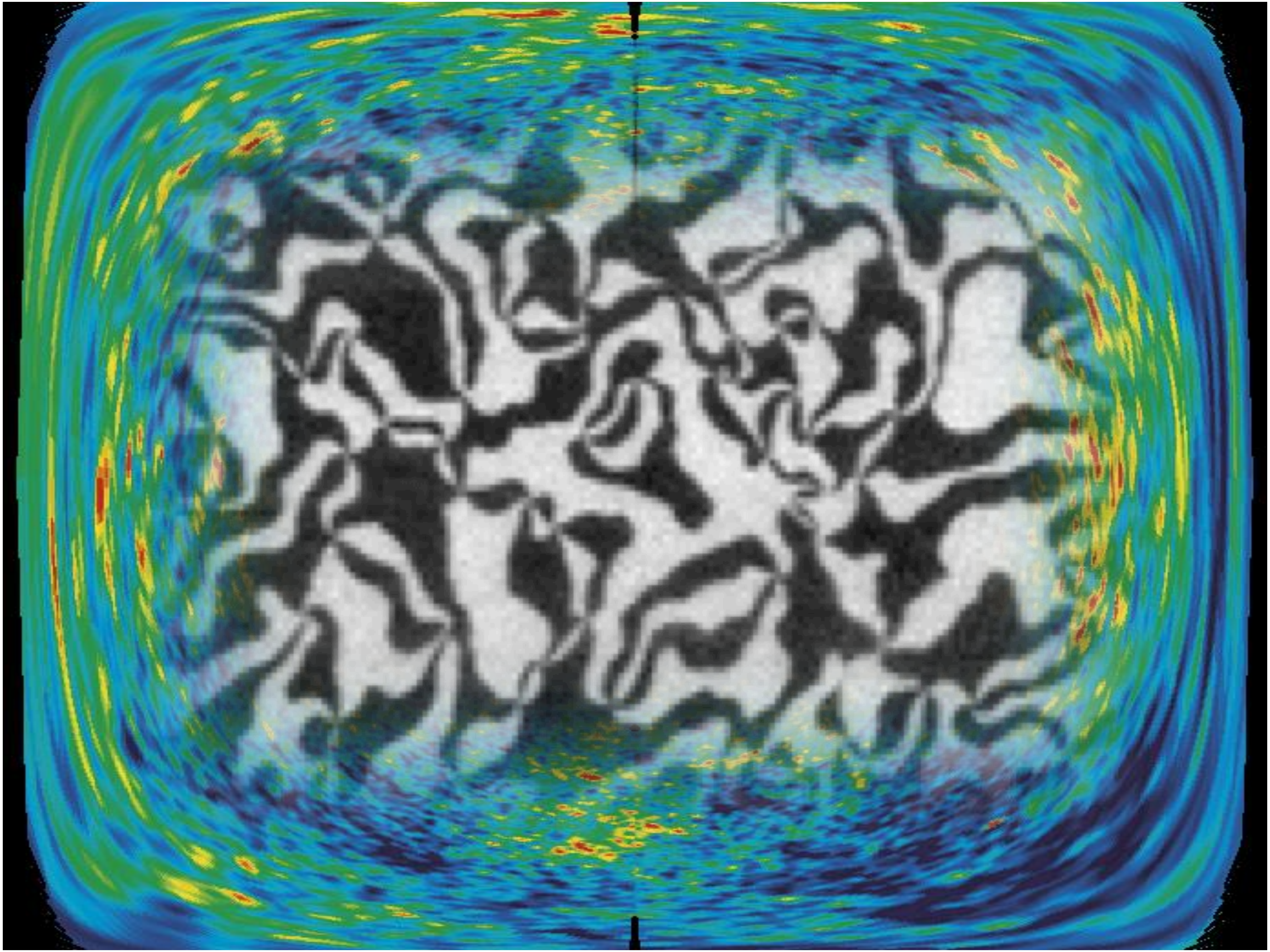
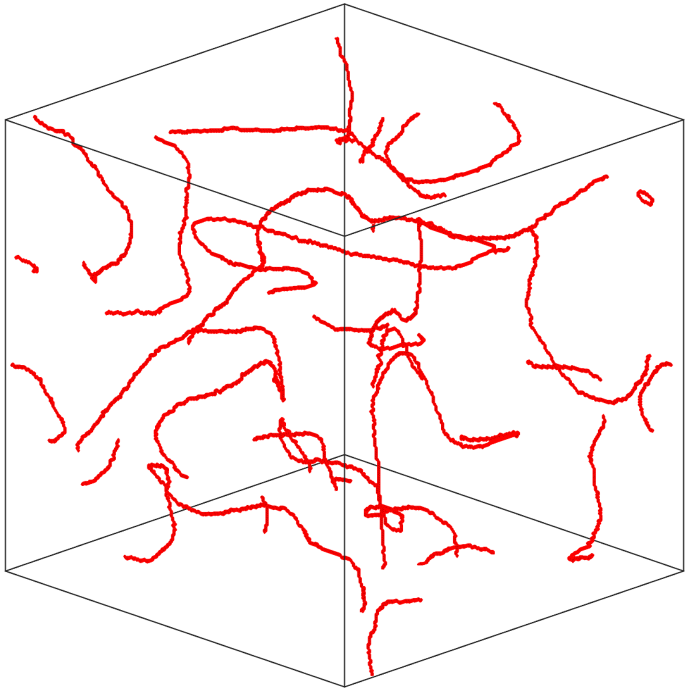
From materials to cosmology
Studying the early universe under the microscope

Nicola Spaldin
Materials Theory
ETH Zürich



Quiz

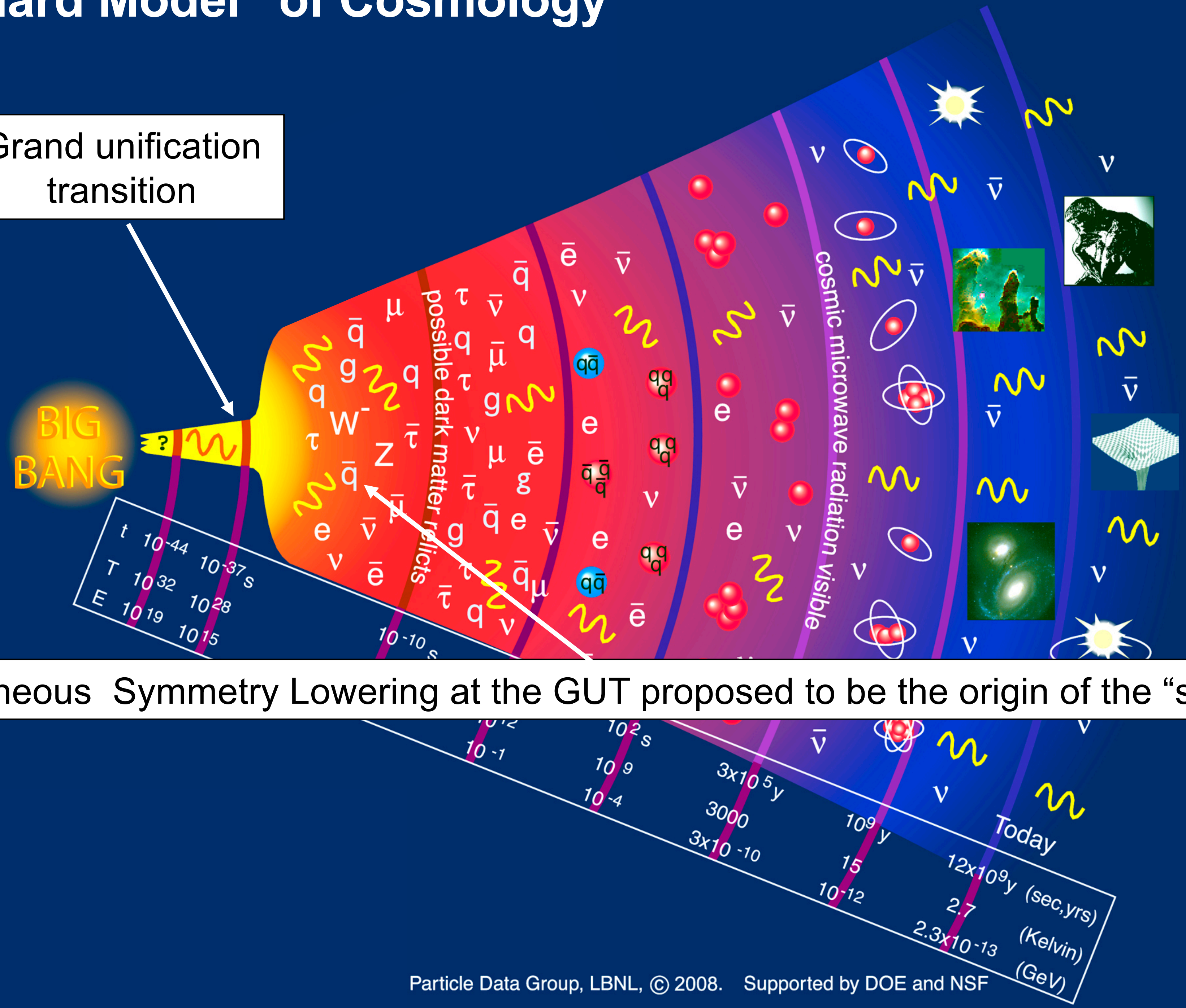


N.A. Spaldin, *Multiferroics, from the cosmically large to the subatomically small*, Nat. Rev. Mater. **2**, 17017 (2017)

"Standard Model" of Cosmology

“Standard Model” of Cosmology

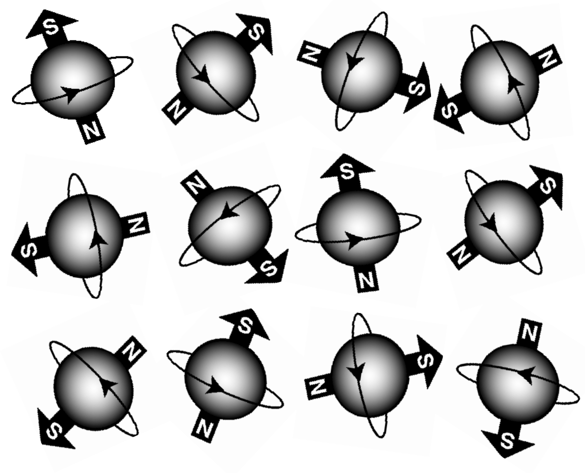
Grand unification transition



Spontaneous Symmetry Lowering at the GUT proposed to be the origin of the “stuff”

Spontaneous symmetry lowering phase transition in a ferromagnet

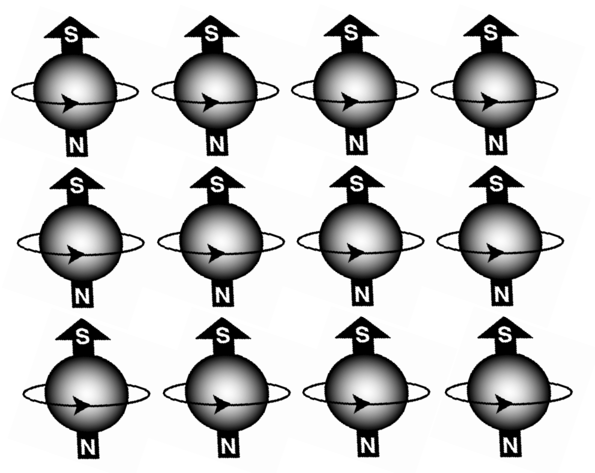
high temperature



high symmetry

Transition (Curie) temperature, Tc

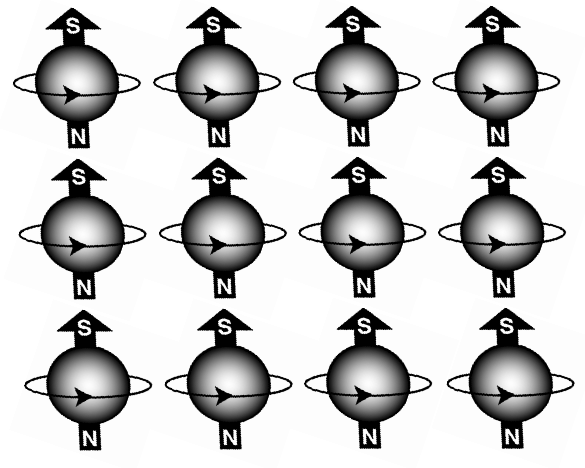
low temperature

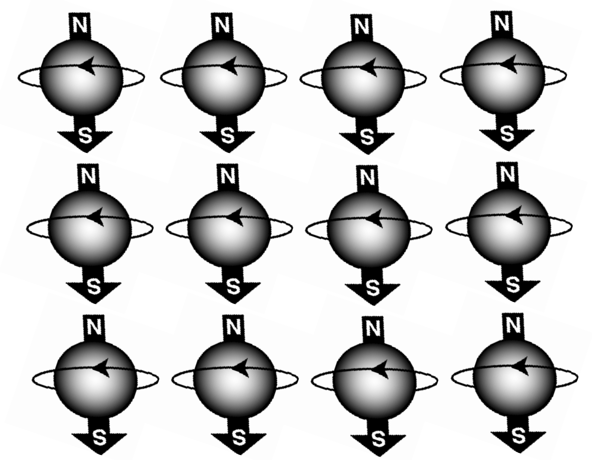


low symmetry

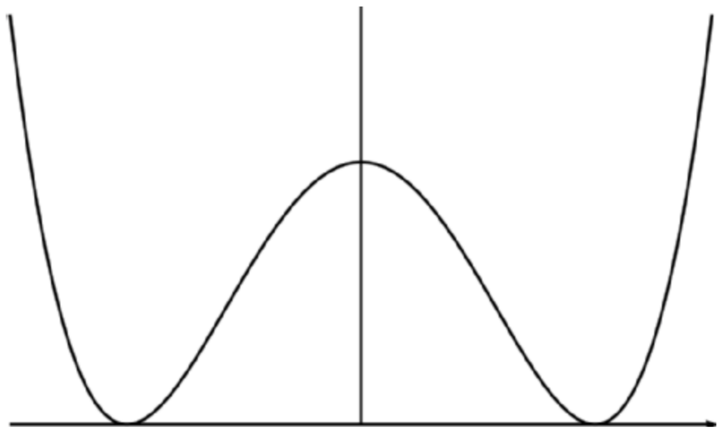
1. Choice of multiple equivalent low-symmetry states

