Hypot-enthuse_ Ziri Younsi on the first ever image of a blac...

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SPEAKERS

Ziri Younsi, Maymana Arefin, Malcolm Chalmers

M Malcolm Chalmers 00:12

Hello and welcome to Hypot-enthuse the podcast from the faculty of mathematical and physical sciences at UCL, as we like to call it MAPS. I'm your host Malcolm with me is my co host, Maymana. And today we are joined by Dr. Ziri Younsi. Ziri is a high energy theoretical astrophysicist working in the astrophysics group at the Milan Space Science Laboratory here at UCL. His background is the he got an MA in maths from Cambridge in 2006, followed by an MSc in physics from UCL in 2008. He then started his PhD in astrophysics at UCL, which he completed in 2014. He was an Alexander von Humboldt fellow at the Goethe University in Frankfurt, and is currently a labor human trust early career researcher Fellow at UCL Ziri, welcome to the podcast.

Z Ziri Younsi 00:58

Thank you. Thank you for having me.

M Malcolm Chalmers 00:59

So one thing that I found when doing a bit of research for this, you speak three languages, which is English, German, and Tamazight. And your name actually means moonlight in Tamazight. So, one question we want to ask was, has your interest in space and in astrophysics predated your university career? Is it something that's been with you since birth, with a name like that

Z Ziri Younsi 01:24

Well, actually, I wasn't always into space and astrophysics, I wanted to I love dinosaurs. So I wanted to be a paleontologist. So I was kind of more into that side of things archaeology, paleontology, and so on. But sort of when I was six or seven, I used to read a lot of sort of pictorial encyclopedias, and so on. And I was really fascinated by space. And the idea that there was just this almost infinite, you know, void out there to explore that was, you know, sparsely filled with stars, and maybe planets and extraterrestrial life, and all sorts of bizarre landscapes. I mean, for me, it was just mind blowing that there are all of these possibilities, there are these objects that we didn't understand, which were like black holes, which, I guess is what we're talking about today, which, you know, more powerful than perhaps even entire galaxies, and so on. And it's just the scale of it all just was mind blowing. So around about six or seven, I sort of really started to get into that television programs, I used to watch those things like sky at night, and even Blue Peter, and just books I used to read as well. So

M Malcolm Chalmers 02:21

So with that in mind, what made you choose to do a maths undergraduate degree rather than go straight into sort of physical

Z Ziri Younsi 02:28

Well, actually, in hindsight, I shouldn't have done maths, which is why I went from astrophysics to astrophysics, but it actually gave me the training that I needed, why I went into maths, well, it was something, I was a subject that I found quite easy at school, but I really enjoyed it, too. And it's something I would sort of study in my spare time as well, in addition to the stuff that we did at school, and I thought, well, you know, it'd be lovely to go somewhere like Cambridge, they have a very good maths course, it's challenging. And I thought at the time that oh, you know, I would solve things like, I don't know, Riemann hypothesis and things like that. I was, well, I was ambitious. Right. And I read things like Simon Singh's book, you know, on Fermat's Last Theorem, and this sort of thing, and it really inspired me. And I studied maths, and I did enjoy it. But I kind of realized that, first of all, there are two aspects to continue a career in academia beyond an undergraduate degree. And the first was actually research and research can either be individual or it can be collaborative. And I realized that I was a much more social person. And mathematics was much more kind of, you know, it's not, I wouldn't say an exclusively individual pursuit, but it is a, you know, it's a very abstract thing. And the second thing was, I realized that I actually liked applied mathematics. It's more towards the physics, and I was more and more interested in physics. And that's when I studied, for example, general relativity, which is Einstein's theory of gravity and my undergraduate, and I sort of fell in love with that side of it. And that's why I ended up going towards physics. And that's how I ended up at UCL. So

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Malcolm Chalmers 04:06

I mean, this is, again, quite similar to the podcast with Christina, where she had an undergraduate in maths and then went off in all these directions. And her response was that basically, you know, she liked doing all these things. But maths seemed to be the one that opened the most doors. And I think that's also kind of filled in from what you said, You know, I don't know if it would have been possible to do an undergrad in physics and then go into doing a master's in pure maths or something in the same way that the reverses.

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Ziri Younsi 04:31

Yeah, absolutely. Answer. That's a really good point. Maps gives you that sort of formal training. It's a sort of a language, if you will, in which a lot of our problems are formulated physics is sort of, you know, it's a phenomenological thing. You see things happening around you try and describe them. But how do you describe them? We describe in the language of, say mathematics. So understanding mathematics, it's not absolutely true. An equation is not the truth. It's a an approximation. It's a description, but knowing the mathematics behind that gives you an understanding of that, how it's all connected. Fundamental Concepts deeper. The mathematics in a sense, connects all of those things. It just, it gives you a kind of insight and like a toolkit. So you can look at different physical problems. And you have a means to, to not just study them and work on them, but to kind of understand them more deeply. So I think it was actually in hindsight, I was pure luck, ended up doing that, actually. So there we go.

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Maymana Arefin 05:25

Sounds like it worked out pretty well. And you've mentioned there as well, the theory of general relativity and how you kind of fell in love with that. And that actually seems like it ties in really well with what you're what you're doing now in black hole research. And we were talking a little bit about this just now how, if you can maybe say a bit more about how your work currently is actually a really beautiful sort of proof of what Einstein predicted with general relativity.

Z Ziri Younsi 05:51

So yeah, so I actually so my master's I did it, I first had my proper experience of research here at UCL in my master's degree in physics, here PNA, actually, and the project I was given at the time was, it was nothing to do with black holes at all. Actually, it was to do with baryon acoustic oscillations, if that means anything to anybody. And I'm sure it'll mean something. And it was it was a fascinating project. But for the PhD, I was offered a what was called radiation transport and strong gravity, which is how to calculate the propagation of light around, say, a black hole or another very compact object with an intense gravitational field around it. And it just sounded amazing. It was a sort of combination of lots of mathematical things, lots of physical things and numerical things. So I saw it as an opportunity to really learn a lot of skills, it was a sort of interdisciplinary project, I didn't know it would lead me to where I am now, sort of on the horizon, no pun intended, we knew about things like the black hole cam project, which is what I ended up joining in Frankfurt. And we knew that there were people working on concepts to do with imaging black holes at radio frequencies. I knew of those things, I talked about them actually in sort of possible future directions in my thesis, PhD thesis. But I at the time, had no idea that I would actually be end up working in that collaboration. And it was only when I was looking for my first postdoc, and there were a few that I applied for. And someone mentioned to me actually was my PhD advisor who put me in touch because he knew one of the guys who was the PI, one of the three p eyes of the European project, black hole cam, and said, put in an application now. And so I did. And I ended up working in this European project in Frankfurt for nearly four years. And pretty much just after I started, we ended up becoming a part of the, into the big international project, the event horizon telescope project that was in sort of October 2014. onwards. And that's how I ended up in there.

