Interplanetary Shocks Observed by STEREO.

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Current Studies:

-Interplanetary shocks (SIR/CIR and ICME)
(+ wave foreshocks, ion foreshocks)

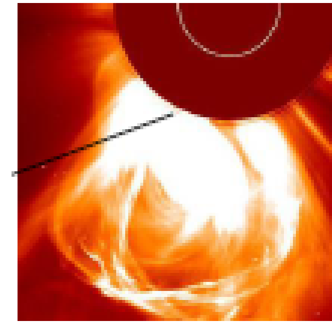
-Interplanetary shocks with multi-spacecraft observations (STEREO, WIND, CLUSTER), to be presented at the AGU.

-Micro-structure of sheaths (behind IP shock) mirror mode storms, waves inside magnetic clouds (ion cyclotron waves, mirror modes).

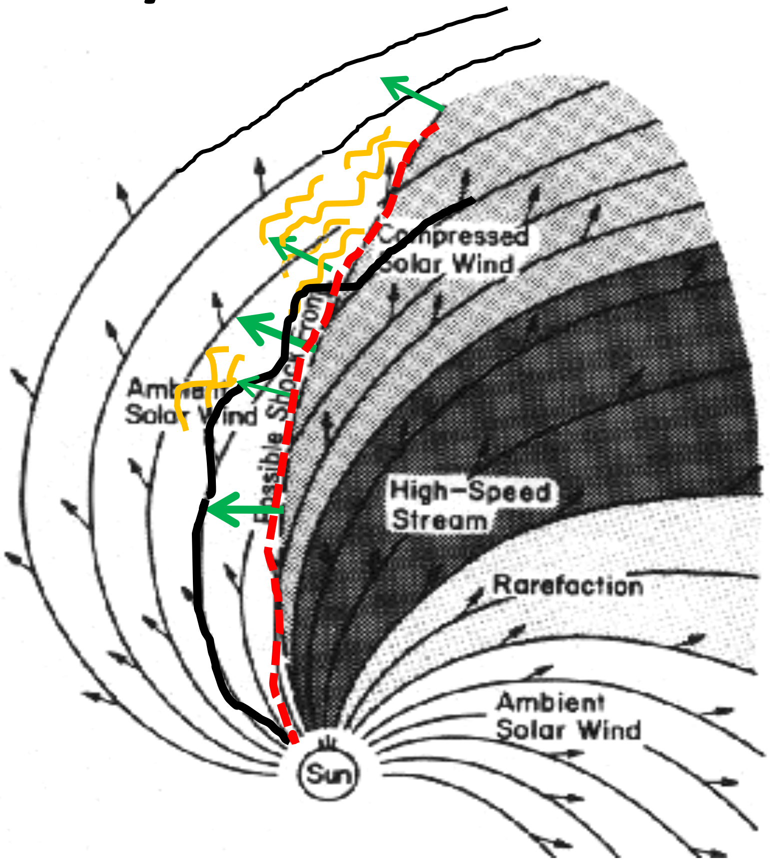
-IP shocks are driven by stream interaction regions and fast ICMEs.

-IP shocks are very important in the heliosphere for shock acceleration, <u>and can be geoeffective (+ ICME).</u>

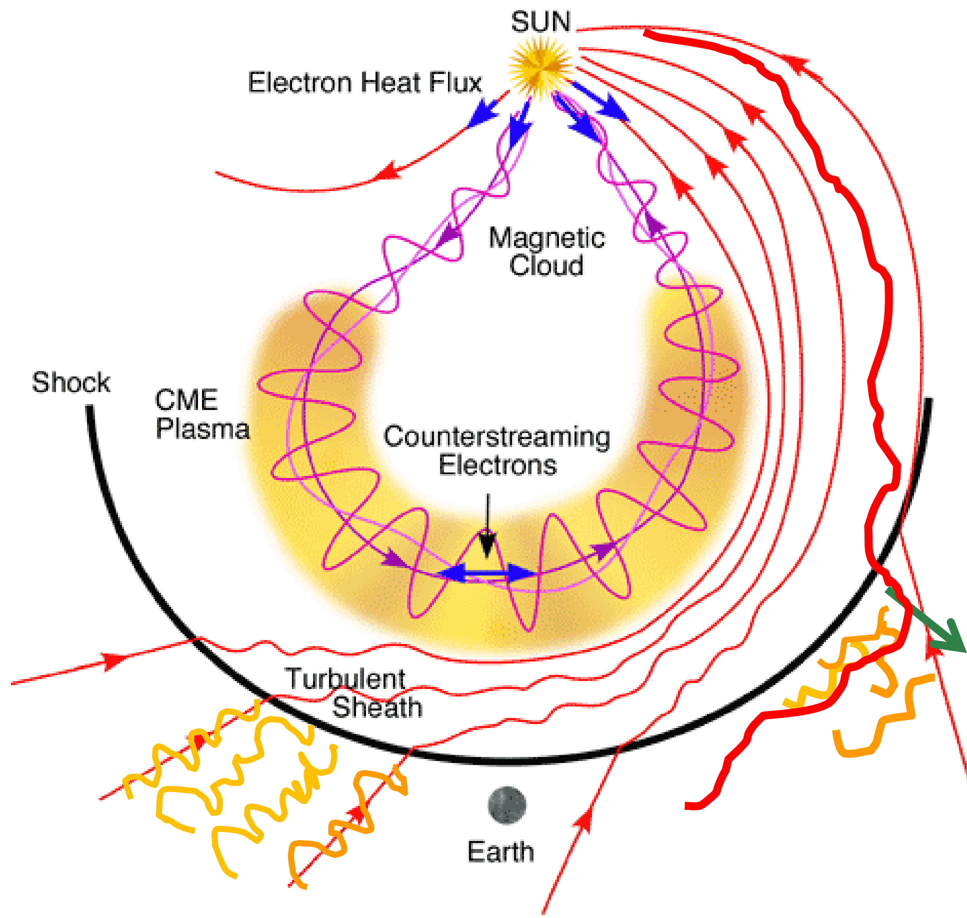
-We have studied shock and foreshock structure.



