BOOKS AND IDEAS PODCAST

with Ginger Campbell, MD

Episode #24:

Follow-up Interview with Dr. Frank Wilczek

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This is episode 24 of *Books and Ideas,* and I'm your host Dr. Ginger Campbell. Today's episode is our second interview with Nobel Prize winning physicist Dr. Frank Wilczek. You can find the links and show notes for this episode at booksandideas.com.

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Before I get into the interview, I want to remind you to go to sciencepodcasters.org to find other podcasts on a wide variety of topics.

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Ginger Campbell: Frank, it's great to have you back on *Books and Ideas.* Did you get much of a response from your first visit on the show?

Frank Wilczek: I got some e-mails which were enthusiastic, so here I am again.

Ginger Campbell: For the sake of people that might not have heard the first episode, I'm just going to do a very, very simple overview of what we talked about last time. We talked about two key ideas, one of which was the fact that matter turns out to be made out of energy.

Frank Wilczek: Yes.

Ginger Campbell: And the other one, the fact that space is not empty. And I'm going to quote from what you said last time. You said, "Space is a medium. It's not just an important component of reality, but the primary component of reality."

Frank Wilczek: Yes, that's we understand things today, with great precision and accuracy, so I think that's a fair philosophical conclusion from science. Those are very good starting points, so let's jump in from there.

Ginger Campbell: We had some questions last time that we didn't get around to talking about.

Frank Wilczek: Yeah, all of them. [laughs] Right.

Ginger Campbell: I do want to make sure we get a little further this week. I thought maybe we might start with talking about the 2008 Nobel Prize for Physics. Could you give us a sort of layman's explanation for exactly what that Nobel Prize was about?

Frank Wilczek: Yes. This is the most recent Nobel Prize, which I guess was awarded just three days ago. The prize had two parts, which were quite distinct actually. Half of it went to Professor Yoichiro Nambu, who is of Japanese origin but has been at the University of Chicago for many years, for his work on what's called spontaneous symmetry-breaking. Spontaneous symmetry-breaking is an extremely powerful concept now in our construction of world models.

Well let's start with symmetry and then we'll go on to the more subtle concept of symmetry-breaking. Symmetry is the idea that you can make transformations on something, and yet these transformations don't change it. For instance, a simple example is when you have a sphere. You can rotate it around its center, and that will be a transformation of this sphere that- for most objects if you rotate it around their center they would not look the same, but a sphere is special because you can rotate it and it does look the same. And that captures the idea of symmetry, that a sphere is very symmetric because you can make many transformations on it without changing it. There's a rough concept of symmetry, but that's a mathematical concept that corresponds to the intuitive idea that an object has symmetry.

What's proved extraordinarily powerful in modern physics is the idea that physical laws, or the equations that express them, have symmetry. So that, for instance, special relativity, which we have been discussing, is based on the idea that the laws of physics look the same to observers moving at finite velocity relative to one another. That can be stated as a symmetry principle- we call it boost symmetry- namely that there are changes you can make, not rotations of a sphere but in this case boosting, that is moving at a constant velocity, which are transformation, and if the laws of physics were not of the right form- if they are the form thought of in pre-relativistic days, for example, the laws would change and physical behavior would change if you made this transformation. But relativity says precisely that there's a symmetry of the laws- that you can make this transformation without changing physical behavior or without changing the equations.

So that's a very powerful concept and it tells you a lot about the laws. It's not easy to construct laws that have this special property that you can transform them without changing their content. And so it give you a guidance as to formulating the laws. That idea was so successful- with special relativity and other ideas- that physicists became very fond of it, especially as we entered into domains where we couldn't do so many experiments easily, and where the familiar experience kind of failed us. We had to grope around for ideas for how to figure out what the laws are, and symmetry was one thing that people tried to hold on to, and that's worked very, very well.

But it seemed to be running out of steam at one point because the fundamental laws looked lopsided in different ways. That's where the idea of spontaneous symmetry-breaking comes in. So the idea is that there are underlying equations that are symmetrical, that have this special property, that you can make transformations without changing the content, but the stable solutions of those equations, in particular if they're equations for the world- the way the world behaves is not symmetric because the stable solutions has less symmetry than the equations themselves.

Ginger Campbell: Like time seems to go only in one direction.

Frank Wilczek: Yes. Well the example I like is, there's nothing in the laws of driving that says it's a good idea for everyone to drive on the right versus for everyone to drive on the left. The stable solutions of the equations of driving see that that better be the case that everyone drives on one side or the other, so the stable solutions have less symmetry than the original situation. That's a very good example, I think, of spontaneous symmetry-breaking. And of course in domains that aren't connected, like the United States and United Kingdom, you could make different choices and either one will work, but any one world, so to speak, has to make one choice or the other.

So that's the way you can have symmetry in the underlying concepts, or in physics in the underlying equations, but still describe reality that doesn't manifestly have the symmetry- is if the stable solutions have less symmetry than the underlying equations. So what Nambu did is find the first powerful specific case of that phenomenon of spontaneous symmetry-breaking where he was able to show that you could have more beautiful and consequential equations for the theory of pi mesons if you assumed that the equations had a kind of special symmetry, this kind of exotic symmetry called chiral symmetry, that the equations had that symmetry but the solution in the world doesn't have that symmetry.

Ginger Campbell: And that's the experimentally confirmed...

Frank Wilczek: That's been experimentally confirmed, right. From that idea he derived consequences that could be checked that turned out to be correct. So that was important in itself, but I would say even more important as an inspiration for further developments in physics where we were emboldened to look for hidden symmetries. That's been a very, very powerful concept. The equations of the world might be more symmetric than they look in appearance. You can save a lot of the consequences of symmetry without having symmetry if the symmetry is spontaneously broken.

Ginger Campbell: And that's what the Nobel Prize is really about, is about discoveries that then sort of chain reaction to other work, right?

Frank Wilczek: Usually, usually. Right. It's things that have important consequences, right. So that was half of the 2008 Nobel Prize. The other half was to two Japanese, so this is Kobayashi and Maskawa, and their theoretical discovery was remarkably simple and yet powerful.

