D2968 | EGU2020-13405

In situ spacecraft observations of structured Electron Diffusion Regions during magnetic reconnection

INSTITUTET FÖR RYMDFYSIK
IRF Swedish Institute of Space Physics

G. Cozzani[1], A. Retinò[2], F. Califano[3], A. Alexandrova[2], O. Le Contel[2], Y. Khotyaintsev[1], A. Vaivads[4], H. S. Fu[5], M. André[1] & the MMS team

1. IRF Uppsala, Sweden; 2. LPP, CNRS, Palaiseau, France; 3. Università di Pisa, Pisa, Italy; 4. KTH, Stockholm, Sweden; 5. Being University, Beijing, China

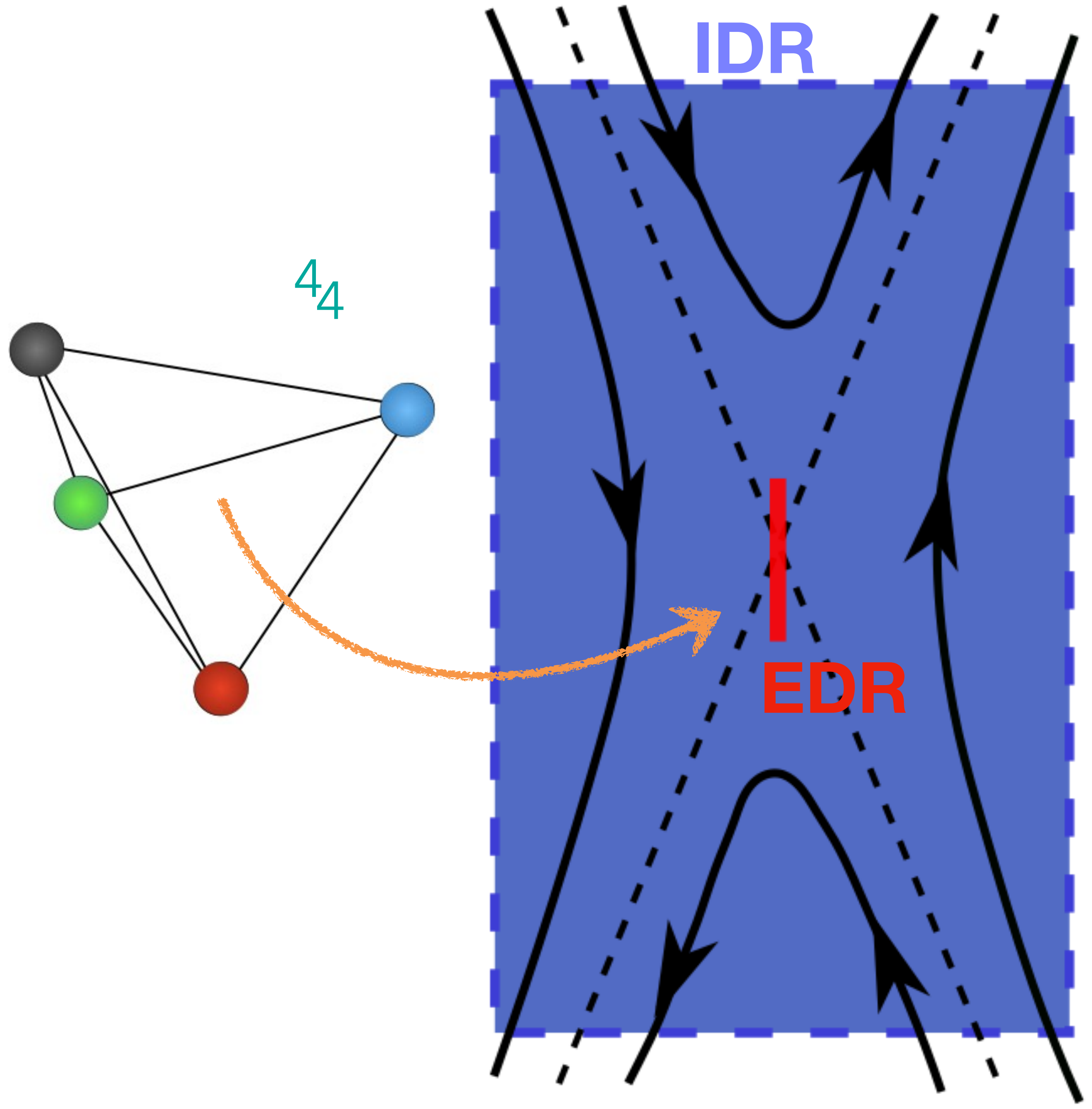
MOTIVATION OF THE STUDY:

The Electron Diffusion Region (EDR) is the region where magnetic reconnection is initiated and electrons are energized.

It is only with the **high resolution** particle data and the **small inter-spacecraft separation** provided by MMS that the structure of the EDR can be studied in detail by means of **multi-spacecraft analysis**.

One of the key unanswered questions is whether the EDR has a **laminar** or a **inhomogeneous structure** at electron scales and below.

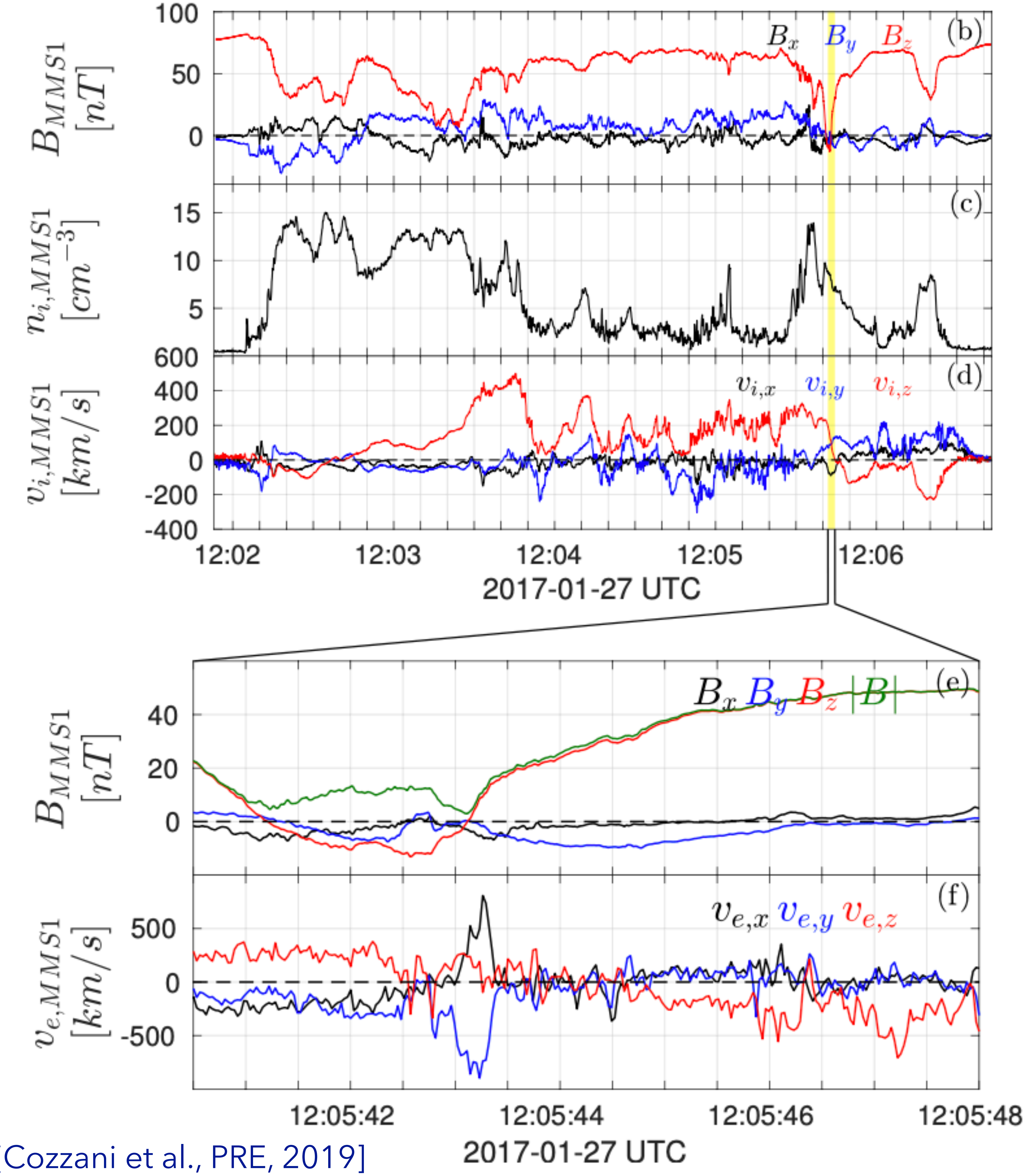
The presence of small scale structure and inhomogeneities within the EDR could influence the overall reconnection process e.g. affecting the **reconnection rate** or the electron **energisation processes** in the EDR.



IN THIS STUDY:

- We present observations of **EDRs** at the Earth's **magnetopause** and **magnetotail**.
- **Magnetopause:** we select an EDR encounter with the **smallest** inter-spacecraft separation of 6 km ~ 3 de. We report evidences of **inhomogeneous current densities** and **patchy energy conversion** over a few de, suggesting that the EDR can be rather **structured**.
- **Magnetotail:** the reported EDR encounter is characterised by an **extended electron demagnetisation** region and by significant **magnetic field fluctuations** (~ 10% of the reconnected magnetic field) with frequencies of the order of f_{LH}

