DJORGOVSKI: The universe is very kind to send us signals-- not intelligent ones, but signals that let us interpret it and find out. So information flows in the universe to us. And things like the stars or galaxies have some physical parameters. What we measure are not directly those parameters. We measure something else and have to infer them.

So for example, you cannot observe mass of a star or a galaxy. That's a pretty fundamental quantity. You can infer it by measuring a few other things and applying physics. And it seems to work fairly well.

Now if you observe sources that are too far to be resolved-- most stars will be like that-- then all they can do is total flux. And of all the inner structure, you cannot see. If you do have result image, like most pictures of galaxies or different nebulae, then yes, absolutely. There is some morphology of the light that tells you a little bit about what's going on.

But by and large, most physics come from taking spectra. Spectra tell you what the thing is composed of, what its physical state, and how fast it's moving. And that's a lot. So usually when astronomers want to understand some phenomenon, taking pictures on any number of wavelengths is great. But until you get spectra, you don't really know what's going on.

A famous example of that were gamma ray bursts. There were discovered in 1967 by satellites that monitored for nuclear explosions. It very quickly became clear that they're not coming from planet Earth, but from somewhere in space. They last on the order of a second or a fractional second. So gamma ray sky is as if every once in a while is a flash bulb just pops.

Now, gamma rays are a little difficult to focus. Anybody know why? That's right. They're very small wavelength. And why is this important?

No, it's not due to the fraction limit of the telescope. Now think about mirrors work. Yes? Go ahead, please.

STUDENT: [INAUDIBLE]

DJORGOVSKI: Well, glass is certainly pretty transparent to gamma rays. Most things would be for a finite energy of gamma rays. Yes?

STUDENT: Do they pass through the mirror?

DJORGOVSKI: Yeah, they do pass through the mirror. Why?

STUDENT: Because the wavelength is so small.

DJORGOVSKI: That's right. That's exactly right. The wavelength is was much shorter than the spacing of atoms in the crystal lattice of material of the mirror. And so gamma rays pass through aluminum or gold, or whatever you like, just like radio waves are now passing through this room. If the wavelength is larger than the obstacle, the material is transparent.

OK, so it's really hard to focus gamma rays. This is why it's was hard to figure out where the gamma ray bursts come from. The way this was solved was that they're observing x-rays. Now x-rays, we know how to focus. We can make an x-ray telescopes. And that narrowed down the positional accuracy from degrees to arc minutes, and then even less. That allowed us to take pictures invisible and see stars that were not there before, so-called after glows of gamma ray bursts.

But only after taking a spectrum of one of those we found out that they're actually of cosmological distances, something that happens many billions of light years away. Up until then, there were literally hundreds of theories to explain them. And most of them are obviously wrong. So spectroscopy is what tells you a lot about the universe. Unfortunately, spectroscopy requires you to disperse the light. That means, at any given wavelength, you have much less than the total amount that you're observing.

Another interesting thing about observing electromagnetic radiation from celestial objects is you can think of it as usually two components. There is a continuum radiation: can be black-body, it can be synchroton radiation, and so on. And on top of that there is a spectrum of lines superposed that could be absorption or emission depending on physical state of the material. That is where the information is, not in the continuum. So it's just a tiny fraction of the energy that actually has information that you care about.

So even the bulk of the energy it could be said, overall, black-body radiation, it's only this tiny little fraction that's been missing of that's added at the top that tells you what's happening. And different phenomena will obviously imprint that information in different parts of the electromagnetic spectrum. So this is an example of a solar spectrum. These pairs were different orders of being stacked on top of each other.

And these black streaks are absorption lines due to the ions in solar photosphere. Those are called Fraunhofer lines, named after Joseph Fraunhofer, who first detected them. You could think of it, he was the father of astrophysics physics because he took first spectra. Back then, of course, people had no idea how to interpret them. But this is how it all began.

And another example of how it's just some tiny signature atop of the bulk of the signal that's important is microwave backbground. The microwave background has some dipole, because Earth moves relative to the local expanding frame. And on top of that, there are these part in a million fluctuations that encode cosmological information. And they're actually some of the best evidence we have for the existence of dark energy.

So it's interesting to think. Their information comes to us all the time in the form of photons from all different wavelengths, but not all of them are equally interesting. So almost everything that we know about universe comes from electromagnetic radiation. And there are good reasons for this, because phenomena in the regime of temperatures and densities and so on that correspond to most of the stuff in the universe mostly emit or absorb invisible light.

