

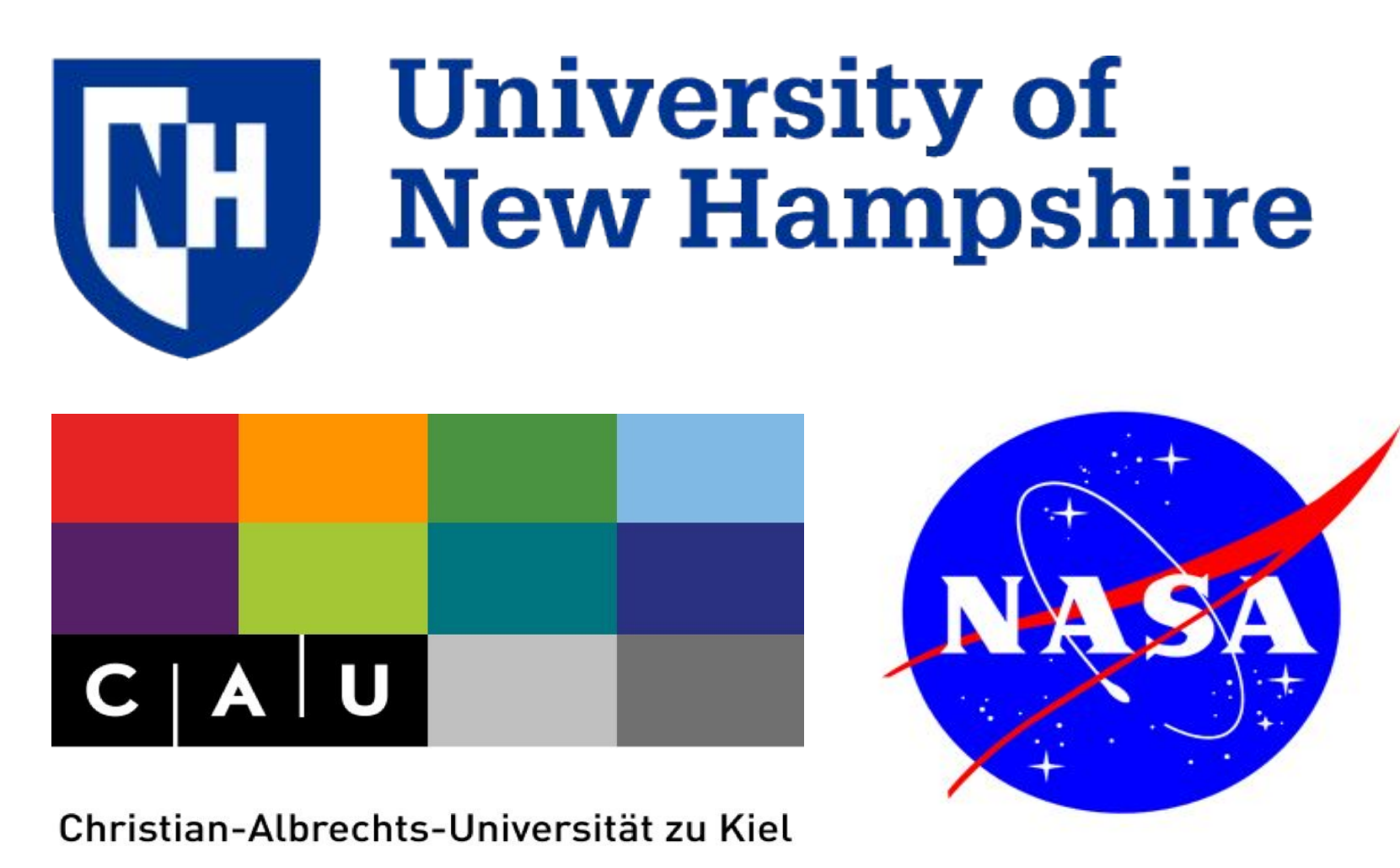
The Effect of SW Compression Regions on the PUI He+ Cutoff Determined ISN Inflow Direction

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Background

IBEX measurements of the interstellar flow parameters yield a four dimensional parameter tube coupling the inflow longitude, latitude, speed and temperature. It has been shown by Moebius et al. (2015) that the pickup ion (PUI) cutoff shift variation in ecliptic longitude can be used as a potentially highly accurate method for measuring the inflow longitude of the ISM, in conjunction with the IBEX measurements, to reduce error for all inflow parameters. However, Saul et al. (2003) found that the PUI velocity distribution function can be modulated by rapid changes in the local solar wind. This study is motivated by the attempt to remove or correct for these effects on the determination of the inflow longitude. For this study we use He⁺ PUI observations sampled between 2007-2014 with STEREO A PLASTIC.

