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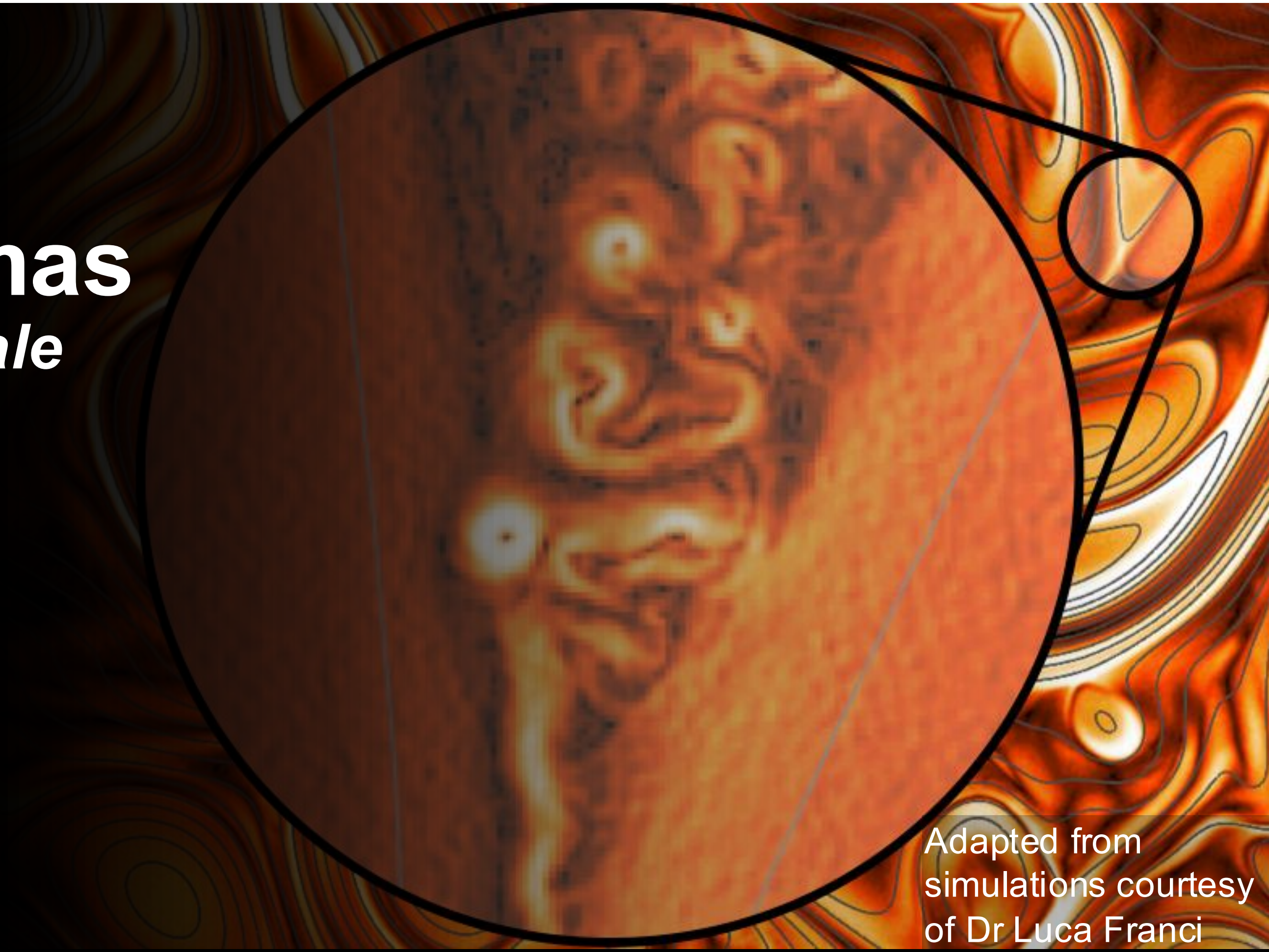
NORDITA Institute
Synergies Between Astrophysical, Space, Laboratory, and Fusion Plasma Physics
Stockholm, Sweden || 25 May 2026

Measuring Turbulence in Collisionless Space Plasmas

From the Era of *Multi-point* to *Multi-scale* Measurements

Julia E. Stawarz
Northumbria University



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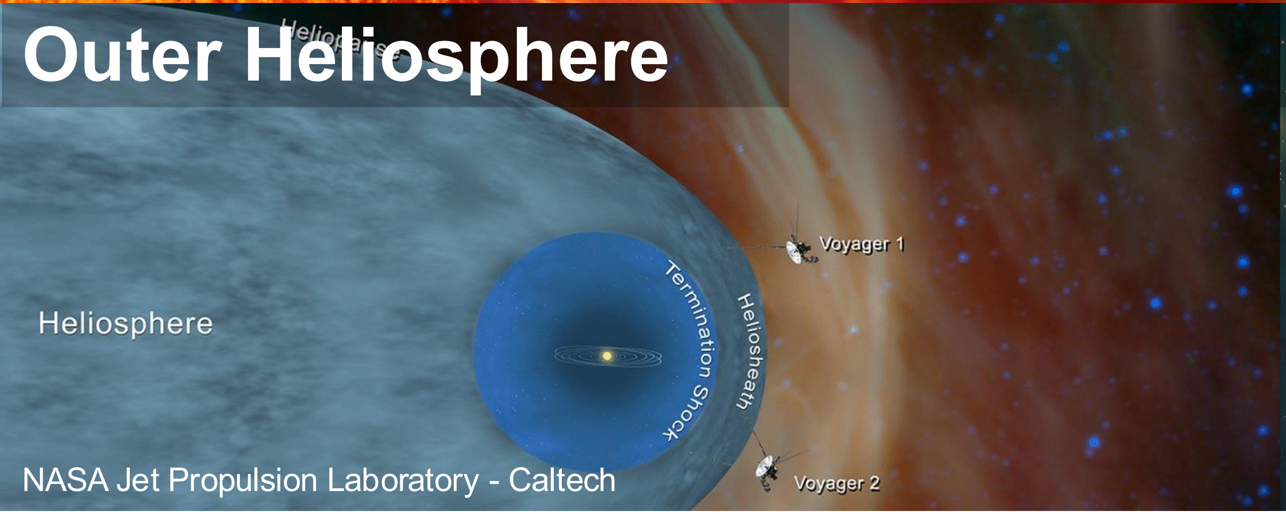
Turbulent Plasmas Throughout The Universe

Near-Earth Space

NASA Goddard Spaceflight Center / ESA Solar & Heliospheric Observatory

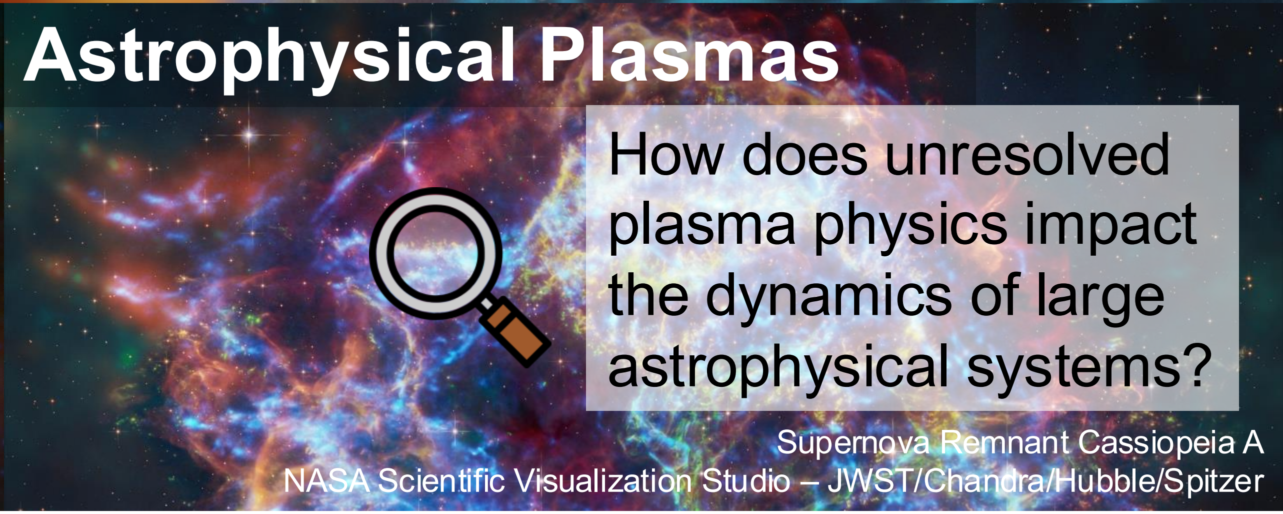
- Highly Nonlinear
- Absence of Collisions
- Electromagnetic Fields

Outer Heliosphere



NASA Jet Propulsion Laboratory - Caltech

Astrophysical Plasmas



How does unresolved plasma physics impact the dynamics of large astrophysical systems?

Supernova Remnant Cassiopeia A
NASA Scientific Visualization Studio – JWST/Chandra/Hubble/Spitzer

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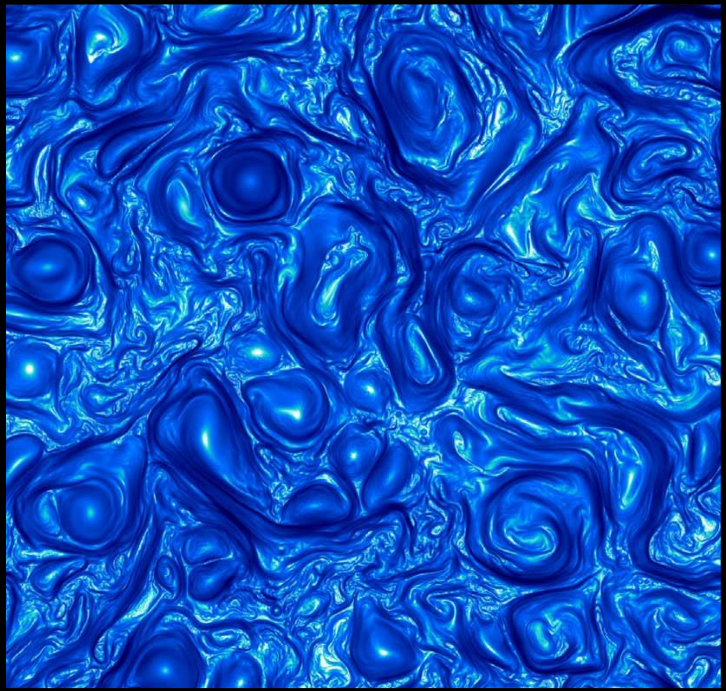
What is Turbulence?

Turbulence arises from the nonlinear terms in the dynamical equations describing the plasma



Franci, Stawarz+ (2020) *ApJ*

Magnetohydrodynamic Equations

Linear Terms (Waves-like) | Nonlinear Terms (Turbulence)

$$\partial_t \delta\rho = -\nabla \cdot (\rho_0 \delta\boldsymbol{u}) - \nabla \cdot (\delta\rho\delta\boldsymbol{u})$$

$$\partial_t \delta p = -\gamma P_0 \nabla \cdot \delta\boldsymbol{u} - \delta\boldsymbol{u} \cdot \nabla\delta p - \gamma\delta p \nabla \cdot \delta\boldsymbol{u}$$

$$\partial_t \delta\boldsymbol{b} = \nabla \times (\delta\boldsymbol{u} \times \boldsymbol{B}_0) + \nabla \times (\delta\boldsymbol{u} \times \delta\boldsymbol{b})$$

$$\partial_t \delta\boldsymbol{u} = \frac{1}{\mu_0\rho_0}(\nabla \times \delta\boldsymbol{b}) \times \boldsymbol{B}_0 - \frac{\nabla\delta p}{\rho_0} - \delta\boldsymbol{u} \cdot \nabla\delta\boldsymbol{u} + \frac{1}{\mu_0(\rho_0 + \delta\rho)}(\nabla \times \delta\boldsymbol{b}) \times \delta\boldsymbol{b} + \frac{1}{\mu_0(\rho_0 + \delta\rho)}\frac{\delta\rho}{\rho_0}(\nabla \times \delta\boldsymbol{b}) \times \boldsymbol{B}_0 - \frac{1}{(\rho_0 + \delta\rho)}\frac{\delta\rho}{\rho_0}\nabla\delta p$$

In the fully nonlinear state, both the linear and nonlinear terms are coupled together

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What is Turbulence?

