

# Disorder-aided early warning signals: Predicting catastrophic shifts in athermal systems

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The early prediction of tipping points, distinguished by sudden and catastrophic shifts from stable states, poses a challenging task that would enable us to assess the impending threat across natural and engineered systems. This threat becomes particularly acute in low-fluctuation environments, where tipping occurs through saddle-node bifurcation without prior warning in noise dynamics. In this study, we investigate the tipping point dynamics of avalanche catastrophes in low-fluctuation domain, employing model system like the zero-temperature random-field Ising model and thermally deposited cobalt films. As the system approaches the tipping point, avalanche activity reveals pronounced critical behavior, including critical slowing-down, variance enhancement, and a growing spatial correlation length—hallmarks that may serve as early warning signals of impending collapse. Crucially, we demonstrate that increasing disorder in the system reduces its vulnerability to catastrophic failure. In highly disorder regimes, these early warning signals emerge well before the transition, thereby providing a large margin for anticipation and mitigation. This key finding suggests a protective role of disorder offering a perspective on resilience in complex systems. Our results not only deepen the understanding of tipping phenomena in disorder materials but also have broader implications for forecasting regime shift in diverse real-world systems.

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## I. INTRODUCTION

Many complex systems such as climate, finances, complex diseases, and social and ecosystems start to switch from one state to another state through a cascade process under tiny external perturbations [1–6]. The inflection points of those chain of events, named tipping points, are extremely hard to predict way before the catastrophe [1,7]. In some positive contexts, large cascade processes can be beneficial to society [6]. However, recent experiments suggest that the “proximity” of a tipping point can be estimated from the recovery response of a perturbed state [8–10]. The recovery rates are slower if a system approaches a tipping point, indicating critical slowing-down as an antecedent of bifurcation [11]. Besides natural complex systems, the prediction of tipping points is gaining attention in real condensed matter systems. For example, strongly interacting Rydberg atom gases manifest

early warning signals during the transition from a low-density state to a high-density state under a driving microwave field [12]. Recently, permutation entropy has been recognized as an anticipation signal of the threshold bifurcation in a complex laser system [13]. The prediction of the threshold pumping current for stimulated emission in lasers has technological applications for the development of integrated laser systems.

Anticipating critical slowing-down from noisy time-series data has become a dominant approach in recent days [14,15]. The slowing-down can equally be detected in the detrended fluctuations of the response function through the increase in variance, decrease in strength of oscillation, the higher correlation of the subsequent states (lag 1), and the increase in autocorrelation time [3,4]. Recently, a rapid growth of noise variance and relaxation time has been observed at the charge-density wave transition [16]. These phenomena occur over an extended temperature range due to the fluctuation-dominated regime, which suggests improved anticipation of the transition.

However, many systems do not recover in the withdrawal of perturbation; rather, they prefer to stay in the deformed state followed by a hysteretic pathway [17]. For example, avalanches, and glacier melting cannot be recovered immediately if we reverse the causing factor [18–20]. Similar locally irreversible phenomena have also been observed in condensed matter systems in terms of athermal dynamics [21,22]. The

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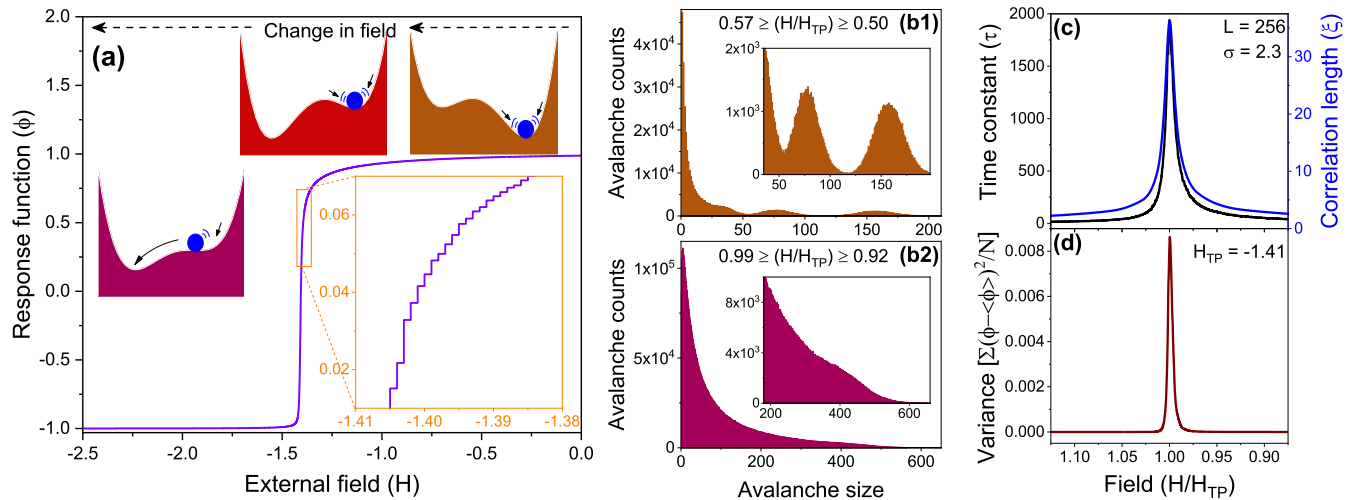


