Unparticle Physics

Howard Georgi
Center for the Fundamental Laws of Nature
The Physics Laboratories
Harvard University

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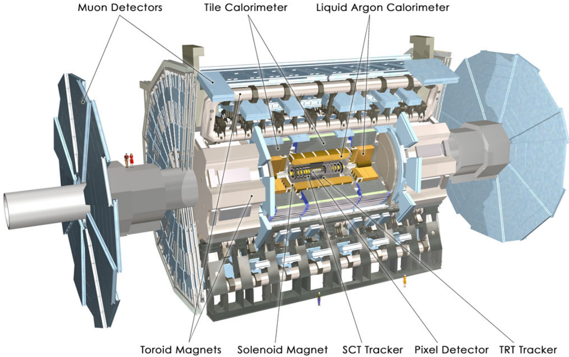
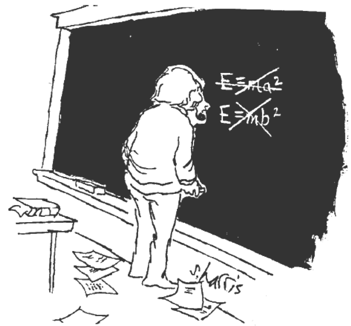
I am honored to be able to address you today. I am embarrassed that I must do so in English, but like many Americans, I am stupidly monolinguistic (computer languages don't count).

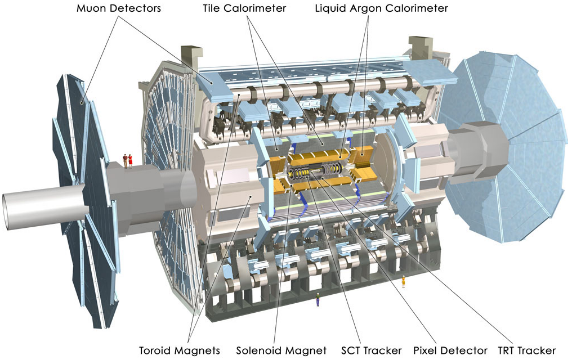


Experiment

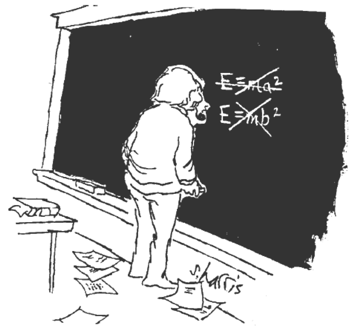


Theory

The next speaker is an experimenter. I am a theorist (though one who actually cares about the results of experiments). You see the difference in the pictures above - on the left is ATLAS - an LHC detector (you can barely see the little people). All I need is a sheet of paper or a black board or a computer.

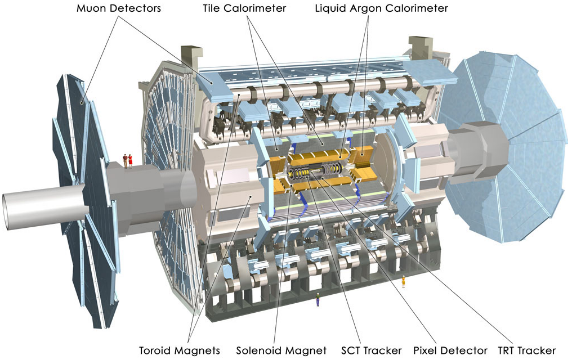


Experiment

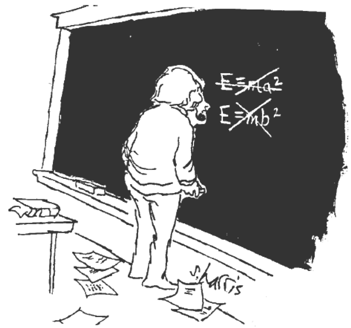


Theory

Unlike experimenters who must stay focused on a set of problems for years at a time because it takes so long to build and run machines and detectors, theorists can be more flighty - working on many different kinds of problems over a career, or even over a few months.

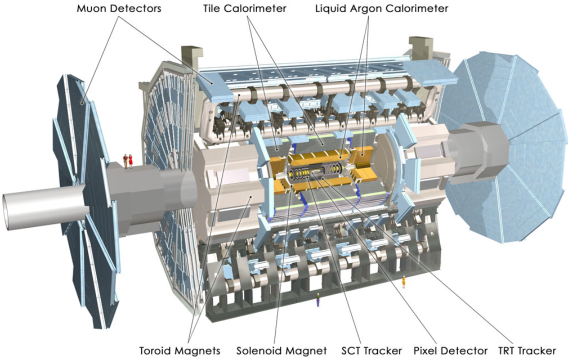


Experiment

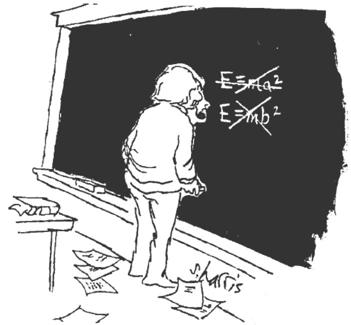


Theory

In particular, I have done many different things, so much so that whatever the LHC finds, it will probably disprove at least one of my theories! So today, I don't mind telling you about an idea that is a bit crazy. I have been a particle physicist most of my life -

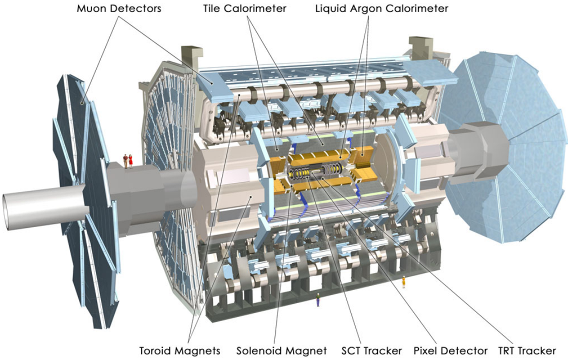


Experiment

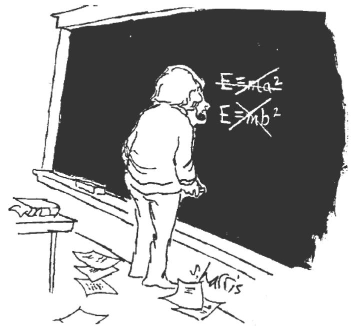


Theory

In particular, I have done many different things, so much so that whatever the LHC finds, it will probably disprove at least one of my theories! So today, I don't mind telling you about an idea that is a bit crazy. I have been a particle physicist most of my life - but for the last year, I have been an unparticle physicist.

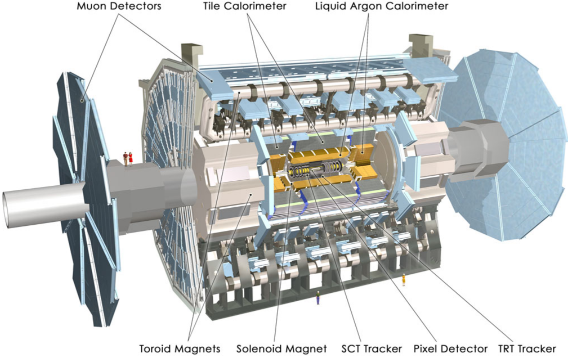


Experiment

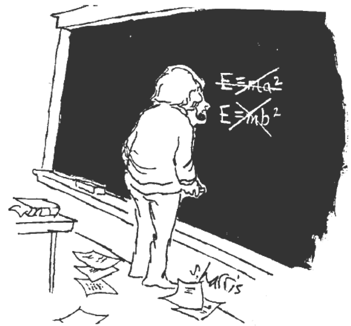


Theory

We unparticle physicists think about what we might see at the LHC and elsewhere if there is energy and momentum in the world not carried by particles. It is hard to explain with almost no mathematics, as I will try to do today. But I hope it will be interesting as an example of how a theoretical idea develops.



Experiment



Theory

While I will try to keep the mathematics fairly simple, I will not promise that the talk will be easy. I don't plan to just give you a bunch of meaningless words and catch phrases. I want to try to make a few difficult things understandable with only high school math. So buckle your seat belts.

the
atomic
hypothesis

I am going to talk a lot today about the size of things. Let me start with the atomic hypothesis - an idea that goes back to the ancient Greeks (that is the philosopher Democritus on the stamp). This idea depends crucially on the idea of size - and dividing things with size into smaller things.

the atomic hypothesis

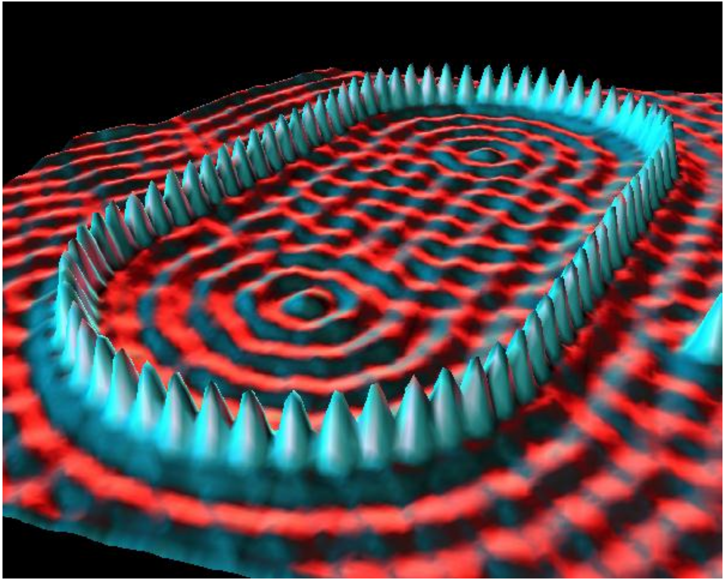
I think the philosophical motivation was something like this. By definition nothing infinitely small has a size. It might then be reasonable to argue that if you put infinitely small things together, you still don't get anything with a size. You could then go on to argue the other way around.

the atomic hypothesis

Because the things we see in the world have a size, they must not be made of infinitely small things. Therefore (one might argue) suppose you divide the things in the world into smaller things, then divide the smaller things into still smaller things, and so on.

the atomic hypothesis

The argument goes that the process must stop at some point, because otherwise you would end up with things that are infinitely small. The process of dividing must stop when you get down to things that are indivisible. These are atoms — the smallest particles of matter. They are very small, but they still have a size.

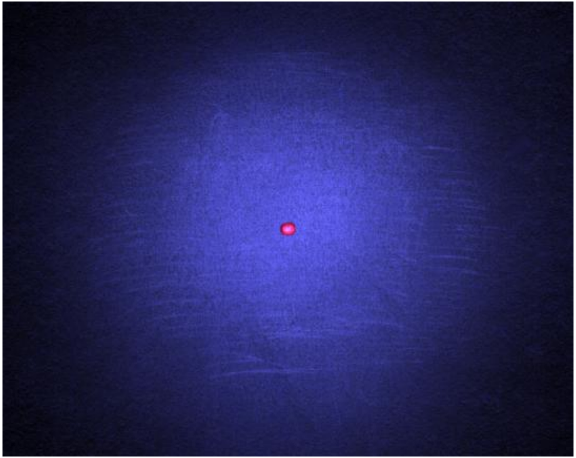


Quantum Corral

Atoms are real! We know their Chemistry and Physics, and with modern technology, we can see them and work with them individually. But they are not indivisible. They are not elementary. We can see inside them. They can be cut up. What went wrong with the philosophical argument?

By definition nothing infinitely small has a size. It might then be reasonable to argue that if you put infinitely small things together, you still don't get anything with a size.

atom with nucleus

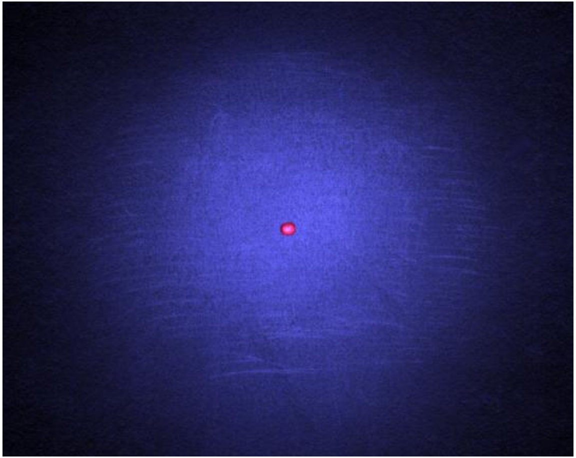


and electron cloud

Remember how the argument started. This is reasonable. It is what common sense tells us -

~~By definition nothing infinitely small has a size. It might then be reasonable to argue that if you put infinitely small things together, you still don't get anything with a size.~~

atom
with
nucleus

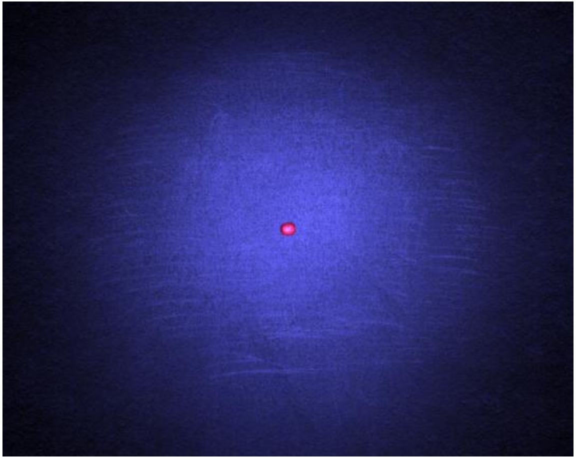


and
electron
cloud

Remember how the argument started. This is reasonable. It is what common sense tells us - but it is simply wrong for small things. Atoms have a size but they are made of much smaller nuclei and electrons. And while the nucleus is in the center, the electrons are spread out over the whole atom.

