Institution: Cardiff University

Unit of Assessment: Physics (9)

Title of case study: Using the first detections of Gravitational Waves to inspire and inform audiences worldwide

Period when the underpinning research was undertaken: 2014 – 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Christopher North	Senior Lecturer	2008 – present
Patrick Sutton	Professor	2007 – present
Stephen Fairhurst	Professor	2007 – present
Mark Hannam	Professor	2010 – present
Bernard Schutz	Professor	1974 – present
Duncan Macleod	Sêr Cymru COFUND Fellow	2017 – present
Vivien Raymond	Lecturer	2018 – present
Bangalore Sathyaprakash	Professor	1996 – present

Period when the claimed impact occurred: 11/02/2016 – 31/12/2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact (indicative maximum 100 words)

Cardiff researchers play key roles in the LIGO collaboration that first detected gravitational waves in 2015. The detection attracted global media attention in February 2016, and the Cardiff team engaged audiences to build understanding and appreciation of this and subsequent discoveries. Impact included workshops which inspired 970 pupils, and, in collaboration with the National Space Academy, trained 640 teachers in the UK. Cardiff public lecture programmes further inspired audiences, with talks by two Nobel laureates attracting over 260,000 online views. Post-event surveys showed a demonstrable improvement in attendees' engagement with, and understanding of, science. Cardiff interactive tools and resources were also promoted by LIGO and used worldwide, including in exhibitions across the USA designed to engage public audiences.

2. Underpinning research (indicative maximum 500 words)

Sathyaprakash and Schutz were founding members of the international Laser Interferometer Gravitational Wave Observatory (LIGO) Scientific Collaboration (LSC) and, before that, the GEO600 detector project. The LSC comprises over 1,000 scientists from more than 100 institutions in 18 countries. Cardiff is the 4th largest organisation in terms of group members, and team members hold multiple leadership roles: Schutz is a member of the Gravitational Wave International Committee (GWIC) coordinating global detector developments, Fairhurst is co-Chair of the LSC Programme Committee coordinating the collaboration's activities, and North is co-Chair of the Multi-messenger Working Group of the International Gravitational Wave Outreach Group. Additionally, Sathyaprakash and Fairhurst are leading scientific cases for the configuration and locations of "3rd generation" observatories, including the Einstein Telescope.

Cardiff research played an important role in the design, operation, and analysis of the international Advanced LIGO (aLIGO) experiment. This work achieved international renown in 2016 with the announcement of the first direct detection of gravitational waves (GW, known as GW150914 **[3.1]**), 100 years after their prediction by Einstein. In late 2017, the first joint detection of a GW source with an electromagnetic counterpart was made (GW170817) **[3.2]**. This permitted the first GW-based measurement of the rate of expansion of the Universe (the Hubble constant), using the method devised by Schutz in Cardiff in 1986 (referenced in **[3.2]**).

The analysis of binary black hole mergers uses predictions of GW emissions developed by Hannam, and to date the properties of all black holes observed by LIGO-Virgo (Virgo is

another laser interferometer in Italy) have been measured using theoretical signal models developed at Cardiff **[3.3]**. This phenomenological approach to black hole emissions is extremely flexible, as demonstrated in the rapid extension of the binary black hole models to include tidal effects in the weeks following the detection of the binary-neutron-star inspiral GW170817, which allowed the first measurements of neutron-star equation-of-state from GW observations. Hannam's group also produced the first model of neutron-star–black-hole (NSBH) interactions, which was then used in the analysis of the potential first NS-BH observation, GW190814 **[3.3]**.

A key objective of GW astronomy is identifying the source using electromagnetic radiation. Sutton and Fairhurst developed the techniques for detecting GW signals associated with phenomena such as gamma-ray bursts (GRB), supernovae, and fast radio bursts **[3.4]**, and have led or co-led all LIGO GRB-triggered search papers since the S5 run of initial LIGO (2005-07). This includes the O1 (2015-16) and O2 (2016-17) joint GW-GRB papers, which culminated with the detection of the first electromagnetic counterpart to a GW source **[3.5]**. Fairhurst also led the *PyGRB* pipeline to search for binary signals associated with short-duration GRBs using matched-filtering techniques, and Sutton led the *X-Pipeline* for generic transients, with no model-based assumptions, associated with long and short GRBs.