M Maymana Arefin 07:52

Okay, so it was really, it wasn't kind of something that you had been really thinking about seriously until kind of

Z Ziri Younsi 07:59

I've been thinking about the science. Yeah, but I hadn't been thinking about getting into that project, I had no idea that there was a way in and it didn't seem immediately obvious at the time, that being a part of something like the event horizon telescope collaboration was possible. But at least there was a way to join this European project. And that project actually was in what's called an ERC synergy grant project. So there were three p eyes is that they are the largest European Research Council grants awarded to astrophysics projects, it was the only one at the time which had been awarded. And it meant that three different Institute's came together as one team basically, working together. And so we had like the Max Planck Institute in Bonn, and they would deal with some of the sort of data correlation and stuff of the radio observations of black holes, which I guess we'll talk about soon. And then we had the group that I was in, which worked more on the sort of theoretical stuff, the maps, the physics and the numerical calculations of what the images would look like, so that we can compare them with the observations. And then there was the group in Nijmegen, who actually did a bit of both, who do do a bit of both, I should say, we're still working together, the project's not over yet. And yeah, and once you know, sort of assemble this critical mass of experts, then I think that people, you know, on the other side of the pond sort of took us a bit more seriously, they saw that we had a lot to offer as well. And, you know, we were part of this, we brought them not as people resources as well, but mostly people. Yeah, it's a great project.

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Malcolm Chalmers 09:24

I was looking through your academic profile, just to see I should say that perfect, perfect for historical information. So the first mention I could find of a black hole on any of your papers, I think was from 2012. Yes, that was my first PhD paper. I have the title here is general relativistic radiative transfer formulation and emission from structured toroid black. So I'm surprised I got through a whim on my friend. But I thought it was interesting to look at something where the First paper you had done is 2012. Obviously, you've been doing work before that in preparation for the paper. And then this leads through to the discovery of the image of the black hole in 2019. Now, it would be very easy for someone like me to just draw a straight line and go, you went from A to B, I'm assuming that it was a much more complex path, should we say

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Ziri Younsi 10:21

yeah, much more complex. the kind of stuff that I was doing in my PhD, yes, it was black hole science and so on. But it wasn't really about black hole imaging, was actually working more on the kind of science which applied to lower mass black holes. So so just for context, Event Horizon telescope presented an image of a supermassive black hole, it's actually one of the biggest in the universe, it's six and a half billion times the mass of the sun. This black hole is, you know, people throwing this word out there all the time, but it's a behemoth, it's enormous. And we could just about resolve the scale of the event horizon of this black hole of this patchy the accretion flow, the matter that's swirling around him becomes hot and bright. And that's that light that we detect, actually. So it's a ring of matter around the black hole. the kind of work that I did in my PhD, which carried over nicely into this project, was actually looking at x ray iron line fluorescence, from accretion disks around black holes, but much smaller black holes. So the physics is quite different.

And so I was working with certain numerical methods and techniques at the time. But after my PhD, there are a few people in the UK working on this sort of stuff, but very few, if any, who are working on doing what we call radiation transport, in very complex dynamical settings, where like, for example, all of that matter, that plasma actually ionized gas swirling around the black hole evolving in time, and it's a messy environment where light can be absorbed, remitted, scattered polarized, and so I had to actually go abroad to have the time to work on that, because there weren't really any postdoctoral opportunities in the UK to do that. Maybe going off topic here. But so how did I end up in the PhD and working on this stuff, by chance, as it happens, really, by chance, not by design, often seems to be the way with some of these big three, I was a absolutely big and it shows you like but it's serendipity is actually a big part of research, I think, you know, it's sort of you have to be ready for those opportunities when they come. Sure. And that's your technical training, you also have to be patient and hope that there's some because I could have gone into something completely different. There were other things I could have done. And in hindsight, it worked out well. But I had no idea at the time. I was also very fortunate in the team that I joined in Frankfort, I what I did, what I do, was unique within that team. So that gave me the sort of room to grow and interact with people on my own terms and sort of lead my own projects. That was very important. They weren't like three other versions of me. They're all of us competing, you know. So it was a really wonderful time for me to develop as a researcher and build collaboration networks with people we've also sort of moved on. I'm here now at UCL, again, others have taken on tenure positions and other universities around the world. But we will work together. That's great.

M Maymana Arefin 13:23

Sounds pretty and what exactly was it that you were doing that was the kind of unique role within that team.

Z Ziri Younsi 13:29

So my job was to basically take what I developed and learn here at UCL and build it further. And what that meant was, for example, we would do what are called general relativistic magnetohydrodynamics simulations, it's very, a very fancy way of basically saying, you have a fluid, it's magnetized, you just put it around a black hole, and you see what happens, it's just pretty much as simple as that you just take that magnetic field and you put a small perturbation to it, and an instability grows. And then that instability causes some of that plasma to fall onto the black hole. And some of it will escape because there's a transport of angular momentum in and out and you get a big relativistic jet, like this huge jets we see in some galaxies. And you ask yourself, what would that look like, because that's just a simulation. So you have to then figure out how the light comes from the simulation and is received here on earth. And it's complicated by the fact that black holes have very strong gravitational fields. So the light doesn't travel in straight lines, it does crazy stuff. So we have to solve the equations for the motion of light rays, so called geodesic equations, we also have to solve on top of those light rays trajectories, the light rays are passing through all this dust and gas and matter. And different things are happening as they propagate. And so you have to build in all of these effects. And then once that's escape from the area around the black hole, it travels for in the case of MHC seven, I think it's 65. Now how many 55 55 million years 55 A million years. So a lot can happen in 55 million years. And so you have to build out models of the intergalactic medium. And worst of all is what happens when it reaches the atmosphere. Because the ht is a network of radio telescopes. So some telescopes are at different altitudes, different geographical locations. So there are many different systematic effects that come into play. And all of that has to be built in now that I didn't work on specifically, I worked with people also when I was in Frankfort, but you can see there's a whole sort of pipeline. Yeah, and there's like no one person who can actually do this. So my job was to calculate what would happen with the light? How does it escape? And then at the very end, we have to involve that we have all of this atmospheric stuff with the depth different telescopes, the observing times, how long are they pointing at the black hole, and they're off because the Earth rotates? Even continental shift is important because those light rays, so that actually, is radio waves, I should say, when they receive that each telescope DHT is a network of radio telescopes, you have to very accurately record the arrival times of those, those radio waves. And you do that using atomic clocks are actually hydrogen lasers. And they have an accuracy of better than one second and 100 million years. And you need that kind of accuracy. Now, to have a precise is super precise. And it's just about enough for us, really. And you use this to basically correlate so you you know that the signal is arriving at slightly different times. And it's interferometry little bit like the sort of goes on shorthand of LIGO and Virgo, and the gravitational wave interferometer. Yeah, it's a similar thing where you know that they arrive at slightly different times in different places. And you have to very precisely measure that difference in time. And so there is an awful lot of science of theory of simulation of engineering that goes into this. And so the DHT is really a huge team of people

