# *Referee A*

*This paper investigates a novel collective excitation phenomenon in d-wave altermagnets. Starting from the random phase approximation (RPA), the authors analyze spin-resolved response functions and discover out-of-phase oscillations between the two spin species, termed a “spin demon”. Compared to conventional charge plasmons, this spin demon exhibits a high quality factor (Q>10), indicating that it is a long-lived quasiparticle excitation. The study reveals that the spin demon carries a magnetic moment with d-wave symmetry, providing new insights into the physical properties of d-wave altermagnets. But it is unsuitable to be published in PRL since there are some issues that need to be fixed.*

*1. The text does not firmly convince the reader that demons are essential to the community. Although the phenomenon of finding a demon in spin response of altermagnet is new compared with the conventional charge plasmons and has a high Q factor, it needs a different detection method like SPEELS. I am very doubtful if the demon is important and interesting since the authors only discuss about the definition of the demon.*

We thank the referee for pointing out that in our text we do not sufficiently explain the need relevance of a spin demon. We have addressed this in our updated manuscript. We would also like to respond here directly with regards to the importance of the spin demon.

Firstly, we want to stress that the (conventional, spinless) demon has been sought after by the plasmonics community, ever since its first theoretical formulation by Pines in 1956.[[1]](#footnote-1) Its importance lies in the fact that it is a novel quasiparticle that **potentially exists in any conducting system with more than one band at the Fermi level**. Furthermore, a demon is gapless, which allows it to **mediate correlated phenomena** – playing a role in phase transitions,[[2]](#footnote-2) Weyl semimetals[[3]](#footnote-3) and high-temperature superconductivity.[[4]](#footnote-4) However, demons are electrically neutral and do not couple to light, and have therefore only been detected in an equilibrium, 3D metal in 2023.[[5]](#footnote-5) In our work, we show that a d-wave altermagnet naturally hosts a spin demon, which brings the concept of spin-polarized demons into the field of plasmonics, opening a new avenue within this existing field. We believe that this satisfies the first of the PRL criteria (*Open a new research area, or a new avenue within an established area.)* Additionally, given the large interest in metallic altermagnets, we believe our work **opens up a wide range of material candidates** in which a demon can potentially be detected.

Furthermore, by showing that a spin version of the demon exists in d-wave altermagnets, we **bring together the communities of** **plasmonics and spintronics**. This makes this work of **relevance to a wider audience**, and thus in our view satisfying the fourth of the PRL criteria (*Be of unusual intrinsic interest to PRL's broad audience.*)

Finally, in the spintronics context, the spin demon could potentially also be used for spin-based applications, since it carriers magnetic moment – as was also proposed by Agarwal *et al*. in the context of acoustic plasmons in a spin-polarized two-dimensional electron gas.[[6]](#footnote-6)

**Action taken**: we have rewritten the second paragraph in the introduction, highlighting the importance of demons.

*2. In 4th paragraph, the authors write, "The spin demon corresponds to the strongly peaked response in the imaginary part of the spin-spin response function, , of an altermagnetic metal, as shown in the altermagnetic spin-split plane in Fig. 1." This conclusion is not so obvious and does not have any demonstration or explanation in both main text and supplemental material for reference. This is a very important conclusion to show the demon effect, which is the basis of the latter discussion. Most of the time, the strongly peaked response in the imaginary part may also correspond to the collective mode, which is a very common phenomenon.*

*So the authors should discuss this in detail and convince the readers of the conclusion that the strongly peaked response of will match the definition of the spin demon.*

Firstly, we apologize for the unclearing wording in the 4th paragraph – we did not mean to imply that any peaked response in the imaginary part of the spin-spin response function is sufficient proof of a spin demon.

**Action taken**: we have rewritten the 4th paragraph to make clear that not any peaked response in the imaginary part of the spin-spin response function is sufficient proof of a spin demon.

Furthermore, upon carefully rereading our *Method* section, we realize that we did not make sufficiently clear how the dielectric function and are related – since zeros of corresponds to poles of . As now explicitly written in the main text, the main properties of collective excitations can be learned from analyzing the zeros of the complex dielectric function . These zeros are then reflected in . The analysis we provide in the main text therefore focusses on , since from here we can learn the frequency and damping of the collective modes. This is the analysis that is performed in the *Method* section, as well as in Sec. VIII (*Analytical solution of spin demon dispersion*) in the SM.

