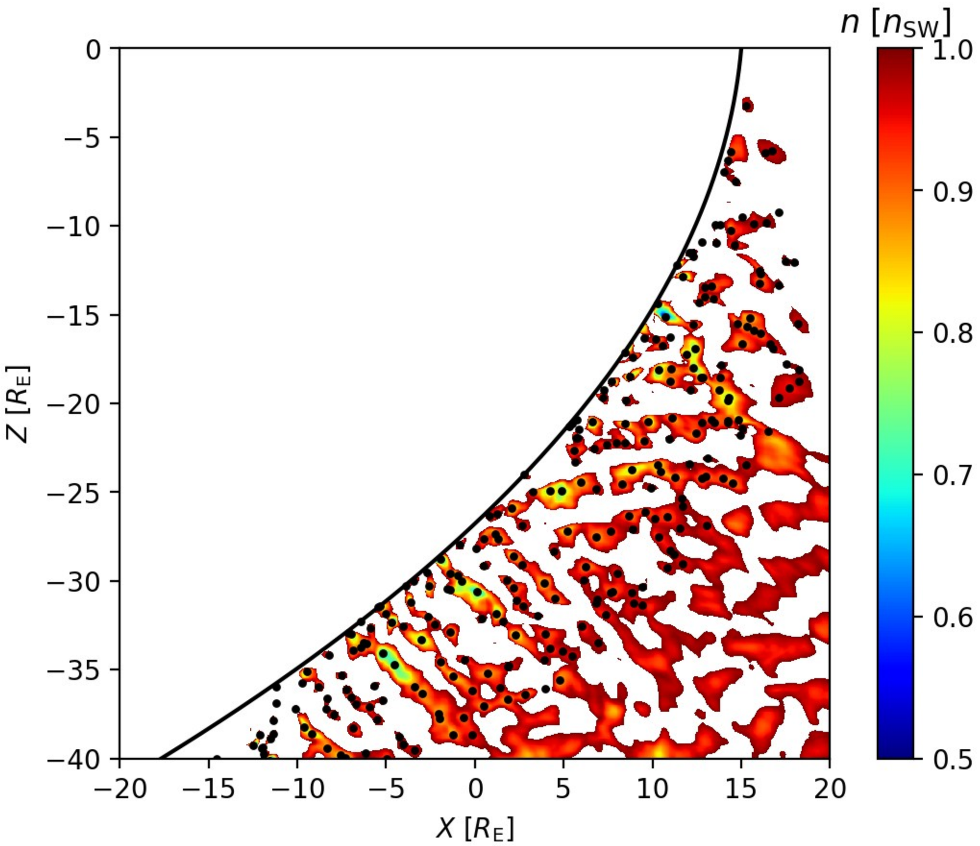
Response to referee no. 1

We thank the referee for providing insightful comments, and believe these will improve the manuscript. Below are responses to each comment individually.

First on a general note, in order to understand the foreshock conditions surrounding the transients, we have compared the plasma properties of the transients to those of the surrounding ULF wave field. We do this by finding the troughs in the ULF wave field, since they can be directly compared to the transients consisting of decreases in density/magnetic field magnitude. This method is illustrated in Figure 1 below. We define the troughs as local minima in the proton number density below the input solar wind value. Unlike cavitons and SHFAs, we do not track the motion of the troughs, but use them only to calculate statistics of various plasma properties (e.g., density, temperature and bulk speed), which are compared to the tracked transients. Only troughs in the relevant region are selected for these statistics (e.g., within 1/4/10 RE from the bow shock). We will refer to these results in the responses below, and also add them to the revised manuscript.



