MMS Science Working Team Meeting

6 – 8 October 2020

# Turbulence in the Era of MMS

## What we have learned and ways forward

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# Overview

**What is turbulence and why do we care?**

**An incomplete review of results from MMS**

- Turbulence-driven reconnection & electron-only reconnection
- Detailed measurements of turbulent spectra
- Velocity-space structure of turbulence
- Novel measurements of dissipation
- MMS in the solar wind

**What is there still left to do?**

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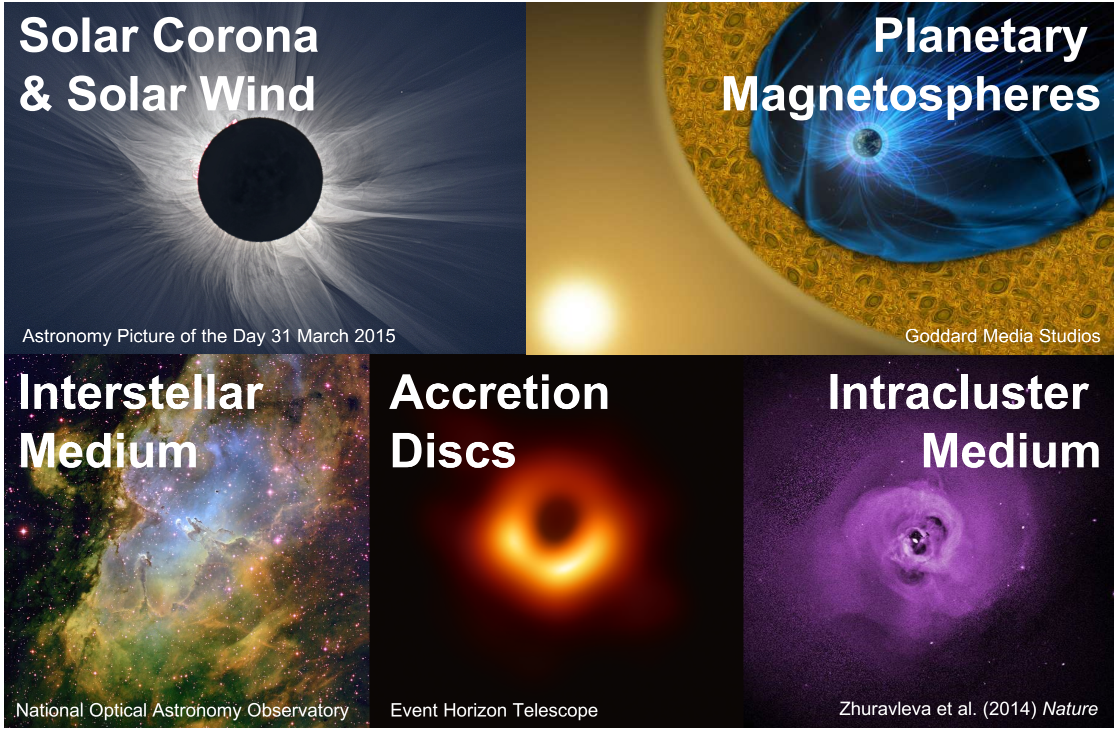
# Plasma turbulence is present throughout the Universe…



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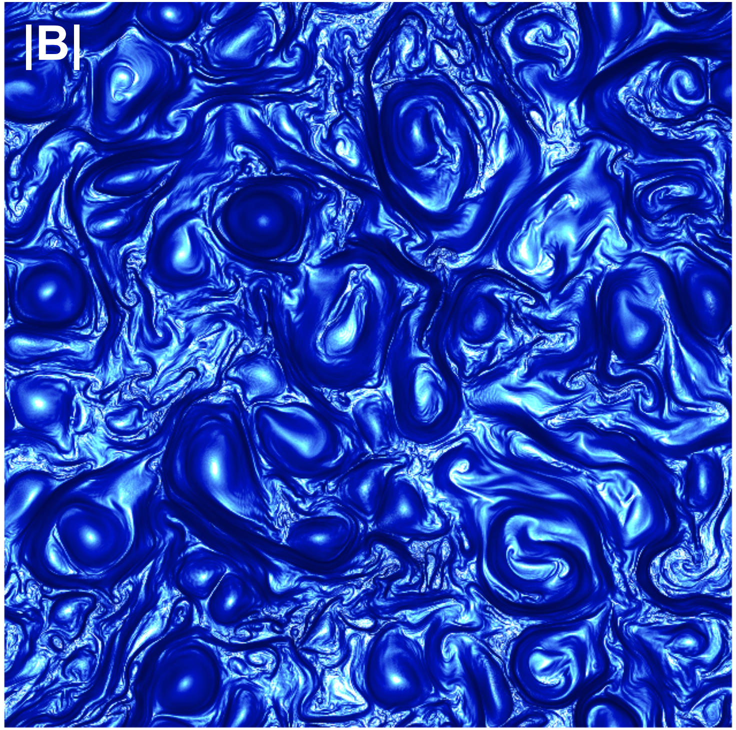
# What is turbulence?