~~By definition nothing infinitely small has a size. It might then be reasonable to argue that if you put infinitely small things together, you still don't get anything with a size.~~

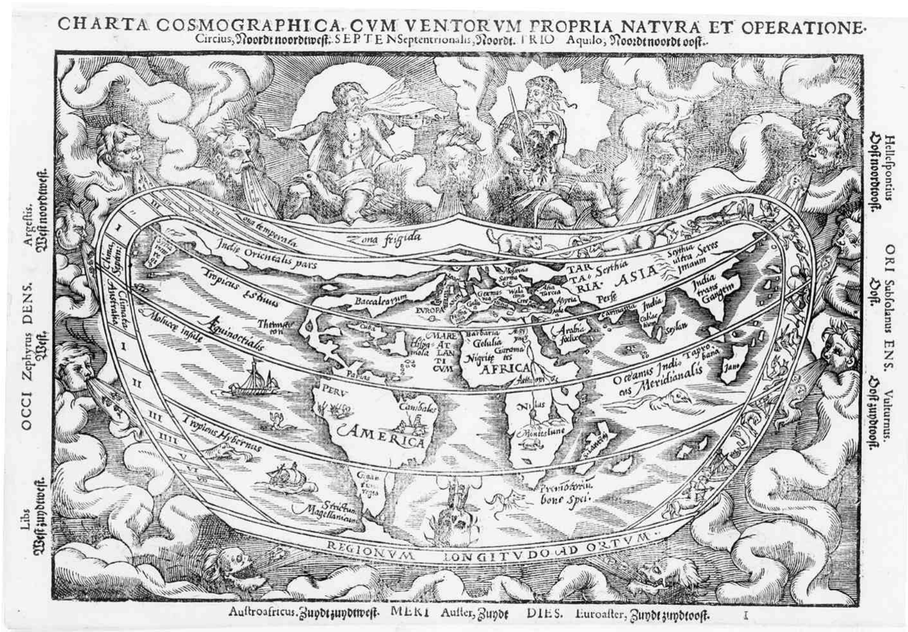
atom with nucleus



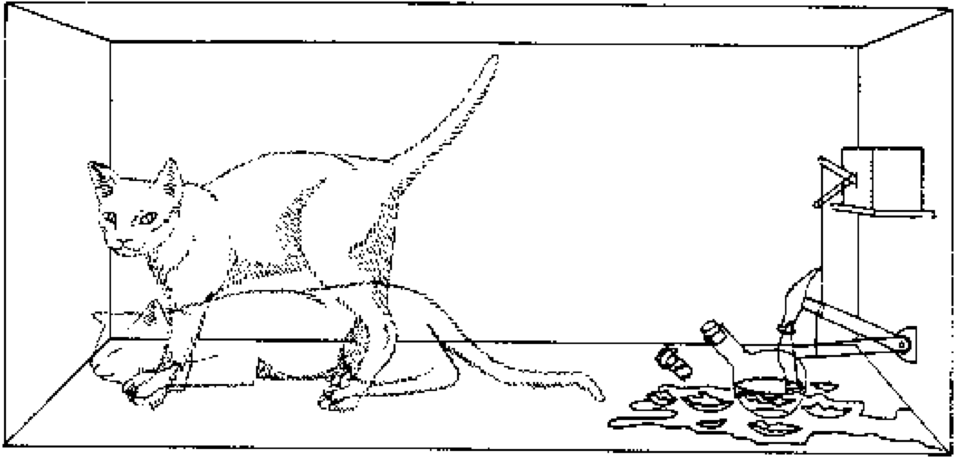
and electron cloud

The size of atoms has nothing at all to do with the size of the nuclei and electrons that make the atom. The rules for putting things together CHANGE dramatically at small distances. Common sense must be replaced by quantum mechanics.

This happens sometimes in science. Physical scientists are explorers. We explore not the earth, but the space of parameters that describe physical processes: size; energy; time; speed; temperature and so on. Like ancient map-makers, we build our picture of physics from the regions we understand out into the unknown.

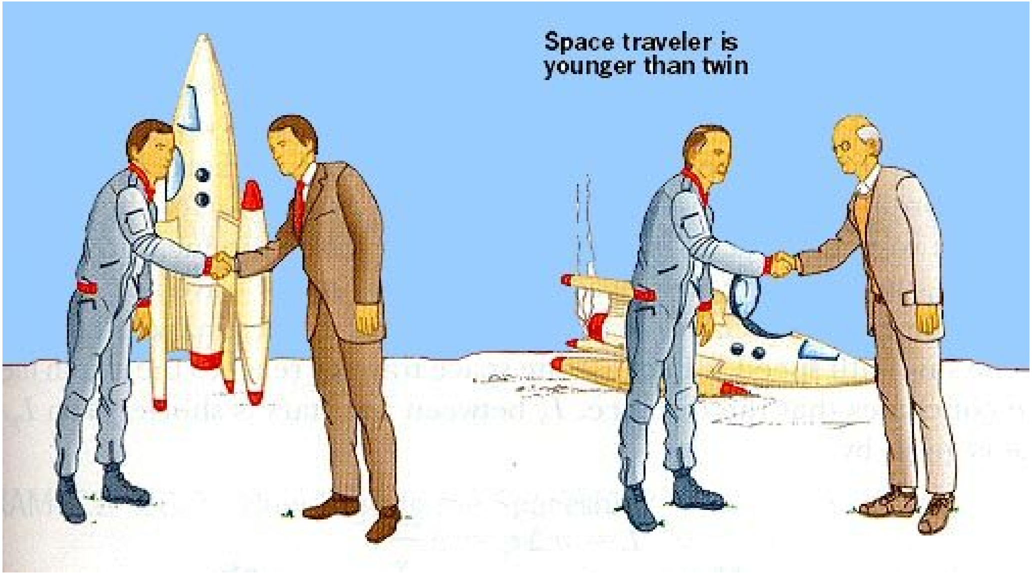


It is on the edges that science is most interesting. Sometimes the whole nature of the map changes. That is what happens with quantum mechanics. The common-sense ideas of measurement that work at ordinary distances break down, along with some of our ideas about what reality is.



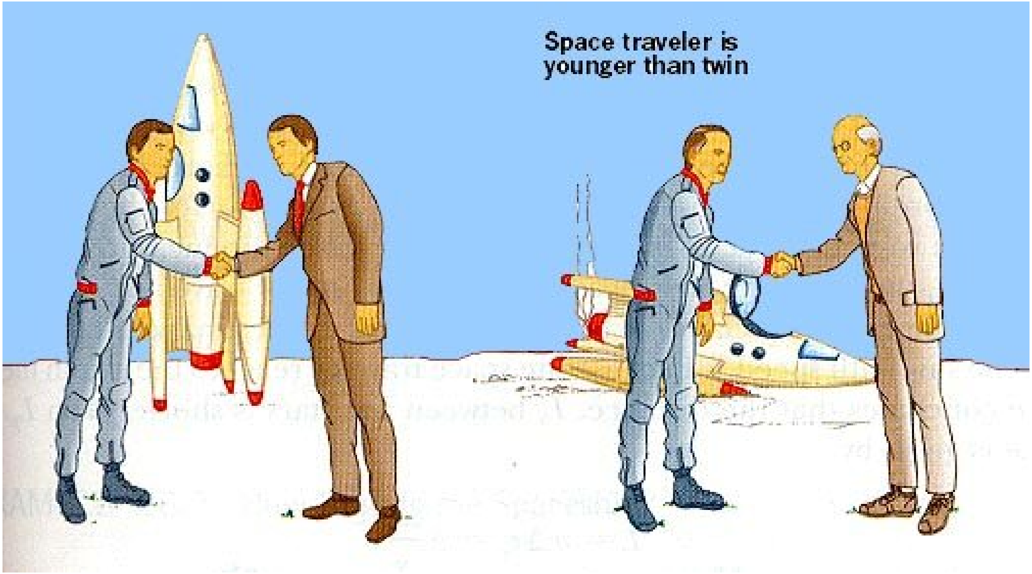
Schrödinger's Cat

It is important to remember that Quantum Mechanics is confusing to us only because we (along with all other living things we know of) are large, complicated creatures, with lots of independent parts. We don't feel in our bones the rules of the quantum world because we are used to something so different.



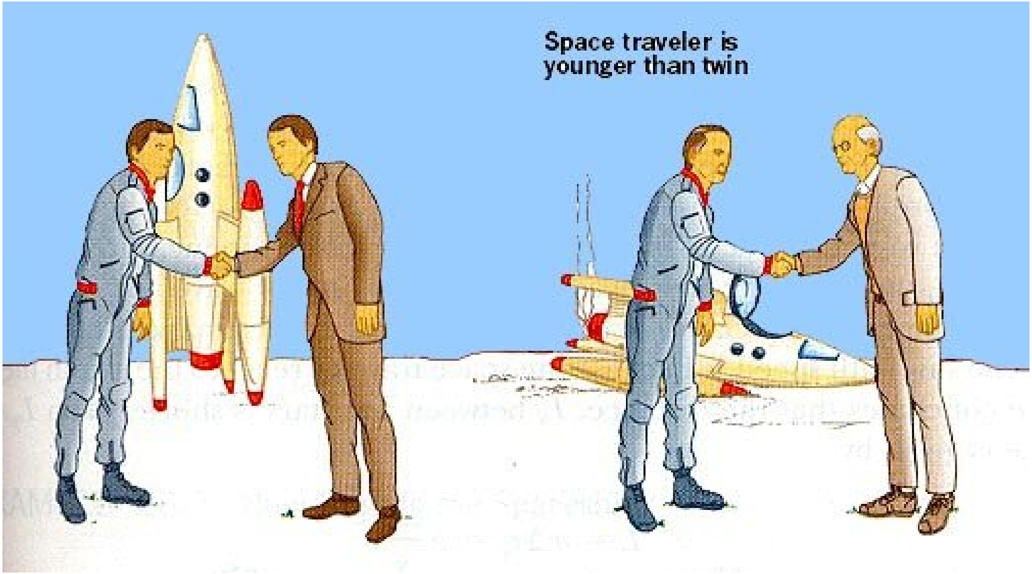
Twin Paradox

There are similar issues with Einstein's Special Relativity. For example, a space traveler who leaves a twin on earth will return to find the earth twin has aged more.



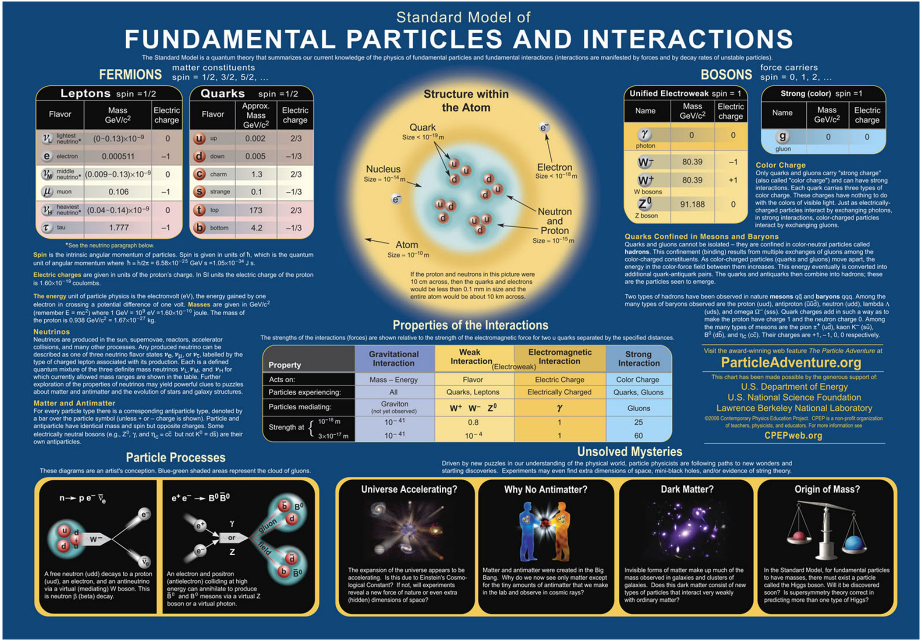
Twin Paradox

There are similar issues with Einstein’s Special Relativity. For example, a space traveler who leaves a twin on earth will return to find the earth twin has aged more. This would be obvious to us, if we were not so slow.

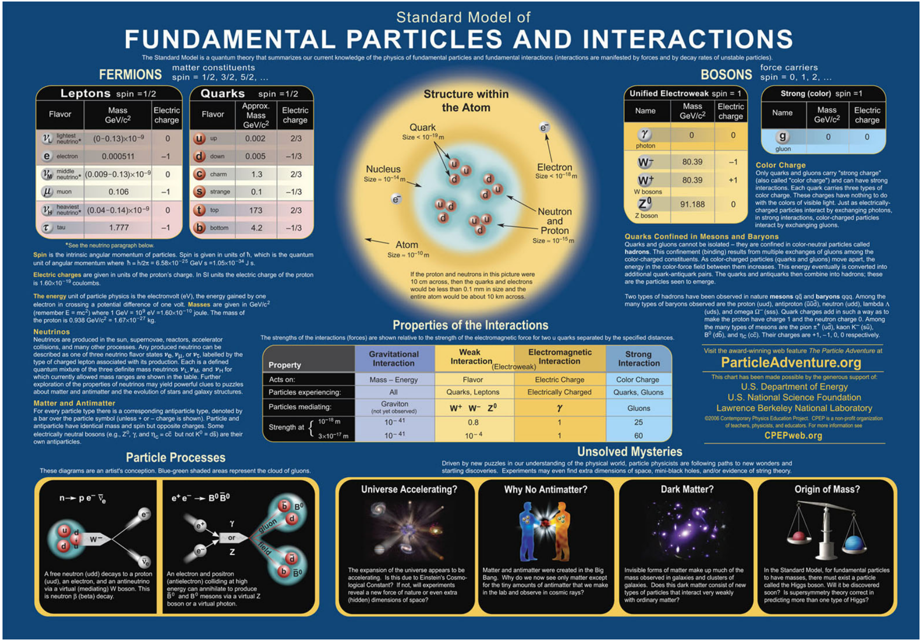


Twin Paradox

If you and I had not spent our entire lives plodding along at relative speeds much much smaller than the speed of light, we would feel the unity of space and time in our bones.

