AGNES TALKS
What is…Dark Matter? with Mark Richardson and Renée Hložek

Charlotte Gagnier (she/her) - Agnes:
Thanks for joining us this afternoon, everyone, my name is Charlotte Gagnier and I'm the Program Assistant at Agnes Etherington Art Centre. I'd like to begin by acknowledging that Queen's University and Agnes Etherington Art Centre are situated on traditional Anishinaabe and Haudenosaunee territory. This is also where I'm joining you from today.

So to acknowledge this territory is to recognize its longer history, one predating the establishment of the earliest European colonies. It's also to acknowledge this territory's significance for Indigenous peoples who lived and continue to live upon it, people whose practices and spiritualities are tied to land and continue to develop in relationship to the territory and it's other inhabitants today. The Kingston Indigenous community continues to reflect the area's Anishinaabe and Haudenosaunee roots. There's also significant Métis community as well as First Peoples from other Nations across Turtle Island present here today. As I share this I'm thinking about how I can move from saying to acting and I know that I have a lot to learn and unlearn. I'm moved to think about my own functionality and the privileges that have led me to being able to live here and work and what reconciliation looks like for me as a settler. I also welcome you to spend some time researching and reflecting on the land that you're coming from and to consider how you can contribute to the work of decolonizing your institutions, your communities and your minds.

And it's lovely to see everyone sharing in the comments. I can see lots of people from Kingston joining us, from Ottawa, someone from Texas. So without further ado we'd like to welcome you to the first iteration of our new series of What is… The impetus for this series is to take big topics relating to current Agnes exhibitions, in this case *Drift*, and discuss them in a casual and accessible way. So discuss these concepts. So today Renée and Mark will be discussing dark matter and how and how it connects eventually to *Drift: Art and Dark Matter*, the current exhibition.

So Renée Hložek is the Assistant Professor at the Dunlap Institute of Astronomy and Astrophysics and the Department of Astronomy and Astrophysics at the University of Toronto. She uses data from telescopes around the world to understand how the universe started, what it's made of, and how it changes with time. She was born in Pretoria, South Africa where she completed her undergraduate degree. She completed her DPhil at Oxford in 2011 as a South African Rhodes Scholar. After four years as the Lyman Spitzer Fellow at Princeton University she moved to Toronto in 2016. She's collaborated with artists Pamela Neil and Anishinabek innovator Melanie Goodchild on an oral performance piece our manifest galaxy about space exploration and colonization and the artist Caecilia Tripp on Interstellar Sleep at the Sharjah Biennial and Going Space and Other Worlding at the AGYU, Toronto Biennale. She was recently named a 2019 CIFAR Azrieli Global Scholar, a 2020 Sloan Fellow and she is a TED Senior fellow.

Our other speaker, Mark Richardson, is the Education and Outreach Officer at the Arthur B. McDonald Canadian Astroparticle Physics Research Institute and an Adjunct Professor at Queen's University. Mark was born and raised in Halifax, Nova Scotia where he fell in love with the night skies. After completing a Bachelor of Science in astrophysics at Saint Mary's University, he escaped the winter weather and did a PhD in astrophysics at Arizona State University. Mark studies how galaxies form and change over time in an effort to understand how our own place, in an effort to understand our own place in the cosmos. He has since held research positions at Oxford University and the American Museum of Natural History in New York. And he joined Queen's University and the McDonald Institute in 2018. So welcome to Renée and Mark. I'm really excited to watch your presentation, learn a bit more about astrophysics, cosmology and dark matter. So I'd like to hand it over to you now and welcome you.

Renée Hložek (she/her):
Thank you so much Charlotte, it's really great to be here.

And super excited for everyone to engage with the Agnes *Drift and Dark Matter* exhibit, and I know we're going to talk about that a little bit at the end. But in order to get as excited about what dark matter is, we need to sort of set the stage for this cosmic mystery. This cosmic conundrum that I am lucky enough to get to try and answer and address in my job.

So let's get started. I um it's yeah absolutely. So let's take it away. This is actually me in cartoon form giving you a super brief introduction into what we're going to be talking about today. Looking up at the night sky we are amazed by how it seems to go on forever. But what will the sky look like billions of years from now? A particular type of scientist, called a cosmologist, spends her time thinking about that very question. The end of the universe is intimately linked to what the universe contains.

Over 100 years ago Einstein developed the theory of general relativity formed of equations that help us understand the relationship between what the universe is made of and its shape. It turns out that the universe could be curved like a ball or sphere. We call this positively curved or closed. Or it can be shaped like a saddle. We call this negativity curved or open. Or it could be flat and that shape determines how the universe will live and die.

We now know that the universe is very close to flat. However, the components of the universe can still affect its eventual fate. We can predict how the universe will change with time if we measure the amount or energy densities of the various components in the universe today. So what is the universe made of? So this is the key question.

Like stars, gas and planets. Sorry. Thank you so much. So the rest of the video please look it up and take a take a look at it. But the key question that we address as cosmologists and astrophysicists is understanding what the universe is made of, and this is really connected to everything else. It seems like we would just be done because there's a lot of stuff in the universe, and we can measure it. But it's not only important to understand what the universe is made of because we care about the universe, in general, but it actually sets how the sky behaves and how galaxies cluster and form.

And, as a corollary, you can actually look at observations of the night sky and things and clustering galaxies moving in the sky and you can kind of back out what the universe is made of. And that's a lot of what I do as an astrophysicist is I do that sort of reverse. I look at the sky, and I say, can I understand how, what the universe contains based on what I see. And if we go to the next slide. I'll illustrate this in a really simple example. So later tonight, if you have a glass of wine and maybe have some candles because it feels good like spring is coming.

