Turbulence in space plasmas:

Observations of energy dissipation in reconnecting current sheets in the magnetosheath

Observations of energy dissipation in reconnecting current sheets in the magnetosheath

Alexandros Chasapis[1], W. H. Matthaeus[1], Tulasi Parashar[1], R. Bandyopadhyay[1], R. Chibber[1], Y. Yang[1], S. Servidio[2], C. C. Haggerty[3], B. Maruca[1],
(1) University of Delaware,
(2) Universita della Calabria,
(3) University of Chigago,

What is turbulence?

Flow characterized by chaotic perturbations

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- Perturbations are chaotic and non-linear
- Turbulence can drastically alters properties of the medium
- Instabilities, waves are present

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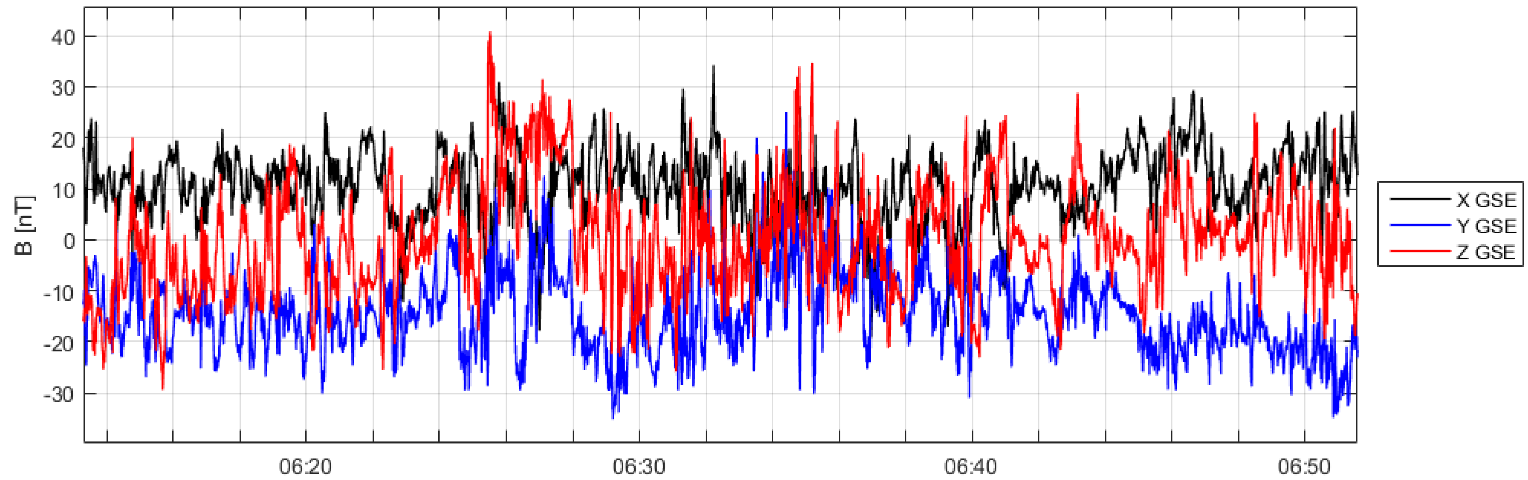
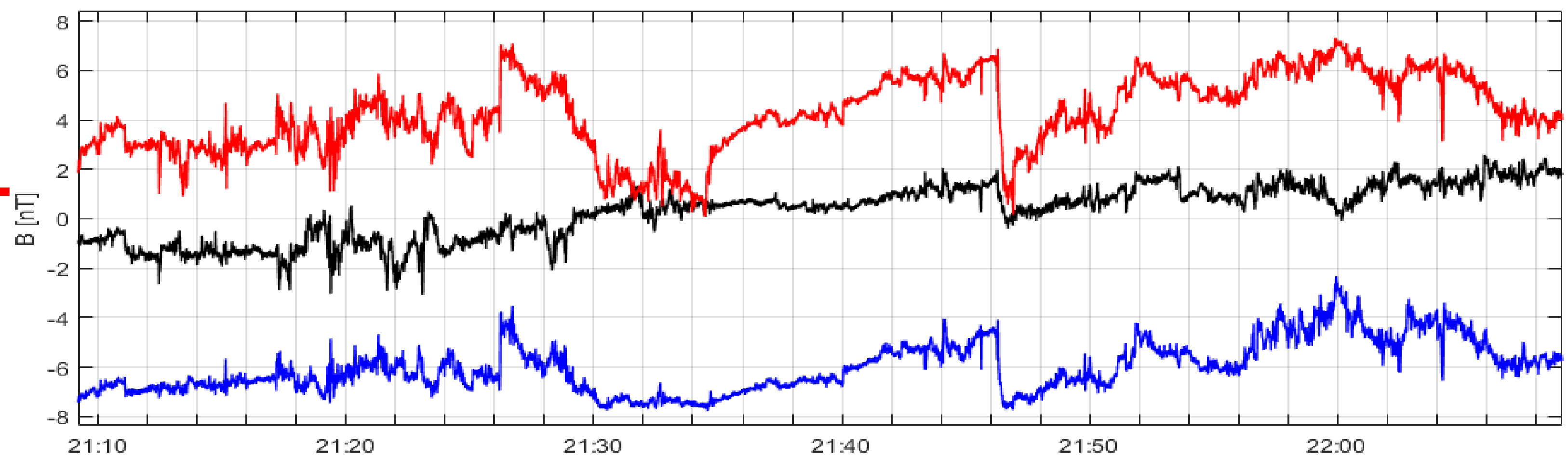
Magnetosheath

ΔB/B~1



Solar wind

ΔB/B~0.1



Turbulence is important for the evolution of the system in both cases

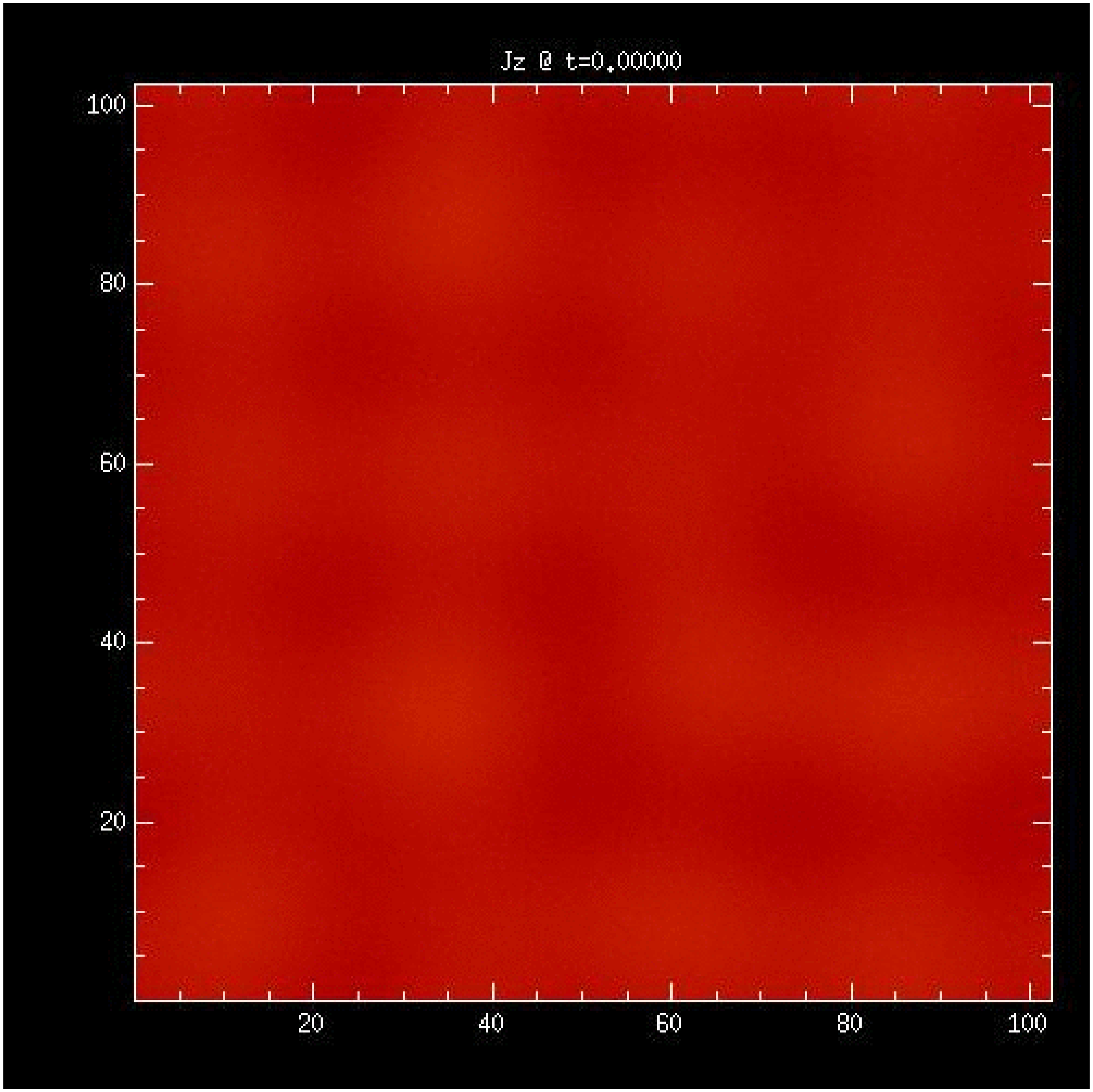
What do we know about turbulence?

