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Authors

Gill, Manraj
Kirn, Georgia
Nuckolls, Kevin
et al.

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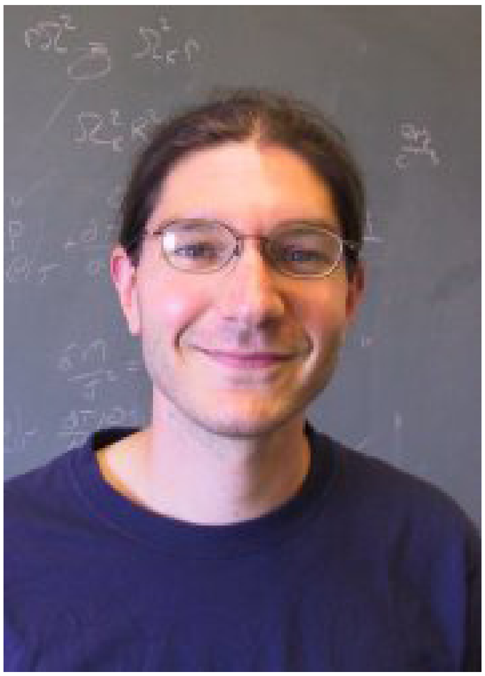
Interview with Professor Eliot Quataert: The Formation of Black Holes

Manraj Gill, Kevin Nuckolls, Saavan Patel, Georgia Kirn

Berkeley Scientific Journal: How did you get into your specific field of study on stars and black holes?



Dr. Quataert: I was, as a kid, always interested in physics and math, not from the tinkering point of view, but more from reading the scientific American type of articles. I was definitely more interested in the theoretical side of things when I was younger.

When I was an undergraduate physics major at MIT, I knocked on 15 people's doors asking about starting research... the first 14 people were particle theorists, string theorists and such, they all said I was a freshman so I should go away. Then I asked an astrophysicist and he said he had a project that might work out. So that's how I got involved in research when I [hadn't taken] any astrophysics courses as an undergraduate physics major. But I got involved in this astrophysics research! That was what really led me into this field of physics research. I knew I wanted to do physics research, I didn't know what kind, and that's what really tipped the scale.

Within astrophysics, I like to work on a wide range of things. That's one of the things that I think is great about specifically doing astrophysics research: you're studying the entire universe. To do so you need all of physics, and you work on a wide range of problems using anything from simple algebra to simulations on massive supercomputers.

BSJ: If it weren't for any of the previous 14 professors…

Q: That's a really interesting question, I've wondered about that. I think I would have been doing physics, but it's hard to know. It's certainly possible I could have done some other type of physics.

BSJ: A lot of your research focuses on both the quantum world and the relativistic mechanical world, and how those mesh together. We were wondering how you incorporate both of those ideas in your research, and how you maintain consistency between the two worlds.

Q: That's a good question! I would say most of the time, we usually take the laws of physics as given. We apply them, and are always on the lookout for when there are tensions between the known laws of physics. This is how people discovered dark matter and dark energy. The honest answer, at some level, when we use these laws of physics, we are not worried about conceptual tensions between quantum mechanics and classical mechanics, or quantum mechanics and relativistic mechanics.

There is no coherent conceptual union between quantum mechanics and relativity. Most of the time, in the systems we can study, both are perfectly applicable. The caveats to that are the very center of a black hole, where things happen and we aren't quite sure what happens there. In some sense, one practical answer is that we utilize the known laws of physics and that conceptual tensions that do exist between different areas of physics don't really enter into what most practical physicists do.

There are objects, for instance, neutron stars, which are unusual objects. To understand them we need aspects of quantum mechanics, and aspects of Einstein's theory of general relativity. They're so small, and their gravity is so strong, that their mechanics can't be described by newton's theory of gravity, you really have to use Einstein's theory of gravity. So, that's an example of where we are pushed into combining both our understanding of quantum mechanics and our understanding of general relativity.

BSJ: After reading your papers, the concept of neutrino cooling is mentioned a lot. From standard quantum physics, we know that neutrinos interact very weakly with regular matter. How does this work for things like stars and neutron stars?

