

Topologically protected remanent vortices in confined superfluid ^3He

Alexander J. Shook ^{*}, Daksh Malhotra, Aymar Muhikira , Vaisakh Vadakkumbatt , and John P. Davis [†]

Department of Physics, *University of Alberta*, Edmonton, Alberta, Canada T6G 2E1



(Received 30 June 2025; revised 22 November 2025; accepted 27 March 2026; published 15 May 2026)

Thermodynamic phase transitions typically involve a transition in the microscopic ordering between a less and a more ordered state. After transitioning into an ordered state, localized structures known as defects may remain, which disrupt the overall macroscopic order. Kibble-Zurek theory predicts that for any second-order phase transition the density of defects that form should be determined by the scaling law for the system coherence time and the phase transition quench time. We have performed measurements of sound dissipation due to vortex mutual friction in thin channels of superfluid ^3He where one spatial dimension is smaller than a characteristic length scale predicted by the Kibble-Zurek theory. In this regime, we find that the density of defects is not determined by quench time, but can be estimated by replacing the Kibble-Zurek length scale with a truncated length set by the channel size. This results in significantly higher defect densities than in a bulk system.

DOI: [10.1103/1795-g151](https://doi.org/10.1103/1795-g151)

I. INTRODUCTION

Phase transitions, the processes by which the microscopic order of a system spontaneously changes, are of fundamental importance to many scientific fields, not only in chemistry and condensed matter physics [1] where the concept finds its origins, but also in cosmology [2], cell biology [3], and economics [4]. One may understand phase transitions in terms of an order parameter, which quantifies the degree to which the system exhibits long-range correlations in a physical quantity specific to the system (e.g., density, magnetic moment, etc.) [5,6]. Such classification naturally gives rise to a length scale known as the correlation length, over which the system is ordered. A general feature of second-order phase transitions is the divergence of the system's correlation length at a critical temperature, representing the change from a disordered system (correlated only at very small distances) to one with long-range order.

Correlation cannot spread throughout a system instantaneously. Shortly after the system crosses the critical temperature, the equilibrium correlation length is limited by the speed at which information propagates through the system. In a discussion of phase transitions in the early universe, Kibble [7] noted that correlation in a field, such as the scalar Higgs field, must be limited by causality since information cannot propagate faster than the speed of light. This implied the existence of cosmic domains where field correlations may only exist within the domain. Because each domain develops

independently from every other, the expectation value of the field in each domain will be independent. Correlation in the Higgs field spreads as these causally disconnected domains propagate outward at the speed of light. As the field evolves in time, the topology of the initial domain structure may be such that topological defects such as domain walls, cosmic strings, or monopoles persist.

This argument was extended by Zurek, who discussed a similar process in the context of the phase transition from normal to superfluid in liquid ^4He . In this transition, the condensate wave function (i.e., the wave function of ^4He atoms occupying the quantum ground state) becomes correlated at long distances [8]. Zurek took an approach to estimating the density of defects by comparing the power-law divergence of the coherence time to the rate at which the system temperature is swept through the critical temperature (see Fig. 1). If the system temperature or pressure is swept through a critical value quickly, then these domains will have insufficient time to propagate, leading to the creation of stringlike defects known as quantized vortices.

This Kibble-Zurek mechanism (KZM) was generalized to describe a wide variety of phase transitions. Kibble-Zurek (KZ) theory describes this process in terms of an equilibrium correlation length ξ and an equilibrium relaxation time τ , both of which diverge at a second-order phase transition [see Figs. 1(a) and 1(b)]. In the disordered phase, the order parameter has a mean value of zero, but fluctuations exist that represent correlated regions of size ξ that exist on a timescale of τ . If a thermodynamic control parameter (such as temperature) is swept through the critical value where τ diverges, then there is a time after the phase transition is reached, known as the “freeze-out time.” This is the time at which correlated regions become long-lived relative to the amount of time required to reach equilibrium. This freeze-out time is therefore a function of the rate at which the control parameter is varied, as well as the temperature scaling of τ . KZ theory predicts that the value of ξ at freeze-out time determines

