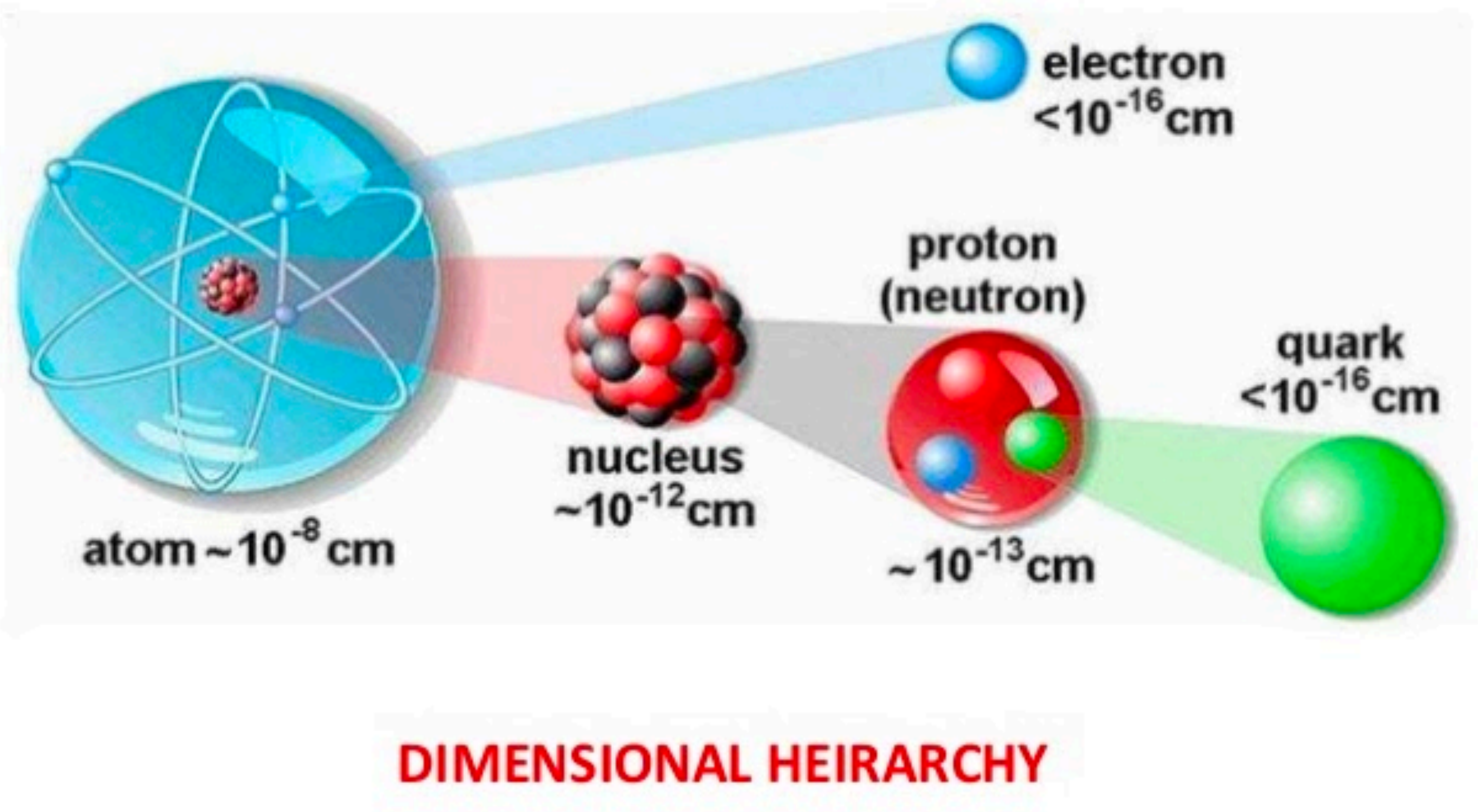
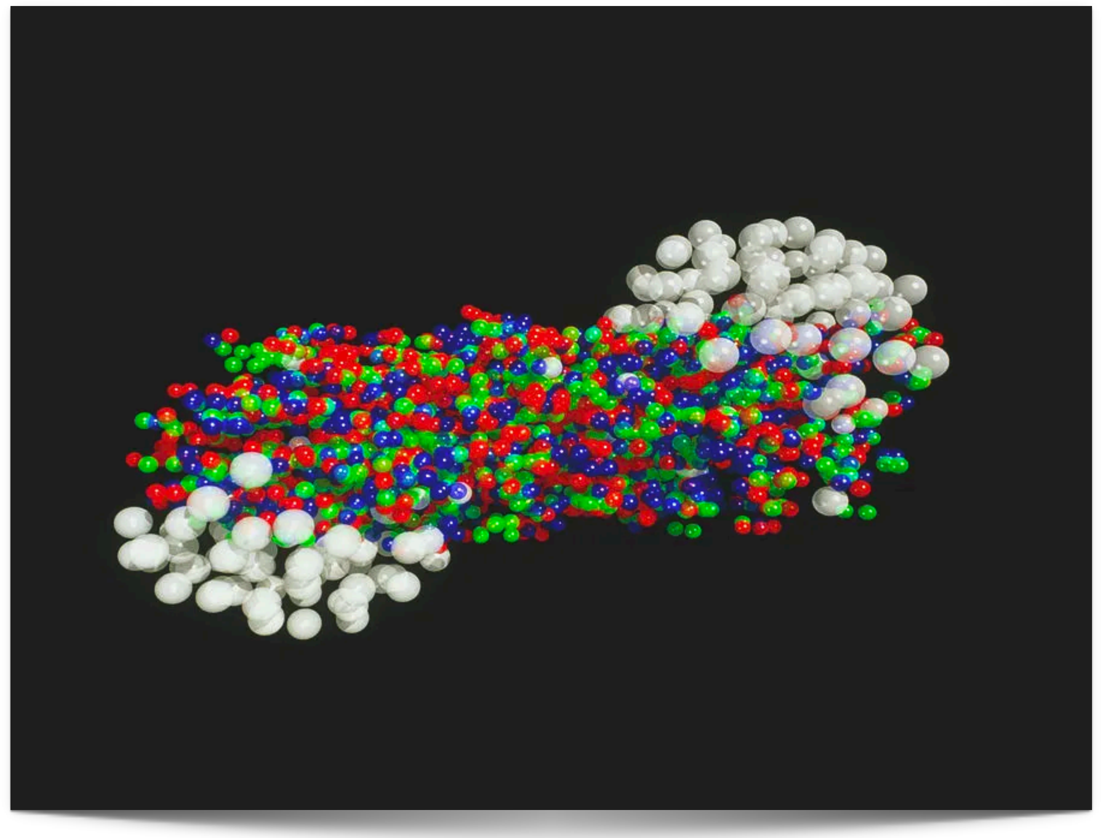
Unsolved problems in physics: Are we an "ice" of quark and gluon?

