Science AMA Series: The discovery of a new particle called Weyl challenged our understanding of quantum field theory and was one of the Physics World's 2015 Breakthroughs of the year. Mazhar Ali is her

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Abstract

My name is Mazhar Ali and I am a researcher with the Max PIank Institute for Microstructure Physics in Halle, Germany and also at IBM in San Jose, California. Before that I was at Princeton where many of us worked on and discovered some of the first Dirac and Weyl materials, including the first "type II" Weyl semimetal, WTe2, which was on the frontpage of r/science last week. Dirac and Weyl materials are a super hot topic in condensed matter physics right now, but has branched out and captured the attention of chemists, particle physicists, materials scientists, electrical engineers and more! These materials host massless dirac electrons (similar to graphene) and so can have "light-like" electrons moving at extremeley high mobilities! Recently, people have been able to use the intracies of the electronic structure of a material to massage these massless dirac electrons into becoming Weyl electrons; still massless, but with the added bonus of having spin up and spin down be energetically different! We will see in the near future what we can do with these new particles, but first we need to understand everything better. Out of the 3 camps of Fermions (Weyl, Dirac, and Majorana) we had previously only realized Dirac fermions in real life. Now we have realized the 2nd camp, Weyl! Majorana might be just around the corner too! It is a very exciting time to be involved! I am here to answer any questions you all might have about Dirac and Weyl materials, physics, chemistry, etc! Or, if you just want to know about solid state and materials chemistry, AMA! A few links to a few of the relevant papers (obviously there are loads more): Titanic Magnetoresistance in WTe2: http://www.nature.com/nature/journal/v514/n7521/full/nature13763.html Type II Weyl Semimetals: http://www.nature.com/nature/journal/v527/n7579/full/nature15768.html Cd3As2, a Dirac Semimetal: http://www.nature.com/nmat/journal/v13/n7/full/nmat3990.html Ultrahigh electron mobility in Cd3As2: http://www.nature.com/nmat/journal/ Type I Weyl Semimetal (open access): http://journals.aps.org/prx/abstract/10.1103/PhysRevX.5.031013 A very nice viewpoint on Weyl electrons by Leon Balents (professor at UCSB): http://physics.aps.org/articles/v4/36 open access, arXiv versions of most of the above articles can be found through google fairly easily as well. I will be back at 2 pm EST (11 am PST, 7 pm UTC) to answer your questions, ask me anything! EDIT: I am back! May go for lunch in about an hour, but then will be back again after! EDIT 2: Hey all! Gonna take a lunch break, be back in about an hour or so! (Currently 12:20 PST) EDIT 3: Back again!

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MAZHAR_ALI R/SCIENCE

ABSTRACT

My name is Mazhar Ali and I am a researcher with the Max Plank Institute for Microstructure Physics in Halle, Germany and also at IBM in San Jose, California. Before that I was at Princeton where many of us worked on and discovered some of the first Dirac and Weyl materials, including the first "type II" Weyl semimetal, WTe2, which was on the frontpage of r/science last week.
Dirac and Weyl materials are a super hot topic in condensed matter physics right now, but has branched out and captured the attention of chemists, particle physicists, materials scientists, electrical engineers and more! These materials host massless dirac electrons (similar to graphene) and so can have "light-like" electrons moving at extremeley high mobilities! Recently, people have been able to use the intracies of the electronic structure of a material to massage these massless dirac electrons into becoming Weyl electrons; still massless, but with the added bonus of having spin up and spin down be energetically different! We will see in the near future what we can do with these new particles, but first we need to understand everything better. Out of the 3 camps of Fermions (Weyl, Dirac, and Majorana) we had previously only realized Dirac fermions in real life. Now we have realized the 2nd camp, Weyl! Majorana might be just around the corner too! It is a very exciting time to be involved!
I am here to answer any questions you all might have about Dirac and Weyl materials, physics, chemistry, etc! Or, if you just want to know about solid state and materials chemistry, AMA!
A few links to a few of the relevant papers (obviously there are loads more):
Titanic Magnetoresistance in WTe2: http://www.nature.com/nature/journal/v514/n7521/full/nature13763.html
Type II Weyl Semimetals: http://www.nature.com/nature/journal/v527/n7579/full/nature15768.html
Cd3As2, a Dirac Semimetal: http://www.nature.com/nmat/journal/v13/n7/full/nmat3990.html
Ultrahigh electron mobility in Cd3As2: http://www.nature.com/nmat/journal/v14/n3/full/nmat4143.html
Type I Weyl Semimetal (open access): http://journals.aps.org/prx/abstract/10.1103/PhysRevX.5.031013
A very nice viewpoint on Weyl electrons by Leon Balents (professor at UCSB): http://physics.aps.org/articles/v4/36
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CORRESPONDENCE:

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I realize that this research is still in the crucial "discovery" phase where you are trying to work out the properties of these newly discovered particles and systems, however, can you speculate a little bit on what you consider an interesting potential application (even if you had to "cross your fingers" regarding an unverified property of the system)? I ask because you mention electrical engineers being very excited about the discovery, so does this have implications in quantum computing or classical

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microprocessor design?

DrGar

Good Question! For one thing, the ultra-high mobility in these materials at least partially results in incredibly large magnetoresistive effects. Magnetoresistance is a very interesting property because it lets us use a magnetic field to modify a materials electrical resistance. Memory works this way! While these effects are currently at low temperature, if we can bring these effects up closer to room temperature, we may be able to use it in memory based devices.

Haha, on the more speculative side? These materials are a stones throw away from being Quantum Spin Hall Insulators. Some of these Dirac/Weyl materials have been theorized to be QSHI at room temperature if we can strain the material, or chemically modify it in the right way. I won't go into too much detail on them except to say that it has been shown that QSHI's can have symmetry protected edge states which host truly quantized conductance (while in the QSHI state) or zero conductance in the normal insulating state. That is very very cool. You have an instant transistor right there in one pure material!

This isn't exactly classical microprocessor design, but it also isn't exactly quantum computing. Sorry but I really don't know that much about quantum computing, so I can't even speculate there!

From /u/Eltargrim

Hello Dr. Ali,

I must confess that I haven't had time to read your work in detail, so please forgive me if you've already addressed this: you characterize WTe2 as a semimetal in part based upon DFT calculations. DFT is notorious for its failure to accurately predict experimental band gaps. While your calculations were converged with respect to plane waves and k-points, I'm curious as to how you account for this systematic concern. Further, have you attempted the use of XC functionals other than PBE?

Thank you for your AMA!

ScienceModerator

Hi! Good Question! One needs to be extremely careful when making claims about properties based off of DFT calculations! You are right that different functionals have various issues and band gap sizes are notoriously difficult to get right! We did check with MBJ, for example, to see if similar results were obtained. WTe2, in particular, was a bit difficult for simple DFT calculations to deal with in great detail so we were careful about our claims. (Left the theory to the real experts)

In the solid state chemistry world, we mostly take band gaps as Yes or No from calculations. You can check the irreducible representations and directly calculate to see whether certain "crossings" are truly degenerate at a point or not. However we also used resistance versus temperature, Hall Effect and optical excitation experiments. These are the most common experimental tools we use to check for metallic versus insulating behavior and to nail down the size of the gap. Basically, everything we claimed from DFT, we tried to confirm with real-life experiment!

It seems a very natural response to ask "What can we make with this?" but after digging in a little deeper, I found myself wondering what *passive* effects these materials would have on their immediate environment. For example, if they work as really high grade conductors, what would the outcome be of the material being struck by a natural electrical event like a lightning strike?

- What kind of passive effects should we be looking at if these materials come into industrial use?

- Are the states involved in their creation sustainable for larger applied projects?
- Are there safeguards, special resistive materials, etc, in the lab environments working on these materials that may also need to be adopted for applied use of the Dirac and Weyl research?

Deightine

Thanks for your questions!

1.) Massless Dirac materials may be useful for their electron transport speeds. Weyl materials have the added benefit of breaking spin-degeneracy, so they could be very useful in spintronics. These are both passive properties of the materials! So far, these really exotic transport properties are seen at low temperature, so the first step is to work on raising them up to higher temperature.

2.) The really amazing thing is that these are actually the ground states in these materials! We purposefully looked for materials where the right features in the electronic structure were predicted to be near or at the Fermi level (essentially the ground state). As in, we are not modifying the materials, in-situ, to really create the Dirac/Weyl states, they are naturally there!

