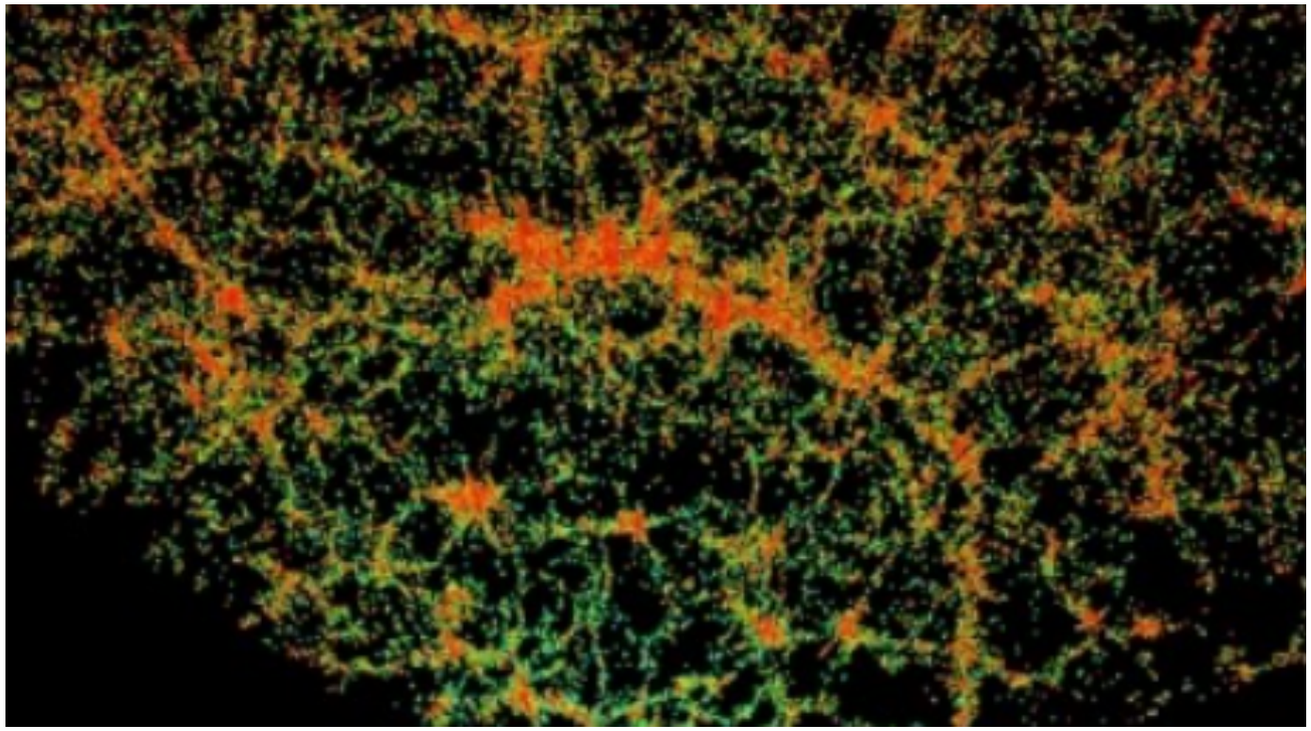
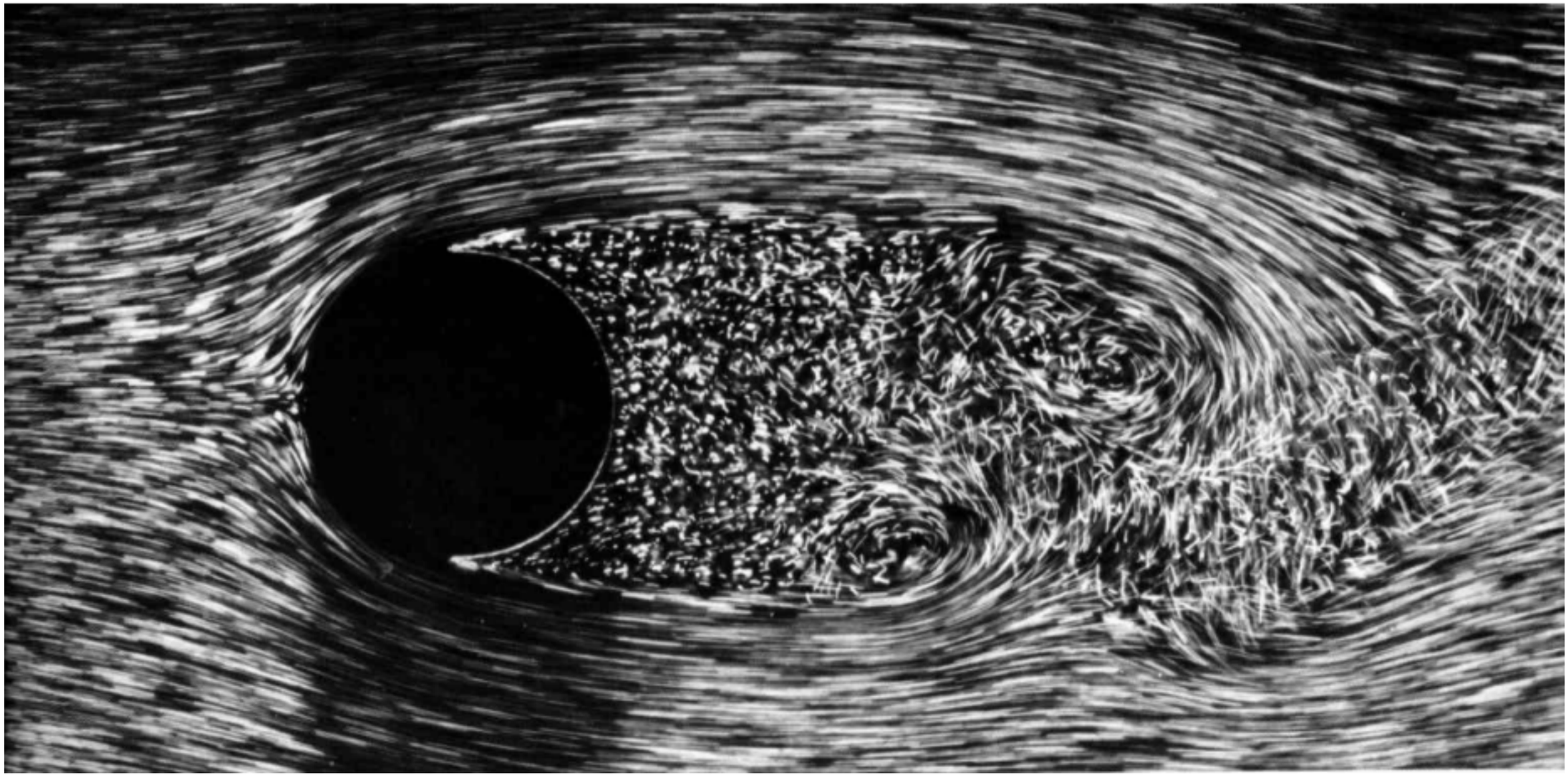
Encounters with Chaos and Order in the Universe



