Communicating the gravitational-wave discoveries of the LIGO–Virgo–KAGRA Collaboration

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Abstract

The LIGO–Virgo–KAGRA (LVK) Collaboration has made breakthrough discoveries in gravitational-wave astronomy, a new field that provides a different means of observing our Universe. Gravitational-wave discoveries are possible thanks to the work of thousands of people from across the globe working together. In this article, we discuss the range of engagement activities used to communicate LVK gravitational-wave discoveries and the stories of the people behind the science, using the activities surrounding the release of the third Gravitational-Wave Transient Catalog as a case study.

1 Introduction: Context and Objectives

Gravitational waves (GWs) can be difficult to imagine. They are ripples in spacetime, created by the acceleration of massive objects, that propagate across the Universe at the speed of light. The strongest GW sources are massive and rapidly moving: the best sources for ground-based GW detectors are coalescing binaries of black holes or neutron stars. After travelling across the cosmos to Earth, GWs are almost imperceptibly small. The strongest signals correspond to a stretching and squeezing of space of 1 part in 10^{21}. Observing GWs has therefore been a great experimental challenge, requiring an international community to design and build the complex, highly sensitive instruments needed to measure the waves, and to create and test the algorithms needed to analyse the data.

In 2015, 100 years after Einstein first calculated the properties of GWs in his theory of general relativity, the first direct observation of GWs was made [Abbott et al., 2016b]. This discovery was confirmation for Einstein's theory, an experimental triumph, and the beginning of a new era for astronomy. The signal GW150914 came from two black holes, each about 30 times the mass of our Sun, coalescing more than a billion light-years away. This was the first time such a binary black hole system was found, the first time black holes of this size were discovered, and the first time two black holes were observed to inspiral and merge. The discovery was a major global news event [Key et al., 2016], building on the public's fascination with Einstein and black holes.

Since 2015, the LIGO–Virgo–KAGRA (LVK) Collaboration, which operates the international network of ground-based laser-interferometric GW observatories (the two LIGO sites in the US [Aasi et al., 2015], Virgo in Italy [Acernese et al., 2015], KAGRA in Japan [Akutsu et al., 2021] and GEO 600 in Germany [Dooley et al., 2016] has made many further GW discoveries. The field has grown rapidly, with the third GW Transient Catalog (GWTC-3) increasing the number of probable detections to 90 [Abbott et al., 2023a]. The latest observing run is ongoing. These observations have revealed a diverse range of black hole and neutron star binaries, and revolutionised our understanding of these sources' astrophysics.

Surrounding each results release are numerous engagement and communication activities. These share the wonder of discovery, what can be learned from GWs, and the technological advances that enable these groundbreaking measurements. Matching the global composition of the LVK, selected resources have been translated into over 20 languages.

Engagement, communication and education activities are carried out by a wide variety of individuals: from those who see themselves as scientists and engineers with a passion for outreach, to those who view themselves as outreach experts with a passion for science. These individuals make commitments as LVK members, and join together in collaboration-wide teams and outreach partnerships.

Discoveries also provide an opportunity to focus on the people behind the science. The LVK includes around 2000 people from diverse backgrounds across the globe. Their activities range from designing instrumentation to operating the kilometre-scale laser interferometers, from coding analysis algorithms to calculating GW emission. Making connections with the people within the LVK reveals the human side of how science works, and provides possible role models for young people interested in science, technology, engineering and mathematics (STEM).

Communicating LVK discoveries faces several challenges. Some, such as explaining complicated ideas using non-technical language or engaging with hard-to-reach communities, are common to other science communications. However, LVK science also faces specific challenges including explaining the concept of GWs, which are alien to everyday experiences; constructing a narrative around the work of a large collaboration, where it is often not possible to identify distinct contributions of individuals, and maintaining interest as the field develops from an era of first detections to using large catalogs to make statistical statements. Each of these challenges also provides an opportunity, enabling us to increase the scientific literacy of those reached: explaining the results of LVK work, how they are produced, and how modern science makes discoveries through carefully combining many pieces of research.

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In this article, we detail communication methods used by the LVK. We first review the range of engagement activities used to communicate LVK GW discoveries and the stories of the people behind the science, and then provide specific examples of activities used for GWTC-3. We conclude with reflections upon these activities and the challenges of communicating LVK discoveries.

2 General communication methods

Discovery announcements from the LVK normally have three components: paper, data release, and educational and engagement resources. Here we describe some general and long-term education and engagement activities of the LVK.

The LVK is a consortium of its three constituent collaborations, each with its own internal organisational structure. Communications efforts are primarily led by a division-level coordinator or chair, who oversees various working groups, committees, and individual efforts working towards shared objectives. Activities organised through these groups are typically undertaken by teams of individuals, who then report their progress through regular meetings, LVK-wide conferences, and annual reports. Some activities, like coordination of press releases, may be done by dedicated communications teams in each of the three collaborations, but most activities are done by volunteers from the LVK. Division leads are responsible for ensuring that these activities complement each other and align with parallel efforts across the observatory sites.

The LVK consists of many individuals with different backgrounds and job roles working in institutions around the world and funded by different sources. This results in a diverse set of public-engagement activities run by different teams. While these may share a broad goal of communicating GW science, they may differ in specific goals, e.g., encouraging schoolchildren to study STEM or informing science journalists. The different activities complement each other, and provide a breadth of resources and expertise for LVK members to draw upon. Below we group in terms of activities (Table 1), reflecting how these are organised within the LVK by different teams.

2.1 Sharing the people behind the science

Discovery science is not just about the results, it is also about the people behind them. Highlighting individuals within the LVK can provide STEM role models, challenge stereotypes, and help to foster a welcoming environment by promoting diversity and inclusion.