What we do not know?

What can MMS do?

What do we know about turbulence?

Turbulence is characterized by formation of intermittent structures across scales



2.5 D
8192^2 grid,
300 particles/cell;
Mass ratio 25
System size 102.4 d_i
(Wu et al. 2013)

Strength of electric current density in shear-driven kinetic plasma (PIC) simulation (see Karimabadi et al, PoP 2013)

- **Energy transfer from large to small scales**
- **Dissipation at small scales**
- **Growth of secondary plasma instabilities**

Turbulent energy cascade

Kolmogorov 1941 &1944

ε: rate of energy transfer across scales

Energy transfer is constant across scales
ε is independent of k

Energy transfer is local in scale
E(k) depends on adjacent k

$\mathbf{E(k) \sim k^{5/3}}$

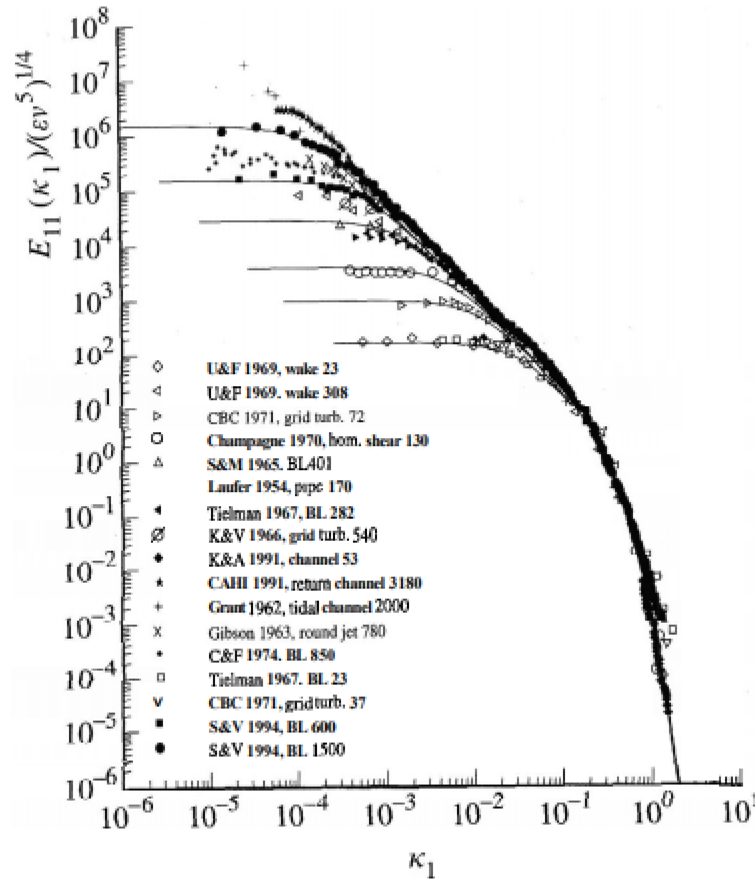
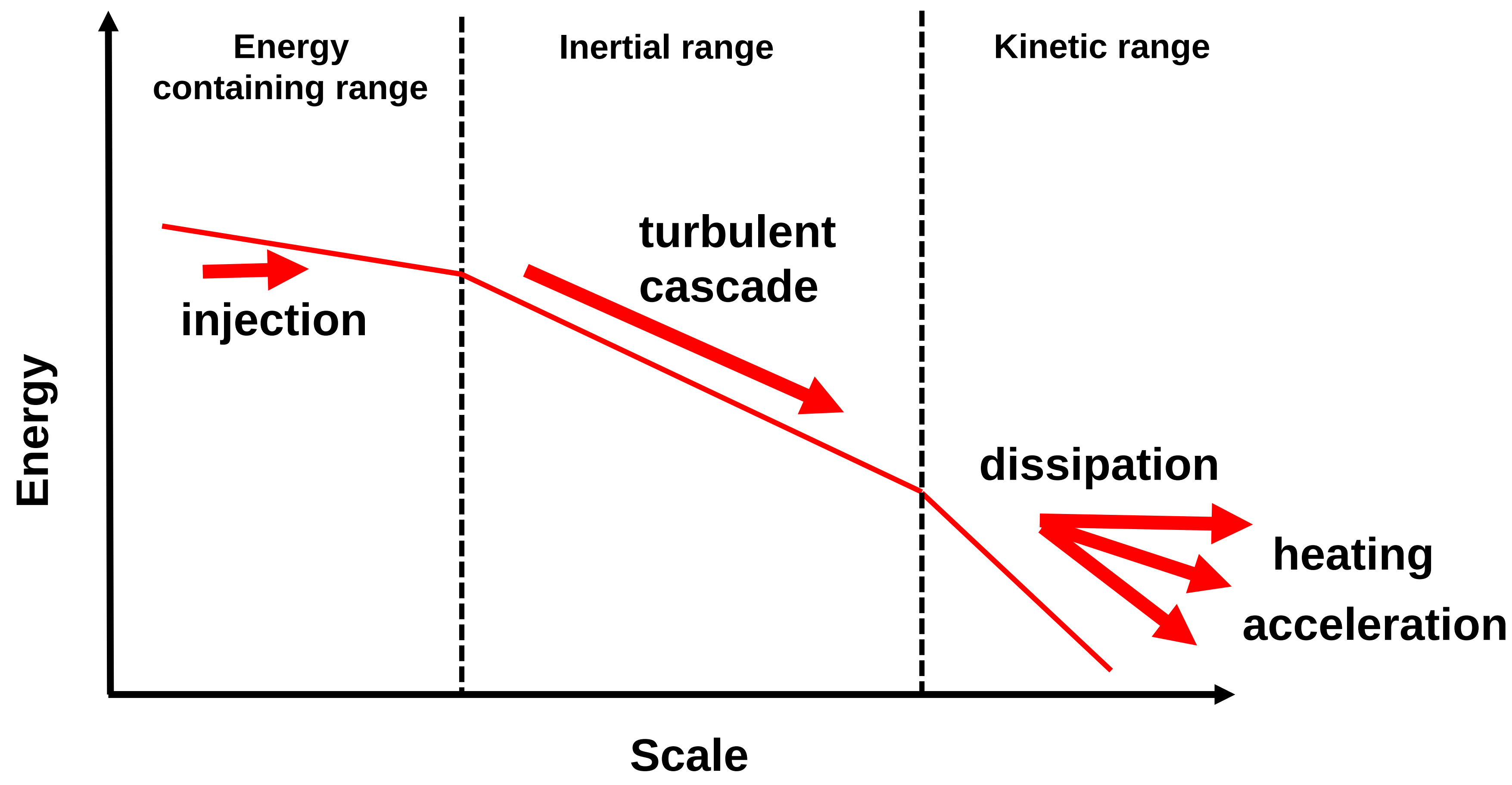


Fig. 6.14. Measurements of one-dimensional longitudinal velocity spectra (symbols), and model spectra (Eq. (6.246)) for R_λ = 30, 70, 130, 300, 600, and 1,500 (lines). The experimental data are taken from Saddoughi and Veeravalli (1994) where references to the various experiments are given. For each experiment, the final number in the key is the value of R_λ.

