Sub-threshold searches for coincidences between gravitational waves and neutrino detected with neutrino telescopes in the depths of the Mediterranean Sea

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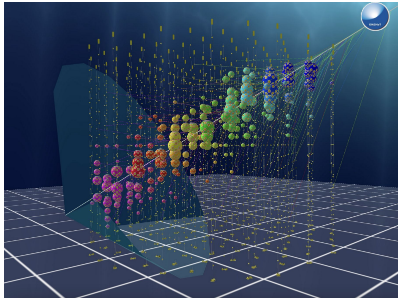
Introduction to GW-HEN



High Energy Neutrino
Localisation ~ 1 deg²
Circumstellar environment

&

Gravitational Waves
Luminosity distance
Localisation >> 10 deg²
Precise time

Multi-Messenger Astronomy
Global picture of the event

1. **Cosmology**
   - **Independent measure of H_0**
2. **Nuclear Astrophysics**
   - **Production site of the High energy Neutrinos**
   - **Acceleration Mechanisms**
3. **High Energy Astrophysics**
   - **GRB population associated to GW**
4. **GW Sources**
   - **GW progenitor:** Identification of new sources beyond compact binary mergers

Overview

Triggered search

Use HEN as a trigger to search for coincident GW signals

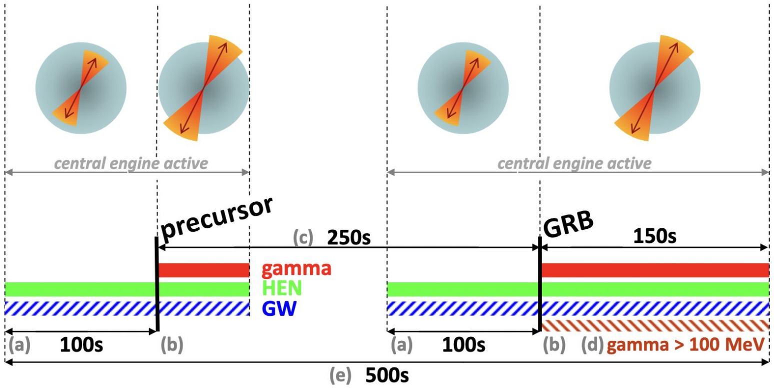
Any GW source: Compact Binary Coalescence (CBC), Supernovae, etc…

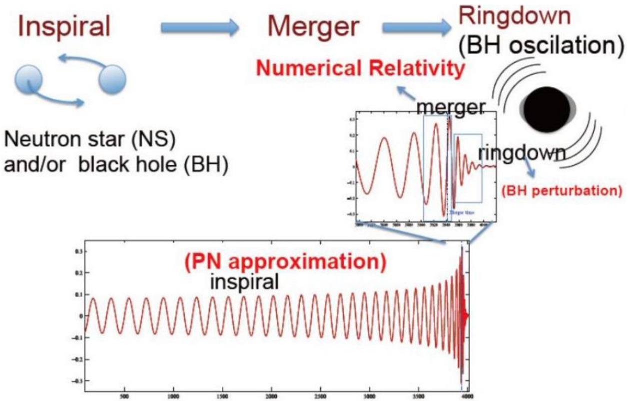
Deep search

Combine all the GW and HEN data to find significant coincidence

Compact Binary Coalescences (**CBC**): Merging Neutron stars or Black Holes - **only source detected so far**

arxiv:1101.4669





Datasets

LIGO/Virgo

Modelled GW search: ~1.4k events

- **PyCBC** - O3 run (Apr 2019 - Mar 2020)
- Compact binary coalescences (**CBC**) candidates with **False Alarm Rate FAR < 2/day**
- See here for the data:
  - Zenodo GWTC-3
  - Arxiv: 2111.03606

ANTARES & ORCA6

ANTARES: ~1.5k events

- Full detector
- $\cos(\theta) > -0.1 \rightarrow$ Up-going events
- Well reconstructed track events

KM3NeT/ORCA6: ~1.5k events

- 6 lines detector
- track-like & upgoing ($\cos(\theta) > 0$)
- with a reconstructed energy > 1 GeV
- BDT used to reject badly-reconstructed muons

Triggered search

General idea:

Use the significant HEN triggers and search for weak generic GW signals

Various GW sources: CBC, SNe, Accretion Disk Instabilities, etc.

