

MMS observations of electron firehose fluctuations in the magnetic reconnection outflow

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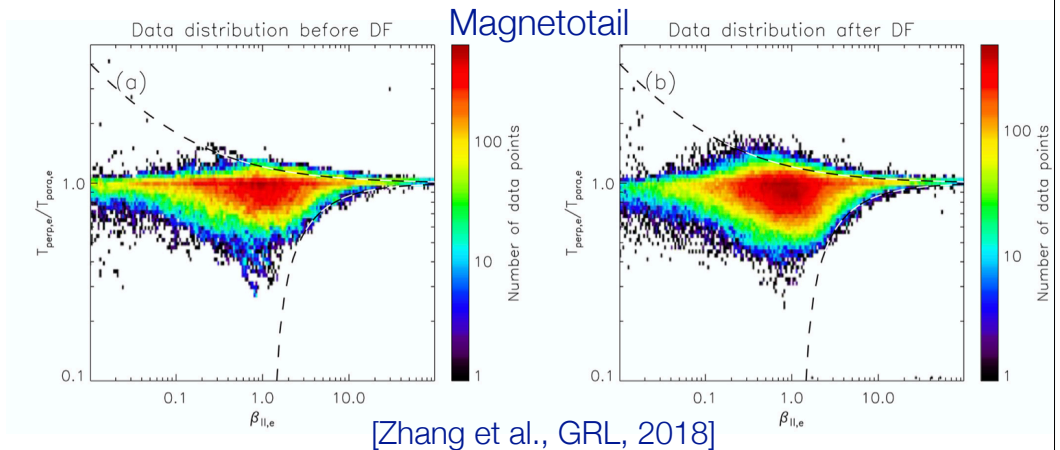
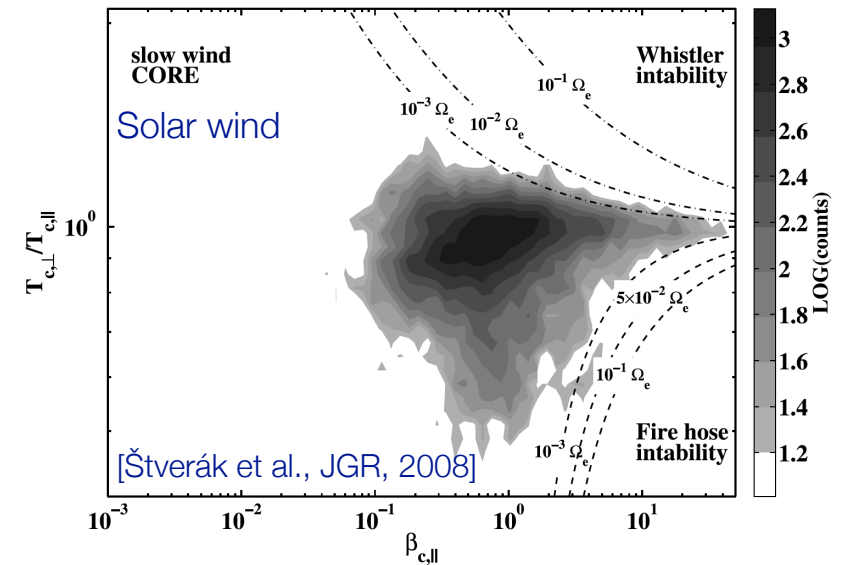
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Electron firehose instability

- Temperature anisotropy driven instability ($T_{e,\parallel}/T_{e,\perp} > 1$)
- constrains the anisotropy of the electron distribution functions
- responsible for particle-scattering and energy conversion between fields and particles

Electron populations are observed to be bounded by the thresholds of kinetic instabilities (whistler and electron firehose) in the parameter space $T_{e,\parallel}/T_{e,\perp} - \beta_{e,\parallel}$

This instability is indeed affecting electron dynamics



[Zhang et al., GRL, 2018]

Electron firehose instability: propagating and non-propagating mode

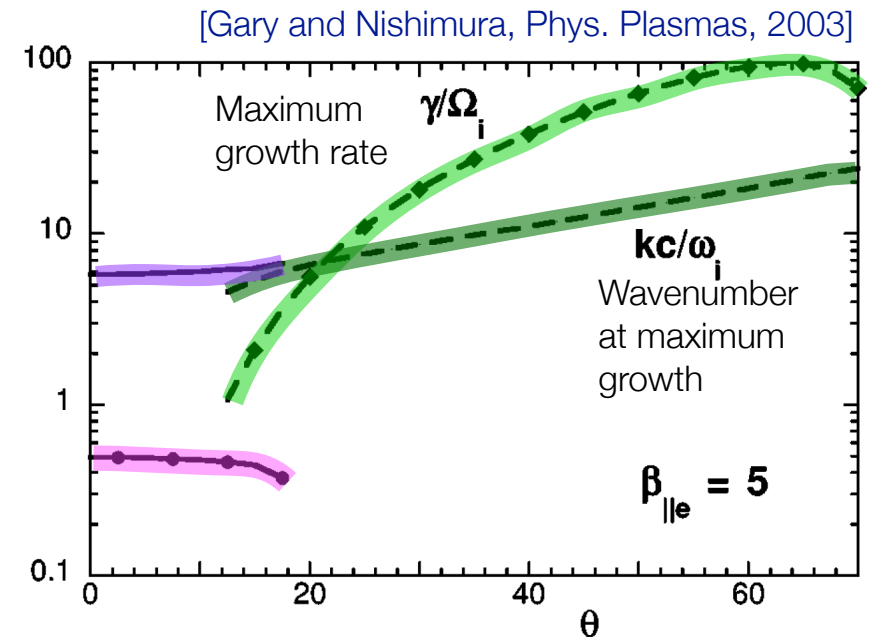
Linear dispersion theory (single bi-Maxwellian eDF) predicts the threshold condition of the instability [Gary and Nishimura, Phys. Plasmas, 2003]

$$\frac{T_{e,\perp}}{T_{e,\parallel}} = 1 - \frac{S'_e}{\beta_{e,\parallel}^{\alpha'_e}}$$

$$1 \lesssim S'_e \lesssim 2 \quad \alpha'_e \lesssim 1 \quad 2 \leq \beta_{e,\parallel} \leq 50$$

Two branches are predicted: a propagating mode ($\omega_r \neq 0$) and a non-propagating mode ($\omega_r = 0$).

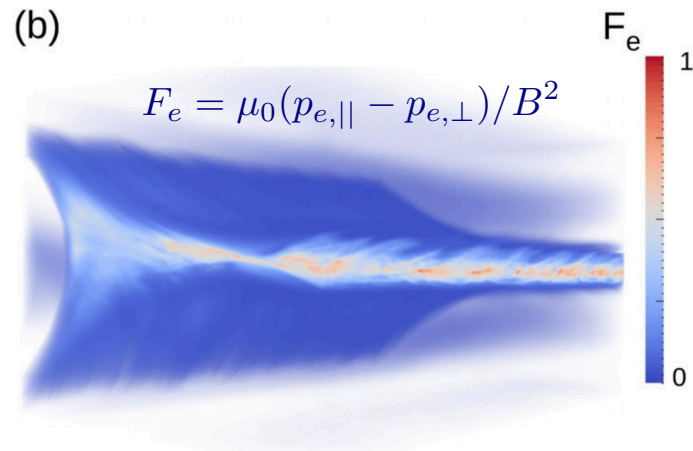
The non-propagating mode has a **lower threshold** and a **larger growth rate** compared to the propagating mode.



