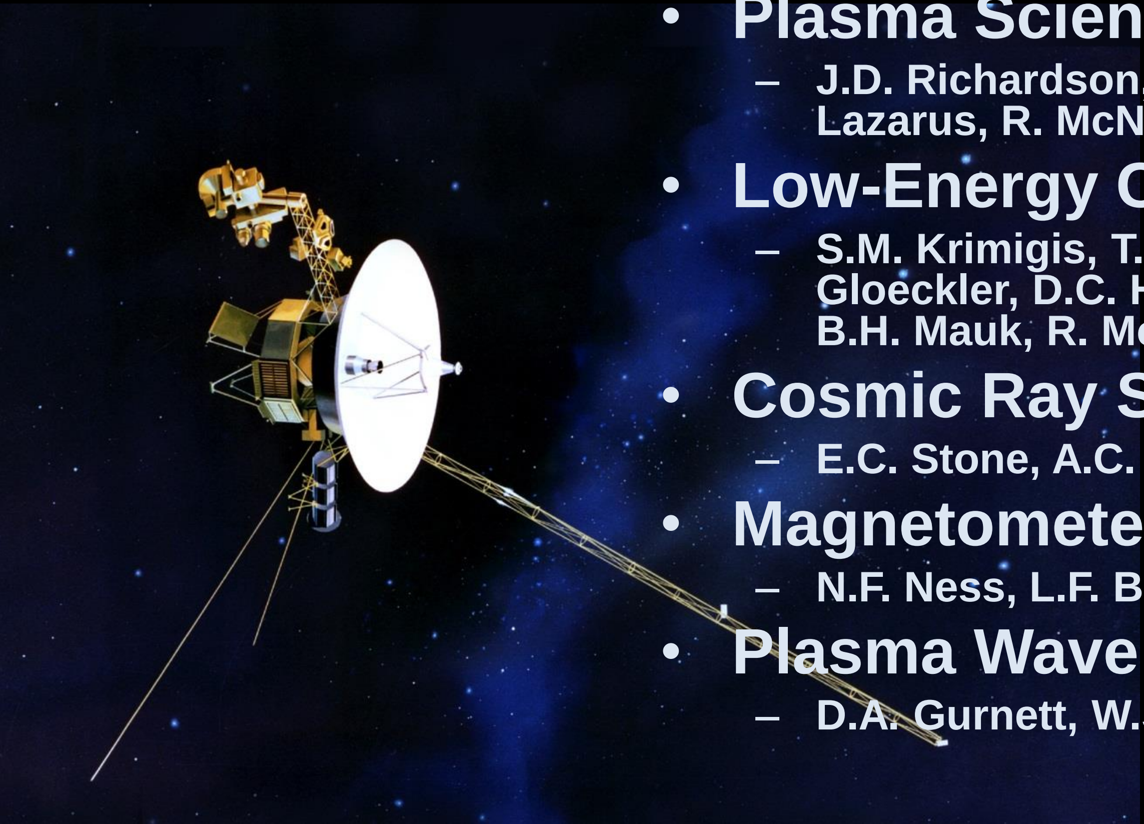
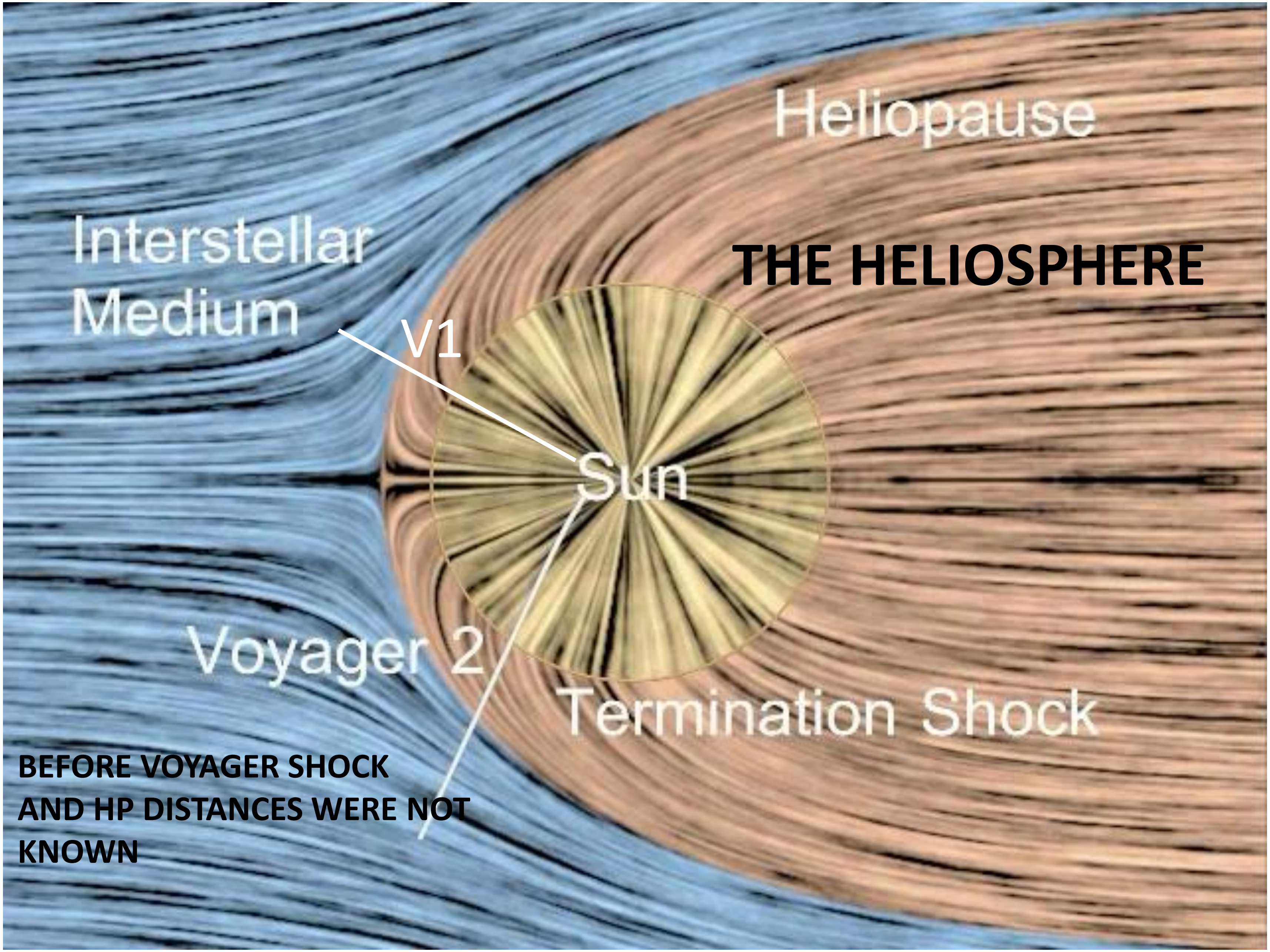
Voyager Observations of the Outer Heliosphere and Interstellar Medium

John Richardson (M.I.T.)
and the Voyager team



- **Plasma Science (Voyager 2)**
  - J.D. Richardson, J. W. Belcher, L. F. Burlaga, A.J. Lazarus, R. McNutt, E.C. Sittler, Jr., C. Wang
- **Low-Energy Charged Particles**
  - S.M. Krimigis, T.P. Armstrong, R.B. Decker, G. Gloeckler, D.C. Hamilton, M. E. Hill, L.J. Lanzerotti, B.H. Mauk, R. McNutt, E.C. Roelof
- **Cosmic Ray Subsystem**
  - E.C. Stone, A.C. Cummings, N. Lal, W.R. Webber
- **Magnetometer**
  - N.F. Ness, L.F. Burlaga
- **Plasma Wave Subsystem**
  - D.A. Gurnett, W.S. Kurth

THE HELIOSPHERE



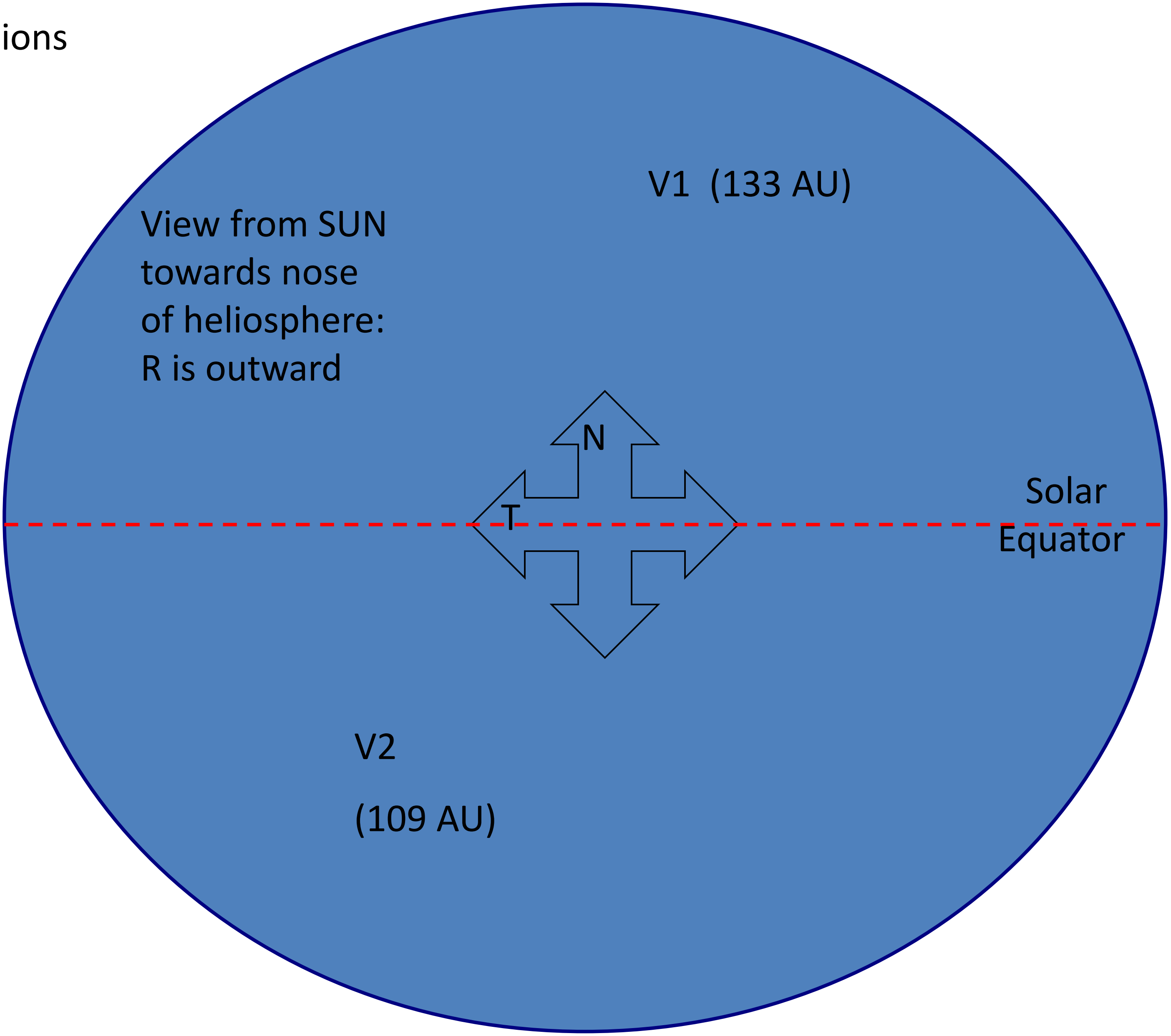
BEFORE VOYAGER SHOCK AND HP DISTANCES WERE NOT KNOWN

Topics:

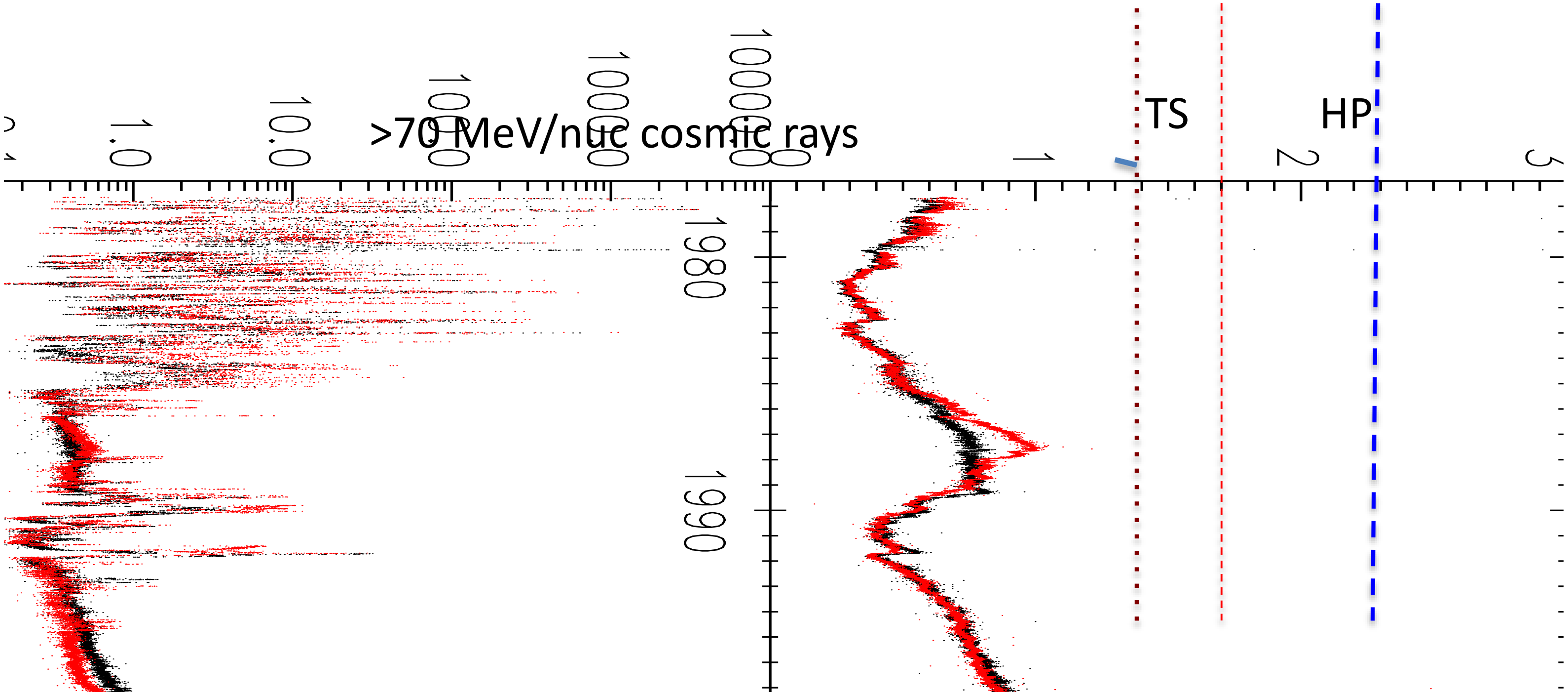
Highlights of Voyager in the Outer Heliosphere

1. Introduction to the heliosphere: structure and particles
2. The termination shock
3. The heliosheath
4. The heliopause
5. The local interstellar medium

Voyager locations

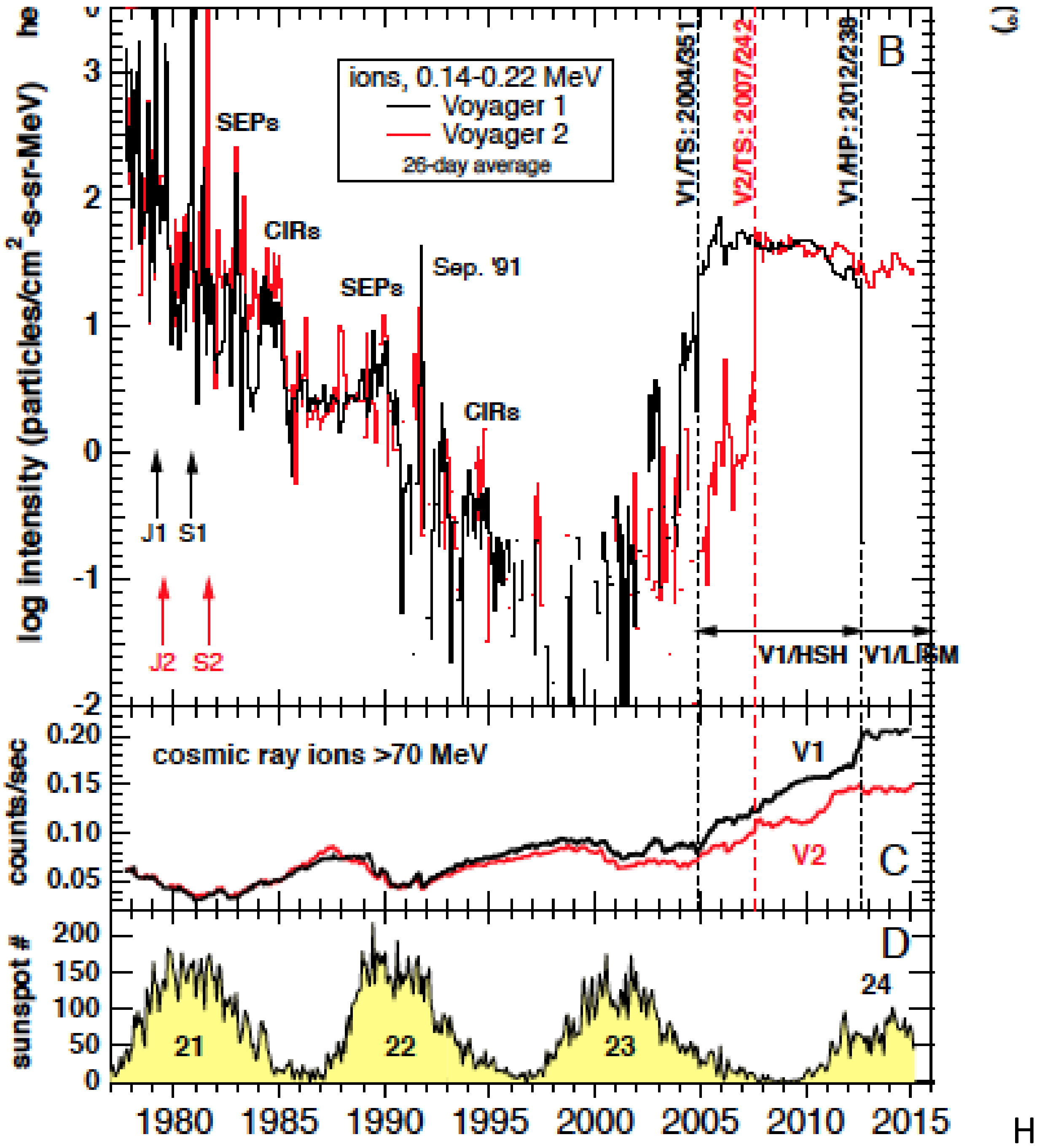


View from SUN
towards nose
of heliosphere:
R is outward



>70 MeV/nuc cosmic rays

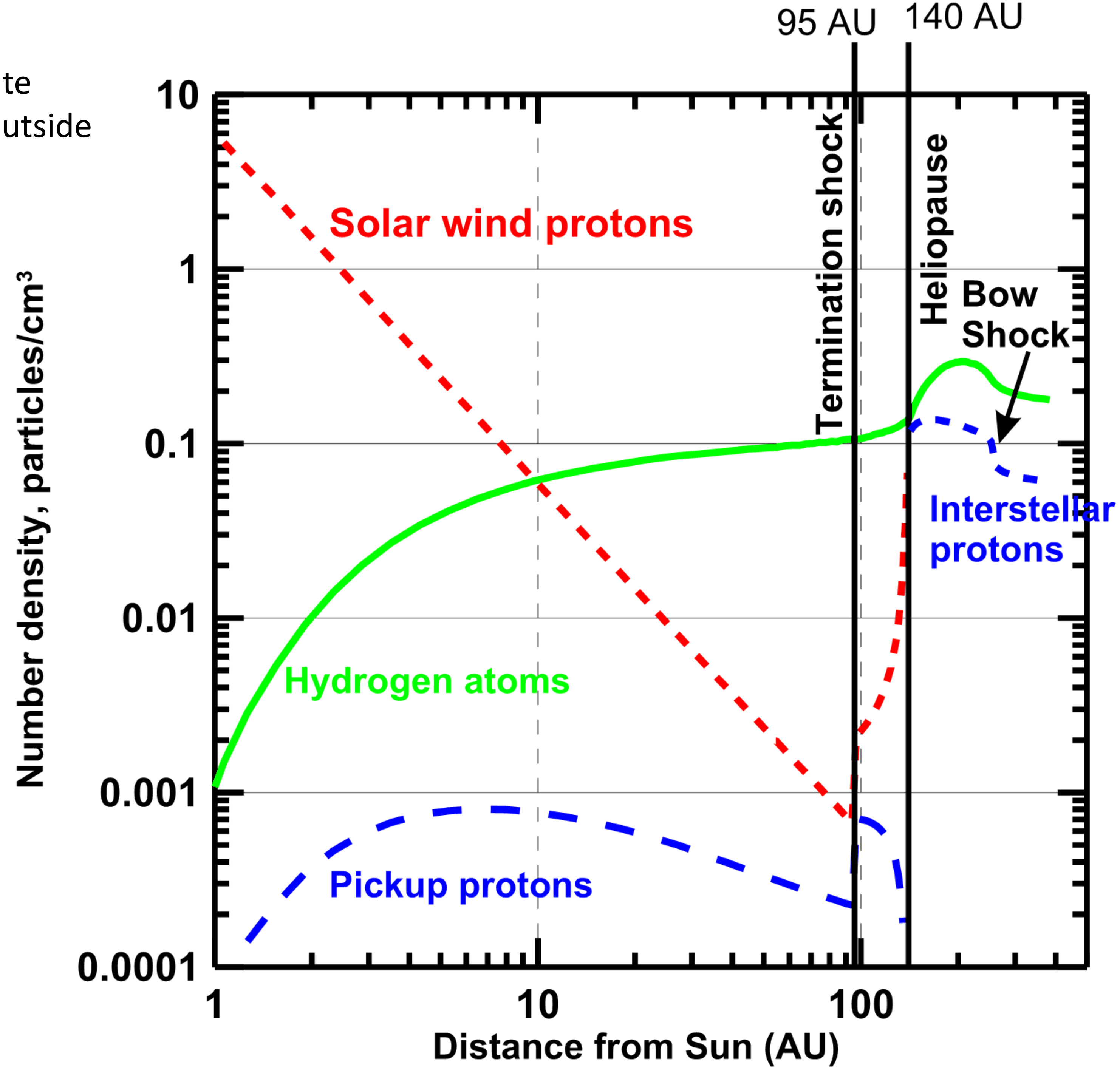
>0.5 MeV/nuc



he
B
ions, 0.14-0.22 MeV
Voyager 1
Voyager 2
26-day average
log intensity (particles/cm^2-s-sr-MeV)
3
2
1
0
-1
-2
SEPs
CIRs
SEPs
Sep. '91
CIRs
J1
S1
J2
S2
V1/TS: 2004/351
V2/TS: 2007/242
V1/HP: 2012/238
V1/HSH
V1/LISM
C
cosmic ray ions >70 MeV
counts/sec
0.20
0.15
0.10
0.05
V1
V2
D
sunspot #
200
150
100
50
0
21
22
23
24
1980
1985
1990
1995
2000
2005
2010
2015

Hill at al.

Pickup ions dominate
Thermal pressure outside
~30 AU

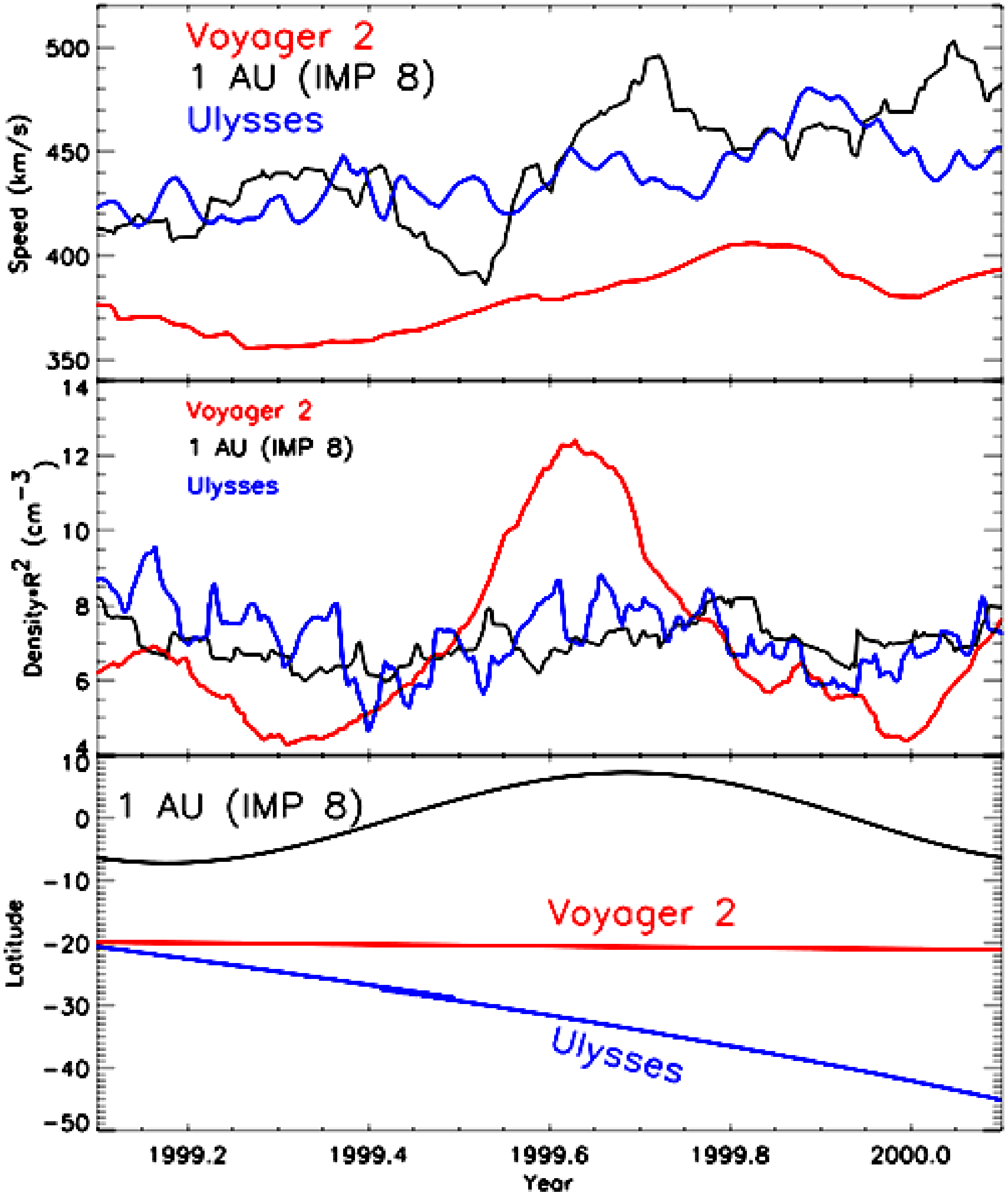


Interstellar Neutral Effects on the SW

- Solar Wind slowdown
- dV/V = 6/7 N_{pu}/N_{sw} =17% at TS

20% of density in pickup ions

~30% of SW flow energy lost before TS



Termination Shock

What we learned:

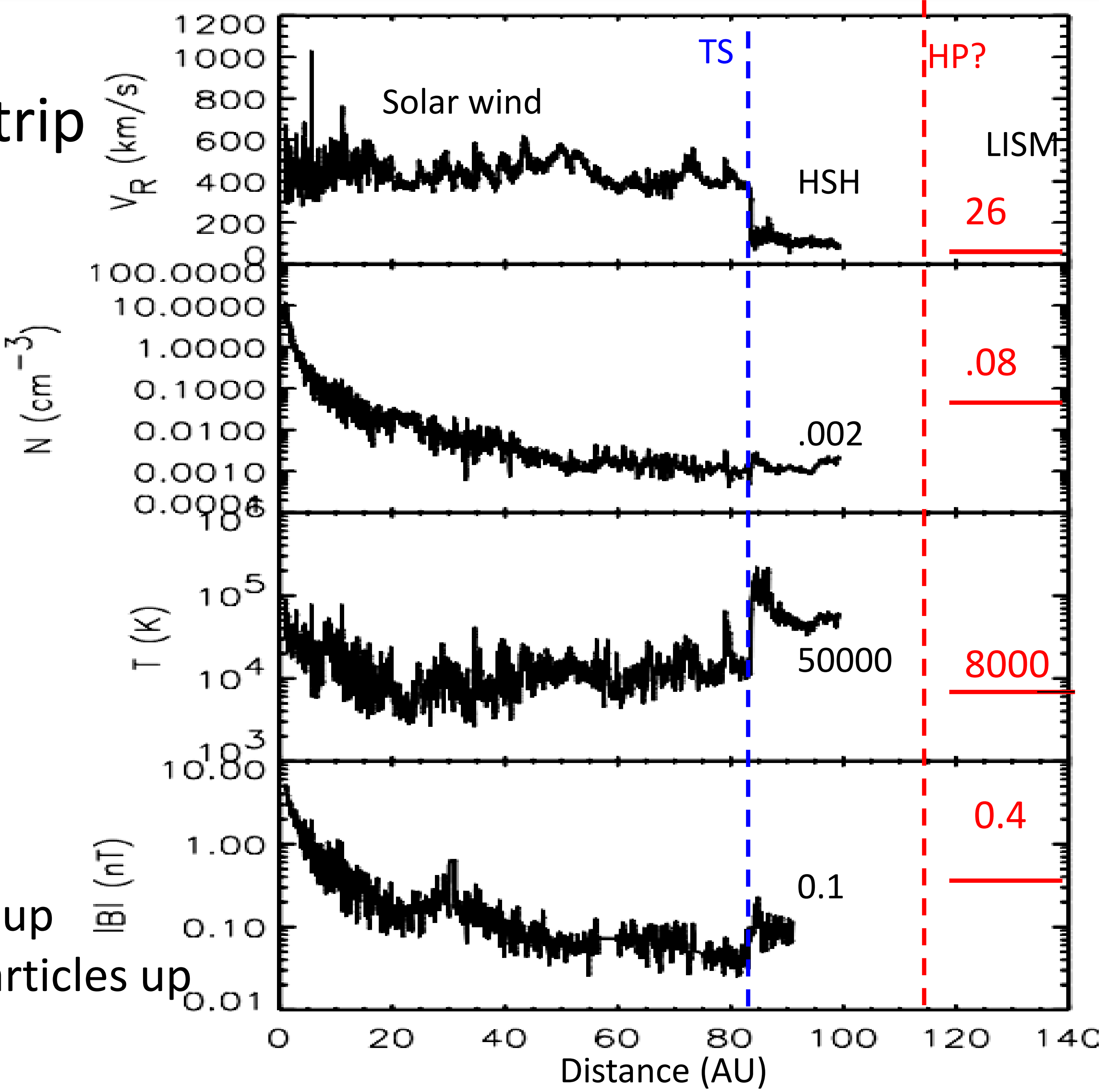
1) Location
2) Strength
3) Asymmetric
4) Acceleration
    - thermal plasma – weak
    - pickup ions – strong
    - 10 – 100’s keV ions – strong
    - ACRs (> few MeV) - weak

