Direct evidence for magnetic reconnection at the boundaries of magnetic switchbacks with Parker Solar Probe

Froment et al. 2021, A&A, 650, A5

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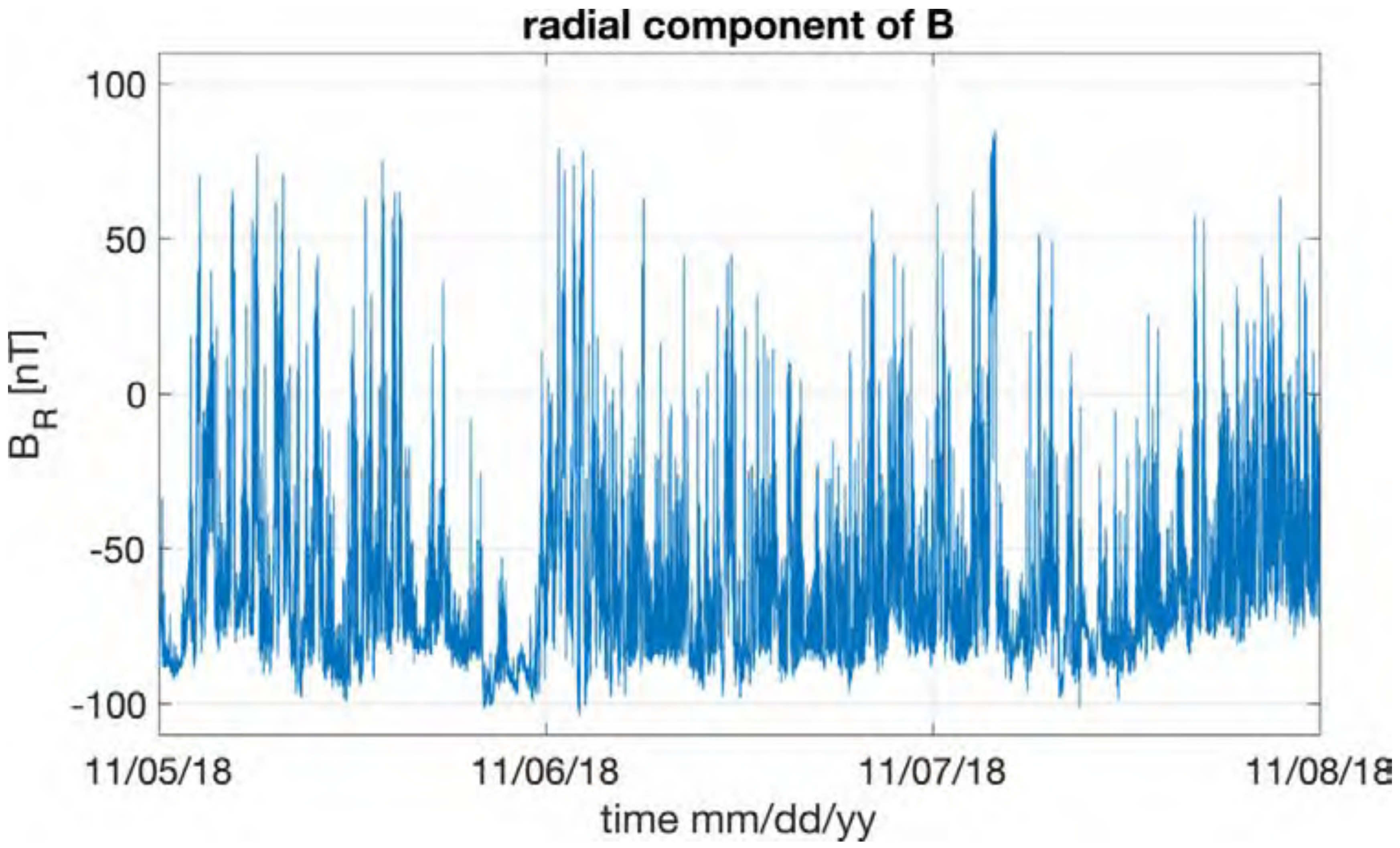
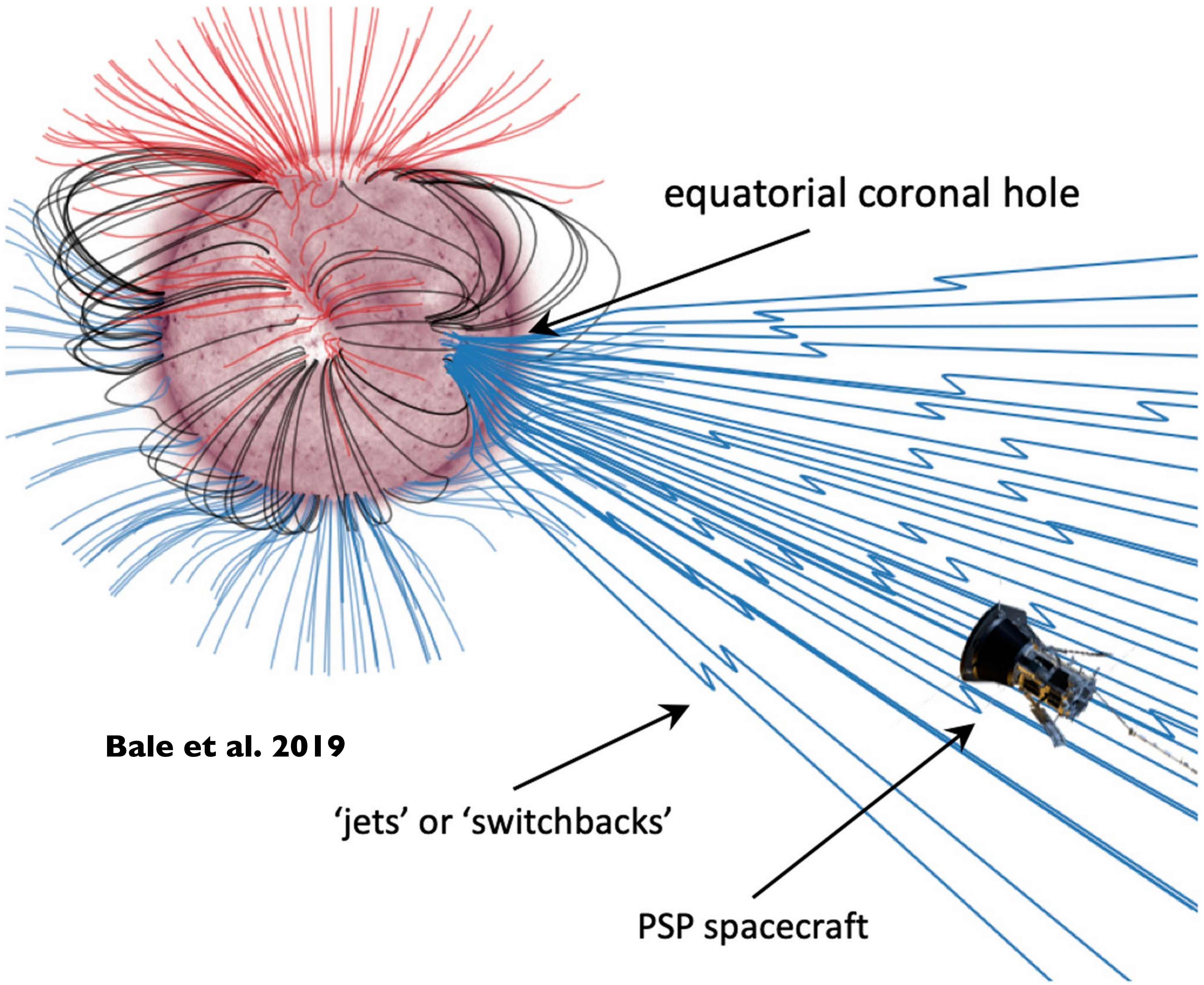
ESPM 16, september 2021

- **Magnetic switchbacks**: localised **deflections** of the magnetic field, mainly in its radial component
- **Ubiquitous** in Parker Solar Probe perihelia observations, they strongly affect the dynamic of the solar wind close to the Sun



Dudok de Wit et al. 2020



Bale et al. 2019

- **No typical angle of deflection** ; many small deflections, full reversal more sporadic
- Can last a few seconds to a few hours

- **Implication for the young solar wind: localised heating? acceleration?**

- **Origin and formation unclear**

In situ

Observations e.g. Ruffolo et al. 2020

Models/numerical simulations

Wave growth generated by the **expansion** of the structures (Squire et al. 2020)

Shear-driven turbulence (Ruffolo et al. 2020)

Reconnection in the atmosphere + fast wind overtaking slow wind (Schwadron & McComas 2021)

Low solar atmosphere

e.g. Dudok de Wit et al. 2020; Krasnoselskikh et al. 2020; Macneil et al. 2020; Woodham et al. 2021; Fargette et al. 2021

Interchange reconnection (Fisk & Kasper 2020; Drake et al. 2021)

Jets (Roberts et al. 2018; Sterling & Moore 2020; He et al. 2020)

If created in the Sun's atmosphere, **the structures can survive long enough in the solar wind** Tenerani et al. (2020)

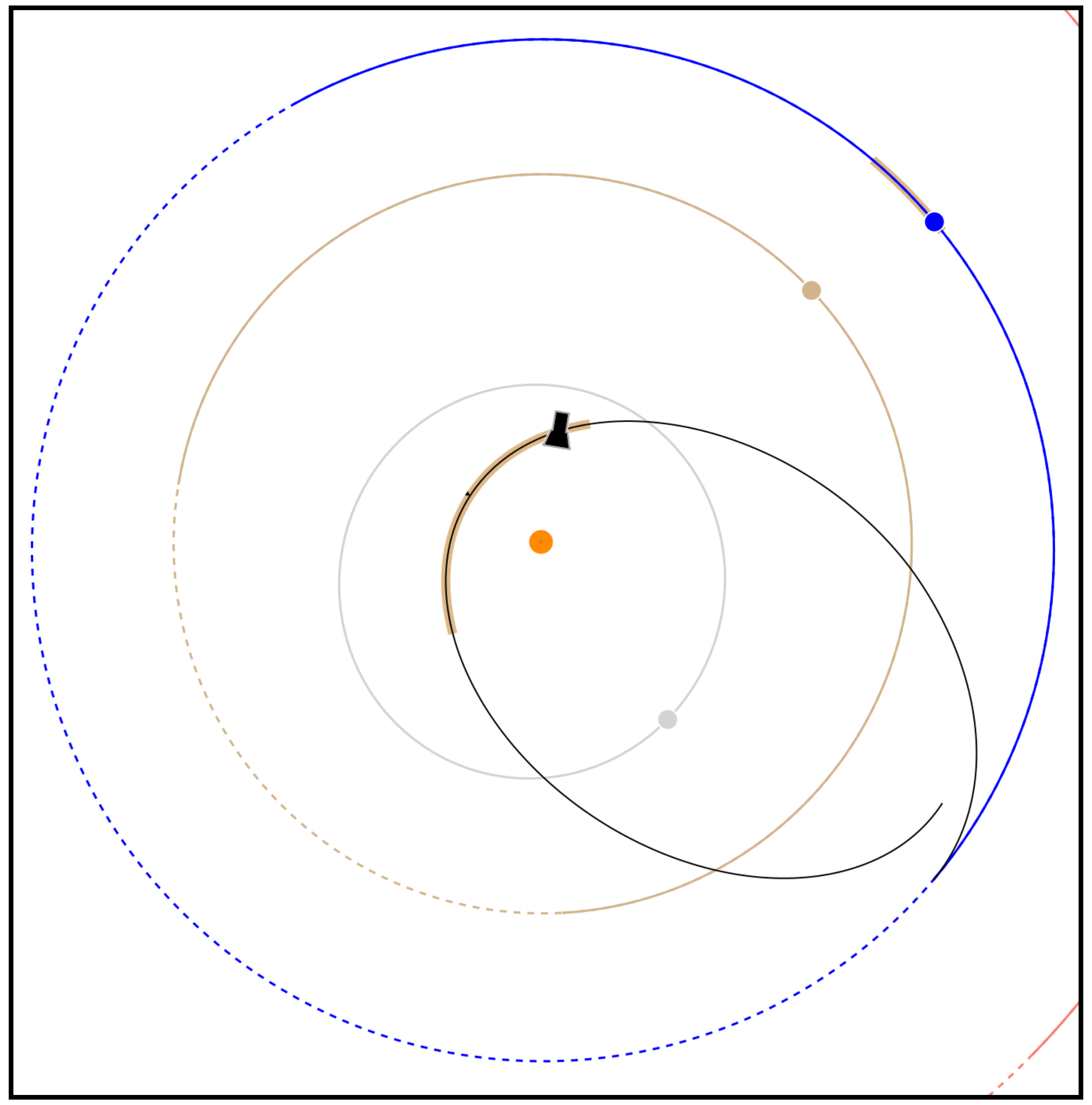
- **Occurence vs. radial distance from the Sun**

