KM3NeT data processing & data analysis

Anna Sinopoulou
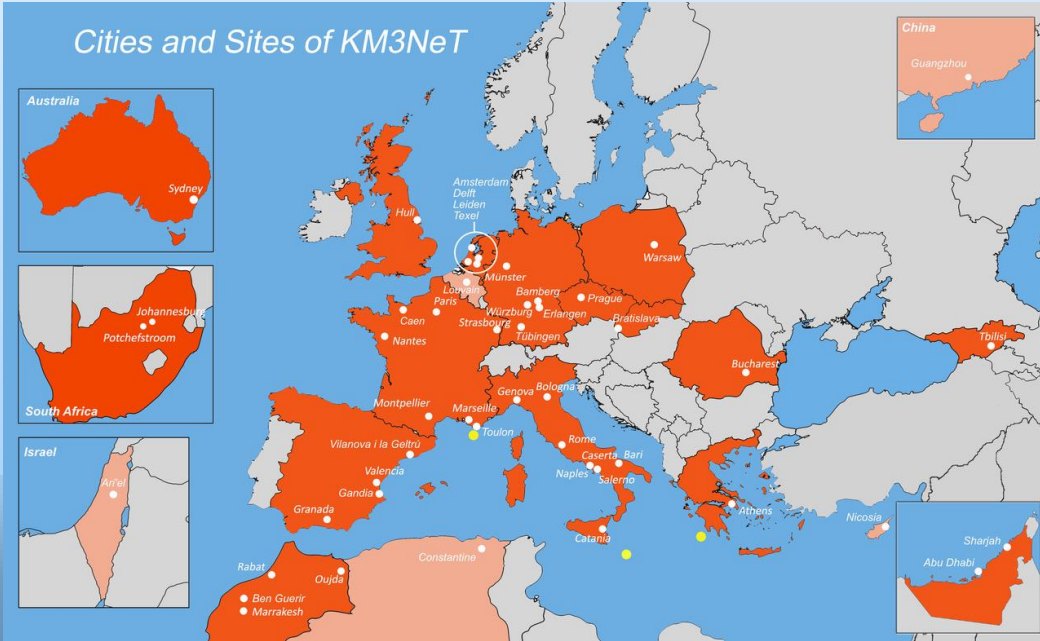
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1st astrophysics in the new era of MM astronomy international conference,
Poços de Caldas, Brazil, 6.12.2023

KM3NeT

KM3NeT is **1 collaboration** contructing **2 neutrino detectors** in the Mediterranean Sea, based on **1 technology**.

KM3NeT/ARCA:
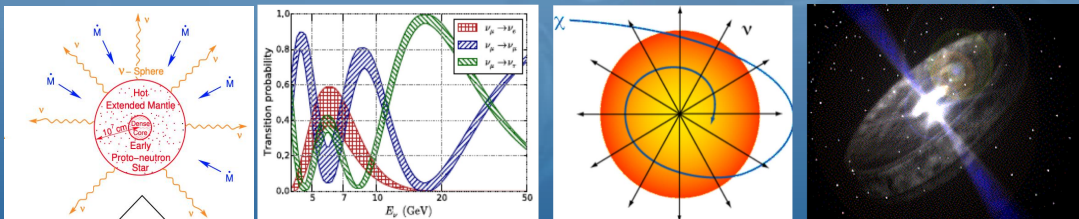observation of high energy neutrinos (GeV - PeV)

KM3NeT/ORCA:
determination of the neutrino mass hierarchy (MeV - GeV)

KM3NeT innovative element
Digital **O**ptical **M**odule (DOM)
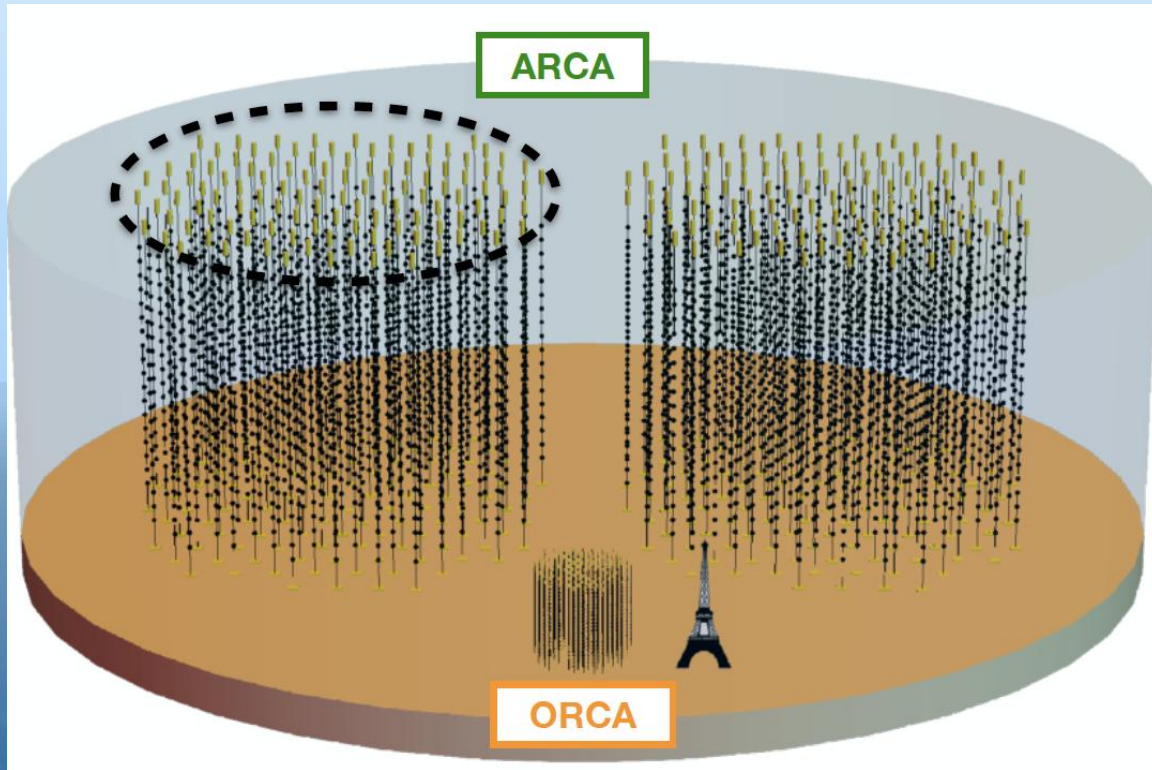
Each DOM is a small detector instrumenting 31 3'' PhotoMultiplier tubes (PMTs)

☺ 4π signal coverage
☺ excellent angular resolution
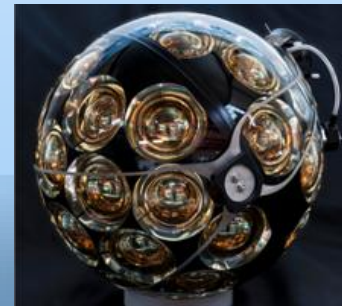(<1º for events with E > 100 TeV)

Physics studies in a wide energy range from MeV to PeV

KM3NeT detector configurations

Different objectives -> different geometries based on same technology !!!

ARCA

ORCA

*115 DUs per building block (BB)

Detection Unit (DU)
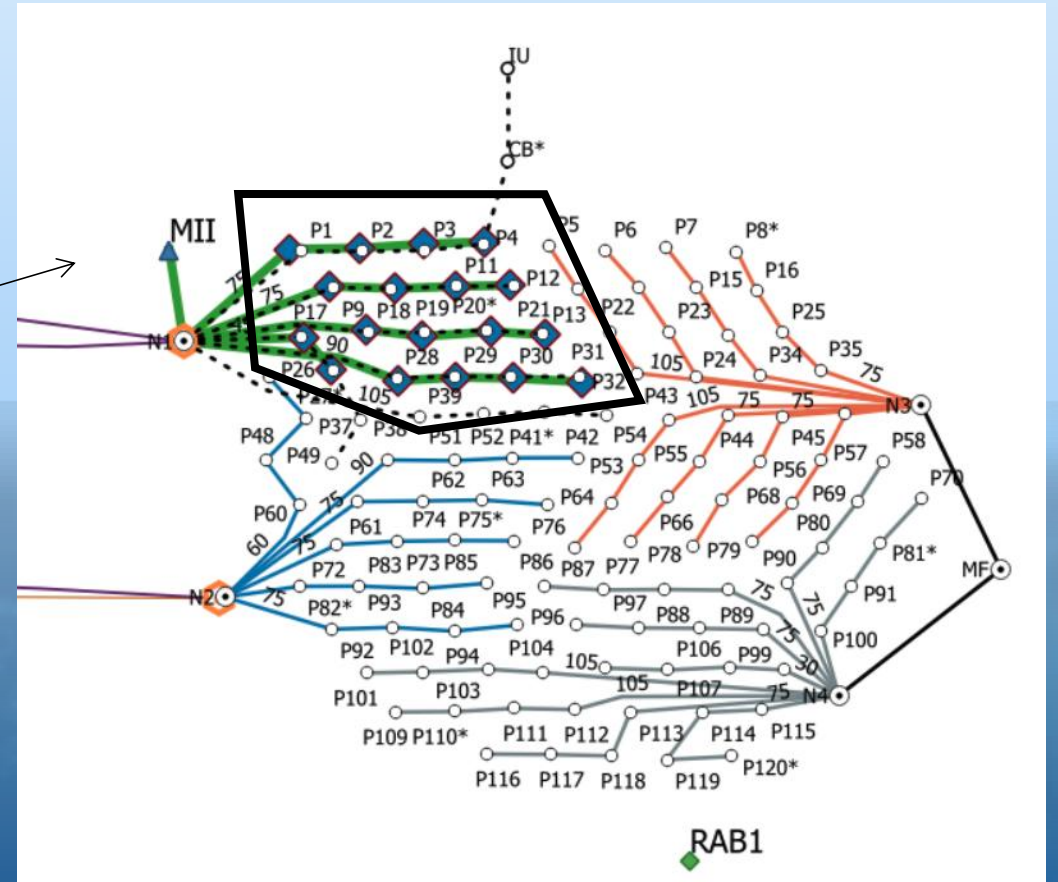
DOM

	ORCA (denser)	ARCA (larger)
Eff. Mass	~ 7 Mt	~ 1 Gt
Line length	200 m	650 m
Interline distance	20 m	90 m
Vertical spacing	9 m	36 m
Depth	~ 2500 m	~ 3500 m