FIG. 1. (a) Regime shift carried by successive avalanches due to a change in the external field with a step size of  $\delta H = 0.0005$  and corresponding schematic basin of attraction. (b1), (b2) Avalanche distribution for small variable intervals ( $\Delta H = 0.1$ ) at different fields before the line of tipping point ( $H_{TP} = -1.41$ ). As the inflection point approaches, large-scale avalanches appear accompanied by a change in distribution from multimodal to unimodal (insets). The system shows critical slowing-down due to the shrinking basin of attraction proximity to the tipping point. The increase in relaxation time constant (c), spatial correlation length (c), and the variance of the response function (d) at the transition point are indications of the slowing-down. The data shown here correspond to the decreasing field, in the step of  $\delta H = 0.0005$ , applied to  $256^3$  system containing disorder strength  $\sigma = 2.3$  (where  $\sigma_c = 2.2$ ). Here, a regime shift has been presented for up-to-down spin polarization due to an increasing negative field, referred to as the decreasing field. The same phenomenon can be observed for the positive branch of the hysteresis (down to up).

system gets trapped in a metastable local minimum and can only cross the activation barrier under external perturbations, such as a field or temperature change [23]. If there are no external perturbations, the system would never shift to another state even in the vicinity of the tipping point [24]. However, once the system shifts to the deformed state it is impossible to recover because of the large basin of attraction and insufficient fluctuation. Such unidirectional systems are very dangerous—here we can only predict the impending threat and take a measure to minimize the losses associated with the disasters. The prediction is also not antecedent, as the associated fluctuations in a deformed state are uncorrelated (see Sec. IIC in the Supplemental Material [24]) and therefore unable to show critical slowing-down through noise spectroscopy, as observed in the previous mechanism [14,25]. However, one would still expect to observe critical slowing-down in averaged signal and increasing variability of macroscopic response functions due to the basin of attraction at the bifurcation point. Near the bifurcation point, a tiny perturbation produces a disproportionately large, often irreversible, response in the system. In the literature, those bifurcation points are defined as tipping points [2].

In the context of a conventional Ising ferromagnet below the critical temperature ( $T < T_c$ ), the free energy has two minima, and reversing the external field  $H$  switches the ground state from up to down spin. In equilibrium, magnetization changes discontinuously at  $H = 0$ ; out of equilibrium, hysteresis arises. As  $H$  varies, the double-well potential evolves, and the system can remain trapped in a metastable state if fluctuations are too small to overcome the barrier [Fig. 1(a)]. In the absence of fluctuations, escape occurs only at the inflection point, producing a finite hysteresis width even in quasistatic limits [26]. This “fluctuationless” case can be modeled

with the zero-temperature (athermal) dynamics, where clean systems show a single-step catastrophic transition [21,22]. Real materials, however, contain defects that induce local fluctuations, breaking the cascade into smaller events and producing critical signatures near the transition (see Sec. I in the Supplemental Material [24]). In athermal dynamics, systems are unable to cross the activation barrier described by Maxwell construction, and the transformation takes place according to the delay convention when the barrier height becomes comparable to the disorder-induced local fluctuations. Magnetic hysteresis, accompanied by avalanches and governed by the delay convention, can be represented within the framework of catastrophe theory [27]. The origin of hysteresis is triggered by an implicit saddle-node bifurcation. Disordered athermal systems are thus ideal for probing how disorder-driven fluctuations influence critical behavior near the tipping point.

