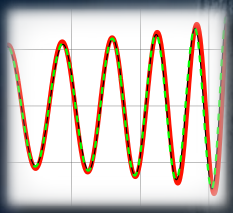
LSC
LIGO
Scientific
Collaboration

LIGO MAGAZINE

issue 2 3/2013

Astronomy with Black Holes p. 10



Finding Black Hole Signals

A challenge p. 14

Upgrading the GEO Input Optics

An inside story p. 20

Title image

Cygnus X-1 is located near large active regions of star formation in the Milky Way. An artist's illustration depicts what astronomers think is happening within the Cygnus X-1 system. Cygnus X-1 is a so-called stellar-mass black hole, a class of black holes that comes from the collapse of a massive star. The black hole pulls material from a massive, blue companion star toward it. This material forms a disk (shown in red and orange) that rotates around the black hole before falling into it or being redirected away from the black hole in the form of powerful jets. [Credit: NASA/CXC/M.Weiss]

Upcoming events (compiled by the editors)

Gravitational Wave Tests of Alternative Theories of Gravity in the Advanced Detector Era (Workshop) Montana State University, Bozeman, USA, April 5-7, 2013, http://www.physics.montana.edu/gravity/workshop/workshop.htm

APS April Meeting 2013 Denver, Colorado, USA, April 13-16, 2013, http://www.aps.org/meetings/april/

The Seventh Huntsville Gamma-ray Burst Symposium Nashville, Tennessee, USA, April 14-18, 2013, http://huntsvilleinnashville.uah.edu/

Black Holes, Jets and Outflows Kathmandu, Nepal, April 29 - May 3, 2013, http://www.iasfbo.inaf.it/events/nepal2013/

Gravitational-wave Advanced Detector Workshop Elba, Italy, May 19-25, 2013, http://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=5484

The Fast and the Furious: Energetic Phenomena in Isolated Neutron Stars, Pulsar Wind Nebulae and Supernova Remnants European Space Astronomy Centre (ESAC), Madrid, Spain, May 22-24, 2013, http://xmm.esac.esa.int/external/xmm_science/workshops/2013_science/

Multi-Time Domain Astronomy Conference Annapolis, Maryland, USA, May 29-31, 2013, http://asd.gsfc.nasa.gov/conferences/TDA_conference.html/

CLEO 2013 San Jose, CA, USA, June 9-14, 2013, http://www.cleoconference.org/home.aspx

ICTS Program and ICTS Summer School on Numerical Relativity Indian Institute of Science, Bangalore, India, June 10 - July 5, 2013, http://www.icts.res.in/program/NRP2013

International Pulsar Timing Array - Student and Science Weeks Krabi, Thailand, June 17-28, 2013, http://ipta.phys.wvu.edu

First TOROS International Workshop Gravitational Wave and Optical Astronomy in the Southern Cone, Salta, Argentina, 27-28 June 2013

CLEO Pacific Rim Conference Kyoto, Japan, June 30 - July 4, 2013, http://www.cleopr-oecc-ps2013.org/

Kerr Conference 4th-5th July 2013, The Albert Einstein Institute, Potsdam, Germany, will host a meeting to commemorate the 50th anniversary of the discovery of the Kerr metric.

20th International Conference on General Relativity and Gravitation and 10th Amaldi Conference on Gravitational Waves Warsaw, Poland, July 8-13, 2013 http://gr20-amaldi10.edu.pl/
The conference includes associated schools: Conformal Symmetry and Perspectives in Quantum and Mathematical Gravity, http://th-www.if.uj.edu.pl/school/2013/, School of Gravitational Waves, http://bcc.impan.pl/13Gravitational/, GR Maple Workshop, http://gr20-amaldi10.edu.pl/index.php?id=23

Caltech Gravitational-Wave Astrophysics School 2013 California Institute of Technology, Pasadena, California, USA, July 22-26, 2013, http://www.cgwas.org

Neutron Stars: Nuclear Physics, Gravitational Waves and Astronomy Surrey, UK, 29 July 2013 - 30 July 2013, http://www.ias.surrey.ac.uk/workshops/neutstar/cfp.php

Hot Topics in General Relativity and Gravitation July 28th — August 3rd, 2013 • Quy Nhon, Viet Nam, http://www.cpt.univ-mrs.fr/~cosmo/GRG_2013/HTGRG.html

September LSC-Virgo Collaboration Meeting Albert Einstein Institute, Hannover, Germany, September 23-27, 2013

Waves and Particles: Multi-Messengers from the Universe Annual Meeting of the German Astronomical Society (150 Years German Astronomical Society) Tübingen, Germany, September 24-27, 2013 , http://astro.uni-tuebingen.de/~AG2013

28th Annual Meeting of the American Society for Precision Engineering Crowne Plaza St. Paul – Riverfront Saint Paul, Minnesota, USA, October 20-25, 2013, http://aspe.net/technical-meetings/aspe-2013-annual-meeting/

Contents

Image credits

Photos appear courtesy of LIGO Laboratory/LIGO Scientific Collaboration unless otherwise noted.

p. 5 Alligator meets Advanced LIGO Commissioners in Lousiana: Photo by Holger Wittel

pp. 6-7 Artist's impression of a BBH merger: NASA/Dana Berry

p. 7 Distribution of progenitor masses: Dominik et al., Astrophys. J. 759 (2012) 52

p. 9 Artist's impression of two stars orbiting each other and merging: NASA/Dana Berry, Sky Works Digital

p. 10 Cygnus Loop Nebula: NASA/JPL-Caltech

p. 12 Orbits of stars in the Galactic Center: KECK/UCLA Galactic Center Group

p. 13 Chandra X-ray Image of Cygnus X-1: NASA/CXC

pp. 14-15 Modelling the coalescing binary waveform: P. Ajith et al., CQG 24 (2007) S689–S699

p. 16 Bank of template waveforms: S. Babak et al., arXiv:1208.3491

pp. 20-23, 31 GEO600 commissioning team

p. 24 Dancing with Black Holes: Erin Auble

p. 32 Cartoon by Jocelyn Read

Welcome to the second issue of the LIGO Magazine!

Andreas Freise
for the Editors

Andreas Freise

I am excited to present the spring issue of the LIGO Magazine. This time our featured articles are all about black holes, in particular the astrophysics and data analysis that LIGO can do to find out more about these elusive objects. Ben Farr and Ilya Mandel explain why black holes are an exciting target for Advanced LIGO and what we can actually learn from their gravitational wave signature. Cole Miller provides the astrophysical context and history on our current knowledge about the existence of black holes, while John Whelan details the data analysis challenges of finding signals from the coalescence of black holes or compact stars in the Advanced LIGO data.

The rest of the magazine is again a colorful mix of conference reports, news items, and stories from the detector sites. We, the editors, would like to thank all of you who provided us with images, articles, updates and comments. Your help makes this a better magazine for the whole collaboration! Our next issue is scheduled for summer this year and we are already looking for new material from everyone. Please get in touch and drop us an email at **magazine@ligo.org**.

LIGO Scientific Collaboration News

Gaby (Gabriela) González
LSC Spokesperson

GGonzález

It is a pleasure to be writing for the *second* issue of the LIGO magazine — the first issue was a resounding success, and I am very glad and grateful to Andreas Freise and his great Editorial Board to keep the magazine going!

At the time you read this issue of the magazine, the LSC may have new people at the helm of several groups: there are ongoing elections for one of the co-chairs in each of the four data analysis groups, dedicated to the search for gravitational waves from compact binary coalescing systems (“CBC”), from un-modeled transient sources (“Burst”), for continuous waves from rotating stars (“CW”), and for stochastic backgrounds from cosmological and other sources (“Stochastic”). There is also an election for Spokesperson; I am one of the candidates, but not the only one — I am glad we have a choice and discuss issues frankly within our Collaboration. I am proud of how seriously we take the democratic process in our academic endeavor, and I hope you all participate either by voting or voicing your opinion with your Council representative!

In the last issue I mentioned several “hot issues” that were being discussed in the LSC and with our partners, and I am glad to report on several decisions that were taken originating from some of those discussions.

Our Bylaws include now a new position for "Assistant Spokesperson" that may be appointed by the Spokesperson, and confirmed by the Collaboration Council. The Spokesperson may delegate some responsibilities to the Assistant Spokesperson, but ultimate authority always remains with the Spokesperson.

A KAGRA-LSC-Virgo MOU was signed to "establish a collaborative relationship between the signatories who are seeking to discover gravitational waves and pursue the new field of gravitational wave astronomy."

We have followed up on several suggestions from the LSC Diversity Working Group chaired by Marco Cavaglià, including the (unanimous!) approval of an "LSC diversity statement" (see story on page 30), and the creation of the position of LSC Ombudsperson to provide confidential, informal, independent, and neutral dispute resolution advisory services. Moreover, we are fortunate that Beverly Berger, a greatly respected colleague and LSC member, has agreed to fill this position for the first year.

On a related matter, we have also approved an "LSC policy for formal complaints" which we hope we don't use often, but we need to have in place. You can read more about the Diversity Working Group and their activities in the article included in this issue.

Our very hard working Publication and Presentations Committee now has two co-chairs, Ray Frey (who had been chairing this committee earlier) and Sergey Klimenko. I take the opportunity here to deeply thank all of you who had helped the LSC by serving in committees at various times in the past: you are very much appreciated!

And talking about committees, two committees chaired by Nelson Christensen and Kent Blackburn have spent large amounts of time and energy studying possibilities for remote communication services to replace the EVO service we learned to love and hate—we'll make some decisions based on their input very soon.

Of course, our mission is scientific, and we have made good progress. We have published several more papers on instrumental science and on results from the latest science runs (story on page 26), and we are also preparing an article about the "Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories", which describes our best estimates for the sensitivity and operation schedule for taking data in the next several years. We are also discussing a plan on how to collaborate with astronomy partners in the follow up of interesting gravitational wave triggers found in the science runs with Advanced Detectors.

I am glad to see the LSC and its partners busily working towards the detection of gravitational waves soon – there's a long but very exciting road ahead, and I thank you all for traveling together towards that goal!

A party of attendees to the Commissioning and Simulation Workshop (see page 27) discovered some of the wilds of Louisiana, including this American Alligator, during a tour of Lake Martin swamp near Breaux Bridge, Louisiana. Photo by Holger Wittel.

Black Holes in Advanced LIGO

the observational payoff!

Ilya Mandel

Ilya Mandel is a Lecturer in astrophysics at the University of Birmingham, UK. He tries hard to persuade the Universe that it should increase the rate of binary mergers in order to improve the prospects for gravitational-wave detections; sadly, the Universe does not feel a sense of obligation.

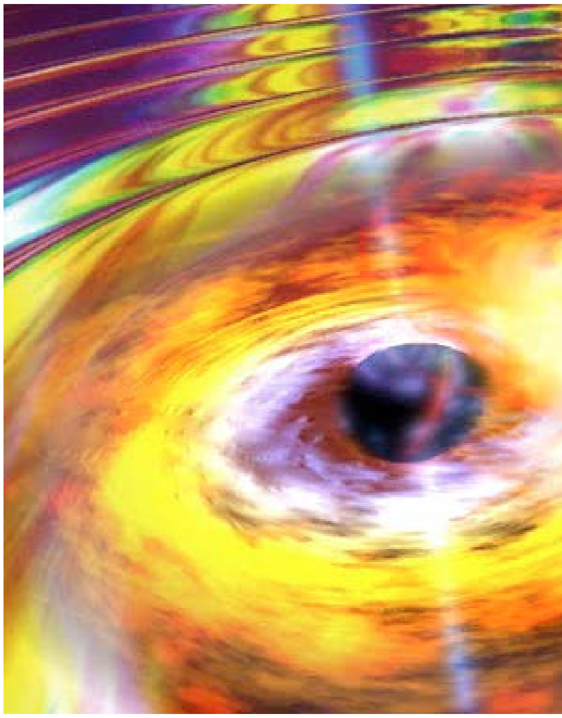
Ben Farr

Ben Farr is a grad student at Northwestern University, working on CBC parameter estimation through their gravitational waves and electromagnetic counterparts. He spends his free time crushing plastic at the local climbing gym.

The current observational knowledge of black holes relies almost exclusively on luminous matter in the proximity of black holes. This restriction has greatly limited our knowledge and understanding of black-hole formation and evolution. In the coming decade, Advanced LIGO will give the astronomical community an opportunity to measure black holes in a completely new way. In this article we discuss some of the prospects for Advanced LIGO observations of black-hole binaries that are most exciting to us personally.

Parameter Estimation

In order to make any astrophysical statements based on gravitational wave observations with Advanced LIGO, we must begin by accurately measuring the parameters of the emitting binary system. These parameters will be encoded in the gravitational waves emitted as the binary spirals in and merges. Parameter estimation algorithms developed to analyze Advanced LIGO signals are currently capable of estimating all fifteen parameters of a circularized, precessing binary black-hole system: component masses, spin vectors, sky position, distance, orientation of the orbital plane, and phase and time at coalescence. However, some parameters are better estimated than others. Advanced LIGO is particularly sensitive to a combination of the component masses, called the chirp mass, which most strongly influences the frequency evolution of the waveform. This parameter is one of the most accurately measured, with typical uncertainties smaller than 1%. The remaining mass parameter, the mass ratio, is less constrained and is often degenerate with the magnitudes of the components' spin. This limits how accurately individual component masses can be measured, which is especially important for characterizing systems based on individual observations. We will first highlight what can be learned from individual gravitational wave observations.

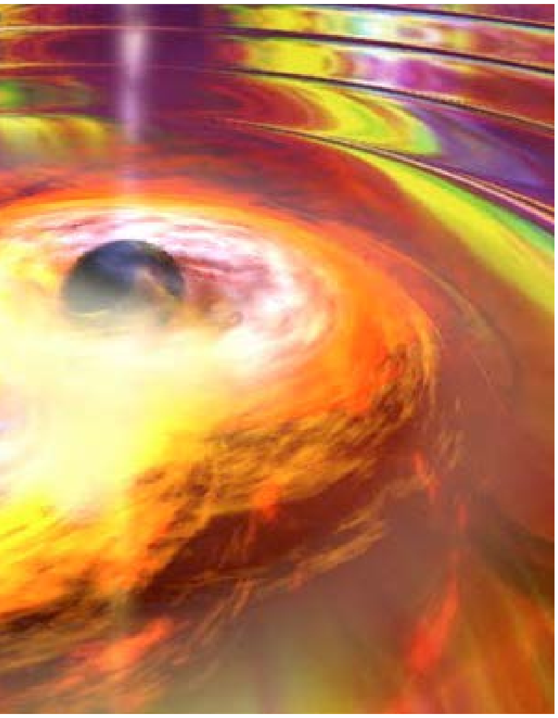


Artist's impression of a BBH merger.

Credit: NASA/Dana Berry

Black Hole Binaries

Our colleagues working with electromagnetic telescopes have not yet detected any binaries consisting of two stellar-mass black holes or a black hole and a neutron star. Even double neutron-star systems are difficult to detect electromagnetically; fewer than ten have been detected in our galaxy so far, and only when at least one of the components can be observed as a radio pulsar. Black-hole neutron-star binaries are expected to be even more rare than double neutron stars. In addition, the neutron stars in them are less likely to be detected as pulsars. This is because they typically won't be spinning as rapidly, since the neutron star would not have spun up by accretion from a companion. It is hardly surprising then that double black holes have not been detected, given the paucity of luminous matter in these systems, although there have been a few in-



teresting, though inconclusive, hints from gravitational microlensing.