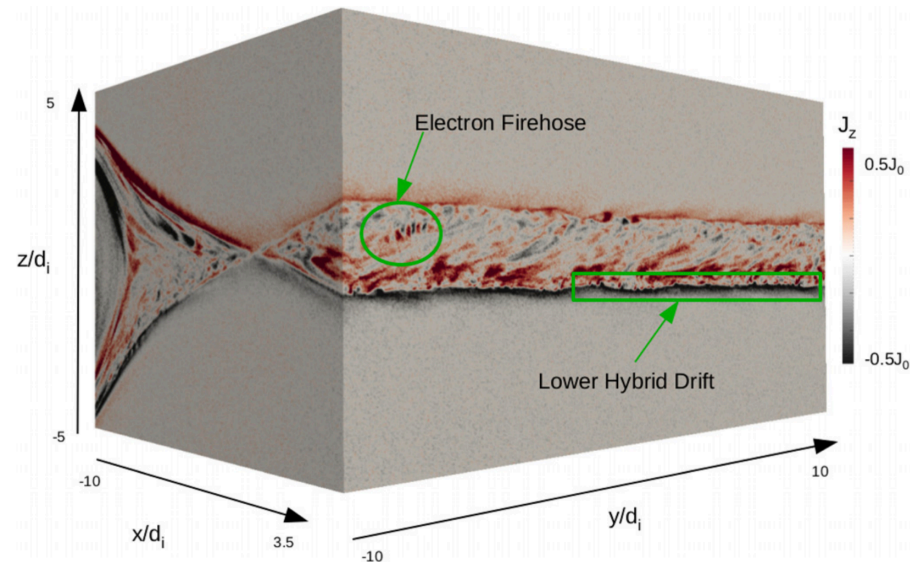
Non-propagating mode properties:

- **oblique** propagation to the background $\mathbf{B}_0$
- **Resonant** with electrons $|\zeta_e^\pm| = \frac{|\omega \pm \Omega_{ce}|}{\sqrt{2}v_{th\parallel e}k} \lesssim 1$

Magnetic reconnection presents regions of strong temperature anisotropy where the electron firehose instability can develop



[Le et al., Phys. Plasmas, 2019]

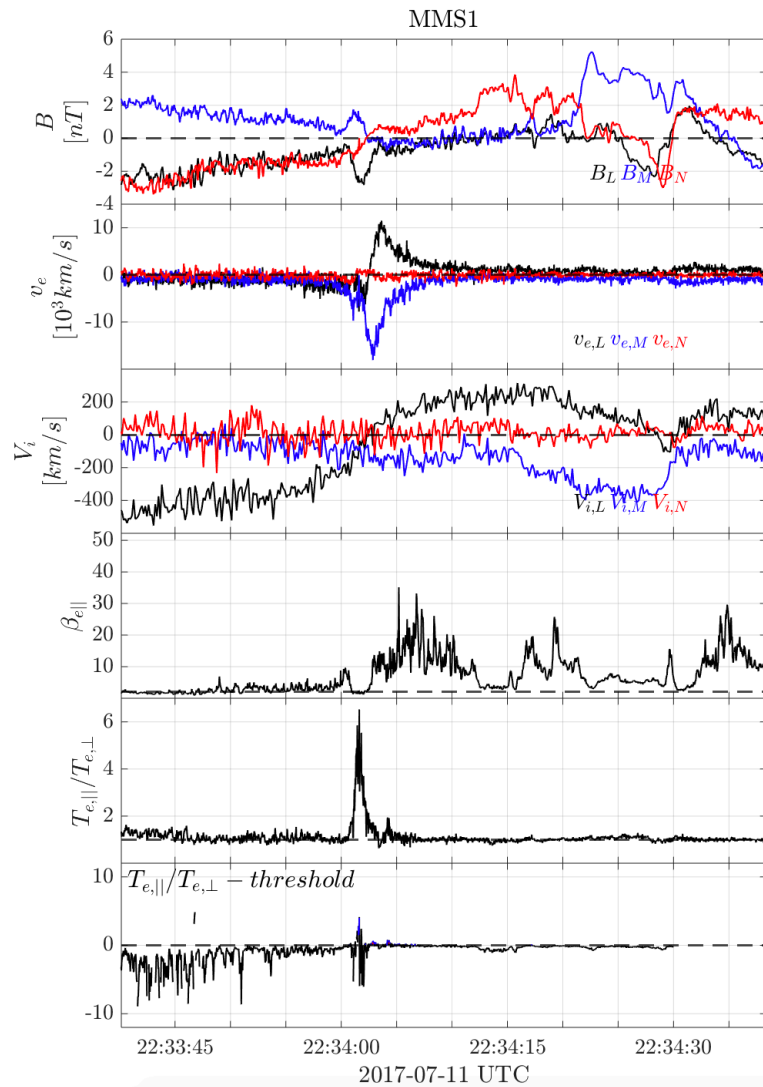


The goal is to use MMS observations to:

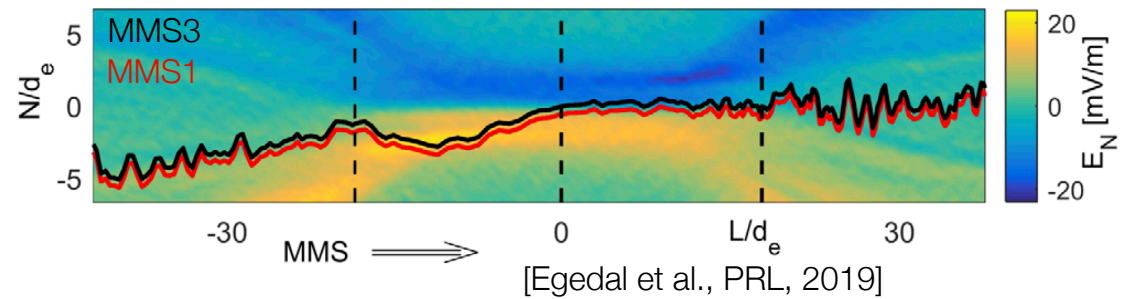
- identify the regions in which the threshold for the instability is reached
- provide **direct observations** of the electron firehose fluctuations, notably the **non-propagating mode**

We use MMS observations during electron diffusion region (EDR) crossings in the Earth's magnetotail

Electron firehose instability analysis: EDR crossing 2017-07-11



[Torbert et al., Science, 2018]



$$\frac{T_{e,\perp}}{T_{e,\parallel}} = 1 - \frac{S'_e}{\beta_{e,\parallel}^{\alpha'_e}}$$

The electron firehose instability threshold is reached at the EDR

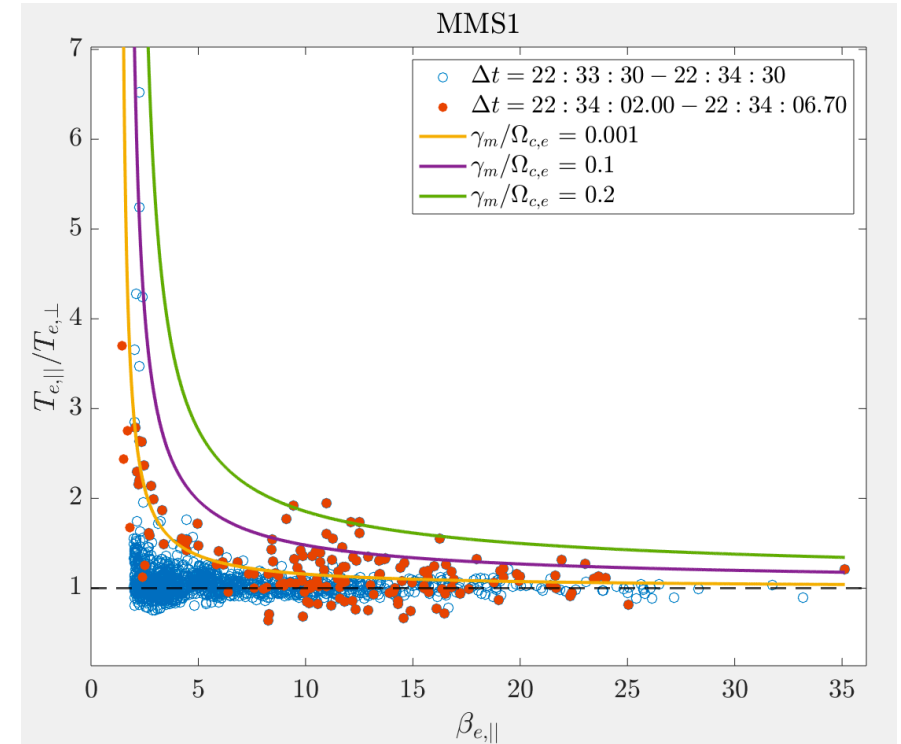
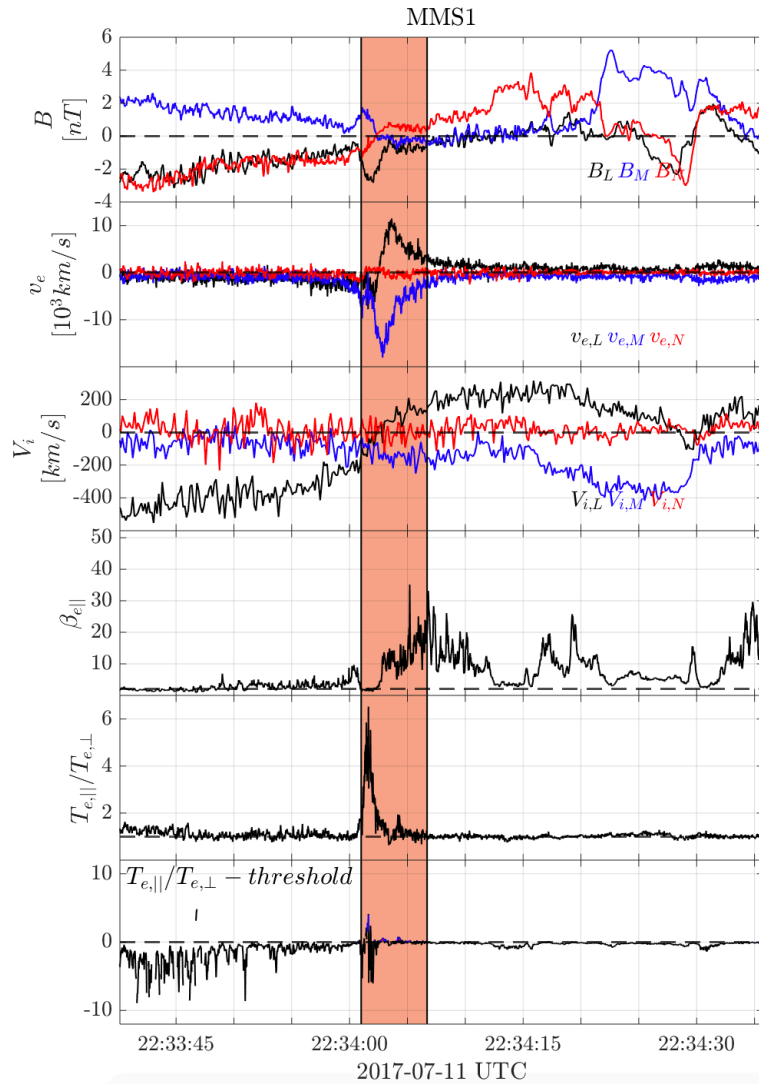


