Statistical Study of Shocks and Their Associated Energetic Particle Populations

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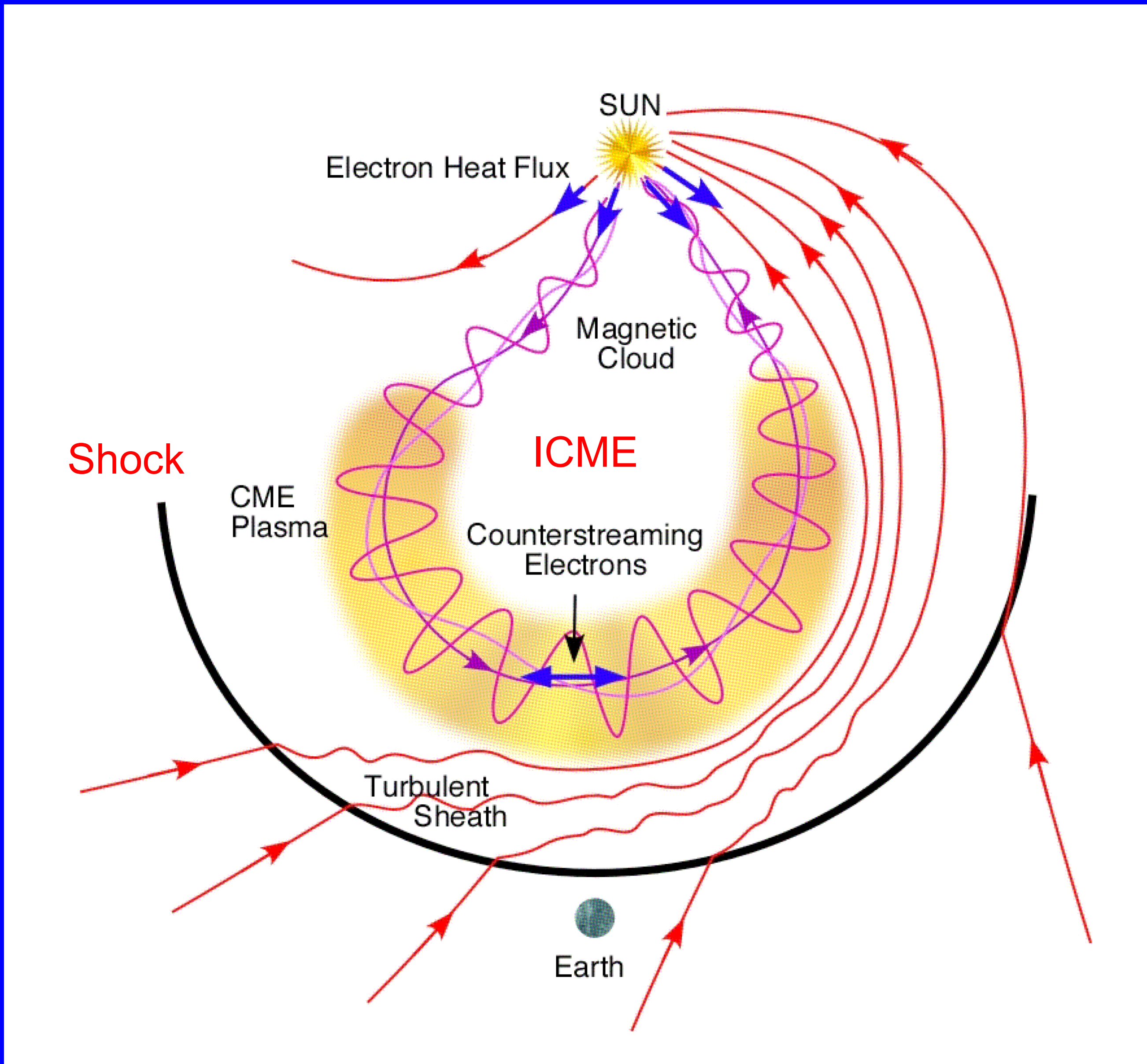
Topic suggested in LWS TR&T proposal using observations from current and previous solar cycles including Helios spacecraft.

David Lario has since published a similar study focusing on SEPs.

Nevertheless, topic may still be worth pursuing.



Interplanetary coronal mass ejection and upstream shock

Zurbuchen & Richardson, 2006

Progress

Have compiled a list of ~250 fast forward shocks in 1996-2005 based mainly on Justin Kasper's IMP, WIND and ACE lists with some contributions from Chuck Smith's ACE list.

Have examined the plasma/field data to confirm that there is a shock; to examine the solar wind context (e.g., flag shocks associated with CIRs)

Plan to integrate ACE shock list and others (e.g., SOHO) to produce a reasonably definitive list.

Some major shocks are missing due to incomplete data (e.g., ACE plasma).

Aldofo Vinas has offered to calculate parameters for shocks of interest.

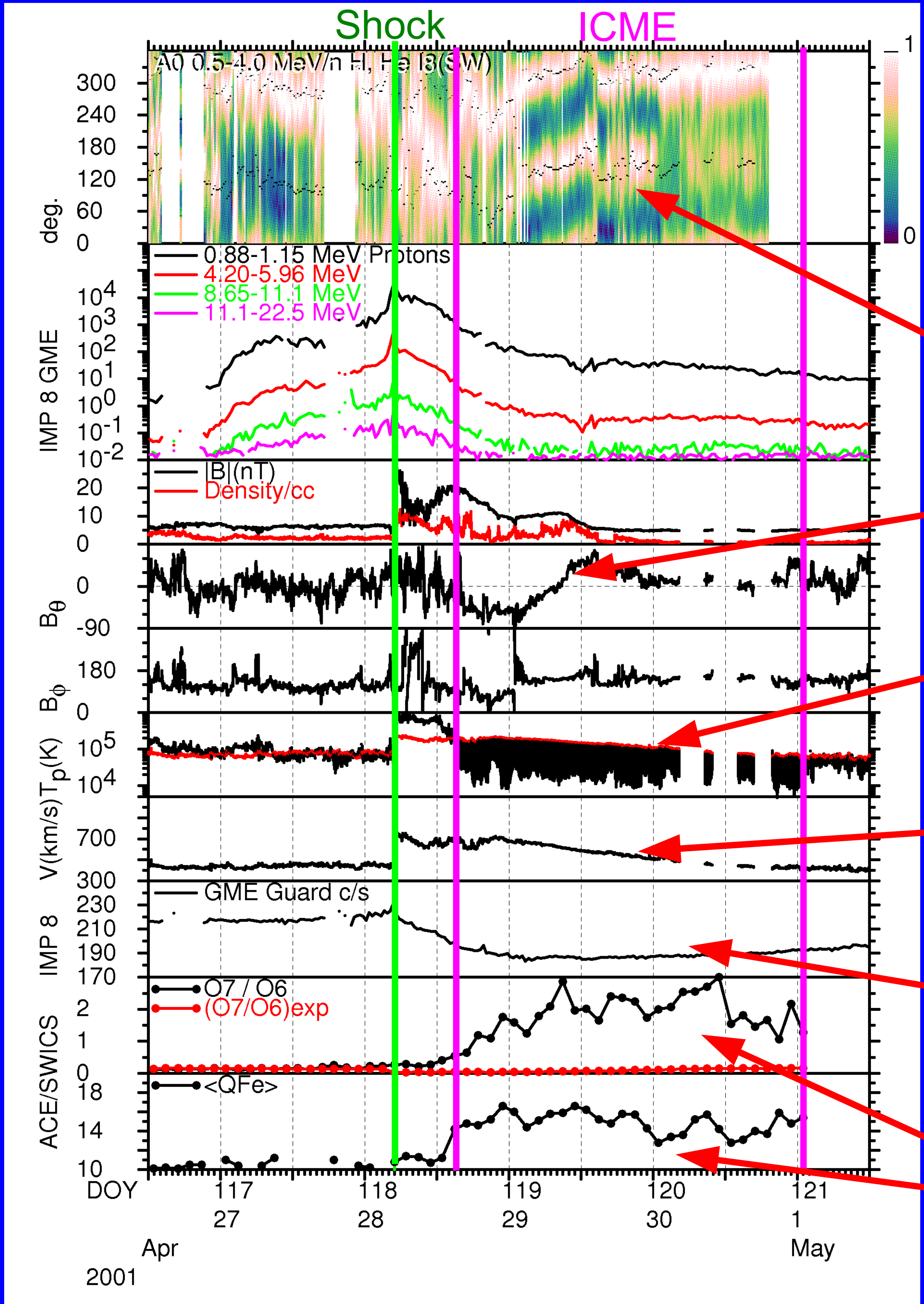
Have identified the solar sources of around a half of these shocks. The majority of these identifications were made during parallel/previous studies of:

- SEP events (HVC/IGR),
- Near-Earth ICMEs (IGR/HVC),
- Type III radio bursts and SEP events (HVC; IGR & Bob McDowell) and
- Sources of intense geomagnetic storms (LWS workshop series; IGR & workshop participants)

Difficult to get reliable source locations for many shocks, especially the weaker cases.

Source features include CMEs, flares, filament eruptions, occasionally quiet sun.

Example of an ICME at 1 AU preceded by a shock



ICME Signatures include:

- Bidirectional 0.5-4 MeV ion flows;
- Organized magnetic field;
- Low solar wind proton temperatures;
- Declining V_{sw} profile;
- Cosmic ray Forbush decrease;
- Enhanced solar wind ion charge states (e.g., O, Fe)

2006 SHINE Meeting:

Energetic Particles Associated with Interplanetary Shocks in Solar Cycle 23

2007 Spring AGU

MeV Ion Anisotropies in the Vicinity of Interplanetary Shocks

Examine particle intensities and anisotropies in the vicinity of shocks in cycle 23 from the:

ACE shock list (Chuck Smith),
MIT shock list (Justin Kasper)

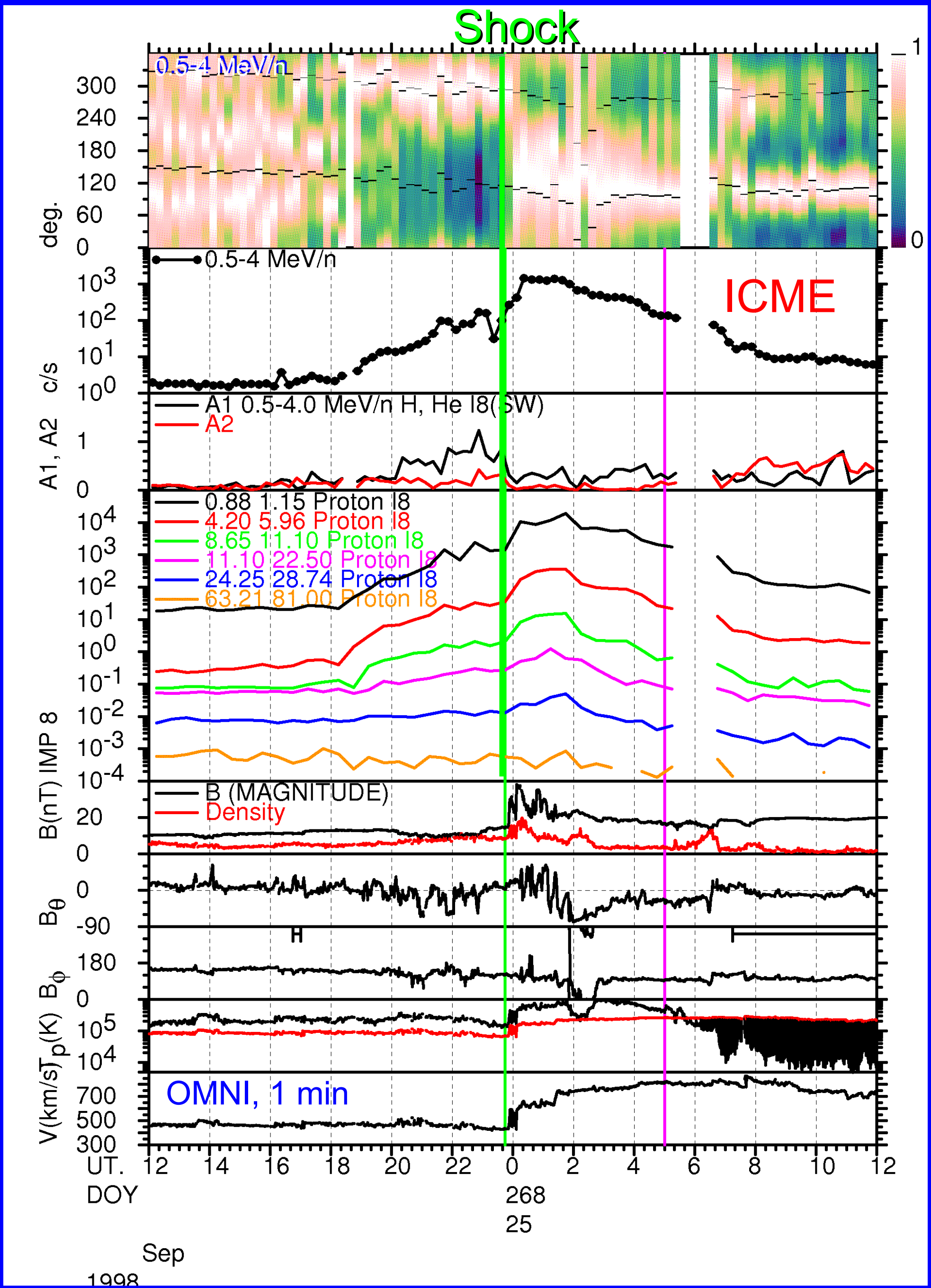
254 shocks in 1996 – 2005

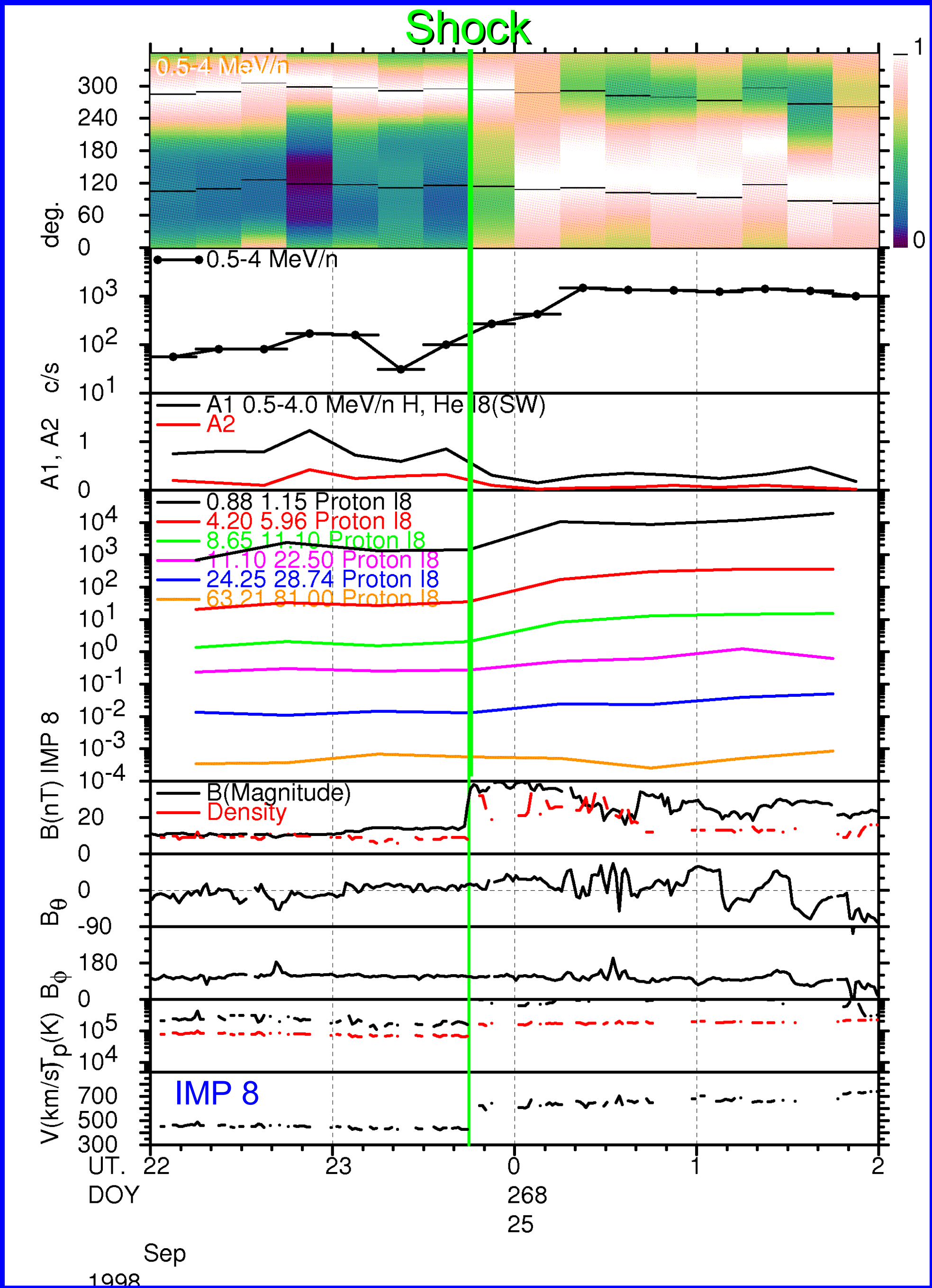
IMP 8 data available for 202 shocks

139 (69%) have 0.8-1.15 MeV proton intensity >1 $(\text{MeV s cm}^2 \text{ sr})^{-1}$

After allowing for intervals of low statistics, data gaps and periods when IMP 8 was inside the Earth's bow shock, adequate 0.5 - 4 MeV/n anisotropy observations are available for ~ 70 of these shocks.