Q: [Under normal conditions, with] normal I mean the sun or normal by astrophysics standards, objects in the universe get rid of heat by light. They emit light, and that's how they get rid of heat and cool down. If you take extraordinarily dense and extraordinarily hot matter, getting rid of heat by light is very ineffective [under these conditions]. The reason [is that it is] so dense that light can't get out, bouncing around, always running into stuff. It can't get anywhere! Under these very unusual conditions, like in collapsing stars that are forming neutron stars or black holes or colliding neutron stars, the primary way that matter gets rid of heat is by neutrinos.

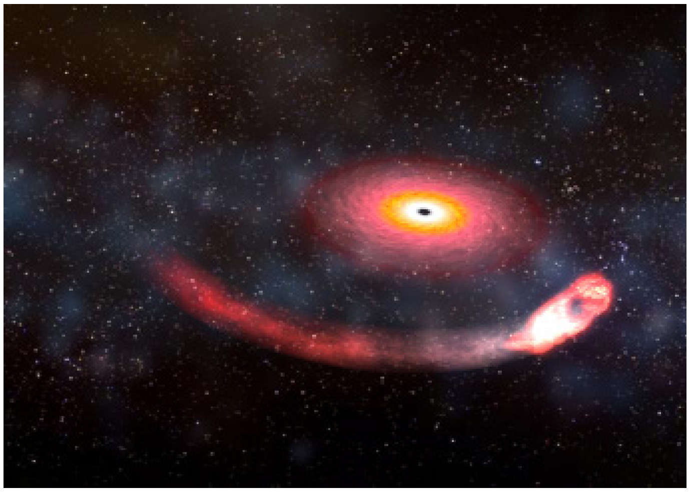


Figure 1. A black hole devours a neutron star.

It's right that neutrinos normally, from what we're used to from the sun or on earth, interact only very weakly. If we have very dense concentrations of matter, far denser than anything else that can be produced in the laboratory or even at the center of the sun, the kinds of things that only happen in neutron stars. Under those extraordinary conditions, neutrinos interact enough that they become the dominant way that matter gets rid of heat.

BSJ: Neutrinos are being ejected in large amounts from these stars?

Q: That's right, the way that we think that neutrons form is that at the end of the life of a massive star when the star collapses under its own weight, it collapses until it's about 10km big. Then it explodes back out afterwards, this is what we call a supernova. This explosion, we think, is mostly driven by neutrinos. Neutrinos are really the most important thing in that very extreme environment [for] moving energy around and moving heat around.

BSJ: How big is big? How do you get a neutron star, how big does the original star have to be?

Q: Neutron stars are unusual, as well as white dwarves, because there is a maximum mass that they can have. If you have a neutron star above a certain mass, it collapses to form a black hole. We don't know, because of this whole issue of not understanding quantum mechanics and relativity in these neutron stars, what the maximum mass of a neutron star is. We estimate that it's about 2.5 times the mass of the sun. We think that stars which have more than 2.5 solar masses at their center when they collapse will collapse to form a black hole rather than a neutron star. That corresponds to stars that, when they formed, had masses of about 8 times the mass of our sun. Above 8 times the mass of our sun, the star will become a neutron star or black hole, below that it becomes a white dwarf. That difference between 8, which is the mass when its formed, and 2.5, which is the maximum mass a neutron star can have, is because stars actually shed lots of their mass during its life. Kind of like the solar wind, but amped up solar wind that gets rid of a lot of their mass over their lifetime.

BSJ: What exactly is a white dwarf?

Q: So, a white dwarf is a star that has a size about the size of the Earth, but has the mass of Sun. So it's about a million times denser than the Earth or the Sun or Jupiter. So, you take a rock, right? Feels pretty dense, but white dwarf material is a million times denser than that. Again, it's one of these very unusual stars where it's held together by gravity, but what is opposing gravity, stopping the star from collapsing down into a black hole is kind of unusual quantum mechanical pressure.

BSJ: What do we currently know about the evolution of black holes? And specifically, which came first: stars or black holes? That is, when we talk about the first non-linear objects…

Q: So, the simplest picture, I think the one that's most certainly right, is the first thing that formed were stars. So, maybe a few hundred million years after the Big Bang, the first stars started to form. People are still not a hundred percent sure what their properties were. But at least some of them were quite massive and those stars, after just a few million years, collapsed to form black holes. So, I think the sequence of events is: stars formed first, then black holes form from stars.

