STATISTICAL STUDY OF FORESHOCK TRANSIENTS IN A GLOBAL HYBRID-VLASOV MAGNETOSPHERIC SIMULATION

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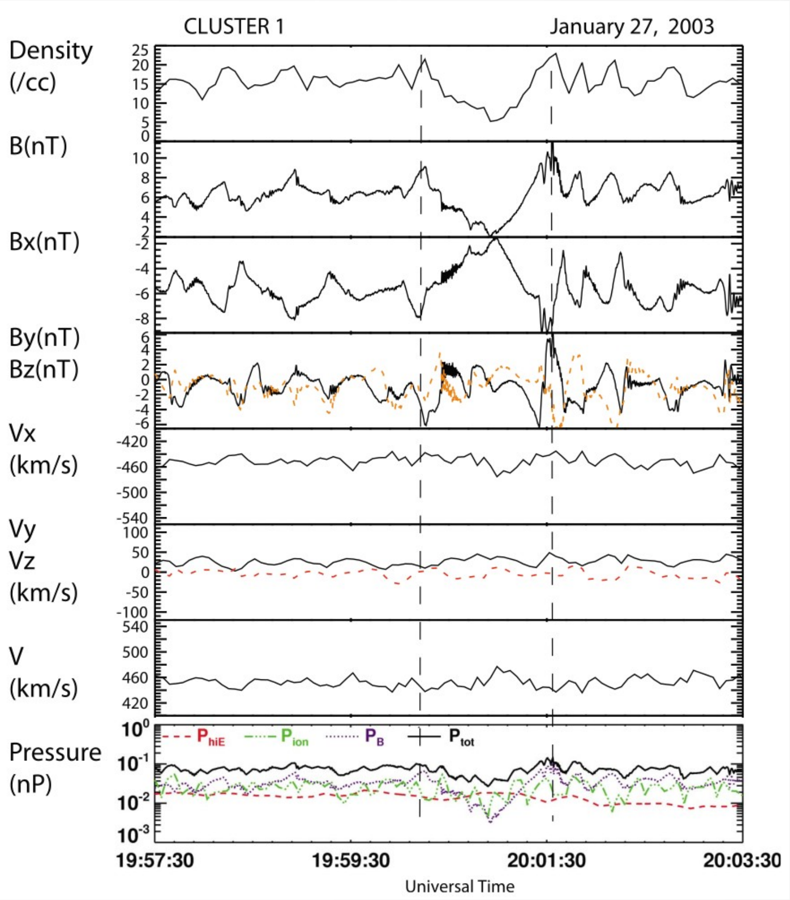
CAVITONS ARE EXAMPLES OF FORESHOCK TRANSIENTS

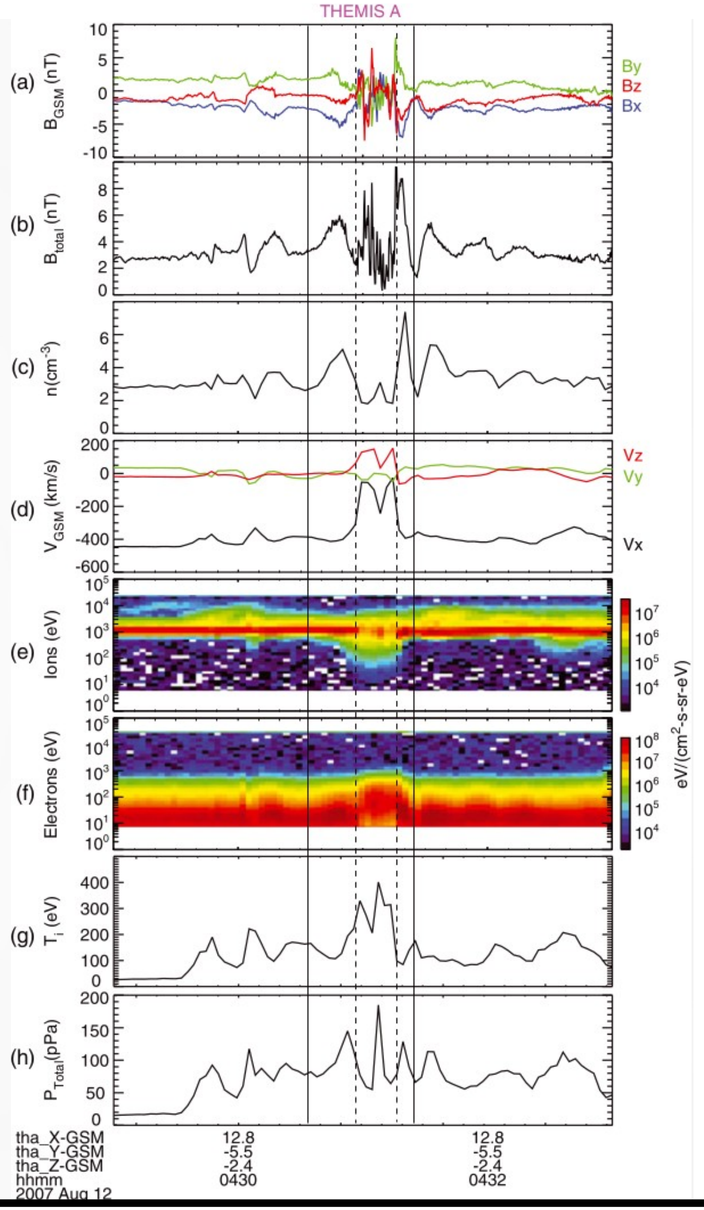
- Upstream of Earth's bow shock lies the foreshock, where bow shock-reflected particles interact with the solar wind and generate Ultra Low Frequency (ULF) waves
- Non-linear evolution of ULF waves can lead to the formation of cavitons, characterized as localized depressions of plasma density and magnetic field
- Observed sizes order of 1 R_E^2



