Particle Transport Driving Nonlinear Plasma Waves at Injection Fronts in the Inner Magnetosphere

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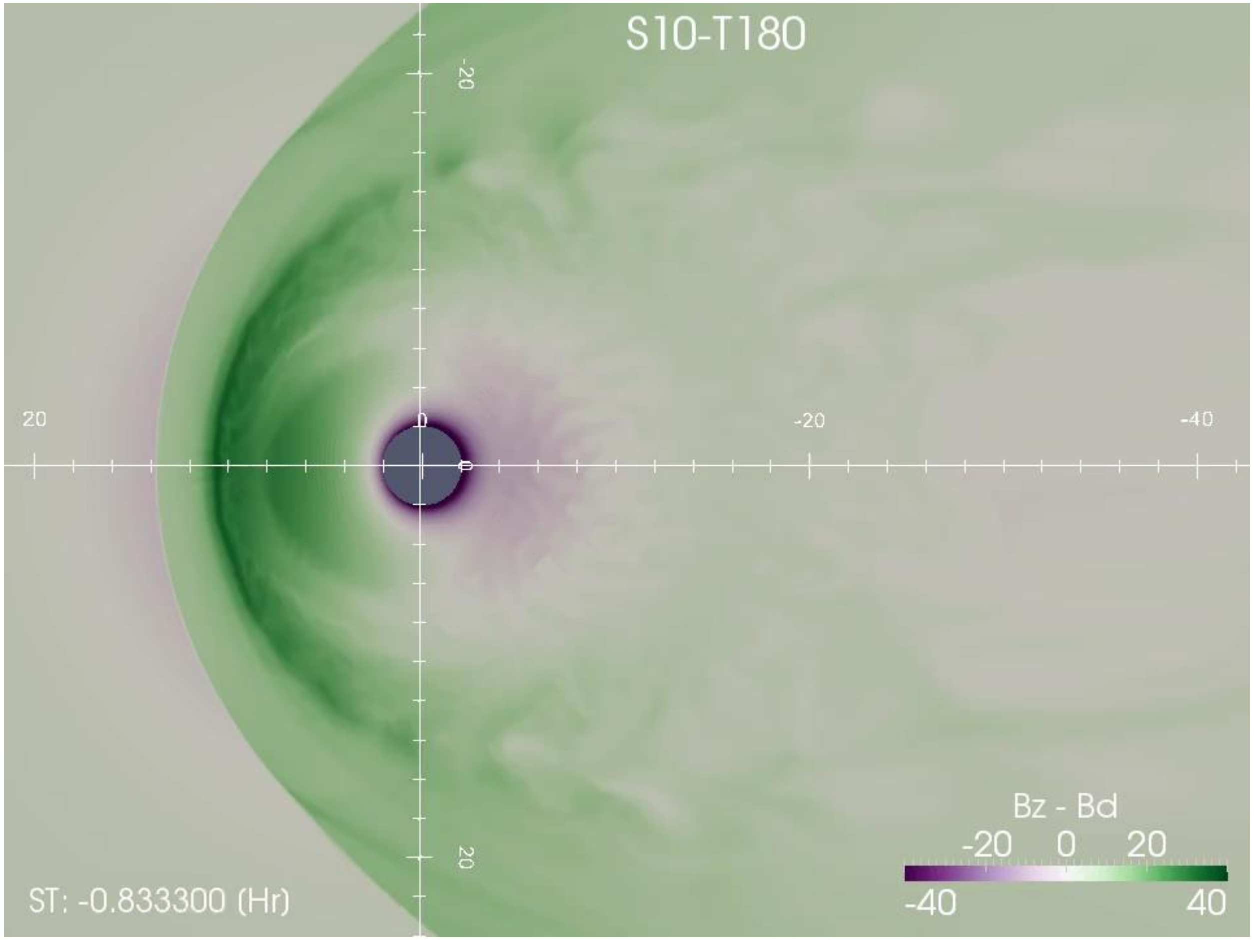
Recently published: D. Malaspina, A. Ukhorskiy, X. Chu, J. Wygant, "A census of plasma waves and structures associated with an injection front in the inner magnetosphere" (2018), JGR

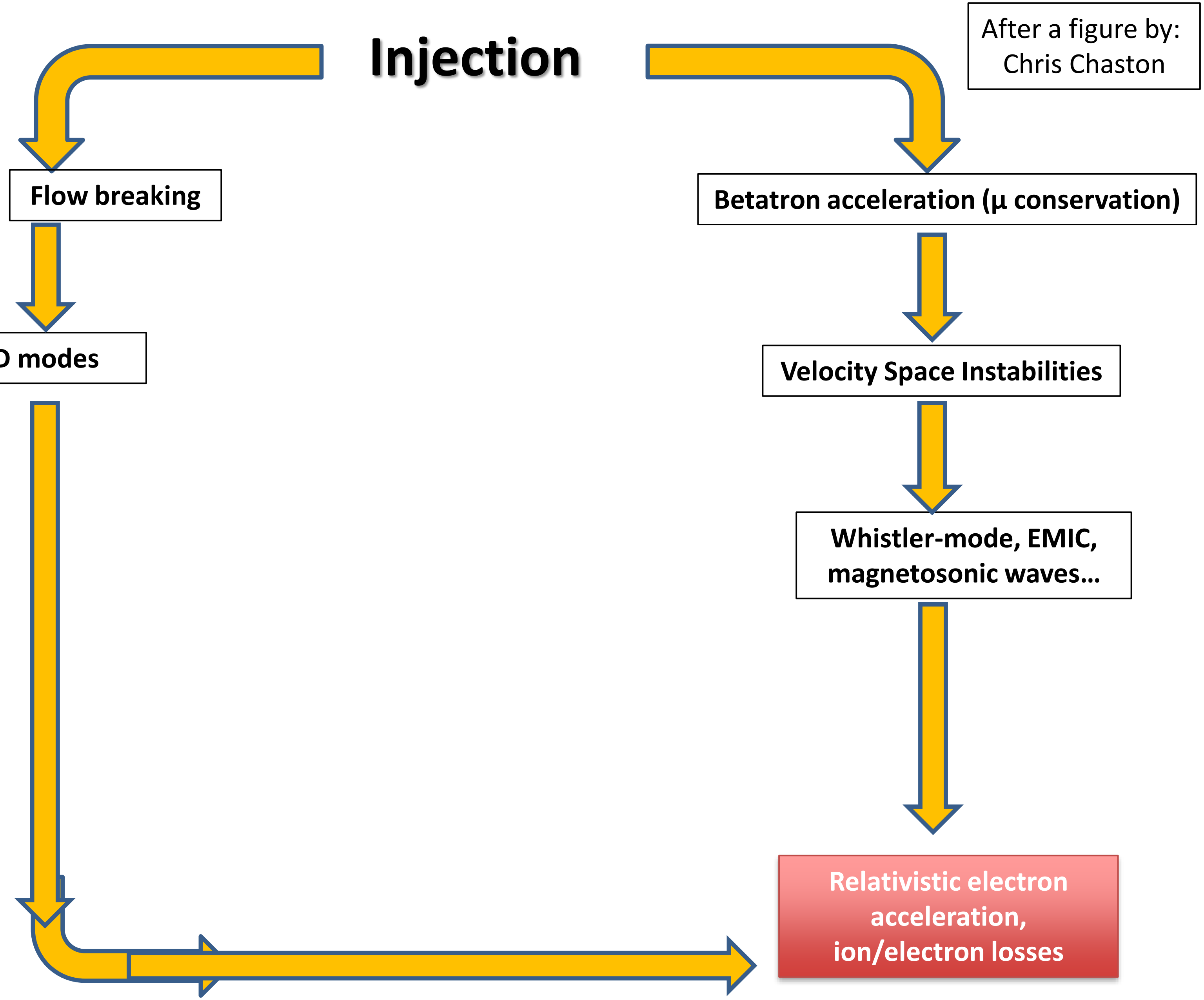
Plasma Injections Into the Inner Magnetosphere

