Episode 69: Super Hyper Fire Hose Bucket Challenge
Physicists: Katie Mack, Hannalore Gerling-Dunsmore

Transcribed by Denny Henke

Ben: Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty episodes now my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on: to present you with your birthright, an understanding of the universe. I've traveled the world seeking out a certain type of genius, masters of not only their academic disciplines but also at explaining their research is understandable ways and I've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

[1:49]

Ben: One of the leading mysteries of general relativity is the problem of the arrow of time. Now, in general relativity we have this idea that time is part of a four dimensional curved surface upon which we all skate from the past towards the future. And there's a problem with thinking of time in this geometric way and that's that in this context time doesn't have its usual, "time is how you only ever get older and never younger" punch. Ah, spacetime geometry doesn't really have a natural way for us to distinguish which direction is the past and which direction is the future. So, how can we tell the difference between the past and the future? Why do these concepts even exist. It turns out, time shows up in more than one way in physics. There are some systems which evolve in only one direction in time. So, think of the simplest clocks. Sand timers, hourglasses, right? Sand starts off in the upper bulb and slowly pours down into the lower bulb and it takes a reliable amount of time for this to happen. And it never happens backwards. So, you can use it to measure out time. All clocks, in one way or another, use increasing entropy to distinguish the past from the future. And, in fact, physicists expect that the universe should be expected to do the same. The overall entropy of the far future should be really high and the entropy of the distant past should be really low and every moment between the two should be accompanied with an increase in entropy. But wait, wait, hold on. What is entropy again? We did an episode on it, it's a measure of how mixed up the system is. When the system is all mixed up it has high entropy and when it's all organized it has low entropy. Wait! You say, I can hear you, by the way, through your earbuds. Wait! You just said. At the start of the universe, during the Big Bang, wasn't the universe all fiery and stuff? Wasn't that really high entropy? Well yeah, the energy density back then really was high. But think about it, back then there was only oneish kind of atom. Mostly hydrogen, right? In the ensuing, evolving, expanding, cooling universe that hydrogen collapsed down into stars which release energy by making new kinds of atoms, increasing the diversity, increasing the entropy. Okay, so what happens? What's the story of the universe? Hydrogen everywhere, it collapses down into galaxies and stars, stars turn their lighter elements into heavier elements until... until what? Eventually you run out of things to burn. All you have left is gas in space. Brown dwarfs, neutron stars, black holes and there's no such thing as a stable orbit. Orbits release gravitational waves which cause orbits to decay. So what? So, eventually everything is going to fall into the black holes. It will take a gabillion years but that's what it will come down to. Since things can go into a black hole but can't come out them, that will be the end of things, just a bunch of black holes and gravitational waves. Okay, now, here's the thing, entropy is always increasing in the story, right? But the entropy is usually given in terms of matter. Types of matter all mixed up in different ways and black holes aren't matter. They're nothing but spacetime curvature. They're smooth and round and they're so simple they can be described with three numbers. And yet somehow a solar mass black hole must have more entropy in it than a solar system full of planets crawling with crazy life. And that's the riddle. How do you connect these two ideas. Entropy which always increases as time passes and spacetime geometry where we can't tell the past from the future. How do we find the arrow of time in spacetime geometry? Well, regardless, it's a mystery for another time I suppose. I just thought you might enjoy, on this autumn night, the fact that every atom you've ever touched or seen in the Earth or heavens will probably one day, end up sliding into the incredible maw of a super massive black hole at the center of the Milky Way galaxy. We'll just have to wait for a long time for our turn to come.

Okay, so, today, on the Titanium Physicists podcast we're talking about super massive black holes. It's been awhile since the introduction had a twist ending like that. So, our guest today is one of the most prominent science communicators of our generation. She's one of the world's most famous skeptics. She founded the skepchick.org network in 2005, she was a co-host for the Skeptics Guide to the universe Podcast for many years and she currently makes YouTube videos and is a popular commentator. If you follow the link on our website you can find her Patreon page with all her current projects. Welcome to the show Rebecca Watson!

Rebecca: Hello, thank you for having me.

Ben: Ha ha, this is going to be so much fun...

Rebecca: I hope so because I'm really depressed after that intro.

Ben: Never be depressed. We'll die long before then!

Rebecca: Ah, well, okay, that's cheery. Thank you.

[6:33]

Ben: So, Rebecca, for you two fantastic Titanium Physicists. Arise Dr. Katie Mack!

Katie: Tadaaa!

Ben: Dr. Katie did her PhD at Princeton University in astrophysical sciences. She's currently at the University of Melbourne in Australia where she's a postdoc and a holder of a Discovery Early Career Research Award. She studies theoretical cosmology. Now, arise Hannalore Gerling-Dunsmore!

Hannalore: Dooodooodalooooo!

Ben: Hannalore got her undergraduate degree at the University of Maryland College Park and she's currently a PhD student at Caltech where she studies super massive black holes. Right on topic! Alright everybody, let's talk about the big monster that no one wants to look at.

Katie: Okay. There are many kinds of black holes and we generally categorize them by their size or by their mass really. So, most of the time you think of a black hole as something where a star has collapsed on itself and it creates a black hole and that's called a stellar mass black hole. And those are really common, we know about a lot of those in our galaxy. But a super massive black hole is a black hole that is significantly more massive than that, usually around a million times the mass of the sun. And these things are found all over the universe, generally in the centers of galaxies. And we know that there's one in our galaxy, it's called Sagittarius A-star and it's in the middle of the galaxy. But we think that there are super massive black holes in the center of pretty much every largish galaxy in the universe. And there are a lot of mysteries around them and they're really useful for certain things in cosmology and observations. And I guess we're going to get into all that but basically a super massive black hole is defined by being significantly more massive than a star. And where that line goes, there's also intermediate mass black holes which are around a 100 or a 1,000 times the mass of the sun and anything above that is generally considered super massive.

Rebecca: Can I ask a question?

Katie: Yes.

Rebecca: Ben mentioned that there are three numbers that can describe a black hole. I'm wondering, what are those three numbers.

Katie: Yeah, so this comes from the no hair theorem of black holes. The statement is that black holes have no hair. And that's just saying that they're very, very simple objects and they can be described by their mass, their spin and their electric charge. And with those three numbers you can describe everything there is to know about a black hole. Now, this is a theorem that hasn't been technically proven yet so there are lots of interesting ideas about other properties that black holes could have where they could have some kind of other fields that interact with them that give them some extra characteristics or whatever. But basically they're extraordinarily simple objects. If you just know the mass and the spin and the charge then every black hole with that mass, spin and charge is exactly the same and completely indistinguishable.

Hannalore: So, one thing is intermediate mass black holes actually are a little bit of a holy grail for observers because we haven't seen what we call an intermediate mass black hole which would be around a 1,000 to 10,000 times the mass of the sun. Um, we see 100 solar mass black holes from core collapse but we actually don't see true, intermediate mass black holes. So, that's one thing that is a huge question and is a part of the issue of super massive black hole formation. Is trying to figure out where are all those intermediate mass black holes because technically if you're starting from the small one and growing into a big one you should stop in the middle sometime.

Katie: It's kind of an interesting question too though because if black holes grow from being stellar mass to being super massive, and pass through this intermediate mass stage they wouldn't necessarily be easy to see.

Hannalore: True.

Katie: There are sort of certain reasons why it's easy to see black holes that used to be stars and only recently became black holes and they're still like in the disc of the galaxy and all of that. And it's easy to see super massive black holes that are, you know, at the centers of galaxies and pulling in a whole lot of matter and stuff like that but it's really, potentially very hard to see the ones in the middle.

