Magnetospheric MultiScale Measurements of Energy Balance in Collisionless Plasma

Souhail Dahani[1], B. Lavraud[1,2], V. Génot[1], S. Toledo-Redondo[3], R. Kieokaew[1], N. Fargette[4], D. Gershman[5], B. Giles[5], R. Torbert[6], J. Burch[7]

[1] IRAP, CNRS, UPS, CNES, Toulouse, France
[2] LAB, CNRS, UB, CNES, Bordeaux, France
[3] Department of Electromagnetism, UM, Murcia Spain
[4] The Blackett laboratory, Imperial College London, London, UK
[5] NASA GSFC, MD, USA
[6] SCC, University of New Hampshire, NH, USA
[7] SwRI, TX, USA

PNST (Programme National Soleil Terre)
Colloque scientifique 08-12 Janvier 2024

sdahani@irap.omp.eu

Outline

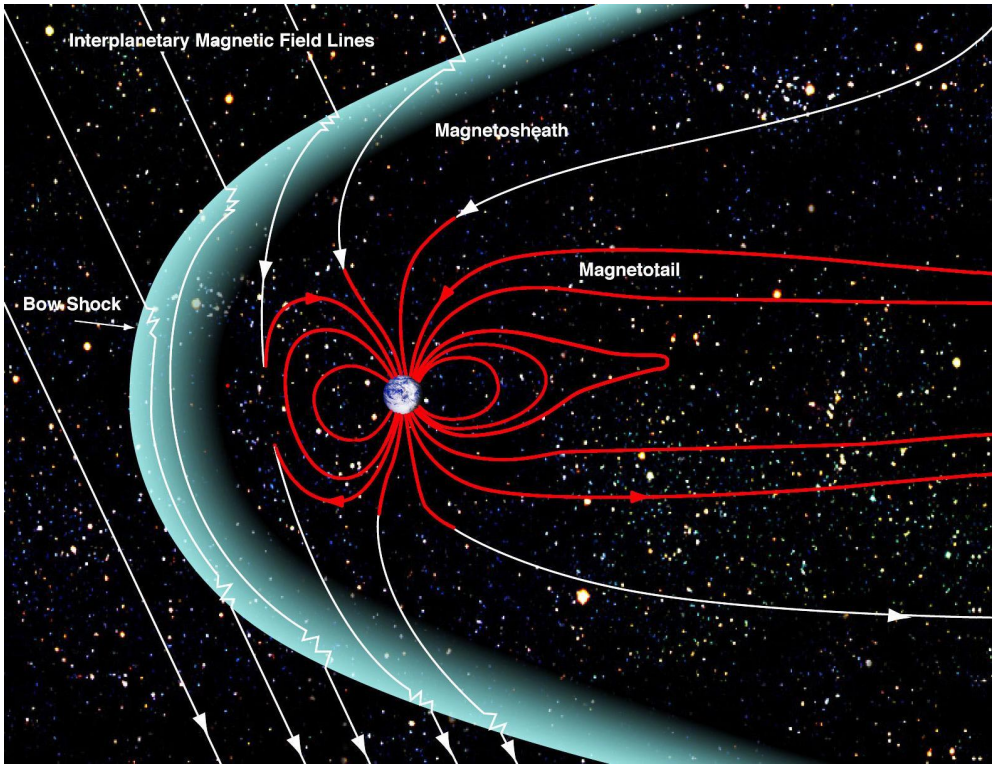
General context and data

Energy conversion and motivation

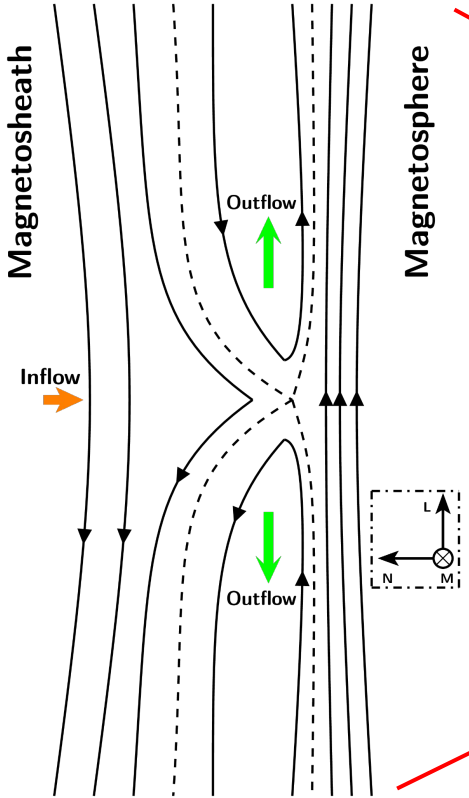
Results and discussion

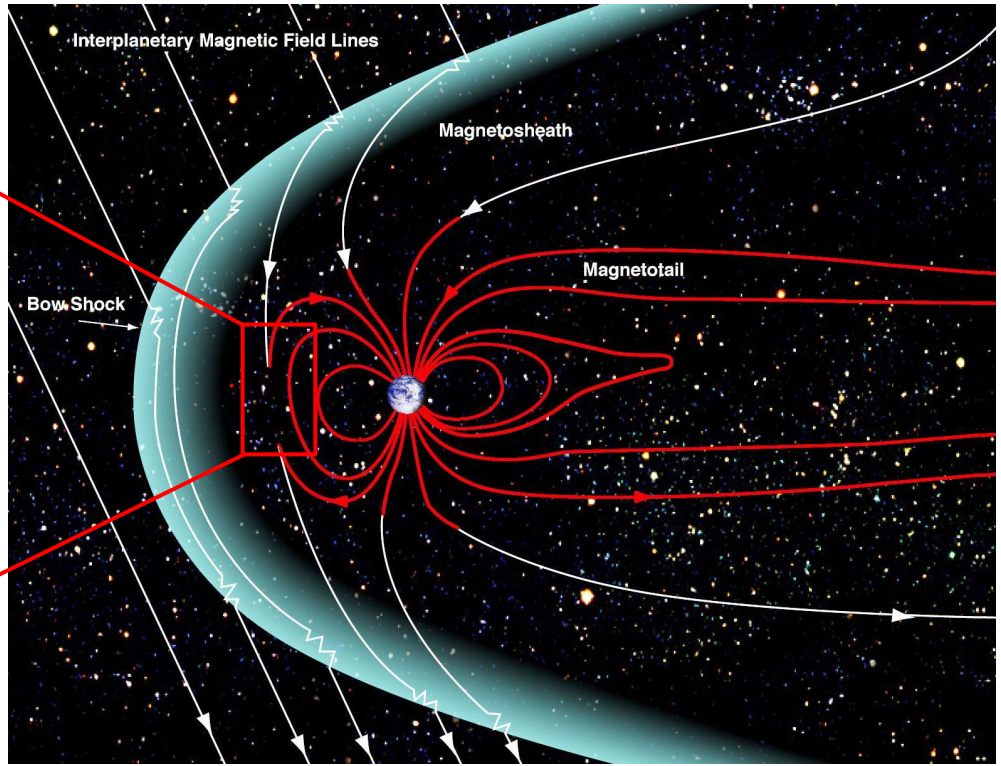
Conclusions

The near Earth environment

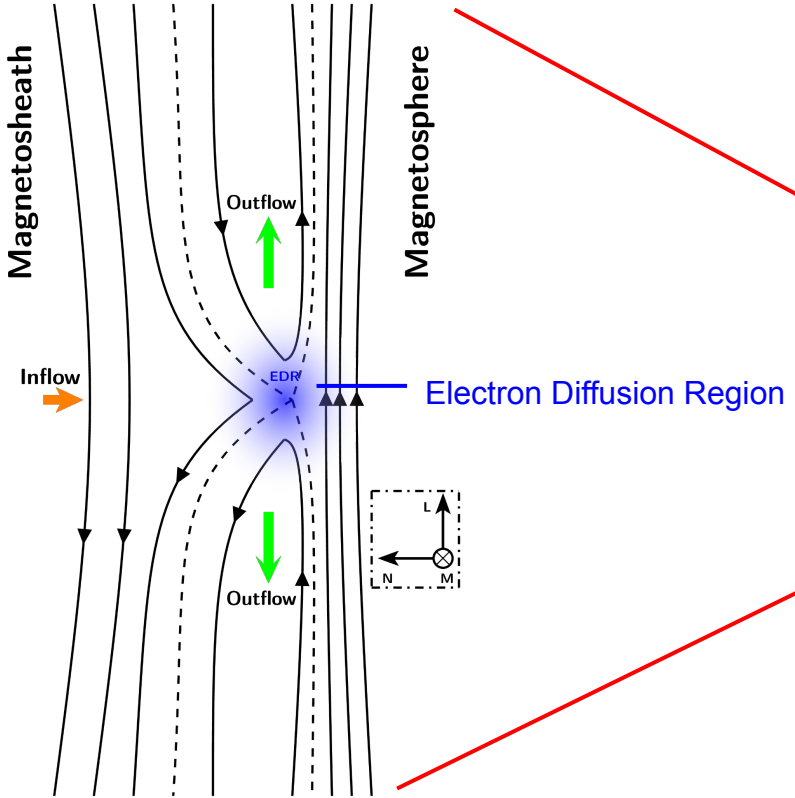


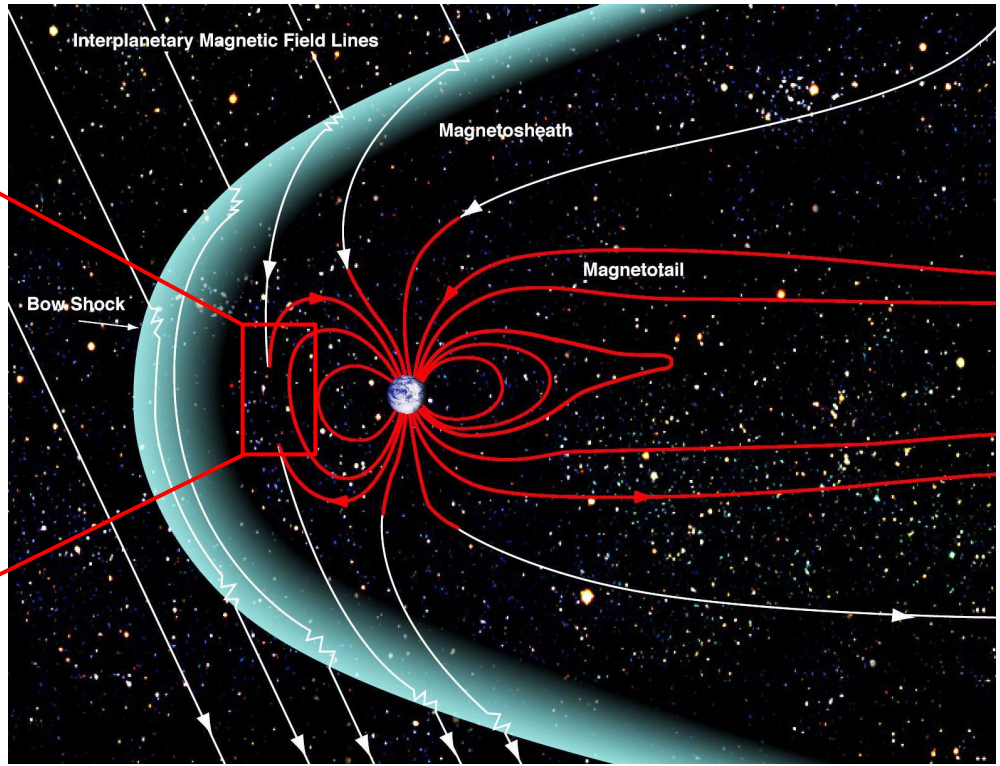
The near Earth environment



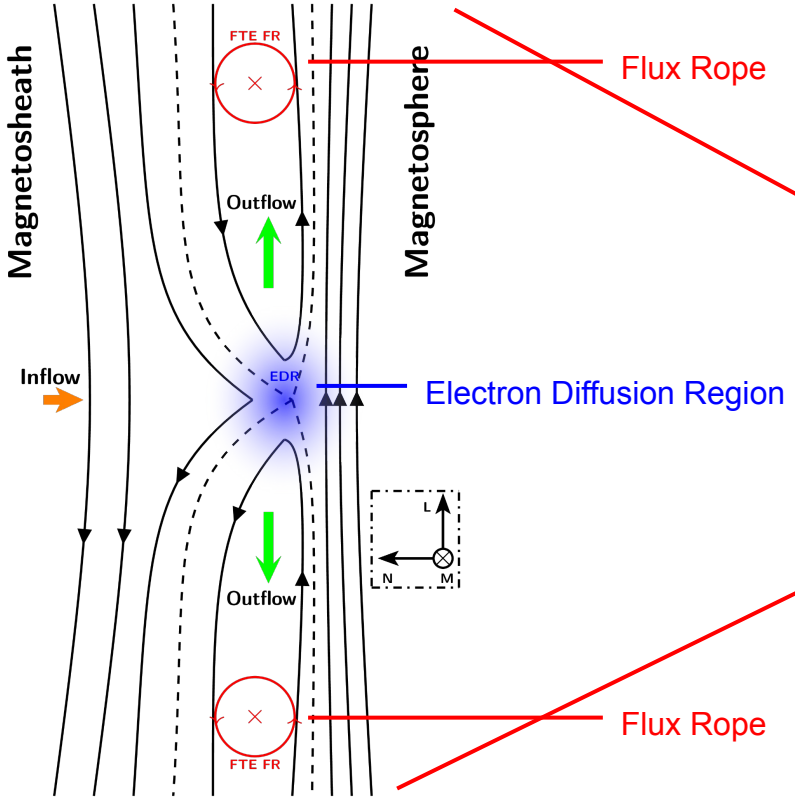


The near Earth environment





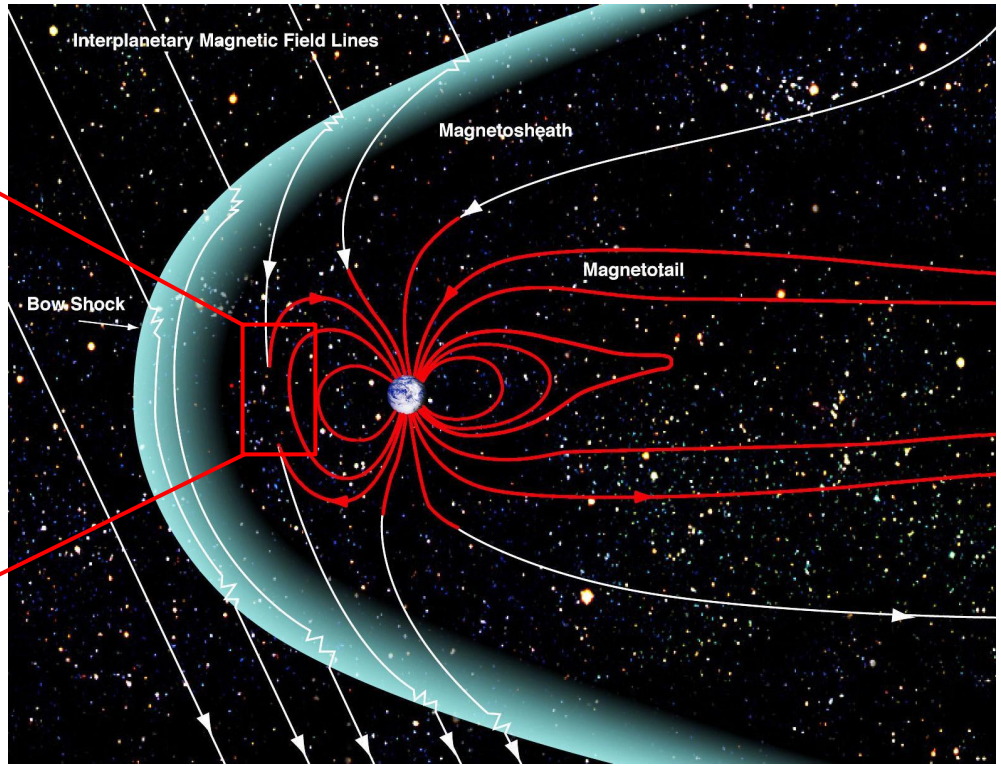
The near Earth environment



