Dissipation and Kinetic Physics of Astrophysical Plasma Turbulence

NSF PRAC project #1614664

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Blue Waters Symposium, Sunriver, OR, May 15-19, 2017

Acknowledgements

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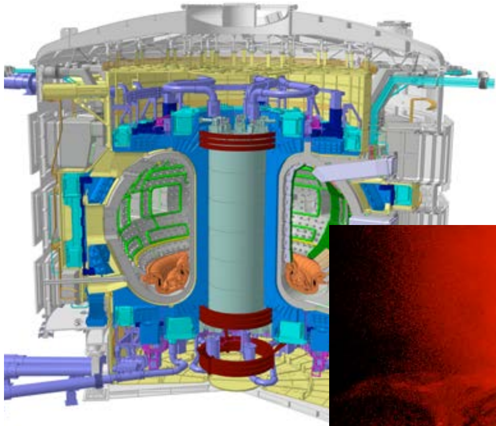
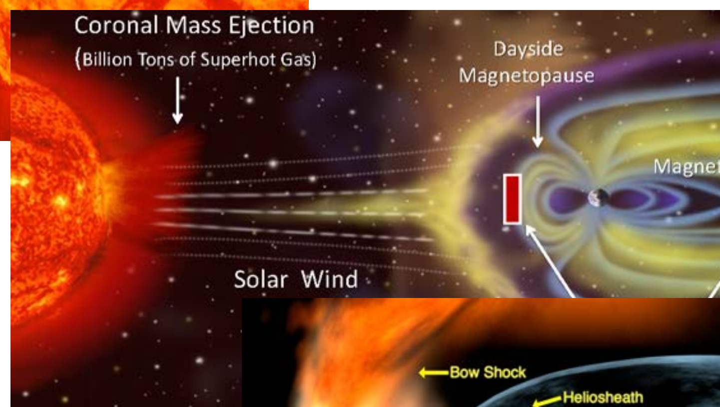
Funding: NASA, NSF