Hannalore: Absolutely. And it becomes a question of is this a selection bias, is this an issue with the way we observe things or is it actually a real deficit.

Katie: Yeah.

Rebecca: And when you talk about seeing them, you're talking about seeing the effects around them? Is that how you figure out where a black hole is?

Katie: Yes, this is a very good question. I mean, the way we usually see the evidence for stellar mass black holes is their accretion. So, the first stellar mass black hole that was ever found, it was found because it was an x-ray source so basically what's happening is that you have a black hole and there's gas falling into the black hole and as the gas is falling in it makes this sort of whirl pool. And so it makes a disc of matter that's coming in that's called an accretion disc. And that disc of matter, because that matter is moving around so quickly, it heats up and it starts glowing in x-rays. And so usually you can see stellar mass black black holes by that x-ray glowing. With super massive black holes you can see that but there are other sort of things that we can pick up on. So, the black hole at the center of our Milky Way, Sagittarius A-star, there are a few pieces of evidence for that. One of them is that we do see brightness fluctuations as little bits of gas are falling into the black hole and we can interpret that as gas falling into a black hole.

[11:32]

Katie: But one of the most compelling pieces of evidence for Sagittarius A-star being a black hole is that we see a cluster of stars orbiting it very, very, very close. So, there's this cluster of stars right in the very center of the galaxy and we can see individual ones because we have really good telescopes and we can do adaptive optics and all this stuff. And we can actually look at these individual stars in this central region of the galaxy that is many light years away from us and we can watch these stars as they orbit around this unseen thing. And, see, our black hole doesn't have this bright accretion disc around it. For whatever reason it doesn't seem to be pulling in a lot of gas right now so we don't see it from that glowing. We occasionally see little fluctuations but we don't see, like, a really bright source. But, what we do see is these stars moving around and we can track their motions and that gives us an estimate of the mass of whatever this object is. We can also see that they pass really, really close to whatever the central object is. And as we watch how close they pass that gives us an idea of how small the object is that they have to be moving around. And it's just much smaller than anything could possibly be without being a black hole. So, you could imagine like, you know, when this was first discovered people thought maybe it could be a cluster of stars or something that these other stars are moving around or some kind of really massive star, whatever. But, as we got better observations and we saw these stars going around we found the total mass of the thing which is somewhere around 4 million times the mass of the sun. But we also saw that it had to be extremely small. And, the way that you define a black hole, really is just by an amount of matter within a certain radius. So, if you get enough matter within a particular radius related to that mass then it has to be a black hole. There's no force known in the universe that can keep it from collapsing into a black hole. So, if you know that you have enough stuff within a certain size then that just has to be a black hole. And that's the sort of strongest evidence for Sagittarius A-star being a black hole, is that stars are passing so close for something that massive, that it really can't be anything else.

Rebecca: How big is it then, approximately?

Katie: The rule of thumb is that the radius for a black hole of the mass of the sun is 3 kilometers. So you can figure it out from that. But anyway... Hannalore, you have the number?

Hannalore: It's, so, if we're assuming a Schwartzchild radius which will give us approximately the order of magnitude, we get that it's about 13 million kilometers.

Rebecca: 13 million kilometers.

Ben: Yeah, that's wider than our sun is in the solar system.

Hannalore: Yeah, it's about 1/3 of the nearest approach of Mercury to the sun.

Ben: Right. So, it's pretty close to the width of the orbit of Mercury is what you're saying.

Rebecca: Okay.

Ben: It's huge as, like as a black hole, right. So, if our sun turned into a black hole it would be 3 km wide and this thing is so big that it's, you know, the width of the orbit of, it's much bigger than our sun which is not, made of, it's not a black hole. Ah I said that badly.

Laughter.

Ben: This video that Katie is talking about is absolutely bananas. I try to show it to everybody I see and I put it on the web page more than once. Essentially, you know how like a video is just photographs taken over time? As things move around? Usually when you take photographs of stars they don't really move around. But the Sagittarius A-star, this like, cluster of stars are all orbiting something. You know the way that comets orbit the sun only they're orbiting this one thing that you can't see and they're stars. They're huge stars, they are incredibly massive. How should I put this. So, our planets orbit the Sun, right? Because the Sun is a jabillion times heavier than the Earth. But our planets around our Sun don't orbit the center of the Sun. They orbit the center of mass which is well within the Sun. I think the Jupiter-Sun system, that center of mass is outside the boundary of the sun so in that case if you were to watch Jupiter and the Sun orbit each other you would see that Jupiter going in a big circle and the Sun going in a little circle, right? But the moral of the story is, like, you need an incredible amount of mass to cause a star to change its position in any kind of visible way. The thing that we can't see is totally throwing these big giant stars around and it's not moving at all... like...

Rebecca: How long does it take those stars to make an orbit?

Katie: I have the animation in front of me so I can just check for this particular star. So, there's this one star called S02, that's the one that's like really given the best evidence, um, for the size being very, very small. Um, it's only like a few years. I think like maybe a 10 year time period or something.

Rebecca: That seems like, that means those stars are like screaming through, right, like...

Katie: They're really, really fast.

Ben: Yeah.

Katie: So, it's something like, 12 or 13 years for that star to make it all the way around.

Rebecca: And would it be, even possible for those stars to have planetary systems or would the black hole throw all that off?

[16:32]

Katie: I think it would be really tough to hold on to anything um, going that close to the black hole. Because some of these stars pass really, really near by. I mean, that particular one, gets to less than a 1/1000th of a parsec. I don't know what that is in, like, normal people numbers. Um, the closest this star gets is 124 AUs. So, an AU is the distance of the Earth from the Sun. So, this goes within 124 times the distance of the Earth from the Sun.

Rebecca: Okay. Are those stars getting closer to the black hole?

Katie: Ah, not really. Um, There's not a lot of gas around for them to run into and like, you know, slow down. So, as long as they're not running into anything and as long as they don't get too close to the edge of the black hole then they can be on a stable orbit. That particular star, that close passage is over 2,000 times the size of the black hole. So, it's okay in the sense that it's not getting close to the edge of the black hole, really. So, the orbit of the star is probably okay for the time being but I think if it had a planet around it, um, that planet could get a lot closer and sort of tidal forces that it would experience would be pretty tough.

Ben: So, Pluto's about 50 AU at it's epihelion. And this one was at 120 did you say?

Katie: 124.

Ben: Okay.

Katie: It's like, probably somewhere around the Oort Cloud.

Hannalore: So, one thing to keep in mind, okay, so let's see, Sagittarius A-star is a million solar masses, approximately, right? So, the outer radius of its accretion disc is going to be approximately 25,000 light years, going by the Bondi-Hoyle approximation. I don't know if that's interesting to anyone.

Rebecca: Sorry, say that again.

Hannalore: Sorry, sorry. That would be the outer edge of where you can get gravitational, like true gravitational capture.

Rebecca: Oh, so it doesn't have an accretion disc because there's not enough gas being captured...

Hannalore: Yeah.

Rebecca: But it still has that edge where you need to stay away or you're going...

Hannalore: Right.

Ben: So, what she's saying is if a bunch of gas did fall in the outer ridge of the accretion disc could be out to 50,000 light years in diameter.

Hannalore: And a light year is about 6 trillion miles.

Rebecca: Wow.

Ben: Great.

