Multi-messenger astronomy with KM3NeT and SVOM/COLIBRÍ

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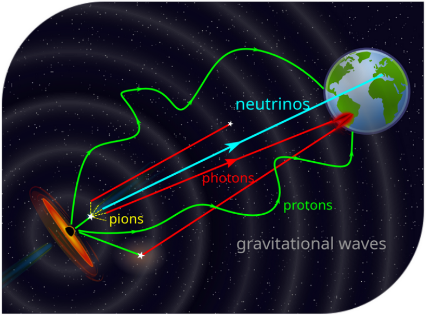
CPPM 3rd-year PhD seminar, December 8, 2025

Multimessenger astronomy

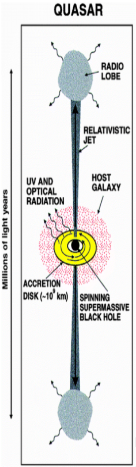
When we talk about multi-messenger astronomy, we refer to the combination of different messengers to study the same astrophysical sources.

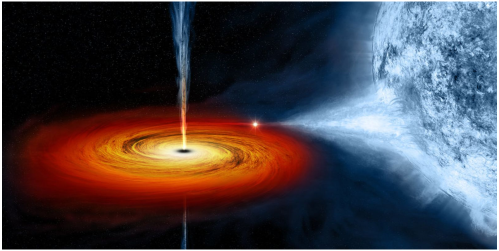


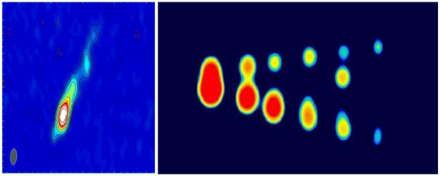
- Cosmic rays: imprints of the acceleration region, but deviated by magnetic fields;
- photons: emitted by both leptonic and hadronic processes, but absorbed in dense sources or by the ISM.
- neutrinos: emitted in hadronic processes only, they can escape dense environments thanks to the low cross-section, but need big volumes to be detected.
- gravitational waves: merge signature of compact objects, and rotational information, but very sensitive interferometers are needed.

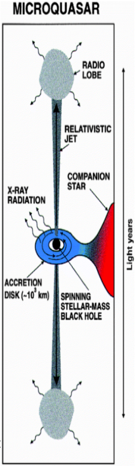
Microquasar general picture

Microquasars are galactic X-ray Binaries with a donor star accreting matter around a compact object, from which, sometimes, relativistic jets are launched (similarly to quasars).







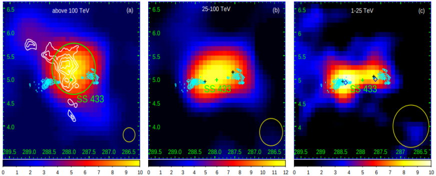


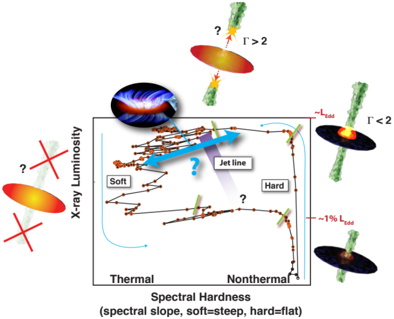
Bottom left: steady marcsec-scale radio jet from Cyg X-1 (A. M. Stirling et al.); Bottom right: transient arcsec-scale radio jet from GRS 1915+105 (Mirabel et al.).

Microquasar states

Microquasars follow an hysteresis cycle that alternates between hard and soft states, during which jets are emitted or quenched, respectively.

The presence of jets allows for particle acceleration. The acceleration can be leptonic, hadronic, or both.





(left) Significance maps of the SS 433 detection by Large High Altitude Air Shower Observatory (LHAASO) at different energy bands, see LHAASO Collaboration. (right) Typical hysteresis cycle of microquasar GX 339-4. Different disk-jet configurations are shown. Figure from Romero at al..

In the case of hadronic accelerations, then neutrinos are produced and can travel straight towards the Earth.

