Role of Multipoint Space Missions In Unraveling Energy Dissipation

L'Aquila School – 2026 Course

The heliospheric space plasma physics in the era of multipoint space missions

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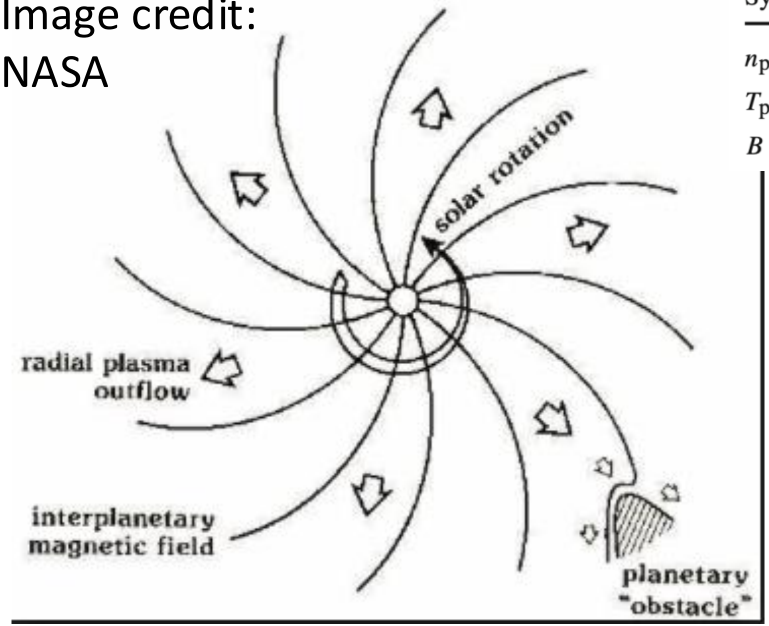
OUTLINE

- Introduction
- Energy Dissipation Measures
  - Pressure-strain interaction
- MMS Analysis
  - Pressure-strain in coherent structures
- Summary
- Open Issues

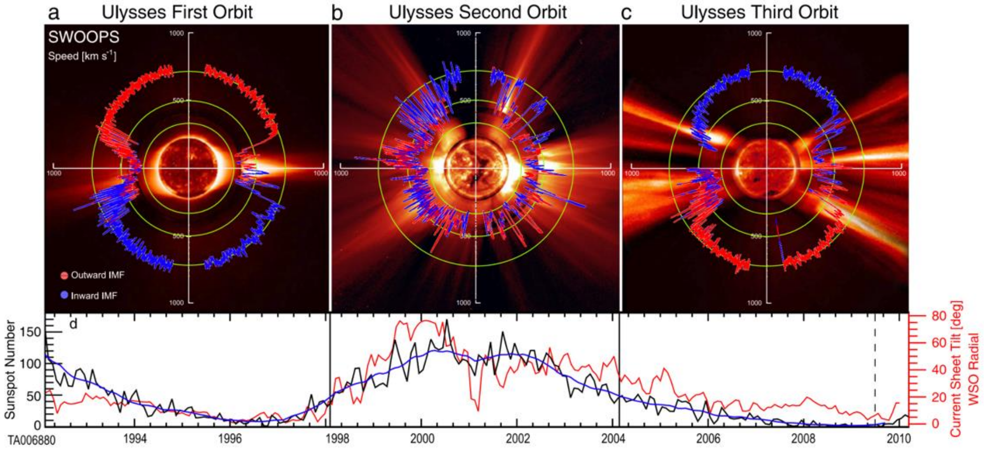
SOLAR WIND

Image credit: NASA



Symbol	Solar wind	(Upper) Corona	Definition
n_p, n_e	$3\,\mathrm{cm}^{-3}$	$10^6\,\mathrm{cm}^{-3}$	Proton and electron number density
T_p, T_e	$10^5\,\mathrm{K}$	$10^6\,\mathrm{K}$	Proton and electron temperature
B	$3 \times 10^{-5}\,\mathrm{G}$	$1\,\mathrm{G}$	Magnetic field strength

Verscharen, Klein, Maruca 2019

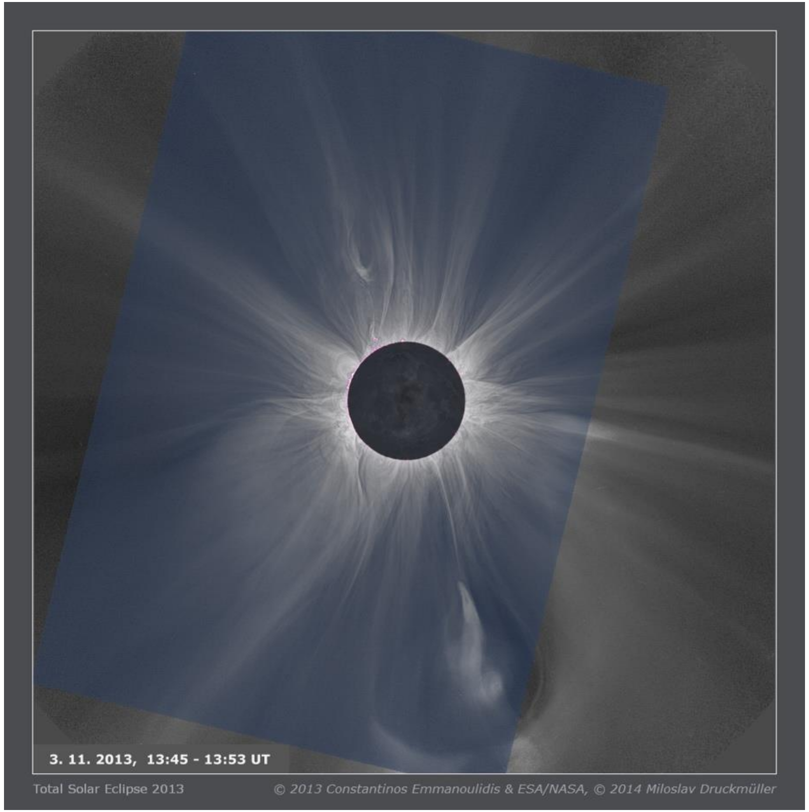


Parker (1958) Proposed by Parker (1958)