Plasma Turbulence is a Ubiquitous Phenomenon



Fusion : magnetically confined, inertially confined, hybrid

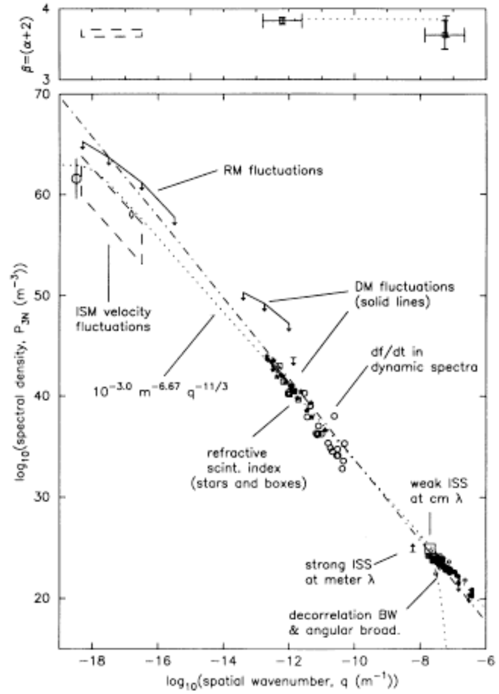
Solar corona



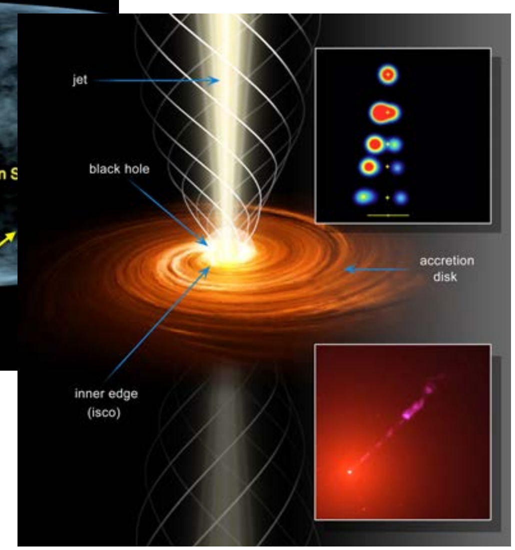
Solar wind, planetary magnetospheres

Heliosphere, interstellar Medium

Local Interstellar Medium

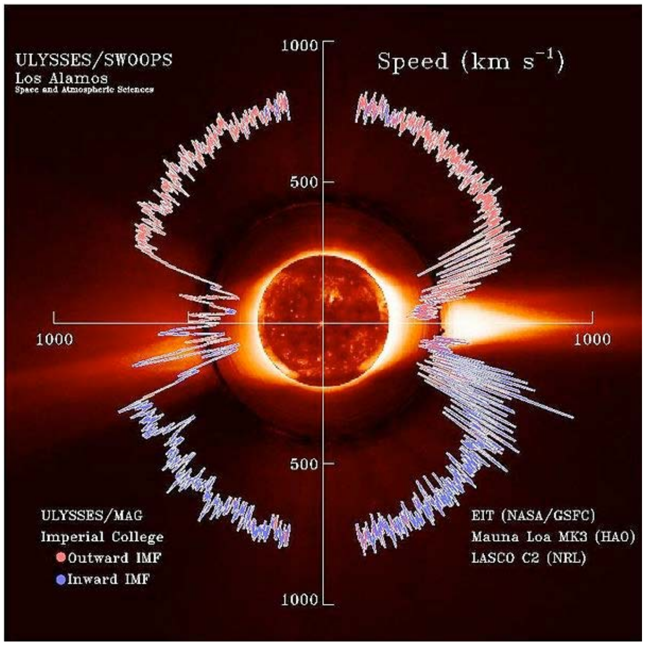


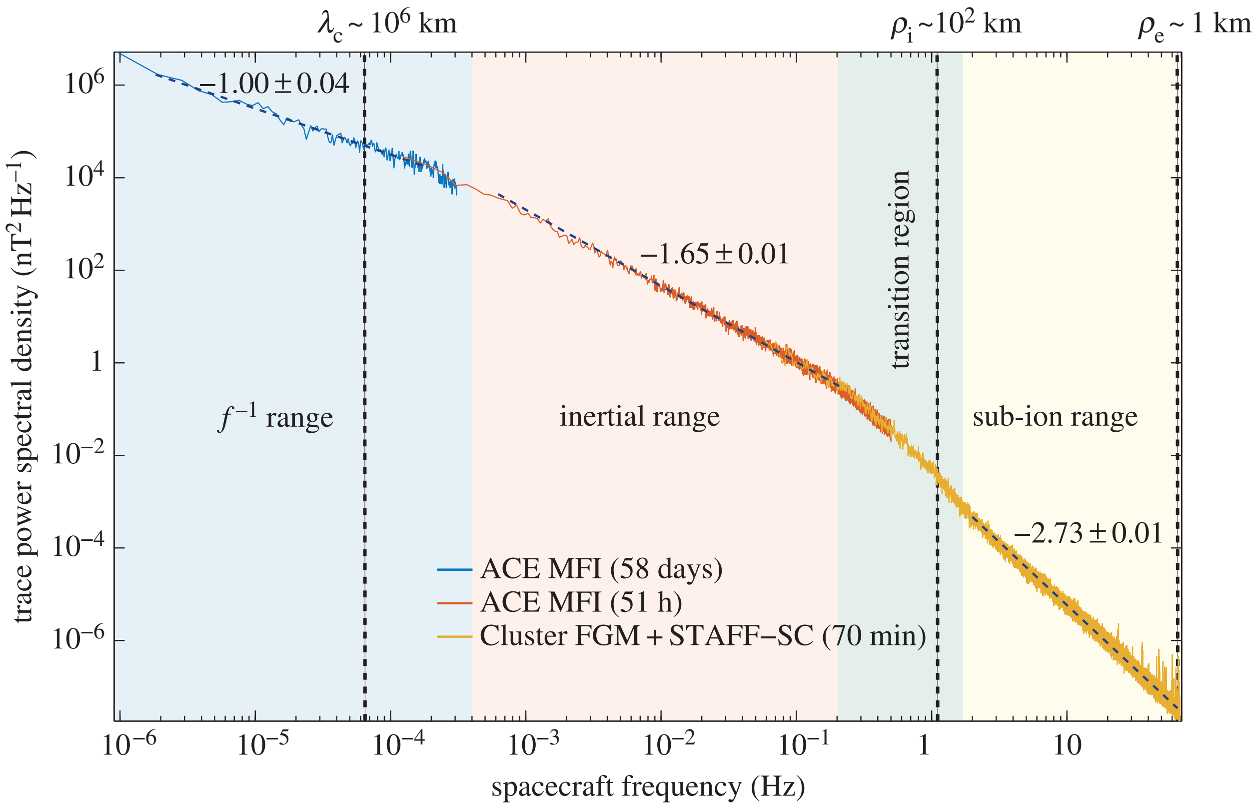
Armstrong *et al.*, 1995



Jets, accretion disks, other astrophysical objects

Focus of This Project: Turbulence in Solar Wind & Magnetosphere

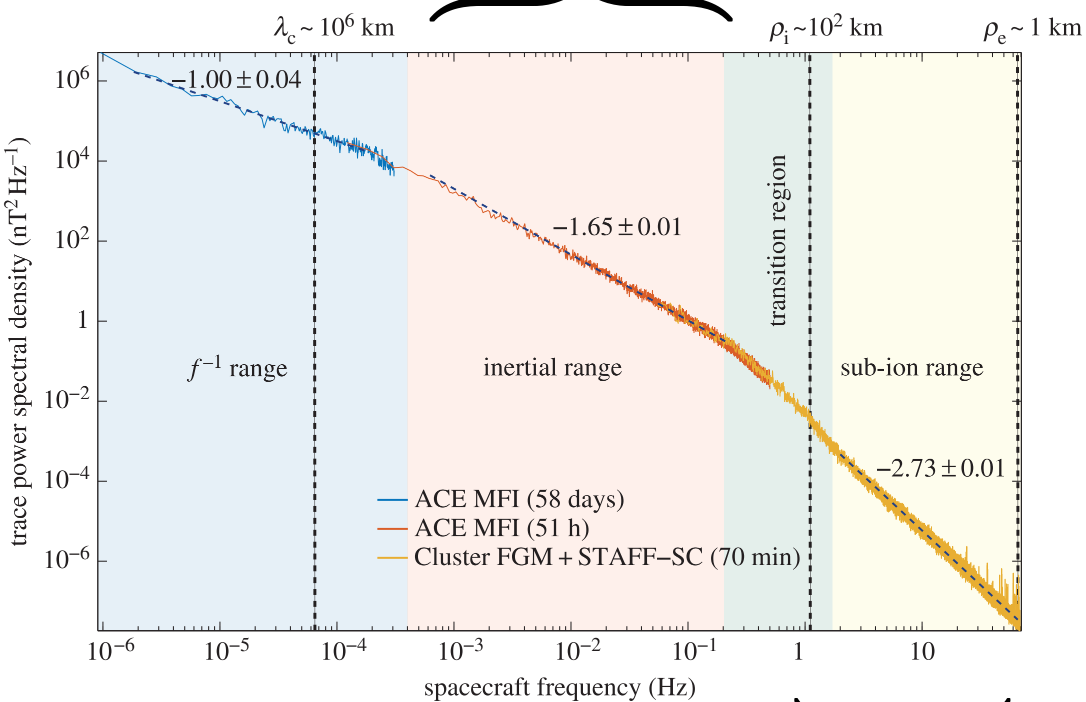




Kiyani *et al.*, 2015

- Turbulence is of interest because of:
    - Local energy input (e.g. to explain famously anomalous temperature profiles)
    - Transport of energetic particles (solar energetic particles, cosmic rays, etc)
- Solar Wind is the best accessible example of astrophysical (=large scale) plasma turbulence

Kinetic Effects in Plasma Turbulence (i.e. the Plasma Physics Aspects)

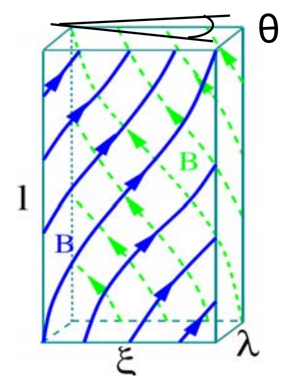


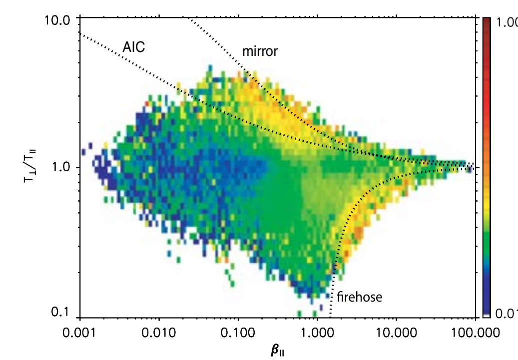
Cross-scale coupling in the inertial range via

- intense current sheets and reconnection
- ion temperature anisotropies
- coupling between compressible and incompressible fluctuations

"dispersion range" or "dissipation range":

- internal kinetic scales are encountered, leading to partial onset of dissipation, but also to change in fluctuation properties;
- in weakly collisional plasma, dissipation is a collective effect





Boldyrev, 2005
Loureiro & Boldyrev, 2016
Mallet et al., 2016

Bale *et al.*, 2009

A Variety of Models & Approximations Are Used to Tackle This Range of Scales

"First-Principle" description of weakly coupled plasmas:

$$\partial_t f_s + \boldsymbol{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left(\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} \right) \cdot \nabla_{\boldsymbol{v}} f_s = \mathcal{C}\{f_s, f_{s'}, \ldots\}$$

