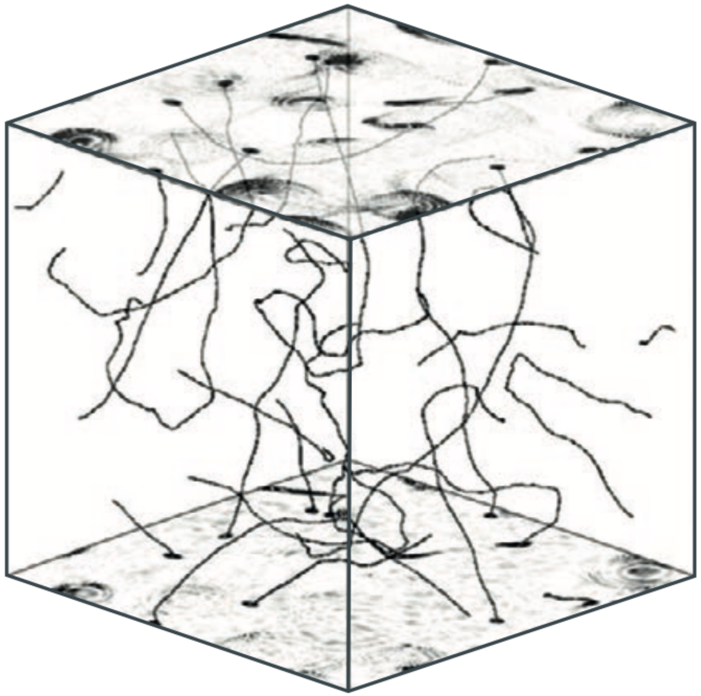
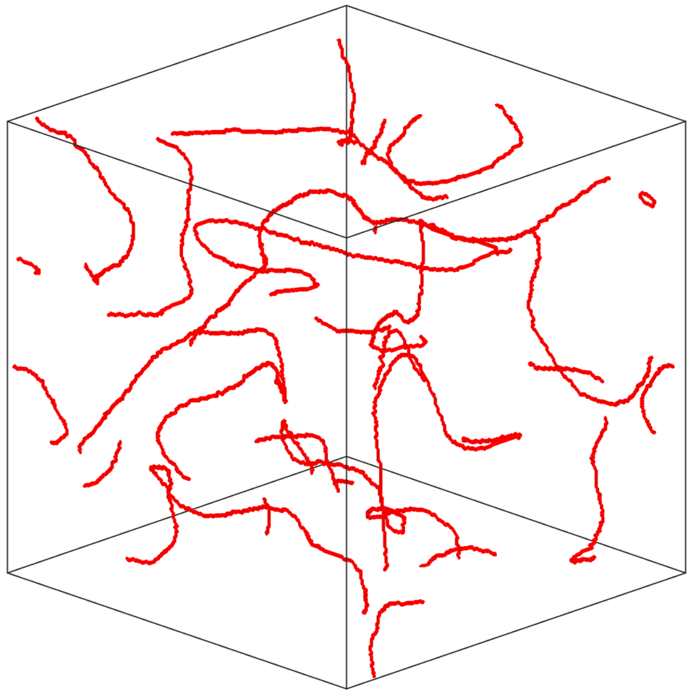
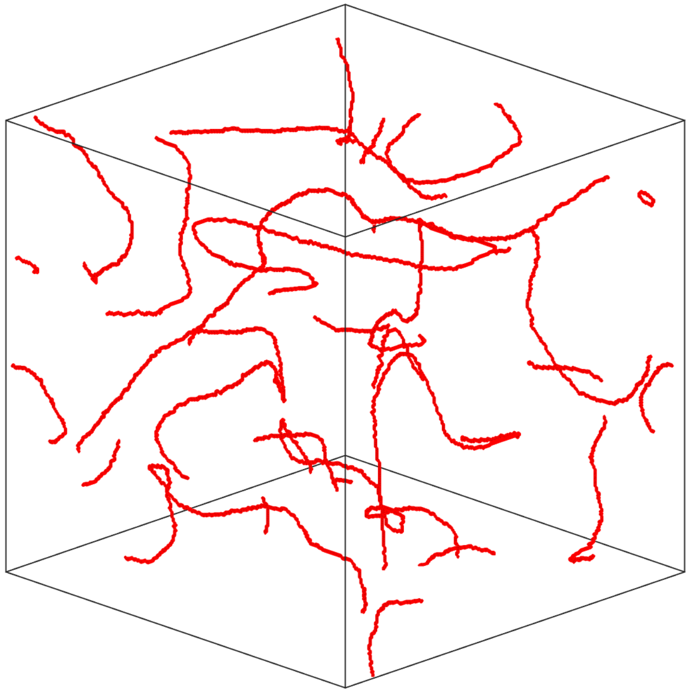
Computing strings, from the atomic to the cosmic

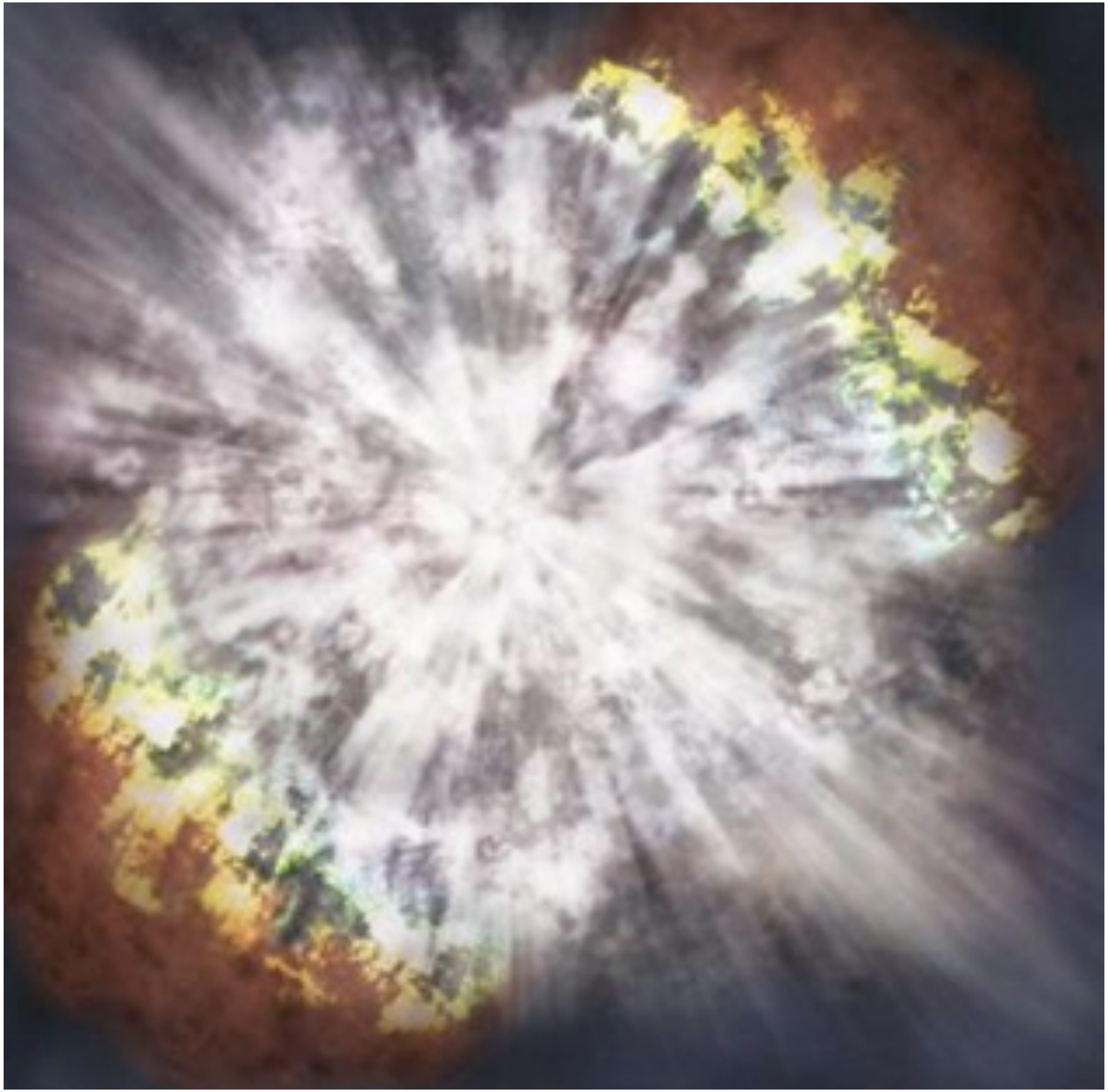
Nicola Spaldin, Materials Theory, ETH Zürich