Katie: Yeah, but fortunately this is not a thing that is happening. I mean, there is a little bit of gas in the vicinity of Sagittarius A-star but, and so we do see stuff falling in once in a while. There was a thing in the news a little while ago about a little bit of gas that was sort of falling toward the black hole and we were all watching for it to heat up and get captured but basically its a very, very quiet black hole. And that's not the case for all of them. I mean, most of the super massive black holes we see in the universe we see them because they're not quiet at all. Because they do have this accretion happening and they can be extraordinarily bright.

Ben: Aw yeah.

Rebecca: So, when something falls into a black hole it's destroyed, utterly.

Hannalore: Yes.

Rebecca: The matter doesn't exist anymore. So, does a black hole get bigger or more massive every time something falls in or does it stay the same size.

Katie: No, it does, yeah. Every little bit of mass that it pulls in adds to the mass of the black hole and it means that that edge radius gets a little bit farther away.

Rebecca: But if that's true then isn't it not be completely obliterated. Isn't that matter still there in some way?

Katie: No, it's being obliterated in the sense that, like, it sort of loses it's character as matter. Like, anything that goes into a black hole, like we don't really know exactly what happens in there but a black hole is basically just a space-time feature. You can think of it as whatever falls into the black hole gets converted to, like, pure spacetime. Pure, like, curvature.

Rebecca: Right.

Hannalore: So, Rebecca, what might help, is, thinking of the fact that mass, really, is just energy, right?

Rebecca: Right.

Hannalore: That's why we use Einstein's name as synonymous for genius, that was his great insight.

Rebecca: Yeah.

Hannalore: And so, what warped space-time is just energy. So, as Katie said, it does add to the mass of the black hole because it adds to the warping of spacetime that makes up the black hole. But, what you loose is information about that matter other than pretty much its mass. And maybe a few other things depending on...

Rebecca: Right.

Hannalore: What theories you subscribe to in terms of information theory. But that's basically the difference. You know, it's not... you can't reconstruct that object that fell in...

Rebecca: Right.

Hannalore: From just the mass. Right?

Rebecca: Right.

Hannalore: Right, so that's what it means. So, it's a really good question, that's a really important research topic.

Ben: It's, essentially, the black hole is the gravitational footprint of whatever matter was used to create it. So, ah, you add a little bit more mass to it, ah, the overall size of the footprint is going to increase. Ah, that said, what happens is the matter crosses the event horizon, goes into the singularity. When it goes into the singularity it has, essentially, exited the universe. So, mathematically the matter isn't there anymore. But, stuff inside the black hole can't communicate anything outside the black hole. And so, all that remains of the matter in terms of our being able to recognize what it is is just this footprint it left behind saying I had this much mass before I joined this other big ball.

[21:38]

Okay. So, so, here's the thing. Katie Mack said something amazing where we were talking about the accretion disc around the black hole. She said, hey, it's a good thing that our super massive black hole in our galaxy doesn't have one of these big accretion discs. And the reason she said that wasn't because she was concerned about all the stars orbiting the black hole because surely they would be crossing this accretion disc and slowing down and their orbits would be unstable and they inevitably would crash into the black hole. That's not why she was saying it. She was saying it because we have observational evidence of black holes. Or, alternatively put, super massive black holes are used to explain one of the big early mysteries in cosmology. Have you ever heard of a quasar?

Rebecca: I have heard of a quasar. Yes.

Katie: The word quasar actually comes from quasi stellar object. So, we often write quasar as QSO, quasi stellar object, because basically astronomers looked at these images and they saw this really bright thing that seemed to be a point, you know. It didn't seem to be an extended thing like a galaxy. It just looks like a really bright star but it had the wrong sort of spectral properties to be a star. And, after awhile, it was figured out that these things were extraordinarily distant. And so, actually, much, much brighter than any star could possibly be. And much, much brighter than galaxies tend to be in terms of, like, if you look at the light from the stars in the galaxies. And so for awhile there was this big mystery, like, what could these things possibly be. And now it seems that they are the, sort of, lit-up accretion discs of super massive black holes in other galaxies. So, in some galaxies the black hole at the center is actively accreting gas so it has this big accretion disc. And that disc is lit up from just the sort of energy of all the stuff falling into it. And so it glows in this extremely bright way at very high energy radiation like x-rays. And it can be so bright that we can see it from, basically, across the entire observable universe. And we've seen quasars out to extraordinary distances. The farthest things we've been able to see, just with our telescopes at all, aside from the Cosmic Microwave Background, which is just the background radiation from the Big Bang, The farthest things we've been able to see are quasars and I think also, gamma ray bursts. But I think quasars might be some of the most distant things. We can see quasars out to a distance that corresponds to when the universe was only a few hundred million years old. And now it's 13.8 billion years old. So, a very long time ago.

Rebecca: That's awesome. Actually, might next question that I had written down was whether or not all super black holes just give up on sucking in those gasses or if it's just ours. So, is that a, is that a recent discovery, that that's what quasars are?

Katie: I don't think it's that recent. I think we've known about quasars being black holes for quite awhile. Maybe a couple of decades. And now that we know that they are black holes, and specifically that they are black holes at the center of galaxies, pulling in gas, we can use them to do, sort of, mapping of how the universe is laid out because we can see where the are in different parts of the universe. And they trace where the galaxies are to some degree. But, you know, not all galaxies have accreting super massive black holes. Sometimes the super massive black hole in the galaxy is just like ours where it's not really doing a whole lot. And sometimes they are accreting a whole lot of gas and they have this quasar thing. But there's also the aspect of the jet of material coming out of it. So not only does the black hole get this accretion disc that lights up because there's all this matter falling in and it's crashing into itself, um, a lot of times these black holes also can propel these huge jets of matter stretching, like, hundreds of thousands of light years. Of just this very, very, like straight jets coming out of both ends of black holes. You have the disc and then at right angles to the disc you have these long straight jets shooting out into the universe. And those jets are also very bright and visible and so we can see some quasars by, you know, seeing jets sort of pointed at us, and that makes them extremely bright as well.

Rebecca: Hmm.

Hannalore: To give you sense of scale, Rebecca, quasars have a luminosity of about 10 to 100,000 times of the luminosity of the entire Milky Way. So this is just one...

Rebecca: Oh my god.

Hannalore: Right? It's just one physical system having the brightness of, you know, at least 10 and up to 100,000 Milky Ways.

Rebecca: Wow.

Hannalore: So, when Katie says really bright, she's not joking. They are some of the brightest, most energetic things in the universe.

Rebecca: Present company excluded.

Laughter.

Rebecca: Obviously. Real quick, um, Katie, you mentioned not all galaxies have super massive black holes that are going to have these accretion discs, but does that mean that it's theorized that every galaxy does have a super massive black hole at its center?

[26:35]

Katie: Well, every, every reasonably massive galaxy seems to have one. I mean, it's hard to rule out entirely that there might be some without. There are certainly dwarf galaxies where we don't know for sure if they have black holes or not. Because those blackholes might be pretty small and they might not be doing a lot but in the cases where we've been able to do the observations well enough um, it appears that that black holes are pretty much ubiquitous in the centers of, of reasonably massive galaxies.

Rebecca: Cool.

Ben: I half remember a factoid that said something like super massive black holes preceded the formation of structure in the galaxy. So, galaxies formed around...

Rebecca: Oh.

Ben: Where these super massive black holes were, is that...

Hannalore: That...

Katie: This is a very complicated question. So, Hannalore can also probably say a lot more about this but it looks like whatever's happening, the black holes and the galaxies are so correlated that they seem to grow together and whether or not one comes first or the other is kind of hard to say at the moment. Is that correct Hannalore?

