MMS observations of ion cyclotron waves in the solar wind

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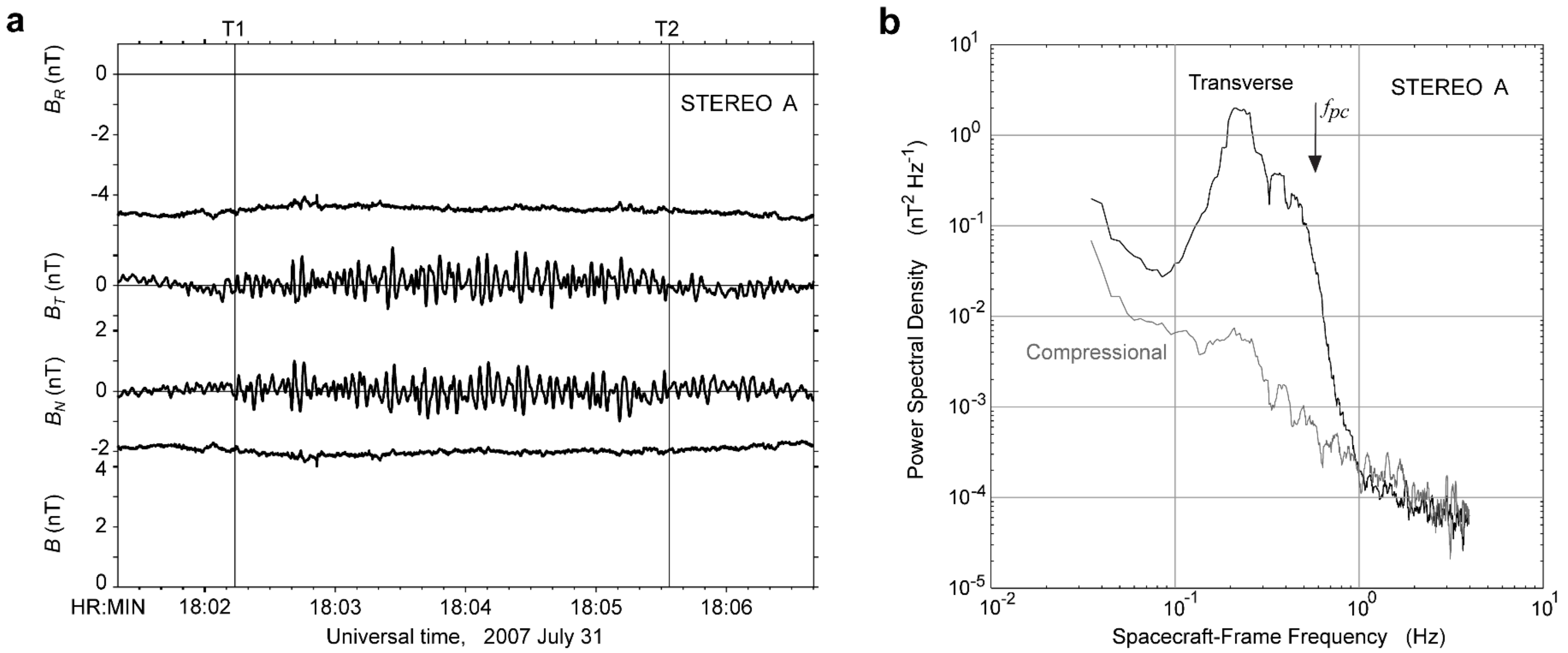
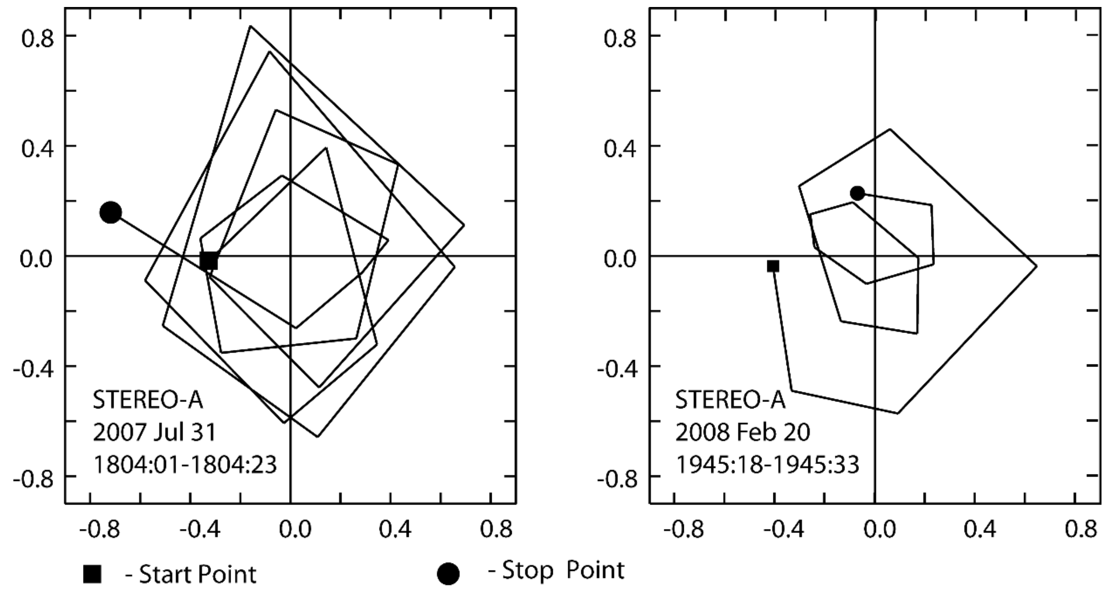
Outline

- Introduction on STEREO observations of ICW in the solar wind
- Open questions on wave energy sources
  - Generation mechanism
  - Energy sources: local vs remote
- MMS to study on the waves at 1 AU
  - Need to avoid the foreshock regions where there are abundant upstream waves
  - Select events based on MAG observations, then examine the plasma data during these events (e.g. temperature anisotropy, etc)
- Three case studies with MMS data:
  - Case 1 & 2: plasma data indicates Ti_para > Ti_perp
  - Case 3: plasma data indicates Ti_perp >/= Ti_para