PUI Cutoff Variation in Longitude

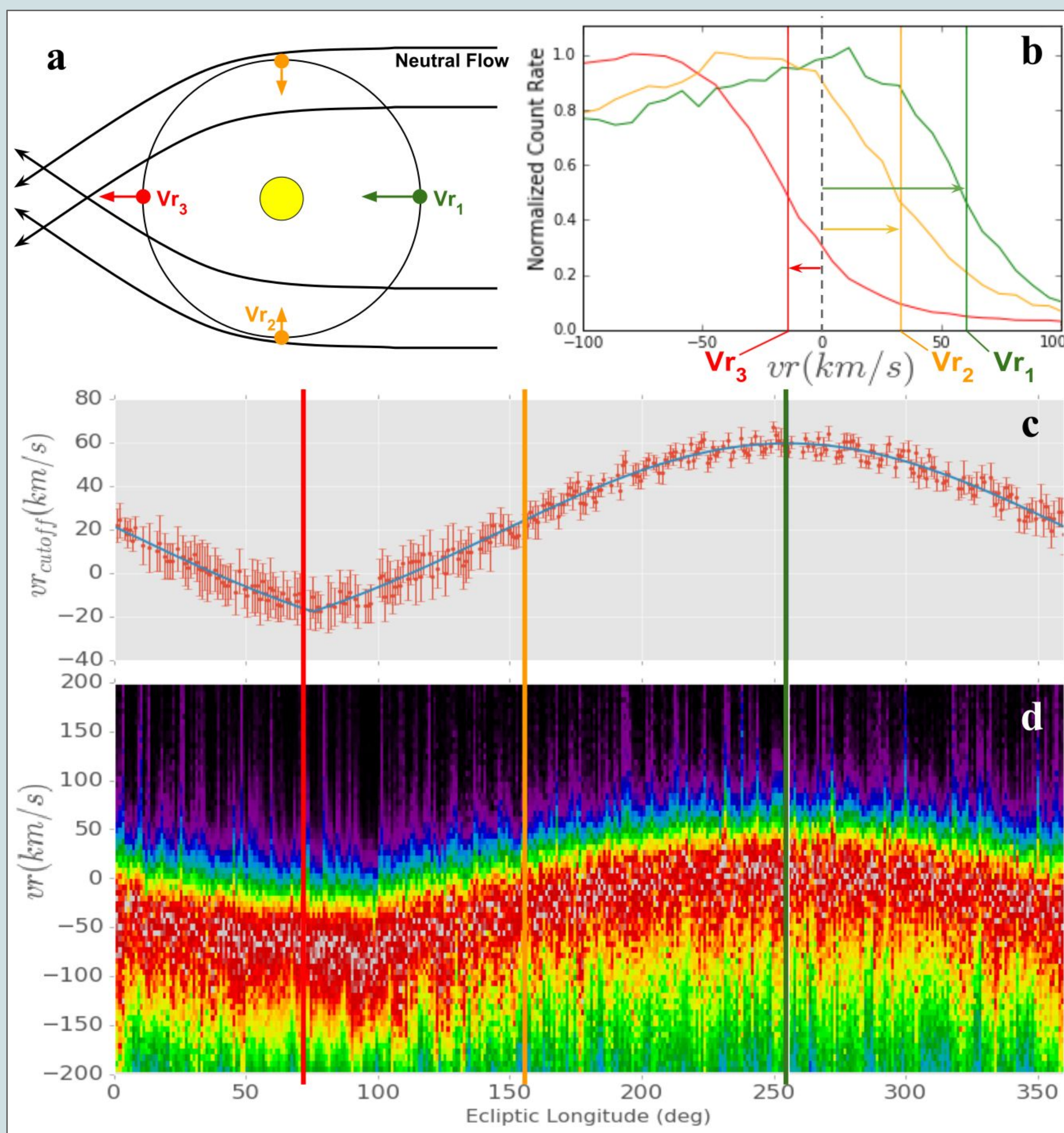


Figure 1: (a) Sample neutral particle trajectories under the influence of the Sun's gravitational pull, leading to a longitudinal dependence of the neutral particle radial speed. (b) Sample velocity distribution functions from three different ecliptic longitudes, with the largest shift in neutral radial speed exactly upwind. (c) Sample velocity distribution functions arranged in ecliptic longitude, showing longitudinal dependence associated with the radial neutral injection speed. The resulting cutoff speeds for each longitudinal bin, and the associated model fit to determine the inflow direction, are shown in (d).