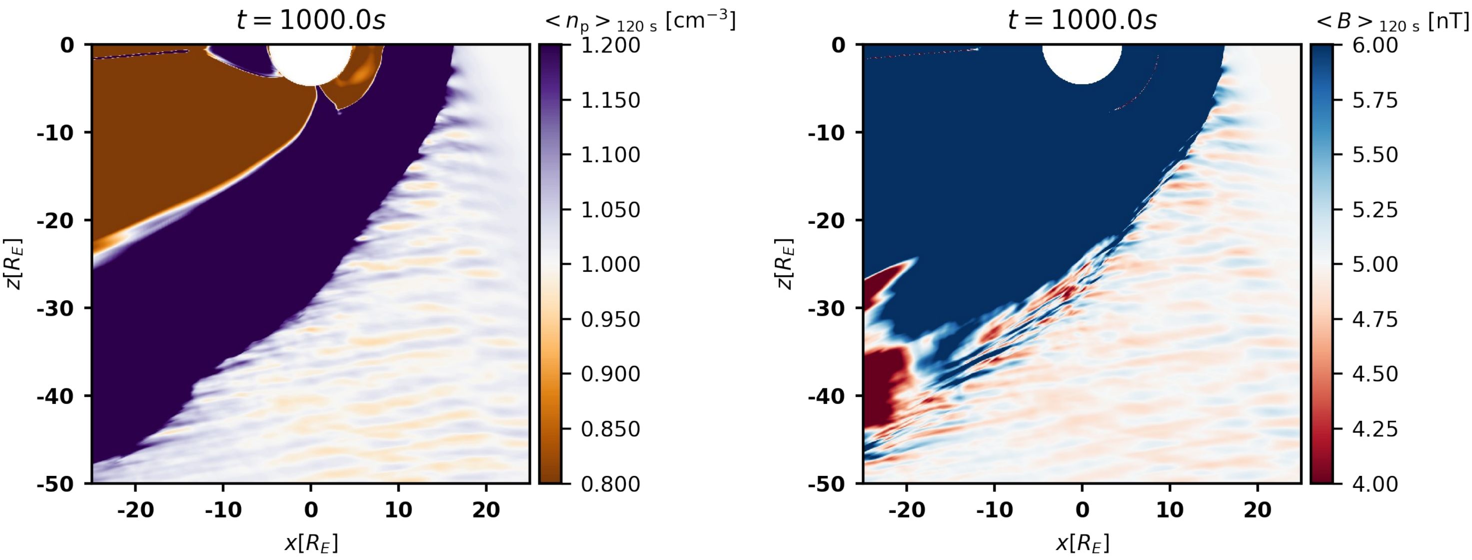
<u>**Above: A plot showing ULF wave troughs / local minima as black dots within 10 RE from the bow shock at time t=900.0 s. The colormap shows values of proton number density below the input solar wind density nSW. The bow shock is modelled with the 4th order polynomial described in the manuscript.**</u>

Major:
1. Lines 131-134: About the event selection criteria, I have the following questions:

1a. Since cavitions are embedded in ULF waves in the foreshock, it is crucial to distinguish cavitions from ULF waves. Cavitons should have lower B and N than ambient waves. Is 20% depletion a good enough criterion to distinguish cavitions from ULF waves? What if the background ULF wave amplitude is greater than 20% of Bsw and Nsw? In line 147, it was mentioned that "several transients exhibit elongated shapes and are found together in "chains" that are aligned with the direction of the IMF." Could they be an ULF wave train with amplitude greater than 20% of Bsw and Nsw?

The choice of a 20% limit is the same as in earlier spacecraft studies by Kajdic et al. (2013, 2017). However, in these studies, the events had to fulfill a subsequent criterion based on a function defined as $\chi(t) = (n(t) - \langle n \rangle) * (B(t) - \langle B \rangle)$ (where n(t) and B(t) are the density and magnetic field magnitude at time t and <> denotes a time average). The criterion requires that the value of χ inside cavitons must be at least 5 standard deviations larger than the temporal average of χ over the observation interval. We have omitted this subsequent criterion in order to be able to detect small transients and study the temporal evolution of the transients.

In general, the density and magnetic field magnitude fluctuate ~5-10% from their solar wind values in the foreshock, and the amplitude of the fluctuations is below our caviton detection criteria. Below shown are temporal averages of proton number density np and magnetic field magnitude B over a 120 s interval.



