Amy: As a last word for you all, I wanted to let you know, if you don't know already, that I'm preparing to retire. I've been director of the museum for 23 years, and I'm ready to pass the baton. I want to thank all of you so much for your support. It's been so important to us, and you can see how popular the museum's programs are, and it's partly because of your support. Thank you, and here's Kira.

[applause]

Kira: Thank you again, Amy, for all of the support for this program, Science Cafes, and many, many other programs over the years. Amy hired me about 24 years ago, 23. Yes. She was assistant director at that time. In any case, tonight we have a very, very special program, and I see that it's had a big draw, so I will get right to it. For those of you who are new to the Science Cafe format, we have about a half hour of presentations at the beginning from our distinguished guests, and then we move to a discussion period at your tables, where you can talk amongst yourself.

There are some ringers in the audience, some table hosts who have some knowledge already on this subject. Can you raise your hand, Miguel? Okay, yes, perfect. Thank you. They have name tags on to help you identify them, and then we will come back together for the last half hour for a group discussion. Finally, there are little blue evaluations on the table, and please fill those out at the end before you leave, and give me ideas for future topics, because even though Amy is retiring, this program is going to go on.

With that, I will introduce our guests. We have two wonderful guests, and they both do extreme science. Bjoern Penning. Professor Penning's research is focused on the search for dark matter. His group is deeply involved in the construction, operation, and analysis of the LUX-ZEPLIN Experiment that is located one mile underground in a former gold mine in South Dakota.

They just set the world's most sensitive constraints on dark matter, and Professor Penning is further designing a novel low-mass dark matter detector using superfluid helium. Wow. He works with theorists on new models for dark matter, and in the past, Penning also worked on collider physics, in particular, the 27-kilometer-long LHC collider in Geneva. I've heard of it, but I've never been there. It sounds fun. The matter-antimatter collider that was hosted at Fermilab, near Chicago.

I'm also going to introduce Marcelle Soares Santos. Professor Soares Santos' research focuses on uncovering the nature of the accelerated expansion of the cosmos. Big stuff. She contributed to the construction of the Dark Energy Camera, one of the largest telescope cameras in the world, which she now employs to search for gravitational wave-emitting collisions of neutron stars and black holes.

The program aims to establish gravitational waves as a completely novel method to study cosmic acceleration. It has been successful in detecting the first neutron star collision ever observed, a discovery heralded as the science breakthrough of the year in 2017. Wow. She was awarded the prestigious 2023 APS Fellowship, 2021 Cultural Scholar Award, and 2019 Sloan Research Fellowship.

While preparing for many more discoveries on the gravitational waves front, she also contributes to the effort of measuring the cosmic acceleration using traditional methods, such as galaxy clusters and gravitational lensing. Together, traditional and novel methods blaze a trail for a major leap in our understanding of the universe. Her research has been featured in the PBS documentary series, *Nova Wonders*, and has been covered by major news outlets worldwide. Please welcome Bjoern and Marcelle.

Bjoern Penning:

Good evening, and thank you for the invitation. Thank you for the nice introduction. I'm really very blown away about the great attendance. I'm also, I'm really happy to see-- I see colleagues from the physics department here. I see students that I'm teaching. I'm sorry, guys. I'm teaching, and now you have to listen to me again. Yes, colleagues in the department other than Marcelle, and I also see a lot of friends and neighbors. That's really great. [chuckles] I'm going to get properly heckled today, so that's good. [laughs]

I'm going to talk to you about the hunt for dark matter today. If you can go to the next slide. What you see here is a very abbreviated version of the last 2,000 years of fundamental science. We went from very simple models, everything is made out of earth, water, wind, and fire, to an understanding that actually everything is made out of atoms. Already the Greek thought of atomos, and then actually the structure of the atom.

Just in the last 100 years, or actually even a bit less, we really understand everything that we know, everything that we can probe. What we see here are all the fundamental particles. On the outside, you have all the particles that make up stuff. The middle ring shows all the forces, except of gravity, and in the very middle, you have the Higgs boson, that was discovered in 2012, with very large contributions by the University of Michigan. With this, we have found everything. We're done. We call it a day. Nope. Next slide, please.

Unfortunately, just around 1998 or late '90s, we realized two things. That all of those 2,000 years of work is just 5% of the energy content of the universe. Another 27%, 30%, five times as much is regular matter, is dark matter, as I'm going to talk about now, and another 70% is actually dark energy, what Marcelle is going to talk about. I luckily got tenure recently. That's nice, but this drops security by itself as a physicist. There's a lot to do. We know that most of the actual matter in the universe is dark matter, and there's a very, very good chance that dark matter is with us in the room right now. We just haven't identified it yet. Next slide, please.

There are plenty and plenty of observations about what dark matter, how we can see dark matter. Dark matter, we can see it in the very early universe, when the universe froze out, became transparent shortly after the Big Bang. We see the ripples of dark matter there. We see dark matter in the present universe. We see it in the orbital mechanics of galaxies. Stars further out move faster than they should be because they're being dragged by dark matter, but the local density is actually very small. The local density is about, in scientific terms, about half of a proton per, even less, 0.4 GeV per cubic meter. It's like half a proton per cubic meter. It's a tiny amount of mass.

In the entire world, this is the other dark matter, on the entire planet, the amount of dark matter is about five pints, right? The entire dark matter in the solar system corresponds to a small moon. You see already from five pints to a small moon, even a small moon is big, right? Because the universe is so big and so empty. Everything that is empty is being filled, like our atoms are mostly empty space, right? There's dark matter.

