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Measurement of Polarization of GWs by 3G Detectors as a Test of Gravity

Investigating the capabilities of up to come facilities on measuring polarization modes of GWs and comparison with current generation ones

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Testing GR with GWs

A broad subject:

- Parametrized post Einsteinian
- Propagation speed and Lorentz invariance
- Extra-polarization modes: ppE and null streams

➔ Main focus → null streams

It has been already described with several degrees of complication
→ **Basic approach** and comparison of performances on simulated data over different networks of ground based detectors (2G and 3G)

➔ Outline of theoretical (null streams definition) and computational (HPC) methods and results

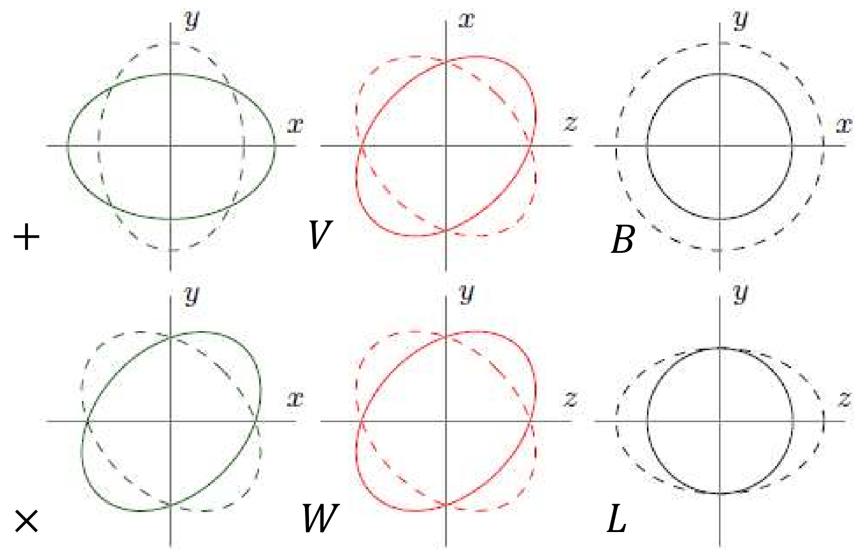
GR and non-GR polarization modes

- GR only predicts tensor modes + and cross
- Modified theories of gravity → huge bestiary
- Number of polarizations is constrained to be $\leq$ 6 (Newman&Penrose, 1962)
- Eardley's classification E(2) for a spin-2 particle (Eardley et al, 1973)
- Such classification, and the effect on a ring of text masses, is general
- Massive gravity theories impose special conditions on the simultaneous presence of different modes → not taken into account (Rham et al., 2011)

GR and non-GR polarization mdoes

The effect of the 6 modes can always be represented as follows:

$z =$ propagation direction



Tensor (GR) modes

Vector modes

Scalar modes (breathing and longitudinal)

Picture from: Isi&Weinstein, 2017

Short summary of Antenna Patterns

- GW detectors are not spherical antennas
- Relative displacement of test masses along IFO's arms:

$$\frac{\delta L}{L} = \sum_{pol} F^{pol}\,(\varphi, \vartheta, \psi) h_{pol}$$

$\boldsymbol{F^{pol} = \frac{1}{2}\, \widehat{d}_{ij}\, \hat{\varepsilon}^{ij}{}_{pol}}$ → **a tensor expression**

Long wavelength approximation!

$$\hat{d}_{ij} = \hat{e}_x^i \otimes \hat{e}_x^j - \hat{e}_y^i \otimes \hat{e}_y^j$$

$\hat{e}_x^i$ = unit vector along the x-th arm of the detector

Measuring polarizations

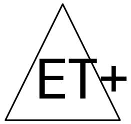
- GR could be tested just by the observation of polarization modes
- Single detector →$S_a = \sum_{pol} F_a^{pol}(\varphi, \vartheta, \psi)\, h_{pol}$
- For the two scalar modes: $F^B = -F^L$

→Just five independent modes → 5 non-coaligned detectors are needed for full disentangling

The antenna patterns need be known with good precision: →optimal localization needed

HLVK+India → Hanford and Livingston are almost coaligned

Only very well-localized events could allow a polarization measure



ET+CE = no more than 4 non co-aligned detectors ☹

Testing GR

- Just checking for the presence of non-GR polarization (with no disentangling) would be enough

→Null stream formalism (localization, Klimenko et al., 2011)

- Three-detector null stream: $\mathrm{NS} = \varepsilon_{ijk}\, F_i^+ F_j^\times S_k$ → if signal is made of tensor modes only: $\mathrm{NS} = \mathrm{AntiSym} \cdot \mathrm{Sym} = 0\ (= noise)$

- Otherwise, NS is generally non-zero

$$¡¡\,\mathbf{NS} = \boldsymbol{\varepsilon}_{ijk}\, \boldsymbol{F}_i^+(\widehat{\boldsymbol{\varphi}}, \widehat{\boldsymbol{\vartheta}}, \widehat{\boldsymbol{\psi}}) \boldsymbol{F}_j^\times(\widehat{\boldsymbol{\varphi}}, \widehat{\boldsymbol{\vartheta}}, \widehat{\boldsymbol{\psi}})\, \boldsymbol{S}_k(\boldsymbol{\varphi}, \boldsymbol{\vartheta}, \boldsymbol{\psi})\,!!$$

Testing GR

Null stream-based tests of GR:

- No outcome so far
- Example application to GW170817: Hagihara et al., 2019

With a network of 4 non-coaligned detectors:

- More stringent analysis can be pursued
- 4-detector null stream: $\mathrm{NS} = \varepsilon_{ijkl}\, F_i^{+} F_j^{\times} F_k^{pol} S_l$

→Allows getting rid of one extra polarization mode

PRO: Allows more testing

CON: Unsensitive to one non-GR mode

Present work

- Testing GR with different networks of detectors
- 1) HLVKI, 2) ETCE
- Both 3 and 4-detector NSs
- Simulated pop. of BBH events (computational limits → no BNS yet)
- Localization (needed for NSs) → gwbench
- Computation of NSs' SNR for different polarization injections.

