Advanced Virgo in the LIGO-Virgo network

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Abstract

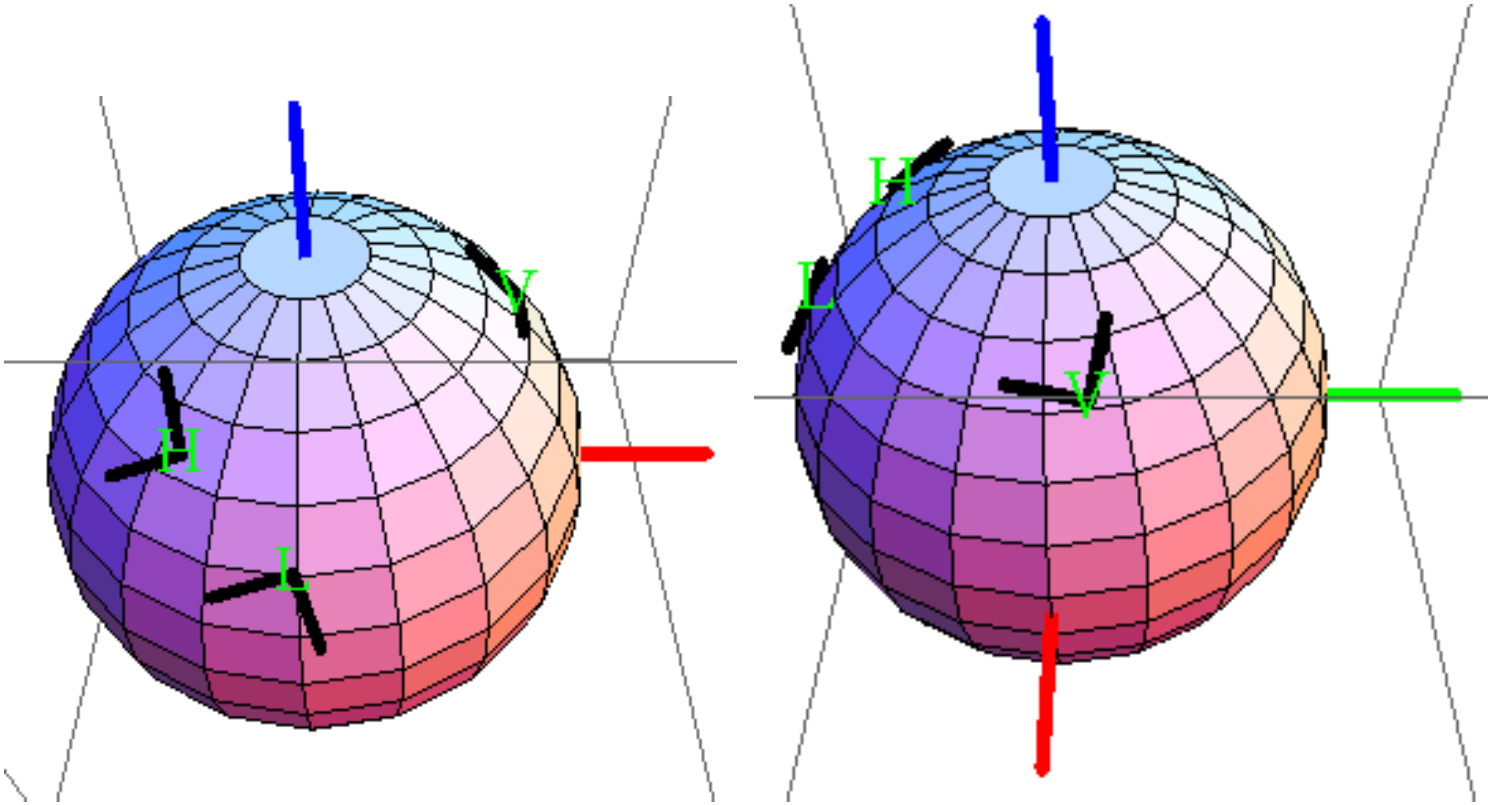
We consider just one case (the detection of Binary Neutron Stars, BNS) to assess how much does Virgo contribute to the network in terms of increase in the detection probability.