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

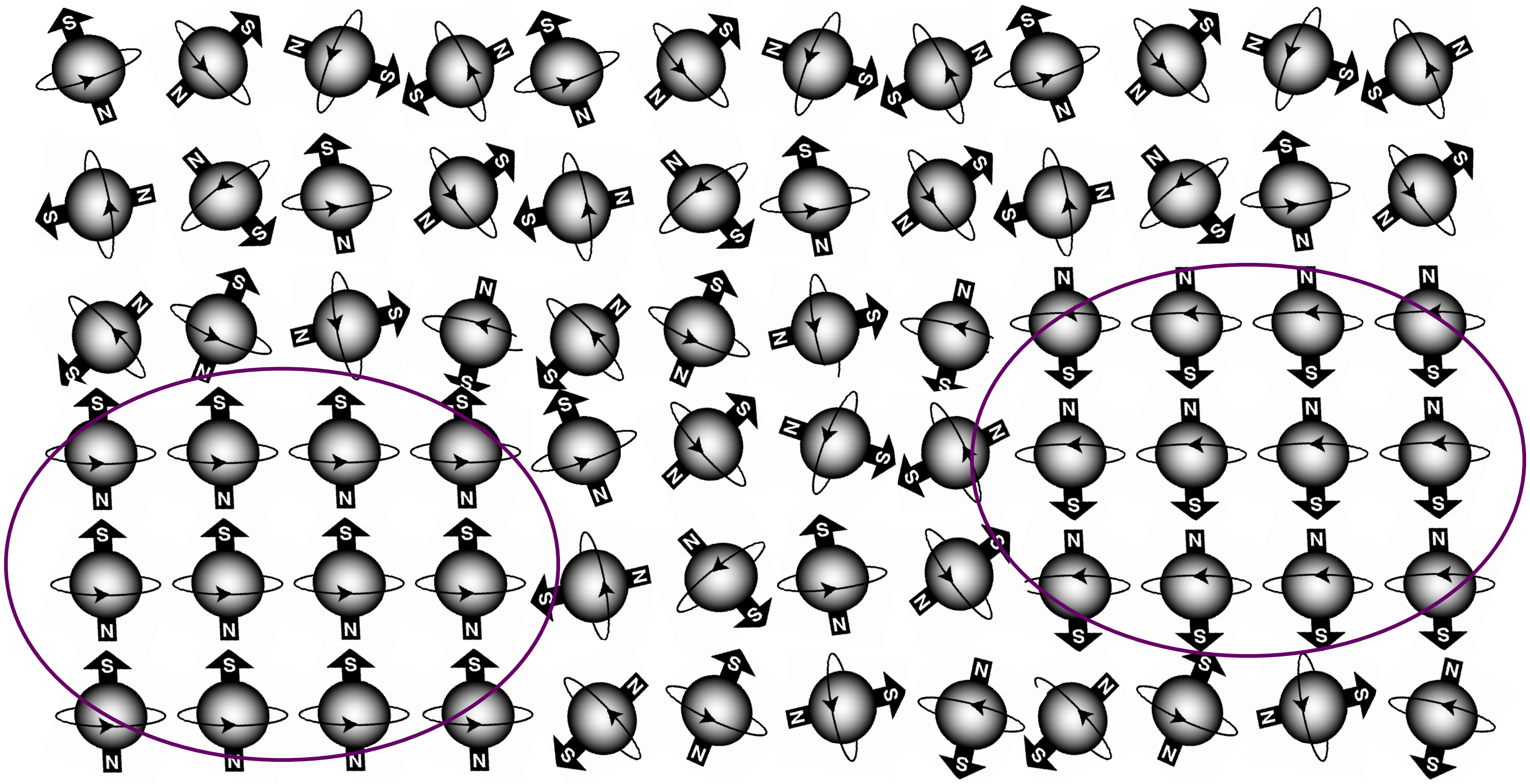




and the symmetry-lowering phase transition is described by a double well potential:



2. Defect formation at symmetry-lowering phase transitions



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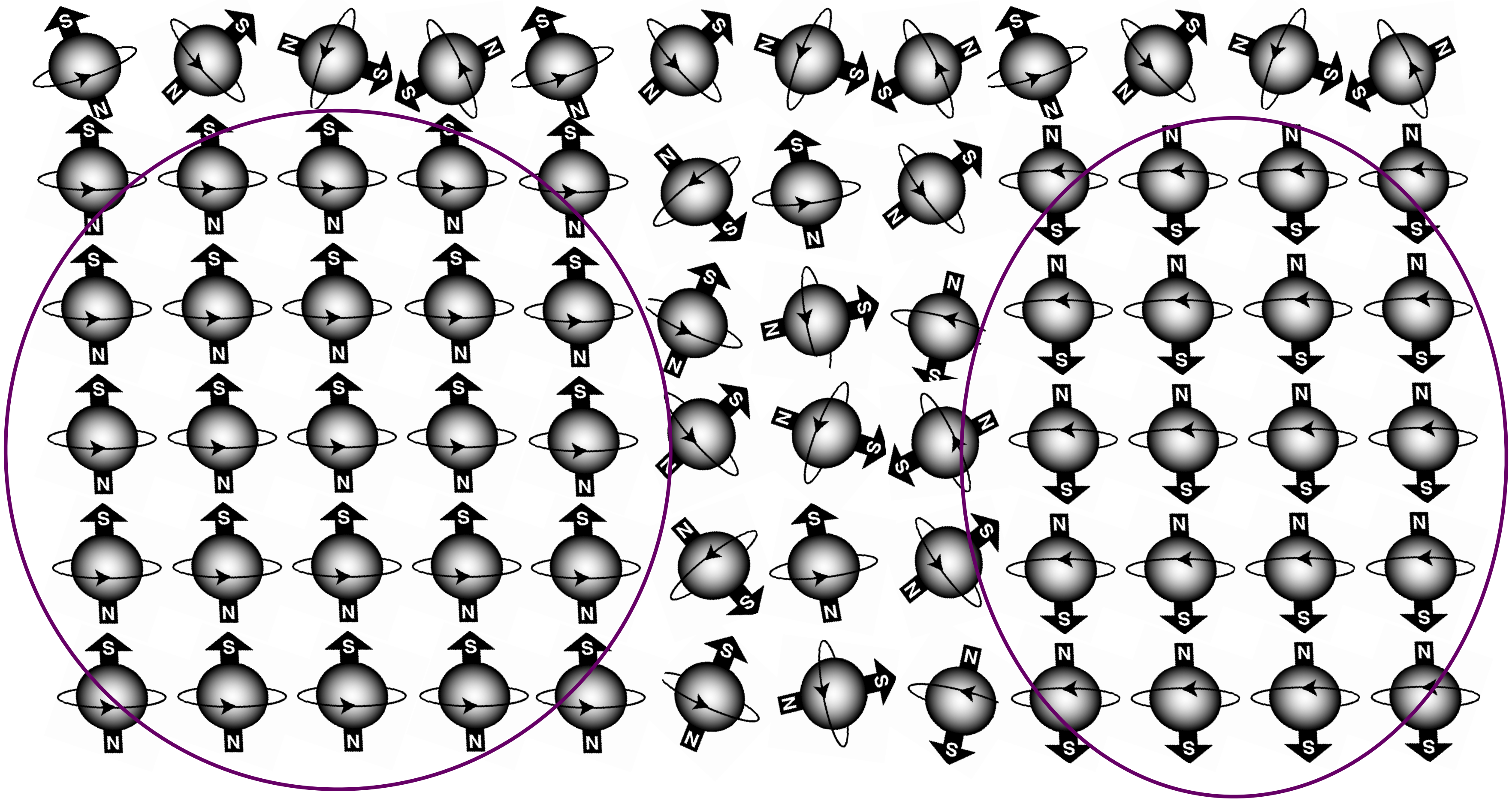

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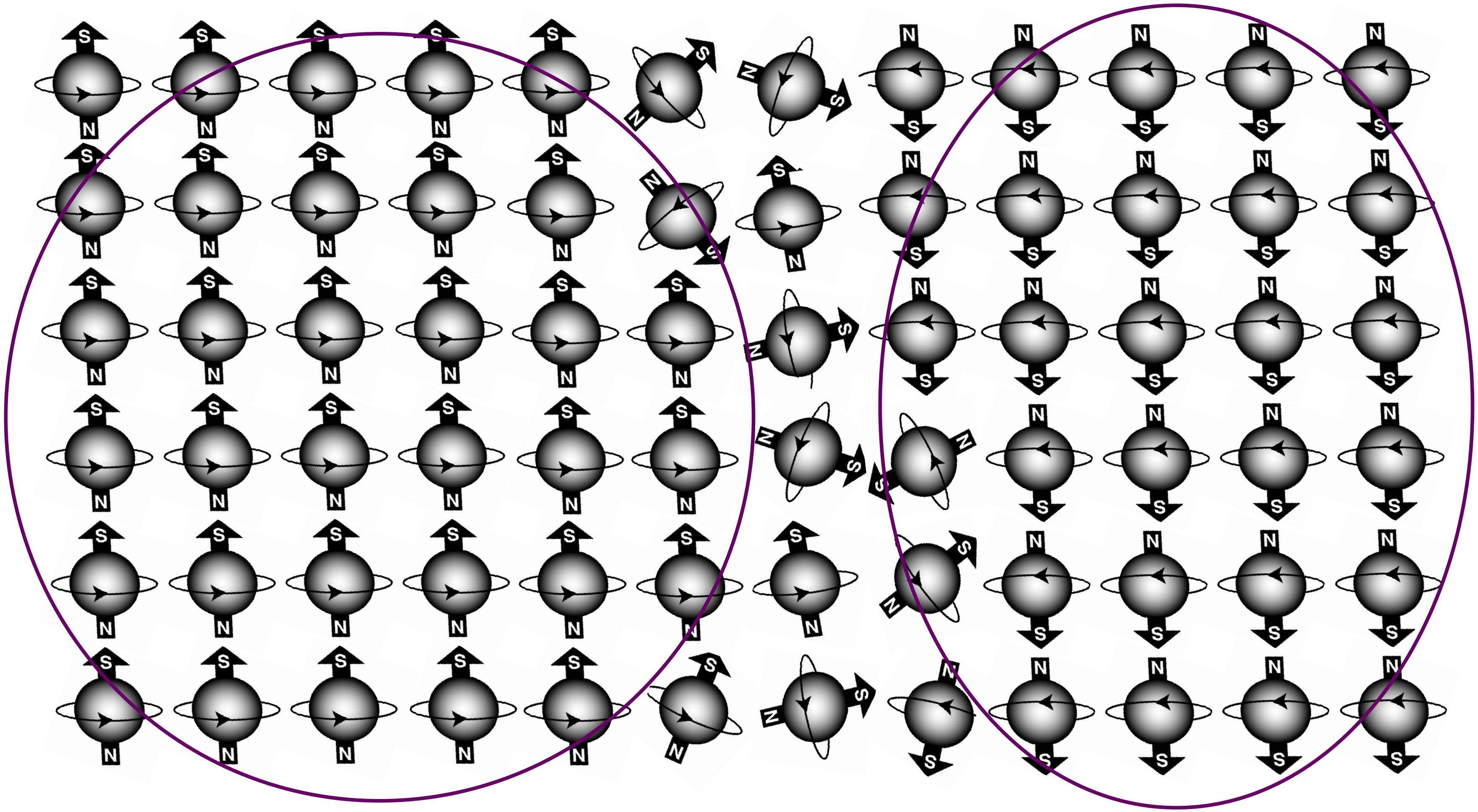