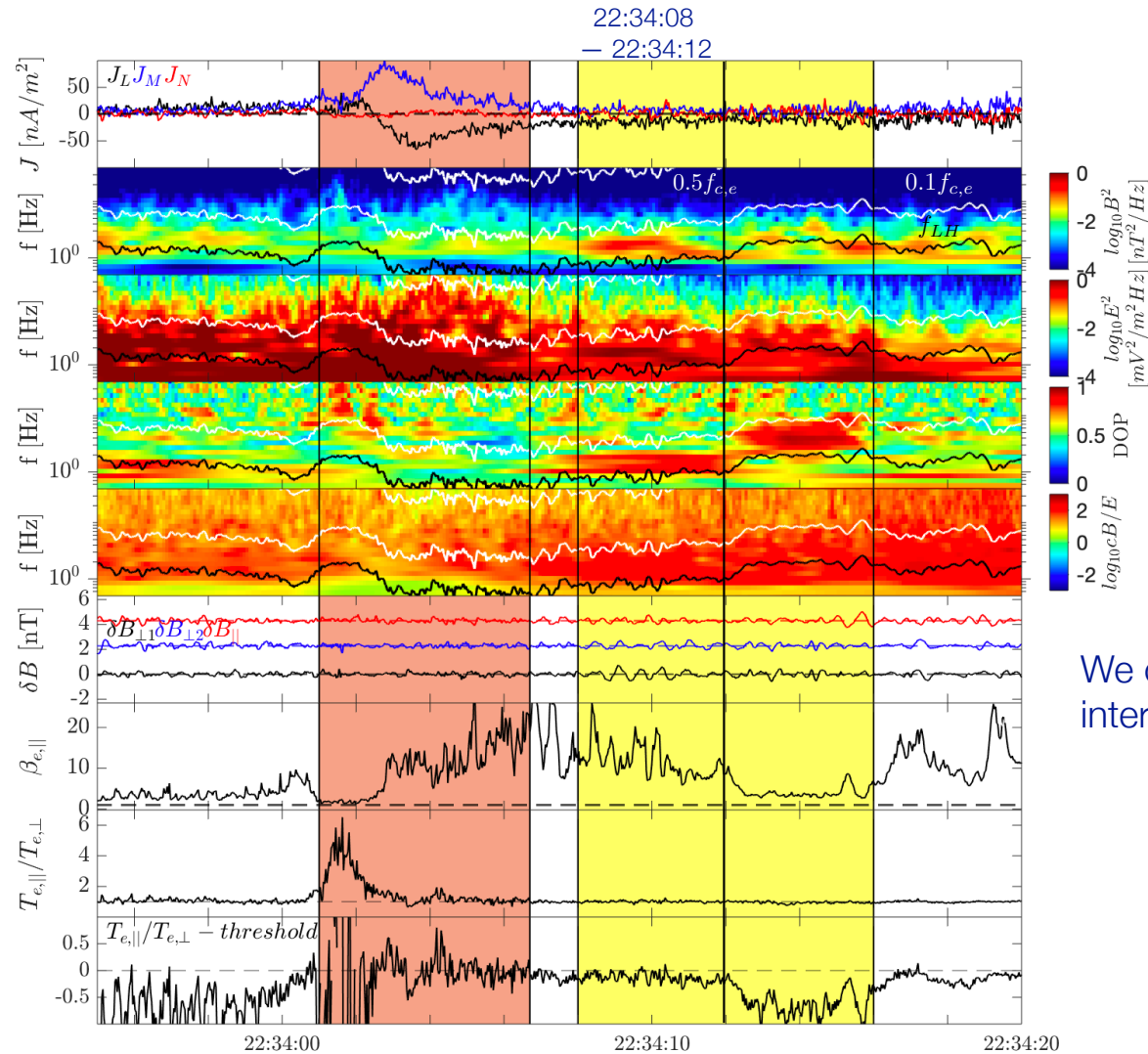
TABLE I. Linear theory results: Fitting parameters for Eq. (1) at thresholds for resonant electron firehose instability.

	$\gamma_m/ \Omega_e $	S'_e	α'_e
→	0.001	1.29	0.97
	0.010	1.23	0.88
	0.025	1.22	0.79
	0.050	1.26	0.71
→	0.10	1.32	0.61
→	0.20	1.36	0.47

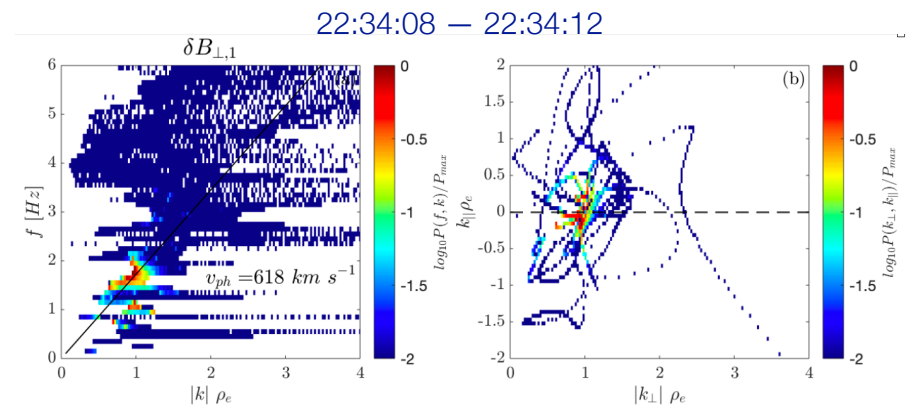
$$\frac{T_{e,\perp}}{T_{e,\parallel}} = 1 - \frac{S'_e}{\beta_{e,\parallel}^{\alpha'_e}}$$

[Gary and Nishimura, Phys. Plasmas, 2003]

