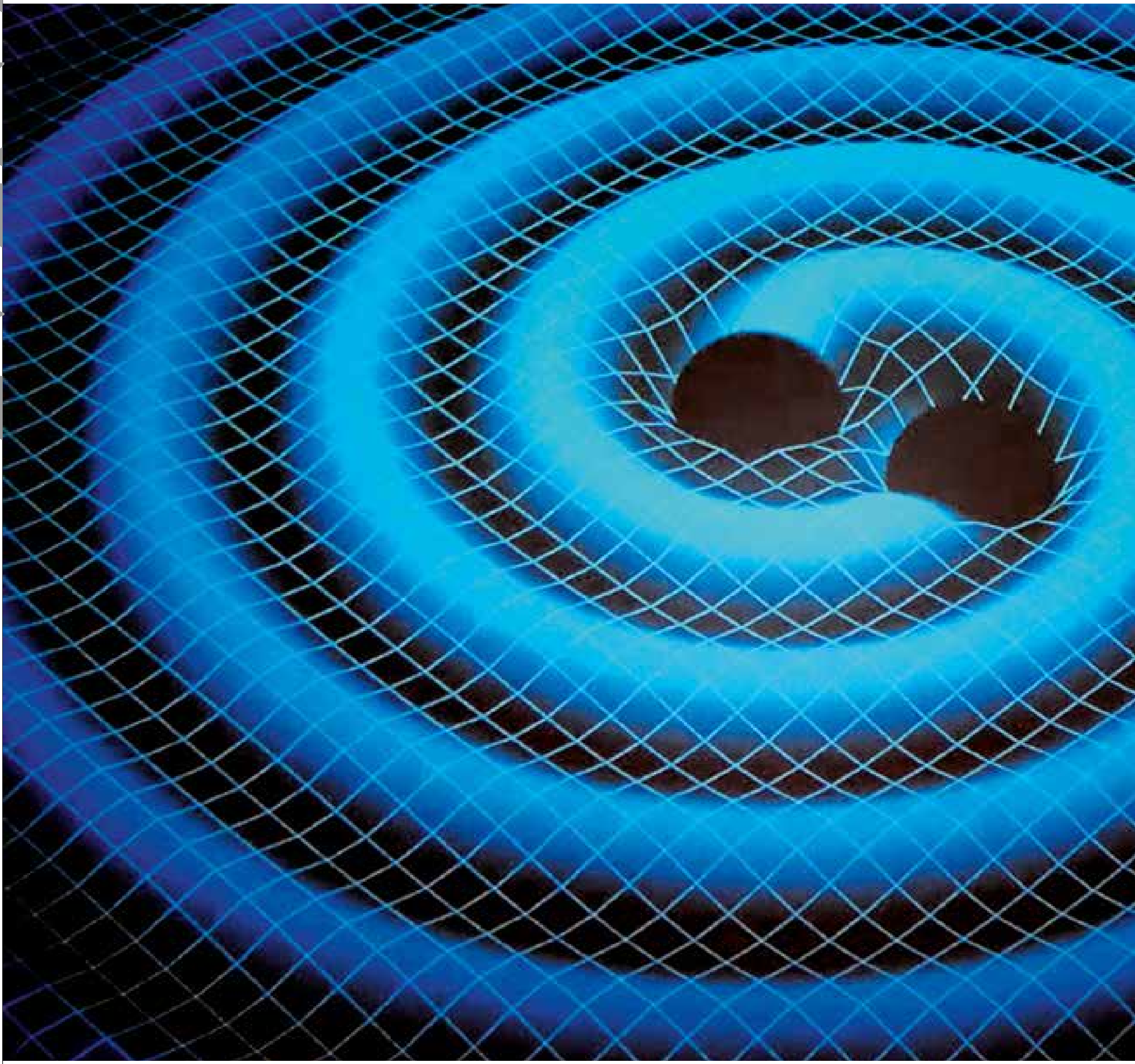
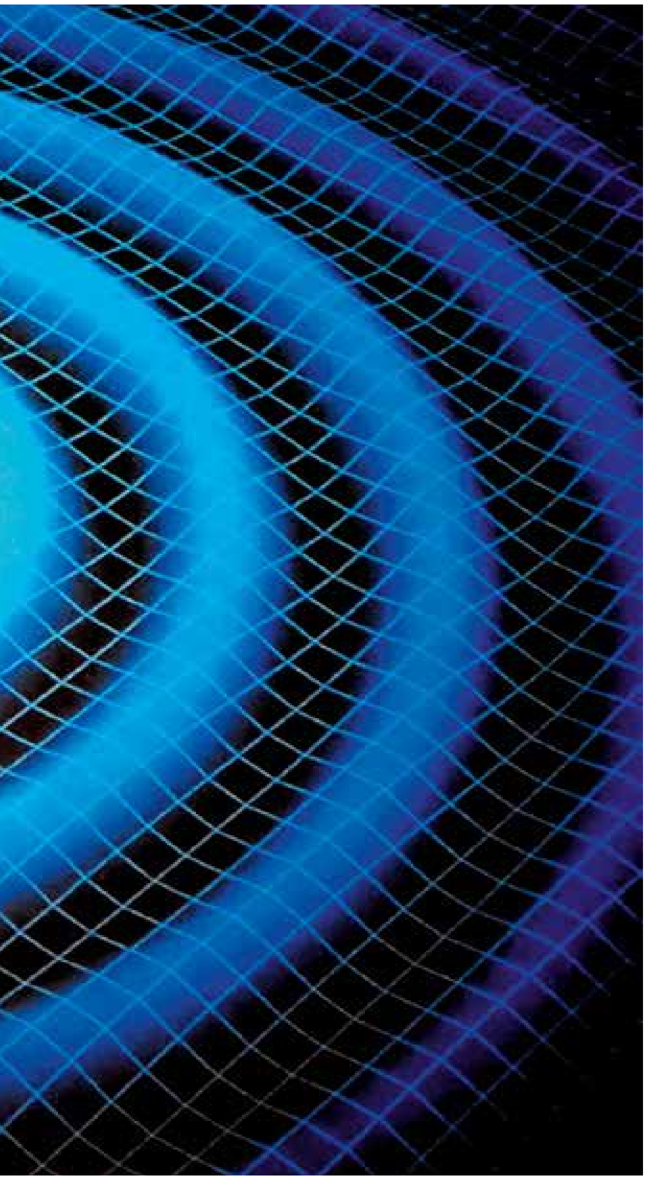


