Opening up a new window on the

Now that their 2016 detection has given us a solid proof of concept, gravitational waves are opening up a new window on the cosmos.

By George van Hal

Proving a 100 year old prediction by none other than Albert Einstein isn't an everyday occurrence, not even for the physicists at Nikhef, where gathering new insights into the fabric of reality is part of the job description. The first direct detection of gravitational waves was the biggest scientific breakthrough of 2016. And yet, physicists working on LIGO, Virgo and potential follow-up detectors like Einstein Telescope are only just getting started. The next few years might hold even greater scientific rewards, as the existing gravitational wave detectors gradually improve their sensitivities, and new detectors join the worldwide network. As a new window on our skies opens up, these detectors are set to give us everything from clear insights into the internal structure of neutron stars and the validity of Einstein's theory of general relativity, to further breakthrough discoveries about the primordial mechanics of the very early universe.

A world first

"Announcing that we had directly detected gravitational waves for the first time, was a truly great moment", says Nikhef physicist Chris Van Den

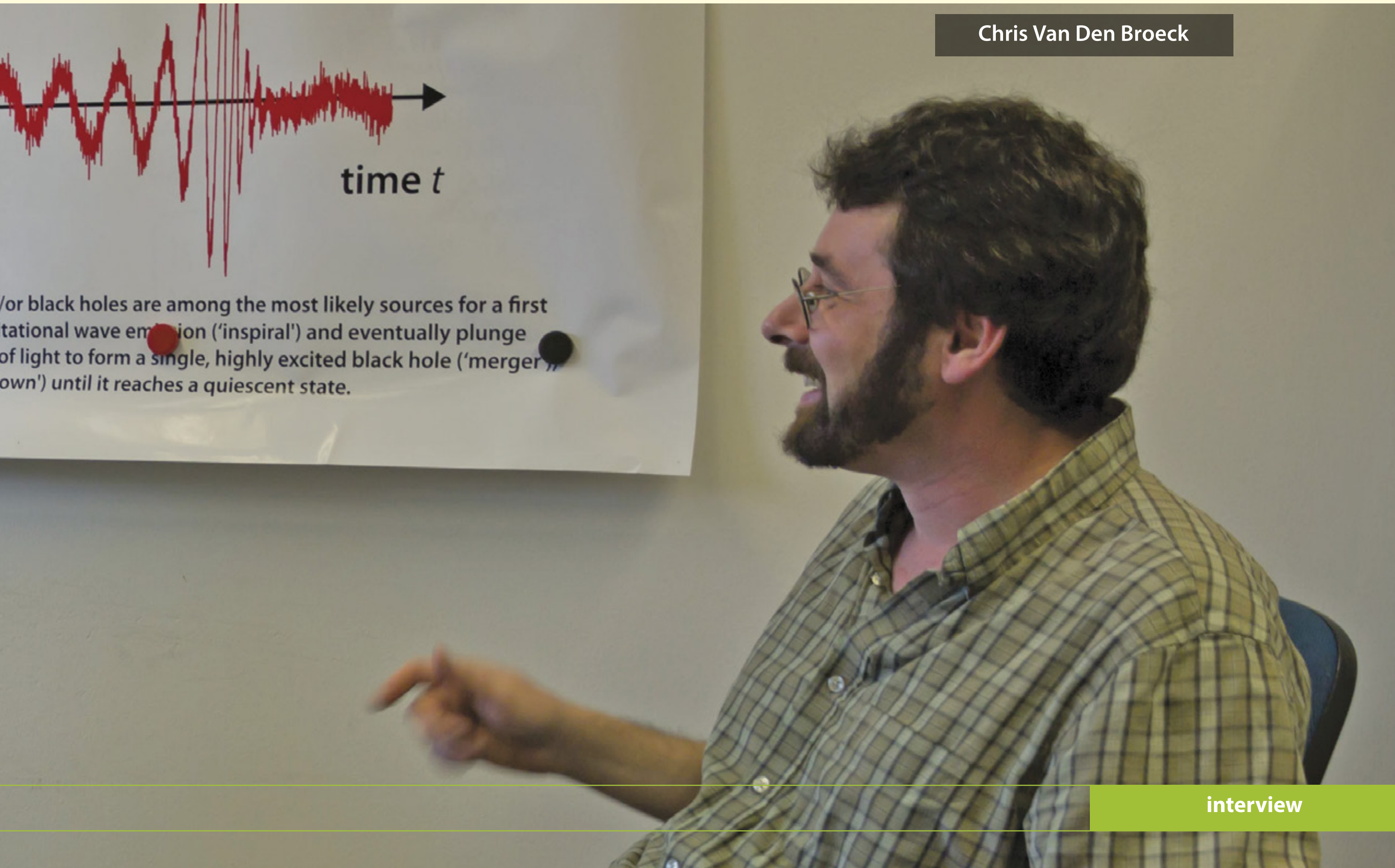
Jo van den Brand

cosmos

Broeck, who spearheaded scientific analyses of the measurements. “We were finally allowed to talk about it in public. And of course, everyone was interested in seeing our results.”