The LIGO Magazine (www.ligo.org/magazine), published twice annually, is commissioned and edited by a team of volunteers from the LIGO Scientific Collaboration. It was conceived to build connections across the diverse GW community and inform the interested public. Since the first edition in 2012, the Magazine has featured 470 authors, representing 237 workplaces in 23 countries (as of Issue 24, March 2024). Articles include perspectives of working on GW science, personal stories, opinion pieces, science explainers, and advice columns. The Magazine provides opportunities for early-career scientists to discuss their behind-the-scenes experiences of working on big GW results, as well as an avenue for current and former LVK members to share their perspectives of working in academia and beyond. The LIGO Magazine has a professional, high-quality design. For each edition, 500 hard copies are printed. Approximately half are sent to LVK Collaboration meetings for participants to take back to their home institutions; the rest are distributed between detector sites and other LVK institutions worldwide. Print copies are also used within LVK as handouts for government representatives, students, and to visitors at detector sites and institutions. The full archive is also online as PDF downloads.

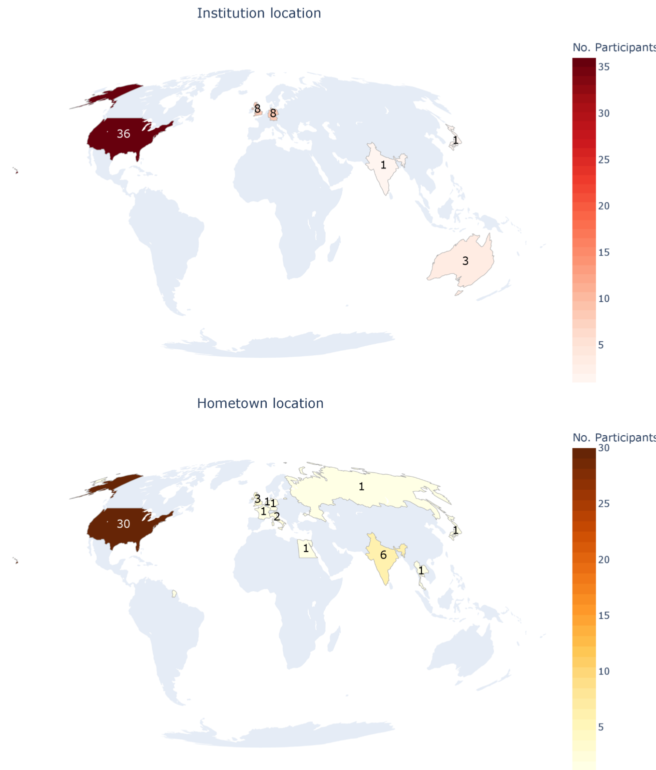

Figure 1: Frequency of Humans of LIGO participants' institution (top) and hometown (bottom) county.

Humans of LIGO (humansofligo.blogspot.com) showcases the lives, backgrounds, and inspirations of LVK members and GW scientists through blog posts. Each post consists of an image of the participant, a direct quote about their experiences, and a short biography including job description and hobbies. The blog posts are shared on LIGO social media, and have reached over $53,000$ views (as of May 2024). Since its inception in 2018, the blog has featured 59 participants from 11 different countries, working at 42 institutions (Figure 1). While profiled scientists come from more diverse locations than just those of LVK institutions, they are still concentrated, reflecting the inequitable distribution of scientific research [King, 2004]. A future goal is to add profiles for scientists from other backgrounds and demonstrate potential opportunities within STEM for people across the world.

Antimatter web comics (antimatterwebcomics.com) by Nutsinee Kijbunchoo features day-to-day experiences and current affairs from the GW community and beyond (Figure 2). Mental health and graduate-student life are focuses of many comics. Based upon webpage views (August 2024), the most popular two comics are about the discovery of the first binary neutron star signal and about living with depression, demonstrating that both communicating discoveries and sharing the lives of the scientists behind them have appeal. Comics have been regularly featured in the LIGO Magazine.

The LIGO-India blog, Glorious Women [LIGO-India, 2024a] showcases STEM role models, highlighting women from across the LVK. Behind-the-scenes interviews feature the daily lives of stu-

Table 1: A selection of LVK communication activities and examples we discuss in this article.

Activity	Examples	Audiences	Media
Sharing the people behind the science	LIGO Magazine; Humans of LIGO; Antimatter comics; LIGO-India blog	LVK members; other academics; undergraduate students; school students; general public	Print; online writing; graphics
Engaging academia	Journal articles; Open Data Workshops; data releases; webinars; direct interventions	LVK members; other academics; undergraduate students; interested public	Academic resources; live and recorded talks; online course materials; online documentation; online correspondence
Supporting formal classroom education	Educator's guide; Einstein-First; Space Public Outreach Team	School educators; undergraduate students; school children	Online written resources; face-to-face communication
Writing reference texts	Science Summaries; press releases; news items	Undergraduate students; science journalists; interested public	Online writing; print
Interacting in person	Science festivals; museum exhibits; visitor centres	School children; general public	Face-to-face communication; talks; live demonstrations; interactive exhibits
Creating graphics	Infographics; simulation visualisations; artistic impressions; Masses in the Stellar Graveyard; LVK Orrery	Academics; undergraduate students; journalists; general public	Images; videos
Employing multisensory resources	Sounds of Spacetime; Tactile Universe; Low Mass Beats	General public	Audio; 3D-printed materials
Combining art and music with science	GravitySynth; GWSciArt; Celebrating Einstein festival	General public	Visual arts; music
Communicating through social and non-traditional media	Podcasts; social-media posting; Reddit Ask-me-anything	Science journalists; interested public; general public	Online correspondence; online writing; audio; graphics; videos
Using interactive technologies	Laser Labs games and apps; Black Hole Hunter; Mission Gravity	School children; general public	Interactive software