An example of ICW observed by STEREO





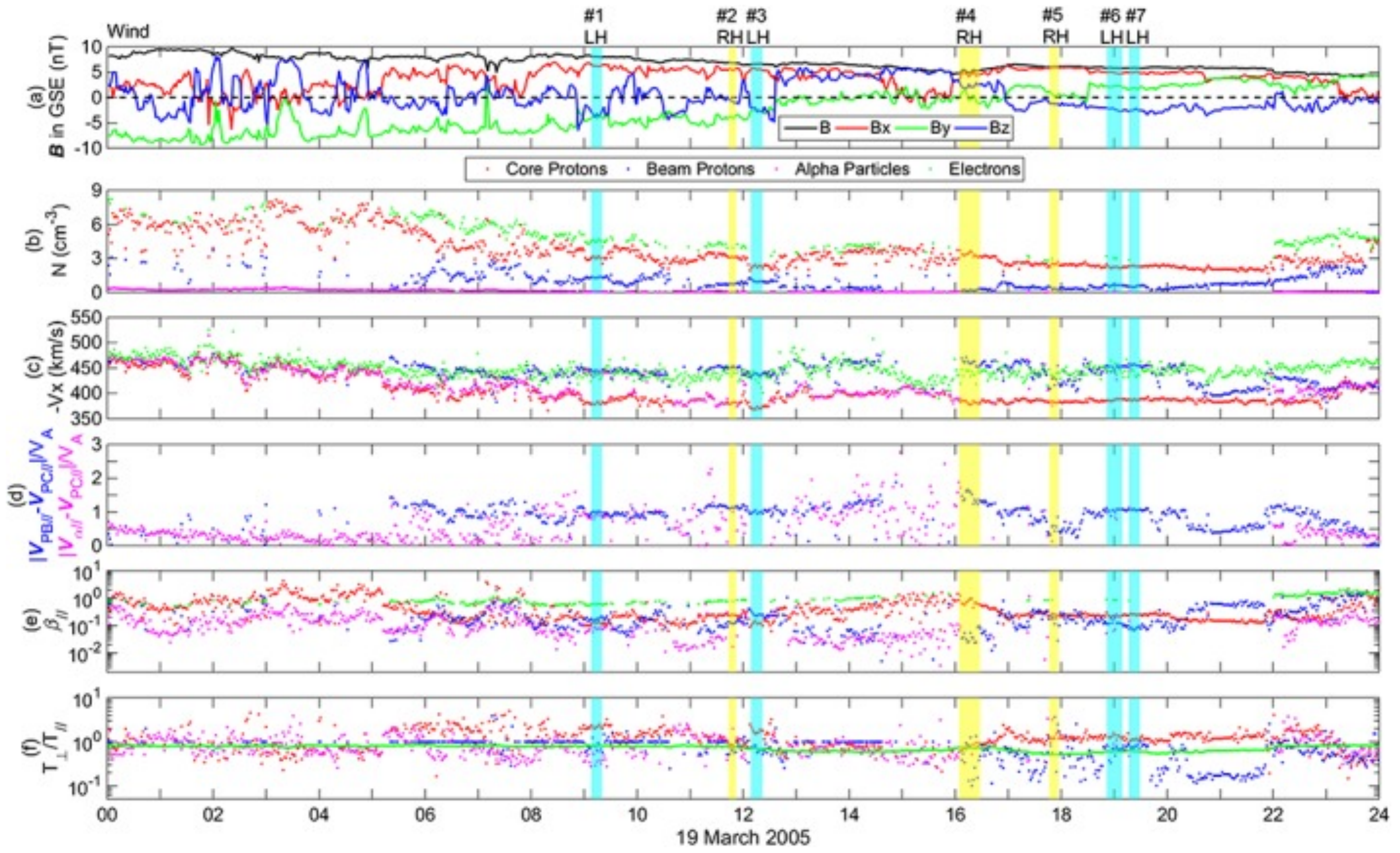
- Ion cyclotron waves (ICWs) were observed by STEREO in the solar wind far away from any planetary or cometary sources.

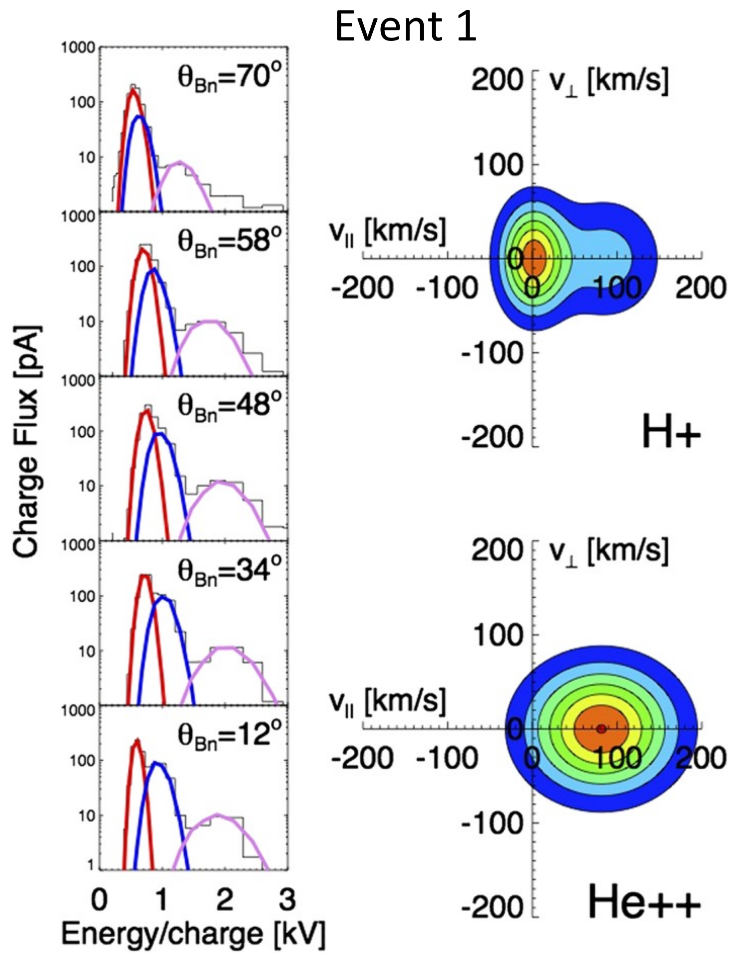
- Generally, these waves have nearly field-aligned propagation, left-handed (LH) or (RH) right-handed circular polarization, and frequencies (in local plasma frame) below the proton gyro-frequency.

Open questions on wave energy sources

- In the solar wind, there are mainly three types of ion-driven instabilities responsible for parallel-propagating ICWs:
    - ion cyclotron instabilities driven by ion component with temperature anisotropies greater than 1,
    - parallel firehose instabilities driven by ion temperature anisotropies smaller than 1,
    - ion/ion magnetosonic instabilities driven by the relative drift between two ion components.
- High quality plasma data is needed to examine the possible unstable mode with dispersion analysis and check if the prediction agrees with the observed wave mode.
- Wave properties may also provide information on the possible energy sources:
    - In the solar wind frame, the waves due to ion cyclotron instability have left-handed polarization, while the waves due to firehose and ion/ion magnetosonic instabilities have right-handed polarization.

