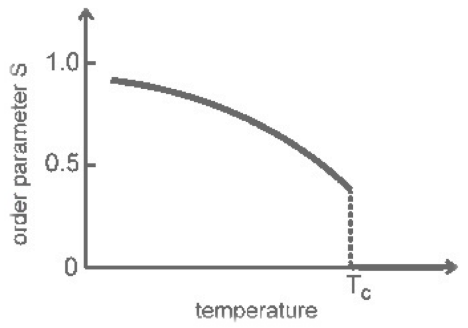
What Multiferroics can tell us about the Origins of the Universe

Sinéad M. Griffin[1] & Nicola A. Spaldin, Materials Theory, ETH Zürich

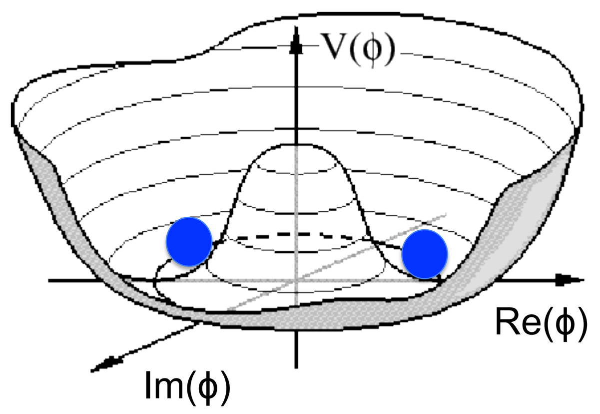
Spontaneous Symmetry Breaking



A **phase transition** is described by the onset of an order parameter at T_C.
- Magnetism in ferromagnets
- Cooper pair wavefunction in Superconductors

Phase transitions are also described by the change of symmetry in going through the transition.

Spontaneous Symmetry Breaking occurs when the symmetry breaking results in *degenerate choice of vacua.*



$$V(\phi) = \frac{\lambda}{4}(|\phi|^2 - \eta^2)^2 \qquad \phi \in \mathbb{C}$$

Interlude on Homotopy Theory

A system undergoes Spontaneous Symmetry Breaking: *G* → *H*

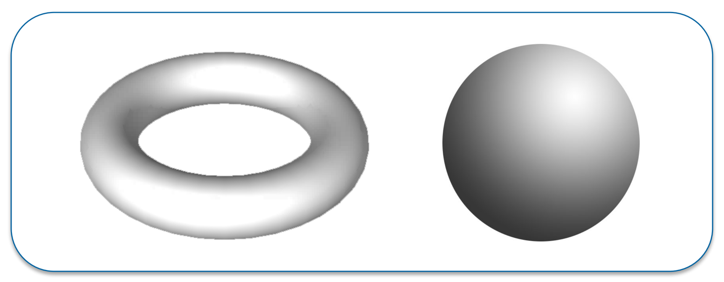
Initial symmetry group ***G***
Final symmetry group ***H***

There are now solutions to the theory which are no longer invariant under *G*. We call these the order parameter.

Order parameter space ***M = G/H***

The topology of two groups is compared using the *k^th^-homotopy group* π_k
- This is trivial if the two groups are homotopic $\pi_k = I$
- Non-trivial homotopic group is needed for defects to form $\pi_k \neq I$

Homotopic



Not homotopic

Kibble Mechanism

When do we get topological defects?

For spontaneous symmetry breaking G → H with M = G/H, we get topological defects when π_k (M) ≠ I.

Conditions for Topological Defect Formation:
1. Spontaneous Symmetry Breaking
2. Non-trivial Homotopy Group $\boldsymbol{\pi_k}$ **(M) ≠ I**

Introduction

Leaping from the expanse of galactic scales to land in the laboratory might seem a gargantuan task. Overcoming this hurdle begins with the uniting of cosmology and condensed matter theory which exhibit similar behaviour in phase transitions and defect formation. Central to both is symmetry breaking.

The Kibble Mechanism describes what sort of systems can accommodate defects and the criteria for defect formation in the physical manifold. Zurek scenarios provide us with quantitative scaling laws linking very large to very small scales. Furthermore, many condensed matter systems exhibit symmetry breaking and form defects analogous to those in cosmological transitions. This poster will focus on a proposal for Kibble-Zurek defect formation in multiferroic $YMnO_3$. Piezoforce microscopy (PFM) gives unique visualisation and insight into the formation of topological defects in this system, advancing our general understanding of the phenomenon of defect formation and nonequilibrium phase transitions.

Zurek Scenario

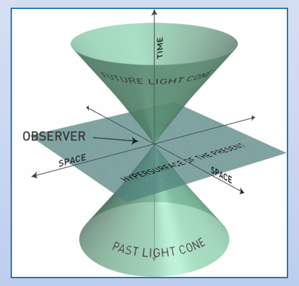
How many defects are formed?

- Based on causal arguments
- Defect density set by competing timescales

1. Information Transfer

How quickly open part of system communicates choice of vacuum with another.

Speed of light, c



2. Order Parameter Relaxation

Fluctuations in the order parameter near the transition.