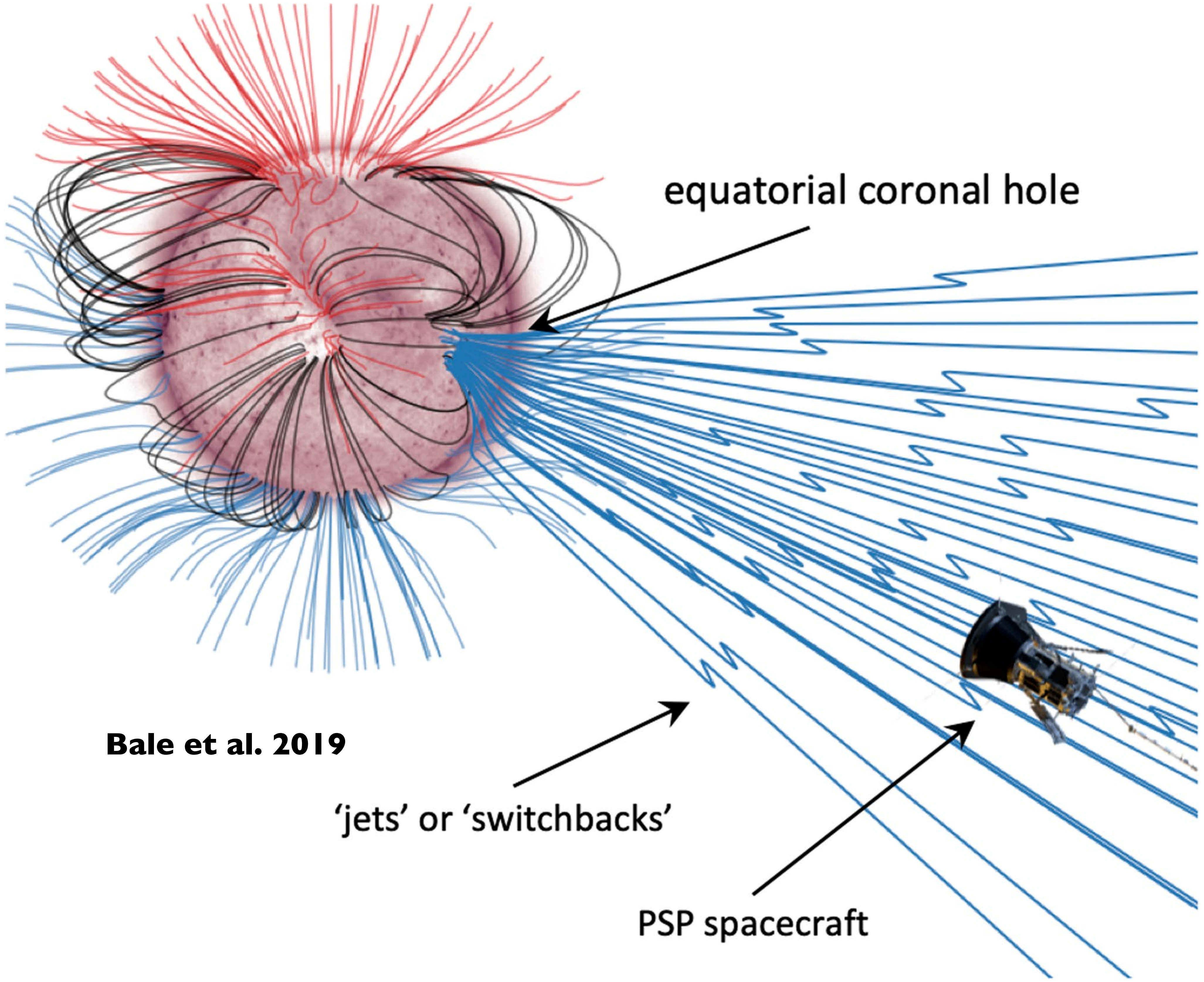
  - **No radial dependance** (Fargette et al. 2021, Mozer et al. 2021), **depends on the source region** (Fargette et al. 2021)
  - **For the same source region, the number of switchbacks decreases with the radial distance from the Sun** (Terenani et al.)

- We analyse the **boundaries** of three **magnetic switchbacks** during PSP's 1st encounter with the Sun

- Data from the FIELDS and SWEAP instruments

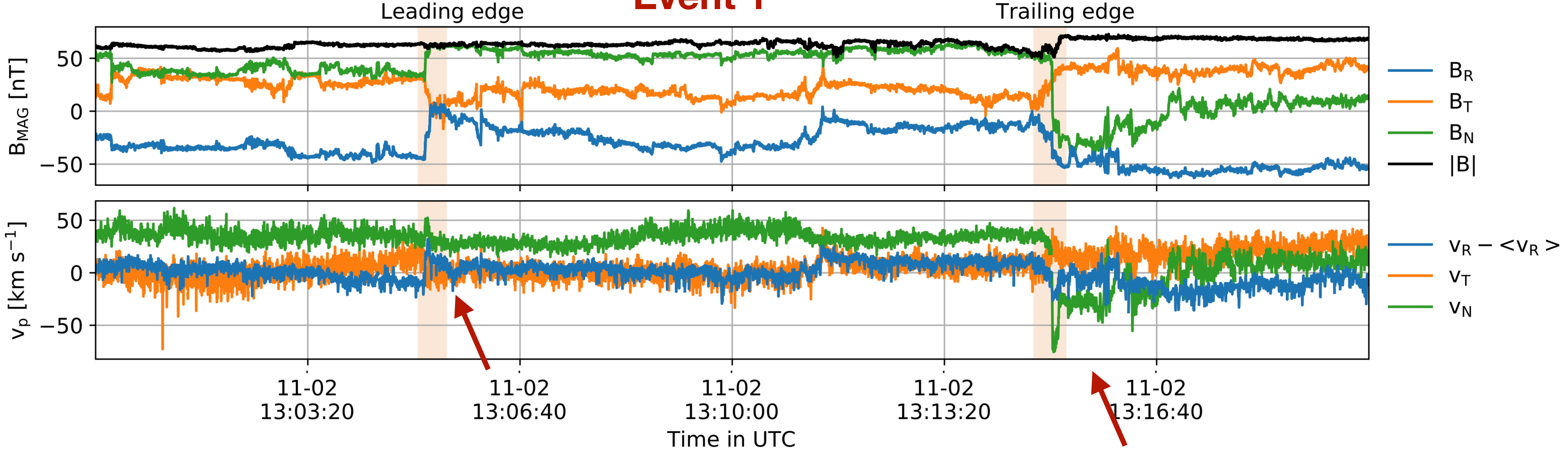
- At that time (Nov, 1 2018 & Nov 2, 2018), PSP was at about **45-48** $R_\odot$ **from the Sun**





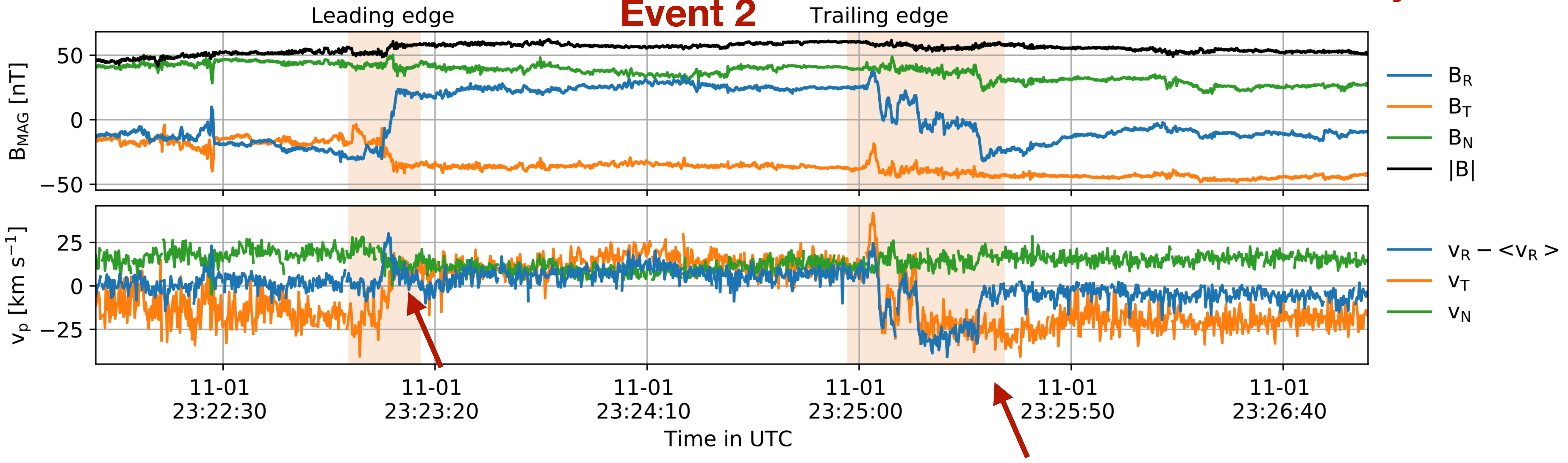
Reconnection exhausts at both boundaries