Electron Diffusion Region encounter at the **magnetopause**: overview



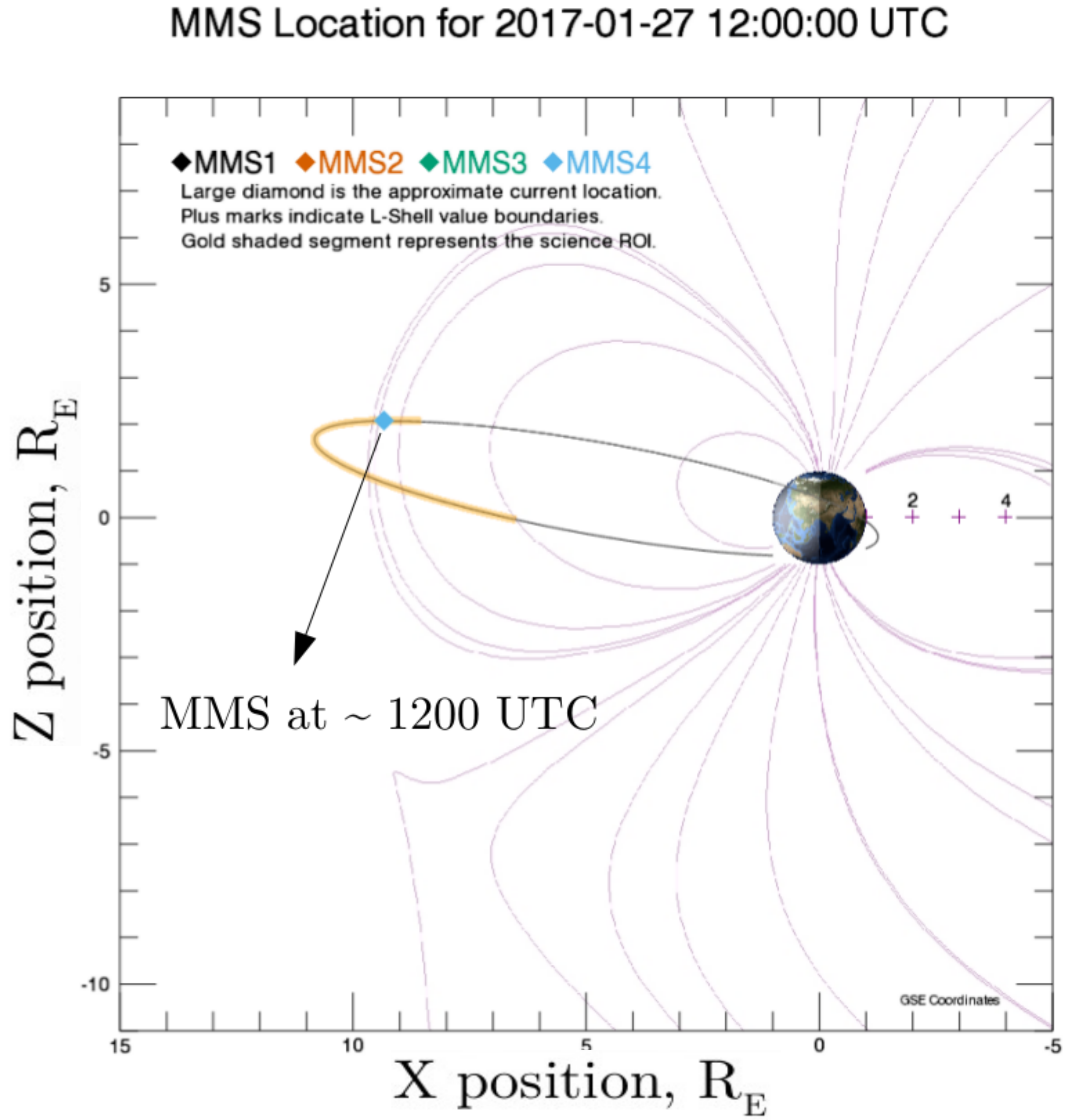
[Cozzani et al., PRE, 2019]

MMS stays mostly in the **magnetospheric boundary layer** (B_z > 0, n ~ 10 cm-3). Between 12:05:41.2 and 12:05:43.2, B_z becomes negative (yellow shaded area).

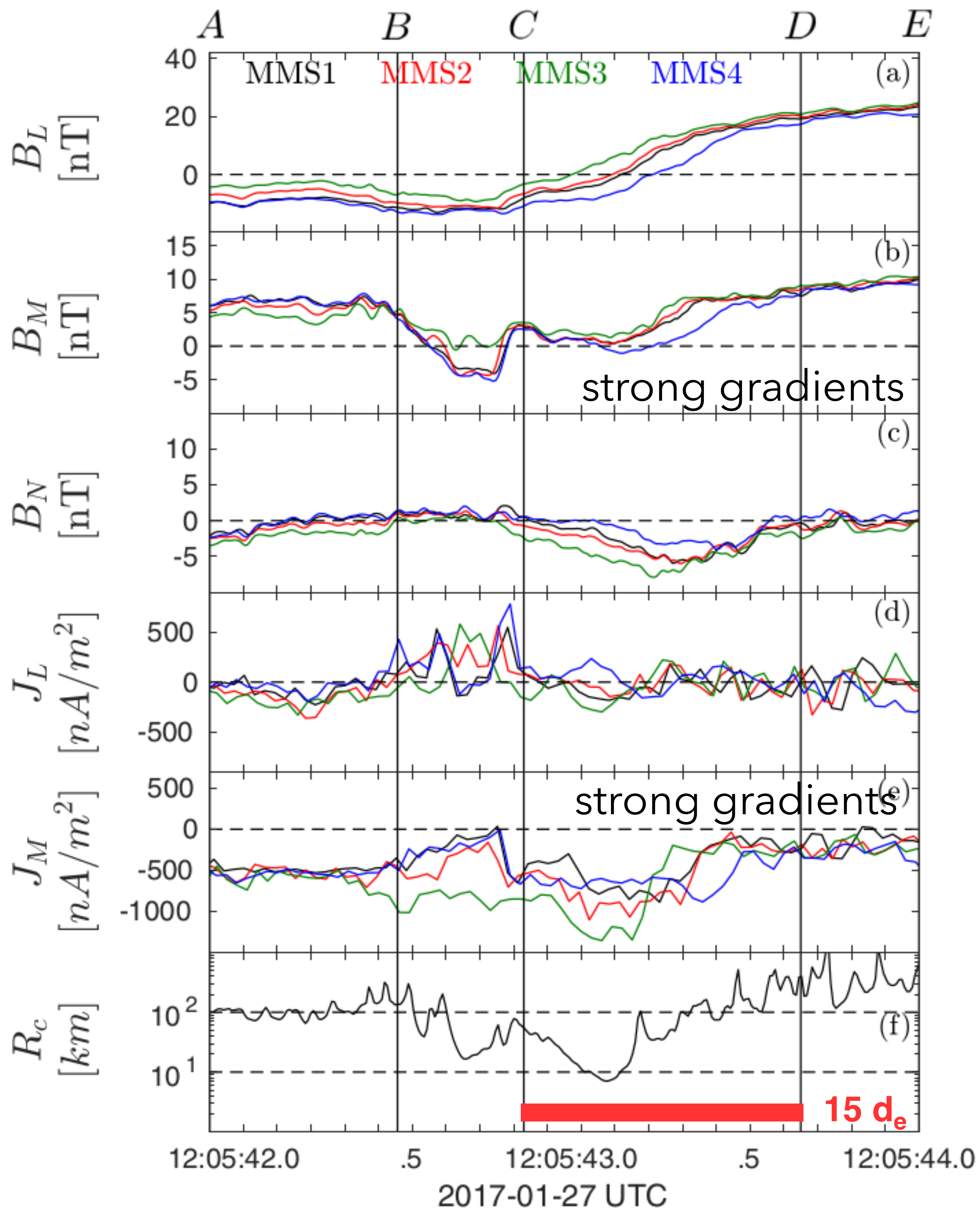
At the second B_z reversal an **ion and electron jet reversal** are observed (V_A ~ 100 km/s).

|B| reaches the minimum value of 3 nT.

A strong peak of v_{ey} ~ -900 km/s is observed.



MMS crosses the magnetopause close to the reconnection site



$$R_c = \mathbf{B} \cdot \nabla \mathbf{B} / B^2$$

[Cozzani et al., PRE, 2019]

The MMS trajectory relative to the magnetopause is established considering the behaviour of B and J and it is represented in the sketch on the right.

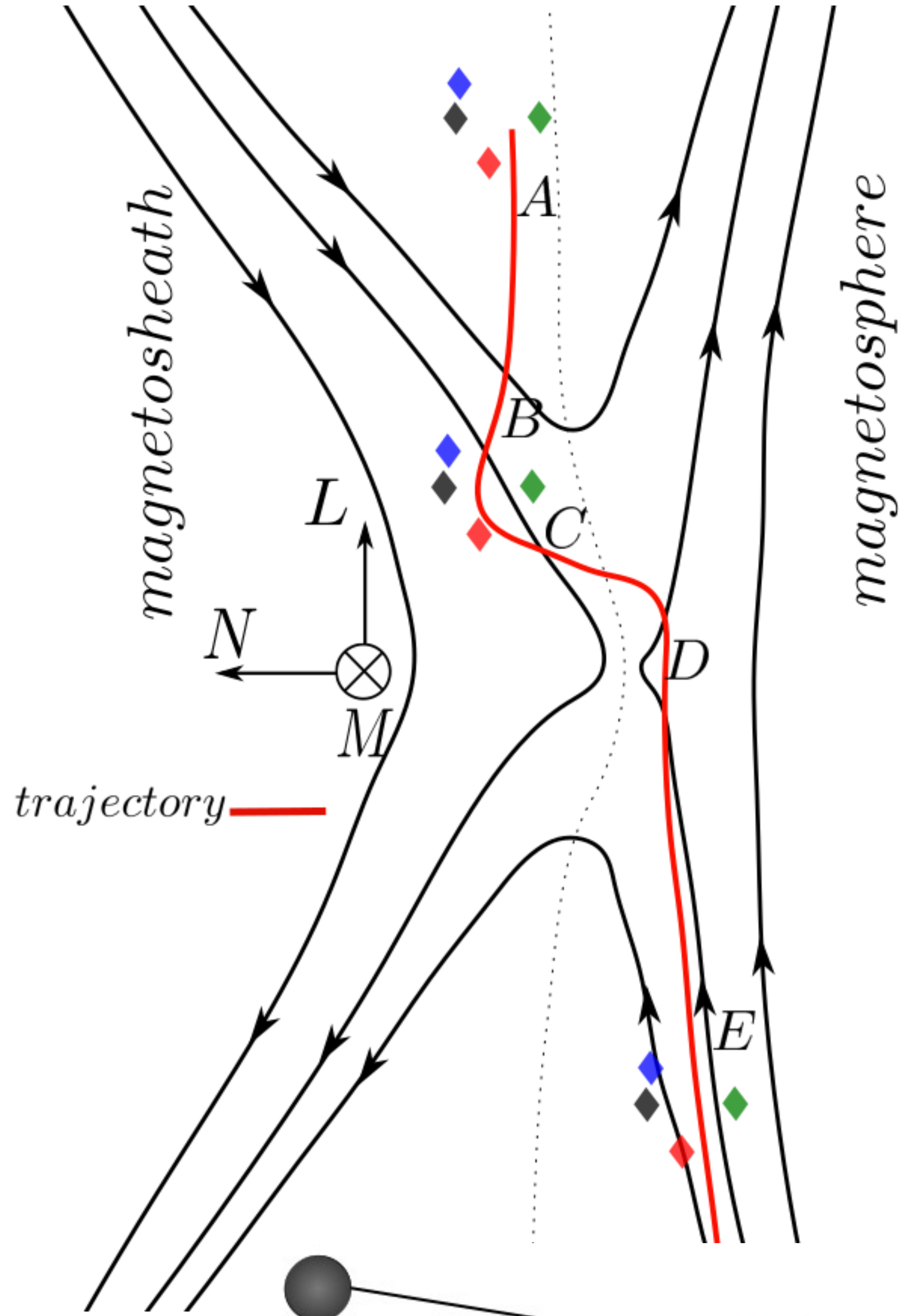
Despite the **electron scale** inter-spacecraft separation, there are **differences among the spacecraft** measurement indicating **strong spatial gradients**.

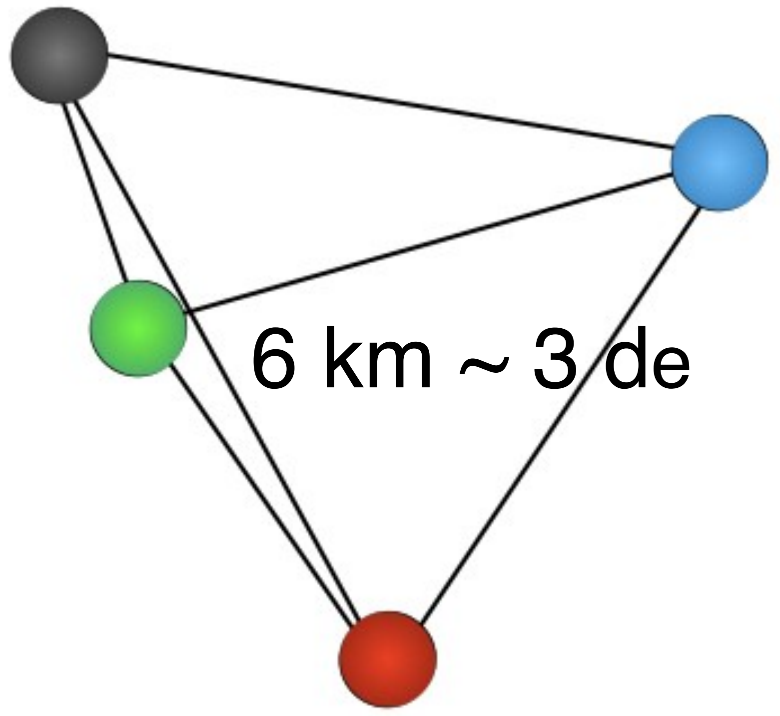
The current sheet **thickness (~15 de)** indicates that the current sheet is at electron scales.