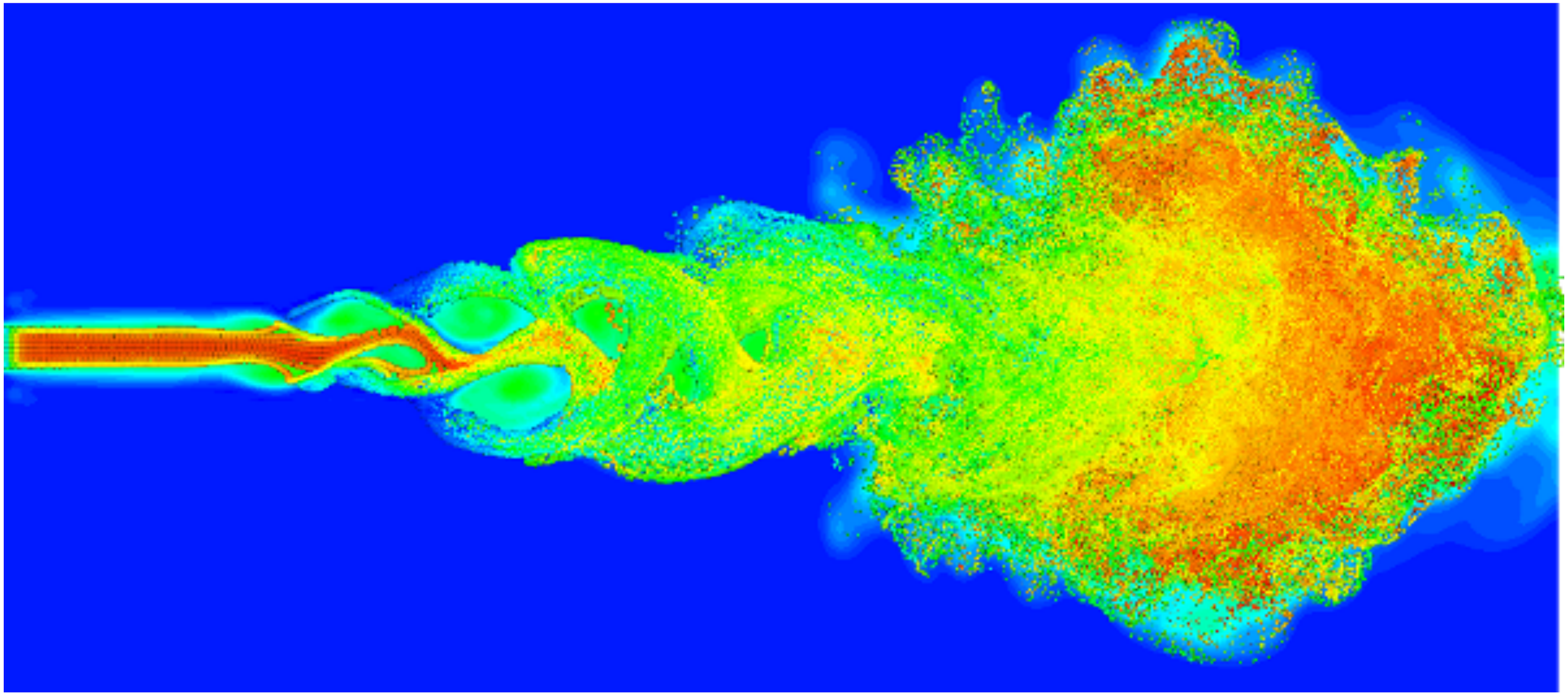
Michael Peskin
LCWS 2016

I have always been fascinated by chaotic patterns in nature. They are not hard to find.