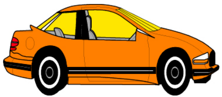


As I mentioned I was an elementary particle physicist for many years before I became an unparticle physicist. The particle concept survives the revolutions of quantum mechanics and relativity. All the particles and almost all the physics we know fits into the standard model, and I am proud that I helped build it.



There are only 12 types of matter particles - 6 quarks - 3 charged leptons - 3 neutrinos - and their antiparticles. There are only 4 types of force particles W, Z, γ (photon) and Gluon. Every particle of a particular type is exactly the same. What exactly does that mean?

Energy



➡

momentum

E

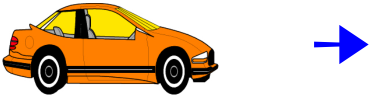
$\vec{p}$

kinetic
energy and mass
are conserved

momentum
has direction
(vector)

Part of the answer is that elementary particles carry energy and momentum, like the larger objects we are familiar with. Momentum describes the object's tendency to keep moving. It points in the direction of the object's motion. Every moving object also carries kinetic energy.

Energy



momentum

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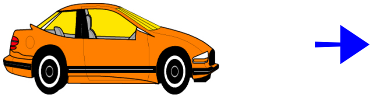
Energy and momentum are conserved.

Energy

E



momentum

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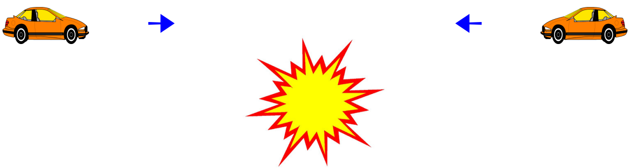
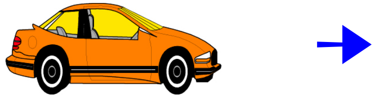


Energy and momentum are conserved. This is most obvious in collisions! But it is always true. For example, when you put on the brakes to slow your car, your car's momentum decreases, but the earth's momentum increases correspondingly though the earth is so massive that you don't notice.

Energy



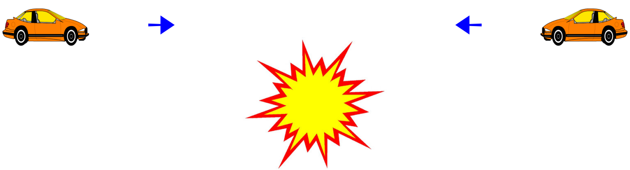
momentum

E

(kinetic energy and mass are conserved)

$\vec{p}$

momentum has direction (vector)

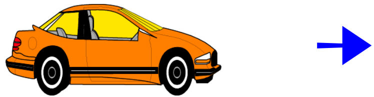


If the total momentum before the collision is zero, all the kinetic energy is available to make a bigger mess. This is what will happen at the LHC. -

Energy

E

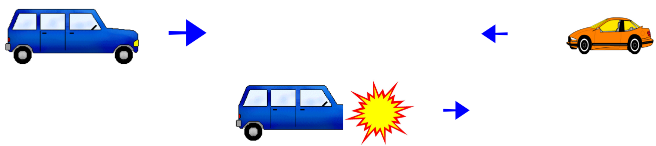
kinetic
energy and mass
are conserved)



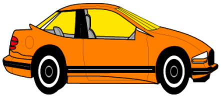
momentum

$\vec{p}$

momentum
has direction
(vector)



If the total momentum before the collision is zero, all the kinetic energy is available to make a bigger mess. This is what will happen at the LHC. - If the momenta don’t add up to zero, some of the energy is still in kinetic energy of motion after the collision.

Energy  momentum

E $\vec{p}$

Energy e^- momentum

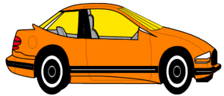
relativistic energy (mass is not conserved)

Electron

momentum has direction (vector)

$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4$$

Now here is the point. Each type of elementary particle is a bundle of energy and momentum with a relation between energy, momentum and mass. This relation is really what makes a particle a particle. Never mind the details if you don't know already. The important thing is there is SOME relation that depends on m.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

Electron

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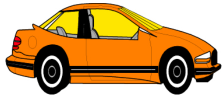
$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

Just for completeness (don't let this scare you), note that in quantum mechanics, particles are also quantum mechanical waves, and there is an analogous relation between the period T and the wavelength λ involving Planck's constant h.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

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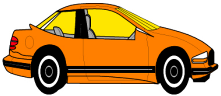
$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

A particle can have any momentum, but once you know the momentum, and the type of particle, you can always find the energy, because all particles of each type have the same mass and satisfy the same relation. This is what it means that all particles of the same type are exactly the same.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

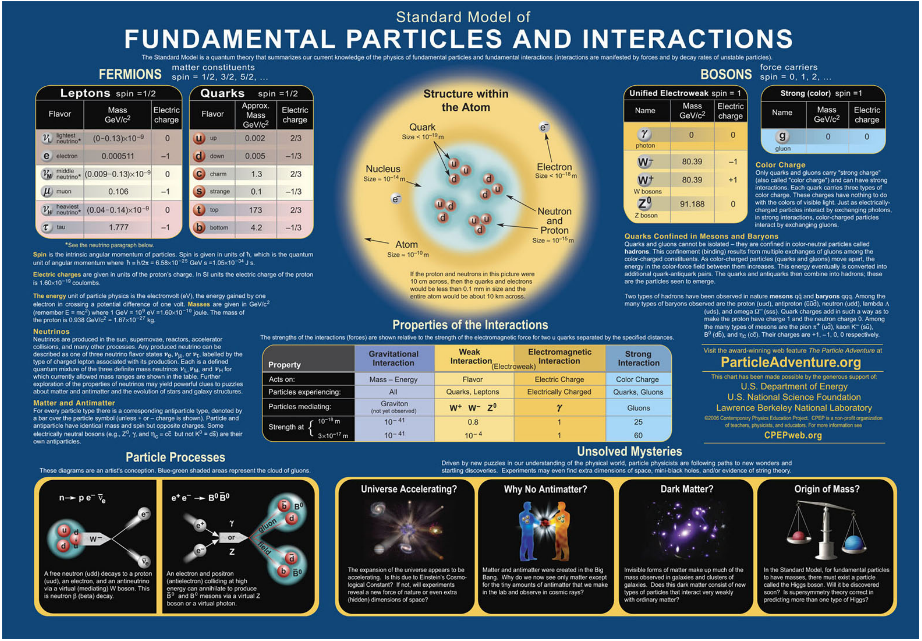
Electron

momentum has direction (vector)

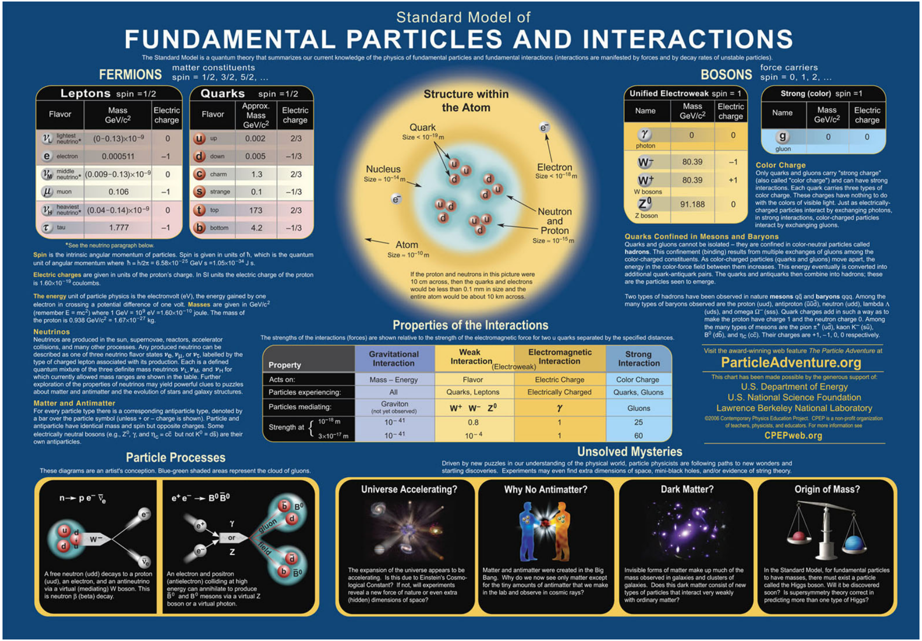
$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

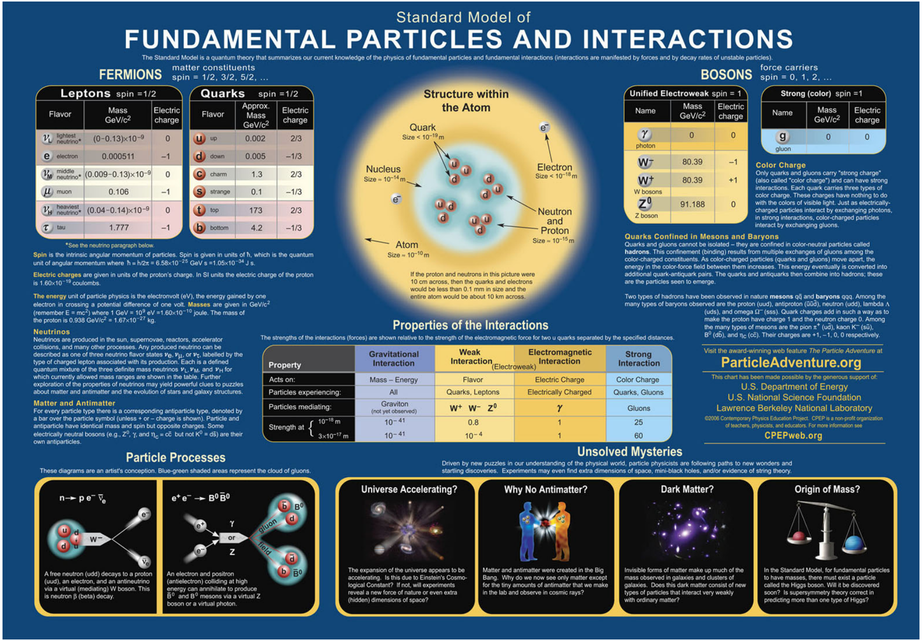
In fact, the velocity of the particle is also related to the momentum, as we know from ordinary objects, so observers moving at different speeds looking at the same particle see different momentum and energy — but they see exactly the same relation between the two, with the same mass. That is what matters.



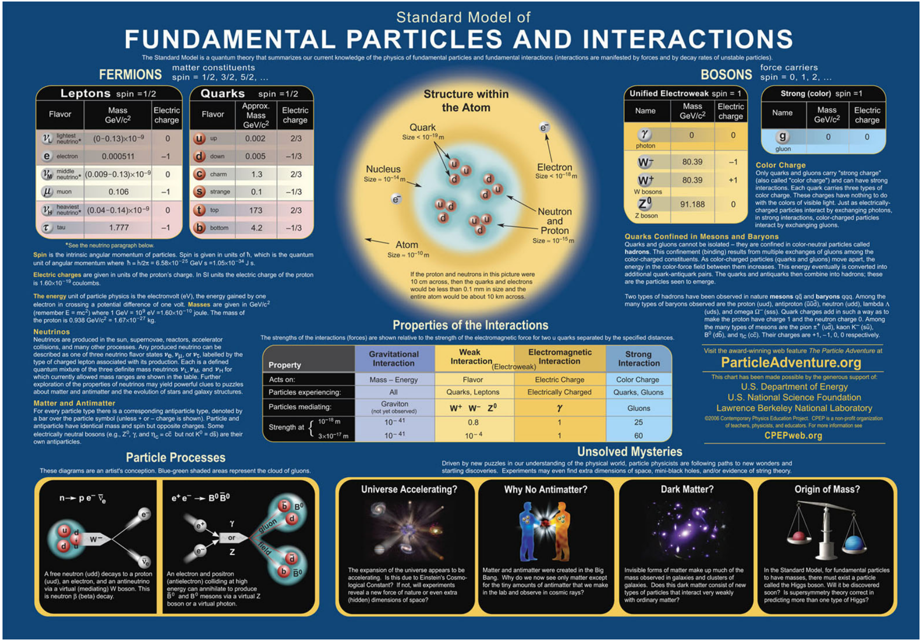
It is remarkable, I think, that all of the energy and momentum we see in labs, in all the varied processes that go on, is carried by the same 16 types of particles. It is not surprising that we have gotten used to the idea that everything must be particles. That's why I grew up calling myself a particle physicist.