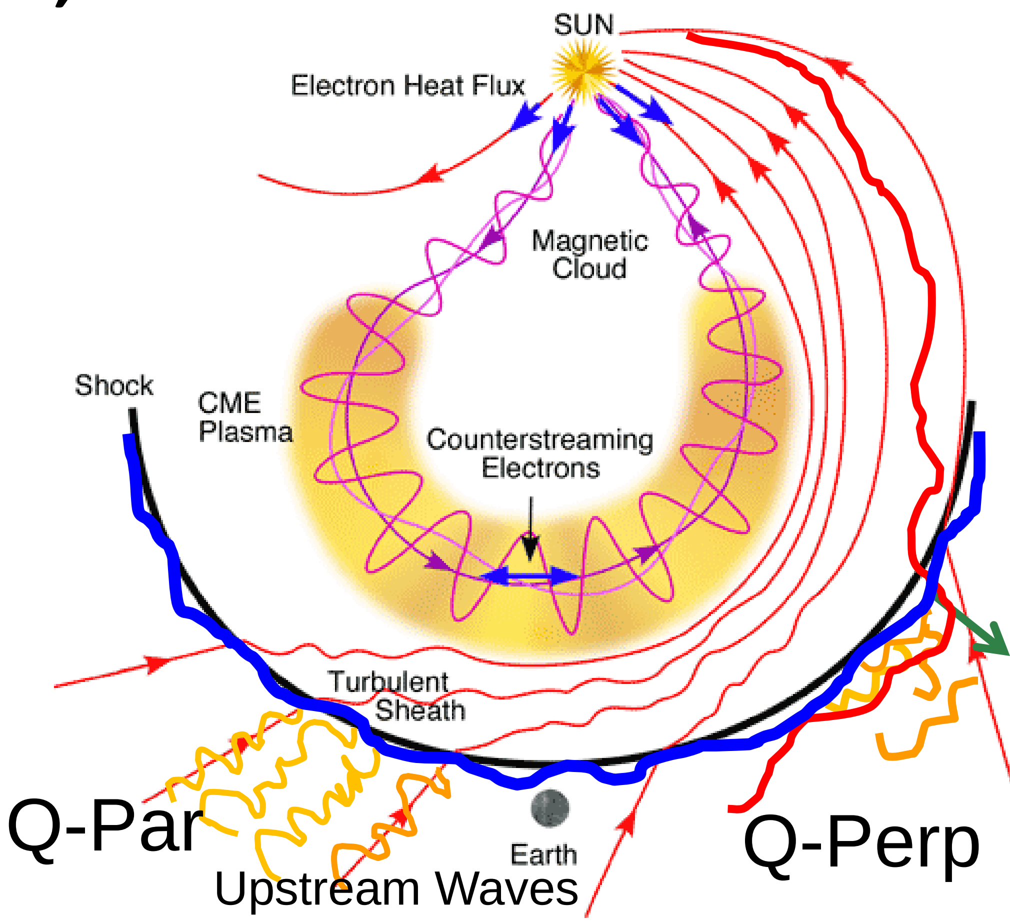
SIRs/CIRs



Fast ICMEs

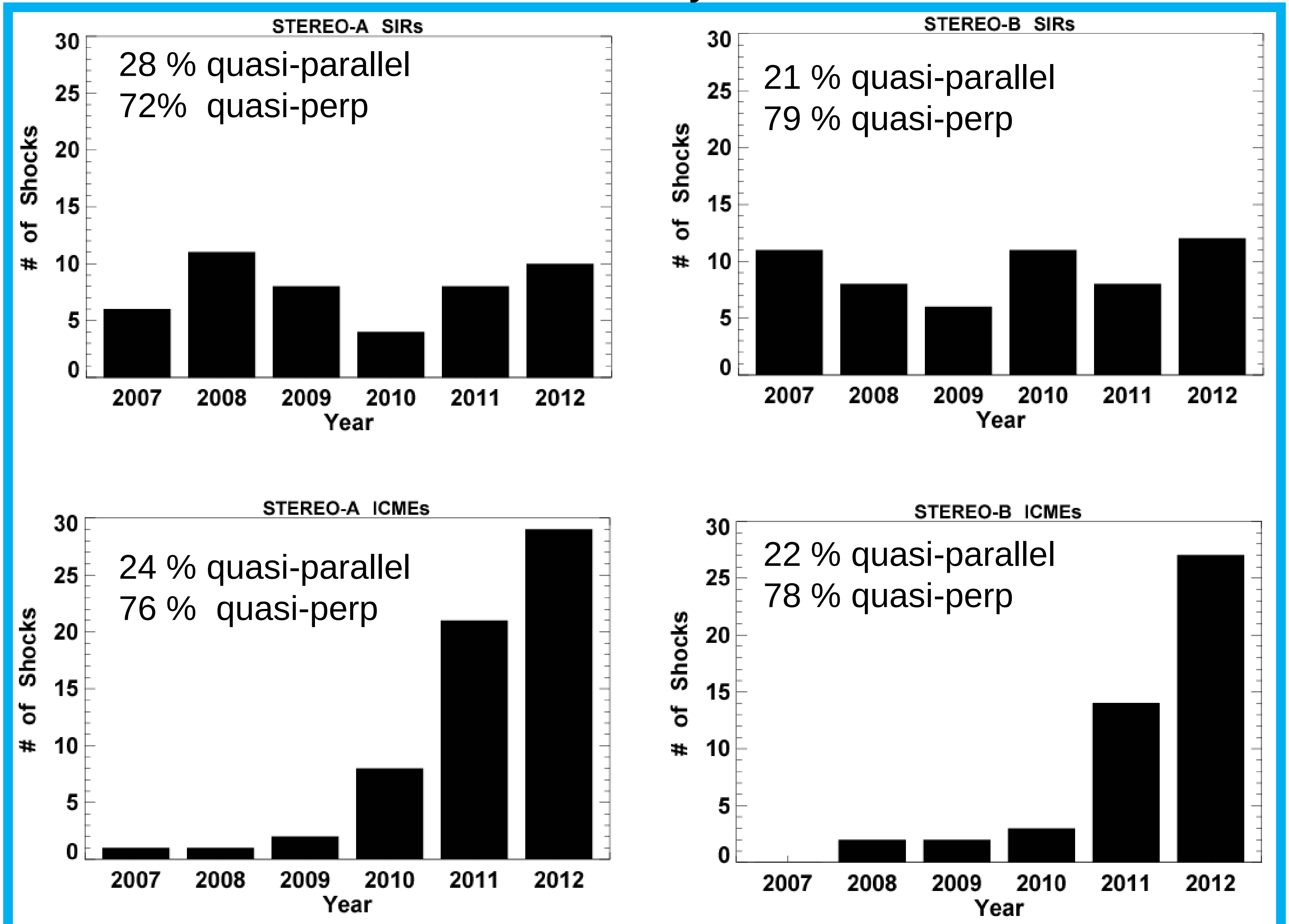


-Shock geometry changes along shock surface due to Parker spiral configuration, changes in the solar wind, and shock rippling:



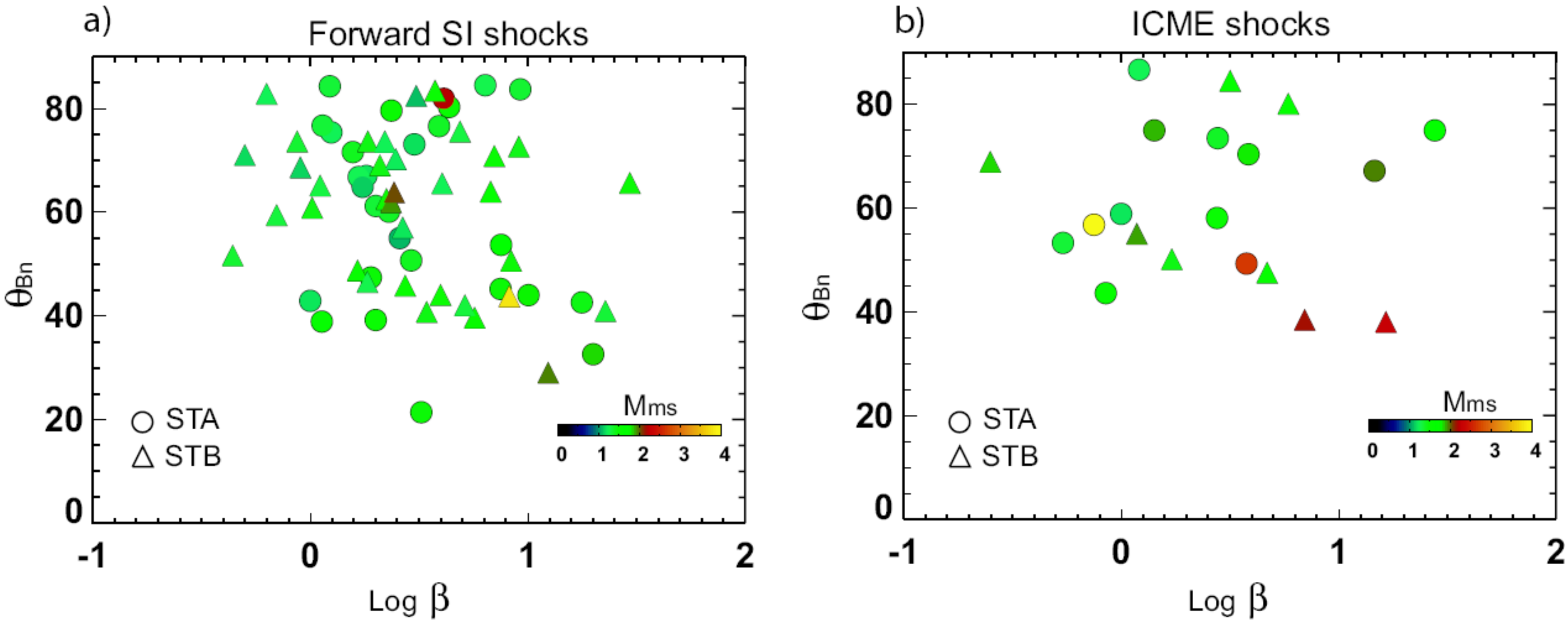
STEREO Shocks per year:

During the solar minimum, few transient shocks are driven by ICMEs. More ICME shocks are observed as the Sun goes into maximum. The number of SIR shocks does not vary as much.



Blanco-Cano et al., 2015, in preparation.

Shock Parameters



Blanco-Cano et al., submitted 2015.

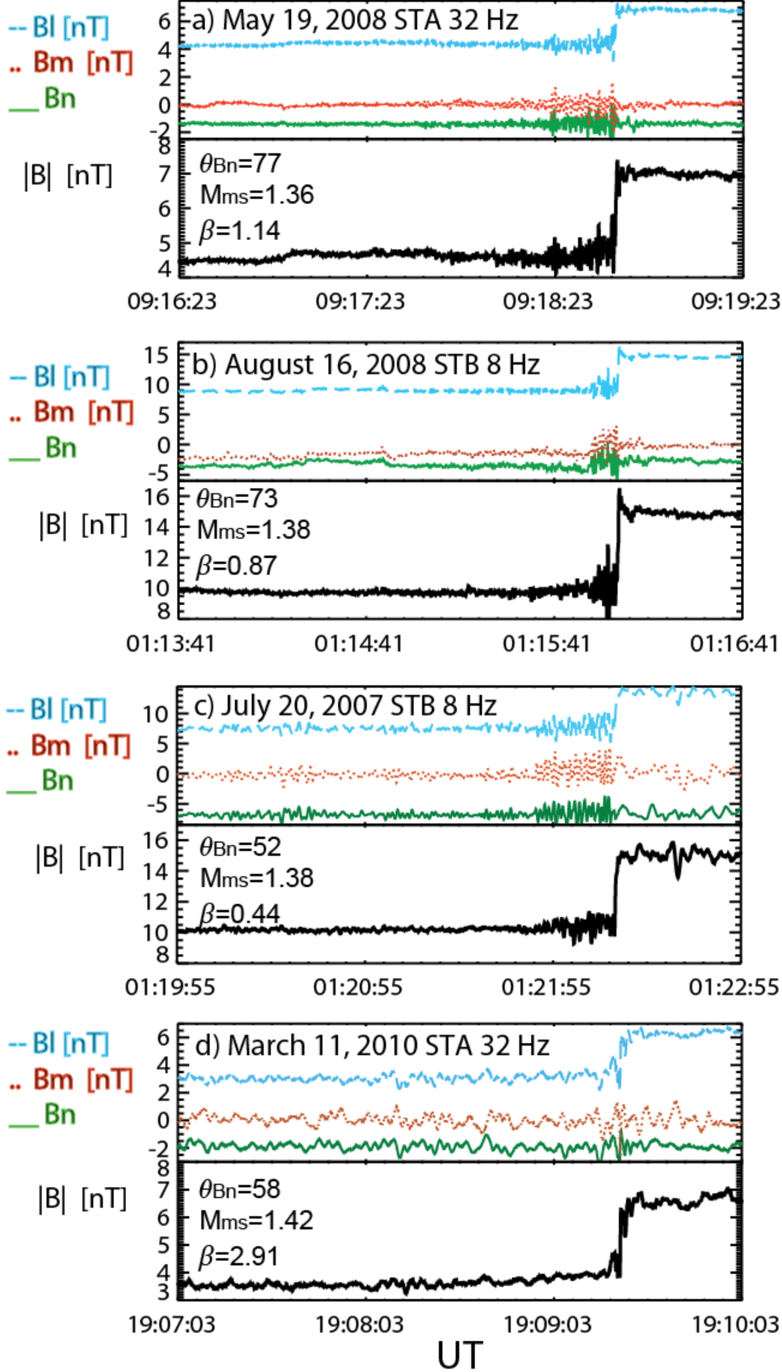
- During the years 2007-2010, STEREO observed ~70 forward shocks driven by stream interactions, and 19 shocks driven by ICMEs.
- Shocks had low-moderate Mach number (M_{ms} 1.1~3.8).

Low lat CH

- In contrast, during the years 2011-2012 STEREO observed ~38 forward shocks driven by stream interactions, and 91 shocks driven by ICMEs.
- More ICME shocks had $M_{ms} \geq 2$ than during the extended minimum.

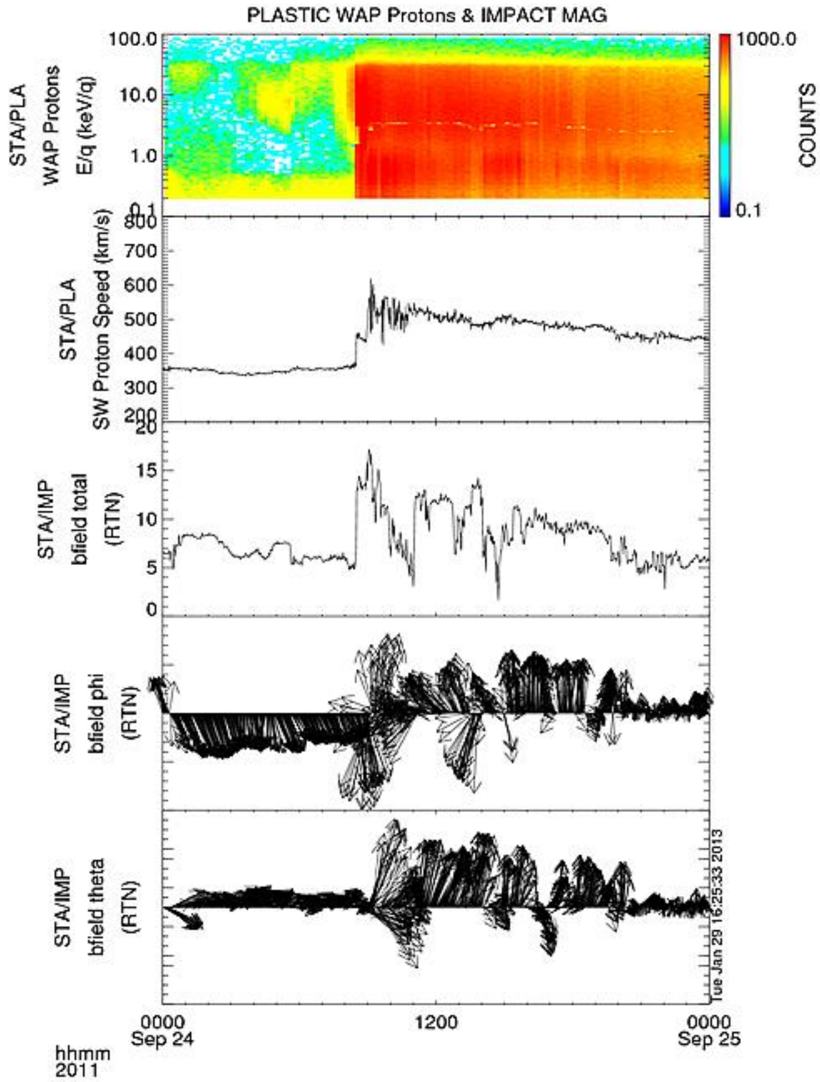
Quasi-Perpendicular SIR Shocks

- Whistler precursors are found upstream of quasi-perpendicular shocks. In all cases the shock profile is sharp and well defined.
- When the Mach number is low whistlers can extend further upstream.
- Some shocks develop a foot and overshoot associated with ion reflection and gyration.
- Note that a whistler precursor can be superposed on the foot region, so that the shock has characteristics of both, subcritical and supercritical shock.



