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GWITCHHUNTERS – A CITIZEN SCIENCE PROJECT FOR THE IMPROVEMENT OF GRAVITATIONAL WAVE DETECTORS

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ABSTRACT

Gravitational wave detectors are complex instruments devoted to the formidable task of measuring spacetime deformations as small as a thousandth of the size of the atomic nucleus, like those produced by the signals originating from the coalescence of compact stars. GWitchHunters is a citizen science project aimed at promoting the study of the Universe carried out with these detectors and the ongoing activities to improve their sensitivity to newer and further sources of gravitational waves. In order to reach the vastest possible audience, we have developed new strategies to present detector data in the form of images and sounds. Moreover, citizens are invited to contribute themselves to the improvement of these detectors by completing simple tasks, inspired by those actually carried out by researchers, that consist in identifying relations and patterns in the data. This constitutes an important aid to the detector characterization activity conducted by the scientists. All of this is proposed via the Zooniverse web platform, where citizens can get to know about the research on gravitational waves and enjoy giving their contribution to this field.

RESUMEN

Los detectores de ondas gravitacionales son instrumentos muy complejos diseñados para la colosal tarea de medir deformaciones del espacio-tiempo tan pequeñas como una milésima parte del tamaño del núcleo atómico, como las producidas por la coalescencia de estrellas compactas. GWitchHunters es proyecto de ciencia ciudadana que tiene el objetivo de promover el estudio del universo y que se lleva a cabo con estos detectores, al igual que las actividades para mejorar su sensibilidad para las diferentes fuentes de ondas gravitacionales, tanto conocidas como por descubrir. Para alcanzar al mayor público posible, hemos desarrollado nuevas estrategias para mostrar los datos del detector en forma de imágenes y sonidos. Además, los ciudadanos estan invitados a contribuir en la mejora de estos detectores a través de tareas simples, inspiradas por las que realizan los investigadores, que consisten en identificar patrones en los datos. Esto representa una ayuda importante para la caracterización del detector, que es una actividad realizada habitualmente por los científicos. Todo esto se realiza a traves de la plataforma web Zooniverse, donde los ciudadanos pueden descubrir la investigación en ondas gravitacionales y disfrutar contribuyendo en este campo.

Key Words: citizen science — gravitational waves — interferometry — LIGO

1. INTRODUCTION

Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) are kilometer-scale interferometric detectors, aimed at detecting *gravitational waves* (GWs), "ripples" in the fabric of spacetime predicted by Einstein's General Relativity (Einstein 1916) and produced by some of the most extreme astronomical events, like black hole and neutron star coalescences, or even the Big Bang itself (Sathyaprakash & Schutz 2009). The information carried by these signals, alongside that provided by the electromagnetic radiation and the astroparticles, is used by researchers to study the origin and evolution of the Universe, as well as for achieving a deeper understanding of the fundamental laws of Nature (Perkins et al. 2021). Many noise sources of terrestrial origin, like disturbance from the detector physical environment or some subsystems malfunctioning, limit the sensitivity of these detectors. In particular, transient noise excesses, colloquially referred to as *glitches* (Nuttall 2018), can mask the presence of the astrophysical signal or even be confused with it. For this reason, a fundamental aspect of the experimental activity carried out by the scientists involved in GW research is the characterization of these glitches. This involves finding and understanding their origin and developing mitigation strategies, which make the detectors more sensitive

