Enhancing neutrino alerts for KM3NeT with multi-wavelength correlation

2024 Fink Collaboration meeting

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Introduction

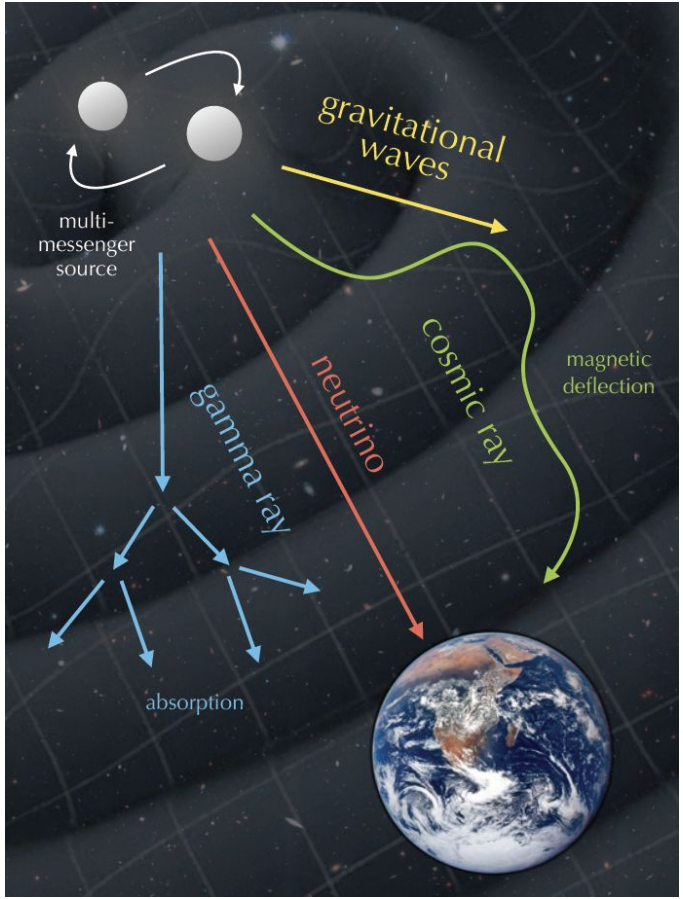
Multi-messenger astronomy and neutrinos

Combining the different messengers emitted by astronomical processes gives a broader picture to understand the physics at play

Neutrinos: good messengers as neutral, stable, weakly interacting -> access to cosmological distances and dense environments

‘Smoking gun’ signature for hadronic processes

Sources of very high energy neutrinos mostly unknown for now



Known(?) neutrino sources

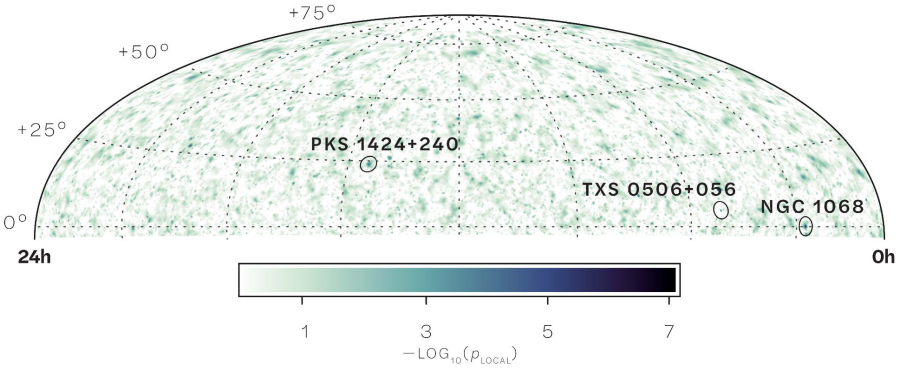
AGN/Blazars/Seyfert/SBG
Previous detection by IceCube of flaring blazar (TXS 0506+056) and galaxy NGC 1068

Less than 1% contribution from those two objects

Optical data very important for model constraints

Tidal Disruption Events
Neutrino happening more than 100 days after the tidal disruption flare
→ classification can be done before the time of neutrino observation