There had been discovered in 1964 experimentally that the equations of physics are not quite the same if you change the direction of time. Of course our experience is far from the same if you reverse the direction of time- the past looks very different from the future. But we're not talking about macroscopic experiment or everyday life, but rather the interactions among various basic particles and the fundamental equations when you have small systems- whether the laws look the same going forwards or backwards in time. Or in other words if you take a movie of what was happening and then ran it backwards, would it violate the laws of physics or not?

And remarkable, through all the centuries of development of physical laws, starting with Galileo and Newton, until 1964 all the evidence was that the equations of physics- the fundamental equations in simple situations with reactions among elementary particles- that the equations *were* symmetric under reversal of time. But in 1964 a very small discrepancy was found between forwards and backwards in time, involving unstable particles at accelerators. Well the details are very, very tricky to describe, but the basic thing is that there are small discrepancies with the hypothesis that the laws of physics look the same forwards and backwards in time.

Of course people tried to explain or accommodate that within the framework of all the known laws, which tended to be symmetric under this operation of reversing the direction of time. And there are many guesses as to why it might be, as to how to change the laws, but Kobayashi and Maskawa came up with a very simple idea that was way out of left field, but that's to be right.

To describe this idea, I have to bring in what may seem a completely disconnected phenomenon, which is that also over the twentieth century, another thing that physicists discovered experimentally and didn't understand and still don't understand, is the so-called family problem or replication of elementary particles. So the electron is a famous elementary particle. It's very important in everyday life. A less famous, and much less important in everyday life but part of the world, is the particle called the muon, which is a heavier version of the electron but has essentially the same properties. It has the same electric charge, the same quantity of intrinsic spin, essentially the same weak interactions. It's the same in all its properties. We don't know why there's this replication of the electron with all the properties the same except the mass.

And then as time went on, people understood that there were quarks as the basis of understanding protons and neutron and other things. It really needs two kinds of quarks to understand those. But then as time went on, people found the strange quark, which is kind of a replication of the down quark, and the charm quark, which is kind of a replication of the up quark, and there are also neutrinos associated with electrons and associated with muons. In short, there was just a doubling of all the particles. Each one had a partner with the same properties but different mass.

Ginger Campbell: Are these replications only observed in experiment or, I guess there's not really any way to...

Frank Wilczek: Yeah they're observed in various experiments. Most of the partners are unstable. They have sub-second lifetimes. They don't occur ordinarily in everyday life. They occur in vary astrophysical situations and were discovered at accelerators, where you pump a lot of energy into a small space and you produce heavy, unstable things routinely. So there was this doubling, but no one knew why there was a doubling. The famous physicist Isidor Rabi, when the muon was discovered, said, "Who ordered that?" And there's no answer to this day. It's one of the great embarrassments of theoretical physics that we don't understand why there are these doublings.

But then in 1972 what Kobayashi and Maskawa realized is that if you had not just a doubling but a tripling, then you could tweak the equations in just a little bit and accommodate this phenomena that they wouldn't look the same backwards in time. You could tweak the equations in a simple but elegant way that would accommodate that possibility, whereas with just two replicas you couldn't do that.

Ginger Campbell: So the tripling idea was kind of out of left field.

Frank Wilczek: Way out of left field. To explain it properly I have to rely on quite a few equations and a lot of patience, starting from scratch to explain the connection. It's very very deep.

Ginger Campbell: What would a regular person come away with as far their Nobel Prize?

Frank Wilczek: Let me just complete the story, which is that shortly afterwards, sure enough, starting in the mid-70s, people started finding that there *were* heavier replicas. This was the tau lepton for the electron and muon, the top and bottom quarks- the top is the partner of the up and charm, and the bottom is the partner of the down and strange, and another neutrino. And so the whole triple thing was found, and furthermore, very detailed investigation of the phenomena of time reversal non-symmetry... not quite time reversal symmetry- violations of this- almost symmetry- verified the theoretical framework that Kobayashi and Maskawa put forward in very considerable detail. So it's been the basis of a whole fruitful field of experimental investigation from this exotic phenomena- exotic but very profound. Not quite validity of time-reversal symmetry to postulate a third family to get a very specific theory for how other experiments involving new particles would work. That was the field-recognized and clearly Kobayashi and Maskawa made the central theoretical contribution.

Ginger Campbell: So then basically it's another example of a theory making it possible to look for experimental confirmation.

Frank Wilczek: Right. It was a theory that made very specific experimental suggestions, first of all the existence of this third family but then beyond that, predictions about the properties and further examples of time-reversal non-symmetry that have kept people very very busy and gainfully employed. Of course the experimenters involved were hoping to find deviations so they could get their own Nobel Prize for new phenomena, but it wound up verifying this theory of Kobayashi and Maskawa so far. I think you were going to ask about the ramification.

Ginger Campbell: I was actually going to ask you, are these two halves of the Nobel Prize- do you consider their work to be related?

Frank Wilczek: It's only very very tenuously related, I would say. I mean they're both in the same broad area of physics- theoretical fundamental or theoretical high-energy physics- but the actually work that is involved is separated by ten years and really it's very tenuously related, which... they're quite distinct ideas.

Ginger Campbell: The Nobel Prizes usually have a significant time lag between the work and the Nobel Prize, so...

Frank Wilczek: Right.

Ginger Campbell: ...none of this work would be considered new to people that are in your field. It's work that you.

Frank Wilczek: No, no. Nambu's work was around 1960 in fact and as I mentioned in passing, I think Kobayashi and Naskawa's work was in 1972. So yeah, so there's a long time.

Ginger Campbell: So is there an important ramification that you feel like we need to bring out before we move on?

Frank Wilczek: In both cases there are tremendous ramifications. I sort of alluded in general to the philosophical consequences or the fact that this idea of spontaneous symmetry-breaking has been tremendously helpful and powerful in guiding us to formulating new laws. So a specific example of that is in the theory of the weak interactions, where it's been possible to find very very beautiful, symmetrical theory with equations of high symmetry- it's called gauge theory- that, however, is too good for this world. The immediate suggestions of the equations, which would include having zero mass particles- w particles and z particles, aren't characteristic of the world. However, the idea that the underlying equations might have those problems but the stable solutions don't made it possible to rescue that framework, and that has been put to very powerful, accurate theories of the weak interaction. That work got a Nobel Prize quite a long time ago- I think in the late 70s or early 80s.