KM3NeT detector status
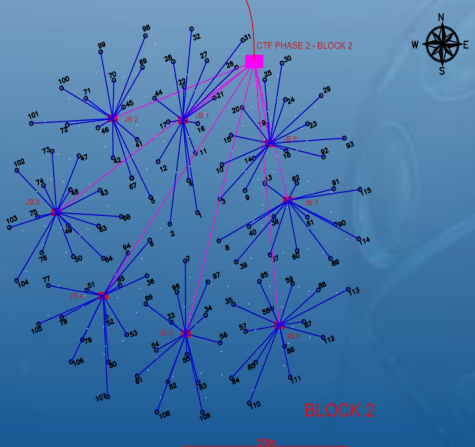
ARCA 2 BB footprint
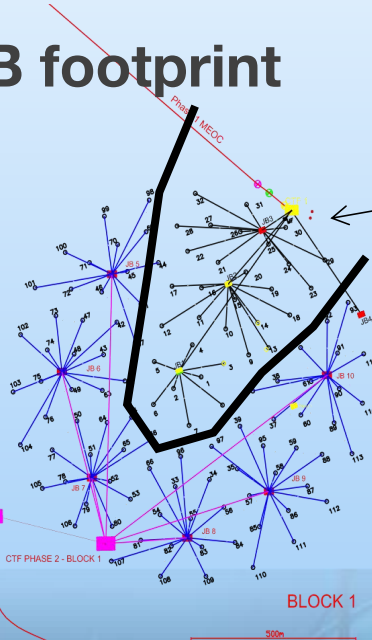
Current data-taking ARCA configuration 28 DUs deployed
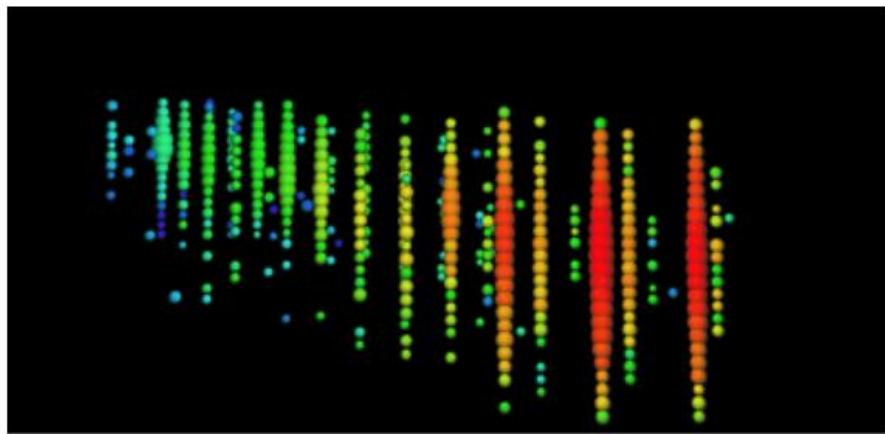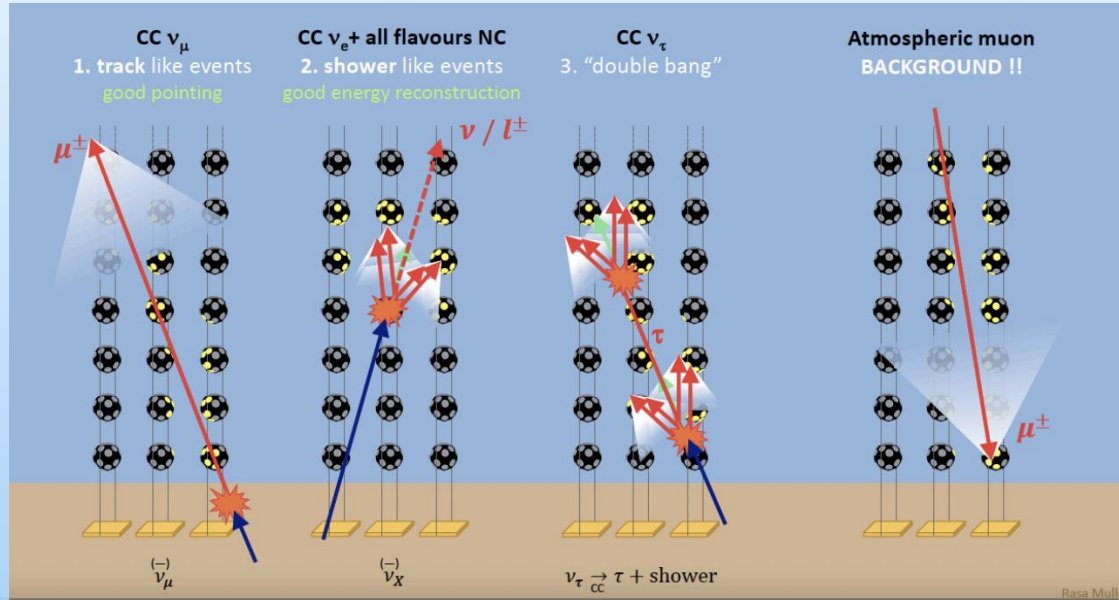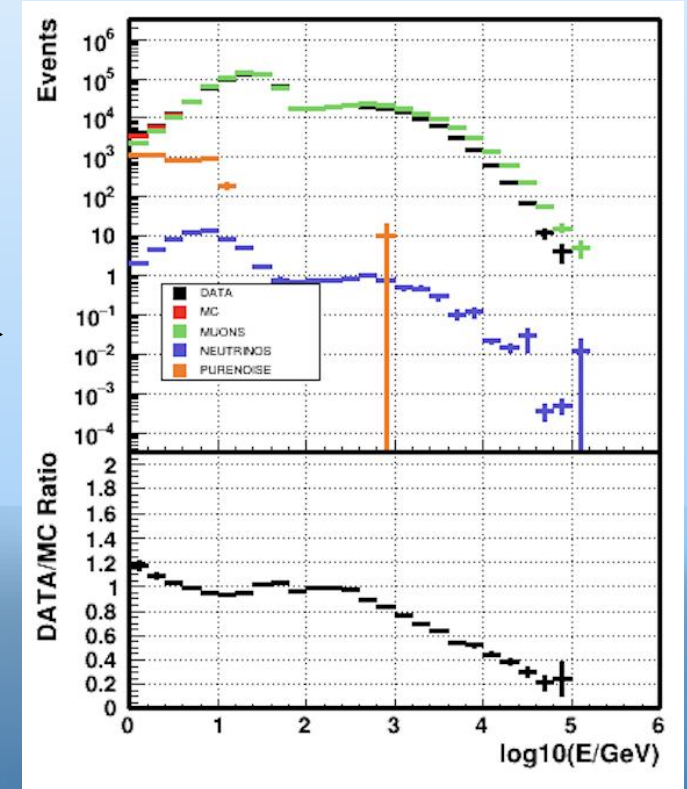
ORCA BB footprint

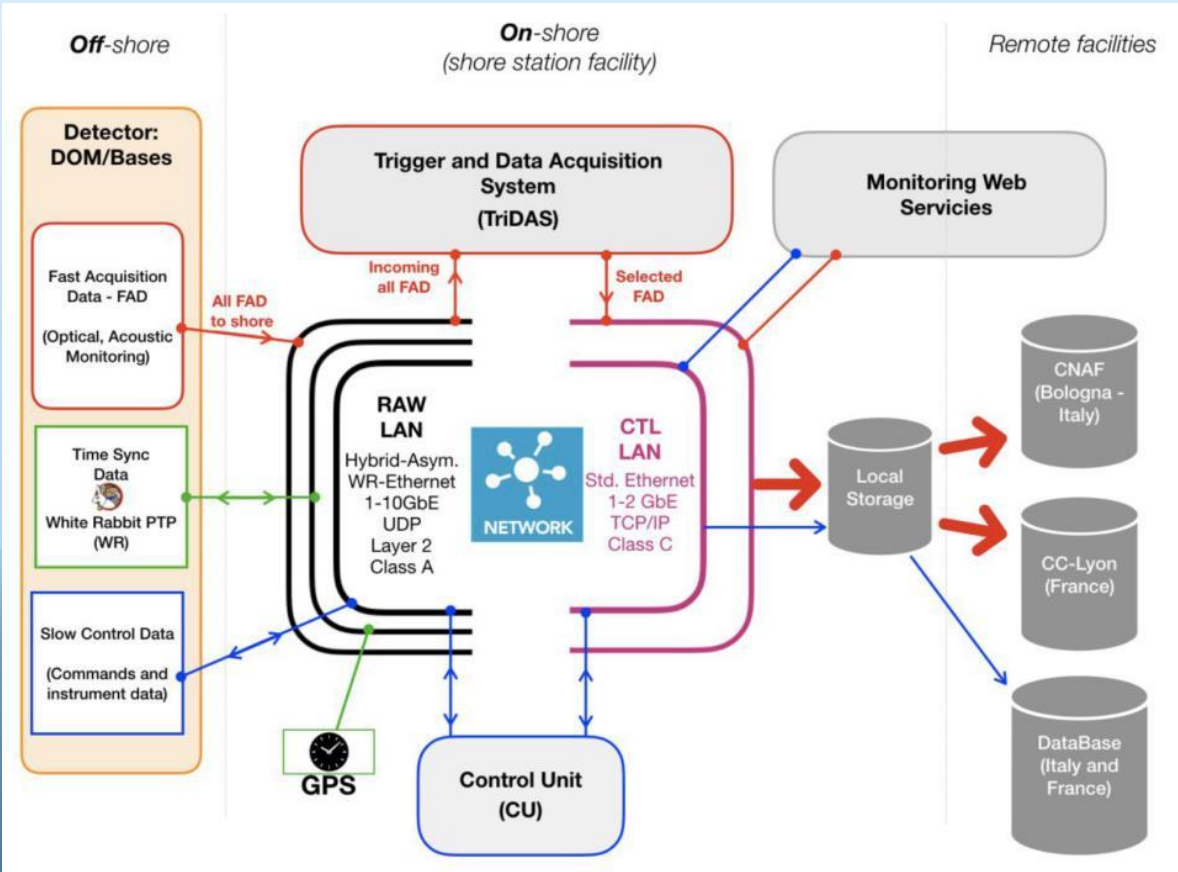**Current data-taking ORCA configuration 18 DUs deployed**

Data: from detection to discovery...

IceCube real-time alert IC170922A was a muon neutrino with an estimated energy of 290 TeV. It pointed within 0.06 degrees at the active galaxy TXS0506+06 located four billion light-years from Earth.
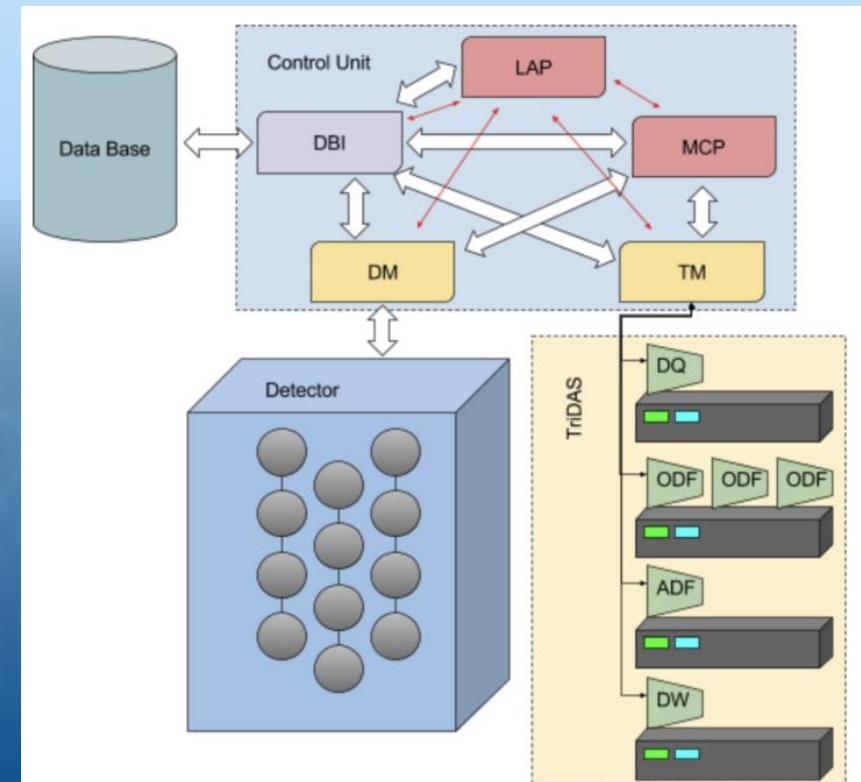
DAQ - how are data recorded and distributed to researchers ?