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Maymana Arefin 16:58

that really have such a complex project, across so many places, as well.

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Malcolm Chalmers 17:04

So there were a number of different questions that came up to me, while I was looking at the details of the black hole image. One thing I noticed was, there were quite a few people, non scientific people referring to this as the first ever photograph of a black hole. Obviously, it's not a photograph in the way that we would strictly think of it. So obviously all you know, when I speak to you, or when we read any of the official documentation, it talks about, you know, imaging a black hole, I think we most people understand how a photograph works, that light goes into a lens hits a sensor or a piece of film, and the image is trapped there. But what you're talking about is radio waves reaching various different telescopes. And those images then having to be combined into something right. So if one were able to be, say, a couple of light years away from this black hole, rather than 55 million, is what you would see with your eyes similar to the image that's created. Is that sort of a fake colored version or that that's a fantastic question will actually sort of an umbrella of many questions. rambling nonsense, no,

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Ziri Younsi 18:16

no? Nonsense is very good. I'll start from the top if that's okay. So is it an image? What does it mean to say we have an image of a black hole I think is the first thing. I've been asked this question many times. And every time I'm asked, I'm always asked it from a slightly different angle. And my answer I'd like to think evolves. And so what I would say is, is ultrasound imaging is sonar imaging, tomography. It is a form of imaging, it is a representation, you would never see it, but it does give you a sense of the structure of an object, or have the scale or whatever property is you're trying to pick up, right. And so then what is this black hole image? Well, first of all, it's not an image of a black hole. Black Hole, by definition is black. So it has an event horizon. And anything which crosses that event horizon, even light, I'm just sure you all know, never comes back. It's it's trapped forever, as far as we know, according to Einstein's theory of general relativity, so there's a boundary at the edge of that boundary is what we call an unstable photon orbit, because you need to see this thing with light. And that's a region where light rays can actually move on spherical orbits around the black hole, and that's a bizarre concept might itself is orbiting around the black hole. So it'd be like if you stood near the edge of the event horizon, you would see multiple images of the back of your own head, because light will be circulating around the black hole. So I thought, you know, it's hard to visualize that. So you have to check out my YouTube channel which used to have my video like messing around with this

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Malcolm Chalmers 19:58

as a man who is rapid balding, the last thing I want to say is multiple head.

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Ziri Younsi 20:06

Light does crazy things around the black hole. And yeah, so so so what we do pick up is is the light that's produced from matter moments before it crosses that threshold, that event horizon. So as that that matter that hot gas starts to fall onto the black hole, it's spinning rapidly, you know, a good fraction of the speed of light, actually, depending on how rapidly that black hole is spinning, and it gets extremely hot and luminous, and it radiates. And it radiates across the entire electromagnetic spectrum. So from radio waves all the way through to x rays, gamma rays, and so on. But there are bands, only bands, which we can observe, because a lot of that radiation will be absorbed by the intervening medium, so dust and gas. And so it turns out that radio waves, for the same reason that we use them for communications here on Earth, also really a very good wavelength for us to pick to observe a black hole, because they can travel long distance and be distances and be weakly attenuated. Okay, just like they can travel around the curvature of the earth, they can travel across mountains, and so on. That's pretty handy, they can cover that void quite well. And it also turns out that because our telescopes are on Earth, you have an atmosphere, and that that atmosphere also has a window. And there are only a few wave bands that you can see through relatively clearly. And it turns out that the wave band or the frequency range that the eh T, Event Horizon telescope is tuned to, which is 230 gigahertz, well, that's a wavelength of 1.3 millimeters. So you can actually measure that on a ruler, that's the wavelength of the radio waves, we detect those, they not only can pass all the way through the matter near the edge of the black hole to the Earth's atmosphere, they can also pass through the atmosphere, so we can detect them. So we're really lucky, actually, that we have that window of opportunity to see. And so it's so it's, it's it's an image of sorts, but it's it's, it's an image of these radio waves. And these aren't like photons like discrete packets, they're waves. And so you have diffraction patterns, course. And so in the end, what you end up with is an a very sparse image, which is more like a set of diffraction patterns. And if you heard of Fourier Fourier analysis, and the Fourier transform is do the inverse Fourier transform of what we get, and you get an image. So that's what we do. And in that inverse process, you have to fold in all of that atmospheric stuff, all of the things that I mentioned earlier, and more. And then once you do that, you get an image a representation. But in Fourier space, you don't have to have a complete Fourier image. So when you do the inverse, you get something but there are gaps. And it's the gaps that we have to fill that devil in the detail. Because

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Malcolm Chalmers 22:54

it suddenly explains Now, one of the things I was reading was about the the various petabytes of data and the various different telescopes that had to be brought together. And when you think of, you know, how many megabytes

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Ziri Younsi 23:07

for the 23 and a half petabytes, I think, roughly for the 2017 observations and how many

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Maymana Arefin 23:13

megabytes are there in 1000 1024

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Ziri Younsi 23:14

megabytes in a gigabyte, 1024 gigabytes in a terabyte? And then again, 2024 terabytes in a petabyte? I hope I'm right here.