3.) Not really! Yes these are currently limited to a handful of materials: Cd_3As_2, Na_3Bi, TaAs (and family), WTe_2 (and family), $YbMnBi_2$. But we are working on finding more (with cheaper, less toxic elements of course)! But otherwise, some of these materials have been very stable in air and even water! These really don't require too much special handling!

I've been waiting for a physics AMA for a long time! I am currently choosing a field to study and physics and mathematics have always attracted me. Advanced mathematics does not scare me (I attend something like pre-calculus in high school). My question is: Which branch holds the best potential? What are the targets/objectives of the branches and where are they heading? (I will name a few branches I am interested in afterwards). By any chance, if you heard of Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering that is the university I am applying to. There are various interesting fields which I know just by a short description. The point of my post is that I would love to participate in some kind of research yet I don't know how to get into one. I am aware that there is a possibility to do research during my studies but I don't know how to get this to be my full time job and if I even want it so. You are a person who works in the field and knows the current state of it and I'd like to know which fields are/will be lucrative and hold interesting range of possibilities. I really like these disciplines from the faculty: Nuclear Physics, Nuclear Fusion, Solid Matter Engineering, Lasers and Electrical Engineering, Optics and Nanostructures, Experimental Nuclear+Particle Physics (this one sounds really tough and scary). Also, which discipline is the closest to your research?

I hope you will find my quesiton relevant and appropriate. I hope you are not dissapointed that I didn't ask you about your research but I've been looking for an opportunity to ask this question for some time and your AMA offered me a great option how to ask somebody who carries out research. Thank you!

Curudril

I am impressed at your questions and how far out you are looking for someone in highschool! Good for you! Now to your questions....

Boy, these are some tough ones. I can't really tell you that one branch of science has more potential than the other *in general*. It all depends on what you want, what you are going for.

You mention lucrative - well the truth is research isn't that lucrative in academia. Of course there are lots of possibilities; consulting on the side, licensing inventions, etc. But you aren't going to make as much salary, for example, as you would in industry.

Of course, there are intangibles other than money. Teaching is incredibly rewarding and, frankly, a lot of fun! Also, being a tenured professor is about as close to "nobody tells me what to do!" as you can get. If you really care about your intellectual freedom, there might not be a better job!

Now as far as the fields you mention; haha, I guess solid matter engineering is as close to me as that list gets. So I will try and offer my sadly non-expert opinion on your questions about them. Pretty much every field you mention has a lot of potential right now, and a wide scope!

Nuclear physics/fusion are in the spotlight right now with fancy reactor attempts being turned on and the ever increasing energy crisis. We *need* good people in this area...the human race *needs* fusion reactors to work. It might be the most rewarding field out of the ones you mentioned in that it is important to everyone, whether they realize it or not.

The others are all interesting too; lasers and electrical engineering are evergreen I think. Optics and nanostructures have a lot of scope as we continue to try and do something useful with all of our nanostructures (someday I think...). Experimental nuclear+particle is also very cool, but a little less applied and more basic science. From your questions it seemed like you wanted more short-term application. Well solid state physics/chemistry is great for that too...we have the Moore's law Si problem everyone knows about! New materials/engineered materials may be one way around the problem!

The main thing, since it seems you are still quite young, is to learn. Learn everything you can! Don't be scared of tough sounding fields! There is NO such thing! You can go into any field; some may be easier at first than others but it is just a matter of time and effort. Let your passion drive you; if you really enjoy something, or want to do something, go after it as hard as you can, even if it isn't what you are "best at" right now!

In the end...you will be best at what you care about. If you really are passionate about something, dedicate yourself to it! Don't take a short-sighted view on things just because you are good at something things and bad at others *right now*!

Good luck.

I'm still trying to get the terminology correct, so please excuse me.

Do Dirac and Weyl materials have any application to batteries or capacitors? Would they allow for higher energy density than current materials allow?

Edit: I can spell

PapaNachos

I don't think they would allow for higher energy density than current materials. It is a different sort of problem, really! Batteries and capacitors work on the separation of charge across a couple of materials. This is more of a change in fundamental particle type within one material!

But good thinking! It is good to try and link ideas/concepts! Sometimes you get surprised!

