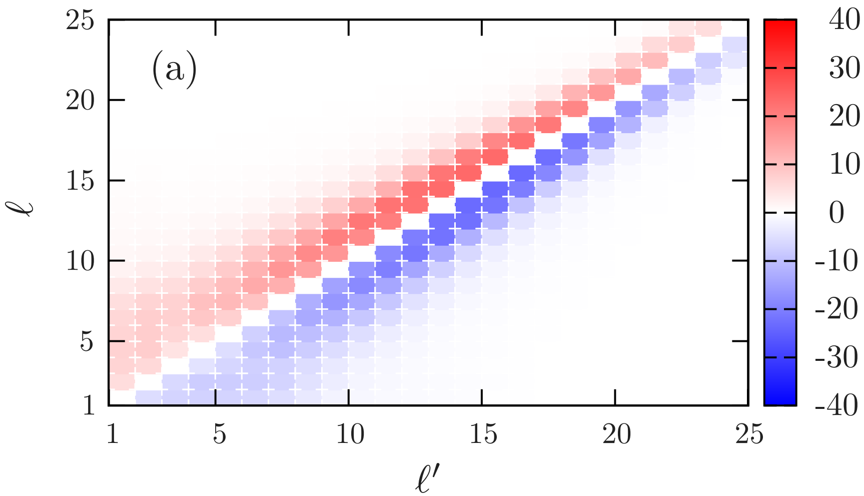
Kinetics: Free energy $\mathcal{E} = U - T_0\, S = K + \mathcal{E}_E + \mathcal{E}_M - T_0\, S$

$$= \sum_j T_{0j} \int \mathrm{d}^3\mathbf{x}\, \mathrm{d}^3\mathbf{v}\, \frac{\tilde{f}_{1j}^2}{2\, F_{0j}} + \int \mathrm{d}^3\mathbf{x} \frac{\mathbf{E}^2}{8\pi} + \int \mathrm{d}^3\mathbf{x} \frac{\mathbf{B}^2}{8\pi}$$