^{*}Contact author: ashook@ualberta.ca

[†]Contact author: jdavis@ualberta.ca

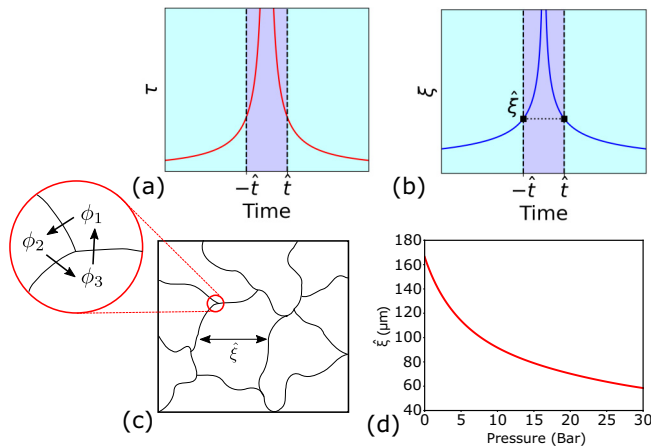


FIG. 1. Domain illustration. (a), (b) Scaling of coherence time, τ , and length, ξ , respectively, as a function of time. Here, it is assumed that the temperature is changed linearly as a function of time. Both quantities diverge when the critical temperature is reached. The freeze-out time $\hat{t}$ is indicated by the dashed line. This time is defined as the moment when $\tau(\hat{t}) = \tau_0 = T_c(dT/dt)^{-1}$. At this moment, there is insufficient time for the domains to grow significantly, so the coherence length is assumed to be “frozen” to first order at the value $\hat{\xi}$. (c) During a rapid quench, domains with average size $\hat{\xi}$ form, giving rise to defects. Each domain will independently select a random phase ϕ . If the phases $\phi_{1,2,3}$ increase sequentially, with a total change in phase close to 2π (clockwise or counterclockwise), the resulting phase winding at the vertex will form a vortex. The density of vortices predicted to form is of order $\hat{\xi}^{-2}$. (d) The average domain size in ^3He for a temperature ramp rate of 0.12 mK/h is predicted by KZ theory to vary between 60 and 160 μm as a function of pressure [9].

the size of the independent order parameter domains in the ordered phase. Afterward, there is a secondary process known as coarsening, where domains continue to grow in the ordered phase.

Each domain has a different microscopic structure, described by its order parameter, which randomly sets in upon formation of the domain. In general, the form of the order parameter is dependent on the symmetries of the system in question. It may be a complex scalar quantity (e.g., in superfluid ^4He) or a vector (e.g., spin or liquid crystal systems), or can have a more complex tensor form (e.g., superfluid ^3He). In all cases, the order parameter is continuous within a domain, but with singular points along the boundaries between domains. Such discontinuities in the order parameter field are called defects. A defect is said to be topological if removing it requires not merely local perturbation, but complete destruction of the macroscopic order [10]. In three-dimensional systems, topological defects may take the form of lines [10] and arise during a quench if the intersection of three or more domains has the correct structure. In the case of a superfluid, line defects form when the complex phase winds by 2π around the line. If a line of intersection between three or more domains is such that the phase increases sequentially around the center, with a total change in phase close to 2π (see Fig. 1), then it may nucleate a vortex once the system reaches equilibrium.

In its simplest form, the KZ theory predicts that the number of defects that form will be set by the average domain size at the freeze-out time $\hat{\xi}$. The areal density of vortices predicted by this theory is $L = \hat{\xi}^{-2}$, based on the number of domains that are expected to form across a given surface area. This prediction has been studied in a number of systems such as liquid crystals [11], Bose-Einstein condensates [12–16], strongly interacting Fermi gases [17], colloidal monolayers [18], and quantum annealing devices [19].

Surprisingly, despite superfluid ^4He being the original model system for Zurek’s theory, experiments in ^4He have not been compatible with the theory [20,21]. The observed density of vortices was at least two orders of magnitude smaller than predicted [21]. The reason for this discrepancy is currently not well understood. More success has been found in studying superfluid ^3He . The order parameter of ^3He has a more complex form, including not just a complex phase, but a matrix structure related to the angular momentum degrees of freedom of Cooper pairs [22]. This may result in multiple types of vortices [23], as well as domain wall structures [24–26]. The types of defects that form depend on the superfluid phase in question (i.e., $^3\text{He-A}$, $^3\text{He-B}$, etc.), as well as the boundary conditions of the system [9]. The KZM has been studied in ^3He using nuclear magnetic resonance to detect vortices [27–31].