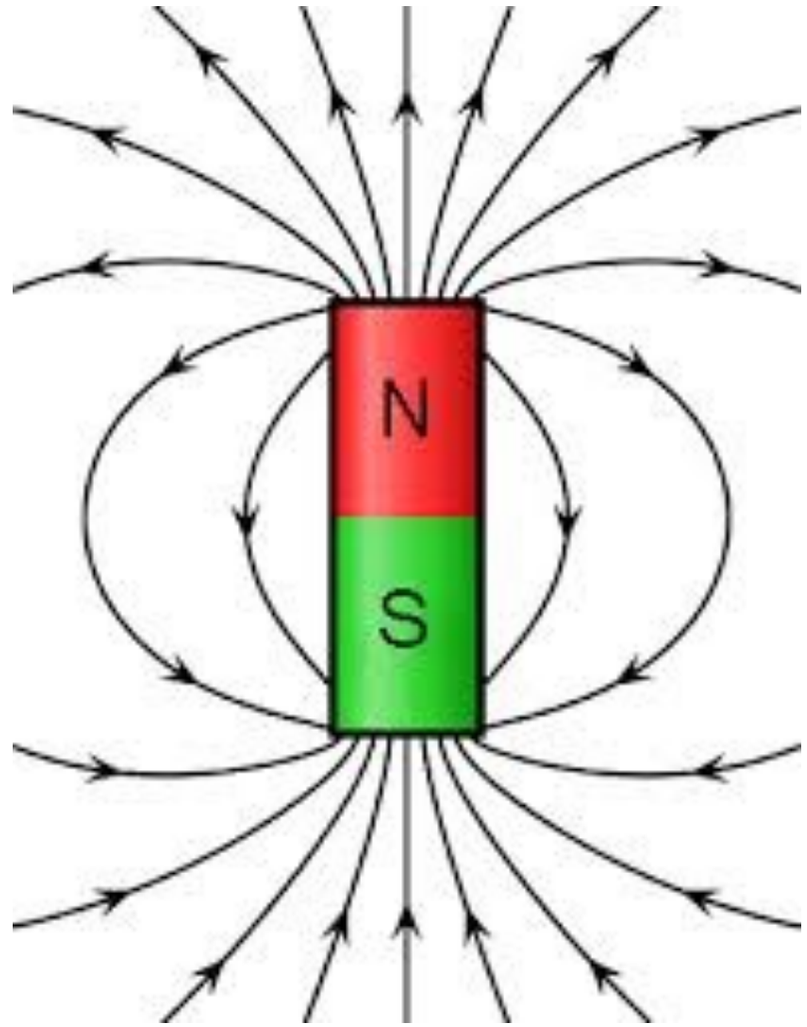


turbulence in fluid flow behind a pipe

H. van Dyke



Fukushima and Westerweel, U of Delft

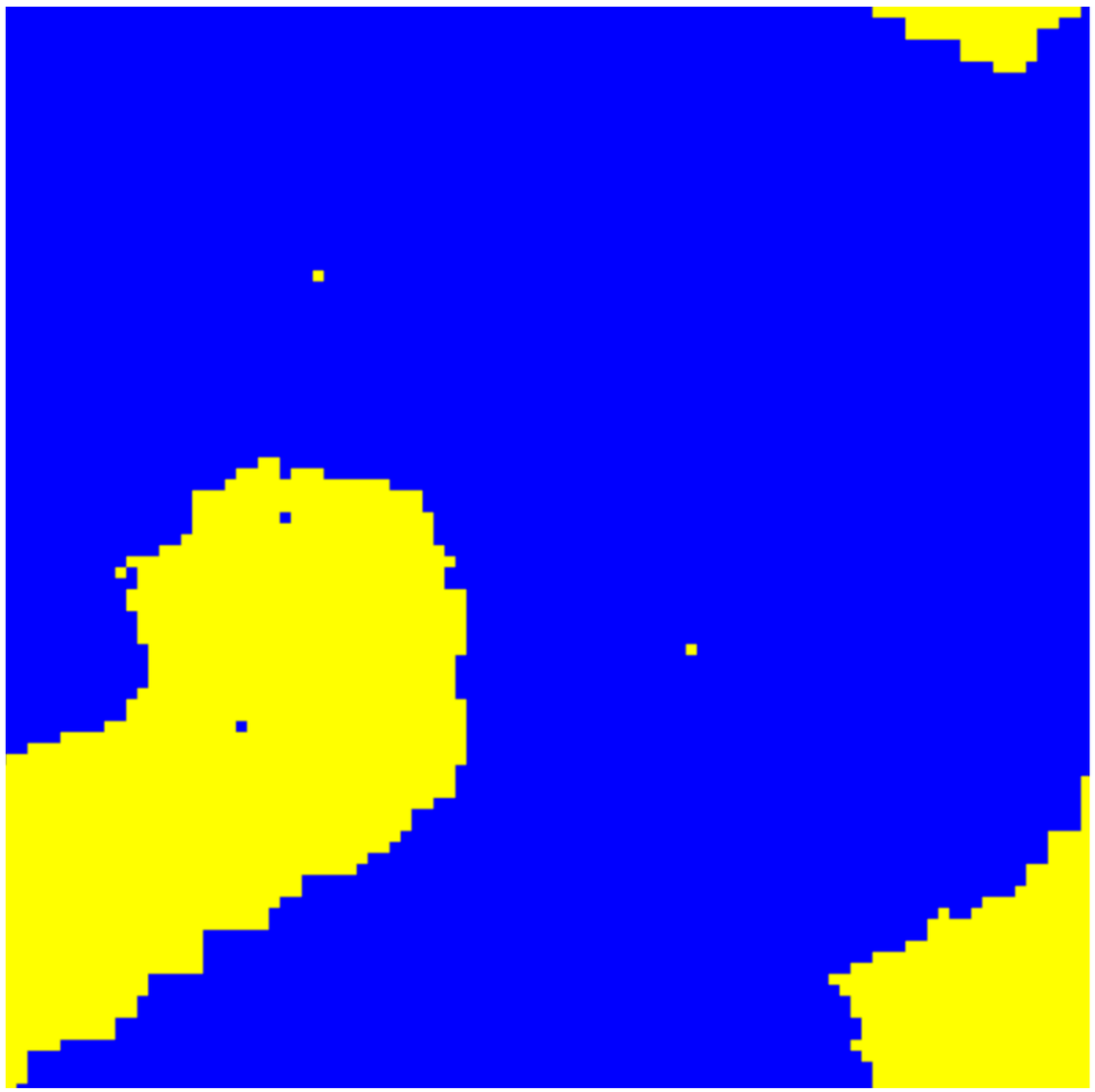


There are circumstances where we understand this chaos completely.

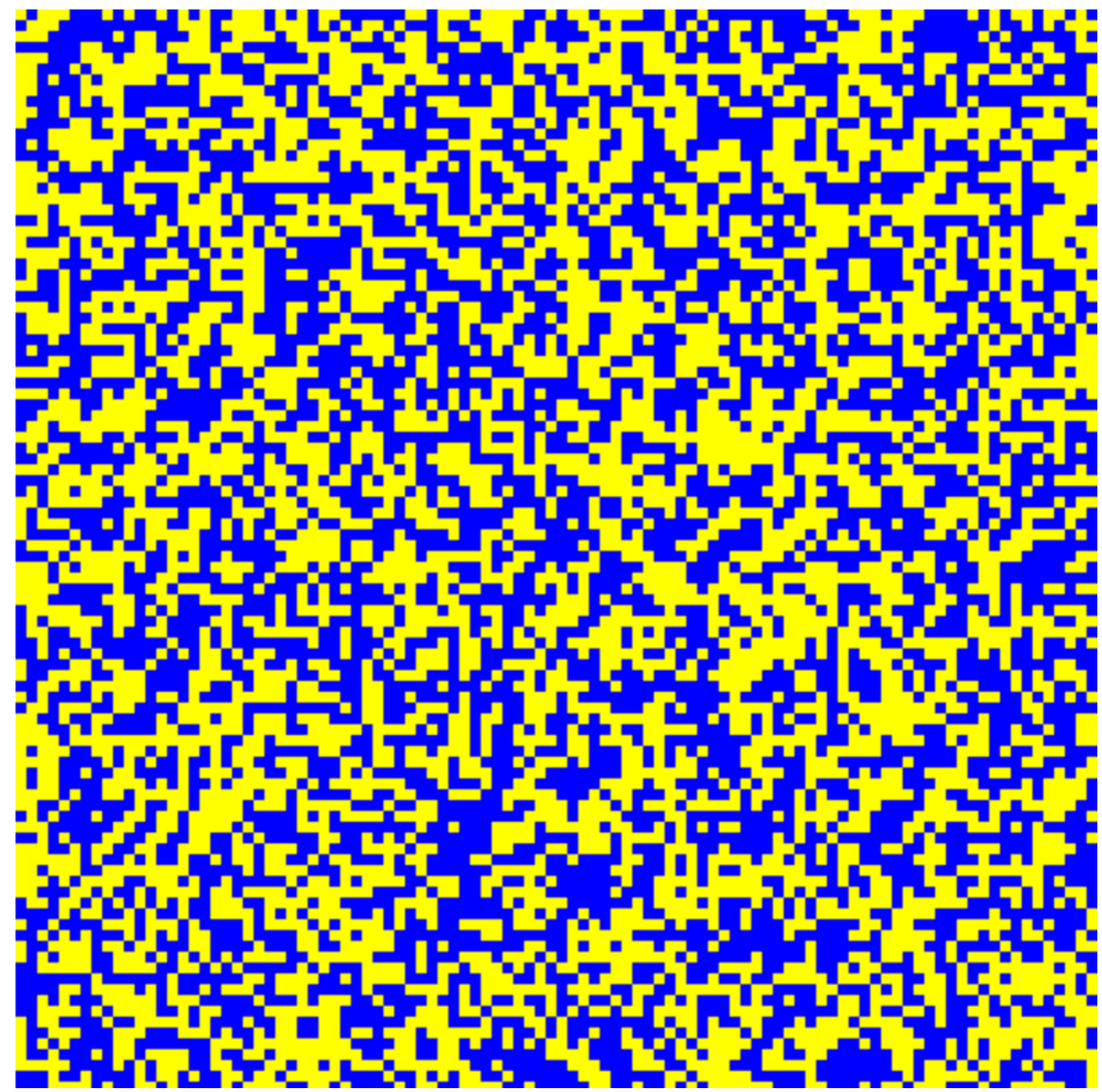
One occurs in a magnet near its phase transition.

simulated magnets:

at low temperature

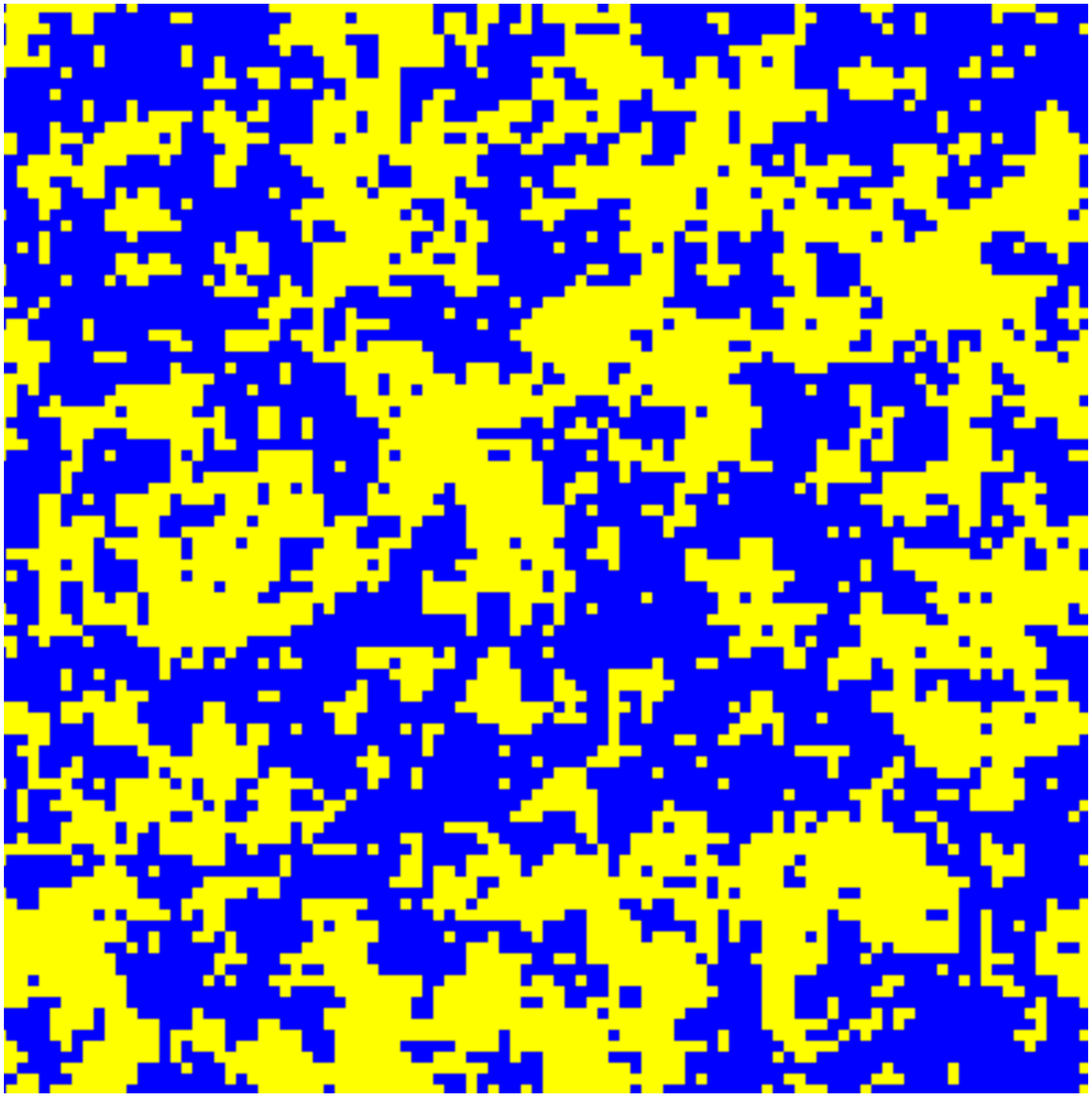


at high temperature

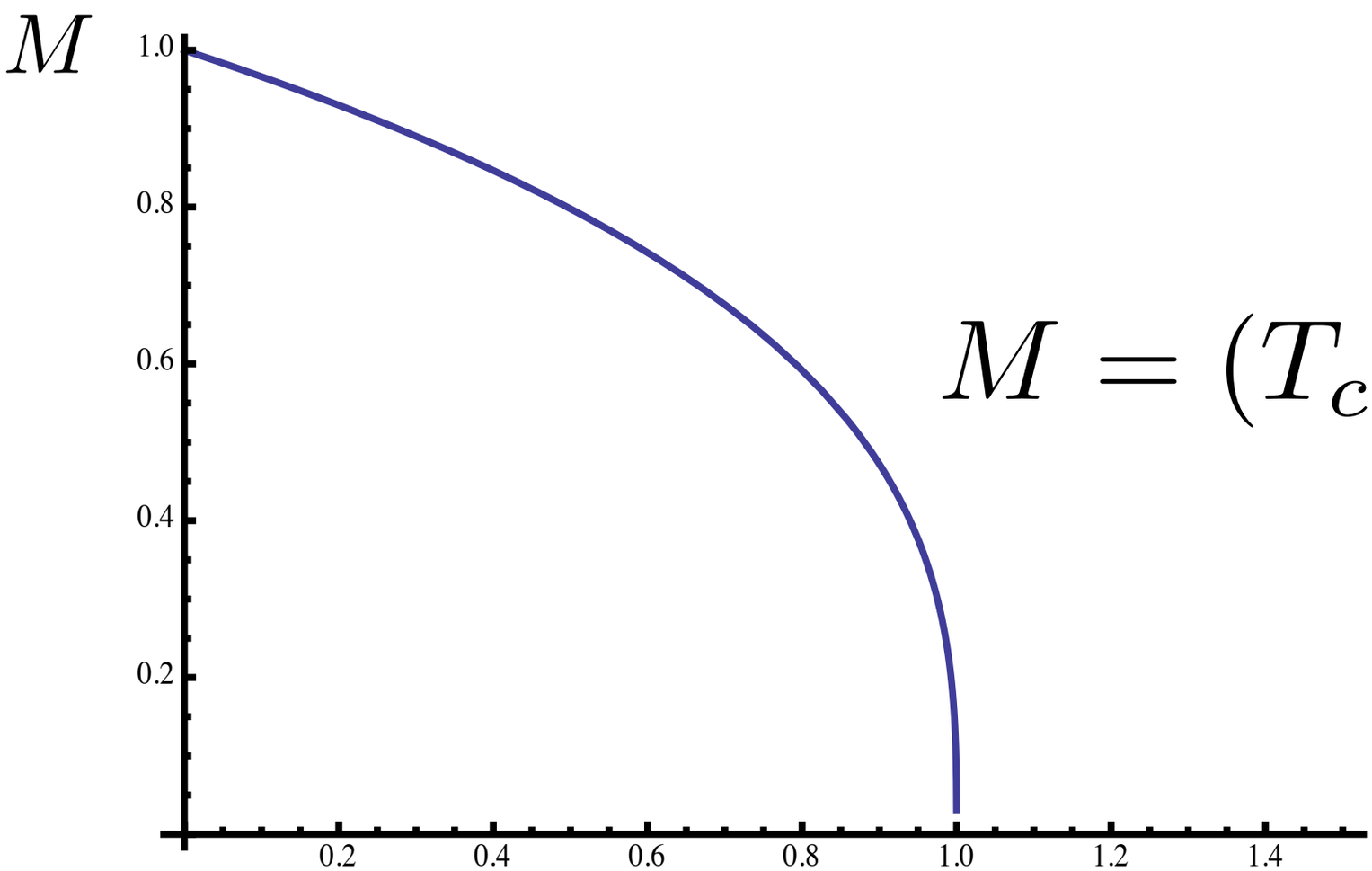


http://physics.weber.edu/schroeder/software/demos/IsingModel.htm

… and just near the critical temperature T_C
where the system forms magnetic order



There are more secrets here. As T goes below T_C, the magnetization turns on suddenly, and with a strange power law.



$$M = (T_c - T)^{0.326}$$

T/T_C

I learned about this when I was in college.

I also learned that the phenomenon was explained by Ken Wilson of Cornell University, using ideas from elementary particle physics.

So I went to Cornell to work on this.