Entropy part (tends to dominate) up to order two in $\tilde{f}_{1j}$

distribution function $\tilde{f}_j$ = Maxwellian distribution function F_{0j}

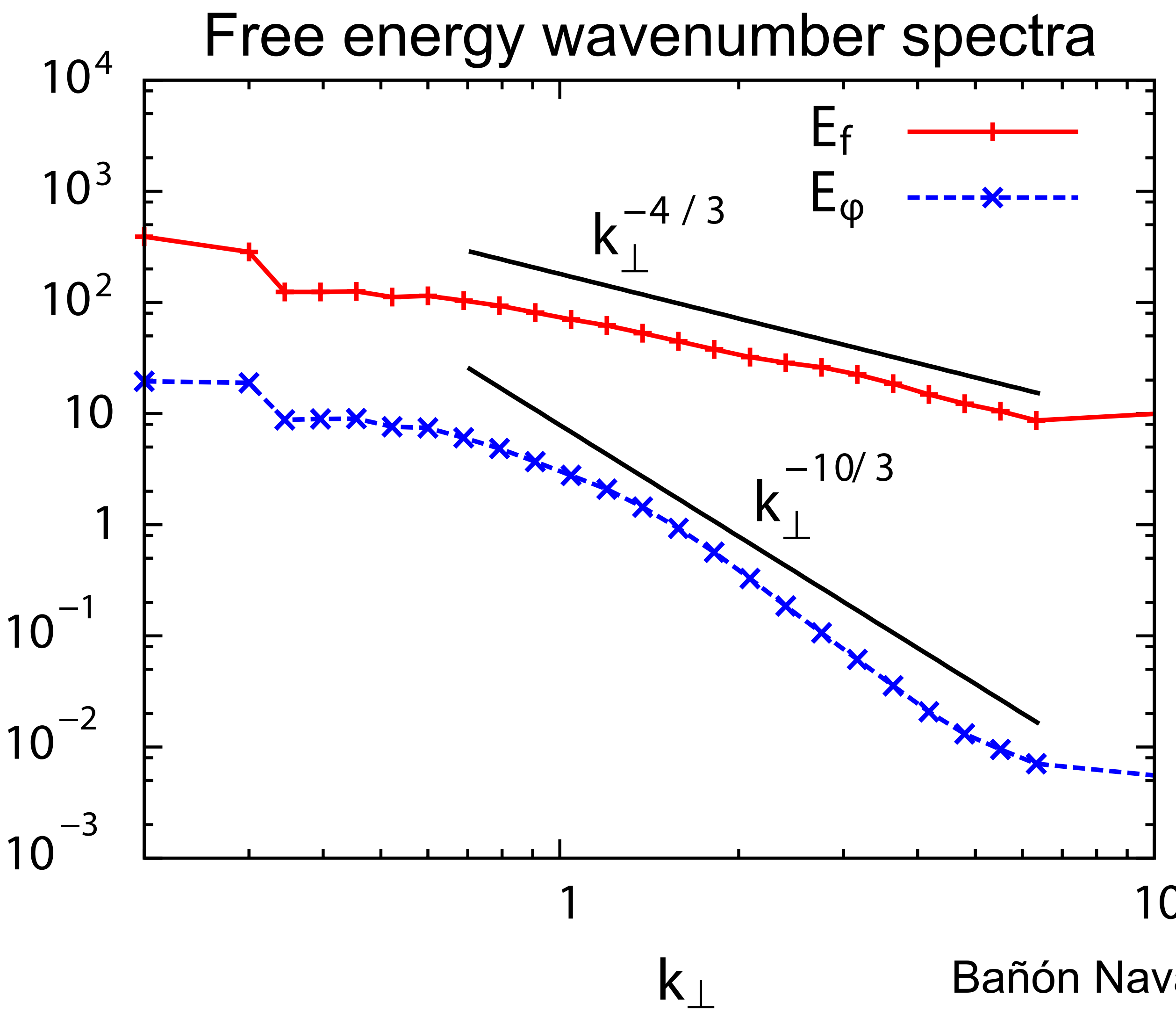
+ fluctuation part $\tilde{f}_{1j}$



Direct cascade of free energy

Bañón Navarro *et al.*, PRL 2011

Power law spectra



Solid lines: Predictions from Kolmogorov-like phenomenology

Bañón Navarro *et al.*, PRL 2011

Remark: Gyrokinetic LES models

Apply LES filter: $$\partial_t f_{ki} = L[f_{ki}] + N[\phi_k, f_{ki}] - D[f_{ki}]$$

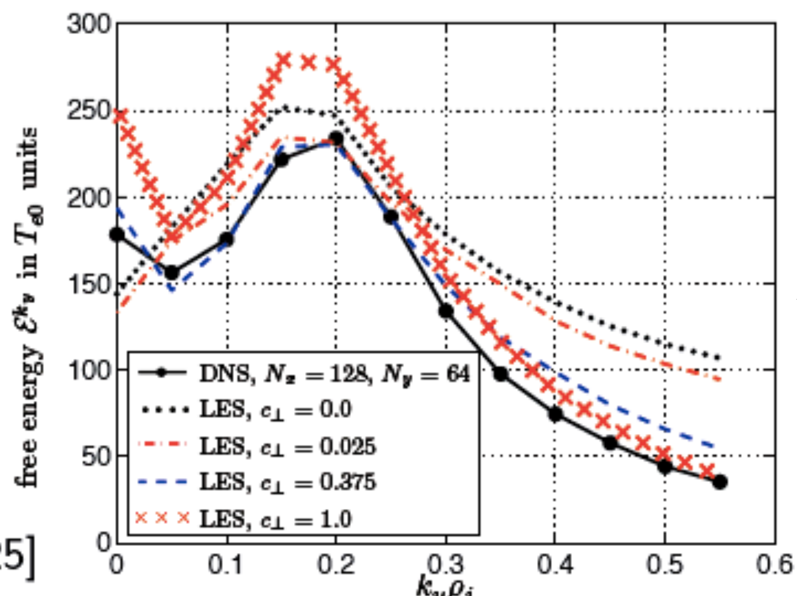
$$\partial_t \overline{f_k} = L[\overline{f_k}] + N[\overline{\phi_k}, \overline{f_k}] + T_{\overline{\Delta},\Delta^{\mathrm{DNS}}} - D[\overline{f_k}]$$

