Numerical investigations of gyrokinetic turbulence and reconnection with GENE

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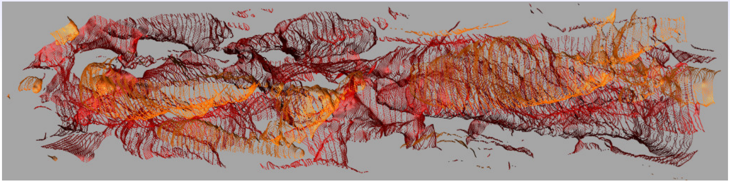

Outline

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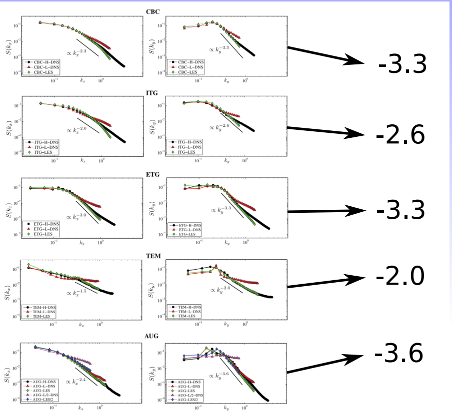
1. **Introduction**
2. 2D electrostatic studies of GK turbulence
3. 2D reconnection studies

Tokamak turbulence: Strongly varying spectral exponents!

A. Bañon Navarro et al. (PoP 2014):



- GK **fusion** applications: Take experimental parameters, perform simulations, **compare observables** to experiment
- Spectral exponents vary **a lot** for different turbulence regimes, plasma parameters

What **determines** these exponents for given parameter settings?

The gyrokinetic code GENE

- **Eulerian code** $\Rightarrow$ solves gyrokinetic equations on a fixed grid in 5D phase space
- Originally developed for turbulence studies in fusion plasmas, but generally applicable to plasma turbulence in strong guide fields
- Full electromagnetic fluctuations, $\delta \boldsymbol{B}_\perp$ & $\delta B_\parallel$ $\Rightarrow$ applicable to high-β plasmas
- GENE website: `http://gene.rzg.mpg.de`

Here: Study simple GK systems, gradually add complexity
2D spatial dynamics, neglect background inhomogeneity $\Rightarrow$

$$\frac{\partial g_j}{\partial t} = \sum_{\boldsymbol{k}'} \left(k'_x k_y - k_x k'_y\right) \overline{\chi}_j(\boldsymbol{k}') g_j \left(\boldsymbol{k} - \boldsymbol{k}'\right) - \omega_{\mathrm{dr}} \left[g_{j,k_y=0} - g_{j,k_y=0}\left(t=0\right)\right] + \mathcal{C}\left[g_j\right]$$

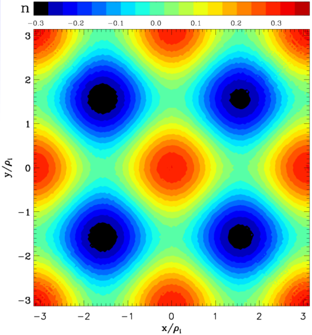
+ GK Maxwell's equations (with $\overline{\chi}_j = \overline{\phi}_j - v_\parallel \overline{A}_{\parallel j}/c + \mu \overline{B}_{\parallel j}/q_j$)

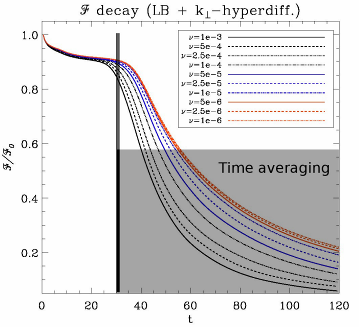
Outline

Study fundamental properties of 2D GK turbulence

Use same setup as in **Tatsuno et al.** (PRL '09):

- electrostatic limit ($\chi \equiv \phi$), focusing on $k_\perp \rho_i \gg 1$
- sinusoidal initial condition
  $f_1 = A\,[\cos(2k_{x,\mathrm{min}}x) + \cos(2k_{y,\mathrm{min}}y)] + B\,\mathrm{rnd}(k_x, k_y)$ with $B \ll A$
- no drive term $\Rightarrow$ **decaying** turbulence
- analyze spectral properties of turbulence in the strong-decay phase when the cascade is fully established
- **new ingredient**: study variation of the spectra as **collisionality** is increased