Example of a caviton observed by the Cluster spacecraft, from *Blanco-Cano et al.,* (2011)

CAVITONS PROPAGATE AND EVOLVE IN THE FORESHOCK

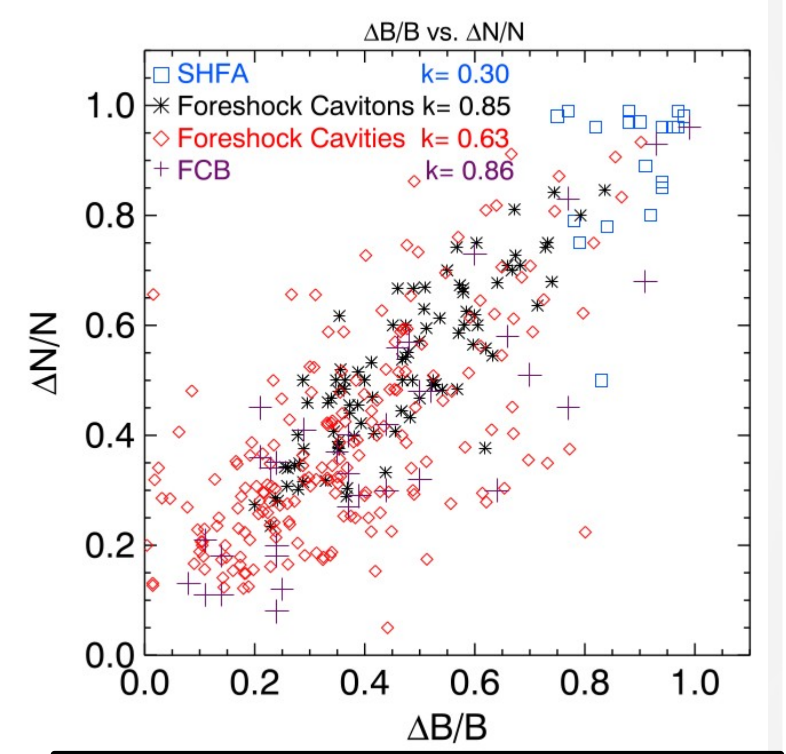
- Cavitons are convected to the bow shock, and they can fill up with backstreaming suprathermal ions, transforming them into Spontaneous Hot Flow Anomalies (SHFAs)
- SHFAs are associated with high temperature, deflected bulk flow and further density and magnetic depletions
- At the bow shock, SHFAs can form magnetosheath cavities [*Blanco-Cano et al., 2018*]



Example of an SHFA observed by the THEMIS spacecraft, from *Zhang et al.,* (2013)