Computing strings, from the atomic to the cosmic





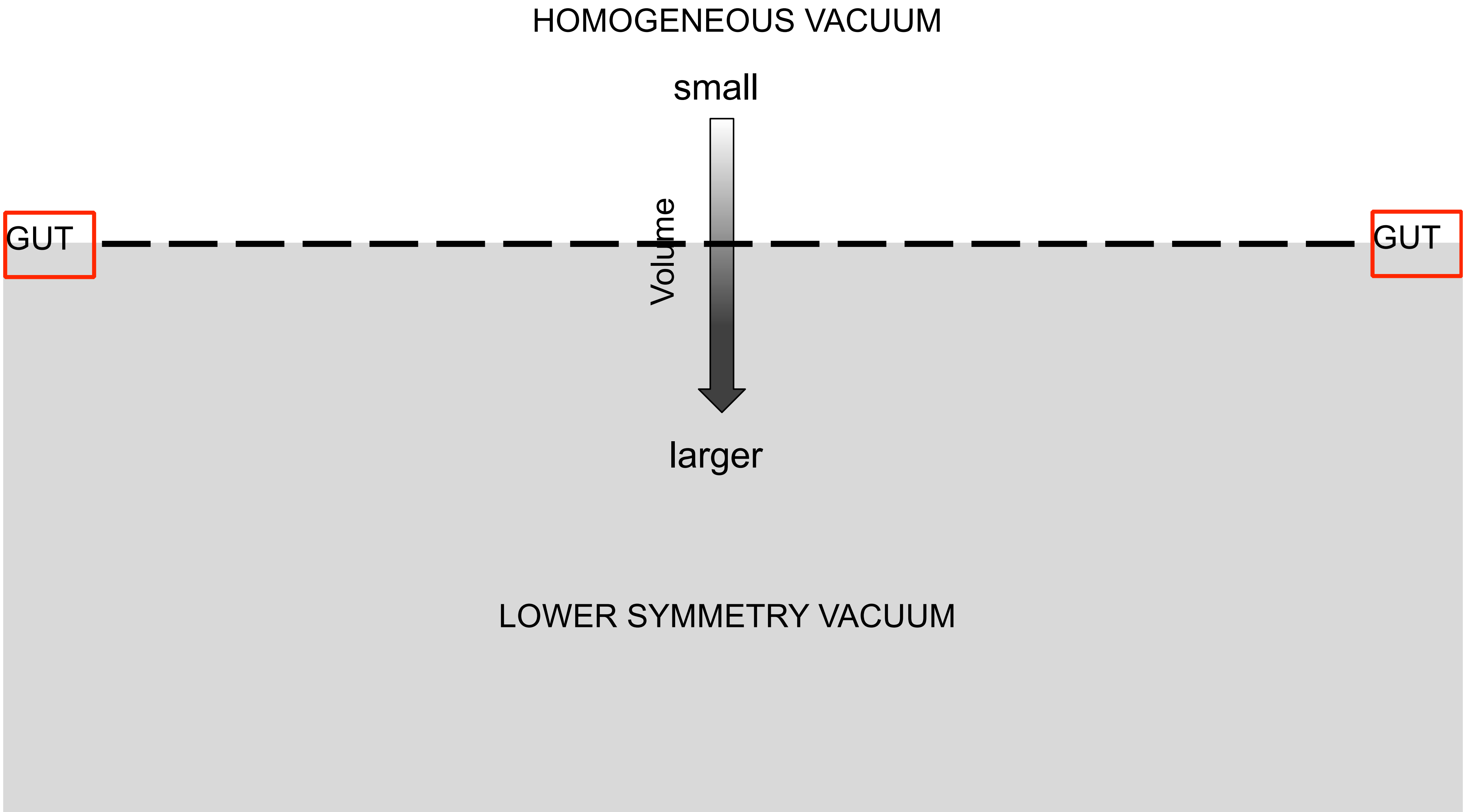
HOMOGENEOUS VACUUM

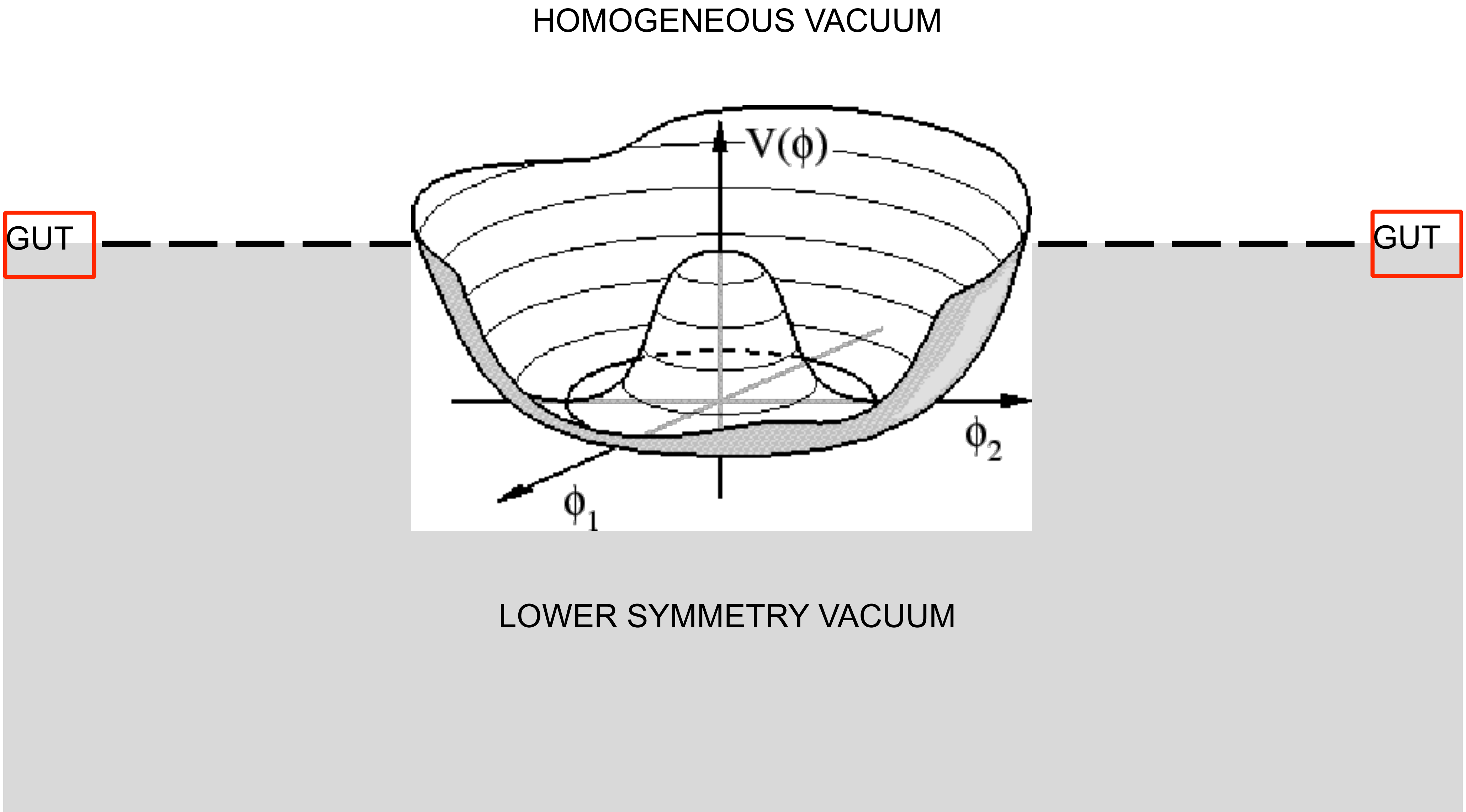
small

After 10^{-37} seconds there is a spontaneous symmetry-lowering phase transition

the Grand Unification Transition (GUT)