I want you to hold up the bottom of the glass over the candle flame and what you'll notice is, as you get closer to being completely in front of the candle flame with the lens and completely face on you'll go from sort of stretchy, wobbly bits and to a full circle. And that we can understand just in terms of optics that the glass is acting like a lens and it is distorting the path of the light of the candle on the way to your eyes. On the way to your eyes, and so the stuff of the lens distorts the light.

Now that's the kind of thing that we would teach children in high school, which is fantastic, but what is so incredible to me is that the same physical principle works in space, and so we actually can look at a picture of galaxy clusters. This is the galaxy the Abell Cluster 2218.

And we see the same thing. So what are we looking at here? What you'll notice is that in the foreground there are these big clusters of galaxies. These big fuzzy blobs, all together, that makes a galaxy cluster. These are massive elliptical galaxies and there's a lot of stuff in that galaxy cluster. The sort of stretched out bits that you see are background galaxies which is sort of like the analog of the candle flame and the light of those galaxies has been stretched out by all the mass in this galaxy cluster in exactly the same way that that glass is moving the candle, the light from the candle. And so we can do this. We can say, well, if we measure the distortion of the light, can we learn something about the mass that's doing the distortion? Can we learn something about that lens? And we do just that.

What we find is that there is too much distortion relative to the galaxies that we can actually see with our eyes. And so we make these measurements to try and figure out what the universe is made of, and if we actually just add up all the things we can see so neutrinos and stars and gas and planets, all the things that we can see.

We actually only make up a fraction of the total stuff in the universe. We know from observations of the galaxy cluster I just showed you that there are a lot of the universe, has to be dark. In fact, we think that about a quarter of the total stuff in the universe is made of dark matter. And it's dark matter is a bit of a misnomer. We should really say matter that we can't see because it's not like actually black, it's just that it isn't interacting with light and we're going to get into that in a lot more detail.

There's also a lot of dark energy which isn't the topic of our talk today and but it's also super super interesting and something I work on. So if we go to the next slide.

Why, how can we live in a universe, where we don't understand the majority of the stuff in the universe? We know that it is there because we see observations of the night sky and observation, and I mentioned one galaxy cluster, but I should say we have multiple different examples of observations that suggests that dark matter is there. So most of the universe is dark.

But what do I actually mean by dark? Because, as I said, it seems like I've seen you know blackness in the sky and it's really important to be quite clear, scientifically what me what we mean by dark. Okay so, we know that, in general, if you, you can either give off light, so this is a movie of the sun, it's actually an hour long, if you want to go and look it up on YouTube.

We're only going to show you just a few seconds of this, but every second in this video is a day and so you'll see how the sun is being super active. And we think the sun is a reasonably typical star, there's nothing special about it. Thanks Mark.

But you see the sun is giving off light. And you can either give off light like the sun or you can reflect light. This is a lovely artistic photo that I found of a building reflecting light. And so the only reason that you know I'm here today is because the light in this room is bouncing off my skin, and that means you can see me. So my body, the material in my body, is interacting with light.

And I also am making my own light if you looked in infrared goggles you would actually see that I'm glowing maybe a little bit more now because I'm nervous giving a talk. But I give off my own light. So you and I, we give off light and we reflect light and that's how you know we're here.

Dark matter doesn't do either of those things efficiently and so when we say it's dark we mean that it doesn't reflect light and it doesn't make its own light. And so that makes it really, really difficult to find and that's partly why it's so exciting. Next slide. Okay how, what observations, can we look at? I showed you the Abell Cluster from before and there are many other observations.

And what I'm going to show you now is what we do. We measure, we take observations of the sky, but we measure them in different frequencies of light and the frequencies of light give you different insights into the physics that's happening.

So, if we look at an optical galaxy, this is something called the Bullet Cluster, you'll see why it's called the Bullet Cluster in a second. But if I take an observation from the Hubble space, from a ground based optical telescope it's interesting. There's lots of stars and galaxies but there's nothing particularly special about it, you just see clusters of galaxies. If I then move to looking at it instead in a different wavelength, so I think the next one, we have actually is gas observations. Oh, the next one is dark matter. Okay so thanks thanks Mark, we'll stick on the gas. So if I look at it in X-ray gas, if I take X-ray observations, they aren’t actually sensitive to what the electrons are doing in this cluster. We know that there are lots of electrons in a gas and they're very hot.

And what you can actually see is that it looks like one of these galaxy clusters has kind of moved through the other one. You actually see the kind of shock that you would imagine from a bullet. So as Mark is pointing out now very kindly out with his mouse the one galaxy really looks like the gas has moved through the other galaxy and there's a shock. But if we use weak lensing observations, like the candle example I talked about earlier we can look at the the galaxy cluster in weak lensing and we can see where the mass actually is. And the dark matter, it hasn't really moved at all. It's almost as if those two galaxies just passed through each other without any shock waves, without any interactions. And that's what we mean by dark matter not interacting. It can pass through it's you know, two pieces of dark matter can pass through themselves without having strong interactions.

And that makes it really difficult but very exciting. So when we're trying to understand the full picture of this cluster we actually really need to look at it, in optical X-ray and make measurements of where we think the dark matter is based on the observations that that we see.

So it's incredibly exciting to be able to make measurements and to look and think about you know what the universe is made of because it gives us this pie chart, this cosmic energy budget. But what I haven't actually done is told you anything about what dark matter is. And Mark is going to take us in another journey, where we actually think well how could we actually figure out what it is.