The magnetic field **radius of curvature** Rc becomes comparable with the spacecraft separation at the center of the current sheet.

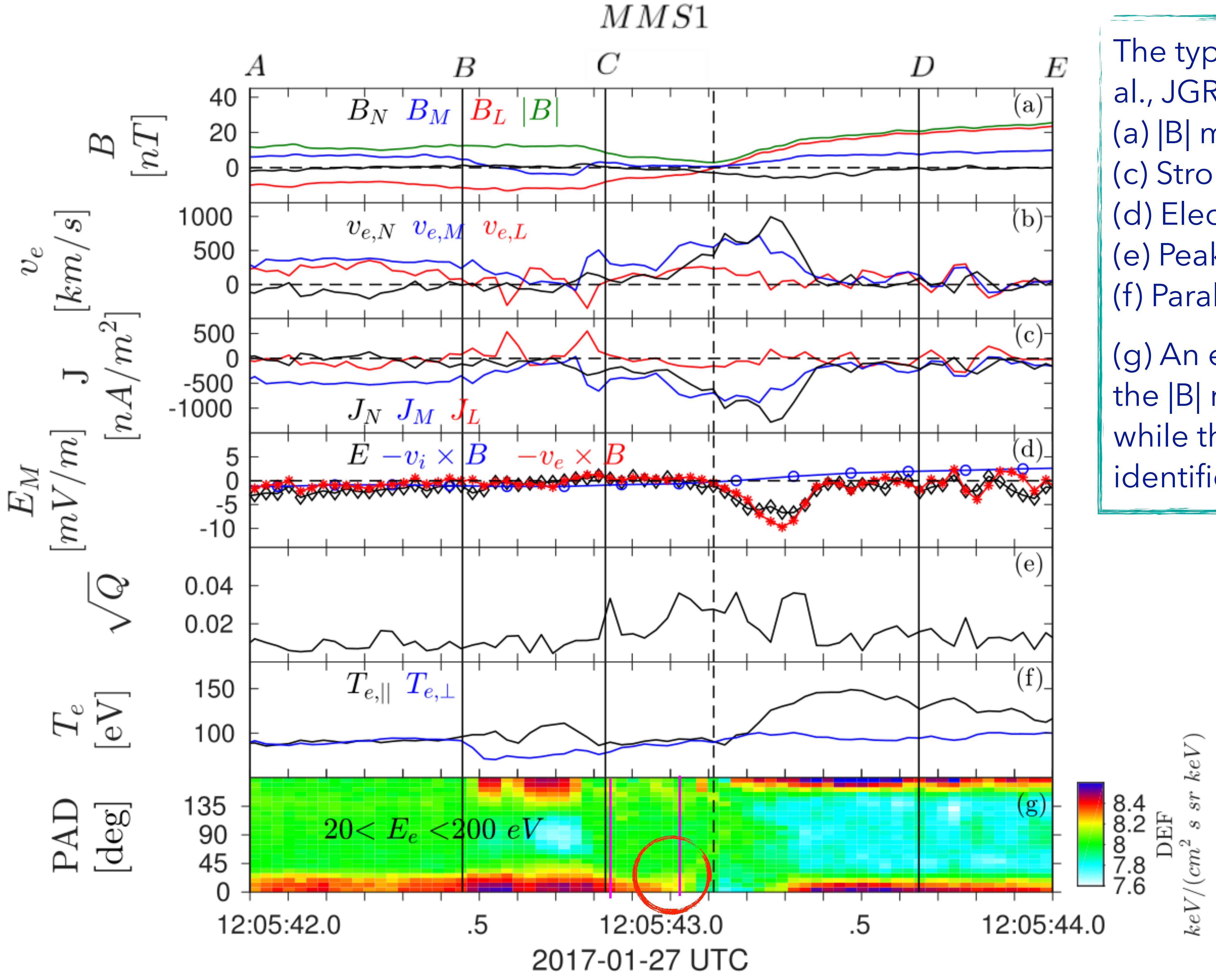
These are indications that **MMS crosses the magnetopause close to the reconnection site.**

LMN = [-0.039, -0.252, 0.967;
-0.301, -0.921, -0.252;
0.954, -0.300, -0.040] GSE





EDR signatures at the magnetopause



The typical **EDR signatures** are observed [Burch et al., Science, 2016] [Webster et al., JGR, 2018]:

(a) |B| minimum (~3 nT)

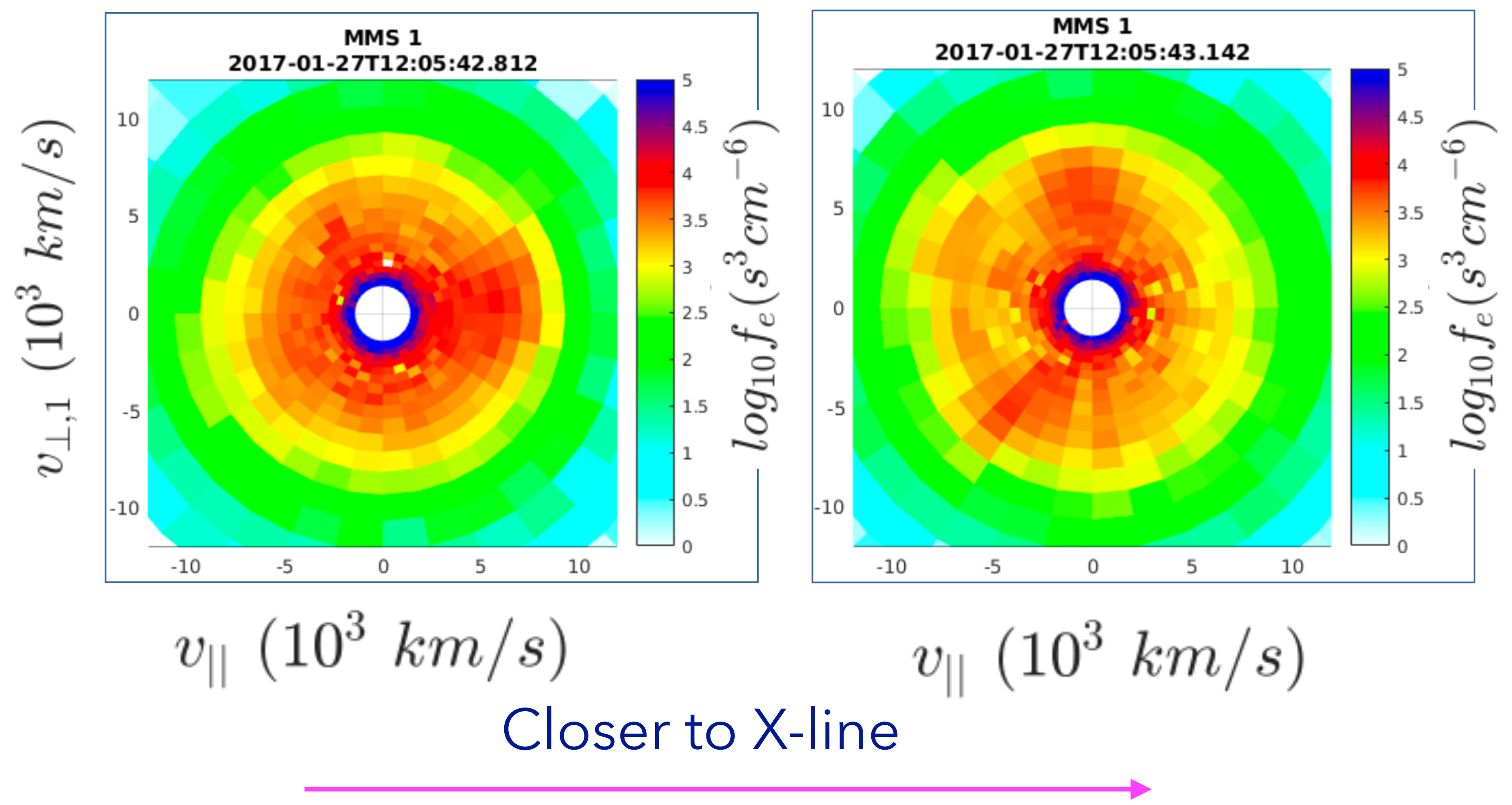
(c) Strong current JM carried by electrons (b)

(d) Electron demagnetisation

(e) Peak electron agyrotropy [Swisdak, GRL, 2016]

(f) Parallel electron heating

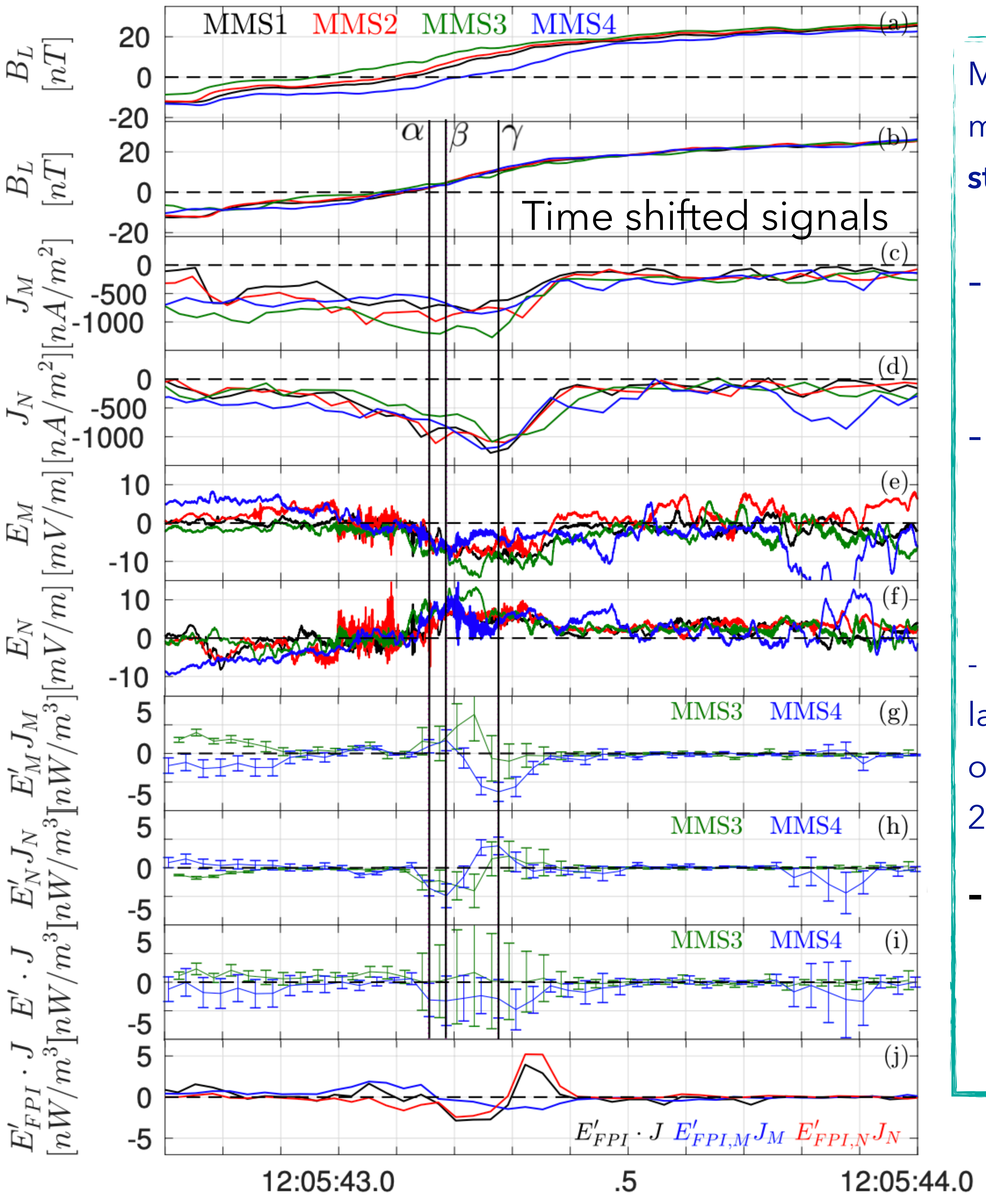
(g) An electron population parallel to B propagates towards the |B| minimum. At the |B| minimum this beam is no longer observed and the PAD looks isotropic while the distribution functions exhibit **oblique beams**. This signature has been identified as indication of **electron demagnetization** [Egedal et al., PRL, 2018].