EINSTEIN'S NEEDLE IN A HAYSTACK

No one could have expected that on the first day that LIGO detectors were running, scientists would register signals of gravitational waves. We discuss the watershed discovery confirming the general theory of relativity with **Dr. Andrzej Królak** from the PAS Institute of Mathematics and **Dr. Michał Bejger** from the PAS Nicolaus Copernicus Astronomical Centre, both members of the Virgo-POLGRAW group.



ACADEMIA: **In February you announced the discovery of gravitational waves. What actually happened?**

ANDRZEJ KRÓLAK: On 14 September last year, the two LIGO detectors in the US registered gravitational wave signals. It turned out that they originated from the collision of two black holes, each with a mass of approx. 30 times that of our Sun, which happened around a billion light years away from Earth. The general theory of relativity predicts the existence of gravitational waves. We already had partial evidence for their existence from our observations of double pulsar systems, and now they have finally been detected using highly sensitive LIGO laser interferometers. The devices are able to measure the distance between the Sun and Earth, for instance, with an accuracy down to the diameter of a hydrogen atom.

Is achieving this degree of precision a major technological challenge?

A.K.: Very much so, both at the construction and analytical levels. Since the signal is incredibly weak and hidden deep in the detector's noise, extracting it required the development of highly sophisticated research methods. Direct work on constructing sufficiently sensitive equipment and developing data analysis methods took around thirty years, but the concept of building a gravitational wave detector dates back several decades.