Franci+ (2020) *ApJ*

Complex highly-nonlinear fluctuations, characterized by:

- Fluctuations across a wide range of length scales
- Coherent structures, intermittency, current sheets

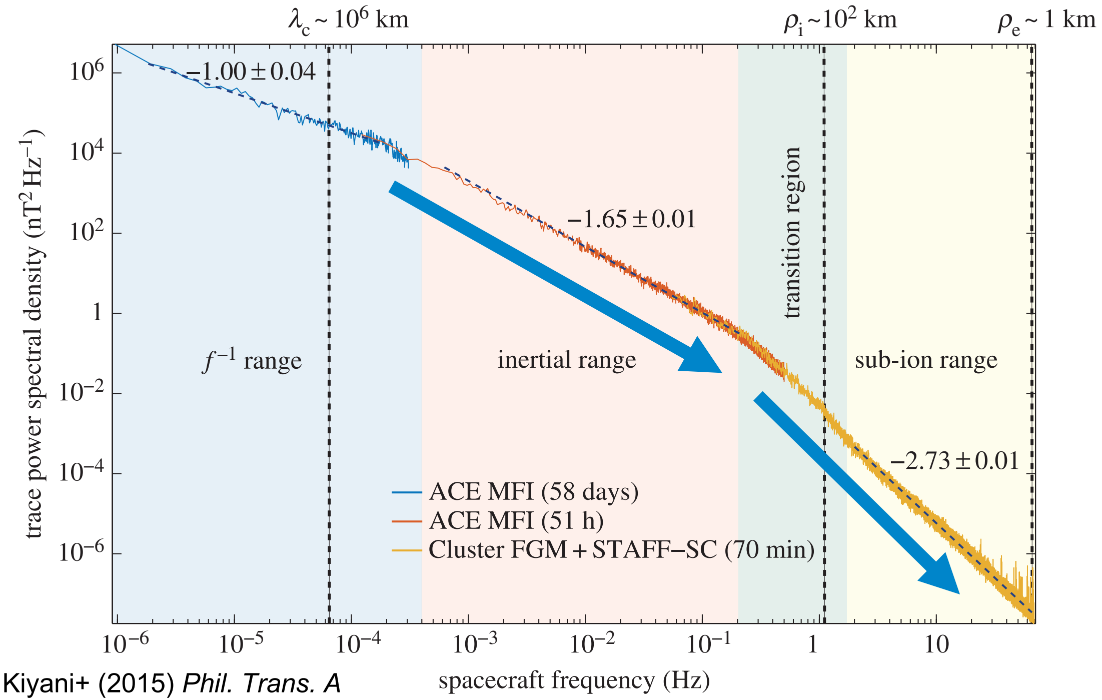
The problem of turbulence is to understand the behavior of the nonlinear terms in the equations

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} = \frac{1}{\mu_0}(\nabla \times \boldsymbol{b}) \times \boldsymbol{B}_0 - \nabla \cdot \boldsymbol{p} - \rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \frac{1}{\mu_0}(\nabla \times \boldsymbol{b}) \times \boldsymbol{b}$$

$$\frac{\partial \boldsymbol{b}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B}_0) + \nabla \times (\boldsymbol{u} \times \boldsymbol{b})$$

# Turbulent Energy Spectrum

Solar Wind Turbulence Spectrum



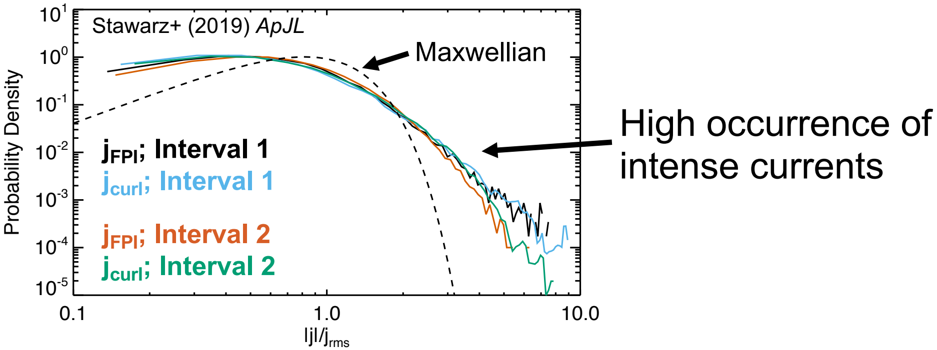

Kiyani+ (2015) *Phil. Trans. A*

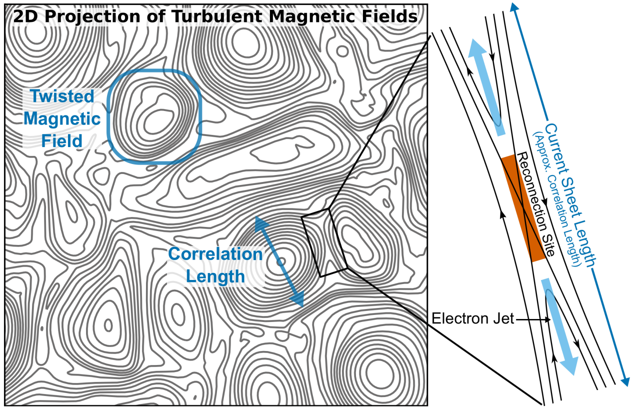
Turbulence tends to transfer energy from large scales to small scales → energy cascade

Slope of the energy spectrum depends on the underlying turbulent dynamics **(i.e. timescale of energy transfer)**

At small scales, energy is dissipated into the “thermal” motions of the particles

# Turbulent Intermittency & Reconnection




adapted from Phan+ (2018) *Nature*

In real space, turbulence produces a non-uniform distribution of gradients called *intermittency*

Turbulence is good at generating many small-scale current structures, which can be site for magnetic reconnection

***What roles does magnetic reconnection play in a turbulent plasma?***

→ nonlinear dynamics
→ energy dissipation

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# What are the important questions?