Hannalore: Yeah, that's exactly right. So, right now, what's called the M-sigma, or basically the size of the black hole and the galaxy itself, the way they co-evolve is a very active area of research so no one can really give terribly precise answers on that. Right now it does look like you approximately get, at least the beginning of a super massive black hole first. But it does, the galaxy does grow along with the super massive black hole. As the super massive black hole gets up to true super massive scale, so, you know, around a million times the mass of the sun.

Katie: So, I just want to clarify one thing because I might have spoken a bit imprecisely before. Whether or not we see an accreting black hole as a quasar, depends a bit on the direction we are looking at it from. So, if a super massive black hole is, is accreting a lot of gas and has this very bright accretion disk, if we see it from the side we might not actually be able to see the accretion disc and so we might call it something else. But when we can see the disc and we can see the jet or, you know, sort of, um, depending on, sort of, how the geometry of it is laid out, then we see it as a quasar. Whereas sometimes if we see it edge on we might see it as some other kind of radio galaxy or something like that. Anyway, just to clarify that.

Hannalore: So, what Katie is talking about is referred to as the Unification model of super massive black holes. And this idea is that actually most super massive black holes are pretty similar but the types of radiation that you see depend highly on where you are viewing it from. So, you can kind of think of it as, you know, if you're shining a flashlight and in one direction you don't have anything in the way of it it's just going to look like a flashlight, right? But if you were to hang, like a red sheet off to the side of it and then observe it from the side it looks like this really soft red light. It's a similar idea of the matter that's around the super massive black hole. There's accretion discs which, as you go farther away from a black hole, gets thicker and thicker, there is actually a torus that's around most or all of the super massive black holes at the centers of galaxies ah, that can obscure a lot of the radiation. There's also winds which aren't quite like a jet but they are an outflow that go along the surface of the disc and those have different radiative properties and different spectra. So, currently people are trying to figure out how viable that is as a theory for how we see different types of radiation from these super massive black holes and exactly how dependent that is from observation angle.

Rebecca: And how are we, how do we try to get around, ah, the angle at which we are observing? I assume that all of these objects are so far away that there's really no easy way for us to do anything except for view them from one particular angle.

Hannalore: One of the, so, you're totally right, Rebecca. And the way that we do that is we run simulations that include all of the physics that we know of at, that we know is going on probably. Um, and then we, from those simulations, we see what the spectra should look like from different viewing angles, essentially. And that's how we try to figure it out, but of course, you know, then we need to check those theories and see if those are valid against other types of observation which makes it a little bit difficult because we don't have too many types of observation from these super high red shift quasars.

Katie: I don't think we've talked about redshift yet but that's just very, very distant quasars. But, I mean, we have a whole lot of quasars to see though. Like, there are many, many quasars that we have done observations of and many, many radio galaxies or other kinds of galaxies that do seem to have accreting black holes. So, there's a huge sample and this Unified model is just kind of an idea that, you know, a lot of these have very, very similar physical properties and although all we really see is kind of a point of light in some cases, we can analyze the spectrum of that light and get an idea of what exactly we are seeing. It's kind of amazing actually. I mean, you can go to these seminars about quasars and accretion discs and stuff like that and they just show the spectrum of light and all you see is like this sort of wiggly line and then they put up this drawing of like this black hole with this disc and this jet and this dusty torus around it and, you know, little chunks of matter falling in or coming out.

[31:36]

And then there's the radiation and you look at, like, this actually physical, like, model, and all they really see is the, like this little squiggly line with the spectrum and you're like how do you figure that out that. But, you know, that's, when you have an understanding of what the physics would give you for these different configurations and you can sort of look at, basically, a continuum between one kind of object that has a lot of radio radiation and a lot of really bright, hard radiation. And then another kind of object that's more in the infrared and stuff like that. Like, you can actually see a kind of continuum between different angles of viewing and put it all together to be one kind of object. It's one of the most satisfying parts of science when you can take a whole bunch of different things that seem to be very disconnected and totally different types of things and say, actually, that's that's just different perspectives on one object. One kind of object.

Ben: It's like that story with the elephant and the blind wiseman. So, essentially the physicists get together and they're like alright, that rope, that tree...

Katie: Yeah.

Ben: That hose, whatever the stories are, ah, what you're talking about is a hypothetical monster.

Laughter.

Katie: Yup.

Ben: That's standing in this room with you and can crush you at any time.

Laughter.

Hannalore: That is sort of how a black hole is.

Laughter.

Ben: Yeah, correct.

Rebecca: It's the elephant in the room.

Ben: So, moral of the story...

Katie: Yes.

Ben: Let's summarize. We see quasars and weird signals from galaxies far, far away.

Katie: Yes.

Ben: So, you see all these galaxies and they're lighting up in weird ways and what we're saying is, all of these can be explained by super massive black holes.

Katie: Yeah.

Ben: By, essentially, gas is flowing into these super massive black holes, it's a really, energetic, dynamic process. That's that crazy energy signature that's brighter than the galaxies that we are observing.

Katie: So, one of the things that's compelling about black holes being the thing responsible for quasar light is that you need, somehow, to get a lot of energy to make something that bright. And, in this kind of situation, there are only a few options for that. But if you have a huge amount of mass and you have stuff sort of moving around in the influence of that mass, then that can be an engine for some of these powerful outflows of this radiation. And I guess that gets into some stuff like the jet and the accretion disc and all of that. But, you can't do this with like just burning fuel, like, you know, like a star does. That just wouldn't be bright enough. You need something much, much more powerful like a super massive black hole. Even though it sounds like all it really does is pull stuff in, that pulling can be kind of harnessed to produce a huge amount of power and to produce something that we can see.

Ben: So, people had a hint that what was going on in these quasars, these really, really, really bright things, was something stellar. In the name, quasi stellar, they knew it wasn't a star but they knew it was something around the size of a star because you can look at the timing of the thing. Sometimes they shift around or the signal might change. And it was a really big object, like the size of several solar systems. If it was a huge object capable of producing all this, it wouldn't be able to, based on it's size, if it was, say, several light years wide, it wouldn't be able to switch or modify its signal at a fast enough rate. So when they were looking at this, based on watching it, say, switch or change it's signal, you could say okay, only an object that's smaller than the amount of time it takes to change, gives you an upper bound for the width of it. Because, you know, say it decides to shut itself off, some signal would need to travel across the whole object...

Rebecca: When you're talking about it switching on and off, what exactly are you talking about?

Katie: It sort of, like fluctuations in the accretion. Like stuff coming in and that sort of makes it brighten up for a bit...

Rebecca: Oh, okay.

Katie: And then stop for a little while. That kind of thing.

Ben: It takes light 3×10^8 meters/second so if flickering happens less than a second then you know that it's less than one light second wide, right? So they could use this as an upper bound on the size of it and they discovered that whatever's making these huge things would have to be a fairly compact object. And then they were like what kind of process could do this? Like, inside the sun, stars, which generate a tremendous amount of light, but no where near this much. The thing that's powering the sun is conversion of, essentially, mass, right? Ah, two hydrogen atoms don't have the same mass. They have slightly more mass than a helium atom. And so when you merge the hydrogen together that little extra difference in energy, in mass between the two, turns into, essentially, light, heat, gamma rays, that then gets radiated off and that's that solar furnace. That's what keeps the sun hot, right? But only a small fraction of an atom's mass get's converted into light in that way. And so they knew, based on what they were seeing that that couldn't be the process that would generate this tremendous luminosity because there's just not enough energy.