MICHAŁ BEJGER: Einstein published the general theory of relativity in 1915, and demonstrated a year later that it allows for wave solutions – disturbances in the distance between events taking place in spacetime which propagate like waves. During the decades that followed, scientists weren't certain whether the waves were a genuine physical phenomenon or simply a non-physical solution of the theory. It wasn't until 1957 that a certain "Mr. Smith," a.k.a. Richard Feynman (inspired by research conducted by, among others, Hermann Bondi and Felix Pirani) presented a thought experiment showing that when a wave passes over two beads on a rigid rod, the beads will slide freely; if the rod and beads aren't perfectly smooth, their relative motion causes friction. This in turn leads to energy transfer, which means that waves are physical phenomena which transfer energy.

A.K.: In the late 1950s and early 1960s, scientists started studying Einstein's equations in more detail. It's often said that it was the great four scientists Andrzej Trautman, Hermann Bondi, Felix Pirani and Rainer Sachs who demonstrated that Einstein's equations really allow for gravitational radiation. This research led to the concept of trying to detect gravitational waves, pioneered by Joseph Weber. He didn't use laser detectors, but aluminum cylinders in which passing waves achieved a specific frequency. In 1970s Weber claimed that he could detect a signal, but no one else was able to confirm this despite the construction of many similar, even more accurate detectors at various research centers. Cylindrical detectors had reached the end of the road.

M.B.: The next important step came when a binary system comprising a pulsar and a second compact object (possibly also a pulsar, though not visible to us) was discovered by Russell Hulse and Joseph Taylor in 1974. Observations revealed that the distance between these objects is getting smaller, which means that the system is losing energy. A natural explanation is that gravitational waves are being emitted by the system. It's a powerful but a partial (indirect) proof of their existence. We currently know of seven systems which behave this way, a fact that served as an incentive for constructing a detector to try to register the waves directly.

The black holes had been in a binary system for millions of years, but had been getting increasingly closer by emitting energy. Eventually they collided.

Prof. Andrzej Królak, the leader of the POLGRAW team, is a professor at the PAS Institute of Mathematics (since 2003) and the National Centre for Nuclear Research, member of the international Virgo Collaboration and its Steering Committee, and coordinator of the Polish consortium of the Virgo Collaboration. He is the vice-president of the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration Continuous Waves working group. He is a two-time winner of the second award of the Gravity Research Foundation in the US.

A.K.: Laser detectors were pioneered by British and German scientists. Their research groups were the first to apply to build interferometers, but unfortunately their proposals were turned down. It wasn't that they required vast amounts of money, but gravitational waves were such a novel concept there were doubts whether it was possible to detect them at all. As a result, the British and German teams built a detector with a relatively short arm of 600 meters, generally used for testing and development. Meanwhile the LIGO detectors which have actually detected gravitational waves are four kilometers long, and those at the sister European Virgo project are three kilometers.

How do consortia able to construct such huge equipment get formed?

A.K.: Concepts originate at laboratories. Next, groups of people interested in the project come together, and their individual personalities are extremely important. The project then needs to be written and developed, which requires efforts of many people. For example, we need to estimate the cost of building a detector so that it fits into a realistic budget, assess technological capabilities and conduct laboratory tests. It's essential for the project to have experienced managers who have a team and a concept for how to develop the project. LIGO submitted the proposal to the National Science Foundation in the US. Due to its financial scale, it was voted on by the US Congress. International collaboration was encouraged, so I remember writing to Congress explaining the opportunities provided by the project and how they will help develop new technologies… I should note that we are talking about significant funds for basic research without obvious applications.

What scale are we talking about?

M.B.: The total cost of the LIGO project – constructing two detectors, R&D and so on – is approximately $600 million over 25 years. In real terms it's not an outrageous amount, even by Polish standards, especially considering certain debatable items in the Polish budget. If we had a billion zlotys spread over these many years, we would have been able to build the detector in Poland.

Who inspired the LIGO project?

A.K.: There were several key people. Prof. Kip Thorne is an astrophysicist working at the California Institute of Technology and the author of many papers on gravitational waves and black holes, and he encouraged a number of scientists and researchers to join the project.