Closer to X-line

[Cozzani et al., PRE, 2019]

Multi-spacecraft analysis reveals differences among spacecraft observations



[Cozzani et al., PRE, 2019]

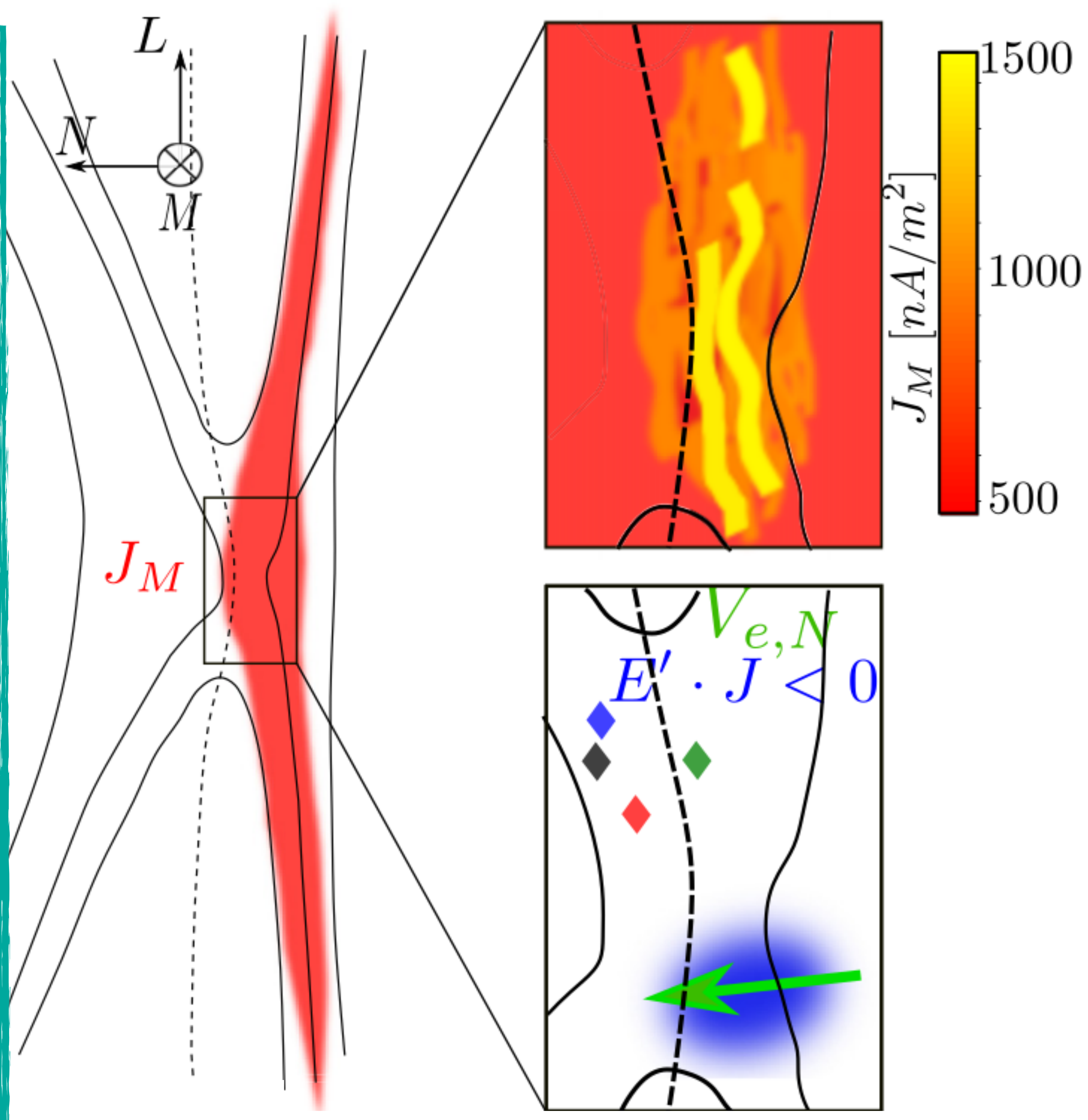
Multi-spacecraft data analysis at the magnetopause reveals that the EDR can be **structured at electron-scale**:

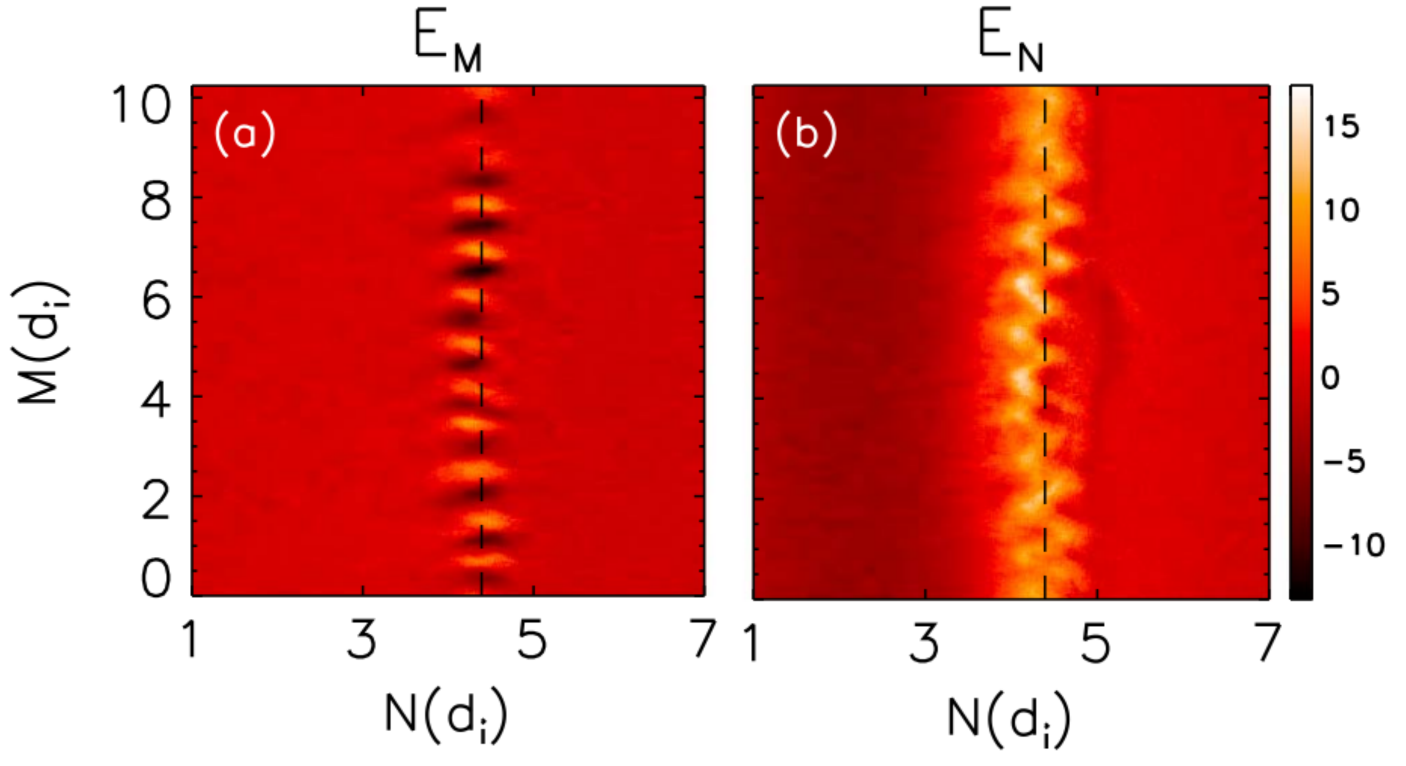
- Current density **JM inhomogeneous at electron scale** (JM ~ 1200 nA/m2 for MM3 and JM ~ 800 nA/m2 for other s/c)
- **JM ~ JN** and JN < 0 so that electrons are moving from from the magnetosphere to the magnetosheath side of the magnetopause (not consistent with inflow)

- **EM ~ EN** in contrast with standard picture of laminar EDR and consistent with simulations of turbulent current sheet [Price et al., JGR, 2017].

- **Energy conversion** is **patchy** at the EDR. The origin of the patchy energy conversion appears to be connected to the large ve,N ~ ve,M.