(Shock normal coordinates)

Quasi-perpendicular shocks preceded by suprathermal ion foreshock:



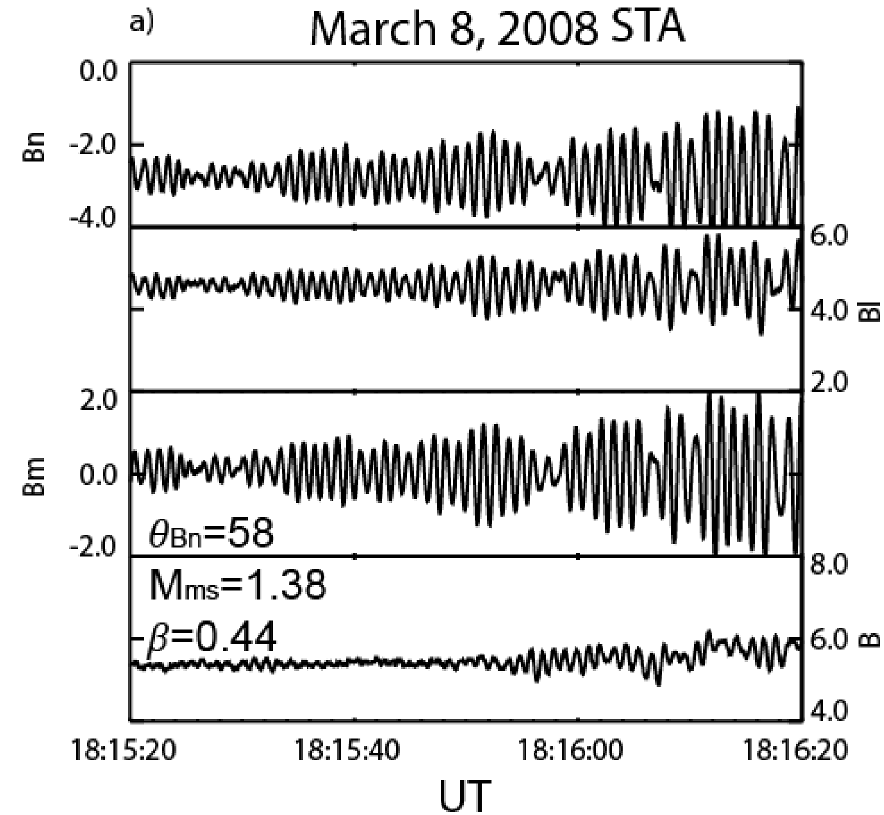
θ_{Bn}=70
M_{ms}=1.22, $\mathbf{M_A}$**=2.86**
β=5.49

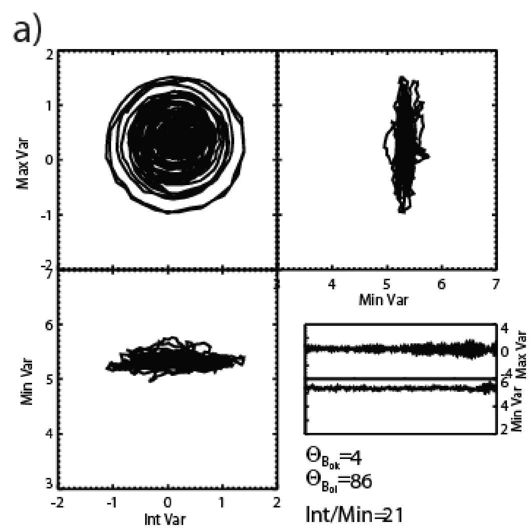
Quasi-Perpendicular Shocks: Upstream Whistlers

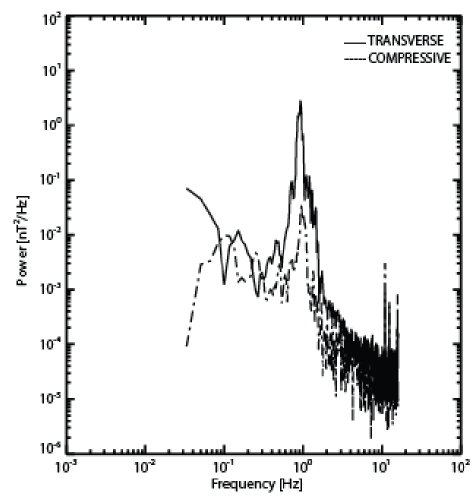
- Whistler wave power peaks at f~1 Hz.
- In most cases whistler precursors propagate at small angles to the magnetic field (θ_{Bn}<30). These waves have clearly a component along the shock normal (**n**) so they are not aligned with **n** as expected for phase standing whistler waves.

- Waves are circularly polarized.
- Right-hand polarized SC frame.

- These upstream whistlers are most probably generated at the shock.
- Not related to the phase-standing whistlers of laminar shock theory (Bismack, 1973). These are not laminar shocks.







Quasi-Perpendicular Shocks: ULF foreshock

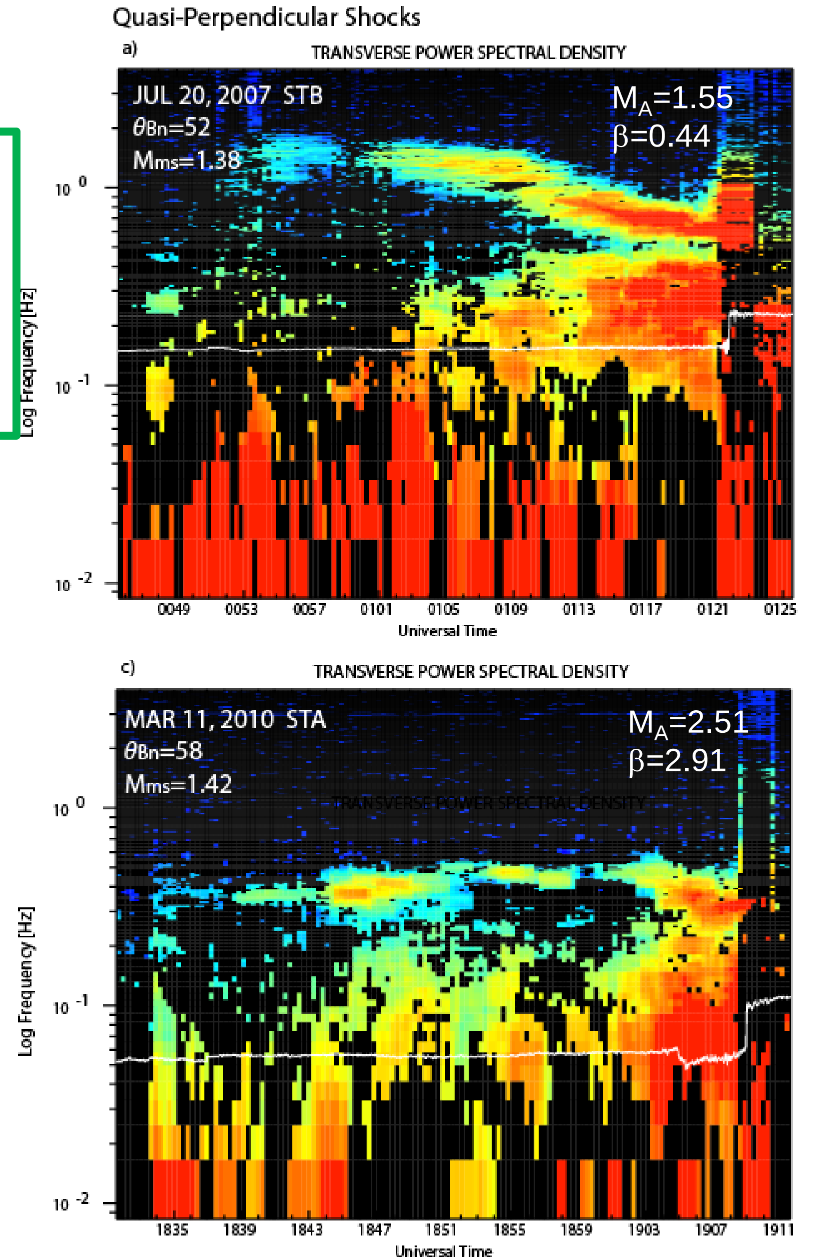
In most cases, whistlers appear upstream adjacent to the shock.

- Some <u>quasi-perpendicular (45°< θ_{BN} <60°)</u> SIR STEREO shocks are preceded by <u>low frequency fluctuations</u> with broad frequency spectra showing peaks on the range f~10^{-2}-10^{-1}.

- The magnetic field components reach amplitudes $\delta Bi/B$ up to ~0.8 (with i=n, l, m).

- The shock transition is sharp as expected for a quasi-perpendicular shock, and waves downstream have smaller amplitudes than waves found downstream of quasi-parallel shocks.

