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Searches for generic gravitational waves transients in the data of current ground-based detectors

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Outline

- Introduction
- Search methodologies
- Sensitivity to generic morphologies
- Sensitivity "conventional" sources
    - Supernovae <- MM connection
    - Neutron star glitches <- MM connection
- Sensitivity to "non-conventional" sources
    - Orphan memory of ultra light black hole mergers <- DM connection
    - Hyperbolic encounters of compact objects
    - Direct capture of black holes
- Conclusions

Introduction

- There are several possible sources of gravitational wave (GW) transients apart from the usual coalescing compact binaries (CBC) for e.g. Core-collapse Supernovae, glitching neutron stars etc
    - Not all aspects of CBC is well modelled e.g. eccentric, hyperbolic, precessing orbits, memory, strong field matter effects etc
    - Other sources mostly are not well modelled and some are not even known
- Searches sensitive to generic morphologies of the GW signals are required to detect any possible GW signal, thus covering the full parameter space made available to us from the detectors
- Generic morphology search which are presented here are the results for the all-sky search for short duration transients (**milliseconds - few seconds**) within frequency band of **24-4096 Hz** without any prior assumptions on the signal morphology or the time of arrival.
    - It should be noted that there is also dedicated generic morphology search for longer duration signals (few seconds - O(100) seconds)
- In this talk I will describe the generic search known as *coherent Wavebursts* , it should be noted that there are various methods for searches of generic transients which are used e.g. BayesWave, Mly, STAMPAS, X-pipeline etc
    - Also cWB and other methods are constantly improving <- Salemi's talk

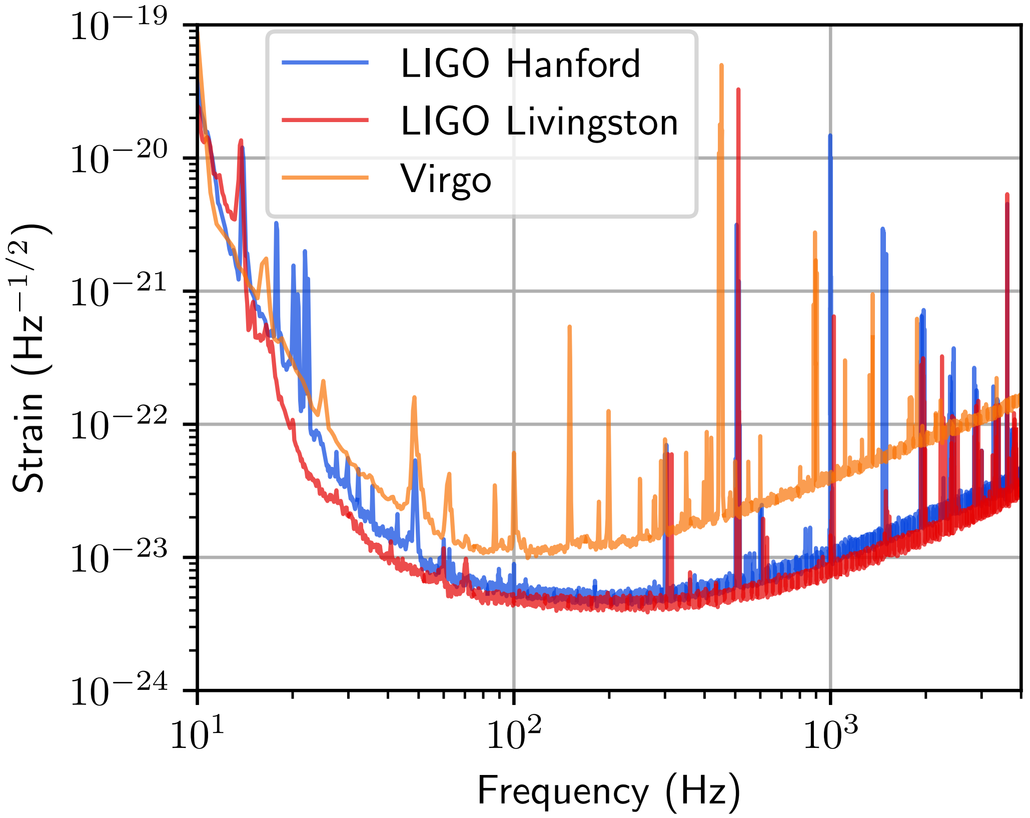


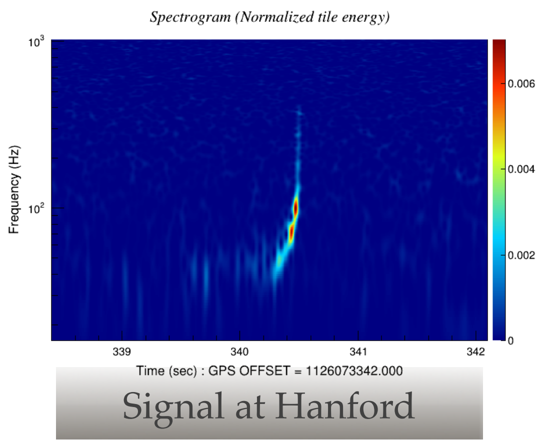
FIG. 1. Representative amplitude spectral density of the three detectors' strain sensitivity (LIGO Livingston 5 September 2019 20:53 UTC, LIGO Hanford 29 April 2019 11:47 UTC, Virgo 10 April 2019 00:34 UTC).

