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1 **Domain wall dynamics in two-dimensional van der Waals**  
2 **ferromagnets**

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19 **Domain wall motion is in the core of many information technologies ranging from storage<sup>1</sup>,**  
20 **processing<sup>2</sup>, sensing<sup>3</sup> up to novel racetrack memory architectures<sup>4</sup>. The finding of magnetism**

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21 in two-dimensional (2D) van der Waals (vdW) materials<sup>5-8</sup> has offered a new frontier for the  
22 exploration and understanding of domain walls at the limit of few atom-thick layers. How-  
23 ever, to use 2D vdW magnets for building spintronics nanodevices such as domain-wall based  
24 logic<sup>9-11</sup>, it is required to gain control of their domain wall dynamics by external driving  
25 forces such as spin-polarized currents or magnetic fields which has so far been elusive. Here  
26 we show that electric currents as well as magnetic fields can efficiently move domain walls in  
27 the recently discovered 2D vdW magnets CrI<sub>3</sub> and CrBr<sub>3</sub> at low temperatures, and robust  
28 down to monolayer. We realize field- and current-driven domain wall motion with veloci-  
29 ties up to 1020 m s<sup>-1</sup> which are comparable to the state-of-the-art materials for domain-wall  
30 based applications<sup>12-16</sup>. Domain walls keep their coherence driven by the spin-transfer torque  
31 induced by the current and magnetic field up to large values of about  $12 \times 10^9$  A cm<sup>-2</sup> and  
32 5 T, respectively. For larger magnitudes of current or field, a transition to a hydrodynamic  
33 spin-liquid regime is observed with the emission of a periodic train of spin-wave solitons  
34 with modulational instability<sup>17</sup>. The emitted waveform achieves terahertz (THz) frequency  
35 in a wide range of field and current densities which opens up perspectives for reconfigurable  
36 magnonic devices. Moreover, we found that these spin-waves can transport spin angular mo-  
37 mentum through the layers over distances as long as 10  $\mu$ m without losses for the transport  
38 of spin information. Our results push the boundary of what is currently known about the  
39 dynamics of domain walls in 2D vdW ferromagnets and unveil strategies to design ultrathin,  
40 high-speed and high-frequency spintronic devices.

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41 Spin-based applications have been broadly explored for high-performance solid-state data  
42 storage technologies<sup>18,19</sup>. A promising strategy is to encode bits in magnetic domains walls which  
43 can be controlled via applied magnetic fields and spin-polarized currents<sup>4,9</sup>. Several approaches  
44 for domain wall-based memory devices with a focus on the domain wall displacement have been  
45 developed. From a field-controlled shift register<sup>9,20</sup> up to the non-volatile multi-turn sensors<sup>21</sup>,  
46 which are commercially available<sup>22</sup>, these emerging technologies provide a new horizon for ad-  
47 vanced materials to be explored. With the discovery of magnetism in vdW layered compounds<sup>5-7</sup>  
48 and proof-of-concept devices<sup>8,23-25</sup> already showing outstanding progress toward applications, one  
49 of the main challenges is the integration of 2D magnets in domain wall microelectronic platforms.

50 Due to scaling reasons and high-density requirements<sup>26</sup>, competitive devices should have  
51 narrow domain walls (ideally in the range of 1–10 nm), use out-of-plane magnetic anisotropy  
52 materials and, in particular for memory devices, develop domain wall velocities of the order of  
53  $\sim 100 \text{ m s}^{-1}$  to achieve rapid operating speed on increasing areal density<sup>4,27</sup>. Sufficiently low  
54 current densities ( $\sim 10^6 - 10^8 \text{ A cm}^{-2}$ ) are also needed to guarantee low power consumption and  
55 to avoid damage due to Joule heating. However, metallic layers inherently suffer with energy  
56 dissipation via the conduction electrons<sup>2</sup> which make magnetic insulators better suited for domain  
57 wall applications. There have been a few reports on the creation of different interfaces using  
58 magnetic vdW materials<sup>28,29</sup> and heavy metal overlayers (e.g. Pt, Ta) where spin-transfer torque  
59 arising from charge-to-spin current conversion can effectively switch the magnetization from one  
60 state to another. Nevertheless, it is unknown how domain walls behave intrinsically in 2D magnets  
61 as current and fields are applied directly into the systems, and how efficient such layered structures

62 would be in domain-wall based functional devices.

63 Here we demonstrate domain-wall motion in monolayer  $\text{CrI}_3$  and  $\text{CrBr}_3$  by spin polarized  
64 currents and magnetic fields in a broad range of densities ( $10^7 - 10^9 \text{ A cm}^{-2}$ ) and field (0.001–2  
65 T). Both dynamics occur over hybrid domain walls with Néel-Bloch characteristics with a domain  
66 wall width of about  $\sim 5.30 \text{ nm}$ . The spin-torque induced by electric currents and magnetic fields  
67 generates a rapid rotation of the magnetization at the domain wall, hence triggering its transla-  
68 tional motion at high velocities. We record speeds of up  $1020 \text{ m s}^{-1}$  and  $100 \text{ m s}^{-1}$  with current  
69 and field, respectively, while keeping the coherence of the wall profile through a steady motion.  
70 As the domain wall velocity approaches the maximum spin-wave group velocity, the domain wall  
71 motion start to exhibit non-linear effects with the emission of magnons at terahertz (THz) fre-  
72 quencies following a modulational instability behaviour. Even though no conduction electrons are  
73 present in the medium due to the insulating characteristics of  $\text{CrI}_3$  and  $\text{CrBr}_3$ , spin-information can  
74 be transported over distances as long as  $10 \mu\text{m}$  which sets a new paradigm for spin-wave-based  
75 technologies at the ultrathin limit.

76 Our starting point is the investigation of the magnetic domain structures in monolayer  $\text{CrBr}_3$   
77 and their dynamic evolution under different temperatures and magnetic fields. The domain wall  
78 structure of  $\text{CrI}_3$  and its cooling dynamics have recently been reported using similar theoretical  
79 framework<sup>30</sup>. We use a large square flake of  $0.4 \mu\text{m} \times 0.4 \mu\text{m}$  to represent a system able to  
80 be measured using imaging techniques, i.e. nitrogen-vacancy scanning magnetometry<sup>31</sup>. We  
81 describe the interactions using the following spin Hamiltonian:

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$$\mathcal{H} = -\sum_{ij} J_{ij}(\mathbf{S}_i \cdot \mathbf{S}_j) - \sum_{ij} \lambda_{ij} S_i^z S_j^z - \sum_i D_i (\mathbf{S}_i \cdot \mathbf{e}_i)^2 - \sum_{ij} K_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j)^2 - \sum_i \mu_i \mathbf{S}_i \cdot (\mathbf{B}_i + \mathbf{B}_i^{\text{dp}}) \quad (1)$$

82 where  $\mathbf{S}_i$  and  $\mathbf{S}_j$  are the localized magnetic moments on Cr atomic sites  $i$  and  $j$  which are coupled  
 83 by pair-wise exchange interactions.  $J_{ij}$  and  $\lambda_{ij}$  are the isotropic and anisotropic bilinear (BL) ex-  
 84 changes, respectively, and  $D_i$  is the single ion magnetic anisotropy.  $\mathbf{B}_i$  and  $\mathbf{B}_i^{\text{dp}}$  represent external  
 85 and dipole magnetic field sources respectively. Eq. 1 was previously found to describe accurately  
 86 the magnetic properties of several 2D magnets<sup>30,32</sup> including CrI<sub>3</sub> and CrBr<sub>3</sub>. Comparisons with  
 87 other spin Hamiltonians such as Kitaev, bilinear Heisenberg, Ising, and Dzyloshinskii-Moriya in-  
 88 teractions, were undertaken in refs.<sup>30,32</sup> as well as in their Supplementary Information files. We  
 89 take into account up to third nearest neighbors for  $J_{ij}$  and  $\lambda_{ij}$  in the description of CrBr<sub>3</sub> in Eq.1.  
 90 All the parameters in Eq.1 are extracted using highly accurate non-collinear ab initio simulations  
 91 taking into account spin-orbit coupling and Hubbard- $U$  corrected density functional theory as de-  
 92 scribed in Ref.<sup>30,32</sup>. We ensure that fine numerical convergence within  $10^{-6} - 10^{-8}$  eV is achieved  
 93 in each computed parameter. We also compared the exchange parameters used in our work with  
 94 those collected from the literature<sup>33</sup>. In the context of the materials studied in our study (monolayer  
 95 CrI<sub>3</sub> and CrBr<sub>3</sub>), Supplementary Figure 1 clearly shows that our exchange magnitudes<sup>32</sup> reproduce  
 96 with high accuracy the critical temperatures measured. Moreover, Eq.1 provides an accurate de-  
 97 scription of the magnon dispersion extracted from inelastic neutron scattering measurements on  
 98 CrI<sub>3</sub><sup>34</sup> as shown in ref.<sup>32</sup>. These results provide a firm background for the modeling of the domain  
 99 wall dynamics as described here.

100 The fourth term in Eq.1 represents the biquadratic (BQ) exchange which involves the hopping

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101 of two or more electrons between two adjacent sites<sup>32</sup>. Its strength is given by the constant  $K_{ij}$ ,  
102 which is the simplest and most natural form of non-Heisenberg coupling. It has recently been found  
103 that several 2D vdW magnets develop substantial BQ exchange in their magnetic properties which  
104 is critical to quantitatively describe important features such as Curie temperatures, thermal stability,  
105 magnon spectra and non-trivial topological spin textures<sup>30,32,35,36</sup>. The magnitude of  $K_{ij}$  for CrBr<sub>3</sub>  
106 is 0.22 meV which is smaller than the BL exchange for the first-nearest neighbours ( $J_1 = 1.66$  meV)  
107 but still sizeable to be disregarded<sup>32</sup>. In our implementation the BQ exchange is quite general and  
108 can be applied to any pair-wise exchange interaction of arbitrary range. Each system is evolved by  
109 solving the atomistic Landau-Lifshitz-Gilbert equation with a Gilbert damping  $\lambda_G = 0.1$  to ensure  
110 better computational efficiency and numerical stability of the time integration. The value of  $\lambda_G$  is  
111 substantially higher than that ( $2 \times 10^{-3}$ ) recently measured for a parent compound<sup>37</sup> (i.e. CrCl<sub>3</sub>)  
112 which a similar magnitude would be expected for CrI<sub>3</sub> and CrBr<sub>3</sub>. The large  $\lambda_G$  also accounts  
113 for the possibility of free-electron doping to raise the conductivity of the system due to different  
114 processes (i.e. dopants<sup>38</sup>, electric bias<sup>39</sup>). Due to the inclusion of dipole-dipole interactions we  
115 explicitly include non-local damping effects in our simulations such as due to domain walls or  
116 different magnetic textures. Hence, our spin-dynamics simulations include an accurate description  
117 of the spin-interactions at the atomistic level (2–20 Å) in a multiscale framework at the lab scale  
118 (a few  $\mu\text{m}^2$ ).

