

Ultrafast space-time optical merons in momentum-energy space

Corresponding Author: Dr Murat Yessenov

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Nature Communications. Mentions of the other journal have been redacted.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

I have reviewed the previous version of this manuscript for [REDACTED]. In the revised version, the authors have convincingly addressed my concerns and have revised the manuscript accordingly. I am pleased to recommend it now for publication in Nature Communications.

Since, in the Introduction, the authors mention examples of skyrmions described recently in various wavefields, they might wish to also mention skyrmions observed in acoustic and water-wave fields:

H. Ge et al., Phys. Rev. Lett. 127, 144502 (2021).

R. D. Muelas-Hurtado et al., Phys. Rev. Lett. 129, 204301 (2022).

B. Wang et al., Nature 638, 394 (2025).

Reviewer #3

(Remarks to the Author)

This manuscript presents an elegant demonstration of a spatiotemporal wave packet that carries a non-trivial topological texture in space and time, with the wave packet remaining propagation-invariant in 3D physical space, resembling a particle. The experimental technique is sophisticated and well-executed, representing a noteworthy advance in the field of topological photonics. The work demonstrates significant potential for impact in optical physics and related areas by showing how topological structures can be realized in spatiotemporal wave packets. The methodology appears sound and the experimental evidence generally supports the main conclusions regarding wave packet generation and propagation characteristics. However, while the core experimental work meets expected standards, there are concerns regarding terminology usage and data interpretation that require clarification rather than prohibiting publication. The methods section provides reasonable detail for reproduction. I would recommend publication in Nature Communications once several terminological and interpretational concerns are addressed to strengthen this already compelling contribution.

The authors make several claims that skyrmions are three-dimensionally localized quasiparticles and consistently refer to them as "3D skyrmions." While I understand the motivation for this terminology, it may benefit from clarification since it is rarely used in the broader literature. In modern physics, a skyrmion typically refers to a magnetic skyrmion, which is by definition 2D, representing a projection characterized by the homotopy group $\pi_2(S^2)$. As discussed in Ref. 13, 3D generalizations of skyrmions are conventionally termed "skyrmion strings/tubes," "chiral bobbbers," and "hopfions" rather than "3D skyrmions." Even in previous work that the authors cite as attempting to realize "3D optical skyrmions," (Ref. 26) this specific terminology does not appear. Clarifying this terminology would help ensure accessibility to the broader audience.

Additionally, I have concerns about the authors' characterization of these structures as "space-time merons." While the momentum-energy-space skyrmion concept is interesting, it is important to recognize that such a structure is fundamentally

different from a quasiparticle in real space-time and should not be conflated with a physical skyrmion. Although the introduction of space-time coupling does produce particle-like wavepackets, the term "space-time merons" may inadvertently suggest to readers that actual quasiparticles with skyrmionic structure have been generated in physical space. This could lead to confusion about the distinction between topological structures in different parameter spaces versus genuine physical skyrmions in real space, and I recommend the authors clarify this important difference.

Regarding the Stokes vector analysis, I found the authors' response to Reviewer #2's second question somewhat unclear. While Stokes vectors are rigorously defined for monochromatic waves and appropriately applied in momentum-energy space, their presentation in physical space-time (Figures 1, 3, and 4) requires careful justification. The authors do provide this justification in the main text through their approximation method:

"The visibility of the interference fringes is maximized only after projecting the combined light fields onto one polarization state. Therefore, by repeating the procedure for different polarization components we retrieve the spatiotemporally resolved Stokes parameters for the ST merons. (Fig.3e and Fig. 4e)."

This approach, where the field is approximately monochromatic and an effective Stokes axis can be identified, is reasonable. However, this important approximation should be explained when first introducing Figure 1 to ensure clarity throughout the manuscript.

To further enhance the presentation, I suggest displaying the Stokes vectors using the color wheel format commonly employed in skyrmion research. This visualization would better highlight the meron structure and strengthen the authors' claim regarding the non-trivial polarization texture in physical space.

Finally, I encourage the authors to discuss the recent work in Nature 638, 394--400 (2025) and explore connections to alternative generation methods using nonlocal periodic structures, as demonstrated in Ref. 29 and Phys. Rev. Lett. 132, 044001 (2024). Such discussion would place this work in broader context and highlight potential future directions.