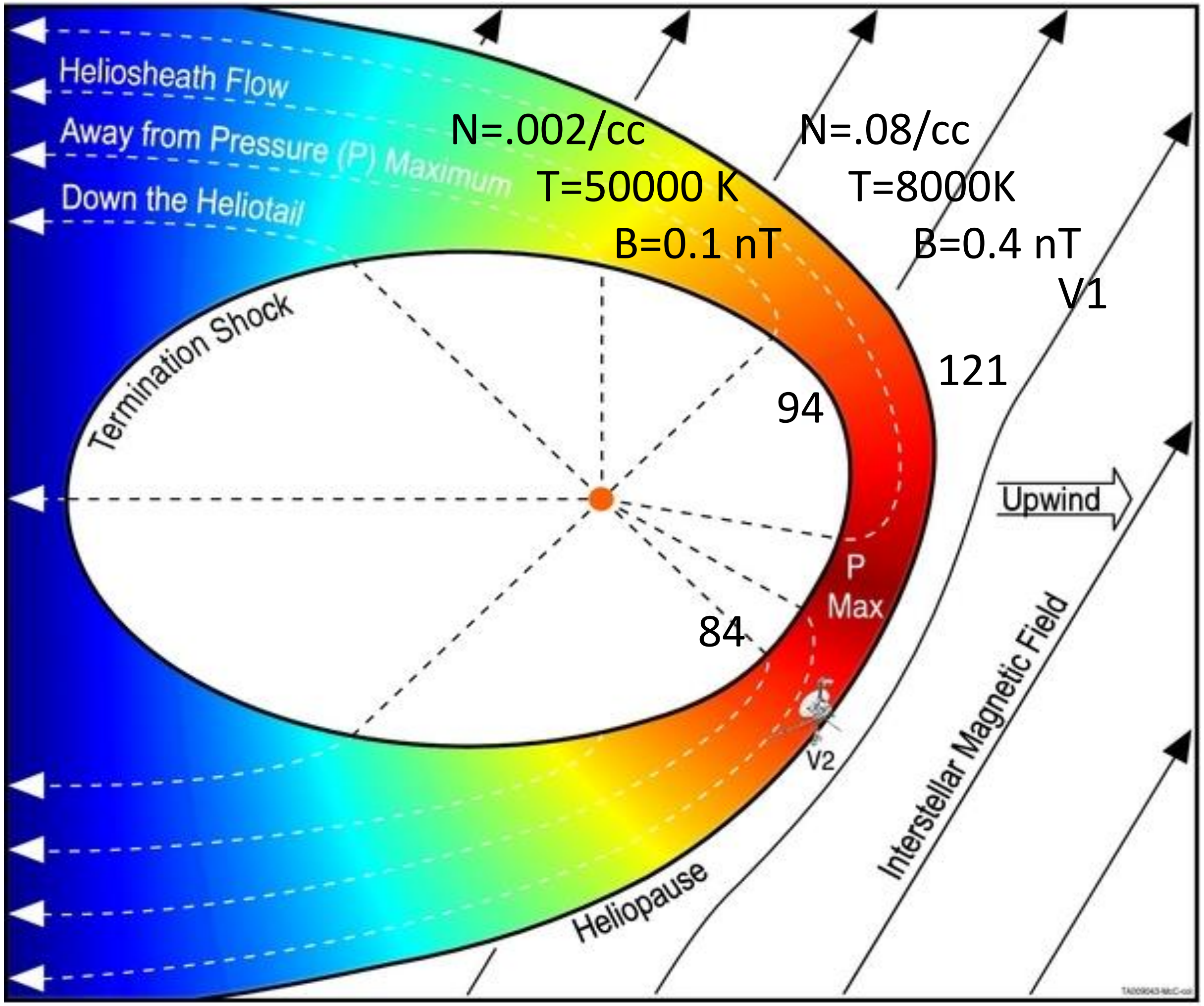
Voyager 2’s trip through the Heliosphere

Termination shock

Weak: ~2.3

1) V down
2) N up
3) T up
4) B up
5) Flow angles up
6) Energetic particles up





V1 TS 94 AU

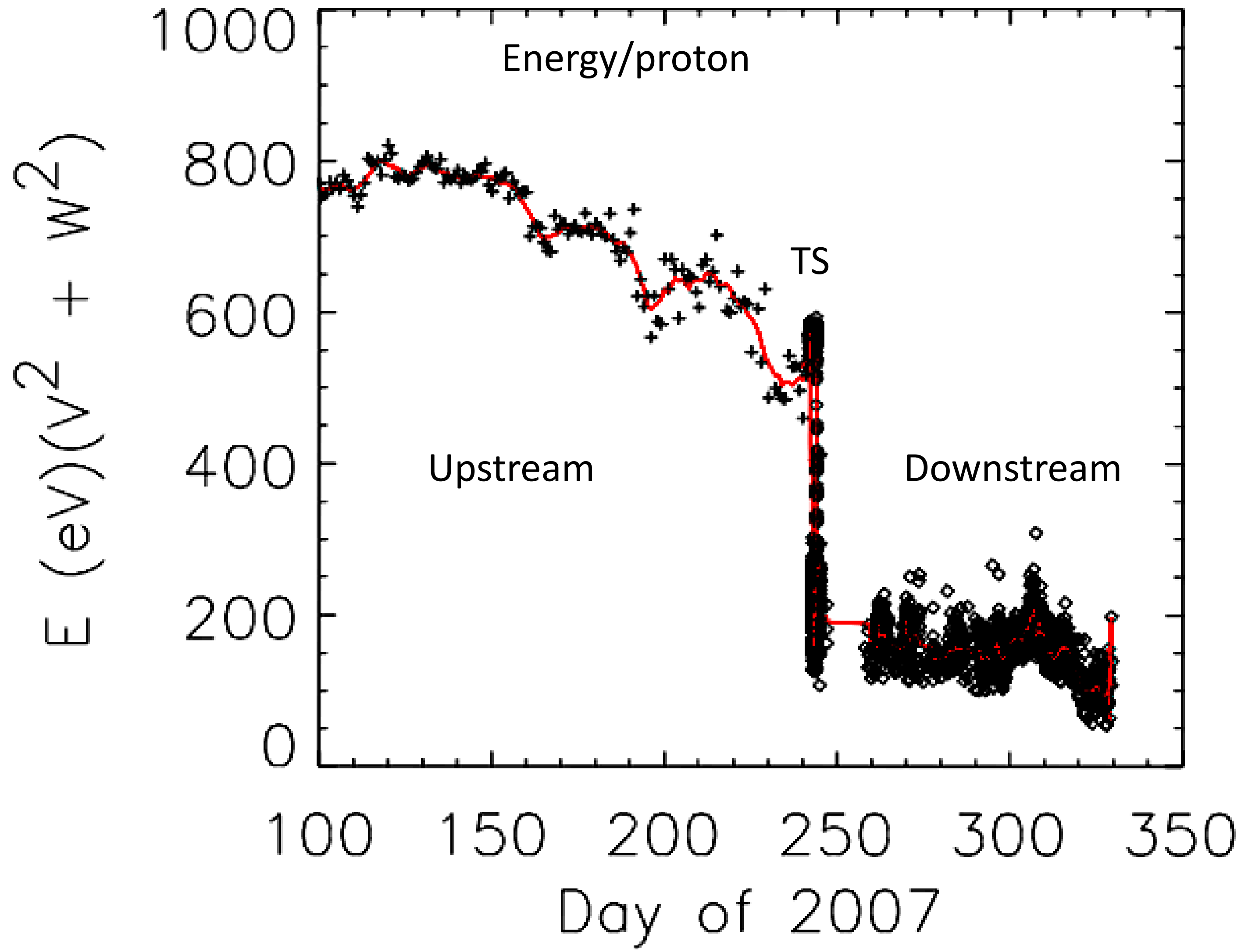
V2 TS 84 AU

So HP 40-60 AU beyond?

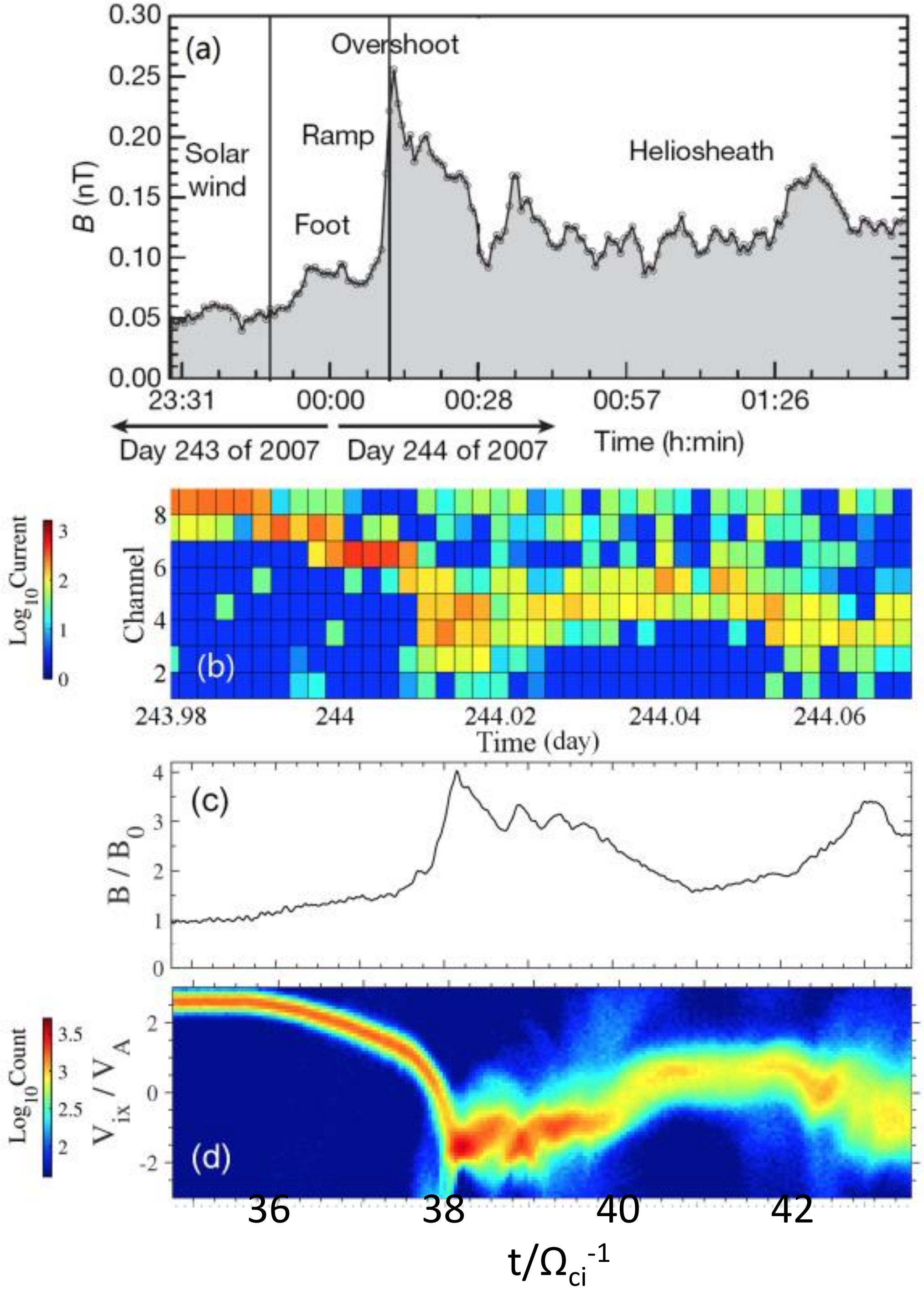
Tilted LISM B field can give this asymmetry.

Need strong B > 3nT. ~ 30° tilt

Figure 2 from Plasma Flows at Voyager 2 away from the Measured Suprathermal Pressures
D. J. McComas and N. A. Schwadron 2014 ApJ 795 L17 doi:10.1088/2041-8205/795/1/L17



Only 20% of SW flow energy is kept by thermal plasma: Rest goes to pickup ions average energy ~several keV (predicted by Zank et al., 1997)



Pickup ions not directly observed
So need models:
Yang et al., Ap J 2015 PIC model

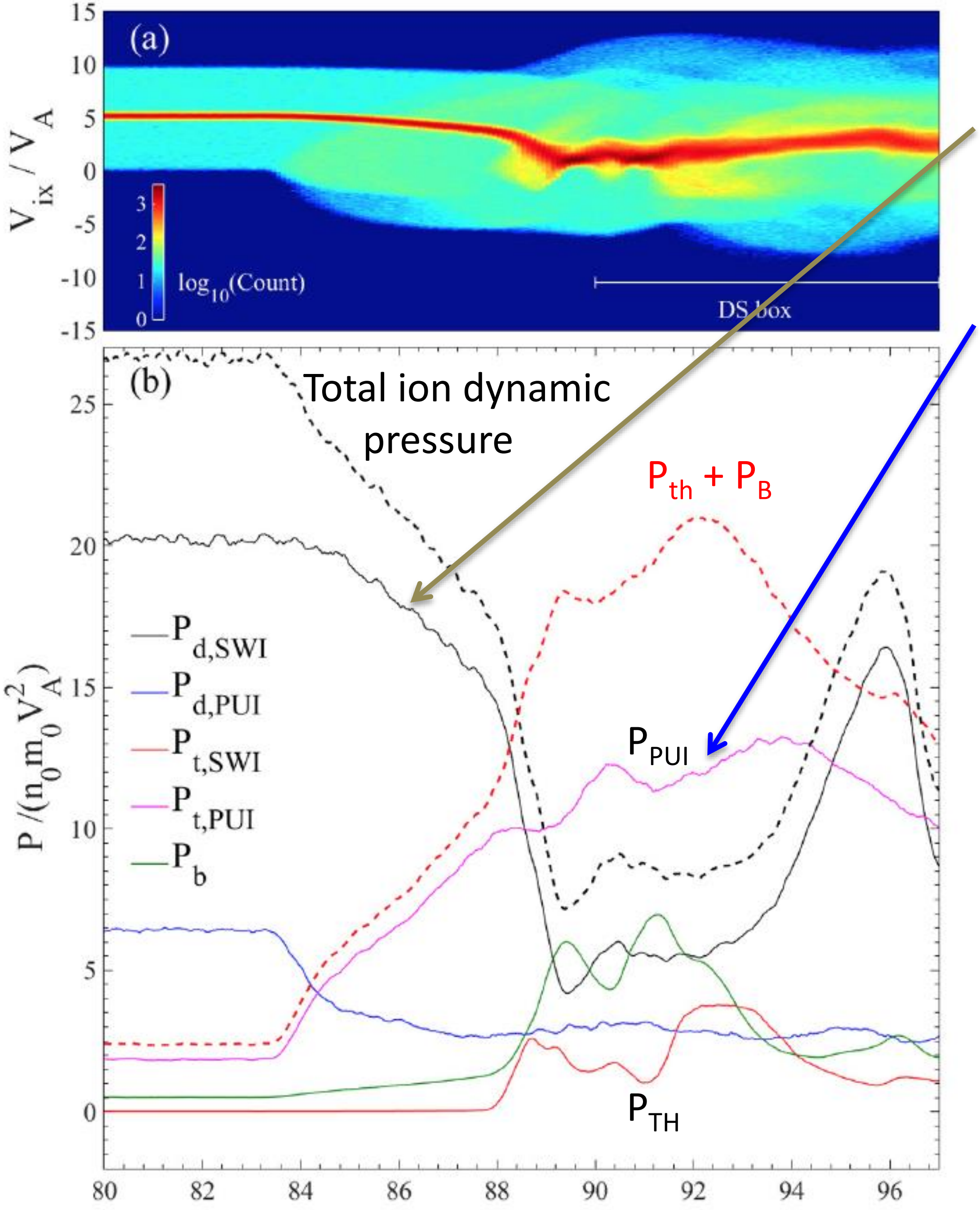
Comparison of model results to
V2 observations of the TS.

Observed B

Currents in the C-cup of the PLS
Instrument

Model B with 25% pickup ions

Model currents: cut off at V2
threshold.



SWI lose ½ of flow energy in foot

Almost 90% of thermal energy
is in the pickup ions.

Ripples cause lots of variability
behind shock

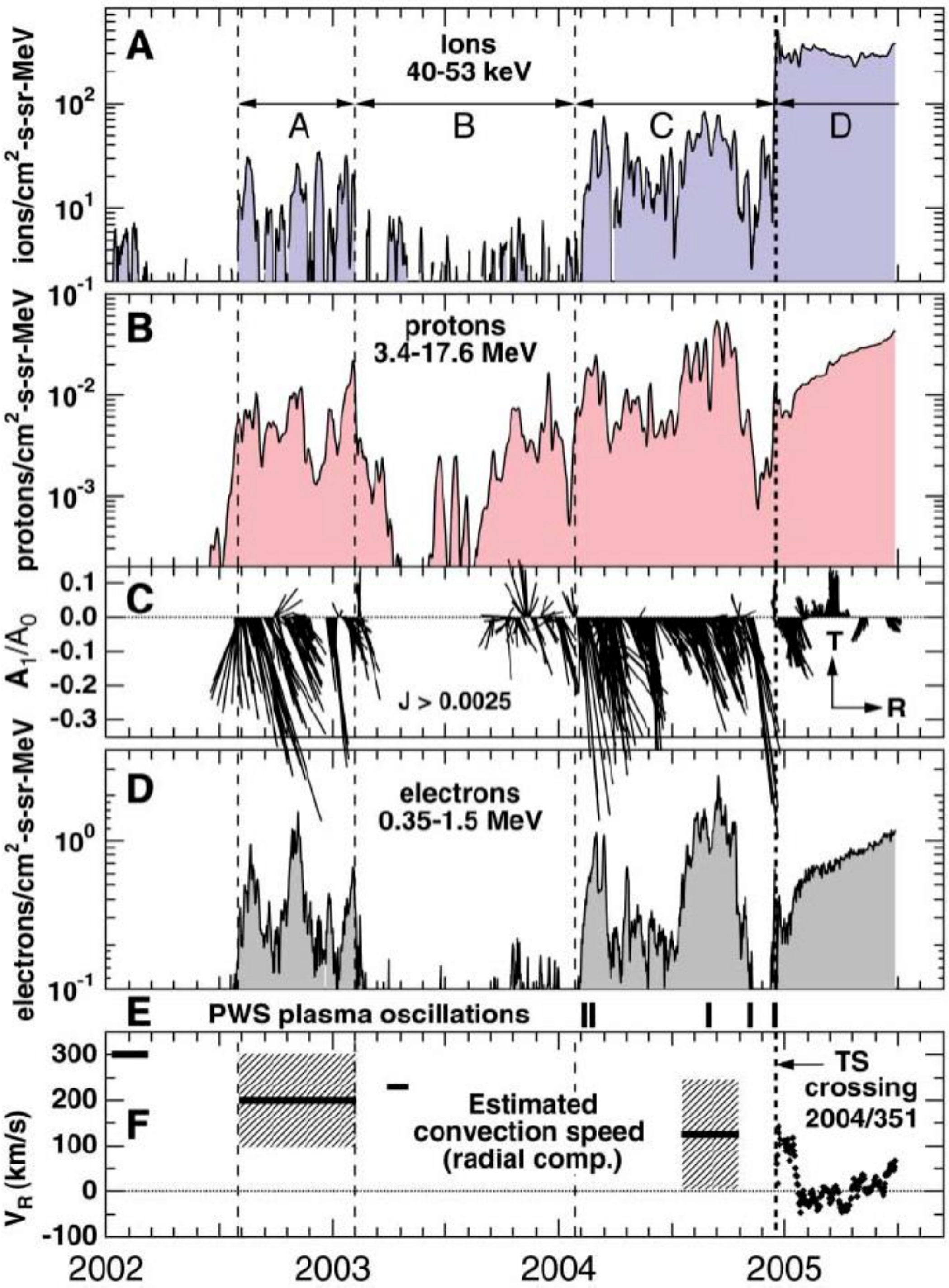
Electrons gain negligible energy

Termination shock:

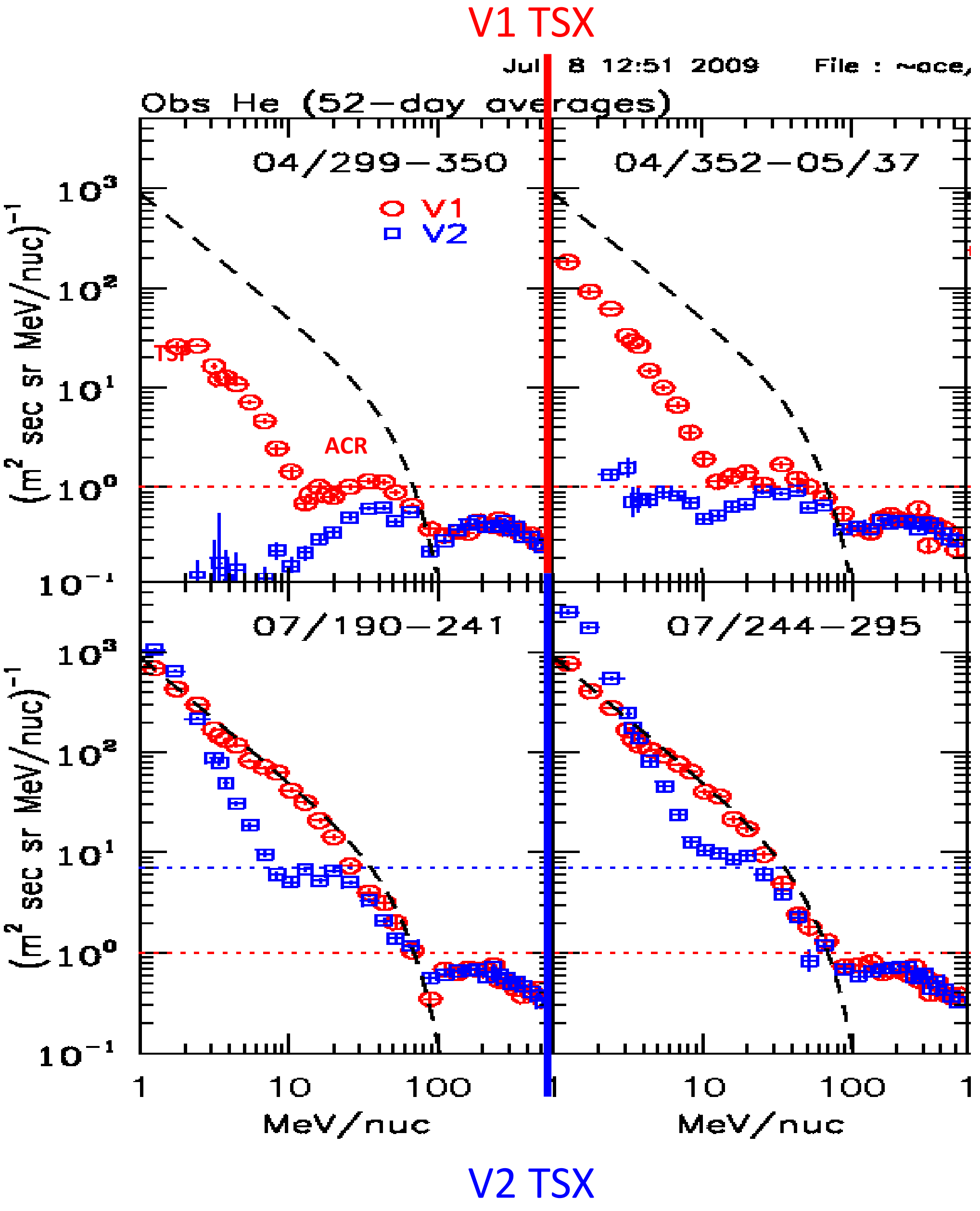
Low energy partciles accelerated.

ACR acceleration small

After TS crossing ion intensities were steady and isotropic in sheath.



Decker et al., 2005

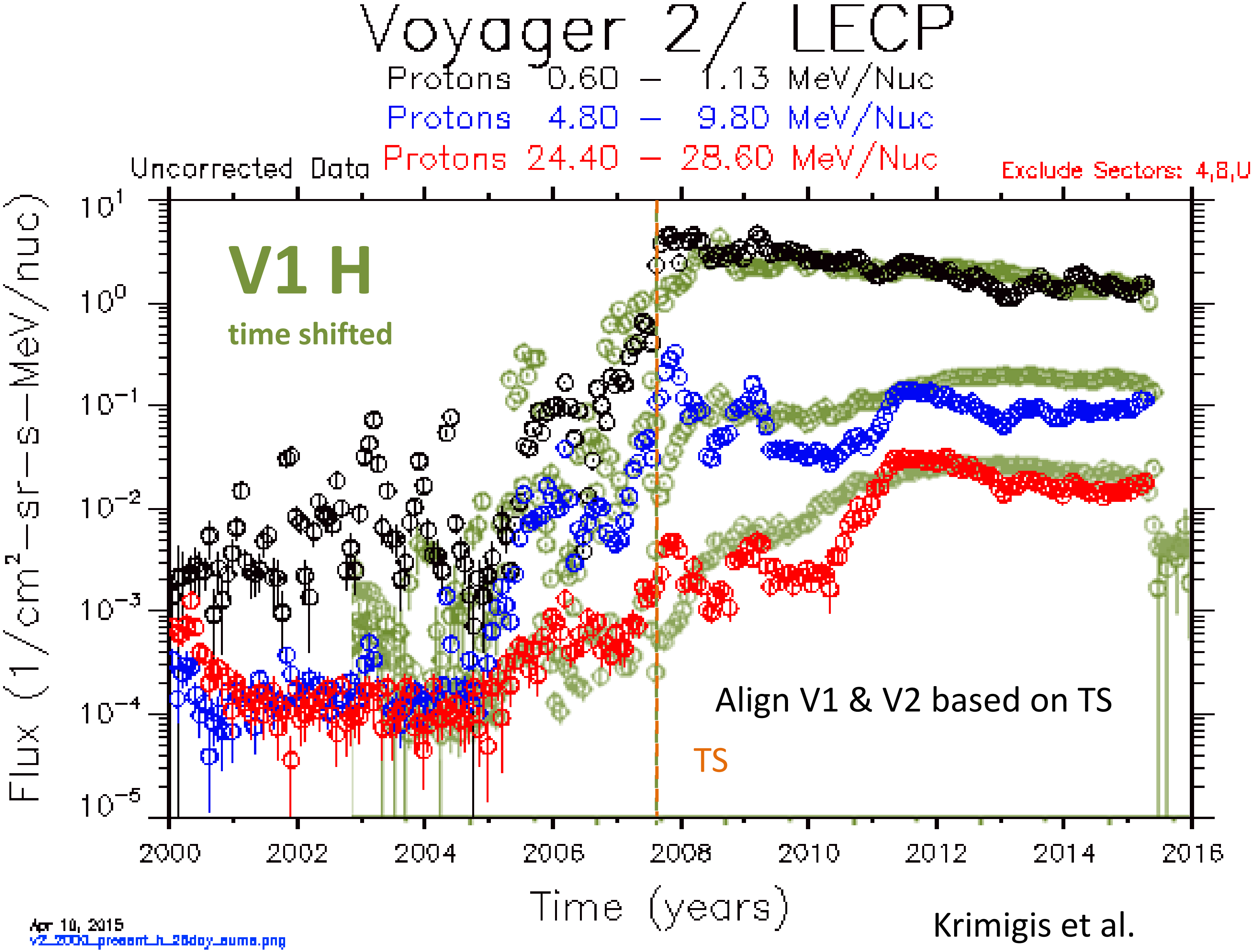


Expected ACR spectrum at shock (black dashed line) not observed at V1 or V2 shock crossings (TSX).

V2 ACR intensity (~10-30 MeV/nuc) at shock was 7x that at V1 at its shock crossing and spectra evolved at both V1 and V2 in the heliosheath, mainly due to decreasing solar modulation between the source and the spacecraft.

Higher energy ACRs not modulated, lower energies are modulated.

(From Alan Cummings)



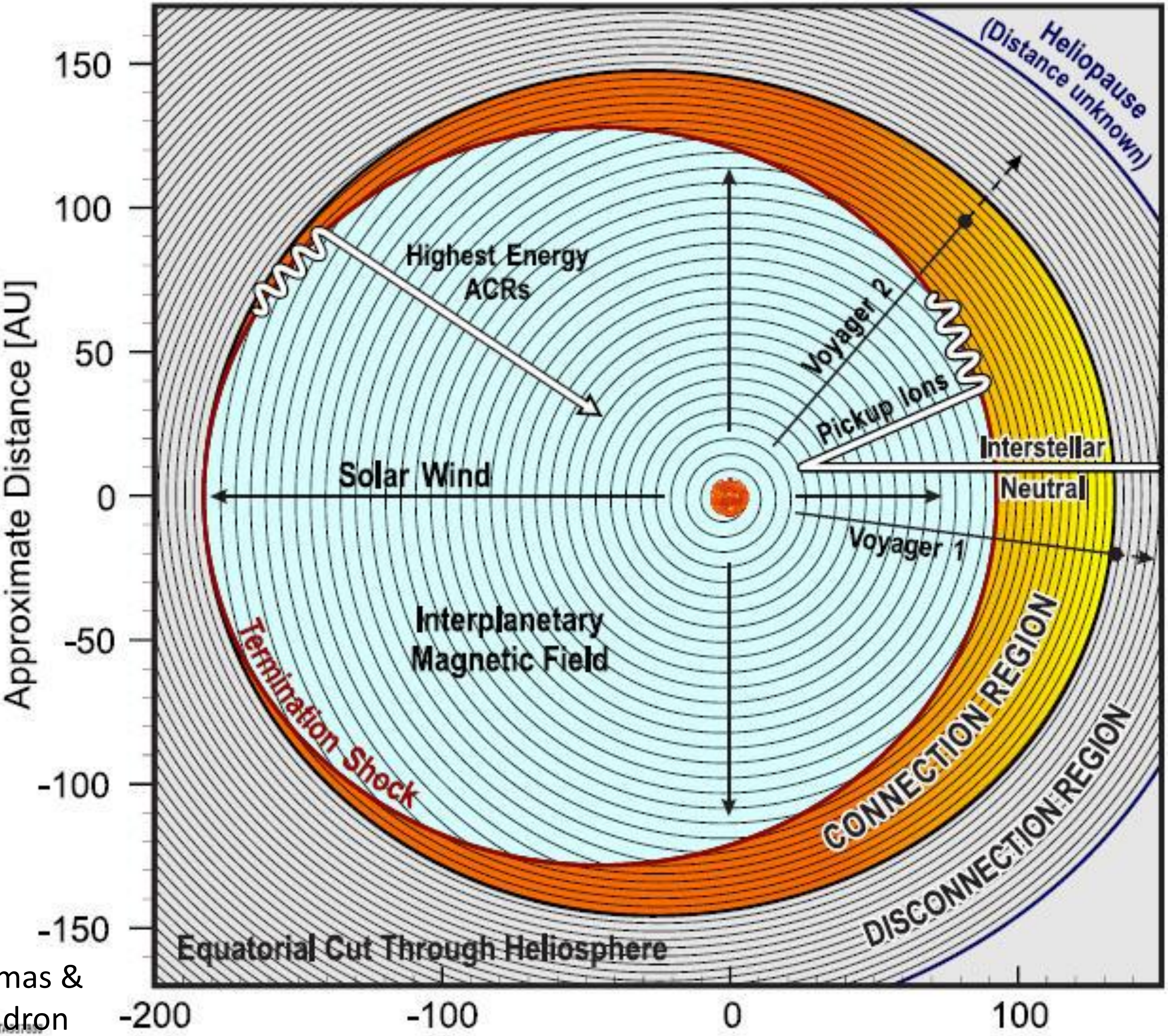
V1 H

time shifted

Align V1 & V2 based on TS

TS

Krimigis et al.



