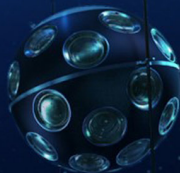




Joint sources of neutrinos and gravitational waves with ANTARES and KM3NeT

Dixième Assemblée Générale du GdR Ondes Gravitationnelles

Mathieu Lamoureux (APC/UPCité)
on behalf of the ANTARES & KM3NeT Collaborations



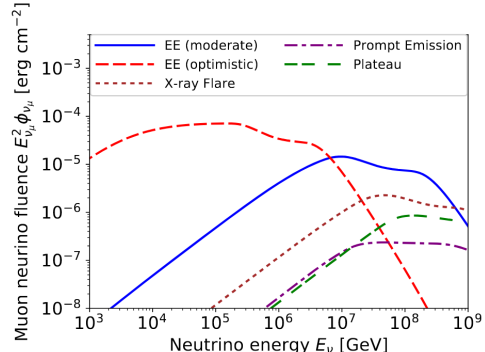
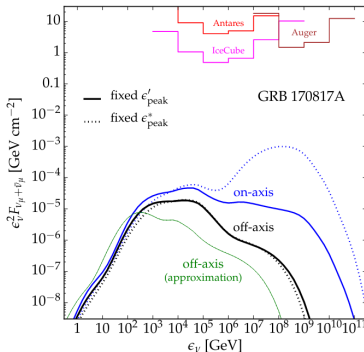
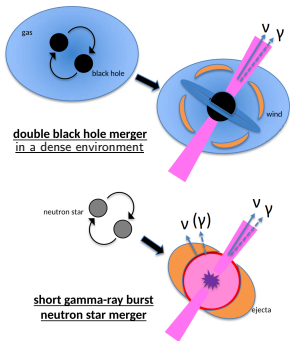
M.L. is funded by the European Union's Horizon Europe Research and innovation programme under Grant Agreement No 101131928.



Funded by
the European Union

Credits: ESO & KM3NeT

- Gravitational wave sources (compact binary coalescences, supernovae...) may also emit neutrinos.
- **No positive detections** so far. Exact timing and spectrum are still unknown.



Combine all available data from LVK runs and from ANTARES and KM3NeT neutrino telescopes to identify common sources and **constrain neutrino production mechanisms**.

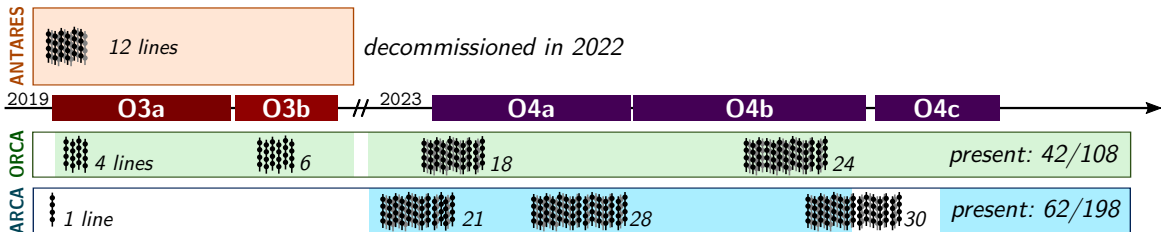
Detection principle: Cherenkov light induced by charged particles from neutrino interactions.

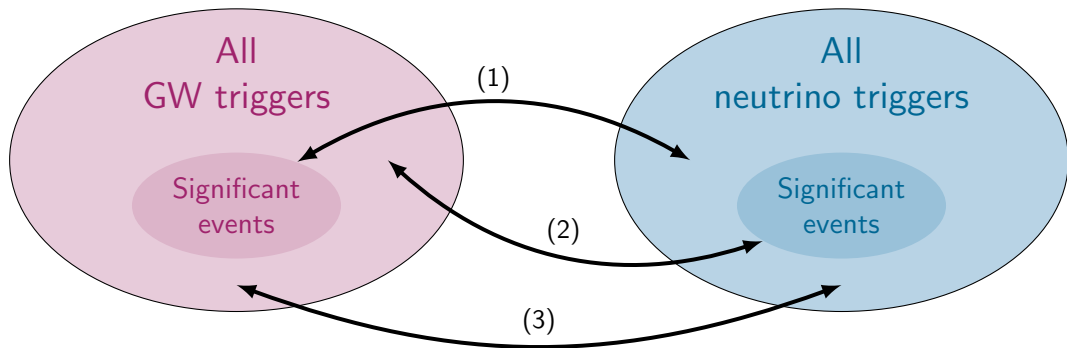
ANTARES

- In operation from 2006 to 2022.
- 40 km off the coast of Toulon (FR).
- 12 lines $\times$ 25 modules $\times$ 1 large PMT.
- Sensitive at TeV energies.