Reviewer #4

(Remarks to the Author)

The manuscript by Yessenov et al. presents a demonstration of space-time optical merons through implementation of the polarization texture onto the open and closed 2D spectral surfaces embedded in the 3D momentum-energy space. The 2D spectral surfaces in 3D momentum-energy space are created by resolving the spectrum via a pair of CBGs, two-to-one spectral mapping via SLMs with designed phase profiles, and coordinate transformation via phase plates, and the polarization textures are imprinted via designed meta-surfaces. In general, this paper is well-organized, with rigorous theoretical analysis, and presents an intriguing approach to construct space-time optical merons in 3D momentum-energy space. The experimental results, particularly the skillfully use of light field manipulation devices such as CBGs and SLMs, are impressive.

Review #2 has raised three concerns for this manuscript, and they are briefly listed below:

1. Stokes vector cannot be confused with spin vector.
2. Whether Stokes vector can be defined for the non-monochromatic field must be clarified.
3. The statement of "they emphasize the monochromatic 2D nature of the earlier approaches" is not accurate because in the previous works 3D vectors of spin or electric field have been reported.

In my opinion, the authors have addressed the second and third concerns of Review #2 in their revised manuscript. For the first concern, the authors have not changed all of term "spin texture" to "polarization texture". For example, in the fourth part of Fig. 2 (a), the authors still remain the term of "Spin-texture implementation". The authors need to check the manuscript carefully and revise all the terms.

I have the following points that I would like the authors to address as well:

- 1) Theoretically, the skyrmion number of meron is 0.5. The authors claimed that the theoretically expected number of the skyrmion number in this system is 0.418. Please explain how this value is calculated in detail.
- 2) The main innovation point of this manuscript is that the authors engraved the meron polarization texture in a surface in 3D space, while in the previous research most optical skyrmion related structures are "baby skyrmions" implemented in 2D space. The skyrmions attracted a lot of research attention due to their ultra-compact size and topological stability, which are regarded as the important features of the next-generation information carrier. The authors mentioned that the progress from 2D to 3D skyrmion can improve the optical communications using higher dimension states of light. It is better for the authors to give detailed discussion of how the results in this manuscript to improve the optical communications and the potential applications of this research.
- 3) One important feature of the skyrmion is that it has the topological protection. Please give some discussions about what kind of perturbation this space-time optical meron will be robust against, and whether the topological number will be changed when this perturbation is exerted on the system.
- 4) It has been reported that the conversion among different types of Stoke vector skyrmionic textures can be realized by polarization devices (Photon. Res. 11, 2042-2053 (2023)). It is important to realize the control of the versatile skyrmionic textures, which represents a crucial step towards developing the skyrmion-based applications (Appl. Phys. Rev. 11, 021408 (2024)). In this manuscript, the polarization texture was implemented through meta-surface, which indicates that the realization of different types of skyrmionic structure depends on fabrication of different meta-surface. Please give some discussion in detail about the control of different types of space-time skyrmionic structures through polarization devices or other methods in the future.

5) There are some typos in this manuscript. For example, in the tenth line of the second paragraph of the fourth page, in the statement of "Previous experimental realizations of optical skyrmions have relied on of three strategies for mapping the vector", it should be "relied on three strategies" and the "of" should be deleted. In the Reference part, the issue and page number should be added for reference 23, and the article number should be added for reference 26.

Version 3:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

My concerns have been addressed in the revisions. I recommend the work's publication in Nature Communications.

Reviewer #4

(Remarks to the Author)

The authors have made several modifications to address all the points. I think the paper is considerably improved. I now recommend for publication.

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REVIEWER COMMENTS

Reviewer #2 (Remarks to the Author):

I have reviewed the previous version of this manuscript for [REDACTED]. In the revised version, the authors have convincingly addressed my concerns and have revised the manuscript accordingly. I am pleased to recommend it now for publication in Nature Communications.

Author's response:

We thank the Reviewer for their comments and suggestions in the previous round of review, and we indeed are pleased to hear that we have been able to convincingly address the Reviewer's concerns. We also thank the Reviewer for recommending our manuscript for publication in Nature Communications.

Since, in the Introduction, the authors mention examples of skyrmions described recently in various wavefields, they might wish to also mention skyrmions observed in acoustic and water-wave fields:

H. Ge et al., Phys. Rev. Lett. 127, 144502 (2021).

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B. Wang et al., Nature 638, 394 (2025).

Author's response:

We thank the Reviewer for bringing up these references, which are indeed relevant to our work. We have now cited them in the revised manuscript (Refs 10-12).