Using gwbench

- It provides a vectorized function for computing antenna patterns

Why vectorized? → The Earth rotates during the inspiral →antenna patterns change

- Makes use of Fisher Information formalism for error estimation (uncertainty on localization → key point):
- $cov^{-1} \approx \Gamma$ with maximum likelihood estimators
- Provides a useful tool for computing the outcome of a NS-based test of GR on several events

→ Borhanian, 2020

Summary of workflow

- Given a network of detectors (HLVKI or ETCE)
  - Simulation of BBH population → 10^5 events
  - for event in the pop:
    - Retrieve coalescence parameters for that given event
    - Data acquisition by a network of dets simulated with gwbench: waveform=IMRPhenomXAS (Pratten et al., 2020)
    - Injection of a non-tensor mode (as in Takeda et al., 2018)
    - Uncertainty on the localization is computed by gwbench
    - A 2D-gaussian distribution of (RA, DEC) values is computed with μ =injection parameters and σ = deviation given by gwbench
    - 100 samples are drawn from this distribution
    - For sample in (100 samples):
      - 3 and 4 dets-NSs are computed in the corresponding (RA, DEC) values for each sample
      - The noise of the NSs is computed is well propagating the noise of the detectors
      - NS power/noise = SNR of single sample
    - Averaging over the 100 samples: average SNR and its fluctuation
    - average SNR/fluctuation = significance of gravity test on single event
  - Cumulative sum of single event significances for different permutations of the order of events
- For which network does this sum provide a more meaningful test of GR?

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BBH population

- Help provided by A. Dhani and Sathya
- Expected number of 10^5 events within $z = 3$ following:

$$p(z) \propto \frac{dV_c}{dz}\frac{\psi(z)}{1+z}$$

→ Madau&Dickinson, 2014

Binaries are uniform in α, δ and ι. Masses are distributed according to the PowerLaw + PeakModel of GWTC-3

GWTC-3 →small spins
Spin effects on localization measure → negligible

} No spin in BBH population

Only high SNR events are chosen: network SNR>12

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Injection of non-tensor modes

- This part has been performed following non-GR injection in Takeda et al., 2018
- Each non-GR mode is obtained by: $h_{pol} = \mathcal{A}_{pol}\mathcal{G}_{pol}\, h_{+}$ with $\mathcal{G}_{pol} = \mathcal{G}_{pol}(\mathcal{M}, \iota)$ taken from Takeda, and $\mathcal{A}_{pol}$ being a dimensionless amplitude weighting the importance of non-GR modes in a signal with respect to GR modes
- $\mathcal{A}_{pol} = 1$ in this work →unrealistic, used for benchmarking networks' sensitivity to the test

What about radiation reaction terms due to additional pol. modes (i.e. ppE)?
→Not considered here as this test depends on localization-ONLY!
But the assumption of localization uncertainty being independent from any waveform variation is SIMPLISTIC

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Computing null streams

As previously pointed out: $\mathrm{NS} = \varepsilon_{ijk}\, F_i^{+}(\hat{\varphi}, \hat{\vartheta}, \hat{\psi}) F_j^{\times}(\hat{\varphi}, \hat{\vartheta}, \hat{\psi})\, S_k(\varphi, \vartheta, \psi)$

→ $S_k(\varphi, \vartheta, \psi)$ is the k-th detector response as given by gwbench (depends on antenna patterns computed at the exact location)

→ $F_i^{+}(\hat{\varphi}, \hat{\vartheta}, \hat{\psi})$ is the i-th detector antenna pattern: depends on the values of $\hat{\varphi}, \hat{\vartheta}, \hat{\psi}$ (which come from the uncertainty driven bi-Gaussian distribution)

→gwbench: Stationary Phase Approx.: $S_k(f) \approx \sum_{pol} F_k^{pol}(f) h_{pol}(f)$; same for NSs: $\mathrm{NS}(f) \approx \varepsilon_{ijk}\, F_i^{+}(f) F_j^{\times}(f)\, S_k(f)$

→$\mathrm{PSD}(f) = |\mathrm{NS}(f)|^2$

→ NSs' uncertainty obtained propagating detector noise through

One last issue

Summary of workflow

- Given a network of detectors (HLVKI or ETCE)
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    - Injection of a non-tensor mode (as in Takeda et al., 2018)
    - Uncertainty on the localization is computed by gwbench
    - A bi-modal gaussian distribution of (RA, DEC) values is computed with μ =injection parameters and σ = deviation given by gwbench
    - 100 samples are drawn from this distribution
    - For sample in (100 samples):
      - 3 and 4 dets-NSs are computed in the corresponding (RA, DEC) values for each sample
      - The noise of the NSs is computed is well propagating the noise of the detectors
      - NS power/noise = SNR of single sample
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  - Cumulative sum of single event significances for different permutations of the order of events
- For which network does this sum provide a more meaningful test of GR?

