Title: Spectrogram correlated stacking: A novel time-frequency domain analysis of the Stochastic Gravitational Wave Background

Speakers: Niayesh Afshordi

Series: Cosmology & Gravitation

Date: April 24, 2023 - 12:00 PM

URL: https://pirsa.org/23040163

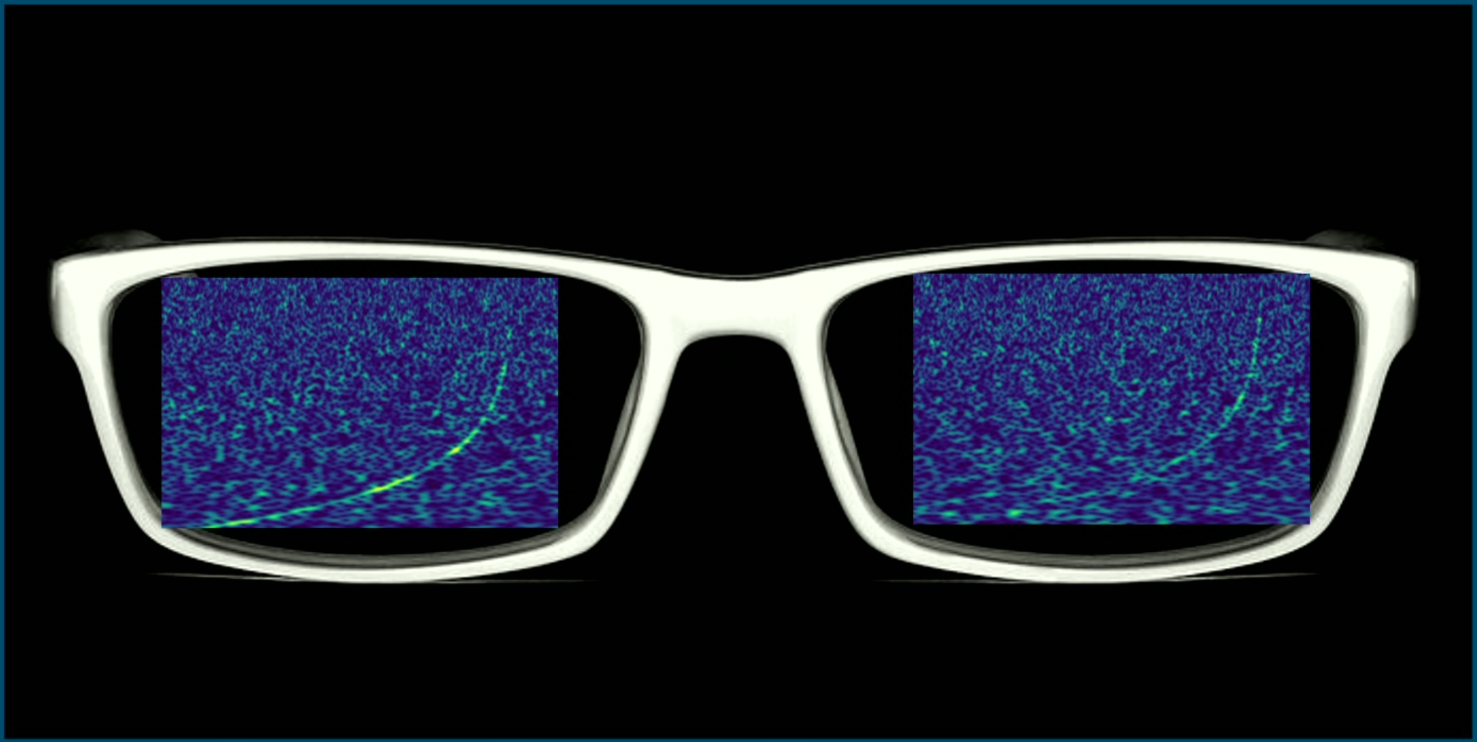
Abstract: The astrophysical stochastic gravitational wave background (SGWB) originates from numerous faint sub-threshold gravitational wave (GW) signals arising from the coalescing binary compact objects. This background is expected to be discovered from the current (or next-generation) network of GW detectors by cross-correlating the signal between multiple pairs of GW detectors. However, detecting this signal is challenging and the correlation is only detectable at low frequencies due to the arrival time delay between different detectors. In this work, we propose a novel technique, Spectrogram Correlated Stacking (or SpeCS), which goes beyond the usual cross-correlation (and to higher frequencies) by exploiting the higher-order statistics in the time-frequency domain which accounts for the chirping nature of the individual events that comprise SGWB.

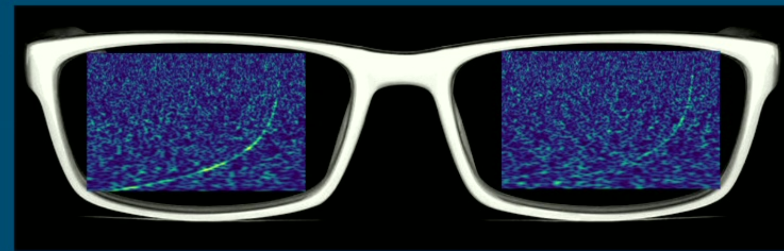
We show that SpeCS improves the signal-to-noise for the detection of SGWB by up to an order of magnitude, compared to standard optimal cross-correlation methods which are tuned to measure only the power spectrum of the SGWB signal. SpeCS can probe beyond the power spectrum and its application to the GW data available from the current and next-generation GW detectors would speed up the SGWB discovery.

based on work with Ramit Dey, Luis Longo, and Suvodip Mukherjee

Zoom link: https://pitp.zoom.us/j/97091817158?pwd=MHNkdjFQT0plVzJJY2lsOHRxdDdwdz09

SpeCS: Spectrogram Correlated Stacking





SpeCS: Spectrogram Correlated Stacking

Ramit Dey, Luis Felipe Longo Micchi, Suvodip Mukherjee, Niayesh Afshordi

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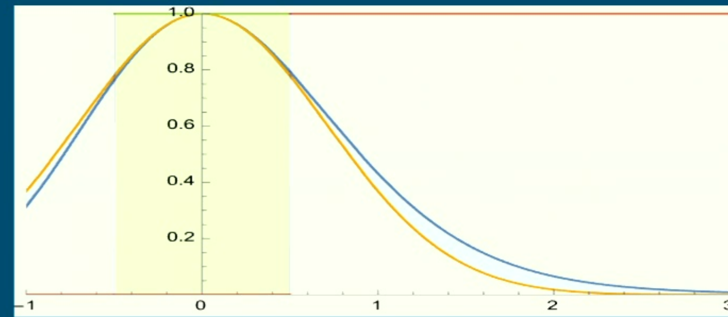
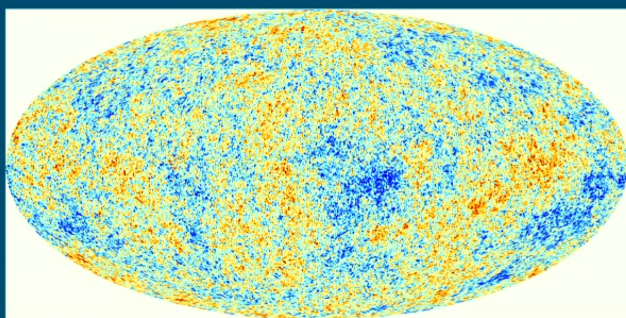
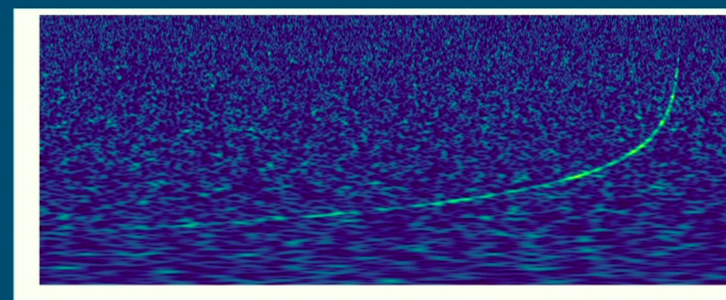
PI Cosmology group meeting, April 24, 2023

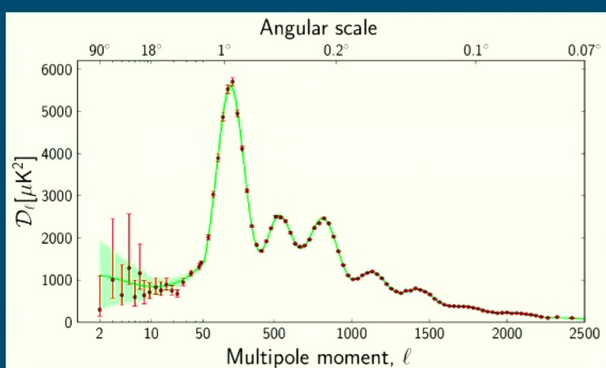
Planck vs LIGO!



Is most of (interesting) Signal-to-Noise-Ratio (SNR) in the variance, or in the tails?