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

The KM3NeT experiment

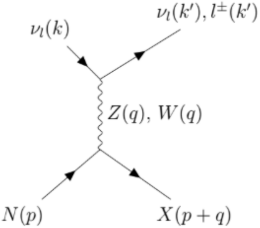
KM3NeT is a neutrino telescope under construction on the seabed of the Mediterranean Sea, located at two sites: offshore Toulon, in France, at ~ 2.5 km of depth (**ORCA**); and offshore Portopalo di Capopassero, in Italy, at a depth of $\sim$3.5 km (**ARCA**).

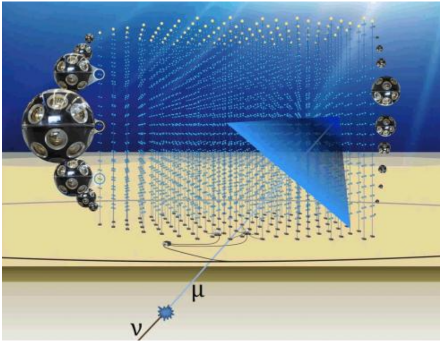
Overall, 68 institutes, in 21 countries, from 5 continents.

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).

Energetic neutrinos interact with nucleons (N) through deep-inelastic scattering, producing charged-current or neutral-current interactions.





The resulting charged lepton travels faster than light in water, hence, Cherenkov radiation is produced.

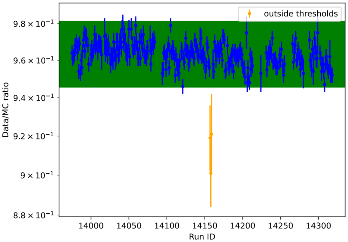
KM3NeT and microquasars - event selection

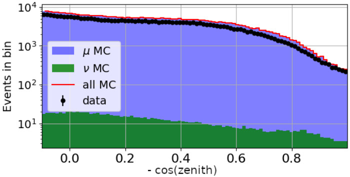
I am leading the search for a neutrino signal from Microquasars within the KM3NeT Collaboration. We want to check if microquasars emit neutrinos that would confirm hadronic accelerations.

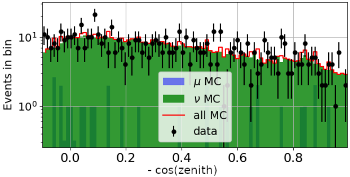
Before starting the analysis with KM3NeT, I took part in the definition of the event selection of ORCA.

1. data quality: assure stable data-taking conditions through the data/MC ratio.

2. Suppress the background: we developed a Boosted Decision Tree to disentangle neutrinos from the sea of atmospheric muons.

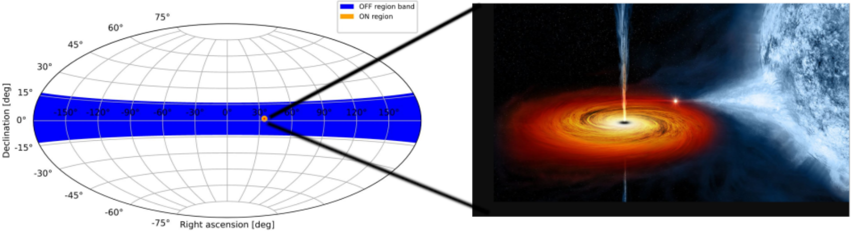






KM3NeT and microquasars - the analysis strategy

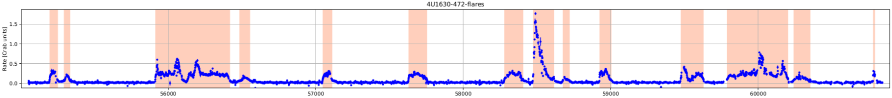
The study is performed on KM3NeT data, from 2020 up to the end of 2023 (a search on more recent data might be performed next year). The following results are obtained with the ORCA detector only, as the ARCA part is currently under revision.



The analysis technique is based on the ON/OFF method: define ON region as the signal region (microquasar), the OFF region to estimate the background.

KM3NeT and microquasars - the analysis strategy

Using X-ray data, we selected the few sources that went into outburst during the KM3NeT data-taking.



MAXI light curve for 4U 1630-472. Along the y-axis, the rate in Crab units, over the x-axis, the MJD. The outbursts are highlighted in salmon.

Objective: discover a flux of neutrinos from microquasars, during outbursts.

