

Episode 39: Pasta Stars with Sean Martin

Dec. 7, 2013

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The Titanium Physicists Podcast

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Ben: Oh! Hello old friend. It's good to see you. Let's talk about this word "fascination". It describes an unquenchable urge which compels our hearts to quest and be captivated. As long as there are elegant explanations to complicated phenomena, science will never lose its romance. Over the years I've traveled the world indulging in my fascination in physics, and now I've found that a new hunger has awoken within me; a fiery need to share these great ideas with the people around me. And so I have assembled a team of some of the greatest, most lucid, most creative minds I've encountered in my travels, and I call them my Titanium Physicists You're listening to the Titanium Physicists Podcast, and I'm Ben Tibbet! And now; *Allez! Physique!*

[1:10]

[*Ted Leo plays*]

Ben: Hey everybody. So, most people think that you probably shouldn't leave a physicist alone to name things, because physicists tend to name things after really stupid jokes. One of the smallest units for area, for instance, is called a Barn. It's 10^{-28} m^2 . As in: you couldn't hit the broad side of one, but for some reason we apply it to atoms. Uh, there's quarks. Quarks are named by Murray Gell-Mann after a phrase from a James Joyce book. I mean there's an Up/Down quark, which were fine when they were inventing the theory, but then they invented a new type of quark called a Strange quark because it was strange. And then after that they named one called the Charm, because charm is the opposite of strange. And then there's Truth and Beauty, because hey, you need two other opposites. Uh, there's something called a Ghost in Physics, as ghost is an impossible quantum state that has negative probability, so you know that your theory's all bunged up because you can make Ghosts. The universe is expanding because it's full of phantom energy, whatever that is. There's something called a Penguin diagram; it's a Feynman diagram where you draw it out and it looks like a penguin. There's something called an Open Moose which is another diagram from Quantum Chromodynamics. There's, uh, position, velocity, acceleration, and then higher time derivatives it's called the jerk, and then the derivative of the jerk is called the snap, and the derivative of the snap is called the crackle, and the derivative of the crackle is the pop. Moral of the story is that you probably shouldn't leave physicists unattended to name things. Today's topic, we're talking about Pasta matter, I guess matter looks like pasta. Anyway, our guest today is a good friend of mine; he's an elementary school teacher at a school in Vancouver. He likes beer and sandwiches and presumably pasta and playing hockey and batman and also he's a dad! Hey Sean Martin!

Sean: Hey Ben, how's it goin'?

Ben: I can't wait! I've gotten two fantastic Titanium Physicists for you today; Arise Dr. Jocelyn Reed!

Jocelyn: RAAAWR

Ben: Dr. Jocelyn did her undergraduate at UBC, her Ph.D. at the University of Wisconsin, Milwaukee, and she's now Faculty in the Physics department at Cal State Fullerton. She's a specialist in neutron stars. And now, arise Dr. Andrew Steiner!

Andrew: [LAUGHS]

Ben: Dr. Andrew's a research Assistant Professor at the Institute for Nuclear Theory at the University of Washington, where he uses neutron stars to learn about nuclear physics. Okay everybody let's talk about pasta matter!

[4:12]

Jocelyn: Hooray! Okay, so somewhere out in that beautiful universe of ours, we think there may be something called pasta phases of matter inside particularly bizarre stars called neutron stars. Which are what happens when a star that's pretty big, but not too too big runs out of fuel, goes supernova and has its core collapse down to a tiny remnant which is like the whole mass of our entire sun collapsed down into something the size of a s[inaudible]. So if you have, say, a graphite pencil, and you look at the tip of it, and it's basically made out of carbon, but you can compress that carbon down and form a diamond. You can keep compressing matter into a neutron star, and weird stuff happens, which is what we're talking about today.

Sean: So it's a diamond to pasta?

Jocelyn: Yes. Although, well, yes. There's something like the neutron stars might have a diamond atmosphere.

Andrew: Ah, yes.

