

Topological Diversity and Scintillating Dynamics of Dipolar Surface Twists in a van der Waals Magnet

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

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have performed Lorentz transmission electron microscopy to study the magnetic textures of a van-der-Waals (vdW) magnet Fe₃GaTe₂ at room temperature. Combined with micromagnetic simulations, they argue that dipolar surface twists emerge and that they exhibit “scintillating dynamics” with electrical current.

I think that the experimental results and the proposed model will attract the attention of the readers. On the other hand, I am not fully convinced that the bright and dark dots in Fig. 2c are ascribed to magnetic twists on the surface but not in bulk. Since Lorentz TEM observations and TIE analyses only provide a projected image of in-plane B field, it is still a challenge to reveal the three-dimensional distribution of B vector. While measurements of LTEM images with tilting samples would provide useful information, a comparison with the simulation is required to pin down the twist position. The TIE analyses shown in Fig. 2d are also confusing. I find several significant discrepancies between the arrow orientations in the lower panels and the color code.

Figure 4 demonstrates various types of textures. I do not exactly understand what ‘magnetic phase’ denotes. The definition should be explicitly provided. In addition, the correspondence between the contrast and the phase value (0 to 2pi) should be shown.

Electrical current-driven dynamics is summarized in Fig. 5. Generation and annihilation are clearly observed, as described. In regard with helicity switching of the right bottom one, I am a bit afraid that it is an “N=2” twist comprising of dark and bright circles.

I also have some comments about micromagnetic simulation.

The double parentheses in the definition of the magnetic quality factor on line 95 are a little confusing. It should appear as $f = Ku/Kd = Ku/(...)$. I also recommend that reference number 28 be moved somewhere else to avoid possible misunderstandings.

Hamiltonian (1) for micromagnetic simulations assumes isotropic exchange stiffness, while it is expected to be highly anisotropic in the vdW magnet. The authors should discuss the validity of the model.

The authors sometimes use a period to express a scalar product, which should be replaced with a dot operator.

The vector $\mathbf{B}_d$ in Hamiltonian (1) is not defined.

The E_D term in Hamiltonian (a) corresponds to DM interaction in chiral systems. The interfacial DM interaction is expressed in a different way.

In summary, I think that the manuscript should be revised before the publication in Nature Communications.

Reviewer #2

(Remarks to the Author)

Lv and colleagues report on topologically interesting spin structures, as well as their dynamics, FeGaTe, a room temperature ferromagnet VdW material, which has been extensively reported to exhibit skyrmion structures. There reports of diverse spin structures, while interesting, does not appear to me to be all that novel, with objects with complex topological charges being

reported in many recent works (detailed later in this report). However, to my knowledge, the study of current driven dynamics does meet the novelty bar required for Nature Communications. Therefore, assuming the following points may be addressed, I believe it may be recommended for publication in Nature Communications.

- 1.) As a technical detail, I believe the defocus value is quite large, and this may lead to complications in interpretation of the resultant spin structures. It's been heavily reported that large defocus values can result in differing interpretations of the same spin state (i.e. see Phys. Rev. B 112, 214455 (2025)), and also may preclude quantitative measurements of size i.e. see discussion in Phys. Rev. Lett. 122, 237201 (2019), which is important in the interpretation of Fig. 2i. How was the size measured? Further, it can complicate interpretation of the complex spin textures shown in Fig. 4. It may be nice to run image simulations showing changes in contrast for the more complex objects. For example, how confident, given the level of defocus, is the N value for larger N structures (i.e. the $N = 11$ and $N = 14$ structures).
- 2.) Regarding the field evolution of these defect states, particularly in regards to the discussion of Fig. 3, the evolution of complex topological charge objects was also seen in discussion of heavy metal/ferromagnetic multilayers (see Phys. Rev. B 102, 214429 (2020), J. Appl. Phys. 130, 153903 (2021), Ann. Phys. 536, 2300480 (2024)), so while interesting, and in a new, very device relevant system, similar observations have been previously reported.
- 3.) On another technical note, a few details should be given about the QPT phase reconstruction. Particularly, the choice of frequency offset (commonly referred to as q_0) can induce artifacts and largely modify the imaged domain structure. As such, it would be good to know the value used, and possibly show in a supplementary figure how this choice modifies the image of interest (i.e. see Journal of Magnetism and Magnetic Materials 454 (2018) 304–313, supplement of Phys. Rev. B 102, 214429 (2020)).
- 4.) With that said, the main interest in this work seems to be the current driven dynamics, and in my view, are the reason why I would consider this work for publication in Nat. Comm. However, before I fully trust all of these observations, I think the authors should account for a key issue. Applying large current densities inherently increases the temperature, and this temperature change can be large in these structures. The authors exclude the temperature rising above T_c due to the lack of an emergence of a complex disordered domain structure, but changes in domain structure do not require increasing T above T_c . Have the authors estimated the change in temperature induced in these structures with current densities approaching 10^{12} A/m², and estimated the thermal effects on stability, below T_c ? Can these transformations that have been observed be explained largely via thermal fluctuations, or how did the authors rule this out? In short, while exciting, I don't believe enough evidence is presented to rule out thermally driven effects.
- 5.) Quite trivially, could the authors also run micromagnetics at finite temperatures, and observe whether the (zero current applied) structures are stable at moderately higher temperature (with or without pinning)? I do think these simulations are necessary.
- 6.) Minor detail: Fig. 5f is difficult to read as it appears very faded in the manuscript.

In summary, I think this work has potential for impact, but the details listed need to be addressed prior to publication, particularly in doing a more robust job of ruling out thermal effects regarding the current driven changes as this, in my opinion, is the important part of the work. While an interesting system, the observation of complex high-N textures is not sufficient on its own owing to its similarity to more traditional heavy metal/ferromagnet multilayers.

Reviewer #3

(Remarks to the Author)

The manuscript "Topological Diversity and Scintillating Dynamics of Dipolar Surface Twists in a van der Waals Magnet" by Xiaowei Lv et al. reports Lorentz transmission electron microscopy (L-TEM) measurements combined with micromagnetic simulations to investigate the magnetic domain structure in the van der Waals magnet Fe_3GaTe_2 (FGT).

The three-dimensional (3D) magnetic structure of the observed domain textures is inferred by matching experimental L-TEM images with simulated contrast derived from 3D micromagnetic simulations. Black and white spot-like features coexisting with stripe domains at zero magnetic field are attributed to so-called dipolar-interaction-stabilized surface twists (DSTs).

The response of these DSTs to external stimuli is further investigated by applying an out-of-plane magnetic field and in-plane electric currents. The DSTs are reported to be stable up to external fields of approximately 160 mT, above which the sample transitions into a field-polarized state. Upon decreasing or reversing the magnetic field, more complex, higher-order DSTs are stabilized. In addition, nanosecond current pulses applied to electrically contacted FGT samples induce a flickering L-TEM contrast of the DSTs, referred to as "scintillation" by the authors. However, no translational motion of the DSTs is observed in response to the applied currents, presumably due to pinning effects.

While the investigation of three-dimensional nanoscopic spin textures, and in particular their surface structures, is of clear interest for potential spintronic applications, the novelty and impact of the present work for the broad readership of Nature Communications are limited. Three-dimensional magnetic structures of (anti-)skyrmionic textures have already been studied in considerably greater depth using advanced X-ray and electron holographic tomography techniques (see, for example, Birch et al., Nat. Commun. 11, 1726 (2020); Wolf et al., Nat. Nanotechnol. 17, 250–255 (2022); Yasin et al., Adv. Mater. 36, 2311737 (2024)).

Although the comparison between experimental and simulated L-TEM images represents a valid methodological approach, a substantially more detailed experimental and micromagnetic analysis would be required to achieve a deeper and more quantitative understanding of the structure and underlying physics of the proposed surface states, particularly with respect to their relevance for spintronic applications.

For these reasons, I unfortunately cannot recommend the manuscript for publication in Nature Communications. Below, I list additional comments and suggestions that I would encourage the authors to address before submission to another journal:

- L. 113: The ring-like contrast is attributed to skyrmions. Please clarify why these features are identified as skyrmions rather than magnetic bubbles. In L-TEM, skyrmions typically exhibit dot-like contrast similar to that observed for the DSTs.
- L. 115 and Fig. 1j: Please explain why the L-TEM contrast of the DSTs does not cancel out upon projection through the sample thickness. Additional discussion or simulation results would help to clarify this point.
- L. 145: What is the influence of Ga implantation and surface damage from focused ion beam (FIB) preparation on the formation and stability of the DSTs? This issue should be discussed, given the surface-sensitive nature of the reported states.
- L. 161: It should be clarified that transport-of-intensity equation (TIE) analysis allows only for a qualitative reconstruction of the projected in-plane magnetic induction, not the magnetization itself.
- L. 201–203: The L-TEM tilt series is performed only for the thinnest sample. Please justify this choice. Additional tilt experiments on thicker samples would significantly strengthen the interpretation of the three-dimensional magnetic structure.
- L. 304: The scintillating mode is presented as a major result of the manuscript; however, there is little physical discussion of the underlying mechanism. In particular, the role of pinning effects (also relevant for the dynamics of the DSTs) related to surface damage and curtaining in the TEM lamella should be addressed in more detail.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I examined the responses to comments raised by three reviewers.

I first raised the question of why bright and dark dots are ascribed to topological surface twists. The authors reply by saying, “the identification of surface-localized twists relies on the combined analysis of L-TEM observations and micromagnetic simulations.”

I would like to note that Figure 1b shows that an unconventional skyrmion string for $f=0.23$ would appear as faint circles, originating from the surface twist, inside clear dark and bright concentric circles due to the Bloch wall in the bulk. The micromagnetic simulation in Fig. 1m demonstrates maze domains and perhaps some surface twists. I guess that also in such a case, the corresponding L-TEM image would comprise clear stripes accompanying some blurred small dots. In their L-TEM observations, well-arranged 180-degree stripes (but not mazed stripes) and some large and clear dots are found. The contrast of dots is even clearer than that of stripes. These results would cast doubt on the validity of their surface-twist model.

I also made some comments on micromagnetic simulation. First, I am glad to say that I am satisfied with their reply to the comment on the anisotropy in exchange. On the other hand, I still have a concern about DM interaction. Although they mention that the term is corrected, it seems that the simulation result is unchanged. I also wonder if they introduce the spatial dependence of the parameter D . The sign of D should be opposite on the top and back surfaces.

Reviewer 2 raised some concerns about possible thermal effect on the observed current-driven dynamics. Although I am not fully convinced that their reply addressed the issue, I approve their efforts.

Reviewer 3 cast doubt about the novelty and impact of the present work for the broad readership. The authors claim that the present work has three new aspects, one of which is “Focus on dynamics and decoupled surface–bulk behavior.” It is hence essential to decouple the surface contribution from the bulk magnetization distribution.

In conclusion, the authors should reproduce the coexistence of bulk 180-degree stripe domains and surface twists by micromagnetic simulation and compared to the experimentally obtained L-TEM images.

Reviewer #2

(Remarks to the Author)

The authors have sufficiently addressed my concerns. As it stands, I believe the results do achieve the novelty criteria required for Nature Communications, and the added detail to the phase simulations allow for the work to be reproduced (as well as ruling out several potential sources for misidentification). Therefore, I am comfortable recommending for publication.

Reviewer #3

(Remarks to the Author)

I appreciate the significant effort made to address my comments and improve the manuscript. The study of dipolar surface twists (DSTs) in Fe_3GaTe_2 presents interesting results, particularly on the distinct dynamics of surface-localized topological states. However, certain critical aspects still require further clarification and experimental validation to meet the standards of Nature Communications. Below, I provide a detailed assessment of the revisions and remaining concerns.

1. Novelty and Impact

The claim regarding fractional topological charges would benefit from more direct experimental evidence, as it currently relies heavily on simulations. Additionally, a more critical comparison with prior works on skyrmion and magnetic bubble systems is required to clarify what is fundamentally new in this study.

2. FIB-Induced Artifacts

The authors argue that the DSTs are intrinsic to Fe_3GaTe_2 and not influenced significantly by FIB preparation. However, the controls presented (e.g., additional tests on other materials and micromagnetic simulations) are not fully convincing. A comparison with alternative sample preparation methods (e.g., mechanical polishing or Ar ion milling) would provide stronger evidence.

Quantitative assessment of the potential impact of FIB-induced damage on surface-localized textures should be included.

3. Scintillating Dynamics and Pinning Effects

The micromagnetic simulations performed to explain the scintillating dynamics are insightful. However, while the authors attribute these dynamics to strong pinning effects, the role of pinning induced by FIB processing or intrinsic defects in Fe_3GaTe_2 requires deeper experimental verification.

The authors should better justify why thermal effects due to Joule heating can be ruled out as the primary driver of the observed dynamics. The finite-element simulations and temperature-dependent micromagnetic simulations help, but additional direct experiments (e.g., temperature-dependent dynamics) would strengthen this claim.

4. Writing and Clarity

The manuscript has improved in clarity, but certain areas remain dense and ambiguous, e.g. a clearer explanation of the experimental limitations (e.g., L-TEM resolution, challenges in quantitative phase reconstruction) would improve transparency.

While the revised manuscript has addressed several key concerns, the responses to critical issues, particularly the novelty of the findings, evidence for fractional topological charges, and controls for FIB artifacts, remain partially inadequate. Therefore, I recommend a Major Revision before the manuscript can be considered for publication in Nature Communications.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

In the previous round, I made a comment about the DM interaction in their micromagnetic simulation. The authors reply that the effective DMI is not assumed to arise from the two external surfaces of the TEM lamella but from inversion-symmetry breaking associated with Fe off-centering along the c-axis. Although I understand what they assume, the authors should re-check the consistency in the manuscript before the publication.

On page 6, the authors mention that the obtained crystal belongs to a centrosymmetric space group $P6_3/mmc$. However, on page 8, they describe that the interfacial DMI is attributed to inversion-symmetry breaking associated with the approximately 0.1 Å off-centering of FeII atoms observed by atomic-resolution HAADF-STEM (Supplementary Fig. 12), consistent with recent reports (Refs. 32, 40). I am afraid that these two statements are clearly inconsistent with each other.

Ref. 40 reported that Fe deficiencies in Fe_3GaTe_2 induce the Fe displacement along the c-axis. As a result, the space group changes from centrosymmetric $P6_3/mmc$ to polar $P3m1$. I recommend that such a possibility should be more explicitly

explained.

One more technical issue: "Supplementary Fig. 18a" on page 34 of Supplementary Information should be corrected (to Fig. 25a, maybe).

Reviewer #3

(Remarks to the Author)

The authors have satisfactorily addressed the concerns raised during the previous round of review. The revisions have strengthened the manuscript, and the additional analyses and clarifications provide sufficient detail to support the conclusions and ensure the reproducibility of the work.

In its current form, I believe the manuscript meets the novelty and quality standards expected for Nature Communications. I therefore have no further concerns and am pleased to recommend the manuscript for publication.

Version 3:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I am completely satisfied with the authors' reply and the revisions of the manuscript. I now recommend the publication of this work in Nature Communications. Magnetic twist objects are clearly observed by cutting-edge Lorentz transmission electron microscopy. The novelty is high enough to deserve the publication in Nature Communications.

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Dear Reviewers:

We really appreciate your letter and the reviewers' valuable comments about this paper, which have helped us tremendously to improve this revised manuscript. We have carefully considered the reviewers' comments and revised our manuscript. The main corrections in the paper and the point-by-point responses to the reviewers' comments are listed below.

Reviewer 1:

1) The authors have performed Lorentz transmission electron microscopy to study the magnetic textures of a van-der-Waals (vdW) magnet Fe_3GaTe_2 at room temperature. Combined with micromagnetic simulations, they argue that dipolar surface twists emerge and that they exhibit “scintillating dynamics” with electrical current.

I think that the experimental results and the proposed model will attract the attention of the readers. On the other hand, I am not fully convinced that the bright and dark dots in Fig. 2c are ascribed to magnetic twists on the surface but not in bulk. Since Lorentz TEM observations and TIE analyses only provide a projected image of in-plane B field, it is still a challenge to reveal the three-dimensional distribution of B vector. While measurements of LTEM images with tilting samples would provide useful information, a comparison with the simulation is required to pin down the twist position. The TIE analyses shown in Fig. 2d are also confusing. I find several significant discrepancies between the arrow orientations in the lower panels and the color code.

Response: We thank the reviewer for the constructive comments and positive assessment of our work. We agree that Lorentz TEM and TIE analysis provide only projected information of the in-plane magnetic induction, and that resolving the full three-dimensional spin configuration remains experimentally challenging. Therefore, in the present work, the identification of surface-localized twists relies on the combined analysis of L-TEM observations and micromagnetic simulations.

Regarding the reviewer’s concern about assigning the bright and dark dots in Fig. 2c to surface-localized twists, we have analyzed the depth-dependent magnetic configurations by examining the averaged spin structures in the top, middle, and bottom layers, as shown in Fig. R1a. The results clearly show that the twist structures are confined to the top and bottom layers, whereas the middle layer is dominated by stripe domains and bubble-like textures. Notably, the twists at the top and bottom surfaces are not in a strict one-to-one mirror-symmetric correspondence, while both contribute to the observed L-TEM contrast. Such depth-dependent behavior is consistent with the reduction of demagnetization energy through surface-localized spin twisting.

We also note that similar bright and dark dot contrasts associated with surface-localized twists have been reported in antiskyrmion systems such as FeNiPdP , where their surface character has been directly confirmed by advanced three-dimensional imaging

techniques, including electron tomography (see, e.g., [*Nat. Mater.* **20**, 335 (2021)], [*Adv. Mater.* **36**, 2311737 (2024)], [*Commun. Mater.* **5**, 80 (2024)]). The consistency with these previous studies further supports our interpretation.

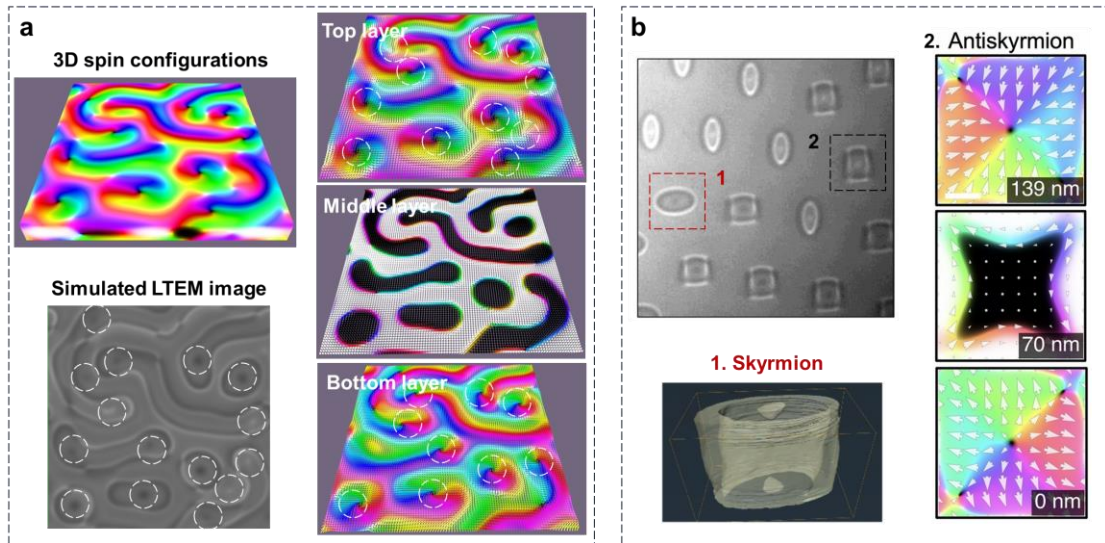


Fig. R1 **a** Simulated three-dimensional spin configuration of magnetic domains, with surface twists highlighted by white dashed boxes. **b** Representative L-TEM image of the antiskyrmion system, with red box 1 and black box 2 indicating elliptical skyrmions and square antiskyrmions, respectively.

Regarding the reviewer's comment on the TIE analysis in Fig. 2d, we thank the reviewer for pointing this out. We carefully re-examined the TIE analysis and corrected the figure presentation in the revised manuscript, as shown in Figs. R2–R3.

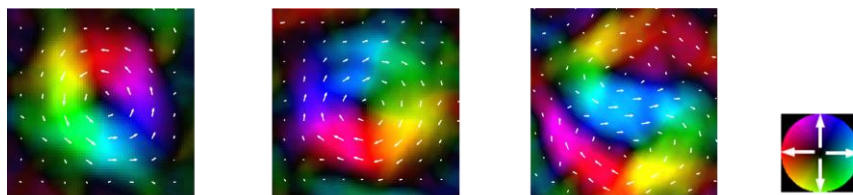


Fig. R2 In-plane magnetization distribution of DSTs with $N=1$ and $N=2$.

