



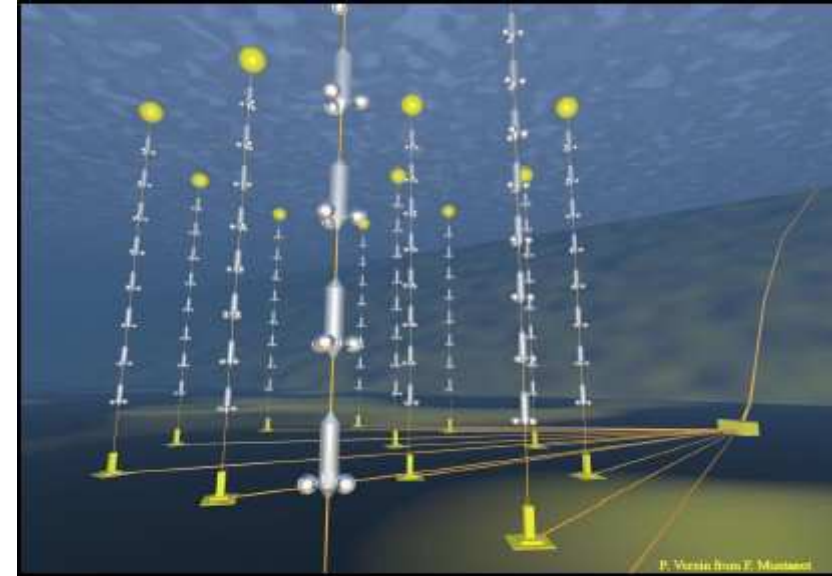
Multi-messenger astronomy: first joint analysis between gravitational waves and high energy neutrinos (*arXiv:1205.3018*)

- Scientific purpose of the analysis project
- Overview of the analysis
- Open box results
- Summary

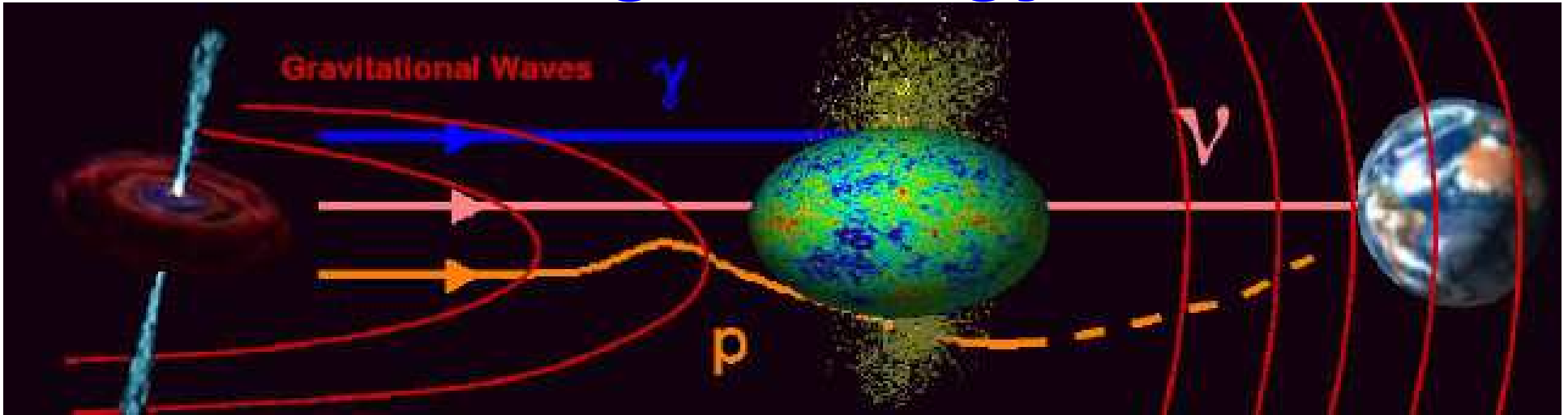
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**on behalf of the ANTARES Collaboration, the LIGO Scientific
Collaboration and the Virgo Collaboration**

Max Planck Institute, AEI, Hannover



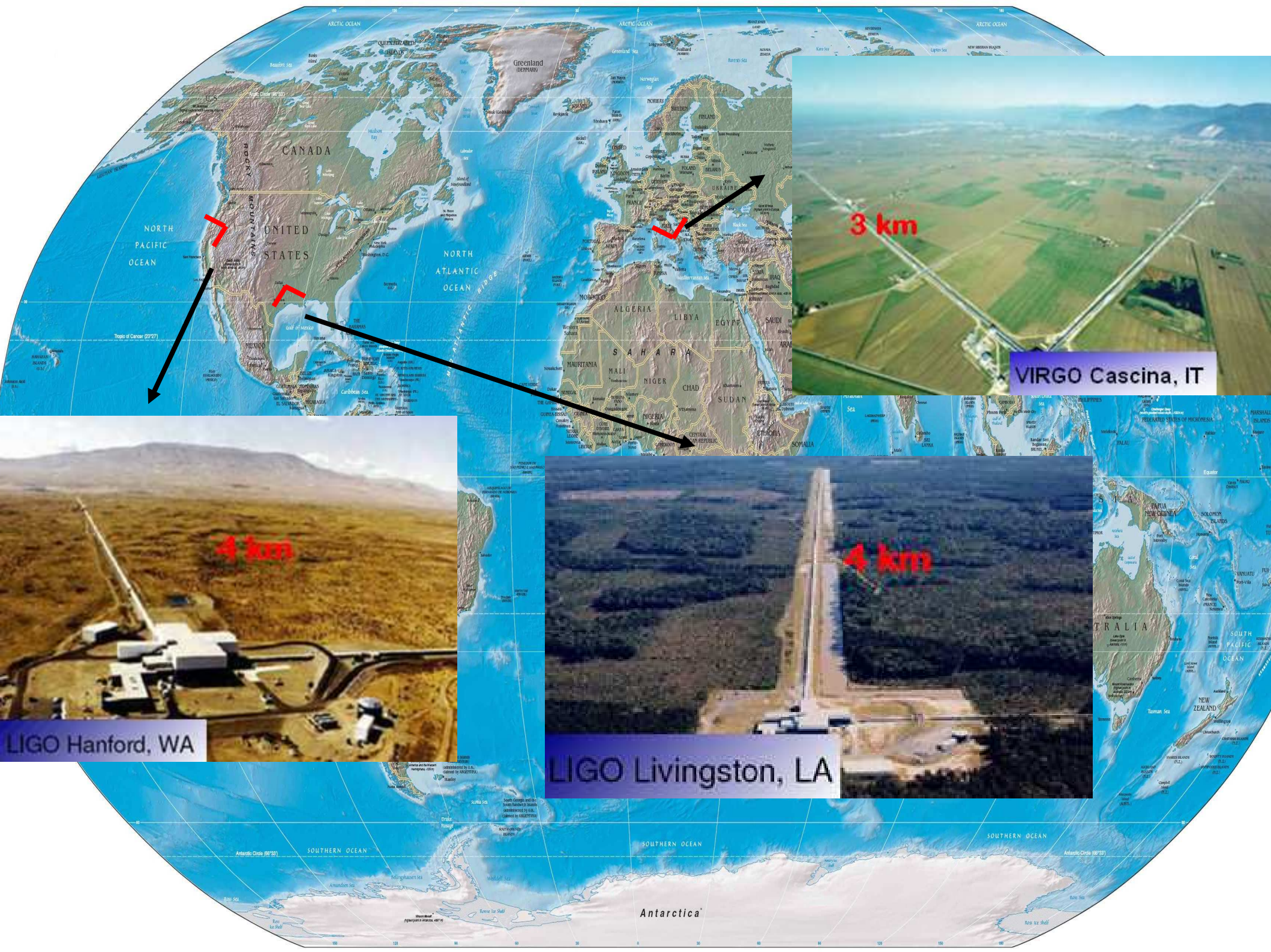
Joint analysis between Gravitational Waves and High Energy Neutrinos



- Gravitational Waves and High Energy Neutrino can escape very dense media and travel unaffected over cosmological distances, carrying information from the innermost regions of the astrophysical engines. Such messengers could also reveal new, hidden sources that are not observed by conventional photon astronomy
- The basic idea is that the accidental occurrence of the coincidence (in time and sky location) of GW and HEN triggers is very unlikely. If such coincidence is observed, this would provide strong evidence that GWs and HENs have been observed and that they originate from a common astrophysical source.