*signal-to-noise ratio extremely disfavoured :*
muon rate (atmospheric dominating) : O(100) Hz/km³
40K decays (~constant) : O(10) kHz/PMT
Bioluminescence (occasional) : O(100) kHz/PMT

- complex DAQ structures in extreme conditions
  (mandatory: minimal underwater complexity)
- different data streams: optical, acoustic, etc.

"All-data-to-shore" principle
(a.k.a. trigger-less streaming readout)
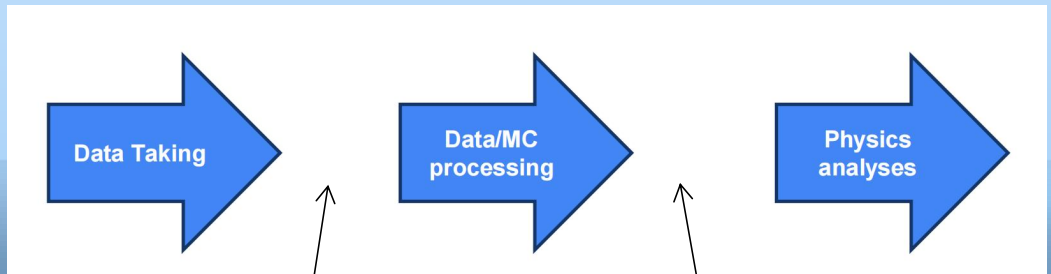
KM3NeT data management

Data management distributed in levels.
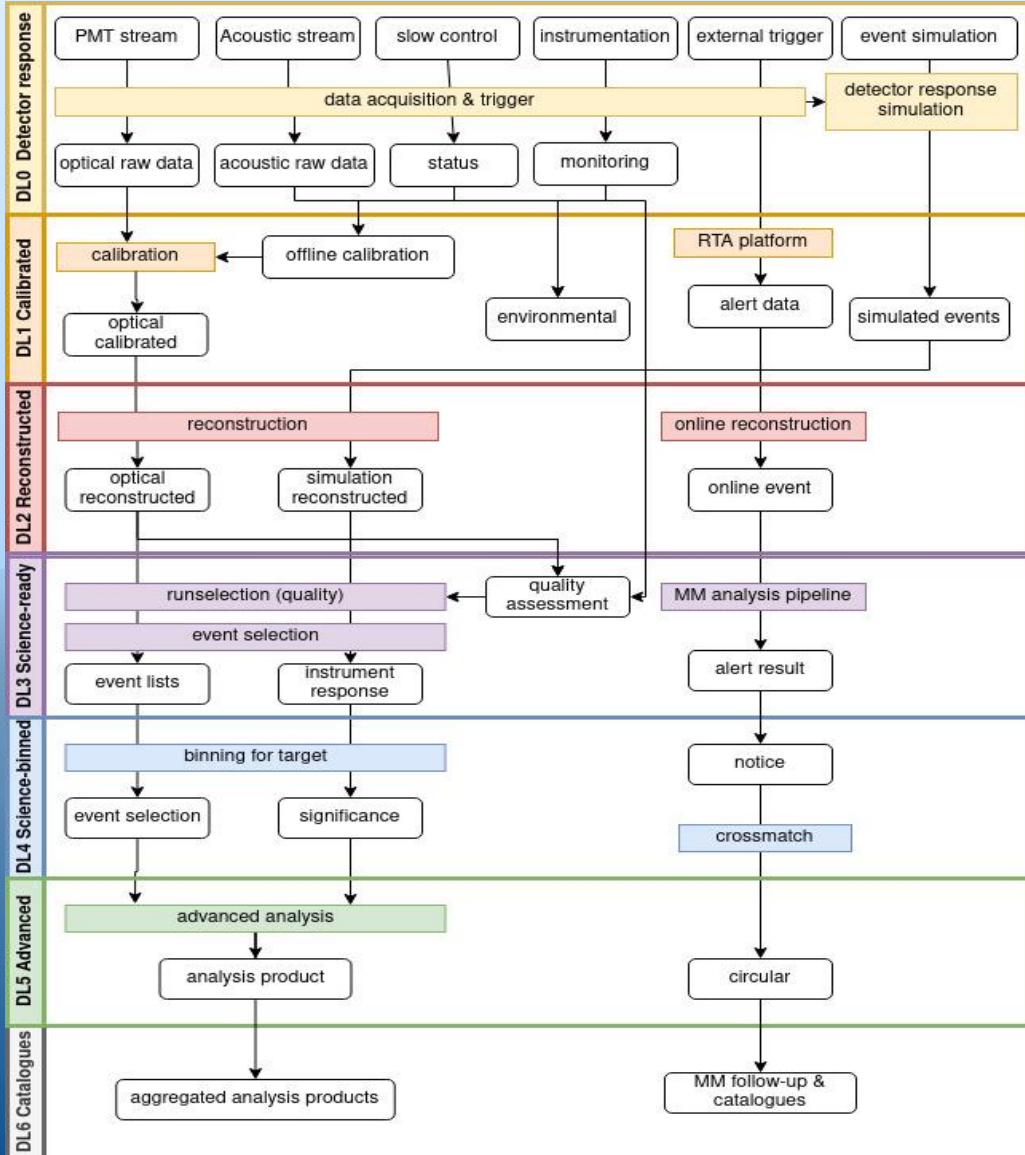
**Data Processing and Data Quality WG**

Goals:
- To **ensure the data taking quality** by performing studies on quality assessments of the KM3NeT.
- To regularly **process the data and to produce MC simulations** ensuring that the input for data analyses are the best obtainable at a given moment.
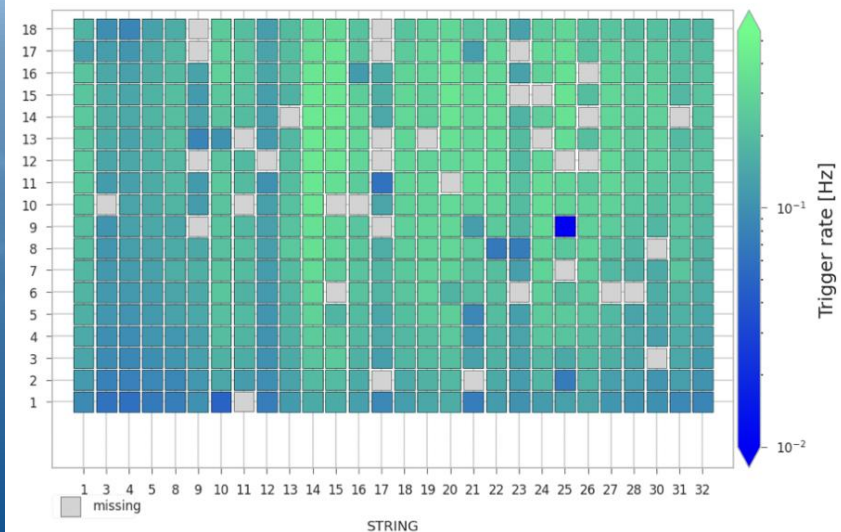

data quality (level 1)
Investigate data "health" for issues, potentially not reproducible, in simulations

data quality (level 2)
Provide "safe" data/simulations to be used for physics analyses

6

Trigger Rates for DetID-160
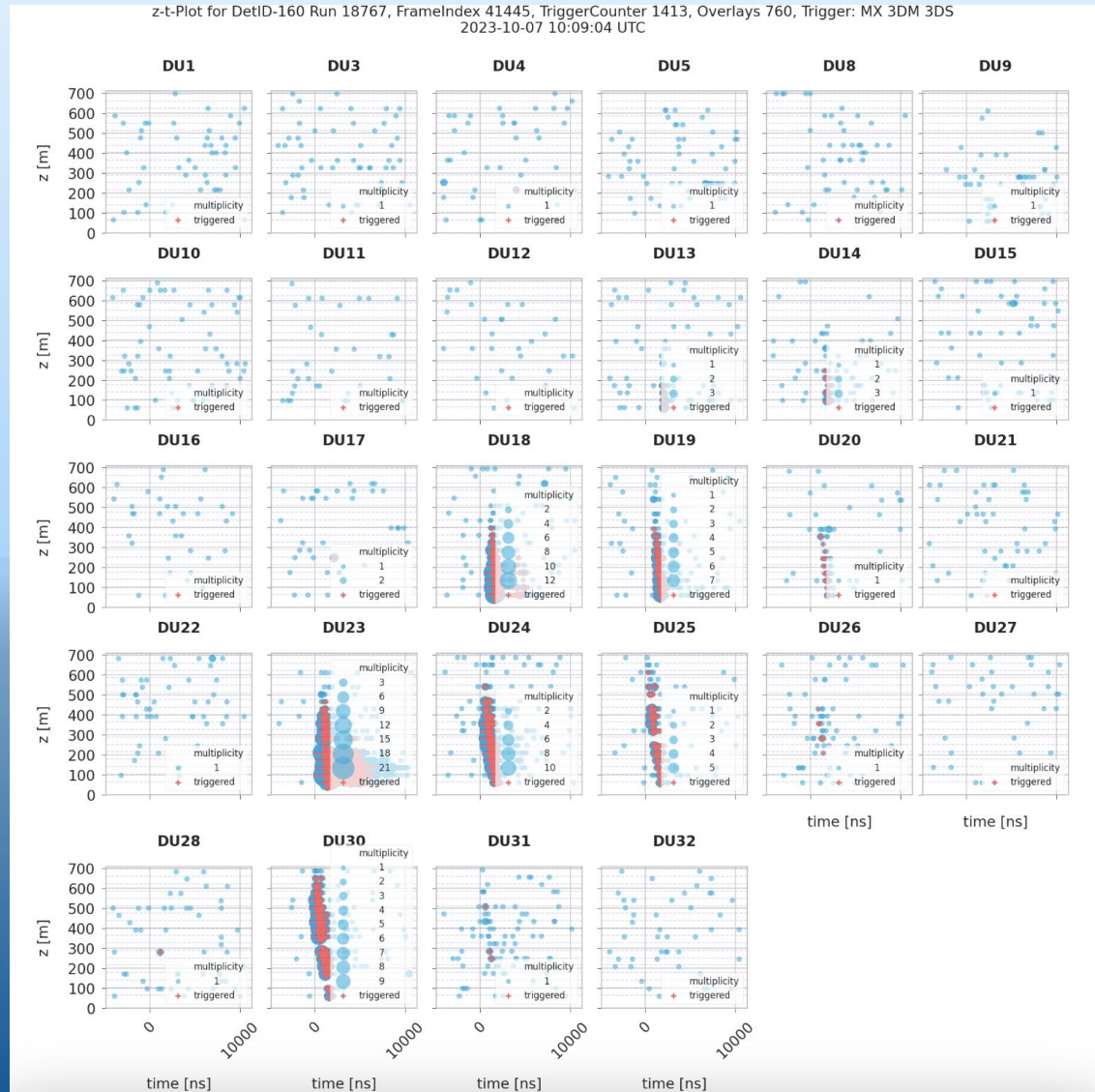Mon Nov 27 08:28:48 2023 UTC
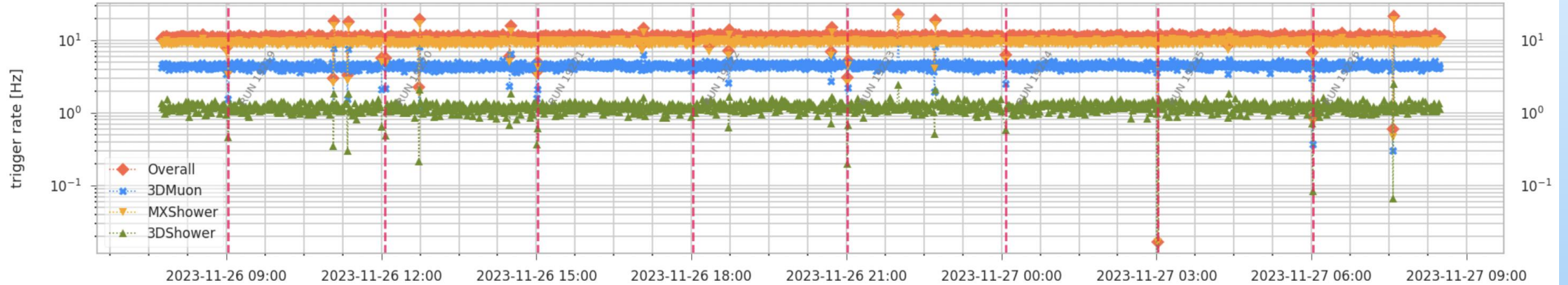
JTRIGGER3DMUON
Mon Nov 27 08:18:09 2023 UTC