What are the underlying nonlinear dynamics at different scales?

How does energy dissipation occur in collisionless plasmas?

What impact does the turbulence have on the overall system?

***MMS is the best mission that we currently have to look at many of these questions!***

→ High-resolution, multi-point measurements of particles and fields
→ Unique analysis techniques
→ Fortuitous encounters with unique environments
(e.g. Kelvin-Helmholtz Instability, Reconnection-Driven Turbulence)

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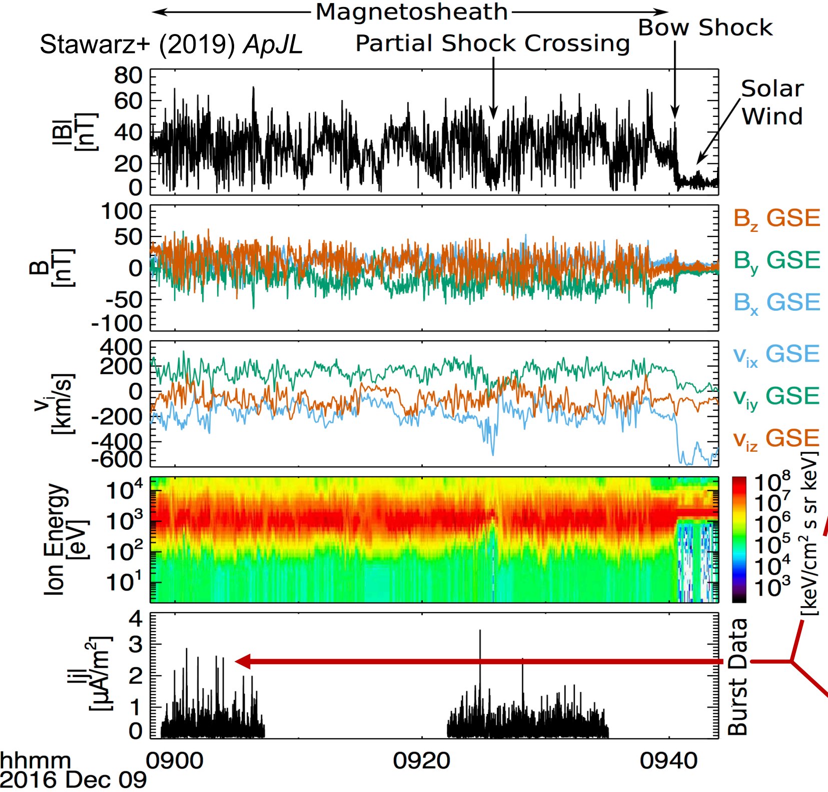
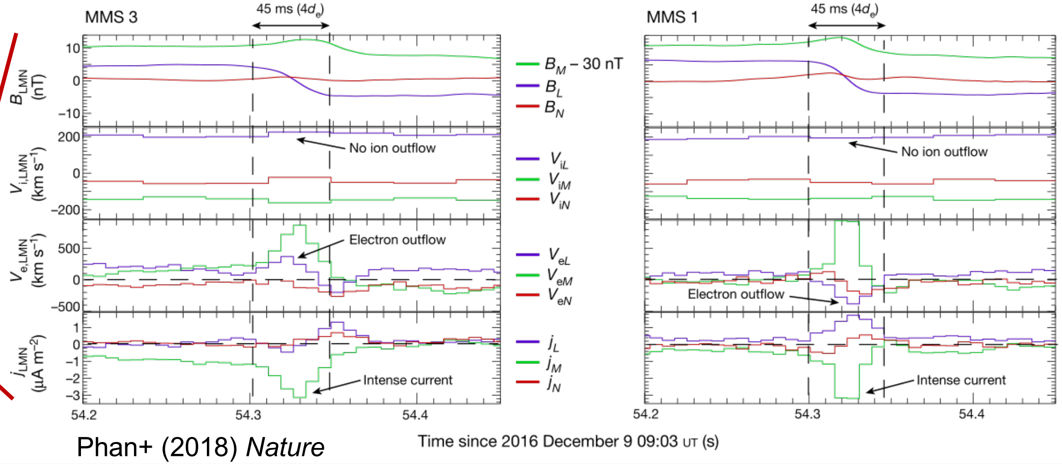
# Turbulence-Driven Reconnection & Electron-Only Reconnection

Stawarz+ (2019) *ApJL*




Phan+ [*Nature*, 2018] discovered *electron-only magnetic reconnection* in magnetosheath

- Key observation – oppositely directed electron jets
- No evidence for ion jets was found