We know today, and really from observations, going all the way back to the early universe and today, things that we see locally, if you call our galaxy locally, and then also the growth of galaxies, the structure of the universe, these superclusters, everything can only be explained with dark matter. We know that dark matter is essentially like a giant bath, like a dark matter fog or halo, we call it a halo, surrounding our galaxy. Even this artistic rendering is not correct, in the sense that it's much, much bigger. Galaxies are ten times larger than they appear to us to the visible eye because of the dark matter, but we cannot see it. It's invisible. That's why we call it dark. Next slide, please.

It's not just some esoteric thing that we do to get grant funding or so, but there's actually real implication. I mentioned that at the very early universe, we see the ripples of the dark matter. What we see here is a rendering of-- If we look at this, what we call the surface of last scatter, essentially, at the last part of the Big Bang that we can see, we see tiny fluctuations, like ripples in a pond when you throw in a stone. These are ripples in space-time. Where there are these ripples, there's more gravity.

Then we see how then over the eons, this gravitation wells attracted first hydrogen. Hydrogen formed the first stars. The first stars burned, blew up, created more stars, created a heavier element, that we are made of and then eventually formed modern galaxies and planets and everything. This all has been seeded by dark matter at the beginning of time, so it's truly important for our existence. Next slide, please.

I could speak about this for an hour, what we know, what we don't know, but to summarize it, what we know, it's a very, very rare process. A billion dark matter particles could stream through us right now and we wouldn't feel any interaction except maybe once in a while. Similar like neutrinos. You might have heard about neutrinos. Neutrinos statistically can pass through a light-year of lead, but once in a while one will get caught, so we need ultra-sensitive detectors.

Because we have some idea about the density of dark matter and we have some idea about performance orbital mechanics, how fast dark matter is, we know that the energy signatures are very faint, so we have to build detectors that are the world's most sensitive detectors. At the same time, being the world's sensitive, we shouldn't be distracted by all the natural radiation around us. We do this by essentially building them very, very deep underground. So next slide, please.

This is my experiment. We call it the LZ, LUX-ZEPLIN Experiment, and we built this experiment one mile underground in the beautiful Black Hills. Who of you knows the movie *Dancing with Wolves*? I love it being in the audience about my age. Finally, I'm not the only one. If the students, it never works out. Sorry, guys, it's your fault, but they never look at me. I make my jokes. They're like, what? It has been filmed there, just around the corner there. It's a beautiful area. I love going there. One mile underground in a former gold mine, we built this experiment.

Why do it so deep underground? Because some of the highest radiation, higher than even the radiation we can create at a large Hadron Collider, comes from cosmic rays. The cosmic rays are constantly raining upon us. Right now, you stretch your hand out, you get one muon per second going through your hand. By going one mile underground, we can get away-- I indicate this with those lines, we get away from the muons, at least from most of them. Only one in a billion will make it all the way down there.

In addition, we built the entire experiment out of the cleanest, and with clean, I mean, a radioactively cleanest material as possible. As you know, when you buy your house, you check it out for radon. Radon is everywhere. Radon is radioactive. Every heavy metal has been baked in a supernova or neutron star merger. Marcelle is going to talk about this. There's trace radioactivity and we source our material, particularly for radiopurity. Next slide, please.

Going underground, this is a very historic place, for good and bad reasons. Historic, in terms of the US history, historic, in terms of Native Americans, but also for science, because the famous Ray Davis experiment has been set in the very cavern with our experiment. A piece of that experiment is actually-- a small piece on exhibition in the Science Museum right now, together with a much bigger exhibition that comes to this.

You see me here on the lower right side. This was just before I became father, so I looked much younger and much-- not happier, but much younger. When you go underground, you're dressed up like a miner. It's not a Halloween costume. That's a mine that they're actually doing excavations, et cetera. Next slide, please.

This experiment consists of two parts. The primary dark matter target, and then an auto veto detector. Because at some point, you cannot get material which is perfectly clean. Even if you're perfectly clean, once in a while, a muon will make it through, or once in a while, a muon will manage to penetrate all the way one mile deep and kick out a neutron and create radiation.

We built a second detector, an auto detector, which is they are to detect everything from the outside because dark matter is so rarely interacting, you would expect it only once. If you see something in the inside and in the outside, we reject it. This is one way we call it active background control. Everything on the auto detector, we have a big footprint in both. Particularly in building, everything on the outer detector essentially has been built by my group here at U Michigan. Next slide, please.

I want to give you some idea about the radiopurity. Bananas contain potassium and potassium is radioactive, so about 15 becquerels, so 15 radioactive decays per second of a banana. That's not a lot. It takes a huge amount of bananas to actually measure this with regular detectors.

Our target purity that we have is what we call two microbequerel per kilogram. This corresponds to one over three-quarters of a million bananas. This is how clean we are in banana-equivalent units. When we built this experiment in the clean room, we did so much cleaning all the time. So much. I'm very traumatized. On the other side, sharing houses in the Black Hills in the winter with colleagues and friends that are all just cleaning all the time. Even in a flat chair, it's very clean, so that's a good thing. Next slide, please.