From /u/ididnoteatyourcat

I imagine that these special electrons are not a new type of fundamental particle. So: what are they, exactly? A type of phonon (if so, in what ways are they similar or different from real electrons -- how do they carry charge)? Or is it that ordinary electrons have different properties in these materials?

ScienceModerator

Ahh, this gets a little funny to think about.

These are indeed quasi-particles in that electrons (the ones you think of) are "Dirac" Fermions. They follow Dirac statistics and the Dirac equation.

"Weyl" Fermions follow the Weyl equation which is essentially the Dirac equation in the limit of the mass going to 0. Weyl electrons are electrons which follow the Weyl equation thus are Weyl Fermions.

Here is a funny way of thinking about it. Your head is your head, right? You can wear different caps, which may change the way you look and, for the sake of this analogy, the way you behave. A cowboy hat makes you rustle cows. A baseball cap makes you play baseball. But it is still your head, even we you change your cap and modify your behavoir!

The Weyl fermions we have currently made are from electrons. "Ordinary" electrons (a.k.a. massive dirac fermions with a -1 charge and 511 KeV rest mass) do indeed behave differently than "Weyl" electrons!

I hope that helps!

What do we know about the optical properties of these materials, i.e., how do Dirac and Weyl materials interact with photons, and are there any interesting optical phenomenon that would allow these materials to be utilized in optical devices?

whiteknight521

Yes! At least in Weyl materials the fact that spin-up and spin-down aren't degenerate allow for the possibility of using circularly polarized light to preferentially excite one type of spin over another! This sort of thing has been done for a long time in other materials and is well understood.

But of course we haven't really done it so much in a material where the electrons are also zipping around so fast. So it will be interesting to see what we learn as we start to do those sorts of experiments on these materials. Mostly we have been hammering away with electron transport and haven't explored too much of their other physical properties!

Hi Mazhar

Just wondering what can be some of the potential future applications for this? Is there a possible role in quantum computing?

ForgottenPhoenix

Haha, people are really interested in that. I generally hate speculating especially on this topic!

But, well the fact that the Weyl particles move so fast and have apparent scattering protections due to symmetry, means that if we can find a way to use them to encode information, they should be more robust to degradation. The Weyl electrons zip along without much of a hello to their neighbors and quantum computing requires this sort of incredible non-interaction with the particles surroundings. So Weyl fermions look to be the right sort of particle for it!

When people say Weyl fermions may be good for quantum computing, this is the sort of thing they mean (for now). I really can't say whether it is likely or not though but it is just too early and there are a ton of other things to keep in mind. But it is something we are definitely investigating moving forward! It would be nice to ditch ultralow-temp superconductors if we could!

from /u/WarrantyVoider

Hi, first off, great work! this isnt directly related to dirac or weyl materials, I more like to know how I could get a job to work in that field. I already have a BSc for SE, and im not afraid of any math (I love it f.e. when I can teach a computer to do some math for me, I mean like simulations of fluids or smoke) but also cant afford to study yet another field. Is there any chance? greetz WV

EDIT: I ask because currently I only see jobs as website or app coder, which isnt really interesting/demanding, so who codes the big super computers to crunch massive amounts of data, like CERN particle accelerator?

ScienceModerator

Thanks!

Well a lot of physicists do the coding (you end up doing a hell of a lot of programming if you go into theoretical physics nowadays!). But of course there are computer scientists and specialists who work on these things too!

I would say to not give up! If you are interested in the science but like the coding, definitely look up the DFT software suits and see if you can try learning how to use them. It sounds like more than predicting materials properties and such, you are interested in the functionals and calculation guts. There is a lot of information out there on all of that!

Also, a PhD program PAYS YOU to go to school (in science). So you could afford it!

Best of luck!

Would these particles potentially help us create new superconductive materials? I'm not much of a physicist at all but if electrons can flow freely (more or less) through them, does that mean that they'd conduct electricity if brought up to a much larger scale?

McFlare92

Good idea! Not particularly at the moment. See superconductivity (so far as we currently know) is either phonon-mediated or (probably) magnon-mediated. These materials have particles which don't interact much with their environment at low temperature, so phonon-mediated superconductivity won't be great. They are also mostly non-magnetic (so far) so magnetically mediated superconductivity won't be great.