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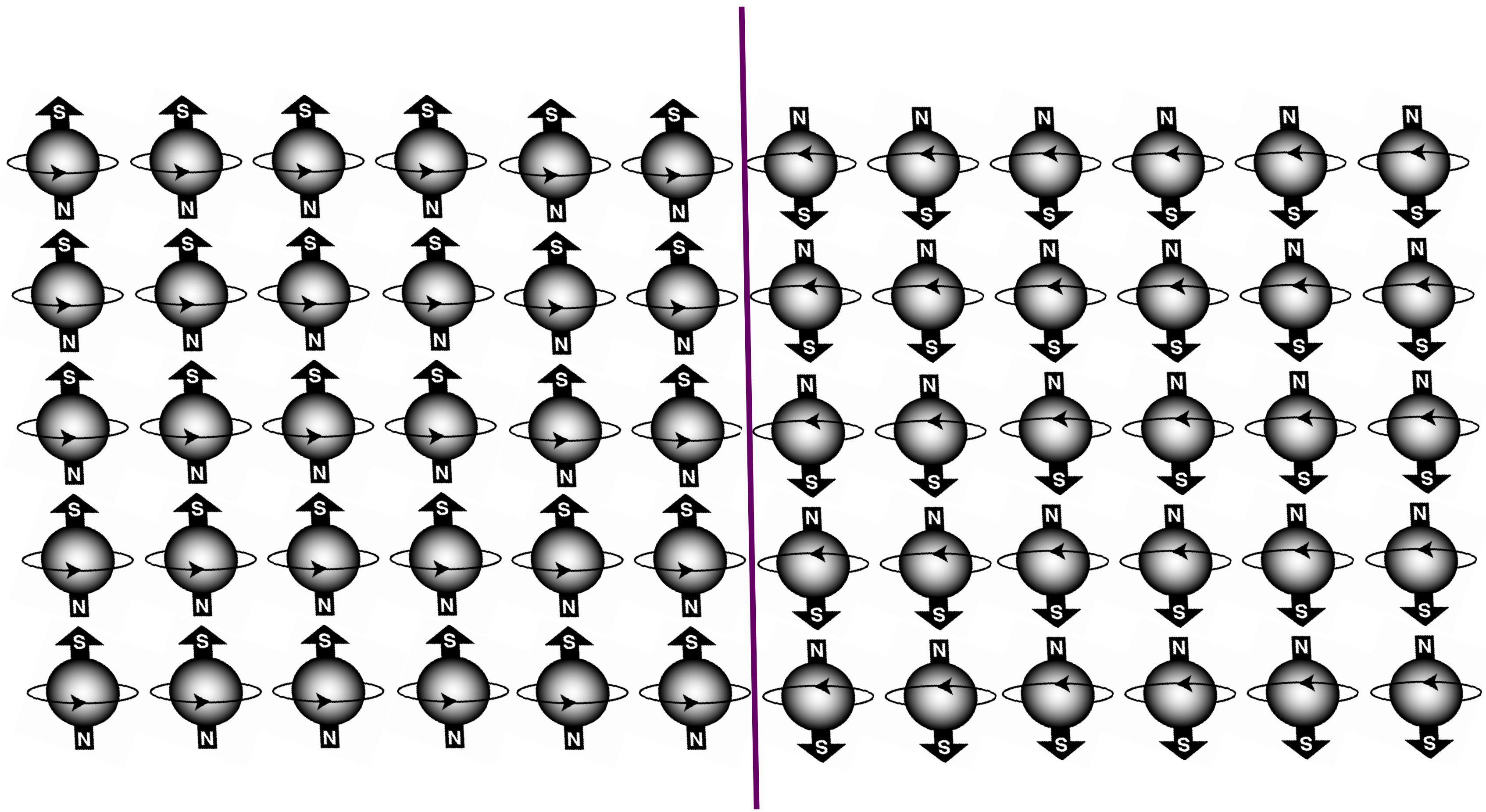
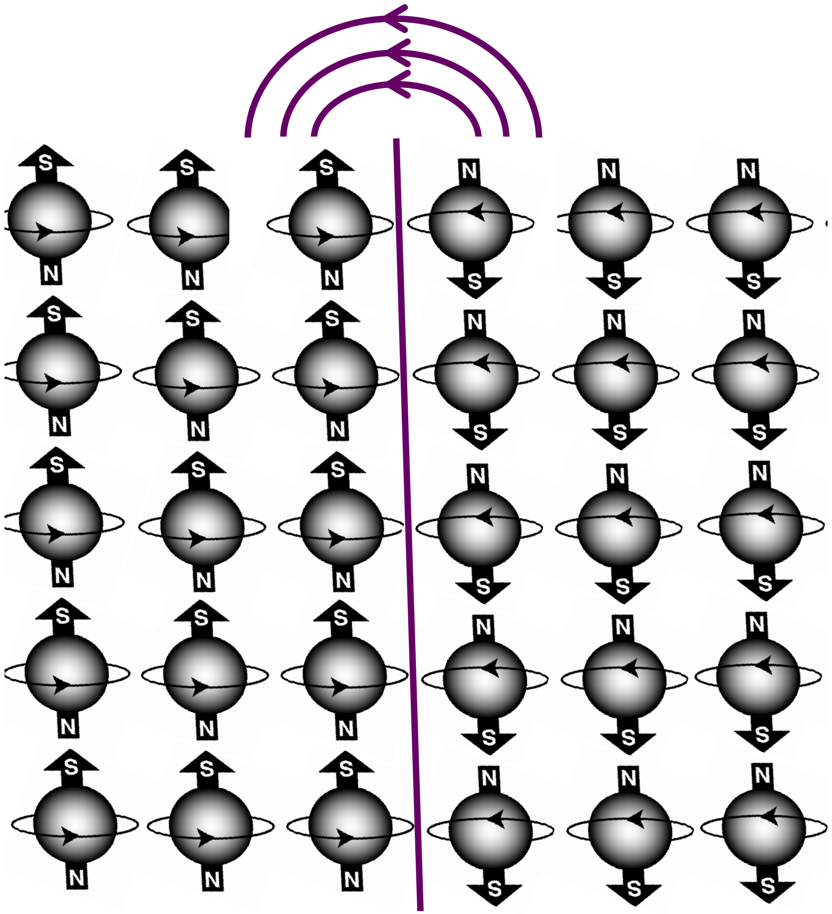
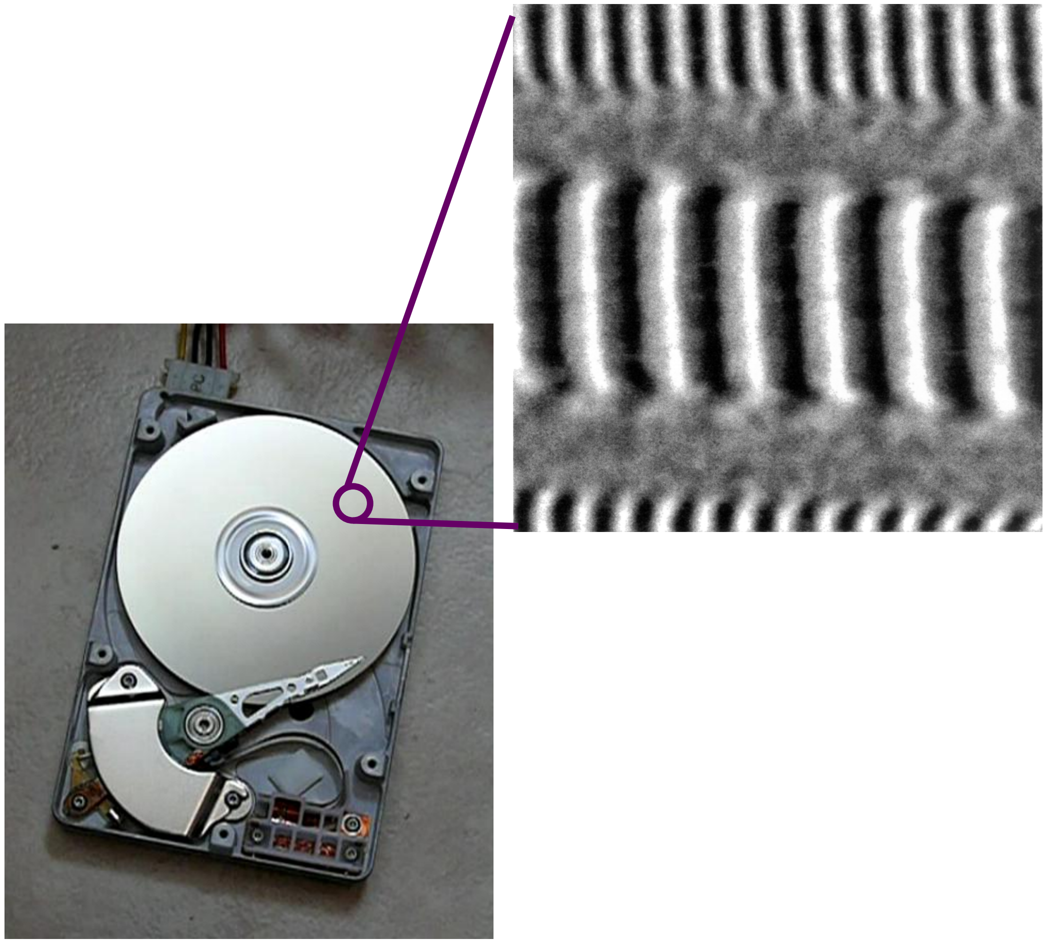


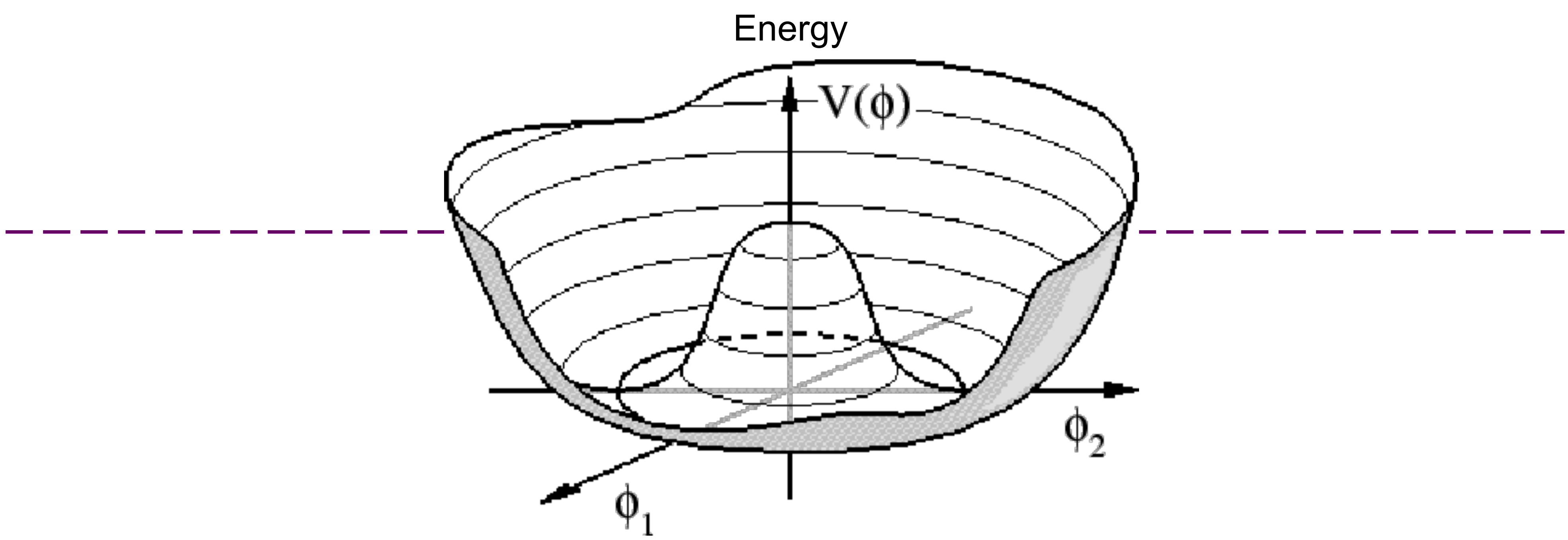
Defects in ferromagnets: Domain walls





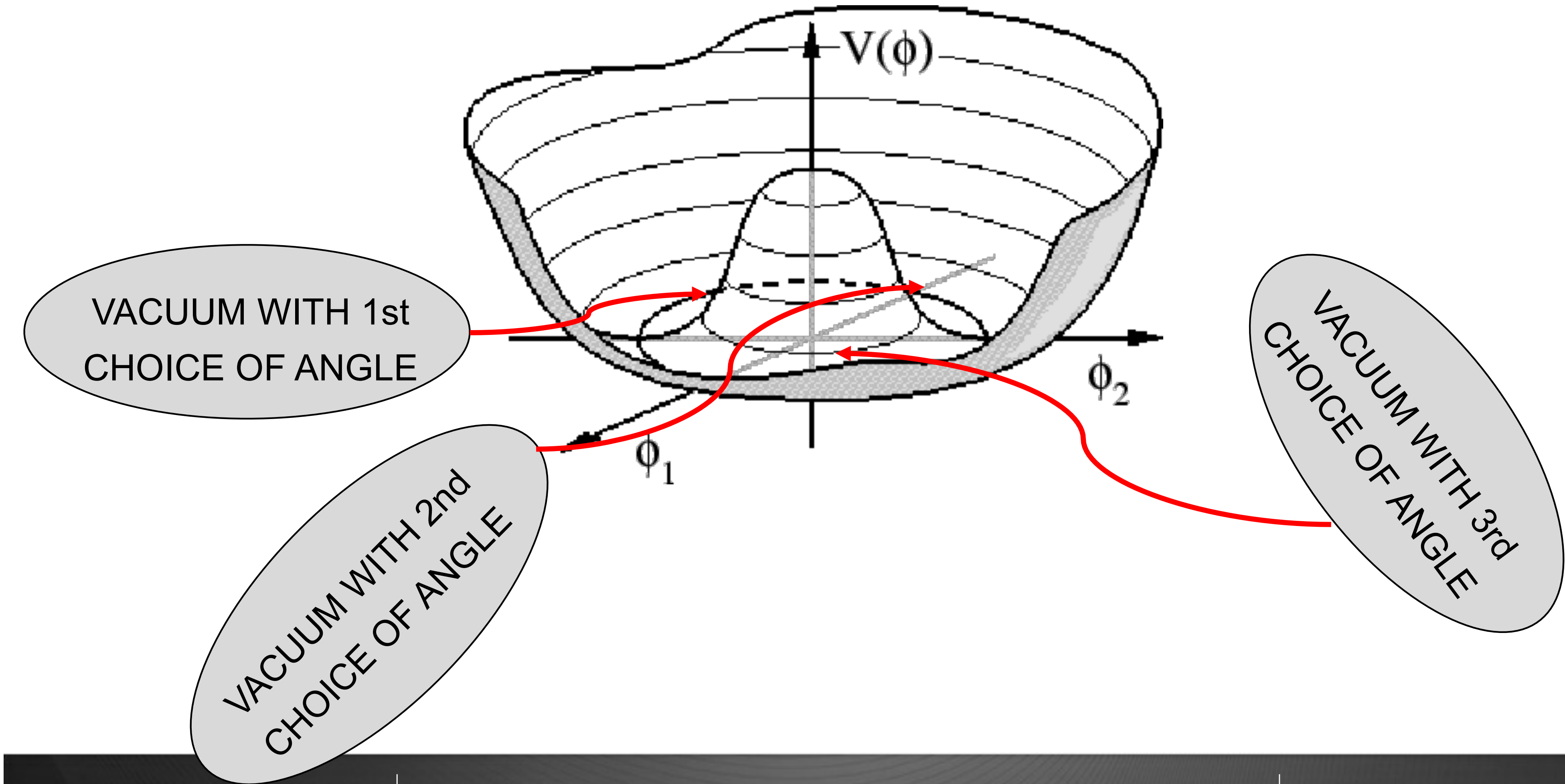
Spontaneous symmetry lowering at the Grand Unification Transition

HOMOGENEOUS VACUUM



LOWER SYMMETRY VACUUM

Different regions of the early universe choose different equivalent ground states