Event 1

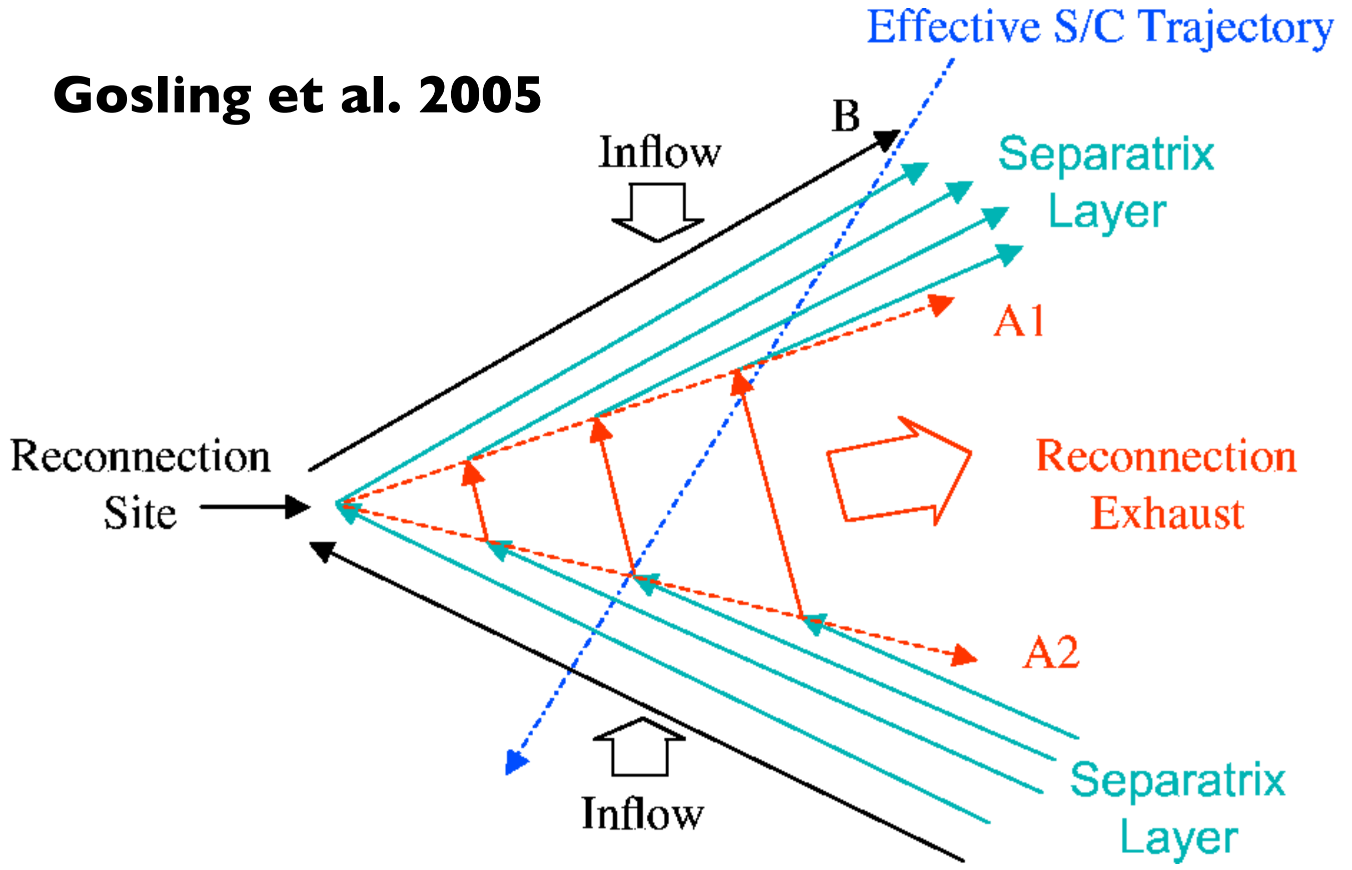


reconnection jets

Event 2



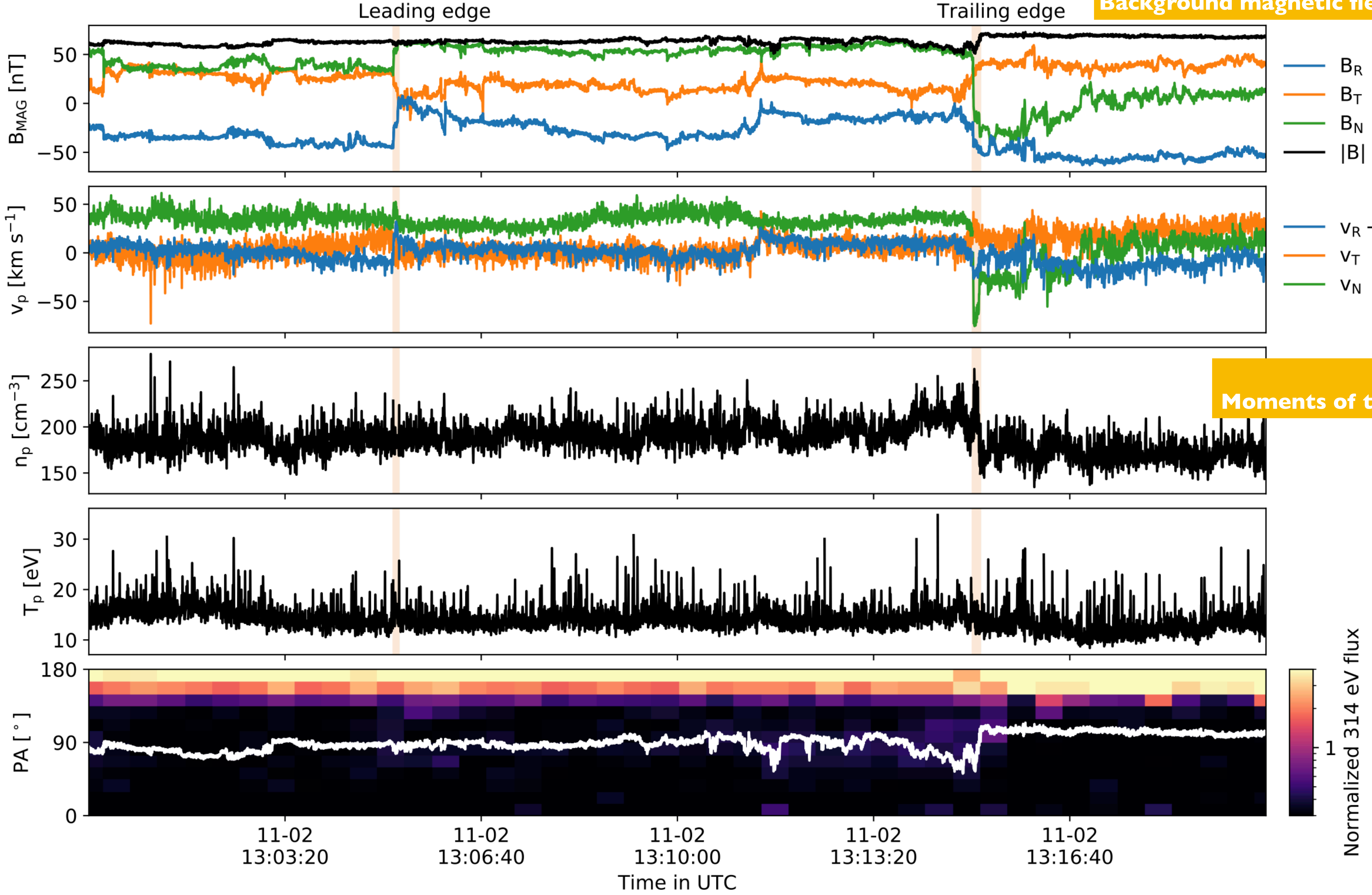
Gosling et al. 2005



Bifurcated current sheet with a central ion flow jet

Event 1: November 2, 2018 13:05 UT

FIELDS/MAG
Background magnetic field vector



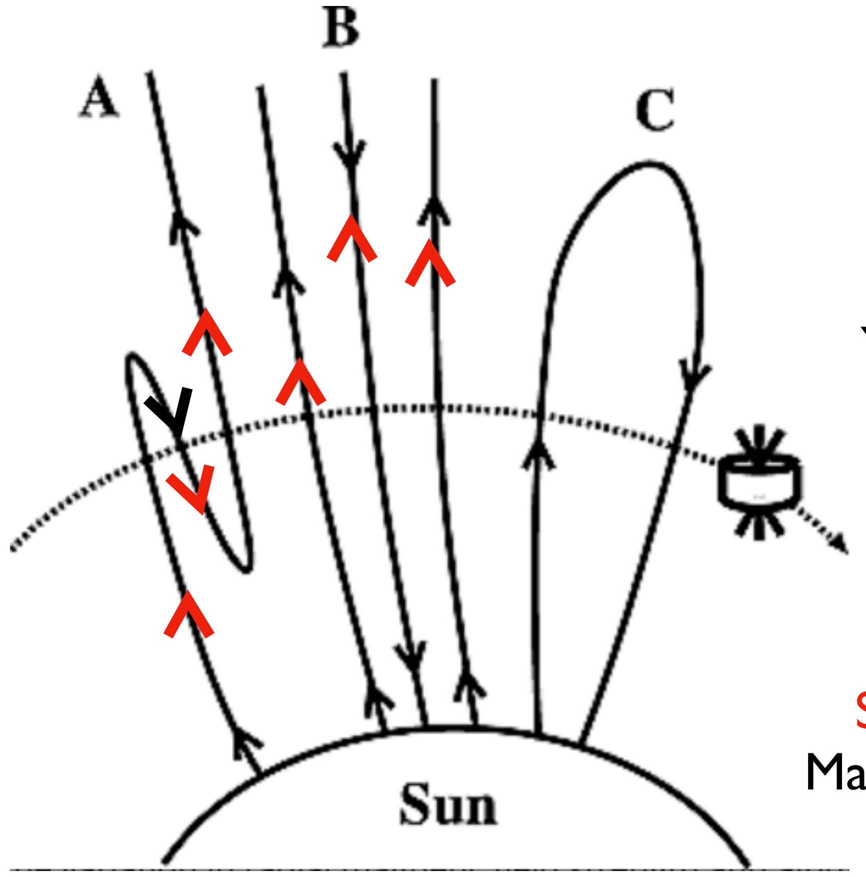
SWEAP/SPC
Moments of the protons distribution functions

SWEAP/SPAN-e
Electrons

Properties of the structure:

- 58°and 81° magnetic shear at the boundaries
- Moderate proton velocity enhancement but consistent with switchbacks properties

The strahl, i.e. the high-energy & field-aligned electron population, **maintains its orientation inside the switchbacks** (Kasper et al. 2019)