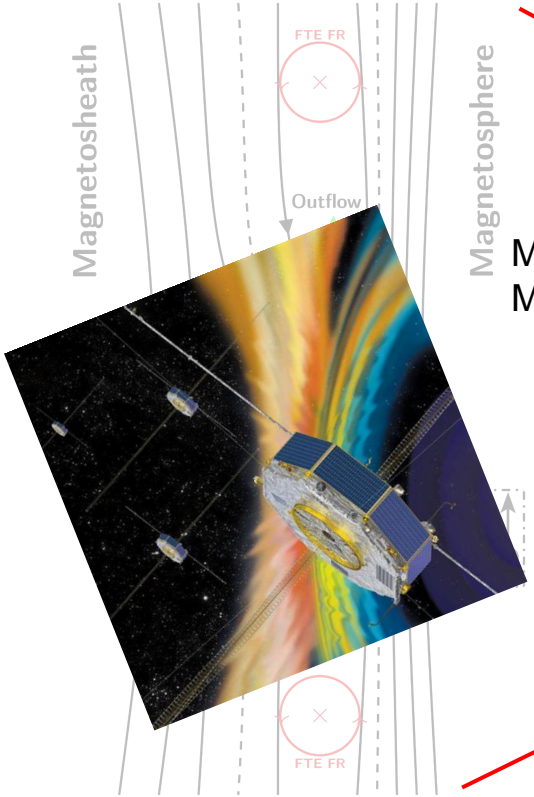
Flux Rope

Electron Diffusion Region

Flux Rope

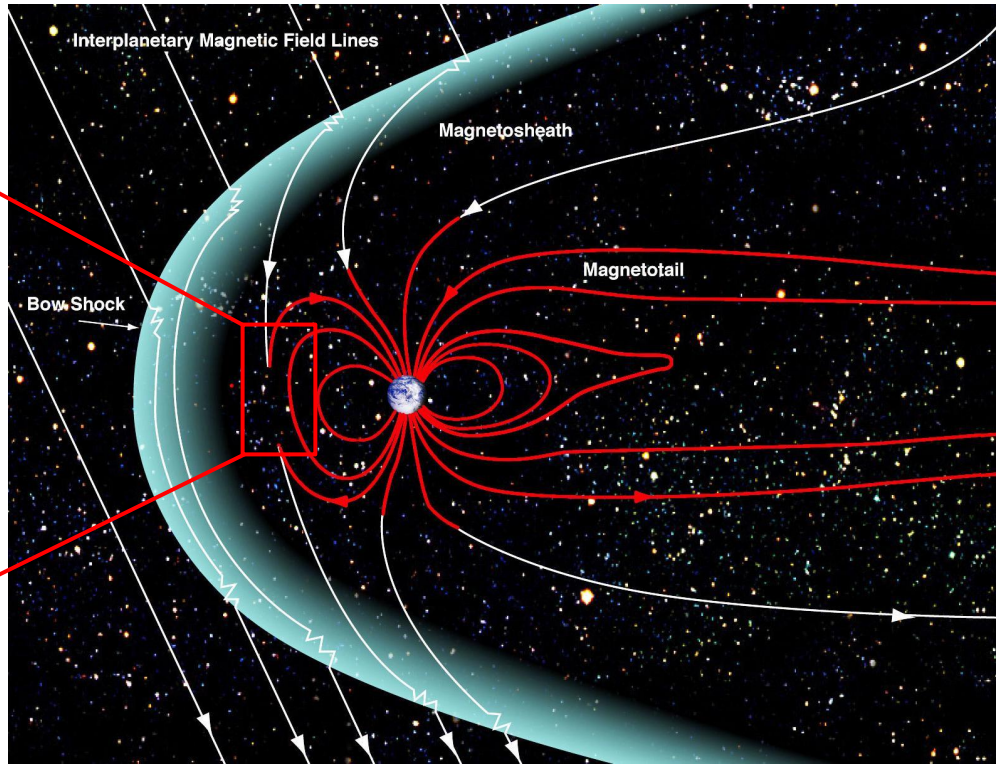


Probing near Earth environment



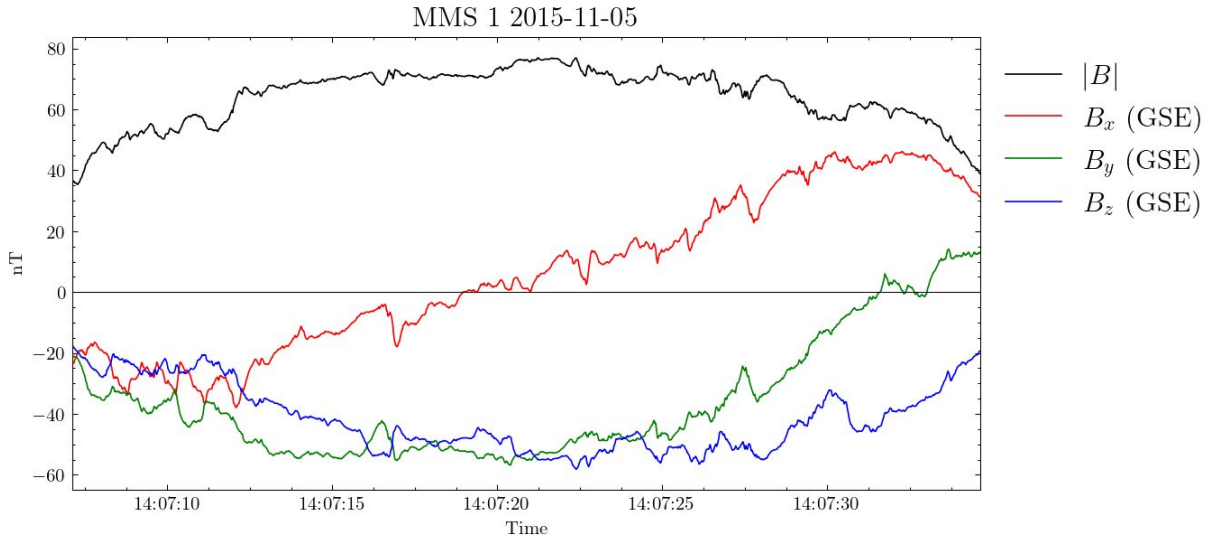
Magnetospheric MultiScale (MMS):

- High resolution
- Multi-point



Data: Flux Transfer Events (FTEs)

Ion scale events

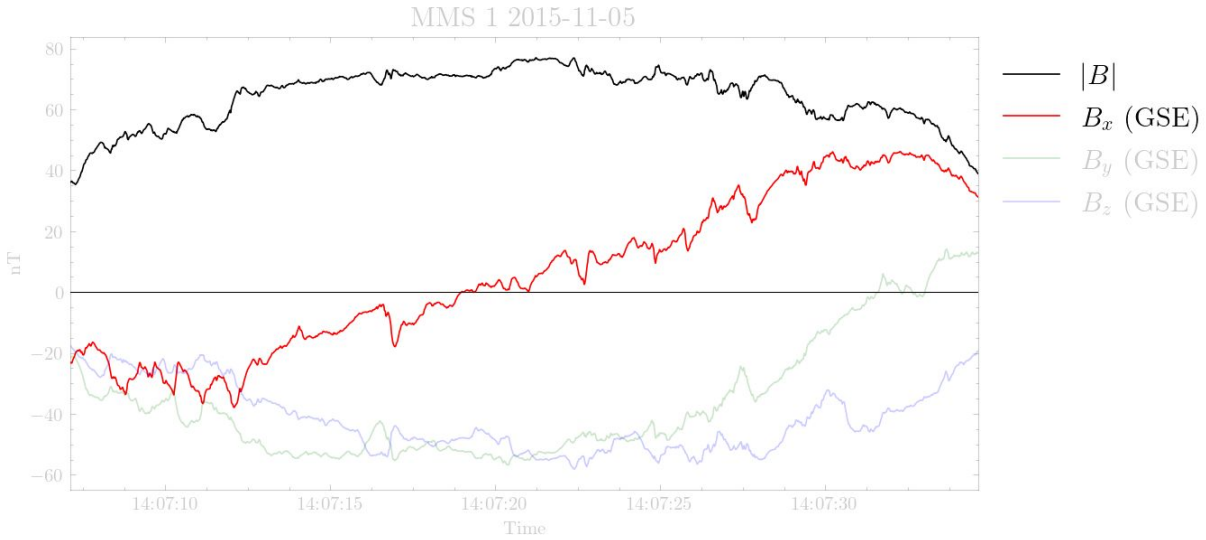


Sublist by Fargette+2019, Kieokaew+2021

Data: Flux Transfer Events (FTEs)

Ion scale events

- Bipolar variation in the normal component
- Enhancement in the total field



Sublist by Fargette+2019, Kieokaew+2021