Just a few pictures of the detector. Of course, now it's running. This is the central dark matter detector. We call it a time projection chamber. This is a technology in which we are able to distinguish different types of radiation based on these novel liquids, a liquid xenon. Because it's so ultra-clean and ultra-pure, we see here on the right, we see some of the components. It's a light sensor, which looks like insect eyes. It's a photomultiplier tube. In real life, it's really beautiful and big and clean, but the entire thing is submerged in liquid xenon. Next slide, please.

Four years ago, we built this over several years on the surface in the clean room, cleaner than any surgical theater, cleaner than most chip industry even uses. Then we hung it on beneath the cage on the over-one-mile drop. There you have years of your life and millions of dollars hanging on a cable a mile down. We brought it down in the drive and shafts. We pulled it out. It's in the upper right. Then on the lower right, we pulled it into the final hole. This shows you what actually sets the final dimension of the experiment. What's the biggest we could get through without having to excavate more? Actually, this gentleman at the very right side is also a former U Michigan graduate student who's one of the leading persons in the experiment. He's now at Berkeley. Next slide, please.

This is then the experiment being put into the cryostat with Charles, one of our engineers. Next slide, please. Then we built this auto detector. I love this picture because this, except of the tanks in the middle, everything here, micro-built. This is the auto detector, which then gets rid of all of the backgrounds and really enables us to get quite a bit more clean. Next slide, please.

How does this look like? If we can click on this, then we should be running. We see how data-taking looks like once it runs. Anyway, we see it in different colors. I started explaining it. We see the different sub-detectors, including the one we built in the TPC where we are leading the calibration. These little spikes, when you zoom into them, they have a lot of structure in them. This structure of different signals allows us to distinguish what type of signal it is, and then allows eventually to say we are rejecting some of the backgrounds and what looks like dark matter.

If we put this all together and we just publish this result a few months ago, we so far have published only 60 days. We have 280 days, about more, and don't tell the competition. There is more data than they can. This is what we call the limit plot. It's too technical to explain, but essentially this is the possible dark matter mass. On the left is the cross-section. It means how small, how faint is the signature we're probing, and everything above the line is excluded.

What matters is the number that we set. If a hydrogen atom would be the size of the sun, then we would be able to see something as small or faint or light as a hydrogen atom. So this presently is the world's most sensitive experiment and the world's most cleanest place in terms of radioactivity, or maybe even the universe is one because I don't know any aliens, but they might have something much better. Next slide, please.

We can do much more having such an ultra-precise detector. You can do many, many more things. For example, instead of only looking for dark matter, the cosmic rays that manage to penetrate one mile of rock are very interesting by itself, and one of my peer students is working on that. We're having novel types of dark matter searches. We can look for very interesting nuclear physics. Miguel is actually working on something like this, looking for very rare decay, which might explain the matter-antimatter symmetry, not to use a better decay in these detectors. We can do supernova physics, multi-messenger astronomy, you can hear more about this, and a whole bunch of very, very interesting things. Next slide, please.

I'm coming to an end. One thing I want to point out, and also say thank you to Amy. Amy helped organizing a wonderful art exhibition with a little bit of dark matter attached to an artist. Professor Gina Gibson from that area up there, the Black Hills State University, brought art here. If you go to the science museum, I think it's on display for another about two months or so.

Then in the exhibition space, you see one room about the experiment with pictures and part of the equipment and things like that and two much bigger rooms and much more interesting with the art that uses parts of different scientific equipment, et cetera, et cetera, for the art. Really interesting to see.

Final slide, please. So much about dark matter and I think I took too much time, but now Marcelle will take over and tell you about dark energy, which is much more than even dark matter. Thank you so much.

Marcelle:

All right. Thank you, everyone, and thank you for coming. All right. We are going to talk about the largest part of the pie, the cosmic pie that we use to describe the components of the universe today. Maybe I should say here for this. Dark energy is fascinating problem. It is everywhere. It really dominates the universe today by a large margin. It will determine the fate of our universe in the future, and yet we really have no idea what it is.

One thing that I would like to highlight on this background image that I'm showing here is not only for your enjoyment, it is actually an example of the types of data sets that we use to study dark energy. What you're seeing here are galaxies. The idea here for the non-astronomers in the room is you can imagine something like this is if each of you a billion people considers yourself a star, the collective of people around the table would be, say, a galaxy. In the case of our own galaxy, for example, we have billions or tens of billions of stars in it.

What we are looking at here, the fuzzy blobs that you see are galaxies about the size or some of them even bigger than our own. Our galaxy is very average-sized, to be honest. A few of the sharp point dots, those are stars that are in the foreground. Those are stars in our own galaxy that are on the way between us and those distant ones. The equivalent here will be your neighbor star on the same table versus a colleague at the other side of the room. Most of the time we cannot resolve individual stars in faraway galaxies. We see the fuzzy blob there, but we can infer how big they are and a number of physical properties by studying them and analyzing those images in great detail.

Now, what we are seeing here is luminous matter. All of this light that we are seeing is made out of the 5% of the pie. Most of it is really dark. Our challenge is try to infer what is the nature of dark energy, something that we don't see, using observables that are made out of only a small fraction, 4% or 5% of the total. That is the idea.

Let's go to the next slide and try to clear our jargon here because oftentimes people say dark matter, dark energy, black holes, and so on, what's the difference and why do I care? The main difference to keep in mind, at least for the purpose of tonight's discussion, is that dark matter behaves-- dark here is a term that you could replace in your mind with invisible. Dark matter will be just like regular matter, but invisible. It doesn't show up in that image that I showed to you before, but it behaves like matter just like everything else, attracts gravity, et cetera, and forms clumps and so on.