Turbulence arises from the nonlinear terms in the dynamical equations describing the plasma

Magnetohydrodynamic Equations

Linear Terms (Waves-like) | **Nonlinear Terms (Turbulence)**

$$\partial_t \delta\rho_k = -\rho_0 \boldsymbol{k}\cdot\delta\boldsymbol{u}_k \quad - \boldsymbol{k}\cdot[\delta\rho\delta\boldsymbol{u}]_k$$

$$\partial_t \delta p_k = -\gamma P_0 \boldsymbol{k}\cdot\delta\boldsymbol{u}_k \quad -[\delta\boldsymbol{u}\cdot\nabla\delta p]_k - \gamma[\delta p\nabla\cdot\delta\boldsymbol{u}]_k$$

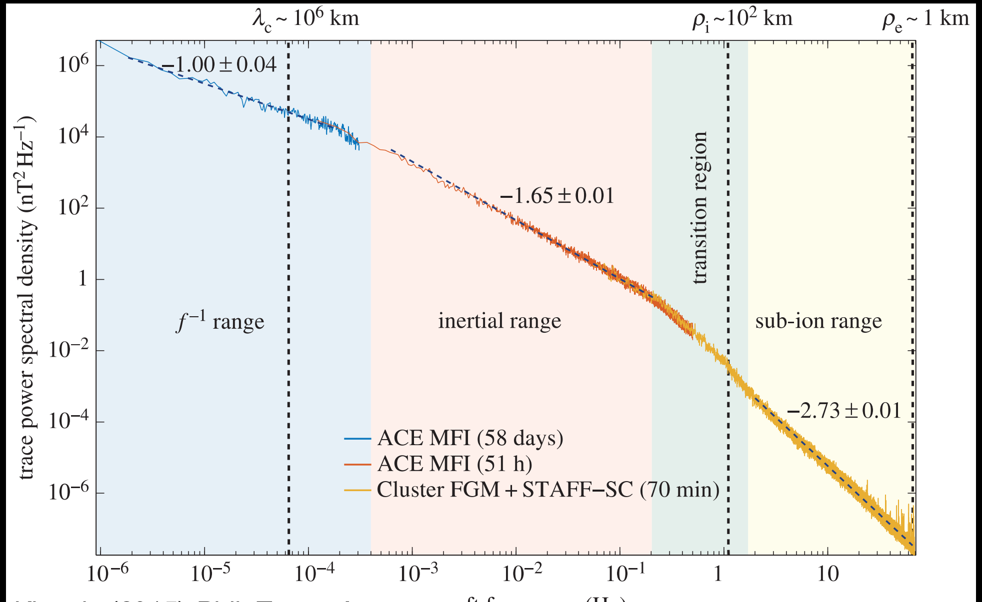
$$\partial_t \delta\boldsymbol{b}_k = \boldsymbol{k}\times(\delta\boldsymbol{u}_k\times\boldsymbol{B}_0) \quad + k\times[\delta\boldsymbol{u}\times\delta\boldsymbol{b}]_k$$

$$[\delta\boldsymbol{u}\times\delta\boldsymbol{b}]_k = \int_{-\infty}^{\infty}\delta\boldsymbol{u}_{k_1}\times\delta\boldsymbol{b}_{k_2}\delta(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})d^3\boldsymbol{k}_1 d^3\boldsymbol{k}_2$$

$$\partial_t \delta\boldsymbol{u}_k = \frac{1}{\mu_0\rho_0}(\boldsymbol{k}\times\delta\boldsymbol{b}_k)\times\boldsymbol{B}_0 - \frac{\boldsymbol{k}\delta p_k}{\rho_0} - [\delta\boldsymbol{u}\cdot\nabla\delta\boldsymbol{u}]_k + \frac{1}{\mu_0}\left[\frac{1}{(\rho_0+\delta\rho)}(\nabla\times\delta\boldsymbol{b})\times\delta\boldsymbol{b}\right]_k + \frac{1}{\mu_0}\left[\frac{1}{(\rho_0+\delta\rho)}\frac{\delta\rho}{\rho_0}(\nabla\times\delta\boldsymbol{b})\right]_k\times\boldsymbol{B}_0 - \left[\frac{1}{(\rho_0+\delta\rho)}\frac{\delta\rho}{\rho_0}\nabla\delta p\right]$$

In Fourier space, nonlinear terms become convolutions that couple evolution of every scale to every other scale

Solar Wind Turbulence Spectrum



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

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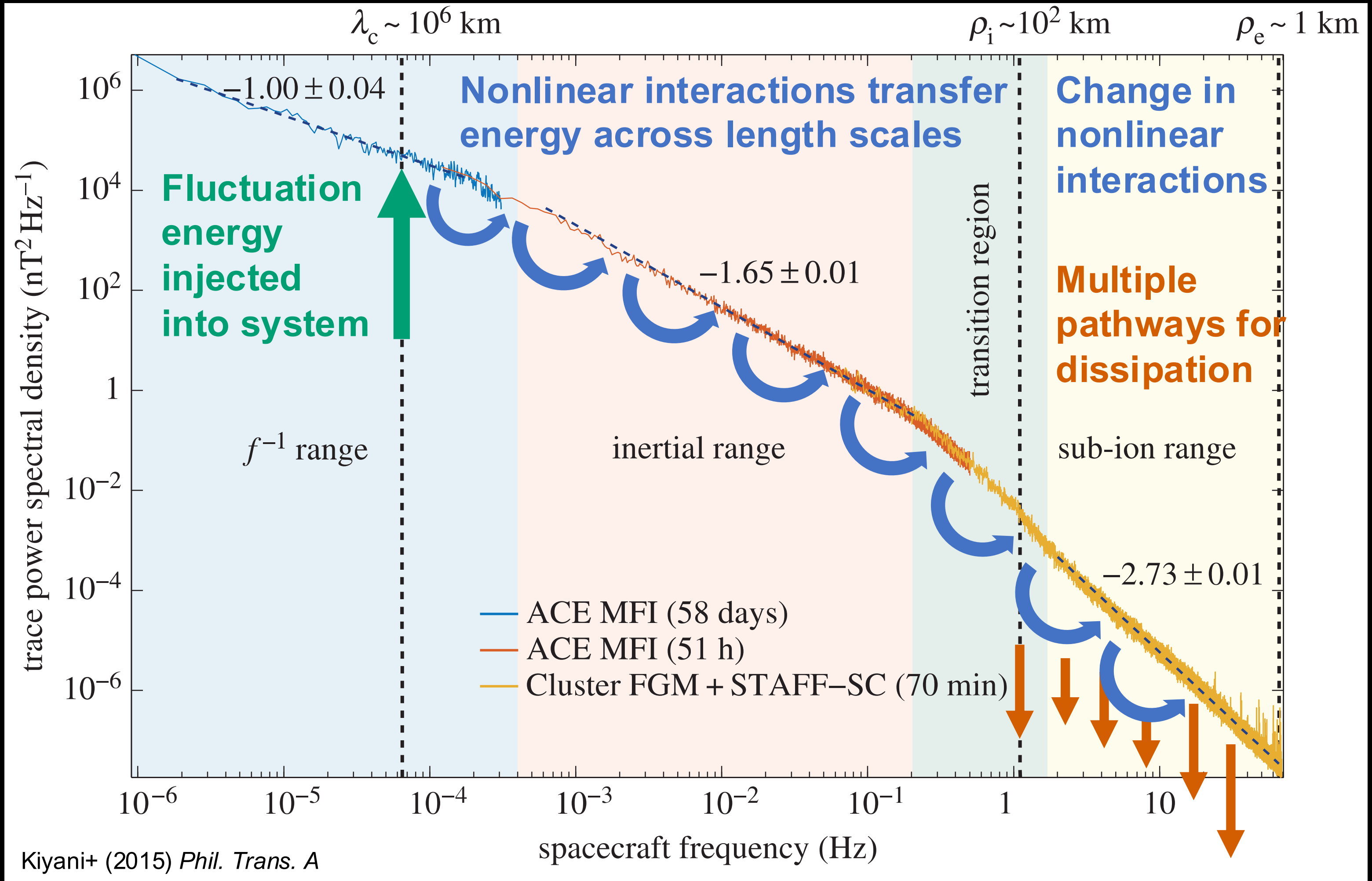
What is Turbulence?

Solar Wind Turbulence Spectrum



Key Areas of Turbulence Research in Space Physics

How much energy is dissipated and how is that energy partitioned?

What is the nature of the nonlinear dynamics across scales and across different environments?

How does turbulence evolve?

How does turbulence impact the surrounding environment?

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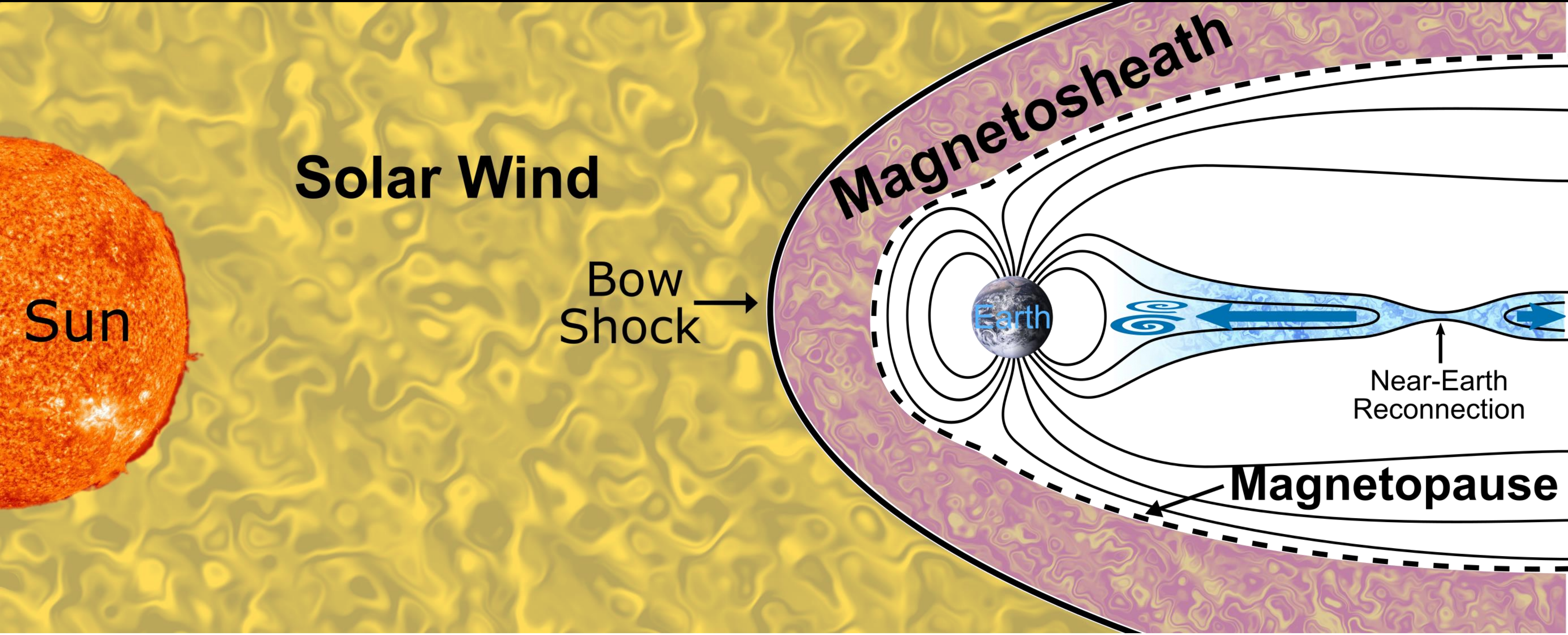
Where Does Turbulence Come From in Near-Earth Space?