Correlation Function
Away from equilibrium, exponential decrease in the correlation function of perturbations

$$\langle \delta\Phi(x,t), \delta\Phi(x+\Delta,t) \rangle \sim e^{\frac{-|\Delta|}{\eta}}$$

Near T_c, propose the system undergoes a linear quench with τ_Q= quench timescale

$$\varepsilon(T) = \frac{T_C - T}{T_C} = \frac{t}{\tau_Q}$$

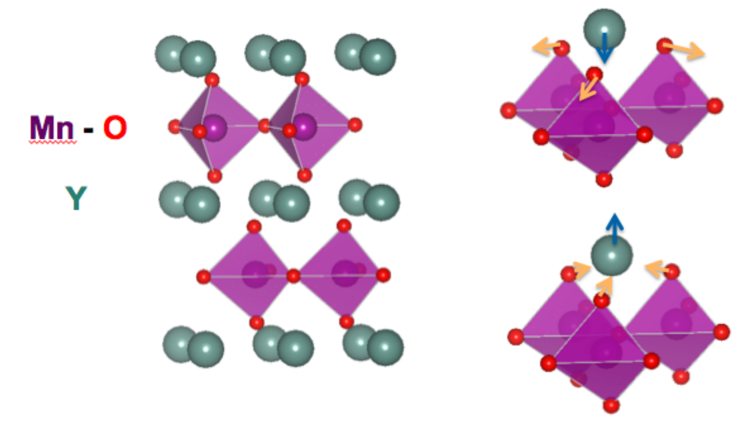
The equilibrium values of ξ and τ will behave exponentially with critical exponents μ and ν

$$\xi = \xi_0 |\varepsilon|^{-\nu} \qquad \tau = \tau_0 |\varepsilon|^{-\mu}$$

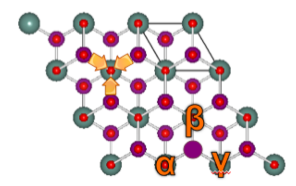
At exponential decrease in relaxation time means that at some stage before the transition, -t', |t|=τ

$$\xi(-\hat{t}) = \xi_0 \left(\frac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+\mu}}$$

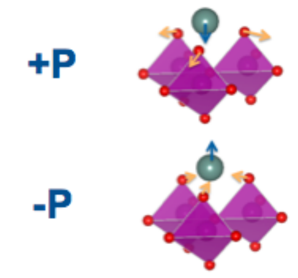
Kibble-Zurek Scenario for $YMnO_3$



- Antiferromagnetic T_N ~ 90K
- Ferroelectric T ~1250K



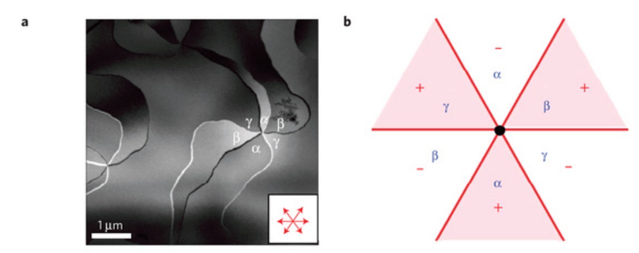
- Trimerization
Choice of 3 sites
Described by Z_3



- Trimerization (+ Ferroelectricity)
+ and - displacement
Described by Z_2

	α	β	γ
+	α+	β+	γ+
-	α-	β-	γ-

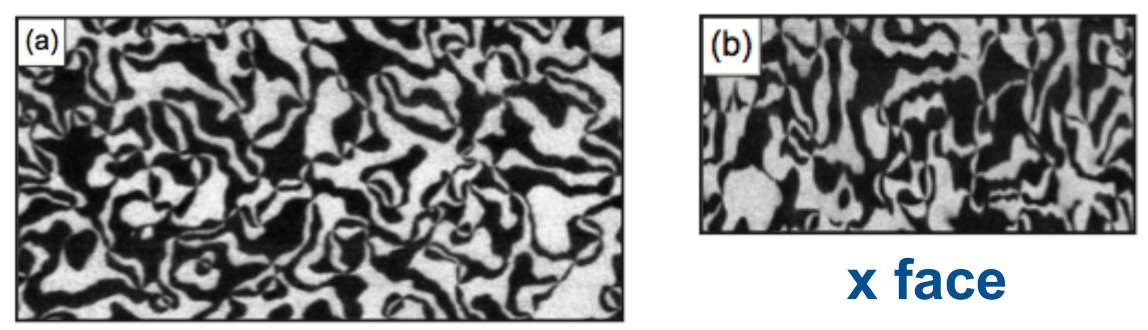
Kibble Mechanism:
$\boldsymbol{\pi_1}$**(M)= Z**
→ Non-trivial homotopy group
→ Strings/vortices



Zurek Scenario:
Competing timescales
1. Information Transfer → Speed of Sound
2. Quench timescale → Ongoing Expts

Preliminary Results

- Density Functional Theory Calculations (*Kris Delaney, UC Santa Barbara*) $\quad v_{xy} \sim 2v_z$
- Comparison of domains in x and z directions by PFM (*Fiebig, Soergel, Lilienblum, Uni. Bonn*)



z face **x face**

Conclusion & Prospects

- Possible verification of KZ scaling law $\quad \xi(-\hat{t}) = \xi_0 \left(\frac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+\mu}}$
- Direct imaging of defects
- Control and evolution of defects (temperature ***and*** magnetic and electric fields)
- How vortices interact with each other: models of cosmic strings in the Universe

[1]sgriffin@mat.ethz.ch