In contrast, gravitational waves emitted by more massive systems carry away more energy than those from lighter double neutron stars, allowing gravitational wave observatories to see them at greater distances. Therefore Advanced LIGO is likely to make the first detections of both black-hole neutron-star binaries and double black holes. By allowing us to measure their masses, as described above, LIGO should make it possible to unambiguously classify some of the components of binary systems as black holes. Beyond first detections, LIGO will also be able to place substantial constraints on the relative formation rates of the three types of compact binaries.

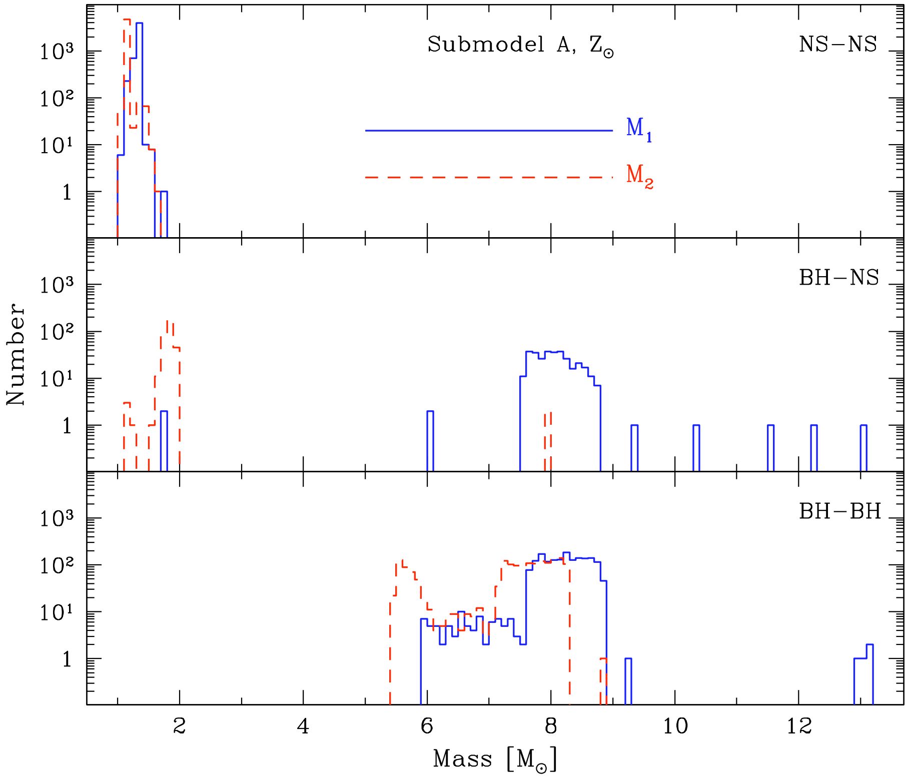
Intermediate Mass Black Holes

Astronomers know of many examples of both stellar-mass black holes (ranging from a few to a few tens of solar masses) and supermassive black holes (millions of solar masses and above). No intermediate-mass black holes in the mass range between these two classes have yet been observed, but that doesn't mean that they aren't there! Despite much observational and theoretical work, the jury is still out on whether intermediate-mass black holes exist. They would be especially tough to detect electromagnetically at the low end of the proposed range, with masses in the vicinity of hundreds of solar masses.

Fortunately, that is precisely the mass range in which Advanced LIGO would be sensitive to intermediate mass ratio inspirals: intermediate-mass black holes merging with neutron stars or stellar-mass black holes. Such mergers are particularly likely to happen in globular clusters, which are dense groups of around a million stars. Hundreds or thousands of globular clusters are present in typical galaxies. Detections of gravitational-wave signatures from intermediate mass ratio inspirals in globular clusters would not only provide the first unambiguous confirmation of the existence of intermediate-mass black holes, but could also probe the dense stellar environments in which they reside. Other possibilities include detections of two intermediate-mass black-holes in a binary, either in globular clusters or in the field of the galaxy, where they may occasionally arise from the evolution of isolated pairs of extremely massive stars.

Detection Rates

Sometimes, as in the cases of intermediate-mass black holes or eccentric binaries, discussed below, individual detections can provide significant astrophysical information. In other situations, we will need to rely on observing populations. Population synthesis models of isolated binaries provide predictions of both merger rates and distributions of parameters, particularly masses, among merging binaries.



The distribution of compact object masses for binary neutron-star, binary black-hole and black-hole–neutron-star systems from one of the population synthesis models presented in Dominik et al., Astrophys. J. 759 (2012) 52

These models depend on many poorly constrained parameters and assumptions, such as natal kicks given to black holes during the supernovae that give birth to them, or the efficiency with which the ejection of a common envelope of hydrogen surrounding a nascent compact binary can carry away the binary's orbital energy. At the simplest level, we can compare the rates of detections of various source types, corrected for selection biases, with theoretical predictions from such models in order to better measure these astrophysical parameters. Even more information can be gained from the observed mass and spin distributions, but these require precise inference on parameters of individual systems.

Mass Gap

Gravitational-wave observations should enable us to probe the existence of a mass gap between the highest-mass neutron stars and the lowest mass black holes. The most massive observed neutron stars are in the vicinity of two solar masses, and theoretically are not expected to exceed three solar masses. Meanwhile, there is some evidence that black holes in X-ray binaries have masses of approximately five solar masses or greater. However, there are only a few available mass measurements, and even these suffer from significant uncertainties and potential systematic biases. Since the distribution of initial stellar masses are governed by a continuous power law, a mass gap between neutron stars and black holes, if confirmed by Advanced LIGO, would shed light on fundamental physics that govern the supernovae which produce such systems.

Measurement of Spin

Of the 25 cataloged stellar-mass black holes, only about a third have had their spins estimated. The tricky business of estimating black-hole spin through electromagnetic observations relies on the measurement of X-ray emission from the accretion disk. This disk is composed of matter from a companion star falling into the black hole. Such measurements, whether in the form of continuum flux from the disk or Doppler shifting of specific emission lines from electron transitions in iron atoms, known as K-alpha lines, are based on the assumption that the inner edge of the disk is truncated at the innermost stable circular orbit allowed by general relativity. They rely on very accurate modeling of disk emission.

Meanwhile, spinning black holes in compact binaries imprint the signature of their spin on the gravitational waveform. Therefore Advanced LIGO measurements of black-hole spins rely on accurately modeling the emitted gravitational-wave signals. For black hole binaries, post-Newtonian models are believed to accurately model most of the inspiral phase of the binary coalescence and Advanced LIGO will be capable of estimating the spin of merging stellar-mass black holes.

Isolated Binaries and Supernova Kicks

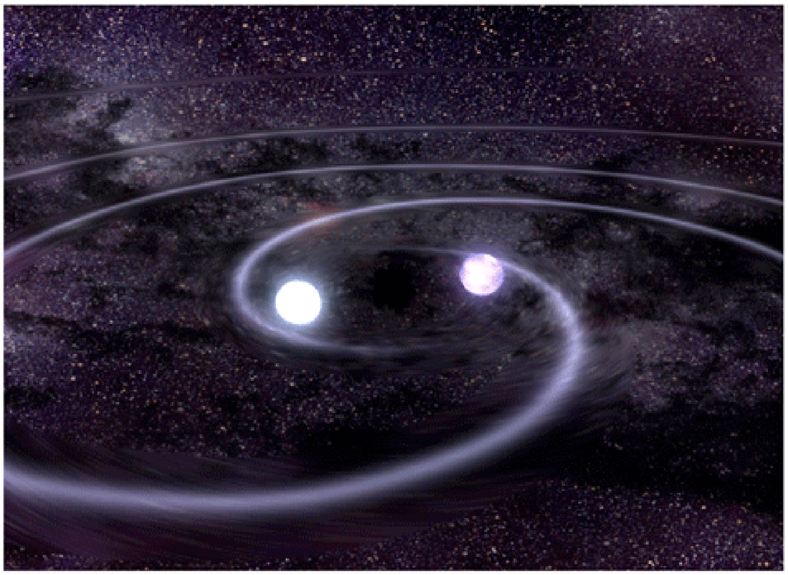
Compact binaries are expected to form through two main channels. The standard channel starts with two massive stars born in a binary system somewhere in the field of a galaxy. The more massive star is usually the first to evolve off the main sequence, eventually exploding in a supernova and leaving a neutron star or black hole. As the second object evolves off the main sequence, it typically goes through a common-envelope phase with the compact object. During this phase the binary orbit shrinks substantially, circularizes if it was eccentric, and the compact object is spun up with its spin aligned with the orbital angular momentum. If both spins are aligned with the orbital angular momentum prior to the second supernova, any spin misalignment measured in a compact binary that formed through this channel is due to asymmetries in the explosion of the last supernova. With Advanced LIGO we should be able to measure the spin misalignment of these systems and put constraints on supernova models.

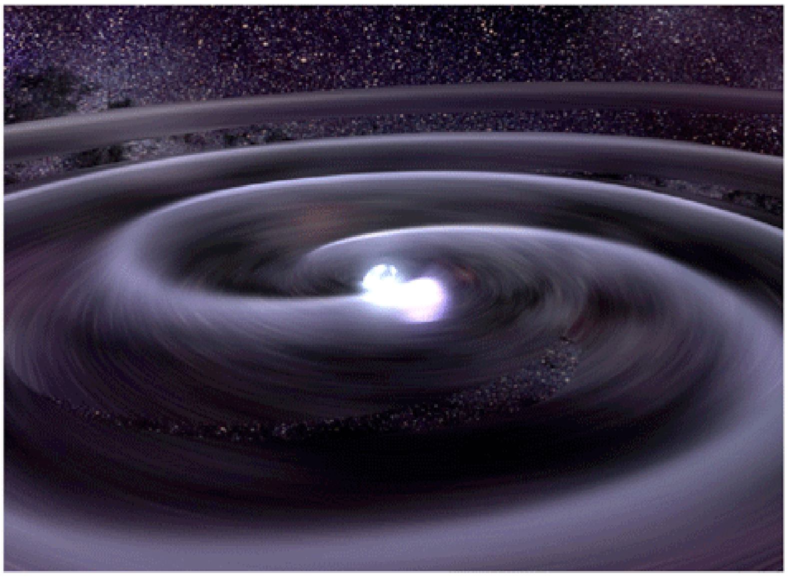
Dynamically Formed Binaries

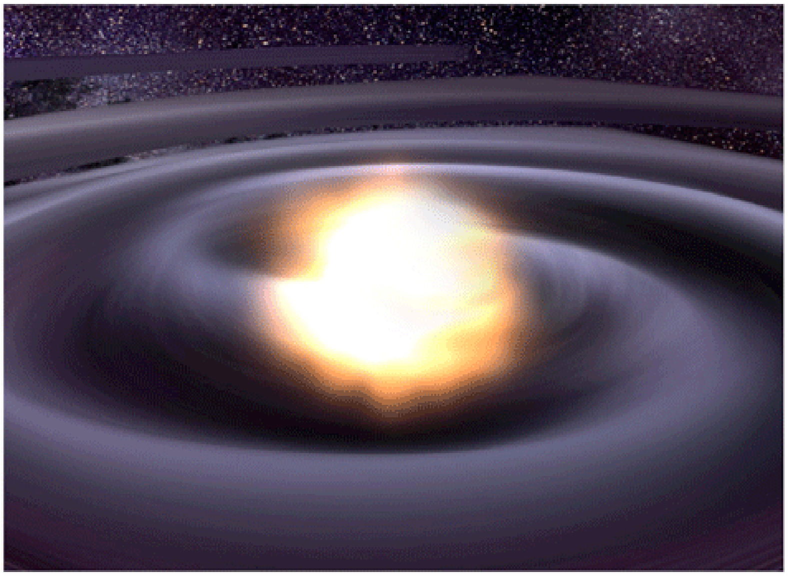
The second major formation channel involves dynamical interactions to bring the binary to the point where it can merge through radiation reaction from the emission of gravitational waves. Dynamical interactions will be important in very dense stellar environments, such as those found in the cores of globular clusters or nuclear star clusters in the centers of galaxies. For binaries formed through this channel, the spin orientations are expected to be completely random, with no preference for alignment as is expected for isolated binaries. By measuring the tilt angles between black-hole spins and the orbit for many systems, Advanced LIGO should be able to differentiate these two populations and determine the relative rate of binary formation for the two channels.

Eccentric Binaries

Isolated binaries, as well as dynamically formed binaries that are gradually made tighter via three-body interactions, are expected to lose any initial eccentricity over their slow evolution and circularize by the time they reach the Advanced LIGO band. However, if two black holes come so close together that they radiate enough energy in gravitational waves at the very first periapsis passage to directly capture each other, they would form a highly eccentric system in the Advanced LIGO band. It has been proposed that, under some optimistic assumptions, such eccentric binaries could form in significant numbers in galactic nuclei - a proposal that we soon hope to test directly.







Testing General Relativity with Black-Hole Binaries

Gravitational waves can teach us a lot about the astrophysical processes that govern the systems that emit them. But even more directly, they are unparalleled probes of strong gravitational fields. One way to parameterize just how deep into the strong-field regime we can probe with a given binary system is with the dimensionless ratio of the binary's orbital velocity to the speed of light. For binary pulsars, which provide some of the best existing tests of general relativity, this parameter is about 0.001. For merging black-hole binaries, this parameter can approach 1. For example, intermediate mass ratio inspirals, which spend many cycles in the strong-field regime, can act as very accurate probes of the spacetime surrounding the intermediate-mass black hole, enabling so-called tests of the no-hair theorem, or, more precisely, measurements of whether the central black hole is, in fact, described by just two parameters - its mass and spin - as expected.

These are just some of the many possible avenues through which Advanced LIGO could teach us about binary astrophysics, dense collections of stars, or the theory of gravity itself. We also hope to observe electromagnetic signatures associated with neutron-star mergers, and to probe the tidal dissipation or even shredding of neutron stars in such encounters, which are among the proposed progenitors of short gamma ray bursts. Meanwhile, the comparison of full inferred distributions of masses and spins of black-hole binaries against population synthesis models can lead to far more precise astrophysical constraints than individual measurements alone.

There are many challenges as well. We will need very accurate waveform models, sophisticated data analysis pipelines, improved astrophysical models to compare against, and robust tools for bringing everything together. The payoffs, however, are well worth the price. We are all very excited about these prospects and we are all working at full throttle to be ready for the exciting science that awaits us in just a few years!

Astrophysics of Black Holes

Black holes are the stuff of dreams for science fiction fans of all ages. They represent what Shakespeare might describe as an "undiscovered country, from whose bourn no traveller returns." Yet astronomical observations suggest that they are also science fact, and may be critical in the evolution of their much-larger galactic hosts. Black holes are some of the key sources whose mysteries will be probed with Advanced LIGO, so in this essay we will begin with their original proposals and then explore our modern understanding and current puzzles.