Jocelyn: So just like, you know, as you go further and further out away from the earth, you have air and then it gets less and less dense, and you have the outer reaches of earth, which is just low density air. The version for neutron stars would be, well, either maybe diamond or some kind of iron is the "atmosphere" of a neutron star. So we're already at, like, weird densities compared to what we're talking about, so what we're planning to talk about today is what happens to our good old friends the atoms as we go into the neutron star and get denser and denser and denser. Eventually getting to a point where all the nuclei of the atoms have joined together into a continuous fluid of protons and neutrons and a few other things mixed together. But on their way, they make all sorts of funny shapes, probably, we're not sure, and those are the pasta phases.

Andrew: I guess that's right. The question is what happens to matter as you compress it, as you—if you could do this—you can't—but if you could put it in a box, and make that box smaller and smaller and smaller, then what would happen? That process of compressing matter is exactly like taking a trip from the outer surface of a neutron star, traveling inwards and seeing what happens to matter as you go deeper and deeper inside the neutron star.

[Shawn] So the idea's like it's being condensed more and more and more and then eventually when you get to that point, you're looking inside after it's been compacted so much, you're looking at it and you have a shape that's, what, like rigatoni, or fusilli, or penne or...

Jocelyn: Well, okay, so, you start with meatballs, kind of-

Sean: Okay-

Jocelyn: Well okay which isn't technically a kind of pasta [LAUGHS], but it's associated with pasta...

Sean: I can follow this...

Ben: I think they call it the gnocci phase

Jocelyn: Oh, the gnocci phase!

Sean: Ooooooh!

Andrew: The gnocci phase, yes that's an option.

[7:01]

Jocelyn: Well you can start out with a nucleus, okay, 'cause if you have regular atoms, in the center of the atoms you have a little ball, basically, of protons and neutrons. And they're super dense and they're all stuck together by this strong nuclear force. And as you get deeper and deeper, the density is increasing so we're pushing them closer and closer together, and they will actually join together to form nuclear spaghetti.

Sean: Okay.

Jocelyn: So instead of the ball nucleus, you'll have a spaghetti of protons and neutrons.

Andrew: And then eventually you go even deeper, and you compress the spaghetti and it turns into lasagna.

Sean: So nice and flat.

Jocelyn: Right, but the lasagna's actually made up of the same thing as the nucleus of the atom, so it's protons and neutrons in sheets instead of in a tiny little ball of a nucleus.

Sean: Balls!

Jocelyn: And then we have after lasagna, it's like inverse spaghetti, isn't it?

Andrew: Anti-lasagna, exactly

Jocelyn: Right, so soon you have more lasagna than non-lasagna. It's like, instead of fillings, you just have noodles with thin layers of sauce inside. It's basically how they serve noodles in Germany.

Andrew: The way I think of it is like the whole world is made of pasta, and all you have is little lasagna-shaped holes...

Jocelyn: [LAUGHS] So it's *anti-pasta*!

[ALL LAUGH]

Jocelyn: Okay, but then you keep going with the anti-things, 'cause then you have anti-spaghetti which is, like, the world is full of noodles, 'cept there's like little tubes running though.

Ben: Yeah, the world is made of pasta dough except for spaghetti shaped tubes running down it.

Jocelyn: Yeah, and then you can get to anti-gnocci.

Andrew: Which sometimes we call swiss cheese, just because it's a little easier...

Jocelyn: [LAUGHS]

Andrew: ...To say. [LAUGHS]

Jocelyn: And then eventually it all smooshes together and you have hot neutron on neutron action...

Andrew: Yeah...

Jocelyn: ...at the core of the neutron star.

Sean: A big ocean of neutrons and protons.

Jocelyn: Which is how you can fit a whole sun into something that's like, you know, 20km across, because all that empty space full of electrons, you don't need that. You're just going to push all the neutrons and protons and nuclei right together.

[9:05]

Ben: Okay! So! Essentially what the aim of today's show is, is we're going to explain to you why it does that. So when you are born in the next life, and you're a god of your own universe, you can make these delicious pasta stars! Got it?

Sean: Sweet

Andrew: Sounds good.

Sean: Just keep it connected to food!

Jocelyn and Andrew: [LAUGHS]

Ben: Okay...

Jocelyn: Did we have to record this right before dinner in, in my time zone, because like...

Sean: Yeah I haven't eaten dinner.

Jocelyn: ...I might need a snack!

Ben: I'm also hungry

Sean: Now I'm getting, myself, it's about lunchtime.

Ben: Well let's keep talking about pasta and maybe it'll help.