Here, we build on previous research in quasi-two-dimensional Bose gases [32,33] by studying the formation of defects due to a phase transition in ^3He that has been confined to a thin channel, where the smallest dimension is less than the KZM length scale. This is a regime where the finite size of the geometry may modify the formation of defects in the complex order parameter of ^3He .

II. METHODS

We have designed an experiment sensitive to vortex dissipation that is distinct from previous studies in helium. It consists of nanofluidic devices, known as Helmholtz resonators, which have been described in detail elsewhere [34–36]. These devices allow for confinement of the helium in channels of thickness $H_{1,2,3} = 636, 805, \text{ and } 1067 \text{ nm}$, respectively. Additional follow-up experiments were later performed with a 750 nm device. Parallel-plate capacitors patterned onto the devices allow for an electrostatic force, which slightly compresses the center of the device, modifying the volume and creating a pressure gradient down the channel. This drives superfluid motion in the channels, but notably does not couple to normal-fluid motion due to the viscous penetration depth being large compared to the thickness of the channel [9]. By driving this superfluid Helmholtz mode, we are able to extract two relevant parameters: a center frequency of the Helmholtz mode, f_0 , the square of which is proportional to the superfluid density, $\rho_s \propto f_0^2$ (i.e., the mass density of the superfluid condensate, excluding the normal fluid contribution); and a linewidth, Δf , which characterizes the resonator’s dissipation. Previously, phase transitions have been observed as kinks in the Helmholtz resonance frequency, allowing mapping of the phase diagram, as described in Ref. [34].

Here, we focus on the dissipation in these devices and find that they exhibit linewidths of several hertz (see Fig. 2),

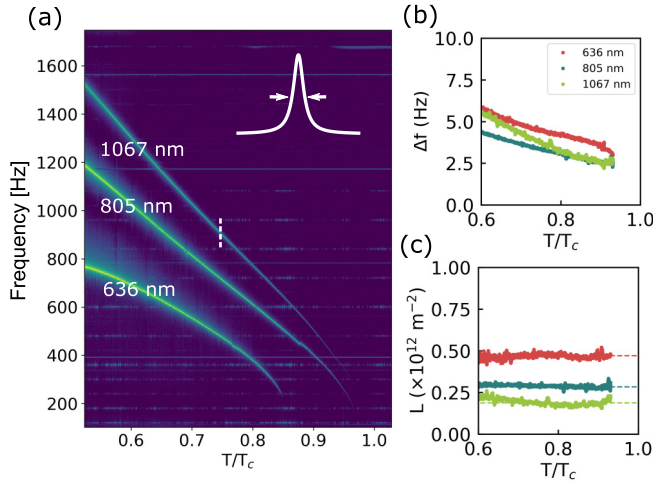


FIG. 2. Helmholtz resonator data. (a) Resonance curves of the three different devices, with varying nanoscale confinements, measured during a temperature sweep carried out at 15 bar. Inset shows the Lorentzian resonance shape at a single temperature. From the center frequency, the superfluid density can be extracted [34]. (b) Additionally, the linewidth of each device can be extracted, plotted here as a function temperature. (c) Resulting vortex densities calibrated from the Helmholtz resonator linewidths and the mutual friction; see main text. Note the lack of temperature dependence and the dependence on confinement.

corresponding to quality factors of a few hundred depending on the temperature and geometry in question. The quality factor is many orders of magnitude lower than that measured in similar devices in ^4He [35]. For this reason, the dissipation must be limited by a process intrinsic to the ^3He system, rather than the quartz substrate that the Helmholtz resonators are fabricated from (which should be much lower in the millikelvin temperature regime compared to the 1 K regime ^4He experiment [35]). We have identified possible dissipation mechanisms that are intrinsic to the superfluid phase of ^3He : surface-bound state dissipation, vortex mutual friction, normal fluid slip, and second viscosity. Additionally, there are phase-specific effects associated with ^3He textures. In a prior publication [37], we have investigated critical velocity by studying the resonance amplitude's drive dependence. A linear regime exists where the amplitude is proportional to the drive, and a change in the slope of the amplitude-force curve marks a nonlinear regime. All of the measurements in this publication were performed in the linear regime for both the A and B phases where we do not expect dissipation due to surface bound-state dissipation. Calculations regarding normal fluid slip, second viscosity, and textural effects have been presented in Supplemental Material [9]. We find that these effects are too small to explain the observed linewidth. Furthermore, these effects do not exhibit the observed temperature dependence of the linewidth.