Introduction

- The ERC asked to compare the LIGO and LIGO+Virgo (LVC from now on) networks.
  - In particular, to evaluate the increase in detection probability P_{DET} resulting by the inclusion of Virgo in a network of advanced detectors.
  - The ERC asked to consider not just coherent analysis strategies, but also a standard coincidence-based strategies.

- The present study is focused on a specific case: the detection of signals emitted by Binary Neutron Stars
  - We evaluate the detection efficiency, as a function of the source distance
  - From the volume integral, we deduce the expected increase in event rate.
  - Although just one of the possible signals, it is a case general enough to draw some conclusions that we believe are fairly general.

The network considered

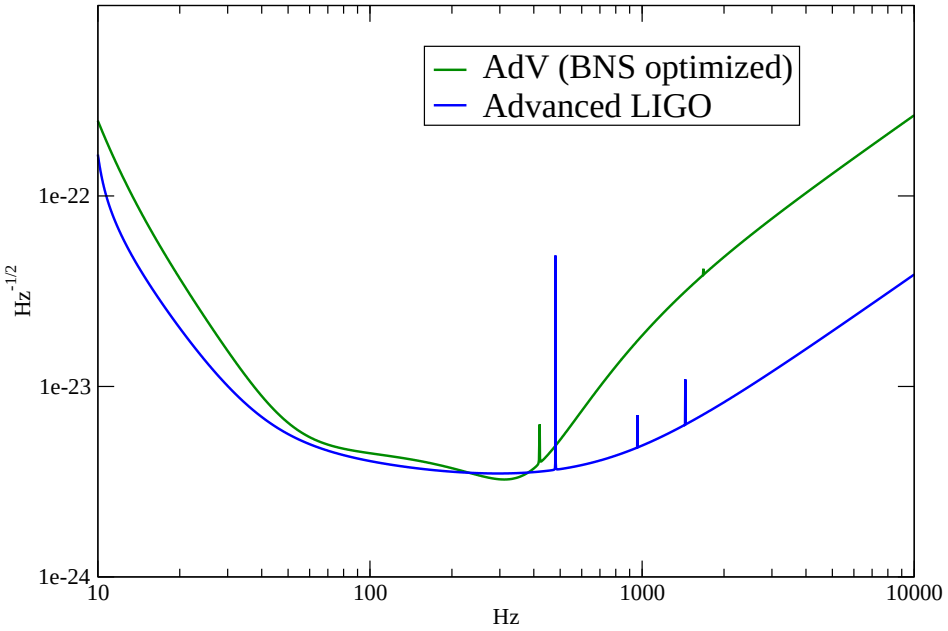


Left: network from above US **Right:** from above EU

Black lines represent the ITF axes.

Colored lines represent the Earth frame: **Z** crosses the North pole, **X** crosses the Greenwich meridian.