Analysis of waves observed in the outflow region



We analyse the waves in the frequency ranges
[1.0 – 2.5] Hz and [2.5 – 6.0] Hz



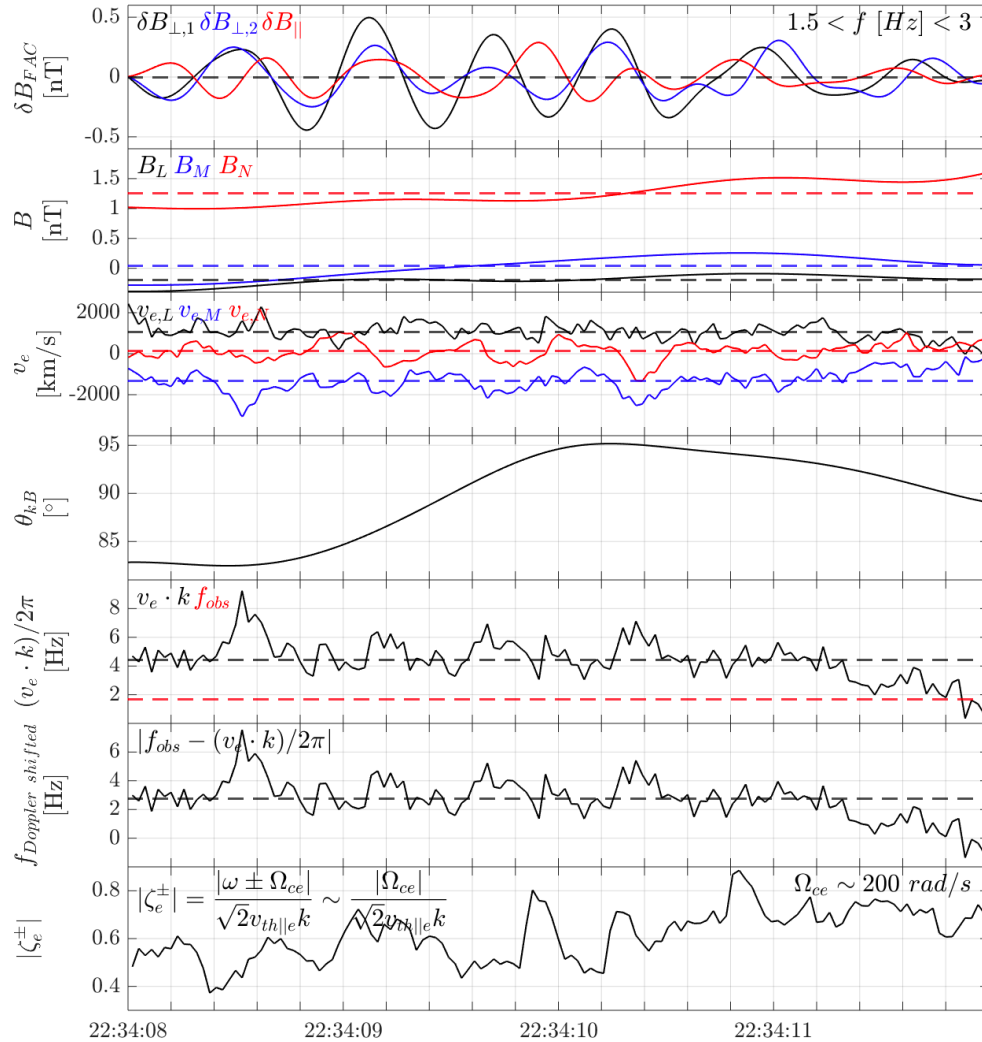
We obtain the dispersion relation using multi-spacecraft interferometry:

$$f(P_{max}(\delta B_{\perp,1})) \sim 1.7 \text{ Hz}$$

$$|\mathbf{k}| \rho_e \sim 1$$

$$\hat{\mathbf{k}} = [0.52, -0.84, 0.11]_{GSM}$$

Analysis of waves observed in the outflow region: subinterval 1 (22:34:08 — 22:34:12)



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We suggest that such fluctuations are consistent with non-propagating electron firehose fluctuations

- $\mathbf{k}$ direction is close to perpendicular to $\mathbf{B}$
- The Doppler shifted frequency $f = f_{obs} - \mathbf{k} \cdot \mathbf{v}_e / 2\pi$ is low
- $|\zeta_e^{\pm}| \lesssim 1$ as expected for the non-propagating firehose mode

The electron firehose fluctuations are observed where the threshold is not reached

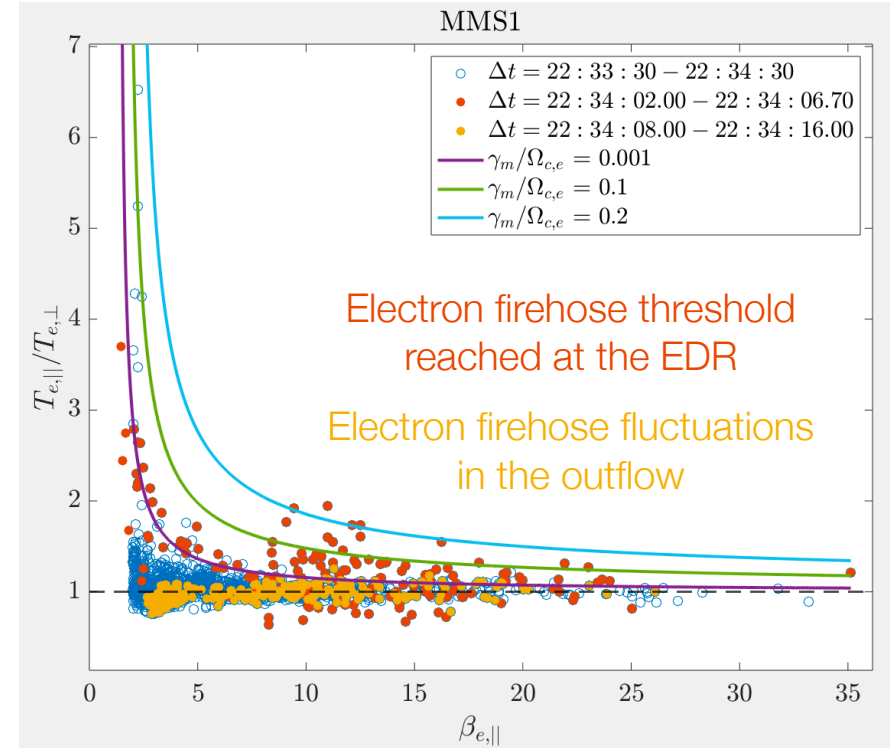
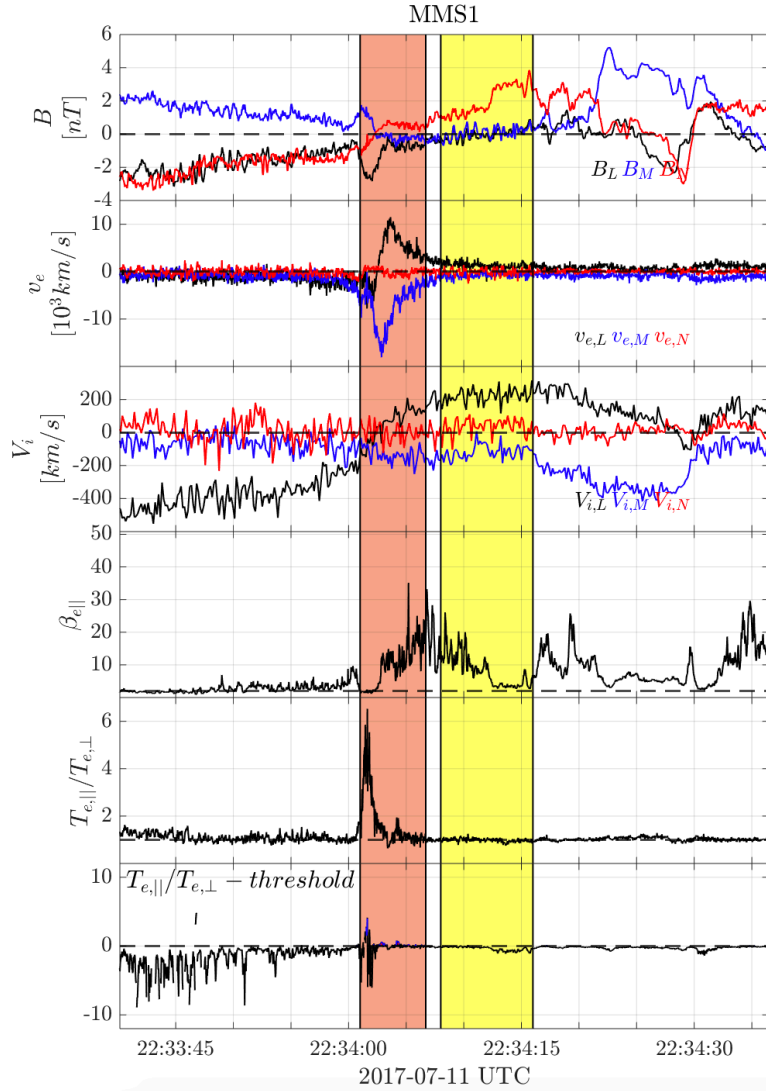


