Title: Comparing the performances of coherent and coincident network searches forbinary black hole mergers

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Abstract: A coherent multi-site search is expected to be more powerful than itscoincident counterpart in discriminating gravitational wave (GW) signals fromthe noise background. This is because the former tests the consistency of thesignals' amplitudes phases and time-delays across the sites with those expected from a real GW source. However the coherent statistic that is optimalin Gaussian noise is not guaranteed to perform as well in real data which arenon-Gaussian. Here we introduce an alternative coherent statistic for searchingcompact binary coalescence (CBC) signals that includes chi-square andnull-stream discriminators for non-Gaussian features in the data. Thisstatistic has been found to perform better than coincident statistics exploredin real data. This alternative coherent statistic is being used in ongoinginspiral-merger-ringdown searches in LIGO-Virgo data and is expected to beuseful in bridging the performance gap between the coincident CBC searchpipeline and the coherent burst search pipeline for detecting signalshigh-mass CBCs especially for systems with total-mass tending toward ahundred solar masses that have only a few signal cycles in band. We planto use this statistics in future NINJA analysis.

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Basic message

- Coherent searches are expected to improve the significance of a GW signal by requiring amplitude and phase consistency with time-delays observed across multiple detector baselines.

- Although demonstrated here in simulated Gaussian data, we find an improvement in performance compared to the simpler coincidence search in real data as well.

- Gaussian runs still pertinent since they test for possible pathological behavior of the search algorithm, such as arising due to the degeneracy of the detector network in resolving GW polarization from certain parts of the sky.

- Coherent searches, however, are expected to demand a greater accuracy of detector calibration.

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Waveforms

- Waveform families studied here:
  Complete (phenomenological) IMR waveforms,
  EOBNR waveforms.

- EOBNR
  Effective one body description of the 2-body problem tuned with the NR simulations and then matched to the quasi-normal mode of BH ringdowns, to get full waveform.

- Phenomenological
  NR waveforms matched to PN waveforms to produce full IMR waveforms

- Mass range:
  Total mass 25-100 $M_{\odot}$ and component masses 1-99 $M_{\odot}$

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The coherent signal-to-noise ratio (SNR)

For 2 *co-aligned* detectors with the same noise power spectral density (PSD):

$$C = (s, h) = \rho e^{i\phi}$$

$$(\text{Coherent SNR})^2 = \frac{1}{2}\left|C_1(t) + C_2(t)\right|^2$$

$$= \frac{1}{2}\left[\rho_1^2 + \rho_2^2 + 2\rho_1\rho_2\cos(\phi_1 - \phi_2)\right]$$

-SB, Pai, Dhurandhar, Phys. Rev D, Volume 64, 042004

For more detectors at different sites and with different orientations, the above expression will involve antenna factors and time-delays.

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Effective SNR for coincident statistics

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$$\rho_{eff} = \rho_{eff}\left(\rho, \chi^2\right)$$

Combined effective SNR

$$\rho_{eff,c} = \sqrt{\sum_i \rho_{eff,i}^2}$$

Null-stream statistic

Instead of maximizing the likelihood ratio, try fitting the data to the signal:

$$\left\|\vec{s}-\vec{h}\right\|^{2},$$

and minimize it to get the "null stream" statistic:

$$\left({}^{2D}N\right)^{2}=\frac{1}{2}\left|\varsigma_{1}^{-1}C_{1}(t)-\varsigma_{2}^{-1}C_{2}(t)\right|^{2}\Big/\left(\varsigma_{1}^{-2}+\varsigma_{2}^{-2}\right)$$

For 3 detectors:

$${}^{3D}N\propto\left|\sum_{k=1}^{3}\varepsilon_{klm}F_{+}^{l}F_{\times}^{m}\varsigma_{(k)}^{-1}C^{k}(t)\right|^{2}.$$