Shock of September 24, 1998 - “Classic” example – Broad peak around shock + clean flow reversal (E09º; θ_{Bn} =78º)



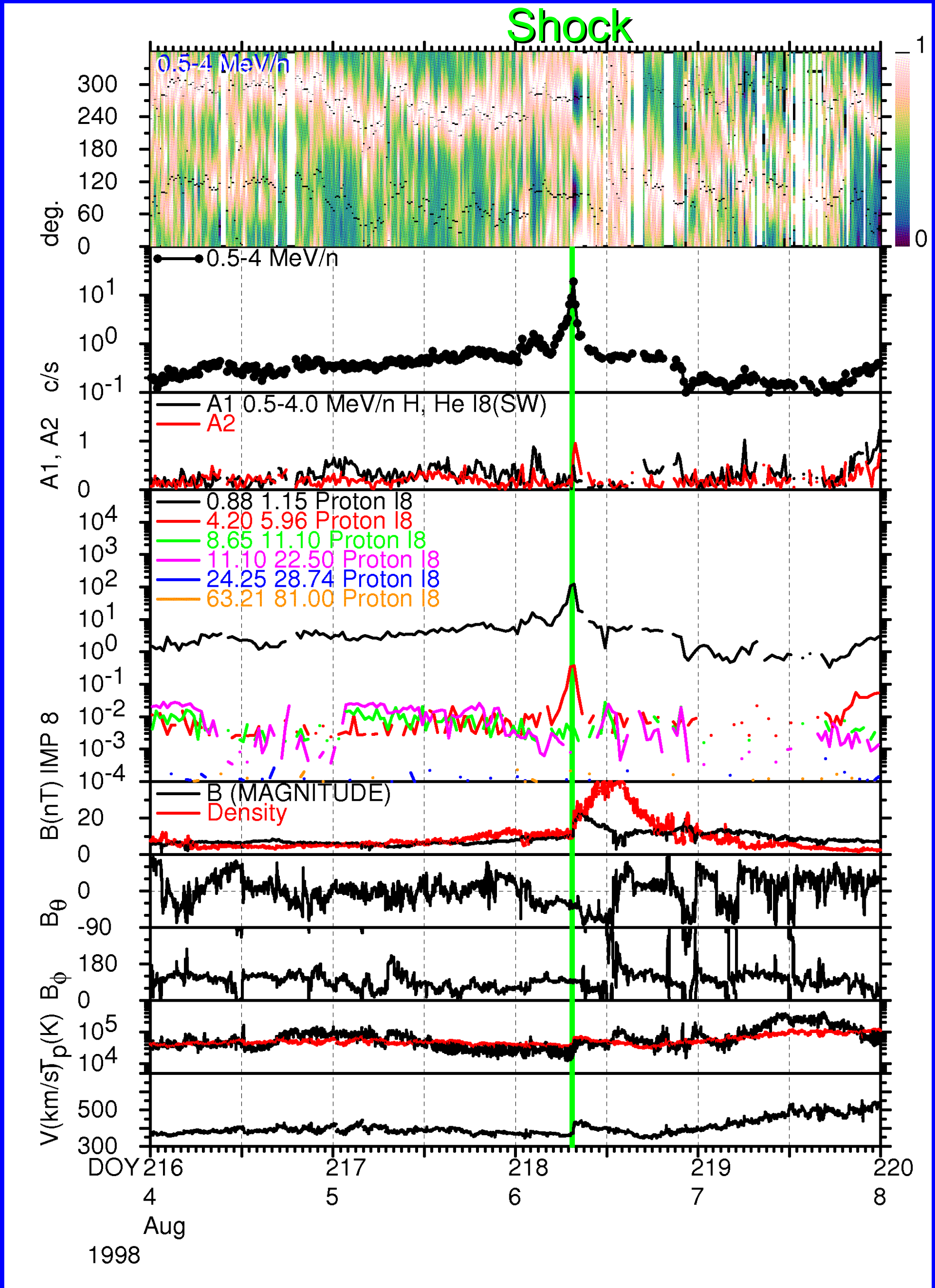


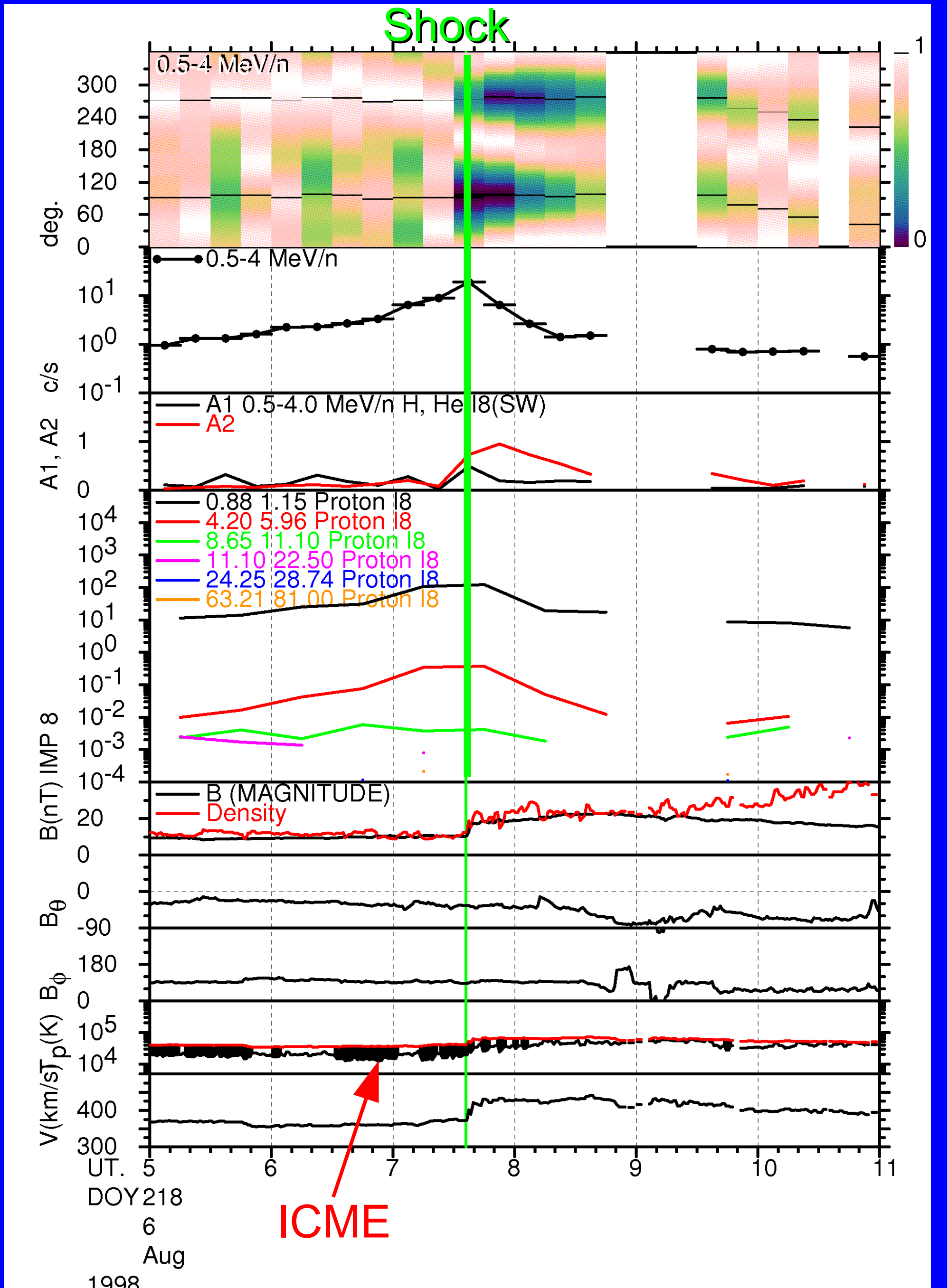
40/202 Shocks show broad (>~several hour) MeV particle increases around shock passage.

Anisotropies can be examined for 20 events.

8 show clear flow reversals in vicinity of shock

Example of Shock Spike (Pancake Distribution => Shock Drift Acceleration; August 6, 1998, θ_{Bn} =80º)





24/202 shocks show brief MeV particle shock spikes.

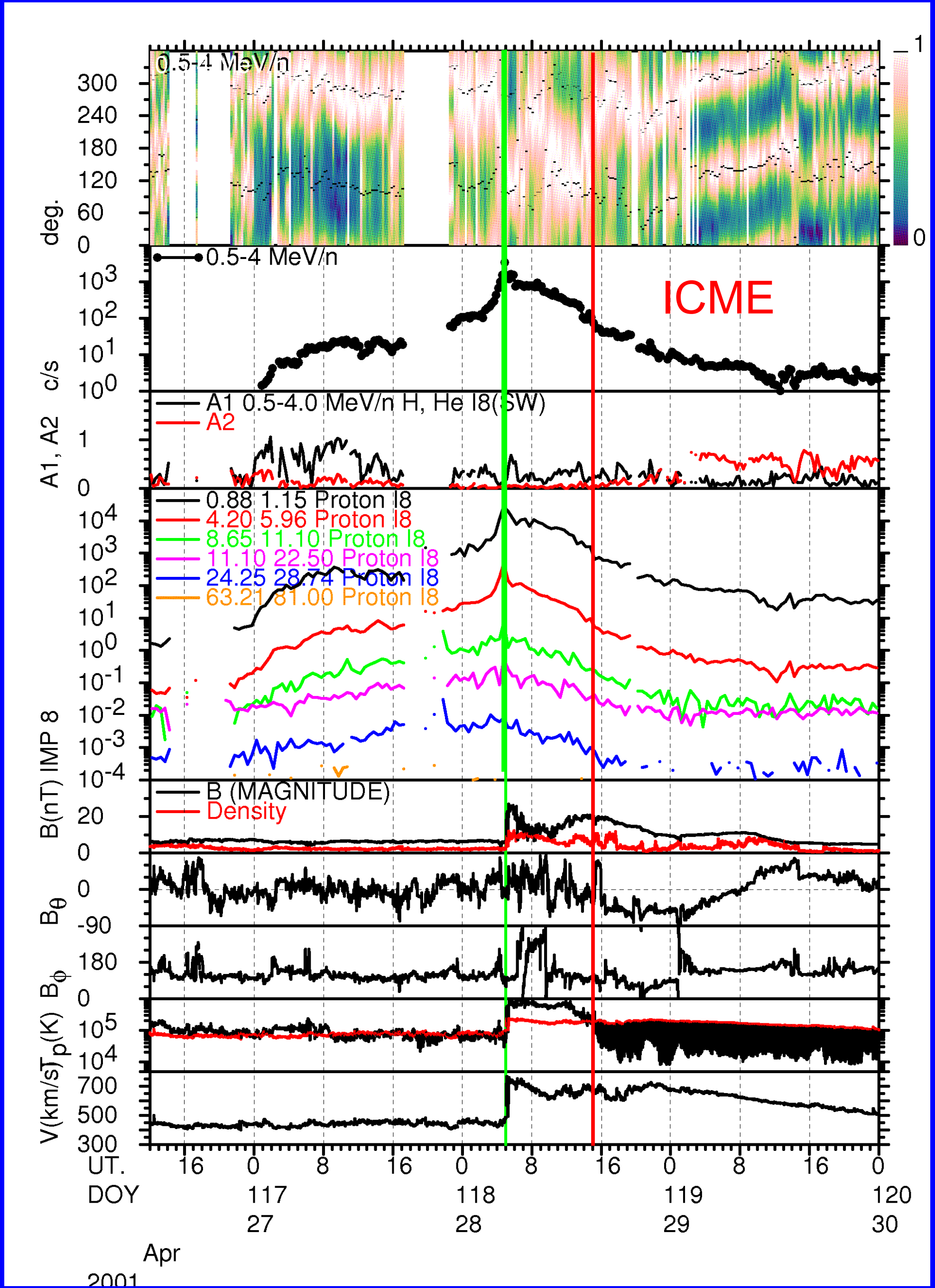
Anisotropies can be examined for 13 events.

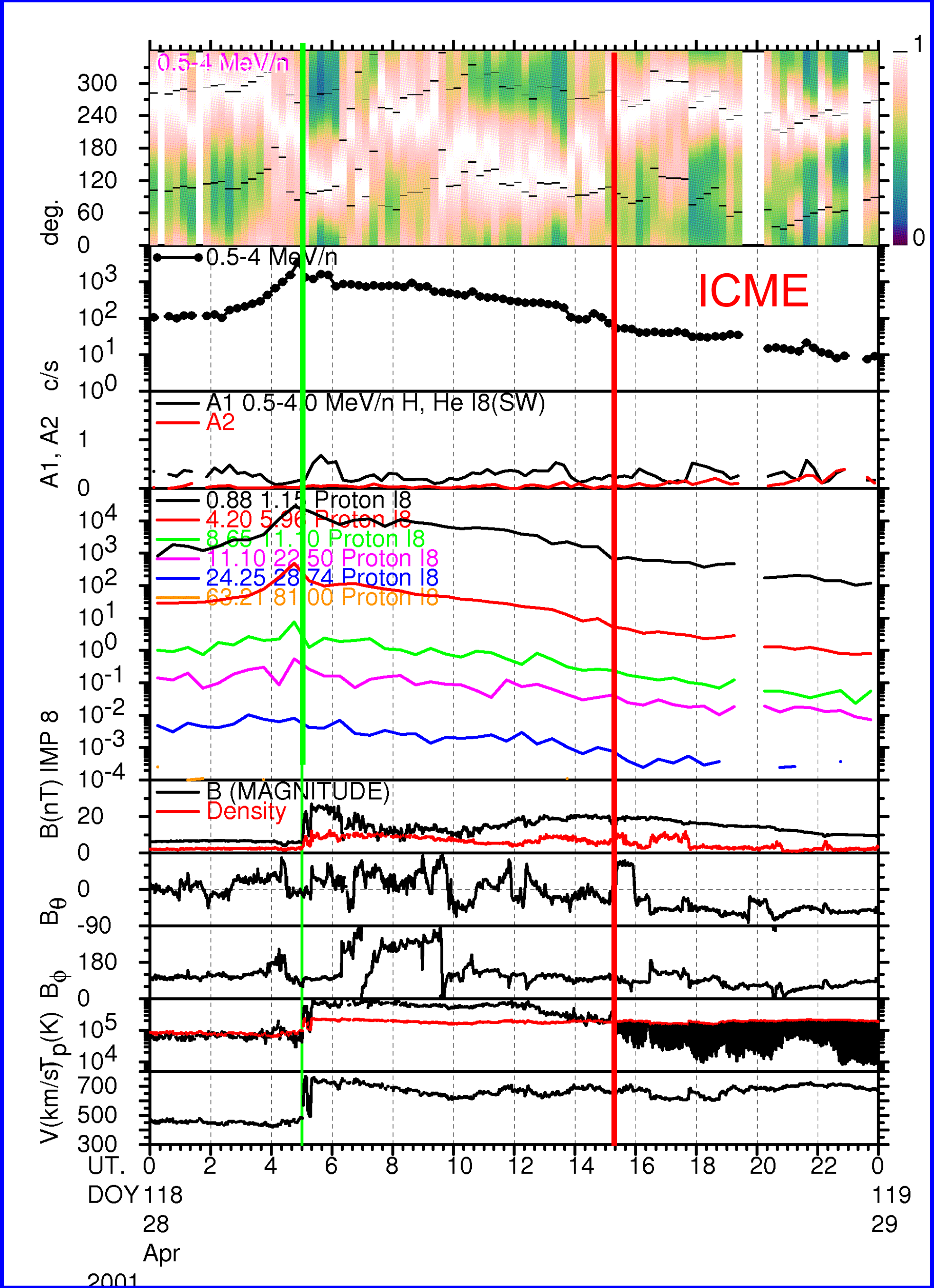
10 show evidence of pancake distributions in vicinity of shock

9 have $\theta_{Bn} \geq 69^{\circ}$ (Kasper); consistent with shock drift acceleration at quasi-perpendicular shocks.

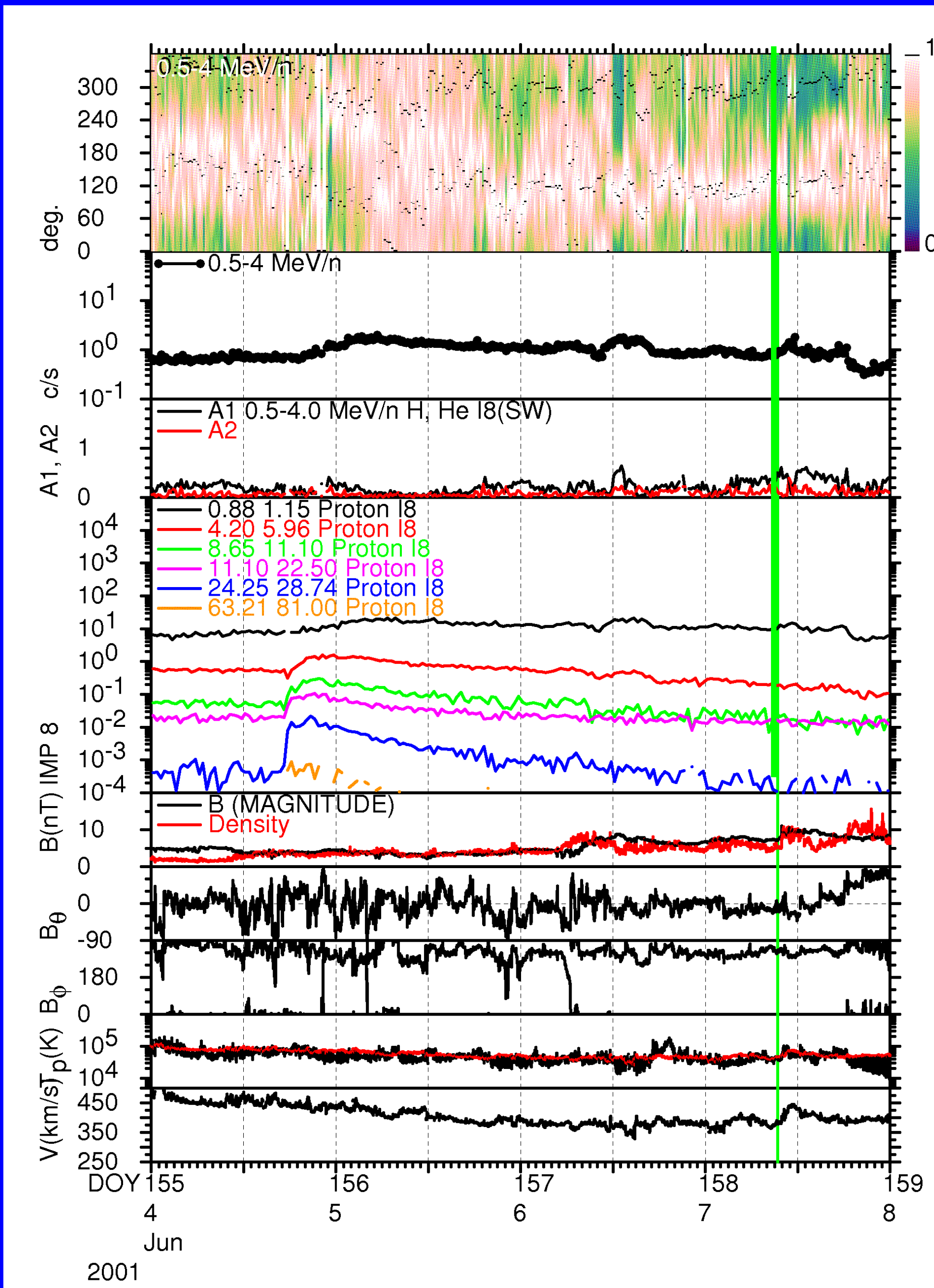
For 5/8 shocks with shock spikes, solar event is on eastern hemisphere.