Introduction

- Potential astrophysical sources of GW+HEN:
 - Galactic sources: Soft Gamma Repeaters (*Duncan & Thompson 1992; Aso et al. 2008, etc.*)
 - Extragalactic sources: Gamma Ray Burst (short and long) (*Narayan & Piran 1992; Eichler et al. 1989; Galama et al. 1998; Fryer et al. 2002; Bahcall & Waxman 1997; Kobayashi & Meszaros 2003, etc.*)
 - Choked GRBs (*Meszaros & Waxman 2001; Bromberg et al. 2012*)
 - Exotic class: Cosmic Strings (*Damour & Vilenkin 2000; Mosquera Cuesta & Gonzalez 2001; Siemens et al. 2006; Berezhinsky et al. 2011*)
 -



3 km

VIRGO Cascina, IT

4 km

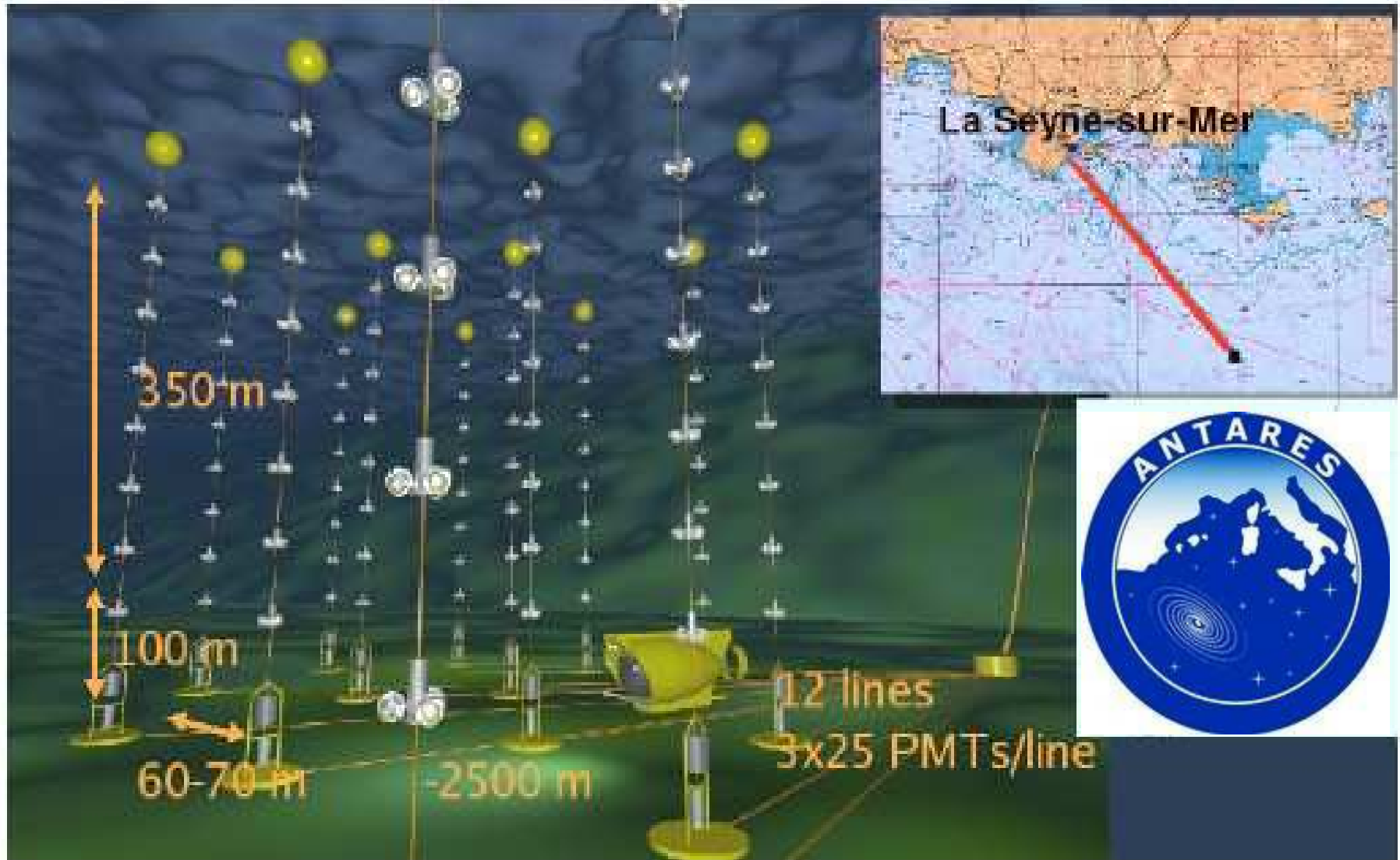
LIGO Hanford, WA

4 km

LIGO Livingston, LA

HEN detector

ANTARES Neutrino Telescope



HEN selection strategy

The ANTARES trigger generation system is composed of multiple steps:

(L0) energy threshold of 0.5 pe for each photomultiplier

(L1) coincident hits in the same storey within 20ns

(L2) relations in time and space between 5 L1 hits in 2.2 μ s.

Different samples of Monte Carlo neutrinos and atmospheric muons are generated to make a comparison with data.

The reconstruction takes a set of PMT hits and estimates the best set of track parameters.

ANTARES produced a list of HEN triggers, we do a triggered GW search around each HEN trigger, and this is just like how we do the GRB search.

Gravitational Wave Bursts

GW bursts are defined loosely as any transient signal for which we do not rely on a specific theoretical model for the GW waveform. Search for GW bursts typically focusses on detecting generic waveform with duration range 1-100 ms.

- **“Untriggered”** searches scan all available data, they look for simultaneous jumps of energy in all detectors in some time-frequency region, with consistent measurement of amplitude or correlation between the detectors.
- **“Triggered”** searches scan a small amount of data around the time of an astronomical event (GRB, neutrinos). These searches exploit knowledge of the time and direction to the astronomical event to improve the sensitivity of the search.

GW search method

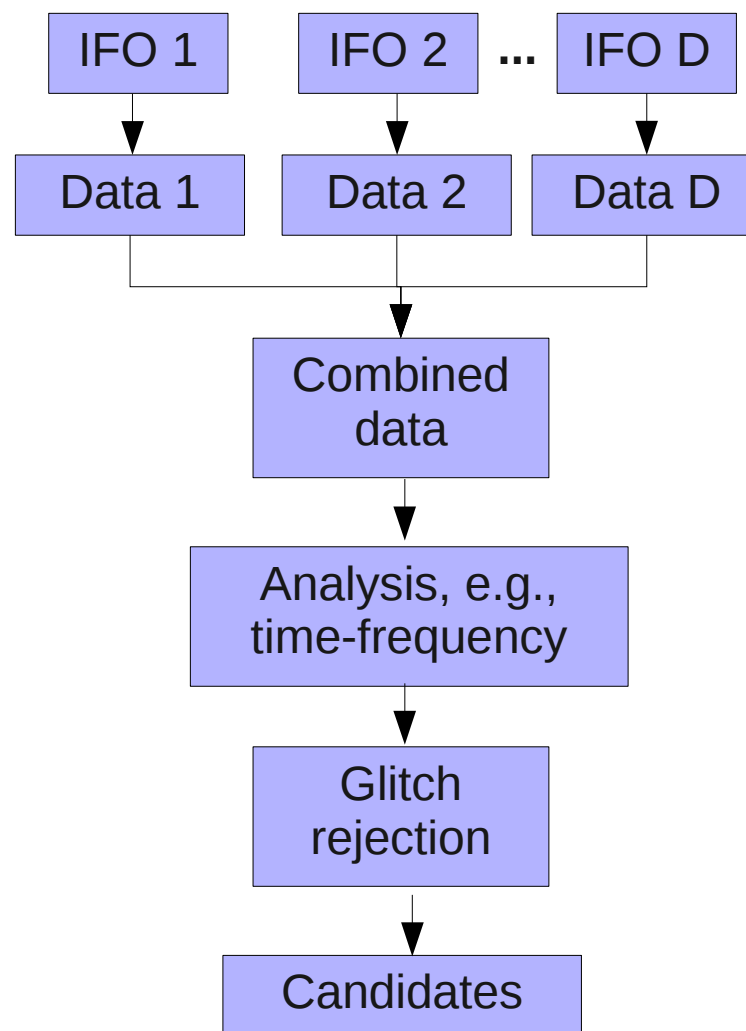
X Pipeline is a matlab-based software package for performing coherent searches for gravitational-wave bursts in data multiple detectors, weighted by relative sensitivity to the sky location of the neutrino.