Above: Temporal averages of proton number density (left) and magnetic field magnitude (right) in the foreshock over a 120 s period.

More specifically, the amplitude of the general ULF wave field can also be compared to the depth of the transients by considering the depletions at the wave troughs (i.e., local minima) below the input solar wind values. In the region where cavitons are found (< ~10 RE from the bow shock), the proton number density in a trough has a mean depletion of ~12%. Structures with density depletions of >20% represent ~17.4% of all minima in the wave troughs. Based on visual inspection, we consider the 20% limit to be representative of a forming, localised transient. We will add these results concerning the general wave field in the revised manuscript to better motivate the chosen selection criteria.

Chains of cavitons form near the bow shock where the foreshock is permeated by multitude of waves propagating at different angles. These conditions are suitable for repeated formation of cavitons as the cross-propagating ULF waves interact with each other. Visually, such chains are a common feature near the bow shock throughout the simulation. Thus, they likely do not correspond to isolated ULF wave trains, but rather to continuous transient formation.

1b. Plasma beta > 10 is used as a criterion to identify SHFAs. Would it be better to use the ion temperature and bulk flow instead of plasma beta to identify SHFAs? First, it is possible that some events with beta > 10 do not show ion heating at all and the high beta is simply due to very low Bt. Using solar wind beta =0.7, for an event with beta = 10 and without heating, B = sqrt(0.07) Bsw =0.26 Bsw. Figure 2b shows that some SHFAs have B below this value. Second, some SHFAs with weak B depletion and moderate heating can also be misidentified as foreshock cavitions. Figure 2c shows that a few SHFAs have low foreshock ion density ratio and some foreshock cavitons have large ratio. Is it possible that these special events were misidentified due to the two reasons mentioned above? Third, the average value of the bulk flow speed inside SHFAs is 19.4% decrease from the solar wind bulk flow speed (lines 210-211). Does this mean that about half of the SHFAs have less than 20% flow decrease and should not be called SHFAs since there is no significant "flow anomaly"?

Beta was originally chosen as a criterion for SHFAs due to the large variation found in the temperature throughout the foreshock, which makes setting an explicit temperature criterion challenging. Similarly, we did not wish to make assumptions on the bulk flow speeds inside the transients. The physical motivation behind the choice of beta is that a large beta indicates that the interiors of the structures are dominated by the plasma instead of the magnetic field. The value of beta > 10 was chosen based on visual inspection. In the end, we retained the beta critetion as it appears to pick the differences between cavitons and SHFAs well, and in order to keep our results comparable with the earlier Vlasiator caviton/SHFA study by Blanco-Cano et al. (2018), where the beta-criterion was originally used. We acknowledge that other SHFA criteria could be also succesfully applied. If a temperature criterion was used instead, a similar classification to the present would be obtained, as panel d) in Figure 2 shows.

On the possibility of transients being miscategorised due to low magnetic field magnitude, we note that all SHFAs in panel d) of Figure 2 have temperatures above the mean temperature of cavitons, and conclude that the impact of the magnetic field magnitude on the categorisation is not statistically significant. For the specific case of transients with B depletions below 0.26 Bsw, we find that the temperature inside these transients ranges between ~8-40 MK, and conclude that they are correctly categorised as SHFAs. For the suprathermal density, we see in panels b) and c) of Figure 3 that for each temperature/bulk flow speed, a large range of suprathermal densities is found, and overlap between cavitons and SHFAs exists although they have different temperatures and bulk flow speeds.

Finally, it is true that there is a large proportion of SHFAs with minor flow deflections. These might be better described as "proto-SHFAs", similar to young structures discussed in e.g., Zhang et al. (2013). We will discuss this in the revised manuscript.

2. The authors did not compare the plasma properties inside cavitons and SHFAs with the ambient foreshock. Without this comparison, the following conclusions are either not convincing or lack of a physical explanation.