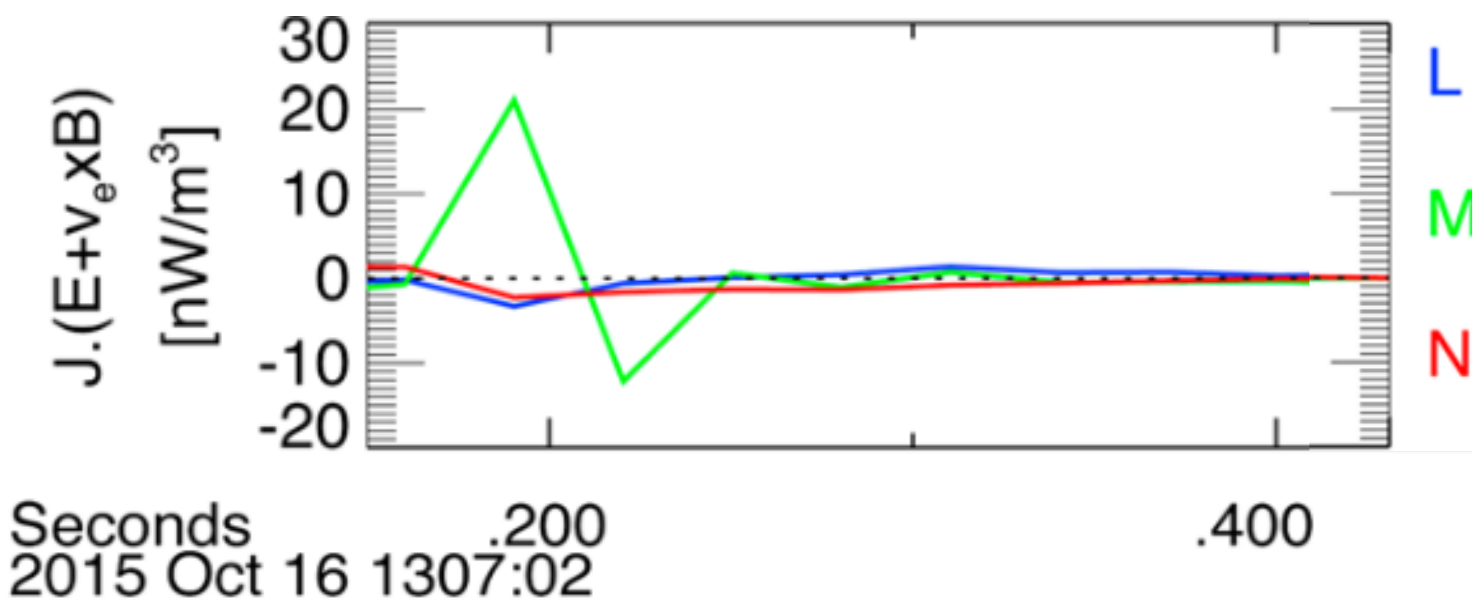
$$\mathbf{E}'_{FPI} = -\frac{\nabla \overline{P}_e}{ne} + \frac{m_e}{e}\mathbf{v}_e \cdot \nabla \mathbf{v}_e + \frac{m_e}{e}\frac{\partial}{\partial t}\mathbf{v}_e$$





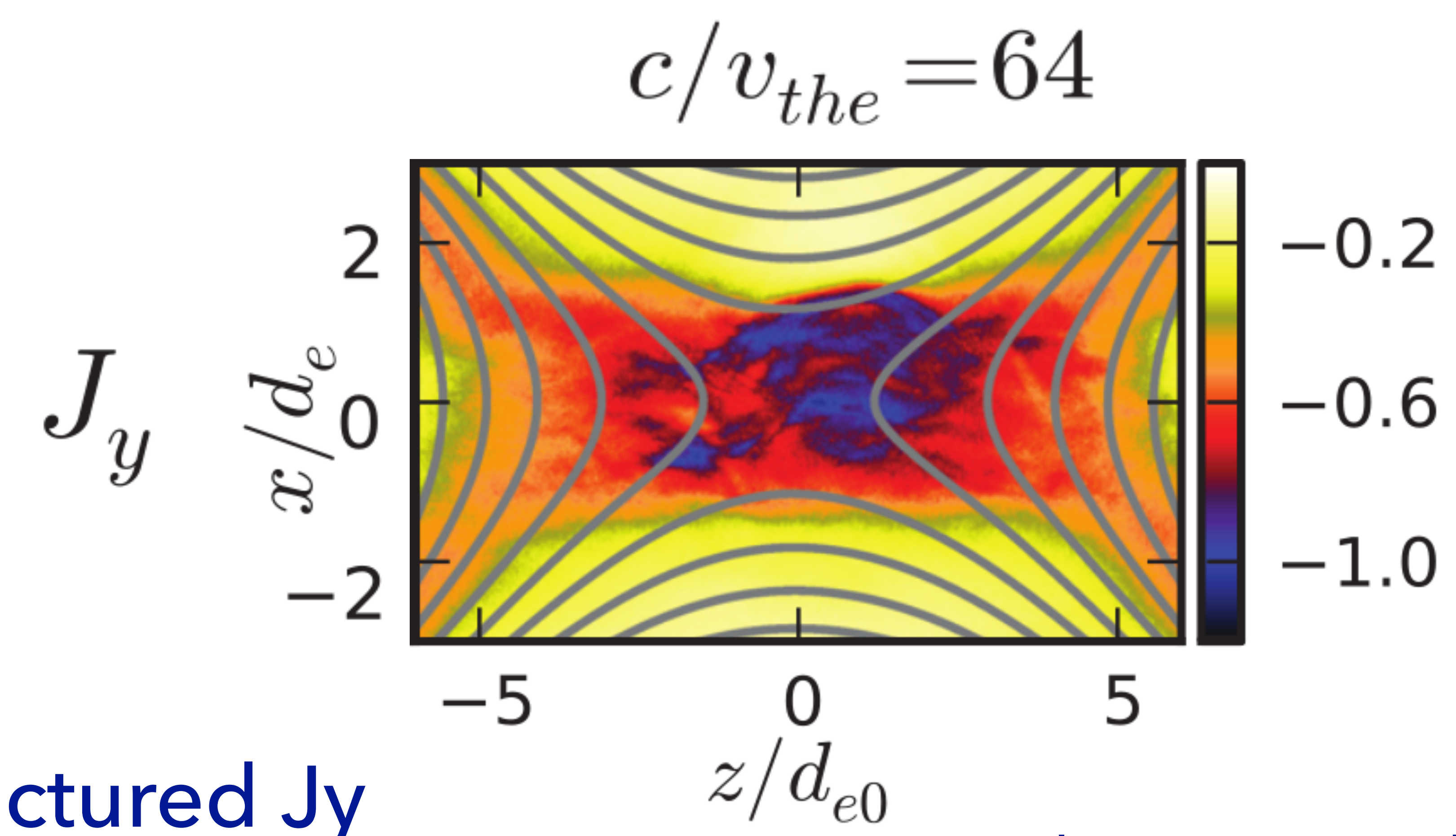
[Price et al., JGR, 2017]

Other observations and simulations are suggesting the idea of a complex EDR



Positive and negative E'.J [Burch et al., GRL, 2018]

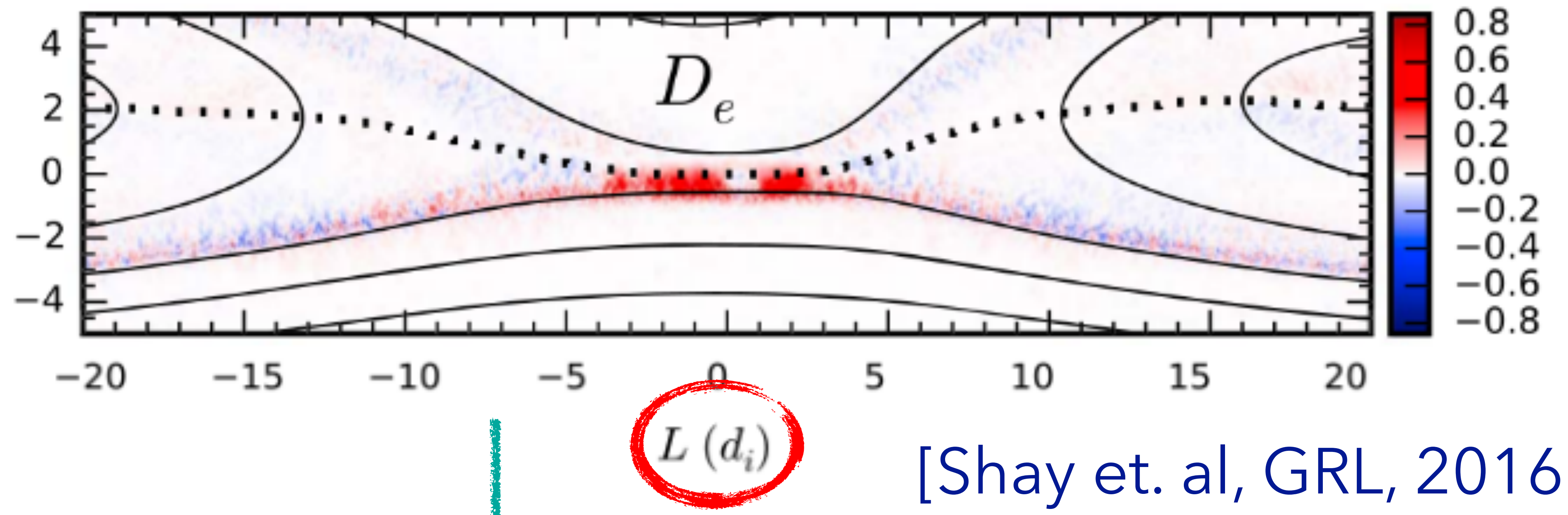
Large scale separation d_e/λ_D



Structured Jy

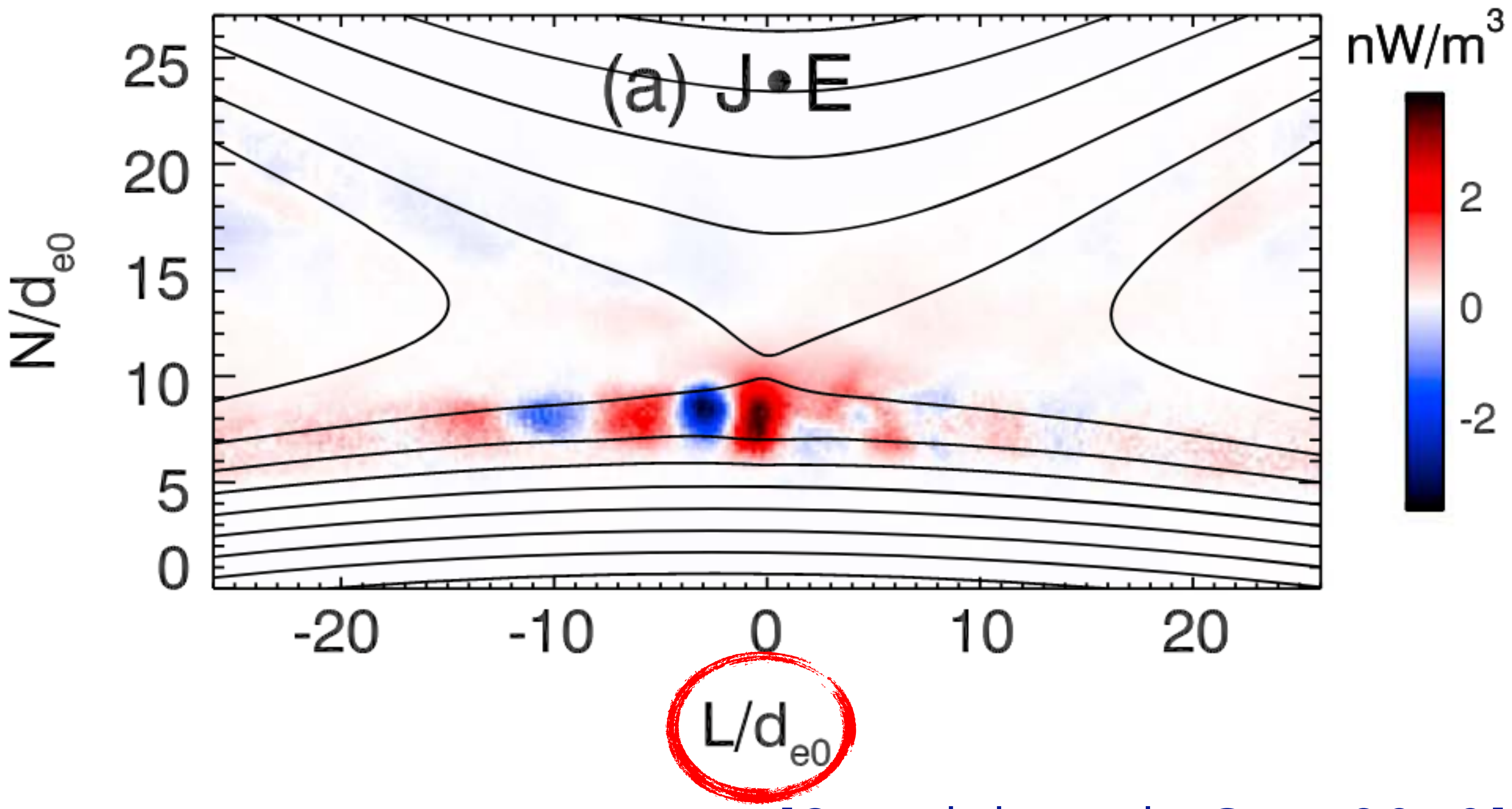
[Jara-Almonte et al., PoP, 2014]