Coherent analysis combines data **before** generating triggers meaning more info can be extracted. Automatically takes into account varying ifo sensitivity and measures similarity in data.

Blind non-biased analysis:

Closed-box analysis: Tune our search parameters on off-source.

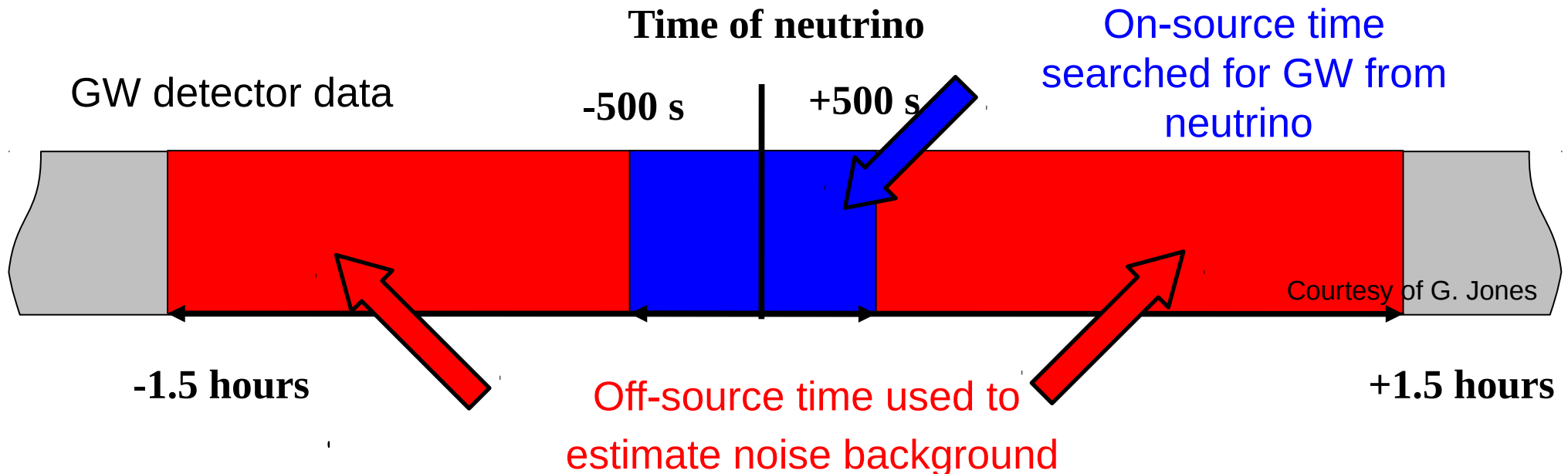
Open-box analysis: Search for GW in on-source with optimal parameters.



*References: astro-ph.0908.3824v1
<https://trac.ligo.caltech.edu/xpipeline/>*

X-Pipeline search

- The data is divided into two sets:
 - **On-source**: $[-500, +500]$ s around each neutrino trigger ([arXiv:1101.4669](https://arxiv.org/abs/1101.4669)).
 - **Off-source**: all other data within ± 1.5 hr of the neutrino, divided into blocks of the same length as the on-source period + time slides.
- The on-source data is searched for large excess energy events.
 - The **significance** of each event is estimated by comparing to typical values in the off-source data.



Data set

ANTARES provided 216 independent neutrino triggers (from Feb. to Sept. 2007):

- 18 events reconstructed with 3 lines and more.
- 198 events reconstructed with two lines, in which case the origin of the neutrino is not uniquely identified and there are 2 possible locations (*LIGO-T1100197-v2*)

reconstructed from 2 Lines

# neutrinos	4 IFOs	3 IFOs	2 IFOs
144	60	59	25

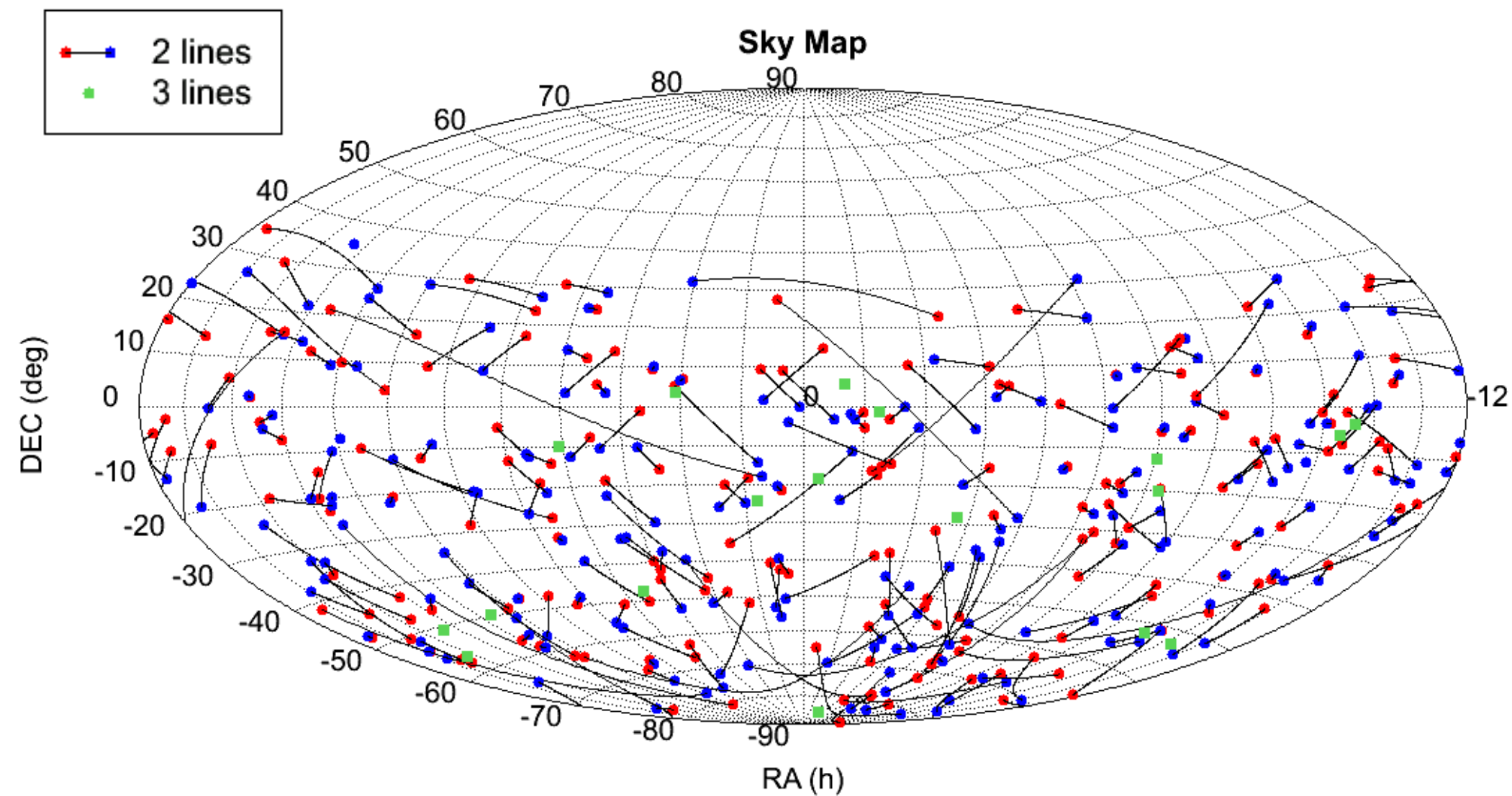
54 triggers cannot be analyzed because there aren't enough IFOs in network.

reconstructed from 3 Lines

# neutrinos	4 IFOs	3 IFOs	2 IFOs
14	3	7	4

4 triggers cannot be analyzed because there aren't enough IFOs in network.