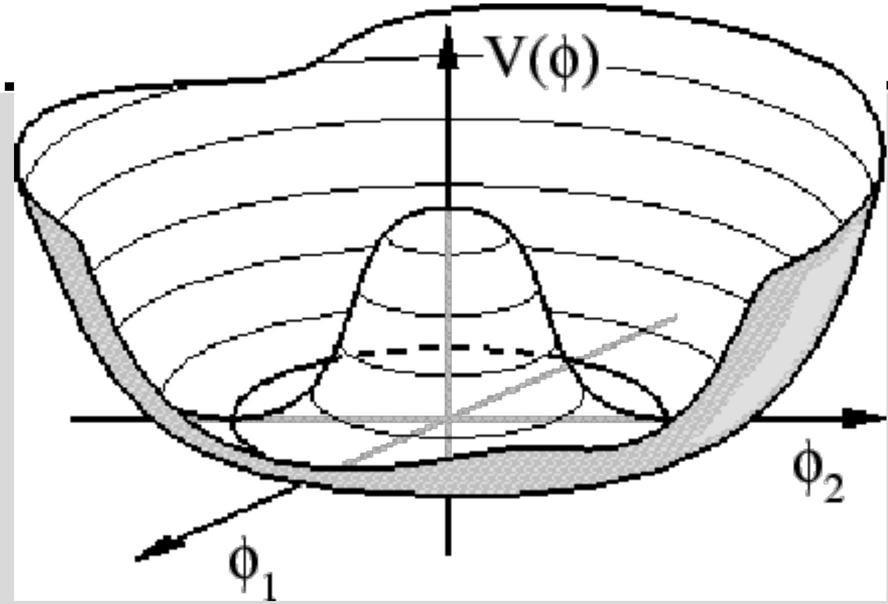
larger


HOMOGENEOUS VACUUM
small
GUT
Volume
GUT
larger
LOWER SYMMETRY VACUUM


HOMOGENEOUS VACUUM
GUT
V(φ)
GUT
φ2
φ1
LOWER SYMMETRY VACUUM

Symmetry lowering at the Grand Unification Transition

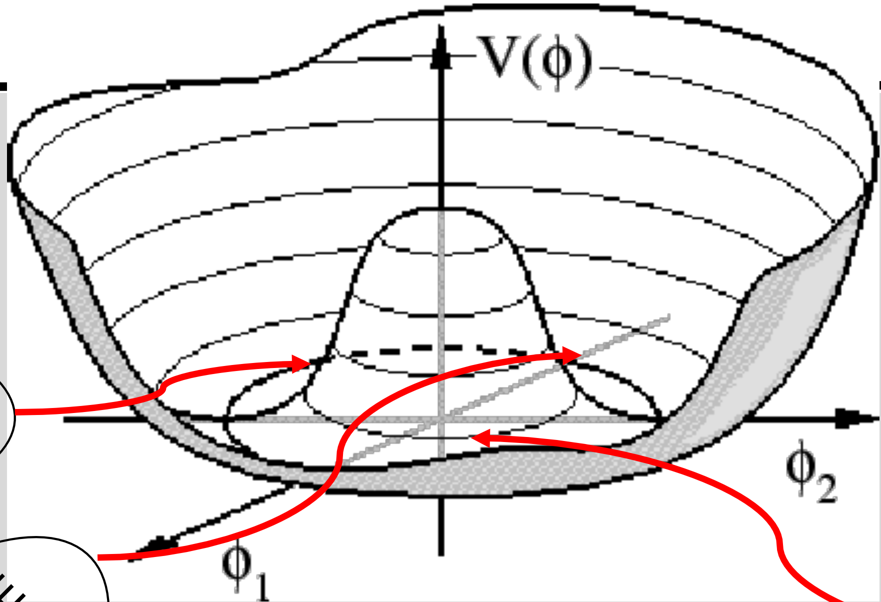
HOMOGENEOUS VACUUM



LOWER SYMMETRY VACUUM

Symmetry lowering at the Grand Unification Transition

HOMOGENEOUS VACUUM



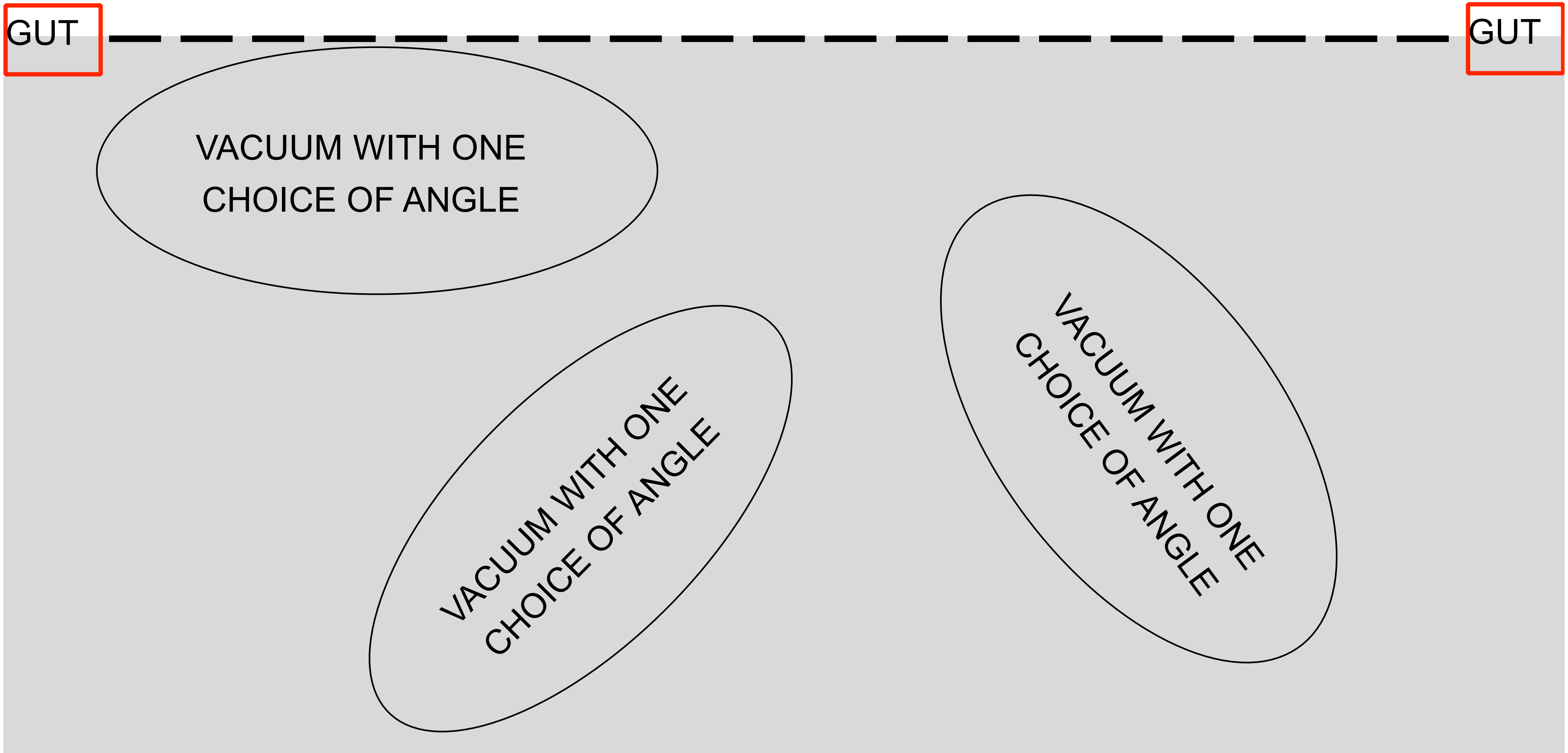
VACUUM WITH ONE CHOICE OF ANGLE

VACUUM WITH ONE CHOICE OF ANGLE

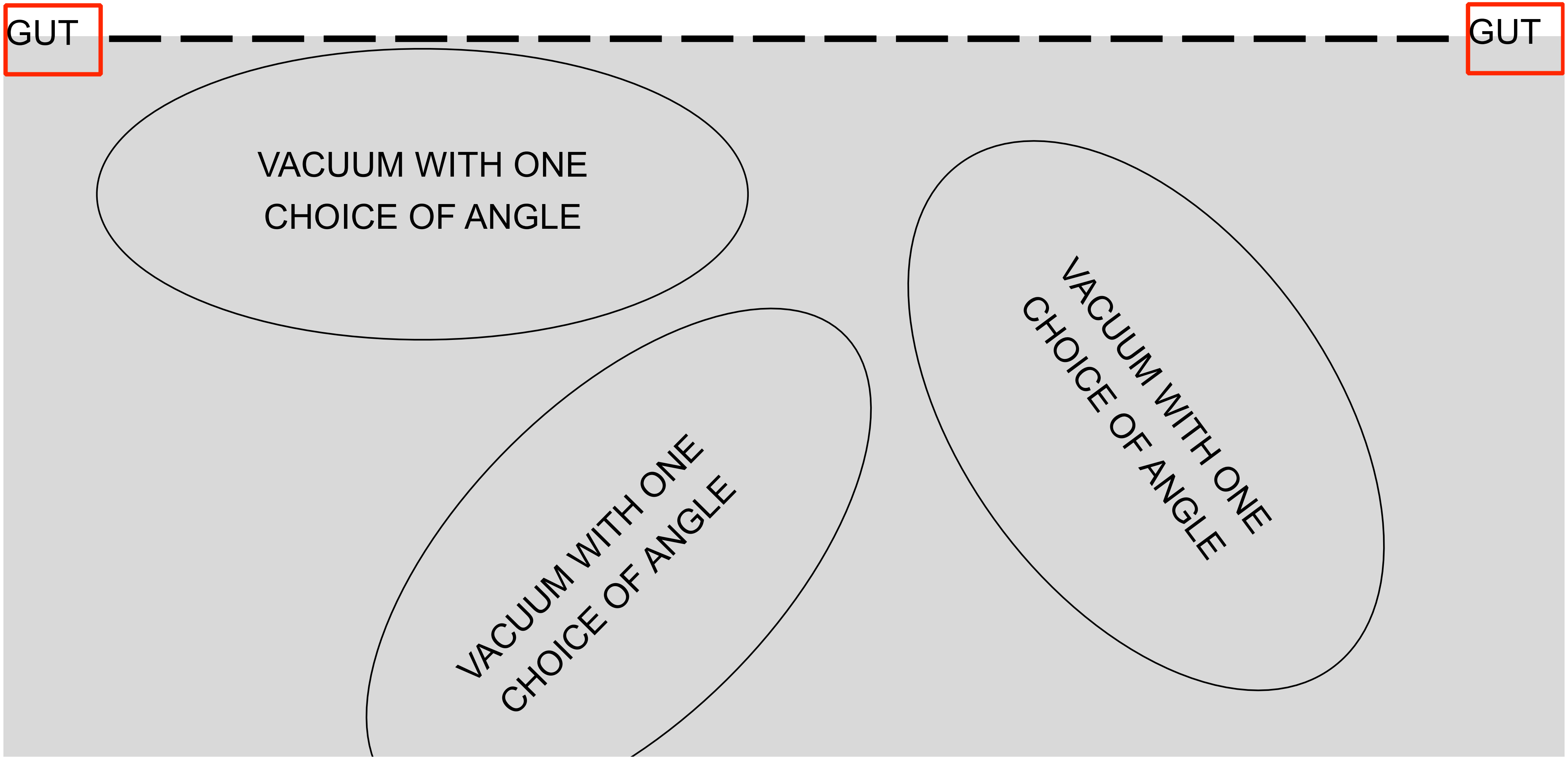
VACUUM WITH ONE CHOICE OF ANGLE

LOWER SYMMETRY VACUUM

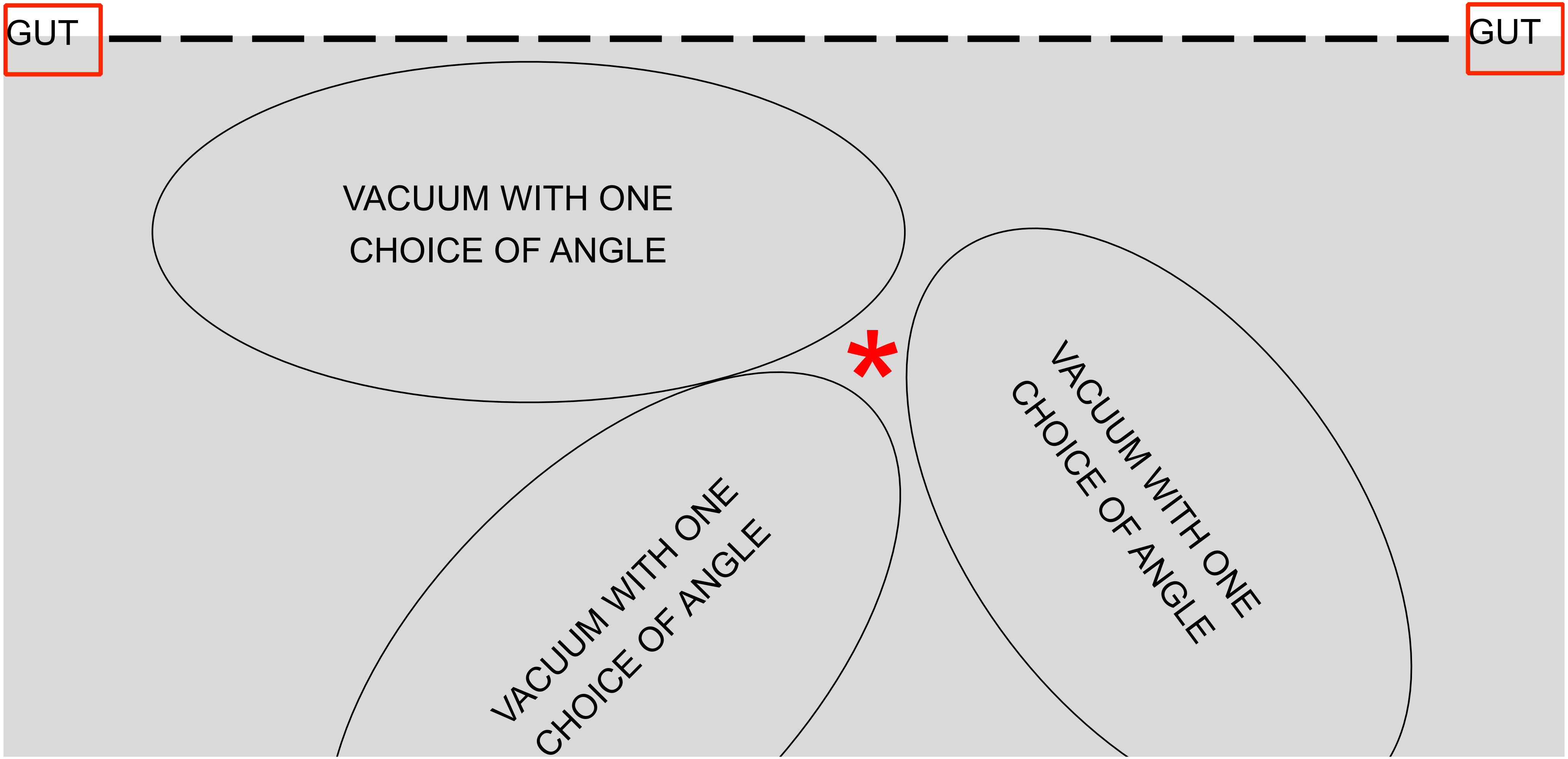
As the universe expands through the transition, the low symmetry regions grow…