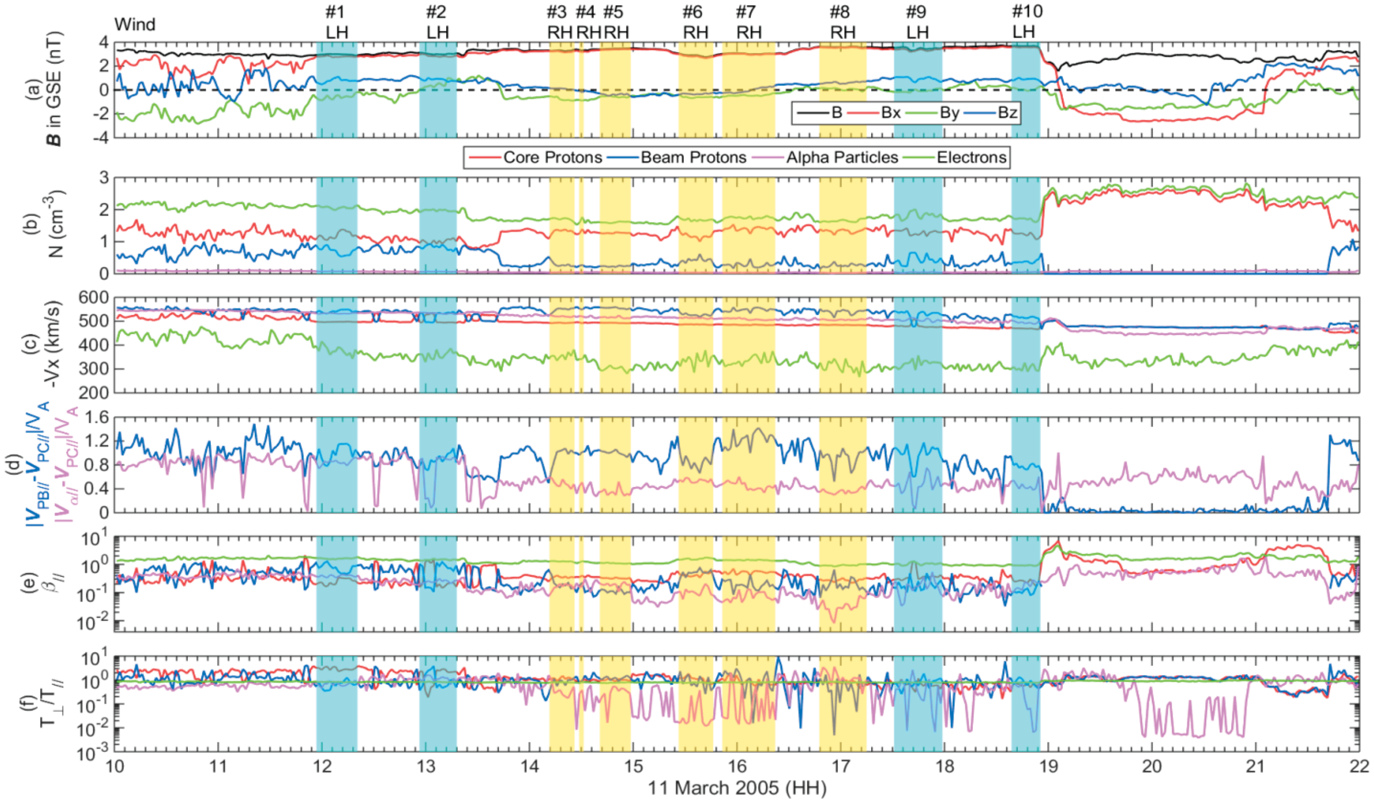
Local sources: Gary et al., 2016





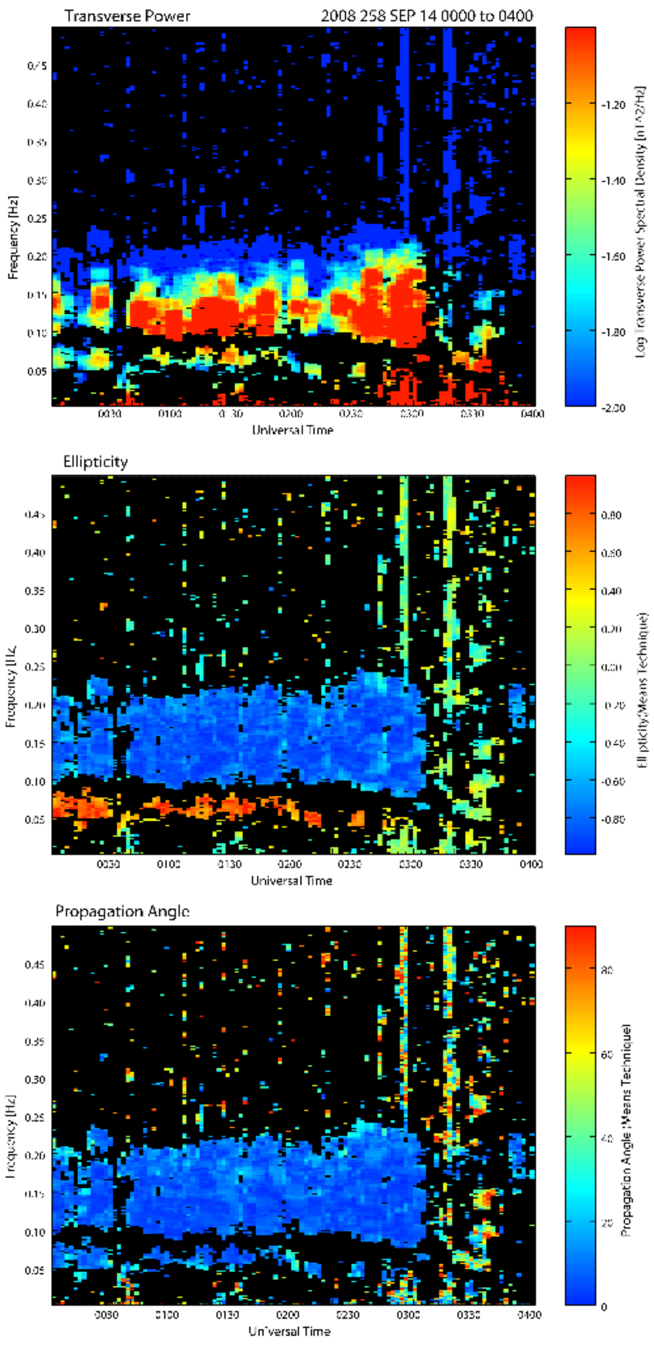
- The LH waves are generated by a proton component with temperature anisotropy, i.e. ion-cyclotron instability.
- The RH waves are generated by ion component relative flows, i.e. magnetosonic instability.

