Multi-messenger search for gravitational waves and high energy neutrinos

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

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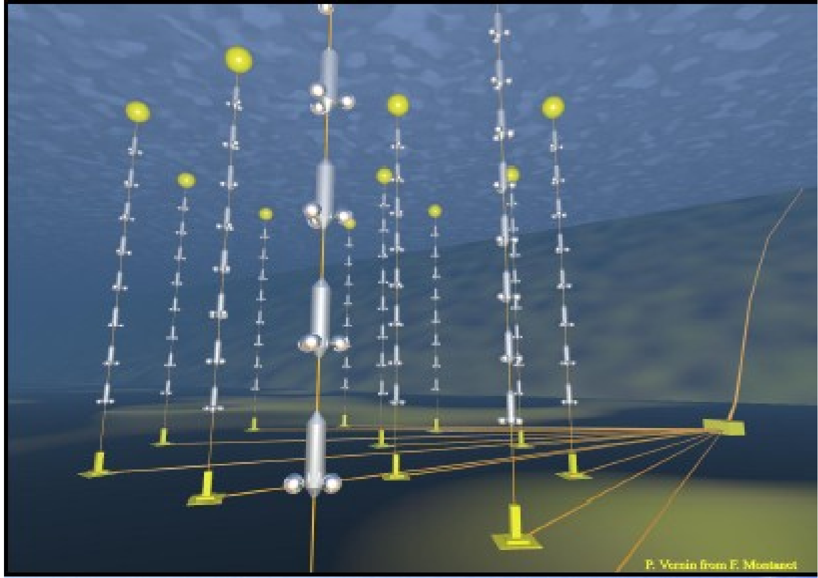
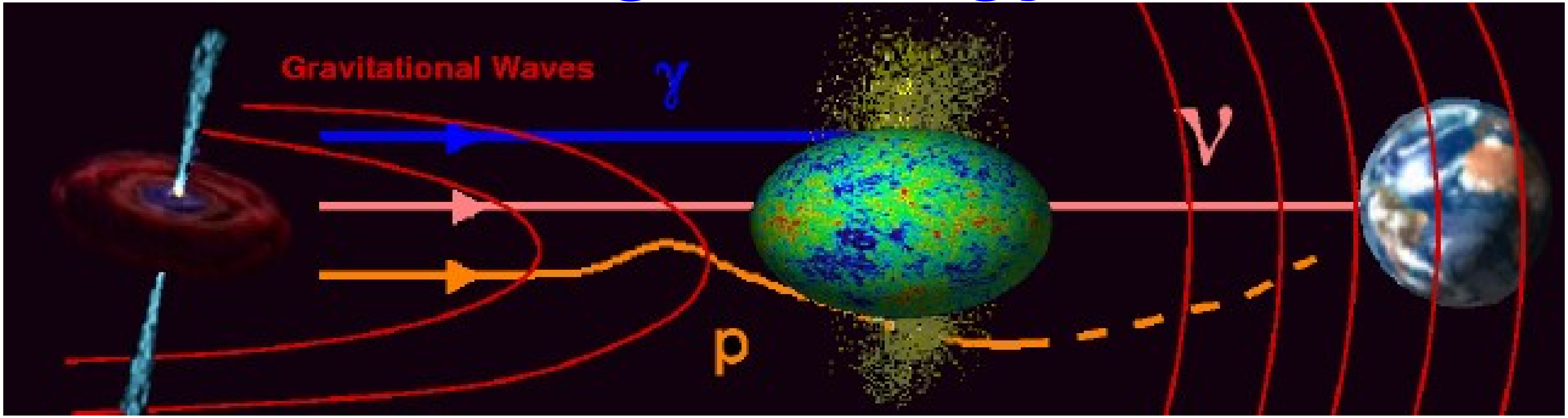


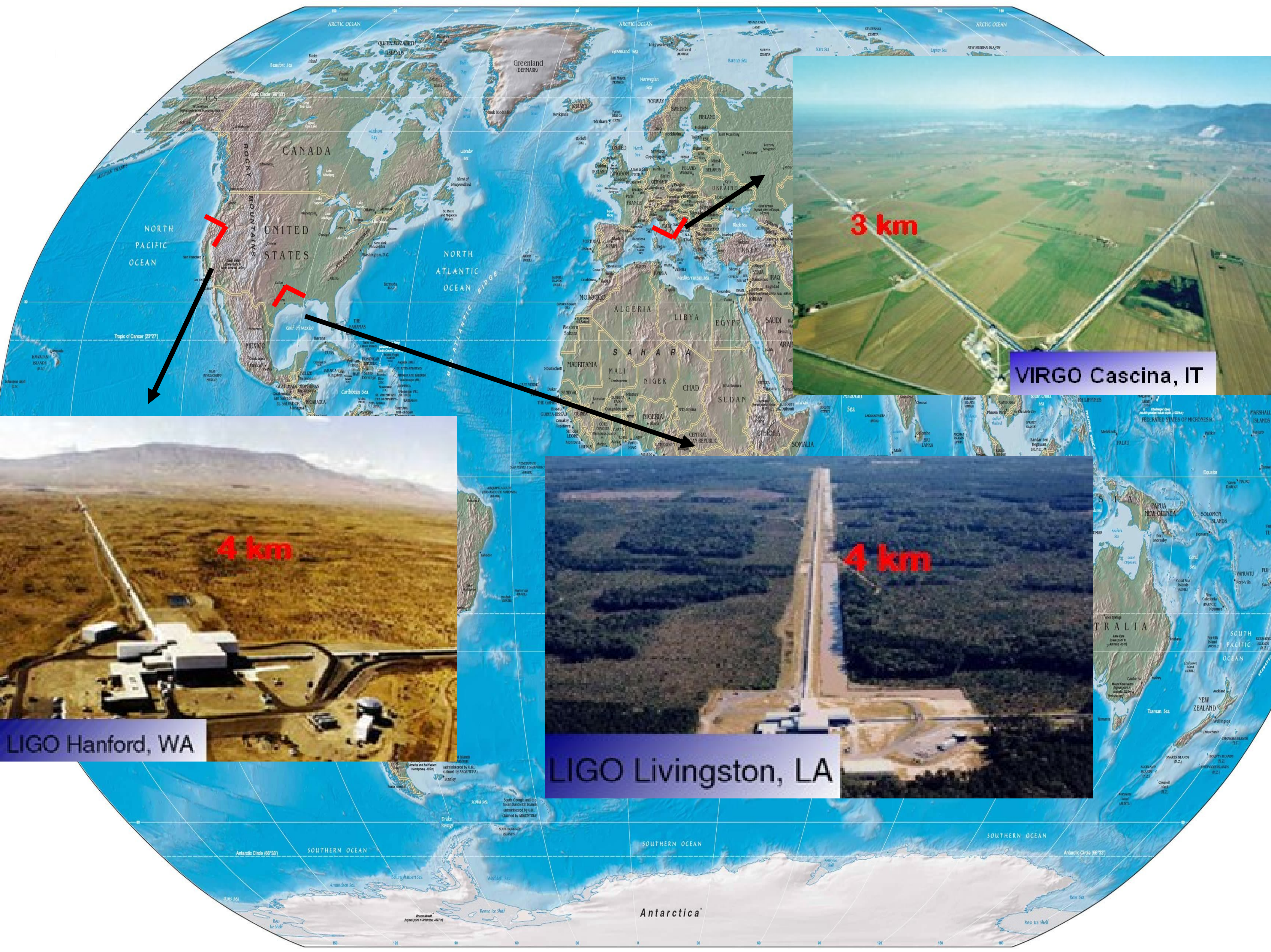
Joint search between Gravitational Waves and High Energy Neutrinos



- 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.

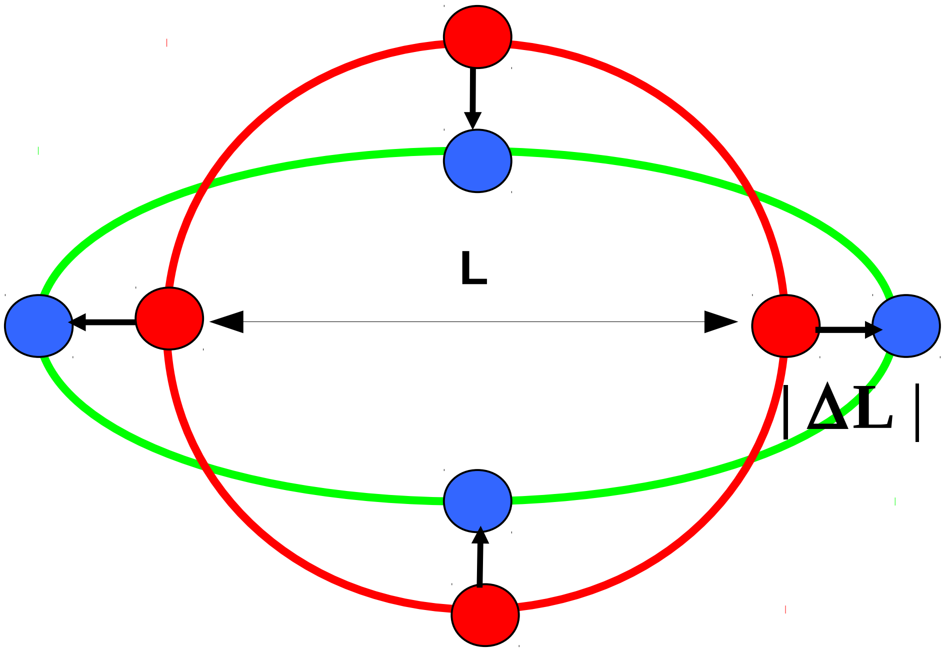
Introduction

- 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; Berezinsky et al. 2011)
  - ....


3 km
VIRGO Cascina, IT
4 km
LIGO Hanford, WA
4 km
LIGO Livingston, LA

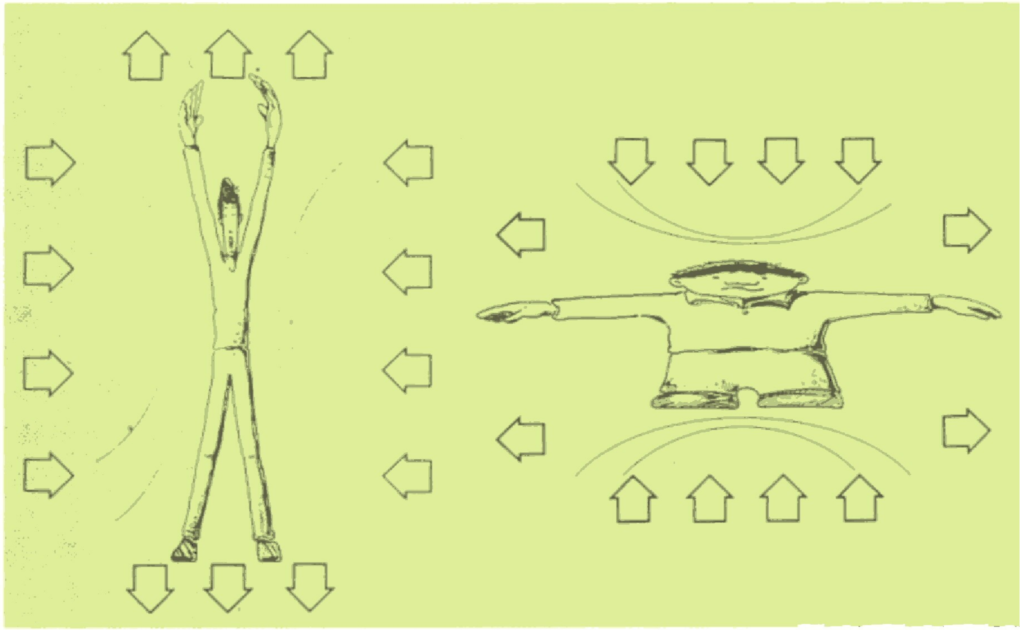
GW Interferometer

The gravitational waves twist the space time and during their crossing, they produce a positive or negative separation among the two free masses.