The origin of the idea of black holes is usually generously extended back to 1784, when a classic 18th century polymath named John Michell (an astronomer, physicist, mathematician, and clergyman!) applied the following line of argument. He noted that according to Newton's law of gravity, a spherical object of mass M and radius R has a surface escape speed of $v_{esc}=(2GM/R)^{½}$, where in the usual idealized physicist's universe air resistance and other complications are ignored. He also knew that the speed of light c is finite, hence he concluded that a star with a radius $R < 2GM/c^2$ would prevent light from escaping and would thus be dark. He speculated that the most massive things in the universe might thus be these "dark stars".

His vision and imagination were impressive, but the relation to our modern concept of black holes is only superficial. For example, he would have imagined it possible to land on a dark star, take samples, have a picnic, and then leave by means of a rocket, i.e., gradually, in the same way that you can go up a flight of stairs one step at a time instead of taking the lot in one giant leap. In contrast, our modern understanding of black holes indicates that once you are inside the horizon (which, for an uncharged non-rotating hole has by coincidence a radius $R_{horizon}= 2GM/c^2$ in the most commonly used coordinates) you can't make any outward progress at all. This is the aspect of black holes that sends a thrill up the spines of science fiction enthusiasts.

Nonetheless, black holes were slow to be accepted. Even Einstein didn't believe they could exist. This disbelief stemmed from a misunderstanding that he and most other researchers had about the nature of the coordinates. They thought that because from a distance falling objects seem to slow down when they get near the horizon, this meant that stars would actually stop collapsing. It took a rediscovery of a more physically transparent set of coordinates by David Finkelstein in 1958 (sadly three years after Einstein died) to rectify this misunderstanding. Even so, the absence of observational evidence meant that black hole study remained the domain of a small group of specialists.

This situation began to change in the 1960s, when quasars were discovered and some researchers suggested that their extraordinary luminosity (often thousands of times that of normal galaxies, concentrated in a region smaller than the Solar System) requires that they are powered by accreting supermassive black holes. Then, in 1971, it was discovered that the Galactic X-ray source Cygnus X-1 probably hosts a stellar-mass black hole. Its strong candidacy as a black hole led to widespread public fascination with these objects (for example, the band Rush recorded the song "Cygnus X-1"; not one of their better efforts, but an indication that black holes were now in the public awareness).

We thus need to understand how it is that a given stellar-mass object is a good black hole candidate. It is useful to appreciate that only a very small fraction of stellar-mass black holes can be identified: only a couple dozen have been established with good confidence, but well-understood stellar evolutionary theory suggests that there should be roughly a hundred million in our Galaxy. Thus special circumstances are required. In particular, because solitary black holes in vacuum are absolutely silent, their presence must be detected by their influence on their surroundings. For stellar-mass black holes, this means that they need to be in a binary with some hapless companion star that donates mass to the hole, leading to bright X-ray emission. Even this is insufficient, because a neutron star can pull off matter in a similar way and produce X-ray emission that is difficult to distinguish from what a black hole would generate. There are ways to tell that a source is not a black hole: for example, regular pulsations or bursts of nuclear fusion caused by accumulation of hydrogen or helium on a stellar surface cannot be produced by black holes. But no one has yet found a spectral or timing property that occurs in all black holes and only black holes.

The key turns out to be the mass of the X-ray producing object. Neutron stars cannot be arbitrarily massive. An argument originally applied to white dwarfs by Nobel Prize winning astrophysicist Subrahmanyan Chandrasekhar applies to neutron stars as well. Essentially, both types of objects are held up by quantum degeneracy. That is, when particles are pushed close to each other, the uncertainty principle guarantees that their momentum will rise. With this rise in momentum (called the Fermi momentum) there is an associated energy (degeneracy energy, or Fermi energy). As long as the degeneracy energy of the particles (electrons for white dwarfs, neutrons for neutron stars) is nonrelativistic, the star will find a stable equilibrium. But if the degeneracy is relativistic, there is a maximum mass beyond which the star is unstable because it can go to more and more negative energies by collapsing.

The maximum mass for neutron stars is poorly known, as it depends on details of high-density nuclear physics that cannot be probed in laboratories. It is at least two solar masses, but no more than three. Thus if one can show that an X-ray emitting object in a stellar binary is at least three solar masses, you don't have a neutron star. Indeed, in about 25 systems, one can rule out a neutron star. It is not a trivial step from there to black holes, but alternatives such as Q-balls and boson stars are ad hoc and unmotivated. Hence black holes are the most conservative explanation for these sources. This is quite a step from the situation just a few decades ago, when the existence of black holes was considered almost disprovable!

In the same way that we now have excellent evidence for stellar-mass black holes, we can say with confidence that some, probably most, galaxies contain supermassive black holes at their centers. As we noted above, the first suggestions came from proposals of how to power quasars. Fairly direct evidence has emerged over the past twenty years from infrared observations of the orbits of the stars in our Galactic center. Many of them are visibly accelerated, and two of them have been seen to go through more than a complete orbit. These orbits unanimously point to a single, unseen, source of gravity that amounts to more than four million solar masses contained within a volume with a radius somewhat larger than the orbit of Pluto.

One might think that this clinches the case for a supermassive black hole, but we have to be careful. That volume, though small by astronomical standards, is enormous by ordinary standards. We could fit many trillions of Suns in that space, so there is plenty of room. One might reasonably object that with that many ordinary stars there would be blindingly bright light, instead of the dim light that we see (the total luminosity is only about that of the Sun). This is, however, easily accommodated by putting a few million white

M. Coleman Miller

Cole Miller is a professor of astronomy at the University of Maryland, and is the current chair of the LIGO Program Advisory Committee. His life's ambition is to use a basketball to demonstrate every concept in astronomy.

dwarfs or neutron stars in the volume instead of ordinary stars. They are dim, and much smaller than normal stars, so they would not even collide. Another argument is necessary.

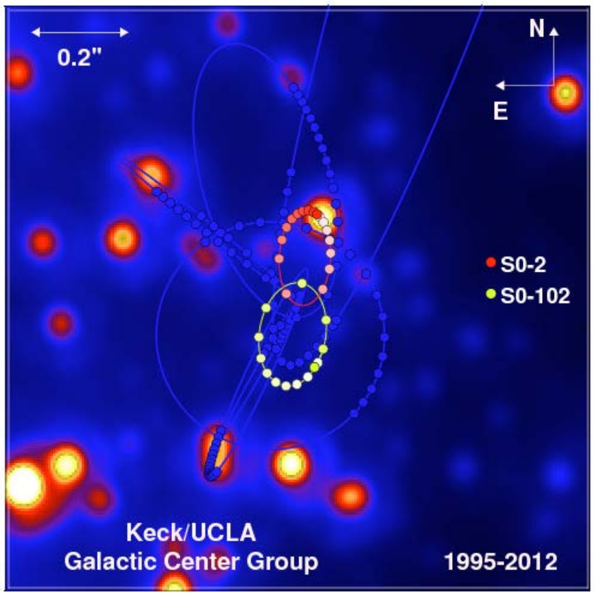
That argument turns out to be that a few million stellar-mass objects crammed into a volume that small will perturb each other's orbits so much that even if you set them up in that volume, within a few thousand years most of them would have been flung out due to mutual gravitational interactions. Thus unless we are profoundly anti-Copernican in our luckiness, it is unreasonable that we are at precisely the right few thousand years in the 10+ billion year lifetime of the galaxy (and tough to see how the situation would exist in the first place). As with stellar-mass black hole candidates there are exotic ad hoc solutions, but a black hole is the best bet here as well.

We obviously cannot observe supermassive black holes in other galaxies with the same precision that we can see ours. Thus a host of less direct techniques have been developed to measure the masses of extragalactic black holes. In some of the best cases (such as the Andromeda galaxy and about forty others), although one cannot see individual orbits one can measure the summed spectra as a function of distance from the center. In these cases we can see Doppler shifts that point to the increase in speed towards the center that signifies a single dominant object. These measurements have shown, remarkably, that the mass of the central black hole is correlated strongly with properties of the surrounding galaxy. This was a real surprise given that a black hole is so much smaller than its galaxy. For example, the horizon radius of our black hole is roughly twenty billion times smaller than the distance from the center to us, and the mass of the black hole is more than ten thousand times smaller than the stellar mass of our Galaxy. A great deal of astrophysical work is devoted to understanding the ways that black holes can co-evolve with galaxies, and it appears currently that much of the distinctive look of galaxies (e.g., the properties of elliptical galaxies) is owed to feedback from radiation and jets from supermassive black holes.

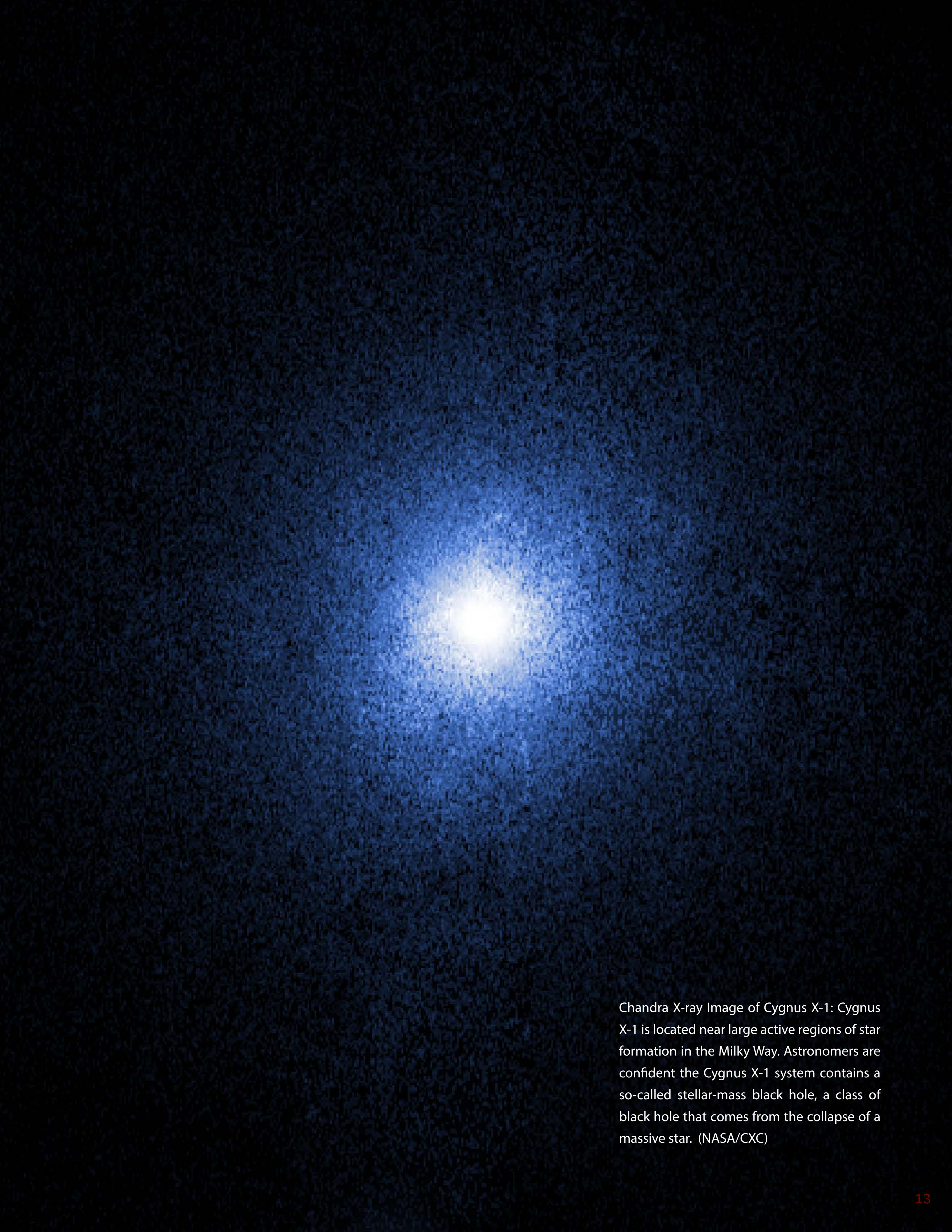
Thus black holes appear to be active participants in astronomy rather than merely selfish consumers of stars and gas. But there are major frontiers not yet reached. Of these, one of the most significant is that the single most important defining characteristic of black holes – their event horizon – has not yet been definitively identified in observations. This is largely because if electromagnetic observations of black holes are possible it is because gas is involved. Where there is gas, there are magnetic fields and other complications, hence interpretation of the observations is not straightforward.

As an example, we mentioned earlier that hydrogen and helium that piles onto a neutron star can become unstable to a flash of nuclear fusion, and hence produce a burst of X-rays. Black holes have no surface, so this can't happen, hence one might imagine that the lack of detection of any bursts from a source would establish that it is a black hole. Indeed, since the late 1970s this has been used as an informal indication of what kind of object it is. The problem is that for sufficiently compact objects one can also have an accretion rate at the surface so high that the hydrogen and helium fuel fuses during accretion instead of being able to build up and flash. In fact, many known neutron stars are in this category, so this is not conclusive evidence of horizons. Different near-future observations may be clearer. For example, there is a push now to have high angular resolution radio observations of our Galactic black hole, in the hopes that the horizon will produce a discernable shadow in the emission from the tenuous matter that is near the black hole. The technology, however, needs further development, and there are details of the emission that are not known and that might complicate interpretation.

Thus Advanced LIGO observations might well be the first that demonstrate conclusively that black holes exist, as predicted by general relativity. The gravitational waves from the inspiral, merger, and ringdown of two black holes can be simulated numerically with great precision. Their characteristics depend intimately on the correctness of general relativity and the existence of horizons. In addition, the emission will be of pure spacetime rather than involving unknowns of magnetic fields and gas, so the interpretation will be clearer than it is in many electromagnetic observations. As a result, gravitational wave observations have every prospect of finally establishing beyond doubt that the long-sought black holes exist as expected.



