Transcription	
First Successful Test of Einstein's General Relativity Near Supermassive Black Hole Full HD Video Compilation July 2018	
Professor Reinhard Genzel, MPE Garching	
00:07 1. *Indeed, in the centre of our own Milky Way- that's only 27,00 light years away, that's for astronomical standards around the corner, a round-the-corner cafe if you like, there lurks a 4 million solar mass black hole. And now what we want to do is to take that black hole and see whether the theory of Einstein also applies there. And that's a very challenging undertaking*	**Reinhard Genzel — Paranal**
00:43 2. *Well you see the centre of our Milky Way, where we suspect there is a black hole, has stars orbiting this central black hole. And these stars are measurement objects, if you like. They test the gravity of the object, and there's one star in particular which we've been following now — believe it or not —for 25 years. That's, you know, more than half of my scientific career, with telescopes here at ESO in particular. And we've charted the orbit of this star. And we know that around this time this object will — this star — will make it as close as four times the distance of Neptune to the Sun. That's seventeen light hours, so that's very, very close. And that's the unique*	**Reinhard Genzel — Paranal**

opportunity to in fact test out gravitational theory because there gravity is the strongest, the star now moves with about 3% the speed of light — or several hundred times the speed of the Earth around the Sun. And that's when these tiny, little warps in space-time which cause General Relativity to be different from Newtonian theory to be most pronounced.	
02:02 3. *So it took us about a decade between 1990 and 2002 to basically come up with robust evidence for this mass. And then in 2002, nature gave us just an absolutely miraculous star which moved so close to this object that you could see it zip around the mass in a matter of only a few years, and that gave us absolutely fantastic information. You could estimate the orbital parameters, the mass, etc., and we were were fairly sure it's a massive black hole. Now the orbital period of this star is sixteen years, and these measurements we took here, on the then new Very Large Telescope, we took in 2002. Take 16 plus 2002 and that's 2018, so our star is coming back to its original very close position near the black hole. That's the time when we want to be there and make these measurements.*	**Reinhard Genzel — Paranal**
03:03 4. *For our work so far what we have done is we've taken pictures with the single big telescopes, the single 8-metre telescopes, and made them as sharp as they can be. The problem is, and you can see this in my hair, is that there's wind! And the wind distorts the waves. And so either you go out in space — very difficult for an 8-metre*	**Reinhard Genzel — Paranal**

telescope — or you take the 8-metre telescope and you repair the distortions which the Earth's atmosphere does, like on a day, on a hot day, when you travel along a road and see the flimmering of the distant approaching cars. So that's what we do, that's called adaptive optics. And that makes the images with single telescopes already very sharp. But that's not sharp enough for what we want to do now. We really need to make still better, still ten, twenty times sharper images to see the tiny effect of general relativity. And that we do, by taking into account that ESO not only has one telescope but four! Of these gigantic 8-metre telescopes, and we can bring them together as if it's one. That's a very challenging experiment, but we've done this now, and so we are ready to make these measurements in unprecedented precision.	
04:30 5. *So, by testing, by measuring, these predicted physical teeny effects — they are a very, very small fraction of what we knew so far, that's we have to make such precise measurements— that's how we can test general relativity in this domain.*	**Reinhard Genzel — Paranal**

04:45 6. *we think we know that this object we have in the galactic centre is a black hole, but to prove that without any doubt you have to come so close that we actually have to measure the fabric of spacetime and see it's that which the theory of Einstein predicts. So that's the concept.* *Then comes the question of difficulty, and I have to say: Uh. That was a long path. It was very, very difficult. Because, while gravity is sort an obvious thing, you stand here on Earth and sort of have an idea of what it is, in reality it's an extremely weak force, and the effects of general relativity are extremely small. So you have to measure to a precision which we are normally not used to in astronomy.*	**Reinhard Genzel — Garching**
05:34 7. *16 years ago... Because 16 years ago was the time when that star which we have been watching for you know about nine years, all of a sudden took a turn. And it was on the other side of what we now know is the black hole. At the time we didn't know that, we saw the star move, but the turn-taking was at the measurement accuracy at that time, a rather sudden, and happened within a few months. And all of a sudden, you know, wow! You put it there and it's on the other side and then, you know, you basically take your little, you know, pen, and you draw an ellipse by hand and you know, you've learned already you know, it's come that close, it moved that fast, and therefore the mass must be this. So that was a similar, a similar experience, but I use the Galactic centre for some reason always delivers.*	**Reinhard Genzel — Garching**