Nambu's underlying concept took longer for people to appreciate properly, I think. Well, he should have gotten the Nobel Prize a long time ago, is what I'm trying to say [laughs]. But in the weak interactions, the story goes on. Now the fact that the stable solution has less symmetry means there has to be some extra part of that solution that's not present in the general solution that spoils the symmetry, some part that actually changes when you make the transformation. The equations don't change but the solution does change.

A metaphorical way of understanding that, which is a different way of looking at it but it's really the same thing, is that it's as if we are fish in an ocean that we have been unaware of for a long time, because we're always surrounded by it. But as we learn more about physics- we're very intelligent fish- we learn more about physics, we learn that we can get a nicer description with prettier equations if we say that we're not moving around in emptiness or in a medium that is unstructured but in this thing called water that changes the laws that, for instance, breaks this boost symmetry of special relativity, because if you're swimming through water it definitely is not the same as if you're not swimming, and this motion really is different- you have to work to keep moving at a constant velocity. So if we were very, very smart fish, we might figure out that, well you have this beautiful theory of relativity if we're willing to accept the idea that we're living in this medium that spoils it. That's very, very much like the situation we have in the weak interactions, where we have much prettier equations if we accept the hypothesis that we live in a all-pervasive medium that spoils the symmetry.

Ginger Campbell: So we're back to the grid.

Frank Wilczek: Yeah, it's an essential element of the grid, as well as the fluctuating fields and the quantum fluctuations that I think we talked about last time. There are these constant fields that are all-pervasive. In this case it's called the Higgs field, and it's a big enterprise now to try to prove directly this hypothesis that we're surrounded by a medium, by sort of breaking off little pieces of the medium or discovering its atomic structure- what it's made out of. That's going to be a big goal of the LHC Large Hadron Collider project.

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Ginger Campbell: *Books and Ideas* is sponsored by Audible.com. I've been a member of Audible.com since 2003. I just got done reading *Ender in Exile* the latest book in the Ender series by Orson Scott Card. If you like science fiction and you haven't read any of these, I suggest trying out *Ender's Game*, which is a classic. It was actually originally published back in 1985. You can get that as a free audiobook download by going to audiblepodcast.com/booksandideas.

[music]

Ginger Campbell: I want to shift gears again and bring us to the issue of string theory, because when I was reading your book, you don't talk much about string theory. Your book has kind of taken a very different, at least to a non-physicist it seems like a whole different approach and maybe...

Frank Wilczek: Yeah.

Ginger Campbell: So, can you just say something about string theory? Does it have a relationship to what you do?

Frank Wilczek: Yes. String theory is an attempt to formulate a theory of strings that obey quantum mechanics, and that leads by a long, long series of stories to many complications, and to implement that idea you're led to various contortions and additions and historically, people have wound up trying to make a consistent theory of that kind into a theory that has quantum mechanics and has gravity and actually lives in a large number of spatial dimensions and so forth. You're led into a very rich line of thought for model construction. But the original hypotheses were sort of of a very mathematical or speculative nature. They weren't derived from any concrete phenomena. So to have led to this kind of world model that has very interesting and suggestive mathematical properties, can have gravity, general relativity in theory in it, as well as quantum mechanics. So it is a world model that is driven initially by hypotheses of a very abstract kind, and it's a very unrooted kind of world model. It's not rooted in phenomena, and its pristine form has all kinds of properties that we don't observe in the world.

Ginger Campbell: Right.

Frank Wilczek: But now, because of the idea of spontaneous symmetry-breaking, it's possible that somehow when you solve the equations, whatever they are, that are suggested these kinds of considerations, that they will match our world. That the solution will match our world, that particular stable solution will have just the properties we observe in our world. And people have been trying now- intensely, I would say, for the past twenty five years, but at some level even for fifteen years before that when the basic ideas emerged- been trying to implement this idea, making contact between the abstract framework and concrete phenomena. But so far it hasn't quite gelled.

Ginger Campbell: Is there any historical precedent for a theory coming from this direction rather than...

Frank Wilczek: One can draw rough historical parallels to one aspect or another. I'd say perhaps to me, the closest parallel is when Newton invented classical mechanics, and his gravity theory, and everything that goes with it in the late 17th century. It made a tremendous impression on people. They tried to make world models based on the idea that you had not just gravity but other forces acting instantaneously with simple laws between point particles and are using concepts of Newton's theory to try to explain not just the phenomena that he did explain (the motion of the planets and tides and many other things) but also the microworld- chemistry, what held things together and so forth. Some people tried to build models with different force laws and they tried to implement that sort of grand vision. But it was always kind of vague and never quite gelled. We now know that essentially new ideas were needed to finish the job. So it's something like that. You have a big, basic idea that suggests a certain kind of model, but then you're trying to implement it concretely and so far it remains kind of vague.

Ginger Campbell: The basic idea is easy for non-mathematicians to grasp even though we really don't have a clue about the math.

Frank Wilczek: You mean the basic ideas that things are made out of strings as opposed to points? But that doesn't really give the flavor of the enterprise, because the difficulties that one finds in trying to implement that idea naively are precisely what lead you to all kinds of elaborations and extra structures so that at the end of the day it doesn't look very much like the original picture of simple strings vibrating in different wave.

Ginger Campbell: Do all those extra structures and all come in from trying to get the theory to fit our actual world?

Frank Wilczek: Some of them do. One way of getting at the starting point is trying to make the idea of having string-like objects consistent with the laws of relativity and quantum mechanics- turns out to be very, very challenging. So in a sense, since relativity and quantum mechanics were derived from the phenomena, you could say, "Yes, it is trying to fit the underlying idea to the world." But it's not detailed. it's not any, you know, detailed phenomena that we didn't know about or just discovered- it's trying to make the theory even consistent with quantum mechanics and relativity. So like trying to make sure that the probability in quantum mechanics for something to happen adds up to 1. You don't get negative probability, things like that. Those complications are what drives it, and also trying to make it consistent with relativity turns out to be not easy. That's what leads to all the complications and the extra dimensions and super-symmetry and x-specific gauge groups -lot of, lot of structures that one wouldn't have guessed and that aren't manifestly properties of the world come out of trying to implement the original idea.