Then there is also an interesting question... So we know at the centers of nearby galaxies, we know there are very big black holes that weigh a billion times the mass of our Sun. And so, we think that those got there because the centers of the galaxies is what stuff kind of falls into. So, as galaxies form, lots of stuff orbits around, like the Sun orbiting around the center of the solar system, but occasionally stuff gets flung into the center, and that grows these big black holes at the

centers of galaxies.
Another "chicken-and-egg" problem that we understand a lot less well is whether the big black holes came first and the galaxy formed mostly around it, or was it the other way around. That the galaxy formed first and then the black hole grew at the center. And that's a really active area of research right now that we don't have a great understanding of.

BSJ: So, along the lines of galaxies with a supermassive black hole at the center, would most things orbiting the black hole be in stable orbit? Or as the black hole increases in mass, would things fall in?

Q: When you're far away from a black hole, Newton basically was right. There's nothing kind of complicated about the gravity of the black hole. Newton's theory of gravity works very well. And, so just like the planets and the solar system orbit around the Sun and don't get pulled into the Sun, [nothing weird happens to matter] orbiting far away from a black hole. It just kind of goes happily around. As the black hole grows, it kind of does pull stuff in a little bit more effectively, but [for] most matter that's kind of orbiting vaguely in the vicinity of a black hole actually, it's kind of a problem [as to how] it actually end up falling into the black hole.
It's analogous to, "Are there situations in which the Earth or a comet would go crashing into the Sun?" Well, most of the time, no. But every once in a while comets do get kicked in from the outer part of the solar system and go crashing into the surface of the Sun. And so the problem we struggle with isn't really, "As black holes grow, do they gobble up more and more of their surroundings?" But it's really almost the opposite. It's "How [do] the gas and stars and things in the neighborhood of black holes, how [do they] actually get down into the center?" Because what it wants to do is just orbit happily around like the planets in the solar system.

BSJ: Does it have anything to do with the nature of the things that are in the surroundings, whether it has an extremely large mass or not?

Q: So, it probably has to do more with if it's [a body of mass, that is whether or not it's a] planet or a star. It's particularly hard to get it to fall in because it just wants to go around and around and around. It's a little easier if it's like a cloud of gas. And the kind of rough intuition is that if you have a bunch of gas, different parts of the gas will feel friction on each other, and friction is a way we know of getting rid of motion. You know, when you roll a pencil on the floor and it stops. And so, the analogy is [that] if you have a gas that's orbiting around, kind of near a black hole, it'll feel some friction and some of the gas will stop orbiting and will fall in. And so it's easier for stuff that isn't held together in a star or a planet or a comet or something like that. It's easier for more distributed gas to fall in than it is for actually bound objects stars.

BSJ: So, it just gobbles up the gas until a point that the black hole is massive enough to actually pull in massive stars?

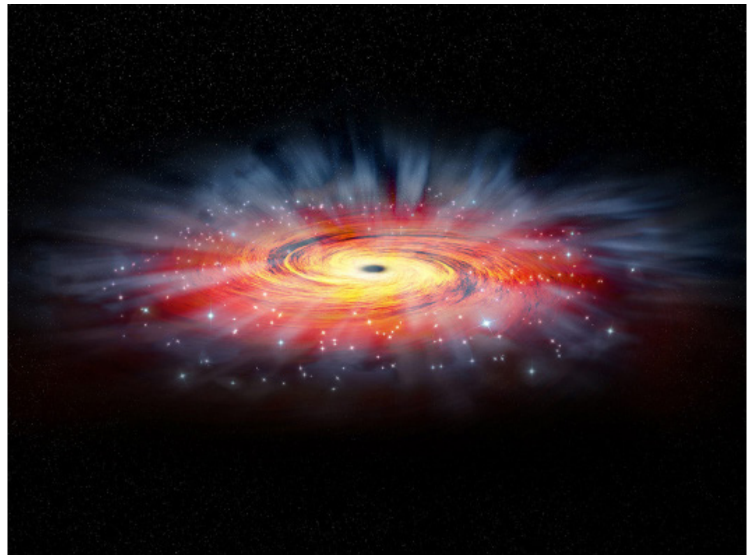


Figure 2. Illustration of Sagittarius A*, the supermassive black hole at the center of the Milky Way galaxy.