DR Frank Eisenhauer, MPE Garching	
06:31 *8. So what we want to observe is the motion of a star around a black hole, and if you would project this motion of the star, say on the moon, then it can give you an example on how accurate we have to measure. So the example would be that the star moves around like a stadium, a football stadium, on the moon, and every day it moves right now by something like a metre. We have to measure the position of this little rock on the moon by ten centimeters accuracy. And to do that we are using the observatory here. We combine the light of all the four telescopes to get to this position.*	**Frank Eisenhauer — Paranal**
07:07 *9. We need to get very sharp images, and the best way we can get sharp images is to make big telescopes, but since we don't have these very big telescopes, we combine telescopes. We create a super telescope — in this case which is 130 metres in diameter.*	**Frank Eisenhauer — Paranal**
07:27 *10. This allows us to make twenty time sharper images than we what we could do with a single telescope.*	**Frank Eisenhauer — Paranal**
07:33 *11. Ok, so what we have done in the past is we have made images with individual telescopes. But right now the star is so close to the black hole that you cannot distinguish the two any more in the images, so you need sharper images. And so now with GRAVITY combining the four telescopes, in every image of the galactic centre we can at the same time see the black hole and the star at a very small separation, something*	**Frank Eisenhauer — Paranal**

which would not have been possible otherwise.	
08:00 12. *Then the last step of the three imagers which we talk about is GRAVITY, so this was to combine now the telescopes to get ever sharper images, to get towards the sharpness of a 100-metre telescope. To do that, you take the four telescopes you see in the background and you bring the light together in the basement here in the middle of the mountaintop. So in there sits an instrument which is called GRAVITY. What you measure now is the interference between the light of the telescopes.*	**Frank Eisenhauer — Paranal**
08:31 13. *Being here means being at the best place for astronomy in the world. There's no other place where you have the four telescopes — these big telescopes —available for this kind of instrumentation which we do. The other thing is the passage of the star around the black hole, and this is a very special event, so it happens once every sixteen years. So the last time it happened it was when we brought the first instrument and now it's coming back, and so it's like the baby's coming back after it's been gone for a while.*	**Frank Eisenhauer — Paranal**
09:00 14. *So we want to measure the effects of general relativity while the star moves very close to the centre of our Milky Way which harbours a supermassive black hole. And to do that, we need to measure very precisely, we need to measure to a precisions of 10 cm on the surface of the Moon. So we combine the light from four telescopes — the very large telescopes — here in*	**Frank Eisenhauer — Paranal**

the centre of the mountain of the observatory. The four telescopes are separated by 130 metres, which means that our super telescope can make twenty times sharper images than a single telescope.	
09:35 *15. So, what were the most exciting moments in the observing campaign? I think actually it was in the very beginning about two years ago when we for the first time pointed towards the black hole and to that star, and actually you see the both of them, and this was too a big surprise for us because we did not expect it actually, it's right at that the field of view of what we have. And so was very .. to actually see it, that we can go to very faint that we see the faint black hole all the time and the star nearby. And the other most exciting probably was this year, when the star was moving so fast at a fraction of the speed of light that you could see it from night to night this was very exciting to see.*	**Frank Eisenhauer — Garching**
10:16 *16. Well, what comes next? For the next years we have a pretty good outlook of what will happen. So the next effect which we'll see is a Schwarzschild precession. This means the orbit of the star will rotate, the ellipse will rotate a little bit. And so this is an effect which we will see next year. Pretty sure about that. Then we come to more subtle effects of general relativity but even more exciting. This is about the spacetime itself around a black hole. So the spacetime around a black hole will rotate with the black hole, and so this will move the orbits of the stars yet in other direction. And this is very exciting, because this property is very unique to general*	**Frank Eisenhauer — Garching**

relativity and we will only be able in that black hole in the centre of the milky way will have the precision to measure that.	
Dr Stefan Gillessen, MPE Gaching	
11:08 17. *In spring 2018, one of our best stars which flies around the black hole in the galactic centre actually comes closest to the black hole. It will be so close the the black hole that the speed of it will reach almost 3% of the speed of light, and that is what we want to observe and that's the event we want to follow.*	**Stefan Gillessen — Paranal**
11:28 18. *We have the chance to actually observe general relativity around a massive black hole, and that's a very exciting opportunity which we don't want to miss. And that's why we're here at ESO's Very Large Telescope.*	**Stefan Gillessen — Paranal**
11:42 19. *So in May 2018, then the star will reach its highest velocity. We actually expect that we can see general relativity- how can we see that? It's actually a slight deviation of how the star is moving. This deviation we can see in the first place with the so-called Doppler effect. It's currently approaching us and it will fly away. This Doppler effect is actually something we can observe by means of spectroscopy, and spectroscopy in turn means that you will need a spectrograph and such a spectrograph is SINFONI, and that is the instrument which will be the one which actually is observing the relativistic effects. SINFONI alone is not good enough — we need to know more about this star, we need to know the orbital trace—*	**Stefan Gillessen — Paranal**