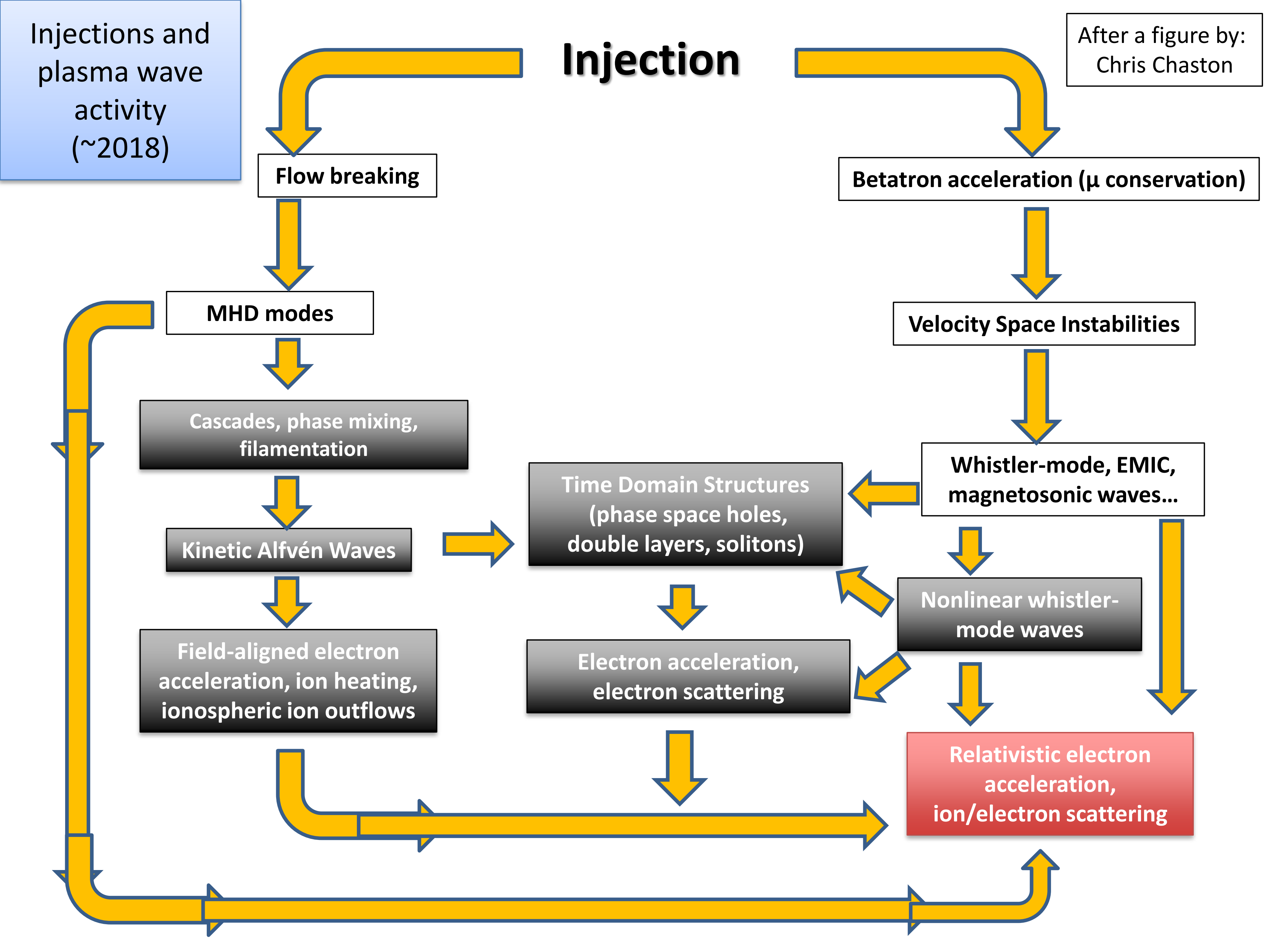
[Wiltberger+ 2015]



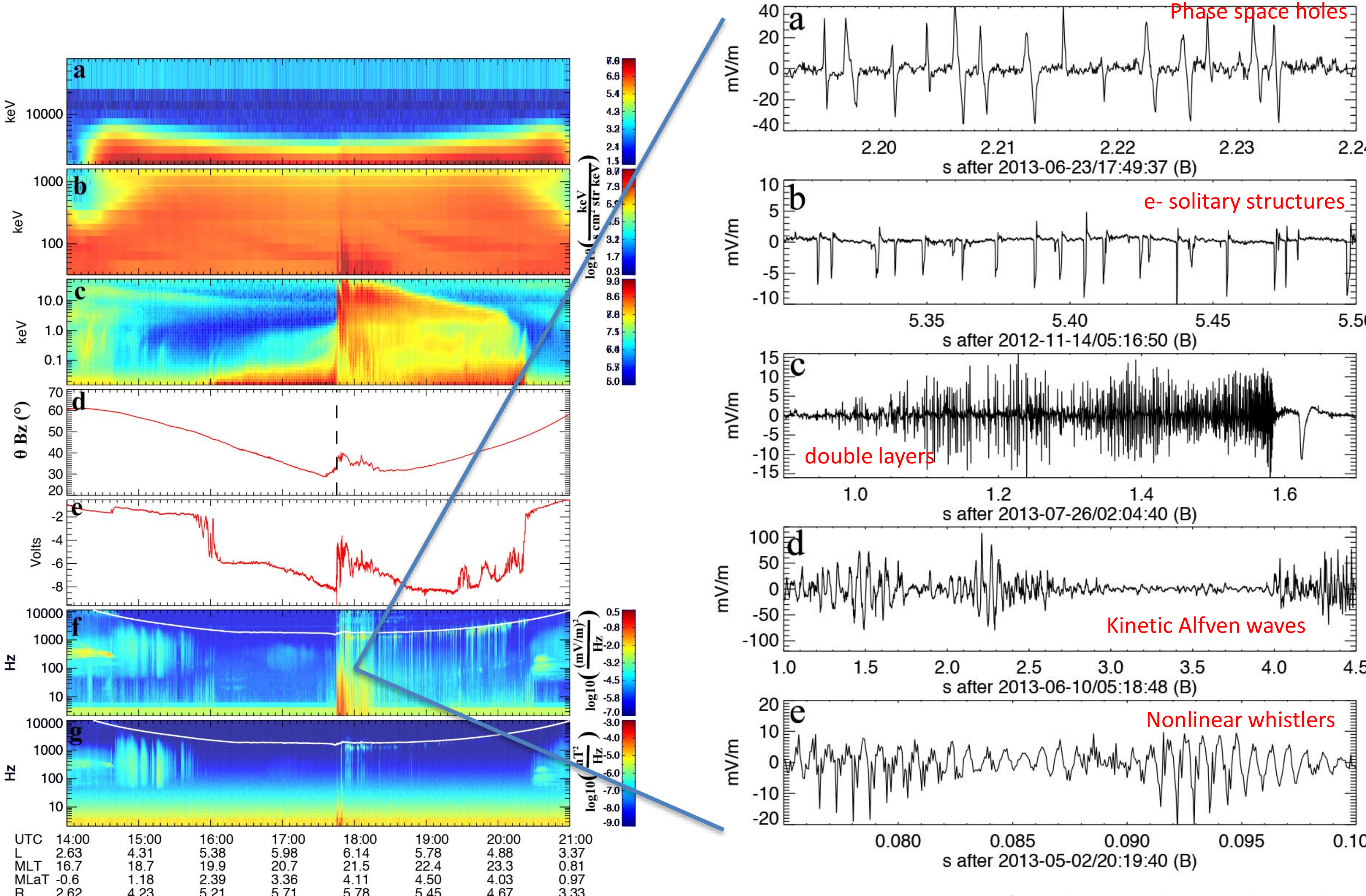
Magnetotail reconnection drives narrow (1 Re)
Earthward injection flow channels:
Bring particles Earthward
And drive waves !

Injections and plasma wave activity (~2011)




Injections and plasma wave activity (~2018)
Injection
After a figure by: Chris Chaston
Flow breaking
Betatron acceleration (μ conservation)
MHD modes
Velocity Space Instabilities
Cascades, phase mixing, filamentation
Whistler-mode, EMIC, magnetosonic waves…
Time Domain Structures (phase space holes, double layers, solitons)
Kinetic Alfvén Waves
Nonlinear whistler-mode waves
Field-aligned electron acceleration, ion heating, ionospheric ion outflows
Electron acceleration, electron scattering
Relativistic electron acceleration, ion/electron scattering

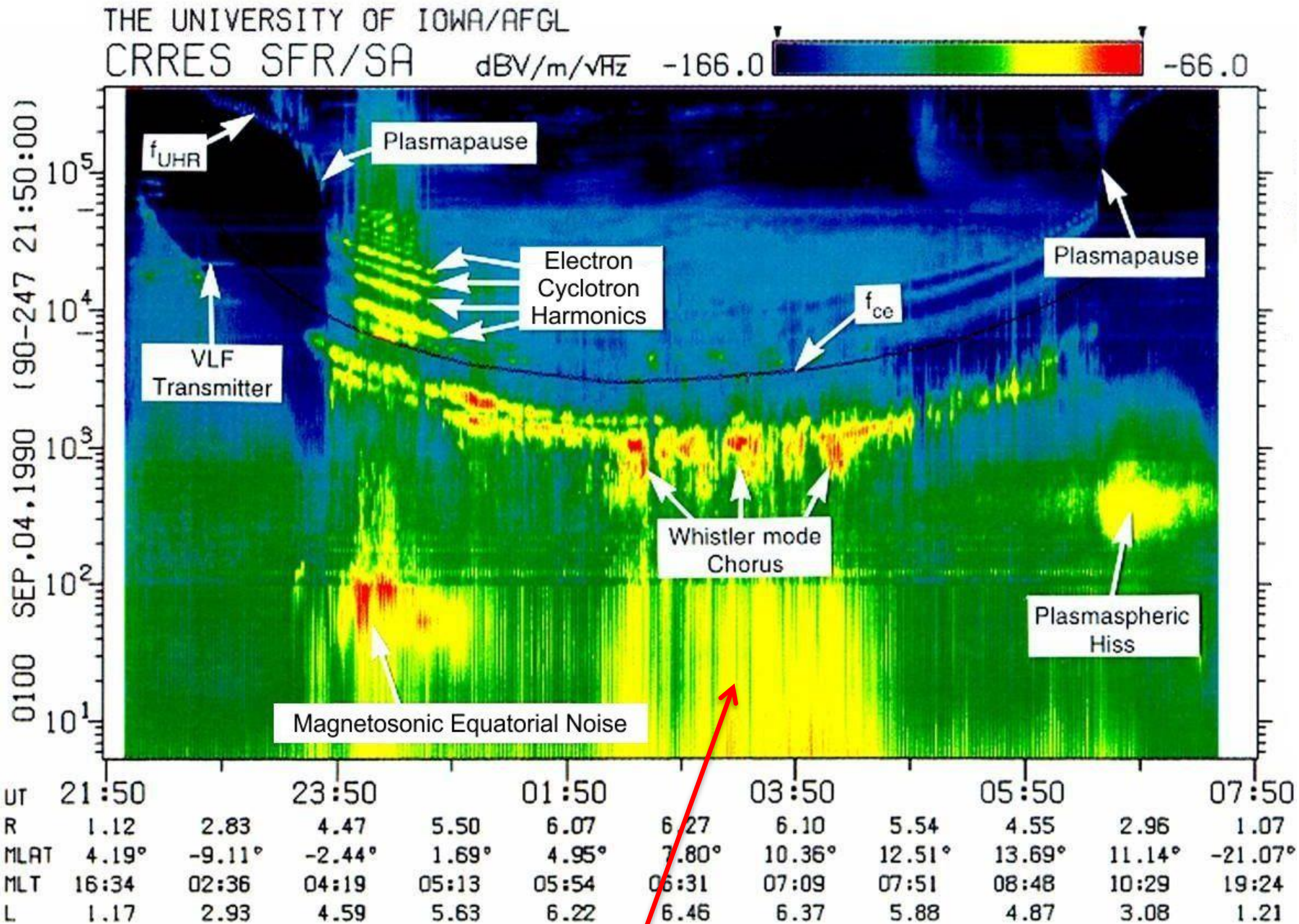
Waves at Plasma Boundaries (burst mode data)