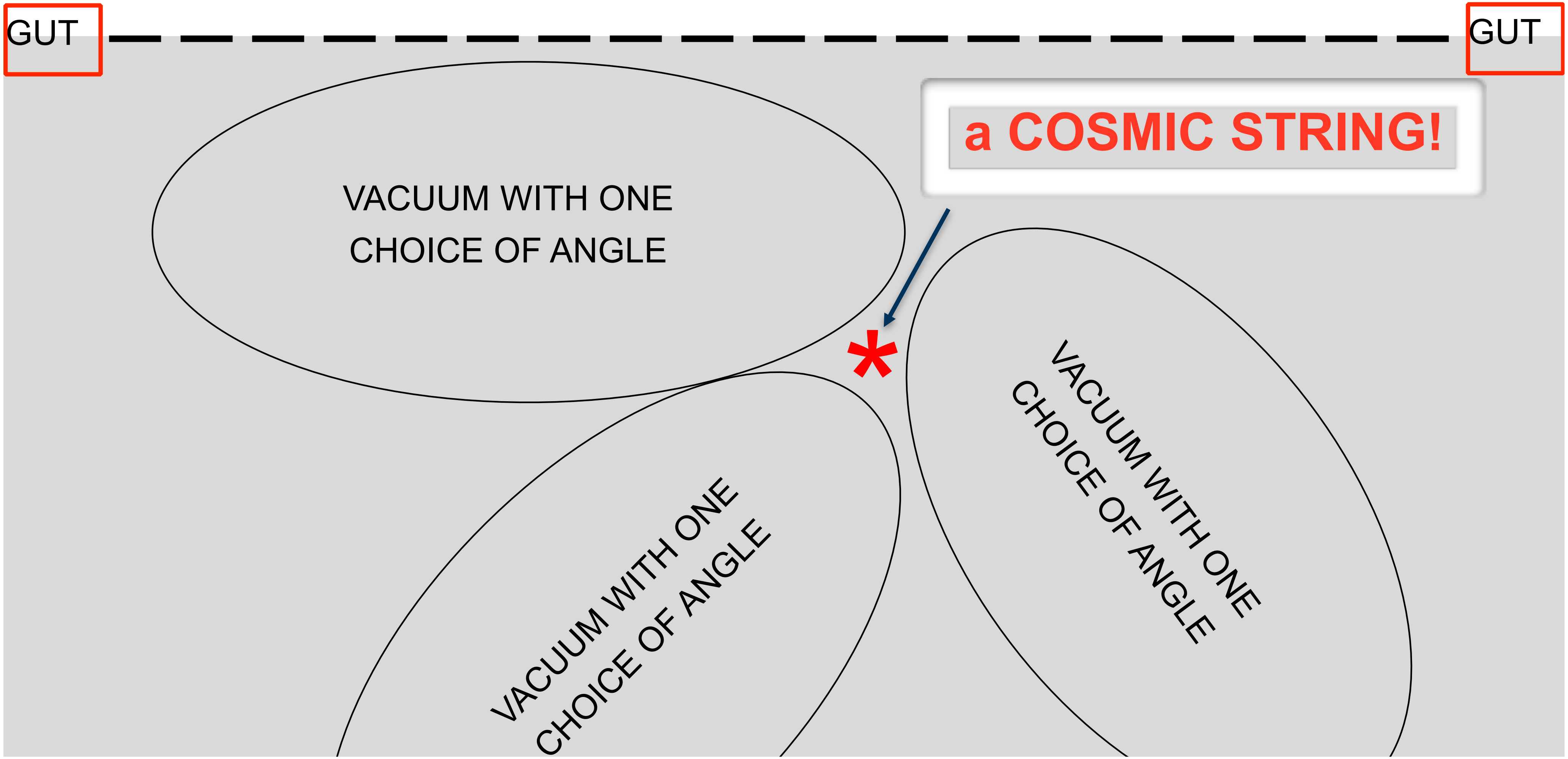
and grow…


GUT
GUT
VACUUM WITH ONE CHOICE OF ANGLE
VACUUM WITH ONE CHOICE OF ANGLE
VACUUM WITH ONE CHOICE OF ANGLE

and eventually meet!

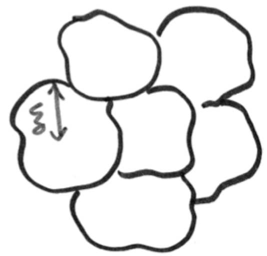


The angle mismatch in the vacuum is a *topologically protected one-dimensional defect* – a COSMIC STRING



A detail: How many cosmic strings should we have?

It depends on the rate of expansion through the transition



Expand slowly: Different regions can communicate their choice of angle

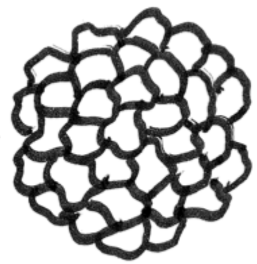
→ **Large regions of the same choice**

→ **Low density of cosmic strings**

Expand quickly: Not much time to communicate choice of angle

→ **Many smaller regions with different choices of angle**

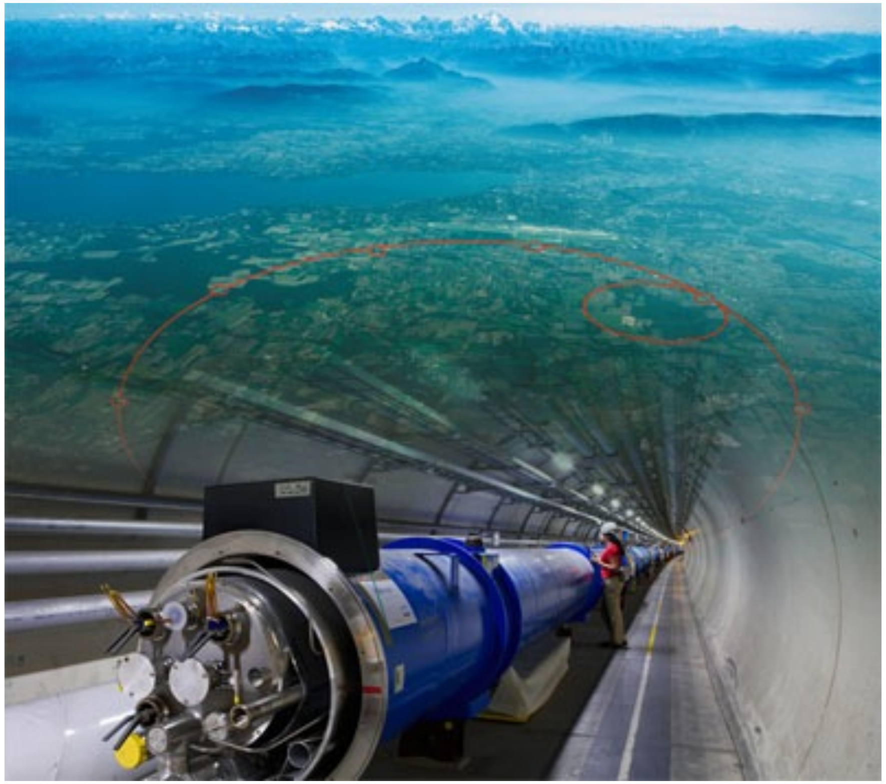
→ **High density of cosmic strings**



Do cosmic strings exist? How can we study them?

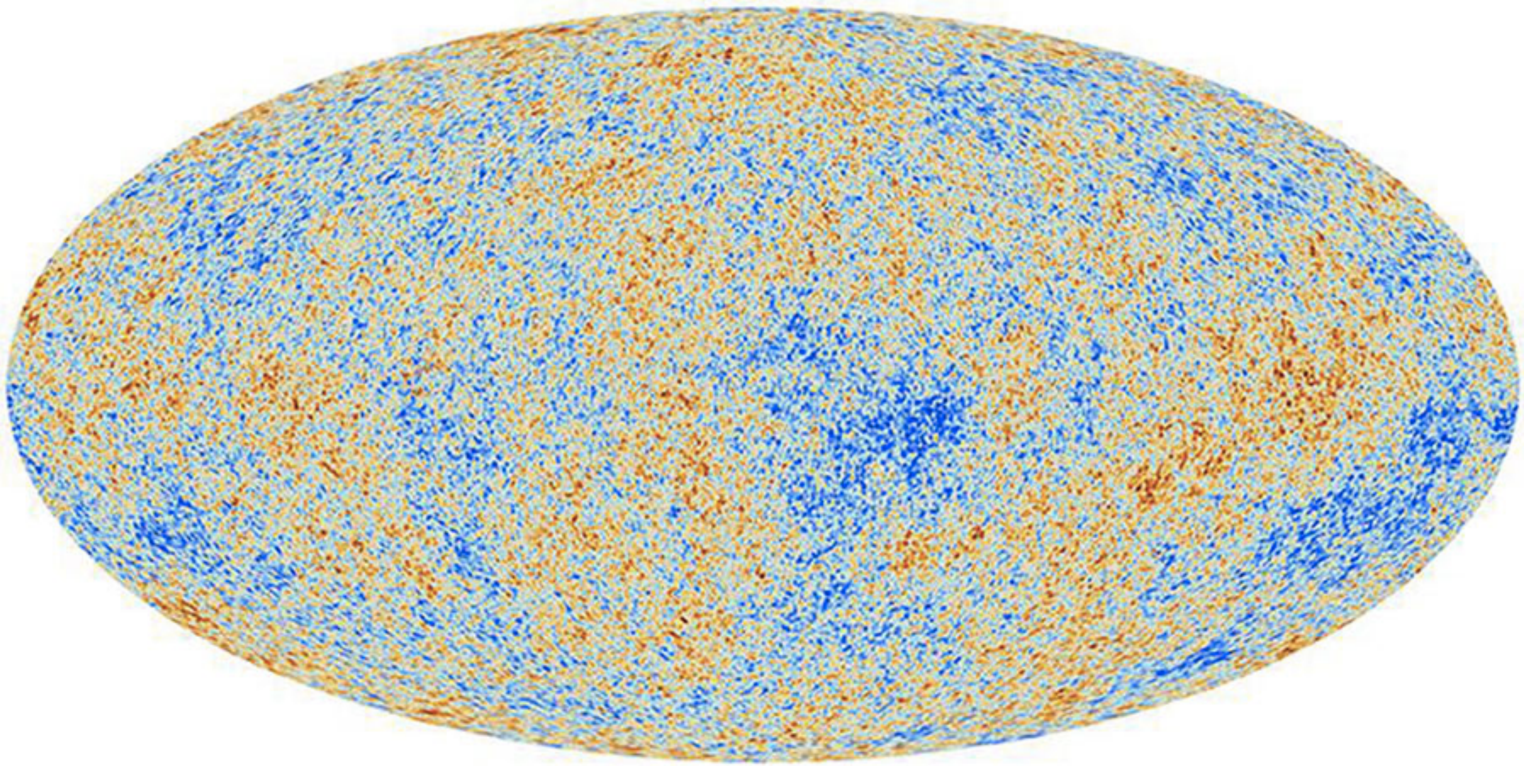
For direct study we need a probe with a similar energy, ~10^{15} GeV

Our highest energy probes, the largest hadronic colliders reach ~10,000 GeV



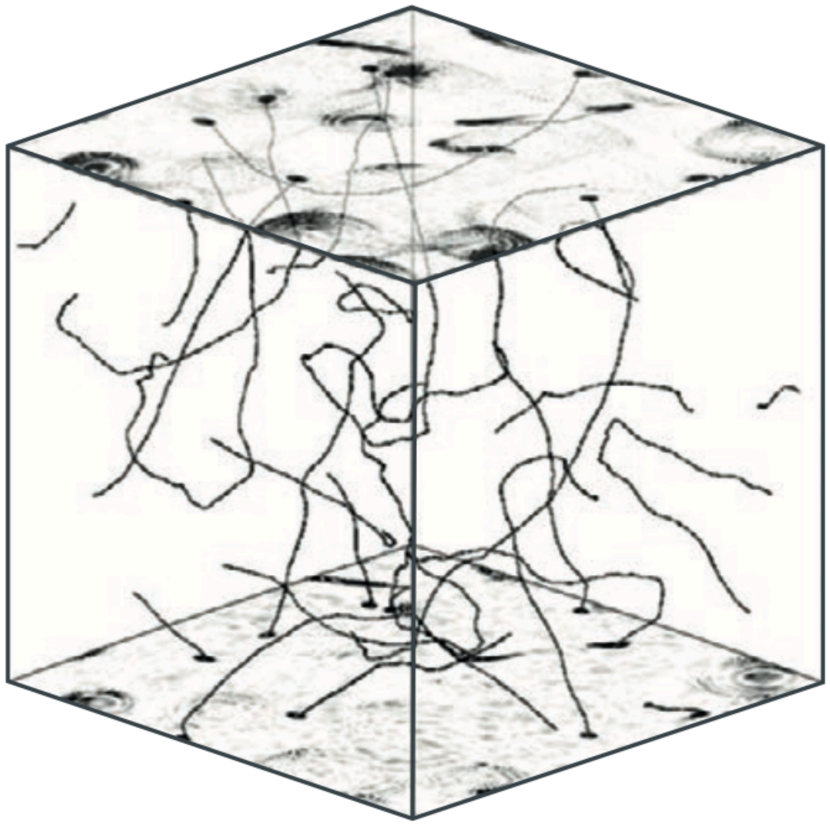
How is Cosmic String Formation at the Grand Unification Transition studied?