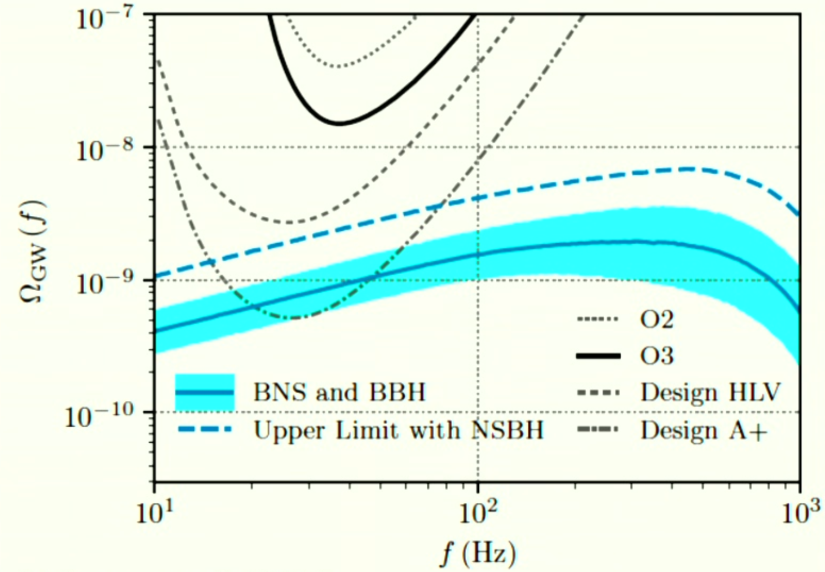


Subthreshold: what if we cannot detect the events?

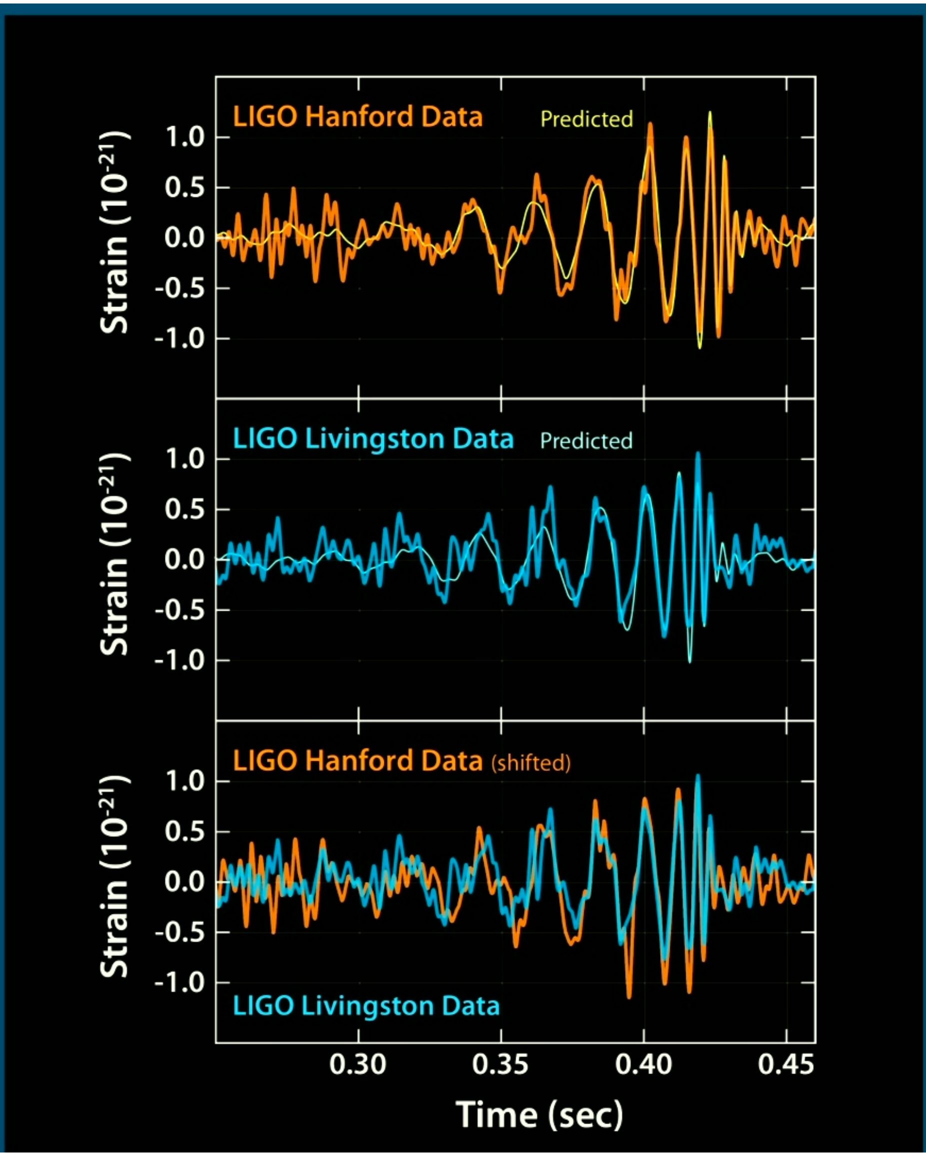
Detecting the Stochastic Gravitational Wave background (SGWB) by

detector signal cross-power spectrum

Time-delay between detectors (± 10 msec) kills SNR at frequency > 30 Hz (for unknown sky position)



Abbott, et al, 2021


LIGO Hanford Data
Predicted
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
0.30
0.35
0.40
0.45
Time (sec)

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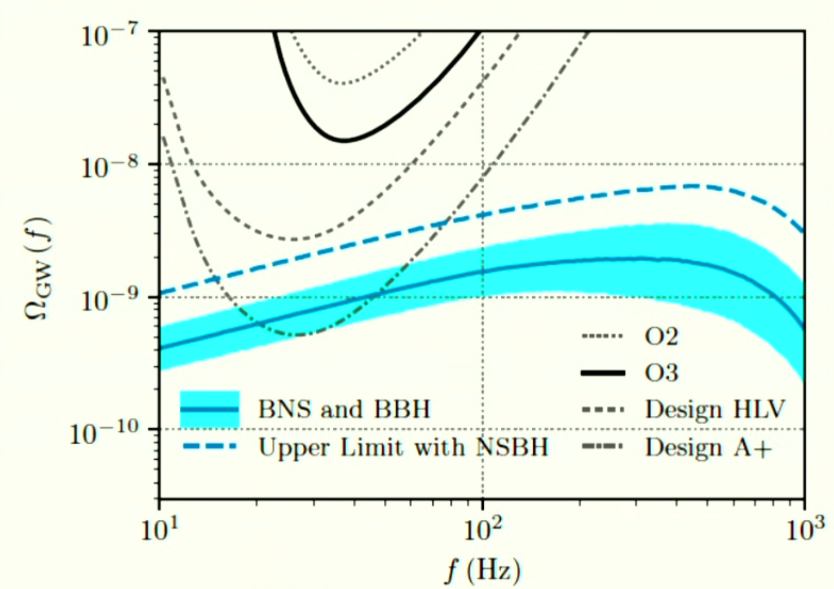

Abbott, et al, 2021

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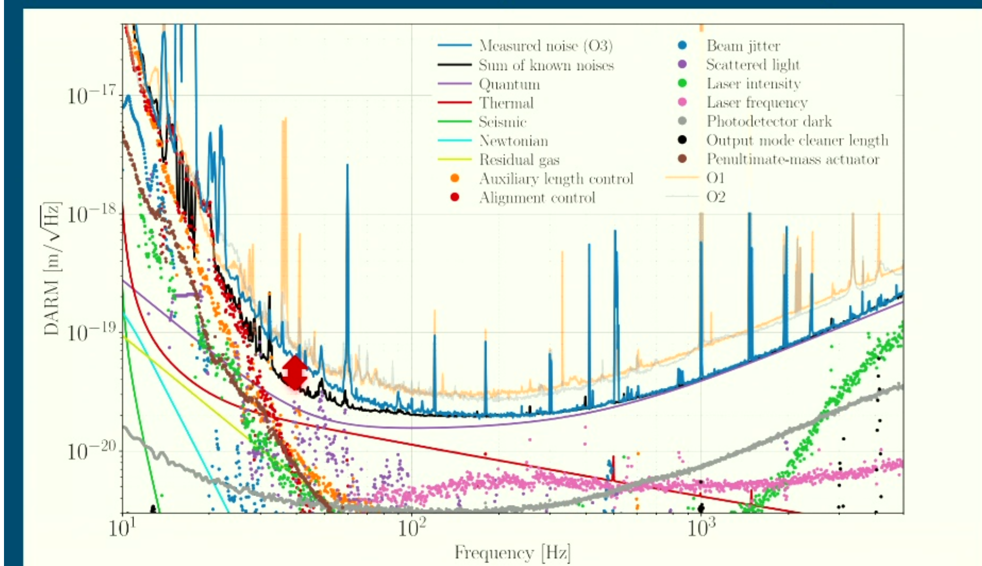
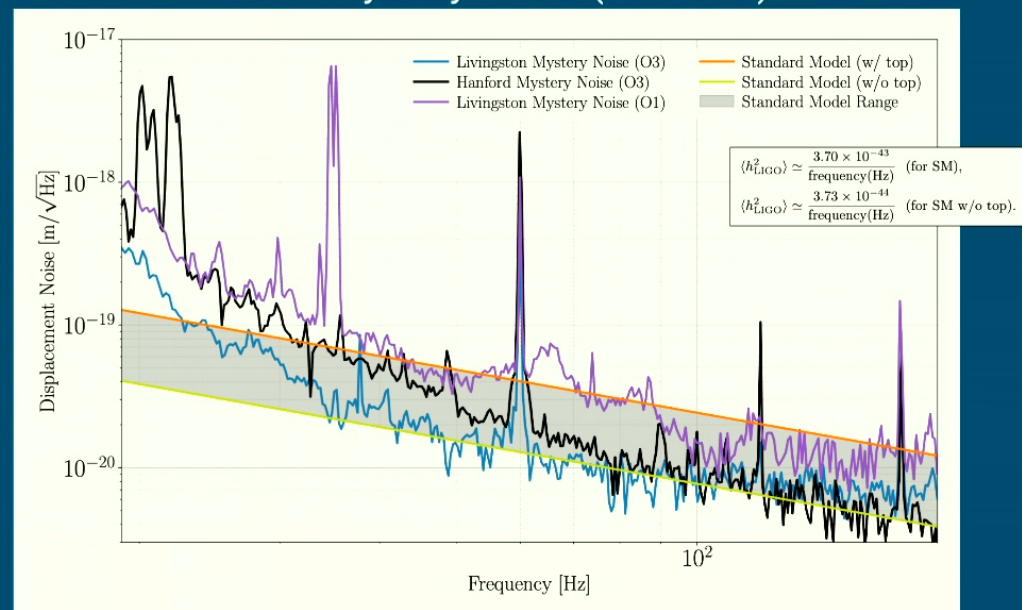
Auto-power spectrum for LIGO remains a mystery (a different talk!)