2D PIC simulations



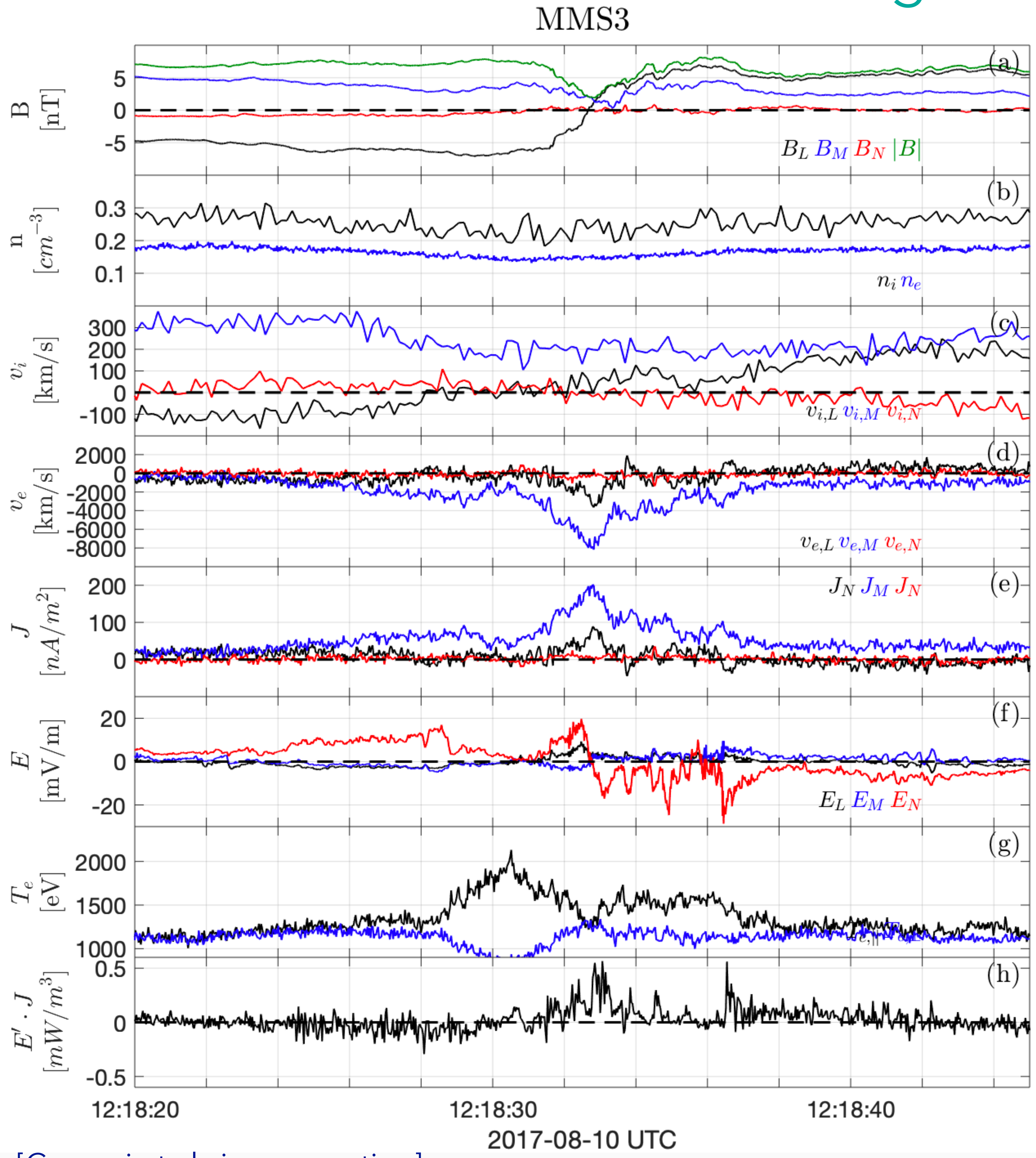
[Shay et. al, GRL, 2016]

Increased #macroparticles



[Swisdak et al., GRL, 2018]

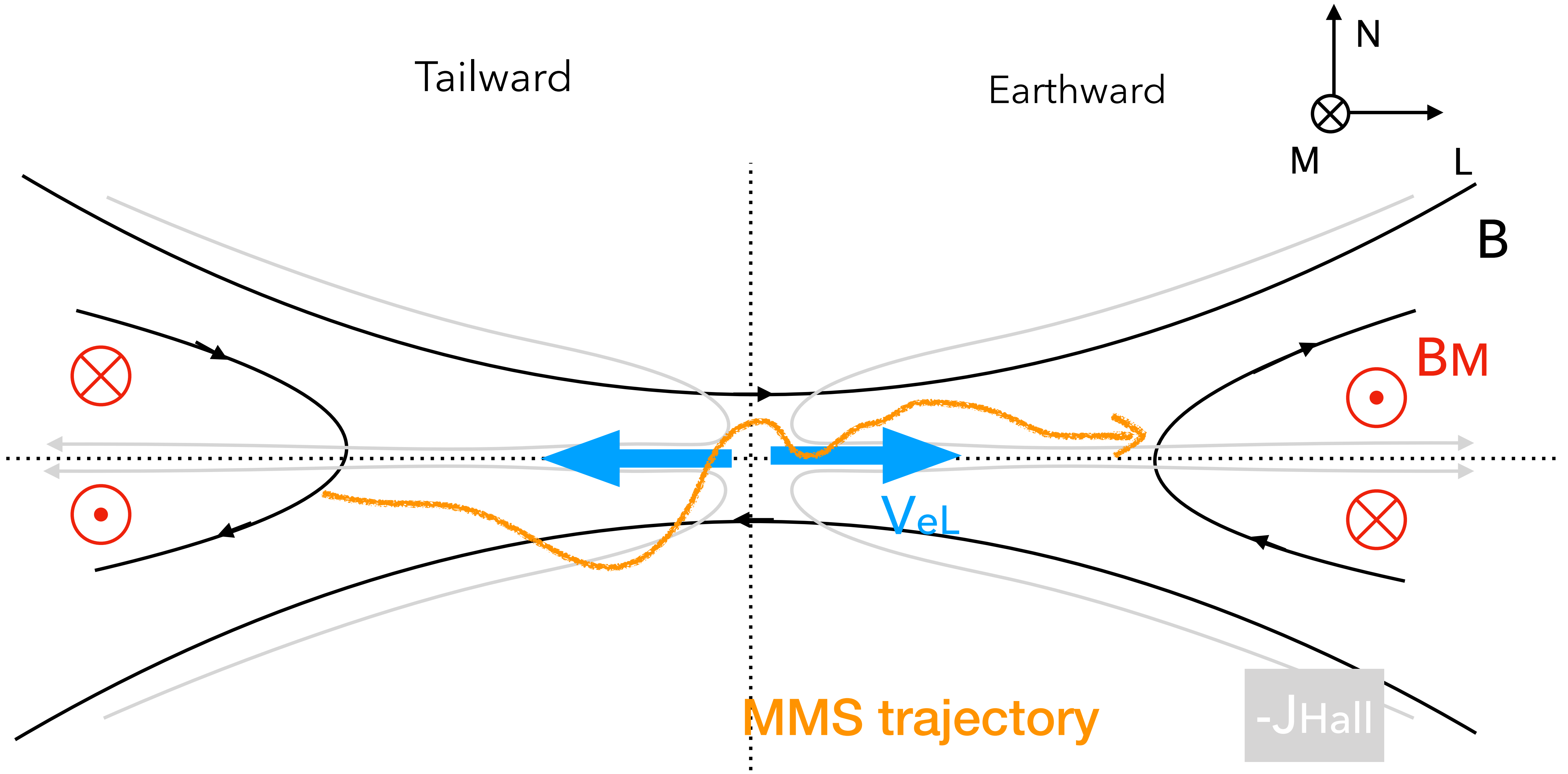
Electron Diffusion Region encounter at the **magnetotail**



This event has been reported by Zhou et al. (ApJ, 2019) as a **magnetotail EDR** encounter with **weak guide field** (13% of B in the inflow region).

MMS stays mostly in the **plasma sheet**. The **EDR signatures** are observed [Burch et al., Science, 2016] [Webster et al., JGR, 2018]:

(a) |B| minimum (guide field ~2 nT)
(c) ion and (d) and electron **flow reversal**
(e) **Strong current** J_M ~ 200 nA/m2 carried by electrons (d)
(f) Hall E
(g) Electron temperature anisotropy closer to the inflow region
(h) Energy conversion E'.J>0