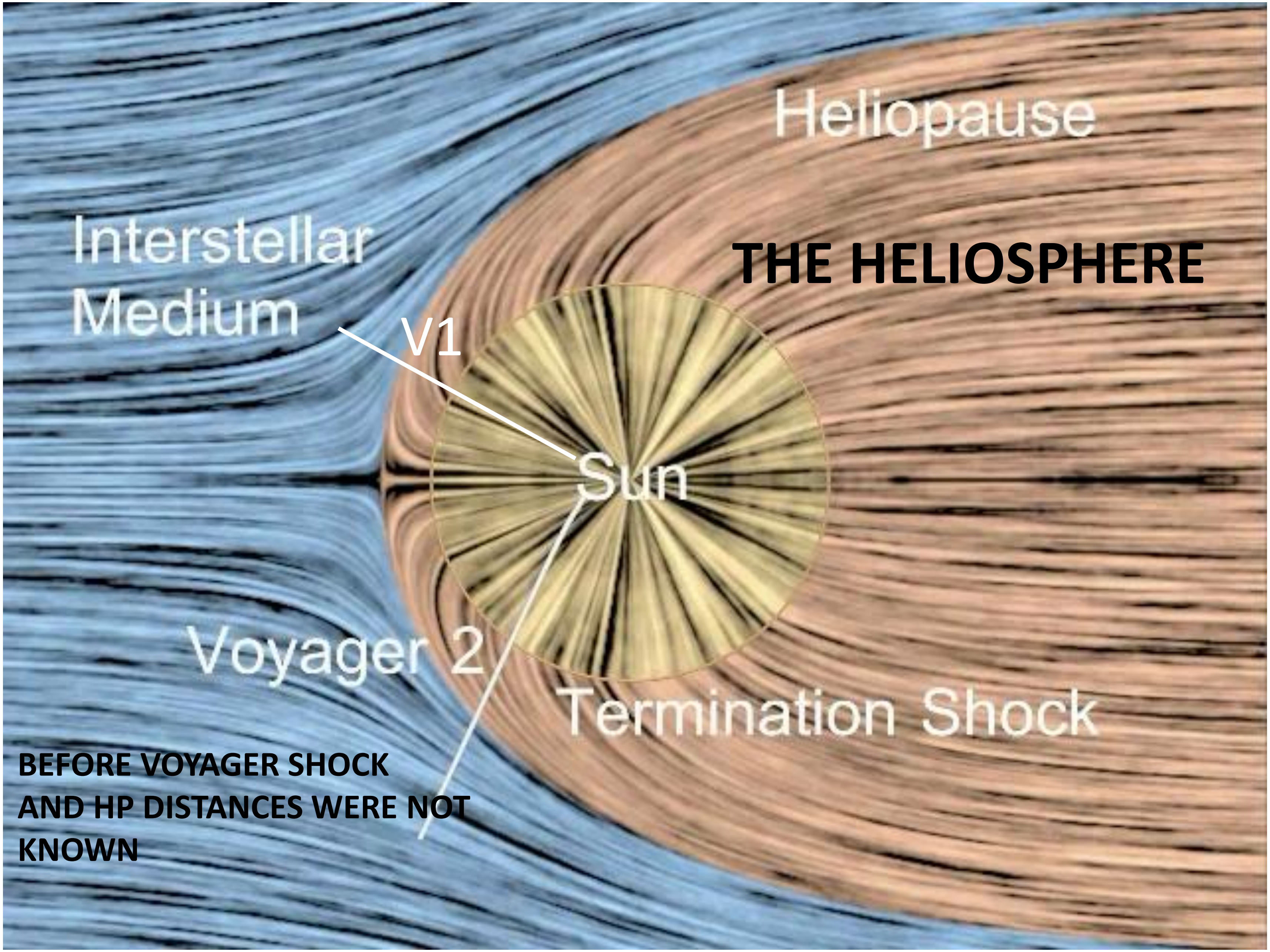
McComas & Schwadron

Heliosheath

Why a stagnation region at V1?

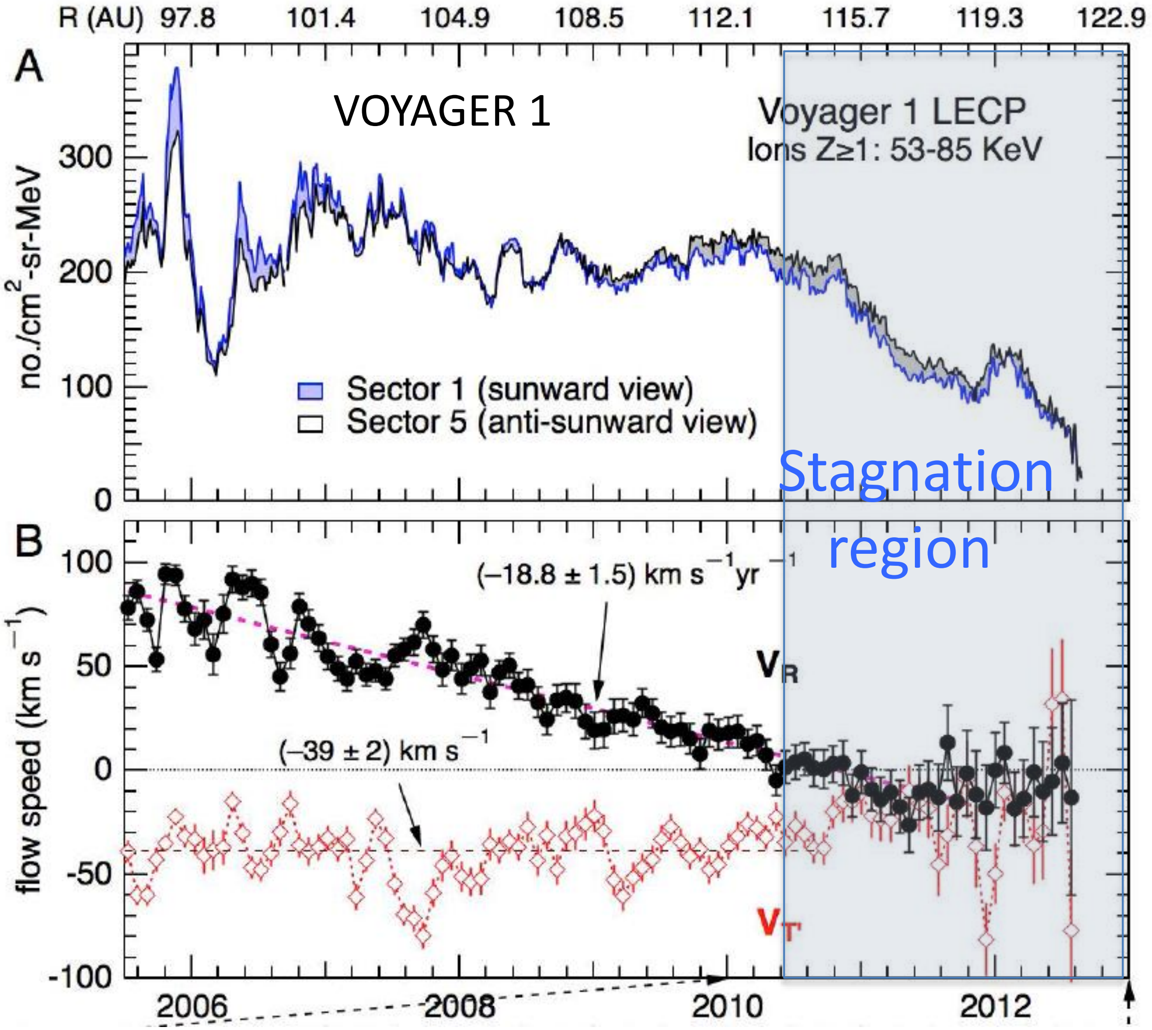
Why are plasma flows and particle intensities so different at V1 and V2?

THE HELIOSPHERE



BEFORE VOYAGER SHOCK AND HP DISTANCES WERE NOT KNOWN

Puzzle: why a stagnation region? V ~ 0



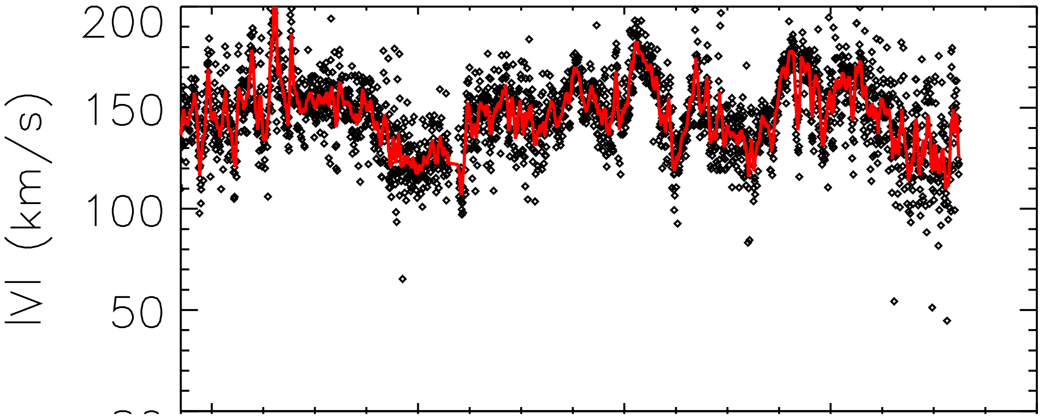
Flow expected to turn tailward as it moves across HSH; VR to ~0 at HP

Intensity ~constant from 94-115 AU, then decreased from 2010 to dropout in 2012.

Radial speed near zero from early 2010 to dropout: **113-121 AU**

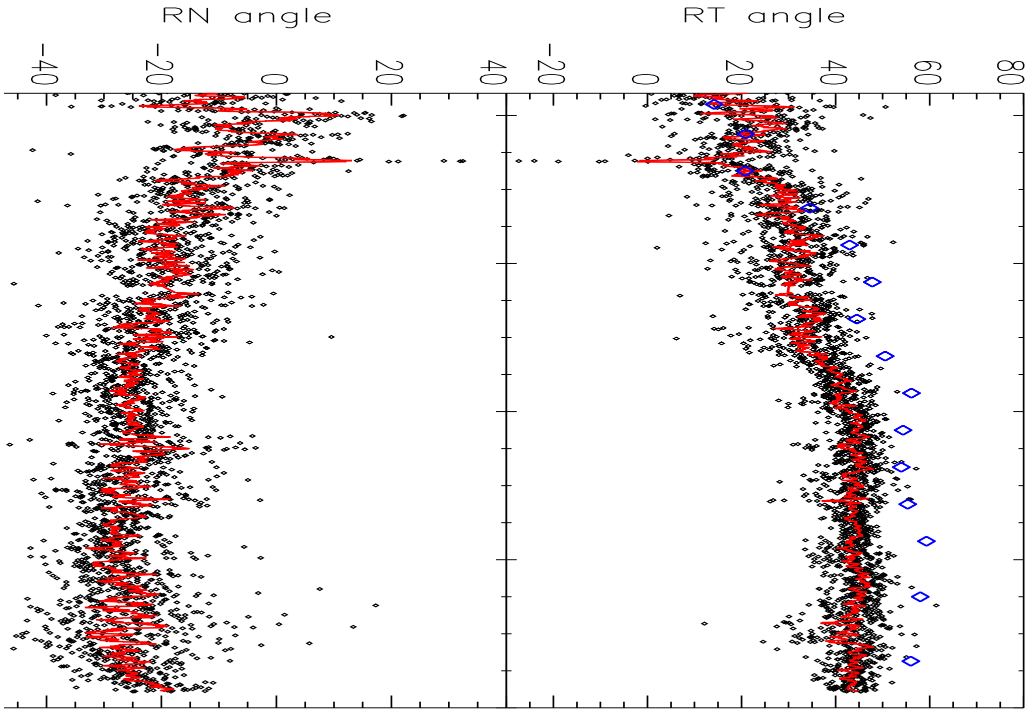
Other flow components also small: **Stagnation region**

Krimigis et al. (2013)



VOYAGER 2

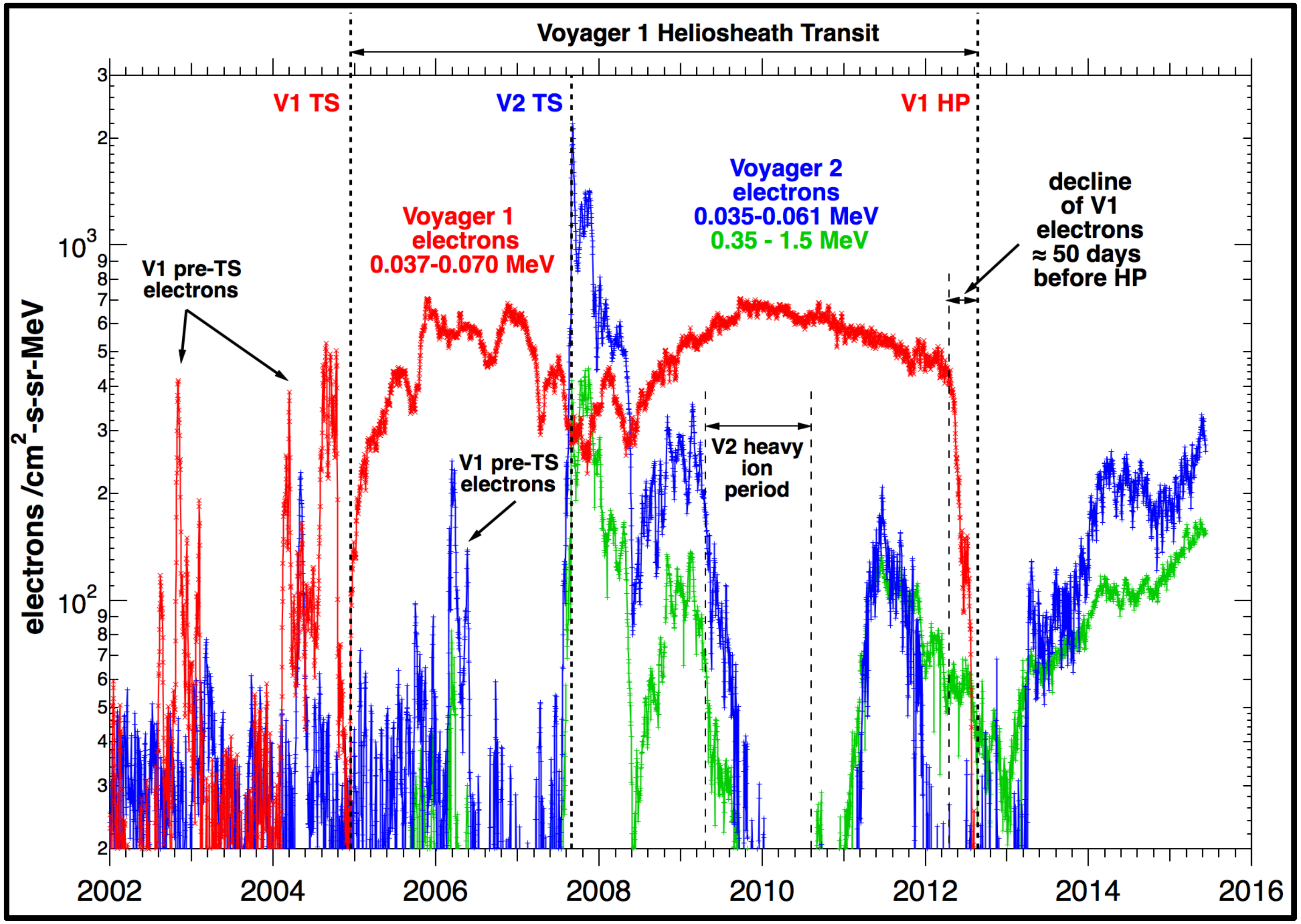
|V| average is constant:
Flow does not slow down.



RT flow angle is ~60°:
Flow has turned tailward.

Flow in RN plane ~30°:
Flow over the poles small.

Electrons 0.04-1.5 MeV in the Heliosheath



- Electrons 40-70 keV at V1 (red), and 35-61 keV (blue) & 35-1500 keV (greens) at V2
- V1 measured pre-TS HS electrons bursts and relatively steady intensity in the HS (with a factor ~2)
- By contrast, V2 has measured 3-4 episodes of HS electrons
- In most recent V2 episode intensities continue to climb

Hill et al.

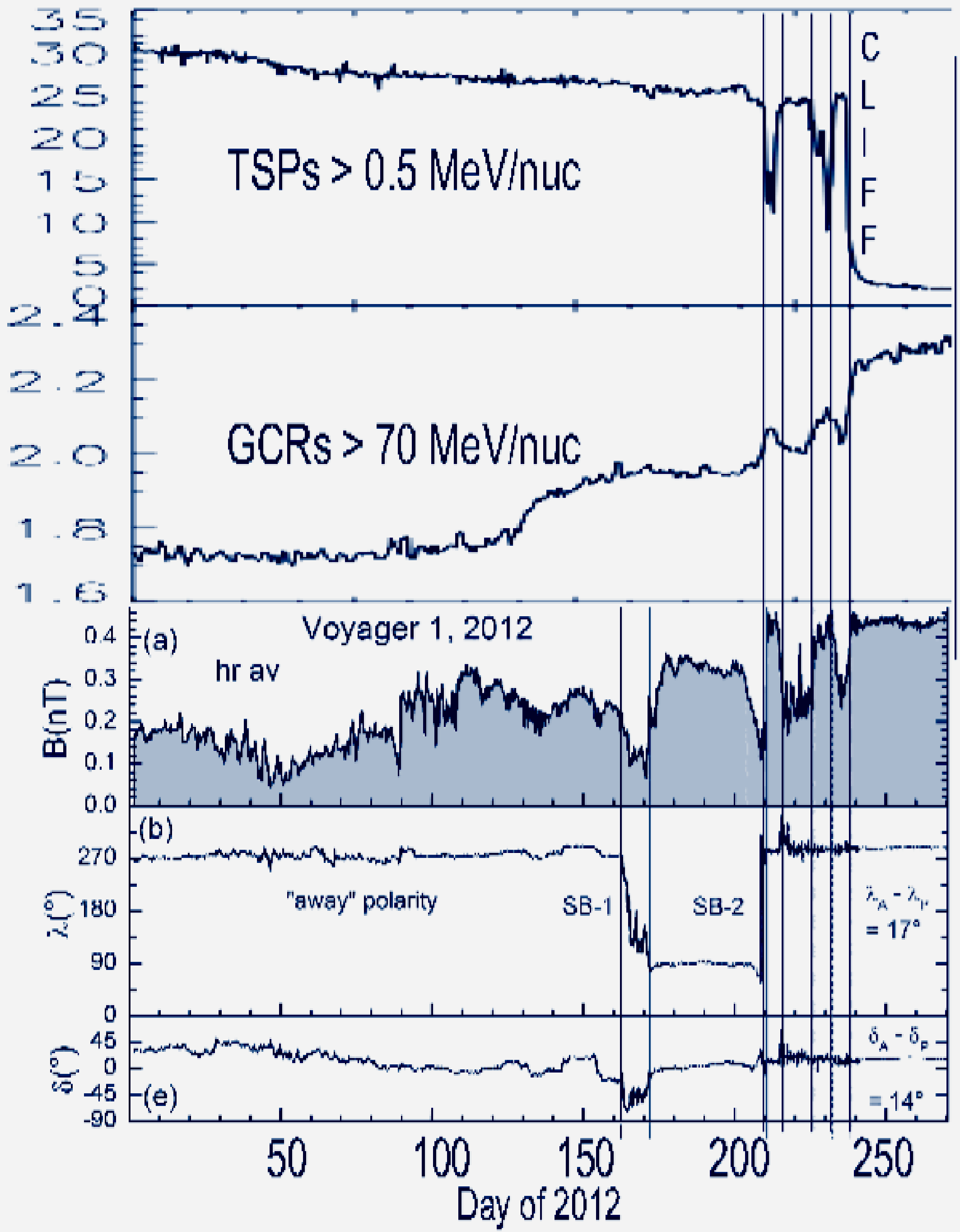
Heliopause

Location

Change of particle intensities

Change in magnetic field

HELIOCLIFF



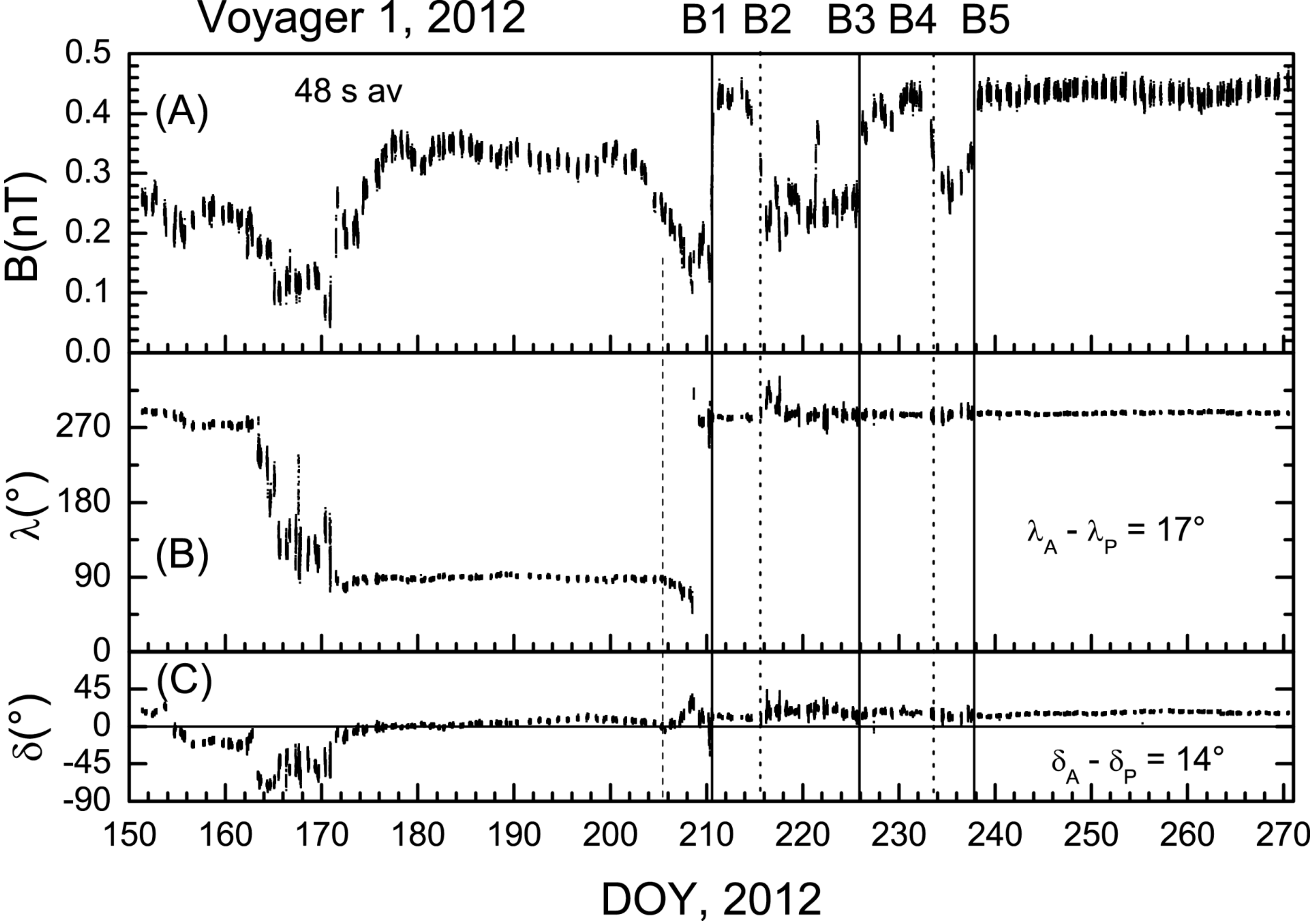
Heliosheath particles disappear

Galactic cosmic rays increase

Magnetic field increases

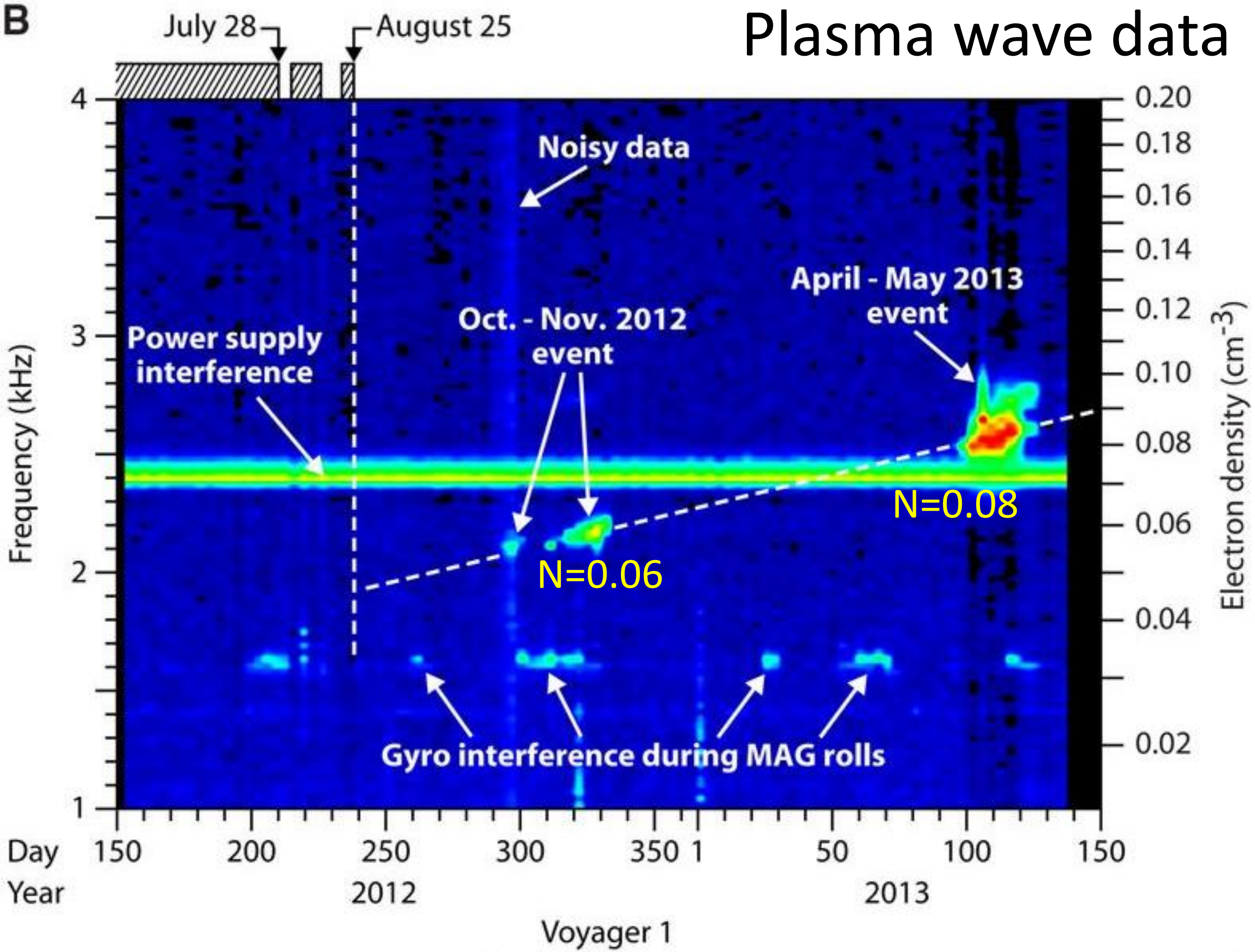
Magnetic field direction does NOT change

Still inside heliopause?



Burlaga et al. 2013

Plasma wave data



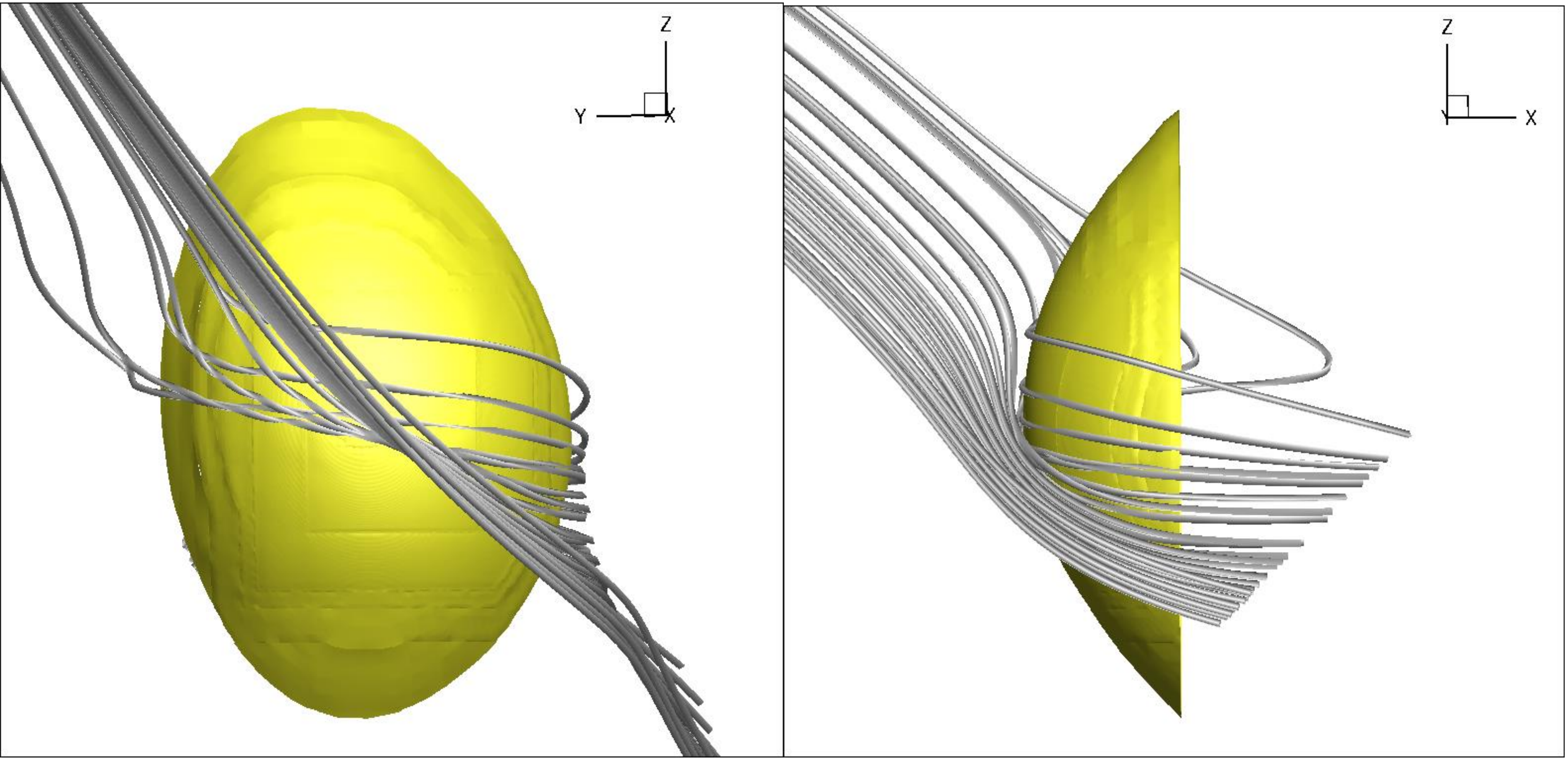
Densities are interstellar medium densities – so V1 crossed heliopause!