Fig1 of arXiv:1905.03457

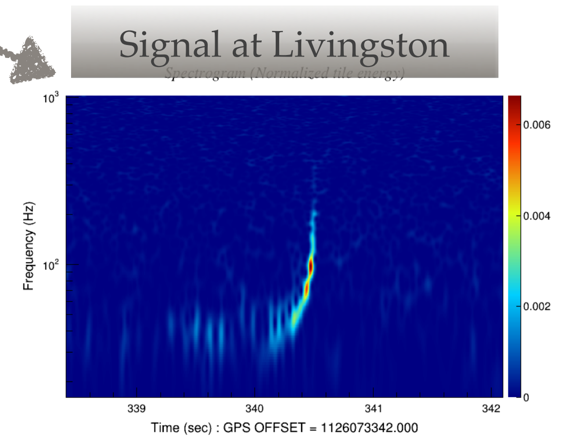
cWB : Phys. Rev. D 93, 042004

Search methodology : cWB

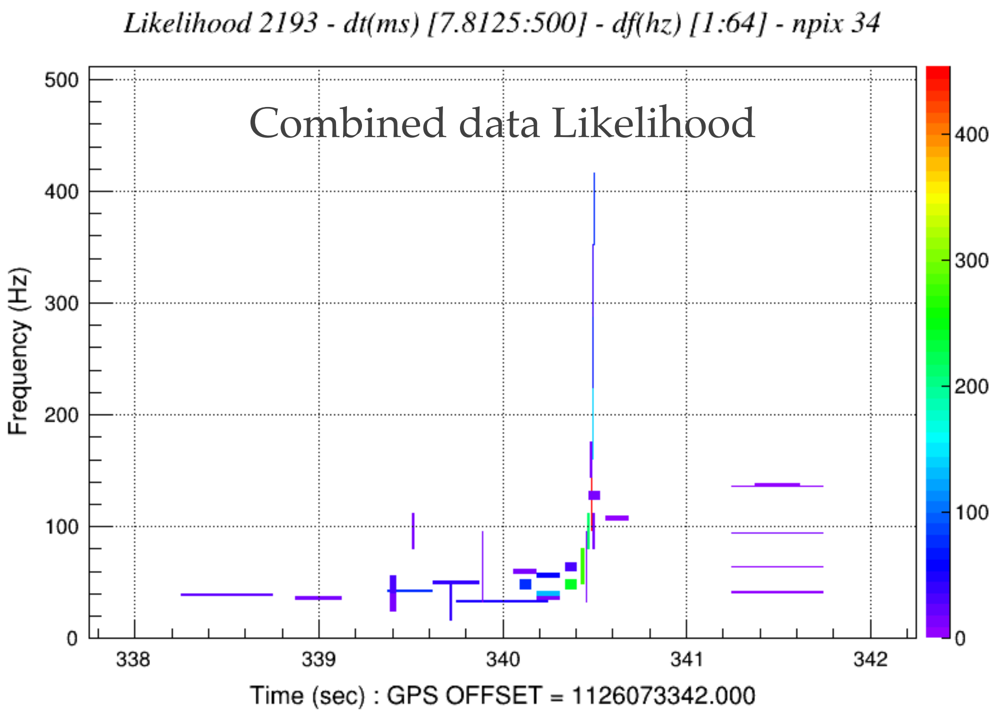
- Uses the estimation of excess energy in the detectors
- Exploits the presence of signal (energy) in multiple detectors to appear coherently i.e. consistent in time and sky location
- Data is combined from the networks of detectors
- No templates/waveforms models are required/used



Signal at Hanford



Signal at Livingston



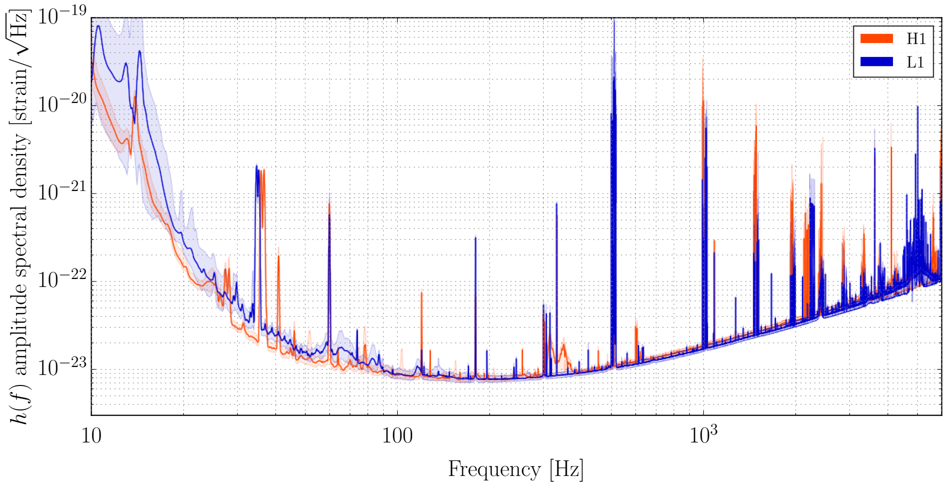
Combined data Likelihood

Search methodology : cWB stages

Read Data ⋯⋯▶ Data conditioning ⋯⋯▶ Time frequency transform and selection of pixels ⋯⋯▶ Clustering* ⋯▶

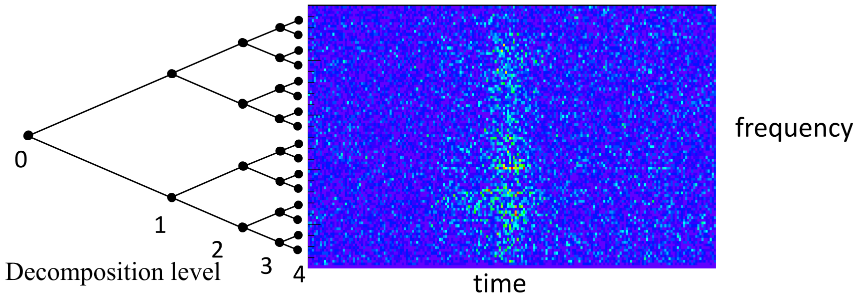
Data conditioning

- Regression to get rid of stationary noise (resonances)
- Non uniform noise in frequency are conditioned with whitening



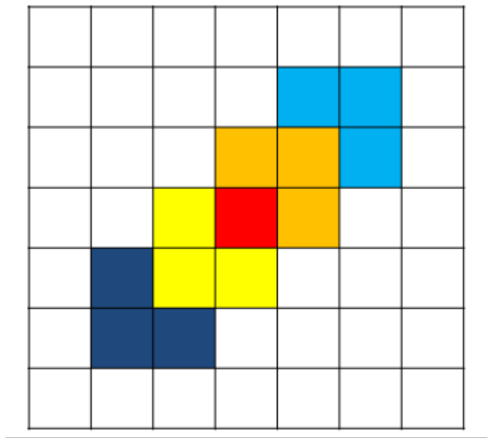
Time frequency transform and selection of pixels

- TF transform such as WDM are used
- Pixels which are over the threshold from the data conditioning step are selected



Clustering*

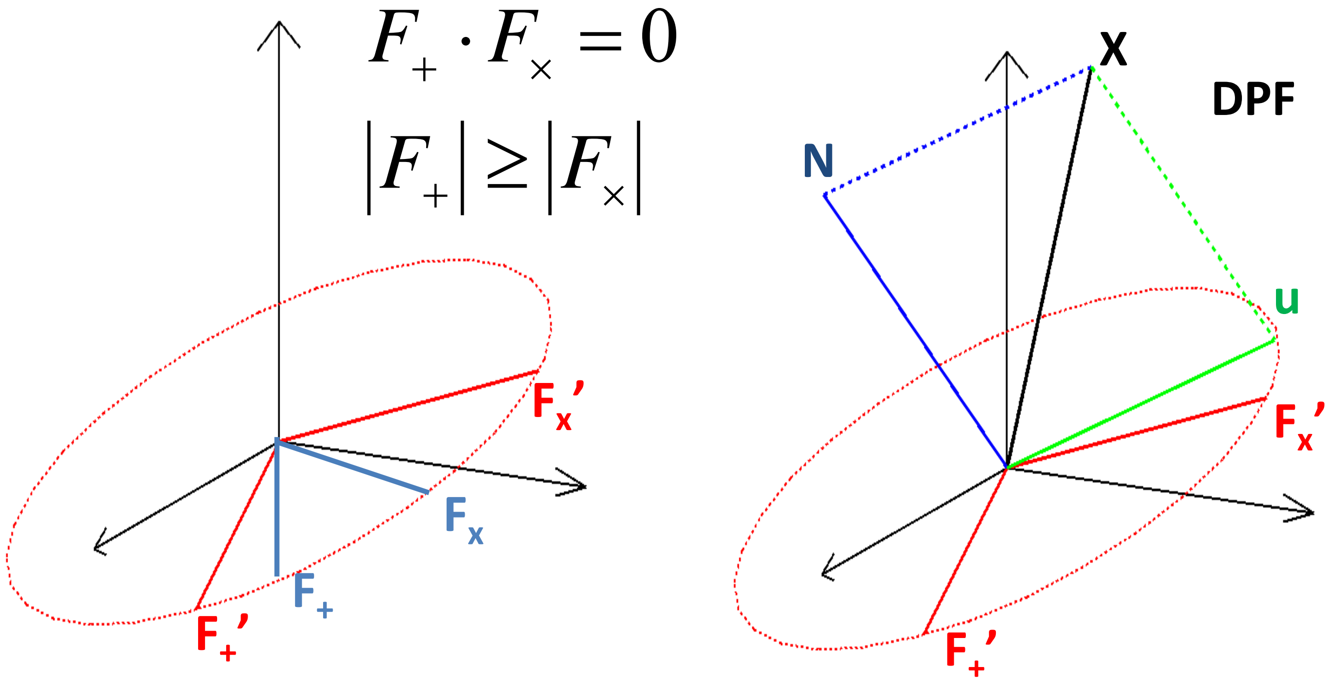
- Pixel with most energy and surrounding pixels are selected
- Various methods to cluster



