Neutrino search from Microquasars with KM3NeT

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Neutrinos from microquasars

The acceleration mechanism in the jets of microquasars is still unclear: both leptonic and hadronic scenarios are proposed.

A neutrino detection would confirm the presence of hadronic interactions and entitle microquasars as galactic cosmic-ray accelerators.

Neutrinos ($>$GeV) would be produced by the interaction of accelerated protons ($p.$) against matter or photons from the radiation field:

$$\left.\begin{array}{r} p. + p \rightarrow \pi^{\pm}, \pi^{0}, .. \\ p. + \gamma \rightarrow \Delta^{+} \rightarrow p\pi^{0} \text{ or } n\pi^{+} \end{array}\right\} \longrightarrow \left.\begin{array}{r} \pi^{\pm} \rightarrow \mu^{\pm} + \{\nu_{\mu}, \overline{\nu}_{\mu}\} \\ \pi^{0} \rightarrow \gamma\gamma \end{array}\right\} \longrightarrow \gamma(\text{GeV}), \nu$$

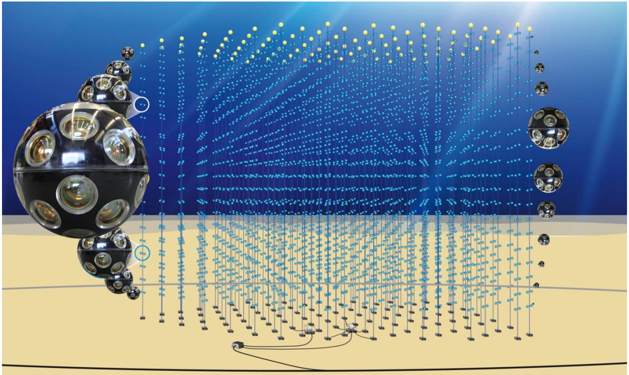
The KM3NeT experiment

KM3NeT is a neutrino telescope under construction on the seabed of the Mediterranean Sea, located at two sites: offshore Toulon, in France, at ~ 2.5 km of depth (**ORCA**); and offshore Portopalo di Capopassero, in Italy, at a depth of $\sim$3.5 km (**ARCA**).

Overall, 68 institutes, in 21 countries, from 5 continents.

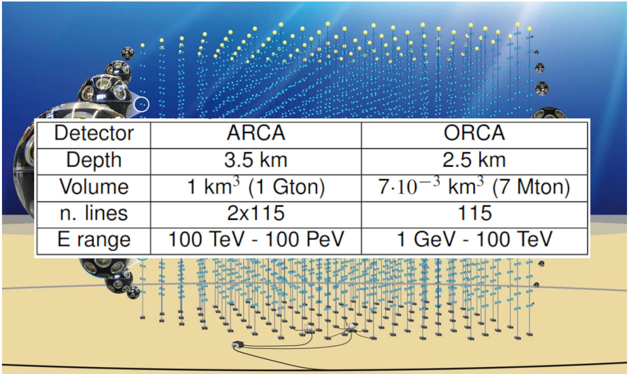
The KM3NeT experiment

The instrumented volume is filled with vertical strings (detection units) of interconnected optical modules (black spheres; 18 modules per line), each one provided with 31 photo-multiplier tubes (PMTs).



The KM3NeT experiment

The detector is **under construction, but already operating** with 33 strings (ARCA) and 28 strings (ORCA). By 2030, the final KM3NeT detector:



Detector	ARCA	ORCA
Depth	3.5 km	2.5 km
Volume	1 km^3 (1 Gton)	$7 \cdot 10^{-3}$ km^3 (7 Mton)
n. lines	2x115	115
E range	100 TeV - 100 PeV	1 GeV - 100 TeV

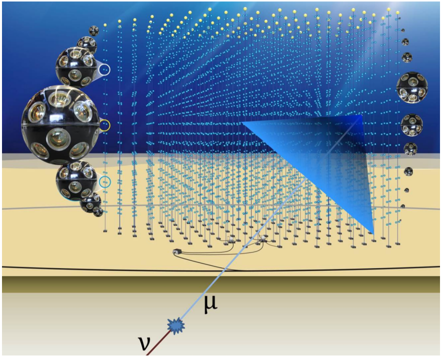
The KM3NeT experiment - neutrino interactions