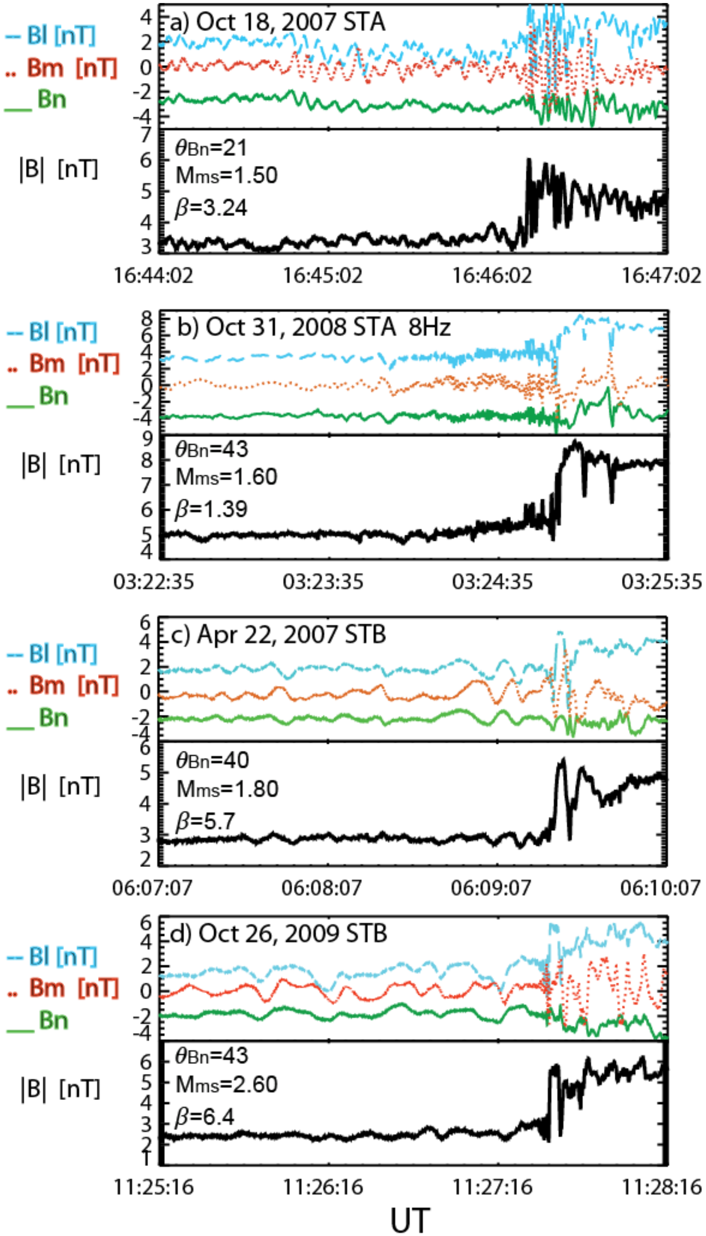
- <u>This suggest that the shock was quasi-parallel at an earlier time and highligths the importance of considering shock history in acceleration models.</u>



Quasi-Parallel Shocks: Upstream Waves

- Shock transition is not as sharp as in the quasi-perpendicular case
- The upstream spectra are formed by higher frequency waves that appear as whistler trains, and lower frequency almost circularly polarized waves which may be locally generated by reflected protons.

- <u>Large amplitude waves are found downstream, which is in contrast to quasi-perpendicular shocks.</u>
- The downstream waves can be formed by both, locally generated perturbations, and shock transmitted waves.

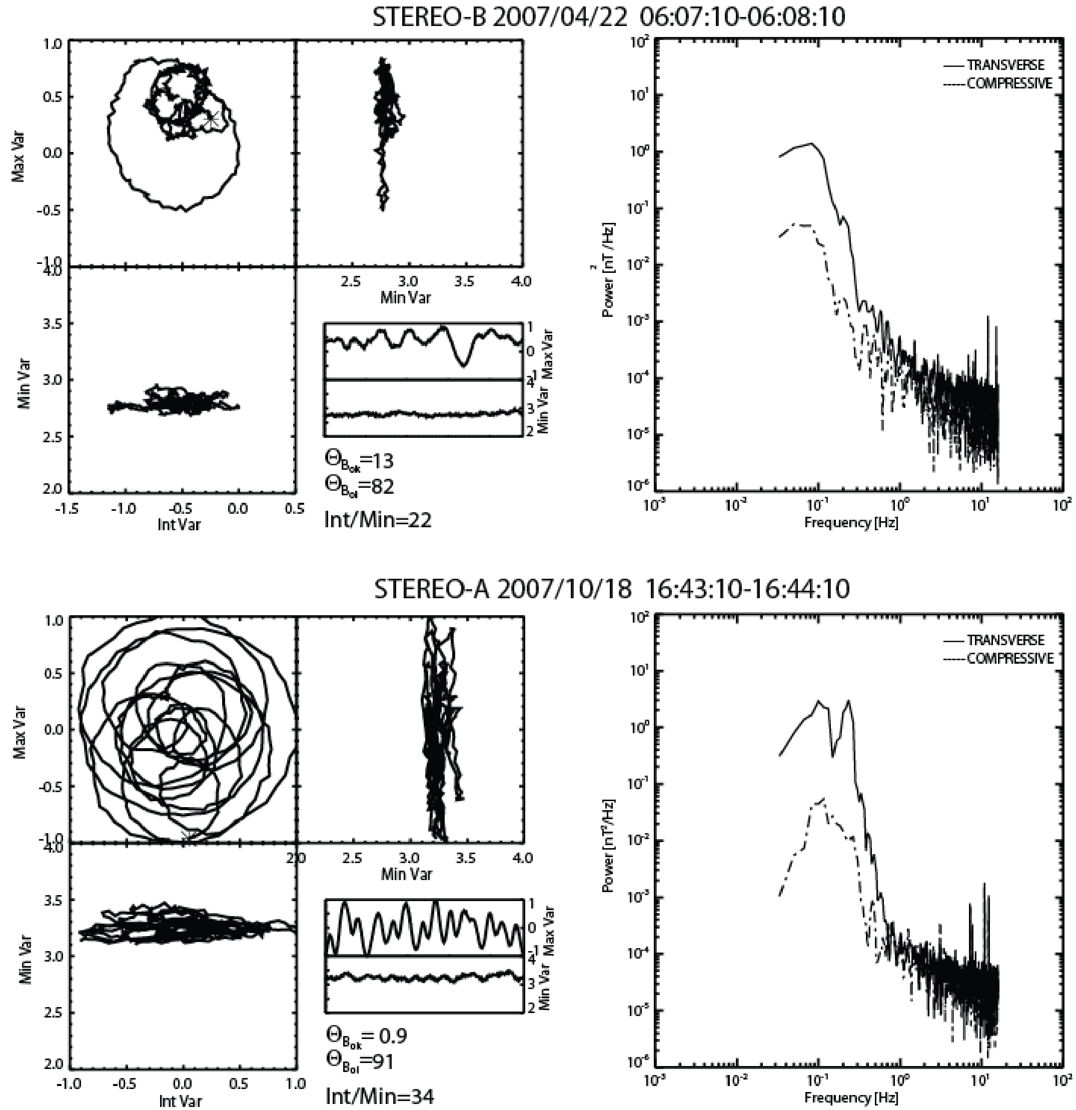


Quasi-Parallel Shocks: Upstream Waves

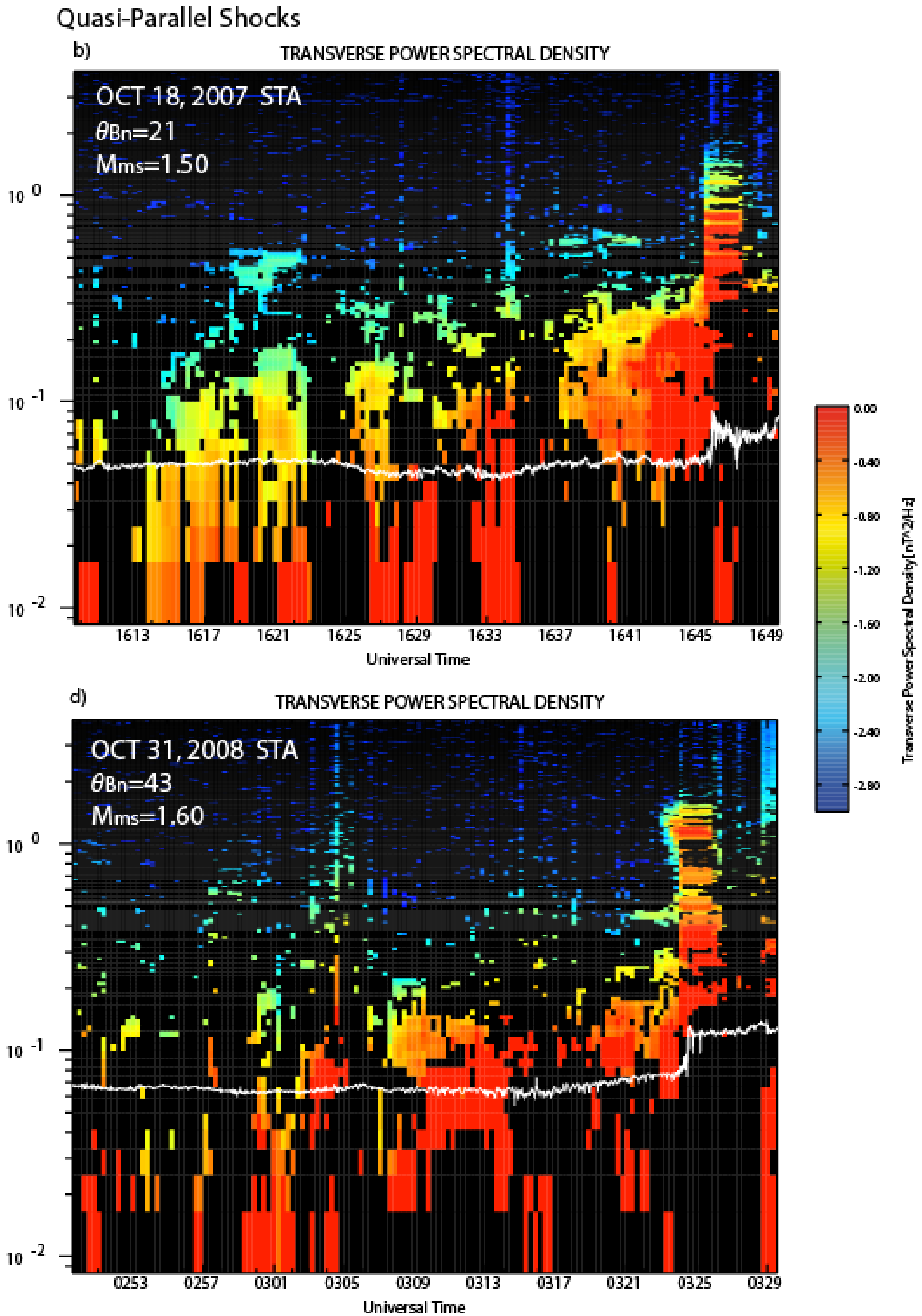
- A double peak spectra is commonly found. Most of these waves are transverse, with RH polarization, and propagate at small (<10°) angles to the background field, B_o.

- This is in contrast to waves in planetary foreshocks, where most fluctuations are very compressive.

- A foreshock is observed in both, ULF waves and ions.