$$\Delta L \sim hL$$

ΔL displacement between mirrors
L = arm length: 4 km



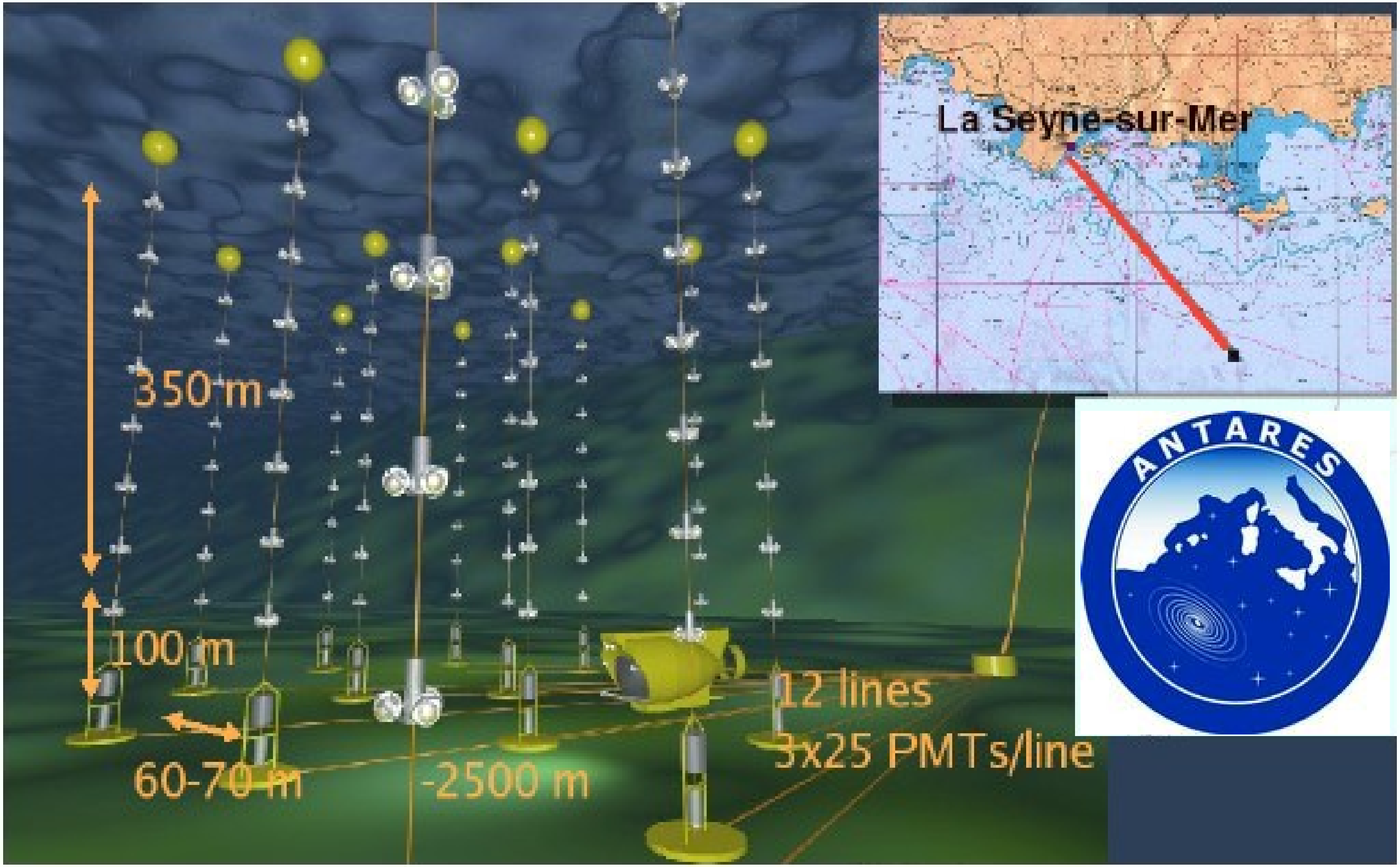
The *h* parameter is the measure of relative variation among the two free masses.

http://www.iop.org/EJ/abstract/0034-4885/72/7/076901

http://arxiv.org/abs/0902.0381

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 μs.

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.

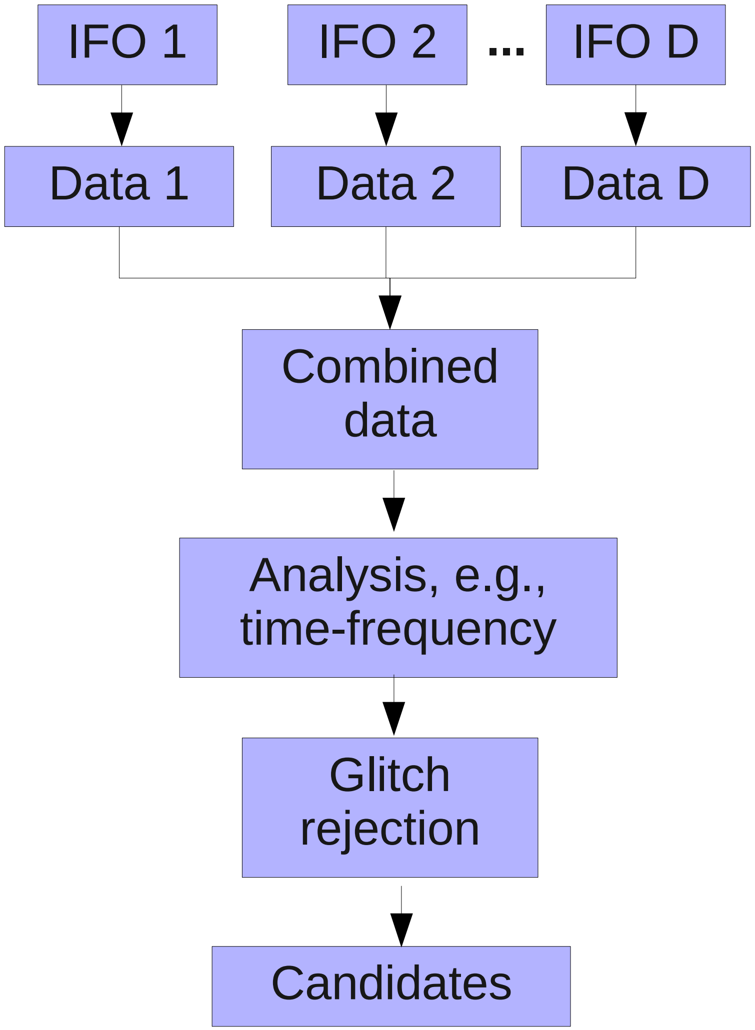
GW search method

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:

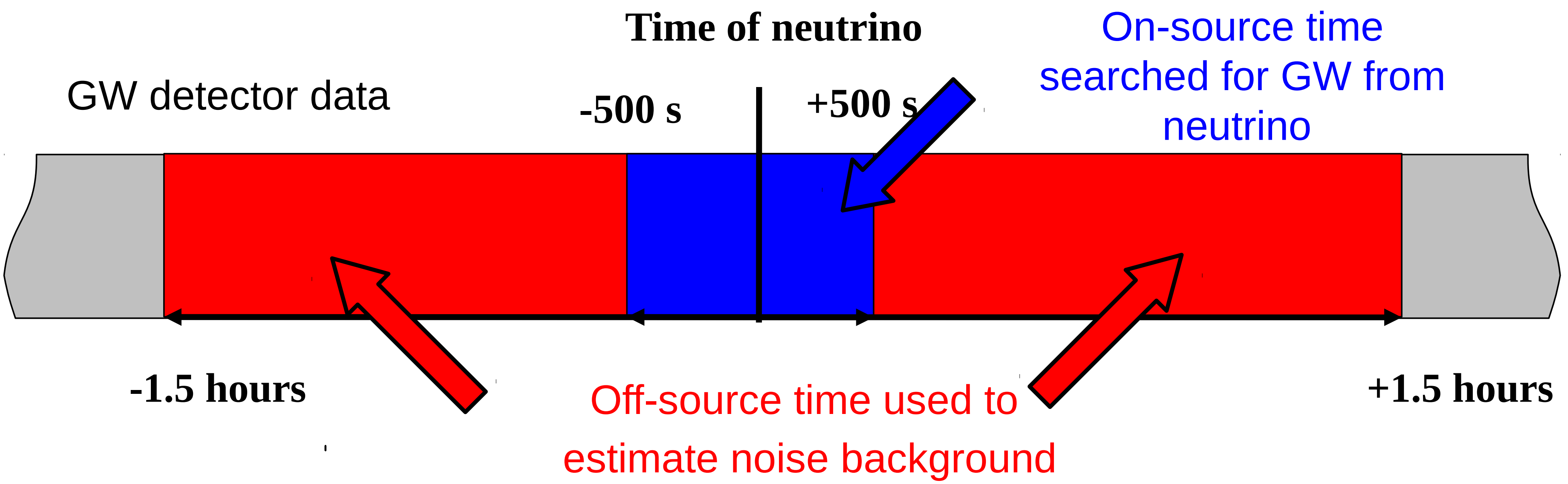
- **Closed-box analysis**: Tune our search parameters on off-source.
- **Open-box analysis**: Search for GW in on-source with optimal parameters.



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)*.
  - 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):
- 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)*
- 18 events reconstructed with 3 lines.

reconstructed from 2 Lines

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

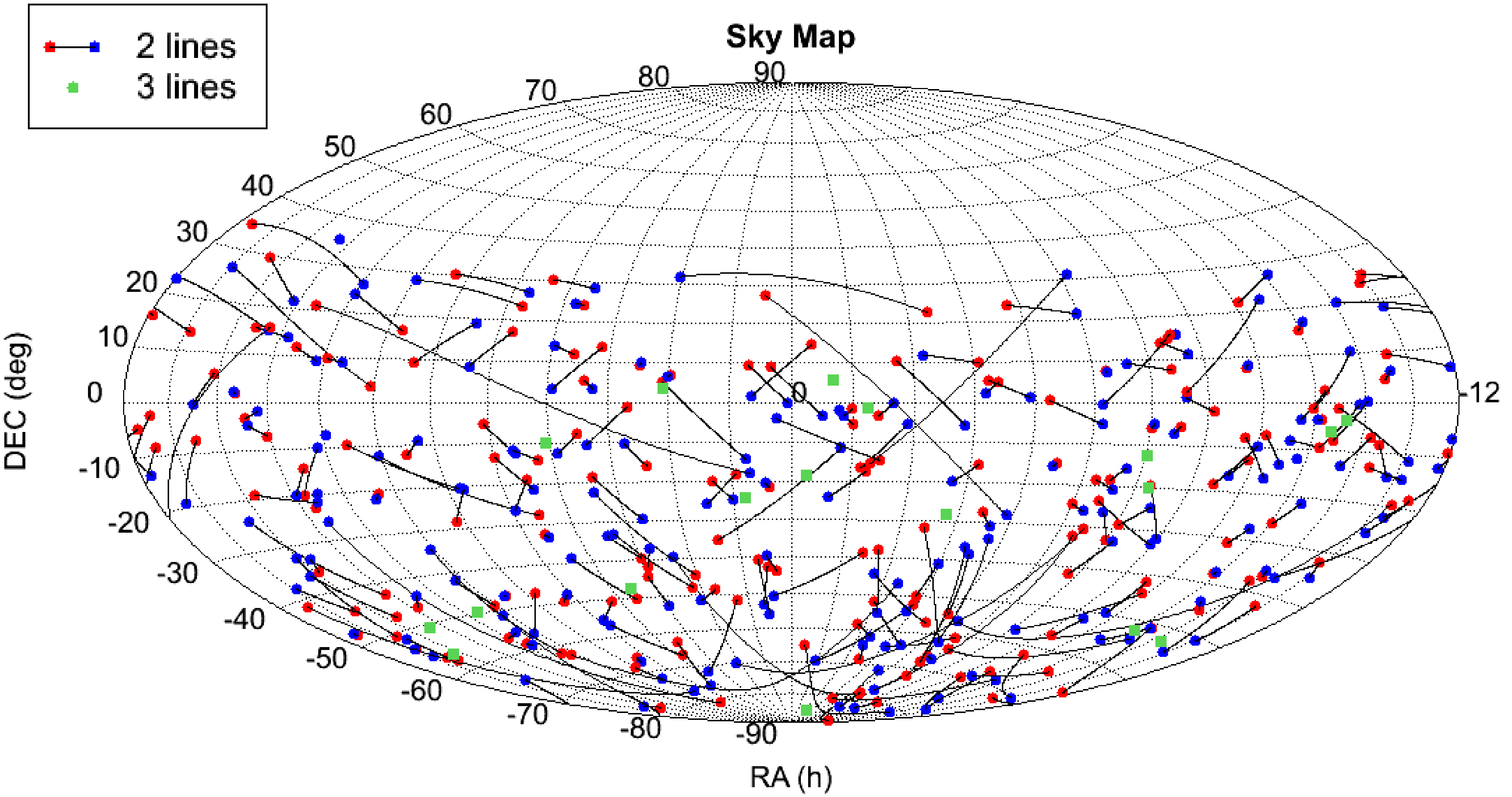
54 triggers cannot be analyzed because there aren't enough IFOs in network.

