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All-sky, all-frequency directional search for persistent gravitational waves

from Advanced LIGO’s and Advanced Virgo’s first three observing runs - O1, O2 & O3

The LIGO, Virgo and KAGRA detectors detect gravitational waves (GW) from all directions of the sky. So far they have been able to detect signals from various compact object mergers, e.g., merging of combinations of Black Holes and Neutron Stars. These signals come as short duration ‘chirps’. There are more kinds of signals that are yet to be detected, one of them is a persistent stochastic gravitational wave background (SGWB).This signal type, which may be detected in the near future, is the result of superposition of unresolved short-duration events and phenomena of cosmological origin.

Since this background is stochastic (random) it cannot be detected with matched filtering which is useful for a signal with a predictable shape. So a cross-correlation technique is used, the idea of which is that the self-generated noise in the detectors will be uncorrelated but an SGWB signal coming from the sky, although random, will be the same in all the detectors. The reading from one detector is used as a filter on the other detector to check if that also detected the same thing. Also since detectors are located in different locations the signal arrives at them at slightly different times. The small delay between the arrival times can be used to tell which direction the signal came from. The technique of aperture synthesis uses these ideas and combines earth's rotation with it to make a full skymap from the cross-correlated results.

So far different searches have been performed to constrain anisotropic SGWBs using the aforementioned techniques. These searches are optimised for certain expected properties of the SGWB and are broadband, that is, distributed over a wide range of frequencies, so narrowband/monochromatic signals will have a very small chance of getting detected. In this paper we present the result of a new search which looks for persistent stochastic GW sources in all directions of the sky in all sensitive frequency bins of the detectors. We call this **All Sky All Frequency (ASAF) radiometer search**. This search has become possible after the implementation of algorithms based on mathematical symmetries, namely data-folding techniques, and some more optimization by a new independent python-based algorithm PyStoch.

We applied the ASAF search on data from the first three observational runs of the Advanced LIGO and Advanced Virgo detectors. We divided the sky into 3072 pixels of equal area (HEALPix scheme) and searched for a persistent GW source in every pixel for each frequency bin. Each frequency bin is of 1/32 Hz in width and in the 20Hz to 1726Hz range. The frequencies that are contaminated with unavoidable instrumental disturbances (e.g. calibration lines, power lines, and their harmonics etc.) are excluded from this search.

In order to search for significant outliers, which could indicate the presence of a signal, we first needed to determine the noise background. Since GW signals may always be present in the detector, it is tricky to directly measure only the detector noise. The background is estimated by introducing a random unphysical time-shift between the data streams from a pair of detectors which is much greater than the light travel time between their locations. This ensures that the resultant correlation must be arising from noise and not from an extraterrestrial signal. This is called the time-shifted (TS) analysis and when the cross-correlation is done without this unphysical delay, it is called zero-lag (ZL) analysis. By comparing the TS and ZL results we can see if the observed outliers are statistically significant.

In conclusion to the ASAF search, no persistent GW signal of a stochastic or persistent narrowband character is detected by our analysis in the first three observing runs from the Advanced LIGO and Advanced Virgo detectors. We nevertheless identified some of the potential frequency-pixel pairs for narrowband signals that are statistically more likely to contain a signal and may be worth following up with a more sensitive matched filtering based analysis. Note that, while the matched filtering based analyses can search for isolated neutron stars at narrower frequency bins and are more sensitive, ASAF analysis can rapidly search for such monochromatic signals with very little computational power and set upper limits at all frequency and sky-locations for the resolutions used here. Another advantage of ASAF search is that since it is relatively general, results of some other searches (e.g. broadband radiometer, isotropic) can be derived from ASAF results (even with arbitrary spectral models), which we have confirmed. While detection of persistent gravitational wave backgrounds has not been possible so far, this analysis is a significant step forward in searches for such signals.