Search methodology : cWB stages

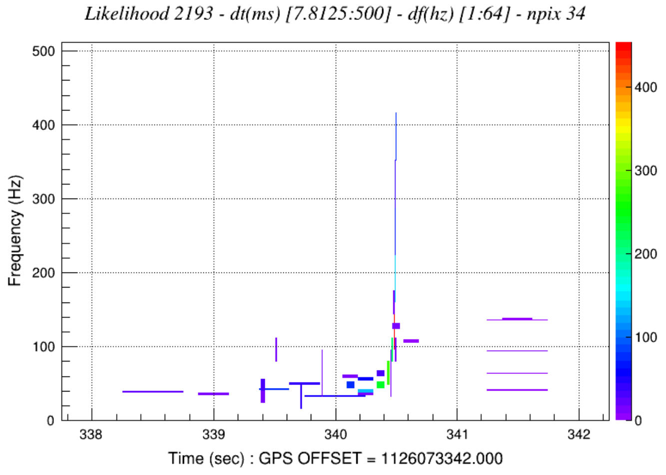
Likelihood analysis

- Define a multidimensional space N = number of detector and detector data on axes
- Likelihood is wave frame rotation invariant
- We rotate it in such a way that the antenna pattern function are orthogonal and + is dominant called dominant polarisation frame (DPF)
- In this frame detector response corresponding to maximum likelihood is projection of data vector X on the DPF
- Orthogonal to this plane is the Null Stream (N) which describes the noise
- Maximum likelihood points to the reconstructed direction
- We get sky map, polarisation, reconstructed waveform and coherent signal strength as output

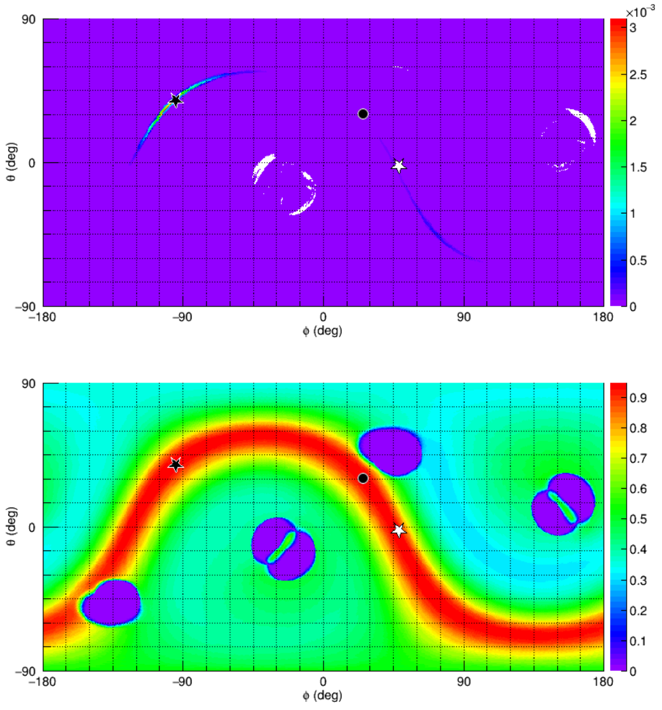


$$F_+ \cdot F_\times = 0$$

$$|F_+| \geq |F_\times|$$



Klimenko, Vedovato, Drago et al PhysRevD.93.042004



Latest available results : Third observing run of LIGO-Virgo-KAGRA

We have employed **two** algorithms

cWB (coherent WaveBursts)

- cWB works in multi resolution time frequency (TF) domain, picking up the TF pixels above the noise floor for various detectors
  - Obtains unique stream of coherent energy from different detectors appearing due to GW signal by considering time delays and antenna pattern factors
- cWB analysis is done in two parts Low Frequency (32-1024 Hz) and High Frequency (1024-4096 Hz)
- Analysed networks are HL, HV and LV for low frequency and HL for high frequency

cWB : Phys. Rev. D 93, 042004

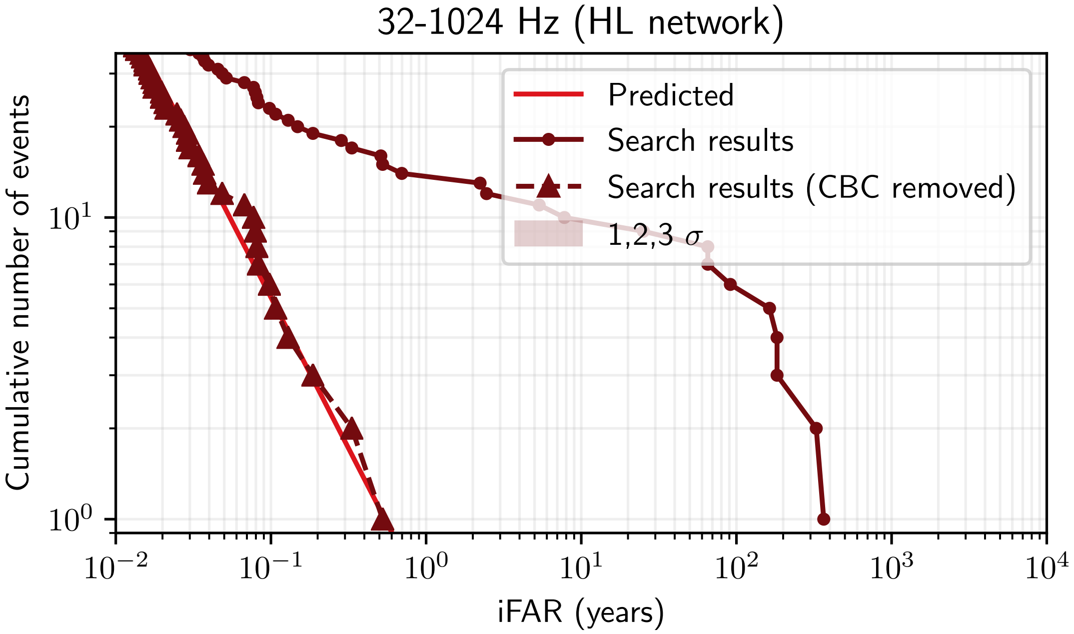
BW (BayesWave)