Since the conditions in the foreshock vary both in space and time, defining ambient properties in the foreshock is difficult. We have evaluated these conditions by considering the troughs in the foreshock ULF wave field, which can be directly compared to the foreshock transients. We define the troughs as local minima of proton number density below the input solar wind value. We will supplement the manuscript to include discussion on this comparison. See below for each individual point.

2a. Lines 295-296: "The low amount of suprathermals beyond 1 RE suggests that the accumulation of suprathermals occurs principally very close to the bow shock." Line 427: "Our results indicate that the accumulation of suprathermals inside cavitons/SHFAs is closely tied to the transients' distance from the bow shock." Background foreshock ion density, temperature, and velocity need to be used to compare with transient values (increase/decrease ratio). Those background values are also very sensitive to thetaBn and distance from the bow shock. Is there really foreshock ion density increase compared to the background foreshock? The high density ratio could also be due to a decrease in Nsw. Therefore, this may not be due to more accumulation close to the bow shock.

As we compare the number density of suprathermal ions directly to the input solar wind ion number density, the presented values of the suprathermal ion density represent an absolute increase in the amount of suprathermals. Within 1 RE from the bow shock, the mean suprathermal ion density in a trough of a ULF wave is ~0.01 nSW. Panel h) in Figure 6 shows that within 1 RE from the bow shock, the number density of suprathermal ions inside SHFAs (~0.05-0.78 nSW) typically exceeds this value. The high amounts of suprathermals inside SHFAs are associated with the rippled bow shock surface, and are not uniformly present in the foreshock.

2b. Line 316: "we observe a clear nose angle dependence in the proton temperature" Line 441: "the temperature inside SHFAs increases towards the bow shock nose." Is it because near the nose, as foreshock ions are more radially sunward, there are larger relative motion between foreshock ions and solar wind ions causing larger measured ion temperature? I suggest to check the background foreshock ion temperature.

As the temperature is evaluated in the plasma bulk frame, both the sunward and lateral components of the velocity affect the calculated temperature of suprathermal ions. In general, the suprathermal population behaves as a quasi-gyrating population that travels along the mean magnetic field direction. The largest field-parallel velocities are found near the foreshock edge, and the velocity decreases deeper into the foreshock, explaining the higher temperatures and lower bulk flow speeds near the shock nose. We will add discussion on this effect to the revised manuscript.

2c. Lines 373-374: "True to their name, the SHFAs in our simulation run are associated with high temperatures and high levels of bulk flow deflection due to the large quantities of suprathermals inside them" It would be more convincing to say

“high temperatures” if they were compared with those in the background foreshock. “high levels of bulk flow deflection” may not be accurate since the average value of the bulk flow speed inside SHFAs is 19.4% decrease from the solar wind bulk flow speed (lines 210-211). See comment 1b above.

In the region where SHFAs are found (within ~4 RE from the bow shock), the mean temperature in a trough of a ULF wave is ~4.3 MK, a bit over half the approximate minimum temperature inside SHFAs (>~7 MK). While the mean decrease in the bulk flow speed inside SHFAs (19.4%) is relatively small, it is roughly 4 times larger than the mean bulk flow speed decrease inside ULF wave troughs (4.8%) in the region where SHFAs are present. However, “high levels of bulk flow deflection” might be better described as “higher levels of bulk flow deflection than cavitons”. We will revise this expression.

Minor:

3. Line 70: “Cavitons were found preferentially during stronger IMF, lower solar wind density and larger solar wind and Alfvén speeds.” Is this conclusion based on Figure 16 in Kajdic et al. (2017)? If so, this conclusion may not be correct since the distributions in this figure are not normalized by the background solar wind distributions. If not, please provide the reference.

The conclusion is taken from section 2.2.1 in Kajdic et al. (2013), where the background values are taken into consideration. Admittedly, the phrasing is ambiguous on line 70. This will be rephrased in the manuscript as: “Kajdic et al. (2013) observed cavitons preferentially during stronger IMF, ...”