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



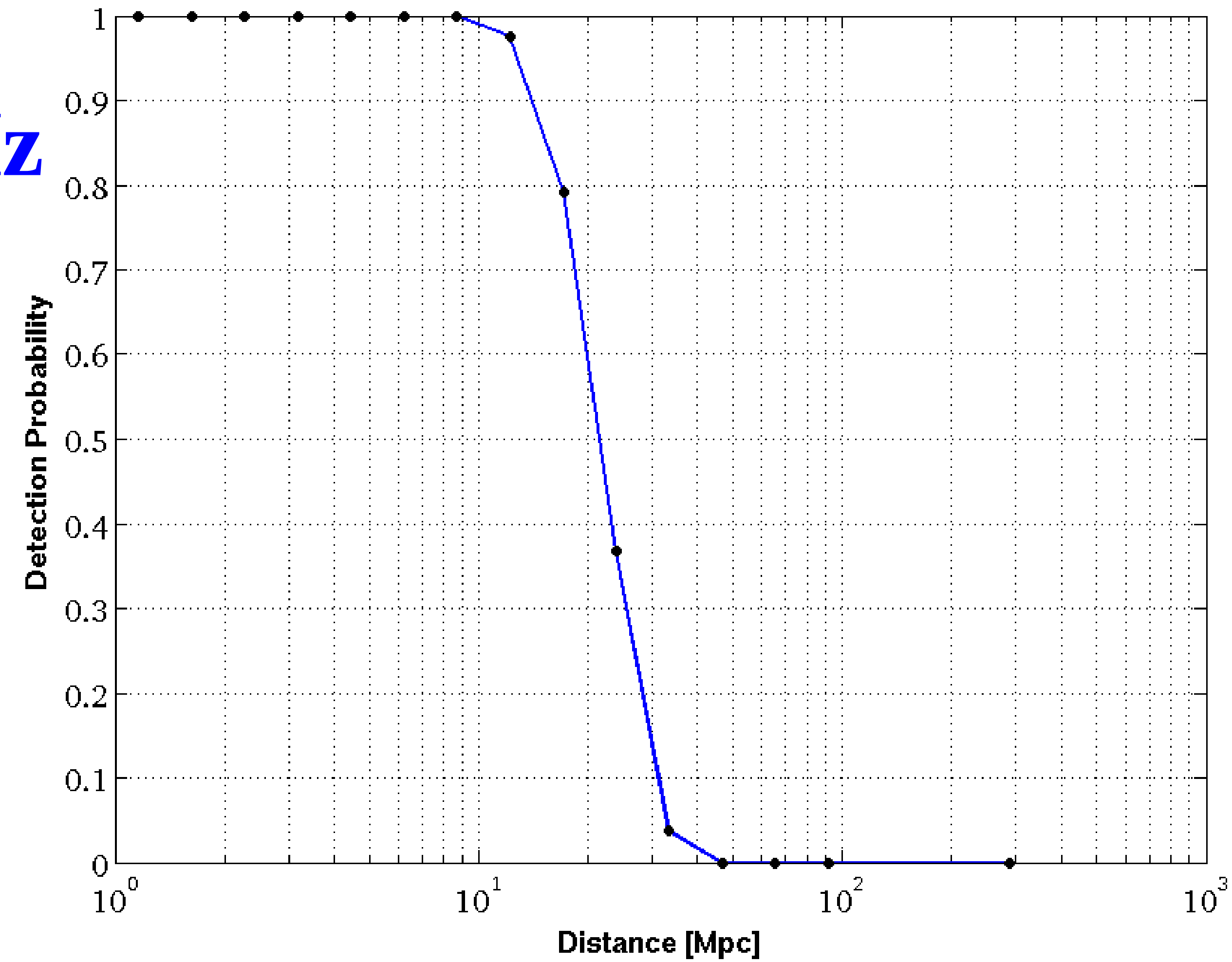
Low and High Frequency Analysis

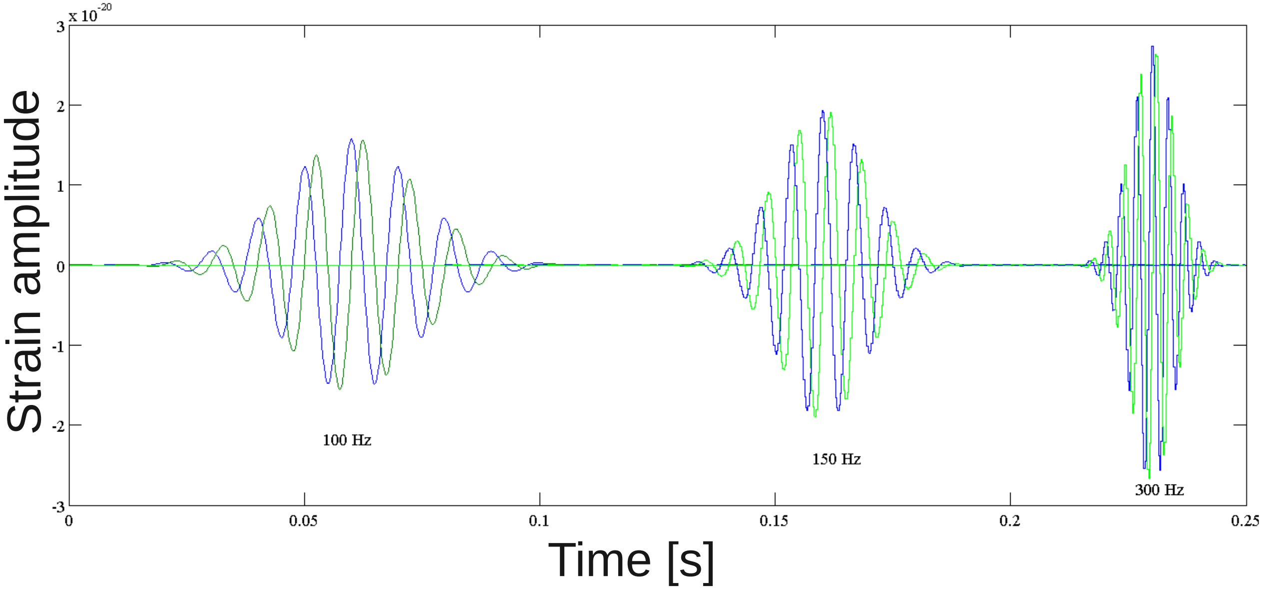
Low-Frequency analysis, (60-500)Hz, this band is analysed for all HEN triggers – such a search is computationally feasible while covering the highest-sensitivity region of the GW detectors. However, compact objects such as neutron stars or collapsar cores have characteristic frequencies for GW emission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