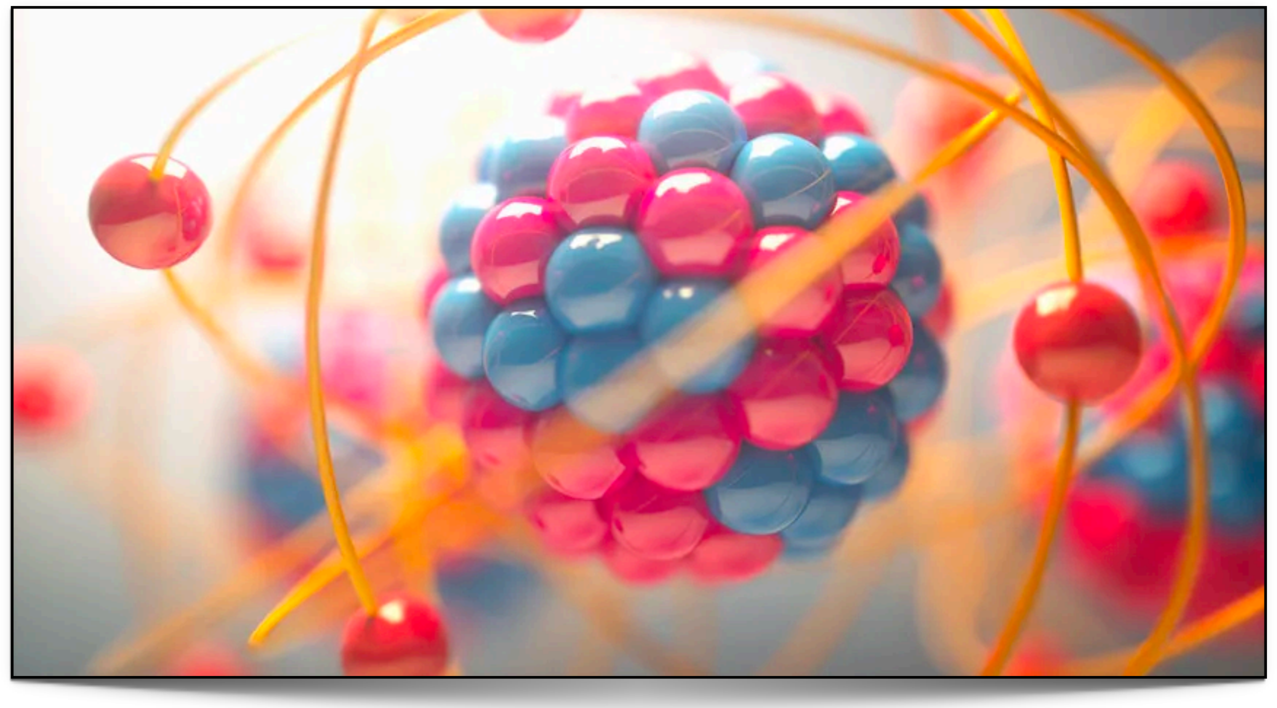


Nick Poovuttikul

Chulalongkorn University

“Free” quarks





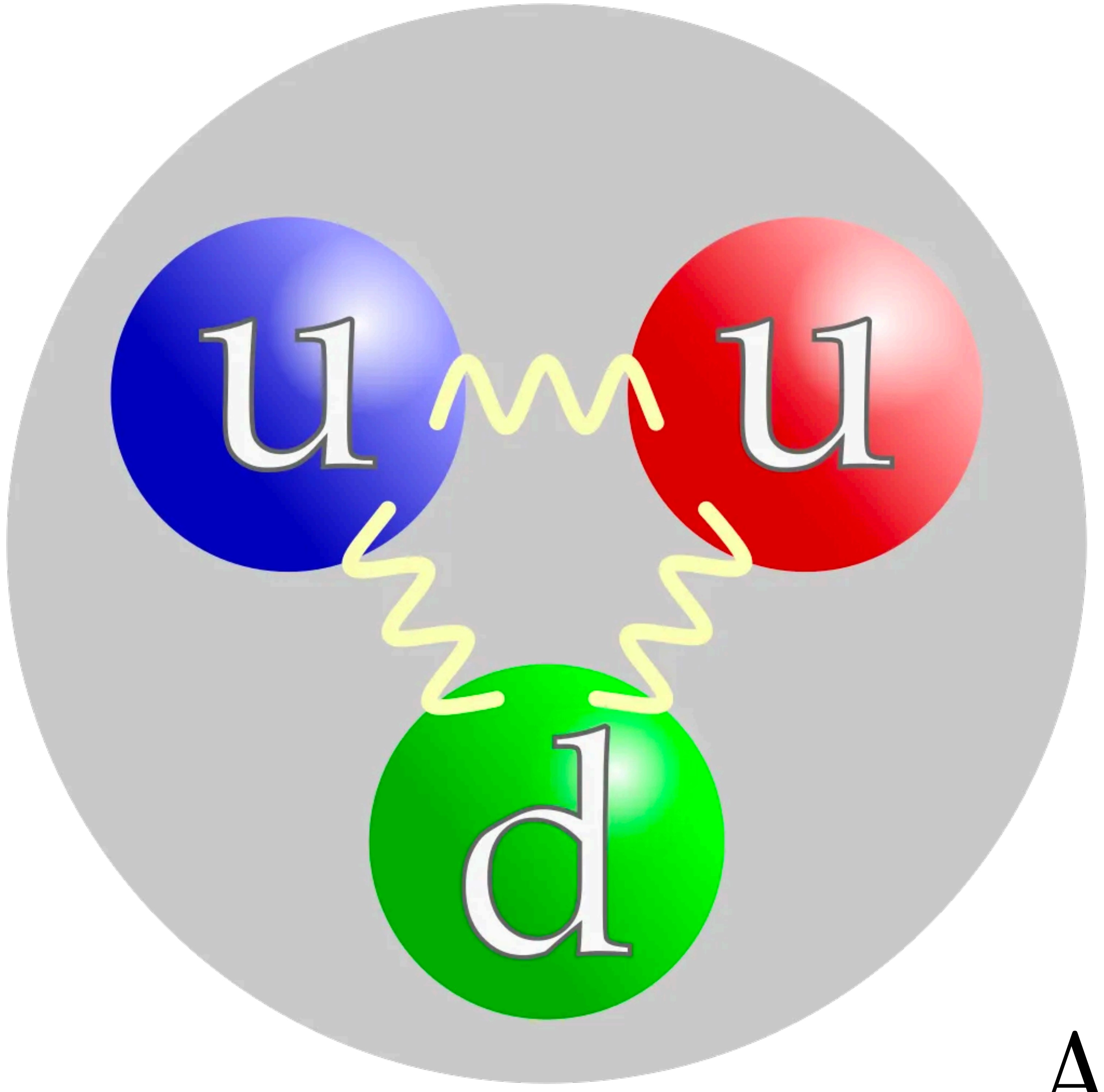
Energy

Temperature

Proton mass $= 1.6726 \times 10^{-27}$ kg

(Up)quark mass $= (4 \pm 1) \times 10^{-30}$ kg

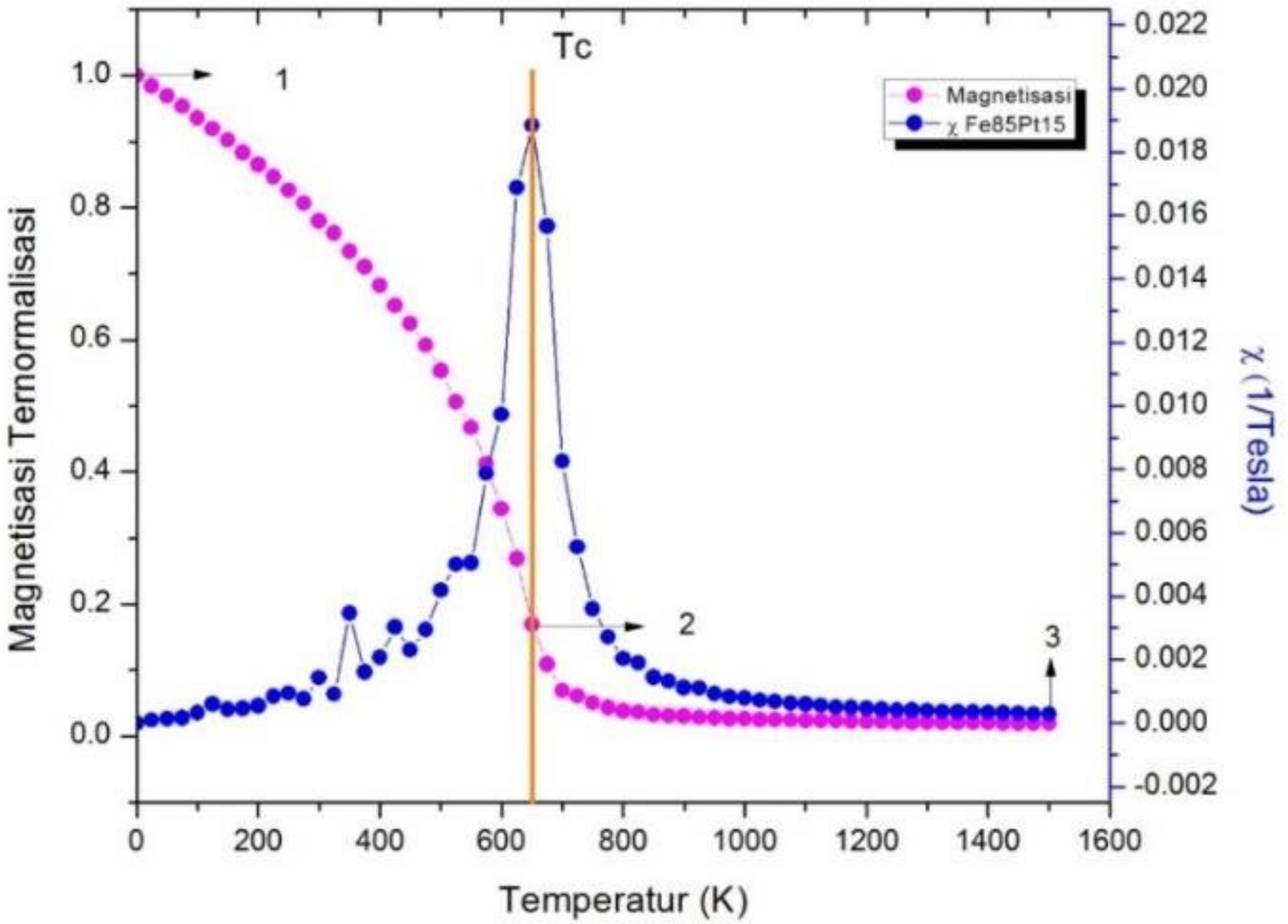
(Down)quark mass $= (8.5 \pm 0.8) \times 10^{-30}$ kg