Rubin Observatory will give lots of opportunity to watch those events



KM3NeT experimental setup

KM3NeT

Water Cherenkov neutrino detector currently in construction at the bottom of the Mediterranean Sea

ORCA

Denser array, volume of 7 Mt, optimized for detection of neutrinos in the tens of GeV, offshore Toulon (FR)

ARCA

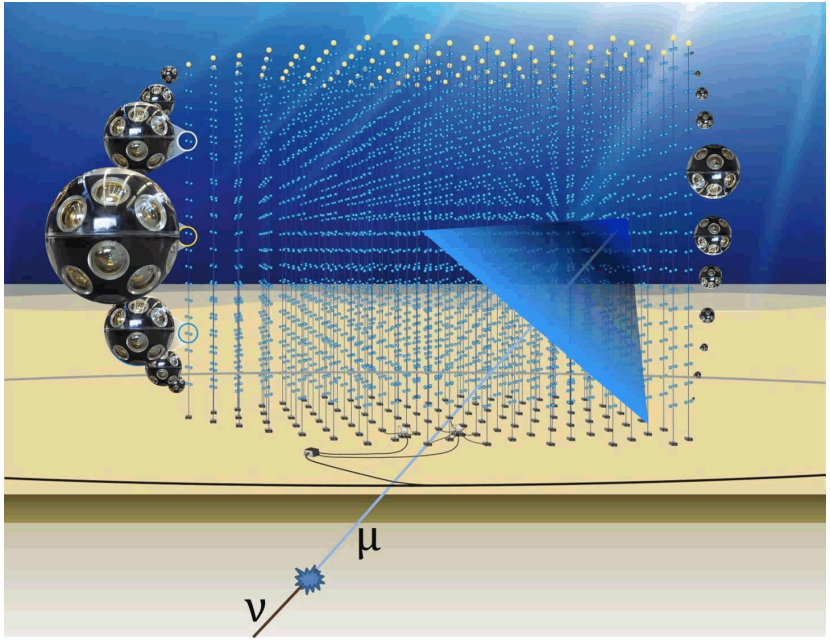
Volume of 1 km³ , optimized for the detection of neutrinos in the TeV to PeV energy range, offshore Sicily

Detector design

DOM (digital optical module): sphere hosting 31 PMTs

ORCA: 115 lines of 18 DOMs each

ARCA: 230 lines of 18 DOMs each



Why do we need neutrino alerts?

As we are limited by the statistic sample of astrophysical neutrinos we can observe, **alerts** are one of the **best strategy to identify likely astrophysical neutrinos** and **characterize their potential sources**.

Performing **follow-up observations** in **all of the electromagnetic spectrum** allows to get as much data as possible from the potential sources, which would allow for **better model fits** and, in the end, to **identify the sources of astrophysical neutrinos**.

The remaining question is: **how to maximize the number of follow-up observations to those alerts?**

ANTARES neutrino alerts

Criteria for alerts

– Neutrino doublet (0.04 evts/yr)

– Single neutrino with direction close to local galaxies (1 TeV, 10 evts/yr)

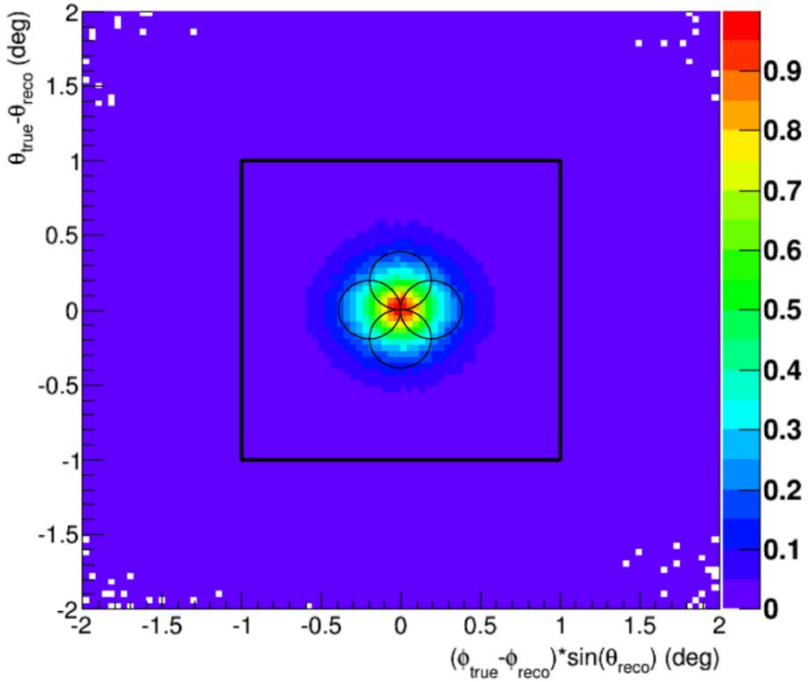
– Single HE neutrinos (7 TeV, 15 evts/yr), with sub-sample of VHE neutrinos (30 TeV, 3-4 evts/yr)