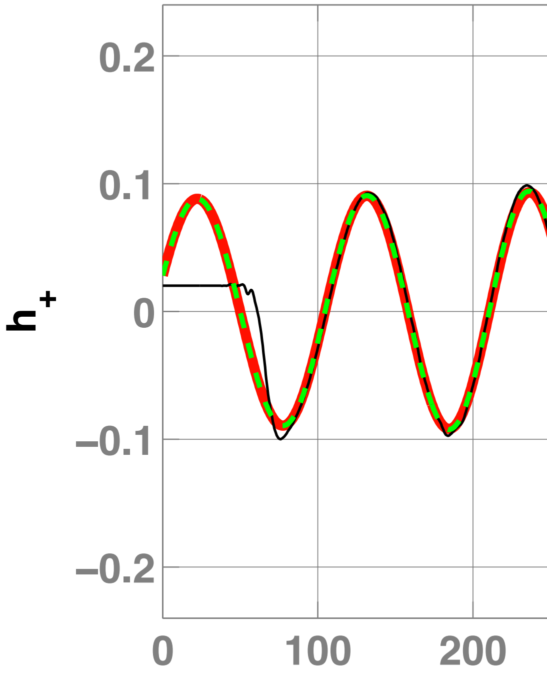
Orbits of stars in the Galactic Center. The two featured stars, S0-2 and S0-102, have been observed over more than a full orbit each, and the orbits of all the pictured stars show that there is a central dark object with mass $4.4 \times 10^6\ M_\odot$*. This image was created by Prof. Andrea Ghez and her research team at UCLA and is from data obtained with the W. M. Keck Telescopes.*



Chandra X-ray Image of Cygnus X-1: Cygnus X-1 is located near large active regions of star formation in the Milky Way. Astronomers are confident the Cygnus X-1 system contains a so-called stellar-mass black hole, a class of black hole that comes from the collapse of a massive star. (NASA/CXC)

Data Analysis

How to find a black hole



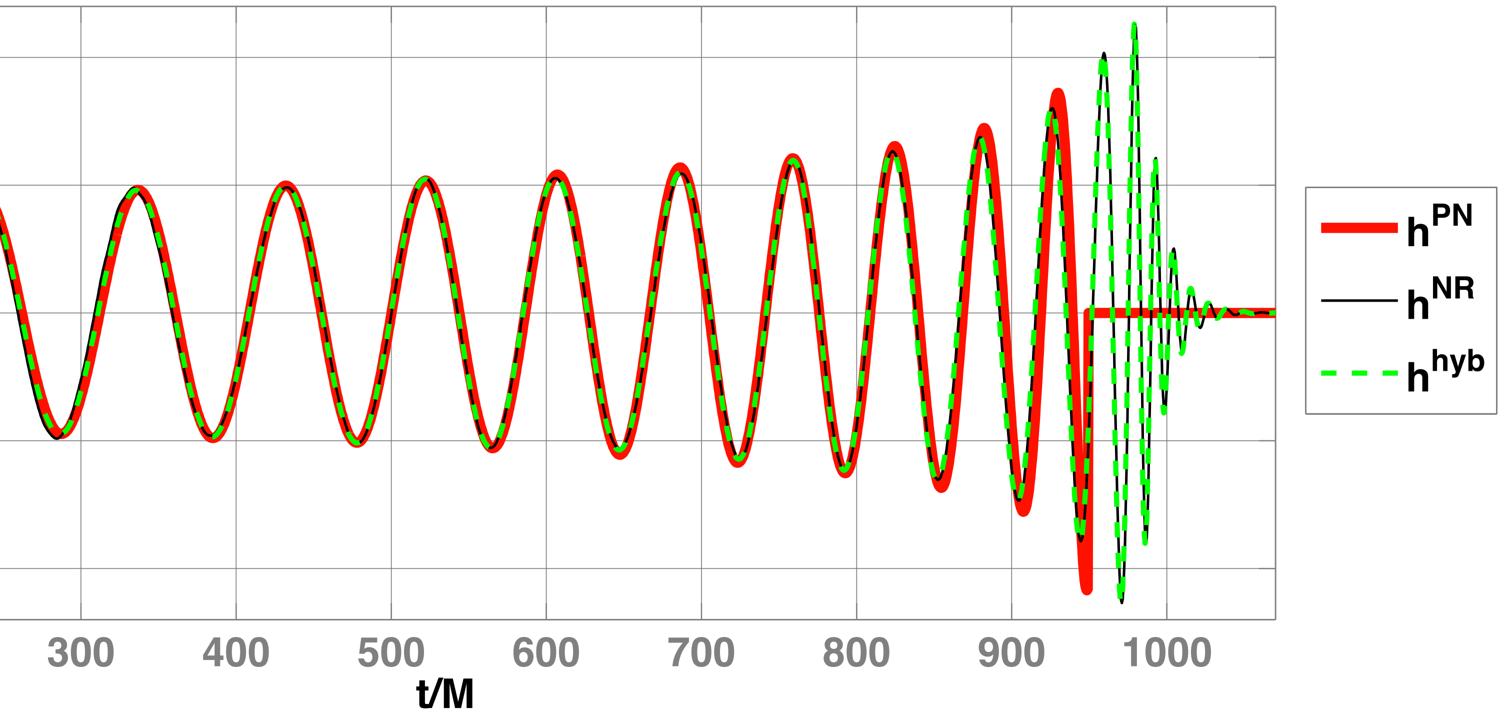
John T. Whelan

John T. Whelan is an Associate Professor at Rochester Institute of Technology, and from 2007 to 2011 co-chaired the committee responsible for reviewing all of the LSC’s searches for gravitational waves from binaries of black holes and neutron stars. When not searching for gravitational waves, John likes to apply Bayesian statistics to college hockey results.

In the world of data analysis, we often think of astrophysical phenomena in terms of the properties of their signals. For that reason, people expecting to hear about black hole inspirals are sometimes surprised to walk into a room full of gravitational wave data analysts and hear us talking about „compact binary coalescences” or „CBCs”. (In fact, the LSC’s inspiral analysis group renamed itself the CBC group a few years into the Initial LIGO science runs.) There are good reasons for this terminology. First, the orbital signatures of black holes are not really that different from those of neutron stars, so it makes more sense to think of binaries of compact objects; their gravitational wave signatures are basically those of orbiting point masses. White dwarfs are also considered compact objects astrophysically, but they’re not compact enough to generate the sort of inspiral signals we are looking for with ground-based detectors. Second, what we expect to see from some compact object binaries is not just the inspiral, but the full coalescence, which can be divided into inspiral, merger and ringdown.

Any orbiting binary system will give off gravitational waves because of the time-varying components of its quadrupole moment, and those waves will carry away energy and angular momentum leading to the decay of the orbit in an inspiral which is initially gradual, but becomes more marked as the masses orbit at relativistic speeds. Since the orbital period is decreasing while the masses are experiencing greater acceleration, the inspiral signal has the familiar chirp form. When the orbital separation has shrunk to about three times the Schwarzschild radius associated with the total mass (the innermost stable circular orbit or ISCO), the objects will stop orbiting and plunge into each other (the merger phase). Finally, after the merger, we will be left with a combined object (almost certainly a black hole, even if we started with a binary of neutron stars), which will ring down from an initially distorted shape to a final stable state.

The details of CBC data analysis strongly depend on whether we need to search for the whole coalescence, or only the inspiral phase. That in turn depends on the frequency of the ISCO, which is determined by the total mass of the system. For less massive systems, such as binary neutron stars, the ISCO occurs at a re-



Modelling the coalescing binary waveform. The "best-matched" analytical Post-Newtonian waveform (red) is attached to the numerical relativity waveform (black) to produce the hybrid waveform (green dashed line). [Credit: P. Ajith et al., Class. Quantum Grav. 24 (2007) S689–S699

latively high frequency, typically out of LIGO's most sensitive band, so an inspiral search is sufficient. For more massive systems, such as the most massive expected stellar black hole binaries, the ISCO can occur at frequencies where LIGO is most sensitive, and the most effective searches will look for the whole coalelescence (inspiral+merger+ringdown) signal.

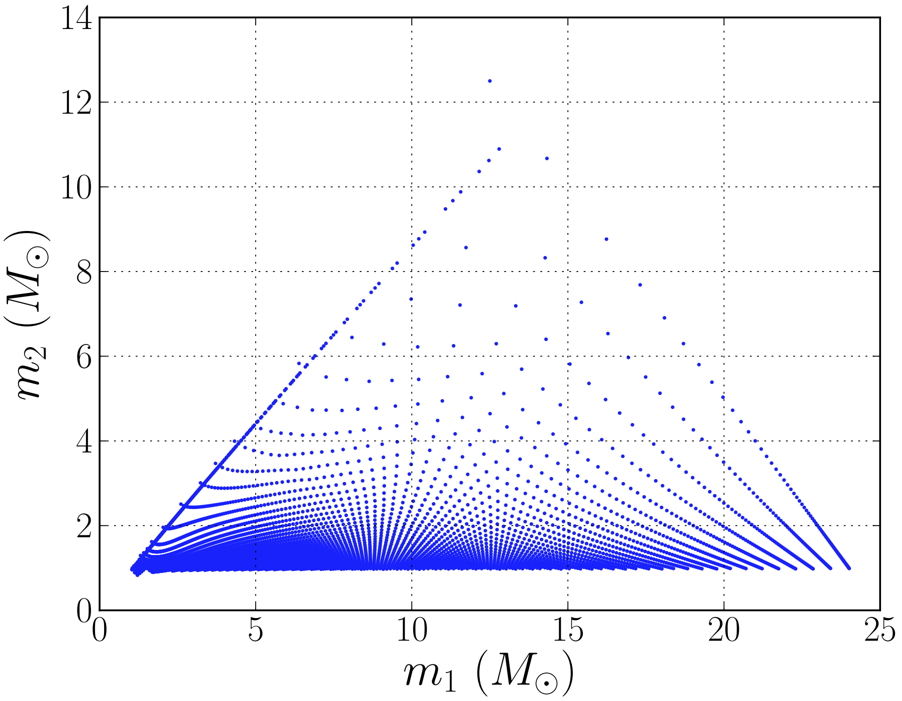
Looking for Signals

To search for gravitational wave signatures in detector data, we need to do several things: first, model the signal itself; second, conduct a matched filter search using the modelled signal as a template; and third, determine the significance of each candidate event returned by the matched filter. To model the signal from a merging binary of black holes of unknown masses, we need to be able to simulate coalescing systems of arbitrary masses. In the earliest part of the inspiral, post-Newtonian approximation methods can be used to determine the orbital evolution of the binary by expanding in powers of the orbital velocity. The final ringdown can also be described by perturbation theory. The merger phase needs to be modelled using numerical simulations. Recent advances in numerical relativity have made it possible to simulate the last few orbits of merging binary black holes, but such simulations are still time-consuming and expensive. This means that we only have the precise merger waveform for the specific mass ratios which have been simulated[1]. To describe a system with arbitrary masses, we fit parameterized families of waveforms to the best numerical simulations we have.

The standard matched filter search constructs a detection statistic which is an integral over frequency of the data multiplied by the signal template and divided by the noise spectrum. This is the most efficient detection statistic we can construct if we know the parameters of the signal, and the noise is Gaussian [1]. There are a number of complications in practice, though. We do not know the parameters of the signal, so we have to try template waveforms corresponding to different mass combinations, as shown in Figure 3. The assumption of Gaussian noise, that means that each Fourier component of the noise can be treated as a random quantity obeying a Gaussian distribution, also does not apply. Loud noise events are much more common than the Gaussian distribution would suggest, so a big challenge is reducing the number of noise outliers that could make us fail to notice a true signal. One important method to achieve this is coincidence: a signal is discarded unless it is seen in two or more

---

[1] *The scale invariance of General Relativity means that a simulation of a given mass ratio describes a whole family of mass pairs. The spacetime for a pair of black holes with masses 6 and 10 times the mass of the sun will look the same as one with black holes of 3 and 5 solar masses, with everything twice as far apart and taking twice as long.*



Bank of template waveforms. In order to search for a signal from a binary system with unknown masses of compact objects, a "bank" of template waveforms is prepared covering all possible combination of masses within the range targeted in the search. On this figure, the total mass of the binary was restricted to be between 2 and 25 solar masses. [Credit: S. Babak et al., arXiv:1208.3491]

different sites (LIGO Hanford, LIGO Livingston and Virgo). Another is signal consistency: a loud noise event will give a big value for the matched filter detection statistic, but the contributions to that statistic from different frequencies will not generally be the same as for a true signal [2]. Our detection statistic is modified to penalize potential signals that don't distribute their signal to noise ratio (SNR) properly.

Although methods like coincidence and signal consistency can reduce the number of loud noise events, they still cannot be expected to obey the theoretical distribution associated with Gaussian noise. So we need a method to assign significance to each candidate event, usually given as an associated false alarm rate (FAR), defining how often we would expect to see matched filter results with that SNR if there were no true binary coalescence signals present. Since we cannot measure this background rate by shielding our detectors against gravitational-wave signals (as is done in some astronomical observations and particle physics experiments), we use our coincidence requirement as a way to simulate these off-source measurements [3]. If we look for events which occur, say, five seconds apart in Livingston and Hanford, we will not see any events associated with gravitational waves hitting both detectors. This „time slide" should, however, contain some accidental coincidences due to independent loud noise events. By doing many of these time slides, we can get a measure of how significant any „zero lag" (i.e., truly coincident in time) candidate signal is. The basic analysis that is run in the CBC search starts with one hundred different time slides, so for example, if a matched filter SNR above a certain threshold is seen 7 times in the 100 time-slides associated with analysis of that month of data, the false-alarm rate corresponding to that SNR is .07 per month. To be a potential first detection of gravitational waves, a signal really has to be a zero FAR event in this first pass. Even if a coincident signal is louder than anything seen in the 100 time slides, we can only say that it had a less than 1% chance of occurring by accident.

Interpreting the Results

Once we have done the signal processing to find the possible signatures of black hole coalescences in LIGO data, we need to interpret them using statistical inference. We can learn about both the rate of binary black hole mergers within the observable universe, and the properties of any mergers we observe. In the process, we use techniques from both major statistical schools of thought: Bayesian and frequentist. A typical Bayesian question is: given the results of the experiment, how likely is it that the rate of binary black hole mergers is within a certain range? A typical frequentist question is: if there were no nearby binary black hole mergers during our observation time, how likely is it that the loudest candidate event would be above a certain SNR? While the Bayesian questions are often the most natural expressions of observational science, the frequentist false-alarm probabilities are the standard measure used to declare a first detection.

The initial and enhanced LIGO runs gave us a fair amount of experience setting limits on event rates. The method used was the "loudest event statistic" [4], which is well suited to setting upper limits when true signals are rare. For a given observing run, the strength of the most significant candidate event (as measured by SNR or associated false alarm rate) is noted. The data are then analyzed with the addition of a population of simulated black hole binary coalescence signals. This allows us to determine the sensitivity limits of the search, for example, the furthest distance from which a signal from a coalescing binary black hole can still be seen. We can then calculate how likely the observed results would have been as a function of the merger rate, and use this to assign a posterior probability distribution to the merger rate given the observations. A nice property of Bayesian statistics is that we can easily combine the results of multiple observations, using the posterior probability distribution from one observation as the prior probability input to the next [5].

We also have some experience considering the properties of a true signal, in the form of the Blind Injection Challenge. The "Big Dog" event, with strong binary coalescence signals in both Hanford and Livingston data, required a meaningful false-alarm estimate well below the 1% level possible with only 100 time slides. In the end, the CBC group was able to simulate millions of time slides by considering all the loud signals in S6, and determine that such a loud coincident signal should happen by accident less often than once in 7000 years [6].

The matched filter search also gave some information about the parameters of the (simulated) system responsible for the Big Dog event, based on the parameters of the best-fitting template. In particular, it was able to pin down pretty well a combination of the two masses known as the chirp mass, which has the biggest impact on how the signal evolves with time. It was also able to make a qualitative statement that spin was likely important, since followup analyses with templates generated from spinning black hole binaries produced an even more significant matched-filter result, and confine the likely origin of the signal to a ring on the sky corresponding to the difference in arrival times at the two detectors. In the end, though, a matched-filter search is not optimized to estimate signal parameters, but to detect the signal. To make more systematic and quantitative statements about the parameters of the signal required the efforts of another subgroup, dedicated to parameter estimation of candidate signals. These parameter estimation analyses use methods such as Markov Chain Monte Carlo to explore the space of possible signals and see how well each of them fits the observed data, producing posterior probability distributions for the various parameters. (An LSC-Virgo parameter estimation paper is in the works, which will explain this in some detail.)