Sub-grid term: $$T_{\overline{\Delta},\Delta^{\mathrm{DNS}}} = \overline{N}[\phi_k, f_k] - N[\overline{\phi_k}, \overline{f_k}] \approx c_\perp k_\perp^4 h_{ki}$$

Free energy spectra vs $c_\perp$:

Cyclone Base Case (ITG)

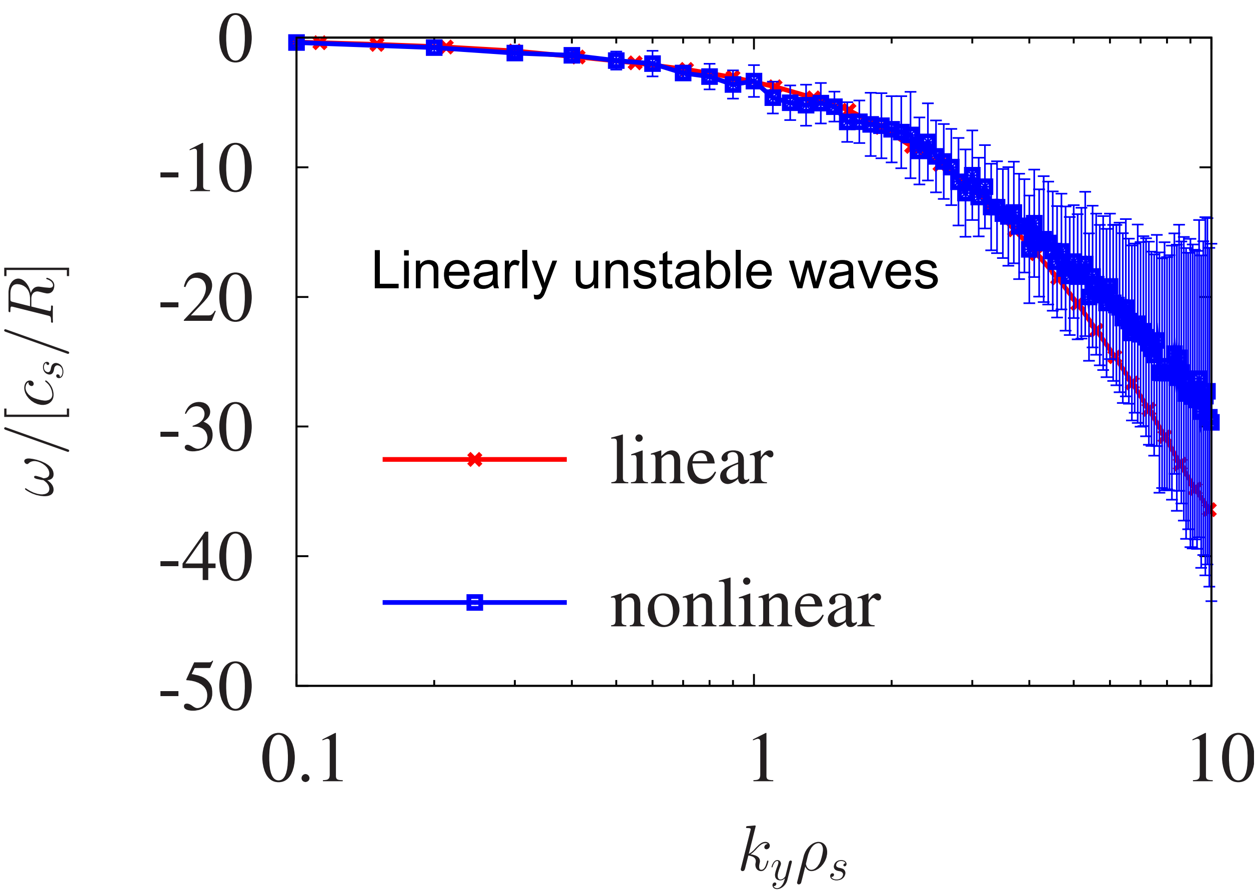
- ⋆ $c_\perp$ too small
  - $\Rightarrow$ not enough dissipation
- ⋆ $c_\perp$ too strong
  - $\Rightarrow$ overestimates injection
- ⋆ $c_\perp = 0.375$ good agreement
  - $\rightarrow$ "plateau" for $c_\perp \in [0.25, 0.625]$
  - $\rightarrow$ holds for k_x