+ Maxwell's equations

L: system size, energy injection scale, correlation scale

collisional scale (collisional)

ion kinetic scales

electron kinetic scales

collisional scale (c-less)

debye length

smaller scales

model complexity

Magnetohydrodynamic approximation (MHD): incompressible, fully compressible, kinetic MHD..

$$\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = \frac{1}{c} \boldsymbol{j} \times \boldsymbol{B}$$

$$\partial_t \boldsymbol{B} = -c \nabla \times \boldsymbol{E} \qquad \nabla \times \boldsymbol{B} = \frac{4\pi}{c} \boldsymbol{j}$$

$$\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} = 0$$

Hall MHD

multi-fluid multi-moments models

hybrid kinetic

…

Landau Fluid

Gyrokinetic

Fully kinetic

…

In many situations, cross-scale coupling play a role an important role global dynamics. Full understanding of global evolution may require multi-scale, multi-physics models

Models

Fully kinetic simulations (microscopic model)

All species kinetic

code: VPIC

Hybrid simulations (mesoscale model)

kinetic ions + fluid electrons

codes: H3D, HYPERES

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left(\boldsymbol{E} + \frac{1}{c} \boldsymbol{v} \times \boldsymbol{B} \right) \cdot \nabla_{\boldsymbol{v}} f_s = \sum_{s'} \mathcal{C}\{f_s, f_{s'}\}$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} \boldsymbol{j} + \frac{1}{c} \frac{\partial \boldsymbol{E}}{\partial t}$$

$$-\frac{1}{c} \frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \boldsymbol{E}$$

$$\nabla \cdot \boldsymbol{E} = 4\pi \rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

Takizuka-Abe collisional model

$$0 = \frac{4\pi}{c} (\mathbf{j}_i + \mathbf{j}_e) - \nabla \times \mathbf{B}$$

$$0 = e n_e \left[\mathbf{E} - \eta (\mathbf{j}_i + \mathbf{j}_e) \right] - \frac{\mathbf{j}_e \times \mathbf{B}}{c} + \nabla p_e$$

$$\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$e n_e = q_i n_i \, , \, \mathbf{j}_e = -e n_e \mathbf{v}_e$$

$$p_e = n_e T_e \sim n_e^{\gamma}$$

~up to 10^{10} cells

~up to 4×10^{12} particles

~120 TB of memory

~10^7 CPU-HRS (~10^3 CPU-YRS)

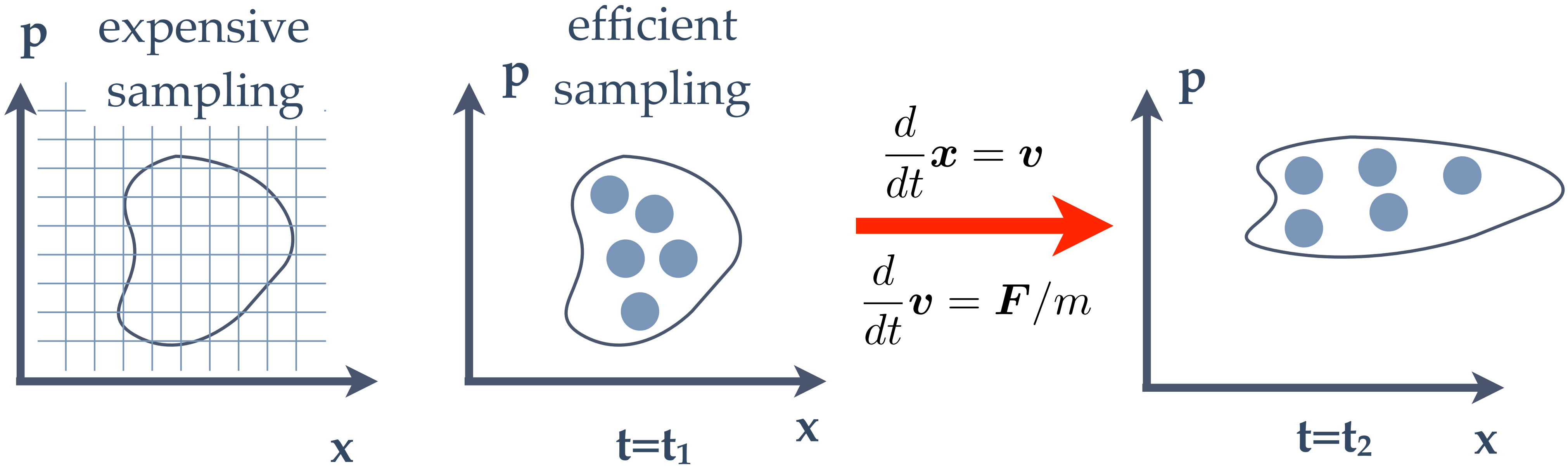
~up to 1.7×10^{10} cells

~up to 2×10^{12} particles

~130 TB of memory

Blue Waters!

PIC: a Monte-Carlo Particle-Mesh Method



$$\frac{d}{dt}\boldsymbol{x} = \boldsymbol{v}$$

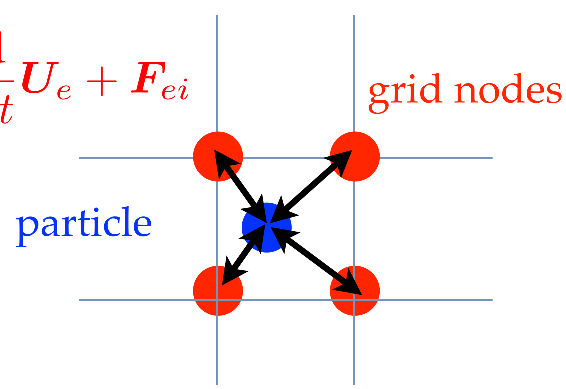
$$\frac{d}{dt}\boldsymbol{v} = \boldsymbol{F}/m$$