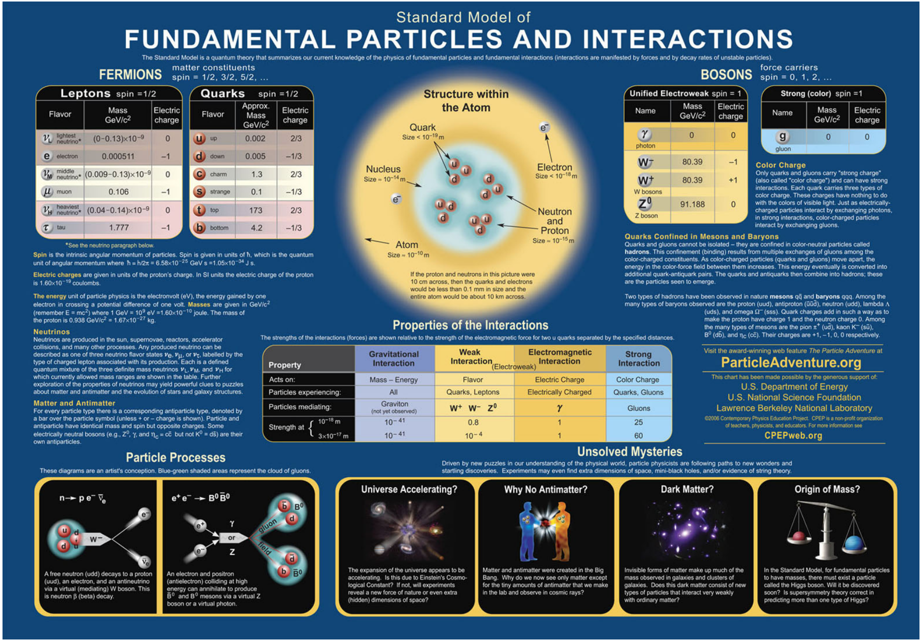
It is true, though, that there are some puzzling things that we cannot understand in terms of these 16 types of particles. Dark matter, dark energy? But I am most interested in the study of the vacuum. What we have learned from the standard model is that the vacuum, the state of nothingness, has structure.



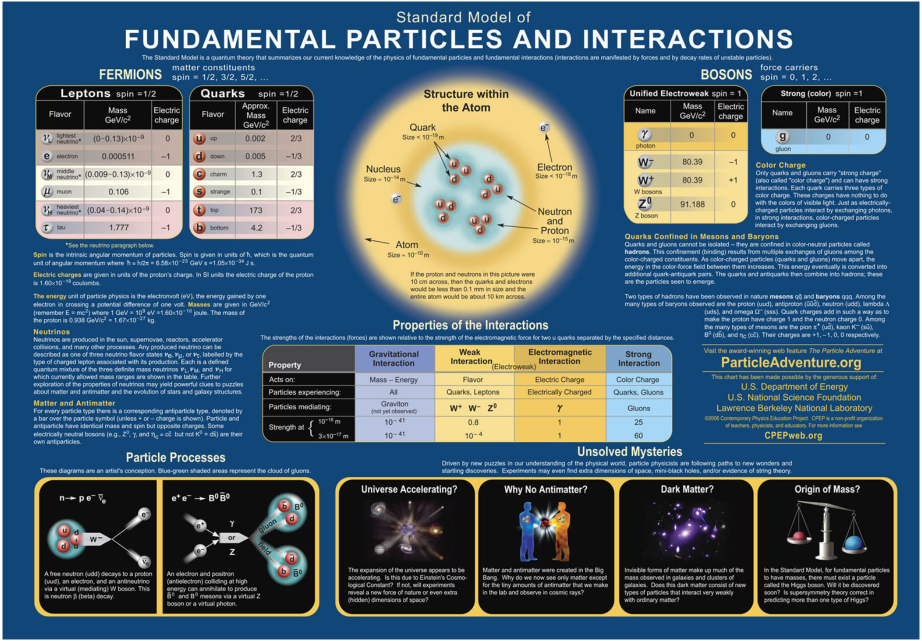
It is a fabulous story that goes with the words “breaking of electroweak symmetry” and I can’t resist a brief aside, even though it is not unparticle physics. The vacuum breaks a symmetry of the underlying interactions of the W, Z and photon, giving a large mass to the W, Z but not to the photon.



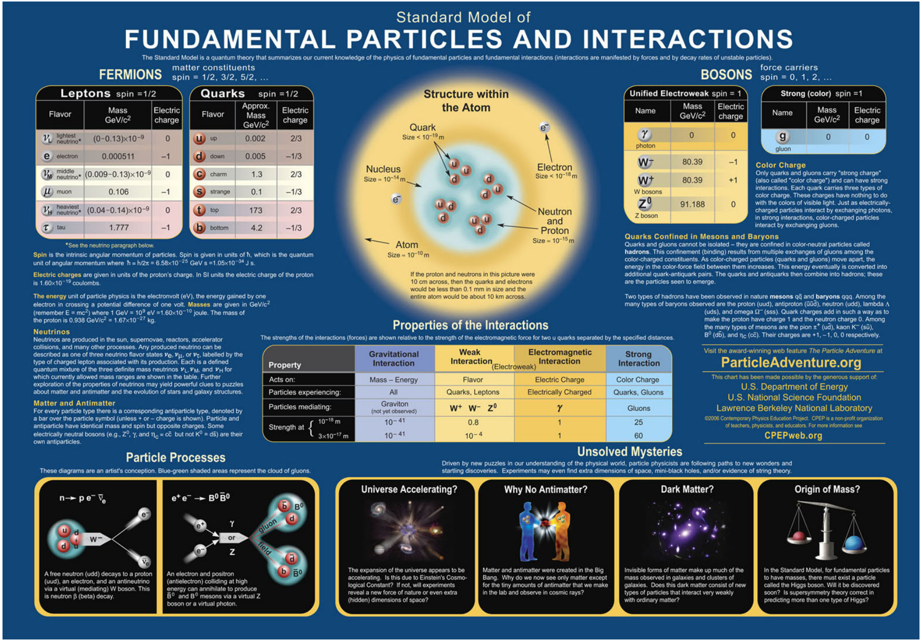
At each point in space, the vacuum can be twisted to mix up the photon with either the W or the Z. Waves built of these twists are welded into the W and Z by the process that makes them heavy, so we actually see aspects of the vacuum structure when we study the W and Z.



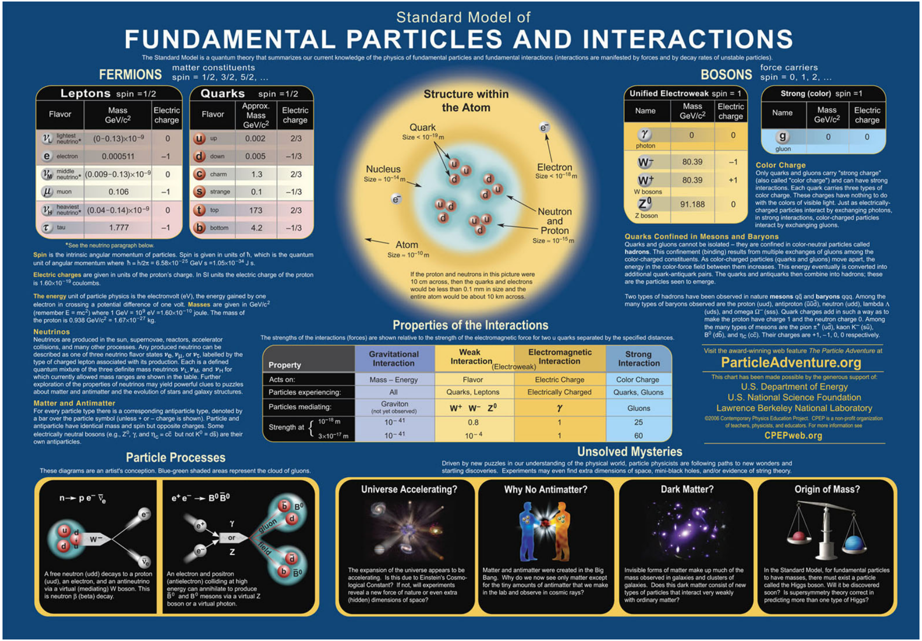
We know almost everything about the beautiful symmetrical structure of the vacuum down to distances of the order of 10^{-16} cm because we have studied the properties of the W and Z at accelerator laboratories like CERN, Fermilab, and DESY.



But at the energies we have reached so far, most of what we see is fixed just by the symmetry, and depends only very weakly on the actual physics that holds the vacuum state together.

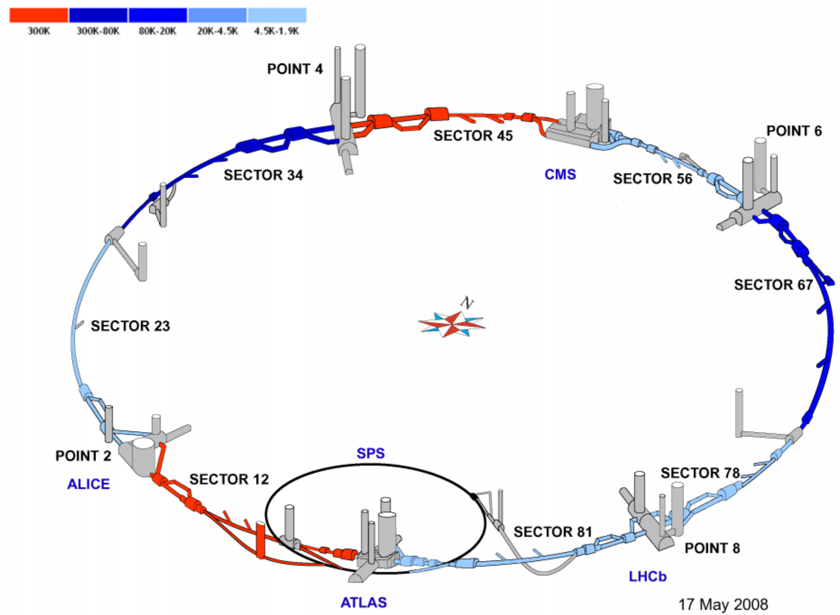


Until we know what the actual physics is that produces this vacuum, all our beautiful theories about what might be happening at shorter distances, below 10^{-16} cm, are just pure speculation.

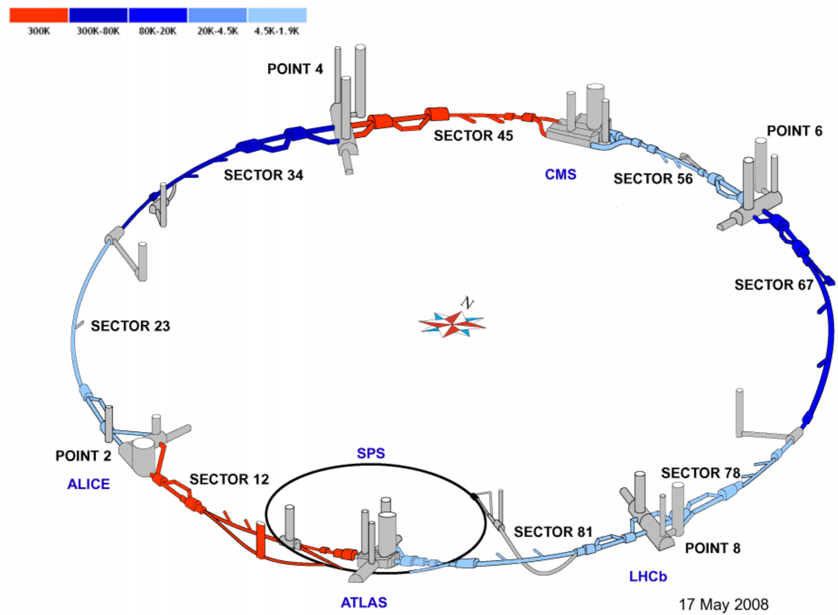


From our study of the standard model, we know enough to predict that if we concentrate enough energy in a small enough region of space, we will be able to disturb the vacuum and probe its structure. Then we should be able to see what holds the state of nothing together.

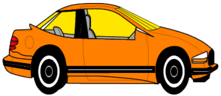
This is what the LHC will do. One possibility - perhaps the most likely - for the vacuum structure predicts the existence of a Higgs particle. But that is only one possibility. This is a machine that will explore the boundary of our map, and who knows what it will find.



We have been waiting for such a machine for 20 years. It is incredible that it is now built and (as this recent figure from the LHC web site shows) cooling down for running. I can't wait to hear more about this from Peter Jenni in the next talk.



Last spring, I was thinking about what new things we might see at the LHC, and it occurred to me that everything I or other people had thought about at the LHC would show up first as particles - either new particles or the usual particles behaving in very different ways. I wondered if there were other possibilities.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

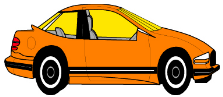
relativistic energy (mass is not conserved)	Electron	momentum has direction (vector)

$$E^2 - \vec{p}^2 c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

I didn't quite know how to think about this, because if you give up the relation between energy and momentum and mass that makes an object a particle, you presumably need some other rule to replace it, unless you want to think about a world with no rules at all.

Energy



momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

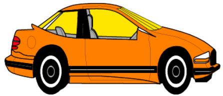
Electron

momentum has direction (vector)

$$E^2 - \vec{p}^{\,2} c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

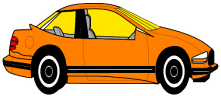
But after a while, I realized that there was one possible rule that might replace the usual particle relation, and that in fact physicists had been playing with this rule for over 50 years. It was the idea of scale invariance. But I also realized for the first time how confused I really was about this.

Energy		→	momentum
E			$\vec{p}$
Energy	e^-	→	momentum
relativistic energy (mass is not conserved)	Electron		momentum has direction (vector)

$$E^2 - \vec{p}^{\,2} c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

A scale invariant theory is one in which all quantities with units – energy, momentum, position, time, almost everything – can get multiplied by arbitrary factors without changing the physics. I'll say more about this shortly.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

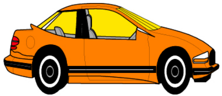
Electron

momentum has direction (vector)

$$E^2 - \vec{p}^{\,2} c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

I knew that such a theory COULD NOT look like a theory of massive particles, because the ms in the energy-momentum relation in a particle theory can't change. They are what the particle is. But when I thought about it, I realized that I had absolutely no idea what the physics of such a theory DID look like!