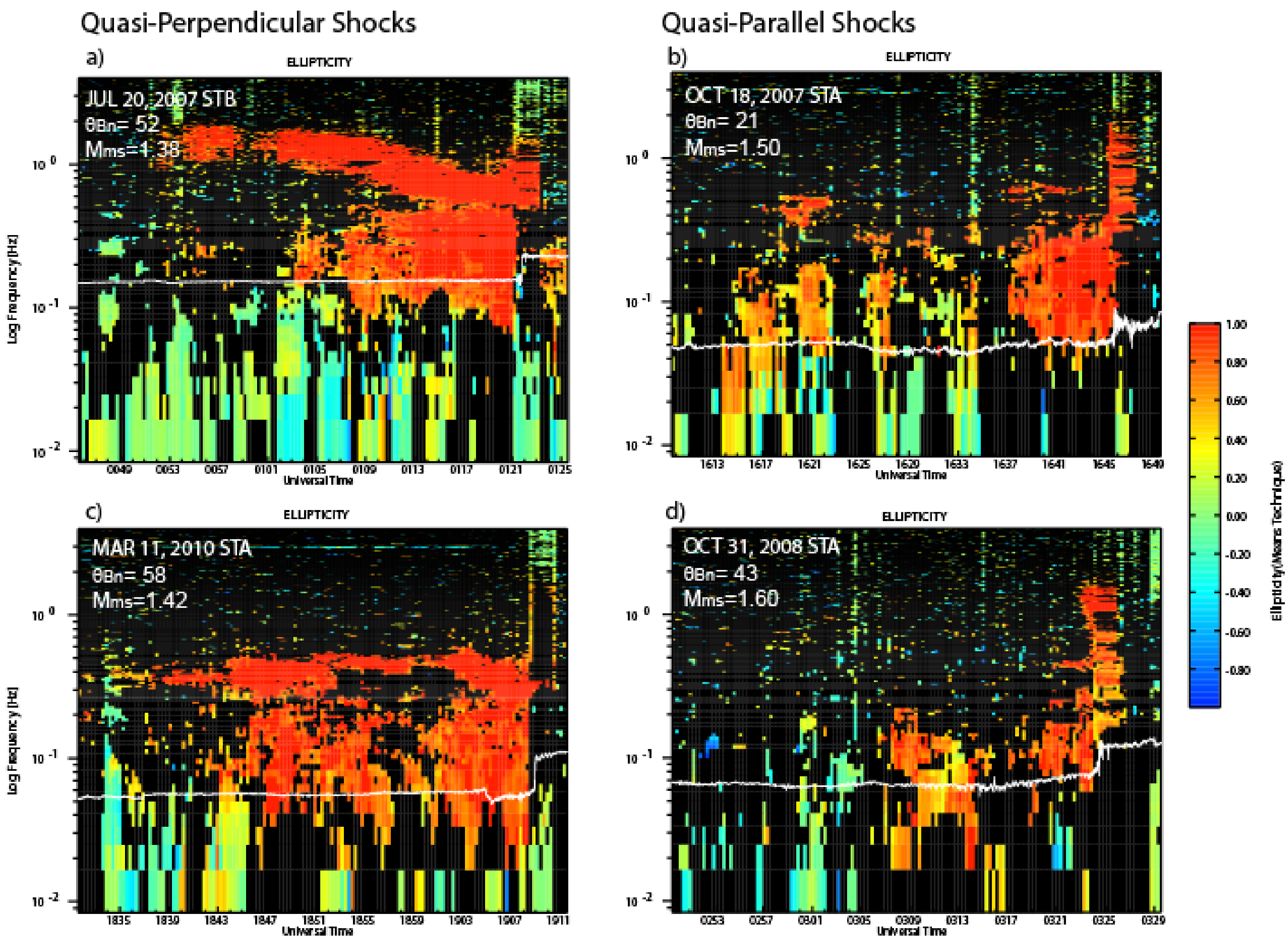


Broad spectra



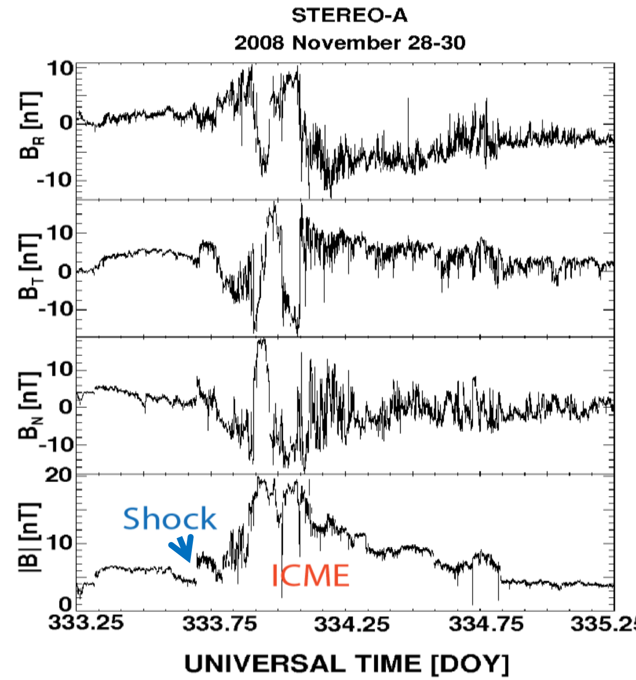
Summary SIR shocks

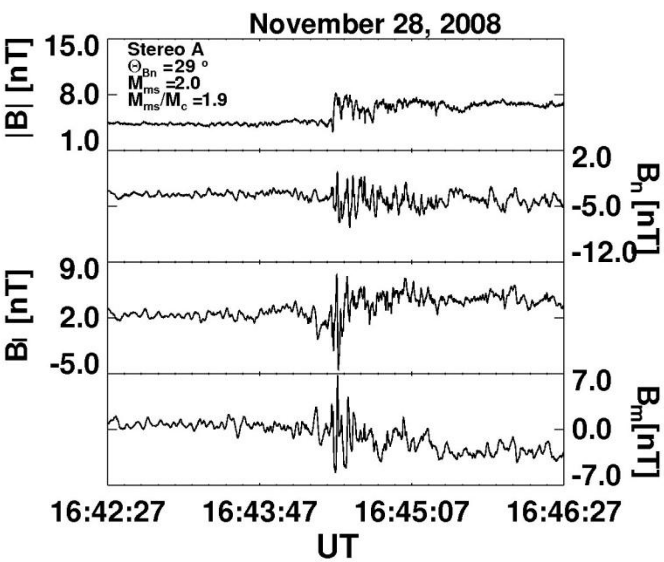
RH polarized waves sc frame
Low angles of propagation with respect to B



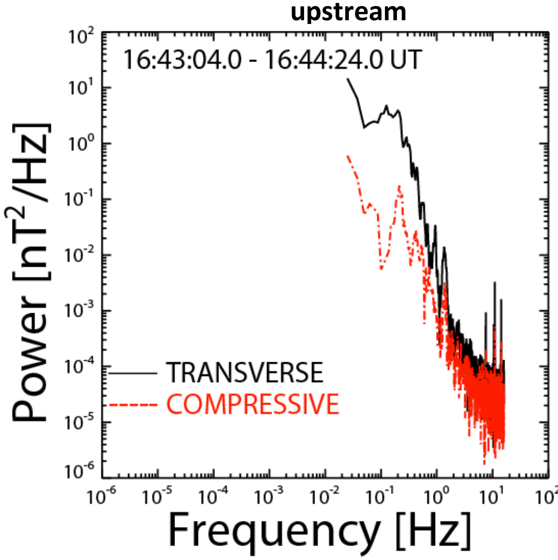
ICME-Driven Shocks

- Most waves upstream of the shocks studied to date show similar characteristics to waves associated to stream interaction shocks.
- These ICMEs were slow, and shocks have $M_{ms} < 4$. It was expected that as the solar cycle evolves, faster ICMEs appear, leading to stronger shocks. <u>However, STEREO shocks during the extended minimum and *mini solar max* have shown little evidence of ustream wave steepening.</u>

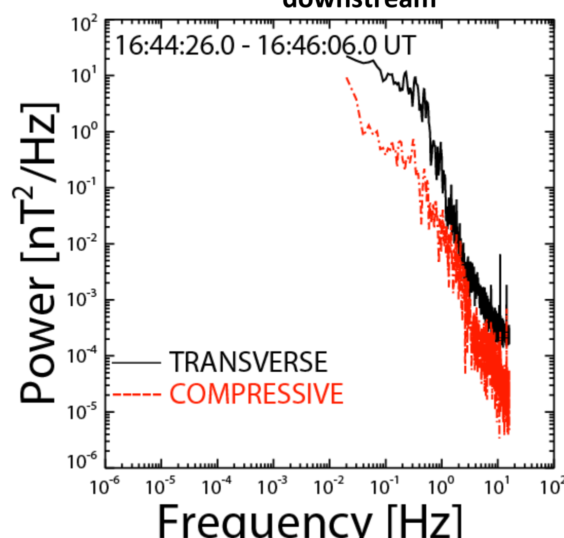




ULF waves upstream

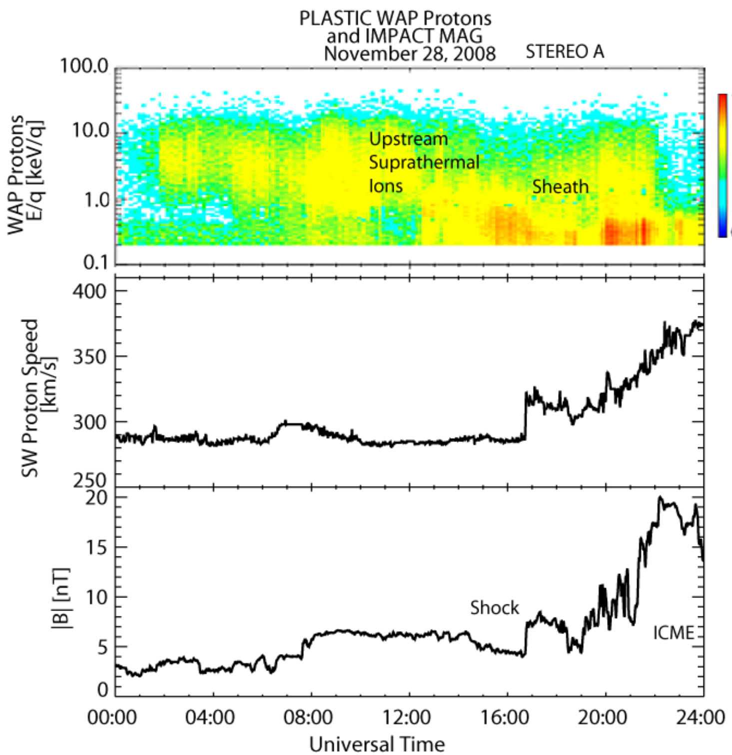


ULF waves downstream

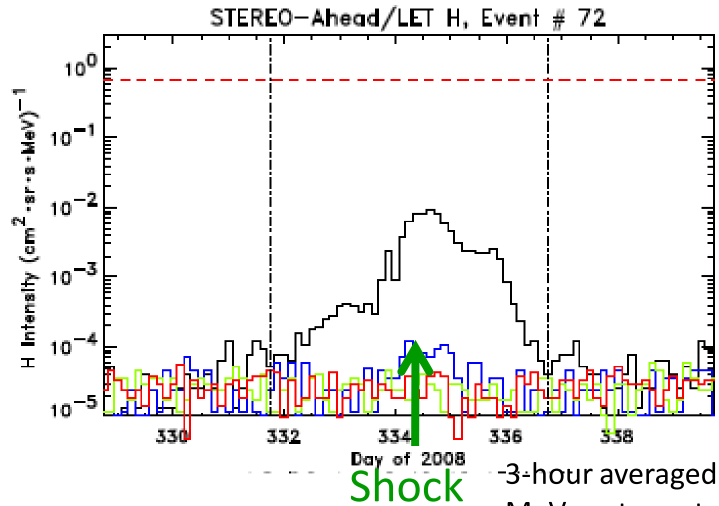


ICME-Driven Shocks: Suprathermal Ion Acceleration

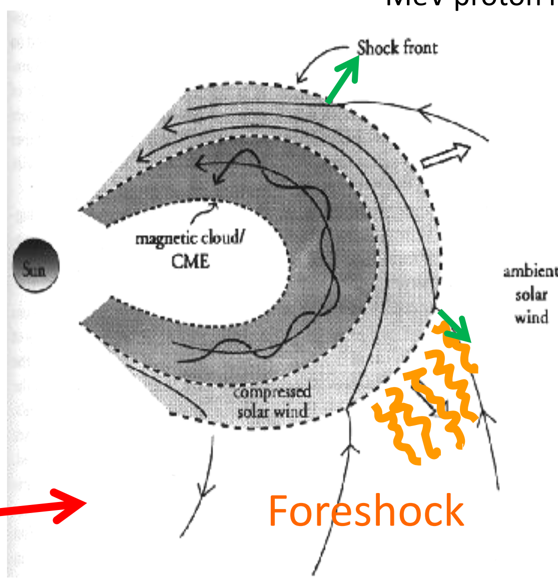
- We find extended foreshocks (dr ~0.1 AU) for ICME shocks.
- Some of the upstream waves may be generated by reflected ions.
- Some of these shocks are associated with SEPs.