Jocelyn: Okay, so we can start talking about, okay why are there nuclei in the first place? Like why isn't our universe just a mish mash of protons and neutrons and electrons flying together all willy-nilly? So, so, I mean, maybe we're used to it so it doesn't seem weird, but, you know, usually what, I guess maybe this is just like, a physicist thing to do, but when in doubt, just assume everything is as boring as possible? I don't know!

Andrew: Or, we, we always like to start with the spherical cow.

Ben: Yeah

Jocelyn: Right

[10:15]

Ben: The question at hand is, so you have protons, right? And you have neutrons. Do you know how to make a neutron Sean?

Sean: Like, personally?

[ALL LAUGH]

Ben: Yeah that's right!

Sean: Is this "God of my own universe stuff" still?

Jocelyn: Yeah!

Andrew: That's right, yeah!

Ben: It's straightforward! You take a proton, and you take an electron, and you smush 'em together and then the charges cancel out, and then stuff happens on the inside, and you end up with a neutron, okay? So you have these protons and neutrons and everything but essentially hydrogen, and even some types of hydrogen is pretty much protons and neutrons stuck together. And so there's two questions you should ask: First, why are the protons and neutrons stuck together? And the second is: If protons are both positively charged, and they're really really close together in a nucleus, how can you stick two positive charges that close together without getting, like if you tried to take two electrons and shove them in a box the size of a nucleus, it would take a ton-ass of energy! Ah...

Jocelyn: [LAUGHS]

Ben: How're you gonna do that...

Andrew: "Ton-ass"

Jocelyn: [STILL LAUGHING]

Ben: ...with protons?

Andrew: The answer is the Nuclear Strong Interaction, right?

Ben: Yeah! So essentially there's this force, called the Strong Nuclear force, and...

Jocelyn: Because it's strong!!!

Ben: Because it's so strong, that you...

Sean: I, that's great nomenclature right there!

Ben: [Laughs]

Andrew: How strong is it?

Sean: Come on!

Jocelyn: Physicists naming things! It's the *strongest* one!

Ben: You get the Strong force, and what happens is, in the insides of stars, you know, you get these stars, it's really really dense, and pressure-filled in the middle. Neutrons and protons end up getting smushed together in the center of stars, and then this Strong force makes them stick together.

Jocelyn: And also release piles of energy in the process of fusing together. Which is known as "fusion"!

Ben: That's right! Fusion energy, wonderful thing! Uh, moral of the story is there's this Coulomb force, this static electric force that wants to keep the protons nucleus apart, but there's this Strong nuclear force that's binding all the nucleons together. And this way, you know, your nucleon doesn't explode apart like a big crappy car.

Jocelyn: Yes, there's sort of the balance of the Strong force that pulls things together, but only when they get close to each other, and the electrical force, the Coulomb force, which tries to push charges apart from each other. Like, if you like, rub a balloon on your head and then all your hairs get positively charged, and then they like kind of stick up, because they're trying to get away from each other, since they all have the same charge. So we have the positive charge trying to, like, push stuff apart, and then the strong force that's sticking them all together, and it ends up that these things balance out when you make a little ball, when you make a sphere. It's the same thing that happens with, uh, water droplets forming in, say, a cloud. So you have the little droplet of water forms, and it forms into a sphere shape. The point is there's surface tension. Because all the water molecules want to be surrounded by the water molecule friends, so they try and get together as close as possible, and that turns out to be a sphere, because [*inaudible*] of the surface area for that particular volume of water. So it's basically, everything's trying to be as close together as possible, and then you get a sphere.

Sean: So some kind of, being, like, pressurized pushing in while at the same time pushing out just kind of rounds it out into a spherical shape.

Jocelyn: Yeah, so they're all sticking together with the Strong force. And I guess it's a bit different in the nuclei, because they're stuck together, but they're trying to get as far apart as possible.

Andrew: In fact, actually, so in a nucleus it's exactly right that there's a, there's sort of a pressure coming in and there's a pressure coming out. There's sort of this special density at which neutrons and protons like to be. The nucleus doesn't want to be too big, it doesn't want to be too small, so they always end up in this sort of Goldilocks zone, where they like to be at this special density.

Sean: And I'm guessing that as we start to turn into pasta, that's being thrown out the window and that's where changes start to happen.