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

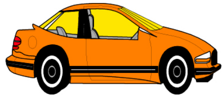
Electron

momentum has direction (vector)

$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

Because I already knew a lot of the mathematics, I focused on the physics of what was created by the mathematical objects in a scale invariant theory to carry the energy and the momentum. I gave it a name - “unparticle stuff.” “Stuff” is a good word because it is not too specific. “Unparticle” was obvious.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

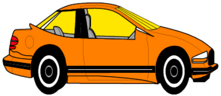
Electron

momentum has direction (vector)

$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

This was the beginning of my life as an unparticle physicist. After inventing a great name, the next thing that an unparticle physicist needs to do is to understand how unparticle physics could possibly exist in our world.

Energy  → momentum

E $\vec{p}$

Energy e^- → momentum

relativistic energy (mass is not conserved)

Electron

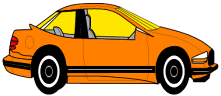
momentum has direction (vector)

$$E^2 - \vec{p}^2 c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

I found a scheme in which this may be possible by keeping the unparticle world and the world of standard model particles separate from one another except at very high energies. Now I could ask physical, rather than just mathematical questions.

Energy



momentum

E $\vec{p}$

Energy e^- momentum

relativistic energy (mass is not conserved)

Electron

momentum has direction (vector)

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I could look at processes in which we collide standard model particles, and ask what happens if unparticles carry off energy and momentum in the collision. Once the question was set up properly, it was pretty easy to find the following result for the simplest case.

Unparticle stuff looks like a fractional number of invisible massless particles.

This was such an odd result, that while I wrote a paper immediately, I sent an advanced copy to some of my smartest former students and grand-students - people like Ann Nelson at Seattle and my colleague Lisa Randall at Harvard - with a note attached that goes like this.

Unparticle stuff looks like a fractional number of invisible massless particles.

The attached hallucination came to me a few days ago and I have been in a trance since then trying to work out the details. I thought it was time to try it out on some of my friends. Since this is very possibly embarrassingly nuts, I would appreciate it if you could keep it to yourselves for a day or so. Several possibilities occur to me.

1 - It is trivially wrong for some reason.

2 - Everyone knows it already and is not interested.

3 - Some other type of bound kills these theories so that the unparticles can never be seen.

I would be grateful for a little sanity check.

Unparticle Physics

Howard Georgi*

Center for the Fundamental Laws of Nature, Jefferson Physical Laboratory, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 24 March 2007; revised manuscript received 20 May 2007; published 29 May 2007)

I discuss some simple aspects of the low-energy physics of a nontrivial scale invariant sector of an effective field theory—physics that cannot be described in terms of particles. I argue that it is important to take seriously the possibility that the unparticle stuff described by such a theory might actually exist in our world. I suggest a scenario in which some details of the production of unparticle stuff can be calculated. I find that in the appropriate low-energy limit, unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a nonintegral number $d_{\mathcal{U}}$ of invisible particles. Thus dramatic evidence for a nontrivial scale invariant sector could show up experimentally in missing energy distributions.

DOI: 10.1103/PhysRevLett.98.221601 PACS numbers: 11.15.Tk, 14.80.−j

Ann and Lisa wrote back assuring me that I was not crazy and that it was kind of interesting. That has turned out to be true, apparently. My first paper on the subject was published in PRL and the paper has spawned almost 150 references. This shows the advantages of inventing a really amusing title!

PRL **98,** 221601 (2007) PHYSICAL REVIEW LETTERS week ending 1 JUNE 2007

Unparticle Physics

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I discuss some simple aspects of the low-energy physics of a nontrivial scale invariant sector of an effective field theory—physics that cannot be described in terms of particles. I argue that it is important to take seriously the possibility that the unparticle stuff described by such a theory might actually exist in our world. I suggest a scenario in which some details of the production of unparticle stuff can be calculated. I find that in the appropriate low-energy limit, unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a nonintegral number $d_{\mathcal{U}}$ of invisible particles. Thus dramatic evidence for a nontrivial scale invariant sector could show up experimentally in missing energy distributions.

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I should perhaps also say that some of the most interesting work extending the original ideas has been done my introducer, Prof, Quiros, and his collaborators. But I am not going to say more about all these papers today.

Unparticle stuff looks like a fractional number of invisible massless particles.

The attached hallucination came to me a few days ago and I have been in a trance since then trying to work out the details. I thought it was time to try it out on some of my friends. Since this is very possibly embarrassingly nuts, I would appreciate it if you could keep it to yourselves for a day or so. Several possibilities occur to me.

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I would be grateful for a little sanity check.

I thought I would try in the rest of my talk to give you a sense of what it means to make such a crazy sounding statement. Of course, part of the issue is that “looks like invisible massless particles” might sound crazy, even without the “fractional” part (which is where the unparticles come in).

Unparticle stuff looks like a fractional number of invisible massless particles.

The attached hallucination came to me a few days ago and I have been in a trance since then trying to work out the details. I thought it was time to try it out on some of my friends. Since this is very possibly embarrassingly nuts, I would appreciate it if you could keep it to yourselves for a day or so. Several possibilities occur to me.

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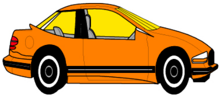
I would be grateful for a little sanity check.

So first I will talk about how we might count invisible massless particles. Then I will go back and talk about scale invariance, and see what it means if we count our invisible particles and get a fractional number.

Energy  → momentum

E $\qquad$ $\vec{p}$

Energy $\quad e^-$ → momentum

relativistic energy (mass is not conserved)

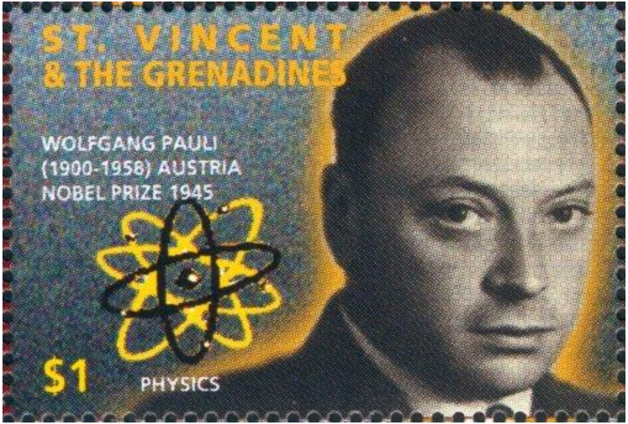
Electron

momentum has direction (vector)

$$E^2 - \vec{p}^2 c^2 = m^2 c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

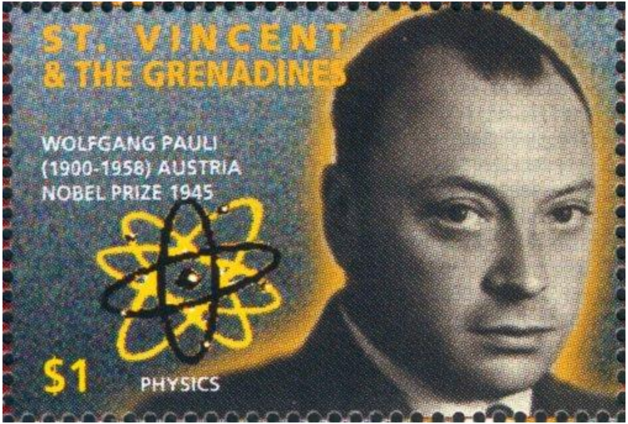
$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

Massless particles? Sure! Nothing goes wrong with the particle relation when $m = 0$. Massless particles always travel at the speed of light - and indeed, the photon, the particle of light, is a good example of a massless particle. It was for taking this seriously that Einstein got the Nobel Prize.



Pauli inferred the existence of the neutrino from conservation of energy and momentum

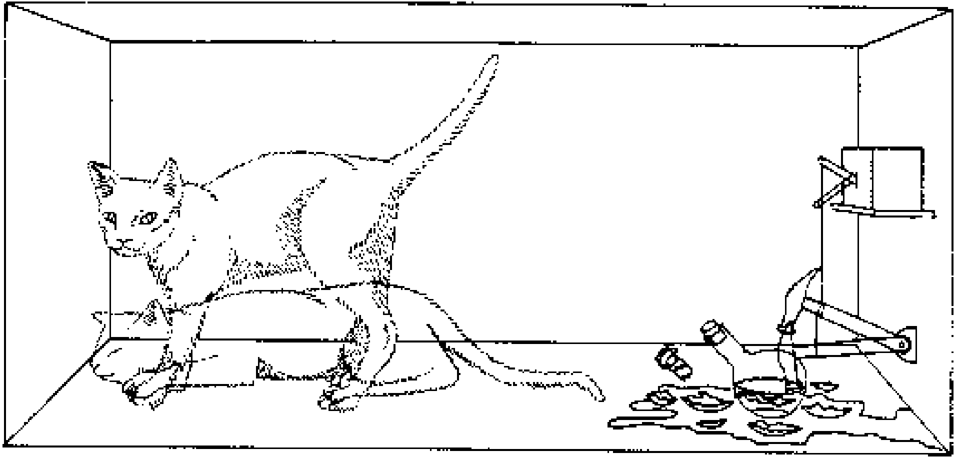
Invisible particles? Use conservation of energy and momentum! Suppose we produce invisible particles in a process. If we know the energy and momentum of our initial particles, and we add up the energy and momentum of all visible final particles, the missing energy and momentum is carried by invisible particles.



Pauli inferred the existence of the neutrino from conservation of energy and momentum

$$E_m^2 - \vec{p}_m^{\,2} c^2 = 0$$

A single invisible particle is easy, because as we have seen, any single particle carries energy and momentum in a very specific combination, tied to the particle's mass. If a single massless particle is invisible, the missing energy E_m squared minus the missing momentum $\vec{p}_m$ squared times c^2 vanishes.

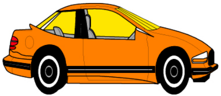


Schrödinger's Cat

But how does this help if there is more than one particle? Here the fundamental strangeness of quantum mechanics comes to our rescue. If two or more invisible massless particle are produced in some process, their energies and momenta are distributed randomly.

Energy

E



→ momentum

$\vec{p}$

Energy

two or more invisible massless particles

→ momentum

relativistic energy (mass is not conserved)

mass is not fixed but can be measured

momentum has direction (vector)

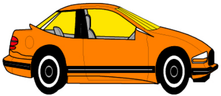
$$E^2 - \vec{p}^{\,2} c^2 = m^2 c^4$$

$$\vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

Here's the trick. Even if there are several invisible massless particles, all we see is the total missing energy and the total missing momentum which are the sums of the energies and momenta of the invisible particles and we can compute m called the "missing mass." For just one invisible particle, the missing mass is zero.

Energy



momentum

E $\vec{p}$

Energy — two or more invisible massless particles — momentum

relativistic energy (mass is not conserved)

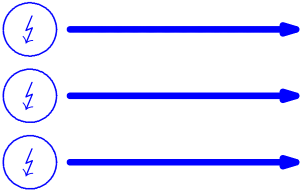
mass is not fixed but can be measured

momentum has direction (vector)

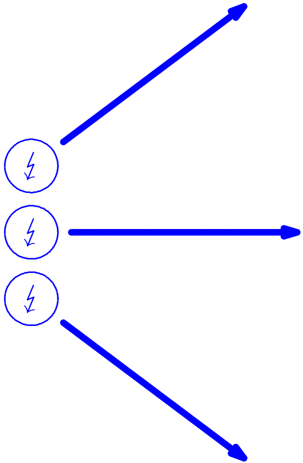
$$E^2 - \vec{p}^{\,2}c^2 = m^2c^4 \qquad \vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2c^4}{h^2}$$

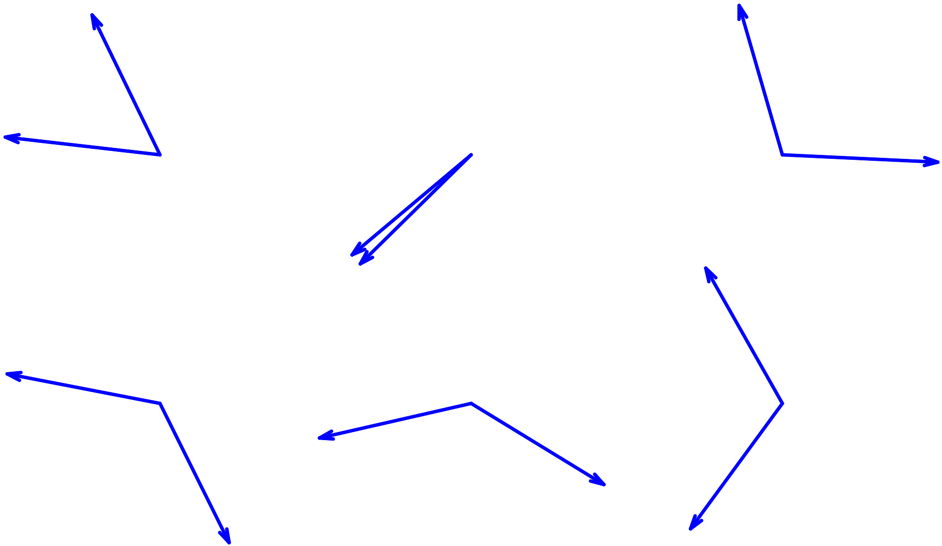
Energies add like numbers but momenta add like vectors. Unless the invisible particle momenta are parallel, the total missing momentum (times c) is less than the energy and the missing mass is not zero.