In this article, we examine the resilience of a fluctuationless system during the transformation from the parent state to the deformed state under a driven external field, both experimentally [cobalt (Co) films] and numerically (Ising system). The zero-temperature random-field Ising model (ZTRFIM) has been considered an athermal model system, primarily applicable for the martensite materials where barrier heights connected to domains flipping (avalanches) are large enough; hence, thermal activation becomes ineffective [21,23,28]. The fluctuationless metastable phase can persist close to the unstable singularity and transform unanticipatedly when the system hits the inflection point (tipping point) [29]. At the same time, the magnetic switching in cobalt at room temperature is unaffected by thermal fluctuations, making it an ideal example of a magnetic system that behaves athermally [30–32].

In theory, depending upon the strength of spatial inhomogeneities, the avalanche events with changing external field

can be classified into three distinct regions [28,33]. A low-disorder regime where field-induced phase transitions occur between up-spin and down-spin states (or vice versa) through an infinite avalanche, or a spanning avalanche in a finite-size system [34]. At a very high disorder regime, phase transition happens through a continual percolation process under the external field change [33]. Between two extreme disorder regimes, avalanches of small and large sizes coexist, and the system shows some critical-like phenomena accompanied by an abrupt phase transition [23,28]. At critical disorder  $\sigma_c$ , the infinite avalanche phase is separated from the critical-like stage through a disorder-induced continuous phase transition [21,34]. In contrast, there is a crossover between avalanche dynamics and percolation dynamics at higher disorder [28]. The percolationlike transition cannot be considered a threat in nature. On the other hand, the infinite avalanche appears unanticipatedly and, therefore, is impossible to predict. Fortunately, natural systems never jump infinitely; instead, they show a series of avalanches at the moderate disorder level [1,17,35].

Here, we observed critical slowing-down, large variance, and an increase in spatial correlation length as early warning signals of tipping points in finite-driven ZTRFIM, which mimic various natural systems. We experimentally verified catastrophic anticipation during magnetic switching in a thermally deposited cobalt film. Most importantly, we found that the early warning span increases with increasing disorder strength, suggesting that the proximity of the anticipated tipping point becomes more apparent in systems with higher disorder.

## II. NUMERICAL SIMULATION

In the random-field Ising model, each spin  $s_i$  in the lattice points interacts ferromagnetically with their nearest neighbors. The disorder acts as an on-site random field  $h_i$  on top of a spatially uniform external field  $H$ . The Hamiltonian of the model is

$$\mathcal{H} = -J \sum_{i,j} s_i s_j + \sum_i [H(t) + h_i] s_i, \quad (1)$$

where  $J$  (here,  $J = 1$ ) is the interaction between nearest-neighbor nodes of a three-dimensional lattice [21,23,28]. The simulation has been carried out for a two-state spin configuration ( $s_i = \pm 1$ ) on a three-dimensional cubic lattice of system size  $L^3$  under periodic boundary conditions. The external field  $H$  is swept in steps of  $\delta H$  from a large positive value (fully up-polarized) to a large negative value (fully down-polarized) and vice versa [36–38]. The on-site random field is assigned from a Gaussian distribution  $V(h)$ , denoted as

$$V(h) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-h^2/(2\sigma^2)}. \quad (2)$$

The variance  $\sigma$  is the disorder strength. At zero temperature, the spin-flip at each site is regulated by the sign change of the local field. The response function (magnetization) under the perturbation (a tiny sweep of an external field) has been calculated as a function of time and field. At zero temperature, the system transforms through avalanches, where a collection of spins flip upon changing the magnetic field, as shown in Fig. 1(a).

It is widely recognized that below the critical disorder ( $\sigma < \sigma_c$ ), nearly all the spins flip when the external field reaches the effective coercive field, which is a combination of the external field and the field due to the disorder. Therefore, the avalanche sizes for different disorder configurations are similar, but their positions ( $H_c$ ) vary depending on the random configurations of the disorder. However, a higher disorder strength spatially restricts the correlation function and causes the avalanches to gradually decrease in size [39]. The dynamics of the field-induced transition change from infinite avalanche (or spanning avalanche for finite-size system) to critical-like and then to percolative nature with the increase in disorder strength [21,34,40].

In the critical-like region, avalanches of different sizes coexist, and their distribution varies depending on how far away the tipping point is. Figures 1(b1) and 1(b2) depict the size distribution of avalanches within 0.1 field intervals across various field strengths preceding the tipping point. As the catastrophic threshold approaches, the distribution undergoes a transformation from a short-range multimodal state to a wide-range unimodal state, thereby unveiling a discernible antecedent manifestation of the imminent tipping point. However, those bumps in the avalanche distribution can only be observed for a driven external field with a finite rate and cannot be seen in the adiabatic limit, where the rate is zero, as explained in the Supplemental Material [24]. Sometimes, a small bump can be present even in the adiabatic limit at the avalanche size distribution cutoff due to the asymmetric interface height [41].