KM3NeT

- Distributed over two sites:
 - **ARCA** (Sicily, IT) optimized for TeV–PeV ν
 - **ORCA** (Toulon, FR) optimized for GeV–TeV ν
- ~ 300 lines $\times$ 18 modules (DOMs) $\times$ 31 PMTs.
- **Still under construction!**



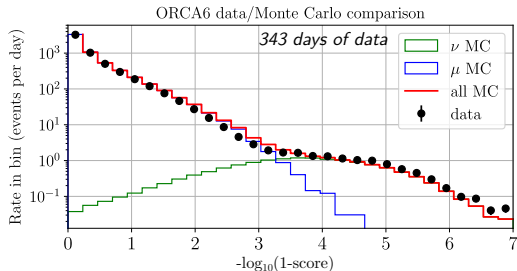


Three distinct approaches:

- ① Search for neutrino counterparts from **significant GW sources** (compact binary mergers).
- ② Search for GW signal in the direction of **neutrino “alerts” with high astrophysical probability**.
- ③ Joint deep search with **all neutrino and GW triggers**.

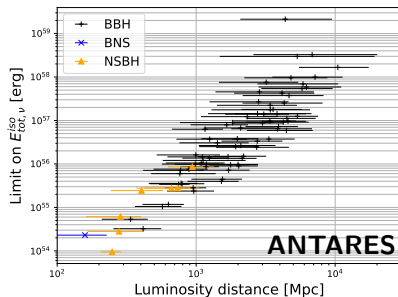
Selection

- Using track-like (**ANTARES**, **ORCA**) and shower-like (**ANTARES**) events.
- Selection robust against **fluctuating experimental conditions** (see current. . .).
 - ANTARES: based on event quality variable
 - ORCA: Boosted Decision Tree to remove muons
- Count events in $t_{\text{GW}} \pm 500 \text{ s}$ **time window**.



Statistical analysis

- Cuts **optimized** to reduce background to $\sim 2.7 \times 10^{-3}$ events in time window.
- Observed number of events **compared** to expected background.
- Bayesian **upper limits** computed with Poisson statistics.



- Define coincidence as at least 4 hits within 10 ns in a single DOM.
- Coincidence level = number of coincidences in a 0.5 s window, across the full detector.
- Compare **observed coincidence level** with the mean expected rate (from OFF windows).
- Convert to constraints on the number of signal events and **isotropic energy emitted in neutrinos** $E_{\text{tot},\nu}^{\text{iso}}$.



Coincidence

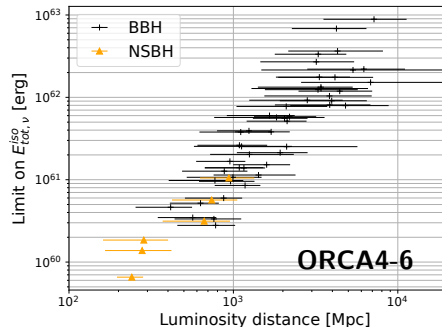
=
≥ 4 hits in 10 ns



Coincidence level

=
of coinc. in 0.5 s

No excess observed → upper limits on the isotropic energy $E_{\text{tot},\nu}^{\text{iso}}$



- Use significant neutrino triggers and search for **weak GW signals**.

- Can be not only CBC, but **also supernovae or other objects**.

- **Analysis process:**

- 1 Select significant triggers in ANTARES and ORCA6 data based on signalness parameter:

$$S(E_{\text{rec}}, \Lambda_\nu) = \frac{N_{\text{signal}}(E_{\text{rec}}, \Lambda_\nu)}{N_{\text{signal}}(E_{\text{rec}}, \Lambda_\nu) + N_{\text{background}}(E_{\text{rec}}, \Lambda_\nu)} > 0.3$$

reconstructed neutrino energy $\rightarrow E_{\text{rec}}$ (blue box)

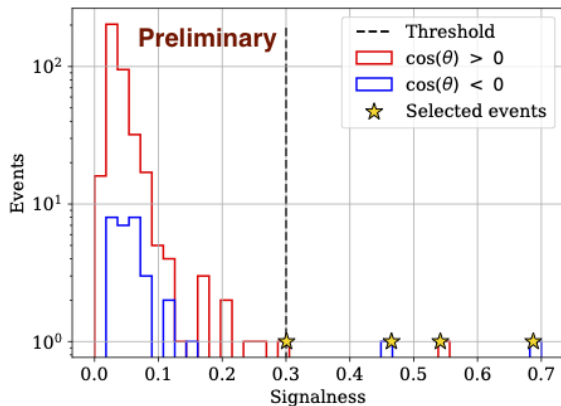
event quality $\rightarrow \Lambda_\nu$ (orange box)

estimated from simulations assuming $E^{-2.58}$ for signal $\rightarrow N_{\text{signal}}$ (grey box)

same cut as in the IceCube searches $\rightarrow 0.3$

- 2 Search for GW signal in a ± 500 s window centered on neutrino time, using the **X-Pipeline** code.
- 3 Background is estimated in 1000 s off-source windows.
- 4 Compute the significance of the association $\rightarrow$ p-value.