Emissions excited when ICMEs hit heliopause and accelerate electron beams.

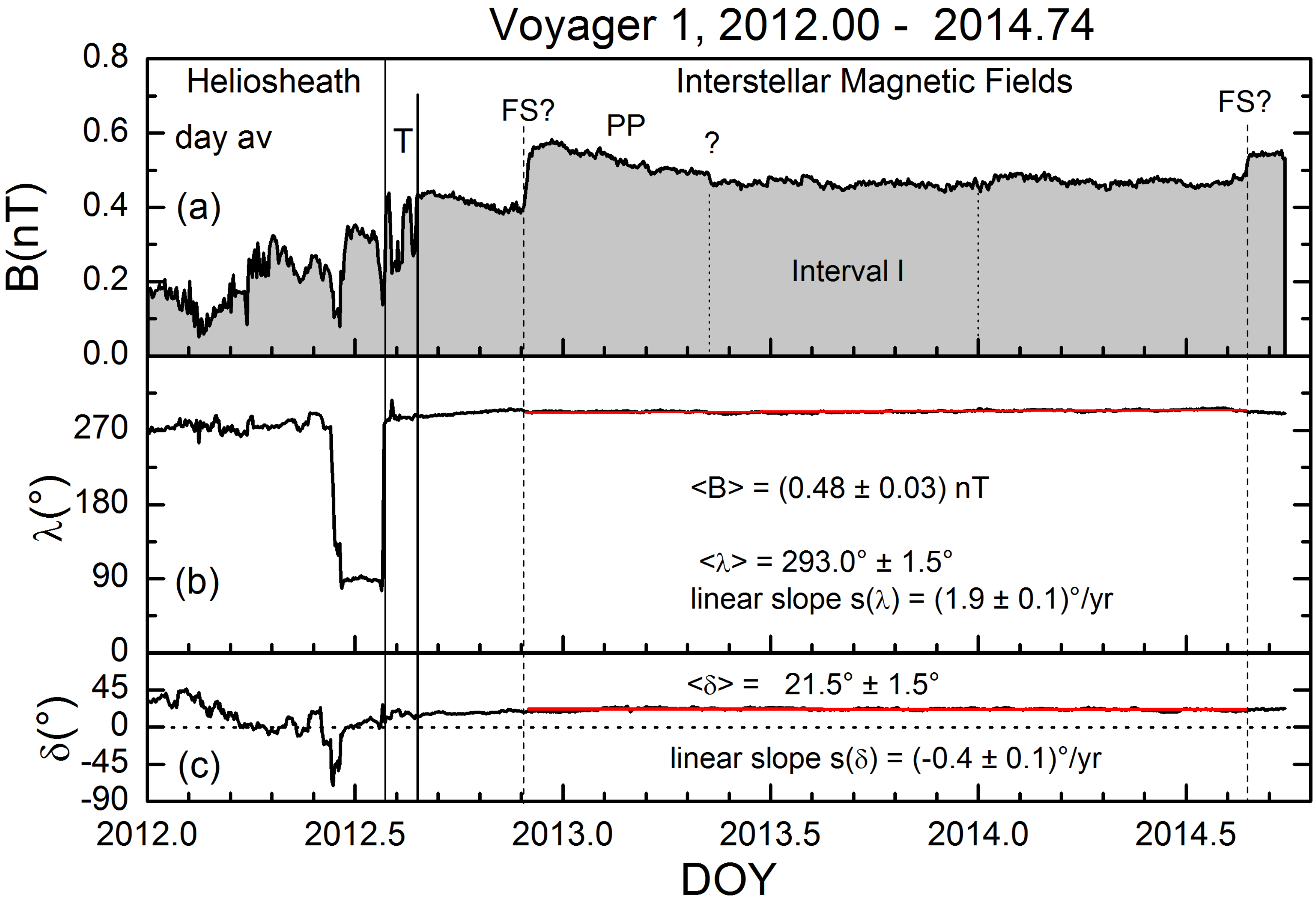
Gurnett et al., Science, 2013

STRONG TWIST OF THE INTERSTELLAR MAGNETIC FIELD ahead of the Heliopause

Opher & Drake *ApJL* 2013

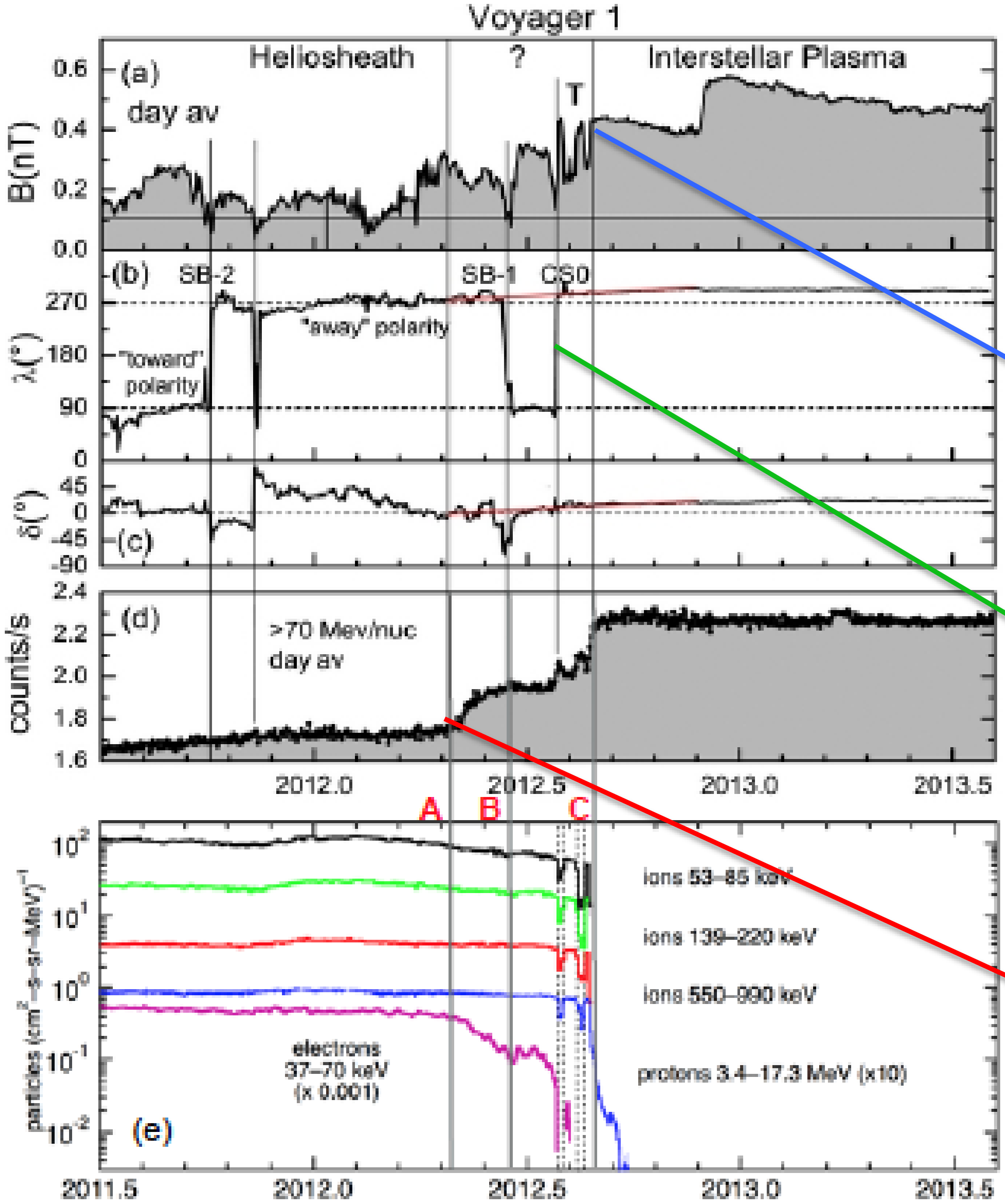


At large distances outside of the HP the interstellar field lines are inclined to the T direction (east-west direction) and then twist dramatically in the T direction as they approach the Heliopause.



Magnetic field is slowly rotating toward expected LISM direction

Question: Where is the heliopause?

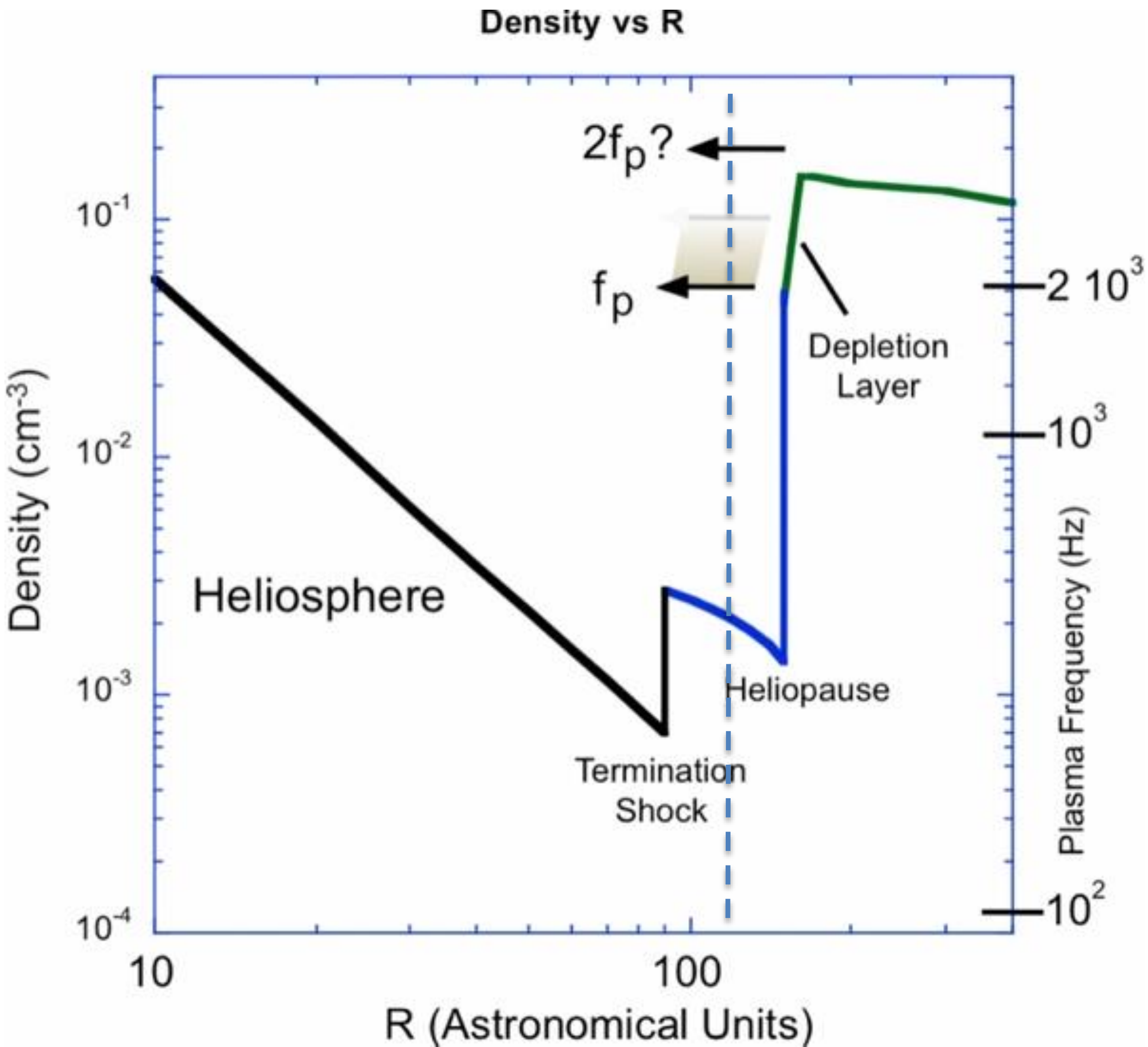


The heliocliff (GCRs and B up, TSPs and ACRs down)?

Magnetic field direction change?

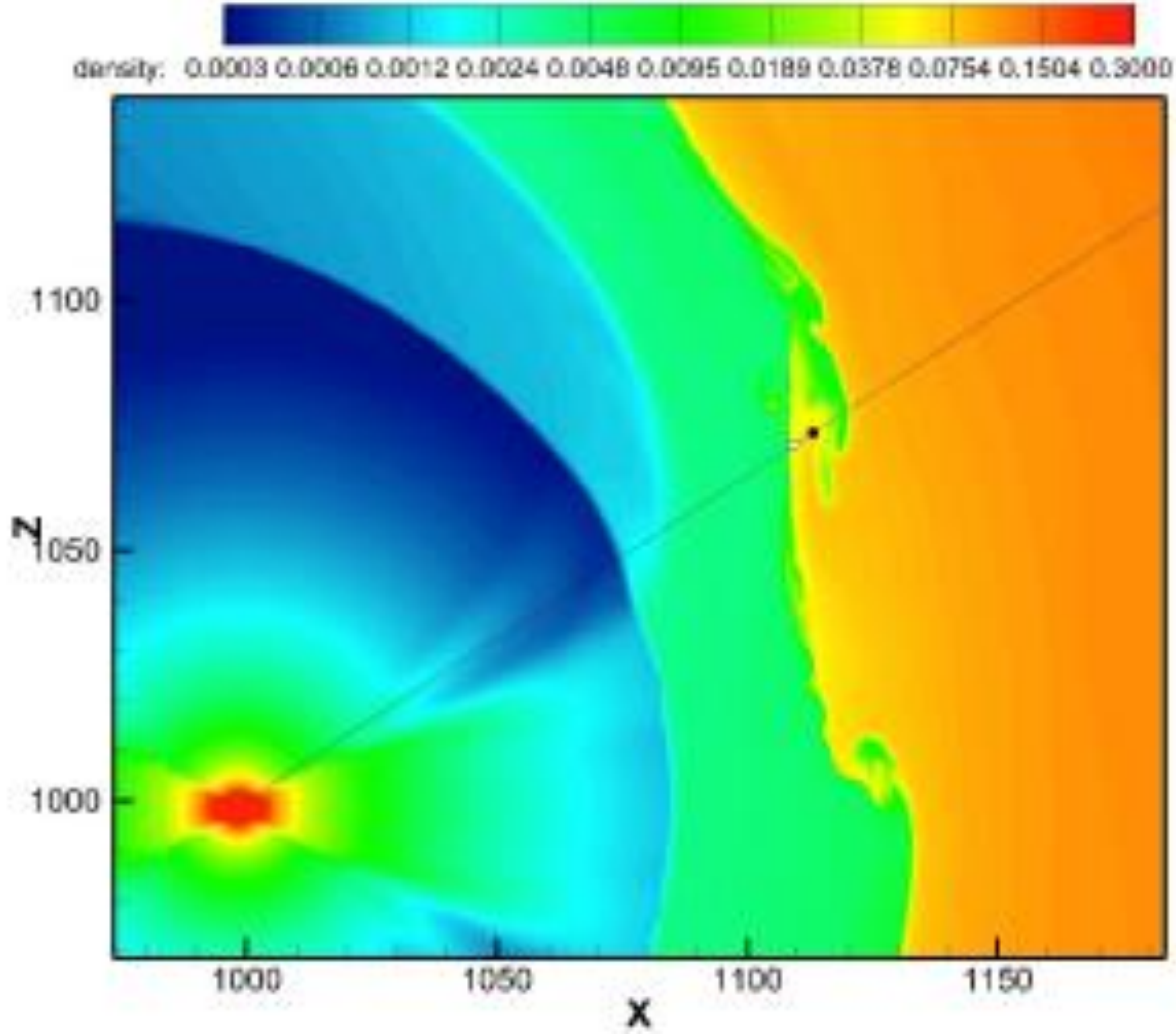
GCR increase, HSH e^- down?

Question: Why is the heliopause so close? At 121 AU, it is only 27 AU from TS. Models predict HP is 40-60 AU from TS



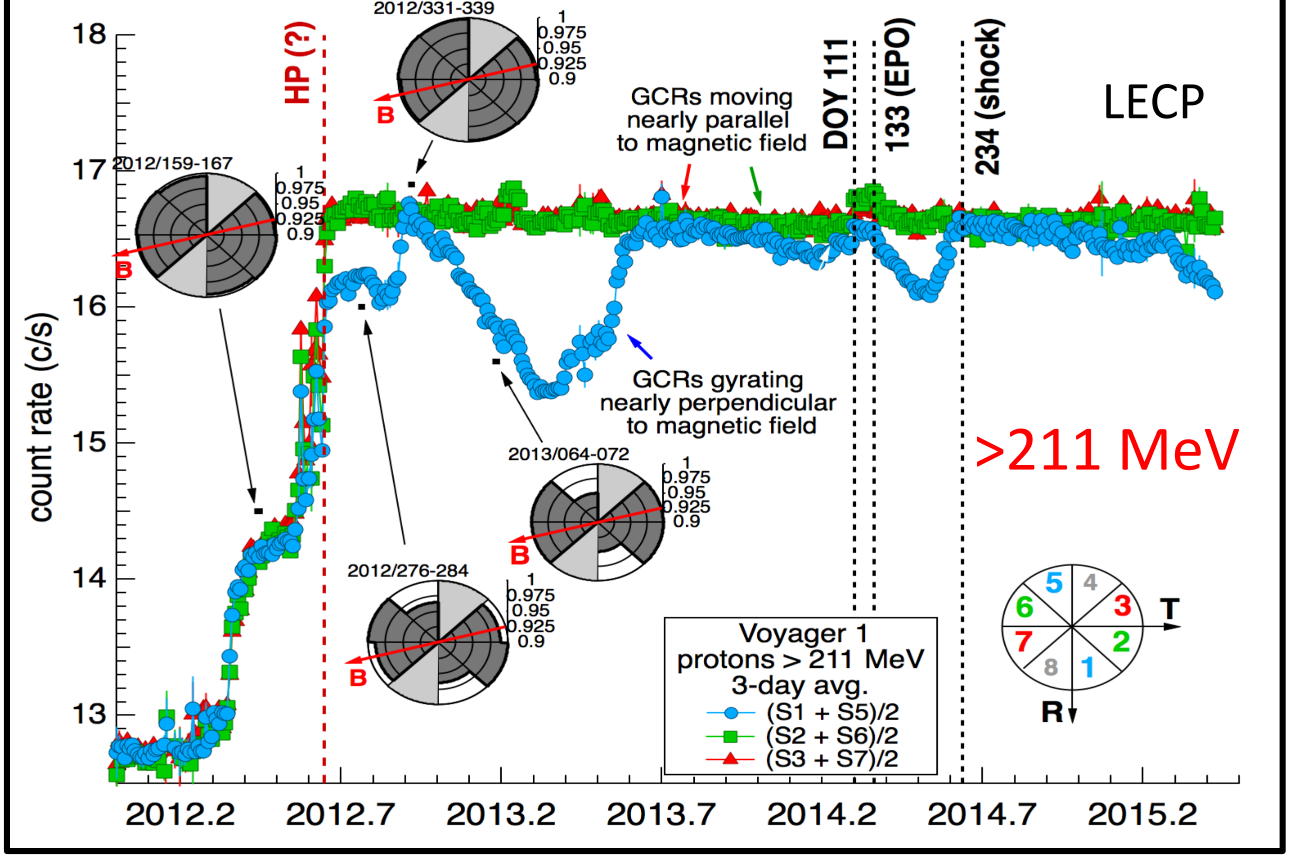
Pogorelov et al

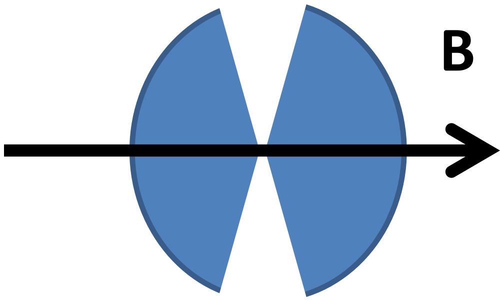
One Solution? Borovikov and Pogorelov: Instabilities on the Heliopause



Local Interstellar Medium

Magnetic field magnitude and direction
Cosmic ray intensities (mostly) unmodulated
Solar disturbances propagating into the LISM
Source of radio emissions





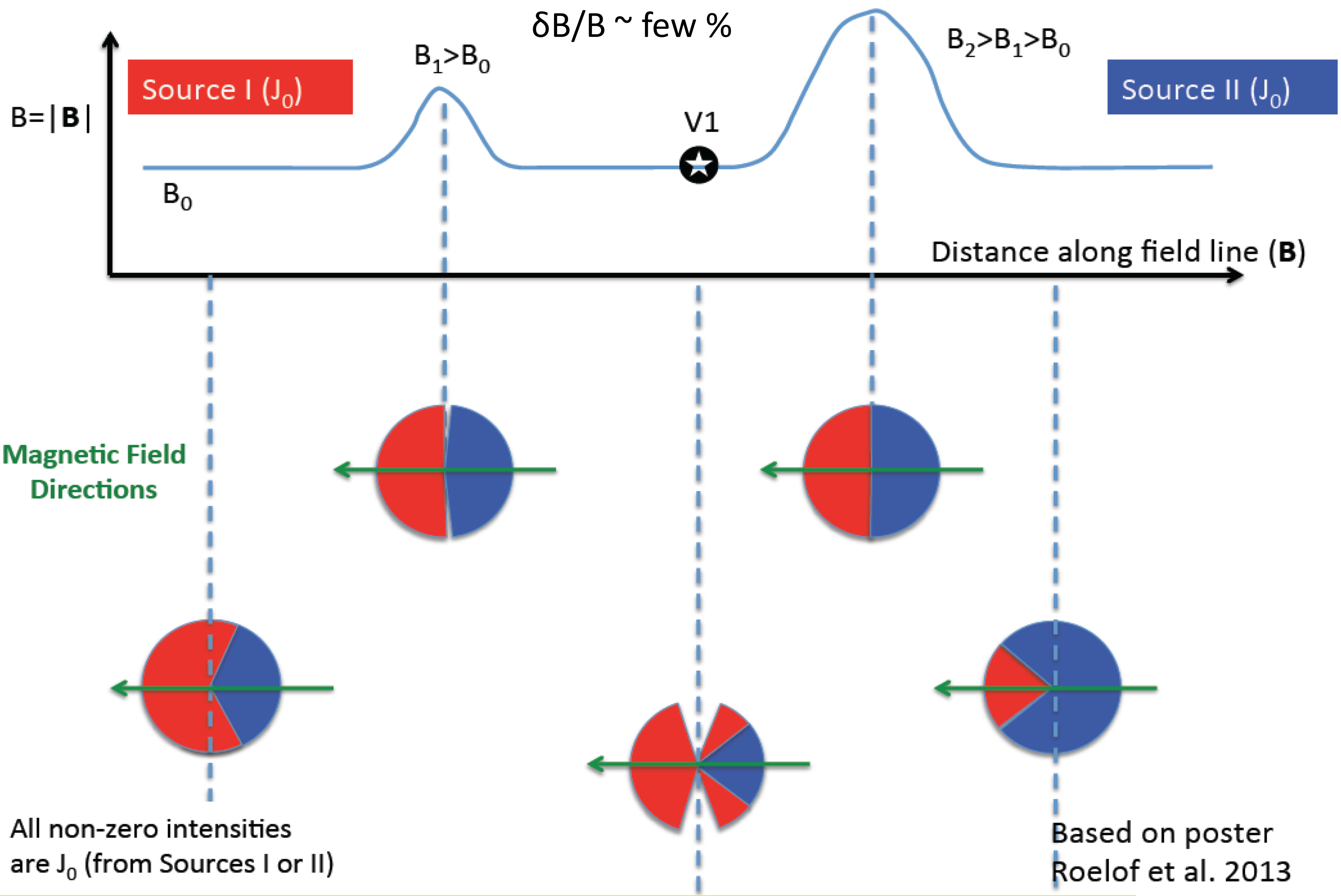
Krimigis et al. 2013

Roelof 2013
Magnetic Mirrors

Strauss & Fichtner 2014
Assume D_{perp} is maximum
for μ=0

Depletions observed in 90° pitch angle particle.
~4° in width

Void in Angular Distributions May be Due to Mirroring off of Multiple Magnetic Perturbations



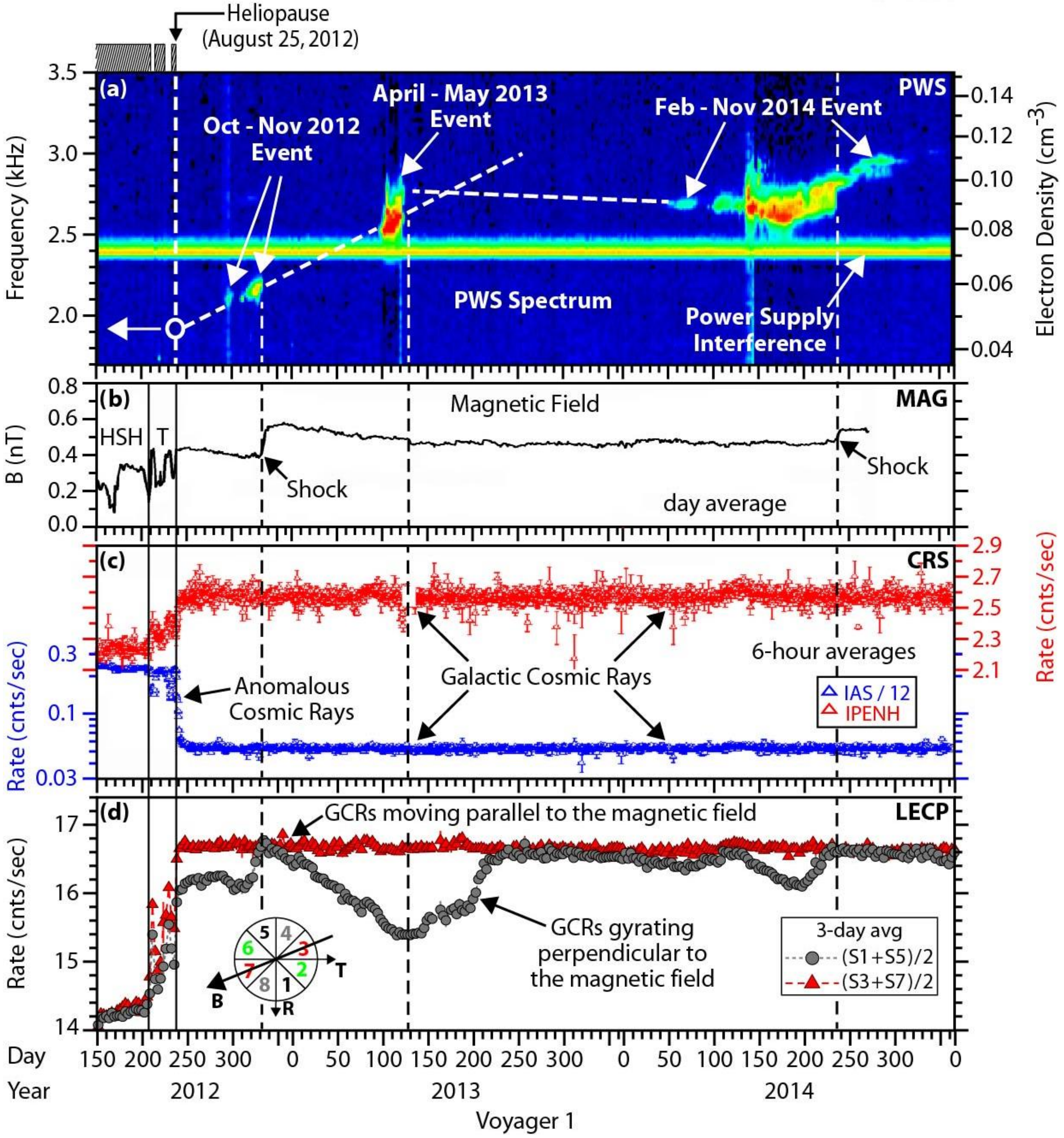
All non-zero intensities are J_0 (from Sources I or II)

Based on poster Roelof et al. 2013

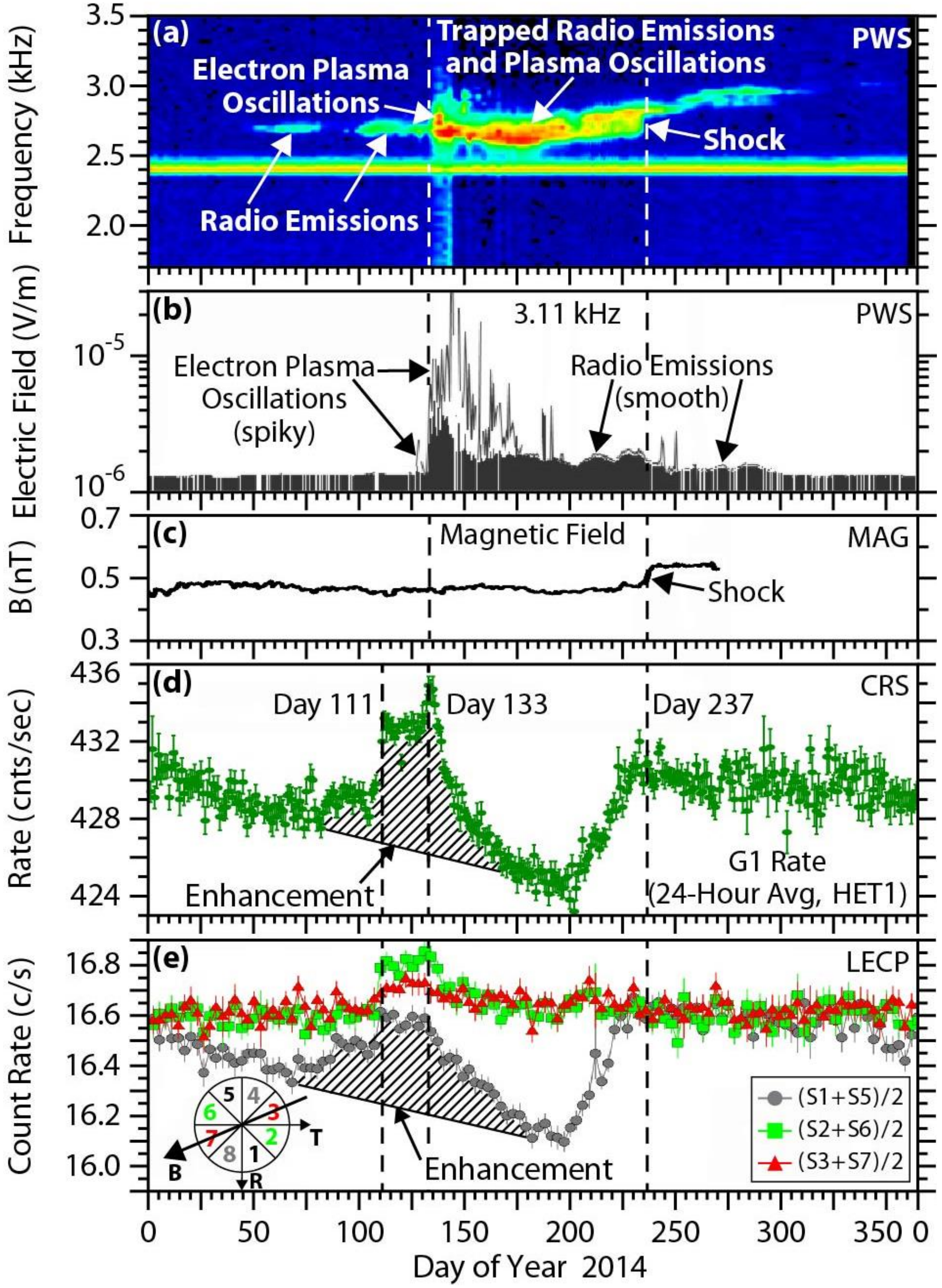
Cartoons of observational "pie plots" not pitch angle distributions (change from Roelof display).