LIGO Noise Sources (Abbott, et al. 2020)



(a) LHO

LIGO Mystery Noise (NA 2019)



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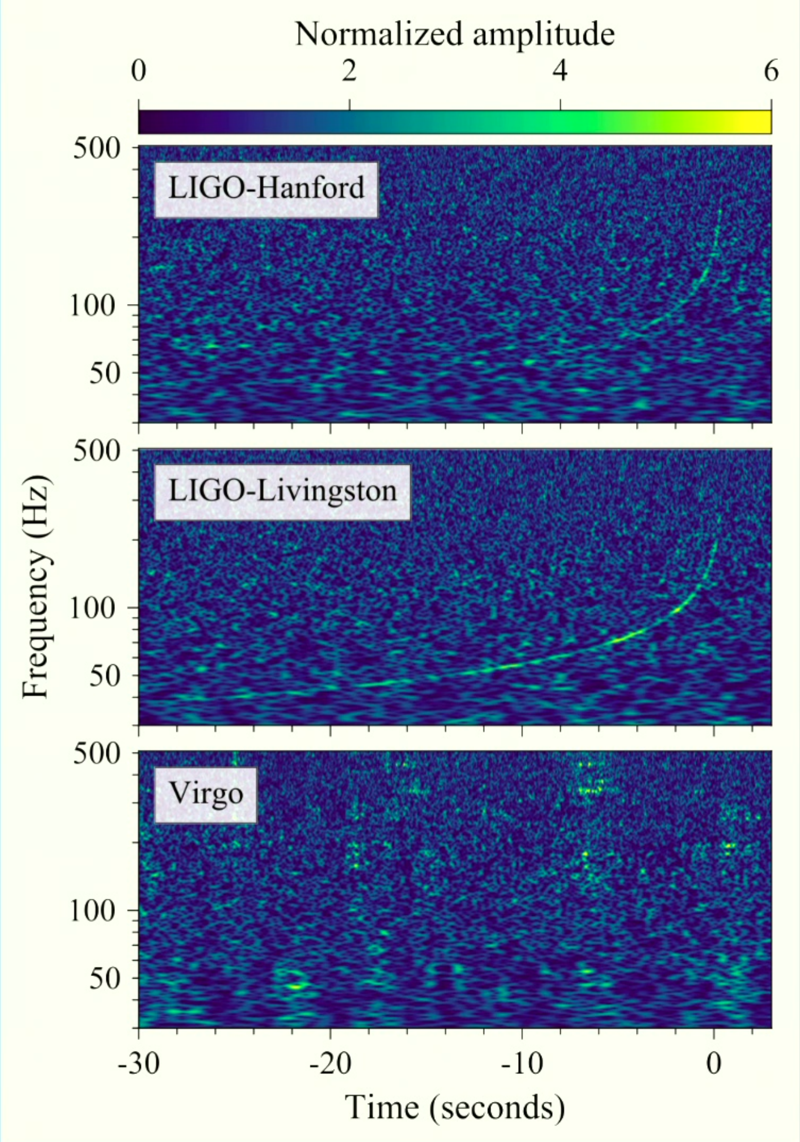
Note that spectrograms remain correlated on much longer times



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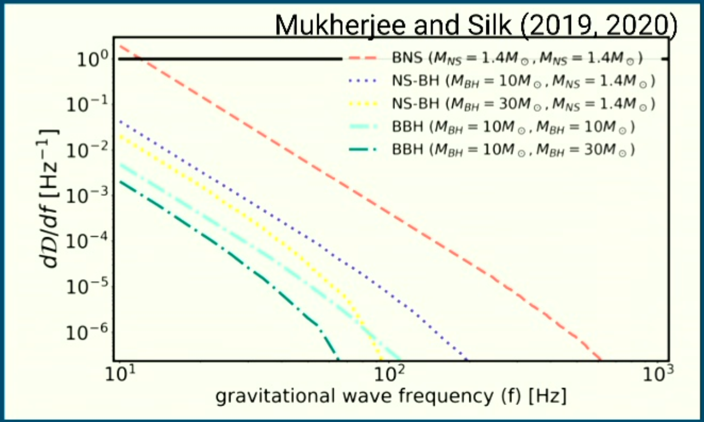
The Astrophysical SGWB is not a constant signal: Can we peek into the non-Gaussian tail?

The dependence of the signal will arise from:

1. Time -scale over which events are overlapping at a particular frequency (Duty cycle).
   a. Astrophysical SGWB has a duty cycle less than 1 sec.