Local sources (cont'd): Jian et al., 2016



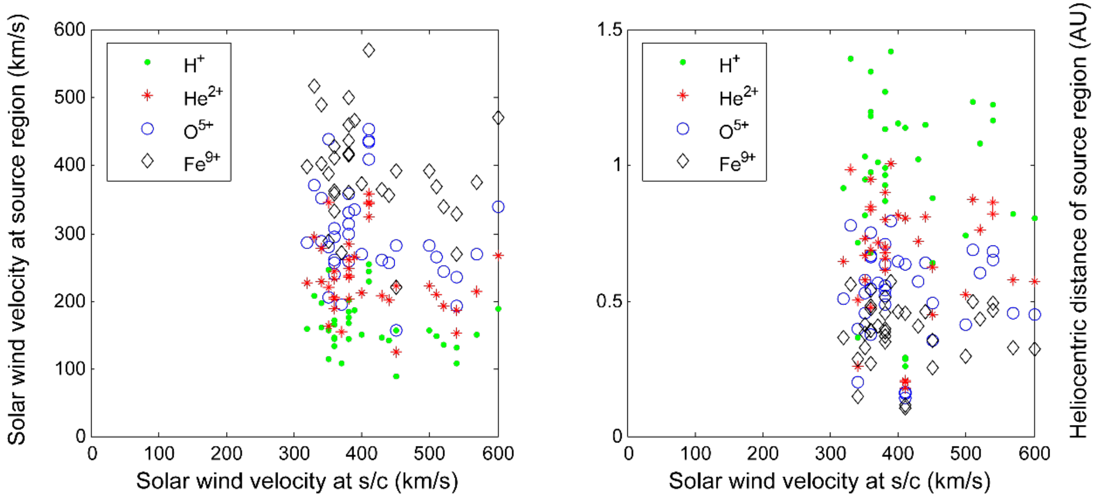
Interval #	1	2	5	6	7	9
V_A/c ($\times 10^{-4}$)	1.45	1.56	1.95	1.55	1.70	1.70
$\lvert V_{PB//}-V_{PC//}\rvert/V_A$	0.37	1.05	1.16	1.04	1.33	0.75
$\lvert V_{\alpha//}-V_{PC//}\rvert/V_A$	1.01	0.27	0.36	0.56	0.52	0.14
N_{PC}/N_e	0.52	0.47	0.79	0.71	0.83	0.61
N_{PB}/N_e	0.40	0.46	0.14	0.23	0.13	0.34
N_α/N_e	0.04	0.04	0.03	0.03	0.02	0.03
$\beta_{//PC}$	0.39	2.97	0.45	0.80	0.68	2.16
$\beta_{//PB}$	2.22	0.33	0.79	2.14	1.34	0.46
$\beta_{//\alpha}$	10.28	7.07	6.87	7.80	3.18	4.27
$\beta_{//e}$	1.73	1.43	1.13	1.76	1.37	1.28
$T_{\perp PC}/T_{//PC}$	3.88	0.18	0.88	0.69	0.80	0.45
$T_{\perp PB}/T_{//PB}$	0.78	2.45	1.20	0.26	0.17	0.54
$T_{\perp\alpha}/T_{//\alpha}$	0.78	1.65	0.11	0.01	0.02	2.70
$T_{\perp e}/T_{//e}$	0.84	0.86	0.78	0.77	0.79	0.78
Polarization in s/c frame	LH	LH	RH	RH	RH	LH
Predicted growing wave	IC2	IC1, RHB	RHF	RHF	RHF	IC1, RHB
γ_{max} ($\times 0.01\Omega_p$)	5.4	0.9, 13	0.6	10.1	6.6	1.2, 2
Matching wave	N/A	ICW	MW	MW	N/A	ICW

- This study found 6 out of the 10 events with instabilities and 4 of them have the observed wave mode in agreement with that predicted by linear dispersion analysis.



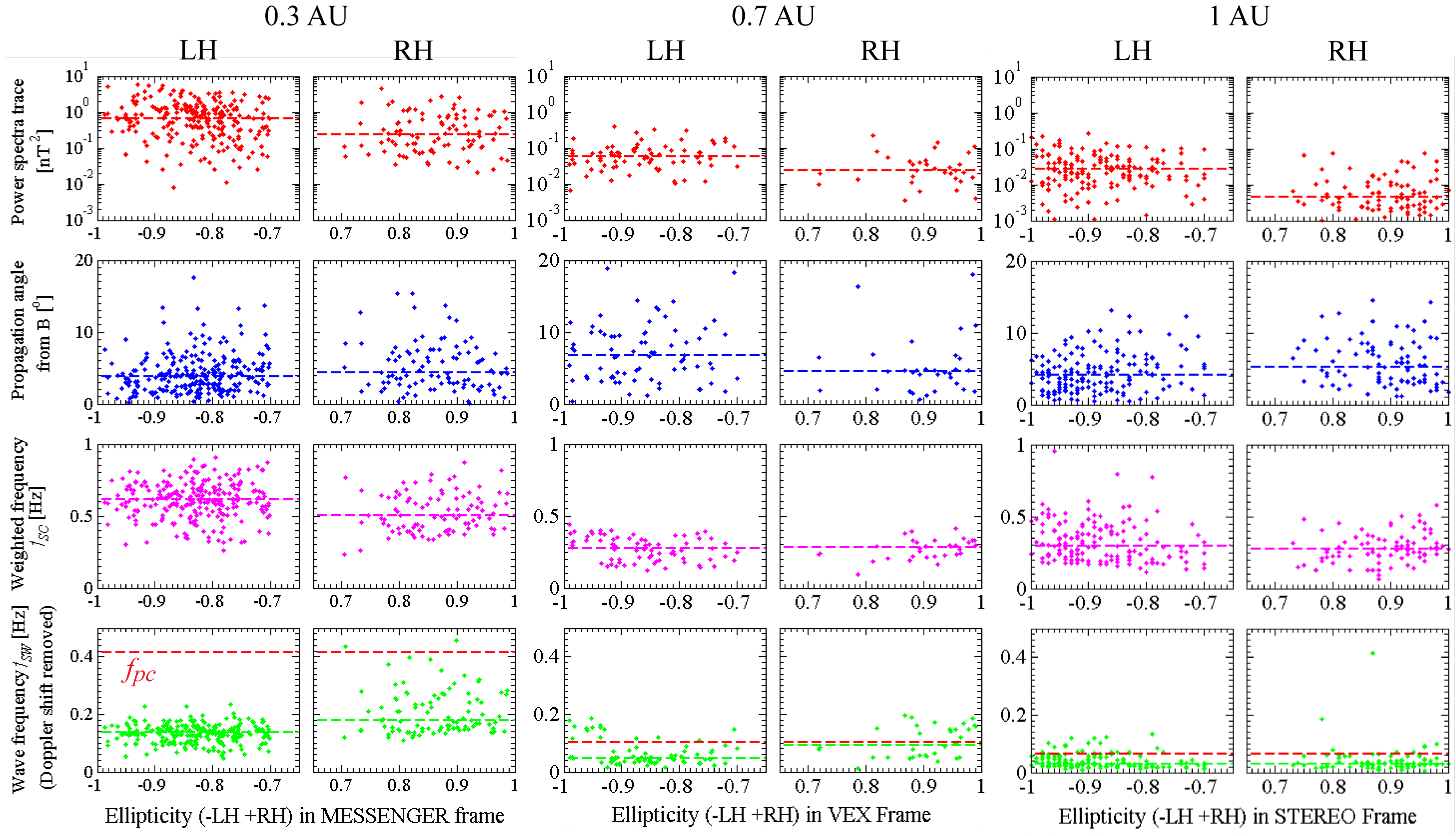
Black - Unmasked values have a coherence between 0.50 and 1.00