Overview of Interstellar Disturbances Detected by Voyager 1.

MIRs drive pressure waves Through LISM

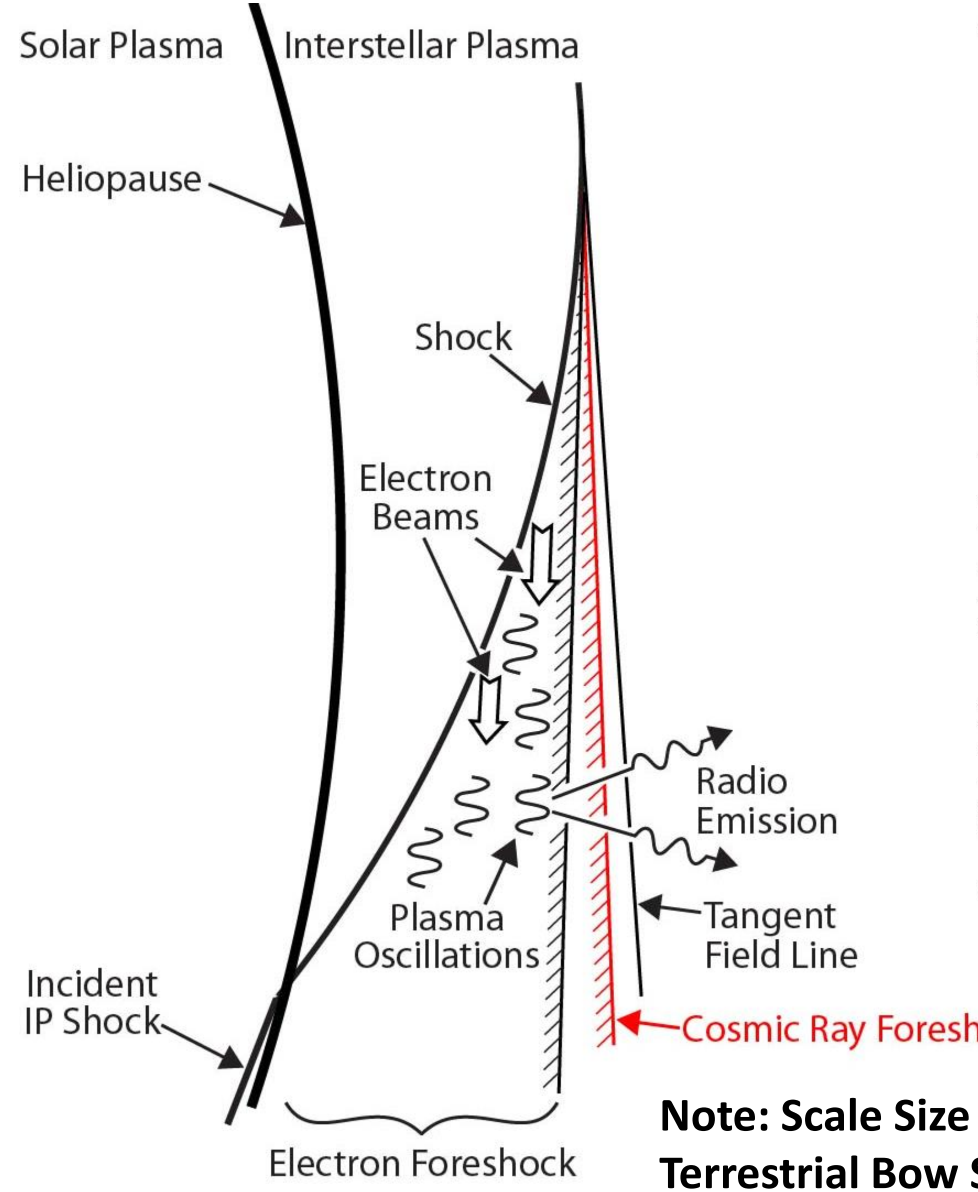


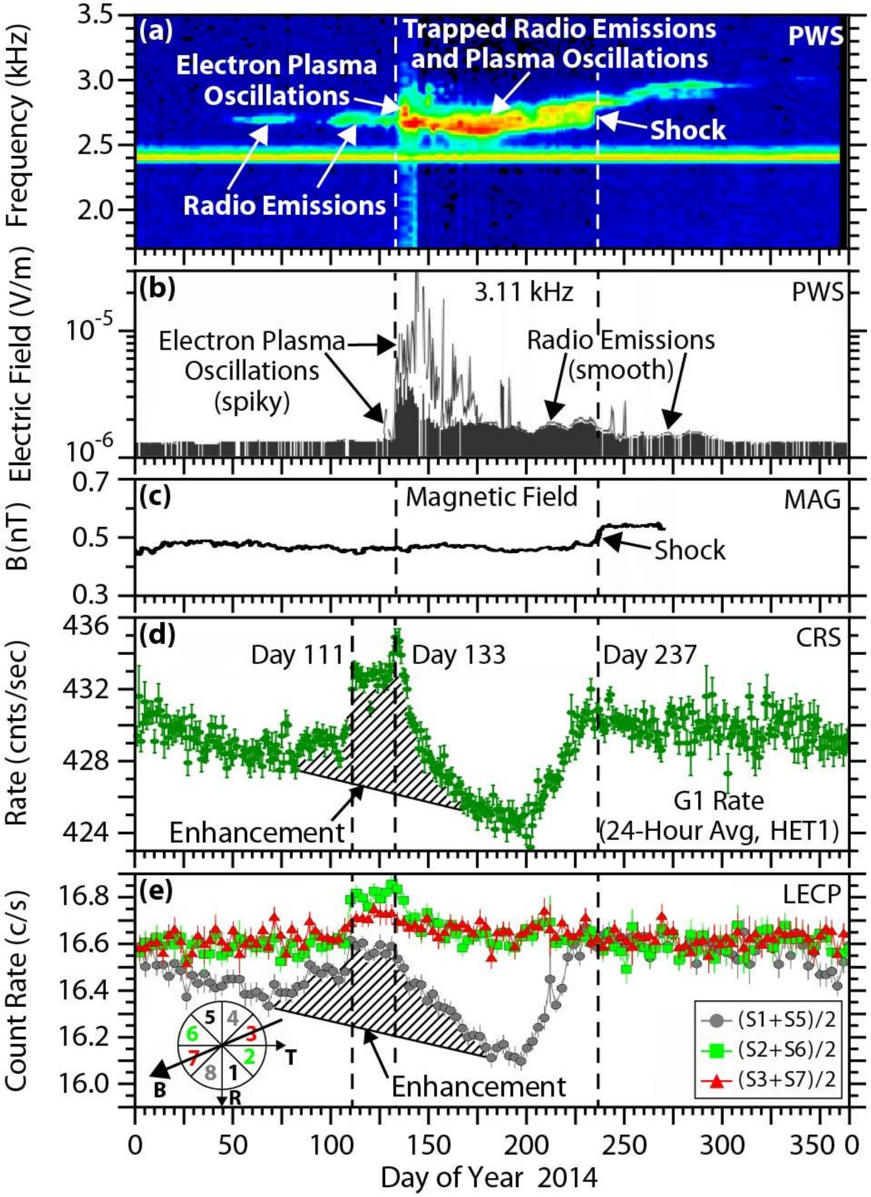
Comparison to Cosmic Ray Observations (2014 Event)



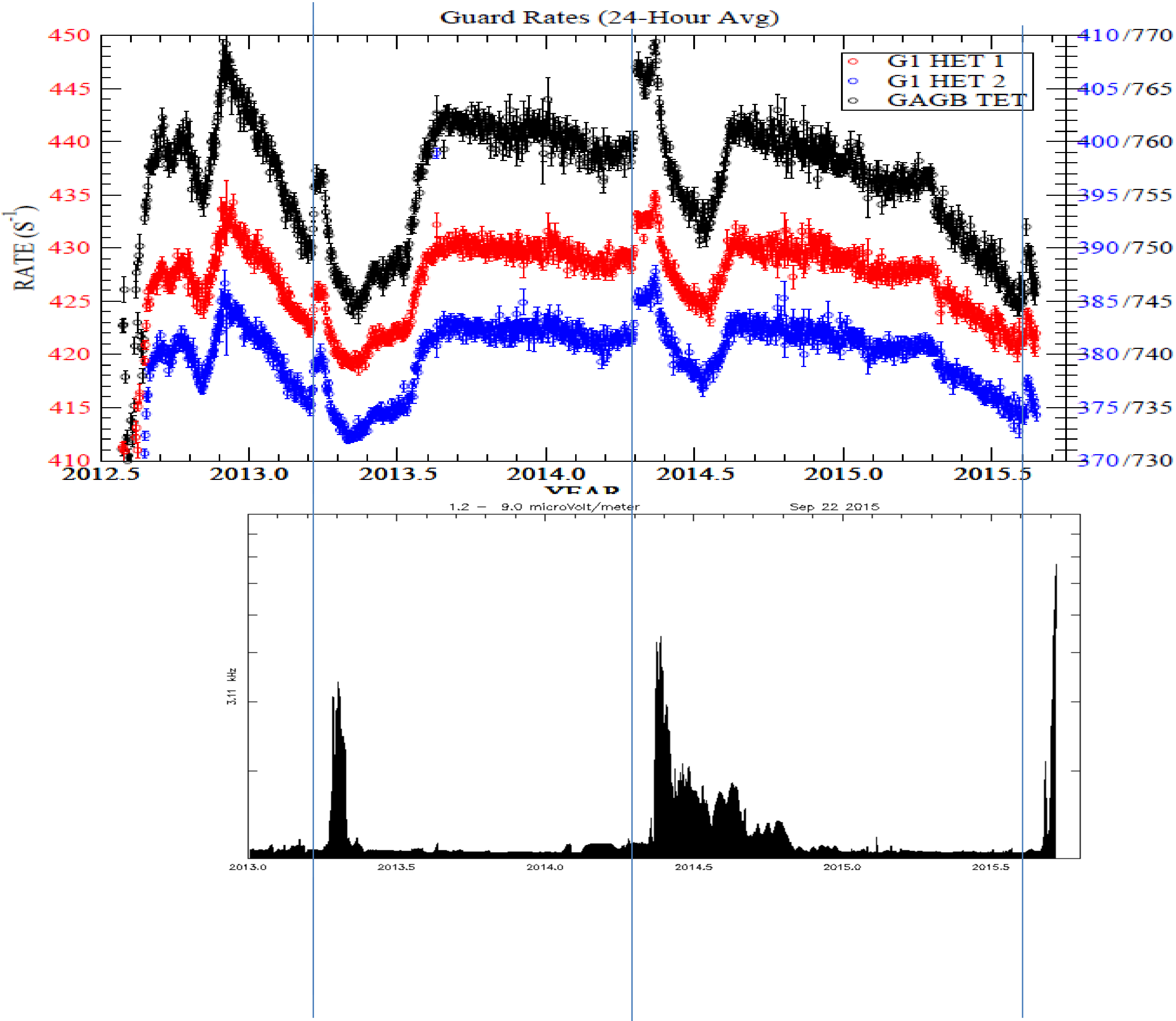
The Cosmic Ray Foreshock Model

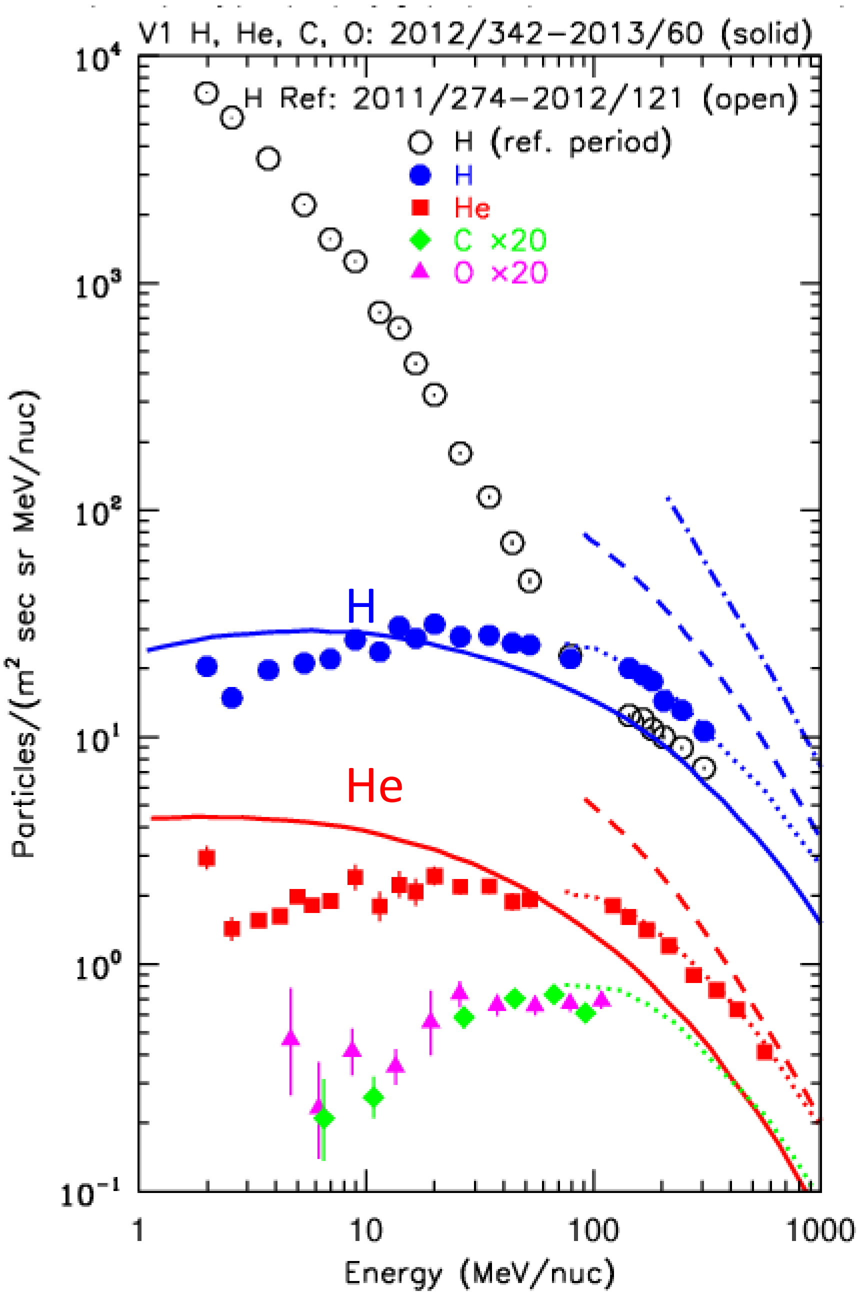
Gurnett et al., 2015





Note: Scale Size is ~ 10,000x Terrestrial Bow Shock


Guard Rates (24-Hour Avg)
RATE (S^{-1})
450
445
440
435
430
425
420
415
410
410/770
405/765
400/760
395/755
390/750
385/745
380/740
375/735
370/730
G1 HET 1
G1 HET 2
GAGB TET
2012.5
2013.0
2013.5
2014.0
2014.5
2015.0
2015.5
YEAR
1.2 – 9.0 microVolt/meter
Sep 22 2015
3.11 kHz
2013.0
2013.5
2014.0
2014.5
2015.0
2015.5



Fisk & Gloeckler 2012 -- pump

Moskalenko et al. 2002 – DC

Webber & Higbie 2009 -- LB

Ip & Axford 1985 – model a

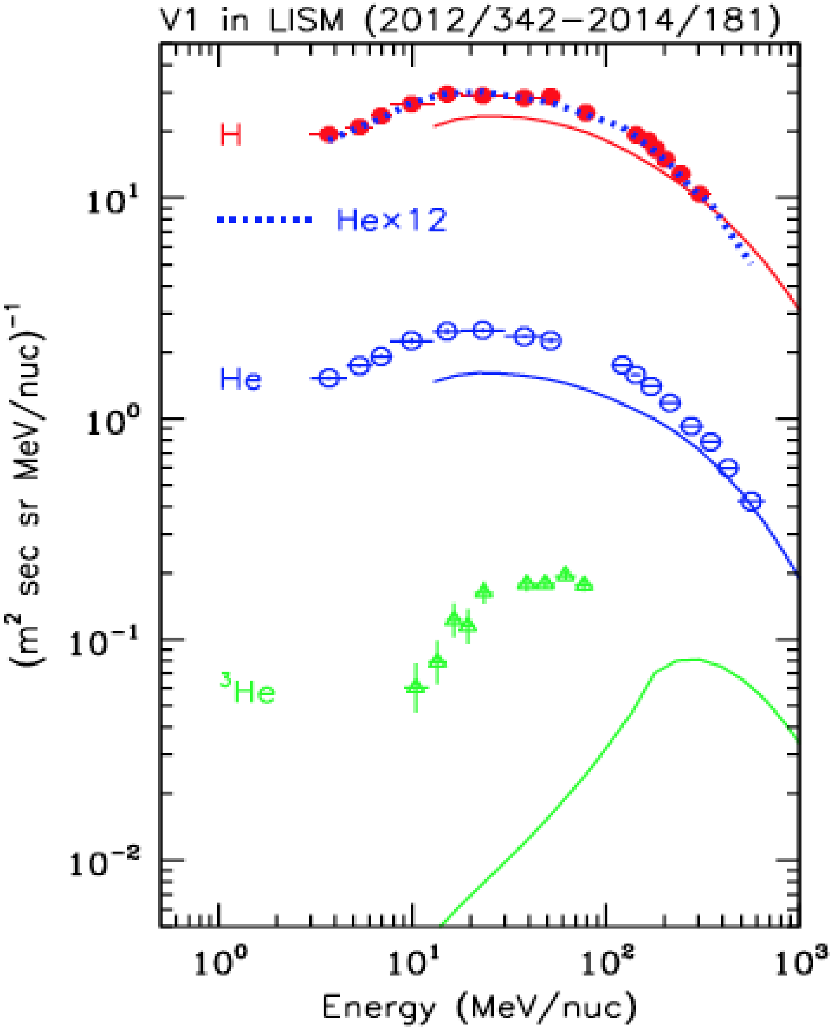
V1 H, He, C, and O spectra for 2012/342-2013/60. Also shown is H spectrum for 2012/274-2012/121.

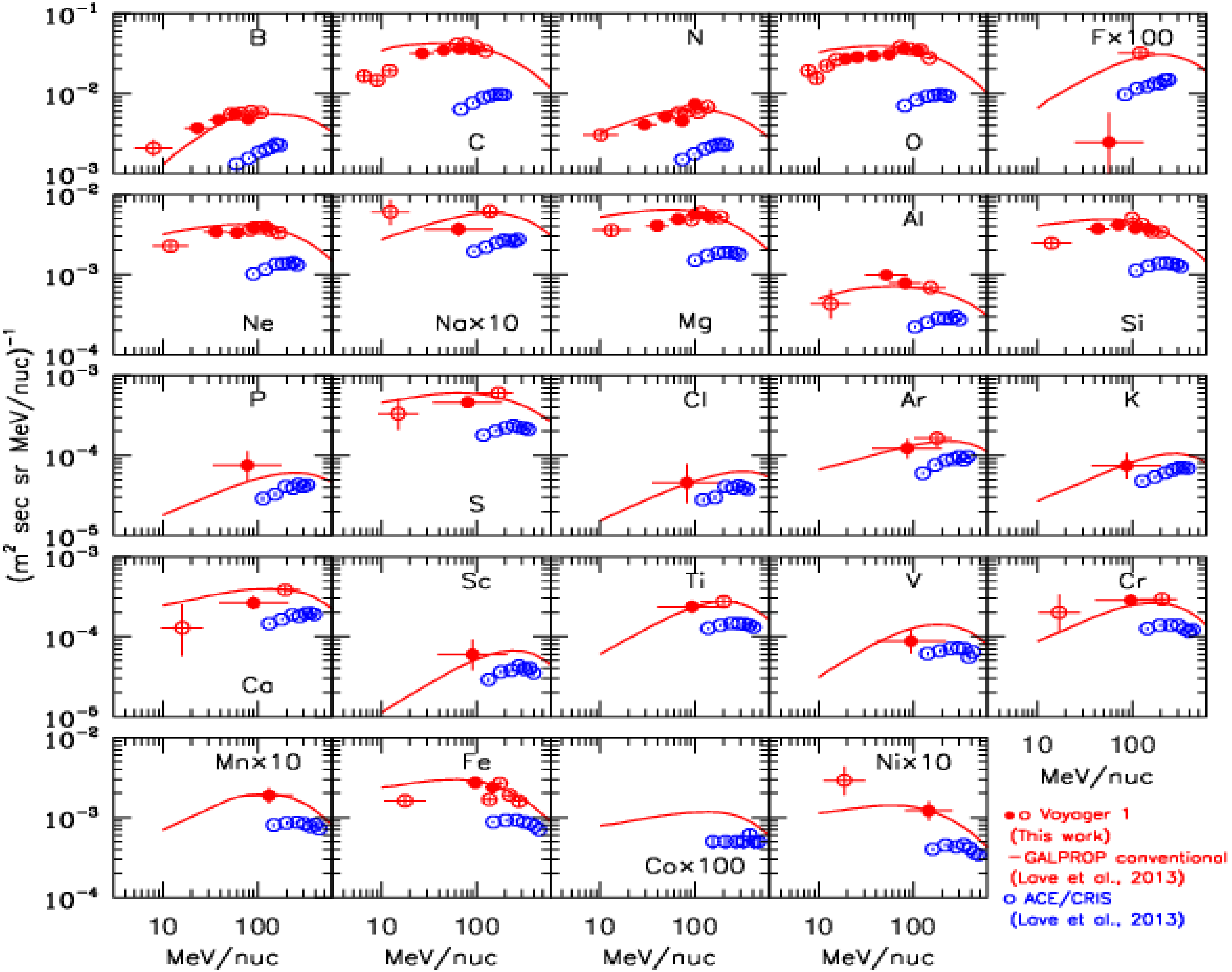
Believe we are observing GCRs down to ~3 MeV/nuc for H and He; C & O down to ~10 MeV/nuc.

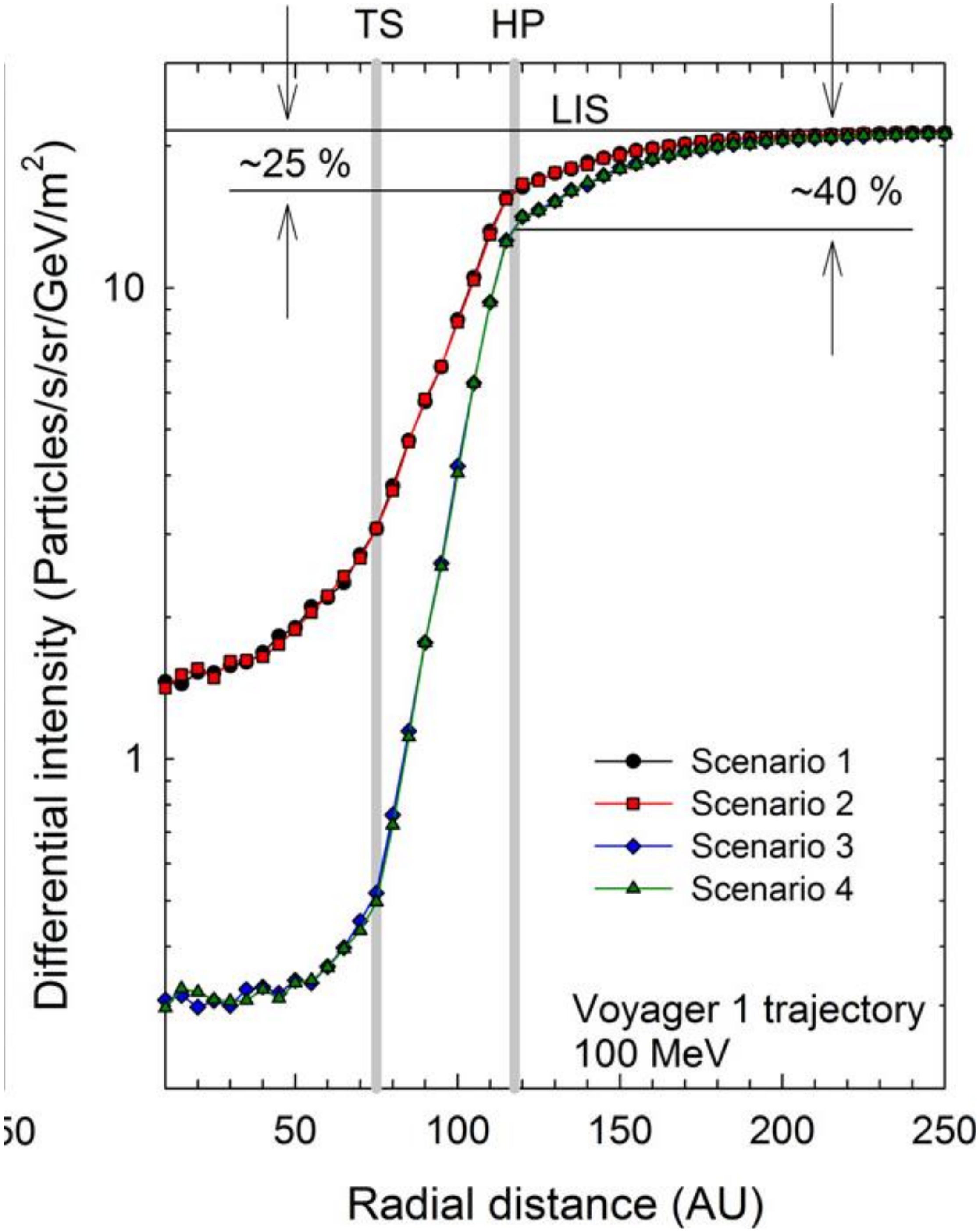
GCR H, He spectra peak at ~20-40 MeV/nuc and are in good agreement at higher energies with leaky box model from Webber & Higbie 2009
-- as is GCR C.

GCR C/O ratio ~1. ACRs not contributing to low-energy GCR spectrum, contrary to Scherer et al 2008.

Cummings et al, 2013


V1 in LISM (2012/342−2014/181)
H
He×12
He
^{3}He
10^{1}
10^{0}
10^{-1}
10^{-2}
$(m^2$ sec sr MeV/nuc$)^{-1}$
10^{0}
10^{1}
10^{2}
10^{3}
Energy (MeV/nuc)


(m^2 sec sr MeV/nuc)$^{-1}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
B
C
N
O
F×100
Ne
Na×10
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn×10
Fe
Co×100
Ni×10
10
100
MeV/nuc
●○ Voyager 1
(This work)
— GALPROP conventional
(Love et al., 2013)
○ ACE/CRIS
(Love et al., 2013)

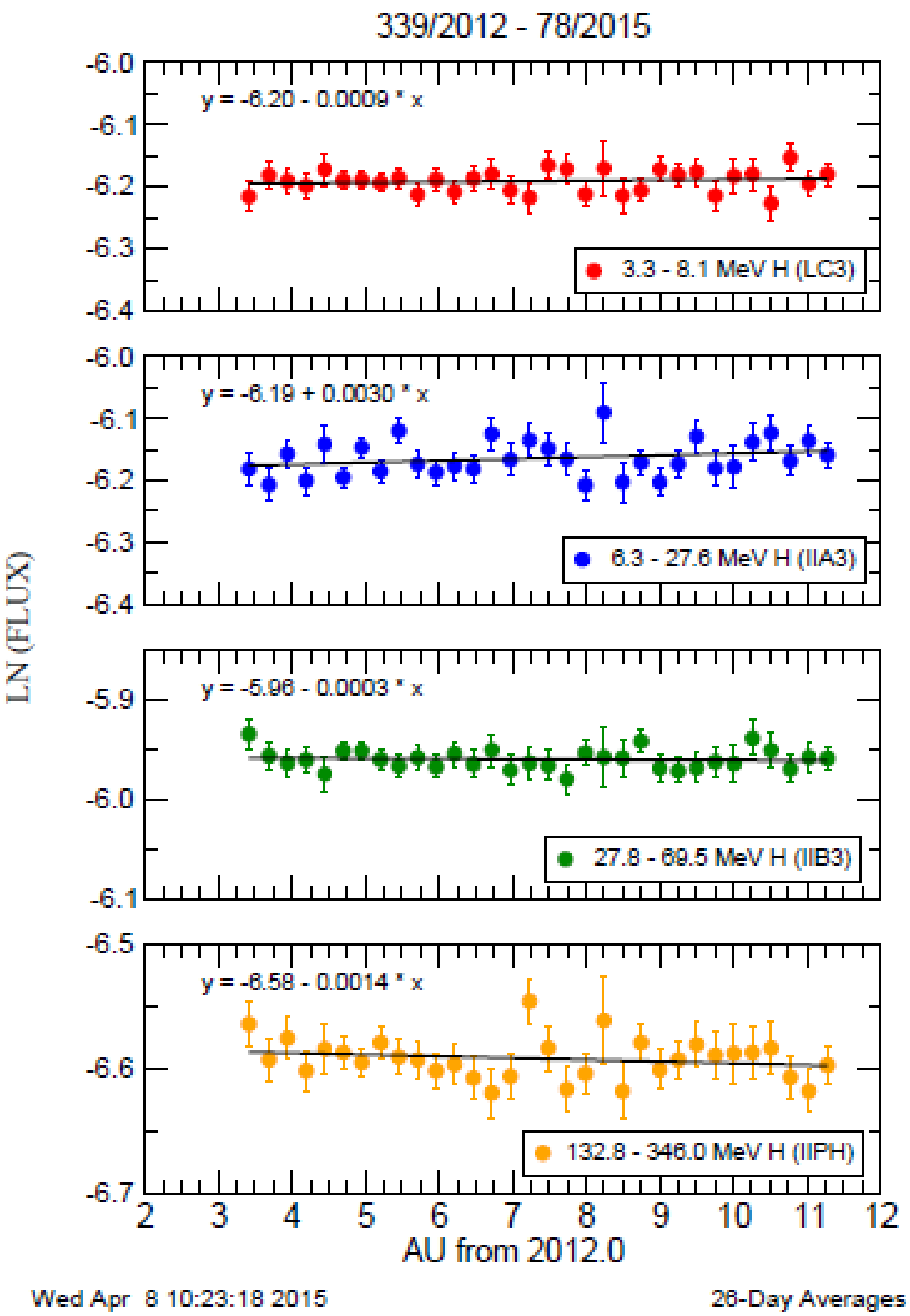


Gradients?