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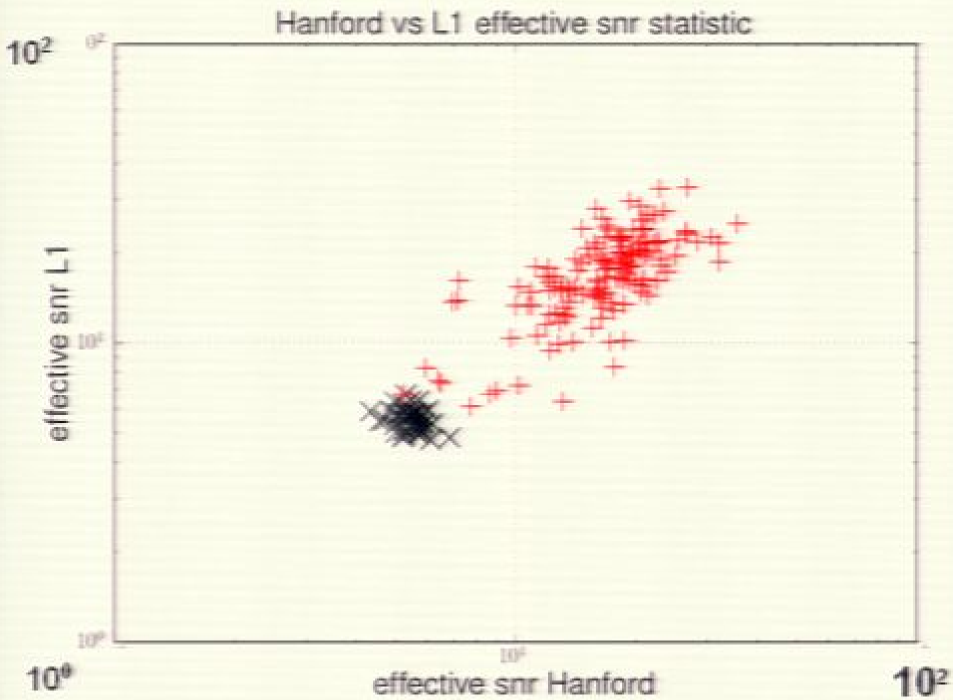
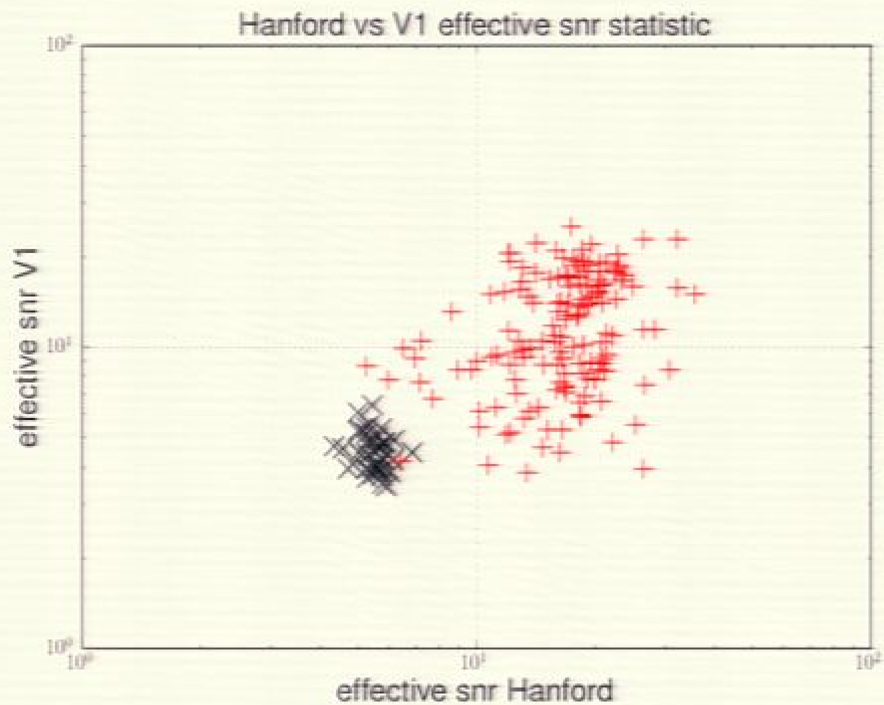
Coincident 3-detector search





All *injection (red pluses)* and *slide (black crosses)* triple-coincidence triggers found in simulated colored (LIGO-I) Gaussian noise in Hanford-Livingston-Virgo detectors. are "triples". Here the injections are of the EOBNR type, with distances 14 to 70Mpc. Two injections would be "lost" but for the 3rd detector, in this Hanford-Livingston-Virgo high-mass search.