Expect inertial range with power law spectra

Theory for small collisionality (Schekochihin PPCF '08, Plunk JFM '10):

- **Nonlinear phase mixing**, particles with different ρ_i see different gyroaveraged potentials
  $\Rightarrow$ small spatial structures create small velocity space structures $\Rightarrow$ **dissipation through collisions**

With $\phi \sim k_\perp^{-1} f$, derive power law exponents

$$\boxed{\alpha_\phi = -10/3, \ \alpha_f = -4/3}$$

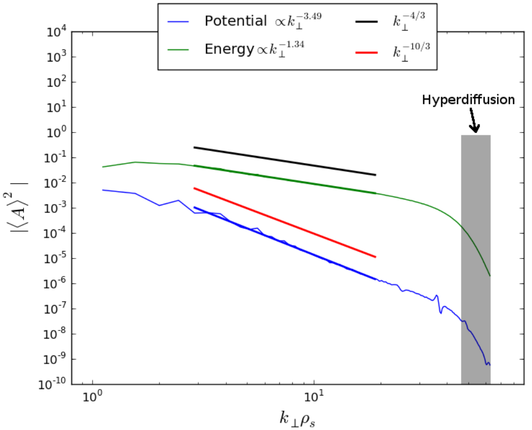
where

$$E_{|\phi|^2}(k_\perp) \propto k_\perp^{\alpha_\phi}, \qquad E_{|f|^2}(k_\perp) \propto k_\perp^{\alpha_f}$$

Scalings confirmed numerically (Tatsuno PRL '09)

GENE simulations: low collisionality example

- Collisionality $\nu = 10^{-6}$, max. grid $256 \times 256 \times 32 \times 96$ in $(x, y, v_{\|}, \mu)$
- Hyperdiffusion in $k_\perp$ (shaded area)

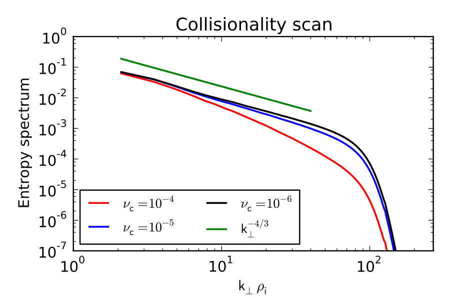


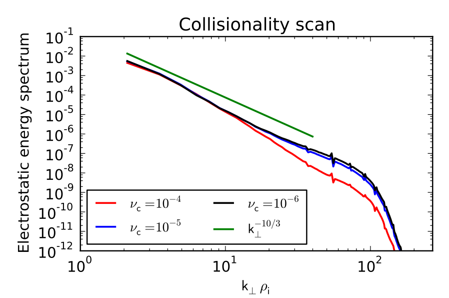
numerically:
$\alpha_\phi = -3.49$,
$\alpha_f = -1.34$

Very good agreement with power law fit to simulation results!

Higher collisionality leads to steeper spectra

Run identical simulations for $\nu = 10^{-5},\ 10^{-4}$

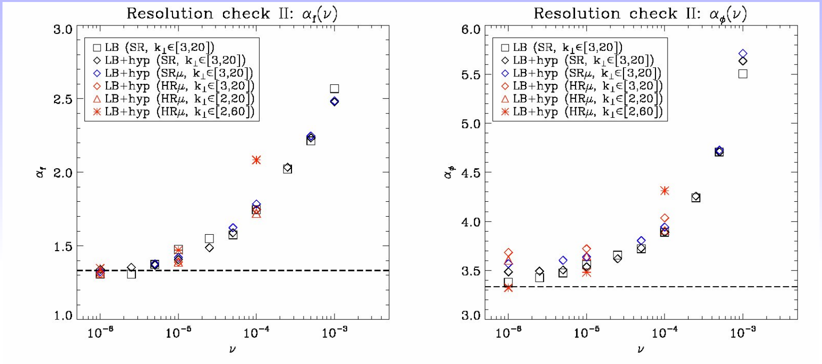




Spectra steepen at higher collisionality, gradual transition to 'power law $\times$ exponential' shape