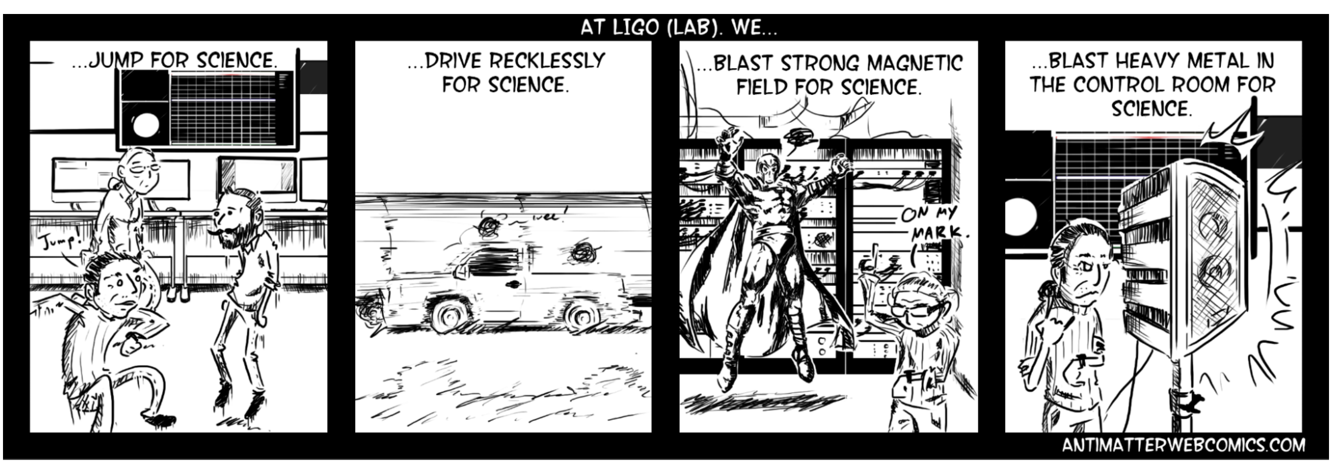

Figure 2: Antimatter comic showing LIGO scientists performing detector checks (credit: Nutsinee Kijbunchoo). A version of this comic featured in the *CQG+* blog accompanying a paper describing detector characterization for GW150914 [Abbott et al., 2016a].

dents, their motivation, contributions and challenges [LIGO-India, 2024b].

2.2 Engaging academia

Sharing our discoveries, and how to use them, is key to ensuring a wider impact on the scientific community.

Communication with academics is primarily through scholarly articles. Since GW astronomy is new, the LVK have written dedicated articles on introductory GW data analysis [Abbott et al., 2020a], our data releases [Abbott et al., 2021, 2023b], and the basic physics of a binary coalescences (suitable for undergraduate teaching) [Abbott et al., 2017].

Data releases are coordinated by the GW Open Science Center (GWOSC), which hosts raw data, links to LVK publications and further data products (gwosc.org). GWOSC maintains lists of open-source analysis software, and provides teaching on data analysis through annual Open Data Workshops. Workshops are delivered in a hybrid format, with 200–300 people participating in-person each year, and over $7,700$ people enrolling online over the last four years. Workshop materials are openly available online.

To accompany the release of key papers, the LVK organises Zoom webinars, with attendees able to submit questions. These provide convenient, direct communication with other scientists, and reach a larger audience than many in-person conferences. Recordings are uploaded to YouTube. YouTube views range from 400 to $3,400$ (August 2024), with the older recordings accumulating more views.

The LVK also engages with the academic community to promote proper recognition of its three constituent collaborations. There is currently a bias in scholarly literature: an abbreviated narrative attributes credit to LIGO, excluding Virgo and KAGRA from LVK achievements, with consequences for scientific careers, accuracy of media and interactions with funding agencies. A year-long project [Barneo et al., 2024] studied this cognitive bias, and tried to educate the community. While intervention has encouraged authors to include proper attribution in their work, it has yet to be seen if this has a long-term impact of reducing incomplete attribution.

2.3 Supporting formal classroom education

LVK members have maintained long-term efforts to introduce GWs and related topics into formal classroom education. Examples include an Educator's Guide [Edeon STEM Learning, 2016], courses for community-college teachers, high-school resources, and undergraduate lab demonstrations [Gardner et al., 2022].

Einstein-First (www.einsteinian physics.com) has developed an eight-year spiral curriculum *Eight Steps to Einstein's Universe* for students aged 7–8 to 15–16 years old. This introduces fundamental concepts (e.g., atoms, molecules, photons and phonons), and in the last year of compulsory science education, a module about GWs, black holes, climate change and Hubble's law [Popkova et al., 2023]. The Einstein-First team is upskilling almost 100 teachers through micro-credentials courses with many teachers now delivering the program. Micro-credential training successfully empowered teachers: 96% agreed or strongly agreed both that they understood why Einsteinian concepts were important to the school curriculum, and that they would feel confident running Einstein-First activities for their students [Kaur et al., 2023a,b]. Efforts are underway to introduce Einstein-First in Australia, India, USA, Greece, and Brazil.

Outreach to schools and STEM education programs provides an avenue for sharing GW discoveries, engaging students and teachers, and additionally provides science-communication training for GW researchers. Assessment of the impact of the Space Public Outreach Team (SPOT) program shows positive outcomes for students at all levels for SPOT programs across a range of geographic locations, benefitting the college-student presenters with improved scientific knowledge and presentation skills, and the audience of school children with greater engagement with science [Key et al., 2024; Des Jardins et al., 2020].

2.4 Writing reference texts

LVK Science Summaries and press releases are both Collaboration-coordinated activities to provide written summaries of our discoveries.

LVK Science Summaries are a long-standing effort to explain LVK publications at a technical level typically higher than in the popular press but still accessible for enthusiastic lay readers. They are published on www.ligo.org, distributed as print copies at outreach events, and shared with journalists. Summaries for discovery announcements may get thousands to tens of thousands of views around publication. Summaries are translated into a variety of languages by LVK volunteers, with discovery papers often receiving the most attention (e.g., the GW190521 summary was translated into 16 languages) [Keitel et al., 2021]. Numbers of summaries and translations over time are displayed in Figure 3, demonstrating significant growth in translation activity especially during the LVK's third observing run (2019–2020). However, translation activity is typically less diverse for summaries of lower-profile (non-discovery) papers, demonstrating a similar pattern of enthusiasm by LVK translators and the target audience

Press releases to accompany discovery announcements are prepared centrally, including quotations from a selection of LVK members, and then adapted by member institutions (often including quotations from their scientists). As a global collaboration, it is not possible to find a single time for press releases to be made public that works for all time zones, which can make it challenging to coordinate local coverage.