Reviewer #3 (Remarks to the Author):

This manuscript presents an elegant demonstration of a spatiotemporal wave packet that carries a non-trivial topological texture in space and time, with the wave packet remaining propagation-invariant in 3D physical space, resembling a particle. The experimental technique is sophisticated and well-executed, representing a noteworthy advance in the field of topological photonics. The work demonstrates significant potential for impact in optical physics and related areas by showing how topological structures can be realized in spatiotemporal wave packets. The methodology appears sound and the experimental evidence generally supports the main conclusions regarding wave packet generation and propagation characteristics.

Author's response:

We thank the Reviewer for this succinct summary and this high evaluation of our manuscript.

However, while the core experimental work meets expected standards, there are concerns regarding terminology usage and data interpretation that require clarification rather than prohibiting publication. The methods section provides reasonable detail for reproduction. I would recommend

publication in Nature Communications once several terminological and interpretational concerns are addressed to strengthen this already compelling contribution.

We thank the Reviewer for recommending our manuscript for publications. We hope to resolve the Reviewer's remaining reservations in this point-by-point response.

The authors make several claims that skyrmions are three-dimensionally localized quasiparticles and consistently refer to them as "3D skyrmions." While I understand the motivation for this terminology, it may benefit from clarification since it is rarely used in the broader literature. In modern physics, a skyrmion typically refers to a magnetic skyrmion, which is by definition 2D, representing a projection characterized by the homotopy group $\pi_2(S^2)$. As discussed in Ref. 13, 3D generalizations of skyrmions are conventionally termed "skyrmion strings/tubes," "chiral bobbars," and "hopfions" rather than "3D skyrmions." Even in previous work that the authors cite as attempting to realize "3D optical skyrmions," (Ref. 26) this specific terminology does not appear. Clarifying this terminology would help ensure accessibility to the broader audience.

Author's response:

The Reviewer is correct in pointing out that well-known examples of 3D skyrmions include skyrmion tubes, hopfions, and chiral bobbars, as discussed in Refs. 2, 4, and 13. However, the field structure demonstrated in this work—three-dimensionally localized optical fields with the skyrmion texture mapped onto a 2D surface embedded in 3D momentum–energy space—does not fall into any of these categories. Unlike skyrmion tubes or strings where 2D skyrmionic textures trivially extended along one dimension, our structure is non-separable across all three dimensions and lacks the periodicity or filamentary form that would justify those terms. Moreover, our configuration lacks the linked field-line topology that defines hopfions, and no Hopf invariant or π_3 mapping is involved. Therefore, for technical accuracy and to avoid confusion among readers, we have decided to use the more general term “3D skyrmion,” as it best describes the field structures studied in our work. Besides, while the term “3D skyrmion” is less common in magnetic contexts, it is commonly used in other fields where such solitons are localized in all three dimensions [Sci. Adv. 4, eaao3820 (2018); Proc. Natl. Acad. Sci. U.S.A. 115 (25), 6386–6391].

Additionally, I have concerns about the authors' characterization of these structures as "space-time merons." While the momentum-energy-space skyrmion concept is interesting, it is important to recognize that such a structure is fundamentally different from a quasiparticle in real space-time and should not be conflated with a physical skyrmion. Although the introduction of space-time coupling does produce particle-like wavepackets, the term "space-time merons" may inadvertently suggest to readers that actual quasiparticles with skyrmionic structure have been generated in physical space. This could lead to confusion about the distinction between topological structures in different parameter spaces versus genuine physical skyrmions in real space, and I recommend the authors clarify this important difference.

Author's response:

We agree with the Reviewer that it is crucial to draw a clear distinction between the realization of merons in physical and momentum–energy space. Therefore, in the introduction, we begin by mentioning that there are two potential pathways for realizing 3D optical skyrmions: producing the closed surface in space–time or in momentum–energy space. The former has been recently attempted in the microwave domain. In this work, we instead aim at the latter, which allows for temporal modulation at optical frequencies (last three sentences of the 2nd paragraph, highlighted in red). We further state that in this work the meron polarization texture is imprinted on curved 2D spectral surfaces, which yields non-trivial 3D topological structures in space–time (5th paragraph of the introduction, highlighted in red). We hope this helps to avoid any confusion that readers might have.

Regarding the Stokes vector analysis, I found the authors' response to Reviewer #2's second question somewhat unclear. While Stokes vectors are rigorously defined for monochromatic waves and appropriately applied in momentum–energy space, their presentation in physical space-time (Figures 1, 3, and 4) requires careful justification. The authors do provide this justification in the main text through their approximation method:

"The visibility of the interference fringes is maximized only after projecting the combined light fields onto one polarization state. Therefore, by repeating the procedure for different polarization components we retrieve the spatiotemporally resolved Stokes parameters for the ST merons. (Fig.3e and Fig. 4e)."