[14:05]

Ben: Yeah, alright, let's start talking about how you make a neutron star, because it's important to understand the story of where a neutron star comes from to get a sense of kind of what's involved and why it's made out of the stuff it's made out of.

Jocelyn: So the big thing about neutron stars is that they're collapsing under gravitational forces, right? So gravity's pulling everything together, and the star has run out of fuel -of fusion processes- to kind of create pressure that repels the collapse, so everything's collapsing in on itself. And if it's a big enough thing collapsing in on itself, it's going to keep collapsing until something stops it. And, like, on Earth, Earth doesn't collapse because of electromagnetic forces between all the atoms. So the electromagnetic forces are just keeping the atoms apart from each other and that's why you can't punch through walls, unfortunately. So gravity's trying to pull you towards the center of the earth, but the atoms are just like, "nope, sorry". The positive charges and negative charges don't want to be too close together so they cancel all that stuff out. Okay, so, the problem is, if you have a star collapsing in on itself, it's gonna get dense enough that it's not enough to overcome the gravitation forces, so you need something else to happen. And then you get cool stuff going on with what's called Degeneracy pressure, which you can basically get from two principles of quantum mechanics, which you may have heard of before. So do you know the Uncertainty Principle?

Sean: Uuuuh, I'm sure I've heard of it. [LAUGHS]

Jocelyn: So it's, you don't know where you are and where you're going at the same time.

Sean: Okay, yeah yeah yeah, okay. [LAUGHS]

Jocelyn: Yeah, so it's that kind of thing, the way quantum mechanics works is that you can't know exactly where something is and how fast it's going at the same time. And there's another thing which is called the Pauli Exclusion Principle, which basically says that you can't put two fermions in the same state. Can't just like, say, I have an electron and I have another electron and they're exactly the same in the same place doing the same things at the same time, because you just can't put an electron on top of another electron

Ben: Electrons don't like posers!

Sean: [LAUGHS]

Jocelyn: They need their own space, man.

Ben: They need to be unique.

Jocelyn: They're all unique in their own ways. So that means that, okay you've got a star, and it's got a bunch of electrons in it, and all the electrons are stuck in the volume of the thing that you're looking at, right?

Sean: Yeah.

Jocelyn: So as the volume gets smaller, that means you know more and more about the position of all those electrons. And as you pin down the position more precisely, just by the fact they're all in the same star and they can't be on top of each other, that means that the position gets more and more well-

known so that the velocity has to be more spread out to balance that. And that velocity ends up just having the electrons going around really fast and that provides the pressure that keeps the star from collapsing further.

Ben: Okay.

Andrew: So this Pauli Exclusion Principle is exactly the same thing that means in Chemistry when you have an atom with lots of electrons, all of those electrons can't be at the center they have to fill their respective shells, and they have to, you add more electrons they have to go farther and farther out. Because they all want to be special and they don't want to be at the same place in the same way.

Sean: They need their space, they gotta be free, okay.

[ALL LAUGH]

Jocelyn: You sound very jaded with this individualism thing.

Sean: I'm just, I'm picturing the rings from Chemistry class, like this penny on the first ring...

Ben: That's right!

Sean: ...this penny on the next ring

Andrew: That's exactly right.

Jocelyn: Except now the rings are all overlapping and getting squished tog...

Sean: the electrons are getting pissed.

Jocelyn: Yeah, yeah! We're trying to put too many electrons in one box and they're getting very agitated about this. And so that creates some pressure, and that's what's called degeneracy pressure. So it doesn't matter how hot the electrons are, but usually you have pressure from heat and stuff just bouncing around because it's hot. But this can be as cold as possible and you still get pressure because of quantum stuff happening.

Sean: Degeneracy because they're degenerates. This physics naming make sense.

Ben: [LAUGHS]

Jocelyn: It's, it's all in the nomenclature.

Sean: [LAUGHS]

[18:25]

Jocelyn: Now the thing that happens is eventually, you run into another problem which is that the electrons can't travel faster than the speed of light. So they can't go as fast as they would otherwise go, and gravity takes over again and starts compressing and compressing and compressing. Right. So we have whole thing that electron plus proton equals neutron.