2. Mass dependence of the SGWB will also affect time-dependence.

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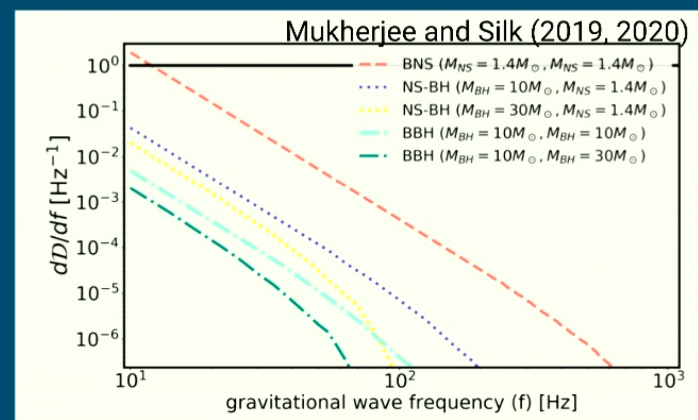
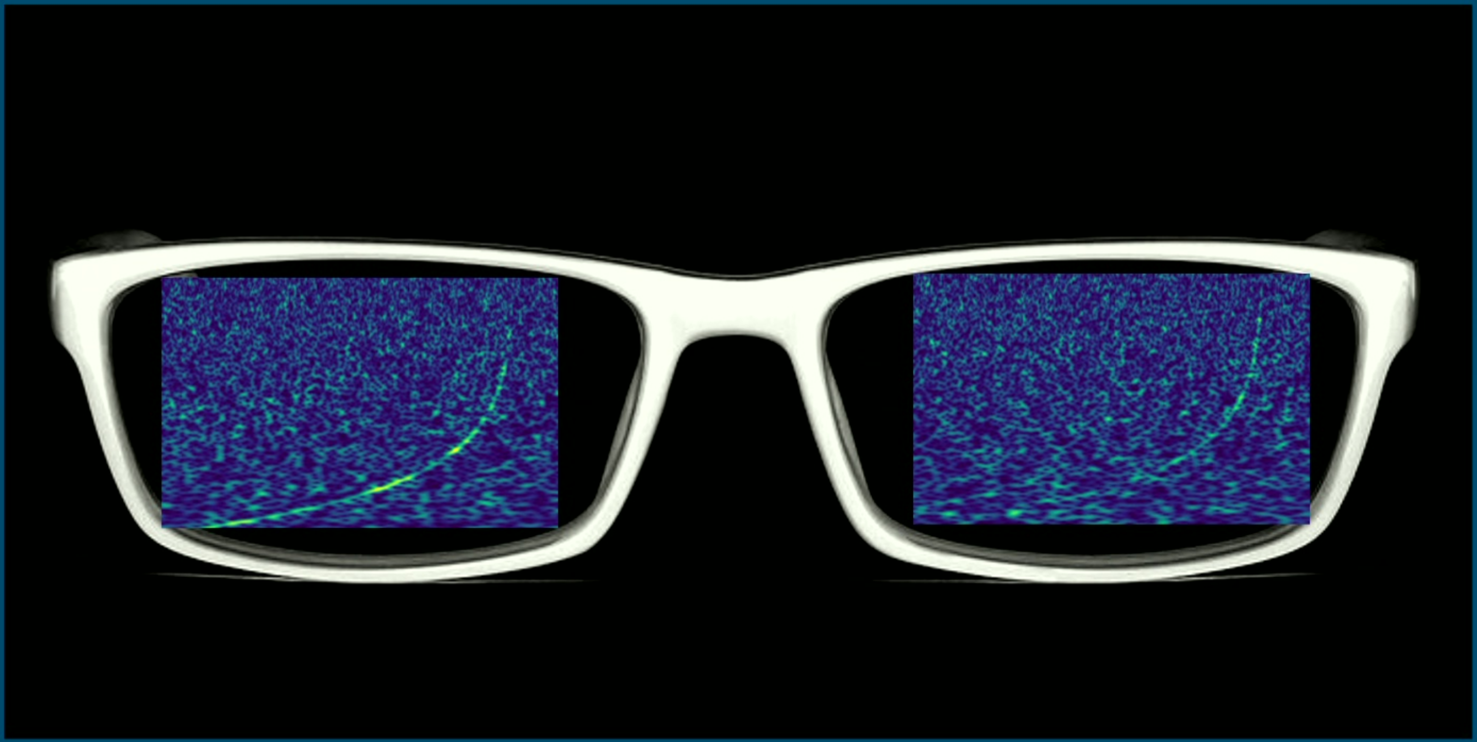
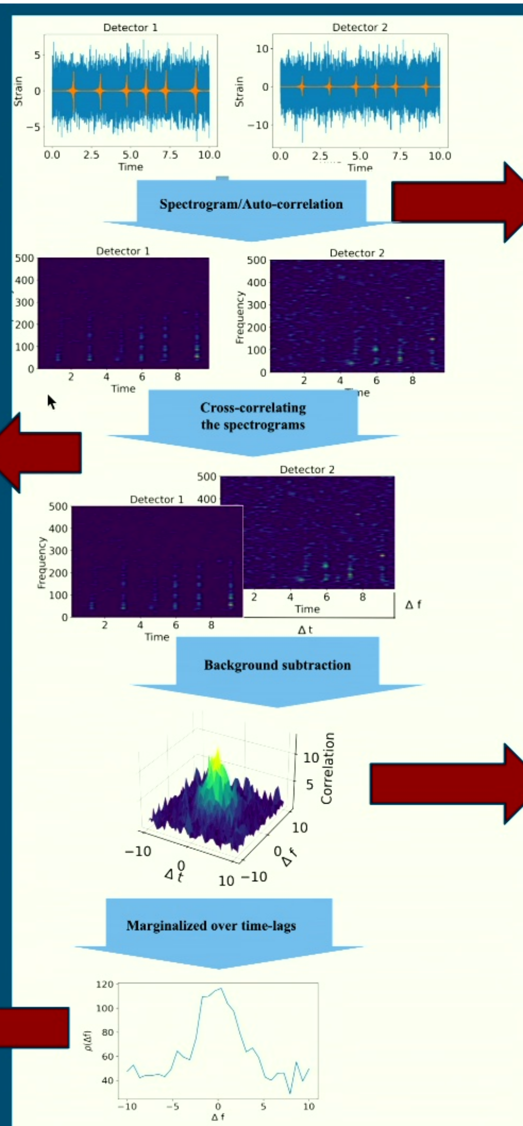


2. Mass dependence of the SGWB will also affect time-dependence.

SpeCS: Spectrogram Correlated Stacking



SpeCS: Flowchart



$$S_{s_i,s_j}(\Delta t, \Delta f) \equiv \int dt \int df W_{s_i}(t,f) W_{s_j}(t+\Delta t, f+\Delta f).$$

$$P_{cc}(\Delta t, \Delta f) \equiv \iint S_{s_1}(t,f) S_{s_2}(t-\Delta t, f-\Delta f)\, dt df \, ,$$

$$P_{cc}^{\text{aperture}}(\Delta t_i \pm \epsilon, \Delta f) \equiv \frac{1}{2\epsilon} \sum_{x=\Delta t_i - \epsilon}^{\Delta t_i + \epsilon} P_{cc}(x, \Delta f),$$

$$\mathbf{P}^{\mathbf{back}}(\Delta f) := \{P_1^{\text{aperture}}(\Delta t_1 \pm \epsilon, \Delta f), P_2^{\text{aperture}}(\Delta t_2 \pm \epsilon, \Delta f), \ldots, P_{N_t}^{\text{aperture}}(\Delta t_{N_t} \pm \epsilon, \Delta f)\}.$$

$$P_{cc}^{\text{clean}}(\Delta t, \Delta f) \equiv P_{cc}(\Delta t, \Delta f) - \bar{P}^{\text{back}}(\Delta f).$$

$$\rho_P(\Delta t = 0 \pm \epsilon) = \sqrt{\sum_{\Delta f \Delta f'} \hat{P}_{cc}^{\text{sig}}(\Delta f) C^{-1}(\Delta f, \Delta f') \hat{P}_{cc}^{\text{sig}}(\Delta f')}.$$

The Astrophysical SGWB is not a constant signal: Can we peek into the non-Gaussian tail?

The dependence of the signal will arise from:

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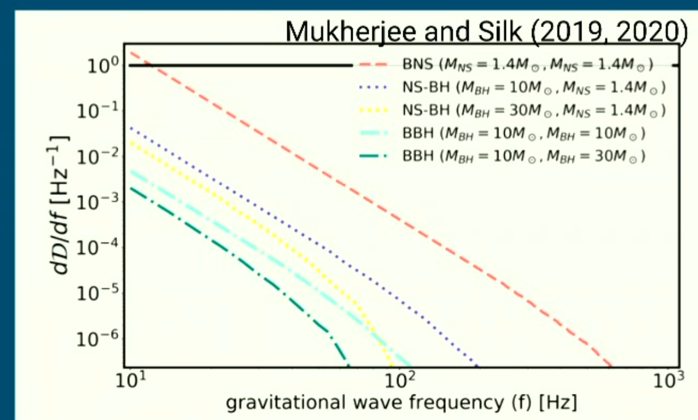
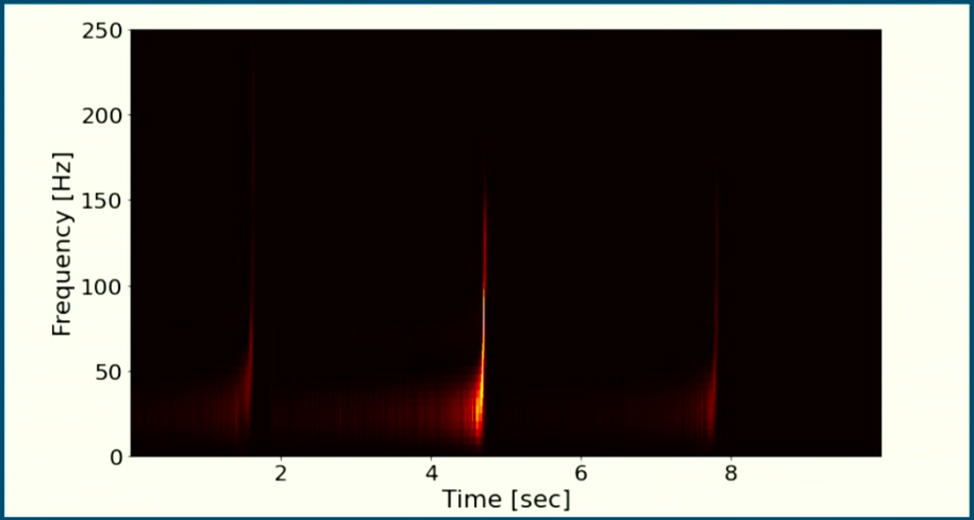
    a. Astrophysical SGWB has a duty cycle less than 1 sec.



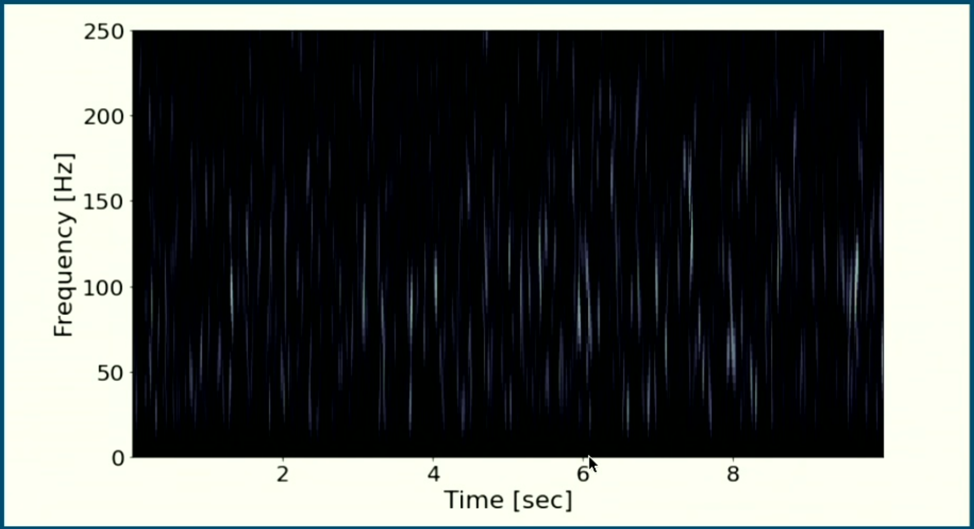
2. Mass dependence of the SGWB will also affect time-dependence.