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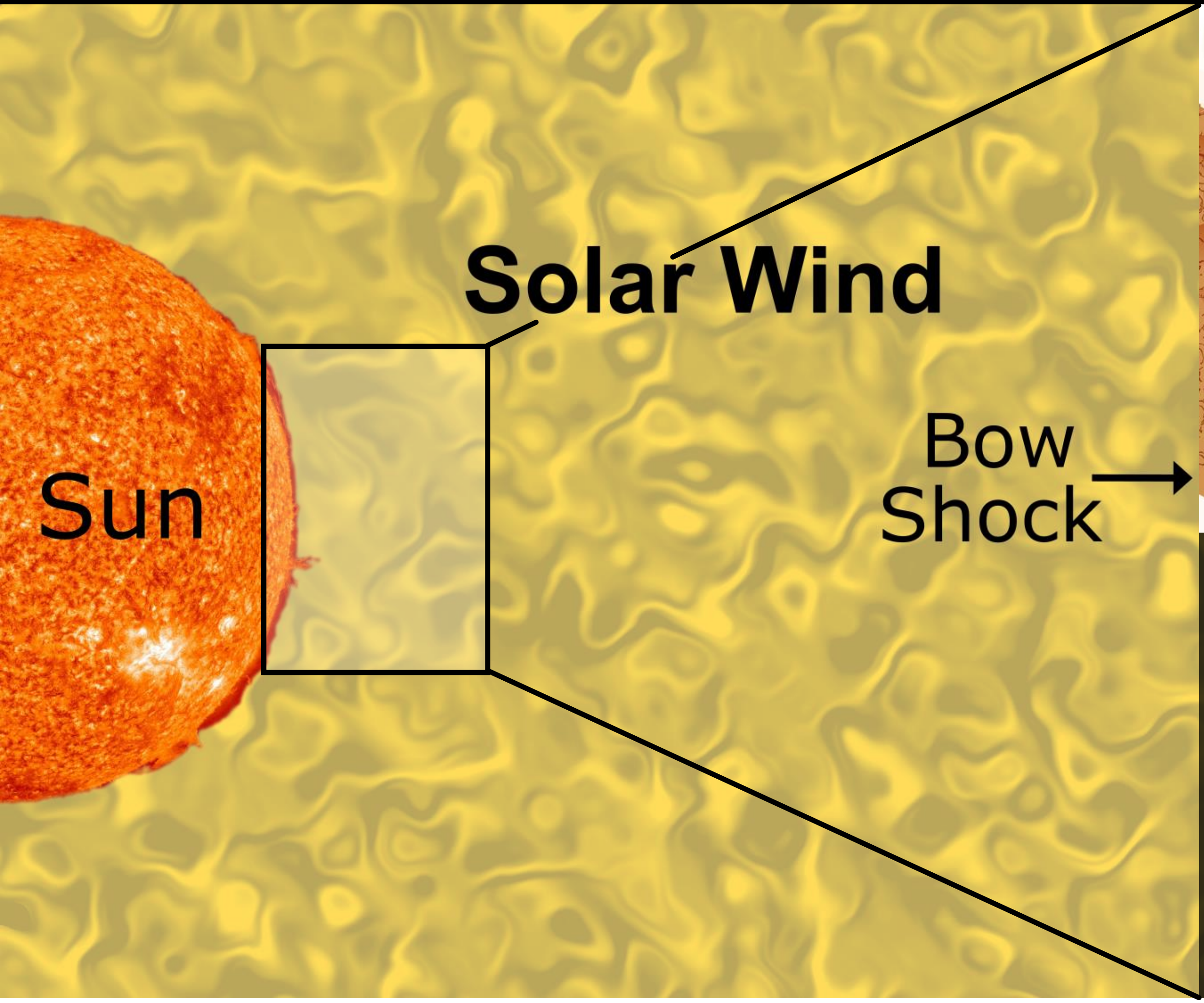

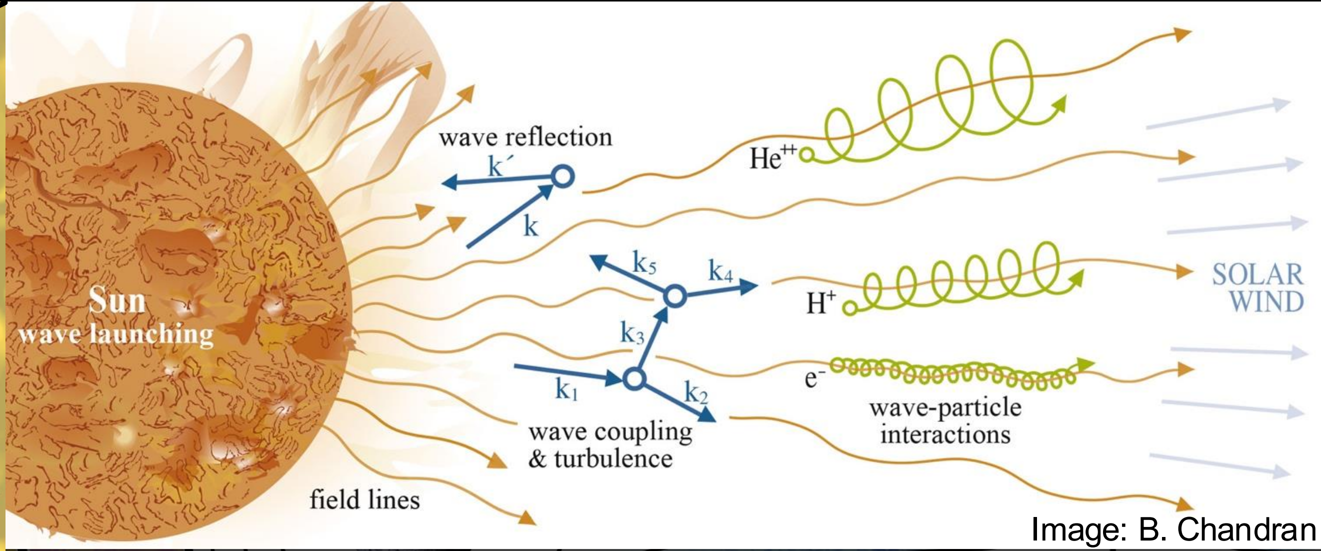

Image: B. Chandran

Solar Wind

- Foot point motions at Sun launch fluctuations into interplanetary space → reflections in non-uniform background drive nonlinear interactions
- May also excite fluctuations through stream interactions and transient structures (CME's, etc.)

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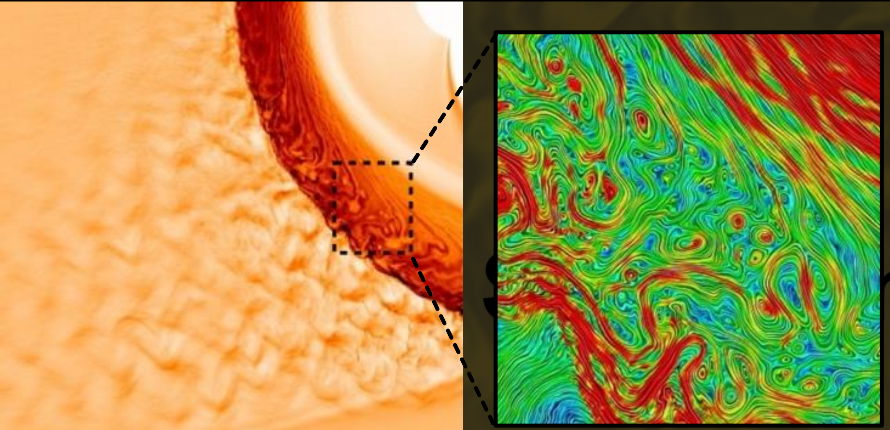
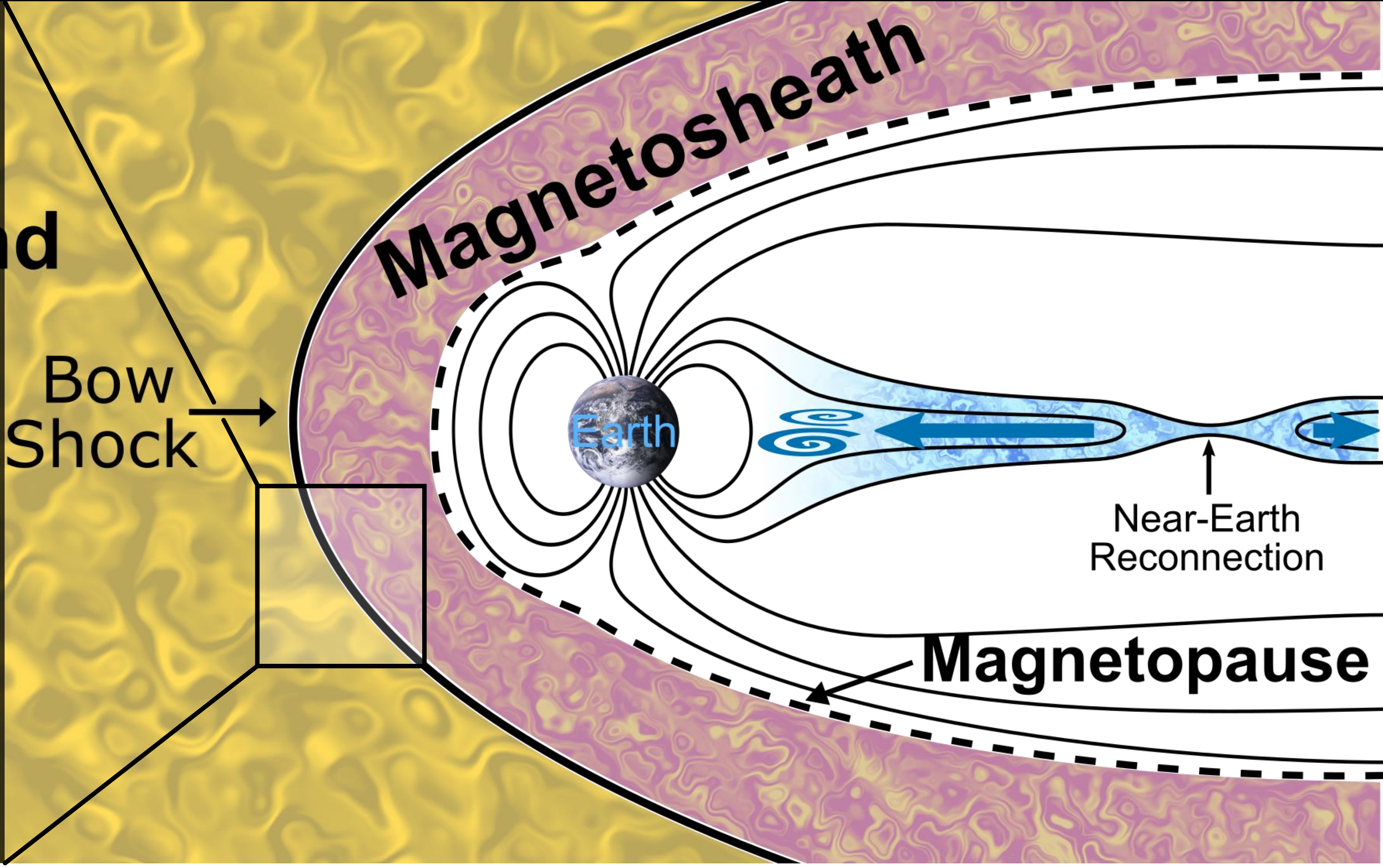

Karimabadi+ (2014) *PoP*

Magnetosheath

- Solar wind turbulence advected through Earth's Bow shock
- Kinetic instabilities excited at the shock and in the downstream plasma inject new fluctuations



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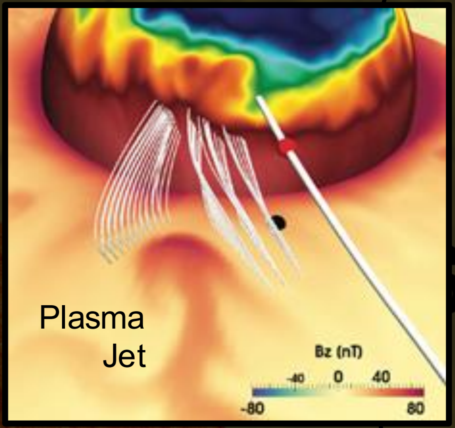
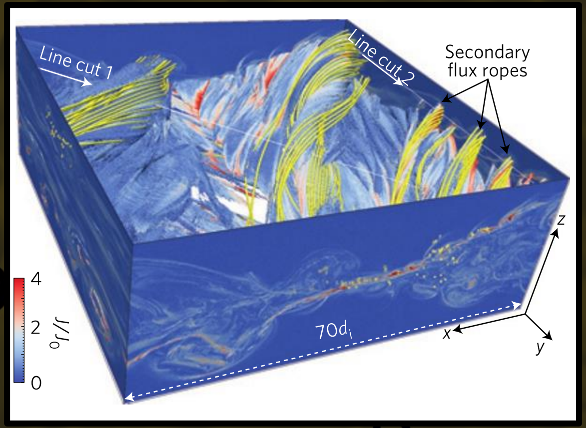


