Response of the PUI VDF to Variable Solar Wind Conditions

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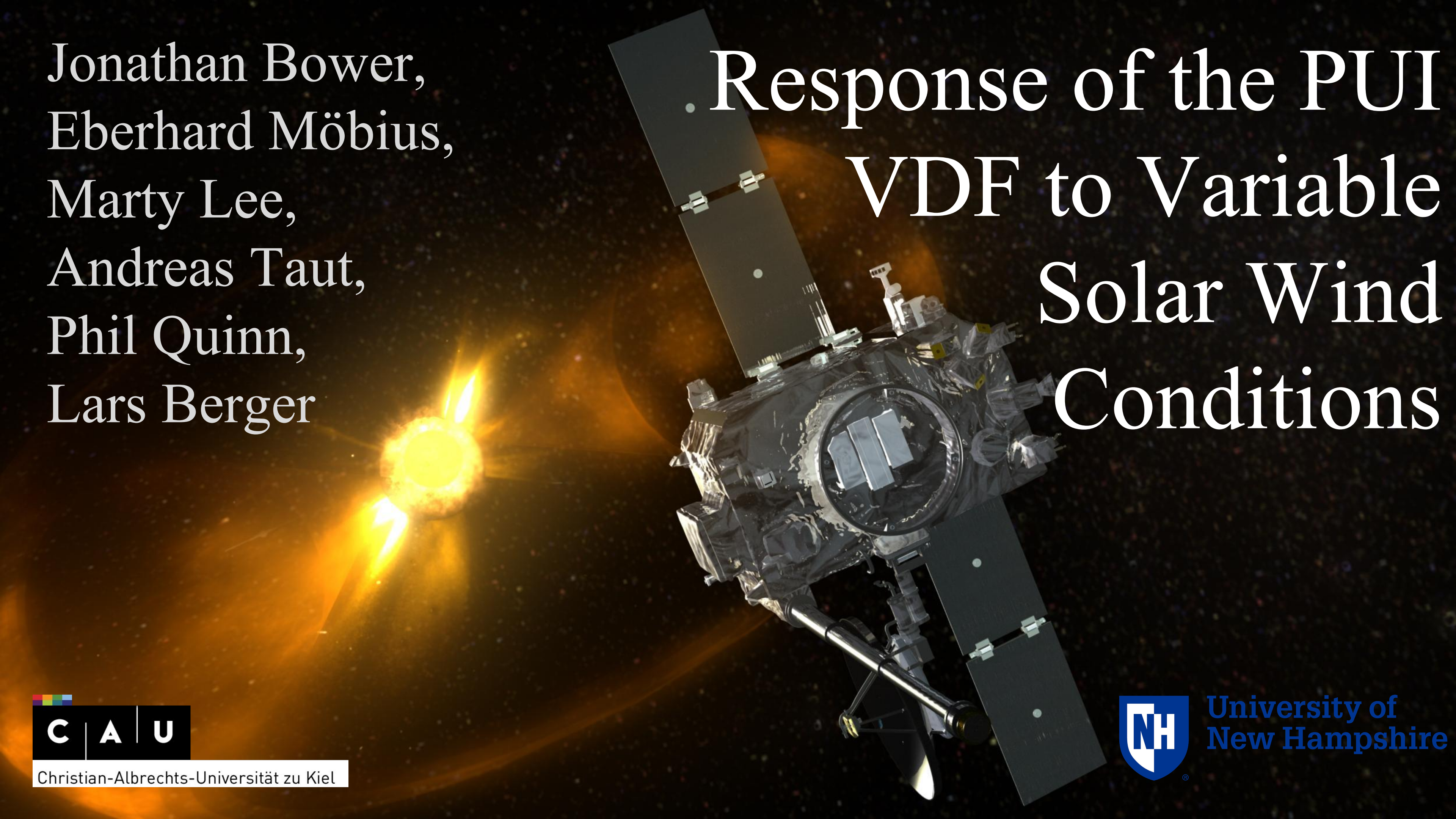


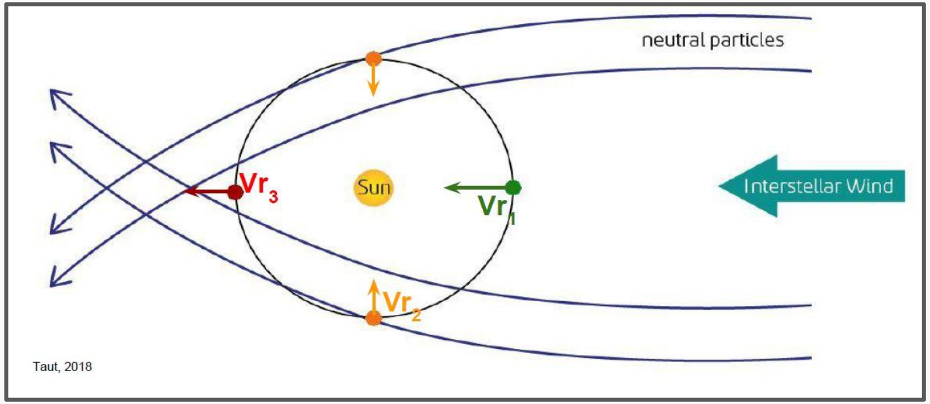
Outline

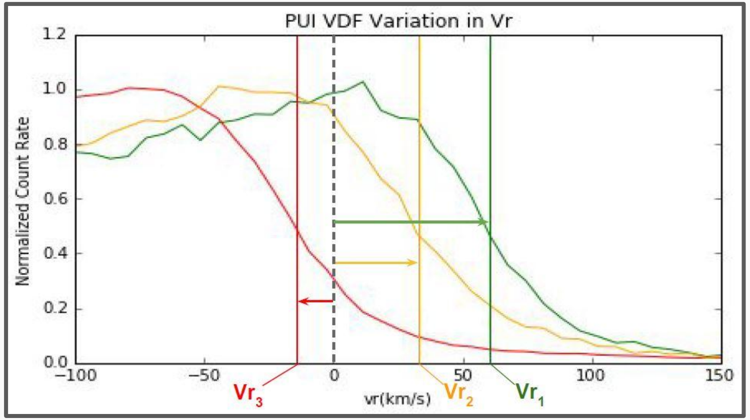
1. Measuring the Neutral Inflow using the PUI cutoff shift
2. PUI VDF in Variable SW conditions
    a. Data Treatment
    b. Local Fluctuations in SW Parameter Dependence
    c. Compression Regions Defined by Structure
    d. Interplanetary Shocks
3. Compression Removal
4. Conclusion

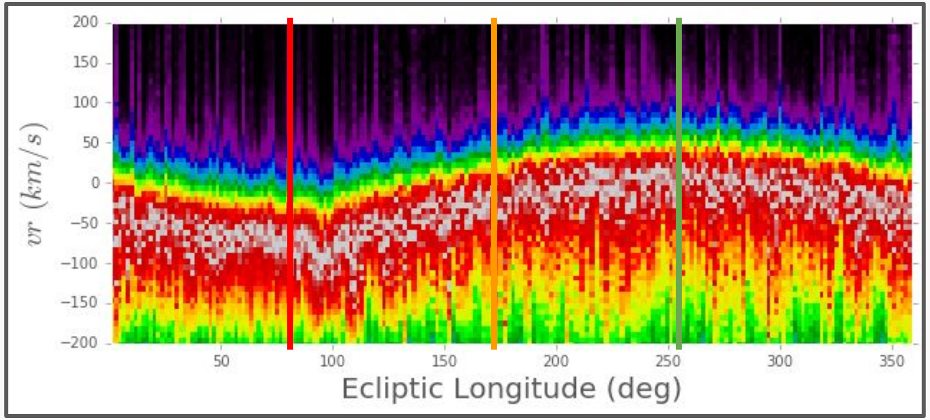
The Cutoff Variation in Vr

The incoming neutral radial speed changes with ecliptic longitude due to gravitational lensing, allowing for measurement of the neutral flow direction.

- Overlay of 7years of STEREO A. He+ PUI measurements
  - 2007-2013







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Determining the Inflow

- Cutoff is measured in 1deg bins
- Inflow can be determined by fitting model vr to the Measured cutoff in Vr