This approach, where the field is approximately monochromatic and an effective Stokes axis can be identified, is reasonable. However, this important approximation should be explained when first introducing Figure 1 to ensure clarity throughout the manuscript.

Author's response:

We thank the reviewer for raising an important question. As noted, our approach relies on the paraxial narrowband approximation, which ensures that the Stokes parameters remain well-defined even in the space-time domain. This approximation is already stated in the Theory section of the manuscript before introducing Fig. 1 b,c,d.

Following the reviewer's suggestion, we now reiterate this statement in the caption of Figures 1, where the spatiotemporal Stokes parameters are presented. Specifically, we clarify that Stokes vectors in physical space shown in Fig. 1c(ii-vi) and Fig. 1d(ii-vi) are constructed under narrowband paraxial approximation (highlighted in blue in the revised manuscript).

To further enhance the presentation, I suggest displaying the Stokes vectors using the color wheel format commonly employed in skyrmion research. This visualization would better highlight the meron structure and strengthen the authors' claim regarding the non-trivial polarization texture in physical space.

Author's response:

We thank the reviewer for this valuable suggestion. We do indeed use color-wheel formatting based on the direction of the Stokes vectors in Figures 1,3,4. However, we noticed that the color palette has been missing in Figure 1, which we have now added.

Finally, I encourage the authors to discuss the recent work in Nature 638, 394--400 (2025) and explore connections to alternative generation methods using nonlocal periodic structures, as demonstrated in Ref. 29 and Phys. Rev. Lett. 132, 044001 (2024). Such discussion would place this work in broader context and highlight potential future directions.

Author's response:

We thank the reviewer for bringing these references to our attention. We have now added discussions relating them to our work and included them in our references (highlighted in blue in the revised manuscript).

Reviewer #4 (Remarks to the Author):

The manuscript by Yessenov et al. presents a demonstration of space-time optical merons through implementation of the polarization texture onto the open and closed 2D spectral surfaces embedded in the 3D momentum-energy space. The 2D spectral surfaces in 3D momentum-energy space are created by resolving the spectrum via a pair of CBGs, two-to-one spectral mapping via SLMs with designed phase profiles, and coordinate transformation via phase plates, and the polarization textures are imprinted via designed meta-surfaces.

Author's response:

We thank the Reviewer for this succinct summary of our manuscript.

In general, this paper is well-organized, with rigorous theoretical analysis, and presents an intriguing approach to construct space-time optical merons in 3D momentum-energy space. The experimental results, particularly the skillfully use of light field manipulation devices such as CBGs and SLMs, are impressive.

Author's response:

We thank the Reviewer for high evaluation of our work.

Review #2 has raised three concerns for this manuscript, and they are briefly listed below:

- 1. Stokes vector cannot be confused with spin vector.**
- 2. Whether Stokes vector can be defined for the non-monochromatic field must be clarified.**

3. The statement of “they emphasize the monochromatic 2D nature of the earlier approaches” is not accurate because in the previous works 3D vectors of spin or electric field have been reported.

In my opinion, the authors have addressed the second and third concerns of Review #2 in their revised manuscript. For the first concern, the authors have not changed all of term “spin texture” to “polarization texture”. For example, in the fourth part of Fig. 2 (a), the authors still remain the term of “Spin-texture implementation”. The authors need to check the manuscript carefully and revise all the terms.

Author’s response:

We thank the Reviewer for pointing out this error, we have now corrected the text to “Polarization texture implementation” in Figure 2a in the revised manuscript.

I have the following points that I would like the authors to address as well:

1) Theoretically, the skyrmion number of meron is 0.5. The authors claimed that the theoretically expected number of the skyrmion number in this system is 0.418. Please explain how this value is calculated in detail.

Author’s response:

We provide detailed explanation of how we calculate the Skyrmion number from the experimental measurements along with the theoretical values in Supplementary Material Section III.C.

We calculate the Skyrmion number from Stokes parameters s_1, s_2, s_3 using a topological method introduced for paraxial optical skyrmions [Suppl. Ref. 30]. The Skyrmion number is calculated via a line integral around the intensity singularity point as opposed to the gradient of the polarization texture, which improves the accuracy of measurement as the gradient is limited within the aperture of the experimental system and is extremely sensitive to noise. Following this method, we determine the Skyrmion number

$$Q = \frac{1}{2} \left(\sum s_3^{(j)} N^{(j)} - s_3^{(\infty)} N^{(\infty)} \right),$$

where $N = (2\pi)^{-1} \oint \nabla \Phi \cdot d\mathbf{l}$ is the winding number at the j^{th} inner singularity and at the beam periphery (∞), and $\Phi = \arg(s_1 + is_2)$ [30]. Singularities are located where $s_1, s_2 \rightarrow 0$ and within the context of our work there is only one singularity $j = 1$ located at the beam center, as seen in Fig. S11 (b). For calculating theoretically expected Skyrmion number Q_{th} , we plug in the polarization texture the birefringent metasurface is designed to introduce, which is given by Eq. S15-S17. In Fig. S11, we choose the periphery circle of radius $r^{(\infty)} \approx 6.1$ mm and obtain theoretically expected Skyrmion number of $Q=0.418$.