Dark energy is another beast. Dark energy is something that is in the empty space where matter is not right. I think the example, if we stretch out our analogy of our galaxies here in the room, the idea would be the following. In this empty space between one table and another, most of the time in classical physics, we would imagine, "Oh, it's just vacuum. There's nothing there. It's just empty."

In this context here, we are saying that's like, "No, it's not really empty." That empty space, there's some energy associated with it. That energy makes this space expand. What that would mean in this scenario, if this would be true, it would be that people will be sitting here this corner of the room and would see people at the other side of the room appear to be becoming further and further away from them, but not because they are just scooching their chairs like this, but actually because space-time is expanding as time progresses. What is causing this expansion, what's the energy that is powering that expansion, that is dark energy.

Now that we have our terminology straight, let's go to the next slide. All right. How do we study something we don't see? As I said, we have to build observables based on the stuff that we do see. One of them is really measuring the distances and what we call the recession velocity. How quickly does a person who's in the other side of the room appear to be receding from me will tell me how fast the universe is expanding or not. That is topic number one over there.

Number two is to measure the rate of growth. Matter tends to attract each other through gravity. Pretty much like people. Somebody else comes here in the room, it's like, "Oh, there's a free seat here, so I'm going to get in and grow this cluster of matter over here and that one over there and so on." That's usually how we behave. Same thing is happening here, but at the same time, these distances are becoming bigger and bigger. If I get here into the room and suddenly the entire room is 1 kilometer wide, then I am less likely to gravitate to the table and the end of the room than I would be otherwise. The rate of growth is the second observable that we can use.

For the topic of today, I think we are going to focus, in the interest of time, only on the first one, which is the measure of the expansion history. The illustration here shows in the Y axis, what would be distance, and the X axis is time where in the corner here we have time equals zero Big Bang when the universe is very small and very compact, and to the right you have the universe today and even to the future. The vertical thin line over there shows where we would be today.

The shape of this line is telling us the following. That closer today and beyond, we are in this accelerated phase of the expansion of the universe. It's not only expanding, but it's becoming faster and faster. It's not easy to do this with conventional physics, but the data tells us that this is what's happening. Before that, things were more normal in the sense that the universe was dominated by dark matter, and so the expansion is still happening, but not so fast.

The third thing that we do in this field is check for consistency. We don't have a perfect observable that allow us to probe the entire universe from the first instance to today. We have, for example, the galaxies, but the first galaxies in our universe were formed only something like, I don't know, 5 billion years ago. What that means is we don't have an easy way to do observations that go beyond that with galaxies. We need other probes or other observables. We have some observations from the early universe. We have something called the cosmic microwave background, but that is a snapshot in the very early universe in the first billion years.

What we want is if things are correct, we want a consistent picture, a consistent model that describes the entire universe over the entire 13 billion years of its history. We are getting there, but not quite yet. Those are the three things to keep in mind, measuring things like the expansion history and the growth and comparing measurements from different observables in a way that you're convinced that you are getting the right answer both ways. Next slide, please.

Tensions. What happens when things seem not to follow the model that you have in mind? Here, the example is of this cartoon made by a fantastic collaborator of mine in the dark energy survey. She produces these cartoons called the Dark Bites. The idea over there, if you squint a little bit, is that, say, you have a model for what dark energy is, in this case, a model is a duck, and you are going to collect data, for example, from the galaxies and from some nearby stars, et cetera.

Imagine a scenario where you've never seen a duck before, but you were, I don't know, mailed pictures, some pictures of the nose, some pictures of the foot. You would look and you say like, "Oh, this looks like a duck." My mental model and the data are consistent with each other. Looks like we are on the right track. Now, what is happening right now is that we have some data sets that seemed to be inconsistent with that, and that seemed to indicate that our simplest model for dark energy, this model I described, like energy from the vacuum, and let's live with that.

That seems to be too naive and incomplete. We may need something more complex and more sophisticated to explain what dark energy actually is. I don't have the solution. We are not going to answer that today, but you can see, I think I have an idea of the magnitude of the challenge. Let's go to the next slide and talk a little bit about Einstein and the theory of general relativity.

This slide here to try to introduce the concept. Without any math or anything, I think one way I like to summarize what is the key concept behind the theory of general relativity of Einstein is the idea that space tells matter how to move, matter tells space how to curve. What you're seeing here is that in a scenario like that where you have the tiny little fast masses moving in a space that is clearly curved, you can see that their trajectory there is going to be determined by what is the curvature of that surface that they're moving in.

What happens in the context of general relativity is that what you would imagine is that if you have a very massive object in the center, the mass of that object would cause that curvature. That's the part of the theory that tells you that matter tells the space how to curve. Then the little pro particles are going to move according to what is the geometry of space. That's your Einstein's general relativity 101 primer. We can see that here with this example.

Next, I think we can have a look of what happens if the second or third in this case, we have many small objects that are subject to move under the influence of the curvature of a much more massive object that is at the center there. Now let's go to the next slide and try to visualize what will happen. This one is not going to be a video, but you can use your imagination. Imagine the following. On the left here I have an example of the sun in our earth system. We can imagine that our earth orbiting the sun is following the path of the curved space-time because the sun is very massive and creates a curved space-time there for us to travel upon.