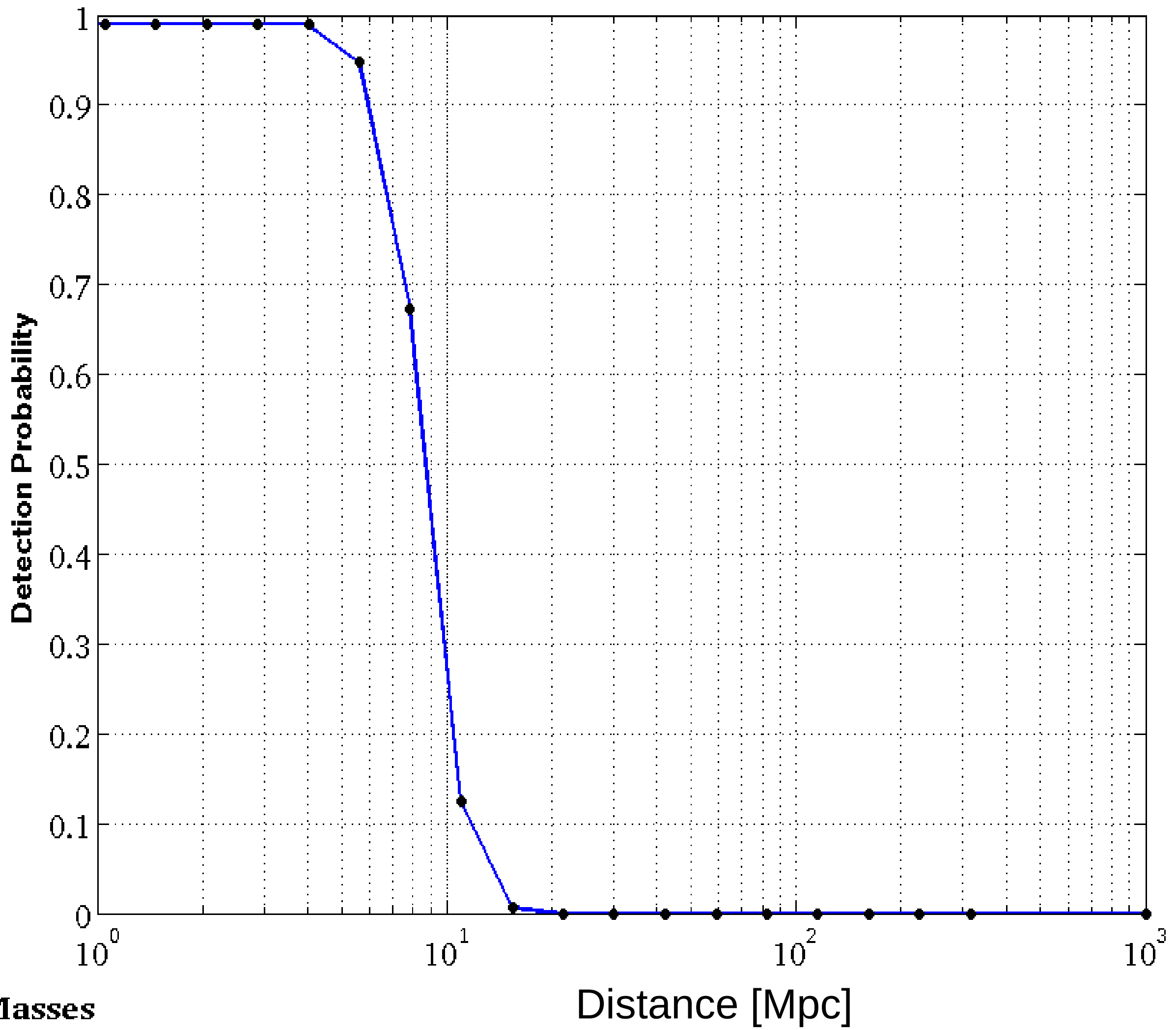


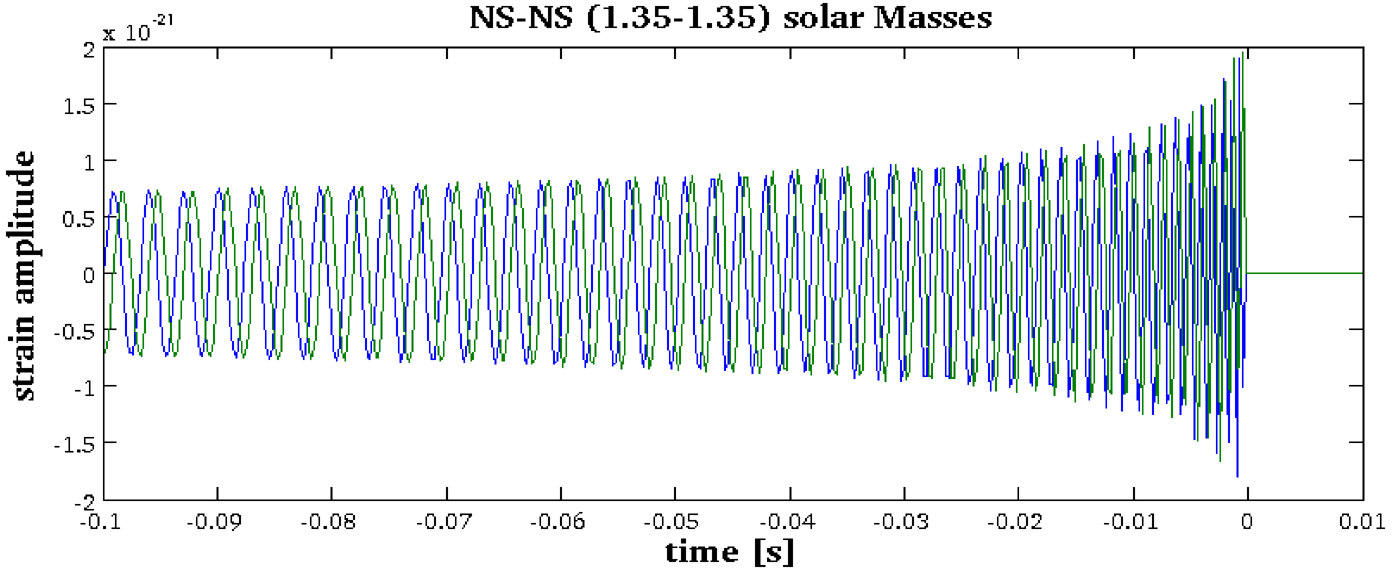


To convert injected signal amplitude into distance we assume that an energy $E_{GW} = 10^{-2} M_{\odot} c^2$ is emitted.

Example of NS-NS Injection

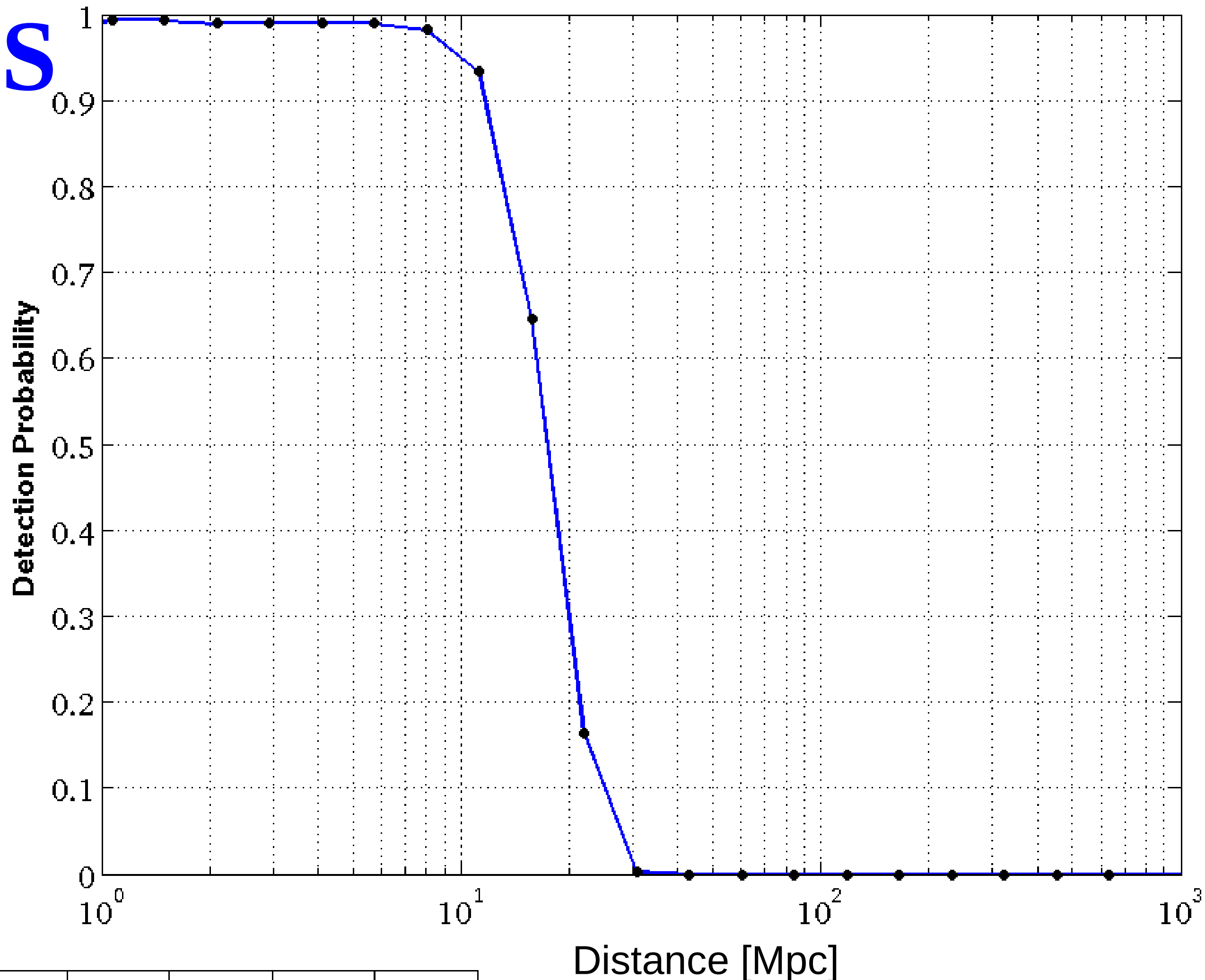
Fraction of simulated Gravitational Waves signals detected at a false-alarm probability of 1%.