Mark Richardson (he/him):
Yeah. Thanks Renée. So I’ll actually start with this picture. So this is giving us information about kind of what it does right. It’s clearly it has gravity and then it's showing its effect but it doesn't kind of reveal itself. I kind of think about maybe like you go out in the woods, when we used to have snow, it's all gone now at least here, and maybe you see footprints so you know there's something there leaving its impact, but you don't know whether it's an elephant, or maybe a fox.

And so you know it's given us these hints, these clues that it exists. There's this dark matter, there's this stuff that has gravity. It's having this gravitational effect, like everything else. But it's not like something that we've ever studied in a lab. It's not something we can do cool experiments with and confirm its nature. And so, all we have right now are just really cool ideas, and so what are some of those ideas? I’m going to start with, probably the favourite at the McDonald Institute.

And that is dark matter could it just be like everything else, after all. And what do I mean when I say everything else? Well, I mean you, me, the planets that Renée spoke about, the Lego castles that you or maybe your kids but I certainly encourage adults to keep playing with Lego, and the stars around us. Maybe it's made of the same kind of stuff as those.

And, of course, when you think about Lego castles you know that they're made out of these smaller pieces of Lego and you can't break them up any smaller, you can certainly step on them and hurt your foot. But actually you know you can take maybe a saw to them or scissors and cut them up even smaller. And you get down to the smallest bits of the universe, the particles that make up everything you and me and the Lego particles and the sun.

And what's really neat is, if you do this to everything we know of in the universe you end up getting down to about 17 different types of particles that we we know exist and we've studied them in labs and we can explore these different particles. And so there's 17 of them and they actually all fit onto this nice chart of what is the standard model of elementary particles.

And in fact you and me, and everything that we meet on every part of our day is actually just made of these three here: two quarks and the electron that make up all the electronics that we use. And so those make up the vast majority of what we do see and study unless you have really, really energetic labs you can study, some of these other other 14 particles.

Okay, so if we know everything that we study in labs that we can tangibly kind of see and experiment with is one of these 17 particles, a really cool idea is that dark matter something like these, it just interacts very rarely, very weakly, and so we call it a weakly interacting massive particle.

That's that's one of these leading theories that it is sometimes known as a WIMP and and if that's the case then that can be quite exciting, because everything else is a particle as well. So, all we know of is a particle, these 17 particles they fit onto this pie chart. I've thrown out the dark energy from Renée's pie chart and we're just focusing on the stuff that's matter.

And so there's kind of 25 versus by 5% of everything in the universe. Like get rid of dark energy I'm left with matter's about 85% of this dark matter, and then the 15% of the stuff that you and I see, the computer that we're looking through today, the desk in front of me. And so, of course, the question that we're trying to ask is what is dark matter?

That's what I'm saying with this idea of weakly interacting massive particle is maybe itself is a particle and if it is andmsomething we can study in a lab, then we can find where it belongs on this table and it becomes just like everything else. It just seems to be very difficult to find.

And that would kind of unite this idea of dark matter and regular matter being the same kind of stuff, just one is a bit more elusive like the camouflage rabbit in winter.

But if it's a particle, how can we detect it? This is a great theory. If everything else we know of in the universe, is a particle that we get to interact with. So makes sense that maybe dark matter is this particle as well. We want to confirm that theory. We want to do cool science, find it in a lab or maybe some results in the universe and be able to study it.

So how do you go about studying a particle? And particularly dark matter as a particle. There's about three different ways, you can go about doing this and we call them affectionately the make it, break it, or shake it approaches.

And so, the first of these is to make it and maybe you're familiar with CERN, this really energetic particle accelerator in Europe. It actually crosses the France and Switzerland borders and in it, we have these ability to accelerate particles extremely quickly and have them smash into each other.

And you can kind of imagine this if you didn't know anything about quantum mechanics it kind of makes sense if you have maybe two pocket watches you accelerate really, really quickly and smash them together they break apart and that's how you find all the little pieces that make up those watches. Quantum mechanics is even weirder. You can smash particles together and when they break apart, they make other stuff that wasn't even there to begin with.

And one of those things that you can make in this kind of collision is dark matter. And so there's a lot of researchers are trying to do just this. That at places like CERN they accelerate these particles together and when they smash they make all these other kind of particles. And actually it’s these kinds of interactions which helped us reveal those other 14 particles on that table, ones that are difficult to form they're rare, but we have found them. And so the idea is maybe with getting more energy we're able to make dark matter.

Of course it's difficult in this situation because dark matter interacts rarely, if it's a particle and so you won't actually detect it in here. What you do is you detect it's missing. You’re putting in various specific amounts of energy and mass when maybe it makes dark matter that leaves the system, and so, when you kind of account for the energy and mass at the endmwhat do you see? You see that that amount of energy or mass that’s in the dark matter has left the system. You don't measure it and so that's what these experiments are looking for is you know how much you put in. If what you get out is lower, then you know something got away without being detected.

This is a very difficult experiment to run and so before we could ever be certain we found it you'd have to do lots of confirmation across different types of experiments and lots of really cool work is moving on that. So that's one of the three ways we could try to detect the particle, the make it approach. The next one is break it.

And this is where the universe, does the job for us. And so we go back to these really cool astronomical objects, these huge structures, like the the Bullet Cluster that Renée highlighted.

And here we see that from all these weak lensing measurements, that we can determine where dark matter is located in these pictures.

And something you don't really see with your naked eye with how sensitive you are to the colour blue but there's actually more of this dark matter at the centre of this blue halo than at the outer outskirts.

So at the centre of these clusters, particularly ones that aren't running into other clusters, it is found from these kind of observations that dark matter seems to kind of be a bit clumpy and really, really clumpy at the centre of these clusters.