- The incoming neutral radial speed, and in turn the PUI injection velocity, changes with ecliptic longitude due to gravitational lensing. An analytic expression describing this effect is derived in Moebius et al. 2015:

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

v_r is a quantity which reflects the radial component of the neutral velocity vector (v_n), normalized to the Earth's rotational speed. $v_{ISN\infty}$ is the neutral flow speed at infinity and $\lambda = \lambda_{OBS} - \lambda_{INFL}$. Contains both the interstellar flow and observer longitude.

- This model can be fit directly to measurements of the PUI cutoff speed (v_c) and observer longitude, providing a statistically accurate measurement of the LISM inflow direction (Figure 1c).

The cutoff is determined through integrating the PUI distribution over time and finding the point of steepest descent in the Velocity Distribution Function (VDF).

- The cutoff v_c is identified by finding the location of $1/2$ the peak height of the smoothed, interpolated VDF.

Goals

- Identify the evolution of the PUI VDF across SPE compression regions and shocks
- Identify possible correlations between compressive strength and PUI heating
- Find criteria to correct for or remove compression regions in the cutoff-inflow analysis
- Gain understanding of physics behind the changing PUI VDF
- Identify any time variability in the LISM flow direction.

PUI Energization in SW Compressions

- Even for freshly injected PUIs, the speed can be additionally through heating processes, produced by Stream Interaction Regions (SIRs), Coronal Mass Ejections (CMEs) or turbulence.
- SIRs occur when fast solar wind rams into preceding slow solar wind, resulting in a heating of the intermittent plasma