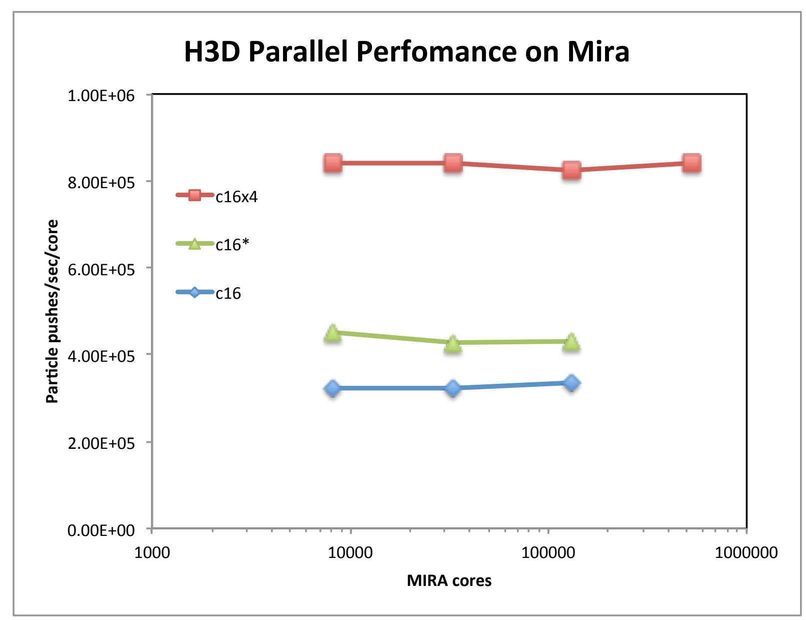
Sample the phase space with computational particles (markers) at $t=t_0$. Move the markers along the characteristics (single-particle equations of motion). Since f(x,v) is constant along the characteristic, we obtain a representation of distribution function at finite $t>t_0$.

$$\partial_t f_i + \boldsymbol{v}\cdot\nabla f_i + \frac{e}{m}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right)\cdot\nabla_{\boldsymbol{v}} f_i = 0$$

$$\partial_t \boldsymbol{B} = -c\nabla\times\boldsymbol{E}$$

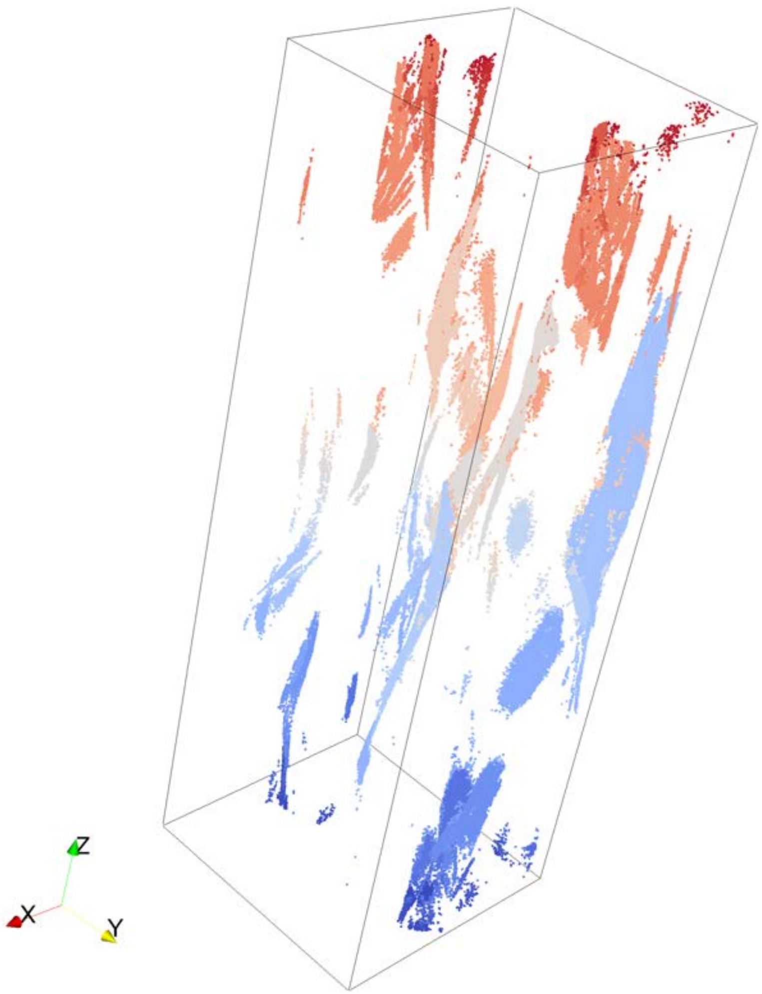
$$\boldsymbol{E} = -\frac{1}{ne}\nabla\boldsymbol{P}_e - \boldsymbol{U}_e\times\boldsymbol{B} - \frac{m_e}{e}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{U}_e + \boldsymbol{F}_{ei}$$



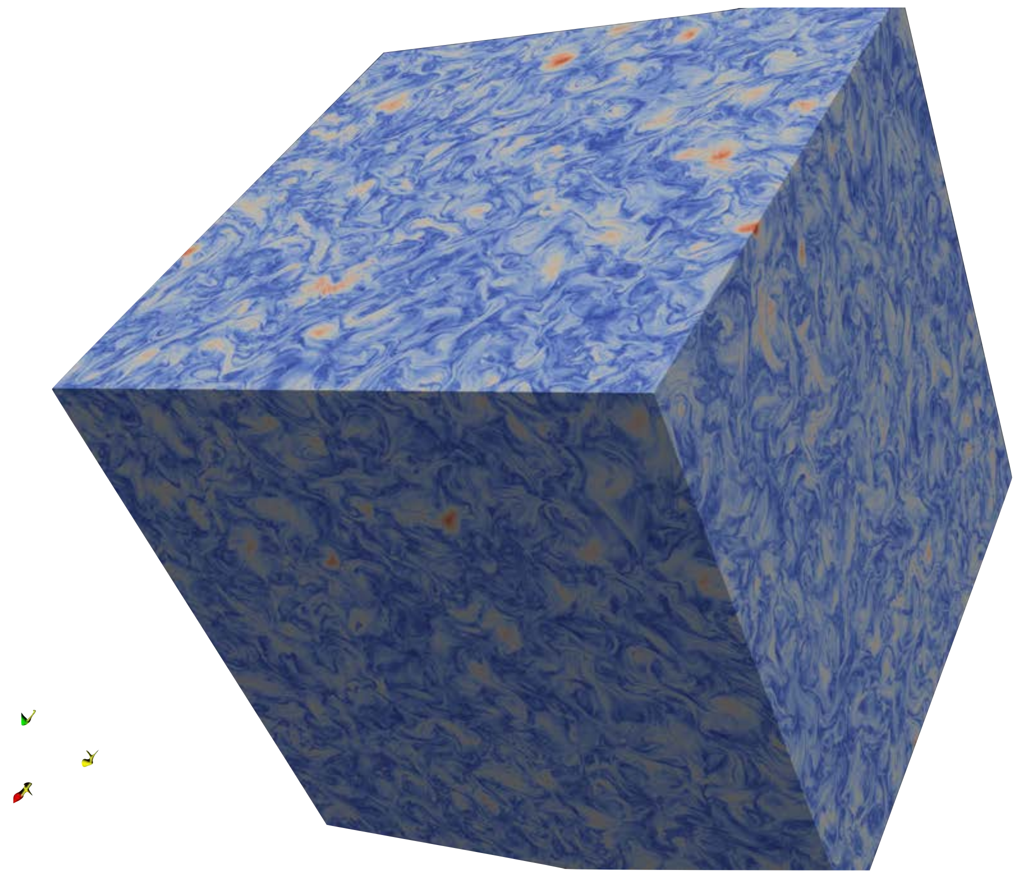


Problems Considered in Year 1

- Generation of intense current sheets at or above proton scales
- Turbulence in low-β plasmas [*in progress*]
- Universality of decay [*in progress*]