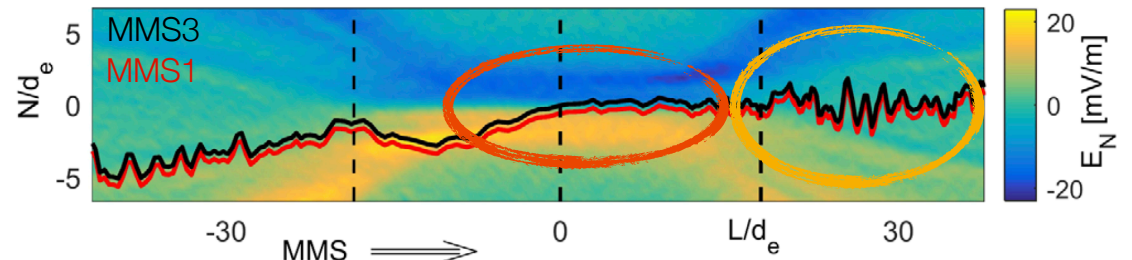
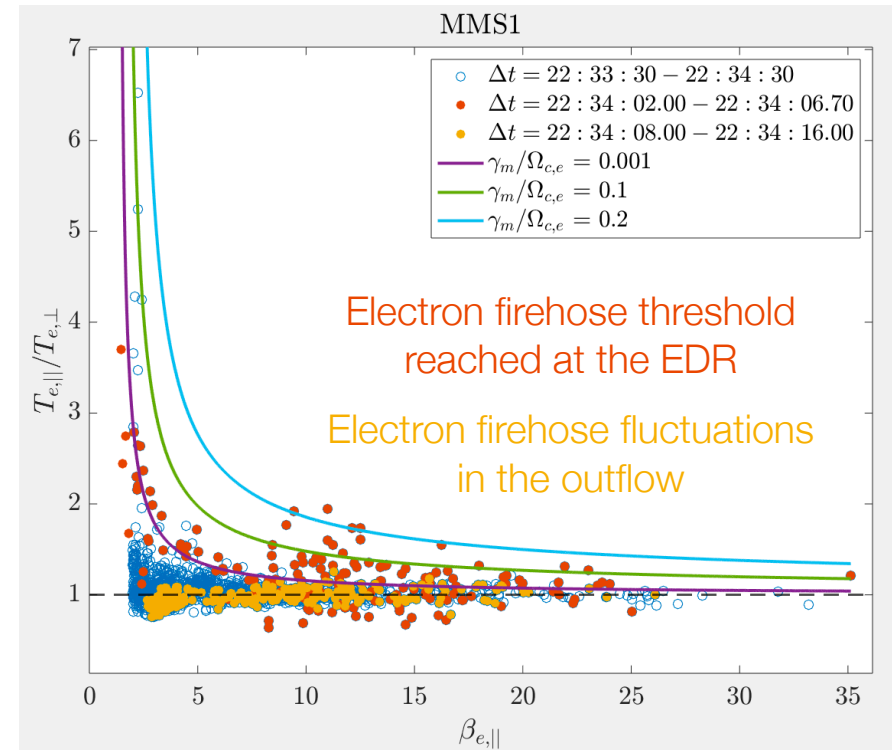
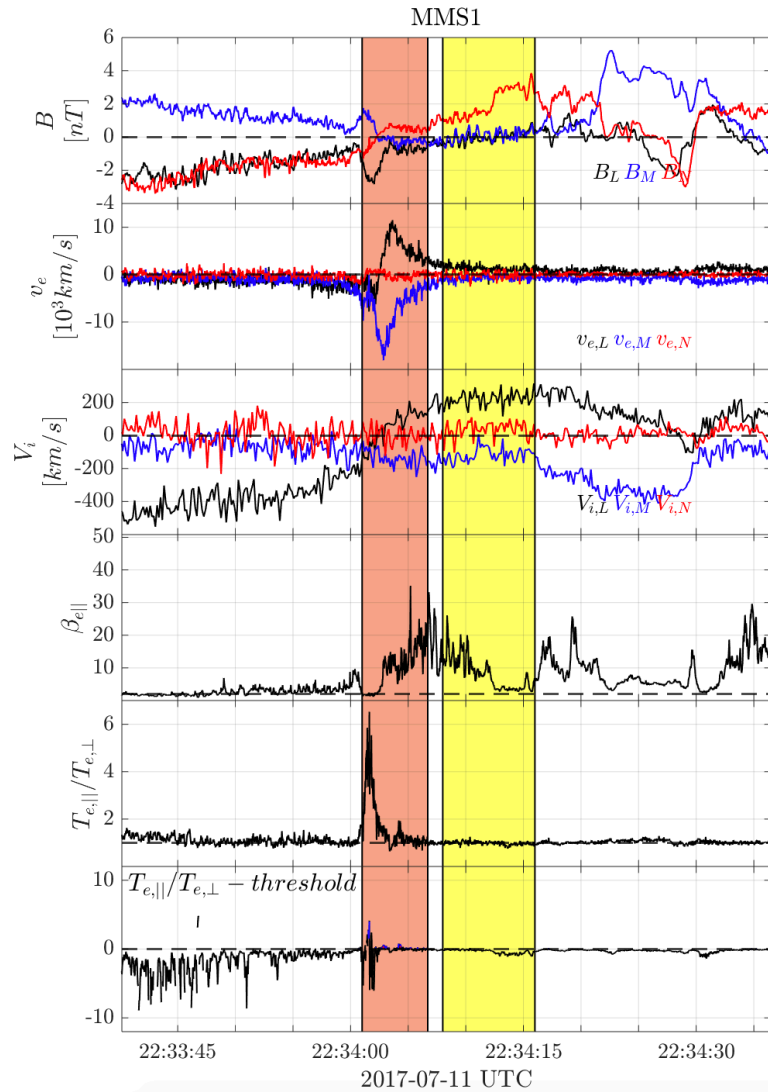
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$$\frac{T_{e,\perp}}{T_{e,\parallel}} = 1 - \frac{S'_e}{\beta_{e,\parallel}^{\alpha'_e}}$$

[Gary and Nishimura, Phys. Plasmas, 2003]