SEP-associated event



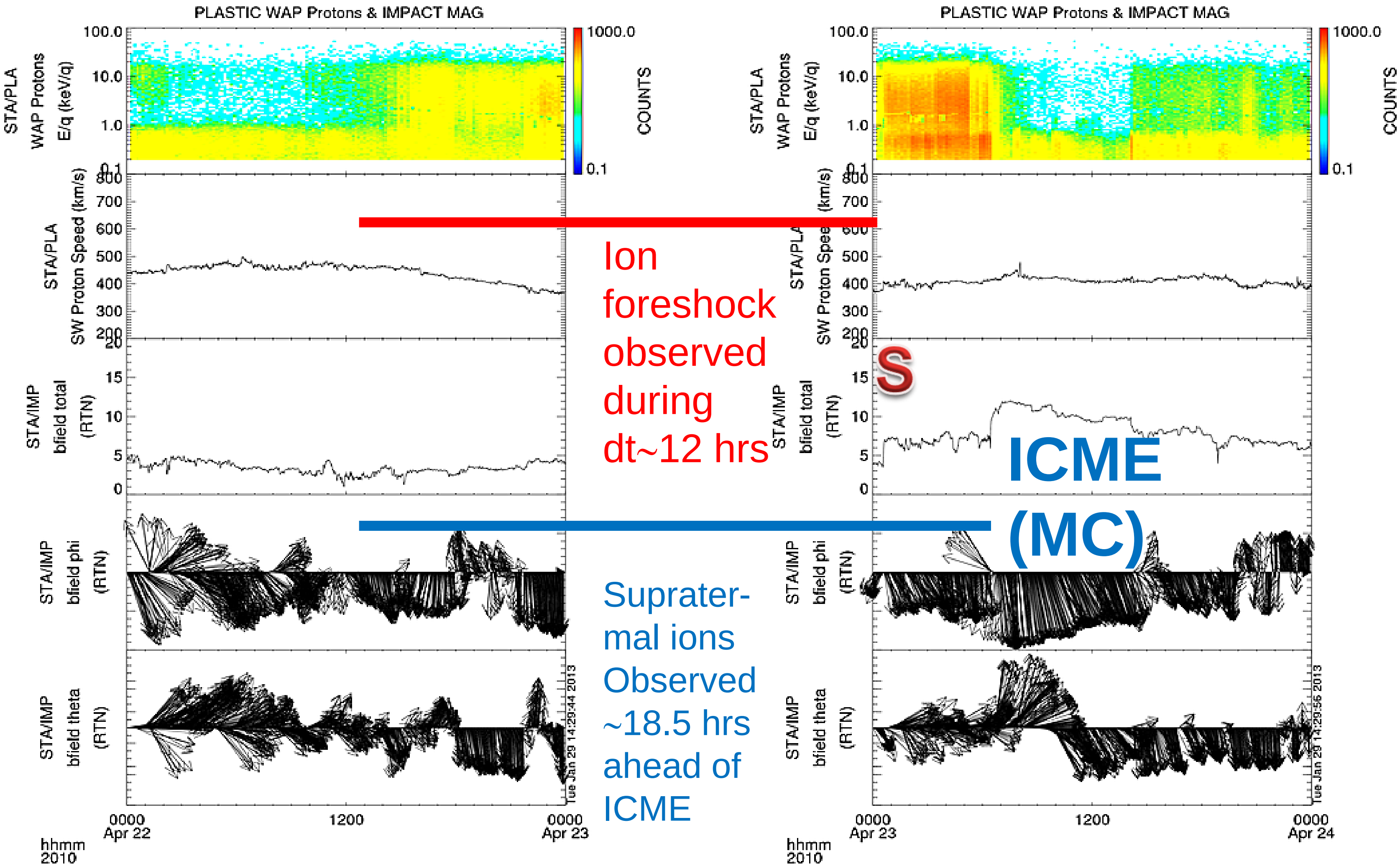
3-hour averaged 1.8-3.6 MeV proton rate



Adapted from Cravens, 1997

- The interaction of ICMEs with the solar wind starts much earlier than the shock arrival due to the existence of a foreshock, permeated by waves and particles.

Extended ion foreshock ahead of ICME driven foreshock: space weather forecast?



However, not all ICME shocks are preceded by an ion foreshock, and ion foreshocks can also be associated to SIR foward shocks.

Proton/ULF Foreshocks:

- We use Plastic WAP Proton data to determine foreshock extensions.

- Ion Foreshocks were observed in <u>47% quasi-parallel</u>, and in <u>35 % quasi-perpendicular</u> SIR shocks.

- Ion Foreshocks were observed in <u>67% quasi-parallel</u>, and in <u>82% quasi-perpendicular</u> ICME shocks.

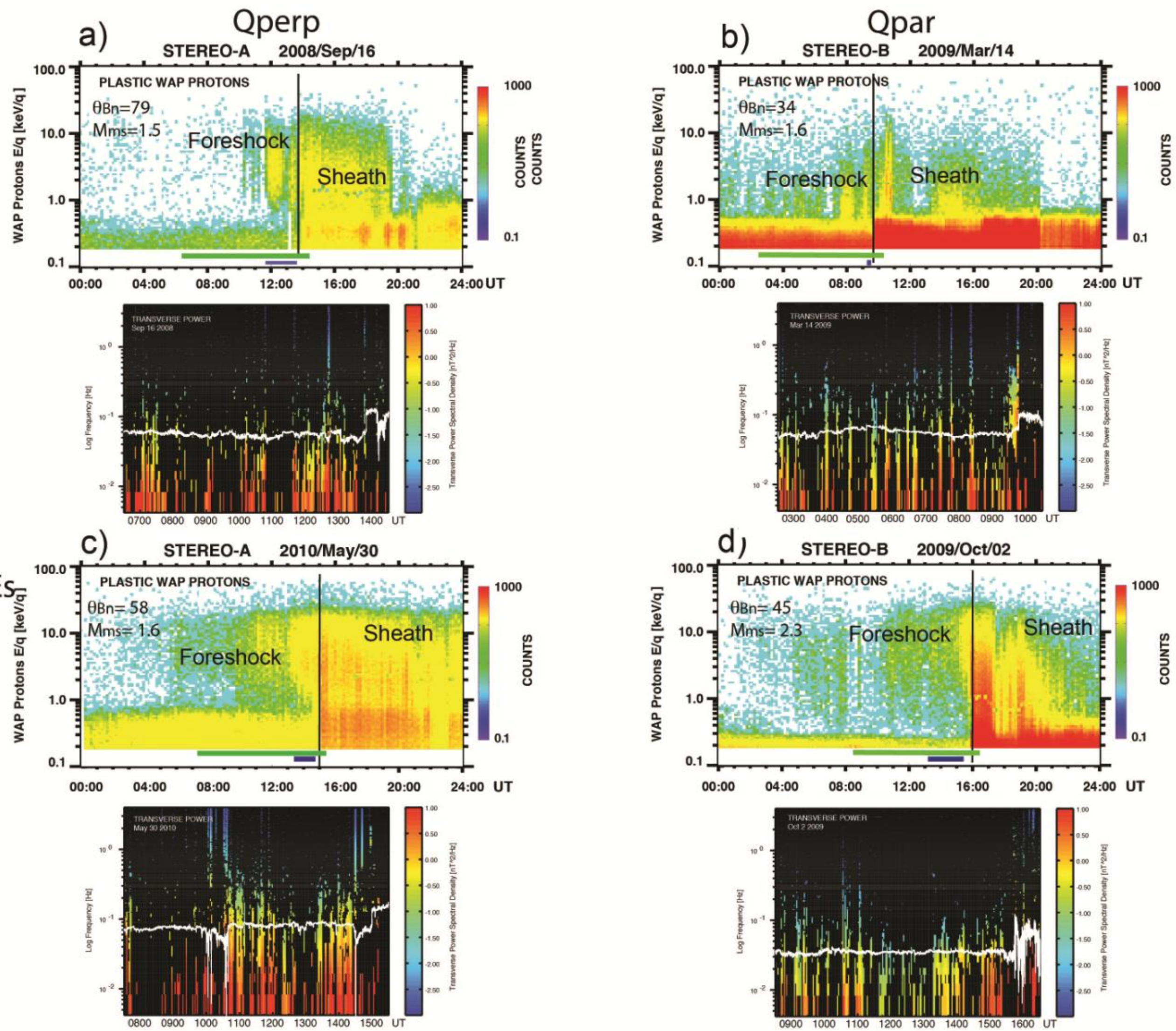
• ICME shocks tend to have larger foreshocks:

-25% of ICME driven shocks have extensions > 0.05 AU.

-In contrast, only 4% of SIR forward shocks have dr > 0.05 AU.