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Malcolm Chalmers 23:25

I was. I was watching earlier, Shepard dolmens TED Talk, where I just had to mention this statistic, which I love where there was a picture of somebody at one of the telescopes that's near the poles, with half a petabytes worth of hard drives in front of them. And Shepard referred to that as the lifetime selfie budget of 5000. People. Wow, that's an interesting way. Which is an interesting way of contextualizing that amount of information. How many selfies are these people taking each year? assuming it's maybe like two or three a day, for their lifetime, but 1000 5000 people is half or even less of the data from one of these telescopes, that gives you some idea of the ridiculous amount involved and growing. So related to this. So there are two things that I want to mention, which I think are interconnected. One, which is a technical point about what the event horizon telescope was doing. And one which was to do with the the public understanding of that information. So start with the public understanding, which was that when the image was first released, we were saying earlier, probably about 80 85% of the people we know were astounded and amazed and astonished about how this wonderful piece of scientific work have been done. And the other 10 to 15% basically looked Sorry, it's a bit blurry, isn't it? added to this. I know that MIT seven was not the only I'm very glad that's tickled. It's just, it's really hard to make that image. The telescope was looking at MIT seven, but I believe it was also looking at how is it Sagittarius A or A stay star? Center, which is 1000 times closer than MIT seven, but also 1000 times smaller. And that's right. So firstly, is the reason why it's an image of MIT second, rather than Sagittarius A. So that was it. Just luck from the weather on that day. Oh, no, no, there's

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Ziri Younsi 25:38

there are very good reasons. And that is a great question. But first, why I laughed, if I may, because so just to give a sense of of the of the insanely high resolutions involved with the DHT. So I always use this analogy, the resolution of the event horizon telescope is so high that you it would be like having eyes. So such high resolution and resolving power that you could resolve an orange on the surface of the moon, from where we are right now, where you can see individual atoms, if you extended your finger arm out in front of you looked at your index finger, you will see the individual atoms which comprise your finger, it you know, it's, it's mind blowing the high resolution, and we can just about resolve the scale of the diameter of that black hole. Wow. So this is the beginning. And of course, we'll get higher resolutions in time. And I guess we'll talk about that later. So yeah, it's actually an amazing feat that we've even been able to do this, by the way to the very cutting edge of technology, of course, and science. So sorry, so the original question, I was gonna ask, why

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Malcolm Chalmers 26:45

not? Why, why the seven rods and Sagittarius? And then as a follow on, if it had been an image of Sagittarius A star, because it's that much closer. Would that have been a, quote, less blurry? unquote?

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Ziri Younsi 26:58

Yes. Okay, great question. So, first of all, why am 8787 because it's a lot more massive, it's more than 1000 times larger, and what and so Einstein tells us that actually, the size of the black hole is effectively proportional to the mass alone. So if you increase the mass by a factor of 10, then you increase the size of the Black Hole by a factor of 10. So there's that linear scaling relation. But you actually have what's called a characteristic timescale. And so actually, the timescale, what we call the gravitational crossing timescale also increases. So, MIT seven has a timescale of around eight and a half hours also. So you don't expect to see significant structural variations in the matter around the black hole on timescales shorten about eight and a half hours. Now, the galactic center black hole, Sagittarius A size is 1000 times smaller, more than 1000 times smaller. So you go from eight and a half hours to around 20 seconds. Right. So now it's very really quickly and even even faster than that. And so it goes from taking a picture of something which is relatively static from day to day, to something which is varying on the timescale of seconds. And you have a certain we call integration time of your observations that they can resolve. And it's very hard to resolve. So it's like, it's like a different the analogy is, like trying to take a picture of a parked car, versus a car on a motorway speeding by, you know, German out, Obama has no speed. So it, there's a technical challenge there. The other issue is that we live in the plane of our Milky Way. And we live towards the edge of one of the spiral arms. And so there's an awful lot of dust for us to have to look through.

Yeah, whereas actually MHC seven, although it's much further away, just look up. And you just have the intergalactic medium, which is a little bit easier for us to deal with. We and partly because it's less turbulent, and and so on. But actually also because we have a lot of sources that we look at, which are extra galactic, so we have calibration. So we know how we have good models of what's happening on different lines of sides, and so on. So it's a little bit easier to see. So the combination of having less systematics in terms of the intergalactic medium, the variation, and also the fact that things are very more slowly, actually meant that m 87 was technically speaking easier to create an image of the Galactic Center has been a lot more challenging, and we're still working on that now. But it's looking promising. results coming soon. Exciting.

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Malcolm Chalmers 29:31

If, if I had to ask, if tomorrow somebody would come to you and go, brilliant, we've we've managed to create an image of Sagittarius A star, what differences would you expect to see because of that, that 22nd inflation rather, is it possible to predict how

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Ziri Younsi 29:49

likely Yeah, it's absolutely possible to predict and that is my favorite question because that's my job. These images and predicts, right, and the predict would be that it's going to what's interesting about Sagittarius A Star Is that so we call galaxies which have a black hole in the center, and we believe all of them have a supermassive rather black hole in the center active galactic nuclei. Now our galaxy is for some reason, not particularly active. And most of the ones which are have huge, enormous relativistic jets, like m 87. But we don't see a huge jet, we do see a lot of variability at different wavelengths, but not on the scale of an anomalous jet, for example, we have a very different viewing geometry. And so when we look at m 87, we're kind of almost looking face on to the black hole. So the black hole is an axis about which it rotates. And we're looking almost down completely down that axis at a very shallow angle of about 17 degrees, we're actually strictly speaking to all the people who are in HD, it's 160 degrees, 63 degrees, I know. It's roughly 17 degrees. And so you're looking at his face on. But for the galactic center, again, because you know, we're in the plane of the Milky Way, you're looking more agile. Now, that totally changes the shape of the lensing of the light coming from the black hole, or from the matter around the black hole. And it will lead to a characteristically different image. Because the shape of that ring, so we see a ring in 97. That's almost a perfect circle, we believe going to ash tonight, because the there's a sort of uniformity, because the light rays are sort of almost symmetrical in their distribution, in terms of lensing. So if you look directly down the pole, you see a perfect circle when we see something very close to that. But if you go towards 90 degrees appendicular to that axis, you'll actually see a distortion and the shadow, if the black hole is spinning moderately or greater, will actually become quite asymmetric. And so you should see something quite different. That's kind of pear shaped for once. Yeah, it's Yeah, it's more pear shaped or more sort of, would be the word like ovulate, perhaps as sort of squash. It's kind of like squatting like take a circle. And you could fix the height of the circle. But you sort of squish the left side more towards the right. expect something a little bit more like that. Yeah. Yeah. And, and so in that m 87 image, which I think everyone has seen. You see an asymmetry and the brightness is brighter in the south. Is this because of the Doppler effect? Because Exactly, exactly. So it's spinning towards us. And that's why it looks brighter in the in the south part Southern part. And in the northern part, it's demo because it's receding away from us. And so there's that competition. But now for the galactic center, the theory and the models that we run, and that I've been working on in HD tell us that actually there should be a greater contrast in the brightness. And so there are a lot of things that we're looking out for, we have some expectations as to what we should see. But there is no consensus, because actually different observations from different observing missions, they actually infer different inclination angles. And so the effect Exactly, so we're not sure. So actually, this is going to be an exciting one, because maybe we will reach a consensus on this. That's extremely cool. This,