Similar searches have performed using IceCube realtime alerts and are ongoing with KM3NeT/ARCA.



4 candidates in ANTARES, 0 in ORCA6.

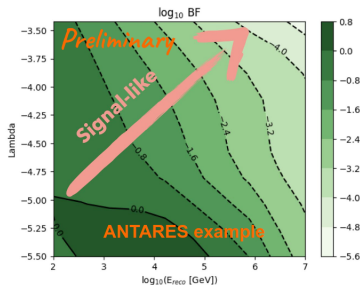
Time [mjd]	RA [deg]	Dec [deg]	$\mathcal{S}$ -	p_{GW} -
58735.75391	92.2	44.8	0.30	0.72
58793.19922	241.5	27.7	0.69	0.44
58813.91406	156.4	-21.9	0.54	0.50
58931.10547	59.0	47.4	0.47	0.24

- 4 triggered searches with X-pipeline and **no significant GW candidate identified.**
- **Upper limits on the rate density** for different types of waveforms:
 - BNS and NSBH
 - Sine-Gaussian Chirplet
 - Accretion Disk Instabilities.

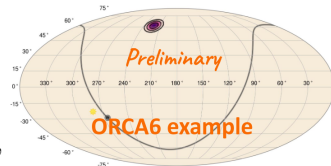
- 1 Get list of pairs of ANTARES or ORCA neutrino events with LVK triggers (O3).
- 2 Evaluate each possible pair with a Bayesian Ranking Statistic:

time overlap between the two candidates (± 500 s and ± 30 s windows)

sky overlap between GW and neutrino skymaps



$$\mathcal{R} = \frac{I_{\Delta t} \times I_{\Omega}}{1 + Q_{\nu} + Q_g + Q_g Q_{\nu}},$$

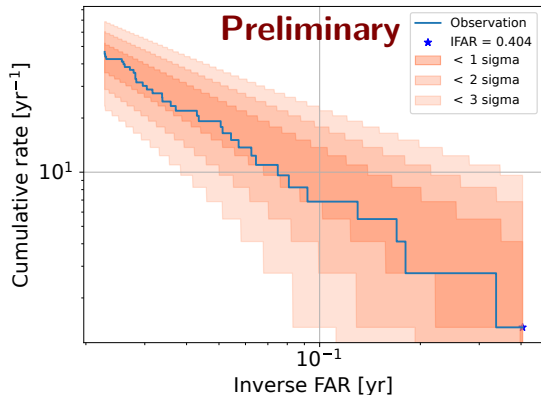


signal probability of the neutrino event

Bayes factor Coherence vs Incoherent from PyCBC

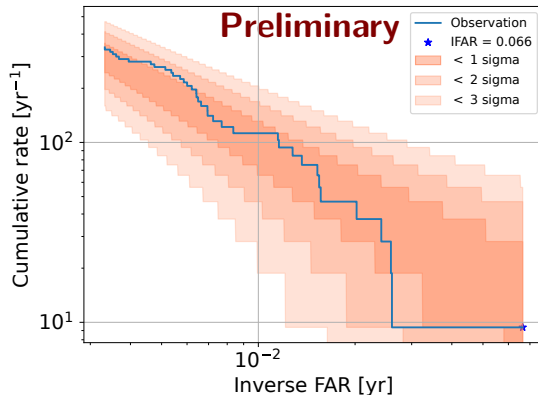
- 3 Compute $\mathcal{R}$ distribution for time-shifted data (background-only).
- 4 For observed pairs (no shift), compute **False Alarm Rate (FAR)** based on background distribution.
- 5 Validate the method by trying to **recover simulated associations**.

ANTARES



34 (3) pairs in ± 500 s (± 30 s)

ORCA6

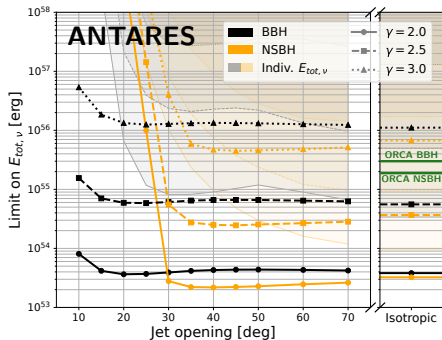


36 (2) pairs in ± 500 s (± 30 s)

No excess above the expected background behaviour.