100 MeV H vs time from Strauss et al. 2013.

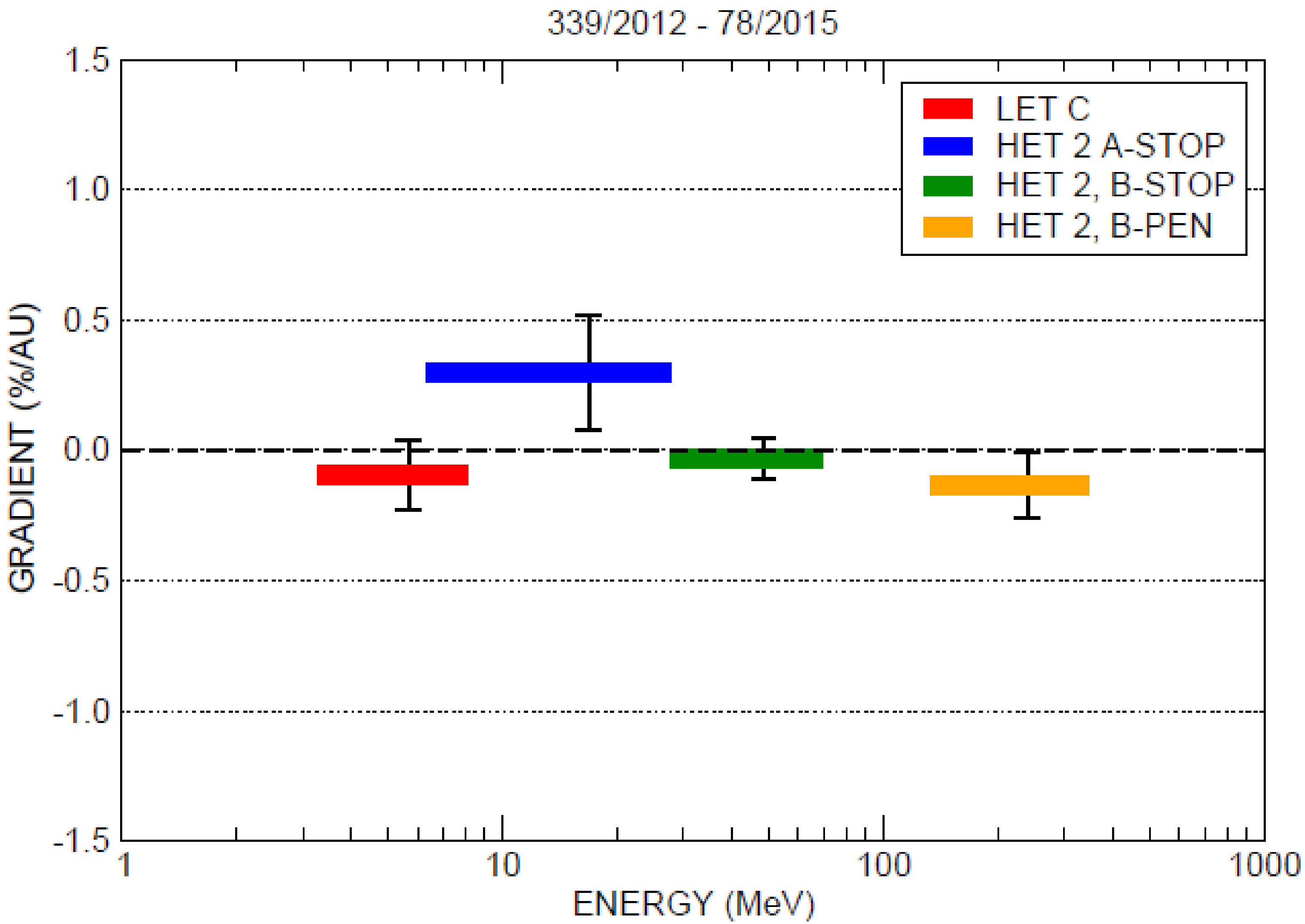
Gradient ~0.5%/AU for ~60 AU after heliopause.

Note: Kota and Jokipii, 2014, dispute the Strauss et al. conclusion that there is a gradient beyond the heliopause.



Intensity vs distance in four GCR energy bands of H.

Fits are shown.



339/2012 - 78/2015

Wed Apr 8 11:08:01 2015

26 Day Averages

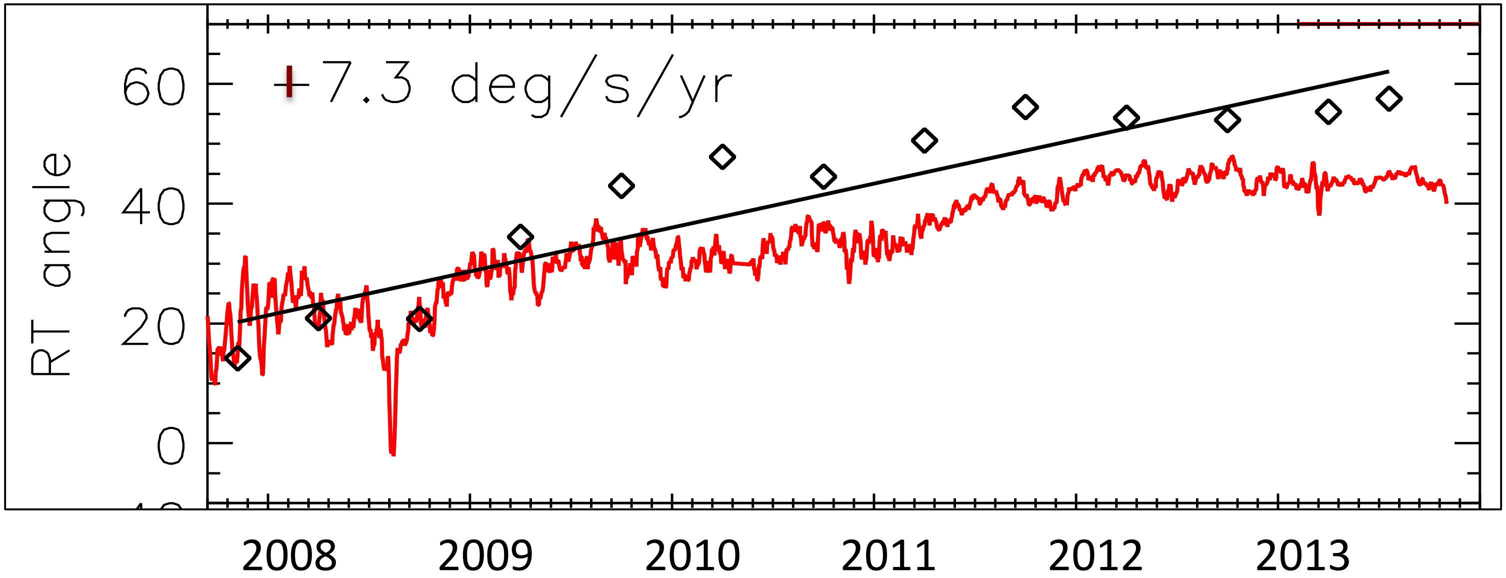
When will V2 reach the Heliopause?

May resolve some of these issues.

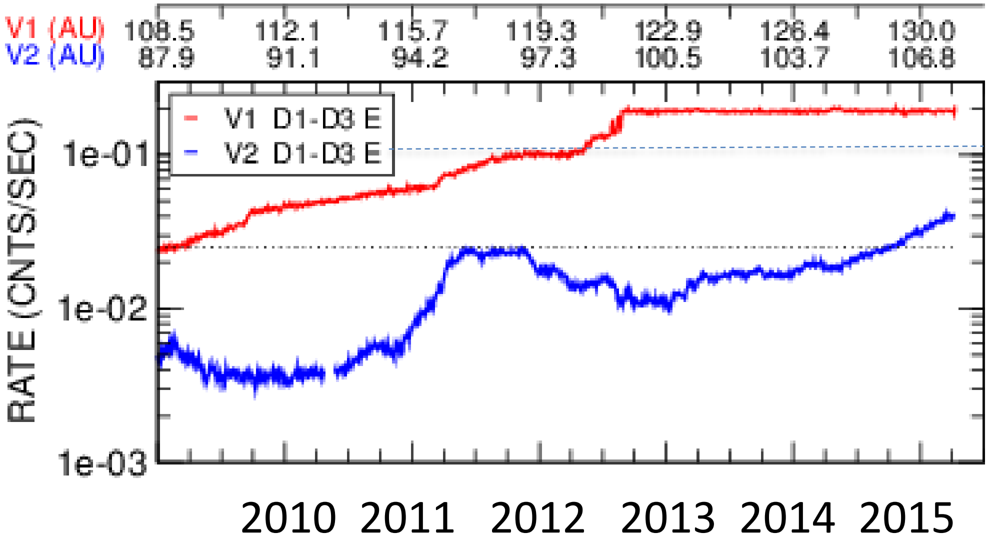
Most simple extrapolation:
If it is 10 AU closer (like the TS) would be at 111 AU;
V2 would cross in 1 year.

When will V2 reach the heliopause?

Extrapolation of the turning of the flow in the RT plane to 90° gives 2.5 years



~2.5 years



Near HP when GCR intensity equals that at V1 GCR increase?

Several more years to heliopause?

(Figure from Stone and Cummings)

Other V1 precursors:

Increase in B
Increase in spectral index of energetic particles

But – don’t know if these were HP precursors or stagnation region signatures. V2 shows no signs of entering a stagnation region.

Summary

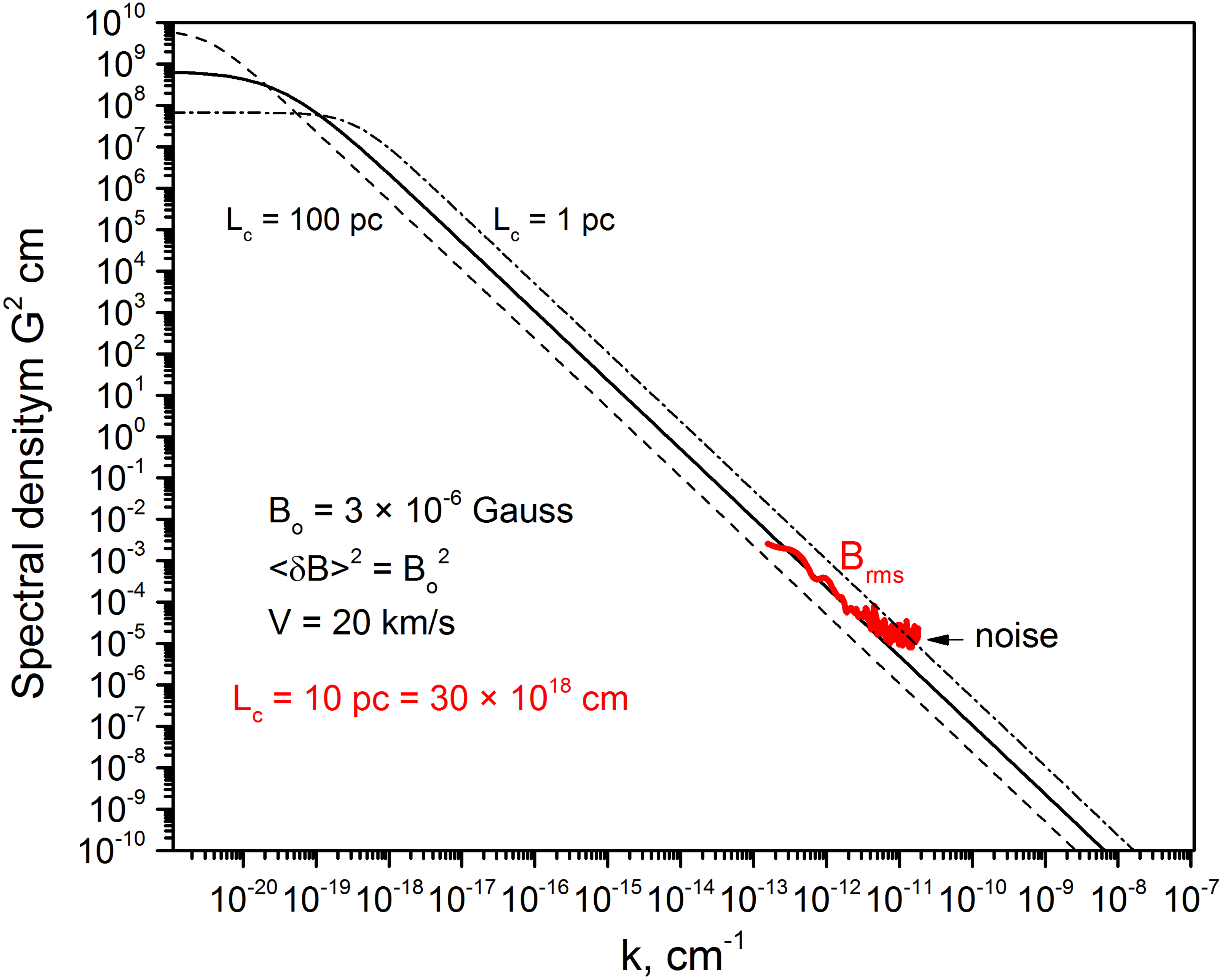
1. V1 and V2 heliosheath have very different flow patterns and electron profiles: these differences are not understood.

2. The heliopause structure is complex: V2 may help understand this region.

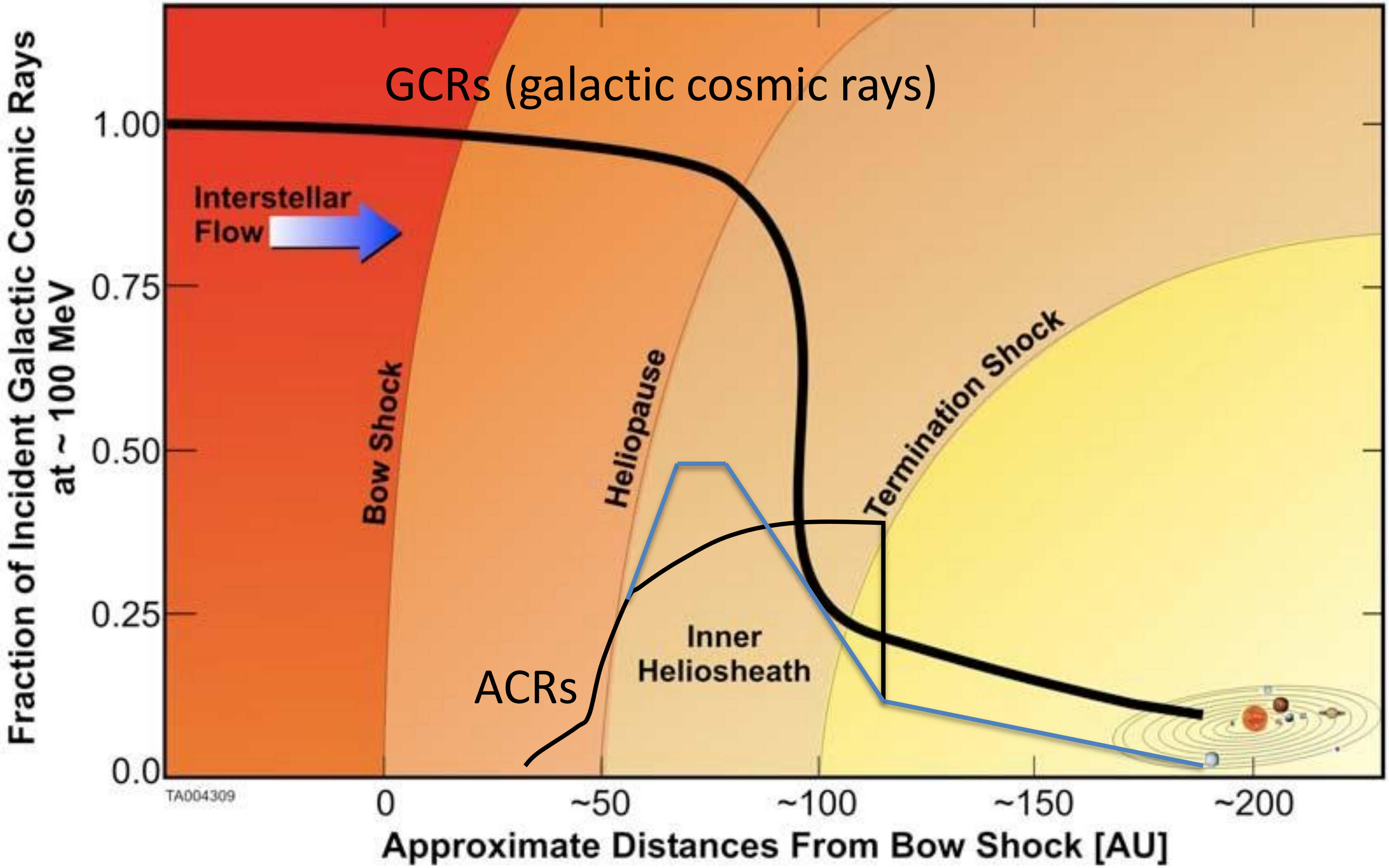
3. The interstellar medium is a very active region apparently driven by solar activity.

4. Have measured LISM CRS intensities down to a few MeV and for many species.

Very weak turbulence SD(§B)/B_{ave} = 0.023



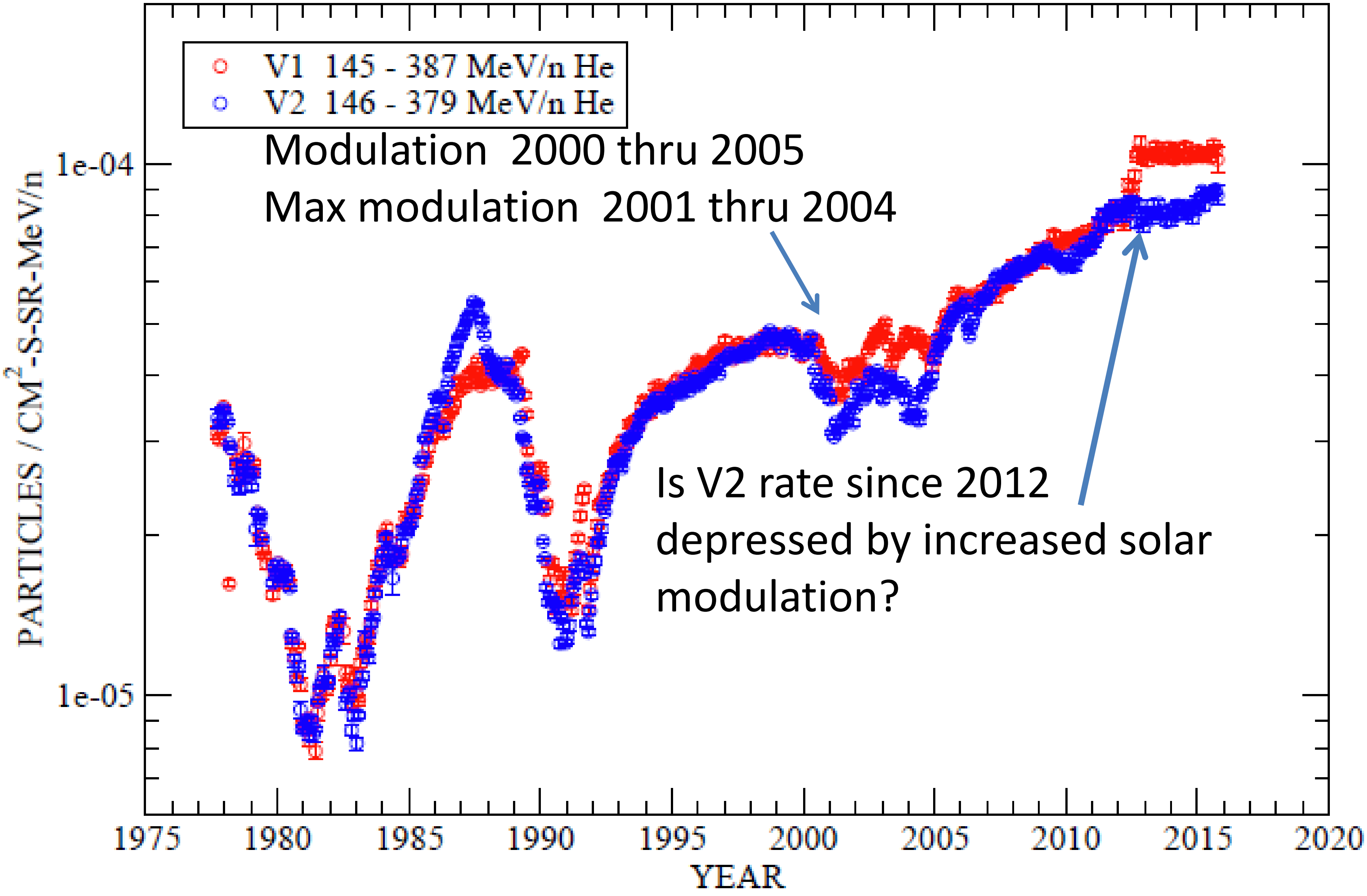
Burlaga, Florinski, Ness



Heliopause signatures: predicted at 135-155 AU

Galactic cosmic rays increase and heliosheath particles decrease.

Cosmic ray overview – Earth to the LISM

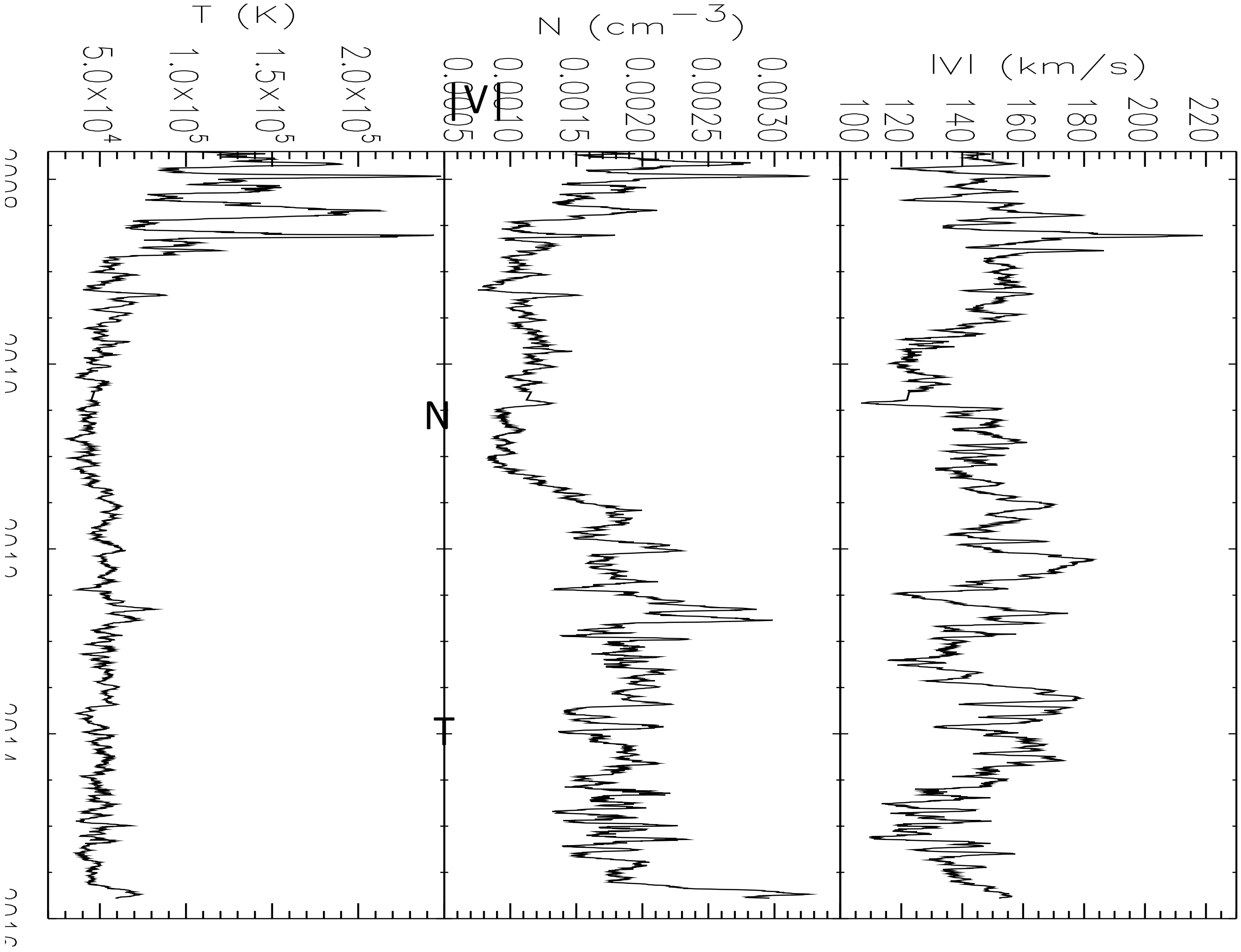


Modulation 2000 thru 2005

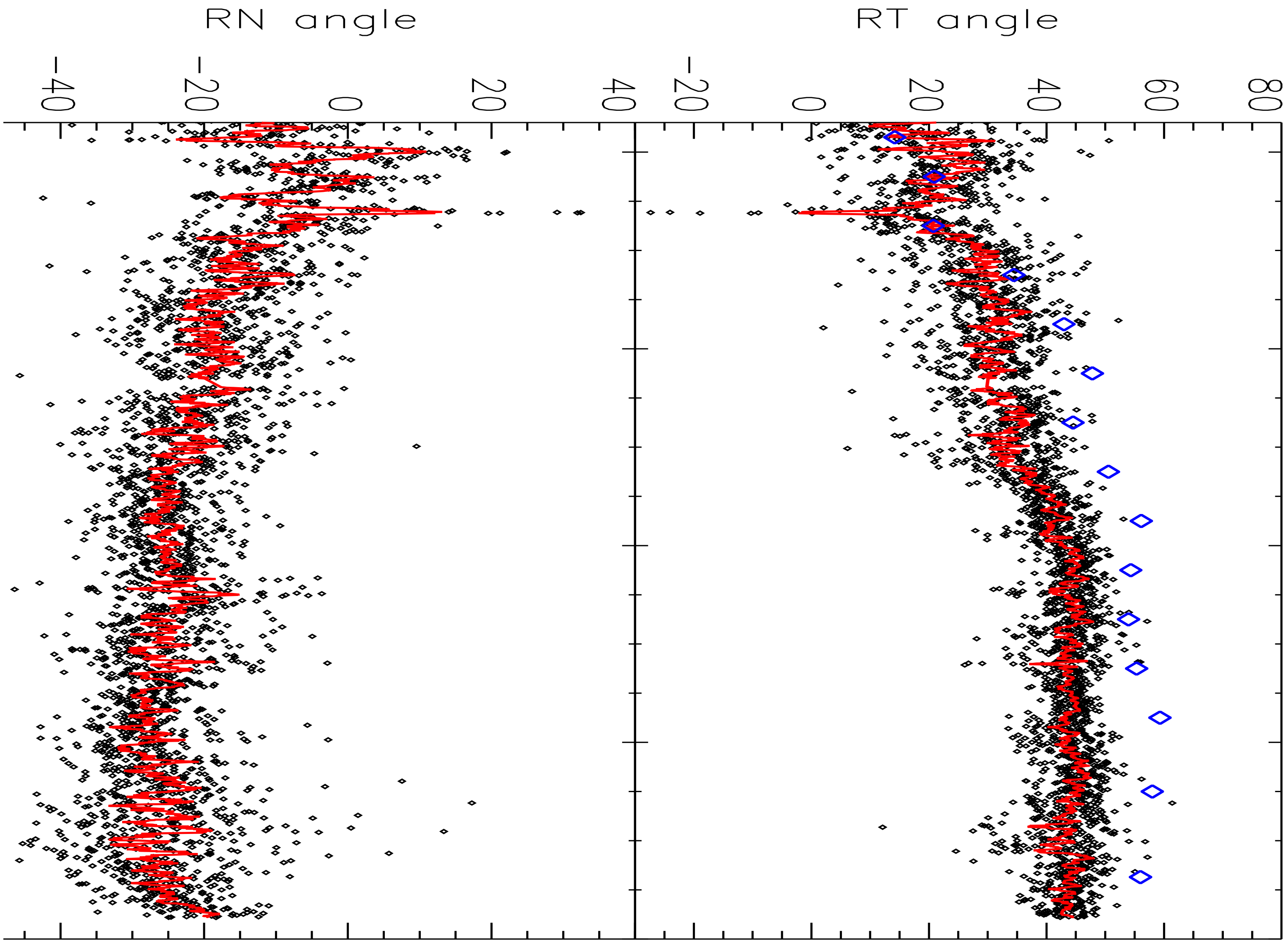
Max modulation 2001 thru 2004

Is V2 rate since 2012 depressed by increased solar modulation?