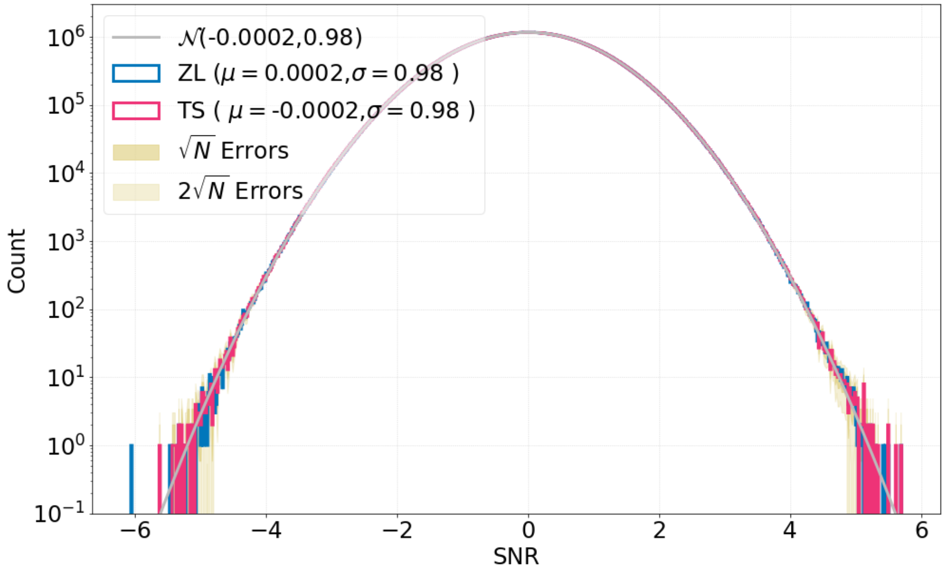

Fig 1: Distributions of SNR from all the combined baselines and all observing runs are shown here. Histogram of SNR from the time-shifted analysis is in red and from zero-lag analysis is in blue. Both the physical and unphysical time-shifted data set are consistent with correlated Gaussian noise (grey histogram) within the acceptable error.

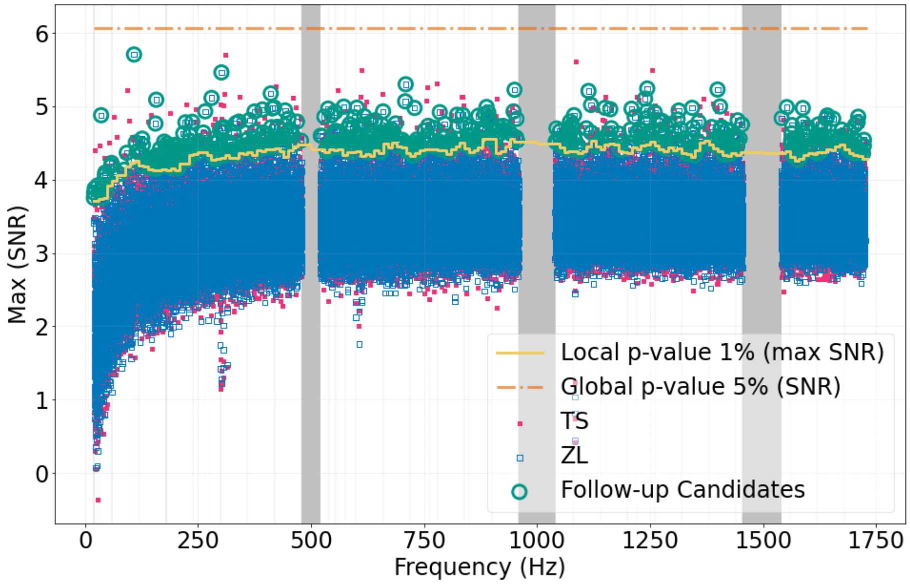

Fig 2: This plot depicts the distribution of maximum SNRs from both time-shifted (TS) and zero-lag (ZL) analyses performed over the combined baselines and all three observing runs. The grey solid lines represent the frequencies that are excluded. The yellow curve shows the 99th percentile of maximum SNR for every 10 Hz frequency bin in the time-shifted analysis, smoothed over 3 neighboring 10 Hz bins. Though we do not find any outliers significantly above the noise background, the teal circles represent 515 candidates which may be followed up by a more sensitive matched-filtering-based analysis.