HEN candidates



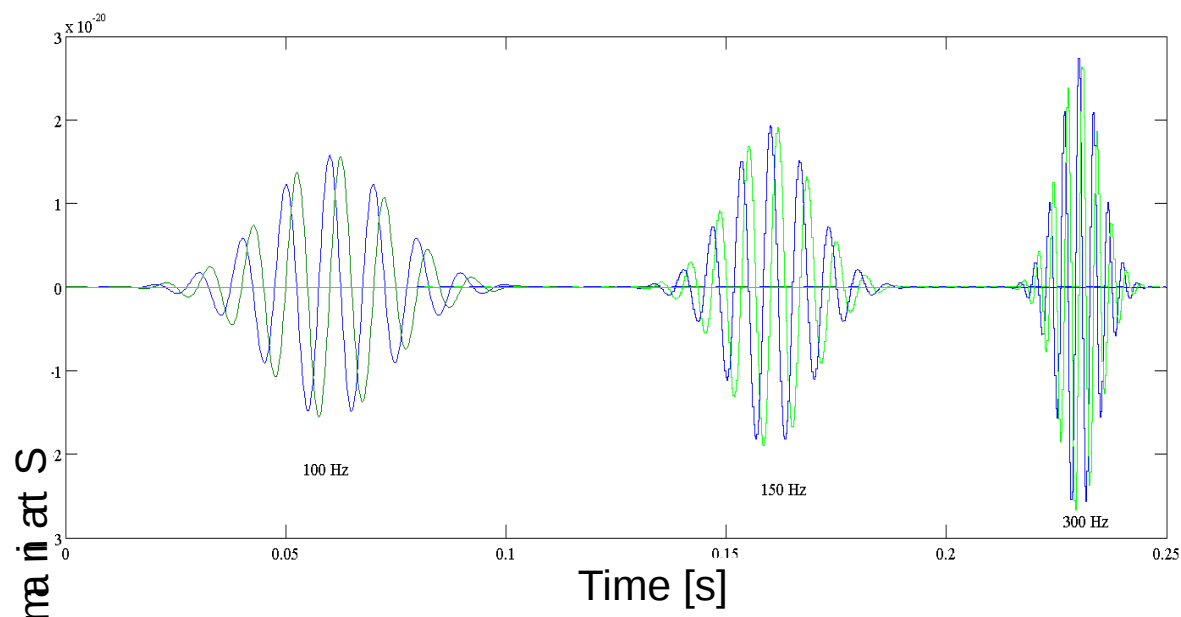
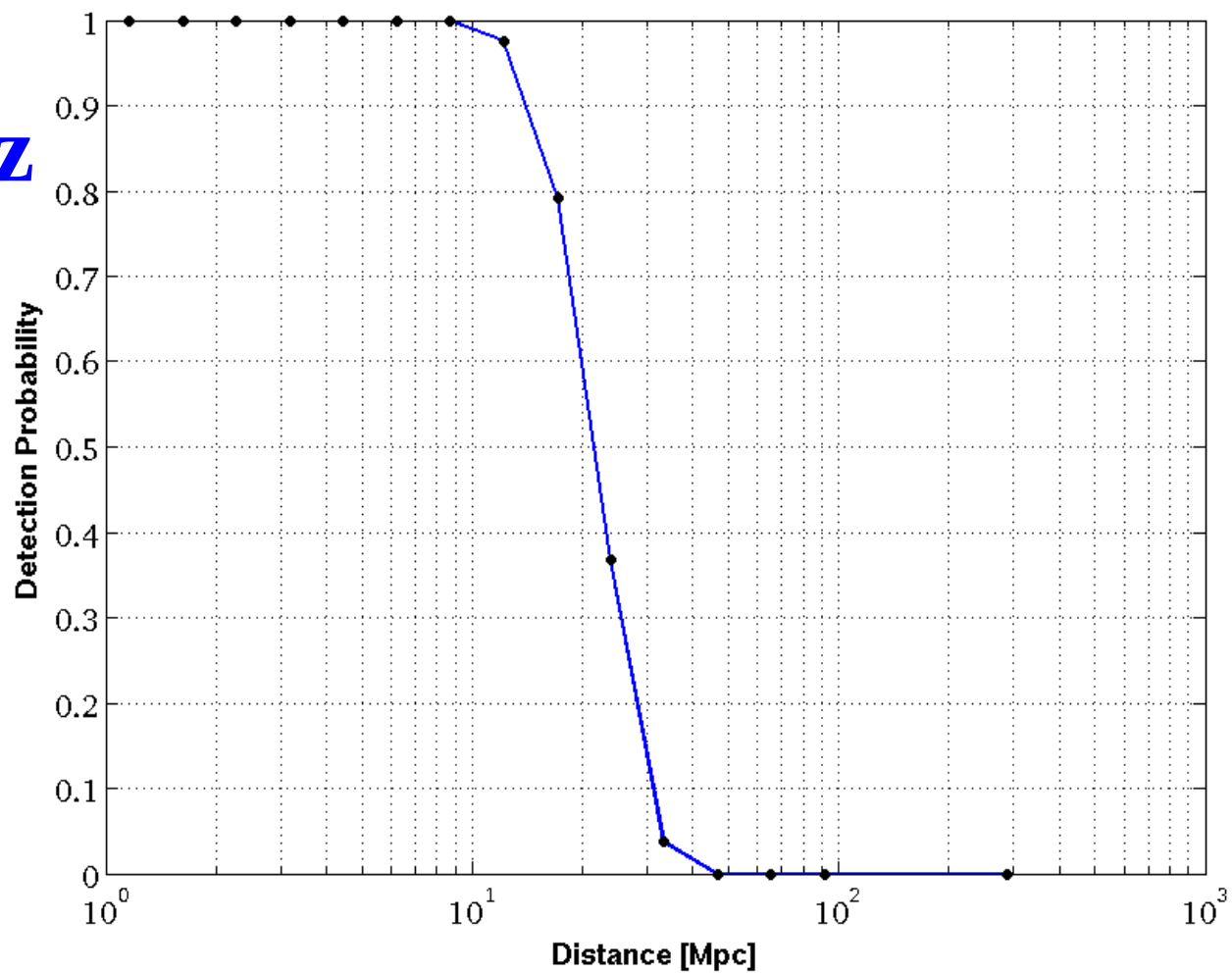
Low and High Frequency Analysis

Low-Frequency analysis, (60-500)Hz, this band is analysed for all HEN triggers – such a search is computationally feasible while covering the highest-sensitivity region of the GW detectors. However, compact objects such as neutron stars or collapsar cores have characteristic frequencies for GW emission above 500 Hz.

High-Frequency analysis: since the computational cost of a high-frequency search for all HEN triggers is prohibitive with the current analysis pipeline, we perform the 500-2000 Hz analysis on the 3-line HEN triggers only. To reduce the computational cost further, we use the same sky grid for the high-frequency search as was used at low frequencies, after determining that the loss of sensitivity is acceptable.

