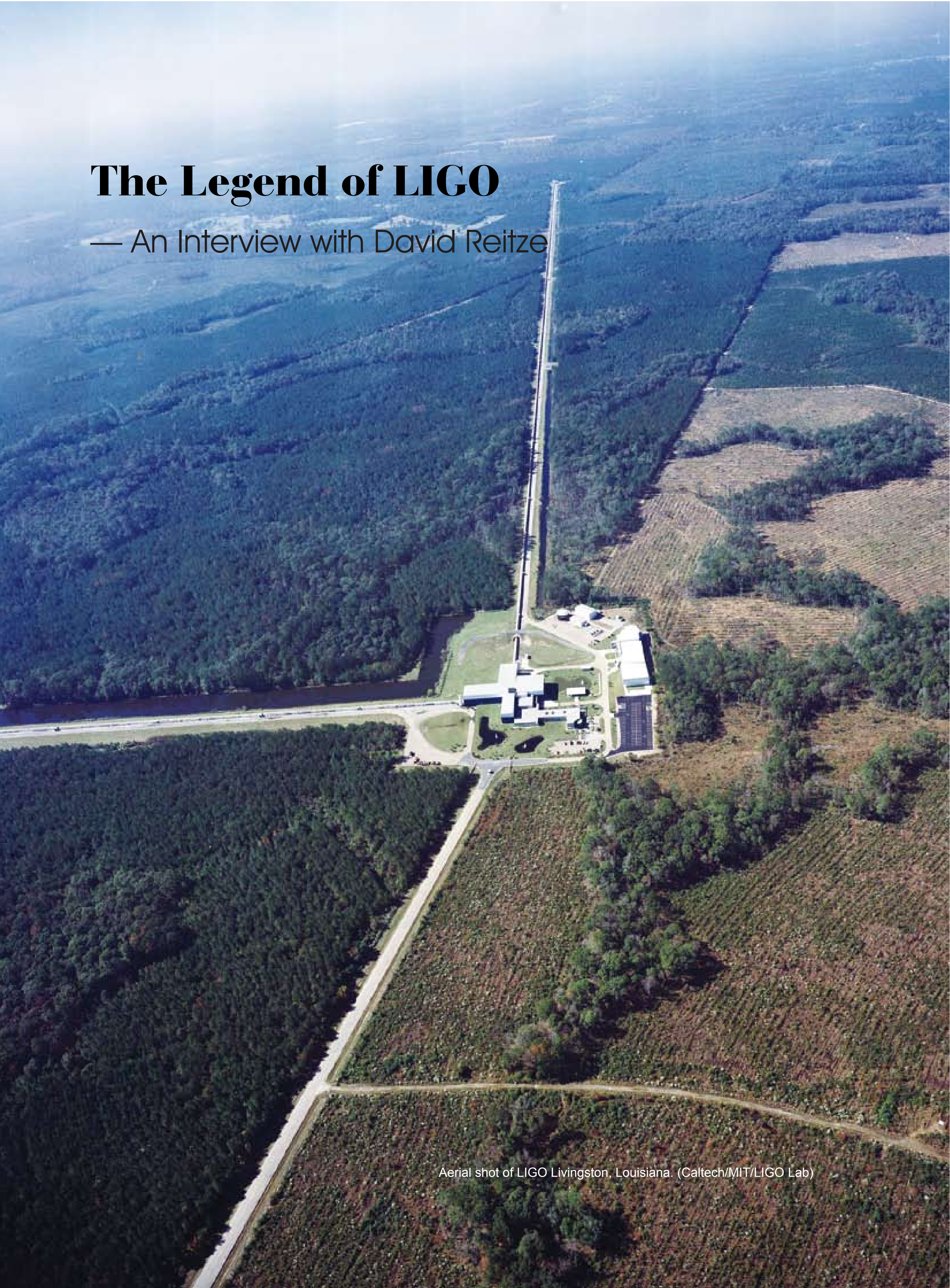
The Legend of LIGO

— An Interview with David Reitze



Aerial shot of LIGO Livingston, Louisiana. (Caltech/MIT/LIGO Lab)

As the most expensive project ever funded by the U.S. National Science Foundation, the Laser Interferometer Gravitational-Wave Observatory (LIGO) aims at fully testing the existence of gravitation waves predicted by Albert Einstein and opening a new gateway for astronomers and physicists alike to explore the universe. In April, 2015, during his stay in Beijing for “The Next Detectors for Gravitational Wave Astronomy” Workshop at the Kavli Institute of Theoretical Physics, Chinese Academy of Sciences in Beijing, laser physicist and LIGO Executive Director David Reitze talked to BCAS reporter XIN Ling about LIGO’s history, its newly finished technology upgrade, the current chances to catch a gravitational wave, as well as China’s opportunities in the upcoming era of gravitational wave astronomy.