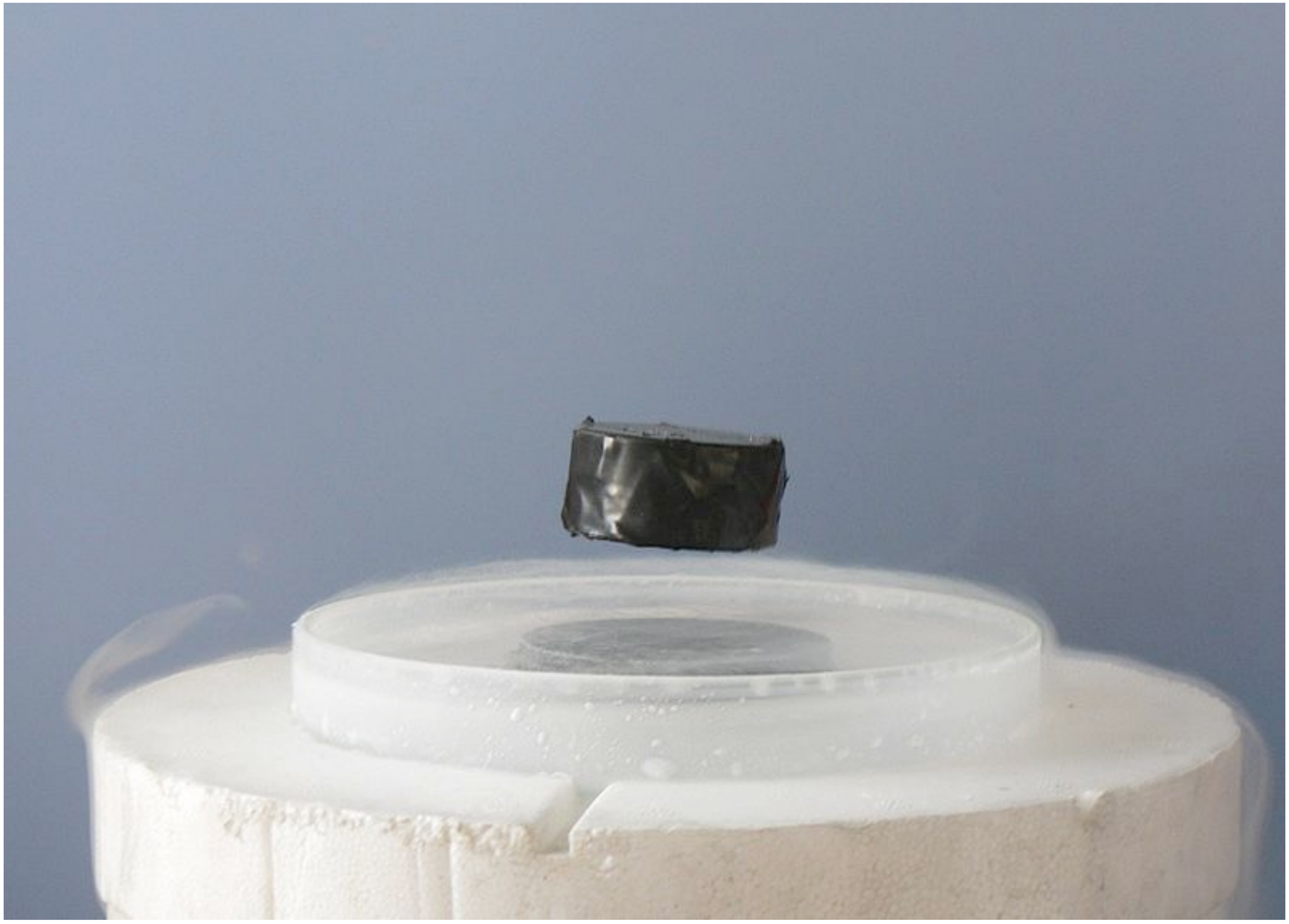
But Ken said that the problem of magnetism was solved. Now it was time to solve the strong interactions.

K.G. Wilson
Nobel Prize 1982

Studying with Wilson, I started to think about the relation between phase transitions and elementary particle physics.

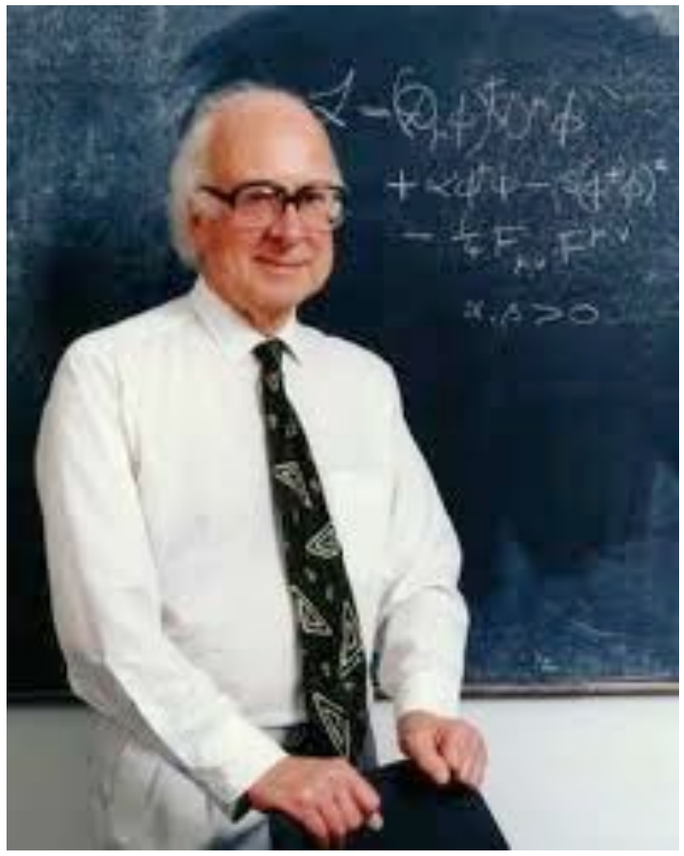
Actually, there is a profound connection.

In our current understanding of elementary particle physics, the masses of all elementary particles come from a phase transition in the early universe.

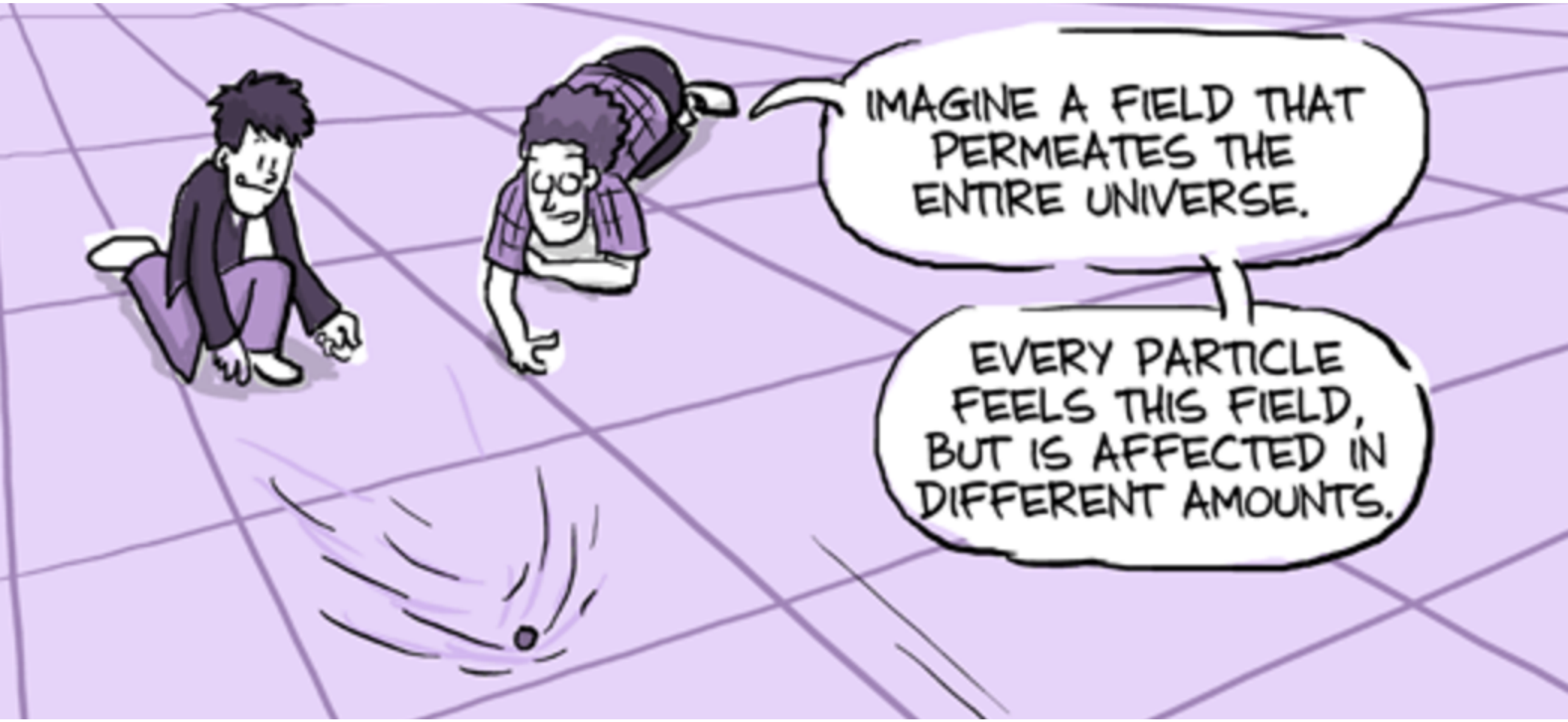


Superconductivity, a property of almost all metals at very low temperature. Electrons in the metal pair up and form a “superfluid”.