Despite the precursor indicator observed in the avalanche distribution, the system displays a more fundamental phenomenon, referred to as critical slowing down. This is manifested through elevated values of the relaxation time constant (sometimes referred to as avalanche durations in the literature; see details in the Supplemental Material [24]), increased spatial correlation, and greater variance of the response function [Figs. 1(c) and 1(d)]. Such manifestations during the transition, particularly in the ZTRFIM, have long been investigated within the framework of critical phenomena and are well documented in the literature [42–44]. However, these distinctive characteristics can be interpreted as initial indicators of avalanche tipping points, providing us with the capacity to foresee the proximity of the catastrophic phenomenon [2–5,8–10,45–47]. Nevertheless, there are limitations to the predictions made by our model. It applies only to smooth disorder distributions and does not account for abrupt propagation, such as in linear distributions. Moreover, abrupt disorder distributions are not often observed in nature. Detailed calculations of the variance, spatial correlation, relaxation time constant, and the limitations of the model under varying disorder distributions are presented in the Supplemental Material [24].

## III. EXPERIMENTS

To verify the early signals of catastrophic failure, we performed tabletop experiments on the avalanche phenomenon in an elemental magnetic metal (cobalt). We used the Magneto-Optical Kerr Effect (MOKE) microscopy to investigate the magnetization dynamics under a small linear change in the