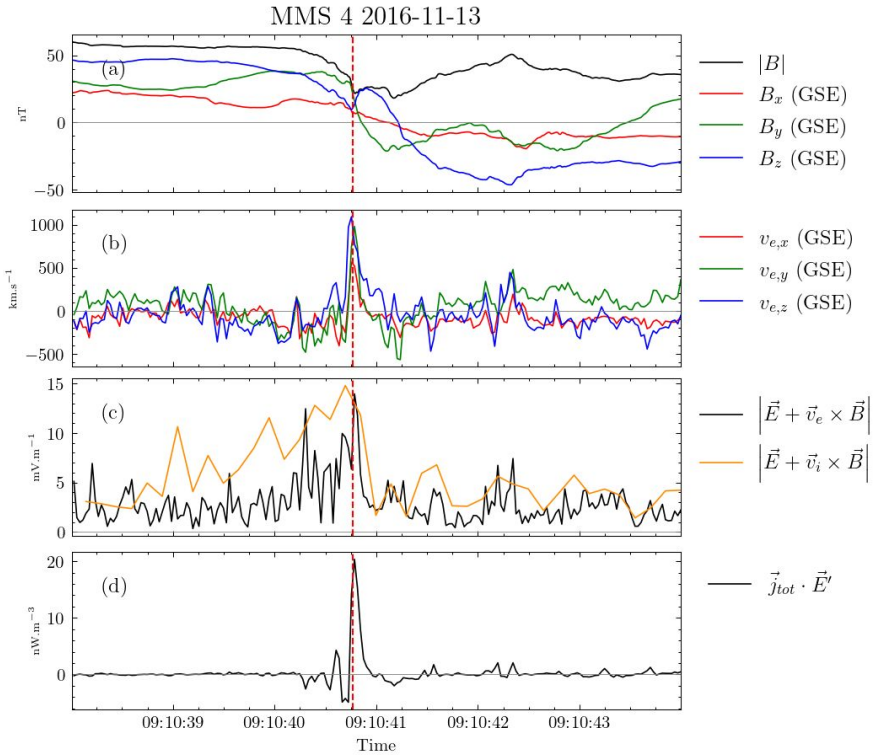
Data: Electron Diffusion Regions (EDRs)

Electron scale events

Electron velocity jet

Electron and ion demagnetization

Energy conversion: EM→kinetic



Lists by Webster+2018, Lenouvel+2021, Lenouvel 2022

Outline

General context and data

Energy conversion and motivation

Results and discussion

Conclusions

Energy equation

In a multifluid description:

Fadanelli+2020

$$d_t K_s = (\partial_t + \vec{v}_s \cdot \vec{\nabla}) K_s = -K_s \vec{\nabla} \cdot \vec{v}_s - \vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s + \vec{j}_s \cdot \vec{E}$$