Possible remote sources



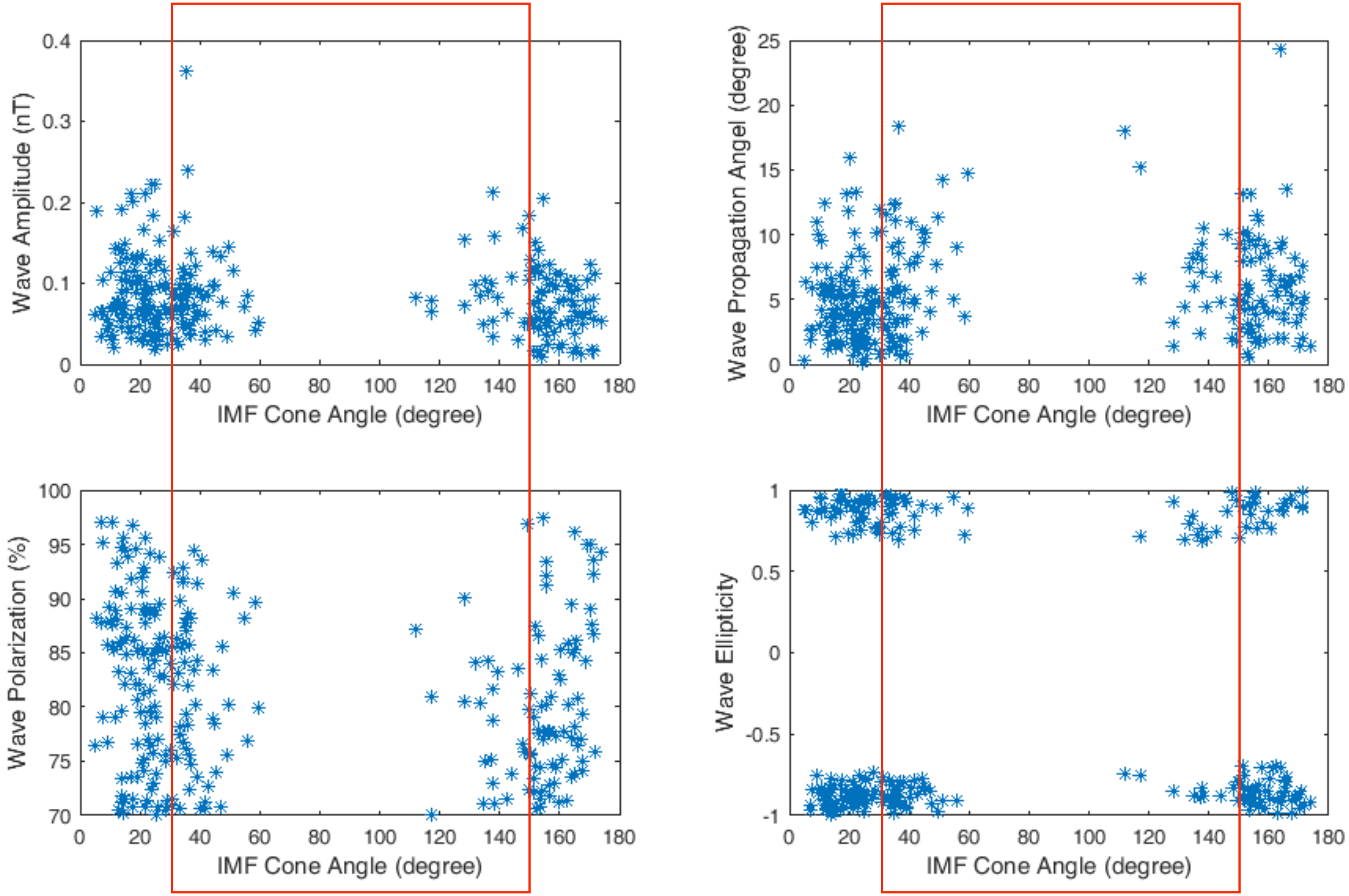
- Performed case studies on a special group of events with the left-handed and right-handed waves observed simultaneously in the spacecraft frame
- Under the assumption that LH and RH waves were generated by the same source remotely in the inner heliosphere, we can estimate the Doppler-shift frequencies and also the location of the source region.

Heliocentric distance variations



- From multi-spacecraft observations (MESSENGER, VEX and STEREO) at 0.3, 0.7, and 1 AU, the wave power and wave frequencies in both spacecraft frame and plasma frame are found to decrease with heliocentric distances slightly .

Wave property variations IMF cone angle

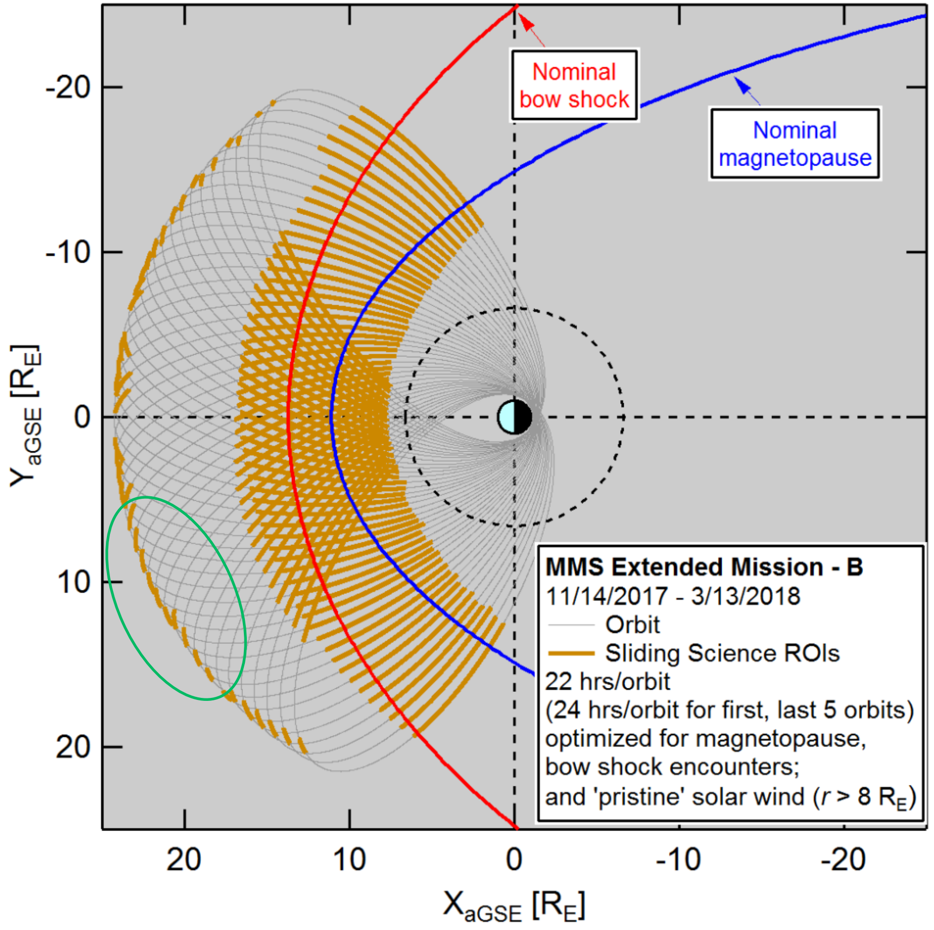


- When |cone| > 30 deg, the waves are more elliptically polarized and have larger propagation angle with larger IMF cone angle.