Confirmed in 1962 by Neugebauer+

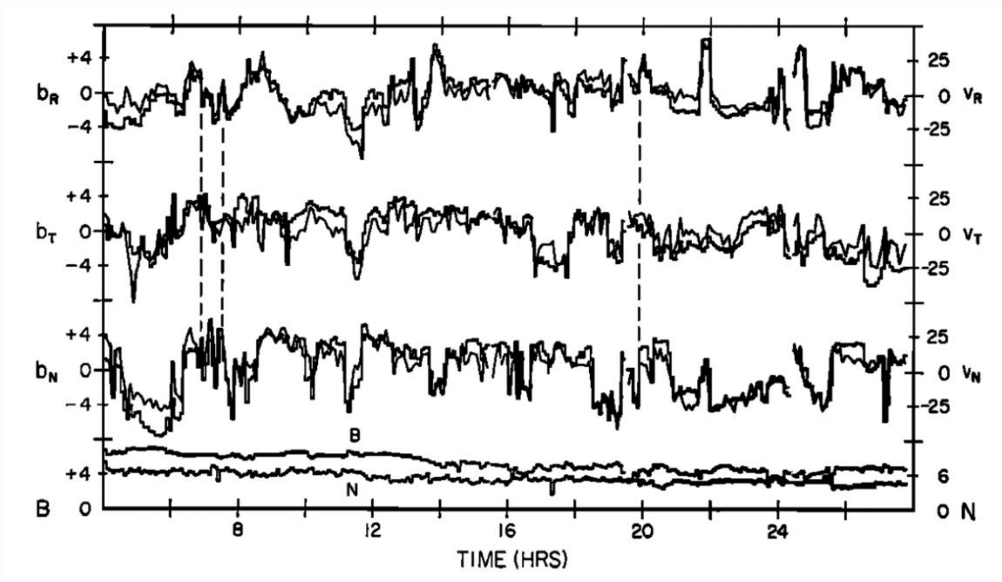
McComas+ 2003

TURBULENCE IN SOLAR WIND

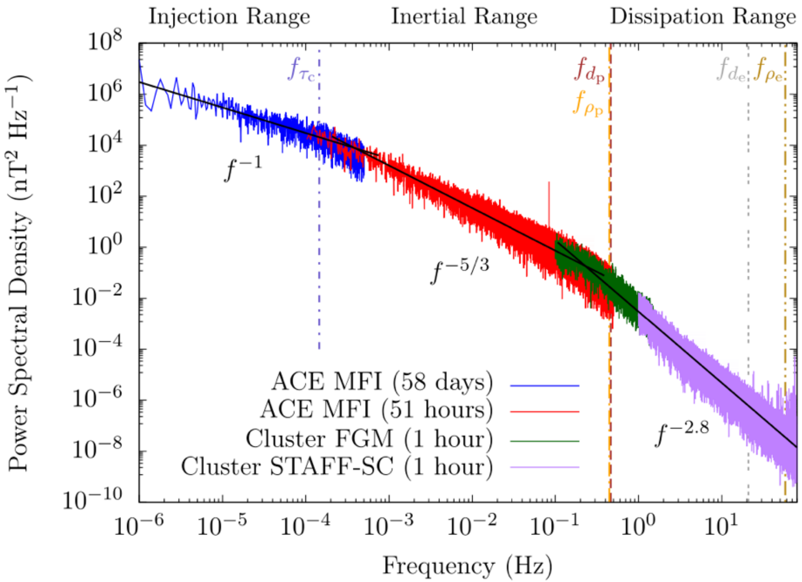


Credit Embry-Riddle Aeronautical University

MULTISCALE NATURE OF SOLAR WIND

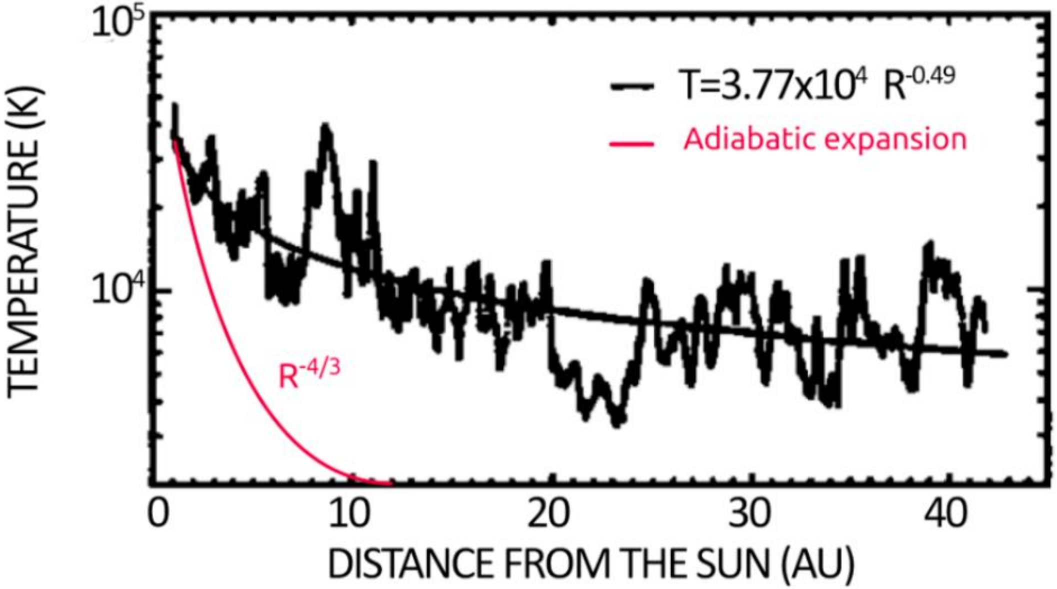


Belcher+ 1971



Verscharen+ 2019

SOLAR WIND HEATING



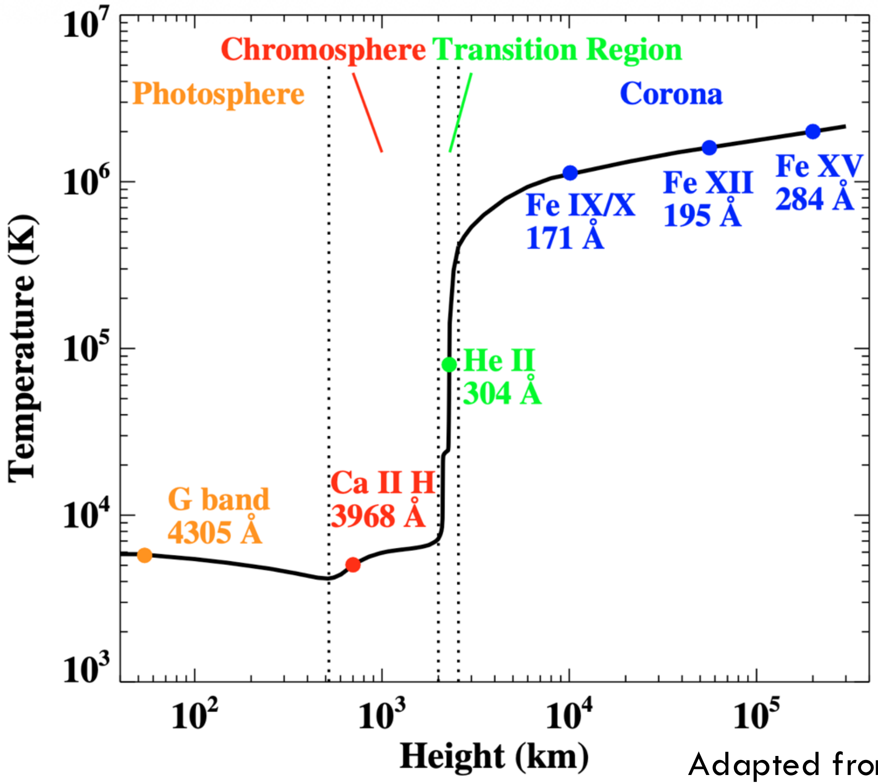
Temperature as a function of the radial distance as Measured by Voyager2.

Red curve: $R^{-4/3}$ spherically symmetric adiabatic expansion.

Black curve: best fit of the data.

Adapted from Richardson *et al.*(1995).

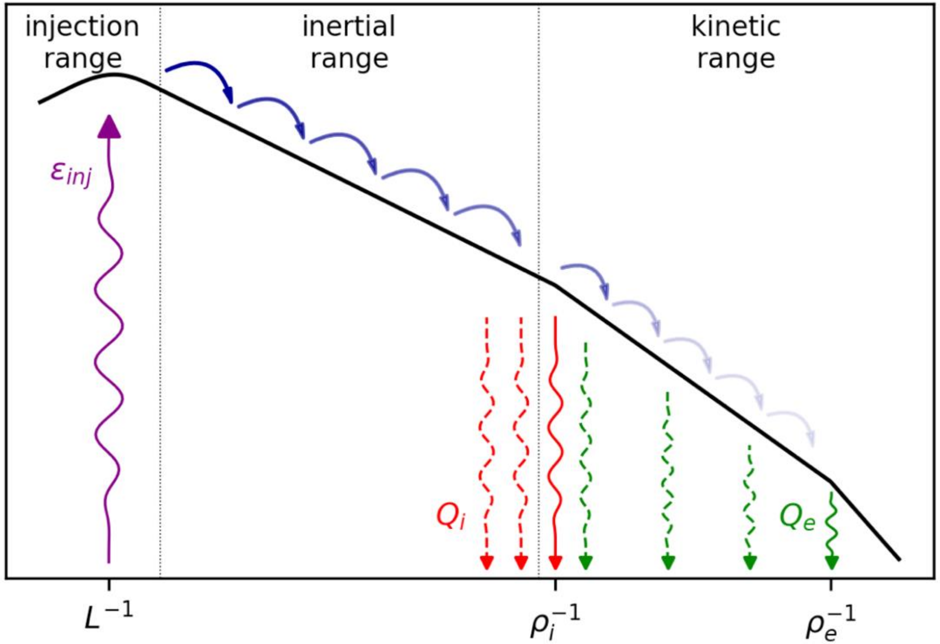
CORONAL HEATING



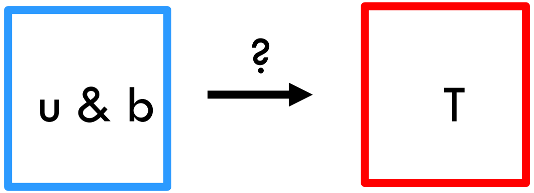
Adapted from Yang *et al.*(2009).