Sensitivities of the detectors



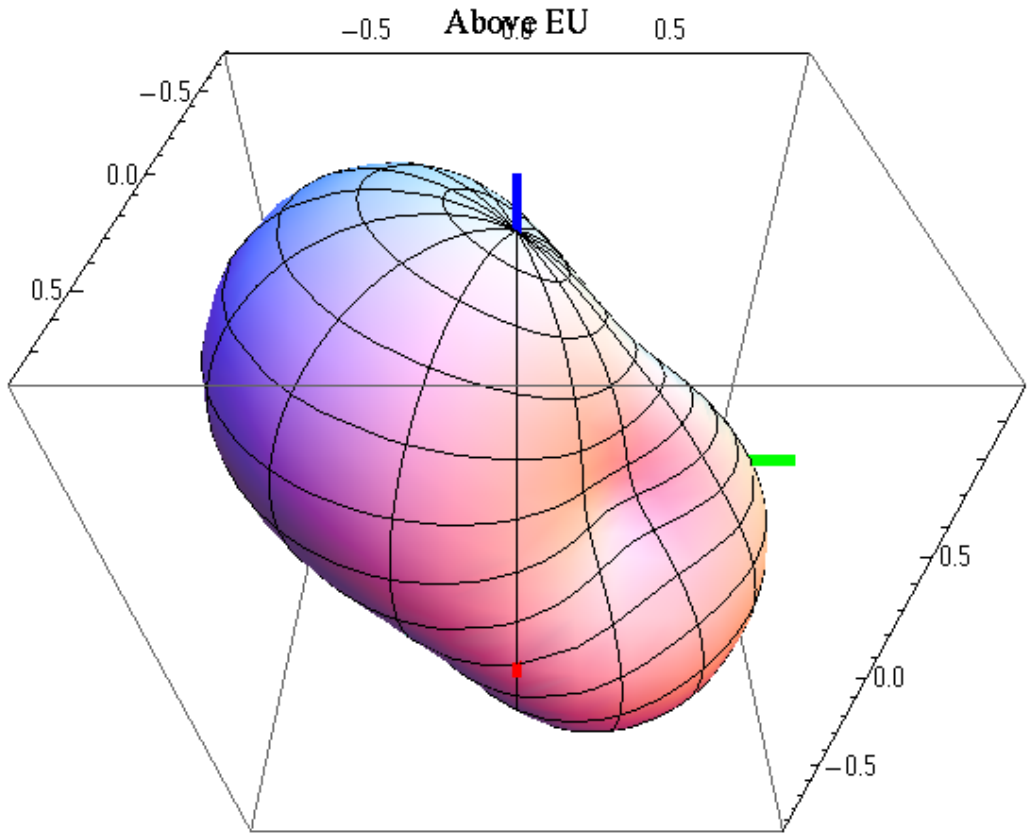
In Virgo, an optimally oriented BNS yields SNR=8 at a distance of 375 Mpc.

In LIGO, the same source yields SNR=8 at 445 Mpc.

These figures, together with the polarization character of the signals, are sufficient to set the scales in this study.