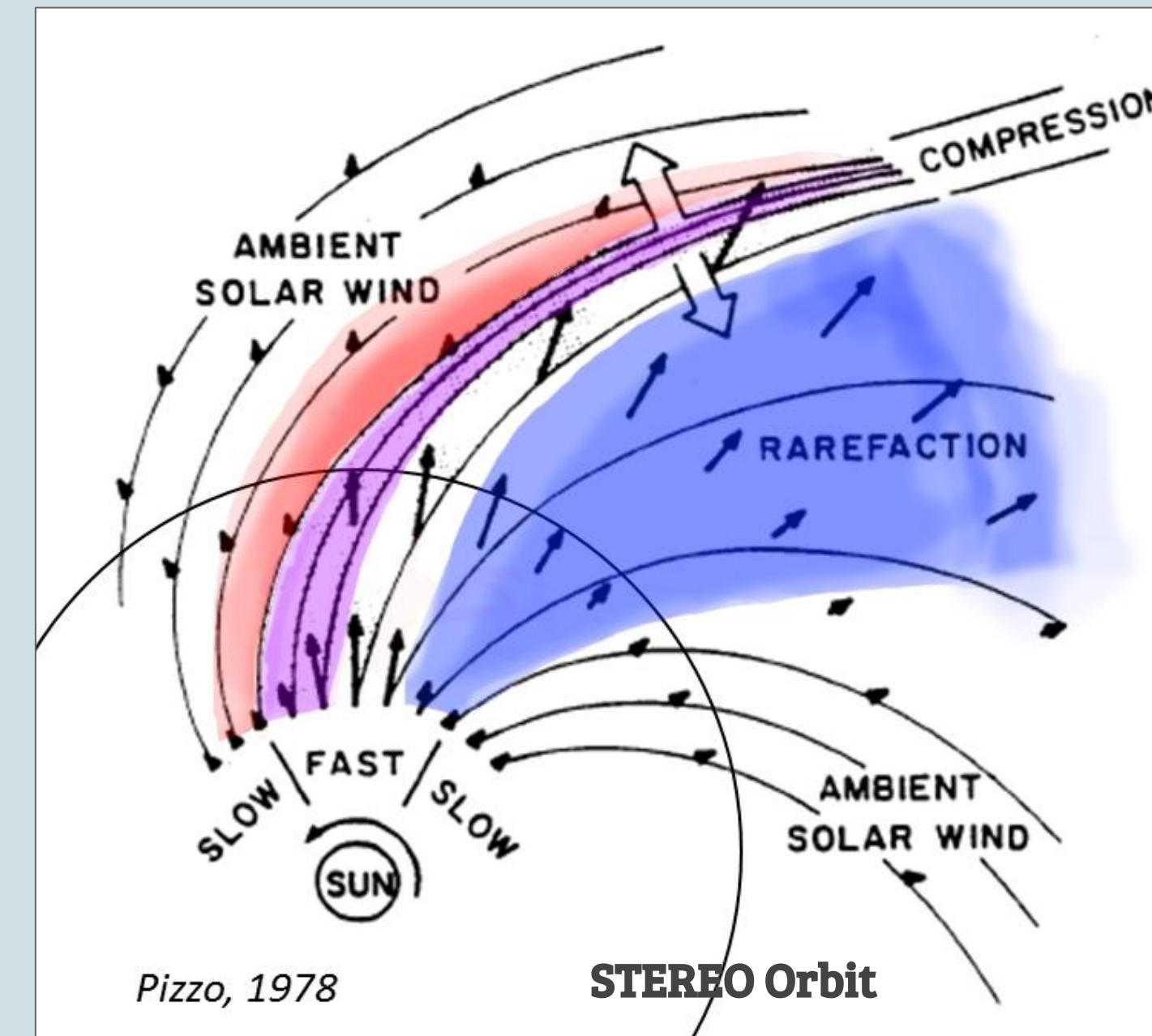


Figure 2: Schematic view of a SIR, showing general regions of compression and rarefaction (Red for the compressed slow wind, purple for the compressed fast wind, and blue for the rarefaction region)

- To isolate SW related effects, the longitudinal dependence is removed according to modeled cutoff shifts [Moebius et al. 2015, Lee et al., 2015] and normalized to the solar wind speed. He⁺ PUIs are resolved using the parameter w^* . Defined as:

$$w^* = (v_r - v_{r,calc}) / v_{sw}$$

Here (v_r) is the measured radial cutoff speed and ($v_{r,calc}$) is the expected radial cutoff speed described by Equation 1.