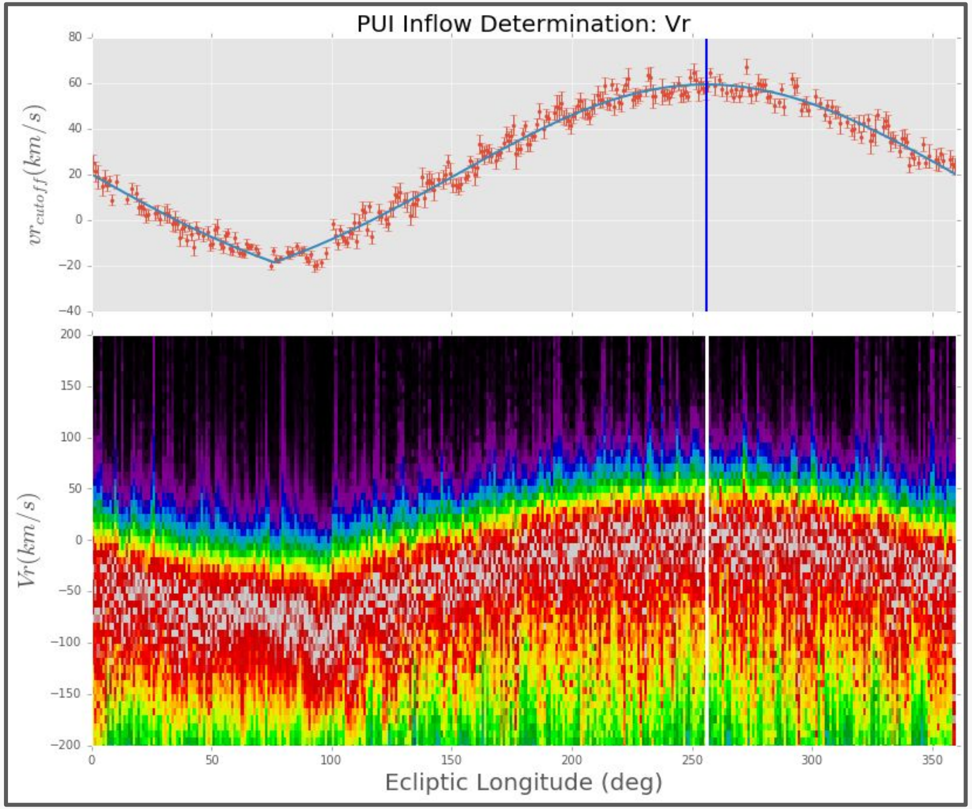
$$v_r^2 = 2 + v_{ISN\infty}^2 - (1 - \cos\lambda) - [v_{ISN\infty}^2 \sin^2\lambda + \{v_{ISN\infty} \times \sin|\lambda|[v_{ISN\infty}^2 \sin^2\lambda + 4(1 - \cos\lambda)]^{1/2}\}]/2$$

Moebius et al. 2015

$\lambda_{Inflow} = 255° \pm .48$

- Mirror correlation around peak yields similar result

**Still need to identify and remove/reduce systematic effects to reduce error in the measurement of the inflow.



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Systematic Effects on Inflow Determination:

- Pickup ion Acceleration
  - Removal routine [Taut et al. 2017]
- Shift of PUI cutoff due to:
  - **Compression Regions**
    - Known examples [Saul et al. 2003]
  - **Interplanetary Shocks**

Scope of Project:

- **First systematic study to understand PUI behavior in compression regions and interplanetary shocks**
- **Develop criteria to eliminate or correct for effect of compressions and shocks on the determination of the ISN flow direction.**

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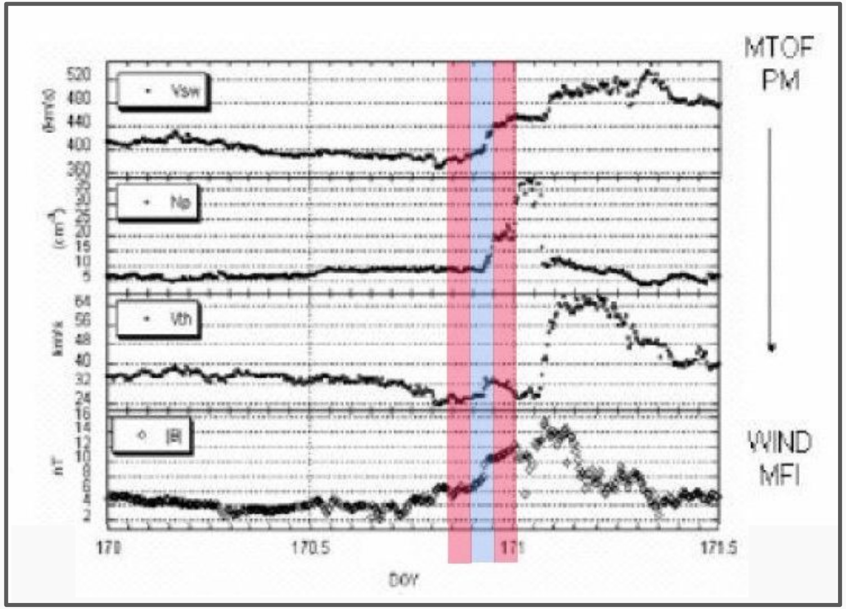
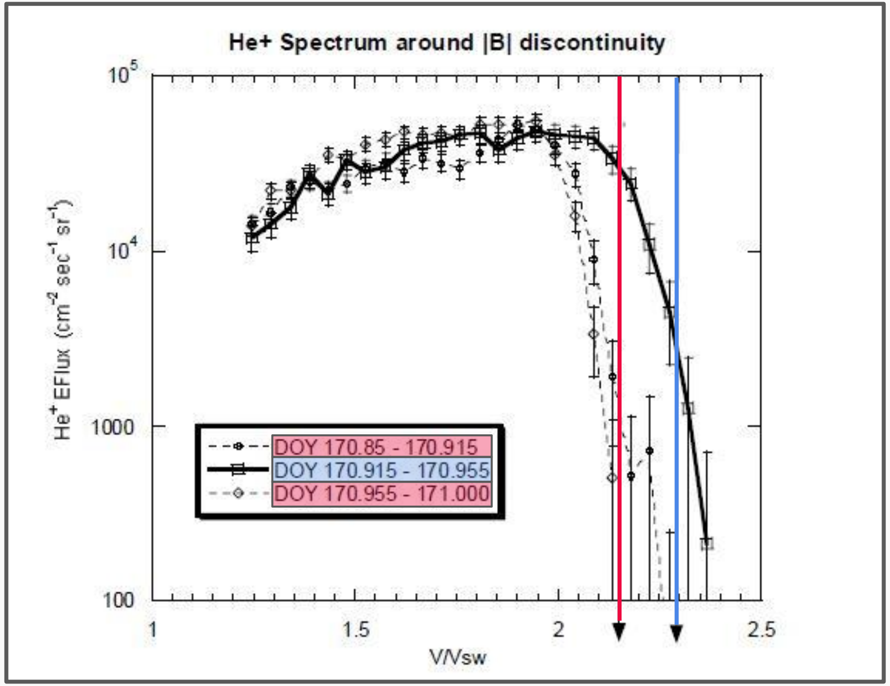
PUI Heating in Compression [Saul et al. 2003]





Individual compression effect discovered, need to identify many compressions in order to see effect

Saul et al. 2003

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Analysis: PUI VDF in Variable SW Conditions

1. Data Treatment
    a. Removal of Longitudinal dependence
2. Local Fluctuations in SW Parameter Dependence
3. Compression Regions Defined by Structure
    a. Compression Region Geometry
    b. Identifying Compressions
    c. Effect of Compressions on PUI Cutoff
4. Interplanetary Shocks

Identifying The PUI cutoff

PUI cutoff determined through several methods:

<u>Half Max Routine</u>

- Smooth Count rate after peak
- Interpolate VDF
- Identify point where function falls to ½ peak height
- Stable with low statistics

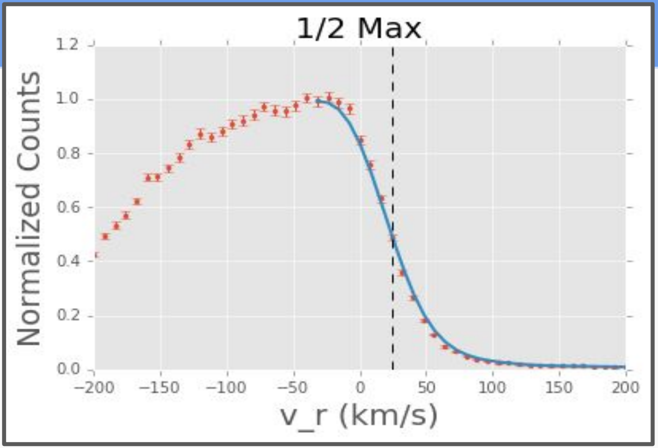
<u>Functional Fitting (Tanh Moebius et al. 2015)</u>

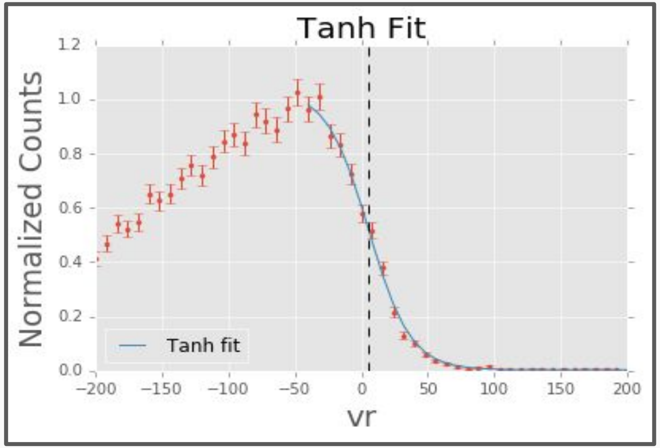
- Fit VDF after peak with Tanh function (least squares minimization).

$$c = (1 - \tanh((w_0 - w_{cutoff}) * a))/2$$

c : counts, w_0: PUI velocity, w_{cutoff}: inflection point, a:steepness

Moving forward only half max routine is used





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Flatfielding Longitudinal Dependence

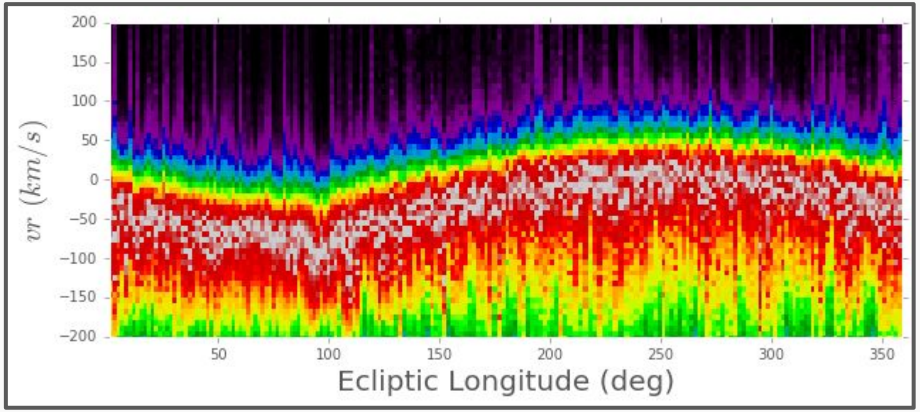
In order to Accumulate PUI counts across all longitude for compression study, longitudinal variation of PUI radial speed must be removed