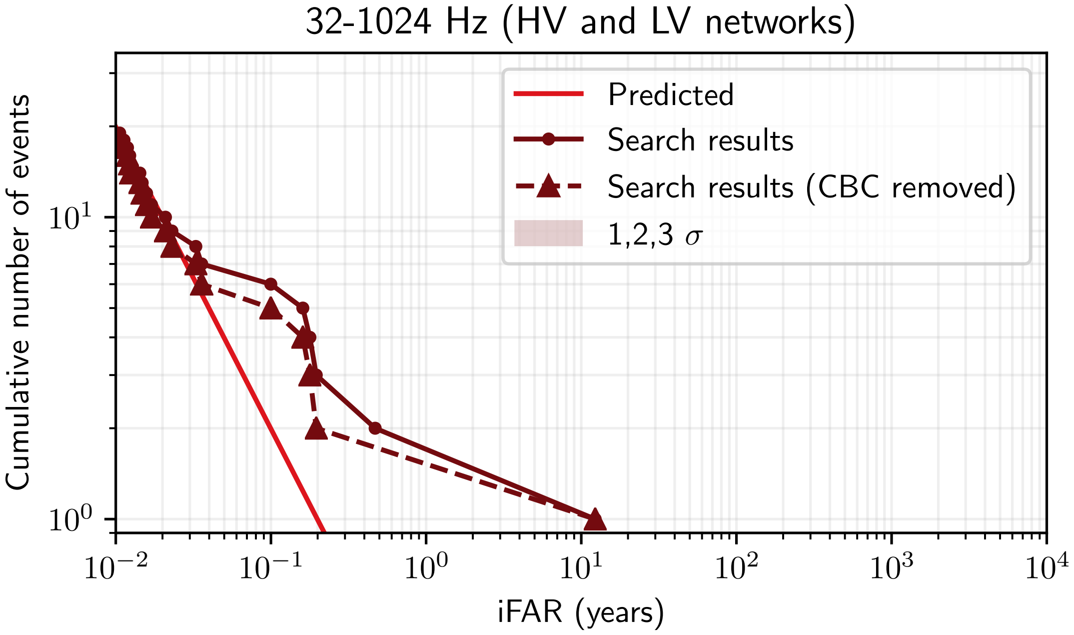
- BW follows up the cWB triggers
  - Uses Bayesian infrastructure which models GW signals and non-Gaussian noise transients (glitches) as the superposition of sine-Gaussian wavelets, obtaining Bayes factor between signal + Gaussian noise model and glitches + Gaussian noise model
- BW analysis is done only for Low frequency

BW : Class. Quant. Grav. 32, 135012
Phys. Rev. D 103, 044006 (2021)

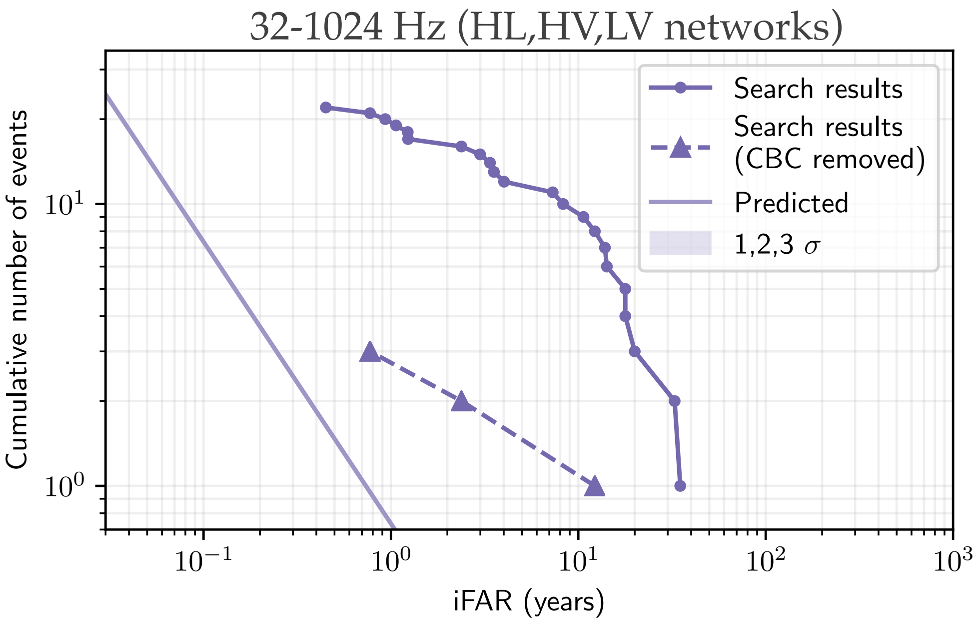
Searches and results : Low Frequency

cWB





BW



- Our detection criteria is iFAR > 100 years
- For low frequency both cWB and BW did not find any events apart from the known CBCs which can be deemed statistically significant

Fig2 and 4 of arXiv:1905.03457

Searches and results : High Frequency

- For High Frequency we just use the HL network since Virgo has significant sensitivity imbalance for high frequencies (> 1000 Hz)
- The search does not find any significant events
- Overall the short duration search has no detections for O3