Andrew: Eventually, gravity is so strong that it's stronger than the electron degeneracy pressure. You have so much mass in such a small space that the gravity can push the electrons together. The gravity sort of wins.

Sean: They can't resist any more, the pressure's too much.

Jocelyn: Yeah

Andrew: Right

Jocelyn: So even though they don't want to be in the same state and this is causing a lot of resistance, eventually gravity wins and they're squished down to merge with protons and become more neutrons. So yeah, so you have more and more neutrons floating around and eventually they start providing the pressure, because the neutrons are actually a lot like electrons, they also want their own state. So eventually you're compressing it so far that the neutrons don't want to be in the same state and they start pressure and then gravity wins over that and then all that you have is just this fluid of basically, mostly neutrons and some protons that are left over and some electrons. But you end up with this nuclear fluid at this super high density and the weird thing is what happens in this transition between when you had nuclei all floating around free and this fluid where the quantum effects are providing pressure from the nuclear side of things.

Ben: Alright, so...

Sean: Electrons are degenerates, but then they get peer pressured by gravity, and then they have to become neutrons, and then they get pissed off too, so, 'cause gravity peer pressures them, too, and then they end up a big lump of liquid.

Jocelyn: Yeah! Yeah that's pretty much it.

[20:21]

Ben: Yeah! So a neutron star, at its core is this weird liquid, and then as you move out it becomes more neutron-y and more proton-y until the very outside it's kind of dense regular matter. So the deal is imagine yourself in some kind of magnificent armor to keep you from getting crushed to death, on top of a neutron star and you've got a great big drill and you drill down to the core, the deal is that as you travel down towards the center, you're gonna go from kinda regular iron and stuff, into these weird pasta phases.

Sean: That wasn't in Journey to the Center of the Earth.

Ben: No, it's Journey to the Center of the Neutron Star, they didn't get past it in Journey to the Center of the Earth cause it was a bad movie!

Andrew: [LAUGHS]

Sean: The original was okay, the Brendan Frasier one was bad.

Ben: [LAUGHS]

Jocelyn: Wait wait wait, what? Brendan Frasier did a Journey to the Center of the Earth?

Andrew: It's too scary to think about, let's just...

Sean: Before, before The Rock took over?

Andrew: [LAUGHS]

[21:11]

Ben: So, just kind of imagine yourself making the transition down from the outside of the neutron star down to the inside. The idea is that you're getting more and more neutron-rich. So the number of neutrons compared to the number of protons is increasing because the deeper you go, the higher the pressure. And the higher the pressure the more electrons are getting squished into protons, so the more neutrons there are gonna be.

Jocelyn: So the starting point, you still have nuclei, but there's a lot more neutrons floating around and so the nuclei kind of grow into these bigger, still spherical, I don't know super nuclei that couldn't exist if there wasn't this huge, huge pressure that...

Andrew: So, your typical nucleus, for example, may have twenty or maybe even as many as two hundred nucleons, little, two hundred neutrons or protons. But eventually the nuclei, as you dig deeper and deeper into the layers of the neutron star, eventually the nuclei become so large they may have as many as a thousand neutrons and protons.

Sean: Okay that's a big jump. [LAUGHS]

Andrew: Yeah, so at some point the density in neutron stars becomes tremendous so that one teaspoon of neutron star matter weighs as much as, you know, all the buildings in Manhattan, combined.

Jocelyn: It's like, you know, trillions of times denser than water.

Sean: Okay.

Jocelyn: I mean it's just so crazy dense that our normal rules don't apply.

Sean: That's what kind of make the picturing part harder, but yeah you guys are painting it a little better for me now, okay.

[22:44]

Jocelyn: So the question is, what shape does stuff make? What you end up having to do is kind of make an estimate, so, like, how much are the protons trying to push them apart and how much are they sticking together from the strong nuclear force, and where is the balance between these things going to be?

Sean: Is the answer pasta

Ben: The answer's pasta!

Jocelyn: The answer IS pasta!

Andrew: That's right the answer's pasta.

Sean: Hooray!!