The best explanation for the observed dissipation in the linear regime is vortex mutual friction. The basis for this is that the temperature dependence of the ratio, $\Delta f/f_0^2$, is well fit by a function linear in the quantity $\alpha(T)$:

$$\frac{\Delta f(T)}{f_0^2(T)} = C_1 \alpha(T) + C_2. \quad (1)$$

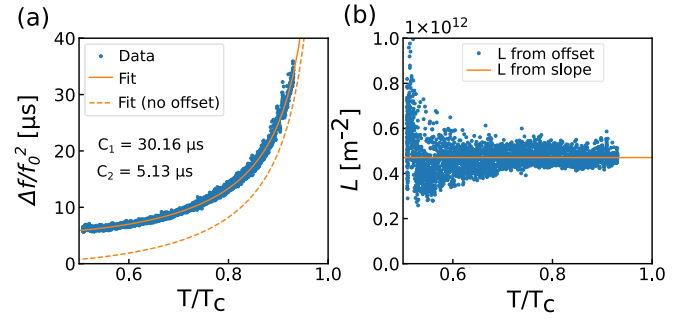


FIG. 3. Vortex density calibration fit. (a) Plot of the experimental ratio $\Delta f/f_0^2$ as a function of temperature at 15 bar for the 636 nm device. These data have been fit to our model and plotted as a solid orange line. The dashed line displays the same curve if the offset is omitted in order to highlight the modification. (b) The vortex density is computed from the fit parameters C_1 and C_2 .

Here, α is the mutual friction parameter associated with dissipative vortex motion, which is calculated following Ref. [38] using the theoretical model developed by Refs. [39,40]. The basic idea is that when the superfluid flows, it induces motion in the vortex lines due to a Magnus force. When a vortex line moves relative to the normal fluid component (which here is static), dissipation is generated due to scattering of excitations with the vortex core. Further details can be found in Supplemental Material [9]. Note that the equation used to calculate α depends on an empirical proportionality factor measured by Bevan *et al.* [38]. Differences in our experiment could affect the magnitude of α , but it will remain within the same order of magnitude. When the experimentally measured ratio $\Delta f(T)/f_0^2(T)$ is plotted against the theoretical $\alpha(T)$, a clear linear trend is observed. To explain this trend, a mutual friction model for our device is introduced, as outlined in Supplemental Material [9]. This model predicts that the slope of Eq. (1), C_1 , should be linear in L , with a temperature-independent proportionality factor γ that is determined by geometric and material parameters. Once this parameter is known, the vortex density can be computed from either fitting constant as $L = C_1/\gamma = (\Delta f/f_0^2 - C_2)/\gamma\alpha$.

An example of the fit to the data can be seen in Fig. 3. The constant offset C_2 is interpreted as being due to other loss mechanisms that scale proportionally with the superfluid density $\rho_s \propto f_0^2$. There are a number of candidates for this, which are discussed in Supplemental Material [9].

III. DISCUSSION

Using this mutual friction model, a vortex density is extracted from the fit parameters of the Helmholtz resonance. The result is then compared to the predicted defect density of the KZ theory. It is worth pointing out that the confined dimension of the devices ($H = 636\text{--}1067$ nm) is orders of magnitude smaller than the KZ length scale of $\xi = 60\text{--}160$ μm . Because of this, it is expected that during the phase transition the propagating domains should rapidly reach both walls. At this point, the domains cannot propagate further in the confined direction but should continue propagating in the two macroscopic directions. In this case, the density of