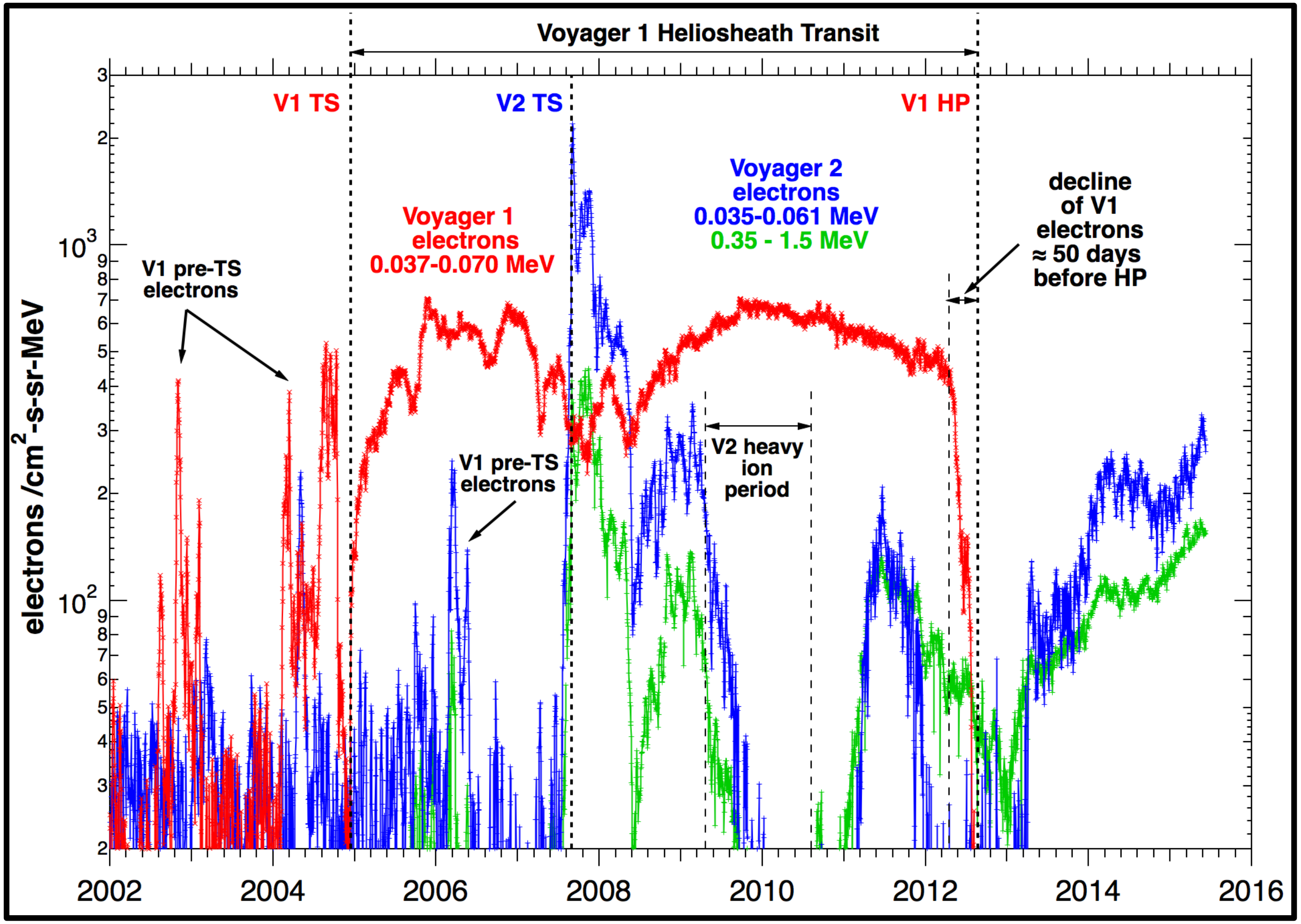
Voyager 2


T (K)
5.0x10^4
1.0x10^5
1.5x10^5
2.0x10^5
N (cm^-3)
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
|V| (km/s)
100
120
140
160
180
200
220
|V|
N
T

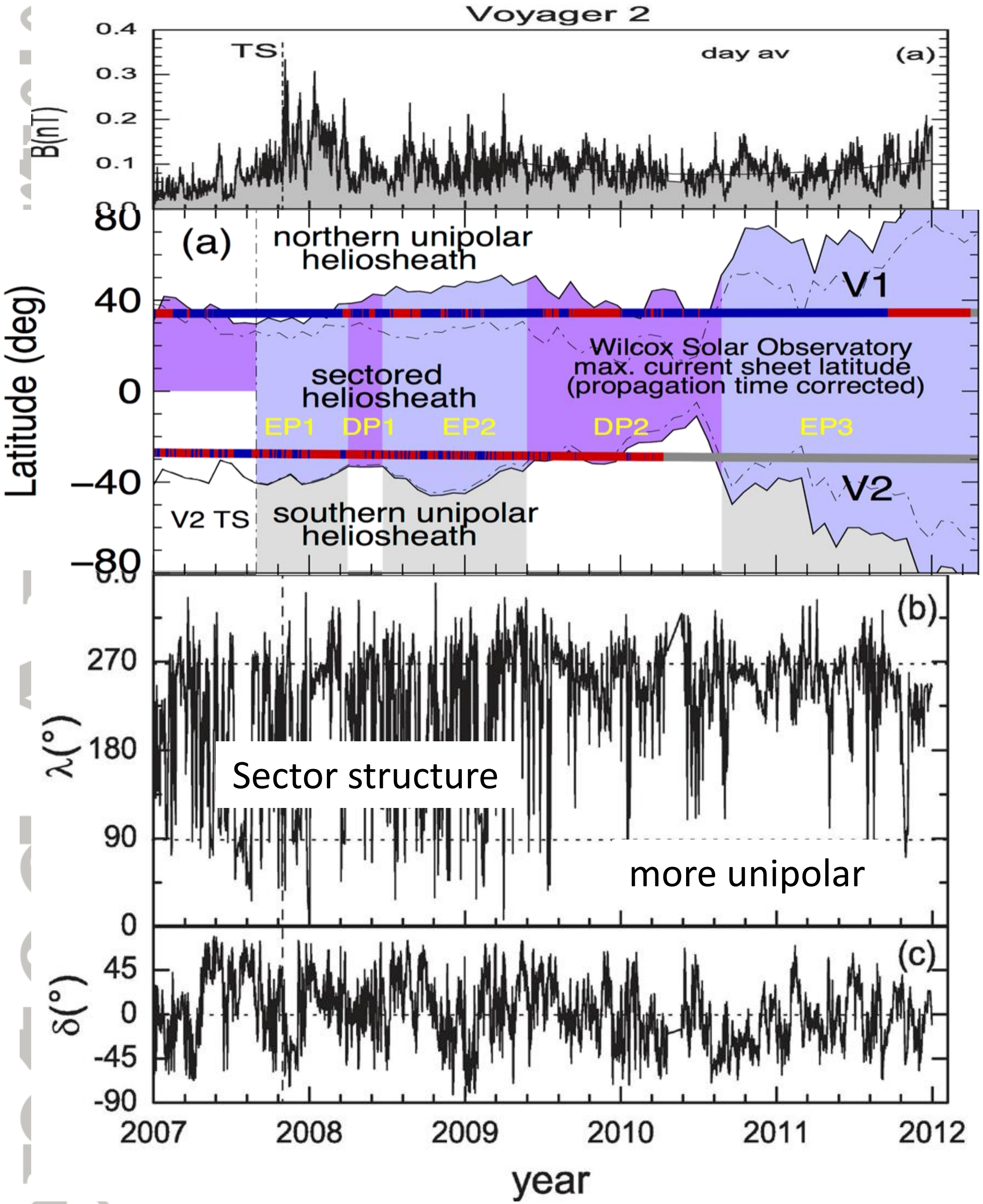
Voyager 2 Flow Angles



Electrons 0.04-1.5 MeV in the Heliosheath



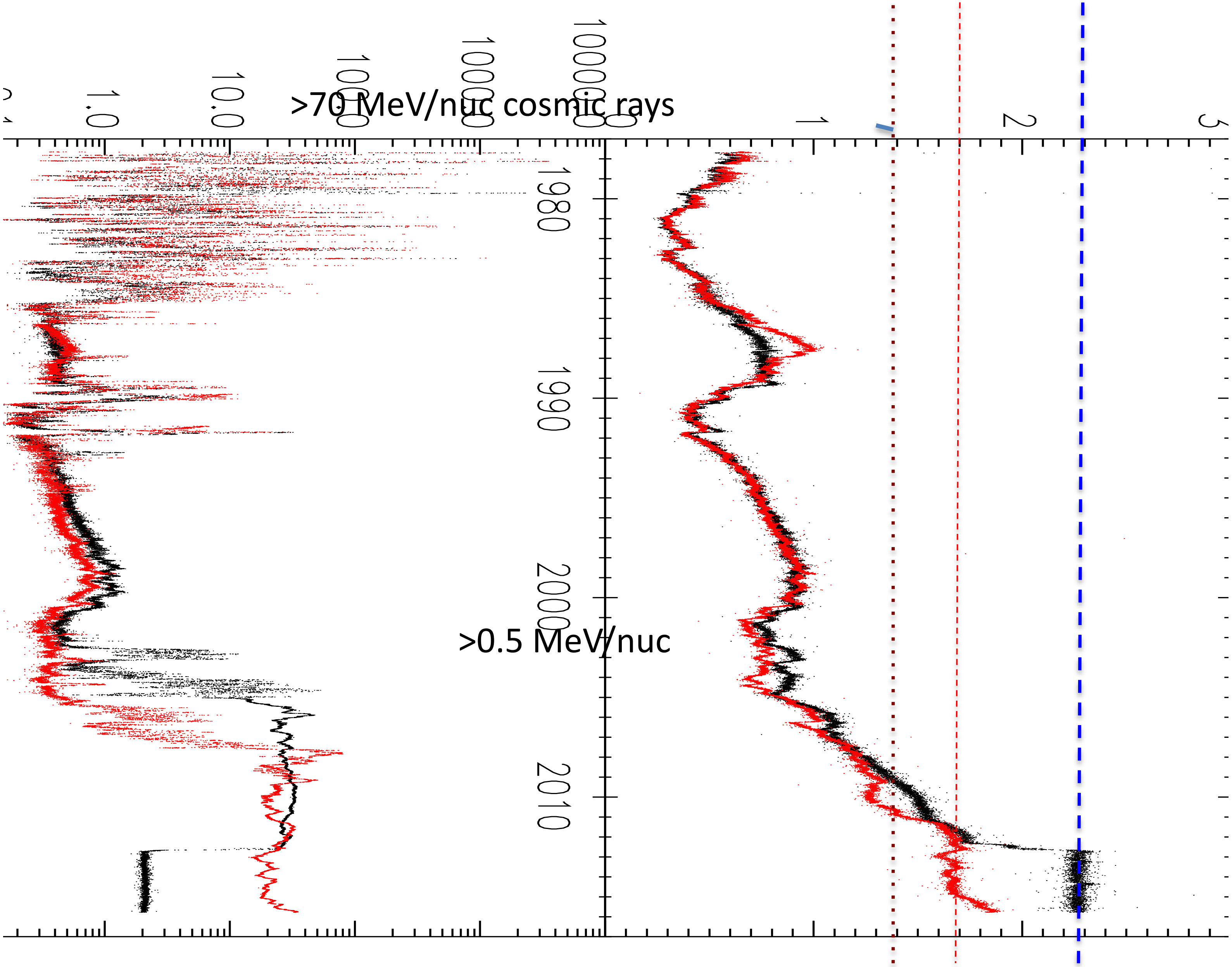
- Electrons 40-70 keV at V1 (red), and 40-60 keV (blue) & 35-3500 keV (greens) at V2
- V1 measured pre-TS HS electrons bursts and relatively steady intensity in the HS (with a factor ~2)
- By contrast, V2 has measured 3-4 episodes of HS electrons
- In most recent V2 episode intensities continue to climb



Sector structure

more unipolar

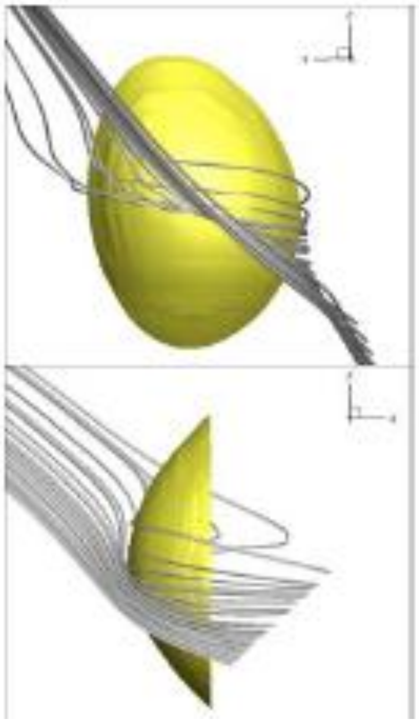
Why isn't V2 in the sectored region given the large "tilt angle" at the Sun? (Plus one might expect the sector zone boundary to be swept up to higher absolute latitudes.)

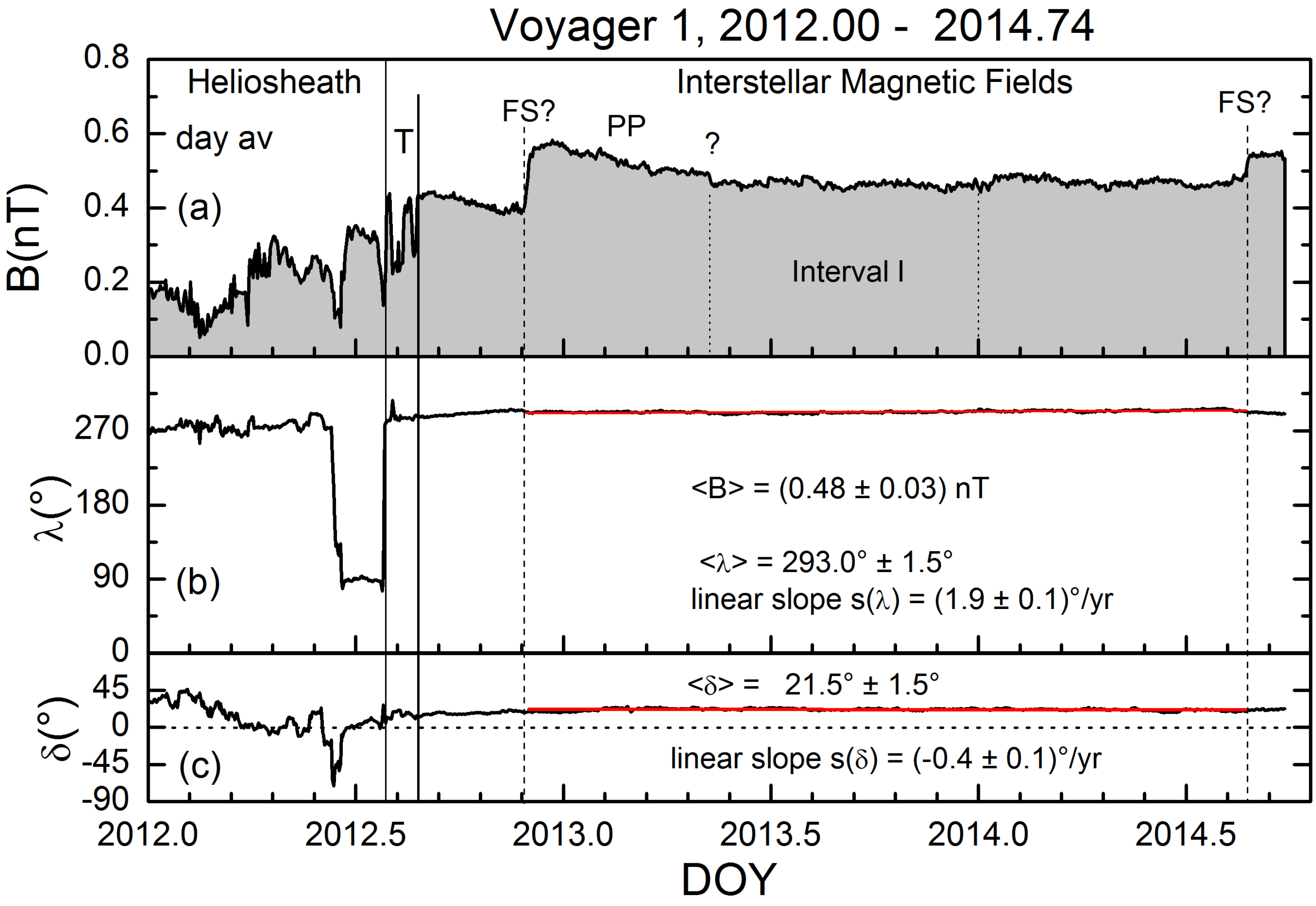


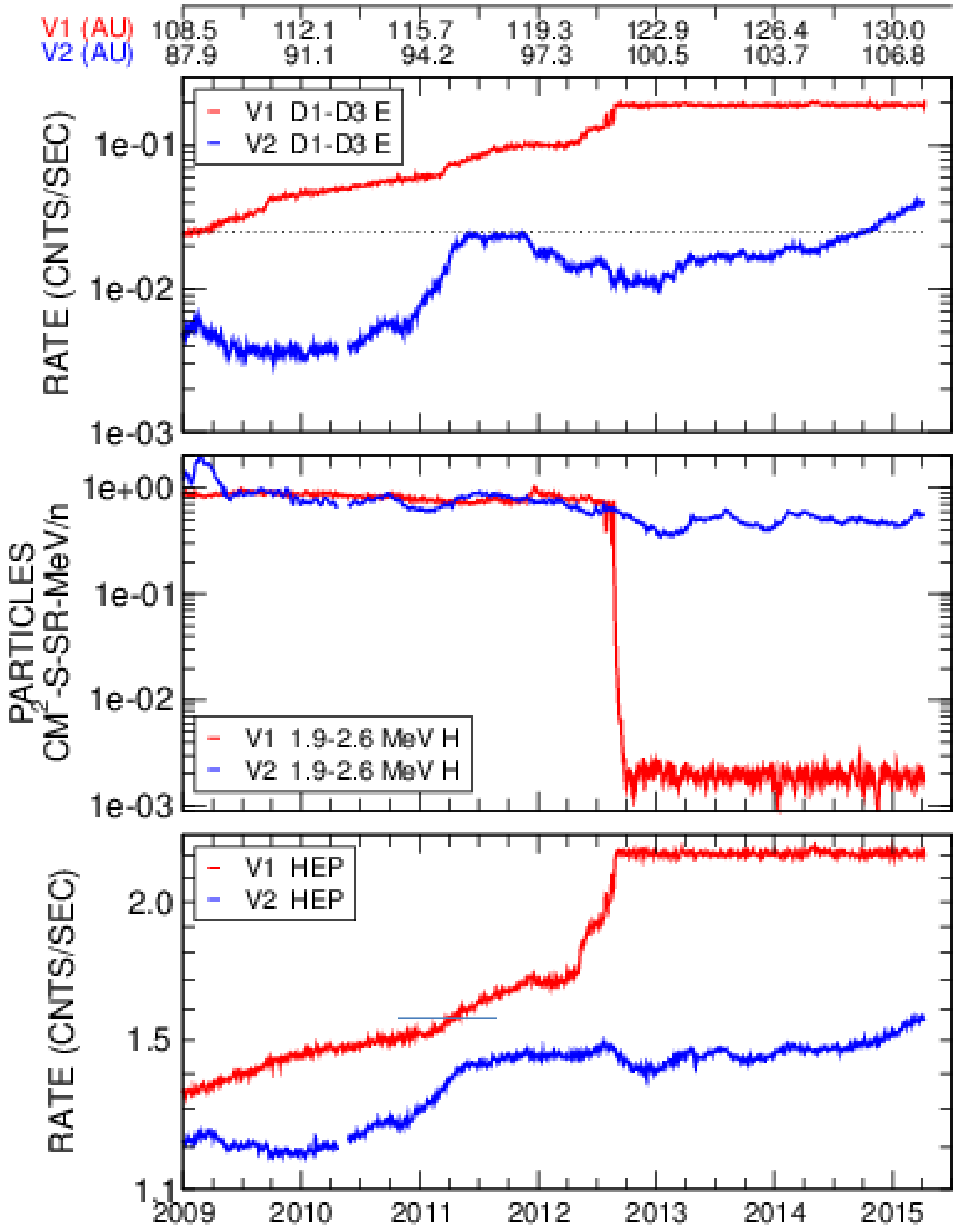
>70 MeV/nuc cosmic rays

>0.5 MeV/nuc

B has rotated after the HP and continues to move away from Parker (consistent with Opher et al. MHD model)







Fri Apr 10 10:04:37 2015

Fig. 1

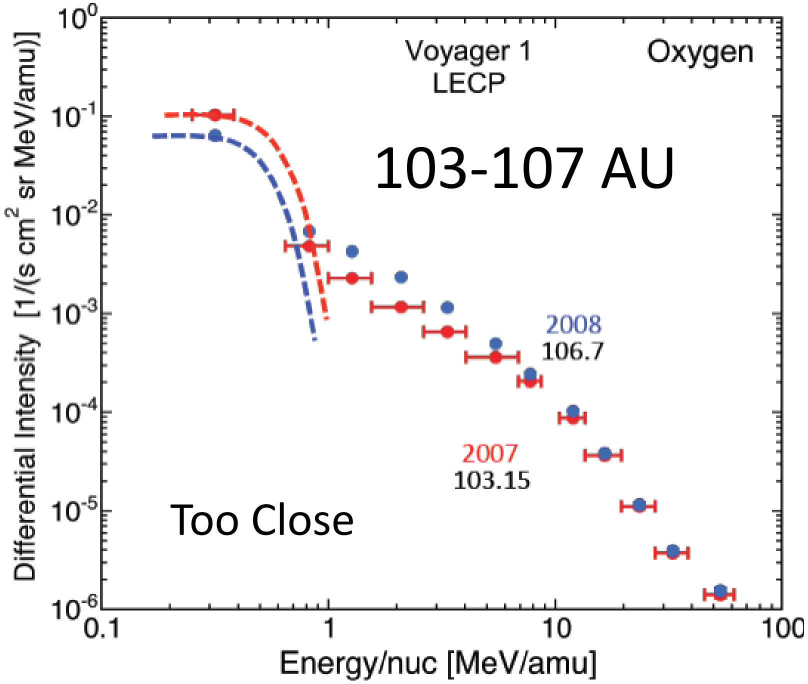
All Data are 5 Day Mvg Avg

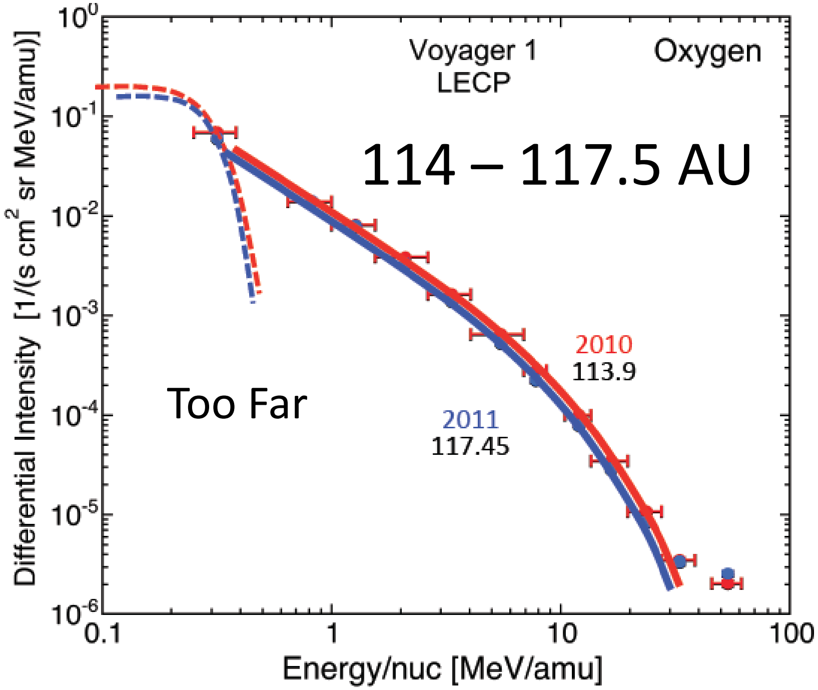
Several more years to heliopause?

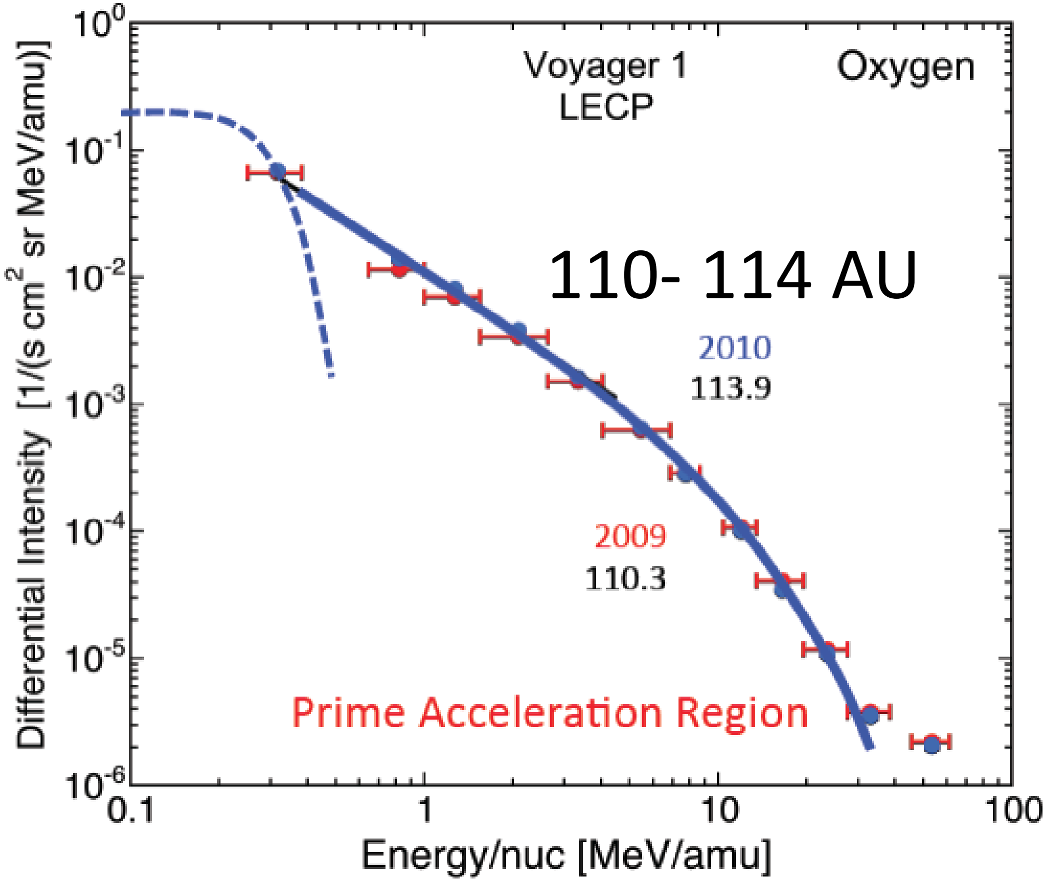
2009 was solar minimum at V1

Now solar maximum at V2

Peak O$^+$ ACR Intensities 16–20 AU past shock

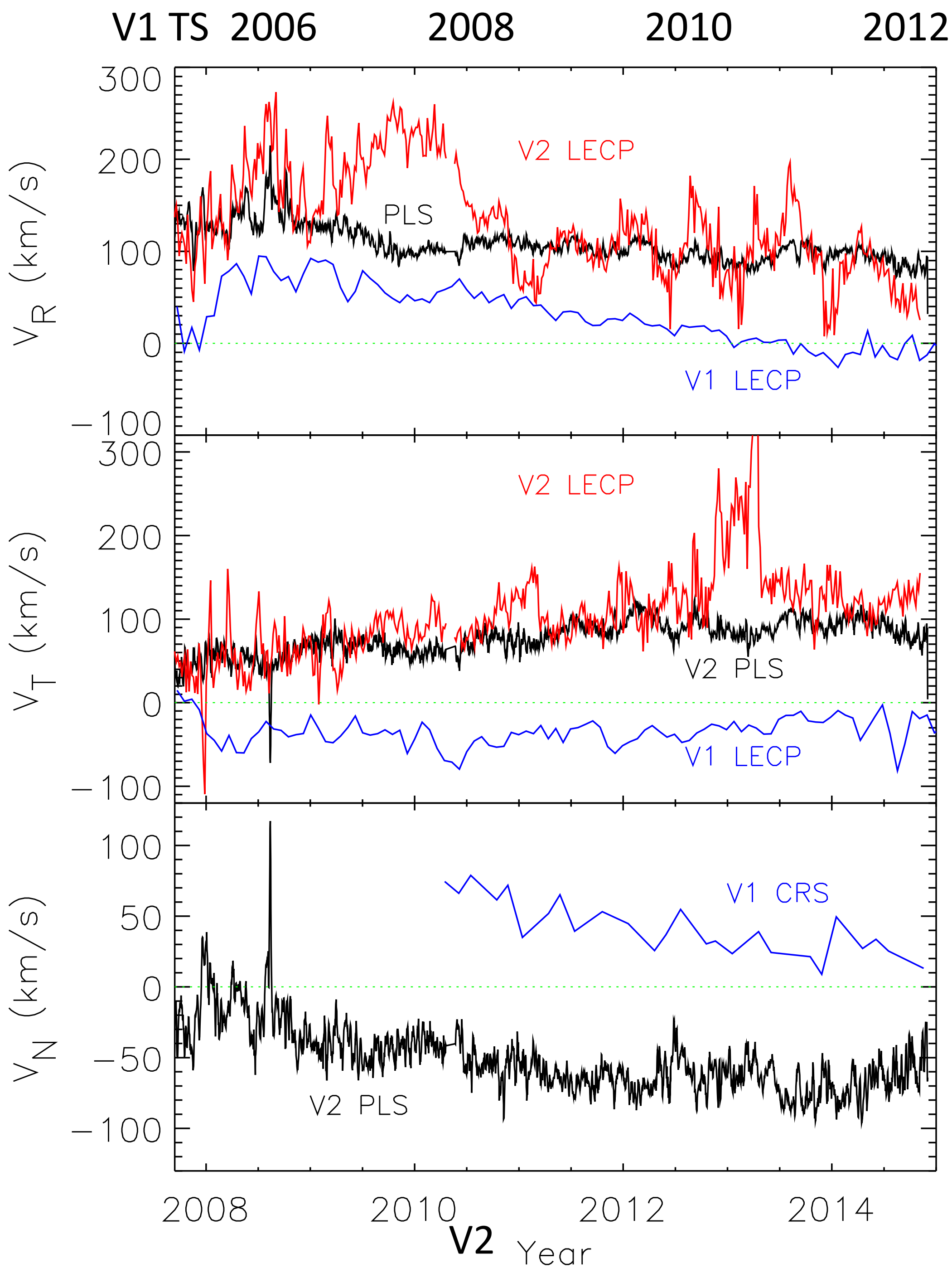






Where is the ACR source?