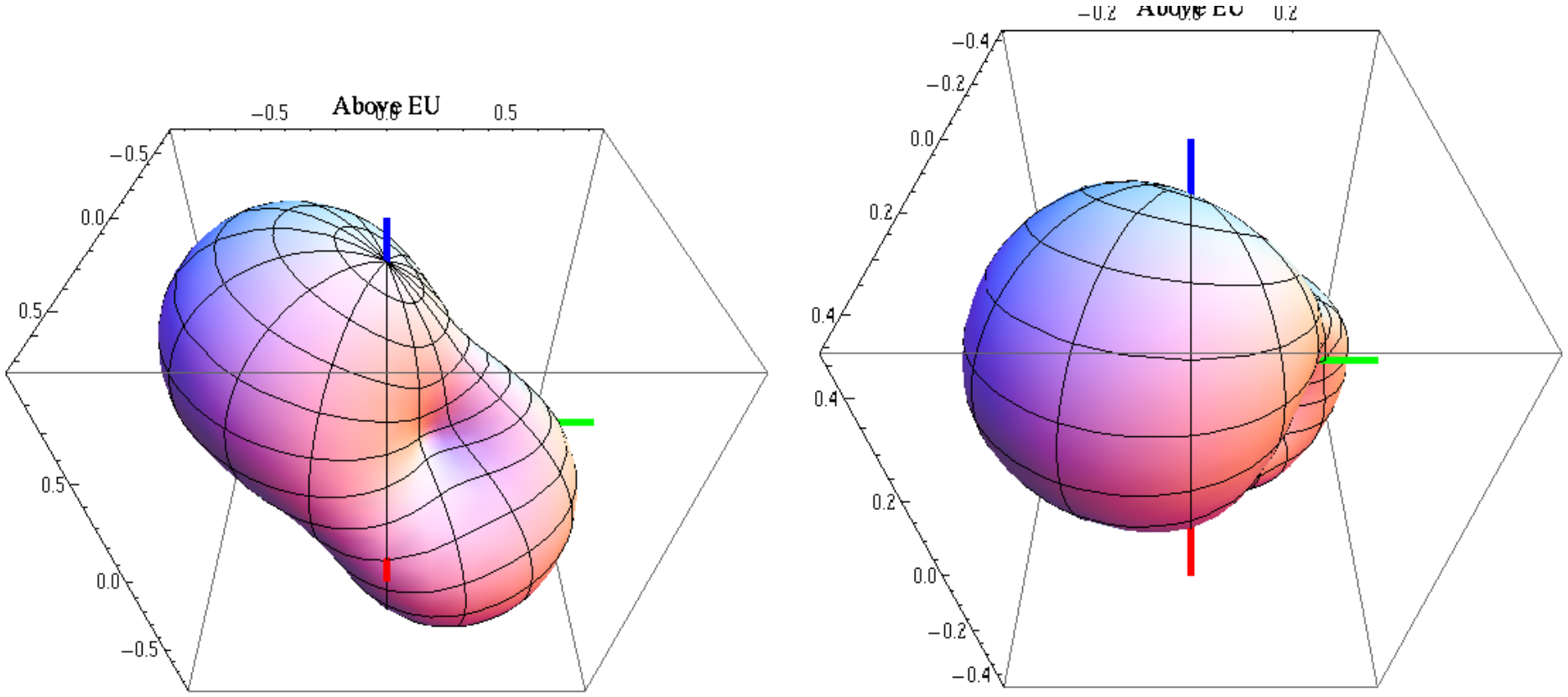
The response of the LVC network

✔ Depends on the source direction ϑ, φ, the binary inclination ε and the wave polarization ψ.



✔ Averaging over ε and ψ one can plot the SNR available to the network as a whole, as a function of the source direction.

Individual contributions to the network SNR



Left: LIGO network; **right;** Virgo

✔ The different antenna pattern is a benefit for sky coverage in coherent analysis, but a potential issue in coincidence analysis

Rules for the comparison

- ✔ For each kind of network or analysis, set the same overall false alarm rate: 1 event/year
  - ✔ Larger FA are certainly ammissible when considering the operation of the network in coincidence with other kind of observatories.
- ✔ Deduce false alarm rates R_{FA} on the individual detectors, depending on the kind of analysis done
- ✔ Generate events with random direction ϑ, φ and source parameters ε, ψ, at a given distance.
- ✔ Compute the SNR seen by each detector, hence local detection probabilities P_{DET} for each sampled direction/polarization.
- ✔ Do the combinatorics to implement a triple coincidence strategy; obtain the network P_{DET}
- ✔ Compare different networks, as a function of the source distance.

Statistics

It is worth recalling that the SNR^2 seen by the individual detectors and by the network obey to different statistics