1. **Select** ORCA6 & ANTARES significant triggers with signalness
2. Search **weak generic GW signal** in LIGO/Virgo in a ±500s on-source window
3. Compute the significance of the pairs → **Associate a p-value to each HEN**

Use the signalness as a metric to select the significant HEN candidates:

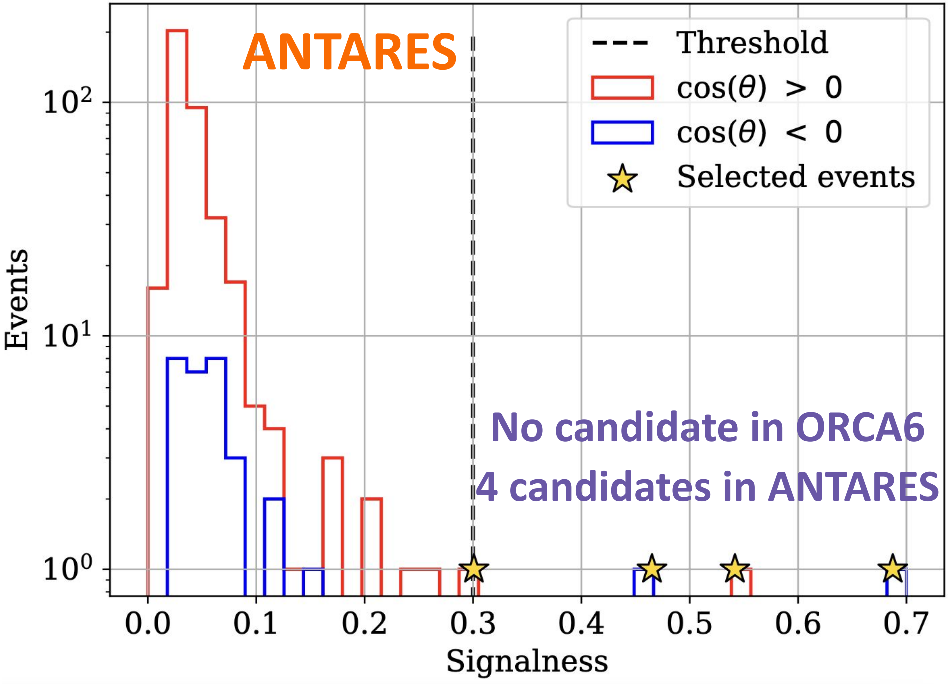
$$\boxed{\mathcal{S}(E_{\mathrm{rec}}, \Lambda_\nu) = \frac{N_{\mathrm{signal}}(E_{\mathrm{rec}}, \Lambda_\nu)}{N_{\mathrm{signal}}(E_{\mathrm{rec}}, \Lambda_\nu) + N_{\mathrm{background}}(E_{\mathrm{rec}}, \Lambda_\nu)}}$$

Method based on the LVK `X-Pipeline` software

Triggered search results

- Signalness threshold
  - $\mathcal{S}(E_{\text{rec}}, \Lambda_\nu)$ > 0.3
- Search for weak GW candidates
  - **±500s** time window
  - **Minimally modelled** signals
  - **Background** estimated in **1000s** off-source windows
  - Compute a **p-value** comparing the candidate's significance to the background

No significant GW-HEN candidates associations



Sub-threshold search

- **Motivation**:
  - No joint GW-HEN detection so far → **subthreshold** allows to search for **weak coincidences** and to **use all the available data**

General idea:

« Two weak candidates in their respective channels can create significant coincidences if they are close in time and sky »