Kinetic waves + structures confined near plasma boundaries
(injections, plasma sheet edge, plasmapause)

[Malaspina+ 2015]

Waves at Plasma Boundaries (burst mode data)

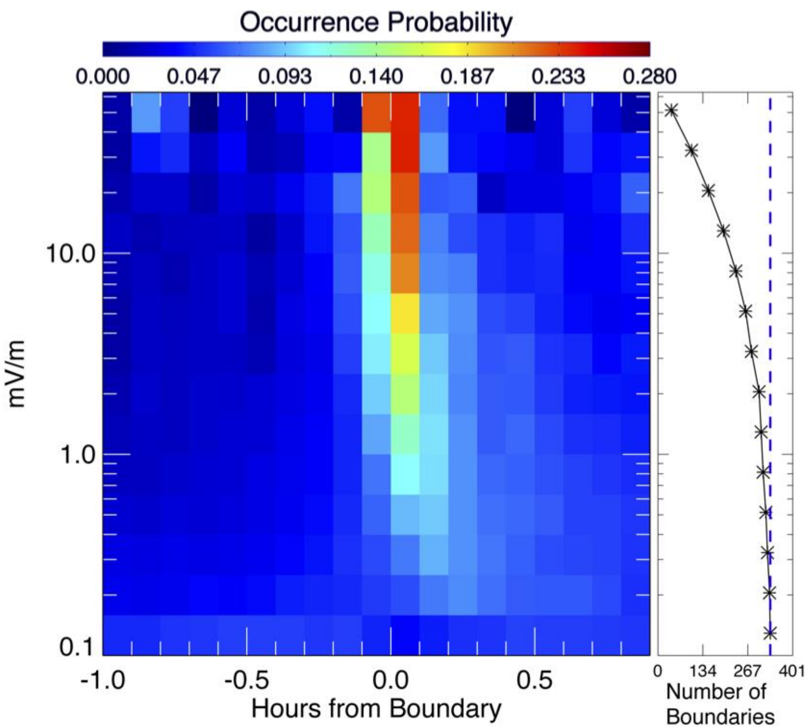


Kinetic waves + structures in CRESS data

Distributions

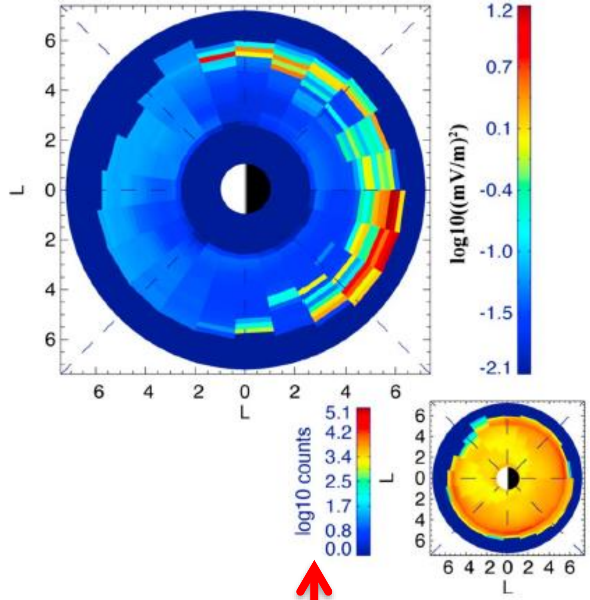
Nearly all boundaries have kinetic structures **AND** nearly all kinetic structures appear at boundaries

(Injections, plasma sheet inner edge, plasmapause)

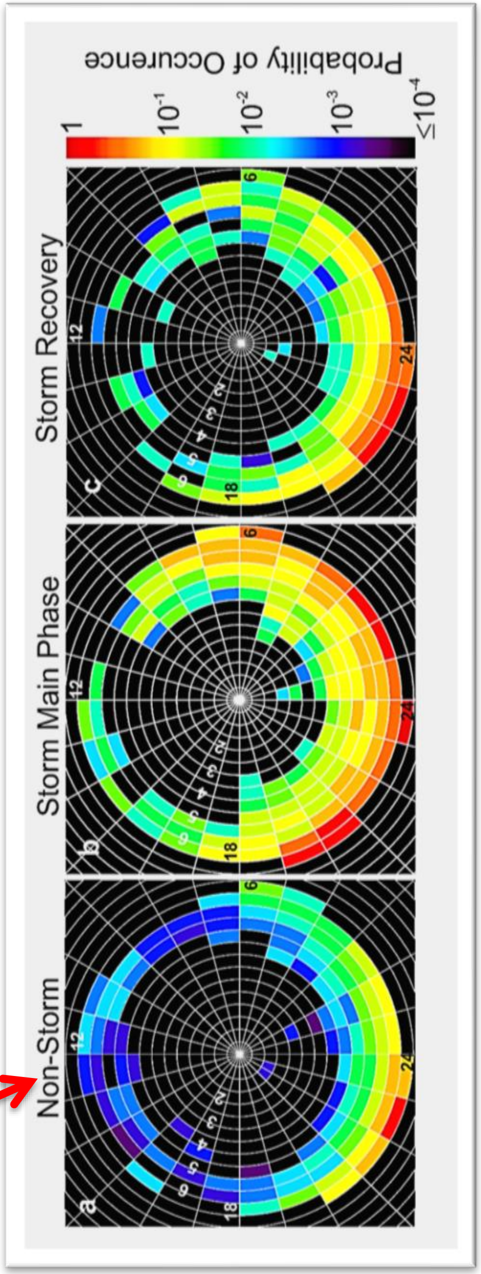


[Malaspina+ 2015]

[Malaspina+ 2014]



Kinetic structures + KAW



Kinetic Alfven Waves

[Chaston+ 2015]

Impacts

[Mozer+ 2014] Direct Observation of Radiation-Belt Electron Acceleration from Electron-Volt Energies to Megavolts by Nonlinear Whistlers

[Artemyev+ 2015] Electron trapping and acceleration by kinetic Alfven waves in the inner magnetosphere (JGR)

[Osmane+ 2016] On the connection between microbursts and nonlinear electronic structures in planetary radiation belts (APJ)

[Chaston+ 2016] Driving ionospheric outflows and magnetospheric O^+ energy density with Alfvén waves

[Vasko+ 2017] Diffusive scattering of electrons by electron holes around injection fronts

[Mozer+ 2017] Pulsating auroras produced by interactions of electrons and time domain Structures (JGR)

[Chaston+ 2017] Radial transport of radiation belt electrons in kinetic field-line resonances

Kinetic Structures and Waves:
Scatter, Transport, and Accelerate the ~few keV and Seed (10 keV – 100 keV) populations

Big Picture

[1] The inner magnetosphere is full of kinetic electric field structures and nonlinear waves [Mozer+ 2013, 2014,2015, Agapitov+ 2015, Osmane+ 2014, 2016, Malaspina+ 2014, 2015, Chaston+ 2014, 2015, 2016, Vasko+ 2015, 2016a,b, 2017a,b,c, Artemyev+ 2015]

[2] Quantifying how these waves / structures impact the plasma requires a census:

- [a] Which waves/structures are most prevalent?
- [b] What are their properties (amplitudes, spatial scales)?
- [c] Where are their preferred growth regions?