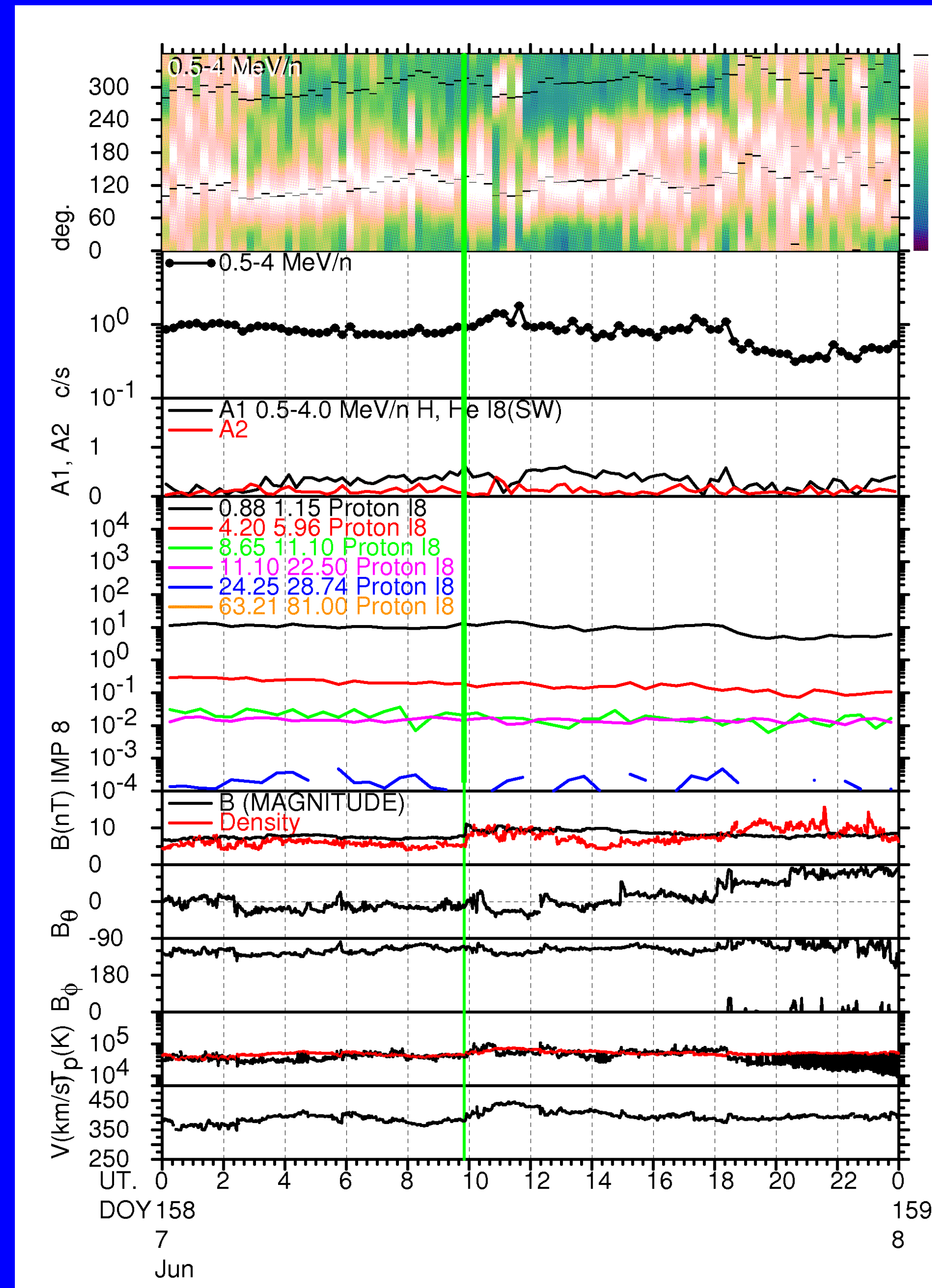
April 28, 2001 – Variable flows downstream of shock related to solar wind structures; W31°, θ_{Bn} = 57°



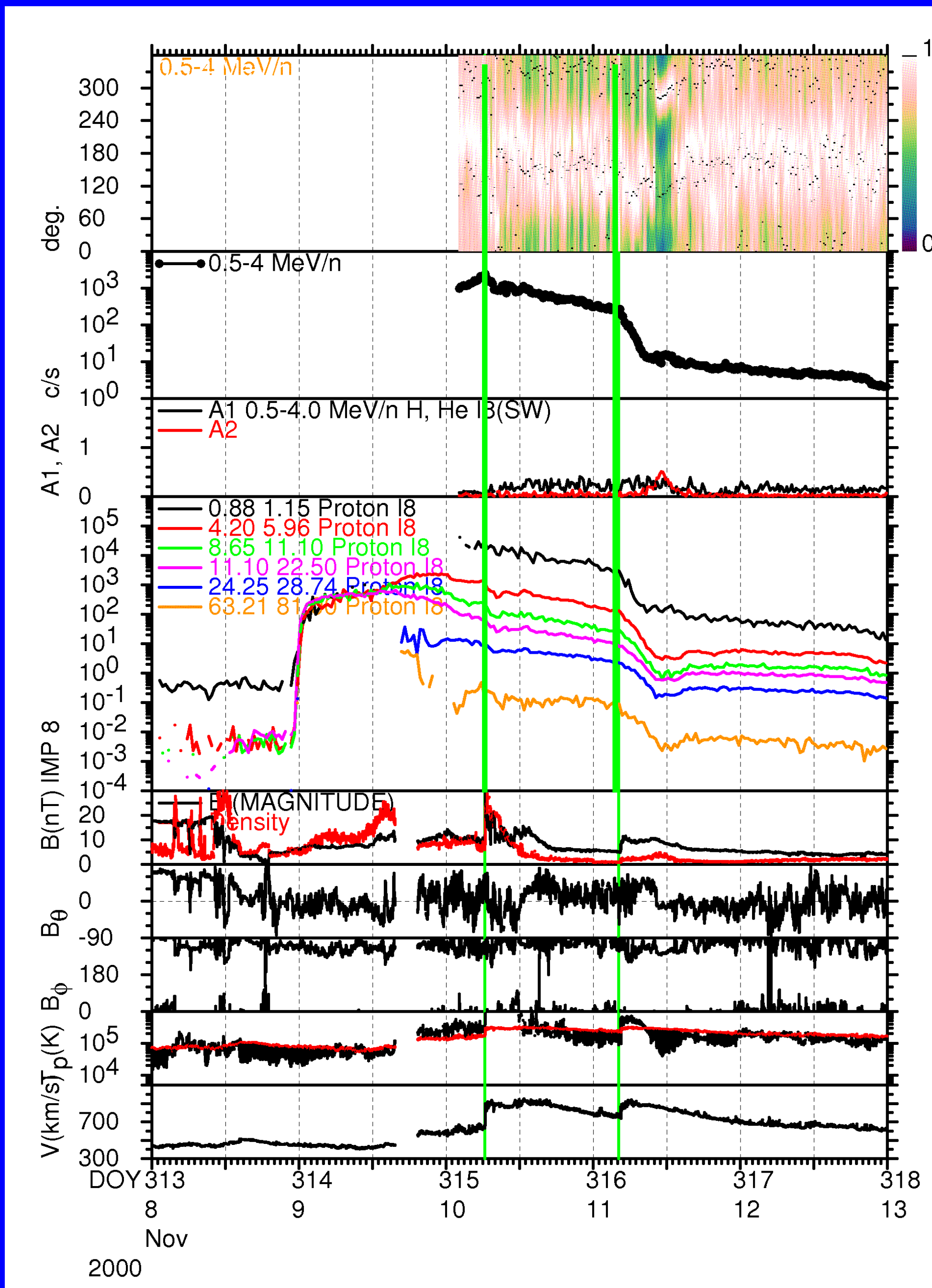


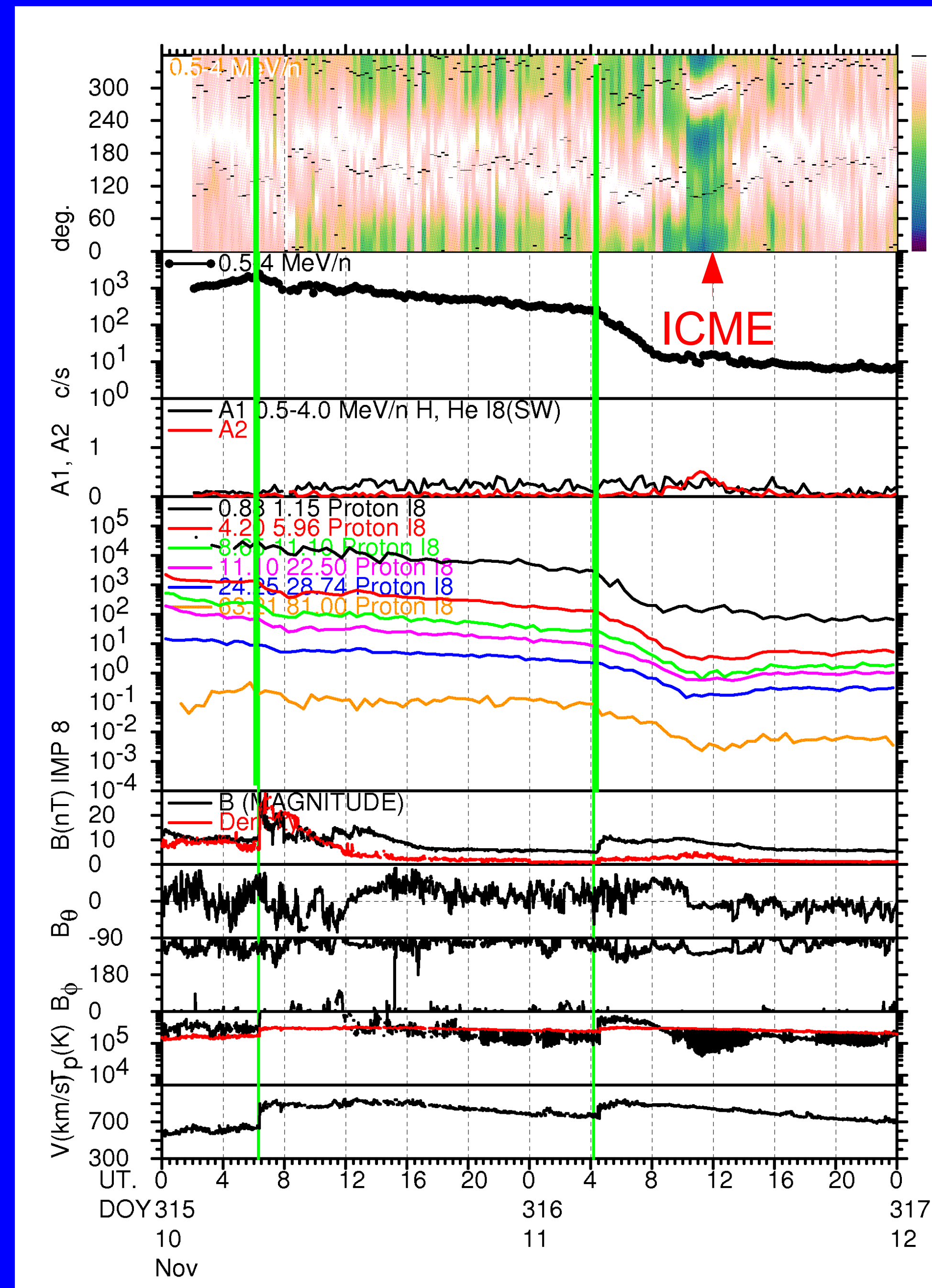
Weak shock during decay of western (W59º) particle event (June 7, 2001; θ_{Bn} = 50º, Vs=413 km/s): No flow reversal





Two strong shocks during decay of W75º event: 2000 November 10 (θ_{Bn} = 74º, V_s =820 km/s) and November 11 (θ_{Bn} = 40º, V_s =890 km/s)





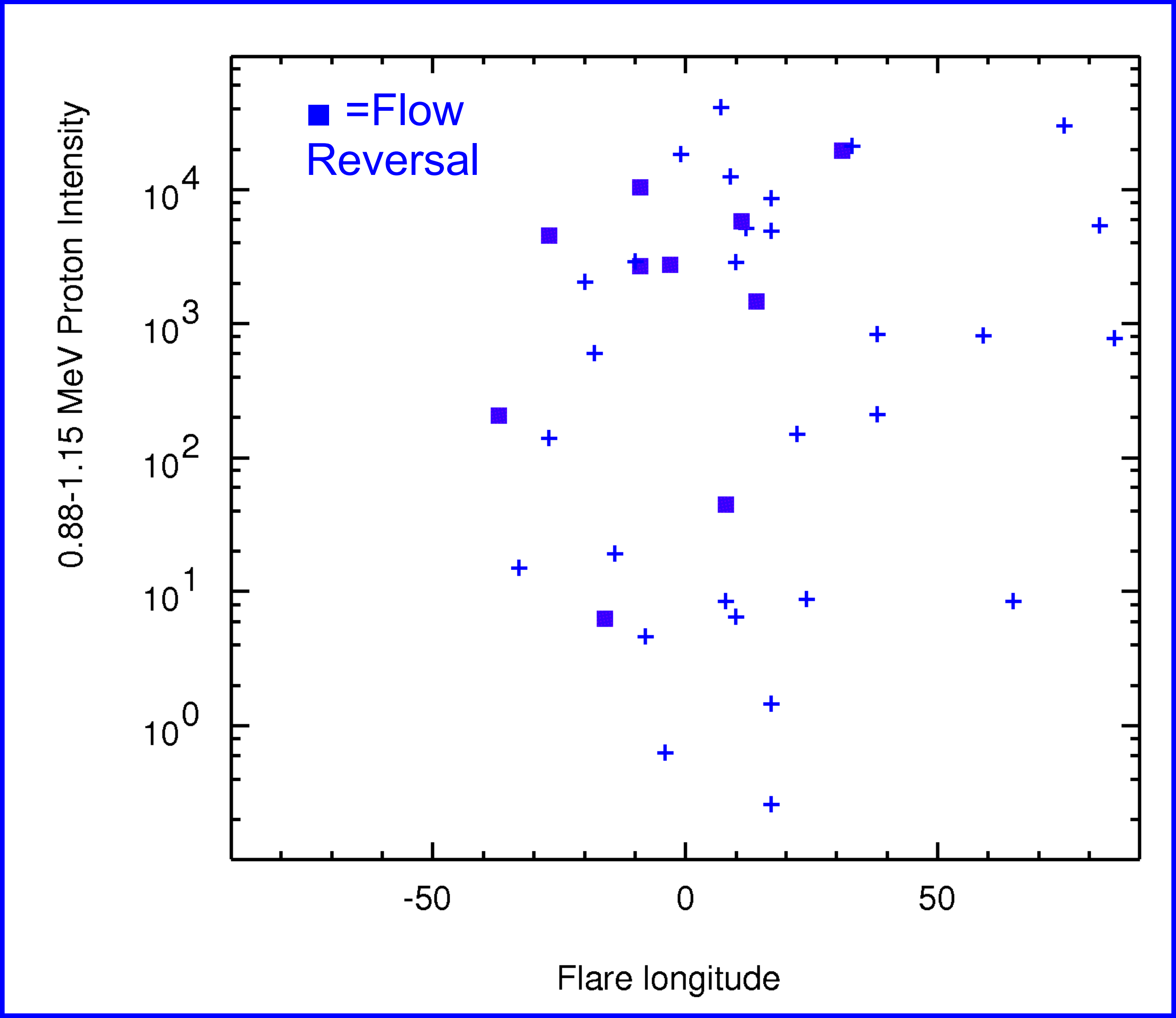
13 shocks show similar MeV proton intensity "modulations"

Of 7 events where anisotropies can be examined, only 1 shows a clear flow reversal.

5/8 shocks have solar sources at >45º W

~32% of shocks (with anisotropy observations) show evidence of flow reversal in general vicinity of shock (inferred from angular distribution plots)

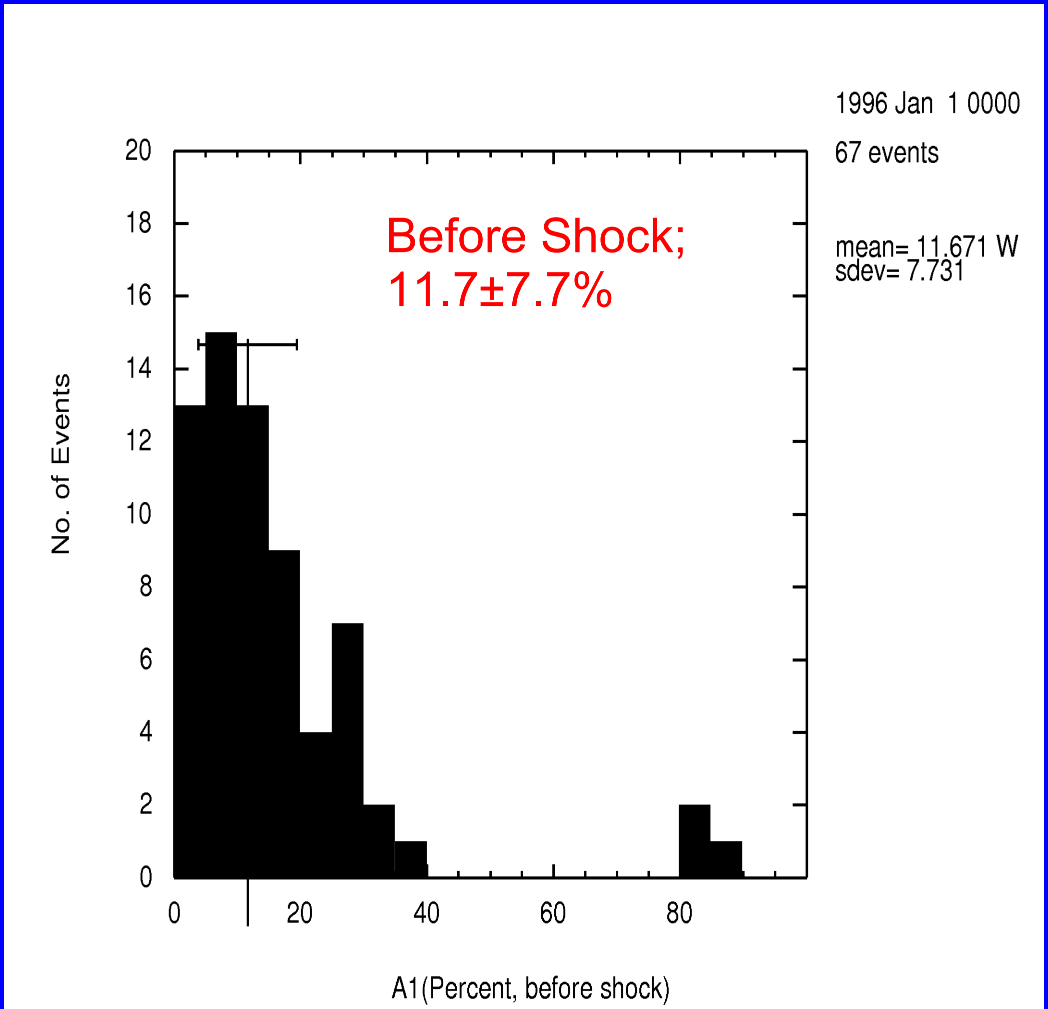
~1 MeV Proton Intensity vs. flare longitude vs. flow reversal for 35 shocks