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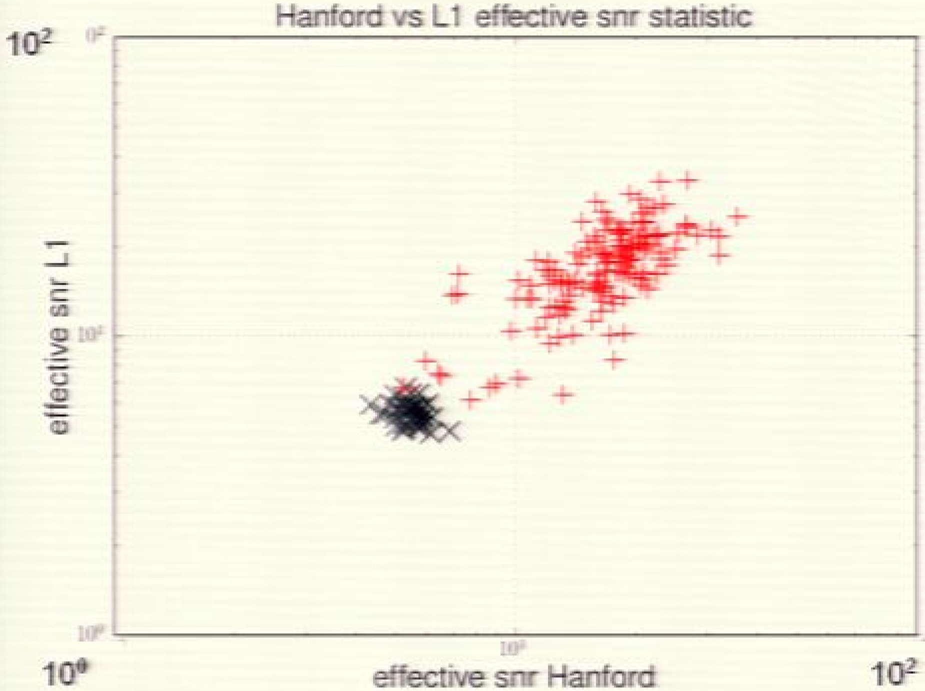
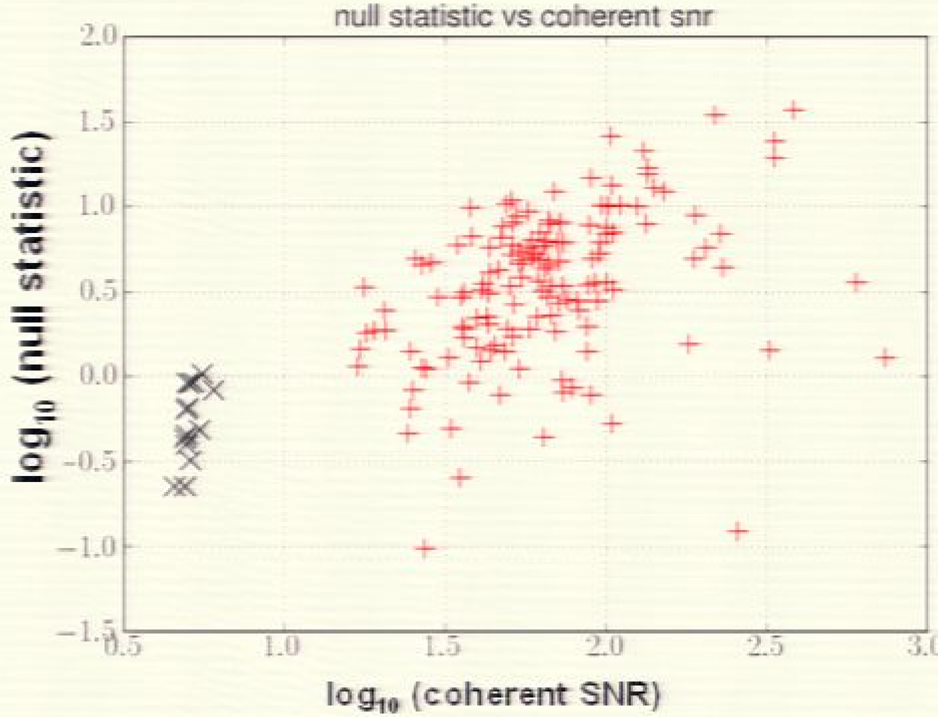
Comparison of search pipeline with and without the coherent stage

Without the coherent stage

With the coherent stage





The coherent stage (right figure) helps by
(1)Reducing the false-alarm rate,
(2)Improving detection efficiency (by recovering weaker injections).