Online trigger rates monitoring
(how many events are triggered per second?)

Which conditions are fulfilled?
(events classification)

Online trigger rates monitoring per DOM
(problematic hardware? activity investigation)

Data Monitoring - (online) interesting events

z-t-Plot for DetID-160 Run 18767, FrameIndex 41445, TriggerCounter 1413, Overlays 760, Trigger: MX 3DM 3DS
2023-10-07 10:09:04 UTC

Online interesting events monitoring
DOM hits in a height vs time plot
Red: Triggered DOMs
Size of a point: The bigger the size the more photons "seen" from a DOM
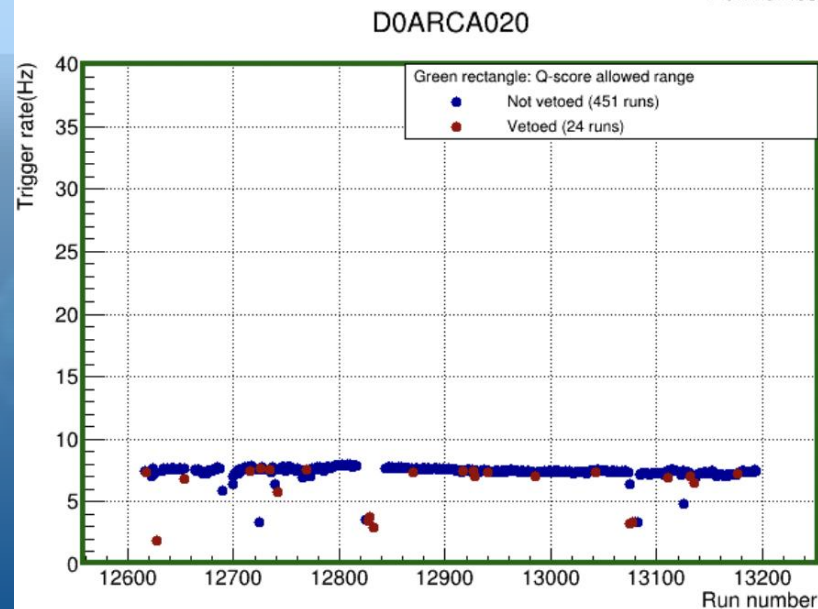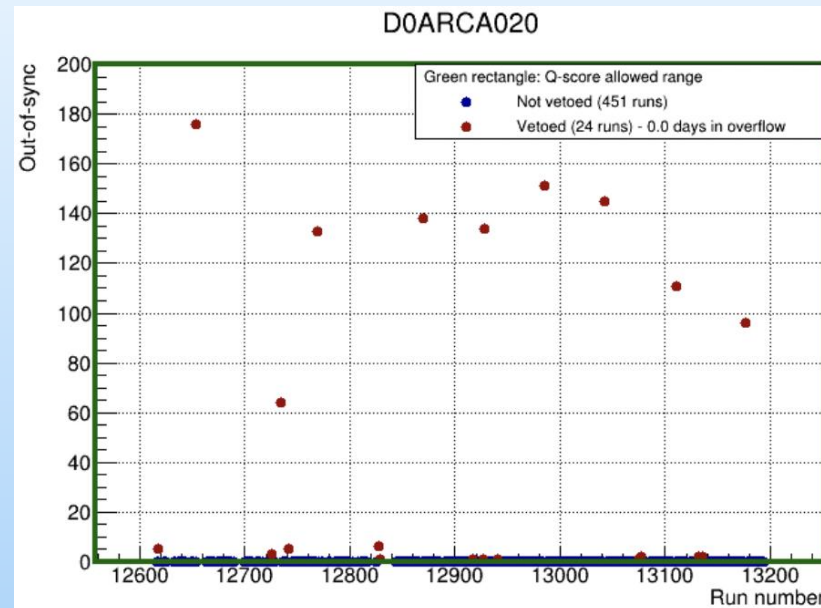
Data Monitoring (offline)
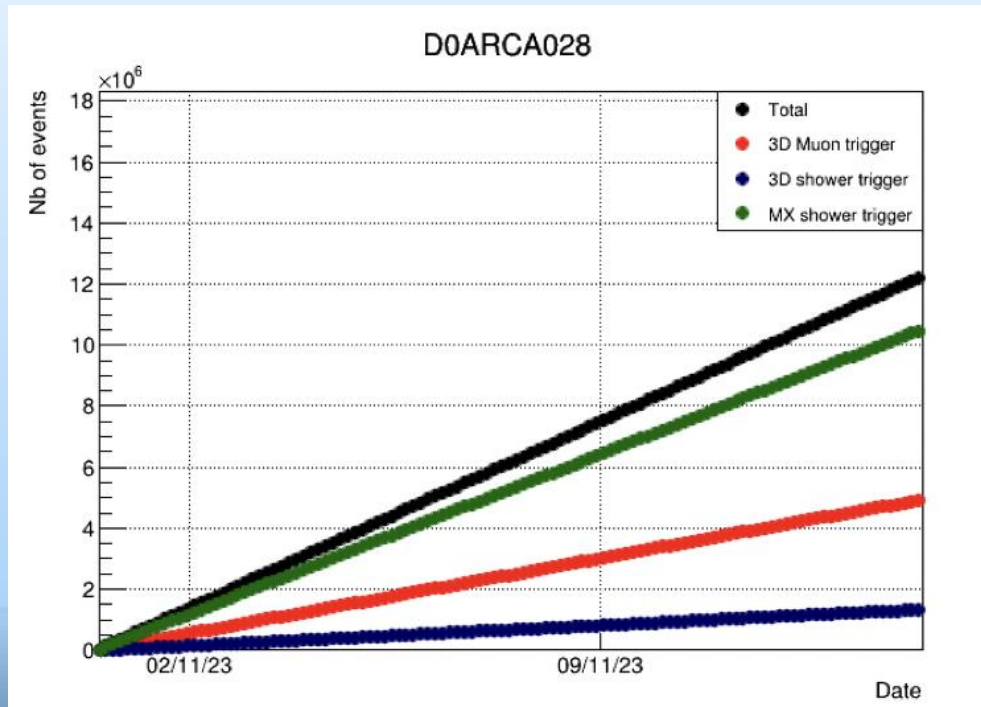
ARCA detector

Number of triggered events is increasing with time (as expected).

We monitor DOMs having lost synchronization (Out-of-Sync DOMs).

Trigger rate monitoring for the full data taking period.

Data quality investigation

- Investigate data "health" -> find probable issues that may not be reproducible in simulations
- Cross check with database and operations reports for potential problems or interruptions in the data taking