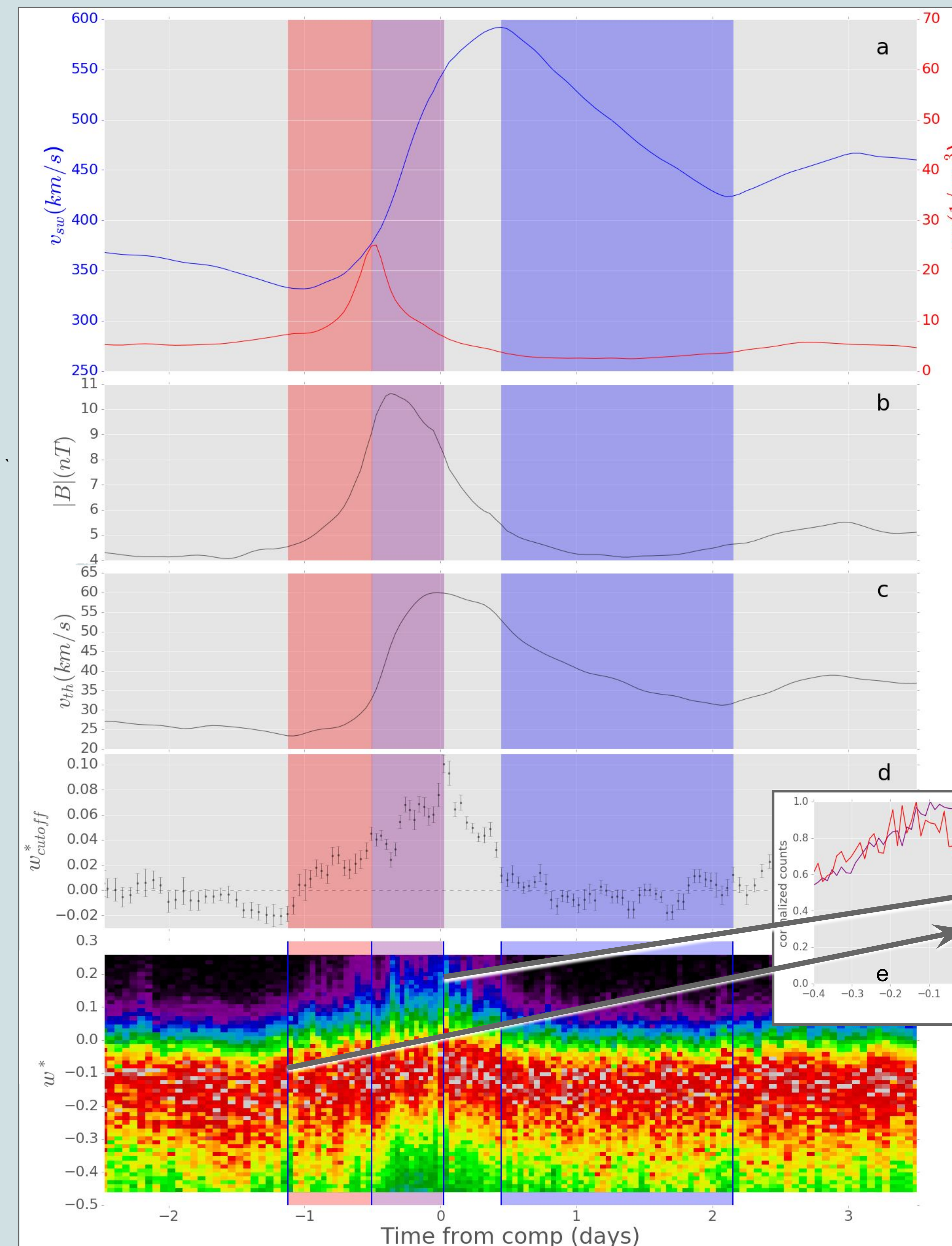


Figure 3: Average temporal evolution across the superposition of compression regions, shown here for, SW velocity (a, blue), density (a, red), magnetic field strength (b), PUI count rate (c), kinetic temperature (d), the magnitude of the fast local solar wind speed fluctuation (e), PUI cutoff (f) and PUI VDF. Shown is the result from an SPE analysis of 100 compression regions selected for large total increase in solar wind speed. Color coding follows Figure 2 (indicating the compressed slow wind (red), compressed fast wind (purple) and rarefaction region (blue))

- A Superposed Epoch analysis (SPE) allows for the accumulation of PUI measurements under similar solar wind conditions, thus improving statistics. This technique enables the study of variations in compression parameters and their effects on the cutoff at short time scales.
- The compression region is characterized by increasing solar wind speed, which contains peaks in density and field strength, as well as high average PUI count rate and strong gradients in local solar wind speed.

Effects of Compression with Variable Strengths

- To identify the cutoff dependence on compression strength, PUIs are accumulated according to the average solar wind speed gradient ($\Delta v_{sw} / \Delta t$) in each region (compressed slow, compressed fast, rarefaction).