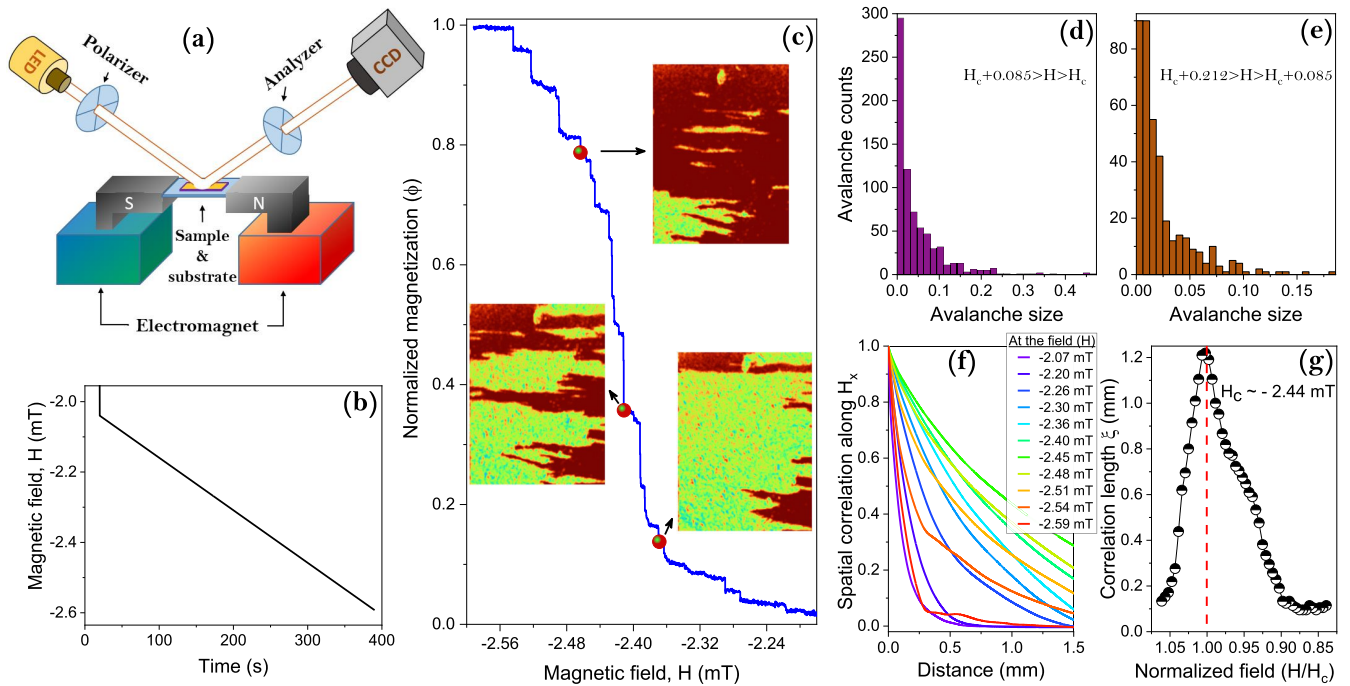


FIG. 2. (a) Schematic of the MOKE microscopy setup. (b) The time-dependent magnetic field sweep at the rate of  $1.5 \mu\text{T/s}$  and corresponding magnetic switching through successive avalanches (c). The snapshots of MOKE microscopy measurements have been presented for three different fields. (d), (e) Avalanche distribution of magnetizations for  $0.085$  and  $0.127$  mT field intervals at two different fields before the coercive field ( $H_c = -2.44$  mT). As field approaches toward transition point, the large-size event appears progressively and the distribution of such events becomes unimodal. (f) The spatial correlation of the MOKE images as a function of distance along the field direction and the characteristic length of the correlation as a function of normalized field,  $H/H_c$ .

magnetic field [Fig. 2(a)] [48,49]. The spin polarization was detected by measuring the change in polarization of the reflected light from a magnetic sample placed in a magnetic field. This technique allows us to directly measure the Barkhausen avalanches of ferromagnetic films [49–52].

In the experiment, a  $100$  nm Co film was thermally deposited on a glass substrate. The sample was mounted on a rotational stage situated at the center of the electromagnetic poles. A polarized light beam illuminated the sample at an incident angle of approximately  $45^\circ$ . The reflected light was imaged by a charged-coupled device camera after passing through an analyzer [48–50]. The MOKE microscopy measurements were restricted to the longitudinal geometry, where the in-plane magnetic field is parallel to the magnetization vector.

Here, we varied the magnetic field linearly by adjusting the electrical current of the electromagnet and simultaneously captured the MOKE images as a function of the magnetic field during the ferromagnetic switching of the sample [Figs. 2(b) and 2(c)]. The transformation fraction of the image represents the normalized magnetization of the sample. The magnetic switching of the entire Co film evolves through a series of distinct magnetic domain flips, indicating an avalanchelike transformation [Fig. 2(c)].

To increase the resolution of our data processing, we divided the total image into four segments to ensure that small avalanches were not masked by averaging. To obtain a good statistical distribution, the measurements were repeated multiple times (40 cycles) to achieve a large number of jumps.

The avalanche size distribution of normalized magnetizations for two small field intervals prior to the coercive field ( $H_c = -2.44$  mT) is depicted in Figs. 2(d) and 2(e). As the external field comes closer to the coercive field, the range of avalanche sizes becomes extensive, as observed in the numerical simulation of the RFIM [Figs. 1(b1) and 1(b2)]. The modes of the distribution in Fig. 2(e) are not as clear as in the simulation [Fig. 1(b1)].

There have been numerous studies on avalanche size distribution integrated over all magnetic fields, aiming to address a fundamental aspect of condensed matter physics—the nature of self-organized criticality [21,34,49–51,53–55]. Proper scaling requires averaging the total number of events over the entire hysteresis loop (from  $H = +\infty$  to  $-\infty$  or vice versa) [35,56]. Several studies have also been conducted for small field windows along the hysteresis loop, which show a change in the scaling exponent as the field approaches coercivity [57], and this change might be considered an indicator of the tipping point. However, the large avalanches that consistently occur near the transition are definitely a signature of the tipping point [Figs. 2(d) and 2(e)] [53,54]. Needless to say, any model, including the random-field Ising system, is unlikely to be effective at predicting avalanches one by one [56].

Therefore, in this article, we rather focus on macroscopic indicators, such as spatial correlation and variance, which are independent of microscopic events and have greater predictive capacity. Figure 2(f) shows that the spatial correlation of the magnetization vectors decays with the distance between them, and this decay becomes slower around the transition.