Now if instead of a system with very different masses like that, we had a system with two for example, neutron stars with masses similar to each other, then the curvature will be perturbed by not only one object, but both of them and they will combine with each other. More than that, when they are orbiting each other, this movement will be periodic. What you are going to have is something that are perturbations in space-time. There are periodic. This is a typical signature of waves. Those are the gravitational waves that have become a topic of so much excitement in the world of physics in this past decade or so.

Gravitational waves are this and you can see that it could be any massive object, any pair of massive objects who're orbiting each other will be producing gravitational waves, but of course, these objects have to be very massive for those gravitational waves to be appreciable. Now, these waves are there, they exist, how do we detect them here on Earth? The next slide should show what type of antenna do we need to detect them.

This example is one of the two antennas from the LIGO system and the idea here is the following. As the waves travel through space and time, what do they do? They make deformation in space. Those deformation means that if I have something that have a standard length, my arm here, and gravitational waves are going through me, what will happen is that the distance between the tip of my hand and my body is going to change according to the amplitude of the waves that are traveling through me.

Now this amplitude changes very small, so you better have a very low arm in order to get something appreciable. That is the idea with the LIGO detectors that have four-kilometer arms. It's a very, very sophisticated marvel of engineering, and that I think it's really exciting and fascinating. These detectors there has been an investment by the community over decades to make them sensitive enough to gravitational waves at cosmic distances, but only in 2015 that limit was achieved. Right now these detectors are operating and detecting signals from merging neutron stars, merging black holes every day or every week basically. Let's go to the next slide.

In my case, gravitational waves are exciting and fun on their own. I think that even if you're not interested in dark energy, you are probably excited about them anyway. Let's say that we are interested in dark energy specifically then, so what? You detect these gravitational waves, how do they help me with my problem? The idea here is that there is a very, very neat property of gravitational waves, which is the shape of the waveform that is captured in your detector. That specific pattern of the wiggles that are drawn here in this cartoon, they are characteristic of the masses of the two objects involved.

If you analyze that well, you can recover what are the masses, and if you know the masses, you know the amplitude. I said it before that you have to have objects that are very massive to generate waves that are of high enough amplitude to be detected, or loud enough in the jargon that people use in the field. It's the same here, and you can reconstruct the masses, and with that what's the implicit amplitude you compare with the amplitude in your detector, which is my L-shaped detector there cartoon, and voila, you have the distances.

As I said, we want to measure distance as a function of a recession velocity over time so that we can map out the history of expansion of the universe. This is a very clean, assuming only general relativity, it is a very clean way to detect distances to objects far away. I tell you, as an astronomer, detecting distance to cosmic objects is not trivial, it's not an easy task. You can imagine, for example-- Yes, I think I'll save that for questions in discussion later. We can talk about how difficult that is later on.

You can see how we can use these gravitational wave events for distances, and this is precious and something that we really want to do. Very good. We are here. We are in a position to make these detections because these gravitational waves experiments are there, but I told you before we need two things to make that graph. We need distances on the Y axis, on the vertical axis, but we also need this recession velocity. How do we get that? Well, that's where the traditional astronomers come in.

Next slide will show the type of instrument that we use. We want now to look at the region in the sky where the signal came from, identify the galaxy, the little bright spot where it came from, and with that we can determine what's the recession velocity relative to us of that object. To do that we use traditional telescopes, in particular, this is one example of a project called the Dark Energy Survey.

The camera that's there on the lower right side, it was built in 2012 and installed on the telescope in Chile, so you see there, the big insert is the actual telescope. The mirror of the telescope is four meter wide in diameter, and that is installed inside of the Blanco Telescope in Chile. We tend to go to locations that have dark sky and clean atmosphere to do this type of measurement. This is an awesome instrument because it can scale large areas of the sky very quickly, and so we can quickly identify what the light corresponding to the object so that we know which galaxy it came from.

If you go to the next slide. This is my cartoon illustration of the type of new subfield of science that we are doing here. We call it multi-messenger physics or multi-messenger science. What the multi-messenger here refers to the fact that you combine information that you get from light, from traditional telescopes, with information that you get from gravitational waves. The analogy with gravitational waves being analogous to sound comes into play here. Imagine you are close to a busy intersection and so on. If you hear a car crash, by the sound of it, you already can tell a few things. You can know when it happened. You can know more or less that it happened perhaps at this intersection, not that other one over there and pretty much, that's it. You don't have that much detail, but if you go outside and you peek around and have a look, then you can tell, "Oh, maybe it was just a fender bender, or, "No, this looks serious. I should call 911."

This is the idea that combining information from both things allows us to know more than we would otherwise. For the job here, the right tools that we have available include the gravitational wave detectors, this is just an artistic impression telling how do we do this in practice, the idea is that the gravitational wave antennas are up and running. When a merger or a collision of two neutron stars occur, that collision will generate gravitational waves that are loud enough to be above the threshold for these antennas to hear.

The LIGO collaboration quickly produces-- they are analysis and says like, "Oh, we have something, it's over there, and it has approximately this distance." Go for it. They just create literally a treasure map. A map in the sky, and that's it. That map is distributed publicly to the community. All of you, if you want, you can sign up in what was the last event that LIGO saw yesterday or last week. You'll also see that those maps are very large areas in the sky. I think that it's easy to understand with the analogy with sound.