- Order of magnitude increase in temperature in the Transition Region.
- Temperature keeps increasing in lower corona with distance.

HEATING BY TURBULENT CASCADE

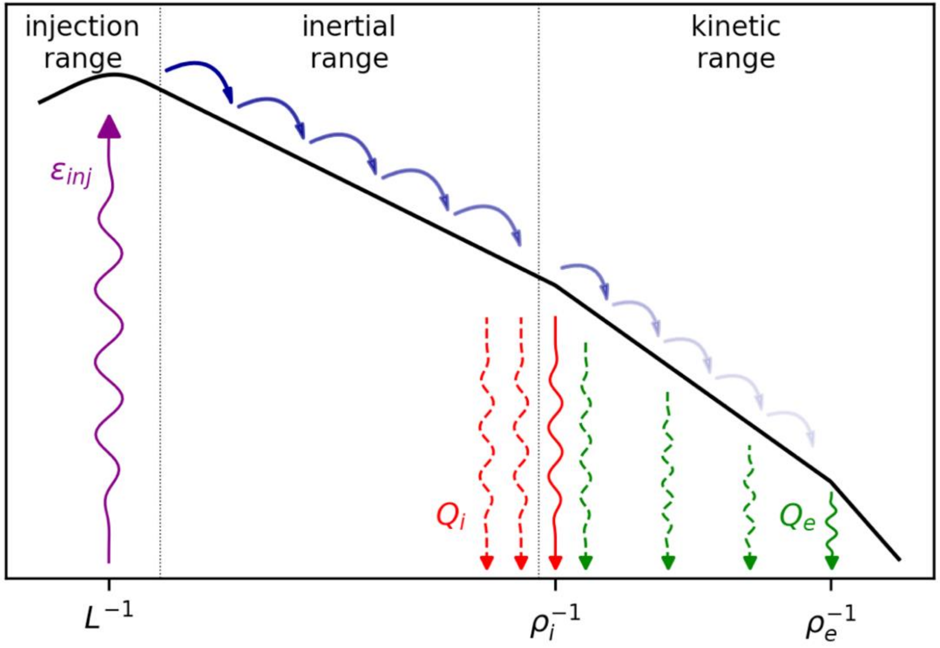


Manzini 2024



How to measure macroscopic energy conversion into “thermal” energy?

HEATING BY TURBULENT CASCADE



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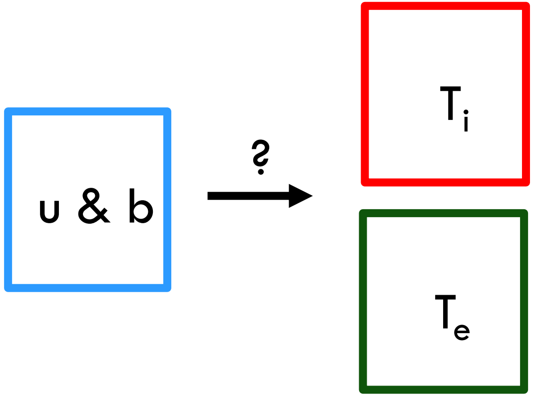
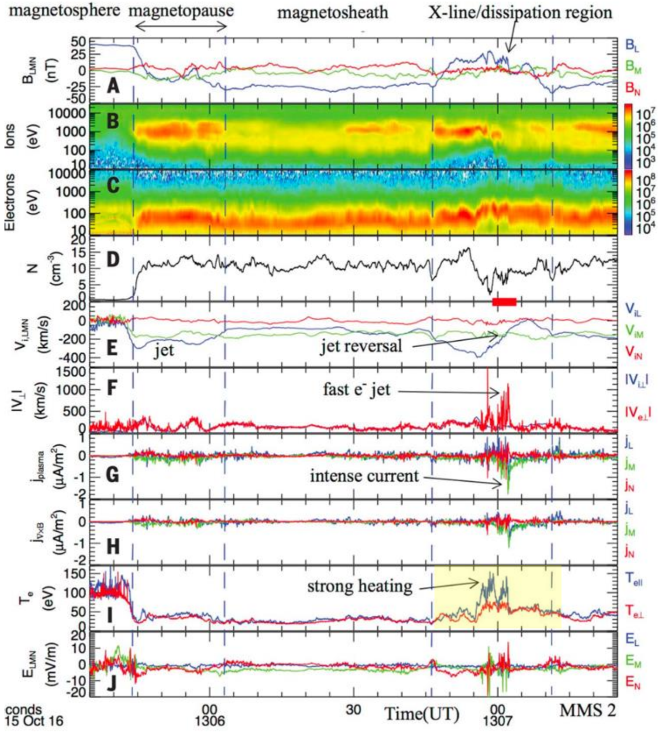
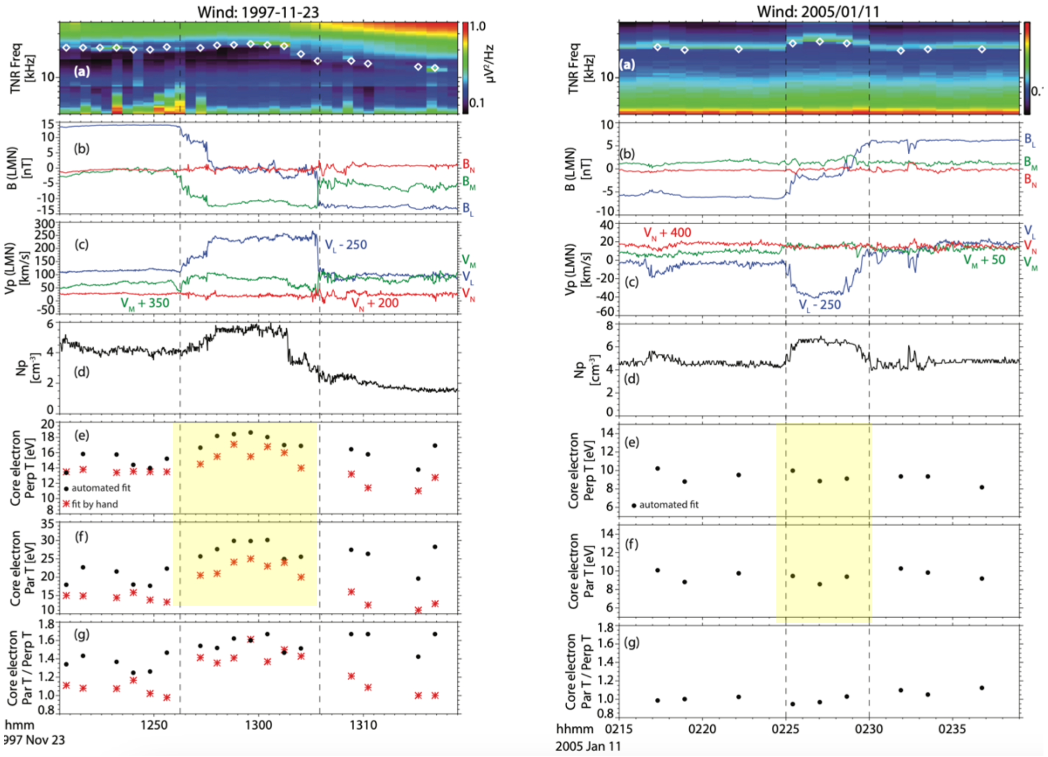


How to measure macroscopic energy conversion into “thermal” energy?

HOW TO MEASURE HEATING?