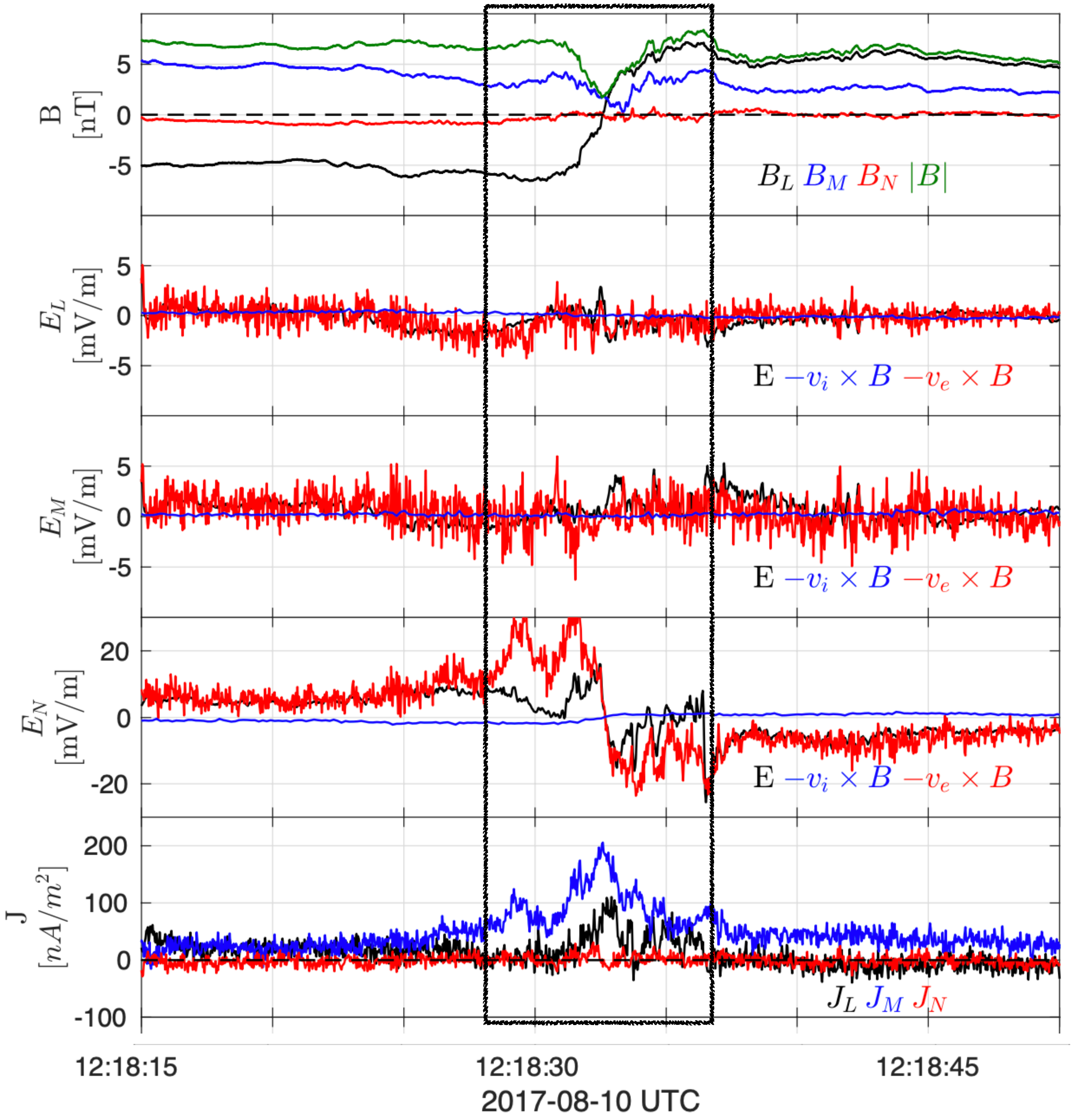
LMN = [-0.98,5 -0.141, 0.097;
0.152, 0.982, -0.109;
-0.080, 0.122, 0.989] GSM

s/c separation ~ 20 km ~1.5 de

[Cozzani et al., in preparation]

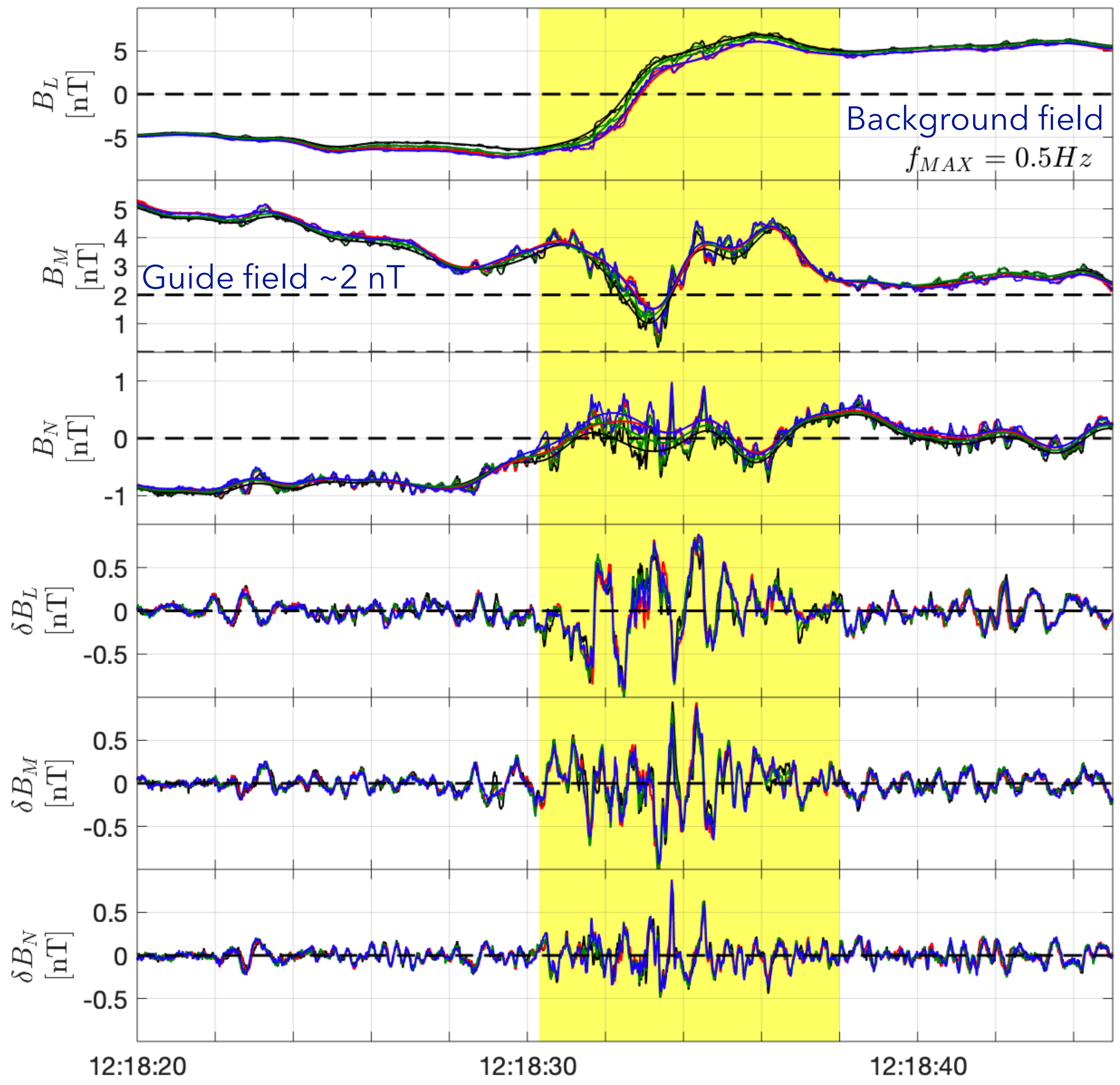
Current sheet width ~ 2 de

Differences from the standard picture of the EDR



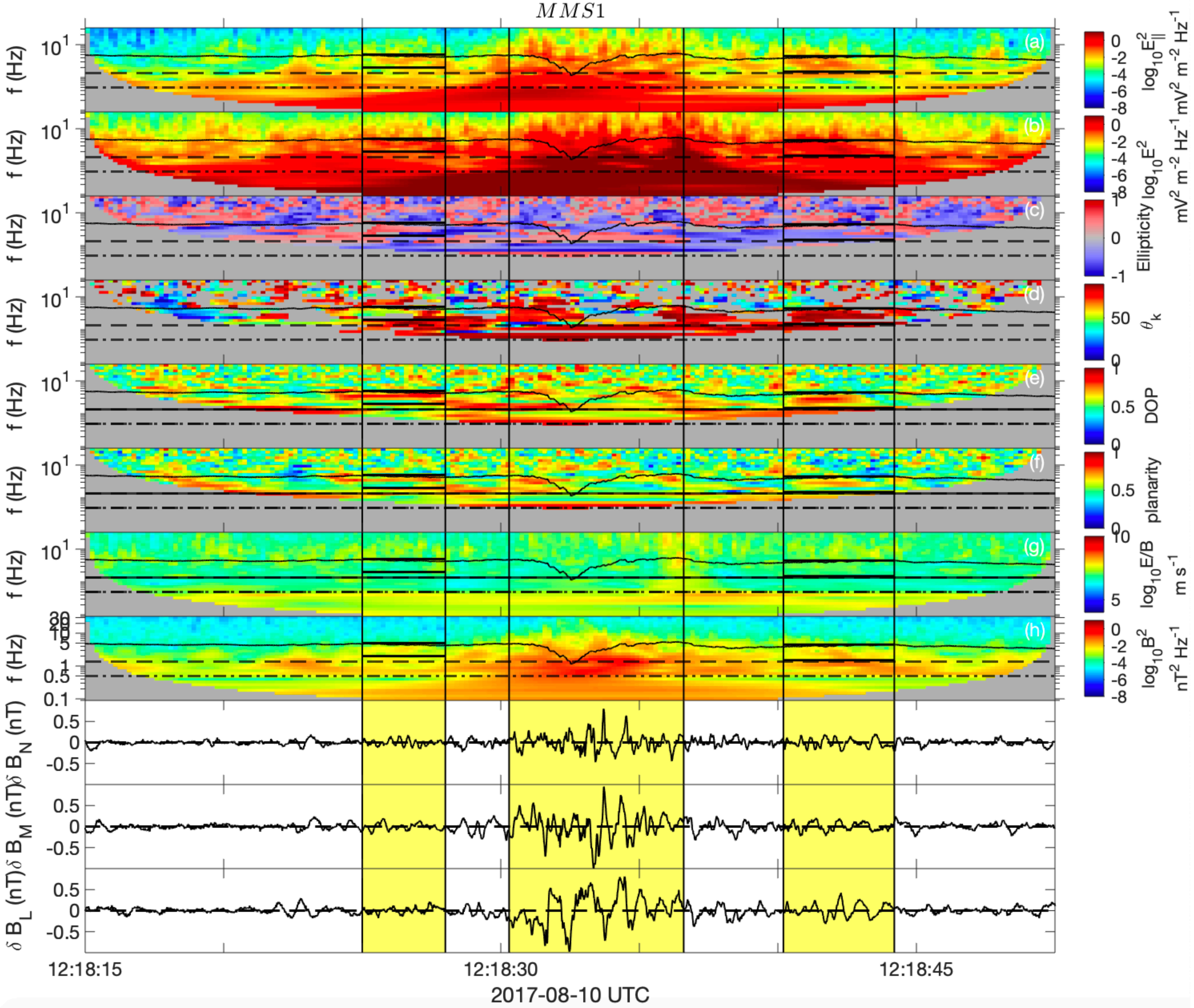
An **extended interval of electron demagnetisation** is observed.

It lasts for at least 6 s with $E_N + (v_e \times B)_N$ reaching 20 mV/m



BN is changing sign several times during the EDR crossing. **Significant magnetic field fluctuations** (>10% of the upstream total field) are observed in all three components.

Magnetic field fluctuations analysis in the EDR



f_{LH}
1.4 Hz
0.5 Hz

We compute the wavelet **spectrograms** of the energy **densities of the electric and magnetic field** observed by MMS1.