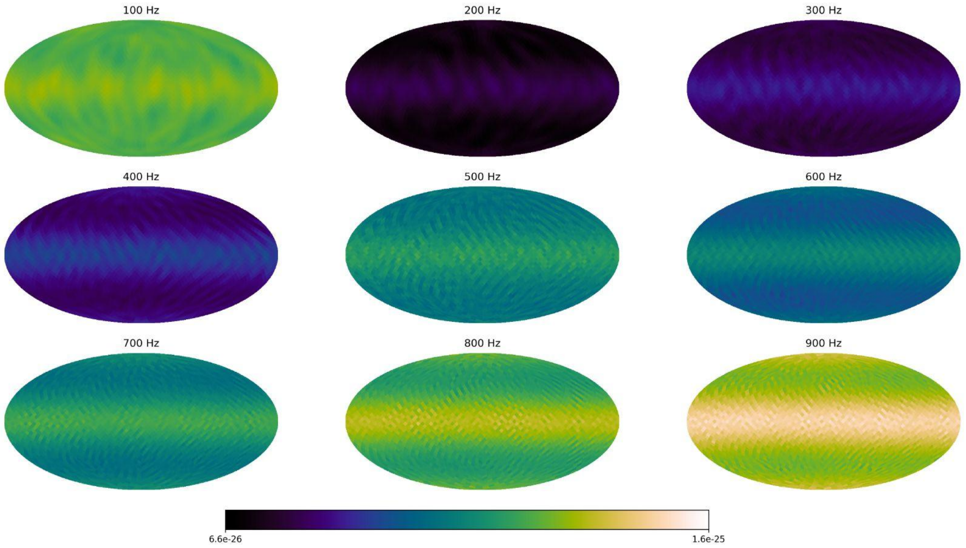

Fig 3: These maps show the upper limits of expected gravitational waves strains at different frequencies. The upper limit means the extraterrestrial signal at these frequencies cannot be more than what is shown in these maps. The color-shading indicates the sensitivity of our search in different frequency bands, and for different sky directions. One can see that the search is generally somewhat more sensitive near the equatorial plane. Moreover, the search is most sensitive in the 200-400Hz range.

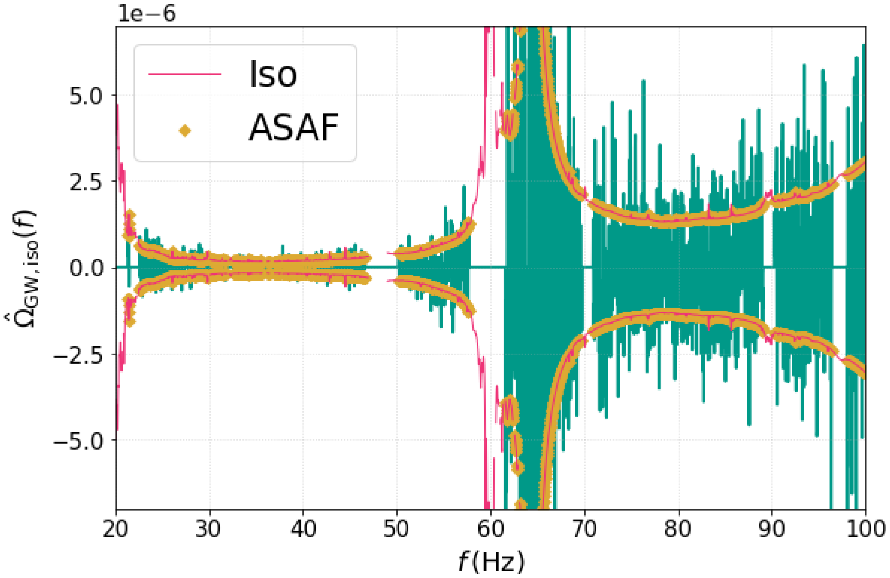

Fig 4: The isotropic cross-correlation spectra derived from the ASAF analysis using the HL baseline data. The red line depicts the estimated value of sigma with the isotropic ORF, while the yellow points show the uncertainty in the cross- power estimator obtained from the ASAF search. It is evident from the plot that these are consistent. The green vertical line, which fluctuates around zero mean, represents the point estimates from the ASAF search.