Phan+ (2018) *Nature*

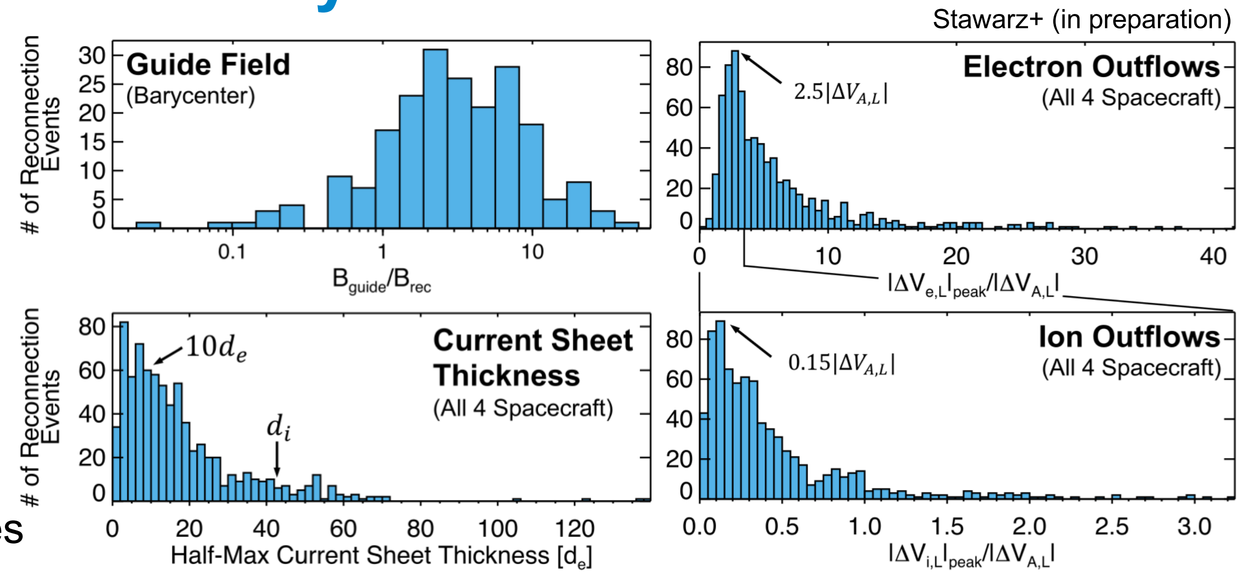
# Turbulence-Driven Reconnection & Electron-Only Reconnection

Statistical survey of turbulence driven reconnection across the magnetosheath:

→ Large guide fields

→ Current sheet thicknesses from a few to 10 $d_e$

→ Fast electron outflows and weak ion signatures




Numerous other related studies on small-scale reconnection:

→ Reconnection at the bow shock

→ Simulation of electron only reconnection

→ Identification of reconnection events in turbulence simulations

# Detailed Measurements of Turbulence Spectra

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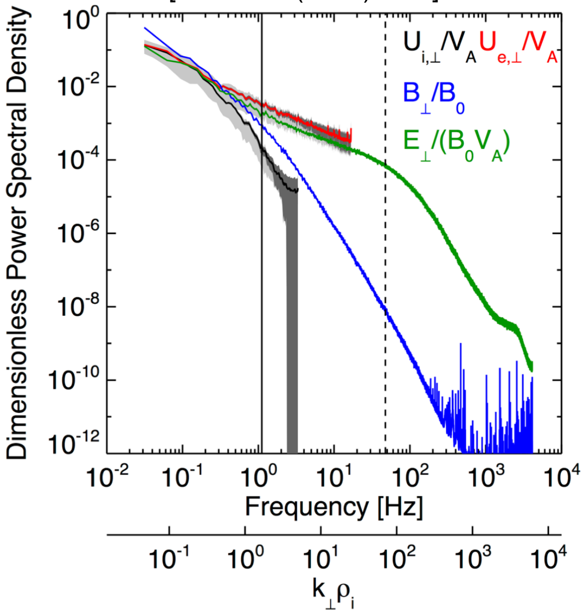
FPI has allowed us to probe velocity spectra at sub-ion and even electron scales!

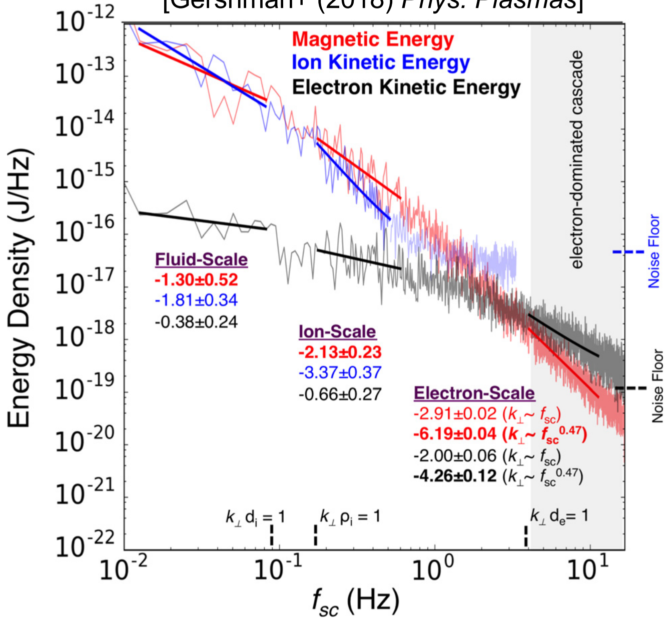
**Kelvin-Helmholtz Turbulence**

[Stawarz+ (2016) *JGR*]