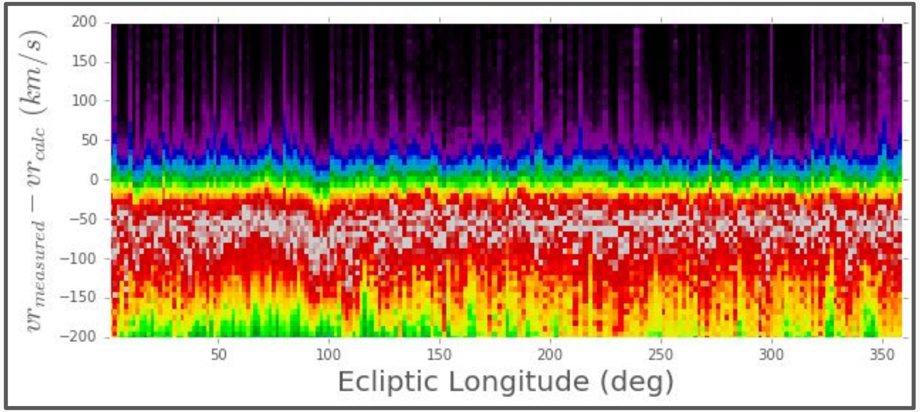
- Achieved by subtracting modeled cutoff shift, Vr(λ), Prior to PUI count binning
- Parameters determined through fitting

$$v_r^2 = 2 + v_{ISN\infty}^2 - (1 - \cos\lambda) - [v_{ISN\infty}^2 \sin^2\lambda + \{v_{ISN\infty} \times \sin|\lambda|[v_{ISN\infty}^2 \sin^2\lambda + 4(1-\cos\lambda)]^{1/2}\}]/2$$

- Motivation- Concentrating on small variations, must get rid of large variations (Longitudinal variation)

PUI measurements now in $w^{*}=(vr_{measured}-vr_{calc})/v_{sw}$





High Time Resolution Parameter Dependence

Demodulated PUI data set on a 10 min resolution is sorted and binned according to:

- Solar wind velocity: **Vsw (km/s)**
- Magnetic field strength: **|B| (nT)**
- Proton number density: **n_p ($1/cm^3$)**
- Velocity Gradient: **dv_{sw}/dt (m/s^2)**
- Field strength Gradient: **d|B|/dt (nT/s)**

The velocity and field strength gradient are derived using Euler's approximation, where for time increment n,

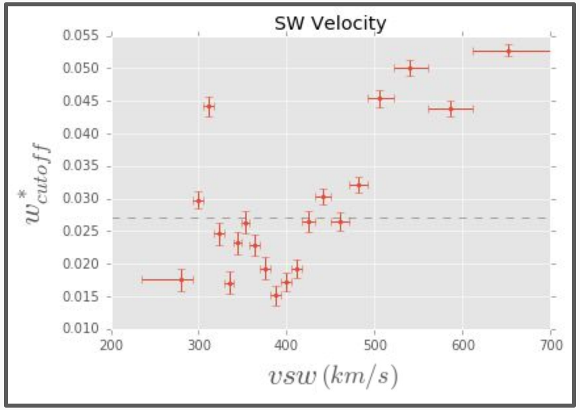
$$dB^n/dt = \frac{B^{n+1} - B^{n-1}}{2\Delta t}$$

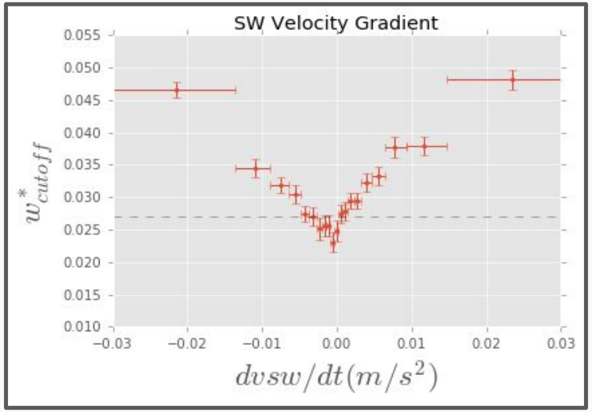
$$dv_{sw}^n/dt = \frac{v_{sw}^{n+1} - v_{sw}^{n-1}}{2\Delta t}$$

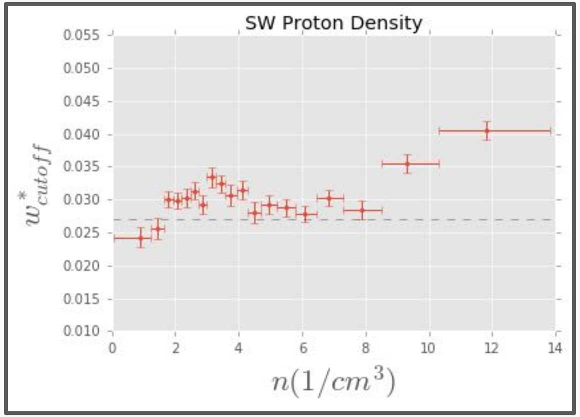
High Time Resolution Parameter Dependence

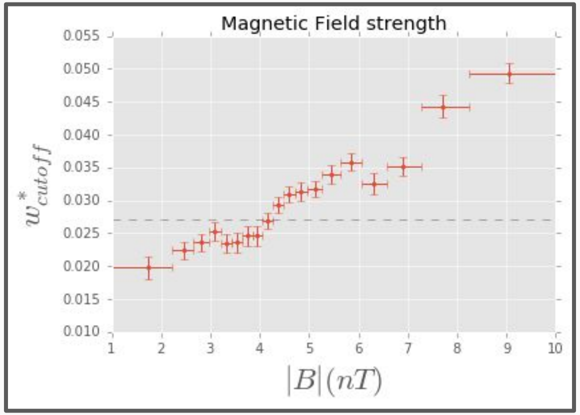
Cutoff shift associated with:

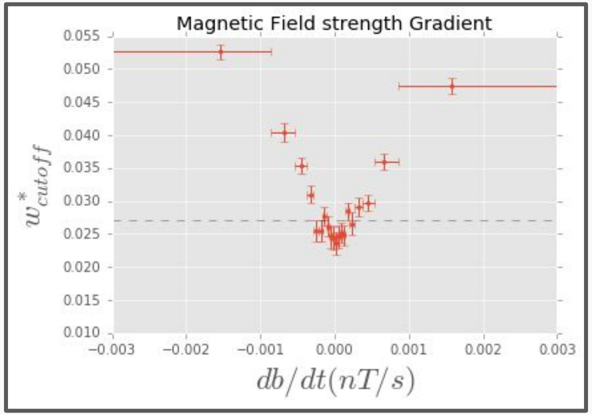
- Large SW velocity
- Large positive or negative Velocity and field gradients
- Approximately linearly associated with field strength