Ben: [LAUGHS]

Andrew: The way I like to think about what happens with the pasta is that you have these large nuclei with neutrons and protons, which of course the protons are all positively charged, so there's all this

positive charge in one space in this nucleus, and then you have this background. All of these nuclei sort of are swimming, if you like in this ocean of electrons, so that the combination of the nuclei plus the ocean is, all together has zero charge. But if you look at the point where the nucleus is, where all these neutrons or protons, that point has a lot of positive charge, because they're all protons there. And if you look at a point outside the nucleus in the ocean, that has, that's negatively charged, because there are not protons and you just have the background electrons. Does that make sense so far?

Sean: Yeah!

Ben: Oh man the sauce is made out of electrons!

Andrew: Actually there are neutrons in the sauce, too, I was trying to...

Sean: ...pasta

Andrew: Yeah... [laughs] Sort of a super sauce of electrons and neutrons and it's a super sauce because they're superfluid, but...

Jocelyn: It's been thickened

Ben: [LAUGHS]

Andrew: Yes. So originally, of course, the nuclei have to play this delicate balance because the strong interaction which wants to keep them together. But then there's the electrostatics. The fact that the two protons have this repulsion because they're both positively charged, and so that's what originally keeps the nuclei spherical. Is this sort of balance between the strong force and the Coulomb. But eventually what happens is these nuclei become so close together that they feel each other and this, these positive and negative charges, it becomes difficult to arrange them in a way that, that's sort of stable and the only way to sort of resolve this difficulty, this funny geometry, the spheres are so close to each other and there's this funny little space between spheres, just like you have, you know, if you put basketballs in a little closet, if you fill the closet with basketballs then there's these funny little spaces in between which are also negatively charged. So there's these positively charged spheres and so eventually you get to this point where this geometry is really complicated and we say "frustrated". This is geometrical frustration and then the way to resolve this frustrated system is to deform the nuclei into ellipsoids or, or even as far as pasta. This is why we get these nuclear pasta, is to resolve this frustration.

[25:18]

Ben: So I've been thinking about how to describe why this happens, and I've come up with the best explanation of all time. Everybody agrees this is the best explanation of all time, are you ready for the best explanation of all time?

Sean: I was born ready

Ben: Okay, so imagine that you're like the mayor of like, a walled in piece of the countryside.

Sean: Alright, I'm there.

Ben: Throw in some people and some caravans and stuff. You're gonna live inside of a camper vans. And uh, there's two types of people that you're gonna throw in, there's going to be bagpipe players, and there's going to be bagpipe groupies.

Sean: [LAUGHS]

Ben: So the bagpipe player groupies love the bagpipe players, and they pair off, but the bagpipe players *hate* each other, it's like this Coulomb force, this electric force, right? Essentially they want to be as far away as possible from each other. But they, they like the groupies, and the groupies really like the bagpipe players. So they end up traveling around in little camper fans all alone and try to stay as far away from each other as possible. But you know, you're the mayor, and you're kinda corrupt, so you keep on throwing more and more people into your walled-in little town. So much so that you know, there's... Pressure gets too much. People are starting to live on top of each other.

Sean: Yeah, yeah.

Ben: And the bagpipe players hate each other! And the nice thing about a camper van is, in any direction you look, you're not up right next against another bagpipe player. But suddenly if there's too many people, something's gotta give. So what the people in the town do is they start making lines. They line up all the camper vans side by side so that two walls of their camper vans are touching. So they have two neighbors, one on the left, one on the right, so they not getting perfect peace and quiet when they're practicing their bagpipes, but you know there's still up, down, front, and back walls, uh, not touching anything and so it's not as loud as it could be. It's still pretty good they can still play their bagpipes. This is essentially, the people in your little community have suddenly started arranging themselves in strings. Kind of one dimensional strands, looks kinda like spaghetti

Jocelyn: Yeah, 'cause you can fit more people in and they still have a little bit of space, just by stringing themselves along.

Ben: I mean their own bagpipe music is fine, but they're not getting bagpipe music from all sides, just from left and right. So it's not the best but it works. But then you know you're a corrupt mayor, so you keep letting more bagpipers into your bagpipe van, more bagpipe groupies. What happens? Suddenly there's too many of them, it's still very packed, so the bagpipers start arranging their vans in kind of like apartment blocks. Long strips of apartments. Okay? So on left and right, you have bagpipe neighbors. Up and down you have bagpipe neighbors, but out the front side of your apartment, out the back side of your apartment it's still non-bagpipers. So you're getting bagpipes from four sides, but not six sides. So at least it's better than nothing.