Disseminating the Results

To end on a personal note, the final step in the analysis is to write up the results and submit the paper for publication. The people performing the analysis have hundreds of co-authors in the collaboration who are ostensibly standing behind the results. The task of the review committees is to act as a proxy for the rest of the collaboration, carefully checking every aspect of the analysis, from the data characterization, to the analysis methods and software, to the handling of the data, to the interpretation, and finally the presentation. Going through an internal review can be a difficult process (for the reviewers as well as the reviewed!), but we put out stronger papers as a result of it. And we have often found that, as a result of external scrutiny above and beyond that of a peer reviewer, we end up with observational results papers which have a smoother time with journal referees than papers which have not been similarly polished.

References

[1] B. Allen et al., Phys. Rev. D 85, 122006 (2012) http://prd.aps.org/abstract/PRD/v85/i12/e122006

[2] B. Allen, Phys. Rev. D 71, 062001 (2005) http://link.aps.org/abstract/PRD/v71/e062001

[3] S. Babak et al., http://arxiv.org/abs/1208.3491

[4] R. Biswas et al 2009 Class. Quantum Grav. 26 175009 doi:10.1088/0264-9381/26/17/175009

[5] J. Abadie et al, Phys. Rev. D 85, 082002 (2012)

[6] LIGO Scientific Collaboration and Virgo Collaboration, The LIGO / Virgo Blind Injection GW100916 (2011), http://www.ligo.org/science/GW100916/

LIGO 2013

Assembly Technicians Building Advanced LIGO

Dale Ingram

Dale Ingram is the Education and Outreach Coordinator at LIGO Hanford Observatory. He joined LIGO in 2004 after serving for 20 years as a science teacher near Portland, Oregon.

The installation of Advanced LIGO is a large project involving hundreds of people. Want to learn more? See our feature story, "Under construction: Advanced LIGO" in the first issue of the LIGO Magazine.

Since 2009, tens of thousands of Advanced LIGO parts have streamed into the Livingston and Hanford Observatories. Assembly technicians provide much of the work force needed to assemble the parts into subsystem components and install the components into the L1 and H1 detectors. These individuals have come to the project from a wide variety of backgrounds. Most were hired in 2009-2010 and will serve four-year or five-year terms of employment.

Two aLIGO assembly technicians, Andres Ramirez and Mitchell Robinson, are making their way through Advanced LIGO construction at LIGO Hanford (LHO). Their histories reveal some of the diversity that exists among this group of employees. Andres spent his early years in Havana, Cuba before coming to the U.S in 1996. He earned an electrical engineering degree in Cuba and has completed an Associates' Degree in networking at Columbia Basin College (CBC). Before coming to LIGO, he served for eight years as an assistant educator, working with children at a local elementary school. Andres works on the suspensions team, building and installing suspensions for large and small optics. Mitchell grew up in Prosser, Washington, a 30-minute drive from LHO. After graduating from Prosser High School, he began taking courses at CBC and was employed at a home improvement store prior to coming to LIGO. Mitchell manages the logistics of supplying parts for the LHO seismic isolation subsystem.

Andres enjoys bicycling the miles of pathways that adjoin the Columbia River in the Tri-Cities. A family man, he often finds himself busy with the activities of his children. He first came to LHO in 2008 as a student intern from CBC and was hired from the internship into the assembly technician position. He welcomes the opportunity to work on the advanced detector and expand his collection of skills and experience. "I'm proud to be a part of the project. It was quite a transition, to move from dealing with dozens of small children simultaneously to working on a small team in a very quiet, very clean environment."

Mitchell dabbles in beekeeping outside of work. At LIGO, he coordinates with the site's clean and bake team and others to ensure that the proper seismic parts will be ready in the assembly chain at the proper time. He participates in installation tasks and contributes to the upkeep of the aLIGO parts database. He regularly interfaces with LIGO personnel at Livingston, Caltech and MIT. When asked what stands out about his current job, he replies, "The cultural diversity in LIGO is remarkable. I regularly interact with people from around the world. I really enjoy being a part of something that has such a large scope not just a local effort, but an international effort."

Both men responded quickly to a question about workplace challenges. "Alignments of multiple-stage suspensions are tough," said Andres. "You can fix an optic's pitch, but perhaps you'll disturb the yaw or the roll. It's difficult to change one alignment parameter without affecting others." Mitchell focused on the human element of the project. "aLIGO exists at several widely separated sites. As much as we try to systematize our practices, differences often crop up because we're so separated. There's a constant need for more communication so we can maintain adequate familiarity with each other's materials and methods.

Mitchell and Andreas, along with other assembly technicians, know that the conclusion of aLIGO installation is on the horizon. Both will be interested to apply for any LIGO openings that could allow them to stay on as permanent staff, and both will prepare themselves to search for new opportunities outside of the aLIGO grant. Both feel that their future prospects will be greatly helped by their experience in LIGO. They will carry into their futures the memory of building one of the world's most sensitive instruments.

Mitchell and several LIGO Hanford colleagues enjoy beekeeping as a hobby. Here he's relocating a feral beehive.

Andres attaches LHO's first production quadruple suspension to an internal seismic isolation platform (ISI) in August, 2011.

Two Weeks at GEO 600

The Input Optics Upgrade

Kate Dooley

Kate Dooley is a postdoc at GEO600, where she is putting her LIGO commissioning experience to use improving the integration of the squeezer with the interferometer. She's finding that German is replacing all of the French she once knew!

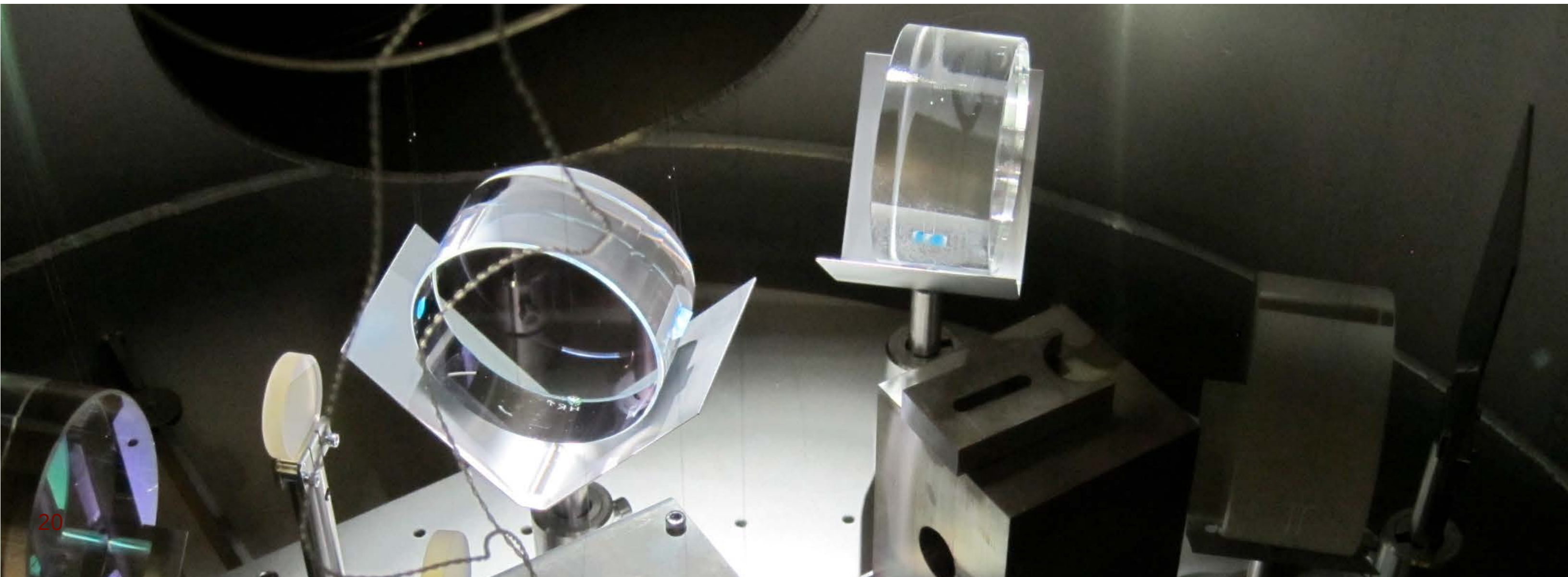
A few weeks in October and November 2012 were highlighted by the most extensive work inside the GEO600 vacuum system in many years. We replaced four of the six mode cleaner mirrors and the two suspended electro-optic modulators. This is part of a program of upgrades intended to improve the sensitivity of GEO at high frequencies (above 500 Hz).

Called GEO-HF, this program involves a combination of demonstrating advanced detector technology, including permanent application of squeezing and an increase in the bandwidth of the signal recycling cavity, and developing solutions to the technical challenges of increasing the circulating laser power from about 2 kW to 20 kW. GEO also serves as the sole gravitational wave detector in operation. Since September 2011, once both Virgo and LIGO were de-commissioned to construct Advanced Virgo and Advanced LIGO, GEO has been operating in astrowatch mode. When we're not actively working on the detector, GEO is collecting data which will be searched in the event of an external trigger, like a supernova in our galaxy.

The upgrade to higher laser power necessitated this vacuum incursion. GEO has an Enhanced LIGO style 35 W laser from Laser Zentrum Hannover (LZH), but until now we've been using at most only a few watts. The reason? Tests show that the lithium niobate ($LiNbO_3$) crystals used in the electro-optic modulaters (EOMs) will become damaged at higher powers. The EOMs generate the RF sidebands used for sensing the interferometer's length and angular degrees of freedom.

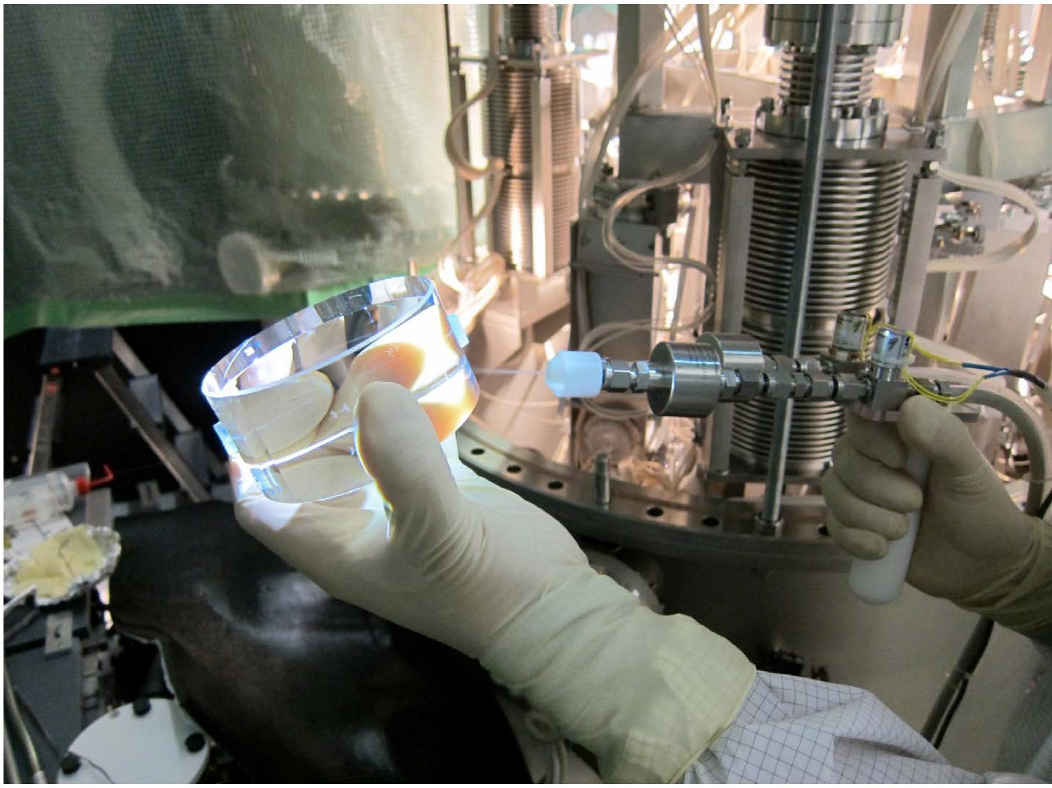
GEO uses two input mode cleaners in series to purify the spatial mode of the laser light entering the interferometer. These mode cleaners were originally built with high finesse. This means they have very good performance as mode cleaners, but it also makes for a very large amount of optical power circulating inside the cavities, which leads to relatively high losses and some radiation pressure effects. In order to use the laser power available, we therefore had to replace the EOM crystals with rubidium titanyl phosphate (RTP) which can withstand higher power, and replace the input and output coupler mirrors of each of the mode cleaners with mirrors of lower reflectivity to decrease the finesse.

What makes this work tricky is that the vacu-



Right: In preparation for installation, a mirror is cleaned of any lingering dust using a carbon dioxide snow jet.

Below: Harald Lück uses a deionization gun to remove any static charge from the optic before it is suspended. A static charge could lead to unwanted forces.



um tanks are small and crowded. Moreover, the laser beam is around one meter below the tank rim, requiring a careful reach into the tank in order to do the work. We gathered a team of long-armed, patient, and careful people to give us the best chance of not breaking any of the twelve double-pendulum suspensions during this work. A lab diary documenting highlights from the weeks of October 15 and October 22, 2012 follows:

Monday, October 15

We vented the mode cleaner vacuum tanks today. They're separated by a gate valve from the central tanks which contain the power recycling mirror and main beam splitter. This will make the final alignment challenging: because the beam is blocked by the gate valve, we won't be able to check that the beam exiting the mode cleaners actually hits the power recycling mirror 4m away!

In preparation, we set up some alignment fiducials prior to venting, making marks on walls where pick-off beams exit the vacuum system through viewports. We also set up an off-the-shelf helium-neon (HeNe) laser, sending it into the mode cleaners from the back, to use as an additional alignment reference.

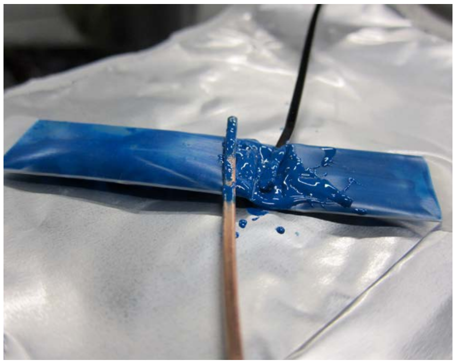
Tuesday, October 16

The vacuum tanks are like bell jars. A crane is required to lift the lid off, but there's only one crane in the main building and nowhere to set the tank lid down, so we can only have one tank open at a time. The mode cleaners and EOMs share two tanks four meters apart. They're the same size, but one has four suspensions in it and the other has eight. We decided to start with the less-crowded tank to get some practice. There's only one mirror to be replaced in this one, and one EOM. Today's work involved removing the old mirror by simply lifting it up and off of the two loops of steel wire that hold it; and we created stands on which to elevate the joint EOM/Faraday isolator suspension platform to make it easier to work on. We also discovered that at least two of the suspension shadow sensor flags had fallen off. The flags are rectangular pieces of aluminum glued onto the magnets used for coil actuation of the upper stage mass. They block half of the light emitted from a diode such that motion of the magnet (and therefore of the mirror) can be sensed. We have to get prepared to glue the flags back on in situ!