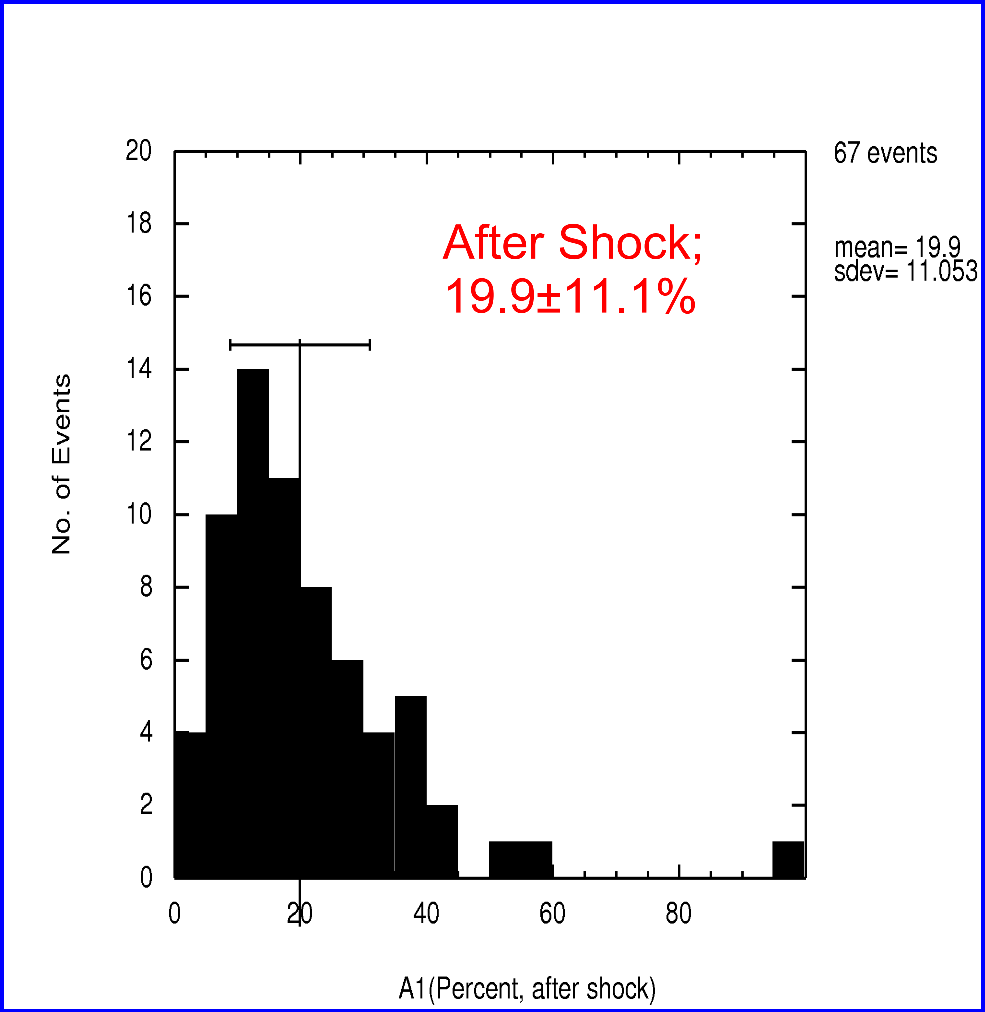


Clear flow reversals are associated with near-central meridian events

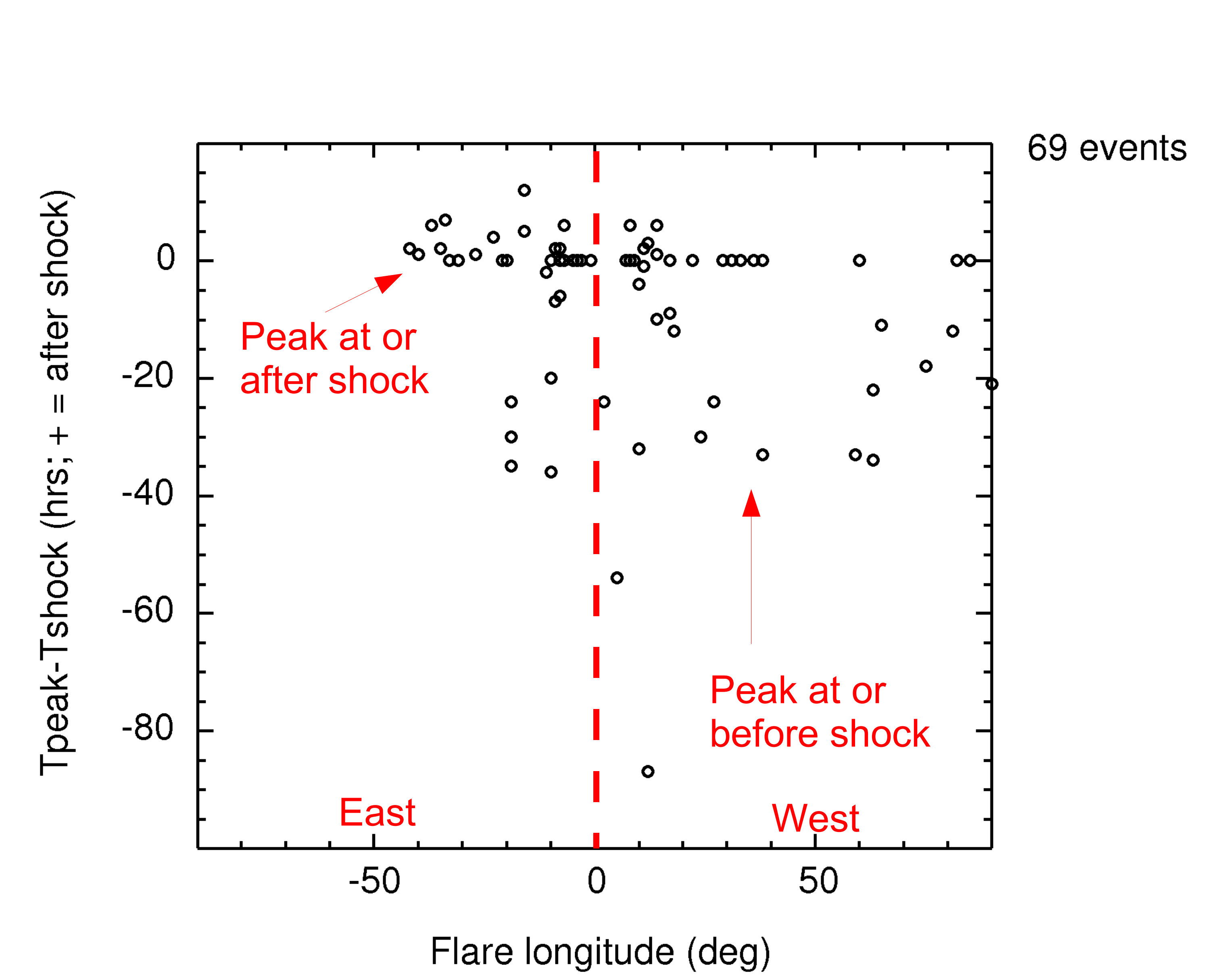
Shocks passing during far western SEP events do not show clear flow reversals.

Summary of First Harmonic Amplitude $|A_1|$ for 0.5-4 MeV Protons During 2 hours Before and After Passage of 67 Shocks

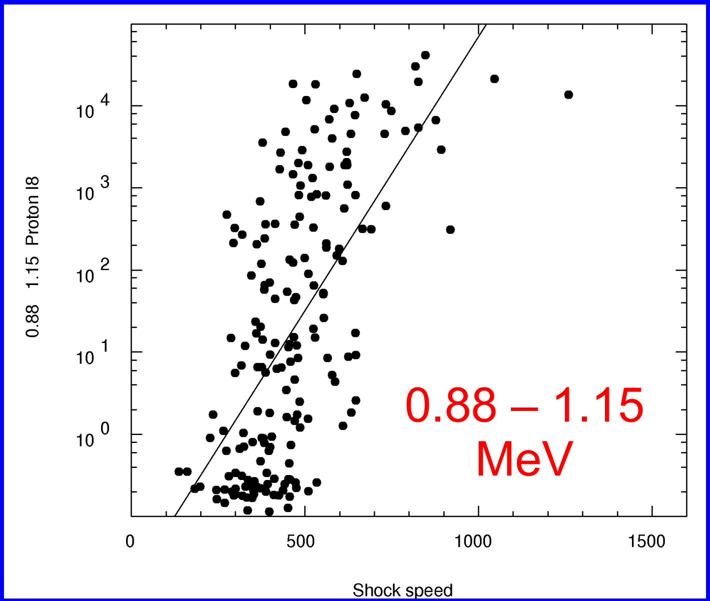


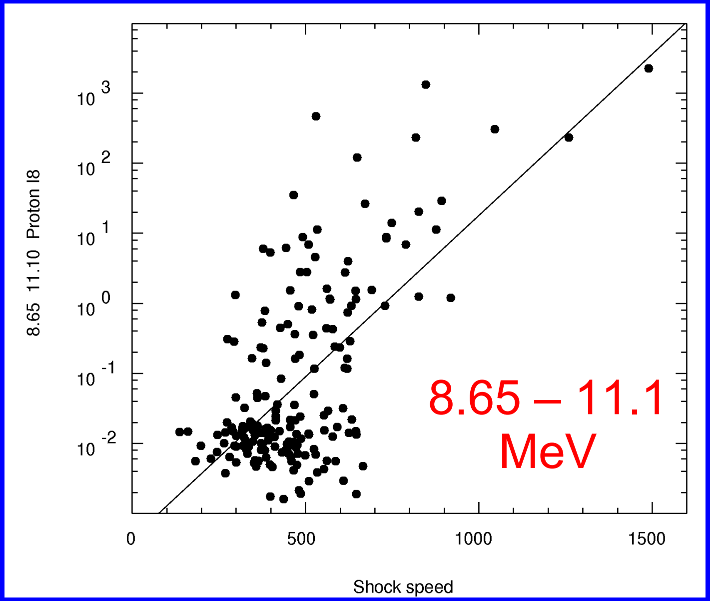


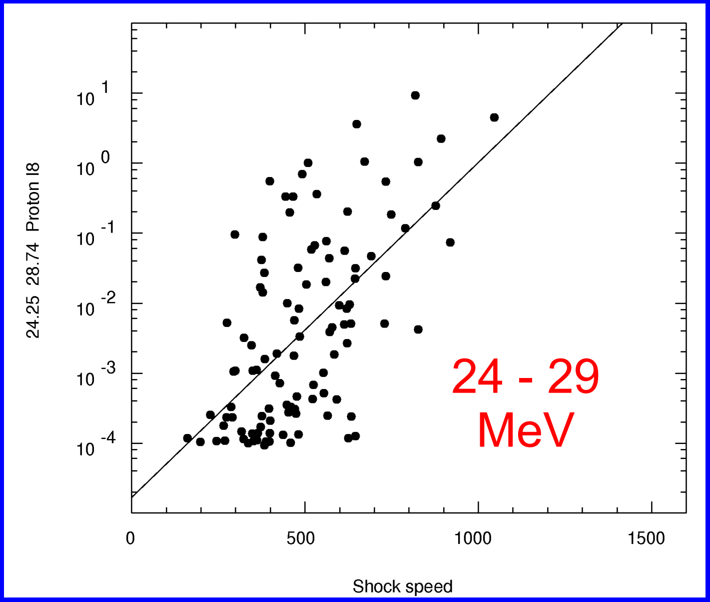
Time(peak)-Time(shock) vs. Solar Event Longitude

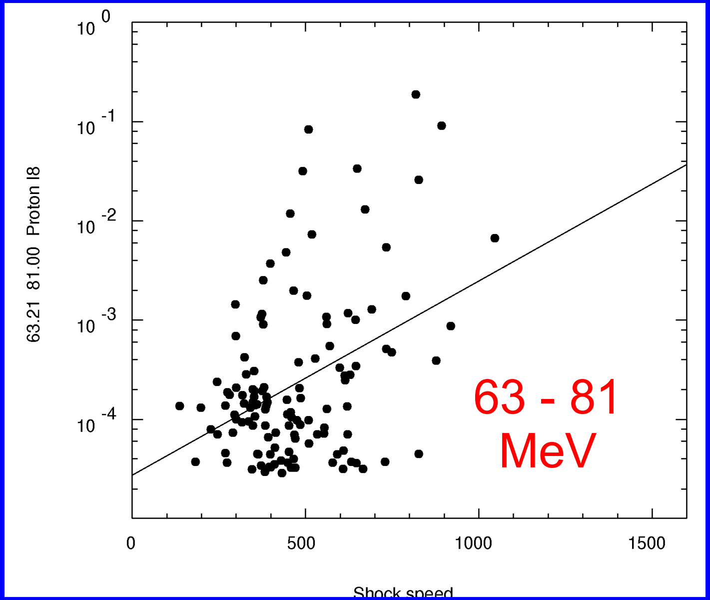


Intensity of 0.88 – 1.15, 8.65 – 11.1, 24 – 29, and 63 – 81 MeV Protons at 190 Interplanetary Shocks During 1996 – 2004 vs. Shock Speed (from Kasper WIND Database)