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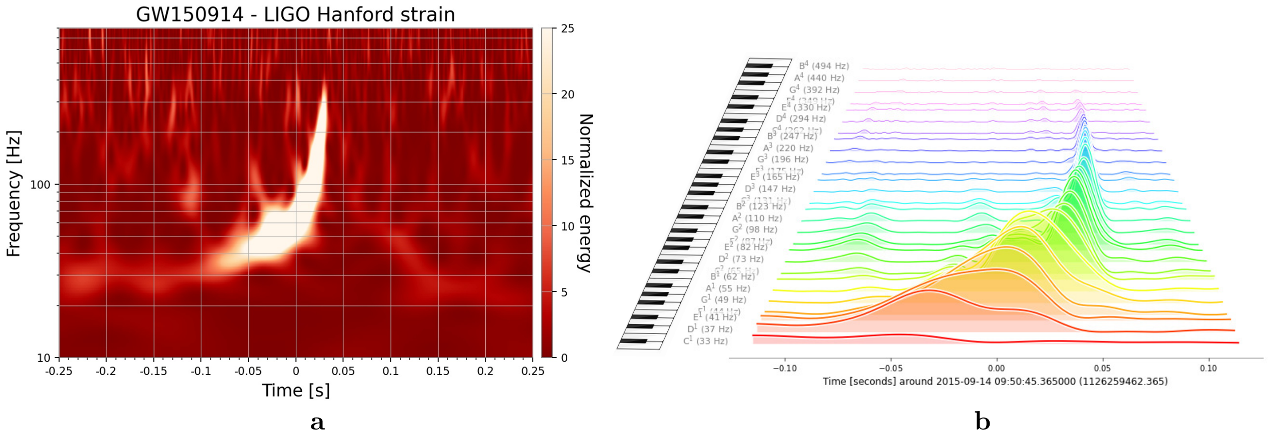

Fig. 1. Spectrogram representations of the GW150914 gravitational wave signal measured by the LIGO Hanford detector. (a) Colormap with the time–frequency representation of the energy of the signal, as in the original article (Abbott et al. 2016), and showing the characteristic "chirp" shape of the signal. (b) Alternative representation where the energy corresponding to the different frequency bands identified by the *C major* scale of Occidental music is represented by the series of curve. The higher the curve, the greater the intensity of the corresponding frequency component of the signal, while the depth dimension represents increasing frequencies.

to the astrophysical signals and better able to filter out noise (Aasi et al. 2012).

GWitchHunters (GW glitch hunters)[4] is a *citizen science* project, part of the REINFORCE project (Research Infrastructures FOR Citizens in Europe) of the European Union,[5] focused on the study of glitches in GW detector data. Our goal is to promote the scientific research carried out at GW detectors, providing public access to the data recorded by these instruments and directly involving the citizens, alongside researchers, in the improvement of the sensitivity of the detectors for the study of the Universe and the fundamental laws of nature. To this end, we have developed new means of communication with which to present the data, traditionally recorded in the form of time series, to the general public in a profitable and enjoyable way, without requiring any scientific expertise or prior data analysis experience. For example, we have released the data corresponding to the transient signals detected by our instruments, either of astrophysical or terrestrial origin, in the form of images and sounds. The prominent features present in them can be easily recognized by citizens of all ages and education level, including also people with visual impairments. This constitutes a fundamental step into promoting GW research and making it as inclusive as possible.

Moreover, citizens are invited to directly contribute to the improvement of these detectors by studying the presence in these images and sounds of specific features and correlations. This activity, directly inspired by that actually carried out by researchers, is of fundamental importance for categorizing the noise present in the detectors and finding its origin. Most importantly, all of this is carried out in the participatory environment provided by the Zooniverse web platform,[6] where citizens and scientists can interact and together take part in the understanding of the functioning of the detectors and cooperate in their improvements.

In the following sections, we describe how this activity is organized and present some preliminary results in the areas of citizen participation and contributions.

2. GRAVITATIONAL WAVE DATA

The fundamental quantity measured by interferometric GW detectors is the differential variation of their arm lengths, called a *strain*. The transit of a GW can produce a strain signal, which can be detected and studied to understand the astrophysical source that has generated the wave. The typical strain produced by such sources is in fact very small, comparable to a difference of one-thousandth of the atomic nucleus radius over distances of one kilometer. In order measure an effect as tiny as this, it has been necessary to build some of the most sensitive instruments ever invented. Unfortunately, many terrestrial effects can produce a similar, if not larger, arm length variation, hence constituting a source of *noise* for the astrophysical searches. An example

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[4] www.zooniverse.org/projects/reinforce/gwitchhunters