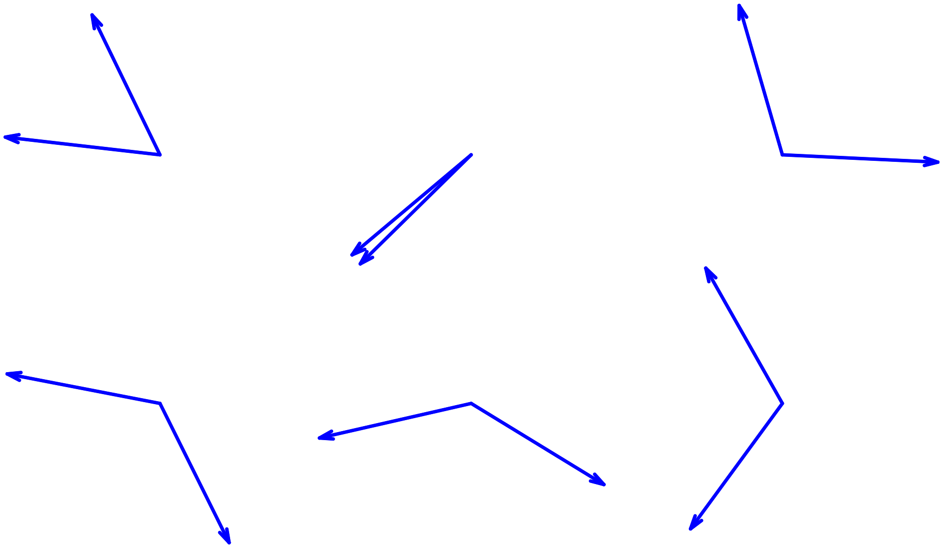
Another way to understand this is to think about what the missing particles are doing in space and time. If the momenta are parallel, all of the missing particles are moving along at the speed of light in the same direction. They stay together and look like a single zero mass particle.



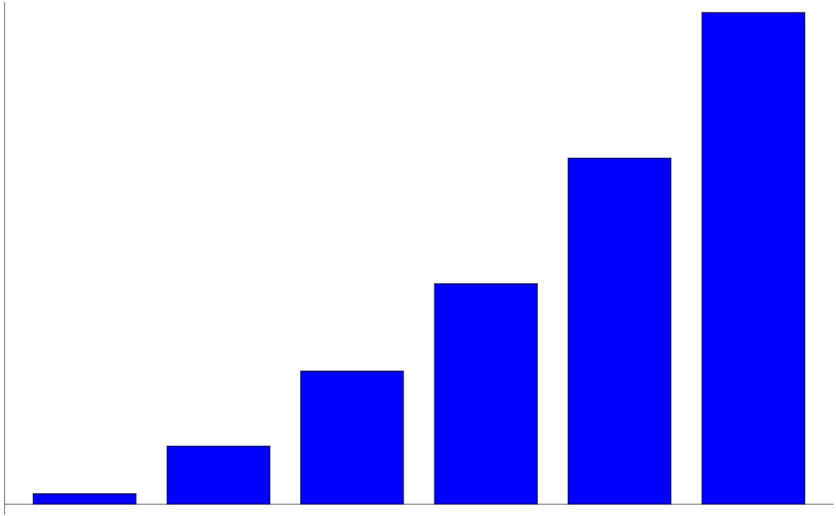
But if the directions of the momenta are different, the invisible particles spread out and do not look like a massless particle. The more the directions are different, the more the momenta cancel when you add the vectors, and the larger the missing mass you get for the total missing energy and momentum.



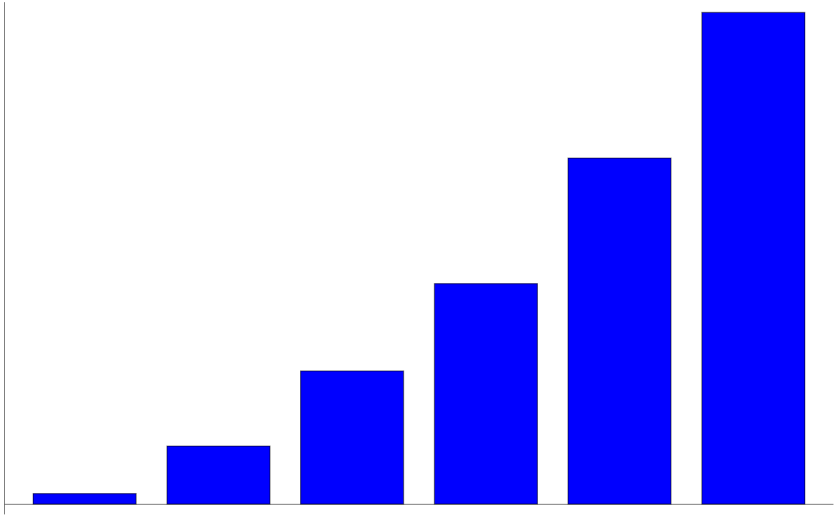
We know the missing mass is zero if there is a single invisible massless particle. what missing mass do we expect for two? In any given event, we don’t know, but if we repeat the process many times, the angle between the two invisible particle momenta will be distributed at random.



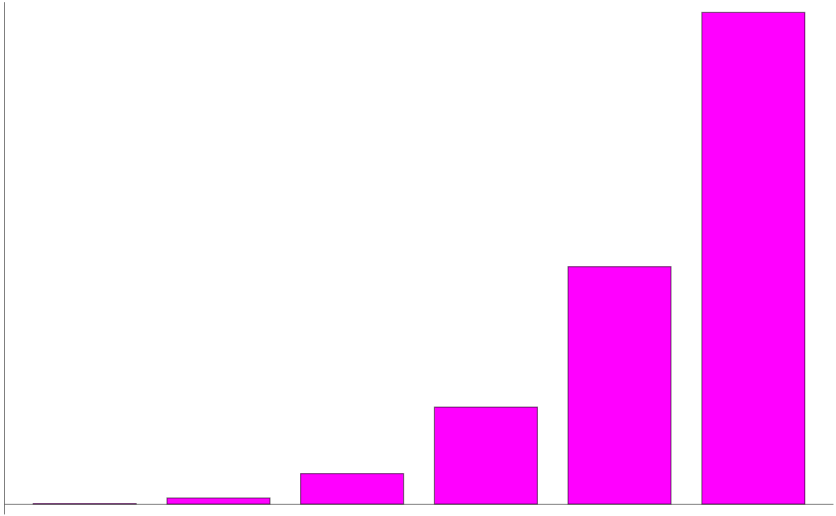
Only if the angle is zero do we get zero missing mass, and this almost never happens. Thus you would expect that if you take many events and plot the number of events versus the missing mass, you will get an increasing function -



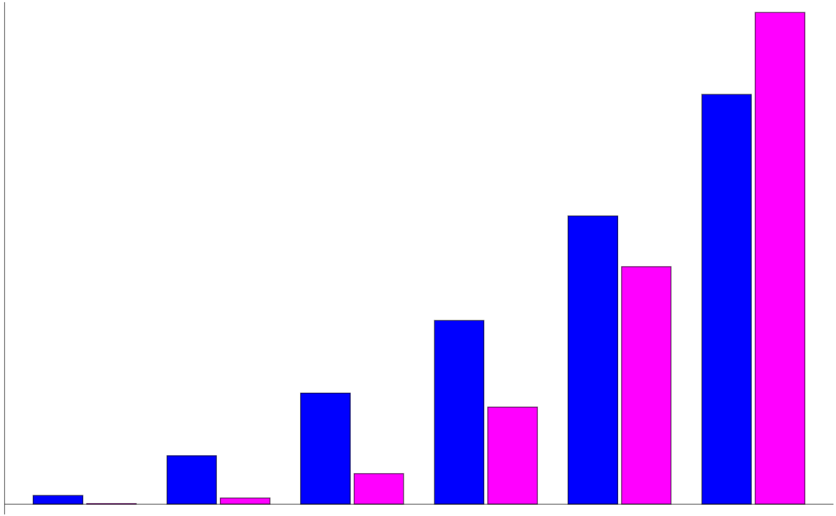
Only if the angle is zero do we get zero missing mass, and this almost never happens. Thus you would expect that if you take many events and plot the number of events versus the missing mass, you will get an increasing function - something like this (very roughly for small mass).



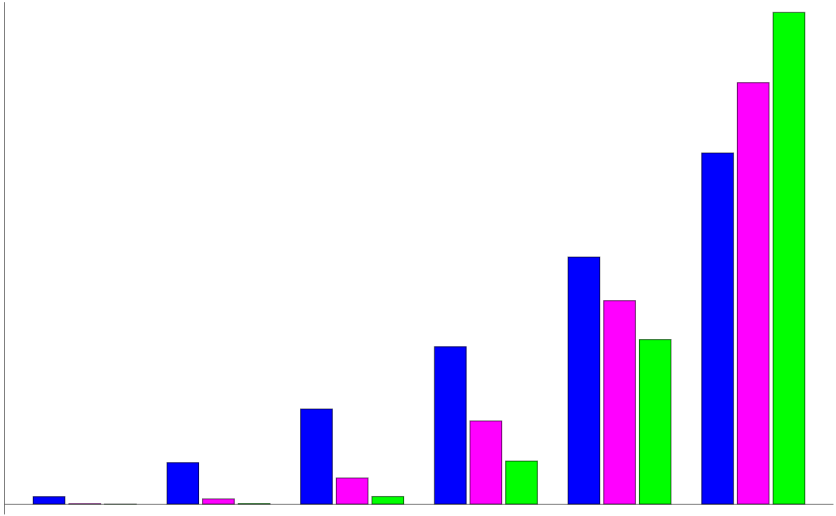
If there are three invisible massless particles, all three momenta have to line up exactly to get zero missing mass, even less likely to happen at random! So small missing mass is even more unlikely, and the number of events as a function of missing mass would increase even faster -



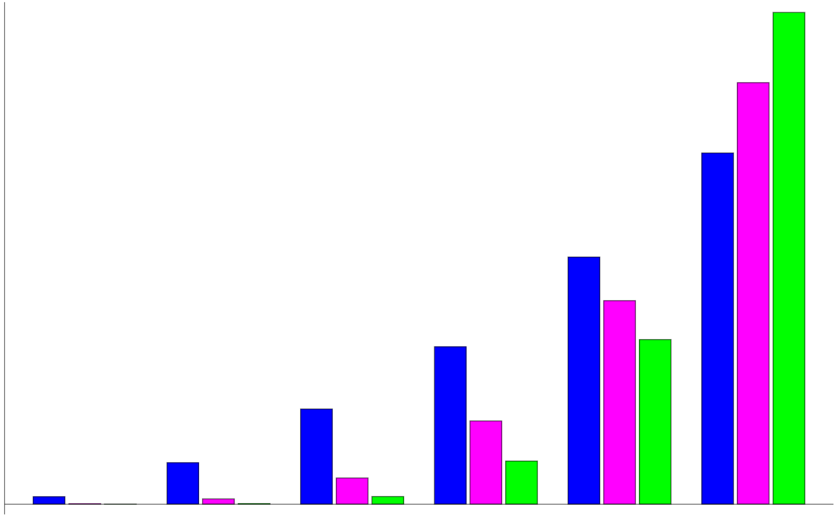
If there are three invisible massless particles, all three momenta have to line up exactly to get zero missing mass, even less likely to happen at random! So small missing mass is even more unlikely, and the number of events as a function of missing mass would increase even faster - and would look something like this.



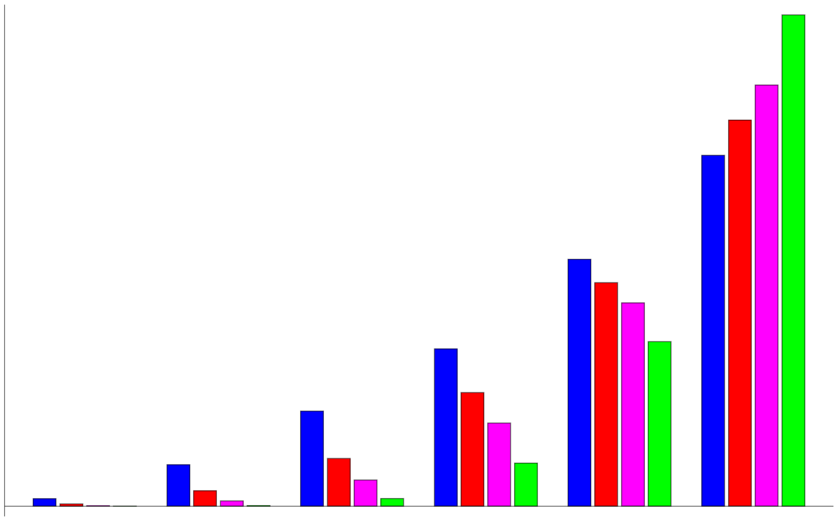
Thus by plotting these event distributions for our process, we can tell whether we have two invisible massless particles (which looks like the blue) or three (which looks like the purple) -



Thus by plotting these event distributions for our process, we can tell whether we have two invisible massless particles (which looks like the blue) or three (which looks like the purple) - and if there are more, the likelihood of them all lining up will be even smaller, so the trend continues (4 is green).

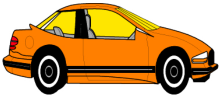


I hope you now see how the randomness in quantum mechanics actually helps to do something that sounds impossible — counting the number of invisible massless particles produced in some particular process. You might now be able to guess how we might see a fractional number of invisible massless particles.