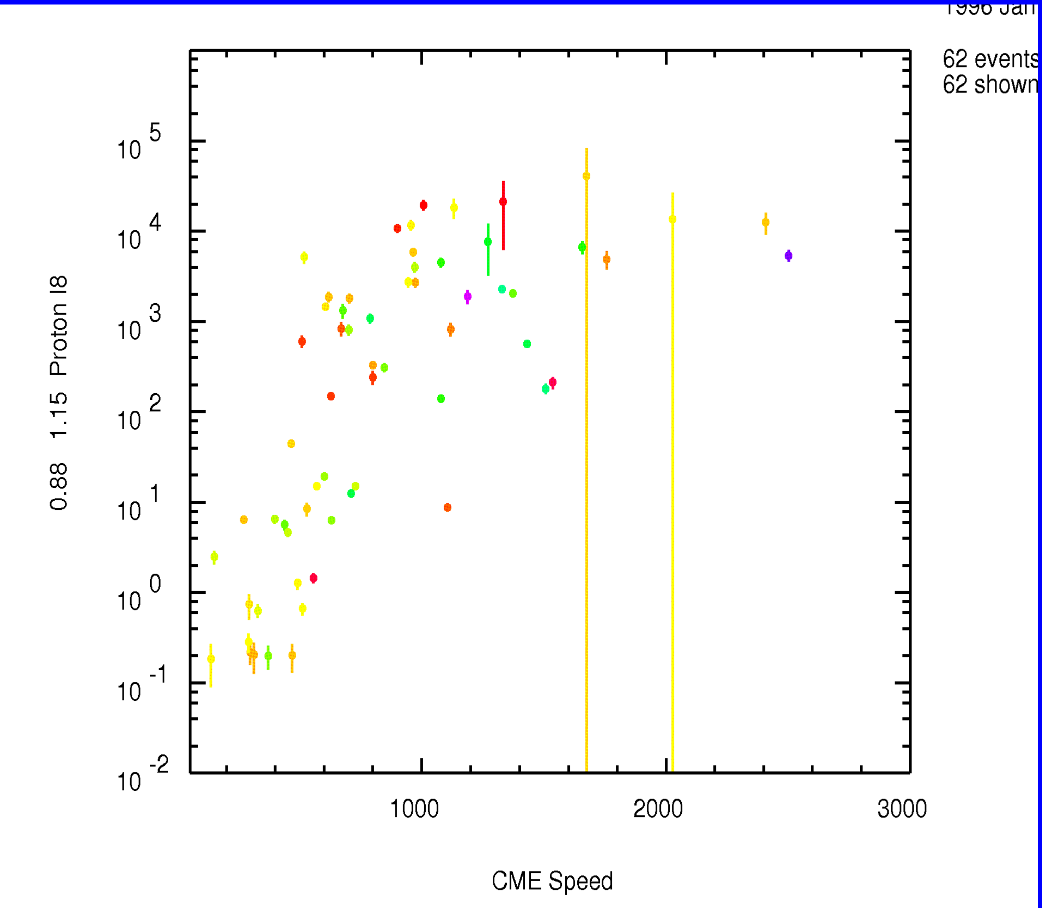


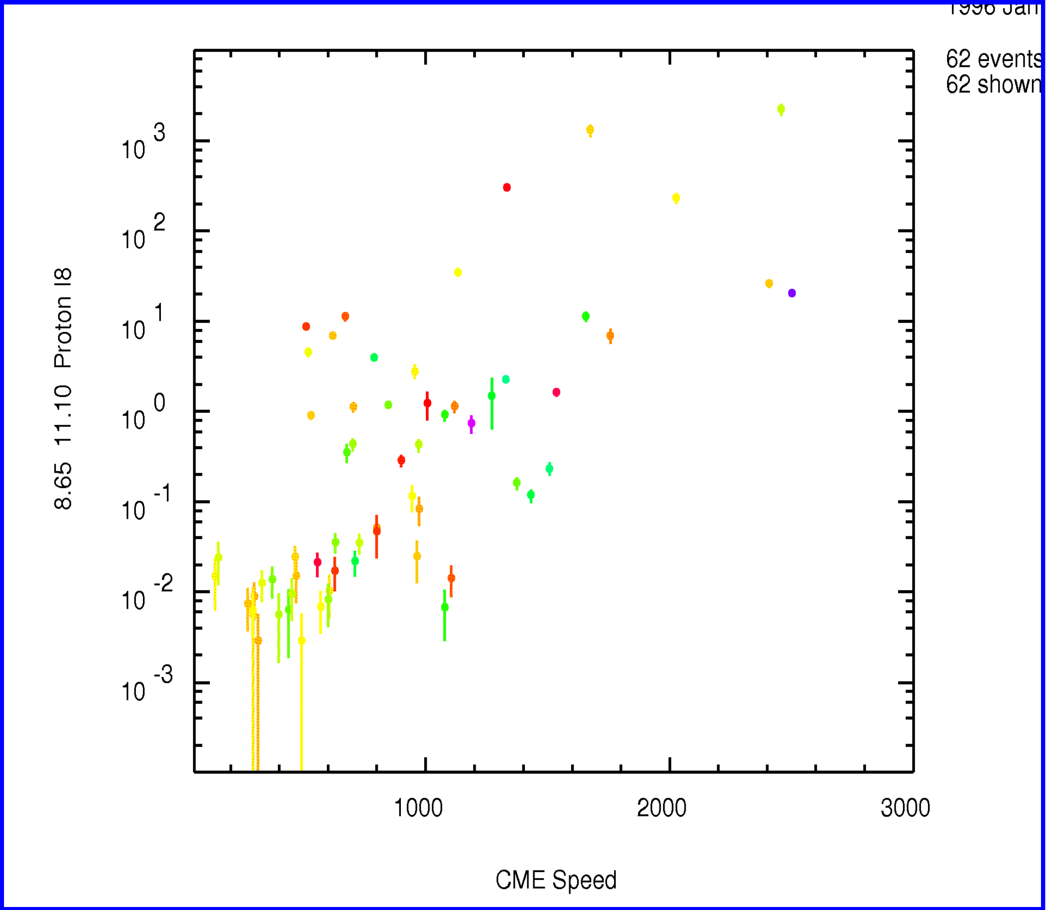




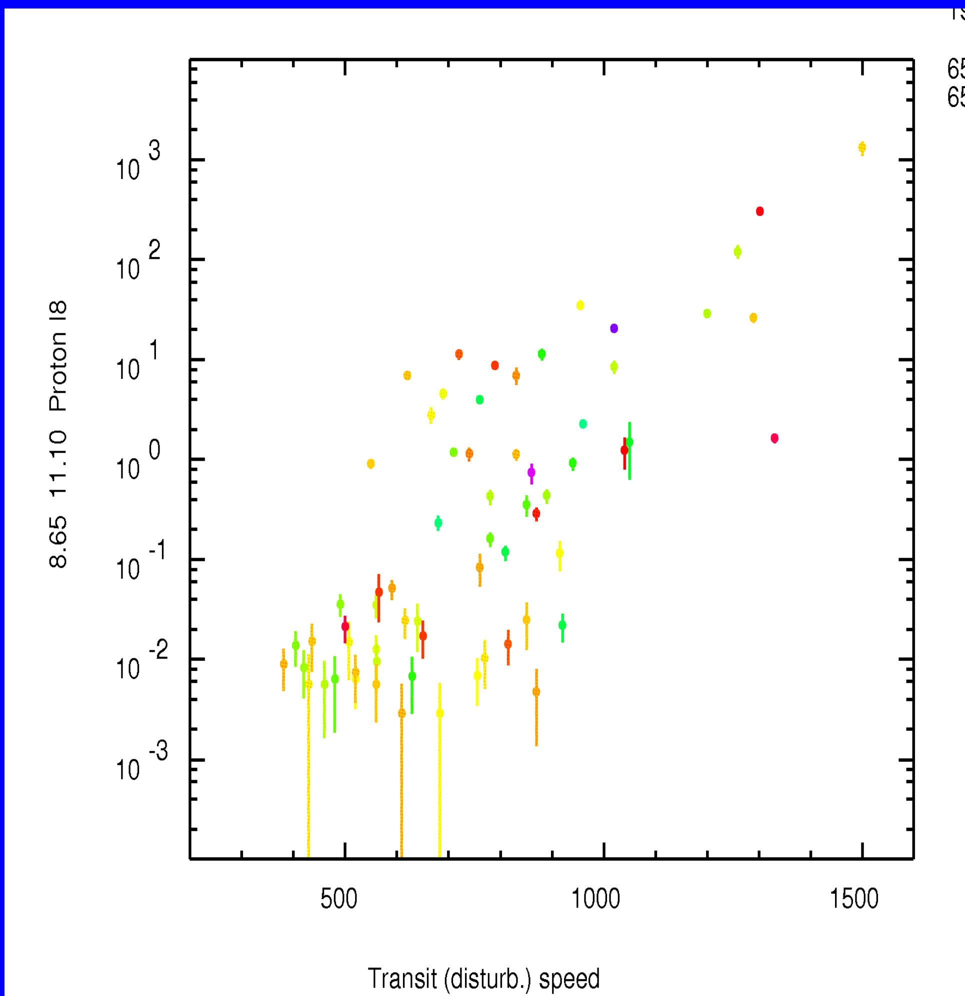


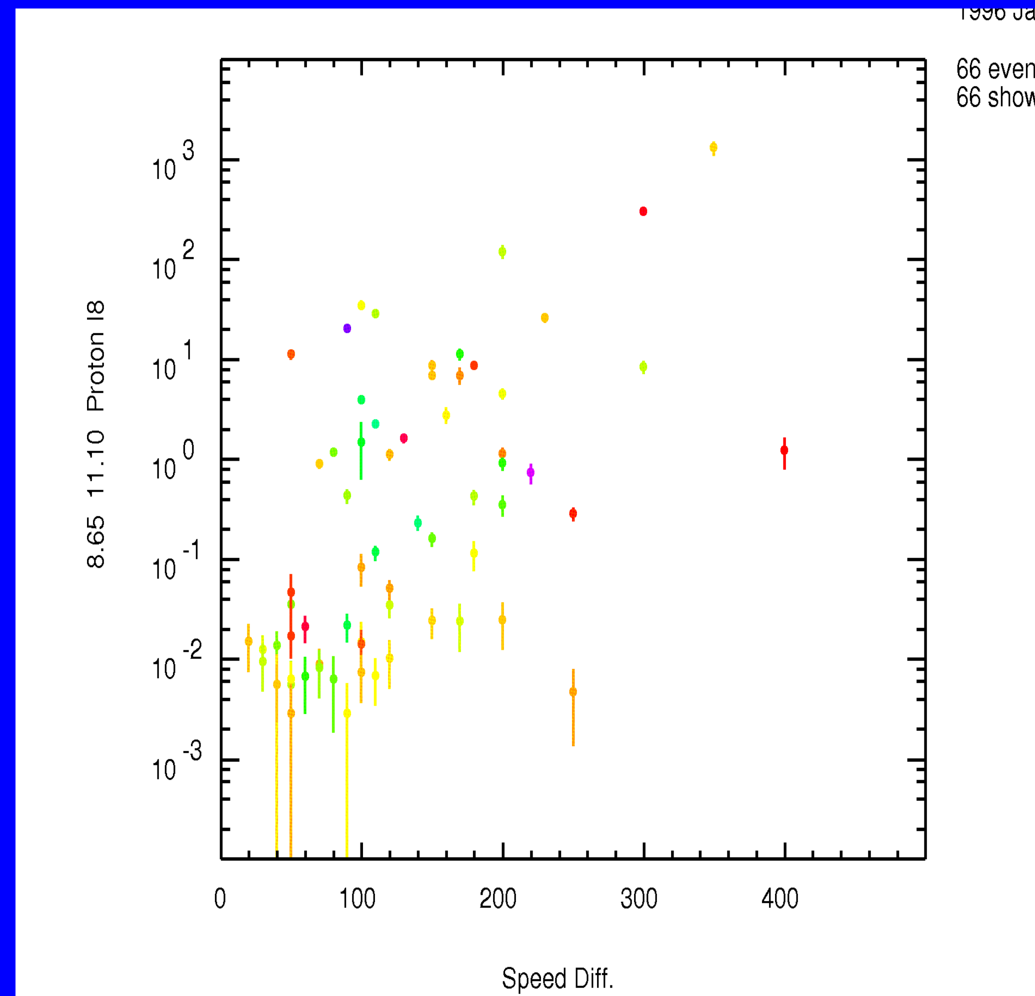
IMP 8 0.88-1.15 MeV and 8.65-11.1 MeV Proton Intensity vs. LASCO CME Speed (ICME events)





IMP 8 8.65-11.1 MeV Proton Intensity vs. Shock/Disturbance Transit Speed and Speed Jump

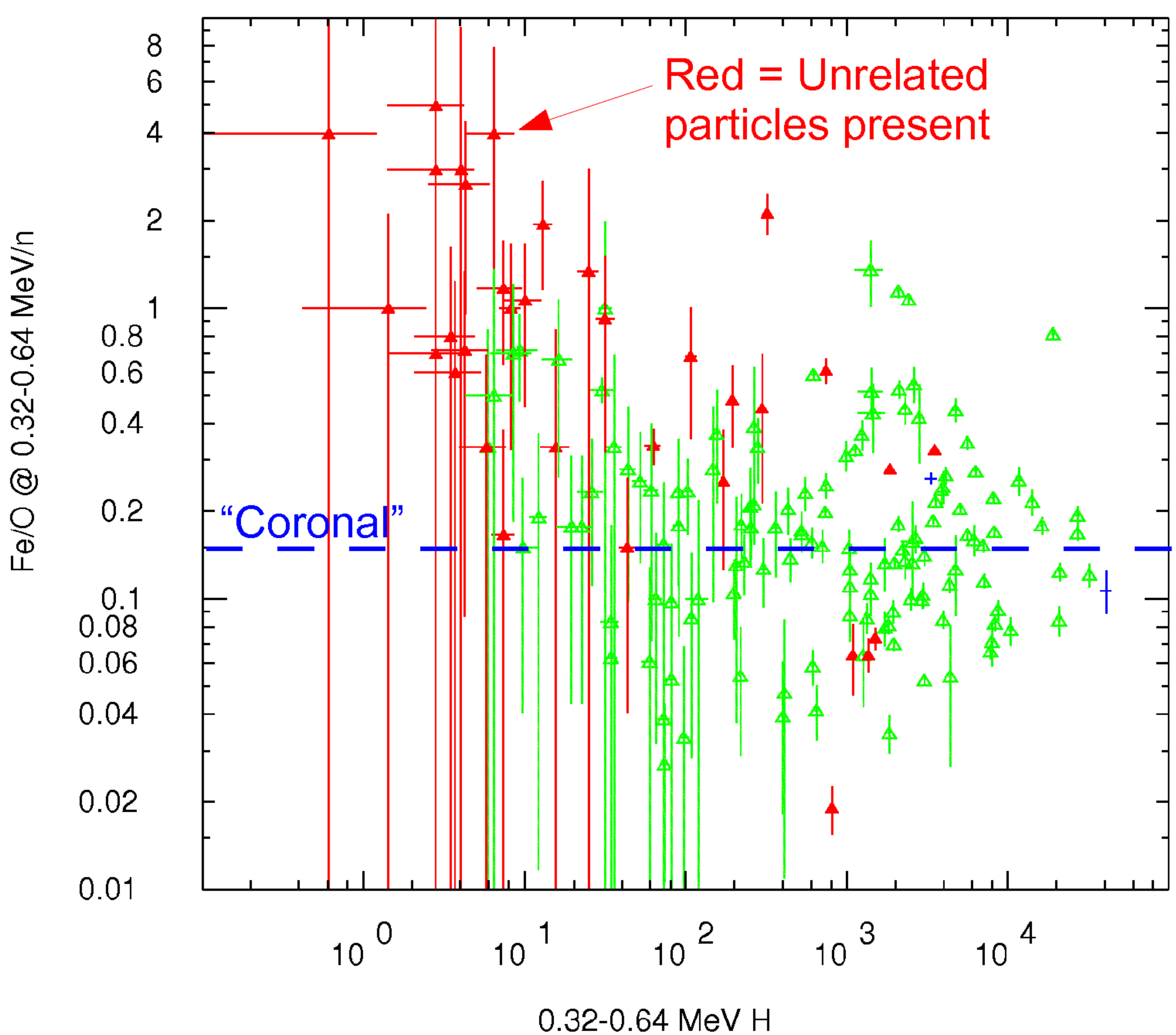


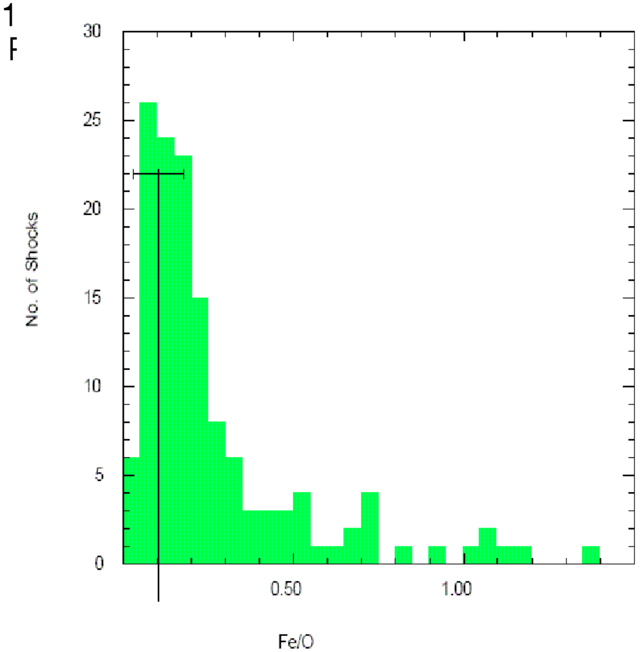


Reasonable correlation between proton intensity and transit speed

Poor correlation between proton intensity and speed jump (some events may not be true shocks)

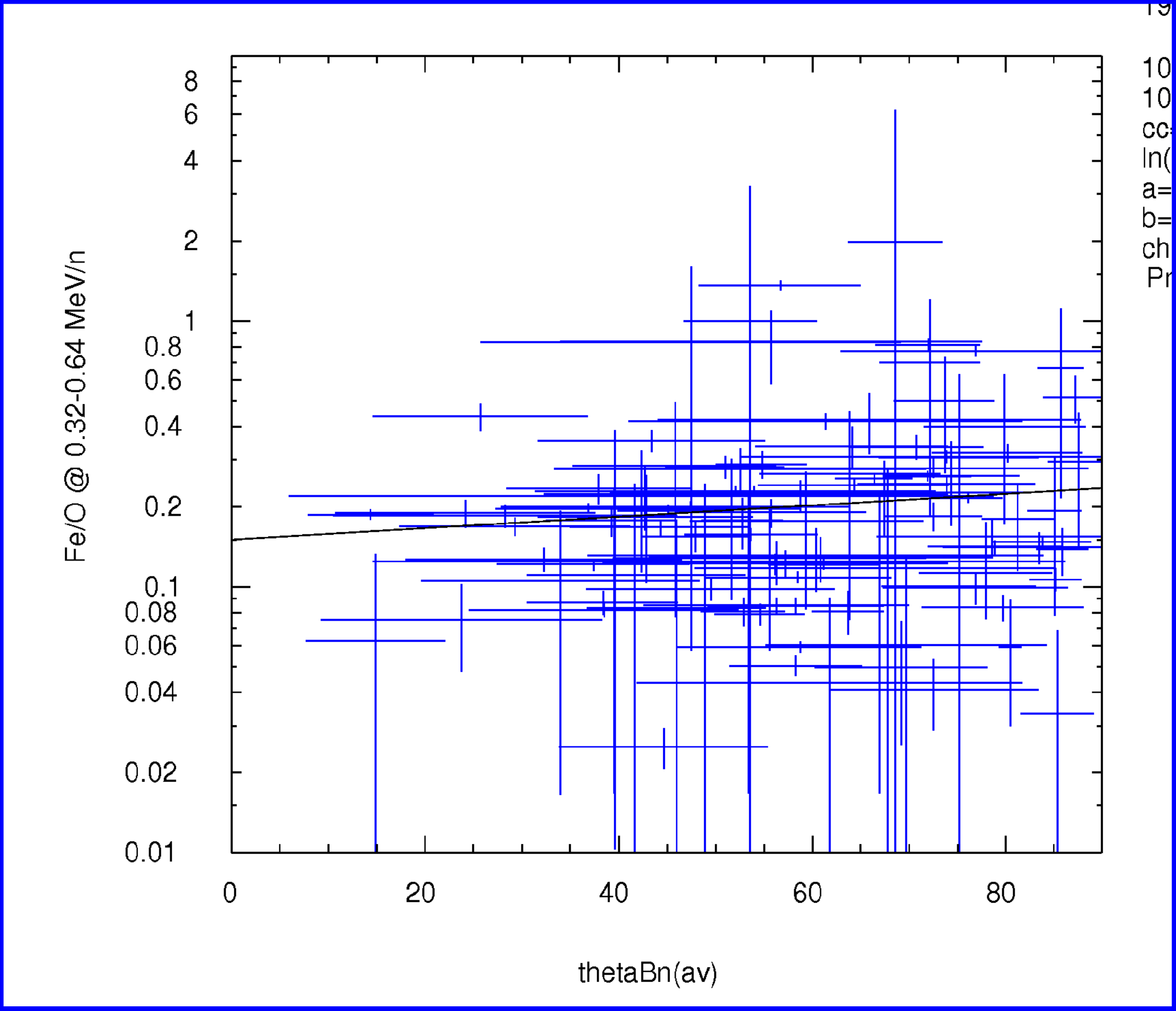
ULEIS 0.32-0.64 MeV/n Fe/O at 166 shocks vs 0.32-0.64 MeV Proton Intensity





Mean Fe/O = 0.105 ± 0.074 (SHINE 2006)

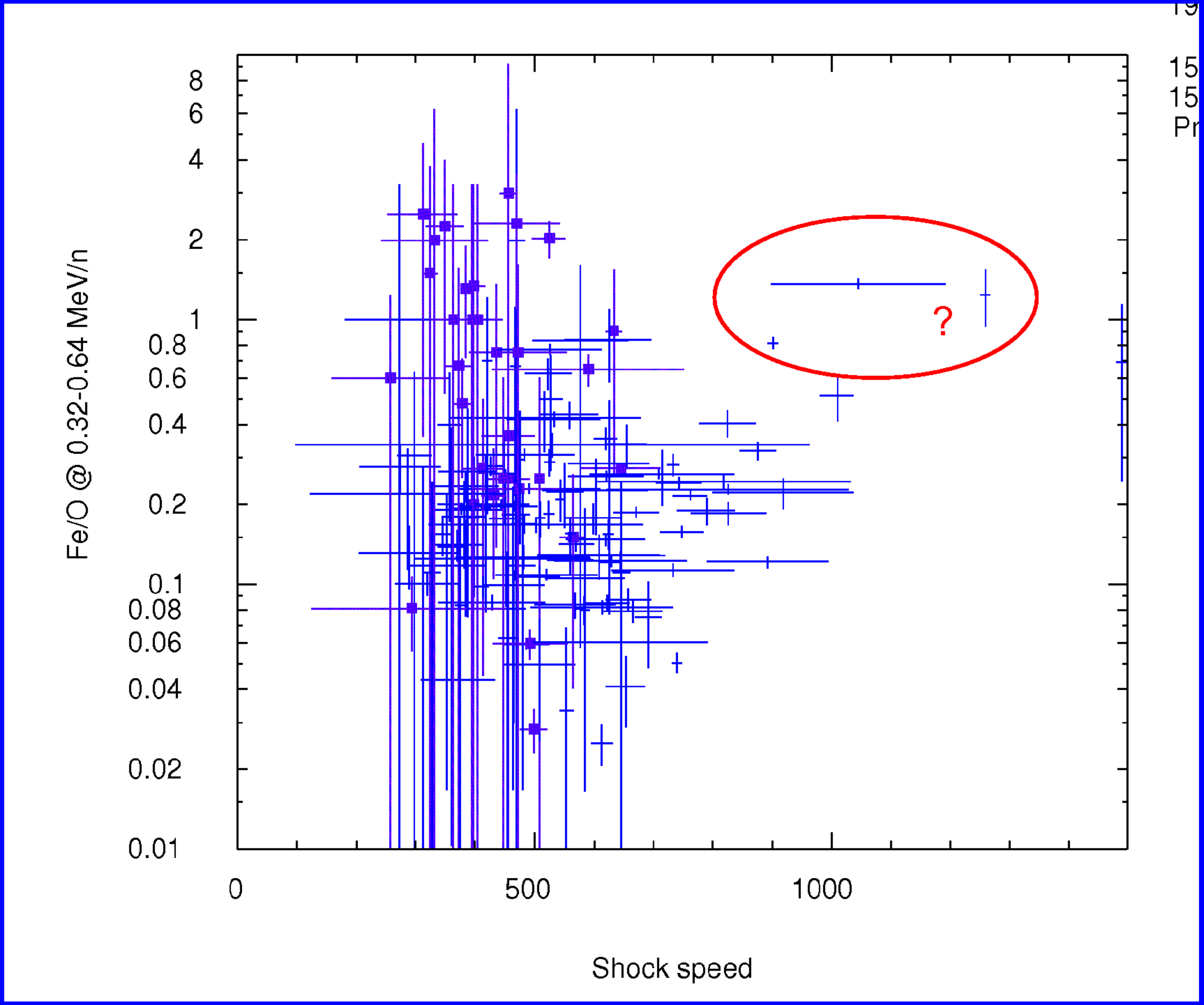
Fe/O @ 0.32-0.64 MeV/n vs. θ_{Bn} for 109 Shocks



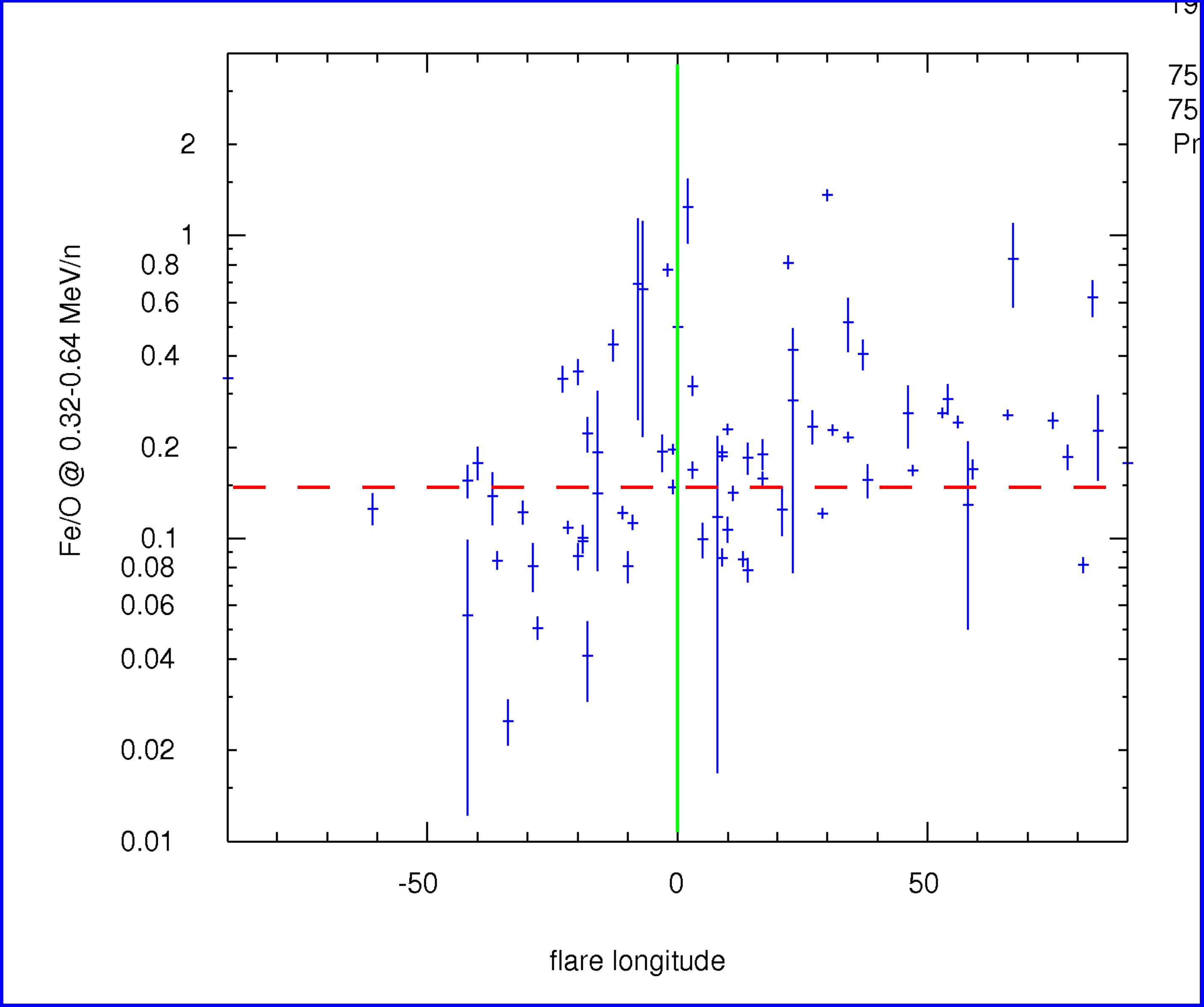
No obvious ordering by θ_{Bn}.