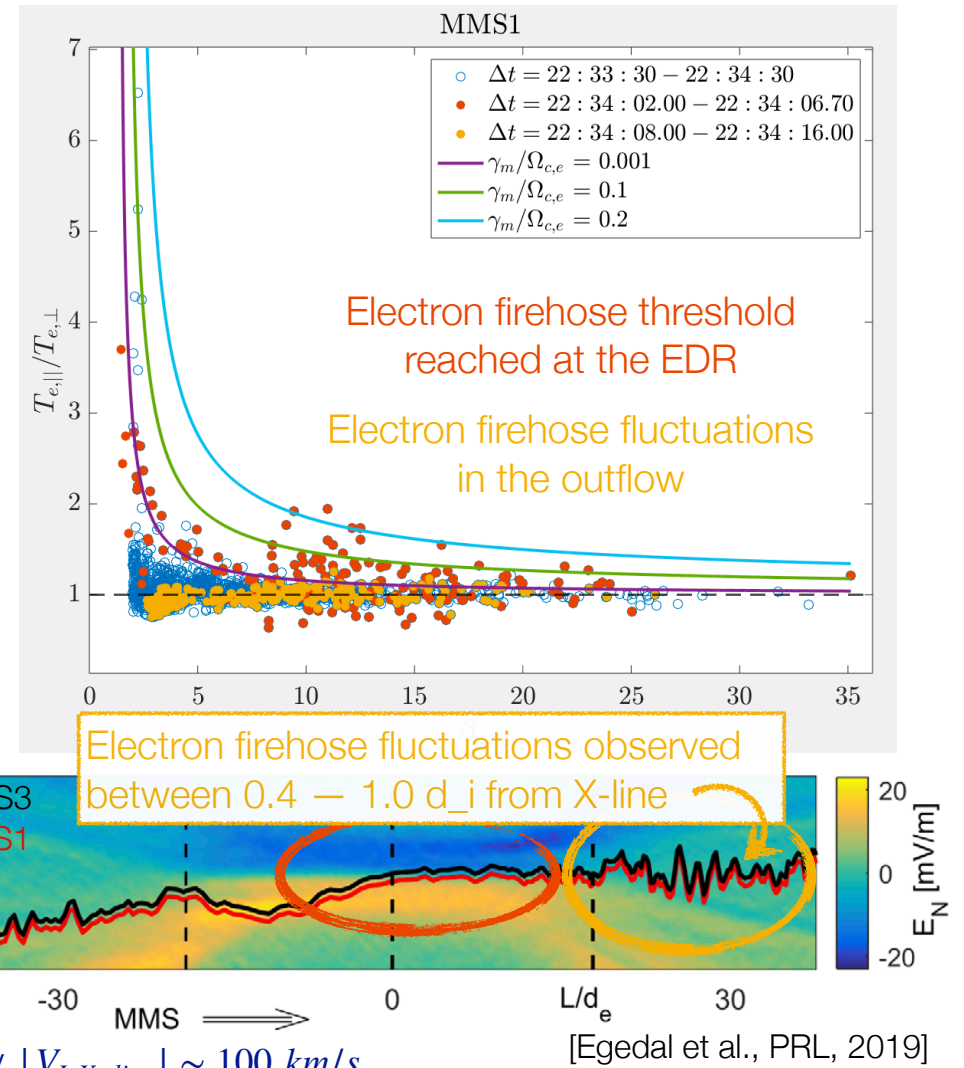
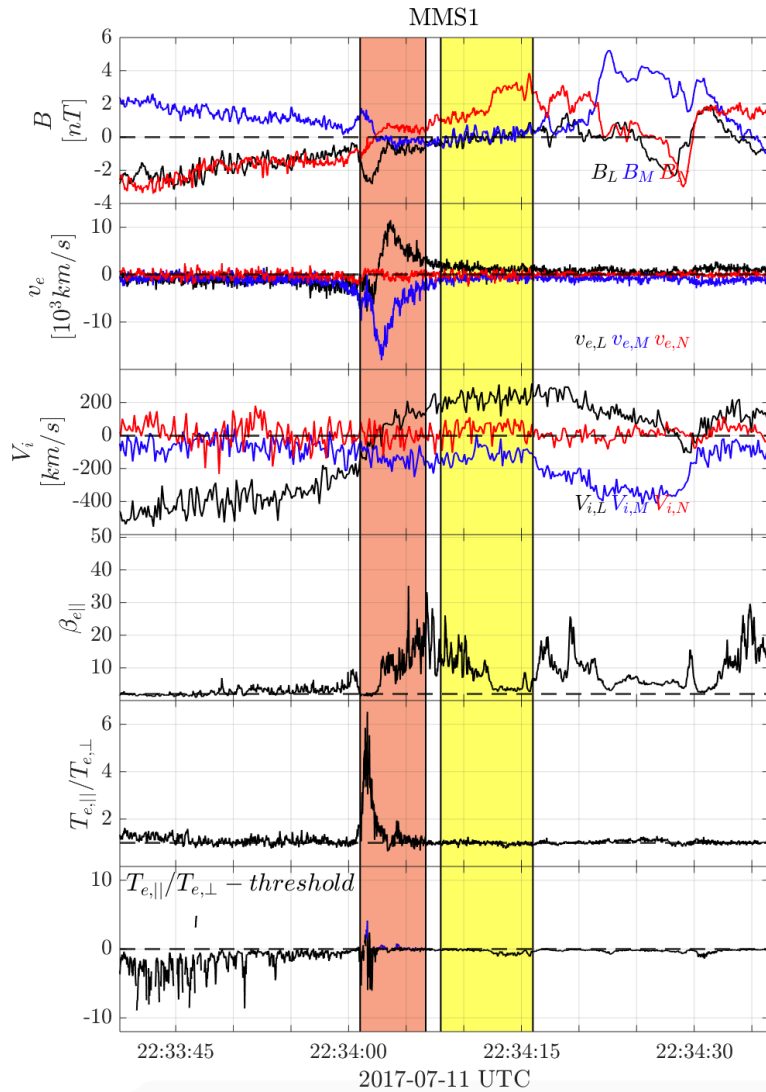
The electron firehose fluctuations are observed where the threshold is not reached



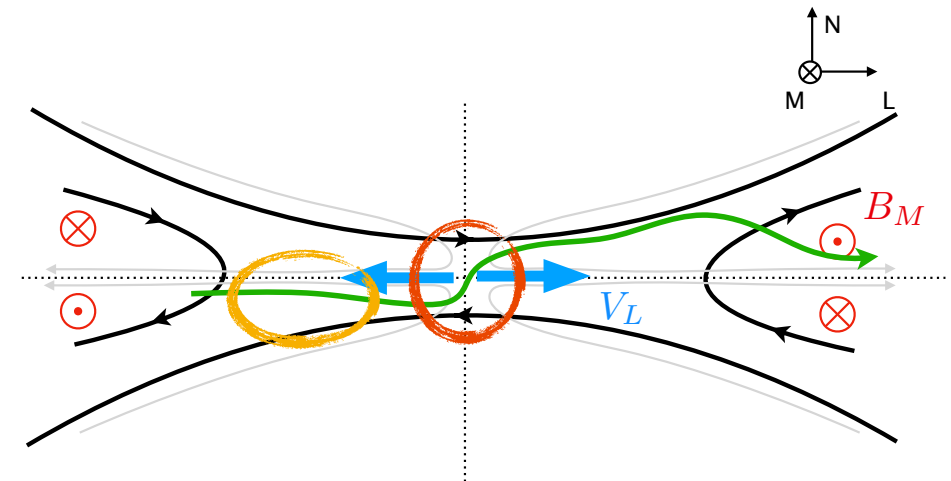
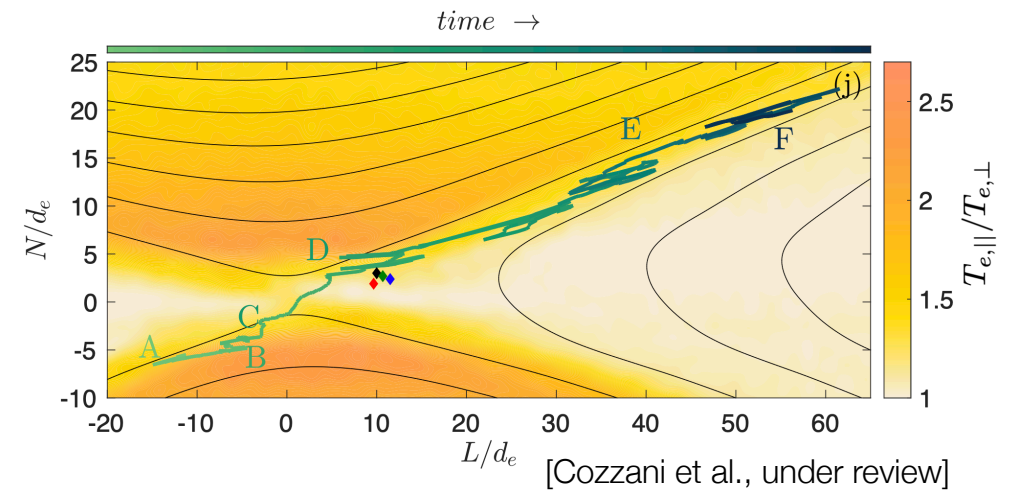
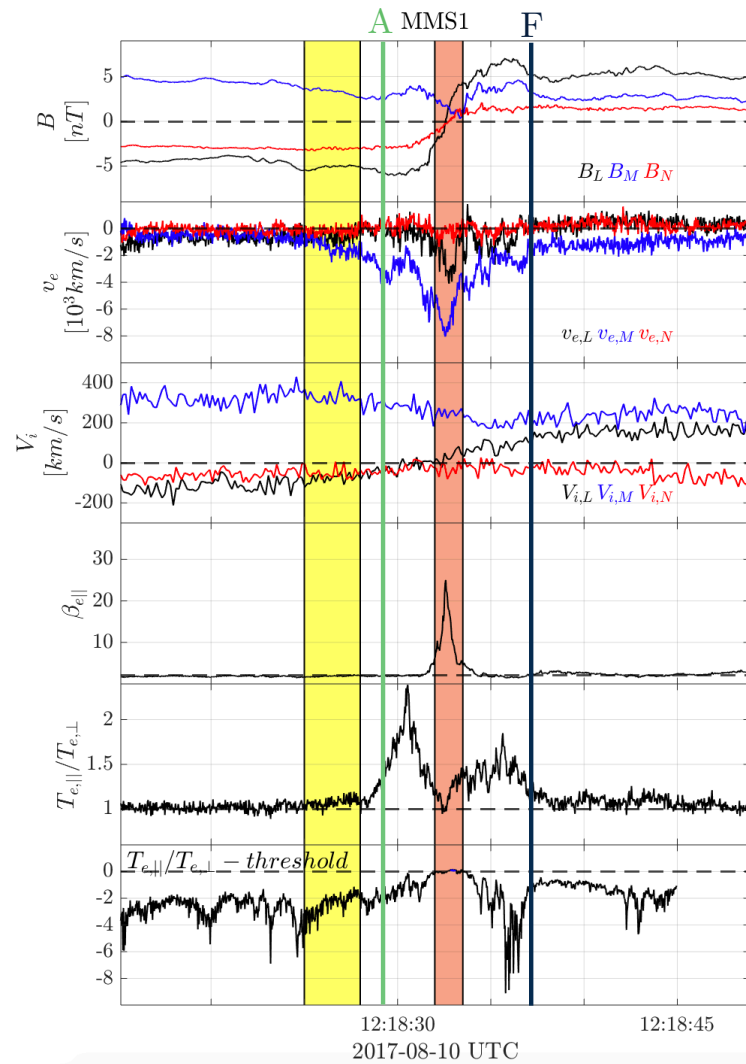
X-line velocity $|V_{L,X-line}| \sim 100 \text{ km/s}$