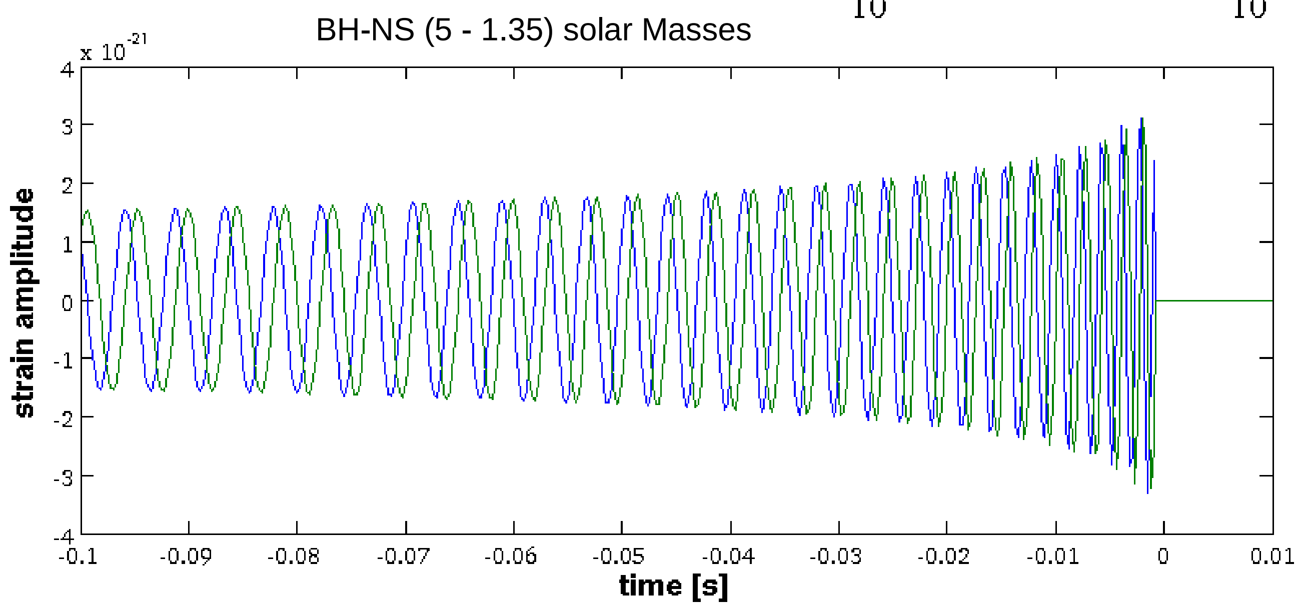




Example of BH-NS Injection

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



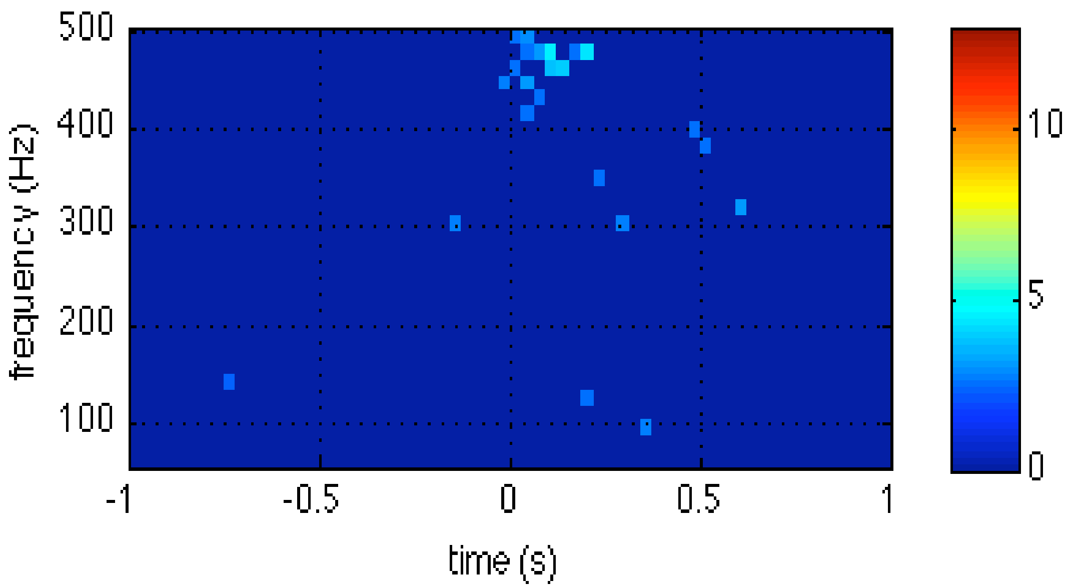


OPEN BOX results

Most Significant Outlier

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

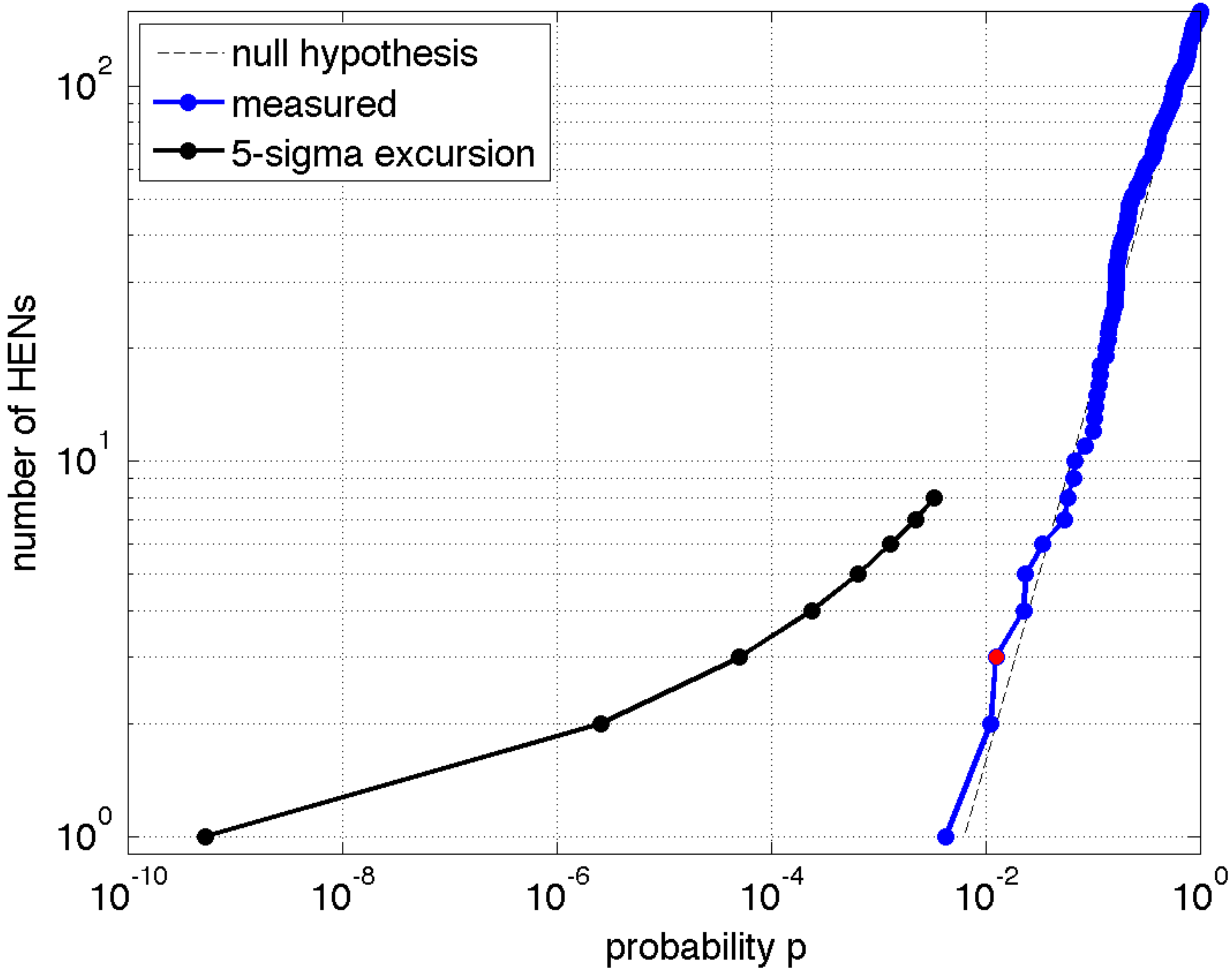
name	Nu385_386
Right ascension	204.404 deg
Declination	-13.027 deg
GPS	873597124.85938
network	H1H2V1
FAP (p-value)	0.004



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.

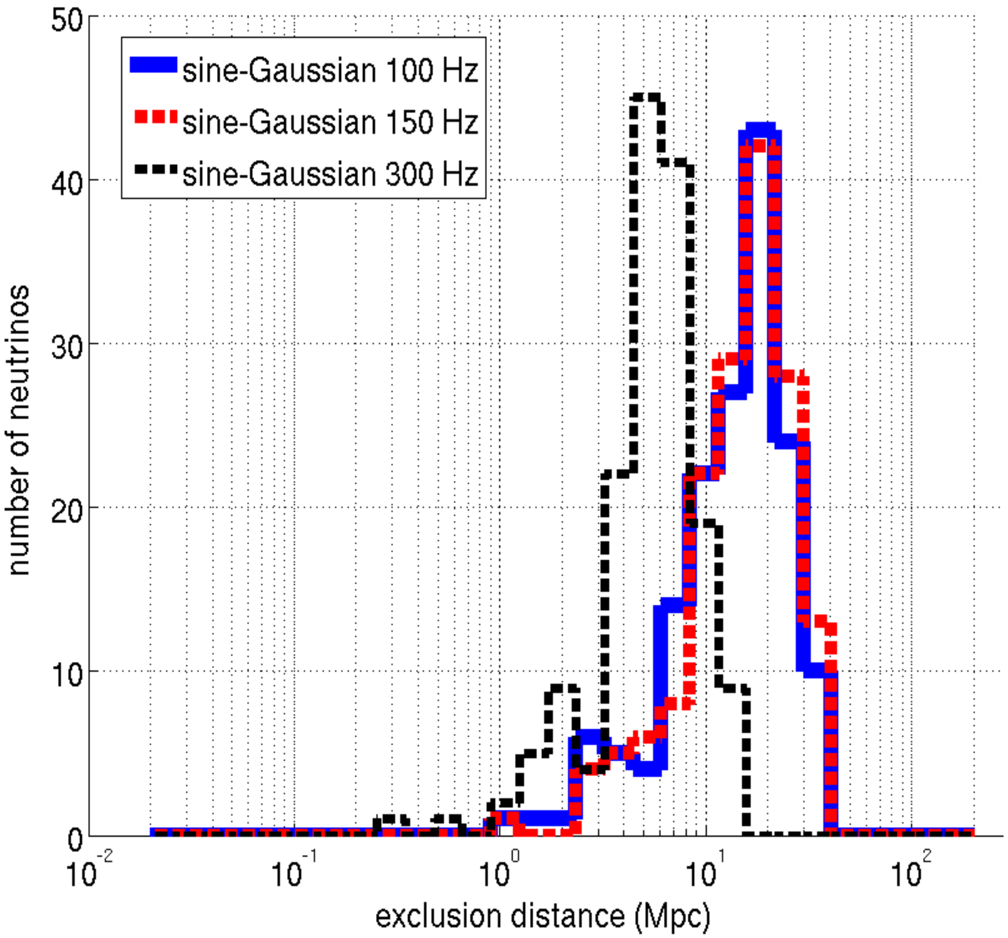
The distribution of p-values is consistent with the null hypothesis (dashed line).

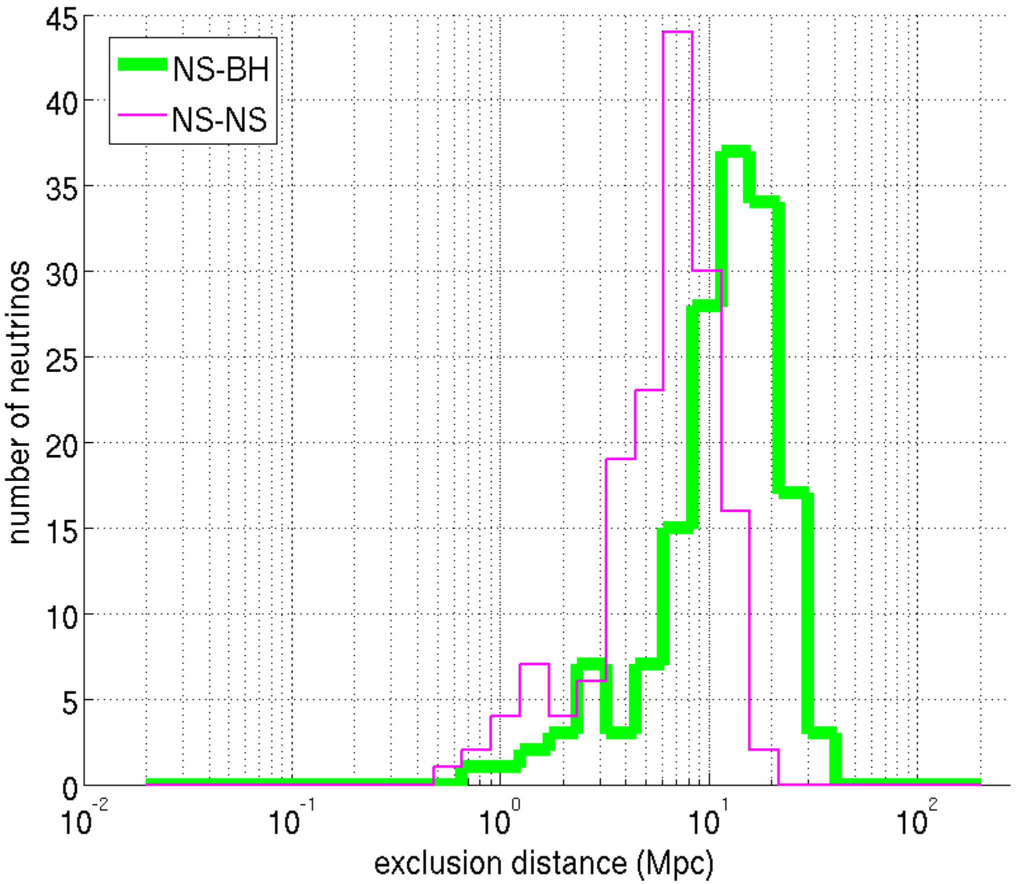
The **red dot** indicates the largest deviation of the low p tail from the uniform distribution null hypothesis.