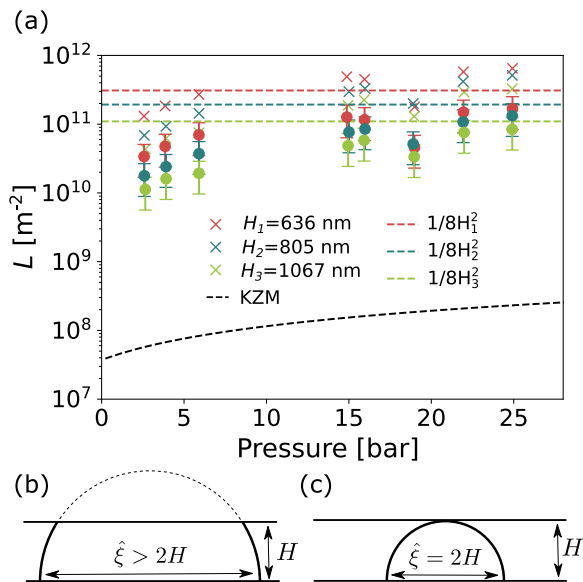


FIG. 4. Comparison of the KZ theory and truncation model. (a) The prediction of the KZ theory, for a ramp rate of $dT/dt = 0.12$ mK/h, is plotted as a dashed black curve as a function of pressure. The superfluid coherence length, and therefore also $\hat{\xi}$, changes with pressure. This curve is compared to the experimental vortex densities—shown as a function of pressure for 636 nm (red), 805 nm (blue), and 1067 nm (green) devices—and found to differ by more than three orders of magnitude. The truncated length-scale prediction of L is shown as colored dashed lines. The x markers represent the fits to the raw data, and the circles are after correction for the artificial broadening of the Helmholtz resonances (see the discussion in Supplemental Material [9]). (b) Cartoon diagram of a domain that propagates from an initial point to a distance $\hat{\xi} > 2H$ (diameter). The walls of the domain become planar due to the confining walls. (c) A domain that has propagated a distance $\hat{\xi} = 2H$. This is when vortex lines joining the two walls first become possible.

defects is determined by the KZ theory (see Supplemental Material [9]) to be $L = \hat{\xi}_{\text{KZM}}^{-2} = \xi_0^{-2} \sqrt{\tau_0/\tau_Q}$, where ξ_0 is the zero temperature coherence length, τ_0 is the relaxation time, and $\tau_Q = T_c(dT/dt)^{-1}$ is a time constant characterizing the temperature ramp rate dT/dt . For the temperature ramp rate used in the majority of the experiments, 0.12 mK/h, this corresponds to $L \sim 10^7$ – 10^8 m⁻² over the range of pressures investigated in this experiment. Contrary to this, vortex densities are measured on the order of $L \sim 10^{10}$ – 10^{11} m⁻², as shown in Fig. 4. Also notable is the clear dependence of vortex density on the confinement of the device, with the most confined channel (636 nm) having the highest density and the least confined (1067 nm) the lowest. Geometric effects do not enter into the original KZ theory, which should depend only on the temperature ramp rate and the pressure. Such high vortex densities (and therefore small domain sizes) would require extraordinarily fast quench rates (approximately 50–200 mK/s depending on the device) if they were dictated by the freeze-out time of the KZ theory.

Although the calibrated vortex area density does not show agreement with the associated KZ length scale, there is a close correspondence with the height of the channel. If the

KZ length scale is replaced with an effective “truncation” length $\hat{\xi}_{\text{KZM}} \rightarrow 2H$, and the vortex area density is estimated in an analogous manner as $L = H/\hat{\xi}^3 = (8H^2)^{-1}$, then a vortex density results that is within an order of magnitude of the calibrated value (Fig. 4). The choice of $2H$ is motivated by the observation that this is the spatial extent of a domain in the nonconfined dimension once the domain has had time to propagate from one wall to the other. This observation is suggestive and seems to imply a qualitatively different process of defect formation than the KZ picture. Although we can only speculate at the nonequilibrium process by which the domains evolve near the transition, note that, unlike the bulk system, the confined channels are expected to produce vortices that terminate at the walls (Fig. 4). At equilibrium, after the phase transition, this should stabilize vortex lines since, unlike a loop, a wall-terminated line cannot shrink indefinitely to the point where it annihilates itself.

Before the freeze-out time, one cannot meaningfully speak of topological defects, since the ordered equilibrium phase has not been established; however, one can speak of statistically independent domains with “protodefects” at the vertices of domains. It is speculated that the presence of the walls may stabilize protodefects during the period of time after the domains are large enough to bridge the two walls, but before the domains have had time to spread and merge in the in-plane directions. This leads to an ensemble of vortices where the mean separation between cores is determined by the size of the channels, rather than the freeze-out time. It is also possible that surface roughness plays a role in stabilizing the formation of defects. Deeper theoretical investigation is required to conclusively resolve this question.

Some degree of overestimation is expected as in the original KZ theory, since not every vertex between domains will nucleate a vortex. This is evidenced in numerical investigations, which have found that the KZ prediction overestimates the defect density and that the true value is obtained by scaling $\hat{\xi}$ by a factor of 5–10 [41–45]. Such scaling has also been observed in ³He NMR experiments where it is estimated that $\hat{\xi}$ should be scaled by 2.3 times the KZM value [31,46]. Finally, note that some vortices may annihilate at the boundaries, or due to vortex recombination during the phase transition [47]. The latter mechanism is expected to depend on the coherence length, which may explain the pressure dependence in the vortex density we observe [9].