Analyzing the Cosmic Microwave Background



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

Computer Simulation

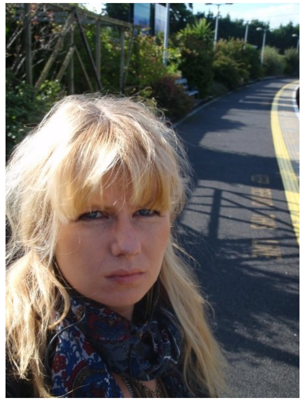


PHYSICAL REVIEW D **76,** 043005 (2007)

CMB polarization power spectra contributions from a network of cosmic strings

Neil Bevis,[1,*] Mark Hindmarsh,[1,†] Martin Kunz,[2,‡] and Jon Urrestilla[1,§]

Instead we will study the GUT in our laboratory!



Sinead Griffin

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?

Outline

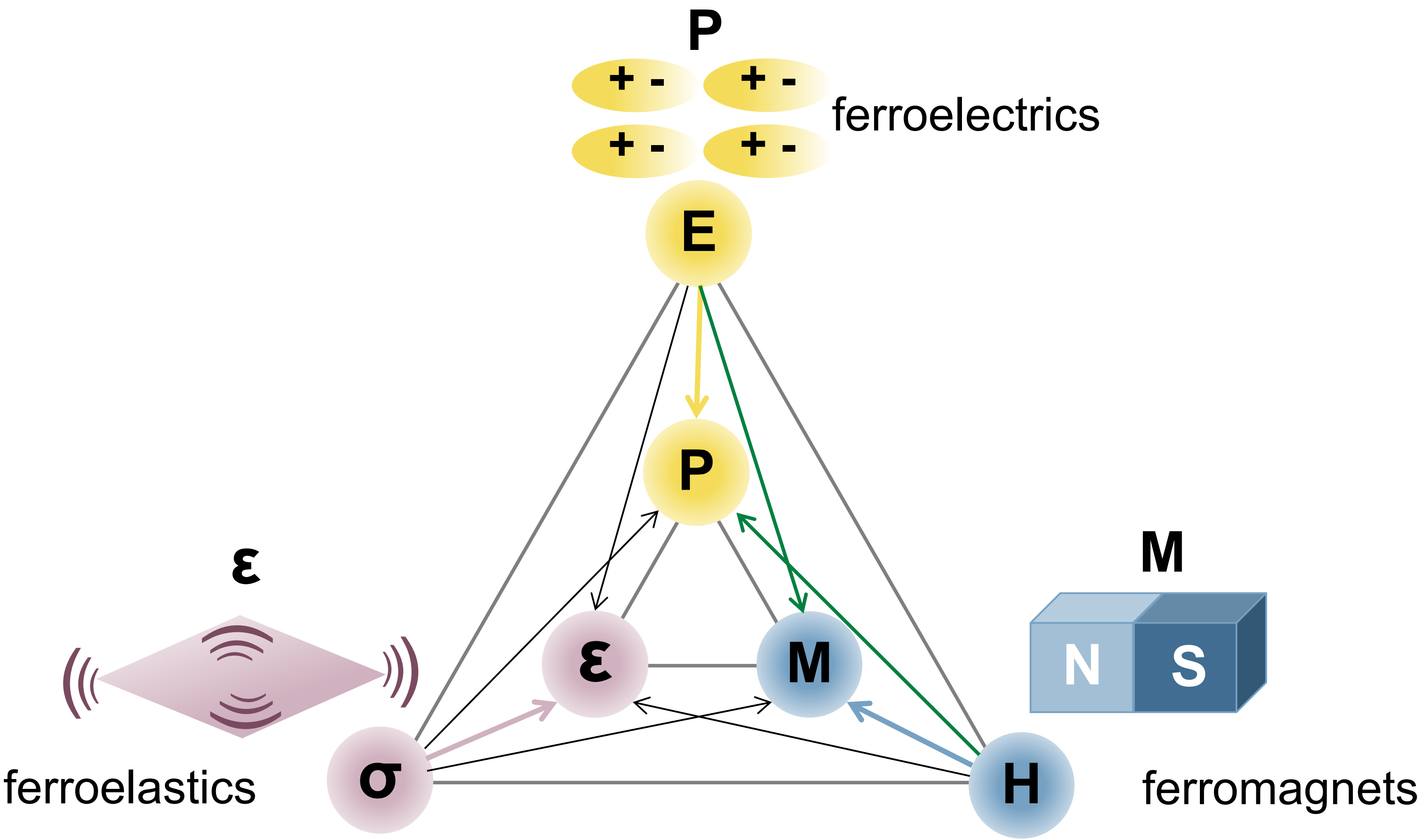
Identify a material with a symmetry-lowering phase transition described by a Mexican-hat potential

Use electronic structure calculations to calculate how many string-like defects should be formed as a function of cooling rate, based on the cosmic-string-formation model

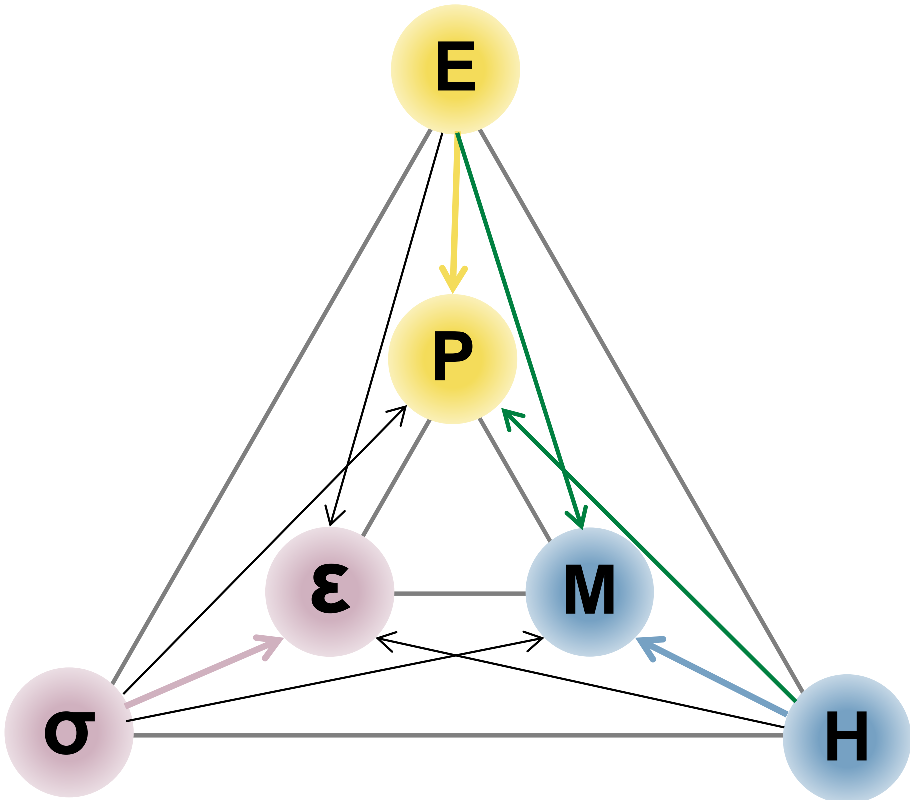
Measure how many string-like defects are formed as a function of cooling rate

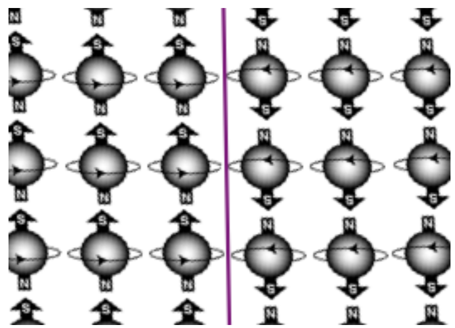
Does a system that is described by the same physics and symmetry as the GUT exhibit the predicted behavior?!