[5] www.reinforceeu.eu

[6] www.zooniverse.org

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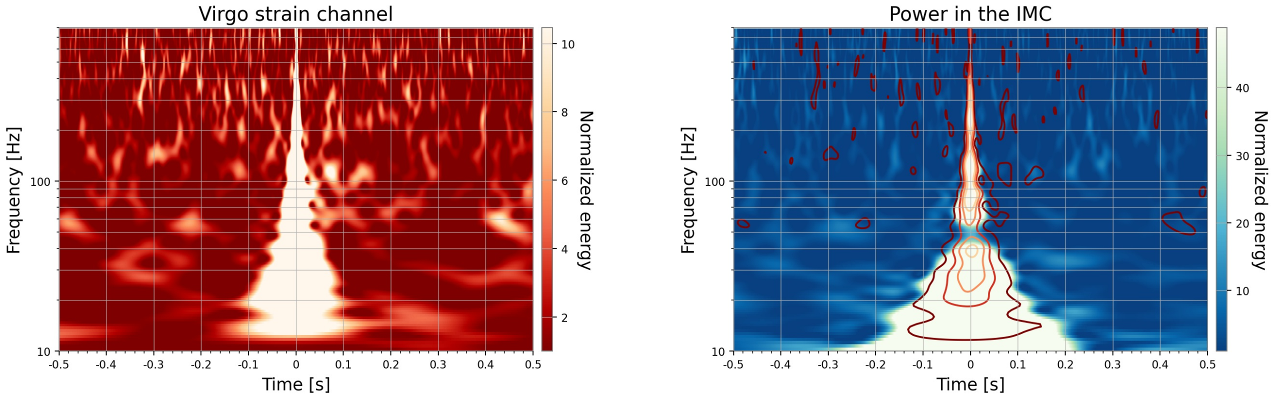

a **b**

Fig. 2. Spectrograms corresponding to (a) a glitch in the Advanced Virgo strain channel and (b) in an auxiliary channel, representing the power circulating in the Virgo Input Mode Cleaner (IMC). This corresponds to the triangular shape excess energy visible in both images. To facilitate the comparison of the excess energy in the two channels, we have superimposed onto the spectrogram in (b) some contour lines representing the energy level of the spectrogram in (a).

of a particularly detrimental kind of noise for these searches is the aforementioned glitches, which are the subject of the GWitchHunters project, the goal of which is their characterization and mitigation in order to increase detector sensitivity.

The signals recorded by GW detectors are typically stored in the form of time series, which renders them not immediately accessible for many. In order to involve citizens in this activity, we first need to make this data available in formats that are useful and enjoyable for the general public. The rest of this section is devoted to the description of how we have implemented this operation.

2.1. *Data Transformation*

The typical time series output of a GW detector, which, most of the time, contains only noise, is highly correlated within itself and, at any given moment, a signal is, to a large extent, influenced by its previous values. This can blur small transient variations that do not belong to the usual behavior of the detector, but which it might be interesting to observe and identify. These variations might be caused by a transient GW signal or some sort of spurious noise, such as a glitch. For this reason, we first transform the data to remove the correlations. This operation, known as *whitening*, involves normalizing of the signal energy to that of its stationary and Gaussian part. This normalization also provides a means with which to quantify the extent of each energy excess and allows for their better identification.

2.2. *Data Visualization by Means of Spectrograms*

Different energy excess may have different features. A useful means to start characterizing them is by means of *spectrograms*, which are representations of the energy of the signal in a time–frequency map. Examples of such a representation are reported in Fig. 1 for the first detected signal from the coalescence of a binary black hole system, observed by the two LIGO detectors on September 14, 2015, and named GW150914 (Abbott et al. 2016). The image on the left corresponds to the standard spectrogram representation, also present in the original article, which represents the evolution over time (horizontal axis) of the normalized energy of the signal (color scale) at various frequencies (vertical axis); the lighter the color, the larger the energy. In this image we can clearly recognize the characteristic signature of a binary coalescence signal, as predicted by Einstein's General Relativity (Pretorius 2005), and represented by the upward curved shape. This corresponds to a signal the frequency of which increases with time. It is called a "chirp" because, if converted to an audio format, it resembles the characteristic vocalization made by birds. This feature can be used to distinguish this signal from others of different origin, such as the astrophysical one produced by a core collapse supernova (Ott 2009) or the transient noise present in the data in the form of glitches (Nuttall 2018). For example, the spectrogram on the left-hand side of Fig. 2 shows a glitch in the Virgo strain channel and is characterized by a sharp triangular shape, clearly distinguishable from the previous one. We will elaborate further on the comparison of different signals in the spectrograms in Section 3.