And we can do a number of different things with that light. We can measure the total amount through some filter. We can take spectra and so on. But one or the other, it's electromagnetic radiation. Now more recently, we started opening new windows on the universe. Cosmic rays can be observed indirectly. Essentially, we have telescopes that are particle detectors. Sometimes they literally are like bubble chambers, or something like that, that detect particles in the same way that an accelerator would do it.

But there is also an interesting phenomenon called Cherenkov radiation, which is the electromagnetic equivalent of a sonic boom. The particle can be moving faster than the speed of light in that medium. Never faster than speed of light in a vacuum, but the speed of propagation of light in a given medium is a little less. And so once you do this, it's like a breaking sound barrier. And there is a light equivalent of a shock wave that accompanies breaking a sound barrier. Turns out to be this blue light. And you can make big telescopes that can actually look for flashes in the sky. And that's been done in studies, and it's one of the more interesting frontiers today.

Then there are neutrinos. For a long time, we've been only able to detect-- even that, barely-- sun that produces neutrinos. It usually includes a big tank of some chemical or super pure water, or something like that. And it is a very difficult particle physics experiment.

And we are now at the dawn of gravitational wave astronomy. LIGO, which is the first gravitational wave observatory, it's been built mostly here and at MIT, is expected to actually start detecting gravitational waves from cosmic phenomena a few years from now. And that will open a whole new way of exploring extreme conditions, like inspiral of stars, or black holes into other black holes, things that simply do not leave, we think, electromagnetic signatures.

But they have to be there. And who knows what surprises we will get? Because every time we open some new window in the universe, we discover things that we did not suspect existed.

And finally, dark matter. That's composed of particles. And there are people who were trying to detect those particles in, again, super-precise experiments which are buried deep in mines, to shield against cosmic rays. Sunil Golwala here is working along those experiments. So it's a particle physics of very high precision. And so someday, we should be able to actually capture dark matter particles and see their dark matter wings, or things like that.

OK, back to good old electromagnetic spectrum. So this is just a simple illustration of what wavelengths correspond to what. But note the frequency scale. So we now observe electromagnetic radiation from about 20 orders of magnitude in wavelength. Some of it has to be in time from space. The temperature of the black-body radiation is directly related to what a peak is through Wein's law. Then this also tells you the range of temperatures that we can be probing.

So why is this interesting? Because universe looks different on different wavelengths. If you had radio eyes, you'll see a completely different sky, or if you had eyes for thermal infrared. And here is the same piece of Milky Way galaxy, and first, near infrared, which is almost like visible light. Visible light shows shadows. Those are dust clouds that are absorbing light behind them. But they're transparent in infrared.

Then you look at ionized gas, the H alpha line. And that shows you all matter of activity in this field that you just simply would not suspect from optical or infrared picture alone. It's indicative of star formations and explosions of supernovae, and so on. And in the lower right, there is far infrared image. This is thermal omission from the dust that's been heated up by starlight. So if you compare that one with the visible light right above it, you'll see they're kind of the opposite. Where there are shadows of the dust clouds in the visible light, this is where you see bright emission from dust clouds-- bright being the relative term.

So observing universe at any given wavelength is going to give you a biased idea of what's out there. And fortunately, now we can pretty much cover full relevant range. And this is why this is sort of a golden age of astronomy, great new discoveries are being made all the time.

OK, but not all of it comes to us. And this is why, among other things, we need to observe things in space. So Earth's atmosphere only lets mostly visible light-- very fortunate that the sun peaks in its emission right there-- and then some parts of infrared. But then they're missing pieces of infrared. Then there is radio, until you go through a very long wavelengths, where ionosphere absorbs them all.

So there are transparency windows. And astronomers have designed filters to correspond to those so we get maximum transparency observations of the sky. We also try to go and build telescopes at places where there is the least amount of atmosphere above you-- some really high mountain, or high plateau, like Atacama in Chile. But that's the planet Earth.

Then there is an atmosphere of the Milky Way of neutral hydrogen that absorbs ultraviolet radiation. And this turns out to be a great cosmic conspiracy. There is only about 10% of all regular barionic matter in the universe that actually we can account for through light or radio or any of the other mechanisms.

So 90% of it is somehow missing. And what appears to be is that that's in form of gas that is heated to right around million Kelvin. And the peak emission is right where it's absorbed by intergalactic hydrogen. So 90% percent of the regular matter content of the universe is hidden from our view. But people can infer its existence through absorption in different regimes. Because by observing spectra of, say, distant quasars and looking at absorption as due to this warm material between us and quasar, you can interpret what its density and so on. This is why we think this is correct.