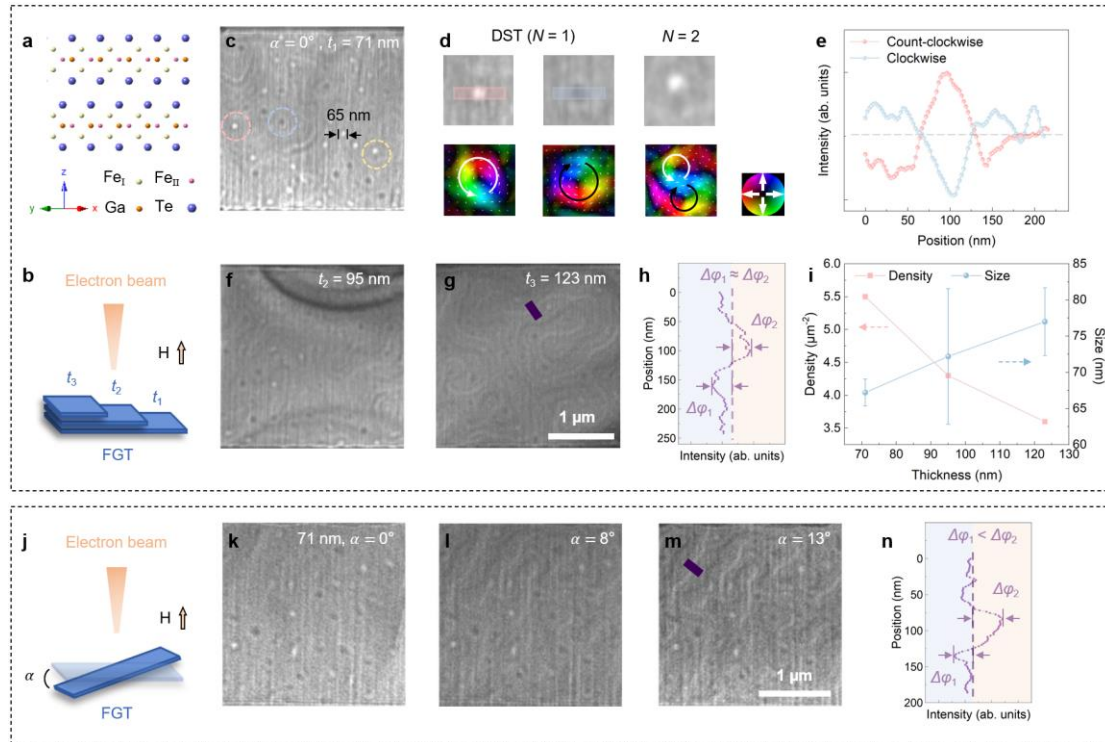


Fig. R3 Identification of domain structures by varying the thickness and tilt conditions at zero magnetic field. **a** Crystal structure of FGT. **b** Schematic of the L-TEM experiments with electron beam and magnetic field both perpendicular to the FGT lamellae plane. **c, f-g** Under-focused L-TEM images of magnetic domains taken at different thickness of 71 nm **c**, 95 nm **f** and 123 nm **g** without tilting the lamellae. **d-e** TIE analysis **d** and line profile **e** of selected spin objects boxed in different colors in **c**. **h** Line profile across the domain wall in **g**. **i** Thickness-dependent density and size of DSTs. **j** Schematic of sample tilting for L-TEM imaging. **k-m** Under-focused L-TEM images of magnetic domains taken under different tilt conditions. **n** Line profile across the domain wall in **m**.

2) Figure 4 demonstrates various types of textures. I do not exactly understand what ‘magnetic phase’ denotes. The definition should be explicitly provided. In addition, the correspondence between the contrast and the phase value (0 to 2π) should be shown.

Response: We thank the reviewer for this helpful comment, which has allowed us to further clarify this point. The “magnetic phase” shown in the original manuscript refers to the reconstructed phase obtained from the transport-of-intensity equation (TIE) analysis, which reflects the projected in-plane magnetic induction. To improve clarity and maintain consistency with standard terminology used in TIE analyses, we have

replaced “magnetic phase” with “reconstructed phase” throughout the revised manuscript (Fig. R4a). We further clarify that the reconstructed phase is a relative quantity determined by spatial variations in the projected magnetic induction, rather than an absolute phase value ranging from 0 to 2π , consistent with conventional TIE-based magnetic imaging analyses (Fig. R4b–c).

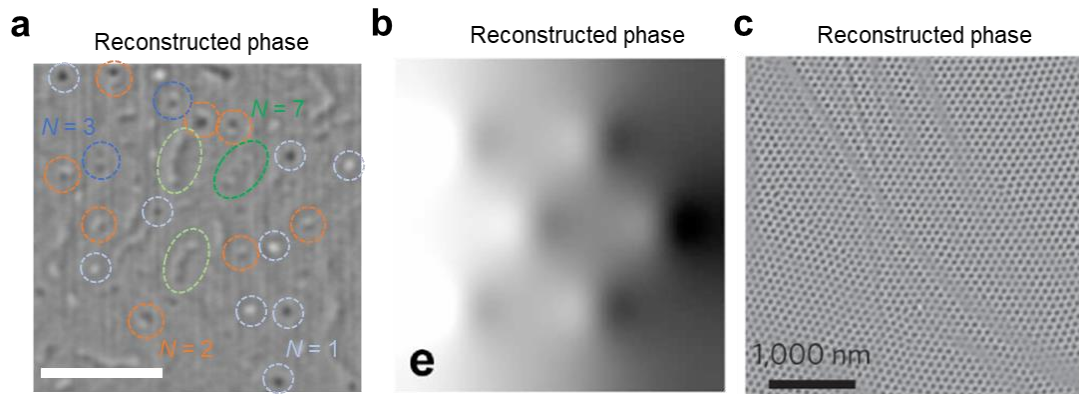


Fig. R4 Reconstructed phase images. **a** Reconstructed phase image showing the coexistence of DSTs with different N values. **b-c** Representative reconstructed phase images reproduced from previous studies [*Phys. Rev. Lett.* **91**, 043904 (2003)] (**b**) and [*Nat. Nanotechnol.* **10**, 589 (2015)] (**c**).

3) Electrical current-driven dynamics is summarized in Fig. 5. Generation and annihilation are clearly observed, as described. In regard with helicity switching of the right bottom one, I am a bit afraid that it is an “ $N=2$ ” twist comprising of dark and bright circles.

Response: We thank the reviewer for this careful observation. In fact, additional topological defects ($N=2$) emerge only transiently as intermediate states during helicity reversal as a result of localized reconstruction of the spin texture. After relaxation, the system evolves into a stable single-twist state.

As discussed in the original manuscript, helicity switching in topological magnetic textures is typically accompanied by the transient formation and annihilation of additional topological defects. For example, “*these processes are typically accompanied by the formation of additional topological defects,^{15, 48}*” and “*such defects are also central to skyrmion–antiskyrmion–bubble transitions reported in chiral magnets with anisotropic DMI.^{49, 50}*” Thus, it reflects a transient configuration

consisting of a primary twist and an additional topological defect (anti-twist), as shown in Fig. R5a.

To further clarify this point, we performed additional micromagnetic simulations and replaced the original Fig. 5g–h with the revised results shown in Fig. R5b. A current pulse was applied for 1 ns and subsequently removed to allow relaxation into a stable state. The simulations show that helicity reversal is accompanied by transient reconstruction of the spin configuration and the formation of additional transient topological defects. After removal of the current and subsequent relaxation, the system evolves into a single DST with reversed helicity. We further investigated the switching dynamics under different pinning strengths ($2 K_u$, $5 K_u$, $7.5 K_u$, and $10 K_u$), and the results have been added to Fig. 5g–h and Supplementary Fig. 24–26. In all cases, transient defects appear only during the switching process, while the relaxed state remains a single DST.

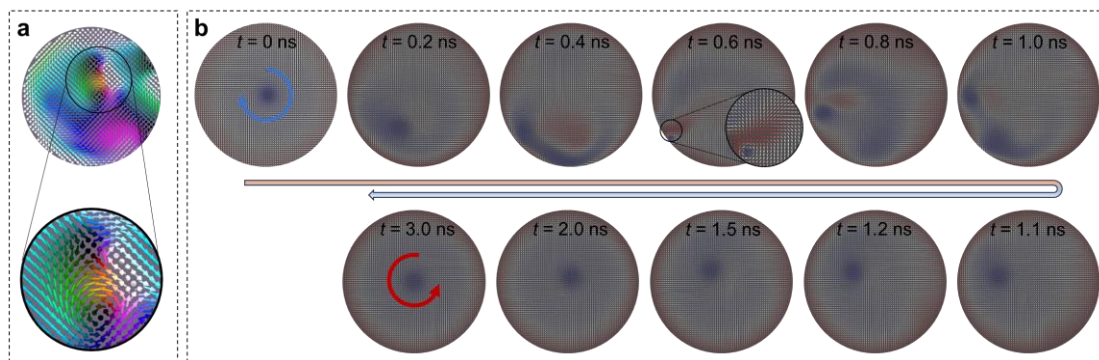


Fig. R5 **a** Representative intermediate state during the helicity switching process. **b** Complete current-driven helicity switching dynamics of a DSTs under $J = 1.37 \times 10^{11}$ A/m², with pinning strength of $5K_u$ and zero magnetic field.

4) I also have some comments about micromagnetic simulation.

The double parentheses in the definition of the magnetic quality factor on line 95 are a little confusing. It should appear as $f = K_u/K_d = K_u/(...)$. I also recommend that reference number 28 be moved somewhere else to avoid possible misunderstandings.

Response: We thank the reviewer for pointing this out. The definition of the magnetic quality factor has been revised to $f = K_u/K_d = K_u/(0.5\mu_0 M_s^2)$ for improved clarity. In addition, Ref. 28 has been removed to avoid possible confusion.

5) Hamiltonian (1) for micromagnetic simulations assumes isotropic exchange stiffness, while it is expected to be highly anisotropic in the vdW magnet. The authors should discuss the validity of the model.

Response: We thank the reviewer for this important comment. We agree that exchange interactions in van der Waals magnets can be anisotropic, particularly between the in-plane and out-of-plane directions. To examine the validity of the model, we performed additional micromagnetic simulations incorporating anisotropic exchange coupling to better capture the layered nature of the system. Specifically, the sample was modeled using 50 discrete layers (slices). The intralayer exchange stiffness is set to $A = 2 \times 10^{-12}$ J/m, while the interlayer exchange coupling is varied as xA , with x ranging from 0 to 1 (Fig. R6).

The simulations show that anisotropic exchange primarily modifies the detailed domain-wall structure, leading to the emergence of multiple Bloch lines, whereas the surface twists remain stable throughout the entire range of interlayer coupling strengths. These results indicate that the formation of DSTs does not rely on the assumption of isotropic exchange, but is governed predominantly by dipolar interactions associated with the low magnetic quality factor.

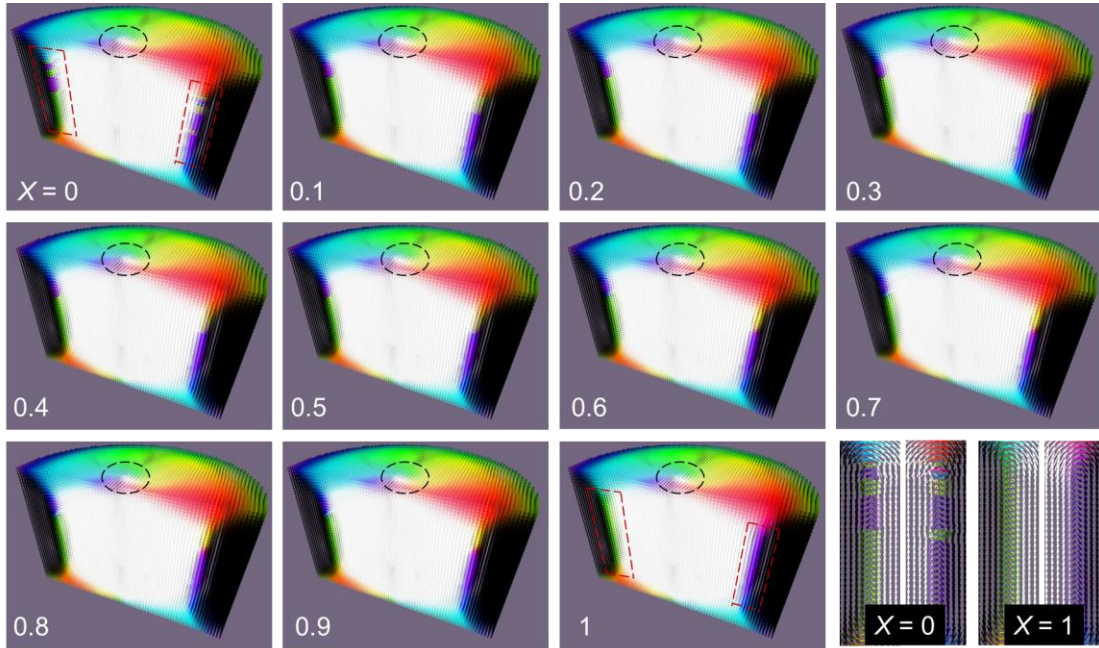


Fig. R6 Micromagnetic simulations of three-dimensional magnetic structures under varying interlayer exchange coupling (xA , with $0 \leq x \leq 1$), where A denotes the

intralayer exchange stiffness fixed at 2×10^{-12} J/m. The bottom-right panels show cross-sectional views of the domain walls, highlighting the variation of Bloch lines with different x values.

We have added these results and the corresponding discussion to Supplementary Fig. 5 and Lines 137–141 of the revised manuscript:

“Additional micromagnetic simulations incorporating anisotropic exchange coupling show that DSTs remain robust over a wide range of interlayer coupling strengths (Supplementary Fig. 5), indicating that their formation is governed predominantly by dipolar interactions associated with the low magnetic quality factor.”

6) The authors sometimes use a period to express a scalar product, which should be replaced with a dot operator.

Response: We thank the reviewer for pointing this out. The notation has been corrected throughout the manuscript by consistently replacing periods with dot operators for scalar products.

7) The vector B_d in Hamiltonian (1) is not defined.

Response: We thank the reviewer for pointing this out. The vector $\mathbf{B}_d$ in Hamiltonian (1), which represents the demagnetization field, has now been explicitly defined in the revised manuscript for clarity.

8) The E_D term in Hamiltonian (a) corresponds to DM interaction in chiral systems. The interfacial DM interaction is expressed in a different way.

Response: We thank the reviewer for this important comment. In the revised manuscript, we have corrected the DMI term from the bulk form to the interfacial form,

$$E_D = D[m_z(\nabla \cdot \mathbf{m}) - (\mathbf{m} \cdot \nabla)m_z]$$

consistent with the symmetry of the system and previous literature [*Phys. Rev. B* **101**, 134431 (2020)].

In summary, I think that the manuscript should be revised before the publication in Nature Communications.

Response: We thank the reviewer for the constructive comments and suggestions. We hope that the revisions and responses provided above satisfactorily address the concerns raised.

Reviewer 2:

Lv and colleagues report on topologically interesting spin structures, as well as their dynamics, FeGaTe, a room temperature ferromagnet VdW material, which has been extensively reported to exhibit skyrmion structures. There reports of diverse spin structures, while interesting, does not appear to me to be all that novel, with objects with complex topological charges being reported in many recent works (detailed later in this report). However, to my knowledge, the study of current driven dynamics does meet the novelty bar required for Nature Communications. Therefore, assuming the following points may be addressed, I believe it may recommended for publication in Nature Communications.

Response: We thank the reviewer for the careful reading of our manuscript and for recognizing the novelty of the current-driven dynamics reported in this work. We have carefully considered all comments and addressed them in detail below.

1) As a technical detail, I believe the defocus value is quite large, and this may lead to complications in interpretation of the resultant spin structures. It's been heavily reported that large defocus values can result in differing interpretations of the same spin state (i.e. see Phys. Rev. B 112, 214455 2025), and also may preclude quantitative measurements of size i.e. see discussion in Phys. Rev. Lett. 122, 237201 (2019), which is important in the interpretation of Fig. 2i. How was the size measured? Further, it can complicate interpretation of the complex spin textures shown in Fig. 4. It may be nice to run image simulations showing changes in contrast for the more complex objects. For example, how confident, given the level of defocus, is the N value for larger N structures (i.e. the $N = 11$ and $N = 14$ structures).

Response: We thank the reviewer for this important comment. We agree that large defocus values can complicate the interpretation and quantitative analysis of L-TEM contrast. In our experiments, to ensure reliable size determination, the measured size was calibrated by comparing the same regions acquired under under-focus and in-focus conditions (Fig. R7). For example, a distance measured from the under-focus image is $2.6257\text{ }\mu\text{m}$, whereas the corresponding actual distance obtained from the in-focus image is $2.7551\text{ }\mu\text{m}$. Accordingly, measurements obtained under under-focus conditions (e.g.,

63 nm) are corrected using a scaling factor (i.e., multiplied by 2.7551/2.6257), yielding the corresponding real-space dimension (66 nm).

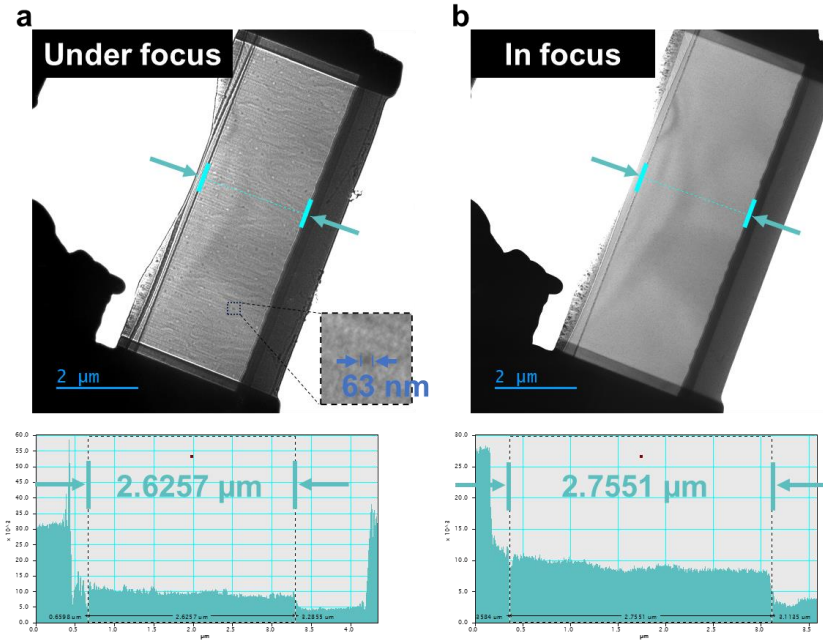


Fig. R7 L-TEM images acquired under (a) under-focus, and (b) in-focus conditions. The corresponding intensity profiles (bottom panels) are used for size calibration. The defocus value is 1 mm.

In addition, we further examined previously reported high-order (anti)skyrmions and skyrmion bundles under relatively large defocus values (2.5 mm, 2 mm, 1.2 mm, and 1 mm), as shown in Fig. R8. These results demonstrate that the magnetic structures can still be clearly resolved and reliably analyzed under such defocus conditions.

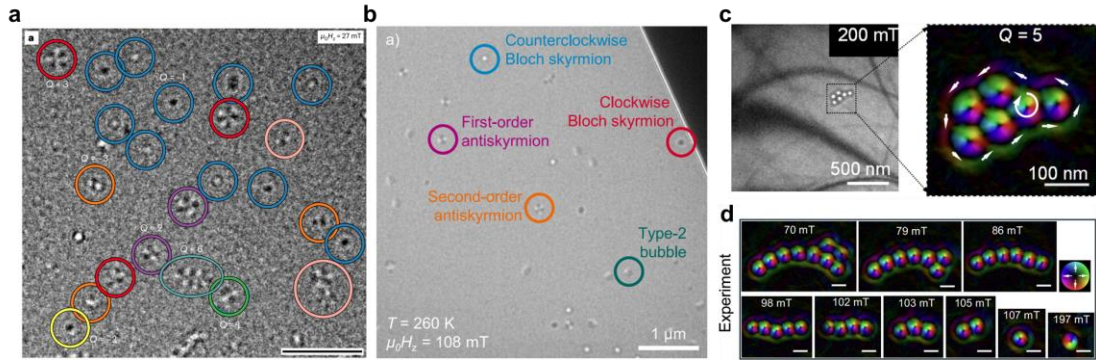


Fig. R8 Under-focused L-TEM images acquired at different defocus values. **a** Under-focused ($\Delta f = -2.0 \text{ mm}$) L-TEM image of a [Co/Ni]₁₀ multilayer sample. **b** Under-focused ($\Delta f = -2.5 \text{ mm}$) L-TEM image of a [Fe/Ir/Gd]₂/[Fe/Gd]₇₆/[Fe/Ir/Gd]₂ sample. **c** Under-focused ($\Delta f = -1.0 \text{ mm}$) L-TEM image showing a complete magnetic skyrmion

bundle with topological charge $Q = 5$. **d** Under-focused ($\Delta f = -1.2$ mm) L-TEM image showing field-driven magnetic evolution from a skyrmion bundle with $Q = 8$. All panels are reproduced from Refs. (a) *Nat. Phys.* **20**, 615 (2024); (b) *Nat. Commun.* **12**, 2611 (2021); (c) *Nat. Nanotechnol.* **16**, 1086 (2021); and (d) *Nat. Commun.* **15**, 3391 (2024).