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Malcolm Chalmers 33:19

this really interests me, because if you think of representations of black holes through popular culture, they're always spherical. Yeah, it's always assumed that they will be a sphere. And I wonder if, by chance, the image had been from Sagittarius instead of ma seven, the fact that it would have been asymmetric in that sense, it might have been less immediately taken on by people because it didn't match up with the image of a black hole that they had in their minds. So it's interesting that the the symmetry of MSM possibly had something to do with how it was taken on so much. This might be an odd question to ask, because I'm asking about something visual, it's going to be a real difficult to try and get across in an audio medium. But if we picture the image of the black hole from MHC seven, you have the very bright ring around the outside, which is the event horizon. And then all the light within that circle is being sucked into the black hole. But the black hole itself is not the size of the void in the center of that image. Black Hole itself is actually smaller than that. So if we picture that image of the event horizon, on that image being say, a meter across, how large is the black hole? Is it sort of most of those in 90 centimeters? Or is it like a pinprick in the middle, or?

Z

Ziri Younsi 34:43

Yep, that's a fantastic question. And that depends on how rapidly the black hole is spinning, which we don't really know. We have some ideas of a kind of magnitude it can be spinning in one direction, it could be spinning in the other. We think it's spinning quite rapidly because you have a very powerful jet. And so on. But we don't know precisely what that number is we call it the dimension of spin parameter. And the magnitude of that can range between zero and one. And we think it's somewhere close to one and zero. And what that means is that the, if it's closer to one, then there's an orbit on which particles can orbit the black hole and remain stable, with the most stable circular orbit. And that will define the edge of that accretion disk of light that that we see. And as you increase the spin towards one, the edge of that that accretion flow can get closer and closer to the event horizon itself. And so effectively, they would coincide if the black hole were were rotating what we say call maximally. But it won't be rotating maximally for various reasons, physically speaking. So there is a gap. And the question, what would the gap be if the black hole itself had a diameter of one meter? Well, let's see. So if the black hole is not rotating, then if it's one meter for the black hole, the edge of the disk would be around six meters, okay. And then if it's spinning maximally, then they would come inside, right? So if it's around 0.9375, to 9.0, point nine, eight, then there may be be like one meter versus one point, gosh, I should know is 1.16 to 1.2 meters, something like this, but still pretty close I

M

Malcolm Chalmers 36:25

call is a large quantity of that, that space in the middle, it's a

Z

Ziri Younsi 36:29

large quantity. But if you were to put a percentage, it's maybe if we think of in terms of radius now, because it's easier for me to think that way, then it would be maybe somewhere like 80 to 90% would be the black hole, if it's spinning kind of rates that we think it is. That's a very rough off the top of the head figure there. But there's a gap. Yes. And that's that's a very important point to raise, actually.

M

Maymana Arefin 36:53

Actually, you were speaking a little bit about the Popular Science sort of imagining of a black hole. And I think that kind of leads into the kind of did you feel surprised at how how sort of far this image spread and how much the public were actually really interested in how this kind of gotten the covers of loads of media publications? Do you think it is because we kind of are fascinated by these really mysterious objects?

Z

Ziri Younsi 37:19

That's a fantastic question. I think, personally, and probably I think most of us were completely taken aback at the reception that this image received. Week. So we actually first saw images around June July 28 2018. Oh, wow. So like, more than a year before? Almost a year before? Yeah. And, and it's sort of because you've because at least for myself, personally, I've been working on such images for years. And so it was kind of I don't want to say underwhelming, but it's just like, oh, wow, it looks kind of like what we expected. That's weird. That's great. But also, what does that mean? And so there were just so many questions. And we, you know, we were divided into various teams to try and understand how to create this image and and reach a consensus using different what we call reconstruction algorithms for images, that we can reach a consensus and that our images are similar enough, and so on, and so forth. And we knew that it was an important result. But I don't think most people had any idea that it would resonate with the public in a way that it has. And I suppose as a sort of beautiful simplicity to the image. It's a ring of light. It's bright. It's mysterious. And I think when you hear black hole, you know, it's mysterious in and of itself. And the image, I feel in a lot of ways, does it justice. And I think the term black hole thanks to people like Stephen Hawking and other great scientists, you know, it has, if you will enter the vernacular, it's become a sort of like a term that everybody's familiar with. Everyone has seen films like Interstellar, and there are much older films which depict black holes as well. So I think it's always been there in the public consciousness. And now finally, we have an image of one I think, people, if you look at the media response, so every time I give a talk show, I opened with sort of, what did Twitter say, or you know, and you see what everybody's here. But they have things like the I have sour on.

M Maymana Arefin 39:28

Malcolm showed me this YouTube video, which is created a simulation of what it might look like to fall into a black hole

M Malcolm Chalmers 39:36

for people who are listening, go on YouTube now and search for falling into a black hole. It's on zero his own YouTube channel. It's got 2.8 million views. It's about three minutes long, and it's absolutely mind blowing.

M Maymana Arefin 39:50

So we were just kind of I just like very targeted perfect guys kind of looking, looking through my phone. But yeah, it's really I made that comparison. Exactly with iosr on it. Look so kind of different to to anything that we would imagine in a university. It's pretty,

pretty cool stuff.