119 Monolayer CrBr<sub>3</sub> is thermally equilibrated above 40 K and then linearly cooled to 0 K in  
120 a total simulated time of 4.0 ns at different magnetic fields (Figure 1 and Supplementary Movies  
121 S1-S4). The time evolution of the out-of-plane magnetization  $M_z$  is utilised to study the nucleation

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122 of the magnetic domains as it determines the easy-axis throughout the layer. For zero-field cooling  
123 (0 mT) magnetic domains are formed for temperatures below 20 K with the free motion of the  
124 domain walls as the temperature drops (Fig. 1a-e). As the system reaches 0 K a continuous  
125 time evolution of the domain structures remains which results in a homogenous magnetization  
126 over the entire crystal (Supplementary Movie S1). Even though thermal fluctuations as well as  
127 their contributions to the energy of the system are inexistent at 0 K, other terms, such as dipolar  
128 fields, exchange interactions and magnetic anisotropy, are still present, further contributing to the  
129 modification of the magnetic domains. Once magnetic fields are applied to the nanosheet (Fig.  
130 1f-t and Supplementary Movies S2-S4) this nucleation-type mechanism is accelerated with a rapid  
131 reversal in the sign of the magnetization  $M_z$ . Indeed, a monodomain feature is observed even  
132 in fields far below the coercivity<sup>40</sup> (10 mT at 5 K) for  $\text{CrBr}_3$ . In a scenario where defects or  
133 pinning sites are not present in monolayer  $\text{CrBr}_3$ , magnetic domains tend to be meta-stable with  
134 a homogeneous magnetisation throughout the surface. This is in sound agreement with recent  
135 NV-center scanning magnetometry measurements<sup>31</sup> on the magnetic domain evolution of  $\text{CrBr}_3$   
136 indicating that pinning effects are the dominant coercivity mechanisms.

137 Strikingly, the interplay between domain metastability and high magnetic anisotropy of  
138  $\text{CrBr}_3$  give additional characteristics to the domain walls (Figure 2a-b). We observe that as the  
139 spins vary orientation from one magnetic domain to another the wall profile assumes components  
140 of the magnetization along different in-plane directions ( $M_{x,y}$ ) relative to the easy-axis ( $M_z$ ) (Fig.  
141 2c-d). In-plane magnetization  $M_x$  displays a variation larger than that for  $M_y$  which is mainly no-  
142 ticed at the core of the domain wall within 1–2.5 nm. These features indicate a domain wall with



143 hybrid characteristics of Bloch and Néel type (Fig. 2e-f). We can extract the domain wall width  
144  $\sigma_{x,y,z}$  by fitting the different components of the magnetization ( $M_x$ ,  $M_y$ ,  $M_z$ ) to standard equations  
145 of the form<sup>41</sup>:

$$M_j = \frac{1}{\cosh(\pi(j-j_0)/\sigma_j)}, \quad \text{with } j = x, y \quad (2)$$

$$M_z = \tanh(\pi(z-z_0)/\sigma_z) \quad (3)$$

146 where  $j_0$  and  $z_0$  are the domain wall positions at in-plane and out-of-plane coordinates, respec-  
147 tively. The domain wall widths are within the range of  $\sigma_{x,y,z} = 5.30 - 5.33$  nm. Materials with  
148 high magnetic anisotropy generally stabilise such small domain wall widths but their magnetic do-  
149 mains are generally stable after zero-field cooling due to long range dipole interactions. We have  
150 checked that the inclusion of dipolar fields in our simulations do not change the results.

151 An intriguing question raised by the hybrid features of the domain walls in  $\text{CrBr}_3$  and  $\text{CrI}_3$ <sup>30</sup>  
152 is the effect of magnetic fields and electric currents on the motion of domain walls. It is well estab-  
153 lished that both driving forces can induce displacement of domain walls in magnetic thin films over  
154 different substrates. Nevertheless, the vdW nature of the nanosheet together with the atomic thick-  
155 ness ( $\approx 0.5$  nm) may induce additional phenomena yet to be observed in 2D ferromagnets. Figure  
156 3a-d shows that either fields or currents can efficiently displace domain walls in layered  $\text{CrBr}_3$  and  
157  $\text{CrI}_3$  magnets. The dynamics is generally initialised with a domain wall at equilibrium position  
158 previously thermalized for several nanoseconds for full convergence of the spin orientations (Fig.  
159 3a). The finite width of the nanowire assists in the formation of the domain walls pinned by the  
160 edges. For field-induced domain wall motion, wall velocities up to  $v = 70 \text{ m s}^{-1}$  and  $v = 98 \text{ m s}^{-1}$

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161 are recorded for CrBr<sub>3</sub> and CrI<sub>3</sub> (Fig. 4a-b), respectively. The wall moves steadily on both sheets  
162 and can be described as  $v = \mu_F(B - B_o)$ , where  $\mu_F$  is the wall mobility and  $B_o$  is the onset field  
163 required to move the wall from structural defects or pinning<sup>42</sup>. The magnitudes of  $\mu = 0.0343$  m  
164  $s^{-1} mT^{-1}$  and  $B_o = 23.89$  mT for CrBr<sub>3</sub> and  $\mu = 0.018$  m  $s^{-1} mT^{-1}$  and  $B_o = 13.33$  mT for CrI<sub>3</sub>  
165 indicate that domain walls move relatively slower than those in metallic ultrathin Pt/Co/Pt films<sup>43</sup>  
166 or thick magnetic insulator TmIG/Pt interfaces<sup>14</sup> but with relatively similar onset field  $B_o$ . The  
167 domain wall moves steadily on both sheets at fields below critical magnitudes ( $B_c$ ) of  $B_c = 1.19$   
168 T and  $B_c = 4.78$  T for CrBr<sub>3</sub> and CrI<sub>3</sub>, respectively (Supplementary Movies S5-S6). For values  
169 beyond  $B_c$  different spin distributions start nucleating ahead of the domain-wall (Supplementary  
170 Movie S7-S8) and induce its collapse within a few hundreds of picoseconds after the motion ini-  
171 tiated. These spin features appear from the edges of the layers and rapidly move into the bulk of  
172 the ribbon. This behaviour is analogous to that observed in Pt/Co/AlO<sub>x</sub> ultrathin microstructures<sup>44</sup>  
173 and highlighted the importance of edges on the magnetic properties of 2D magnets in device in-  
174 tegration. A preference for unreconstructed edges or dangling bonds rather than on zig-zag edges  
175 (Fig. 3b at 1.50 T) has been observed in the nucleation of reversed domains during the wall dy-  
176 namics. The local variation of the exchange interactions at dangling-bonds with spins being less  
177 restricted to change their directions with an external field than at zig-zag edges is one of the main  
178 ingredients for this behaviour. This observation shall trigger further experimental studies of the  
179 atomic structure at the edges of the monolayer magnets via scanning probe microscopies<sup>45,46</sup> and  
180 their connection to the device performance.

181 In the case of current-driven domain wall motion, we state that such behaviour can be ac-

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182 accomplished in two ways. First, by using an adjacent conducting layer as recently demonstrated for  
183 insulating  $\text{Tm}_3\text{Fe}_5\text{O}_{12}$  on top of a Pt substrate<sup>14</sup>. Charge current will flow in the heavy metal gen-  
184 erating spin currents that exert a spin-transfer torque (STT) on the ferromagnetic material. Second,  
185 by doping the  $\text{CrX}_3$  ( $X=\text{Br}, \text{I}$ ) magnets in order to generate significant carriers in the host<sup>27,47</sup>. Such  
186 strategies are well established and would provide a feasible platform to confirm our predictions.  
187 Indeed, we recorded domain wall velocities up to  $530 \text{ m s}^{-1}$  and  $1020 \text{ m s}^{-1}$  for monolayer  $\text{CrBr}_3$   
188 and  $\text{CrI}_3$ , respectively, under applied currents (Fig. 4c-d). These velocities are higher than those  
189 observed in a wide range of systems including skyrmions ( $100 \text{ m s}^{-1}$ )<sup>13</sup>, ferromagnetic semicon-  
190 ductor (Ga, Mn)As ( $22 \text{ m s}^{-1}$ )<sup>47</sup>, synthetic antiferromagnets ( $750 \text{ m s}^{-1}$ )<sup>12</sup>, metallic layers ( $380 \text{ m}$   
191  $\text{s}^{-1}$ )<sup>48</sup>, Pt/CoFe/MgO and Co/Ni/Co interfaces ( $\sim 10 \text{ m s}^{-1}$ ,  $400 \text{ m s}^{-1}$ )<sup>16,49</sup>, and insulating oxides  
192 ( $400 \text{ m s}^{-1}$ )<sup>14</sup>. It is worthwhile highlighting that low current densities within the experimental  
193 range of  $10^{-8} \text{ A cm}^{-2}$  (insets in Fig. 4c-d) already resulted in domain wall speeds (i.e.  $100 \text{ m s}^{-1}$ )  
194 similarly as those achieved in established racetrack platforms with more complex materials<sup>4</sup>. The  
195 domain walls displace freely as a function of the current density  $j$  in a viscous flow motion (Supple-  
196 mentary Movies S9-S10). The high velocities predicted for  $\text{CrBr}_3$  and  $\text{CrI}_3$  are only limited by the  
197 spin-wave group velocity  $v_g$  intrinsic to the systems. By using a spin-wave theory for 2D magnetic  
198 materials<sup>32</sup>, which includes biquadratic exchange and Dzyaloshinskii-Moriya interactions (DMI),  
199 we estimate from the magnon dispersion (Supplementary Figure 2) maximum values of  $v_g$  within  
200 the range of  $584\text{--}891 \text{ m s}^{-1}$  for  $\text{CrBr}_3$  and  $1326\text{--}6400 \text{ m s}^{-1}$  for  $\text{CrI}_3$  (Supplementary Figure  
201 3). These values are close to those computed from the atomistic simulations ( $530 \text{ m s}^{-1}$  and  $1020$   
202  $\text{m s}^{-1}$  for  $\text{CrBr}_3$  and  $\text{CrI}_3$ , respectively) although slightly larger. This is due to the damping of

203 the domain wall motion by the emission of spin-waves<sup>50</sup> not taken into account into the model as  
204 commented in the following.