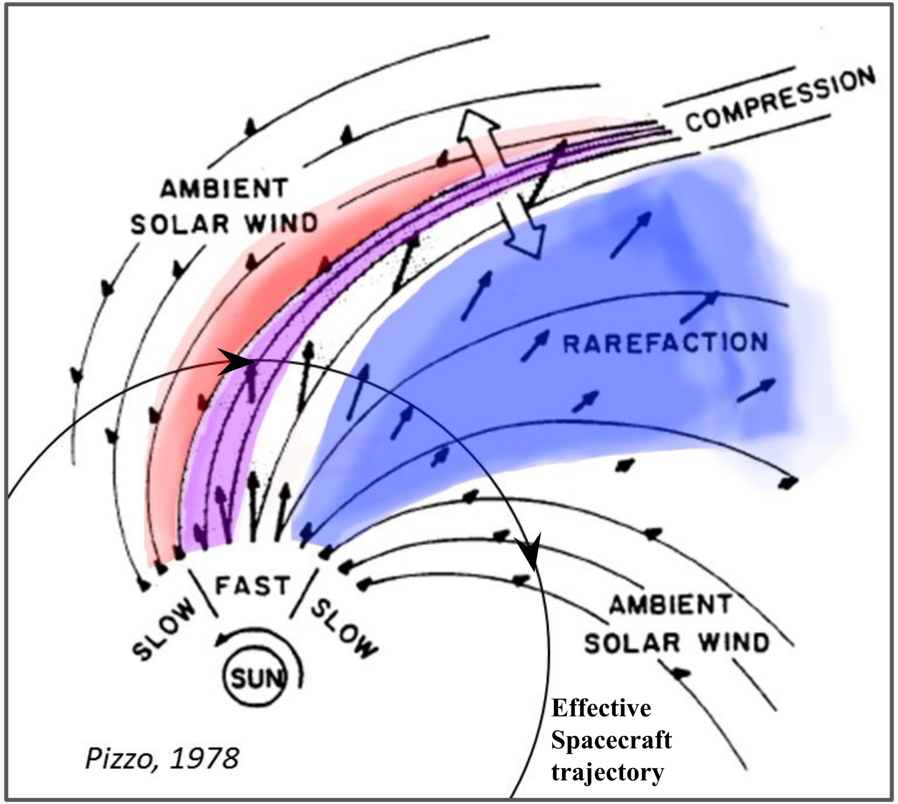






SW Compression Regions

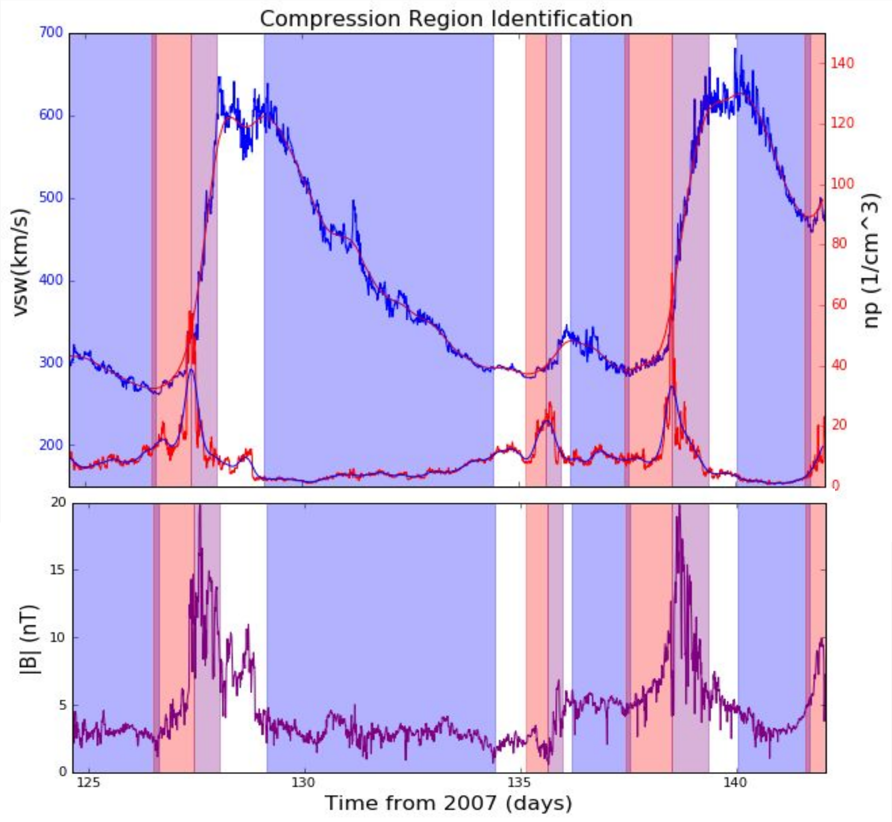
- Fast solar wind rams into preceding slow solar wind
  - heating of the intermittent plasma
- Compression Region Expands into both the Compressed slow and fast wind
- Largest heating of the SW takes place at the stream interface bounding the fast and slow streams
- Types of compressions respond similarly in PUI heating
  - Corotating Interaction regions (CIR)
  - Transient Interaction Regions (TIR)
  - Coronal mass ejections (CME)
- Some large compressions have shocks at 1AU



Compression Region Identification

Compression regions are identified explicitly utilizing structures in the solar wind speed and number density.

- Perform smoothing of np and vsw, every 10 pts (50mins)
- Identify approximate stream interface (large isolated peaks in the number density) [Gosling et al., 1996]
- Integrate PUI measurements in regions of increasing SW speed, separated by the stream interface
    - Prior to the stream interface: compressed **slow SW (Red)**
    - Following the stream interface: compressed **fast SW (Purple)**
- PUIs are accumulated in the **rarefaction region (Blue)** in order to Identify the effect of SW cooling
- Compression region strength is characterized using: Δnp, ΔVsw, $\Delta Vsw/\Delta t$, and ΔB



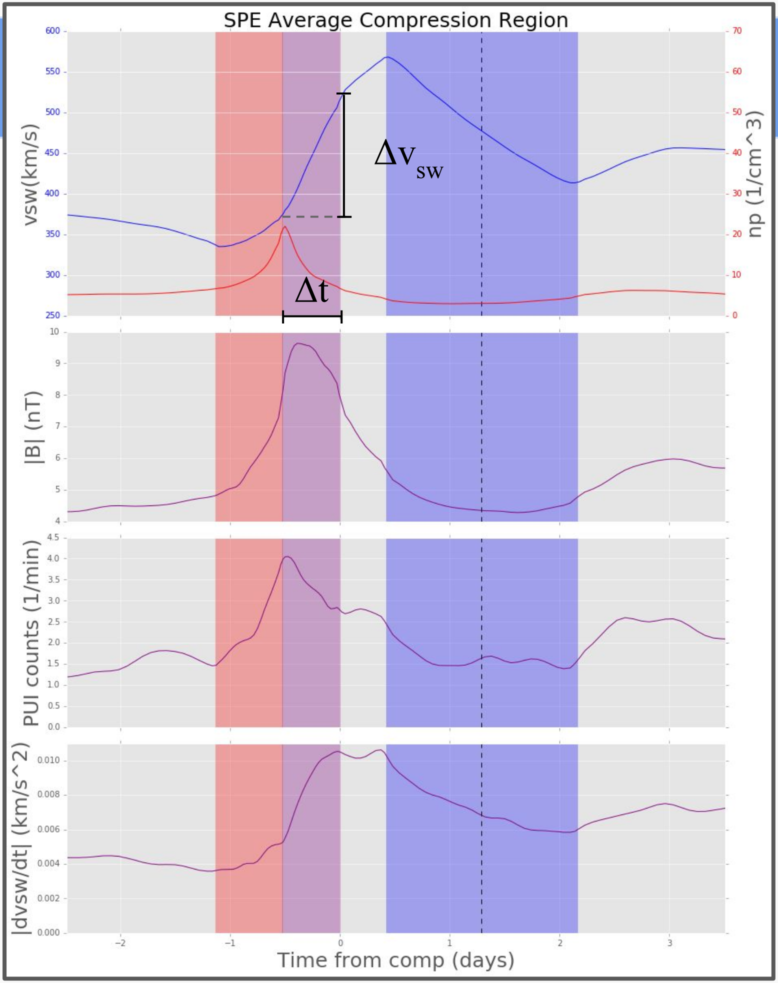
SPE Compression Region

A superposed epoch analysis (SPE) of a typical compression

- Allows for accumulation of PUI statistics
- Epoch- end of the compressed fast wind
- Each region (slow, fast, top, rarefaction) is stretched or compressed to the average region time sale
- 1.75hr time resolution

SPE compression & PUI cutoff

- Evolution of PUI cutoff across SPE compression
- Characterize each section of each compression by $\Delta v_{sw}/\Delta t$
    - Parameter dependence between compression steepness and PUI cutoff