[Egedal et al., PRL, 2019]

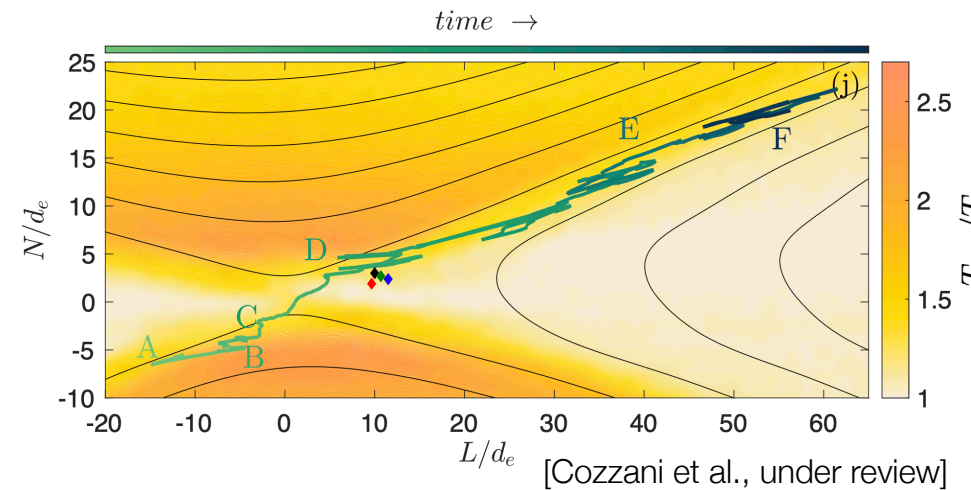
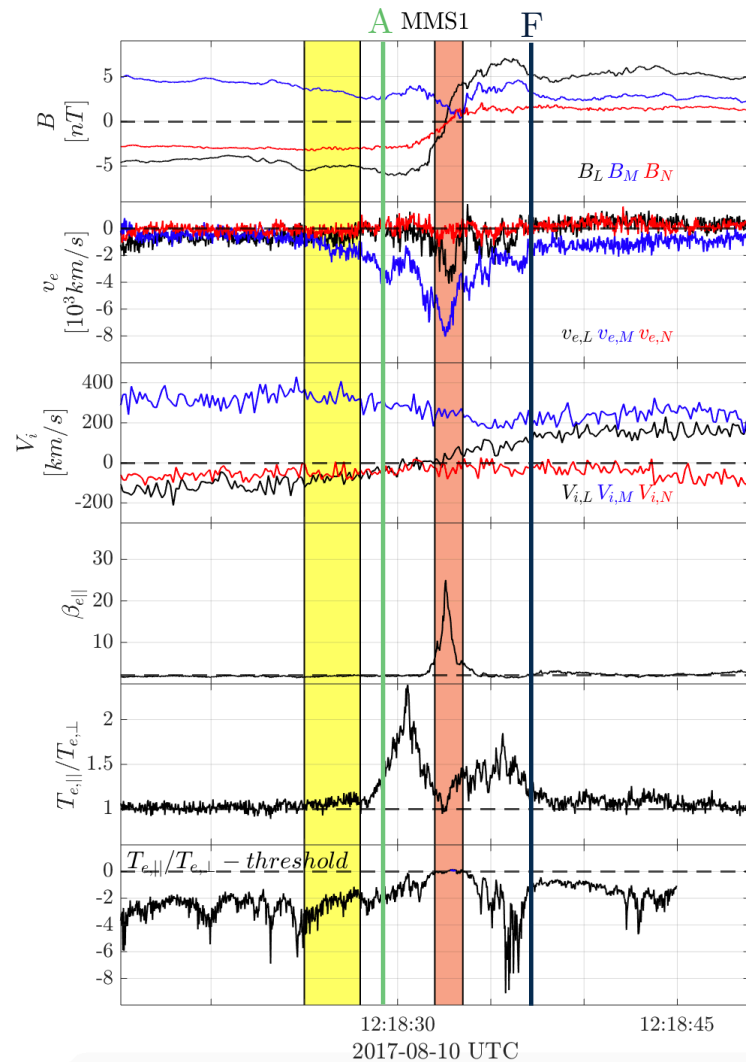
The electron firehose fluctuations are observed where the threshold is not reached



Similar fluctuations are observed in another EDR crossing: 2017-08-10 event



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The electron firehose instability **threshold** is reached **at the EDR**

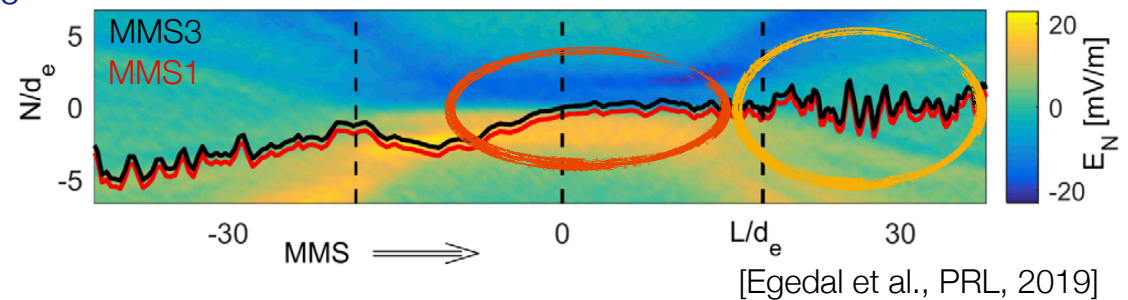
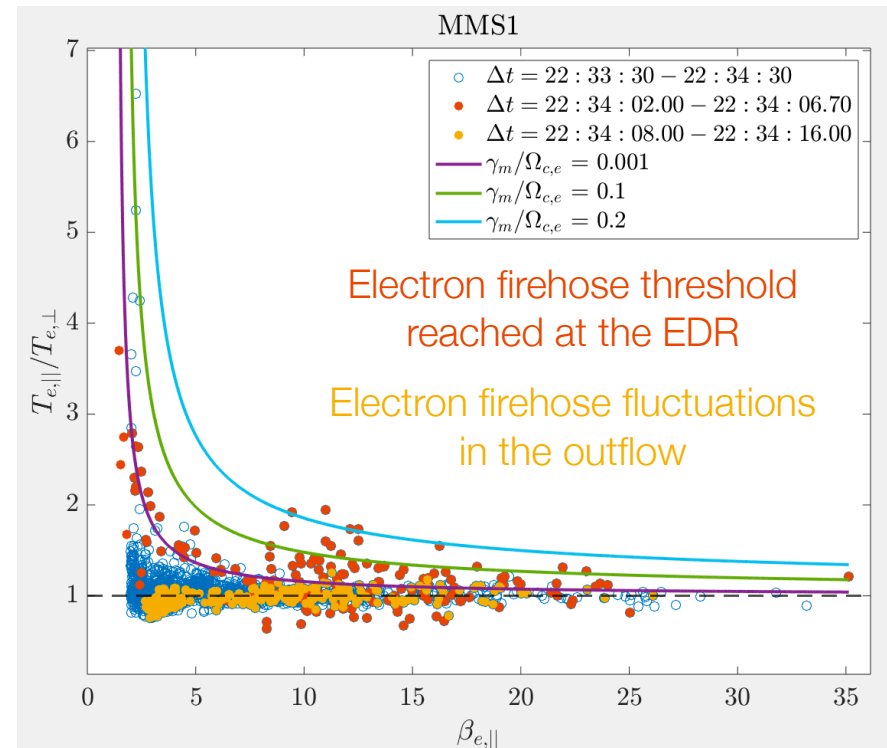
Fluctuations consistent with the **non-propagating electron firehose** mode are observed in the **outflow region**, 1 – 1.8 d_i from the X-line

