From materials to cosmology
Studying the early universe under the microscope

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Quiz

“Standard Model” of Cosmology
"Standard Model" of Cosmology

Grand unification transition

Spontaneous Symmetry Lowering at the GUT proposed to be the origin of the “stuff”
Spontaneous symmetry lowering phase transition in a ferromagnet

Transition (Curie) temperature, $T_c$
1. Choice of multiple equivalent low-symmetry states

e.g. in a uniaxial ferromagnet there are two equivalent low symmetry states

and the symmetry-lowering phase transition is described by a double well potential:
2. Defect formation at symmetry-lowering phase transitions
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Defects in ferromagnets: Domain walls
Spontaneous symmetry lowering at the Grand Unification Transition

HOMOGENEOUS VACUUM

LOWER SYMMETRY VACUUM

Energy

$V(\phi)$

$\phi_1$

$\phi_2$
Different regions of the early universe choose different equivalent ground states
As the universe expands through the transition, the low symmetry regions grow…

VACUUM WITH 1st CHOICE OF ANGLE

VACUUM WITH 2nd CHOICE OF ANGLE

VACUUM WITH 3rd CHOICE OF ANGLE
and grow…

VACUUM WITH 1st CHOICE OF ANGLE

VACUUM WITH 2nd CHOICE OF ANGLE

VACUUM WITH 3rd CHOICE OF ANGLE
and eventually meet!
The angle mismatch in the low-symmetry vacuum is a topologically protected one-dimensional defect (Kibble)
A detail: How many cosmic strings should we have?

It depends on the rate of expansion of the early universe (Zurek)

**Expand slowly:** Different regions can communicate their choice of angle
  - Large regions of the same choice
  - Low density of cosmic strings

**Expand quickly:** Not much time to communicate choice of angle
  - Many smaller regions with different choices of angle
  - High density of cosmic strings
Do cosmic strings exist? How can we study them?

For direct study we need a probe with a similar energy, $\sim 10^{15}$ GeV.

Our highest energy probes, the largest hadronic colliders reach $\sim 10,000$ GeV.
How is Cosmic String Formation at the Grand Unification Transition studied?

Analyzing the Cosmic Microwave Background
How is Cosmic String Formation at the Grand Unification Transition studied?

Computer Simulation

PHYSICAL REVIEW D 76, 043005 (2007)

CMB polarization power spectra contributions from a network of cosmic strings

Neil Bevis,¹,* Mark Hindmarsh,¹,† Martin Kunz,²,‡ and Jon Urrestilla¹,§
Instead we will study the GUT in our laboratory!

Outline
First we will identify a material with a symmetry-lowering phase transition described by the same mathematics as that proposed for the GUT.

spontaneous symmetry breaking described by a Mexican hat potential

Then we will do experiments on the material to answer questions about the GUT:

Do cosmic strings exist?
Did they form as we think?
How did they evolve?
What are their properties?
Where to find a suitable material? Multiferroics: Multiple ferroic orders…

- Ferro-electrics
- Ferro-magnets
- Ferro-elastic
...and multiple defects from spontaneous symmetry-lowering transitions
Our material: Multiferroic YMnO$_3$
Our material: Multiferroic YMnO$_3$

High temperature

Paraelectric

Low temperature

Ferroelectric

Symmetry-lowering phase transition at $\sim 1000K$
Look at these distortions in more detail:

**Trimerization / Tilting**

Three possible origins
Look at these distortions in more detail:

**Trimerization / Tilting**

Three possible origins

Results in six domains

**Polarization**

Two possible orientations
Calculate the form of the potential using symmetry analysis and density functional theory

Landau free energy

\[ f_u = \frac{a}{2} Q^2 + \frac{b}{4} Q^4 + \frac{Q^6}{6} \left( c + c' \cos 6\Phi \right) - gQ^3 P_z \cos 3\Phi \]

- \( Q \) is amplitude of tilting
- \( \Phi \) is angle of tilting
- \( P_z \) is polarization

The phase transition is described by a Mexican-hat-like potential!

And the details of our “Mexican Hat-like” potential make it easy for us to measure!

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Piezoforce Microscopy Image of ferroelectricity in YMnO$_3$

The meeting points of the ferroelectric domains are in fact one-dimensional “strings”

Piezoforce Microscopy Image of the Defects in YMnO$_3$

3-D Simulation

Thomas Lottermoser, Fiebig group
The structural phase transition in multiferroic YMnO$_3$ provides an analogue to the Grand Unification Transition

Does the GUT behave as cosmologists predict?

What experiment would we like to do on the early universe?

We’d like to expand it at different rates, crossing the GUT, and see how many cosmic strings form in each case (“Kibble-Zurek scaling”)

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Instead we will cool YMnO$_3$ at different rates through the structural phase transition and count how many “strings” form
Testing the predicted “Kibble-Zurek scaling” for defect formation

domain size (for linear quench),

\[
\xi_0 \left( \frac{\tau_q}{\tau_0} \right)^{\frac{\nu}{1+\mu}}
\]

defined as \( T_c (\sim 1000K) \) / cooling rate

Critical exponents: ratio = 0.58 from MC simulations for 3D XY model

\( \nu \) th


zero-temperature relaxation time

\( = \frac{\xi_0}{\text{speed of sound}} \)

speed of sound = 640 m/s (DFT)

Yu Kumagai and NAS, Structural domain walls in polar hexagonal manganites, Nat. Comm. 4, 1540 (2013)

Comparison of predicted Kibble-Zurek scaling with experiment

Red line: our calculations with $\xi_0 = 0.06$ Å

Red points: measured

REMARKABLE AGREEMENT!


"Beyond-KZ regime" and unexpected dependence on chemistry

(TmMnO_3 from S. Chae et al.)

Global Formation of Topological Defects in the Multiferroic Hexagonal Manganites

Open questions:

What causes the chemistry dependence?
What is the origin of the turnaround?
What is the physics of the beyond-KZ regime?

Is it relevant for early-universe behavior?
Summary

Multiferroics provide the first example of Kibble-Zurek scaling in a solid-state system

Cosmic strings formed the way cosmologists think ;)

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The Economist

How to build a multiverse

Small models of cosmic phenomena are shedding light on the real thing

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Whether all this ingenuity unravels any cosmic truth is uncertain. Cliff Burgess, a theorist at Perimeter Institute for Theoretical Physics in Ontario, has his doubts. But he thinks that such experiments are nevertheless worth pursuing. “Like tap-dancing snakes,” he says, “the point is not that they do it well, it is that they do it at all.”