DJORGOVSKI: Let's now talk about perennial favorite, black holes. And first we'll talk about black holes in general and stellar black holes. Then we'll turn to their bigger cousins.

This is one slide, condensed version of general theory of relativity. As you probably know, Einstein first came up with special relativity which postulated that all inertial observers are equal, and then came up with lorentz transformations, and e equals mc squared and whatnot.

General theory says that all frames of references must be equivalent. Gravitational mass, inertial mass must be the same, and when you work all this through, one important consequence, the most important consequence is essentially described here. Presence of mass, or energy for that matter, changes the geometry of space time around it, induces curvature of space.

Now usually we have this two-dimensional rubber sheet analogy, but you can imagine that same thing in 3-D. And this is a unique prediction of general relativity, that this will happen. So general theory of relativity in one Tweet is this, that mass changes the geometry of space, and space changes where the mass moves. And if you can solve that in a consistent fashion, that's what Einstein's equations are, you've got yourself a theory.

So this was obviously the way to test it. And Einstein figured this one out very early on, but World War One was going on, and that's not the best time to do astrophysics. But right after that, Eddington and collaborators went to expeditions that they measured positions of stars behind sun during a total eclipse, compared those with plates of the same part of the sky taken some other time, and compared the positions of stars. And if the general relativity was right, you'll see stars move out a little bit. Because see the geometry is if the light ray's been bent, and you extrapolated backwards, you're extrapolation would miss the actual source.

This is behind gravitational lensing as well. And sure enough, they found the value that maximum displacement was a little shy of two arcseconds, which was not an easy thing to measure with photographic plates back then. And then this has been, of course, vastly improved since then. But this was seen as a very clean cut demonstration that theory was actually correct. This is where Einstein really became famous.

So black holes. Now simple Newtonian gravity, right? If you have a mass particle you wanted to escape gravitational pull of say Planet Earth, you have to toss it with high speed. Such a high speed as its kinetic energy overcomes the potential energy. And so there is a value of critical velocity called escape velocity. And if you shoot the thing faster than that, you'll have enough kinetic energy to escape. Otherwise it's going to fall back.

Now the formula is very simple, and so for a given mass you can make radius smaller, and velocity will go up. Or for a given radius, you have to add more mass for velocity to go up. So now if you have a big, massive star and you don't get rid of most of the mass from the collapsing core or shrink the core sufficiently, there is a point in which this escape speed reaches the speed of light, and from that point onward nothing can escape the collapsing core. So that region of the space is called a black hole.

If you actually follow up this simple algebra, you'll get answer that's wrong by a factor of two, and that's because there were some relativistic corrections, but intuitively it's the exact same thing. So black holes are very simple. There is a point, and there is a sphere, at least if they're not rotating.

So as far as gravitational collapse is concerned, it keeps going and going and going, until the whole thing is condensed into a single point which then has finite mass, and therefore, infinite dense and infinite gravitational pull. That's called singularity. Now in reality, who knows what really happens? I mean there some point quantum gravity effects must come into play, something else. But in any case, mass gets to be squeezed into a really, really small region.

This is not the event horizon. Event horizon is just the surface in space. It's not like a crust of any kind. It's a surface in space at which the escape speed reaches speed of light. So if you're not rotating black hole, the radius of that is given by this [? quantiful ?] Schwarzschild radius which for our sun is 3 kilometers. Therefore, it will be 9 millimeters. So you were to squeeze Earth to a pebble size, it will be a black hole.

Any mass, no matter how small or how big, can become a black hole if you fulfill this relationship. And since, notice that this radius is proportional to the mass. So what do you think will be the behavior of density with mass? Are the more massive black holes denser or less dense?

Well, the density is mass divided by cube of size. So divide both sides of this equation by cube of radius. You get the density on the right side, and you get 1 over radius square on the other side. And since radius is proportional to mass, density is inversely proportional to square of the mass. More massive black holes have lower densities. And actually if you were to look at the black hole that is size of the universe, the density inside would match the one that we observe in cosmology. So we could be living inside a gigantic black hole.

If the black hole spins, things get a little more complicated, but don't need to go into that. And the only other thing you can possibly know about black holes electric charge, but since positive and negative charges seem to be mixed very well, usually that's not important.