Macleod developed the detector performance monitoring system used by the LIGO, Virgo, and GEO observatories, and had major involvement in detector characterisation, removal of noise, and providing public access to both raw and processed data. From 2016 to 2020, Raymond co-led the LIGO-Virgo collaboration group responsible for characterisation of observed GWs and their astrophysical inference **[3.6]**. Raymond's contributions were instrumental in the mitigation of instrumental effects and characterisation of GW170817, and high-mass events such as GW190521, with a total mass of 150 solar masses.

In recognition of his work in founding the field of gravitational wave data analysis, and the measurement of the Hubble constant using gravitational wave detections, Schutz was awarded the 2019 RAS Eddington Medal and the 2020 American Physical Society Richard Isaacson Award, and in 2019 was elected to the US National Academy of Sciences. In 2017 the Nobel Prize for Physics was awarded to Rainer Weiss, Barry Barish and Kip Thorne for "decisive contributions to the LIGO detector and the observation of gravitational waves". In their joint Nobel Lecture the recipients credited Schutz's research, and when delivering a presentation at Cardiff in October 2019, Kip Thorne said "*I'm happy to be an icon for the team, but it really was a huge team effort with Cardiff playing a major role*" **[5.9]**.

3. References to the research (indicative maximum of six references)

[3.1] Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of gravitational waves from a binary black hole merger*, Phys. Rev. Lett. 116, 061102, 2016. https://doi.org/10.1103/PhysRevLett.116.061102 (4,937 citations)

[3.2] Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW170817: Observation of gravitational waves from a binary neutron star inspiral*, Phys. Rev. Lett. 119, 161101, 2017. https://doi.org/10.1103/PhysRevLett.119.161101 (3,114 citations)

[3.3] Hannam, M., et al., *Simple model of complete precessing black-hole-binary gravitational waveforms*, Phys. Rev. Lett. 113, 151101, 2014. https://doi.org/10.1103/PhysRevLett.113.151101 (272 citations)

[3.4] Abbott, B. P., (LIGO Scientific Collaboration and Virgo Collaboration), *Observing gravitational-wave transient GW150914 with minimal assumptions*, Phys. Rev. D 93, 122004, 2016. https://doi.org/10.1103/PhysRevD.93.122004 (84 citations)

[3.5] Abbott, B. P., *Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A*, Astrophys. J. Lett. 848, L13, 2017. https://doi.org/10.3847/2041-8213/aa920c (1,168 citations)

[3.6] Veitch, J., et al., *Parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library*, Phys. Rev. D, 91, 042003, 2015. https://doi.org/10.1103/PhysRevD.91.042003 (406 citations)

4. Details of the impact (indicative maximum 750 words)

Cardiff's expertise in analysis of gravitational wave (GW) data was a key contribution to the LIGO collaboration, and the group has drawn upon its research to inspire and help audiences understand the implications and impact of the research. The public outreach during the REF period included: 1) global news coverage, 2) educational resources, and 3) public engagement events.

4.1 Global news coverage

On 11 February 2016, the first detection of GW became worldwide news. With the announcement, members of the Cardiff team were cited on national media including *BBC News*, *The Independent* and *The Guardian*, and worldwide media coverage including *Buzzfeed*, India's *The Hindu*, and Pakistan's *AryNews* **[5.1]**. Hannam also gave televised interviews on *BBC World News*, *BBC Wales* and *S4C*, and radio interviews on *Radio New Zealand*. Following the announcement, the discovery featured on the front page of 961 newspapers worldwide **[5.1]**. The day after the announcement, a representative YouGov poll of the British public found that 1 in 3 people stated that the discovery of gravitational waves personally mattered to them **[5.2]**. Younger people were particularly impressed: 50% of people aged 18-25 stated that the discovery personally mattered to them **[5.2]**.

The discovery has continued to attract public interest and media platforms regularly drew upon the expertise of the Cardiff group: *Scientific American* and *New Scientist* published articles quoting Sathyaprakash on interpreting the results, *Nature* and *Vice* quoted Schutz on the implications of the results, and *Wired* quoted Hannam in an article on the history of the project **[5.1]**. The lasting significance of the discovery is demonstrated by numerous popular science outlets citing the detection as one of the most important discoveries of the decade, including *Nature*, *National Geographic*, and *New Scientist* **[5.1]**.