[3] A census requires:

- [a] lots of time-domain fields burst data (non-unique spectral signatures)
- [b] automated identification algorithms

[4] In this work, we:

- [a] Identify periods of unbroken burst data
- [b] Develop and apply ID algorithms
- [c] Reveal the zoo of waves/structures and their properties, statistically

21 Dec. 2016
Van Allen Probe B

Electron injection

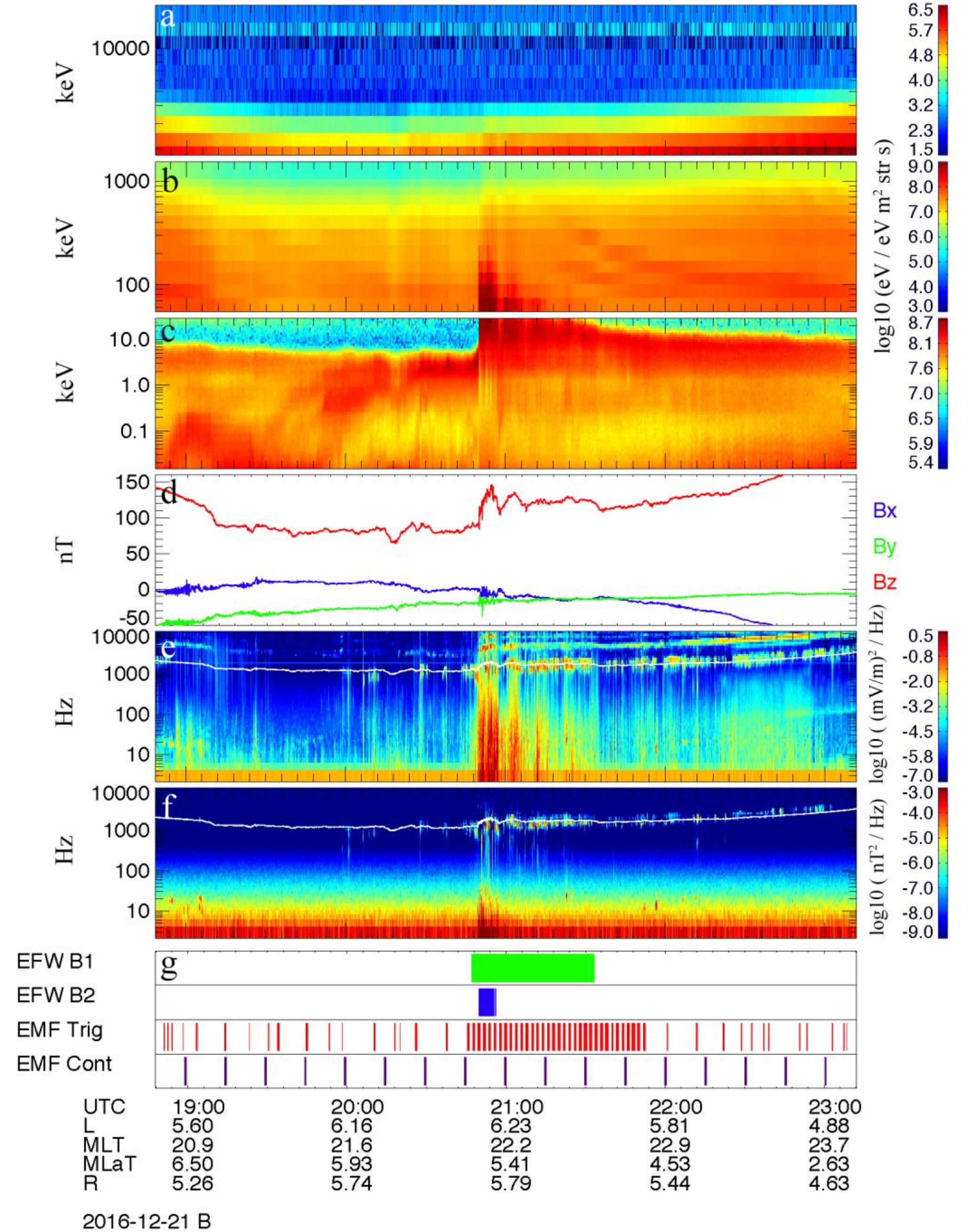
- MeV flux ~steady
- Dispersionless e- increase

Fields burst systems:

- EFW B1
  - 6V, 3 SCM @ 16.4 k sample/s
  - scientist-selected interval
- EFW B2
  - 6V, 3E, 3 SCM @ 16.4 k sample/s
  - s/c selected 6 s bursts
- EMFISIS Trig.
  - 3E, 3 SCM @ 35 k sample/s
  - s/c selected 6 s bursts
- EMFISIS Continuous
  - 3E, 3 SCM @ 35 k sample/s
  - timed 0.5 s bursts (each 15 min)

This event:

- 45 min of unbroken B1 coverage !



Particle Injection

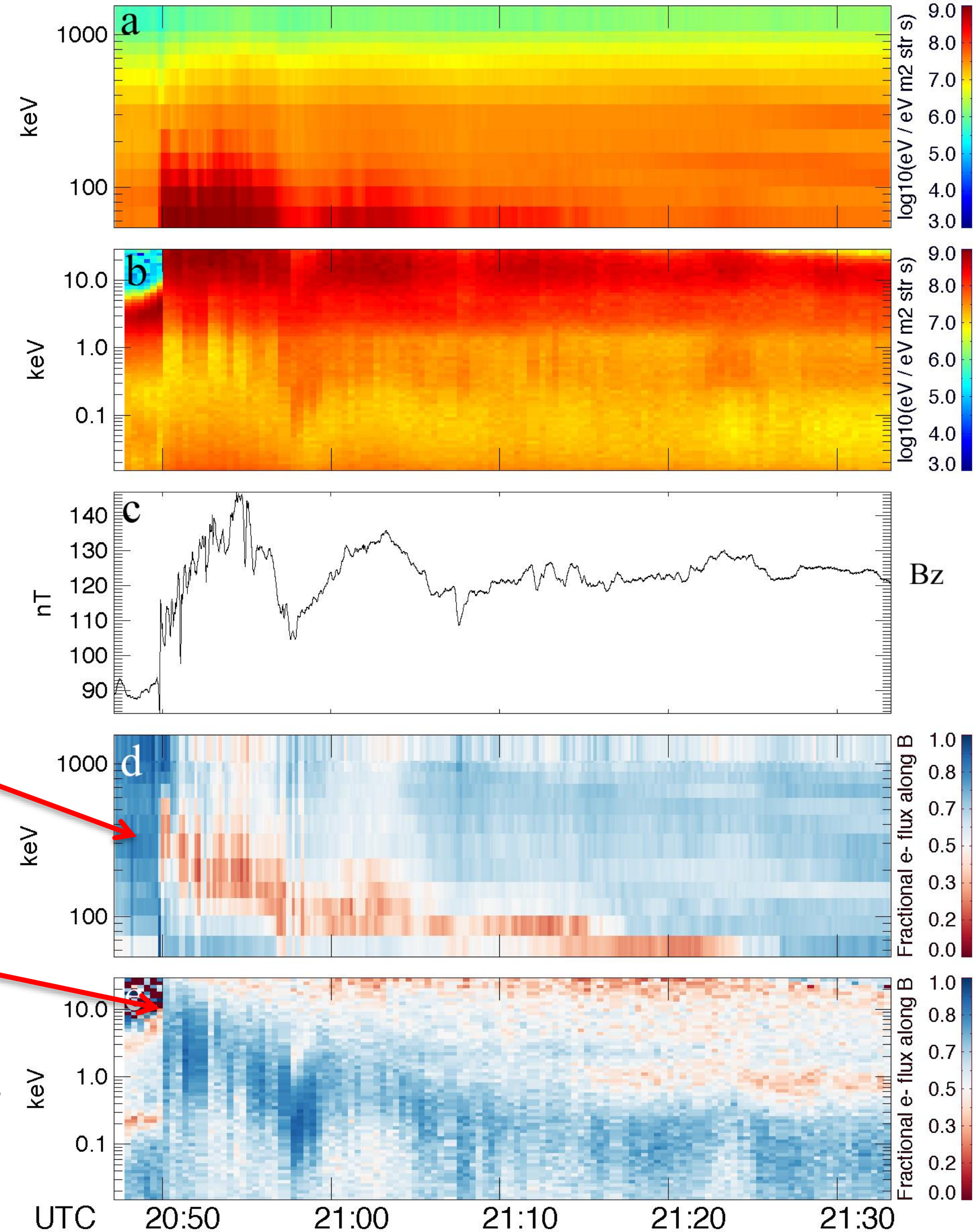
“Dispersionless” injection
shows dispersion of anisotropy

Consistent with: Injection far Earthward of plasma sheet inner boundary
(Assume conservation of μ)

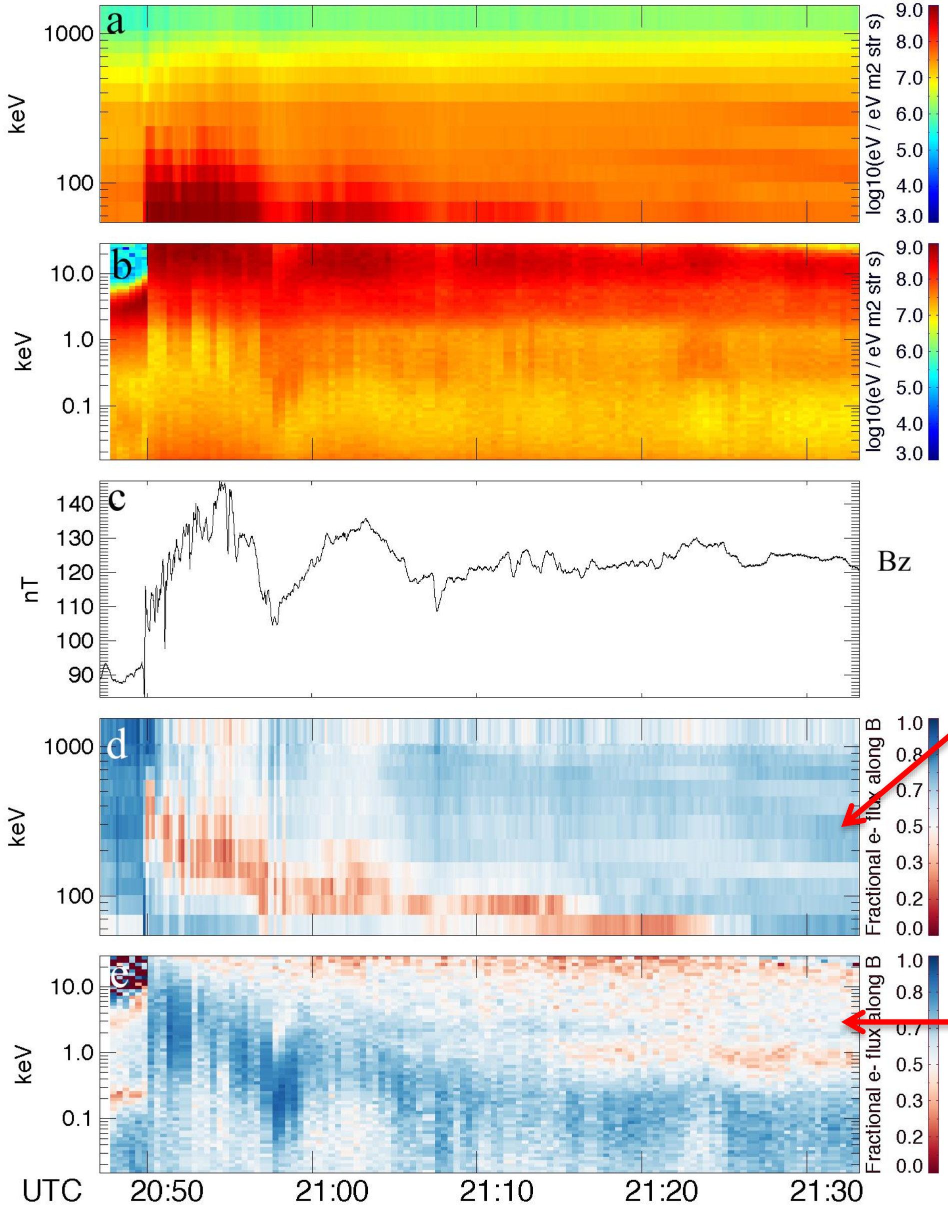
Perpendicular electrons:
300 keV e- near front
traveled at least 6 Re