Q: Yeah, [but] even then, black holes grow mostly by gobbling up surrounding gas. Only occasionally do they gather surrounding stars.

BSJ: Is that just because of the prevalence of the gas around them?

Q: It [has to do with] prevalence [of the gas in the vicinity] but in galaxies as a whole, there's more mass in stars than there is in gas. In that sense, there's more fuel supply in stars. There's even more fuel supply in dark matter. But, it's the gas that feels friction the most and is most easily able to fall to the center. So, for those of you who are doing physics, the fact that the gas can get rid of its angular momentum more easily than the stars can that allows the gas to fall in and kind of lose its orbital motion.

BSJ: What is the timescale of the creation of the black hole in terms of a few years, a few months, up to a few seconds before?

Q: Yeah, great question! So, that actually depends. One of the things we've learned from Einstein is that the duration of events depends on where you view them from. So, I think I would answer it this way… I would say that it takes a black hole that weighs 10 times the mass of the Sun. When it forms, it forms in, probably, a few seconds. That's the time it takes the center of a star to collapse inwards, and realize that it can't be a neutron star, and then collapse inwards to be a black hole.

And that probably takes about a second. From an observer far away, it's a little trickier because then there's this whole thing that Einstein taught us about time ticking differently when gravity gets stronger and stronger and stronger. So for us far away, let me give a specific answer. Imagine a clock or an astronaut or something falling in with the black hole as it's forming, and you ask the question viewed far away, if the astronaut's sending you signals, "This is how long it's taking me to fall in", that would actually take a very very long time. And this is the extreme effect of the strong gravity of the black hole stretching out time as viewed from far away.

BSJ: So, in our reference frame, we wouldn't be able to properly see the creation of a black hole?

Quataert: That's right, exactly. So for us, it would look like the in fall took a very long time. That, as it got closer and closer to the event horizon, things would look like they slowed down. But that's, in some sense, an artifact of our reference frame. And this actually is an interesting story about the history of how the ideas of black holes developed. That black holes were, in the Russian literature, they were called "frozen stars" for this reason. Sort of, as they formed, they would seem to freeze because they were doing everything viewed from far away, so that seemed like a good name. And it took people a long time, actually, to realize and to really understand that the answer was different if you just imagined falling in yourself with the black hole versus viewing it from far away.

BSJ: So, the observations that you can make on a black hole, are those just based on the nature of things closer to where you believe the black hole is?

Q: So, we have two really good observational handles on black holes, one is in very nearby galaxies. We can actually watch stars orbit around black holes at the center of galaxies. You can watch them orbit around in a manner very similar to comets and planets in a solar system. And you can use those orbits to figure out how much stuff is there to make them orbit the way they do. But those stars are actually very far away in the sense that they are not so close to the black hole that you need to use Einstein's theory of gravity to describe how

they move, you can use Newton's theory of gravity.
So, the kind of probe that we have of matter really close to black holes where you really need to use Einstein's theory of gravity is gas spiraling into the black hole. As the gas spirals in, there's the friction that we talked about that heats the gas up and produces tremendous amount of radiation which you can study. It's the great paradox that these objects that are defined as not emitting any light are actually the brightest sources of light that we know of in the universe. The light all comes from outside the point of no return, the event horizon, so it's consistent with the fact that nothing can get out once it's inside the grasp of the black hole. But just outside that point, matter is moving round at nearly the speed of light and gets incredibly hot and produces huge amounts of light. So, we have a lot of ways of studying black holes through the light produced by gas as it spirals around black holes.

BSJ: You mentioned a lot about friction and we read in one of your papers about dynamic friction between distant stars and we were wondering if you could explain how you incorporate this idea of friction into your simulations? How do you take into account the very different types of frictions?