The steady displacement of the domain walls occurs up to a certain threshold ( $j_w$ ) defined as the Walker breakdown<sup>42</sup>. For values below  $j_w$ , the wall dynamics can be well modelled by a simple 1D model<sup>51,52</sup> through a linear dependence of  $v$  and  $j$ :

$$v = \mu_I j \quad (4)$$

205 where  $\mu_I$  is the current-driven domain-wall mobility which gives  $\mu_I = 0.12 \times 10^{-10} \text{ m}^3 \text{ A}^{-1} \text{ s}^{-1}$   
206 and  $\mu_I = 0.10 \times 10^{-10} \text{ m}^3 \text{ A}^{-1} \text{ s}^{-1}$  for monolayer CrBr<sub>3</sub> and CrI<sub>3</sub>, respectively. These values  
207 are of the same order of magnitude as those recorded on thin metallic interfaces<sup>49</sup> or permalloy  
208 nanowires<sup>53</sup> which have been studied more intensively. For values near  $j_w$  or above, the spins  
209 at the domain wall precesses inducing disruption of the wall at longer times with the nucleation  
210 of magnetic domains with a different polarisation ahead of the displacement of the domain-wall  
211 (Fig. 3c at  $4.35 \times 10^9 \text{ A cm}^{-2}$ ). A close look at these features (Fig. 3d) indicates that they  
212 may start from both edges although dangling-bonds may induce more curvature to the domain  
213 wall since a dragging on the motion is observed generating retardation relative to the zig-zag edge.  
214 We can model qualitatively the dynamics at  $j > j_w$  for both CrBr<sub>3</sub> and CrI<sub>3</sub> via the time average  
215 velocity of the domain wall<sup>51,52</sup>. This suggests that the domain-wall dynamics in 2D magnets is  
216 similar as that in magnetic nanowires which allows faster integration into existing devices<sup>27</sup>. We  
217 also observe that as the domain wall moves spin-waves or magnons are emitted (Fig. 4e-f). The  
218 spin frequencies driven by the field ( $\omega_B$ ) and current ( $\omega_J$ ) are in the terahertz (THz) regime with  
219 maximum magnitudes of  $\omega_B^{max} = 0.43 \text{ THz}$  and  $\omega_J^{max} = 0.60 \text{ THz}$  for CrBr<sub>3</sub> and  $\omega_B^{max} = 0.50 \text{ THz}$

220 and  $\omega_j^{max} = 0.66$  THz for CrI<sub>3</sub>. These frequencies are in sound agreement with those estimate from  
 221 the magnon dispersion along different points of the Brillouin zone for both halides (Supplementary  
 222 Figure 3). We found that the maximum frequencies with the field are close to those at the M–point  
 223 (0.47 THz for CrBr<sub>3</sub>, and 0.57 THz for CrI<sub>3</sub>), whereas with the applied current are around the  
 224 K–point (0.63 THz for CrBr<sub>3</sub>, and 0.64 THz for CrI<sub>3</sub>). Indeed, the variations of  $\omega_B$  and  $\omega_J$  can be  
 225 well fitted using:

$$\omega_B = \omega_0^B + \alpha_B B \quad (5)$$

$$\omega_J = \omega_0^J + \alpha_J j \quad (6)$$

226 where  $\omega_0^B(B = 0)$  and  $\omega_0^J(j = 0)$  are the onset frequencies resulting in  $\omega_0^B = 0.29$  THz and  
 227  $\omega_0^J = 0.31$  THz for CrBr<sub>3</sub>; and  $\omega_0^B = 0.25$  THz and  $\omega_0^J = 0.43$  THz for CrI<sub>3</sub>. We also notice  
 228 that the magnitudes of  $\omega_0^B$  and  $\omega_0^J$  may also change due to the inhomogeneous spatial distribution  
 229 of the emitted spin-waves (Supplementary Movie 11) even though with a similar behaviour with  
 230 the field and current. The coefficient  $\alpha_B$  differs moderately between both halides converging to  
 231  $0.13$  THz T<sup>-1</sup> and  $0.05$  THz T<sup>-1</sup> for CrBr<sub>3</sub> and CrI<sub>3</sub>, respectively, with  $\alpha_J \approx 0.04$  THz 10<sup>-9</sup> A  
 232 cm<sup>-2</sup> being similar to both systems. On the field-driven spin-wave emission, the domain wall pre-  
 233 cesses with a frequency near the Larmor frequency  $\omega_0 = \gamma B$ , where  $\gamma$  is the gyromagnetic ratio,  
 234 similarly as in nanowires<sup>54</sup>. We noticed that in both layered materials the spin wave frequencies  
 235 are enclosed between odd- and even-numbered harmonics. That is, CrBr<sub>3</sub> is within  $4\omega_0$  and  $5\omega_0$   
 236 ( $\omega_B - \omega_0^B = 4.81\omega_0$ ), and CrI<sub>3</sub> is within  $\omega_0$  and  $2\omega_0$  ( $\omega_B - \omega_0^B = 1.70\omega_0$ ). This indicates that the  
 237 spin waves and their overtones can be excited with a combination of fundamental modes which  
 238 gives additional flexibility for terahertz source of magnetic signal using atomically thin layers. In

239 addition, the emission of spin waves electrically-driven can be associated with the Doppler effect  
240 on the frequency shift<sup>55</sup>. As the domain wall moves the current changes the spin-waves disper-  
241 sion and incidentally causes an effective flow of the magnetic medium. This is reflected by the  
242 linear dependence of  $\omega_j$  on  $j$  (Fig. 4f) in agreement with the spin-transfer-torque Doppler shift. A  
243 similar approach has been successfully used to study the effect of electric signal into magnons in  
244 permalloy strips<sup>56</sup>, Ni<sub>80</sub>Fe<sub>20</sub> wires<sup>57</sup> and thin films<sup>58</sup>.

245 A substantially different phenomenon is observed when the domain wall is subject to large  
246 current densities,  $j > 10^{10}$  A cm<sup>-2</sup>, with the appearance of spin hydrodynamic effects in CrBr<sub>3</sub>  
247 and CrI<sub>3</sub>. The dynamics is illustrated in Figure 5a-c where we plot line-cuts of the  $M_z$  and  $M_x$   
248 components of the magnetisation at width 25 nm and selected times for monolayer CrI<sub>3</sub>. We  
249 observe that shortly after the electric pulse starting propagating into the system within 18-78 ps  
250 the  $M_x$  projection exhibits a wave propagating ahead of the domain wall. This amplitude tilts  
251  $M_z$  into the plane and increases exponentially (Fig. 5d) until  $M_z$  is completely suppressed and  
252 eventually switches, nucleating a new domain wall. The first period of the wave in  $M_x$  or shock  
253 wave continues to propagate with no appreciable dissipation and new domain walls are nucleated  
254 in its wake with a certain periodicity (Fig. 5a-c). This nonlinear phenomenon is indicative of a  
255 modulational instability (MI) as observed in fluid dynamics<sup>17,59</sup>. This type of instability occurs in  
256 focusing media and describes the exponential growth of waves within a band of wavevectors until  
257 non-linear effects favour their spatial localisation into solitons. MI are ubiquitous in dispersive  
258 physical problems and have been observed in several systems such as in water waves<sup>60</sup>, nonlinear  
259 optics<sup>61</sup> and Bose-Einstein condensates<sup>62</sup>. In magnetic materials however MI has been invoked

260 so far as a pathway for the nucleation of dissipative droplets in perpendicular magnetic anisotropy  
261 (PMA) ferromagnets<sup>63</sup>, as well as the spatial localisation of high-energy magnons in PMA ferri-  
262 magnetic alloys excited with ultrafast optical pulses<sup>64</sup>, and the disintegration of short-wavelength  
263 spin-superfluids in planar ferromagnets<sup>65</sup>. In contrast, we find clear evidence of spin hydrodynamic  
264 behaviour manifested the onset of MI and its nonlinear dynamics driven by electrical currents in  
265 2D magnetic materials. We emphasize that the nonlinear effect observed here is fundamentally  
266 different from Walker breakdown and the subsequent precessional regime so far observed in bulk  
267 magnets.

268 We also observe that MI is visible already at 20 ps as the wavefront exhibits a transverse  
269 structure and can be more generally regarded as a spin shock wave (Fig.6a-c). At 200 ps, there are  
270 rich transverse features in the nanoribbon, from which we can identify a modulationally unstable  
271 region where new domains are established. These domains are bounded by the trailing domain-wall  
272 (soliton edge) and the spin shock wave. At 600 ps, the shock wave is already outside our simulation  
273 profile and the domain walls continue to propagate further (see Supplementary Movie S12 for the  
274 full sequence). The salient features of the MI dynamics can be visualized in Fig. 6d by a colour-plot  
275 of the  $M_z$  component line-cuts as a function of time. After an initial translation of the domain wall,  
276 there is a split of behaviours at  $\approx 0.01$  ns where we can define two characteristic speeds (dashed  
277 lines in Fig. 6d). The shock wave (SW) (Fig. 6b) translates with a speed of  $s^+ = 5.77 \text{ km s}^{-1} \pm$   
278  $0.84 \text{ km s}^{-1}$  which is in sound agreement with the maximum group velocity calculated for CrI<sub>3</sub>  
279 (Supplementary Figure 3). The soliton edge exhibits a phase-shift and subsequent translation with  
280 a speed of  $s_1^- = 1.33 \text{ km s}^{-1} \pm 0.002 \text{ km s}^{-1}$  (Fig. 6b). Consequently, the wavelength  $L$  of the

281 nucleated domains can be extracted from the spectral function at a constant speed, such at  $s^+$   
282 (Fig. 6e). The obtained frequency of the wavefront or SW is computed as  $v_{SW} = 177.5 \text{ GHz} \pm 1.25$   
283 GHz. We can immediately extract  $L$  through a simple speed and frequency relationship via  $L =$   
284  $s^+ / v_{SW} = 5.77 \text{ km s}^{-1} / 177.5 \text{ GHz} = 32.50 \pm 0.23 \text{ nm}$  which is equivalent to a wave-vector of  
285  $k_{SW} = 2\pi / L = 0.19 \text{ nm}^{-1} \pm 0.00003 \text{ nm}^{-1}$ . Indeed, the shock-wave speed corresponds to the  
286 group velocity of the most unstable magnon with a wave-vector given by  $k_{SW}$ .

287 The growing region bounded by the speeds  $s^+$  and  $s_1^-$  is reminiscent to the development of  
288 dispersive shock waves (DSWs)<sup>17</sup> which is located at the modulationally unstable region high-  
289 lighted on Fig.6b. DSWs are ordered structures that smoothly connect the wavevectors at the front  
290 and soliton edges, and have been fully characterised for planar ferromagnets<sup>66</sup>. However, the MI  
291 in our system induces periodic domain-wall nucleation defined by the most unstable wavevec-  
292 tor. Therefore, we can regard the scenario of Figs.6b-c as an unstable generalization of a DSW.  
293 The periodicity of the nucleated domains leads to initially similar domain-wall speeds (parallel  
294 features in the wake of the wavefront) that are later perturbed by interactions, annihilation, and  
295 nucleation events. These can be potentially related to turbulence, thermodynamic behaviour as a  
296 soliton gas<sup>67</sup>, or rare events such as rogue waves<sup>60</sup>. At a later time ( $\approx 0.04 \text{ ns}$ ), a second char-  
297 acteristic domain-wall speed  $s_2^- = 0.88 \text{ km s}^{-1} \pm 0.001 \text{ km s}^{-1}$  is observed. This second speed  
298 appears to be related to an additional source of MI in the wake of the soliton-edge that opposes the  
299 current-driven torque. We can extract the frequency of this domain-wall wake (Fig.6f) resulting  
300 in  $v_{wake} = 6.66 \pm 1.66 \text{ GHz}$ . Given the value of  $s_2^-$ , we can extract a wavelength of  $132.28 \pm 32 \text{ nm}$   
301 which corresponds to the periodicity of where new domain wall appears into the system induced



302 by the wake of the domain-wall motion.

