Multi-satellite MMS Analysis of Electron Holes in the Earth's Magnetotail: Origin, Properties, Velocity Gap, and Transverse Instability

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solitary waves around fast plasma flows

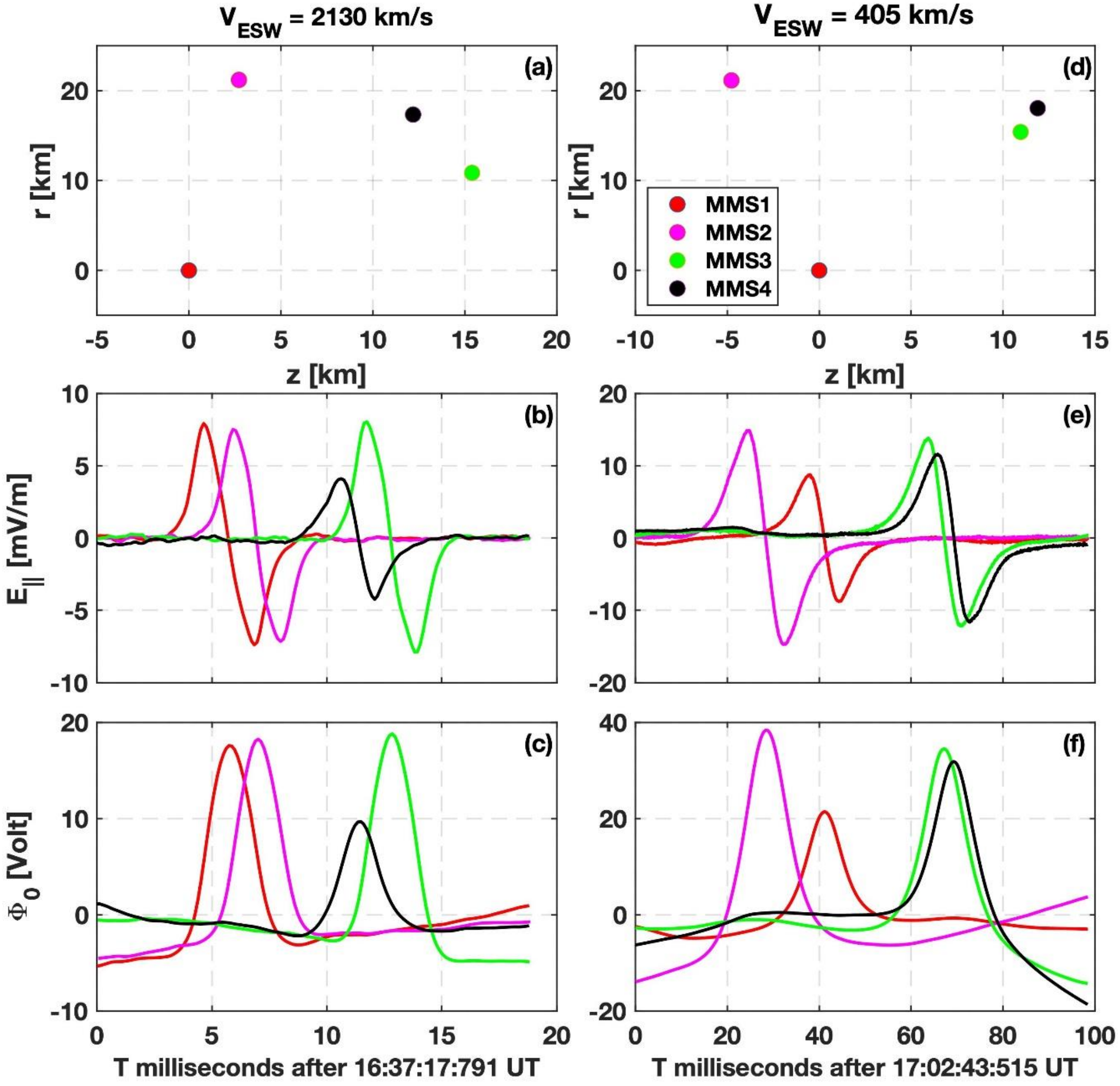


Table 1
List of the Fast Flow Event Considered in the Statistical Analysis

No.	Date	Time	ESW observed on: One spacecraft	Three spacecraft	Four spacecraft
1	2017-07-29	15:45–16:10	905	538	232
2	2017-08-04	16:15–17:10	895	280	216
		19:10–19:25	641	234	68
		09:00–09:10	3,339	162	119
3	2017-08-06	05:09–05:16	265	30	21
		09:21–09:33	576	141	88
4	2017-08-07	16:00–17:00	1,776	1,041	638
	Total		8,388	2,426	1,382