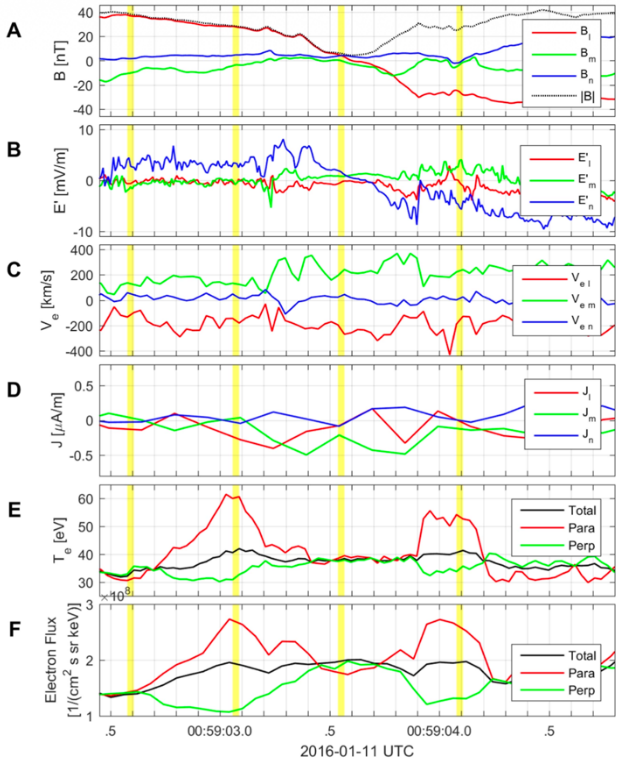


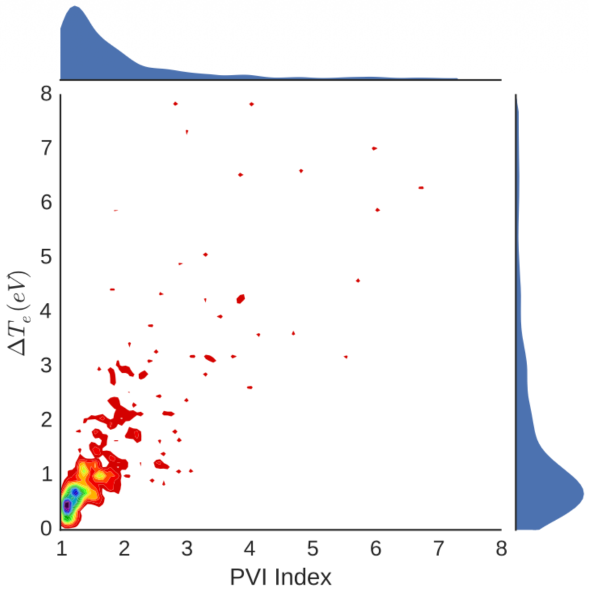
Burch et al. 2016 Science



Pulupa et al. 2014 ApJL

HOW TO MEASURE HEATING?



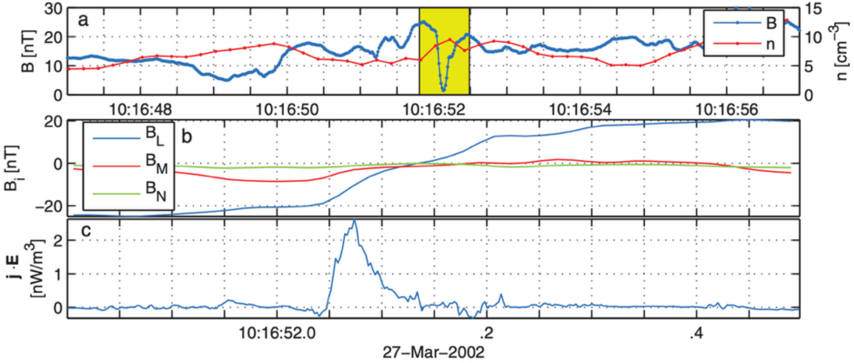


Hot ≠ Heating

Chasapis et al. 2017

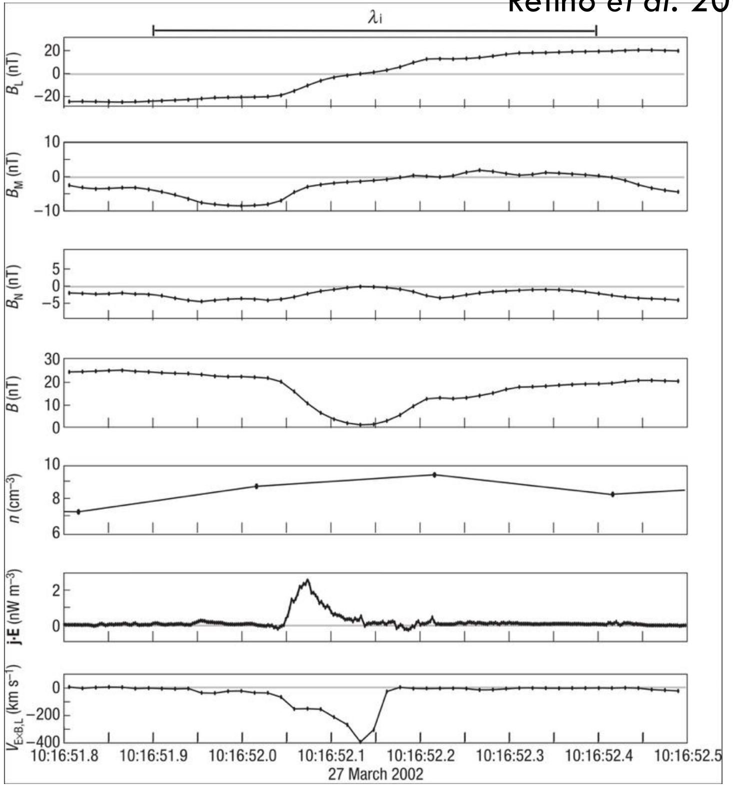
HOW TO MEASURE HEATING?

j.E **?**



Sundkvist *et al.* 2007

Retino *et al.* 2007



However, ***j.E*** only gives partial dissipation

ENERGY EQUATIONS

Consider the full Vlasov-Maxwell equations

Yang *et al.* 2017, see also Cerri 2016

Bulk flow energy	$\partial_t \mathcal{E}_s^f + \nabla \cdot \left(\mathcal{E}_s^f \mathbf{u}_s + \mathbf{P}_s \cdot \mathbf{u}_s \right) = \left(\mathbf{P}_s \cdot \nabla \right) \cdot \mathbf{u}_s + n_s q_s \mathbf{E} \cdot \mathbf{u}_s$
"Thermal" or internal energy	$\partial_t \mathcal{E}_s^{th} + \nabla \cdot \left(\mathcal{E}_s^{th} \mathbf{u}_s + \mathbf{h}_s \right) = -\left(\mathbf{P}_s \cdot \nabla \right) \cdot \mathbf{u}_s$
Electromagnetic energy	$\partial_t \mathcal{E}^m + (c/4\pi) \nabla \cdot (\mathbf{E} \times \mathbf{B}) = -\mathbf{j} \cdot \mathbf{E}$

Which terms in the Eqs can cause *conversion* of energy?

ENERGY EQUATIONS

Averaged over periodic box or infinite domain

Yang *et al.* 2017, see also Cerri 2016

Bulk flow energy	$\partial_t \langle \mathcal{E}_s^f \rangle = \langle (\mathbf{P}_s \cdot \nabla) \cdot \mathbf{u}_s \rangle + \langle n_s q_s \mathbf{E} \cdot \mathbf{u}_s \rangle$
"Thermal" or internal energy	$\partial_t \langle \mathcal{E}_s^{th} \rangle = -\langle (\mathbf{P}_s \cdot \nabla) \cdot \mathbf{u}_s \rangle$
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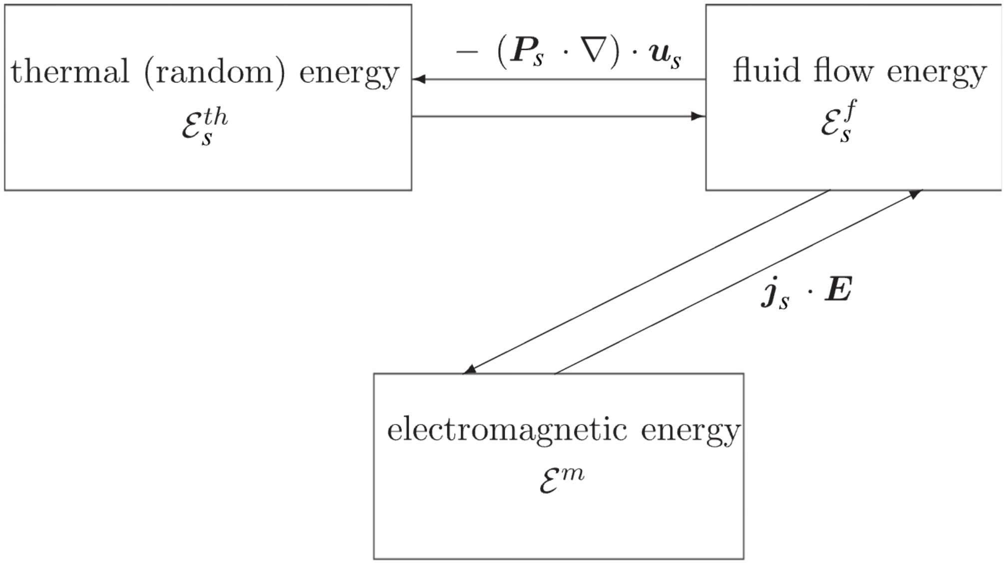
All processes that "heat" the plasma (i.e. increase its thermal energy) must go through (minus) the pressure-strain interaction