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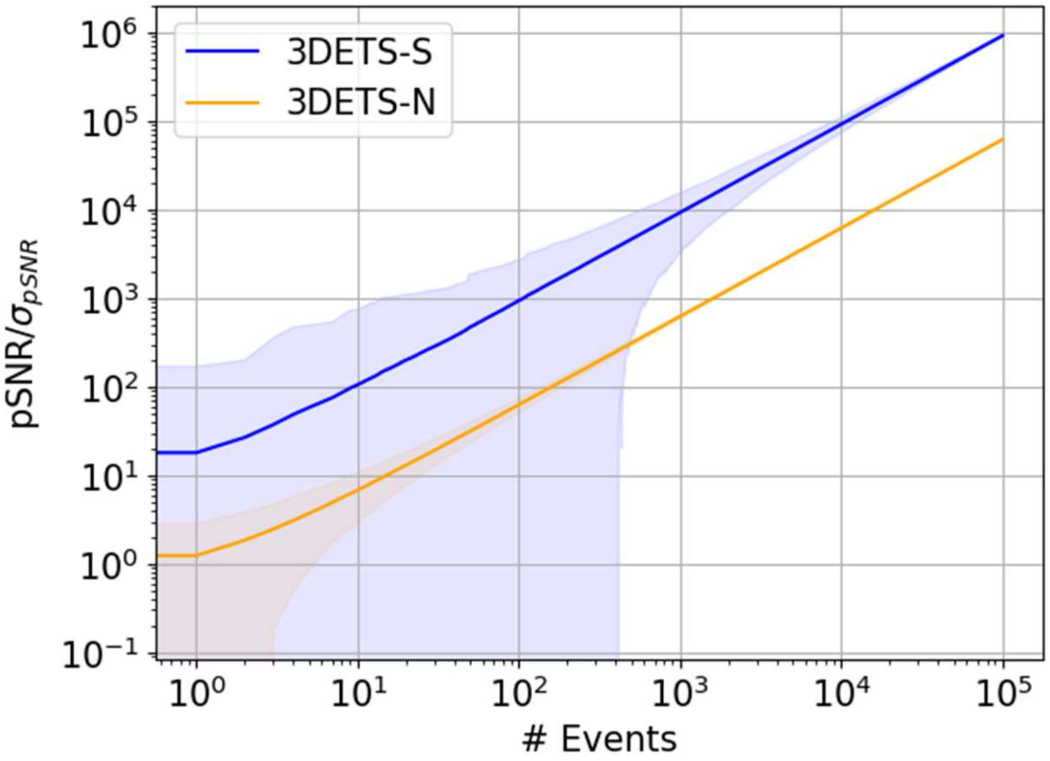
330k computing hours

Code for HPC structures

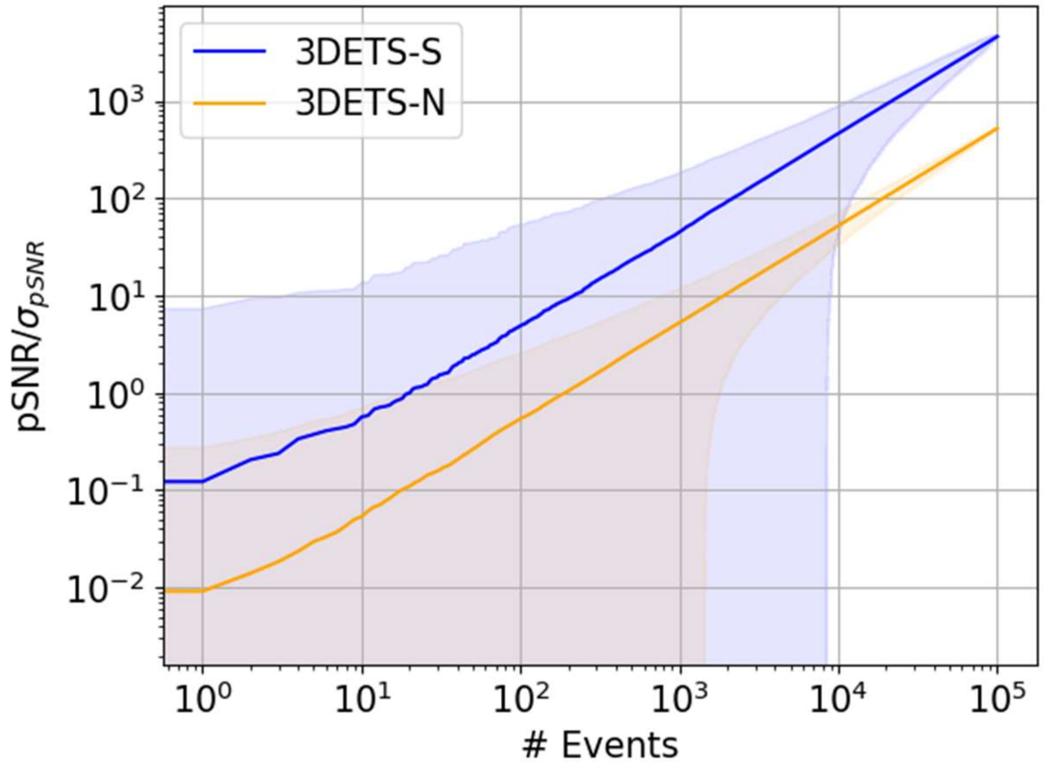
Gwave (PSU cluster) → https://computing.docs.ligo.org/guide/computing-centres/psu/

- In house version of gwbench for computing antenna patterns of several detectors for multiple events simultaneously
- Multiprocessing istance in the code: each of the 100 (RA,DEC) draws has a process which is assigned to the first available core →not a for loop
- Multiple batches of 1000 BBH events each are assigned to different nodes
- Just using multiple core architecture (no GPU) →34 h ($\ll$ 330k)