The analog of the superconducting electron-electron superfluid is called the Higgs field.



Peter Higgs, Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, Robert Brout (Nobel Prize 2013)

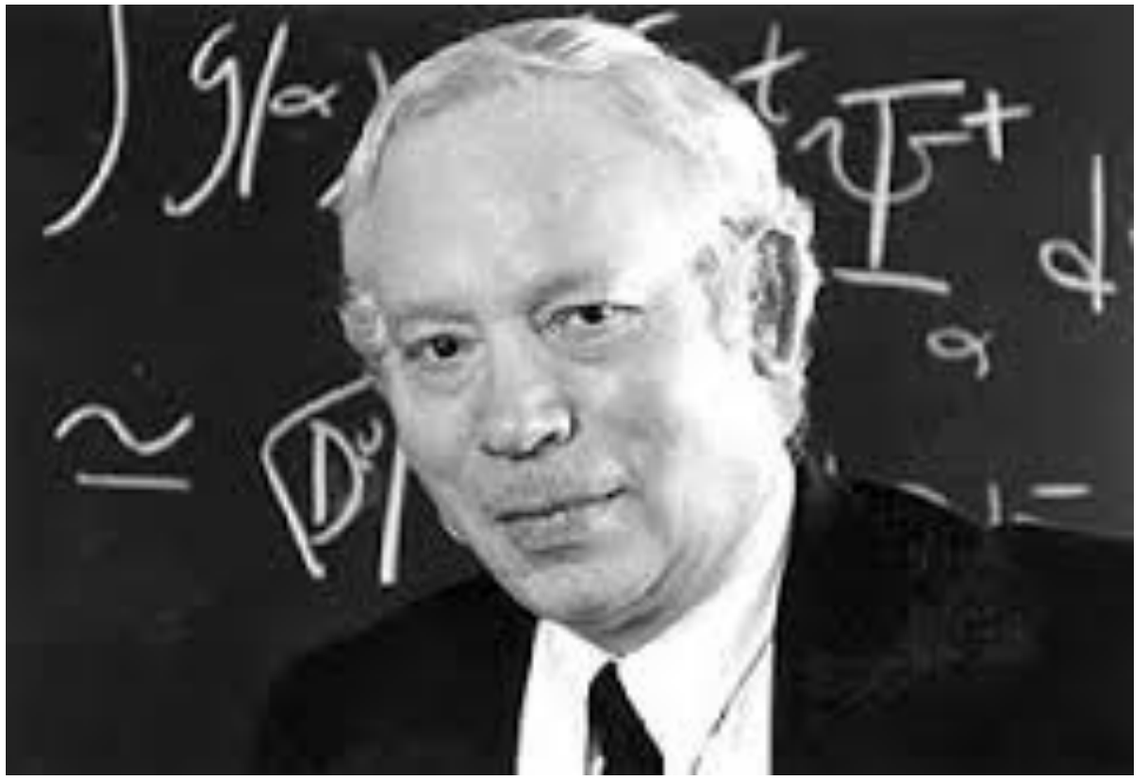


“The Higgs Boson Explained”
Jorge Cham and Daniel Whiteson

After Cornell, I went to work with Steven Weinberg, who applied the Higgs theory to quark and lepton mass.

Weinberg had a theory called “Technicolor”, that the Higgs field was a bound state of new particles, exactly like superconductivity.

I worked on Technicolor models for many years.



S. Weinberg
Nobel Prize 1979

Finally, I killed this theory.

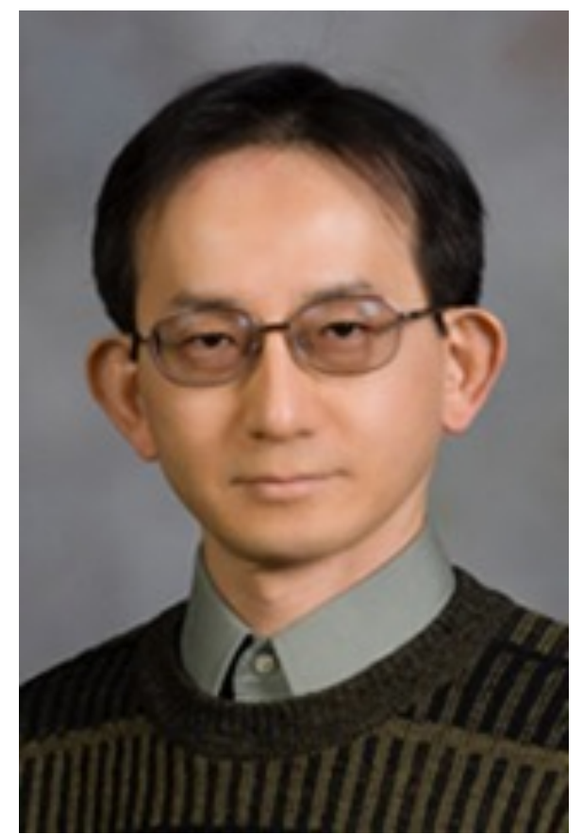
Tatsu Takeuchi and I showed that the idea was inconsistent with new precision measurements of the properties of the Z boson.

A New Constraint on a Strongly Interacting Higgs Sector

MICHAEL E. PESKIN AND TATSU TAKEUCHI*

Stanford Linear Accelerator Center

Stanford University, Stanford, California 94309



T. Takeuchi

The Higgs boson was discovered in 2012.