While the wave itself hit the North-American based LIGO detectors in September 2015, scientists involved in the LIGO and Virgo collaborations had to sit and wait until February 2016 when they had finished their painstaking scientific analyses and were allowed to share their findings with the world. “We knew on the first day that what we had was real”, says detection committee member and Nikhef programme leader for Gravitational Waves Jo van den Brand, who oversaw all the scientific analyses. “And we knew it was from a source we never would have expected; not a collision of neutron stars, but a collision of black holes.”

“That first week was pure euphoria”, says Van Den Broeck. “But after that, the real work started.” The first order of business was to hit that time-honoured physics benchmark of statistical measurement reliability: a 5 sigma result. “Reaching that bar required some work”, Van Den Broeck remembers.



Chris Van Den Broeck

Still, making sure they had their measurement in statistical order wasn't the only thing that needed to be done. "The day after we published our results, we published 12 companion papers", says Van Den Broeck. Those papers covered everything from the astrophysical implications of the measurement to a world-first analysis run by Van Den Broeck and colleagues; a rigorous test of Einstein's theory of general relativity, which probed the genuinely strong-field dynamics of space-time for the first time.

"We knew we could test the theory in ways that had never been done before", says Van Den Broeck. Earlier tests of the effects predicted by general relativity were all done in weak field regimes. Physicists were looking at things like the twisting of light paths due to the gravity of stars, or the movement of planets: low mass, low energy situations where objects were moving relatively slowly when compared to the speed of light. "With this result we were observing the strongest possible curvature of space-time in a physical system. We were watching giant masses move at half-light speed. It was a unique opportunity."

The new analyses by Van Den Broeck and colleagues turned out to be the most popular – in citations – of the 12 companion papers. Not surprising, when considering their world record result. "We now know that also in the strong-field regime, Einstein's theory of general relativity cannot be off by more than 10 percent", says Van Den Broeck. "Anything larger we would have seen."

And the scientists had another surprise in store. As media all over the world were scrambling to report on their February results, they knew of a second detection. "But we could not yet discuss it", says Van Den Broeck. That second signal was also detected in 2015, on 26 December to be precise. "A beautiful Christmas present", according to Van den Brand.

And because the masses of the black holes involved were much smaller, the wave they measured was much longer, giving Van Den Broeck the opportunity to test some other general relativity predictions about the way the inspiral of black holes happens before a collision. So far, Einstein's predictions are holding up.

New results

These detections, while massively interesting in and of themselves, also prove that the current generation of gravitational wave detectors is up to the task of measuring those tiny ripples in space-time. Because of that, a new window is opening up on the cosmos, one beyond the confines of the electromagnetic band that scientists have been using for years – and physicists and astronomers alike are hoping for unexpected results.

"I'd be surprised if there weren't any surprises", Van den Brand says. Because of that, physicists are keeping an open mind while looking for new signals, so as not to miss any waves with unexpected shapes. "Every time the old electromagnetic telescopes opened up a new wavelength range, they found a new kind of object", Van Den Broeck says. "And what we're doing here isn't just a broadening of the spectrum, it's utilizing an entirely new messenger, the gravitational field."

In the short term, however, Van den Brand and Van Den Broeck are expecting spectacular new insights about the objects they already know of. "We want to

December 2016 issue of Science Magazine: the discovery of gravitational waves as the breakthrough of the year.

see more black hole mergers", says Van den Brand. And if the two signals from 2015 are any indication, new observations from a measurement run that started at the end of 2016, are set to bring around several new signals by the summer of 2017.

"Those might give us a clue where these black holes are from and how they're formed", says Van den Brand. That's a relevant question, given the fact that scientists were not expecting to see such massive black holes merging. "The first one especially, with its 65 solar masses in total, was a big surprise", says Van Den Broeck.