As the referee correctly notes, a collective mode corresponds to a peak in the imaginary part of the response function. In a system with broken spin-degeneracy, there are three response functions that fully characterize the spin-dependent response: and . These three response functions share a common denominator, namely the dielectric function . Zeros of the dielectric function , which correspond to collective excitations, produce poles in all three response functions ( and ). However, whether the collective excitation has a finite response in a specific response function depends on whether it has support in this specific response function. This we show in Fig. S2 in the SM, which we reproduce below for convenience.



Figure 1 The three fundamental response functions (Fig. S2 in the SM).

Here it is clear that while and have a peak at the spin demon frequency, does not. This we attribute to the out-of-phase oscillations of the spin demon, which cancel in the response function. This is further reinforced by our analysis of the eigenvalue problem [Eq. (10) in the main text], where we show explicitly that a spin demon consists of out-of-phase oscillations of the two spin densities. We therefore take as the primary indication of the existence of a spin demon.

Finally, we note that we have approached this problem in three different ways: (1) numerical evaluation of ; (2) analytically finding the zeros of the dielectric function and (3) solving the eigenvalue problem to find [Eq. (11) in the main text)]. Since all three approaches find a quasiparticle with the properties we ascribe to a spin demon, we take this as conclusive evidence for the existence of a spin demon in d-wave altermagnets.

**Action taken**: we have rewritten the *Method* section to explicitly spell out the connection between the dielectric function and the response functions and to make clear why we can identify the strong peak in as the spin demon.

3. *As the authors said write in the abstract, the main point of the manuscript should be, "Here, we show that d-wave altermagnets, a recently discovered class of collinear magnetism, naturally realize a spin demon." But I could not find any conclusions that show the readers how to step by step map the demon.*

We would like to first apologize to the referee, because we are not sure we understand what the referee means with step-by-step mapping the demon. We would therefore like to explicitly state what we understand the spin demon to be, and why we believe the evidence we present to be consistent with this definition.

To be explicit, we define a spin demon as an out-of-phase oscillation of the two spin densities, which vanishes as . Because of the out-of-phase oscillation, the spin demon is also imbued with a magnetic moment, and can thus be seen as a quasiparticle with well-defined “spin”.

From the above definition, we expect that the spin demon appears in a spin-sensitive probe. In our work, we focus on , since we find that the response is strongest here. Our first proof is the existence of a linearly dispersing, gapless mode, appearing in , indicating the existence of a collective mode. We can trace this collective mode to a zero of the dielectric function, which vanishes along of the spin degenerate directions in the altermagnetic spin-split plane. This highlights that the spin demon is the effect of the altermagnetic spin splitting. Finally, by analyzing the eigenvalue problem, we can explicitly show the spin demon to be an out-of-phase oscillation of the two spin densities. We thus believe the above to constitute a complete mapping of the spin demon in d-wave altermagnets.

*4. Eq.10 originates from the Eq. 1, but Eq. 1 is , while in Eq. 10, the authors use to replace . Since Eq. 11 is the solution of Eq. 10, which is the demonstration of the out-of-phase effect, and important to showing the demon effect, a detailed derivation should at least be given in the supplemental file or at least be presented with some description.*

We thank the referee for pointing out this inconsistency. We had forgotten an inverse matrix sign, and the correct expression for Eq. (1) should be:

We apologize to the referee for this error, and we have corrected it in the updated manuscript.

**Action taken*:*** the inverse matrix sign has now been corrected.

*5. When the authors address the definition of , they also introduce the spin-dependent Fermi velocity . However, in the supplemental material, the authors only give the definition of spin-independent Fermi velocity Could the authors give some explanation about the*

We apologize for missing this definition in our text. We have now correctly defined .