So the things that I explain in my book are not necessarily inconsistent with string theory, because string theory is so vague, or the solution of it is so poorly understood and vague in practice that it's hard to say that anything is inconsistent with certainty. But my approach is much, much more rooted in the phenomena and trying to build on what we already know and make improvements on that directly rather than starting from some very, very remote hypothesis and hoping that the models you get from that luckily turn out to match reality.

Ginger Campbell: I got an e-mail from a physics professor in Canada who seemed to be arguing that my claim, or understanding, that string theory isn't testable was wrong. She was saying that there *was* going to be some kind of testing of some version of string theory at the Large Hadron Collider.

Frank Wilczek: Well, I don't know precisely what she is referring to. One could certainly imagine that there are phenomena at the Large Hadron Collider that would be suggestive of strings. Strings have vibrations, and in quantum mechanics they can be in different states of vibrations. Those would have different energies and so would be associated with different kinds of particles with different masses. So if particles with exactly the right kinds of properties started to be discovered, then you *would* be driven to a description using strings.

Ginger Campbell: Are we talking about new particles?

Frank Wilczek: They would have to be new particles, yeah. You definitely can't describe the particles we know about as being different states of a vibration of a string- they don't have the right properties. So these would have to be new particles. So that's one possibility. Another possibility is, you might find that you have new particles that can most easily be described as having a structure in extra spatial dimensions.

Another thing, which is close to my heart and is explained in great depth in *Lightness of Being*, is that there's an extension of the equations of physics called super-symmetry that I think is suggested by actual phenomena. That's explained in the book. That is attractive in many ways that extend the laws of physics and leads to the prediction of new particles that could be observed at the LHC. And I think there are real prospects because there is this circumstantial evidence already. I think there are real prospects, much more realistic prospects that some of the particles of super-symmetry would be discovered at the LHC. String theory *uses* super-symmetry as a spontaneously-broken symmetry, but I would say that super-symmetry is an independent idea that stands on its own, so you could certainly have super-symmetric theories that aren't based on strings. It would probably encourage advocates or evangelists for string theory, but it certainly wouldn't qualify as direct evidence.

Ginger Campbell: Right.

Frank Wilczek: So there are different levels. You could actually see, in some sense, the strings, or you could see evidence for ideas very much suggested by string theory, or you could see evidence for ideas that are conceptually related to string theory. It's a complex situation, so it's somewhere between string theory not being testable and string theory being testable. Certainly if you start to see evidence for particles that have internal vibrations that suggest that they really are strings, that would be very very impressive. If you find super-symmetry that's very important and great in many ways, but its connection to super-symmetry is a little weaker. It stands on its own.

Ginger Campbell: So from your standpoint we wouldn't really need string theory unless something really unexpected was to come up that couldn't be explained by the models that you're already using?

Frank Wilczek: Well it's a question of value added. This often comes up in science and it's often discussed under the name of Occam's Razor, as William of Occam, who long ago in the Middle Ages put forward the principle that you shouldn't multiply hypotheses without cause. Newton said things very similar- *hypotheses non fingo*- I do not multiply hypotheses. That is an important principle in data fitting and philosophy and Bayesian statistics and many other domains- that when you have a body of phenomena to describe you should try to use the theory that is most parsimonious in hypotheses.

Ginger Campbell: Mm hm.

Frank Wilczek: And certainly you don't use a theory with many, many, many extraneous hypotheses. Or you can't claim evidence for a theory with many, many extraneous hypotheses based on evidence that only gives evidence for a small number of those hypotheses or maybe some only tenuously related hypothesis. That's the situation. So given the complexity and the vagueness of string theory as it exists today, I think Occam's Razor really gives it a big shave.

Ginger Campbell: [laughs]

Frank Wilczek: Unless the phenomena really call for it.

Ginger Campbell: There was one other objection that Smolin brought out in his book that impress me, which was the principle of the fact that it seems as if, if I understand this correctly, that first of all you already alluded to the fact that right now it doesn't seem to fit any known thing in the world, but also that it has- seems to have- infinite solutions.

Frank Wilczek: Well it has many, many solutions. That's not necessarily to say it's wrong. It just means that it's difficult to draw consequences from, so you have to hope that many of the solutions have common properties or that there are phenomena that are very difficult to accommodate in a different framework that do fit into this framework.

Let me give you an example. Right now, I would say the fundamental theoretical basis of theoretical physics is not string theory but in practice, quantum field theory. Quantum field theory has a very powerful set of hypotheses that basically realize special relativity and quantum mechanics. But there's not a unique quantum field theory- there are many, many of them. So you could say that quantum field theory doesn't give you a theory of everything, however all quantum field theories have certain highly non-trivial properties in common. So even though there's not a unique solution or a unique example, unique realization of quantum field theory, the fact that they all have some properties in common makes them still powerful.

So for instance, all quantum field theories have anti-matter together with matter, and make very specific predictions for what this anti-matter should be. It should have lots of the same properties of matter but the opposite charges. Quantum field theory also makes the unique connection between forces and particles. When you have a force like, specifically, the electric force, it has to be mediated by a particle, which in that case is the photon. That is a general consequence of quantum field theory. So when you have the strong force there has to be a particle responsible for it- that's the gluon. And so on. In some cases we discover the particle first. In other cases we discover the force first. Either way, you get a prediction. Having found one, you have to find the other. So they're very powerful principles.

Now it's conceivable that by studying string theory you'll find some very, very powerful principle that transcends the difference between the different solutions. So far there's nothing like that that I know of. But I think the best hope is not that- I think the best hope is that you'll find some phenomenon, either in cosmology or in high-energy physics, that's awkward or impossible to describe within the framework of quantum field theory. And then you'll be looking for new principles and string theory might suggest it.

Ginger Campbell: Mm hm.

Frank Wilczek: That hasn't happened yet, but it certainly could happen.

Ginger Campbell: You really, I guess, belong to the generation that came along before the popularity of string theory.

Frank Wilczek: Well I destroyed string theory. String theory was originally invented as a theory of the strong interaction. You would describe things like protons and neutrons and the other strongly interacting particles as vibrating strings. And that had already existed as a theory and was very popular when I was a graduate student, but out of my work came the realization that a much better description of the strong interaction was based on the idea that protons and neutrons and these other particles are described in terms of quantum fields based on particles, not strings. The particles are the quarks and the gluons. It put string theory out of business at that time, in its original incarnation.

Ginger Campbell: Right.