Classify runs based on quality score (Q) and veto score (V); calculated by important observables of data taking.


```
JDataQuality \
  -D "$DETECTOR_ID"
  -R "${RANGE%%-*} ${RANGE##*-}"
  -f   $QUALITY_TXT
  -Q "livetime_s;                                      1200    60000"  \
  -Q "(UTCMax_s - UTCMin_s) - livetime_s;              -100    +100"   \
  -Q "JDAQEvent / livetime_s;                          0.05    50.0"   \
  -Q "HRV;                                             0.00    0.2"    \
  -Q "DAQ;                                             0.95    1.05"   \
  -Q "WR;                                              0.95    1.05"   \
  -Q "FIFO;                                            0.00    0.01"   \
  -Q "MEAN_Rate_Hz;                                    4500    15000"  \
  -Q "RMS_Rate_Hz;                                     200     5000"   \
  -Q "Acoustics / livetime_s;                          0.0     100.0"  \
  -Q "AHRS        / livetime_s;                        0.0     100.0"  \
  -V "(JDAQEvent - JTriggerReprocessor) * 1.0 / (JDAQEvent + 1.0e-10); -5.0e-3  +5.0e-3" \
  -V "out_sync;                                        0       0"      \
  -V "out_usync;                                       0       0"      \
  -o $QUALITY_ROOT
  -d $DEBUG --!
```
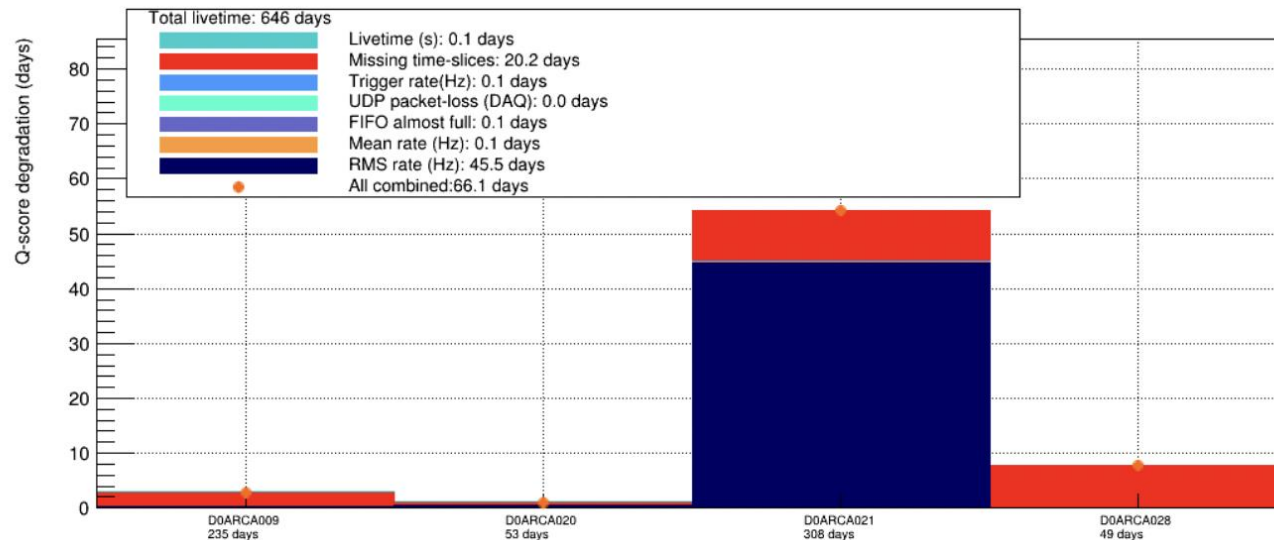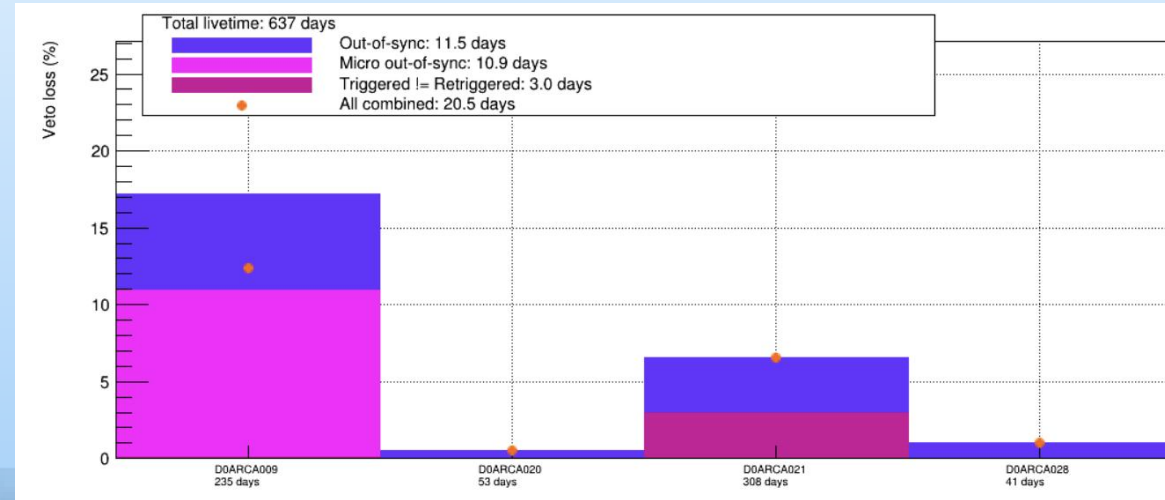
ARCA with active DUs: Veto-score monitoring and Quality-score monitoring

10

Data processing - General idea

In data processing, **recorded data are reconstructed**, **simulations are produced**, **triggered** according to the detector condition by the time of the data taking **(Run-by-run)** and **reconstructed.**
Part of the group task is to verify the "correctness" of the processing and the input by performing a primary **data analysis** (data/MC comparisons etc.).

Run-by-run approach: using the detector conditions from a given run for: hit rates (including HRV), detector geometry, PMT efficiency from K40 analysis etc. -> reproducing the run conditions as good as possible.


Simulation chain:
Event generation (atm. muons, neutrinos) -> Light simulation ->
Detector response simulation (data conditions) -> Event reconstruction (track, shower)

Processing checks & investigations - input optimization

- Comparing distributions of "basic" variables for data and MC.
- Example: Investigating the atm. muon simulation parametrization tunings.

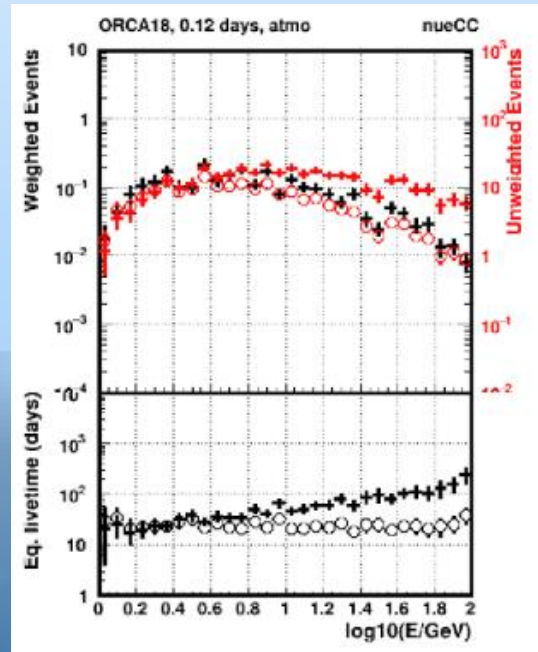**Atm. Muon simulation tuning 1**

Atm. Muon simulation tuning 2
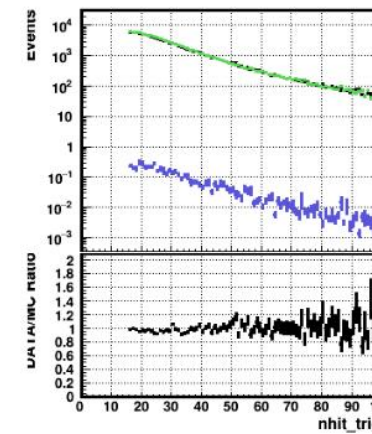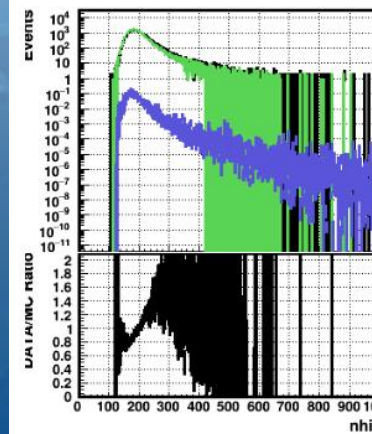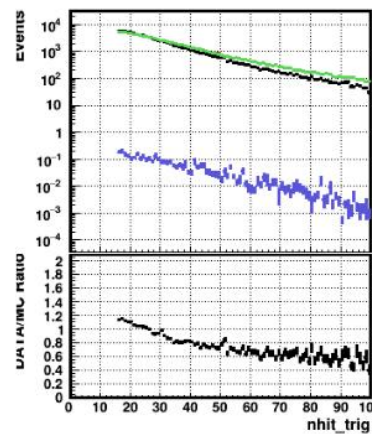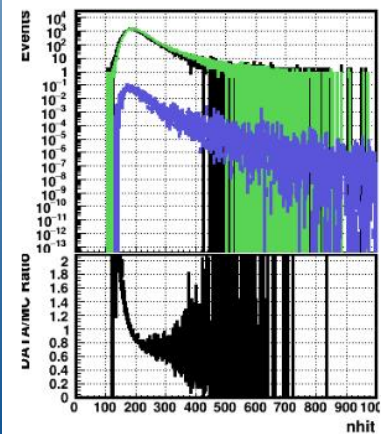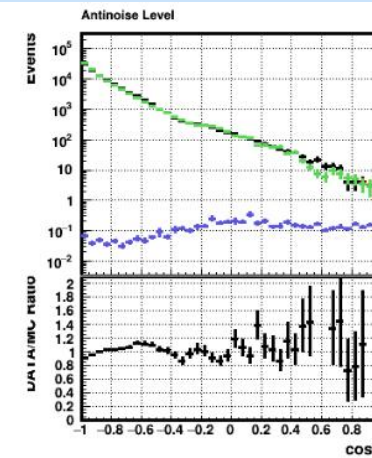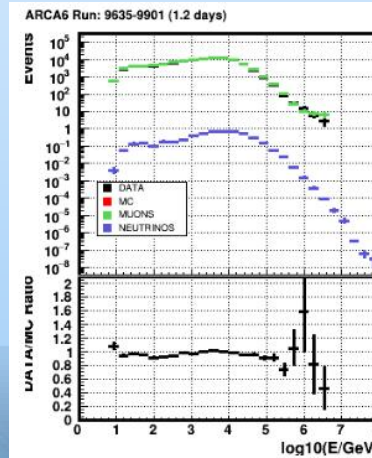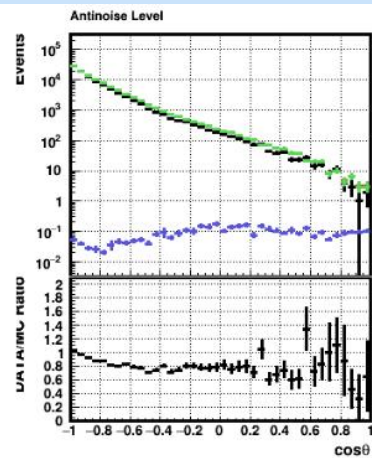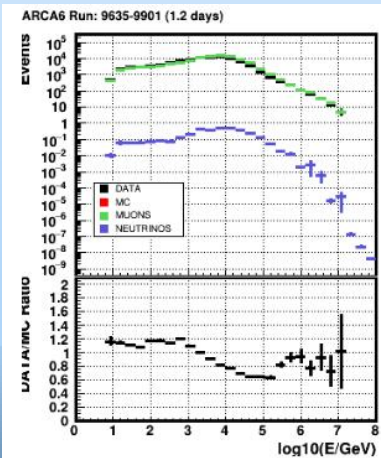
Important variables compared in the first checks:
LogEnergy
CosTheta
N. of reconstructed hits
N. of triggered hits etc.