Z Ziri Younsi 40:08

It was, it was an amazing result. And I think on the day, everyone was just, you know, inundated with requests, and commentry, you know, requests for comment and so on and a bit the specialist opinion. And, yeah, I'd say that it was only then that you sort of really appreciated what it meant. But there's also the sort of burden as a scientist of, you know, you don't have so much time to sit back and say, Hey, you know what, this is amazing. We've done great work here. Let's take it easy. Now. You kind of have to think Well, what's next? And what does it mean? What can we learn from this image? And that actually, we're doing a lot of work now to try and understand this, because it is an image. And as we mentioned earlier, we discussed earlier that, you know, what, what is an image? And what can we say about that? And these are important questions. And we're trying to understand things like, Can we estimate the mass of the black hole? Yes, we can. 6.5 plus or minus 0.7 times so billion. So the masses, that sounds like it's not a good margin of error, it's actually fantastic. It's the best so far. And you know, so we've got a very good constraint on the master spin we're working on, we'll see soon, if we have better constraints, maybe. And we're looking at the galactic center, too. So there is a lot of science too. But what's great is that it's something which I think the public really appreciates. And we're very lucky, really to work in sort of science at a time where people are more interested in, in science because of people who work very hard in reaching out to the public and communicating science.

M Malcolm Chalmers 41:49

I mean, you you briefly touched on Interstellar, and images of black holes. Now, I know that there's, I think, as you mentioned, the the image that was produced was very, very similar to the kind of simulations that you'd already predicted, which is obviously quite satisfying to see that thing of, you know, it's like when they dropped a hammer and a feather on the surface of the world and Galileo, you were you were correct. Having done this work, what are your opinions about some of the representations of black holes in popular culture? You know, do you watch Interstellar and go on? No, they've got this completely wrong. Sure. Did you? Yes. Okay. Have you played fortnight by any chance?

Z Ziri Younsi 42:34

I know of it. And I know of its depiction of the black hole when they took a break. Right? Yeah, saw this. And there was a colleague, actually, who wrote an article about, you know, how does he feel as a video game player who plays fortnight about this wasn't a bad depiction. But you know, there are there are various things which could be improved. You know, as as a as a as Christopher Nolan, who was the director of interstellar or, you know, the producers of fortnight, their job is to actually communicate a sense of or, you know, that black hole image could be more dramatic. If it were higher resolution, you see more swirly structure, you'd see stuff plunging in, and we can't we're not at that stage. Yeah.

M **Maymana Arefin** 43:15

Speaking of the ponding, and thing, is that something that I mean, that's something that I definitely would be really interested to see how, how about color? Would you say like, it's feeding, I guess,

Z **Ziri Younsi** 43:24

yeah. It's gobbling up matter and doing something inside it. And there are big jets, which flow out. Some people think it's burping, but nothing can escape the black hole. So it's, you know, I think that the black hole feeds. And so actually, that brings me on to a thing that is quite fascinating about black holes. But they are they they really aren't black holes at all, because a hole you can fill, and you feed a black hole and it keeps growing. That's the first thing. And the second thing is they're not really black. Because, you know, Hawking predicted, for example, that there would be a small amount of thermal radiation that will be produced from a black hole, the so called Hawking radiation. In fact, there's a 50 pence coin with the Hawking bergisch, nine entropy formula printed on it that was released last year and re released this year by the Royal Mint, which has that equation. So black holes can emit radiation in principle. There's also some radiation if the wavelength is larger than the size of the black hole, and the black hole could be a small black hole, it wouldn't be captured by the black hole would be scattered. So they're not blocking animals, but perfectly named. So yeah, that name was coined, I think, by john Archibald Wheeler,

M **Maymana Arefin** 44:41

I think, is it true that they were called something else before black holes? Maybe? Was it dark stars or something? Yeah. And do you think that potentially was more accurate

Z **Ziri Younsi** 44:50

or so I that's a great question. In fact, that that's a for me quite a sort of, thing I always like to talk about when I speak about black holes. Prior to the notion of people understanding that the black hole was an object with a with a boundary and event horizon and so on that came about some time between when Einstein first came up with his general theory of relativity cash flow shield, found the first solution of the Einstein field equations in late 1950s, published in 1916. And this was a special black hole, this was a non rotating black hole, it wasn't understood to be a black hole at the time was fought off to just be the sort of exterior of a star. And there was an interior where at the edge of the interior, things broke down, and there were infinities. That was the event horizon. People thought that that was just a mathematical problem later was shown that that event horizon could be removed, because it's what's called a coordinate singularity, rather than a physical Singularity, and so on. And so, long story short, there was a sort of journey between the, you know, the turn of the century, just after Einstein's theory, and the acceptance of black holes. But well, before Einstein and his theory of gravity, we had Newton's theory, right. And within Newton's theory, there is the so called corpuscular theory of light. So light was understood to be particular to nature. Exactly. And so particles feel gravity, right? Yeah. So, a chap called Reverend john Michell, he was basically a polymath. He was at Queens College, Cambridge, he was a British scientist, he came up with the idea of what he called a Dark Star. And this dark star was basically an experiment in his mind, taken off mass concentrated into small enough space. And eventually, the light produced by that star would not be able to escape the surface of the sky could not radiate away its own light that light is producing inside. And this is the so called Dark Star. And this works because of Newton's theory in the corpuscular theory of light. And then Thomas young came up, I came around sort of the end of that century. So I think this was like 1783, or 1786. That was fine. But towards the end of the century, he did a double slit experiment. And he showed the diffraction pattern of light and interference. And then it was thought, well, light isn't particle, it's a wave. Therefore, when it's gone, yeah, so actually, Laplace, Pierre Simon Laplace also came up with the same kind of idea of the darkstar, independently, a few years later. But that fell out of favor completely. But I so my feeling is actually met, perhaps darkstar is more appropriate, that maybe it's something extremely compact, so compact that the light can't escape. But Einstein's theory tells us it's a singularity. At the center, there's actually an event, there's a singularity. And the black hole is characterized by a singularity surrounded by an event horizon. So you can never see past that event horizon and hiding behind the singularity, and that tells us there's a problem, because you shouldn't have infinities in nature, unless the singularity really exists. But if you had instead some ultra dense object more dense than a neutron star, then perhaps you could get around this, but that's highly, that's conjecture, okay. Black Hole is quite special in Einstein's theory, it's, it has localized mass energy, it's not really a star per se. So the truth is, we don't know what happens beyond the event horizon at all. And this is not really my area either. And the prospect of knowing what happens beyond the event horizon? Well, I don't think at least with the techniques we have right now, we we have a means to understand that this is the realm of basically quantum gravity. And that's a very difficult problem, because we don't have a quantize theory of gravity. So that's a very active area of research. Still big unknowns.