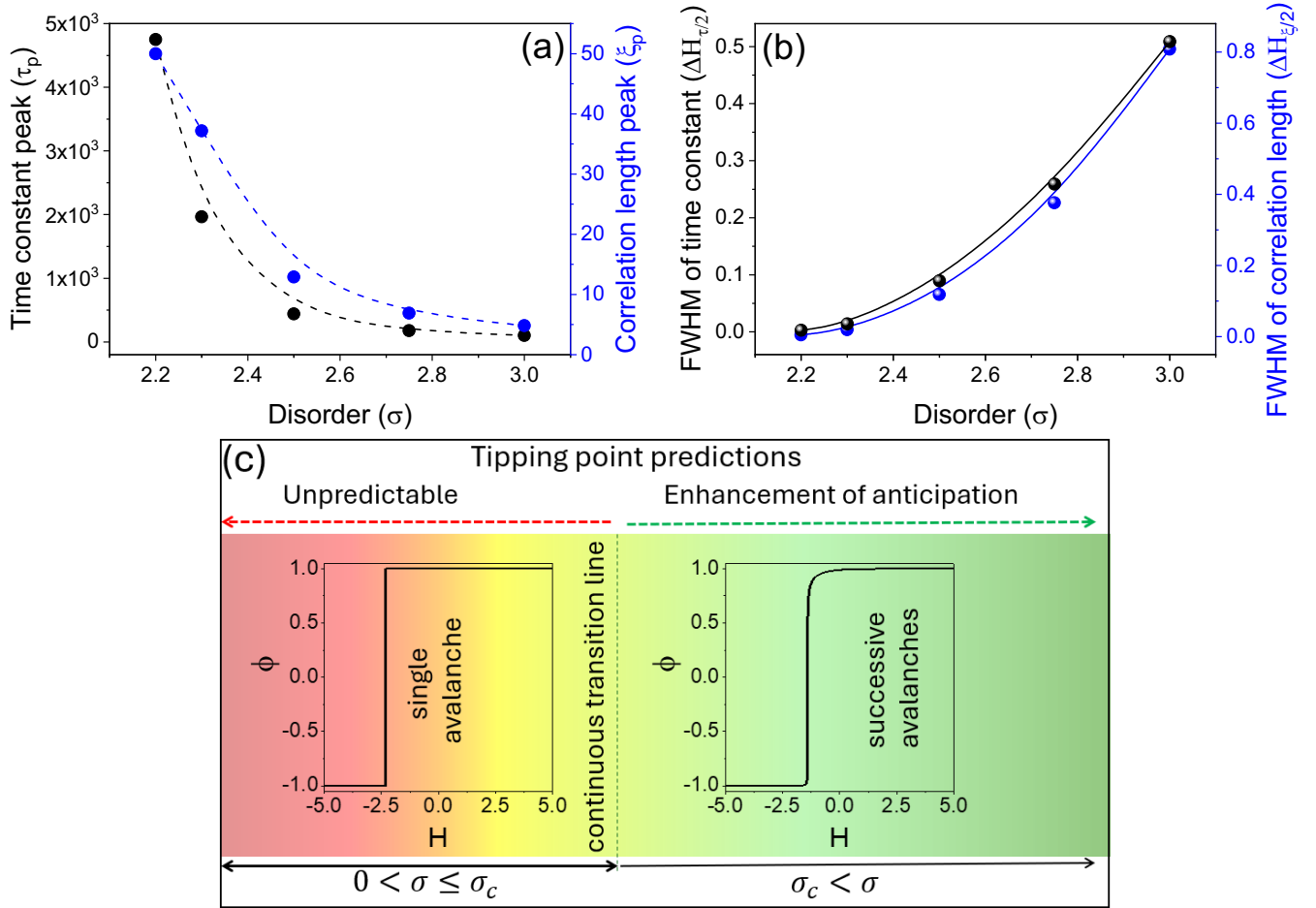


FIG. 3. (a) The maximum value ( $\tau_p$ ) and (b) the FWHM of the correlation length and the time constant peaks as a function of disorder strengths. (c) Tipping point prediction possibility diagram on the disorder line of ZTRFIM.

Consequently, the correlation length increases at the transition [Fig. 2(g)]. Along with these indications, an increase in variance around the transformation has also been observed and reported in the Supplemental Material [24]. The detailed calculations of variance and correlation length are explained in the Supplemental Material [24].

Briefly, the critical signatures that start to showcase before the catastrophic failure in the generalized fluctuationless (zero temperature) Ising model also qualitatively hold for the magnetic avalanches in an elementary magnetic material (Co) way below the Curie temperature [30,34,50–52,58]. Therefore, we can argue that such signs can be considered as early warning indicators of impending catastrophic failure in systems with low fluctuations [2–5,8–10,45–47].