CONDUCTING STATISTICAL STUDY OF CAVITONS AND SHFAS

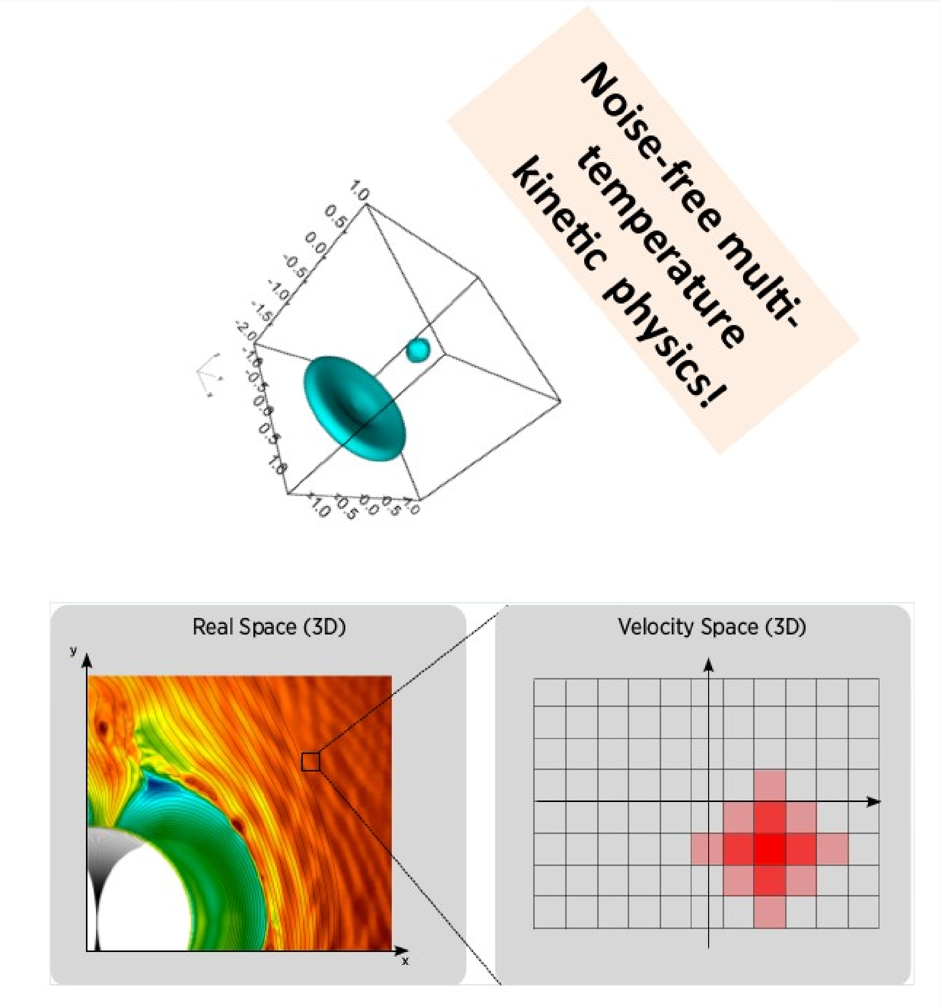
- Statistical studies of cavitons [*Kajdič et al., 2013*] and SHFAs [*Kajdič et al., 2017*] with the Cluster spacecraft found that the transients can be observed under a wide range of solar wind conditions
- Density and magnetic depressions well-correlated inside cavitons, deep but weaker correlation inside SHFAs
- Using Vlasiator, we conduct the first comprehensive computational statistical study of the transients, providing us with the largest sample to date



Correlations between observed density and magnetic field depressions, from *Kajdič et al.,* (2017)

VLASIATOR

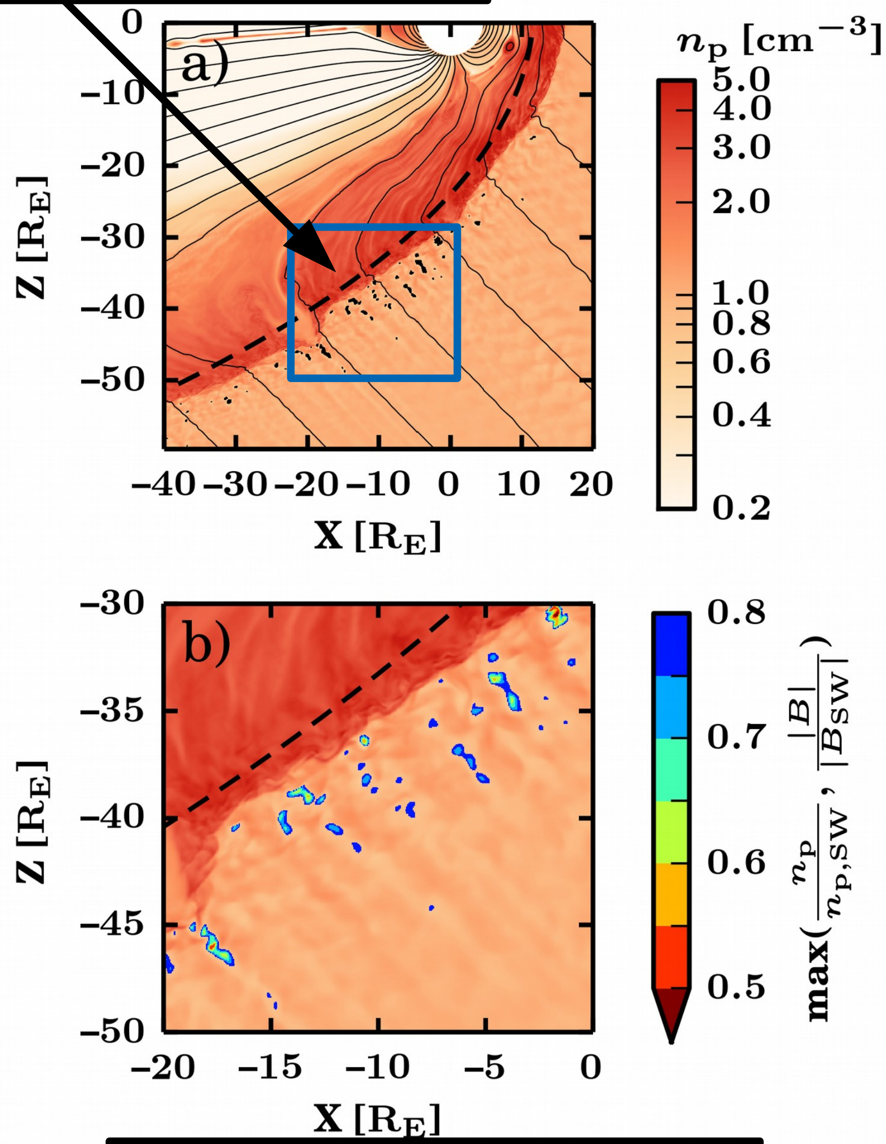
- A hybrid-Vlasov code for performing global magnetospheric simulations [*Palmroth et al., 2018*]
- Ions modelled as velocity distribution functions evolving according to Vlasov’s equation, with cold electrons as a charge-neutralizing fluid
- Up-to-date runs mostly 2D in ordinary space with 3D velocity space
- https://www.helsinki.fi/en/researchgroups/vlasiator