[36:38]

And so, more than a small percentage of an object's rest mass would have to be turned into heat and that's the trick. The thing that's turning into light is gravitational potential energy. Do you remember your gravitational potential energy Rebecca?

Rebecca: No.

Laughter

Ben: Gravitational potential energy is like when you take a rock and you lift it, like a meter off the ground and then you drop it.

Rebecca: Oh, so just regular potential energy?

Ben: It speeds up. Yeah, yeah, yeah. Well, from gravity.

Rebecca: I know, I'm with you now.

Katie, Yeah, so like if you want to accelerate a rock to a really high speed you just have to carry it up to the top of a building and drop it right? And then it will, it'll suddenly be moving very fast and you can...

Rebecca: Or you could throw it, but I follow.

Katie: Well, yeah, yeah. But like you can use the building instead, but, anyway, if you have a really massive black hole you can use that energy to power stuff. And it, it's counter intuitive because we're powering stuff that's going away from the black hole and so that's, that get's very complicated. So for instance, if you're looking at, like a whirlpool in a river or something like that, you can see the water moving around very quickly and that's to do with like the flow of the water and the gravity pulling the water down. So, that sort of makes the whirlpool visible. Where the water itself might be transparent but the whirlpool becomes visible because all this stuff is moving around and it sort of makes bubbles and you know all this whitewater kind of stuff. And so, in a similar way, this gas falling into the black hole, it is accelerated by the black hole's gravity and it becomes visible when it wouldn't otherwise be.

Ben: All this gas is in orbit around the black hole, right? The closer in the radius of the orbit of this gas the faster it's moving. And it has to move really, really fast. Where does the energy come from to make it go that fast? That's gravitational potential energy. It started at rest somewhere really far away from the black hole. As it fell into the black hole it ends up going faster and faster and faster. Once it bounces off stuff and settles into an orbit it ends up moving really, really fast. Now, what causes heating is like the gradient in the velocity profile, right?

Katie: Yeah, there's a couple of different things. I mean, it's the bits of matter running into each other is heating it up a lot as, just as it's kind of moving around there are these collisions. But then you also have some of this is charged particles, you know, like, um, because it's been heated up and it's um moving very fast. And so you end up with this sort of ionized particles and just accelerating an ionized particle also creates some radiation as well. It's called synchrotron radiation. There's a whole, there's a range of different things but the fact that it's moving around and having collisions, those things together make an extremely bright disc.

Hannalore: So, since Katie mentioned ionized matter, gas itself is generally considered to be neutral, charge neutral. It doesn't have any charge. Well, when you ionize a cloud of gas, like you do in the accretion disc of a black hole, ah, it becomes something called a plasma, which sometimes people call, you know, a forced state of matter. And the thing about plasmas is that because they have a charge they can interact with magnetic fields. And another thing that can cause energy which is thought to potentially help launch this radiation that we see is that these magnetic field lines get pulled, sort of like the string on a bow. And what happens when you release the string on a bow? It snaps back, right? Something kind of similar is happening with these magnetic field lines. That as they are getting warped and pulled closer together, you know, they want to spring back apart because they want to repel each other. So, you can kind of think of it as a spring. And there's this natural spacing that these magnetic field lines "want to have" and if you push them closer together it's just like pushing together a spring from it's rest length. When you let go of it its going to spring back, right?

Rebecca: Right.

Hannalore: Sort of a similar idea here. And that's another source of energy that the black hole, essentially, provides for this radiation.

Katie: Alright, so, one more thing about the magnetic fields is that you know how like Earth has a magnetic field and you can see like the magnetic lines and stuff. So the centers of the galaxies, the black hole and the accretion disc, they have these magnetic fields and because the accretion disc is spinning around so fast and the magnetic fields are getting sort of trapped in that. That mechanism, somehow, in a way that we don't really understand completely, can transfer the energy of that sort of spinning and that acceleration and the twisting of that magnetic field. Somehow that can convert that energy into the these giant jets that are going, you know, hundreds or thousands of light years out of the sort of central region of the galaxy. Not out of the black hole because nothing's leaving the black hole, per se, but sort of out of the atmosphere around the black hole, the accretion disc around the black hole. And it can propel this charged matter out and that, it's just the power of the fact that you have this extremely massive object that's pulling the stuff in with its gravity. Just that pulling in with the gravity can propel these extremely long, straight, powerful jets. And it's just really, really fascinating.

[41:32]

Ben: Yeah, yeah, oh, it's amazing. Let's review what we just heard because there's a lot of material in there. Okay, so, suppose some gas wants to fall into a black hole. As it does it's going to form an accretion disc. But there's an important point here which is that over the course of it collapsing down, getting closer and closer, to the black hole, it speeds up. And a substantial amount of energy gets released in the process. I mean, it's gravitational potential energy. So, like, some large percentage of its mass will turn into kinetic energy on the way into the black hole. And then, this accretion disc, it's, this matter isn't going to make it into the black hole right away. It's going to run into other matter. And so, these little bits of matter are traveling really, really fast as they collide. And those collisions, and then, that disc thats made of kind of bouncy gas pushing off each other, is traveling, is so energetic, that it heats up. It's heat is what we can see as that ridiculous amount of brightness but also the fact that it ionizes, it generates magnetic fields, and the interactions between the ions and the magnetic fields, because we're talking about matter traveling so fast, almost the speed of light, as it orbits this black hole, you end up with ridiculous amounts of energy being released. And so, the result is you get way more energy released from that system than you would just by simply merging hydrogen atoms into helium atoms. A larger percentage of that rest mass gets released. But, another result is that the matter trying to go into the black hole, it gets messy. It gets really messy really fast. A lot of the times that we describe stuff falling into black holes we're just like hey, a rock, it goes into the black hole. Boom. Maybe the mass of the black hole increases. It's a very fine picture. But in the real spacey world where there's dust and gas, it's not going to be easy for the gas to necessarily fall into the black hole because on the way to falling into the black hole there is other gas that's falling into the black hole and when those two bits of gas bounce off each other it releases a tremendous amount of energy and that energy could prevent other dust and gas from falling in. And so, it's not a simple process of stuff from the outside falls in. Stuff from the outside, it's kind of like a concert venue where there's like, a parking lot, inside the concert dome we can't see. Because once the fans, the fans of Rush are inside the Rush concert they're never coming back out. But the parking lot to get into the Rush concert is so busy, so energetic, that we can hear the noise that those tailgate partiers and fist fight line-up people...

Rebecca: I'm starting to feel like you've never been to a concert

Ben: ...are making... for miles

Laughter.

Ben: What, like, a Rush concert? Or any concert? You know who Rush is.

Rebecca: Ahhhh, I do know who Rush is.

Ben: Canada's favorite band. Well yeah, why wouldn't this explanation make sense?

Rebecca: I'm sorry, continue.

Laughter.

Ben: So, moral of the story, we see them everywhere because if enough stuff falls into it it makes an accretion disc. Those accretion discs are tremendously energetic and they create all sorts of visible, recognizable signals that we can detect. But there's a mystery about super massive black holes.

Katie: And it has to do with this fact that it's really, really hard to put things into black holes. Very counter intuitively, but it's really hard to fall into a black hole.

Ben: So, where do they come from? Exactly. Now, the last time I did any research on it, this was like 10 years ago, the rule of thumb was, for super massive black holes to exist in our galaxies, it would take longer for them to form than the current age of the universe.

Rebecca: Well that can't be right.

Laughter.