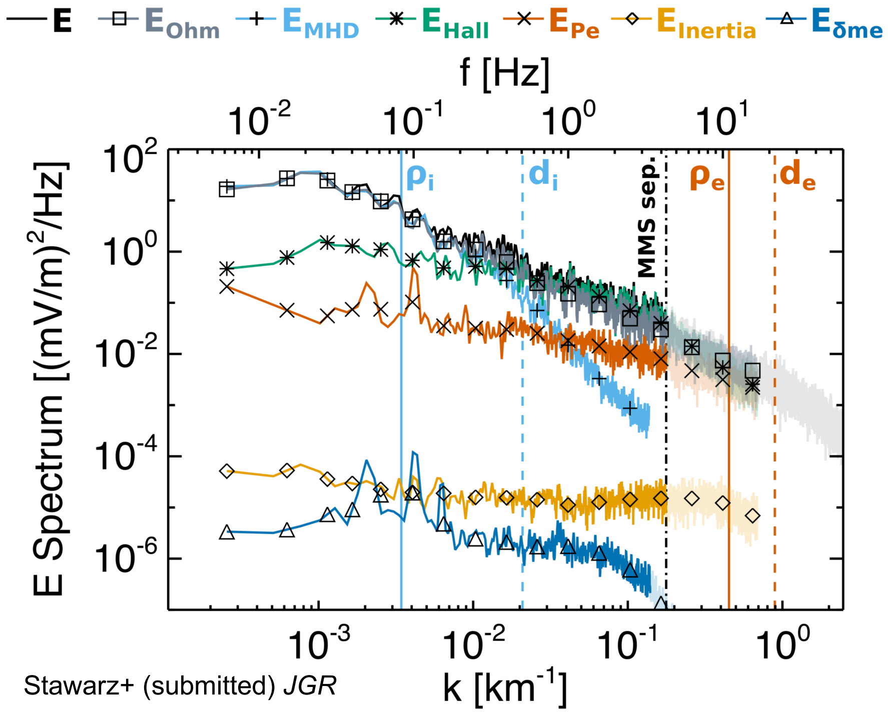



**Electron Energy Dominated Cascade in the Magnetosheath**

[Gershman+ (2018) *Phys. Plasmas*]



# Detailed Measurements of Turbulence Spectra

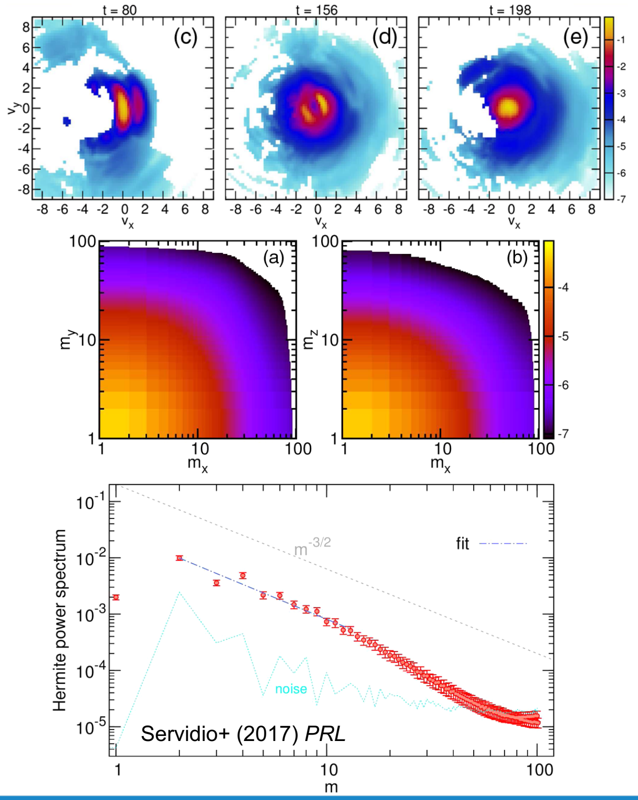



Stawarz+ (submitted) *JGR*

Using high-quality measurements from MMS, we have been able to look at how generalized Ohm's law shapes the turbulent electric field
[Stawarz+ (submitted) *JGR; preprint on ESSOAr]*

Provides insight into the relative role of:
→ ion and electron diamagnetic effects
→ linear and nonlinear terms

# Velocity Space Structure of the Turbulence




3D Hermite transform of ion velocity distributions
[Servidio+ (2017) *PRL*]

$$\psi_m(v) = \frac{H_m\left(\frac{v-u}{v_{th}}\right)}{\sqrt{2^m m!\sqrt{\pi}v_{th}}}\exp\left(-\frac{(v-u)^2}{2v_{th}^2}\right)$$

$$H_m(v) = (-1)^m \exp(v^2)\frac{d^m}{dv^m}\exp(-v^2)$$

Can examine the "spectrum" of velocity space deformations, which seems to follow phenomenological scalings.