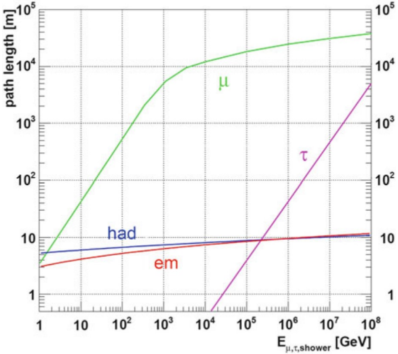
Neutrinos ($>$GeV) interact with a nucleon N in the detector, through charged-current (CC) or neutral-current (NC) interactions (X refers to the nucleon fragmentation):

$$\text{CC:} \quad \{\nu, \overline{\nu}\}_{\{\mu,e,\tau\}} + N \rightarrow \{\mu, e, \tau\}^{\pm} + X$$

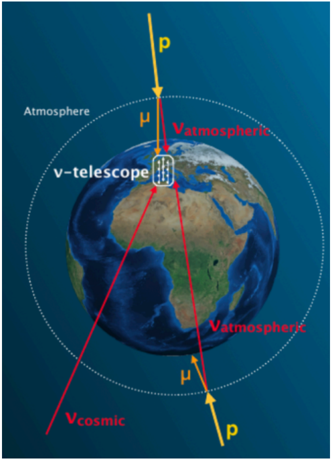
$$\text{NC:} \quad \{\nu, \overline{\nu}\}_{\{\mu,e,\tau\}} + N \rightarrow \{\nu, \overline{\nu}\}_{\{\mu,e,\tau\}} + X$$

The events generated by muon neutrinos (CC) are called track-like events, as the lepton travels great distances in a straight line:





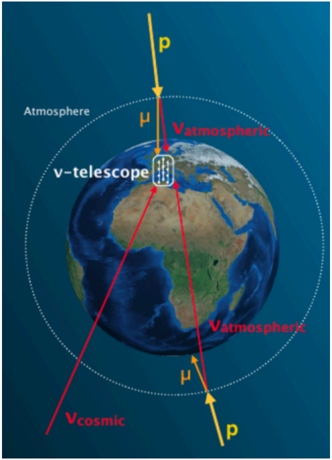
The KM3NeT experiment - neutrino interactions



Cosmic ray interactions in the atmosphere generate a background of energetic muons that reach the detector before decaying (atmospheric muons), and neutrinos that can cross the Earth, given the low cross-section (atmospheric neutrinos).

Particle	Rate	Direction
Atm. μ	$10^8 - 10^{10}$/yr	down-going
Atm. ν	$10^5 - 10^6$/yr	all-sky
Cosmic ν	100 - 500 /yr	all-sky

The KM3NeT experiment - neutrino interactions



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One way to reduce the atmospheric background is to look for neutrinos in a <u>short time window</u> and <u>going upward</u>.

The analysis

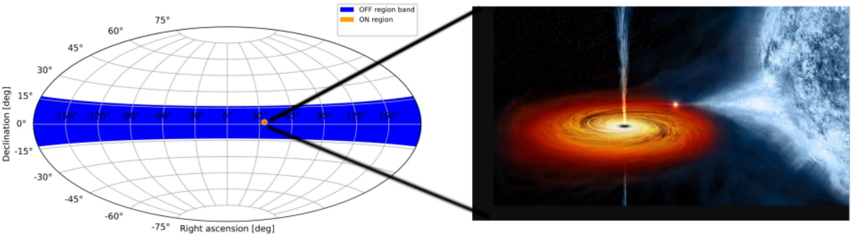
Data collected between February 11, 2020, and August 31, 2023, for about $\sim$**1000 days of livetime** (after data quality criteria + up-going track event selection), i.e., from ORCA6 to ORCA18*.

We run the **search in correlation with X-ray flares** (days-long time windows) associated with periods of hard X-ray states and state transitions, since they correspond to phases where relativistic jets are present.

*With ORCAX we refer to the geometry containing X detection lines.

The analysis

The analysis is based on the ON/OFF technique: use the OFF region to estimate the background expected in the ON region.