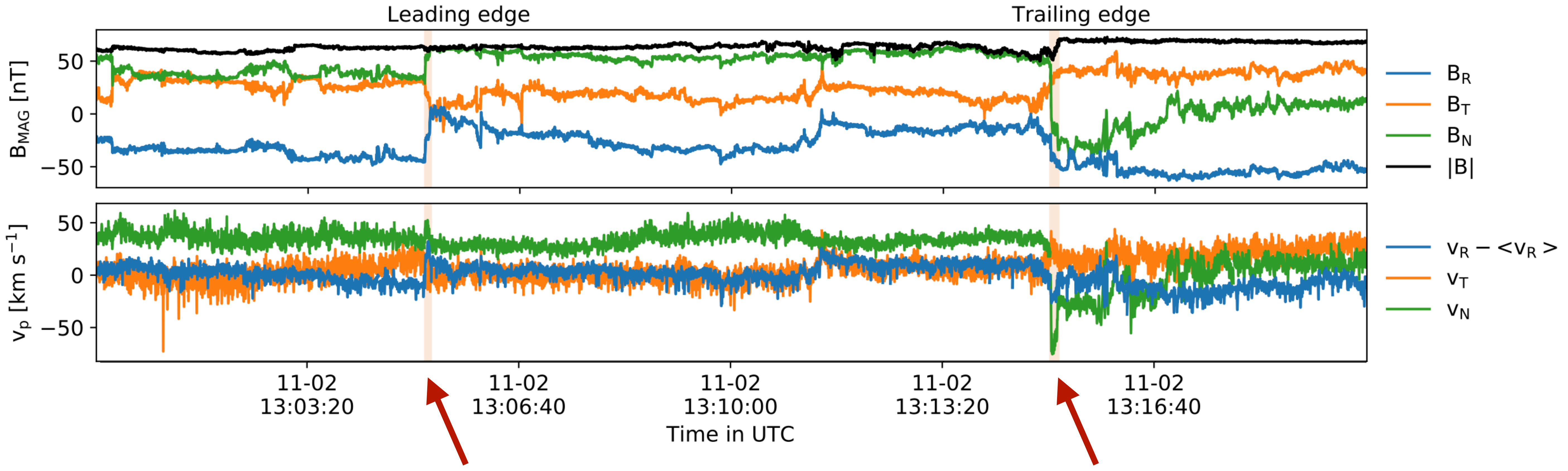


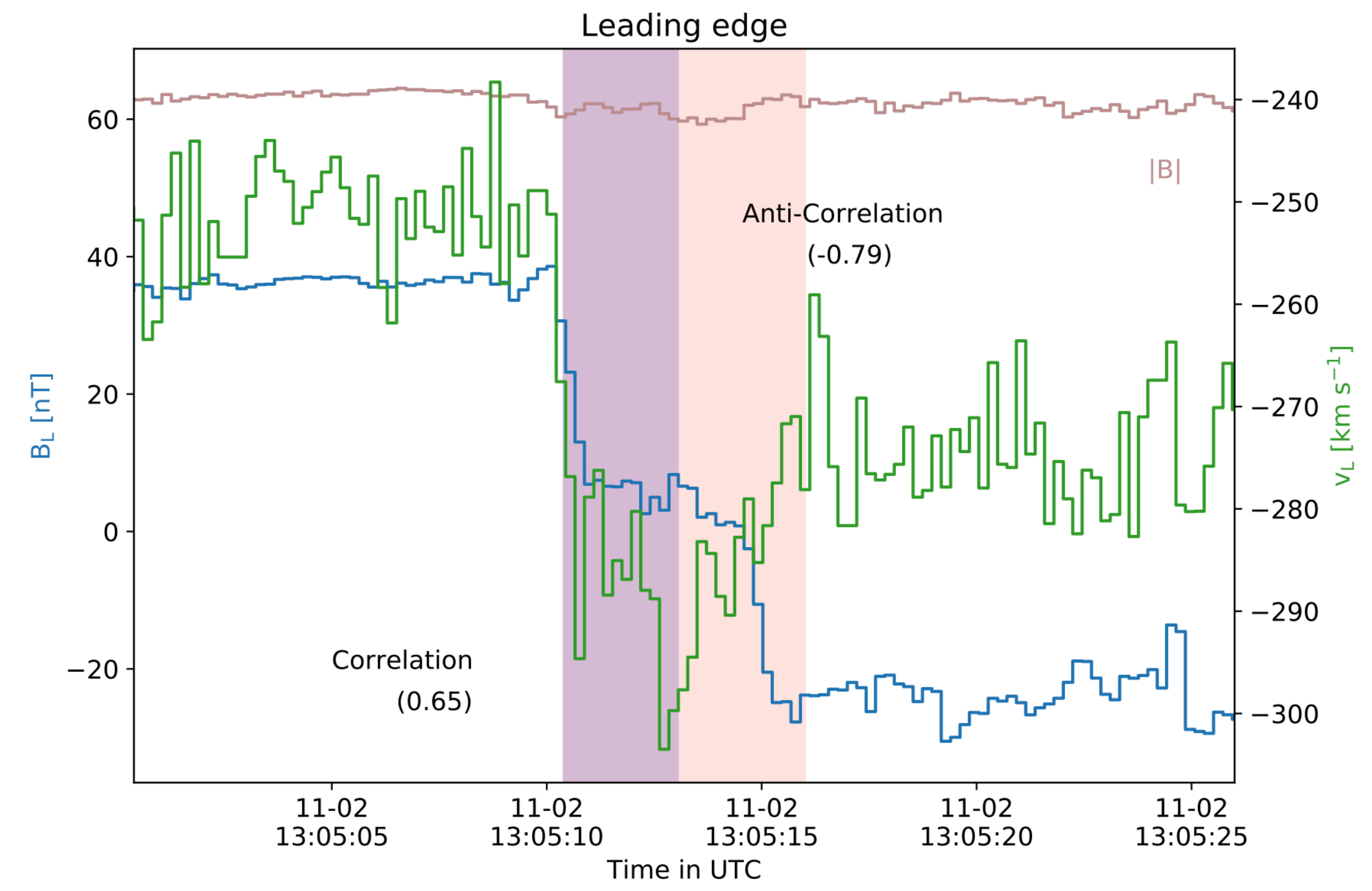
Yamauchi et al. 2004

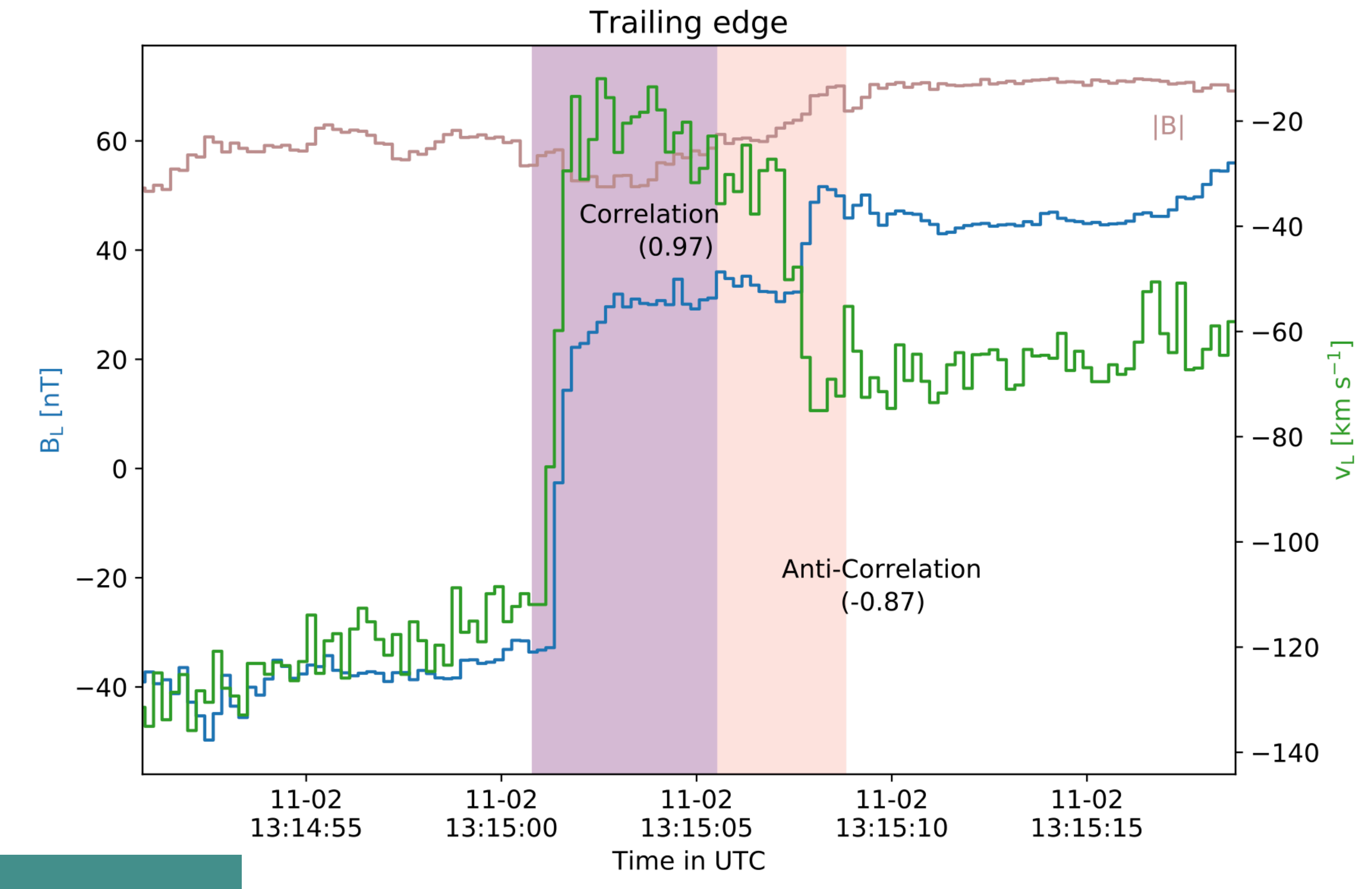
Strahl orientation
Magnetic field polarity

⇨ **Local folds ≠ polarity reversal**

Event 1: November 2, 2018 13:05 UT







Local current sheet coordinate system

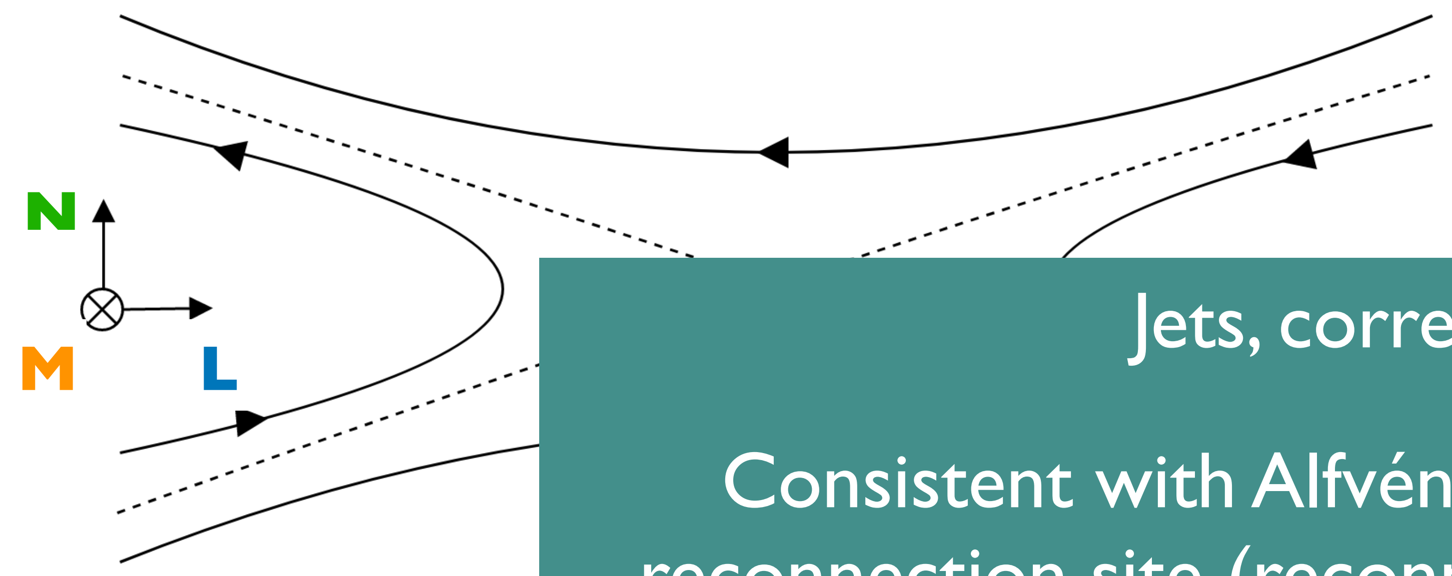
Hybrid minimum variance method (e.g. Gosling & Phan 2013)

$$N = B_1 \times B_2 / |B_1 \times B_2| \qquad M = N \times x_{max} \qquad L = M \times N$$

Current sheet normal

Out-of-plane direction
Guide field direction

Main current sheet direction
Outflow direction



Jets, correlated B_L & v_L changes

Consistent with Alfvén waves propagating away from the reconnection site (reconnection exhausts Gosling et al. 2005)

Strong evidence for reconnection

at ~50 % and 100 % of the Alfvén velocity
ckness of the current sheets: ~1000 and 1700 km
ance to the X-line: ~ 5000 and 9900 km

- How frequent are such reconnection-like events? Only 3 clear events detected (but not a statistical study)
- Seem rare, the most striking examples we report here are all at a distance close to 50 Rs for the Sun
- **News cases detected with Solar Orbiter** (Lavraud et al. 2021 at 0.64 AU ; Fedorov et al. 2021)
- The velocity enhancements inside the switchbacks reported here are moderate

- Reconnection destabilising the structures $\longrightarrow$ decay?
- Strong velocity enhancements inside the switchbacks that would prevent the reconnection to happen at the boundaries

Diamagnetic drifts suppress reconnection with the velocity of the moving structure is comparable to the Alfvén velocity
Swisdak et al. 2003: Reconnection rate depending on the magnetic shear and β
Akhavan-Tafti et al. 2021: reconnection-favorable plasma and magnetic conditions but instabilities may not be able to develop

- **These reconnection events could contribute in blending of the structure (at least the largest ones) with the regular solar wind**
- Dissipation of the structures?

- **Could explain why there are less switchbacks encountered further away from the Sun** (Tenerani et al. 2021)

Thank you for your attention!

Supplementary material

Wide range of reconnection properties (and switchbacks properties)

Table 1. Summary of the individual indications for magnetic reconnection.

Event	Leading/trailing edge	Correlated/anti-correlated B_L & v_L changes	Jet	Strahl suppression	Whistlers
1	Leading	Yes	Yes	No	No
1	Trailing	Yes	Yes	No	No
2	Leading	Yes	Yes	No	No
2	Trailing	Yes	Yes	No	No
3	Leading	Yes (not resolved)	Yes (not resolved)	Likely	No
3	Trailing	Yes (weak anti-correlation)	No	Yes	Yes

Table 2. Characteristics of the reconnection events detected in the current sheets (CS) constituting the switchback boundaries.

Event	Leading/trailing edge	$\|\mathbf{B}\|$ dip [%]	Guide field	Rotation $\mathbf{B}$ [°]	β_p	j [nA m^{-2}]	Density increase [%]	CS Thickness [d_i] ([km])	Distance to the X-line [d_i] ([km])	Jet velocity [%v_A]
1	Leading	6	2.3	58	0.4	47.7	–	60 (1004)	301 (5019)	50
1	Trailing	27	1.3	81	0.7	36.9	25	107 (1770)	539 (8851)	113
2	Leading	16	2.3	67	0.9	75.5	–	40 (640)	203 (3205)	26
2	Trailing	12	2.6	60	0.9	18.3	37	164 (2569)	821 (12847)	60
3	Leading	22	1.4	61	2.3	181	–	10 (155)	50 (776)	75
3	Trailing	90	0.05	168	112.6	15.2	15	186 (3083)	945 (15416)	–