Unlike the KZ model, where the vortex density is determined by a freeze-out time, the interpretation here depends only on a spatial length scale and is therefore ramp rate independent. After initial measurements of the 636, 805, and 1067 nm devices, additional follow-up experiments were performed using the 750 nm device to investigate any possible ramp rate dependence. This was achieved by varying the temperature ramp rate from 0.03 to 0.36 mK/h while passing through the critical temperature. The maximum temperature ramp rates possible were limited by both the thermal time constant of the experimental cell and the requirements that the nuclear demagnetization process used to cool the apparatus be adiabatic. Assuming the KZ scaling of $L \propto \sqrt{dT/dt}$, a factor of 10 increase in the ramp rate will increase the vortex density by ~ 3 times, which should have been observable in the experiments. Despite this, no evidence of a change in

linewidth is seen when the temperature was ramped at different rates through T_c [9].

Ramp-rate-independent remanent defects have also been observed in a Bose-Einstein condensate system with a quasi-two-dimensional trapping potential [32,33]. For fast ramp rates, they observed a scaling compatible with the KZ mechanism, but at low ramp rates, they found that the defect density saturates when the KZ domain size would be comparable with the smallest dimension of their system. The authors speculate that for slow cooling, the small scale variations in the trapping potential might dictate the probability of forming remanent vortices. This is not dissimilar to the present experiment, except that here the temperature ramp is in a regime where the KZ length scale is always large compared the confined dimension. It would be interesting in future experiments to investigate the role of surface roughness on vortex formation using an established technique of preplating the surfaces with ^4He [48]. Also potentially relevant are the observations of Xia and Zeng [49] in a superconducting ring, where below a critical circumference the defect scaling becomes ramp rate independent. It should be noted that these observations are distinct from truly two-dimensional systems that lack a transverse length scale, such as Ref. [18], and may still exhibit KZ scaling with a different dimension.

IV. CONCLUSION

We have performed measurements of the dissipation of ^3He fourth-sound resonances, which is consistent with mutual friction due to a fixed density of remanent vortices. The density of

vortices is found to be independent of temperature ramp rate, but is a function of the channel thickness. A model of vortex formation, distinct from the KZ model, is proposed in which a spatial length scale of the system sets the estimated defect density rather than the quench rate as is the case in the KZ model. This interpretation is found to be within an order of magnitude of the observations, comparable to the agreement seen in tests of the KZM, and the scaling with confinement is in reasonable agreement. These measurements are part of a growing body of work demonstrating that remanent defect formation is modified in systems where one or more dimensions are small compared to the KZ length scale [31,32,49] and motivate further studies into phase transitions in noninfinite systems.

ACKNOWLEDGMENTS

The authors acknowledge that the land on which this work was performed is in Treaty Six Territory, the traditional territories of many First Nations, Métis, and Inuit in Alberta. They acknowledge the support from the Canada Foundation for Innovation, the Natural Sciences and Engineering Research Council, Canada (Grants No. RGPIN-2022-03078 and No. ALLRP 602120-2024), and Alberta Innovates (Grant No. 242506367).