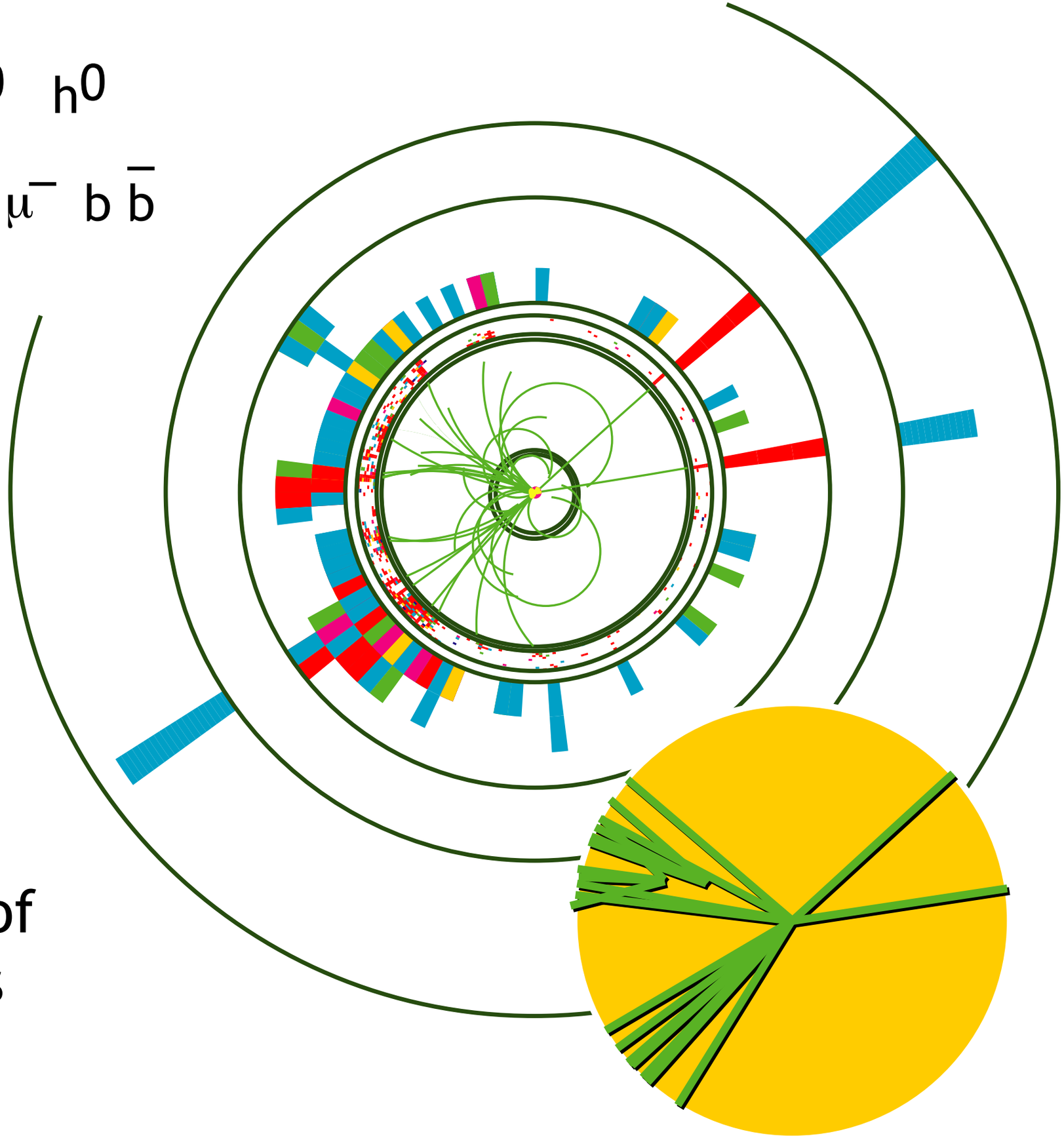
However, we still do not understand its phase transition.
We do not know what makes the Higgs condensate form.

This is one of the most important questions in physics.

We hope that, through precise measurements of the properties of the Higgs boson at the ILC, we will solve this mystery.