Follow-up numerical work has examined the relationship of the Hermite spectrum with intermittent structure [Pezzi+ (2018) *Phys. Plasmas*]

# Velocity Space Structure of the Turbulence

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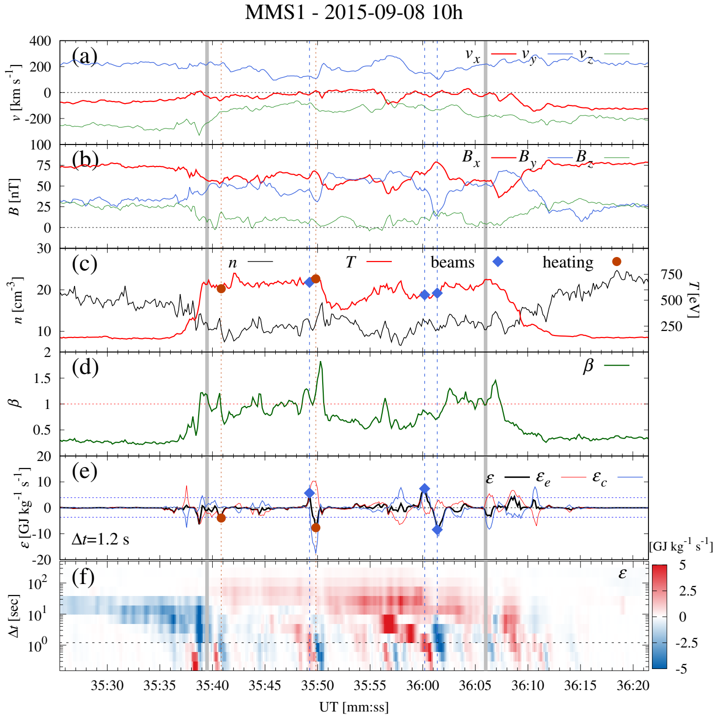
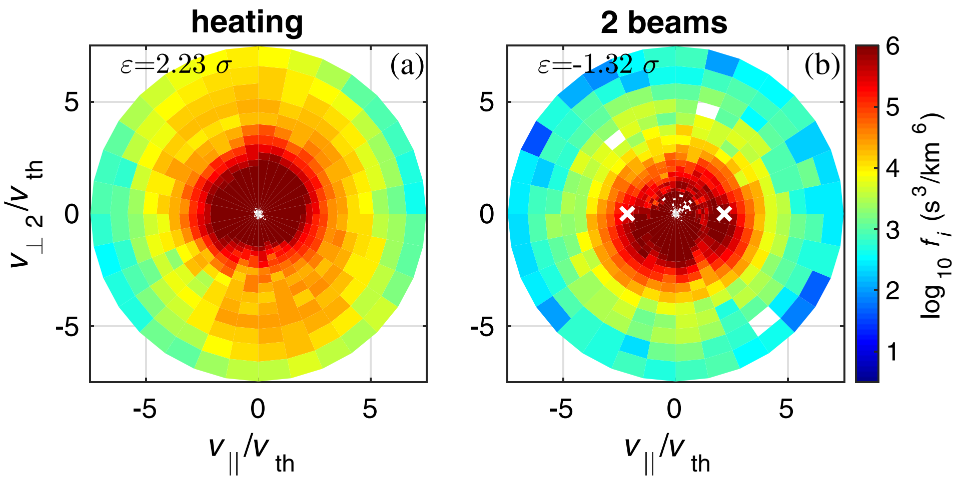



Sorriso-Valvo+ (2019) *PRL*

Sorriso-Valvo+ [(2019) *PRL*] categorize different distribution function morphologies (e.g., beams, heating) and compare with local measures of turbulent dissipation



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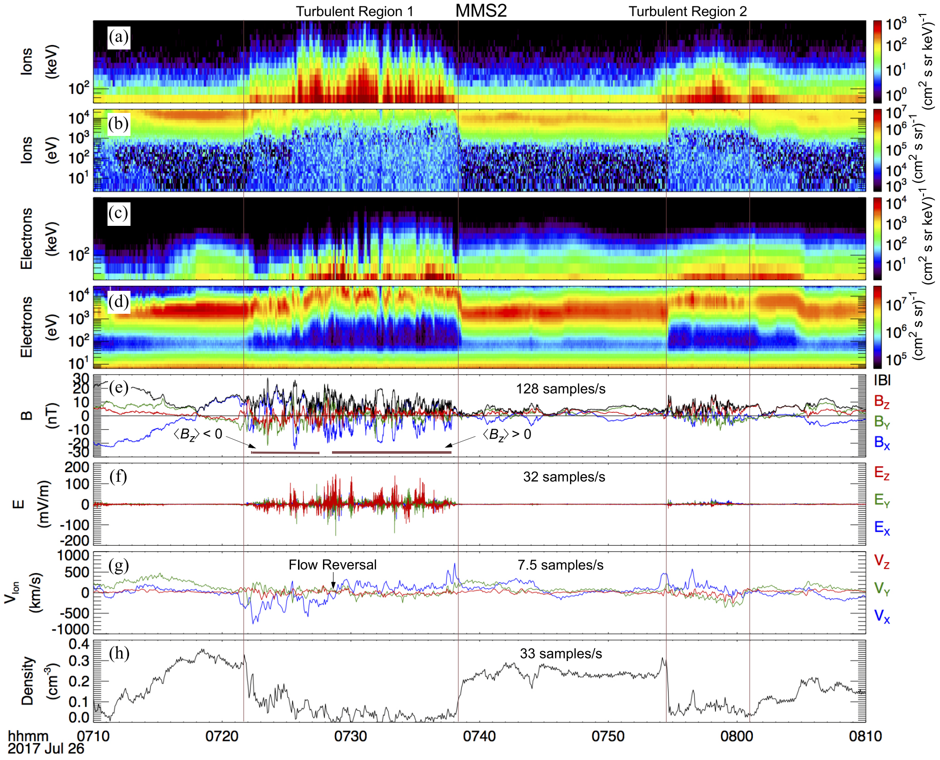
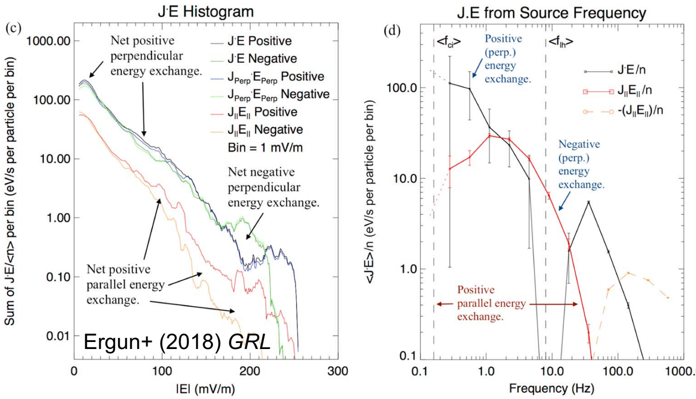
# Novel Measurements of Dissipation