1. **Take the full list** of ORCA6 & ANTARES events & LIGO/Virgo triggers from O3
2. Search **symmetrically** in LIGO/Virgo **-** ORCA6/ANTARES data for coincidences in a determined on-source window
3. Rank the pairs with a **Bayesian ranking statistic**
4. Compute the significance of the pairs → **joint FAR**

Method inspired from Pillas et al 2023, Stachie et al 2020 for GW-GRB associations

Bayesian Ranking statistics

$$\boxed{\Lambda = \frac{I_{\Delta \mathrm{t}} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}}$$

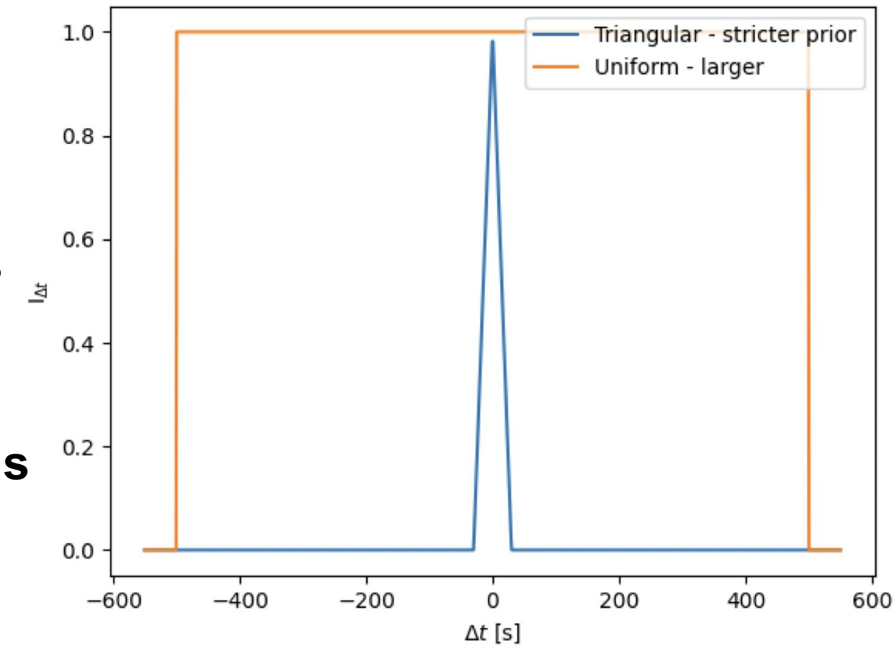
Bayesian Ranking statistics

$$\Lambda = \frac{I_{\Delta\mathrm{t}} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}$$

$I_{\Delta\mathrm{t}}$ → **Time overlap**

- Prior 1) on-source window **±30 s** around the GW - **triangular**

- Prior 2) on-source window **±500 s** around the GW - **uniform**

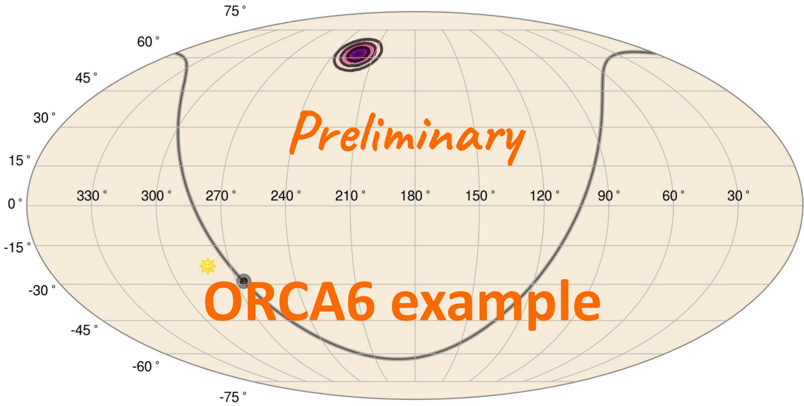


Bayesian Ranking statistics

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}$$

I_{Ω} → **Sky overlap** based on Ashton 2018: 1712.0539

$$I_{\Omega} = \int \frac{P(\Omega|D_g) P(\Omega|D_\nu)}{P(\Omega)} d\Omega$$



- **ORCA6/ANTARES** skymaps:
  - Assume Gaussian distribution around true localisation
  - FWHM function of reconstructed neutrino energy, determined from simulations
  - Compute the angular separation vs reco energy of MC astro
  - Take the 68th percentile of the separation per bin of energy
- **LVK** skymaps:
  - **PyCBC**: Produced by BAYESTAR