IDENTIFYING TRANSIENTS IN VLASIATOR

- We study cavitons and SHFAs in a single Vlasiator run in the GSE X-Z plane
  - n_{SW} = 1 cm^{-3}, B_{SW} = 5 nT at a 45° cone angle, T_{SW} = 0.5 MK
  - $\mathbf{V}_{SW}$ = (-750,0,0) km/s, M_A = 6.9, M_{MS} = 5.6
- Cavitons consist of cells where $n < 0.8n_{SW}$, $B < 0.8B_{SW}$
- SHFAs are a subset of cavitons, with a requirement of $\beta > 10$ in at least 60% of the transient cells

Cavitons and SHFAs in the foreshock



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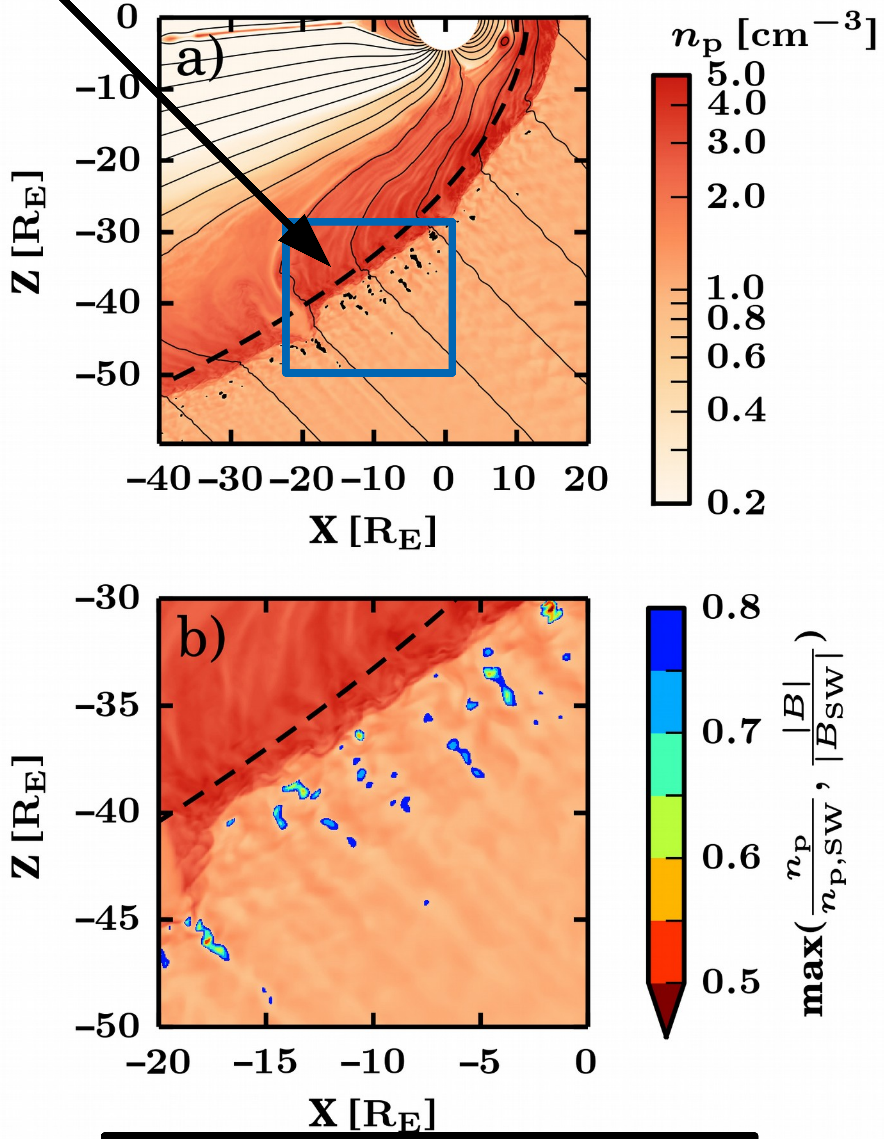
WE TRACK INDIVIDUAL TRANSIENTS