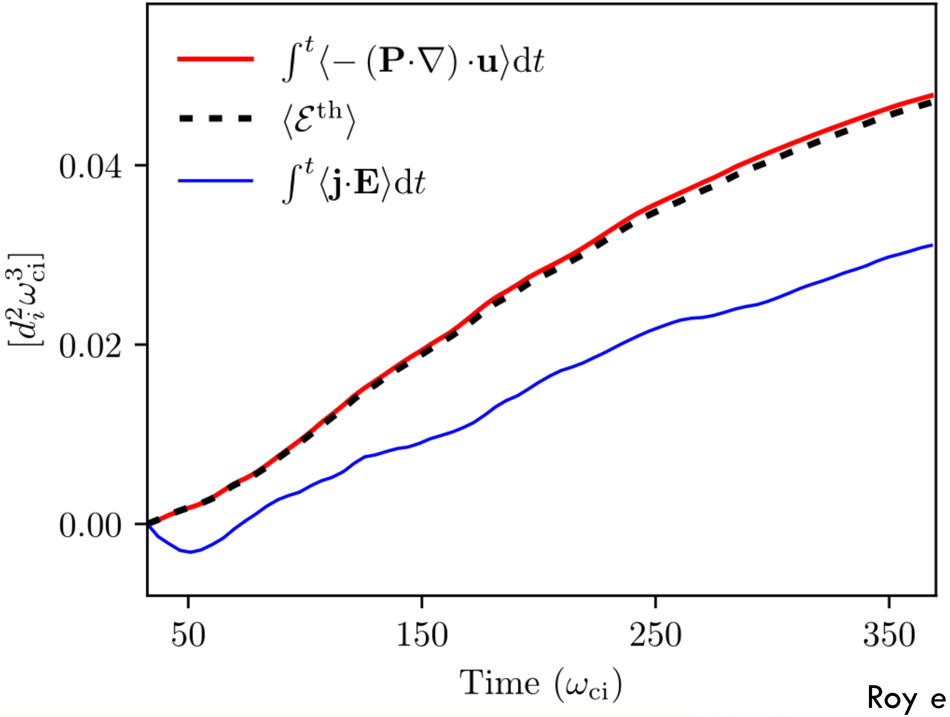
ENERGY CONVERSION CHANNELS



- ***j.E*** converts energy between EM fields and bulk flow but not into thermal energy
- Pressure-strain converts bulk flow into thermal motion
- No direct channel for EM field --> Thermal motion

Yang *et al.* 2017a & b, 2019, Matthaeus *et al.* 2020, 2021 …

PRESSURE-STRAIN AS HEATING



Dim	L	Grid	m_i/m_e	B_0	ppg
2.5D PIC	$149.6d_i$	4096^2	25	1.0	3200

- Volume averaged pressure-strain follows the thermal energy curve
- Integrated ***j.E*** does not

Roy *et al.* 2022, also Pezzi *et al.* 2019, Yang *et al.* 2022

CAVEATS

- Not irreversible heating
  - In MHD dissipation is reversible at the end of cascade
  - Pressure-strain can be $\pm$ at a given point
  - However, large volume/time average → heating (previous slide)
- Ignores energies in higher order moment fluctuations in the VDF
  - Other dissipation measures (see Pezzi *et al.*, 2021, Cassak *et al.*, 2025)
- Ignoring collisions

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Observational Data

However, measurement of PS was not possible before MMS

$$-(\boldsymbol{P} \cdot \boldsymbol{\nabla}) \cdot \boldsymbol{u}$$

$$\mathbf{P} = \begin{pmatrix} P_{xx} & P_{xy} & P_{xz} \\ P_{yx} & P_{yy} & P_{yz} \\ P_{zx} & P_{zy} & P_{zz} \end{pmatrix}$$

Difficult to measure

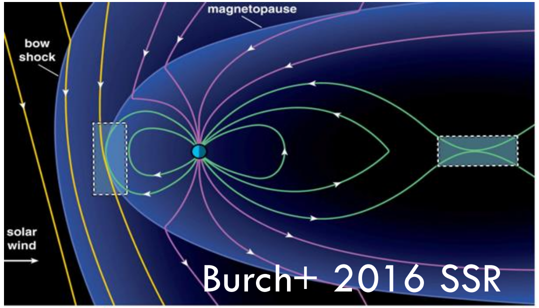
$$\nabla \mathbf{u} = \begin{pmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} & \frac{\partial u_x}{\partial z} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} & \frac{\partial u_y}{\partial z} \\ \frac{\partial u_z}{\partial x} & \frac{\partial u_z}{\partial y} & \frac{\partial u_z}{\partial z} \end{pmatrix}$$

Only possible in multi-s/c

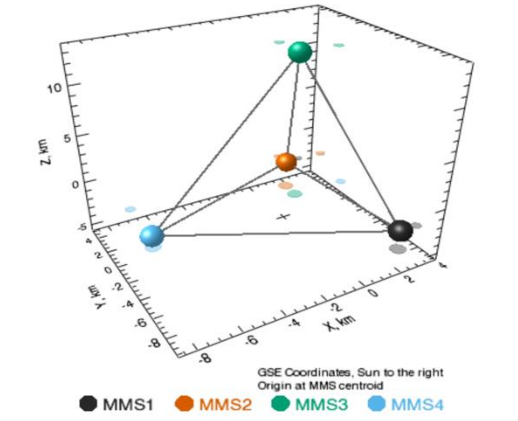
Difficult in simulations too

MANGETOSPHERIC MULTISCALE MISSION

Source: MMS SDC



Burch+ 2016 SSR



- 4 spacecraft in tetrahedron
- Very high cadence measurement
- Using a generalized curlometer technique it is possible to evaluate pressure-strain down to kinetic scale (Alexandros Chasapis talk)

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COMPONENT DECOMPOSITION

- Pressure-strain distinguishes compressive and incompressive contributions
- Also possible to decompose ion and electron contributions

$$-(\boldsymbol{P} \cdot \nabla) \cdot \boldsymbol{u} = -p\theta - \Pi_{ij} D_{ij}$$

$$p = \frac{1}{3} P_{ii} \quad \theta = \nabla \cdot \boldsymbol{u}$$

$$\Pi_{ij} = P_{ij} - p\delta_{ij}$$

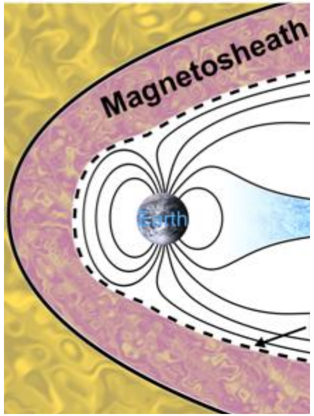
$$D_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i) - \frac{1}{3}\theta\delta_{ij}$$