303 Interestingly, we also found that in principle there is no spatial limit for the propagation of  
304 the shock waves in the systems. Simulations undertaken at a mesoscopic level (Supplementary  
305 Figure 4) showed that once an electrical excitations is applied into the system, the transmission  
306 of short-wavelength spin waves can extend for long-distances with minor disturbance from the  
307 medium. We record lengths up to  $10\ \mu\text{m}$  with a group velocity above  $\sim 2000\ \text{m s}^{-1}$  where spin-  
308 waves can work as nanoscale information carriers. The spatial distance is at the same order of  
309 magnitude as those previously obtained in the magnetic insulator yttrium iron garnet (YIG)<sup>68</sup>, and  
310 ferromagnetic nanowires grown on thick YIG thin-film<sup>69</sup>, with both have been proposed as plat-  
311 forms to controllable transmission of spin information. The combination between small damping  
312 ( $\approx 2 \times 10^{-3}$ ) in this class of 2D ferromagnets<sup>37</sup>, the insulating nature of  $\text{CrI}_3$  and  $\text{CrBr}_3$  with no  
313 conduction electrons available to induce decay in the spin signal<sup>70</sup> and the relative low magnon  
314 scattering<sup>71</sup> make magnetic layered materials a new endeavour for magnonics applications.

### 315 Discussion

316 The possibility to manipulate and control domain walls precisely on 2D vdW  $\text{CrX}_3$  ( $X=\text{Br, I}$ )  
317 magnets opens up a pathway to design a range of novel and highly competitive applications in  
318 the thickness of a few atoms. As some of the critical parameters to domain-wall based devices  
319 are domain wall widths, which control the information density, domain wall motion, directly gov-  
320 erning access time, and pinning processes, that determine the energy consumption, 2D magnets

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321 show features that are fundamental for integration in novel memory technologies, such as race-  
322 track memories<sup>4</sup>. The large domain wall speeds achieved in both CrBr<sub>3</sub> and CrI<sub>3</sub> at the limit of  
323 1020 m s<sup>-1</sup> compete side-by-side with the best materials used for racetrack applications (e.g. syn-  
324 thetic antiferromagnets<sup>12</sup>) where complex interfaces need to be fabricated to induce fast domain  
325 wall shifting. This remarkable result, along with recent advances in the scalable bottom-up growth  
326 of CrX<sub>3</sub> in the monolayer regime<sup>72,73</sup>, clearly presents as an opportunity for reduction on man-  
327 ufacturing and time-consuming device preparation. There is still a challenge that needs to be  
328 overcome to enable current-driven excitations in these 2D magnetic halides, for instance, the en-  
329 hancement of the conductivity and the consequent reduction of the current densities used to move  
330 domain walls. One route is to use doping, which is a well-known strategy that has been widely  
331 employed in other prototypical ferromagnetic semiconductors (such as (Ga,Mn)As)<sup>47</sup>. In fact,  
332 carrier doping has been found to induce half-metallicity and enhance the ferromagnetic stability  
333 in CrI<sub>3</sub> monolayer<sup>39,74</sup>, such that current-induced phenomena become feasible without compro-  
334 mising the magnetic properties. It is worth mentioning that some trade-off between conductivity  
335 enhancement and dissipation through the conduction electrons would have to be achieved for low-  
336 power consumption. It is well known that large Gilbert damping  $\lambda_G$  allows fast relaxation of the  
337 magnetization to equilibrium, whereas low damping enables energy-efficient processes. Several  
338 approaches<sup>75-78</sup> were previously developed on metallic systems that may assist in the pursue of the  
339 modelling of conduction electrons on doped-2D magnets. If the electrical conductivity of CrX<sub>3</sub>  
340 (X=I, Br) is enhanced due to different chemical or physical processes, the values of the domain  
341 wall speeds shown in Figure 3 would be robust against such variations. Since the magnitude of

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342 the Gilbert damping  $\lambda_G$  utilised in the simulations ( $\lambda_G = 0.10$ ) is high than that expected for  $\text{CrI}_3$   
343 and  $\text{CrBr}_3$ <sup>37</sup>, we intrinsically take into account additional dissipation effects in our simulations.  
344 Furthermore, investigations to clarify the effect of different dopants, concentration and their im-  
345 plications on both damping and the magnetic properties of 2D magnets are promptly needed. The  
346 emission of spin waves in the THz regime and the spin hydrodynamic behaviour observed for both  
347 halides, also merit further exploration on novel information technologies. On one hand, the de-  
348 sign of sources, detectors and prototypes functioning in the THz-gap (0.3–30 THz)<sup>79</sup> provides the  
349 groundwork for the developments of high-end electronics on the low-end of the electromagnetic  
350 spectrum. The ultrathin character of 2D magnets, their flexibility in generating tunable frequen-  
351 cies, and inexpensive sample cost relative to expensive bulky compounds<sup>79</sup>, make vdW layered  
352 materials a playground for applications. On the other hand, the use of magnons for information  
353 carrier at the  $\mu\text{m}$ -scale puts vdW sheets in the roadmap of post-semiconductor spin-wave tech-  
354 nologies. The characteristic soliton features observed on the shock-waves in both ferromagnets  
355 and consequent low dissipation indicate that magnon-based data operations may be explored for  
356 information processing. In this sense, the development of an energy-efficient spin-wave transducer  
357 through vdW materials is one of the key steps for the ultimate goal of hybrid spin-wave computing  
358 systems.

### 359 **Supplementary Materials**

360 Methods, Supplementary Figures S1–S4, and Supplementary movies S1–S12.

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361 **Data Availability**

362 The data that support the findings of this study are available within the paper and its Supplementary  
363 Information.

364 **Competing interests**

365 The Authors declare no conflict of interests.

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373 **References**

374

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 375 1. Beach, G. S. D., Tsoi, M. & Erskine, J. L. Current-induced domain wall motion. *Jour-*  
376 *nal of Magnetism and Magnetic Materials* **320**, 1272–1281 (2008). URL [http://www.](http://www.sciencedirect.com/science/article/pii/S0304885307010141)  
377 [sciencedirect.com/science/article/pii/S0304885307010141](http://www.sciencedirect.com/science/article/pii/S0304885307010141).
- 378 2. Tatara, G., Kohno, H. & Shibata, J. Microscopic approach to current-driven domain wall  
379 dynamics. *Physics Reports* **468**, 213 – 301 (2008). URL [http://www.sciencedirect.](http://www.sciencedirect.com/science/article/pii/S0370157308002597)  
380 [com/science/article/pii/S0370157308002597](http://www.sciencedirect.com/science/article/pii/S0370157308002597).
- 381 3. Ralph, D. & Stiles, M. Spin transfer torques. *Journal of Magnetism and Magnetic Materi-*  
382 *als* **320**, 1190 – 1216 (2008). URL [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0304885307010116)  
383 [pii/S0304885307010116](http://www.sciencedirect.com/science/article/pii/S0304885307010116).
- 384 4. Parkin, S. S. P., Hayashi, M. & Thomas, L. Magnetic domain-wall racetrack memory.  
385 *Science* **320**, 190–194 (2008). URL [https://science.sciencemag.org/content/320/](https://science.sciencemag.org/content/320/5873/190)  
386 [5873/190](https://science.sciencemag.org/content/320/5873/190). <https://science.sciencemag.org/content/320/5873/190.full.pdf>.
- 387 5. Huang, B. *et al.* Layer-dependent ferromagnetism in a van der waals crystal down to the mono-  
388 layer limit. *Nature* **546**, 270 EP – (2017). URL <https://doi.org/10.1038/nature22391>.
- 389 6. Gong, C. *et al.* Discovery of intrinsic ferromagnetism in two-dimensional van der waals crys-  
390 tals. *Nature* **546**, 265–269 (2017). URL <http://dx.doi.org/10.1038/nature22060>. Let-  
391 ter.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 392 7. Guguchia, Z. *et al.* Magnetism in semiconducting molybdenum dichalcogenides. *Science Ad-*  
393 *vances* **4** (2018). URL <https://advances.sciencemag.org/content/4/12/eaat3672>.  
394 <https://advances.sciencemag.org/content/4/12/eaat3672.full.pdf>.
- 395 8. Klein, D. R. *et al.* Probing magnetism in 2d van der waals crystalline insu-  
396 lators via electron tunneling. *Science* **360**, 1218–1222 (2018). URL [http://](http://science.sciencemag.org/content/360/6394/1218)  
397 [science.sciencemag.org/content/360/6394/1218](http://science.sciencemag.org/content/360/6394/1218). <http://science.sciencemag.org/content/360/6394/1218.full.pdf>.
- 398
- 399 9. Allwood, D. A. *et al.* Magnetic domain-wall logic. *Science* **309**, 1688–1692  
400 (2005). URL <https://science.sciencemag.org/content/309/5741/1688>. <https://science.sciencemag.org/content/309/5741/1688.full.pdf>.  
401
- 402 10. Luo, Z. *et al.* Current-driven magnetic domain-wall logic. *Nature* **579**, 214–218 (2020). URL  
403 <https://doi.org/10.1038/s41586-020-2061-y>.
- 404 11. Xu, P. *et al.* An all-metallic logic gate based on current-driven domain wall motion. *Nature*  
405 *Nanotechnology* **3**, 97–100 (2008). URL <https://doi.org/10.1038/nnano.2008.1>.
- 406 12. Yang, S.-H., Ryu, K.-S. & Parkin, S. Domain-wall velocities of up to 750 m s<sup>-1</sup> driven by  
407 exchange-coupling torque in synthetic antiferromagnets. *Nature Nanotechnology* **10**, 221–226  
408 (2015). URL <https://doi.org/10.1038/nnano.2014.324>.
- 409 13. Woo, S. *et al.* Observation of room-temperature magnetic skyrmions and their current-driven  
410 dynamics in ultrathin metallic ferromagnets. *Nature Materials* **15**, 501–506 (2016). URL  
411 <https://doi.org/10.1038/nmat4593>.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 412 14. Vélez, S. *et al.* High-speed domain wall racetracks in a magnetic insulator. *Nature Communi-*  
413 *cations* **10**, 4750 (2019). URL <https://doi.org/10.1038/s41467-019-12676-7>.
- 414 15. Siddiqui, S. A., Han, J., Finley, J. T., Ross, C. A. & Liu, L. Current-induced domain wall  
415 motion in a compensated ferrimagnet. *Phys. Rev. Lett.* **121**, 057701 (2018). URL <https://link.aps.org/doi/10.1103/PhysRevLett.121.057701>.  
416
- 417 16. Ryu, K.-S., Thomas, L., Yang, S.-H. & Parkin, S. Chiral spin torque at magnetic domain  
418 walls. *Nature Nanotechnology* **8**, 527–533 (2013). URL [https://doi.org/10.1038/](https://doi.org/10.1038/nnano.2013.102)  
419 [nnano.2013.102](https://doi.org/10.1038/nnano.2013.102).
- 420 17. Rabinovich, M. & Trubetskov, D. *Oscillations and Waves: in Linear and Nonlinear Sys-*  
421 *tems*. Mathematics and its Applications (Springer Netherlands, 2011). URL [https://books.](https://books.google.es/books?id=cUYfswEACAAJ)  
422 [google.es/books?id=cUYfswEACAAJ](https://books.google.es/books?id=cUYfswEACAAJ).
- 423 18. Parkin, S. & Yang, S.-H. Memory on the racetrack. *Nature Nanotechnology* **10**, 195–198  
424 (2015). URL <https://doi.org/10.1038/nnano.2015.41>.
- 425 19. Baltz, V. *et al.* Antiferromagnetic spintronics. *Rev. Mod. Phys.* **90**, 015005 (2018). URL  
426 <https://link.aps.org/doi/10.1103/RevModPhys.90.015005>.
- 427 20. Cowburn, R. P. & Welland, M. E. Room temperature magnetic quantum cellular automata.  
428 *Science* **287**, 1466–1468 (2000). URL [https://science.sciencemag.org/content/287/](https://science.sciencemag.org/content/287/5457/1466)  
429 [5457/1466](https://science.sciencemag.org/content/287/5457/1466). <https://science.sciencemag.org/content/287/5457/1466.full.pdf>.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 430 21. Allwood, D. A. *et al.* Submicrometer ferromagnetic not gate and shift register. *Science* **296**,  
431 2003–2006 (2002). URL <https://science.sciencemag.org/content/296/5575/2003>.  
432 <https://science.sciencemag.org/content/296/5575/2003.full.pdf>.
- 433 22. Diegel, M., Glathe, S., Mattheis, R., Scherzinger, M. & Halder, E. A new four bit magnetic  
434 domain wall based multiturn counter. *IEEE Transactions on Magnetics* **45**, 3792–3795 (2009).
- 435 23. Kim, H. H. *et al.* One million percent tunnel magnetoresistance in a magnetic van der waals  
436 heterostructure. *Nano Letters* **18**, 4885–4890 (2018). URL [https://doi.org/10.1021/](https://doi.org/10.1021/acs.nanolett.8b01552)  
437 [acs.nanolett.8b01552](https://doi.org/10.1021/acs.nanolett.8b01552).
- 438 24. Ghazaryan, D. *et al.* Magnon-assisted tunnelling in van der waals heterostructures based  
439 on crbr3. *Nature Electronics* **1**, 344–349 (2018). URL [https://doi.org/10.1038/](https://doi.org/10.1038/s41928-018-0087-z)  
440 [s41928-018-0087-z](https://doi.org/10.1038/s41928-018-0087-z).
- 441 25. Cantos-Prieto, F. *et al.* Layer-dependent mechanical properties and enhanced plasticity in  
442 the van der waals chromium trihalide magnets. *Nano Letters* **21**, 3379–3385 (2021). URL  
443 <https://doi.org/10.1021/acs.nanolett.0c04794>.
- 444 26. Chappert, C., Fert, A. & Van Dau, F. N. The emergence of spin electronics in data storage.  
445 *Nature Materials* **6**, 813–823 (2007). URL <https://doi.org/10.1038/nmat2024>.
- 446 27. Manchon, A. *et al.* Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic  
447 systems. *Rev. Mod. Phys.* **91**, 035004 (2019). URL [https://link.aps.org/doi/10.1103/](https://link.aps.org/doi/10.1103/RevModPhys.91.035004)  
448 [RevModPhys.91.035004](https://link.aps.org/doi/10.1103/RevModPhys.91.035004).