And so universe, the universe through it's like use of gravity seems to be kind of doing the job for us and making kind of a cosmic accelerator at the centre of these clusters where dark matter is dense and it actually is probably moving pretty fast. And so that could be an interesting place where dark matter could actually hit itself.

And when this happens, it will actually maybe convert into stuff that we are used to seeing. Things like light or other really energetic particles.

Of course there's lots of, so there are actual observations of this kind of excess light coming from the centre of galaxies. And it's a big question is is this a sign of dark matter? Is it a sign of just really massive supermassive black holes at the centre that are creating this energy?

Is it star formation? And to answer those questions we have to go to these cool simulations where we put in everything that we think we understand about the laws of physics and they are able to fortunately take the millions of years that we would have to wait as astronomers to see these galaxies interact with each other and recreate them in the computer over maybe a month.

And or the big ones like this one, I think, took about a year or so. And when you do these simulations you're recreating these environments and we can now do comparisons and say like is could dark matter be able to explain what we see? And this is kind of this idea of confirming these these this data, these experiments by recreating what we think we understand about the systems. And so these simulations are very, very effective for basically saying if dark matter behaves in this way, if it is this kind of weakly interacting massive particle, then it should be seen as using X-rays or whatnot and we're able to confirm that between observations and these theories. And so this is the idea of breaking it. It's very hard process to do to try to detect this because there's so much kind of messy physics involved at the centre of these objects, but a lot of really cool scientists are working on just that.

Now the last way that you can try to detect these particles is the shake it. And I’m all about the dances so I will always like to shake it to the particles. And so one of the ways we do this is you build a detector and you wait for dark matter to basically hit your detector and shake your detector.

And so this is a detector that we have at the McDonald Institute called a cloud chamber.

And it's specifically designed to measure some particles, unfortunately not dark matter.
And you can see it in action here, you should be able to see a collection of different particles. This is a muon coming in, which is the heavier cousin of the electron. You see, these little tracks, those are the electron particles, the beta particles and then there was a particle that you just saw there called an alpha particle.

So this and and all of these particles are coming from maybe radioactive gas in the air. Some of them are coming from energetic particles from outer space hitting the earth's atmosphere.
And you can see it's extremely busy. We can make it even busier if I put in some more radioactive gas into the cloud chamber, and you can see these alpha particles are going crazy, you get a lot of them. And so it's with this kind of technology, where particles are kind of shaking your detector that you can study the nature of those particles.

But this is happening very often. This isn't sped up in any way. You're seeing this live and dark matter as we've seen seems to interact very rarely. We've never detected it before. So if we want to detect that we need to, we need to be a little bit more sensitive. And so, when I'm kind of picturing here is, we need to build some other kind of detector, not a cloud chamber, that's going to be very sensitive to maybe this special type of particle. And so what you can imagine, is we have the idea, the theory that dark matter sits on this collection of other 17 particles. Maybe we can build a special detector not a cloud chamber but I'm using a picture of a cloud chamber and wait for that particle to come along and shake our detector.

And so that's what's happening at a place called SNOLAB. And so, if you remember the cloud chamber it was going on and on, always seeing these particles and that's because they're coming in from outer space. And so this is an animation they made by Zac Kenny, the Communications Officer at the McDonald Institute showing you where some of those particles are coming from.

But, fortunately, if you go deep underground you start having so much earth above you that it prevents many of those particles from hitting your detector. And the only ones that are likely to get through are the ones that interact very rarely, like perhaps a dark matter particle that could interact with your detector. And so the next part of our journey today about the effort of what dark matter is and confirming that and trying to detect it is to go to SNOLAB. So this is the cleanest, deepest lab in the world. It's in an active mine in Sudbury. To go there you have to get on and I'm just going to…

Hopefully you can still hear me. It looks like I can't mute it. Maybe I'll pause it then. Cause I know that that can sometimes cut off your ability to hear me. So you go two kilometres underground and then you still have to walk almost two more kilometres through the mine to get to this facility where they are building all. Well, this is, this is what SNOLAB looks like. It's a bit, can you hear me with sound? Well then I'll let it play so you're not waiting forever.

And so, when you get to SNOLAB and it’s a facility with lots of different rooms. It kind of looks like a strip mall with all these different types of experiments that I want to talk to you about. And I want to show you what that experience is like to go into SNOLAB because it's really kind of like going to another world.

You get you’re all dressed up similar to going with the miners and you have to go underground with the miners and walk through that facility to get to the space. I think I’ll just let this play. And I’ll stop there.

So it's a really, really cool facility, where, and I say it's the cleanest deepest lab the room, in the world, it's a little bit like going into an operating room. After you've walked two kilometres through a mine getting covered in mine dust and everything you have to shower when you get there.

It's a really cool facility. And when you're there that's where you're in a really cool position to try to look for dark matter. But you're probably wondering… dark matter detection, it's really about finding something when you don't quite know what you're looking for.

And so maybe what you saw here if you've looked closely is, these are a lot of names of different types of experiments. I just want to give you a taste of some of them that are happening at SNOLAB to appreciate that again and again we don't quite know what dark matter is there's a whole bunch of ideas of maybe it has this mass or maybe it has these characteristics and each one of those things will change how it's going to be detected by a detector.

And so there's like PICO, which is actually the world's best at finding dark matter if it has a particular particle characteristic called spin. And so you can see this being built here. So this is the chamber for the detector and actually still even though you're deep underground in the clean lab, they still put it in a giant water tank and fill that with water just to give you that much more shielding from all the stuff you don't care about which is everything that we already have studied on the earth.