Indian contribution

The Advanced LIGO and Advanced Virgo experiments are funded by an international consortium of universities and education and research agencies. More than a thousand professors, researchers and students work on this experiment. It is not possible for this experiment to be fruitful without their contributions. Incidentally, most people who worked on this particular paper are past and present affiliates of IUCAA, Pune, India. The predominant part of the analysis was performed by a young PhD student Deepali Agarwal who is pursuing her PhD from Inter-University Centre for Astronomy & Astrophysics (IUCAA) under the guidance of Prof. Sanjit Mitra who was also the project manager for this analysis. The paper writing team was chaired by Dr. Jishnu Suresh, the development of the pipeline was led by Dr. Anirban Ain, significant contributions were made by Dr. Shivaraj Kandhasamy to determine the appropriate data quality criteria for this analysis and Prof. Sukanta Bose chaired the review team. Dr. Ain (presently in

INFN-Pisa, Italy) and Dr. Suresh (presently in ICRR Tokyo, Japan) are respectively past PhD student and post-doctoral fellow of IUCAA.

Glossary

- **Advanced LIGO/Virgo:** The second epoch of LIGO/Virgo, using upgraded detectors which are (to date) about three times more sensitive than the initial ones, with further improvements in sensitivity planned. (LIGO webpage, Virgo webpage)
- **Stochastic gravitational wave background:** A stochastic background of gravitational waves produced by accumulation of unresolved short-duration sources (such as neutron stars and black holes) and events of cosmological origin which is indistinguishable from background noise in a single detector. (Wikipedia)
- **Black hole:** A region of space-time with gravity so intense that it prevents anything, including light, from escaping. (Wikipedia) Black holes come in different sizes: the stellar-mass black holes originate from stellar collapses and their masses range from a few solar masses to about 65 solar masses. (Wikipedia) The intermediate-mass black holes range in mass from around 100 solar masses to 105 solar masses. (Wikipedia) Finally, the supermassive black holes range from more than 105 solar masses to more than 109 solar masses. (Wikipedia)
- **Chirp:** A chirp is the gravitational wave signal or waveform shape we typically observe as a pair of superdense objects, such as black-holes or neutron stars, inspiral towards each other before merging. In a chirp signal, both frequency and amplitude increase with time, and reach a maximum when the objects merge. (Wikipedia)
- **Compact Binary Coalescence:** The merger of two dense, compact objects like neutron stars and black holes orbiting around each other. (SoundsOfSpacetime, MPG-AEI)
- **Isotropic:** to appear the same in every direction or viewing angle.
- **Matched Filtering:** A technique to detect signals buried within noisy data. Templates of gravitational waveforms calculated from general relativity are scanned across the data, and ring off when matching patterns are found in the data.
- **Noise:** At LIGO, "noise" is any vibration or variation in laser light that is NOT caused by a gravitational wave. Sources of noise include things like earthquakes, nearby traffic, stray photons bouncing around inside the vacuum system, electromagnetic coupling from devices around the site, atoms passing through the path of the laser beam, thermal noise from the agitation of the charge carriers in the instruments and circuits and even wind or lightning strikes.
- **Observing Run:** A scheduled period of time in which the LIGO, Virgo, and KAGRA detectors "turn on" and listen for gravitational waves. More details on current and future observing runs are available here.
- **Radiometry:** a method of searching for persistent signals, based on time delay between detectors that potential signals would induce.

- **Signal-to-noise Ratio (SNR):** the ratio of the signal power to the noise power, used to compare the level of signal to the level of the noise. It measures the strength of the signal compared with the sources of noise that could potentially contaminate it.

