top quark

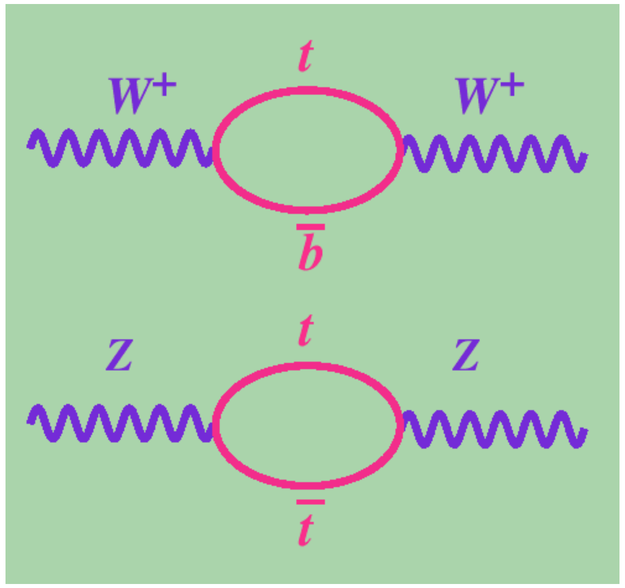
pursuit of the top quark

Because of "vacuum fluctuations" hints about top quark were found in very, very precise measurements of a variety of quantities - most notably the mass of the *W* and the mass of the *Z*.

- For 5 years the mass of the W was pursued to a precision of 0.3% by Eric Flattum, an MSU student and myself at Fermilab.
  - There are 2 large experiments at Fermilab, each with international memberships of ~650 PhD's each. MSU is in both.
  - *The mass of the Z had been known to a precision of about 0.1% by work at CERN...*

So, we had the information to box-in the mass of the top quark

- *In the first days of this effort, many thought that the mass of the top quark might be as much as* 40 GeV*...then the precision measurements began to emerge*
  - firm lower limit of *80GeV* by 1989
  - the direct searches began to raise that lower limit a bit at a time, until we knew that it had to be larger than *130GeV*!



This is very exciting - the Standard Model goes right to the heart of what it means for an elementary particle to have mass. The W and Z are crucial to this argument..

- and here's a crummy quark with a mass significantly larger than them!!

1995: Discovery of the top quark

The two experiments at the Fermilab collider frantically searched

- We collected data for three straight years of running, 24 hours a day, 7 days a week.
- An intense analysis effort actually kept up with the data-collection...

  including another huge effort of simulating the experiment in computer codes which actually take longer to run than the data take to collect!

  must simulate all scenarios, true ones, as well as possible fake ones
- DØ, our experiment, found a single event and published it in 1992...

  suspicious, but one event is not definitive
- CDF, the other experiment, thought they had "evidence" in spring of 1994

  published it, cautiously - the rate of production was too high, according to expectations by x2

discovery

In the winter of 1994-95 we began to think we had it, led by Harry Weerts, an MSU professor

We thought we were on to something and wanted to be first, but we needed to be sure

- that meant 2 months of furious argument, calculations, writing, and yelling
- “Was it background?” “How significant was the signal?”
- Things fell apart, and came together over and over.

The laboratory management and Department of Energy were monitoring both experiments’ progress and managed to let enough information leak in both directions that the pace to announcement was similar.

Observation of the Top Quark

The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat) ± 10(syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

finally

On Friday, February 24, 1995, after a week of shared information, the discovery was announced and two papers were submitted to the Physical Review Letters.

- The earlier CDF "evidence" was partially correct, but there was a mistake which made the rate too high
- The D0 first event, indeed, turned out to be Top - a near-perfect event.

The mass of the top, is huge. Originally:

- CDF: $m_t = 176 \pm 8 \pm 10$ GeV/c^2

  27 events over background of 7
- D0: $m_t = 199 \pm 20 \pm 22$ GeV/c^2

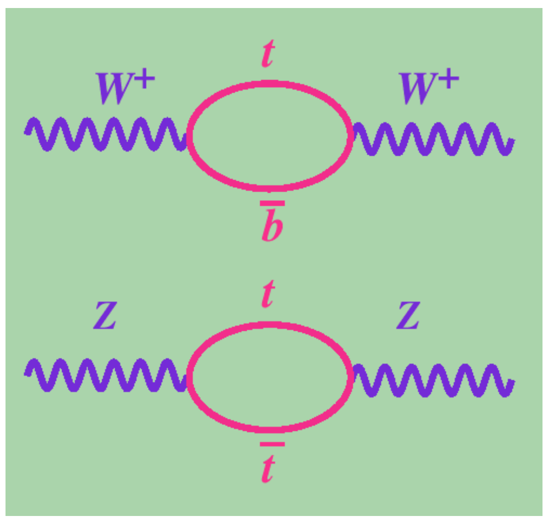
  17 events over background of 3.8

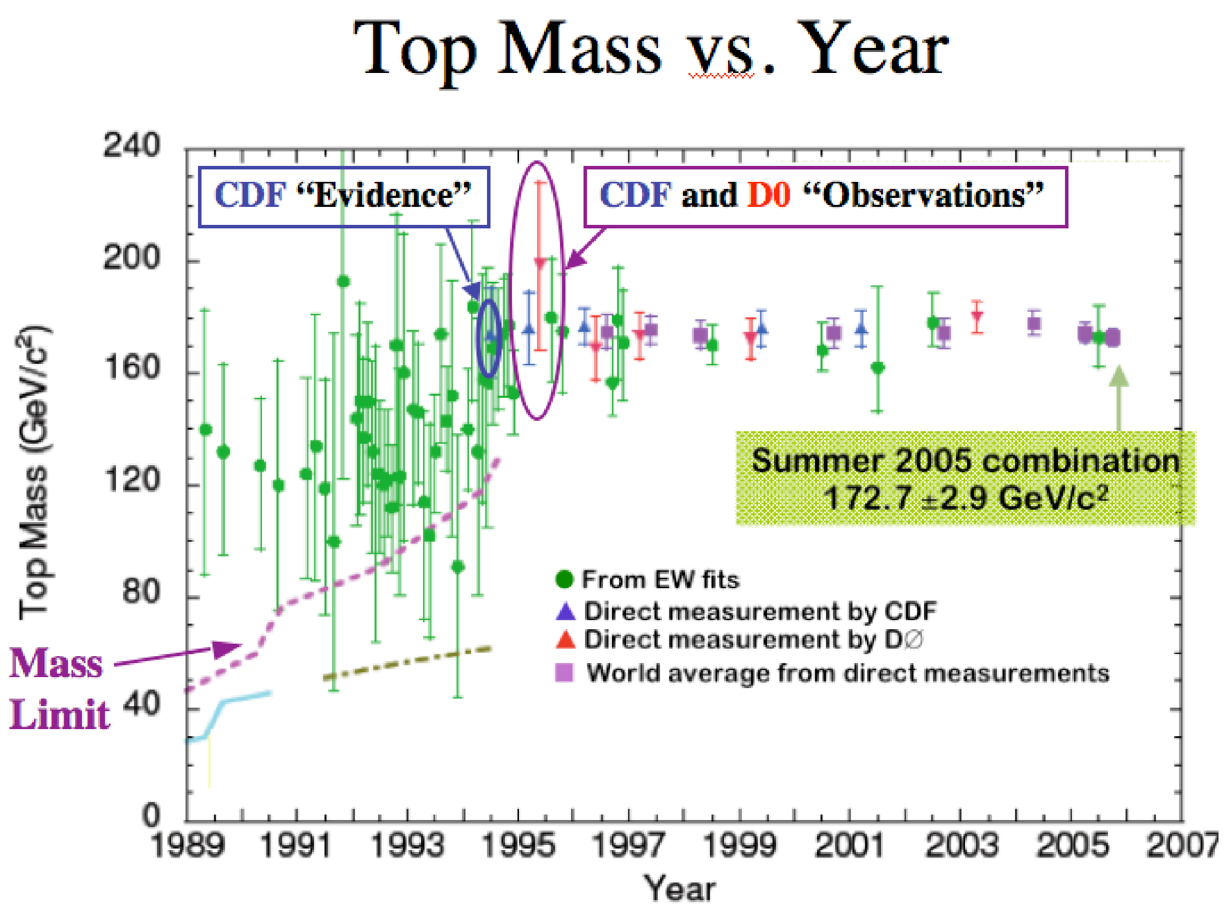
Subsequently, we had more data and better analyses. We now believe:

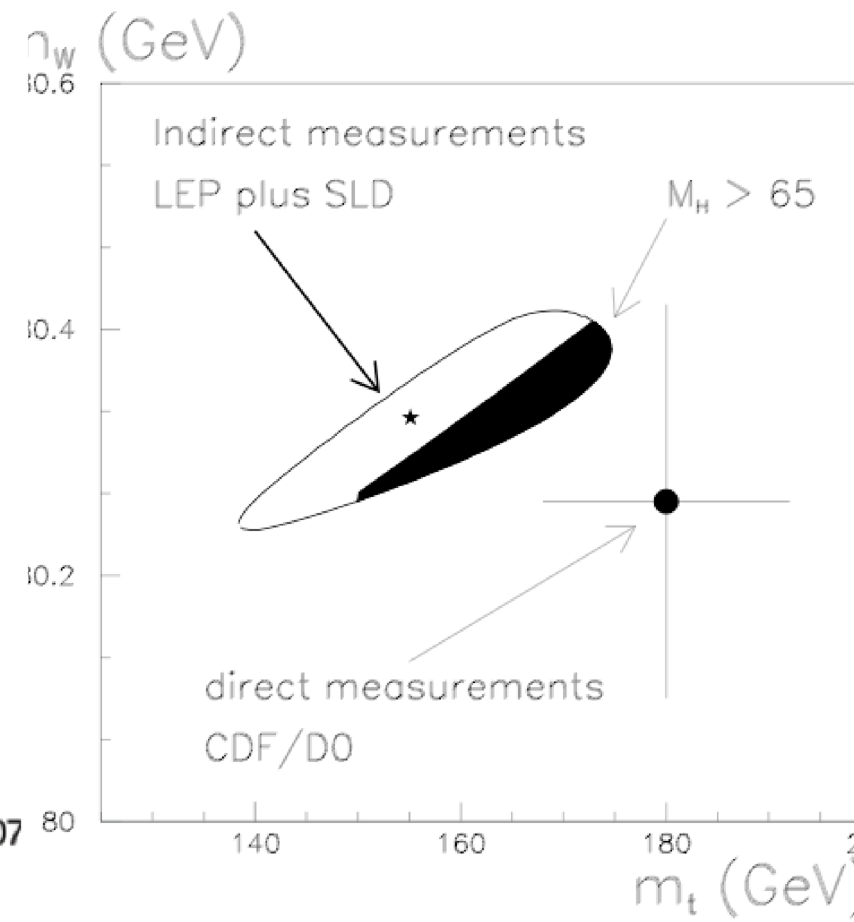
- $m_t = 171.4 \pm 2.2$ GeV/c^2
- roughly the mass of a gold atom...