If in some process, we get the result shown in red, which is in between the blue we expect for 2 invisible massless particles and the purple we expect for 3, how else could we interpret it than to assume that we are making some number of massless particles between 2 and 3 - something with a fractional part like 2.5?

Energy



→ momentum

E $\vec{p}$

Energy → momentum

unparticle stuff mass is not fixed but can be measured

relativistic energy (mass is not conserved)

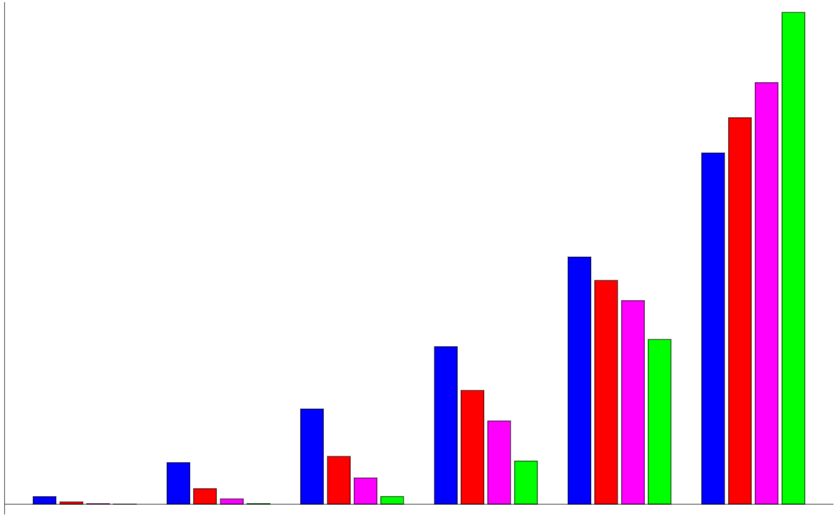
momentum has direction (vector)

$$E^2 - \vec{p}^{\,2} c^2 = m^2 c^4$$

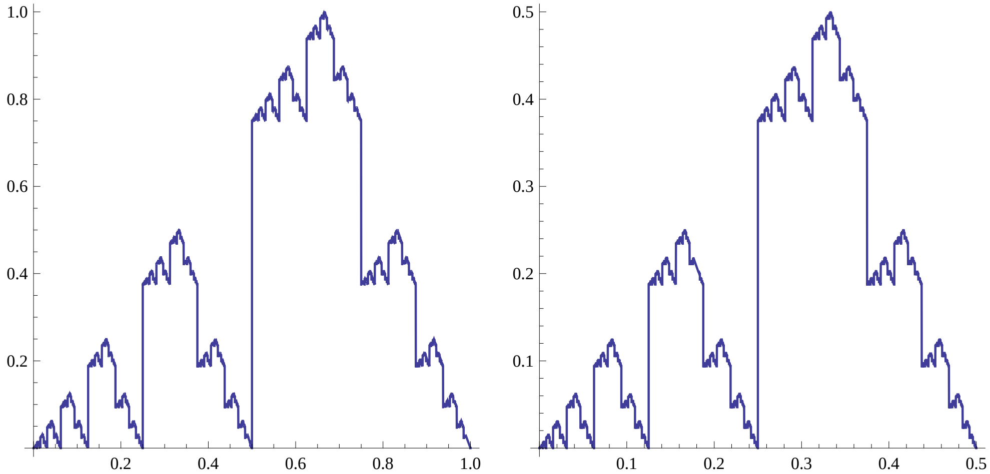
$$\vec{p}/E = \vec{v}/c^2$$

$$\frac{1}{T^2} - \frac{c^2}{\lambda^2} = \frac{m^2 c^4}{h^2}$$

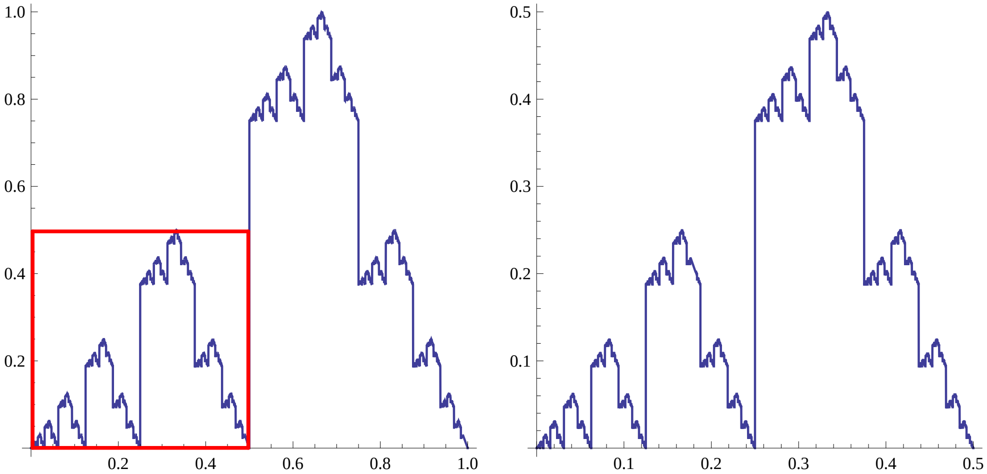
Why might we expect the production of unparticle stuff to do something like this? We can measure the missing energy and momentum of unparticle stuff in the same way as we do for any other invisible particles. And we can make the same plot.



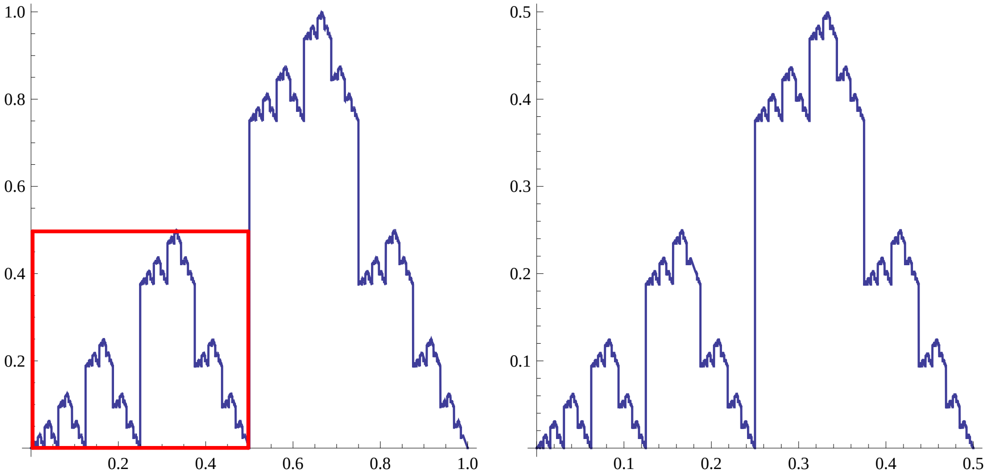
But we certainly cannot talk about the probability that a fractional number of particle momenta will have the same direction. Fortunately there is another way. This is where scale invariance comes in. So let’s change gears and discuss that. Then we will come back to these distributions.



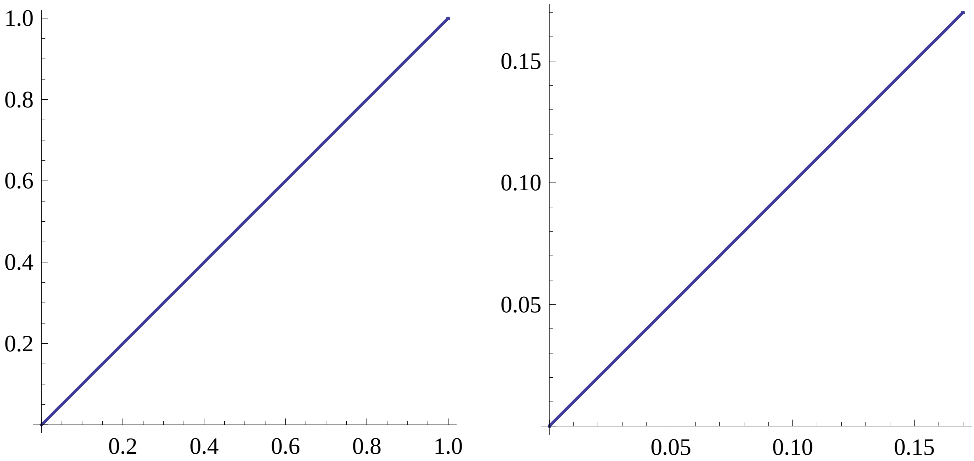
This is one of my favorite fractal graphs. It is a very jagged function. If this were a more technical talk, I would write down the formula. But let’s just look at it. The graph on the left is a plot of the fractal. So is the graph on the right. The difference is that both axes are divided by 2. The graphs look just the same.



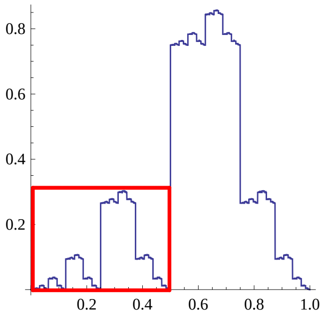
An equivalent way of saying the same thing is that the small rectangle in the graph on the left, if scaled up by a factor of 2, is exactly the same as the graph on the right. This graph has a discrete scale symmetry.

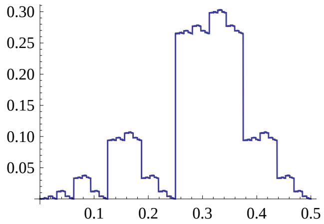


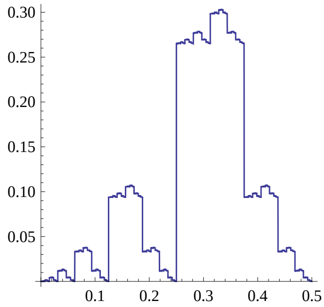
We call this trivial scaling because when the x axis is stretched by a factor of two, we need to stretch the y axis by exactly the same factor to get an identical graph.



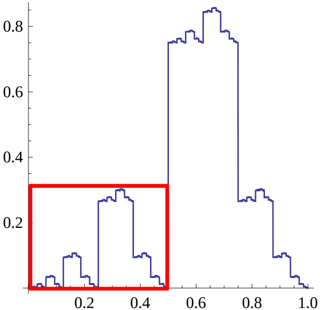
We are actually more interested in what is called continuous scale symmetry, in which you can stretch the x axis by any factor, you can stretch the y axis by the same factor and get the same graph. This leads to very boring pictures. Here on the right, the axes have been stretched by 5.88, but anything would have worked.

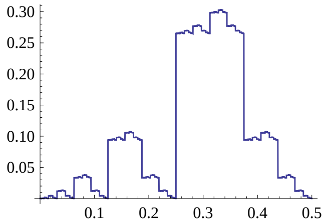


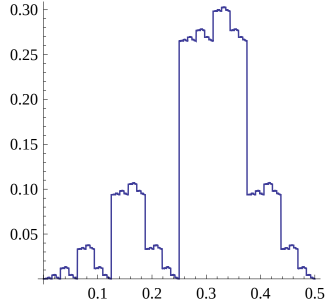




Here is a fractal with non-trivial scaling. This time, if we stretch the x and y axes of the graph on the left by a factor of 2, we get the graph in the middle, which doesn't look the same as the graph on the left.

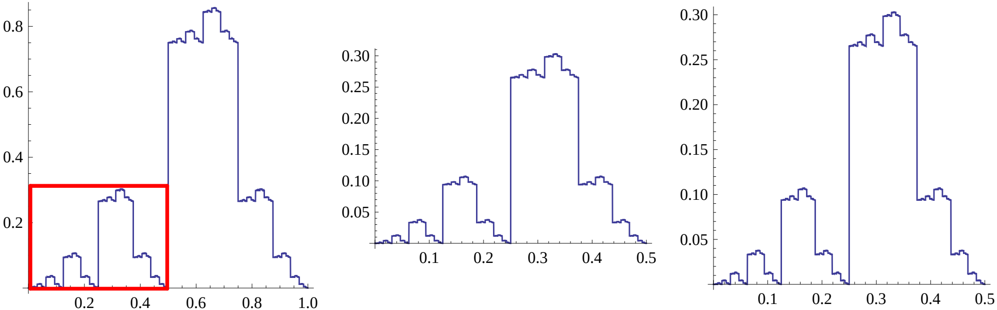






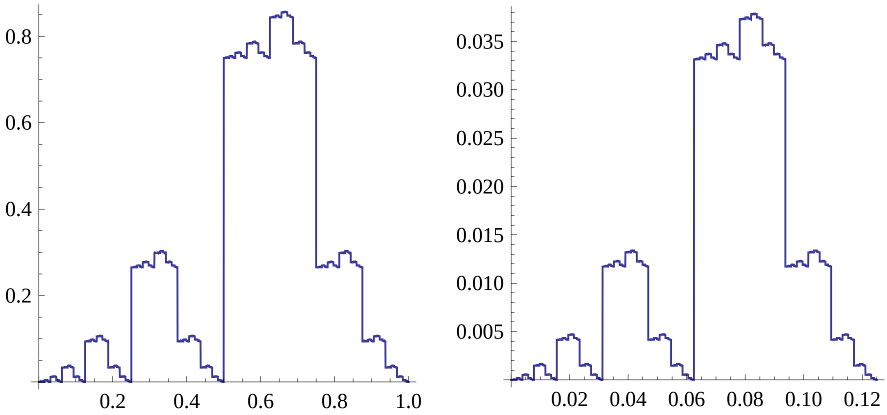
x stretched by 2 y stretched by $2^{1.5} = 2 \times \sqrt{2} \approx 2.83$

What we need to do to get the graph on the right, which looks the same as the graph on the left, is to stretch the x axis by a factor of 2 and stretch the y axis by a bigger factor - 2 to the power 1.5 - about 2.83.