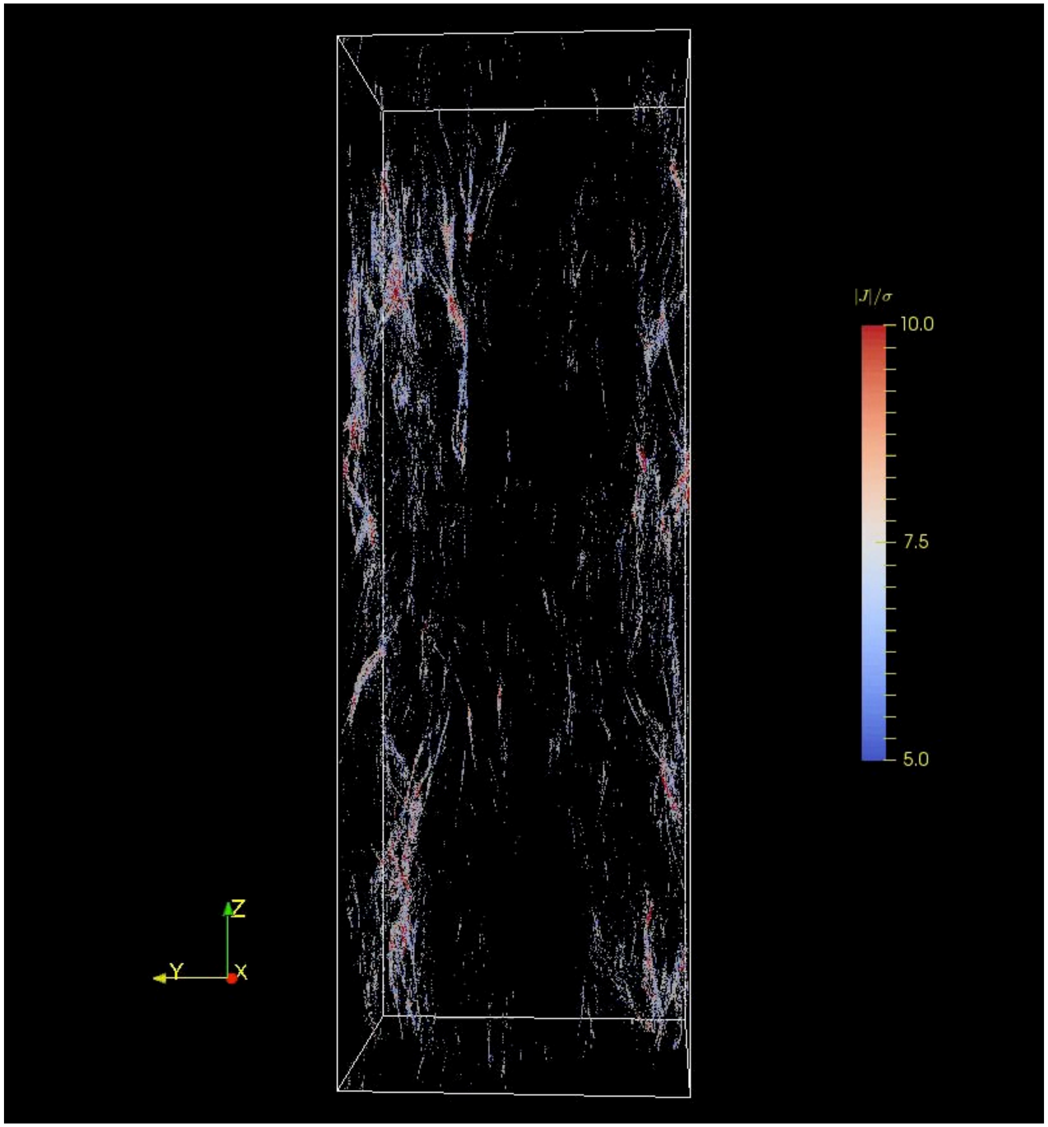


3D hybrid simulation of solar wind-like turbulence



3D hybrid simulation of decaying turbulence

Intense Current Structures: Comparison of Hybrid Simulation with Observations



Current sheets (regions of large gradients in magnetic field) **are typically preferred sites of energy dissipation and reconnection.**

C.S. evolution is an example of cross-scale coupling:

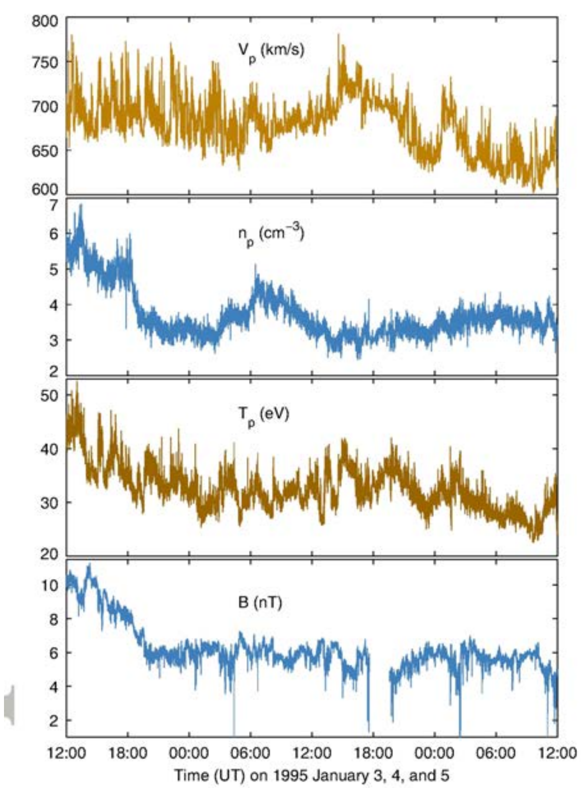
- **C.S. are formed by large-scale dynamics**
- **Evolution of c.s. (e.g. their stability) depends on microscopic effects**
- **The first order of business is classification of c.s.**
- **What's known: some observations, some MHD results, but no kinetic simulations (i.e. no simulations with adequate microscopic physics).**
- **Our goal:**
    - **validate techniques for interpreting spacecraft data**
    - **Make sure that our models reproduce observations**