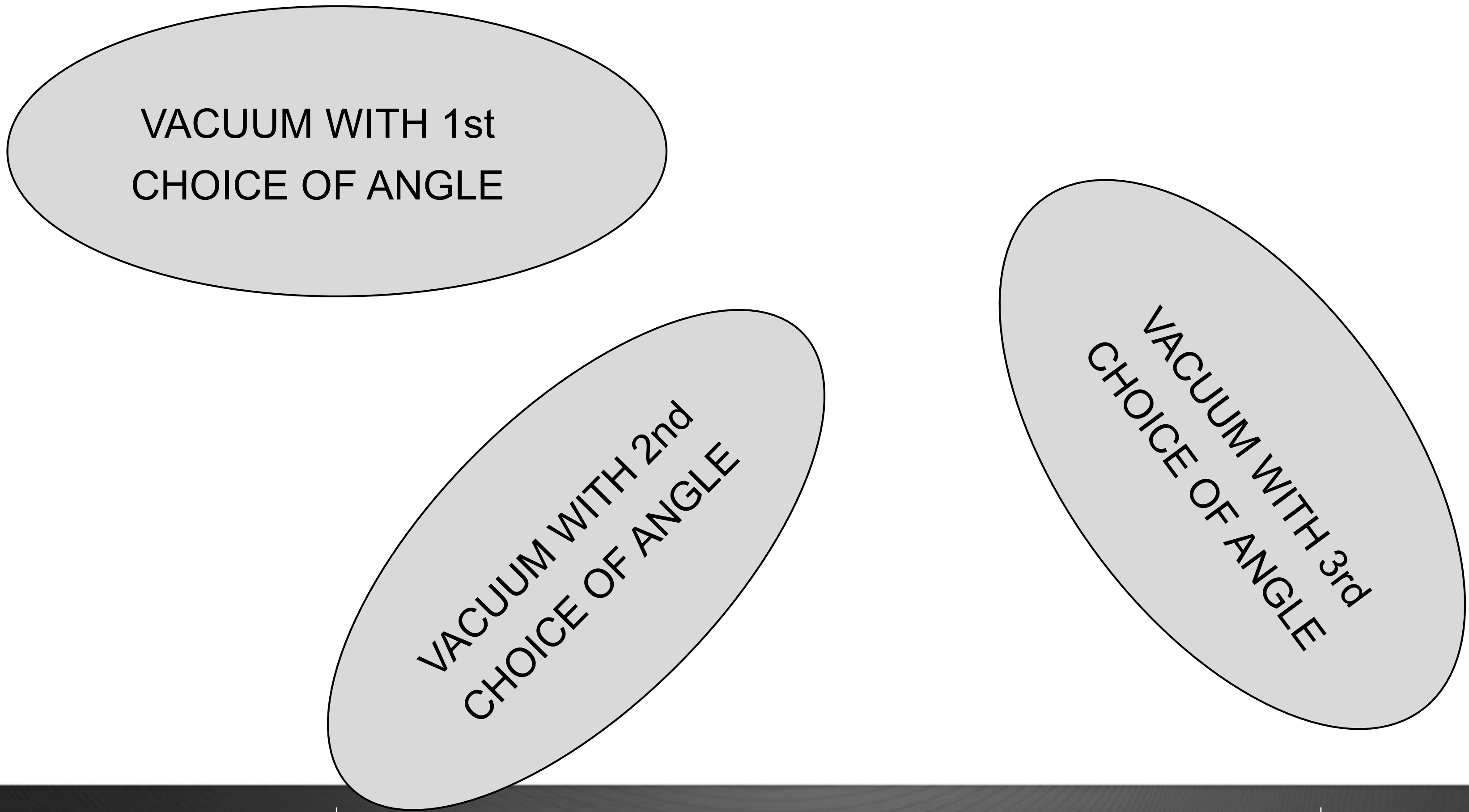


VACUUM WITH 1st CHOICE OF ANGLE

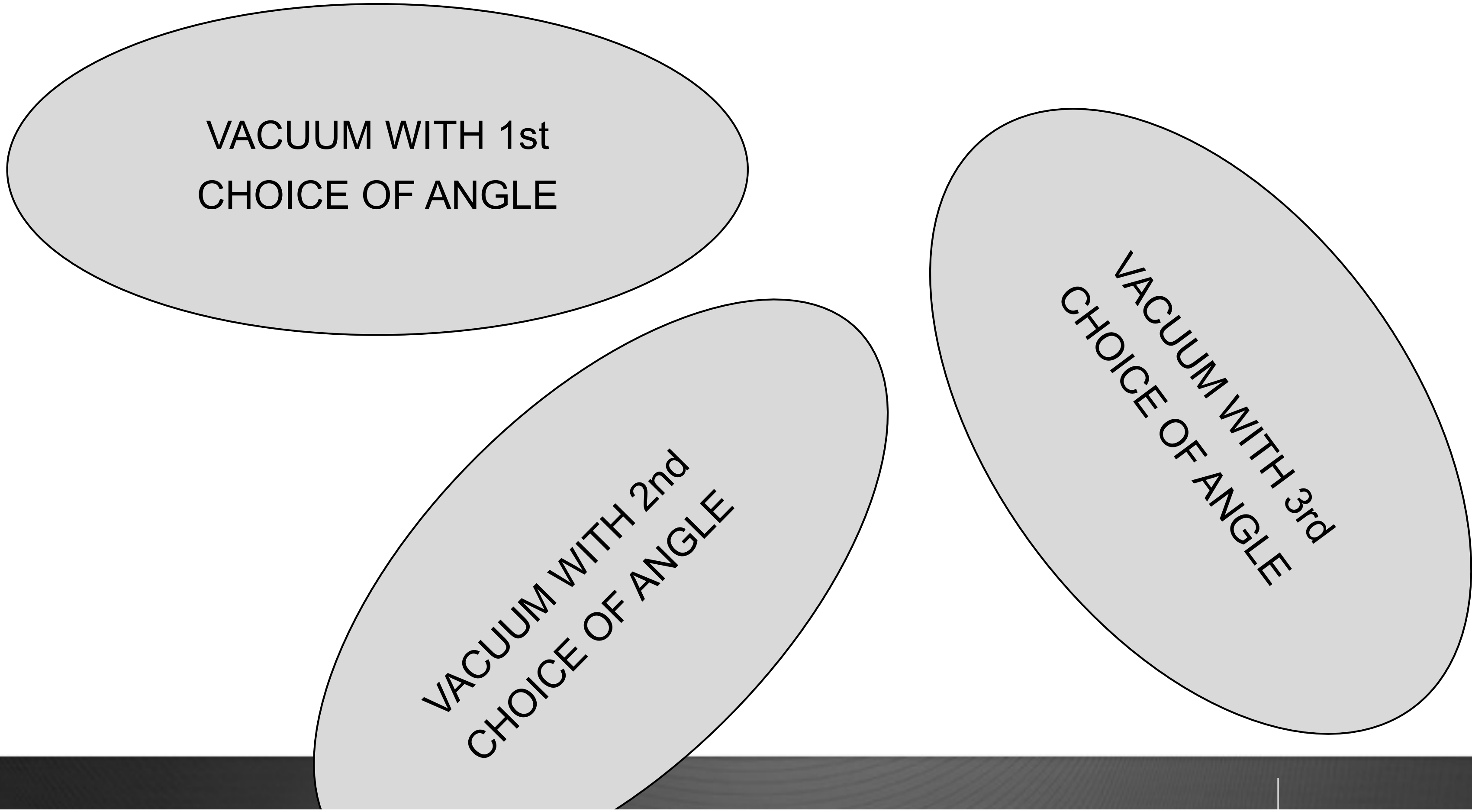
VACUUM WITH 2nd CHOICE OF ANGLE

VACUUM WITH 3rd CHOICE OF ANGLE

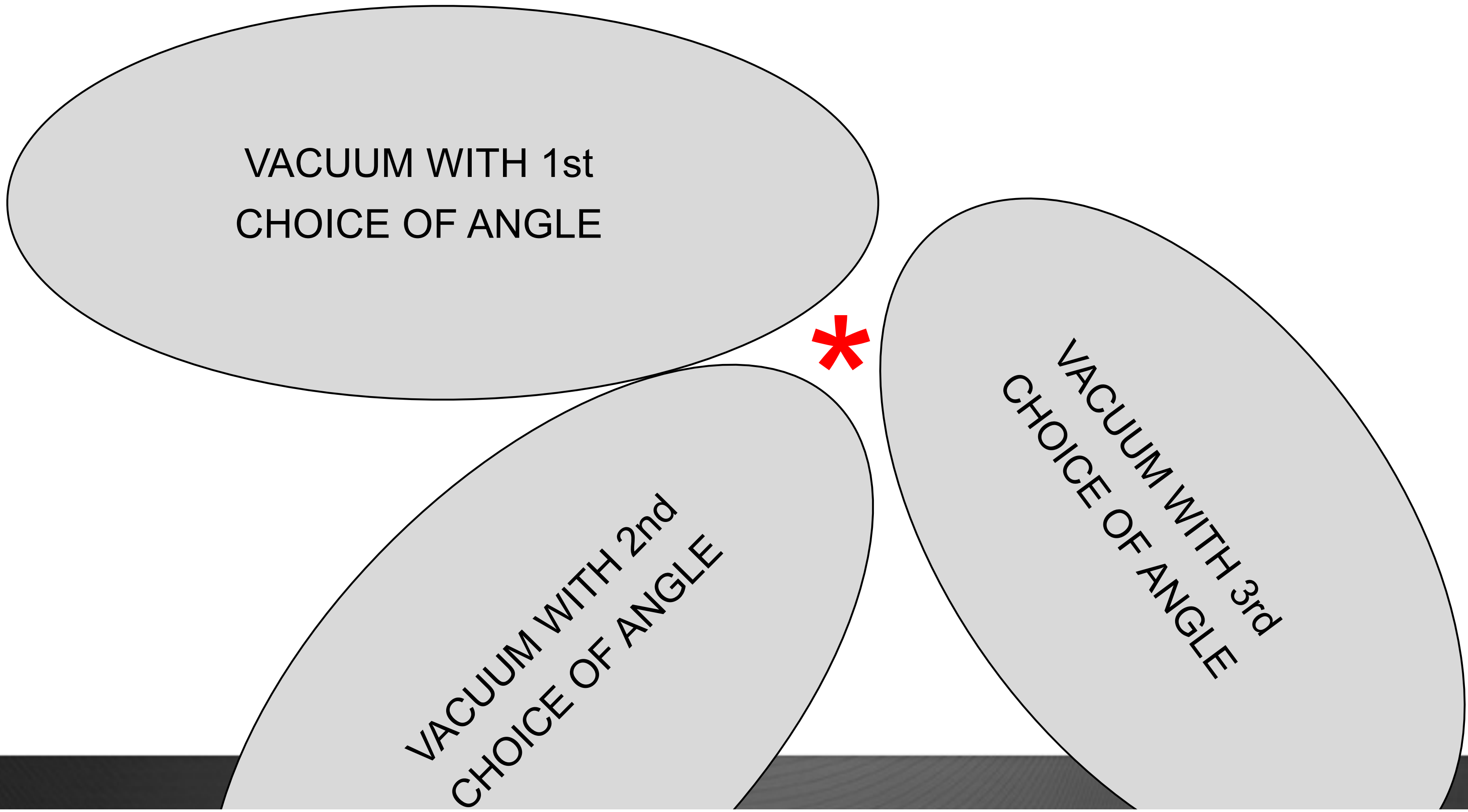
As the universe expands through the transition, the low symmetry regions grow…



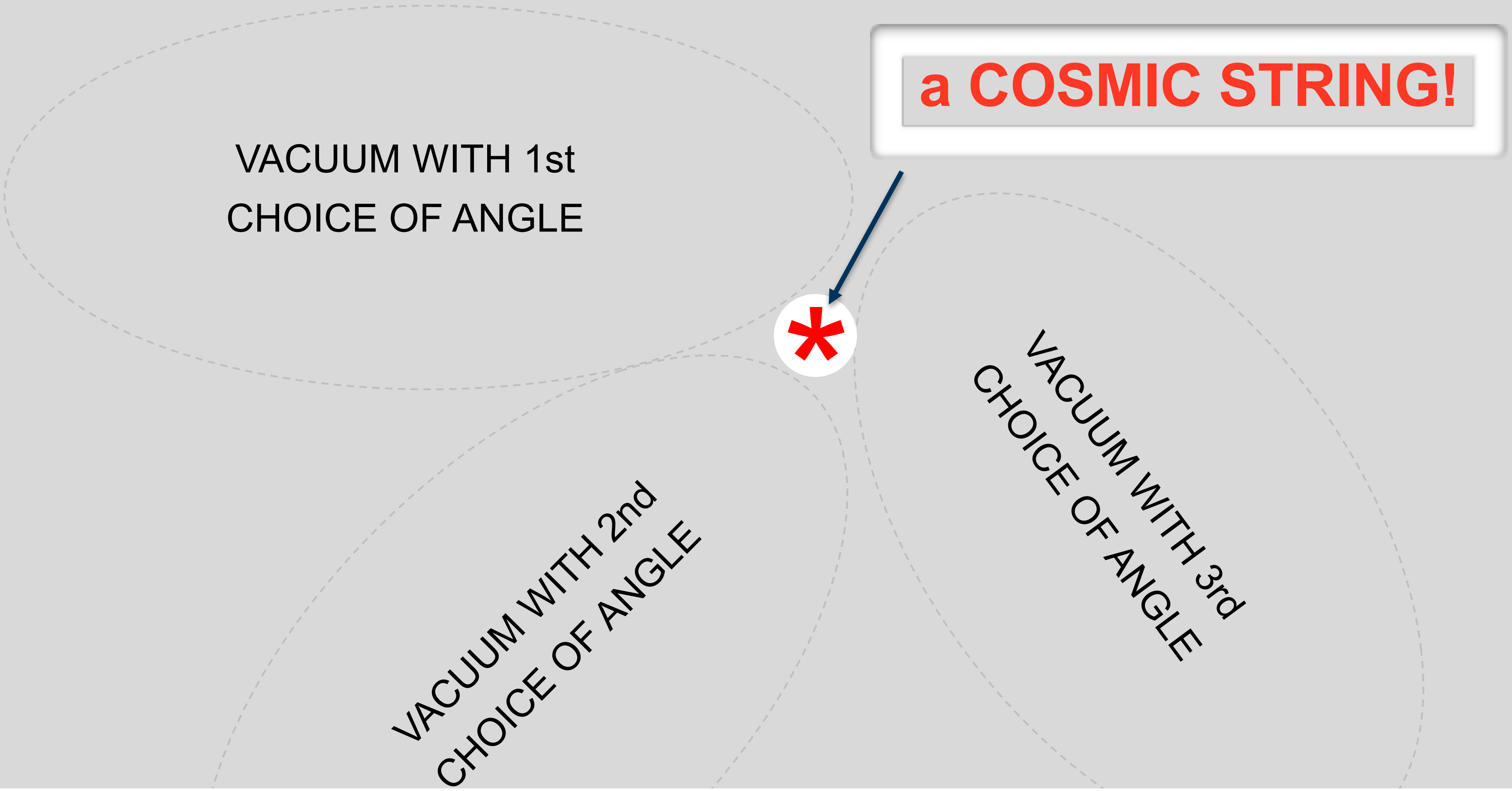
and grow…


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)



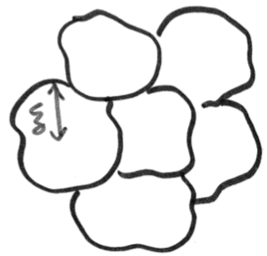
A detail: How many cosmic strings should we have?