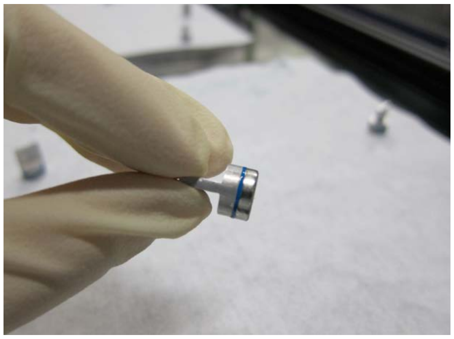
Wednesday, October 17

We installed the first new mode cleaner mirror this morning. The 0.004 inch diameter steel wires have slightly furled up on themselves since removing the old mirror, so the first task was to carefully pull them straight without introducing kinks, and then place the new mirror on them. This last step took a couple of tries because you have to have the mirror rotated correctly so that its magnets line up with the coils, and you need to make sure the wires end up approximately centered along the barrel. The fact that the wires are made from ferromagnetic steel and like to stick to the magnets did not make it any easier. Once it's in place, we can perfect the rotation and wire placement.

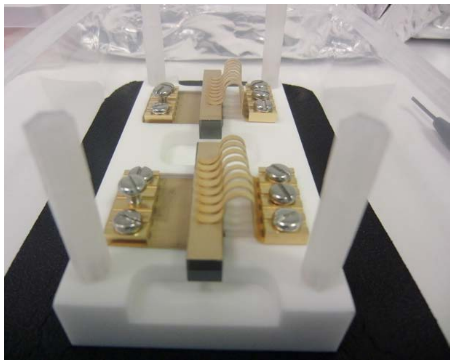
We also installed the new EOMs today, which involved dealing with screws in hard-to-reach places. There are two 6 mm cross-section RTP crystals in series, to provide the RF sidebands for the Michelson and signal recycling cavities. With a little tuning of the new RF matching circuits, less than 10% of the RF power gets reflected — not bad!



A batch of TraBond epoxy is prepared. The epoxy is used to glue shadow sensor flags onto the optics.



Here the flag is glued to a magnet using freshly-prepared epoxy. The magnet will be glued to the upper-stage mass in the suspension chain.



Two rubidium titanyl phosphate (RTP) crystals in series are used as electro-optic modulators. The top and bottom surfaces of the crystals are coated with gold to make electrodes. The index of refraction (and thus the optical path length) in these crystals is changed by applying a voltage across these electrodes. Applying a voltage varying at radio frequencies generates RF sidebands around the laser carrier. These sidebands are used to produce signals which allow the state of the interferometer to be sensed.

Thursday, October 18

With the new EOMs and mode cleaner mirror now in place, we spent today preparing to close the tank. We discovered that the alignment of the mode cleaner mirror to the HeNe laser fiducials was not accurate after all: yet another of the upper mass shadow sensor flags had fallen off. The change in weight affected the whole suspension's tilt. We will have to readjust the balance weights atop the top mass to match our alignment fiducial once we glue the flag back in place.

Another aspect of the input optics upgrade is the mode matching to the interferometer: the diameter of the laser beam and the curvature of its wavefronts must match the resonant mode of the interferometer. Matching these modes is done in part with lenses.

The convex back side of the output mirror of the mode cleaner and a lens work together to bring the laser beam to a 1 cm focus at the power recycling mirror. Until now, only 80% of the light incident on the power recycling cavity was coupled into the cavity. Upon opening this tank, we learned why: we were surprised to find that the installed lens has a 1m focal length, while, according to our model, it should be 2m. Because we have to order this new lens and wait for it to arrive, we're closing up this tank without re-suspending the EOM/Faraday isolator unit with the plan that we'll return to it next week with the lens in hand. We'll work on the other tank in the meantime.

Friday, 19 to Thursday 25

We opened the other mode cleaner tank on Friday, and at least nine flags broke off! Needless to say, we've learned that the glue that was used years ago becomes brittle in vacuum. We spent the next days removing the remaining mode cleaner mirrors to be replaced and all of the broken magnets and flags, noting the polarity of the magnets as they were removed from the flags. We scraped away the old glue and cleaned all surfaces with isopropanol. Finally, we prepared a packet of vacuum compatible epoxy and worked in parallel to glue the glass prisms to the barrels of the new mirrors and the magnets to their flags before the glue set.

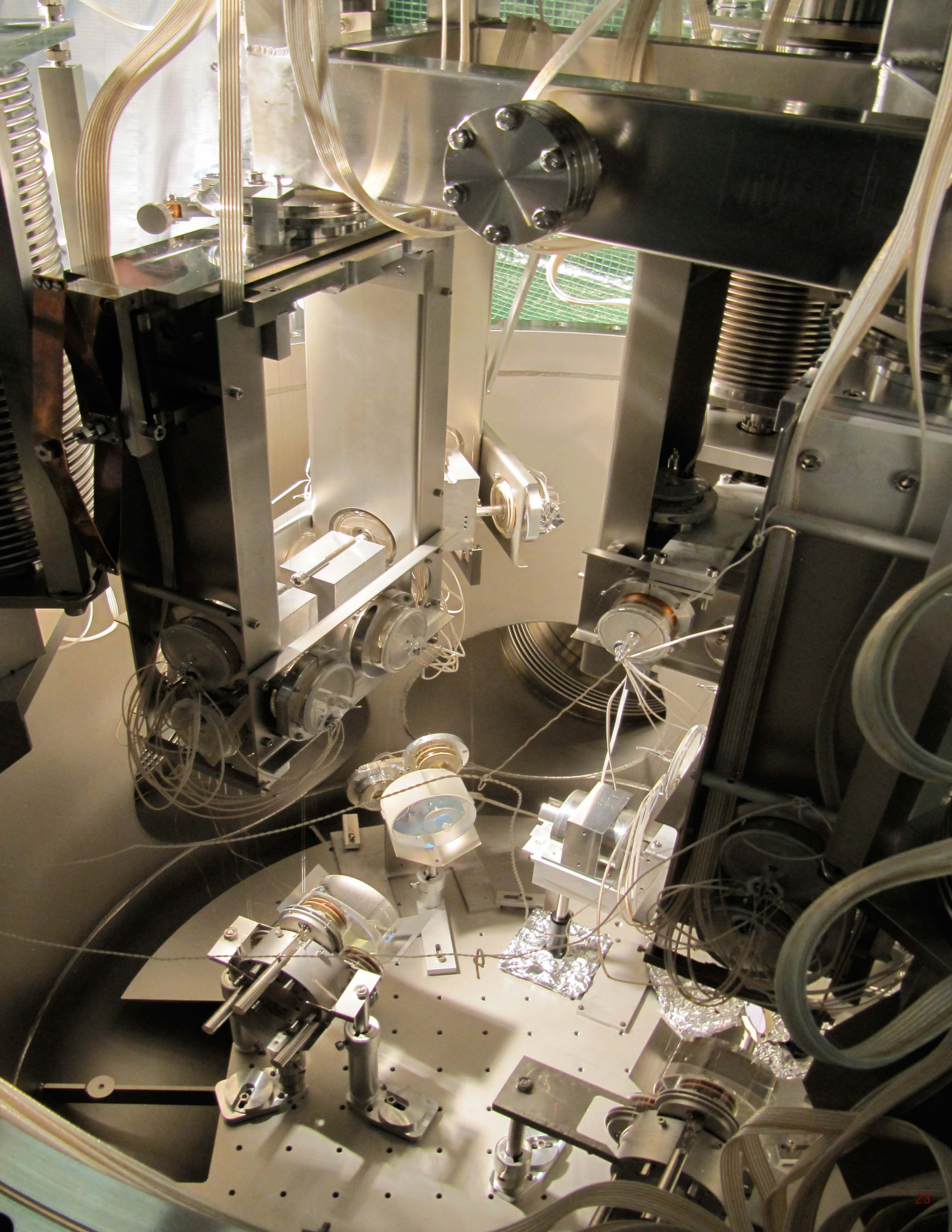
On Wednesday, we spent the morning installing the flags and magnets we had removed and repaired over the course of the last two days. In some cases we had to remove the actuator coils to install the flags, which often involved creative hand positions! We installed all but two successfully. When those pieces are re-installed, we will have replaced bad glue joints for 23 out of the 32 flags in this tank.

On Thursday we installed the three new mode cleaner mirrors and positioned all coils to middle of full range and made sure damping was on and working. The next step is unblocking the laser and aligning the MC1 mirrors in an attempt to see flashes.

Epilogue

After any major work on the guts of a complicated interferometer system, it takes time to return the machine first to its original performance before reaping the rewards of the work. After a few weeks GEO was back up and running and we began turning up the laser power. Now we are using up to 60% more laser power and are working towards increasing the power further.

There is much work to be done to understand this state and to progress to yet higher powers. Our grad students, post-docs, scientists, and technicians are hard at work commissioning a new thermal compensation system, investigating the effects of scattered light, optimizing the output mode cleaner, improving the squeezed light injection system, and improving the frequency noise servo. What we learn will speed the commissioning of the advanced detectors and also give GEO all the better chance of making that first astrowatch detection.



Manuela Campanelli

Manuela Campanelli is a professor of astrophysics and mathematics at Rochester Institute of Technology. She is also the director of the Center for Computational Relativity and Gravitation, and leads the AstroDance project.

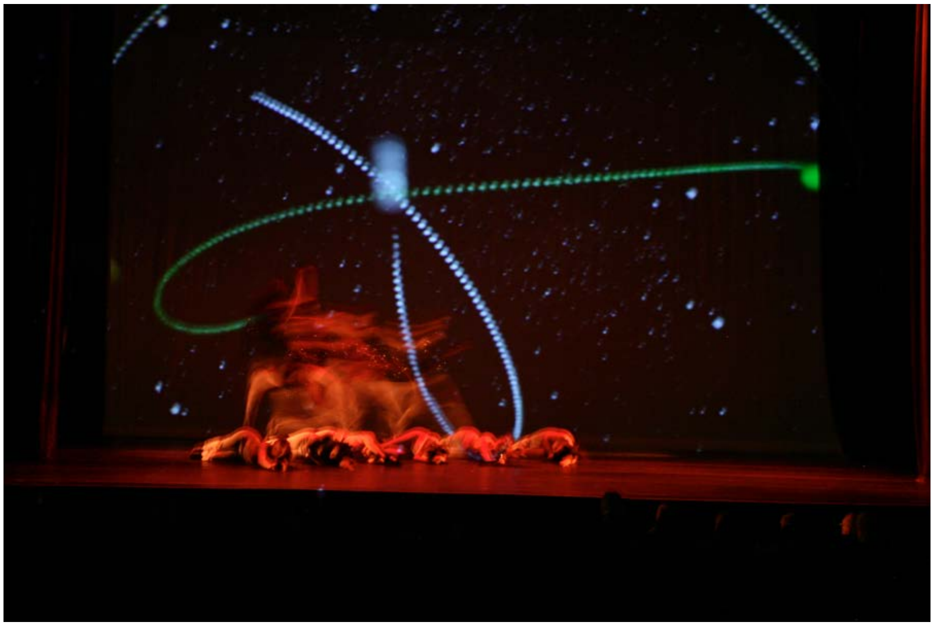
Astrophysics and dance at RIT

A team of astrophysicists, computer scientists, theater artists and designers, social scientists, science educators, dancers and choreographers from the Rochester Institute of Technology's Center for Computational Relativity and Gravitation (CCRG) and the National Technical Institute of Deaf (NTID) worked together to develop a novel dance-based performance to educate the general public about LIGO and gravitational wave astronomy.

Sponsored by the National Science Foundation (NSF) program "Communicating Research to Public Audiences" (CRPA, DRL-1136221), the production features a fictional superman-like character "Gravity Man" capable of explaining how the universe evolved, from the Big Bang to the formation of our solar system, according to gravitation and other fundamental laws of physics. Doing so, he introduces challenging concepts described by Einstein's general theory of relativity, such as spacetime, gravitational waves and black holes, to deaf and hearing audiences. The performance includes music, dance, multimedia displays and visualizations. A photo of the performance can be seen below.

Manuela Campanelli, who is the principal investigator of the project and the Director of the CCRG, and her RIT colleagues, Jake Noel-Storr, Yosef Zlochower and Jason Nordhaus, have created a storyline that presents these concepts in easily understandable vignettes that correspond to the dance elements being presented. This is aided by computer generated graphics and high-end visualizations of gravitational wave phenomena produced by Hans-Peter Bischof, a professor of computer science at RIT and a member of the LSC Education and Public Outreach group. The dance includes student performers from the NTID/RIT Dance Company and choreography developed by a well-known artist, Thomas Warfield, who has worked with many of the world's leading artists, including directors Franco Zeffirelli and Spike Lee, composers John Adams and Marvin Hamlisch, scientist Carl Sagan, singer Placido Domingo and others. The performance is highly visual and incorporates the use of American Sign Language to make it accessible to both deaf and hearing audiences. The choreography is designed to connect the dance to key building blocks of astrophysics. Joseph Bochner, department of Cultural and Creative Studies at NTID, is responsible for oversight of the traveling production and project evaluation.

The production is traveling to various locations in the northeastern United States. Performances are planned for select sites in New York, Ohio, Connecticut, Rhode Island, Washington DC, Pennsylvania and Maryland. It is estimated that the project will directly impact 7,000 individuals, approximately half of whom will be deaf or hard-of-hearing. Project activities will be disseminated through the website hosted by the Rochester Institute of Technology, as well as social networking sites including Facebook, Twitter, and Google+. The project will also be promoted through science festivals and media events.



Dancing with Black Holes [Credit Erin Auble]

We Hear That ...

Awards

Lynn Cominksy was named a Fellow by the AAAS (Astronomy) division for "her work in outreach for X-ray and gamma-ray Astronomy (NuSTAR, Fermi, XMM, Swift) and for her inspiration to undergraduate students at Sonoma State".

Several articles by LSC members were selected by *Classical and Quantum Gravity* to be included in their "Highlights of 2011-2012." See **http://iopscience.iop.org/0264-9381/page/Highlights** for a list.

The following LSC members were elected Fellows of the American Physical Society in 2012, nominated by the Topical Group in Gravitation: **Balasubramanian Iyer** (Raman Research Institute), **Sergey Klimenko** (University of Florida, Gainesville), **Carlos Lousto** (Rochester Institute of Technology), and **Sheila Rowan** (University of Glasgow). Also elected was **Raymond Beausoleil**, former LSC member in the Stanford group and now at Hewlett-Packard, nominated by the Forum on Industrial and Applied Physics, and **Thomas Carruthers** recently retired LIGO program officer at the National Science Foundation.

David McClelland (Australian National University), **Nergis Mavalvala** (MIT) and **Roman Schnabel** (University of Hannover) were granted the 2013 American Physical Society Joseph F. Keithley Award for Advances in Measurement Science "for seminal contributions to the development and application of quantum metrological methods, in particular of squeezed light sources and optical springs, enabling sensitive measurements beyond the standard quantum limit."

Tarun Souradeep, Professor at IUCAA, Pune, was elected a Fellow of the Indian Academy of Sciences in 2013.