And since you only know three numbers, it doesn't matter what black hole is made of. Stars, gas, dark matter, pineapples, cars, TV sets, it doesn't matter as long as it has a mass. That means that information about building material has been destroyed. So black holes are the biggest generators of entropy in the universe by far, because you have vast amount of information describing all the material that was going to fall in, and then you have three numbers in the end or effectively two.

If they have entropy, then they might actually have temperature, and they do. I will come to that in the end. But here's the interesting thing. This is a completely fake artist impression, just trying to indicate that there is somehow a hole in the space time. Interesting things happen. As you fall towards event horizon, the clocks slow down. There is a slow down of clocks as you approach probably in higher gravitational field. And in fact if you look from far away, the time stops at the event horizon. And things that fall into black hole actually never fall into black hole. They just get squished right before event horizon forever.

However, for the astronaut that's jumping into black hole, nothing happens. It just goes through the surface, doesn't notice, and well, might get stretched by infinite tidal forces. But aside from that that inconvenience, it takes a finite amount of time to fall all the way down into singularity.

So different observers, one far away, one actually dipping in, for one of them this is a finite duration of time. For the other one, it's infinite. Well, this is why it took Albert Einstein to figure this one out.

So how do we make them? Well, it's again same thing as making up neutron stars. This time the equivalent of Chandrasekhar mass is three solar masses. It' actually called Oppenheimer Volkoff Limit, and it corresponds to degenerate pressure of neutrons instead of electrons.

So if you have core that's less than three solar masses, you can arrest collapse, have a big neutron star, more than that nothing can help. It just has to go through a complete gravitational collapse, and so that point in the middle is actually called singularity because some physical values reach infinity, which of course never happens in reality, but that's math. And that finite volume around it, within the event horizon which is the surface at which escape speed is equal to speed of light, that's a black hole.

So how do we know such things exist? Well, just like with x-ray binaries you had a dense companion white dwarf. Some stuff falling from companion star, converting its binding energy to kinetic energy, comes to a stop in the middle, radius away the kinetic energy. Put the neutron star, you're going to get even more spectacular version of the same thing. Put them in block hole, same thing will happen. You get even more spectacular conversion of binding energy into first kinetic energy and then radiation.

And generic expectation was that material that stops right shy of black hole will be shining in x-rays, just like neutron star binaries, but there is a way to tell. Because you may remember that for neutron star binaries there are pulses. And if you x-ray binary with the right kind of properties, it doesn't pulse. Then chances are it's powered by a black hole. A very famous one is called Cygnus X-1.

And in some cases, if there is a magnetic field that was leftover that can accelerate particles again just like pulsar, except this time this is a black hole, and tends to be well aligned with rotation axis. Those are called microquasars. So those are pretty spectacular objects. In fact they're most spectacular objects inside our galaxy on stellar scale, but the really spectacular ones are those that are on galactic scales.

So one last thing about black holes, and this is Hawking radiation. So remember I told you that black holes generates considerable amount of entropy, but it also has a temperature. And it works like this. In quantum physics, we believe and they're excellent experimental reasons to believe this, that physical vacuums constantly bubbling, creating particle, anti-particle pairs, but they annihilate within interval given by the Heisenberg's Uncertainty Principle, so that normally you never see any.

Well, what happens if you do this just outside event horizon and is electron positron pair? Well, one of them falls in black hole. Then the other one remains free, looks for some other partner, annihilates with that. But they're doing this outside the black hole, and so that radiation can escape. I mean this is little more complicated, but that's the basic idea.

And so black hole radiates by sucking up 1/2 of these virtual particle pairs. The other are annihilating. That energy has to come out of somewhere. It comes out of the rest mass energy of black hole. So they have temperature. They have luminosity, and they have entropy and a lot of thermodynamical quantities. And they're the most perfect black bodies, and this is no pun, ever.

Now nobody's ever actually observed this. This is purely theoretical construct, but it's pretty convincing one. Now interesting thing about this is that the temperature of a black body black hole is inversely proportional to its mass. The smaller ones are hotter, and therefore, radiate faster. And so the rate of operation accelerates in time, as you go to smaller mass gets hotter, lose more mass and so on. And in the end, there is like a flare, and black hole is gone.

If you ask yourself the question, how long does it take? You can compute that formula and match that to age of the universe. You find out that those are some pretty small black holes. So the ones that we know about, this like stellar black holes or galactic ones, they'll last a long, long, long time, so we won't be able to observe this.