Conclusions

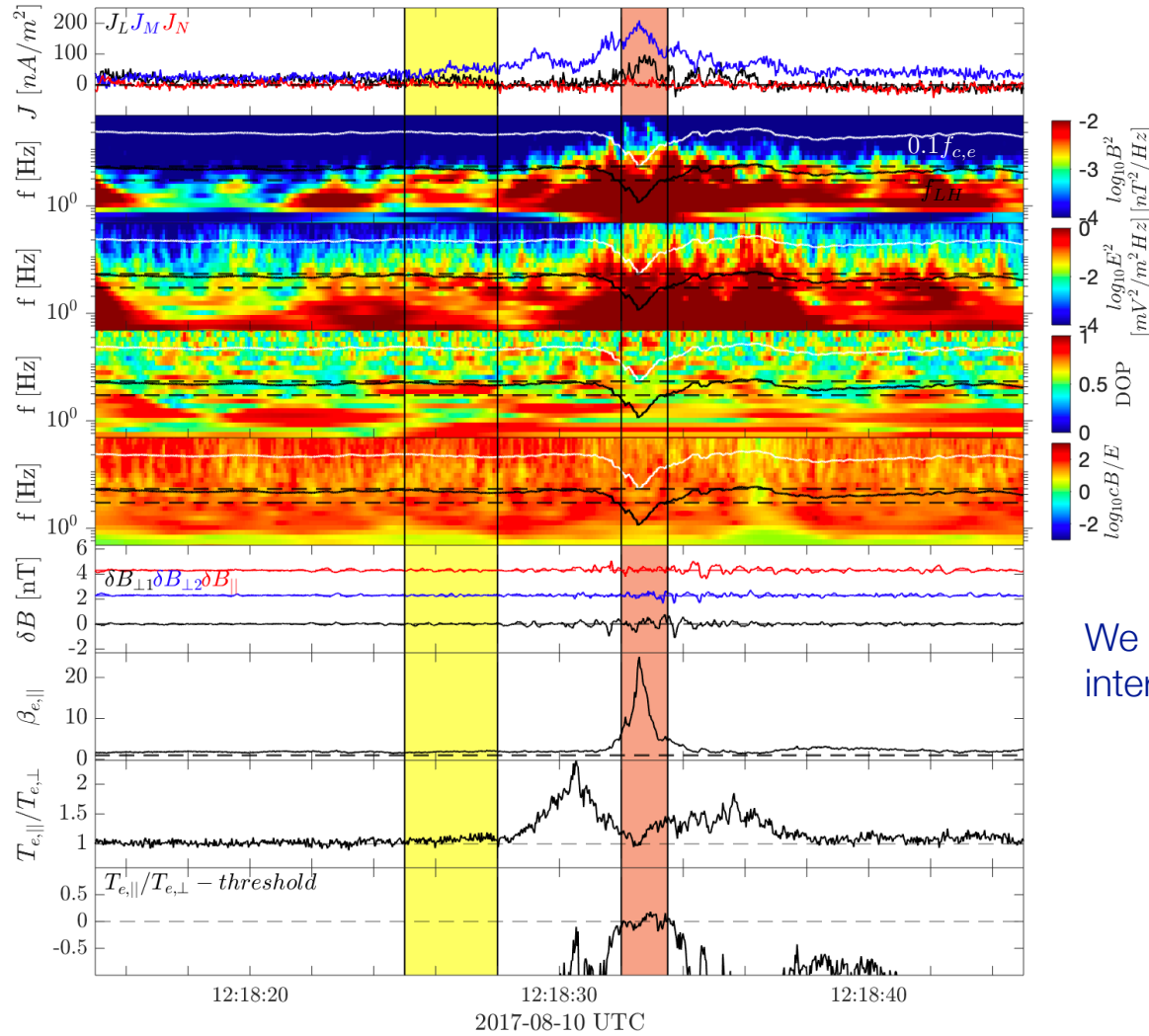
- The electron firehose instability **threshold** is reached **at the EDR**
- Fluctuations consistent with the **non-propagating electron firehose** mode are observed in the **outflow region**, $1 d_i$ away from the X-line
- Similar observations are found in two different EDR crossing in the magnetotail
- We suggest that such fluctuations are originated at the EDR and then *advected* by the reconnection jet in the outflow region
- This is a work in progress!
How are these waves not damped? Which kind of distribution functions are related to the anisotropy close to the EDR?

Thank you for your attention!

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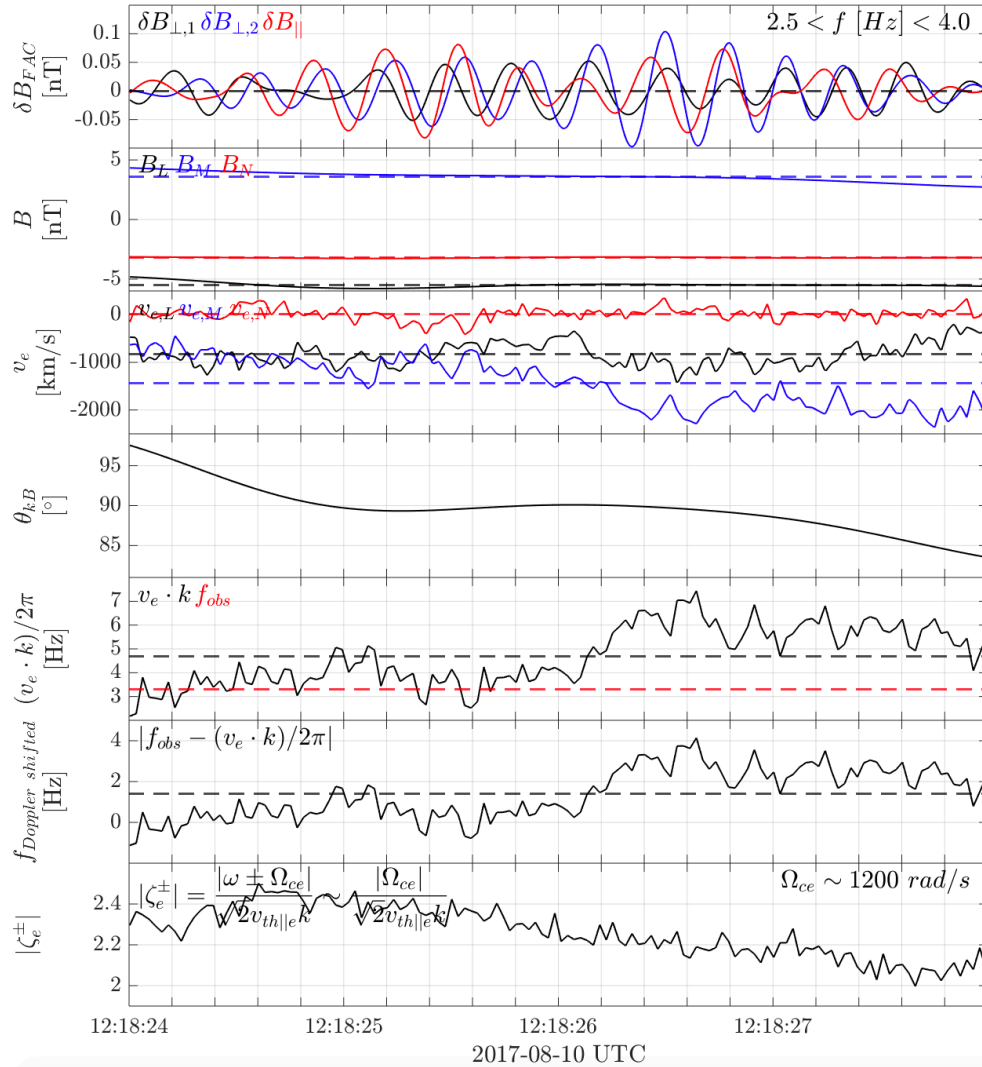
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[2.5 — 5.0] Hz

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$$f(P_{\max}(\delta B_{\perp,1})) \sim 3.3 \text{ Hz}$$

$$|\mathbf{k}| \rho_e \sim 0.4$$

Analysis of waves observed in the outflow region: EDR 2017-08-10



$$f(P_{max}(\delta B_{\perp,1})) \sim 3.3 \text{ Hz}$$

$$|\mathbf{k}| \rho_e \sim 0.4$$

$$\hat{\mathbf{k}} = [-0.60 \quad -0.79 \quad 0.14]$$

We suggest that such fluctuations are consistent with non-propagating electron firehose fluctuations

- $\mathbf{k}$ direction is close to perpendicular to $\mathbf{B}$

- The Doppler shifted frequency $f = f_{obs} - \mathbf{k} \cdot \mathbf{v}_e / 2\pi \sim 0$

- $|\zeta_e^{\pm}| \sim 2$ ($|\zeta_e^{\pm}| \lesssim 1$ is expected for the non-propagating firehose mode)