Morel *et al.*, PoP 2011

Large savings in computational cost; use *dynamic procedure*…

Linear waves in a turbulent environment



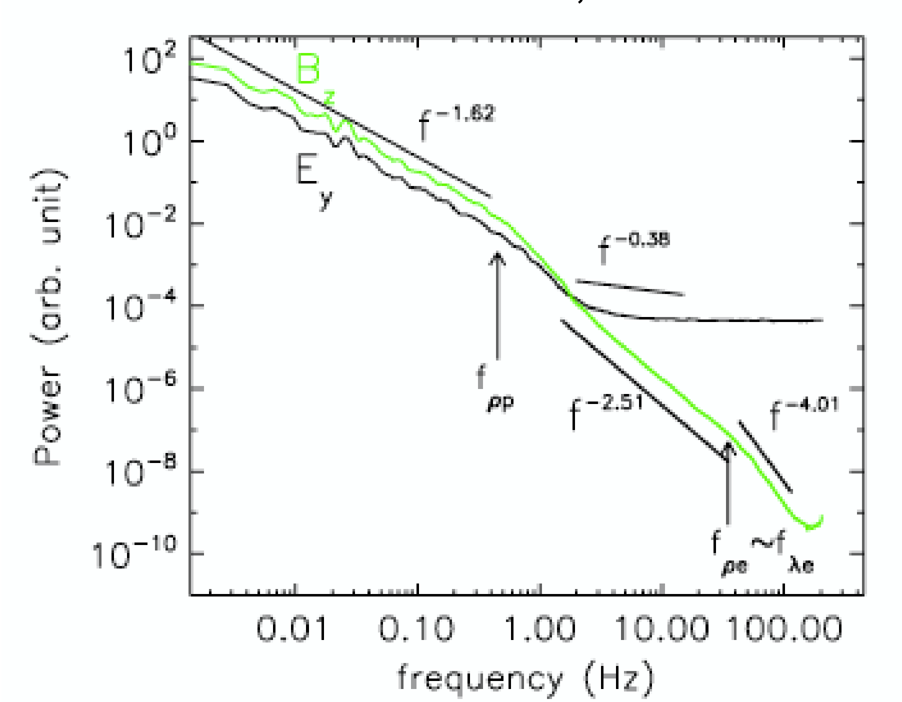
Görler & Jenko, PoP 2008

See also:
Plunk, PoP 2013

Role of collisionless damping not clear *a priori*

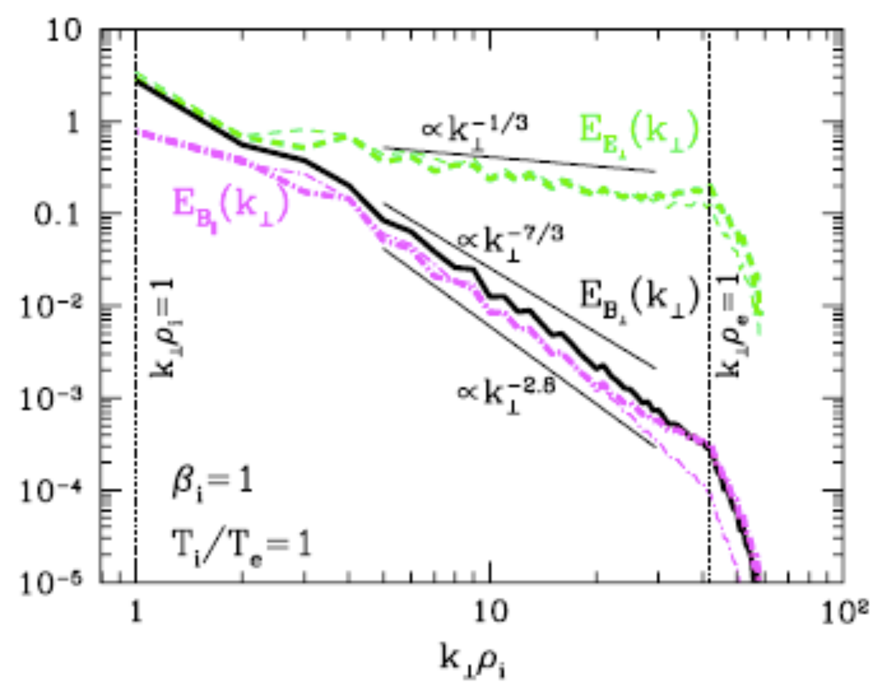
Gyrokinetic simulations of the solar wind dispersion / dissipation range

Sahraoui *et al.*, PRL 2009