Example of sine-Gaussian 150 Hz injection

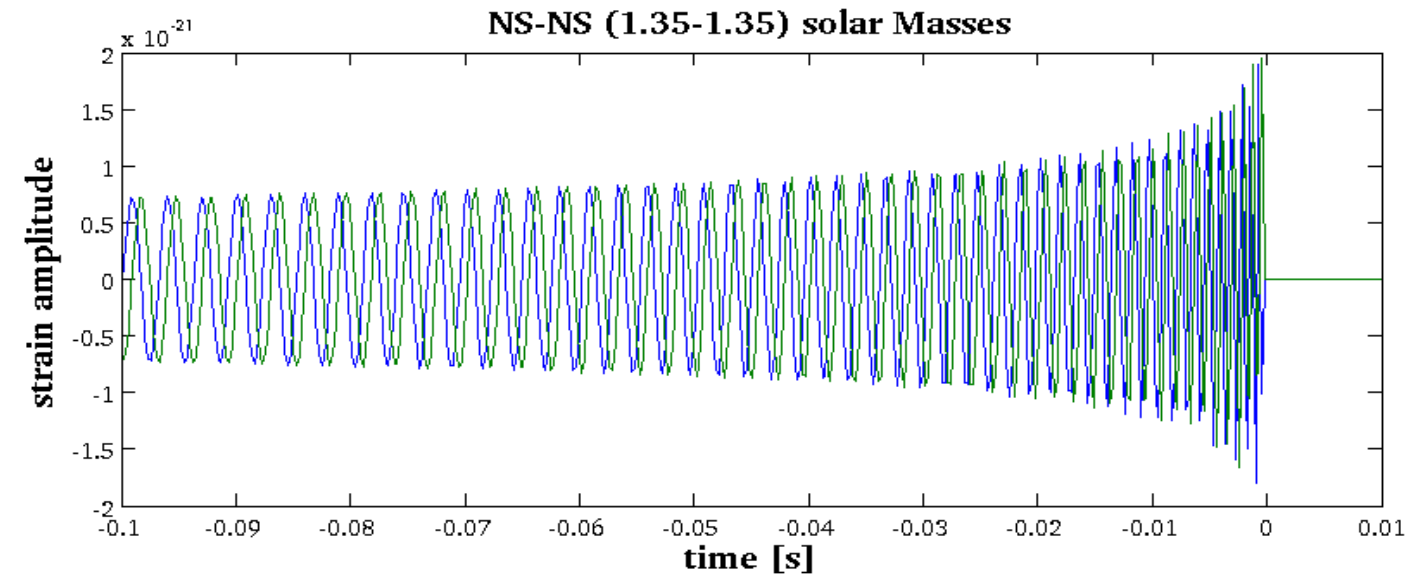
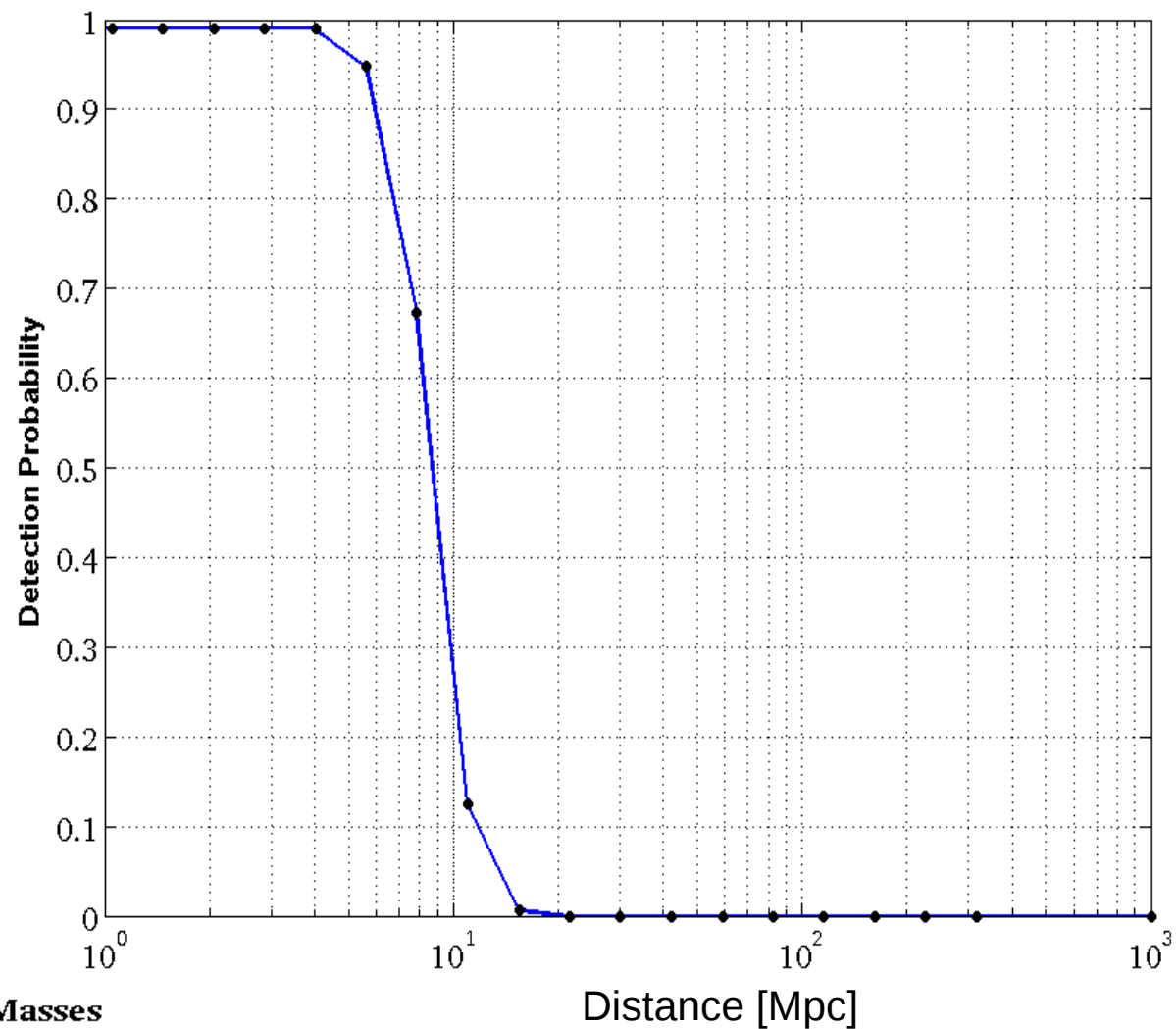
Fraction of simulated Gravitational Waves signals detected at a false-alarm probability of 1%.



To convert injected signal amplitude into distance we assume that an energy $E_{GW} = 10^{-2} M_{\odot} c^2$ is emitted.