Cavitons and SHFAs in the foreshock

- During a 537.5 s interval, we find 1445 individual transients evolving in time
- Tracking them allows us to study their formation, propagation and evolution in addition to their physical properties
- We find that ~25% of tracked transients are cavitons that evolve into SHFAs, ~50% are purely cavitons and ~25% are purely SHFAs



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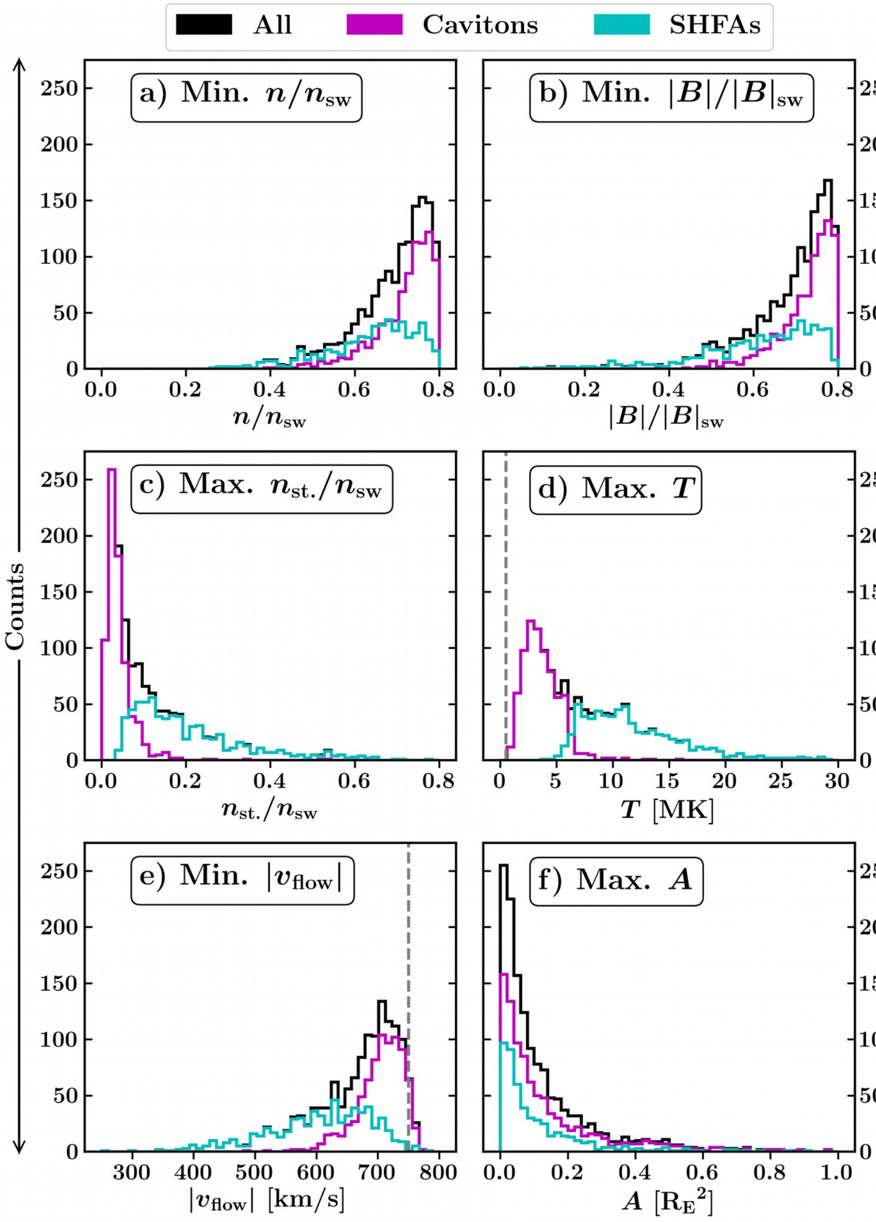
PHYSICAL PROPERTIES