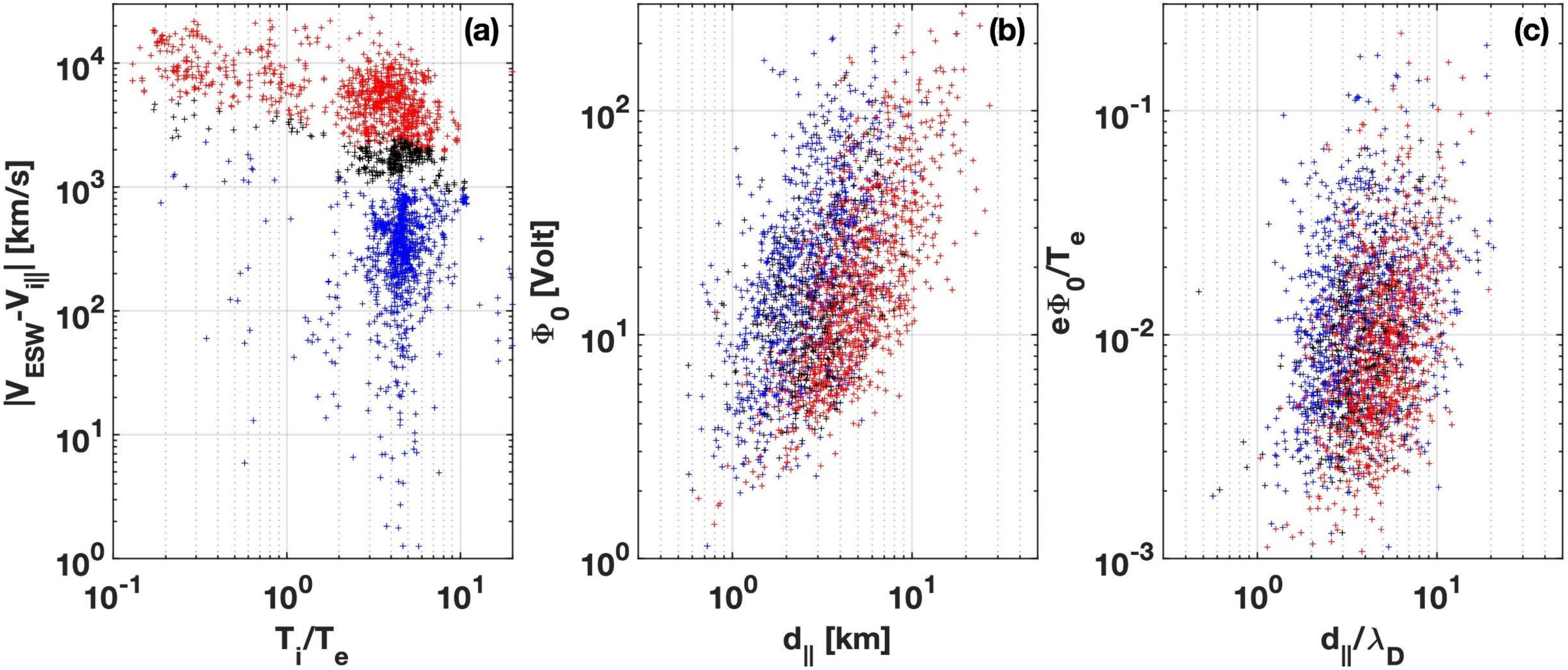
- We have selected more than **8300 ESW** measured aboard at least one of MMS spacecraft
- Among these ESW more than **2400 ESW** were measured aboard at least three MMS spacecraft and more than **1300 ESW** were measured aboard all three MMS spacecraft
- The use of multi-satellite interferometry allows accurate estimates of velocity and other properties of ESW