Parallel electrons:
10 keV e- near front
local e- caught in flow
(accelerated locally?)

$$\frac{\text{Flux} \,||}{\text{Flux prp.}} = \frac{8.18^\circ,\ 24.5^\circ,\ 155.45^\circ,\ 171.8^\circ}{90^\circ}$$



Particle Injection



Behind the front:
300 keV e- are local
(closed drift paths)
did not travel with the front

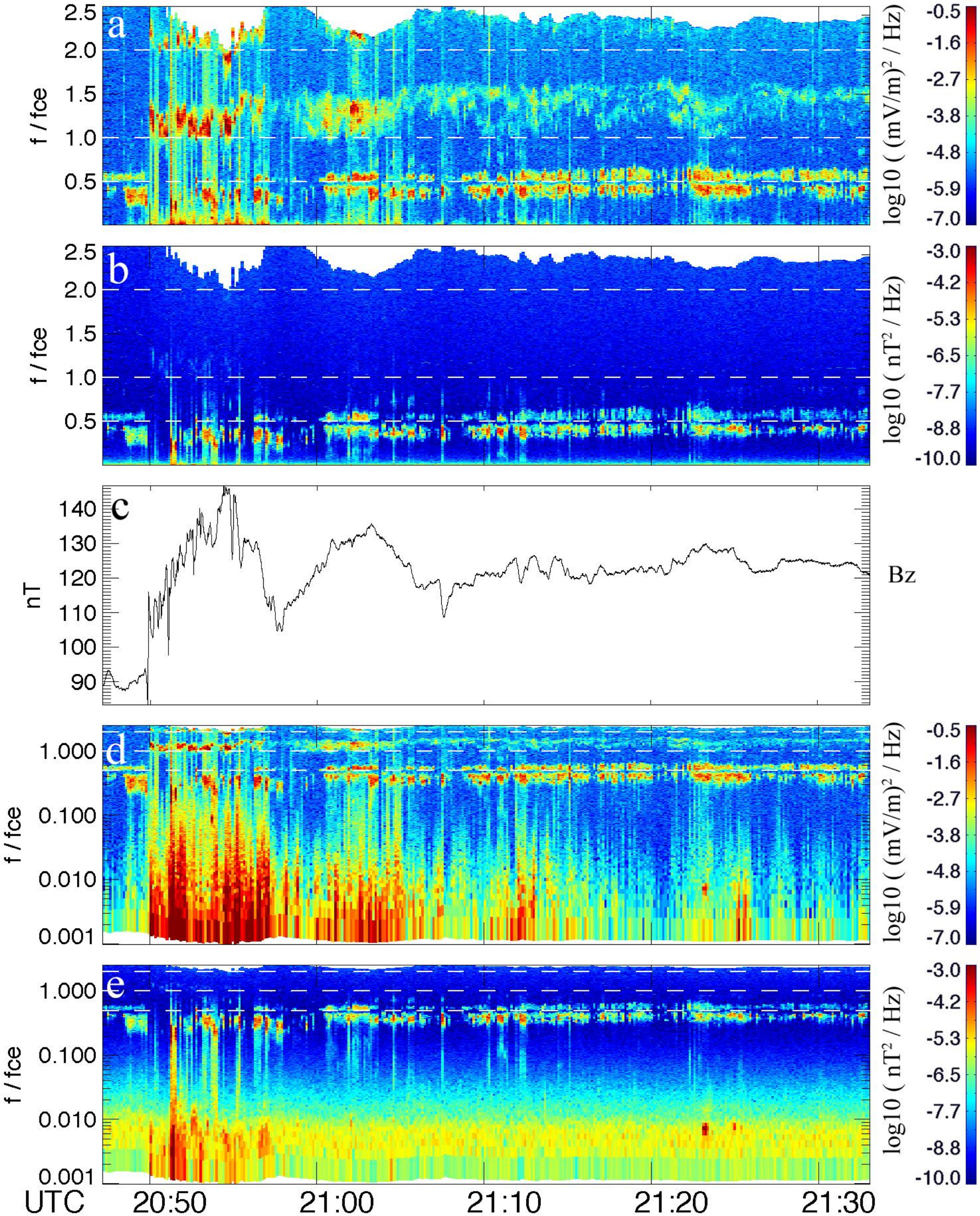
Behind the front:
10 keV e- traveled with front
(but not very far)

Injection as wave driver

Four distinct Bz enhancements

Each drives a full spectrum of waves

- ECH
- whistler-mode
- KAW
- phase space holes



Injection as wave driver

Each Bz enhancement drives full spectrum of waves

> 2fce
(ECH)

fce < f < 2 fce
(ECH)

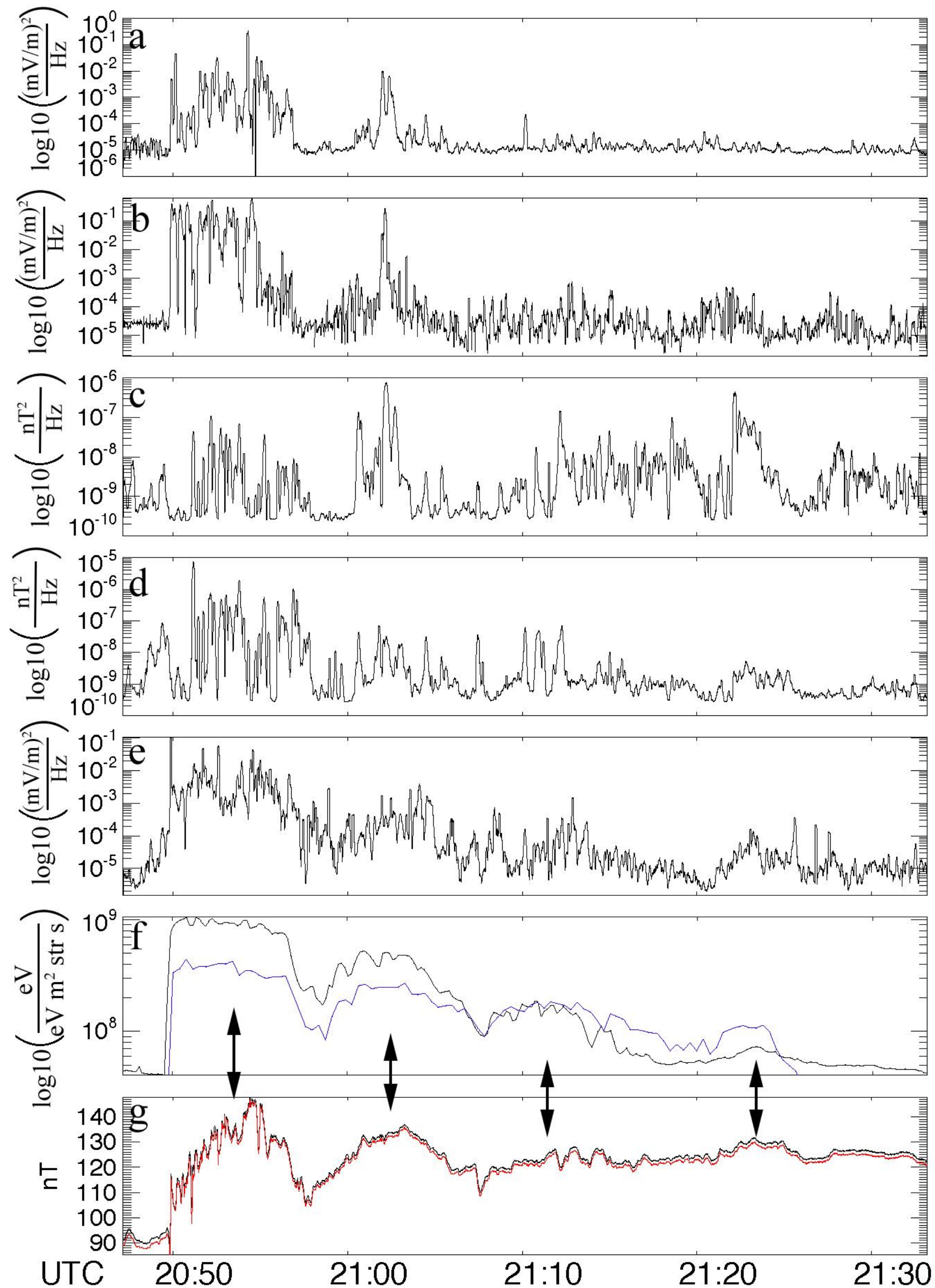
0.5 fce < f < fce
(UB Whistler-mode)