Processing checks & investigations - data/MC comparisons

- Detailed investigations of the processings to be used for physics analyses.
- Investigations at different levels (generation, light simulation, reconstruction).
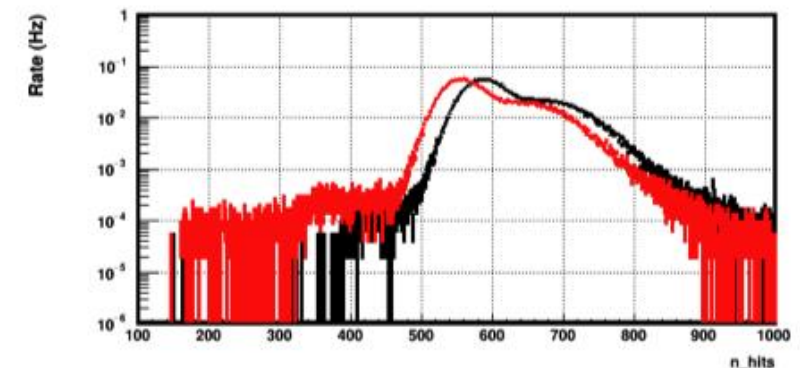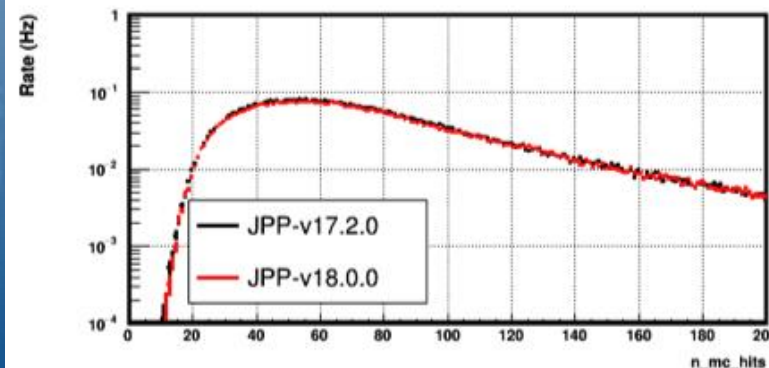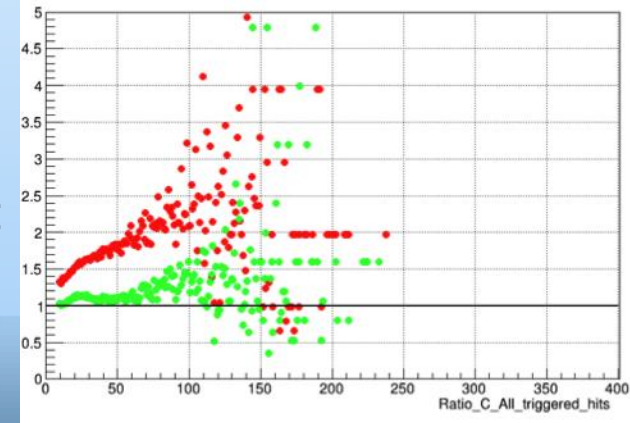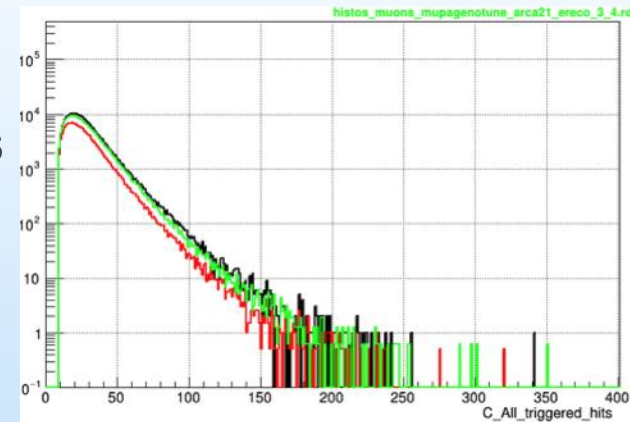
Generation level:
Unweighted/weighted with atm. or astro. flux
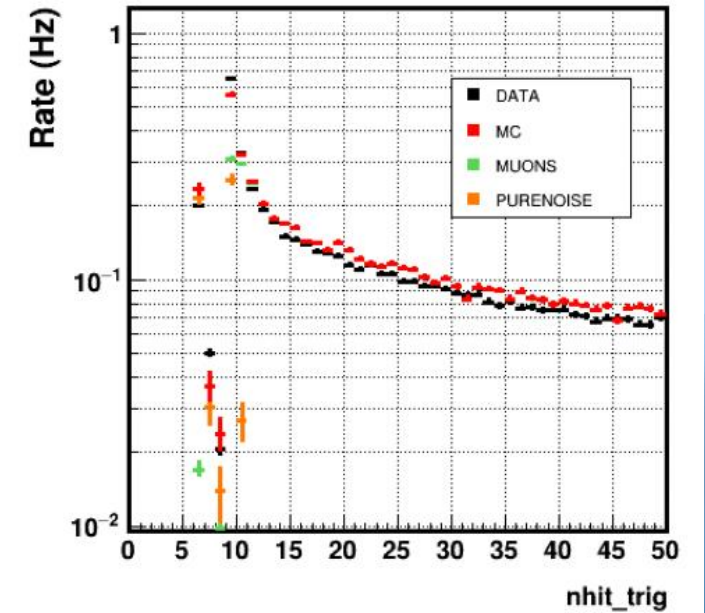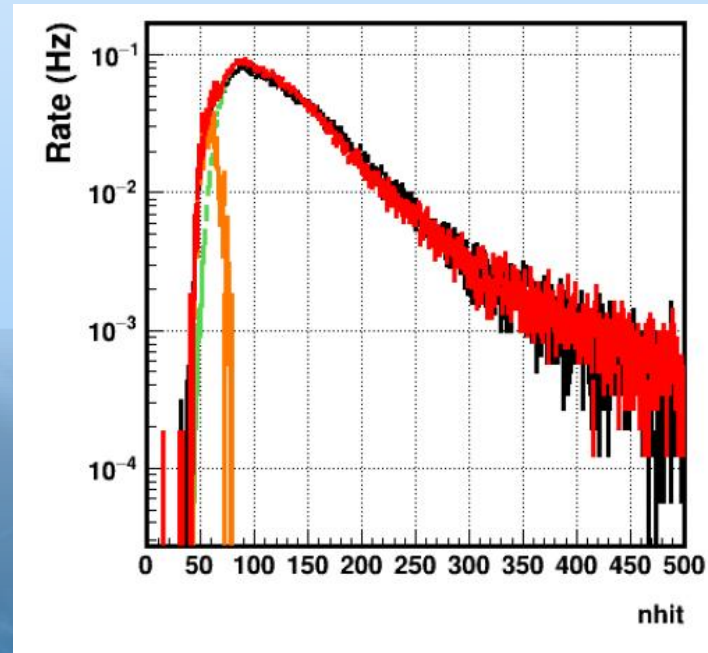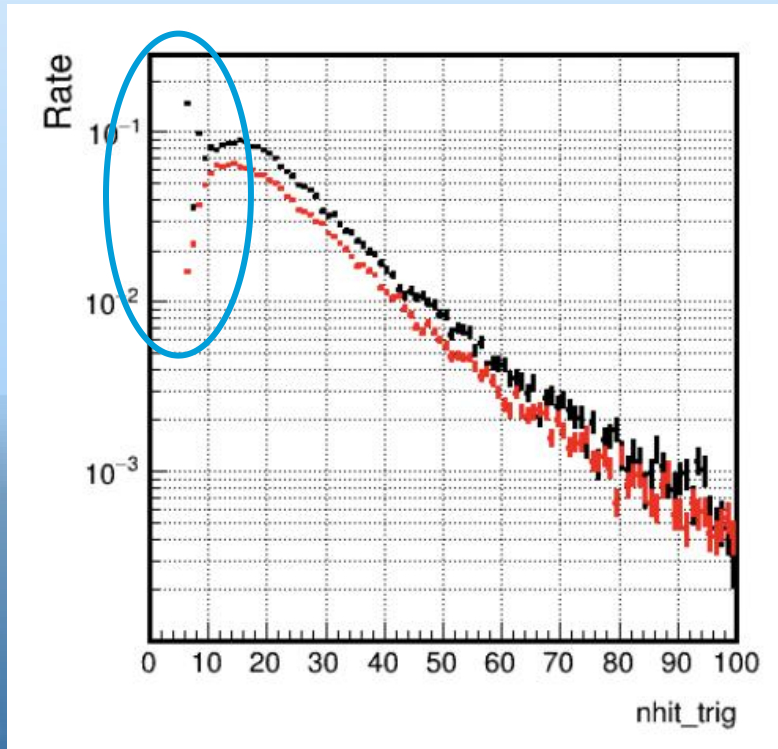 events investigation

Reconstruction level:
Comparison of data with 2 different
atmospheric muon simulations (tunings)

Trigger level:
Comparisons of productions with different software versions

13

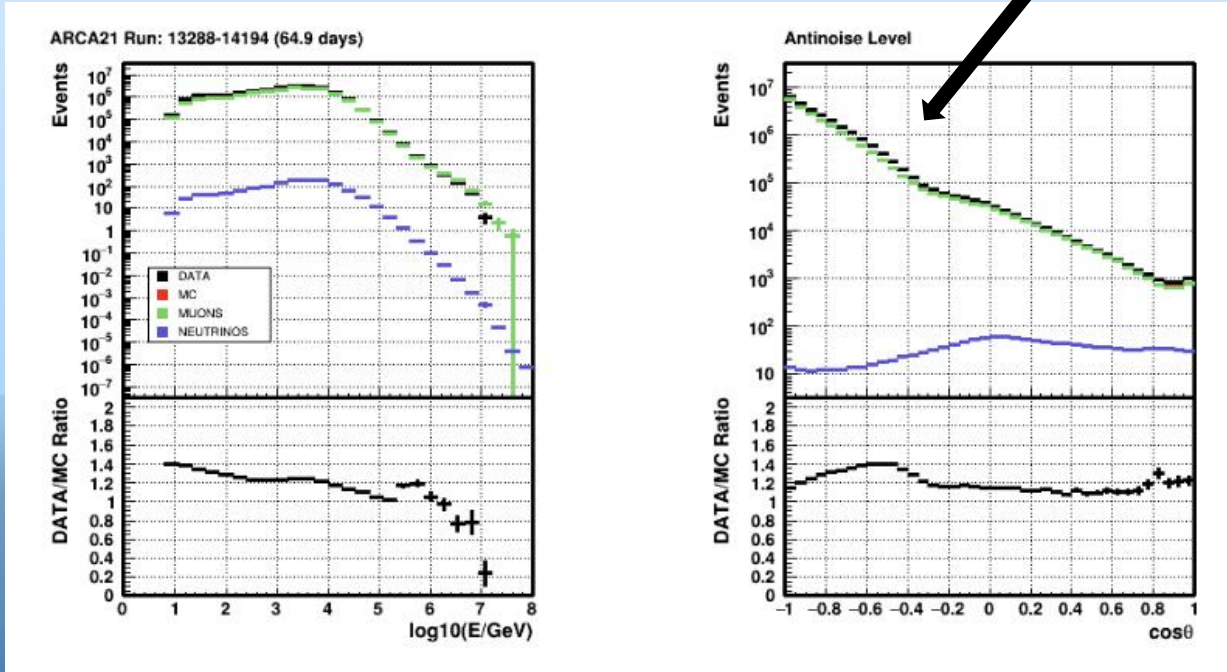## 1. Description/understanding of our detector