Where to find a suitable material?
Multiferroics: Multiple ferroic orders…

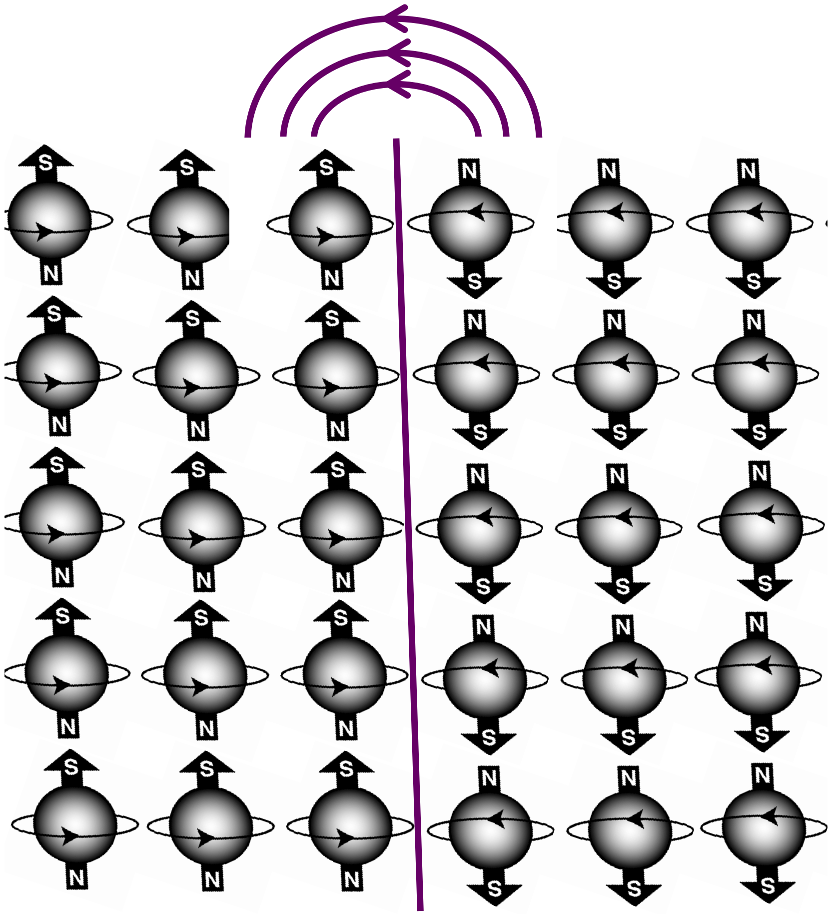


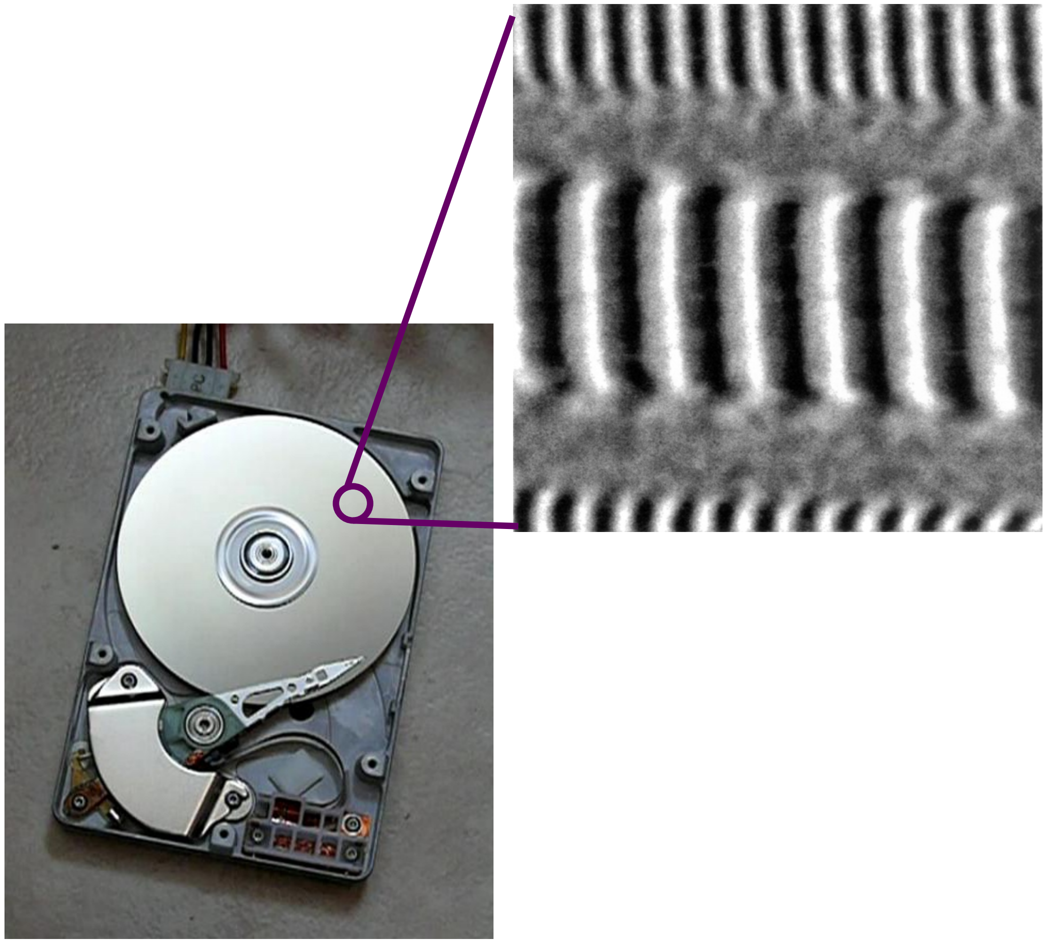
…and multiple defects from spontaneous symmetry-lowering transitions



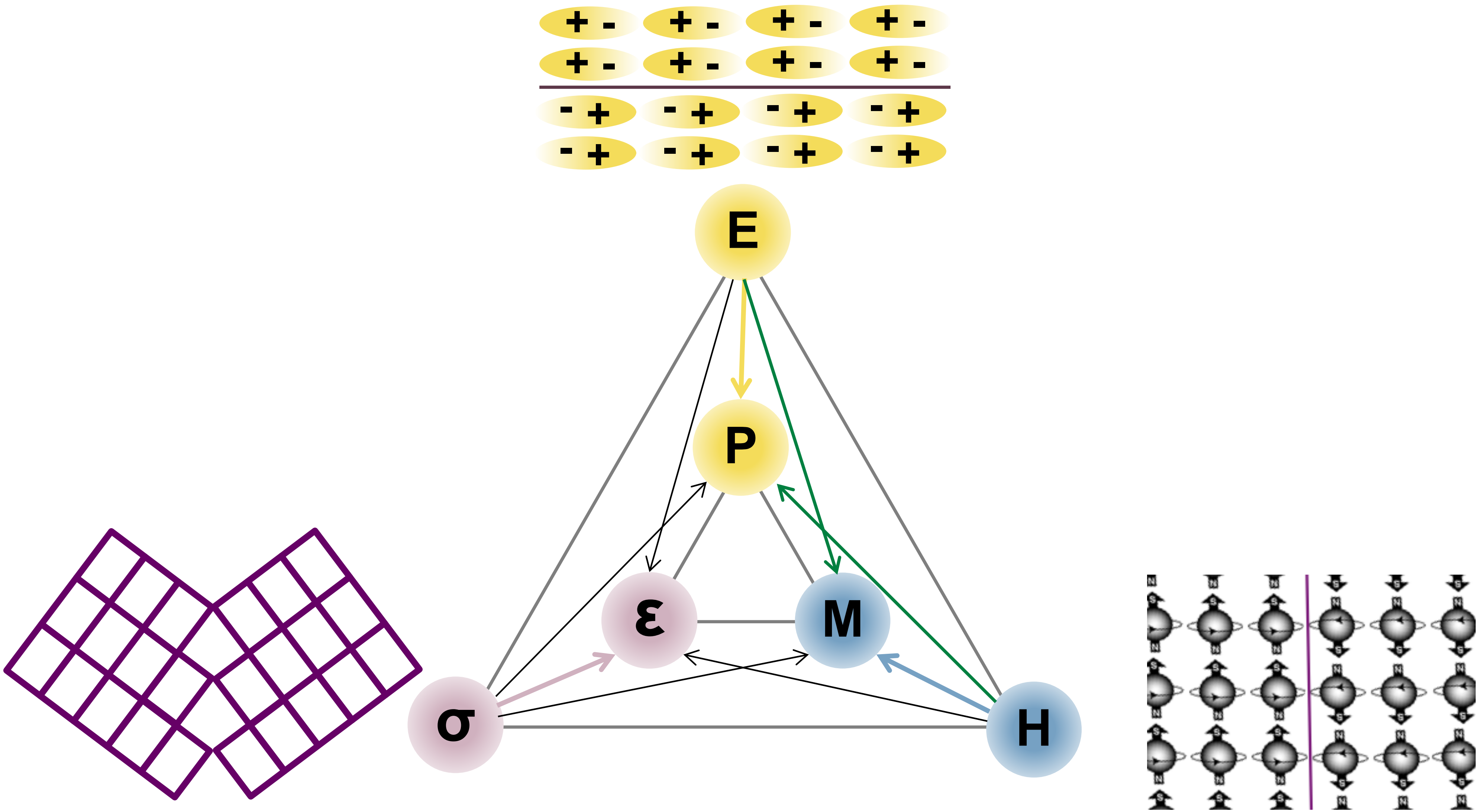


Ferromagnetic domain walls

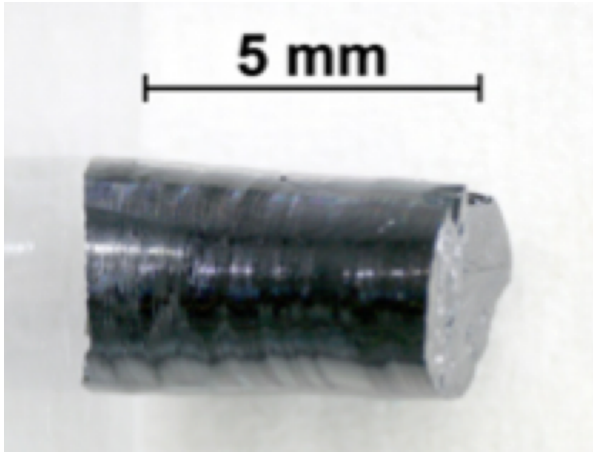




…and multiple defects from spontaneous symmetry-lowering transitions



Our material: Multiferroic $YMnO_3$

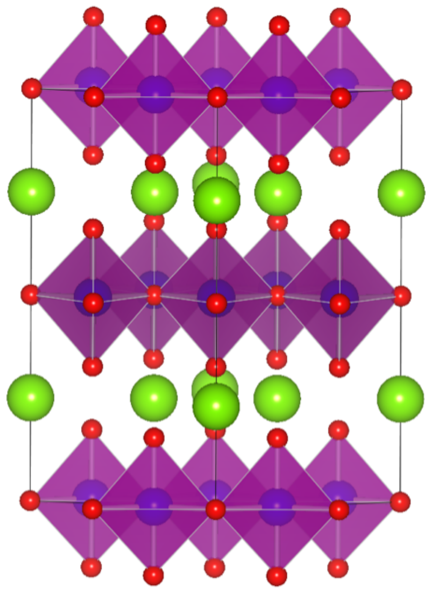


Frank Lichtenberg

Our material: Multiferroic $YMnO_3$

High temperature

$P6_3/mmc$

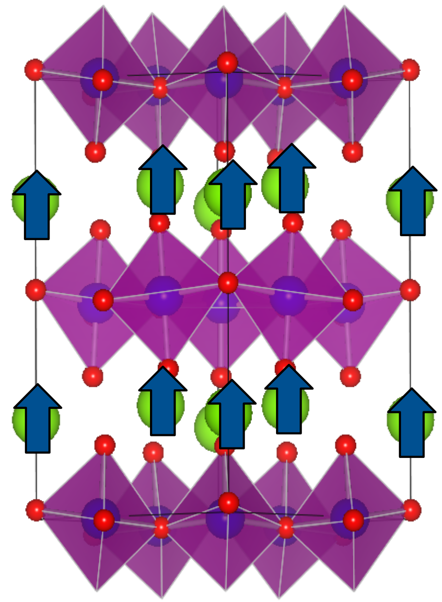


paraelectric

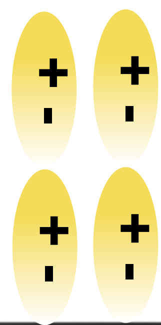
Symmetry-lowering phase transition at ~1000K

Low temperature

$P6_3cm$



ferroelectric



Use symmetry analysis and electronic structure calculations to determine the form of the potential

Landau free energy

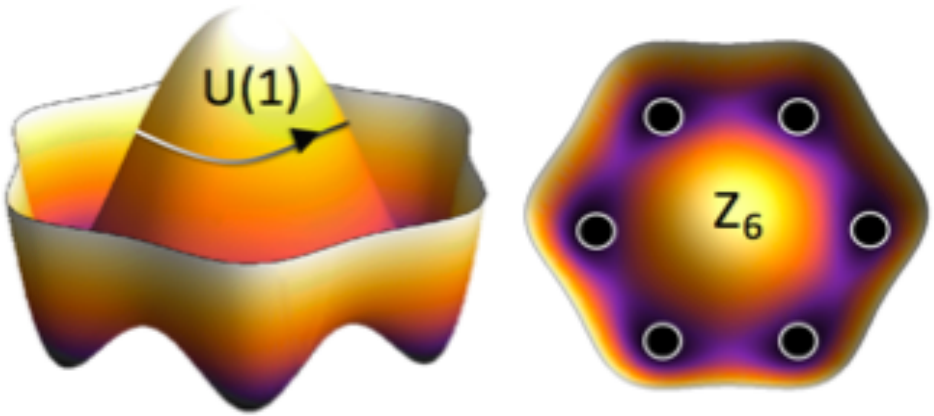
$$f_{\mathrm{u}} = \frac{a}{2}Q^2 + \frac{b}{4}Q^4 + \frac{Q^6}{6}(c + c' \cos 6\Phi) - gQ^3 P_z \cos 3\Phi$$

