

Online Analysis Framework for Multi-Messenger Astronomy with KM3NeT

Vincent Cecchini - IFIC Valencia, KM3NeT-INFRADEV2 WP4 On behalf of the KM3NeT collaboration.

2nd Astro-COLIBRI MM astrophysics workshop 21/11/2023



Funded by

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the the European Union European Union or the European Research Executive Agency (REA). Neither the European Union nor the REA can be held responsible for them.





Multi-messenger astronomy



Photons

Neutrinos



Credit: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

CRs accelerated in astrophysical sources \rightarrow emits secondary neutrinos (and gammas) from pions decay.

Neutrino advantages: No deflection, low absorption.



MM Astronomy \rightarrow Require to share the observations 2

KM3Ne¹ INFRADE

The KM3NeT collaboration

KM3NeT INFRADEV-2

20 countries, 47 institutes:



Two sites:

ARCA (Astroparticle Research with Cosmics in the Abyss)
 → Optimized for studies > TeV.

- ORCA (Oscillation Research with Cosmics in the Abyss)
- \rightarrow Optimized for studies @ ~GeV.

The KM3NeT detectors

	ARCA	ORCA
Location	100 km off Sicily (It.)	40 km off Toulon (Fr.)
Depth	3450 m	2450 m
Energie range	> TeV	GeV - TeV
DU Height	~ 800 m	~ 200 m
Number of Building Block	2	1
Instrumented Volume	~ 1 Gton	~ 7 Mton



1 **DU** = 18 **DOMs** (Digital Optical Modules)⁴

J. Phys. G: Nucl. Part. Phys. 43 08400

KM3NeT construction timeline

First lines of ARCA: 12/2015 ; ORCA 09/2017. Phase 1: 24 DUs ARCA ; 6 DUs ORCA.

Construction phase, currently:

- > ARCA 28 (9 lines deployed this summer)
- ORCA 18 (sea operation foreseen by the end of the year)

Completion of the full detector ~ 2028.

ORCA 18 muon event reco





Credits: R. Coniglione, NeuTel23

Detections principle and event topologies

KM3NeT INFRADEV-2

Detect the **Cherenkov light cone** from the secondary particle produce at neutrino interaction.





High Energies studies: use earth as target.

KM3NeT in MM astronomy





Perform HE follow-up

ALERTS

- Triggered by externals alerts
- Search for v counterpart / Refine alert position (GW)





Send HE neutrino candidates

ALERTS

- Continuously running
- Work in progress: neutrino selection, alert sending program



KM3NeT MM programm

KM3NeT INFRADEV-2

Combination of:

- RTA: Real-Time Analysis framework (reconstruction of events from data)
- ➢ KOAP: KM3NeT Online Analysis Pipeline (run the physics analysis)

Aims at:

Looking for spatial and temporal coincidences of KM3NeT reconstructed events with active astrophysical sources.

High-energy analysis: ON/OFF regions searches, with event selectionsdepending on the trigger type+ MeV Pipeline for Core-Collapse SuperNovae (CCSN).

Online analysis framework



Real-Time Analysis: events rate and processing time



Expect ~ 100 Hz rate for full detector

KM3NeT

MM follow-up analysis method: ON/OFF technique



- **Signal (ON) region** = <u>Rol</u> (Region of Interest, source direction with its uncertainty + 1.
- extension*) + <u>search time window</u>. $\rightarrow N_{on}$ Background region = <u>OFF band</u> defined in local coordinates + <u>1-2 weeks data before</u> 2. the alert.
- Estimate the expected background of Rol: $N_{bkg} = \sum_{i \in \text{ bands}} N_{OFF,i} \times \frac{LT(sig)}{LT(bkg)} \times \frac{\Omega_{ON,i}}{\Omega_{OFF,i}}$ 3.
- P-value: compare N_{on} with N_{bkg} 4.



*to cover for detector angular resolution \rightarrow analyses performed using **only track-like events** (include showers still in progress).

Alert follow-up

Follow-up from 11/2022 to 06/2023



 \rightarrow Alerts received from the GCN (General Coordinate Network) broker through the Apache Kafka protocol.