ESW properties & origin I

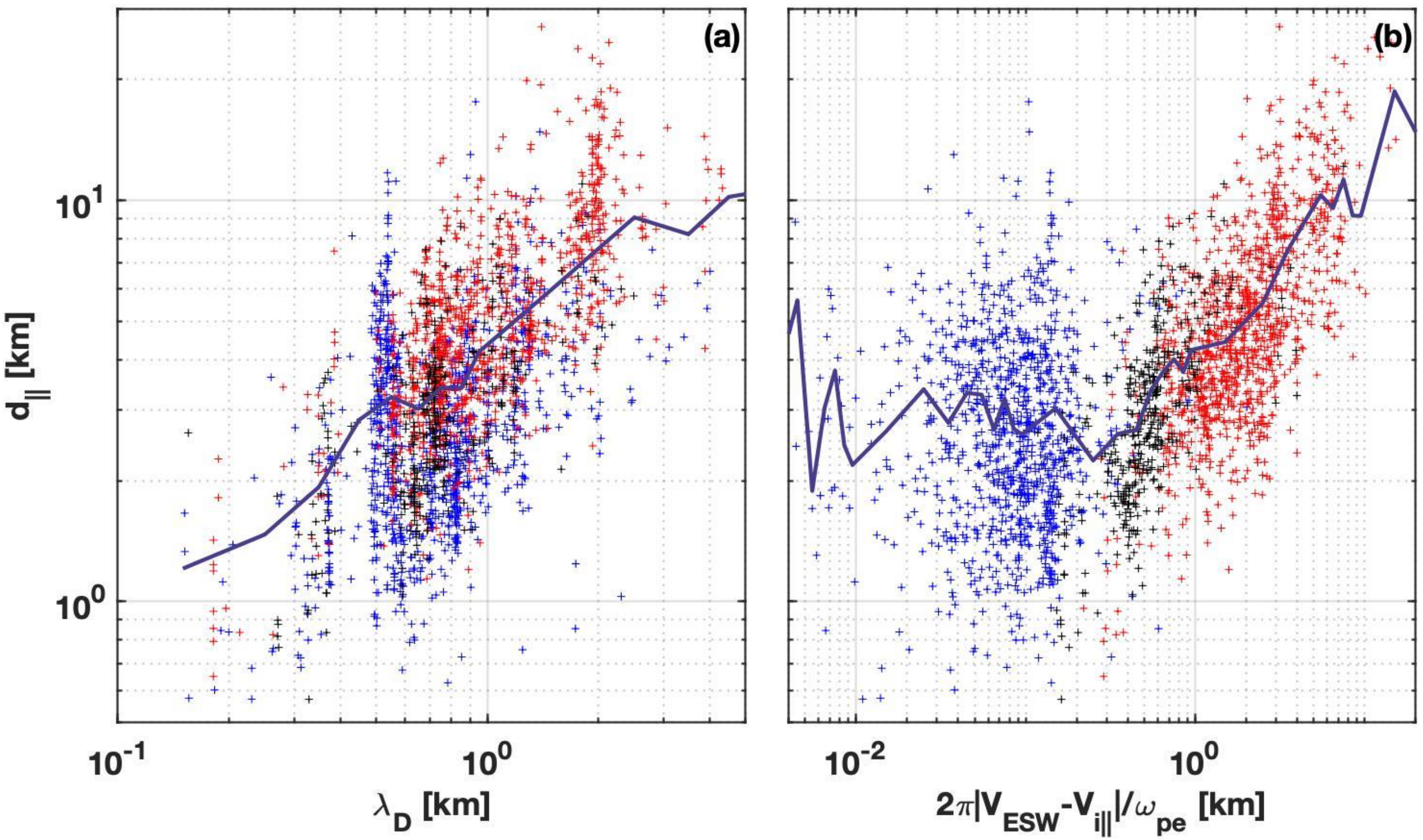
slow EHs: $|V_{ESW} - V_{i||}| < 0.05\,V_{Te}$