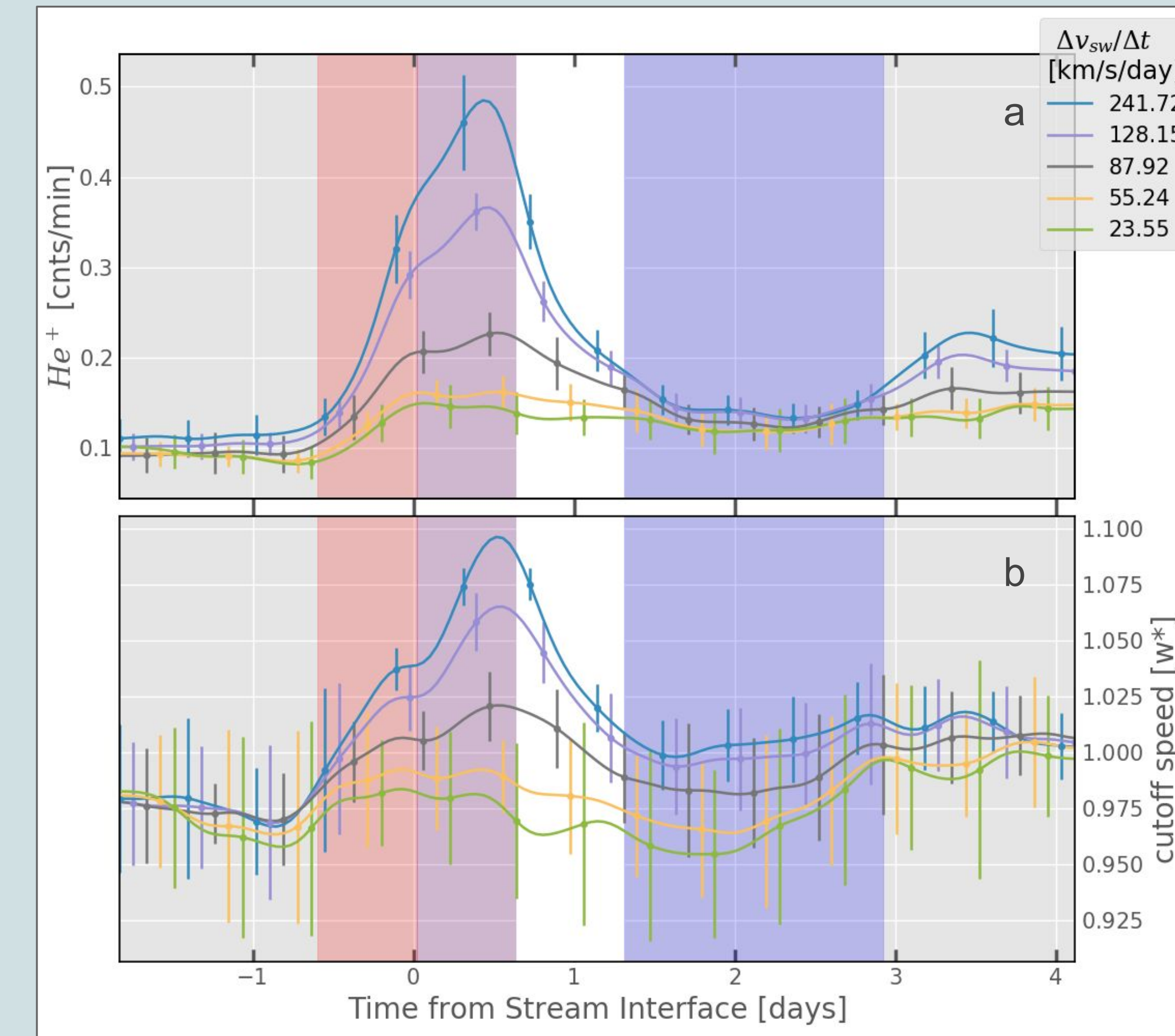


Figure 4: Average temporal evolution of the He⁺ PUI count density (a) and PUI cutoff speed (b) across 5 compression regions of varying strength. The density and cutoff speed increase substantially across the interaction region with a magnitude that increases according to the compression SW speed gradient.

- The PUI cutoff shift and density increase substantially in the compression interaction region, with a magnitude that increases with the compression strength.
- The PUI cutoff shift is correlated with the strength of the solar wind speed increase across the compression.
 - Both compressed slow and fast wind show a similar dependence on the gradient.
- In the rarefaction region, one would expect to see cooling of the PUI VDF, but the cutoff speed does not return to pre-compression levels.

Correcting For The Effects of Compressions

We can account for the compression effects in the analysis to determine the inflow, in two ways:

- Remove times where the spacecraft observes these compression
- Flatfield for their effects using the known response of the PUI cutoff and density.