High rates of low number of triggered hits in data but NOT in atm. muon simulations due to pure noise (a.k.a K^{40} decays)
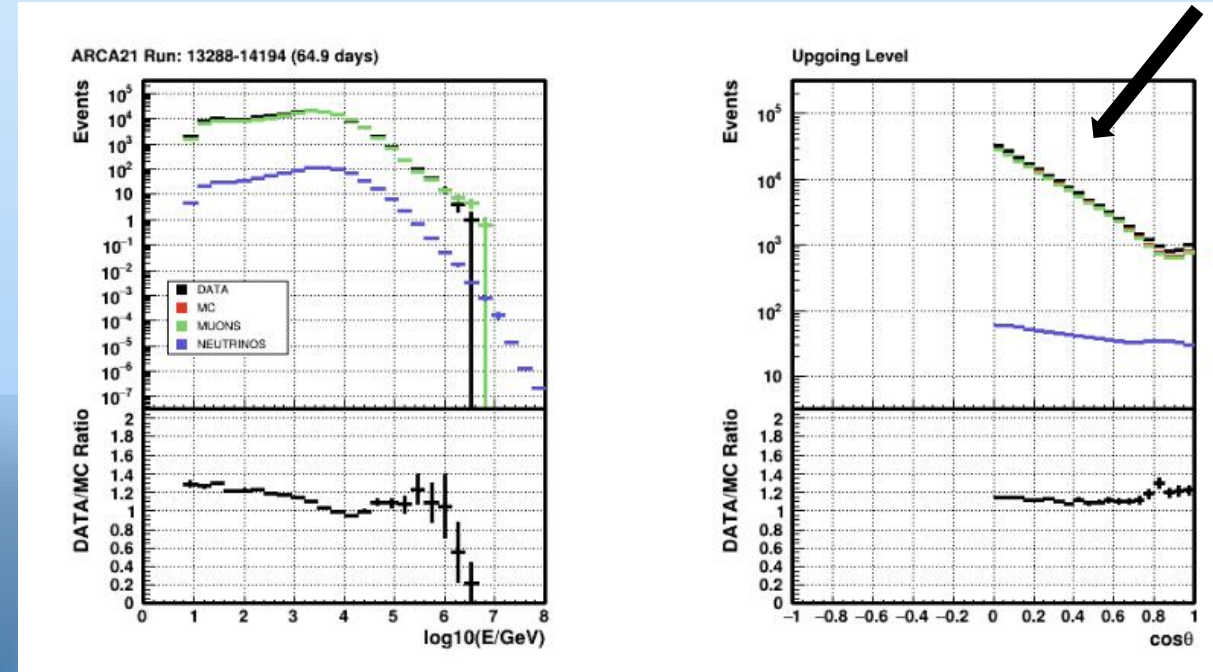*Verified by simulating pure noise events!

Data analysis - step II

2. Background rejection

All events

Upward going events

For neutrino astronomy, main background contribution comes from atm. muons!
*Looking for upward going events should reject atm. muon contribution (muons can not travel Earth without interacting) - neutrinos + misreconstructed as muon events events are observed!

3. Event selection (high-energy neutrino events)

No misreconstructed atm. muons contribution. **Data described only by neutrino simulations**!
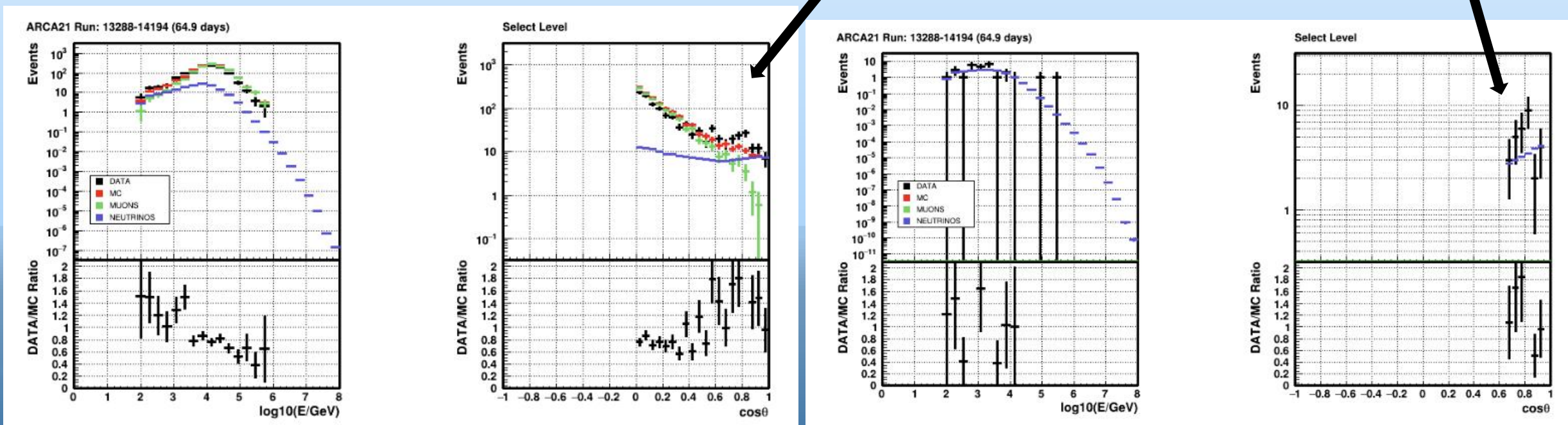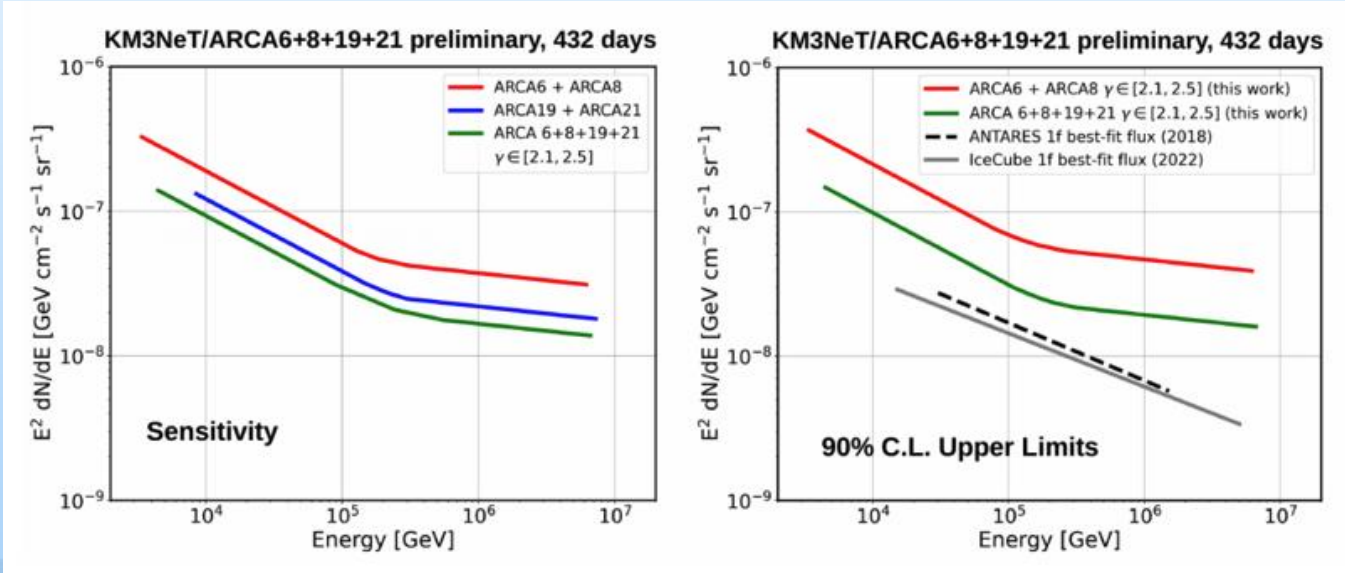

There is no way to differentiate between astrophysical and atmospheric neutrinos (reconstructed energy can help!)
Selection on important observables in order to select high energy neutrino events (e.g. reconstructed track, # of hits)

**Physics data analyses -
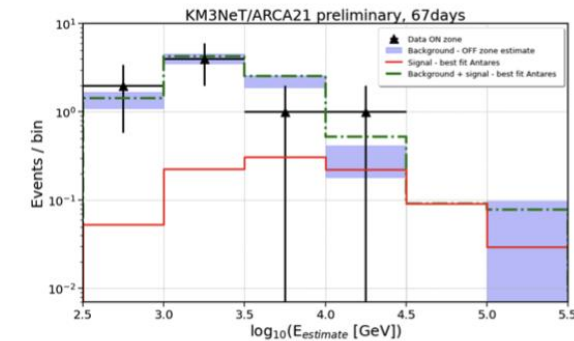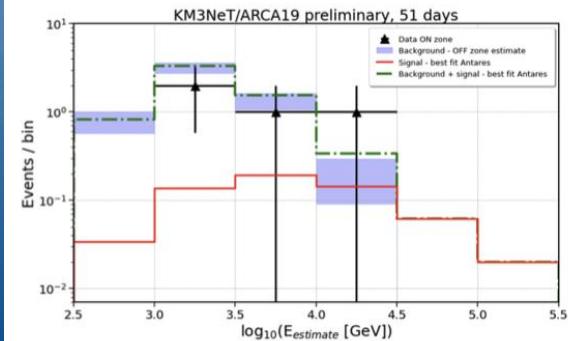Astrophysical analyses performed with KM3NeT data**
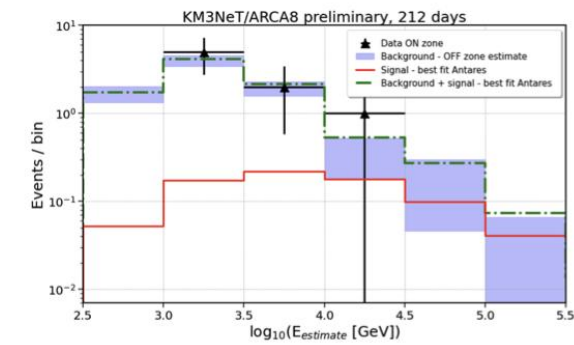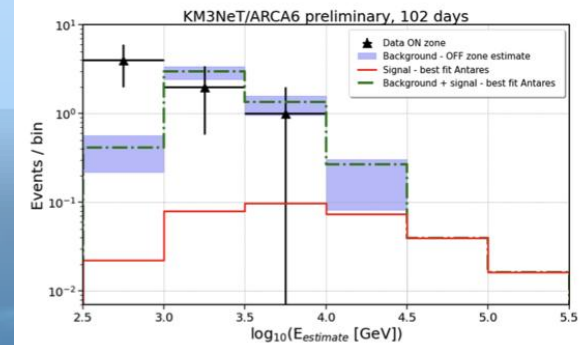
**Search for a diffuse astrophysical neutrino flux
from the Galactic Ridge using KM3NeT/ARCA data**
https://pos.sissa.it/444/1190/pdf