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**

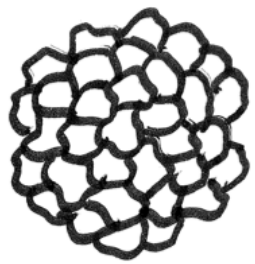
→ **Low density of cosmic strings**



Expand quickly: Not much time to communicate choice of angle

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

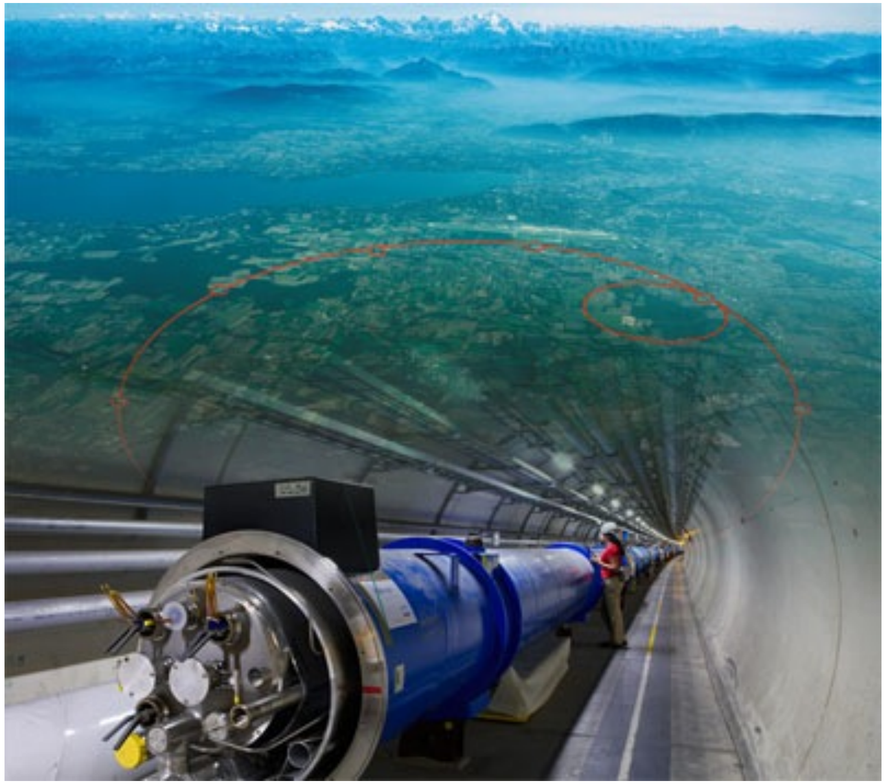
→ **High density of cosmic strings**



Do cosmic strings exist? How can we study them?

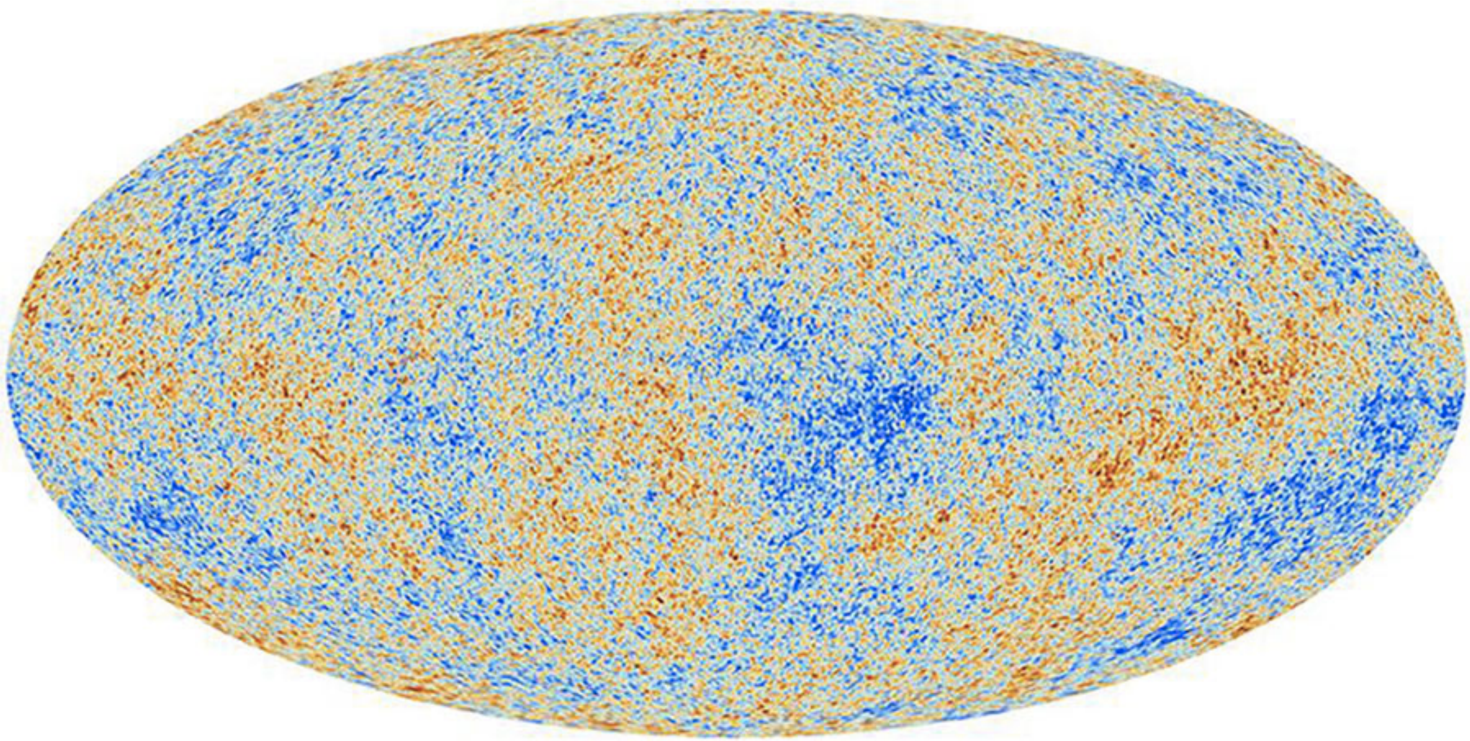
For direct study we need a probe with a similar energy, ~10^{15} GeV

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



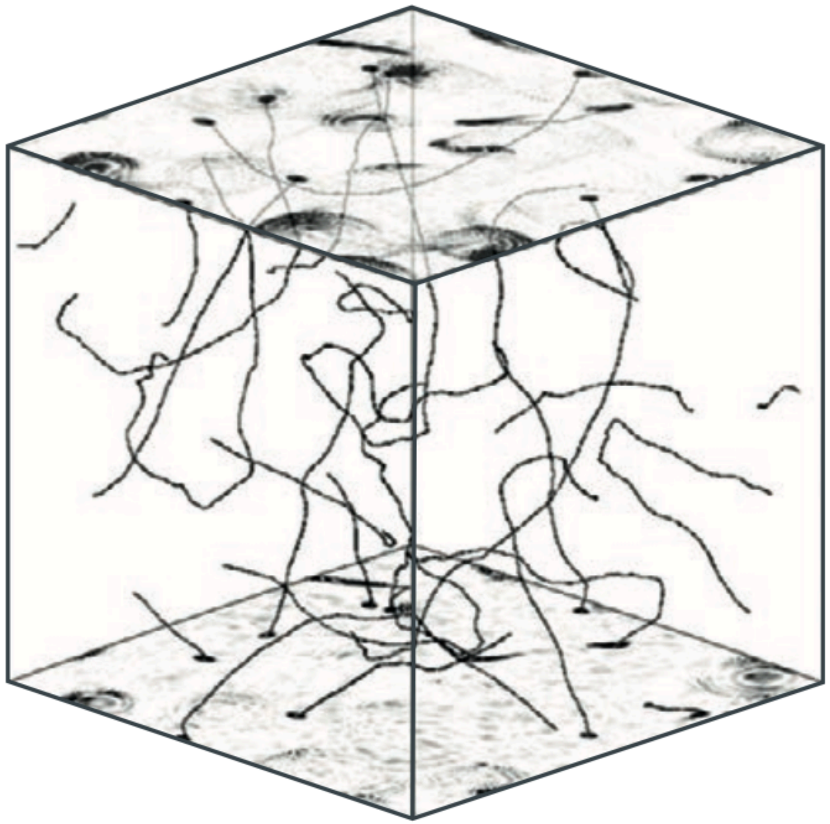
How is Cosmic String Formation at the Grand Unification Transition studied?

Analyzing the Cosmic Microwave Background



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

Computer Simulation

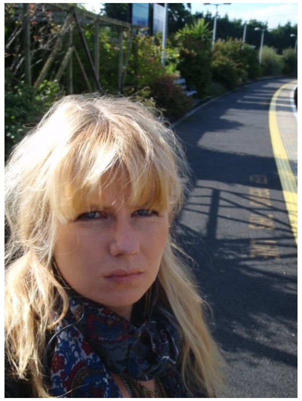


PHYSICAL REVIEW D **76,** 043005 (2007)

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

Outline

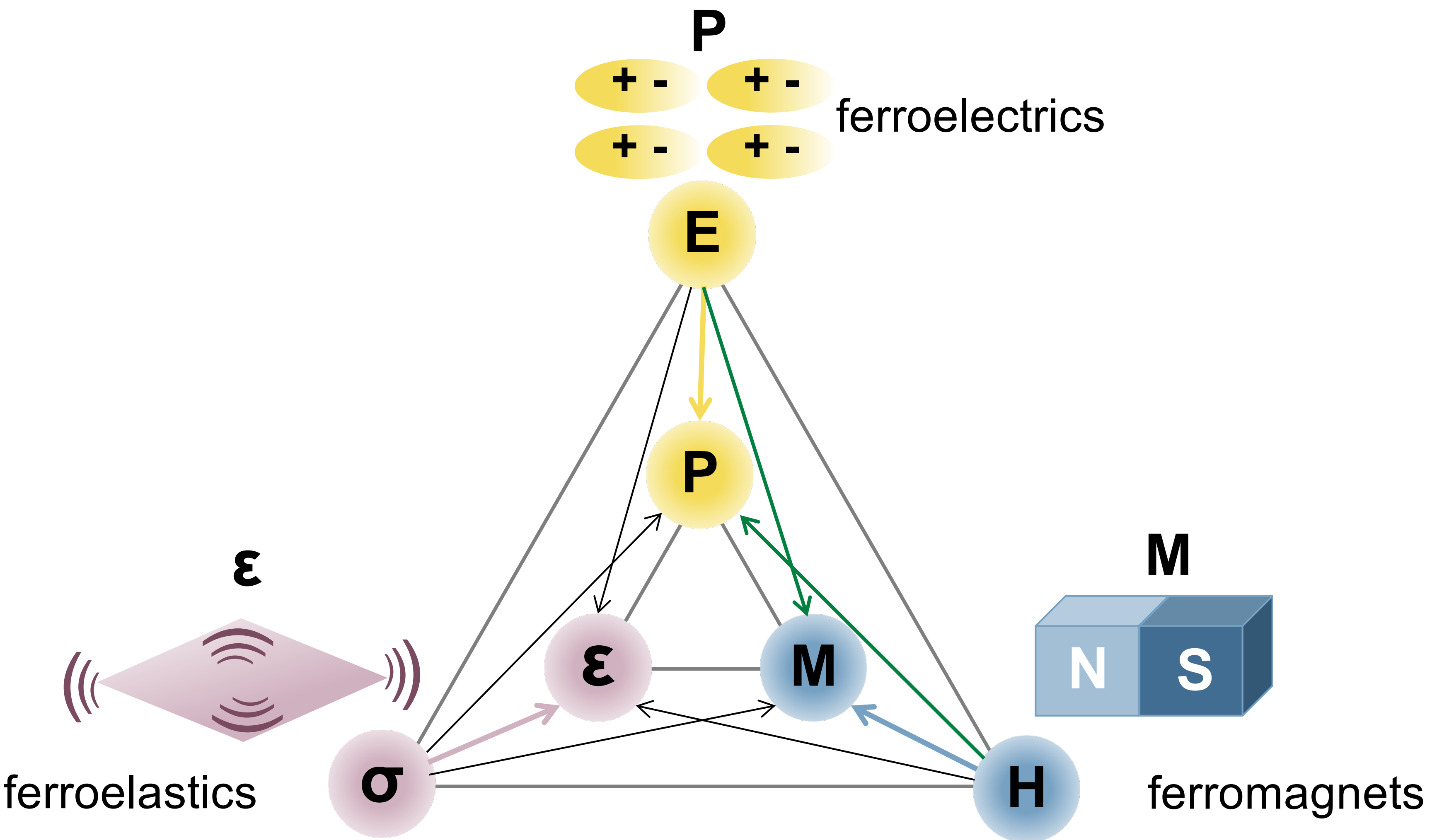
First we will identify a material with a symmetry-lowering phase transition described by the same mathematics as that proposed for the GUT