Kinetic energy: $K_s = \frac{1}{2} m_s n_s \vec{v}_s^2$

Current density: $\vec{j}_s = q_s n_s \vec{v}_s$

Species:	s
Pressure tensor:	$\bar{\bar{P}}_s$
Velocity vector:	$\vec{v}_s$
Elementary charge:	q_s
Density number:	n_s
Electric field vector:	$\vec{E}$
Mass:	m_s

Energy equation

In a multifluid description:

Fadanelli+2020

$$d_t K_s = (\partial_t + \vec{v}_s \cdot \vec{\nabla}) K_s = -K_s \vec{\nabla} \cdot \vec{v}_s - \vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s + \vec{j}_s \cdot \vec{E}$$

Kinetic energy: $K_s = \frac{1}{2} m_s n_s \vec{v}_s^2$

Current density: $\vec{j}_s = q_s n_s \vec{v}_s$

Species:	s
Pressure tensor:	$\bar{\bar{P}}_s$
Velocity vector:	$\vec{v}_s$
Elementary charge:	q_s
Density number:	n_s
Electric field vector:	$\vec{E}$
Mass:	m_s

Energy balance

$$\partial_t K_s + \vec{\nabla} \cdot (K_s \vec{v}_s) = -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s + \vec{j}_s \cdot \vec{E}$$

$$\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s = \vec{j}_s \cdot \vec{E}$$

Energy balance

$$\partial_t K_s + \vec{\nabla} \cdot (K_s \vec{v}_s) = -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s + \vec{j}_s \cdot \vec{E}$$

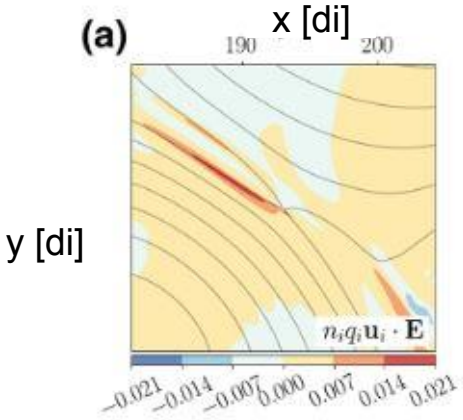
$$\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s = \vec{j}_s \cdot \vec{E}$$

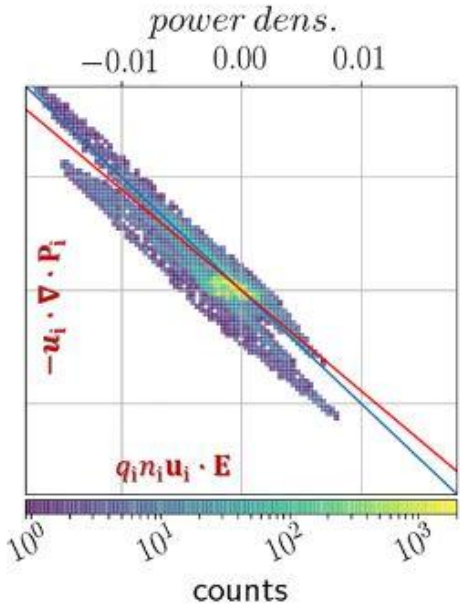
$$\vec{\nabla} \cdot \bar{\bar{P}}_{tot} = \vec{J}_{tot} \times \vec{B}$$

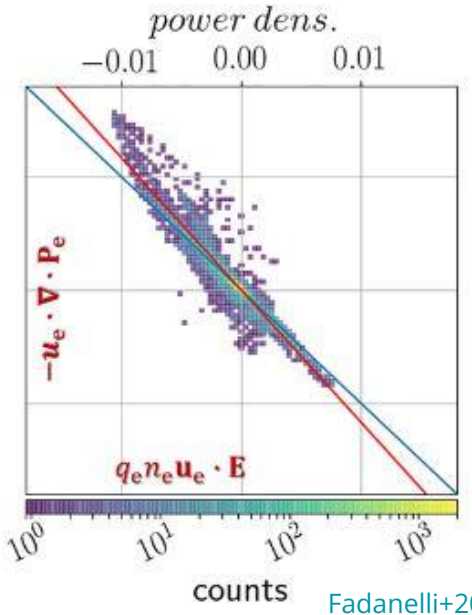
Motivation

Reconnection site in turbulent plasma using hybrid Vlasov-Maxwell code (Fadanelli+2020)

$$\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s = \vec{j}_s \cdot \vec{E}$$







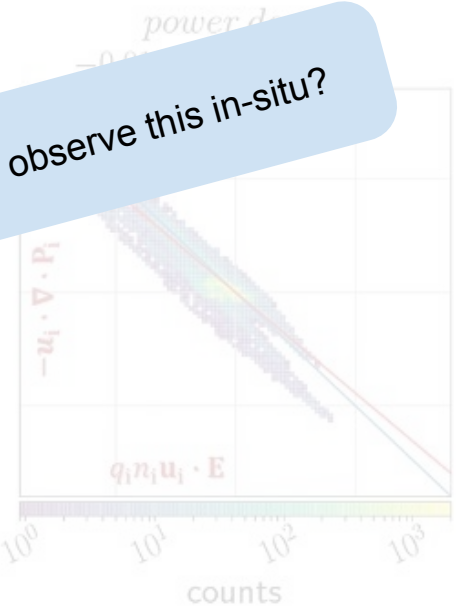
Fadanelli+2020

Motivation

Reconnection site in turbulent plasma using hybrid Vlasov-Maxwell code (Fadanelli+2020)

$$\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s = \vec{j}_s \cdot \vec{E}$$

Do we observe this in-situ?



Fadanelli+2020

Outline

General context and data

Energy conversion and motivation

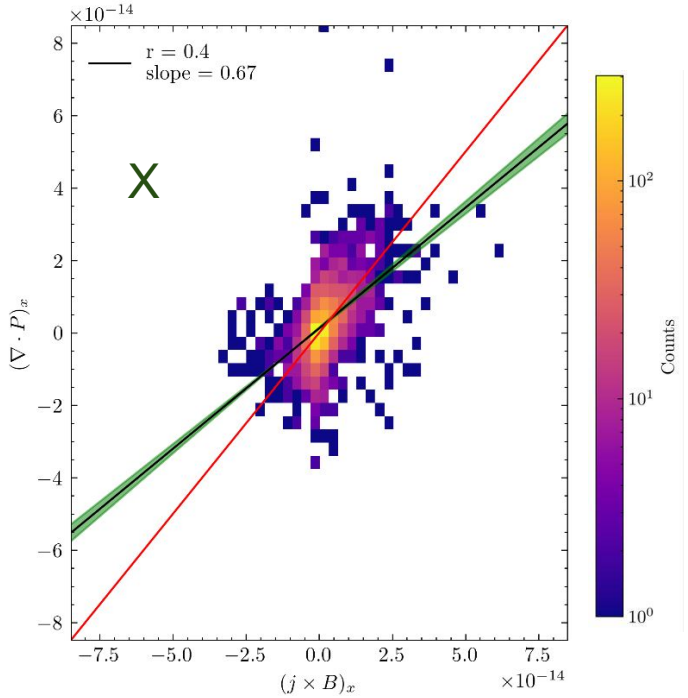
Results and discussion

Conclusions

Force balance: mono-fluid case

- The expected relationship in the force and mono fluid version is promising
- Similar representation for energy terms is less clear

$$\vec{J}_{tot} \times \vec{B} \quad \text{vs} \quad \vec{\nabla} \cdot \bar{\bar{P}}_{tot}$$