PhD graduations

Christina Bogan defended her thesis on "Stabilized High Power Lasers and Spatial Mode Conversion" in February at the Albert Einstein Institute and currently works in Hannover as a post-doc.

Irene Di Palma defended her thesis in August 2012, "A first search for coincident gravitational waves and high energy neutrinos."

Philip Graff completed his PhD at the University of Cambridge. His thesis is titled "Bayesian Methods for Gravitational Waves and Neural Networks" and was defended on June 18. Philip is now a post-doctoral fellow at NASA Goddard Space Flight Center in Greenbelt, MD working on Bayesian parameter estimation and machine learning.

Erin Macdonald completed her PhD at the University of Glasgow. She defended her thesis, titled "Continuous Gravitational Waves in the Advanced Detector Era" on 7 August 2012 and started a postdoctoral position at Cardiff University.

Satya Mohapatra successfully defended his thesis "Searches for gravitational waves from binary black hole coalescences with ground-based laser interferometers across a wide parameter space" on July 13, 2012. His work was advised by Prof. Laura Cadonati.

Adam Mullavey defended his thesis in December 2012, on "Arm Length Stabilisation for Advanced Gravitational Wave Detectors". He is a postdoc at Louisiana State University now.

Alexander Wanner completed his thesis titled "Seismic Attenuation System for the AEI 10m Prototype" at the Albert Einstein Institute and is now Chief Operating Officer at the Centre for Quantum Engineering and Space-Time Research (QUEST).

Updates

LIGO-India has been named as one of the Mega-Science Projects recommended by the Planning Commission in the Indian Twelfth Five-Year Plan, and a request for in-principle approval is being prepared for Cabinet approval. The nodal institutes in India are gearing up for formal project start by assembling teams, studying the LIGO requirements and designs, and performing an initial evaluation of possible sites.

For the first time, on January 3rd 2013, **Einstein@Home** passed the 1 Petaflop mark in computing power. (One Petaflop is 1,000,000,000,000,000 floating point operations per second.) To put this in context, on the current list of the world's 500 fastest computers, only 23 are faster.

The **Einstein Telescope** is taking the next step on the long road to construction. The ET science team has secured one million euro in funding for a three-year pan-European R&D project starting in March 2013. Cryogenic optical properties of silicon, long term seismic site surveys, ET specific control issues, noise correlations in the three ET detectors and ET mock data challenges are the project targets. Teams from 16 institutions in the UK, Poland, Russia, the Netherlands and Germany are funded, while another 8 non-funded groups from France, Italy, Spain, Hungary, and Russia are joining the effort. The ET science team remains open for all interested scientists.

Thanks to translations provided by the LSC and Virgo groups at UIB and Annecy, the online gravitational-wave game **Black Hole Hunter** (www.blackholehunter.org) is now available in Spanish and French, in addition to English.

The **University of Texas at Brownsville**, along with its Center for Gravitational Wave Astronomy (CGWA), are hosting a conference to celebrate 10 years of gravitational-wave research since the creation of the CGWA at UTB. This conference will feature sessions on all aspects of GW research highlighting contributions made by scientists who have worked at the CGWA and researchers from the global GW community. It will be held concurrently with the 2013 Fall meeting of the Texas section of the APS which will be hosted by UTB.

Career Updates

Marc Favata, previously a post-doc at UWM, is now an assistant professor of physics at Montclair State University in New Jersey.

Stefanos Giampanis, previously a postdoctoral fellow at UWM, is now a software engineer at Teradata Aster. Stefanos is testing and developing SQL Map Reduce functions for database analytics applications. With his wife Christina and 8 month old daughter Leeza they live in Redwood City CA.

Jan Harms, previously Senior Research Fellow at Caltech, is joining the Virgo project as INFN fellow at Urbino University working on future detector R&D.

Patrick Kwee, previously a postdoc at MIT, has returned to Europe to take an engineering position at ASML, a Dutch company producing photolithography systems for the semiconductor industry. Patrick will be working on an extreme ultraviolet laser source for the next generation of lithography scanners.

Frank Seifert, previously a postdoc at Caltech, has joined NIST's Quantum Measurement Division in Gaithersburg, Maryland, working on a new definition of the kilogram in terms of quantum measurements rather than a physical artifact.

Alberto Stochino, currently working on GRACE Follow-On and Advanced LIGO at the Australian National University will be starting a post-doc in Prof. John Lipa's group at Stanford, working on laser frequency stabilization with molecular gases and development of displacement sensors for small satellites.

Recent papers (compiled by Ian Harry)

In the inaugural issue of LIGO Magazine we wrote about the papers published by the LIGO and Virgo collaborations in the six months leading up to the publication of that issue. Another six months have passed since then and it has been another busy six months for LIGO scientists. While it simply would not be possible to do justice here to each and every paper written by LIGO scientists in this time, we want to give our readers a flavor of the work that our members are up to. We have therefore decided to make the "Recent LIGO papers" a regular feature of the LIGO magazine where we will describe the papers recently released that carry the full LIGO (and Virgo!) author list.

In this second issue of LIGO magazine we discuss an article that is in surprising synergy with this issue's theme. The paper "Search for Gravitational Waves from Binary Black Hole Inspiral, Merger and Ringdown in LIGO-Virgo Data from 2009-2010" can be found at **http://prd.aps.org/abstract/PRD/v87/i2/e022002**. It describes and presents the result of a search for the gravitational wave signature of "high mass" binary black hole coalescences, where in this context 'high mass' is used to mean that the combined mass of the component black holes is greater than 25 times that of our Sun. Such systems present some novel challenges for observation. For lower mass systems, such as binary neutron stars or binary black holes with smaller masses, LIGO is most sensitive to the "inspiraling" of the binary, that phase where the two objects emit gravitational energy as they move inexorably closer to each other. For such systems, the gravitational waves emitted during the merger, when the two bodies collide, actually happens at a frequency that is higher than LIGO's most sensitive window. For high mass systems, in contrast, the merger happens right at LIGO's sweet spot of sensitivity.

The sensitivity of searches for compact binary coalescences relies on the accuracy of waveform models. It is therefore vital that we use waveform models including the merger and post-merger ringdown phase when searching for high mass binary black hole mergers. However, accurately modeling the final merger of two black holes is hard; accurate analytical models exist for the pre-merger inspiral and the post-merger ringdown, but no-one has yet managed to analytically solve Einstein's equations for the actual collision. Instead, the field of "numerical relativity" has arisen in the last decade or so, which aims to produce accurate merger waveforms by using large-scale computer simulations to numerically model the merger of such bodies. With this new tool, we are able to model the coalescence of two black holes, from their coming together, through their collision and into the post-merger ringdown as the resultant black hole settles down.

Unfortunately, even with these state-of-the-art data analysis techniques, no binary black hole waveforms were observed in the latest initial LIGO and Virgo data. We were, however able to evaluate the distance at which we would have been able to observe binary black hole coalescences during the run. This allows us to place upper limits on the merger rate of black holes in the universe. In this case even not seeing something is a result! You can see more details, view the main plots and even watch and listen to a black hole collision at **http://ligo.org/science/Publication-S6CBCHM/**.

LIGO 2013

Conferences

Commissioning meeting at LIGO Livingston

Holger Wittel

Holger Wittel is a graduate student working on thermal compensation at GEO 600, Hanover, Germany. In his free time, he builds Arduino projects and tries to outsmart the stock market.

At the end of January, the state of Louisiana hosted not only the Super Bowl, but also the Commissioning Workshop, at LIGO Livingston Observatory. This was a joint meeting of simulation experts and commissioners, i.e. people who work closely on the detectors. The workshop addressed several important issues: for instance, how do thermal effects influence the control of an interferometer, and what is the best design for an output mode cleaner? We then compared how several simulation tools answer these questions. I enjoyed the meeting's open structure, and, as a working meeting, everyone got their hands dirty with code. It certainly helped to get people to put their heads together, even between the coffee breaks. This style sparked new ideas and was a good way to get in contact with colleagues from other parts of the world. As this was my first trip to the LIGO site and to the U.S., finally seeing the LIGO site was a great experience. I recommend walking along one of the 4km long LIGO interferometer arms; it does give you a sense of scale. Furthermore I very much enjoyed the surroundings to the meeting. Particularly the swamp tour, including alligators and turtles, was awe-inspiring (there's a photo on page 5). Overall I had a great time, both professionally and privately speaking. And I am looking forward to the next one, which will be set at my home base, GEO. It will have a strong focus on commissioning. The topic to be discussed is 'scattered light.'

LIGO 2013

Gravitational Waves: New Frontier

First GW meeting in Korea

On January 16-18, 2013, Seoul National University hosted the first Korean-based international conference on gravitational waves, "Gravitational Waves: New Frontier". This meeting gathered together the world's leading experts on gravitational wave detector technology, astrophysics and astronomy to discuss the current status of the detectors, the research efforts to improve the existing detectors and develop new ones, and the worldwide efforts to prepare the scientific community for the new era of gravitational wave astrophysics and astronomy. In addition, this meeting introduced the Korean scientific community to this very international and rapidly growing scientific area which depends on multiple, widely separated detectors and requires a broad range of cutting edge technologies to address many fundamental physics problems, open a new window to the universe and answer many questions in astrophysics and astronomy. Korea joined the endeavor in 2009 to work initially on data analysis and theory but is now also contributing for example the laser system to the KAGRA detector in Japan.

The conference program covered the currently operating GEO detector and the status and schedule of Advanced LIGO, Advanced Virgo, and KAGRA, which are all under construction. Some presentations focused on estimates for neutron star merger rates that compare well with GRB data from SWIFT, other presentations emphasized the need for more detectors to improve parameter estimation and detection confidence and discussed the prospects for future detectors such as LIGO-India or the Einstein Telescope. The program also covered the International Pulsar Timing Array which searches for modulations with periods around a year in the arrival times of pulsars and could reach critical sensitivity in this decade.

The progress and situation surrounding the space-based observatories LISA and DECIGO were also discussed. The launch of Pathfinder in early 2015, the L2 call in Europe, the activities in China, and the revitalized US community all point towards a potential launch in the second half of the next decade. The audience was also exposed to new ideas like TOBA, futuristic detector ideas and techniques based on atom interferometry, and the inflation probe which searches for B-modes in the microwave background caused by gravitational waves during the inflationary period. This led to a discussion of the astrophysical perspectives and theoretical expectations of all detectors in the context of open questions in cosmology, astrophysics, fundamental physics, and astronomy.

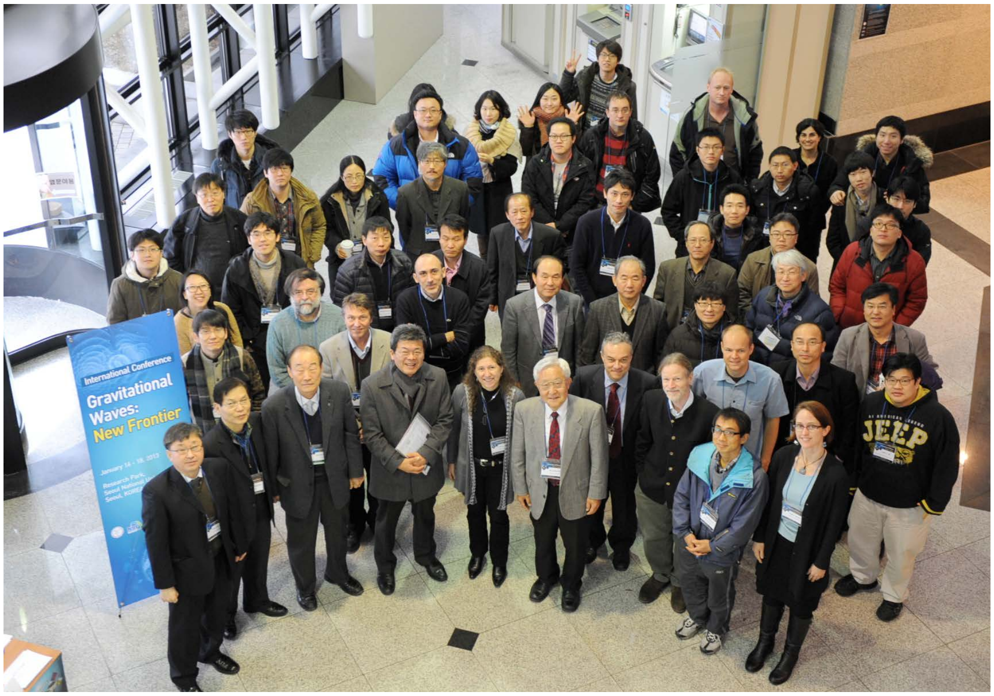
The program and the presentations are available at the conference website **http://astro.snu.ac.kr/gw2013**. The internet magazine '*Science-on*' published by one of the major Korean newspaper companies featured our meeting on January 17. More detailed coverage appears in the March issue of *Dong-A Science*, a monthly science magazine in Korea.

Hyung Mok Lee

Hyung Mok Lee is a professor working on various aspects of theoretical astrophysics including the possible role of gravitational radiation on the dynamical evolution of dense stellar systems. He is a leader of the Korean Gravitational Wave group, and spend his weekends in his country house with a small garden.

Guido Mueller

Guido Mueller is a professor at the University of Florida, he leads the Advanced LIGO Input Optics Subsystem and chairs the Gravitational Wave Science Analysis Group of NASA's Physics of the Cosmos Program. He is so dedicated to his profession that he spends several hours every Sunday with his graduate students and postdocs on soccer fields and basketball courts.



LIGO goes to SACNAS

SACNAS, a society devoted to advancing Hispanics, Chicanos, and Native Americans in science, welcomed 3700 students and professionals to its annual national conference in Seattle, Washington during mid-October 2012. LIGO brought a large group, including four staff members from LIGO Hanford, LSC Spokesperson Gaby González, California State University, Fullerton Physics Professor and LSC member Josh Smith, three Fullerton undergraduate physics majors, and two undergraduate students from the Tri-Cities, WA (the home of LHO).

LHO's Corey Gray and Gerardo Moreno staffed a LIGO table at Community College Day on the opening day of the conference, sharing information about LIGO, physics, and engineering with regional community college and tribal college students. Corey, Gaby, Josh and LHO's Fred Raab provided invited talks at a conference session on gravitational wave physics chaired by LHO's Mike Landry. The Fullerton students presented posters. Gaby, Josh, Fred and Mike served as judges for student poster sessions. Most members of the contingent helped staff the LIGO booth in the exhibit hall during the three-day meeting. Tri-Cities students Pedro Guarjardo (Washington State University Tri-Cities) and Manuel Mendoza (Columbia Basin College) participated in a nonstop stream of conference activities and gained a vision for their future involvement with SACNAS.

LIGO's participation in the SACNAS conference began in 2008 and continues as part of the project's effort to increase its visibility in diverse communities. For LIGO, the Seattle effort grew out of a very successful engagement at the 2011 conference. In San Jose, California, Josh and several Fullerton students, LSC member Peter Beyersdorf from San Jose State University and LSC members from University of Texas at Brownsville (UTB - a regular SACNAS participant) combined with LIGO Laboratory to create a substantial presence. Knowing that the 2012 meeting would occur in LHO's back yard, Corey, Fred and Gerardo from LHO, along with Outreach Coordinator Dale Ingram, began communicating with SACNAS staff members about ways to maximize LIGO's participation in Seattle. Community College Day, the conference session of gravitational waves, poster judging and the partial sponsorship of Pedro Guajardo and Manuel Mendoza all arose from suggestions made to LIGO by SACNAS former Director Judit Camacho, current Director Tina Garza and Program Director Yvonne Rodriguez.