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Complications of real data: Alternative statistics

- Some glitches in real data hard to discriminate against signals:
  - Especially so since high-mass templates are of short durations, sometimes only a few cycles long, similar to glitches, for which signal-based vetoes (chi-square, etc.) don't work well

- Some of these glitches have a large auto-detector term and thus result in large coherent SNRs, which therefore result in poor performance.

- However, here too the phase consistency check helps in the form of
  - The cross-detector pieces of the coherent SNR statistic.
  - The null-stream statistic.

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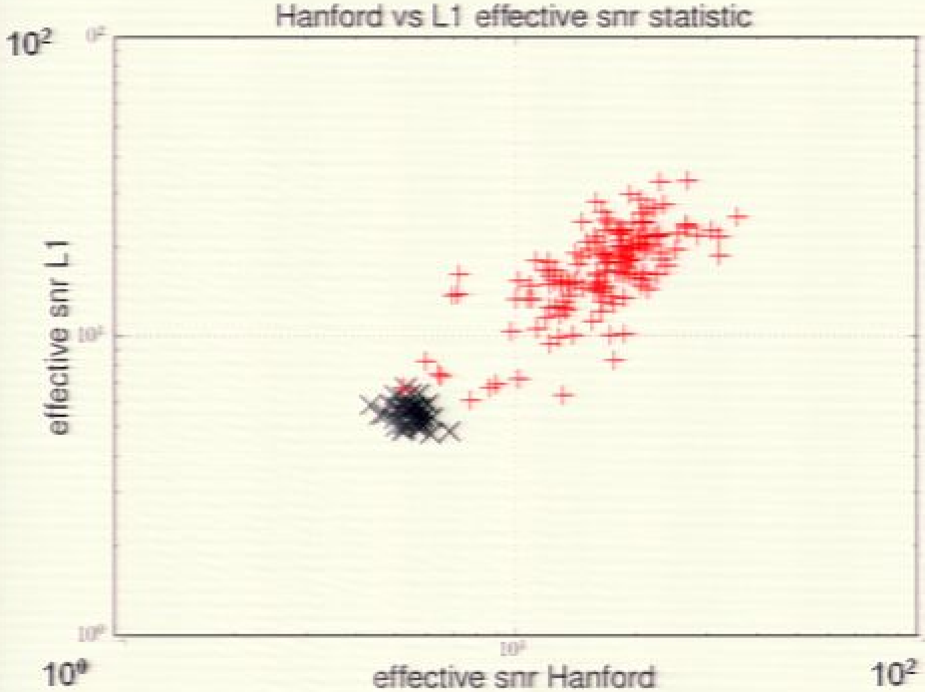
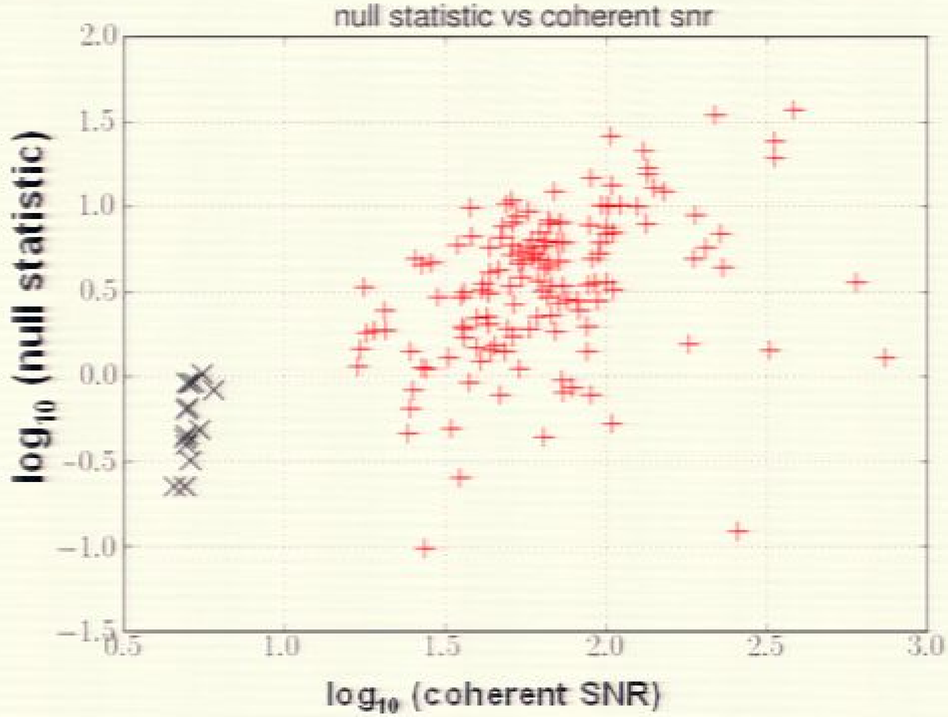