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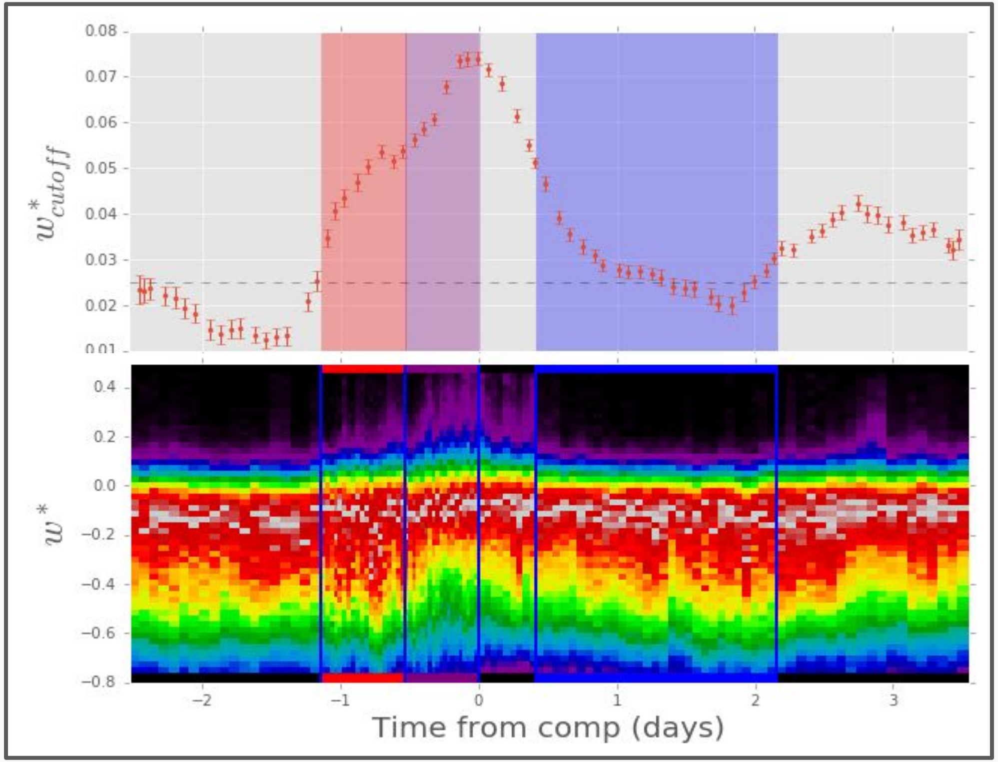
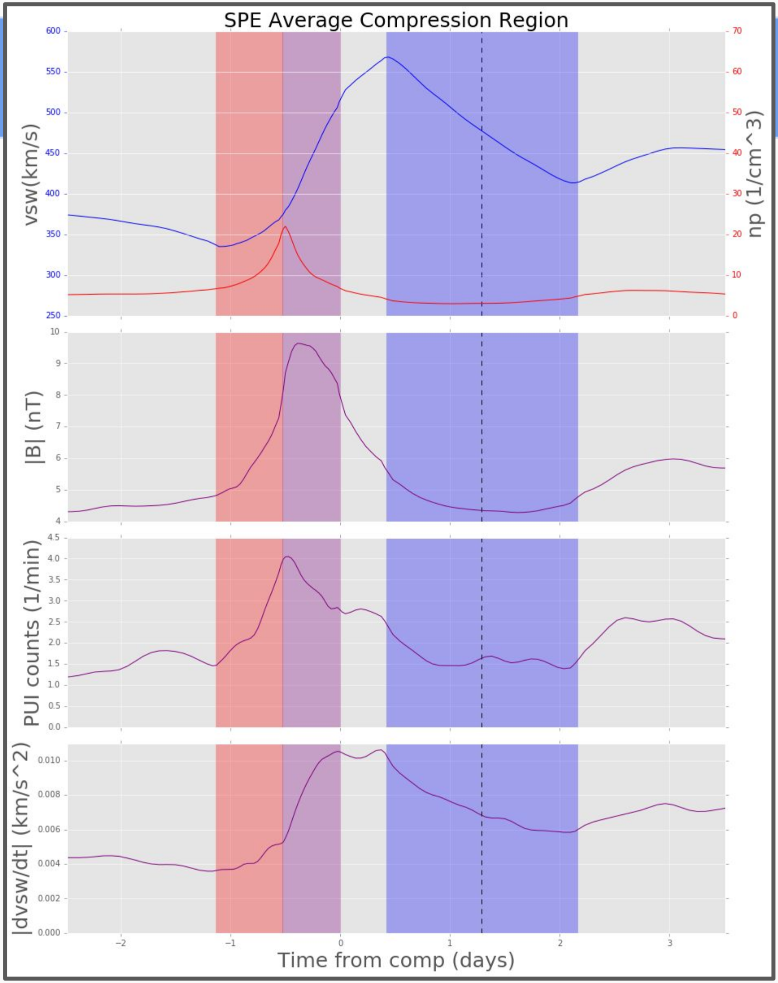
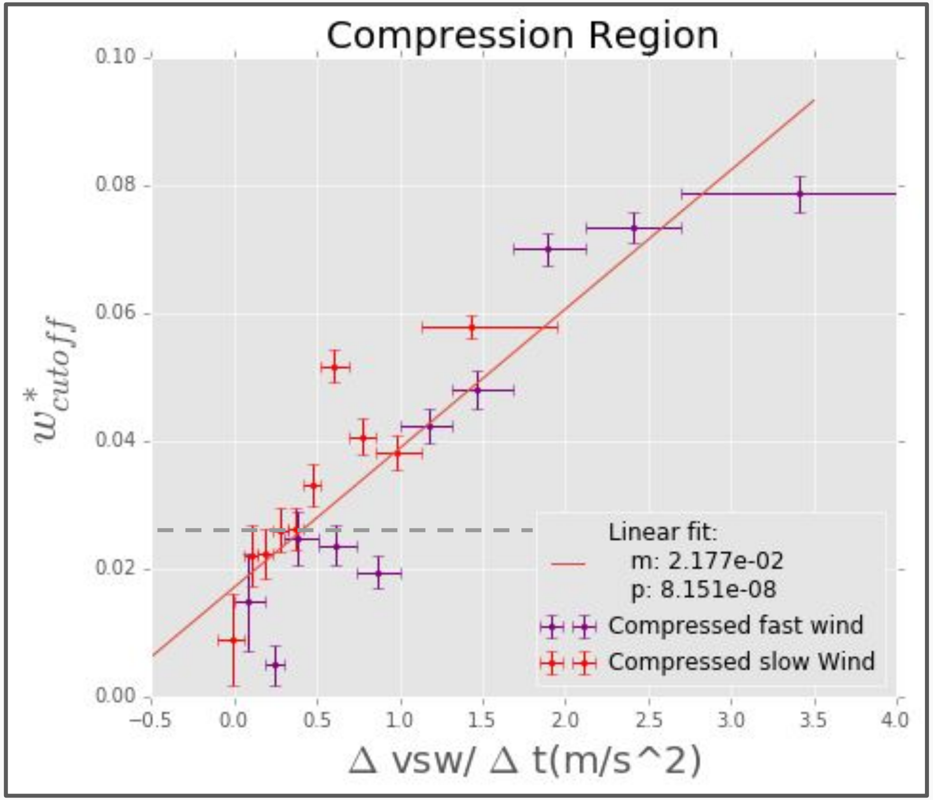
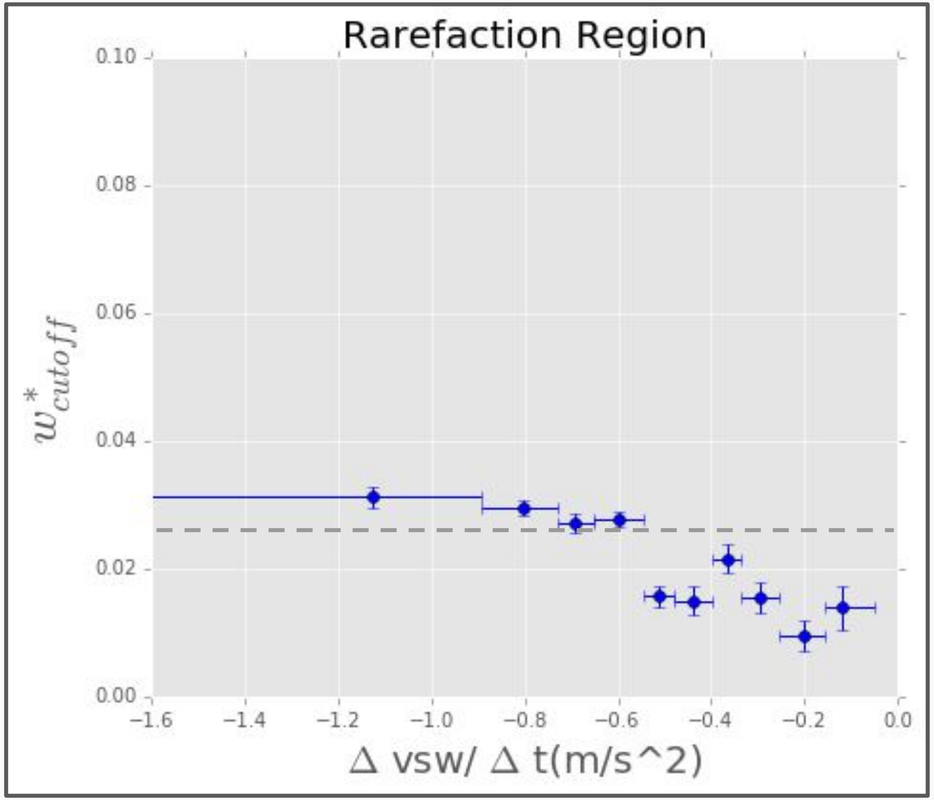
SPE PUI Cutoff and VDF





Compression Region Parameter Dependence





Interplanetary Shocks

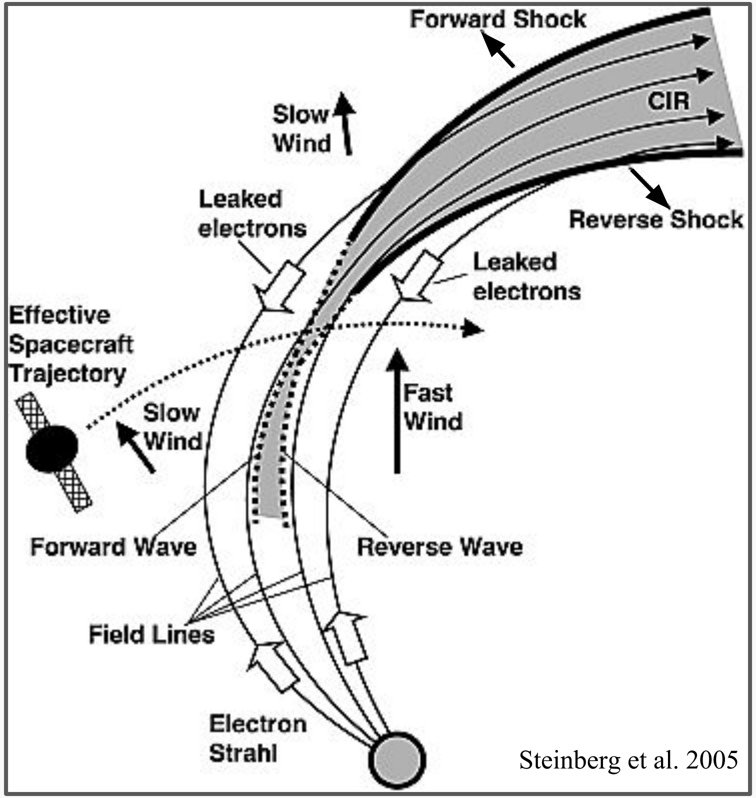
Shock List provided by STEREO team:

- Fast Forward (FF) shocks: 154 events
- Fast Reverse (FR) shocks: 41

Most stream interactions have not developed shocks at 1AU

- Forward shocks flow from the fast wind into the slow wind
    - Develope in CMEs
- Reverse shocks propagate from slower wind into faster wind
    - Not developed in CME’s (lowe statistics)
    - Generally stronger in magnitude

To preserve statistics, forward and reverse shocks are separately superimposed with shock front as the epoch.