 \rightarrow Ongoing implementation of additional brokers (TNS, µQuasar, FlaapLUC).

 \rightarrow Each alert trigger all sky analysis for both ARCA and ORCA, as well as the MeV analysis pipelines.

Information returned: Versioning, search parameters, expected background, observed number of events, p-value, and flux upper limits.

KM3Ne¹

Internal online monitoring: shifter tools



External triggers



 Filter

 Name Tag (D)
 Status

 All
 Mall

 RA
 DEC

 Radius

 Between
 And

 j/mn/aaaa
 j/mn/aaaa

 Foor
 Rest

							Mark an as read	Doministry
ihowing alerts 1 to 20 of 3	254 in total.							
ntries per page: 10 2	0 50 100							
• <u>1</u> 2 3 4	5	162 163 *						
Event ID	Туре	Event date (UTC)	Validity	RA (deg)	Dec (deg)	Links		
717313591	GRB	2023-09-25 05:46:26	Excluded	64.2	-60.3833	GCN_n	Details	
new 717305385	GRB	2023-09-25 03:29:40	Excluded	157.8333	30.65	GCN_n	Details	
new S230925k	GW	2023-09-25 02:26:25	Excluded		0	GCN_n Link	Details	0
new 717299390	GRB	2023-09-25 01:49:45	Selected	6.88	-57.33	GCN_n	Details	Analysis
new S230924bl	GW	2023-09-24 23:29:19	Excluded	× .		GCN_n Link	Details	
(new) S230924ao	GW	2023-09-24 13:04:17	Excluded	14 - C	-	GCN_n Link	Details	
5230924an	GW	2023-00-24 12:44:53	Selected	2		GCN n Link	Details	Analysis

RTA monitoring for both ARCA and ORCA (Event rates, Processing time, Physics variables)

MM follow-up monitoring:

- Alerts ID, type, trigger status
- Details of the alerts and link to GCN notices
- Plots and results of the online analyses

 \rightarrow Internal tool.