Frank Wilczek: Then it came back as a theory not of protons and neutrons. Now the quarks and gluons themselves are made out of strings, and many other things are supposed to be made out of strings. So it was reincarnated in a different form. I'm not as old or out of it as you might think. [laughs]

Ginger Campbell: I'm glad you explained that timing, because I had kind of forgotten the basic story of the fact string theory has really kind of had at least, if not more, incarnations.

Frank Wilczek: Right.

Ginger Campbell: But why does string theory seem to appeal to so many young theorists? Or is that still true?

Frank Wilczek: It's had its ups and downs. This is a question of psychology as well as physics. [laughs]

Ginger Campbell: Right.

Frank Wilczek: And really also I must say, it's into questions of academic politics when you really analyze it.

Ginger Campbell: Mm hm.

Frank Wilczek: Putting all that to one side, it's an appealing subject with a lot of mathematical structure, a lot of work for people to do. And not without promise [as physics? 0:36:00]. So it's taken on a life of its own and has led to truly remarkable developments in pure mathematics and no blatant inconsistency has shown up so far. You know it's something that deserves investigation and is an attractive thing for young people to investigate, just because there's a lot of work to do and also because it has a community that appreciates it.

Ginger Campbell: It's a valuable field as long as it doesn't just like try to eat everybody else.

Frank Wilczek: Yeah, I think there has been some off-putting kind of academic politics- aggressiveness that I find very off-putting, and not my image of what the scientific community should be in. This kind of dispute is more characteristic of philosophy departments or English departments or literature departments than scientific departments, and I would like to keep it that way.

Ginger Campbell: The last question that I wanted to ask you last time, and didn't get around to, was about- what is dark matter and dark energy?

Frank Wilczek: Well in the mid-70s, physics had a golden age and what's usually called the core model- I'm sorry- the standard model (I like to call the core theory) emerged as a very accurate description of all phenomena known at that time, and this postulates that the world of matter as we know it is made out of things called quarks and leptons (of which the essential one is electrons) and photons and gluons. Basically that's it. It was a very reductionist, very powerful theory of what normal matter is. So we were very pleased with ourselves and so we had a permanent foundation for biology and chemistry and engineering, and I still think so. But we also thought we had a sound foundation and complete foundation for astronomy- in that case it hasn't turned out that way because the astronomers discovered that there's some extra stuff in the universe that can't be made out of the stuff in the core theory.

Ginger Campbell: Lots of extra stuff.

Frank Wilczek: Yeah, which adds up in the universe as a whole to 95% of the mass. So this normal matter- the stuff we do understand, we do have a powerful theory of, that we're made out of, that we study in every other branch of science- is only 95- I'm sorry- is only 5% of the mass of the universe and the rest is... other stuff is 95%. We know very little about the other stuff. It's only been detected through its gravitational influence on normal matter- the stuff we *can* observe with telescopes and our other tools of astronomy.

So we find that different clumps of normal matter have objects that are moving too fast to be held gravitationally by the amount of normal matter that is in their neighborhood, and so people were led to postulate that there's extra matter there. At first the evidence was quite tenuous but then this kind of need for extra matter was found at many different scales, ranging from galaxies to cluster of galaxies to the universe as a whole. And then further study revealed other surprises. And now we have not just one mystery but two mysteries, because there seem to be at least two separate components to this extra 95%. One component is called dark matter and that's about 25% of the mass of the universe. And the other is called dark energy, which is about 70% of the mass of the universe.

Dark matter could be some kind of new particle- that's the leading idea. It would be a particle that interacts very, very weakly with normal matter. That's why it hasn't been observable in telescopes and how it escapes our notice for many, many years. There's a kind of model for that. We know there is one kind of normal matter called neutrinos that interact extremely, extremely weakly with ordinary matter. But dark matter would be even more so, even more extreme. But our minds are expandable and our equations are certainly expandable, and we can speculate about what this dark matter might be, and the leading idea is that it's a new kind of particle.

Some of the ideas about super-symmetry that are suggested by attempts at unification of forces suggest the existence of new particles that might have the right properties. These are usually called wimps- weakly interacting massive particles. If that's the case, we'll discover what the dark matter is at the LHC by producing it. So this would be a particle that's very weakly interacting with ordinary matter, that's stable even on cosmological scale, so it has to have a lifetime of 13 billion years or more, and then also has to be something that's produced in the right amount in the Big Bang. So we would have to sort of observe the properties of the particle at the LHC or other accelerators in sufficient detail that we could run it through the history of the early universe and see how much had got produced and see that it was the right amount. And then you could also try to detect it directly because although it interacts very, very weakly with ordinary matter, just like neutrinos it does interact some. And once you know what it is, experimentalists are very, very clever. They'll find ways to find very, very weak interactions with ordinary matter.

There are other ideas too. One I'm fond of is axions, which is another kind of particle which makes our theories prettier in a different way, that I named because it cleans up a problem with an axial current- I named it after a detergent named Axion. And that's very viable- that's my favorite idea for what the dark matter is.

Ginger Campbell: Could that be discovered at the LHC?

Frank Wilczek: That wouldn't be discovered at the LHC. There are other kinds of experiments that are on the lookout for axions, and that's also a very exciting field but they're quite different experiments. They are more like hanging out big radio dishes. Whereas radio dishes, of course, are meant to look for radio waves from the sky, these special antennas that are designed with axions in mind look quite different, but the principle is the same. You have a special kind of setup that resonates with axion vibrations, if they exist. You hope to find them that way. Those experiments are underway- very exciting.

Ginger Campbell: But dark energy is a whole different problem.

Frank Wilczek: And dark energy is something completely different. Whereas dark matter clumps around galaxies and seems to have more or less normal properties, dark energy is perfectly uniform as far as we can tell. So it has the same density everywhere, and even more amazing, has the same density also in the past as now, because since the speed of light is finite, by looking at distant galaxies we can reconstruct the universe in the past and see what kind of mass was around. And this dark energy seems to have the same density also in the past, which is ridiculous [laughs]. Remember that the universe is expanding. Any kind of conventional matter would get dilute. Its density would go down as the universe expands, but not this dark energy.