Further reading:

1. Detection of anisotropies in the gravitational-wave stochastic background, Bruce Allen and Adrian C. Ottewill Phys. Rev. D 56, 545
2. Sanjit Mitra, Sanjeev Dhurandhar, Tarun Souradeep, Albert Lazzarini, Vuk Mandic, et al., "Gravitational wave radiometry: Mapping a stochastic gravitational wave background," Phys.Rev. D77, 042002 (2008), arXiv:0708.2728 [gr-qc].
3. Joseph D. Romano and Neil J. Cornish, "Detection methods for stochastic gravitational-wave backgrounds: a unified treatment," Living Rev. Rel. 20, 2 (2017), arXiv:1608.06889 [gr-qc].
4. A. Ain, J. Suresh, and S. Mitra, "Very fast stochastic gravitational wave background map making using folded data," Phys. Rev. D 98, 024001 (2018), arXiv:1803.082851397 [gr-qc].
5. R. Abbott et al. (LIGO Scientific, Virgo, KAGRA), "Search for anisotropic gravitational-wave backgrounds using data from Advanced LIGO's and Advanced Virgo's first three observing runs," (2021), arXiv:2103.08520 [gr- qc].

Read the free preprint on LIGO DCC or on arXiv.

MEDIA CONTACTS

Analyst

Sanjit Mitra (IUCAA, Pune) E-mail: sanjit@iucaa.in, Tel. 8275067686

LSC-LISC Principal Investigator

Sukanta Bose (IUCAA, Pune) E-mail: sukanta@iucaa.in, Tel. 020 2560 4500

LSC-LISC Co-Principal Investigator

Bala Iyer (ICTS-TIFR) E-mail: bala.iyer@icts.res.in, Tel. 9739373144

LIGO-India spokesperson

Tarun Souradeep (IISER Pune and IUCAA Pune) E-mail: tarun@iiserpune.ac.in, Tel. 9422644463

CMI - Chennai Mathematical Institute, Chennai

K.G. Arun E-mail: kgarun@cmi.ac.in, Tel. 9500066350

ICTS - International Centre for Theoretical Sciences (TIFR), Bengaluru

P. Ajith E-mail: ajith@icts.res.in, Tel. 9164594474

IISER-Kolkata - Indian Institute of Science Education and Research Kolkata

Rajesh Kumble Nayak. E-mail: rajesh@iiserkol.ac.in, Tel. 9903507977

IISER-Pune - Indian Institute of Science Education and Research Pune, Pune

Tarun Souradeep. E-mail: tarun@iiserpune.ac.in, Tel. 9422644463

IIT Bombay - Indian Institute of Technology Bombay, Mumbai

Archana Pai E-mail: archanap@iitb.ac.in, Tel. 9037573123

IIT Gandhinagar - Indian Institute of Technology Gandhinagar

Anand Sengupta E-mail: asengupta@iitgn.ac.in, Tel. 8758146696

IIT Hyderabad - Indian Institute of Technology Hyderabad

Surendra Nadh Somala E-mail: surendra@ce.iith.ac.in, Tel. 9398213383

IPR - Institute for Plasma Research, Gandhinagar

Arnab Dasgupta Email: arnabdasg@ipr.res.in; Tel: 8306098020

IUCAA - Inter-University Centre for Astronomy and Astrophysics, Pune

Sanjit Mitra E-mail: sanjit@iucaa.in, Tel. 8275067686

IIT Madras - Indian Institute of Technology Madras, Chennai

Chandra Kant Mishra E-mail: ckm@iitm.ac.in, Tel. 8748816343

RRCAT - Raja Ramanna Centre for Advanced Technologies, Indore

Dr. Yogesh Verma E-mail: yogesh@rrcat.gov.in, Tel: 0731 2442627

SINP - Saha Institute of Nuclear Physics, Kolkata

Arunava Mukherjee Email: arunava.mukherjee@saha.ac.in, Tel. 8317813612

TIFR - Tata Institute of Fundamental Research, Mumbai

A. Gopakumar E-mail: gopu@tifr.res.in, Tel. 9869039269

C. S. Unnikrishnan E-mail: unni@tifr.res.in, Tel. 9869564290