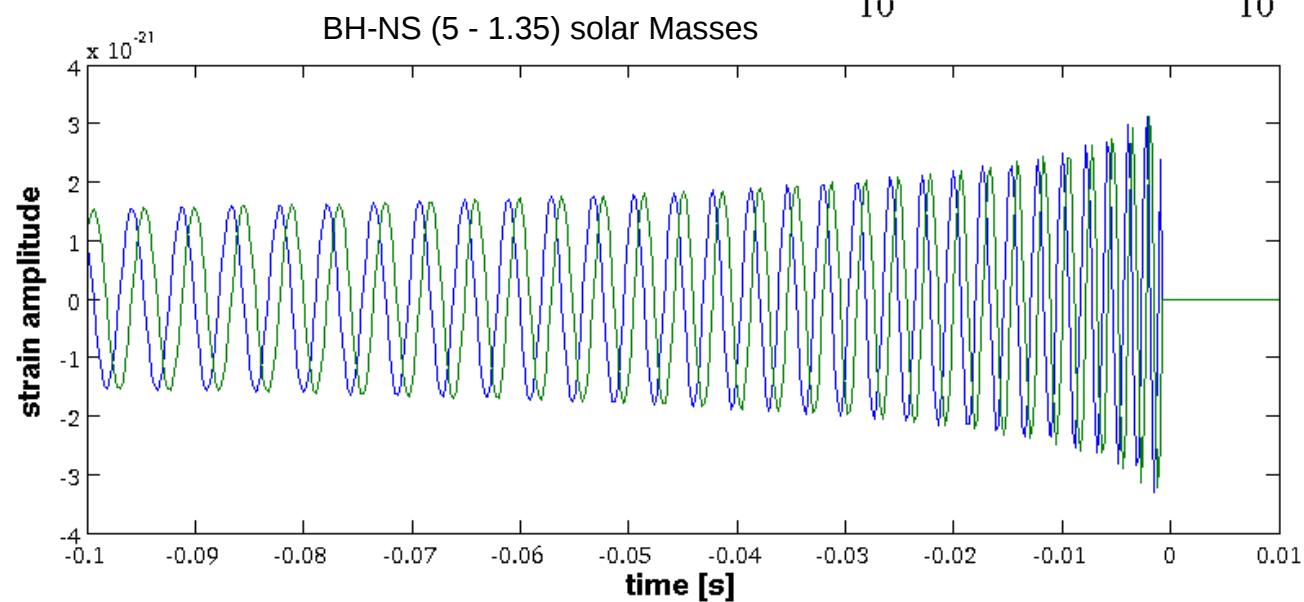
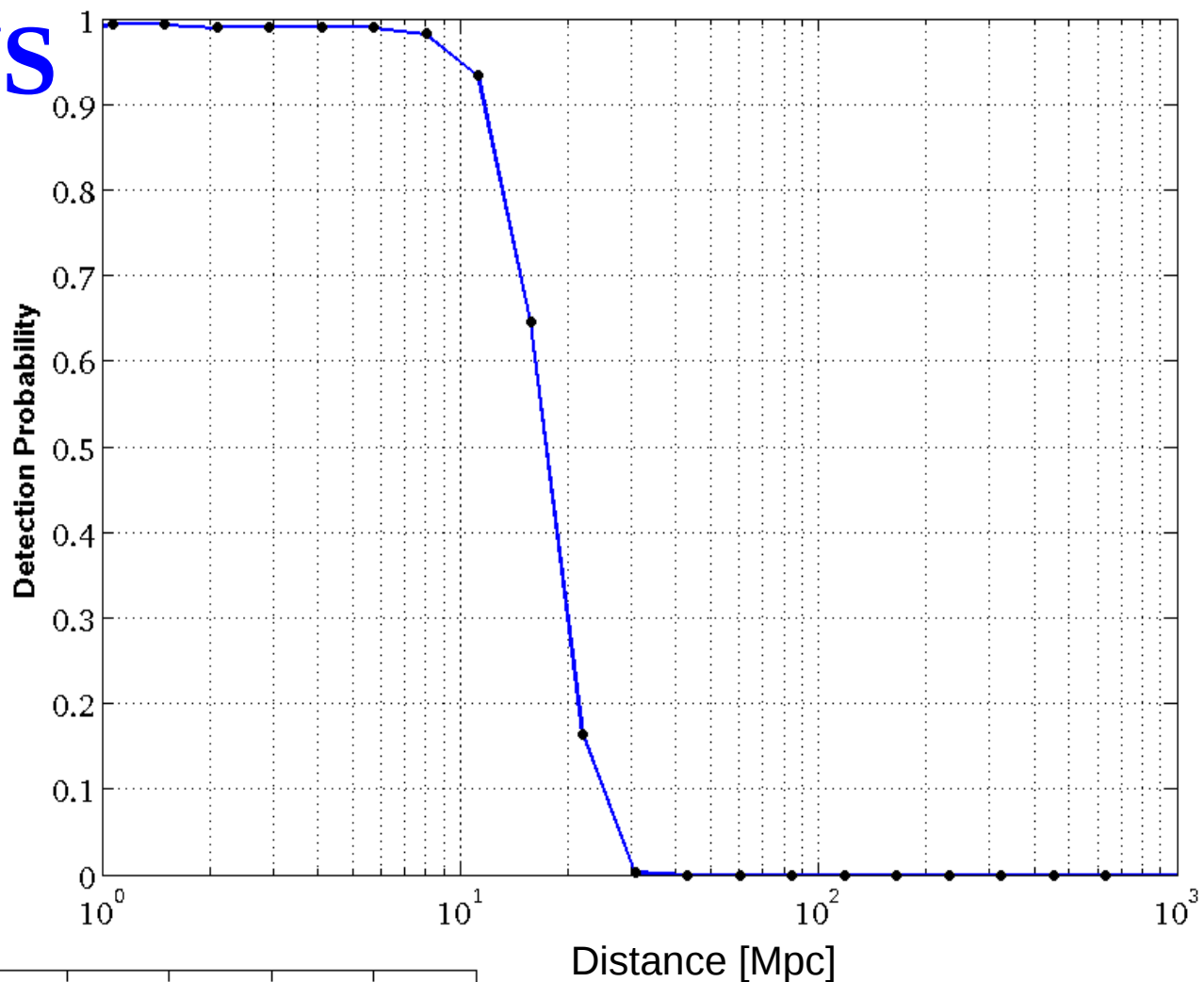
Example of NS-NS Injection

Fraction of simulated Gravitational Waves signals detected at a false-alarm probability of 1%.



Example of BH-NS Injection

Fraction of simulated Gravitational Waves signals detected at a false-alarm probability of 1%.



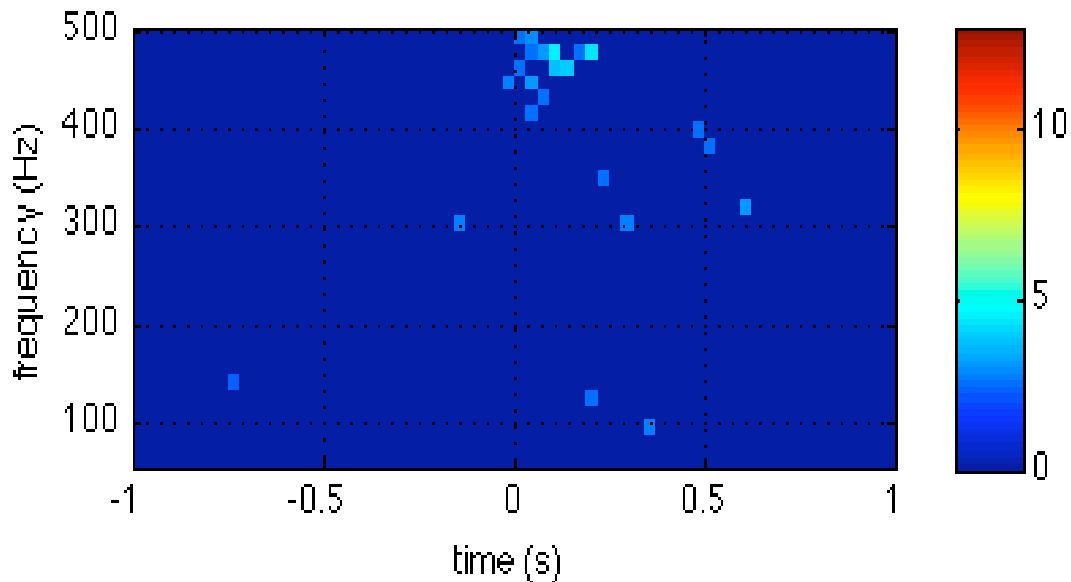
OPEN BOX

results

Most Significant Outlier

Having one event like this, with $FAP=0.004$, given $O(200)$ neutrinos triggers is entirely consistent with background.

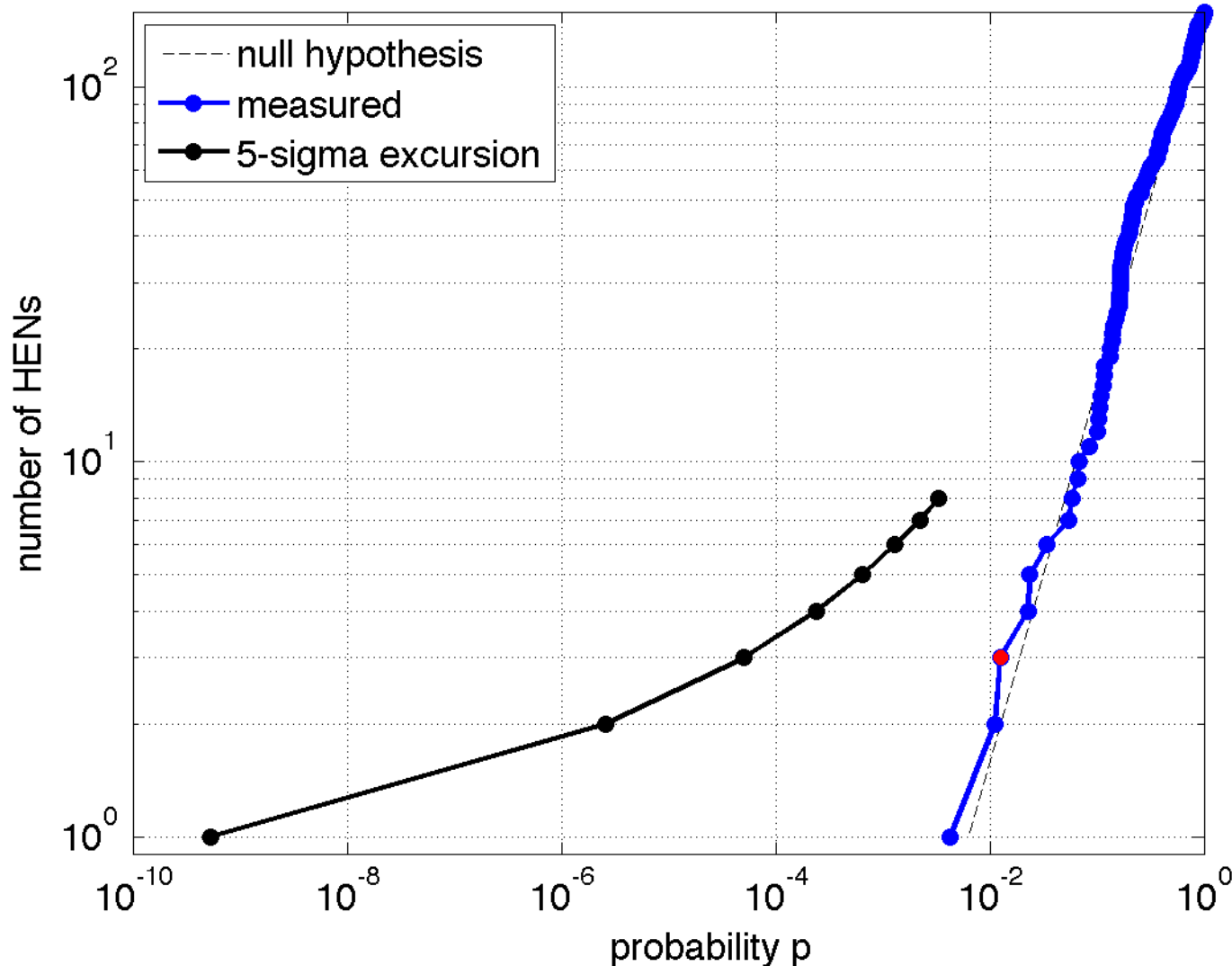
name	Nu385_386
Right ascension	204.404 deg
Declination	-13.027 deg
GPS	873597124.85938
network	H1H2V1
FAP (p-value)	0.004