So the candidates for it are pretty exotic. They link up in surprising ways with this idea of spontaneous symmetry-breaking. I mentioned the Higgs field before. It turns out that if you have not particles but fields that fill all space, that could give you the dark energy. So that's an interesting story too, but the prospects for sorting it out experimentally are much more iffy in large part because we don't have such good ideas about it [laughs].

Ginger Campbell: Do you think calling it *dark energy* is an accurate name or...

Frank Wilczek: No, it's a terrible name.

Ginger Campbell: Because it's not really energy in the sense we think of.

Frank Wilczek: No, no it's not. And furthermore there was a perfectly good name for it. Einstein, when he developed general relativity and started to apply it to cosmology, realized that besides Newtonian gravity there was another effect that was natural within that framework, which is precisely this effect.

Ginger Campbell: The cosmological constant?

Frank Wilczek: Yes- what he called the cosmological constant. Precisely this effect that space would have a finite density. So it already had a name- cosmological constant or the cosmological term- but for some reason, I guess it suggests that maybe it wasn't precisely the kind of thing that Einstein anticipated so we should leave it open, the name dark energy caught on. But it's not a very good name because it suggests...

Ginger Campbell: [laughs] ...all kinds of things.

Frank Wilczek: Yes, it suggests all kinds of things that don't really correspond to what it is. It's become quite standard unfortunately. Unlike axions or anyons, that's not my responsibility.

Ginger Campbell: I think that there's a confusion that probably I'm not the only one that might fall into that I wanted to bring up, and that's the issue of anti-matter.

Frank Wilczek: Yes.

Ginger Campbell: And how it's not the same thing as dark matter.

Frank Wilczek: Right. No, anti-matter is a very different concept from dark matter. Anti-matter- we can illustrate it probably most concretely and best by example. The first kind of anti-matter that was discovered was the anti-electron, or positron. So that's a new kind of particle that has exactly the same mass as the electron and exactly the same spin, but the opposite electric charge.

Ginger Campbell: So anti-matter is normal matter, right?

Frank Wilczek: In a sense it's very normal matter, right. It's not so different from conventional matter. It's just that the charges are opposite. It's rare in this present universe to have anti-electrons, because one property is that anti-electrons, or positrons, when they come into contact with electrons, they annihilate so no anti-electron is left. They annihilate into photons or, well generally into photons.

Ginger Campbell: Is that where the science fiction idea of the anti-matter energy generator or whatever it's called comes from?

Frank Wilczek: Yes. There were some proposals to try to use anti-matter as a source of fuel for interstellar travel. That's not entirely crazy, because you can get a lot of energy stored in a small space. It's an extremely efficient source of energy to have matter and anti-matter annihilating- that liberates enormous amounts of energies. In principle you could build a great battery that way.

Ginger Campbell: [laughs]

Frank Wilczek: By having separate containers with matter and anti-matter and just gradually letting the contents mix. That would be the most compact kind of battery we know how to think about right now.

Ginger Campbell: But wouldn't it take a lot of energy to make?

Frank Wilczek: Exactly. So it's not very efficient. So it takes a lot of energy to make the anti-matter in the first place, so it's not a very efficient way to generate energy, but if you want to economize on weight- to make something very compact, so for interstellar travel for instance- it's not crazy to think that even though it's expensive to make that energy, the fact that it could give you a very light battery with enormous amount of energy stored that you could take up into space might be a very useful thing or useful for propulsion. In a conventional rocket, the payload is a tiny, tiny fraction of the original rocket. So here we can have a much better ratio of payload to weight of the whole thing.

Anti-matter could also in principle be used for bombs, and this was the basis of *Angels and Demons*, where anti-matter was smuggled out of of CERN [the European Organization for Nuclear Research in Switzerland] and used to make a bomb. As a bomb it's really bad, both because it would be a very expensive bomb, and also it would be a very, very...

Ginger Campbell: ... unstable? [laughs]

Frank Wilczek: You really don't want to mess with this thing or carry it around. [laughs]

Ginger Campbell: It would make nitroglycerin look stable.

Frank Wilczek: Very much so. [laughs] I don't think it's a very promising bomb, but [laughs].

Ginger Campbell: [laughs] Well that's good to know.

Frank Wilczek: We're straying from the main point, which is that anti-matter is not related to dark matter at all. Although it's an exotic chapter of physics in the 1930s when it first arose, by now it's not exotic at all. We know not only that electrons have anti-particles, but also protons have anti-protons that have the same mass and spin but opposite charge- you know, exactly the properties they're supposed to have according to theory. And every other particle that's been discovered at accelerators also, people immediately look for its anti-particle or...

Ginger Campbell: Mm hm.

Frank Wilczek: ...often discover them at the same time, so that's a very well-established feature of the world that, I think we mentioned before, is one of the neat, general properties of quantum field theory- that you expect to have with any new particle also an anti-particle with very predictable properties. But it's not conceptually related in any direct way to dark matter, because these anti-particles generally interact very strongly with ordinary matter, but if the dark matter were made out of anti-matter, we'd know it long ago, right? [laughs]

Ginger Campbell: Right.

[music]

Ginger Campbell: I want to take a moment to mention a small podcast from Australia that you might enjoy. It's called *Brains Matter*, and you can find it at brainsmatter.com. The host calls himself just an ordinary guy, and he interviews scientists from a wide variety of fields. Recently he's done a series of interviews with Professor Roger from the University of Melbourne about Asian elephants. The first interview was episode 73 and 74, but he just aired a follow-up, which is episodes 77 and 78. Both interviews contain information that is both surprising and disturbing. If you're like me and you've always liked elephants, you'll definitely want to check this out. You can also find *Brains Matter* at sciencepodcastors.org and in iTunes.

[music]

Ginger Campbell: I don't think that the last time that we talked I had a chance at all to ask you about what you're working on now.

Frank Wilczek: Right. Actually I'm working on this axions as dark matter that we mentioned, trying to think of additional tests and whether it naturally predicts the right amount of dark matter, which it seems to do. I'm very encouraged and excited about that again. But most of my effort recently in physics research has been on a kind of exotic electronics that came out of the mathematics of trying to deal with high energy physics and elementary particles and cosmology but really, one of the beautiful things about modern physics is that the same mathematics of quantum mechanics and field theory and so forth also describes ordinary matter at low temperatures. And so there's a kind of exotic electronics.

Ginger Campbell: Superconductors?