Study collisionality dependence

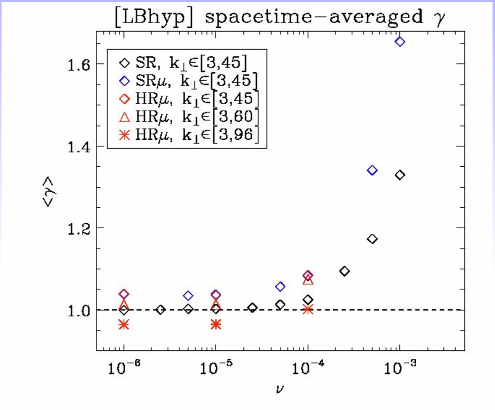
- Tests performed with various resolutions, fit ranges, time windows (and collision operators!)
- Smoothly rising exponents with increasing collisionality



Find steepening of both potential and entropy spectra at higher collisionality

What causes the steepening?

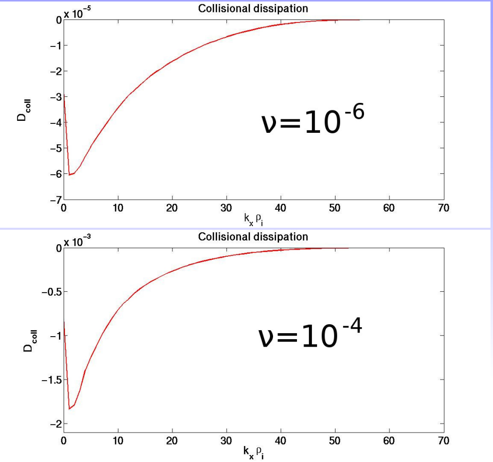
- **Test assumptions** which enter into theoretical scalings
- First: $\phi \sim k_\perp^{-\gamma} f$ with exponent $\gamma = 1$, still true for higher collisionality?
- Evaluate γ from numerical simulations



At high collisionality $\gamma > 1$, but α_ϕ and α_f begin to steepen **even earlier**!

Second assumption: k-independent energy flux

Plots:
spectral dependence of collisional free energy dissipation

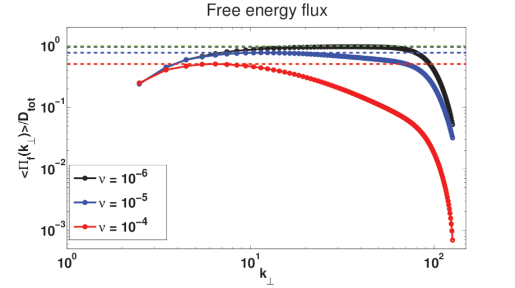


Two observations:

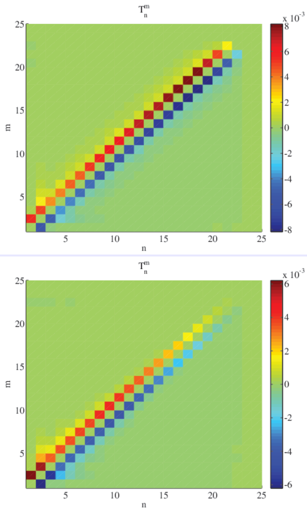
- identical spectral shape
- most dissipation occurs at large scales!

How does this affect the energy flux?

Modified power laws caused mainly by local dissipation



- At low collisionality, **all free energy passes through the cascade**
- At higher collisionality, **increasing fractions** of the total free energy **are dissipated** before passing through the cascade
- Nonlinear transfer is **local** in both cases
- see also Hatch et al. PRL (2013)



Further systems with local dissipation effects

- Bratanov et al. (PRL 2013): Non-universal power laws (set by nonlinear transfer vs. linear dissipation) in modified Kuramoto-Sivashinsky turbulence

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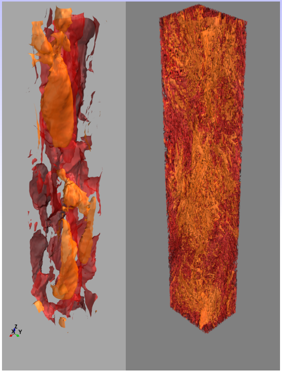


$A_{\parallel}$ $j_{\parallel}$

- Kinetic Alfvén wave turbulence in driven simulations
- Here: energy injection using Langevin antenna current as described in TenBarge et al., CPC (2014)
- How does Landau damping (for different β, T_i/T_e) affect the spectral exponents of KAW turbulence?