This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 449 28. Gupta, V. *et al.* Manipulation of the van der waals magnet  $\text{Cr}_2\text{Ge}_2\text{Te}_6$  by spin-orbit torques.  
450 *Nano Letters* **20**, 7482–7488 (2020). URL [https://doi.org/10.1021/acs.nanolett.](https://doi.org/10.1021/acs.nanolett.0c02965)  
451 [0c02965](https://doi.org/10.1021/acs.nanolett.0c02965).
- 452 29. Wang, X. *et al.* Current-driven magnetization switching in a van der waals ferromag-  
453 net  $\text{Fe}_3\text{GeTe}_2$ . *Science Advances* **5** (2019). URL [https://advances.sciencemag.](https://advances.sciencemag.org/content/5/8/eaaw8904)  
454 [org/content/5/8/eaaw8904](https://advances.sciencemag.org/content/5/8/eaaw8904). [https://advances.sciencemag.org/content/5/8/](https://advances.sciencemag.org/content/5/8/eaaw8904.full.pdf)  
455 [eaaw8904.full.pdf](https://advances.sciencemag.org/content/5/8/eaaw8904.full.pdf).
- 456 30. Wahab, D. A. *et al.* Quantum rescaling, domain metastability, and hybrid domain-  
457 walls in 2d  $\text{CrI}_3$  magnets. *Advanced Materials* **33**, 2004138 (2021). URL  
458 <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202004138>. [https://](https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202004138)  
459 [onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202004138](https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202004138).
- 460 31. Sun, Q.-C. *et al.* Magnetic domains and domain wall pinning in atomically thin  $\text{CrBr}_3$  revealed  
461 by nanoscale imaging. *Nature Communications* **12**, 1989 (2021). URL [https://doi.org/](https://doi.org/10.1038/s41467-021-22239-4)  
462 [10.1038/s41467-021-22239-4](https://doi.org/10.1038/s41467-021-22239-4).
- 463 32. Kartsev, A., Augustin, M., Evans, R. F. L., Novoselov, K. S. & Santos, E. J. G. Biquadratic ex-  
464 change interactions in two-dimensional magnets. *npj Computational Materials* **6**, 150 (2020).  
465 URL <https://doi.org/10.1038/s41524-020-00416-1>.
- 466 33. Soriano, D., Katsnelson, M. I. & Fernández-Rossier, J. Magnetic two-dimensional chromium  
467 trihalides: A theoretical perspective. *Nano Letters* **20**, 6225–6234 (2020). URL [https://](https://doi.org/10.1021/acs.nanolett.0c02381)  
468 [doi.org/10.1021/acs.nanolett.0c02381](https://doi.org/10.1021/acs.nanolett.0c02381).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 469 34. Chen, L. *et al.* Topological spin excitations in honeycomb ferromagnet  $\text{CrI}_3$ . *Phys. Rev. X* **8**,  
470 041028 (2018). URL <https://link.aps.org/doi/10.1103/PhysRevX.8.041028>.
- 471 35. Wildes, A. R., Zhitomirsky, M. E., Ziman, T., Lançon, D. & Walker, H. C. Evidence for  
472 biquadratic exchange in the quasi-two-dimensional antiferromagnet  $\text{FePS}_3$ . *Journal of Applied*  
473 *Physics* **127**, 223903 (2020). URL <https://doi.org/10.1063/5.0009114>. <https://doi.org/10.1063/5.0009114>.
- 474
- 475 36. Augustin, M., Jenkins, S., Evans, R. F. L., Novoselov, K. S. & Santos, E. J. G. Prop-  
476 erties and dynamics of meron topological spin textures in the two-dimensional magnet  
477  $\text{CrI}_3$ . *Nature Communications* **12**, 185 (2021). URL <https://doi.org/10.1038/s41467-020-20497-2>.
- 478
- 479 37. Kapoor, L. N. *et al.* Observation of standing spin waves in a van der waals magnetic ma-  
480 terial. *Advanced Materials* **33**, 2005105 (2021). URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202005105>. <https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202005105>.
- 481
- 482
- 483 38. Abramchuk, M. *et al.* Controlling magnetic and optical properties of the van der waals crys-  
484 tal  $\text{CrI}_3\text{XBr}_x$  via mixed halide chemistry. *Advanced Materials* **30**, 1801325 (2018). URL  
485 <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201801325>. <https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.201801325>.
- 486
- 487 39. Jiang, S., Li, L., Wang, Z., Mak, K. F. & Shan, J. Controlling magnetism in 2d  $\text{CrI}_3$  by  
488 electrostatic doping. *Nature Nanotechnology* **13**, 549–553 (2018). URL <https://doi.org/>