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] P. Papon, J. Leblond, and P. H. Meijer, *Physics of Phase Transitions* (Springer, 2002).
 - [2] A. D. Linde, Phase transitions in gauge theories and cosmology, *Rep. Prog. Phys.* **42**, 389 (1979).
 - [3] G. H. Pollack and W. C. Chin, *Phase Transitions in Cell Biology* (Springer, 2008).
 - [4] H. Stanley *et al.*, Self-organized complexity in economics and finance, *Proc. Natl. Acad. Sci. USA* **99**, 2561 (2002).
 - [5] L. D. Landau and E. M. Lifshitz, *Statistical Physics: Landau and Lifshitz: Course of Theoretical Physics* (Elsevier, 2013), Vol. 5.
 - [6] S. N. Burmistrov and E. M. Lifshitz, *Statistical and Condensed Matter Physics* (Springer, Singapore, 2025).
 - [7] T. W. Kibble, Topology of cosmic domains and strings, *J. Phys. A: Math. Gen.* **9**, 1387 (1976).
 - [8] W. H. Zurek, Cosmological experiments in superfluid helium? *Nature (London)* **317**, 505 (1985).
 - [9] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/1795-g151> for a discussion of topological defects, mutual friction, and details of the Helmholtz resonator model.
 - [10] N. D. Mermin, The topological theory of defects in ordered media, *Rev. Mod. Phys.* **51**, 591 (1979).
 - [11] I. Chuang, R. Durrer, N. Turok, and B. Yurke, Cosmology in the laboratory: Defect dynamics in liquid crystals, *Science* **251**, 1336 (1991).
 - [12] J. Goo, Y. Lim, and Y. Shin, Defect saturation in a rapidly quenched Bose gas, *Phys. Rev. Lett.* **127**, 115701 (2021).
 - [13] L. Sadler, J. Higbie, S. Leslie, M. Vengalattore, and D. Stamper-Kurn, Spontaneous symmetry breaking in a quenched ferromagnetic spinor Bose-Einstein condensate, *Nature (London)* **443**, 312 (2006).
 - [14] D. R. Scherer, C. N. Weiler, T. W. Neely, and B. P. Anderson, Vortex formation by merging of multiple trapped Bose-Einstein condensates, *Phys. Rev. Lett.* **98**, 110402 (2007).
 - [15] G. Lamporesi, S. Donadello, S. Serafini, F. Dalfovo, and G. Ferrari, Spontaneous creation of Kibble-Zurek solitons in a Bose-Einstein condensate, *Nat. Phys.* **9**, 656 (2013).
 - [16] M. Anquez, B. A. Robbins, H. M. Bharath, M. Boguslawski, T. M. Hoang, and M. S. Chapman, Quantum Kibble-Zurek mechanism in a spin-1 Bose-Einstein condensate, *Phys. Rev. Lett.* **116**, 155301 (2016).
 - [17] B. Ko, J. W. Park, and Y. Shin, Kibble-Zurek universality in a strongly interacting Fermi superfluid, *Nat. Phys.* **15**, 1227 (2019).
 - [18] S. Deutschländer, P. Dillmann, G. Maret, and P. Keim, Kibble-Zurek mechanism in colloidal monolayers, *Proc. Natl. Acad. Sci. USA* **112**, 6925 (2015).
 - [19] Y. Bando, Y. Susa, H. Oshiyama, N. Shibata, M. Ohzeki, F. J. Gómez-Ruiz, D. A. Lidar, S. Suzuki, A. del Campo, and H. Nishimori, Probing the universality of topological defect formation in a quantum annealer: Kibble-Zurek mechanism and beyond, *Phys. Rev. Res.* **2**, 033369 (2020).
 - [20] P. Hendry, N. S. Lawson, R. Lee, P. V. McClintock, and C. Williams, Generation of defects in superfluid ^4He as an