**Action taken**: After Eq. (5), we have now defined .

# *Referee B*

*The manuscript presents an investigation of charge-neutral collective excitations in d-wave altermagnetic metals. These are zero magnetization systems with spin-split Fermi surfaces that break spin-rotation symmetry. Employing a spin-resolved RPA analysis, they demonstrate the existence of a spin-demon mode with a d-wave form factor. The various properties of this mode turn out to be anisotropic. The authors analyzed both the three and the two dimensional case.*

*The work is timely, building on recent interest in altermagnets. It introduces a conceptually novel spin-demon mode with no net charge motion but carrying a magnetic moment. The key point that makes it stand out is that this spin mode is stabilized by the special band structure of altermagnets, with a momentum-dependent spin splitting, and not by spin-spin interactions. Indeed, the authors considered a purely density-density interaction of the Coulomb form in their analysis, which is based on linear response theory, and directly interpretable in spectroscopic terms.*

*In my opinion, the manuscript makes an original contribution to the theory of spin dynamics in altermagnets and will likely stimulate further work on spectroscopy and spin-transport in these systems. In light of this, I believe the manuscript would be suitable for publication in PRL, after the authors have had a chance to consider the following comments.*

We thank the referee for their kind words and their positive assessment of our work. Below we address their comments in detail.

*1. It seems that the total Sz is a conserved quantum number in the models studied. If Sz non-conserving terms were present but weak (say due to weak spin-orbit coupling), then the band structure around theta = pi/4 would be modified due to the appearance of a gap between the spin-resolved bands and the removal of the crossing point of the two Fermi surfaces. How would this affect the existence and region of stability of the spin-demon modes?*

In the presence of spin-orbit coupling, the band crossings around indeed hybridize, as the referee already noted. Along the strong-spin splitting directions, i.e., along the x and y axis, spin-orbit coupling would not have a strong effect. We therefore expect that the quality factors along these directions in the Brillouin zone are unaffected. The spin-orbit coupling could therefore only reduce the critical angle where the spin demon ceases to exist – but we note that for the spin demon already does not exist. We therefore do not expect the effect of spin-orbit coupling to be significant, potentially only reducing the critical angle where the spin demon ceases to exist.

*2. The authors consider an isotropic (and spin-independent) interaction in the system. However, since the band structure is nematic and also breaks spin-rotation symmetry, it could be more realistic to consider an interaction whose strength depends on the spin and the direction, perhaps with a d-wave form factor? How would the presence of such spin and direction anisotropies affect the results?*

We thank the referee for pointing out the possibility of an anisotropic Coulomb interaction in d-wave altermagnets. Here we note however that even though the spin-resolved band structure is anisotropic, the total charge density – which is the sum of the spin-resolved electron density – is not anisotropic. We therefore expect that the screening of the Coulomb interaction is isotropic, and therefore does not necessarily carry a d-wave form factor.

*3. While this article focuses on spin-demon mode, is it possible to discuss the existence of regular demon modes within the same framework? Since both demons and spin-demons are charge-neutral modes that may exist in systems with a spin-split Fermi surface, it would be useful for the readers if the authors could include a brief description of the difference between the two (in the context of altermagnets) in the manuscript.*

We thank the referee for their suggestion to consider conventional demons, but we note here that the demon we consider here is the charge-neutral density mode present in the two-band model we consider. If the two bands are spin-split, then this charge-neutral density mode automatically becomes spin-polarized and is thus a *spin demon.* Within our framework, we thus have only one demon.

**Action taken**: we have clarified in the third paragraph that the spin demon is a spin-polarized version of the conventional demon.

*4. Fig. 2 shows 3 zeros of the dielectric function along a fixed direction. The authors should provide a trace of these 3 zeros evolve as the direction of q is varied from x to y, along with the position of the 2 particle-hole band edges. The second zero is the spin-demon, for which this has been presented. It would be useful to see how the other two zeros evolve with direction of propagation.*

We thank the referee for this suggestion, which we have implemented and now show in the SM.

**Action taken**: We now show the evolution of all three zeros of the dielectric function in the altermagnetic spin-split plane in the SM.

*5. The authors should comment on the universality of this result, across different altermagnetic symmetries. Can similar modes appear in non-d-wave altermagnets?*

As we noted in the main text, a spin demon does not exist in g-wave altermagnets, and we therefore believe the spin demon to be specific to d-wave altermagnets. A separate analysis of g-wave altermagnets is presented in the supplementary material.