Bayesian Ranking statistics

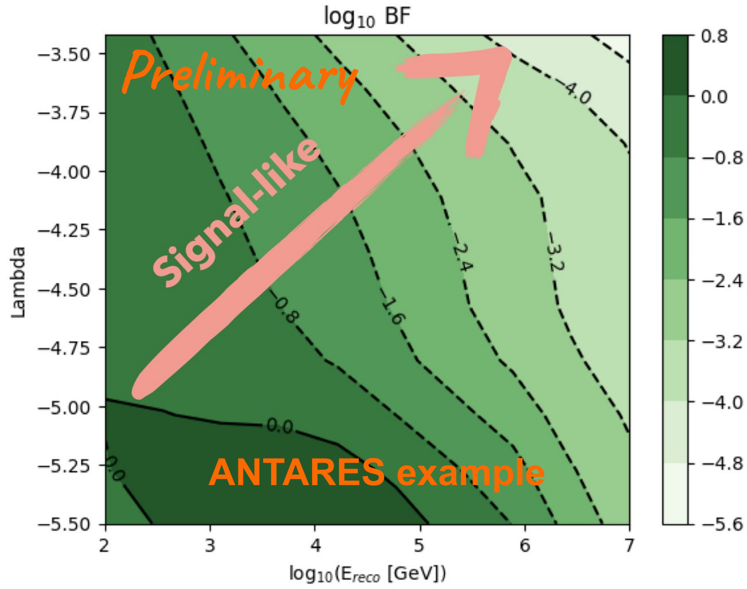
$$\boxed{\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}}$$

$\boxed{Q_\nu}$ → **Neutrino Bayes factor:** Estimate whether the HEN is astrophysical

KDE-based method trained on simulations:

$\log_{10}$(E$_{reco}$[GeV]) VS. **BDT score** (**ORCA6**)

$\log_{10}$(E$_{reco}$[GeV]) VS. Λ_ν (**ANTARES**)



Simulations:

Signal sample:
MC astrophysical neutrinos with **E$^{-2.5}$ spectrum** (see Naab 2023: 2308.00191)

Background sample:
MC atmospheric muons + neutrinos

Bayesian Ranking statistics

$$\boxed{\Lambda = \frac{I_{\Delta\mathrm{t}} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}}$$

$\boxed{Q_g}$ → **GW Bayes factor:** How likely is the GW candidate from astrophysical origin?

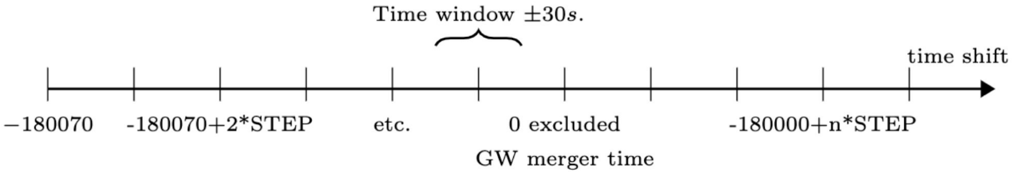
For **PyCBC:**

- Based on **Pillas et al. 2023** (2306.04373)
- Use the **BCI** :
  - Bayes factor estimating of the probability of the GW candidate to be coherent in the network

$$\frac{P(D_g | C + \text{Gaussian noise})}{P(D_g | I + \text{Gaussian noise})}$$