Pope, *Turbulent Flows*, 2000

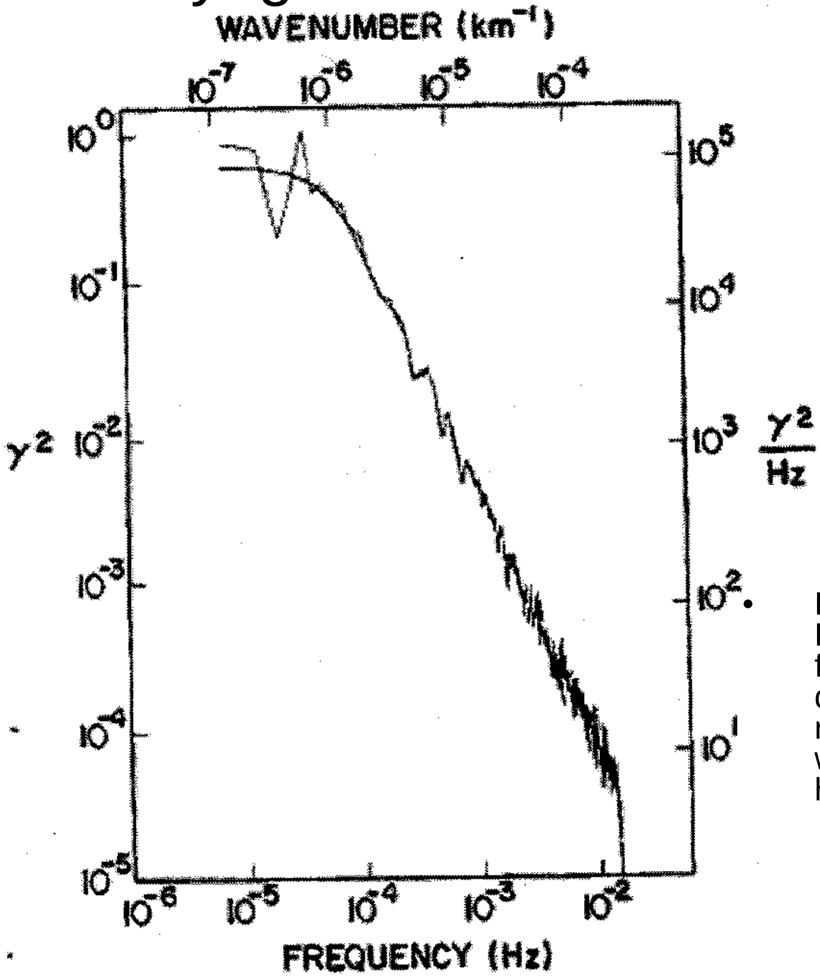
Turbulent energy cascade



Turbulent energy cascade in the solar wind

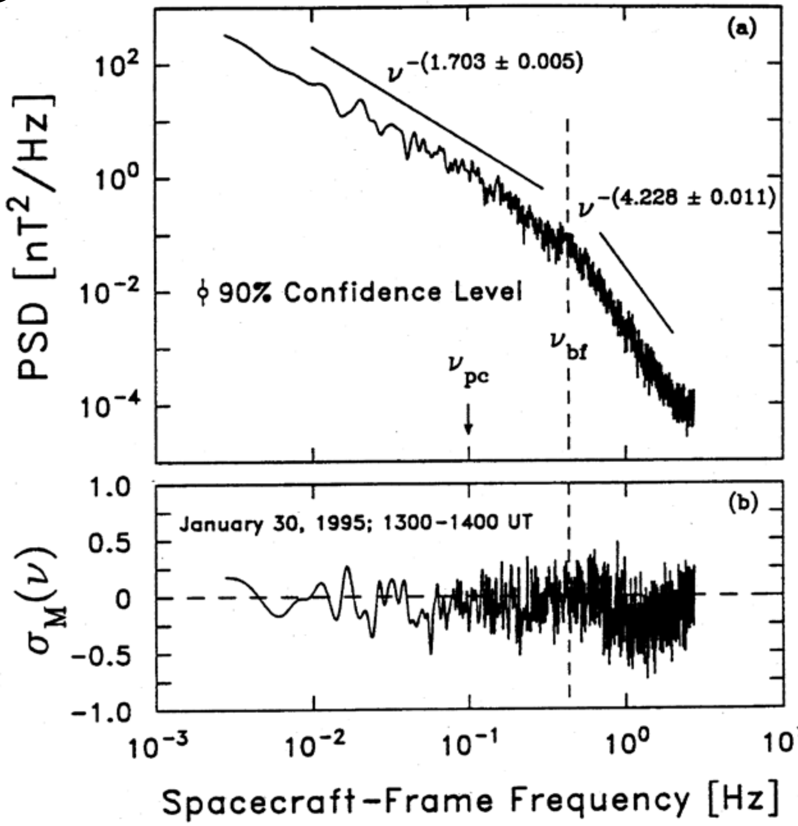
- ION SCALES: steepening at 1 AU –near ion inertial scale

Voyager at 2.8 AU

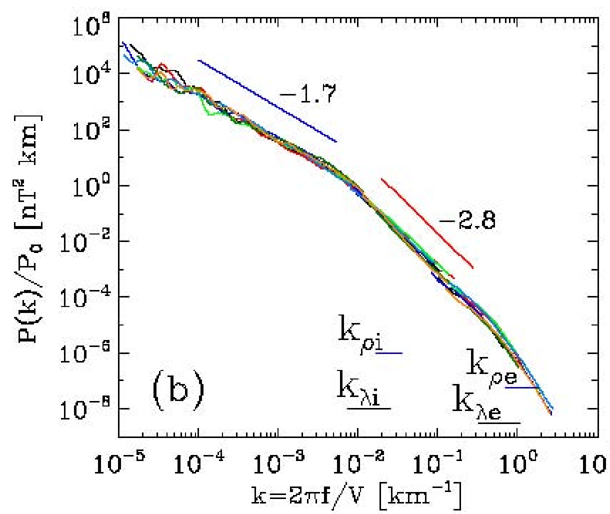


Matthaeus & Goldstein, JGR 1982

Cluster at 1 AU



- BETWEEN ION AND ELECTRON SCALES: further steepening dispersion/dissipation range, kinetic Alfven waves? What's going on here?



Alexandrova et al, PRL 2009

Turbulent energy cascade in incompressible MHD

Politano & Pouquet 1998

Estimating ε:

Elsasser variables: $$\boldsymbol{Z}^{\pm}(t) = \boldsymbol{V}(t) \pm \frac{\boldsymbol{B}(t)}{\sqrt{\mu_0 m_p n_i(t)}}$$

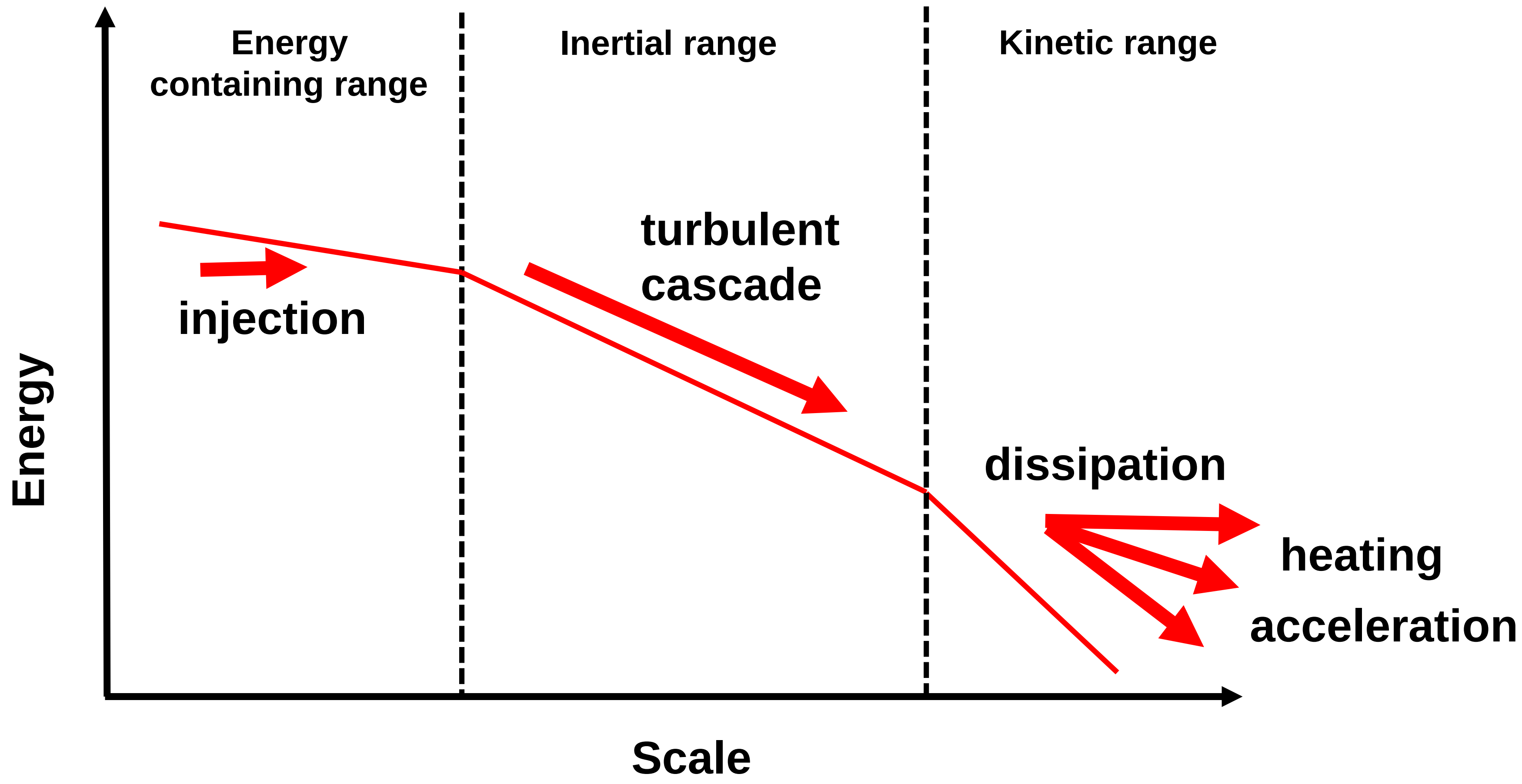
Ensemble average of increments $$Y^{\pm}(r) = \langle \hat{\boldsymbol{r}} \cdot \Delta \boldsymbol{Z}^{\mp}(\boldsymbol{r}) |\Delta \boldsymbol{Z}^{\pm}(\boldsymbol{r})|^2 \rangle$$