$e^+e^- \rightarrow Z^0 \quad h^0$

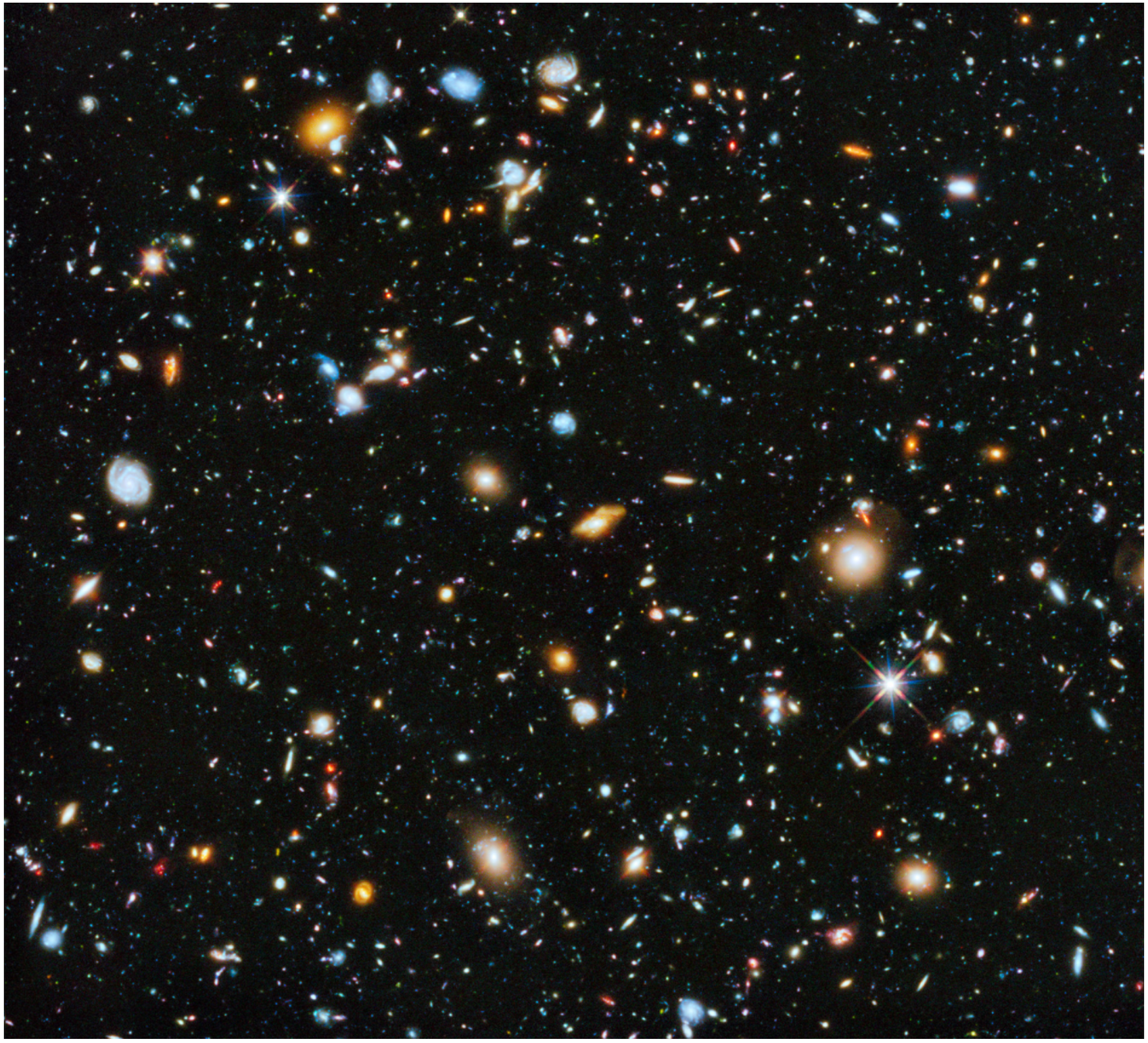
$\rightarrow \mu^+\mu^- \; b\,\bar{b}$



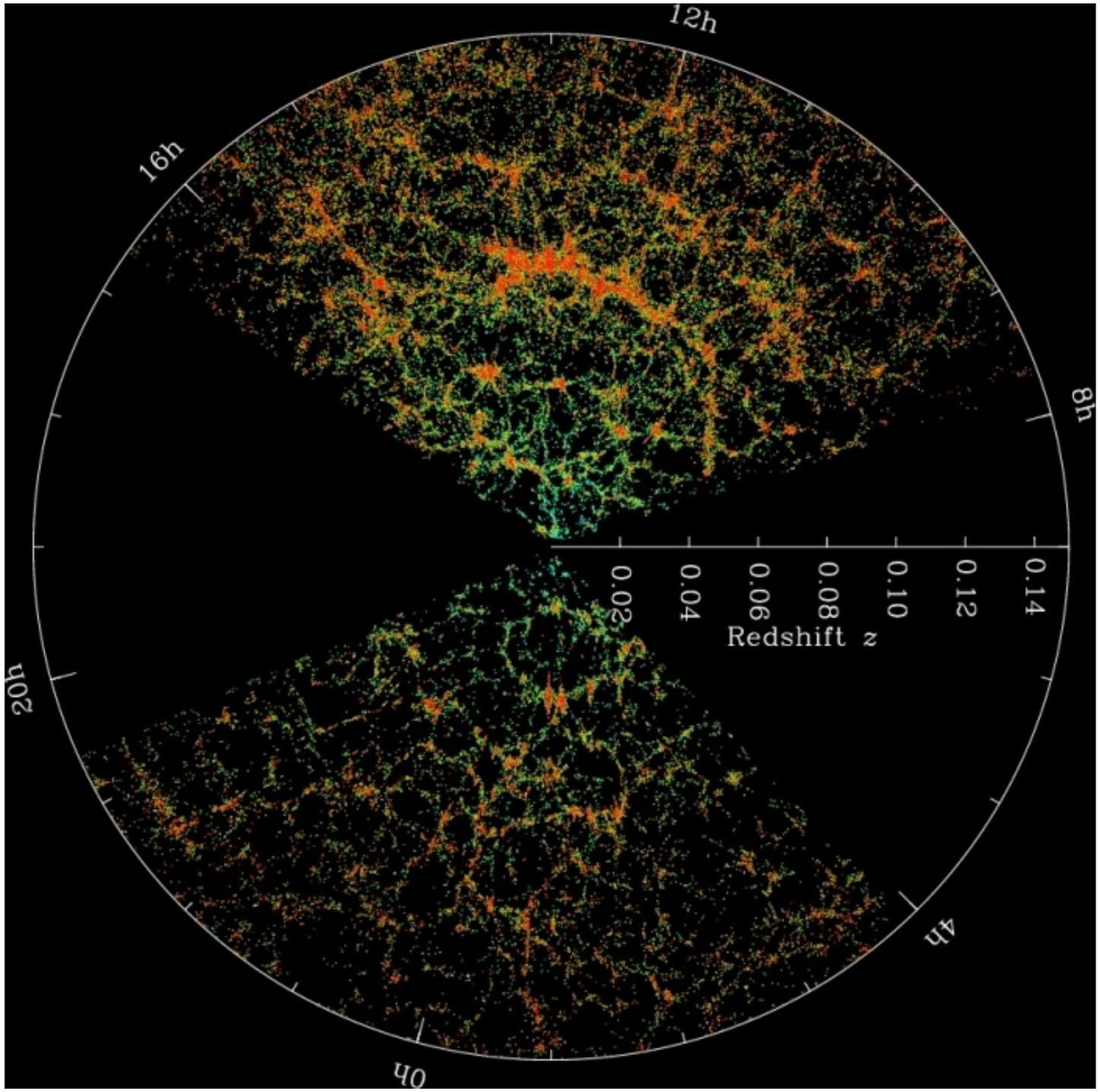
Simulation of an ILC Higgs event.

These ideas of chaos and order also apply to another area of physics

— the overall distribution of matter in the universe.



Hubble telescope deep field



sky coordinates for galaxies observed in the Sloan Digital Sky Survey

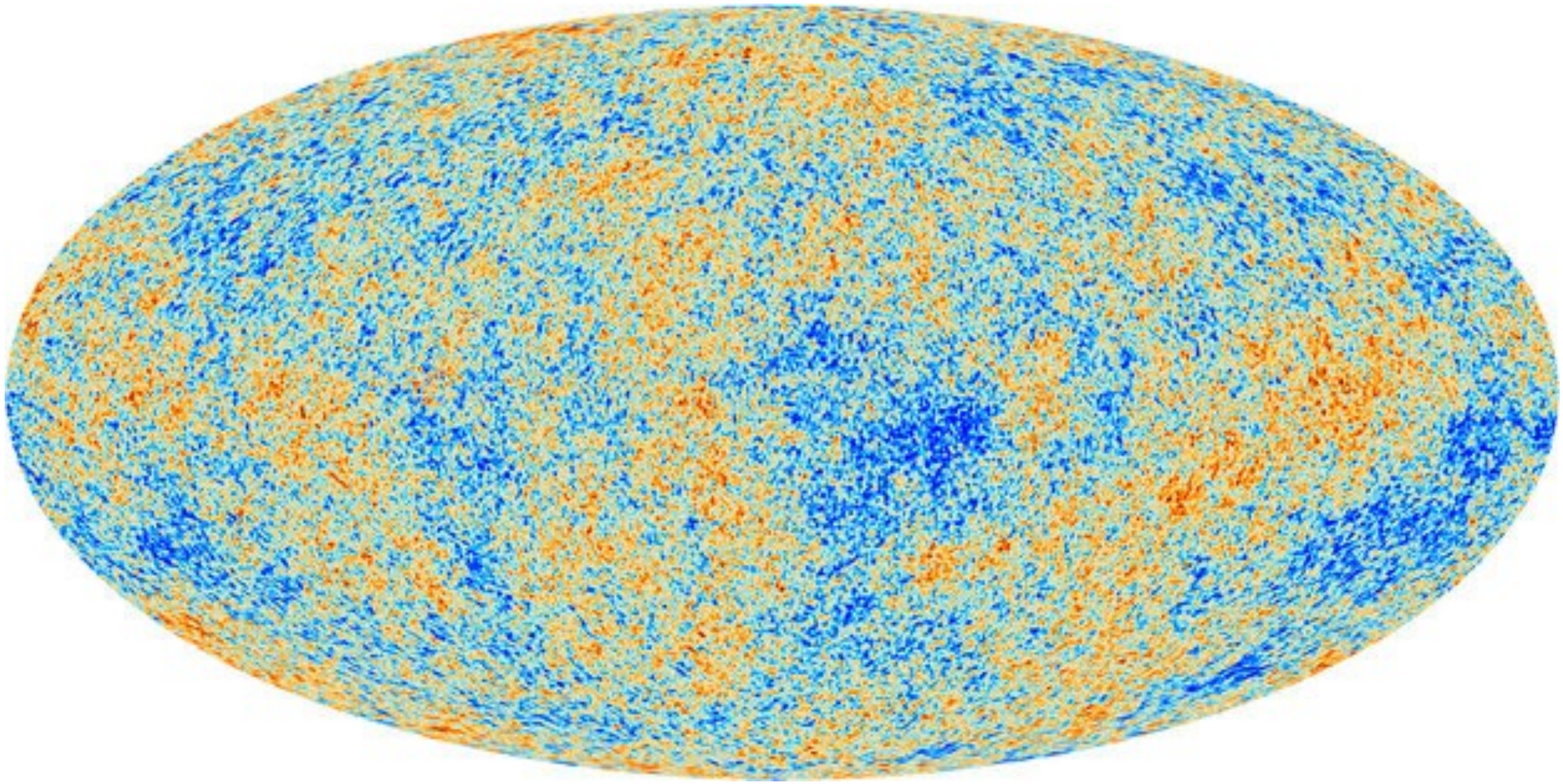
This complex pattern of knots and voids can be generated by gravitational collapse of matter, starting from small perturbations of a uniform universe.

Edward Harrison and Yakov Zel'dovich:

The primordial distribution of perturbations was scale-invariant.

But, this is not correct:
from the Planck satellite experiment:

$$\rho(\lambda) \sim \frac{1}{\lambda}\, \lambda^{n_s - 1} \qquad n_s = 0.9645 \pm 0.0049$$



Planck collaboration

What can generate this strange power law?

Alan Guth, Andrei Linde, and others showed that this can be the result of a phase transition just after the Big Bang.

This is the theory called cosmic inflation.

Linde showed that the theory of inflation implies the existence of many universes, possibly with completely different laws of physics.

A. D. Linde
Nobel Prize
soon (I hope)

The idea of phase transitions is one of the unifying principles of physics.

Phase transitions have a major role in

physics of materials, magnets, superconductors

physics of elementary particles

physics of the large-scale structure of the universe

However much we know today, there is much more that we do not know.

Please join our quest to uncover the deep secrets of nature.