We get the best sensitivity by minimizing the Model Rejection Factor (MRF), assuming a neutrino spectrum distributed as E^{-2}.

$$\mathrm{MRF} = \bar{\mu}_{90} / n_s \qquad \bar{\mu}_{90}(n_b) = \sum_{n_{obs}=0}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{(n_{obs})!} \exp(-n_b)$$

$\overline{\mu}_{90}$ is Feldman-Cousins upper limit the expected background n_b (OFF band background rescaled to ON region) averaged by the poisson probability with mean = n_b.
n_s is the total expected cosmic signal in ON region.

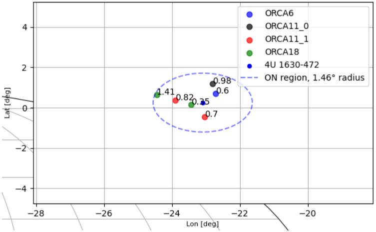
KM3NeT and microquasars - ORCA results for 4U 1630-472

Reminder: ORCA results only so far; ARCA analysis under revision.

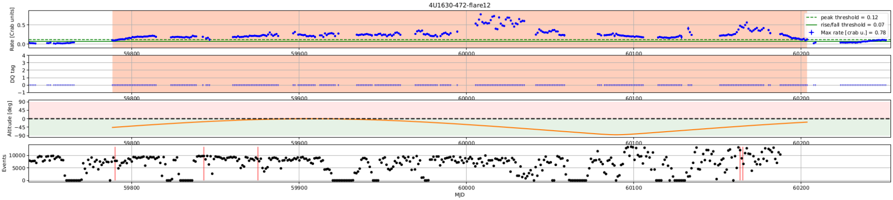
PRELIMINARY

Exp. Bkg	Exp. Sgn.
2.91	9.54e-2

nON (< 1.46 deg)	**p-value** (post-trial)
6	17.5%



Five ON events come from the same flaring period.



The interpretation is still ongoing...

Not only neutrinos from microquasars...

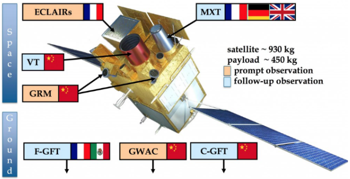
COLIBRÍ: an optical/NIR telescope

1.3m-diameter telescope located at the National Astronomical Observatory of Mexico, in San Pedro Mártir, Baja California, at 2.8 km.

Two instruments in three simultaneous channels:

- DDRAGO: 26’ FoV, two optical channels: (B, g, r, i, gri), and (z, y, zy)
- CAGIRE (from 2026): 21’ FoV, one infrared channel J/H

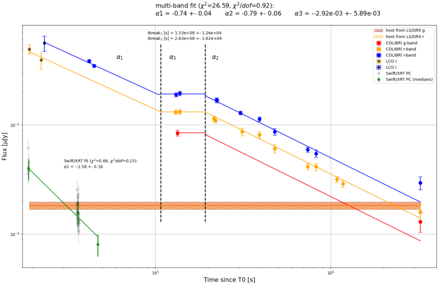
Key member of the SVOM mission for the identification and the ground follow-up of GRB optical afterglows.



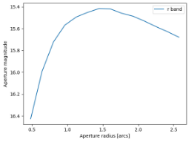
COLIBRÍ reduction and analysis pipeline

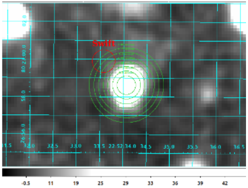
The main science of COLIBRÍ is the follow-up of GRB, in which I am also involved.

In particular, every month I perform multiple shifts and I am leading a paper on a GRB:



PRELIMINARY



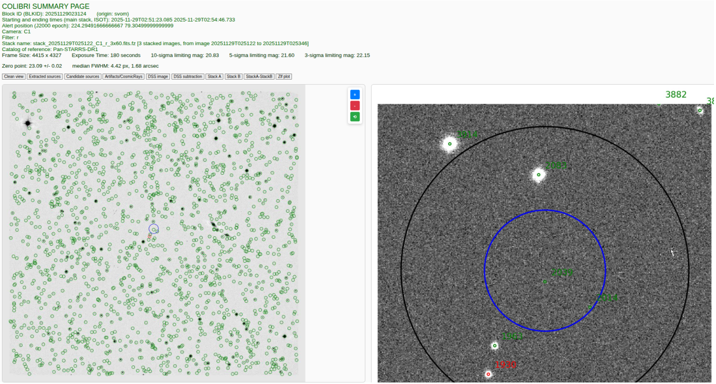


GRB models fitting and host photometry SED studies.