Note that θ_{Bn} will vary with location/time due to variable IMF direction.

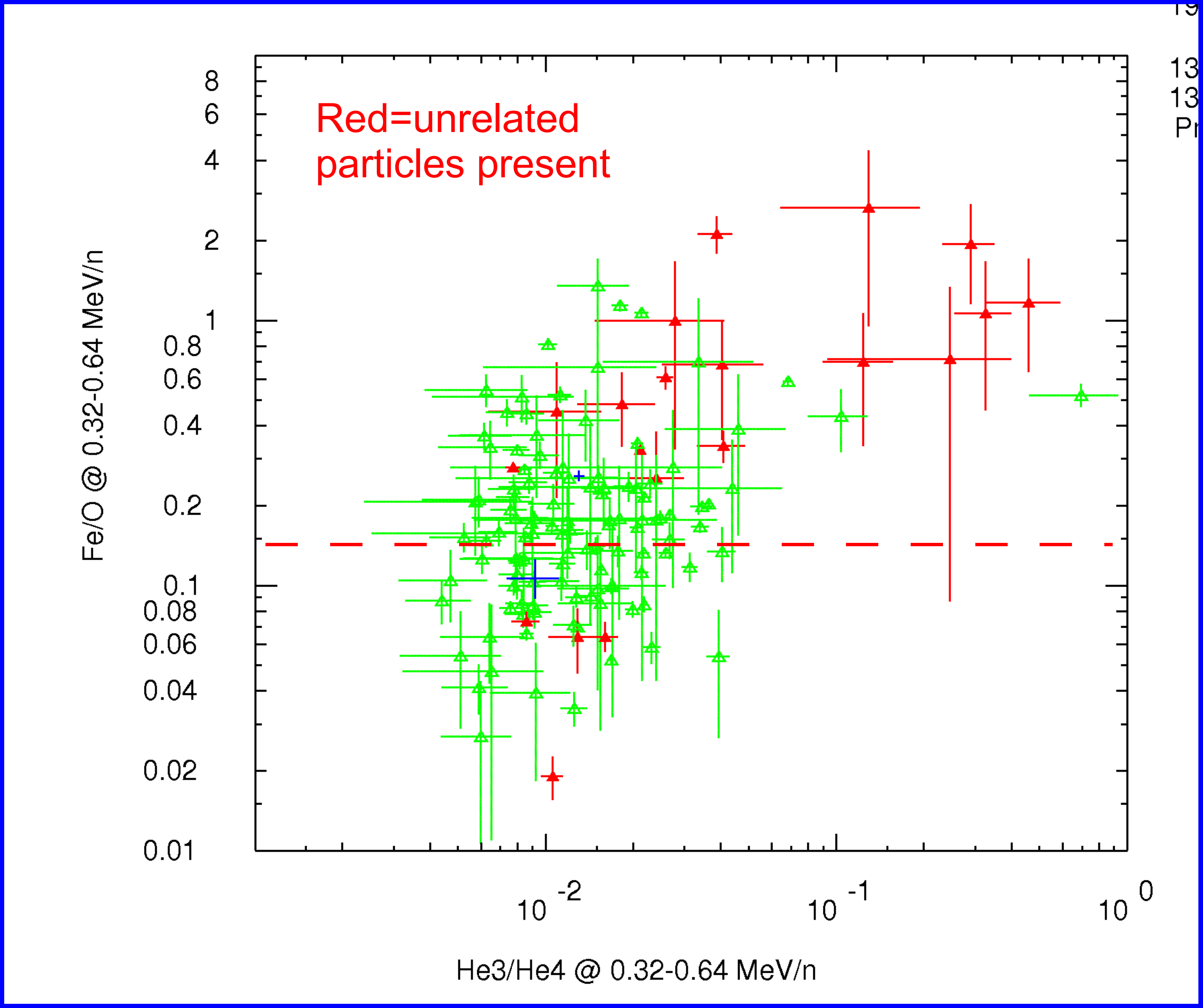
Fe/O @0.32-0.64 MeV/n vs. Shock Speed (Kasper)



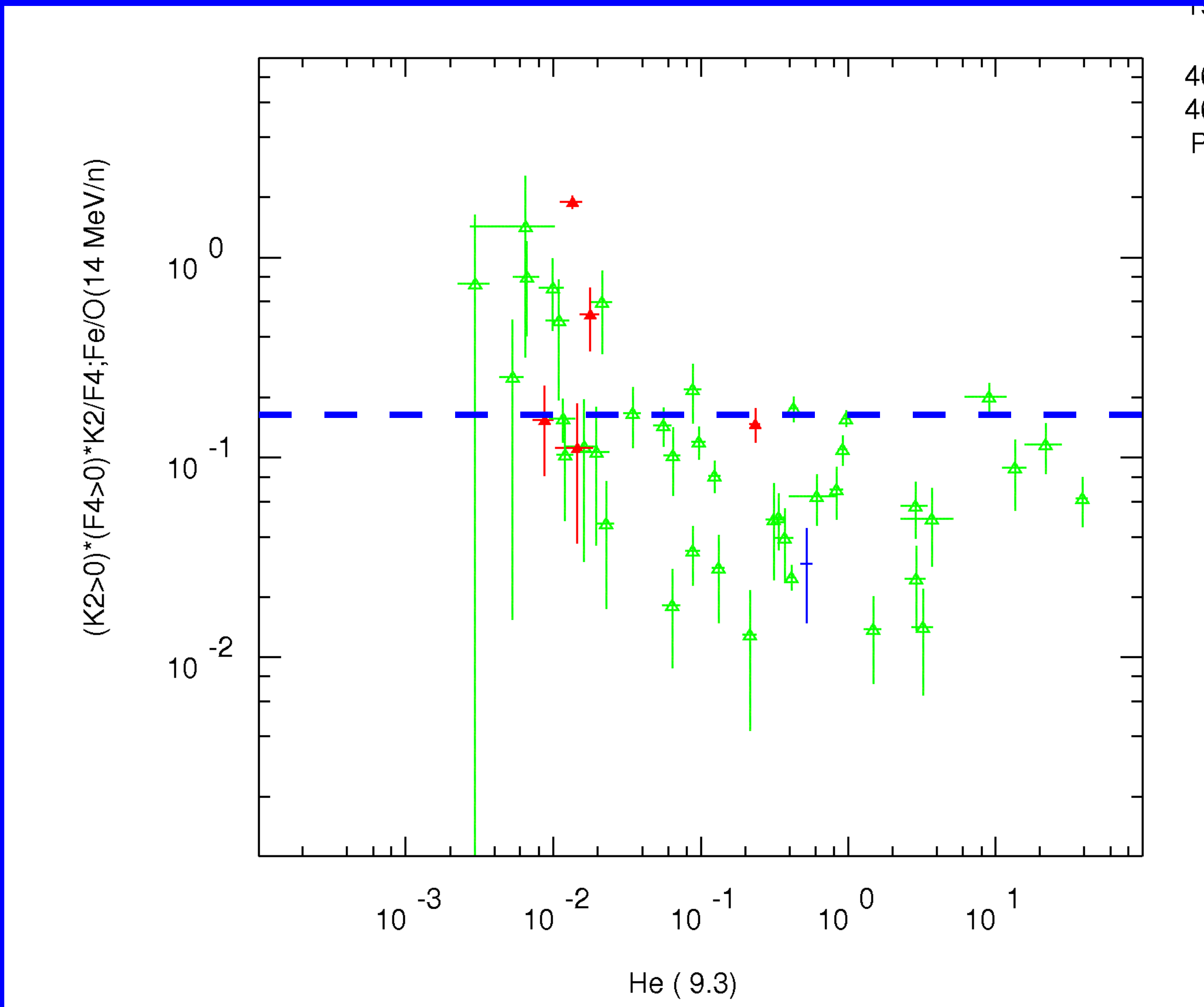
Fe/O @ 0.32-0.64 MeV/n vs. Source (Flare) Longitude



Fe/O vs. He3/He4 @ 0.32-0.64 MeV/n

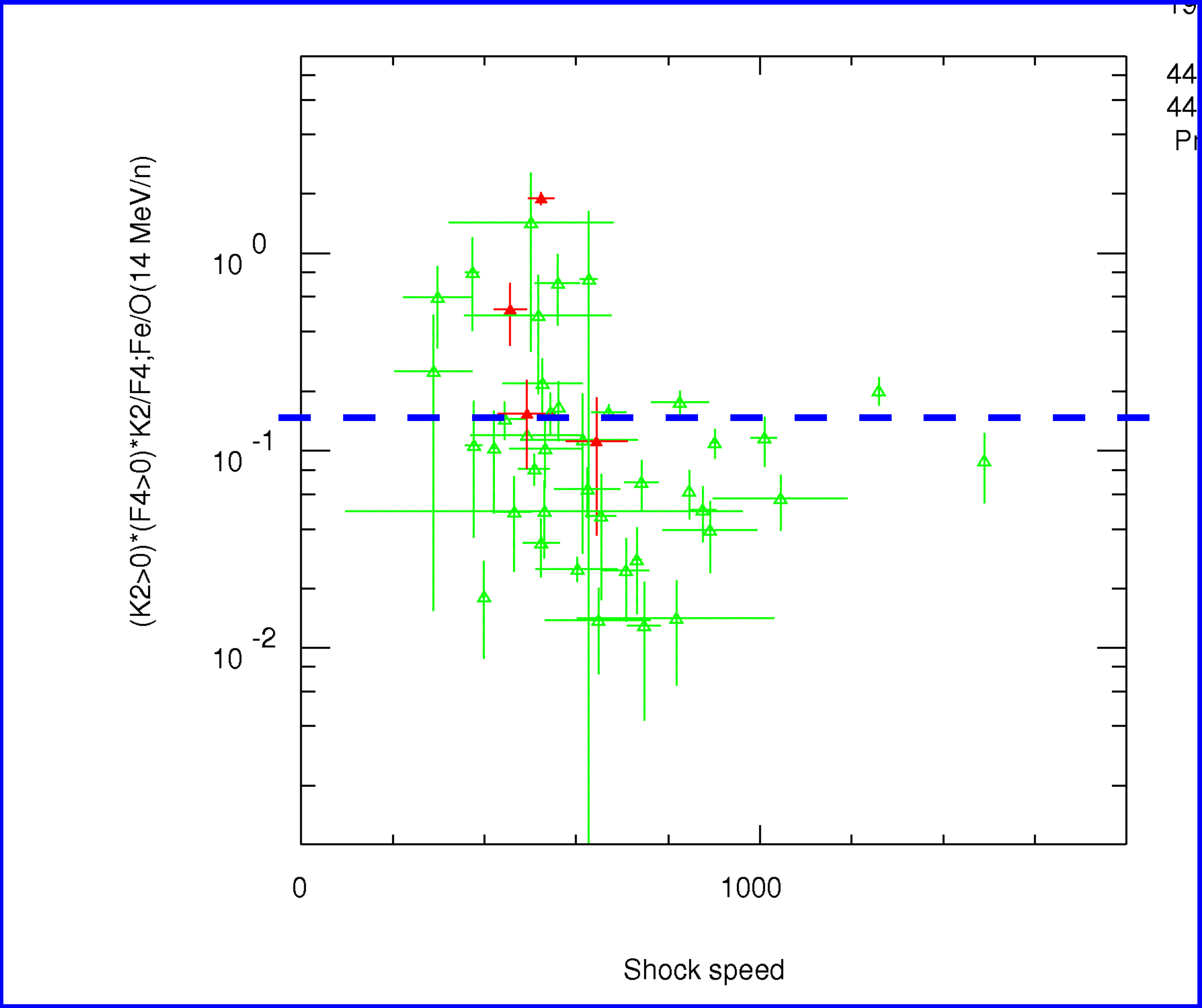


SIS Fe/O @ 14 MeV/n vs 9.3 MeV He at 46 Shocks

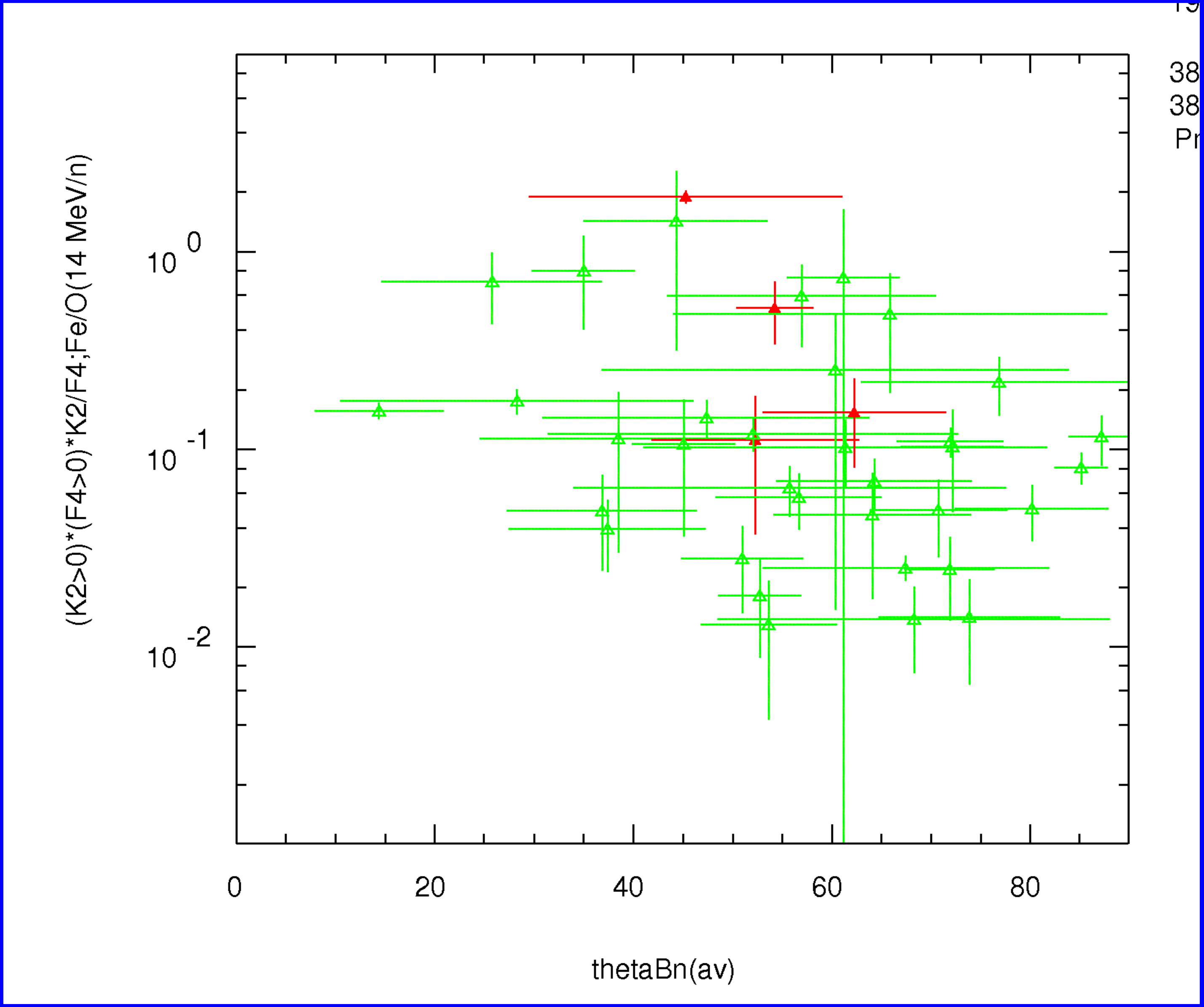


Fe/O is typically at or below coronal

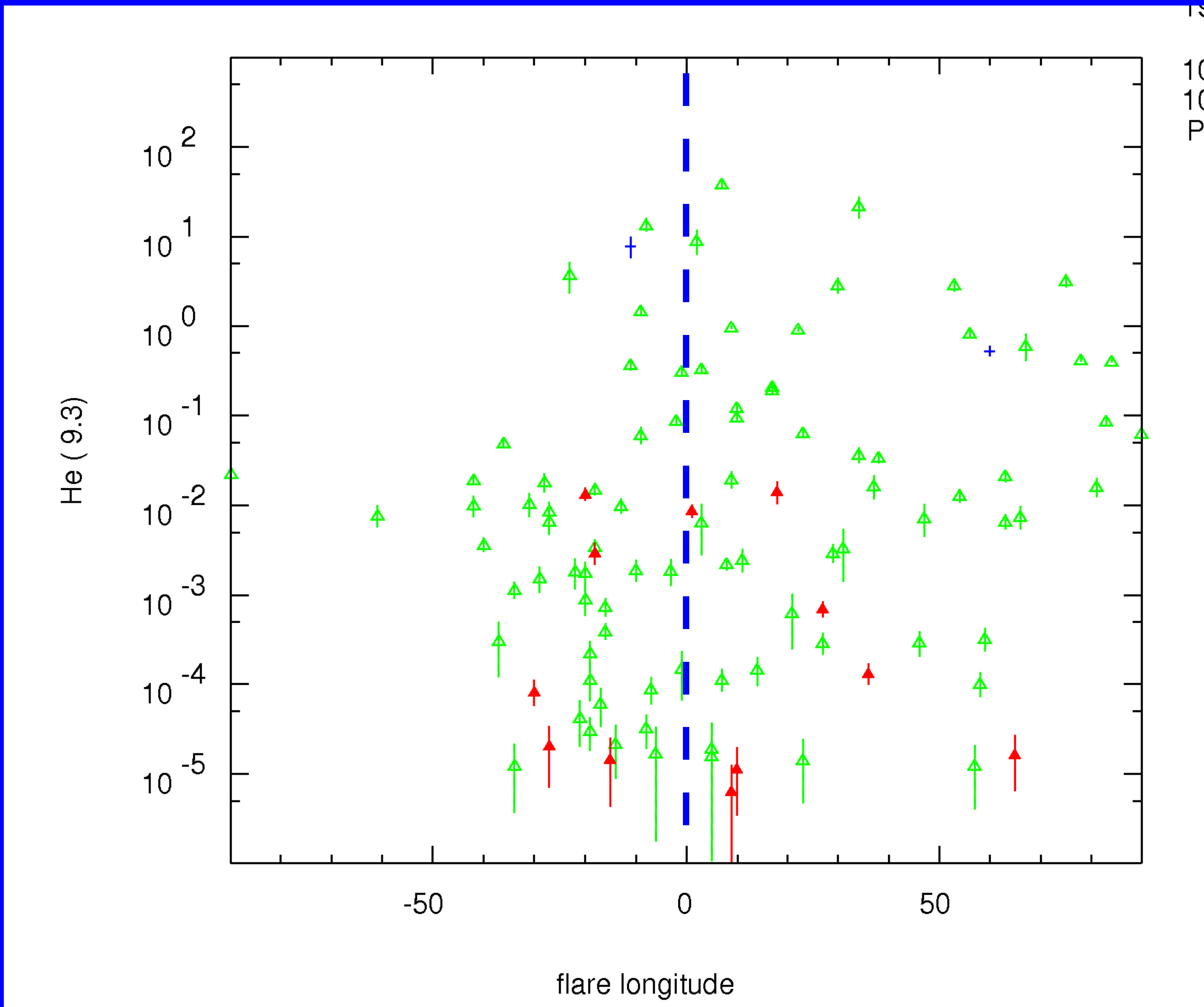
SIS Fe/O @ 14 MeV/n vs Shock Speed at 44 Shocks