Steinberg et al. 2005

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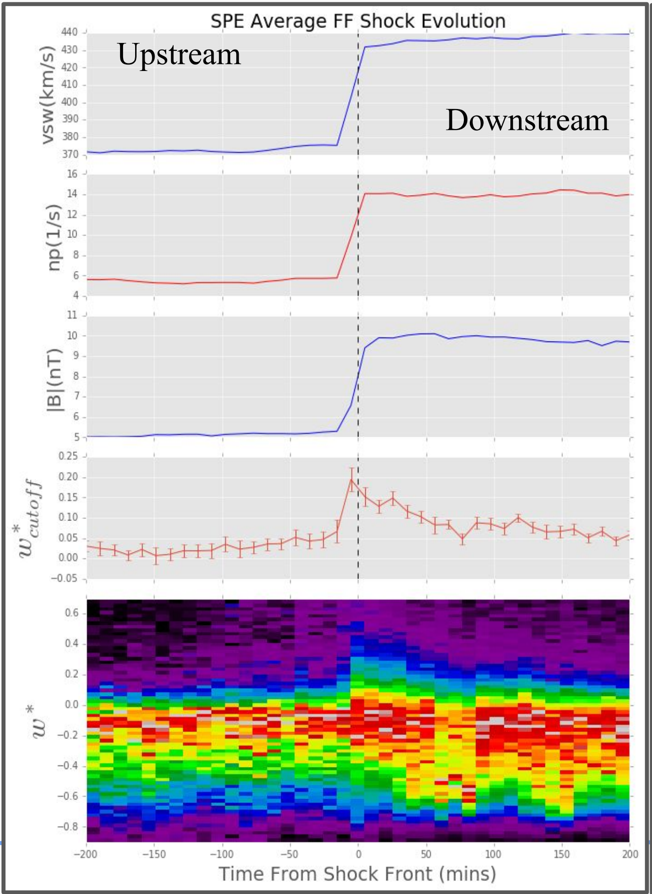
Effect of Shocks on the PUI VDF

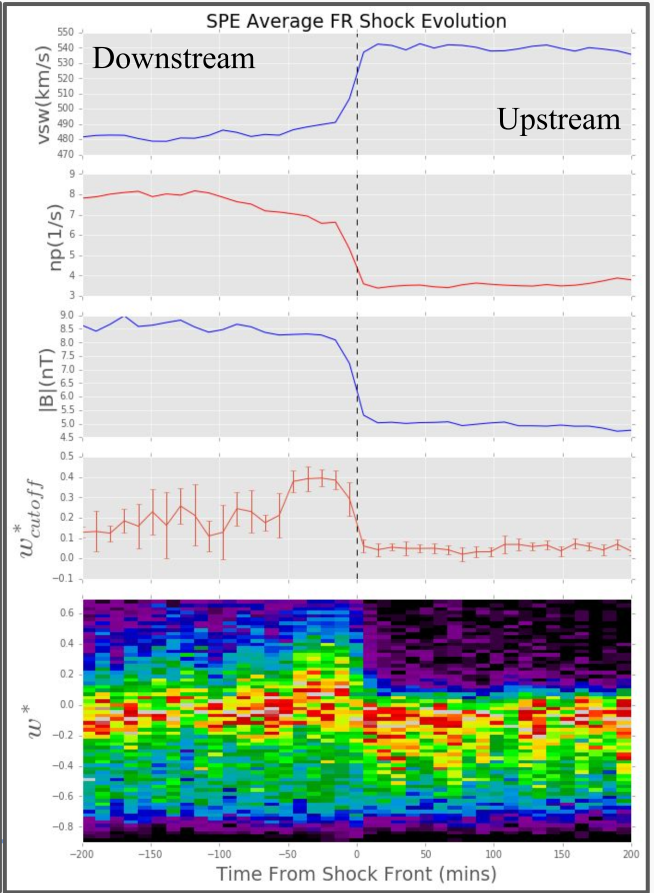
- Propagation Direction seen in SW parameters
- Considerable cutoff shift downstream of shock front
- PUI heating considerably larger than in compression
- Largest cutoff shift comes at discontinuity
- PUI heating not sustained far from shock as density and Magnetic field are still high

Shock times removed directionally, 20 min upstream 130 min downstream

Forward Shock



Reverse Shock



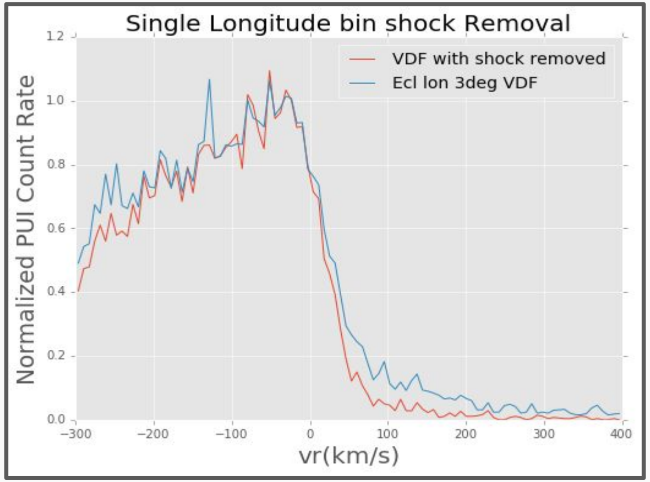
Compression and Shock Removal

Removal:

Compression: times from beginning of compressed slow wind to start of rarefaction

Shocks: 20 mins before to 130 mins after shocks

- Compressions removed in lower thresholds of $\Delta v_{sw}/\Delta t$
- Minimal reduction in fit error
  - Stochastically distributed fluctuations increases data fidelity but reduces statistics
- Inflow direction stable for removal of compressions/shocks
- Develop process to correct for these effects rather than remove them to increase statistics



Comps Removed #	λ	$\delta\lambda$	$\min(\Delta v_{sw}/\Delta t)$	$\max(\Delta v_{sw}/\Delta t)$	Data Removed
0	255.48	.48	-	-	0 %
115	256.03	.42	$1.35m/s^2$	$5.39m/s^2$	5.0%
288	255.00	.45	$.70m/s^2$	$5.39m/s^2$	14.3%
518	255.45	.46	$.00m/s^2$	$5.39m/s^2$	23.1%

Shocks Removed #	λ	$\delta\lambda$	FF Shocks	FR shocks	Data Removed
242	256.06	.46	196	46	.8 %

Conclusion

- First systematic measurement of the effect of SW compressions on the PUI VDF
- Identified dependence between PUI cutoff and magnetic field strength, velocity gradients and field strength gradients at high time resolution.
- Determined Cutoff shift increases with higher compression strength
- Largest cutoff shift immediately downstream of shocks
    - Much larger than in strongest compression region
- Removing compressions not effective in reducing error on the inflow measurement
- Inflow longitude is stable in removing compressions/shocks

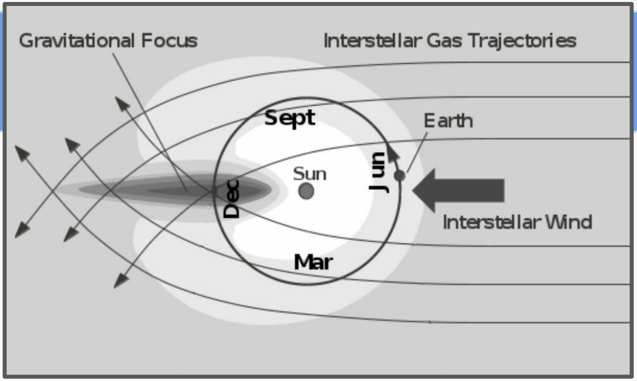
What's Next?

- Develop way to correct for rather than remove compressions
- Link trends in the cutoff shift to simulation that can distinguish between different drivers

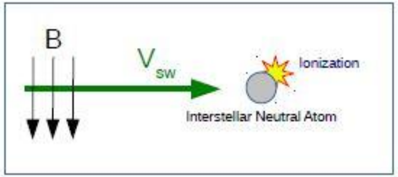
Questions?

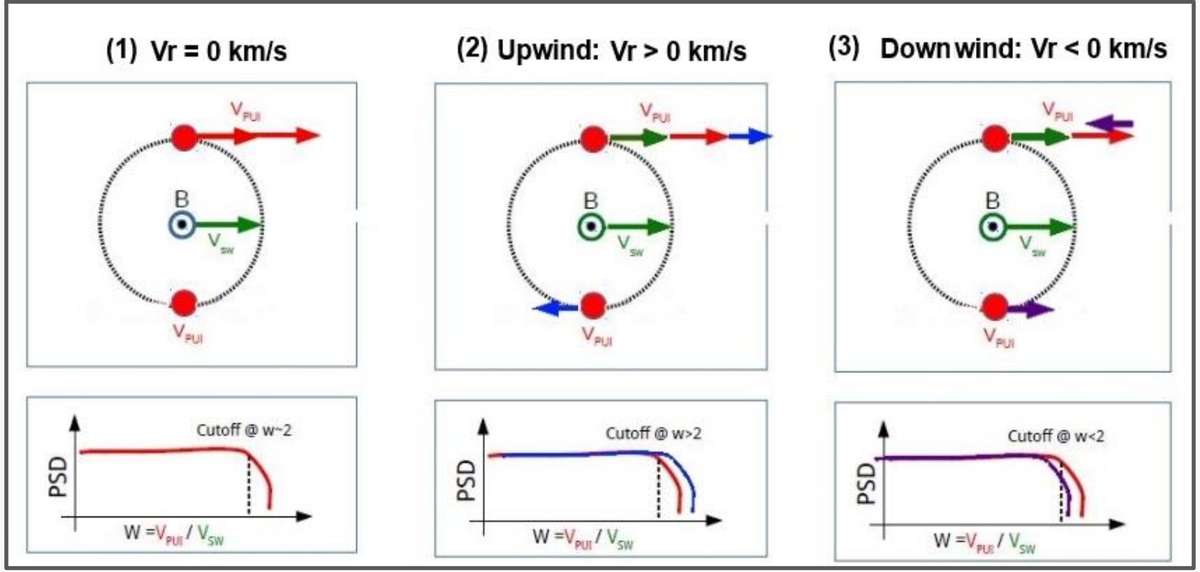
Appendix:

PUI Generation and Transport



- Neutrals ionized by
  - Charge exchange collision
  - Photoionization
- Ions picked up by SW
- Gyrate around Field lines
  - Cyclotron motion
  - $0<v_{PUI}<2*v_{sw}$ (for $\vec{\mathbf{B}} \perp \vec{\mathbf{v}}_{sw}$)
- Convect out radially with the solar wind





Problem:

- PUI cutoff is dependent on magnetic field direction and the ecliptic longitude

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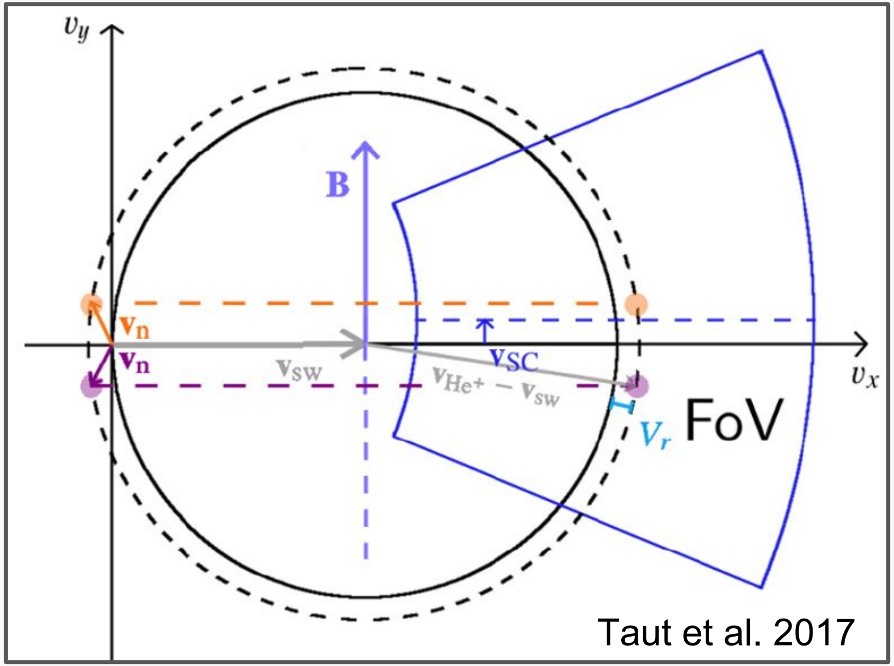
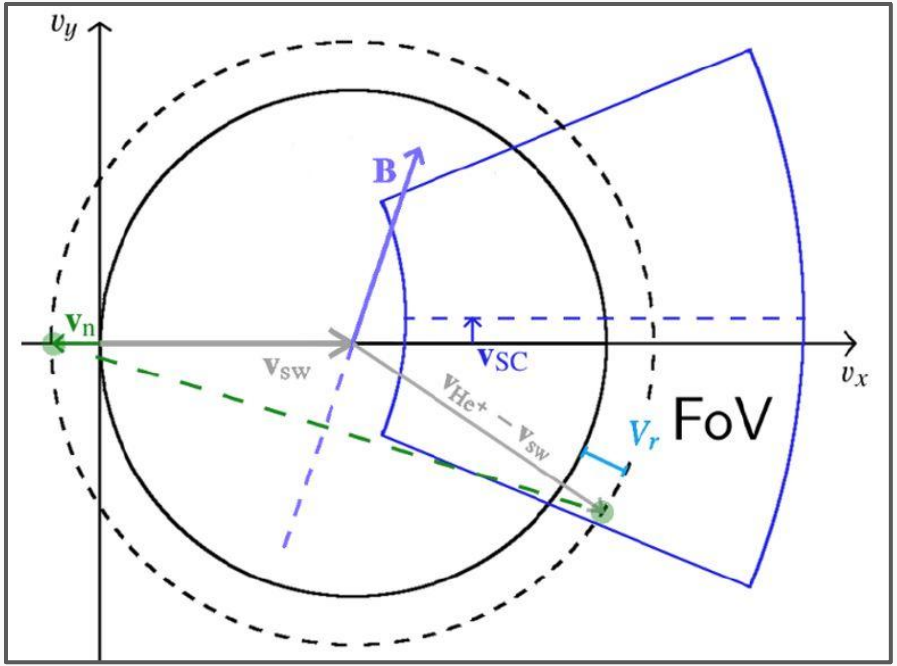
PUIs in 2d Velocity Space





- PUIs injected onto shell with radius of v_{sw} in velocity space

- Transforming into SW frame restricts yields a PUI cutoff of approximately v_{sw} for all field angles

STEREO PLASTIC

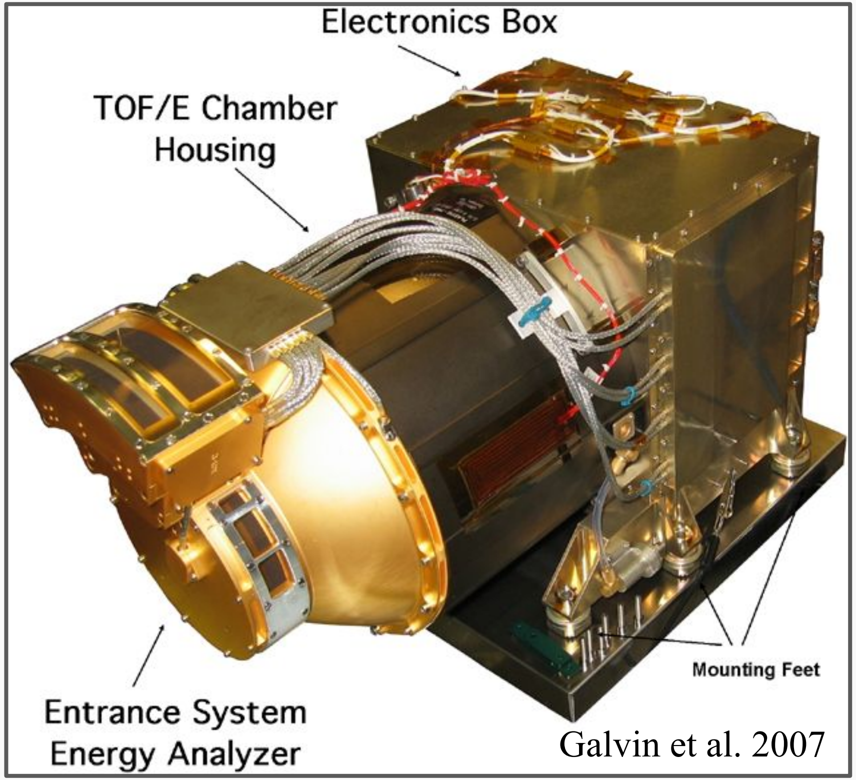
Solar **TE**rrestrial **Re**lations **O**bservatory

- Launched October 26, 2006
- Two (almost) identical satellites allow us to image the entire sun, and see the origins and evolution of coronal mass ejections!