0.1 fce < f < 0.5 fce
(LB Whistler-mode)

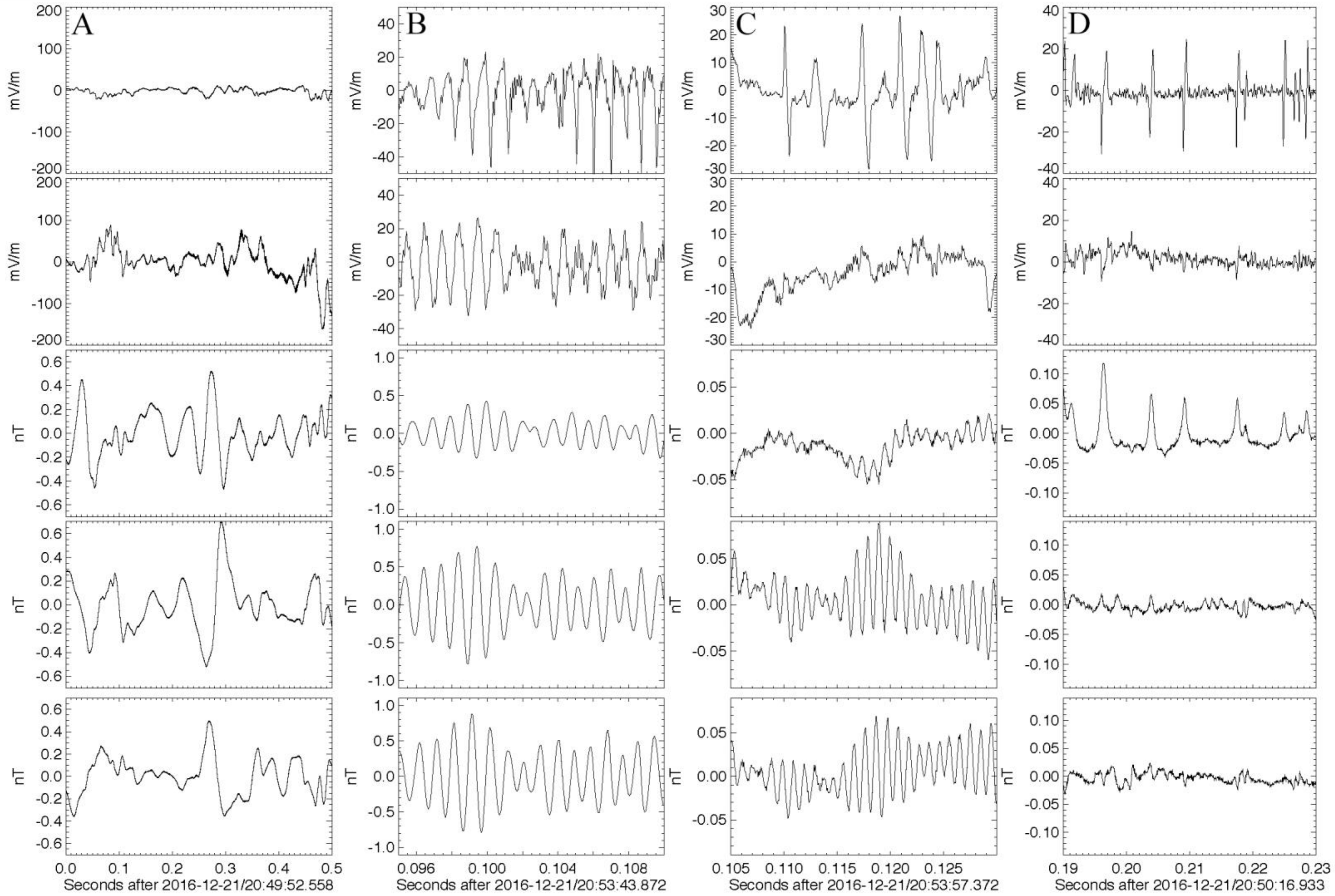
f < 0.1 fce
(Kinetic Alfven)

Electron Flux
(~30 keV)

|B| and Bz



A Zoo of waves



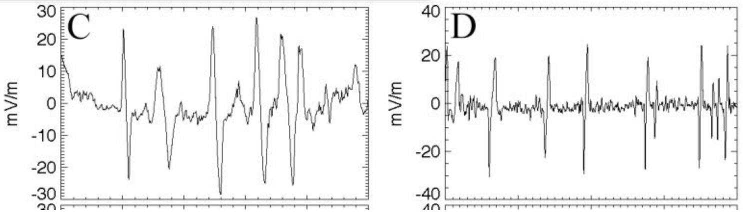
Kinetic Alfven waves
(Chaston+ 2014, 2016)

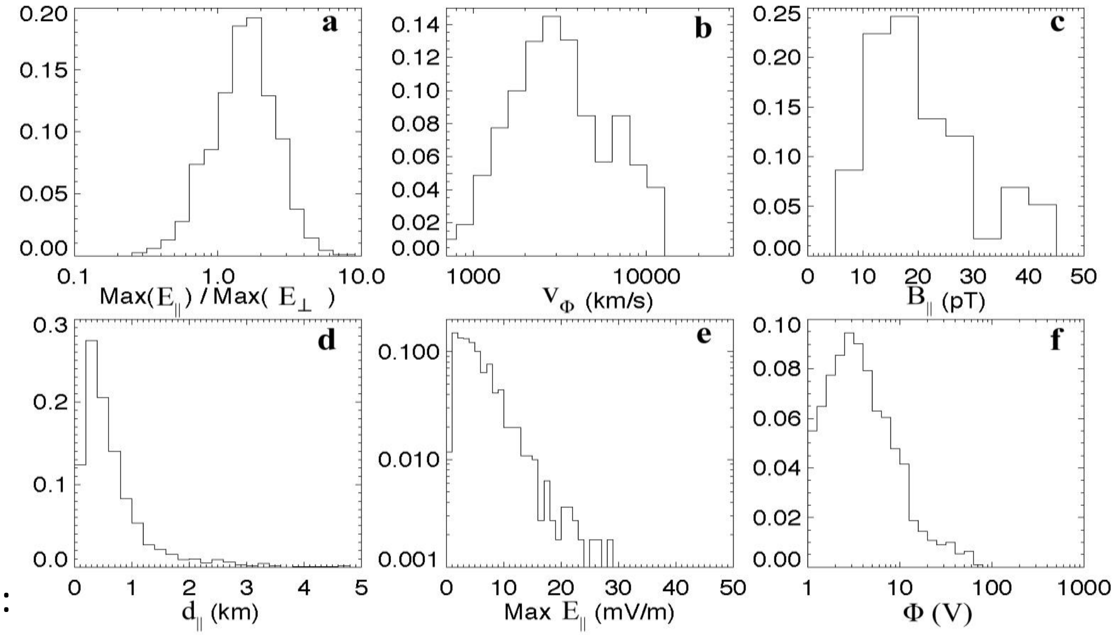
Nonlinear whistler-mode waves
(Mozer+ 2013)

Phase space holes
(Mozer+ 2013
Osmane + 2017
Artemyev+ 2014)

Phase space holes with |B| spikes
(Malaspina+ 2014
Vasko+ 2015)

Electron Holes



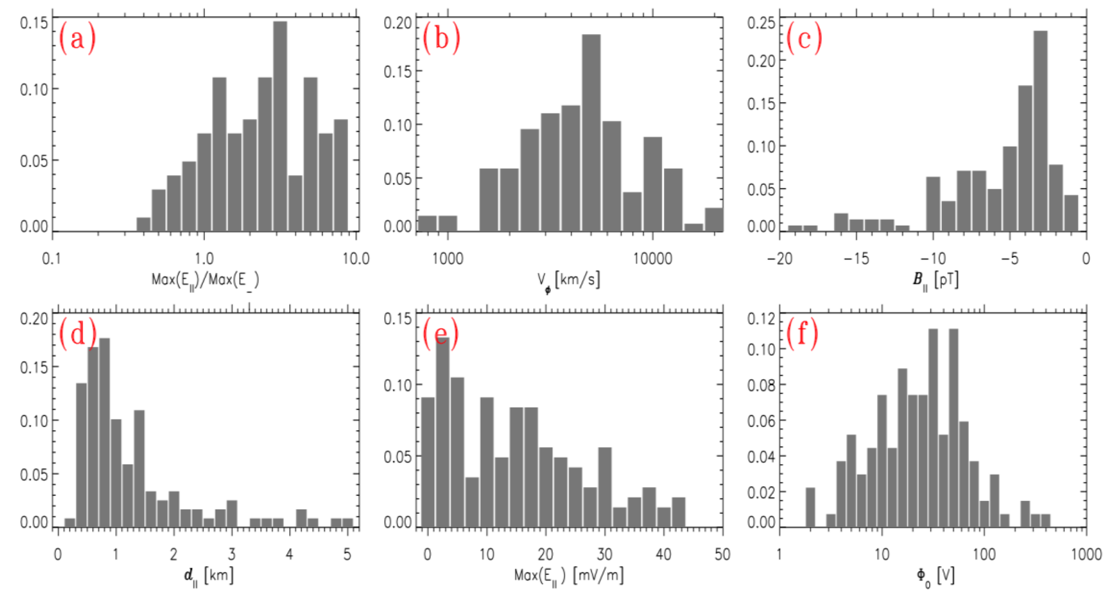


<u>Compare hole properties</u>

- Burst 1 (this work) ~4,200 EH
- Burst 2 [Vasko+ 2017] ~100 EH

[Vasko+ 2017] EH Diffusion coeff (lead factor):

$$D_0 = \left(\frac{2\pi}{m_e^2\omega_0^3}\right)\left(\frac{1}{L_\parallel L_\perp^2}\right)\left(\left(\frac{d_\perp}{d_\parallel}\right)^2\frac{1}{d_\parallel}\right)\phi_0^2$$