Now, we study top quarks in bulk...

predictions of the top quark mass abounded







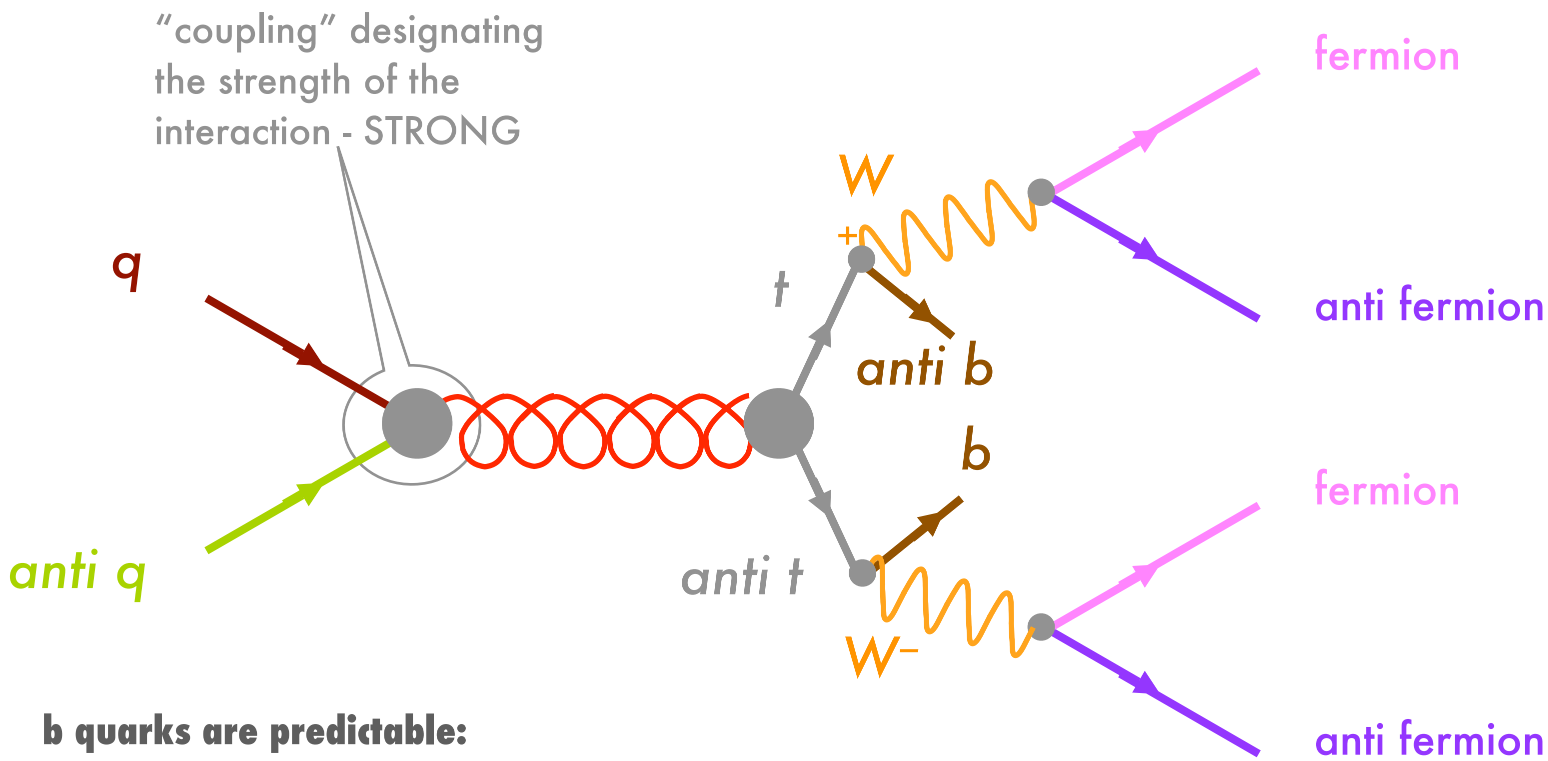
Peter Renton, Oxford
1995

So, if the theory is correct…then the top quark will be the mass of ~180 protons…and at Fermilab they would have to be produced in pairs - so, need to make 360 protons' worth of mass

Here, $E = mc^2$ comes to the rescue!

Our colliding beams are each 1000 protons' worth of energy, so we can manifest heavy few objects traveling slowly…out of the available total energy of the beams

top quark production and decay



The W products can be:

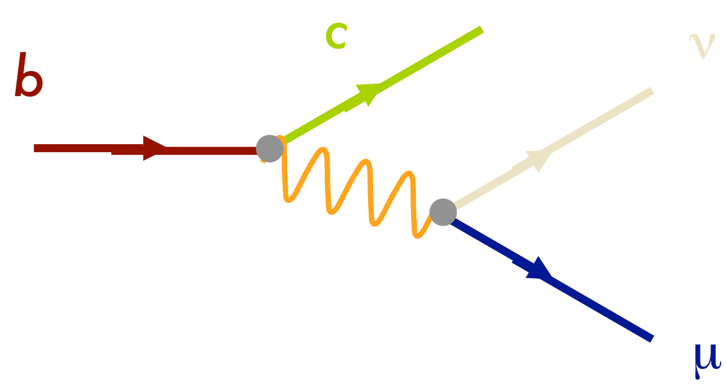
quark + antiquark

electron + electron neutrino

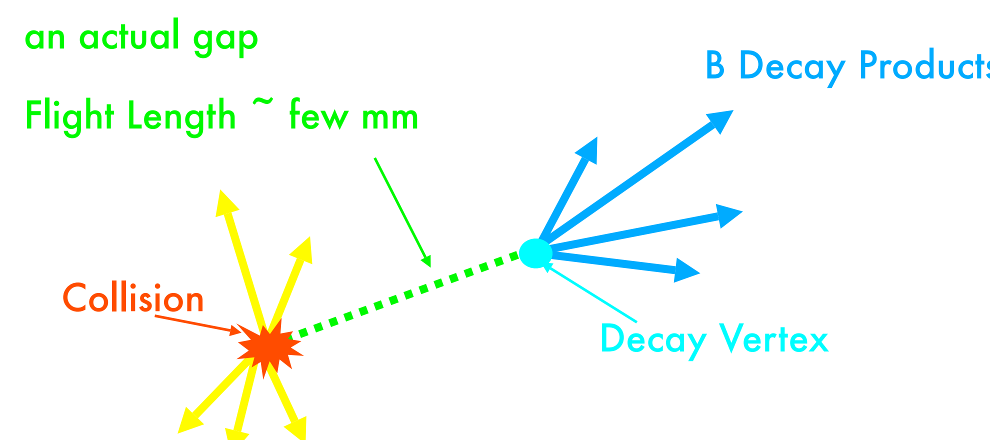
muon + muon neutrino

tau + tau neutrino

b quarks are predictable:



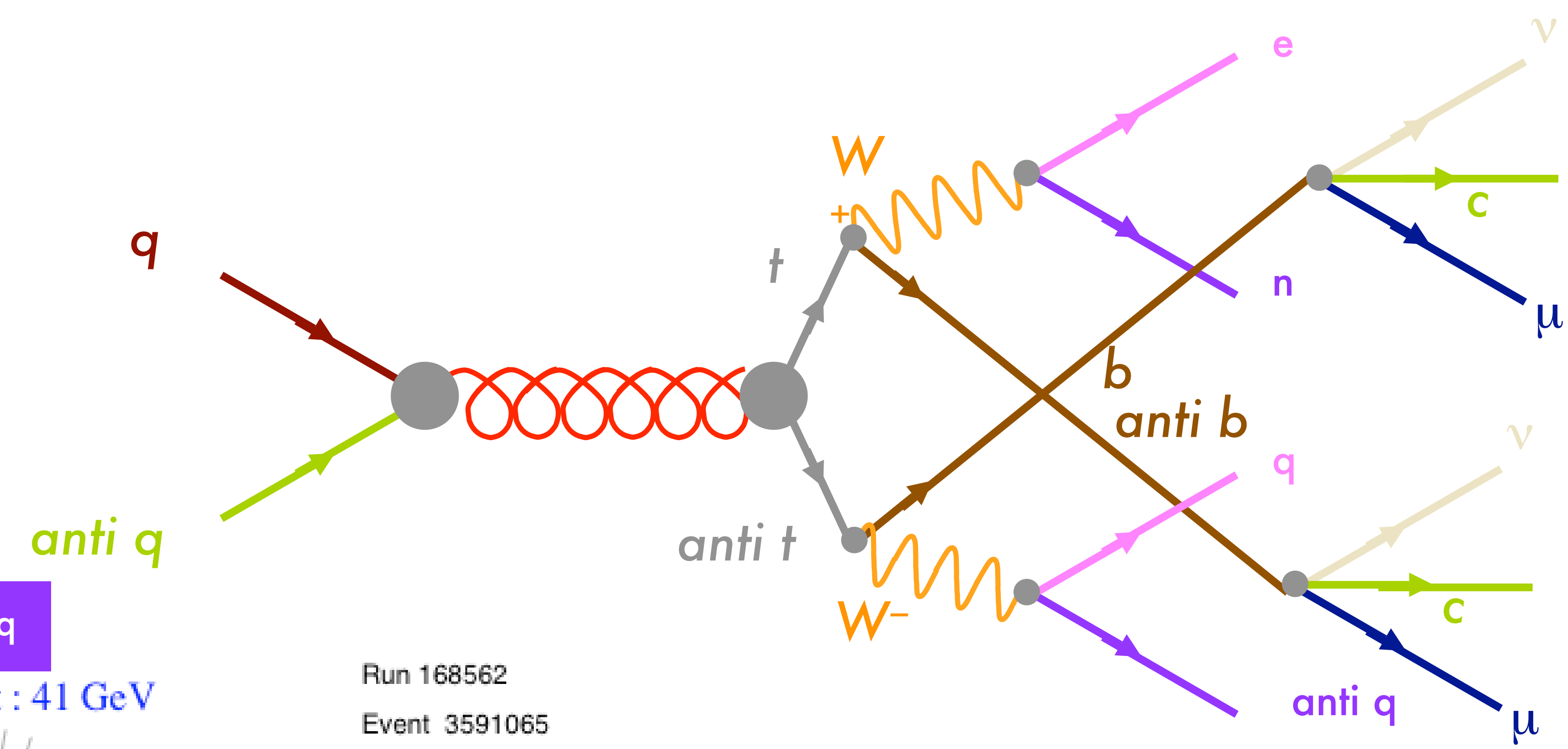
but they also decay visibly

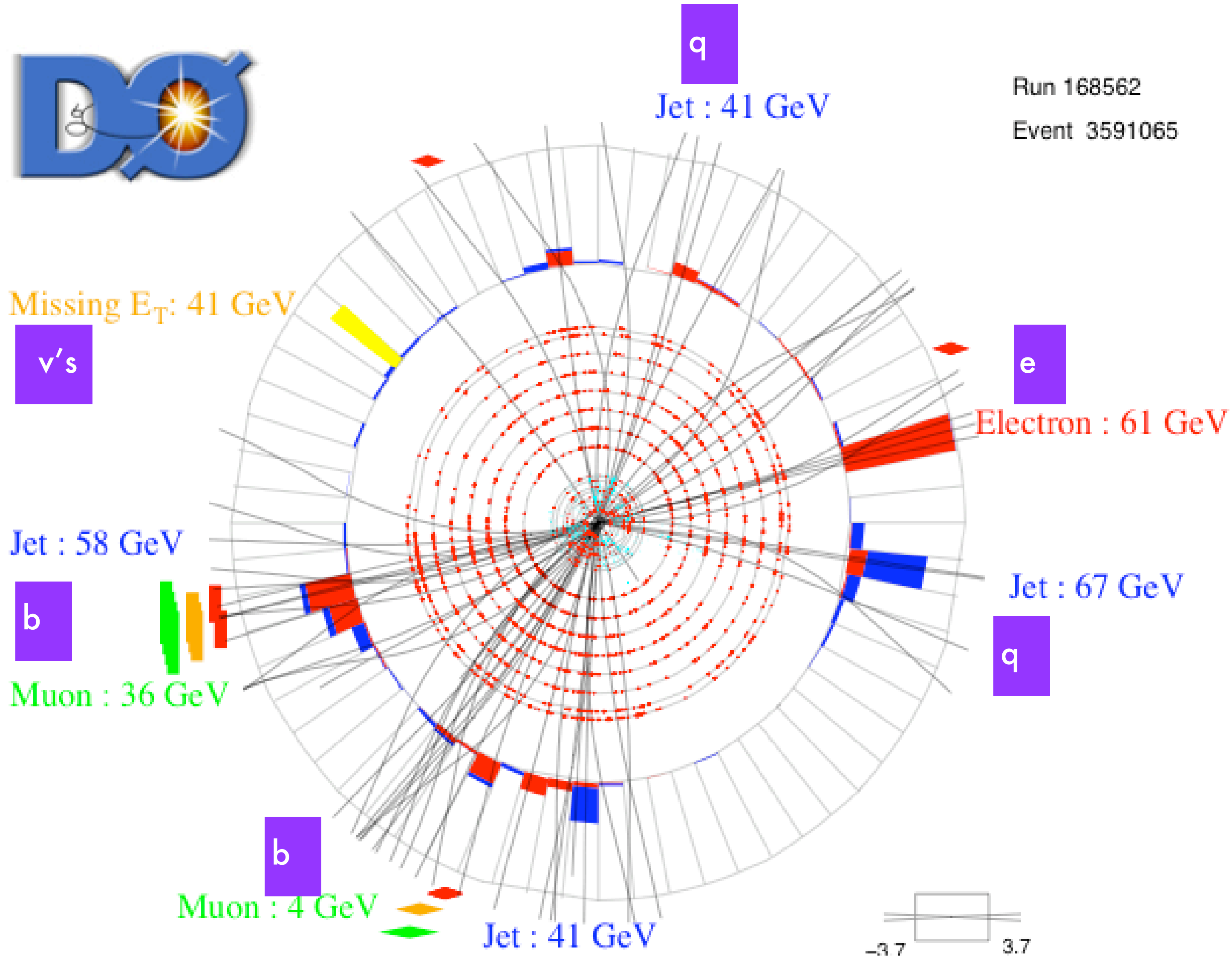


The highest probability scenario is:

one W decays to quark plus anti quark …this produces hadron jets

one W decays to electron plus neutrino





what's produced in the final state:

electron → electron shower	one W
neutrino → nothing, missing E/p	
quark → hadron jet	other W
antiquark → hadron jet	
c quark → hadron jet	one b
muon → track in iron magnet	
neutrino → nothing	
c quark → hadron jet	other b
muon → track in iron magnet	
neutrino → nothing	

at Fermilab, we own the top quark

We will collect thousands of top quarks

- with all characteristics measured

  Why is it so massive?

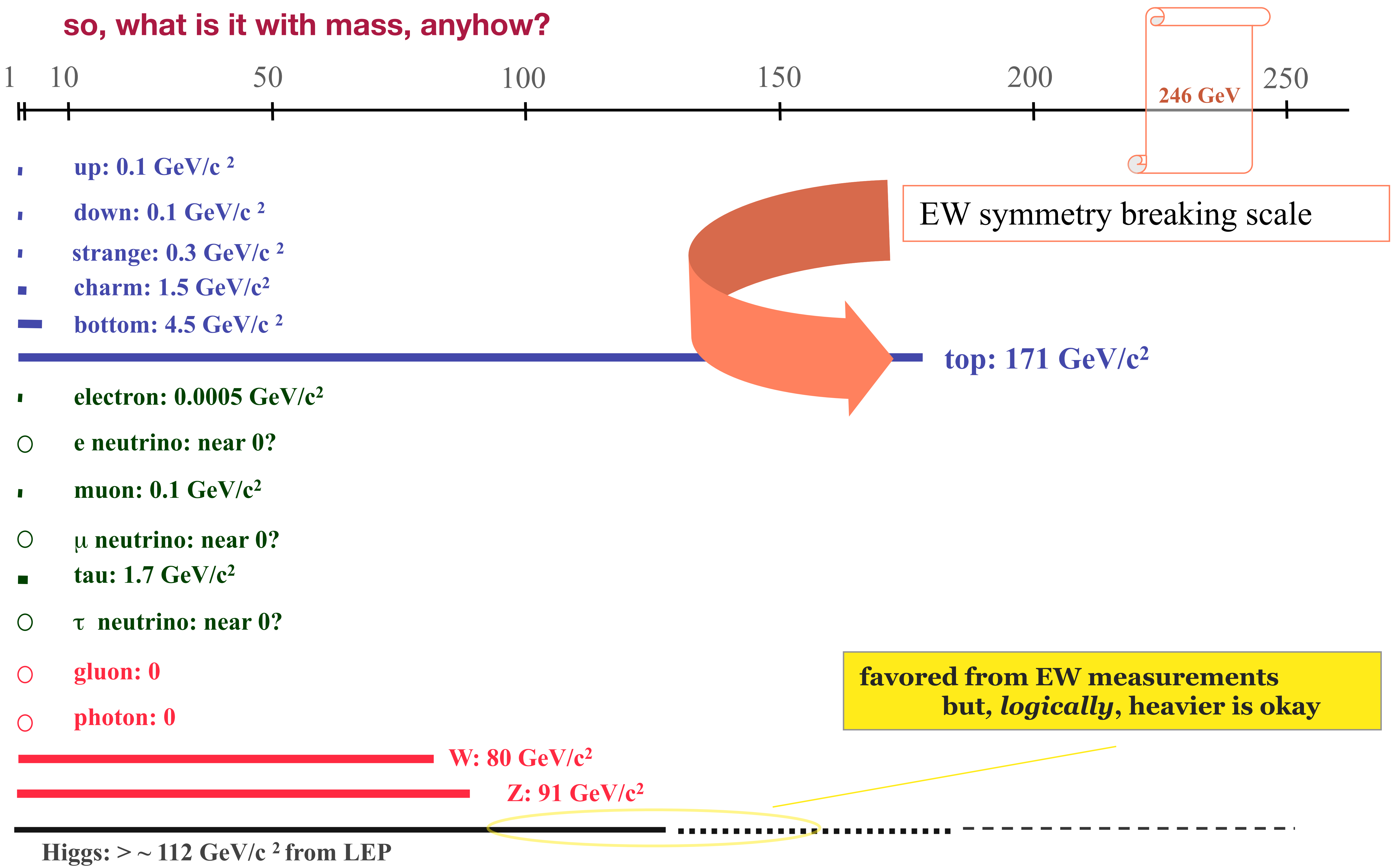
  Are its decay characteristics what we expect?

  Could its mass be a hint of something unusual?

It’s a living, okay?

The puzzle: masses

so, what is it with mass, anyhow?



The Higgs Boson

The Higgs particle is central to this…and relevant to the old questions of the ether - here's a poor analogy to what the mathematics suggest -

- Suppose you are viewing someone walking up the stadium steps from far off

  they are proceeding briskly, but suddenly they slow down and I ask you to tell me from what you remotely observe whether

  a. The steps abruptly got sticky or

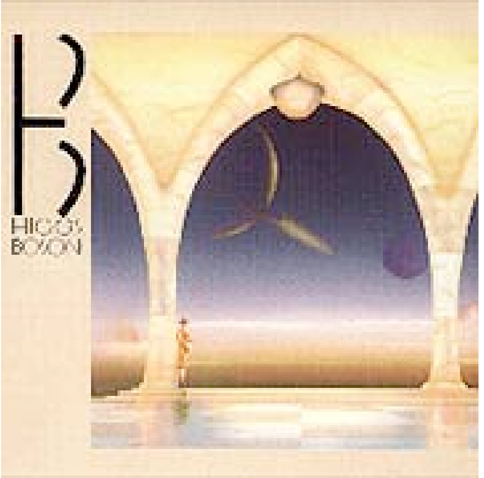
  b. The climber suddenly found her pockets full of lead (forget how for the sake of argument!)

  An increase of the climber's mass could be <u>indistinguishable</u> from having to slog through a sticky, viscous environment

The Standard Model presumes an early universe in which the stairs are clean (or the pockets, empty) - all massless particles

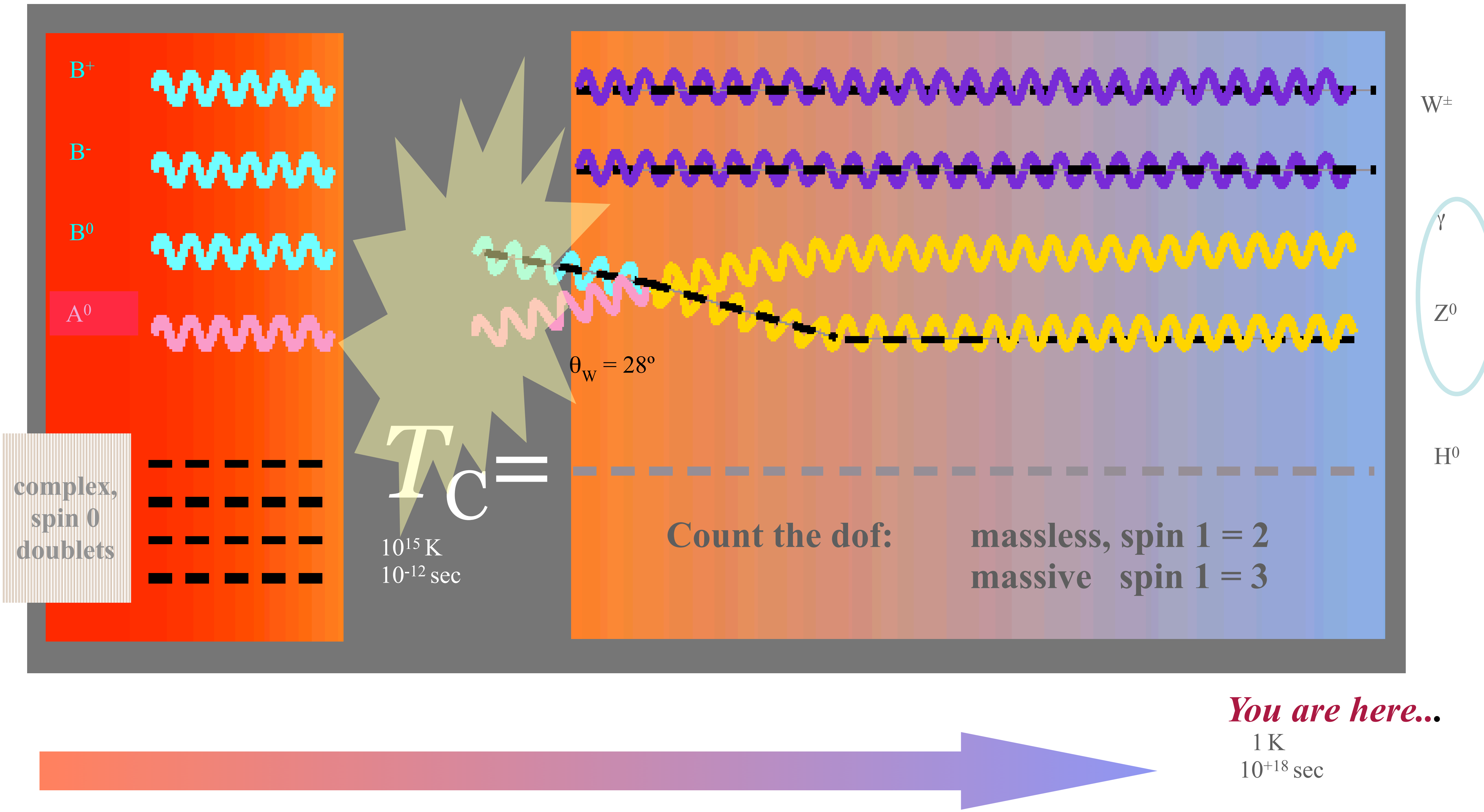
- However, something happens and the medium through which all particles move essentially <u>becomes quantum mechanically "viscous"</u>

  We see this as the creation of the massive particles - W and Z



The phase transition...