medium EHs: $0.05\,V_{Te} < |V_{ESW} - V_{i||}| < 0.1\,V_{Te}$

fast EHs: $|V_{ESW} - V_{i||}| > 0.1\,V_{Te}$



ESW properties & origin II

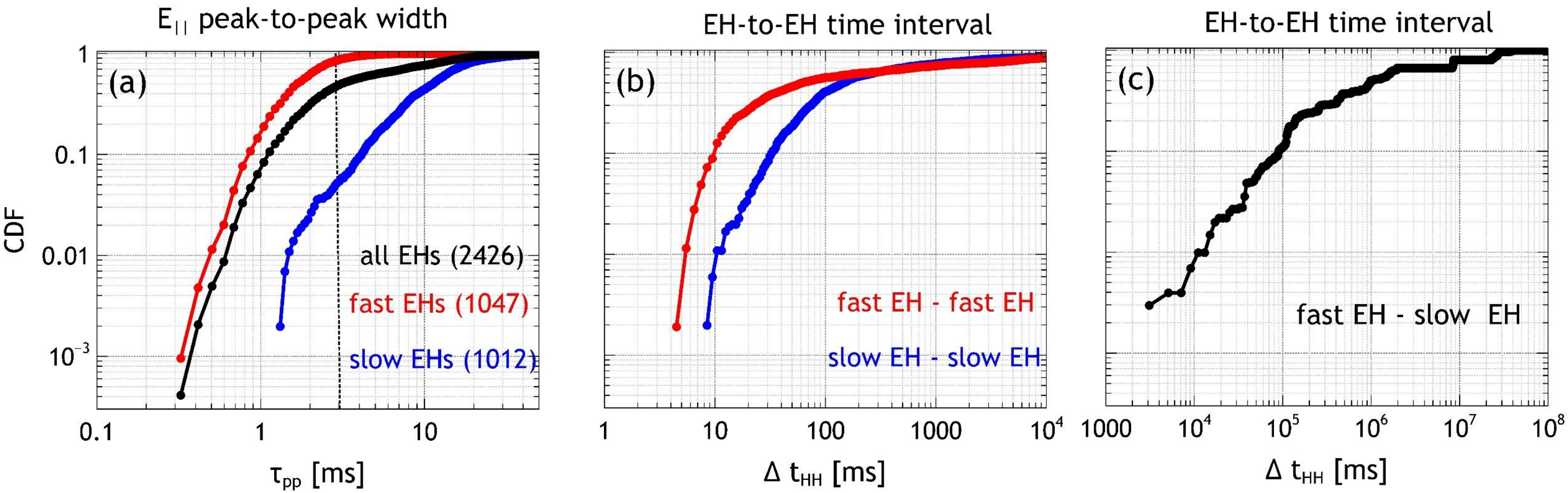


There is a correlation between velocity and spatial scale of fast EHs and there is no such correlation for slow EHs

ESW properties indicate that

- fast EHs are produced by electron bump-on-tail instabilities
- slow EHs can be produced either by Buneman or electron two-stream instability, but we excluded classical Buneman instability as a potential source of slow EHs

slow and fast EHs are produced by instabilities operating independently!