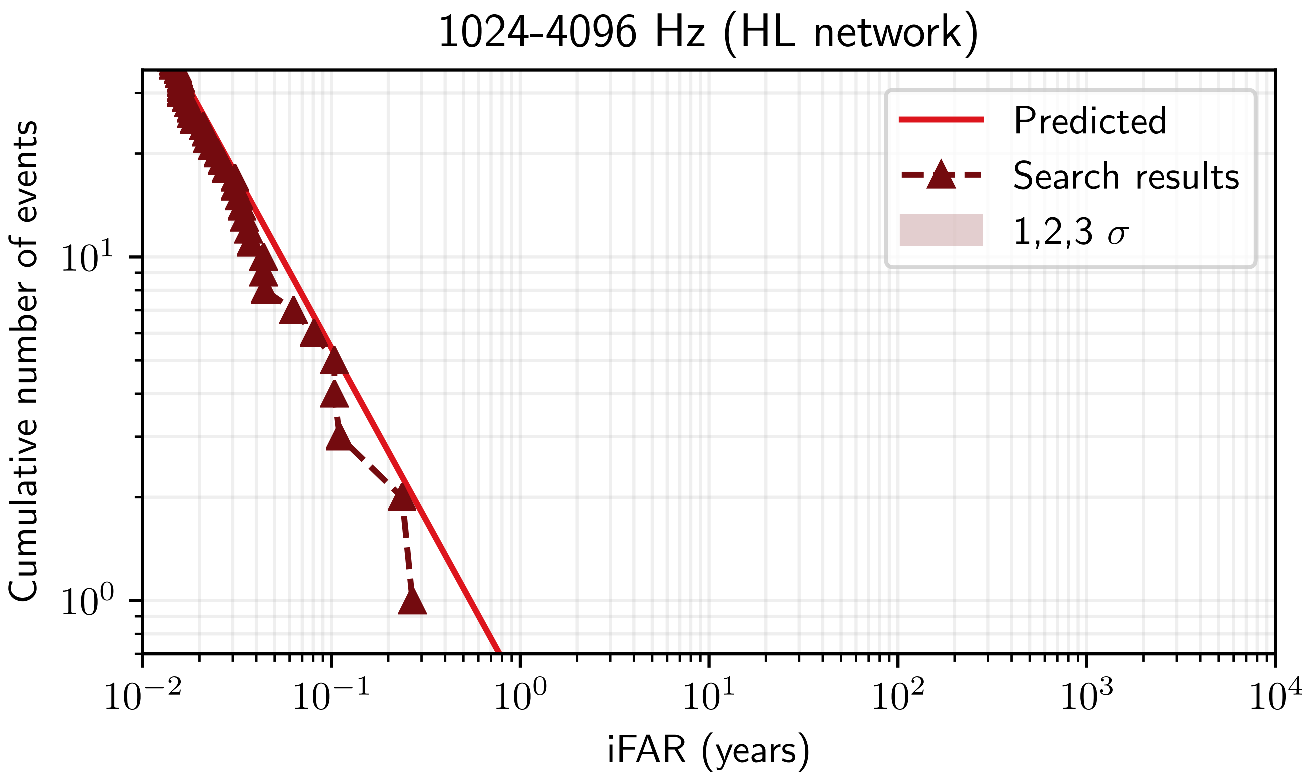
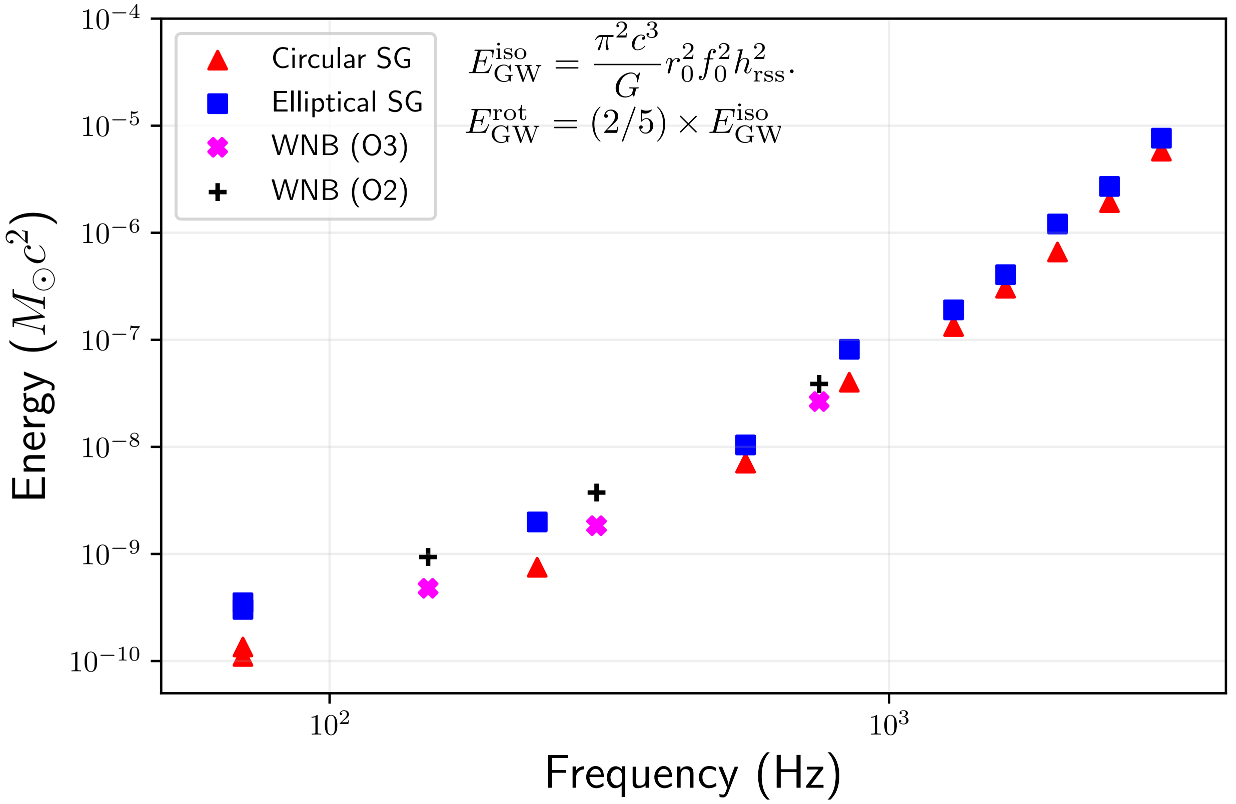
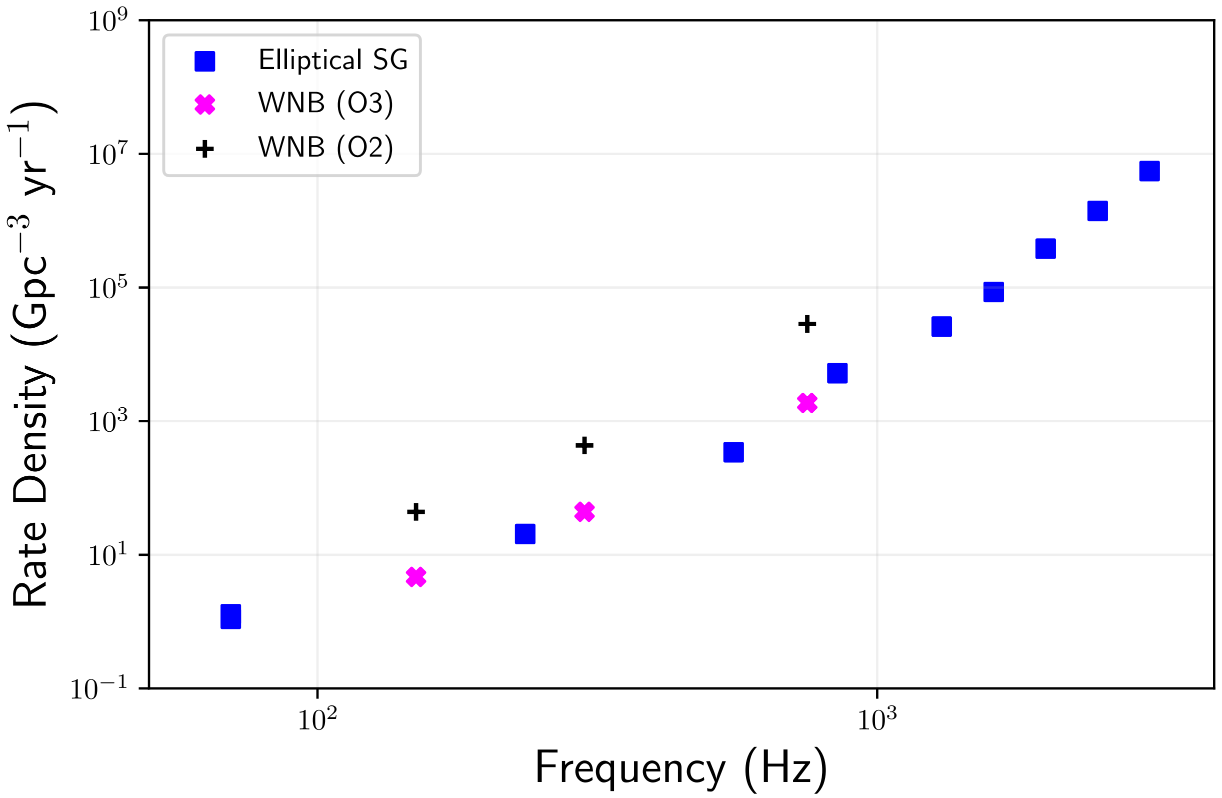