Sean: This still sounds like the worst apartment building ever.

[Jocelyn, Andrew laugh]

Ben: Now the moral of the story is, suddenly the people in the town have arranged themselves into sheets instead of strips. It's too dense for strips, but sheets can still give them a little bit of space so that they're not bagpiping 24 hours a day. Now, what do you do? You decide to throw in more people you say hey more people, go into my town, I can get more tax dollars and I won't let you out once you go in. And the population keeps rising. More bagpipers more bagpipers. What happens? They start building themselves structures where, you know, essentially it's kind of like an apartment building. You know how sometimes apartment buildings have long straight courtyards that are surrounded on all sides by apartments? So you get these tall apartment blocks with essentially the only air anybody gets, these long shafts that go straight to the bottom.

Sean: [LAUGHS]

Ben: [CLEAR THROAT] So the deal is

Jocelyn: [LAUGHS]

Ben: [CLEAR THROAT]

Sean: You missed what you said, it's okay

Ben: [CLEAR THROAT] I certainly didn't...

[Jocelyn, Ben, Andrew laugh]

Ben: So the deal is...

Andrew: You just chose to be adult about it.

Sean: Hey, hey, I...

Ben: I know, this is gonna get an explicit rating thanks to you, Sean.

Andrew: There, it was just laughter, I mean...

Sean: Straight to the bottom!

Jocelyn: ...it's not like we spent the entire...

Ben: Listen, life in these apartment buildings is really hard!

Sean: Yeah it is!

Andrew: [LAUGHS] Especially with all these groupies!

[Jocelyn, Ben, Sean laugh]

Ben: So what you end up with is instead of long one-dimensional strips of bagpipe players, you end up with essentially long vertical strips of non-bagpipe players. But essentially that's all the space they can get. And finally you throw in more bagpipe players, more players, and the only way they can arrange themselves so that anybody ever gets any peace is essentially it'll be, it'll be like one of those office buildings where nobody has a window, and everything's really dense, but there are atriums, there are big bubbles you can go and have a little break. And so essentially you get a big block of bagpipe players but occasionally they can go out to one of these big open rooms like a gymnasium and not have to hear bagpipes from all direction at all times. Moral of the story is this is essentially what happens to the neutron matter on the inside of the neutron star. As the pressure goes up and gets higher and higher and higher, and the neutron density count increases and increases, the matter ends up forming itself around similar principles, where instead of bagpipe music and the bagpipers hating each other, you have this Coulomb force, and the moral of the story is the matter inside of the neutron star shapes itself like the different pasta phases. First balls, and then strings, and then sheets, and then anti-strings and then anti-bubbles, and then it's just pure neutrons all the way around.

[30:39]

Jocelyn: Except we're not sure that this actually happens.

Sean: One of the exciting questions in nuclear astrophysics is, is there really this nuclear pasta in neutron stars or not? And so one of the big goals is we would like to be able to, to smell the pasta. We would like to be able to go, in a telescope, and look at a neutron star and say "yes, that has pasta, I have smelled it."

Jocelyn: And it's tricky because of course all these neutron stars are really really far away, and we don't get very good looks at them, so one of the main ways that we see neutron stars is that they end up having actually strong magnetic fields, and as they spin faster and faster pulling all their legs and arm in and spinning and spinning really fast on the ice. So they spin really fast and they have strong magnetic fields and they end up giving off these beams of radiation, like a lighthouse beam that sweeps past earth and so we can say "boop boop boop boop" okay that that's a neutron star and it's spinning this many times a second. And as they spin there, they're actually losing some energy so they're slowing down, so they're slowing down a little bit every time. But sometimes the rate that they spin changes suddenly. Okay and that's what's called a glitch. So that has a change of the spin rate. And then there's also, there's something where if there's pasta phases change how fast they spin down.

Andrew: It's actually sort of indirect, you look at a neutron star which is spinning with pasta and you look at the neutron star which spins without pasta and you compare them, and you find that if they don't have pasta, then they don't spin down as efficiently as if they do have pasta. So actually this is a question of electrical resistivity. So because these pasta are actually charged, the pasta has more resistivity than non-pasta would.