Implementation of SpeCS on injections II

signal

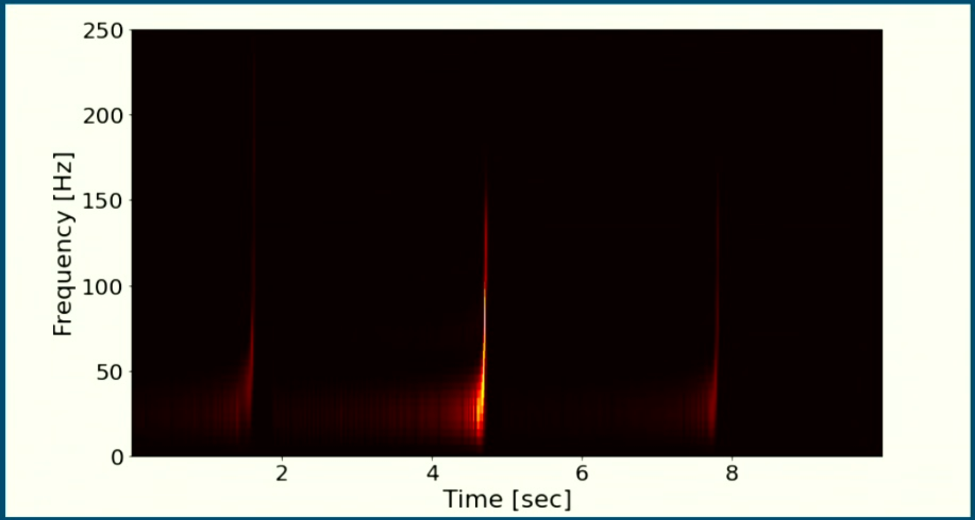


noise

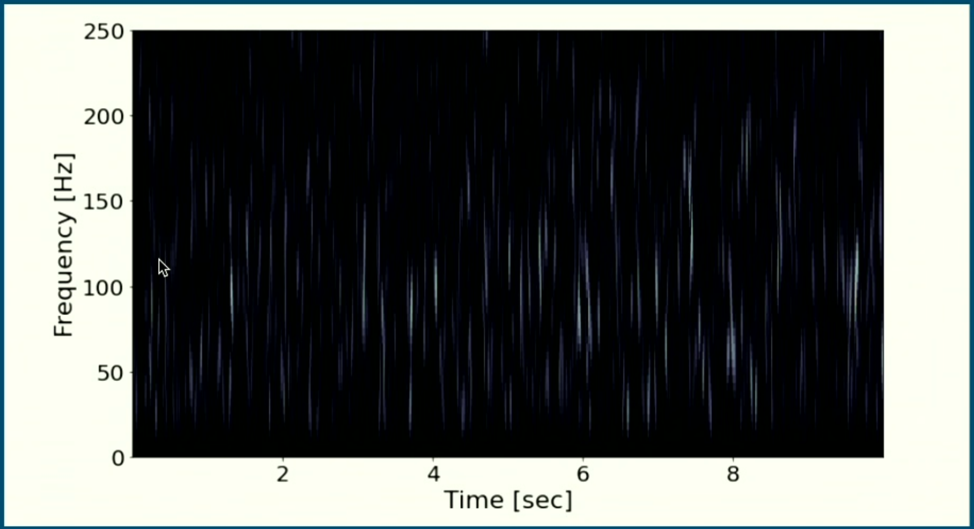


Implementation of SpeCS on injections II

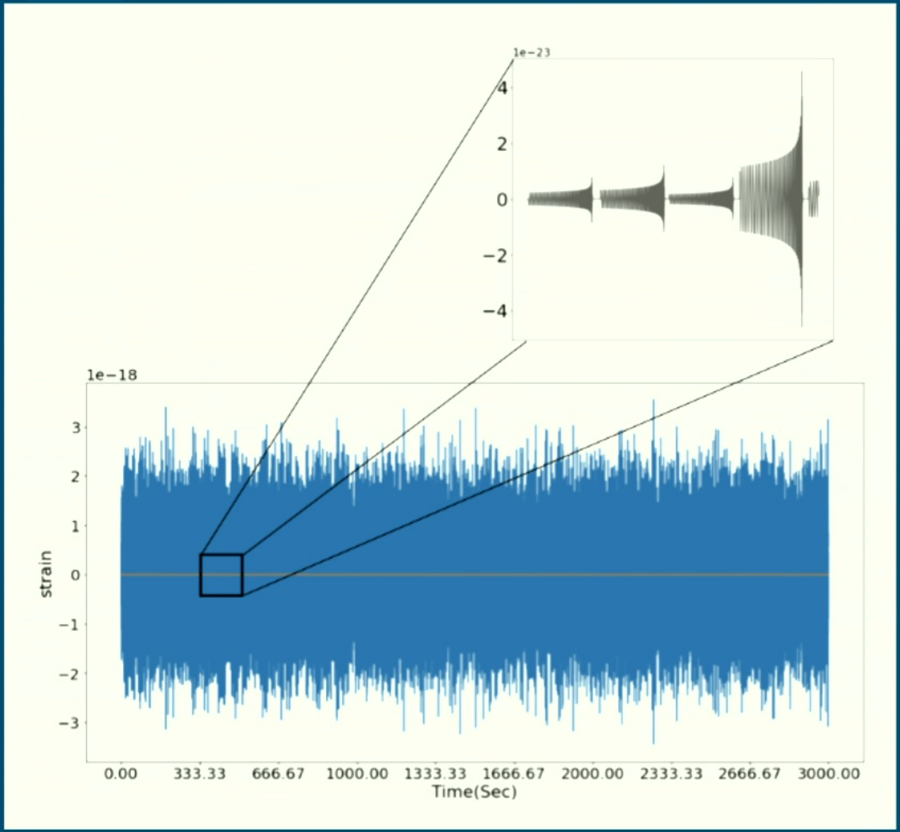
signal

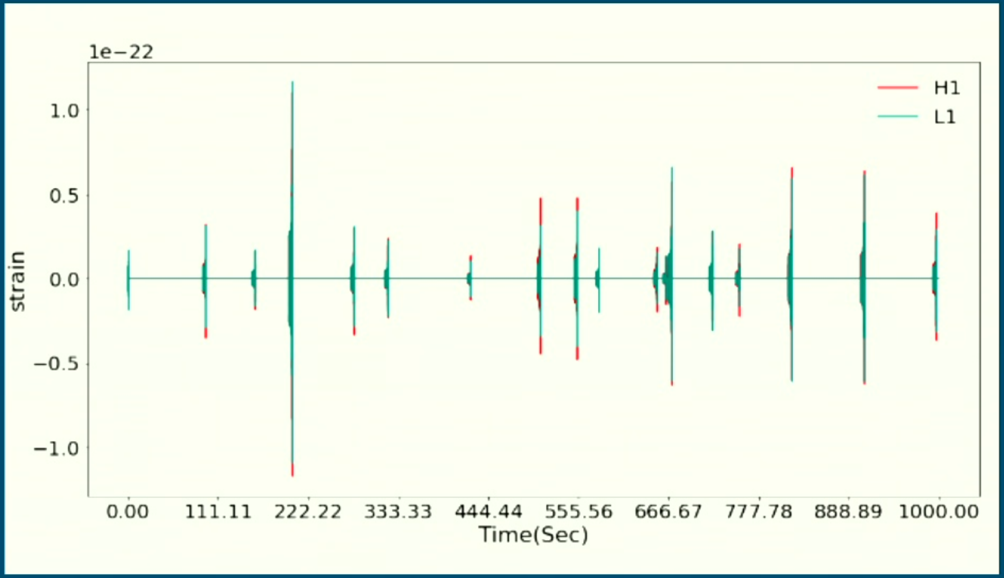


noise



Implementation of SpeCS on injections I





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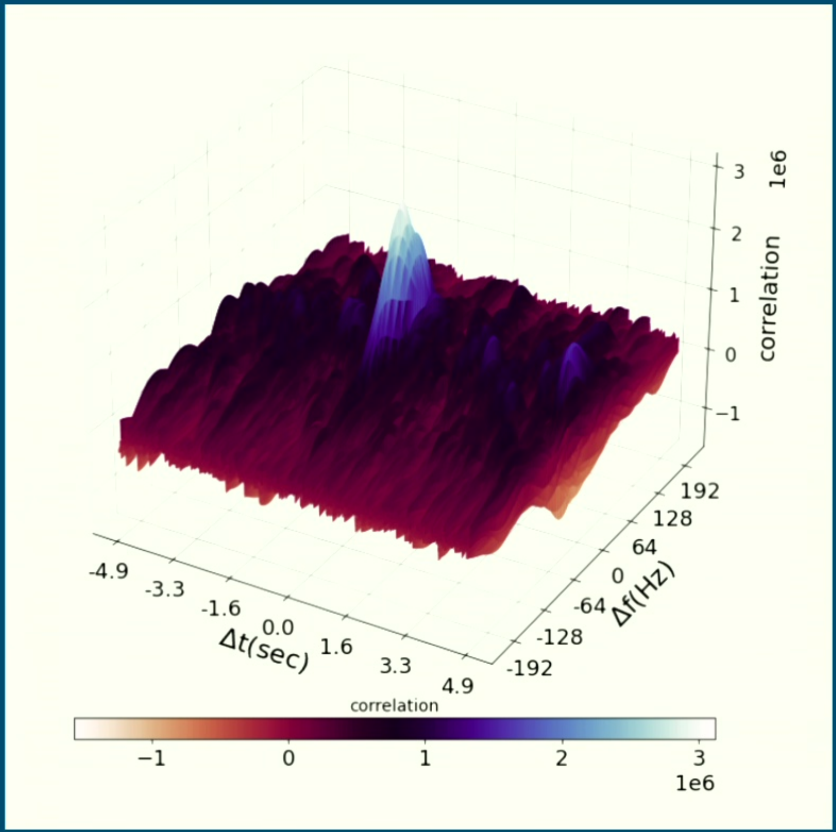