Ergun+ (2020a) *ApJ*




Ergun+ (2018) *GRL*

Ergun+ [(2018) GRL; (2020a,b) ApJ] examine particle acceleration by reconnection-driven turbulence in the magnetotail

Low densities mean s/c separation is comparable to Debye scale providing exceptional $\boldsymbol{J} \cdot \boldsymbol{E}$ measurements!

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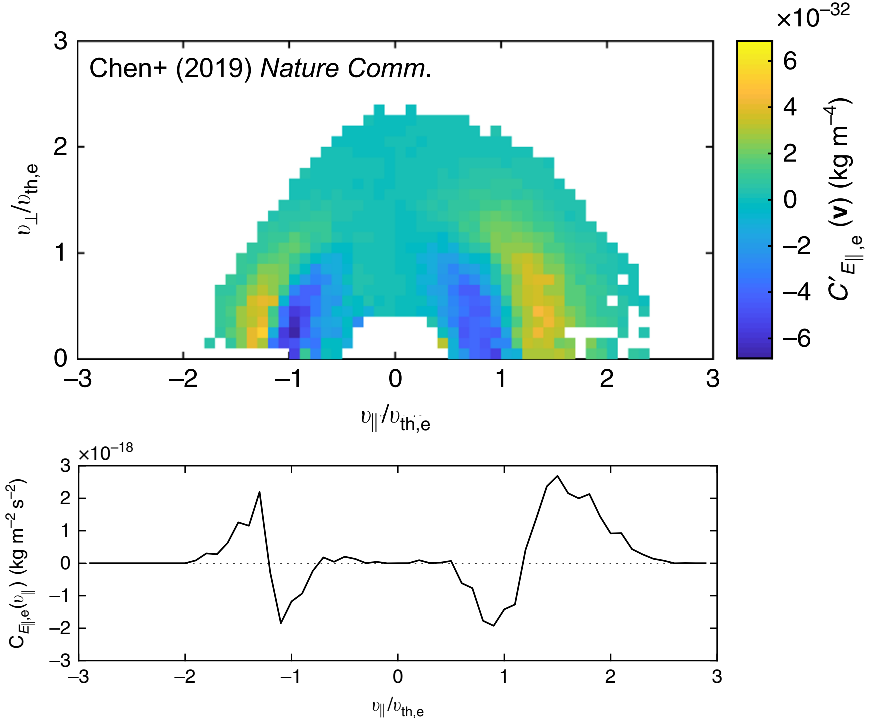
# Novel Measurements of Dissipation




Chen+ [(2019) *Nature Comm.*] apply field-particle correlation techniques to MMS data in the magnetosheath

Pulls apart $J \cdot E$ across velocity space and uses profile to identify dissipation mechanism

Chen+ [(2019) *Nature Comm.*] tailored it to specifically look for signatures of Landau damping, but it could be adapted to look for other mechanisms as well

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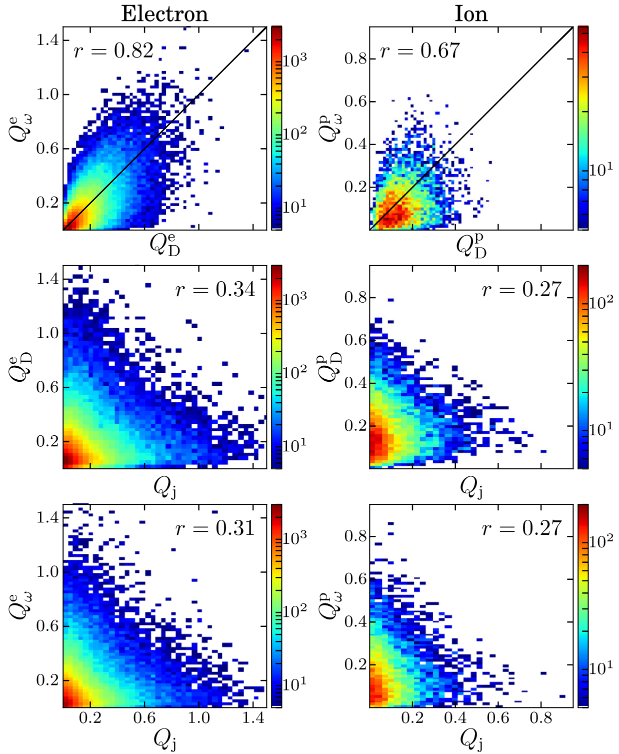
# Novel Measurements of Dissipation