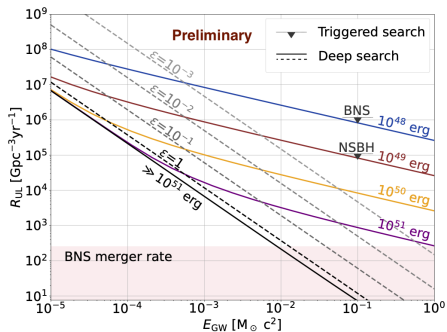
Approach (1)

- No neutrino excess observed.
- Limits on the **typical emission** per source:
 - total ν energy (isotropic or jetted emission)
 - ratio between ν and GW energy ($f_{\nu/\text{GW}}$)
- Stacking separately for BBH and NSBH.



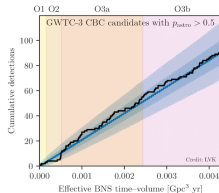
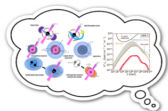
Approaches (2) and (3)

- Non-observation of significant associations.
- Constraints on the **joint source rate density**.

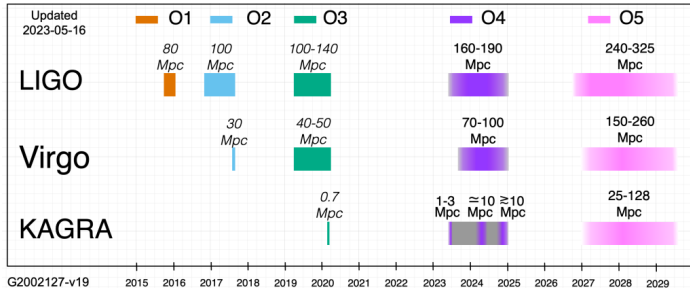


Factor 7 improvement compared to ANTARES + IceCube + LIGO O1 study.

- Some astrophysical sources may emit both neutrinos (MeV–PeV) and gravitational waves.
- **Three approaches** to identify common sources:
 - ① Search for neutrinos from detected CBCs.
 - ② Search for GW signal in temporal/spatial coinc with neutrino triggers.
 - ③ Symmetric searches using subthreshold $\text{GW} + \nu$ data.
- **No significant detection** so far:
 - Constraints on the total energy emitted in neutrinos from confirmed CBCs.
 - Upper limits on the rate of joint $\text{GW} + \nu$ sources.
- **Prospects:**
 - Common analyses will be reiterated with O4 period (using KM3NeT/ARCA).
 - Searches for neutrino counterparts of GW alerts are also performed in realtime with ORCA+ARCA.



Backups



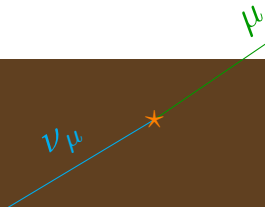
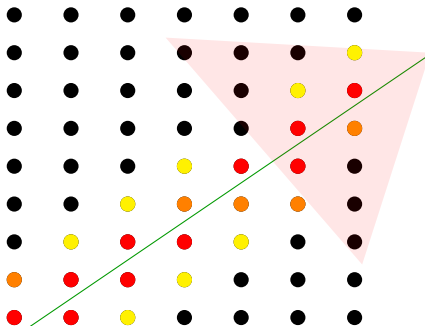
- Observations **since 2015**.
- Hundreds of significant detectors released in **published catalogs**.
- Thousands of subthreshold triggers.
- **Realtime alerts** shared with the community: $\sim 2 - 3$ significant alerts per week.
- Most critical characteristics for **multi-messenger analysis**:
 - nature of the source
 - localization
 - time

1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

TRACK EVENTS

$$\nu_{\mu} + N \rightarrow \mu^{-} + X$$

- fit line $\rightarrow$ direction
- amount of light $\rightarrow$ energy



- Define a **search time window** around the GW detection time.
- Look for neutrino events **in time window** and **in spatial correlation with GW localization**.
- Compare observations to the **expected background** (computation of significance, ...).
- Convert to **constraints on the incoming neutrino flux** assuming a given spectrum.

$$F(E) = \Phi \times (E/\text{GeV})^{-\Gamma} \Rightarrow \Phi^{\text{up}} = \frac{n_{\text{sig}}^{\text{up}}}{\int A_{\text{eff}}(E) \times (E/\text{GeV})^{-\Gamma} dE}$$

- Convert to **constraints on the source emission**.

$$E_{\nu, \text{iso}} = \frac{4\pi D_L^2}{1+z} \int F(E) \times E dE \quad \text{and} \quad f_{\nu/\text{GW}} = \frac{E_{\nu, \text{iso}}}{E_{\text{GW}}}$$

- Eventually perform **population studies** using **stacked analyses**.