A useful way to think about things: think back...*way* back



Unraveling the vacuum

The Vacuum.

- The model presumes that it is not empty

  Rather, like the old days, that the vacuum is full -

  of a special particle called the Higgs particle

- The Higgs comes about, so the story goes, because everything in the universe underwent a phase transition like Ferromagnetism, Superconductivity, Superfluidity, etc. long ago

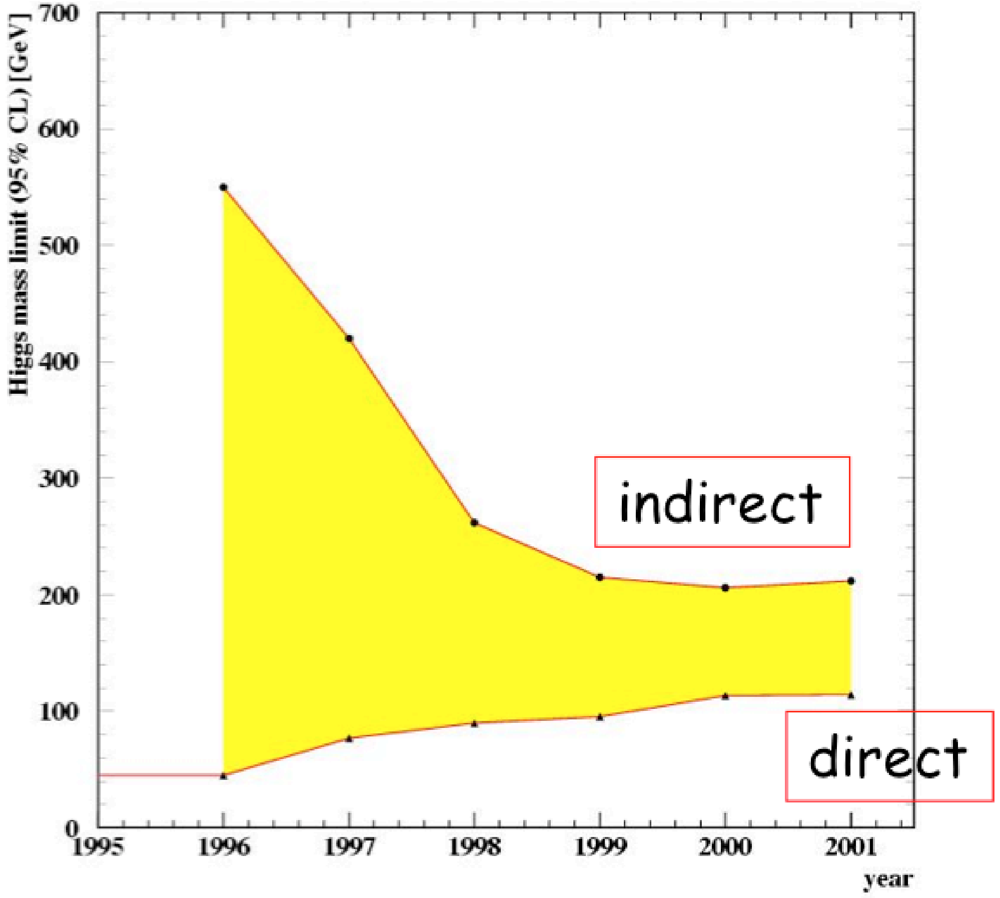
  Before this, the weak and electromagnetic interactions were identical and the ancestors of the W *and* Z *had no mass*

  After this, the two interactions separate into the distinct forces of nature that we measure in our currently cold universe

The model makes predictions regarding the relationships among the masses of the *W*, the *Z*, the Higgs, and all quarks -

- especially the heaviest ones, bottom and top
- The apparently large top mass plus the ability to measured these correlations form the most important experimental problems today.

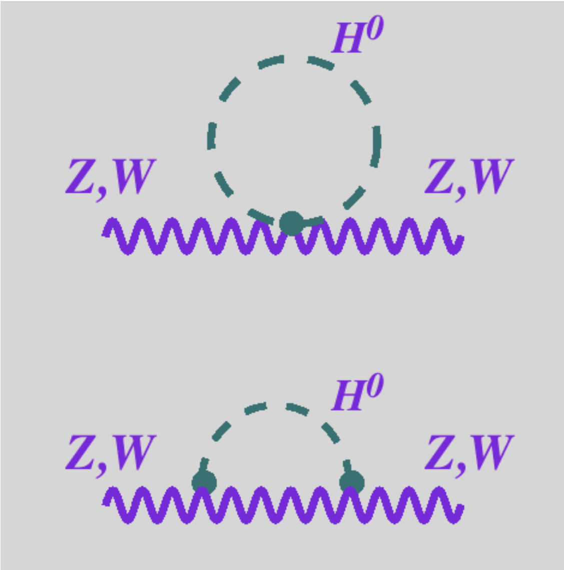
doing it again: The Higgs Boson

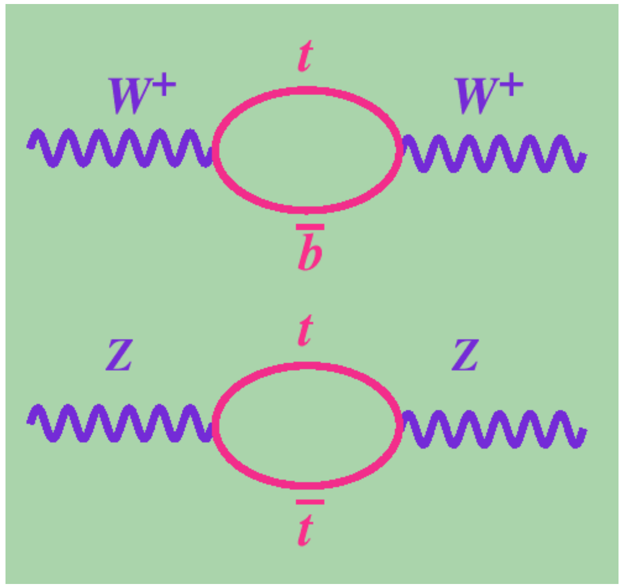


…through its interactions

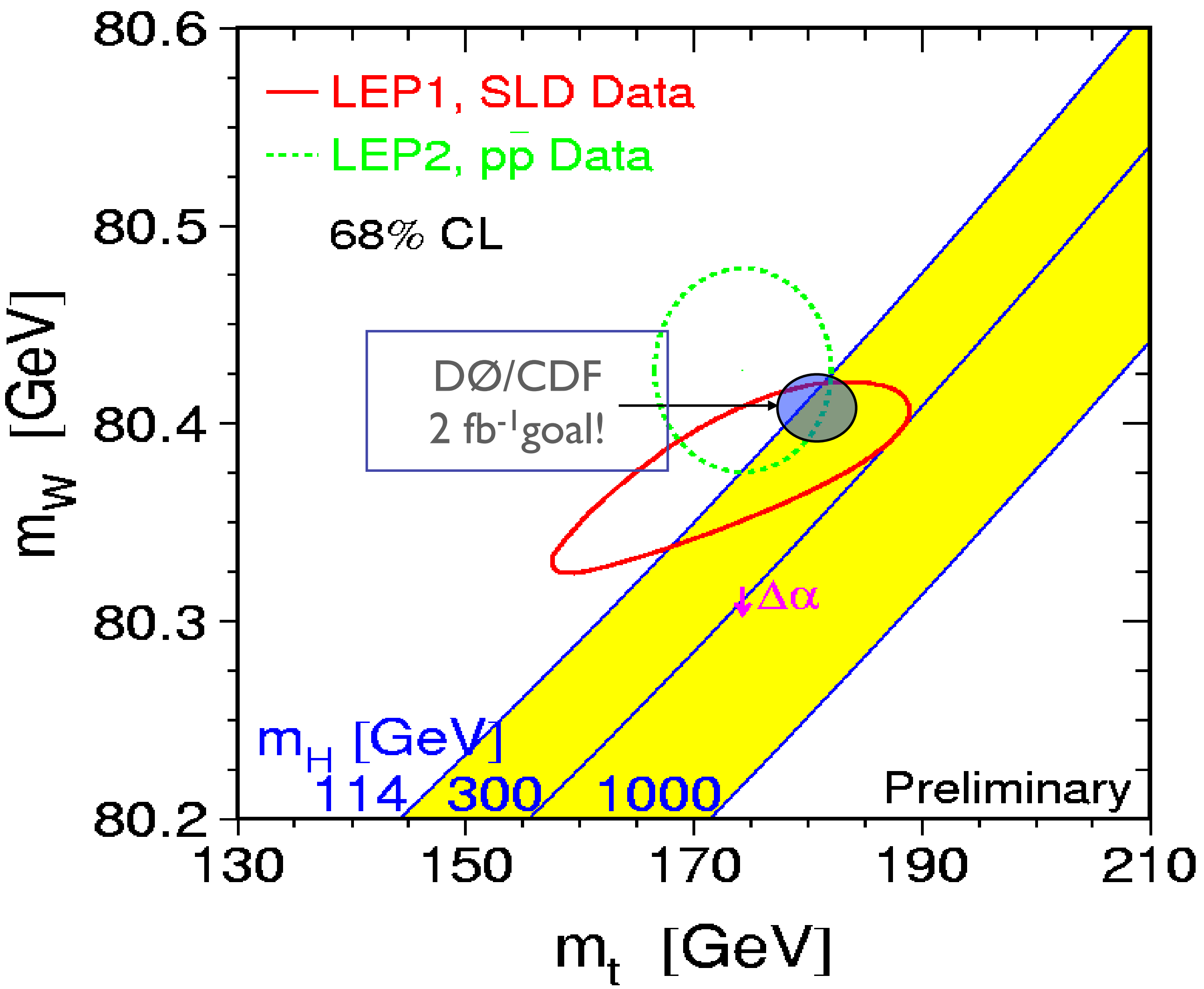
- gives mass to all particles (we think!)
- We're looking for the Higgs boson, but have not found it yet

the quantum loops help us to narrow it down





The theory correlates the masses of the top quark with that of the W boson



HIGGS Contribution ~ $\ln(m^2_{Higgs} / M^2_W)$

How we know where to look

Masses come from the Higgs Mechanism. An analogy:

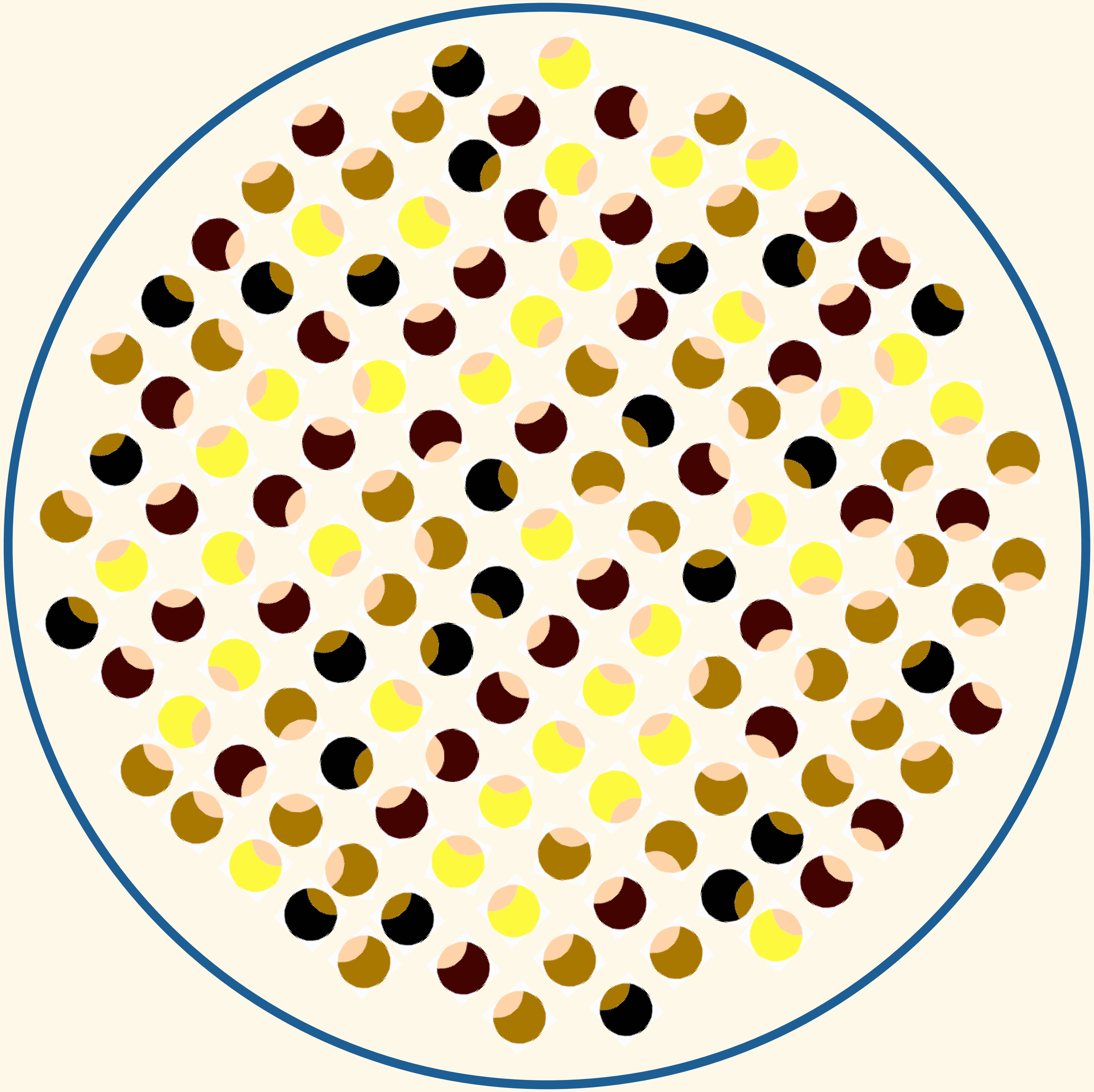
a room full of people, randomly oriented talking…

the noise (energy level) in the room is constant and forms a background (ground state) energy which is largely ignored by each member in his individual conversation

There is no ordering to the orientation of the people - a highly symmetric configuration

The room is the vacuum.
The people are collectively a higgs boson field.

…the ground state energy level is unimportant and tuned out

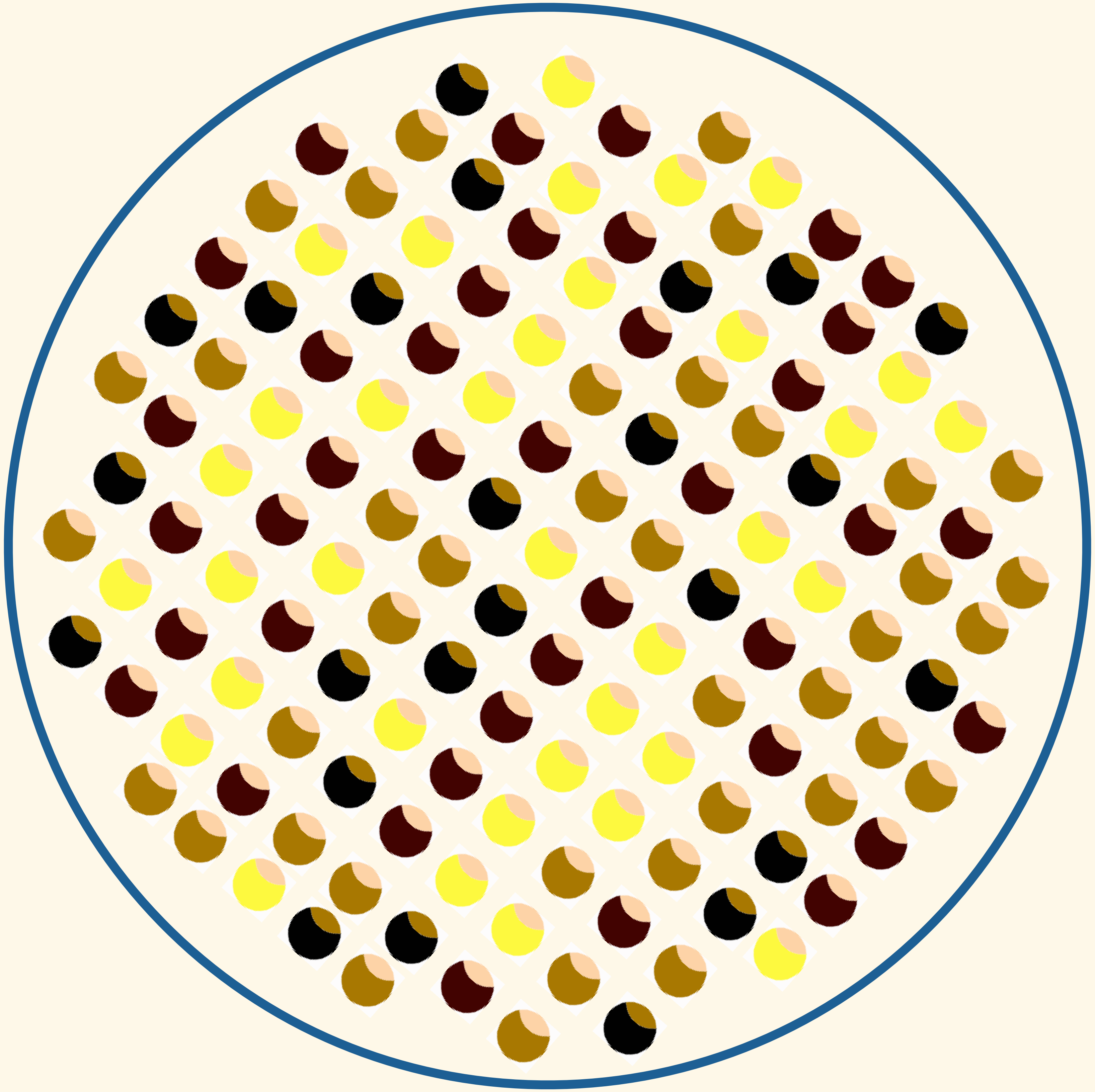


(after David Miller)

sleigh bells ring from the NE corner of the room…

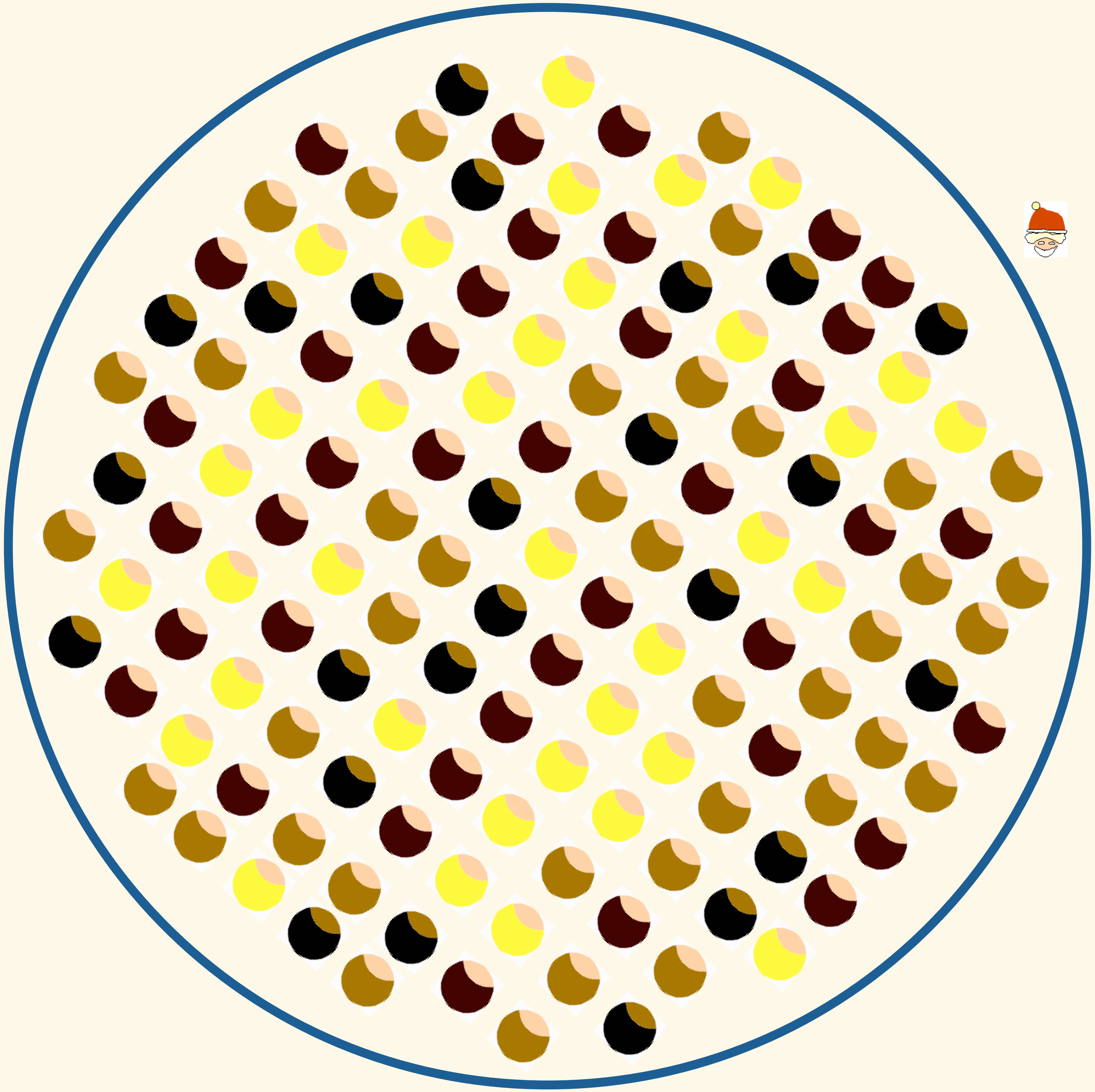
everyone turns to the sound and is immediately silent - so, the energy level in the room is lowered when the randomness is removed