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 489 10.1038/s41565-018-0135-x.
- 490 40. Kim, H. H. *et al.* Evolution of interlayer and intralayer magnetism in three atomically thin  
491 chromium trihalides. *PNAS* **116**, 11131–11136 (2019).
- 492 41. Hubert, A. & Schafer, R. *Magnetic Domains: The Analysis of Magnetic Microstructures*  
493 (Springer Science and Business Media, 2008).
- 494 42. Schryer, N. L. & Walker, L. R. The motion of 180° domain walls in uniform dc magnetic  
495 fields. *Journal of Applied Physics* **45**, 5406–5421 (1974). URL [https://doi.org/10.](https://doi.org/10.1063/1.1663252)  
496 [1063/1.1663252](https://doi.org/10.1063/1.1663252). <https://doi.org/10.1063/1.1663252>.
- 497 43. Metaxas, P. J. *et al.* Creep and flow regimes of magnetic domain-wall motion in ultrathin  
498 Pt/Co/Pt films with perpendicular anisotropy. *Phys. Rev. Lett.* **99**, 217208 (2007). URL  
499 <https://link.aps.org/doi/10.1103/PhysRevLett.99.217208>.
- 500 44. Pizzini, S. *et al.* Chirality-induced asymmetric magnetic nucleation in Pt/Co/AlO<sub>x</sub> ultrathin  
501 microstructures. *Phys. Rev. Lett.* **113**, 047203 (2014). URL [https://link.aps.org/doi/](https://link.aps.org/doi/10.1103/PhysRevLett.113.047203)  
502 [10.1103/PhysRevLett.113.047203](https://link.aps.org/doi/10.1103/PhysRevLett.113.047203).
- 503 45. Bode, M. Spin-polarized scanning tunnelling microscopy. *Reports on Progress in Physics* **66**,  
504 523–582 (2003). URL <https://doi.org/10.1088/0034-4885/66/2/203>.
- 505 46. Casola, F., van der Sar, T. & Yacoby, A. Probing condensed matter physics with magnetometry  
506 based on nitrogen-vacancy centres in diamond. *Nature Reviews Materials* **3**, 17088 (2018).  
507 URL <https://doi.org/10.1038/natrevmats.2017.88>.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 508 47. Yamanouchi, M., Chiba, D., Matsukura, F., Dietl, T. & Ohno, H. Velocity of domain-wall  
509 motion induced by electrical current in the ferromagnetic semiconductor (Ga,Mn)As. *Phys.*  
510 *Rev. Lett.* **96**, 096601 (2006). URL [https://link.aps.org/doi/10.1103/PhysRevLett.](https://link.aps.org/doi/10.1103/PhysRevLett.96.096601)  
511 96.096601.
- 512 48. Miron, I. M. *et al.* Fast current-induced domain-wall motion controlled by the Rashba effect.  
513 *Nature Materials* **10**, 419–423 (2011). URL <https://doi.org/10.1038/nmat3020>.
- 514 49. Emori, S., Bauer, U., Ahn, S.-M., Martinez, E. & Beach, G. S. D. Current-driven dynamics  
515 of chiral ferromagnetic domain walls. *Nature Materials* **12**, 611–616 (2013). URL <https://doi.org/10.1038/nmat3675>.
- 516 //doi.org/10.1038/nmat3675.
- 517 50. Wieser, R., Vedmedenko, E. Y. & Wiesendanger, R. Domain wall motion damped by the  
518 emission of spin waves. *Phys. Rev. B* **81**, 024405 (2010). URL [https://link.aps.org/](https://link.aps.org/doi/10.1103/PhysRevB.81.024405)  
519 [doi/10.1103/PhysRevB.81.024405](https://doi.org/10.1103/PhysRevB.81.024405).
- 520 51. Zhang, S. & Li, Z. Roles of nonequilibrium conduction electrons on the magnetization dy-  
521 namics of ferromagnets. *Phys. Rev. Lett.* **93**, 127204 (2004). URL [https://link.aps.org/](https://link.aps.org/doi/10.1103/PhysRevLett.93.127204)  
522 [doi/10.1103/PhysRevLett.93.127204](https://doi.org/10.1103/PhysRevLett.93.127204).
- 523 52. Thiaville, A., Nakatani, Y., Miltat, J. & Suzuki, Y. Micromagnetic understanding of current-  
524 driven domain wall motion in patterned nanowires. *Europhys. Lett.* **69**, 990–996 (2005). URL  
525 <https://doi.org/10.1209/epl/i2004-10452-6>.
- 526 53. Hayashi, M. *et al.* Influence of current on field-driven domain wall motion in permalloy  
527 nanowires from time resolved measurements of anisotropic magnetoresistance. *Phys. Rev.*

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 528 *Lett.* **96**, 197207 (2006). URL [https://link.aps.org/doi/10.1103/PhysRevLett.96.](https://link.aps.org/doi/10.1103/PhysRevLett.96.197207)  
529 197207.
- 530 54. Wang, X. S. & Wang, X. R. Spin wave emission in field-driven domain wall motion. *Phys. Rev.*  
531 *B* **90**, 184415 (2014). URL [https://link.aps.org/doi/10.1103/PhysRevB.90.184415.](https://link.aps.org/doi/10.1103/PhysRevB.90.184415)
- 532 55. Lederer, P. & Mills, D. L. Possible experimental test of the band theory of magnetism. *Phys.*  
533 *Rev.* **148**, 542–547 (1966). URL [https://link.aps.org/doi/10.1103/PhysRev.148.](https://link.aps.org/doi/10.1103/PhysRev.148.542)  
534 542.
- 535 56. Vlaminck, V. & Bailleul, M. Current-induced spin-wave doppler shift. *Science* **322**, 410–  
536 413 (2008). URL [https://science.sciencemag.org/content/322/5900/410.](https://science.sciencemag.org/content/322/5900/410) [https://science.sciencemag.org/content/322/5900/410.full.pdf.](https://science.sciencemag.org/content/322/5900/410.full.pdf)
- 537
- 538 57. Zhu, M., Dennis, C. L. & McMichael, R. D. Temperature dependence of magnetization drift  
539 velocity and current polarization in  $\text{ni}_{80}\text{fe}_{20}$  by spin-wave doppler measurements. *Phys. Rev. B*  
540 **81**, 140407 (2010). URL [https://link.aps.org/doi/10.1103/PhysRevB.81.140407.](https://link.aps.org/doi/10.1103/PhysRevB.81.140407)
- 541 58. Sekiguchi, K. *et al.* Time-domain measurement of current-induced spin wave dynam-  
542 ics. *Phys. Rev. Lett.* **108**, 017203 (2012). URL [https://link.aps.org/doi/10.1103/](https://link.aps.org/doi/10.1103/PhysRevLett.108.017203)  
543 [PhysRevLett.108.017203.](https://link.aps.org/doi/10.1103/PhysRevLett.108.017203)
- 544 59. Whitham, G. B. *Linear and nonlinear waves* (John Wiley & Sons Inc, 1974).
- 545 60. Bonnefoy, F. *et al.* From modulational instability to focusing dam breaks in water waves.  
546 *Phys. Rev. Fluids* **5**, 034802 (2020).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 547 61. Marcucci, G. *et al.* Topological control of extreme waves. *Nature Communications* **10**, 5090  
548 (2019).
- 549 62. Kevrekidis, P. G., Frantzeskakis, D. J. & Carretero-González, R. *The Defocusing Nonlinear*  
550 *Schrödinger Equation* (SIAM, Philadelphia, 2015).
- 551 63. Mohseni, S. M. *et al.* Spin torque generated magnetic droplet solitons. *Science* **339**, 1295–  
552 1298 (2013).
- 553 64. Iacocca, E. *et al.* Spin-current-mediated rapid magnon localization and coalescence after ul-  
554 trafast optical pumping of ferrimagnetic alloys. *Nature Communications* **10**, 1756 (2019).
- 555 65. Iacocca, E., Silva, T. J. & Hofer, M. A. Breaking of galilean invariance in the hydrodynamic  
556 formulation of ferromagnetic thin films. *Phys. Rev. Lett.* **118**, 017203 (2017).
- 557 66. Ivanov, S. K., Kamchatnov, A. M., Congy, T. & Pavloff, N. Solution of the riemann problem  
558 for polarization waves in a two-component bose-einstein condensate. *Phys. Rev. E* **96**, 062202  
559 (2017).
- 560 67. Gelash, A. *et al.* Bound state soliton gas dynamics underlying the spontaneous modulational  
561 instability. *Phys. Rev. Lett.* **123**, 234102 (2019).
- 562 68. Cornelissen, L. J., Liu, J., Duine, R. A., Youssef, J. B. & van Wees, B. J. Long-distance  
563 transport of magnon spin information in a magnetic insulator at room temperature. *Nature*  
564 *Physics* **11**, 1022–1026 (2015). URL <https://doi.org/10.1038/nphys3465>.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

- 565 69. Liu, C. *et al.* Long-distance propagation of short-wavelength spin waves. *Nature Communi-*  
566 *cations* **9**, 738 (2018). URL <https://doi.org/10.1038/s41467-018-03199-8>.
- 567 70. Kajiwara, Y. *et al.* Transmission of electrical signals by spin-wave interconversion in a  
568 magnetic insulator. *Nature* **464**, 262–266 (2010). URL [https://doi.org/10.1038/](https://doi.org/10.1038/nature08876)  
569 [nature08876](https://doi.org/10.1038/nature08876).
- 570 71. Xing, W. *et al.* Magnon transport in quasi-two-dimensional van der waals antiferromagnets.  
571 *Phys. Rev. X* **9**, 011026 (2019). URL [https://link.aps.org/doi/10.1103/PhysRevX.](https://link.aps.org/doi/10.1103/PhysRevX.9.011026)  
572 [9.011026](https://link.aps.org/doi/10.1103/PhysRevX.9.011026).
- 573 72. Bedoya-Pinto, A. *et al.* Intrinsic 2d-xy ferromagnetism in a van der waals monolayer.  
574 *arXiv:2006.07605* .
- 575 73. Kezilebieke, S. *et al.* Electronic and magnetic characterization of epitaxial crbr3 mono-  
576 layers on a superconducting substrate. *Advanced Materials* **33**, 2006850 (2021). URL  
577 <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202006850>. [https://](https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202006850)  
578 [onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202006850](https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202006850).
- 579 74. Wang, H., Fan, F., Zhu, S. & Wu, H. Doping enhanced ferromagnetism and induced half-  
580 metallicity in CrI<sub>3</sub> monolayer. *EPL (Europhysics Letters)* **114**, 47001 (2016). URL [https://](https://doi.org/10.1209/0295-5075/114/47001)  
581 [doi.org/10.1209/0295-5075/114/47001](https://doi.org/10.1209/0295-5075/114/47001).
- 582 75. Zhang, S. & Zhang, S. S.-L. Generalization of the landau-lifshitz-gilbert equation for con-  
583 ducting ferromagnets. *Phys. Rev. Lett.* **102**, 086601 (2009). URL [https://link.aps.org/](https://link.aps.org/doi/10.1103/PhysRevLett.102.086601)  
584 [doi/10.1103/PhysRevLett.102.086601](https://link.aps.org/doi/10.1103/PhysRevLett.102.086601).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50062541

- 585 76. Kim, K.-W., Moon, J.-H., Lee, K.-J. & Lee, H.-W. Prediction of giant spin motive force due to  
586 rashba spin-orbit coupling. *Phys. Rev. Lett.* **108**, 217202 (2012). URL [https://link.aps.](https://link.aps.org/doi/10.1103/PhysRevLett.108.217202)  
587 [org/doi/10.1103/PhysRevLett.108.217202](https://link.aps.org/doi/10.1103/PhysRevLett.108.217202).
- 588 77. Petrović, M. D., Bajpai, U., Plecháč, P. & Nikolić, B. K. Annihilation of topological solitons  
589 in magnetism with spin-wave burst finale: Role of nonequilibrium electrons causing nonlocal  
590 damping and spin pumping over ultrabroadband frequency range. *Phys. Rev. B* **104**, L020407  
591 (2021). URL <https://link.aps.org/doi/10.1103/PhysRevB.104.L020407>.
- 592 78. Weindler, T. *et al.* Magnetic damping: Domain wall dynamics versus local ferromagnetic  
593 resonance. *Phys. Rev. Lett.* **113**, 237204 (2014). URL [https://link.aps.org/doi/10.](https://link.aps.org/doi/10.1103/PhysRevLett.113.237204)  
594 [1103/PhysRevLett.113.237204](https://link.aps.org/doi/10.1103/PhysRevLett.113.237204).
- 595 79. Dhillon, S. S. *et al.* The 2017 terahertz science and technology roadmap. *Journal of Physics*  
596 *D: Applied Physics* **50**, 043001 (2017). URL [https://doi.org/10.1088/1361-6463/50/](https://doi.org/10.1088/1361-6463/50/4/043001)  
597 [4/043001](https://doi.org/10.1088/1361-6463/50/4/043001).