M

Malcolm Chalmers 48:45

So mid seven is 55 million light years away. So the image that we have created is actually a representation of something that has happened roughly 55 million years ago. So do we know what is happening now? Or can we hypothesize what is happening now

Z

Ziri Younsi 49:04

we need to observe for a lot longer. Sure, we've only observed on four nights, there were two nights, then a gap of two or three days and then another two nights over the course of a week we observe for four nights, that's not very long. If we can build up more of a dynamical picture of what's happening, then perhaps we can see some of the more longer term properties of that matter swirling around the black hole. So there's always the prospect that the image that you take is at a particular episode, if you will, within the evolution of that matter. It could be a flaring episode where it gets very hot and bright. And that may not be representative of the sort of quiescent state of the black hole and its environment. So we need to observe for a very long time and see those structural variations, and then we can build up a picture. And then maybe when we learn a little bit more about the black hole through that, we can extrapolate somewhat and think more about what's happening towards the future. But we don't even really know what a black hole is, you know, it's it's there they are, in principle, very simple objects. They're characterized in terms of really just two parameters, their mass and their spin, we assume that they're charged neutral. So mass and spin. And we have some estimate of the mass and we're still working on the spin, although that's, you know, that's that's a work in progress, yet, they're so they're so simple. And yet, it's still very, very hard to say, what is the nature of the beast? And that that's not something I think that we can answer. By looking at radiation produced in the vicinity of a black hole, we won't be able to say what it is, you can characterize it in terms of its mass and its spin, you know, its size, and so on. But what it is, that's more fundamental, yeah. So knowing where it's going to be, in a million years, 55 million years, why is it still there. So first of all, it probably will still be there and 55 million years, because they just like to keep growing. And they get so they can only in principle, as far as we know, decay, through Hawking radiation, which is a very, very, very, very slow process. So black holes will probably be some of the last objects in the universe, if we believe the universe is accelerating in its expansion, and we'll just, you know, continue to do so it'll be very cold, desolate place, but they'll still be lots of black holes, because they'll take a very long time to go from six and a half billion solar masses down into both nothing. So there will still be a black hole. The question is, what will be the future of the galaxy? Because the black hole is the engine of the galaxy?

M

Maymana Arefin 51:40

That's a really interesting point, actually. Because then I think that leads quite well on to how, how, looking at and trying to measure and understand buy cause actually really can teach us around about the universe more broadly. Yeah, that that makes a lot of sense. Do you? Do you want to say a little bit more about that relationship?

Z

Ziri Younsi 51:57

So we Yeah, that's a fantastic question. So we do believe and have very strong evidence that to say that black holes, they play a very important role in regulating regulating the transport of energy, throughout galaxies, and actually into the intergalactic medium, and so on. So we have jets, for example, they can transport a lot of energy, that the galaxy is powered by this central engine, you have a gravitational Well, that is the black hole, the galaxy can rotate, for example, that you need a black hole to attack, you need some mechanism by which this energy is regulated. So we simply don't have long term, observational data of the supermassive black hole, we do have observations of black holes at other wavelengths for longer periods of time. But those wavelengths of radiation are produced in regions, which are for the most part anyway, much farther away from the event horizon. And what we're looking at now with the event horizon telescope, is radiation which is produced very close to the event horizon. So we're seeing a very different picture of the black hole, where it's gravity becomes a dominant effect, which shapes the emergent radiation, as opposed to Bob less dominant? And, you know, I'm giving a very long winded answer, because the truth is, I've never I think about it deeply. It's very hard to say that there will be a black hole, what will happen to the galaxy? Well, maybe we need to look at more galaxies at much higher redshift so much further back in the early universe. So if we see the first like, almost proto galaxies, some people wonder, why are some galaxies spiral shaped? why some elliptical, their ideas about the age of the galaxy is based on its morphology, and so on. So maybe with missions like James Webb Space Telescope, when that eventually launches? We'll see galaxies much earlier on in the universe. And maybe we'll learn something about the black holes in them as well. Did they start off as smaller black holes? And did they grow? Over millions? billions, they get so big, you know. So these are really these are just these are huge questions. And they are very open questions. And we simply don't have definitive proof of this. yet. There are many ways that black holes could do this. But if we believe black holes, that if we were to say that black holes are formed from the collapse of a massive star alone, then you would only have a black hole of a few times the mass of the Sun, there how to go from, let's say, 10 times the mass of the Sun, to 10 billion times the mass of the Sun, over the period of the history of the universe of 13 billion years or so, what's actually a little bit less than that, because you have to actually have stars we can collapse in the first place. And that takes a very long time to So in the end, you three murders alone, it's not possible because it has to have a certain rate at which they encounter each other as well. But the universe is expanding. Things are moving further apart. So when you think about it, there has to be something else. So maybe some black holes are born big. And maybe they don't form through the collapse of a single star alone, maybe through huge amounts of clouds of dust and gas. So, you know, there are many ideas out there. We don't know. So we need more evidence. There's much more to and we need a lot more evidence. I mean, we need to look back much earlier in the universe.

M Maymana Arefin 55:23
I was actually curious about whether there was anything sort of hiccups on the journey of producing that image, because I guess we only see that final result, but I'm sure there was some unexpected moments as well.

Z Ziri Younsi 55:35
Yeah, definitely, always challenges. So it's a big team. And so you know, the coordination is always is always a challenge. But actually, it was a challenge, which was met head on, and I think we delivered on fantastically. So in terms of like things which slowed us down maybe a little bit, well, you know, that the different telescopes are spread all around the world, South Pole Telescope, for example, that you saw the pictures, and all of those hard drives there. Well, there's a winter, and in that winter, you can't fly. It's a no fly zone. So you have to wait a very long time to go and collect those hard drives, for example, containing that data. That seems like a not a big deal. But you're kind of you know, that's a bottleneck of at least a few months, because that data needs to be shipped from the different telescope sites to a central location, actually two central locations, one in the US at MIT haystack observatory, the other is at the Max Planck Institute for radio astronomy in Bonn. And they are basically passed through huge supercomputers that do all sorts of fun stuff to do with correlation and fringe fitting, and so on. And basically, in a sense, putting that data together, instead of it being one telescope, set of individual telescopes, it's sort of put together in such a way that it's like it's recorded by one massive telescope, that's very long baseline interferometry, that was a challenge, it was a challenge to work to a very tight timeframe. So once we had this data, we, in a sense, had a self imposed deadline, which was this all needs to be published in an Astrophysical Journal. And we didn't have much time. So we really, really had to work hard, and fast and properly. And so we were, there were six papers. And in a sense, different groups were working on different papers, but there was a lot of overlap, obviously, because it's that sort of project. And the papers, in a sense, told a story about how that image was made from different perspectives from an observational perspective, from an engineering technical perspective, from an image reconstruction, perspective, interpretation, theoretically, that