FAR estimation for the GW-HEN associations

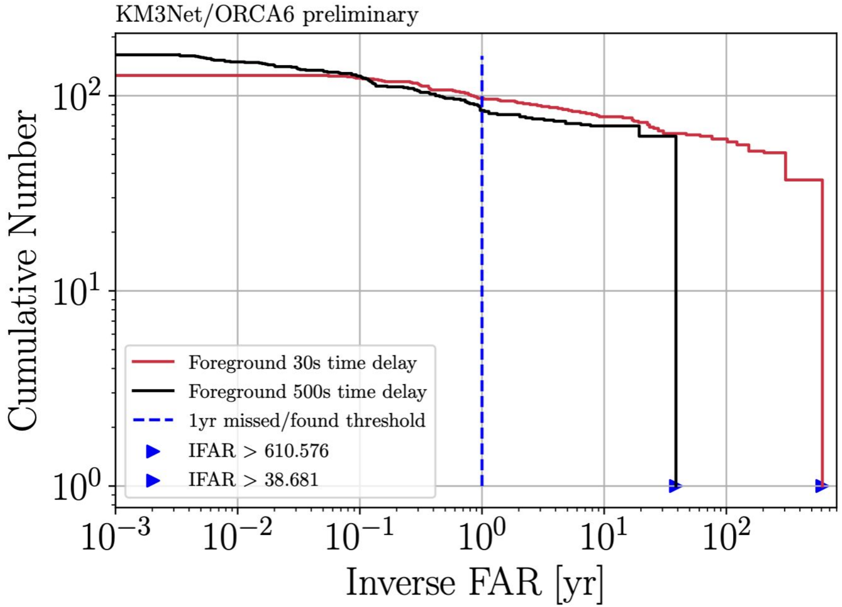
- Estimation of the Bayesian ranking statistic **foreground distribution**
- Time slides → Estimation of the RS **background distribution:**

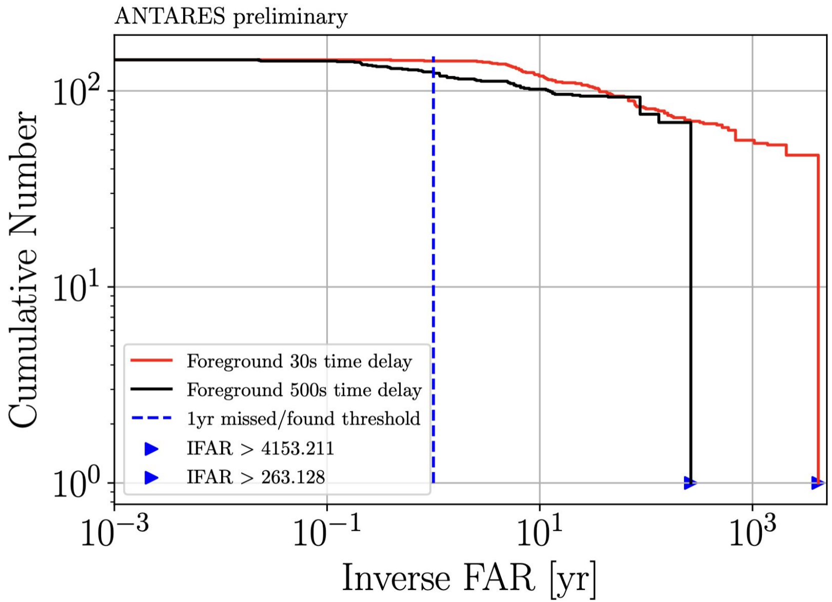


Time offset prior 2: Time window 500 s & STEP = 1100 s

- **False alarm rate** (FAR) estimated as: $$FAR = \frac{1 + n_b}{T_{coinc}}$$
  - n_b Number of background associations with RS > RS foreground association
  - T_{coinc}: Background livetime (Joint LVK and ANTARES/ORCA)