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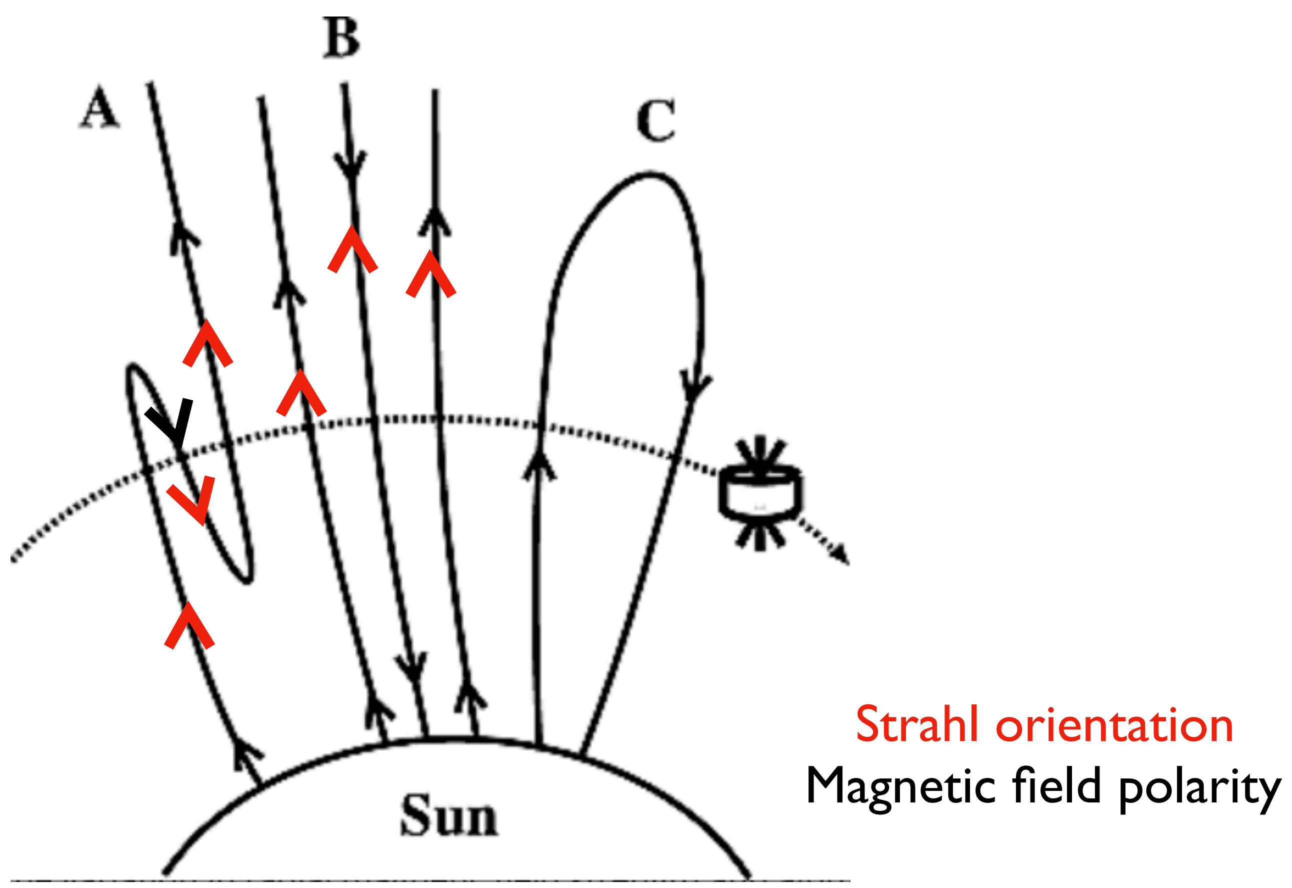
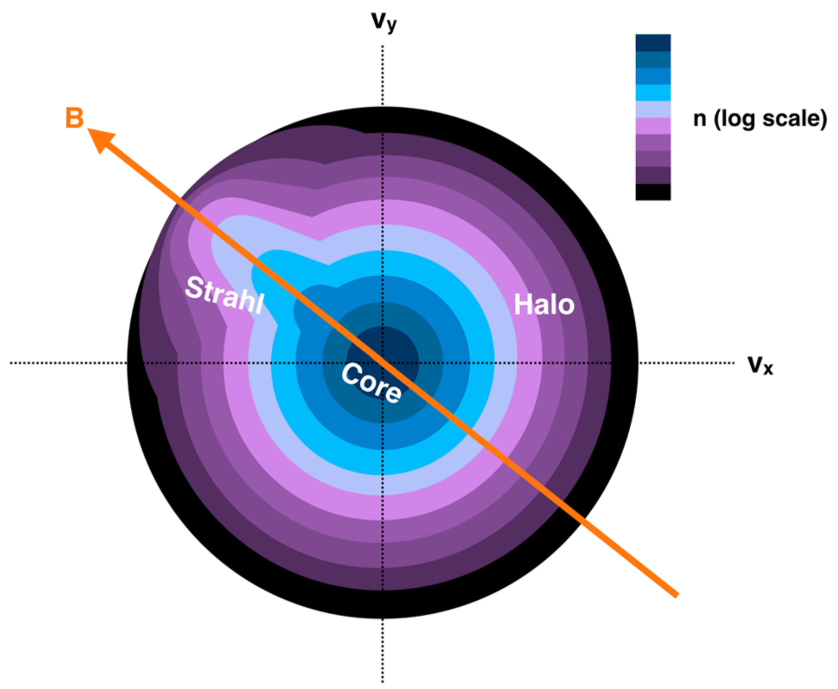
The strahl, i.e. the high-energy & field-aligned electron population, **maintains its orientation inside the switchbacks** (Kasper et al. 2019)



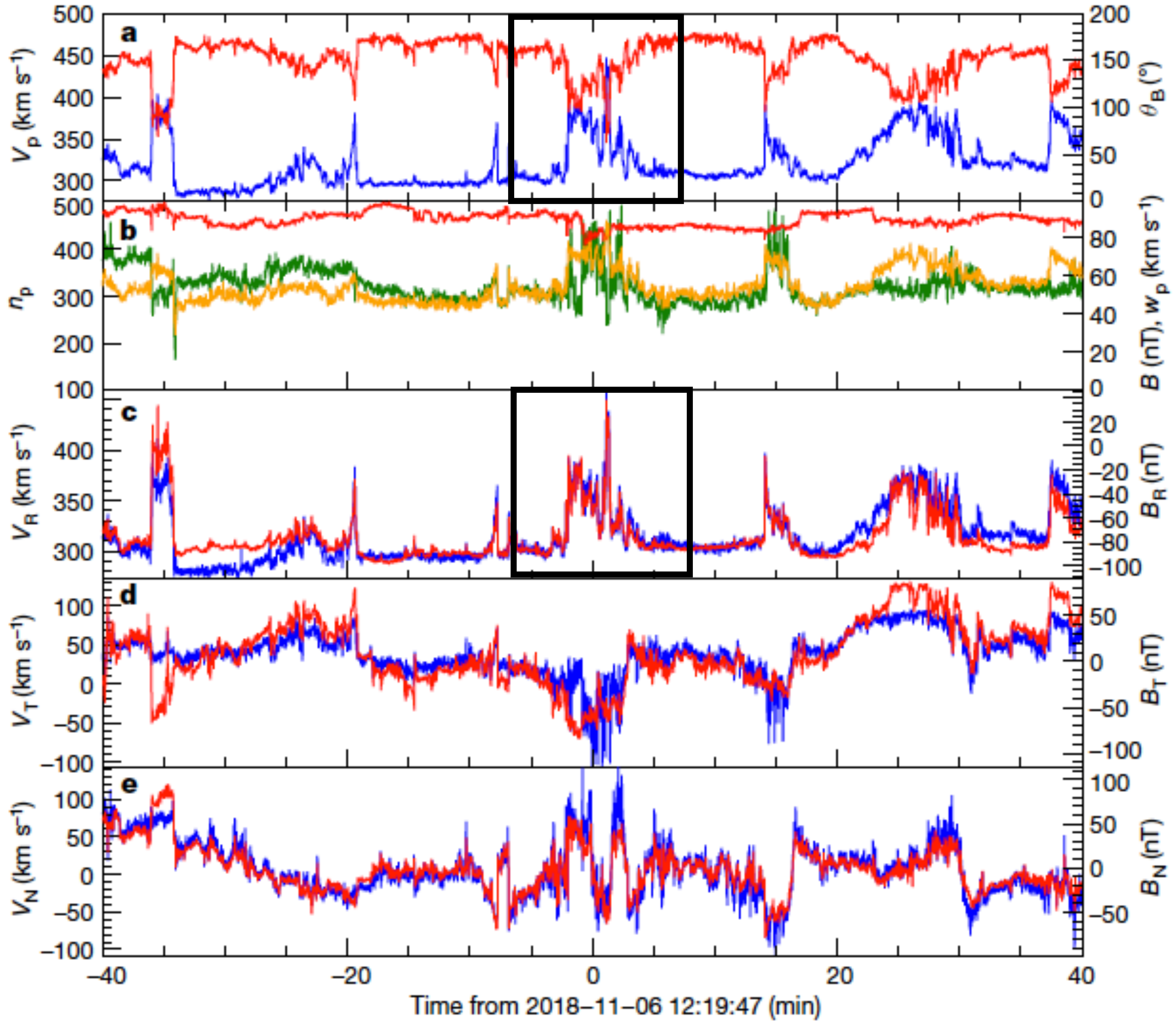
Yamauchi et al. 2004



Graham et al. 2017

➪ **Local folds ≠ polarity reversal**

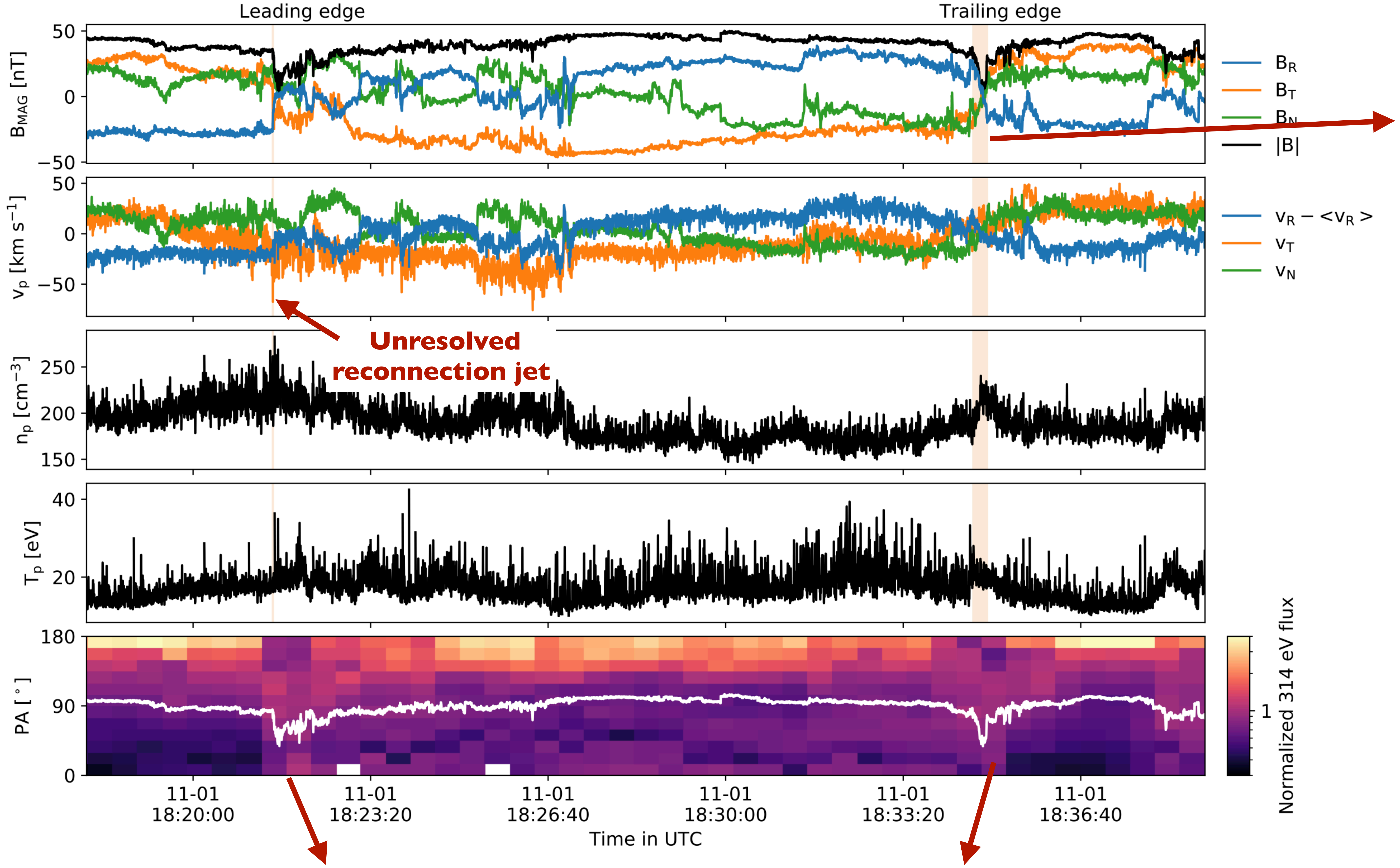
➪ **Associated with proton velocity spikes**



Kasper et al. 2019

➪ **Most of the structures are Alfvénic**
(~3/4 in Larosa et al. 2021)