Following the reviewer's suggestion, we also performed additional image simulations for representative structures (for example, $N = 11$ state) under different defocus conditions. The simulations show that, for defocus values of ≤ 2 mm, the magnetic contrasts remain sufficiently distinct to clearly resolve the number of DSTs without complicating the interpretation of the complex spin textures.

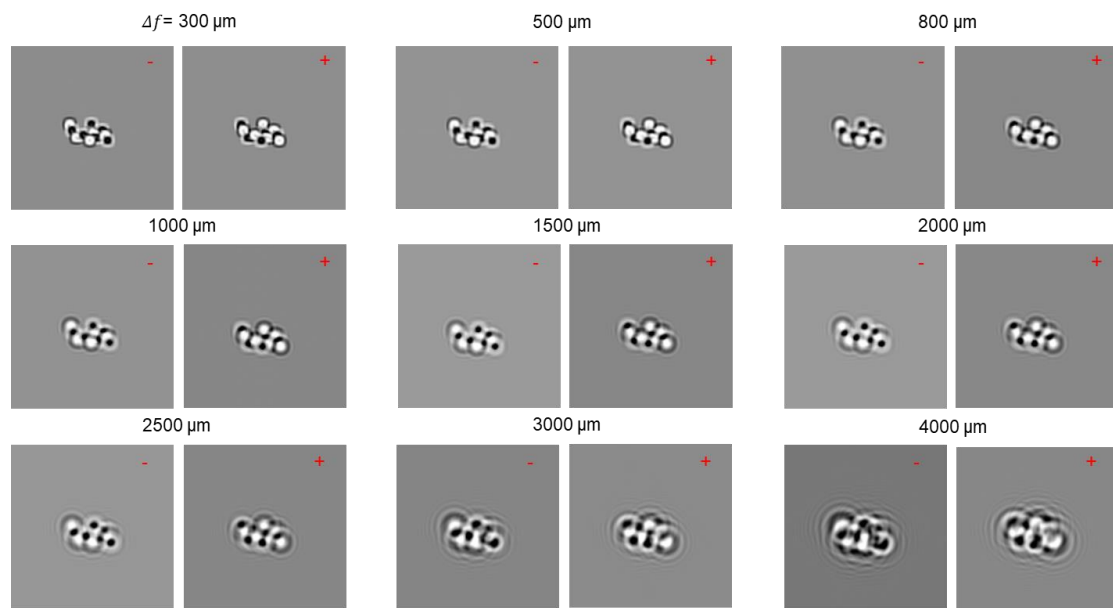


Fig. R9 Simulated LTEM images of DSTs ($N = 11$) as a function of defocus. The “-” and “+” signs in the upper right corner of each panel denote under-focus and over-focus conditions, respectively.

2) Regarding the field evolution of these defect states, particularly in regards to the discussion of Fig. 3, the evolution of complex topological charge objects was also seen in discussion of heavy metal/ferromagnetic multilayers (see *Phy. Rev. B* 102, 214429 (2020), *J. Appl. Phys.* 130, 153903 (2021), *Ann. Phys.* 536, 2300480 (2024)), so while interesting, and in a new, very device relevant system, similar observations have been previously reported.

Response: We thank the reviewer for pointing out these relevant previous studies. We agree that the evolution of complex topological defect states has previously been

reported in heavy metal/ferromagnetic multilayer systems. In those works, the observed textures were primarily discussed within an effectively two-dimensional framework associated with domain-wall substructures and skyrmion-related states. In contrast, the textures discussed here are surface-localized states carrying fractional topological charge in a three-dimensional dipolar magnetic system, whose evolution requires a fully three-dimensional description.

To better position our work in relation to these studies, we have added the following discussion and included the suggested references in the revised manuscript (lines 266–272, page 9):

“The field evolution of complex topological defect states has also been discussed in magnetic multilayers in the context of domain-wall substructures^{44,45} and skyrmion-related textures⁴⁶, where they are typically interpreted within an effective two-dimensional framework. In contrast, the textures observed here exhibit an intrinsic three-dimensional character, and their evolution requires a fully three-dimensional description.”

“44 Garlow, J. A. *et al.* Unconventional domain-wall pairs and interacting Bloch lines in a Dzyaloshinskii-Moriya multilayer thin film. *Phys. Rev. B* **102**, 214429 (2020).

45 Li. M. *et al.* Magnetic domain wall substructures in Pt/Co/Ni/Ir multi-layers. *J. Appl. Phys.* **130**, 153903 (2021).

46 Dorokhin, M. V. *et al.* Exotic Topological Magnetic States in Thin Co/Pd Ferromagnetic Films. *Ann. Phys.* **536**, 2300480 (2024).”

3) On another technical note, a few details should be given about the QPT phase reconstruction. Particularly, the choice of frequency offset (commonly referred to as q_0) can induce artifacts and largely modify the imaged domain structure. As such, it would be good to know the value used, and possibly show in a supplementary figure how this choice modifies the image of interest (i.e. see Journal of Magnetism and Magnetic Materials 454 (2018) 304–313, supplement of *Phys. Rev. B* 102, 214429 (2020))

Response: We thank the reviewer for this important suggestion. We have systematically investigated the influence of the frequency offset q_0 on the phase reconstruction by testing a range of values from 0 to 9 pixels, as shown in Fig. R10.

The results indicate that for very small q_0 values (0–1 pixels), the magnetic features cannot be reliably reconstructed. A appropriate offset is therefore required to separate the magnetic signal from the background. In this work, we use $q_0 = 5$ pix. In contrast, excessively large values (8–9 pixels) lead to degraded reconstruction quality, as the phase becomes increasingly sensitive to noise and background inhomogeneities. Within a moderate range of q_0 , the reconstructed spin textures remain qualitatively robust. Note that the optimal choice of q_0 depends on imaging conditions and the characteristic length scale of the magnetic structures, with larger values generally required for lower magnification or smaller features. The corresponding description has been added as follows:

“High-resolution in-plane magnetic induction maps were reconstructed using QPT software based on the transport-of-intensity equation (TIE), with a frequency offset parameter of $q_0 = 5$ pix applied during the phase reconstruction.” (lines 431–434)

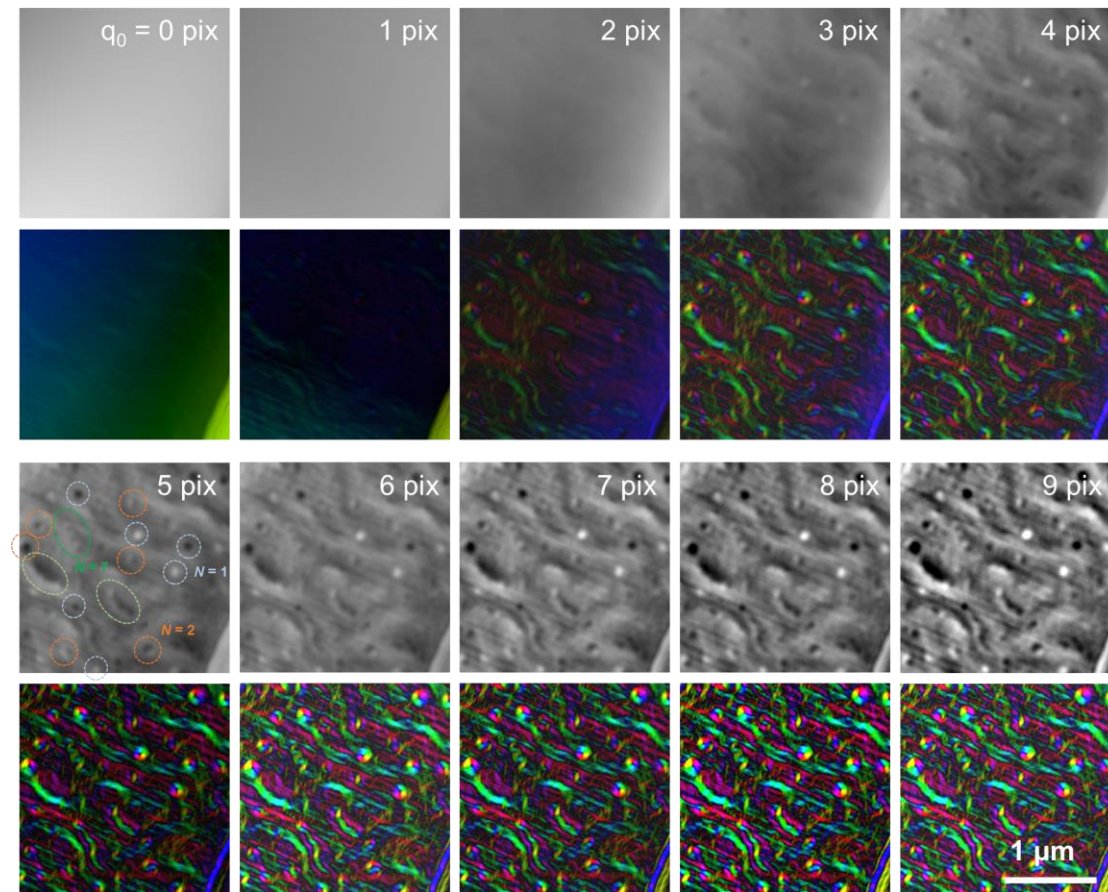


Fig. R10 TIE-reconstructed magnetic domain structures obtained using different q_0 values. The upper panels show the reconstructed phase, while the lower panels display the corresponding magnetization distributions.

4) With that said, the main interest in this work seems to be the current driven dynamics, and in my view, are the reason why I would consider this work for publication in Nat. Comm. However, before I fully trust all of these observations, I think the authors should account for a key issue. Applying large current densities inherently increases the temperature, and this temperature change can be large in these structures. The authors exclude the temperature rising above T_c due to the lack of an emergence of a complex disordered domain structure, but changes in domain structure do not require increasing T above T_c . Have the authors estimated the change in temperature induced in these structures with current densities approaching 10^{12} A/m², and estimated the thermal effects on stability, below T_c ? Can these transformations that have been observed be explained largely via thermal fluctuations, or how did the authors rule this out? In short, while exciting, I don't believe enough evidence is presented to rule out thermally driven effects.

Response: We thank the reviewer for this important and insightful comment. We agree that Joule heating must be carefully evaluated under large current densities. In our experiments, the maximum applied current density is below 7×10^{11} A/m², and the pulse width is systematically reduced at higher current densities to minimize heating (Supplementary Fig. 20).

To quantify the temperature increase, we performed finite-element simulations using COMSOL Multiphysics 6.0, incorporating Joule heating and heat transfer modules. The model (approximately $2 \mu\text{m} \times 2 \mu\text{m} \times 77 \text{ nm}$) includes two electrodes, and the device resistance was experimentally measured to be 80Ω . As shown in Fig. R11a, a pulse with $j = 2.18 \times 10^{11}$ A/m² and $w = 40$ ns raises the device temperature from room temperature to ~ 330 K, remaining below the Curie temperature ($T_c \sim 350$ K). Notably, this current density is already sufficient to induce both the scintillating behavior of DSTs and the directional motion of stripe domains (see Fig. 5b–e and Supplementary Video 3). Furthermore, reaching temperatures close to T_c would require significantly higher current densities (e.g., 7.6×10^{11} A/m² with $w = 5$ ns), exceeding the conditions used in this work. These results confirm that the applied current pulses do not drive the system across T_c . In addition, we performed temperature-dependent experiments to directly evaluate the thermal stability of the DSTs. As shown in Fig. R11b, no helicity switching or annihilation of DSTs is observed upon increasing the temperature from

300 K to 330 K, demonstrating their robustness against thermal perturbations. This conclusion is supported by additional micromagnetic simulations (see response to the comment 5).

Most importantly, we further rule out a dominant role of thermal fluctuations based on three key observations. First, at lower current densities (e.g., $1.37 \times 10^{11} \text{ A/m}^2$), only DSTs exhibit scintillating behavior, while the surrounding stripe domains remain stable; a purely thermal effect would affect all magnetic textures similarly. Second, thermal fluctuations would lead to stochastic reconfiguration upon cooling, whereas the observed DSTs repeatedly fluctuate at fixed positions without random relocation. Third, at higher current densities (e.g., $2.18 \times 10^{11} \text{ A/m}^2$), stripe domains exhibit directional motion correlated with the current flow, indicating a deterministic, current-driven mechanism rather than thermally activated behavior.

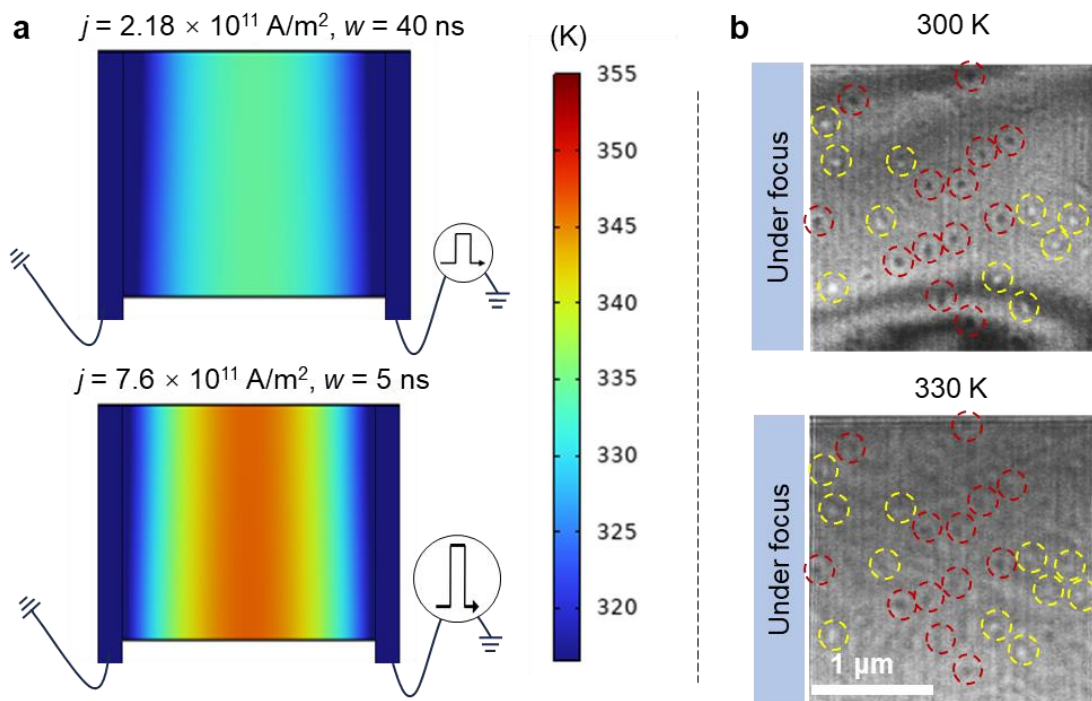


Fig. R11 Temperature-dependent stability of DSTs. **a** The temperature distributions in the FGT microdevice under different current density. **b** Under-focused L-TEM images showing the temperature-dependent evolution of DSTs. DSTs with clockwise (black contrast) and anticlockwise (white contrast) helicities are marked by red and yellow circles, respectively.

In the revised manuscript, we have incorporated Figs. R11–R12 into the Supplementary Information and expanded the discussion to explicitly address the role of thermal effects.

“The nearly fixed positions of DSTs during scintillation indicate that the applied current does not raise the temperature above T_c , as thermal demagnetization would lead to a reconfiguration of the magnetic domains and a random redistribution of DST positions. This is supported by finite-element simulations showing that the temperature increase remains well below T_c (Supplementary Fig. 27a), as well as temperature-dependent measurements and finite-temperature micromagnetic simulations confirming the thermal stability of the spin textures at elevated temperatures (Supplementary Fig. 27b–c).” (Lines 381-388)

5) Quite trivially, could the authors also run micromagnetics at finite temperatures, and observe whether the (zero current applied) structures are stable at moderately higher temperature (with or without pinning)? I do think these simulations are necessary.

Response: We thank the reviewer for this helpful suggestion. In response, we performed finite-temperature micromagnetic simulations to evaluate the stability of the zero-current spin structures. The results show that DSTs and surrounding stripe domains remain stable at moderately elevated temperatures, in agreement with the experimental observations (Fig. R11b). These findings confirm the thermal robustness of the observed spin configurations.

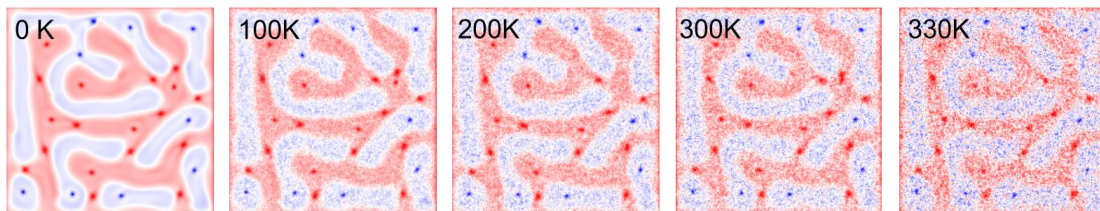


Fig. R12 Temperature-dependent spin textures from micromagnetic simulations, showing that DSTs remain stable at moderately elevated temperatures, confirming their thermal stability.

The corresponding simulations and discussions have now been included in the revised manuscript.

“This is supported by finite-element simulations showing that the temperature increase remains well below T_c (Supplementary Fig. 27a), as well as temperature-dependent measurements and finite-temperature micromagnetic simulations confirming the

thermal stability of the spin textures at elevated temperatures (Supplementary Fig. 27b–c).” (Lines 384-388)

6) Minor detail: Fig. 5f is difficult to read as it appears very faded in the manuscript.

Response: We thank the reviewer for pointing this out. The contrast of Fig. 5f has been enhanced in the revised manuscript to improve its clarity.

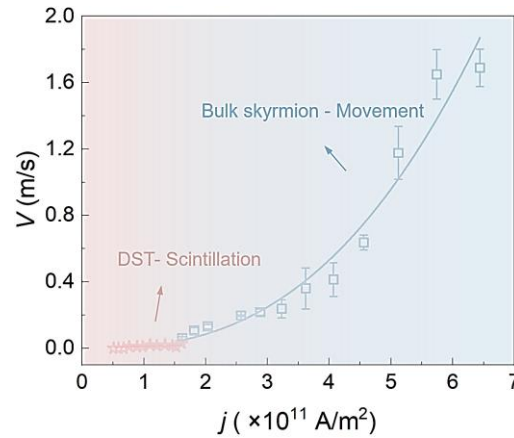


Fig. R13 Revised version of Fig. 5f. Average velocity of DSTs and bulk skyrmions as a function of current density. Error bars represent the standard deviation from five independent measurements.

7) In summary, I think this work has potential for impact, but the details listed need to be addressed prior to publication, particularly in doing a more robust job of ruling out thermal effects regarding the current driven changes as this, in my opinion, is the important part of the work. While an interesting system, the observation of complex high-N textures is not sufficient on it's own owing to its similarity to more traditional heavy metal/ferromagnet multilayers.

Response: We thank the reviewer for the constructive summary and valuable suggestions. In response, we have carefully addressed the concern regarding possible thermal effects associated with the applied current. Additional finite-element simulations, temperature-dependent measurements, and finite-temperature micromagnetic simulations have been included in the revised manuscript, which together provide a more robust basis for excluding thermally driven mechanisms and support the current-driven origin of the observed dynamics.

Reviewer 3:

1) The manuscript “Topological Diversity and Scintillating Dynamics of Dipolar Surface Twists in a van der Waals Magnet” by Xiaowei Lv et al. reports Lorentz transmission electron microscopy (L-TEM) measurements combined with micromagnetic simulations to investigate the magnetic domain structure in the van der Waals magnet Fe_3GaTe_2 (FGT). The three-dimensional (3D) magnetic structure of the observed domain textures is inferred by matching experimental L-TEM images with simulated contrast derived from 3D micromagnetic simulations. Black and white spot-like features coexisting with stripe domains at zero magnetic field are attributed to so-called dipolar-interaction-stabilized surface twists (DSTs). The response of these DSTs to external stimuli is further investigated by applying an out-of-plane magnetic field and in-plane electric currents. The DSTs are reported to be stable up to external fields of approximately 160 mT, above which the sample transitions into a field-polarized state. Upon decreasing or reversing the magnetic field, more complex, higher-order DSTs are stabilized. In addition, nanosecond current pulses applied to electrically contacted FGT samples induce a flickering L-TEM contrast of the DSTs, referred to as “scintillation” by the authors. However, no translational motion of the DSTs is observed in response to the applied currents, presumably due to pinning effects.

Response: We thank the reviewer for this careful observation and for the clear summary of our work. We would like to clarify that, contrary to the impression that no translational motion occurs, the DSTs do exhibit translational motion under applied currents when the current density is sufficiently high to drive the surrounding stripe domains. This is demonstrated in Fig. R14 (see below and Supplementary Video 3), where sample defects (marked by red circles) serve as fixed reference points. Two DSTs with clockwise (black contrast) and anticlockwise (white contrast) helicities, indicated by black and white arrows, respectively, show discernible translational motion during current injection.

At the same time, the DSTs exhibit pronounced scintillating dynamics, including helicity reversal and intermittent annihilation/reformation processes. For example, the black-contrast DST disappears at 36 s, whereas a DST with opposite contrast emerges at 43 s. Consequently, the DSTs do not propagate as rigid spin textures, but instead undergo continuous dynamical reconstruction during motion. This behavior precludes a reliable quantitative determination of the propagation velocity of individual DSTs

over extended distances.