Cluster spacecraft measurements

Howes *et al.*, PRL 2011



Gyrokinetic simulations below ρ_i

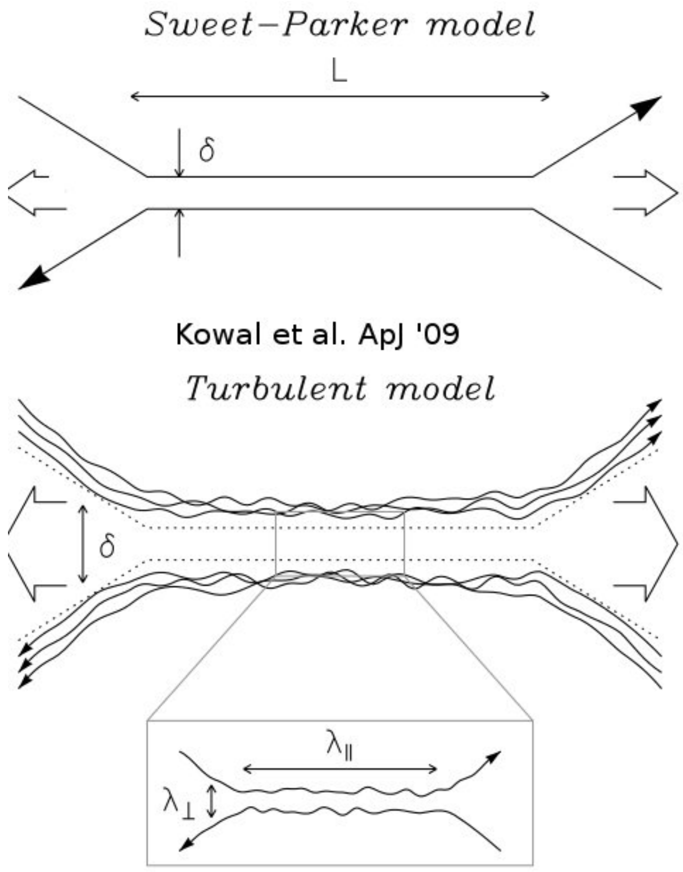
Reconnection in turbulent environment

Traditional reconnection models assume **simplifed geometries**

In practice, reconnection often occurs in a **turbulent environment**

Recent attempts to attack this problem (e.g., Kowal 09, Loureiro 09, Servidio 09-12)