Follow-up

Private alerts in the GCN format

Follow-up observations with optical (ROTSE-III and TAROT) and X-ray (Swift) telescopes

218 alerts followed within 1 day, 55 alerts followed within 1 minute



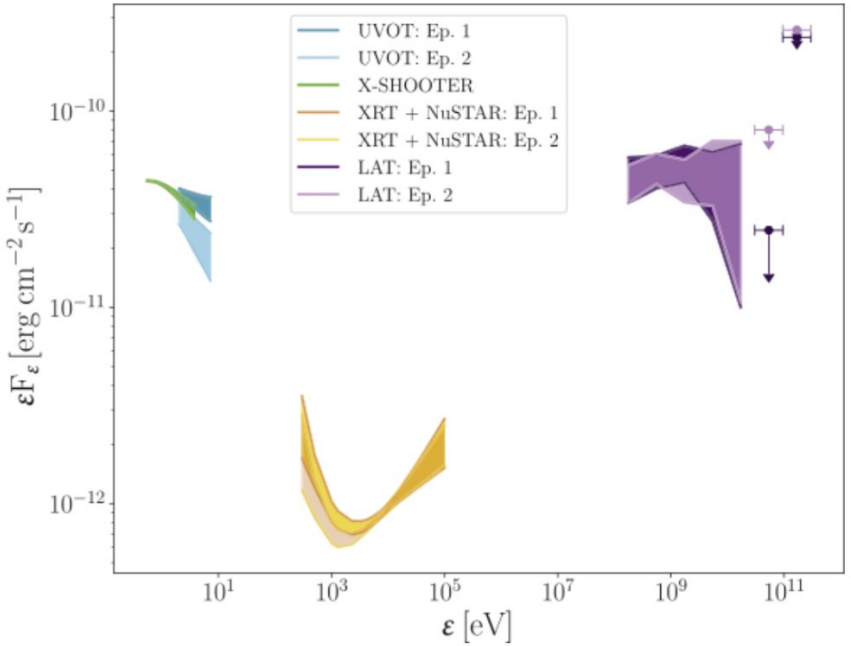
Angular resolution for a typical HE neutrino alert. Black square: optical telescopes FOV, black circle: Swift FOV

IceCube neutrino alerts

IceCube alerts
Since 2019, improvement on background rejection and selection on “signalness” (~probability of astrophysical origin) for muon neutrino tracks, with two classification (GOLD for 50% and BRONZE for 30%)

Automatic public alerts through GCN notices, GCN circular few hours later with refined reconstruction and sometimes astrophysical data

TXS0506+056 example
Correlation between a neutrino and a flaring blazar at 3σ on September 2017
One of the biggest follow-up observation to date (Swift, Fermi, AGILE, MAGIC, VLA, VLT)