Validity check with PyCBC



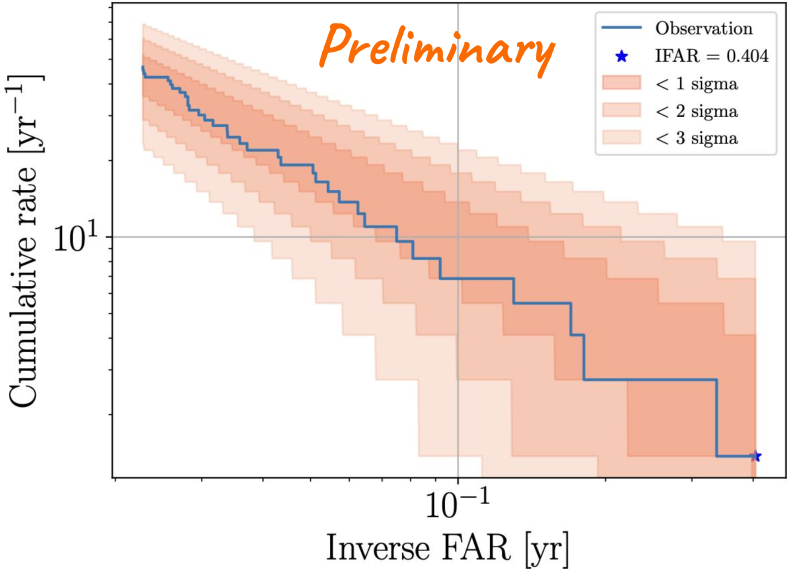


- Method validated on simulated associations
- Most of the injections are recovered
- Associations missed because of single detector GW obs and glitches in GW data

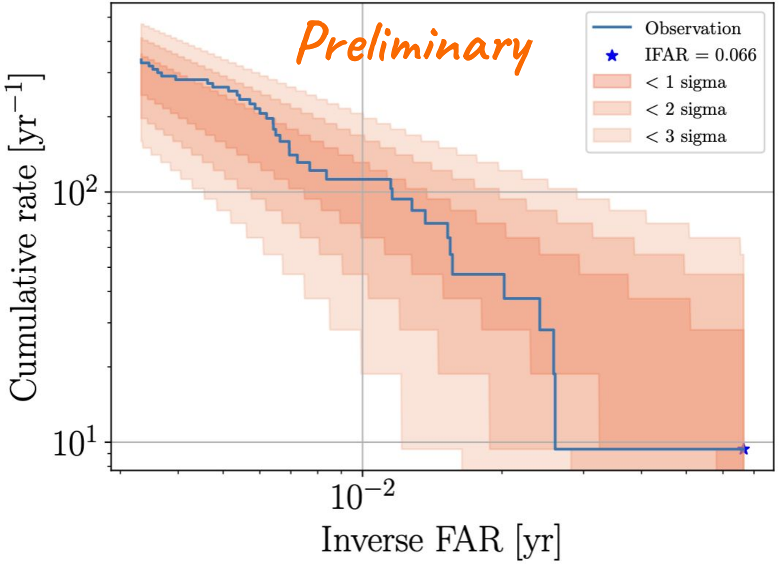
Results for PyCBC triggers

- For ANTARES: **3 associations** for **±30s prior** and **34 for ±500s**
- For ORCA: **2 associations** for **±30s prior** and **36 for ±500s**