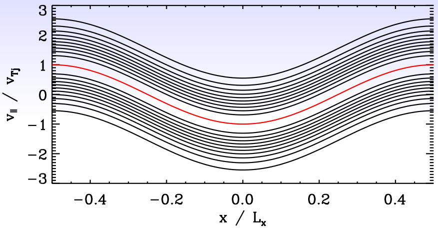
Outline

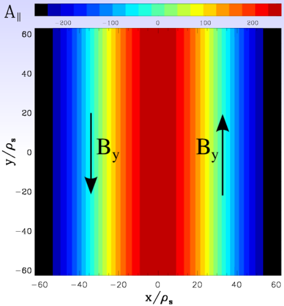
Current sheet setup

- Here: periodic boundary conditions $\Rightarrow$ study sinusoidal current sheet
- Initialize f_1 with shifted Maxwellian in $v_\parallel$:

$$f_1\left(x, v_\parallel, \mu\right) = C \exp\left\{-\frac{1}{T}\left[\frac{m}{2}\left(v_\parallel - \Delta v \cos\left(N k_x x\right)\right)^2 + \mu B\right]\right\}$$

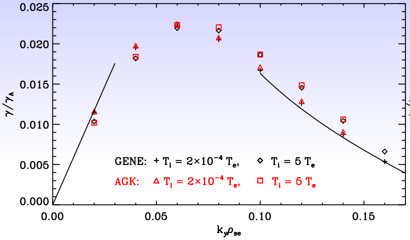
- Counterflowing species; add small-amplitude white noise as perturbation

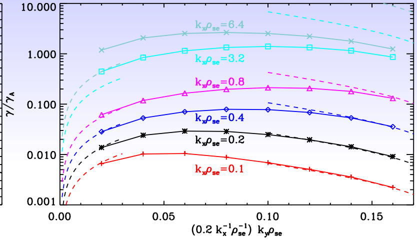




Linear benchmark (Pueschel *et al.*, PoP '11)

- Compare linear growth rates to results from Rogers *et al.*, PoP '07
- Excellent agreement between GS2/AstroGK and GENE
- Good agreement with Porcelli's fluid model (PRL '91) in limits of $k_y \to 0$ (large Δ') and $k_y \to k_x$ (small Δ') within limits of applicability in ($\beta_{\rm tot}$, k_x, m_e/m_i)





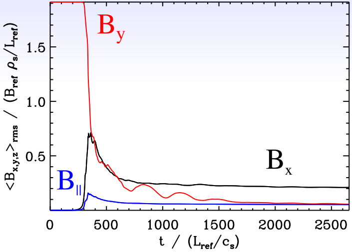
$k_x\rho_s = 0.2$, $m_e/m_i = 1/100$, $\beta_e = 0.2$

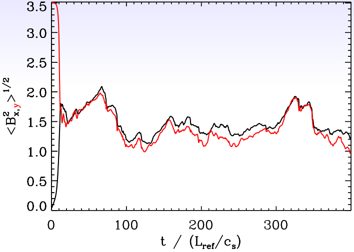
Decaying vs. driven turbulence

- Initialize many modes, follow evolution into nonlinear phase
- Particle acceleration: $E_\parallel = \frac{1}{B_0}\boldsymbol{B}_\perp \cdot \boldsymbol{E}_\perp - \frac{1}{c}\partial A_\parallel/\partial t$, heating rate $j_\parallel E_\parallel$

- no driving term
- transient generation of $E_\parallel$

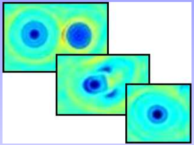
- Krook-type forcing term fuels initial current sheets (acting only on $k_y = 0$), rate $\omega_{\rm dr}$
- quasi-steady state