We can tell by the sound of things that there's a source maybe this side of the room, versus that side of the room, but it's hard to pinpoint if you don't turn your head and look. It's similar here. The triangulation is relatively poor, especially with only two or three antennas working at once at a given time. What we do with this information, as soon as we receive the trigger signal, and that will be minutes, maybe a couple of hours after the merger has happened and the processing by LIGO has occurred.

We have our own observing plan and Isaac can tell you all about the, I know the struggles of getting to be ready on time because the bright source corresponding to that event is short lived. It'll be the equivalent of saying, "Okay, again," if each table here is a galaxy, et cetera, a merger like that will be somebody saying cheers at a table somewhere over there.

If you don't look quickly enough, it's over and you missed it and you cannot tell anymore if it was this table on that table anymore. Same idea. We have to look quickly and we have to analyze the images quickly as well to make sure that, "Oh, really, we had a source that went bright in that galaxy." That's the one we are looking for and not any of the other, 300 million literally galaxies that we have. That's what we do with our telescope on the other side. Let's see. How well do we do this. Next slide. We've been doing this for a while. I told you that LIGO started operating with good sensitivity since 2015.

We have been attempting to do discoveries of the sources since then. These are three examples of how we do that. You see there are the sky maps and we cover the sky maps with our camera. The red hexagon shapes are corresponding to the footprint of our camera in the sky. You can see that even with a large camera as we have, here we have mid 20, sometimes 100 shots to cover the entire area. It's not trivial, and we get many candidates in that area and sifting through them is fun and exciting nights that we have with all of that.

All right, next slide. We'll show you the one success story that we have. This is an event known as GW170817. In this field, we are very, very non-creative with naming things. GW4 gravitational waves and 170817 is when it happened, August 17th, 2017. You can see here that our team was probably not paying much attention to what we were writing on our emails or not thinking that those would become shown in the **[unintelligible 00:44:12]** at some point. I thought it was relevant to show it here. We were one of the first teams to make the discovery of the bright counterpart of that merger event in 2017.

You can see they are marked with the cross hairs that was at the outskirts of a bright galaxy nearby. For us, it was really a transformative moment because we knew the physics is telling us that this should happen. We should be able to detect this event but we had not made a detection like this ever yet. This was the very first. It's very exciting and there was a lot of excitement around it in 2017.

I think that that also translated into a lot of excitement even now where we are actively pursuing and attempting to make new discoveries. The last slide that I have is just a few words saying that this was really exciting to be able to participate in the discovery of the very first detection of a Neutron Star Merger. It's a great start for this program in the sense that we now know that we can do this. We just have to do it again and many, many times. That's what we are pursuing right now. The challenge is to accumulate a large sample and make this often enough and precisely enough so that we can finally tell if it's not a duck, what it is. Thank you very much.

Kira: I hope y'all enjoyed those presentations as much as I did. Now's the time where we have our group discussion and I have agreed to moderate and I will let speakers know when they have the floor and when they do not. Would anybody like to start us off with a question or comment?

Audience member 2:

Hello. Regarding the multi messenger slide, has any work been done with using radio astronomy as well as optical and the gravity waves? Thank you.

Marcelle: It's multi messenger and it's also multi wavelength activity. In my presentation, I focused only on the optical signatures, but we also see, and we expect to see emission in other wavelengths and radio astronomers were able to see the signal from that particular event. That signal came in late. I keep saying the radio summers were late to the party but they were also the last ones to leave the party. The emission from that event was bright in the optical bands that we can detect with our camera for two weeks, but they were detectable for almost a year in radio wavelengths. That was very powerful in providing information about it.

Audience member 3: A question, what observations led to the idea that there is dark matter?

Bjoern: Historically, the first one was, I think it should now say American astronomer, Vera Rubin. One of the great slides of the Nobel Prize Committee not giving it to women who detected that usually, what you would have, if you would look at the velocity of all the planets would follow a very strict **[unintelligible 00:47:31]** created law. It's just basic gravity and you expect the same everywhere and everyone's like, "Yes, whatever, it's just happening." She noticed it straight up.

For a long time people were like, "Well, this just astronomers, they're pi times." Then in particular in 1998 or 1997, they did the first precise measurement of this last surface of last **[unintelligible 00:47:58]** in the early universe. There was reason to doubt systematics astronomy is very difficult because your lab is far away. This was really nailing it down and really driving it home and there's no way you can explain this and in the same year time, two years, the dark energy happened, and then as essentially as I mentioned, we understand it all to, we don't know nothing.

Kira: Thank you friends. As someone who got a B in physics at Michigan, I feel very lucky to have two physics professor friends to ask such questions to. Marcelli and I were just chatting about, "Yes, you paid attention over there," about observables and how that concept is new to me and interesting and these types of discoveries. I know this gentleman mentioned radio, radio, radio. Are there other potential observables or things that you can imagine happening in your lifetime that would put this work even farther forward?

I know a lot has happened recently and in a short amount of time, whether it's technology getting a lot better, or types of things that you can observe that would really accelerate this work.

Marcelle: Thank you for this question. I'm already going places here in my mind with this one. In the case of traditional astronomy, we obviously started with wavelengths that our eyes are sensitive to. Then later, we built equipment that allowed us to see further away and focus it more and so on. Then much,

much later we learned how to build detectors that would allow us to see in different bands that our eyes are naturally not suitable for, for example, radio bands or X-ray bands and so on. Every time that we made progress in these technological advancement, we opened what people call a new window into the universe.