In the original manuscript, we stated: “*With the pulse frequency fixed and j increased to $2.18 \times 10^{11} \text{ A/m}^2$, reaching the threshold to drive the bulk stripe domain, these DSTs became difficult to capture due to their changed positions (Supplementary Video 2).*”

To clarify this point, we have revised the corresponding sentence and added Fig. R14 to explicitly demonstrate the current-driven translational motion of DSTs. The sentence has been revised as follows:

“*With the pulse frequency fixed and j increased to $2.18 \times 10^{11} \text{ A/m}^2$, reaching the threshold required to drive the bulk stripe domains, the DSTs become difficult to track due to the coexistence of translational motion and scintillating behavior (see Supplementary Video 3 and Supplementary Fig. 18).*” (Lines 331-334)

We appreciate the reviewer’s comment, which helped us clarify this point in the revised manuscript.

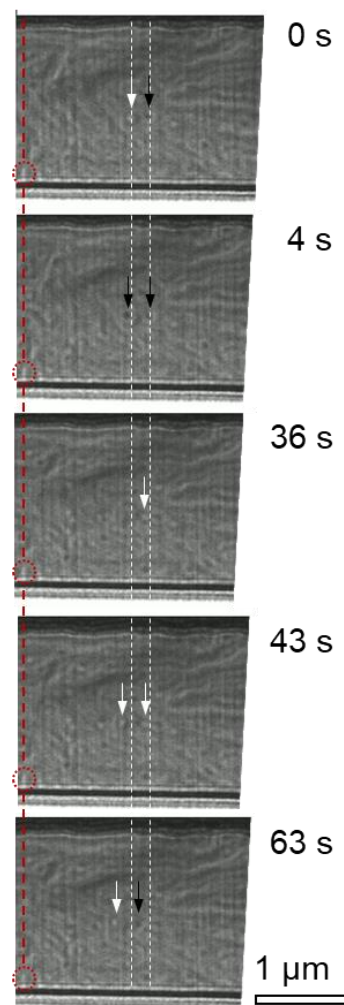


Fig. R14 Current-driven dynamics of DSTs at zero magnetic field and room

temperature. The applied current density is $j = 2.20 \times 10^{11} \text{ A.m}^{-2}$ with a pulse width of 40 ns. Red circles mark sample defects serving as fixed reference points. Clockwise and anticlockwise DSTs are indicated by black and white arrows, respectively.

2) While the investigation of three-dimensional nanoscopic spin textures, and in particular their surface structures, is of clear interest for potential spintronic applications, the novelty and impact of the present work for the broad readership of Nature Communications are limited. Three-dimensional magnetic structures of (anti-)skyrmionic textures have already been studied in considerably greater depth using advanced X-ray and electron holographic tomography techniques (see, for example, Birch et al., Nat. Commun. 11, 1726 (2020); Wolf et al., Nat. Nanotechnol. 17, 250–255 (2022); Yasin et al., Adv. Mater. 36, 2311737 (2024)).

Response: We thank the reviewer for acknowledging the scientific relevance of three-dimensional spin textures for spintronic applications. We also appreciate the valuable references provided, which highlight important advances in three-dimensional magnetic imaging. While these studies provided important insights into static three-dimensional magnetic configurations, the present work differs fundamentally in both physical focus and observed phenomena:

- i. **Focus on dynamics and decoupled surface–bulk behavior.** Unlike the studies cited by the reviewer [Birch *et al.*, Nat. Commun. 11, 1726 (2020); Wolf *et al.*, Nat. Nanotechnol. 17, 250–255 (2022); Yasin *et al.*, Adv. Mater. 36, 2311737 (2024)], which primarily focused on static three-dimensional magnetic structures, our work centers on the field- and current-driven dynamics of dipolar surface twists (DSTs). Even compared with previous studies on dynamical three-dimensional textures such as hopfions and heliknotons [Nat. Mater. (2026), <https://doi.org/10.1038/s41563-025-02450-0573–579>], which generally evolve as rigid objects with coupled surface and bulk motion, our results demonstrate that surface-localized and bulk magnetic textures can exhibit distinct dynamical responses under current excitation. Specifically, the surface-localized DSTs exhibit a scintillating mode involving helicity reversal together with intermittent annihilation and reformation, whereas the bulk stripe domains predominantly undergo translational motion. Importantly, these two dynamical modes possess

markedly different critical current densities. To our knowledge, such distinct surface–bulk dynamical responses have not been reported previously in three-dimensional magnetic systems.

- ii. **Distinct topological nature and enhanced topological diversity.** The DSTs investigated here are not merely surface manifestations of (anti)skyrmionic textures, but instead constitute a distinct class of topological surface states with fractional topological charge, in contrast to the integer topological charge that characterizes (anti)skyrmions. Moreover, these surface spin textures can continuously evolve into more complex topological magnetic states under controlled magnetic fields. The ability to stabilize and manipulate multiple topological states within a single material platform introduces an additional degree of freedom for emergent electromagnetic phenomena and unconventional information-processing functionalities [*Nat. Phys.* 20, 615 (2024); *Nat. Commun.* 12, 2611 (2021); *Nat. Nanotechnol.* 16, 1086 (2021); *Nat. Commun.* 15, 3391 (2024)].
- iii. **Extension to van der Waals magnets with enhanced functionality.** Most previous studies of three-dimensional topological spin textures have focused on bulk chiral magnets. Here, we extend this research direction to layered van der Waals magnets, which possess distinct intrinsic magnetic parameters, including low Gilbert damping, reduced exchange stiffness, and weak Dzyaloshinskii–Moriya interaction, leading to markedly different stability and dynamical behaviors for topological spin textures. Importantly, the DSTs observed in FGT remain stable well above room temperature (~ 330 K), in contrast to many conventional chiral magnets such as FeGe. This combination of robust thermal stability and unconventional dynamics highlights the potential of van der Waals magnets as a platform for novel topological spintronics.

Taken together, our results reveal a distinct class of surface topological states with fractional topological charge and demonstrate that **surface** and **bulk** magnetic structures in a three-dimensional dipolar system can exhibit decoupled **dynamics**. To better highlight these distinctions from previously studied three-dimensional magnetic textures, we summarize several key aspects in Table R1 and have added the following discussion to the revised manuscript:

“This characteristic distinguishes DSTs from the surface configurations of three-

dimensional (anti)skyrmions, which have been extensively investigated using advanced imaging techniques and are characterized by integer topological charges.” (Lines 143-146)

“These distinct dynamical behaviors, together with the low critical current density, highlight the fundamental differences between surface and bulk spin textures and establish surface-localized states as a tunable degree of freedom in three-dimensional spintronics, with potential applications in energy-efficient information encoding¹¹, stochastic number generation^{51,52}, and hybrid computing architectures⁵³.” (Lines 404-408)

Table R1.

Reference	Spin texture	Topological charge	Current-driven dynamics (Yes/No)	Room-temperature stability (Yes/No)	Material system
Ref. 1 (<i>Nat. Commun.</i> 11, 1726 (2020))	Skymion	Integer	No	No	Bulk magnet
Ref. 2 (<i>Nat. Nanotechnol.</i> 17, 250–255 (2022))	Skymion	Integer	No	No	Bulk magnet
Ref. 3 (<i>Adv. Mater.</i> 36, 2311737 (2024))	Antiskyrmion	Integer	No	Yes	Bulk magnet
<i>Nat. Mater.</i> (2026). https://doi.org/10.1038/s41563-025-02450-0	Heliknoton (Hopfion)	Integer	Yes (Translational motion)	No	Bulk magnet
This work	Dipolar surface twist	Fractional	Yes (Scintillating behavior and translational motion)	Yes	Van der Waals magnet

3) Although the comparison between experimental and simulated L-TEM images represents a valid methodological approach, a substantially more detailed experimental and micromagnetic analysis would be required to achieve a deeper and more quantitative understanding of the structure and underlying physics of the proposed surface states, particularly with respect to their relevance for spintronic applications.

Response: We thank the reviewer for this constructive comment. We agree that further experimental and micromagnetic analyses are important for a deeper understanding of the proposed surface states and their relevance for spintronic applications.

To address this point, we have substantially expanded the analyses in the revised manuscript. Specifically, we have included: (i) additional temperature-dependent measurements; (ii) thickness-dependent studies; (iii) finite-element simulations of Joule-heating effects under current injection; and (iv) extended micromagnetic calculations incorporating anisotropic exchange interactions and variable effective pinning strengths. Together, these complementary investigations provide stronger

support for the proposed physical picture of the DSTs and further reinforce the robustness of our interpretation.

We have also expanded the discussion regarding the potential implications of these surface states for spintronic applications. In particular, the coexistence of low-current-driven dynamics, fractional topological character, and distinct surface–bulk dynamical behaviors suggests that DSTs may provide a new platform for tunable topological functionalities in van der Waals magnetic systems.

The following discussion has been added to the revised manuscript:

“These distinct dynamical behaviors, together with the low critical current density, highlight the fundamental differences between surface and bulk spin textures and establish surface-localized states as a tunable degree of freedom in three-dimensional spintronics, with potential applications in energy-efficient information encoding¹¹, stochastic number generation^{51,52}, and hybrid computing architectures⁵³.” (Lines 404-408)

4) For these reasons, I unfortunately cannot recommend the manuscript for publication in Nature Communications. Below, I list additional comments and suggestions that I would encourage the authors to address before submission to another journal:

Response: We thank the reviewer for the careful assessment of our work. We understand the reviewer’s concern regarding the distinction between the present study and previous investigations of three-dimensional magnetic textures associated with (anti)skyrmionic states. However, the DSTs investigated here are not merely surface manifestations of (anti)skyrmionic textures, but instead represent a distinct class of topological surface states characterized by fractional topological charge.

More significantly, whereas previous studies primarily focused on **static** three-dimensional magnetic textures, our work reveals that surface and bulk magnetic structures can exhibit decoupled **dynamical** behaviors under current excitation. Specifically, surface-localized DSTs exhibit a distinct scintillating mode, whereas the bulk stripe domains predominantly undergo translational motion. Moreover, these two dynamical modes possess markedly different critical current densities. To our knowledge, such **decoupled surface–bulk dynamics have not previously been reported** in three-dimensional magnetic systems.

In response to the reviewer's comments, we have substantially revised the manuscript, incorporated additional experimental measurements and micromagnetic simulations, and further clarified the underlying physical mechanisms. We believe these revisions substantively address the reviewer's concerns and better demonstrate the novelty and potential impact of this work for the readership of *Nature Communications*. Detailed point-by-point responses are provided below.

5) L. 113: The ring-like contrast is attributed to skyrmions. Please clarify why these features are identified as skyrmions rather than magnetic bubbles. In L-TEM, skyrmions typically exhibit dot-like contrast similar to that observed for the DSTs.

Response: We thank the reviewer for raising this important question regarding the identification of skyrmions and dipolar surface twists (DSTs) in this work. Here, the term “skyrmions” specifically refers to dipolar skyrmions in centrosymmetric magnets, corresponding to type-I magnetic bubbles with an integer topological charge. In contrast, conventional type-II magnetic bubbles are topologically trivial and typically contain Bloch lines.

To clarify the distinction between these magnetic textures, we performed additional micromagnetic simulations combined with simulated L-TEM imaging for several representative spin configurations, including dipolar skyrmions (type-I bubbles), type-II magnetic bubbles, DSTs, and chiral skyrmions, as shown in Fig. R14. The simulations demonstrate that dipolar skyrmions exhibit characteristic ring-like L-TEM contrast arising from their closed spin structure with a pronounced out-of-plane core. By contrast, type-II magnetic bubbles display a distinct half-black/half-white contrast due to the presence of two Bloch lines (indicated by red arrows), which is clearly different from the ring-like features observed experimentally. Based on these comparisons, we identify the experimentally observed ring-like contrast as originating from dipolar skyrmions.

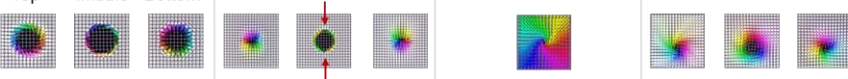
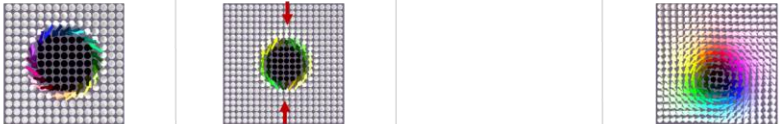
Centrosymmetric magnets (without bulk DMI)				Chiral magnets (with bulk DMI)
a	Dipolar skyrmion	Type- II bubble	Dipolar surface twist (DST)	Chiral skyrmion
				
b	Top Middle Bottom			
				
c				
				
d				
				
e	Mn ₄ Ga ₂ Sn; (Mn _{0.55} Ni _{0.45}) ₆₅ Ga ₃₅	Mn ₄ Ga ₂ Sn; Fe ₃ Sn ₂	Fe ₃ GaTe ₂ (This work)	FeGe; CoZnMn

Fig. R14 Simulated Lorentz TEM contrast for different magnetic structures. **a** Schematic three-dimensional spin configuration of representative magnetic textures, including dipolar skyrmions, type-II bubbles, DSTs, and chiral skyrmions. **b** Corresponding magnetic configurations at the top, middle, and bottom layers. **c** Enlarged views of the magnetic configurations at the middle layer, highlighting the characteristic in-plane spin arrangements. **d** Simulated L-TEM contrast of the corresponding magnetic structures. **e** Representative material systems in which these magnetic structures are typically stabilized.

Regarding the dot-like contrast features, we attribute these to DSTs rather than skyrmions. In magnetic systems such as Fe_3GaTe_2 , skyrmions generally exhibit ring-like contrast due to the absence of strong bulk DMI. Although dot-like contrast is commonly associated with skyrmions in chiral magnets with strong bulk DMI, such as FeGe or CoZnMn , this contrast mechanism is not applicable to the present system. Instead, the experimentally observed solid black/white dot-like contrasts are fully consistent with the simulated L-TEM signatures of DSTs.

In our original manuscript, the distinction between dipolar skyrmions and DSTs based on their L-TEM contrast has already been discussed, as shown below:

“Correspondingly, their simulated L-TEM images and line profiles (Fig. 1g–h, k–l) exhibit solid black or white contrasts, resembling chiral skyrmion strings in DMI-

stabilized magnets but distinct from the conventional ring-like signatures of dipolar skyrmion strings in centrosymmetric crystals. This distinction enables direct identification of spin textures in dipolar systems: ring-like contrasts indicate skyrmion strings, whereas solid black or white dots correspond to DSTs with opposite helicities.” (Lines 122-128)

To further clarify why the observed features are identified as skyrmions rather than magnetic bubbles, we have added the following discussion in the revised manuscript (page 7):

“Note that trivial magnetic bubbles in centrosymmetric systems typically exhibit a characteristic half-black/half-white contrast due to the presence of Bloch lines, which is clearly distinct from the ring-like features observed here (Supplementary Fig. 3).” (Lines 117-119)

6) L. 115 and Fig. 1j: Please explain why the L-TEM contrast of the DSTs does not cancel out upon projection through the sample thickness. Additional discussion or simulation results would help to clarify this point.

Response: We thank the reviewer for this insightful comment. In general, complete cancellation of the L-TEM contrast upon projection through the sample thickness would require the in-plane magnetization at the top and bottom surfaces to be both strictly antiparallel and laterally aligned. However, neither condition is satisfied for the DSTs observed here, as illustrated in Fig. R15 and Fig. R16.

Because DSTs are surface-localized magnetic states, they can form independently at the top and bottom surfaces of the magnetic texture without strict lateral correlation across the thickness. In addition, the corresponding surface spin configurations are not necessarily exact opposites in helicity or in-plane magnetization. Consequently, the projected in-plane magnetic induction remains finite, giving rise to observable L-TEM contrast rather than complete cancellation. This behavior is further supported by our micromagnetic simulations.

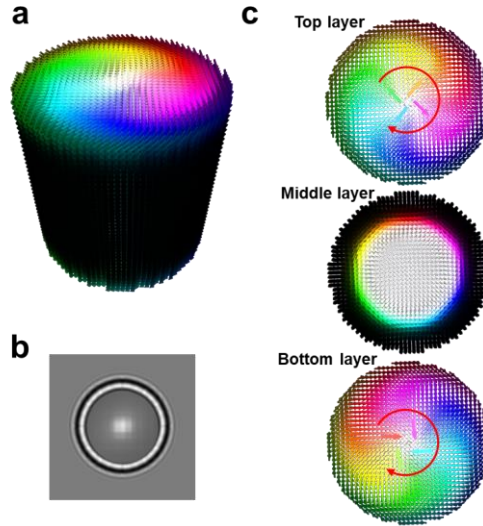


Fig. R15 Simulated three-dimensional (3D) spin configurations (a) and L-TEM image (b) of DSTs on the surface of a skyrmion string. **c** Spin configurations at top, middle and bottom layer. For clarity, the magnetization directions are indicated by four distinct color-coded arrows. Notably, both the top and bottom layers exhibit a clockwise rotational component, as highlighted by the red arrows.

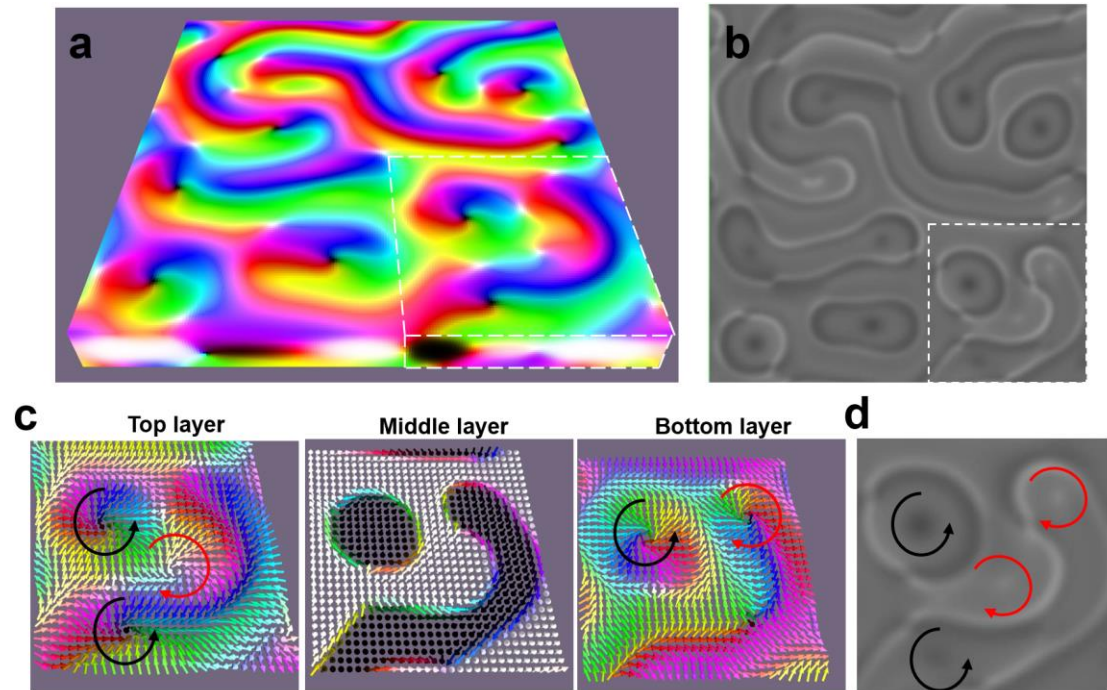


Fig. R16 Simulated three-dimensional (3D) spin configurations (a) and L-TEM image (b) of DSTs on the surface of stripe domains. (c–d) Enlarged views of the regions marked in (a–b), displaying spin configurations at different depths (top, middle, and

bottom) together with the corresponding simulated L-TEM contrasts. The DSTs are denoted by black and red arrows, indicating anticlockwise and clockwise helicities, respectively.

To clarify this point, we have added additional discussion in the revised manuscript.

“Owing to their surface-localized nature, the L-TEM contrast of DSTs does not cancel upon projection through the sample thickness, as the spin configurations at the top and bottom surfaces do not simultaneously satisfy both lateral alignment and opposite helicity, resulting in a finite projected in-plane magnetization (Supplementary Fig. 4).” (Lines 130-134)

7) L. 145: What is the influence of Ga implantation and surface damage from focused ion beam (FIB) preparation on the formation and stability of the DSTs? This issue should be discussed, given the surface-sensitive nature of the reported states.

Response: We thank the reviewer for raising this important point regarding the potential influence of Ga implantation and surface damage associated with FIB preparation. We agree that a certain degree of surface modification and Ga implantation is generally unavoidable during FIB milling. Therefore, in the present work, additional low-energy polishing (5 kV, 10 pA) was performed to minimize surface damage and implantation effects.