PLAsma **A**nd **S**upra**T**hermal **I**on **C**omposition

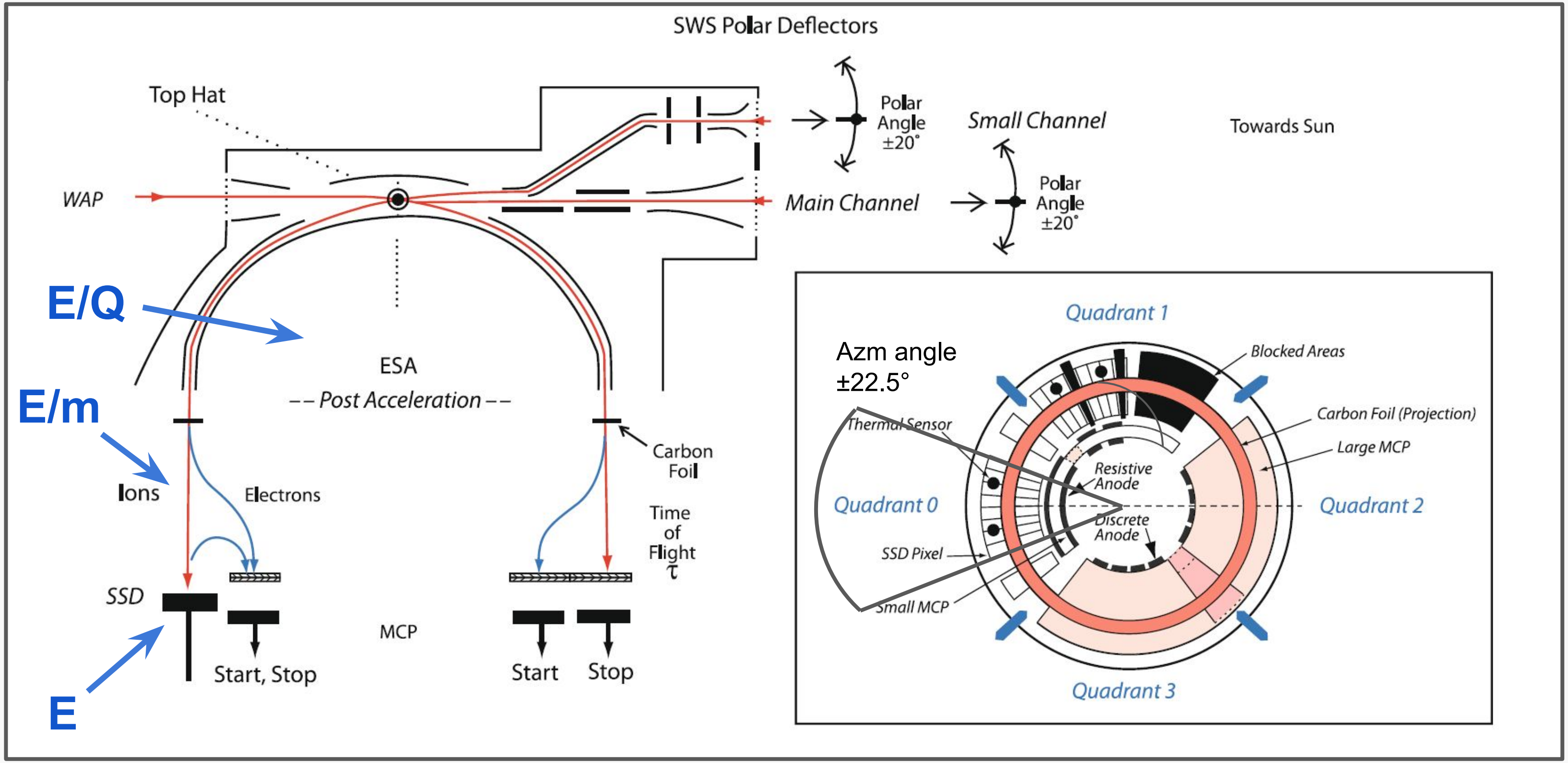
- Used to determine flux, composition and Velocity of SW protons and suprathermal ions
- Developed right here!
- FOV of SW sector
  - ±22.5° with 1.4° deg pixel width in ecliptic
  - ±20° with 1.3° pixel width out of ecliptic

Allows PLASTIC to resolve ion and velocity with enough angular resolution to transform into the SW frame



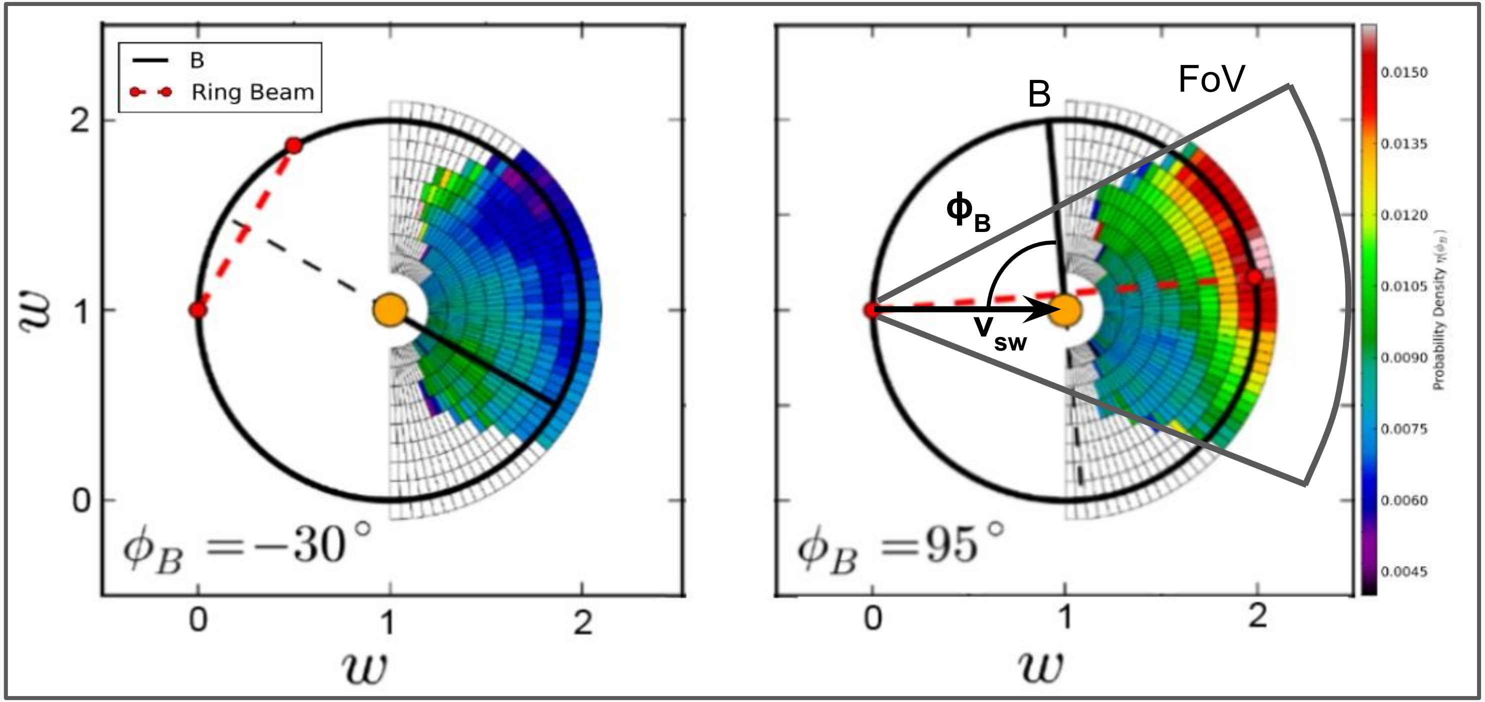
Galvin et al. 2007

PLASTIC



Galvin et al. 2007

The PUI VDF as Measured by PLASTIC



Drews et al. 2015

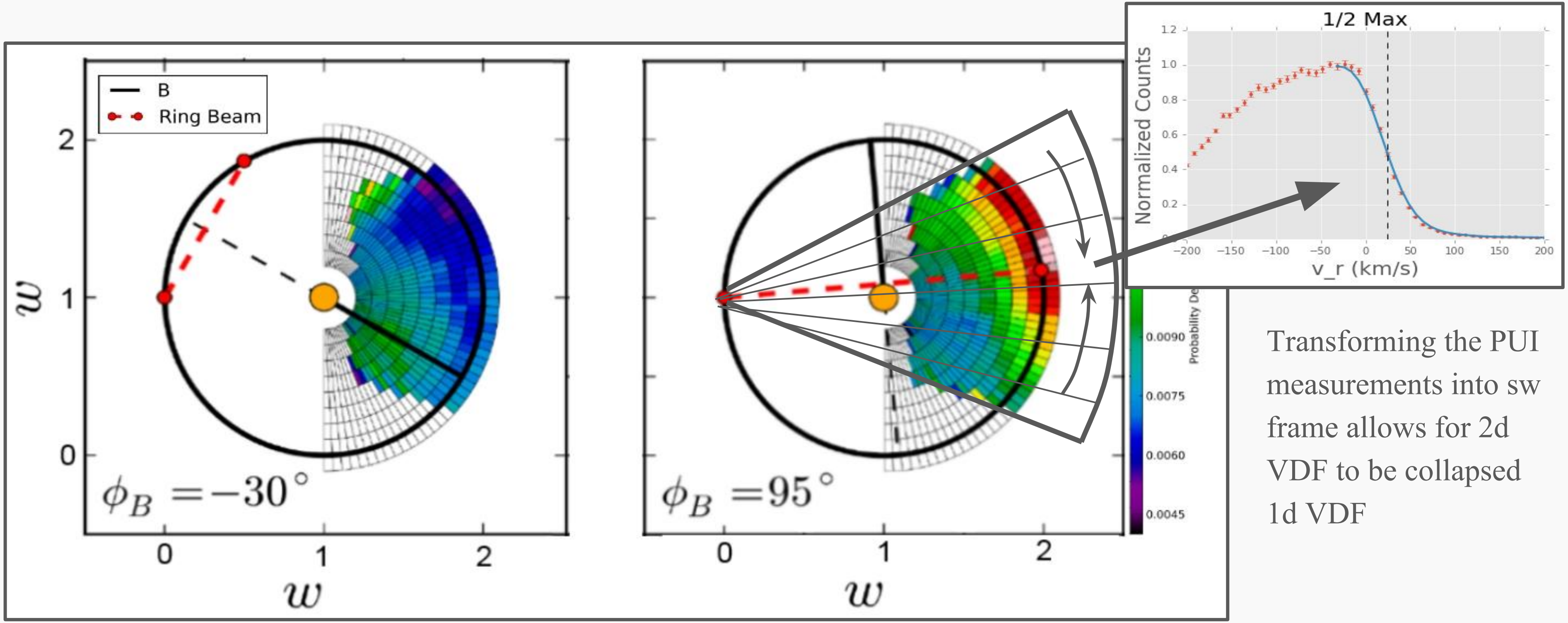
2d VDF plane created by direction of SW flow and B

- PUI torus falls on outermost shell

FoV is restricted to:

$70° < \phi_B < 110°$

Collapsing The 2d PUI VDF



Drews et al. 2015

Transforming the PUI measurements into sw frame allows for 2d VDF to be collapsed 1d VDF

Parameter Coupling