Third-order law: $$Y^{\pm}(r) = -\frac{4}{3}\epsilon^{\pm} r$$

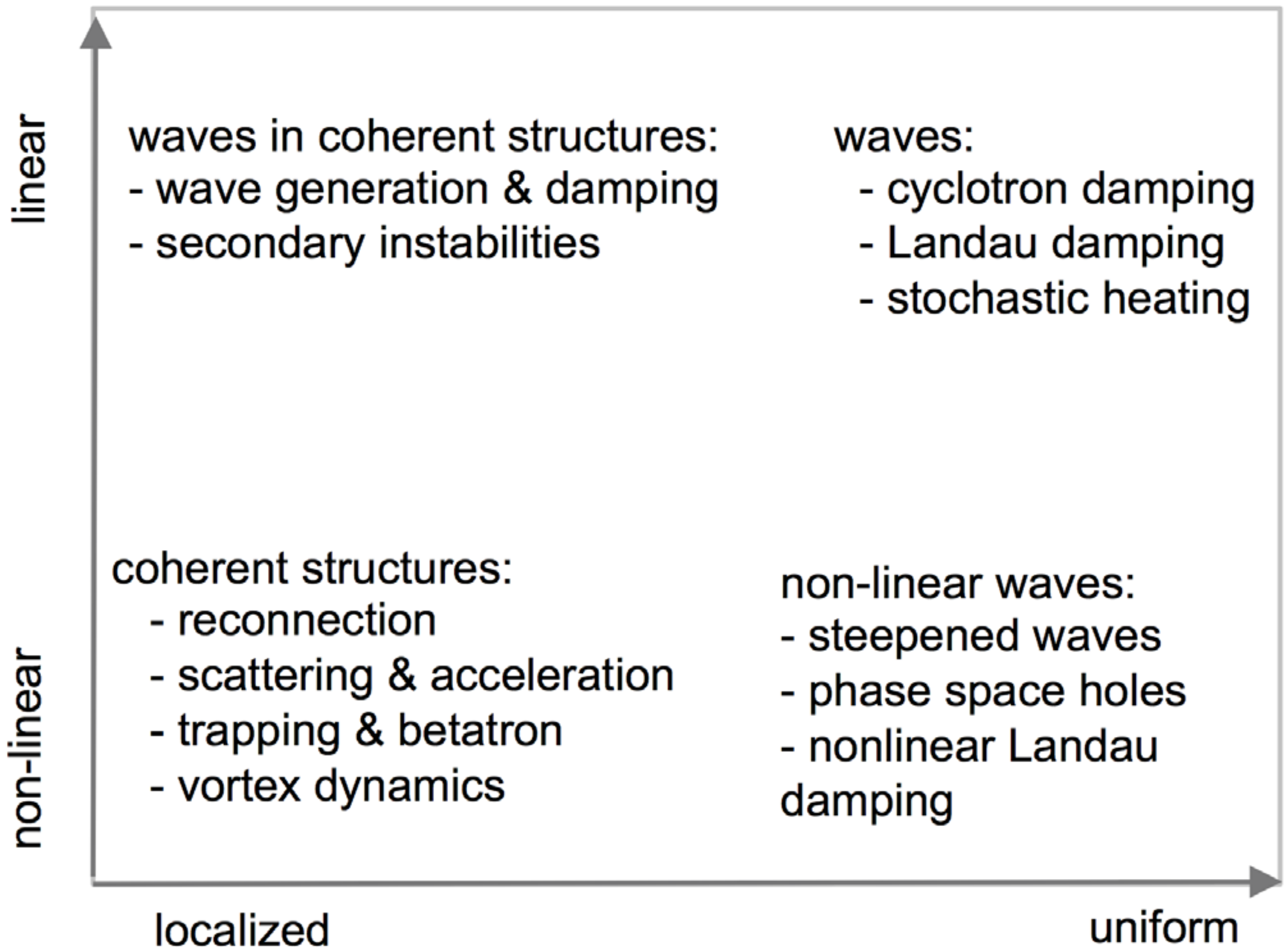
What do not know?

How does turbulent energy dissipate at kinetic scales

Turbulent energy cascade

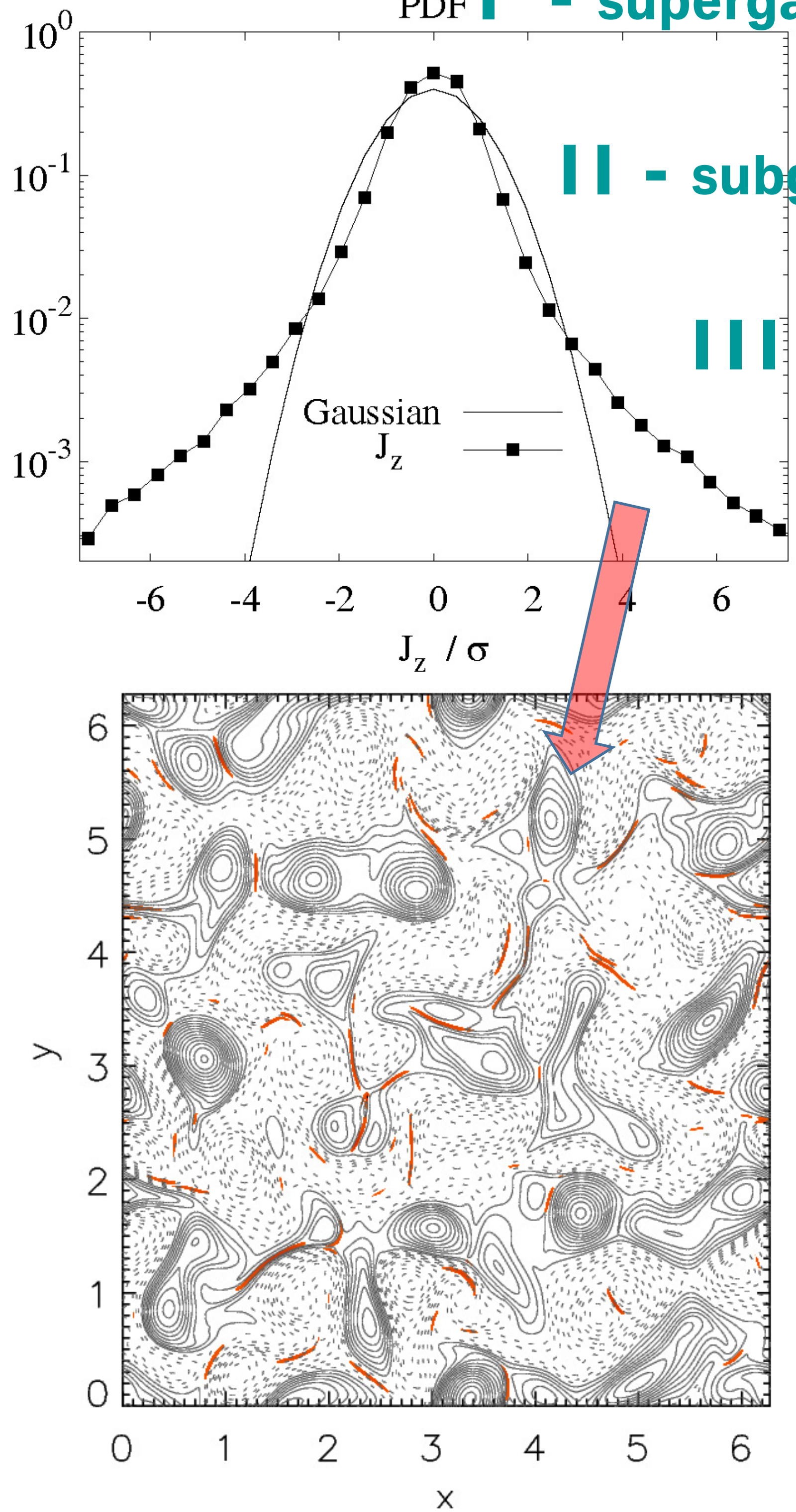


Dissipation pathways at kinetic scales



Intermittency and the spatial organization of current density
(or small scale increments)

Evidence that dissipation preferentially
Occurs in coherent structures!