To examine whether FIB-related effects are responsible for the formation or stability of the DSTs, (i) we carried out control experiments on several other layered magnetic materials, including Fe_5GeTe_2 , and $\text{Cr}_{1.9}\text{Te}_2$, prepared under the same FIB conditions. As shown in Fig. R17a, no DST-like contrast is observed in these systems, indicating that FIB-induced damage or Ga implantation alone does not lead to the formation of such states. (ii) Furthermore, micromagnetic simulations (Fig. R16b) indicate that the formation and stability of DSTs are primarily governed by the magnetic quality factor, without requiring additional contributions from FIB-induced effects. (iii) Further support comes from a recent experimental study reporting related surface-localized magnetic bobbles in bulk Fe_3GaTe_2 samples prepared without FIB processing [*Phys. Rev. X* **15**, 021032 (2025)] (Fig. R16c), further supporting the intrinsic origin of these surface twist states.

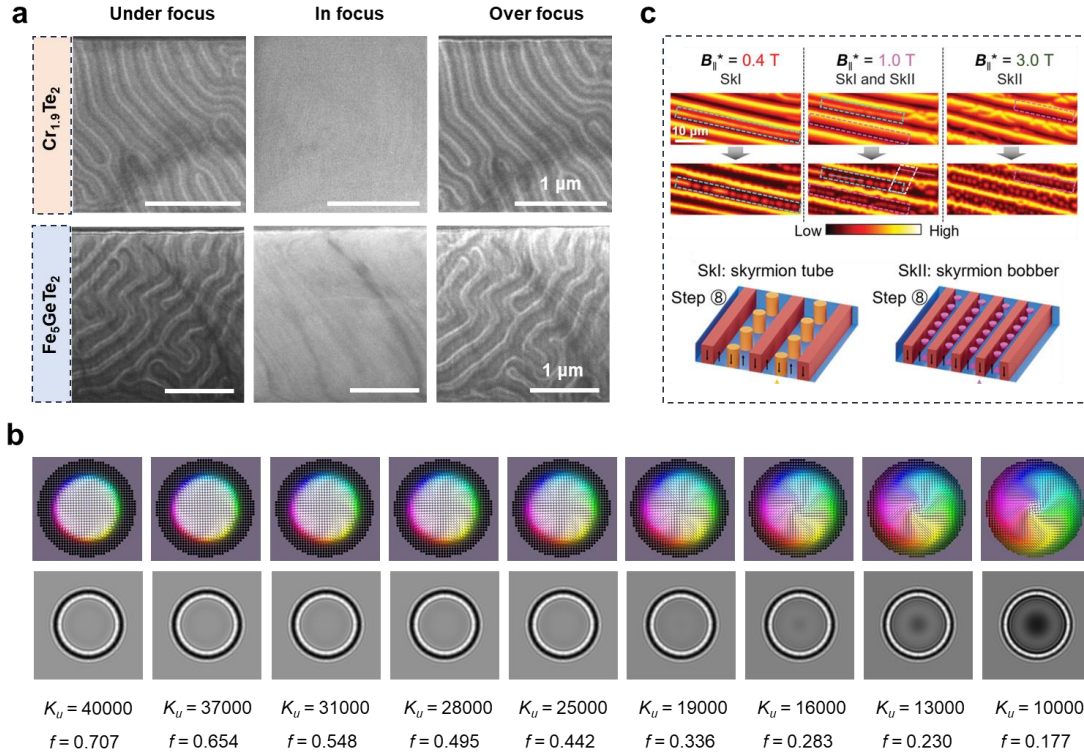


Fig. R17 a Defocused Lorentz TEM images of magnetic domains in $\text{Cr}_{1.9}\text{Te}_2$ and Fe_5GeTe_2 at zero magnetic field. **b** Magnetic quality factor (f)-dependent spin configurations in the top layer and the corresponding simulated L-TEM images. **c** Magnetic domains induced by different magnetic fields, revealing two distinct skyrmion formation mechanisms. Reproduced from [*Phys. Rev. X* **15**, 021032 (2025)]

These results collectively indicate that the formation and stability of DSTs originate primarily from the intrinsic magnetic properties of Fe_3GaTe_2 , rather than from Ga implantation or FIB-induced surface damage. At the same time, we acknowledge that preparation-induced defects may locally influence the current-driven dynamics of DSTs by introducing additional pinning sites. To clarify this point, we have added the following discussion to the revised Supplementary information:

“Micromagnetic simulations show that the formation of DSTs is governed primarily by the intrinsic magnetic properties of the material, particularly its low magnetic quality factor. Although Ga implantation and FIB-induced surface damage are unlikely to play a dominant role in their nucleation, such defects may locally influence the current-driven dynamics and stability of DSTs through additional pinning effects.”

8) L. 161: It should be clarified that transport-of-intensity equation (TIE) analysis allows only for a qualitative reconstruction of the projected in-plane magnetic induction, not the magnetization itself.

Response: We thank the reviewer for this important clarification. We agree that transport-of-intensity equation (TIE) analysis provides a qualitative reconstruction of the projected in-plane magnetic induction rather than the magnetization itself. In the revised manuscript, we have corrected the relevant descriptions in the revised manuscript as follows:

“To elucidate the underlying spin structures of these skyrmion-like dots, transport-of-intensity equation (TIE) analysis³⁶ was performed using the QPT software (Fig. 2d), providing a qualitative reconstruction of the projected in-plane magnetic induction.” (Lines 172-174)

9) L. 201–203: The L-TEM tilt series is performed only for the thinnest sample. Please justify this choice. Additional tilt experiments on thicker samples would significantly strengthen the interpretation of the three-dimensional magnetic structure.

Response: We thank the reviewer for this helpful comment. We first clarify that the primary purpose of the L-TEM tilt series in this work is to identify the domain configurations (i.e., Bloch- or Néel-type), rather than to directly determine the three-dimensional magnetic structure. As stated in the original manuscript (lines 185–187), “*analysis of the magnetic contrasts under different imaging conditions have been proved to be essential and useful to recognize the domain configurations.*” By applying positive and negative sample tilts, we observe a systematic reversal of contrast in the stripe domains, which is a characteristic signature of Néel-type configurations.

We also agree that three-dimensional magnetic structures become more pronounced in thicker samples, and that tilt-series measurements could further support the interpretation of the underlying three-dimensional spin structures. However, direct reconstruction of the full three-dimensional magnetic configuration generally requires large tilt angles (typically $\geq \pm 50^\circ$), as used in “electron tomography” [*Commun. Mater.* **5**, 80 (2024)], which are beyond the present experimental conditions. Instead, we combined tilt-dependent L-TEM measurements with three-dimensional micromagnetic simulations, which consistently reproduce the experimental contrasts and support the

proposed spin configurations.

Following the reviewer's suggestion, we have now performed additional L-TEM tilt-series measurements on thicker FGT samples (80, 102, and 130 nm) over a range of tilt angles ($\pm 15^\circ$, $\pm 10^\circ$, $\pm 5^\circ$, and 0°), as shown in Figs. R17–R18. The results consistently demonstrate that, for all thicknesses, the stripe-domain contrast reverses under opposite tilt angles, further confirming their Néel-type configurations. These additional data have now been incorporated into the revised Supplementary Information.

“Clearly, increasing α enhances the contrast of stripe domains, with high-density DSTs embedded within, while the contrasts are completely reversed at opposite tilt angles, a characteristic feature of Néel-type configurations (Supplementary Fig. 9-S10).” (Lines 203-205)

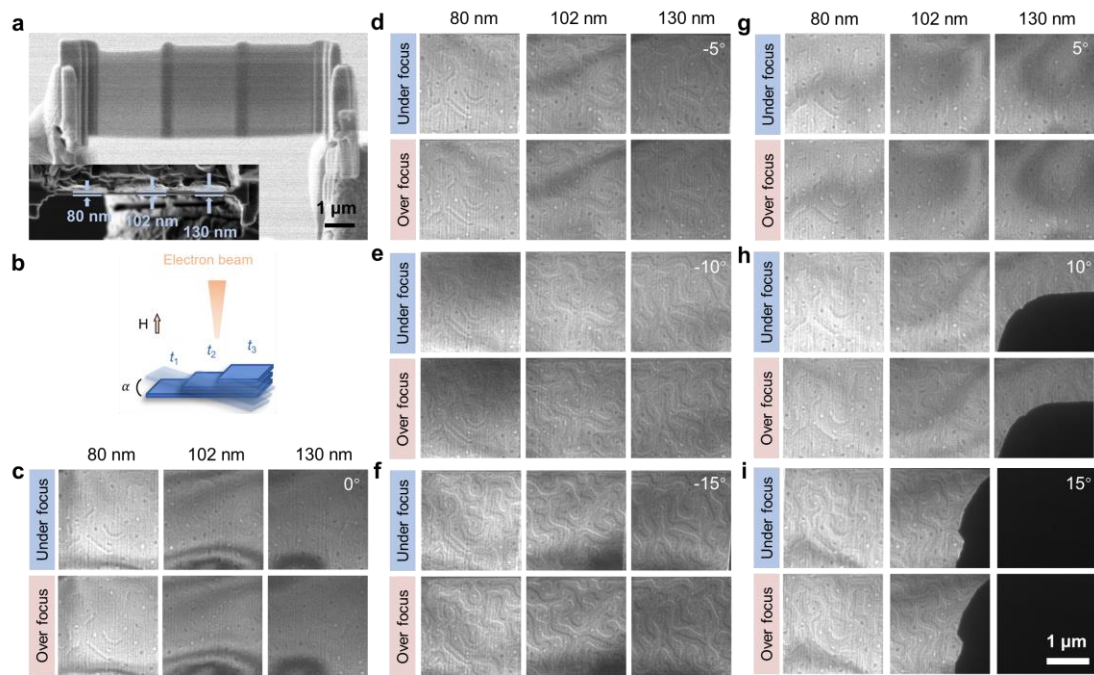


Fig. R18 Thickness- and tilt-dependent L-TEM contrast of magnetic domains. **a** Cross-sectional SEM image with an inset (bottom left) showing the corresponding top-view image, highlighting three regions with thicknesses of 80, 102 and 130 nm. **b**, Schematic illustration of sample tilting for L-TEM imaging. **c–i**, L-TEM images of samples with different thicknesses acquired at various tilt angles; upper and lower panels correspond to under-focused and over-focused conditions, respectively. The dark regions in **h–i** arise from Pt shadowing during sample tilting.

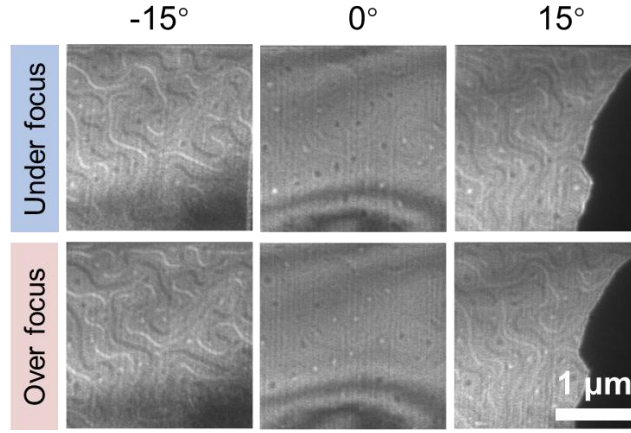


Fig. R19 Representative L-TEM images of a 102 nm-thick region at 0° and ±15° tilt, showing a systematic reversal of contrast in the stripe domains, characteristic of Néel-type configurations.

10) L. 304: The scintillating mode is presented as a major result of the manuscript; however, there is little physical discussion of the underlying mechanism. In particular, the role of pinning effects (also relevant for the dynamics of the DFTs) related to surface damage and curtaining in the TEM lamella should be addressed in more detail.

Response: We thank the reviewer for recognizing the importance of the scintillating mode and for the insightful comment regarding its physical origin. We agree that pinning effects are essential for understanding the current-driven dynamics of DSTs.

We first clarify that the formation of DSTs is governed primarily by the intrinsic magnetic properties of the material rather than by FIB-induced surface damage or curtaining artifacts (see response to Comment 7). Nevertheless, FIB preparation inevitably introduces a certain degree of surface disorder and defects, which may serve as additional pinning centers and influence the current-driven dynamics of DSTs.

To further clarify the mechanism underlying the scintillating behavior, we performed systematic micromagnetic simulations with different pinning strengths ($K_{pinning} = 2K_u$, $5K_u$, $7.5K_u$, and $10K_u$, where K_u is the magnetic anisotropy constant), as shown in Figs. R20-24. In all simulations, a current pulse was applied for 1 ns and subsequently removed to allow relaxation into a stable state. The simulations reveal a pronounced

dependence of the DST dynamics on the pinning strength. Under weak pinning conditions (e.g., $K_{\text{pinning}} = 2K_u$), DSTs readily depin and predominantly undergo translational motion, eventually annihilating without helicity reversal. This behavior indicates that rigid displacement constitutes the energetically preferred relaxation pathway when pinning is insufficient to constrain the texture. By contrast, stronger pinning ($K_{\text{pinning}} \geq 5K_u$) suppresses translational motion and instead promotes localized reconstruction of the spin texture. In this regime, the injected spin-transfer torque drives substantial deformation of the DST, resulting in helicity reversal through transient reconstruction of the spin configuration. The reversed-helicity state can remain stable after relaxation. Such helicity reversal occurs only when the spin torque exceeds the energy barrier associated with this reconstruction process; otherwise, the original helicity is recovered after removal of the current (Fig. R24).

These results indicate that the experimentally observed scintillating dynamics originate from the competition between spin-transfer torque and pinning effects. Weak pinning favors translational motion, whereas stronger pinning suppresses rigid displacement and instead drives transient reconstruction of the DST spin texture, giving rise to helicity reversal and the observed scintillating contrast.

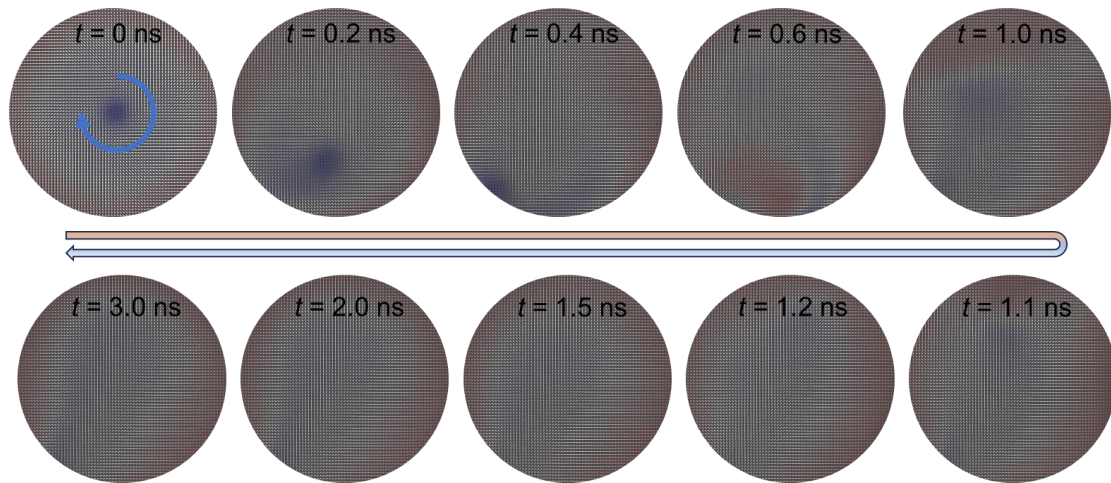


Fig. R20 Simulated current-induced dynamics of DSTs with $K_{\text{pinning}} = 2K_u$ at $j = 8 \times 10^{11} \text{ A/m}^2$.

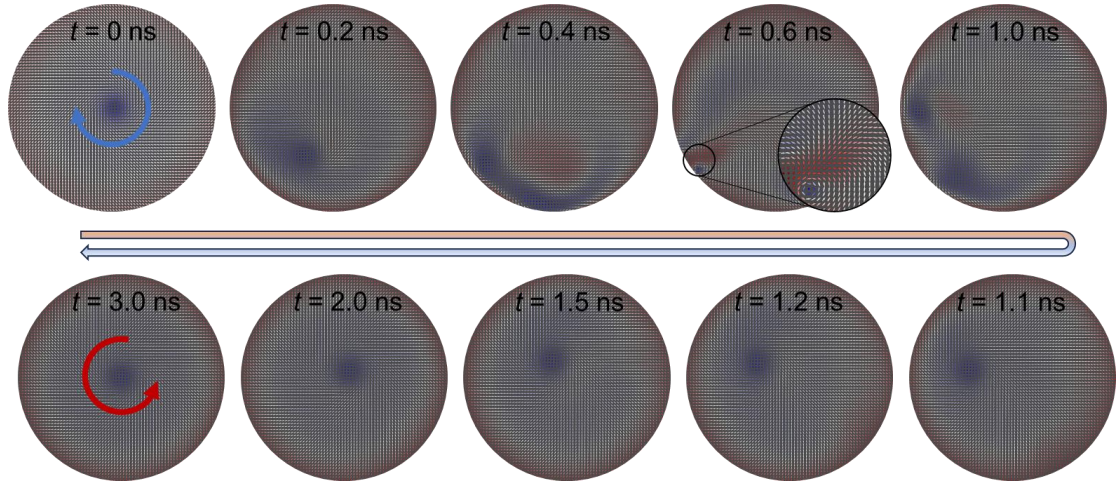


Fig. R21 Simulated current-induced dynamics of DSTs with $K_{\text{pinning}} = 5K_u$ at $j = 8 \times 10^{11} \text{ A/m}^2$.

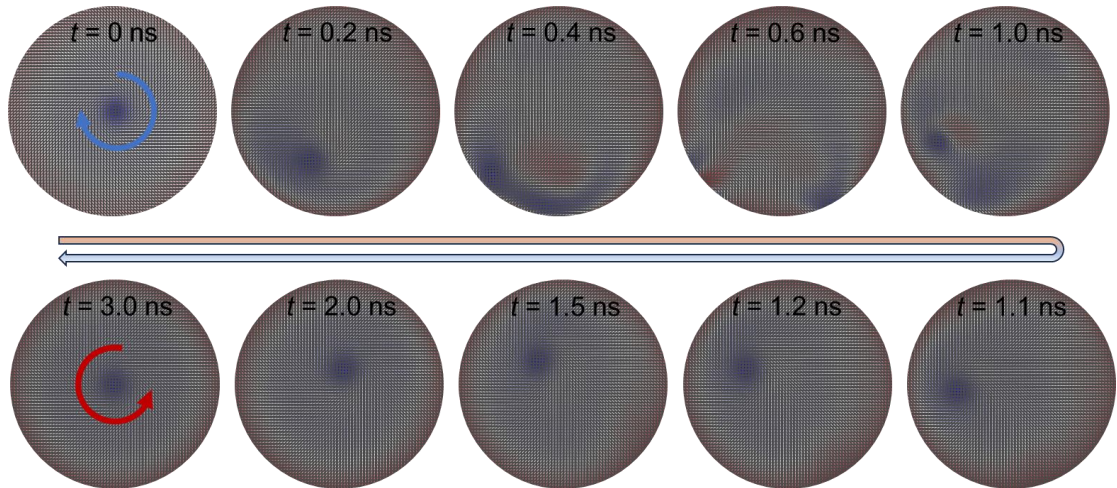


Fig. R22 Simulated current-induced dynamics of DSTs with $K_{\text{pinning}} = 7.5K_u$ at $j = 8 \times 10^{11} \text{ A/m}^2$.

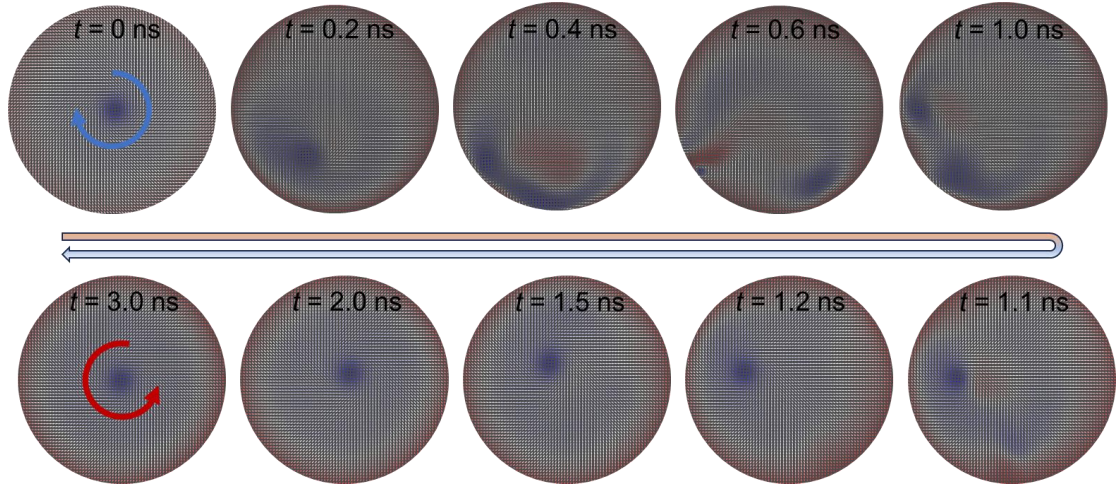


Fig. R23 Simulated current-induced dynamics of DSTs with $K_{\text{pinning}} = 10K_u$ at $j = 8 \times 10^{11} \text{ A/m}^2$.