With the coherent stage



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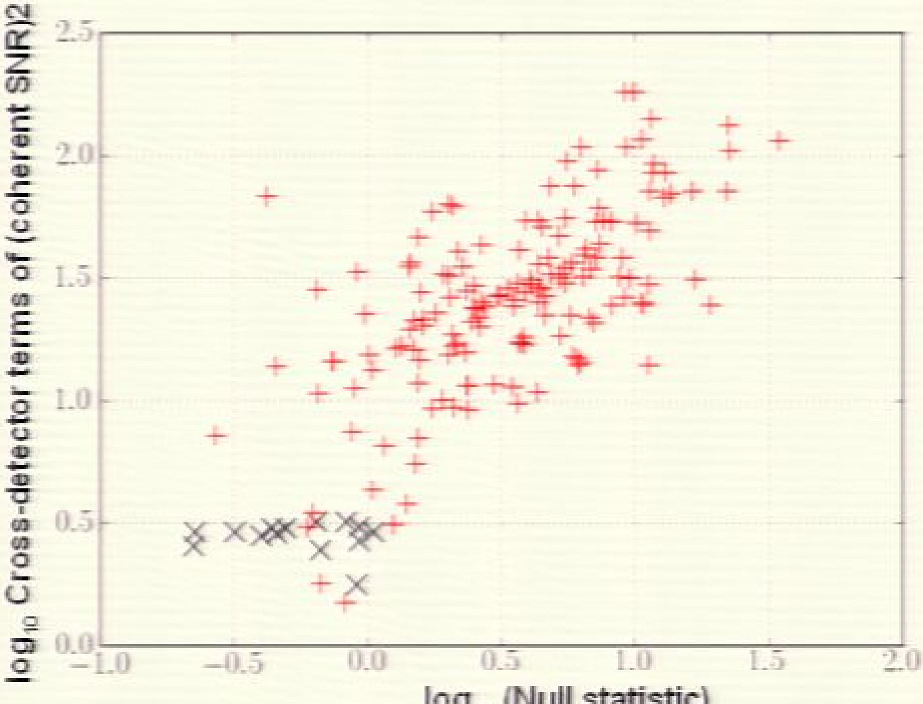
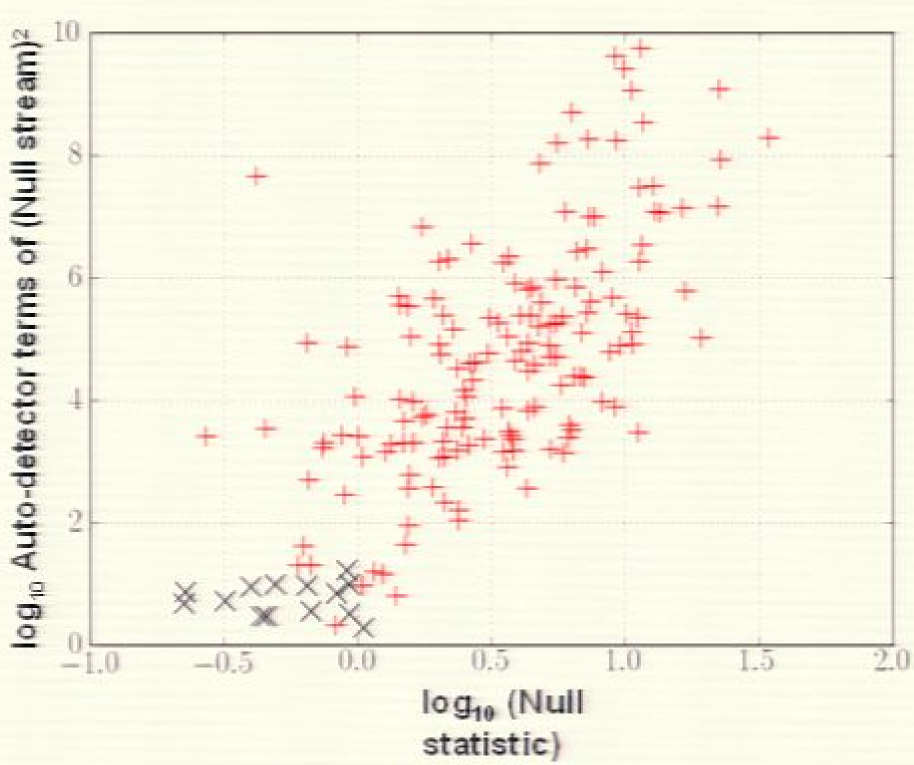
Alternative statistics: pieces of coherent SNR and Null-stream