SIS Fe/O @ 14 MeV/n vs θ_{Bn} at 38 Shocks



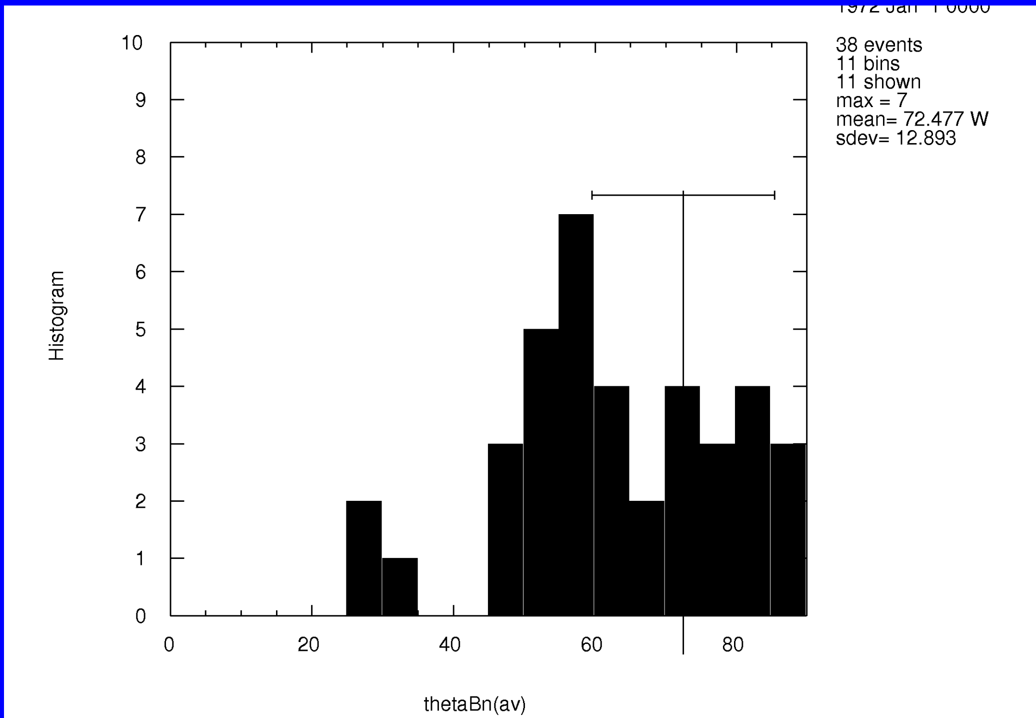
SIS 9.3 MeV He at 101 Shocks vs. Solar Event Longitude

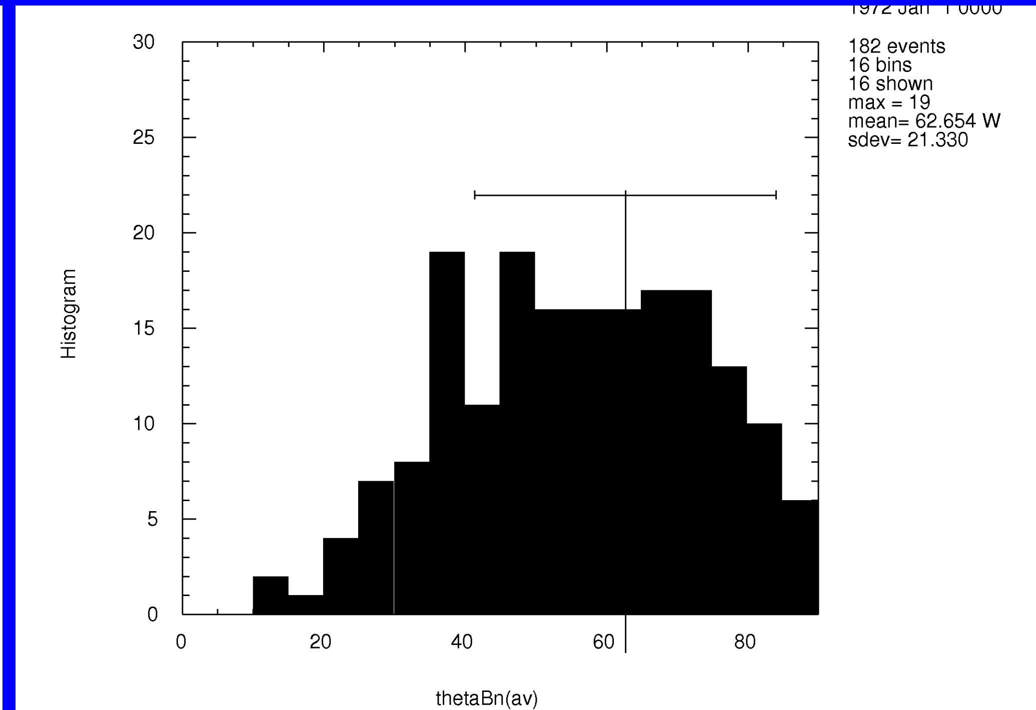


East-West asymmetry; Maximum intensities ~2 orders of magnitude lower beyond ~E30 than further west.

The few low intensity events from mid-far west may be due to:
1) Only shocks from relatively strong events propagate far from the event longitude;
2) Associations are difficult to make for less energetic events far from central meridian.

Distributions of θ_{Bn} for Shocks Propagating into ICMEs (left) or into "Normal" Solar Wind

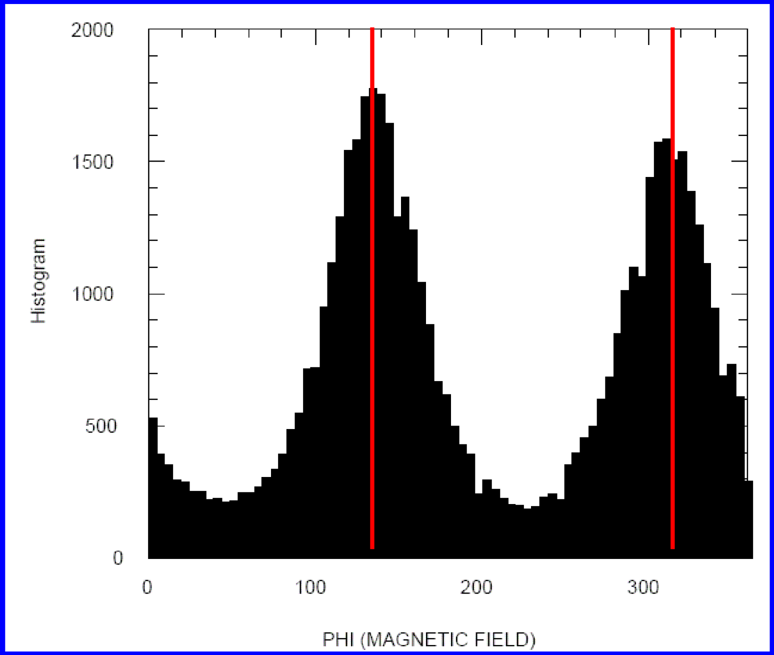




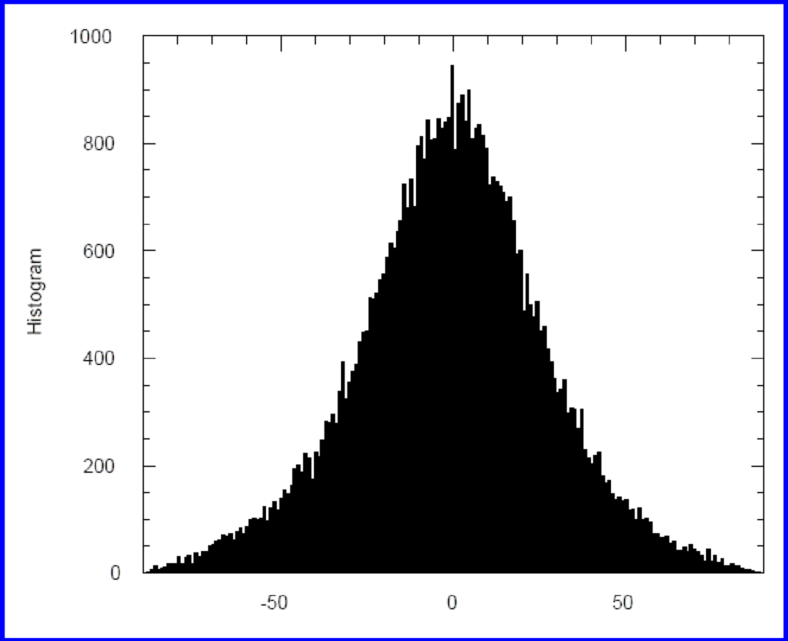
Though statistics are poorer, shocks propagating into ICMEs tend to have large values of θ_{Bn}, while other shocks have a decreasing occurrence of θ_{Bn} approaching 90º. About a third of shocks (7/22) with θ_{Bn} = 80 – 90º are propagating into an ICME.

41% (11/27) of shocks with IMP 8 "shock spikes" are propagating into an ICME

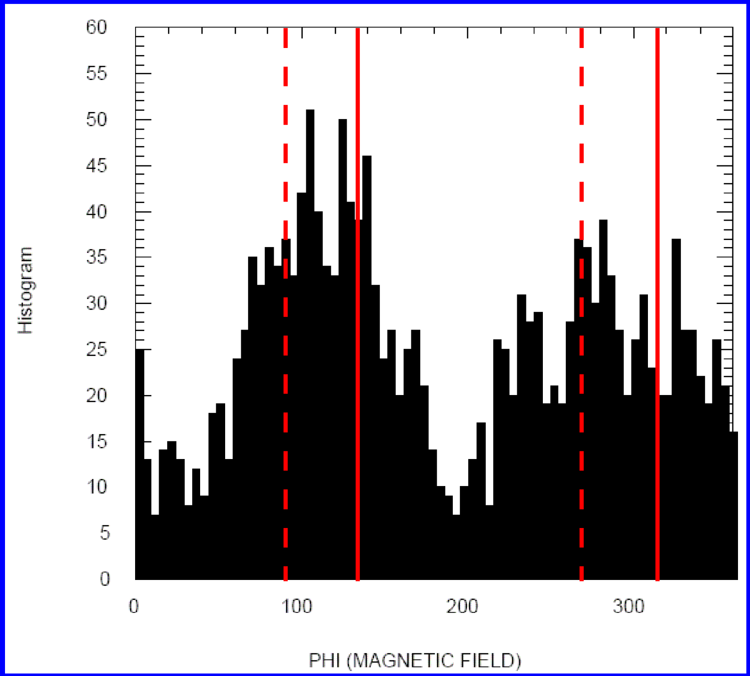
Φ Distribution, ambient (non-ICME) Solar Wind



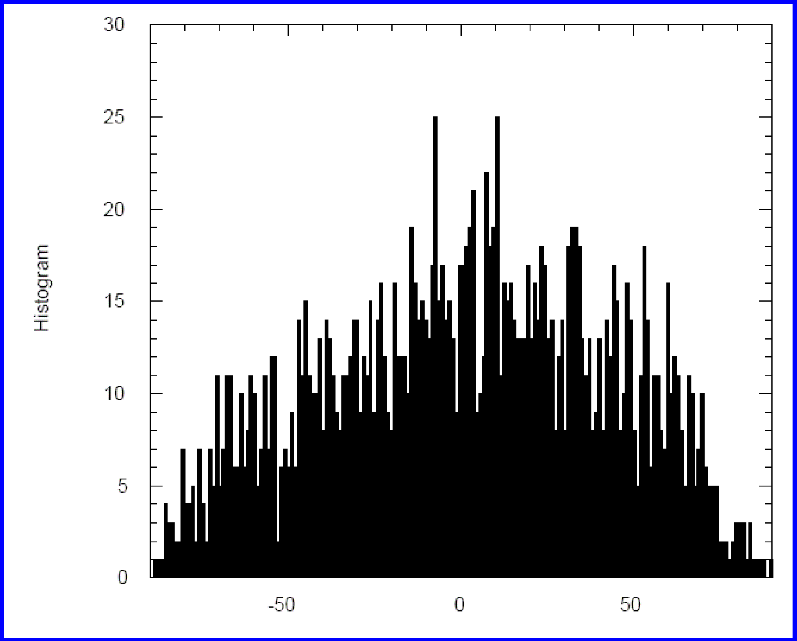
θ Distribution, Ambient Solar Wind



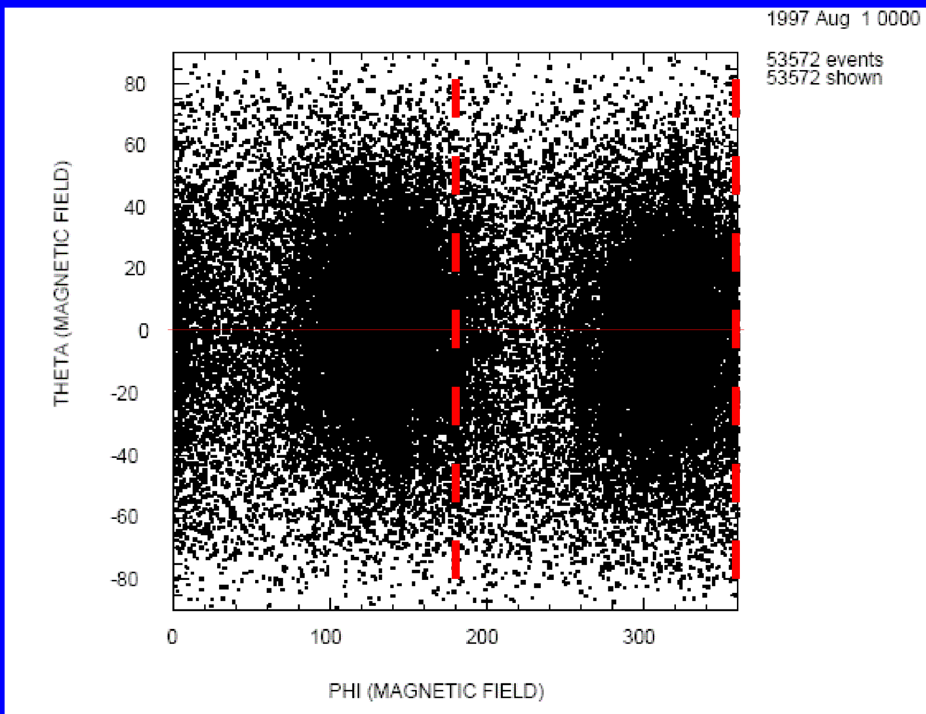
Φ Distribution, Magnetic Clouds Only



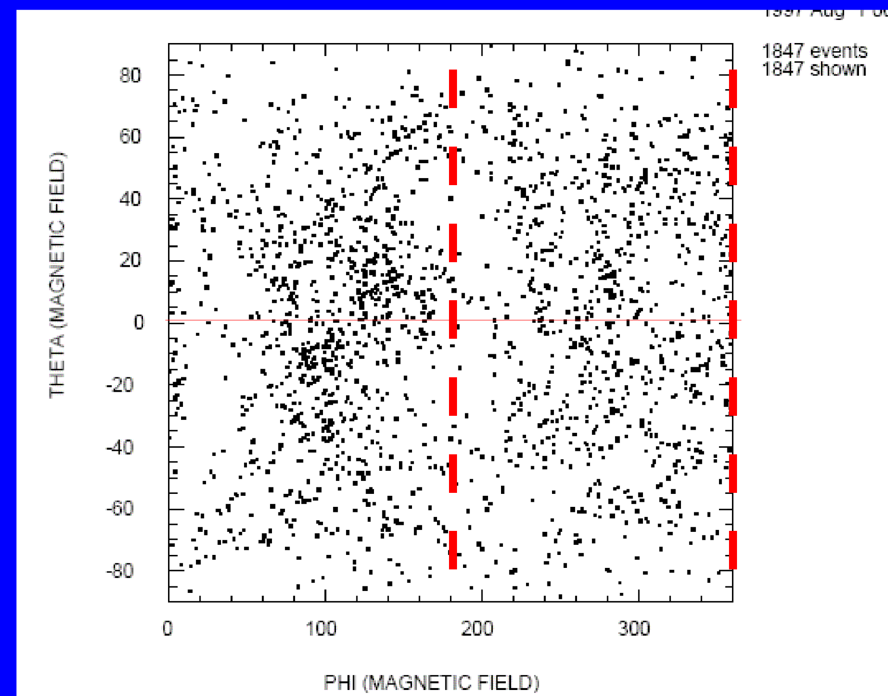
θ Distribution, Magnetic Clouds
(~10% of all |70-90|° Contributed by MCs)