The vision of SACNAS is that the national conference will spur capacity-building in the regions where the conference occurs. In a conversation with LIGO, SACNAS Director Tina Garza said, "We want to return to a conference site years after a conference occurs and see strength and connectedness that grew out of the conference. Student and professional SACNAS chapters, more and stronger mentor-student relationships, and clearer pathways for students into advanced degree tracks are the types of outcomes that we want to promote and facilitate." Tri-Cities students Pedro Guajardo and Manuel Mendoza returned from Seattle expressing interest in helping to start a student SACNAS chapter in LHO's region. Discussions currently are underway with the students and staff members at their institutions to explore how this can happen.

Other diversity-oriented national conference venues in which LIGO exhibited in 2011 and 2012 include AISES (American Indian Science and Engineering Society), the Society of Women Engineers and the National Societies of Black and Hispanic Physicists.

Corey Gray

Corey Gray has served as an operations specialist at LIGO Hanford since 1998. A graduate of Humbolt State Unversity with a B.S. in physics and mathematics, Corey enjoys participating in public outreach activities that connect with students and adults of all ages. He is a member of the Siksika Nation.

The LIGO delegation to SACNAS 2012 in Seattle. From left: Corey Gray, Fabian Magaña-Sandoval, Cinthia Padilla, Josh Smith, Gabriela Serna, Fred Raab, Gaby González, Mike Landry, Gerardo Moreno.

Introducing the Diversity Working Group

Our Collaboration has continued to grow and this growth has introduced a proliferation of smaller working groups who support the advancement of gravitational wave detection and astronomy. There are many groups whose existence is widely known among LSC members. Here, we would like to introduce a new working group whose existence is not yet particularly well known: the Diversity Working Group.

The DWG meets at non-regular intervals to discuss topics relevant to diversity in the LSC, and the LSC's diversity in relationship to the global scientific community. There are no doubts that the LSC would benefit from increasing its diversity in human resources to match the diversity found in the general population. Diversifying our community will introduce more perspectives; each perspective is colored by an individual's training and life experiences. Introducing multitudes of experiences offers researchers a rich collection of heterogeneous ideas, ideas that would be less likely to occur in a homogenous collection of research experience and training.

To explore these topics the DWG created a forum, **https://diversity.ligo.org/**, that LSC members can use to discuss best practices, brainstorm on new initiatives and exchange thoughts and ideas on the diversity climate of the Collaboration. A report with concrete recommendations on how to improve our diversity was presented to the LSC at the September 2012 LSC-Virgo meeting in Rome. One of the first recommendations to be implemented by the LSC was the recent creation and adoption of a statement on diversity (see box).

Our next step is to support this diversity statement and the DWG is currently working to map out concrete courses of action to achieve its goals. Many of the ideas of the diversity report are being used to prepare for and promote the growth of a diverse LSC. We are familiarizing ourselves with what other organizations or groups have done or failed to do in the past. Our ultimate success will also depend on properly assessing the diversity climate of the LSC, so we are planning to measure our current diversity and monitor our progress. Our other initiatives to promote diversity include organizing family-friendly events at the LSC-Virgo meetings, advocating for the LIGO Academic Advisory Council (LAAC) proposal for a peer-mentoring program for junior LSC researchers and other activities outlined in our first LSC diversity document.

> *"As members of the LIGO Scientific Collaboration, we recognize the importance of diversity to enrich our research and scholarship. We pledge to provide a welcoming, inclusive environment to talented individuals regardless of characteristics such as, but not limited to, physical ability, race, ethnicity, gender, sexual orientation, economic status, or personal religious practices, and to support the professional growth of all collaboration members.*
>
> *We also pledge to work to increase the numbers of women and under-represented minorities that actively participate in the LSC, to pursue recruitment, mentoring, retention and promotion of women and under-represented minority scientists and engineers and to maximize their contribution to excellence in our research. As a collaboration, we will strive to create a professional climate that encourages inclusion and that respects and values diversity."*
>
> LSC Diversity Statement, adopted February 2013

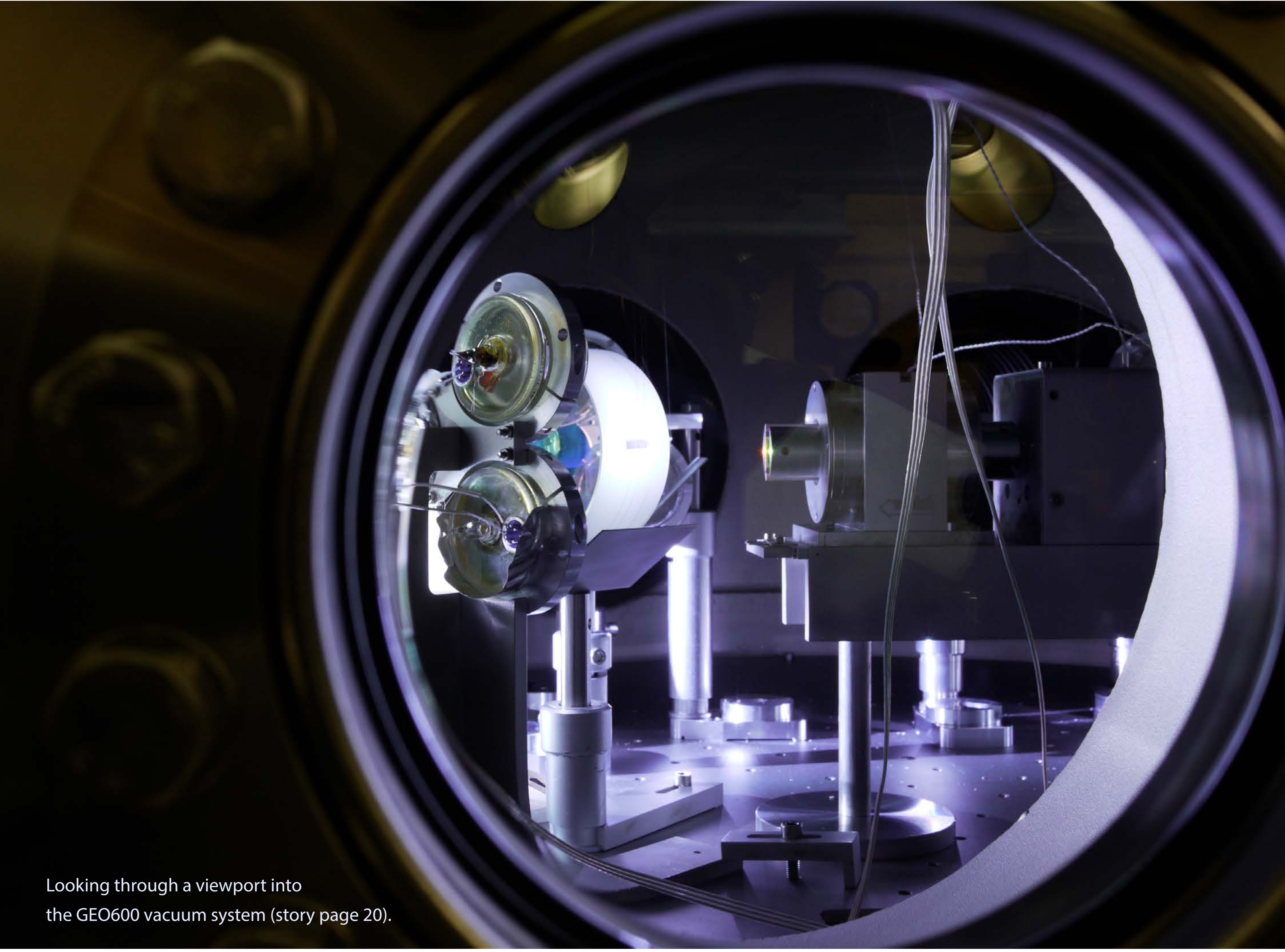
With help we could make our community an example for diversity in science and provide an even more welcoming and inclusive environment for all our members. Achieving these goals will require as much assistance as possible from as many LSC members as possible. That's why we would like to invite all of you to join in this effort, indirectly through your ideas and feedback or directly by joining the DWG. It is our sincere hope that we succeed in creating a collaboration culture where diversity is the norm and the "diversity working group" is our entire collaboration.

Cristina
Valeria Torres

Cristina is a Research Assistant Professor for the Center for Gravitational Wave Astronomy at the University of Texas at Brownsville. When not being a physicist, she is busy with her family, rugby, Brazilian Jui-Juitsu, guitar, and performing as a dancer.

Marco Cavaglià

Marco Cavaglià is Associate Professor of Physics and Astronomy and PI of the LIGO group at University of Mississippi. When he does not work on LIGO's "stuff," this biker enjoys getting his motor running and heading out on the highway.



Looking through a viewport into
the GEO600 vacuum system (story page 20).

LIGO Magazine

LIGO is funded by the **National Science Foundation** and operated by the **California Institute of Technology** and **Massachusetts Institute of Technology**. This material is based upon work supported, in part, by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. We also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d'Economía Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

Title: LIGO Magazine
Online ISSN: 2169-4443
World Wide Web URL: **http://www.ligo.org/magazine**
Publisher: LIGO Scientific Collaboration, Pasadena, CA, USA
LIGO DCC: LIGO-P1300029
Contact: magazine@ligo.org

Editor-in-Chief: Andreas Freise

Editors:
Hans-Peter Bischof
Marco Cavaglià
Tobin Fricke
Gabriela González
Dale Ingram
Ian Harry
Mike Landry
David Ottaway
Brian O'Reilly
Jocelyn Read
Ruslan Vaulin

Layout & production: Tobin Fricke, Andreas Freise, Lucía Santamaría, Erin Macdonald

How does it work? Weird stuff in tiny stars

Is it possible to explain “compact binary coalescence” using only simple words? Here we give it a try, inspired by Randall Munroe’s “Up Goer Five” cartoon, in which he explains the Saturn V rocket using only the “ten hundred words people use the most often” (**http://xkcd.com/1133/**).

There are some tiny but heavy stars that are left over after normal stars die. Imagine our whole sun – hundreds of hundreds of our worlds – forced down to fit inside a city. We don’t know exactly what’s inside such tiny stars because the stuff there is pretty weird, but we have some ideas.

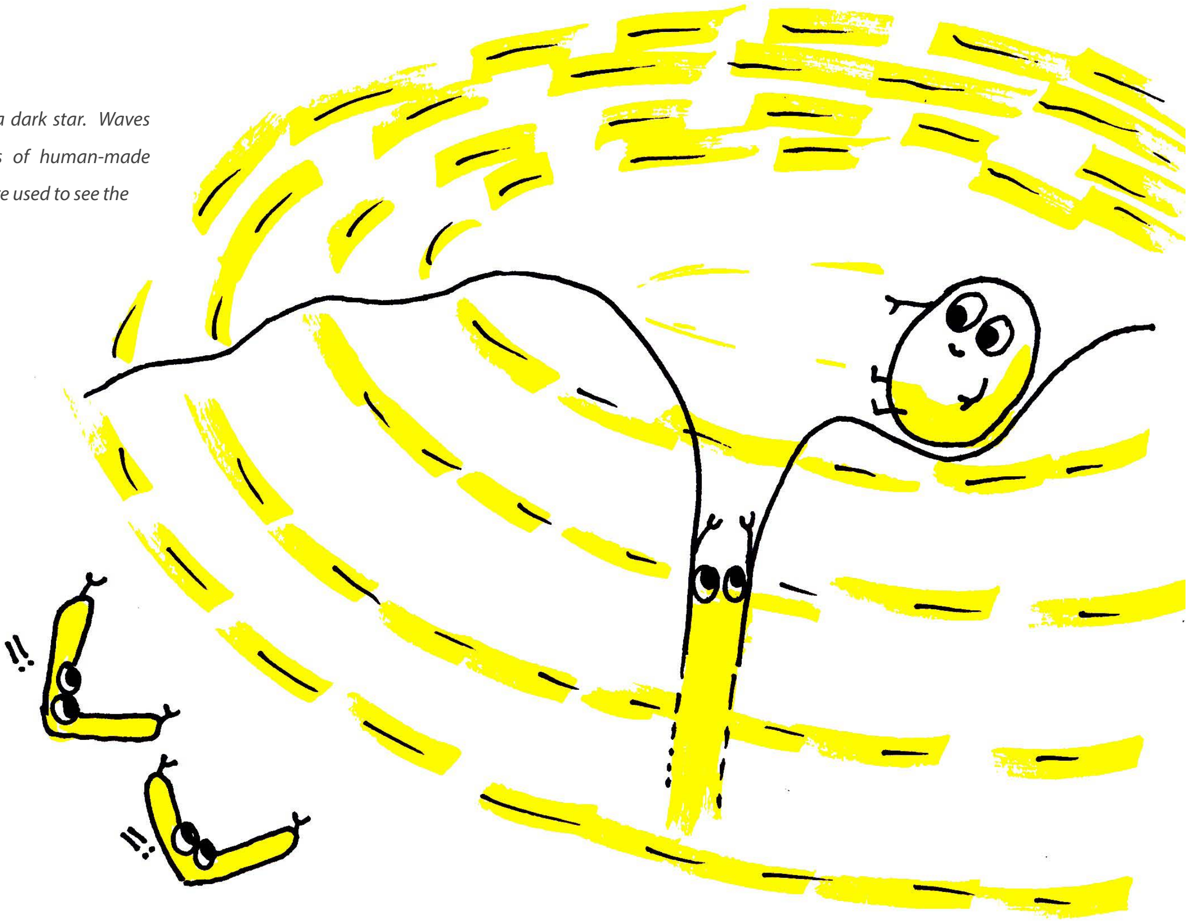
Just like we fall to the ground on our world, stuff in space will fall toward heavy things. Sometimes, after a really big normal star dies, the left-over stuff falls in toward the middle of that star until it disappears. The star gets so small that if light tried to go away from it, moving straight out and as fast as anything can go, it would still end up falling back toward the middle, never to be seen again. We sometimes call these dark stars.

Sometimes two of these tiny or dark stars go around each other, like our world goes around the sun. When they go around really fast and close together they make waves in space and time that we try to see from our world. As the waves go out the stars move closer and closer together. They go around faster and the waves get bigger, until the stars hit each other.

The way that the waves look can tell us how the stars were turning and how heavy they were. The stuff inside the tiny stars gets moved around when they’re very close together, so different kinds of stars make different waves. Also, when two stars hit each other, sometimes they make a new star which sends out more waves, or sometimes everything falls together to make a bigger dark star. If we see these space-time waves, the way they look at the end will tell us something about the weird stuff in these tiny stars.

Jocelyn Read

Read more at **tenhundredwordsofscience.tumblr.com** or write your own at **http://splasho.com/upgoer5/** .



A tiny star falls toward a dark star. Waves go out, and some sets of human-made arms with lots of parts are used to see the waves.