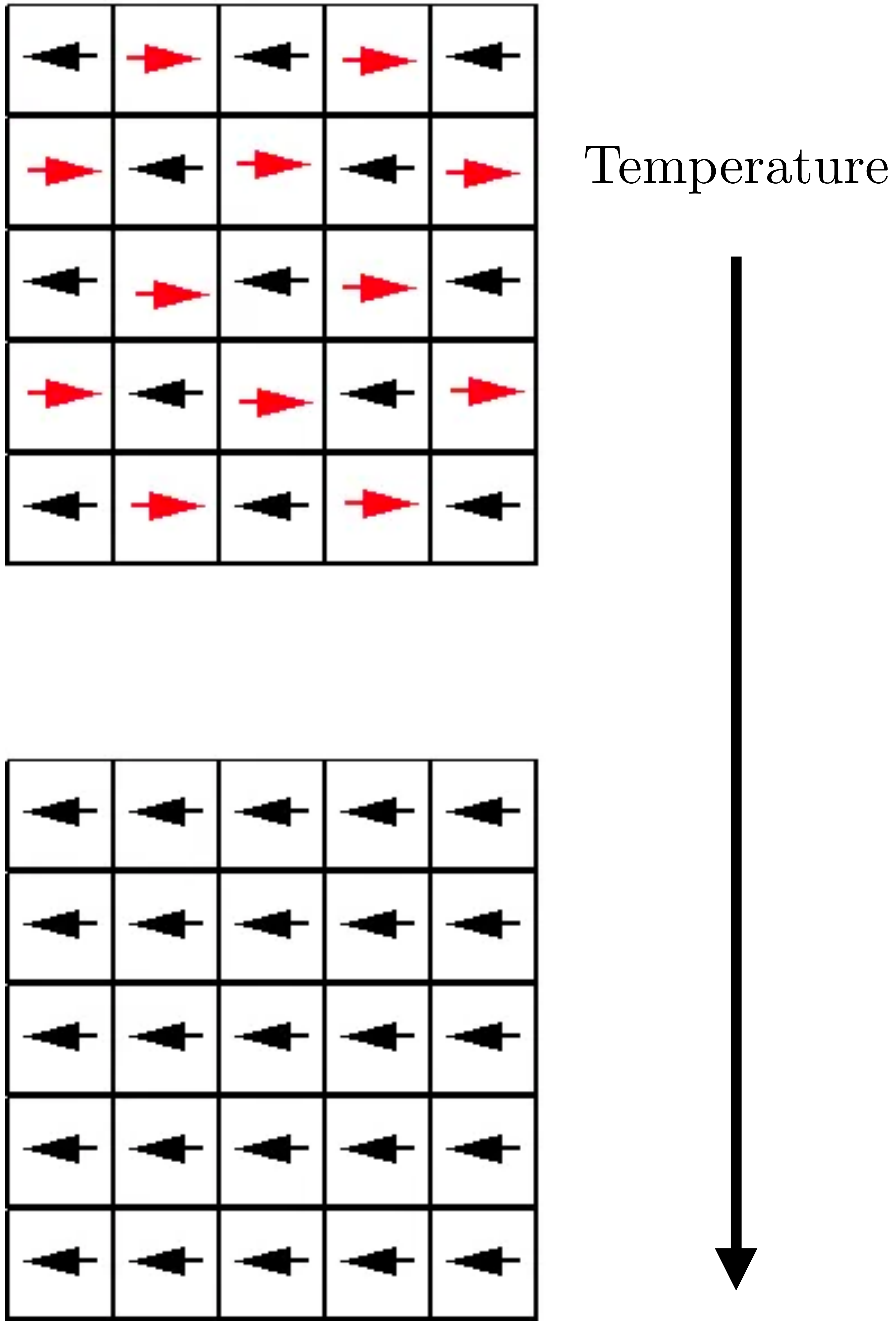


So how come protons are so heavy !?

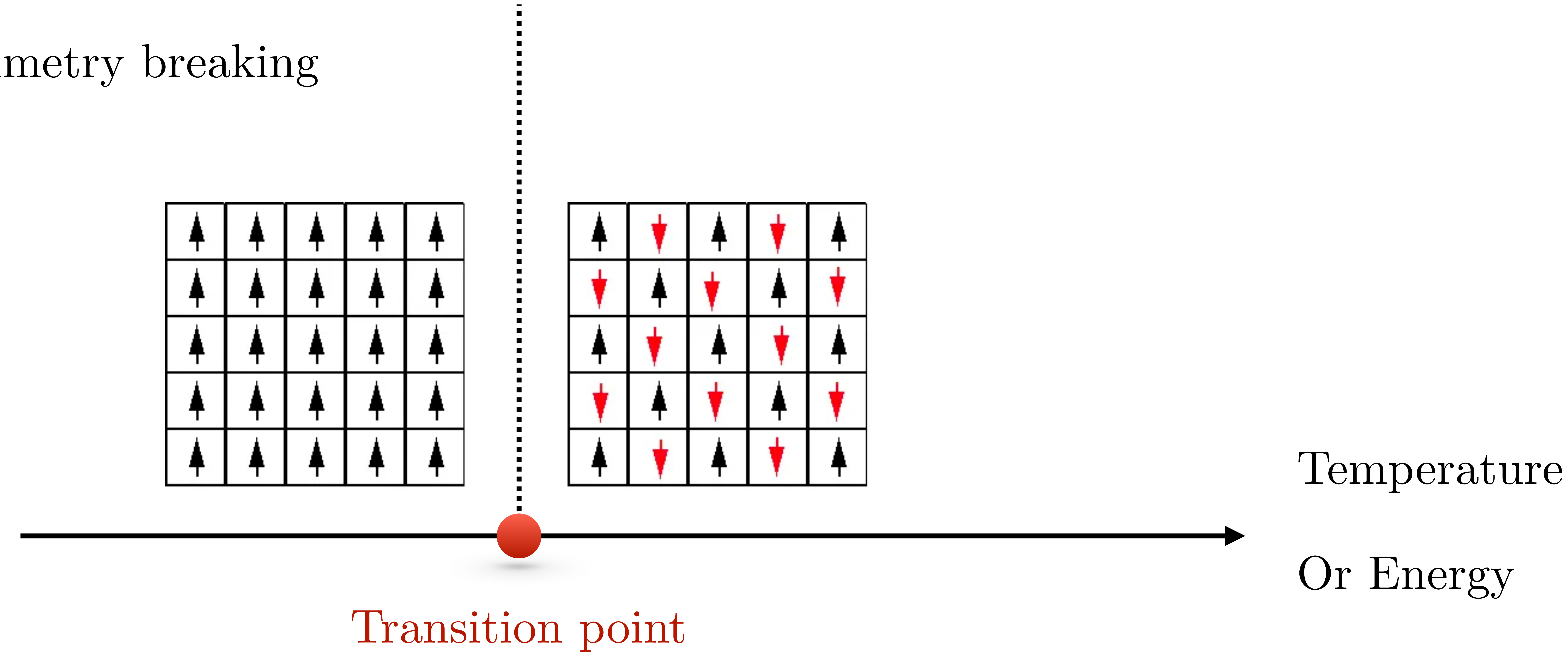
And how come we never see any free quark?