#### IV. EFFECT OF DISORDER

The anticipated proximity to catastrophic failure varies in accordance with the intensity of the disorder. To explore this, we have numerically calculated the time constant and spin-spin correlation over the full range of fields for different disordered systems. Detailed simulations and calculations are provided in the Supplemental Material [24]. In the domain of field-driven transitions within the successive avalanche region, both the relaxation time constant and spin correlation

increase for all disorder values. However, it is noteworthy that while the peak height of both timescale and length scale decreases, the peak width broadens with increasing disorder for both cases [Figs. 3(a) and 3(b)], as expected. Smaller peak values indicate a lesser threat to the tipping point, whereas a broader peak begins to manifest a warning signal well before the onset of a cascade catastrophe. Therefore, forecasting becomes more feasible for systems with higher disorder levels. Within the signal avalanche region ( $\sigma < \sigma_c$ ), the catastrophic occurrence cannot be attributed to a cascade effect; instead, it seems to arise unexpectedly at the tipping point. Fortunately, the majority of intricate natural systems do not exhibit such phenomena [1]. Figure 3(c) showcases the potential for predicting tipping points across the entire disorder spectrum within the field-induced transition in ZTRFIM.

In experiments, precisely controlling and characterizing the strength of disorder across multiple samples is challenging. However, we can qualitatively study the disorder dependence of the samples by performing MOKE measurements on another comparatively thin cobalt sample (grown under identical conditions) with the magnetic field applied at an angle ( $\theta$ ) to the sample axis. We observe that, depending on the field angle relative to the axis of magnetization, the switching can be abrupt or smooth, a behavior consistent with increasing disorder. When an external field is applied