Available analysis for event S230919bj

TaG RES_AL TaG RES_AL Notice_Name USC_NF D_Ferrit S20011 D_Enert S20011 Dare Ferrit CRCA Detector CRCA Seach firms indow S20050 Dubring(Mg) Caryot 10.05 Dubring(Mg) Caryot 10.05 Dubring (Mg) Caryot 10.05 Dubring (Mg) Caryot 10.05 Dubring (Mg) Caryot 10.05 Dubring (Mg) Caryot 0.0000 Contact Cars on Classification/Grove 20.0000 Dubring (Mg) Caryot 10.05 Dubring (Mg) Caryot	ALRT NITAL 1986 0 49171 25 1 2000 1 0 0 20172 26 1 12 2000 1 0 0 20172 26 1 12 2000 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
with N-C/A with Sere, Therme U/C/A D. Dennt S20001 D. Benet S20001 Debeteor ORCA Populare S20001 Debeteor ORCA Populare ORCA Debeteor ORCA	NUTY NTAL I Rej 09. 1972 1 57 12 000 A GW 09. 3070 401 64 341 000-000 101 Lefer 4 hour 1.00 2
bits 1.0, min 1.0, min Detector 1.0, min 1.0, min Date_Event 2020-00 2020-00 Date_Event 0.002.0 2020-00 Date_Event 0.002.0 2020-00 Date_Event 0.002.0 2020-00 Date_Event 0.002.0 2020-00 Date_Events 0.002.0 2020-00 Date_Events 0.001.0 2020-00 Livetime(rig) [secondul 0.001.0 1.040 Detector 0.001.0 0.001.0 CM 0 0.007 0.202.0.2 CM 0.001.0 0.0000.0 0.0000.0 Date_Event Background 0.0000.0 0.0000.0 0.0000.0 Date_Event Background 1.0200.0 0.0000.0 0.0000.0 Date_Event Background 0.0000.0 0.0000.0 0.0000.0 Date_Event Background 0.0000.0 0.0000.0 0.0000.0 Date_Event Background 0.0000.0 0.0000.0 0.0000.0 Date_Event Background 0.0000	NY ING. (20) 1972 15.71 2000 () () 20) 2076 4 0 1 0, 381 400-byth 116-c 4002 000 15 300 5000 10 10 tyther 4 Hour 10 5 5 5 5 5 5 5 5 5 5 5 5 5
U_permit 320011 U_permit 320011 Detector 052A Detector 10.40 Detector 11.40 Bemaining fraction after rate cuts 11.54 OK 0 OFF 0.22.22 Detector 0.3055 Date Analysis 0.3055 Date ClassificationScove 0.99999 Date ClassificationScove 10.99999 Dates ClassificationScove 10.99999 Dates ClassificationScove 10.999999 Dates ClassificationScove 10.999999 Dates ClassificationScove 10.9999999 Dates ClassificationScove 10.9999999 Dates ClassificationScove 10.99999999 Dates ClassificationScove 10.99999999 Dates ClassificationScove 10.999999	1149 1
and power 2000 06 Margeneric CRCA / CRCA / Npoline CRCA / CRCA / CRCA / Notice CRCA / CRCA / Notice Name Name 1 Name 0.3.4 dbr S200.0 Solds / Version 0.3.4 dbr Lafet 5 Name Name 1.01 Name 0.010 1.01 CRCA / Strained Sale 1.02 1.01 CRCA / Strained Sale 0.0200.0 0.0000 CRCA / Strained Sale 0.0000 0.0000 CRCA / Strained Sale 0.0000 0.0000 Sale 0.01 0.0000 0.0000 Sale 0.0000 0.0000 0.0000 Sale 0.0000 0.0000 0.0000 Sale 0.0000 0.0000 0.0000 Sale 0.0000 0.0000 0.0000 Sale 0.00000 0.0000 0.0000 Sale 0.00000 0.00000 0.00000 Sale 0.000000 0.00000 0.00000 Sale </td <td>0 1112 17 12000 1, GW 20 20704 01 04 391 400-0-gAbri flac00200015 5500 second TO 1, aleri-4 hour 1.0 2 2 2 2 2 2 2 2 2 2 2 2 2</td>	0 1112 17 12000 1, GW 20 20704 01 04 391 400-0-gAbri flac00200015 5500 second TO 1, aleri-4 hour 1.0 2 2 2 2 2 2 2 2 2 2 2 2 2
VEX. OEX. Vector OEX. Vector <td>GeW GeW devis-ghth the devision devis-ghth the devision devis-ghth the devision devision of the devision of the devision</td>	GeW GeW devis-ghth the devision devis-ghth the devision devis-ghth the devision devision of the devision of the devision
uptomb ORL0_5 uptomb ORL0_5 serian 0 bate_Analysis 2000-05 bate_Analysis 0.01.4 de bate_Analysis 2000-05 bate_Memory 1.040 intermine big1 (second) 2000-05 bate_Memory 1.040 bate_Memory 0.000 OR 0 OFF 0.000 bate 0.0000 bate 0.00000 bate 0.0000000 bate	Law 20 20754 or 04.991 devi-gåbt frits.20020015
instance 1 set Analysis 2010 odd, Version 0.2.4 dm search time inclose Line 15 wettine(big) (seconda) 1.054 memining faction after rate cuts 1.054 ON 0 OFF 2.2.2.2 peerdel Background 0.005 uisto on ClassificationScore 2.9.9999 value 1.0.9 value 1.0.9 value 1.0.9 value 0.010 Cold Cold Cold Cold Cold Cold Cold Cold	09 50764 01 04 581 decol-gibb 1 bit, douzson 15 5.000 second TD 1, jalenta (hour 1.0 5 5 5 5 5 5 5 5 5 5 5 5 5