Results in a nutshell



ETCE

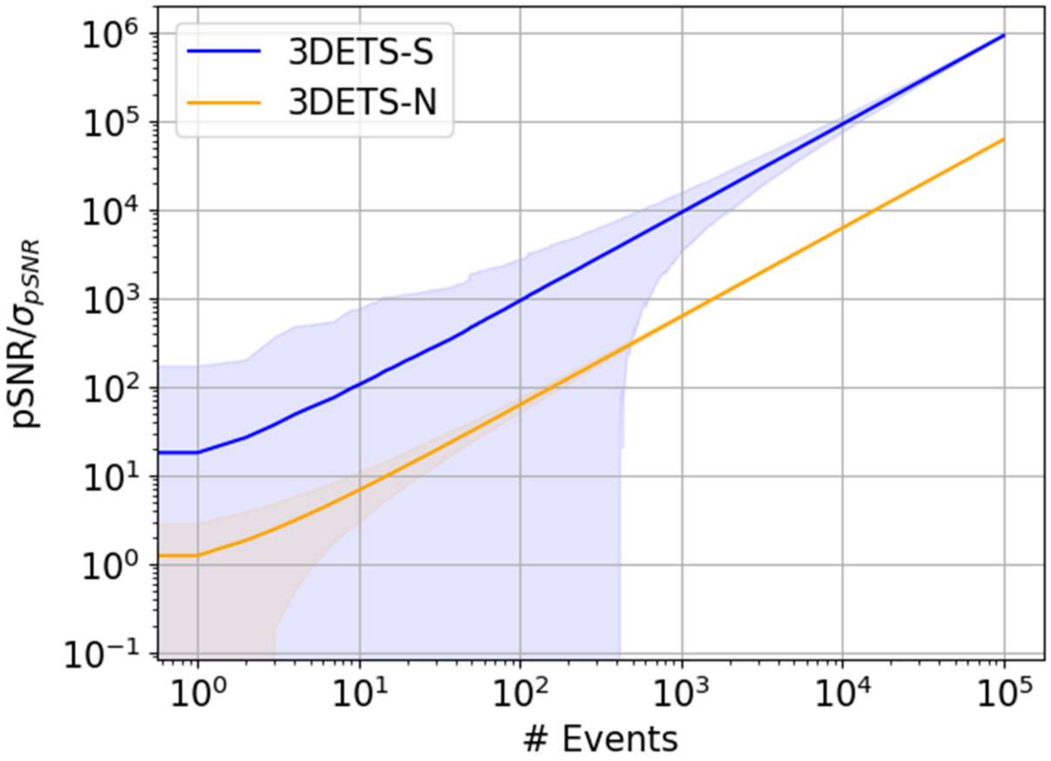


HLVKI

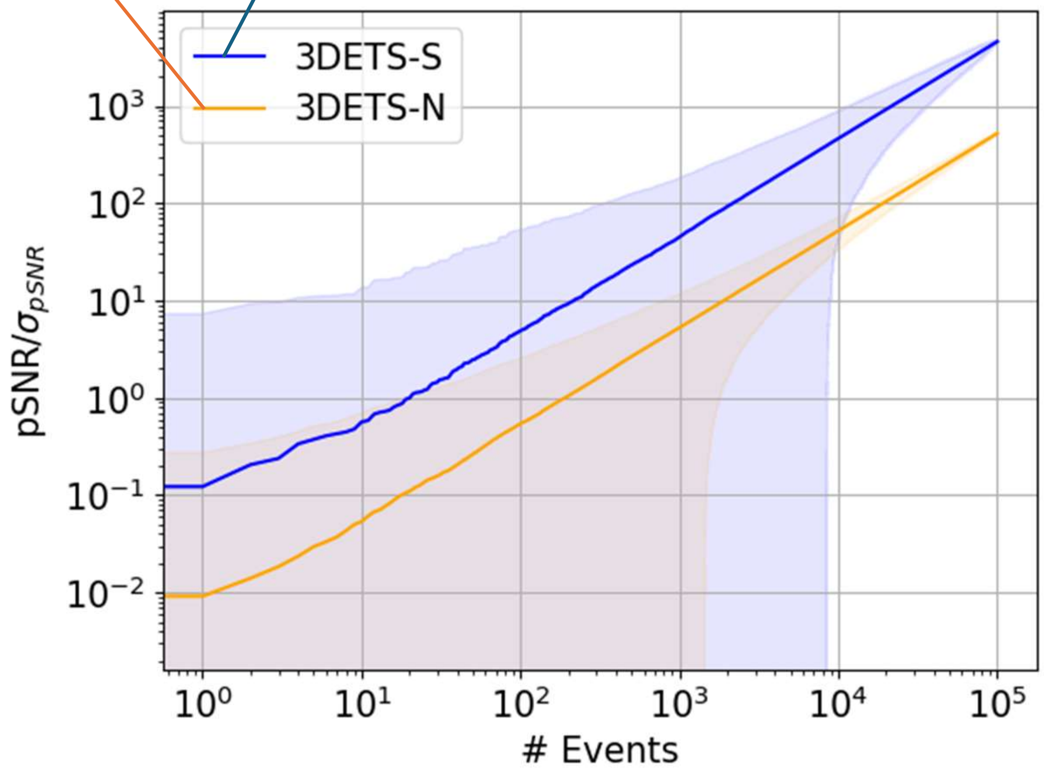
Results in a nutshell

3 dets NS, tensor + breathing mode