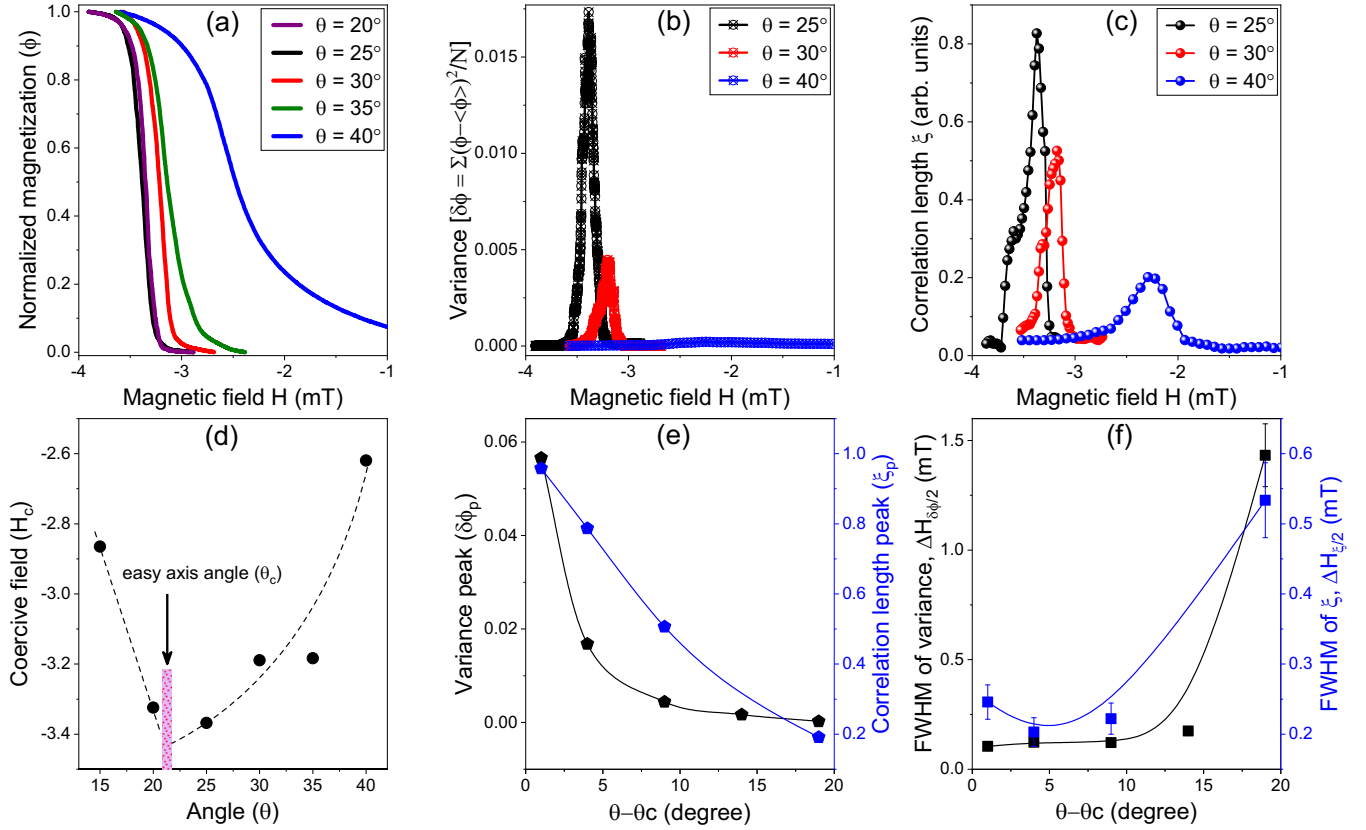


FIG. 4. (a) Normalized magnetization as a function of the external magnetic field applied at different angles  $\theta$  with respect to the sample axis. Variances were estimated from multiple measurements for each angle, with some examples shown in panel (b). (c) The corresponding calculated correlation lengths for those angles. (d) The coercive field as a function of the measurement angle. The shaded region indicates the easy-axis angle ( $\theta_c \approx 21^\circ$ ) of magnetization, including the possible error margin. (e) The peak values of variance and correlation length as functions of the relative angle to the easy-axis angle. (f) The increasing broadness of the early warning signals, expressed in terms of the FWHM of variance and correlation length, as a function of  $\theta - \theta_c$ .

at an angle  $\theta - \theta_c$ , where  $\theta_c$  is the easy axis angle of the anisotropic ferromagnet, the magnetostatic Zeeman energy smears the abrupt transition in a manner analogous to how disorder restricts the correlation length. Therefore, one can phenomenologically map the disorder strength  $\sigma$  to the angle of the field direction relative to the easy axis,  $\theta - \theta_c$ .

Here, Fig. 4(a) shows that, as the angle increases from the easy-axis angle  $\theta_c$ , the transitions become broader. A similar change in the shape of the magnetization curve during switching has been observed in the random-field Ising system when the disorder strength is increased [28]. Most importantly, the variance and correlation length peaks become wider, and the peak height diminishes as the magnetic field direction deviates further from the easy axis of magnetization [Figs. 4(b) and 4(c)]. The easy axis angle ( $\theta_c \approx 21^\circ$ ) has been estimated from the coercive field versus angle of measurement graph [Fig. 4(d)]. The intensity and proximity of the switching threat are evaluated from the peak value and the broadness of the variance and correlation length peaks. Figure 4(e) shows that the transformation becomes continuum at higher relative angles  $\theta - \theta_c$ . At the same time, warning signals can be observed far earlier than the actual switching event [Fig. 4(f)].

Therefore, Figs. 3 and 4 effectively demonstrate that, with increasing disorder, the capacity to identify the threat earlier becomes more pronounced. However, we acknowledge

that the ZTRFIM model presented in this work does not explicitly incorporate the angle-dependent magnetic field or the anisotropic properties of the material. Experimental data suggest that a magnetic field applied away from the easy axis can induce a transverse component of the field with a strong interplay with random fields. Developing a detailed model and conducting an in-depth analysis of such a scenario remain important challenges for future research.

## V. CONCLUSION

We confirm that critical-like signatures, such as increases in correlation length, critical slowing-down, and variance enhancement, offer a powerful framework for predicting impending threats and measuring the breaking point due to external causes. The complex interplay of activation barriers, disorder, and fluctuations provides these critical indicators, collectively contributing to our understanding of the critical phenomena at the tipping points within the framework of abrupt phase transition in various materials [29,54,59,60]. The hallmarks of critical behavior in abrupt transitions can be associated with well-established spinodal instability, offering mechanisms applicable for predicting tipping points across diverse complex natural systems [59–61]. Additionally, the thermodynamic quantities that are commonly measured in

conventional statistical physics for such instability may be used to predict the threats [62].

The study further sheds light on the diverse trajectories that systems undertake during transformations, where the nature of transition varies from cascading to abrupt, influenced by the presence of disorder. The interplay between the correlation length and disorder-induced local fluctuations provides insights that resonate with a wide range of disordered systems in nature. From the predictive indicators, our results suggest that a reduction of disorder makes the system more critical and demands for urgent measures to tackle the threat. First and foremost, this article highlights that the threat can be mitigated by externally introducing defects into the system. This knowledge not only enhances our ability to anticipate and manage potential crises in condensed matter systems but also provides insight into the behavior of various complex natural systems [60].

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### DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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