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

Coincident search results

Low-Frequency analysis





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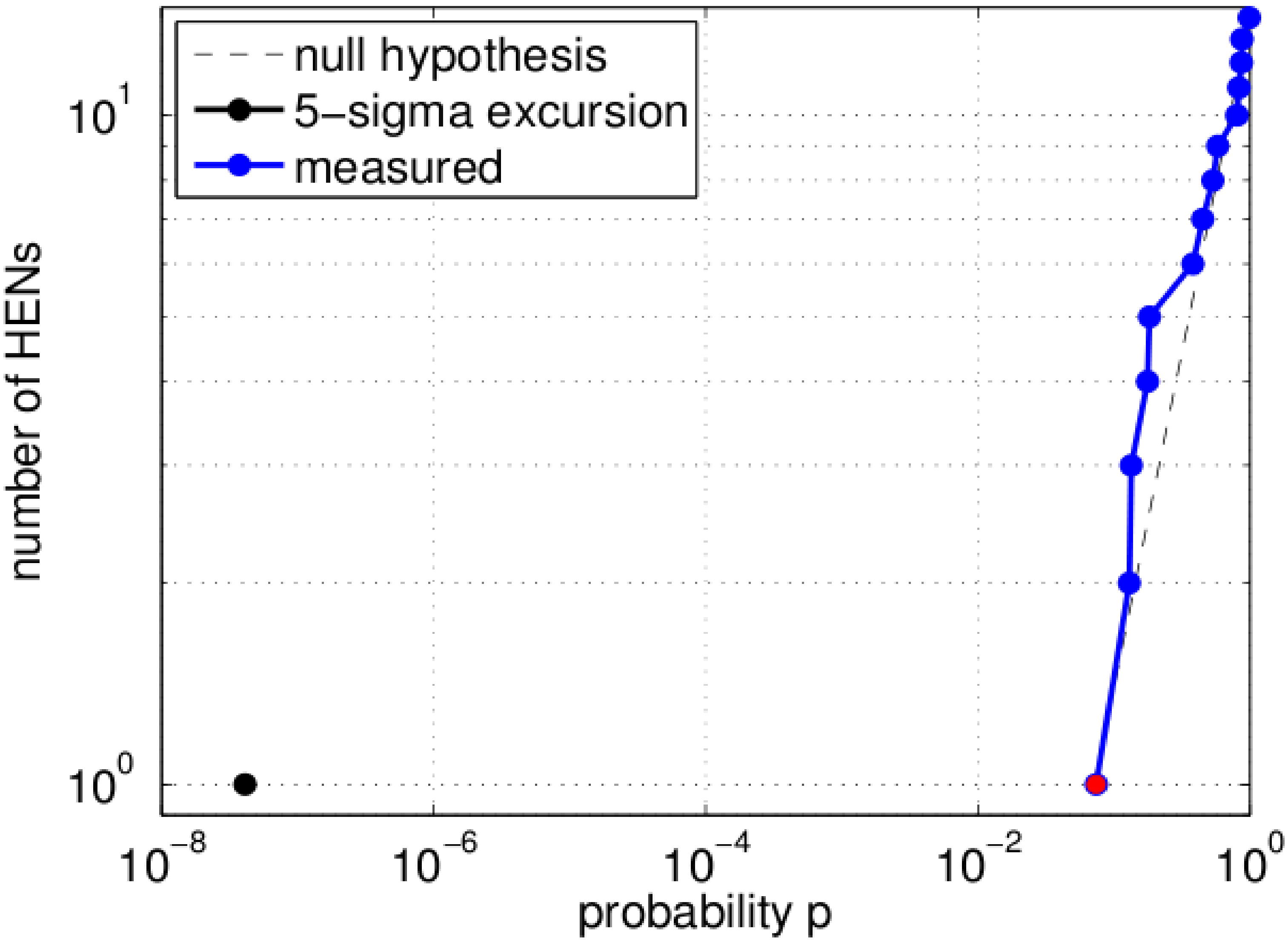
Coincident search results

High-Frequency analysis: Binomial Test



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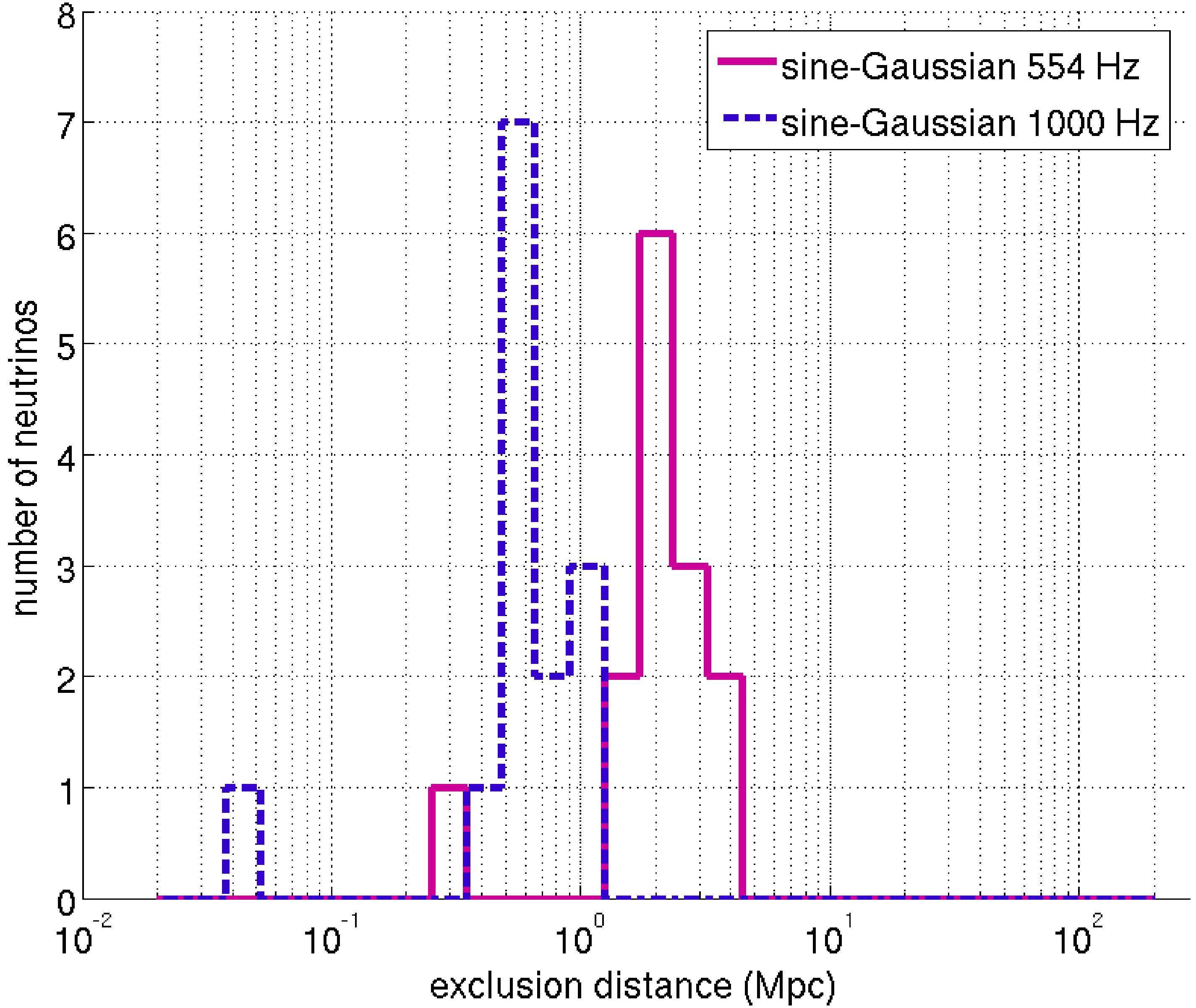
Coincident search results

High-Frequency analysis



Conclusions

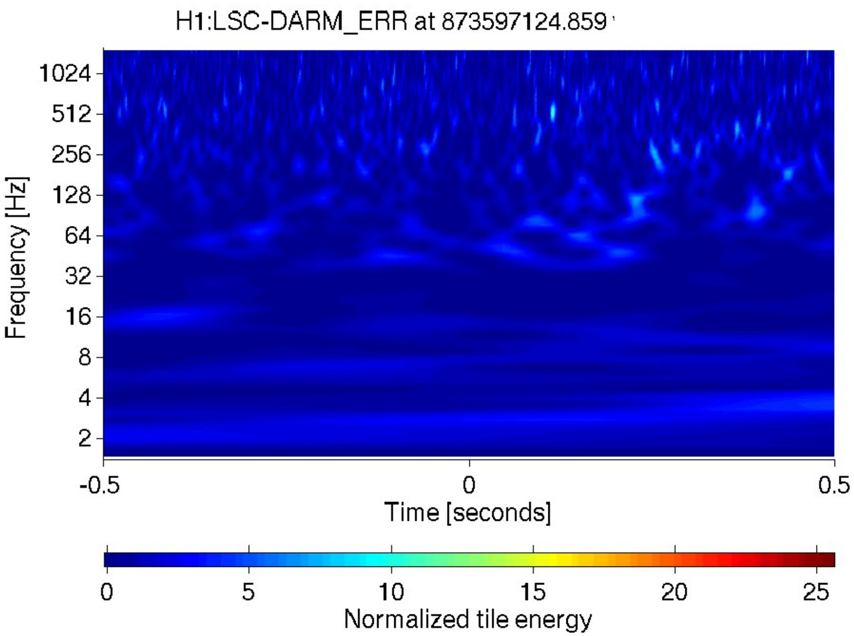
→ No evidence for coincident events. We are able to rule out the existence of coalescing binary neutron star systems and black hole-neutron star systems up to distances that are typically of 5 Mpc and 10 Mpc respectively. For generic waveform limits in the low frequency band typical distance limits can be as high as 17 Mpc (***arXiv:1205.3018***).

→ The analysis of more recent data, acquired during S6–VSR2-3 in coincidence with Antares (12 lines), is ongoing.

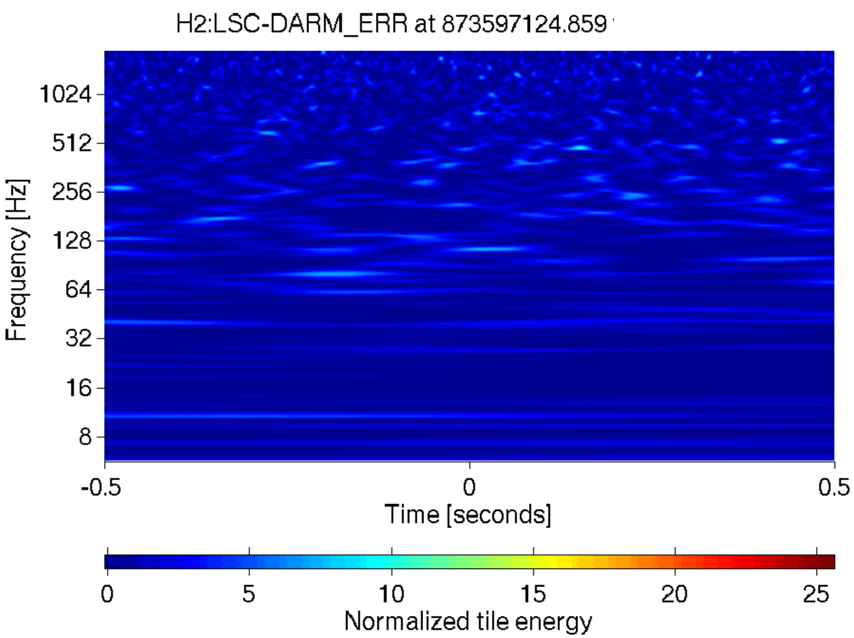
→ A similar join search between Ligo/Virgo and IceCube is under review.

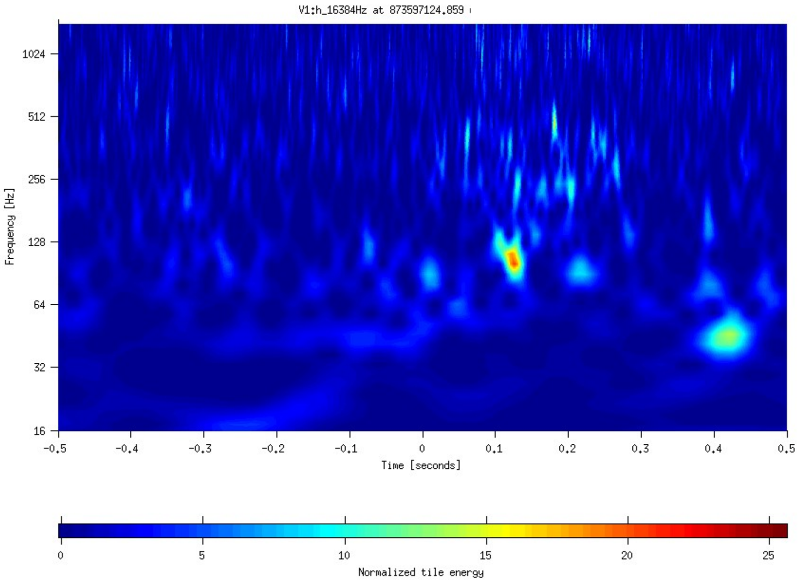
THANKS FOR LISTENING!