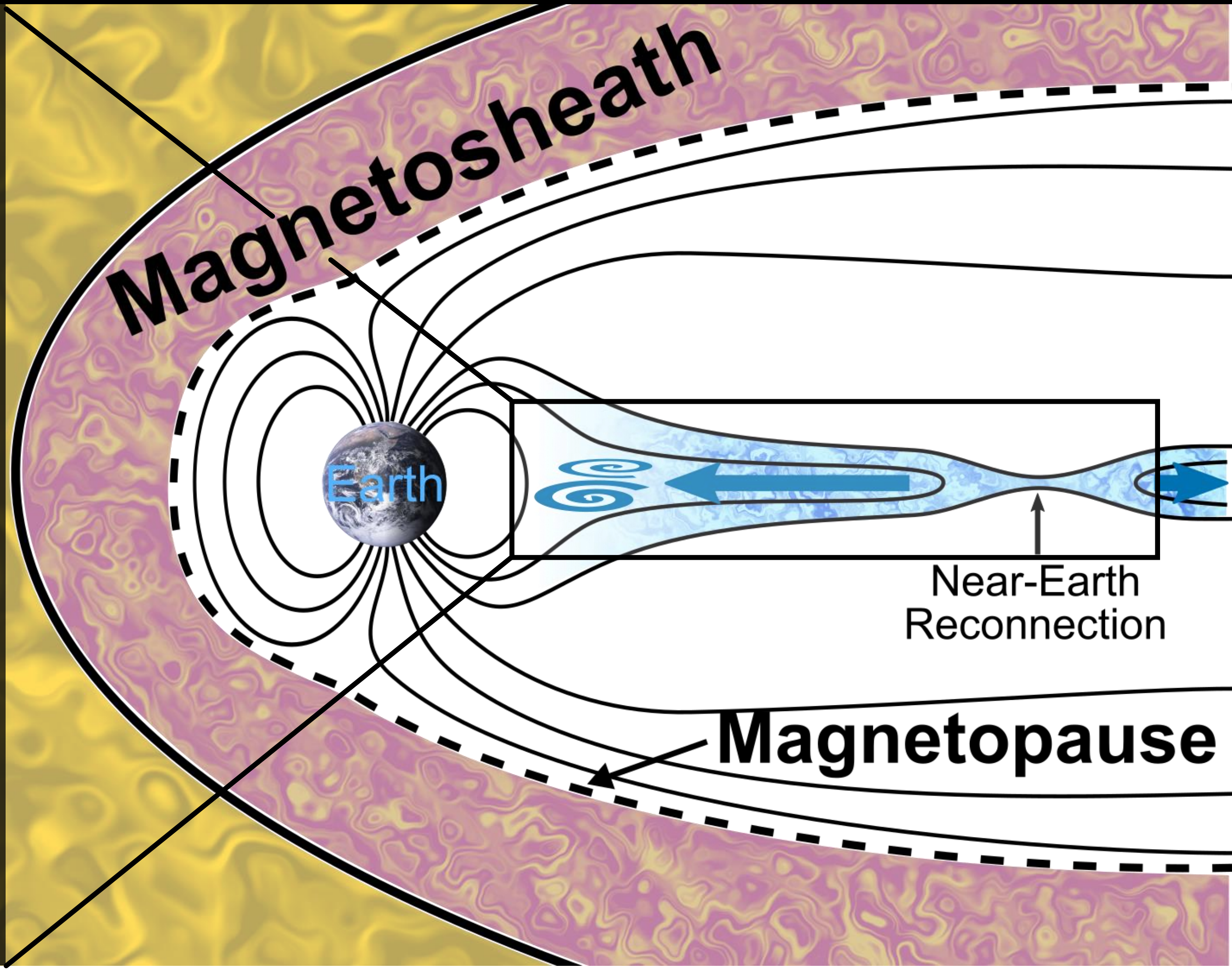
Merkin+ (2019) *JGR*



Daughton+ (2011) *Nature Phys.*

Plasma Sheet

- Instabilities at the reconnection site itself (e.g., plasmoid, LHDI, etc.)
- Interaction of fast flows with the surrounding environment (e.g., shear instabilities, braking of flow as it impinges on dipolar field near Earth)



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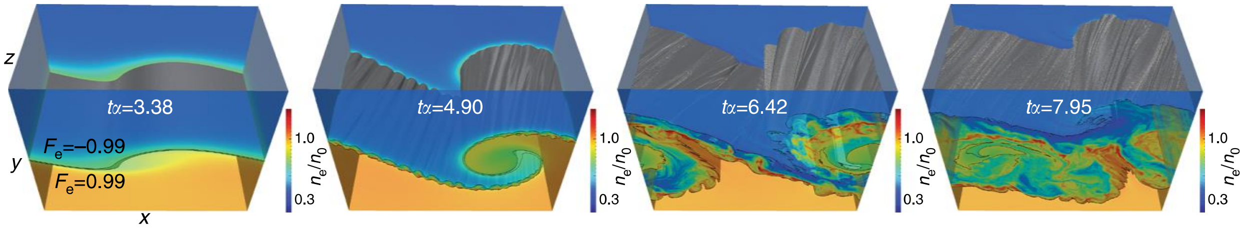
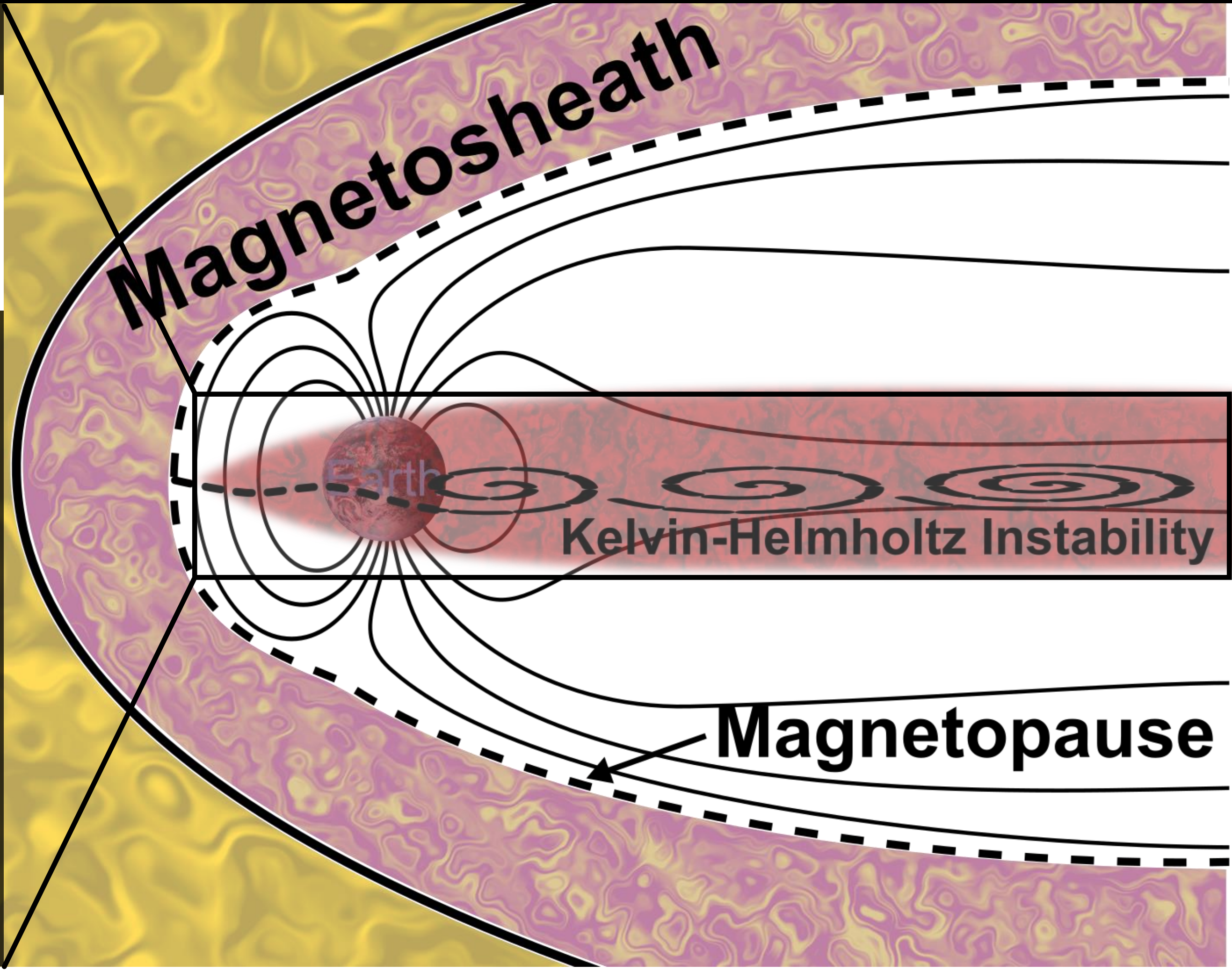


Nakamura+ (2017) *Nature Comm.*

Magnetopause

- Kelvin-Helmholtz in stability can develop due to velocity shear with the magnetosheath on flanks of Earth's magnetosphere
- Secondary instabilities and magnetic reconnection within the vortices lead to development of turbulent boundary layer



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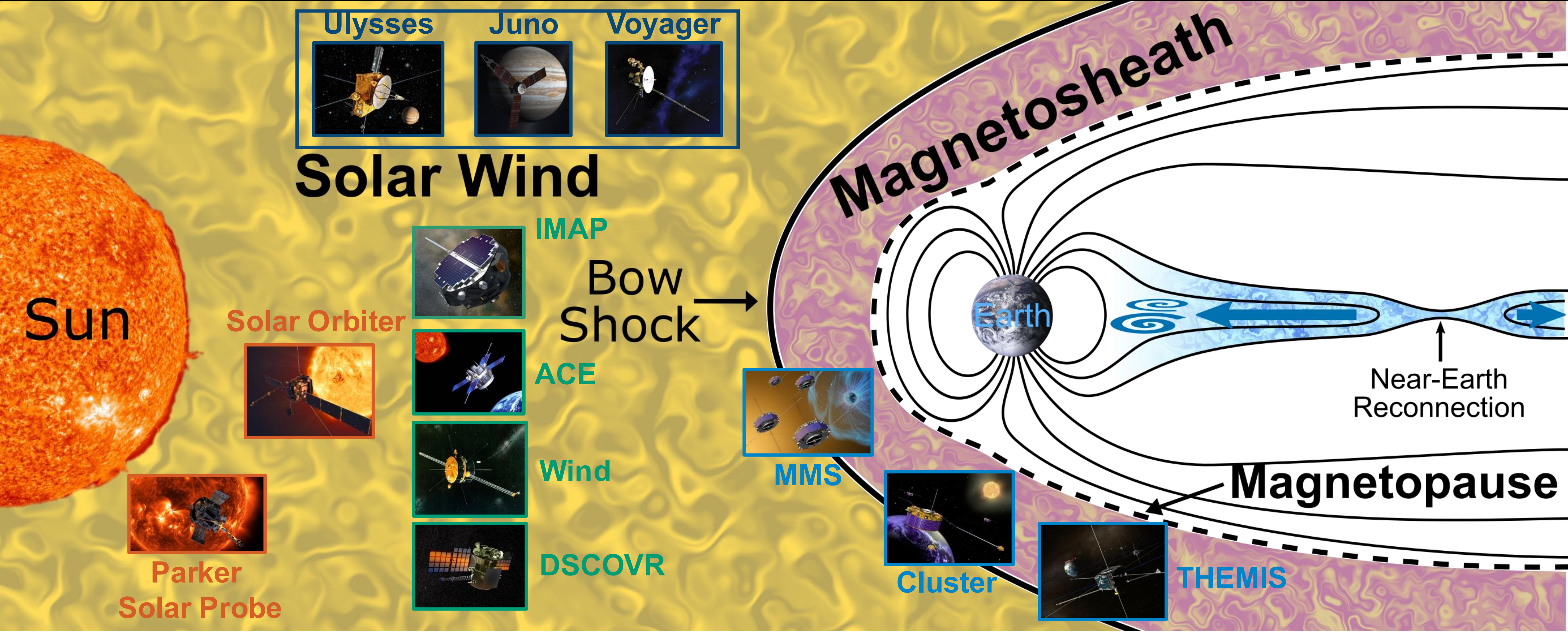
Measuring Turbulence in Near-Earth Space