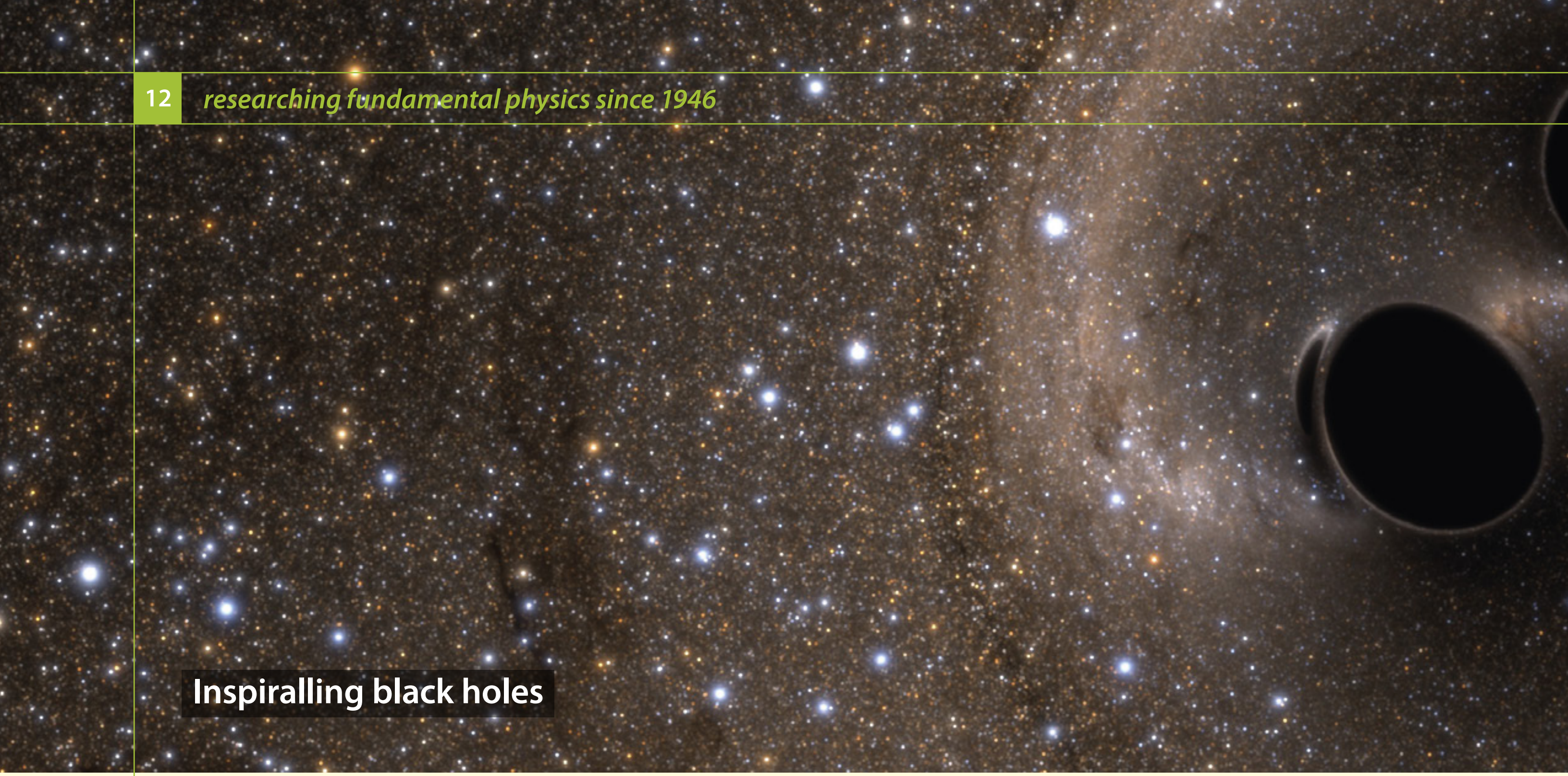
Currently there are some theories as to how these black holes may form, but no definite results. One theory states that they may form from two heavy stars in a binary system, while others think they might form in star clusters, where they eventually run into each other. By looking at the spins of both black holes – and if they're aligned or misaligned – researchers might finally learn which of these two scenarios fits the facts. The physicists are also hoping to catch a few colliding neutron stars. "At this moment, we know very little about their internal structure", says Van Den Broeck. "There's all kinds of theoretical models for their equations of state, and with current measuring techniques there's little opportunity to distinguish between them."

Gravitational waves will allow physicist to peer much deeper into these mysterious objects. "When these stars move very close to each other, they pull on each other and start to deform", explains Van Den Broeck. "How strongly they deform is determined by their equation of state". This deformation in turn impacts the trajectory of these neutron stars and the shape of the gravitational waves they send out. "Gravitational waves give us a way to understand which of our theoretical models are real", says Van Den Broeck.

Virgo update

Next year the third gravitational wave detector will go online, the Advanced Virgo at Cascina near Pisa. This will give physicists the opportunity to accurately triangulate the location of a detected signal. They will be able to ask astronomers to independently observe the same area in the sky with other instruments.