And in this in this detector you make liquid so hot it wants to be gas. But it's so pure that it will not change and boil on its own. But if dark matter comes in and hits something in that detector it puts that enough energy in to trigger it to start boiling. And so inside this detector is a sequence of cameras and microphones to capture that moment and be able to determine, is it really dark matter, or is it something else that we're not trying to study.

And this actually has some of the best constraints, for what dark matter at least isn't at this point. Likewise there's another experiment NEWS-G. This is a world leader for finding dark matter if it's a little bit lighter than most of these weakly interacting massive particles theories say it should be.

And it was recently installed as the SNOLAB, just started in December. There's a cool video that's on their website of them doing this install. And it's a completely different way of doing this kind of detection.

It's just to kind of really showcase that like these different particle detectors, the different dark matter detectors really can be built in different ways that make themselves sensitive to different types of particles. And so again, this is if dark matter's particularly lighter.

And the last one, is what was at the tail end of that video that I showed, which is the DEAP experiment. This actually is quite sensitive over a range of possible masses. And here there's liquid argon inside, and these are actually all the collection of very sensitive almost like cameras that are sensitive to any light that is generated, which would be generated if dark matter comes into the detector and interacts with some of that argon.

And so, these are very, very different types of detectors that I'm showing you. And the reason I want to say that is like all of them kind of look for this idea of looking for that shake it. So when dark matter comes in it shakes the detectors in slightly different ways. And we haven't found anything yet, but we've done a fantastic technology development demonstrating that these technologies do work and that we understand them. And they're kind of the precursor to bigger and better versions of these experiments.

And along the way, all of these detectors have other implications for us in society. Some of these detectors can improve our medical procedures that we use for detecting cancer. Others have really cool implications for industry and maybe speeding up how our cameras work or our other communication channels do too. And so you know, in trying to solve these big problems and trying to build a detector for something that we really don't entirely understand we we end up kind of making really cool progress in other ways.

All of this depends on the idea that dark matter is a weakly interacting massive particle. But what if dark matter isn't described by that? What else could dark matter be? And for this I want to pump it back to Renée to pick up this part of the story.

Renée Hložek (she/her):
You know I hope, and thanks Mark, I hope you all at least started to get a taste of the kind of continuous creativity that we need to have as scientists, because this is really, really hard. So we've seen ways to detect weakly interact interacting massive particles or WIMPs for short, but what if dark matter isn't like that at all? So, as a an observer of the universe what we know as Mark said earlier, we know the properties, so we see those footprints.

But we need to guess what the animal is and we know it doesn't interact with light, dark matter and it doesn't interact or it does interact gravitationally because we can see these observations.

One suggestion is that there are MAssive Compact Halo Objects, which is a bit of a mouthful. The acronym is MACHO and it was sort of came up with, so that it could be WIMPs versus

MACHO. And but the question is, what if there are small objects that don't give off enough light for us to see?

So what if there are tons more planets in the universe, they don't give off a lot of light if they're very, very small and so maybe we couldn't see them. And what if there was small black holes? What if there are neutron stars? Unfortunately, if you actually do the calculation, given how much matter we do see and we know something about the early universe, and how particles were created in that early universe, you would need so many more planets and neutron stars and black holes, to make the observations that we see that it's not really a good fit. So at the moment we're searching for WIMPs and haven't found any strong evidence yet and we don't think it could be tons of planets that we forgot to count, and so what else could it be?

Well, what if there are primordial black holes? So these black holes could have been formed, really, really early on in the universe and they would again be very small. If they were big black holes, we could find them because big black holes would typically be in a galaxy and there'd be lots of interaction.

But what if there were these tiny orphan black holes everywhere that we couldn’t see from the early universe.

Some people come up with ways to generate these primordial black holes, but again it's pretty hard to do so, to get the right volume and density of objects that we need okay. So that's tricky. And what if it's an not at the same kind of particle that Mark was talking about earlier in terms of the WIMPs, but what if it is a scalar field? Now scalar field, the the term scalar field sounds very scary because it's not a particle that we think of.

But actually all of us know scalar fields and I love to use this analogy, because it kind of demystifies some physics. So you may have heard about the Higgs field and that's a little bit of what what Mark was introducing earlier.

And, but we actually know of scalar fields, if we think of the distribution of temperature as a function of position on earth, which we all care about a lot, especially going into summer. So the word scalar just means that you can tell everything with one number in this case it's the temperature. There's no direction, you just have the temperature. And the field part is that it's distributed in space, all over the earth.

And now in cosmology and physics, we can take that idea of a scalar field but make it cosmological. So instead of being temperature we have a different property that we put into a field. And so one of the things that I study is the axion, it's a really cool name.

And, but the axion is an ultra-light scalar field. So we think that the axion is it's it's a proposed particle. It’s one more idea in our search for what dark matter could be.

But the axion has to be a scalar field and we need it to be ultra-light. What do I mean by ultra-light? Well astronomers sometimes change the units of measurement because we don't like a lot of decimal points.

So instead of measuring things in kilograms when we go to very small things in the universe we actually start measuring them in electron volts. So if you hear someone say a certain electron volt they it's just a unit of mass in this case, or a unit of mass energy. And so, one electron volt is roughly 10 to the minus 36 kilograms. So a fraction of a fraction of a fraction, super super small fraction of a kilogram.

To put that in perspective, a proton weighs almost a billion electron volts so it's very heavy in electron volts units. The axions that I study, they have to be 10 to the minus 22 electron volts so they are minuscule super, super tiny. They have very little mass.

But on the largest scales in the cosmos these axions can change the way galaxy cluster, they can change the way that lensing occurs as we looked earlier and they are actually at for some masses they seem to be indistinguishable from dark matter, which means they could be a dark matter candidate.