Podesta and Roytershteyn, under review in JGR

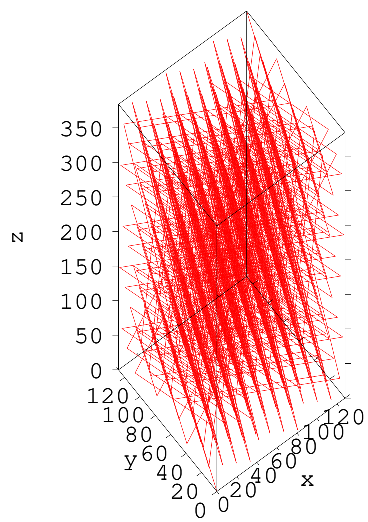
Example of Direct Comparison With Spacecraft Data: Properties of Intense Currents Sheets

In many cases spacecraft data is 1D - a sample along spacecraft trajectory (with the exception of multi-spacecraft missions, e.g. MMS, CLUSTER, THEMIS, etc)

Plasma data from the Wind 3DP instrument and magnetic field strength data from the Wind MFI instrument for the two day interval (Podesta, 2017)



Sample periodic box along 1D trajectory to model spacecraft data acquisition



Remarkable agreements between simulation and data

Table 1. Characteristics of 5σ events in the simulation with $L_\perp = 128d_i$

Property\Physical variable	$J_{\rm true}$	J_P	$dB_x/d\lambda$	$dB_y/d\lambda$	$dB_z/d\lambda$
Mean (in units of B_0/d_i)	0.204	0.103	0	0	0
Standard Deviation (B_0/d_i)	0.122	0.0649	0.0822	0.0562	0.0697
Number of events	365	459	244	168	197
Mean separation distance (d_i)	381	299	563	814	697
Median separation distance (d_i)	214	203	377	544	366
Mean event size (d_i)	1.80	1.75	1.6	1.5	1.2
Mean peak value (B_0/d_i)	0.949	0.508	0.489	0.330	0.403
Maximum peak value (B_0/d_i)	1.68	0.922	0.864	0.761	0.584

Table 2. Characteristics of 5σ events in the simulation with $L_\perp = 256d_i$

Property\Physical variable	$J_{\rm true}$	J_P	$dB_x/d\lambda$	$dB_y/d\lambda$	$dB_z/d\lambda$
Mean (in units of B_0/d_i)	0.109	0.0746	0	0	0
Standard Deviation (B_0/d_i)	0.0748	0.0479	0.0603	0.0416	0.0499
Number of events	2,881	4,249	2,522	1,349	2,033
Mean separation distance (d_i)	386	261	440	823	547
Median separation distance (d_i)	269	160	277	506	302
Mean event size (d_i)	2.83	1.95	1.7	1.8	1.3
Mean peak value (B_0/d_i)	0.581	0.381	0.366	0.250	0.299
Maximum peak value (B_0/d_i)	1.36	1.06	0.818	0.633	0.799

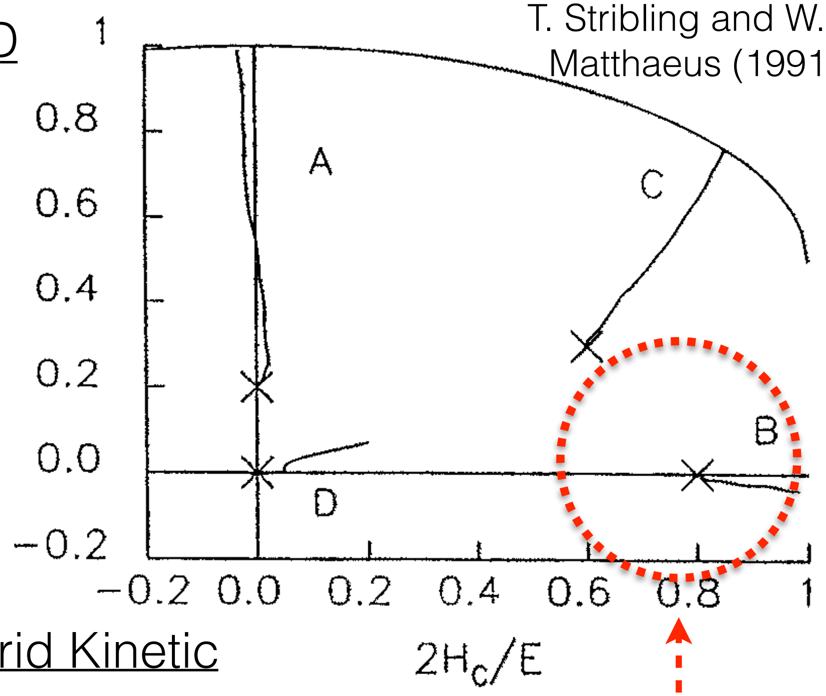
Table 3. Characteristics of 5σ events in high speed solar wind data

Property\Physical variable	$J_{\rm true}$	J_P	$dB_x/d\lambda$	$dB_y/d\lambda$	$dB_z/d\lambda$
Mean (pA/cm^2)	?	0.0952	0	0	0
Standard Deviation (pA/cm^2)	?	0.0725	0.0566	0.0698	0.0791
Number of events	?	1,336	660	977	879
Mean separation distance (d_i)	?	336	680	459	504
Median separation distance (d_i)	?	57.4	108	49.6	71.2
Mean event size (d_i)	?	3.2	3.1	2.8	3.1
Mean peak value (pA/cm^2)	?	0.606	0.363	0.467	0.536
Maximum peak value (pA/cm^2)	?	1.84	1.09	1.72	1.84