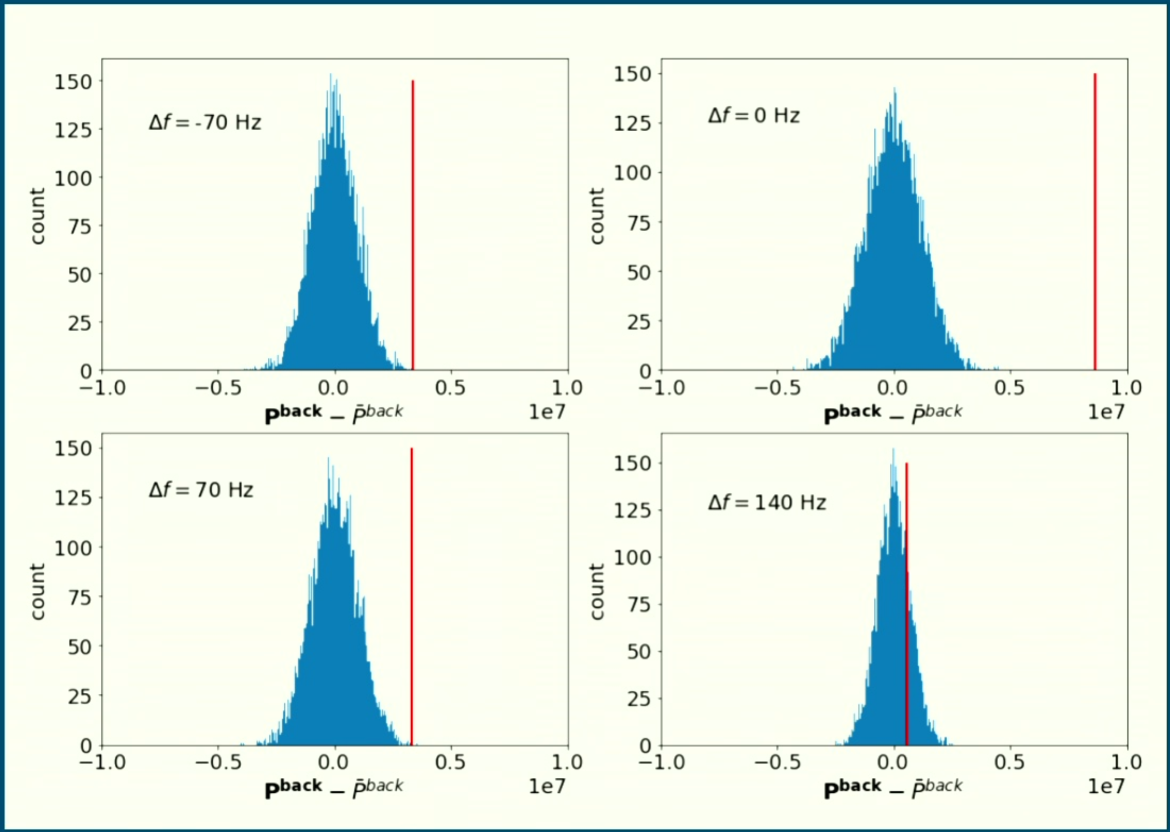
SpeCS: Results on the injections



Distribution of the background for a Gaussian noise



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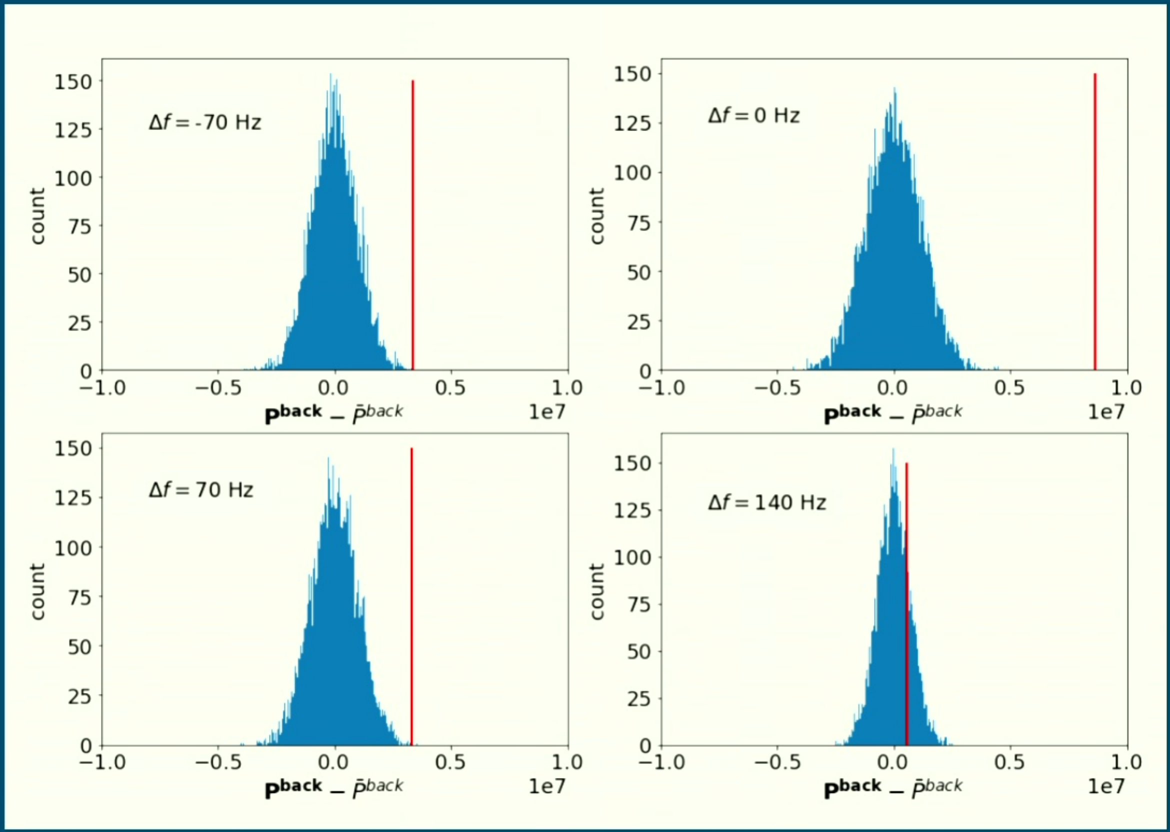
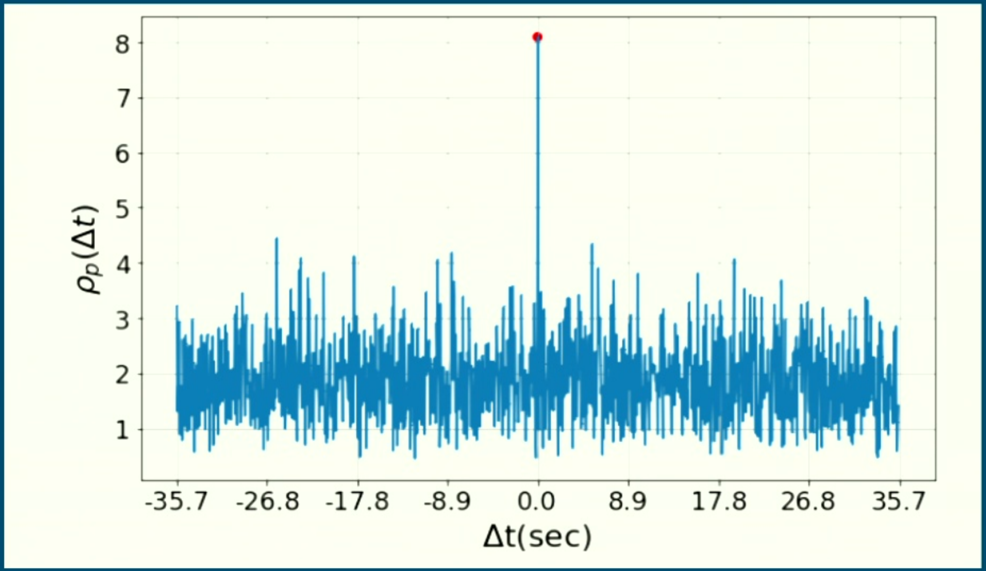
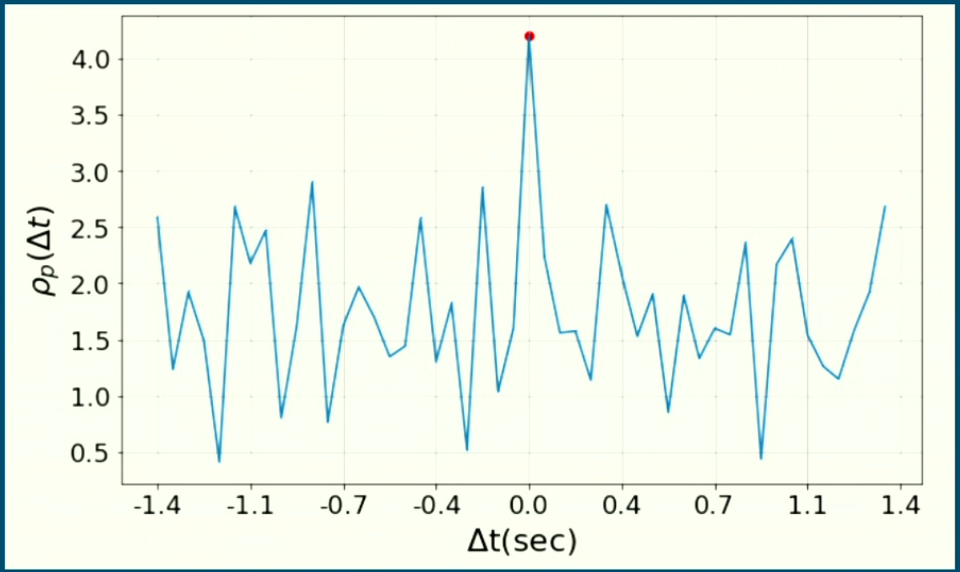
Distribution of the background for a Gaussian noise