And they have all the same properties that we know we need in the cosmos to explain this kind of dark matter. But we haven't detected an axion, we've just said an axion could do the job of what we need dark matter to do and that's the fundamental difference in the in the sort of shake it analogy. Mark and the folks who are building the detectors are actually a building a thing, where they're expecting a result from a particle. In cosmology I'm more looking at how I can describe the universe and make sense of it with new ideas.

Maybe you don't like dark matter particles, maybe you don't like the axion. So what else? What could be going on? Well, there are some people that don't like any of this idea of dark matter. They say we don't need a new thing in the universe, why can't we just explain everything with what we know already?

But in order to do that, you have to say, well, what if the laws of physics themselves are a little bit weird that we don't fully understand them. In particular, we when we're describing how galaxies move or their relationship between light and mass and a galaxy, we're often using relatively simple physical laws and and some of them on you know Newtonian, they come from Newton and just describing the way mass reacts and and moves.

And there was some theorists say, well, what if that model, what if Newtonian dynamics or the motion of things, described by Newton's laws, what if we need a different description? And so there is a theory called Modified Newtonian Dynamics or MOND which says basically we missed we incorrectly did the calculation that that links the lights, the light of stars and galaxies into the mass and if we fix that up, we can make galaxies rotate correctly, we can make that lensing work and that's fine. However, and as you add more and more observations theories like Modified Newtonian Dynamics don't really work. And, in fact, there are some super exciting observations that come from Canadian scientists. So, what, in particular, we are finding galaxies that appear to have almost no optical lights, so almost no light but they're very massive. So they're entirely dark matter dominated. Or we're finding galaxies where it looks like the relationship between the the light that we see and the mass effect to the gravitational effect seems to match perfectly. So we're finding galaxies that have almost no dark matter in them and that have a lot. And these are detected by my colleague, Bob Abraham at the University of Toronto, and some folks in the US, they built this telescope called Dragonfly. And I love the idea of Dragonfly because basically they realized instead of a building a huge telescope, which is very expensive, they would take modern technology, so these are very telephoto lenses, the kind of lenses that you use for sport photography, and they put them all together and with really good filters on them so that they can measure different wavelengths of light and so they operate the small telescope together.

They're obviously extending the telescope and they want to add more but they're sort of doing the reverse. Instead of generating new technology in the labs they're using existing technology to do science. And what they're finding is that there are lots of teeny fuzzy galaxies that seem to either have a lot of dark matter or no dark matter. And so we're getting more observations that allow us to understand it's not as simple as just a couple of objects are lensing light incorrectly. And so as we think about these observations and think about the theories, we have to sort of expand our creativity.

And so I like to say that scientist is a very creative profession, but it's creative in a particular way. So in order for me as I’m coming up with a new theory or trying to make some observations work, I have to ask myself, you know what properties must my model have to explain the data? How does it change say the distribution of matter? So how, what are the observations that I could think of doing?

How will it change galaxies clumping on the sky? How will it change the early universe? What signal would I expect from a collider experiment like Mark is talking about? From a detector experiment? If I come up with a new theory for dark matter and I apply it the make it, break it, shake it tests, what am I going to see?

And then also what predictions, new predictions can I make instead of just explaining the observations that we see, I require my model to tell me something new, because what I really want to do is be able to build a new experiment that can maybe rule out my model, tell me I’m wrong. We’ll figure something out.

And, and so this creativity, where it's always iterative. It's coming up with an idea and then kind of thinking about why it could be wrong or thinking about a new test to design is part of the scientific journey that we have to go on all the time, and it can be super exciting and and also kind of exhausting because you have to continue to be creative. So if we go to the next slide, the key piece is matching our generative creativity, coming up with new models, with an observational sanity check out on on the models and their validity. And this process is something that I really love to do. So, an example is the image that you have here is a map made from a telescope that measures light that comes from just after the big bang, the cosmic microwave background radiation.

And we put a telescope in space about a decade ago that just measured the temperature of this light as a function of position on the sky. So what are there, are there big cold spots or big hotspots? And you can see there's a little distribution on the sky and we can go from a two dimensional representation which is like a map or a picture and we can also look at a one dimensional representation or a graph.

And so, in this graph all we're saying is as a function of the size of the blob which is shown on the X-axis, the angular scale or blob size, how many fluctuations, how many positive or or hot hot spots are there, relative to the average or cold spots. And we see this very characteristic distribution. Now one of the reasons why I put this graph in I realized it’s a Saturday afternoon, no one wants to look at graphs.

But I want to illustrate a very specific point. So the red data points are observations that we made. In fact the map that I just showed you, we turned that into this one dimensional representation. It’s the same data just squashed into 1D.

But the green curve is a theoretical prediction that we have for our model including dark matter. So we don't know what dark matter is, but if we include the properties of dark matter that we observe the model fits the data incredibly. So we're in this very constrained space where we are being creative but we don't have a lot of wiggle room, because the observations in the sky really have to be met and we have really, really pristine data. So when people talk about a dark matter theory I don't want you to take away that we don't know what we don't necessarily know what we're doing we're throwing anything against the wall.

We are coming up with new ideas, but they always have to be constrained by data and it's a really fun way to be doing science and it really encourages us to be continually being creative. And so I’m going to hand over to Mark for the for the rest of the talk, talking a little bit more about this creativity.

Mark Richardson (he/him):
Thanks Renée. And I think you know being creative, I think we are all you know we all have our own ways of being creative but the benefit of really looking for new creativity is to make sure that we value the importance of different perspectives. And in recognizing maybe some of the some of the limits of any individual’s experience. And so I’m going to in the next two slides are kind of like aside stories to try to motivate this which then feeds into some of what motivated the Drift artists exhibit or artist residency that we have here at the Agnes and the McDonald Institute.