Figures from G. Gloeckler

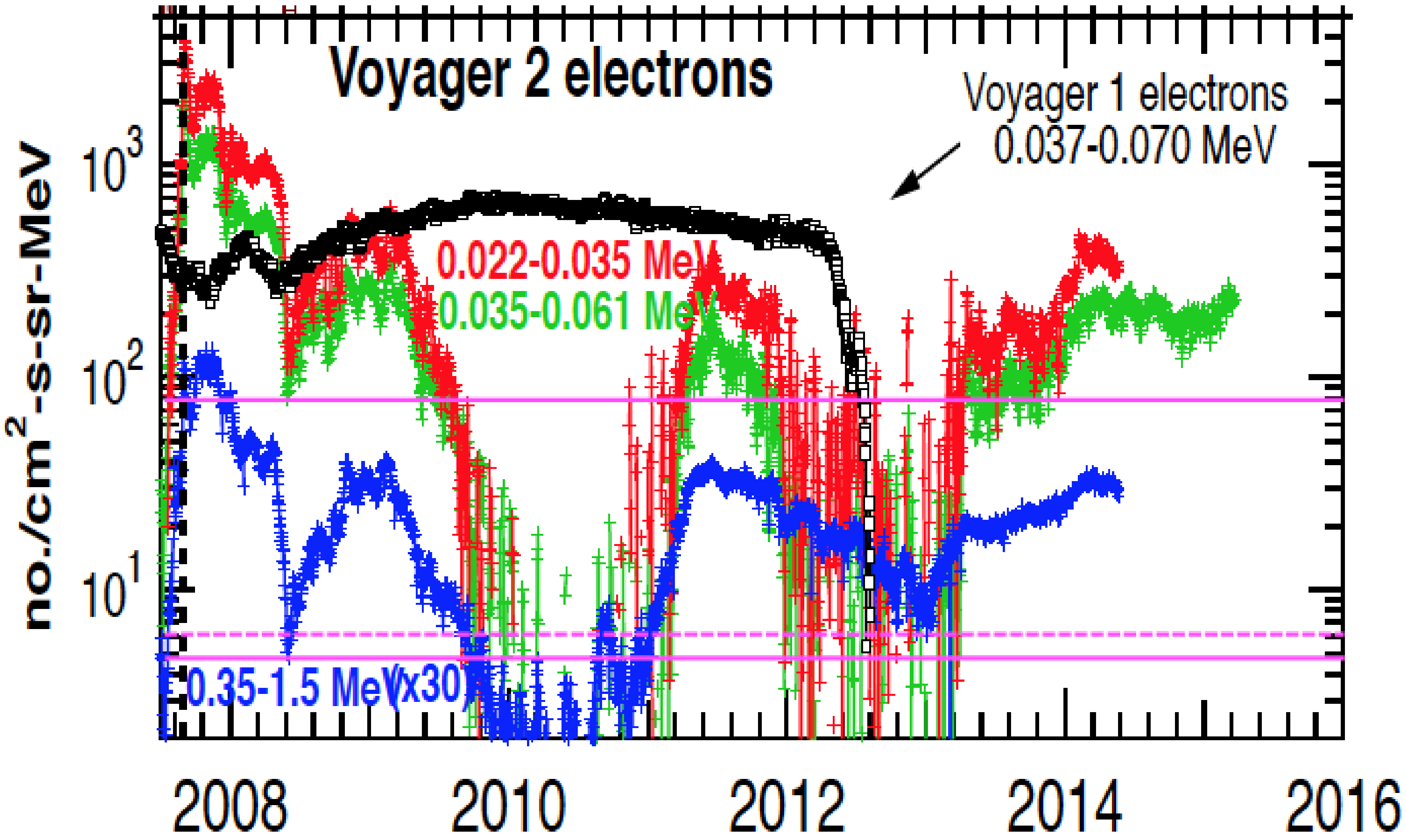


V1 and V2 velocity (left axis is TS for both V1 and V2; flows at V1 and V2 are very different. V1 flows are derived from energetic particle (LECP) fluxes using the Compton-Getting effect assuming isotropic protons . V2 flows are measured directly by PLS.

V2 LECP and PLS speeds match well except in two time periods. In period A, VR from LECP is larger than for PLS. The plasma in this region may contain oxygen ions, which would give an overestimate of the speed.
In region B, VT from LECP is too large; in this region they observe particle streaming along the magnetic field so the Compton-Getting requirement of isotropy is violated.

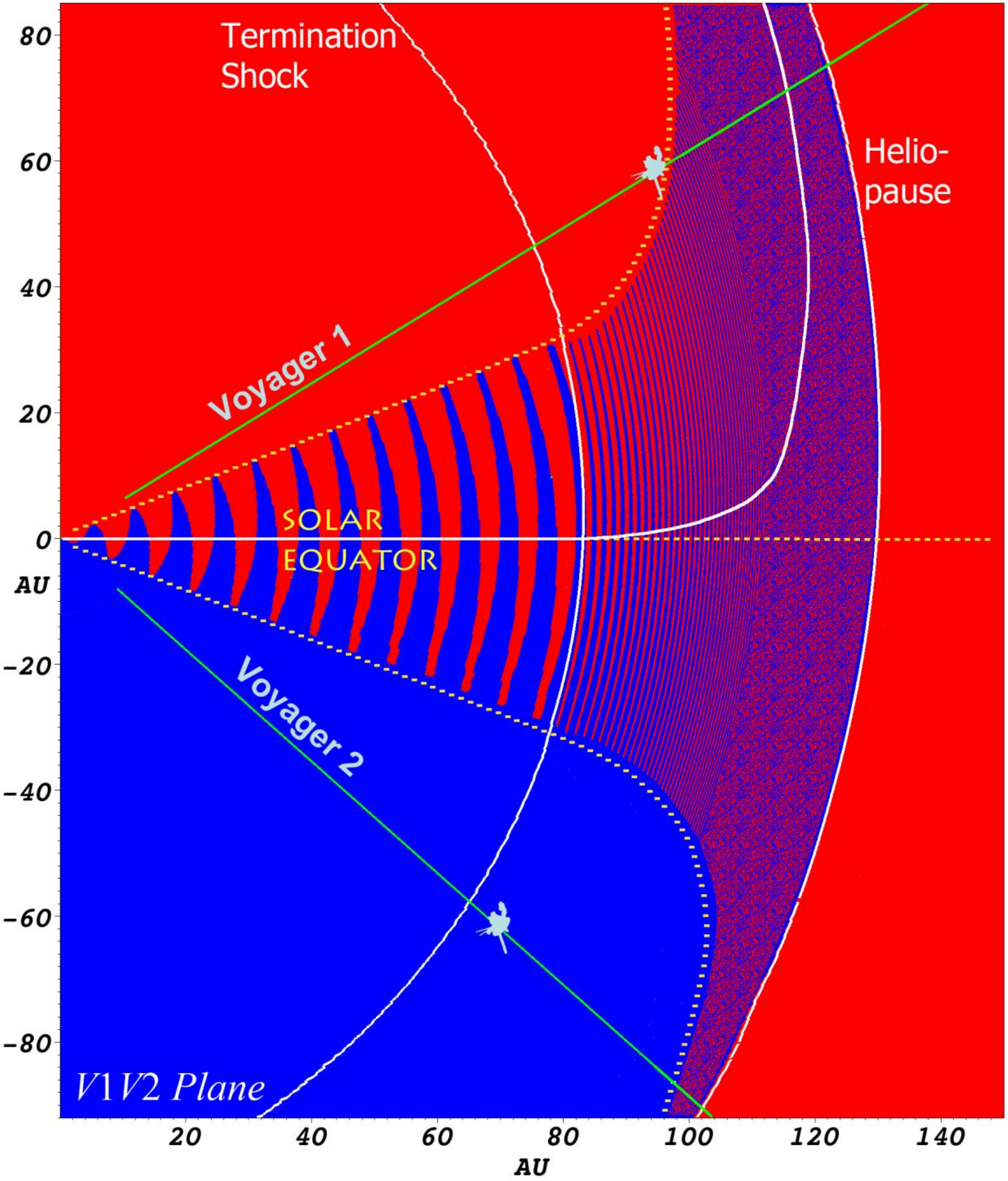
So LECP and PLS speeds generally agree at V2, so we expect the LECP V1 speeds are accurate.

(Richardson and Decker, 2014)


Voyager 2 electrons
Voyager 1 electrons
0.037-0.070 MeV
0.022-0.035 MeV
0.035-0.061 MeV
0.35-1.5 MeV(x30)
no./cm2-s-sr-MeV
10^3
10^2
10^1
2008
2010
2012
2014
2016

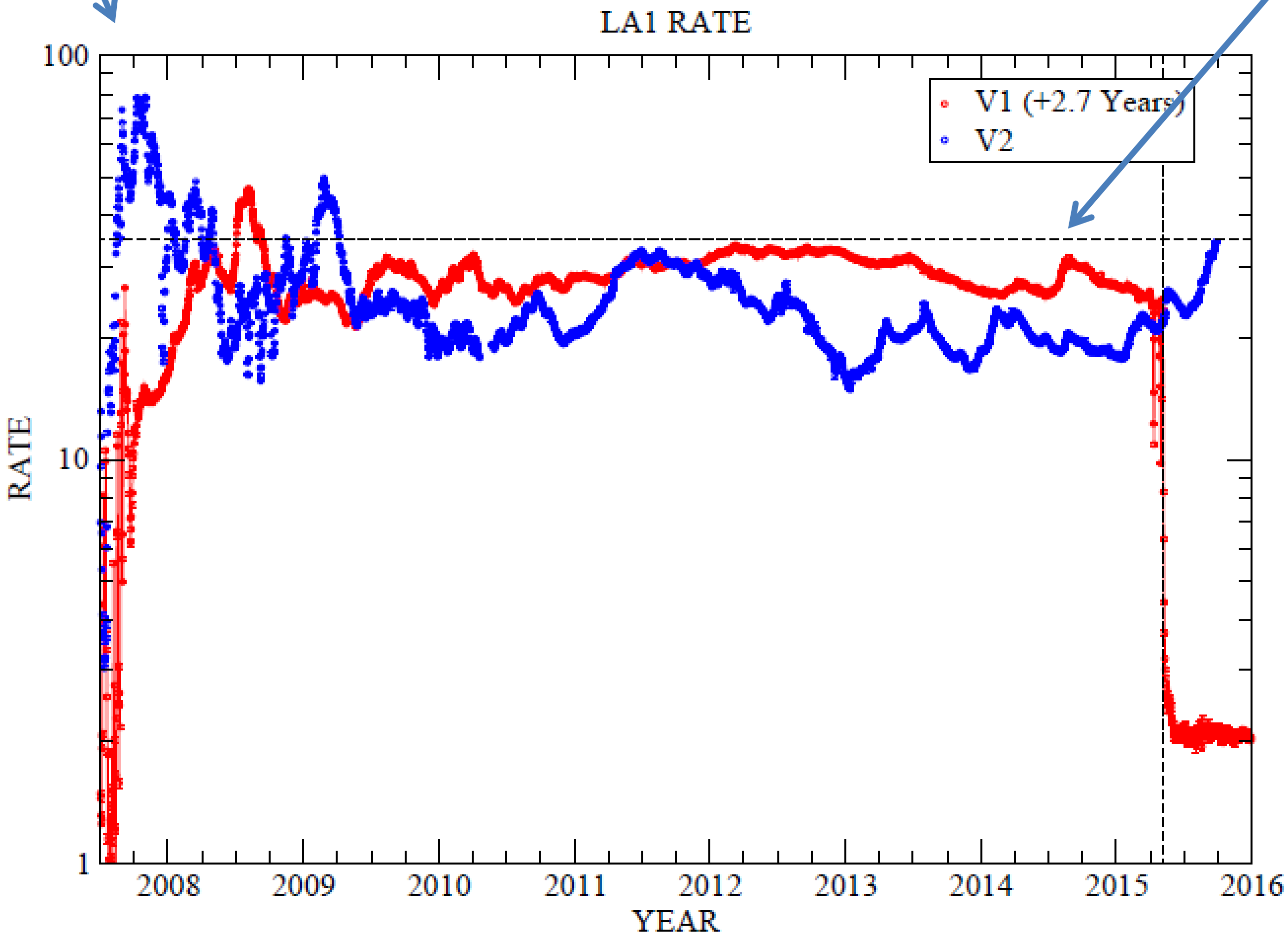
Magnetic Reconnection?
(Opher, Drake, Lazerian)

HCS are compressed,
Reconnection could
Lead to formation of
Magnetic bubbles and
Particle acceleration.

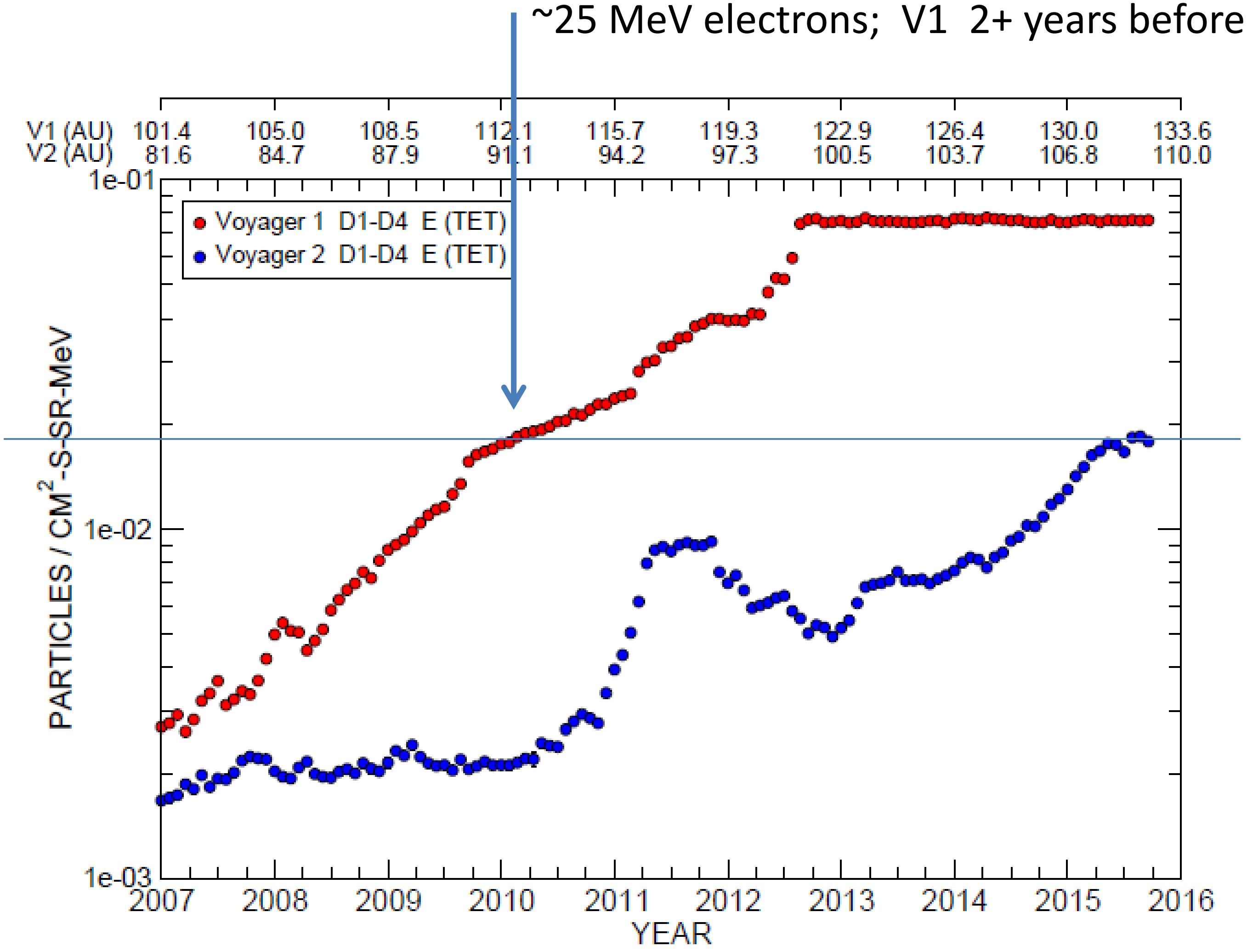


Shifted V1 to match V2 TS crossing

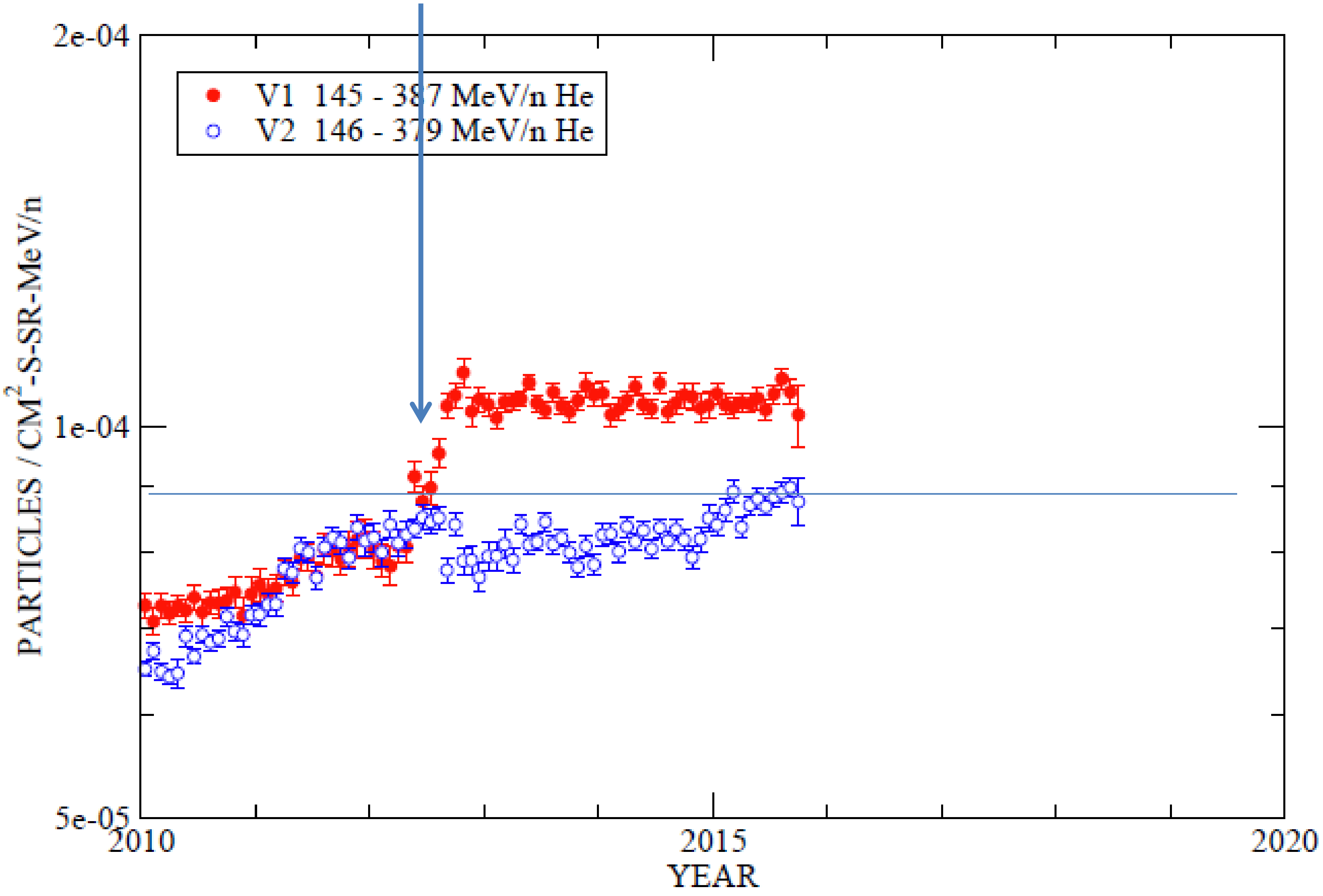
>0.5 MeV; V1 decreasing for year prior to HP
V2 has increased over last year



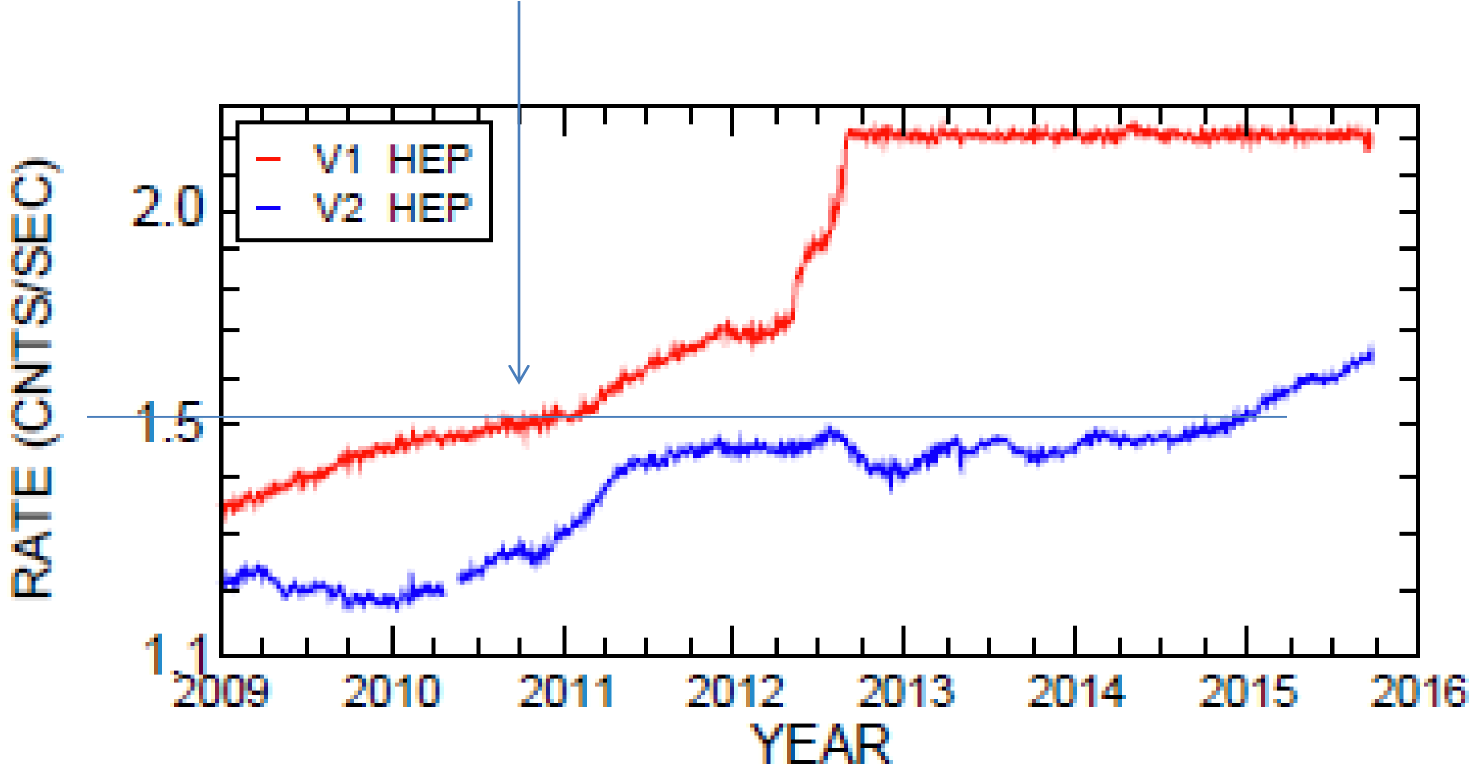
~25 MeV electrons; V1 2+ years before HP



~270 MeV He; V1   4 months before HP



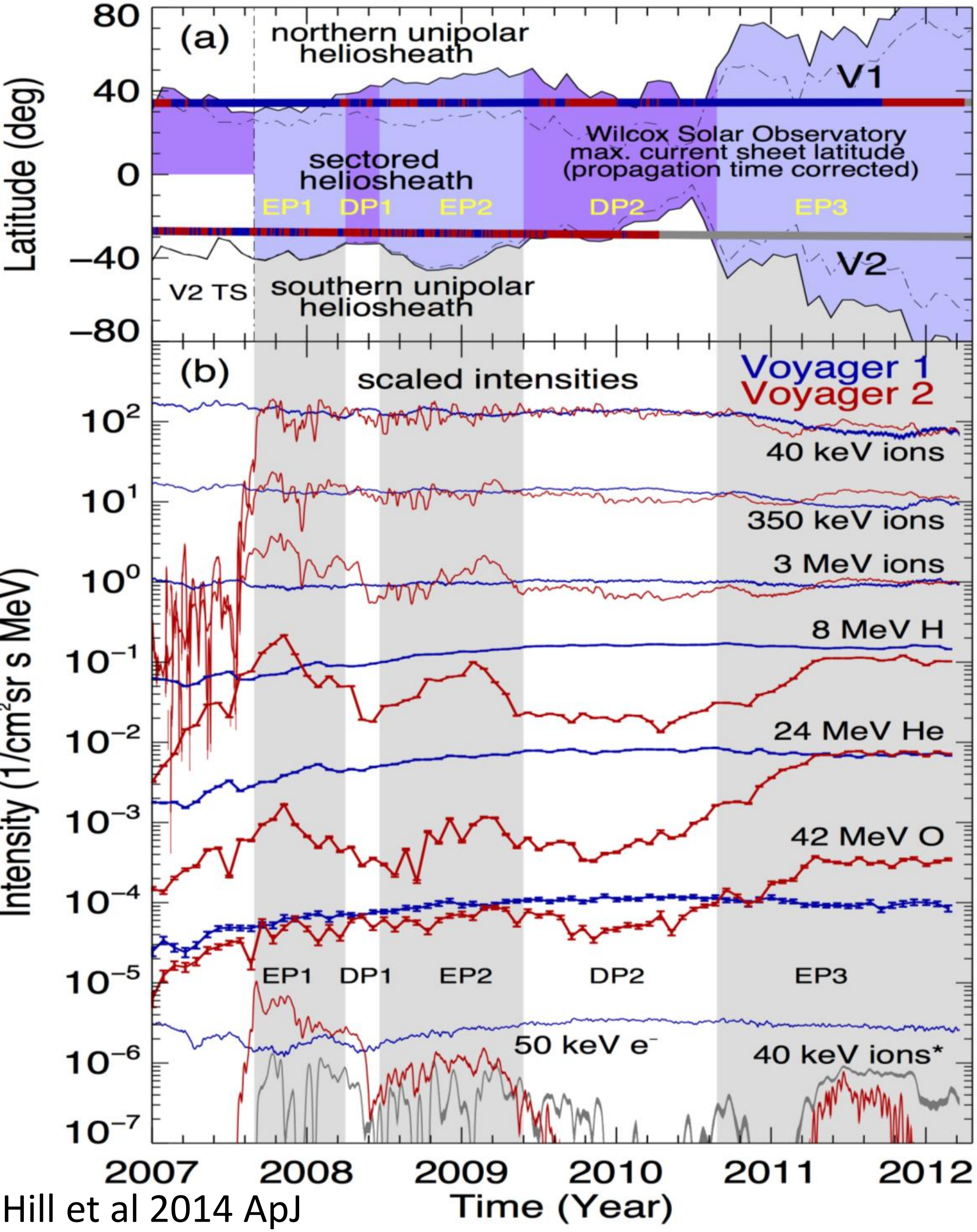
> 70 MeV   ~1 year before HP



Thu Sep 24 17:23:39 2015

Fig. 1

All Data are 5 Day Mvg Avg



Hill et al 2014 ApJ

Voyager 2

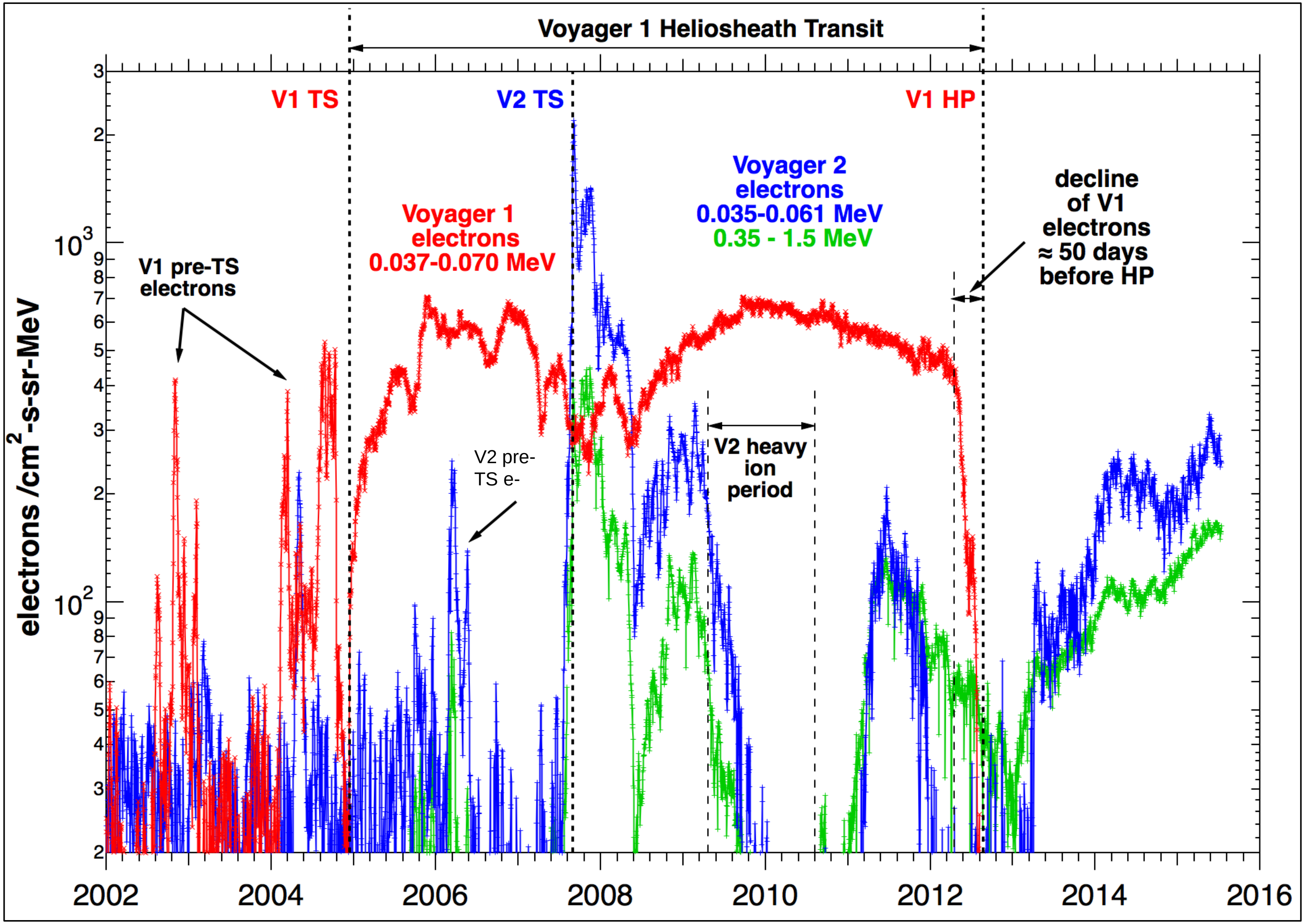
Prime Observation that we're trying to explain.

V1 particle data (blue): slowly varying flux.

V2 particle data (red): "Rapidly" varying flux with up to 2 order-of-magnitude change over ~10^4 range in rigidity from ~50 keV local e- to >200 MeV GCR protons.

- Why so different?
- Why do so many particles vary coherently?
- Is there a relationship to the global magnetic field structure.

Electrons 0.04-1.5 MeV in the Heliosheath



Voyagers 1 and 2:

Launched Sept 5 and Aug 20, 1977:

38 years old!

At 133 AU and 109 AU

(~18 and 15 light hours)

We receive 8-12 hours of data/day

Plasma data only from V2.