Q: So there are many different kinds of friction that we worry about. So, the friction that you're familiar with from everyday life if friction due to your hand rubbing on a table or pencil on a floor is the molecules colliding and rubbing against each other. That's one kind of friction that we worry about but also worry about other kinds in astrophysics.
An analogy to one kind of friction that we think about is in airplane design. In designing airplanes, they try to minimize the friction between the air and the wing and that'd due really to the bulk motion of the fluid that is kind of the random turbulent motion of the fluid. And it's analogous that this complicated motion is similar to a boiling pot of water. So, that actually is a form of friction where the friction is mediated by the complicated motion of the gas. That type of friction is actually the friction that we worry about the most in astrophysics, the friction produced not by actual collision between particles but friction produced by large scale motion of gas or liquid.
And then there's yet another kind of friction that we worry, which is friction due to gravity itself. If you have a star moving through a collection of other stars or through dark matter, the star doesn't actually collide with its surrounding neighbors but it just feels the force of gravity. But the force of gravity can actually slow down its speed. So, if you throw a high speed star through this collection of stars, the star slows down due to the action of gravity so that's called gravitational friction or dynamical friction. It's really just the force of gravity but it behaves in many ways like friction so we call it friction and also model it as such in most cases. And so depending on what I'm studying or what problem we're worrying about, you might have to include just one of these types of friction or all

three. It depends really on the kind of problem at hand.

BSJ: So, another intriguing aspect was the accretion that the black holes are giving out as some sort of matter leaving. How does that work and what is the role of the spin on this accretion disk?

Q: So, accretion is kind of the general name for this gas spiraling onto a central object. It's how the sun formed, it formed with gas spiraling in and eventually concentrating into a rotating disk of stuff out of which the planets formed. It's more general that black holes and happens for a wide range of different astrophysics objects. So, as this gas spirals in, one of the things that we observe and sort of understand is that in addition to some of the stuff falling into the black hole, some material also gets flung off at nearly the speed of light. So, you have both… as the matter spirals in, you have the matter falling in that gets very hot and radiates a lot of light. But also, matter gets flung off away from the vicinity of the black hole. And so as matter spirals in, there are these different ways that energy gets put into the surroundings. One is by light and one is by actual stuff getting flung out.

Figure 3. An artist's conception of a supermassive black hole surrounded by a hot accretion disk. Along with matter being flung out into the blue jet.

So, the spin that you mentioned could mean a couple of different things, it could mean the spin of matter spinning around the black hole. That's because the matter is orbiting around and slowly spills into the black hole. There's also spins of black holes themselves… According to Einstein, you can describe everything about black holes using how much they weigh and how fast they are rotating. That describes everything about the gravity of the black hole. So, when we talk about the spin on the black holes, that's a way of saying that the gravitational pull exerted by black holes doesn't depend only on what you would think it does. That is, how much it weighs. It also depends on this other property which is about how fast it is spinning.

So, when we make models about gas spiraling in and picture what that would look like, we have to take into account the fact that the gravity of the black hole depends on the actual spin and rotation of the black hole. So, just to give you a feel of how this works, if you consider matter very close to black hole spinning very fast, the gravity of the black hole will tug on the matter and cause the matter to want to orbit around the black hole in the same direction the black hole is orbiting. So, that's the sense in which the gravitational pull the black hole produces kind of [tells] about the rotation of the black hole as it pulls matter to rotate in the same direction.

BSJ: Is there a reason behind different black holes having different spins? And what factors would lead to this variety in spins?

Q: So, it is almost certainly true that different black holes have different spins and we don't observationally know what the spins of black holes are. The general thinking is that if you have a star that is rotating slowly, then when it collapses to form a black hole, it will form a slowly spinning black hole. If you have a star that is rotating kind of fast, then when it collapses it will form a more rapidly rotating black hole. So, probably, the spin of a black holes is really determined by how it is formed and whether the material it forms from and whether the material it forms from had a lot of rotation or not.

BSJ: We also read about changing spins… How do black holes progress in spin?

Q: If you have a black hole that is initially not spinning and it gathers some matter rotating around, then it will get the black hole to start to spin but then at a later time, it could gather up some material that is rotating in the opposite direction which will cause the spin of the black hole to halt and go in the other direction. So, it is a complicated process where it is spinning in one direction until something else comes in leading it to spin in the other direction. Exactly how that black and fourth process works, is really not that well understood and that's what people are working on a lot right now is trying to understand that interplay.

BSJ: So it's not as simple as applying angular momentum equations…

Q: It is applying angular momentum. The problem is that the angular momentum direction of the stuff coming in is constantly changing so that's the complication. The constantly changing angle of the stuff coming in and [this complication is] particularly true for the big black holes at the centers of galaxies we think.