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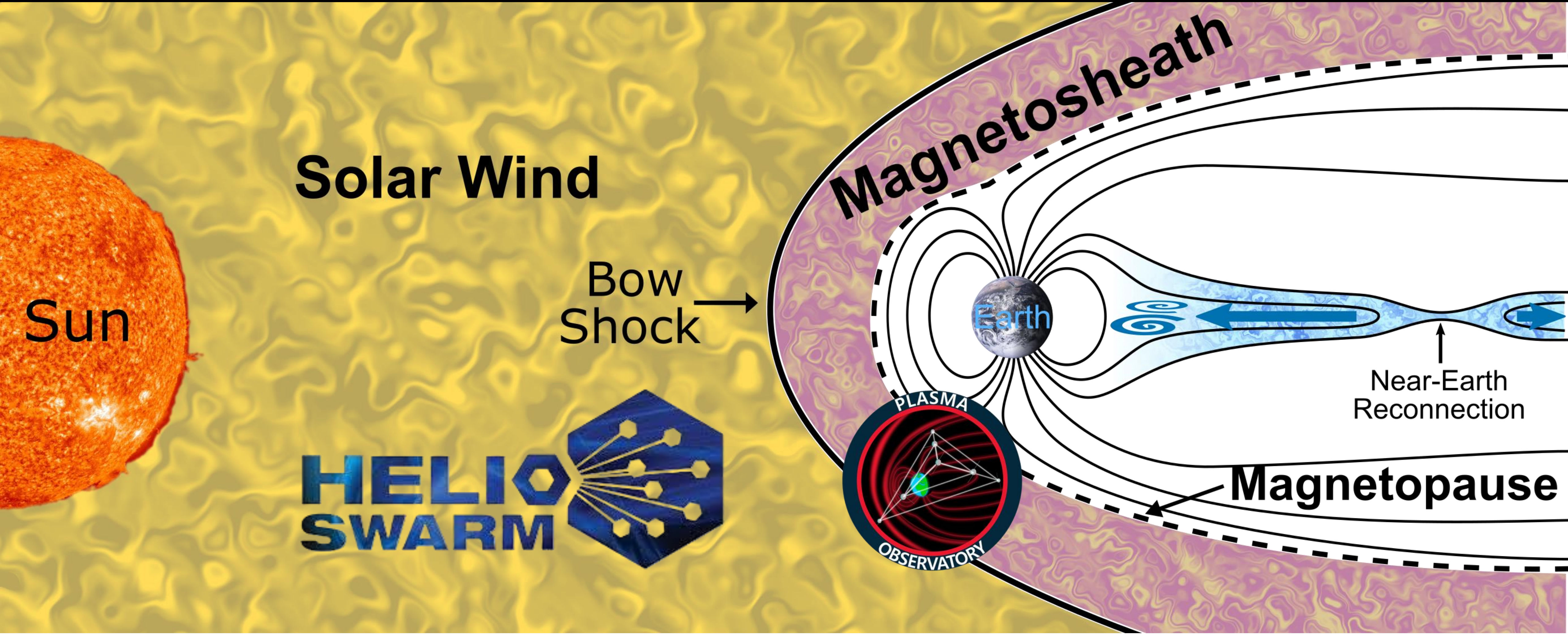
A New Era of Multiscale Measurements



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Measuring Plasma Turbulence with *Magnetospheric Multiscale*

Four identical Earth-orbiting spacecraft launched in 2015 in a small-scale ($\gtrsim$5 km) formation

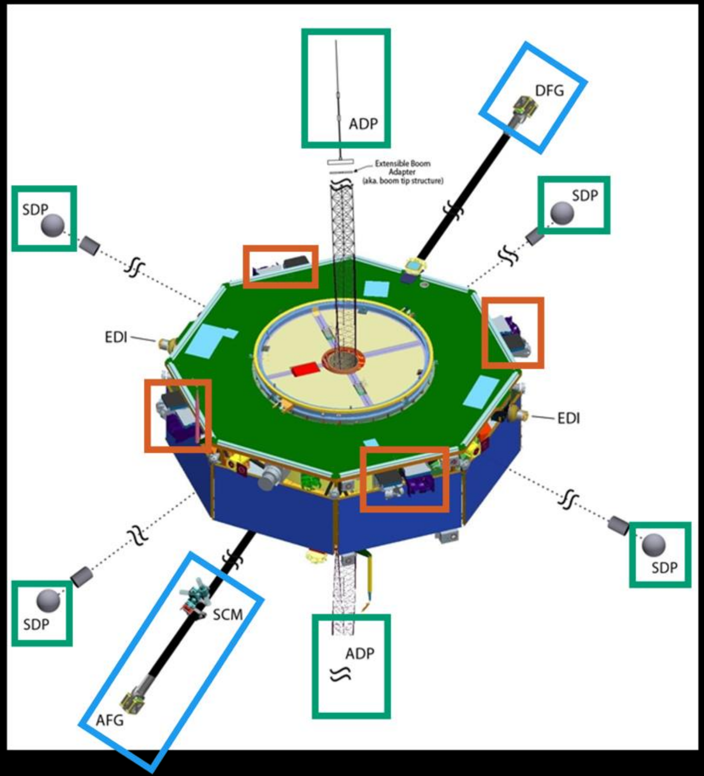
Magnetometers → 3D Magnetic Fields

Voltage Probes → 3D Electric Fields

Particle Detectors → High-resolutions particle data

Multi-Spacecraft Measurements → Allows calculation of gradients in the plasma

NASA's *Magnetospheric Multiscale*



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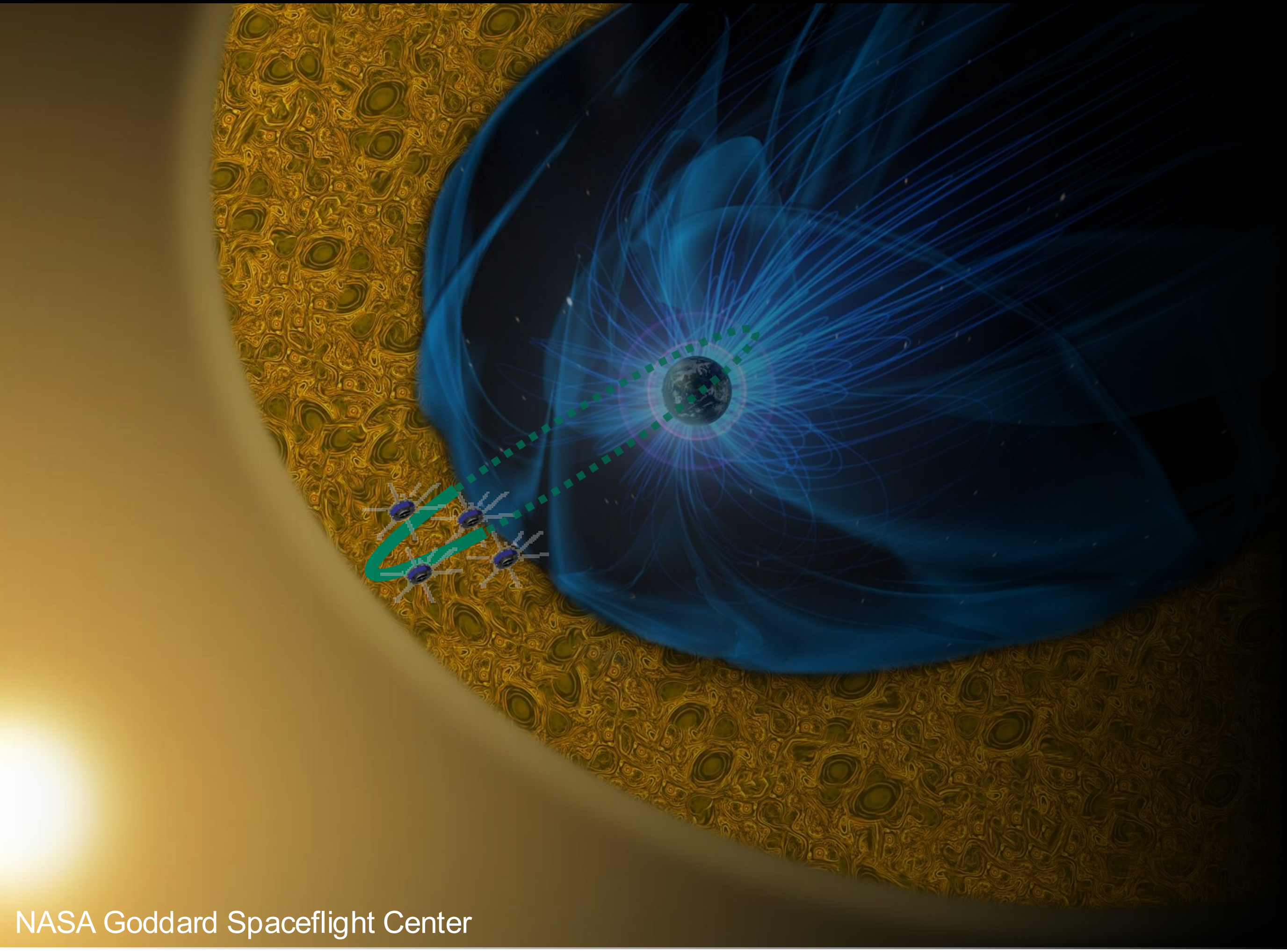
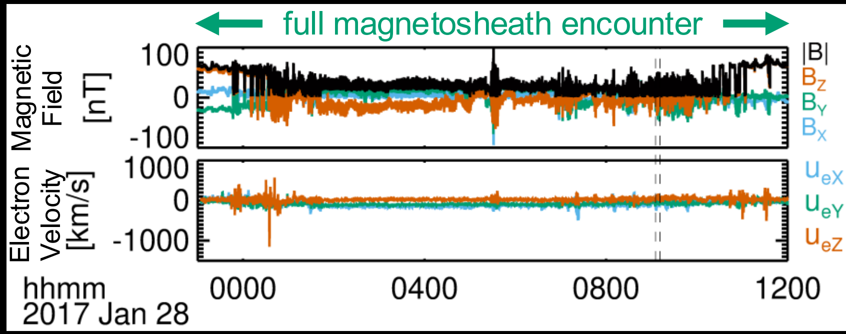
Zooming in on the Plasma





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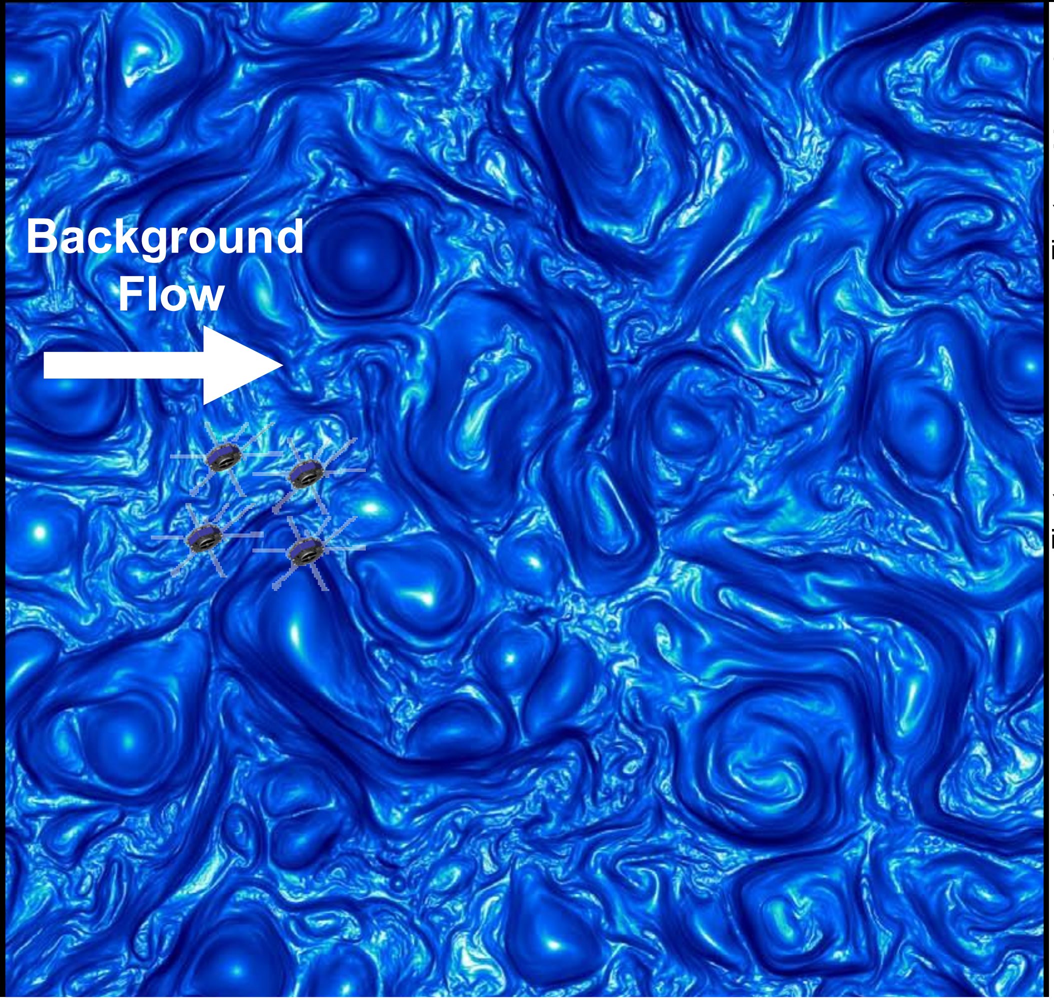
Zooming in on the Plasma