sort of thing. I was involved more in the theoretical interpretation. So we had to, we had to effectively run 1000s of simulations and generate hundreds of 1000s of images, because you'd have no idea about which, so when you have a simulation, you have a snapshot in time. But the question is, what is the state of the black hole at that instant in time that we observe? And we don't know. So we need to create as many possible snapshots, as you say, to compare, and then use that to sort of work backwards and infer the properties of that black hole, statistically speaking, and that was tough. Very little time. Yeah. So we have to pool our resources, computing facilities, you know, you need very large computing clusters to do these sorts of calculations. And people's time, you know, we're not paid to work on this project. This is something we do because we're passionate about it, and we enjoy working together. And people have responsibilities and their faculties. You know, a lot of people gave up a lot, I say, gave up, that's the wrong word. Excuse me, they put forward a lot of their time into this at all, and, you know, very intense period of our lives. And I think everybody was just relieved that it went so well. Because it was, it was challenging to do it all in a very small space of time.

M

Maymana Arefin 58:59

Absolutely. I think it really captures actually exactly what I was wondering, because it sounds like kind of managing such a huge operation over so many different countries, was difficult, but also really, you reap the benefits of that and having so many different perspectives. And yeah, it sounds it sounds phenomenal.

M

Malcolm Chalmers 59:17

But the last thing I was going to ask was that following all of this fantastic, world famous work. What's the next step? What are you moving on to next? I believe I saw some mention of the Lisa Consortium. Yeah,

Z

Ziri Younsi 59:31

so Lisa is it's, it's a concept for a space based gravitational wave detector interferometer. And that's, that's very much in the future that's sort of 2030s anticipated that that'll be launching. But that's a whole other form of astronomy. That's, that's, that's, that's listening in for ripples in space time gravitational waves. So when you have two very massive objects, Einstein's theory is a geometrical theory of gravity. When two objects with a lot of mass like two black holes, let's say they get close to each other, they start to circle each other. And they eventually coalesce and merge. And in that process, as they start to slowly coalesce, they start to radiate some of the energy away in the form of gravitational waves. And as they get closer, more and more energy is radiated. And it's those rate waves that we detect. And so what that enables us to do is to detect sources of gravitational waves. So these cosmic events, mergers of black holes and neutron stars, and so on, that maybe we can easily detect with conventional telescopes, so called electromagnetic wave observatories, anything from radio to X ray, gamma ray, gravitational waves, you will hear it. And then it's you can say, Well, okay, point our telescopes are now something interesting has happened. So it provides you at the most basic level with a means to listen into things that you would otherwise never know were there because they're so faint. But what it also does is it gives you an ability, first of all, why gravitational wave discovered the gravitational wave discovery was so important, it was in crucial validation of Einstein's theory of gravity. And I think that is a phenomenal thing. But it also gives us the means to study gravity in a very what we call strong field regime, where where the gravity is very strong in the field is very strong. And this is not so easy to do. And what Liza won't be able to do is look at many more events, and we should be able to detect things other than just black holes and neutron stars, even white dwarfs, for example, in the galactic center. And because it's a triangle, rather than L shaped interferometer, in principle, you have some vectorial information about the wave, so you kind of know where it's coming from. So you can measure what like a polarization for example of that wave. Now, gravitational waves and Einstein's theory have two modes of polarization. But in another theory of gravity, or an extended theory of gravity of Einstein is not complete, which we have very many good reasons to believe that his theory is incomplete. We may see evidence for that. And you cannot, you can't really do that with electromagnetic waves, but gravitational waves, you have that opportunity to do so. So they offer they give you a whole new window on the universe, basically, to give you a means to see things that you could never normally see. So I think that's a long term thing. But I think everybody in the community realizes and recognizes the importance of this science. But coming back to the eh, two, has a awful lot of great science still to come. Yeah, so there is there is the stuff in the galactic center, we haven't got a picture yet. But you're working away working towards it was gonna be really cool, it's going to be quite special, I think, because our environment and our galactic center is close, relatively speaking. And what that means is we don't just have the eh t image, we have a lot of other data from other observatories that are looking there. So we can really build quite intricate picture of what's happening. And that's, that's a lot easier to do with the galactic center than is with CMS is very far away. So we can learn a lot about that environment. And we can learn a lot, not just about the black hole, but actually what's happening with magnetic fields, and how that sort of matter is sort of being channeled along them and so on, we see huge filaments like with Meerkat telescope, you see huge filaments of matter along them and the galactic center, we can learn about the history of the black hole. So there are things called Fermi bubbles, which are huge galactic bubbles, huge bubbles, which are, you know, extending above and below the plane of the Milky Way. And you wonder where they come from. So at some point, there must have been like a huge explosion or some some event. And then the galactic center, as I mentioned, at the beginning, is quite sort of not very active, but it was active, presumably. And the question is, will it become active again? And what would that mean for us, suddenly, bang, you know, those huge platforms, sagging? Now, I'm being silly. But you know, there's a future where that could happen, and maybe learning about what's going on there. Now in this state. So MHC seven, and Sagittarius A star are in very different states in history, and they sort of almost represent opposite ends of the spectrum. One is a black hole, which doesn't seem to be feeding much at all. The other is a black hole, which seems to be feeding a lot. Yeah. And so they're really interesting cases.

M

Maymana Arefin 1:04:42

Absolutely. Well, it sounds like you're able to build a really complex picture, hopefully, especially with this new new project. Yeah, I'm gonna, I've learned that there are bubbles and filaments that make up Fermi bubbles. Yeah, a whole new world. Really, really cool.

M

Malcolm Chalmers 1:05:00

Today I have learned so many things. Well, I think having successfully blown all of our minds, it is the job of myself in my mind not to say thank you to Dr. Ziri Younsi for coming on to the podcast today.

Z

Ziri Younsi 1:05:14

Thank you for having me. My pleasure to be here.

M

Malcolm Chalmers 1:05:17

And yeah, thank you to Maymana. And we'll be back next month with another episode of Hypot-enthuse. Thanks very much for listening.