M.B.: He was also recently able to use Hollywood money to conduct realistic simulations of an accretion disc around a black hole in the film "Interstellar" (dir. Christopher Nolan, 2014 – ed.).

A.K.: Prof. Rainer Weiss from the Massachusetts Institute of Technology (MIT) was one of the designers of the detector, and he made suggestions on how to improve its sensitivity. I think Thorne and Weiss are potential candidates for the Nobel Prize. We should also mention Prof. Ronald Drever from Caltech who devised an extremely important method of improving the detector's sensitivity by effectively enhancing the laser. Due to certain conflicts he left the project relatively early on, but his input in enhancing the detector's power around tenfold is extremely important. Kip Thorne worked with Prof. Bernard Schutz on data analysis. I had a postdoctoral scholarship with Bernard Schutz when he was a professor at the University of Cardiff in Wales, which was the starting point of my adventures with gravitational waves. Thanks to Schutz I was one of the first people working on developing data analysis methods.

LIGO was built in the US. What about Europe?

A.K.: France and Italy have teams interested in building gravitational wave detectors, led by scientists including Alain Brillet and Adalberto Giazotto. They received funds from French and Italian agencies and built the Virgo detector, starting a close collaboration with LIGO; the two now act like a single project. Data analysis is conducted jointly and all members of both projects have exclusive rights to the data.

When did Poland join the research?

A.K.: I started recruiting team members once I returned from my scholarship. The first was Prof. Piotr Jaranowski. We started solving theoretical problems of data analysis and working out how detectors can define certain parameters of gravitational wave signals. Once the Virgo detector was built, we got in touch with astrophysicists and experts in programming and data analysis. We formed a larger team, and thanks to personal contacts we joined the Virgo project as a Polish group. Before us the project was joined by a Dutch and then a Hungarian team, so today Virgo comprises five countries: Italy and France which made the main financial investment in constructing the detector, the Netherlands which also made a major financial contribution, and Poland and Hungary which conduct research and analyze data. We also study the sources of astrophysical gravitational signals and build models of gravitational wave signals, and we are contributing to the expansion of the Virgo detector which is currently being modernized and will be brought online later this year. Its basic sensitivity will continue being improved, and we hope to play a part in this.

M.B.: Of course this depends on whether we'll have the funding.

We keep coming back to the money. It's not a huge amount, but it is a problem.

A.K.: But it's more than funds required for basic research and it requires approval not just from funding agencies but on a governmental level.

M.B.: For Virgo, we're talking about ten million euro per year over the course of twenty years.

Ten million for everything?

M.B.: That's right – development, maintenance, construction of equipment. One needs many engineers – more than scientists. It's a major engineering undertaking, and at this stage theoreticians and data analysts are right at the back. The Polish contribution has also involved a Polish engineer working on site.

But Poland's contribution is mainly in data analysis, is that right?

M.B.: We're developing analytical methods. The other thing is their implementation – calculations requiring powerful super-computers. That's why our codes must be optimized and fast in order to conserve electricity and funds. Searching for gravitational waves is difficult, because they can't be seen. The signal is usually deeply hidden in noise and it needs to be extracted using statistical methods like those developed by Prof. Królak. Since we don't know what the signal is like, we must first check all the possibilities, which requires vast calculations. It's very much like looking for a needle in a haystack.

And this needle…

M.B.: …was found last year.

A.K.: Interestingly, it was on 14 September, when the detector started operations.

M.B.: It had already been working for a few weeks, and after its preliminary launch, it was due to officially come online in the next few days. And it immediately came across a signal.

A.K.: One of the distinctive aspects of LIGO and Virgo is that major funds were invested without any guarantee of success. It came down to the clout and persuasion of people who were assembling the project team, but no one expected that the first string of data following an upgrade, when LIGO detectors were brought online and Virgo wasn't even working yet, would contain a gravitational wave signal. It was a huge surprise.

M.B.: We thought that perhaps we might pick something up during later stages, once we had optimized the detector. Predictions on how frequently these phenomena occur depend on the number of such systems, and we simply don't know that. Perhaps there's one signal per century, maybe more or less. We didn't know whether nature would be kind to us or whether the detector would have to remain operational for a decade to detect just a single instance.