Signal to Noise Ratio from SpeCS



dataset I (high merger rate)



dataset II (low merger rate)

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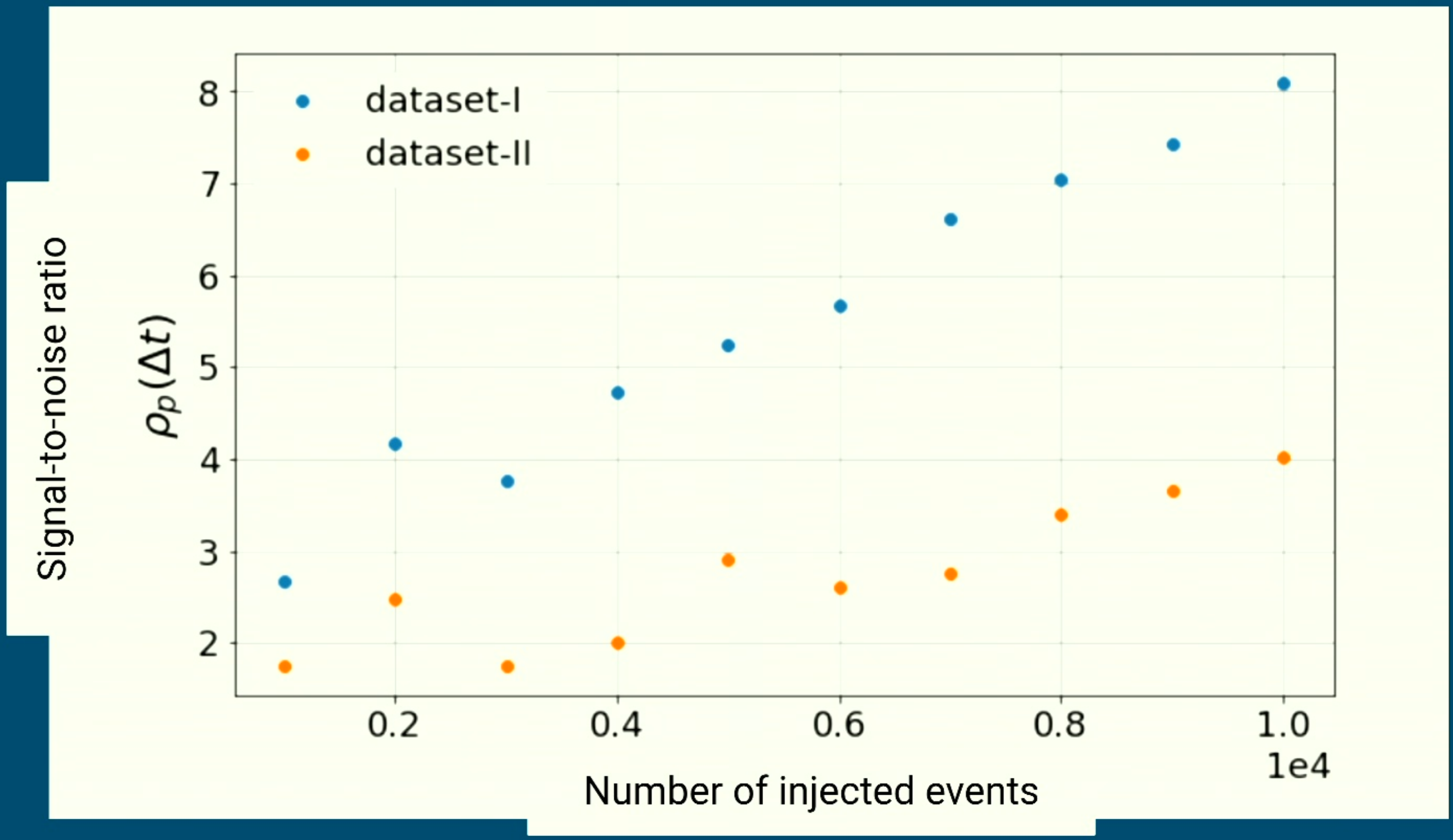
Variation in the signal to noise ratio with total number of events