- analogue of the formation of cosmic strings, *Nature (London)* **368**, 315 (1994).
- [21] M. E. Dodd, P. C. Hendry, N. S. Lawson, P. V. E. McClintock, and C. D. H. Williams, Nonappearance of vortices in fast mechanical expansions of liquid ^4He through the lambda transition, *Phys. Rev. Lett.* **81**, 3703 (1998).
- [22] D. Vollhardt and P. Wölfle, *The Superfluid Phases of Helium 3* (Dover Publications, Mineola, NY, 2013).
- [23] M. M. Salomaa and G. E. Volovik, Quantized vortices in superfluid ^3He , *Rev. Mod. Phys.* **59**, 533 (1987).
- [24] M. M. Salomaa and G. E. Volovik, Cosmiclike domain walls in superfluid ^3He -B: Instantons and diabolical points in (k, r) space, *Phys. Rev. B* **37**, 9298 (1988).
- [25] P. M. Walmsley, I. J. White, and A. I. Golov, Intrinsic pinning of vorticity by domain walls of $\hat{\ell}$ texture in superfluid ^3He -A, *Phys. Rev. Lett.* **93**, 195301 (2004).
- [26] N. Gluscevic and J. A. Sauls, Kibble-Zurek dynamics & statistics of topological defects in chiral superfluid ^3He films, *Phys. Rev. B* **111**, 214526 (2025).
- [27] V. Ruutu *et al.*, Vortex formation in neutron-irradiated superfluid ^3He as an analogue of cosmological defect formation, *Nature (London)* **382**, 334 (1996).
- [28] C. Bäuerle, Y. M. Bunkov, S. Fisher, H. Godfrin, and G. Pickett, Laboratory simulation of cosmic string formation in the early universe using superfluid ^3He , *Nature (London)* **382**, 332 (1996).
- [29] S. Autti, V. V. Dmitriev, J. T. Makinen, A. A. Soldatov, G. E. Volovik, A. N. Yudin, V. V. Zavjalov, and V. B. Eltsov, Observation of half-quantum vortices in topological superfluid ^3He , *Phys. Rev. Lett.* **117**, 255301 (2016).
- [30] S. Autti *et al.*, Exceeding the Landau speed limit with topological Bogoliubov Fermi surfaces, *Phys. Rev. Lett.* **2**, 033013 (2020).
- [31] J. Rysti, J. T. Makinen, S. Autti, T. Kamppinen, G. E. Volovik, and V. B. Eltsov, Suppressing the Kibble-Zurek mechanism by a symmetry-violating bias, *Phys. Rev. Lett.* **127**, 115702 (2021).
- [32] L. Chomaz *et al.*, Emergence of coherence via transverse condensation in a uniform quasi-two-dimensional Bose gas, *Nat. Commun.* **6**, 6162 (2015).
- [33] J. Beugnon and N. Navon, Exploring the Kibble-Zurek mechanism with homogeneous Bose gases, *J. Phys. B: At. Mol. Opt. Phys.* **50**, 022002 (2017).
- [34] A. J. Shook *et al.*, Stabilized pair density wave via nanoscale confinement of superfluid ^3He , *Phys. Rev. Lett.* **124**, 015301 (2020).
- [35] X. Rojas and J. P. Davis, Superfluid nanomechanical resonator for quantum nanofluidics, *Phys. Rev. B* **91**, 024503 (2015).
- [36] F. Souris, X. Rojas, P. H. Kim, and J. P. Davis, Ultralow-dissipation superfluid micromechanical resonator, *Phys. Rev. Appl.* **7**, 044008 (2017).
- [37] A. J. Shook, E. Varga, I. Boettcher, and J. P. Davis, Surface state dissipation in confined ^3He -A, *Phys. Rev. Lett.* **132**, 156001 (2024).
- [38] T. Bevan *et al.*, Vortex mutual friction in superfluid ^3He , *J. Low Temp. Phys.* **109**, 423 (1997).
- [39] N. Kopnin, G. Volovik, and Ü. Parts, Spectral flow in vortex dynamics of ^3He -B and superconductors, *Europhys. Lett.* **32**, 651 (1995).
- [40] N. Kopnin, Theory of mutual friction in superfluid ^3He at low temperatures, *Physica B* **210**, 267 (1995).
- [41] A. Das, J. Sabbatini, and W. H. Zurek, Winding up superfluid in a torus via Bose Einstein condensation, *Sci. Rep.* **2**, 352 (2012).
- [42] P. Laguna and W. H. Zurek, Density of kinks after a quench: When symmetry breaks, how big are the pieces? *Phys. Rev. Lett.* **78**, 2519 (1997).
- [43] A. Yates and W. H. Zurek, Vortex formation in two dimensions: When symmetry breaks, how big are the pieces? *Phys. Rev. Lett.* **80**, 5477 (1998).
- [44] N. D. Antunes, L. M. A. Bettencourt, and W. H. Zurek, Vortex string formation in a 3D $U(1)$ temperature quench, *Phys. Rev. Lett.* **82**, 2824, (1999).
- [45] L. M. A. Bettencourt, N. D. Antunes, and W. H. Zurek, Ginzburg regime and its effects on topological defect formation, *Phys. Rev. D* **62**, 065005 (2000).
- [46] M. M. Rams, J. Dziarmaga, and W. H. Zurek, Symmetry breaking bias and the dynamics of a quantum phase transition, *Phys. Rev. Lett.* **123**, 130603 (2019).
- [47] V. Eltsov *et al.*, Vortex formation and annihilation in rotating superfluid ^3He -B at low temperatures, *J. Low Temp. Phys.* **161**, 474 (2010).
- [48] M. R. Freeman and R. C. Richardson, Size effects in superfluid ^3He films, *Phys. Rev. B* **41**, 11011 (1990).
- [49] C. Y. Xia and H. B. Zeng, Winding up a finite size holographic superconducting ring beyond Kibble-Zurek mechanism, *Phys. Rev. D* **102**, 126005 (2020).