We saw new things. We learned about new structures, new classes of objects that we had never seen before. With gravitation waves, it's something similar. We knew via the theory, as long as the general relativity from Einstein works, we know that gravitation waves have to be there. Now that we can detect them, we are able to see, for example, that there are black holes of different masses and many neutral stars and details about their physics and so on.

Now, the LIGO detectors, they are sensitive within a band as well. You can imagine that in the future, we are going to have other gravitational wave detectors that will be sensitive to gravitation waves in different frequencies. I don't know what that will bring, but this will be awesome. I'm looking forward to that.

Audience member 5:
Yes, thank you. This was a question that was raised on our table, and that is this research is all fascinating and such, but how do we apply this knowledge in our daily lives? What can we benefit from it in our daily lives?

Bjoern: Not at all.

[laughter]

You could have asked the same question a hundred years ago and say, "Great, you have this thing called transistor. Who gives a crap?" Now our economy is running off it. First time Wilhelm Röntgen put his hand, actually his wife's hand, dude wasn't a good husband, beneath the radiating thing, Pechblende in German, and the photo plate. He was like, "Whatever. I just make a picture of my wife's hand, the bones of it, and that is fundamental." We're a culture people. It's not always about-- I was just the other day in the Henry Ford Museum. You go there. None of us goes there. If not, you wouldn't be here so now I'm preaching to the choir.

If we go to the Henry Ford, in the Smithsonian, we look at the first plane and we look 50 years later, Moon landing, we're like, "Wow, What happened the last 20 years?" Those things became a bit thinner. It's not about what we can do with it right now, it's about how we learn more and the application will follow. We do not care where we came from, where we go to, then we would still live in caves, to be honest.

Audience member 6:

Thank you for wonderful presentations. I'm wondering, so huge expanse in terms of where you can identify using LIGO, what part of the sky it looked like 400 square degrees or so of sky. I'm guessing that you must have some way to identify the optical transient in terms of knowing that it fits the neutron star collision model. How long do you have to do that with all of that space? Will LISA and other gravitational detectors help narrow that down a little bit?

Marcelle: The analogy is like the needle in a haystack. We have in the sky many bright objects, and we want to find the one bright object of interest in that. Our analysis pipeline, it takes into consideration what we know of the physics, that we expect it to be this bright or this color and so on, so we take that into consideration. We also know that there's a lot of uncertainty on those models, so we tend to be more inclusive. We better err on the side of caution and include more things that later we reject, then reject completely and throw away the signal. This is a challenge.

With GW170817, we were very lucky because that event was very close to us, very well localized in the sky, so it was "relatively easy" to get there. Even in that context, we had about 1,300 objects to reject, and it's not trivial. With more detectors, so LISA and so on, those are space missions that will be detecting on different frequencies, going back to the question over there.

Ground-based observatories, we are expecting them also to get better, and we are expecting to have a network with more of those detectors as well relatively soon, within the next decade. That includes a detector in Japan that's being built, and some plans as well for a future detector similar to LIGO in India. With those detectors, the localization vision becomes smaller, then our jobs will become much easier. But it will take a few years before we get there.

Kira: I'm looking at this and I'm going, one of the things that is critical in our current society is finding sources of power. We are killing our planet. Electrical is a good response, but not the end response. Is anyone studying dark energy as a source of power for our use on our Earth?

Marcelle: No. I think right now, we don't know what it is. More than that, we know that dark energy is something that is relevant in the cosmic scales between our galaxies. We don't know, even if you were able to devise a way to harvest that energy out of the empty space, no, I think we are not going there. Those challenges, they are big challenges for all of us. I think that will be better addressed with other approaches. I think that here in terms-- again, maybe at some point in a few decades from now, somebody will say, "Oh, that person told me, and she was totally wrong."

The way I see it right now, we are in a quest of our understanding of the fundamental nature of the universe we live in. It is very true that with only 5% of knowledge that we have right now, of that tiny piece of the chart, we already transformed our world in an incredible way. Who knows what will happen when we learn about what dark energy really is. Right now, I don't think that practical applications like that are not on the menu.

Audience member 7:
Hi. I'm wondering, since the James Webb Space Telescope has been launched, and more recently, the Euclid, which I guess focuses more on the infrared spectrum, have either these telescopes done anything to advance your fields, or have they created more questions than answers?

Marcelle: Just for context, so James Webb is a space telescope, and Euclid also is a space mission aiming to survey the Cosmos from space. That means that because they don't have the atmosphere to deal with, they can get very precise measurements of shapes of objects, and also they can have sensitivity to wavelengths closer to infrared that allow us to see further out. In our field, the way we see these multiple surveys is this complementary data set.

In some cases, they're going to see the same objects, the same sky. In other cases, they're going to see complementary areas of the sky, but in different bands and so on, and form a data set that's more complex and rich. In the case of the James Webb, the field of view is very small. There, specifically for the science that I discussed here today, the main way that I see that being a killer project is to study in detail the sources that we find in the future. Because once you have scanned-- something that has a narrow field of view, it's not good to scan a large area.

Once you have scanned a large area somewhere from the ground and identified it, it's like, "Oh, this is the one. Let's go for it." That is a very good instrument to get detailed information about the physical processes that are happening in them.

Audience member 8:
My question is on dark matter. I believe that neutrinos were once thought to be massless and are not quite massless. Is there any possibility there are enough of them to account for dark matter?