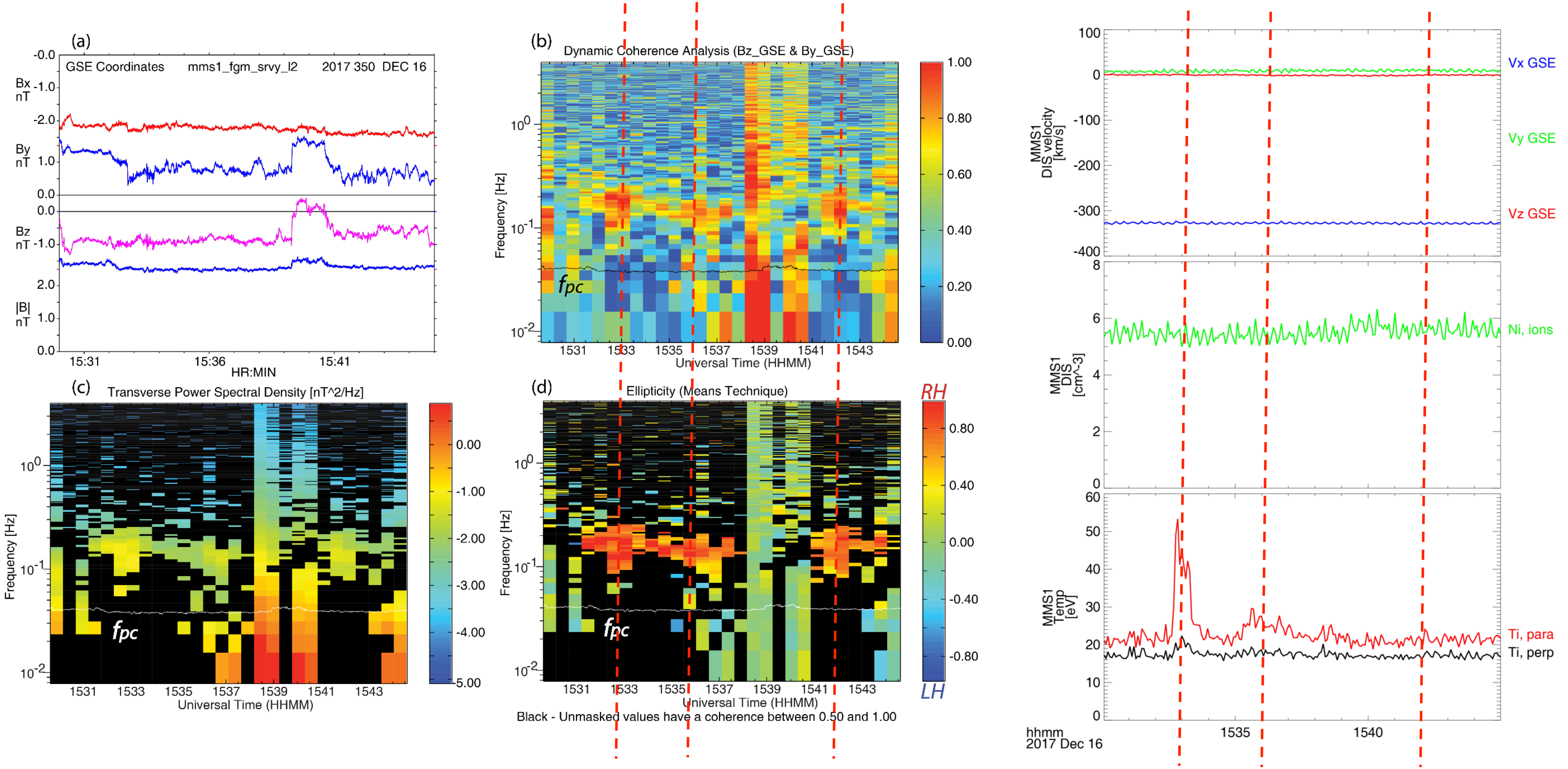
- This indicates the waves are created in region with smaller cone angles, e.g. cone < 30 deg

Statistical and case studies with MMS data

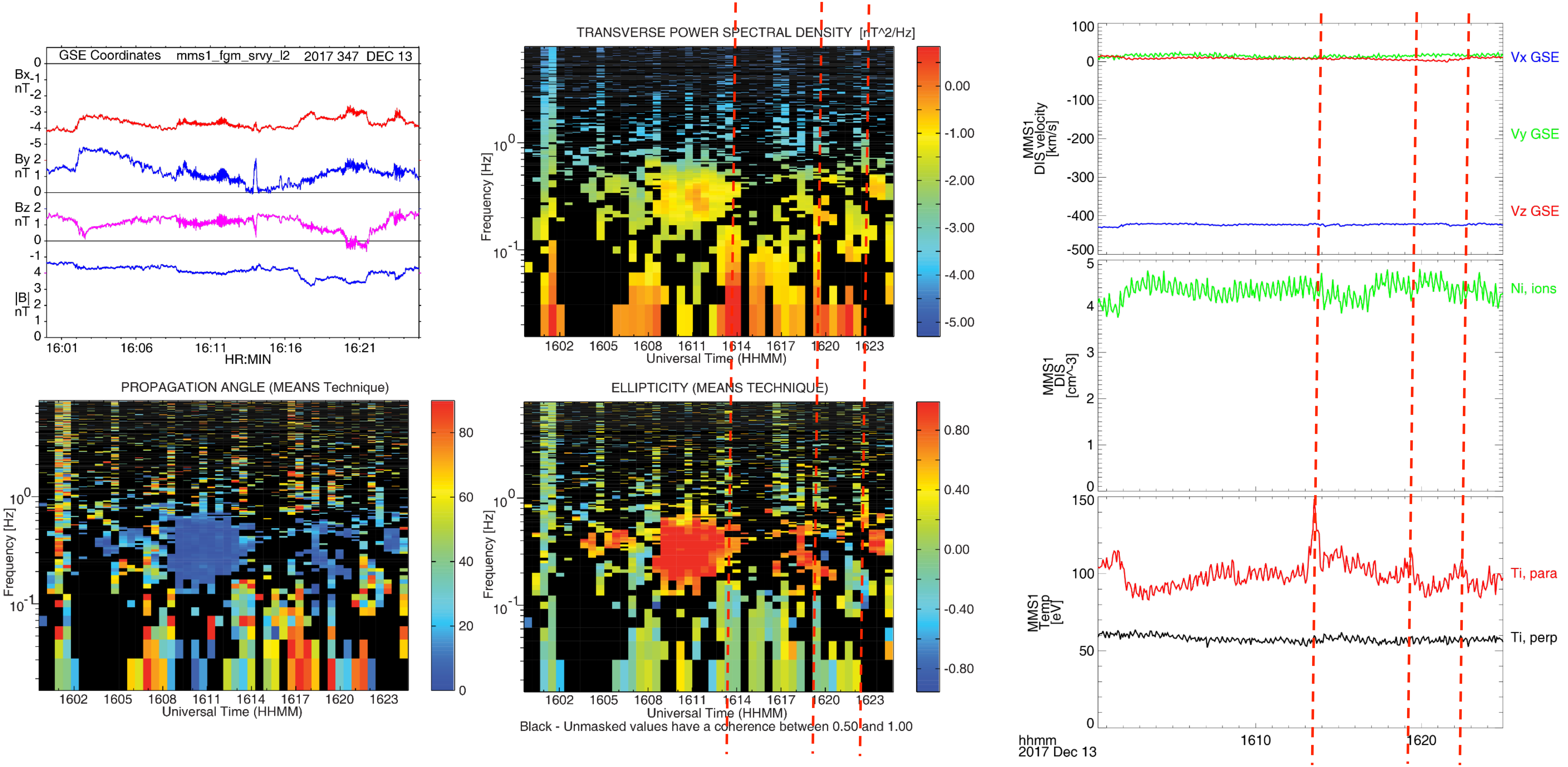
- In one month of MMS (2017/12), over a hundred events selected, and about 42 events lasting longer than 10 min (i.e. ICW storm events), but only very few of them have plasma data available.
  - Far from the shock, occurred outside 23 Re
  - Outside the foreshock region
  - The longest event lasts over 2hr, but no plasma data for it
- Need to obtain more cases studies with both fields and plasma data.