HOW DO WE EVEN KNOW THERE IS A PHASE TRANSITION

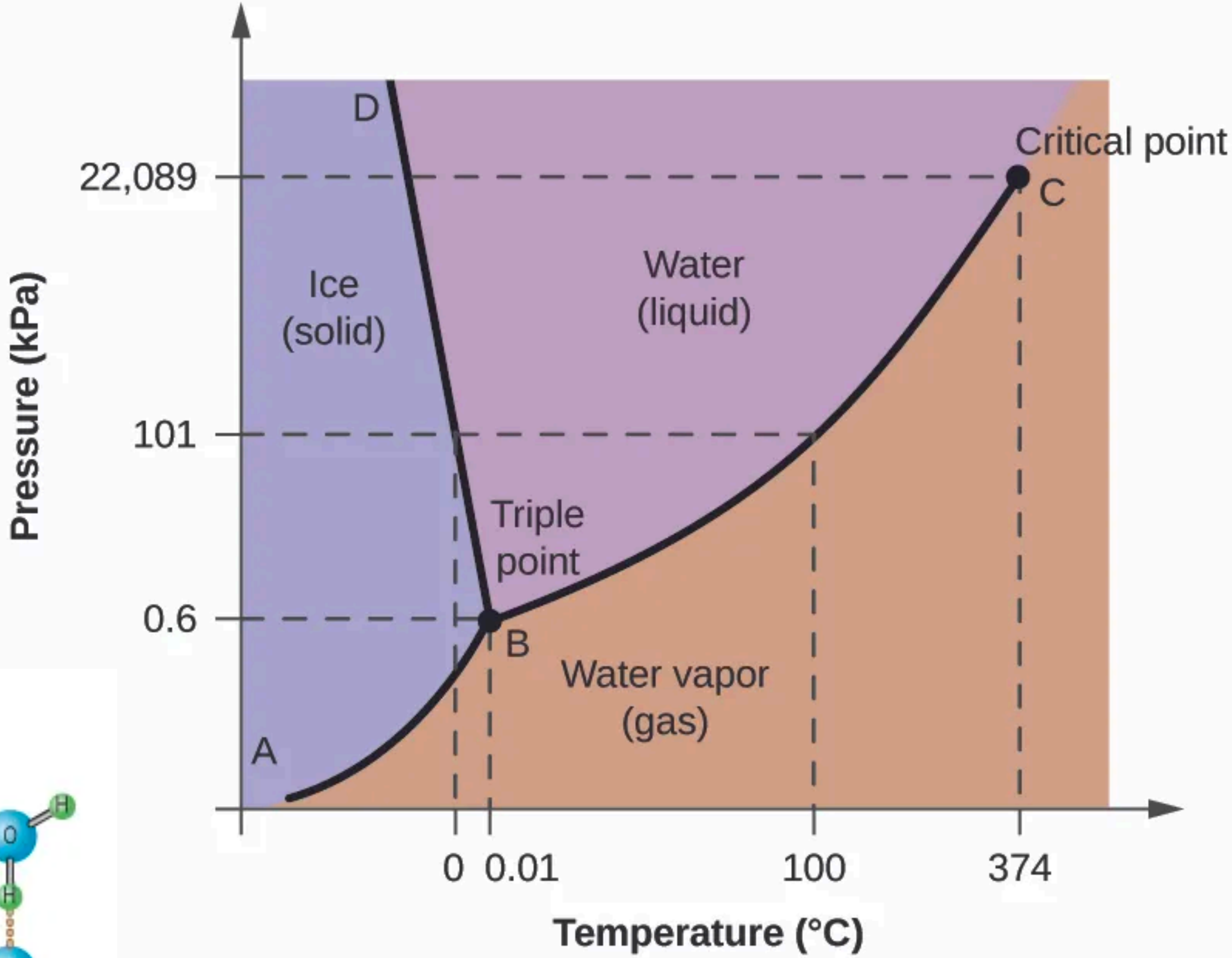


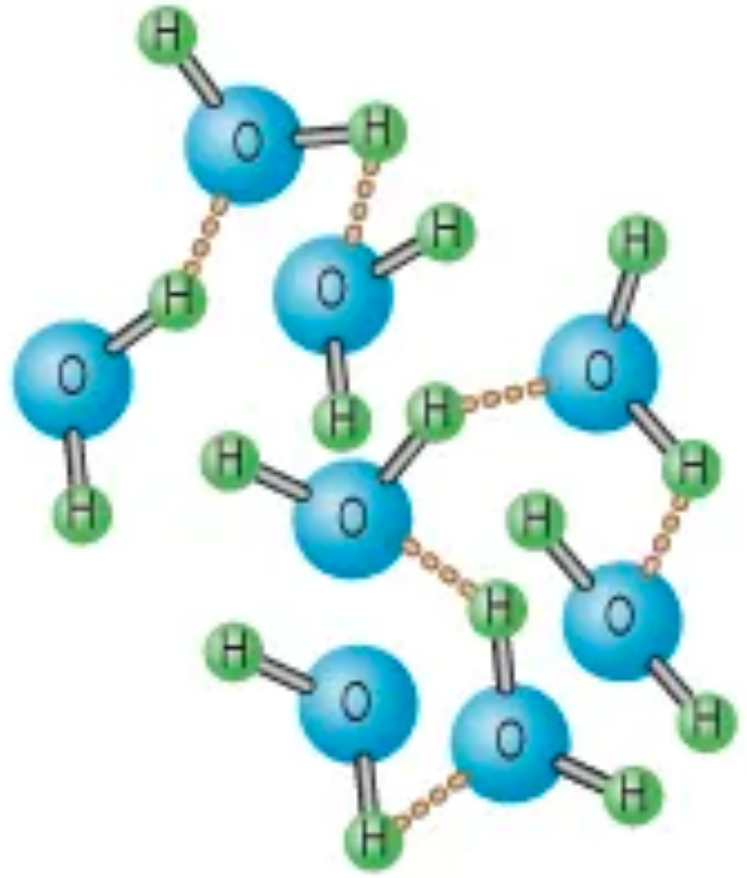


Z2 symmetry breaking

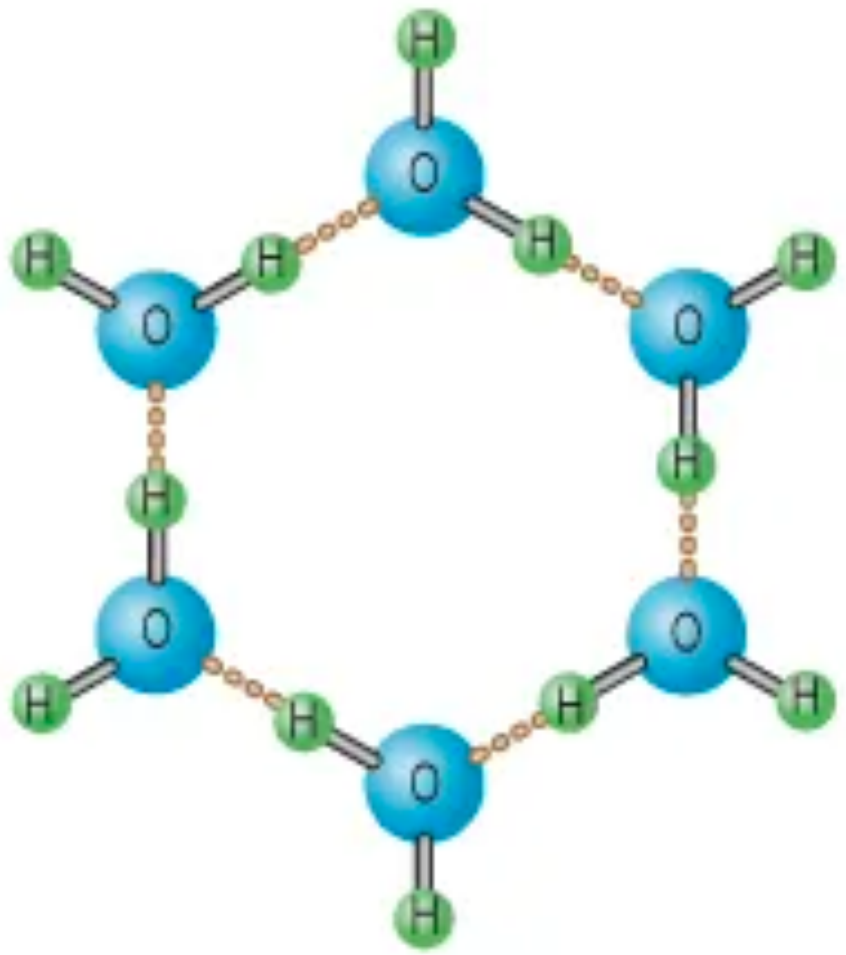


Phase diagram of water



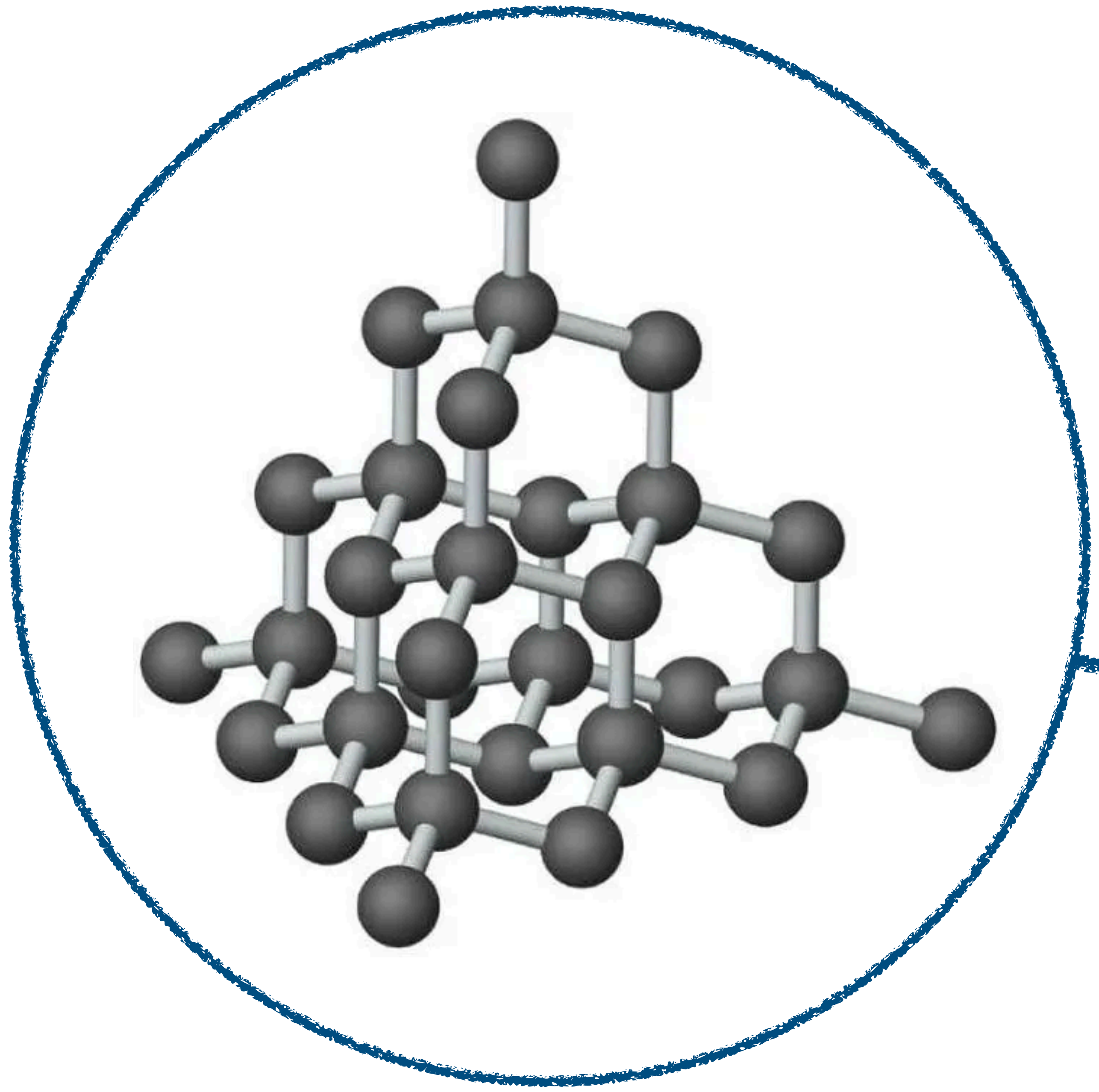