3 dets NS, tensor modes only



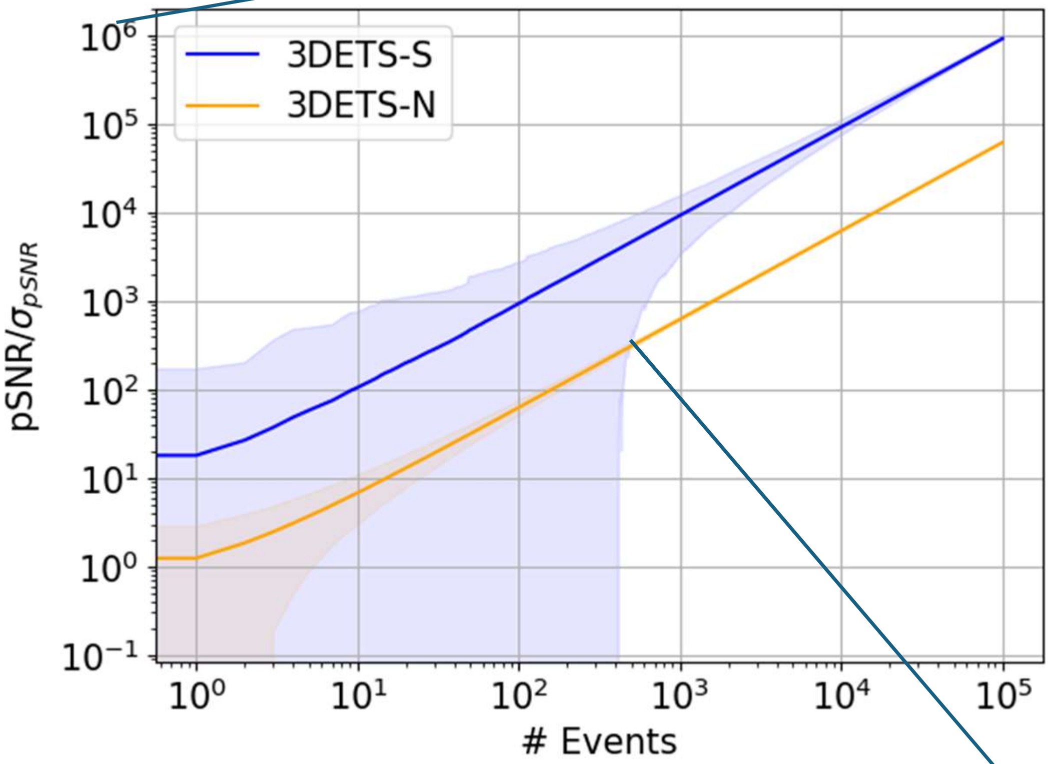
ETCE



HLVKI

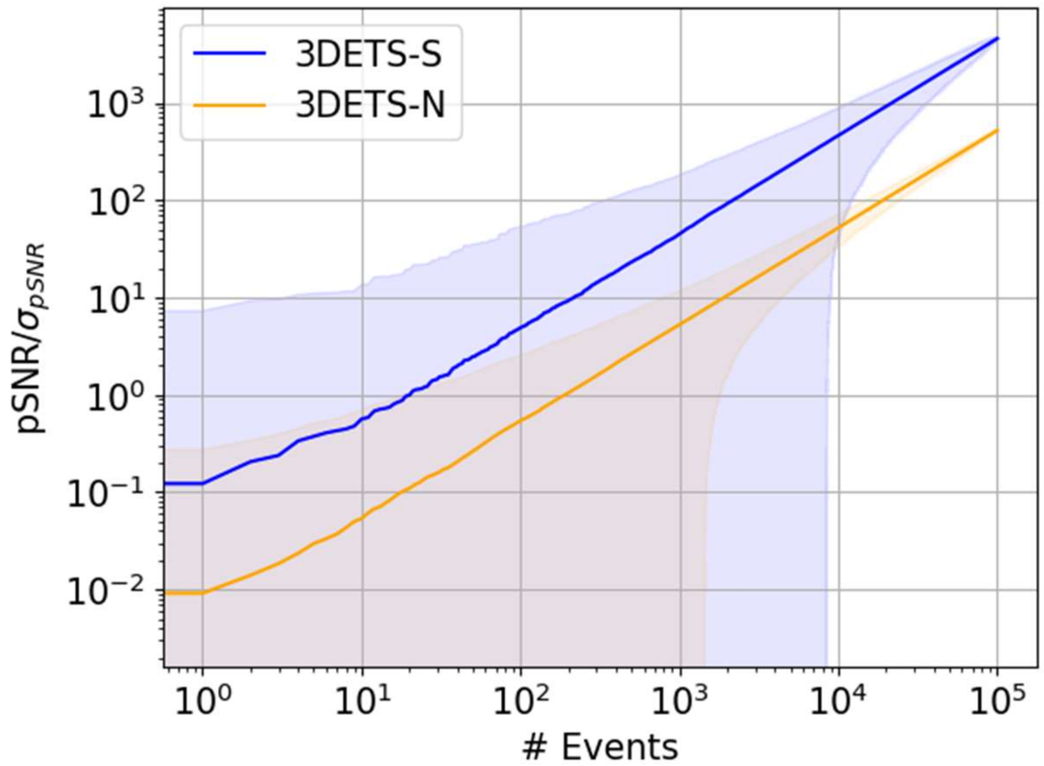
Results in a nutshell

Higher pSNR values