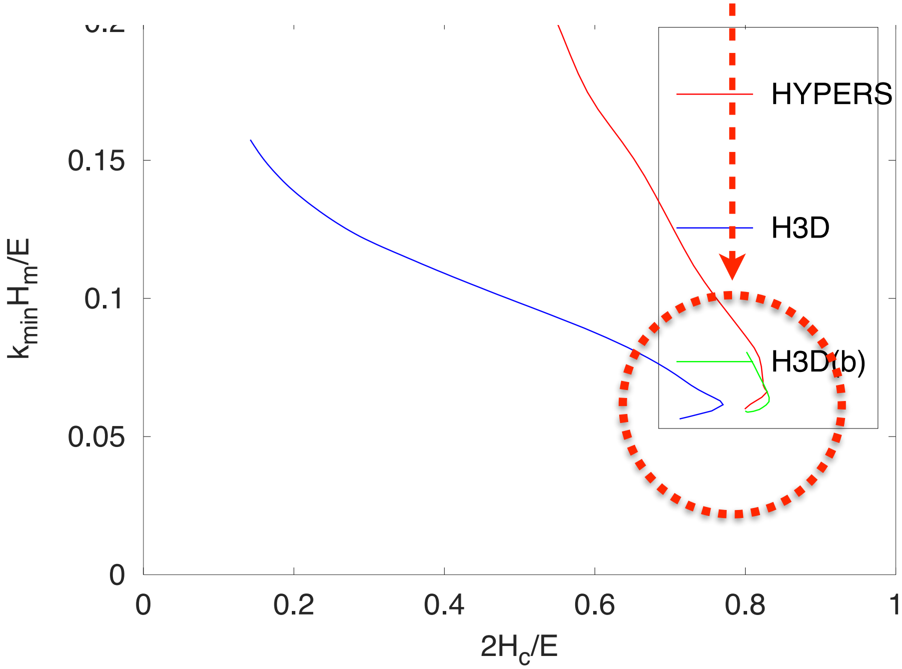
Universality of Decaying Turbulence

MHD

T. Stribling and W. H. Matthaeus (1991).



Hybrid Kinetic



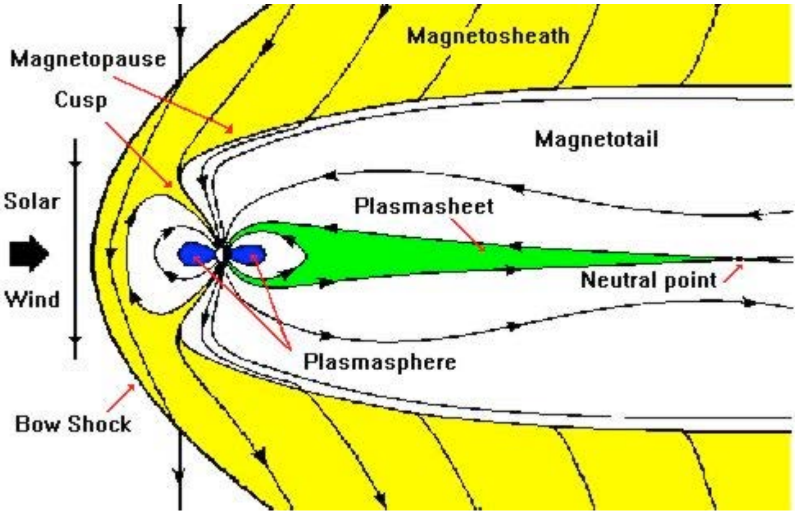
- Collisionless plasma dynamics approximately conserves important quantities (rugged invariants) magnetic helicity, kinetic helicity, energy

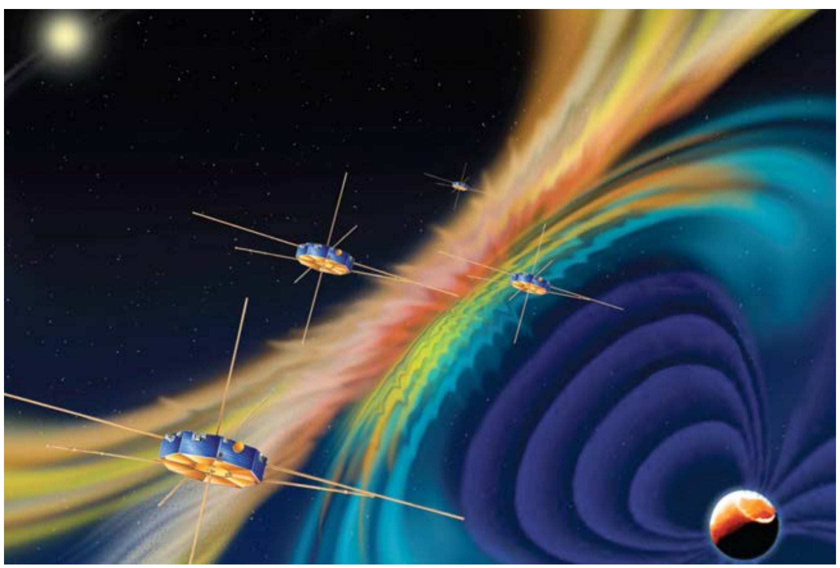
$$H_c = \frac{1}{V}\int (\boldsymbol{v}\cdot\boldsymbol{B})\,dV$$
$$H_m = \frac{1}{V}\int (\boldsymbol{A}\cdot\boldsymbol{B})\,dV$$

- In a real system, the rates of decay are typically different. This results in a decay towards “special” final states.

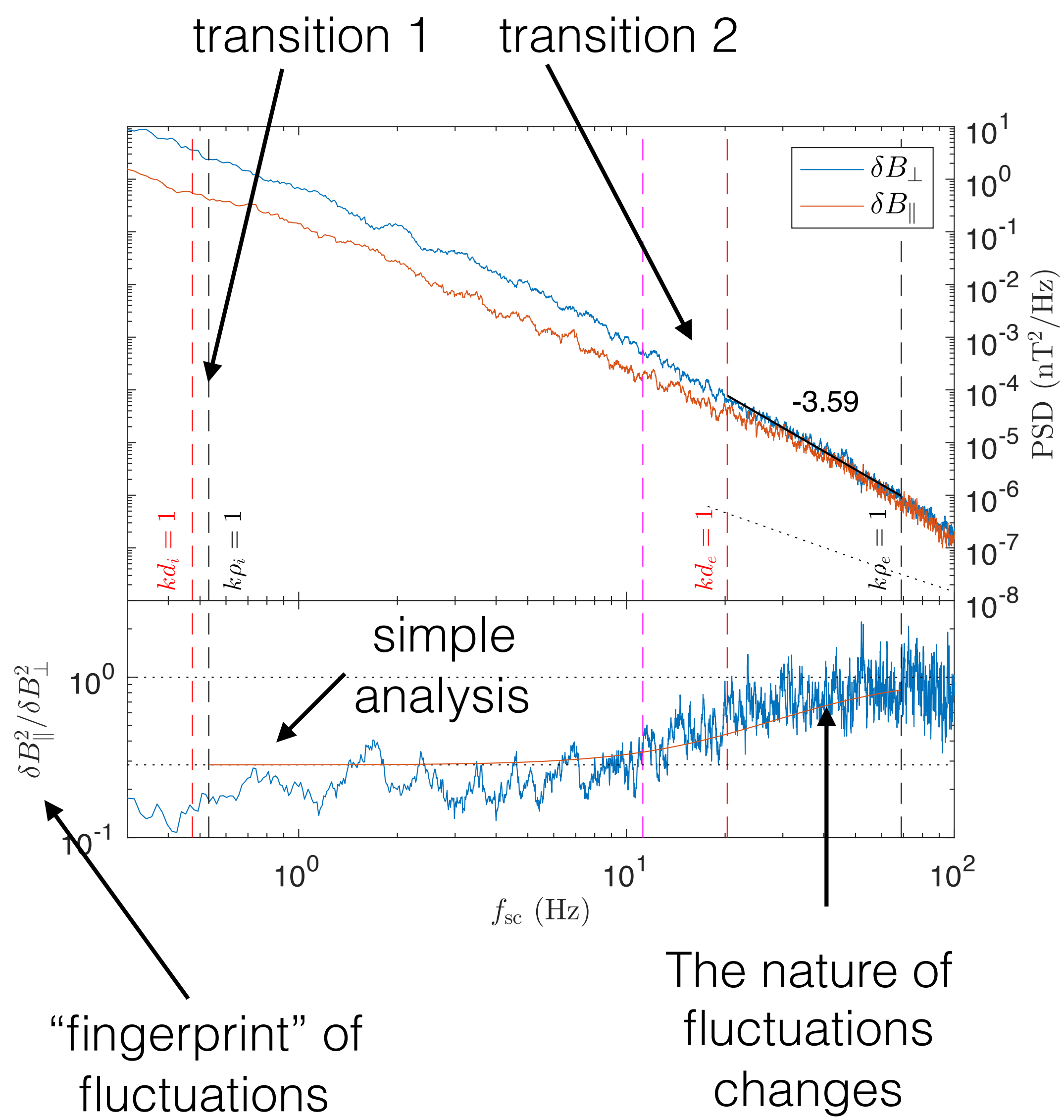
- The existing paradigms are based on idealized approximations.
- One way of interpreting these results is to say that we are putting constraints on how applicable those idealized models are to real plasmas