HOWEVER! We already found that WTe2 and MoTe2, type II weyl materials (theory only so far, but I believe we will see experimental confirmation very soon), superconduct under pressure. We are still working out exactly what happens, but it is likely the structure distorts and the band structure changes and we lose the Weyl state, but get a SC one at low temperature. This is interesting! The SC appears to be odd...it dramatically increases in critical temperature with very small changes in pressure (like 50 times higher). That is odd, and we will see if it means anything interesting as time goes on!

But these materials are indeed some of the most low resistivity materials we know of! Cd3As2 at low temperature like ~20 nano-ohm-centimeters!

From /u/msgbonehead

Did you have any "Huh, I can't believe that worked" moments during this?

ScienceModerator

Haha, absolutely. Also, several, "What the...that can't be right...is that right?....Holy shit that's right?!" moments!

From /u/orion3179

And once again I realize I'm too ignorant to know wtf someone is saying...

What are potential uses for this stuff? (explain like I'm 5 please)

ScienceModerator

These particles can move crazy super fast through their host materials. This means we can build crazy super fast electronics. That is good! Also, they have large magnetoresistive effects. Computer memory really cares about large magnetoresistive effects! So that is also good.

These particles don't really interact with their environment as they move, for a variety of reasons. Quantum computing needs particles that don't interact with their environment because that would degrade the information dramatically. These particles fit the bill, and at reasonably high temperatures (e.g. 30 Kelvin instead of 0.5 Kelvin). But of course, it gets more complicated than that.

From /u/bheklilr

How stable are these materials at room temperature? When you say "electrons moving at extremely high mobilities" that makes me think of super conductors, are these Weyl materials related in any way? Could we, in theory, build electronics that are stable at room temperature that have super conducting properties?

ScienceModerator

Weyl materials aren't related to superconductors really. Superconductivity occurs when electrons pair up and move through the material in "cooper pairs" which allows them to essentially form another sort of quasi-particle that stops behaving as a Fermion and really behaves as a Boson. This is important; Bosons aren't unique; they can all share the same quantum numbers and so occupy the same ground state. Fermions are much more temperamental particles and can't do this. They have a limit; 2 per energetic state.

So Weyl materials host Weyl fermions while superconductors (in their superconducting state) host Cooper pairs, Bosons. However, could Weyl fermions pair up to form Cooper pairs? I think so. Not sure if this would be hugely interesting though...once you start being a Cooper pair, you stop being 2 Weyl electrons. I don't know whether the fact that the electrons were once Weyl will make a difference. But it is a neat idea to study!

That is why this is all so much fun! All of these wacky ideas are really not readily acceptable or dismiss-able! The field is too new to do that! We have to look closely because we don't know what we will find!

Why are these dirac particles considered electrons despite being massless? Is it a matter of carrying the same charge and/or are they derived from normal electrons?

It's interesting to think of particle properties being uncoupled from their mass.

XIllusions

It is odd to think of things that way, you are right. So we do have to be careful with the wording; we often say "mass" when we mean "effective mass".

So the effective mass of an electron flying around in a material is dependent upon the second derivative of the energy with respect to the momentum. When looking at the electronic structure of a material (the plot of energy versus momentum of electrons in the material), one can find when electrons reach a place where a band arrives at a linear dispersion. These electrons have 0 effective mass (the second derivative of a straight line is 0).

These are still electrons and they still have a rest mass; however as they fly through the particular potential, at certain points they *effectively* have no mass! They still carry the same charge and spin however! Yes indeed they are derived from "normal" electrons.

Think of it this way; we tuned the environment around the electron to make it behave as though it doesn't have any mass, even though it still does. This is very cool in my opinion!

The distinction between when something stops being defined by what it intrinsically is and what its environment makes it be...it might be best left to the realm of metaphysics.

Nature vs. Nurture in physics?

It is fun to have a beer and think about it!

Where do you stand on the Majorana vs. Dirac debate for neutrinos? Also, what do you think that about the studies of the last few years claiming to discover Majorana modes in solid-state systems?

dark_magnetar

I think we haven't yet seen a smoking gun result in the search for the Majorana, but I think we are closing in. I wouldn't be at all surprised to see that inside the next 3 years. I know Yazdani at Princeton is hot on the trail...