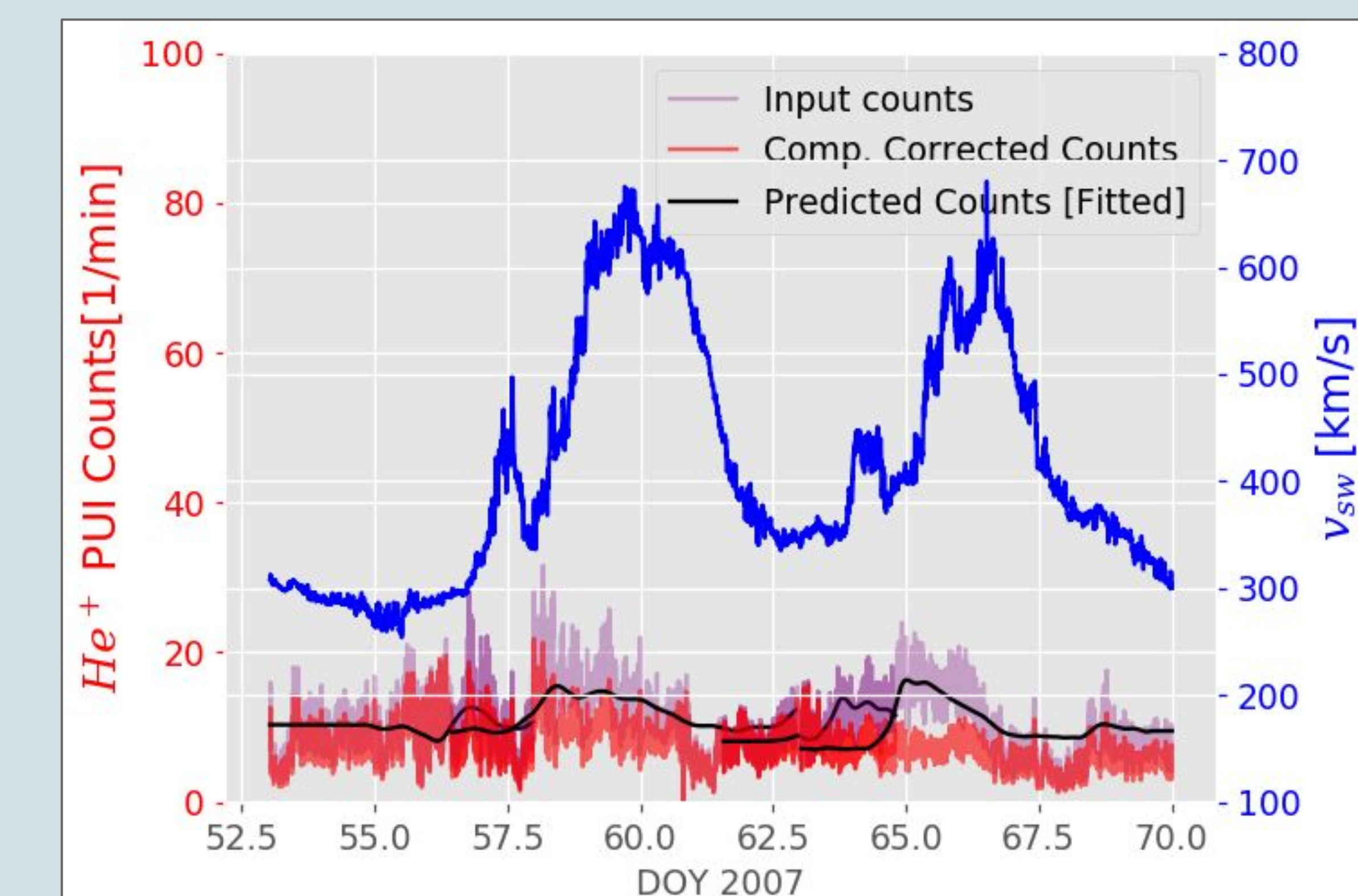


Figure 5: Illustration of the methodology to flatfield for the effects of the compression regions in the PUI count density. Two Stream interaction regions are shown in the SW speed (blue) at DOY 58 and 65. PUI count density (purple) increases in the SW compression regions. We construct a model to predict the temporal variation in density (black) and flatfield for the predicted effect (red).

To flatfield for the compression effects in the PUI density:

- Utilize observations showing that the density varies systematically across the compression and according to compression strength (Figure 4).
- Interpolate SPE observations to develop a heuristic model that predicts the density variation according to the strength of each compression ($\Delta v_{sw} / \Delta t$).
- Divide observed PUI count density by predicted values to statistically reduce their impact.

Results

Annual Inflow Variation

- We measure the annual inflow direction by integrating over three consecutive years in one year steps, between [2008, 2013], with sliding boxcar binning and determine the inflow through fitting eq. 1.
- Repeat this process for three treatments of the compression regions. 1) Including the compression regions 2) Removing the compression regions 3) Flatfielding the compression regions.