I - supergaussian

II - subgaussian

III – supergaussian-
(PVI > 4)

Greco et al, 2009

III – supergaussian
current sheets

Observations indicate such regions correspond to active reconnection
(Osman et al. 2014)

In kinetic plasma, dissipation (D_e: work done on particles by E/M field) is concentrated in thin regions of strong current

From Wan et al, PRL 2012; see also Karimabadi et al, PoP 2013

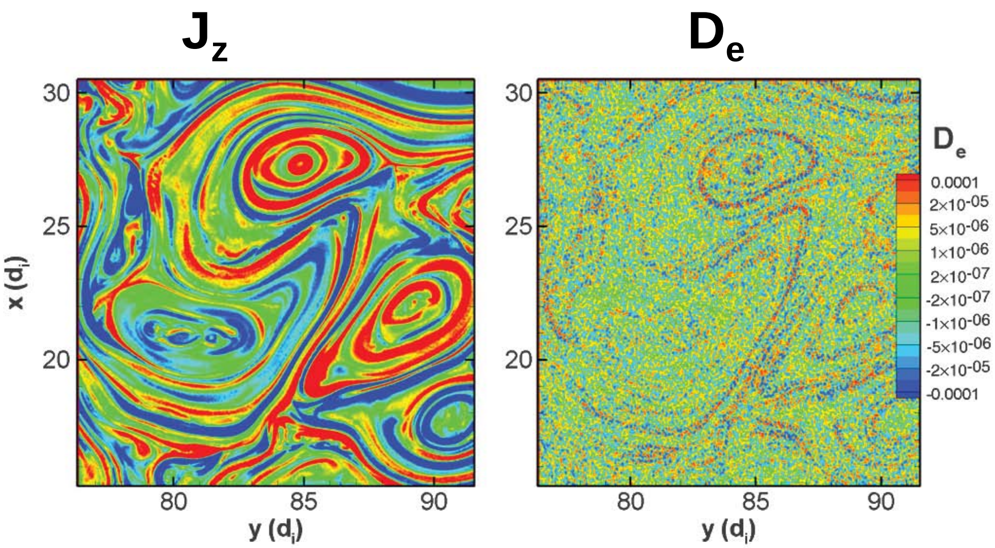
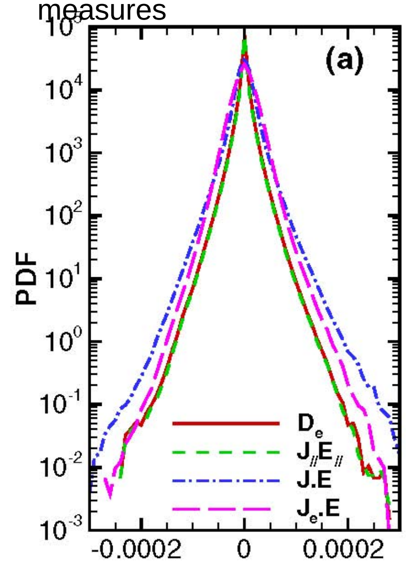
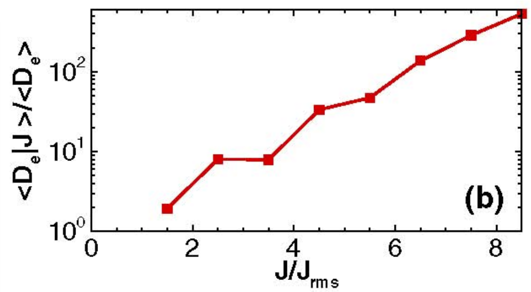


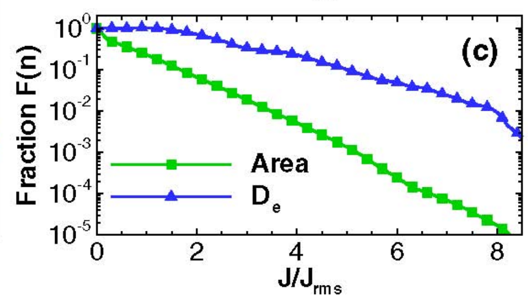
FIG. 2 (color). (Left) J_z in a close-up region of the simulation domain showing hierarchy of coherent structures; (right) Contour of electron-frame dissipation D_e for the region shown in left.

Pdfs of dissipation measures



Averages of Diss Conditioned on Jz





Fraction of volume
and
Fraction of dissipation
vs |Jz|

MMS and turbulence

New capabilities:

- High time resolution

- Multi-spacecraft

- Divergence & curl
- multi-spacecraft increments

- Wide range of plasma environments

MMS and turbulence

Diagnostics:

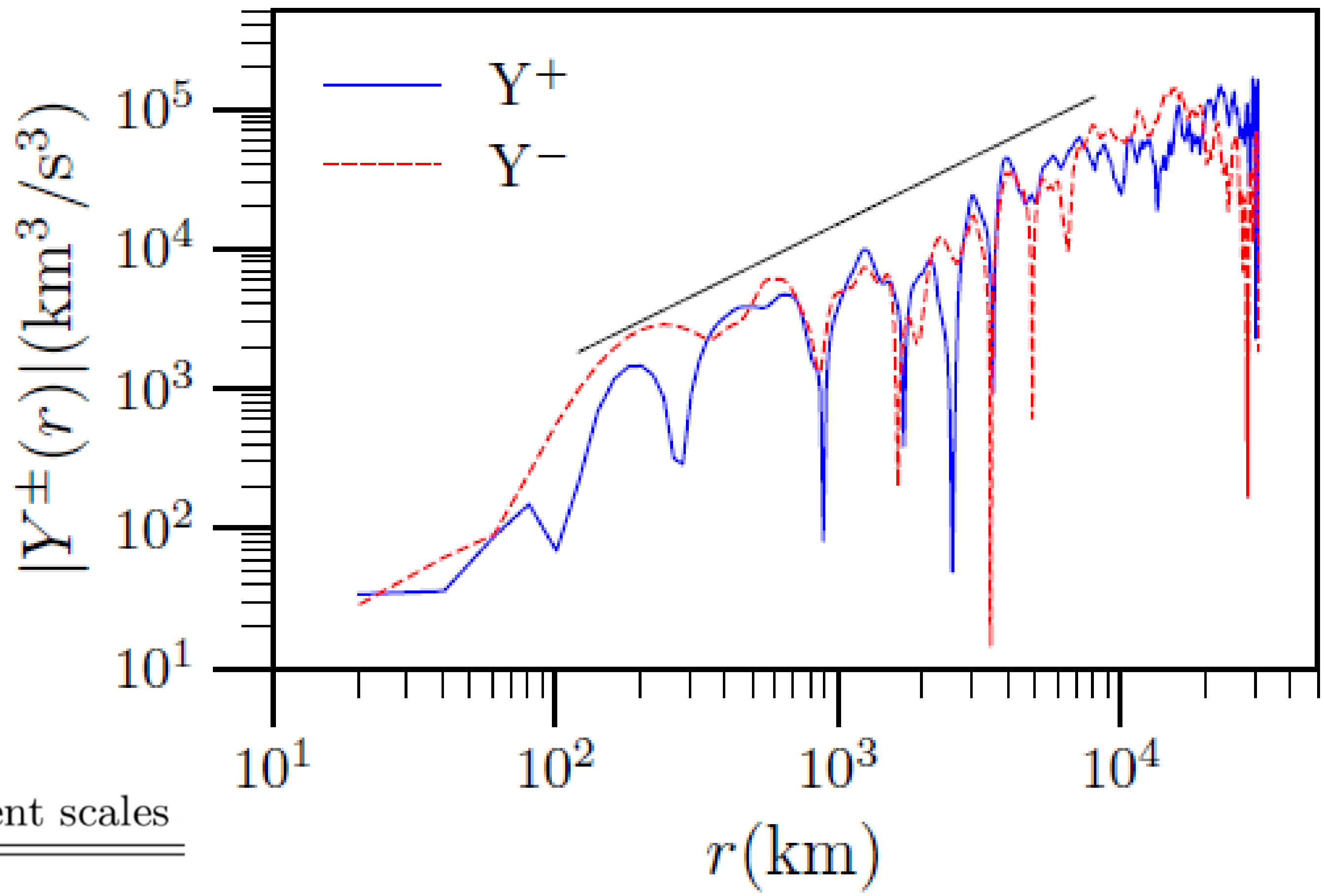
- Temperature
- E.J
- Particle VDFs
- Non-maxwellianity, agyrotropy
- Velocity-space cascade
- Vlasov measures of dissipation, Pi-D
- Measurement of ε