598 **Figure captions**

Figure 1: **Magnetic domains at different temperatures and fields.** **a-e**, Dynamical spin configurations of monolayer  $\text{CrBr}_3$  during zero-field cooling (0 mT) at different temperatures. The out-of-plane magnetization  $M_z$  (a.u.) is used to follow the evolution of the magnetic domains from 40 K down to 0 K. **f-j**, **k-o**, and **p-t**, Similar as **a-e**, but at magnetic fields of 5 mT, 11 mT and 50 mT, respectively. Temperatures at the top row correspond to all panels in the same column. Time scale spanned up to 2.5 ns till 0 K is achieved. Further evolution are observed at later times as shown in Supplementary Movies S1-S4.

Figure 2: **Hybrid domain walls with Néel-Bloch characteristics.** **a-b**, Global and local views, respectively, of a snapshot for one of the spin configurations projected along  $M_z$  (colour map) showing the formation of a domain wall in monolayer  $\text{CrBr}_3$ . The total strip in **a** is  $400 \times 50$  nm. Only Cr atoms are showed in the honeycomb lattice arrangement of monolayer  $\text{CrBr}_3$ . The system is at 0 K without any external fields or currents. **c-d**, Side and top views, respectively, of the rotation of the magnetization along the domain wall. Both  $M_x$  and  $M_y$  show variations along the wall altogether with  $M_z$  which indicate a hybrid character of the domain wall with Néel and Bloch features. Colours follow the scale bar in **a**. The small area around the domain wall highlighted in **a** corresponds to **c**. **e-f**, Variation of the magnetization along the domain wall projected along the in-plane components ( $M_x$ ,  $M_y$ ) and  $M_z$ , respectively. Fitting lines are obtained using Eqs.2-3.

Figure 3: **Current- and field-induced domain wall dynamics in 2D ferromagnets.** **a**, Initial domain wall configuration for monolayer CrBr<sub>3</sub> at no external driving forces ( $j=0$ ,  $B=0$ ). The domain wall is initially equilibrated for up to 4 ns to ensure convergence of the spin orientations along the wall and width. The same final configuration is utilised for both field- and current-driven domain wall motion. Similar procedure is undertaken to monolayer CrI<sub>3</sub>. **b-c**, Snapshots of the domain wall dynamics in CrBr<sub>3</sub> induced by magnetic fields (0.05 T, 1.50 T) and electric currents ( $8.7 \times 10^9$  A cm<sup>-2</sup>,  $4.3 \times 10^9$  A cm<sup>-2</sup>), respectively. The edges used in the simulations are highlighted at  $B=1.50$  T with dangling-bond and zig-zag at the top and bottom of the layer, respectively. Deformations observed near the domain wall at  $j=4.3 \times 10^9$  A cm<sup>-2</sup> are highlighted by the dashed rectangle. **d**, Zoom-in of the local spin-configurations at  $j=4.3 \times 10^9$  A cm<sup>-2</sup> with colour scale showing the variations of the spin orientations along  $M_z$  induced by the large current density.

Figure 4: **Domain wall speeds and spin wave frequency.** **a-b**, Calculated domain wall velocities  $v$  versus the applied magnetic field  $B$  for CrBr<sub>3</sub> and CrI<sub>3</sub>, respectively. The vertical solid lines indicate the region where the nucleation of magnetic bubbles starts in each material as those shown in **b** at 1.50 T for CrBr<sub>3</sub>. A fit using  $v = \mu(B - B_o)$ , where  $\mu$  is the domain wall mobility and  $B_o$  is the onset field, reproduces accurately the atomistic simulation data with linear regression coefficients  $R^2 = 0.99$  and a root-mean-square-error of 0.0074. The field is applied perpendicular to the surface following the easy-axis of the materials. **c-d**, Variations of  $v$  as a function of the current density  $j$  for CrBr<sub>3</sub> and CrI<sub>3</sub>, respectively. Two regimes are observed in the internal dynamics of the wall before and after the Walker breakdown ( $j_w$ ) with the wall motion being in steady and precessional states, respectively. We could extract  $j_w^{CrBr_3} = 4.8 \times 10^9$  A cm<sup>-2</sup> and  $j_w^{CrI_3} = 12.0 \times 10^9$  A cm<sup>-2</sup>. Both steady and precessional regimes on the domain-wall dynamics can be modelled using a 1D model as described in the text. The insets show the velocities at lower values of current within  $j \leq 8.5 \times 10^8$  A cm<sup>-2</sup>. **e-f**, Frequencies  $\omega_B$ (THz) and  $\omega_j$ (THz) of the emitted spin-waves during the domain-wall motion as a function of  $B$  and  $j$ , respectively, for CrBr<sub>3</sub> and CrI<sub>3</sub>. Dashed lines are corresponding fits to Eqs. 5–6. Similar data labelling applies for **e** and **f**.

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Figure 5: **Modulational instability in 2D magnets.** **a-c**, Snapshots of the magnetisation along  $M_z$  and  $M_x$  magnetisation components at different times at 18 ps, 40 ps and 78 ps, respectively. **d**, Amplitude of  $M_x$  as a function of time at different current densities.

Figure 6: **Long range spin-wave propagation.** **a-c**, Snapshots of spin-dynamics at 20 ps, 200 ps and 600 ps, respectively, under a current density of  $1.56 \times 10^{10} \text{ A cm}^{-2}$ .  $M_z$  is used to show the variations of the domain wall with the colour scale along the length of the ribbon. A separation of the motion of the original domain wall (soliton edge) and the shock waves can be observed between a wave train (modulationally unstable) propagating throughout the system. **d**, Colour-plot of the variations of  $M_z$  with the propagation time along a  $2\text{-}\mu\text{m}$  ribbon of  $\text{CrBr}_3$  at a current density of  $1.56 \times 10^{10} \text{ A cm}^{-2}$ . The different line-cuts correspond to the several waveforms moving into the systems as shown in **e-g**. The dashed lines are given by  $s^+ = 5773 \text{ m s}^{-1} \pm 0.84 \text{ m s}^{-1}$ ,  $s_1^- = 1328 \text{ m s}^{-1} \pm 1.7 \text{ m s}^{-1}$  and  $s_2^- = 882 \text{ m s}^{-1} \pm 1.8 \text{ m s}^{-1}$ . **e-f**, Spectral density (arb. units) extracted from the fast Fourier transform of the  $M_z$  component as function of time in **d** along velocities  $s^+$  and  $s_2^-$ , respectively. The characteristic frequencies of the shock waves and the domain-wall wake can be identified as  $v_{SW} = 177.5 \text{ GHz} \pm 1.25 \text{ GHz}$  and  $v_{wake} = 6.66 \pm 1.66 \text{ GHz}$ , respectively.

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599 **Figures**

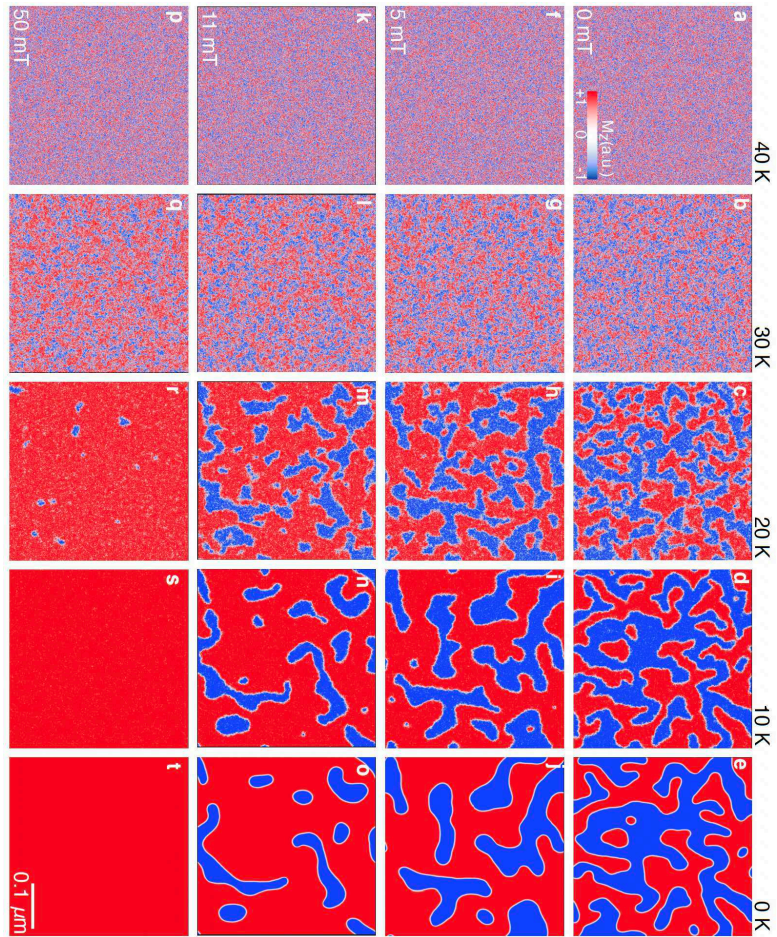


Figure 1

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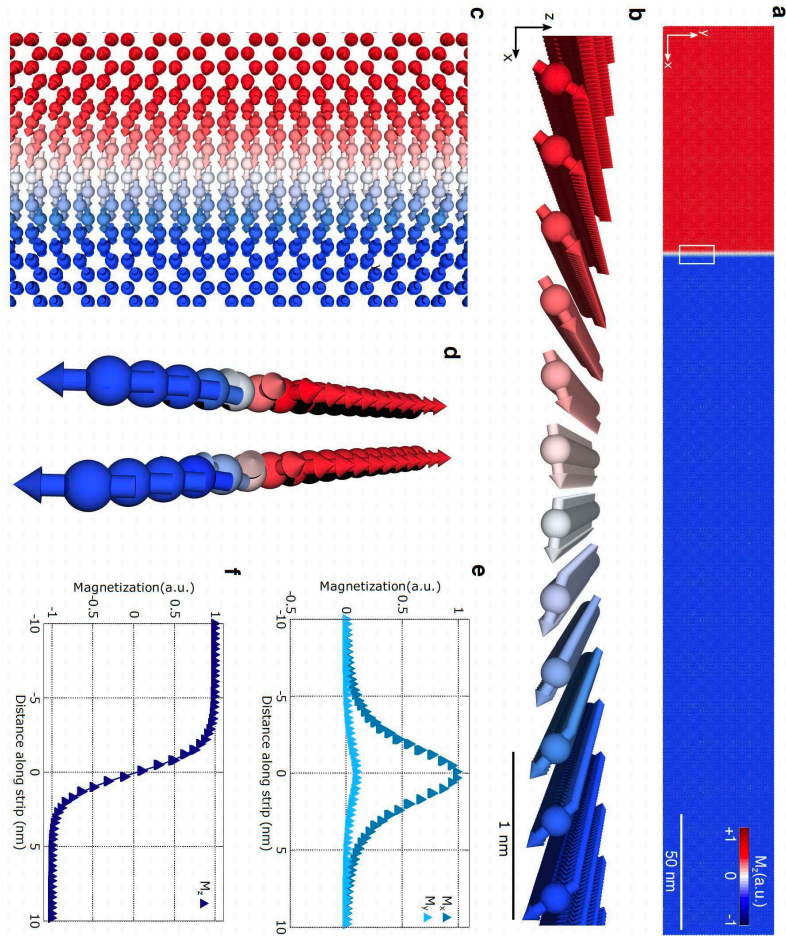