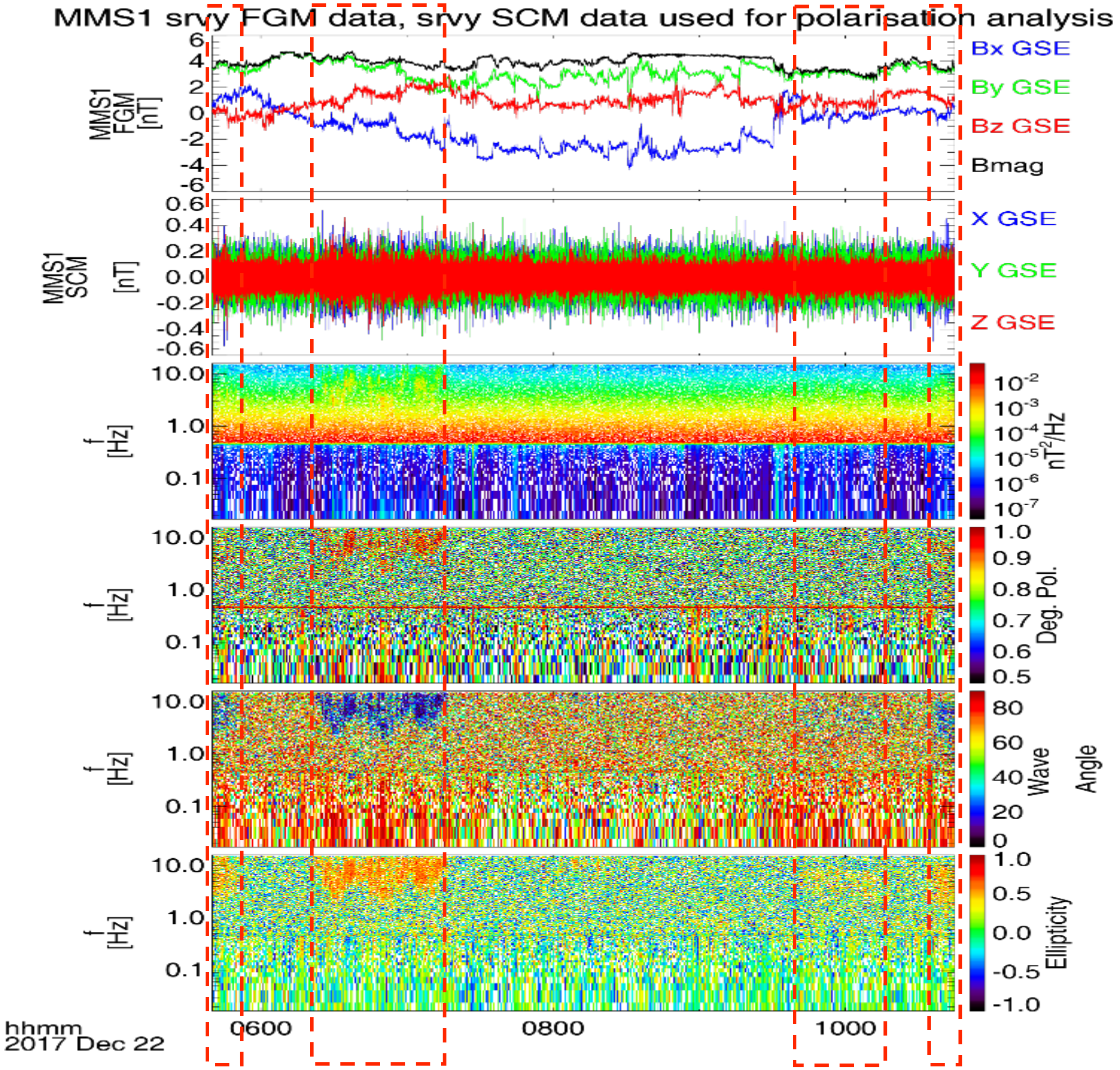
MMS observations: case 1, Ti_para > Ti_perp