Spectral energy distribution for TXS0506+056

KM3NeT neutrino alerts

General overview

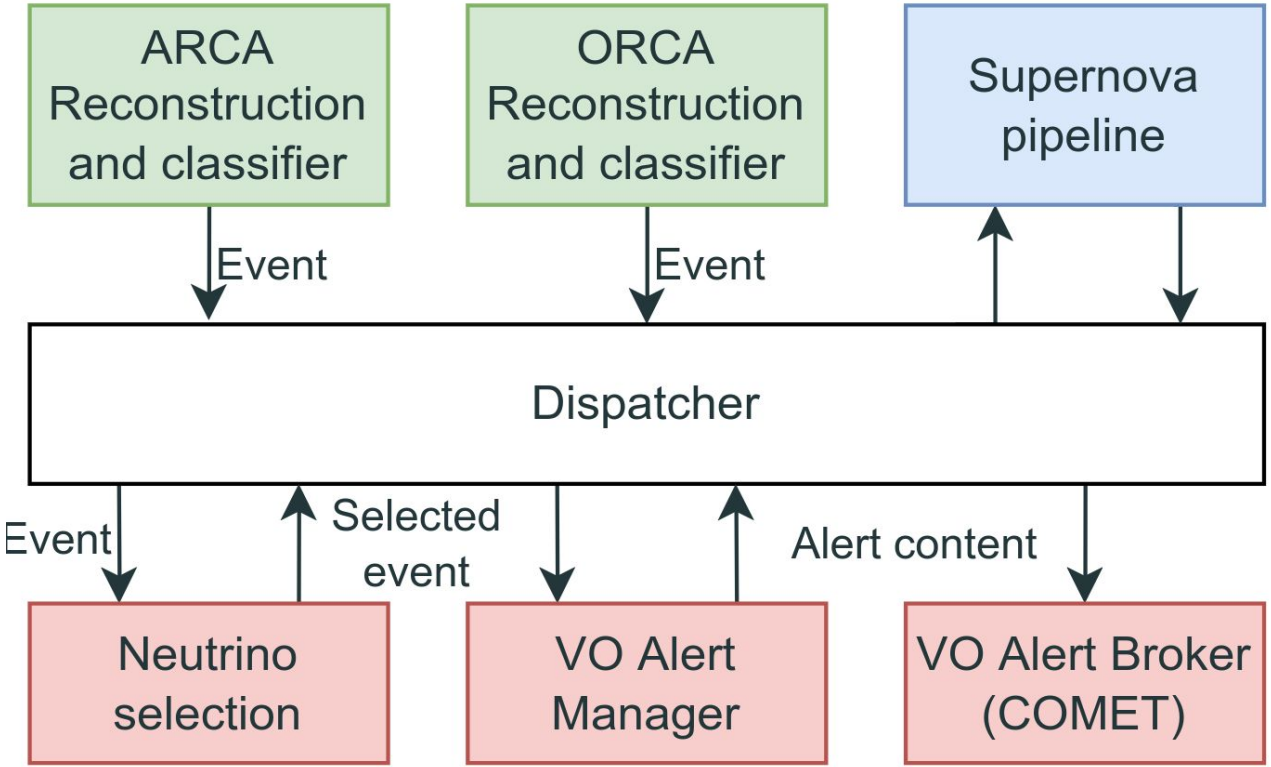


Diagram describing the alert generation

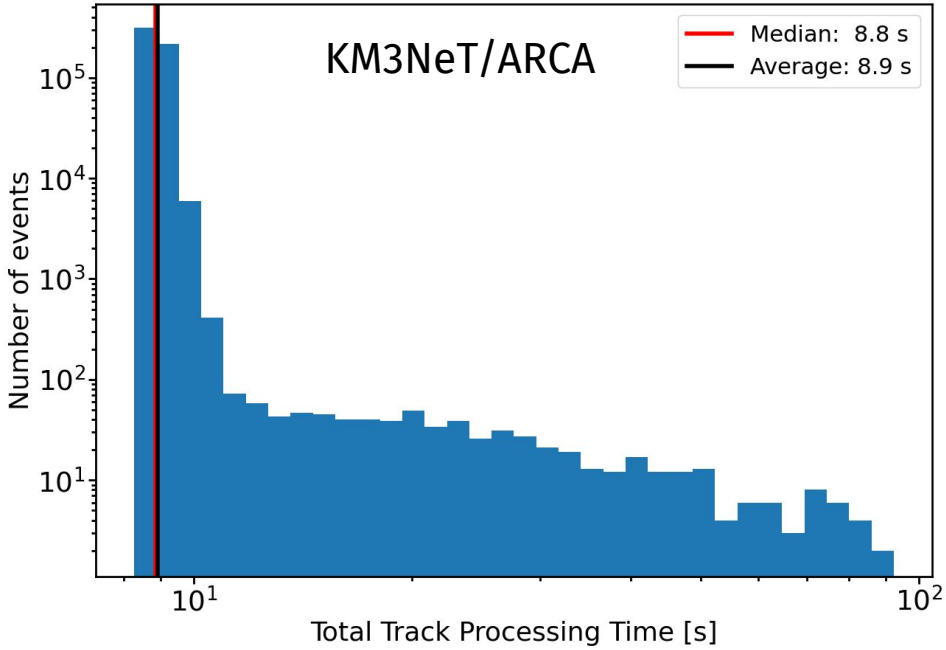
What data can KM3NeT provide?