And so, this first story I like to tell is the idea behind these sequence of numbers. So I don't know if anybody at home recognizes these numbers. They date backup almost 1000 years.

They are the Fibonacci sequence, and so Fibonacci himself, he was born in the late 1100s so it's quite a while ago. He's a famous mathematician that helped really kind of restart mathematics in Europe, in a sense of a reappreciation of numbers.

And he was somebody that looked at these numbers, he was not the first to kind of think about this sequence, but what he recognized is they're kind of cute, kind of an interesting thing. And I think lots of mathematicians love just looking at numbers that have cool and strange properties.

And so the sequence of numbers is 1 1 2 3 5 and so on. And what you do is, if you take any two numbers in a row, they add together to give you the next one, and you just repeat this process. And when you do this they actually make something called the Golden Ratio and I'm sure many of you are familiar with this, and this is me kind of stacking cubes of sides equal to the numbers in the Fibonacci sequence. And they end up stacking in this really nice way such that each time you add another piece of the cube to grow the size of the rectangle, the rectangle's growing by about 60% and actually as you get bigger and bigger this number tends exactly to something called the Golden Ratio. Which ends up, you can kind of connect these corners of this cube in such a way to make this spiral, and this is known as the golden spiral. And it's not thought that Fibonacci alone actually recognized this idea of the golden ratio present in his numbers. He just, you know as a mathematician he was very interested in the numbers alone.

They have some interesting applications to solving kind of neat problems that you wouldn't think about. But it wasn't until maybe some artists looked at this and started to see some of the aesthetics, that they were seeing in nature. And when you connect on this golden spiral actually biologists were recognizing that, for example, seeds as they're oriented in a sunflower also seem to exhibit this pattern of the spiral. That conch shells they seem to grow following the golden spiral ratio. Even Leonardo da Vinci recognized the the presence of the golden ratio in the anatomy of the human body and the different proportions of our limbs and our bodies.

And overall what I'm trying to emphasize here is when you want to see like maybe solve certain problems or when you see something of interest to really maybe understand all the different aspects of it, it really benefits to get people that are used to maybe being quite creative, but in their own ways.

And so, whether that's bringing biologists and artists, mathematicians maybe psychologists because humans apparently really find the golden ratio present having a lot of aesthetic beauty.

So why is it like convenient maybe for humans to look at this ratio kind of in their art. There's lots of different ways that this sequence of numbers apparently 1 1 2 3 5 8 and so on has cool implications. And so now this is one just example where I'm trying to motivate why we want to have different kind of sets of eyes looking at particular problems. There's another one, which actually comes out of kind of Oxford University. I've heard it and I know that Renée is familiar with it too from her time at Oxford, which is the idea of Hanny's Voorwerp, which is a Dutch word for "object".

So it turns out there was, I think he was a postdoc at Oxford, somebody doing research and the research question he wanted to answer was: galaxies come in a variety of shapes and sizes and when we do simulations we're recreating some of these galaxies or at least we're trying to.

Remember in the video I showed earlier we do simulations of galaxies that we can then use those to tell us where we should expect dark matter, depending on how it interacts, depending on that break it model. Well, those simulations we put in what we think are the laws of physics, so they should recreate nature.

And it's totally okay when they don't. That tells us that we're wrong and scientists actually loved being told they're wrong. That allows them to do more work.

When they are shown to be right it's like okay yeah I'm right, and they have to move on to something else. When they're told they're wrong, then that means they have work to do. And so simulations if they're trying to recreate these universes, they're trying to recreate galaxies in the universe, then they should make galaxies that look like real galaxies. And so um why am I blanking on his name? Renée do you remember his name at Oxford who started Galaxy Zoo?

Renée Hložek (she/her):
Kevin Schawinski.

Mark Richardson (he/him):
Thank you yeah. Kevin Schawinski. So he realized that I want to know how often do galaxies kind of look like this, where they have nice discs versus those those football shaped galaxies that we saw in the clusters like Abell Cluster that Renée showed. You know how often you get one versus the other?

And so, in wanting to answer this problem Kevin looked at all the pictures that he had a galaxies and realized, there were over a million of them. And I think he loves looking at galaxies but he thought this is going to take a long time. And as far as the question of is this galaxy a disc or is this galaxy more like this elliptical football, really, I think anybody can be kind of told the things they need to know before they could tell me the answer to that question. And so Kevin and Chris Lintott at Oxford they started citizen science project called Galaxy Zoo. Which is getting everybody else involved in this project, where people that are not astronomers, not scientists had the opportunity to look at that data and report back on whether a galaxy is a disc or a football. And I think within a week, they went through the million data. It was this really, really cool story of just how quickly they had eyes on all these images.

And one of those images was this. And so in this image, you can see a very clear galaxy and then you have this weird green blob next to it.

And the story that I hear about this image and it could be not quite accurate, but my understanding is astronomers did look at this image. They saw that the galaxy was there and could clearly be seen, and it would be one that the public could look at it and tell them whether they think of the disc or not. And the idea was this green blob might not even be real. There might have been something wrong in the detector or maybe it's real and this is not of interest, and so they didn't spend a lot of time looking at this, they kind of quickly dismissed it as not particularly interesting.

And so it was part of this collection of a million images. But then we have these different perspectives, where we now have many people looking at this image, one of which was Hanny van Arkel. And so, when Hanny looked at this, the nice thing about this Galaxy Zoo platform is there's the ability to leave a comment. Basically say this is an interesting image, I think more people should look at it.