ANTARES



ORCA6



Population Study

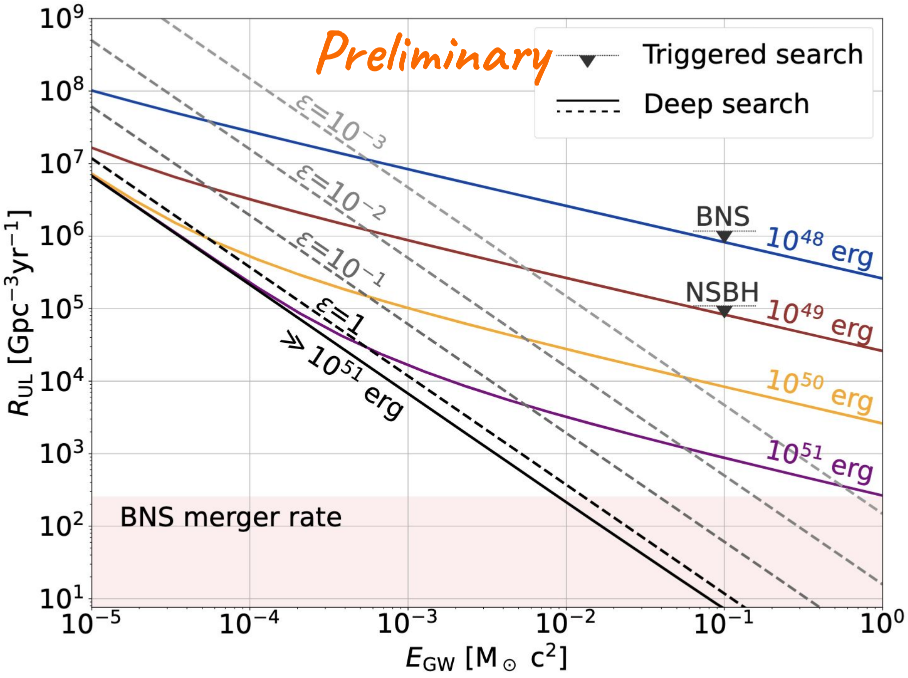
- No significant GW-HEN associations
- Use the significance to constrain the joint sources rate density

$$R_{\mathrm{UL}} = \frac{3.9 f_b}{T_{\mathrm{obs}}} \left[\int_0^{\infty} 4\pi r^2 p_{\mathrm{det}} dr \right]^{-1}$$

where:

$$p_{\mathrm{det}} = f_{\mathrm{GW},\nu,\mathrm{A}} \cdot p_{\mathrm{det},\nu,\mathrm{A}} + f_{\mathrm{GW},\nu,\mathrm{K}} \cdot p_{\mathrm{det},\nu,\mathrm{K}} - f_{\mathrm{GW},\nu,\mathrm{A}} \cdot f_{\mathrm{GW},\nu,\mathrm{K}} \cdot p_{\mathrm{det},\nu,\mathrm{A}} \cdot p_{\mathrm{det},\nu,\mathrm{K}}$$

- **Improvement by a factor ~7** compared to the O1 study by ANTARES, IceCube and LIGO collaborations 2018



Conclusion

Triggered search:

- Using Signalness for selecting HEN events - No candidates in ORCA6, 4 in ANTARES
- Used X-pipeline for finding weak GW signals
- **No significant foreground** associations found in O3 data

Modelled search:

- Used all the GW and HEN data available
- Bayesian ranking statistics
- **No significant coincidence found**

Population study:

- Improvement by a factor ~7 compared to O1 analysis

Future work:

- Ongoing work on the O4 data with both KM3NeT and IceCube
- Use the upcoming real time alerts for the triggered analysis (See M. Marconi’s Talk)
- Population study with KM3NeT using a Bayesian approach