BSJ: Can we account for the shape of the spiral of some

of the galaxies as accounted for by the spin of the central black hole of galaxies?

Q: At the distances that we see the spiral structure, the gravity of the black hole is completely irrelevant and the gravity that matters is the gravity of starts and dark matter. I think an analogy for the spiral structure of galaxies is that if you throw a rock into a pond you create ripples and in a rotating disk of material like a galaxy the natural ripples are these spiral structures. It traces out a spiral because of the rotation fundamentally rather than just spherical concentric ripples that you get in a pond.

BSJ: You mentioned interactions with dark matter… Could you explain how they affect the creation of galaxies and the progression of how galaxies form?

Q: We think that most mass in a galaxy like our own galaxy is in what we call dark matter, and that really is a name for another type of particle not in the periodic table of elements, but rather some other fundamental particle and because there's more dark matter than there is normal matter by a factor of about 7, the gravity of dark matter is more important than the gravity of normal matter in the universe. So, if you ask how galaxies move, the motion of galaxies as a whole is dominated by the gravity of dark matter. So really, it's the gravity of dark matter that then determines how galaxies move and where they are. Regions that have more dark matter have stronger gravity so they pull in more dark matter and more normal matter and those become the places that galaxies form.

So really, dark matter creates the backbone on which galaxies form and starts and planets form. And so, it's actually amazing you can describe a surprising amount about the properties of galaxies, how they are distributed on the sky for example, without saying anything about starts or gas and just looking at distribution and properties of dark matter. And it's because [they produce most of the gravity that they] dominate the gravity, which is the most important force for the universe as a whole. [And as a result, dark matter is] the thing that dominates kind of where galaxies are and at least the first approximation determines where galaxies formed.

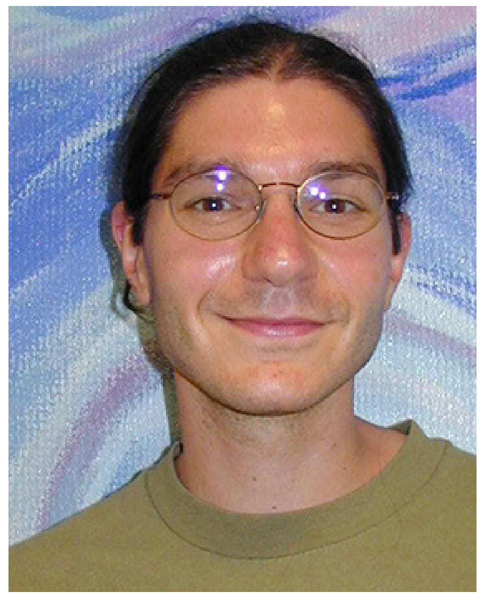
BSJ: How was the factor of 7 determined?

Q: It was through painstaking work for many decades. The best way we know that number is from observations of a thermal background microwave radiation. So, there is a glow of microwaves, like your microwaves, a type of radio wave, that fills the sky. It looks roughly the same from every direction and is left over from the early history of the universe from when the universe was much hotter and denser than it is today and it turns out that the properties of this light encode tremendous information about mass and energy content about the universe.

Very roughly one way to think of it is that this light has been travelling through the universe for the past billions of years so how it [has been] bent and moves by stuff in the universe depending on exactly how much stuff there is. And turns out it also depends on whether it's dark matter or normal matter so you can use the observations of this light to measure the amount of dark matter to normal matter. That's kind of our best way that we know how to do it now.

BSJ: What do you see as the future of your research in astrophysics and that of the field in general?

Q: For my own research I have no idea. That's the kind of research I do. [It is] theoretical and mostly about ideas. [It is] often not appreciated but the hardest part of research is the idea and not the calculations. Because it's a very creative process it's very hard to know where you are going to go.



In astronomy as a whole… I think it is driven more by where are there going to be big new observational breakthroughs, which is what drives most of the discovery in the field. And I suspect that'll come in a bunch of different areas. So looking at the first starts and galaxies when the universe was very young, trying to discover earth like planets, and projects to directly study matter near the event horizon of black holes. Those are just a few areas that on a decade timescale will probably have a lot of discoveries. What we know from the history is that some of the most interesting discoveries are ones we had no idea of.

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