Fig3 of arXiv:1905.03457

Sensitivity : Generic Morphologies





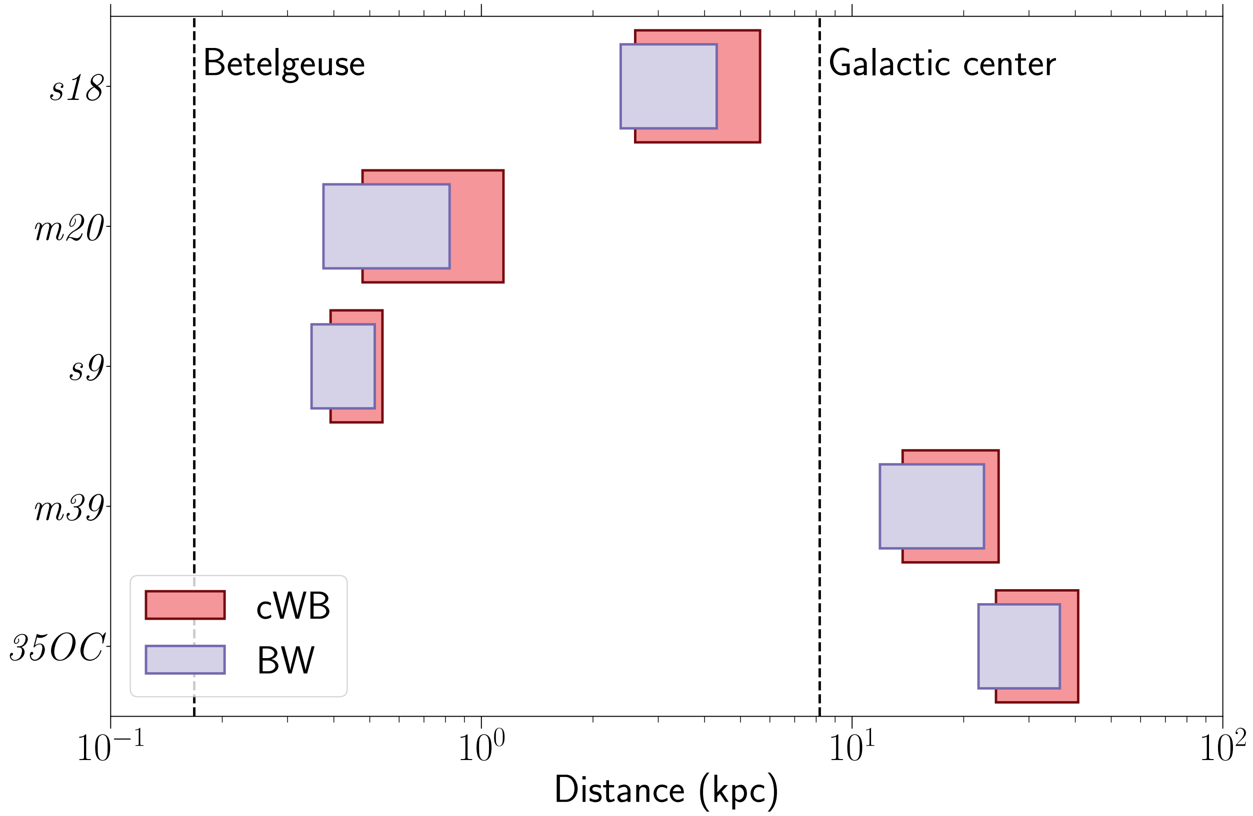
- We present the results of the sensitivity of the search for a wide variety of ad-hoc waveforms which contains Gaussians, sine-Gaussians and white noise bursts at iFAR > 100 years
- These results can be transformed into quantities shown above namely, the energy emitted assuming narrow band signals with source at 10 Kpc at 50% detection efficiency and rate density upper limits at 90 % assuming 1 solar mass of GW emission
- For comparison with the previous observing run (O2) we have representative white noise bursts injections

Fig5 and 6 of arXiv:1905.03457

Sensitivity :Core Collapse Supernovae

- Our low frequency short duration search is also sensitive to a wide variety of core collapse supernovae (CCSN) models
- We have picked 5 models which provide a pseudo complete picture of the physical phenomena and different modelling methods
- The injections are done uniformly in sky location to obtain the distance at which 10% and 50% efficiency is achieved for each model
- We also compute the total efficiency for galactic distribution of CCSN in distance and sky direction

Uniform in sky direction



Galactic Distribution

Model	*s18*	*m20*	*s9*	*m39*	*35OC*
cWB	1.2%	<0.1%	<0.1%	69.4%	89.8%
BW	0.3%	<0.1%	<0.1%	65.4%	89.1%

Fig7 and table 2 of arXiv:1905.03457

Sensitivity : Isolated neutron stars emitters

- The high frequency search is sensitive to the excitations of isolated neutron stars (NS)
- We assume the bulk of the energy in GW goes into the f-mode emission modelled by damped sinusoids
- We present the sensitivity at 50% efficiency and iFAR>100 years in terms of detachable glitch size by assuming Vela as the standard candle (distance and spin) and also all the glitch energy being converted to GW
- The source is assumes to be uniformly distributed in the sky and has optimal orientation
- We present the results for various masses of NS and also two EoS (soft and hard)
    - the box sizes represent the variation of the detectable glitch size due to the mass
- Observed glitch sizes are 2-3 orders of magnitude weaker than what we expect the glitch size to be
- In future observing runs we will probe the glitch sizes which are observed*