I think solid state systems is where we will find the Majorana first. Honestly, I thought we would find that before Weyl...Weyl was sort of less popular both with scientists and with the media (at first)...but it is frankly more accessible research.

Massless Dirac, Weyl, Topological Insulator materials; all of these have been relatively simple materials and crystal structures. For far less money than it takes to build an STM theoretically capable of finding the Majorana in a particular setup and one specially made sample; we were able to make hundreds of materials and attempts both from experiment and theoretical perspectives! Many more people were able to join in the hunt and so it has reached break-neck speeds as of late! It is great fun!

I have been tangentially involved in WTe2 in the past, and from my own experience know it to be really unstable as it has a tendency to oxidize back. Anyway, we are just around the corner towards growing few-layer WTe2 - would Weyl fermions exist there too? Would they exist even in monolayer WTe2?

I am asking this because for transition metal dichalcogenides there are dramatic differences in electronic properties and bandgap between single layer, few layer and bulk materials.

N1H1L

That's right! Scaling down from bulk to few layer and even monolayer has been shown to cause huge changes in many different types of compounds! Just look at Graphite -> Graphene!

We are indeed getting very close to being able to get to few layer and even monolayer WTe2. There are two approaches; either growing few layers on top of substrates (something I am playing around with as well) and exfoliating down to few layer from bulk.

As with Graphene, the silly but amazing scotch-tape method really works here too! Since WTe2 has a fairly large (I think ~3 Angstroms if I remember correctly?) van der waals gap in between WTe2 layers, the layers are very easily displaced from one another. Simply sandwiching a WTe2 xstal in between two pieces of scotch tape is enough to pull the layers apart!

Indeed it is hard to say what will happen. Current theoretical calculations believe that the monolayer will lose the Weyl behavoir because the band struture will change slightly and stop being semi-metallic and just become metallic. However few layers (more than one basically) should still have the Weyl fermions.

But yes, the thinner you go with WTe2, the more the oxidation becomes an issue! It passivates as it oxidizes after a few nanometers (like Al for airplanes) so the oxidation doesn't consume a whole xstal. However, if you have a sample that is 0.7 or 1.4 nanometers thick, this small oxidation no longer seems small! Hahaha, nature.

I certainly don't have a great understanding on exotic materials so forgive me if I sound like I don't know what I'm talking about. In the article, Cd3As2 used ARPES to observe the dispersion relation in Dirac semimetals. Has such work been done for Weyl semimetals and are the Hamiltonians similar (would there be a similar dispersion relation)?

paperhawks

Good Question! Yes quite a bit of work has been done for Weyl semimetals already (via Angularly Resolved Photoelectron Spectroscopy, ARPES). There are several very nice papers on type I weyl semimetals where they used ARPES to experimentally verify the calculated electronic structure! They saw the characteristic "Fermi Arc", and the Weyl Nodes!

The dispersion of the band structure leading up to the Weyl node is very similar to a Dirac material's dispersion leading up to the Dirac point; both are linear!

In what quantities can these particles be created, and at what cost? How much could this cost be brought down if we ever had an industrial application?

monkeydave

These particles aren't really created in the way you might be thinking! We aren't using huge 3-country-spanning particle colliders to do this (although man that is cool).

In recent years (although it is something that P.W. Anderson has been saying for a loooooong time, but hey, he is a Nobel prize winner and sees things a bit differently than the rest of us) we realized we can use the periodic potentials inside crystals as very good analogs for high energy particle physics and nowadays, even astrophysical phenomena. This is because of some very neat analogies.

So, basically here we searched for and found materials with the right arrangement of the right types of atoms to give rise to the right periodic potentials to make the right electronic structure with the right features at the right energies for us to realize these cool physics!

We "make" the particles for free! They exist as the ground state. Now we do have to do some things for now, like cool the system way way down to see the effects of these particles, but we are just in the infancy of all of this research. I think we will figure out some really ground-breaking stuff in the next 5-10 years as we bring this closer to being technologically useful.

Do these discoveries have any bearing on the multiverse vs. Supersymmetry debate?

Slowdrippin

Sorry, I don't think so! Although I am really not a good enough expert on that type of physics to answer with conviction.