The earlier symmetry is “broken”



Santa appears

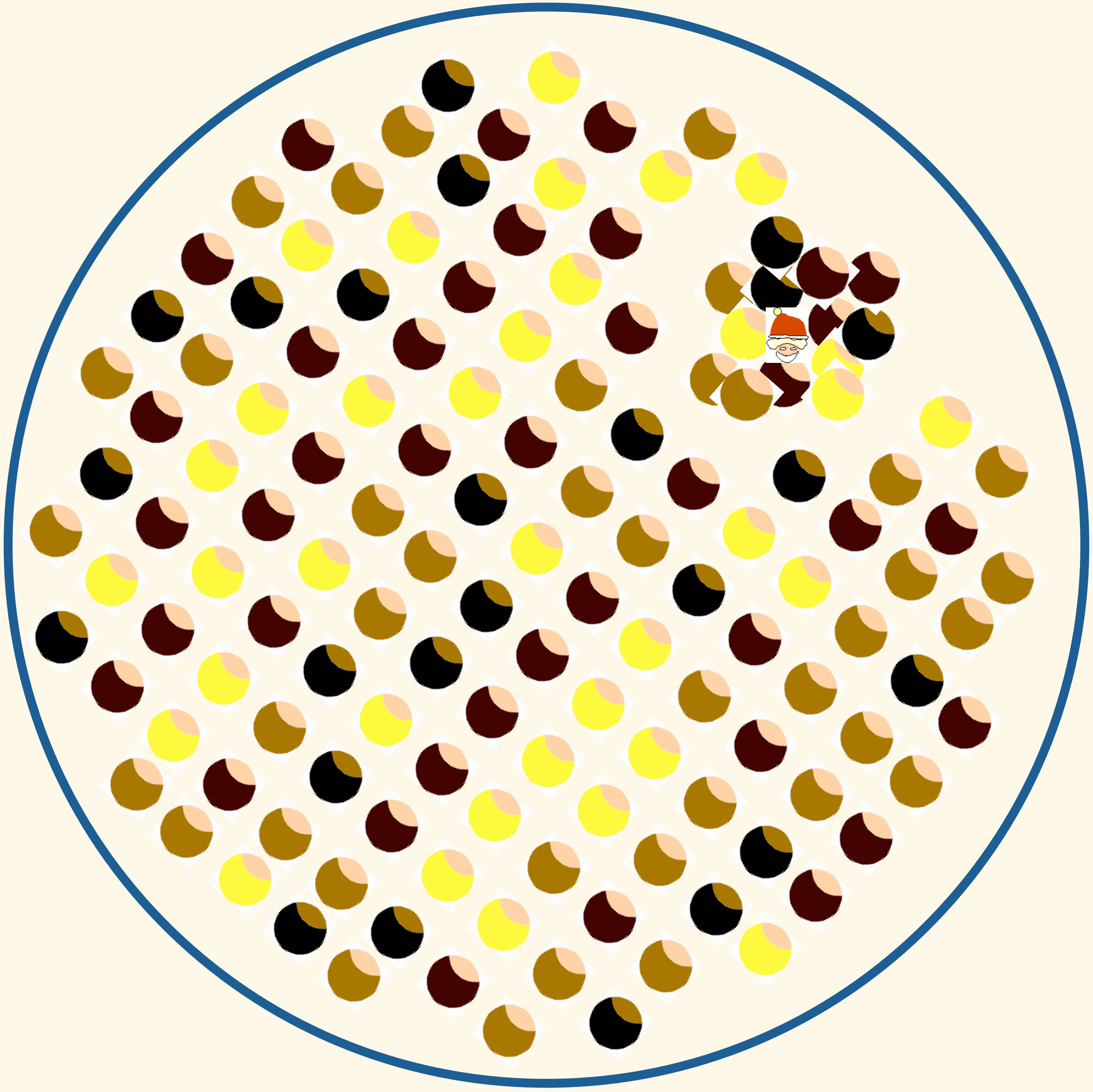
Santa is a W boson.

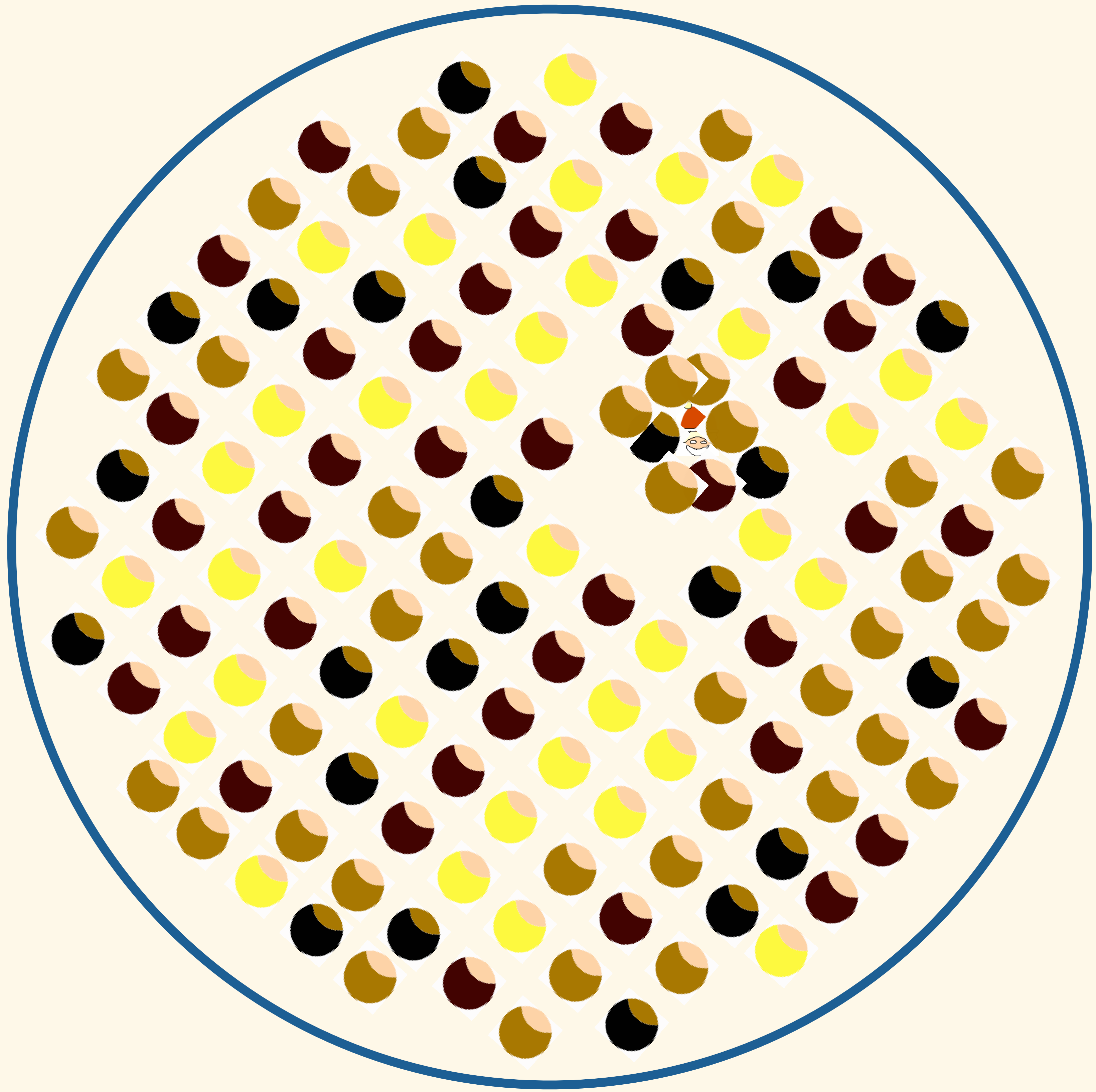


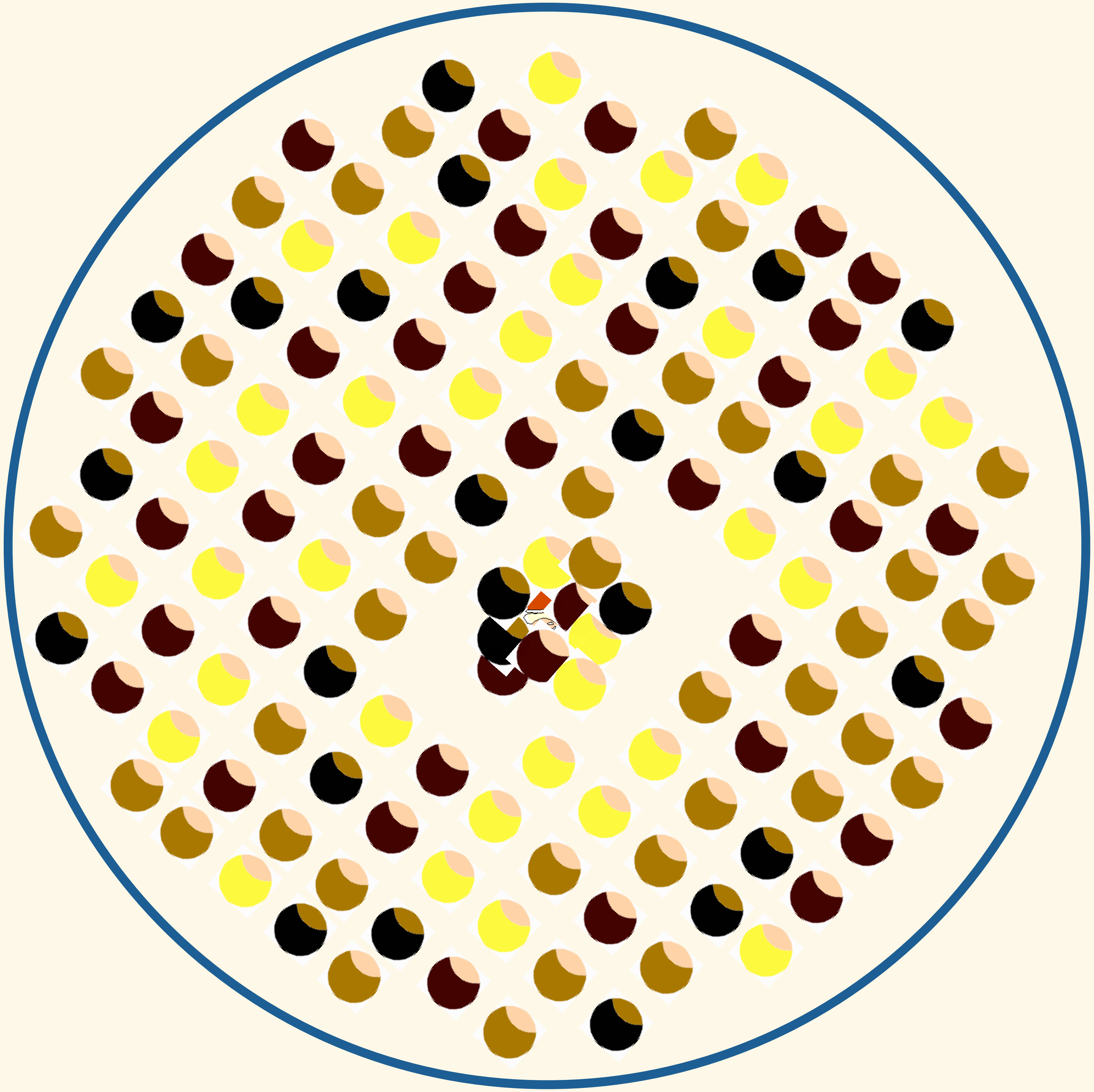
Santa enters the room and attempts to make it across...