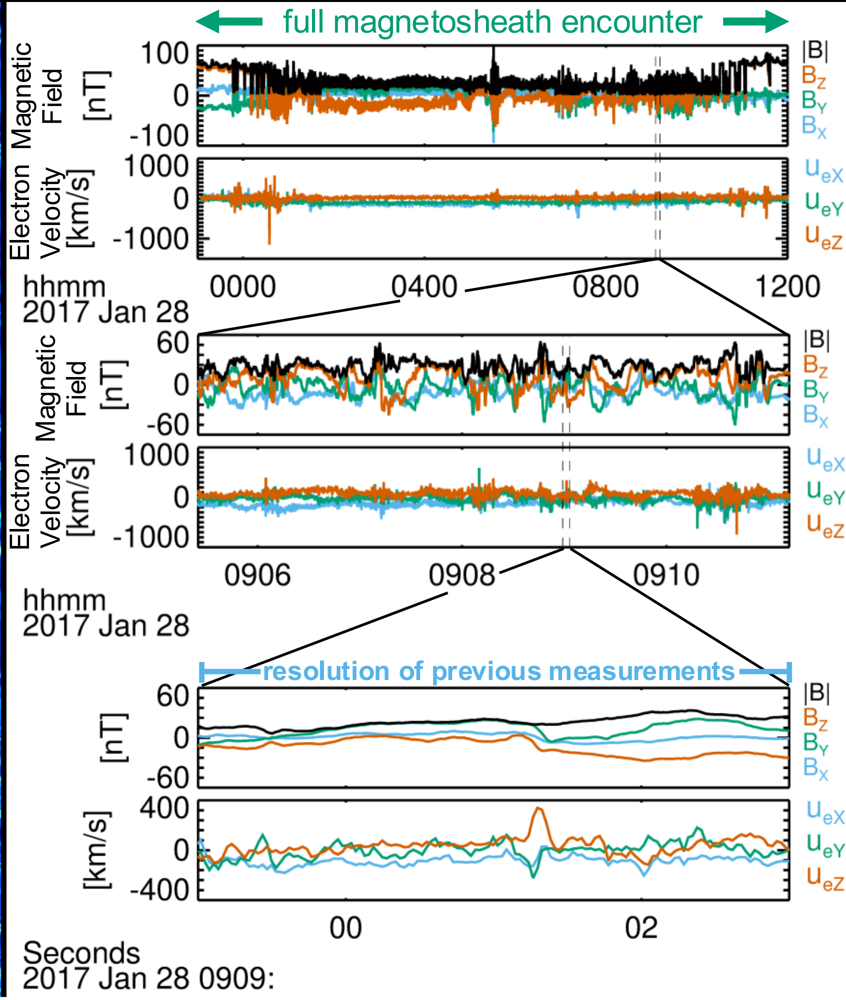
Often spacecraft motion much less than plasma motion

Observed variability due to **advection by U_0** and **temporal variability**

If **advection** is much faster → Taylor hypothesis

1s/c → must rely on Taylor hypothesis
4s/c → measure a single scale in 3D directly





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Electric Fields in Collisionless Plasmas

In collisionless plasmas, $\boldsymbol{E}$ is governed by a generalised Ohm's Law in which the different terms correspond to different dynamical processes

$$\boldsymbol{E}_{Ohm} = -\boldsymbol{u}\times\boldsymbol{B} + \frac{1}{en}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{en}\nabla\cdot\boldsymbol{P}_e + \frac{m_e}{e^2 n}\nabla\cdot\left(\boldsymbol{uJ} + \boldsymbol{Ju} - \frac{\boldsymbol{JJ}}{en}\right) + \frac{m_e}{e^2 n}\frac{\partial \boldsymbol{J}}{\partial t} + \sum_{\ell=1}^{\infty}\left(-\frac{m_e}{m_i}\right)^{\ell}\boldsymbol{\mathcal{M}}_{\ell}$$

- $\boldsymbol{E}_{MHD} = -\boldsymbol{u}\times\boldsymbol{B}$: Magnetic Field "Frozen-In" to ion fluid
- $\boldsymbol{E}_{Hall} = \frac{1}{en}\boldsymbol{J}\times\boldsymbol{B}$: Magnetic Field "Frozen-In" to electron fluid
- $\boldsymbol{E}_{P_e} = -\frac{1}{en}\nabla\cdot\boldsymbol{P}_e$: Correction due to electron thermal motions
- $\boldsymbol{E}_{Inertia} = \frac{m_e}{e^2 n}\nabla\cdot\left(\boldsymbol{uJ} + \boldsymbol{Ju} - \frac{\boldsymbol{JJ}}{en}\right) + \frac{m_e}{e^2 n}\frac{\partial \boldsymbol{J}}{\partial t}$: Correction due to difference between ion and electron inertia
- $\boldsymbol{E}_{\delta m_e} = \sum_{\ell=1}^{\infty}\left(-\frac{m_e}{m_i}\right)^{\ell}\boldsymbol{\mathcal{M}}_{\ell}$: Finite electron mass corrections

$$\boldsymbol{\mathcal{M}}_{\ell} = \frac{2}{en}\boldsymbol{J}\times\boldsymbol{B} - \frac{1}{en}\nabla\cdot(\boldsymbol{P}_e + \boldsymbol{P}_i) + \frac{m_e}{e^2 n}\left[\nabla\cdot\left(\boldsymbol{uJ} + \boldsymbol{Ju} - (1+2\ell)\frac{\boldsymbol{JJ}}{en}\right) + \frac{\partial \boldsymbol{J}}{\partial t}\right]$$

$\boldsymbol{E}_{MHD} + \boldsymbol{E}_{Hall}$:

$$\boldsymbol{E}_{Ohm} = -\boldsymbol{U}_0\times(\boldsymbol{B}_0 + \delta\boldsymbol{b}) - \delta\boldsymbol{u}\times\boldsymbol{B}_0 + \frac{1}{en}\delta\boldsymbol{j}\times\boldsymbol{B}_0 - \delta\boldsymbol{u}\times\delta\boldsymbol{b} + \frac{1}{en}\delta\boldsymbol{j}\times\delta\boldsymbol{b} + \dots$$

- $-\boldsymbol{U}_0\times(\boldsymbol{B}_0 + \delta\boldsymbol{b})$: Frame transformation to plasma frame
- $-\delta\boldsymbol{u}\times\boldsymbol{B}_0 + \frac{1}{en}\delta\boldsymbol{j}\times\boldsymbol{B}_0$: Linear Terms
- $-\delta\boldsymbol{u}\times\delta\boldsymbol{b} + \frac{1}{en}\delta\boldsymbol{j}\times\delta\boldsymbol{b}$: Nonlinear Terms

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Measuring Generalized Ohm's Law

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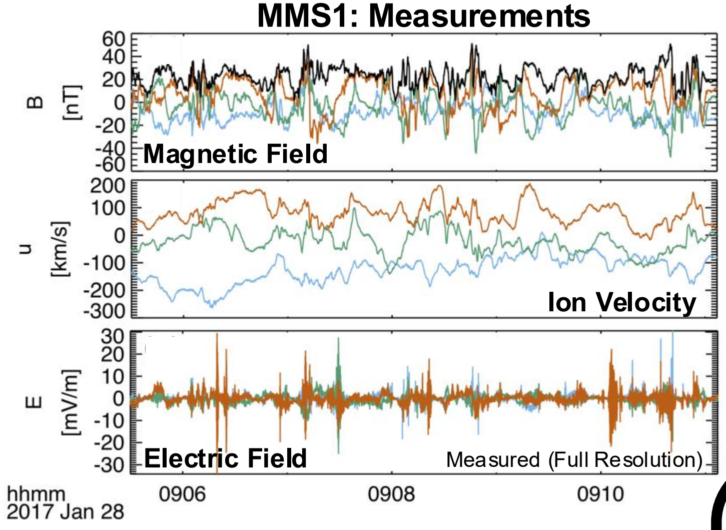
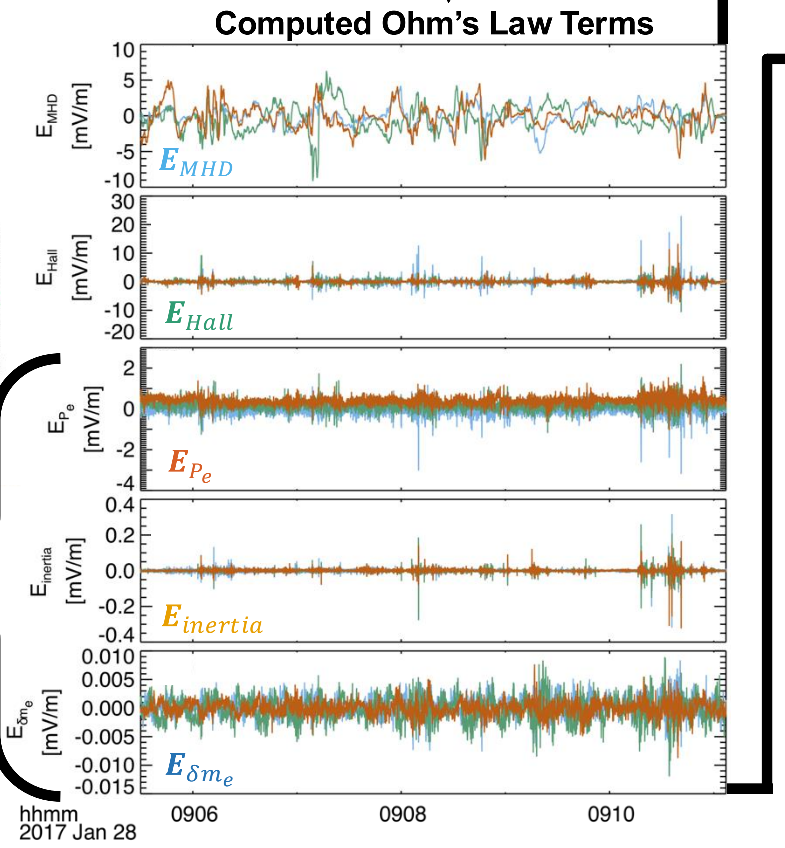
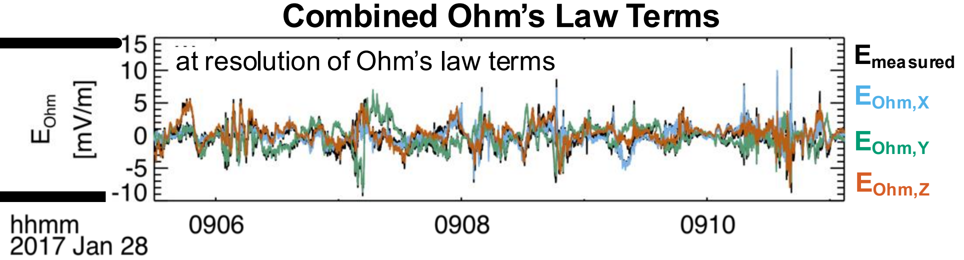
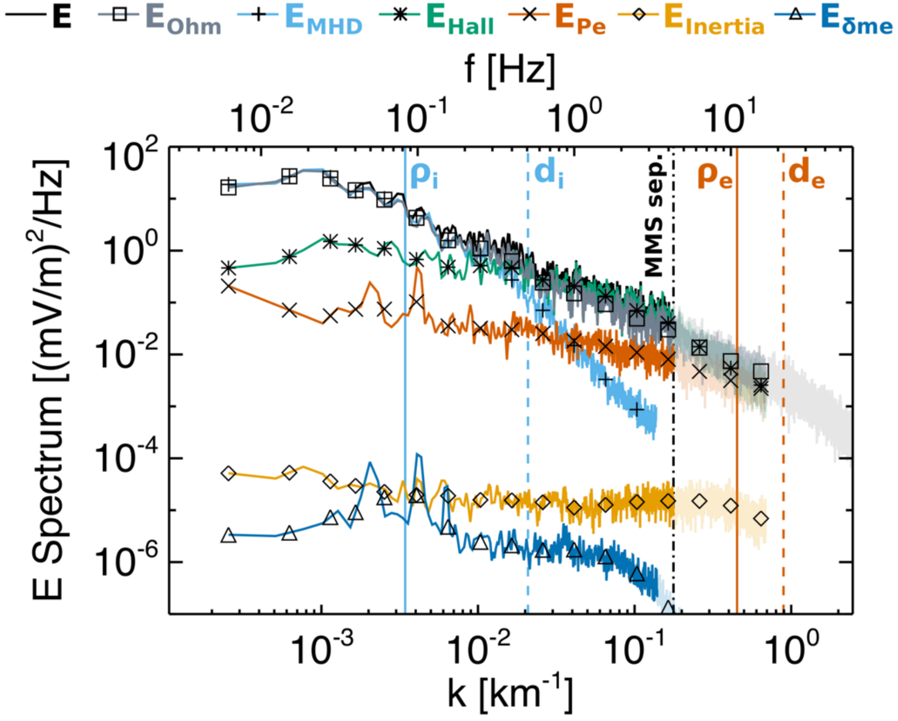