we need to know how the car is moving actually, so to say. And for that we use NACO, an adaptive optics imager, and actually what is bringing most of our constraints for the orbit is GRAVITY, the instrument which is combining the light of the four telescopes.	
12:53 20. *So the experiment we're doing is extremely simple in some sense. We are just measuring the motion of stars around the black hole. That is very much like Earth goes around the sun and you can actually calculate the mass of the Sun from the knowledge that Earth takes a year to go around the sun, and essentially we try to do the same, we try to measure the mass of the black hole be seeing how stars fly around it.*	**Stefan Gillessen — Paranal**
Dr Odele Straub, Observatoire de Paris	
13:22 21. *A pericentre passage. In the case of S2 this happens only once in sixteen years. In comparison, in the case of the Earth orbiting around the Sun, the pericentre passage, it happens once per year, and it is called the perihelion. And right now we are observing this passage as the star moves into this critical curve around the black hole. We have all four telescope working together, and in addition to these telescopes we have a beam combiner, and this combines the light from all four telescopes and this is GRAVITY.*	**Odele Straub — Paranal**

14:02 22. *GRAVITY of course is the best because we can really trace the orbit of this star very very carefully with really good accuracy, so we can now get very nice orbits and we're trying to test all our theories with this very nice data we have now.*	**Odele Straub — Paranal**
Dr Maryam Habibi, MPE Garching	
14:22 23. *Yeah, these unique telescopes allow us to have the highest resolution that we need and also to look in infrared, to look through all the gas and cloud, to look at the very heart of our galaxy. And so the monitoring of the heart of our galaxy has been happening since...uh...since almost like twenty years, but now it's a special event.*	**Maryam Habib — Paranal**
14:51 24. *Now this event which is like one of these stars — the brightest one — is going very close to the black hole. It is...uh...is exciting in some different way in that is probing the orbits of the star and their dynamic, we can probe the gravity in a strong regime that has not been probed before.*	**Maryam Habib — Paranal**
15:15 25. *Yeah, the beauty of it is that it's a very simple experiment in the phenomenon. Yeah, there are some technical challenges that you have to overcome to build the instrument and perform the experiment but the concept is very simple.*	**Maryam Habib — Paranal**

15:30 26. *You can probe the black hole properties and then you can probe the gravitational field, which a very strong one. And up 'til now whatever test of general relativity, or this geometrical theory of gravity which we have, have been in the Solar System — and also in some pulsars — but in this very strong regime it has not been tested.*	**Maryam Habib — Paranal**
16:00 27. *This is just a starting point for it. With the developments, like instruments, and developments of the new telescopes we will do more and more of this.*	**Maryam Habib — Paranal**
Dr Françoise Deplancke-Ströbele, ESO	
16:15 28. *For the discovery a combination of three instruments of ESO were used, NACO, GRAVITY and SINFONI, and all three of those are unique in the world. NACO is adaptive optics in the infrared — we don't have so many in other telescopes. SINFONI is a high-resolution spectrograph, very important to measure at which speed the star is coming towards or going from us, and GRAVITY is an interferometric instrument, the only one in the world that can combine four big telescopes —8-metre telescopes— with a baseline of 130 m, so having the same resolution as a 130 m telescope. And it has in addition the capability to do astronometry, very accurate astronometry, so it measures movement which is the equivalent of an astronaut on the moon moving a flashlight by about 10 cm.*	**Françoise Delplancke-Ströebele — Garching**
17:05	**Françoise Delplancke-Ströebele —**

29. *And the combination of all these instruments — interferometry, classical spectroscopy, adaptive optics — is what makes ESO unique. It's having all of them on the same site in a position where you can observe the galactic centre in good conditions.*	**Garching**
Dr Linda Taccomi, MPE Garching	
17:22 30. *This is one of the huge benefits of ESO, and the way ESO works is that there is always a very strong collaboration between ESO and institutes in its member states, which is very unique in the world because it enables ESO and the ESO Members to undertake projects like GRAVITY which are so complicated that you need a strong team.*	**Linda Tacconi — Garching**
17:52 31. *So the engineers at MPE have worked together, side-by-side, with the engineers at ESO and the scientists at MPE and the scientists ad ESO, and that's just one example that's happening all through ESO and its Member States.*	**Linda Tacconi — Garching**
18:07 Observations at the Very Large Telescope (VLT)	