spontaneous symmetry breaking described by a Mexican hat potential

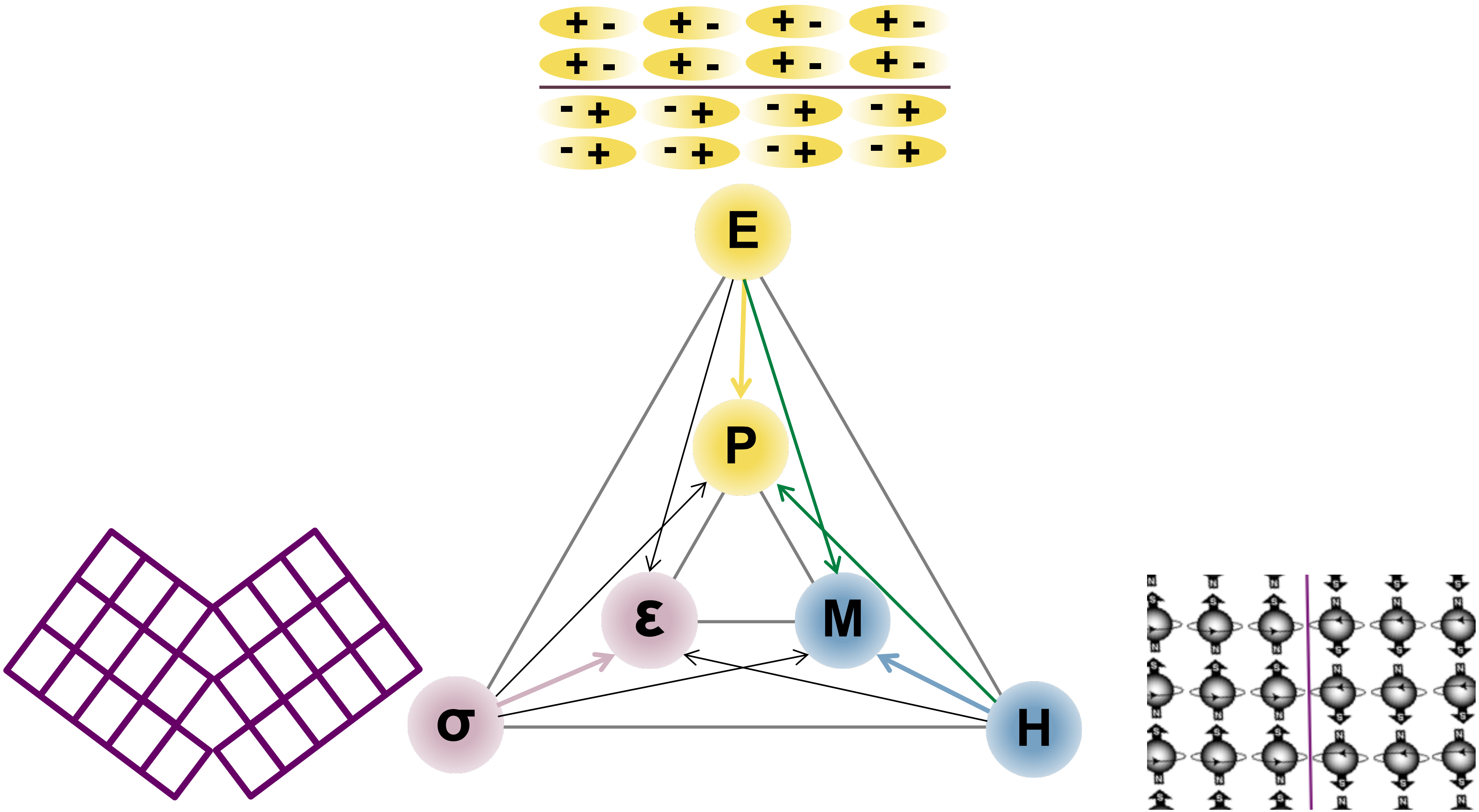
Then we will do experiments on the material to answer questions about the GUT:

Do cosmic strings exist?
Did they form as we think?
How did they evolve?
What are their properties?

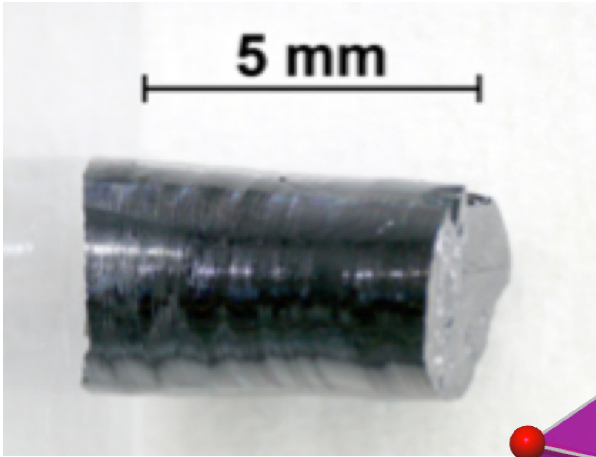
Where to find a suitable material?
Multiferroics: Multiple ferroic orders…



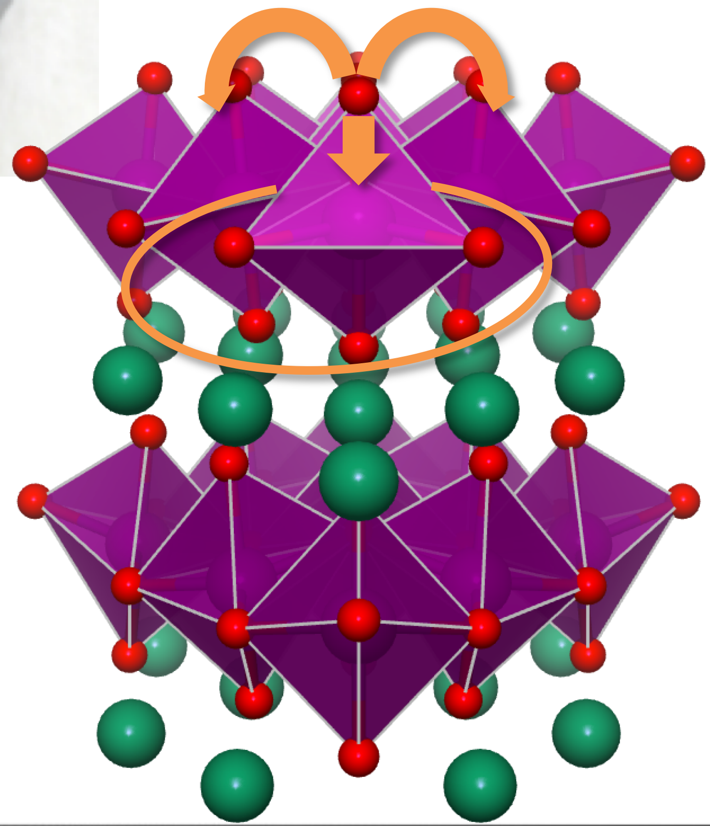
…and multiple defects from spontaneous symmetry-lowering transitions



Our material: Multiferroic $YMnO_3$



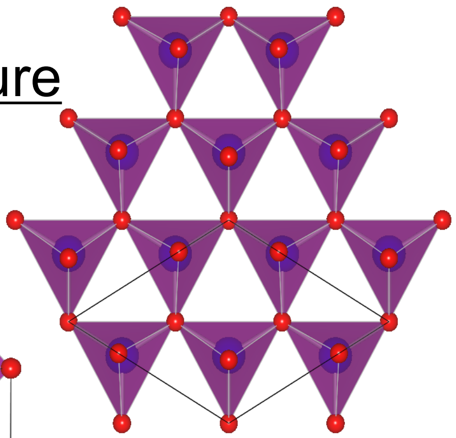
Frank Lichtenberg

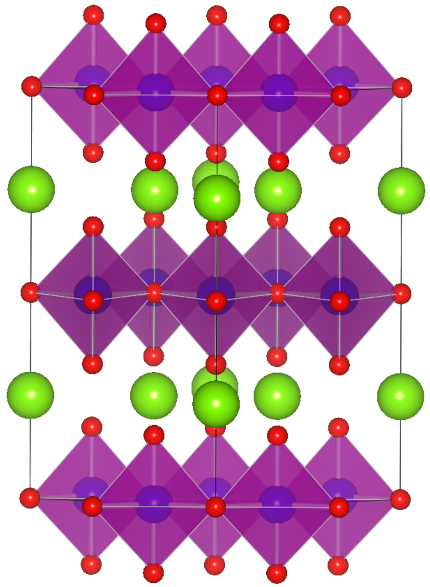


Our material: Multiferroic $YMnO_3$

<u>High temperature</u>

*P*6$_3$*/mmc*



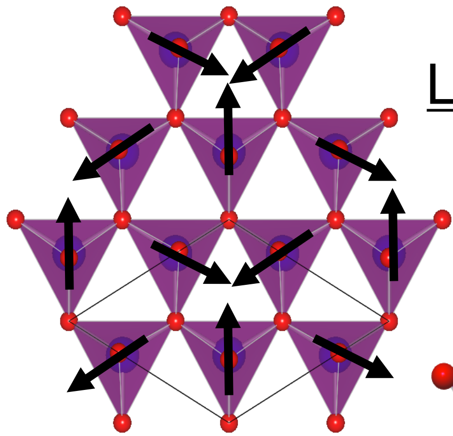


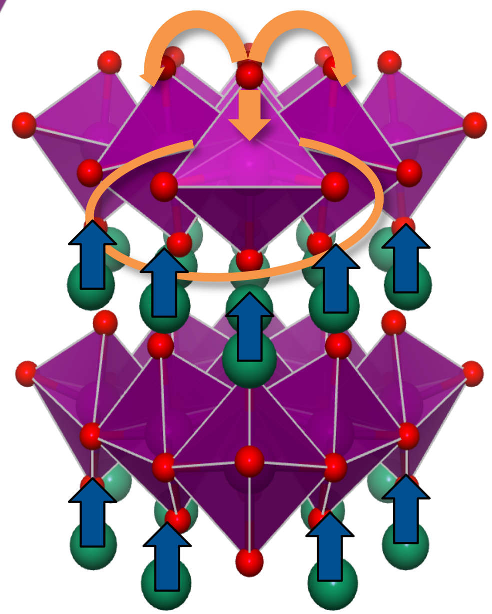
paraelectric

Symmetry-lowering phase transition at ~1000K

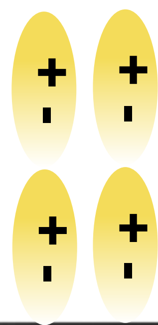
<u>Low temperature</u>

*P*6$_3$*cm*



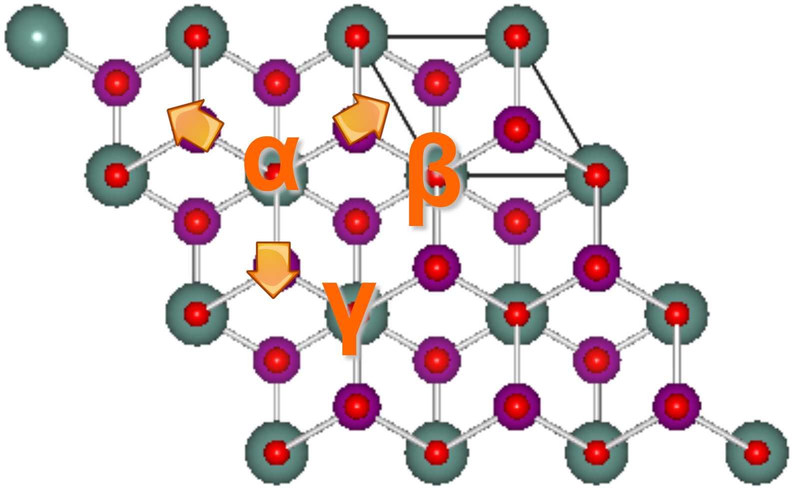


ferroelectric



Look at these distortions in more detail:

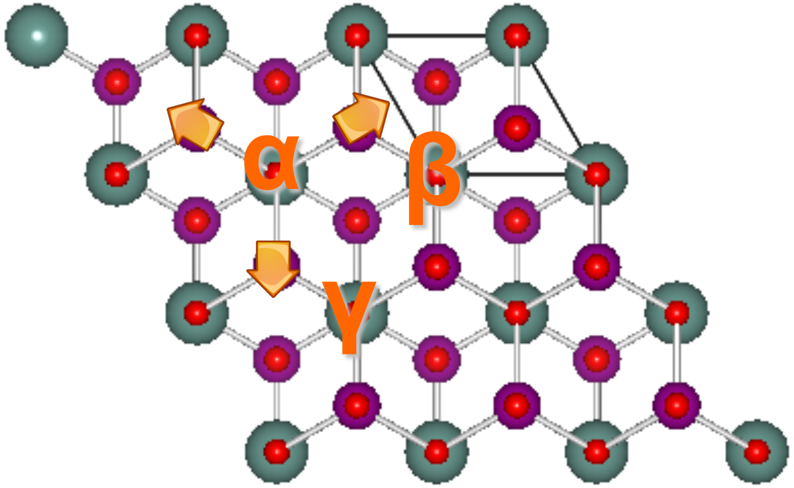
Trimerization / Tilting



Three possible origins

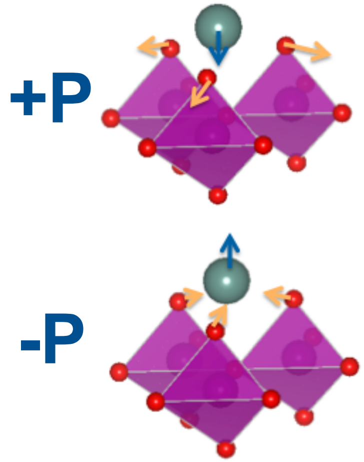
Look at these distortions in more detail:

Trimerization / Tilting



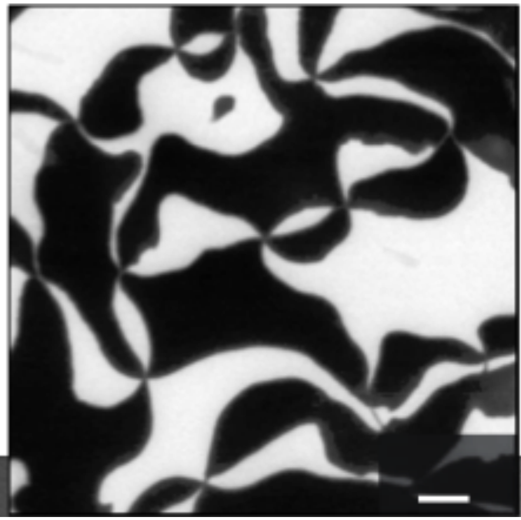
Three possible origins

Polarization



Two possible orientations

Results in six domains



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

Landau free energy

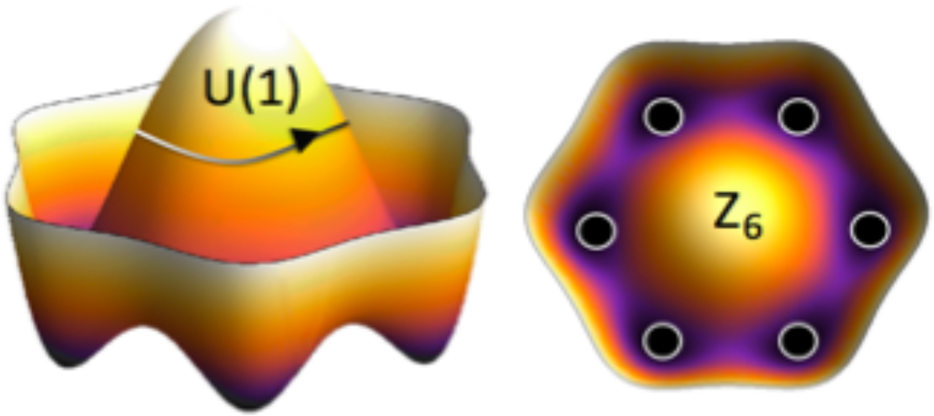
$$f_u = \frac{a}{2}Q^2 + \frac{b}{4}Q^4 + \frac{Q^6}{6}(c + c' \cos 6\Phi) - gQ^3 P_z \cos 3\Phi$$

