Empty Space is NOT Empty

Derek Muller (DM, Veritasium) with Derek Leinweber (DL)
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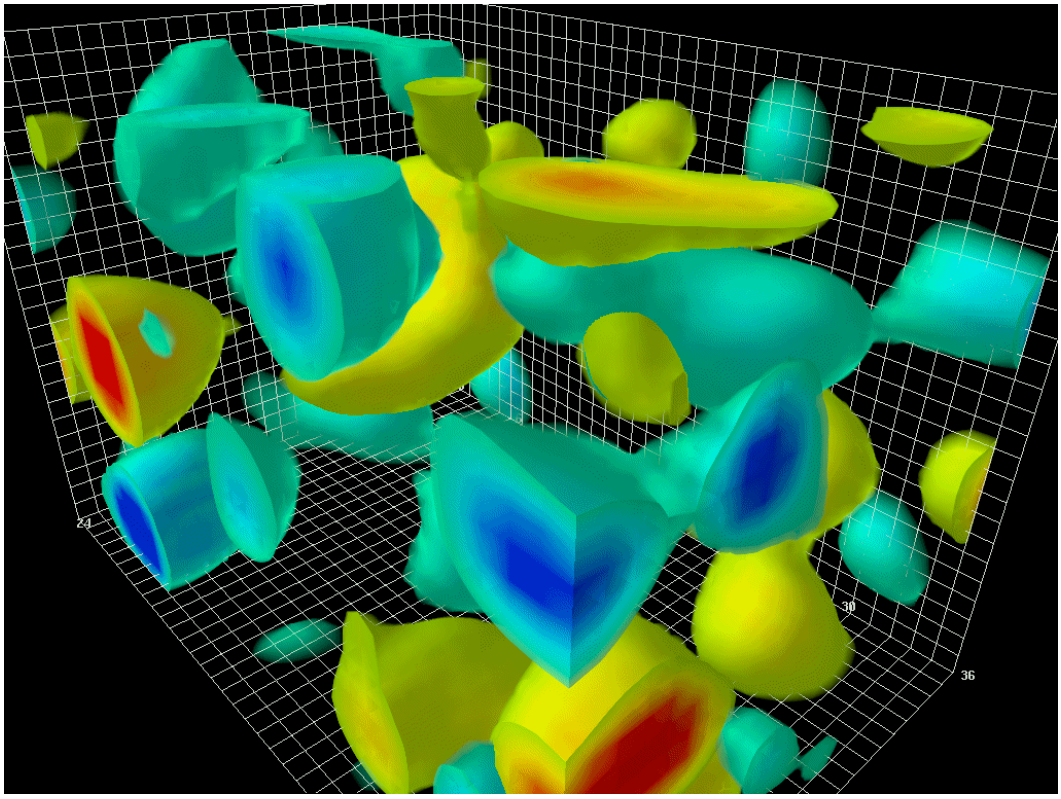
https://youtu.be/J3xLuZNKhlY

DM: [0:01] One of the most amazing things about atoms is that they're mainly empty space. If an atom were as wide as your arm span, then the electrons would all be whizzing about inside the volume enclosed by your fingertips. [0:14] Meanwhile, the nucleus would be sitting in the center, and its diameter would be smaller than the width of a single human hair. [0:23] So all of the atoms that make up you and me and all the seemingly solid things in the universe are mostly empty space.

DM: [0:31] Now, this is incredible. But what is even more mind-boggling is that empty space is not truly empty. [0:39] I know because I've seen it. This is a simulation by Prof. Derek Leinweber at the University of Adelaide:



Derek Leinweber CC BY 4.0 - Visualizations of Quantum Chromodynamics
https://upload.wikimedia.org/wikipedia/commons/2/2a/Quantum_Fluctuations.gif

[0:46] It was made using a supercomputer to crunch the calculations of Quantum Chromo-Dynamics. Now, that is the theory of fundamental particles called 'quarks' — the building blocks of protons and neutrons — and how they interact with each other through 'gluons.'

DL: [1:01] *"What you're looking at here is the energy density of the gluon field fluctuations.* [1:07] *Where the little red spots come out, the energy density is very high, and it fades down through the colors so, at the lowest energy, the field fluctuations are not rendering in this animation, so we can actually see into it."*

DM: [1:19] And what we see is a bubbling soup of quantum field fluctuations that come and go incredibly quickly. [1:26] The frame rate of this simulation is one million billion billion frames per second. Now that is truly high speed! [1:35] The dimensions of this box are absolutely tiny: They are a millionth of a billionth of a meter, roughly enough space to stick two protons. [1:45] But there are no protons here. This is a simulation of the vacuum 'on its own,' what we normally think of as 'empty space.'

DL: [1:53] *"Empty space is actually full of this quark-and-gluon field fluctuations. And, on average, it is possible to annihilate a quark from empty space 'cause it's not empty!"*

DM: [2:07] "That just sounds like the most ridiculous idea that you meant to have empty space — and yet, you can go and get rid of stuff from it!"

DL: [2:15] *"That's right. So it isn't empty!"*

DM: [2:17] Now it seems counterintuitive — that the vacuum, at its lowest energy state, should contain all of this stuff. [2:23] But, in fact, to clear out the fluctuations and create a truly empty vacuum would require a lot of energy.

DL: [2:31] *"The empty vacuum actually costs an enormous amount of energy to create, and if you were able to create it, you'd discover that that is actually unstable — that any sort of perturbation would push that empty vacuum into something where the vacuum is actually full of quantum field fluctuations."*

DM: [2:49] Well, this may not be as strange as it first appears. [2:53] I mean, consider a permanent magnet. It has a magnetic field around it at low energy, at room temperature. [3:00] And that's because the individual little magnetic moments of all the atoms inside are lined up. [3:05] But if you were to heat it up, you would give thermal energy to all those particles, and at a certain point called the Curie Temperature, they would be so randomly aligned that there would no longer be an overall magnetic field. [3:17] So, it actually takes energy to get rid of the permanent magnetic field.

DM: [3:22] Now, this is just like the quantum vacuum, and understanding how the quantum vacuum fluctuations work gives us a sense of what the fundamental particles do, like, 'where are you most likely to find a quark?'

DL: [3:36] *"And it turns out that the quark likes to sit on top of those lumps.* [3:40] *Now those lumps come into and out of existence fairly quickly, and so we like to think of the quarks as hopping from one lump over to the next lump, as it appears, and then on to another one.* [3:51] *I like to think of it as a hiker trying to cross a stream that's running around. Every now and then, a stone pops up because the water is swirling around it.* [4:02] *So, you put your foot there, and you're looking for the next spot — and if you go quickly enough — you might not get your feet wet.* [4:07] *So I think quarks are very much doing… well, we know quarks are doing very much doing the same thing."*

DM: [4:13] So while it is true that you and I and all of the other atoms in the universe are mostly empty space, it is also true that empty space isn't truly empty. [4:24] And, in fact, it is these vacuum fluctuations that are essential for our existence.