Ben: We don't know where they come from. Yeah, I know, right?

Rebecca: Even I know that can't be...

Ben: Hannalore.

Hannalore: So, the reason why, at first blush, it seems like it should take longer than the current age of the universe for super massive black holes to form, it borders on something called the Eddington limit of luminosity. And, essentially, a very, very smart astronomer, Eddington, figured out that there's a limit on how bright things can be. That is to say, what their luminosity can be and that's called the Eddington limit of luminosity. And, on top of that, at the time it was believed that there is a constant relationship between the luminosity of an object and how rapidly it is accreting, it's accretion rate. And, as a result, people derived an Eddington limit on accretion. And if you follow the Eddington limit of accretion it takes way longer than the age of the universe to go from you know, black holes that we know can form from the death of stars up to super massive scales.

Katie: I mean, there's a fairly simple chain of logic for where the Eddington limit comes from and the idea is that if stuff is falling into a black hole then that necessarily creates heat because of, you know, as everything is falling in it collides and everything. And that heat will kind of create this push outward for other stuff that wants to fall in.

[46:32]

So, if you're some gas that's trying to fall into a black hole, you know the gas before you created this really hot energetic environment and so you're more likely to kind of be pushed away by that than you are to fall in some more. And so, when you're creating luminosity by accretion, that luminosity itself can prevent further accretion. That's basically the chain of logic behind the Eddington limit.

Hannalore: Exactly, going back to the concert metaphor, it's really easy to get into the mosh pit at the very beginning of a concert, right? Everybody, there's a lot of space, everyone show's up there. But once the mosh pit actually get's going it's really hard to get into it because people kinda keep getting shot out by the fact that everyone's running into each other.

Rebecca: Right.

Hannalore: Same deal. Later on, the matter is showing up to the concert too late and they're getting kicked out of the mosh pit.

Rebecca: Is this the same concert? Is this still at the Rush concert?

Hannalore: I've never been to a Rush concert so I don't know...

Ben: Yeah.

Hannalore: If they get a pit going... may have, may have.

Laughter.

Hannalore: So, this parameter that's relating the luminosity with the accretion rate is called the radiative efficiency. Basically, how efficient a system is at turning this in-falling matter into luminosity. Because, we see the luminosity by way of radiation. What was later realized, a few decades ago, was that the radiative efficiency can actually change. And so that started to bring up the option of what is called super Eddington accretion which is when, as the name implies, the accretion rate is greater than the Eddington limit for accretion. And this shouldn't beat the Eddington limit on luminosity which is the real limit that we've got here. So, that seems to be promising, right?

Katie: The basic idea behind that would be that just because you're having a lot of accretion doesn't mean that you necessarily know how much radiation you're getting and how much radiation pressure that's creating to prevent further accretion. Because, like, instead of creating a disc where you have this very understandable mechanism, it might be that stuff is falling in on a different axis or there is some kind of, you know, chunky accretion where it doesn't create this nice, beautiful disc or something like that.

Rebecca: So, the limit is still valid.

Hannalore: The luminosity limit is still valid. Yes.

Rebecca: Okay.

Katie: Yeah, the luminosity limit is, based on just how much energy you can get out of stuff falling in. Like, how much energy is possible to produce from accretion.

Rebecca: Okay.

Hannalore: Right. It's sort of like the exchange rate between the accretion rate and the luminosity decreases as the accretion rate goes higher and higher. So, you get less luminosity per increase in accretion rate if that makes sense.

Rebecca: Yes.

Ben: Okay. So, the idea here is, originally they said there is a limit on how much radiation pressure the in-falling matter can generate. Because if it makes too much pressure the stuff behind it can't fall in and so there's a limiting valve on how quick stuff can fall in.

Katie: Originally the idea was that if you know how much matter is falling in, the accretion rate, then you also know exactly how much radiation pressure you're creating by the glowing of the disc. And so, the original assumption was that was just 1 to 1. So, based on the accretion rate, that tells you exactly what the luminosity is and the luminosity tells you the accretion rate. That kind of thing. But, basically, you just can't have more luminosity than the amount of matter coming in. Because, you know, you can have stuff falling in in ways that doesn't create a lot of luminosity, maybe. That's the part that's, you know, there's still an upper limit on the luminosity just because you need something to fuel that. Um, so, you can't have more than the Eddington luminosity, but it might be that the other direction isn't so solid so you could have more accretion than the luminosity is telling you. Like, it might be less efficient at creating that pressure to push stuff out. So, the luminosity and the radiation pressure and the accretion are all kind of different things but the original idea was that they all determine one another. And now this sort of super Eddington idea is that maybe you can have more accretion but not necessarily have the standard increase in radiation pressure.

Ben: So, just to get this straight. Stuff goes in, we thought there was a relationship between the rate at which stuff goes in and how much radiation it generated. That relationship limits the rate at which more stuff can fall in because if it generates radiation on the way in that radiation will push the other stuff falling in behind it back, slowing the rate. Okay? So, there's a natural limit to the rate at which stuff can fall in regularly. Right? And what we're saying is, we're kind of throwing that assumption out the window. In newer models there's no longer a correlation between the rate at which stuff goes in and the luminosity that it's generating. In other words, it's like a concert. Imagine we've got this stupid concert hall. Summer concert hall, imagine it's got, I don't know, ah, doorways all the way around the arena. So, we're theoretical physicists trying to describe this concert and we're saying, there's a natural limit at the rate people can go into the concert. And that's limited by how rowdy the people are. So, people go in, they bump into each other, they start fights, they make lots of noise and then the people behind them, coming in after them, slow down and they go, maybe I'm going to go in a bit slower because I don't want to run right into a fist fight. Those Rush fans.

[51:37]

Hannalore: Those crazy Rush fans.

Rebecca: Rowdy Rush fans, yeah.

Ben: So, what we're allowing for in our newer models is saying hey, maybe that relationship between the rate that people are going in and how rowdy they are getting isn't necessarily the case. What if they are forming lines on the way in so that everybody lines up and goes straight to their seat and is really quiet. In that case they're not making so much noise and so the people behind them aren't panicking and slowing down and you can get a nice efficient entry into the thing.

Hannalore: Approximately, yeah.

Rebecca: Yeah. That makes sense.

Hannalore: I mean, the thing I'm having the most trouble with is the idea of rowdy Rush fans, to be perfectly honest.

Laughter.

Rebecca: Yeah. I'm still stuck on that but I'm just going to...

Ben: Are Rush fans not rowdy?

Rebecca: I mean, in my head, they're just nerds.

Laughter.

Hannalore: Yes, that is the accurate, I'm thinking like some sort of death metal concert. Like that's the rowdy group.

Rebecca: Yeah.

Hannalore: That's the group that's going to hurt you.

Rebecca: Yeah. Rush is just a bunch of math majors.

Hannalore: Exactly. Just sitting around and being like, yes, quite...

Laughter.

Ben: Rush is pretty rowdy for Canada you guys.

Hannalore: Yeah, that's...

Rebecca: Oh

Hannalore: Don't give me that, don't give me that... Canadian, there are ton of amazing Canadian punk bands that have amazing shows. So, don't even give me that.

Laughter.

Ben: Yeah, I, well, I mean. Rowdy for Canada is a good band name...

Rebecca: Rowdy for Canada would be a great punk band.

Hannalore: It's almost like, that sounds like some sort of Indy pop band that like gets mildly energetic.

Ben: Sure. Yeah. Well, rowdy for Canada.

Hannalore: Well, yeah, moving on.