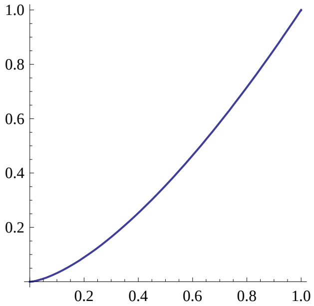
x **stretched by** 2 $\quad$ y **stretched by** $2^{1.5} = 2 \times \sqrt{2} \approx 2.83$

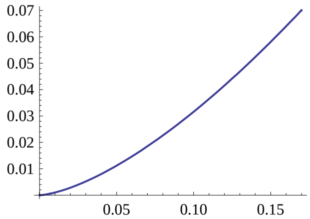
The exponent 1.5 in $2^{1.5}$ here is an important number called the scaling dimension. The reason we write $2^{1.5}$ rather than just 2.83 is that we can scale this fractal in an infinite number of other ways and still get the same graph, but the scaling dimension 1.5 is always the same.

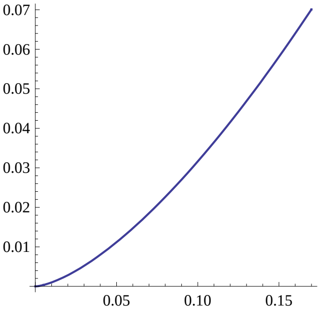


x stretched by 8 $\qquad$ y stretched by $8^{1.5} \approx 22.63$

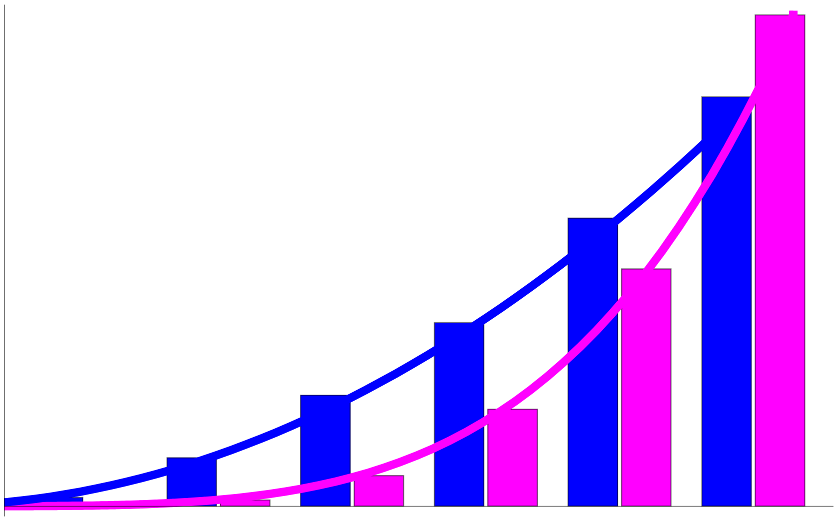
Here is the graph with the x axis stretched by a factor of 8 and the y axis stretched by $8^{1.5}$ which is about 22.63. The scaling symmetry of the fractal means that we can stretch or shrink the x axis by any power of 2, and we get the same graph if we stretch or shrink the y axis by the same factor to the power 1.5



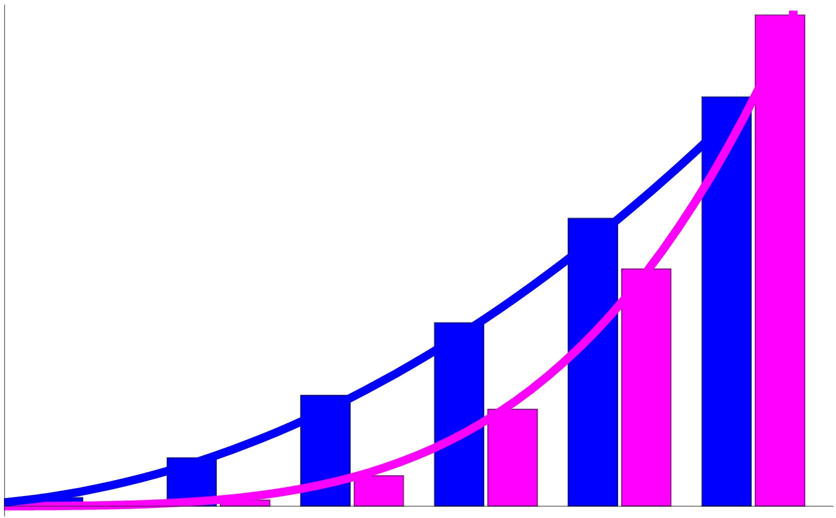




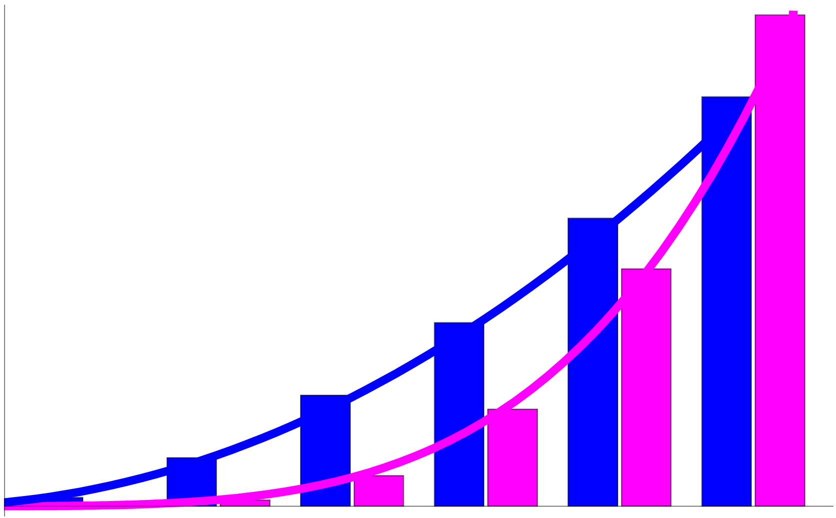
Here is an example of nontrivial scaling with scale dimension 1.5 in the continuous case. Now that we have discussed scaling, let's go back to our mass distributions that we use to count invisible massless particles.



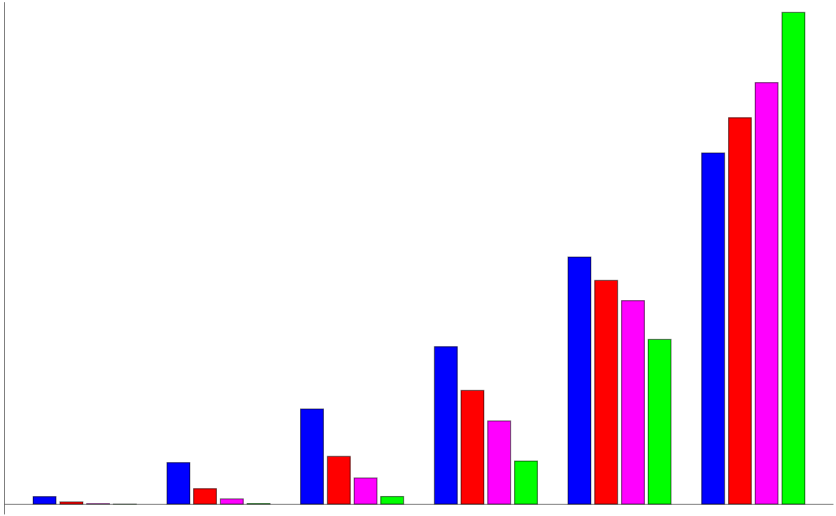
Here again are the distributions for two and three invisible massless particles (in blue and purple) Now I have drawn smooth lines through the histograms, and these are just graphs of simple powers of x. These scale with scale dimension 2 (a parabola) and 4.



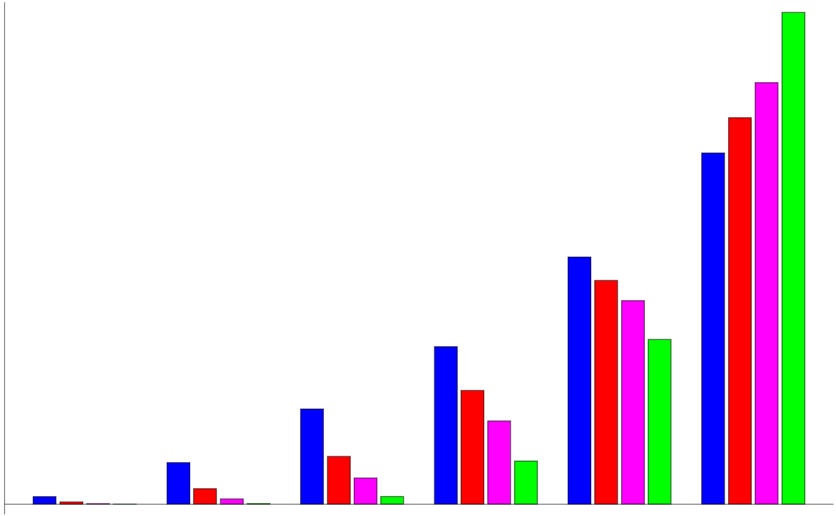
This is the connection with scale invariance. The distributions we use for counting invisible particles scale with integral scaling dimensions. Integral scaling dimensions don’t indicate any unusual physics. In fact, we use the word “dimension” here because they arise naturally in 2 and 3 dimensions.



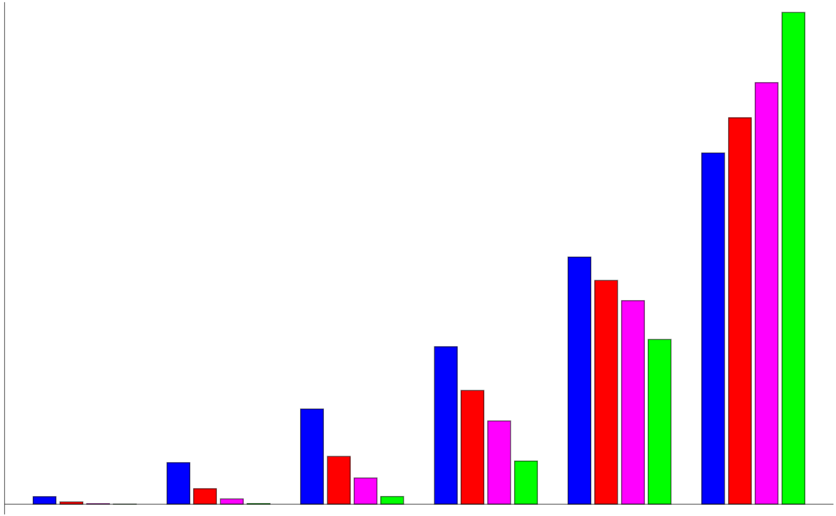
The area of a 2-dimensional object has scale dimension 2 - because the area goes like the square of the size. Similarly, The volume of a 3-dimensional object has scale dimension 3. But if we get scaling with a nonintegral dimension, we know that there is some interesting physics going on.



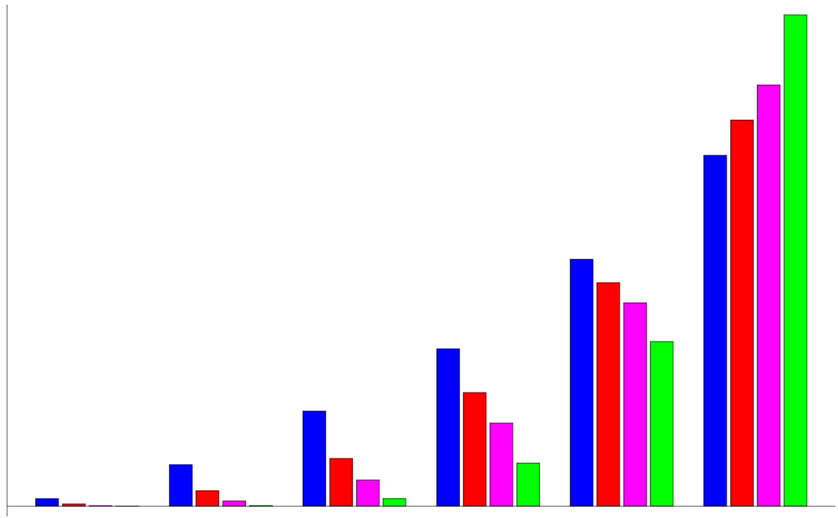
One thing we know about an unparticle theory if it has scale invariance is that we expect things to scale with nonintegral scaling dimensions. And in fact, one can show with more math than I will use here that the distributions you expect in missing mass experiments are just like the red bars we talked about earlier.



So as promised unparticle stuff (IF it exists and IF we can make it in collisions of ordinary particles) “looks like” a fractional number of invisible massless particles. And now you know what “looks like” means in more detail.



I hope that we are very early in the process of thinking about the other unusual properties of unparticle stuff. The process could go on for a long time if either one or both of two things happens.



1: It could be that the theory will be a rich source of theoretical ideas. In a sense, unparticle stuff is a new metaphor for mathematical structures that we understand in other ways. New metaphors can be powerful, and can tie things together in new ways, leading to theoretical progress.

2: It could be that the LHC will discover evidence for unparticle stuff, or phenomena so puzzling that unparticle physics is in the mix of possible explanations. If both of these things happen, then unparticle physics will be here to stay. If neither, it will eventually go to the graveyard of failed theoretical ideas.

Whatever happens, it is the process of exploration and discovery that is the fun part. What we discover is important, and will, we hope, lead future scientists to push back the boundary of the unknown still further. But here and now, we want to do the exploring ourselves! So ON TO THE LHC!