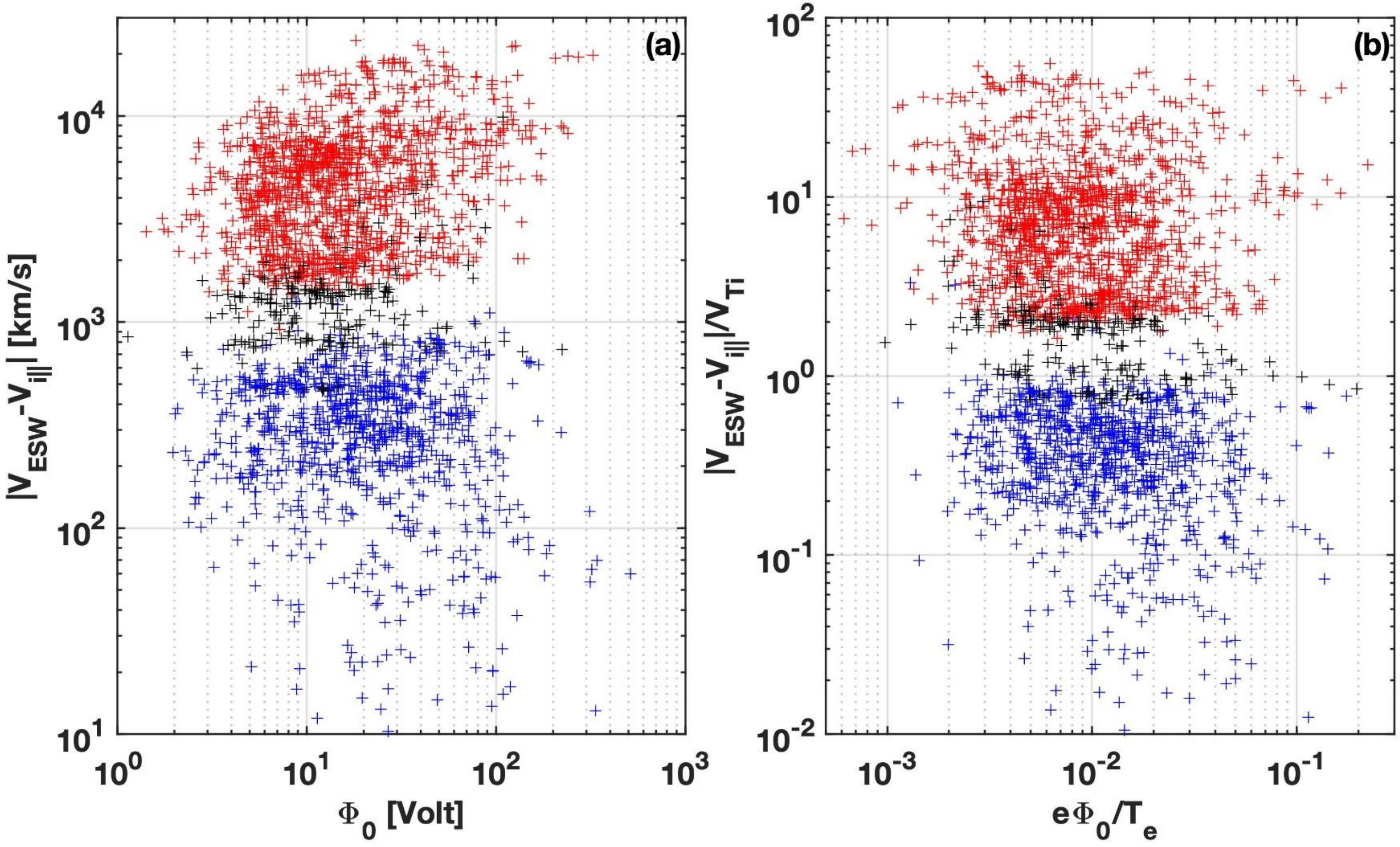


temporal widths of fast and slow EHs differ by one order of magnitude

the time delay between fast-fast and slow-slow EHs is 1 ms -100 ms (some EHs are rather isolated)

the time delay between fast and slow EHs is statistically larger than 10 seconds

ESW velocity gap: ion Landau damping or self-acceleration?



There is a gap in the distribution of EH velocities at

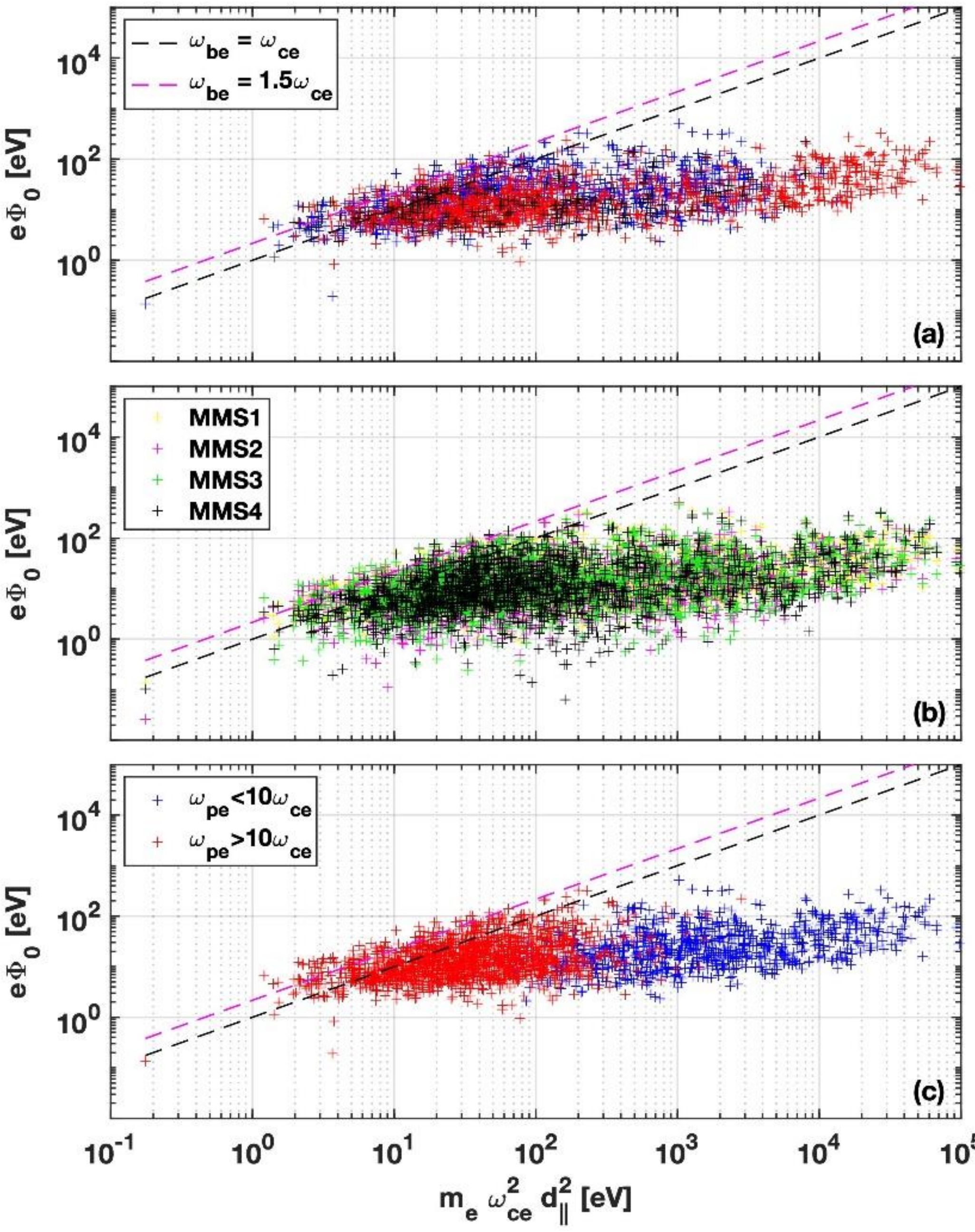
$$V_{Ti} < |V_{ESW} - V_{i||}| < 2\,V_{Ti}$$