Laughter.

Ben: Moving on Hannalore, you can do it.

Hannalore: Yeah, so. We've established that there is this Eddington limit for luminosity and that previously people thought that there was an Eddington limit on accretion. And that would limit how quickly a black hole could grow via accretion. And, now we also have established that hey, that's not so true. You can accrete faster than the Eddington limit for accretion. And in order to give you a physical intuition of this, lets think of trying to fill up a bucket. If you're trying to fill up a bucket, you know, in your yard, and you've got a garden hose. Alright, you just stick the garden hose in the bucket and it fills up. And if you increase the water pressure it will fill up the bucket faster. Right?

Rebecca: Yes.

Hannalore: But imagine now, you have a fire hose and you are trying to fill up this bucket with a fire hose? What's going to happen.

Rebecca: You're going to obliterate your bucket.

Hannalore: Exactly. Even if you bolt the bucket to the ground for some reason, the water is going to bounce right out of that bucket. Right?

Rebecca: Right.

Hannalore: That's what is essentially happening with super Eddington accretion. We are hitting this bucket with a firehose and as a result you are actually getting a bunch of radiation that, rather than flowing out and creating this luminosity, is actually pushing in-falling material out with its energy. Does that make sense?

Rebecca: Yeah.

Hannalore: So, super Eddington accretion actually doesn't give you black hole growth much faster than the Eddington limit. So, people say oh, we're back to square one. Back to the drawing board. And so they come up with this idea called direct collapse black holes . So, direct collapse black holes. What does that mean? Well, the idea is that you get this whole cloud of gas and usually, in space, if you've got a big cloud of gas its going to turn into stars and those might turn into solar systems, all sorts of things. But we're seeing that doesn't happen. We're seeing that this cloud of gas just gets bigger and bigger and bigger. Up until, let's say it's about 10,000 times the mass of the sun in size. And all of the sudden, that cloud of gas collapses in on itself and makes a black hole. And it's predicted that if you get the cloud of gas up to that size you're going to get, basically, 100% efficiency on converting the mass of the cloud to the mass of the resulting black hole. So, the idea is, alright, then you can get a 10,000 solar mass black hole and once a black hole is about 10,000 solar masses it dominates the local gravitational potential. Sort of like if you put a bowling ball on a trampoline with a bunch of ping pong balls and things will accrete towards it. And then, considering the Eddington accretion limit actually can grow within the time limits that the observations that Katie was talking about, indicate that we have to get super massive black holes, within.

Katie: Yeah, so the idea there is that if you can somehow create the black hole, faster, like make it start out large then it's easier to get it to the masses that we see in the early universe. Because we see black holes that have like a billion solar masses within the first billion years of the universe and that's really hard to do with just growing from a stellar mass black hole. So, like, if you start with a black hole that's just the mass of a sun and just accrete, that's really hard. But if you, if you use this direct collapse idea, you never had a black hole the mass of the sun, you just had this huge cloud of gas that just collapsed into a black hole that was already, maybe 100,000 times the mass of the sun.

Rebecca: But, is it hard to get a cloud of gas that big without it...

Katie: Yes it is.

Rebecca: Resulting in... okay.

Katie: That's a big problem.

Hannalore: And that's exactly the issue Rebecca, is that, in order for that to happen you have to have really, really precise property of this gas in order to keep it from turning into stars. And the problem is we have to get these super massive black holes pretty regularly because every sizable galaxy that we know of has one. So, that's kind of been the issue and one of the big arguments against direct collapse black holes.

[56:38]

And, fortunately, we have a new challenger for most popular theory of super massive black hole formation which is a very niche popularity contest, I guess. Um, that has arrived in the last few years and that's something called hyper Eddington accretion.

Rebecca: I'm sorry, what?

Hannalore: Hyper Eddington accretion.

Rebecca: Oh, got it.

Hannalore: So, the name sounds pretty similar to super Eddington accretion but there is a fundamental difference. It's accretion that's way faster than the Eddington limit of accretion. But it's so rapid that it actually smothers the radiative processes that usually would blow off that extra accreting matter which killed our theory of super Eddington accretion. So, you can kind of think of it as okay, so, you've got your bucket bolted to the ground, because, for some reason you decided you were going to do that. And you're now trying to fill it with a firehose and the water still bounces out. Now, let's say a torrential downpour starts. It's just going to fill up the bucket because even though there's water splashing out there's so much of it that that doesn't really matter. Does that make sense?

Rebecca: I mean, your metaphor makes perfect sense. I just have to say that the name that physicists have given it make it sound like this is this just grasping at straws. I mean, like...

Hannalore: Oh, absolutely.

Rebecca: Okay, but what if there was like, ultra super mega Eddington....

Laughter.

Hannalore: You will never hear me say that physicists come up with good naming conventions....

Rebecca: Okay.

Hannalore: Because we really don't. No, but it actually has been holding up under simulation. So, this is a new theory that is currently being poked around at to see, does this actually hold up? And of course, one of the big things you have to do is find observables. So, this is cutting edge science that you are now up to date on, essentially. So, congratulations Rebecca.

Rebecca: Nice.

Hannalore: You're ready to jump on in.

Rebecca: Thanks. I feel ready to jump in. It might have been this glass of wine I've been drinking while you've been talking but I feel very confident in my understanding of super massive black holes.

Ben: Hannalore, does hyper Eddington accretion require really fine tuned initial conditions.

Hannalore: So, actually studies have been showing that it really doesn't. That the main thing that it requires is a moderately dense environment but no denser than what we actually already see in the modern universe, ah, pretty regularly.

Katie: To clarify the physics behind this, the idea is basically that with regular super Eddington accretion you're trying to put a whole lot of matter in at once but it kind of pushes back against itself. But with hyper Eddington it's happening so fast that there isn't actually, time for the pushing back to have any effect. Is that right?

Hannalore: Yeah, that's basically it. It's just so overwhelming, it's so much mass that the energy that's able to be created from the radiation driven by the rapid accretion, it doesn't have enough energy to unbind the gravitational energy of the matter that's coming in super, super fast.

Rebecca: To, relate back to our concert analogy, everyone's at the Rush concert, and if the show ends and they all want to leave at once but there's only one door at first you're going to have this pushback and people are not going to be getting out very fast. But if Nickleback gets on stage...

Hannalore: Everyone is just sprinting, just running.

Rebecca: Right, it will be a stampede and it will be...

Katie: They'll just knock the door down...

Hannalore: They'll just knock the wall down. They will knock anything they have to before they start playing photograph. Like they are booking it. Exactly.

Laughter.

Hannalore: That is exactly what happens. This entire episode is all about trying to make this concert joke work.

Rebecca: It works. This is going to be in a textbook soon.

Hannalore: Fabulous.

Ben: Yeah, that's...

Hannalore: I'll make sure this is in my thesis.

Ben: Is that it for accretion? The moral of the story is our models keep getting better and we go back and forth between self-limiting processes and it looks like it's not?

Hannalore: Right. And so, what we're currently doing, in addition to making sure that this holds up to what we currently know, both direct collapse and hyper Eddington accretion. We're also looking for observables. Because ultimately, physics is a science, nature is the referee and we have to be able to check this against what we observe. One of the big differences between direct collapse and hyper Eddington accretion is that hyper Eddington accretion predicts that there should be something called intermediate mass black holes. Black holes that are about a 1,000 to around 10,000 times the mass of the sun. Because we know how we can get black holes that are about a 100 solar masses and smaller from the death of big stars. And we know that super massive holes exist, somehow. But what we don't see are these black holes in the middle. And so hyper Eddington accretion would predict that they do exist but it might might be that they are really hard to see which is why we are not seeing them and that would be what hyper Eddington accretion is arguing. Or, they might just not exist at all and that's why we don't see them. And then that would be more in favor of direct collapse. So, right now people are thinking about how can we compare these predictions against observations.