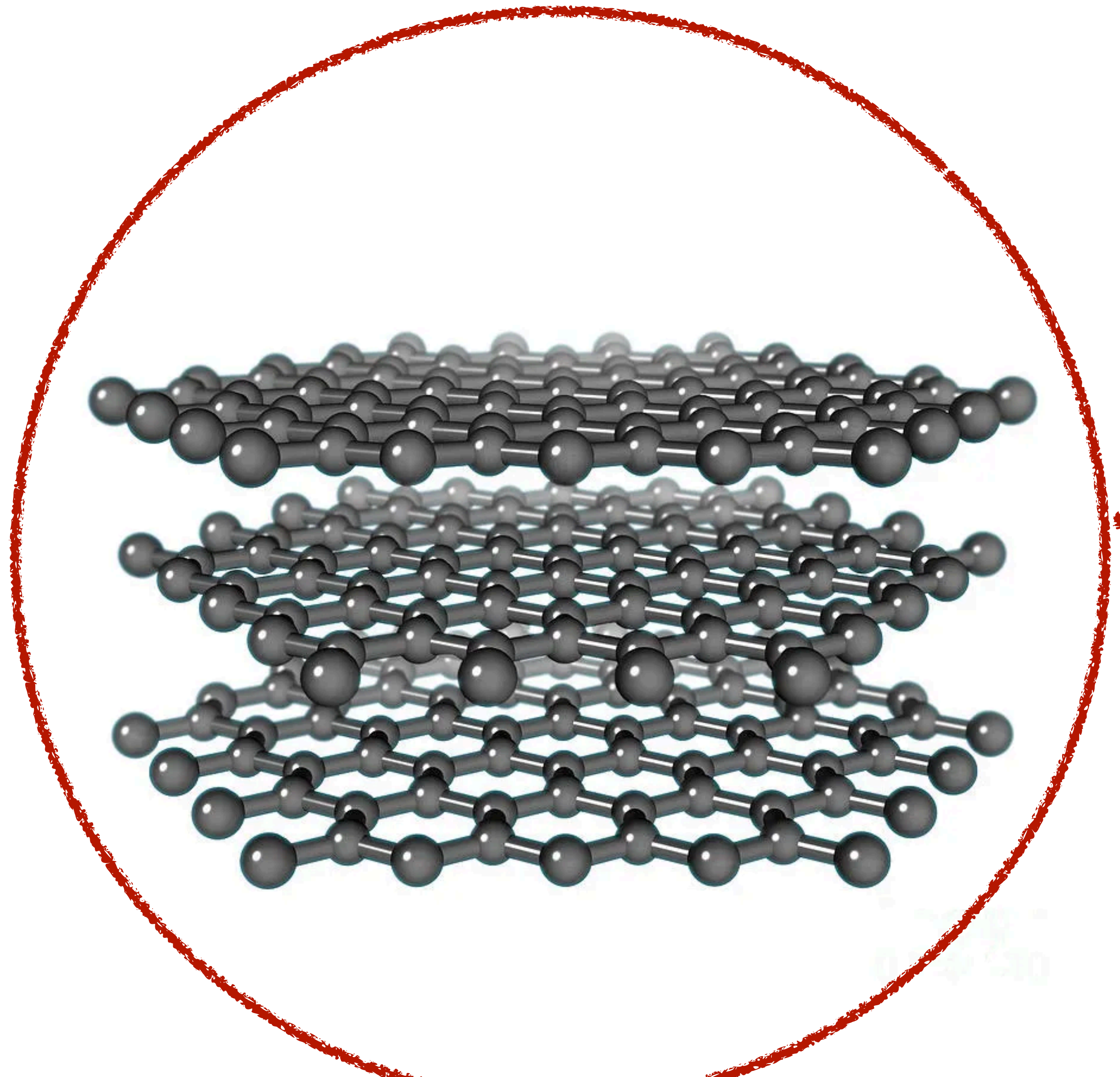
Structure of molecules in water

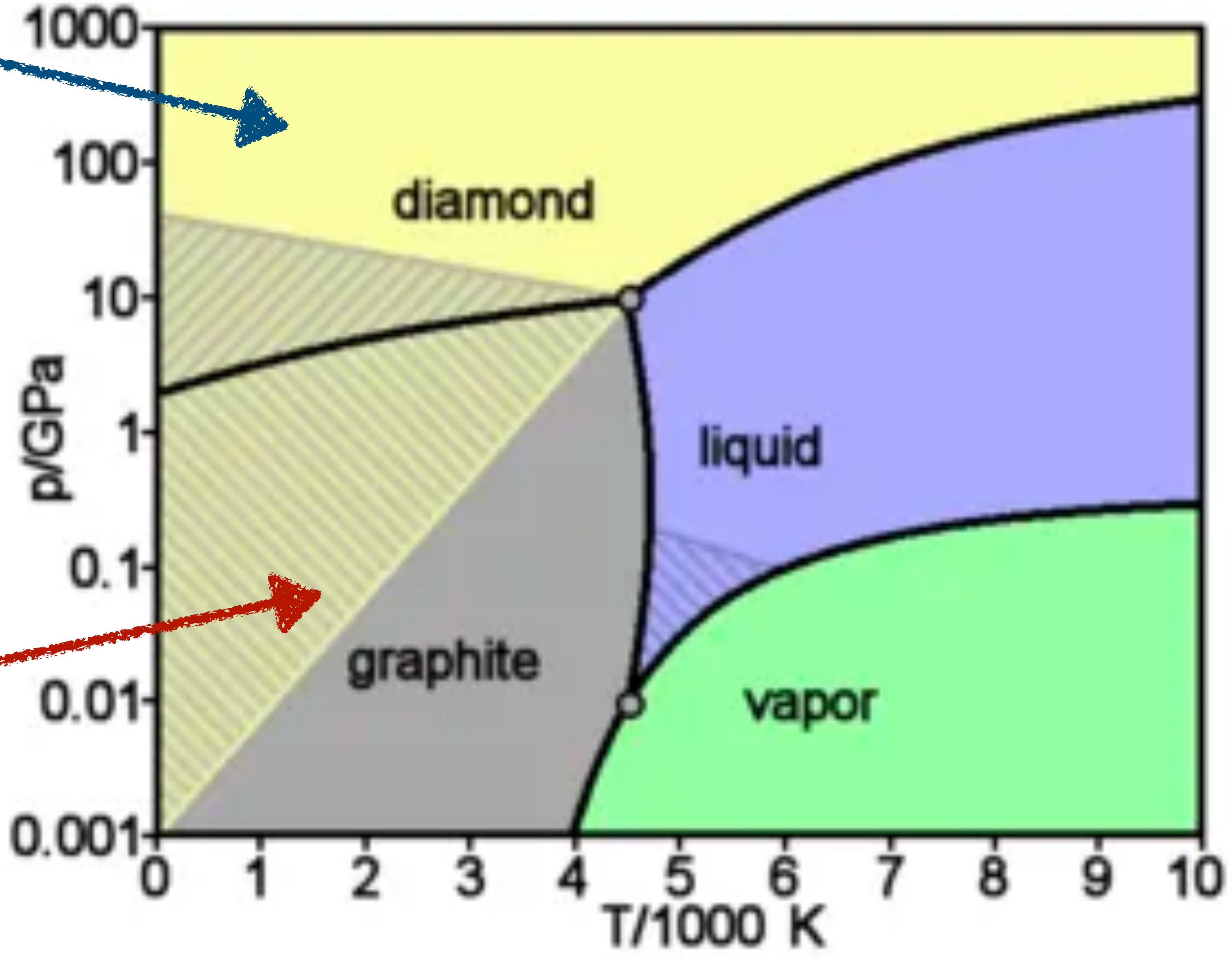


Structure of molecules in ice

Phase diagram of carbon







A more precise question:

Is proton a **phase** with different symmetry compared to free quarks?