David Reitze. (Kim Fetrow Photography)

BCAS: How did you get interested and involved in LIGO?

Reitze: I started doing my research in ultrafast phenomena, looking at really fast processes in condensed matter and developing laser systems. About twenty years ago, I was reintroduced to LIGO through a personal connection. One of my colleagues when I was at the University of Florida was a friend of the then director of LIGO, and at that time LIGO was very small in terms of the number of people that were working on it, maybe fifty people worldwide, and they were mostly from Caltech and MIT. At that time, LIGO had already been funded by the National Science Foundation (NSF) and they were starting to build the facilities. But there wasn’t a community of people to actually do the science. So the director at the time, Barry Barish, started reaching out to people, mostly in the high energy community, to try to get those acquainted with an interest in LIGO. I found out about this in 1996, and because I’d already known about it from my first work at the University of Texas in Austin, I said ‘sure, this would be great!’ So I was actually involved in the building of the Initial LIGO detectors.

What I like about LIGO is that it combines laser physics and general relativity in the same field, and that’s not easy to do. They are both very interesting to me. So I’ve been doing LIGO and gravitational waves physics for twenty some years now.

BCAS: As a LIGO veteran, please tell us about the project.

Reitze: There has been two phases of LIGO. For the first phase, which we call ‘Initial LIGO’, the observatories were built between 1997 and 1999, and the three interferometers, one in the Livingston Observatory and two in the Hanford Observatory, were installed between 1999 and 2001. And then we operated them from 2003 until 2010. During that time, we were also designing an advanced detector called ‘Advanced LIGO’. The idea of Advanced LIGO got started about the same time that we were building Initial LIGO, around the year 2000. There was a lot of research and design work until 2008, which was when it was funded. Then from 2008 to 2010 we started building the components for it. In 2010, when we turned Initial LIGO off, we took it out of the observatories and started installing Advanced LIGO. The installation of the Advanced LIGO went from October 2010 until earlier this year, when we finished the installation—well, Livingston was finished last year, Hanford late last year. We’ve actually just completed the project as of March 31st of this year.

“Advanced LIGO is a complete rebuild of Initial LIGO... It’s like trading in a 2001 Mercedes-Benz and buying a 2015 Mercedes-Benz.”

BCAS: How is Advanced LIGO different from Initial LIGO?

Reitze: It is a complete rebuild of LIGO. We took out the initial interferometers; we decommissioned the lasers, the optics, the electronics, the suspension systems, the isolation systems… everything. The only thing we left was the vacuum system. And then Advanced LIGO was a complete

Advanced LIGO was officially dedicated on May 19, 2015 in a ceremony held at the LIGO Hanford facility in Richland, Washington. (Kim Fetrow Photography)

rebuild of the lasers, the optics, the suspensions, the seismic isolations and the electronics.

It's like trading in a 2001 Mercedes-Benz and buying a 2015 Mercedes-Benz—completely different with much better technology. Advanced LIGO is ten times more sensitive than Initial LIGO in terms of displacement. That translates to a thousand times more volume of space. So basically we can increase the detection rate by a thousand times.

BCAS: Why did you decide to build Initial LIGO in the first place?

Reitze: When Initial LIGO was proposed in the 1980s, it took a long time for the NSF to fund it. But when it was proposed, LIGO was actually proposed as a two phase experiment or two phase detector. Phase I was Initial LIGO, which was designed to detect gravitational waves in the event that there were lots of sources. At the time we didn't know much about the number of sources, or the rates for the kinds of events we were looking at. So Initial LIGO was an experiment that would allow us to actually learn how to build a big detector and *possibly* detect gravitational waves. The second phase, which was also proposed in the first proposal, was Advanced LIGO. Advanced LIGO was designed to be a detection machine. In some sense it's based on our understanding of the astrophysics, and it's almost *guaranteed* to detect gravitational waves.

BCAS: So it has nothing to do with Initial LIGO's seeing nothing in the past decade.