Omega scans



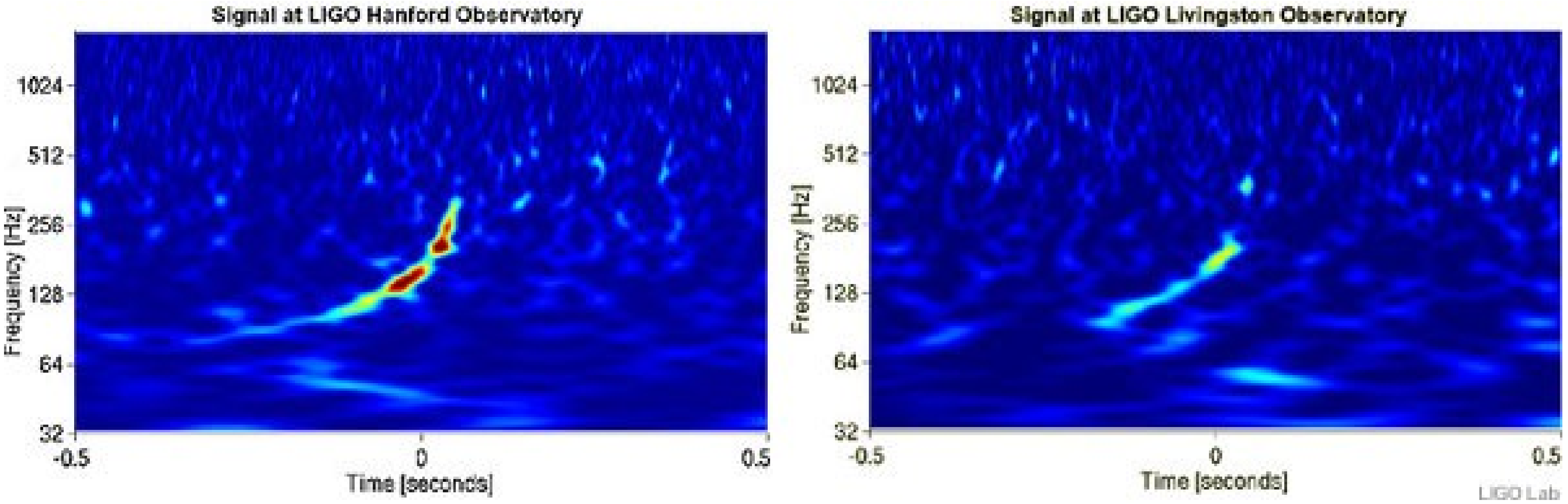
Frequency range	(480-504) Hz
Duration	250 ms
SNR H1	6.7
SNR H2	6.3
SNR V1	7.2





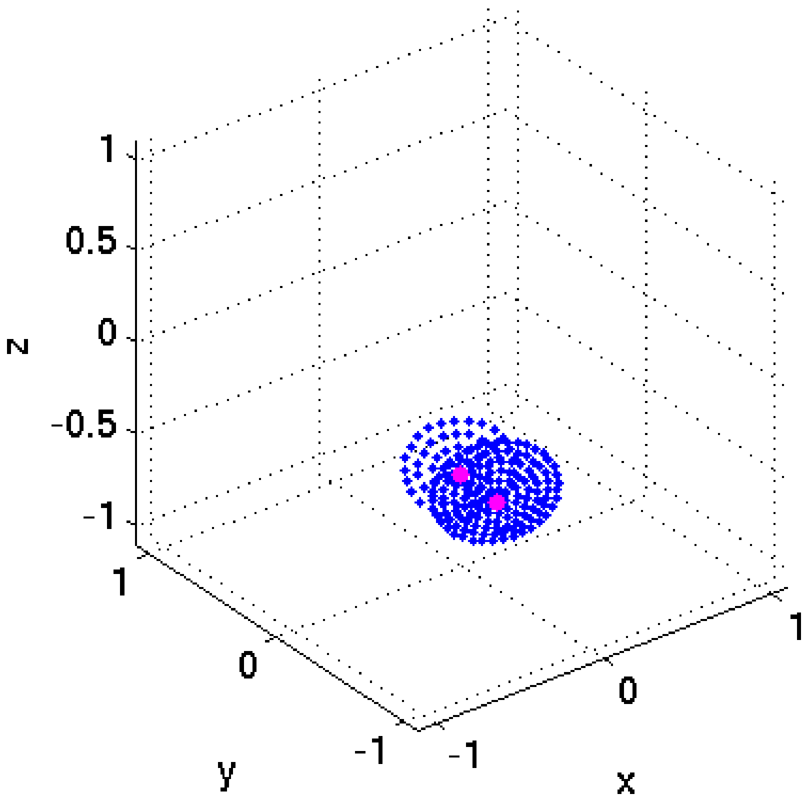
What a real signal would look like

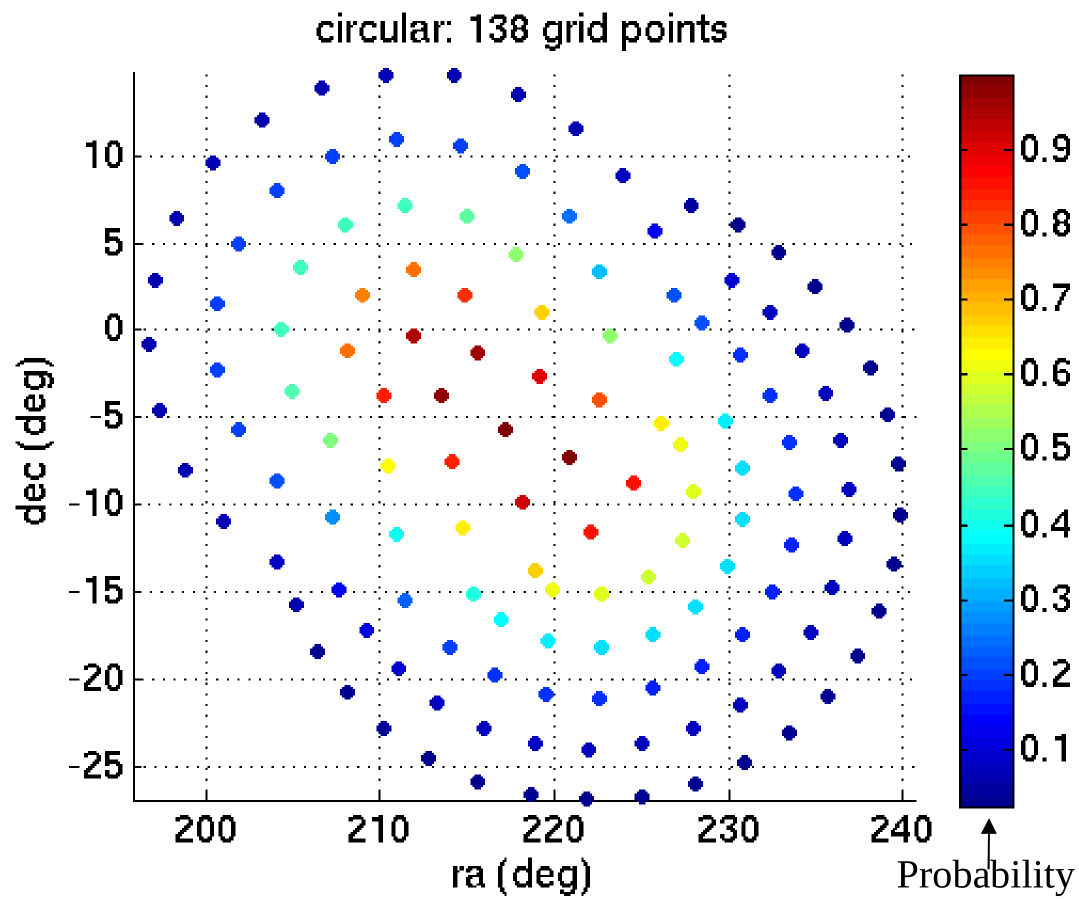
http://www.ligo.org/news/blind-injection.php



Searching for one point and its mirror image at once: Example

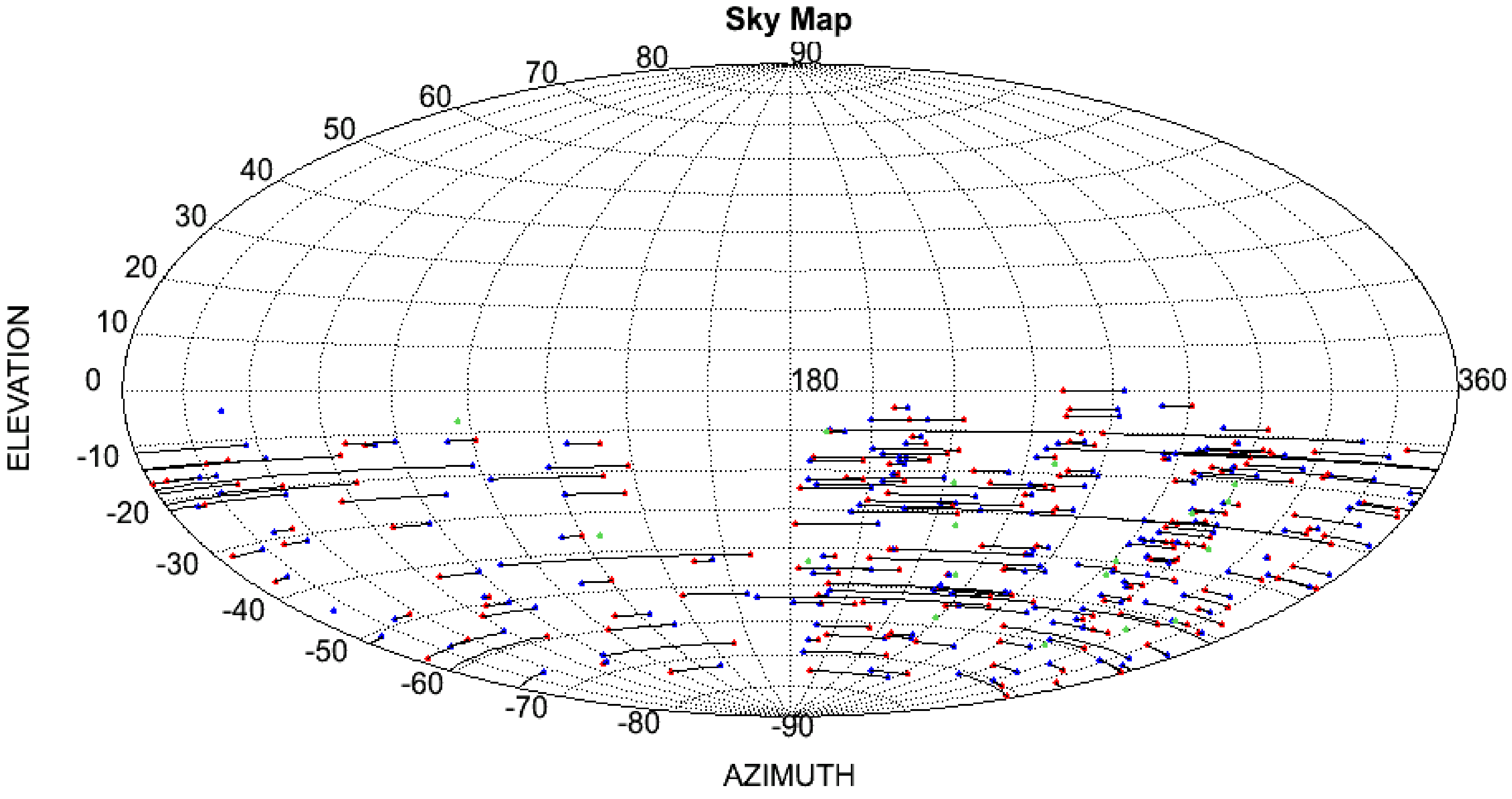
ra1 = '221.99' ; dec1 = '-9.38'; [deg]
ra 2= '211.85'; dec2 = '-0.36'; [deg]
gps = '864109778';
sigma_deg = '10~10';