These spectrogram images provide a useful means to represent GW detector data and to help to make its features evident to people with no ex-

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pertise in signal analysis. However, apart from the visual impact, establishing an understanding of what the signal energy and its evolution over the various frequencies represents, may not be immediate. For this reason, we decided to propose the alternative spectrogram representation shown on the right-hand side of Fig. 1. To make the concept of frequency of a signal clearer, we decided to emphasize its correspondence with sounds and referred to the frequencies of the seven musical notes A–B–C–D–E–F–G, or in the solfège naming convention: do–re–mi–fa–sol–la–si (Christensen 2006). We then considered the energy evolution of the signal in a frequency band given by the frequency of one of these notes and the next one in the *C major scale* of Occidental music. We reported these notes, together with their frequencies in Hertz on the depth axis of Fig. 1 for various *octaves* from the low C (do, 33 Hz), corresponding to the first octave, C^1, to the fourth octave B (si, 494 Hz), B^4.[7] The previous choice is entirely arbitrary, but has the great advantage of being directly comparable to the white keys of a piano, which enforces the understanding of what different frequencies represent. Moreover, the normalized energy in each of the previous bands is directly transposed to the intensity of the corresponding note. Together, musical notes succeeding in time with varying volumes, constitute a spectrogram representation that is understandable and enjoyable by a vast public. In practice, what we are doing is to interpret spectrograms as musical scores. The GW150914 chirp signal can now be imagined as a succession of notes with increasing pitch, one after the other, more and more rapid, until a maximum of about 392 Hz, corresponding to G^4, is reached. The glitch on the left-hand side of Fig. 2 corresponds instead to many notes rapidly played all at once. We have found at public outreach events that, with this representation, the conversion from the spectrogram image to the corresponding sound is easy and intuitive for people of all ages and with little or no musical experience. The support of a piano keyboard was enough to be able reproduce the “sound of spectrograms”.

2.3. *GW Data Sonorization*

The previous spectrogram representation also provides a direct recipe for the conversion of our data to sound. Indeed, with a MIDI player one can chose any instrument and map the intensity of the various curves on the right-hand side of Fig. 1 to the sound of the corresponding notes, creating an audio version of the data. Different instruments can be chosen to make the result clearer. Also, as the lowest notes, such as C^1, can be unpleasant on the ear, these can be shifted, for example by one or more octaves, to better match the sensitivity of the human hearing range.

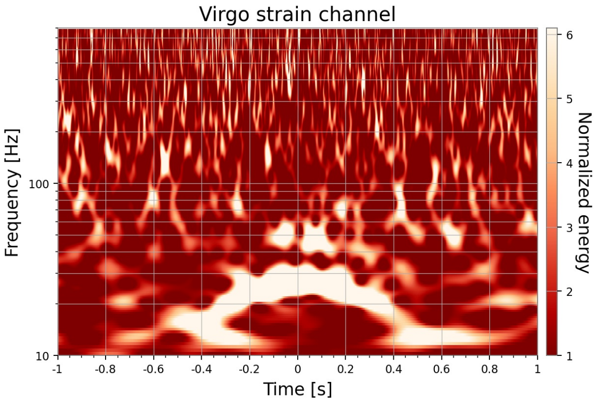

Fig. 3. Spectrogram of Advanced Virgo strain data representing a Scattered Light glitch, recognizable as the lighter arch-like shape at the center of the image.