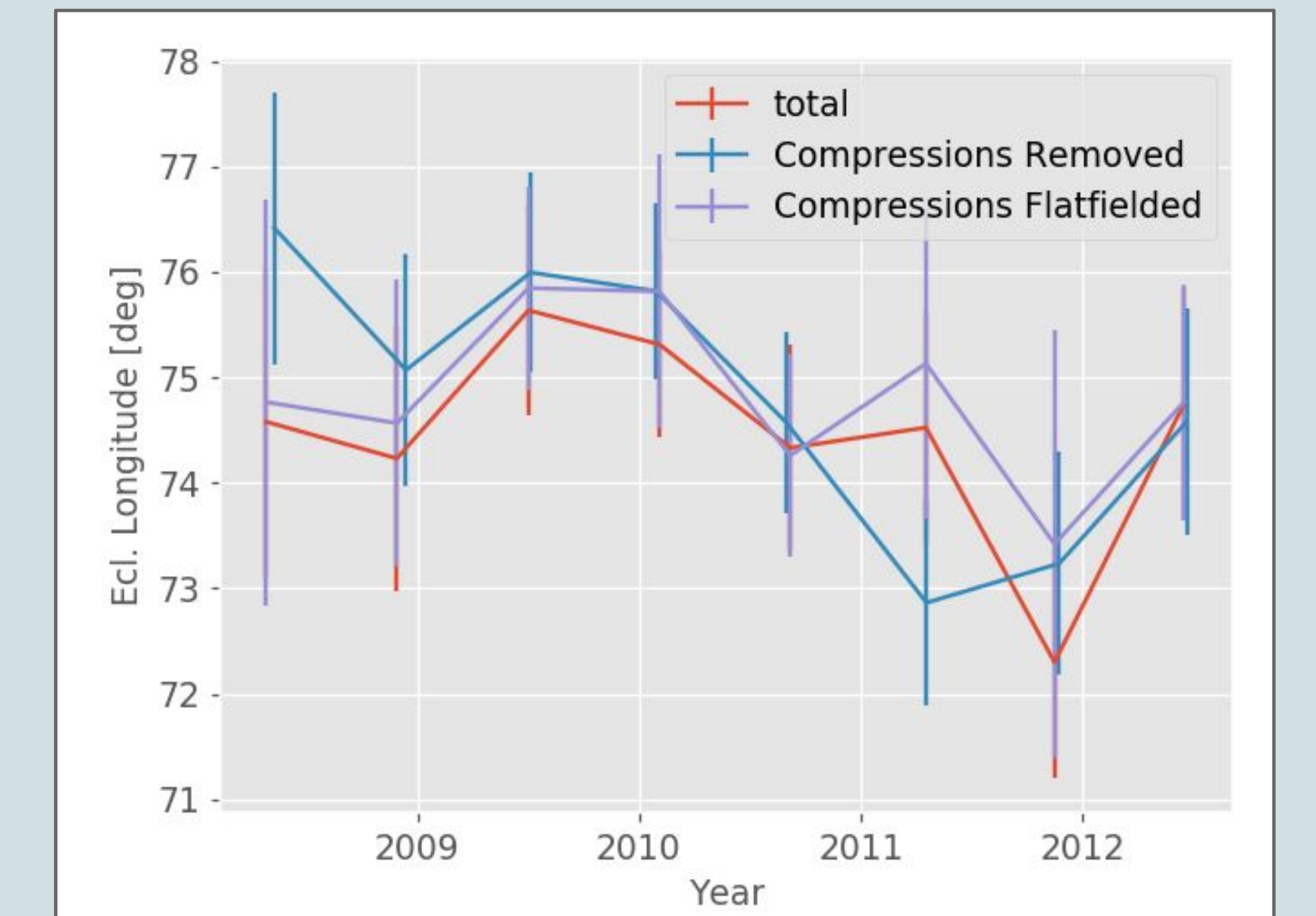


Figure 6: Annual variation of the PUI cutoff determined LISM inflow direction, for three compression treatments, including the compressions red), removing the compression periods from the data set (blue) and flatfielding for the known change in the PUI count density (purple)

Effect on the PUI cutoff Determined Inflow Error

Stochastic error of the total inflow direction:

- Compile PUI counts over two consecutive years with random starting times
- Determining the inflow direction through fitting.
- Process is repeated 50 times, the standard deviation of the inflow measurements is reported as the "Stochastic Error"

	Inflow Longitude [deg]	Fit Error [deg]	Stochastic Error [deg]
Total	74.688	0.634	1.220
Compressions Removed	75.082	0.563	0.672
Compressions Flatfielded	74.698	0.575	0.951

Conclusions

- The highly dynamic environment of the SW substantially influences the PUI cutoff, even when viewing freshly injected particles.
- Positive cutoff shifts in the SPE rarefaction regions imply substantial transport effects, or turbulent heating processes.
- Both methods for accounting for the compressions lead to a slight reduction in the statistical error and a substantial reduction in the stochastic error.
 - Method of flatfielding for compressional effects requires improvement.
- Resulting longitude is robust within the fit error.
- The inflow longitude does not show any significant variation with time over the range of this data set.
- Improve on these measurements statistically by expanding the STEREO He⁺ PUI data set to more years.
- Having STEREO overlap operationally with IMAP will provide key long term data set to analyze PUI transport, as well as the flow properties of the LISM.

References & Acknowledgements

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