Using different pieces of coherent SNR and null stream we can construct different alternative statistics to improve the detection probability at any given false-alarm rate in real data.

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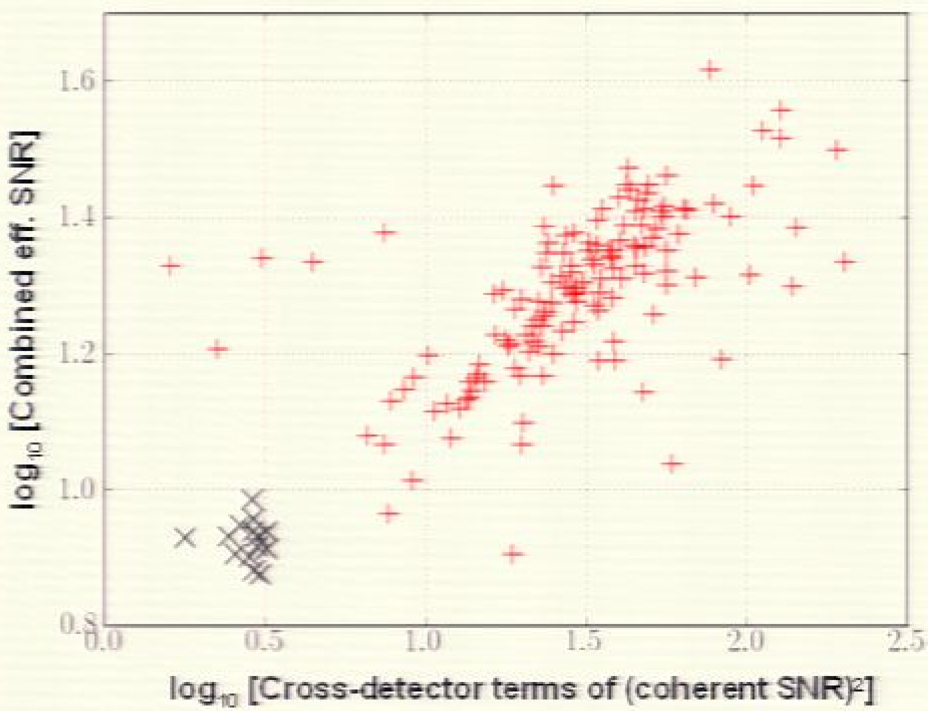
Further improvement with combined effective SNR…



Using combined effective SNR with the cross correlation terms of coherent SNR can also yield a better separation of injections from background.