Q is amplitude of tilting

Φ is angle of tilting

P_z is polarization

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



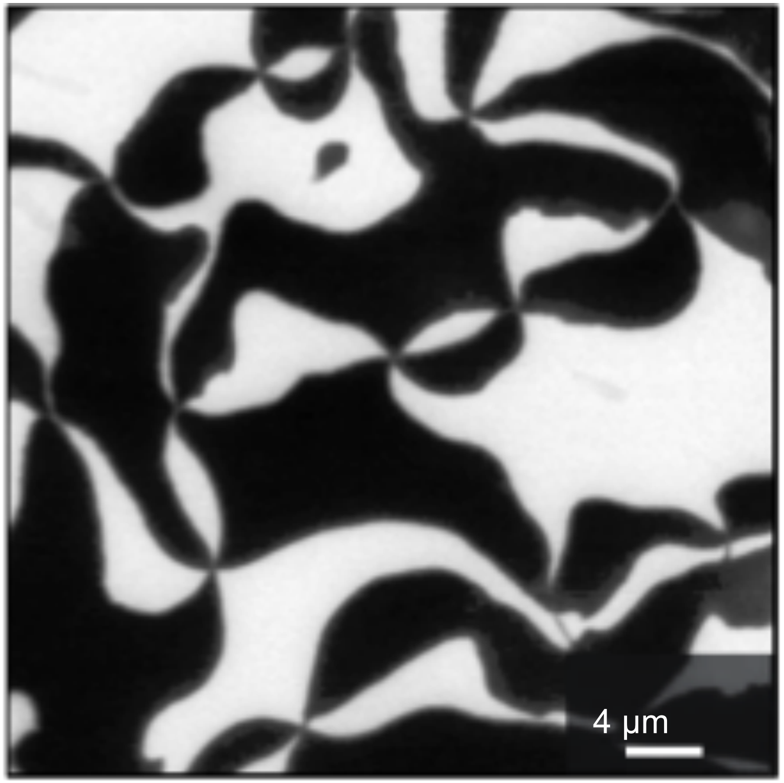
S. Artyukhin, K.T. Delaney, NAS and M. Mostovoy, *Landau theory of topological defects in multiferroic hexagonal manganites*, Nature Materials, 13, 42 (2014)

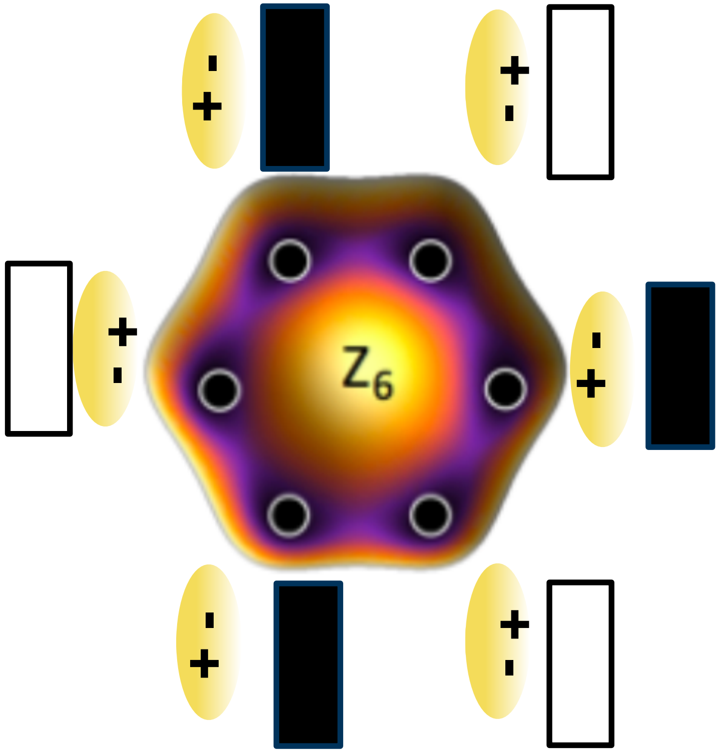
And the six minima give us six low-symmetry polar domains

Martin
Lilienblum

Manfred Fiebig

Piezoforce Microscopy Image of ferroelectricity in $YMnO_3$

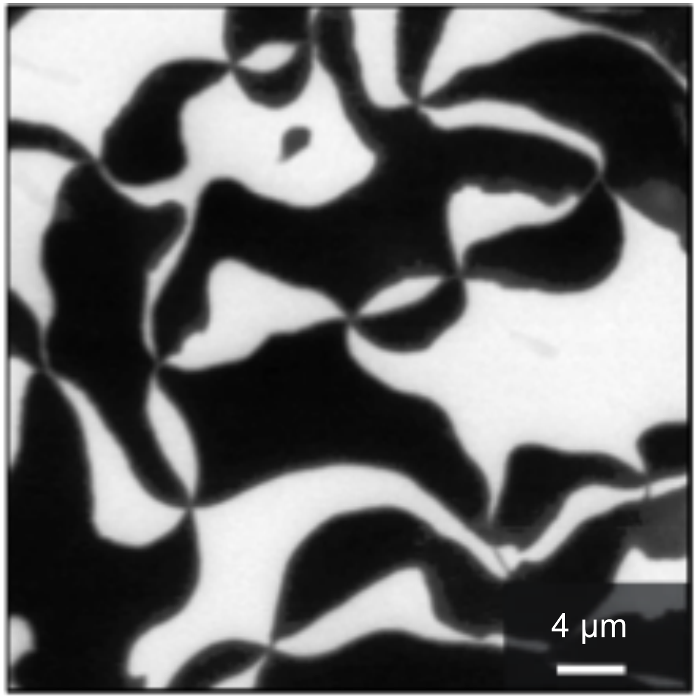




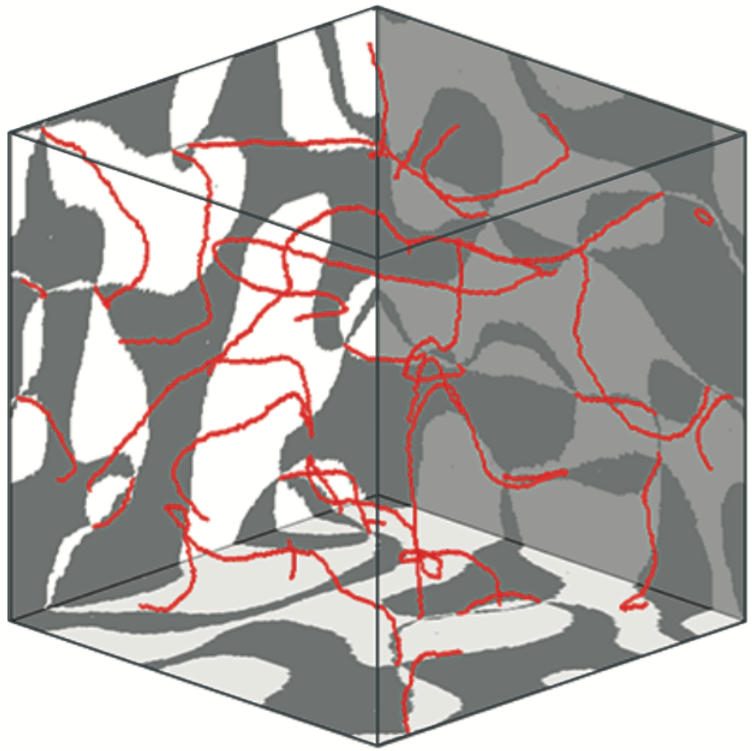
S. Artyukhin, K.T. Delaney, NAS and M. Mostovoy, *Landau theory of topological defects in multiferroic hexagonal manganites*, Nature Materials, 13, 42 (2014)

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

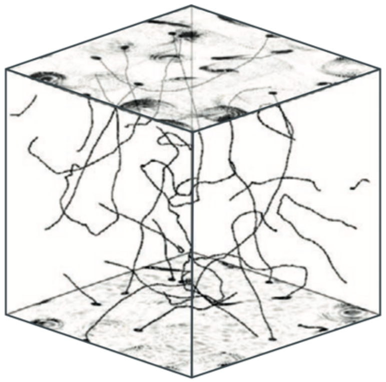


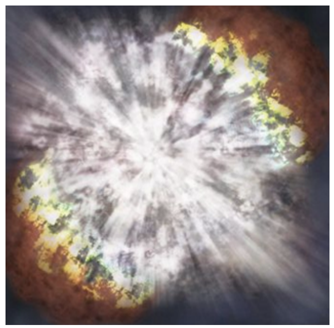
The structural phase transition in multiferroic $YMnO_3$ provides an analogue to the Grand Unification Transition