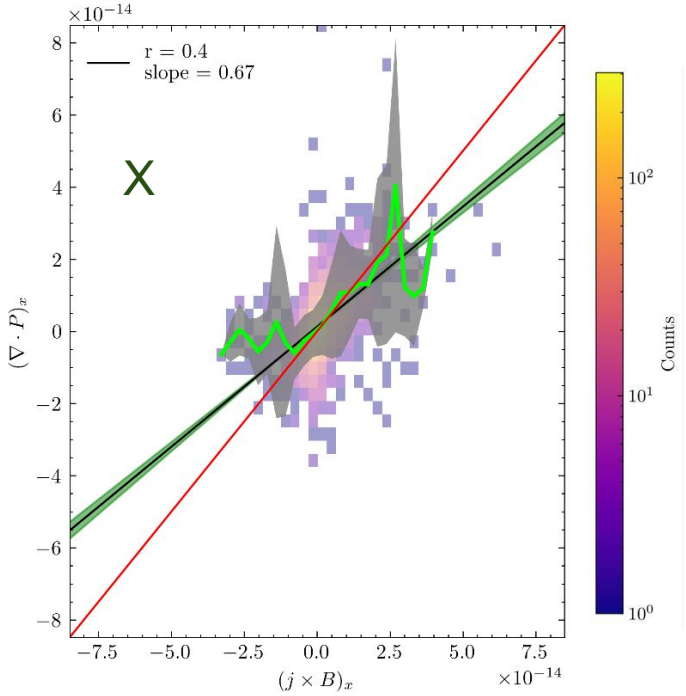


Force balance: mono-fluid case

- The expected relationship in the force and mono fluid version is promising
- Similar representation for energy terms is less clear

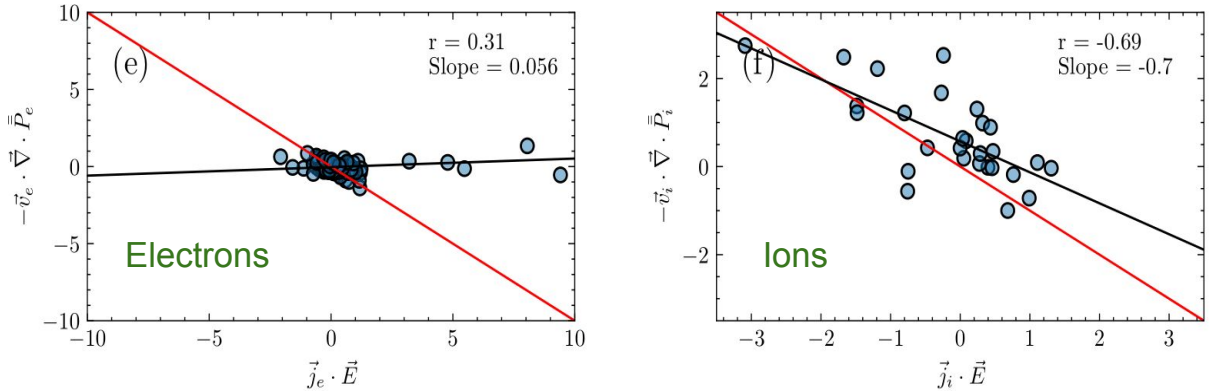
The addition of binned means supports linear regression results

$$\vec{J}_{tot} \times \vec{B} \quad \text{vs} \quad \vec{\nabla} \cdot \bar{\bar{P}}_{tot}$$



Case study

$\vec{j}_s \cdot \vec{E}$ vs $-\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$

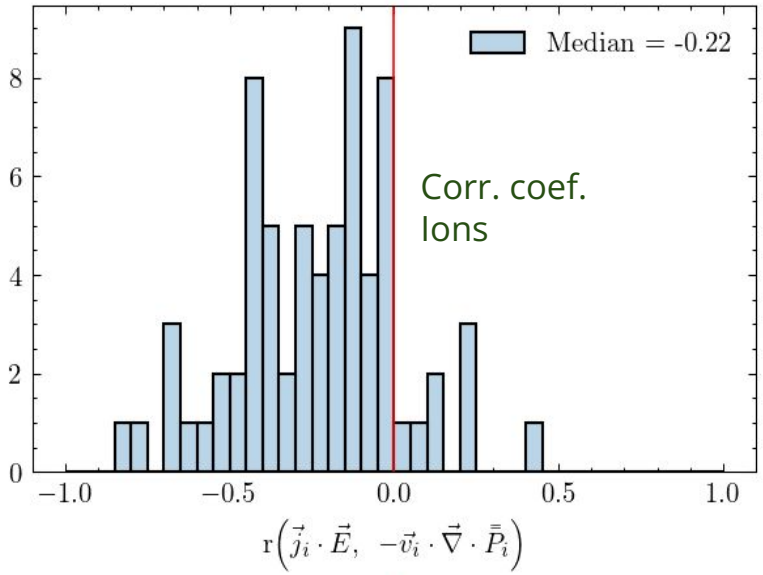


The expected relationship is approximately found for ion measurements but not for electrons

Statistical study

$\vec{j}_s \cdot \vec{E}$ vs $-\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$

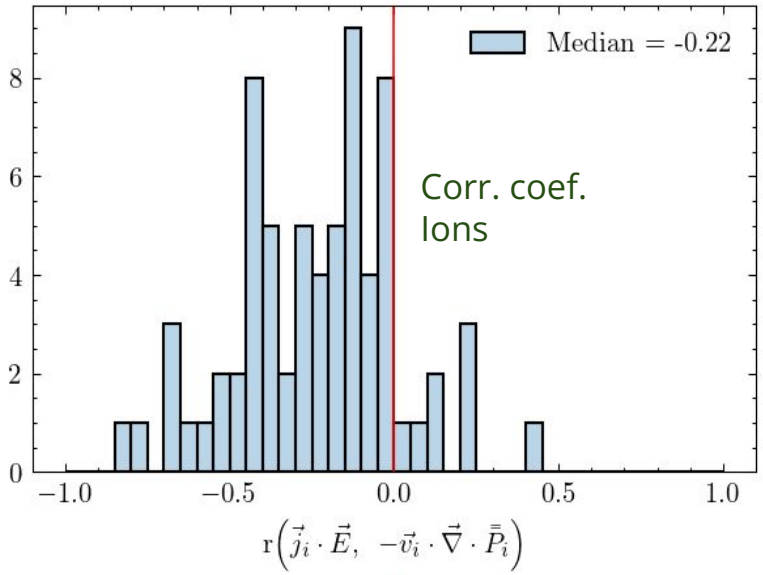
- The linear relationship between the two terms is overall negative for ions
- This relationship is not found for electrons despite the slight negative tendency in r