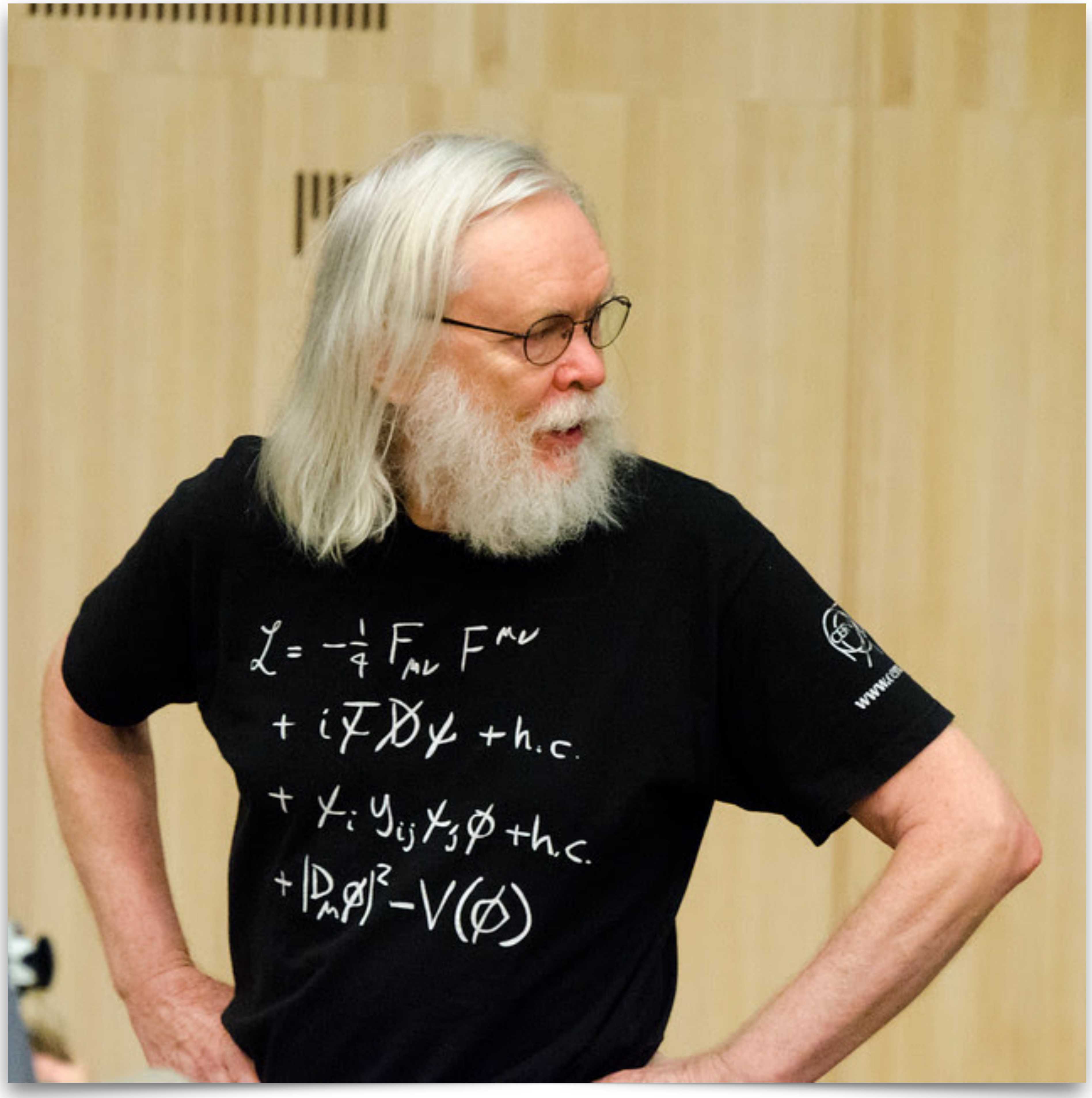
But what do we means by symmetry of quarks & proton?

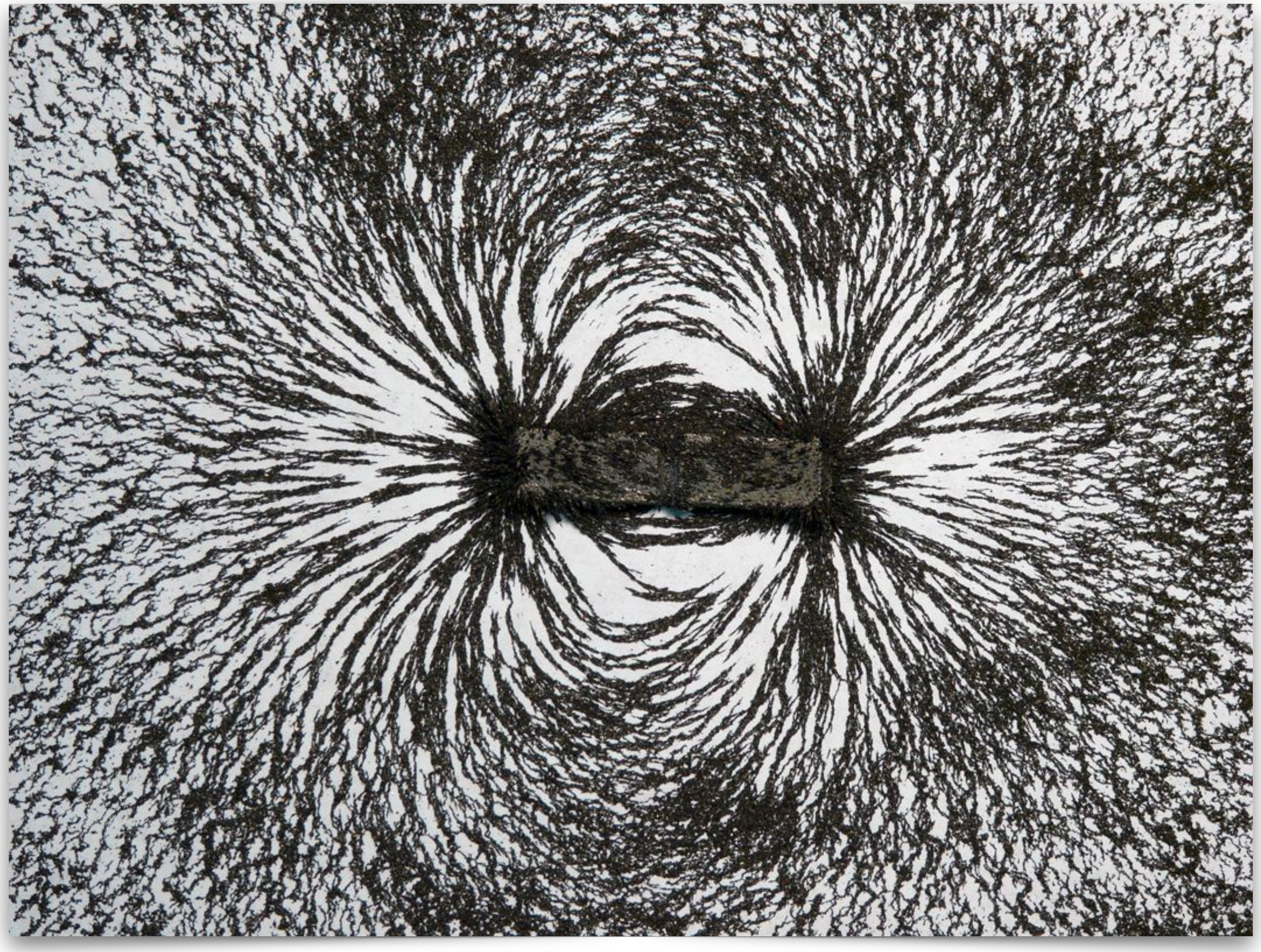
Actually...what do we even mean by symmetry??

Go to the roots of these calculations! Group the operations. Classify them according to their complexities rather than their appearances!