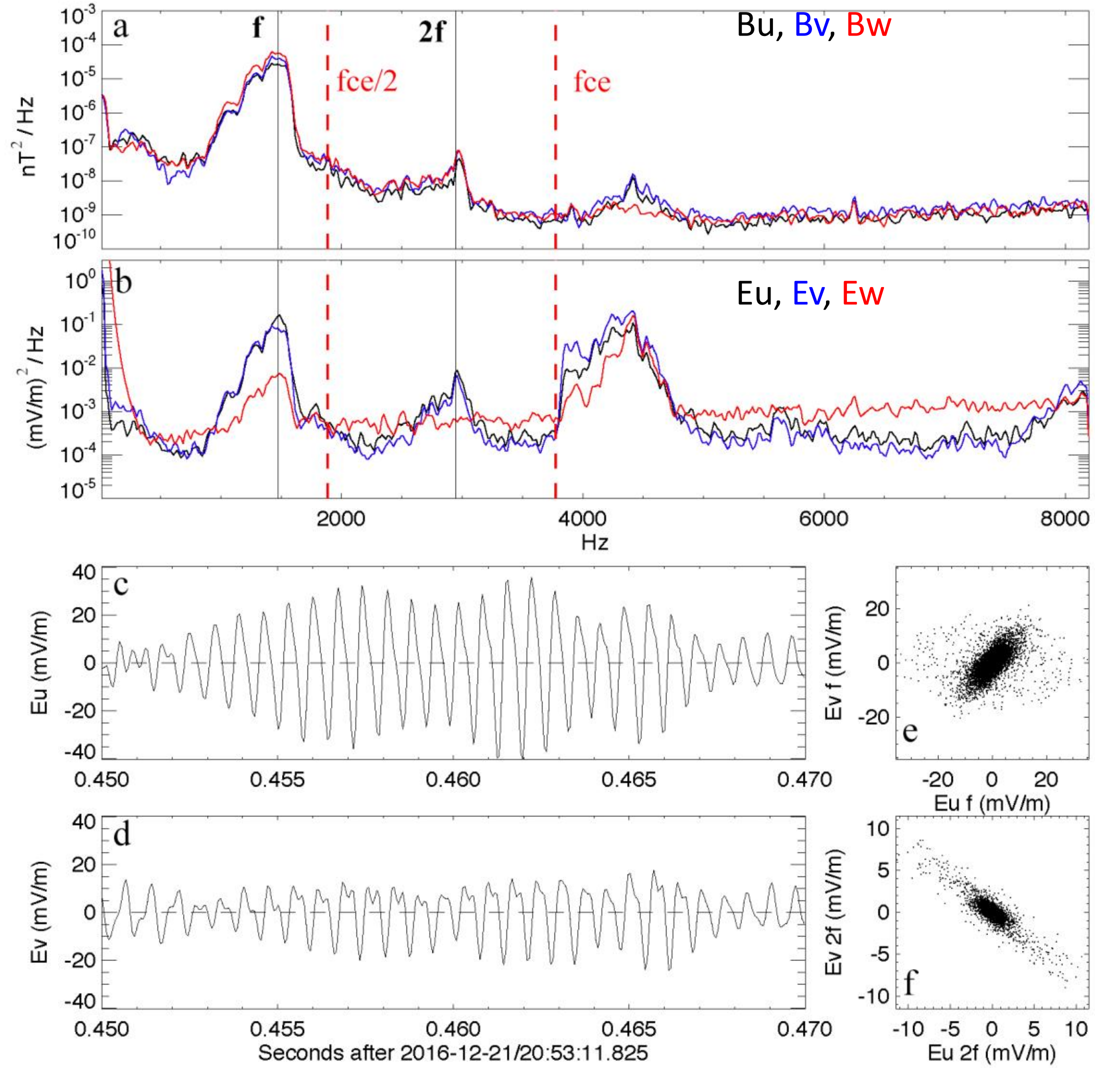
<u>Burst 1 holes:</u>

- shallower 'typical' potential

- Implies 10x to 100x weaker diffusion than estimated using triggered bursts

What about event-to-event variation?

Nonlinear Whistler-Mode Waves



<u>Lower-band whistler-mode waves</u>

- Both E and B show harmonics
  - signals at 2f for waves at f
- Harmonics above f only
- Distorted waveforms indicate strong harmonics
- Harmonics more electrostatic than primary waves
- not strong enough to be noticed in SCM time-series, but often exist

Nonlinear Whistler-Mode Waves

<u>Harmonic vs. Primary signals</u>

3,192 of the 5,400 intervals (0.5 s each) are dominated by whistler-mode waves

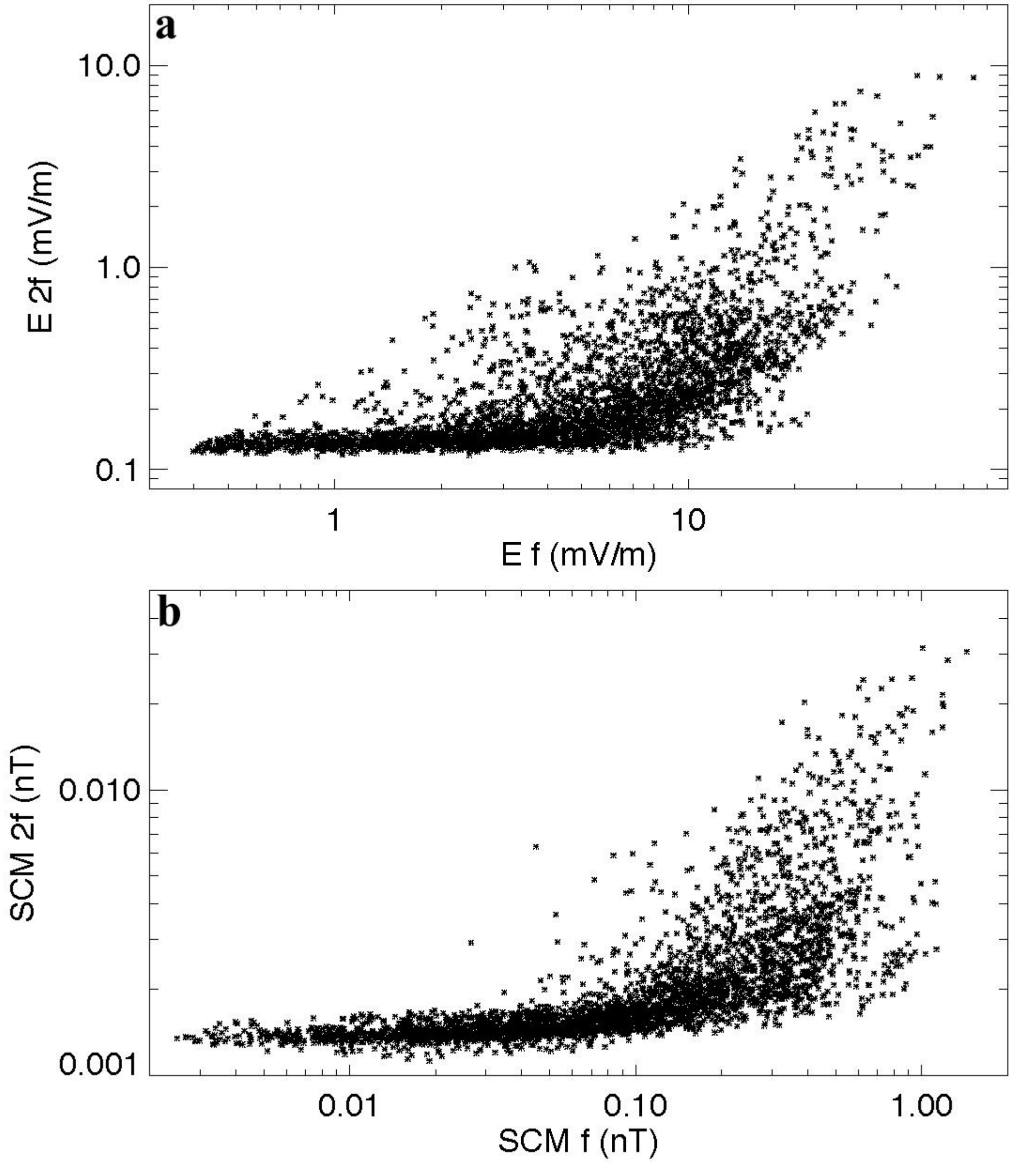
E-field harmonics:

- E_{2f} increases with E_f
- E_{2f} as large as 14% of E_f
- E_{2f} observable for waves > 1 mV/m

B-field harmonics:

- B_{2f} increases with B_f
- B_{2f} as large as 3% of B_f
- B_{2f} observable for waves > 0.1 nT

Nonlinear behavior is common,
not exceptional,
for lower band whistler-mode waves



(amplitudes from sum of spectral data, bandpass of +/- 100 Hz about f or 2f)

Conclusions

[1] The studied injection transported e- at least 6 R_E
from plasma sheet into inner magnetosphere

[2] This injection had four separate magnetic compressions
Each compression drove waves across the observed spectrum

[3] A zoo of nonlinear waves and kinetic structures are observed
(though not all previously identified were found)

[4] 'Typical' phase space holes are weaker than estimated using triggered burst data
degree of event-to-event variation?