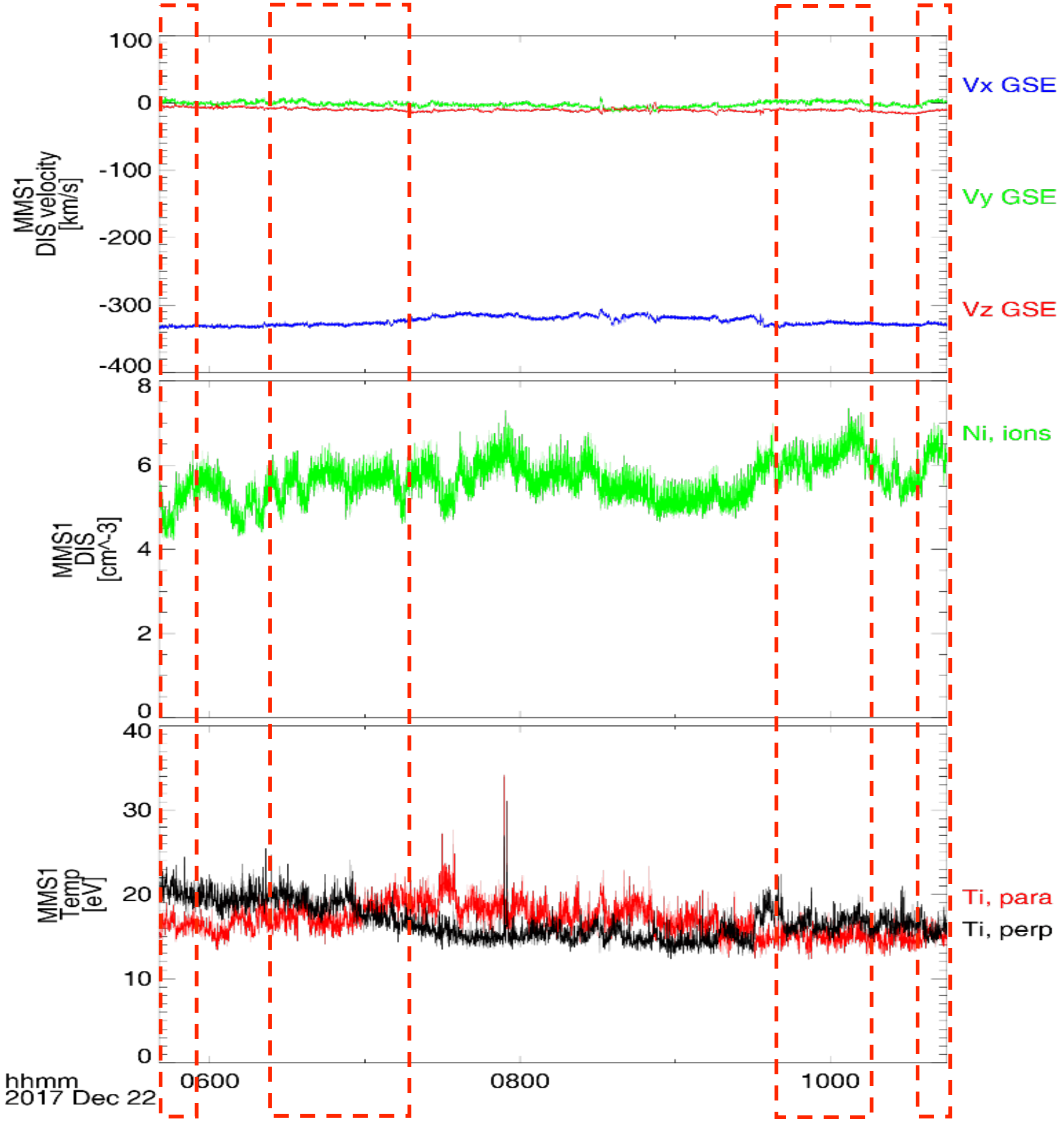


MMS observations: case 2, Ti_para > Ti_perp

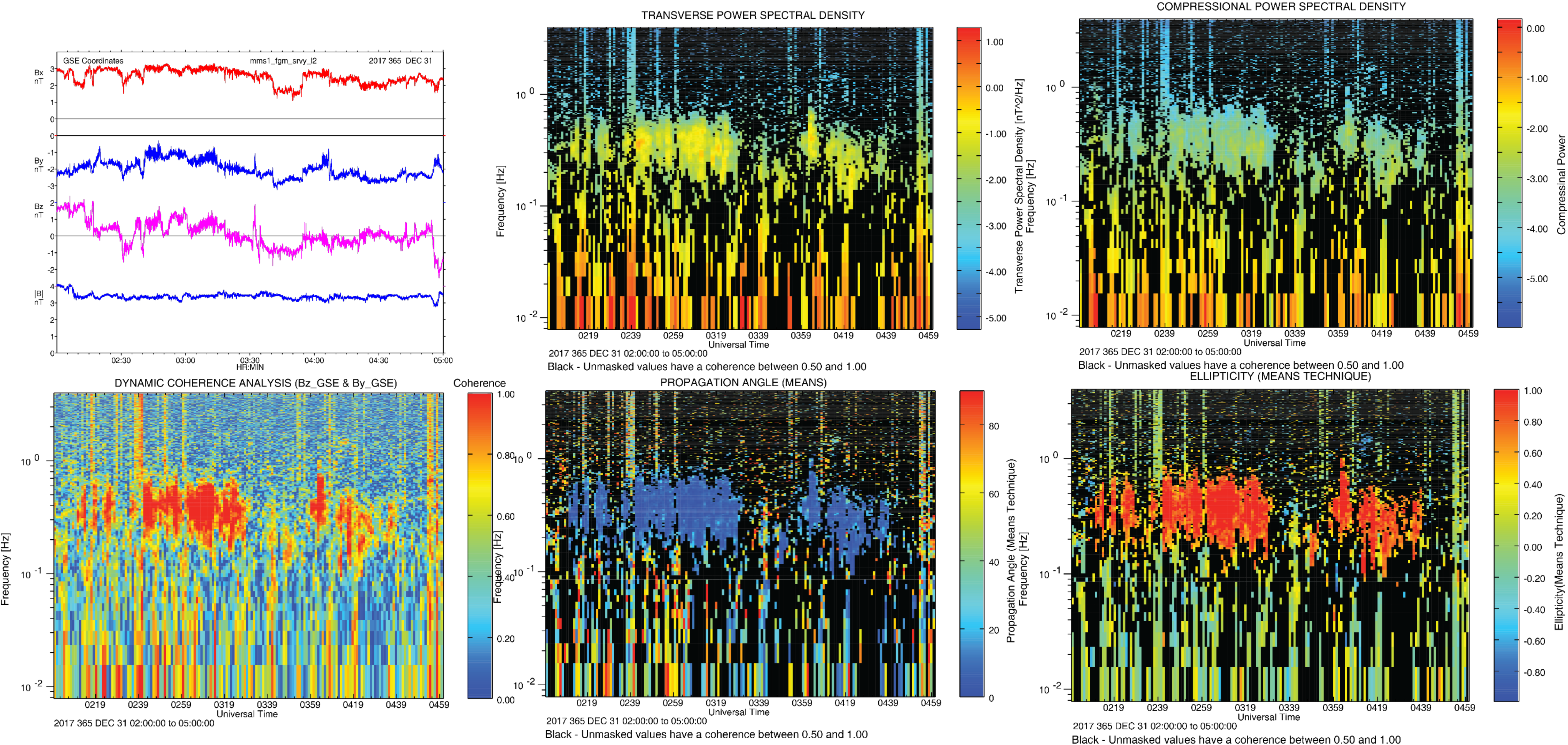


MMS observations: case 3, Ti_perp > Ti_para





Longest event observed by MMS: no plasma data



Concluding Remarks

- ICWs have been observed extensively from 0.3 to 1 AU by multiple missions.
- Both scenarios of remote or local energy sources have been examined by previous studies and they both have some supportive and inconsistent facts.
- To further understand the sources of these waves, we use high quality field and plasma measurements of MMS to determine the wave propagation properties and plasma instabilities.
    - For case 1 & 2, there are strong temperature anisotropy due to Ti_para > Ti_perp, leading to magnetosonic instability
    - For case 3, some wave intervals are associated with ion cyclotron instability due to Ti_perp > Ti_para, while some wave intervals have no temperature anisotropy and could be remotely generated.