Since the neutrino distribution is uniform in right ascension, then the background is estimated in a declination band around the source (in blue, the OFF region). The signal is estimated in a circular region (in orange, the ON region), through Monte Carlo simulations of neutrinos generated from an E^{-2} spectrum.

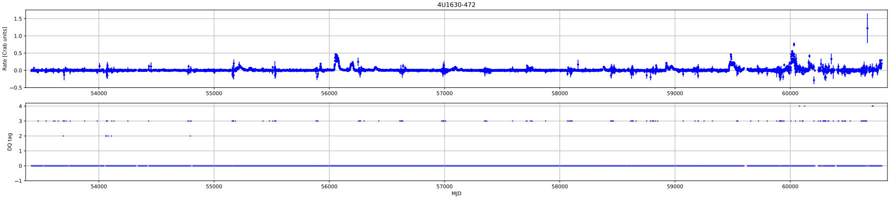
Sources selection

We select sources that flared either in the soft or hard X-ray band, during the ORCA data-taking, visible by the detector.

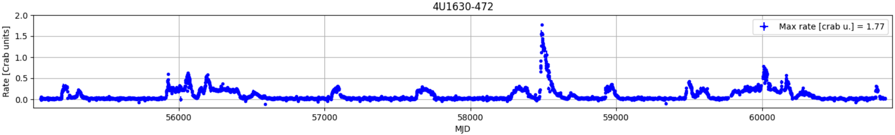
Name (alternative name)	Type	RA (J2000)	DEC (J2000)	Light curves
4U 1630-472 (Nor X-1)	LMXB/BHC	Swift: 248.504 MAXI: 248.502	Swift: -47.3930 MAXI: -47.394	Swift/BAT MAXI
Aql X-1 (V1333 Aql)	LMXB/NS	Swift: 287.817 MAXI: 287.817	Swift: 0.58500 MAXI: 0.585	Swift/BAT MAXI
GRS 1915+105 (V1487 Aql)	LMXB/BH	Swift: 288.798 MAXI: 288.798	Swift: 10.9460 MAXI: 10.946	Swift/BAT MAXI
GX 339-4 (V821 Ara)	LMXB/BH	Swift: 255.706 MAXI: 255.706	Swift: -48.7900 MAXI: -48.790	Swift/BAT MAXI
IGR J17091-3624 (SAX J1709.1-3624)	LMXB/BHC	Swift: 257.282 MAXI: /	Swift: -36.4070 MAXI: /	Swift/BAT MAXI: /
XTE J1701-462 ([KRL2007b] 214)	LMXB/NS	Swift: 255.243 MAXI: 255.244	Swift: -46.1860 MAXI: -46.186	Swift/BAT MAXI

X-ray light curves

The daily-averaged light curves are downloaded from the Swift/BAT transient monitoring webpage and the MAXI website.



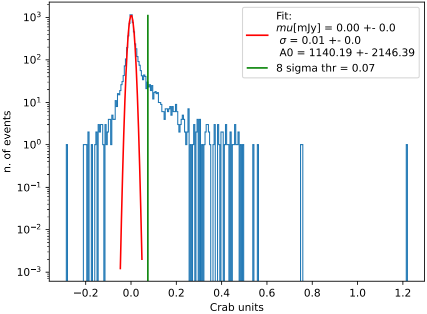
Top: Swift/BAT light curve in Crab units for 4U 1630-472; bottom: Swift/BAT data quality flag associated with each point.



MAXI light curve in Crab units for 4U 1630-472.

Flare selection

The flare selection is as straightforward as it might look.



We first fit the baseline rate (figure on the left), where μ is the mean, σ the standard deviation of the Gaussian curve (in red). Subsequently, we identify the peaks of the flares by selecting rate points that are 8σ above the mean, even considering their error:

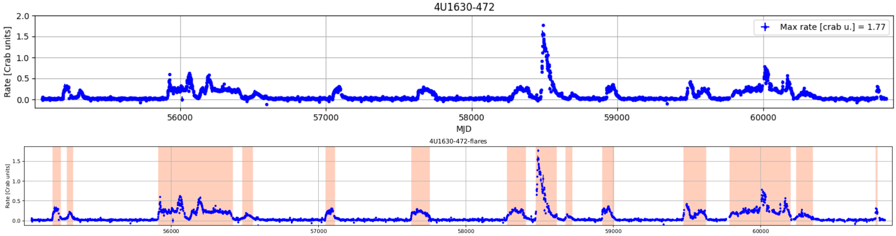
$$r - \Delta r > \mu_{\mathrm{BL}} + 8\sigma_{\mathrm{BL}}$$