Q is amplitude of tilting

Φ is angle of tilting

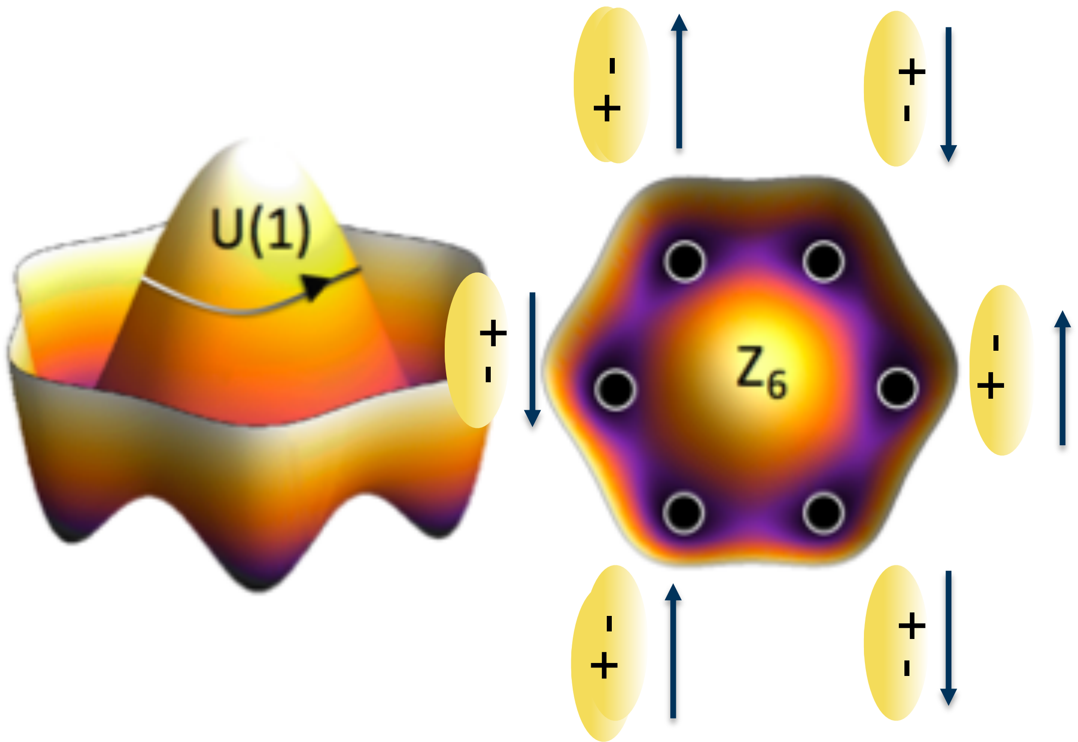
P_z is polarization

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 details of our "Mexican Hat-like" potential make it easy for us to measure!



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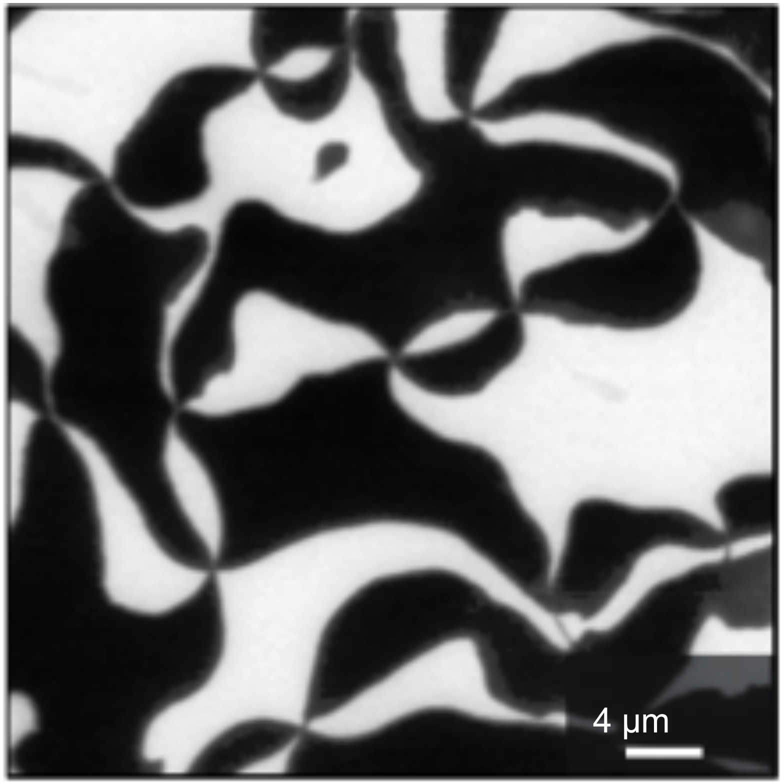
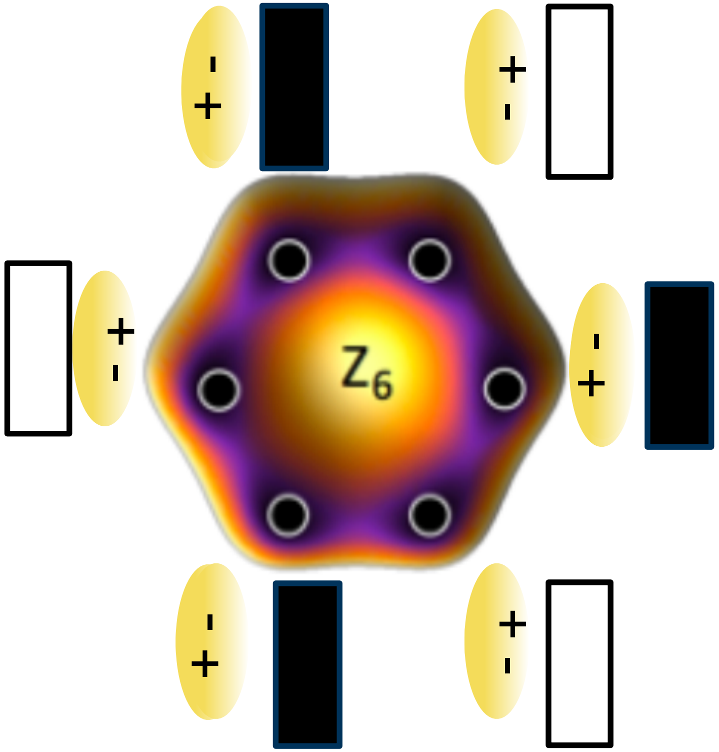
And the details of our "Mexican Hat-like" potential make it easy for us to measure!

Martin Lilienblum

Manfred Fiebig

Piezoforce Microscopy Image of ferroelectricity in $YMnO_3$

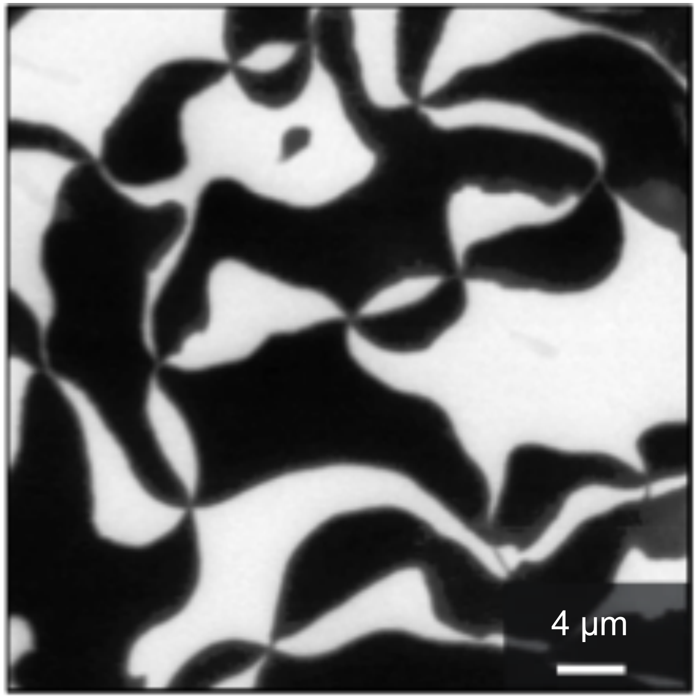




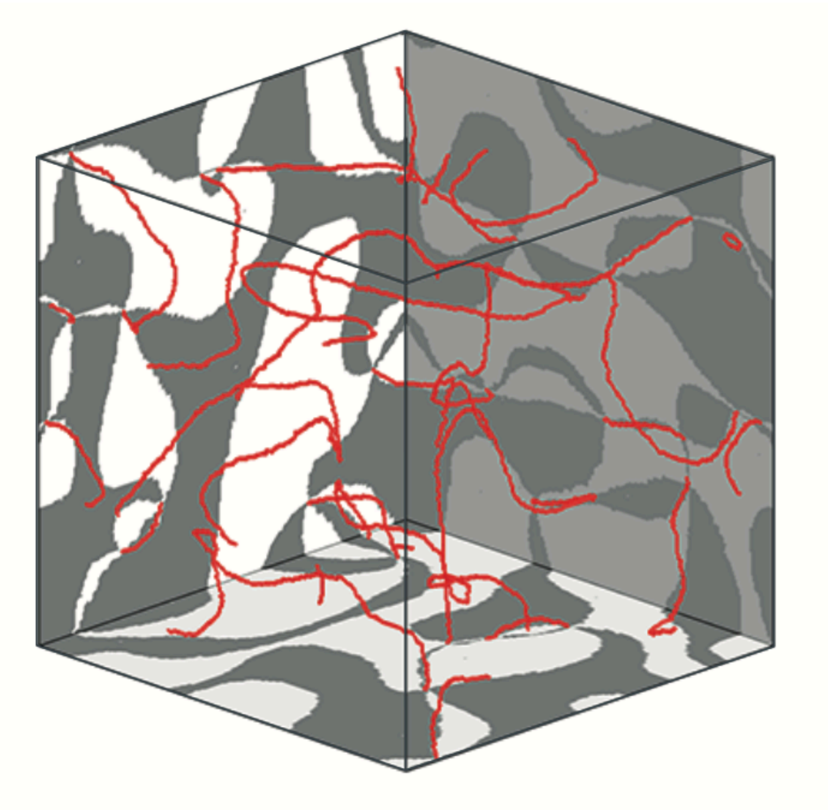
S. Artyukhin, K.T. Delaney, NAS and M. Mostovoy, *Landau theory of topological defects in multiferroic hexagonal manganites*, Nature Materials, 13, 42 (2014)

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



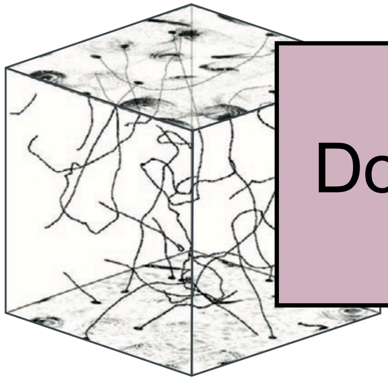
Thomas Lottermoser, Fiebig group

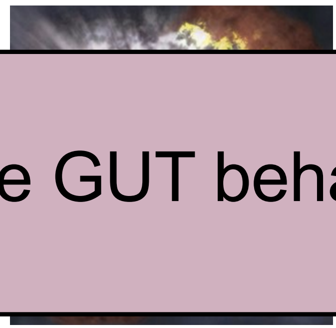
The structural phase transition in multiferroic $YMnO_3$ provides an analogue to the Grand Unification Transition

Early Universe

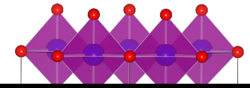
$YMnO_3$

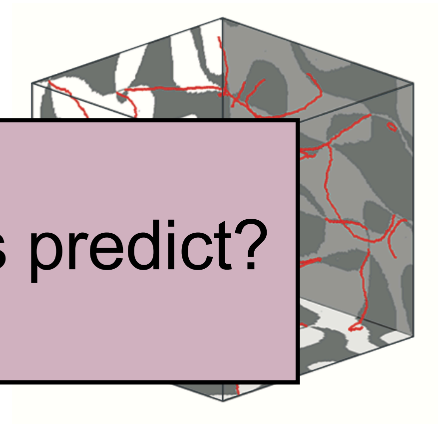
High symmetry vacuum





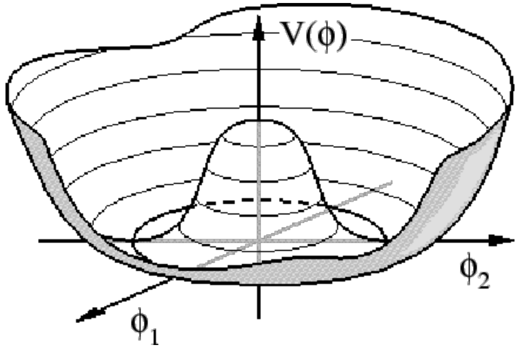
P6$_3$*/mmc*

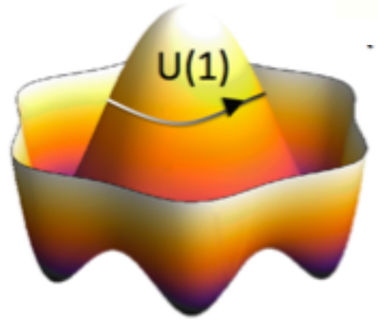




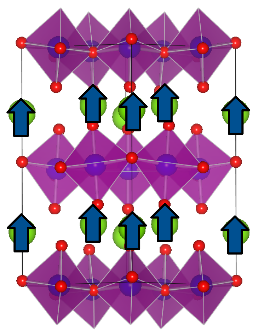
Does the GUT behave as cosmologists predict?

Low symmetry vacuum





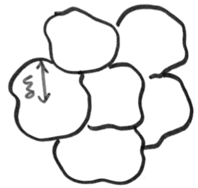
P6$_3$*cm*



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?