# *Referee C*

*The manuscript, "Spin demons in d-wave altermagnets“ by P. M. Gunnink, J. Sinova, and A.Mook discusses spin demons as a universal feature of d-wave altermagnets. The spin demon has been shown to be long-lived by high-quality factor calculations. The theoretical approach considers a model dispersion, it is rigorous and addresses 2D and 3D dimensional cases, pointing to a stronger effect in 2D cases.*

*1. As the authors use the RPA approach, a short discussion concerning the standard Fermi-liquid based demons would clarify possible distinctions.*

We thank the referee for this suggestion. Fermi-liquid descriptions of conventional demons have found no considerable differences compared to the RPA approach,[[7]](#footnote-7) and we expect the same conclusion to hold for the spin demon in d-wave altermagnets. We have also commented on the Fermi-liquid approach in the updated manuscript.

@ALEX/JAIRO: the referee might also be referring to the other spin demon in altermagnet paper (<https://arxiv.org/abs/2505.07083>). Since we are now aware of this paper, is it necessary to cite this paper?

**Action taken**: We have added a line in the *Conclusion* section discussing the fermi liquid approach.

*2. The work lacks the microscopic context of real materials, therefore, the suggestion to use SPEELS or cross-polarized Raman would require more detail on the energy scales confirming the experimental feasibility assessment.*

SPEELS has a resolution in the 10 to 100 meV range, while the spin demon can exist up to energies of half the Fermi energy – which is in the 500 meV to 2 eV range. We therefore believe SPEELS to have the necessary resolution to measure the spin demon in d-wave altermagnets.

**Action taken**: We have added a comment regarding typical energy scales of SPEELS in the *Conclusion* section.

*3. The term "spin demon“ may not be universally recognized, and authors are asked to support the necessity of introducing it alongside established spin plasmons or paramagnons.*

We agree with the referee that the term spin demon will not be universally recognized, since it to the best of our knowledge has not been used to describe a spin-polarized demon before. We believe it to be an accurate description of the spin-polarized demon in d-wave altermagnets however. In particular, previous works have referred to similar phenomena in two-dimensional ferromagnets as *spin-polarized acoustic plasmons*; cf. Agarwal *et al*.[[8]](#footnote-8) Here we have chosen to instead refer to this as a demon, for two reasons. Firstly, to prevent confusion with the gapless plasmon found in bilayer systems, which is also typically referred to as an acoustic plasmon, and with the overdamped acoustic plasmon in single-component electron gasses. Secondly, the term demon was introduced by Pines to refer to exactly the mode we describe, except Pines considered only spin-degenerate bands. We therefore believe it to be the most accurate to refer to this as spin demon, following also Husain *et al*,[[9]](#footnote-9) who made the first experimental discovery of a demon in a 3D metal.

*Recommendation:*

*Publish in PRL as written or after minor revision.*

We thank the referee for their positive recommendation.

1. D. Pines. *Can. J. Phys.* 34, 1379–1394 (1956) [↑](#footnote-ref-1)
2. C. M. Varma. *Rev. Mod. Phys.* 48, 219–238 (1976) [↑](#footnote-ref-2)
3. A. N. Afanasiev *et al.* *Phys. Rev. B* 103, 205201 (2021) [↑](#footnote-ref-3)
4. J. Ruvalds. *Advances in Physics* 30, 677–695 (1981) [↑](#footnote-ref-4)
5. A. A. Husain *et al.* *Nature* 621, 66–70 (2023) [↑](#footnote-ref-5)
6. A. Agarwal *et al.* *Phys. Rev. B* 90, 155409 (2014) [↑](#footnote-ref-6)
7. A. N. Afanasiev. *Phys. Rev. B* 106, (2022) [↑](#footnote-ref-7)
8. A. Agarwal *et al.* *Phys. Rev. B* 90, 155409 (2014) [↑](#footnote-ref-8)
9. A. A. Husain *et al.* *Nature* 621, 66–70 (2023) [↑](#footnote-ref-9)