htt, Andyra 2000 49 dock/Version 0.3.4.64 seach time window 1,3815 seach time window 1,3815 horing half (digs) 1,1645 beneinsking function after rate cuta 1,584 ON 0 OFF 2,2,2,2 spected Background 0,0005 value 1,0 imita on FlassificationScore 1,0000 imita on FlassificationScore 1,0 spected Scoregoreand 1,0 scoregoreants 1,0 Scoregoreants 1,0	00.2016.01.01.91 00.2016.01.01.01.01.01.01.01.01.01.01.01.01.01.
0.3.4.6 seek hime window 1,04.6 ivetime[sig] (second) 2000.0 uvetime[sig] (second) 10.64 break methods 10.64 OM 0 OFF 0.2.0.22 undown ClassificationScore 0.99999 value 1.0 immin on Place (Second) 0.99999 value 1.0 second 1.99999 value 1.0 second 1.99999 value 1.0 second 1.99999 value 1.0 second 1.999999 value 1.0 second 1.999999 value 1.0 second 1.999999 value 1.0 second 1.999999 value 1.9 second 1.9 second 1.9 second 1.9 second 1.9 second 1.9 se	Beford geffet The Laboration IS
search time window Laint 5 wettime/bagi (seconda) 2000.0 wettime/bagi (seconda) 11.054 wettime/bagi (seconda) 10.054 ON 0 OFF 2.2.2.3. penetid Background 0.0000 ution of Classification/Score 0.00000 value 1.0 unima on Flag (GeV~1 cm ~2) - onoments -	200 second TD t_alerts Flour 10 5 2.2.2.2.2 53 53 53 50 50 second TD t_alerts Flour 54 55 56 57 56 57 57 58 59 59 59 59 59 50 50 50 50 50 50 50 50 50 50
vertime/big/(seconds) 2000.0.0 vertime/big/(dopu) 11.042 vertime/big/(dopu) 0 ON 0 OPFP 22.22.2 zupsected Background 0.0053 uits on ClassificationScore 0.99999 value 0.0 ministo nFlar (docV-r.t.or2) . valuements 0	10 5 4 2.2.2.2.2 53 59 59 59 50 50,5,5,5,5,5,5,5,5,5,5,5,5,5,5,5,5,5
winters/big/(idys) 11.035 maining fraction after rate outs 81.584 N 0 ON 0 OPF 2.2.22 upsched Background 0.0053 uits on ClassificationScore 5.99999 vabe 1.0 minito on Flux (DeV'-t om ~2) - minito na Flux (DeV'-t om ~2) - streaments - SOCORE_Stream []	5 2.2.2.2.2 23 29 297755-0 (1,3 99996230e d) (1,3 99996231e d) (1,3 99997445e d) (1,3 99964753e d) (1,3 99964916e d) (1,3 99964854e 20064875e d)
emaining basilon after rate outs \$1.584 ON 0 0 OFF 0 22.22.2 Opperted Basignound 0 00050 uts on Classification5Core 0.5399 value 10 imite on Play (GeV~1 cm~2) - commonts 0 CORE_Break 1	4 2.2.2.2 3 29770-0.1 3.99999530-0 1.9.99998331-0 1.9.99997440-0 1.9.99984753-0 1.9.99985918-0 1.9.99944844- 980419-0 1
ON 0 OPF 32.22.2 spected Background 00003 uits on ClassificationScore 01.999 value 1.0 imits on Flux (GeV+1 cm*3) - XECORE, Seream []	2.3.3.3.3 23 397700- 01 5. 99999630- 01 5. 99998331- 01 5. 99997468- 01 5. 99964753- 01 3. 99969518- 01 3. 99964846- 98064179- 01
OFF 2.2.2.2 spected Background 0.0005 uits on ClassificationScore 0.000 walue 1.0 imits on Flax (GeV*-1 cm*-2) - comments - OSCORE_Stream 0.	2.2.2.2 3 99006 of 1.8 99999306 of 1.8 9999831 (e of 1.8 99997448e of 1.8 99944732e of 1.8 99946918e of 1.8 99946944e. 9904813e of 1
Spected Background 0.02503 Lits on ClassificationScore \$9.99992 value 1.0 imits on Flux [GeV*-1 cm*-2] - comments - OSCORE_Stream []	93 1970 – 11.3. 90006226e 61.3. 90068331e 61.3. 90097448e 61.3. 90064753e 61.3. 90068518e 61.3. 90064854e. 98064878e 61
Luts on ClassificationScore 9 59999 01,9399 -value 1.0 imits on Plux [GeV*-1 cm*-2] - comments - DSCORE_Stream []	99700-013 99999030-013 99999331-013 99997446-013 99994753-013 99999318-013 99949518-013 9994966- 9804919-01
value 1.0 imits on Flux [GeV^-1 cm^-2] - iomments - DSCORE_Stream []	
imits on Flux [GeV^-1 cm^-2] - comments - DSCORE_Stream []	
comments - DSCORE_Stream []	
DSCORE_Stream []	
Shape OCA GV SJDDISH Shape OCA GV SJDDISH	Pice of the relation of the re