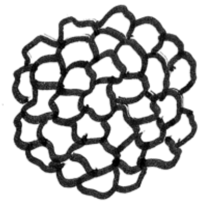
We'd like to expand it at different rates, crossing the GUT, and see how many cosmic strings form in each case ("Kibble-Zurek scaling")



Expand slowly: Different regions can communicate their choice of angle

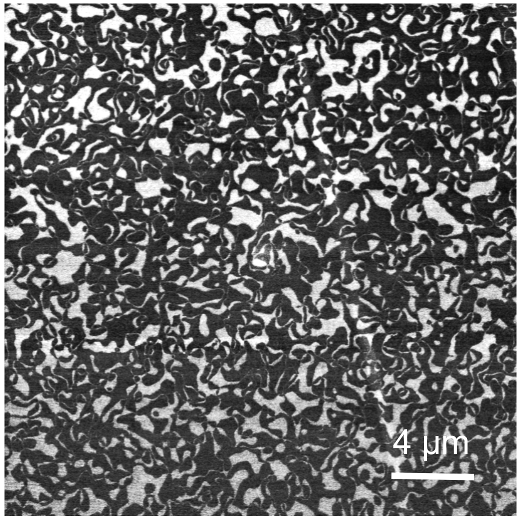
→ **Large regions of the same choice**
→ **Low density of cosmic strings**

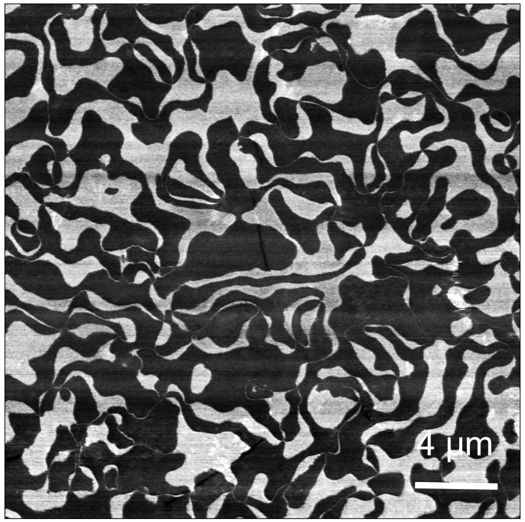
Expand quickly: Not much time to communicate choice of angle

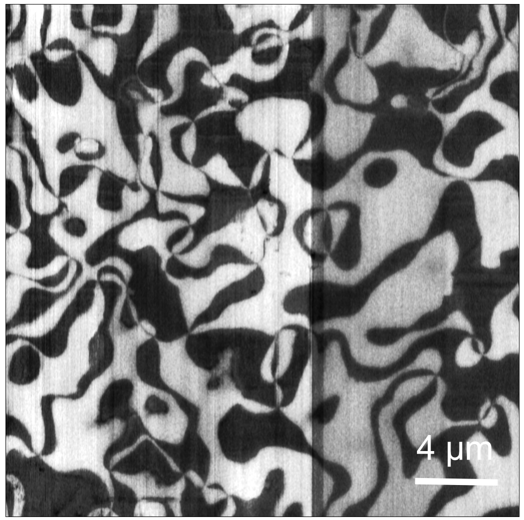


→ **Many smaller regions with different choices of angle**
→ **High density of cosmic strings**

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

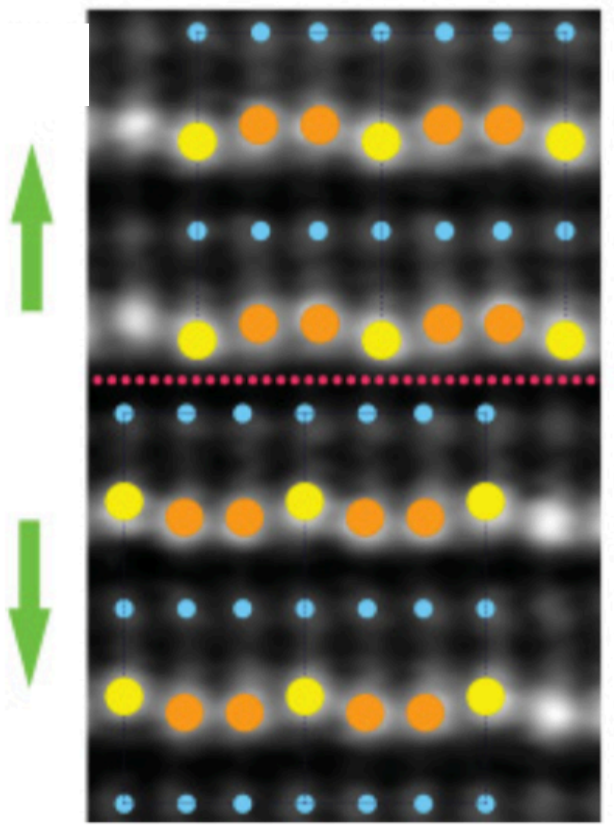






Testing the predicted "Kibble-Zurek scaling" for defect formation

domain size (for linear quench),



fined as Tc (~1000K) / cooling rate

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

th

cs

Critical exponents: ratio = 0.58

from MC simulations for 3D XY model

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

zero-temperature relaxation time

= ξ_0 / speed of sound

speed of sound = 640 m/s (DFT)

Yu Kumagai

Q. Zhang et al, *Direct observation of interlocked domain walls in hexagonal RMnO3*, Phys. Rev. B **85**, 020102 (2012)

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

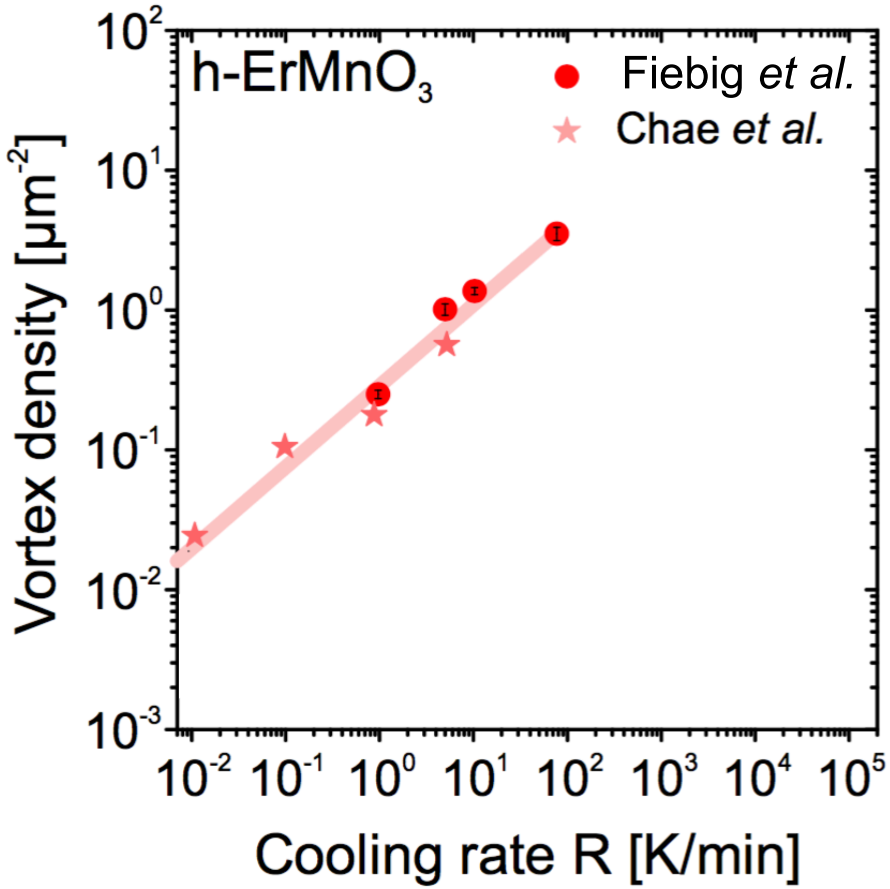
Comparison of predicted Kibble-Zurek scaling with experiment

Red line: our calculations

with ξ_0 = 0.06 A

Red points: measured

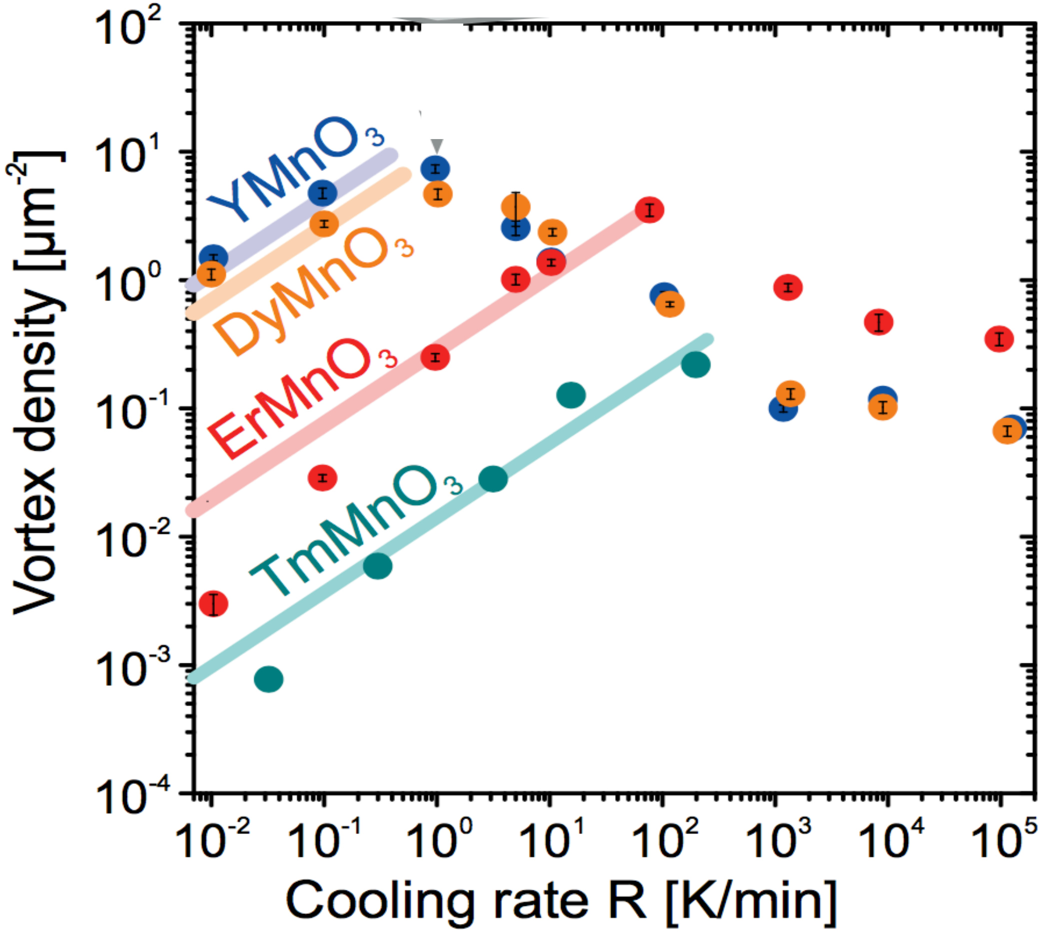
REMARKABLE AGREEMENT!



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)

"Beyond-KZ regime" and unexpected dependence on chemistry



(TmMnO3 from S. Chae et al.)

PHYSICAL REVIEW X **7,** 041014 (2017)

Global Formation of Topological Defects in the Multiferroic Hexagonal Manganites

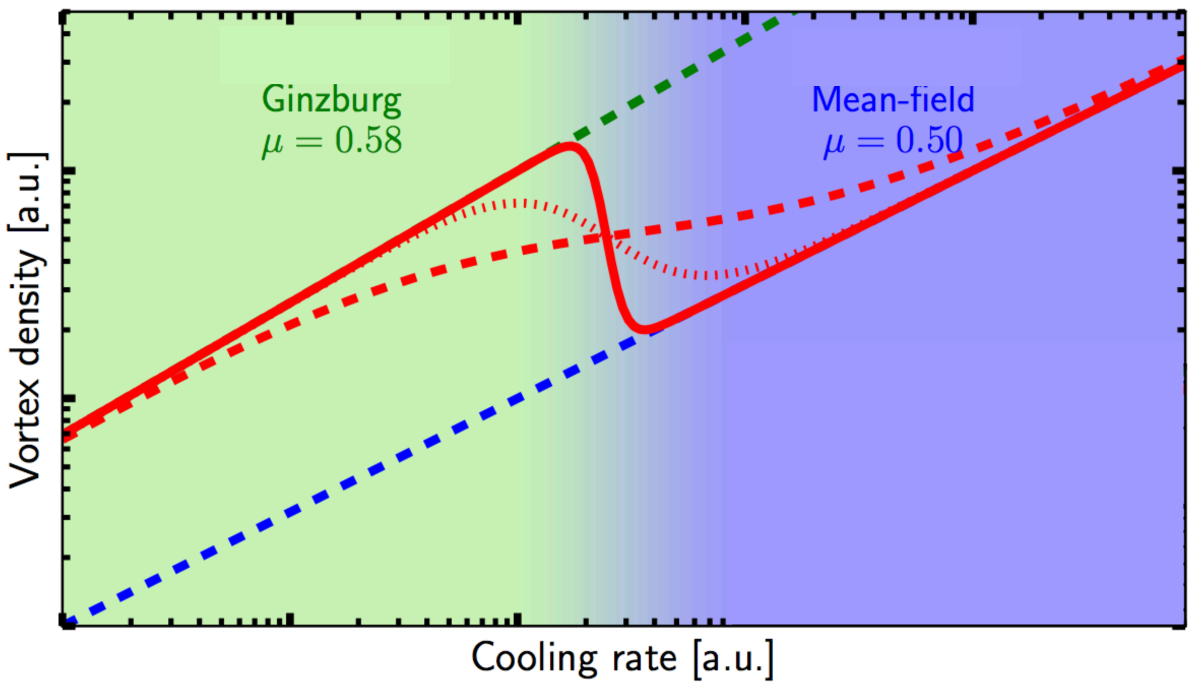
Q. N. Meier,[1] M. Lilienblum,[1] S. M. Griffin,[2] K. Conder,[3] E. Pomjakushina,[3] Z. Yan,[4,5] E. Bourret,[4] D. Meier,[6] F. Lichtenberg,[1] E. K. H. Salje,[7] N. A. Spaldin,[1] M. Fiebig,[1] and A. Cano[1,8]

Open questions:

What causes the chemistry dependence?

What is the origin of the turnaround?

What is the physics of the beyond-KZ regime?



Quintin Meier

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 ;)

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

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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."