✔ On a single detector the SNR^2 is a χ^2 with 2 DOF, hence if ξ is a threshold

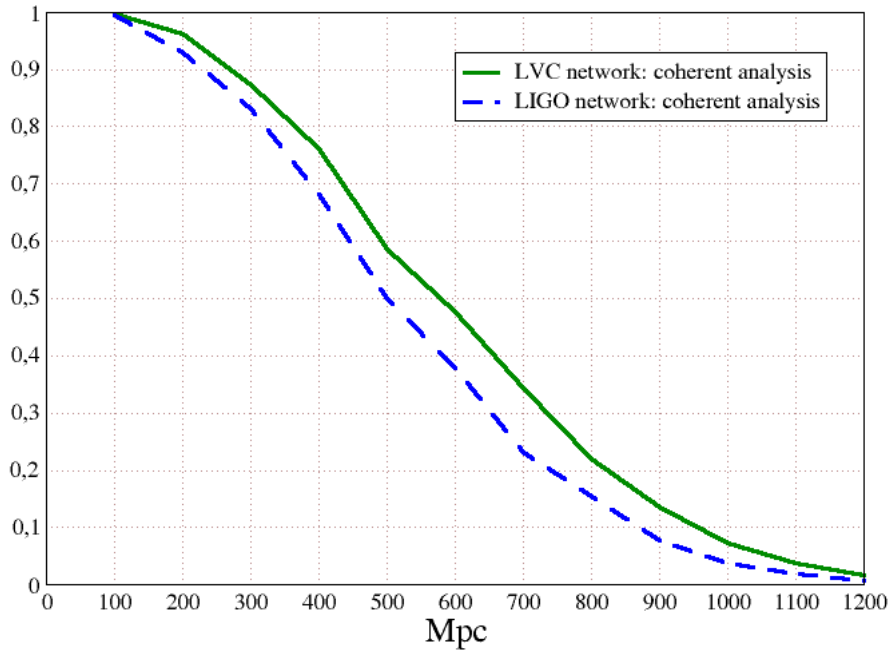
$$P_{FA}\left(\xi\right) = e^{-\xi}; \quad P_{DET}\left(\xi,\, E_{sig}\right) = \int_{\xi}^{\infty} e^{-E-E_{sig}} I_0\left(2\sqrt{E * E_{sig}}\right) dE$$

✔ On the network, the corresponding quantity is a χ^2 with 4 DOF, hence

$$P_{FA}\left(\xi\right) = \left(1+\xi\right) e^{-\xi}; \quad P_{DET}\left(\xi,\, E_{sig}\right) = \int_{\xi}^{\infty} \sqrt{\frac{E}{E_{sig}}} e^{-E-E_{sig}} I_1\left(2\sqrt{E * E_{sig}}\right) dE$$

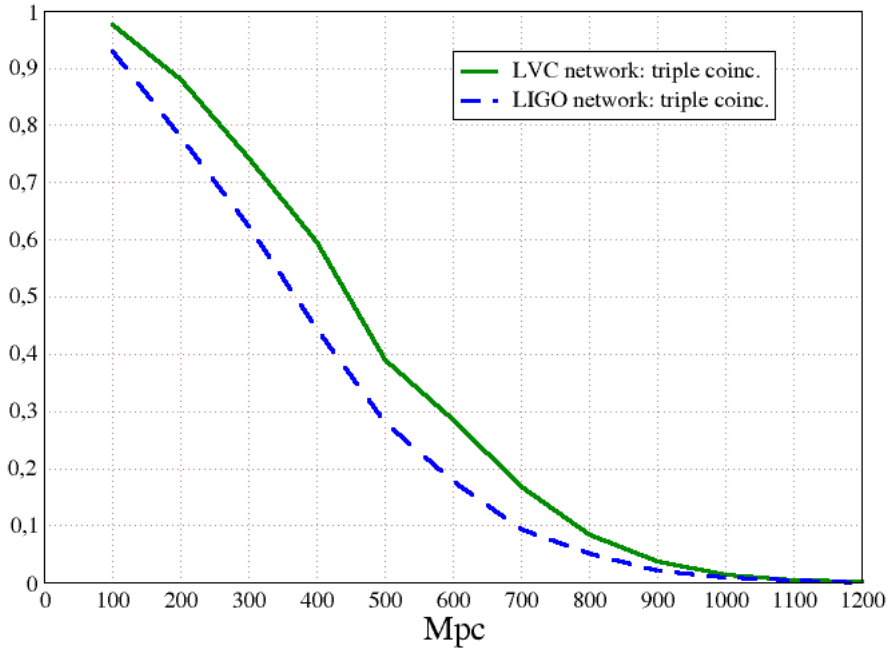
Just to remind that the interpretation of the SNR clearly depends on the kind of statistic, and we have to refer to P_{DET}, P_{FA} for a meaningful comparison.