4.2 Educational resources

Cardiff developed educational workshops using real GW data, targeted at GCSE and A-Level physics students, allowing them to apply their knowledge in a way which reflects real-world research. The Cardiff team held these workshops with over 30 schools across the UK, and directly engaged over 970 students, with feedback demonstrating greater understanding of the topic:

- Workshops increased understanding of gravitational waves (with average scores on knowledge rising from 4.4 to 6.5, out of 10) **[5.3a]**.
- Participants' appreciation of the relevance of their school studies to cutting-edge research increased from 38% to 61% **[5.3a]**.
- 62% of students attending workshops in August 2018 said they were more likely to study physics at university as a result of the workshops **[5.3b]**.

Cardiff workshops and resources are now promoted to UK and international schools, including by the National Space Academy. The Academy's Lead Physics Teacher, Sophie Allen, stated that use of Cardiff's resources "*give students a taste of what it is like to be researchers*" by applying their knowledge to real GW data, and "*In this way, the resources increase the relevance of students' A-level studies to real research*" **[5.4].** The Academy also run a yearly GCSE Masterclass programme for around 200 students, and feedback from those sessions confirmed that Cardiff's resources had increased students' desire to do further study in STEM disciplines **[5.4]**.

Cardiff gravitational wave resources were presented to UK teachers through 11 Continuing Professional Development (CPD) events that trained 394 teachers. Sophie Allen confirmed that the resources "*enhanced [National Space Academy staff's] understanding of space topics […], so that they can bring that into CPD sessions that they run"* with teachers across the UK

and estimated "*at least 300 teachers*" have used Cardiff resources **[5.4]**. Surveys at four of these CPD events showed that teachers improved their understanding of gravitational waves ("above average" knowledge increased from 27% to 71% of teachers) and 80% of teachers surveyed intended to use Cardiff's activities in their classrooms. Teachers also indicated that the detection of gravitational waves became more relevant to their teaching following the training (an increase from 44% to 74%) **[5.4]**. At least 690 teachers have been directly reached through these and similar training events by members of the Cardiff Gravitational Exploration Institute (GEI).

UCAS personal statements of undergraduate physics applicants from across the UK demonstrate how the detection inspired them to study physics: "*one of the biggest influences in making me sure that I wanted a career in physics was the detection of gravitational waves at the LIGO facilities*" **[5.5]**. Applicants often cited Cardiff's workshops and lectures as direct inspiration to study physics **[5.5]**:

- *"This is where I developed a particular interest in Astrophysics and Particle Physics … If given the opportunity, I would like to go into further education and complete a PhD, I would love to be able to study Gravitational Waves and how they interact with the rest of the Universe"* **[5.5]**.
- *"I attended an undergraduate open day lecture given by Dr. Patrick Sutton about Gravitational waves. The lecture inspired me to do my Welsh Baccalaureate individual Project on this topic"* **[5.5]**.
- *"Attending a lecture on gravitational waves at Cardiff University has helped me to further my knowledge on this topic and increased my desire to learn more"* **[5.5]**.

GEI members contributed their gravitational wave research expertise to the development of the comic series *Ada's Adventures in Science*, written by Edward Gomez who is hosted by the Cardiff School of Physics and Astronomy. The comic uses a real-life example to tell a story about a young girl's journey from school student to research scientist working on gravitational waves. A public Kickstarter campaign raised £7,000 to distribute 15,000 copies to schools and educators across 17 countries in five languages, with over 50% of copies going to disadvantaged areas. Paul Hardaker, CEO of the Institute of Physics praised the project: " *the Ada comics have served to raise awareness of not only the nature and excitement of research and the role it plays in society, but also, and importantly the value of cultural diversity in science and the importance of inclusion.*" **[5.6]**.

4.3 Public events

Cardiff's strong links to the LIGO project have led two of the Nobel laureates for the gravitational wave discovery to deliver bespoke public lectures at Cardiff. In May 2018 Cardiff hosted Barry Barish who delivered a public talk to over 300 people on the discovery, with 96% of attendees reporting that they were inspired by the science **[5.7]**. In October 2019 Cardiff organised a lecture programme which featured Kip Thorne in his only UK appearance. The first talk, entitled "Gravitational Waves: A Nobel Prize-winning Discovery", was delivered to 90 Key Stage 4 and 5 pupils, and pre/post surveys confirmed that students' understanding increased after attending the talk **[5.7]**:

- Self-rated understanding as "above average" increased from 16% to 57%.
- Correct responses to a technical question increased from 64% to 99%.
- Relevancy of the research to student's studies increased from 38% to 45%.