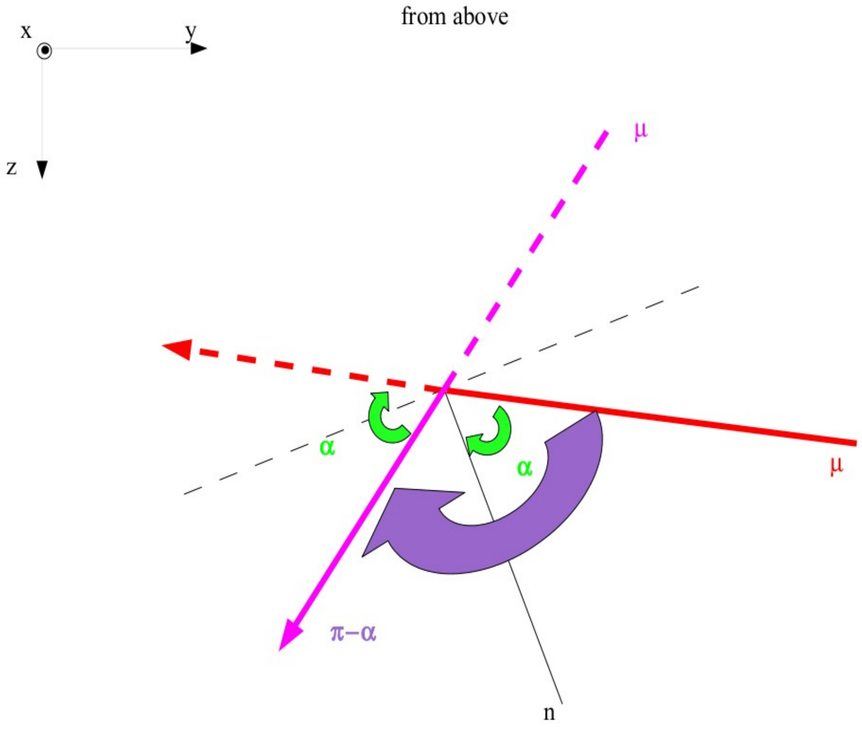


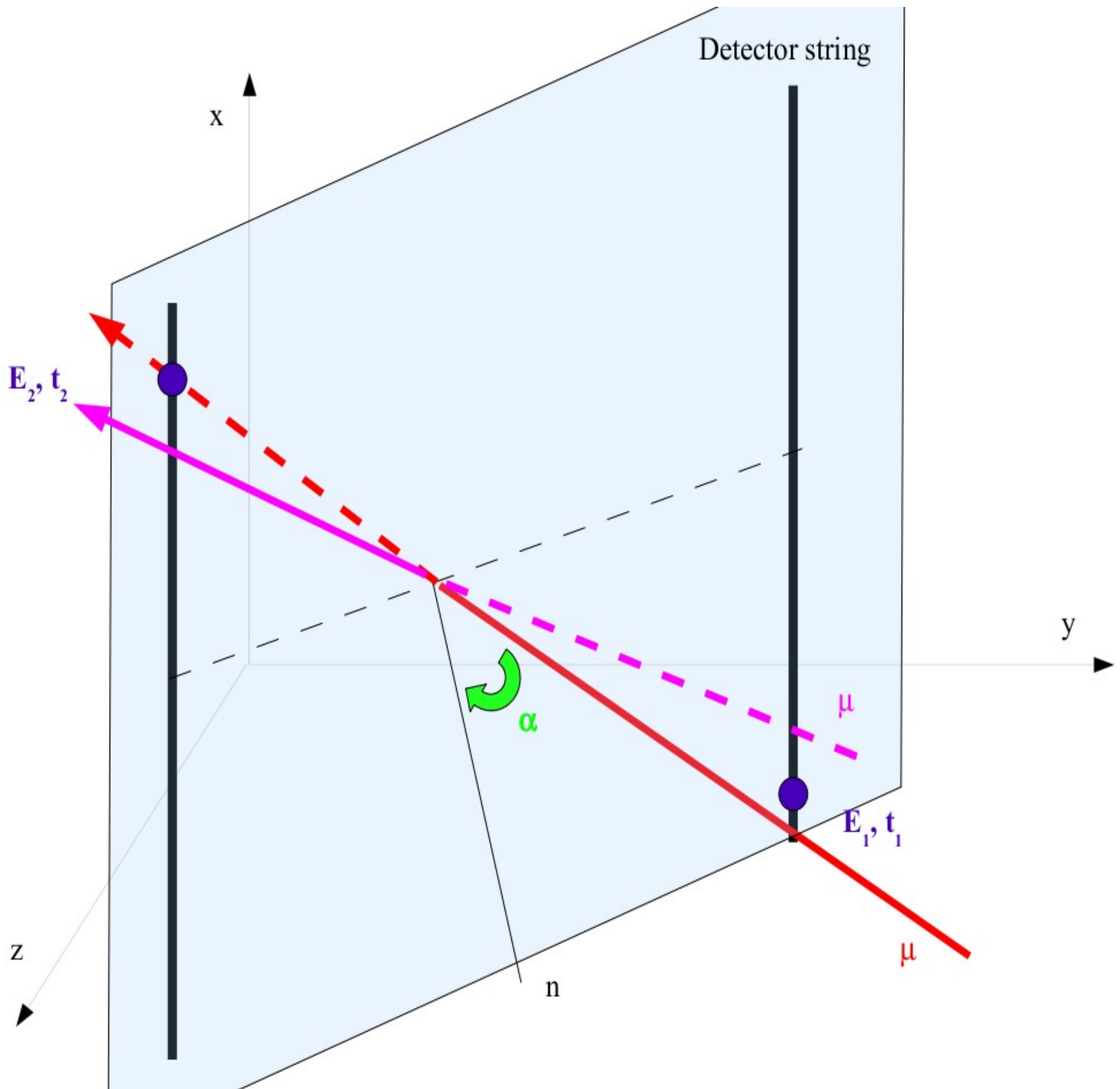
Given the estimated locations and errors in sky location measurement, the code generates a list of sky positions which we should search over to keep time-delay errors into account.

Sky Map of trigger positions



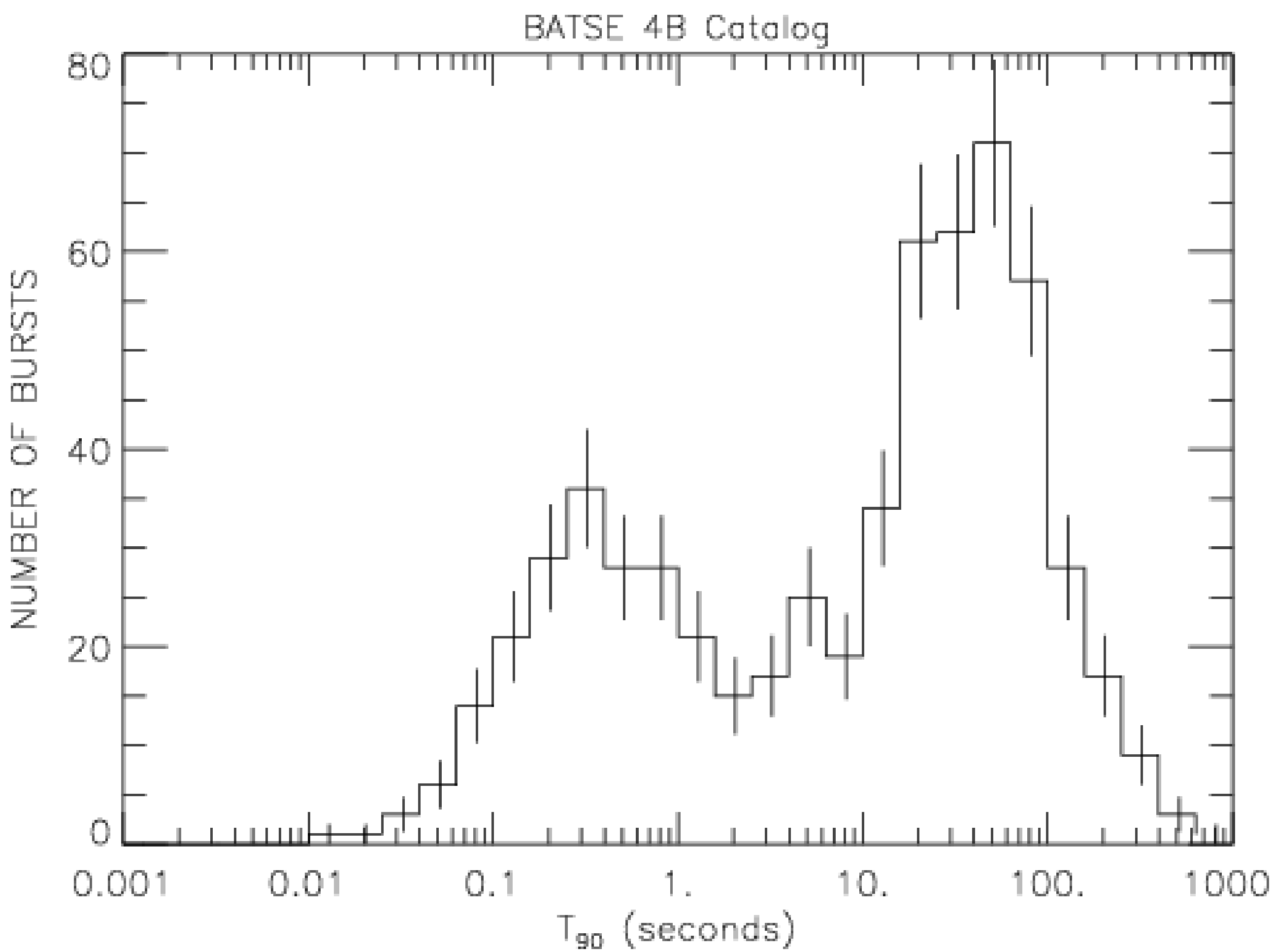
2 line cases





A muon that impinges the geometrical plane passing through the two lines with an angle of incidence (α, angle between the normal to the plane and the muon track) is undistinguishable from a muon that impinges with the mirror angle π − α because the two cases generate the same hits at the same time.
The indetermination results from the symmetry of the detector.

Search window



Durations of the 4B Catalog Gamma-Ray Bursts recorded with the Burst and Transient Source Experiment on board NASA's Compton Gamma-Ray Observatory. ***http://www.batse.msfc.nasa.gov/batse/grb/duration***

internal shocks can be produced before the visible outflow emerged from the stellar envelope, so the production of high energy neutrinos can happen before the observed gamma-ray emission. The inner object, responsible for a precursor phase, can be already in activity up to ~ 100 s before the gamma prompt emission.

ˆ According to the model, during the precursor phase we expect prompt neutrino emission to overlap with prompt gamma-ray emission of GRBs. The BATSE (Burst Alert and Transient Source Experiment) Collaboration studied more then 2000 GRBs and determined the precursor time for this data set to be ~250 s.

ˆ In most of observed GRB cases (95%), the duration of the emission due to inner compact object's activities is order of 150 s and both GW and HEN can be emitted.

ˆ We cannot exclude a potential joint emission of GW and HEN from the afterglow phase, but it's not possible at the moment to dene a unique time scale for this emission p