Coherent analysis



- ✔ We plot detection efficiency P_{DET} averaged over source location, inclination and polarization
  - ✔ Somewhat limited statistics -> lines not smooth
- ✔ LVC has P_{DET} =90% at 270Mpc; LIGO at 230Mpc. Yield roughly a 35% event rate increase when *integrating* over volume.

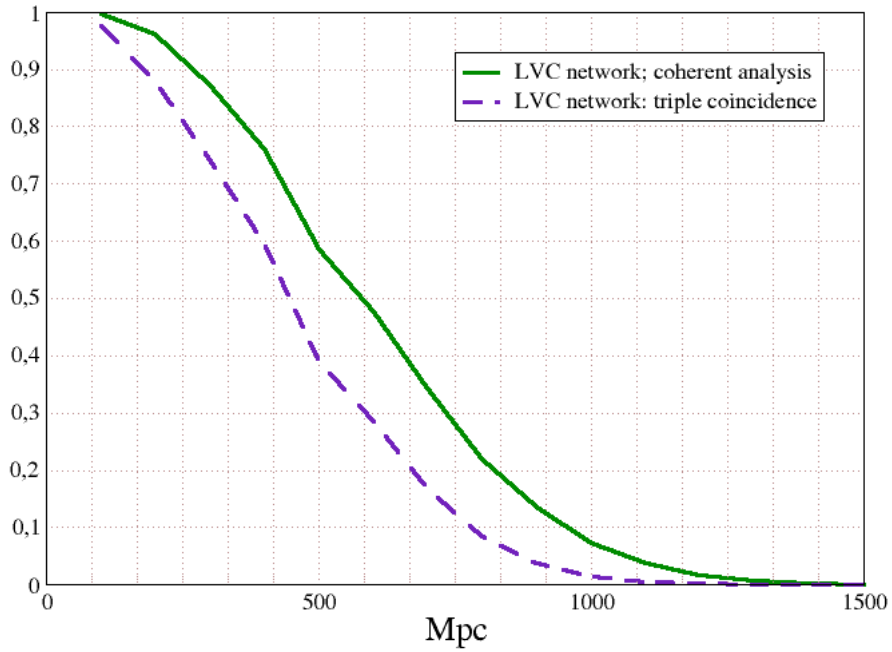
Coincidence analysis (triples)



✔ The detection efficiency, as expected, is inferior to the coherent case.

✔ Still Virgo brings a significant advantage: 90% efficiency moves from ~120Mpc to ~170Mpc. When integrating over volume, this leads to about a 40% increase of the overall detection efficiency.

Coincidence vs coherent analysis



- ✔ This plot shows that a coherent analysis is significantly better than coincidence analysis.
  - ✔ When integrated over volume, P_{DET} is increased by 90%, in the LVC network.
- ✔ However this result depends upon the noise being gaussian. In presence of non-gaussian tails, a coherent analysis has to be complemented by vetoes, not included in this Monte Carlo.

Conclusions

The main limitation of the study is the gaussian noise; furthermore, only BNS signals have been considered.

Anyway, it is possible to conclude that:

- ✔ **the LVC network can deliver about 40% more events than LIGO alone;**
  - ✔ this result is **robust**, that is does not depend on the analysis method used, whether coherent or triple coincidence.

- ✔ In gaussian noise the coherent method can deliver as much as 90% more events than the triple coincidence analysis;
  - ✔ this result can probably be fully achieved, though, only if vetoes on individual detectors succeed in rejecting non-gaussian tails, or by exploiting other techniques, like the null-stream one.

It is possible to quickly extend this study to other binary coalescences, including BBH; there may be quantitative difference, but we do not anticipate them to be large.