Frank Wilczek: Things like that, right. I call it anyonics based on the almost-certain fact that there are states of matter in which the elementary excitations- so the things you would see as elementary particles if you lived inside those materials- that those have properties that I first realized were consistent possibilities back in the early 80s. People thought for a long time that the only possibilities were things called fermions and bosons, but there are more possibilities- these are called anyons. There seem to be states of matter in which you have these anyons, and they have possibilities for making new kinds of electronic devices that would use quantum mechanics in creative ways. I've been trying to work on that, trying to think of more examples and make them more practical.

Ginger Campbell: Do you have quite a few graduate students working with you, or...

Frank Wilczek: I have only one who's working on that. Well I have one working on axions and one working on that, one working on more general kind of dark matter issues. I've been traveling a lot recently so I was reluctant to take on students, but think...

Ginger Campbell: Right.

Frank Wilczek: ...now that I settled down a bit I think I will be looking for more help. And also I think it's a great opportunity for young people. This is going to be a growth area. The experiments are just finally catching up with these possibilities and there's tremendous room for creativity, and it might even be useful.

Ginger Campbell: Yeah, it sounds like it. Well as I mentioned to you before, this podcast is kind of small compared to the *Brain Science Podcast*. I get a lot of e-mails from students that have gotten interested in neuroscience because of that show, so I hope that between your book and our conversation- and I know you've done a lot of public speaking and interviews and all- to let people know about the fact that there's so much other exciting stuff going on.

Frank Wilczek: Yeah, great. Well I'm, you know, you're one of my heroines now for doing this. I think it's a wonderful thing you're doing. I listened to several of the *Brain Science* one, and I really enjoyed it. It's very helpful to me because, well that's what I started out wanting to study way back when I was an undergraduate. I've kind of kept in touch with it, but, you know, it's impossible to get oriented in the literature now, it's just so fast.

Ginger Campbell: Yeah.

Frank Wilczek: Just by looking at it directly, but having these podcasts has been helpful.

Ginger Campbell: I'm hoping next year that I'm going to be able to interview Eric Kandel. I met him...

Frank Wilczek: Uh huh, I just saw him, well, on December 10th- that's Nobel's birthday. Over in Stockholm they have the award ceremonies and banquet, but a much smaller thing in New York at the Swedish Consulate . They have a little dinner party where Nobel Prize people in the neighborhood can come, and I saw him there. Yeah, I guess about 20 Nobel Prize winners came this year.

Ginger Campbell: I went to the Society for Neuroscience meeting, which was in Washington, D.C. in November.

Frank Wilczek: Right.

Ginger Campbell: And I managed to catch him because he was there to say hi to Brenda Milner. She was giving a historical lecture. You know, she's 90.

Frank Wilczek: Right.

Ginger Campbell: And I managed to catch him with nobody near him. He did agree to come on the show- I've just got to follow up with contacting his secretary.

Frank Wilczek: Yeah. He's busy but he's basically a very kindly fellow.

Ginger Campbell: So I'm looking forward to that, because...

Frank Wilczek: Yeah.

Ginger Campbell: His work is one of the things that really encouraged me to do my podcast.

Frank Wilczek: Very good.

Ginger Campbell: Well great. I appreciate you taking so much time to talk.

Frank Wilczek: Sure. Well it's been a joy and it's very interesting for me and it's really good practice, also.

Ginger Campbell: Maybe next year when the Nobel Prizes are announced for Physics I'll talk to you again so you can explain what they're for.

Frank Wilczek: Sure, I'll try. Yeah.

Ginger Campbell: Because a lot of times we don't really, us non-physicists, it's hard for us to appreciate what a particular Nobel Prize, why it's important and...

Frank Wilczek: Yeah.

Ginger Campbell: It's good to have that translation.

Frank Wilczek: It's a great opportunity to educate people because, you know, it focuses interest on one particular thing. And usually they pick something important.

[music]

Ginger Campbell: Dr. Wilczek was very gracious in spending time with me for this follow-up interview, which included answering some questions from listeners. So before we close today, here are a couple of questions that Dr. Wilczek answered from *Books and Ideas* listeners.

The first question comes from long-time listener Mr. Edgar Valderrama. I always call him Mr.

V.

Frank Wilczek: [laughs]

Ginger Campbell: He claims to be my oldest listener. He's 83 and he's been listening since the beginning. He listens to both my shows. And he asks, "What happened to the ether drag that was supposedly disproved by the Michaelson-Morley experiment in 1887?"

Frank Wilczek: Well it was in fact disproved by the Michaelson-Morley experiment. One aspect of Einstein's special relativity was to sort of promote the failure of experiments like that to detect a definite state of rest associated with the ether. Could not be successful. Maybe that was a basic postulate of the relativity theory, which led to very successful consequences. So although the ether has made a comeback in the sense that the idea that space is a medium full of activity and primary reality and has many specific properties that I discussed in *Lightness of Being*, for instance, the new ether- what I call the grid- has to have the property that Einstein relied on in the special theory of relativity. That is, it has to look the same whether you are looking at it while stationary or while moving at a constant velocity. So we still have an ether, it just has this special property that it looks the same to different kinds of observers.

Ginger Campbell: So that's kind of why you are sort of going toward calling it the grid rather than...

Frank Wilczek: That's why I want to call it something else, right. So it doesn't have the connotations of the old failed concept.

Ginger Campbell: Okay. That makes sense. I have one question from my discussion forum, and this comes from Dr. Luc Beaudoin, who- I may be mispronouncing his name, I think it's a French Canadian name. I'm just going to take the question out of his post. He said, "I would like to get more insight into the reasons why things are as the theory says they are, i.e. why are things not different? Hopefully it's possible to explain some of these things to non-mathematicians as Einstein did for relativity."

Frank Wilczek: Well, the question why things are as they are and not different can be answered at several levels. I'm not sure which level the question was asked, so let me try to elucidate it at several levels.