We have a single outlier that passed a first-stage threshold but has not reached the level of a candidate.

Coincident search results

Low-Frequency analysis: Binomial Test



Test for a cumulative signature associated with our neutrino sample.

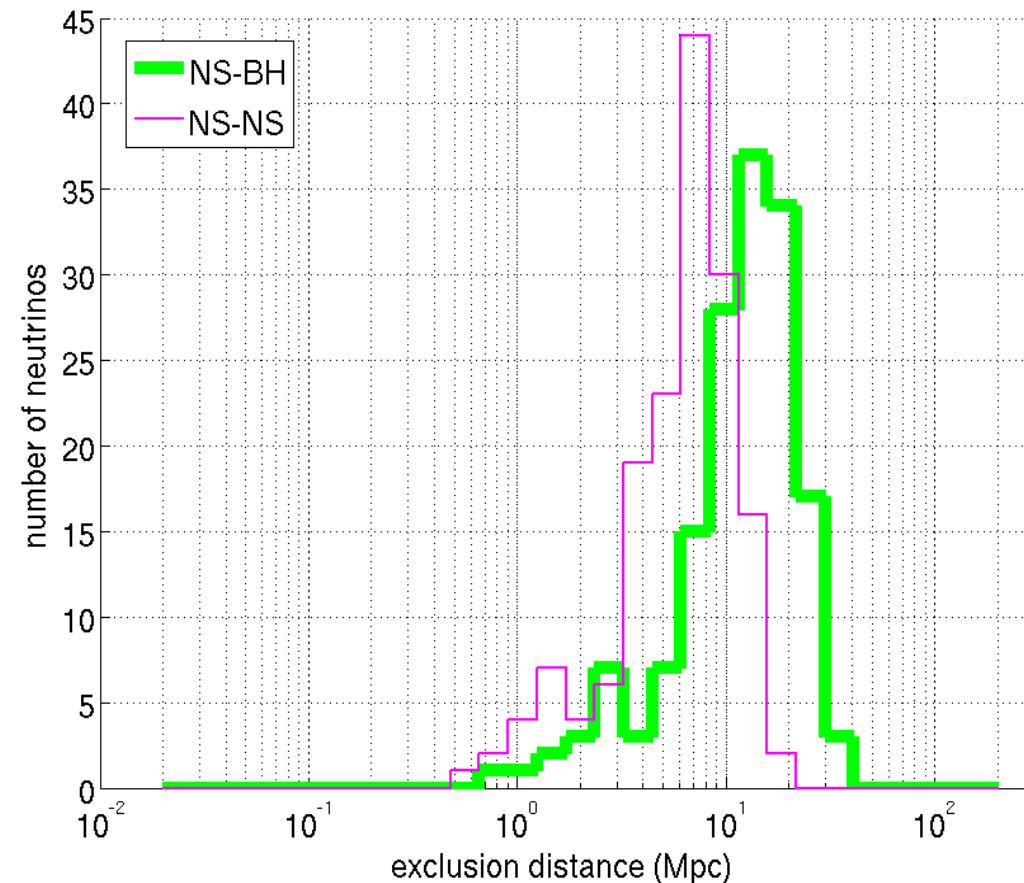
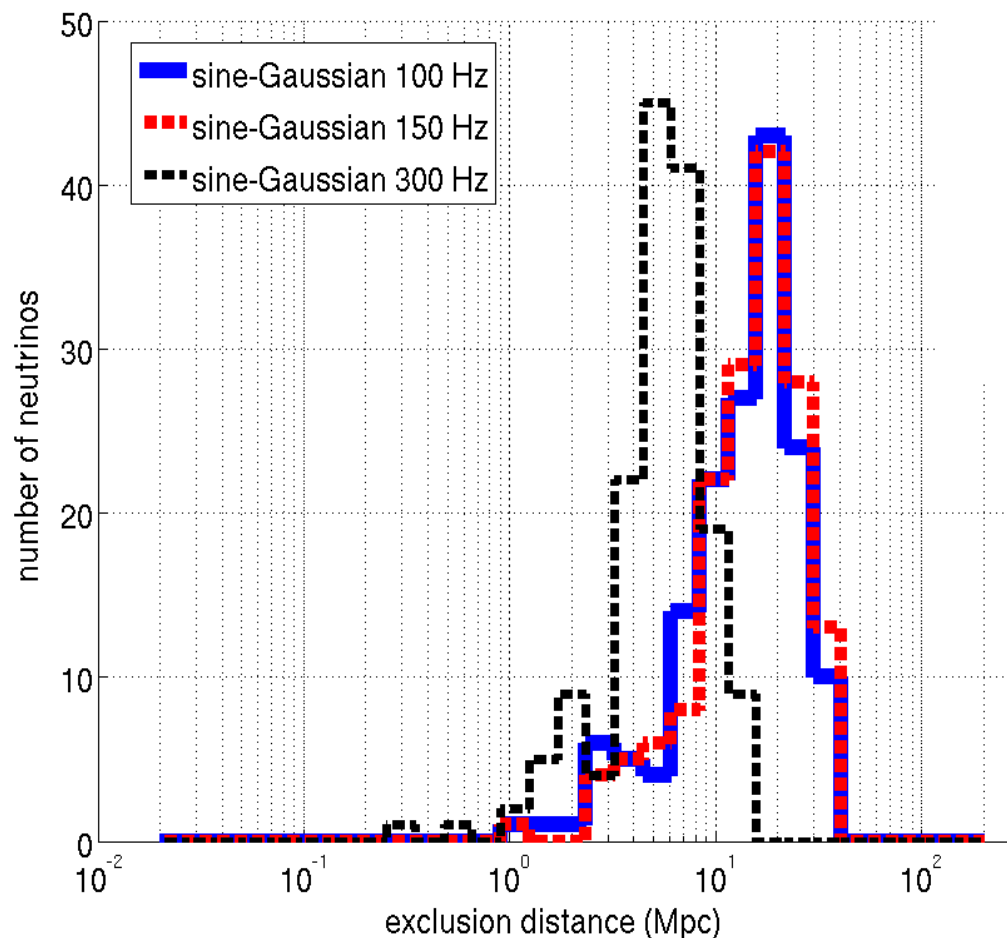
The distribution of p-values is consistent with the null hypothesis (dashed line).

The **red dot** indicates the largest deviation of the low p tail from the uniform distribution null hypothesis.

The **black line** shows the threshold for a 5-sigma deviation from the null hypothesis.