What data can KM3NeT provide?

In less than 1 minute, **full reconstruction of tracks and showers with direction and energy estimation** (for now few seconds buffer that will be removed soon)

For every event, we have access to reconstruction as tracks and as showers with:
– probability of neutrino (all flavors) vs muon for low energy
– probability of track vs shower for high energy

With a full detector (230 lines for ORCA, 115 lines for ORCA), we expect **between 100 and 200 neutrinos per day**



Neutrino selection and alert content

From hundreds of neutrinos per day, we select a few alerts per month:

(Very) High energy selection
Selection of single neutrinos, the ones which reconstructed energy are the highest of the month

Multiplet selection
In situations where multiple neutrinos are seen from the same direction within a limited time, an alert will be sent

Alert content
General template (VOEvent) filled automatically and checked before sending
Alert distributed publicly through a broker (COMET)

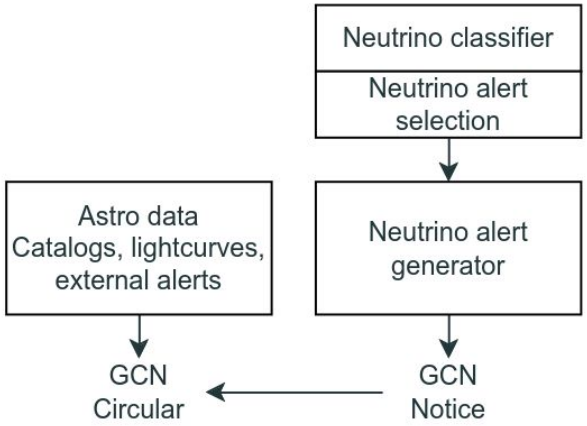
- ID
- Detector (ARCA/ORCA)
- Type of alerts triggerrs
- Number of events in given time and space widows
- Flavor
- Energy
- IsRealAlert
- Time
- RA, Dec, Longitude, Latitude
- Error box 50% and 90%
- Reconstruction quality
- Probability of neutrino
- Probability of astrophysical neutrino

How to maximize the scientific interest of our alerts?

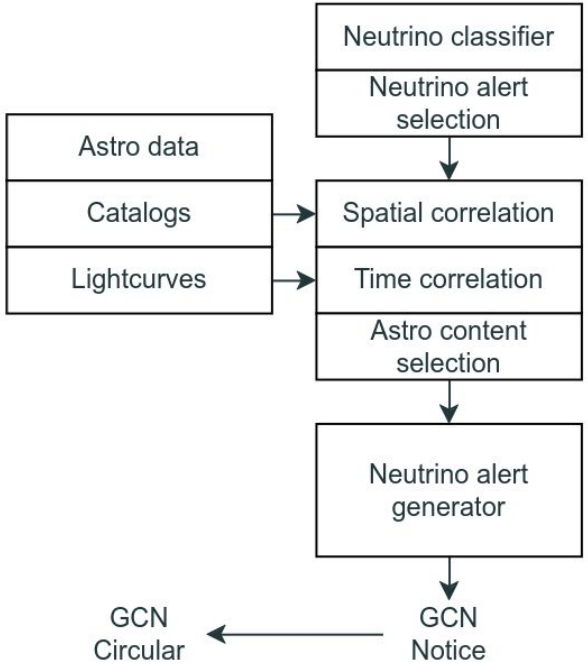
Two parallel selection

Pure neutrino selection
(Very) high energy and multiplet selection

Kept to not introduce bias in case of an unexpected source



Mix neutrino-astro selection
Selection of neutrinos based on both the neutrino properties and the properties of the potential astrophysical source