Sub-Proton Range in low-β plasma: Fully-Kinetic Simulations





Spectrum of Magnetic Fluctuations in the Earth's Magnetosheath



C. H. K. Chen and S. Boldyrev, 2017

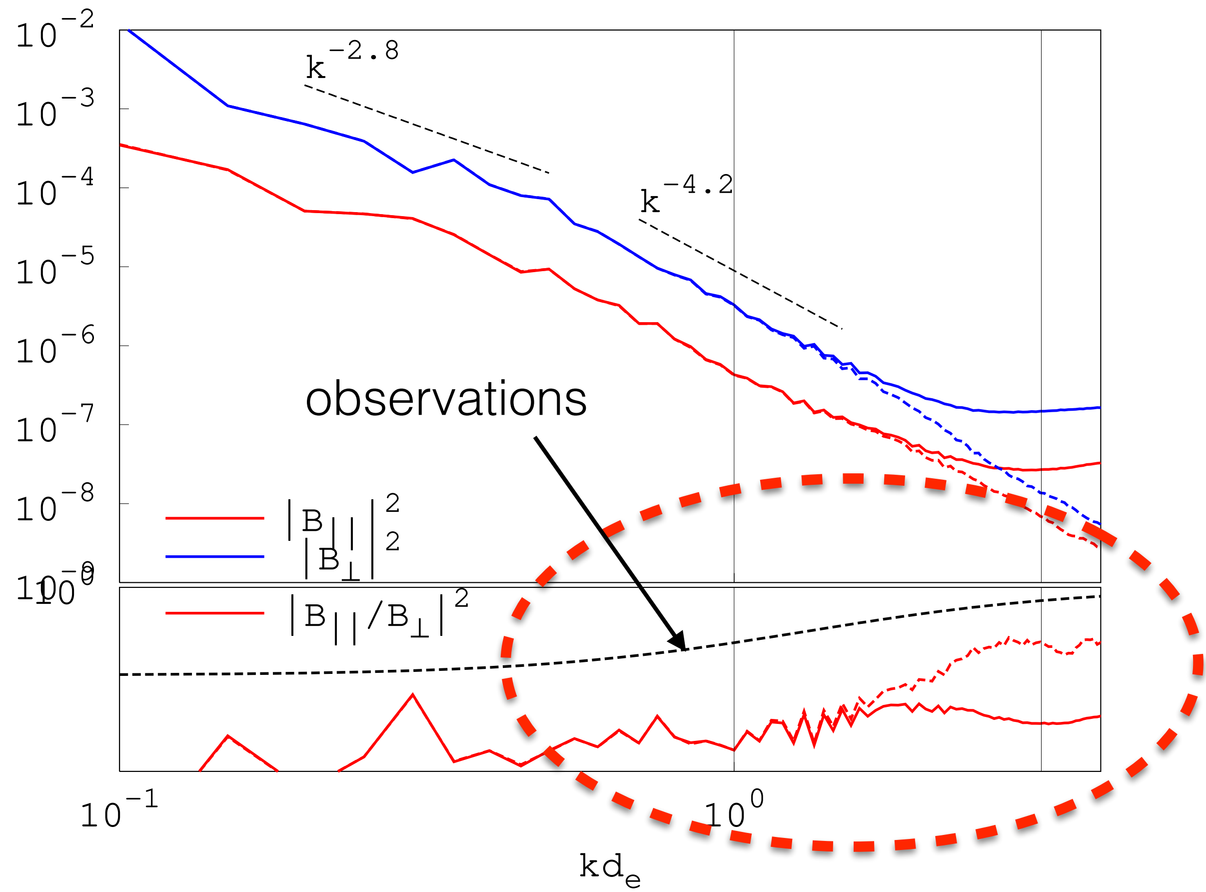
Simulations Revealed Surprising Results

Puzzle:

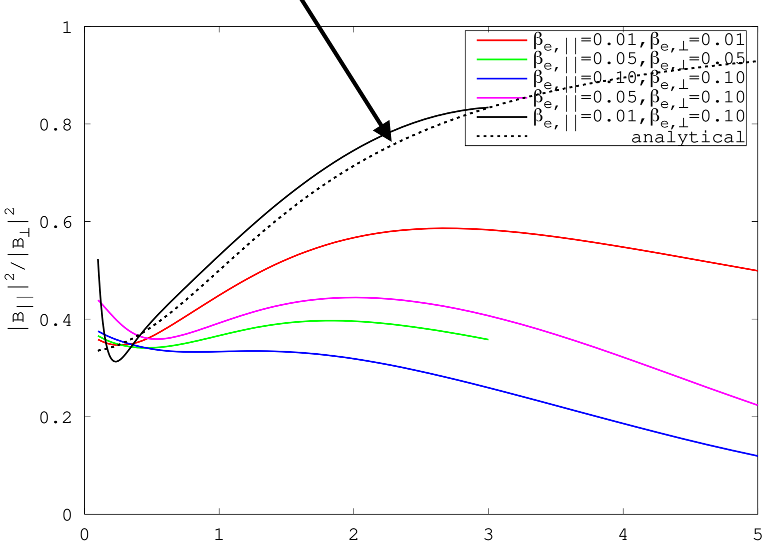
- simplified analysis agrees with observations
- Simulations and "exact" analysis do not

<u>Something very interesting is going on</u>

fully kinetic simulation



"simple" analysis



kinetic linear analysis
("exact solution")

Summary

1. Understanding of plasma turbulence is a grand challenge problem.
2. We are using Blue Waters to study some aspects of this problem, namely kinetic effects associated with turbulence dissipation.
3. Year 1 has yielded exciting results, some of them await explanation

Publications & data products

J. Podesta and V. Roytershteyn, “The most intense electrical currents in the solar wind: Comparisons between single spacecraft measurements and plasma turbulence simulations”, *under review* in JGR

3 more manuscripts in preparation

1 new project has just began with the simulation data produced in BW

Database of large-scale simulations to be used for years to come (hopefully).