Reitze: Correct. Initial LIGO in some sense was a test; it is such a complicated experiment that I think many scientists didn't necessarily believe it would work. And the story I've been told is that there was this program officer who was responsible for LIGO at the NSF, and when Initial LIGO met its designed sensitivity, he ran out of his office, carrying this piece of paper in his hand, yelling 'They did it! They did it!' You know, he was amazed that we did it.

BCAS: Why is gravitational wave detection so important?

Reitze: Everything we know about the universe mostly comes from electromagnetic astronomy, looking at light, X-rays, gamma rays, radio waves. Some of what we know comes from neutrinos, some from cosmic rays, but the vast majority is from telescopes. Telescopes are sensitive to the motion of charge. Gravitational waves are sensitive to the motion of mass. Processes that involve charge and involve matter may behave quite differently, and if you are not sensitive to matter you might not be able to see certain core things.

For instance, electromagnetic astronomy cannot directly see black holes. A gravitational wave is a direct probe of black holes. It can tell you what a black hole's mass is, what gravity is doing there, and the dynamics of formation of a black hole. You can't get that in any other way. Gravitational waves can probe cataclysmic events such as supernovae. Right now we don't understand how supernovas actually explode; there's a missing piece of the puzzle. Gravitational wave observation could, not necessarily will, provide that missing piece.

Of course, by detecting gravitational waves, you can validate Einstein's theory. People believe it's correct, but all theories are approximation to better theories, and at some point Einstein's theory is not going to be correct. We might discover something that invalidates Einstein's theories; that would be a huge result.

And ultimately—maybe LIGO could do this—we can see the birth of the universe. Gravitational waves from the birth of the universe. There's no other way to get that directly.

What else is cool about gravitational waves? The technology is cool. The optics that we use is the best optics in the world, so we've actually advanced the state of the art in optics development. The lasers that we use are the most stable in the world, so we've advanced the state of the art in laser development. The control systems that we use, which is actually LIGO is all about, are the most sophisticated in the world, so we've done control systems in a way that nobody else has done. These are all the reasons to study gravitational waves.

Every time we invent a new instrument that can study a new phenomenon, you'll discover things. When Galileo invented the telescope, he discovered all kinds of things. The first time microscope was invented, we discovered things much smaller than we could see. The first particle accelerators allowed us to realize that atoms are made up of nuclei, while the nuclei are made up of quarks and quarks are made up of fundamental particles. So chances are that we'll know something about the universe and nature using gravitational waves that we haven't seen yet. It's a new way of looking at the universe, and that's always exciting.

BCAS: What are the odds of catching a gravitational wave?

Reitze: That's a complicated question. Basically, it depends on the sources. There are different types of sources that will produce gravitational waves. The source that we are most confident that we'll detect is a binary neutron star coalescence. So you have two neutron stars that are locked in orbit with each other. As they are orbiting, their orbit decays. As it decays, they radiate gravitational waves—actually that's the reason it decays because they are producing gravitational waves. And eventually their orbit decays at the point where they are moving at half the speed of light, and they collide.

So we know those sources exist. The problem is we don't know how many exist. Therefore, the rates for detection of those sources are uncertain by three orders of magnitude. Astrophysicists tell us that at the upper end of the uncertainty range, Advanced LIGO could detect one event per day, once it's operating at designed sensitivity. At the low end of the range, it could be one event every two years. So the right number is probably in between that, around ten per year. But it could also be five or twenty per year. This is the case for binary neutron star sources.

There are also binary black holes, black hole neutron stars, etc. We know very little about those sources; no one has ever seen a binary black hole system, at least with stellar masses. So their rates are more uncertain. A very rough estimation is that we could see one event every few hours at designed sensitivity for a binary black hole. It could also be one event every ten years. So it's hard to know.

And then there is another source that's very interesting, but we'll have to get lucky: galactic supernova. If there is a galactic supernova and we are operating, there's a reasonable chance—though not 100%—that we will see something from it. The rates for that is about one in fifty years. So we have to be on at the right time.