Jocelyn: Right, so if the electrical properties change, the [*way that it*]t's interacting with the environment around it changes a bit, and so you look at the neutron stars and you see, have they slowed down a lot or are they spinning really fast still?

Andrew: And then the limitation that they haven't slowed down is because of the pasta. The pasta has more resistivity so you cannot for the currents that allow for spin down. There's this upper limit of twelve second on the period of magnetars.

Jocelyn: Right.

Andrew: Sorry, this is a bit technical, but...

Jocelyn: So we do see that they're not spinning very slowly. Anyway, it's a bit complicated.

Sean: Pasta's faster?

Jocelyn: Yes, pas[ta s]pins faster

Sean: Okay, and then I guess you guys are trying to conserve that more, to prove that pasta exists.

Andrew: It turns out it's actually just very difficult to really determine with...

Sean: It's hard to get a plate of pasta over here.

Andrew: ...100% certainty that this pasta is there. Because it's, it's very deep, and it's sort of a subtle thing. It's just this little shape change.

Jocelyn: So it doesn't necessary have a big impact on how big the star is, or a lot of things, if you see that the star form[inaudible]. The details of what configuration is supporting it at what layer turns out not to change very much with or without pasta.

Sean: So it's not something that you can just look out and go "Oh! There it is!" it's a lot more complicated.

Jocelyn: Yeah. But it's sort of this interesting prediction of some of the nuclear theory that we're not certain about so we try and figure out what on earth can we map from observations of a bunch of little blips in the sky to learn about nuclear physics. So now you can make yourself some dinner and contemplate the mysteries of the universe.

Sean: Hell no I'm headin' to a bagpipe bar later.

[ALL LAUGH]

[34:09]

Ben: Well that was fun! Thank you Andrew, thank you Jocelyn. You've pleased me. Your efforts have borne fruit and that fruit is sweet here's some fruit. Andrew you get a spaghetti squash!

Andrew: Raghr raghr raghr.

Ben: Nice. And Jocelyn you get some uh flattened plums.

Jocelyn: [smack smack smack smash]

Ben: Nice. Alright, I'd like to thank my guest. Sean Martin thanks for coming on.

Sean: My pleasure thanks for having me.

Ben: I hope you had fun learning about spaghetti!

Sean: Tons of fun!

Ben: Listen TiPhyters, listen. Some of you may want to support our show, financially. That's understandable. We don't just have hosting costs to take care of, we've got dues to pay in the Brachiopemedia network, and we could use our money to improve our hardware. Maybe buy Jocelyn a microphone!

Jocelyn: I have a mic-r-

Ben: We could buy you a BETTER microphone.

Andrew: [LAUGH]

Ben: And we could, we could send our physicists to podcasting conferences. Let's suppose you want to support us. You can do so in a variety of ways. Firstly there're donations. There is now a donation button on the Titanium Physicists website where you can set up a one time or recurring donation. Secondly, there's a podcast app called Podiversity for the Android phone; Android phones are very popular. Now, it's a subscription-for-content-based app, kind of like Netflix for podcasts and they pay us cash money for episode downloads. Uh. So if you'd like to get an app, then listen to our show, cha

ching! Anyway, uh, I think they have a trial period if you'd like to try it. So thirdly, T-shirts! Go to our store off the Titanium Physicists website and buy a sweet t-shirt. Some of them were designed by our brilliant designer Chelsea Anderson. Are the shirts expensive? Yes. They're a little bit expensive based on the t-shirt website we're getting them from, but Titanium Physicists gets a cut of each shirt sold, and they're really good quality shirts. Bethany bought one two years ago and has worn it once or twice a week ever since and it still hasn't worn out, so the t-shirts are really nice, so have a look at them. Anyway. Remember if you like listening to scientists talk about science in their own words, you might also want to listen to other shows on the Brachiolope Media network. There's a new show on the network I'd like you to know about. It's called Astrarium, with Titanium Physicist James Sylvester and his buddy, and they talk about Astronomy. It's so good, you should go outside and lie down and look at the stars and listen to it. Anyway. Editing support for the Titanium Physicists Podcast hwas provided by John Heath. Thanks John. This episode was probably pretty hard to edit. The intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Until next time, my friends, good evening and remember to keep science in your hearts.

[Vanderslice plays]