- For each tracked transient, we record the extrema of physical properties over transient lifetime
- We find that the caviton properties are peaked near their respective solar wind values, with low amounts of suprathermal ions
- SHFAs have large suprathermal densities, high temperatures and significantly decreased bulk flow speeds
- The depths and sizes of the transients appear small compared to observations



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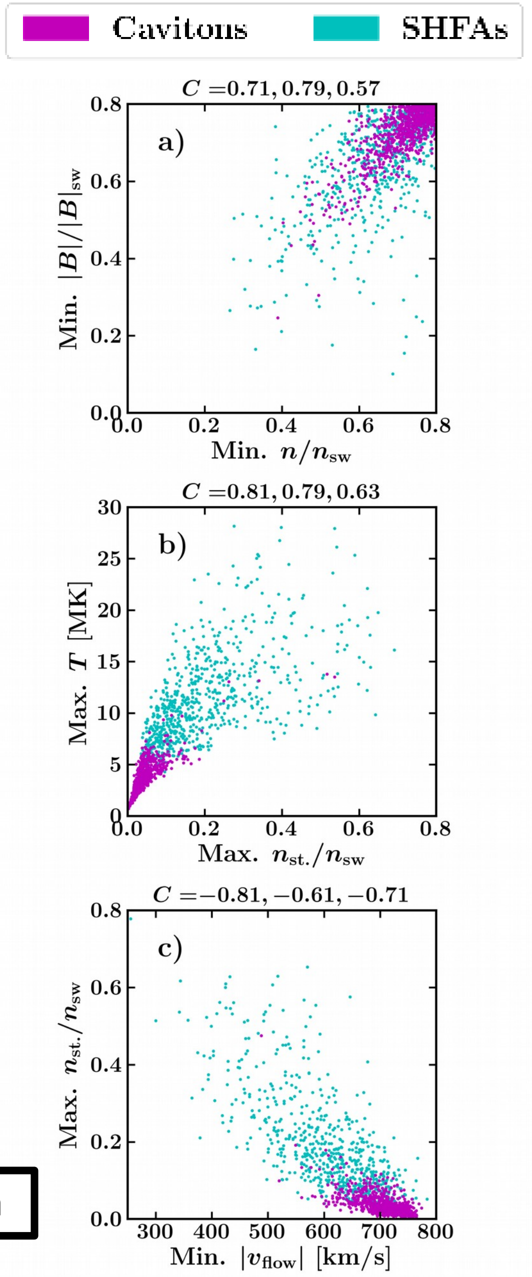
CORRELATIONS BETWEEN PHYSICAL PROPERTIES

- In agreement with observations, density and magnetic field strength are well correlated inside cavitons
- Weaker correlation inside SHFAs, due to the increased amount of suprathermal ions
- The presence of suprathermals increases the temperature and reduces the bulk flow speed inside SHFAs



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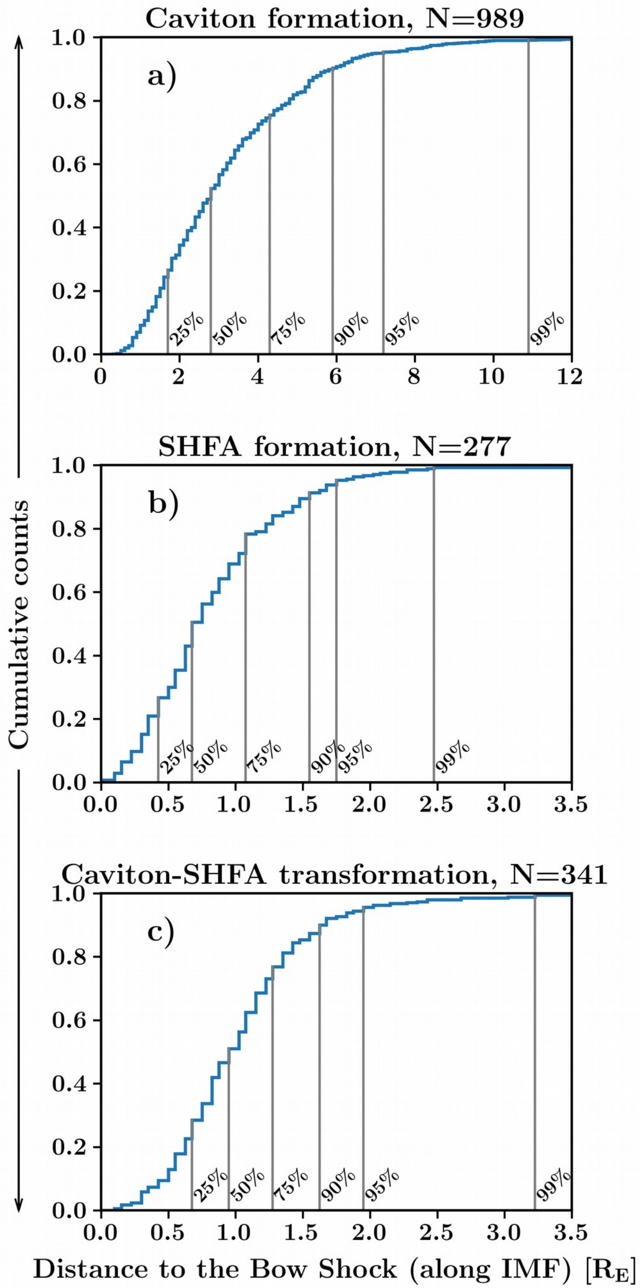
TRANSIENT FORMATION AND EVOLUTION