Nextly, we include the rise and the fading of each flare by including points that satisfy:

$$r - \Delta r > \mu_{\mathrm{BL}} + 4\sigma_{\mathrm{BL}}$$

Flare selection

The final flare selection for 4U 1630-472 looks like the following:



When the same flare is recorded by both Swift/BAT and MAXI, we take the greatest time window expansion as the total flare duration.

Results

Source	**4U 1630-472**	**GX339-4**
R_{ON} [deg]	1.46	1.84
N_{ON}	6	2
Flaring time [days]	461	325
Exp.Bkg	2.91 $\pm$ 0.06	2.92 $\pm$ 0.08
p-value (pre-trial)	7.50%	78.89%
p-value (post-trial)	17.50%	100%
Φ_0^{UL} [GeV-1 cm-2 s-1]	1.20e-05	7.41e-06

Preliminary!

Source	**Aql X-1**	**GRS 1915+105**	**IGR J17091-3624**	**XTE J1701-462**
R_{ON} [deg]	1.96	2.22	2.96	1.73
N_{ON}	1	0	0	1
Flaring time [days]	139	106	9	136
Exp.Bkg	$(9.77 \pm 0.41) \cdot 10^{-1}$	$(8.62 \pm 0.44) \cdot 10^{-1}$	$(3.40 \pm 0.40) \cdot 10^{-1}$	1.36 $\pm$ 0.05
p-value (pre-trial)	62.36%	100%	100%	74.28%
p-value (post-trial)	98.90%	100%	100%	99.60%
Φ_0^{UL} [GeV-1 cm-2 s-1]	2.44e-05	2.12e-05	7.66e-04	6.42e-05

Post-trial p-value computed through 1000 pseudo-experiment generation.

The most relevant source is **4U 1630-472** with **6 ON events** at post-trial = **17.5**%. Yet, the number of detected neutrinos is not enough to claim any neutrino emission.

Summary and perspective

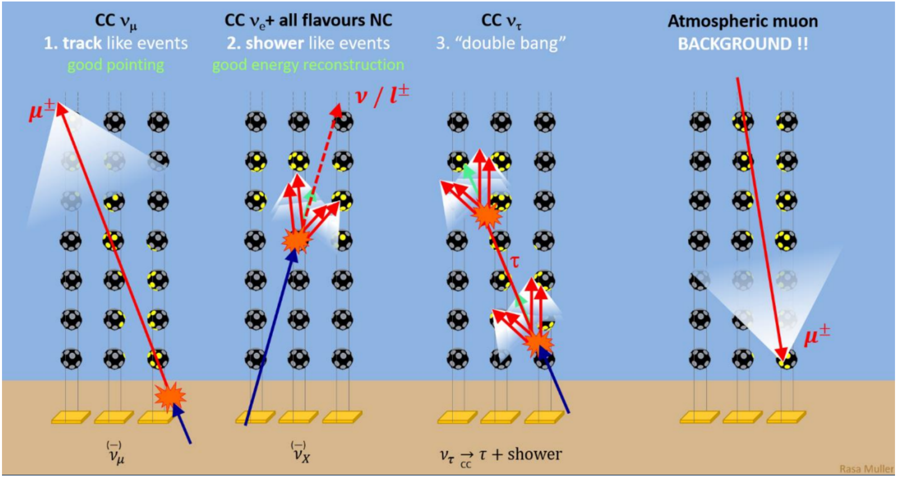
A first analysis of multiple flaring microquasars was performed with KM3NeT/ORCA data. No significant excess was found.

- The ARCA data set is being included these days.
- Also, we are working on a selection of shower events as well.
- include ARCA33 and ORCA28 data.

Neutrino telescopes can put constraints on microquasars relative to their hadronic accelerations and high-energy production.

Backup slides.

The KM3NeT experiment - event topology



Sources selection - KM3NeT visibility