There are other sources too, but they are much less likely to be detected. For instance, pulsars are very weak emitters because they don't have a lot of dynamic mass motion. In order to see them, you'll have to run for years

LIGO Hanford achieved interferometer lock in December 2014. (Caltech/MIT/LIGO Lab)

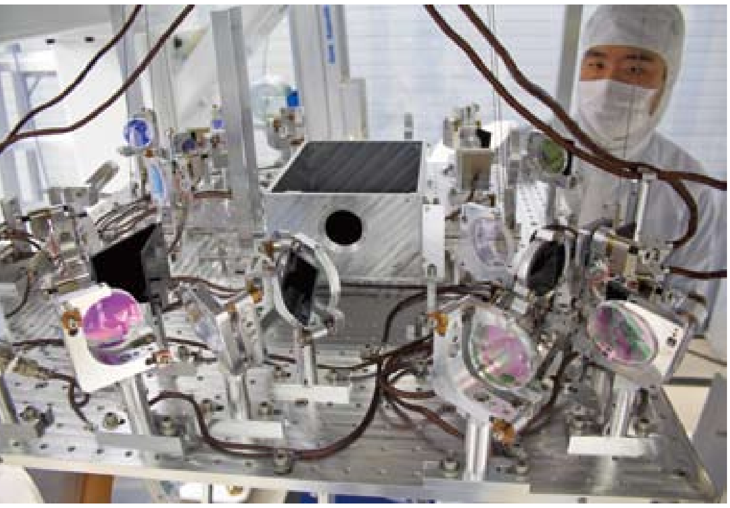
and years and years.

And probably the most interesting but the least likely to be detected is the primordial gravitational background. That's really interesting because standard cosmology says that we don't actually see light from the universe until about 400,000 years after the Big Bang. The universe was opaque, and then duration something called the Reionization Epoch, light was able to escape. The problem is if you're trying to study the universe using any kind of electromagnetic radiation, such as microwaves, you can only see back to that 400,000 year epoch. But if you can directly detect gravitational waves, you can actually look back right into the moment of the birth of the universe—literally 10^{-20} or 10^{-30} seconds. So if you can directly measure primordial gravitational waves, you will be looking at the birth of the universe.

But the amplitudes of those waves are billions of times smaller than what we can detect. So if we do detect something, it would be revolutionary, but I think it's highly unlikely.

BCAS: What is the major challenge for Advanced LIGO?

Reitze: I think the biggest challenge is that these instruments are ultrasensitive. We worked very hard to isolate the instruments from external perturbation. Anything that exerts force on LIGO's mirrors will cause us to lose the gravitational wave signal; the force will overwhelm it. So we have to keep the mirrors very still, and we have to understand all of the ways that the environment, or the fundamental properties of the detectors, can influence how those mirrors move. We've done careful studies, and we can now predict what kinds of forces or environmental



A LIGO engineer is working on the LIGO transmission monitor suspension (TMS) system which is used to relay light in and out of end test masses. (Caltech/MIT/LIGO Lab)

perturbations will come into the mirrors. We designed the system to get rid of them. But we may have forgotten something; we may not have gotten it right. The physics is very complicated. So getting these instruments to perform at their best sensitivity is going to take us three or four years just because there's so much work to do.

I'll give a very technical but illustrative example. So we use lasers that are very powerful—200W lasers. When they actually get into the interferometer, due to the tricks that we play, we make the laser power actually look like it's almost a megawatt power inside the arm of the interferometer. That's a huge amount of power. It cooks the mirrors up. The mirrors actually absorb the laser light just a little bit, but that distorts their performance. The light can scatter. You'll have to make sure that the light doesn't get into your detectors unless it's through the gravitational wave channel. Another problem is what we call parametric instability. The photons in the light field have pressure. When they hit the mirror, they actually exert a force on the mirror. It turns out that these forces have a certain regular pattern, and just drums sticks hitting on a drum they cause the mirror to actually ring. This instability causes the interferometer to quit working. So we have to identify all of the sources of this instability.

Another challenge is anything looks like a gravitational wave. Ultimately gravitational wave is read out by two little photodiodes. The entire gravitational wave detector relies on two little photodiodes. Those photodiodes are dumb. Any kind of change to the interferometer, for example when the mirror moves because of some perturbation to scattered light, that's a gravitational wave. But it's *not*. So we have to be able to tell the difference between external perturbation and a true gravitational wave. A huge amount of work will go into understanding data quality issues, making sure the data is very 'clean'.

BCAS: Anyway, Advanced LIGO is very promising to detect gravitational waves within a few years' time. What's your schedule?

Reitze: So now Advanced LIGO is going to begin taking science data and we will start operating Advanced LIGO probably in the late summer, between August and September of 2015. And we will operate it just for three or four months, look at the data, and then improve its sensitivity. The detectors are not like television sets. When you turn them on, they don't work perfectly the first time, and it takes time to bring them up to designed sensitivity. Next year, we'll work very hard to get them up to almost their designed sensitivity, and again we'll do another science run. Then in 2017 and 2018, we hope to be operating near designed sensitivity, and we'll do a really long run then. So that's the plan for the next three years.