Turbulent energy cascade in incompressible MHD

Politano & Pouquet 1998

Third-order law:

$$Y^{\pm}(r) = -\frac{4}{3}\epsilon^{\pm} r$$



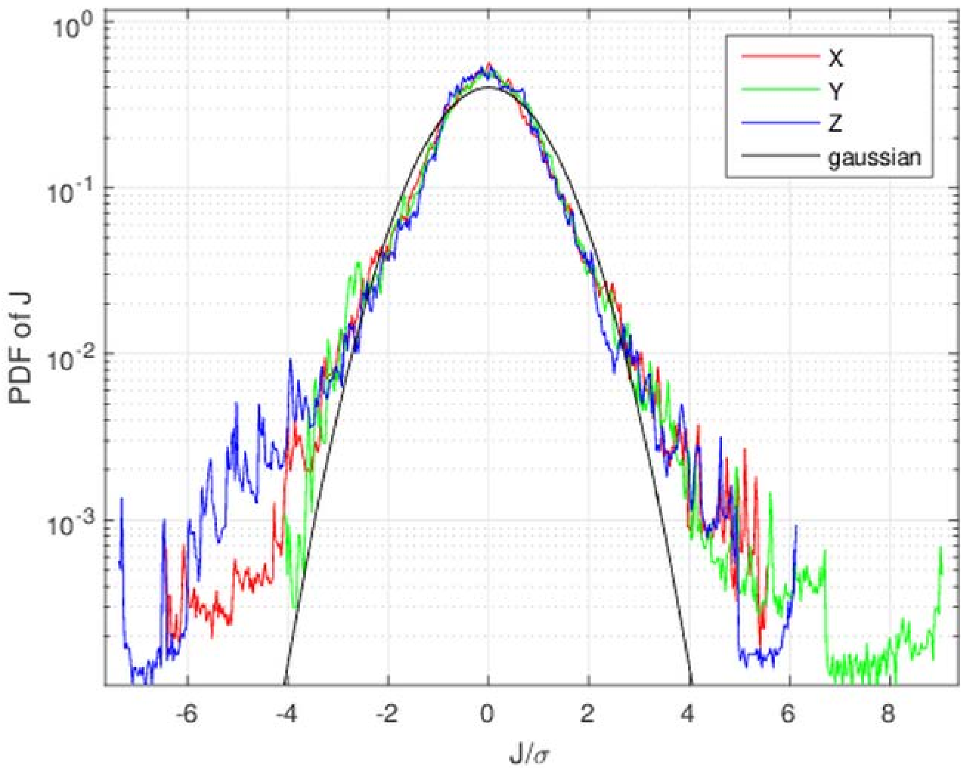
Estimation of cascade rate at different scales

	ϵ_1 (J kg^{-1} s^{-1})	ϵ_2 (J kg^{-1} s^{-1})
ϵ^+	$(5.8 \pm 0.5) \times 10^6$	$(7.1 \pm 0.9) \times 10^6$
ϵ^-	$(5.6 \pm 0.2) \times 10^6$	$(4.8 \pm 0.5) \times 10^6$

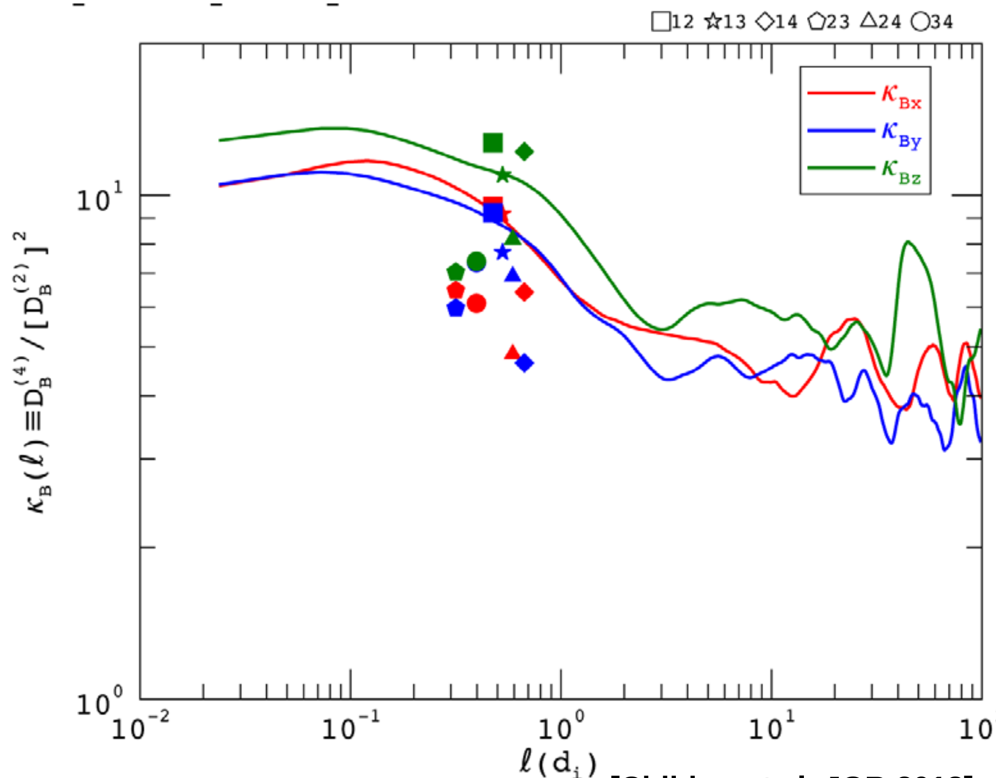
Bandyopadhyay et al. ApJ, 2018

Statistics of dissipation and particle energization

kinetic-scale structure in magnetosheath turbulence



Distribution of current density in magnetosheath turbulence



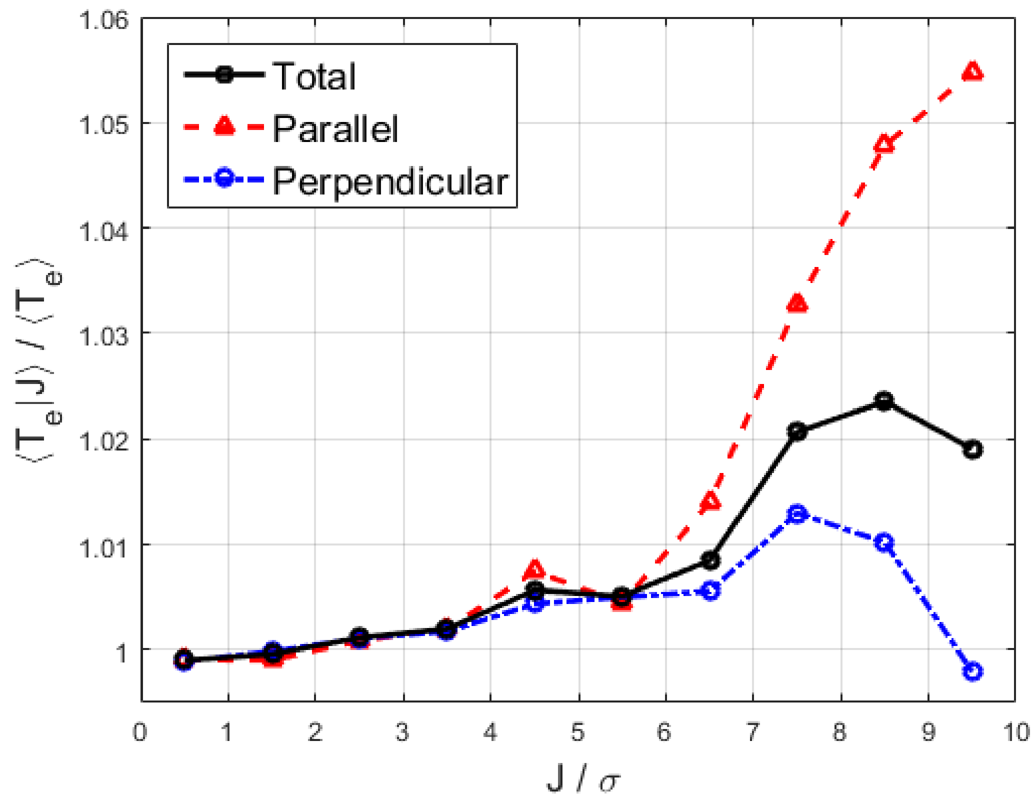
[Chibber et al. JGR 2018]