> "I took my first steps in detecting gravitational wave signals by developing mathematical models on paper. I found it simply fascinating," says **Prof. Andrzej Królak.**

How did this happy coincidence happen?

M.B.: Data is still coming in. The chain starts with a program which analyses data without human input and this automated process detected the signal very quickly. This is followed by offline analysis in which all known models are checked against the signal to find the best fit. You can then determine the model parameters. That's how we know the signal was the result of a collision between two black holes, and were able to estimate their masses.

Where were you when you got the news?

M.B.: I was on a research grant at the computer center in Karlsruhe.

A.K.: And I was in Warsaw. We couldn't quite believe it at first and we thought it was an artificial signal – this is often done to test research methods, when a small group of team members covertly introduce a signal at a random point to check if data analysts will catch it.

Do they just detect it, or are they also expected to establish that it's a false positive?

A.K.: If it's done right, analysts aren't able to determine whether it's a real or artificial signal. That's essential. During the first stage of the detector's operation such tests were conducted frequently, so we suspected that someone had added this signal as well. But after thorough checks we established that this wasn't the case.

Could it have been a different error?

M.B.: The two detectors registered the same signal at slightly different times, since they are at different locations. This means that the wave passed through one detector and then the next, and they started vibrating in the same rhythm with a shift. That makes for powerful evidence that the signal has astrophysical origins.

A.K.: The signal was detected in real time, and it was analyzed using several independent methods – they all confirmed that it was the result of a collision between two black holes with similar masses. It fits the predictions very well, and we have the best models of such binary systems.

"I joined the team in 2011 when the detectors stopped working, so for me the last few years have been very dark, without any new data," says **Dr. Michał Bejger.**

When you say 'we,' do you mean Polish researchers?

A.K.: I mean everyone on our team. The Polish group of course made contributions to the models, but it was really the result of efforts by dozens of people and hundreds of publications. Such a signal has three stages. First the black holes orbit one another – this increases the frequency and amplitude. Then they collide. Finally a single black hole remains which continues to vibrate, and it is these vibrations which are the source of gravitational waves. We have extremely detailed numeric models for each stage.

But initially you were worried that it was just a test...

M.B.: If there was a concern whether the signal was artificial, it was quickly dispelled – the signal detected in September was almost immediately known to be genuine, because the artificial signal injection system was simply not operational yet. We did have such tests a few years ago, although at the time we knew from the start that the signal could be artificial. Even so, the data were seriously analyzed up until the point when the results were ready for publication, and only then the envelope containing a 'yes' or 'no' answer was opened. The point is to test the instruments and computer programs, as well as being an experiment in sociology to find out how the large team interacts. Effective work requires that people split into smaller groups – some individuals become leaders, others write the text, others check the code and others still make corrections. Everything is tested in all conceivable ways. The text is written by several people but all participants in the project read it and submit comments and ideas. It's also important to assign managerial roles – the LIGO project has around a thousand participants, Virgo approximately three hundred.

So it's not just about testing equipment but also the individuals and the entire team. Who came up with that?

A.K.: This system is used in many projects – numerical codes are always tested on artificial signals. Data analysis is statistical and it detects a signal with a certain probability which needs to be determined. This brings in the human factor. If someone knows the signal was added and knows how to detect it, it affects the measurements.

M.B.: And the whole point is for the code to detect the signal without human intervention.

A.K.: We have to decide whether we can say we have really detected a gravitational wave signal. That's why we are so cautions, since there have been other reports about gravitational waves being detected in the past and none have been confirmed, including the Weber case, which turned out to have been wrong and somewhat slack.

M.B.: Still, as Sherlock Holmes was wont to say, when you have eliminated the impossible, whatever remains, however improbable, must be the truth.

After 14 September, you also had to eliminate the possibility that the detector might be activated by Earth's motion.