And Hanny did just that and this started a whole bunch of other people looking at it and also writing their own comments. And so this image was suddenly getting a lot of interest in this collection.

And the the system is able to tell the astronomers the non astronomers are really interested in this image, you should look at it some more. And that made them stop and pause and and bye Ruhi! Nice to see you again.

And so stop and pause and maybe just take a second look at this image, something that they looked at very quickly before with their kind of eyes used to looking at galaxies and very much thinking they knew the question they wanted to answer. And pause and bring in another kind of ability and creativity to this question.

And when they stopped and looked they found something that is mind bogglingly fascinating. This is one of the coolest images that I know of in astronomy and what has happened is there's a gas cloud here. Or we're pretty sure this is what happened, I should say that we’re never entirely certain.

And this galaxy we think about 100 to 200,000 years ago was really, really, really bright, a lot brighter than it is right now and emitting very energetic light from the centre which is supermassive black hole. When this light shined, some of it hit the earth, some of it hit this gas cloud and caused it to light up itself to fluorescent form a bunch of stars. And then, as those stars formed they then bust and kind of emitted their own light.

But because of how this is oriented it actually took a few hundred thousand years or so, for that light to then be reprocessed and then emit from this cloud, and in that time this galaxy kind of shut off to look more like a normal galaxy.

So what you see here is actually the afterglow of what this galaxy was doing up several hundred thousand years ago. And the moral of the story is just kind of going back to this idea of creativity. That sometimes it's really beneficial to have a fresh pair of eyes to look at things.

To really make us check all of our biases and the things that we kind of have preconceived ideas about the particular field that we're looking at. And scientists are very aware that any human has some bias and we make efforts to account for that, to take our kind of the human bias out of the equation.

But it's never perfect and sometimes just having a fresh pair of eyes, can do just that. And so, with this in mind, this led to something called the Drift artist residency, the Drift: Art and Dark Matter Residency where scientists and administrators at the McDonald Institute, along with the Agnes art exhibit or Art Centre wanted those fresh kind of artistic eyes to look at what is a really exciting science that's happening here in Canada at SNOLAB. And so what we did as a partnership is we brought in a number of artists to come in to meet with the Agnes, to come to the McDonald Institute and see things like the cloud chamber and understand and learn about dark matter and how and what we think it is. All these different creative ideas, we have to explain what it could be, and the way that we are trying to kind of answer these big questions. And those artists went down to SNOLAB too and got to meet with scientists there as they're building things like the PICO detector.

And then those artists, had the opportunity to speak with the scientists about their own their own approaches and process as well. And at the end of the day, those artists created art pieces that are trying to bring in those kind of fresh eyes to look at this science, dark matter and how we try to do this kind of detection. So this is an image from of Jol Thoms' artwork at the exhibit. I really encourage you go to the Agnes now and get to see things like this and Josèfa's work here. This is this illuminated liquid, very similar to kind of the liquid that's used in some particle detectors in that it's sensitive to some energy or some particles and then reemits light. And I did want to just maybe end with one more anecdote.

Which is that it's I think this is really motivating the idea of having the artists come in, having those fresh eyes on the science and then get to reshow this this their interpretations of this work, and what that that experience meant to them and hopefully reengage the public with maybe getting fresh eyes on this science and maybe that's also what kind of help motivate you to tune in today.

But in the process artists are also speaking to scientists about you know questions that had never been asked and one of those happened actually to me in one of these engagements with the artists. And so last June, it was pride month and we were on a call with Dr Cindy Lin at SNOLAB and Jol Thoms and I had a pride flag on behind me, and we were talking about not just dark matter, but also the neutrino physics that happens at SNOLAB and Art McDonald, the McDonald Institute is named after him, he won the Nobel Prize in understanding that neutrinos change their their flavours, they change their type.

And suddenly I just suddenly realized that most particles that we think of in the universe, if you think about that plot of 17 things, most particles that we think are a little bit fixed. They come in a certain way, and they don't change. And I think we're very kind of used to thinking about things that way. But when Jol asked me about pride it did make me think about the idea of how our social construct of gender or something itself that has been changing recently.

And now we think of things, maybe as being a bit more socially constructed, gender fluid and that with that kind of hat on, it totally changed how I thought it was something like neutrinos. The way that they're able to change the way that they they interact with the universe, they stop being electron neutrinos, they become muon neutrinos. And so neutrinos, although they’re fixed in some ways they really they are something that can maybe change or almost like a gender fluid particle and they can change their type. And so the moral of this it's just that the connection that we seem to have it might be just a cute allegory, but I think it's important to realize that sometimes how we view social norms, how we assign labels or whatnot to things, they experience periods of kind of expanding in our horizons. That we have new definitions and that could apply to things in science, like looking for dark matter.

So humans are weird. We like to label things and associate new ideas with old ones, and I think that's what comes in, when you bring in new perspectives. And so with Drift having these new perspectives on dark matter and the quest to kind of search for dark matter, it's stopping us. It's allowing us, the astroparticle physicists doing this, to stop and maybe make sure that you know we're maybe there's other cool ideas we should bringing into this.

And so that's the end of that story, and I think at the end of all of this, you know what is dark matter, I hope that you do understand that we don't know and that's okay. This means that it's fertile grounds for new ideas and discovery and having really cool new conversations with other people and have conversations between us and you tonight or today. I’m used to doing these events at night. Um so yeah. So I hope you hope you understand a little bit more about what is dark matter or what dark matter could be, and you have the opportunity to check out the Drift exhibit as well, and I think now we have lots of time for questions and so Renée and I are really, really happy to hear what you guys, what you guys think.