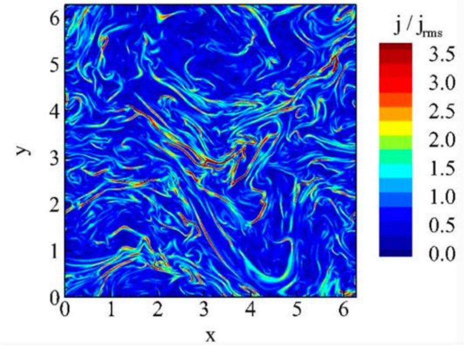
"pθ"
Pressure dilatation: isotropically

"Pi-D"
Strong collisions: $-\Pi_{ij} D_{ij} \sim \mu\, D_{ij} D_{ij}$

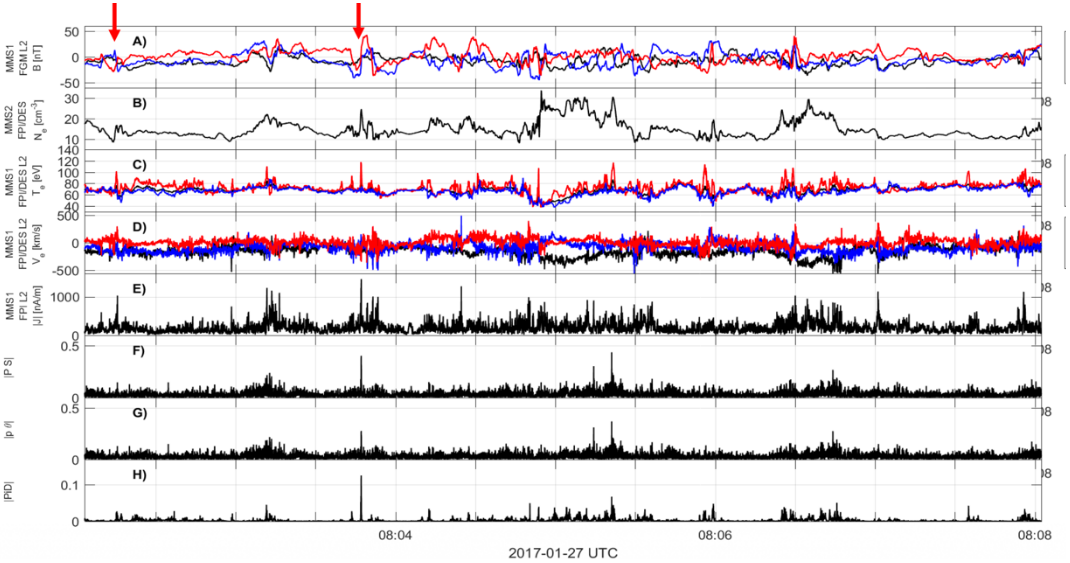
PRESSURE-STRAIN IN MMS

- First report of pressure-strain in observational data (MMS)
- Ion-scale current sheets in magnetosheath





Yang *et al.* 2016



Chasapis *et al.* 2018

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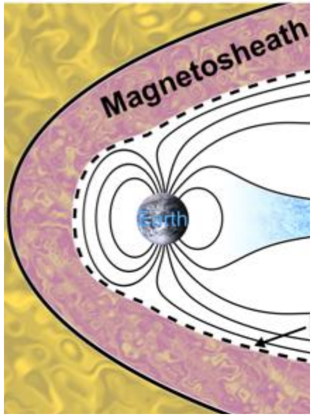
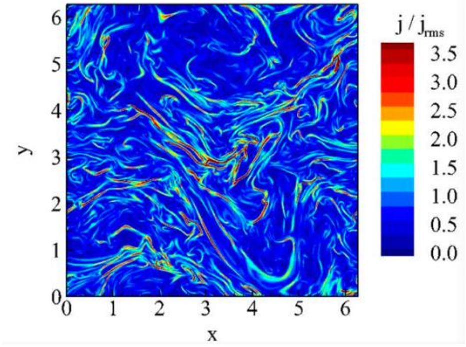
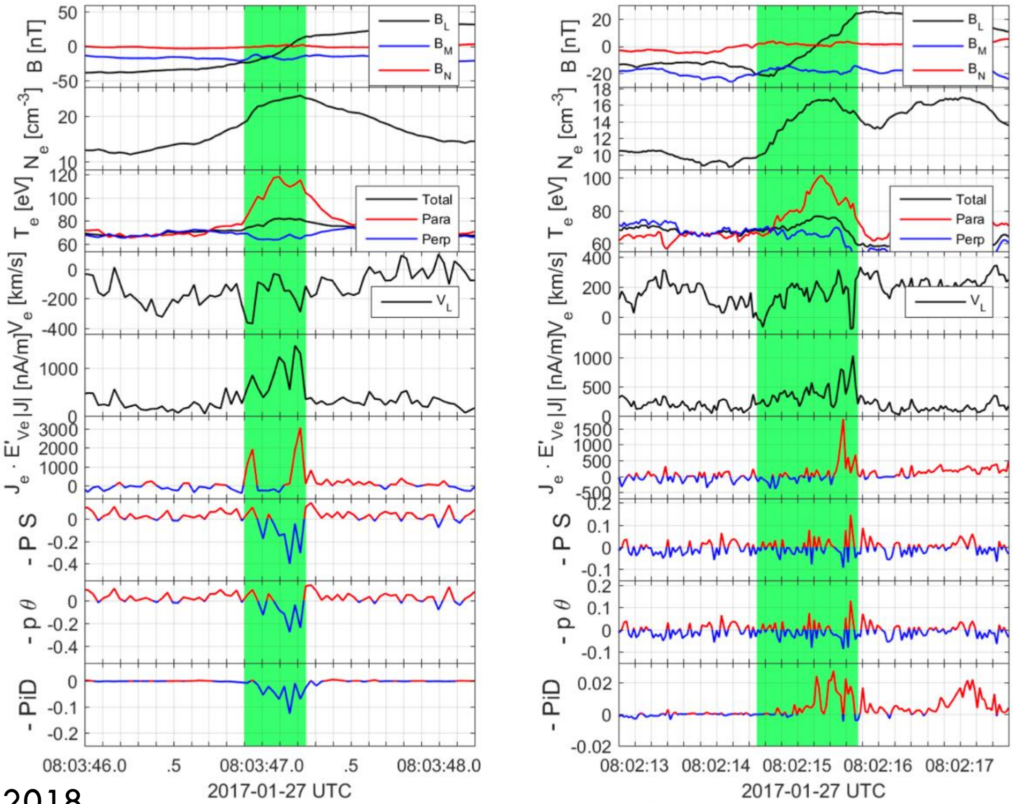




Yang *et al.* 2016

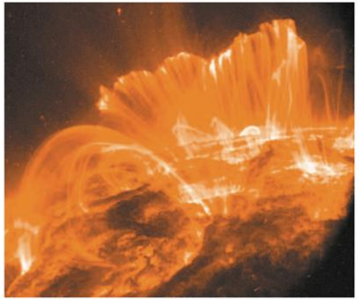


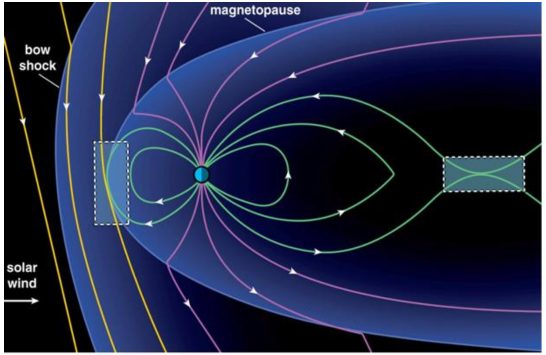
Chasapis *et al.* 2018

MAGNETIC RECONNECTION

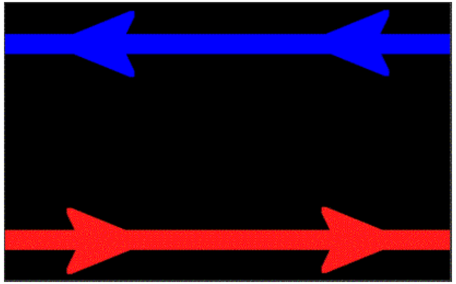
Reconnection

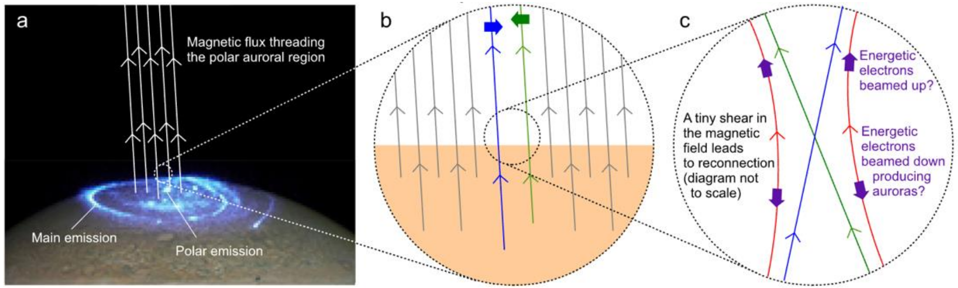
- Topological change of magnetic field lines
- Rapid conversion of energy