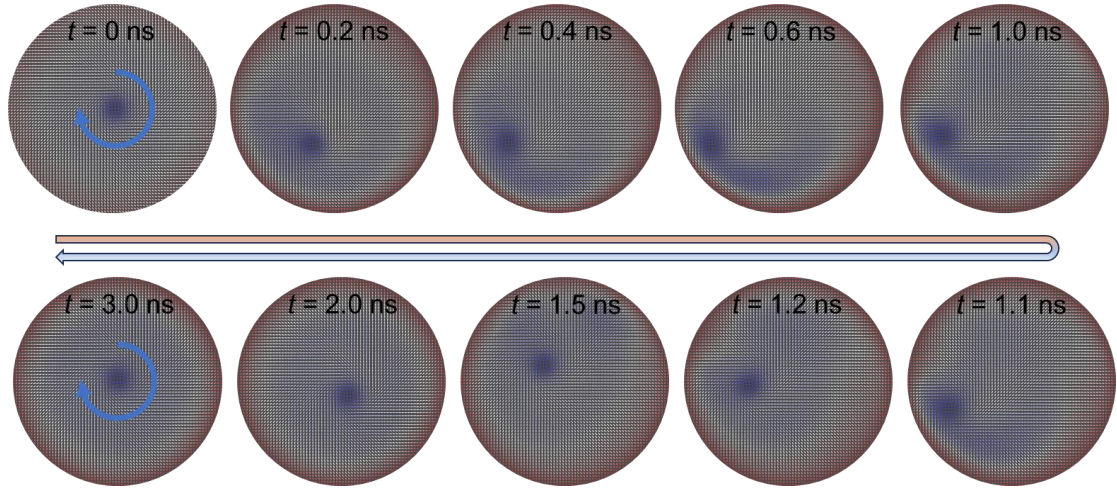


Fig. R24 Simulated current-induced dynamics of DSTs with $K_{\text{pinning}} = 10K_u$ at $j = 5.6 \times 10^{11} \text{ A/m}^2$.

In the revised manuscript, we have updated Fig. 5 and expanded the discussion of the scintillating dynamics to clarify the underlying physical mechanism and explicitly address the role of pinning effects, as shown below:

“To further elucidate the origin of the observed dynamics, we performed micromagnetic simulations of a confined DST using the material parameters of FGT. In addition to the STT effect, pinning potentials with different strengths ($K_{\text{pinning}} = 2K_u$, $5K_u$, $7.5K_u$, and $10K_u$, where K_u is the magnetic anisotropy constant) were introduced,

while the external magnetic field was set to zero to match the experimental conditions. A current pulse was applied for 1 ns and subsequently removed to allow relaxation into a stable state. These results reveal a pronounced dependence of the DST dynamics on the pinning strength. Under weak pinning conditions ($K_{\text{pinning}} = 2K_u$), DSTs readily depin and predominantly undergo translational motion, indicating that rigid displacement constitutes the preferred relaxation pathway (Fig. 5g). By contrast, stronger pinning ($K_{\text{pinning}} \geq 5K_u$) suppresses translational motion and instead promotes localized reconstruction of the spin texture (Fig. 5h and Supplementary Fig. 24-25). In this regime, the injected spin torque drives pronounced deformation of the DST, resulting in helicity reversal through transient reconstruction of the spin configuration. These reconstruction processes are accompanied by the formation of additional topological defects,^{15,48} where the local magnetization becomes highly nonuniform (see enlarged region in Fig. 5h), leading to a significant increase in exchange energy. Such defects are also central to skyrmion–antiskyrmion–bubble transitions reported in chiral magnets with anisotropic DMI.^{49,50}” (Lines 356-370)

“In addition, helicity reversal occurs only when the injected spin torque exceeds the energy barrier associated with this reconstruction process; otherwise, the original helicity state recovers after removal of the current (Supplementary Fig. 26). Possible sources of pinning include intrinsic crystal defects, such as atomic vacancies, as well as extrinsic disorder introduced during FIB fabrication.” (Lines 376-381)

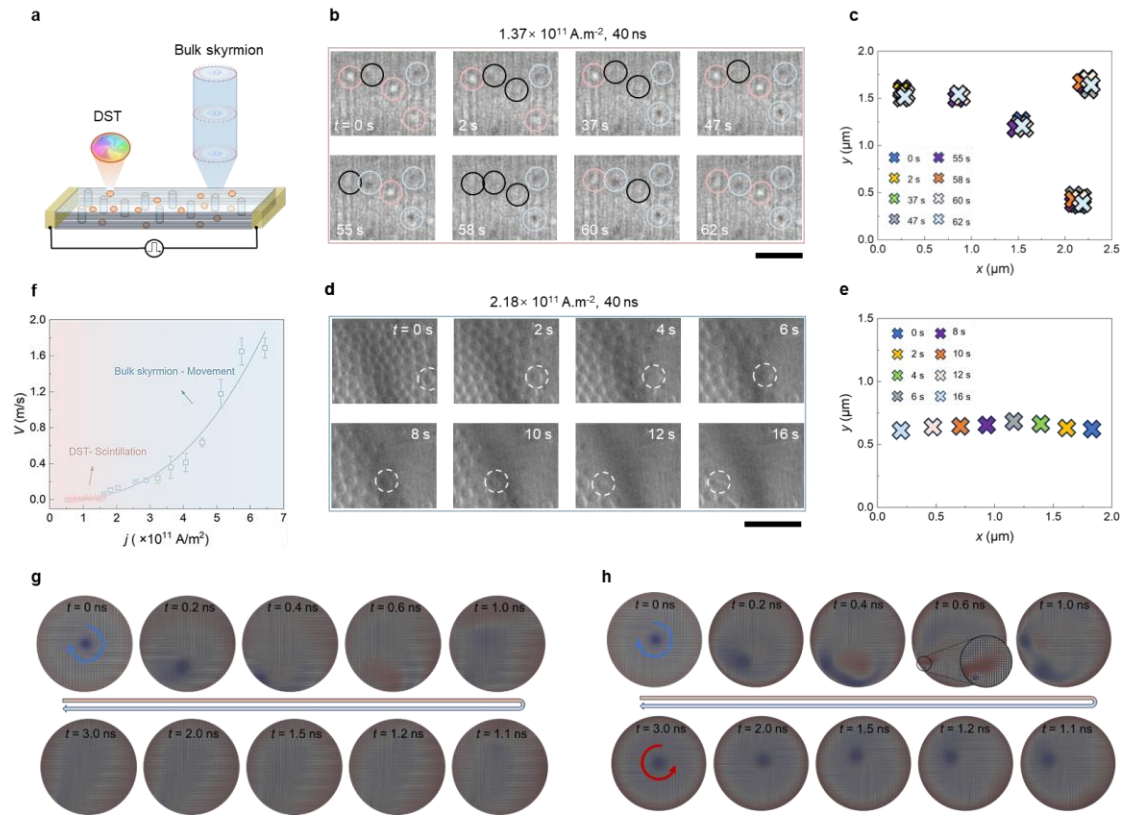


Fig. 5 | Two distinct current-driven dynamic behaviors at room temperature. **a** Schematic illustration of DSTs and bulk skyrmion driven along a track by an electric current. **b** Over-focused L-TEM snapshots of several DSTs recorded over a total duration of 62 s under current at 0° tilt and zero magnetic field. Five boxed regions highlight representative behaviors: blue and pink boxes correspond to clockwise and counter-clockwise DSTs, while black indicates their absence. **c** Summary of the dynamic behaviors of the five target regions in **b**. **d** Over-focused L-TEM snapshots of the bulk skyrmion lattice recorded over a total duration of 16 s under current at 15° tilt and zero magnetic field. A single bulk skyrmion, marked by a white dashed circle, is tracked. **e** Trajectory of the bulk skyrmion in **d**. **f** Average velocity of DSTs and bulk skyrmions as a function of current density. Error bars represent the standard deviation from five independent measurements. **g-h** Simulated snapshots of STT-induced dynamics at the top surface showing annihilation **g** and helicity switching **h** of a DST. The pinning strengths are $K_{\text{pinning}} = 2 K_u$ for **g** and $5 K_u$ for **h**, respectively. The scale bars in **b** and **d** are $1 \mu\text{m}$.

Once again, we would like to thank the reviewers for their time spent preparing their valuable feedback on our work. We hope that our responses to their comments and updates to the manuscript and well received.

Point-by-point responses and revisions in response to reviewer comments:

Reviewer #1 (Remarks to the Author):

(1) I examined the responses to comments raised by three reviewers.

I first raised the question of why bright and dark dots are ascribed to topological surface twists. The authors reply by saying, “the identification of surface-localized twists relies on the combined analysis of L-TEM observations and micromagnetic simulations.” I would like to note that Figure 1b shows that an unconventional skyrmion string for $f=0.23$ would appear as faint circles, originating from the surface twist, inside clear dark and bright concentric circles due to the Bloch wall in the bulk. The micromagnetic simulation in Fig. 1m demonstrates maze domains and perhaps some surface twists. I guess that also in such a case, the corresponding L-TEM image would comprise clear stripes accompanying some blurred small dots. In their L-TEM observations, well-arranged 180-degree stripes (but not mazed stripes) and some large and clear dots are found. The contrast of dots is even clearer than that of stripes. These results would cast doubt on the validity of their surface-twist model.

Response: We thank the reviewer for the careful comparison between the simulated and experimental L-TEM contrasts. We would like to clarify two points regarding the domain morphology and the relative contrast of the dot-like objects and stripe domains.

First, the stripe domains observed in our L-TEM experiments are more appropriately classified as maze-like or labyrinthine stripe domains rather than well-aligned 180° stripe domains. As summarized in Fig. R1a, similar disordered stripe-domain morphologies have been reported in previous studies and are commonly described as labyrinthine or maze-like stripes. The L-TEM images in the present work show the same disordered stripe arrangement, supporting this assignment. By contrast, 180° stripe domains, as shown in Fig. R1b, refer to ordered stripe states with nearly parallel domain walls. Most importantly, such ordered 180° stripes generally require an in-plane magnetic field or an additional in-plane anisotropy to select a preferred stripe orientation. For magnets with perpendicular magnetic anisotropy, the absence of an in-plane symmetry-breaking field naturally leads to maze-like stripe patterns rather than uniformly aligned stripes. Therefore, the stripe domains observed in our samples

are distinct from ordered 180° stripe domains and are more accurately described as maze-like stripe domains.

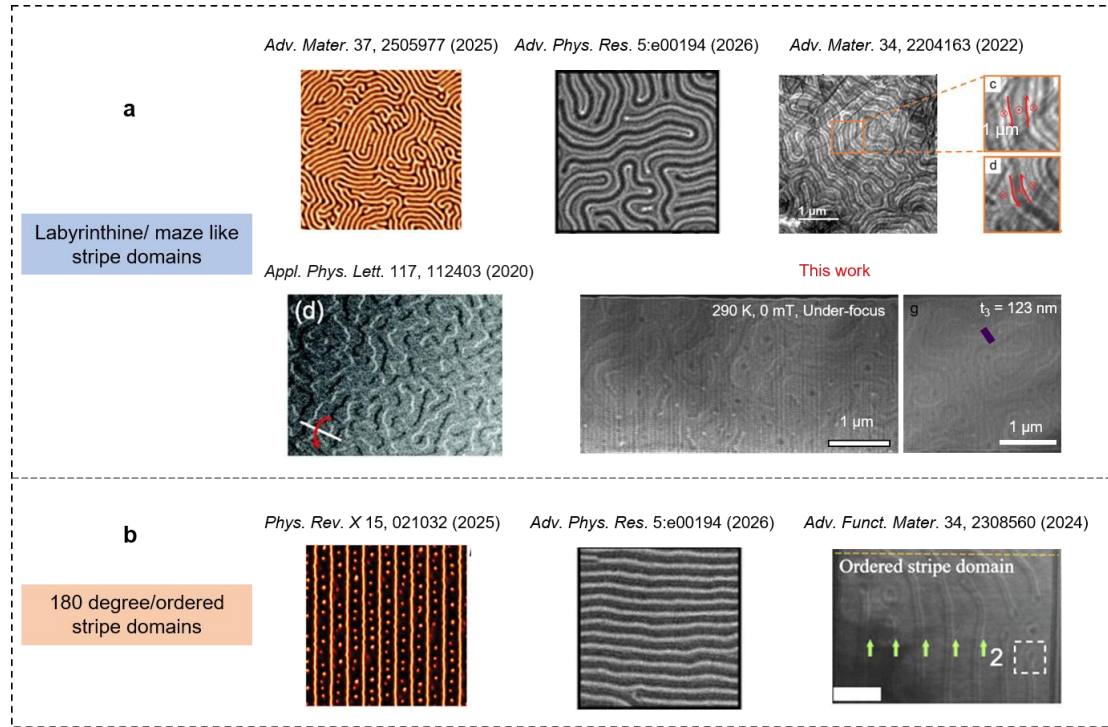


Fig. R1 | Comparison of contrast features between maze-like and ordered 180° stripes. **a** Representative labyrinthine, or maze-like, stripe domains reported in previous studies. **b** Representative ordered 180° stripe domains reported in previous studies. The literature source of each image is indicated above the corresponding panel. The stripe-domain contrast observed in the present work is consistent with labyrinthine stripe domains and is distinct from ordered 180° stripes.

Second, the more pronounced dot-like contrast relative to the stripe-domain contrast does not contradict the surface-twist model, but it can be understood from two aspects of L-TEM contrast: thickness- and tilt-dependent nature. (i) In thin lamellae, the large surface-to-volume ratio enhances the projected contribution from surface twists, giving rise to clear solid black/white dot-like contrast. As the thickness increases, the bulk magnetic contribution becomes more dominant, leading to enhanced stripe-domain contrast and reduced relative visibility of the surface dots. This thickness-dependent evolution is reproduced in our experiments (Fig. R2b, upper panel) and is consistent with the behavior of surface-localized states reported in antiskyrmion systems (Fig. R2a) [*Nat. Mater.* **20**, 335-340 (2021)]. (ii) The tilt-dependent contrast further supports this assignment. At normal incidence, the stripe-domain contrast is relatively weak because the effective interfacial-type DMI favors Bloch–Néel hybrid

domain walls, whose Néel-type components contribute only weakly to L-TEM contrast without sample tilt. Upon tilting, the stripe-domain contrast is strongly enhanced, whereas the solid dot-like contrast remains nearly unchanged (Fig. R2b, lower panel).

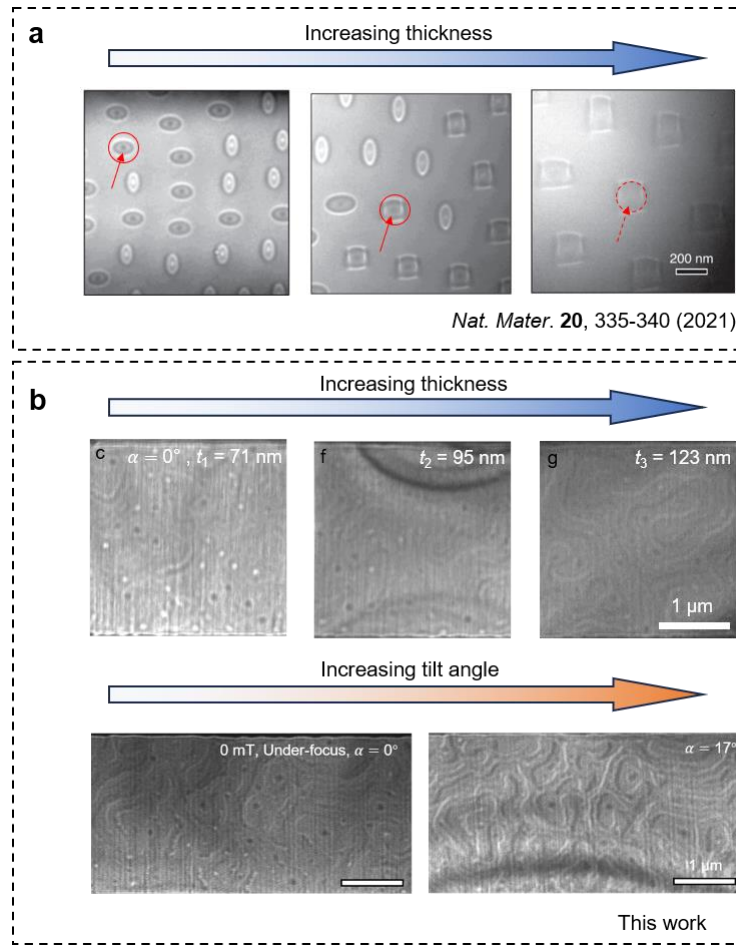


Fig. R2 | Thickness- and tilt-dependent contrast evolution of surface dots and stripe domains. **a** Thickness-dependent evolution of surface-localized magnetic states reported in an antiskyrmion system [*Nat. Mater.* 20, 335–340 (2021)]. The relative visibility of the surface-dot contrast decreases rapidly with increasing sample thickness, as indicated by the red circles and arrows. **b** Thickness- and tilt-dependent L-TEM observations in the present FGT sample. The upper panels show that increasing thickness enhances the stripe-domain contrast while reducing the relative visibility of the dot-like features. The lower panels show that sample tilting strongly enhances the stripe-domain contrast, whereas the solid dot-like contrast remains nearly unchanged.

Therefore, the different contrast evolutions of the dot-like features and stripe domains provide experimental evidence that they originate from distinct magnetic contributions, corresponding to surface-localized twists (DSTs) and bulk stripe domains, respectively. Accordingly, increasing sample thickness strengthens the bulk stripe-domain contrast while reducing the relative visibility of the surface-dot contrast.

This trend is directly observed in an approximately 150-nm-thick FGT lamella (Fig. R3), where the DST contrast is weaker than the bulk magnetic contrast. The corresponding line profile further demonstrates the reduced relative DST contrast, supporting its surface localization.

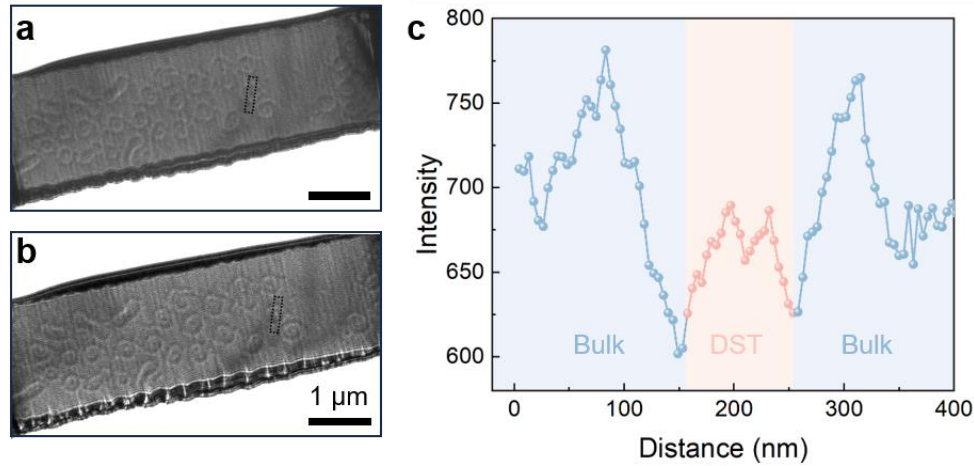


Fig. R3 | Reduced relative DST contrast in a thicker FGT lamella. **a,b** Under- and over-focused L-TEM images acquired at room temperature from an approximately 150-nm-thick FGT lamella. **c** Intensity line profile across an individual DST and a bulk magnetic texture, showing weaker DST contrast. The reduced relative contrast is consistent with the surface localization of DSTs.

(2) I also made some comments on micromagnetic simulation. First, I am glad to say that I am satisfied with their reply to the comment on the anisotropy in exchange. On the other hand, I still have a concern about DM interaction. Although they mention that the term is corrected, it seems that the simulation result is unchanged. I also wonder if they introduce the spatial dependence of the parameter D . The sign of D should be opposite on the top and back surfaces.

Response: We thank the reviewer for raising this important point. The discrepancy was confined to the written expression of the DMI energy in the original manuscript. In the MuMax3 calculations, DMI was implemented throughout using the “Dind” term, corresponding to an interfacial-type DMI functional. Correcting the equation therefore did not change the numerical implementation or the resulting spin configurations.

We further clarify that the effective DMI considered here is not assumed to arise from the two external surfaces of the TEM lamella. In FGT, the effective DMI originates from layer-intrinsic inversion-symmetry breaking associated with Fe_{II} off-centering along the c -axis within each Fe_3GaTe_2 structural layer, as shown in Fig. R4.

To quantify this displacement, we integrated the atomic-resolution image intensity and extracted the corresponding line profile (Fig. R4b). Using the midpoint between the two neighboring Te atomic columns as the reference position, the Fe_{II} atomic column was found to be displaced by approximately 0.1 Å along the *c*-axis direction (Fig. R4c). This layer-intrinsic inversion-symmetry breaking provides the physical basis for the effective DMI used in our simulations, consistent with previous reports on Fe-off-centering-induced DMI in Fe-based van der Waals magnets [*Nat. Commun.* **15**, 4472 (2024); *Adv. Sci.* **10**, 2303443 (2023); *Nat. Commun.* **15**, 3278 (2024)]. Accordingly, we model the effective DMI as spatially uniform throughout the sample thickness, $D(z) = D_0$, using the “Dind” term in MuMax3.