COLIBRÍ reduction and analysis pipeline

COLIBRÍ has a dedicated reduction and analysis pipeline, for which CPPM is the laboratory responsible. I took part in the development, mainly of the analysis part.

In a few minutes from a GRB alert arrival, we are able to produce: (1) a summary page with all the analysis information (cataloged sources, uncataloged sources, cataloged sources with high magnitude variation)



COLIBRÍ reduction and analysis pipeline

In a few minutes from a GRB alert arrival, we are able to produce: (1) a summary page with all the analysis information (cataloged sources, uncataloged sources, cataloged sources with high magnitude variation); (2) a list of candidates ordered by brightness; (3) for each candidate, all the information necessary for posting a GCN are provided, together with a preliminary fit of the light curve.

Source 1930

Trigger summary (external alert)

Trigger time [ISOT]	2025-11-29T02:31:24.697
Trigger coordinates (J2000)	224.2949 79.3050 +/- 0.0070 deg (0.4200 arcmin, 25.2000 arcsec)

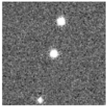
COLIBRÍ summary (main stack)

Coordinates [J2000]	Distance from alert [deg]	Magnitude [AB]	Detection (main stack)	Detection (stack A)	Detection (stack B)
224.3287 79.2930 +/- 0.0001 deg (0.5 arcsec)	0.0135 (0.81 arcmin, 48.6 arcsec)	18.24 +/- 0.03	92σ	58σ	75σ

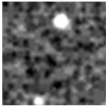
Catalogs summary

Coordinates (Pan-STARRS-DR1)	Magnitude (Pan-STARRS-DR1) [AB]	Coordinates (LegacySurvey-DR10) [J2000]	Magnitude (LegacySurvey-DR10) [AB]	Solar system object [J2000 epoch, AB mag]
none none	none +/- none	none none	none +/- none	none

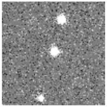
Source visualization



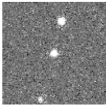
Full stack frame



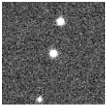
DSS frame



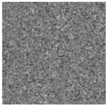
Median stack



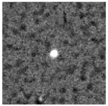
Stack A frame



Stack B frame



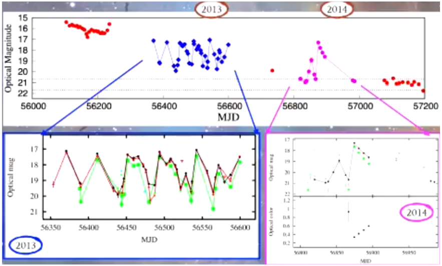
stackA-stackB subtraction

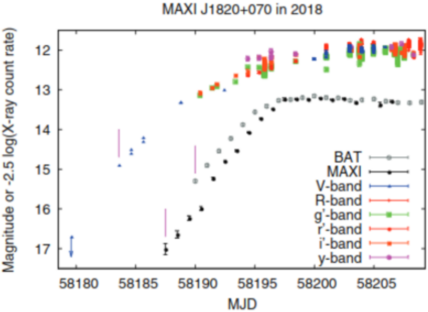


DSS subtraction

Microquasars in optical

Recently, I have worked on the writing of two proposals to observe microquasars with COLIBRÍ: (1) monitor and study the quiescent phase, when L_X is too low; (2) catch the beginning of an outburst and correlate the optical emission during full duration with X-rays (SVOM ToO, Swift/BAT, MAXI).





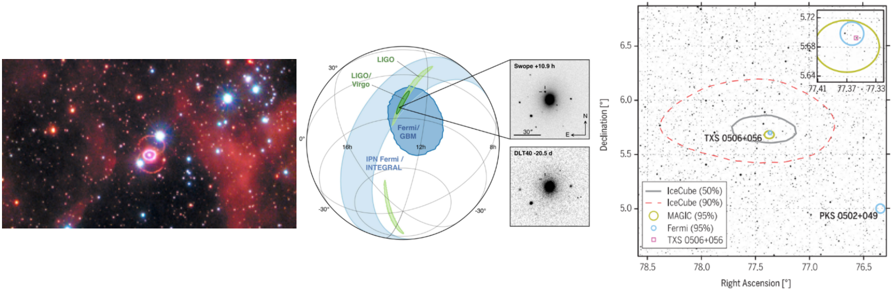
The observations will start soon.