SIRS

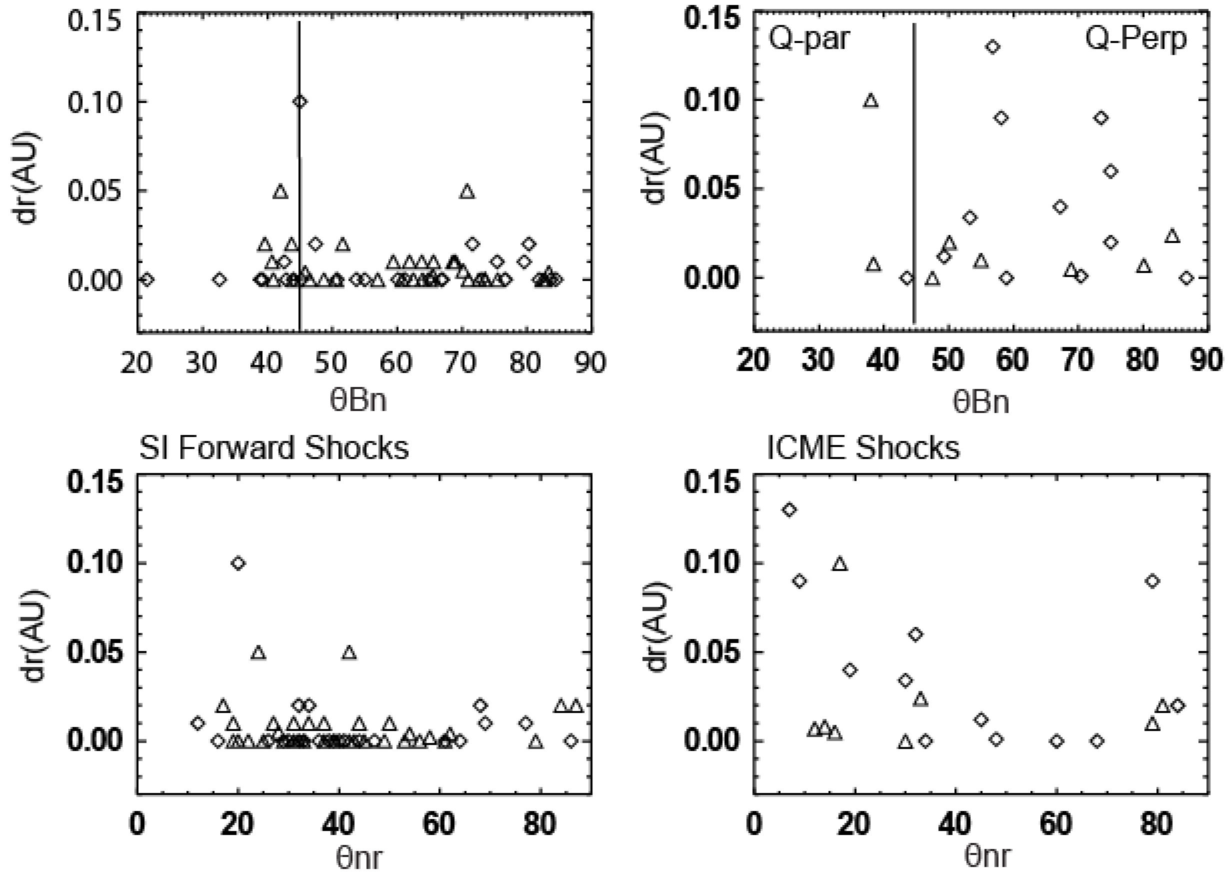
ICMEs

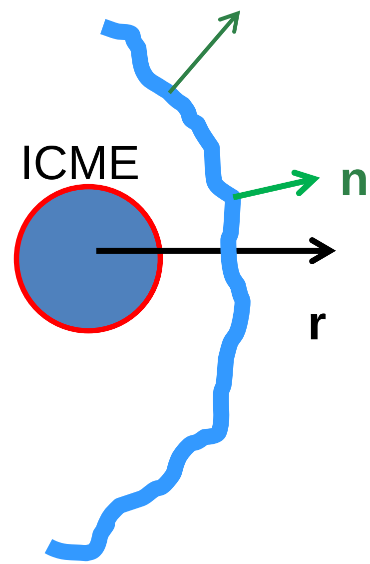


-The largest proton foreshock extension is dr =0.13 AU (ICME shock with θ_{Bn}=57°, and M_{ms}= 4

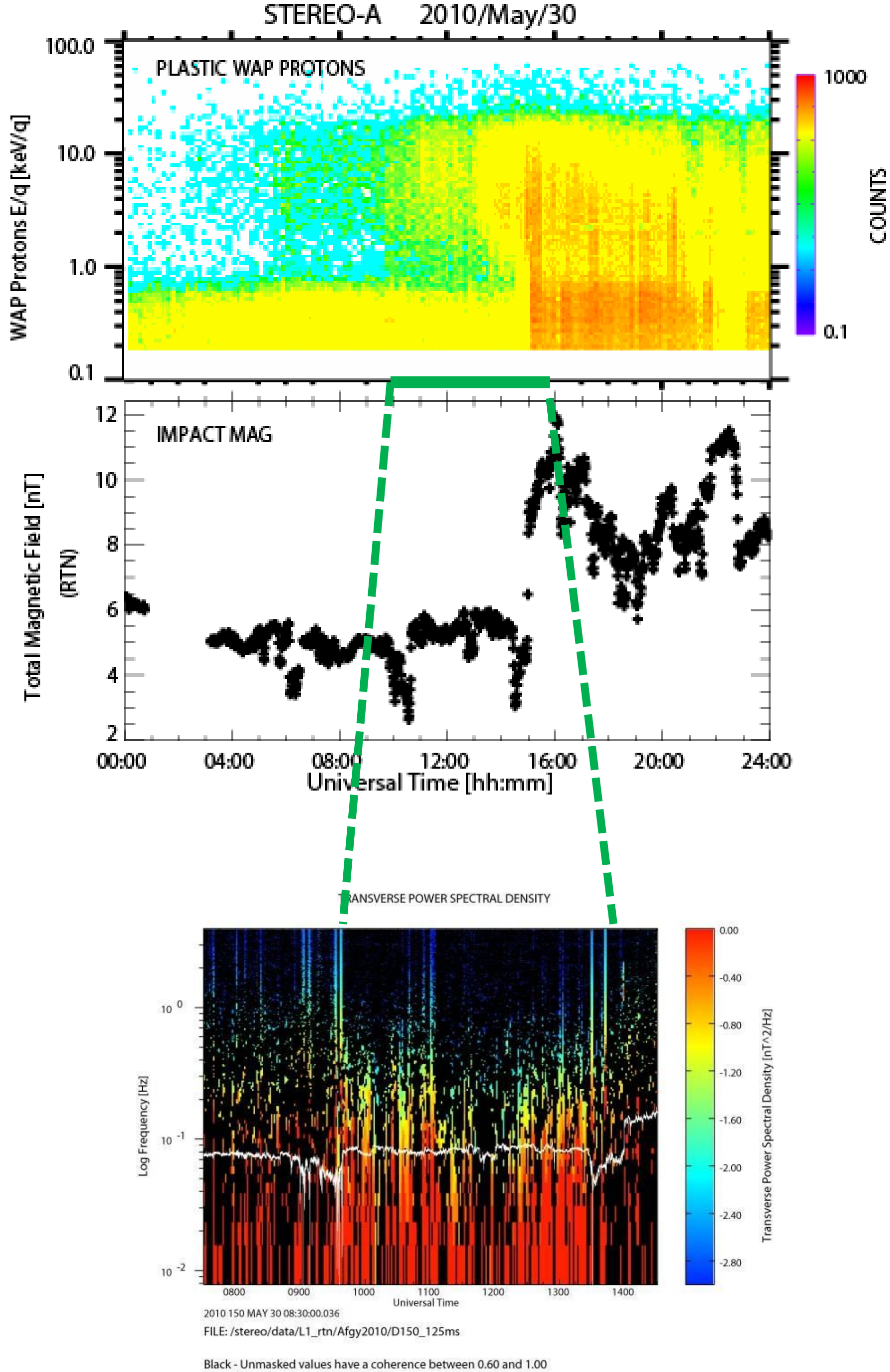
Ion foreshock extension dr vs θ_{Bn} and vs θ_{nr}

SIR ICME





Suprathermal ion Foreshock is more exteded than ULF waves foreshock



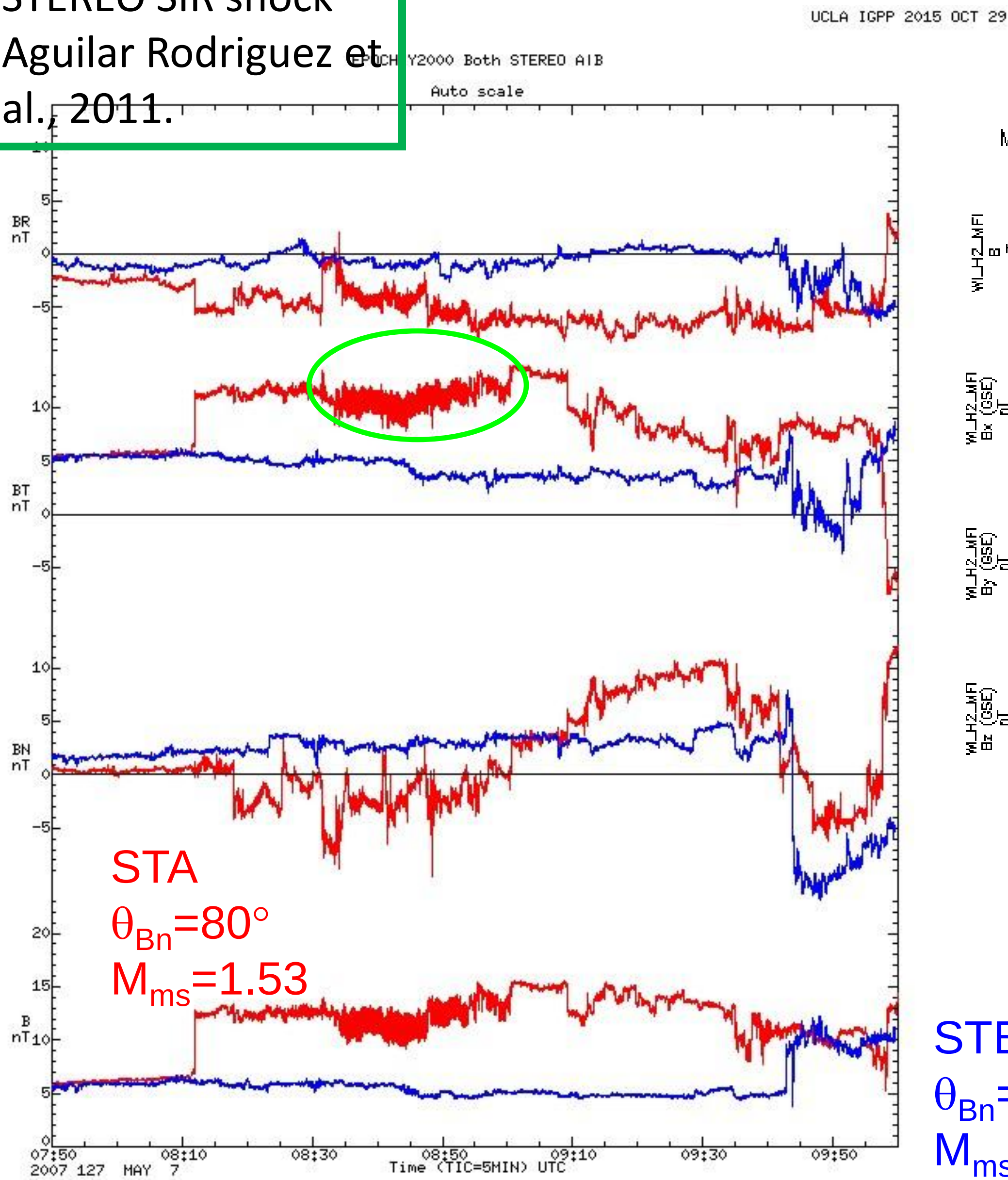
Wave and foreshock extensions, ICME (MC) driven shocks
Kajdič et al., JGR 2012.