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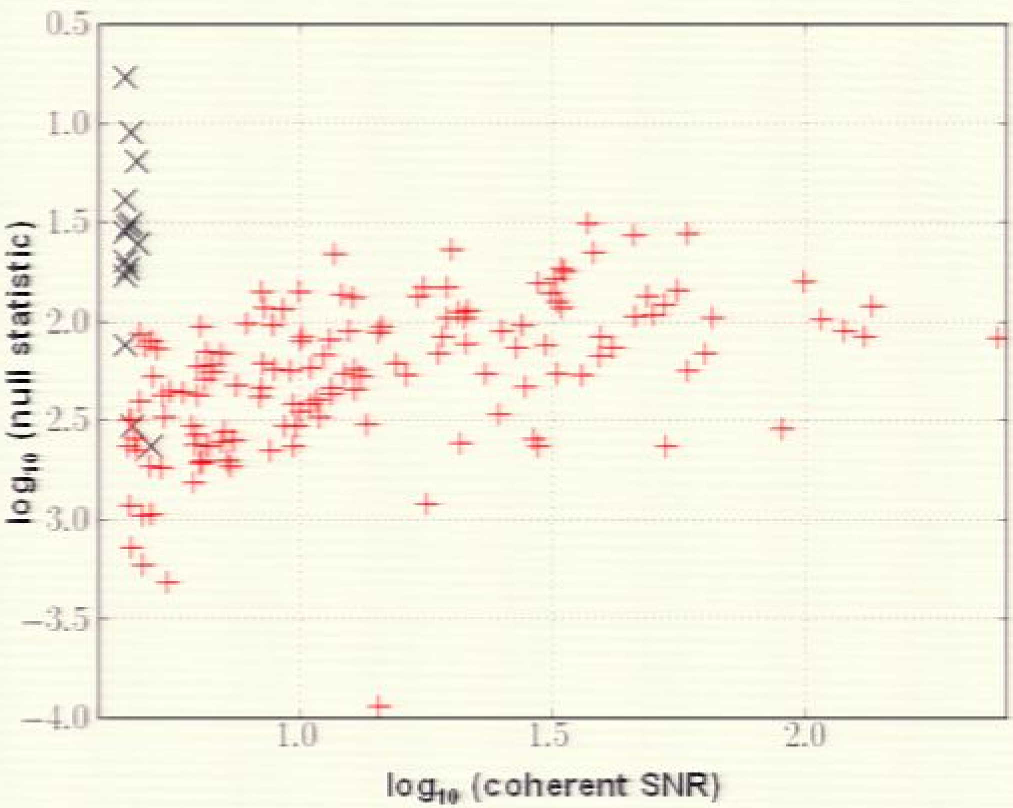
…and alternative clustering



Another method for distinguishing signals from glitches is to minimize the null-stream. In real data, this does NOT work very well. What works better is maximizing:

Ratio statistic = A_N / N.

This statistic favors triggers with low null-stream values but, at the same time, with large auto-detector terms, as expected of real signals.

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Requirements

1. Calibration accuracy:
   - For a source rate-loss of 10%, a phase error of up to 0.5 radian and relative amplitude error of ~5% across different detectors can be tolerated.
   - If all ifos have the same systematic phase error, the signal detectability is not affected.
   - Allowing the mass-templates to be different in different detectors can help mitigate the effect of calibration errors.

2. Computational costs:
   - The coherent-stage involves scanning a sky-grid, with O(1e4) sky-positions. Any finer is not useful. [S. Fairhurst, NJP 2009]
   - This increases the number of FLOPS by about 25% compared to a two-stage coincidence search.

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Summary

1. Studies in Gaussian data were helpful in testing that the LIGO-VIRGO high-mass search pipeline performs better when the coherent stage is added, while being unaffected by network degeneracy.

2. We employ alternative statistics, such as the null-stream, to aid the performance of the coherent stage in real data.

3. We plan to study the NINJA-2 data set with the high-mass search pipeline, including the coherent stage.

4. As part of my PhD thesis, I am using hardware injections (which are affected by calibration errors) for comparing the performance of coherent searches that allow the binary component masses of a coincident trigger to vary in different detectors.