Thank you :)

Backup slides.

Multimessenger astronomy milestones

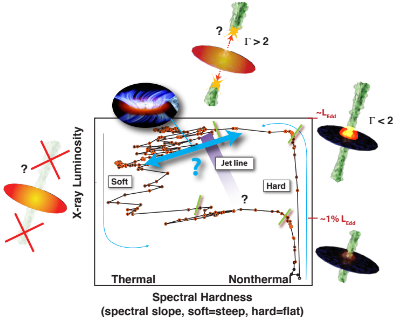
Young research field, but a few (important!) milestones:



From left to right: (1) neutrinos from SN 1987A (Kamiokande, IMB, Baksan); (2) gravitational waves from neutron star binary merge GW170817/GRB170817 (LIGO, VIRGO, Fermi, ...); (3) neutrinos from blazar TXS 0506+506 (IceCube, Fermi).

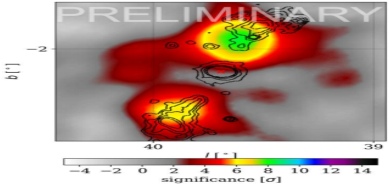
Microquasar states

- Quiescence: cold and trunkated disk; low accretion rate
- Hard State: hard X-ray spectrum; steady compact jet; increase in the accretion rate, and at a certain point, the heat waves are generated (due to disk instabilities).
- Hard State → Soft State transition: when the heat waves reach Rin → outburst release; violent, rapid and relativistic jet.
- Soft State: quenched/suppressed jet

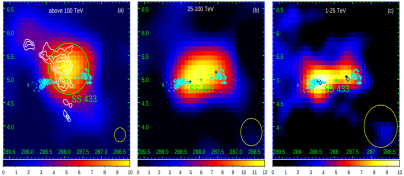


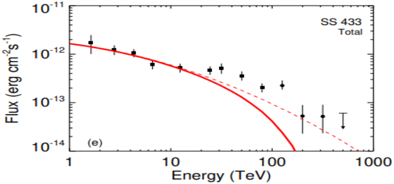
Microquasars at high energy

Electromagnetic radiation observed from soft (100 keV) to VHE (100 TeV) energies:



(left) The High-Altitude Water Cherenkov experiment (HAWC): a cosmic and gamma-ray observatory located on the Sierra Negra volcano in the Mexican state of Puebla, at an altitude of 4.1 km. (right) HAWC's detection of SS 433 at TeVs. The lobes are detected at 7 and 9σ significance; the red cross is the compact object; the black lines are the X-ray contours by ROSAT. See O. Tibolla et al..

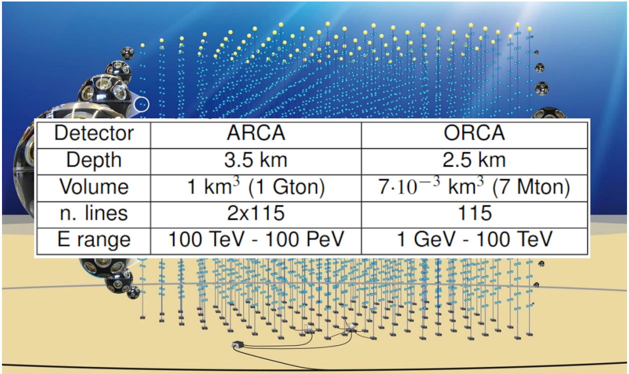




(left) Significance maps (three, left) and the SED (right) of the SS 433 detection by Large High Altitude Air Shower Observatory (LHAASO), a cosmic- and gamma-ray observatory in DaoCheng (Sichuan, China), at an altitude of 4.4 km. In dashed red, a leptonic fit with the IC contribution as a thick red line. See LHAASO Collaboration.