Both Science Summaries and press releases have been drawn upon by journalists [e.g., Carlise, 2021]. Translation of Science Summaries is especially important for use in non-English media.

2.5 Interacting in person

In-person outreach to the general public reaches fewer people than other means, but it can yield impactful interactions, and may be perceived as having more value [Baucum, 2022]. As reported by one young attendee to in-person events: "one of the activities that most fostered my connection to the STEM world was attending in-person talks, conferences, and panel discussions [. . .] ultimately leading me to pursue a degree in physics."

LVK members participate in science festivals, classroom visits, the creation of museum exhibits (such as interactive detector models [Cooper et al., 2021], or the *Black Hole and Gravitational Wave* circular exhibitions, lectures and panel discussions across Taiwan and Japan), visitor centers, and tours of the GW observatories. The face-to-face format allows staff to customize the experience to the visitor.

LVK's visitor centers merge artifacts from the detectors with interactive exhibits that put the visitor in the role of a scientist or

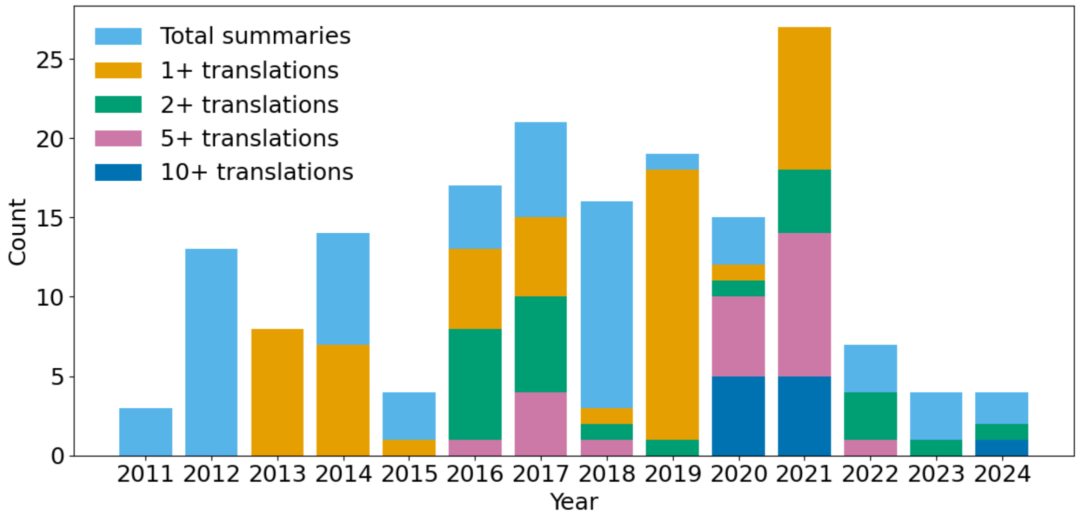

Figure 3: Number of Science Summaries by year of posting, and their number of translations. There were fewer papers in 2021–2024 while waiting for the results of the latest observing run.

engineer. The exhibits explore the underlying science and engineering of GW detectors, from the importance of pendula to concepts underpinning gravity. In-person and virtual tours of the detectors give a glimpse to the heart of operations. Over $330,000$ visitors have interacted with the LVK visitor centers; 2024 attendance is projected to reach $30,000$.

Science festivals and local outreach efforts around the world connect with classrooms and the general public. Outreach is performed by seasoned scientists, engineers, graduate students and undergraduates new to GW science. Such efforts positively impact the undergraduates who perform the outreach [Carpenter, 2015; Inverness Research Associates, 2014; Young & Katzman, 2023]. A 2023 survey revealed that 95% of undergraduates said "their experience has changed the way they interact with their communities" and over half of LIGO Livingston program undergraduates said it "helped them decide to go into a STEM field or educational field" [Inverness Research Associates, 2023]. Undergraduates often note soft-skills development, one said "My experience as a LIGO docent has changed my life and how I interact with everyone. From conducting my presentations at school, teaching my kiddos, conducting business, or simply talking to others."

2.6 Creating graphics

Unlike electromagnetic observatories, GW data does not naturally lend itself to the stunning images that are commonplace throughout astronomy. Nevertheless, visualisations, infographics and cartoons [e.g., Kijbunchoo et al., 2016; Thompson et al., 2020] form key parts of our outreach activities, e.g., infographics displaying key facts accompany discoveries; simplified plots of results may be created for Science Summaries, and artistic representations of our sources may accompany press releases

Videos and images are also produced from numerical-relativity simulations of sources and the GWs they emit. Since new simulations are often produced to better understand the physics of novel sources, fresh visualisations have accompanied discovery announcements.

Images accompanying LVK discovery announcements have been selected as NASA Astronomy Pictures of the Day, e.g., to accompany the first detection, an artistic representation of a binary black hole coalescence (Figure 4) and a corresponding numerical-relativity simulation were featured (11 and 12 February 2016), and to accompany GW190521, an artistic representation of the GW emission from two spinning black holes was featured (8 September 2020).

2.7 Employing multisensory resources

Sound is a common analogy when describing GWs. While GWs are not sound, the GW frequencies observable by the LVK are similar to audio frequencies of human hearing. The signals lend themselves to audification (www.soundsofspacetime.org): the technical name for the signal from a binary inspiral is a "chirp" in reference to its sweep up in frequency.

GWs can also be communicated through touch. The GW150914 signal has been translated to a 3D-printable model, specifically tailored to the needs of visually impaired people. By running fingers along the edges of the shape, one can appreciate the features of a GW and perceive the details of the signal evolving in time. This design is freely available [EGO-Virgo, 2021], along with suggestions for classroom activities.