But again it depends on the universe. If the universe is kind, we could see gravitational waves in two to three years. If the universe in unkind, we might not see a gravitational wave for another five or six. If the universe is very kind, we'll see a gravitational wave next year. Basically that's just a statement of the uncertainty.

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BCAS: Do you have pressure to see the waves?

Reitze: Well, there's always pressure to deliver scientific results. So I would say yes we have pressure to see one. The field of gravitational waves has been around for fifty years. It was started by a group of people that built bar detectors, big mass aluminum bars. The most famous—and really infamous—was the guy from the University of Maryland named Joseph Weber. Weber built these bars and he claimed he saw gravitational waves. He didn't. But because he claimed he saw gravitational waves, other physicists thought that gravitational wave physicists were crazy. So consequently we had a bad reputation. We don't anymore, because we built these detectors that are exquisitely sensitive. But because it's been going so long and we haven't seen anything, it's a field that has been in existence for fifty years and has measured nothing. We have lots of published papers, but the papers are known as 'upper limits papers'. We need to see something. Because after a while, taxpayers will start asking if their tax money is being spent properly. So I'd say there is pressure on us to see a gravitational wave in the next five to ten years, or the entire field will suffer from lack of funding.

BCAS: In fact, the field is getting a lot of money at the moment. For instance, the NSF has just decided to set up a 14 million dollar gravitational wave center.

Reitze: Yes. It's a multi-institutional center, with the leading institution from the University of Wisconsin-Milwaukee. Compared with LIGO, they are looking for gravitational waves from much larger and lower frequency sources using pulsar timing.

There's actually a race. It is possible, but I think unlikely, that pulsar timing could make a detection before LIGO. But if they win the race, that's good for everybody.

Speaking of race, a space-based system which is under development by the European Space Agency called LISA, now eLISA, will look for gravitational waves at a frequency higher than pulsar timing and lower than LIGO. This is very exciting because it's almost certain to see gravitational waves as soon as it turns on. But they won't be operational until at least 2030 or 2035, so twenty years from now.

BCAS: I didn't see a lot of Chinese scientists in this field.

Reitze: Yes. I think the Chinese scientists are starting to get more interested, like this workshop is organized in Beijing jointly by Chinese and Australian organizers. I think the goal of the workshop is to try to get a community in China that can actually support gravitational wave research. Australia just funded a major collaborative initiative between China and Australia to start a gravitational wave program, and I think China has also done some funding, too. So I think there's interest in it, but just not at the level that exists in the United States or in Europe, because there are more people there.

BCAS: What about China's participation in LIGO now?

Reitze: LIGO is supported by a large collaboration, about 950 scientists from all over the world. One of the collaborators is a data analysis group from Tsinghua University, led by CAO Junwei. Right now that's the only group from China that works in LIGO scientific collaboration. But at this meeting I learned there is an effort to actually grow the number of Chinese scientists that are going to be involved in the collaboration.

BCAS: Do you see any opportunity for Chinese scientists here?

Reitze: Absolutely. There are many. I'm an optimist. I believe that we'll detect gravitational waves within the next few years. I believe that the detections would be significant enough that the scientific community will want to continue the field and build bigger detectors. The usefulness of the detectors we have now will probably expire in about ten years. What comes next? Bigger detectors. And there are two aspects of that. One is a bigger ground-based detector, like LIGO, but bigger and more sensitive; and the other is a space-based detector.

If the community of scientists in China gets really interested in gravitational waves, they should think about how to be ready to build a detector, which won't be operational until 2025 or 2030 but would be ten times better than LIGO. One thing that has been proven is that you guys could do that. You could be a world leader in gravitational wave physics. But it's very expensive. This could be off by as much as 50%, but the first digit is probably right—to do this is probably a two-billion effort, in US dollars. In order for that to happen, there needs to be a community of hundreds of scientists who are interested in the field, who learned the field, and who can get the agencies to fund that. And I think you can go either way—you could do the space, or the ground.

We are working with the Indian government right now to try to build an interferometer in India. We would provide the components for the interferometer, and they have to provide the vacuum system, the land and so on. They are very interested in this because they think they can learn something about the technology from LIGO. They are interested in science, but they are also interested in technologies that come from LIGO. So you'll learn something by building these detectors.

You've got to dream big. You've got to go for it.