Figure 2

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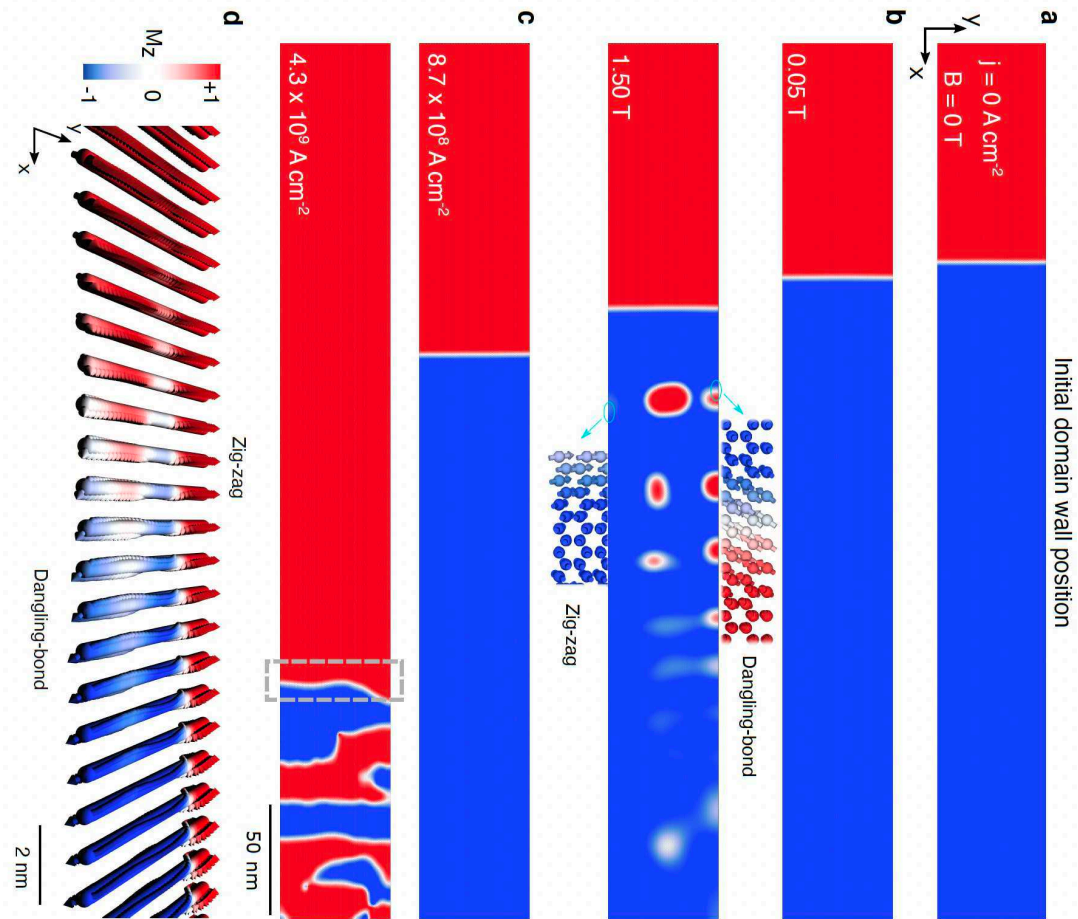


Figure 3

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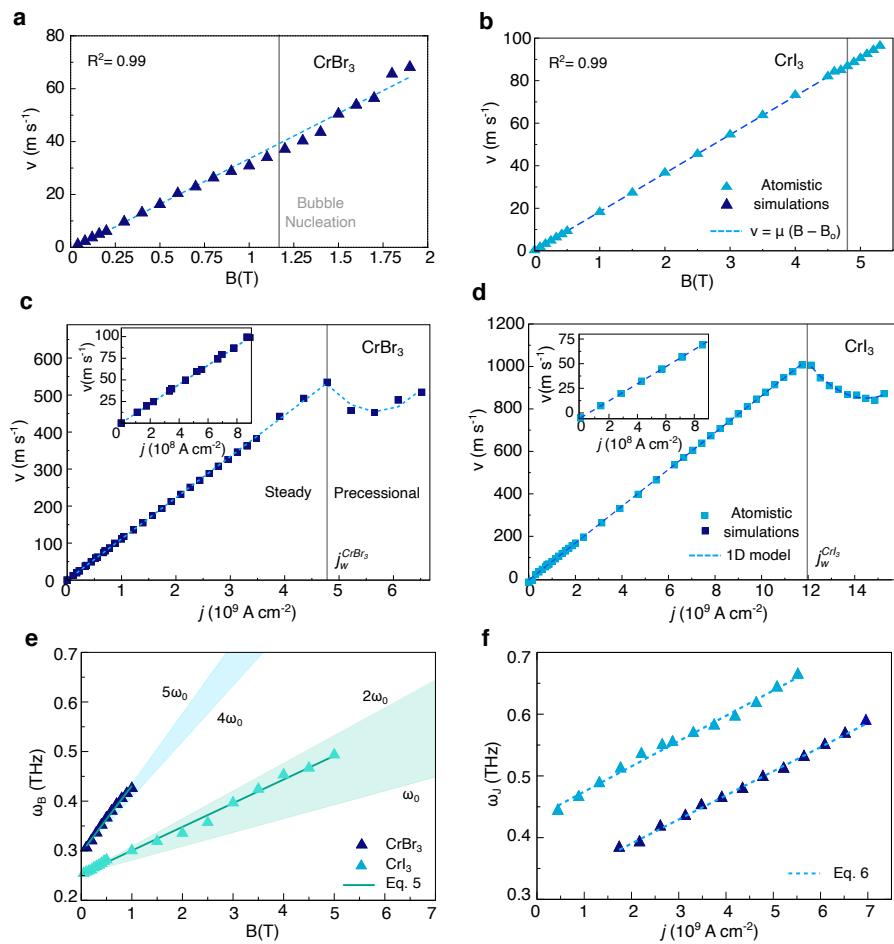


Figure 4



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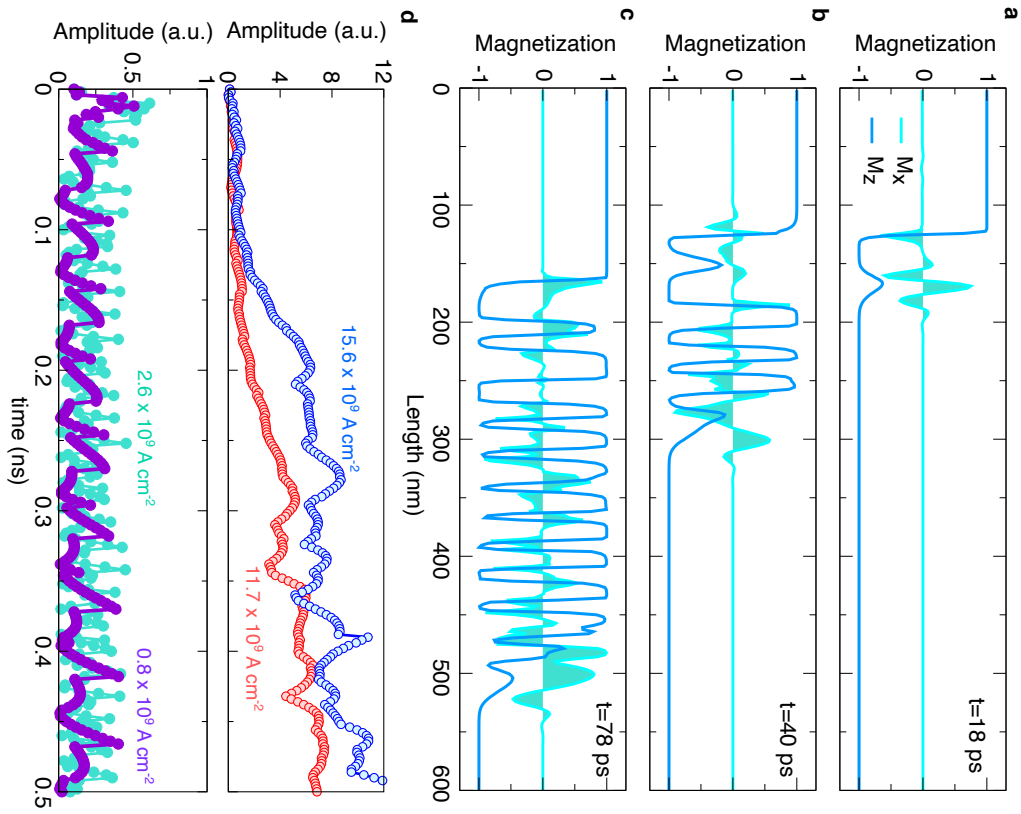


Figure 5



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PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0062541

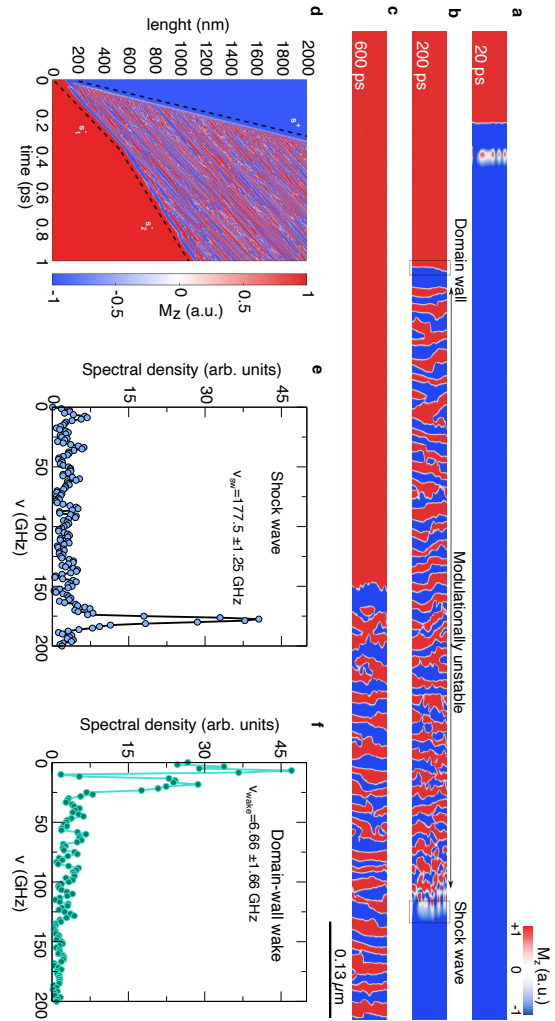


Figure 6