Making GW data available in the form of sounds alongside images fosters a *multisensorial* approach to the understanding of the information contained therein. Moreover, this enables the involvement of people with visual impairments in research for GWs and the study of the Universe. The LIGO and Virgo collaborations have long been active in this area, periodically publishing audio representations of the detected GW events, obtained from the direct conversion of the measured signal to frequency.[8] With this newly proposed method, we aim to improve upon this, providing a more versatile approach and more pleasant results from actual music sounds.

3. CITIZEN INVOLVEMENT

GW detector data, in the form of images and sounds, has been made available to citizens via the GWitchHunters project on the Zooniverse web platform. Simple but challenging tasks are proposed to participants, in both web and mobile device versions, in order to involve them in the improvement of the detectors. The Zooniverse platform also provides a useful forum space in which citizens can interact with scientists, asking questions about the functioning of these instruments but also remain up to date with the most recent developments and results in GW research, and cooperate to achieve a better understanding of detector noise.

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[7] International Pitch Notation.

[8] The Sound of Two Black Holes Colliding, by Caltech/MIT/LIGO Lab.

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3.1. *Glitch Classification*

In the images in Figs. 1 and 2, we are able to distinguish the characteristic signature of a compact binary coalescence signal and that of a glitch, respectively. Similarly, we are able to identify various *classes* of glitches from their shapes. For example, Fig. 3 shows a glitch with a very peculiar arch-like shape, different to that in Fig. 2, and also to the astrophysical signal in Fig. 1. This kind of glitch is known to be produced by the vibrational motion of the ground, amplified during bad weather conditions, which causes part of the light circulating inside the interferometer to be scattered by vibrating surfaces and reinjected back into the main beam, producing this peculiar kind of energy excesses (Accadia et al. 2010). Because of its origin, this is referred to as a *Scattered Light* glitch.

One of the tasks proposed to the citizens is that of classifying glitch images on the basis of the shape of their energy excess and associating them to one of the labels, such as Scattered Light, introduced to characterize and distinguish their possible forms (Bahaadini et al. et al. 2018). The idea is that glitches belonging to the same class also share a common origin; having a large sample of similar glitches can guide the investigation of what was the status of the detector and its various subsystems at those moments, with the aim of finding what was the specific noise source causing these disturbances.

3.2. *Correlation with the Auxiliary Channels*

Classifying glitches is just the first step into their characterization. A much deeper insight into what may be their origins can be obtained by also examining the auxiliary channels monitoring the various detector subsystems and their environment, such as accelerometers, microphones, and photodiodes measuring the amount of light in specific parts of the interferometer. GW detectors have thousands of such sensors, which we can investigate for correlations with the strain channel. The idea is that channels that often glitch together, and with similar shapes in their respective spectrograms, can also be related in some way. In particular, an auxiliary channel witnessing some kinds of glitches can point to a specific part of the detector and kind of disturbance, for example vibrational, electric, etc.

On the right-hand side of Fig. 2, a glitch in an auxiliary channel of the Virgo detector is shown. The channel is measuring the circulating power in the Input Mode Cleaner (IMC) cavity and the glitch is occurring in coincidence with the glitch in the Virgo strain channel, reported on the left-hand side of the image. The overlaid contours representing the energy levels of the strain channel also suggest that their shapes are very similar. This is a hint that this glitch might be related with this detector subsystem.

Finding correlations between channels is one of the activities routinely performed by the researchers investigating detector noise, and it has also been proposed as one of the tasks of GWitchHunters. Citizens are invited to find similarities in images similar to those in Fig. 2, referred to the strain channel and other various auxiliary ones.

4. CONCLUSIONS AND PERSPECTIVES

With GWitchHunters we have proposed a framework for the promotion of GW research by introducing citizens to the data recorded by GW detectors and involving them in this research with simple activities, inspired by those performed by the researchers working on the characterization of detector noise. In the first two months following the launch, more than two thousand volunteers contributed to this project with more than 150, 000 glitch classifications. This outstanding result is incredibly valuable in helping to guide the mitigation of detector noise and the improvement of detector sensitivity.

5. ACKNOWLEDGMENTS

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