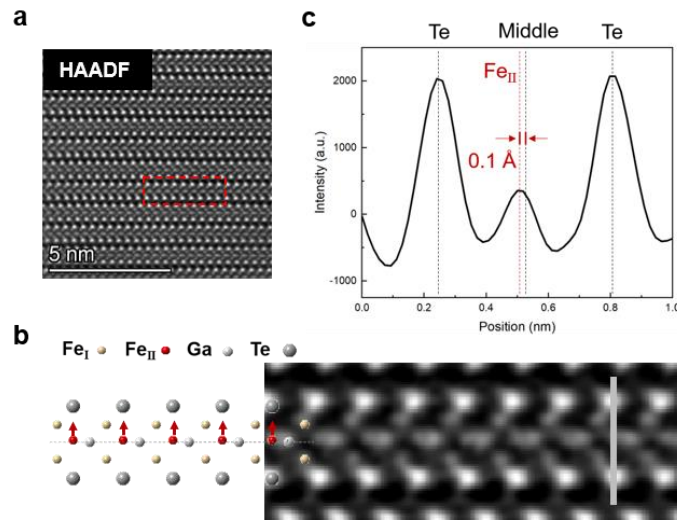


Fig. R4 | Quantification of Fe_{II} off-centering in FGT. **a** Atomic-resolution HAADF-STEM image of FGT showing the atomic stacking along the *c*-axis direction. The red dashed box marks the region selected for analysis. **b** Enlarged HAADF-STEM image and corresponding atomic structural model showing Fe_{II} off-centering along the *c*-axis. **c** Intensity line profile extracted from **b**. Taking the midpoint between the two neighboring Te atomic columns as the reference, the Fe_{II} atomic column is displaced by approximately 0.1 Å along the *c*-axis direction.

For better clarity, we have added this atomic-scale structural characterization to Supplementary Fig. 12 and revised the corresponding discussion in the main text as follows:

“The DMI is attributed to inversion-symmetry breaking associated with the approximately 0.1 Å off-centering of Fe_{II} atoms observed by atomic-resolution HAADF-STEM (Supplementary Fig. 12), consistent with recent reports^{32,40}.” (please see: page 8, lines 211-214)

(3) Reviewer 2 raised some concerns about possible thermal effect on the observed current-driven dynamics. Although I am not fully convinced that their reply addressed the issue, I approve their efforts.

Response: We thank the reviewer for acknowledging our efforts. We have further refined the discussion to state this point more cautiously. While Joule heating may assist thermal activation, the available experimental and simulation results indicate that it is unlikely to be the primary origin of the observed scintillating dynamics.

For better clarity, we have revised the description:

“This is supported by finite-element simulations showing that the sample temperature remains below T_c during current-pulse injection (Supplementary Fig. 29a), together with temperature-dependent L-TEM measurements and finite-temperature micromagnetic simulations confirming the thermal stability of the DSTs at elevated temperatures (Supplementary Fig. 29b–c). In these temperature-dependent L-TEM measurements, heating weakens the DST contrast but does not induce contrast reversal. Thus, Joule heating alone cannot account for the scintillating dynamics, which instead originate mainly from spin-transfer torque acting within a local pinning landscape, although thermal effects may assist the process by lowering local energy barriers.” (please see: page 13, lines 389-398)

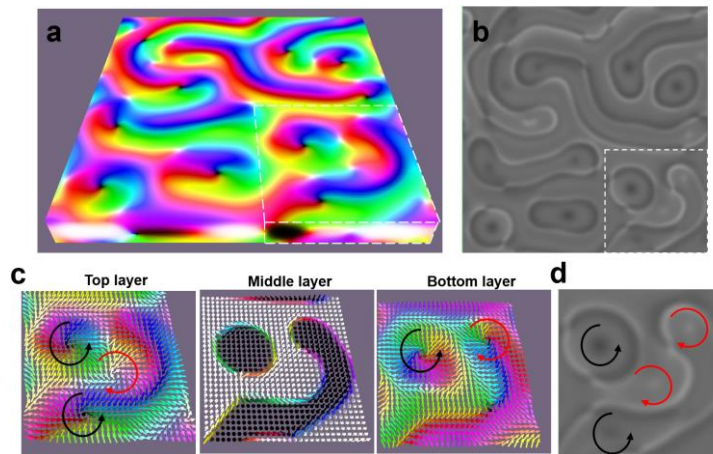
(4) Reviewer 3 cast doubt about the novelty and impact of the present work for the broad readership. The authors claim that the present work has three new aspects, one of which is “Focus on dynamics and decoupled surface–bulk behavior.” It is hence essential to decouple the surface contribution from the bulk magnetization distribution.

Response: We thank the reviewer for this important comment. We agree that the surface contribution should be clearly distinguished from the bulk magnetization background to support the claim of decoupled surface–bulk behavior. To address this point, we have revised both the main text and the Supplementary Information.

First, we added a clarification in the revised manuscript to explicitly state how the thickness- and tilt-dependent contrast evolutions separate the surface-twist contribution from the bulk stripe-domain background:

“Together, these thickness- and tilt-dependent contrast evolutions distinguish the DSTs contribution from the bulk stripe-domain background. The dot-like contrast is most visible when the relative surface contribution is enhanced, whereas the stripe-domain contrast is strengthened by increasing sample thickness and upon sample tilting.” (please see: page 8, lines 223–226)

Second, we revised the caption of Supplementary Fig. 4 to make the depth-resolved surface–bulk separation more explicit, as shown below. Supplementary Fig. 4 shows the simulated spin configurations at the top surface, middle layer, and bottom surface, together with the corresponding simulated L-TEM contrasts. The surface layers contain localized DSTs and reproduce the solid dot-like contrast, whereas the middle layer mainly represents the bulk stripe-domain background. This directly clarifies how the surface-localized DST contribution is distinguished from the bulk magnetization distribution.



Supplementary Fig. 4 | Depth-resolved separation of surface DSTs and bulk stripe domains. **a** Simulated three-dimensional spin configurations of DSTs on the surfaces of stripe domains. **b** Corresponding simulated L-TEM image. **c,d** Enlarged views of the marked regions in **a,b** showing the spin configurations at the top surface, middle layer, and bottom surface, together with the corresponding simulated L-TEM contrasts. The surface layers contain localized DSTs and give rise to the solid dot-like contrast, whereas the middle layer mainly represents the bulk stripe-domain background. Black and red arrows denote DSTs with anticlockwise and clockwise helicities, respectively.

These results distinguish the dot-like contrast of surface-localized DSTs from the bulk stripe-domain background. Together with the current-driven dynamics shown in Fig. 5, where surface DSTs exhibit localized scintillation whereas bulk magnetic textures undergo ordered translational motion, they establish both static and dynamic

surface–bulk decoupling.

(5) *In conclusion, the authors should reproduce the coexistence of bulk 180-degree stripe domains and surface twists by micromagnetic simulation and compared to the experimentally obtained L-TEM images.*

Response: We thank the reviewer for this important comment and suggestion. As clarified above, the experimentally observed bulk domains are maze-like stripe domains rather than ordered 180° stripes. To further assess the consistency between simulation and experiment, we directly compared the relative L-TEM contrast of DSTs and bulk stripe domains. As shown in Fig. R5, both the simulated and experimental intensity profiles show weaker DST contrast than the surrounding bulk stripe-domain contrast. The experimental comparison was obtained from an approximately 150-nm-thick FGT lamella, in which the bulk contribution is enhanced relative to the surface contribution because of the various magnetic interaction and coupling effect. By contrast, the thinner lamellae used in the main experiments enhance the relative surface contribution and reduce masking by the bulk stripe-domain background. Together with the thickness- and tilt-dependent L-TEM measurements, these results support the surface localization of the DSTs and the proposed surface-twist model.

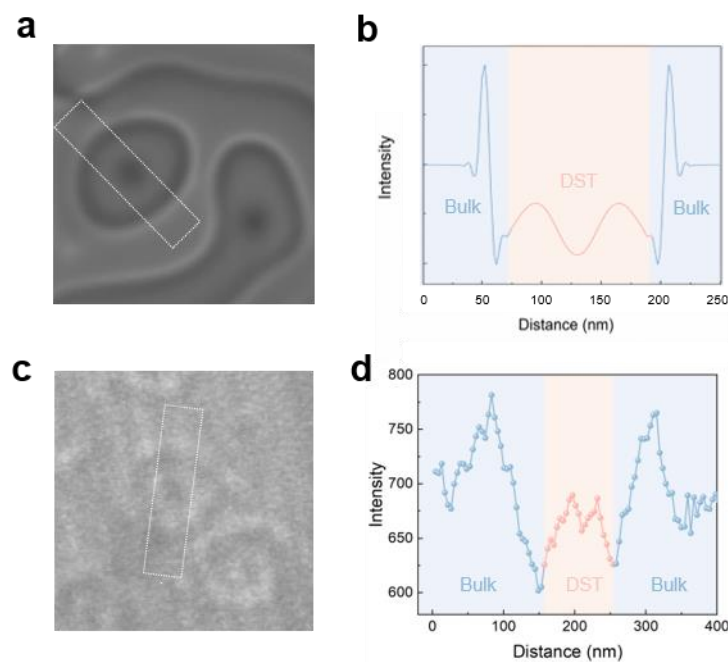


Fig. R5 | Comparison of DST and bulk domain contrast in simulated and experimental L-TEM images. a Simulated L-TEM image showing a DST

superimposed on the bulk domain background. **b** Intensity profile extracted from **a**, comparing the relative contrast of the DST and adjacent bulk domains. **c** Experimental L-TEM image acquired from an approximately 150-nm-thick FGT lamella. **d** Corresponding intensity profile extracted from **c**. In both the simulated and experimental images, the DST contrast is weaker than the bulk domain contrast.

Again, we thank again Reviewer #1 for the helpful comments, questions, and suggestions.

Reviewer #2 (Remarks to the Author):

The authors have sufficiently addressed my concerns. As it stands, I believe the results do achieve the novelty criteria required for Nature Communications, and the added detail to the phase simulations allow for the work to be reproduced (as well as ruling out several potential sources for misidentification). Therefore, I am comfortable recommending for publication.

Response: We sincerely thank the reviewer for the positive assessment and for recognizing the revisions made to address the previous concerns. We are grateful for the reviewer's recommendation for publication.

Reviewer #3 (Remarks to the Author):

I appreciate the significant effort made to address my comments and improve the manuscript. The study of dipolar surface twists (DSTs) in Fe_3GaTe_2 presents interesting results, particularly on the distinct dynamics of surface-localized topological states. However, certain critical aspects still require further clarification and experimental validation to meet the standards of Nature Communications. Below, I provide a detailed assessment of the revisions and remaining concerns.

Response: We thank the reviewer for the careful re-evaluation of our manuscript and for recognizing the efforts made in the previous revision. We also appreciate the reviewer's constructive assessment of the remaining issues. In response, we have further revised the manuscript and Supplementary Information to clarify these points and to provide additional experimental and analytical support, as detailed below.

1. Novelty and Impact

The claim regarding fractional topological charges would benefit from more direct experimental evidence, as it currently relies heavily on simulations. Additionally, a more critical comparison with prior works on skyrmion and magnetic bubble systems is required to clarify what is fundamentally new in this study.

Response: We thank the reviewer for this constructive comment and suggestion. We have revised the manuscript to clarify the evidential basis for the fractional topological charge and to provide a more critical comparison with previously reported skyrmion and magnetic-bubble systems.

Regarding the fractional topological charge, we acknowledge that the exact value of the topological charge cannot be directly obtained from L-TEM alone. The topological charge is defined as $Q = \frac{1}{4\pi} \int \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m}) dx dy$. It quantifies the degree to which a two-dimensional magnetization texture wraps the unit sphere. For a closed skyrmion-like texture, the magnetization completes a full wrapping of the unit sphere, giving an integer topological charge, as schematically shown in Fig. R6a,b. By contrast, for spin textures connected to an open boundary, or for a standard magnetic vortex, the mapping to the unit sphere is incomplete and the topological charge is no longer constrained to an integer, as illustrated in Fig. R6c,d. This provides a physical

criterion for distinguishing integer and fractional topological character.

We applied this criterion to the present DSTs. In previously reported surface twists associated with integer- Q skyrmions or antiskyrmions, the magnetization texture in the surface plane remains closed and completes a full wrapping of the unit sphere; the corresponding surface texture therefore retains integer topological character (Fig. R6e). In contrast, the DSTs observed in the present work reside on the surface of stripe domains and are connected to open stripe-domain boundaries, analogous to the configuration shown in Fig. R6c. Their spin wrapping is therefore incomplete, supporting a fractional topological character. The specific fractional Q values were then calculated from the simulated spin configurations (Fig. R6f,g).

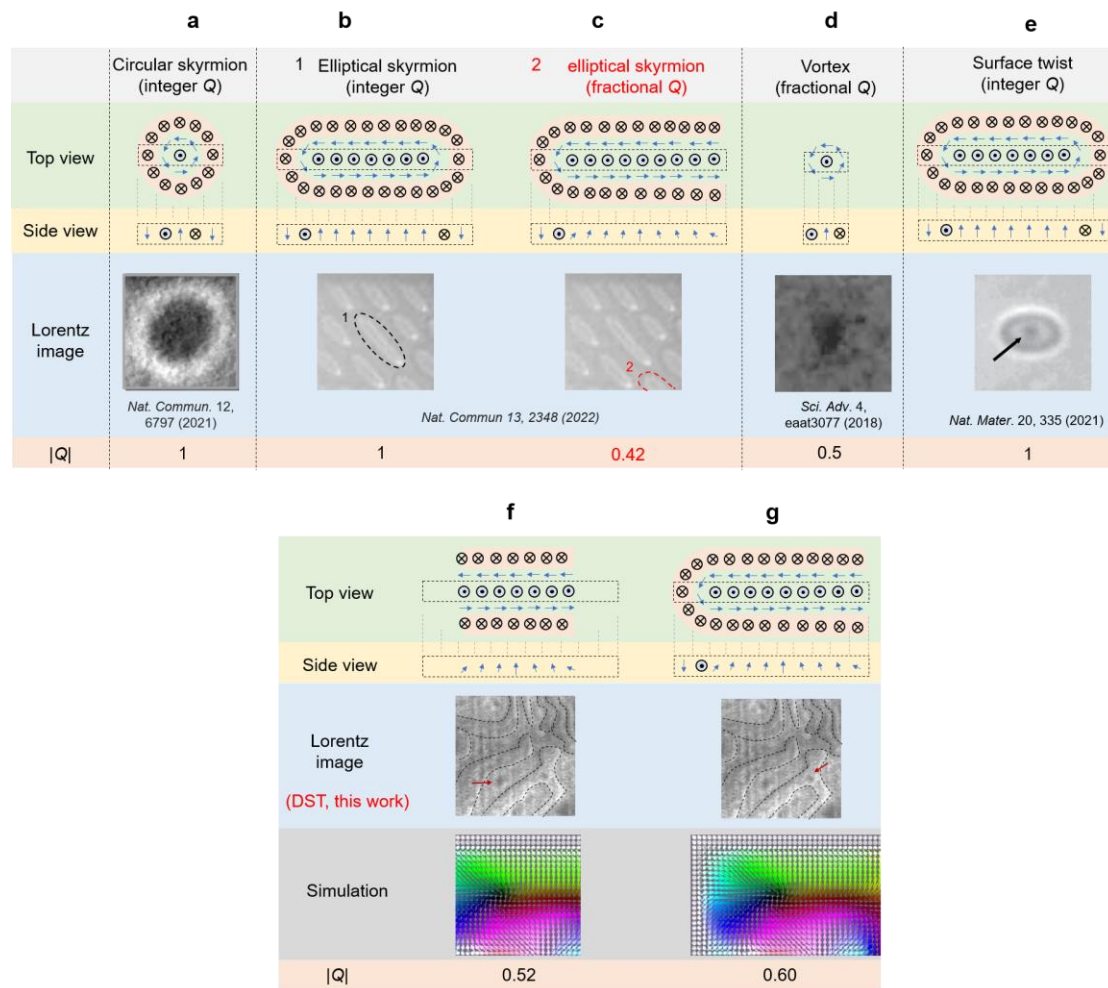


Fig. R6 | Comparison of integer and fractional topological spin configurations. **a,b** Closed skyrmions with complete spin wrapping, corresponding to integer topological charge. **c** Opened skyrmions connected to the domain boundary, where incomplete spin wrapping gives rise to fractional topological charge. **d** Standard magnetic vortex with fractional topological charge. **e** Surface twist associated with an integer-topological-charge antiskyrmion system. The surface-twist contrast is indicated by black arrows. **f,g** Representative DSTs observed in the present work and the corresponding

micromagnetic configurations. The DSTs reside on the surface of stripe domains, the latter of which terminate at open boundaries, analogous to the configuration in **c**, supporting their fractional topological character.

In addition, we have expanded the comparison with prior skyrmion and magnetic-bubble systems. Generally, skyrmions ($|Q|=1$) and topologically trivial magnetic bubbles ($|Q|=0$) are treated as complete magnetic objects extending through the sample thickness, with their surface and bulk contributions considered as a **unified texture** in field- or current-driven dynamics. By contrast, the present work experimentally **separates** surface-localized DSTs **from** the bulk magnetic texture through their distinct **static L-TEM contrast** and **current-driven dynamics**. Increasing the sample thickness strengthens the bulk stripe-domain contrast while reducing the relative visibility of the DSTs (Fig. 2c,f–g). Sample tilting further enhances the stripe-domain contrast, whereas the DSTs contrast remains nearly unchanged (Fig. 2k–m). Under current excitation, surface DSTs exhibit localized scintillation through nucleation, annihilation, and helicity switching, whereas bulk textures undergo ordered translational motion at higher current densities (Fig. 5).

Thus, the central advance of this work lies **not** in the observation of skyrmion- or bubble-like contrast itself, but in the **first experimental demonstration** of static and dynamic **surface–bulk decoupling**. The topological diversity, distinct current-driven dynamics, and lower excitation threshold of DSTs relative to bulk magnetic textures establish surface-localized magnetism as **an additional tunable degree of freedom** for **three-dimensional** spintronic applications.

To clarify this distinction in the revised manuscript, we have further revised the Discussion section:

“In summary, we identify DSTs as surface-localized topological spin textures coexisting with bulk stripe domains in FGT at zero magnetic field and room temperature. Systematic measurements show that dipolar interactions govern their formation, density, and size, while tailored field-sweeping protocols enable diverse composite surface states, including assemblies of up to 13 DSTs and ring-like configurations. Their thickness- and tilt-dependent contrast evolution distinguishes them from the bulk magnetic texture, while current-pulse experiments reveal localized scintillation, including nucleation, annihilation, and helicity switching, in stark contrast

to the ordered translational motion of bulk stripe domains. Micromagnetic simulations further indicate that this localized scintillation arises from the interplay between spin-transfer torque and local pinning. This surface–bulk distinction sets the present DSTs apart from conventional skyrmions or magnetic bubbles, which extend through the sample thickness and whose surface and bulk characteristics are usually treated as a unified magnetic entity in field- or current-driven dynamics. Together with the low critical current density, these results establish surface-localized states as a tunable degree of freedom in three-dimensional spintronics, with potential applications in energy-efficient information encoding¹¹, stochastic number generation^{51,52}, and hybrid computing architectures⁵³.” (please see: page 14, lines 403-420)

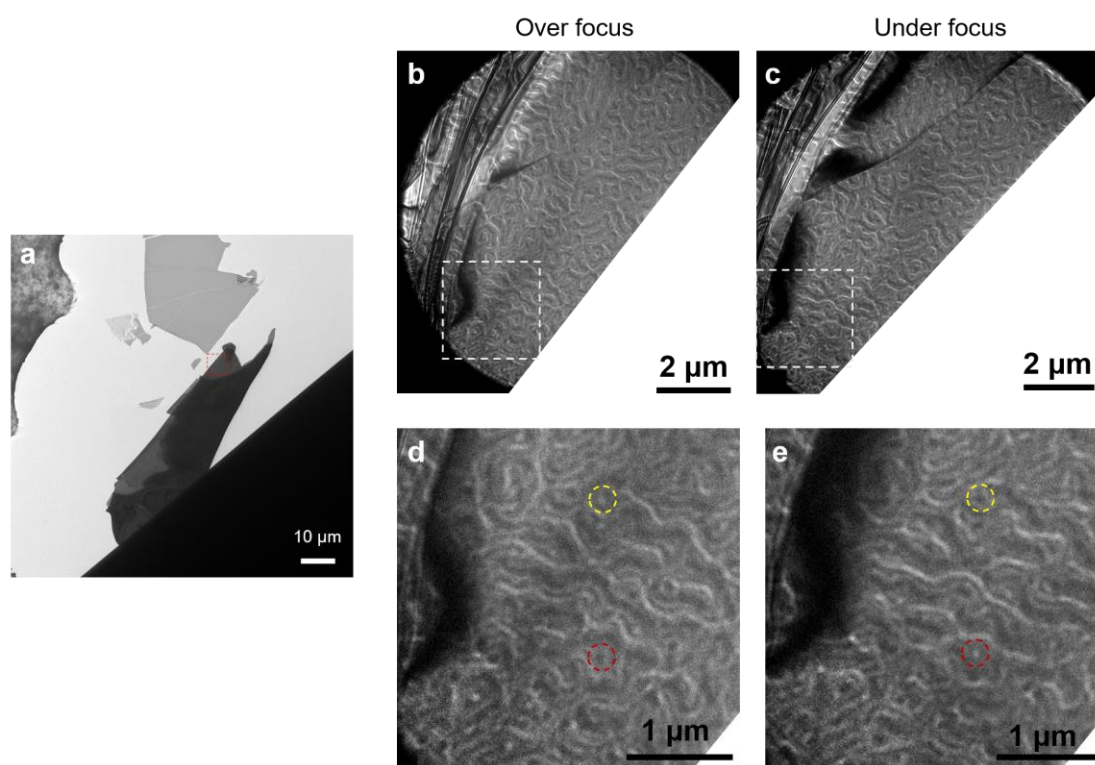
2. FIB-Induced Artifacts

(1) The authors argue that the DSTs are intrinsic to Fe₃GaTe₂ and not influenced significantly by FIB preparation. However, the controls presented (e.g., additional tests on other materials and micromagnetic simulations) are not fully convincing. A comparison with alternative sample preparation methods (e.g., mechanical polishing or Ar ion milling) would provide stronger evidence.