4. Line 74: This conclusion is based on observations of “19 SHFAs found in the Cluster data between the years 2003 and 2011” by Kajdic et al. (2017). It is very likely that very strict criteria were used and only very significant SHFAs were included in this study because the following studies based on 300 SHFAs from Cluster data and 66 SHFAs from 3 years of THEMIS data showed less than 90% depletion in many SHFAs. Please see Figure 3 in Wang et al. (2013) and Figure 5a in Chu et al. (2017).

The statement on line 74 will be supplemented with the provided references as follows:

“...However, the magnitude of the depletions inside SHFAs listed by Kajdic et al. (2017) may be a product of the strict criteria used to detect the events. Other spacecraft observations of potential SHFAs by Wang et al. (2013) and Chu et al. (2017) show numerous examples with depletions having magnitudes less than 90%.”

5. Lines 156, 218-219: Is there any reason to set the lower limit of the event size to 5 cells (0.011 RE)? Why are the transients in the simulation smaller than those observed?

A lower size limit is employed due to our automated transient tracking method. Since the method is based on the overlap between transients at consequent timesteps of the simulation, a minimum size limit ensures that small transients can be tracked consistently. A minimum size of 5 cells was selected as a good trade-off to ensure consistent tracking and a large sample of transients.

The sizes of the transients in our simulations are affected by the following factors; First, the spatial resolution of the simulation can limit the steepening of ULF waves, also limiting the sizes of foreshock transients, as discussed also in Blanco-Cano et al (2018). Second, as we define the transients as structures below 80% of solar wind ion density/magnetic field magnitude, only the area below this limit is taken into account. This does not take into account the “shoulders” surrounding the transients, where the density/magnetic field magnitude are enhanced. These shoulders typically have a finite width, and they are not identified by our automated transient detection algorithm. Finally, the size difference can partially result from the selection of the transients. Our data set includes a number of small transients which might be discarded by selection criteria used in past spacecraft studies.

6. Lines 182 and 187: SHFAs tend to be more depleted (up to 94%) than cavitons. This is partially due to the SHFA selection criterion of beta > 10. See comment 1.2 above.

For the large majority of SHFAs in our study, the relative increase in the temperature (T) is much greater than the relative decrease in the magnetic field strength (B). While beta has a stronger dependence on B than T, the decrease in B is countered to some extent by the comparable decrease in plasma number density (n), so that beta = nT/B^2 behaves as ~T/B. Since the change in T is much larger than the change in B, B should not impact the classification of the transients.

7. Lines 192-193: “Figure 2c shows that nst rarely exceeds 15% of the solar wind density inside cavitons,” This is true, but many of them can still have density ratio larger than that in the background foreshock causing higher ion temperature. The ion temperature inside foreshock cavitons should be similar to that in the ambient foreshock.

The temperature in the foreshock is dependent on the distance to the bow shock, and a similar temperature dependence is found inside both cavitons and the surrounding ULF waves. For all troughs within 10 RE from the shock, the mean temperature is ~2.8 MK. Panel i) in Figure 6 shows that the temperatures inside cavitons far from the shock (~5-10 RE) are comparable to this value. Near the shock (< ~2 RE), where the temperatures inside cavitons are considerably higher, there is a similar temperature increase inside ULF wave troughs, showing a mean temperature of ~5.8 MK within that range. We will add discussion about the temperature to the manuscript.

8. Lines 203-205: Figure 2d shows that the proton temperature separating cavitons and SHFAs is 14 times the solar wind ion temperature. What is the ion temperature in the background foreshock? Are the ion temperature inside foreshock cavitons similar to that in the ambient foreshock?

Please see the response no. 7 above. The foreshock contains a range of temperatures, and the temperature generally depends on the location in the foreshock. Hence, it is not possible to define a single foreshock temperature. The temperatures inside cavitons and ULF waves are similar, and show similar dependence on location, as demonstrated above.