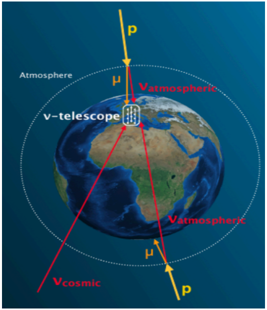
The KM3NeT experiment

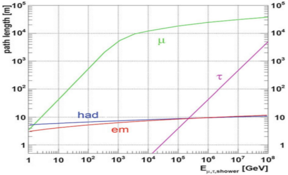
The detector is **under construction, but already operating**. Currently, 51 strings (ARCA) and 28 strings (ORCA) are deployed on the seabed. By 2030, the final KM3NeT detector:



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 - event topology





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

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

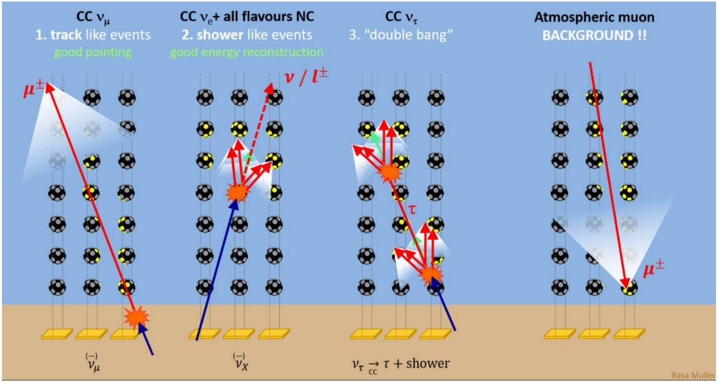
One way to reduce the atmospheric background is to look for neutrinos in a short time window and going upward.

The KM3NeT experiment - event topology

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):

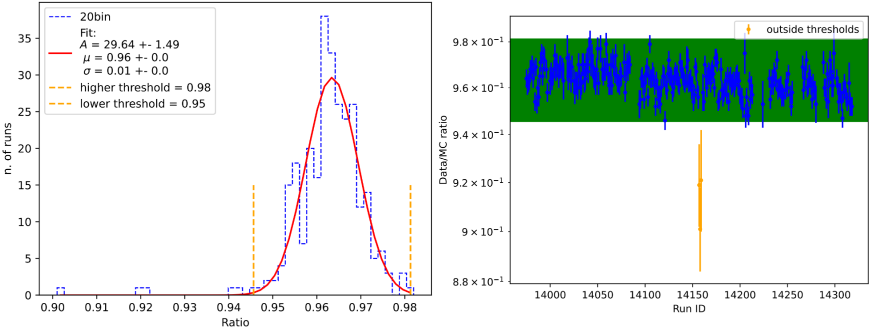
$$\text{CC:} \quad \{\nu, \overline{\nu}\}_{\{\mu,e,\tau\}} + N \rightarrow \{\mu, e, \tau\}^{\pm} + X$$

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



KM3NeT data quality

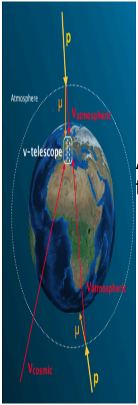
We reject data runs on the basis of the data/MC agreement.

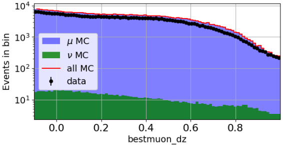


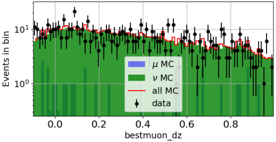
The data/MC ratio distribution is fairly Gaussian: the runs falling outside μ +/-3σ are rejected.

KM3NeT background suppression

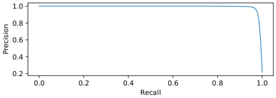
Atmospheric muons make up a huge background.

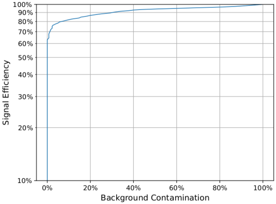




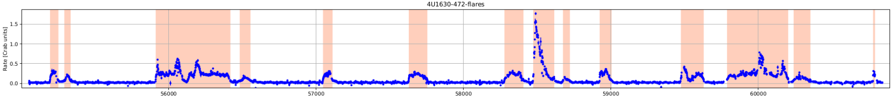


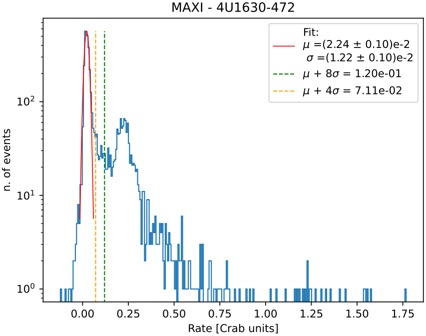
A Boosted Decision Tree is trained to classify atmospheric muons and neutrinos.