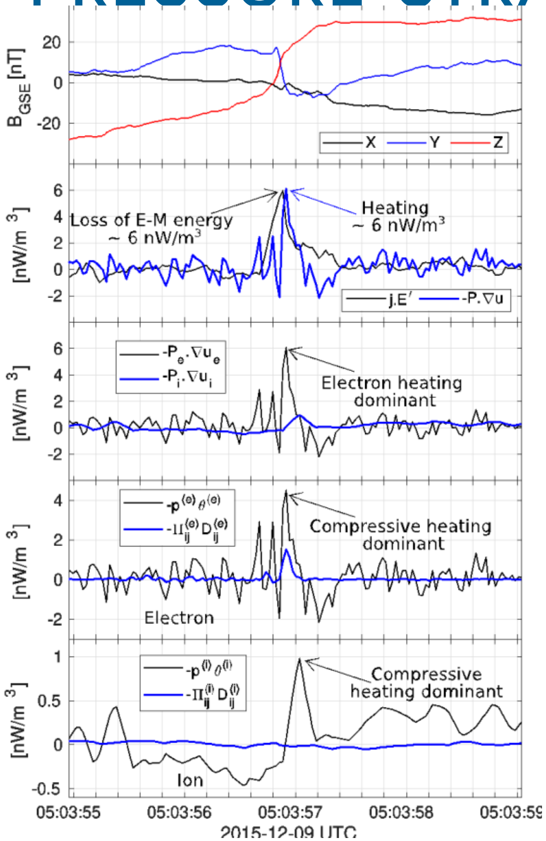
Burch+ 2016 SSR





Masters+ 2021 JGR

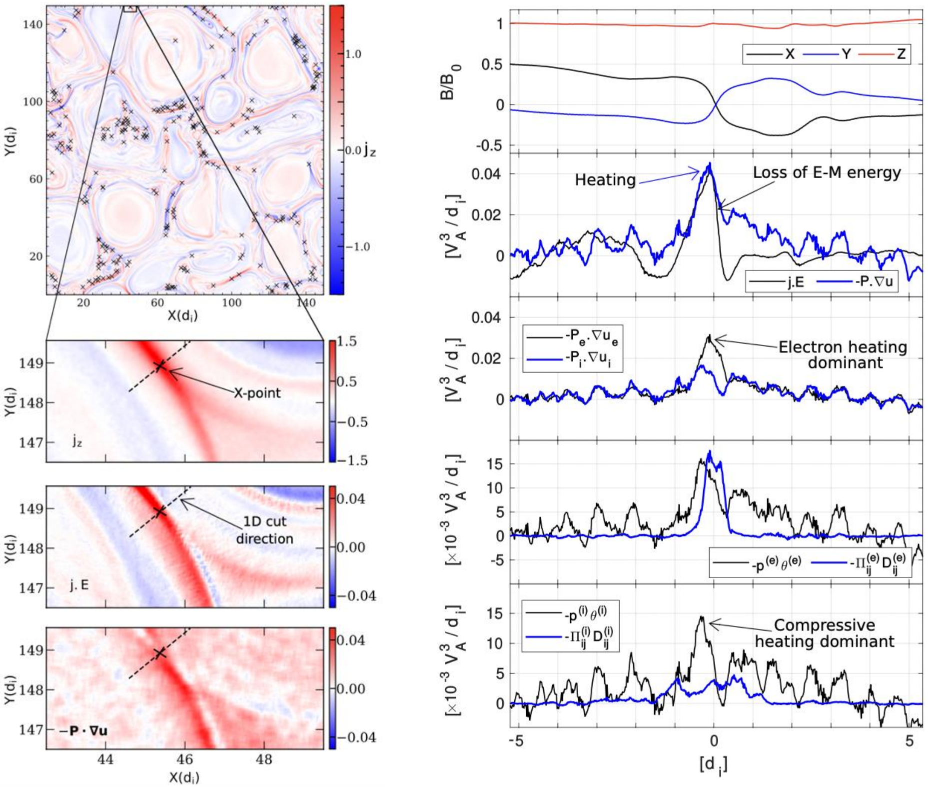
PRESSURE-STRAIN IN RECONNECTION



- Strong dissipation at X-line (in addition to ***j.E***)
- Electron heating > Ion heating
- Compressive heating > Incompressive heating (both ions and electrons)

Bandyopadhyay *et al.* 2021

PRESSURE-STRAIN IN RECONNECTION



Bandyopadhyay *et al.* 2021

- Strong dissipation at X-line (in addition to ***j.E***)
- Electron heating > Ion heating
- Compressive heating > Incompressive heating
- Consistent with MMS

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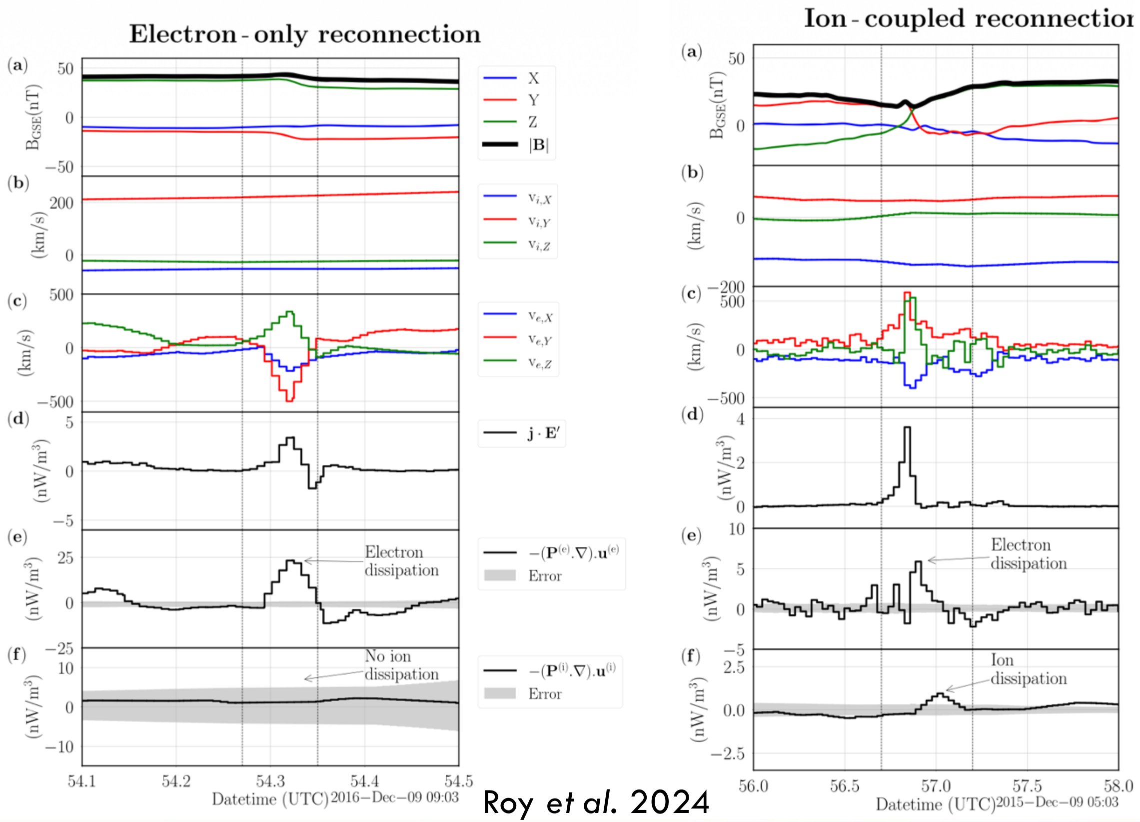
ELECTRON-ONLY RECONNECTION