Detectable glitch size of a NS O3

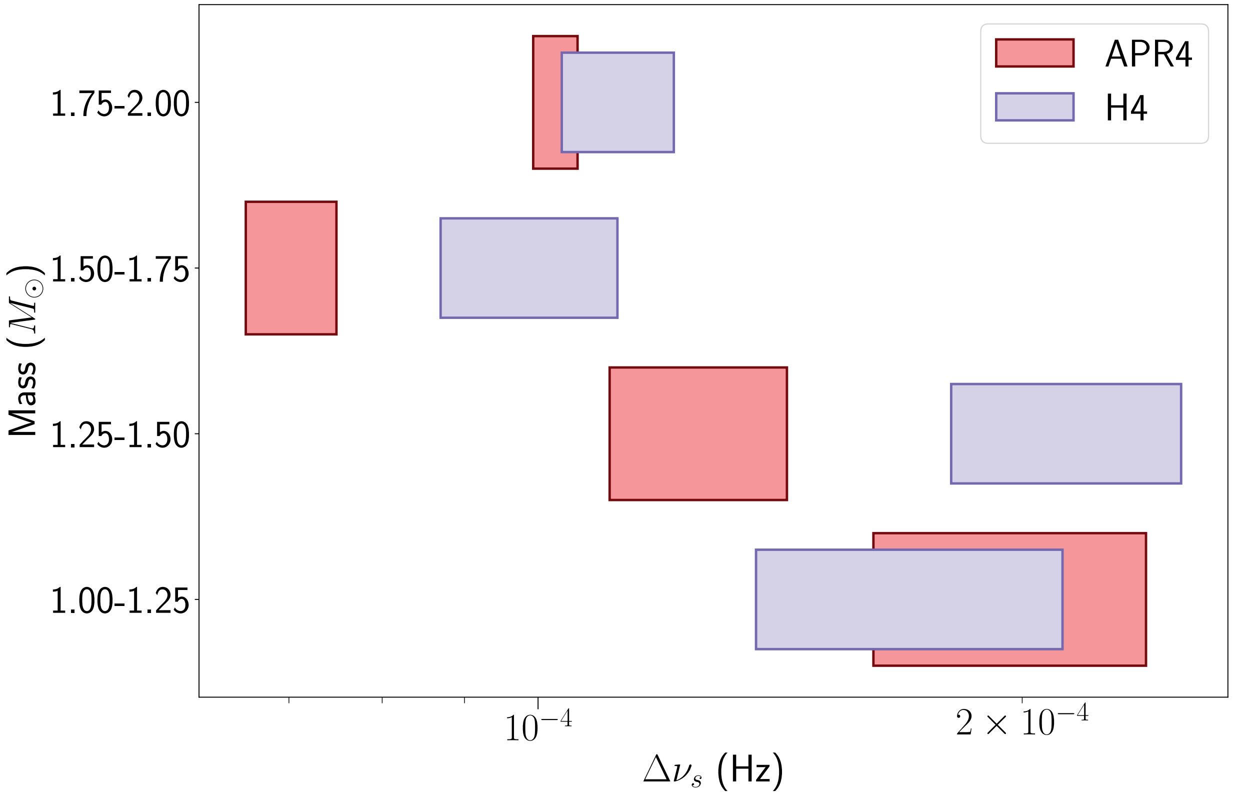


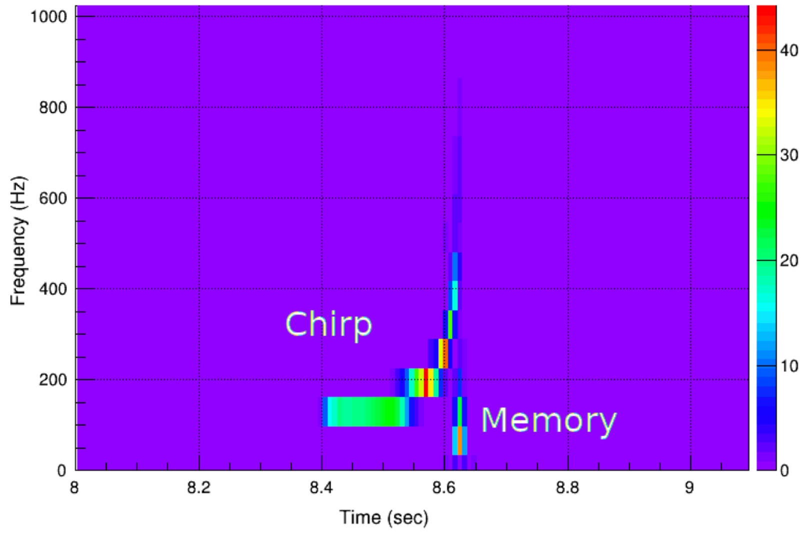
Fig8 of arXiv:1905.03457

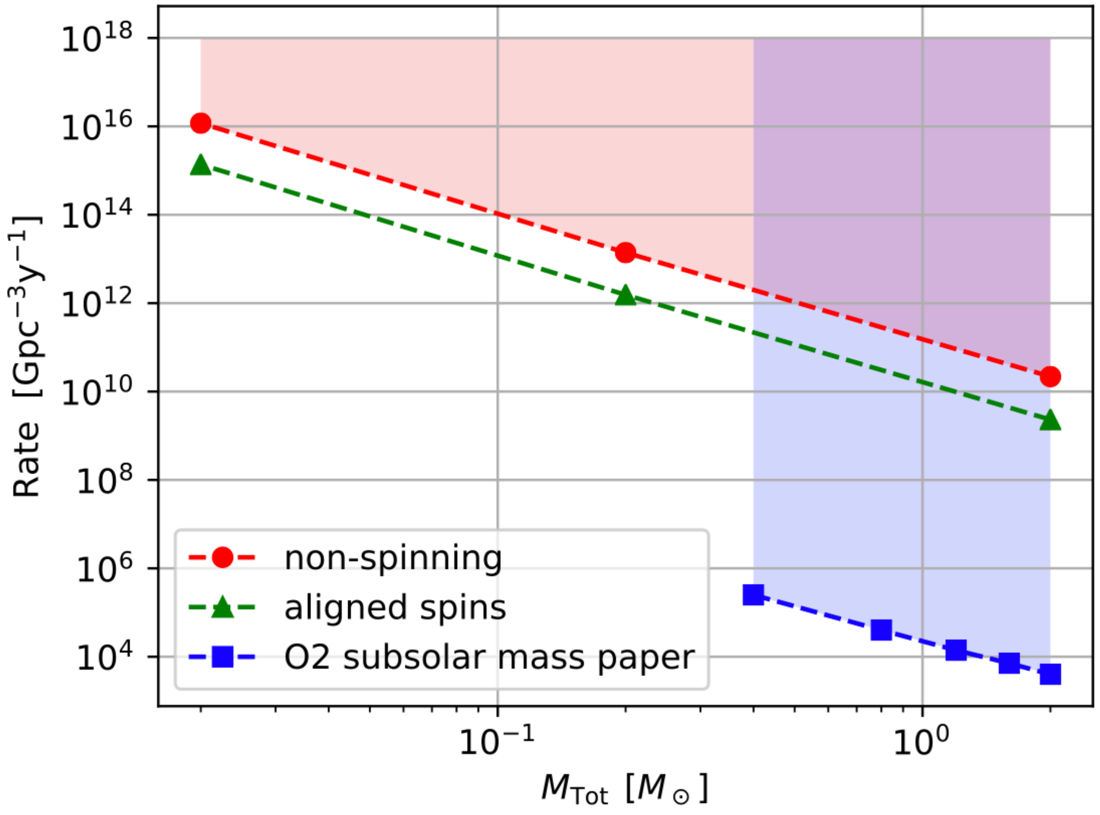
**Lopez, Tiwari et al Phys.Rev.D 106 (2022) 10, 103037*

Sensitivity : Memory of ultra light BBHs

- We note that the merger of CBC which are less than 0.4 solar masses the memory will lie in the band of out present day detectors for very nearby events
- cWB search is indeed sensitive to memory bursts
- We find the range (iFAR ≥ 1yr) of the search by injecting 6 different memory signals in O2 data (equal masses, 3 non-spinning, 3 with 0.8 aligned spins)
- Constraints from memory are not competitive with matched-filter searches for the corresponding oscillatory signal (reported e.g. in LV O2 subsolar mass paper, arXiv:1904.08976)
- However, memory only search expands the parameter space to masses below MTot ≤ 0.4M⊙

Memory in TF domain





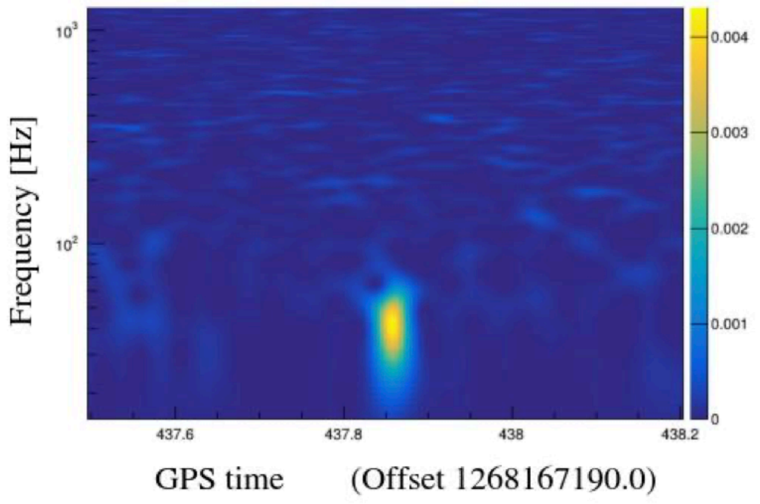
Upper limit on binary merger rate

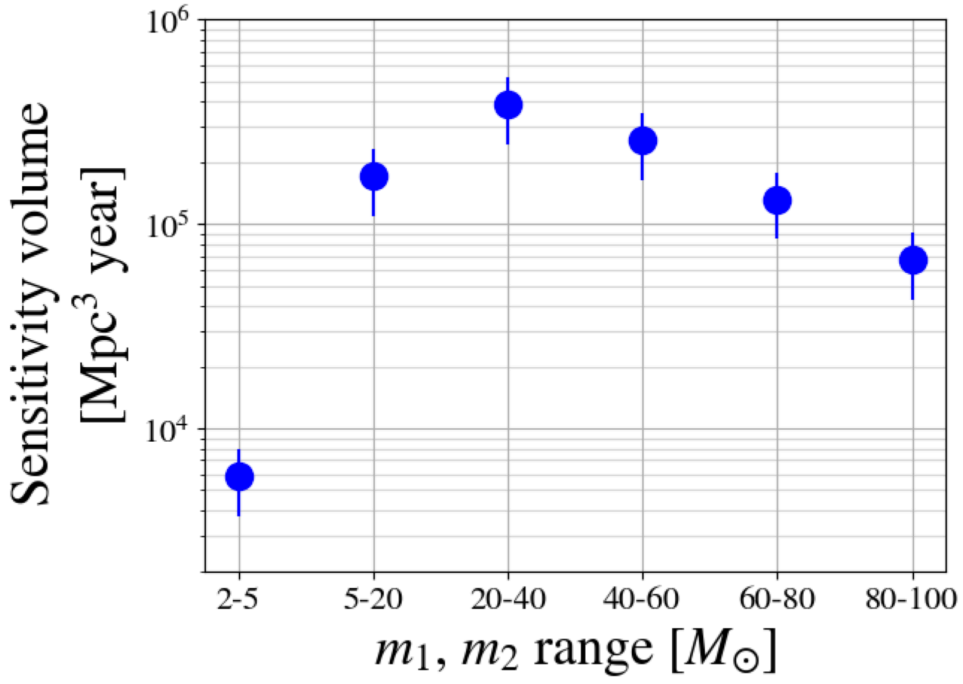
Ebersold and Tiwari Phys.Rev.D 101 (2020) 10, 104041