Require multipoint measurements to compute gradients





See Stawarz+ (2021) *JGR* and Lewis+ (2023) *PoP*

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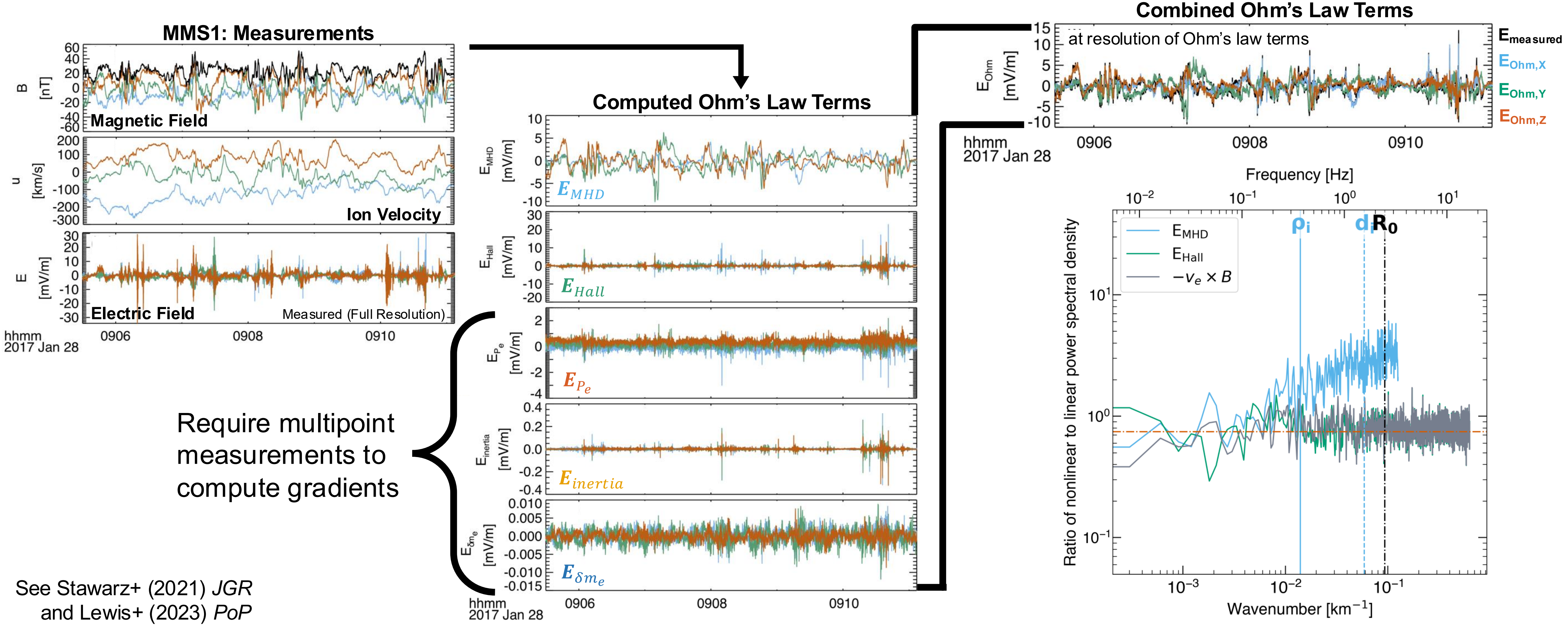
Measuring Generalized Ohm's Law



Require multipoint measurements to compute gradients

See Stawarz+ (2021) *JGR* and Lewis+ (2023) *PoP*

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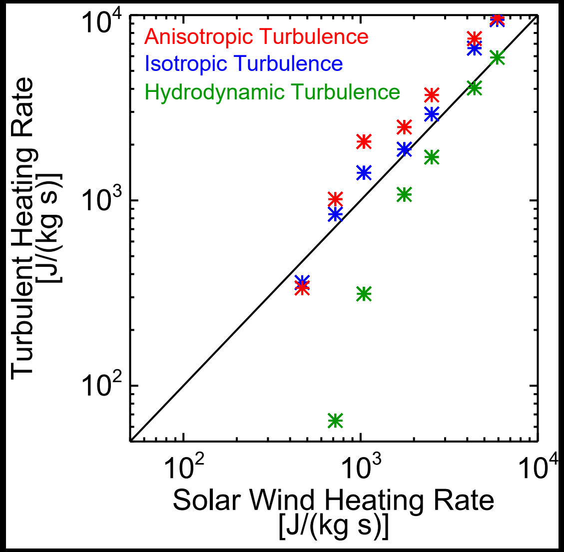
Turbulence Dissipation

Adapted from Stawarz+ (2009) *ApJ*



What is the net amount of energy dissipated by turbulence?

One way to address this is with the Politano-Pouquet relation and related methods

$$\partial_t \left\langle \left|\Delta \boldsymbol{z}^{\pm}\right|^2 \right\rangle + \nabla_\ell \cdot \left\langle \Delta \boldsymbol{z}^{\mp} \left|\Delta \boldsymbol{z}^{\pm}\right|^2 \right\rangle - 2\nu \nabla_\ell^2 \left\langle \left|\Delta \boldsymbol{z}^{\pm}\right|^2 \right\rangle + 4\epsilon^{\pm} = 0$$

$$\nabla_\ell \cdot \left\langle \Delta \boldsymbol{z}^{\mp} \left|\Delta \boldsymbol{z}^{\pm}\right|^2 \right\rangle = -4\epsilon^{\pm}$$

How is that energy partitioned between different particle populations?

We can try to measure energy conversion terms directly, either in a fluid [$\boldsymbol{j} \cdot \boldsymbol{E}$, $(\boldsymbol{P} \cdot \nabla) \cdot \boldsymbol{u}$] or kinetic sense [see presentation by Jack Parker this week]

We can also try to identify dissipative processes of interest and estimate how they are contributing to dissipation

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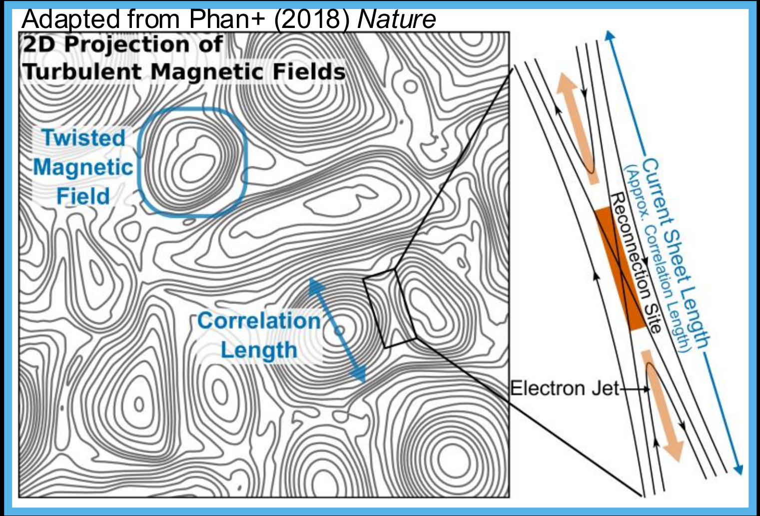
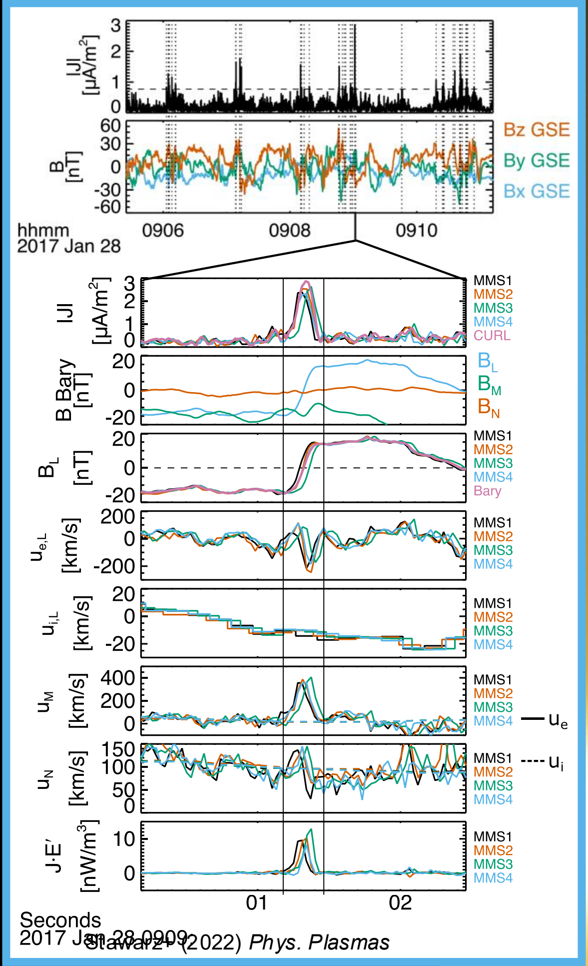
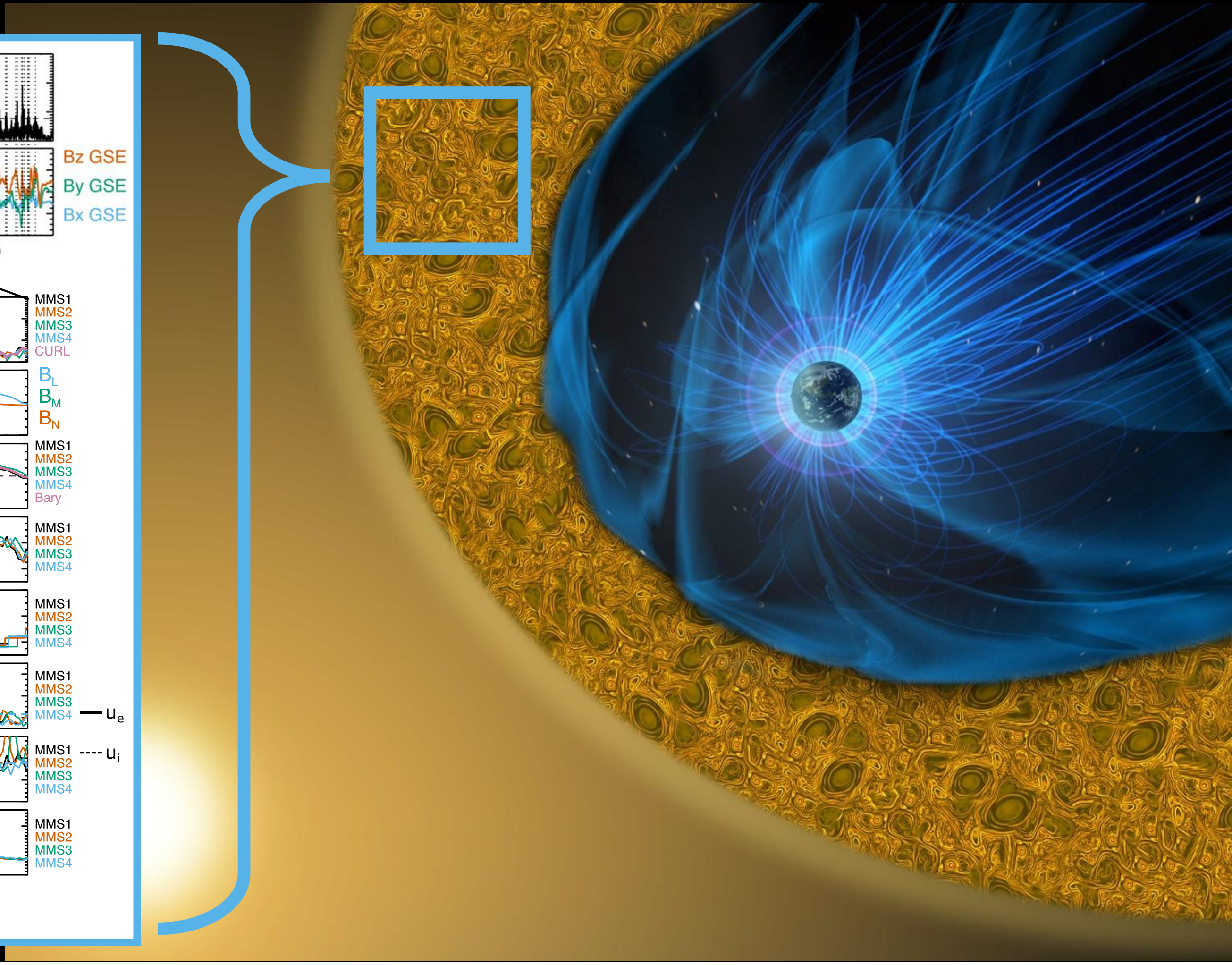
Identifying Turbulence-Driven Reconnection