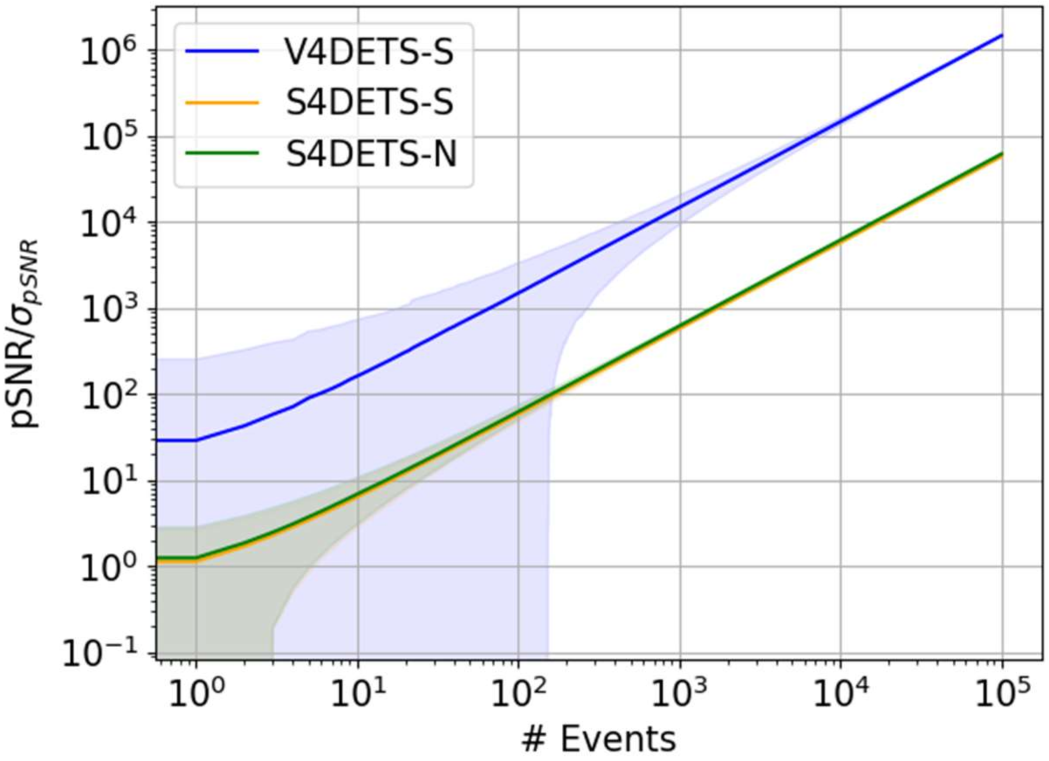
ETCE

Probability of fake claim $< 1\%$
after ~ 500 events

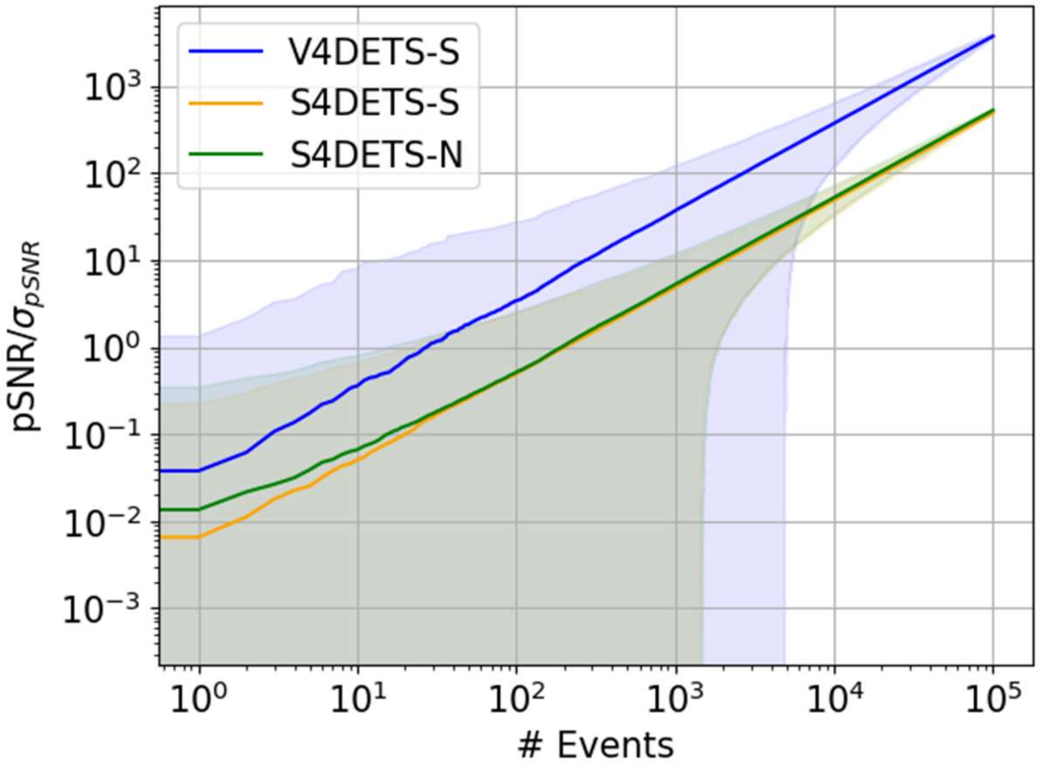


HLVKI

Results in a nutshell



ETCE