**Search for a diffuse astrophysical neutrino flux
with KM3NeT/ARCA**

https://pos.sissa.it/444/1195/pdf

Physics data analyses -
Astrophysical analyses performed with KM3NeT data

Search for cosmic neutrino point sources and extended sources with 6-21 lines of KM3NeT/ARCA
https://pos.sissa.it/444/1018/pdf

and many more to come soon...
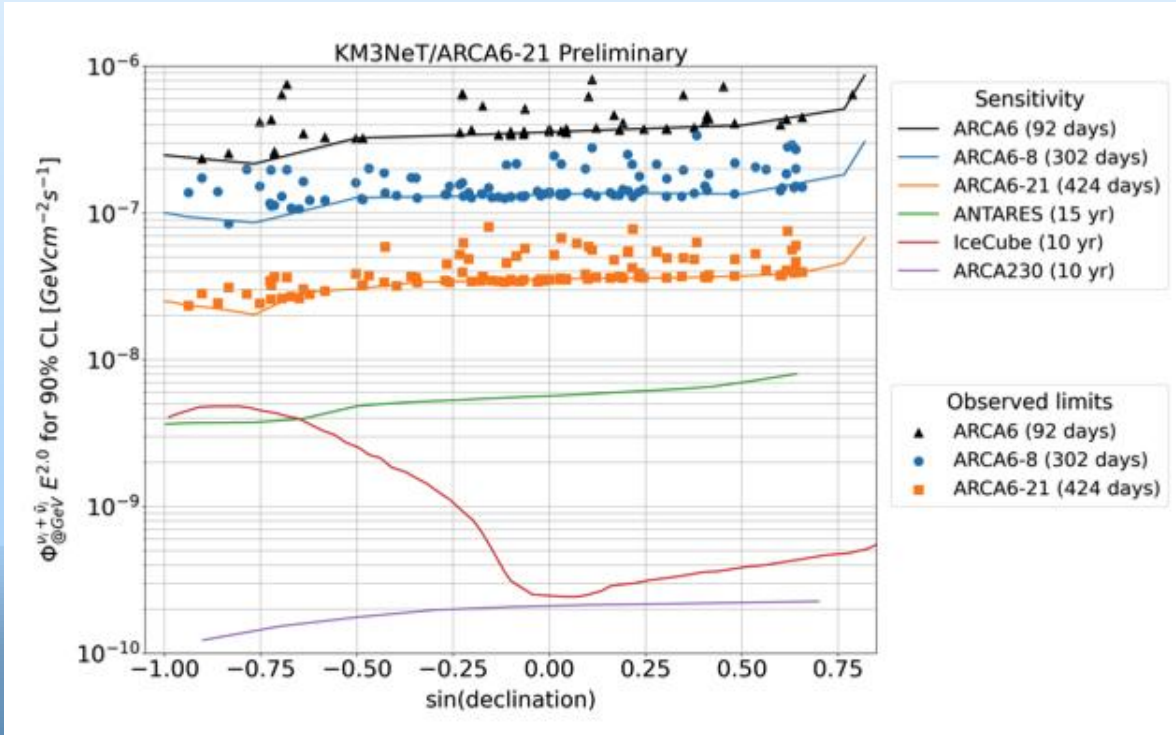
KM3NeT upper limits quickly reaching the ANTARES 15yr limits

Indirect Search for Dark Matter with the KM3NeT Neutrino Telescope
https://pos.sissa.it/444/1377/pdf

Physics data analyses - Multimessenger program
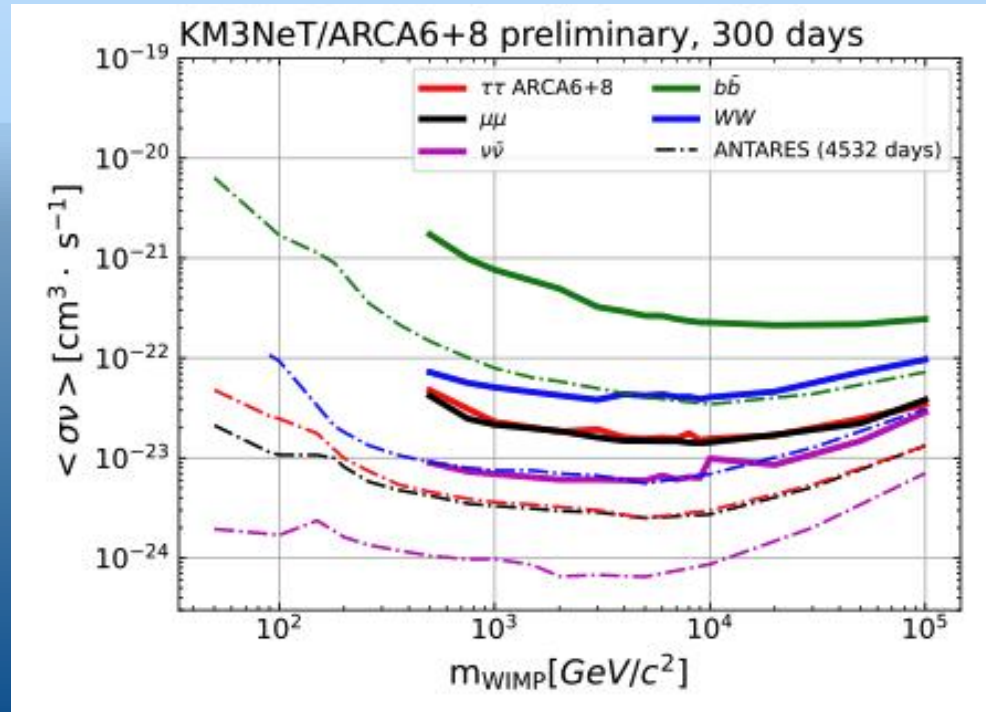
With the Real-Time Analysis platform, we perform:
- Auto-correlation searches
- Follow-up studies

starting automatically whenever an interesting external alert is received

By 2024, high-energy neutrino alerts will be sent in real-time!!!

The RTA platform of KM3NeT
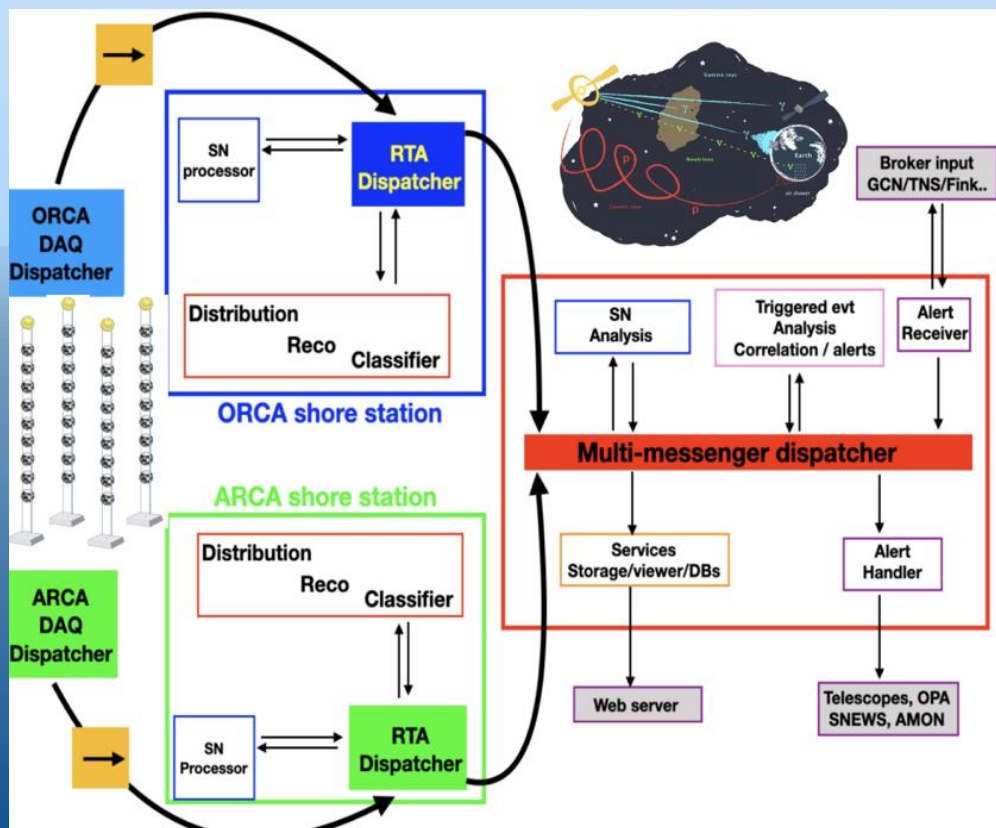
In ARCA21 **a median delay of 3.6 s is obtained from data filtering to classification,** including event buffering, dispatching and reconstruction times.

https://pos.sissa.it/444/1125/pdf

Summary

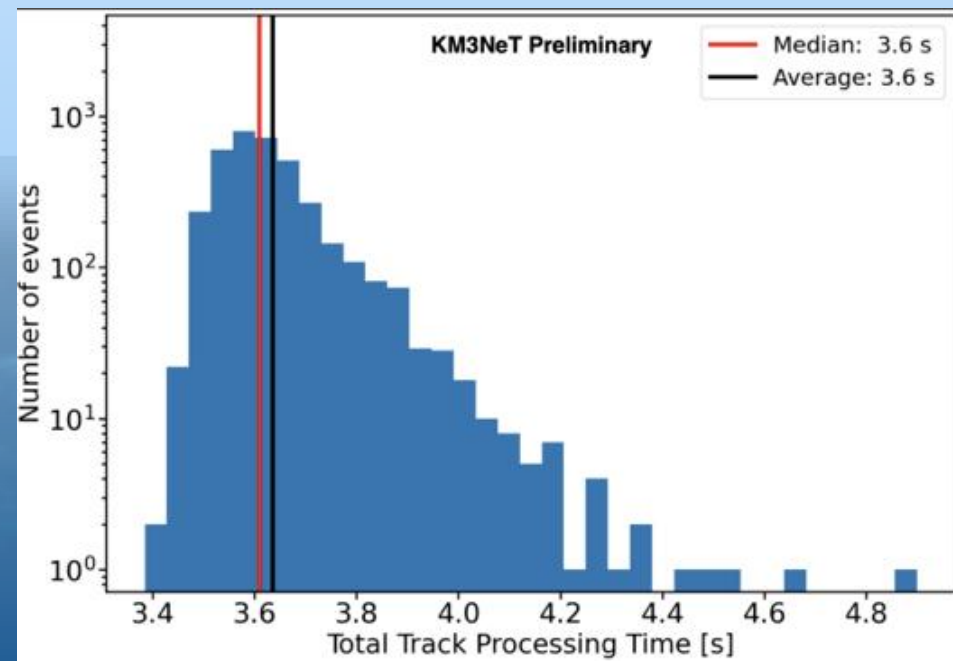**KM3NeT is expected to *open a new window to our Universe!***

Data management is an essential part of the work "behind" such big experiments; a great amout of data (mainly coming from background) is expected.

Monitoring of the data taking is performed both online and offline, in order to inspect data "health" and to classify data taking periods based on the recorded conditions.

Monte Carlo simulations production is performed in *run-by-run approach* in order to describe as good as possible the coresponding data taking conditions.

Detailed investigations of the reconstruction performance and for the optimization of the simulations input are performed within the corresponding working group of KM3NeT.

Astrophysical physics analyses using KM3NeT data are presented.

KM3NeT is already collaborating with other experiments in the MultiMessnger (MM) program.

Thank you for your attention!

A.Sinopoulou
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Stay tuned:
[km3net.org](km3net.org) Instagram Twitter Facebook