Évariste Galois, 1832
supposedly before he died in the duel next morning

There is no particle, only fields

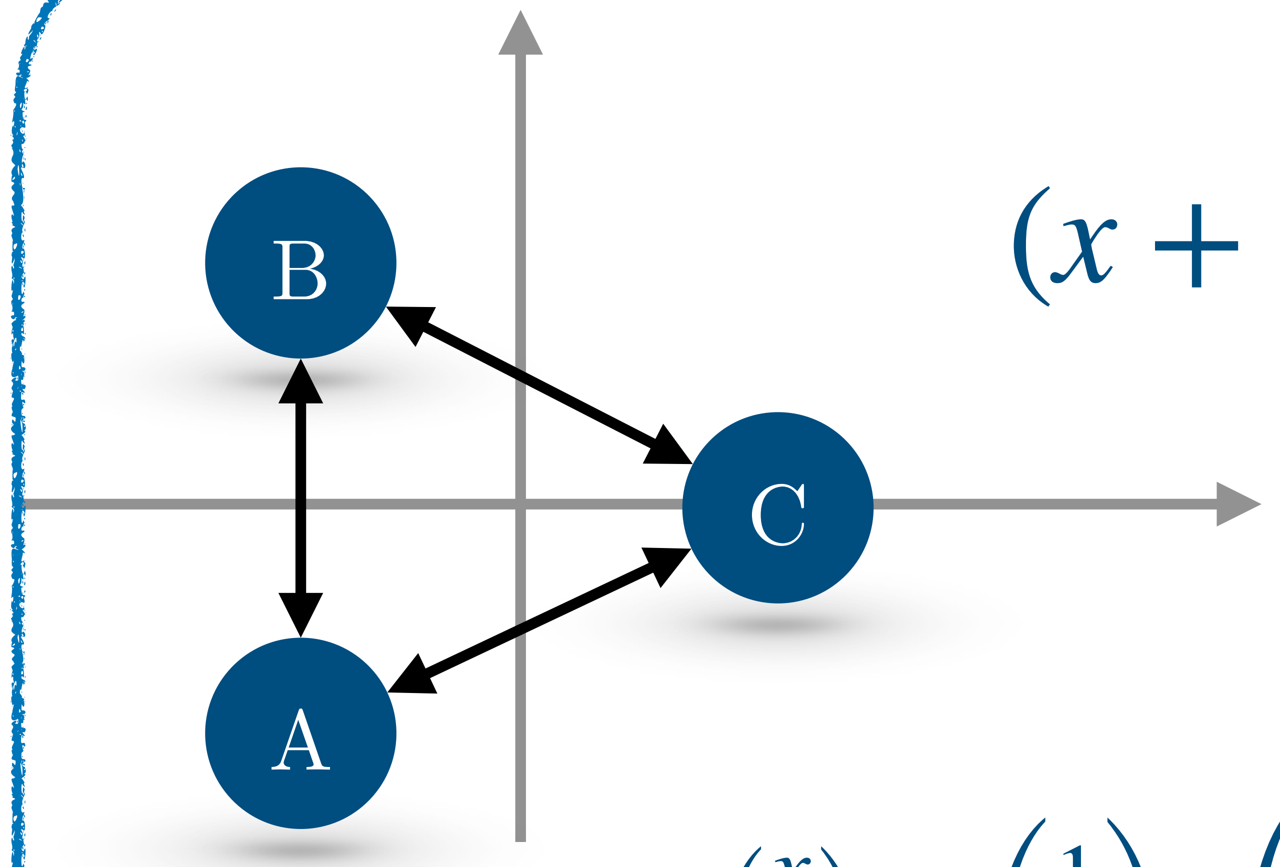




This might sound crazily complicated
But we know and use field every day

Standard model: capturing equations describing fields that made up everything we see

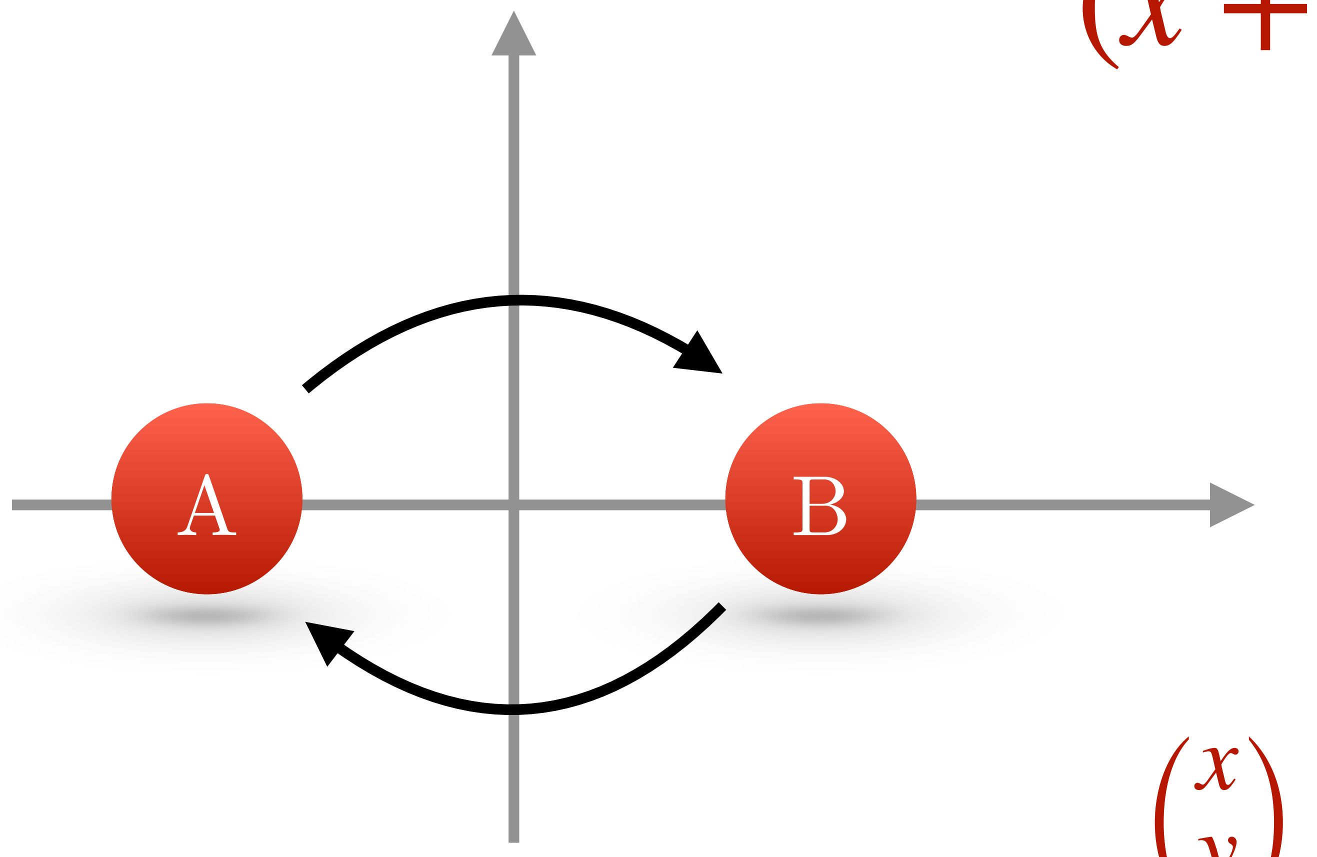
WHAT IS SYMMETRY



$$(x+iy)^3 = 1$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1/2 \\ \sqrt{3}/2 \end{pmatrix}, \begin{pmatrix} 1/2 \\ -\sqrt{3}/2 \end{pmatrix}$$

$$(x+iy)^2 = 1$$



$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} a_1 & b_1 \\ c_1 & d_1 \end{pmatrix} \begin{pmatrix} 1/2 \\ \sqrt{3}/2 \end{pmatrix} = \begin{pmatrix} a_2 & b_2 \\ c_2 & d_2 \end{pmatrix} \begin{pmatrix} 1/2 \\ -\sqrt{3}/2 \end{pmatrix}$$