Table 2. ICME Driven IP Shocks Observed Between the Years 2007 and 2010

Date	Time (UT)	32 Hz Data	θ_{Bn} (deg)	θ_{nR} (deg)	M_{ms}	Criticality Ratio	β_{up}	ULF Waves		HF Waves		ULF Foreshock Size (10^{-3} AU)	HF Foreshock Size (10^{-3} AU)	Suprathermal Ions (AU)
								Up	Down	Up	Down			
Jun 7, 2010	04:08:50	y	85	33	1.7	1.7	3.2	n	y	y	y		0.002	0.04
Apr 23, 2010	00:34:37	n	77	83	1.3	1.1	2.8	n	n	y	y	2.5		0.10
Jun 19, 2009	00:23:34	y	77	12	1.9	1.6	5.9	n	n	n	y			0.02
Jan 25, 2009	18:22:52	y	76	45	1.5	1.2	3.1	n	n	n	n			
Nov 19, 2010	20:26:00	n	72	81	1.5	1.1	1.7	n	y	y	y		0.10	
Apr 29, 2008	14:10:08	n	68	16	1.8	1.1	1.0	n	n	y	n		0.13	0.06
Aug 5, 2009	22:35:20	y	54	30	1.7	1.5	4.4	y	y	y	n	4.6	0.11	
Jul 5, 2008	00:47:54	y	52	60	1.7	1.3	2.1	n	n	y	n		0.22	
Oct 16, 2009	14:56:55	y	48	34	1.2	0.8	0.9	n	n	n	n			
Oct 2, 2009	15:43 50	y	38	17	2.3	2.3	16.5	y	y	y	n	2.2	0.02	0.06

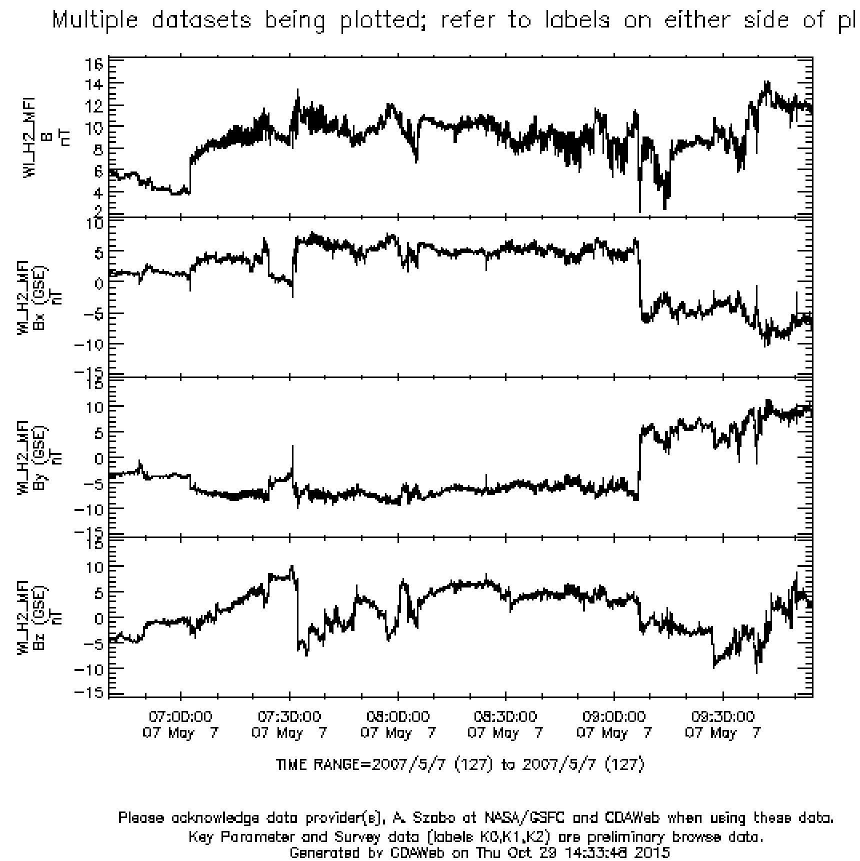
Work in progress I, multispacecraft …

STEREO SIR shock
Aguilar Rodriguez et al., 2011.



STA
θ_{Bn}=80°
M_{ms}=1.53

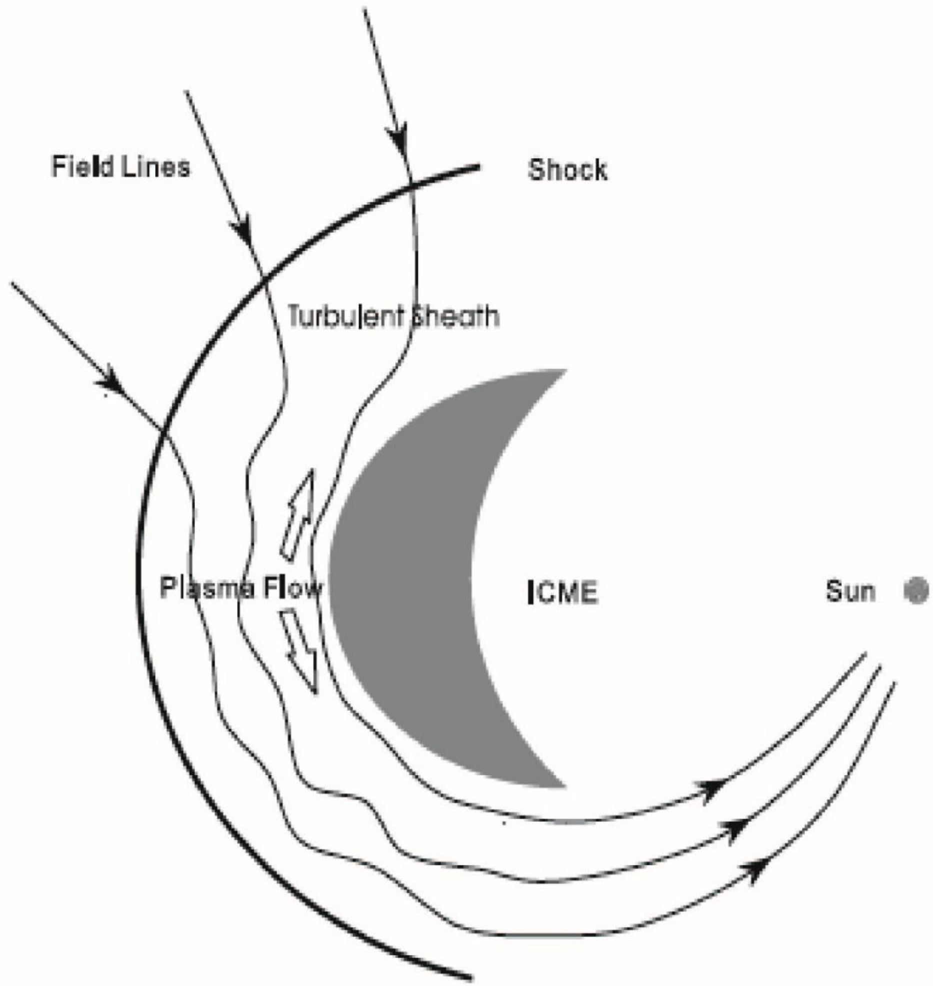
WIND…



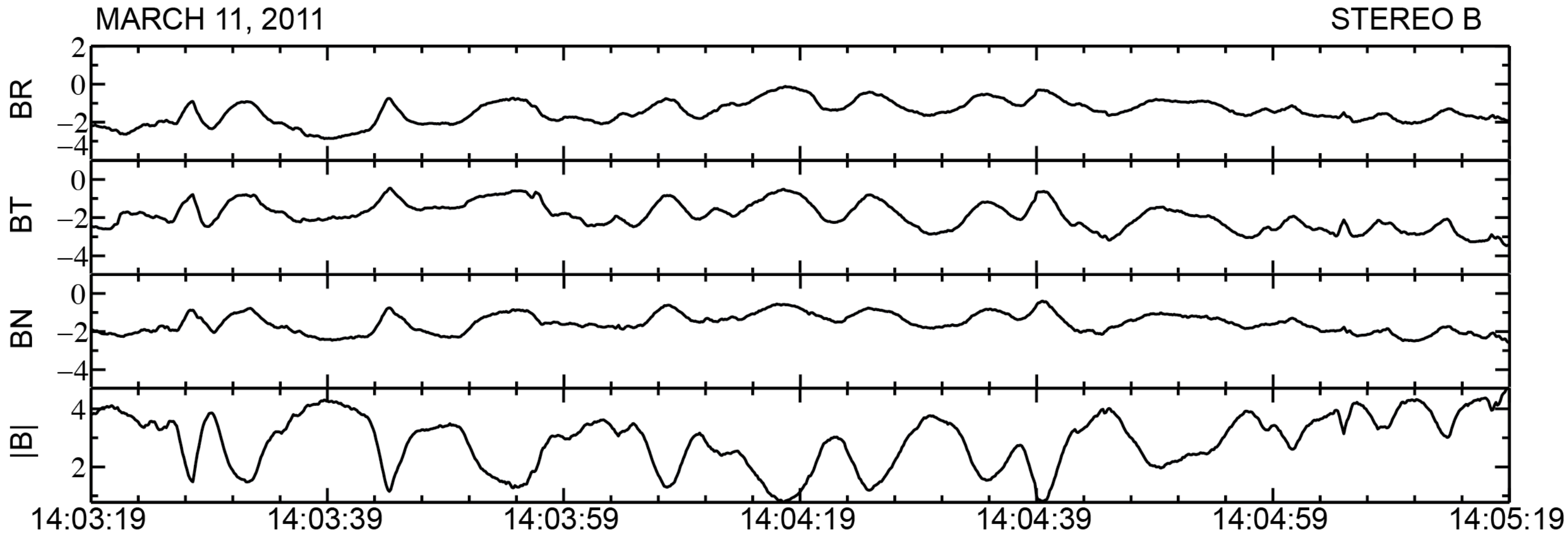
STB
θ_{Bn}=63°
M_{ms}=1.55

ICME sheath waves (Enriquez-Rivera et al-2013, AGU) + work in progress….

Here, the shocked solar wind plasma is compressed in the direction perpendicular to the magnetic field which causes enhancements in the plasma temperature in the perpendicular direction and depressions along B. As a result anisotropic ion distributions are produced (e.g. Crooker and Siscoe,1977). When the threshold condition is satisfied, the plasma is unstable to the mirror mode instability (Chandrasekahr et al., 1958). Likewise, plasmas where temperature anisotropies are present can be unstable to the ion cyclotron instability (Gary, 1993). Little is known about the characteristics of both types of waves in association with ICMEs.



Mirror mode inside ICME sheath



+ some cases with ion cyclotron waves
(similar to Earth's magnetosheath)

(Enríquez-Rivera et al., in preparation)

Important Points

-Some quasi-perpendicular shocks are preceded by an ion/wave foreshock, indicating that the shocks geometry (θ_{Bn}) can change with time. **Shock history important for models…(ripling and shock surface structure also)**

-Foreshocks associated to ICMEs shocks tend to be larger than foreshocks of SIR shocks. ICME shocks observed during 2007-2010 have similar parameters to SIR shocks. Thus, the larger foreshock extensions are due to the fact that ICME shocks form earlier (closer to the Sun) than SIR shocks.

-Shocks can have large longitudinal variations, this is due to variations in Parker spiral geometry, different sw conditions, and to shock interaction with wave fronts, rippling, etc.

-More works on sheath structure needed.