Event 3: November 1, 2018 18:20 UT



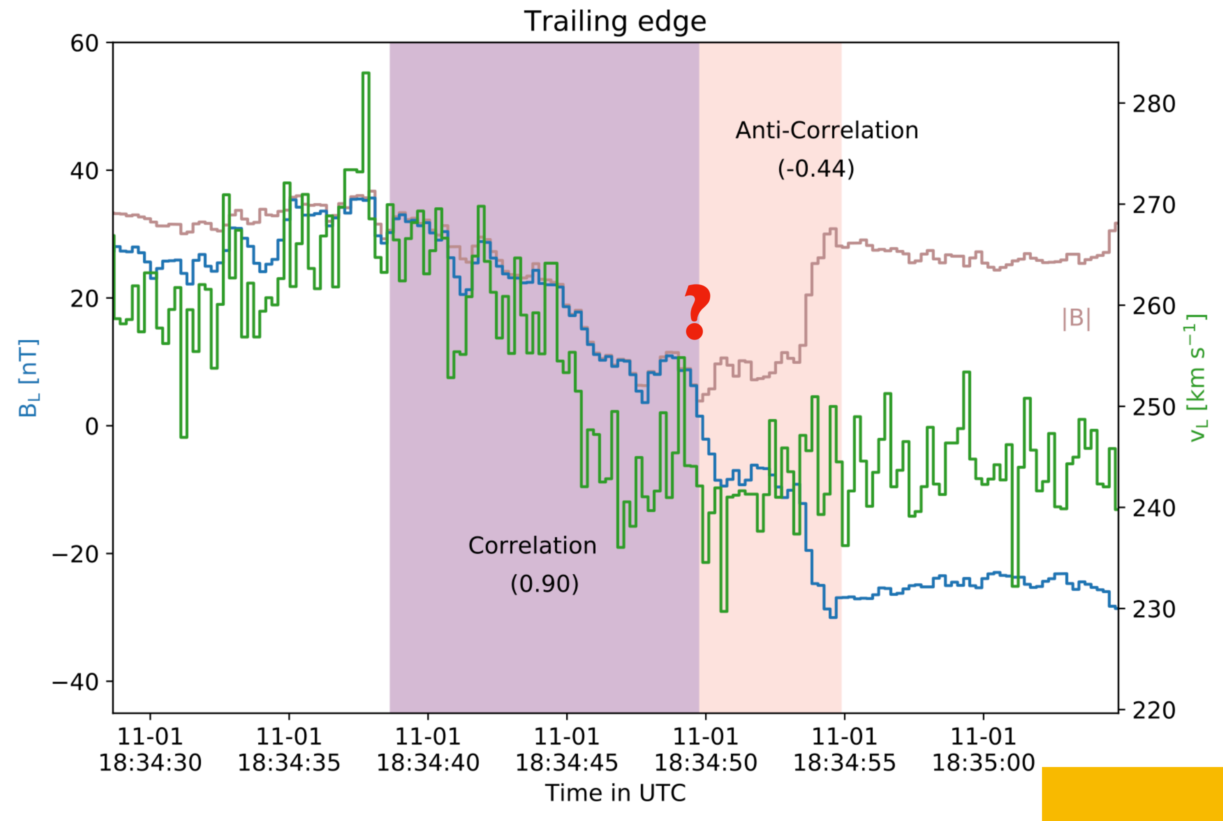
Suppression of the strahl at the boundaries

- **But quite far from the X-line: ~15 000 km, thus we should see an ion jet**

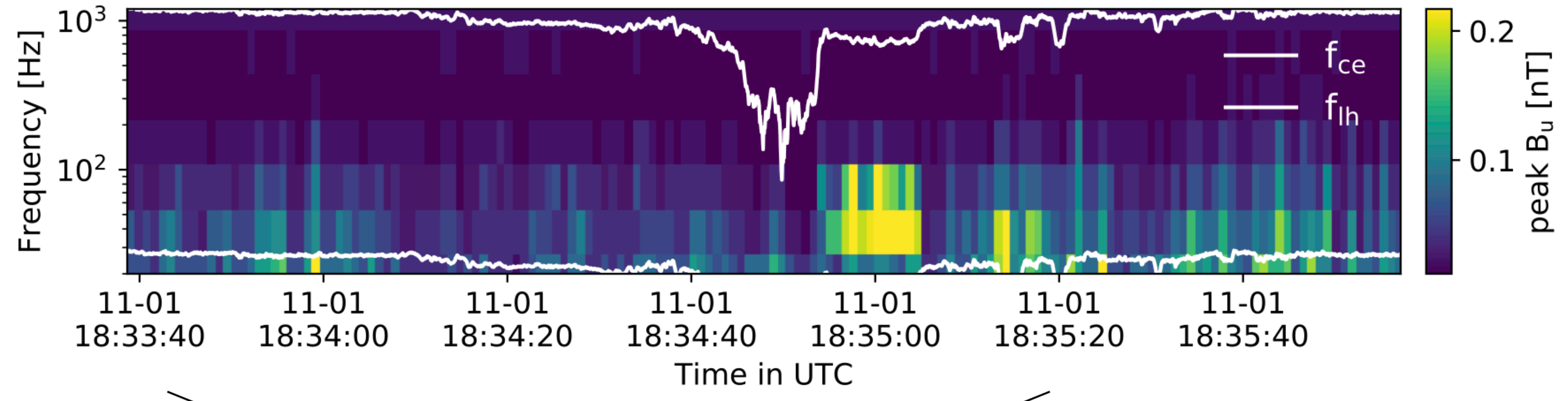
- strong magnetic field shear: 165°
- strong |B| drops: 90%

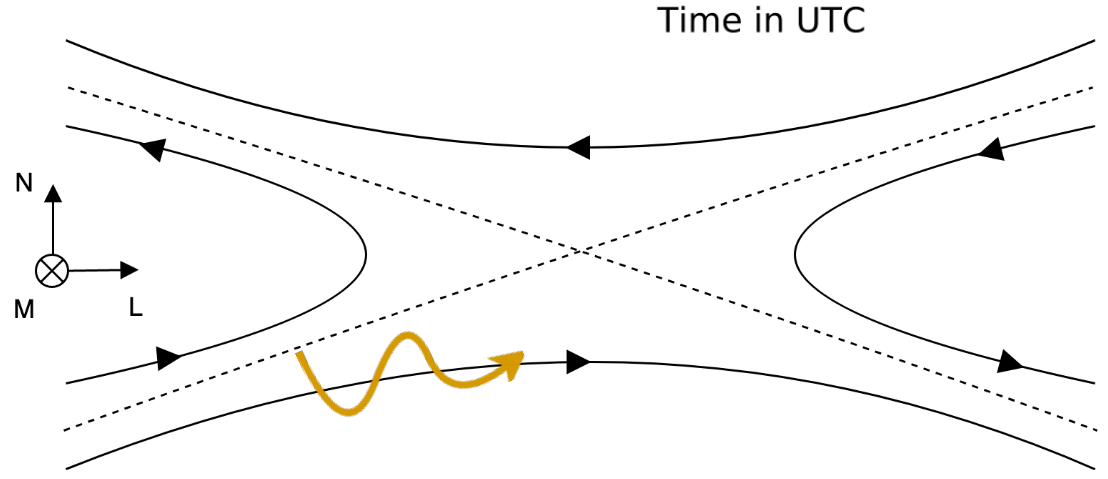
full inversion of the three components of B

quasi anti-parallel reconnection?



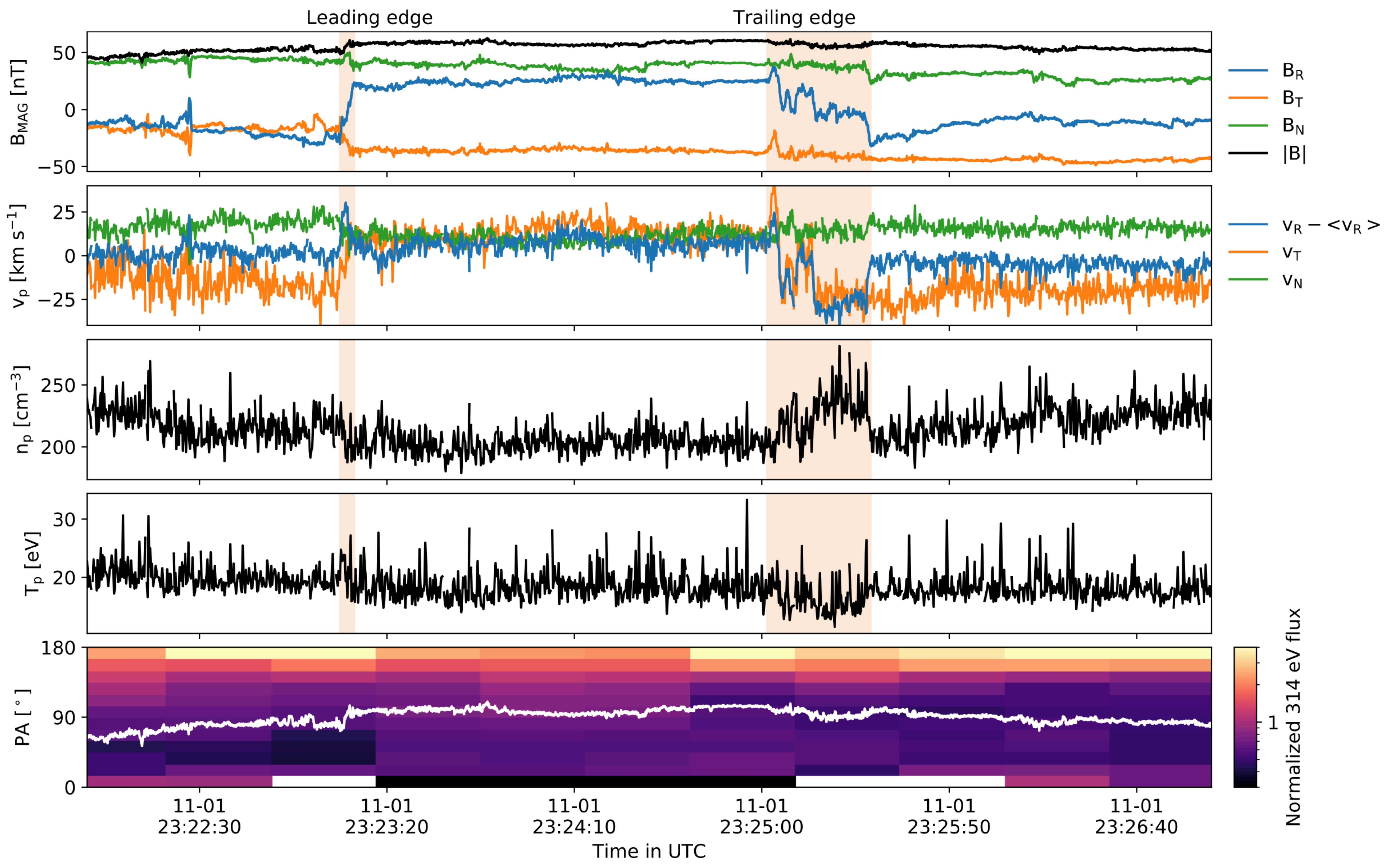
FIELDS/SCM
Fluctuation of the magnetic field