his progress is impeded
as if his inertia has increased

ie, as if his *mass* has
increased by virtue of his
interaction with the people
around him.







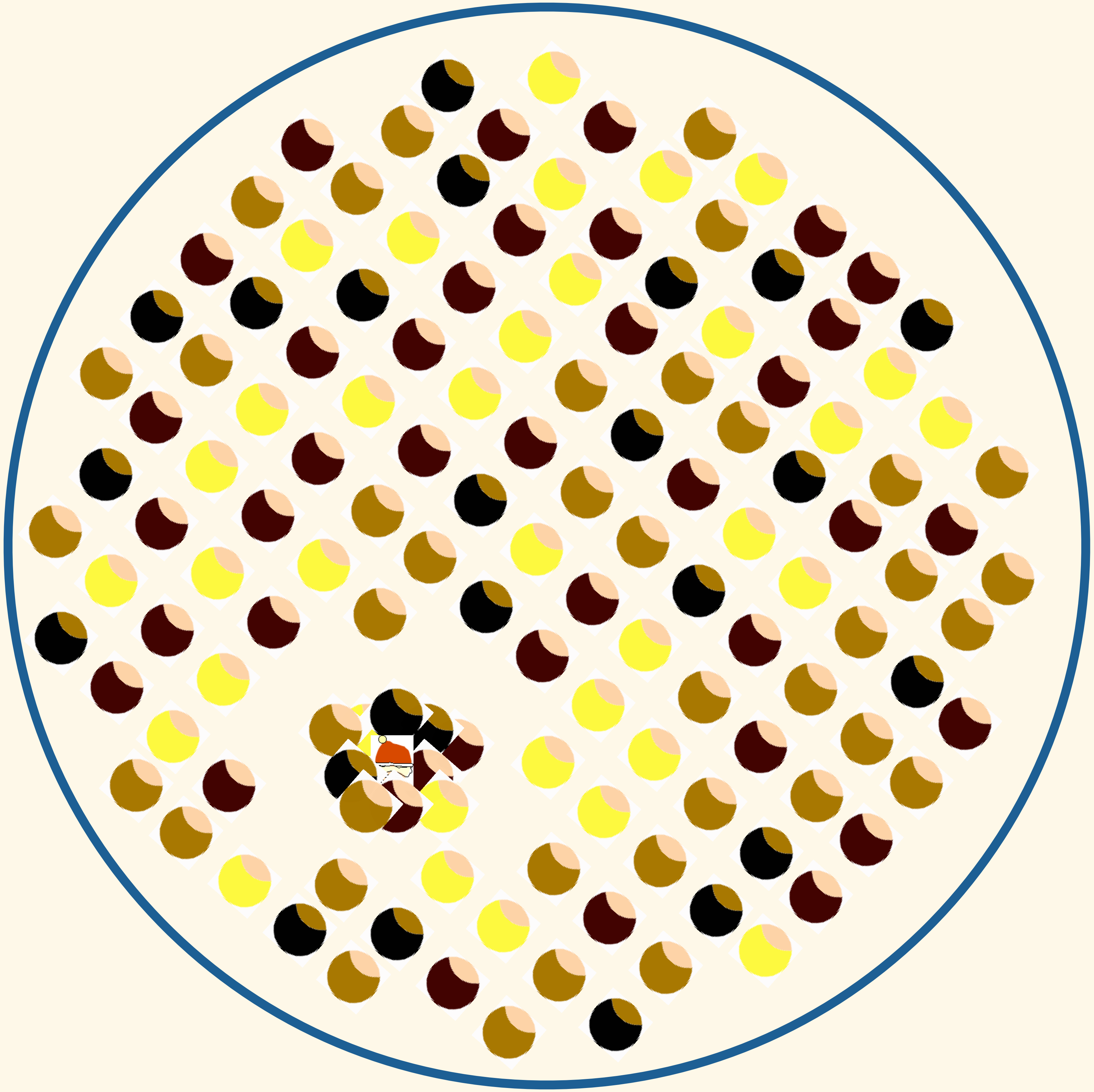
This is the generation of mass.

The circle is the Universe

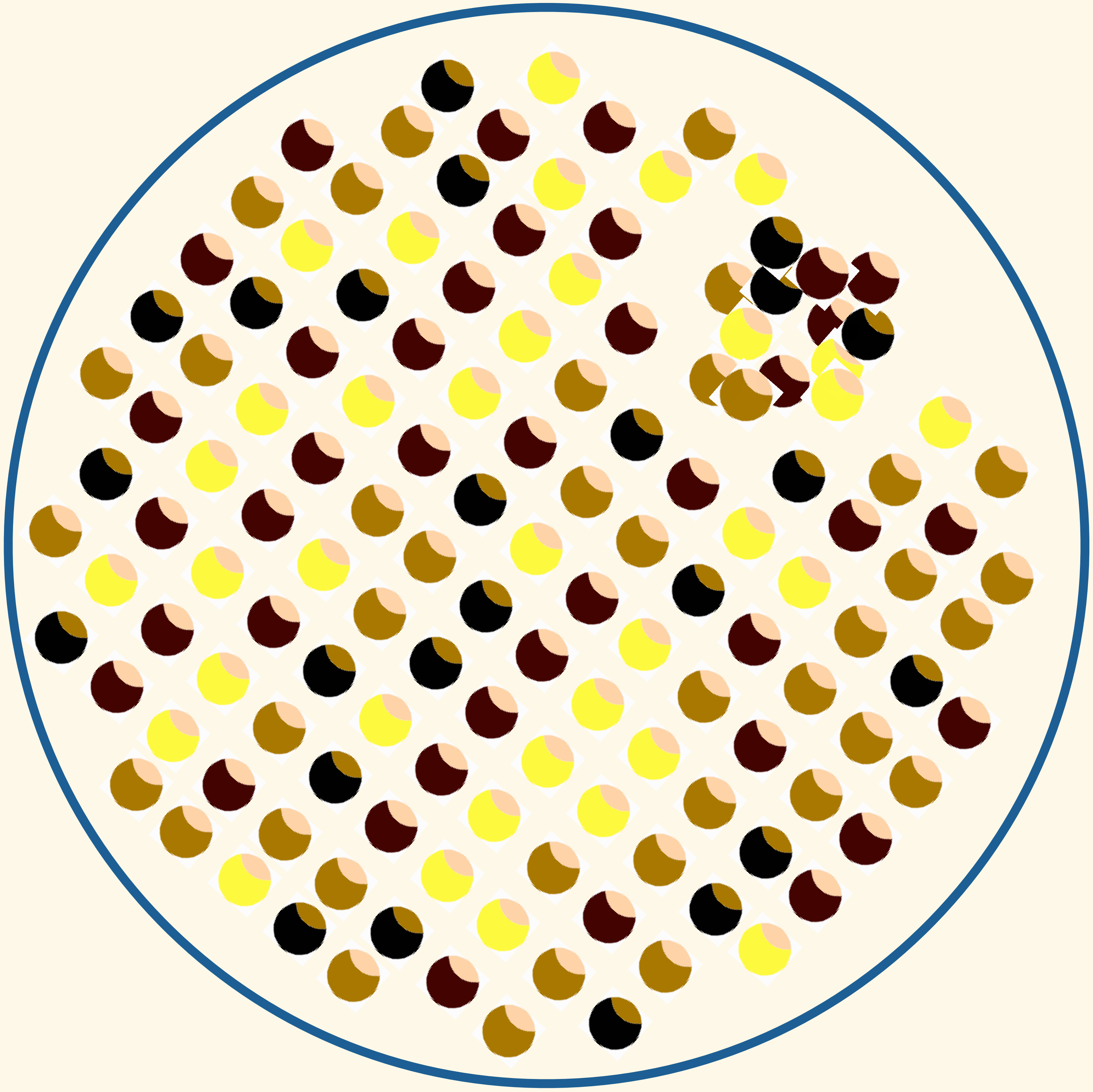
The people are the analog of the Higgs field, triggered by the phase transformation inherent when they turned NE and lowered their energy.

They give "mass" to Santa (particles) by interacting with him…

mass is generated by particle's interaction with the Higgs field…in the vacuum.