Φ, θ Distribution, Ambient Solar Wind

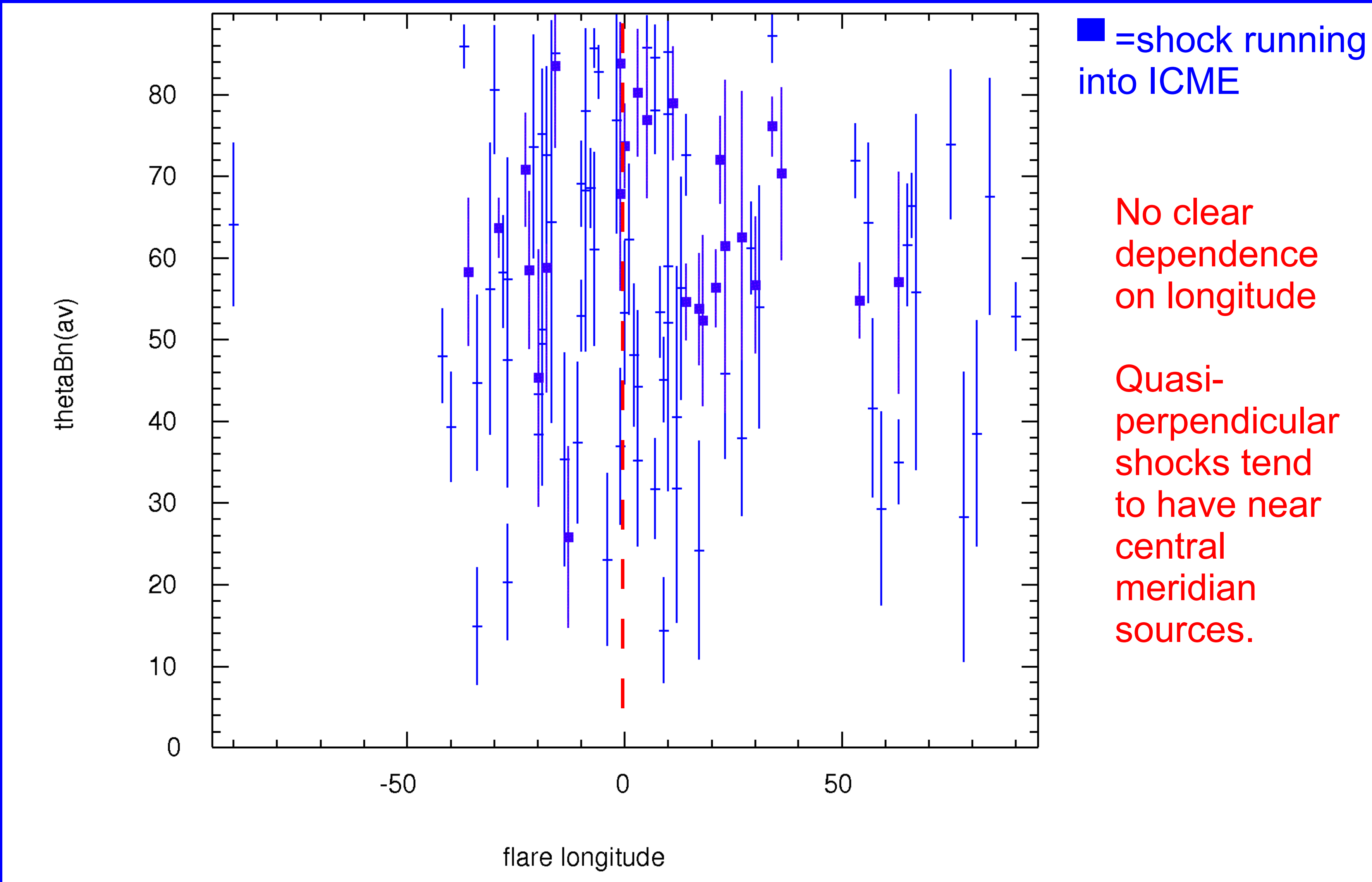


Φ, θ Distribution for Magnetic Clouds



ACE Magnetic Field Data, 1997 - 2002

θ_{Bn} vs. Source Longitude for 99 Shocks



No clear dependence on longitude

Quasi-perpendicular shocks tend to have near central meridian sources.

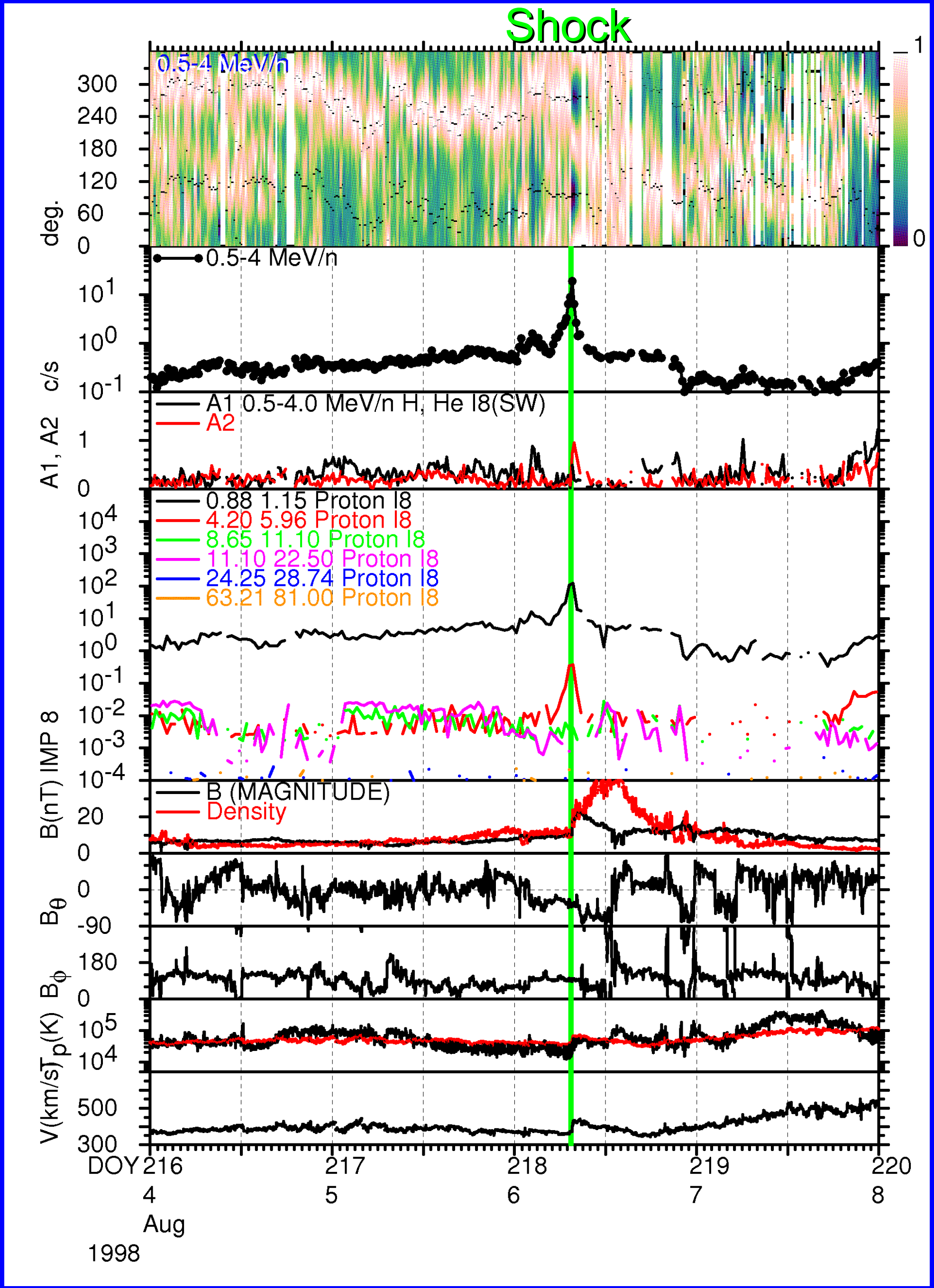
Local SW structures such as ICMEs may play an important role in shock geometry at 1 AU, e.g., $\theta_{Bn.}$

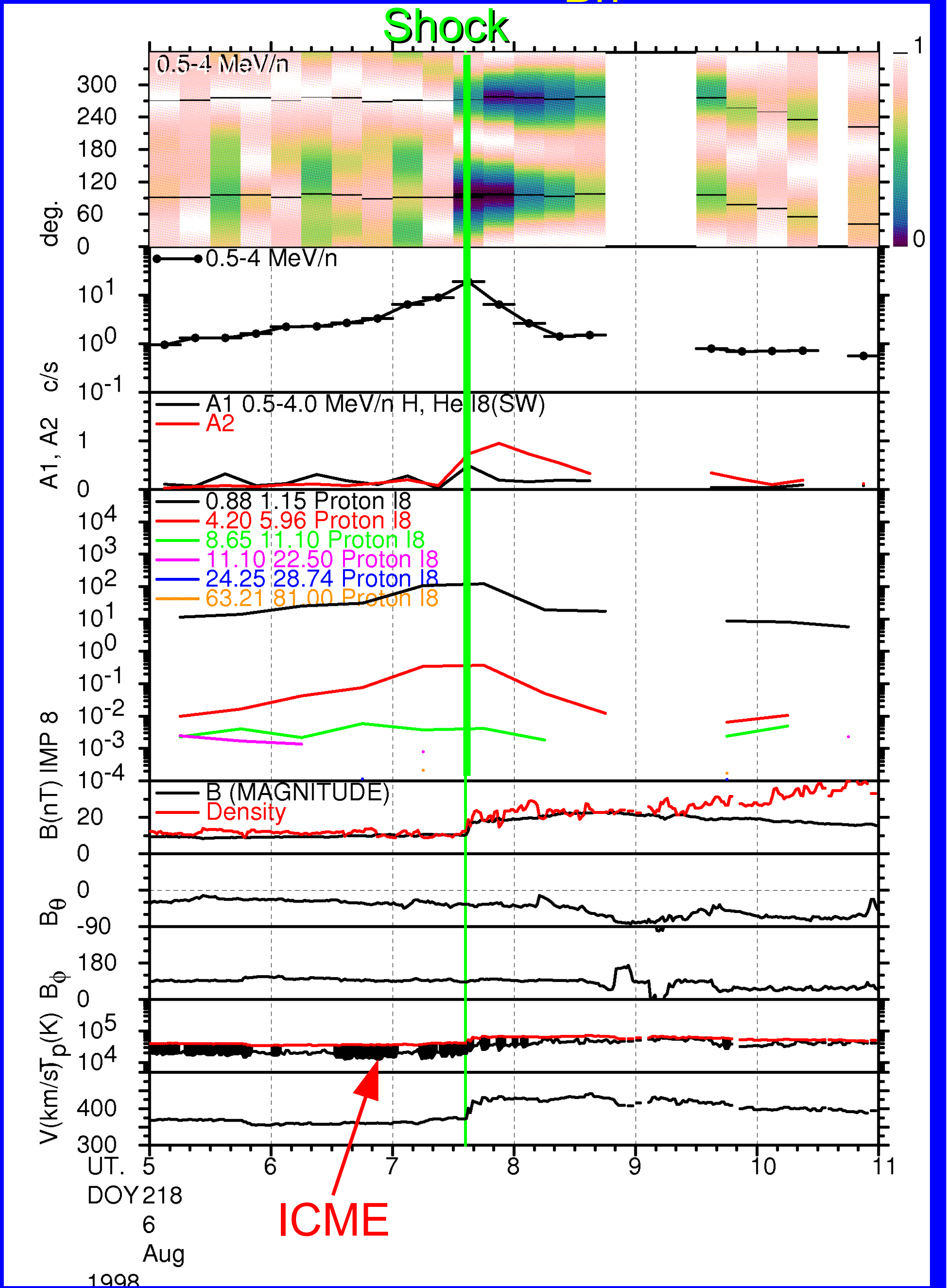
Shock drift acceleration in ICME + shock events may commence when shock encounters non-Parker fields in the ICME => particles are accelerated by this method for ~ only a few hours, not over 1 AU transit time;

Fields inside ICMEs tend to be smooth, so near quasi-perp. configuration may be maintained for extended time/distance scales, whereas θ_{Bn} may be more variable in “normal” solar wind.

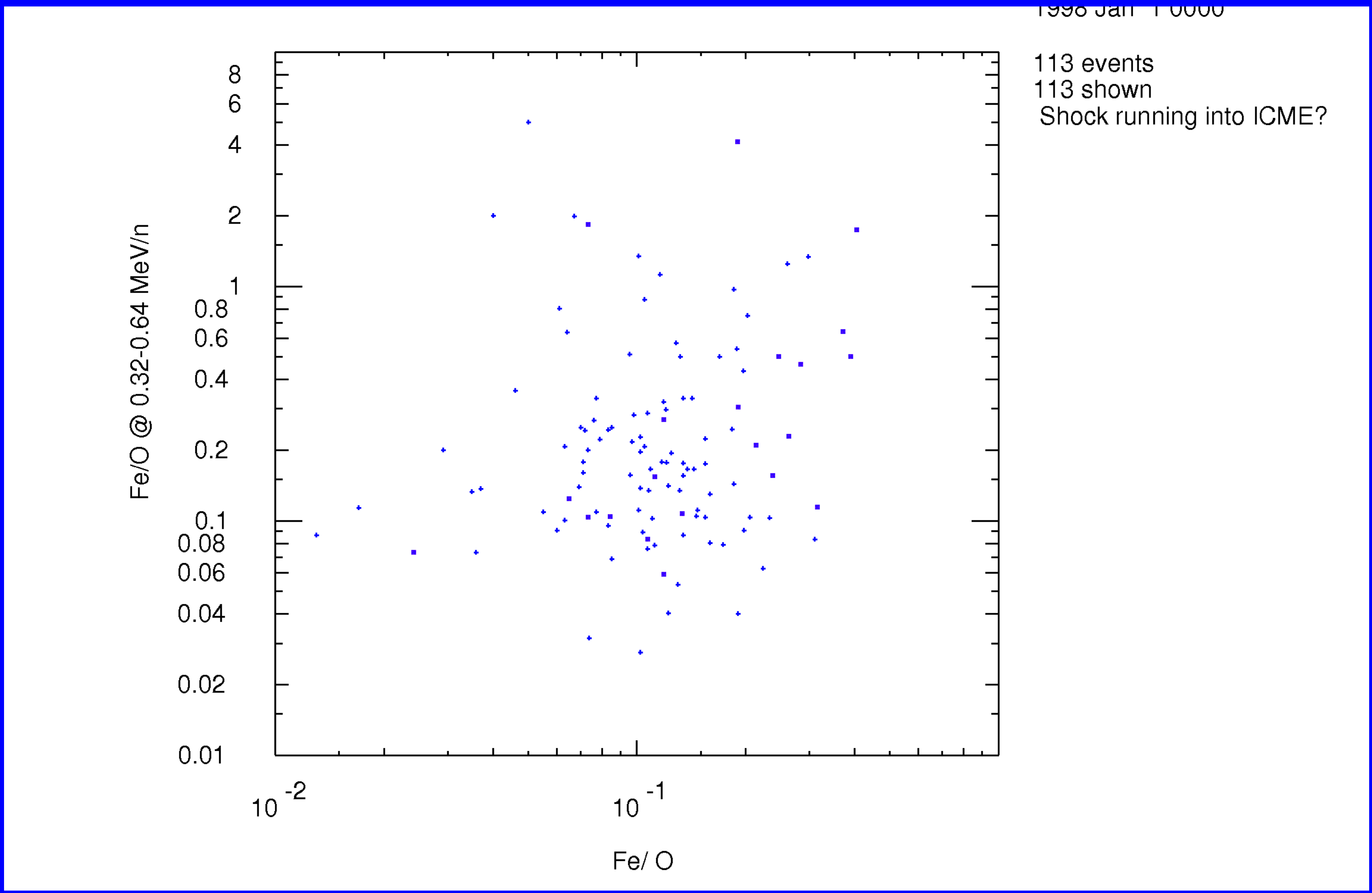
Solar wind source population/composition/charge states may be different than for “normal” solar wind.

Example of Shock Spike (Pancake Distribution => Shock Drift Acceleration; August 6, 1998, θ_{Bn}=80º)



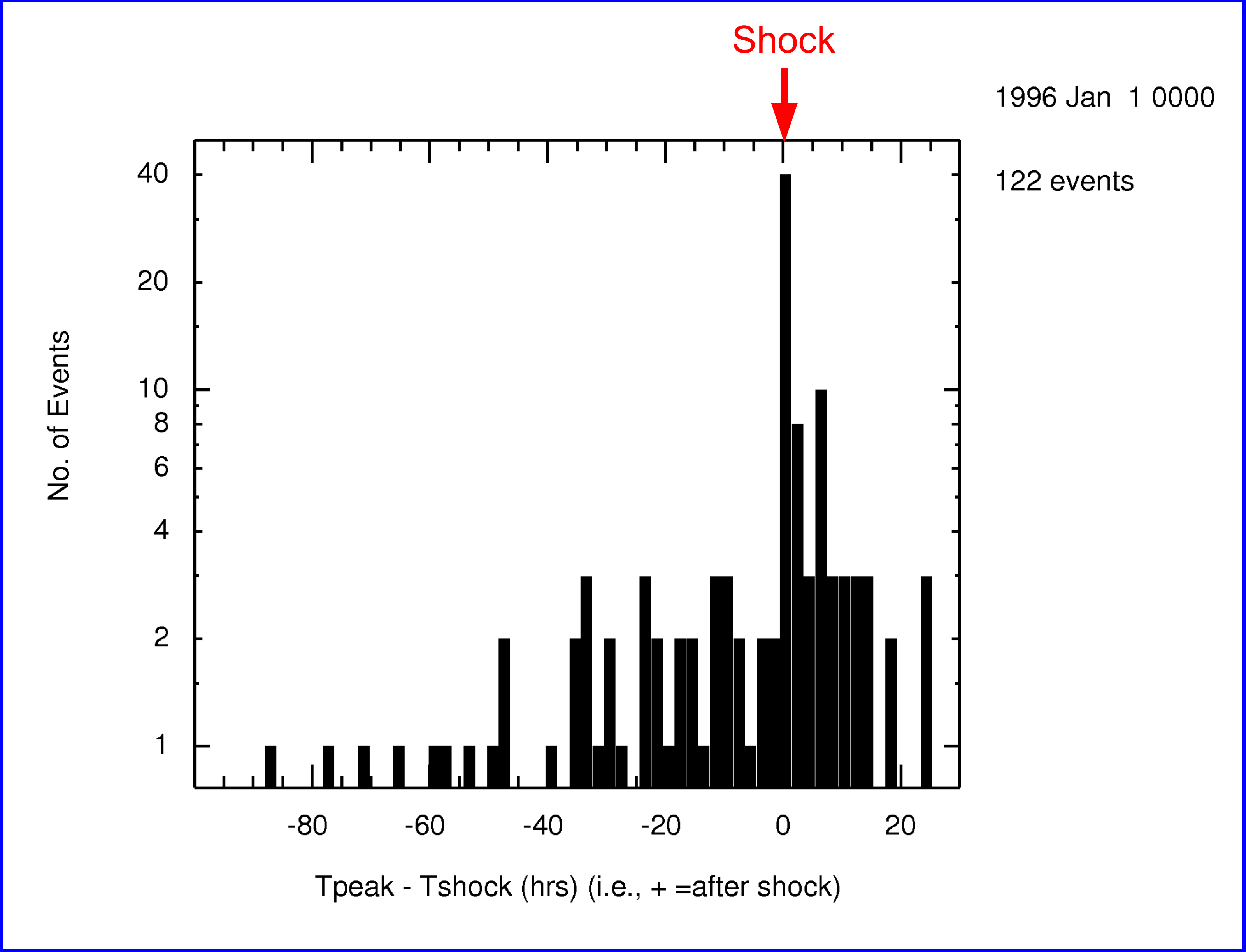


ULEIS Fe/O @ 0.32-0.64 MeV/n vs. SWICS Fe/O at 113 Shocks



Use anisotropy data from the GME instrument on IMP 8, principally 0.5 - 4 MeV/n proton + He channel (observations 1973 – 2006, 3 solar cycles); Transform into the solar wind frame using solar wind data from IMP 8 (when available) or OMNI (1 minute)

Summary of Time(Peak)-Time(shock) for 0.5-4 MeV Protons at 122 Shocks



Fe/O @ 0.32-0.64 MeV/n vs. Source (Flare) Longitude