Coincident search results

Low-Frequency analysis



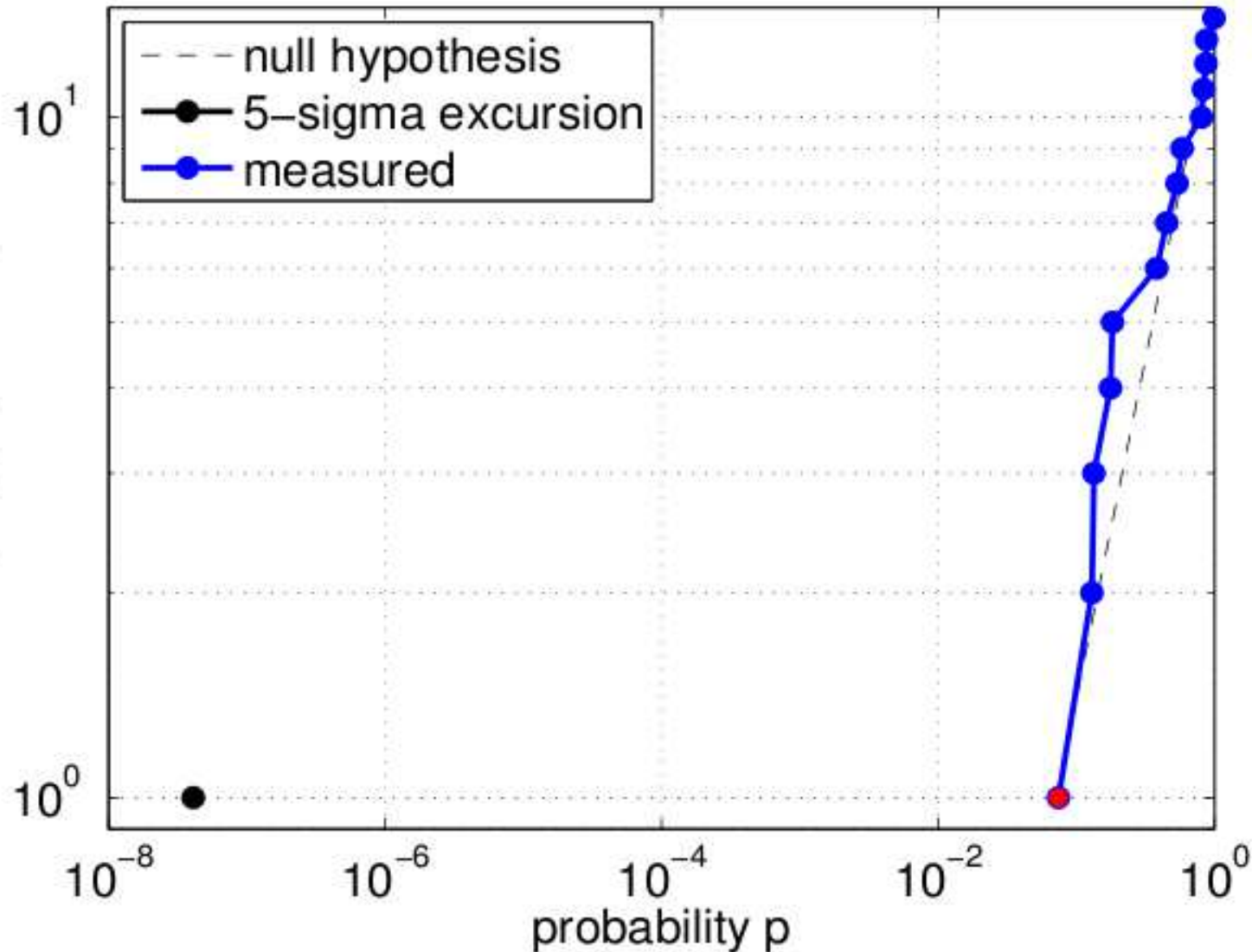
To convert injected signal amplitude into distance we assume that an energy

$$E_{GW} = 10^{-2} M_{\odot} c^2$$

is emitted.

Coincident search results

High-Frequency analysis: Binomial Test



Test for a cumulative signature associated with our neutrino sample.

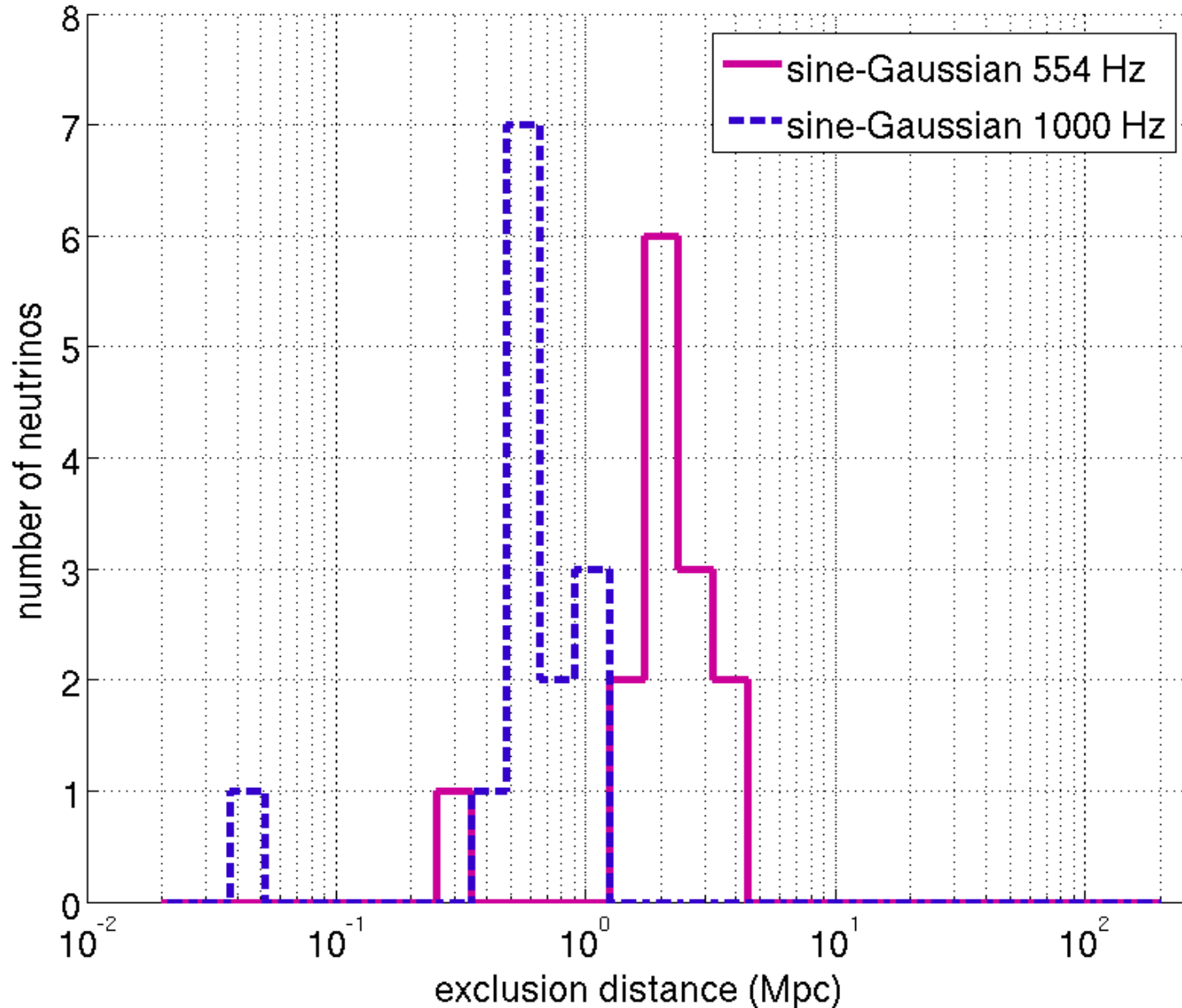
The distribution of p-values is consistent with the null hypothesis (dashed line).

The **red dot** indicates the largest deviation of the low p tail from the uniform distribution null hypothesis.

The **black dot** shows the threshold for a 5-sigma deviation from the null hypothesis.

Coincident search results

High-Frequency analysis



Conclusions

- No evidence for coincident events. We are able to rule out the existence of coalescing binary neutron star systems and black hole-neutron star systems up to distances that are typically of 5 Mpc and 10 Mpc respectively. For generic waveform limits in the low frequency band typical distance limits can be as high as 17 Mpc.
- The analysis of more recent data, acquired during S6 - VSR2-3, is ongoing.
- We are getting ready to analyze data from the advanced LIGO and Virgo detectors, in coincidence with Antares in its final configuration (12 lines).