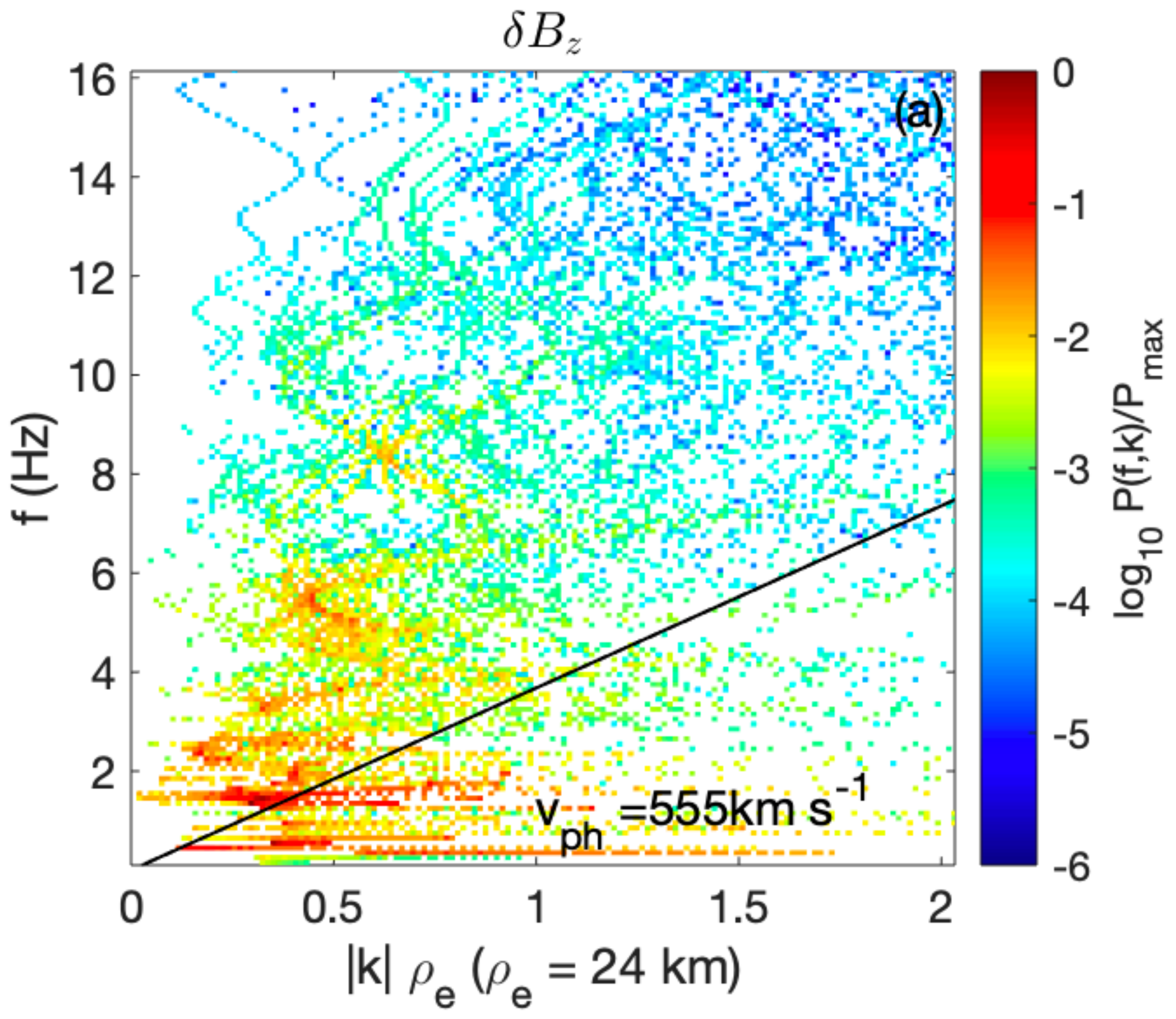
Enhancements are observed for **frequencies up to the lower hybrid frequency f_{LH}** (black solid line).

At the center of the current sheet (|B| minimum), the frequency associated with the maximum in the magnetic field energy ~ f_{LH} (see next slide).

These **electromagnetic** fluctuations propagates **perpendicularly** to the magnetic field ($\theta_k \sim 90^{\circ}$).

They are characterised by a rather **high planarity** and **degree of polarisation** (DOP).

Magnetic field fluctuations analysis in the EDR



Power spectra of the magnetic field fluctuations along the z direction for the interval 12:18:30.3 - 12:18:36.3.

$$f(P_{max}(\delta B_z)) = 1.4\ Hz$$

$$v_{ph} = 555\ km/s$$

$$\hat{\mathbf{k}} = [0.0423,\ -0.9484,\ 0.3141]\ GSM$$
$$= [0.2059\ \ -0.9595,\ 0.1916]\ LMN$$

$$|\mathbf{k}|\rho_e = 0.3$$

$$|\mathbf{k}|\sqrt{\rho_e\rho_i} = 2.5$$

$$\lambda = v_{ph}/f = 396\ km = 1.8\ \sqrt{\rho_e\rho_i}$$

The **k** vector is obtained with four spacecraft method based on the phase differences between the difference spacecraft pairs. **k** is mainly aligned in the **direction of the current** in the EDR (-M direction).

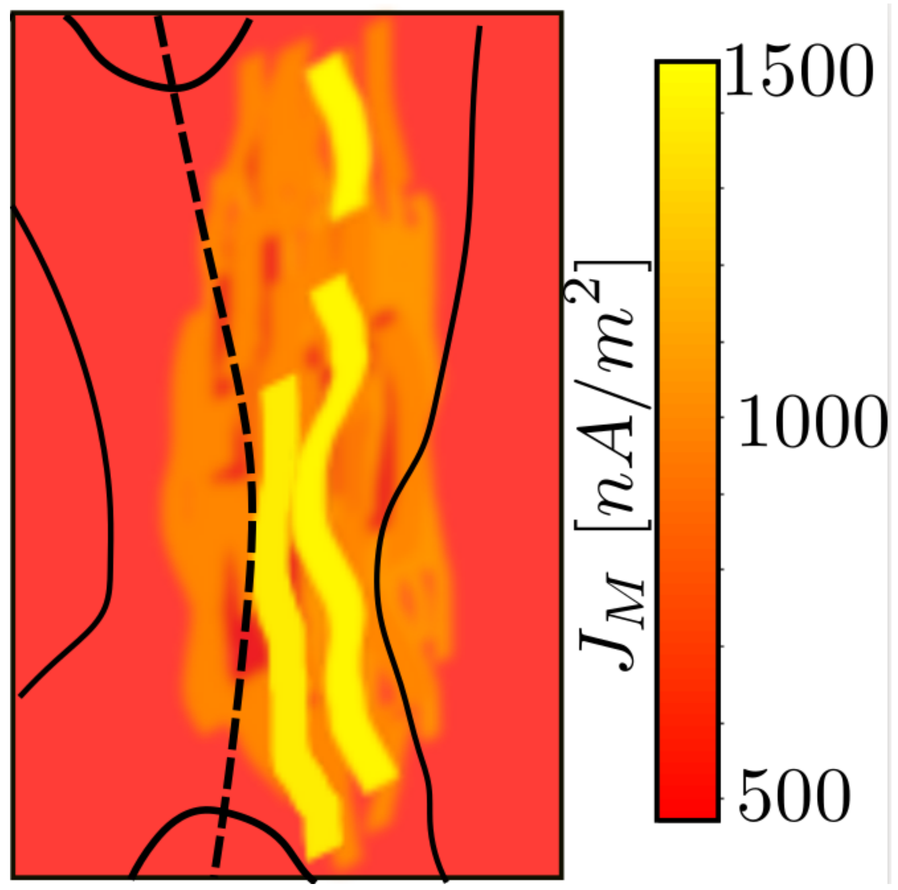
The fluctuations observed in the EDR and in its closest surroundings appear to be characterised f ~fLH and by a rather **long wavelength**. Also, they propagate **perpendicularly** to the magnetic field.

Summary

MAGNETOPAUSE:

Multi-spacecraft data analysis at the magnetopause revealed that the Electron Diffusion Region can be structured at electron-scale. Main findings are:

- Current density J_M is inhomogeneous at electron scale
- $E_M \sim E_N$ in contrast with standard picture of laminar EDR
- Energy conversion is patchy at the EDR

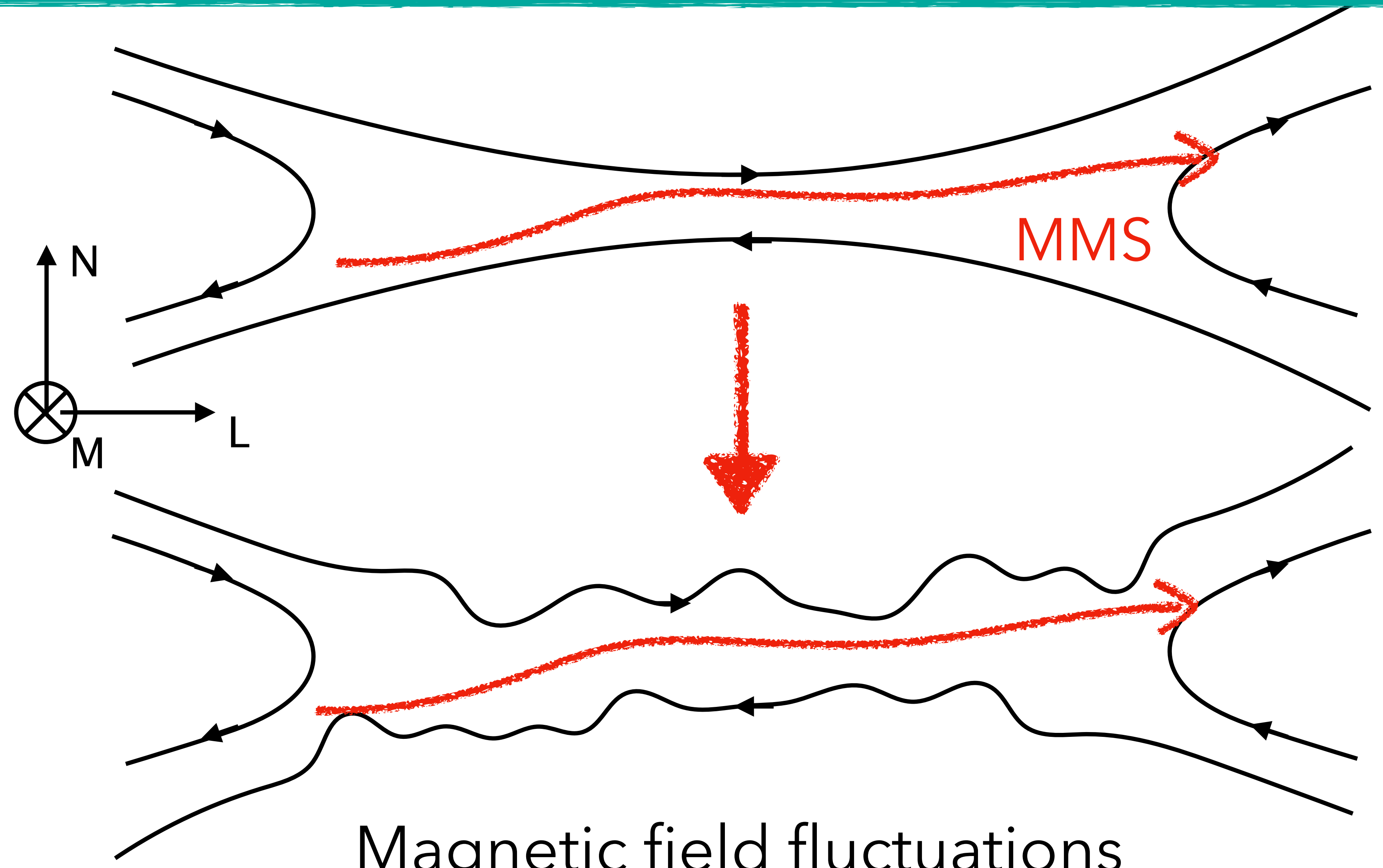


MAGNETOTAIL:

We analyse the magnetic field fluctuations observed during an EDR encounter with weak guide field.

The fluctuations are characterised by frequency close to the lower hybrid frequency and by rather long wavelength. They propagate perpendicularly to the background magnetic field, along the direction of the current density. The amplitude of the fluctuations is >10 % of the upstream total magnetic field in all the three directions.

These fluctuations could possibly impact the structure of the EDR.



Thank you for reading!

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