Magnetic field increments

$$k(\tau) = \frac{< (\delta u_\tau\ (t))^{\,4} >_t}{< (\delta u_\tau\ (t))^{\,2} >_t^{\,2}} \qquad k^{ij} = \frac{< (\delta u_{ij}\ (t))^{\,4} >_t}{< (\delta u_{ij}\ (t))^{\,2} >_t^{\,2}}$$

Statistics of dissipation and particle energization

- **Electron heating predominantly parallel to the magnetic field for regions of strongest current**
- **Possibly consistent with active reconnection**

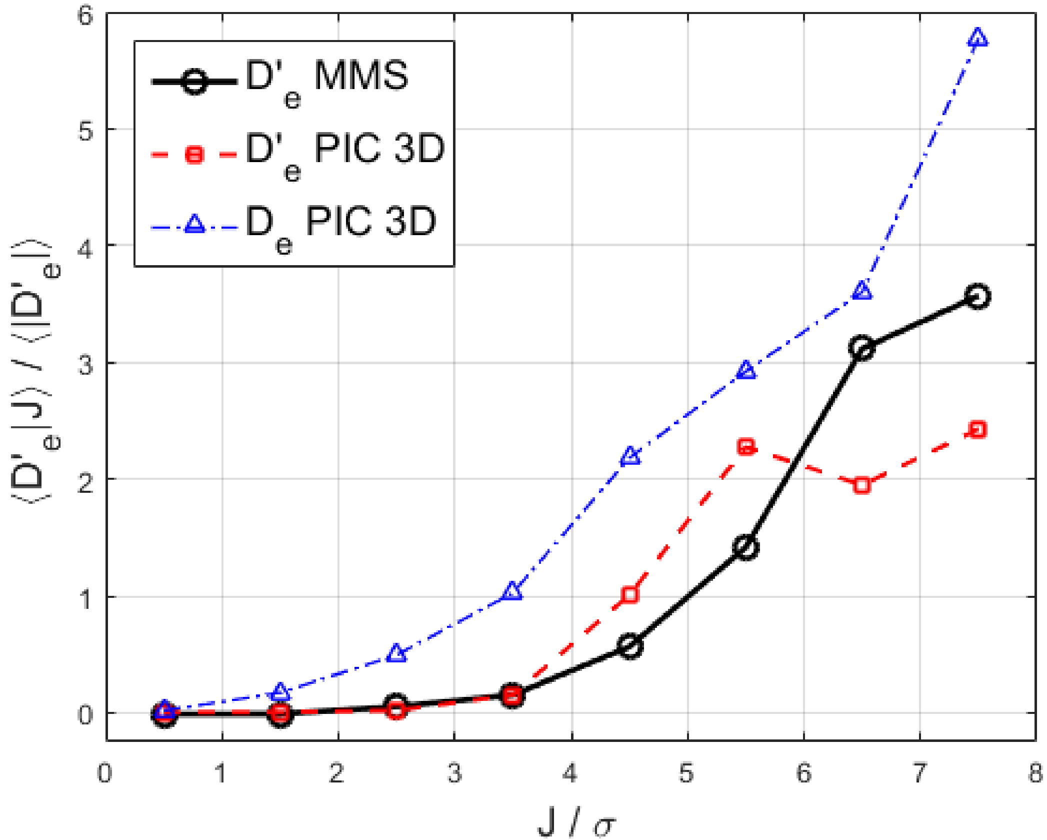


[Chasapis et al. ApJLett, 2018]

Statistics of dissipation and particle energization

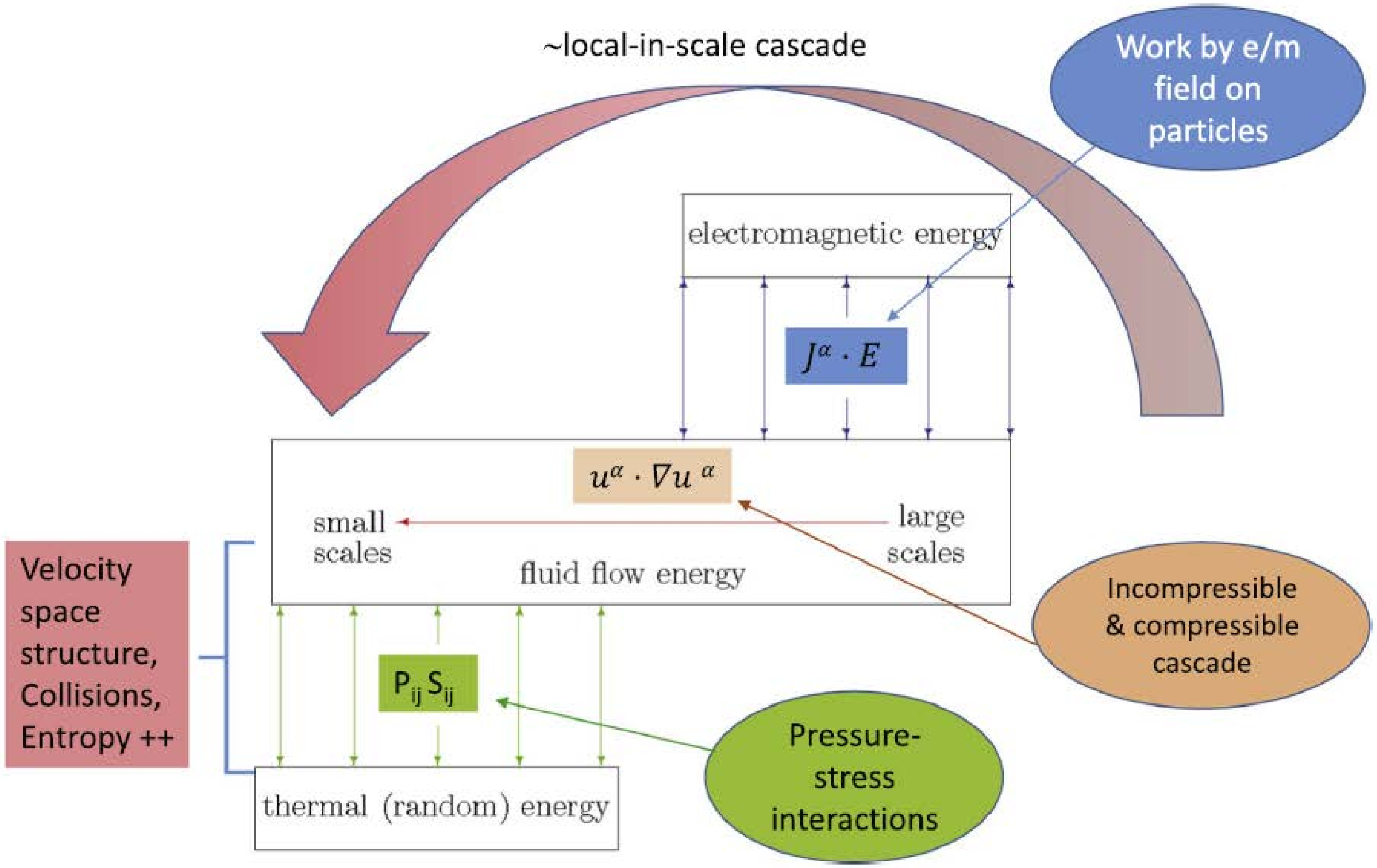
- **Significant dissipation in regions of strong current**

- **Consistent with results from 3D PIC simulations (e.g. Wan et al. 2015)**



[Chasapis et al. ApJLett, 2018]

Pathways of Energy conversion in turbulence



- Fluid energy $$\partial_t \langle E^f_\alpha \rangle = \langle (\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha \rangle + \langle n_\alpha q_\alpha \boldsymbol{E} \cdot \boldsymbol{u}_\alpha \rangle,$$
- Thermal energy $$\partial_t \langle E^{th}_\alpha \rangle = -\langle (\boldsymbol{P}_\alpha \cdot \nabla) \cdot \boldsymbol{u}_\alpha \rangle,$$
- Magnetic energy $$\partial_t \langle E^m \rangle = -\langle \boldsymbol{E} \cdot \boldsymbol{j} \rangle.$$