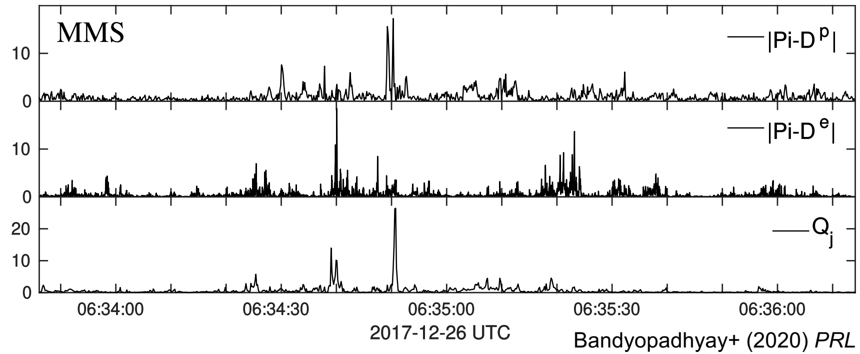

Bandyopadhyay+ (2020) *PRL*

Examination of the "PiD" pressure-strain interactions in the magnetosheath [e.g., Chasapis+ (2018) *ApJ*; Bandyopadhyay+ (2020) *PRL*]

$$\partial_t \mathcal{E}^f_\alpha + \nabla \cdot (\mathcal{E}^f_\alpha \mathbf{u}_\alpha + \mathbf{P}_\alpha \cdot \mathbf{u}_\alpha) = (\mathbf{P}_\alpha \cdot \nabla) \cdot \mathbf{u}_\alpha + n_\alpha q_\alpha \mathbf{E} \cdot \mathbf{u}_\alpha.$$

$$\partial_t \mathcal{E}^{th}_\alpha + \nabla \cdot (\mathcal{E}^{th}_\alpha \mathbf{u}_\alpha + \mathbf{h}_\alpha) = -(\mathbf{P}_\alpha \cdot \nabla) \cdot \mathbf{u}_\alpha.$$

$$\partial_t \mathcal{E}^m + \frac{c}{4\pi} \nabla \cdot (\mathbf{E} \times \mathbf{B}) = -\mathbf{E} \cdot \mathbf{j}$$




Bandyopadhyay+ (2020) *PRL*

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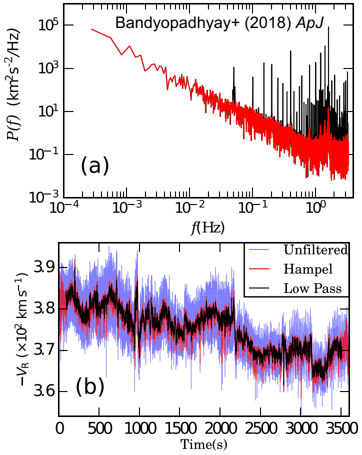
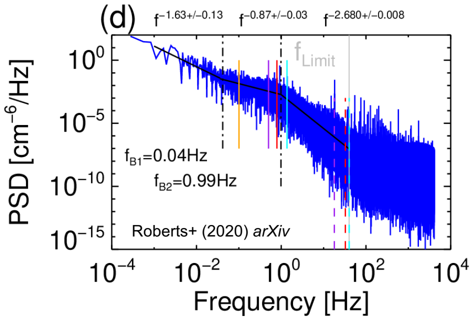
# MMS in the Solar Wind



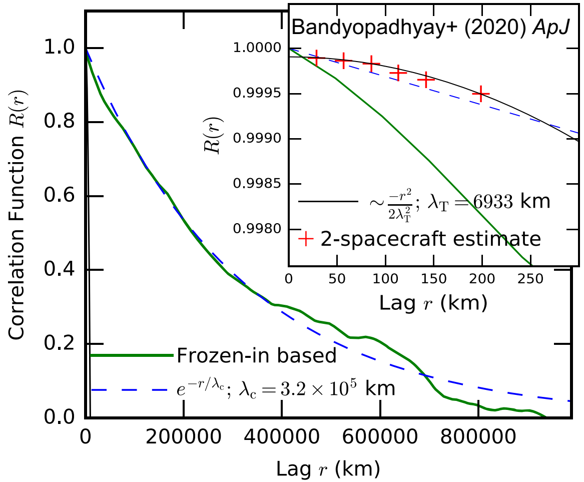

MMS observations can be more challenging to use in the solar wind, but there has been work exploring how to use them for turbulence studies

→ Filtering of the FPI measurements [Bandyopadhyay+ (2018) *ApJ*]

→ Spacecraft potential density measurements [Roberts+ (2020) *arXiv*]




Using turbulence campaign data, where MMS was in a string-of-pearls configuration, Bandyopadhyay+ [(2020) *ApJ*] characterized the Taylor microscale in the solar wind



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# Where do we go from here?

***MMS is still our best tool for the detailed analysis of plasma turbulence and we have only scratched the surface of the dataset so far…***

→ Is magnetic reconnection playing a role in turbulent dissipation?

→ There is potentially more work we can do directly evaluating the linear and nonlinear dynamics, both in the fluid equations and Vlasov equation

→ Systematic examinations of how the nonlinear dynamics and dissipation change under different conditions by comparing different turbulent environments

→ Global scale evolution of turbulence and its impact on the solar wind – magnetosphere interaction, potentially using the new formations proposed in the senior review and in conjunction with other missions

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