The Tactile Universe (www.tactileuniverse.org) [Bonne et al., 2018] has partnered with LVK groups to design tactile resource sets for use with blind and vision-impaired pupils in upper secondary education. A mix of 3D-printable (Figure 5) and more basic tactile resources, paired with existing sonifications, are tied to 20 minute workshops about black holes and neutron stars, GW signals and detection, and core science topics like waves and gravity. The 3D-printable resources, example lesson scripts and guides are available on the website. Students have enjoyed interacting with the tactile resources; teachers have praised the accessibility and pacing of the workshops, and in post-session feedback, students have demonstrated an understanding of the concepts discussed.

The audifications and tactile resources have also proved effec-

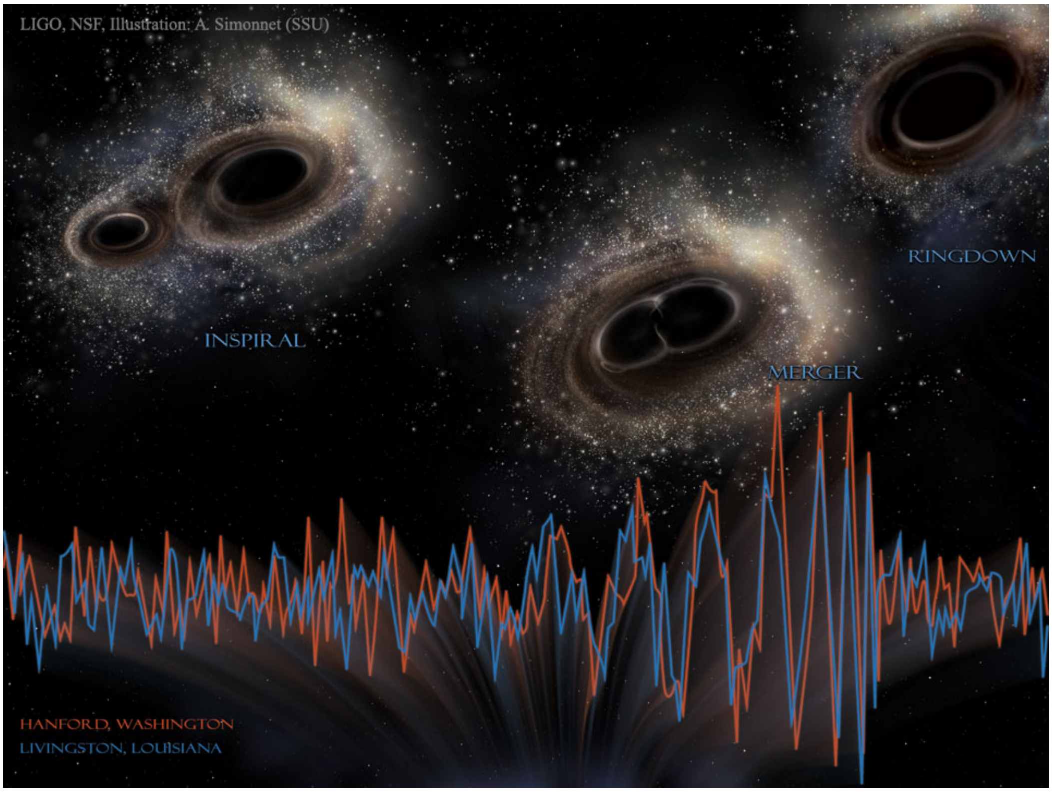

Figure 4: The detector data for GW150914, and an artistic representation of its binary black hole source (credit: LIGO/National Science Foundation/Aurore Simmonet/Somona State University).

Figure 5: A Tactile Universe 3D printed surface of the inspiral of two black holes and the resulting GWs

tive at science festivals, with members of the public appreciating having the diverse means of explaining unfamiliar concepts. This demonstrates how providing multisensory resources makes ideas accessible to a wider audience as well as more comprehensible to existing audiences.

2.8 Combining art and music with science

Art, music, and science collaborations explore novel approaches to GW communication, showcase the science through a different point of view, and bring the topic to new audiences. Works have been created by professional artists and musicians, and LVK members [e.g., Azure et al., 2021]. Examples include music compositions [Instituto de Física Corpuscular, 2023; Penguin Cafe, 2023], open land art installations [Virgo, 2022], museum exhibits [EGO, 2019] and novel musical instruments such as GravitySynth which combines the technology of GW detection with modular synthesisers [Trimble, 2024; Azure et al., 2021]. The LIGO-India blog has a virtual gallery GWSciArt that showcases GW-inspired artistic projects [LIGO-India, 2024c].

Combining art with science can help reach new audiences and provide a memorable experience. For example, the art and science festival *Celebrating Einstein* merged dance, music, and film with GWs. Assessment of the festival audience demonstrated that those who attended were a mix of those interested in science and art; that non-physics experts gained knowledge (e.g., 75% of physics novices improved their score between pre- and post-event surveys), and that attendees typically had a positive emotional response to the event [Grimberg et al., 2019]. Similarly, *Into the Quadrivium*, a collaboration between GW researchers and musicians, which blended baroque and contemporary music with spoken-word explanations of GW science, was positively received by the audience [Into the Quadrivium, 2023].

Table 2: Social-media followers (August 2024).

Platform	Account	Followers
X	LIGO Scientific Collaboration	$110,600$
	European Gravitational Observatory and Virgo	$12,500$
	KAGRA	$2,500$
	LIGO Hanford Observatory	$10,800$
	LIGO Livingston Observatory	$5,300$
	LIGO India	$6,700$
	LIGO Magazine	690
Facebook	LIGO Scientific Collaboration	$33,000$
	European Gravitational Observatory and Virgo	$7,000$
	LIGO Hanford Observatory	$6,100$
	LIGO Livingston Observatory	$6,800$
	LIGO India	$9,600$
Instagram	LIGO–Virgo	$14,900$
	LIGO India	$5,600$
Mastodon (Astrodon)	LIGO Scientific Collaboration	$1,500$

2.9 Communicating through social and non-traditional media

Non-traditional media provides an opportunity to present our science to broad audiences. Activities like social-media posts, blogs, and podcasts or interviews can communicate science in an informal way.