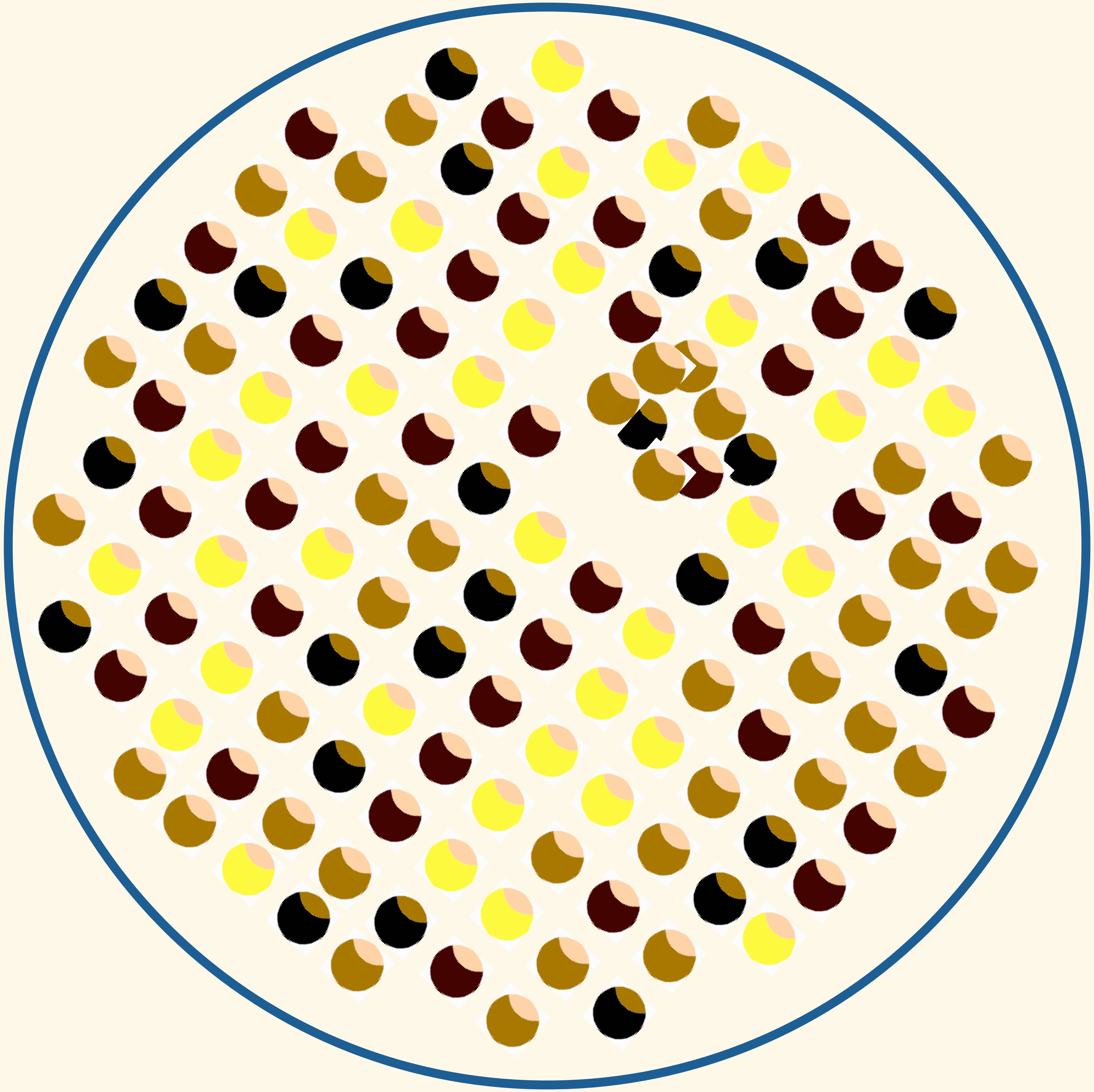


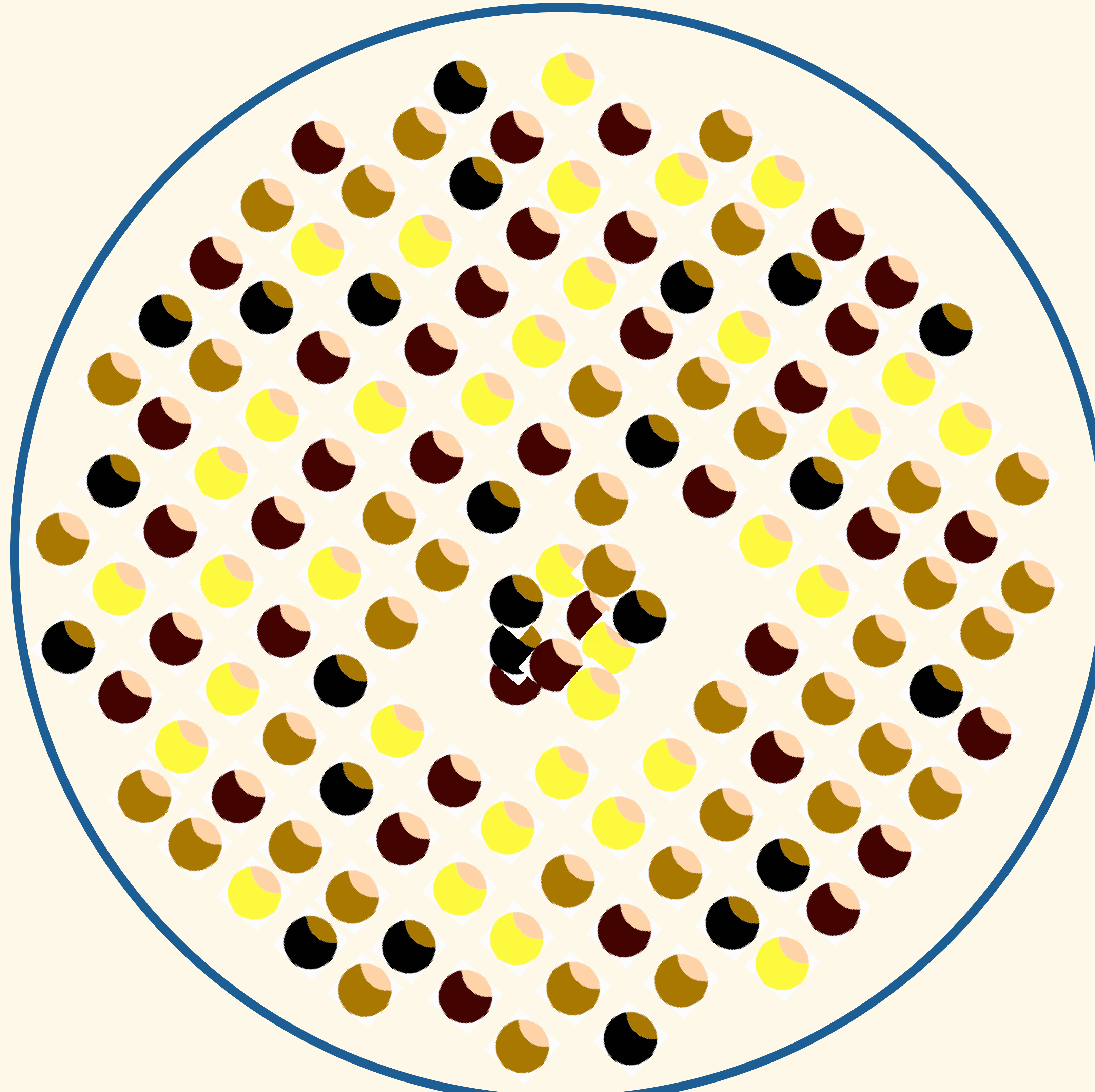
Suppose now, that only the rumor that Santa might arrive starts at the NE corner



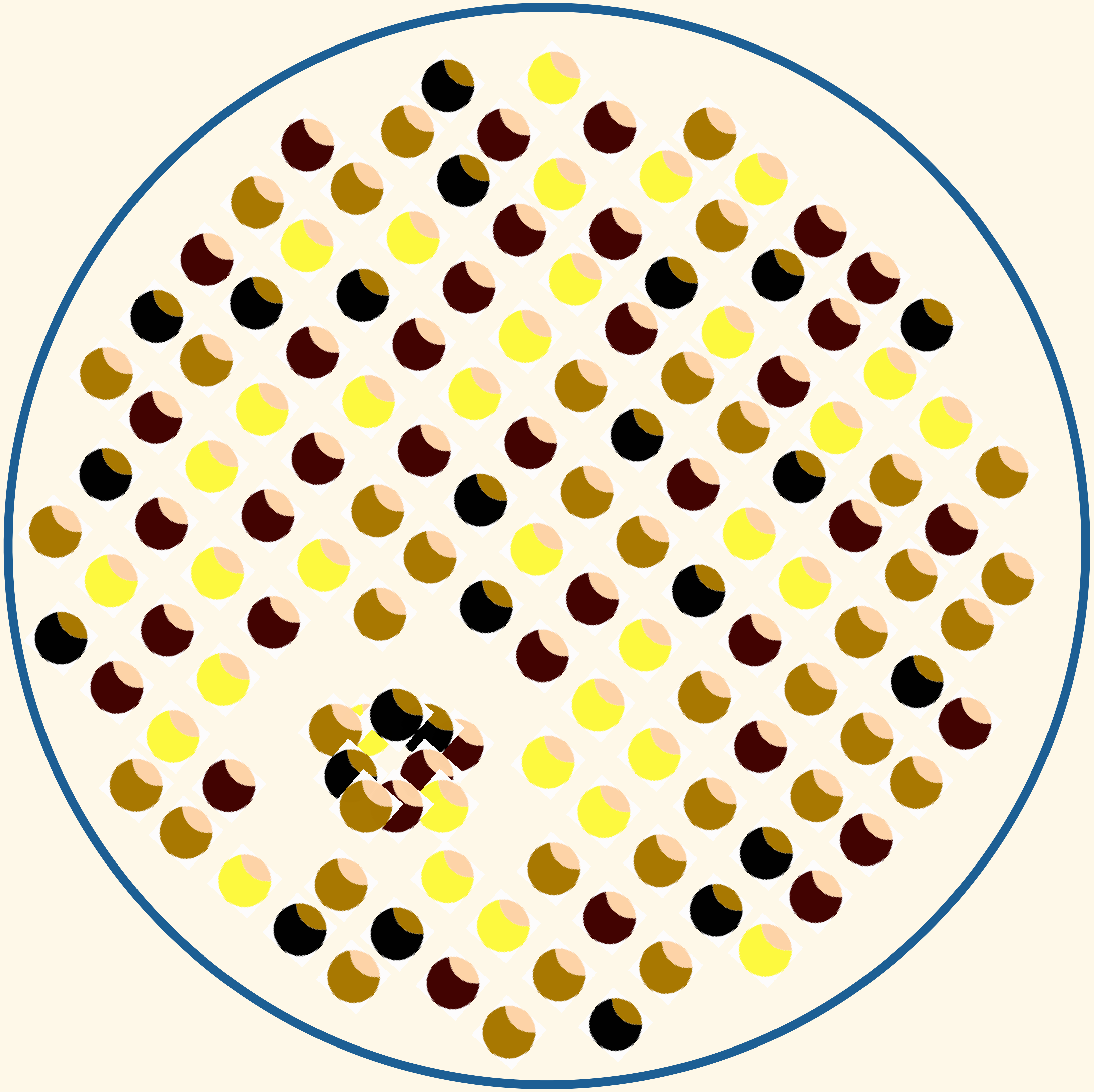
The rumor migrates across the room...

the clustering is the Higgs particle -
the quantum of the Higgs field





Finding the Higgs Boson is of fundamental importance to confirming the Standard Model and the veracity of the phase transition, Spontaneous Symmetry breaking scheme.



so…

If we find the Higgs boson - that will be exciting!

- it will confirm a 20 year struggle with the Standard Model
  - *and will demonstrate rather conclusively that we understand the holy grail of physics since Newton - how objects get their masses*
  - *it will also set us off on a new journey…to understand just what kind of Higgs boson it is (as there are more complicated models that follow)*
  - *as I've said many times…it will mean that the Standard Model is at least a part of the truth*

If we don't find the Higgs boson - that will be exciting!

- because that means that something is terribly wrong with a model of nature that makes incredibly precise predictions
  - *but apparently doesn't work*

If it's found, or if it's not…MSU will be heavily involved

- we should know within 2 years if Fermilab finds it
  - *or 5 or so years if CERN finds it.*