Katie: One of the funny things about being a cosmologist is there are a lot of things that we just kind of deal with all the time as data points that if you talk about them to, you know, regular people, it will like, freak them out.

[61:38]

Katie: So, one of the things is that as, in cosmology, for us, super massive black holes and quasars are just like little dots on our graphs that we use to map the universe. So, you know, this incredibly, you know, violent, massive, unbelievably powerful thing, we use them a lot just to say, you know, oh that's where a galaxy is and that's where the matter in the universe is and that's a way we can map out sort of how everything in the universe is laid out. And the we can use that to learn something about how galaxies evolved and how matter got to be where it is and the progression from the early universe to the universe we have today where there are, you know, these galaxies laid out in a kind of cosmic web of matter. And so, for us, quasar surveys are a way to do that and to see, you know, the large scale structure of the universe. And it's actually really fascinating if you look at galaxy surveys and quasar surveys you can see that, you know, that galaxies are clustered and there are these sort of filaments of matter, and then these big voids. And quasars are the things that allow us to trace out the very, very distant part of the universe because they are so very bright. And they are very easy to spot in these surveys. And so we can see them from mapping the universe but we can also see them for learning how the universe is evolving over time by looking at features in the spectrum that tell us about all the matter the light passed through on its way from there to us. Because the universe isn't totally empty in between galaxies, there is some gas there. And so looking at quasars is a way to figure out what's been going on with the universe as a whole between our time now and the time of when these, these quasars were shining, which is like, you know, 12, 13 billion years ago. So, quasars are fantastically useful as, sort of, light posts and mapping tools for the universe even though they are fascinating in their own right and especially for things like how they got here and what that tells us about processes of the early universe but also they're incredibly useful just for understanding the large scale structure of our universe and understanding how the universe has evolved over time.

Rebecca: Alright, I'm convinced, I'll buy it. I would like one super massive black hole please.

Laughter.

Rebecca: Sold. Sold.

Katie: Excellent.

Ben: Well, that was wonderful. Thank you Hannalore. Thank you Katie Mack. You've pleased me. Your efforts have born fruit and that fruit is sweet. Here is some fruit. Katie, you get a mangostein. It's the darkest of the fruit.

Katie: It's very good thank you.

Ben: Alright, Hannalore. You get a bread fruit. The biggest of the fruit.

Hannalore: Nom nom nom. Yeasty.

Ben: Awesome! I'd like to thank my guest, Rebecca Watson, queen of skepticism. Visit our website to find a link to her Patreon account with all of her projects as they come out. Thank you Rebecca Watson!

Rebecca: Thank you for having me on, this was a lot of fun. What fruit do I get? Everyone got fruit

Laughter.

Ben: Well, you got the fruit of knowledge. You got the fruit...

Rebecca: Not...

Katie: Do you want my mangostein?

Hannalore: Do you want my bread fruit?

Rebecca: I'd love it, thanks, yes. Give me all...

Ben: Come on! Don't give ... your fruit...

Laughter.

Hannalore: It's yeasty fruit.

[65:00]

Ben: Hi everybody! That was a fun episode, wasn't it. Okay, announcement time. Again, please give us an iTunes review. I know, everybody asks you to give them an iTunes review and we're no different. And the reason is, because if you're up on iTunes people find you and if people find you more people listen to you and it's great. So, if you give us an iTunes review other people might hear about us and that would be fantastic. Alternatively you could just go up to your grandma and say hey, grandma, I know you're always asking me about muons, here's a podcast you might want to listen to.

On another note, we're still humbly soliciting your donations. Your donations go to paying the server fees and our project to transcribe all the episodes as they come out and our ambitious attempt to buy people microphones. So, if you want to help out with that you can send us one time donations through our off of our website or you can go to our sweet Patreon site and give a recurring $2 donation. This particular episode of the Titanium Physicists podcast has been sponsored by a collection of generous people. I'd like to thank the generosity of Jacob Summers, James Blake and Elsy Campbell for their donations. I'd also like to thank Brittany Crooks, James Crawford, Mr. Mark Simon, Two Songs Gang of One, Mr. Lawrence Lee, Mr. Sixton, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, a gentleman named Peter, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and always, a Mr. Robert Stietka. So, that's it for Ti-Physicists this time.

Remember that if you like listening to scientists talking about science in their own words there are lots of other lovely science shows on the Brachiolope Media Network. The intro song is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

[68:57]

Ben: Ah, accretion discs...

Hannalore: I mean, honestly, it's black holes, so I get excited, literally, about every detail. And so, I'm sorta like a dog where it's like, man this dog loves tennis balls, don't they but hey we've got a stick in front of this dog. This dog is super amped about this stick. Is the dog thinking about maybe I should ignore the stick so I can play with the tennis ball? No, the dog is just super amped about the stick. This is how I am when it comes to black hole stuff. Just...

Ben: I understand.

Hannalore: Everything

Ben: Is that Katie? Is Katie back? Hey Katie Mack. Oh, click, click. She's getting her gun out.

Hannalore: Oh no.

Ben: Well, there are big spiders in Australian bathrooms. I'm not sure if you seen on the internet.

Hannalore: I've seen so many things... so I know an Australian grad student, well, he's here at Caltech, but he's Australian. And for all that I'm terrified of the wildlife in his country, he's terrified of the guns in the U.S. Yeah, like, literally, just walks around scared of the guns. The same way that...

Rebecca: I think that's fair.

Hannalore: I mean, I think it's a fair, it's just kind of interesting that we're all like, oh my god Australia's terrifying because there's spiders and everything that will kill you and Australians are like, that's fine. But it really alarms me that people are as into guns as they are.

Ben: I was surprised. I thought you were going to say they were afraid of bears. Because I've heard Australians are afraid of Bears.

Hannalore: He's afraid of bears too. I'm afraid of bears as well. Bears are terrifying. They run so fast. They can swim. They can climb. You can't get away from a bear. There's no safe place when it comes to bears. Like...

Ben: Hey, and you think, like, going up north where everything is dead would get you away from a bear.

Hannalore: Never. If anything it encourages them.

Ben: Because at least... no, never. That's where they live.

Hannalore: No. I am... like, I'm scared of mountain lions but I'm more scared of bears.

Ben: You should be.

Hannalore: I am, aw, god, no. My mom sent me, like, a video of a bear drinking from a hummingbird feeder when she was in Minnesota last time. It was terrifying. It was like, why are you so nonchalant about this. This is a killing machine. This is basically an apex predator. Like, you really should be praying to any gods you can think of that you get out of this alive...

Katie: Wait, wait, wait. I just come back to Hannalore saying somebody, with death? I'm confused.

Laughter.

Ben: She's afraid of bears.

Hannalore: I'm afraid of bears Katie, they're terrifying.

Laughter.

Katie: Okay, because it sounded like you were going to kill us all. That's all I'm saying.

Hannalore: How would I get to you Katie, you're so far away. This is impractical. No, I'm...

Katie: I don't know.

Hannalore: I'm talking about my mother, like having videoed a bear and I'm saying what she should have been doing but I guess we can also say that everybody. It's okay, it's fine.

Laughter.

Ben: Okay.

Katie: Right.