Interviews have been hosted on the Spanish podcasts "Oscilador armónico" [Cordero-Carrión et al., 2023] ($7,800$ listens as of August 2024), "A ciencia cierta" [Rivera, 2021] ($33,100$ listens) and "Coffee Break: Señal y Ruido" [Socas-Navarro, 2021] ($40,800$ listens). The last podcast coined the term "gravitondas" ("graviwaves") for GWs. Communicating with audiences in their local language makes science more accessible. The podcast format is more flexible than traditional radio programming allowing more time and in-depth discussion needed to explain complicated ideas.

The LVK has several social-media accounts, for the Collaborations and the observatory sites, across different platforms (Table 2). The greater following for LIGO compared to Virgo and KAGRA may be a consequence of the same bias that leads to LIGO preferentially receiving credit. Content includes educational resources, news stories, and discovery announcements. Special posts are scheduled for events such as detection anniversaries or the International Day of Women and Girls in Science. The observatory accounts often share posts about local news, such as pictures from the sites or events at the science centres, while the Collaboration accounts take the lead on big announcements.

Social-media content is reshared across platforms with suitable adaptations. The microblogging X and Mastodon platforms are well-suited to threads; these are useful for linking many resources or explaining a topic from many angles. Facebook and Instagram allow for longer posts, enabling more in-depth explanation per post, but posts must be spaced further apart to avoid cluttering followers' feeds. Across all platforms, the most popular posts often feature a graphic or video (all Instagram posts include a graphic or video), and hence these are sought whenever possible.

The different social-media platforms reach different numbers of people and demographics. Table 3 shows metrics for the GW230529_181500 discovery announcement (April 2024). While X has the most views/users reached; Mastodon has the most shares per follower (as a newer platform it potentially has a higher proportion of active users), and Instagram has the most likes per follower.

Social media allows the LVK to interact directly with the public, and threads in response to questions have often proved popular. On Reddit, the LVK has run occasional Ask-me-anything discussions. The Ask-me-anything accompanying GW150914 has $2,300$ comments. Posting answers to questions online enables them to be searched out in the future.

2.10 Using interactive technologies

Interactive apps and games are engaging and fun ways to convey GW science. Interactive apps and games are engaging and fun ways to convey GW science. Physical interaction with virtual environments incorporates additional modes for audiences to engage with content. Activities have ranged from computer games [Carbone et al., 2012] (www.laserlabs.org; blackholehunter.org) to classroom and science festival teaching with virtual reality (www.scivr.com.au) [Parks, 2023] .

Mission Gravity [Bondell & Myers, 2021; Kersting et al., 2023] is an interactive virtual-reality environment designed for secondary school students to collaborate to better understand black holes and neutron stars. Since 2018, the program has been delivered to over 23,000 students across over 400 schools, as well as to over 1,100 teachers through professional-development workshops. One student reported: "The virtual reality component of it was engaging and enjoyable [...] I was able to understand ideas that I previously struggled with."

3 Case Study: GWTC-3

GW discoveries from the LVK are published in catalogs: papers accompanied by data releases. GWTC-3 [Abbott et al., 2023a] is the most recent of these, presenting results up to the end of the third observing run. Thanks to the continued improvements in detector sensitivity [Abbott et al., 2020b], the rate of discoveries has increased with time, meaning that each catalog includes a significant number of new GW candidates. GWTC-3 represents the most sophisticated and comprehensive analysis published by the LVK to date.

Production and publication of a catalog is a multi-year project directly involving hundreds of experts. Given the significance of the results and the importance of easy-to-use data releases, effective communication is a priority. However, communication of catalog results faces challenges: catalog results consist of comprehensive analyses of many signals (making them overwhelming), and the majority of detections have properties similar to those observed in the past (lacking the excitement of a novel discovery).

For GWTC-3, the project team included a member responsible for coordinating communication and outreach activities from the beginning. This embedding allowed for these activities to be planned as the project progressed, developed in tandem with the data releases, and coordinated with those compiling the results. Delaying this work until the project was nearly complete may not have left sufficient time to produce and review resources, and risked the team being too exhausted to contribute to these tasks. LVK paper teams typically have a designated person responsible for producing data products and for writing the Science Summary, but

Table 3: Social-media performance as of August 2024 for LIGO posts about GW230529_181500 (GW230529) and the GWTC-3 Orrery. Statistics are not directly comparable between platforms but qualitatively similar. Numbers per follower are given in parentheses.

		Platform							
Post	**Metric**	**X**		**Facebook**		**Instagram**		**Mastodon**	
GW230529	Reposts/shares/boosts	155	(0.0014)	89	(0.0027)	72	(0.0048)	18	(0.0120)
	Likes/reactions/favorites	328	(0.0030)	261	(0.0079)	662	(0.0444)	26	(0.0173)
	Views/reach	46,000	(0.42)	18,300	(0.55)	5,200	(0.35)	n/a	
Orrery	Reposts/shares/boosts	113	(0.0010)	48	(0.0014)	51	(0.0034)	25	(0.0167)
	Likes/reactions/favorites	350	(0.0032)	144	(0.0043)	813	(0.0546)	32	(0.0213)
	Views/reach	192,000	(1.74)	7,800	(0.24)	9,600	(0.64)	n/a	

these may not necessarily be integrated into the team throughout the project, and there is not typically one person responsible for coordinating communication and outreach more generally. We recommend following an approach similar to GWTC-3 of having a dedicated team member responsible for communication and outreach, and starting work on the resources early.

The variety of activities designed to communicate the discoveries from GWTC-3 span the diverse range of audiences targeted and platforms used by the LVK.

3.1 Sharing the people behind the science

LIGO Magazine issue 20 featured an 8 page article by 23 members of the analyses, paper-writing, and engagement teams [Berry et al., 2020]. They wrote about their experiences of working on the catalog and associated results. Although the article authors represent only a fraction of those providing input to GWTC-3, features like this give readers a behind-the-scenes insight of working on big LVK results.