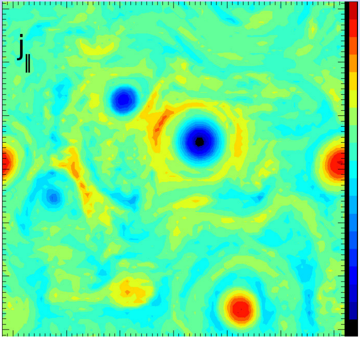




Self-generation of plasmoids

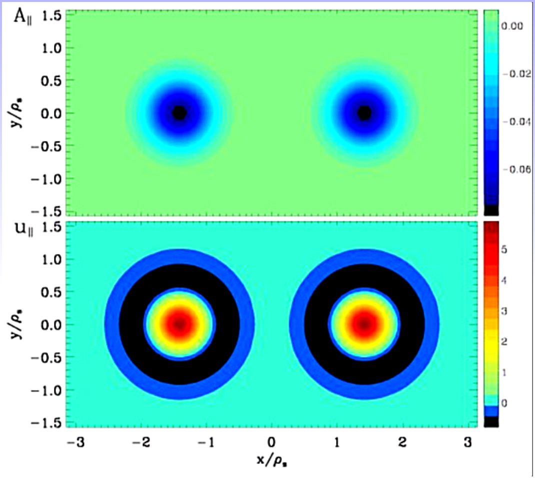
- In nonlinear phase, plasmoids (=parallel current filament with ∼circular cross-section) are formed
- Same-sign plasmoids attract each other, larger ones more stable
- Bursts in both $E_{\|}$ and $j_{\|} E_{\|}$ are associated to plasmoid merging events



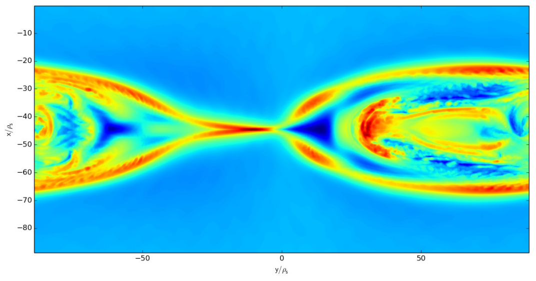


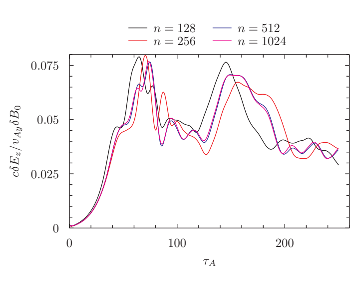
Isolated plasmoid mergers

- Set up initial condition with two same-sign plasmoids
- May provide useful testbed for benchmarking of different models (possibly in 3d?), studying associated dissipation/acceleration



New activity: reconnection benchmark





Activity within Max-Planck Princeton Center:

- 2D reconnection benchmark PIC & Gyrokinetics, following TenBarge et al., PoP (2014)
- First scans agree reasonably well with AstroGK (and thus NPIC/VPIC), but sensitive to precise initialization

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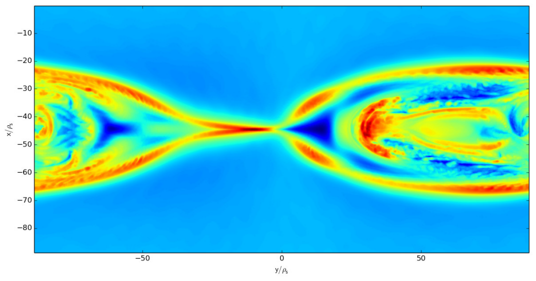

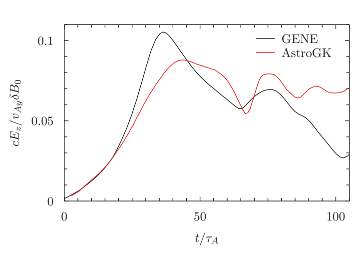

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Summary

2D study of electrostatic gyrokinetic turbulence properties

- In collisionless limit, find **excellent agreement** with theory (Schekochihin & Plunk)
- Deviations at higher collisionality, leading to **steeper power law decays**
- Steepening caused by local collisional dissipation $\Rightarrow$ energy partially **dissipated before entering the cascade**

Gyrokinetic simulations of reconnection

- Linear regime: successful benchmarking of tearing mode growth rates against AstroGK and Porcelli's fluid model
- Driven turbulent reconnection:
  find **self-generation of plasmoids**, associated with strong local parallel electric fields ($\Leftrightarrow$ particle acceleration)
- Nonlinear **reconnection benchmark** also **shows good agreement** with AstroGK (and thus PIC)