Statistical study

$$\vec{j}_s \cdot \vec{E} \quad \text{vs} \quad -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$$

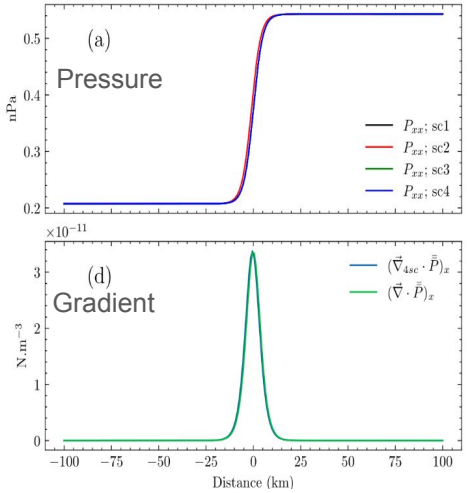
- The linear relationship between the two terms is overall negative for ions
- This relationship is not found for electrons despite the slight negative tendency in r



What can be improved ?

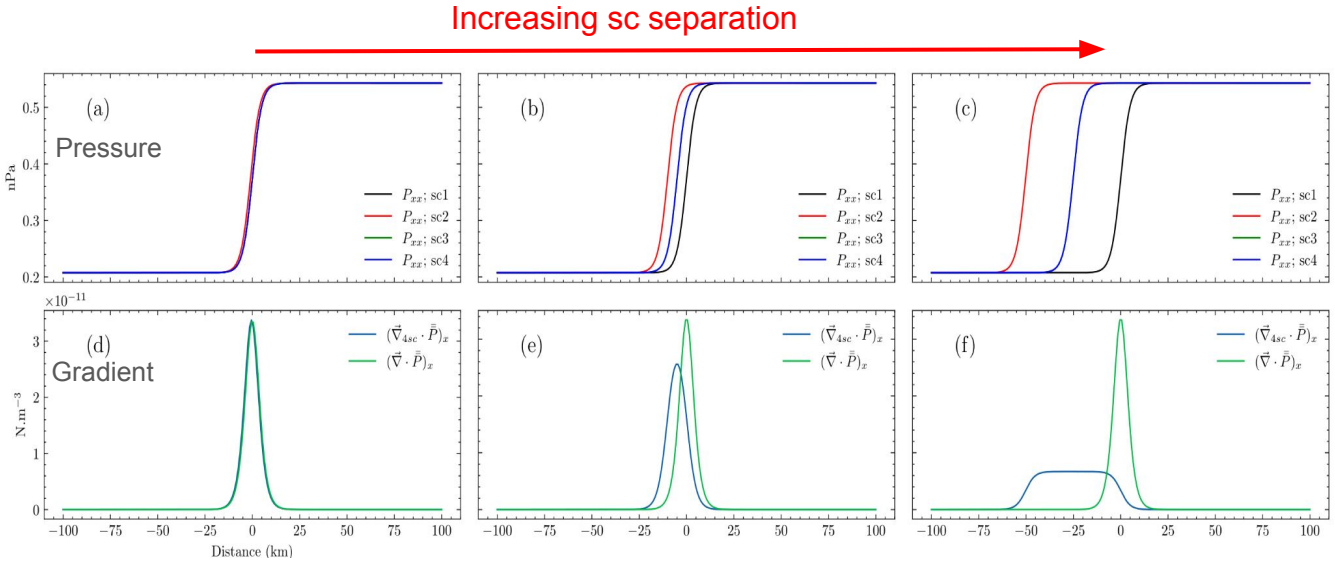
An attempt at quantifying errors

- Modelling pressure gradient
- Comparing gradient from
  - analytical derivative
  - 4sc method $\vec{\nabla}_{4sc} \cdot \bar{\bar{P}}$



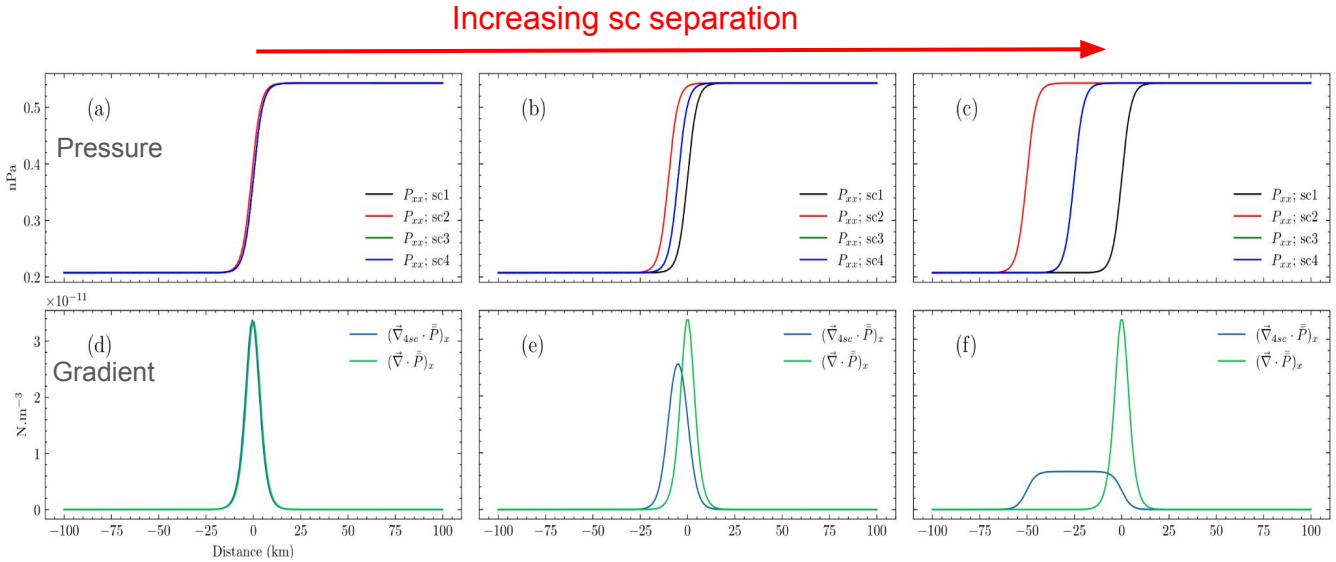
An attempt at quantifying errors

- Modelling pressure gradient
- Comparing gradient from
  - analytical derivative
  - 4sc method $\vec{\nabla}_{4sc} \cdot \bar{\bar{P}}$



An attempt at quantifying errors

- Modelling pressure gradient
- Comparing gradient from
  - analytical derivative
  - 4sc method $\vec{\nabla}_{4sc} \cdot \bar{\bar{P}}$



If the separation is:

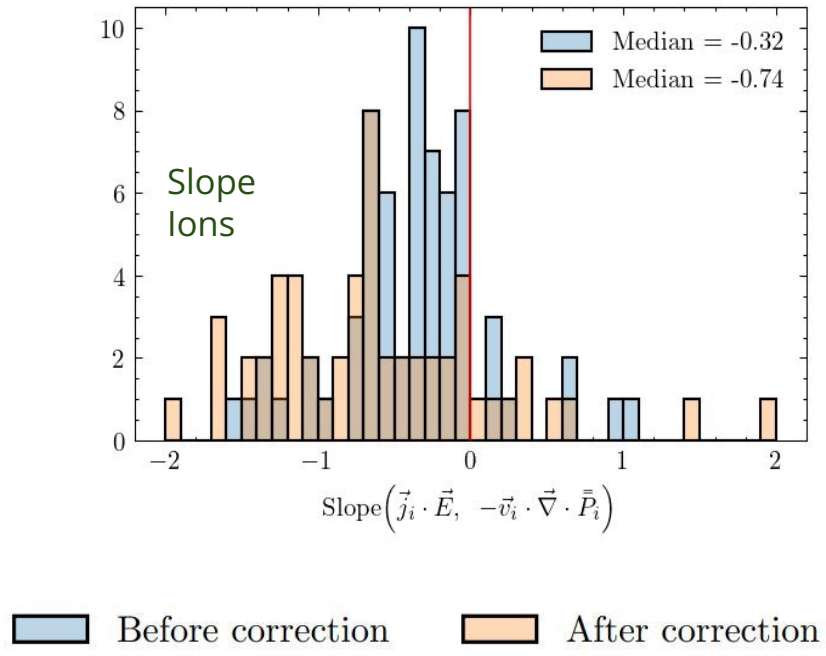
- comparable or smaller than the scale: small errors
- larger than the scale: large errors→ underestimating the gradient

In agreement with Forsyth+2009 in Cluster context for current estimation

Statistical study: corrected version ?

$$\vec{j}_s \cdot \vec{E} \quad \text{vs} \quad -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$$

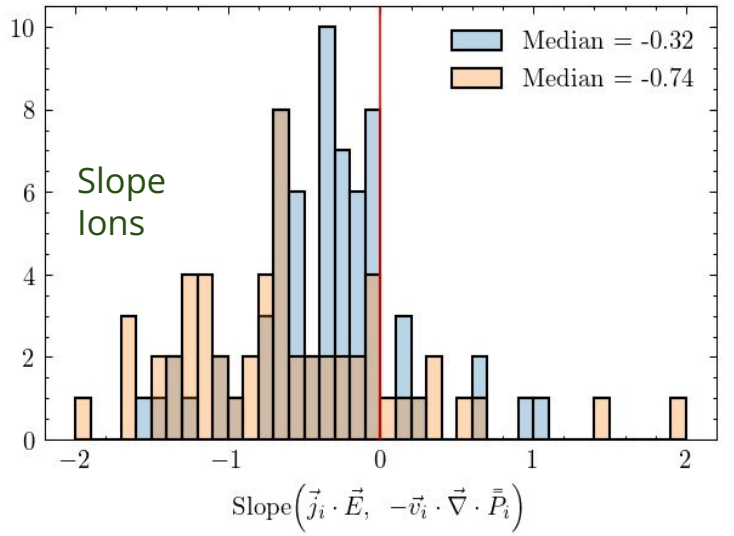
- Corrections do not fix correlations but improve ions slope.



Statistical study: corrected version ?

$$\vec{j}_s \cdot \vec{E} \quad \text{vs} \quad -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$$

- Corrections do not fix correlations but improve ions slope.



- Simple model: regular tetrahedra, no background noise, …
- Other errors: plasma moments errors propagation (Roberts+2023), linear regression errors, …

Outline

General context and data

Energy conversion and motivation

Results and discussion

Conclusions

Conclusions

- The expected balance is weakly observed for ions but it is less clear for electrons, despite the attempted correction. This is different from what was found in simulations (Fadanelli+2020).
- The relationship is statistically present in the monofluid version of the force balance and it appears to be more favourable than the multifluid version.
- Signs of the terms are opposite for ions and electrons as expected from the balance between those terms.
- Overall the pressure gradient is observed to be underestimated. Taking into account thi aspect improves ions slope. Other source of errors should be considered.

What's next?

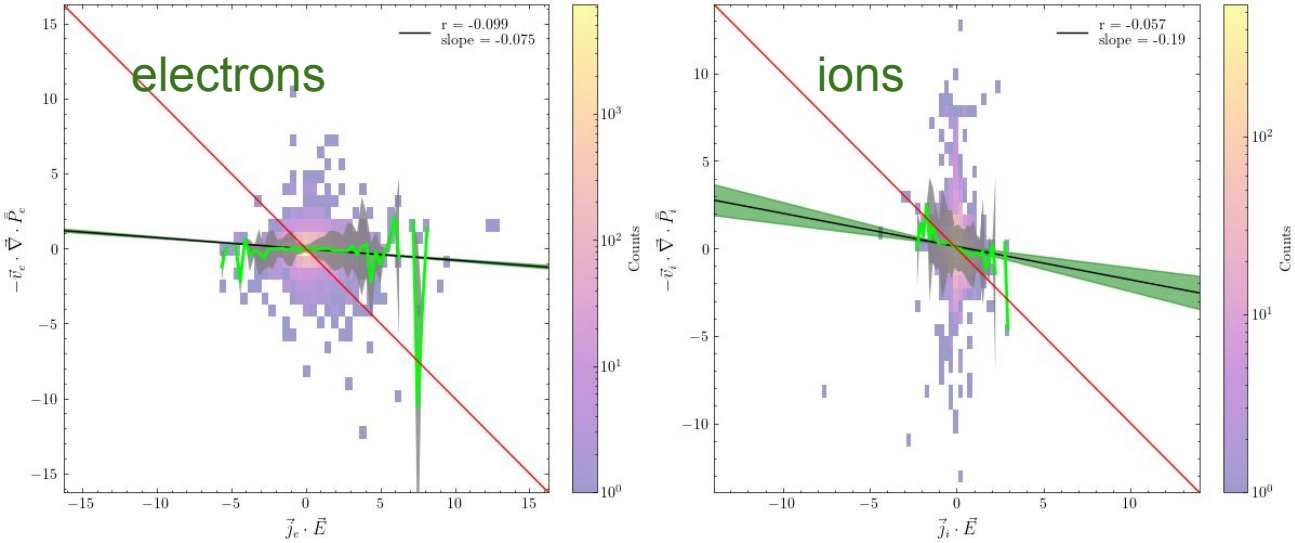
- Improve the model
- Extending our study to the bow shock region
- Role of each term in accelerating, heating the plasma and producing or annihilating magnetic energy

Merci de votre attention

sdahani@irap.omp.eu

Energy balance

The expected relationship is not clear!



$$\vec{j}_s \cdot \vec{E} \quad \text{vs} \quad -\vec{v}_s \cdot \vec{\nabla} \cdot \bar{\bar{P}}_s$$

An attempt at quantifying errors

- Modelling pressure gradient
- Comparing gradient from
  - analytical derivative
  - 4sc method $\vec{\nabla}_{4sc} \cdot \bar{\bar{P}}$