Kip Thorne's second lecture was delivered to over 450 members of the public **[5.7]** and discussed the history of LIGO and the gravitational waves discovery, specifically drawing upon his work with Schutz and the Cardiff team. Pre/post surveys of the audience showed that 75% confirmed an increased understanding of gravitational waves, and 87% were inspired to attend similar events in the future **[5.7]**. This lecture was uploaded to YouTube in October 2019, and has already received over 260,000 online views, with visits logged from 69 countries.

Additional public events by the Cardiff team include co-organising and co-presenting at the 2017 Royal Society Summer Exhibition, with post-event surveys indicating that 70% of

respondents said their knowledge of gravitational waves increased after the exhibit, and the proportion of people rating their knowledge as "high" also increasing, from 20% to 80% **[5.8]**. In June 2016 members of the Cardiff team (Sutton, Sathyaprakash) presented a sold-out event (over 400 paying attendees) at the 2016 Hay Festival on the Oxfam Moot stage highlighting Cardiff's research supporting the discovery **[5.8]**. Fairhurst also presented at the 2018 *New Scientist Live* event on "Gravitational Wave Hunting", and *New Scientist*'s 2018 "Instant Expert: Big Physics, Big Questions" **[5.8]**.

Additionally, the team developed and hosted online public engagement tools that are endorsed and promoted by LIGO **[5.9]**. These include:

- ***Black Hole Hunter**,* a game in which users identify simulated GW signals, which has had 30,000 unique users since February 2016, with 94% from outside the UK, spanning 161 countries. The LIGO team promoted an offline version in travelling exhibits across the USA, across over 20 venues each reaching "*a few hundreds of visitors*" **[5.9]**. The game is now on permanent display at the LIGO Science Education Centre in Livingston, Tennessee, which receives around 12,000 visitors a year (visits are limited to specific times to avoid excessive vibrations) **[5.9]**.
- ***Gravity Spy***, a Zooniverse citizen scientist project to inspect and categorise LIGO data glitches, with over 20,000 international users making three million classifications. Results have led to a more efficient data quality and calibration system used by LIGO thanks to this engagement by non-scientists.
- A suite of education tools demonstrating black holes detected by LIGO, including ***Black Hole Bubble Diagram*** showing the scale and type of black holes informed by GW data, and the ***LIGO Gravoscope*** showing the location of detected black holes. These resources are developed and hosted by GEI staff and showcased on the LIGO website, receiving over 6,300 unique users, 85% from outside the UK.

LIGO has promoted Cardiff's resources in its announcements, such as *SkyMaps*, which "*communicate the locations of new black hole discoveries in a beautiful and immediately accessible fashion*" **[5.9]**. In December 2017 and 2020, North also led development of a LIGO/Virgo Advent Calendar. Promoted by the LIGO and Virgo Twitter accounts, this published new pictures, stories, videos and activities throughout December and was widely advertised to UK teachers. The calendar was hosted by Cardiff and received 5,000 unique visits from 93 countries, with over 700 individuals visiting more than 10 times **[5.8]**.

The LSC Spokesperson Patrick Brady, praised Cardiff's public engagement activities and resources, and noted that: "*Cardiff's public outreach work has undoubtedly encouraged greater public understanding and worldwide engagement with the fundamental research happening at LIGO. Public understanding of gravitational waves is of a far higher standard than can be said of most fundamental physics, and we attribute a large portion of that to the work of Dr Chris North and colleagues at the Cardiff Gravitational Exploration Institute*" **[5.9]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] Collated list of media coverage of the detection of Gravitational Waves

[5.2] Gravitational Waves Results, YouGov Poll, 12 February 2016

[5.3] Record of engagement with Student Workshops & Lectures

[5.4] Testimony: Sophie Allen, Lead Physics Teacher, National Space Academy, and feedback from Cardiff CPD workshops

[5.5] Quotations from Undergraduate Applicant Statements

[5.6] Testimonial from Paul Hardaker, CEO, Institute of Physics

[5.7] Collated feedback from Nobel laurate public engagement events

[5.8] Record of engagement with public events

[5.9] Testimonial from Patrick Brady, LIGO Scientific Collaboration Spokesperson