Ion Landau damping

self-acceleration [Zhou and Hutchinson, 2018]

the gap at around ion thermal velocity naturally separates electron holes into Fast EHS and Slow EHs

ESW transverse instability



transverse instability criterion

$$\omega_{be} < \Upsilon \omega_{ce}$$

Hutchinson, pre, 2019
Muschietti+, prl, 2000

$\omega_{be} = (e\,\Phi_0/m_e)^{1/2}/d_{||}$ - bounce frequency of trapped electrons

$$e\Phi_0 < \Upsilon^2 m_e \omega_{ce}^2 d_{||}^2$$

MMS measurements show that EH amplitudes are indeed below the transverse instability threshold with Υ~1.5 !

But in addition MMS measurements indicate that EHs at $\omega_{pe} < 10\ \omega_{ce}$ are well below the transverse instability thresh

Saturation by trapping: $\boldsymbol{\omega_{be} < \gamma}$

$$e\Phi_0 < m_e \varpi^2 d_{||}^2$$

$$\varpi = \min(\gamma, \Upsilon\omega_{ce})$$

conclusions

- Electron holes have distinctly different velocities in the plasma rest frame in the range from just a few km/s up to 20,000 km/s, electrostatic potential amplitudes are from a few up to a few hundred Volts and parallel spatial scales are from 0.5 up to 30 km. In normalized units the spatial scales and amplitudes are typically from one to ten Debye lengths, while amplitudes are below 0.1 of electron temperature. The parallel spatial scales are shown to be correlated with a local Debye length.
- The comparison between parallel spatial scale and $|V_{ESW}-V_{i||}|/\omega_{pe}$ revealed that fast electron holes (velocities in the plasma rest frame above 0.1 Vte are highly likely produced by the bump-on-tail instability. The observed parameters of slow electron holes (velocities below 0.05 Vte) do not contradict the generation by warm bi-stream instabilities and we cannot rule out Buneman type instabilities either.
- There is a gap in the distribution of electron hole velocities around a local ion thermal velocity The gap is suggested to be the evidence for self-acceleration process of electron holes recently reported in Vlasov simulations, while the alternative/additional interpretation is the ion Landau damping. The gap naturally separates slow an fast electron holes in the velocity space.
- We have shown that electron hole parameters are below the transverse instability criterion, $\omega_{be} < \Upsilon\omega_{ce}$, and provided arguments in favor that the nonlinear saturation criterion, $\omega_{be} < \gamma$, also restricts electron hole parameters. The amplitudes of electron holes at $\omega_{pe} > 10\,\omega_{ce}$are more likely to be controlled by the transverse instability than the amplitudes of electron holes at $\omega_{pe} < 10\,\omega_{ce}$, because the increments of electron streaming instabilities are proportional to ω_{pe}.
- The analysis of temporal characteristics demonstrated that fast and slow electron holes in the Earth's magnetotail can be generally distinguished by the temporal peak-to-peak width of a bipolar $E_{||}$ signal. More than 95% of fast electron holes have t_pp<3 ms and more than 95\% of slow electron holes have t_pp>3 ms.
- The statistical analysis of time intervals between sequentially observed fast and slow electron holes showed that electron holes of the different types are not associated with each other and produced by instabilities, which operate independently.