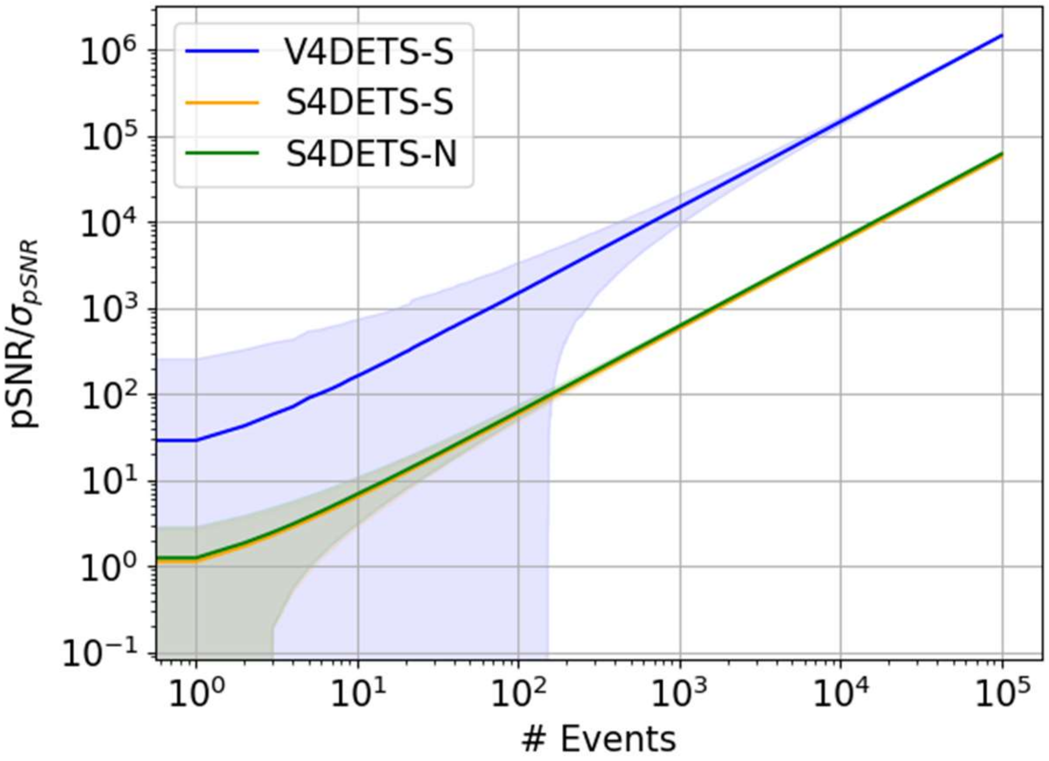
HLVKI

Results in a nutshell

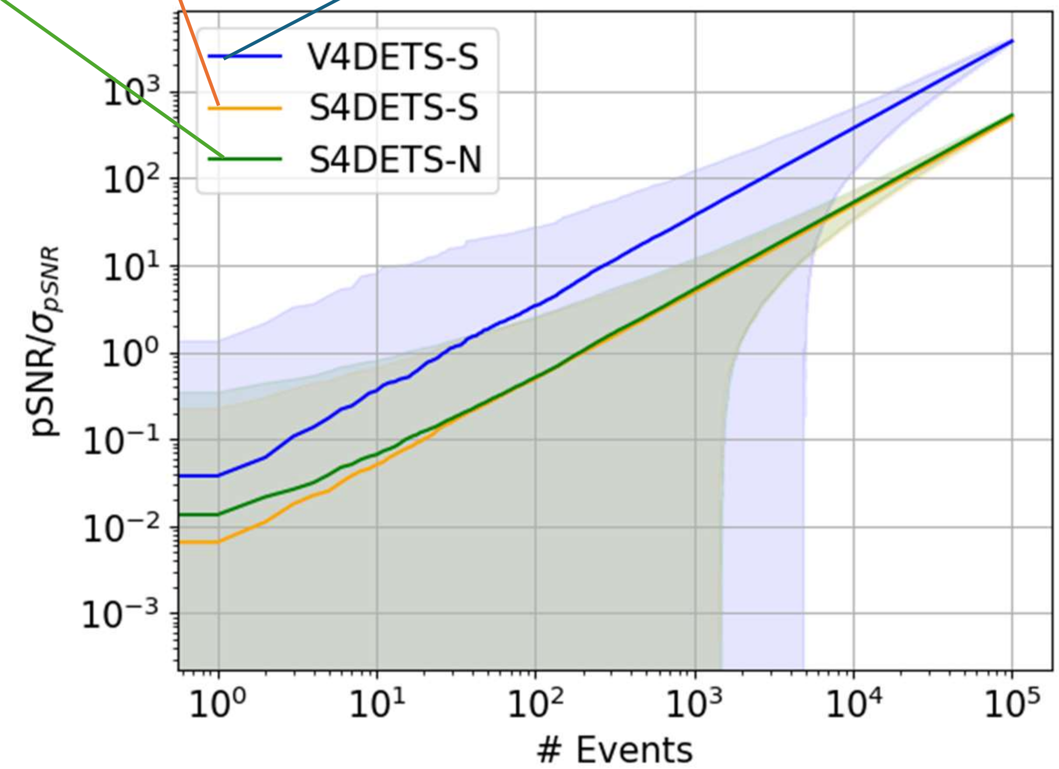
$\varepsilon_{ijkl}\, F_i^+ F_j^\times F_k^B S_l$, tensor + breathing mode