All right, so to recap that part, we do have many different information channels. And there are always limitations of sorts, but we do have fairly comprehensive and polychromatic view of the universe today. So let me wrap up with somewhat a general discussion.

How do we make discoveries? Well, we can think of conceptual discoveries, like quantum mechanics, relativity. You get a smart person like Einstein or Niels Bohr, and they figure out something important about the universe which turns out to explain some observations, make some predictions, and so on. So often, these theoretical discoveries are inspired by observations or experiments, but they also make predictions.

The other way is phenomenological discoveries. You just look at the world in some way that nobody's looked before. And this is when you discover there are things like dark matter and quasars, and what have you, which were not predicted by theories, or sometimes predicted in such a way that nobody knew how to look for them. And they can be sometimes motivated by a theory, but usually they're not. Usually they have some surprise.

And those are driven entirely by be available technology of measurements-- what wavelength can we see, with what precision, how deep, and so on. So technical capabilities then lead to these observational discoveries. And then there is a healthy interplay of observation and theory feeding off each other.

Now you can do this in two ways. One is that you can do better in some relevant fashion, like you can observe larger pieces of sky, or go deeper, or go to a new wavelength regime, or look sharper. Push along one of those axes of observable parameter space. Another one is you start making connections from previously disjoint observations. A good example of this is the discovery of quasars.

Quasars were actually noticed in the 1920s. And they were mistaken for variable stars, they do vary. And they were given names like variable stars, like BL-30 is a name for a variable star. But it took until 1960s, until radio astronomy came along, and the resolution of radio telescopes got good enough to find it in radio sources. And then through a lot of careful work, a connection was established between some of those funky blue stars and sources of radio waves in universe-- which up until then were unknown.

And we discovered a new phenomenon of nature-- a gigantic black hole accreting amounts of material, and being the most luminous objects in the universe. There are many examples like that through history of astronomy. And so again, you can always, by making connections, by making things touch on the edges, this is where you usually see new stuff.

And some things you have to actually go to a particular part of parameter space to discover. Like to find gamma ray bursts, you have to have gamma observations to begin with. And then you have to do all this other stuff, connecting it from gamma to x-ray to optical and so on.

All right, well, that's all I have for you today. And let's hear some questions. Yes? I'm sorry?

STUDENT: When you said earlier, you said that there was [INAUDIBLE]?

DJORGOVSKI: People are shuffling, so I can't hear you.

STUDENT: [INAUDIBLE]

DJORGOVSKI: Oh, [INAUDIBLE] microwave background? Well, microwave background is pure black-body emission. Actually, it's the best black-body we know, better than any we can make in the lab. So the peak of that black-body is some frequency. And so we immersed in this thermal bath of radiation. So if we move in a particular direction, we'll be encountering more photons. And so it would be Doppler shift-- red on one side, blue on the other side. And that corresponds to slightly hotter or slightly cooler temperature of the microwave background radiation.

Turns out, we're moving at about 600 kilometers per second in a particular direction. And we think we know why. And so you if you can measure things to part in thousand, you can detect it. It's superficially like the ether drift, but it isn't. And when we talk about cosmology, we'll do more. And so that this sort of part in 1,000 effect. Then you have to go another factor of thousand in precision to see those little bumps that correspond to early density fluctuations in universe. Yes?

STUDENT: Could you expand more on Cherenkov radiation?

DJORGOVSKI: Well, yeah. It is more or less what I described to you earlier. The speed of propagation of electromagnetic radiation in any medium is less than the speed of light in vacuum. And a particle that moves faster than that will interact electromagnetically with fields of atoms, or whatever it's going through. And that will generate radiation that's very much equivalent to the sonic boom. So there's a cone of blue radiation that comes until the particle slows down or decays, or hits something. And that flash can be detected with sufficiently large telescope on the ground.

There's an interesting story how that whole field of astrophysics began. This was actually predicted at some level by theories, but nobody knew that such things really happen. And two people in the UK-- I can't remember their names at the moment-- decided to try. And they got a mirror. It was surplus, military surplus, from one of those signalling mirrors that you see in all the movies, ship to ship, and then got a trash can. Put the mirror in the trash can, put the photomultiplier in the focus. And the very first night, they detected the flashes. Now that is experimental physics.