M.B.: The detector measures the difference between arm lengths (or, perhaps more precisely, the travel time of light), since the beams enter the device where they are reflected by mirrors and then come back and cancel each other out. If nothing happens, no light emerges from the output port of the device. If the length of the interferometer arms changes, a light flashes with a frequency proportional to the distortion. This is one of the measurement channels, but there are many others such as seismometers, magnetometers and microphones. There are tens of thousands of such auxiliary channels and they are all analyzed to eliminate the influence of other factors on the gravitational wave signal in the main channel.

So with all these precautionary measures, you realized that this was it?

M.B.: This particular signal is very powerful and clear in the channel. Nothing else was happening at that time – there were no earthquakes or other disturbances. It's extremely convincing.

How long did it take after 14 September for the signal to be officially recognized as authentic?

A.K.: Around a month. Since the procedure to follow when a potentially genuine signal is detected involves many steps, it's impossible to say exactly when this happened, but after a few weeks the signal was hailed as a strong candidate for a gravitational wave. All methods pointed to the same thing: the same signal, the same black holes with the same masses and at the same distance.

What did you learn?

M.B.: Many fundamental things. First and foremost, we have evidence for the existence of a black hole. Until then we used the term to describe non-light-emitting massive objects of a small size. Our result was the manifestation of a dynamic interaction of two event horizons, their joining and the creation of something new. Our other achievement was observing a binary system of black holes, which had never been done before since they don't emit light. Additionally the black holes are more massive than others in our galaxy (not counting the one at the center of the Milky Way).

How long had they been "dancing" around one another?

M.B.: They had been in a binary system for millions of years, but had been getting increasingly closer by emitting energy. The phenomenon observed by the LIGO detector lasted 0.12 seconds.

A.K.: The black holes were so close that they orbited one another just eight times before colliding during this 0.12 seconds. The detector wasn't able to pick up earlier stages because it isn't sufficiently sensitive.

M.B.: We saw the spiraling stage, then the collision between the event horizons and the third phase when just a single black hole remained; the vibrations of its event horizon resemble those of a bell being struck.

A.K.: It's really two discoveries in one – one of gravitational waves, and the other a binary system of black holes. And it all follows the predictions of Einstein's general theory of relatively. Over the last century, many other gravitational theories have been proposed, but Einstein's remains the strongest.

M.B.: It is possible that deviations from Einstein's theory haven't been detected because the signal wasn't sufficiently strong.

A.K.: Until now, tests of the theory of relativity have been conducted for systems in which speed is of the order of one thousandth of the speed of light – a few thousand kilometers per second. These black holes were moving at half the speed of light – 150,000 km/s. It was the most extreme test of the general theory of relativity ever conducted.

I understand that up until 14 September you were mainly waiting. Does it get frustrating having to be so patient all the time?

M.B.: Very much so, for me.

A.K.: I'm a theoretician and I took my first steps in detecting gravitational wave signals by developing mathematical models on paper. I found it simply fascinating. Actual detection was such a distant prospect we simply didn't consider it.

M.B.: I previously studied very dense matter in neutron stars. I joined the team in 2011 when the detectors stopped working, so for me the last few years have been very dark, without any new data.

How do you feel now? Tired or hopeful for new discoveries?

M.B.: Our first publication describes the first 16 days of the four months of data collection. We are currently analyzing data from the subsequent days of this period…

A.K.: …and we're hoping to detect more signals, in particular those following a collision of neutron stars rather than black holes. Our team also specializes in detecting signals of rotating neutron stars.

M.B.: If a supernova explodes nearby, it may also be a source of a signal and of course we very much hope to capture it.

Prof. Andrzej Królak and Dr. Michał Bejger were interviewed by **Anna Zawadzka, Katarzyna Czarnecka and Agnieszka Pollo**.
Photos: **Jakub Ostałowski**

Dr. Michał Bejger is an astrophysicist. He received a grant from the Mare Curie programme at the Paris Observatory and the Marie Curie integration grant from the PAS Copernicus Astronomical Centre. As well as analyzing data from gravitational wave detectors, his areas of interest include neutron star physics, processes occurring near event horizons and numerical simulations in the general theory of relativity. He is the editor of the astronomy section in the journal *Delta*.