Early Universe

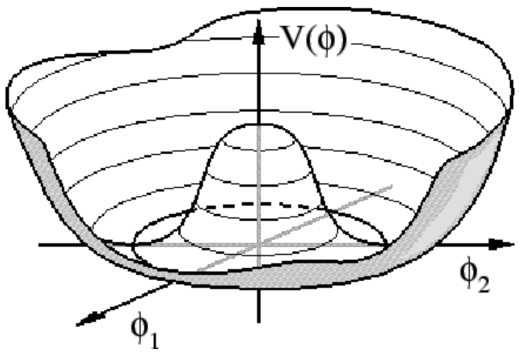
$YMnO_3$

High symmetry vacuum

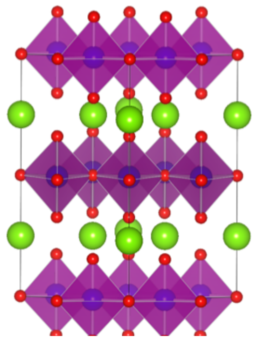


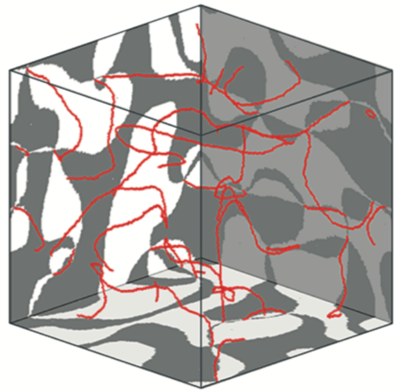


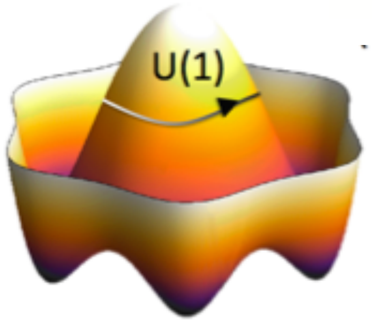
Low symmetry vacuum



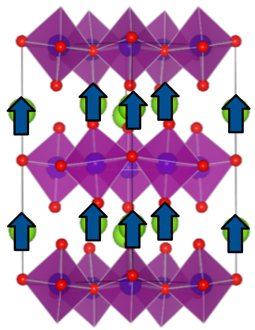
$P6_3/mmc$







$P6_3cm$

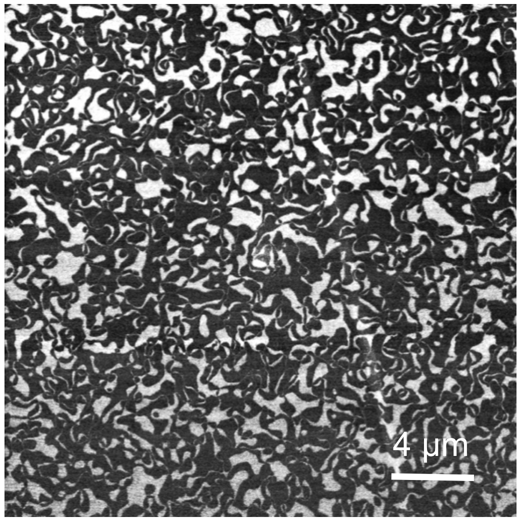


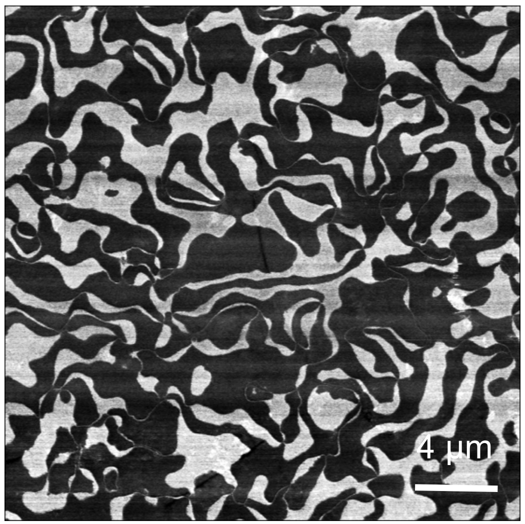
N.A. Spaldin, *Multiferroics, from the cosmically large to the subatomically small*, Nat. Rev. Mater. **2**, 17017 (2017)

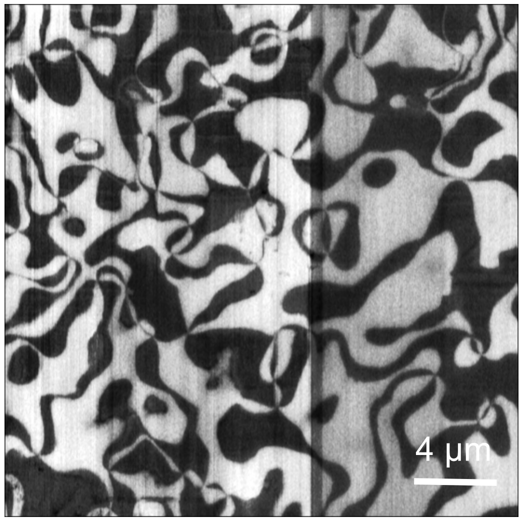
What experiment would we like to do on the early universe?

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”)

Instead we will cool $YMnO_3$ at different rates through the structural phase transition and count how many domain intersections form







Test of quantitative prediction of string formation (Kibble-Zurek scaling)

domain size,

defined as Tc (~1000K) / cooling rate

$$d = \xi_0 \left(\frac{\tau_q}{\tau_0} \right)^{\frac{\nu}{1+\mu}}$$

Critical exponents: ratio = 0.58

from MC simulations for 3D XY model

M. Campostrini et al., Phys. Rev. B **74**, 144506 (2006)

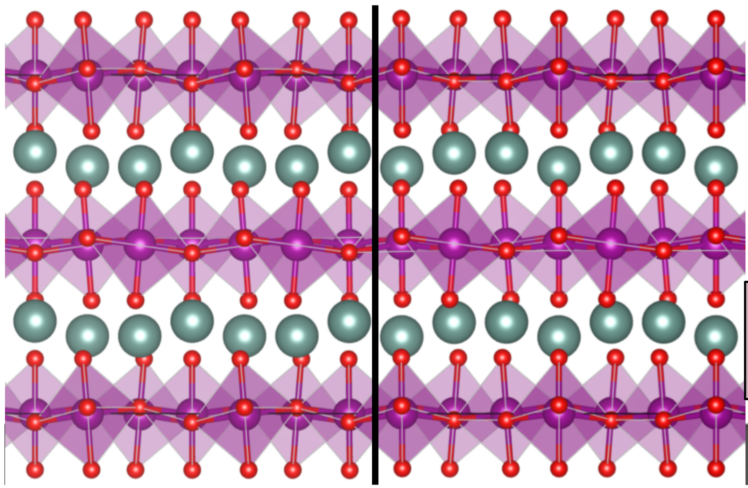
zero-temperature correlation length

~ domain wall width in ferroelectrics

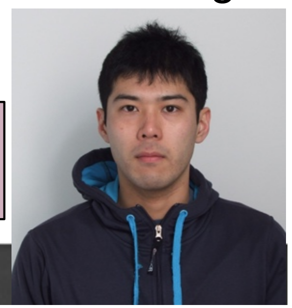
zero-temperature relaxation time

= ξ_0 / speed of sound

speed of sound = 640 m/s (DFT)



Yu Kumagai



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

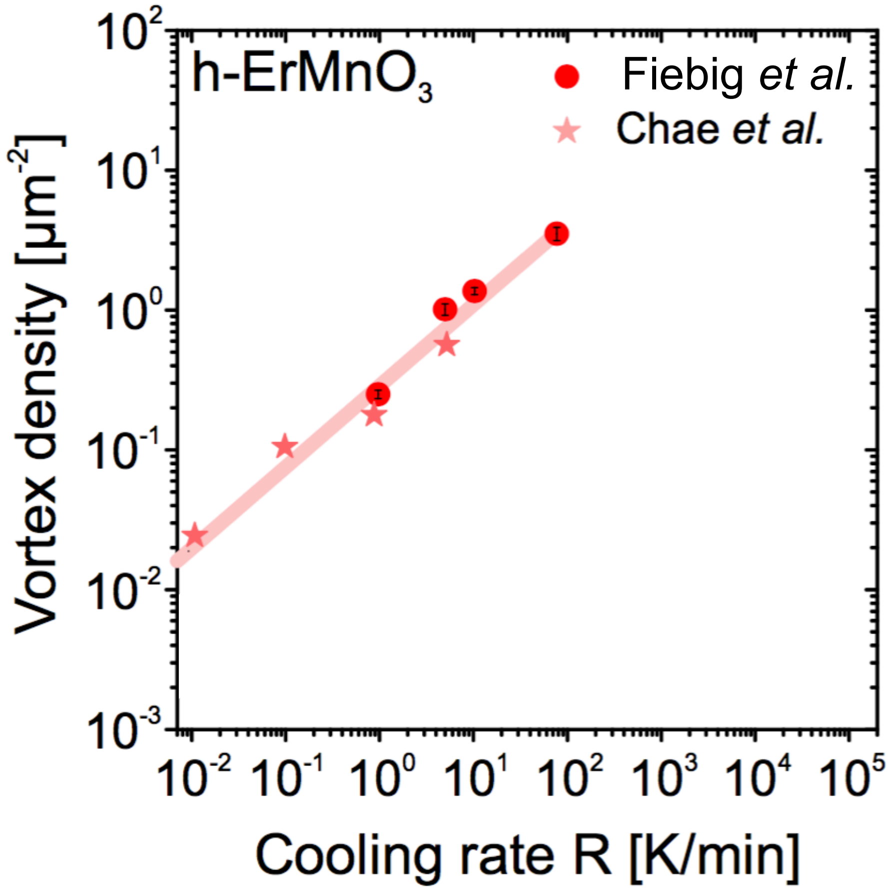
Comparison of predicted Kibble-Zurek scaling with experiment

Red line: our calculations

with ξ_0 = 0.06 A

Red points: measured

REMARKABLE AGREEMENT!



S. C.. Chae et al., *Direct observation of the proliferation of ferroelectric loop domains and vortex-antivortex pairs,* PRL **108**, 167603 (2012)

S. Griffin, M. Lilienblum, K. Delaney, Y. Kumagai, M. Fiebig and N. A. Spaldin, *Scaling behaviour and beyond equilibrium in the hexagonal manganites*, PRX **2**, 041022 (2012)

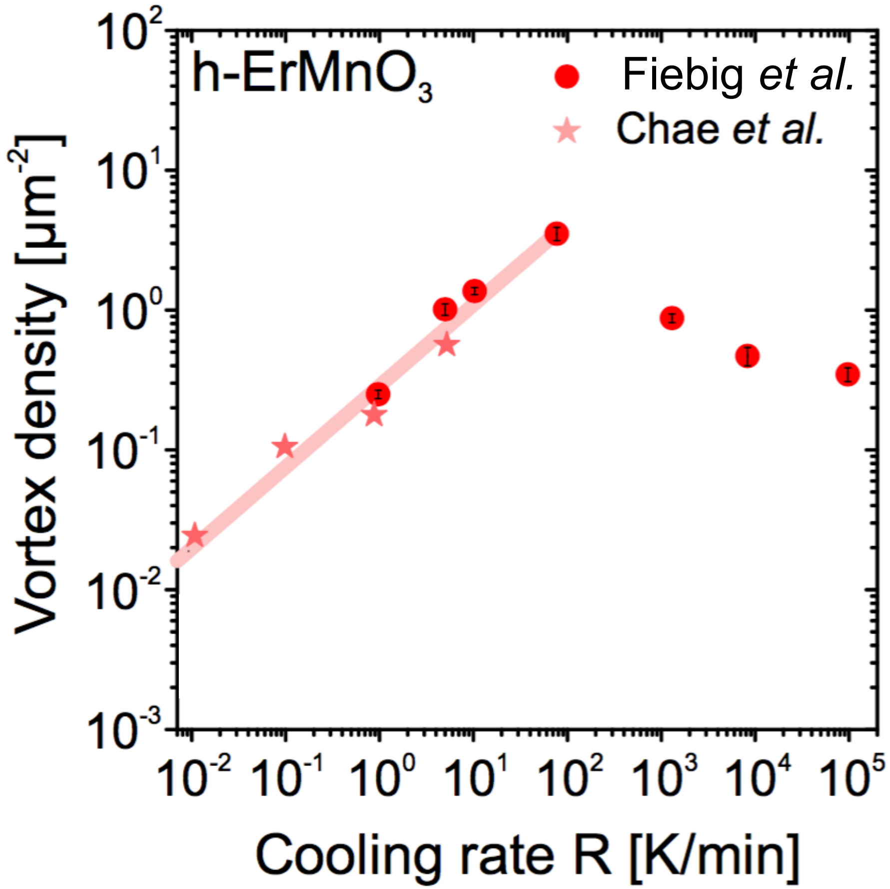
Comparison of predicted Kibble-Zurek scaling with experiment

Red line: our calculations

with ξ_0 = 0.06 A

Red points: measured

REMARKABLE AGREEMENT
AT SLOW COOLING RATE!



Discovery of a "beyond-Kibble-Zurek regime" at fast cooling

Open questions:

What is the origin of the turnaround?

What is the physics of the beyond-KZ regime?

Is it relevant for early-universe behavior?

Quintin Meier

Summary

$YMnO_3$ seems to provide the first example of Kibble-Zurek scaling in a condensed matter system

Cosmic strings formed the way cosmologists thought ;)

The Economist

Table-top astrophysics

How to build a multiverse

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

Mar 16th 2013 | From the print edition

Like 953

> 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.”

Always go to the SERC (CSCS) annual meeting!