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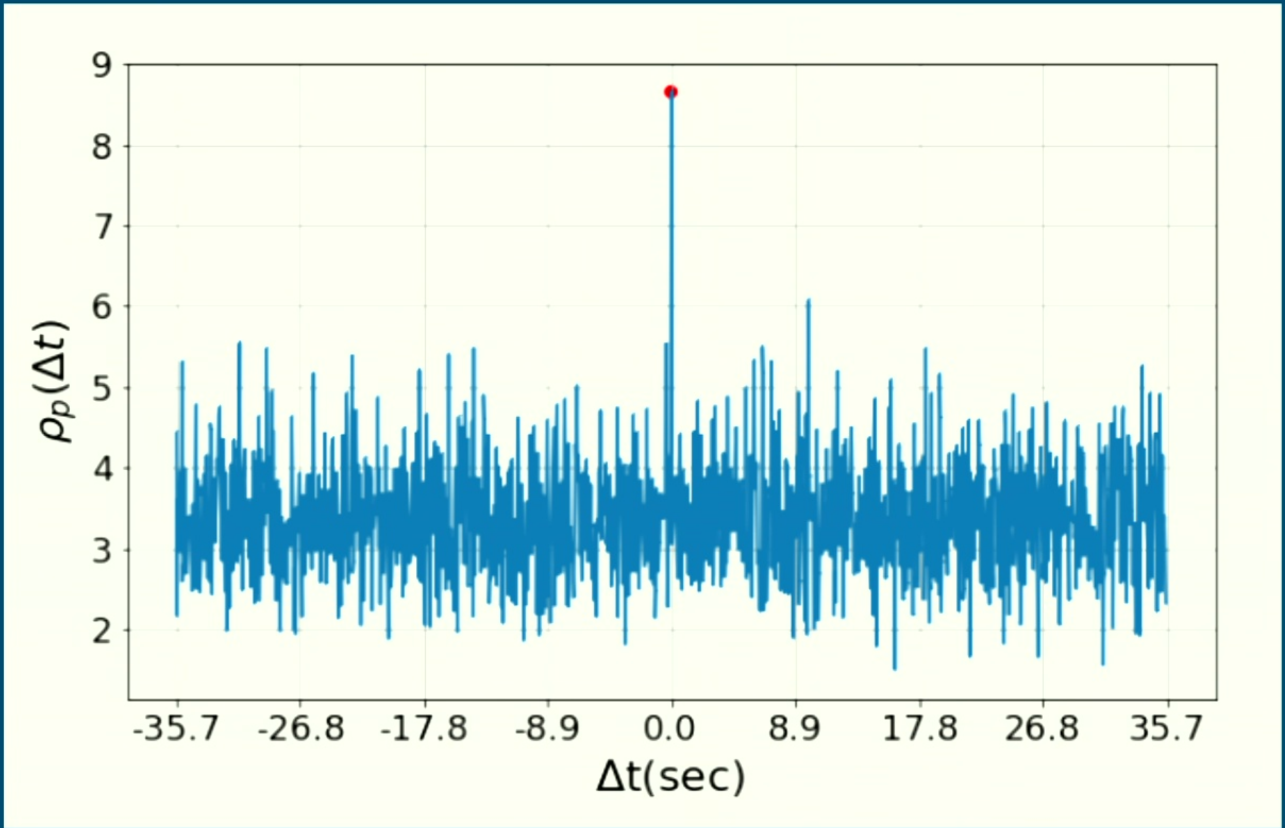
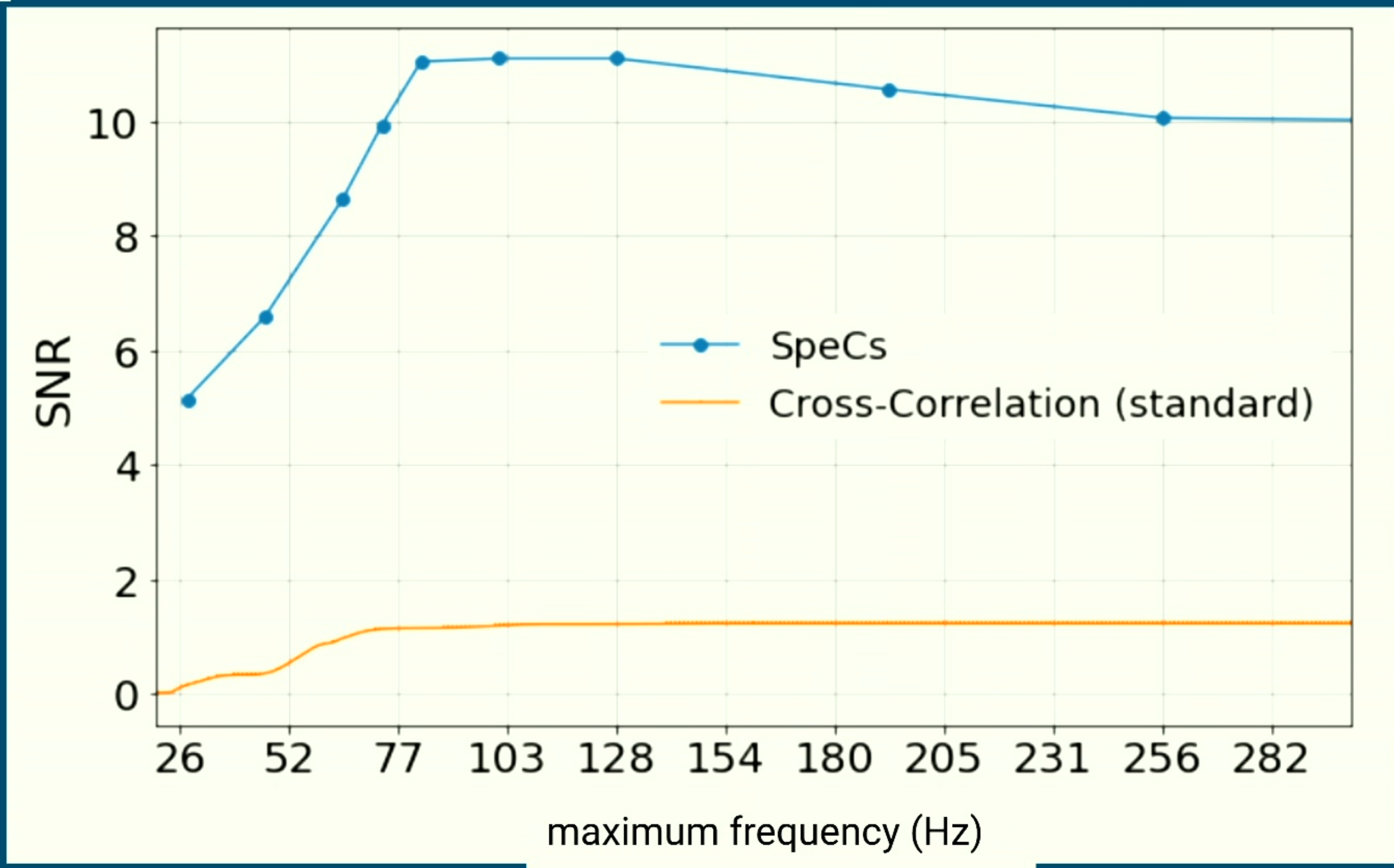
SNR by combining LHV detectors



Comparison with the cross-correlation technique



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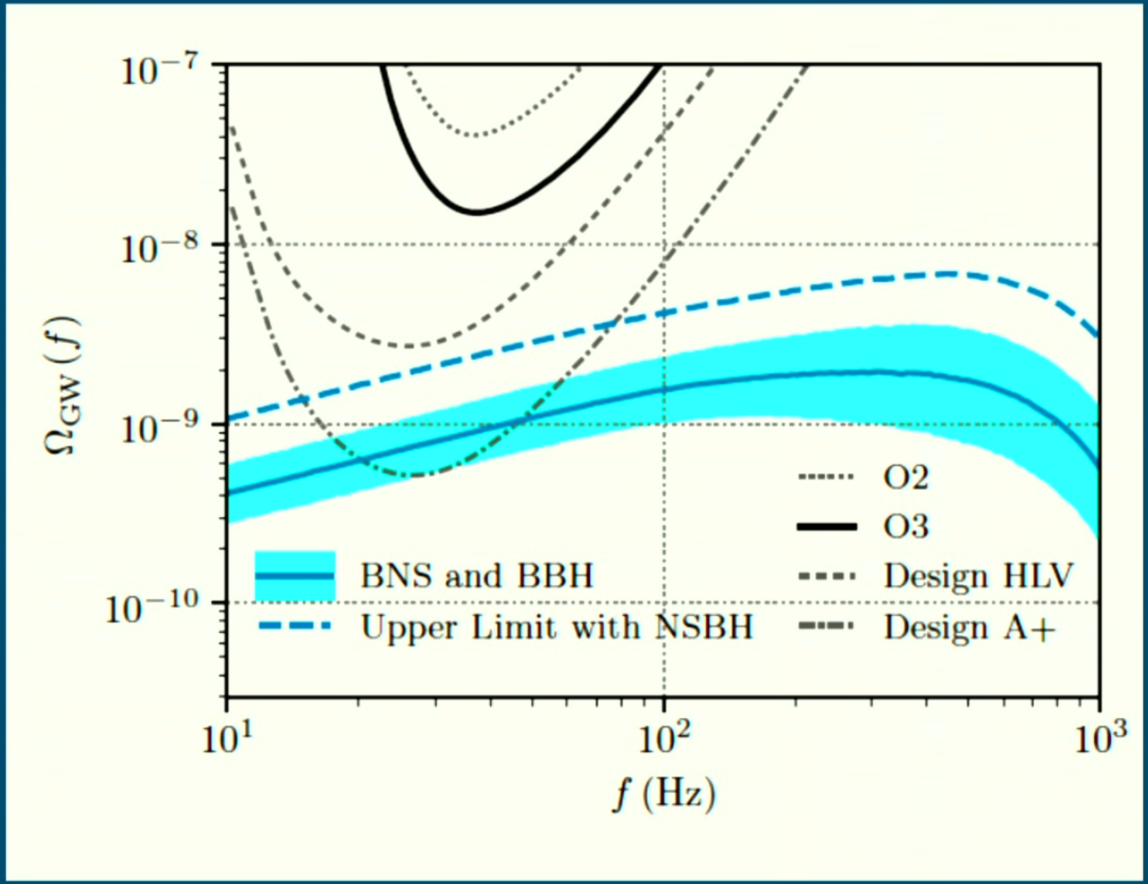
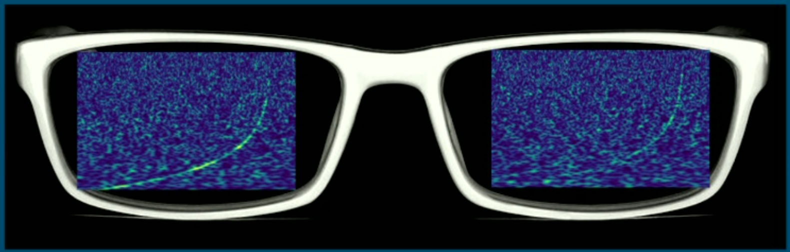
SpeCS improves (astrophysics) SNR by ×8



Take home messages



SpeCS: A new method to detect time-dependent (low duty cycle) stochastic GW background.

Difference in the underlying statistical property of the SGWB and noise helps in finding the signal.

The method is capable to capture more information than the cross-correlation method for a signal with low duty cycle.

Thank you!