MMS



Stawarz+ (2022) *Phys. Plasmas*



With MMS we can systematically identify reconnection events embedded in turbulent plasmas!

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Estimating Energy Dissipation Associated with Reconnection

[Stawarz+ (2022) *Phys. Plasmas*; Shay+ (2018) *Phys. Plasmas;* Stawarz+ (2024) *Space Sci. Rev.*]

By considering energy budget of each turbulence-driven reconnection event, we can develop an expression for the energy dissipation rate associated with the ensemble of reconnection events

[Dissipated energy per unit time per unit mass] = [Sum over all reconnecting current sheets] [Fraction of particles processed by reconnection event] [Fraction of energy converted to heating] [Available reconnected magnetic energy per unit mass] [Inverse timescale over which reconnection occurs]

"Cascade Rate"

$$\epsilon_{rec} = \sum_j f_{rec,j} \left(\alpha_{i,j} + \alpha_{e,j}\right) V_{A,inflow,j}^2 \left(\frac{V_{A,inflow,j}}{\lambda_{inflow,j}} \mathcal{R}_j\right)$$

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Estimating Energy Dissipation Associated with Reconnection

[Stawarz+ (2022) *Phys. Plasmas*; Shay+ (2018) *Phys. Plasmas*; Stawarz+ (2024) *Space Sci. Rev.*]

Dimensionless factors parameterizing turbulence-driven reconnection

Reminiscent of $\epsilon \sim \delta u^3/L$ but based on local δb_L at reconnecting current sheets

$$\epsilon_{rec} \sim \left(\frac{N_{rec}}{V}\lambda_{C\perp}^2\lambda_{C||}\right)\left(\frac{\tau_{disrupt}}{\tau_{rec}}\right)\left(\frac{n_{inflow}}{n_0}\right)(\alpha_i + \alpha_e)\mathcal{R}\left(\frac{V_{AL,inflow}^3}{\lambda_{C\perp}}\right)$$

Normalized prevalence of reconnection in turbulent volume

Relative time for turbulence to destroy a reconnection event

Local density enhancements or depletions at reconnection sites

Parameterization of “heating” enabled by reconnection

Turbulent reconnection rate

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Estimating Energy Dissipation Associated with Reconnection

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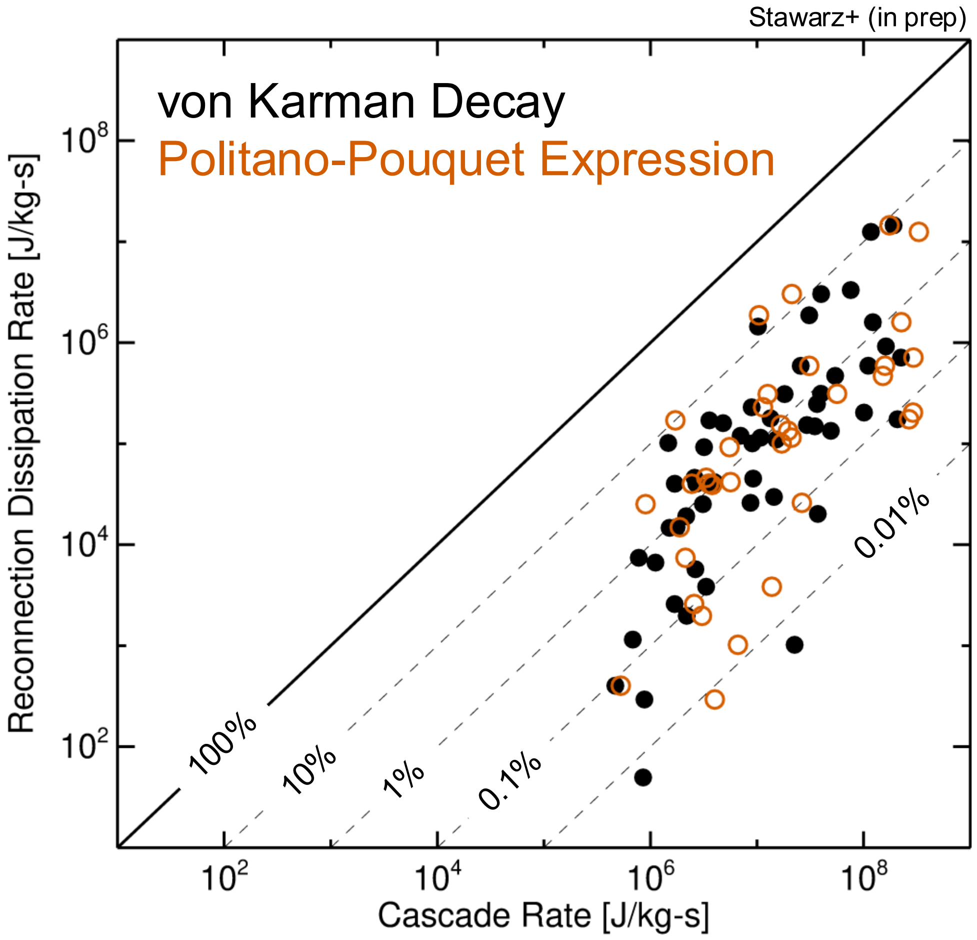

Many terms can be observationally constrained with *MMS* and compared with estimates of the turbulent cascade rate

Key Assumptions

$\mathcal{R}$ nominal values [e.g., Burch+ 2020] or analytical expressions for ion coupled and electron-only reconnection [e.g. Liu+ 2022, 2025]

$\alpha_i + \alpha_e \sim \frac{3}{2} 0.147$ consistent with Phan+ (2013, 2014) estimates for collisionless reconnection

$\tau_{disrupt} \sim \tau_{NL}$ based on the few studies that have looked at this in simulations [e.g. Zhdankin (2015)]

$V \sim 0.1\pi\lambda_C^2 U_0 T_{interval}$ reconnection occurs at interface of correlation length magnetic structures and current sheets randomly distributed and isotopically oriented with respect to s/c trajectory

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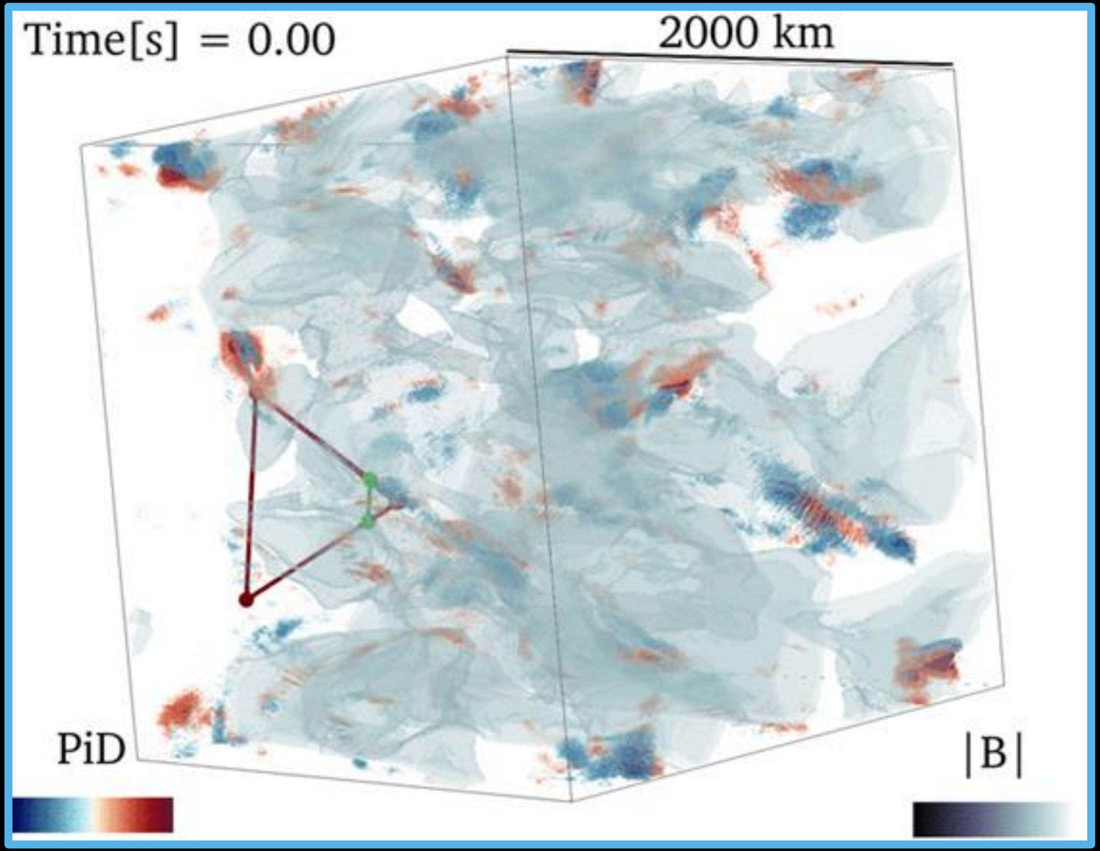
The Need for New Multiscale Measurements



Courtesy of Jeffersson Agudelo Rueda

Many of the key assumptions related to spatial distribution and lifetime of dissipative structures in 3D

These assumptions are not possible to fully constrain with current numerical simulations or theory

Distributed multiscale measurements of turbulent plasmas are needed to enable new advancements

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Summary

A wide variety of different turbulent environments with different plasma properties and dynamics are present in near-Earth space that are directly accessible with *in situ* satellite measurements offering an excellent laboratory for studying turbulence in natural plasmas

The most recent generation of *multi-point* measurements, particularly from NASA's *Magnetospheric Multiscale*, have provided us with some of the best observational datasets currently available for studying these complex systems

A new generation of multiscale measurements is on the verge of enabling new advancements by allowing us to directly measure the 3D *multi-scale* structure of the plasma

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