3.2 Engaging academia

A series of LVK webinars were organised to coincide with the release of GWTC-3. The first on GWTC-2.1 [Abbott et al., 2024], a reanalysis of previous data using updated methods consistent with GWTC-3. Subsequent webinars presented the GWTC-3 results and implications for cosmology, astrophysics and tests of general relativity. Presenters were drawn from those who made key contributions to the work, with preference given to early-career scientists, and balancing geographic location and demographics.

The data release was a key component of the GWTC-3 results. It included Jupyter notebooks and Python scripts to demonstrate use and how to reproduce plots from the paper. As of August 2024, the data release for the inferred source properties of the new GWTC-3 detections is the most viewed of all Zenodo-hosted LVK data releases, with approximately 8,000 views (27,500 file downloads); the second most viewed is the equivalent set of results for the GWTC-2.1 analysis, with approximately 5,600 views (21,800 file downloads). The popularity of the data release indicates that the community appreciates the value of the results, and understands how to use data products.

As the detection rate increases, it becomes more difficult to manage all the analyses, and curate data releases that include all the relevant results (especially if there have been multiple reanalyses to obtain final results). We recommend automating the process to reduce the chance of human error in data-release production, and efforts are underway to develop such automation tools [e.g., Williams et al., 2023].

For GWTC-3, a Streamlit app was created to interactively make plots of source parameters enabling users to customise paper plots without needing to download data (gwtc3-contours.streamlit.app/).

3.3 Writing reference texts

Like the paper itself, the GWTC-3 Science Summary [LIGO-Virgo-KAGRA, 2021] had a broad scope to cover. It was written in close collaboration between outreach experts and the analysis and paper-writing teams. It includes background information needed to understand the catalog, and a subset of highlight discoveries. The summary has been translated into 9 languages.

A LVK news item, rather than a press release, was drafted for GWTC-3. This was used by individual institutions to draft their press releases. The decision to not have a LVK press release reflected the expectation that GWTC-3 would be more difficult to communicate, and hence less attractive to write about, than a single discovery. Despite this, several science journalists did write articles about GWTC-3 [e.g., Carlise, 2021; Castelvecchi, 2021; Plait, 2021]. This demonstrates that the LVK did at least partially succeed in efforts to communicate the science of GWTC-3 to journalists, and (assuming similar communications efforts are organised in the future) that there may be an audience for press releases for future catalog releases.

Resources, including the news item and institutional press releases, were made public at 01:00 UTC on Monday 8 November 2023. The time was chosen to coincide with the paper preprint appearing on arXiv, while the date was chosen to correspond to the predefined detector data release timeline. An embargo period was offered from 18:00 UTC on Thursday 4 November when trusted journalists could be contacted about the upcoming release. Providing such an embargo period gives time for journalists to prepare and check their stories, which is beneficial; however, this embargo period was mostly over the weekend. Therefore, for future discovery announcements, it may be beneficial to have a longer embargo period, or to choose the day of the week for release more carefully.

3.4 Creating graphics

Updates to some long-standing LVK visualisations were made for GWTC-3. The new results were added to the Masses in the Stellar Graveyard plot (Figure 6). This plot is now generated from GWOSC data products, making it easy to add large numbers of detections. An online version allows for customisable images [Geller et al., 2024]. The LVK Orrery was also updated, which shows a stylised animation of the GWTC-3 binaries.

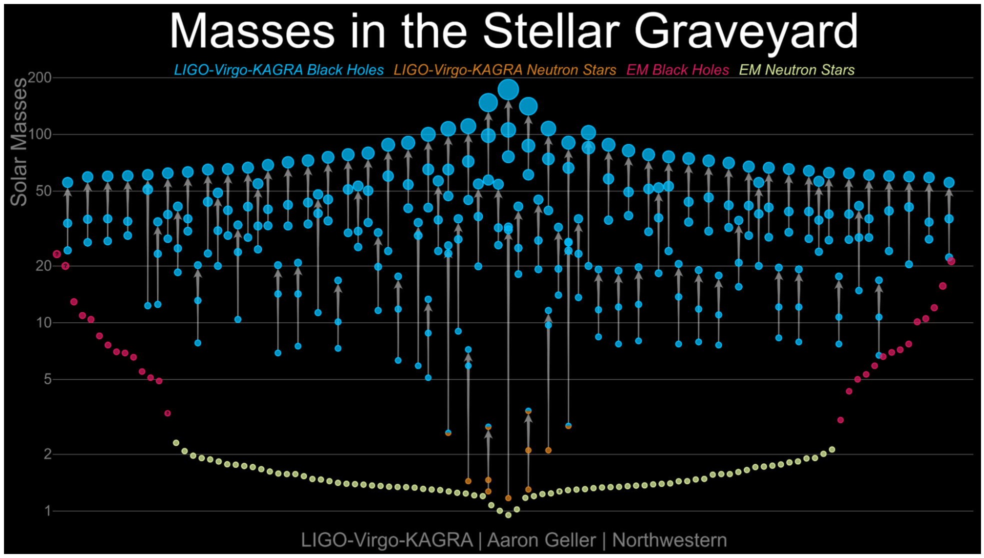

Figure 6: GWTC-3 version of Masses in the Stellar Graveyard (credit: LVK/Aaron Geller/Northwestern). The plot shows the known masses of stellar-mass black holes and neutron stars observed electromagnetically and with GWs.

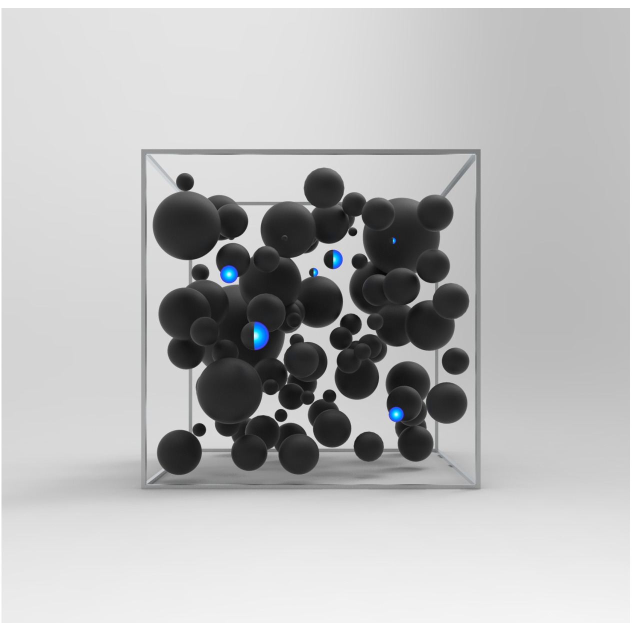

Figure 7: An artistic representation of GWTC-3 sources which accompanied the journal publication (credit: Carl Knox/OzGrav Swinburne).