Broadcasting policy and alert sending



If a **follow-up** shows interesting results or an **astro event is notable enough**:

- → Send a GCN circular or an Astronomer's Telegram (write by shifters/online coordinator and approved within 12h by the decision group)
- → Set-up an offline analysis with refined detectors knowledge (MC, calibration, reco, analysis methods ...), if needed.

Future: If a **HE neutrino candidate is identified** \rightarrow Send a **notice** (GCN with VOEvent format, SNEWS through Kafka)

Example: The online follow-up of GRB 221009A

2022, 9 Oct. at 13:16.59 UT: Long GRB at RA, Dec = (288.3, 19.8) deg detected at z~0.15 (2.4 billion light-years away)

- GRB with highest energy ever detected by Fermi LAT (99 GeV, ATel #15656).
- LHAASO detected photons of the order of ~10 TeV (among highest energies for a GRB, GCN #32677).
- One of the largest worldwide follow-up campaigns ever (among which KM3NeT).



TITLE: GCN CIRCULAR NUMBER: 32741 SUBJECT: GRB 221009A: search for neutrinos with KM3NeT DATE: 22/10/13 18:57:37 GMT FROM: Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

The KM3NeT Collaboration (https://www.km3net.org/) reports:

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+50005], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the KM3NeT horizon (mean elevation of about ~40deg) during the search time window, significantly reducing the point-like source sensitivity. In both detectors, zero events were observed in the search window, while o(0.1) were expected from the background. The online fast processing uses preliminary calibrations and detector alignment, which will be superseded in a future elaborated analysis.-br>

KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors, sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection lines are currently in operation in ARCA and ORCA, respectively.

KM3NeT ARCA21, ORCA10 \rightarrow No event found in signal region, see <u>PoS (ICRC2023) 1503</u> for refined offline analysis.

KM3NeT

Circular 32741

Recent astronomy results from KM3NeT





Diffuse neutrino emission from Galactic Ridge, 90% upper limits (KM3NeT/ARCA6+8 and 6-21), compared to ANTARES and IceCube best fitting fluxes.

- No excess over background founded
- Not yet competitive limits

Perspectives: 6 more month of data with KM3NeT/ARCA21 + detector growth

Point Source sensitivity and observed limits (KM3NeT/ARCA6-21 424 days) for 101 sources.

- Not significant neutrino excess observed.
- Sensitivity factor 4 from ANTARES (1.5 vs 13 y live-times).
- Astronomy potential rises fast with growing detector.

NB: KM3NeT already better than ANTARES for transient sources.

KM3Ne¹

Astronomy potential for KM3NeT/ARCA 230





3 and 5 σ discovery values for a neutrino flux with spectral index of 2.37 (as reported by IceCube, blue line).

 \rightarrow detection (5 σ) of the all-sky diffuse neutrino in $\frac{1}{2}$ year.



Point source sensitivity for spectral index of 2 (black) compared with 15 years of ANTARES and 7 years of IceCube.

 \rightarrow Improvement of current limits over the full-sky

 \rightarrow Unprecedented sensitivity in the Southern Sky





- → KM3NeT RTA for online event reconstruction and classification is functional, current rate of tens of Hz.
- Analysis pipelines for follow-up are in nominal production mode.
 3 GCN Circulars + 1 ATeL already submitted.

→ Alert sending status is work in progress.

→ The detector growth will bring exciting detection capabilities.

Thanks for listening





Questions ?

Effective area comparison KM3NeT/ANTARES





ANTARES better than KM3NeT when looking at steady sources due to live-time.

But KM3NeT better than ANTARES for Transients sources detection thanks to an higher effective area (reached since KM3NeT/ARCA19, now KM3NeT/ARCA28).