"The astronomical community is showing a lot of interest in what our instruments can do", says Van Den Broeck. More than 80 astronomy collaborations, including big ones like Swift, Fermi and LOFAR, have agreed to look at the approximate location of the source indicated by the LIGO-Virgo network.
"In our group, we're working with astronomers and astrophysicists from Nijmegen, like Paul Groot and Gijs Nelemans", adds Van den Brand. "Our collaboration with these communities is one of the great things about this project."



Inspiralling black holes

Before astronomers can start their more precise searches, Advanced Virgo needs to come online. In the original planning, it should have been up and running already, but the team experienced a major setback in 2016. “The quartz wires we were using to suspend the mirrors in the detector, were breaking after a week or two inside the vacuum”, says Van den Brand. After a long analysis, the physicists discovered the problem: the vacuum pumps they were using gave off minute dust particles, which were hitting the wires. “We now need to encase, or replace, the vacuum pumps”, says Van den Brand. “But at least we finally have a solution.”

As things look now, Advanced Virgo will begin measuring in March. Perhaps at a slightly lower sensitivity than planned, but enough to triangulate a signal. And if it proves to work as promised, the physicists will slowly increase the sensitivity – an important step, because more sensitive detectors can look for signals in a larger volume of space.

The current instruments, Advanced LIGO and Advanced Virgo, are set to continue running until at least 2022. “We’ll be at our highest sensitivity then”, says Van Den Broeck, but plans are already underway for a second life after that time. “We can inject squeezed light, change the mirrors, change the lasers – there’s all kinds of options to improve these detectors when the time comes”, says Van den Brand. In the meantime, physicists are setting their sights on the next generation of gravitational wave detectors, including the space-based telescope LISA, which, according to Van den Brand, has ‘fantastic prospects’ and is garnering a lot of enthusiasm. The most promising new detector is Einstein Telescope, which – like the Cosmic Explorer in the US – is shaping up to be the European ground-based detector of the future.

Plans for this third generation instrument are already underway, with the southern part of the Dutch province of Limburg emerging as one of the prime candidates for the detector site as a result of its unique geology. “Einstein Telescope is featured in every roadmap”, says Van den Brand. “The fifth route of the *Nationale Wetenschapsagenda* (the national science roadmap), has named it game changer number 1, a decision in which people from all kinds of disciplines were involved.” And while the road ahead for Einstein Telescope is still unclear, it certainly looks promising. Negotiations with governments, universities and local industries are ongoing. “It’s a complicated process”, says Van den Brand. “The only thing that isn’t, is the science case.”

The dark ages of the Universe and beyond

Detectors like Einstein Telescope will allow physicists to look at a time in the history of our Universe just after the Big Bang, but before the first stars were born. Those early times, which astronomers call the dark ages, are

still mostly a mystery. At that time the Universe was very dense, and gravity was the main driver of structure formation. As of yet, no one knows what might be glimpsed from looking at this strange period.

“I'm hoping to see primordial black holes”, says Van den Brand. These early black holes might prove to be the seeds for the supermassive black holes in the centres of galaxies that we know are there today. If primordial black holes existed, they could have grown throughout the 15 billion year history of the Universe, into the huge ‘monsters' we see today.

“Einstein Telescope will give us the opportunity to discover completely new physics”, says Van den Brand. He believes the new instrument may also provide an opportunity to observe primordial gravitational waves, which – if they exist – will have originated a split-second after the Big Bang. It is generally assumed that, in that same timeframe, the Universe underwent a period of inflation, during which space-time grew exponentially. “Inflation was driven by the inflaton field, which has a corresponding particle, the inflaton”, says Van Den Broeck. “When this inflaton decays into other particles, gravitational waves should be created, which could still be measurable today.” Measuring those kinds of primordial gravitational waves may be the only way to prove this popular idea of cosmic inflation.

Such a discovery is certainly possible, given the fact that the energy scales Einstein Telescope will uncover are unlike anything mankind has looked at before. “It's twelve orders of magnitude higher than what they”re currently observing at CERN”, says Van den Brand. “We don't even know what kind of particles and fields are present in those kind of regimes, making it difficult to predict what we'd see”, he says. “With this instrument we could take a leap and look, for the first time ever.”

As people measure more and more gravitational waves, with new and improved detectors, scientists are standing at the beginning of a new golden era in astronomy, cosmology, and fundamental physics. “Just think”, says Van den Brand. “More than a year ago, theoretical physicists were arguing about the true nature of black holes, invoking theoretical ideas like firewalls”, he says. “Now they have to be careful. For the first time ever, we can actually see these things, and measure them. The enormous implications of that are now slowly starting to be understood by the rest of the scientific community.”