The first level is just the level of fact. Why is the description of the world that we have the way it is and not different? And the fact is that people sort of had to be dragged kicking and screaming over centuries to the world picture that we now have that's so strange and counterintuitive, and each step along the way was motivated by observations that didn't make sense and people having to give up cherished concepts in order to accommodate them. This sort of thing goes back to the ancient Greeks discovering that the earth turned on its axis once a day- so we are actually in motion- and Copernicus reviving that idea, to the most advanced parts of modern quantum mechanics that we have to give up the idea that laws are deterministic, that everything has a cause, to the idea that we live in a central place in the universe, to the idea that mankind has some special status in the universe which is again put into question by Darwin. Or going back to physics, to the idea that when we don't see something there's nothing there. We had to, many times, especially in modern physics, question and abandon ideas that seemed like obvious generalizations or abstractions from everyday experience but turn out to be inadequate when you push harder and harder.

So that's at the level of how we got there, so why we use the descriptions we use and not another description. It's not by whimsy or choice, it's because we're forced to do it, and if you examine the weight of evidence and the process by which we arrived at the modern world picture, it's difficult to imagine going back. We may have to expand our concepts even more and introduce even weirder things, but it seems very unlikely that we'll arrive at essentially simpler and older- I shouldn't say simpler, but more familiar concepts- as the basis as time goes on. We have, in science, often revolutions, but very rarely if ever counterrevolutions.

Ginger Campbell: So really what you're saying is that the reason- and this is, like you say, at one level- the reason why things are as the theory says they are is because the theory has...

Frank Wilczek: The theory has adapted to the way things are. [laughs] So it's a process of selection and evolution that got us, in a sense, to our world model being the way it is. Now there's another level, which you could ask the question which is, "Okay, here's the system of the world. We now have a model that's very accurate that describes a wealth of phenomena. It evolved from a long series of attempts to come to grips with the facts. Then you can keep asking why? Why why why why? At some point you just have to say that's the way it is. [laughs]

Ginger Campbell: [laughs]

Frank Wilczek: There's the famous story of a person who said the world was supported on a turtle, and then the question was, well what is the turtle supported on? And then it's another turtle. You know, what's supporting that turtle? It's another turtle. Well, isn't that getting ridiculous? He says, "No it's turtles all the way down."

Ginger Campbell: [laughs] Yeah.

Frank Wilczek: At some point, the description of the world- I don't we'd reach this point, but it's possible that the description of the world would be so complete and so pretty and so difficult to change that we'll declare victory and say that's the system of the world. That's the theory of everything, if you like. That's the final theory. But even if we had that, you could still ask why. I don't think there'd be any philosophically or logically satisfactory response to that except to say, "Well that's the way it is."

Ginger Campbell: I think I should probably read the second piece of Luke's post.

Frank Wilczek: Sure.

Ginger Campbell: Because it might give some context. I'm going to quote this part directly. He says, "Also, I can't help but suspect that despite the fit with the data, we're dealing with a theory and therefore something which might be radically superseded at some point. He" (I think he's referring to you) "said that physics now is radically different from where it was thirty years ago."

Frank Wilczek: Yes.

Ginger Campbell: He says, "I can decide with Popper as well, more specifically with Imre Lakatos, a writer of the philosophy of physics."

Frank Wilczek: Mm hm. Well, it is true that physics is radically different from what it was thirty years ago, but it really has been a process of deepening and extending, as opposed to throwing out what we had before, and I think that's really characteristic, because our theories at every stage are based on a tremendous- I mean the theories that are accepted and regarded as the basis of our worldview- are based on very impressive bodies of evidence that they explain by very specific long chains of deduction, that get better and better in a very specific sense. That is, the hypotheses get to be smaller in number and more abstract on the one hand, and on the other hand the consequences you deduce from them get more sweeping and, if it's working, more accurate.

And so if you want to get more compact hypotheses or things that draw more consequences or more accuracy, it just gets harder and harder as time goes on. So it can happen, but it's harder and harder, and certainly the revolutions in physics that I was talking about in the 1970s made our models of the world much more specific, much more powerful. But really, to a remarkable extent were John Wheeler called radically conservative theories.

Ginger Campbell: Mm hm.

Frank Wilczek: That is, they took existing principles, specifically the principles of special relativity and quantum mechanics, very very very seriously and tried to push them as hard as they could to see if they broke. And instead of breaking they held up. But in the process of trying to break 'em we really bent them and put them into new shapes that we didn't know were possible before. We sort of realized the potential of these theories when you take them fully seriously and put them together. It was a radically conservative revolution.

Now it is certainly logically possible that extremely radical changes of concepts will take place in the future. Certainly a model for that was in the early 20th century, when the general theory of relativity by Einstein gave a theory of gravity based on radically different principles from Newton's theory of gravity, which had help up very well for more than 250 years. On the other hand, necessarily, just because Newton's theory was known to be so accurate and successful, Einstein's theory had to reproduce Newton's theory as a limiting case. So if the velocities aren't too big and the masses aren't too big, Einstein's equation gives Newton's theory as a very good approximation, and that's what we use to plot satellite orbits and do most of astrophysics and so forth is Newton's theory, because it's easier to work with.

So I think that although it's conceivable that we'll be led to conceptual changes that would change the way in which the ideas are formulated and may even lead to radically different consequences in domains that have not yet been explored- the extraordinarily early universe, or the middle of black holes in the case of physics. Those theories, I think, necessarily will have to include our current theories as very very good approximations that work almost all the time. They do in fact work very very well in a tremendously wide variety of circumstances, and not just crudely, but with extremely delicate tests, and attempts to break have come up empty.

Ginger Campbell: That really kind of goes in sort of a philosophical direction. You make a very good point there.

[music]

I hope that you have enjoyed these interviews with Dr. Frank Wilczek. Next month I'm going to be interviewing Carmen Flowers, the author of a very unusual book that is coming out in January called *Grave Expectations* [full title: *Grave Expectations: Planning the End Like*

There's No Tomorrow]. Don't forget, you can now keep up with everything that I am doing at gingercampbellmd.com. I hope you will subscribe to my blog and to both of my podcasts. In 2009 the *Brain Science Podcast* and *Books and Ideas* will be coming out once a month. You can send me e-mail at docartemis@gmail.com, or share ideas with other listeners in our discussion forum at brainscienceforum.com. I would love to hear from you.

Thanks again for listening. I look forward to talking with you again very soon.

[music]

Theme music for *Books and Ideas* is "The Open Door" by Beatnik Turtle. Be sure to visit their website at beatnikturtle.com. Beatnik is spelled B-e-a-t-n-i-k.

-transcribed by Jenine John