[5] Lower band whistler-mode waves show amplitude-dependent nonlinearities (harmonics)
These harmonics are common over a range of amplitudes

[6] Statistical study under way
Are there 'typical' wave / structure properties at these boundaries?
How is injection energy partitioned into various wave types?

[7] **How important are these structures/waves for the inner magnetosphere?**

Fin

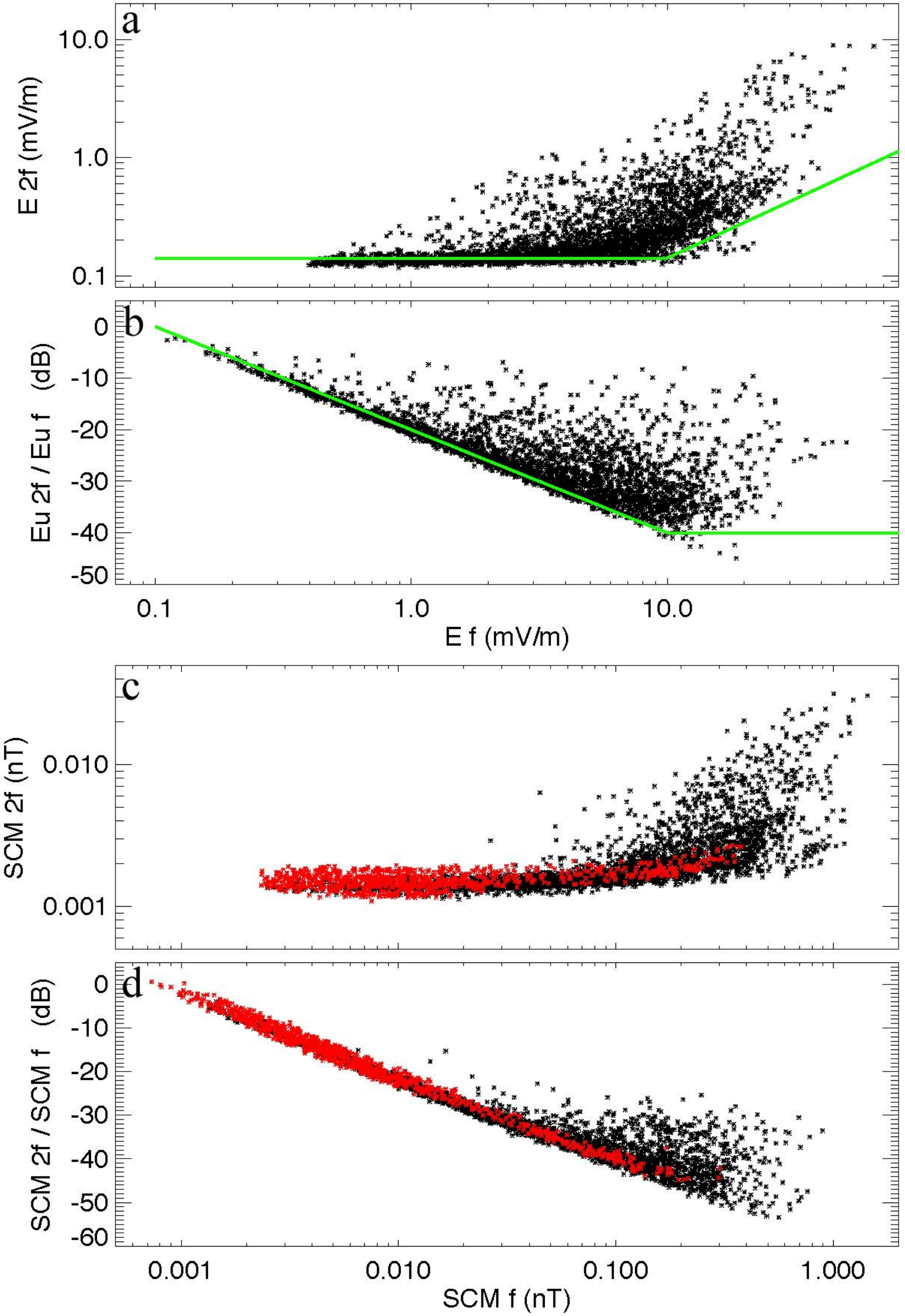
Instrumental Harmonics?

Black: E_{2f} vs. E_f (from earlier figure)

Green: E_{2f} vs. E_f (assuming -40 dB of instrumental harmonic distortion)

Black: B_{2f} vs. B_f (from earlier figure)

Red: B_{2f} vs. B_f (for upper band whistler-mode waves, when upper band is stronger than lower band)



Instrumental Harmonics?

Harmonics in the electronics?

THD = total harmonic distortion = 2f + 3f + 4f …

- EFW receiver board verified ~ -70 dB THD
- EFW preamps, bias board verified ~ -40 dB THD

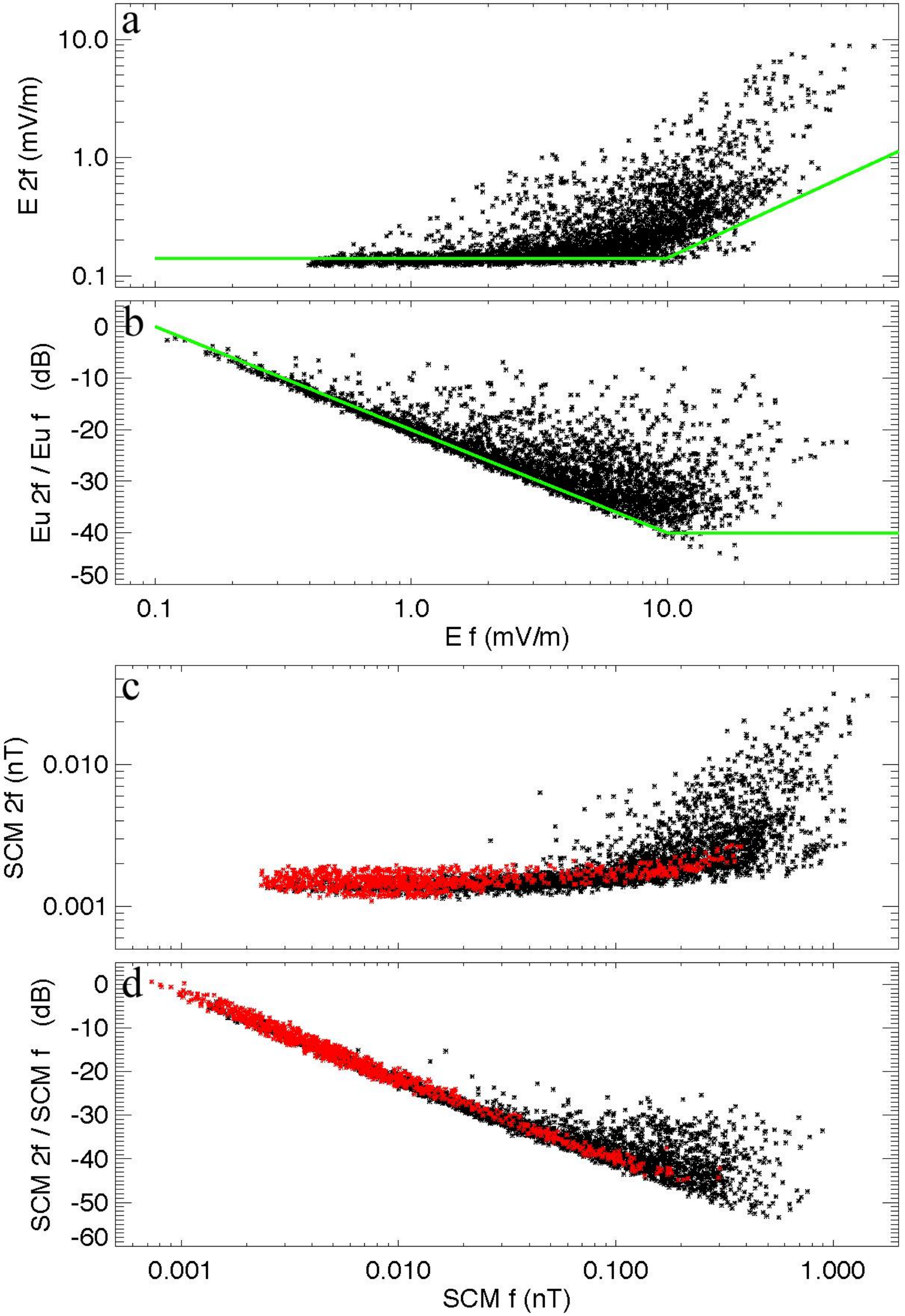
- SCM sensor (?)
  - No strong B_{2f} for upper band waves

Harmonics in the plasma sheath?

- SCM has no plasma sheath effect

- E_{2f} envelope does not follow E_f envelope
  (expected for sheath harmonic [Boehm+ 1994])

Eliminated electronics, sheath, left with:
Harmonics are real !



Instrumental Harmonics?

- E_{2f} envelope does not follow E_f envelope