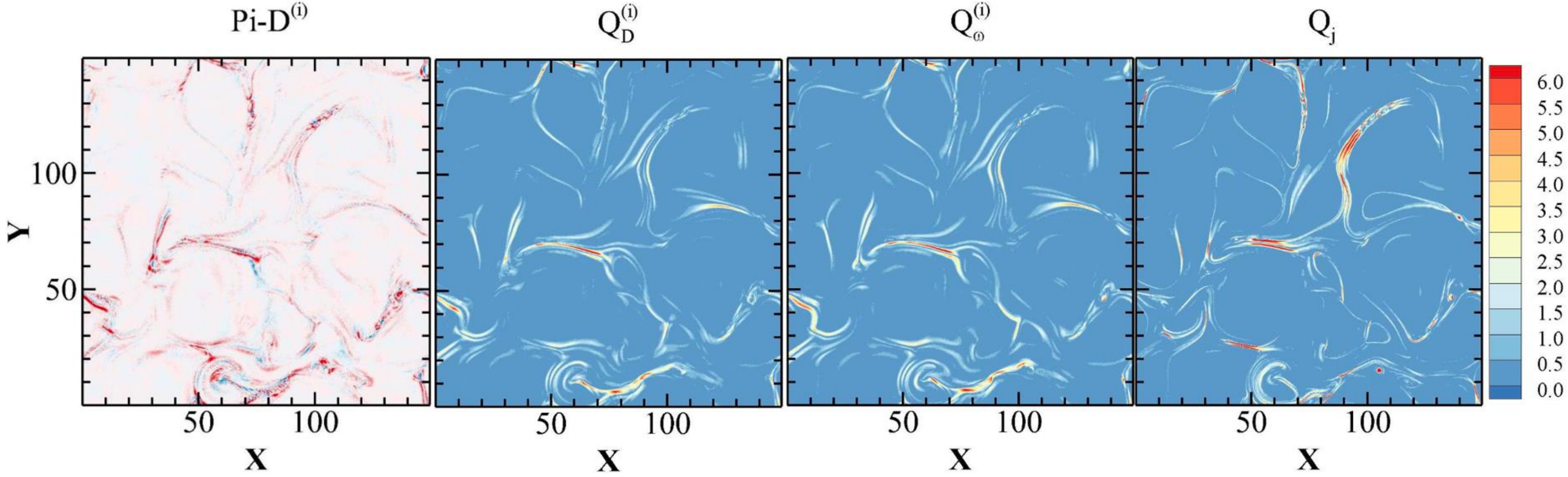
Roy *et al.* 2024

No ion dissipation at electron-only reconnection

RELATION WITH COHERENT STRUCTURES

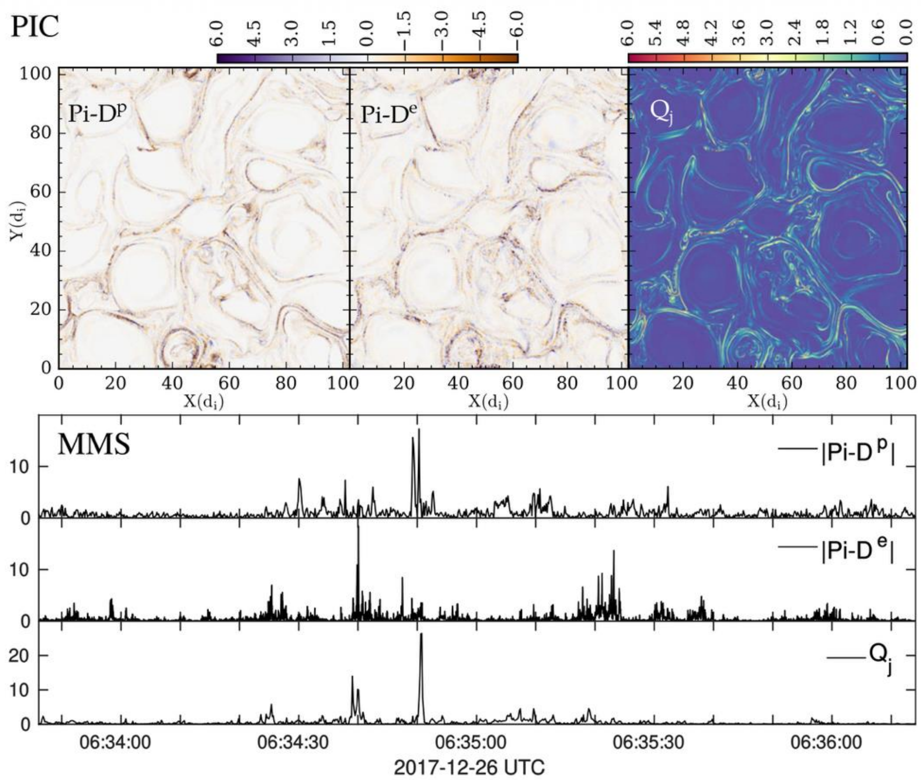
Turbulent systems generate small-scale coherent structures, e.g., current sheets

$$Q_D = D_{ij}D_{ij}/\langle D_{ij}D_{ij}\rangle; \quad Q_\omega = \omega^2/\langle\omega^2\rangle; \quad Q_j = j^2/\langle j^2\rangle.$$



Yang, Springer, 2019

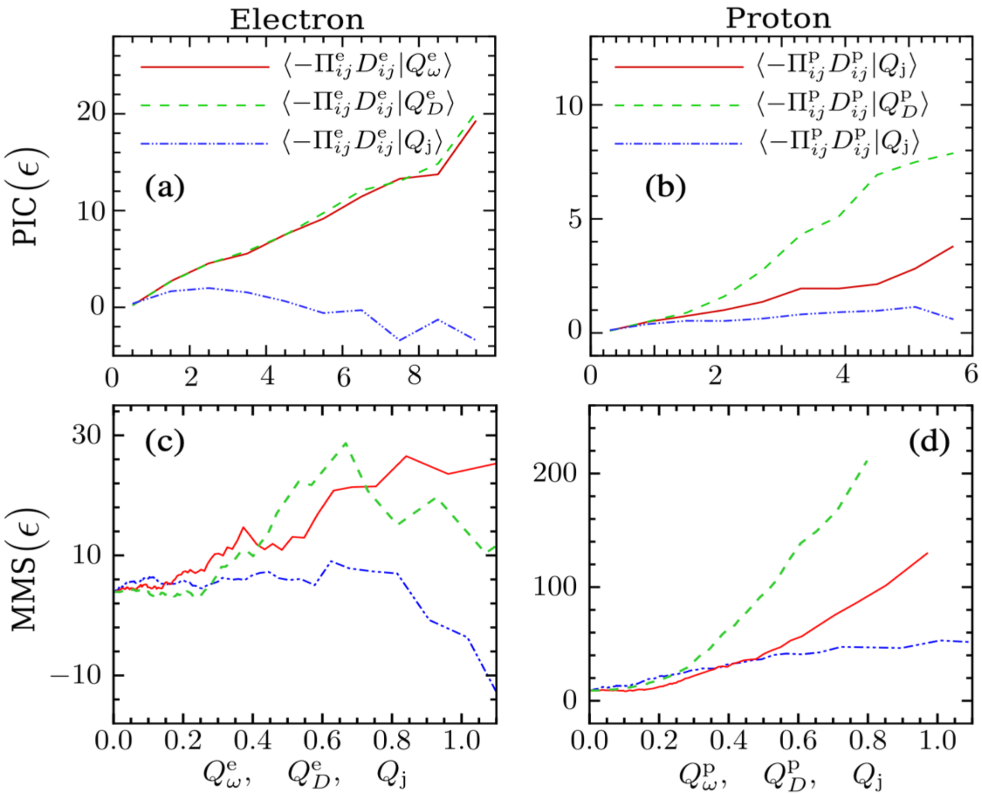
RELATION WITH COHERENT STRUCTURES



- Strong dissipation (pressure-strain) signals near current sheets
- But which one is most closely related?

Bandyopadhyay *et al.* 2020

RELATION WITH COHERENT STRUCTURES



- Dissipation (both ion & electron) occurs closest to strain rate
- Near current sheet, not at them

Bandyopadhyay *et al.* 2020

SUMMARY

- Role of pressure-strain in energy dissipation

- Accurate measurement of pressure-strain is possible with MMS data

- MMS investigations
  - Dissipation at current sheets
  - Dissipation at reconnection X-line
  - Electron-only reconnection
  - Relation with coherent structures

OPEN ISSUES

- Accurate determination of pressure-strain in solar wind (and other parts of the magnetosphere).
- Pressure-strain for heavy ions?
- Parallel versus perpendicular heating.
- How does cascade affect energetic particle acceleration?
- Energy dissipation in higher order fluctuations in VDF.
- Entropy in collisionless plasmas.

Thank you

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