- Caviton formation is found to take place mainly within ~10 R_E from the bow shock (as measured along the IMF)
- SHFAs are found within ~3.5 R_E from the bow shock
- In this region, formation of both cavitons and SHFAs is abundant and cavitons may evolve into SHFAs



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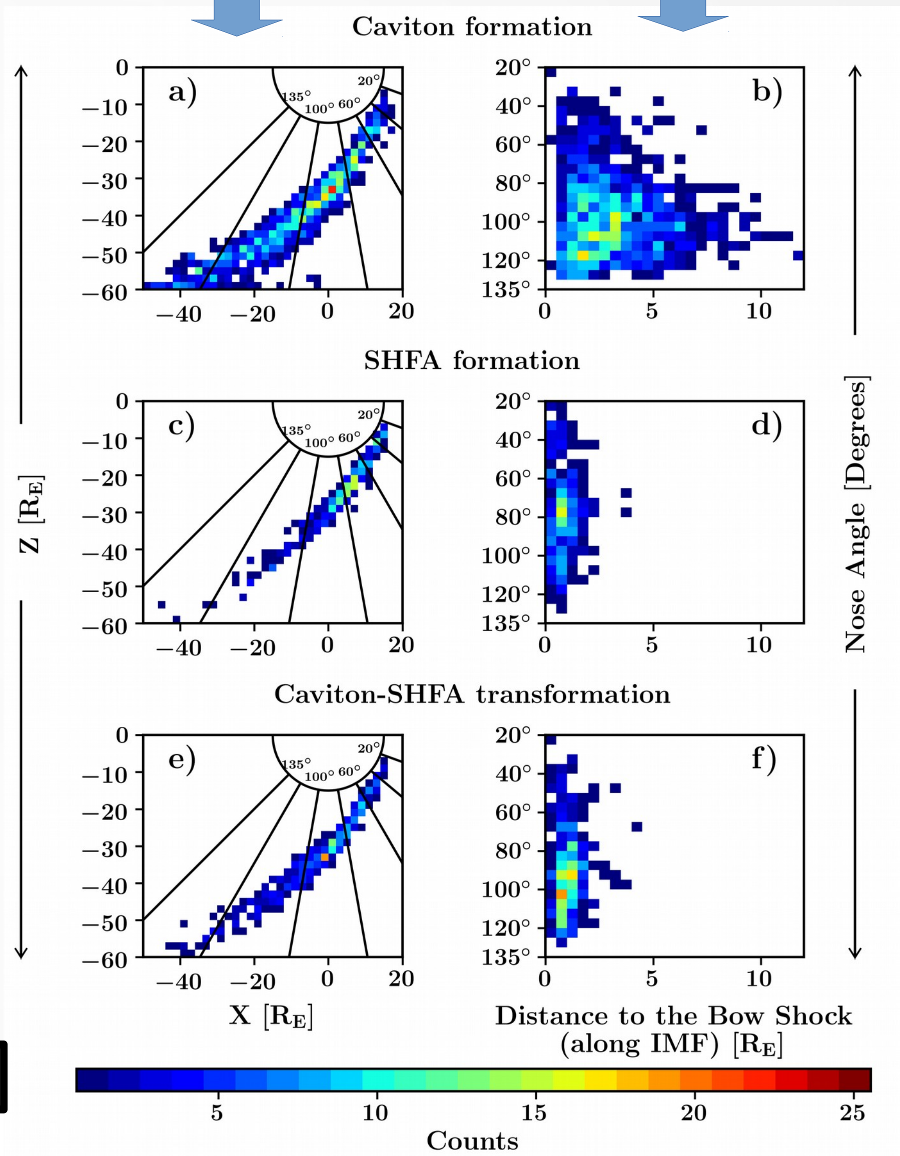
TRANSIENT FORMATION AND EVOLUTION