Flare selection





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:

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

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

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

Source selection

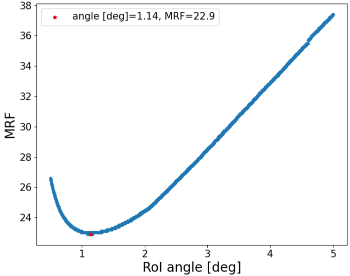
We select sources that flared either in the soft or hard X-ray band, during the KM3NeT data-taking, and that are visible in the up-going sky.

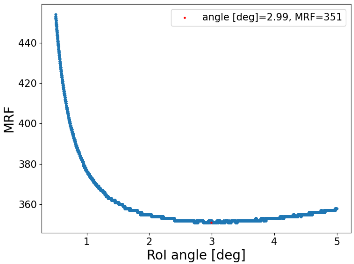
Name (alternative name)	Type	RA (J2000)	DEC (J2000)	Light curves
4U 1630-472 (Nor X-1)	LMXB/BHC	Swift: 248.504 MAXI: 248.502	Swift: -47.3930 MAXI: -47.394	Swift/BAT MAXI
Aql X-1 (V1333 Aql)	LMXB/NS	Swift: 287.817 MAXI: 287.817	Swift: 0.58500 MAXI: 0.585	Swift/BAT MAXI
GRS 1915+105 (V1487 Aql)	LMXB/BH	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

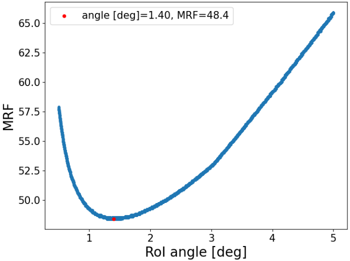
LMXB = Low-Mass X-ray Binary; BH = the compact object is a Black Hole; NS = the compact object is a Neutron Star; BHC = the compact object is more probably a Black Hole.

A couple of additional sources could be included.

Optimization

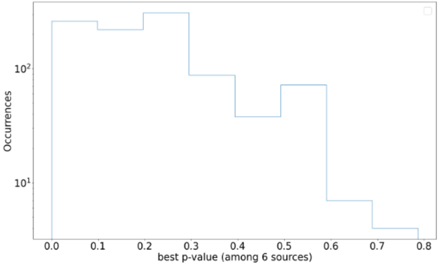


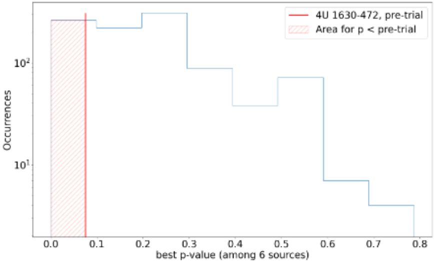




Post-trial correction

Single p-values do not take into account for the possibility of getting a better p-value just by chance.
To correct for this, we run 1000 pseudo-experiments for each analyzed source. The best p-value among all the sources is stored for each pseudo-experiment, and the final distribution looks like the plot below (left):





A *post-trial* p-value is obtained for each source, by integrating the best p-value distribution from the *pre-trial* p-value to the left (as shown in the right-hand plot above).

ORCA 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 ± 0.06	2.92 ± 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

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 ± 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

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.

The SVOM mission

The Space-based multi-band astronomical Variable Objects Monitor (SVOM) is a French-Chinese Collaboration dedicated to the study of the most distant explosions of stars, the gamma-ray bursts.

The mission consists of three main characters: (1) the SVOM satellite; (2) the Ground Follow-up Telescopes (GTCs); (3) the Ground Wide Angle Camera (GWAC) to detect prompt optical emission.

The satellite consists of:

- ECLAIRs: to detect and localize GRB in X-rays and the low gamma-ray band (4-250 keV)
- MXT (Microchannel X-ray Telescope: GRB in the soft X-ray range (0.2-10 keV)
- GRM (Gamma-Ray burst Monitor): to measure the spectrum of high-energy GRBs (15-5000 keV)
- VT (Visible Telescope): to detect the visible emission soon after a GRB