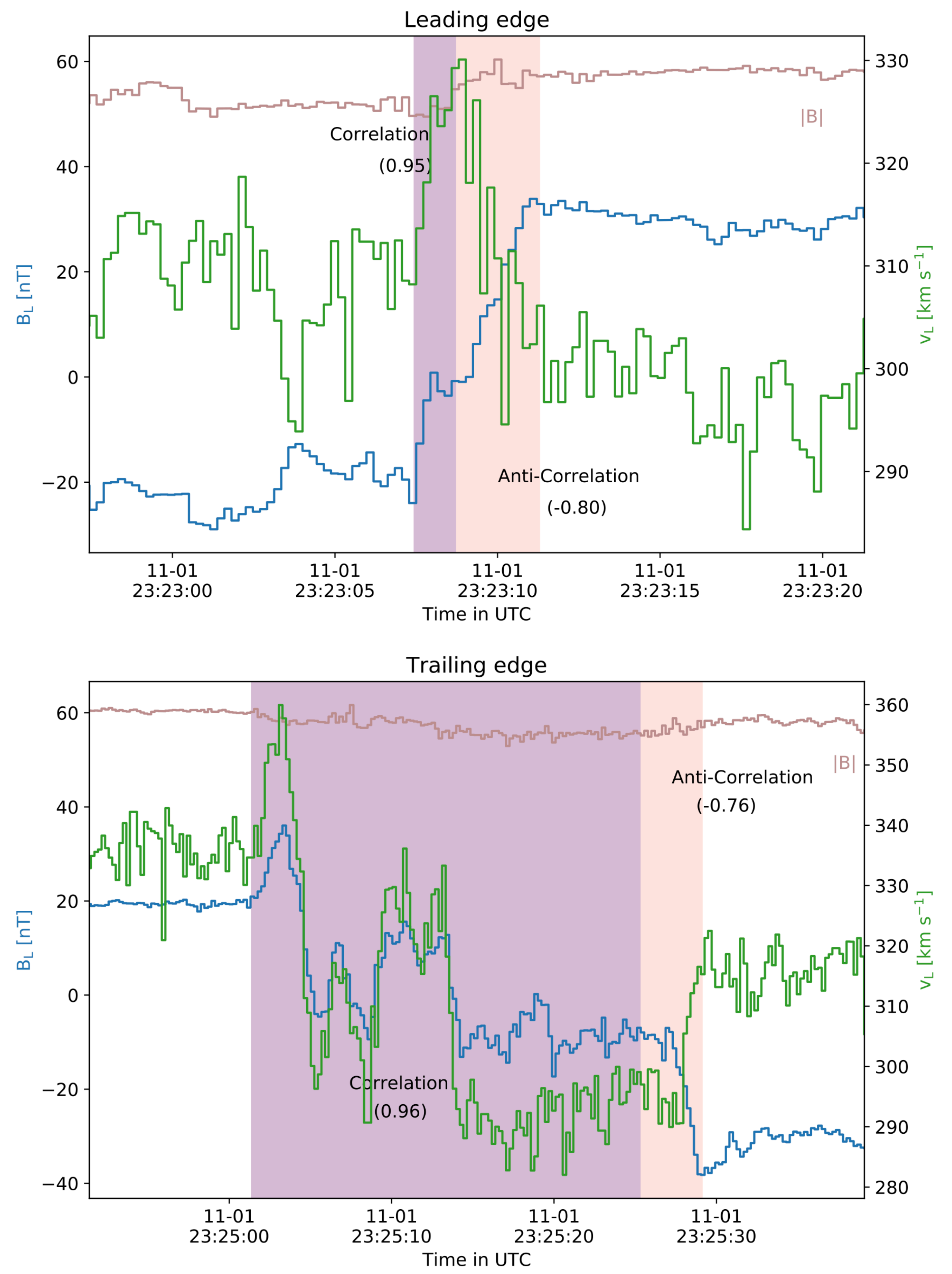




Quasi-parallel whistlers are expected close to reconnecting X-points (e.g. Wei et al. 2007; Graham et al. 2016; Vörös et al. 2019)

Event 2: November 1, 2018 23:23 UT

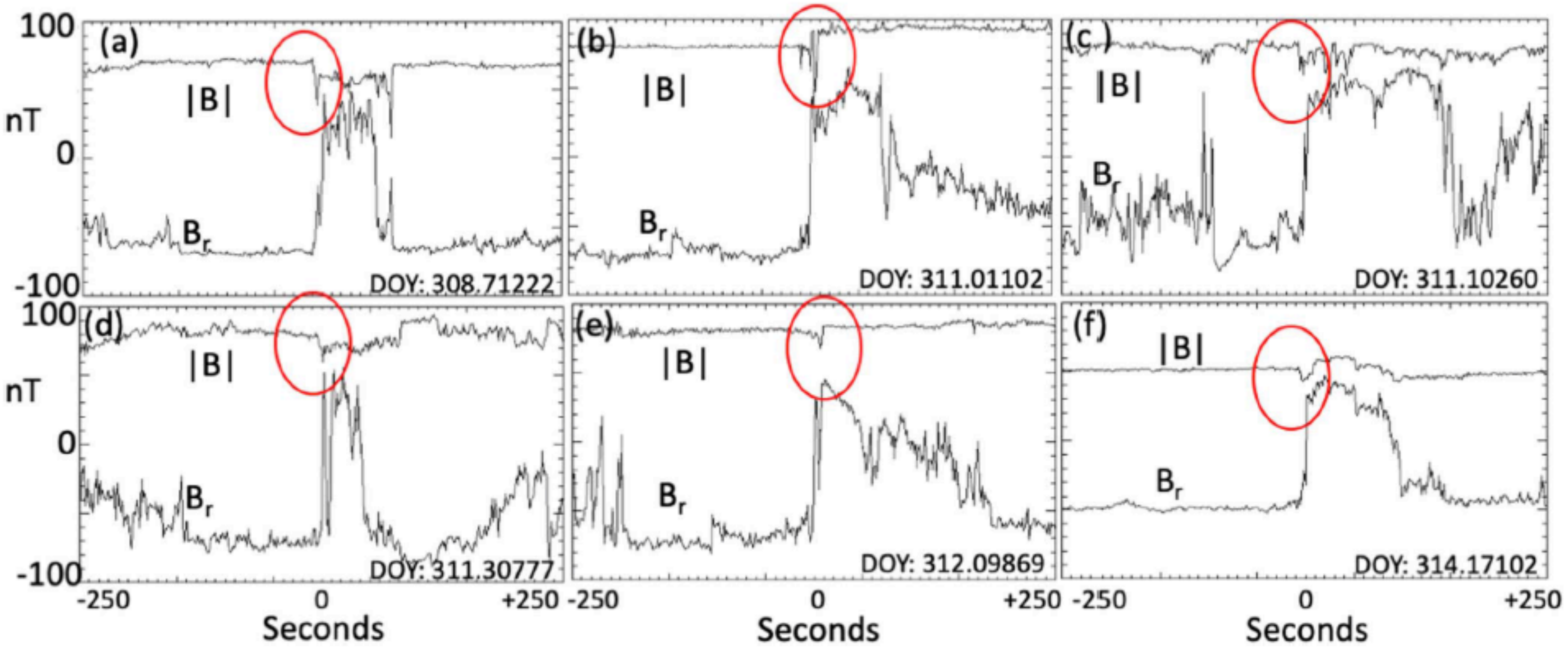




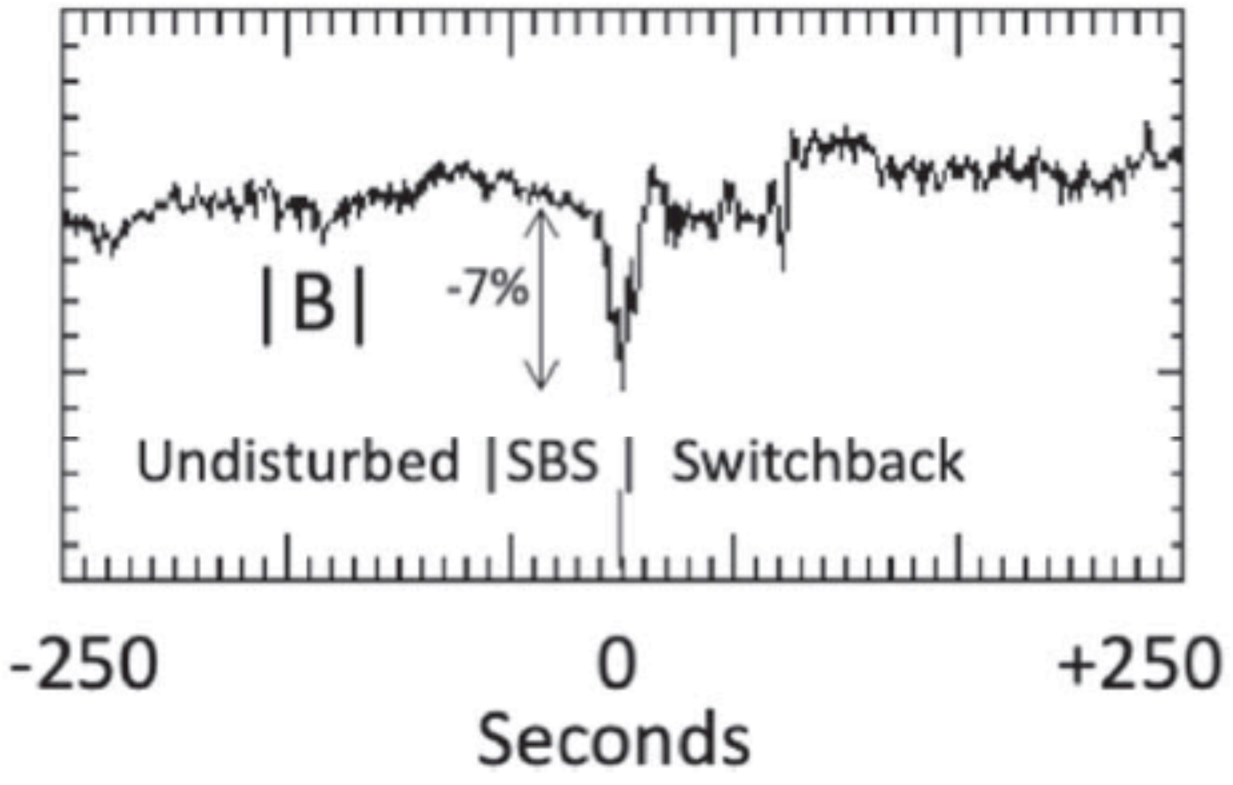
Similar to event 1: Reconnection exhausts at both boundaries

Jets: at ~26 % and 67 % of the Alfvén velocity
Thickness of the current sheets: ~650 and 2500 km
Distance to the X-line: ~ 3000 and 1300 km

- Significant decrease of the magnetic field magnitude at the boundaries for some of these structures (Agapitov et al. 2020; Farrell et al. 2020).
- About 50 cases detected in Farrell et al. 2020



Farrell et al., 2020

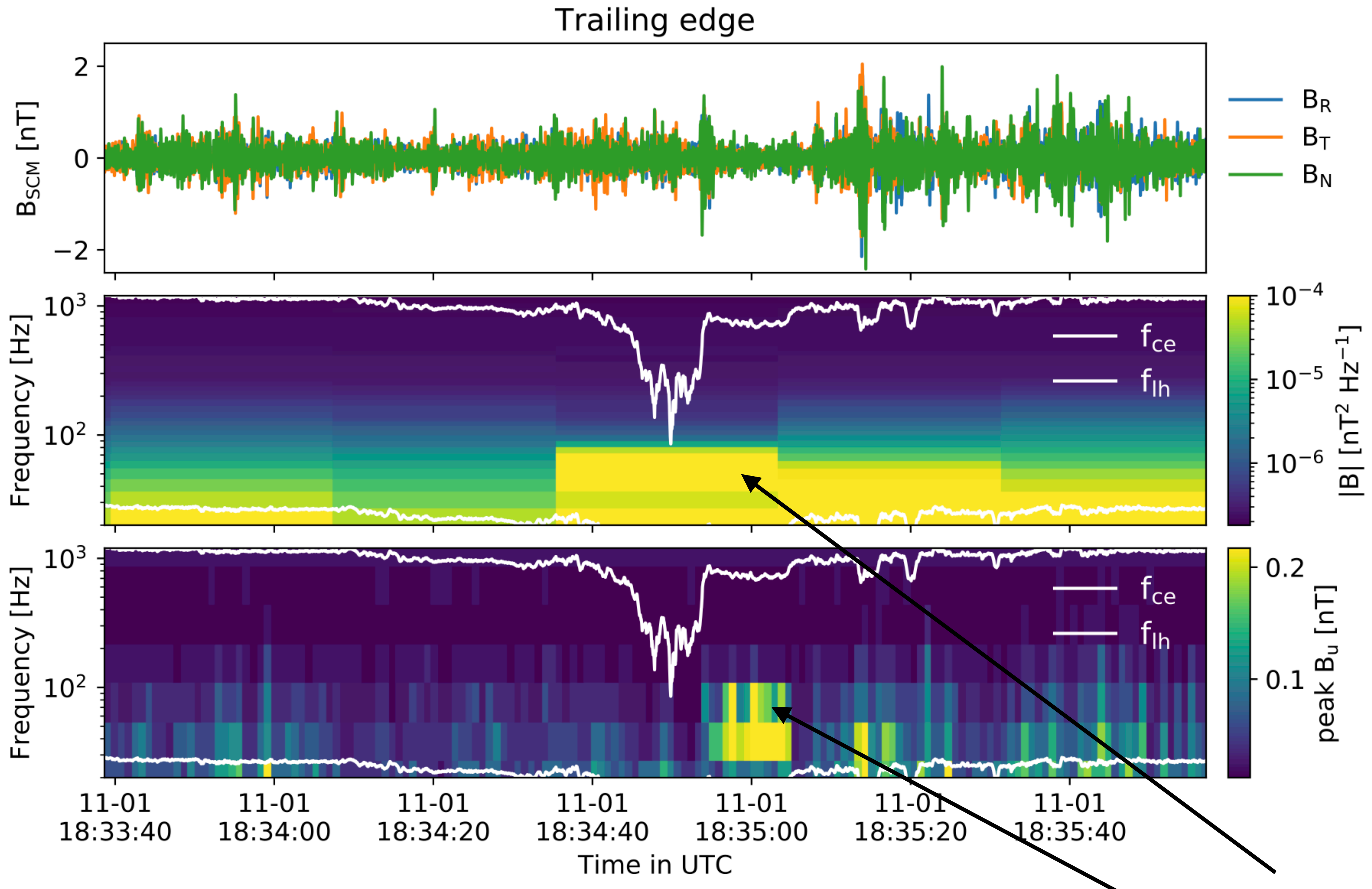


Adapted from Farrell et al., 2020

- **Diamagnetic current creating the magnetic dips? (Krasnoselskikh et al. 2020; Farrell et al. 2020)**