Two different matrices

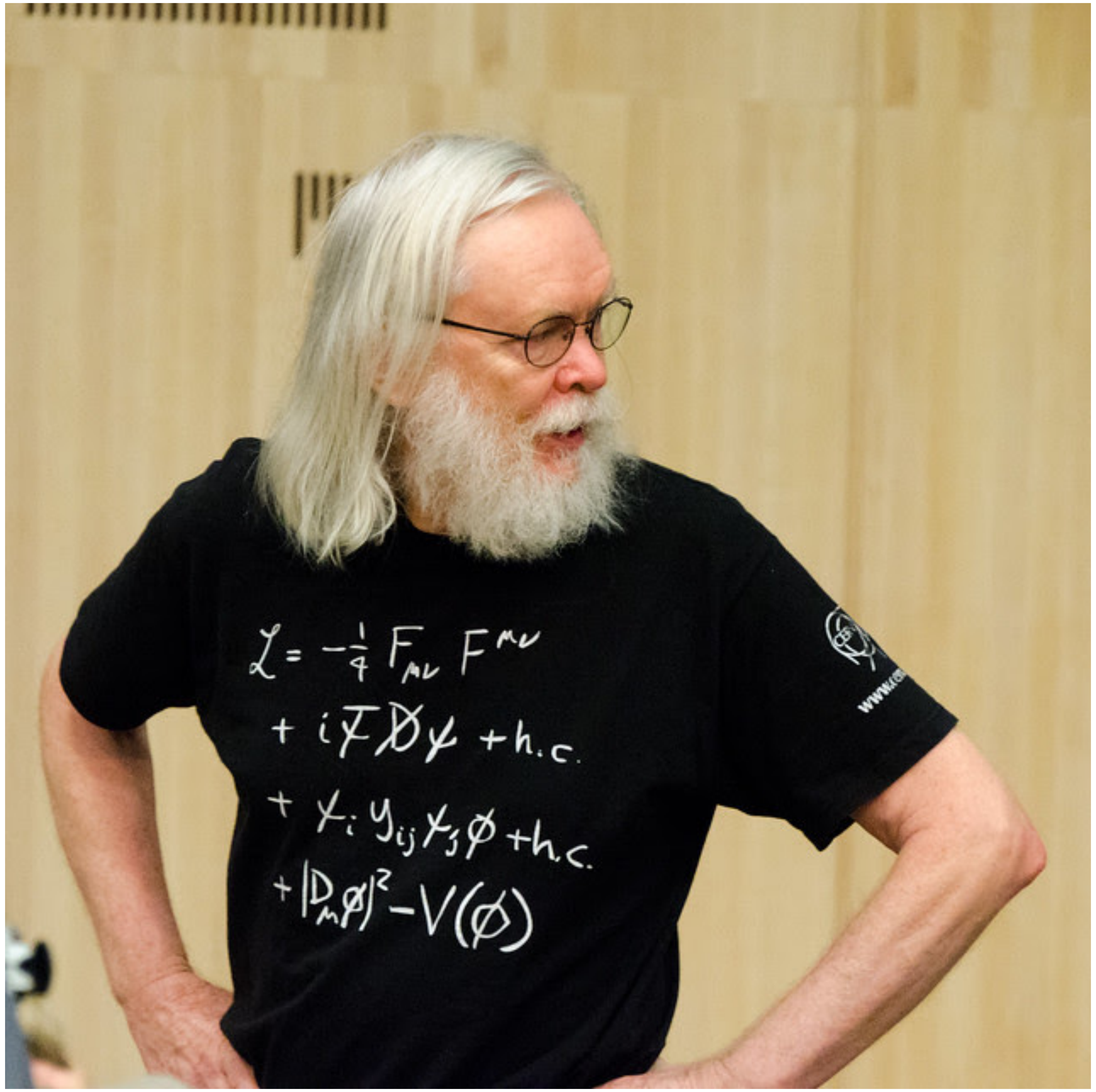
RELATIONS AMONG SOLUTIONS

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} -1 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} -1 \\ 0 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Solutions of these equations related by $O = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ Every possible O are manifestation of symmetry

Symmetry of fields

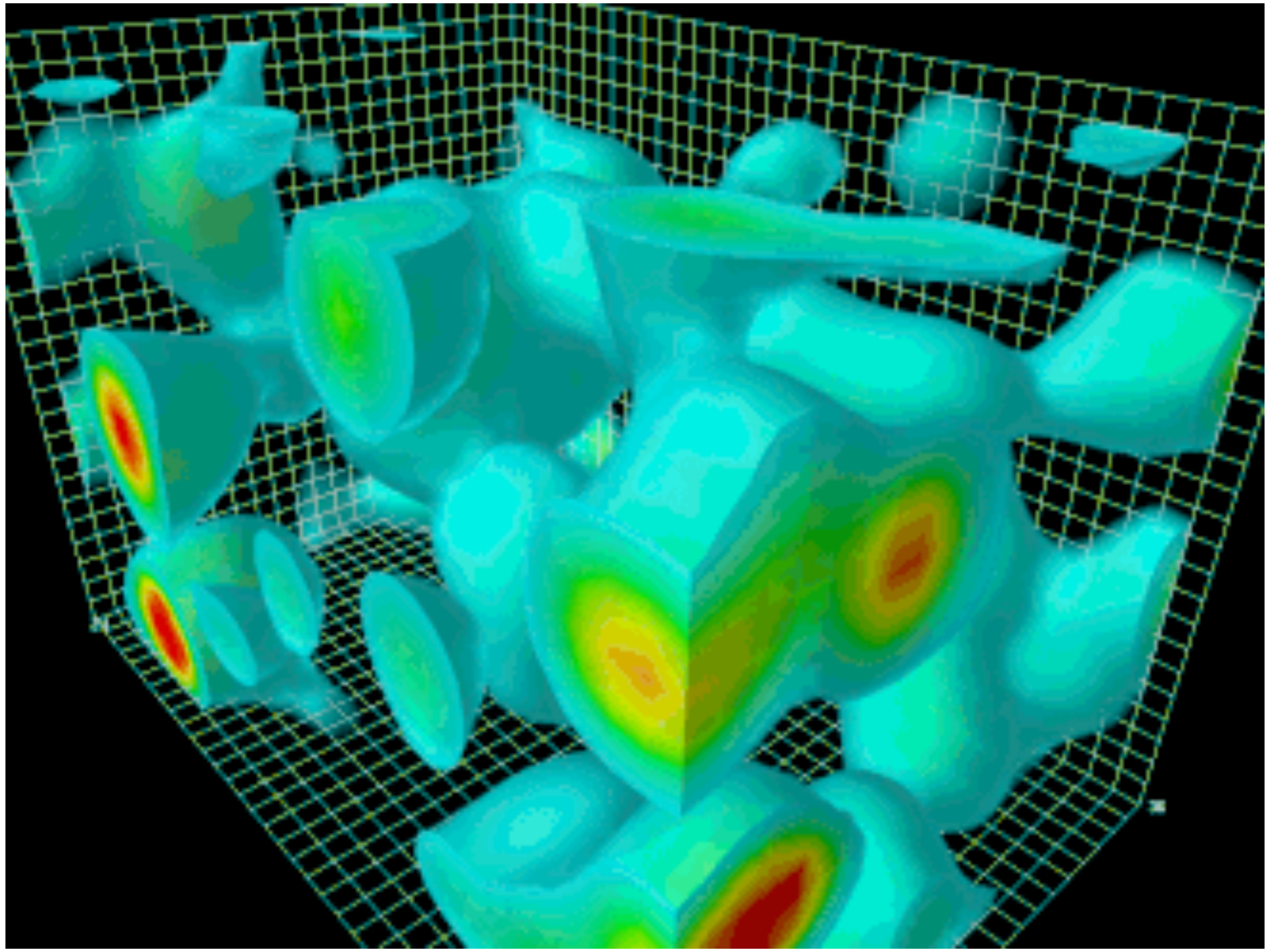


Find solution of $F_{\mu\nu}, \psi, \phi$ from J. Ellis shirt

- High temperature (free quark)
- Low temperature (proton)

Then compare how many matrices O that relates solutions in these two regimes

So what went wrong?



Find solution of $F_{\mu\nu}, \psi, \phi$ from J. Ellis shirt

- High temperature (free quark)
- Low temperature (proton)

This regime is absurdly difficult

There is also a theorem that symmetries we found in high temperature phase cannot be broken in a "good" quantum system

C.Vafa & E. Witten Nucl. Phys. B 234, 173 (1984)

Then compare how many matrices O that relates solutions in these two regimes

What's the point of all these

This whole idea of comparing proton to solid is simply wrong.
We need entirely new way to think about it

Or there might be new symmetry we didn't know about!

Proton is still heavy and we haven't seen any free quark. So...

Thank you!

Further reading

- Ideas on symmetry breaking in proton

  - G. 't Hooft, *On the Phase Transition Towards Permanent Quark Confinement*, Nucl.Phys.B 138 (1978) 1-25
  - S. Mandelstam, *Vortices and Quark Confinement in Nonabelian Gauge Theories*, Phys.Rept. 23 (1976) 245-249
  - Y. Nambu, *Magnetic and Electric Confinement of Quarks*, Phys.Rept. 23 (1976) 250-253

Mathematicians are also desire rigorous understanding of confinement
See 1 million dollar problem: https://www.claymath.org/millennium-problems/yangmills-and-mass-gap

Also, ideas where confinement is symmetry breaking is realised in a toy model called $\mathcal{N} = 2$ SU(2) supersymmetric Yang-Mills (or Seiberg-Witten model)

- N. Seiberg & E. Witten, *Electric-Magnetic Duality, Monopole Condensation, And Confinement In $N = 2$ Supersymmetric Yang-Mills Theory*, Nucl.Phys.B426:19-52,1994
- For a recent review see, Y. Tachikawa (arxiv:1312.2684)