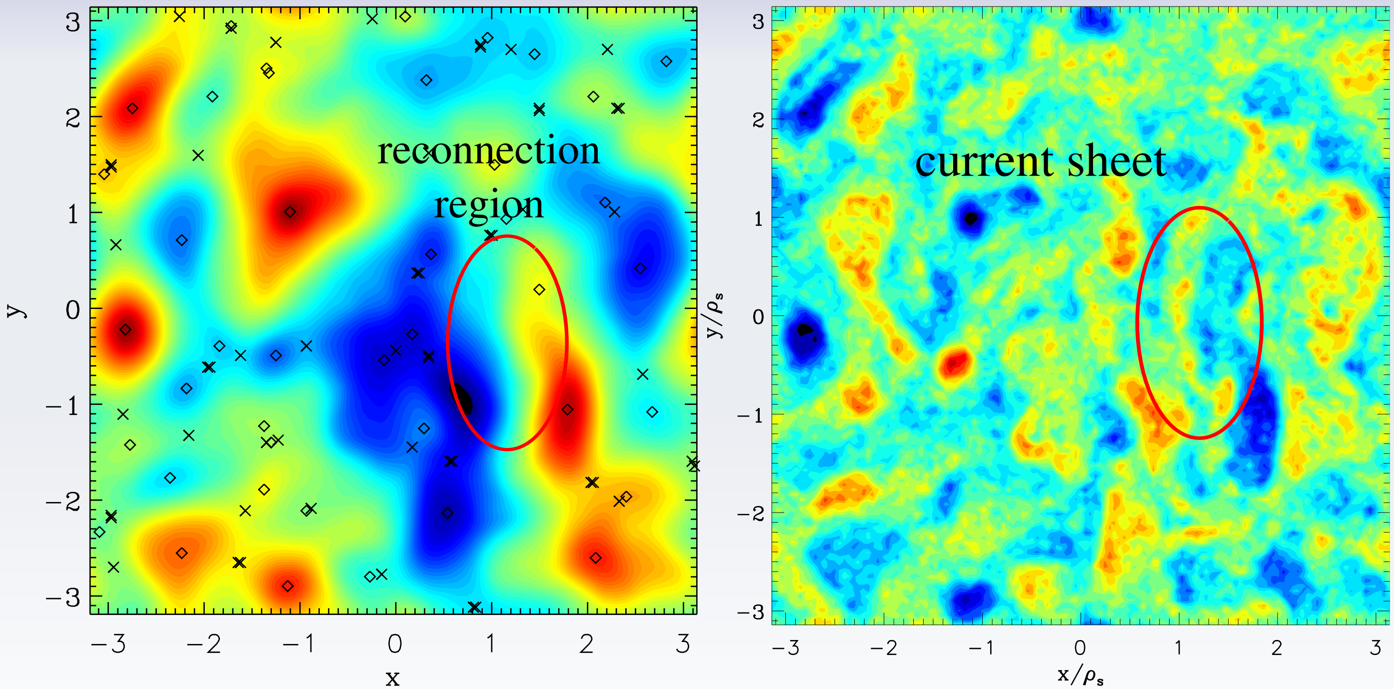
Efficient approach in the presence of a strong guide field: **gyrokinetics**



Gyrokinetic turbulent reconnection

Use random $f_1(t=0) \propto k_x^{-1} k_y^{-1}$ + small v-space perturbation

- Islands in $A_{\|}$ (left)
- Current sheets visible in $j_{\|}$ (right), aligned to magnetic potential, typical scale $\lambda = d_e = \frac{c}{\omega_{pe}}$



Pueschel, Jenko, Told & Büchner, PoP 2011

Generation of parallel electric fields by the turbulence

Key issues to explore

- Better understanding of MHD inertial range physics
  - Defines interface to kinetic dissipation range physics
  - Quantitative description of anisotropy

  Talk by W. Matthaeus

- (Gyro-)Kinetic studies of dissipation range physics
  - *Ab initio* approach, no free parameters
  - Window of opportunity (HPC & observations)

  Talk by W. Daughton

- Applications to various space and astrophysical problems

  Talk by J. Stone