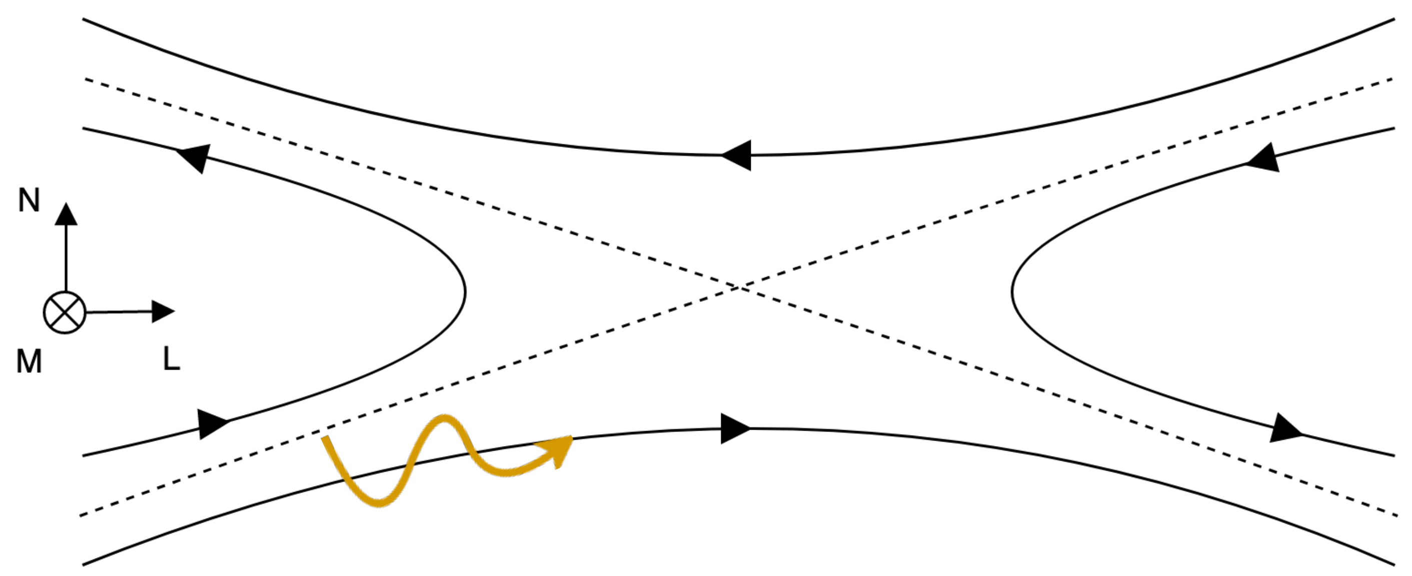
Quasi anti-parallel reconnection?

FIELDS/SCM
Fluctuation of the magnetic field



High planarity and ellipticity,
Angle (k,B) ~ 6° ± 180°

- Whistler waves ($f_{lh} < f < f_{ce}$)
- Polarisation and obliquity with spectral matrices
  Singular Value Decomposition (Santolík et al. 2003)

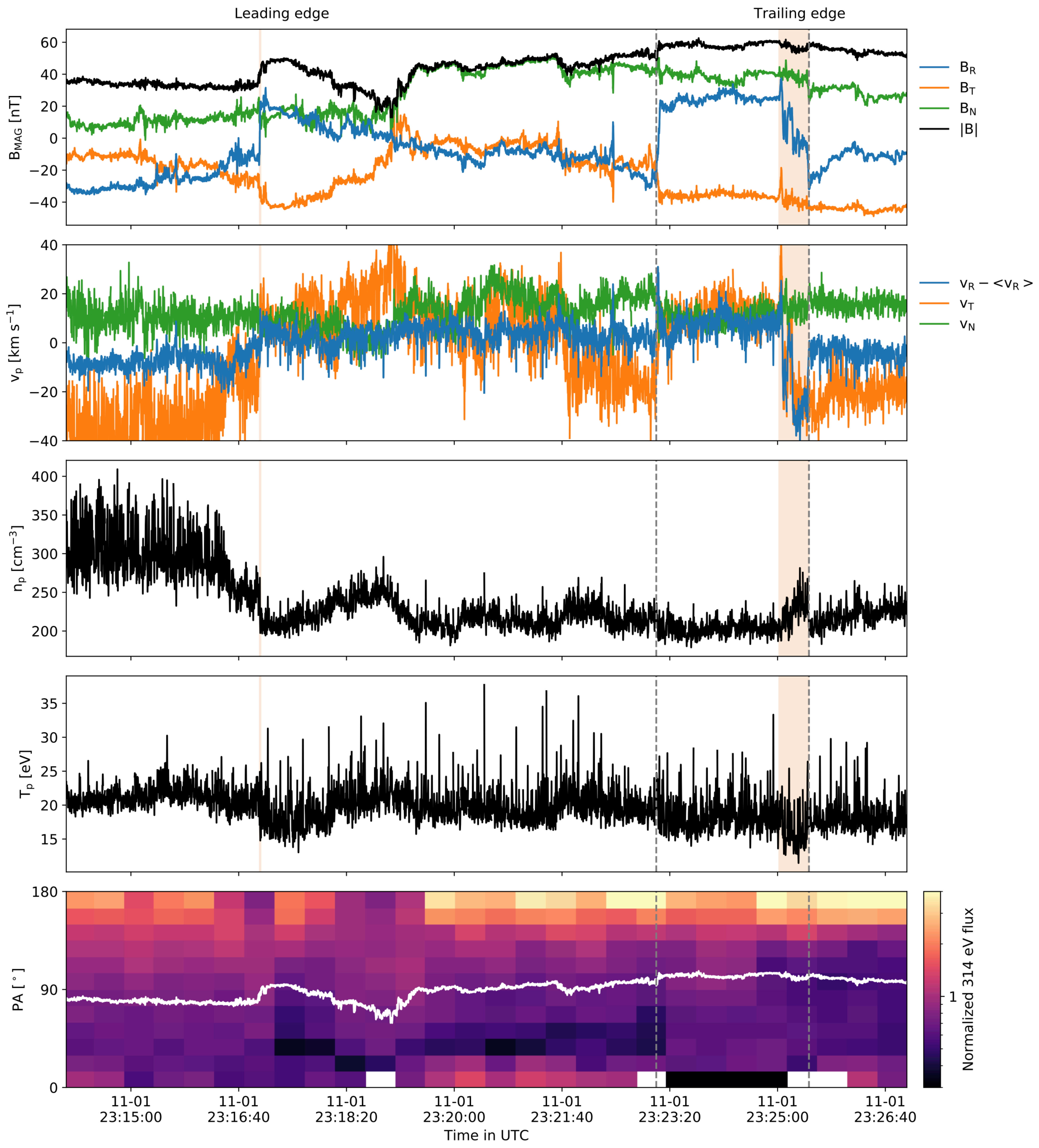


Quasi-parallel whistlers are expected close to reconnecting X-points
(e.g. Wei et al. 2007; Graham et al. 2016; Vörös et al. 2019)

Reconnection?
- **Correlated changes in B_L and v_L**
- The clear suppression of the strahl at the X-point indicates **a disruption of the connectivity with the Sun**
- **Quasi-parallel whistlers** at the boundary of the current sheet, right after the steepest variation in B_L: close to the ion-diffusion region?

Could explain why we don't observe a jet (also inversion of the three B components and large |B| dip)

BUT:
- **No Hall perturbations** (bipolar variations in B_M)
- **Computed distance to the X-line: ~15000 km i.e. 945 ion-internal length**

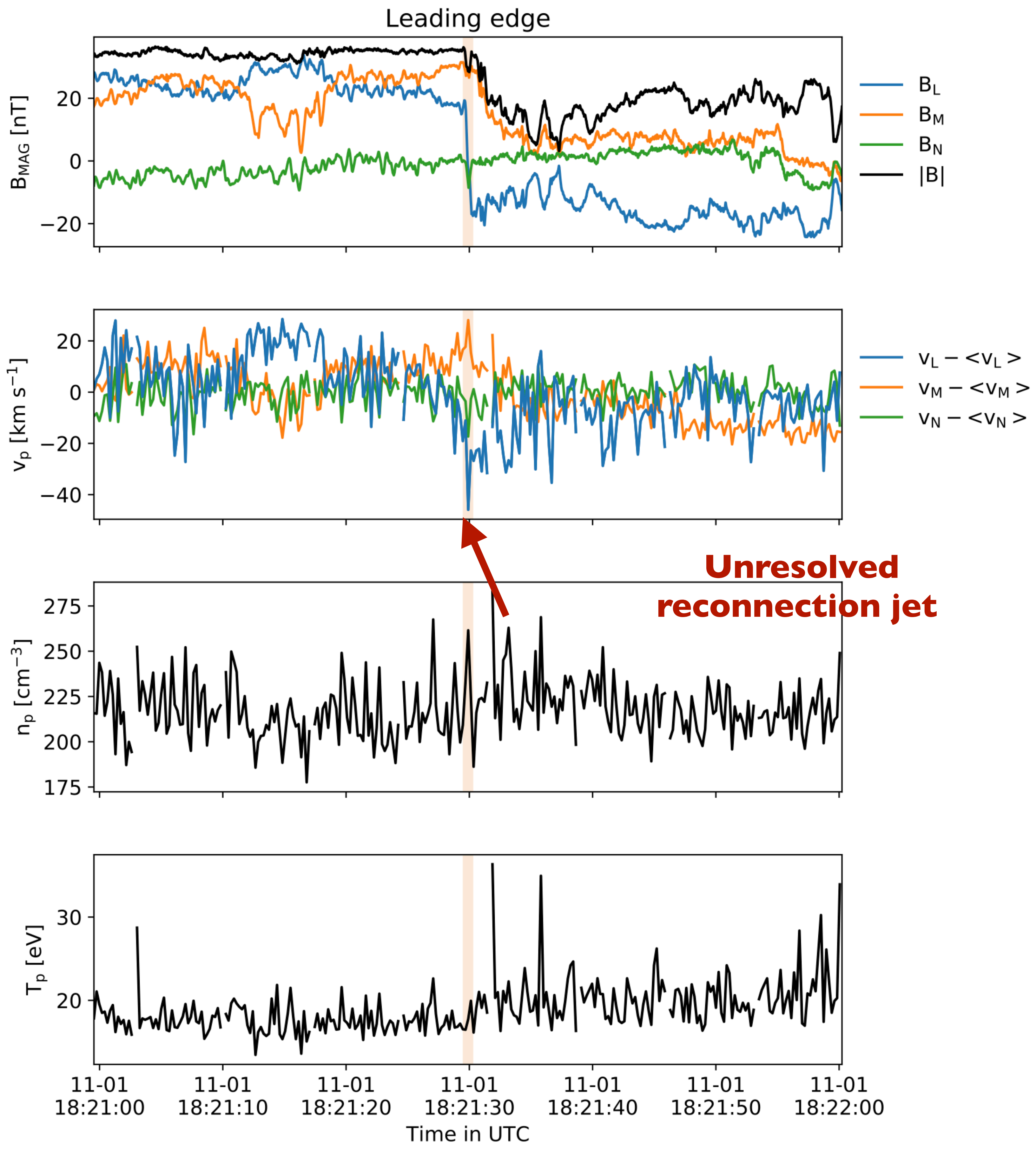


Structure embedded in an other switchback

Anti-correlated |B| and density:

Consistent with a slow magnetosonic perturbation

Event 3


Leading edge
B_{MAG} [nT]
20
0
−20
B_L
B_M
B_N
|B|
v_p [km s^{-1}]
20
0
−20
−40
$v_L - \langle v_L \rangle$
$v_M - \langle v_M \rangle$
$v_N - \langle v_N \rangle$
Unresolved reconnection jet
n_p [cm^{-3}]
275
250
225
200
175
T_p [eV]
30
20
11-01 18:21:00
11-01 18:21:10
11-01 18:21:20
11-01 18:21:30
11-01 18:21:40
11-01 18:21:50
11-01 18:22:00
Time in UTC