Sensitivity : Hyperbolic encounters

- BH and NS are expected to experience single scattering events in dense stellar clusters. Such events, called hyperbolic encounters (HE), manifest as GW burst signals, and are potential GW sources.
- cWB in its most generic form is sensitive to hyperbolic encounters, but due to high rate of short and loud “glitches” the sensitivity is subdued.
    - We use targeted ML algorithm to enhance the sensitivity of cWB to hyperbolic encounter and did the search and sensitivity estimates for second half of third observing run

HE in TF domain



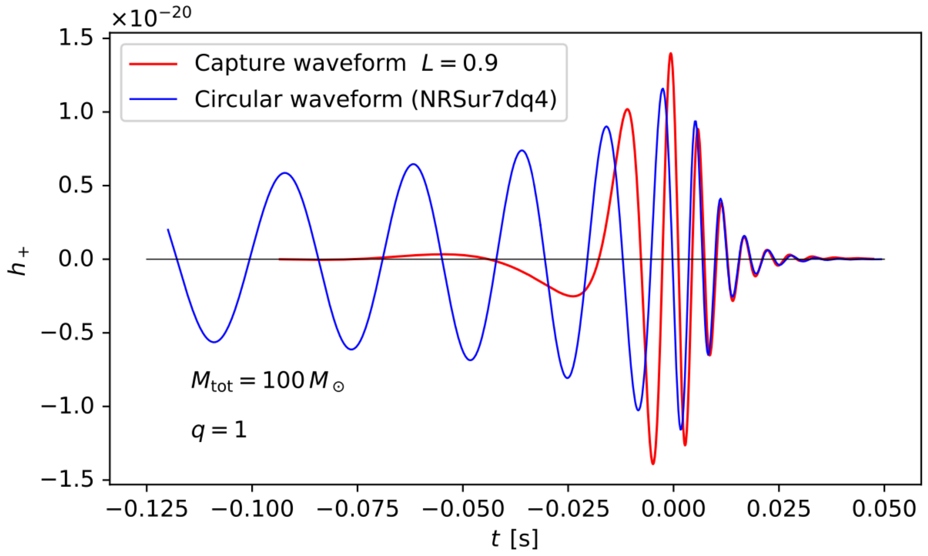


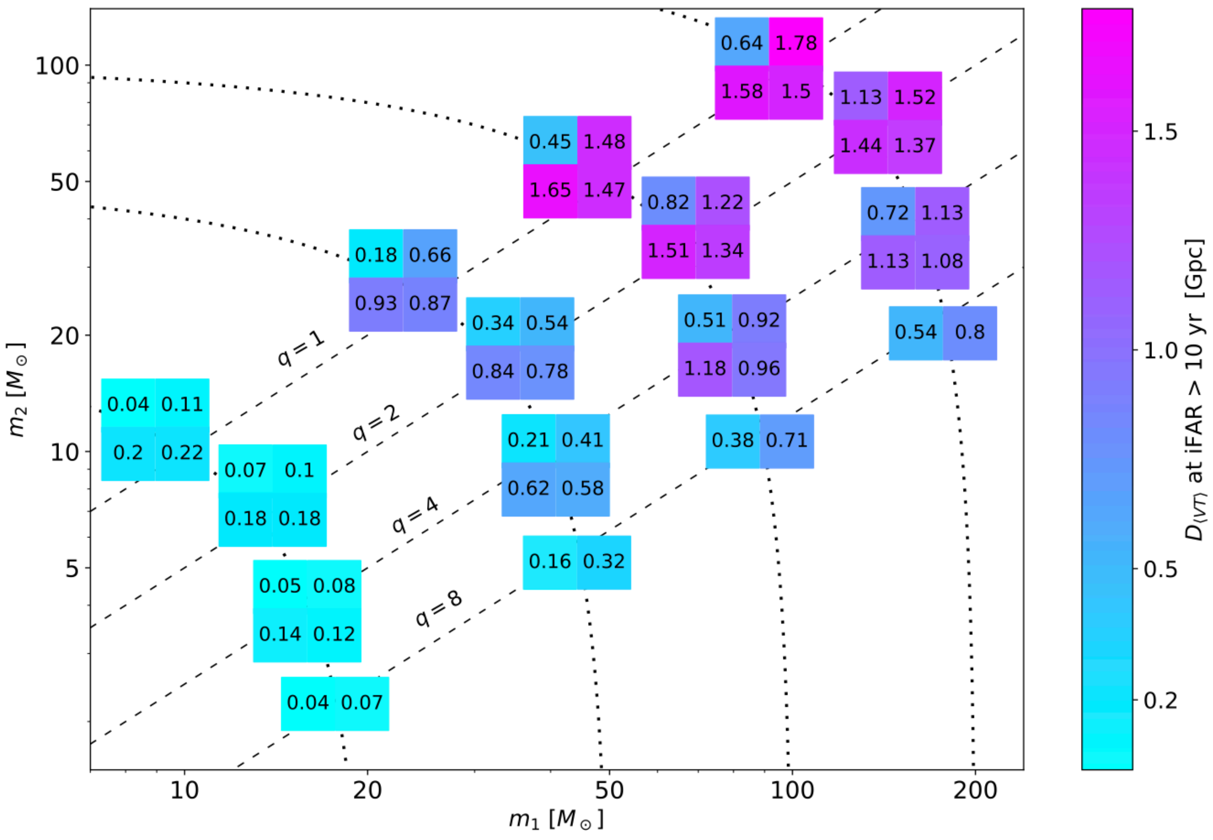
iFAR>10 years

Bini, Tiwari et al Phys.Rev.D 109 (2024) 4, 042009

Sensitivity : Direct capture of BHs

- In very dense stellar environments (like AGNs) if the emitted GW due to binary encounters is large enough to make the total energy of the system negative it undergoes radiation driven capture.
- The waveform is dominated by the strong field regime i.e. merger part, and hence we only have NR simulations for these
- We performed sensitivity studies for cWB for various mass, mass-ratios and we find that these sources are detectable to relatively high redshifts.





Ebersold, Tiwari et al Phys.Rev.D 106 (2022) 10, 104014

Conclusions

- No significant events were found by the all-sky short duration search for O3
- We have updated the upper limits for the GW emission and rate density upper limits
- We have also interpreted the null results of this search to astrophysical sources CCSN and isolated NS
- The outlook is promising, with improvements in the detector sensitivities for the next observing run we expect to have the full galactic coverage of CCSN for various models and also probe the glitch size of observed NS
- There are also consequences of generic searches for a wide variety of scenarios which needs to be looked at more deeply