- In 2D, we plot the bow shock-distance against the angle from the GSE X-axis (”nose angle”)
- The caviton formation region widens with increasing distance from the bow shock nose
- SHFAs are found within the same bow shock-distance in all parts of the foreshock

In Cartesian GSE-coordinates

Distance from the bow shock vs. angle from X-axis



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TRANSIENT PROPAGATION

- Both cavitons and SHFAs propagate at a uniform speed along the Sun-Earth direction
- In the solar wind rest frame, the propagation is sunwards (~144 km/s), in agreement with observations by *Kajdič et al.*, (2011)
- We find that the transients propagate southwards in the out-of-ecliptic direction

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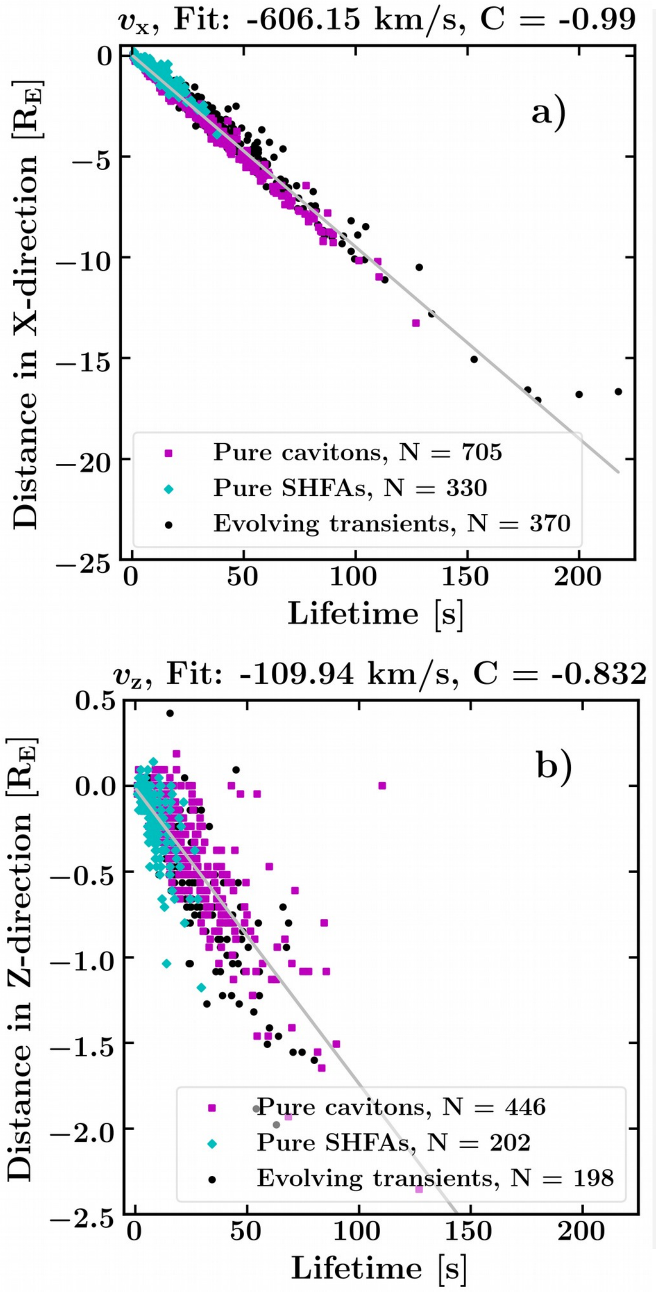

CONCLUSIONS

Good agreement is found between the statistical Vlasiator results and spacecraft observations:

- Cavitons have well-correlated density and magnetic field depressions
- The transients' sunward propagation speed in the solar wind rest frame agrees well with observed speeds
- Simulated transients are smaller than those in spacecraft observations, possibly due to limited wave steepening in the simulation [*Pfau-Kempf et al., 2018*], and difficulty of resolving small transients in spacecraft data

CONCLUSIONS

- Cavitons form in a well-defined region deep in the foreshock
- Spontaneous Hot Flow Anomalies are found close to the bow shock, the observed heating and bulk flow deflection in their interior corresponds to an increase in suprathermal density
- SHFAs form on their own and evolve from cavitons in roughly equal amounts, but not all cavitons evolve into SHFAs