BACKUP

Acronyms

BNS : Binary Neutron Star merger

NSBH : Neutron Star Black Hole merger

BBH : Binary Black Hole merger

AGN : Active Galaxy Nuclei

KDE : Kernel Density Estimator

ORCA6 : KM3NeT-ORCA detector with the 6 Data Units deployed

EM : Electromagnetic

FoV : Field of View

MMA : Multi-Messenger Astronomy

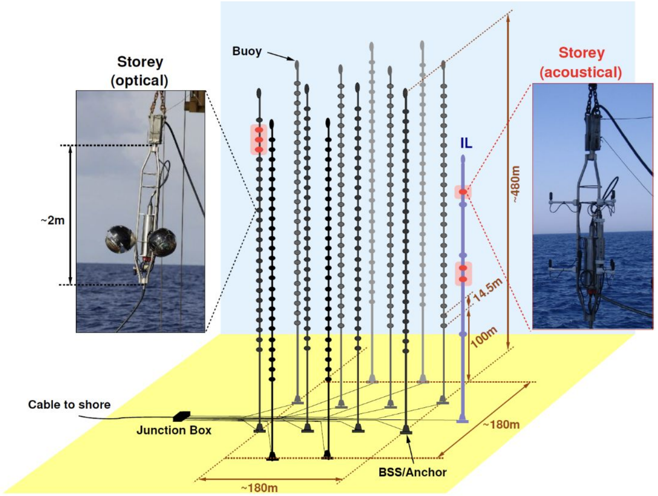
Triggered search results

HEN	Time [mjd]	Ra [deg]	Dec [deg]	E_{rec} [TeV]	Λ_ν -	β -	$\cos(\theta)$ -	Signalness $\mathcal{S}$	1σ sky localization error [deg]	p-value GW candidate
#1	58735.75391	92.2	44.8	47	-5.10	0.4	0.039	0.30	0.77	0.72
#2	58793.19922	241.5	27.7	513	-5.02	0.5	-0.0079	0.69	0.54	0.44
#3	58813.91406	156.4	-21.9	154	-4.88	0.3	0.55	0.54	0.64	0.50
#4	58931.10547	59.0	47.4	159	-5.16	0.5	-0.019	0.47	0.64	0.24

Waveform type	Frequency [Hz]	Duration Parameter [s]	E_{GW} $[M_\odot c^2]$
SGC-A	70	14×10^{-3}	0.01
SGC-B	100	11×10^{-3}	0.01
SGC-C	150	6.9×10^{-3}	0.01
SGC-D	300	3.4×10^{-3}	0.01
ADI-A	135-166	38.8	0.02
ADI-B	110-209	9.4	0.22
ADI-C	130-251	236	0.25
ADI-D	119-173	142	0.02
ADI-E	111-260	76	0.17

Datasets

2504.09473



- 12 lines - 70m appart
- 40 km offshore Southern France
- Started in 2007 - decommissioned in 2022
- Detects Cherenkov light emitted by the muons
- 10 GeV - 100 TeV sensitivity band

ANTARES & ORCA6

ANTARES: ~1.5k event

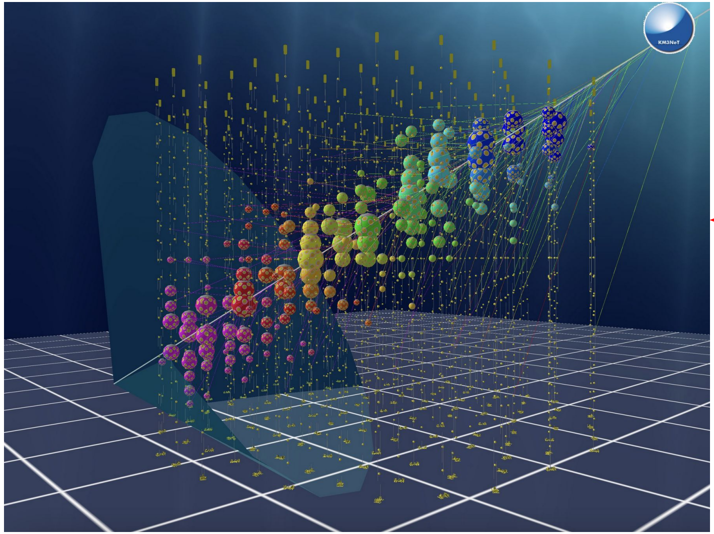
- Full detector
- $\cos(\theta)$ > -0.1 → Up-going events
- Λ_ν > -5.5 → Well reconstructed events
- 0 < β < 1 → Point-like sources

KM3NeT/ORCA6: ~1.5k events

- 6 lines detector
- track-like & upgoing
- with a reconstructed energy > 1 GeV
- with a BDT score > 1

Datasets

- 2 parts: ARCA (offshore Italy) and ORCA (offshore France)
- 6 lines deployed for ORCA at the end of O3
- Construction still ongoing
- Detects Cherenkov light emitted by the muons
- GeV - PeV sensitivity band for ORCA



ANTARES & ORCA6

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KM3NeT/ORCA6: ~1.5k events

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