9. Line 213: Could the few examples of cavitions with less than 600 km/s flow speed be SHFAs?

The majority of the cavitons having such low bulk flow speeds are evolving transients, which fulfill our SHFA classification later in the simulation (7 out of 11 transients). In these cases, the overall minimum of bulk flow speed has occurred while the transients were still classified as cavitons.

The last four cavitons that do not evolve into SHFAs according to our criteria, propagate close to the bow shock (≤ 1 RE). Their temperatures are in the range 5-7 MK. According to panels i) and j) in Figure 6, these temperatures are in the low end of SHFA temperatures at those distances. These examples may be cavitons that are beginning to evolve into SHFAs, but do not reach a fully developed stage before they disappear near the shock.

10. Lines 219-220: “Cavitons have a slightly larger average maximum area than SHFAs which could be due to SHFAs forming only near the bow shock, where they do not have time to grow large.” This might be true for SHFAs that form independently. How about SHFAs that evolve from cavitons? Shouldn't they be larger than cavitions?

The statement on lines 219-220 does not account for the evolution of the transients, so that independently forming SHFAs and SHFAs evolving from cavitons are counted in the same category. When they are considered separately, it is indeed seen that cavitons evolving into SHFAs have the largest average size, followed by cavitons that do not evolve and SHFAs that do not evolve from cavitons:

- Cavitons evolving into SHFAs; ~0.27 RE
- Cavitons not evolving into SHFAs: ~0.11 RE
- Independently forming SHFAs: ~0.08 RE

This will be clarified in the revised manuscript.

11. Line 271: Should “along the bow shock” be “along the bow shock surface”?

This will be rephrased as suggested.

12. Lines 270, 299, 316, 438: The parameters are organized as a function of the nose angle. “There is no single trend controlling the properties of cavitons and SHFAs as the nose angle varies.” How about organizing them as a function of thetaBn? “The amount of SHFAs decreases towards the flank of the bow shock.” The physics behind this is likely the occurrence rate of SHFAs depends on the thetaBn and the local shock Mach number which decreases towards the flank.

ThetaBn is not used in this study since most of the analysed transients are located at the flank of the bow shock, where thetaBn has a narrow value range. Thus, we chose to use the nose angle instead, as it is better suited for analysing the spatial variation of transient formation and properties. We will add discussion on the range of thetaBn in the revised manuscript.

13. Line 371: “we observe a clear difference in the amount of suprathermal protons inside cavitons and SHFAs” There is “a clear difference”, but there is also some

overlap. What about the ratio of suprathermal protons to Nsw in the ambient foreshock?

A general estimate of the suprathermal proton number density in the foreshock surrounding the transients can be obtained by looking at the number densities in the troughs of ULF waves. In the region where both cavitons and SHFAs are present (within ~4 RE from the bow shock), the suprathermal proton density at a trough of a ULF wave has a mean value of ~0.05 nSW. This value is similar to that found inside cavitons, and lower than the values found inside SHFAs.

14. Line 392: "pick up even the smallest transients that may not be resolvable from spacecraft data amidst ULF waves." Are they really transients or waves? Why are they not resolvable from spacecraft data?

Since cavitons evolve from interacting ULF waves, there is no clear threshold for identifying an event in which a caviton forms from the ULF wave field. Due to our automated detection method, our study includes small structures that might be discarded by the more stringent selection criteria used in spacecraft observations, such as those employed by Kajdic et al. 2013. In spacecraft data, only fully developed transients can be detected, i.e., they need to be visually identifiable from the surrounding ULF waves. We will rephrase the sentence quoted in the comment as follows to make its meaning clearer:

"...pick up even the smalles transients that may not be identifiable from spacecraft data amidst ULF waves."

15. Line 446: "larger reductions in the bulk flow speed inside SHFAs near the bow shock nose" As backstreaming foreshock ions are more sunward, which can reduce more bulk speed (same reason as the high ion temperature near the nose).

We will include this point in the revised manuscript.