Pathways of Energy conversion in turbulence

Yan et al. PoP 2017

- Two reconnection events in the magnetosheath

(reported in Wilder et al. JGR 2018)

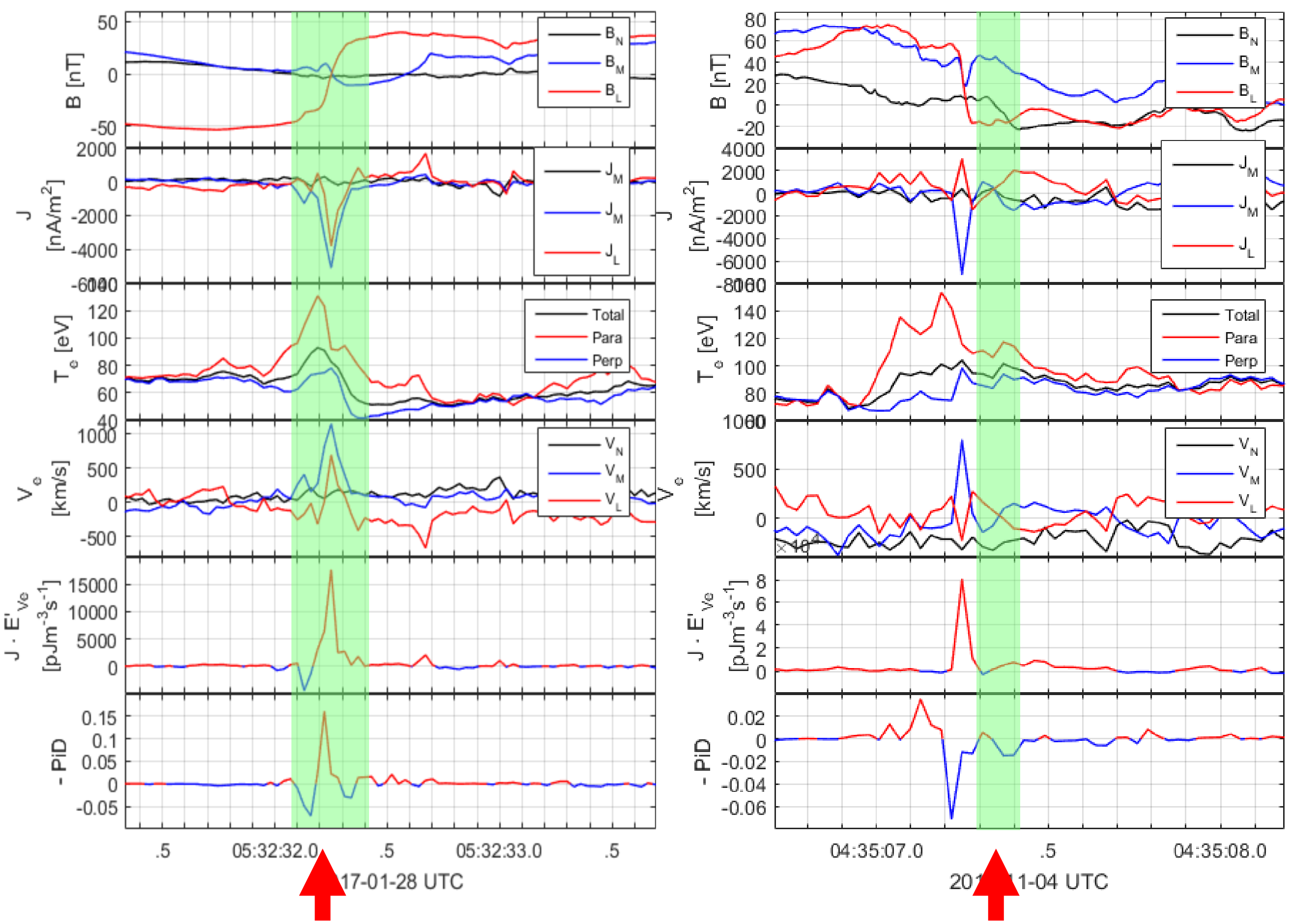
- Both show:
  - increase of electron temperature
  - positive E.J

Energy transfer from the fields to the particles

At the point of observation:
Electron heating vs cooling

Anti parallel, Low guide field Reconnection (plasma β ~1.3)

Stronger Guide-field (~1.3) Plasma β~10



Electrons are being heated here

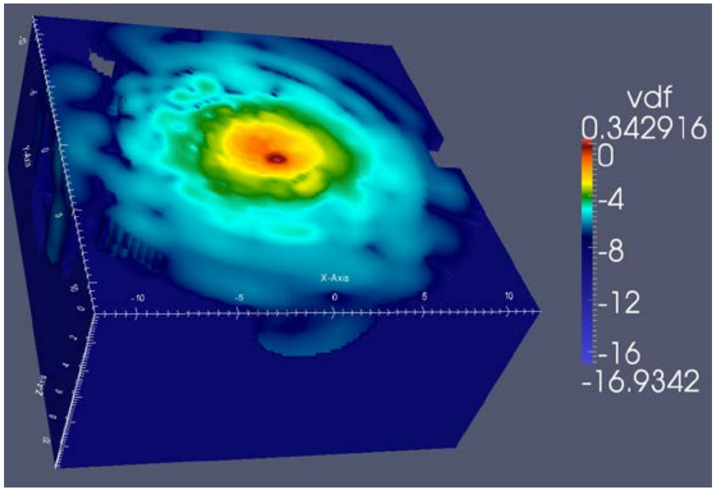
Electrons are cooling here

Velocity-space cascade

Hermite decomposition of velocity distributions

- Decomposition of particle distributions using Hermite polynomials
- Used to study perturbations in velocity space

MMS particle distributions in the magnetosheath (ions)



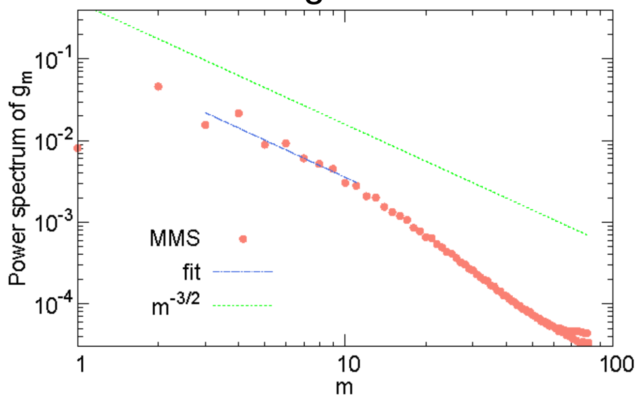
MMS observations in the Earth's magnetosheath.
(Left) Visualization of 3D ion measurements by FPI.
Fine scale distortions are visible.

Velocity-space cascade

Hermite decomposition of velocity distributions

Hermite spectrum

MMS magnetosheath data



Hybrid Vlasov 5D simulation

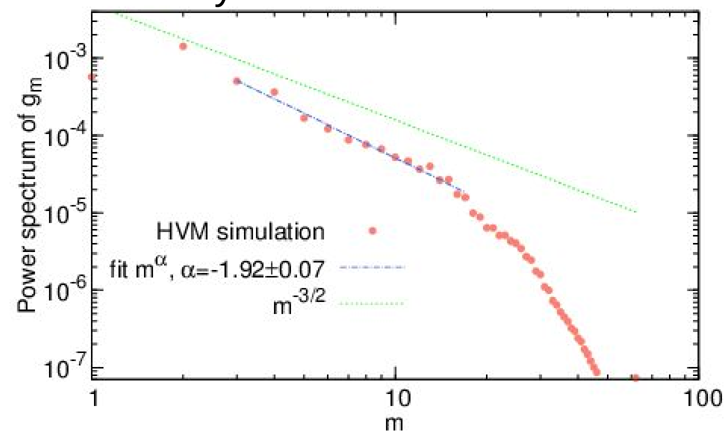


FIG. 1: Power spectrum of the Hermite modes, for the MMS dataset. The best fit to a power law m^{α} gives $\alpha \sim -1.5$, with an error of $\sim 12\%$.

- Observations suggest “cascade” in velocity space
- Agreement with Vlasov simulations and some theoretical predictions

[Servidio et al. PRL, 2018]

Afterword:
MMS turbulence campaign

- Unequal separation allows direct measurements at scales of interest

- Long time-series permit meaningful statistics

- High time resolution for kinetic scale phenomena

Neither was done before in solar wind plasma

Thank you