$\varepsilon_{ijkl}\, F_i^+ F_j^\times F_k^V S_l$, tensor + breathing mode

$\varepsilon_{ijkl}\, F_i^+ F_j^\times F_k^B S_l$, tensor modes only



ETCE

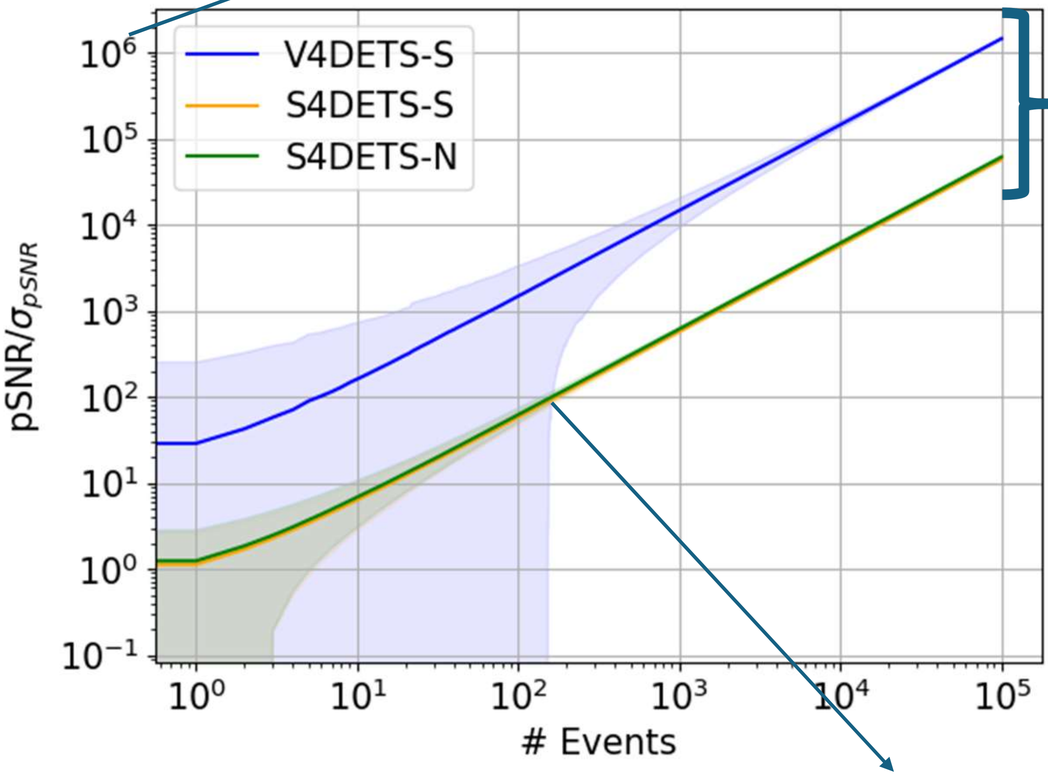


HLVKI

Results in a nutshell

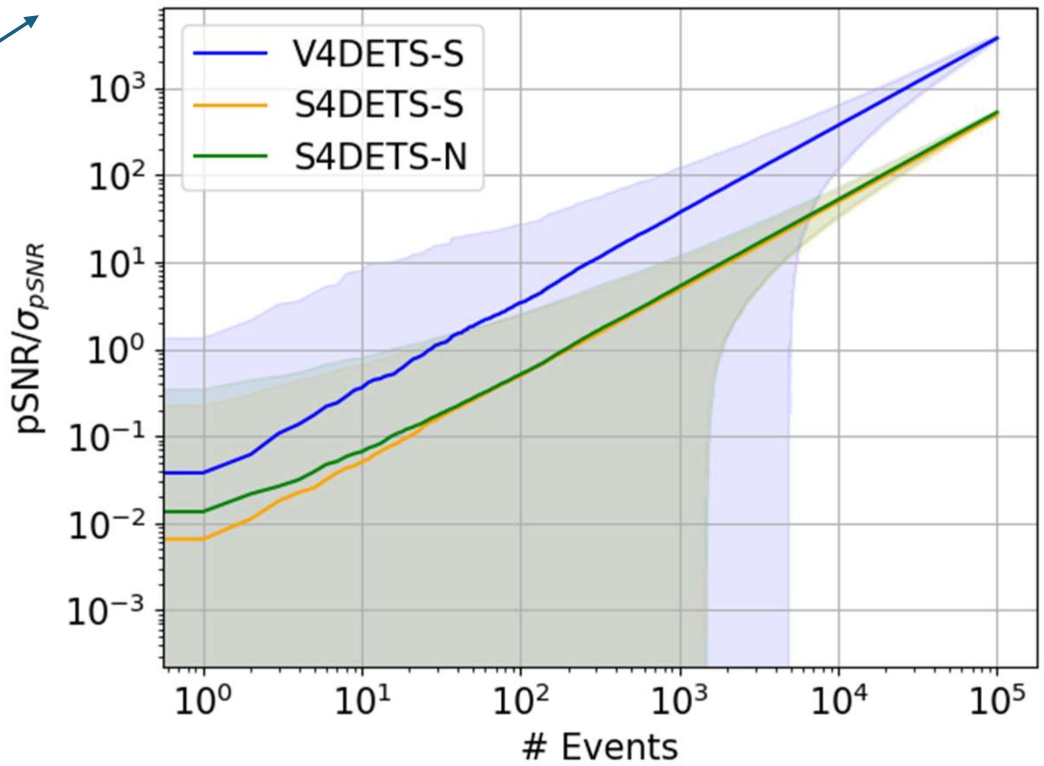
Higher SNRs

Better distinction



ETCE

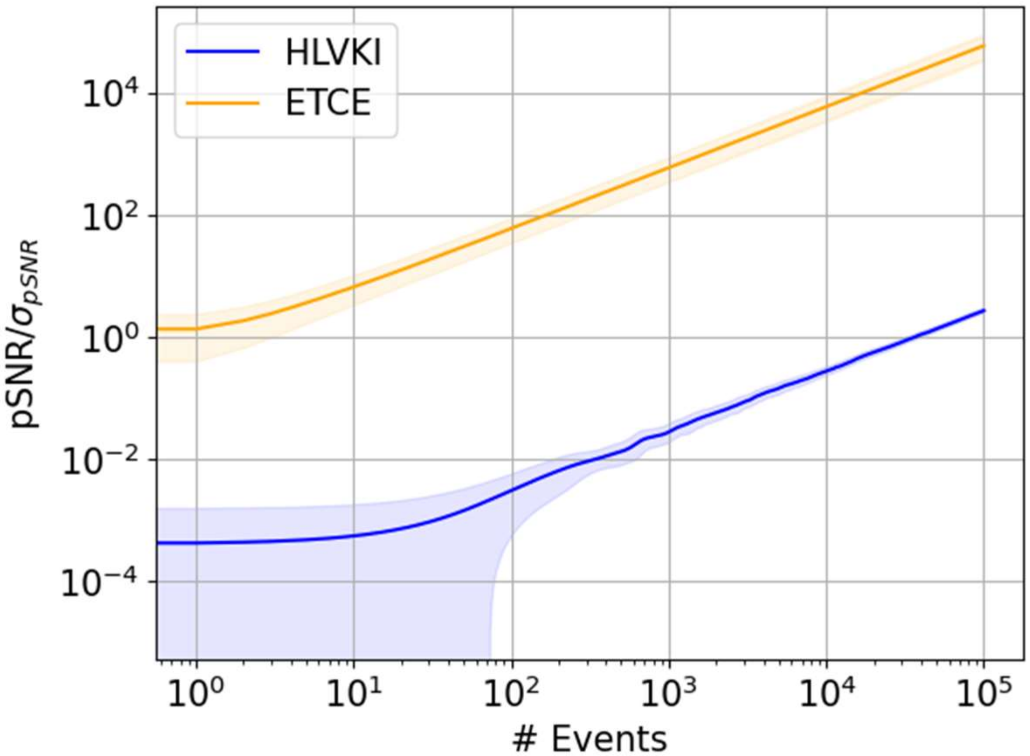
Probability of fake claim $< 1\%$
after $\sim$200 events



HLVKI

Importance of 4-dets NSs

When observing GW, one can use all of the 4-dets NSs and see which one is minimized. Performing the ratio between one of the other NSs and the «silenced» one, one gets a more powerful test of gravity: silent NS is a proxy for tensor signals



For instance:
Scalar mode in signal.

→ $\varepsilon_{ijkl}\, F_i^+ F_j^\times F_k^B S_l$ **is null**

→ **Proxy for tensor signal**

→ $\varepsilon_{ijkl}\, F_i^+ F_j^\times F_k^V S_l$ **is not null**

→ Cumulative sum of their significances' ratio

4-dets NSs allow for a great enhancement in the precision of the test by ETCE: $\mathcal{A}_{pol}{}^{ETCE} < 10^{-2}\mathcal{A}_{pol}{}^{HLVKI}$

Conclusion

- ETCE would provide a significant claim in shorter time
- The precision of the test is slightly enhanced
  - Effect of the SNR>12 cut→when dropping the threshold to 8 one recovers a larger difference in the precision of the test
- The localization as achieved with CE and ET for loud and short events is only slightly better than that achieved by HLVKI for similarly high network SNRs
- →short events: localization error depends linearly on the inverse global SNR of the event.
- 4-dets null streams provide a stronger test for testing GR, but only when one non-tensor mode only is present

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