New visualisations were also created. One was a poster reminiscent of a periodic table showing the catalog after each observing period. The poster was used in a variety of articles, a double-page LIGO Magazine spread [Knox, 2022], and in the GWTC-3 webinar. An artistic representation of the detected sources in a box accompanied the publication in *Physical Review X* (Figure 7). An image showing spectrograms for the 90 GWTC-3 signals was featured as NASA Astronomy Picture of the Day (7 December 2021).

3.5 Employing multisensory resources

Low Mass Beats is a audification of the catalog, converting masses into pitch for each black hole or neutron star: the greater the mass, the lower the pitch. This lighthearted project provides an entertaining perspective on the catalog. (SoundCloud: soundcloud.com/user-889003031)

3.6 Communicating through social and non-traditional media

GWTC-3 material was shared via a social-media campaign in two bursts using the hashtag #GWTC3. The first burst coincided with the release of the preprint and associated data. Special attention was given to advertising the webinars and data releases. The second burst coincided with the publication of the journal article and priority was given to any resources developed since the initial release, such as the Streamlit plotter and Low Mass Beats.

For both bursts, posts were spaced over multiple days to catch the attention of people in different timezones. Material was translated into regional languages [LIGO-India, 2024d]. The pacing also made it natural to integrate popular-science articles written immediately after the release.

From the second burst, the most popular post was for the Orrery. Statistics are shown in Table 3. It is generally less shared than the GW230529_181500 post, but there were more posts for GWTC-3 than for GW230529_181500 spreading out attention: that numbers are comparable demonstrates that catalog results can capture interest similarly to new detections. The Orrery has high X views having been reposted by accounts with large followings.

Resources were subsequently reused, e.g., Low Mass Beats was shared on Halloween because of its spooky sound, and the Orrery was shared during NASA's Black Hole Week.

The impact of the social-media campaign can be partially assessed via the Altmetric score. As of August 2024, the GWTC-3 paper has a score of 714 (including 56 news outlets and 6 Wikipedia pages). This score is in the 99th percentile of all tracked outputs.

4 Conclusions

GW astronomy is a new branch of astronomy. After decades of research, the first observation was made in 2015, and the field has grown rapidly since. These discoveries have been led by the LVK, an international collaboration of thousands of scientists. Sharing these discoveries has been a priority for the LVK. As a new field, communication has been essential to both publicise and explain results.

LVK activities span a range of audiences and media. Within the LVK, different activities are run by different teams, some coordinated Collaboration-wide, while others reflect individual interests. This provides a rich environment, where science-communication resources can be shared between different communications efforts. Many resources are used in multiple contexts, such that utility can be amplified beyond the original target, e.g., paper plots used on social media, infographics in talks, and data audifications in musical performances.

Communicating LVK discoveries has a unique set of challenges, but each provides an opportunity:

- GWs are an unfamiliar means of performing astronomy. Unlike traditional astronomy, GW astronomy does not directly image sources. However, GW data is suitable for audification, and a variety of tactile resources have been made. These make GW astronomy accessible to people with vision impairments, who are often excluded from accessible astronomy communication [Bell & Silverman, 2019], in addition to providing a novel way to explain these physical concepts.

- LVK results are produced by large teams. This makes it difficult for those outside to understand how discoveries are made, or to construct human-interest stories. However, this enables emphazization of the importance of teamwork and international cooperation to science. The LVK's breakthroughs are a contrast to the popular perception that scientific breakthroughs come from lone geniuses [Larivière et al., 2015; Aksnes & Aagaard, 2021]. The diversity of the LVK's membership also allows us to draw upon many different lived experiences, and demonstrate that scientists may come from any background.

- After the initial first observations, many detections were similar to those discovered previously. The increase in the LVK's detection rate is an experimental triumph—what was once extraordinary is now everyday. It is therefore necessary to concentrate on the science enabled by a large set of detections. This has a benefit of reflecting that most scientific progress comes from careful study rather than a dramatic breakthrough.

Elements of each challenge may translate to other communication efforts:

- When abstract or theoretical concepts are being communicated, having diverse explanations (combining multiple views of the concept and engaging multiple senses) may aid audience comprehension.

- When results come from large collaborations, which is increasingly common in physics and astronomy [Smith, 2016; Battiston et al., 2019], drawing upon the diverse experiences of collaboration members may help engage members of the public with similar backgrounds.

- When a new field is founded, charting the way the field will evolve long term may help increase scientific literacy regarding how scientific progress is made through many small advancements (in addition to through big discoveries).

Consequently, while we do not expect the exact circumstances faced by the LVK will be replicated, we anticipate that insights into GW-science communication may benefit others across science.

In communicating GW discoveries, the LVK has benefitted from existing interest in black holes and space. It has also faced hurdles, such as a tendency to misattribute discoveries to LIGO alone. This highlights the importance of taking a holistic approach to planning and reviewing communication: it is advantageous that an audience correctly understands how science is done, as well as what the discoveries are, and it cannot be assumed that just because the audience is interested they will absorb all relevant information.

As GW astronomy continues to mature, we expect that communication strategies will need to evolve to reflect both the state of the field, and audience interest and awareness.

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Andrew Spencer is a Lecturer at the Institute for Gravitational Research at the University of Glasgow, his research focus is laser interferometry and technology development for future gravitational wave detectors. He has a special interest in outreach resource development, making education and communication resources for classrooms, science centres and festival events in addition to working on crossover projects that span science and creative arts.
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