Response: We thank the reviewer for pointing it out and the helpful suggestion. To directly examine whether DST formation is related to FIB preparation, we performed an additional control experiment using FIB-free FGT samples. Mechanically exfoliated FGT flakes were transferred onto SiN membranes without Ga-ion irradiation or FIB milling and were characterized by L-TEM. As shown in Supplementary Fig. 9 in the revision, high-density solid dot-like DST contrasts are clearly observed in the mechanically exfoliated flakes at zero magnetic field, together with labyrinthine stripe domains. This observation shows that DST formation does not require FIB processing or Ga-ion irradiation, supporting an intrinsic origin. This interpretation is consistent with micromagnetic simulations, which identify the material’s intrinsic magnetic parameters and dipolar interactions as the primary factors stabilizing DSTs. We have included these control results in Supplementary Fig. 9 and revised the corresponding discussion in the main text as follows:

“Similar dot-like contrasts were also observed in mechanically exfoliated FGT flakes prepared without Ga-ion irradiation, indicating that their formation does not

depend on FIB processing (Supplementary Fig. 9).” (please see: page 7, lines 173-175)



Supplementary Fig. 9 | Observation of DSTs in mechanically exfoliated FGT flakes. **a** Low-magnification TEM image of mechanically exfoliated FGT flakes transferred onto a SiN membrane. The red box indicates the region selected for L-TEM imaging. **b-c** Over-focused (**b**) and under-focused (**c**) L-TEM images acquired from the selected region at zero magnetic field and room temperature. **d-e** Enlarged views of the white-boxed regions in **b,c**, showing high-density dot-like DST contrast. Representative dark and bright dots marked by the red and yellow boxes in (**d**) reverse to bright and dark dots in (**e**), respectively. The observation of DST contrast in mechanically exfoliated flakes prepared without Ga-ion irradiation or FIB milling demonstrates that DST formation does not require FIB processing.

(2) *Quantitative assessment of the potential impact of FIB-induced damage on surface-localized textures should be included.*

Response: In accordance with the reviewer’s suggestion, we further characterized the FIB-affected surface region by cross-sectional HAADF-STEM and FFT analysis. As shown in Fig. R7a,b, a thin amorphous FGT layer with a thickness of approximately 15 nm is observed between the Pt protection layers and the underlying crystalline FGT. FFT analysis confirms its amorphous character, showing diffuse intensity without well-defined diffraction spots, whereas the underlying FGT region exhibits sharp periodic diffraction features and retains clear crystallinity. These observations separate the

origin of DSTs from the possible influence of FIB processing: FIB is not required for DST formation, although the resulting surface disorder may modify local pinning and current-driven dynamics. To reflect the reviewer’s point, we have added these results in the Supplementary Information (Supplementary Fig. 12) and revised the manuscript accordingly.

“Similar dot-like contrasts were also observed in mechanically exfoliated FGT flakes prepared without Ga-ion irradiation, indicating that their formation does not depend on FIB processing (Supplementary Fig. 9).” (please see: page 7, lines 173-175)

“The observed Fe_{II} off-centering may be related to defects such as Fe vacancies and/or interstitial Ga and Te atoms, while the FIB-induced amorphous surface layer may provide additional extrinsic pinning sites (Supplementary Fig. 12).” (please see: pages 13-14, lines 399-402)

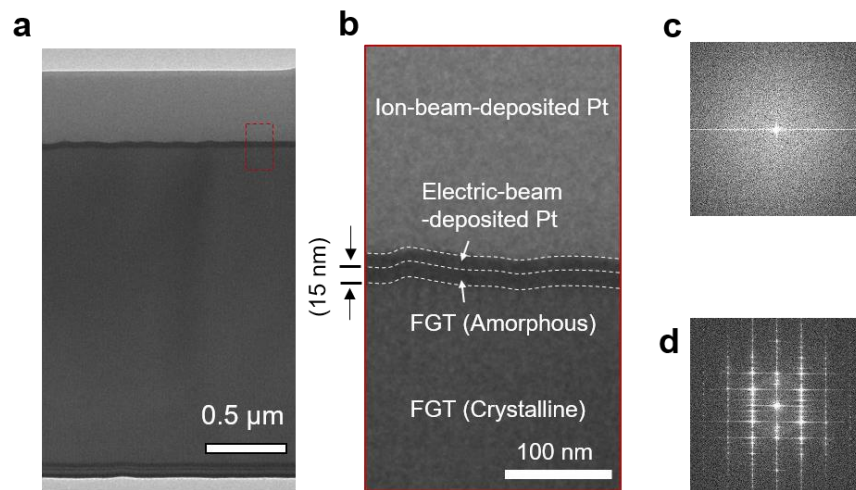


Fig. R7 | Cross-sectional TEM analysis of the FIB-induced surface damage layer. **a** Low-magnification cross-sectional HAADF-STEM image of the FGT lamella. The red dashed box marks the region selected for enlarged imaging. **b** Enlarged HAADF-STEM image of the marked region in **a**, showing, from top to bottom, the ion-beam-deposited Pt layer, electron-beam-deposited Pt layer, amorphous FGT surface layer, and crystalline FGT region. The amorphous surface layer has a thickness of approximately 15 nm. **c,d** FFT patterns obtained from the amorphous surface layer and crystalline FGT region, respectively. The diffuse FFT pattern in **c** confirms the amorphous character of the surface layer, whereas the sharp diffraction features in **d** confirm the crystallinity of the underlying FGT.

3. Scintillating Dynamics and Pinning Effects

(1) The micromagnetic simulations performed to explain the scintillating dynamics are

insightful. However, while the authors attribute these dynamics to strong pinning effects, the role of pinning induced by FIB processing or intrinsic defects in Fe₃GaTe₂ requires deeper experimental verification.

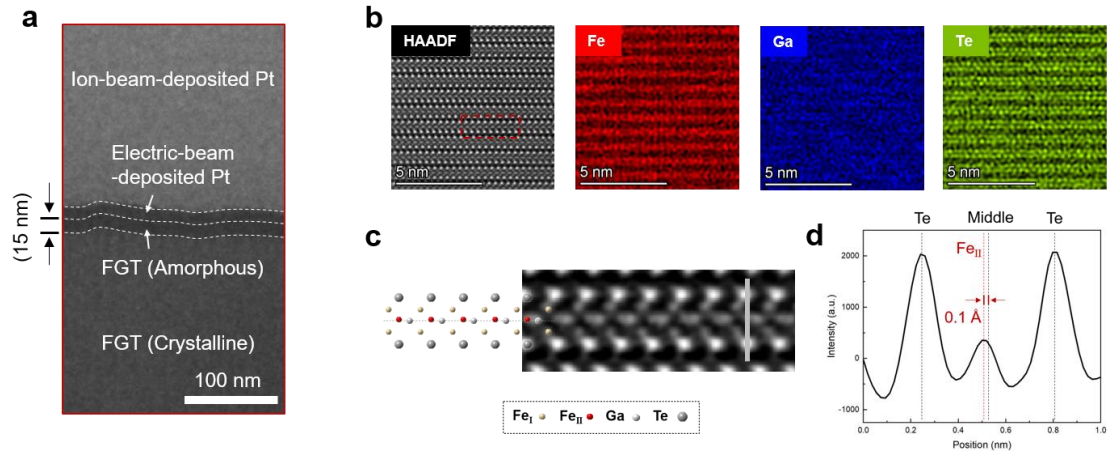
Response: We thank the reviewer for this helpful comment and the suggestion. We added structural characterizations to identify possible intrinsic and extrinsic sources of the local pinning landscape.

As shown in Supplementary Fig. 12a, cross-sectional HAADF-STEM imaging reveals a thin amorphous FGT layer at the surface of the FIB-prepared lamella. The interface between this amorphous layer and the crystalline FGT region is locally uneven, indicating that FIB processing introduces surface disorder and structural inhomogeneity. Such disorder may provide extrinsic pinning sites and influence the local current-driven response of DSTs.

We also examined the intrinsic crystal structure of FGT by atomic-resolution HAADF-STEM imaging and elemental mapping. As shown in Supplementary Fig. 12b,c, the crystalline region retains clear atomic ordering, while the Fe_{II} atomic column is displaced by approximately 0.1 Å along the *c*-axis. Previous studies have suggested that Fe_{II} off-centering may be associated with intrinsic defects, such as Fe vacancies or interstitial Ga/Te atoms [*Nat. Commun.* **15**, 4472 (2024); *Adv. Sci.* **10**, 2303443 (2023); *Nat. Commun.* **15**, 3278 (2024)], although the exact defect chemistry cannot be determined from the present STEM measurements alone. Defect-related variations in this atomic displacement may locally modify the magnetic energy landscape and contribute to pinning.

These measurements identify potential structural sources of pinning, although they do not establish a one-to-one correspondence between individual defects and the local DST switching dynamics. To reflect the reviewer's point, we have included these structural characterization results in Supplementary Fig. 28 and revised the manuscript as follows:

“The local pinning landscape may arise from both intrinsic defect-related atomic displacements and extrinsic surface disorder. The observed Fe_{II} off-centering may be related to defects such as Fe vacancies and/or interstitial Ga and Te atoms, while the FIB-induced amorphous surface layer may provide additional extrinsic pinning sites (Supplementary Fig. 12).” (please see: pages 13-14, lines 398-402)



Supplementary Fig. 12 | Structural evidence for FIB-induced surface disorder and intrinsic atomic displacement in FGT. **a** Cross-sectional HAADF-STEM image of the FIB-prepared FGT lamella, showing an amorphous FGT surface layer above the crystalline FGT region. The non-flat interface indicates local structural disorder introduced by FIB processing. **b** Atomic-resolution HAADF-STEM image and corresponding elemental maps of Fe, Ga and Te acquired from the crystalline FGT region. **c** Enlarged HAADF-STEM image of the red-boxed region in **(b)**, together with the structural model **(d)** Intensity profile showing an Fe_{II} displacement of approximately 0.1 Å along the *c*-axis.

(2) The authors should better justify why thermal effects due to Joule heating can be ruled out as the primary driver of the observed dynamics. The finite-element simulations and temperature-dependent micromagnetic simulations help, but additional direct experiments (e.g., temperature-dependent dynamics) would strengthen this claim.

Response: We thank the reviewer for pointing it out and the suggestion. A related concern was addressed in our previous response to Reviewer 2, and we should have described our results in the original manuscript with more clarity on this aspect: why Joule heating can be ruled out as the primary driver of the observed DST dynamics.

At the current density used to induce DST scintillation, $J = 1.37 \times 10^{11} \text{ Am}^{-2}$, the sample remains below its Curie temperature, T_c . This conclusion is supported by two points. First, COMSOL finite-element simulations show that the current-induced temperature rise does not exceed T_c (Supplementary Fig. 29a). Second, at an even higher current density ($J = 2.18 \times 10^{11} \text{ Am}^{-2}$), the stripe domains exhibit ordered translational motion correlated with the current direction, as shown in Fig. 5d,e and

Supplementary Video 3. Such directional motion is consistent with the preservation of magnetic order at this higher current density, supporting the conclusion that the sample remains below T_c . Therefore, the lower current density used to induce DST scintillation is even less likely to heat the sample above T_c .

The remaining possibility is that heating below T_c could still induce helicity switching. To test this, we used temperature-dependent L-TEM control measurements, as shown in Fig. R8. When the sample was heated from 300 K to 350 K without current pulses, the DST contrast gradually weakened and eventually disappeared, but no black-to-white or white-to-black contrast reversal was observed. Thus, heating alone does not reproduce the helicity switching or localized scintillation observed under current pulsing.

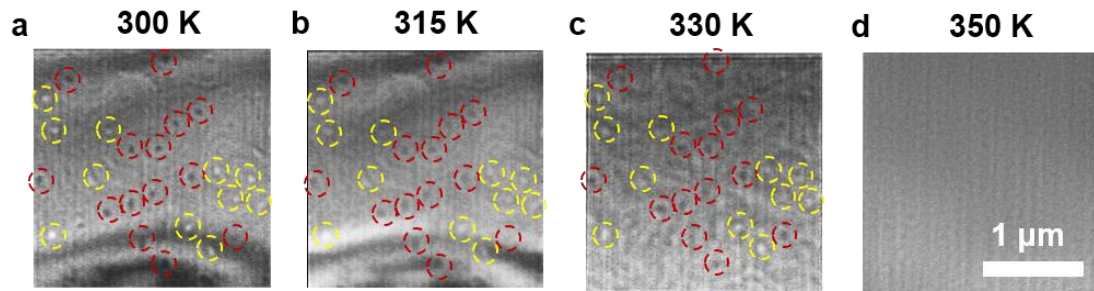


Fig. R8 | Temperature-dependent under-focused L-TEM images of DSTs. a–d Under-focused L-TEM images acquired at different temperatures during heating. Representative black and white dot contrasts, corresponding to DSTs with clockwise and counterclockwise helicities, are marked by red and yellow circles, respectively. The DST contrast progressively weakens and eventually disappears upon heating, with no contrast reversal observed.

These results show that Joule heating is not the primary driving mechanism. We do not exclude a secondary thermal contribution, as heating may lower local energy barriers. However, the localized reconstruction of DST spin textures induced by current pulses is more consistent with spin-transfer torque acting within a local pinning landscape. For better clarity, we have added these results (Supplementary Fig. 29b) and revised the description:

“This is supported by finite-element simulations showing that the sample temperature remains below T_c during current-pulse injection (Supplementary Fig. 29a), together with temperature-dependent L-TEM measurements and finite-temperature micromagnetic simulations confirming the thermal stability of the DSTs at elevated temperatures (Supplementary Fig. 29b–c). In these temperature-dependent L-TEM

measurements, heating weakens the DST contrast but does not induce contrast reversal. Thus, Joule heating alone cannot account for the scintillating dynamics, which instead originate mainly from spin-transfer torque acting within a local pinning landscape, although thermal effects may assist the process by lowering local energy barriers.” (please see: page 13, lines 389-398)

4. Writing and Clarity

(1) The manuscript has improved in clarity, but certain areas remain dense and ambiguous, e.g. a clearer explanation of the experimental limitations (e.g., L-TEM resolution, challenges in quantitative phase reconstruction) would improve transparency.

Response: We thank the reviewer for pointing it out and the helpful suggestion. We have revised the relevant Results, Discussion and Methods sections to improve readability and to state the experimental limitations more clearly. In particular, we now clarify the scope of the L-TEM/TIE analysis, including the finite spatial resolution of defocused L-TEM imaging and the challenges associated with quantitative phase reconstruction. Accordingly, we revised the Results section as follows:

“To visualize the projected in-plane magnetic induction associated with the underlying spin textures, transport-of-intensity equation (TIE) phase reconstruction³⁶ was performed using QPt software (Fig. 2d), yielding a qualitative thickness-integrated map.” (please see: page 7, lines 176-179)

We also added the following clarification to the Methods section:

“Because TIE reconstruction is based on defocused projection images, its effective spatial resolution is limited by the applied defocus and image signal-to-noise ratio. Uncertainties in phase retrieval further reduce the quantitative accuracy of the reconstructed magnetic induction, while the thickness-integrated nature of L-TEM limits depth-resolved interpretation of the magnetization. We therefore use the reconstructed induction maps qualitatively to support the assignment of projected spin configurations and helicities, and calculate the topological charges from the micromagnetic spin configurations.” (please see: page 15, lines 446-453)

(2) While the revised manuscript has addressed several key concerns, the responses to critical issues, particularly the novelty of the findings, evidence for fractional topological charges, and controls for FIB artifacts, remain partially inadequate. Therefore, I recommend a Major Revision before the manuscript can be considered for publication in Nature Communications.

Response: We thank the reviewer for the comment and the constructive recommendation. We have substantially revised the manuscript and Supplementary Information to address the remaining critical issues.

We have clarified that the principal advance is the separation of surface-localized DSTs from the bulk magnetic texture within a single dipolar van der Waals magnet. This surface–bulk distinction is supported by thickness- and tilt-dependent L-TEM measurements, depth-resolved micromagnetic simulations, and the distinct current-driven dynamics of surface DSTs and bulk stripe-domain textures. We have also distinguished the experimental evidence for fractional topological character from the simulation-based evaluation of the corresponding Q values. Finally, mechanically exfoliated FGT samples establish that DST formation does not require FIB processing, while cross-sectional STEM quantifies the FIB-affected surface layer and its possible contribution to local pinning.

Together with the temperature-dependent controls, structural characterization of possible pinning sources, and explicit discussion of the limitations of L-TEM/TIE analysis, these revisions provide a substantially stronger experimental and analytical basis for the conclusions. We believe that these revisions substantially strengthen the manuscript and address the concerns raised by the Reviewers while preserving the central objective of the work.

Again, we thank again all reviewers for their helpful comments, questions, and suggestions.

Point-by-point responses and revisions in response to reviewer comments:

Reviewer #1:

(1) In the previous round, I made a comment about the DM interaction in their micromagnetic simulation. The authors reply that the effective DMI is not assumed to arise from the two external surfaces of the TEM lamella but from inversion-symmetry breaking associated with Fe off-centering along the c-axis. Although I understand what they assume, the authors should re-check the consistency in the manuscript before the publication. On page 6, the authors mention that the obtained crystal belongs to a centrosymmetric space group $P6_3/mmc$. However, on page 8, they describe that the interfacial DMI is attributed to inversion-symmetry breaking associated with the approximately 0.1 Å off-centering of FeII atoms observed by atomic-resolution HAADF-STEM (Supplementary Fig. 12), consistent with recent reports (Refs. 32, 40). I am afraid that these two statements are clearly inconsistent with each other. Ref. 40 reported that Fe deficiencies in Fe_3GaTe_2 induce the Fe displacement along the c-axis. As a result, the space group changes from centrosymmetric $P6_3/mmc$ to polar $P3m1$. I recommend that such a possibility should be more explicitly explained.

Response: We thank the reviewer for pointing out this inconsistency in the description of crystal symmetry. Our previous wording directly assigned the centrosymmetric space group to our as-grown crystals without considering the possible symmetry lowering associated with Fe deficiency. To reflect the reviewer's point, we have revised the relevant descriptions on Pages 6 and 8 accordingly.

On Page 6, we have removed the statement assigning the centrosymmetric space group to our as-grown crystals. As noted in Ref. #40, Fe deficiency in Fe_3GaTe_2 can induce FeII displacement along the c-axis, break inversion symmetry, and lower the crystal symmetry from centrosymmetric $P6_3/mmc$ toward polar $P3m1$. The approximately 0.1 Å FeII off-centering observed in our sample is consistent with such symmetry lowering.

In addition, the revised paragraph on Page 8 (Lines 209~214) is as follows:

“The DMI is attributed to inversion-symmetry breaking associated with the approximately 0.1 Å off-centering of FeII atoms observed by atomic-resolution

HAADF-STEM (Supplementary Fig. 12). Such Fe_{II} off-centering may be associated with Fe deficiency and could lower the crystal symmetry from the centrosymmetric $P6_3/mmc$ toward the polar $P3m1$, which is consistent with recent reports^{32,40}.

(2) *One more technical issue: “Supplementary Fig. 18a” on page 34 of Supplementary Information should be corrected (to Fig. 25a, maybe).*

Response: We thank the reviewer for pointing out this error. We have corrected “Supplementary Fig. 18a” to “Supplementary Fig. 25a” in the revised Supplementary Information.

Reviewer #3:

The authors have satisfactorily addressed the concerns raised during the previous round of review. The revisions have strengthened the manuscript, and the additional analyses and clarifications provide sufficient detail to support the conclusions and ensure the reproducibility of the work. In its current form, I believe the manuscript meets the novelty and quality standards expected for Nature Communications. I therefore have no further concerns and am pleased to recommend the manuscript for publication.

Response: We sincerely thank the reviewer for the positive assessment of our revised manuscript and for recommending it for publication. We greatly appreciate the reviewer's constructive comments throughout the review process, which have helped us improve the quality and clarity of the manuscript.

Again, we thank again all Reviewers for the helpful comments, questions, and suggestions.