2) The main innovation point of this manuscript is that the authors engraved the meron polarization texture in a surface in 3D space, while in the previous research most optical skyrmion

related structures are “baby skyrmions” implemented in 2D space. The skyrmions attracted a lot of research attention due to their ultra-compact size and topological stability, which are regarded as the important features of the next-generation information carrier. The authors mentioned that the progress from 2D to 3D skyrmion can improve the optical communications using higher dimension states of light. It is better for the authors to give detailed discussion of how the results in this manuscript to improve the optical communications and the potential applications of this research.

Author’s response:

The key advantage of moving from 2D to 3D skyrmion textures lies in the increased information-carrying capacity offered by the added degrees of freedom. Traditional optical communication protocols encode information in scalar properties such as intensity, phase, or polarization state at a single point in space or time. In contrast, our 3D space-time meron structures encode information in its topological structure that is distributed over momentum-energy space. This inherently high-dimensional structure could be used to define novel information channels based on global topological features, rather than local field values, potentially offering greater resilience to noise and perturbations.

In addition, the spatiotemporal localization of the wavepacket enables high-speed, addressable delivery of information-carrying pulses at longer distances via free-space communication channels, which could be advantageous for ultrafast optical interconnects or quantum photonic processors where spatial and temporal mode control is essential. Combined with recent developments in metasurface-based modulators and spatial light modulators, this approach could be extended toward programmable, reconfigurable topological photonic platforms.

We have now added this discussion in the last sentence of the revised Introduction section (highlighted in blue).

3) One important feature of the skyrmion is that it has the topological protection. Please give some discussions about what kind of perturbation this space-time optical meron will be robust against, and whether the topological number will be changed when this perturbation is exerted on the system.

Author’s response:

Although the topological resistance of optical skyrmions is yet to be studied, we speculate in final sentences of the Discussions the physical systems under which they may preserve its topological structure. Considering recent demonstrations of using space-time coupled fields for speckle-resistance and self-healing, it is intriguing to determine the degree of topological resilience of optical ST merons against external perturbations in complex media, such as highly scattering media or media with physical obstructions, which has not been conclusively studied yet and will be a topic of future research.

4) It has been reported that the conversion among different types of Stoke vector skyrmionic textures can be realized by polarization devices (Photon. Res. 11, 2042-2053 (2023)). It is important to realize the control of the versatile skyrmionic textures, which represents a crucial step towards

developing the skyrmion-based applications (Appl. Phys. Rev. 11, 021408 (2024)). In this manuscript, the polarization texture was implemented through meta-surface, which indicates that the realization of different types of skyrmionic structure depends on fabrication of different meta-surface. Please give some discussion in detail about the control of different types of space-time skyrmionic structures through polarization devices or other methods in the future.

Author's response:

Reviewer is correct pointing out that in our setup the skyrmionic texture is introduced by birefringent metasurface, whose polarization distribution is specially designed. However, direct access to the momentum-energy space in our technique allows integrating skyrmionic conversion devices, such as in Photon. Res. 11, 2042-2053 (2023), after the metasurfaces, which would enable dynamic tunability between different types of 3D ST skyrmions (Neel, Bloch type). We now have added the possibility of skyrmionic conversions for 3D ST merons in the revised Discussion section (highlighted in blue in the revised manuscript).

5) There are some typos in this manuscript. For example, in the tenth line of the second paragraph of the fourth page, in the statement of “Previous experimental realizations of optical skyrmions have relied on of three strategies for mapping the vector”, it should be “relied on three strategies” and the “of” should be deleted. In the Reference part, the issue and page number should be added for reference 23, and the article number should be added for reference 26.

Author's response:

We thank the reviewer pointing out the typos – all of the typos have been corrected.

We thank the reviewer for carefully reading the manuscript and for all the comments, and suggestions. Hopefully we have addressed all his/her concerns, and the revised manuscript is suitable for publication in *Nature Communications*.