Bjoern: Excellent question. Unfortunately not. We do not know the mass of the neutrino, but we know a upper limit, so we know maximum mass. Actually, the fact that neutrinos have mass, it all starts in the same mind and working. What happens, neutrino travel at the speed of light, and this type of cosmological structures that we see in Marcellus' research, and the way dark matter seeded these superclusters in galactic structures. If dark matter would be with the speed of light, it would draw them out and wash them out like a wave across the sand, washing out the structure.

We know it's not neutrinos. Actually, one crucial property of dark matter is that it's not moving with the speed of light.

Audience member 9:
This is just a short comment, but in reply to the question or the comment earlier about the practical applications of it, I just wanted to reinforce the amazingness of using gravitational waves to detect things that are happening. We're seeing things electromagnetic aggregation with our eyes and we can hear things. This is a completely new sense of detection in the universe that humans have just developed in the past 10 years to detect vibrations in the space-time continuum, to see things, is amazing and remarkable. I just want to say this is astounding. To turn it into a question, I was unclear how exactly what ways of using the gravitational waves help us see and detect dark energy.

Marcelle: I think I identified two pieces of your question. On one side, I think the research we do is not inherently motivated by solving a practical problem. It's really motivated by fulfilling our curiosity as human beings. Now, on the path to that goal, we require and we do develop new technologies, new things. One example that I like to use is we all have amazing little cameras in our pockets right now. The technology to make them so good, so small, and so cheap, in part, has to do with developments that were made for astronomy in the early days. There's that. There's that component.

Gravitational waves, in particular, I think that are a new area where, again, new technology had to be developed. The specifics of how that will change applications and so on, for example, in laser technology, computing technology, and so on, some of those are already in place and others I think we have not yet seen what shape and form that will take. That is not the key motivation. It's not, at least for me or for us, when we are thinking of like, "Okay, we want to do this project and we want to solve this problem."

The motivation is the science, not so much that component. Not that that component is not there, but it's not the key driver of the decision-making process.

Marcelle: Thank you again so much for your talk. It was great. Just like matter, we can see it takes many states, solid, liquid, gas, plasma, and energy that we can't see electrical, light, heat, and so forth. Are there reasons to believe that dark matter and dark energy take on different forms?

Bjoern: Yes. I talk about dark matter. The thing is, of course, when we saw something is happening differently, we expect the first thought was space rocks. They're just rocks in space we don't see, and then there are maybe planets we don't see, but at the end, what we did, we have a full list of all possible astronomical objects, and then particle physics objects and possible forces and neutrinos belong on the list, and we check if it makes sense.

Sir Arthur Conan Doyle, author of J-- oh, James Bond is the other guy, Sherlock Holmes, said in his books, he let Sherlock Holmes say, when you're looking for an explanation and you exclude all the possibilities, whatever remains must be the truth. We didn't jump to a conclusion like, "Hey, I need to write a ground proposal, let's call it dark matter." The first time dark matter was written, actually in German in a paper written by Zwicky back then in Caltech, but in German **[unintelligible 01:04:08]** was 100 years ago. This paper has been cited five times through the 1960s, and since the '90s, goes up like crazy.

It took 50, 60 years to exclude all the simple explanation. This is why it's so hard to look for it because the low-hanging fruits are unfortunately gone and we haven't found it. We know now it's something that is not known to man for sure.

?Audience member 6:
Again, on dark matter. The dark matter does not interact with anything except through gravity, and it's spread throughout the universe. Why has it not gravitationally coalesced into itself and formed one giant black hole in the past 13 billion years?

Bjoern: Good question. First, not everything that gravitation interacts coalesces into a black hole, because in that case, all the matter would be in one black hole. Dark matter has, like anything else, an escape velocity. If it's fast enough, it's not going to bind. Actually, its escape velocity is slower than for a microscopic object because it's lighter, it can escape faster.

Some of our dark matter researches are based on the idea that dark matter is coalescing a little bit, for example, in neutrino telescopes, we are looking for particular signatures of dark matter in neutrinos coming from the sun because we would expect slightly more dark matter sitting in the sun than in earth. It's a correct thought and we consider this, but there is escape velocity.

?Audience member 6:
Thanks. Actually, I think I have a question. It's going to be two questions. In regard to dark matter, do we hypothesize that dark matter interacts with space-time the same as visible matter? Then in regard to observation, I've sat behind a pole at Fenway Park, do we feel earth is a decent place to try to search from, or we wish we could be over in the box seats over there?

Marcelle: We cannot choose our vantage point, so we have to do the best we can. I have to say that compared to other galaxies we've seen out there, we are in a fairly good spot. Many other galaxies have very active, super-massive black holes in the center. We do have a super massive black hole in the center of our galaxy, but it's quiescent to some extent. It doesn't affect our observation so much. Otherwise, it would be more difficult in other ways.

I feel like most of the time we don't think about that. We think about like, "Okay, how can we--" For us the jargon is foreground. Whatever is tough that's between us and the signal that we want to get from out there, how can we handle it the best we can? We actually have improved a lot in that direction in the last few decades, but overall, I think our seats are okay.

Bjoern: Then probably the last comment about black matter and space-time. I love it when it sounds like *Star Trek* by the way. [laughs] One of the primary ways we can see dark matter in the present universe is we have something called gravitational lensing. We know dark matter follows space-time and general relativity. Yes, it does interact with it.

Kira: Thank you so much. Have a good evening, everyone.

[applause]

[01:07:55] [END OF AUDIO]