Building a prototype for blazars

For a given cone search in the sky:

- Get the number of blazars within the cone search
- For every blazar, report fluence(s), type, distance from the center of the cone
- Query light curves in different wavelengths and compute variability of the blazars

How to give a “score” to every blazar?

- Conversion from every “property” to a 0 to 1 score (linear, quadratic, exponential, logarithmic, ...)
- Multiplication of every score

  No need to weight for a particular property

Catalogs for spatial correlation

4FGL: Fermi Gamma-ray Space Telescope, energy range from 50 MeV to 1 TeV

TeVCat: online catalog for TeV Astronomy (not on CDS)

Radio Fundamental Catalogue: 20 000 extragalactic radio sources (not on CDS)

3HSP: catalogue of extreme and high-synchrotron peaked blazars (radio and X-ray data)

BZCAT: multifrequency catalogue of blazars

```
#+begin_src sql
SELECT *
FROM "IX/67/4fgldr3" AS p
WHERE 1=CONTAINS(
  POINT('ICRS', p.raj2000, p.dej2000),
  CIRCLE('ICRS', 70.66, -0.30, 1)
)
#+end_src
```

recno	4FGL	dr	raj2000	dej2000
1090	J0442.6-0017	1	70.6612	-0.2961
recno	4FGL	dr	raj2000	dej2000

Getting light curves

Short term:

- γ-ray using Fermi-LAT data
- optical using ZTF and Rubin Observatory data *via* the Fink broker

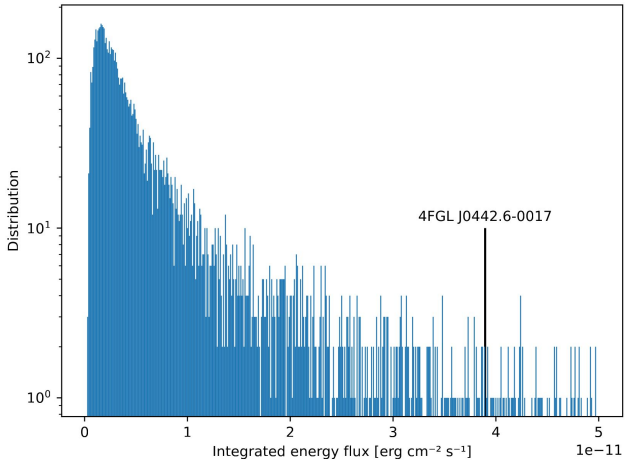
Longer term: other wavelengths and experiments
(radio and X-ray are very important for neutrino astronomy)

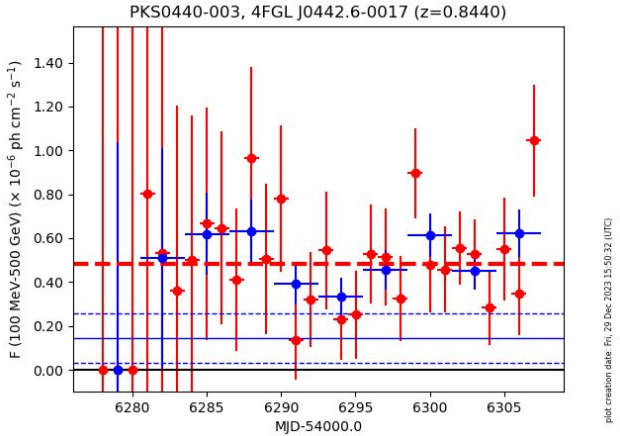
γ-ray
Use of FLaapLUC (Fermi-LAT automatic aperture photometry Light C<->Urve), quick and dirty Fermi-LAT analysis

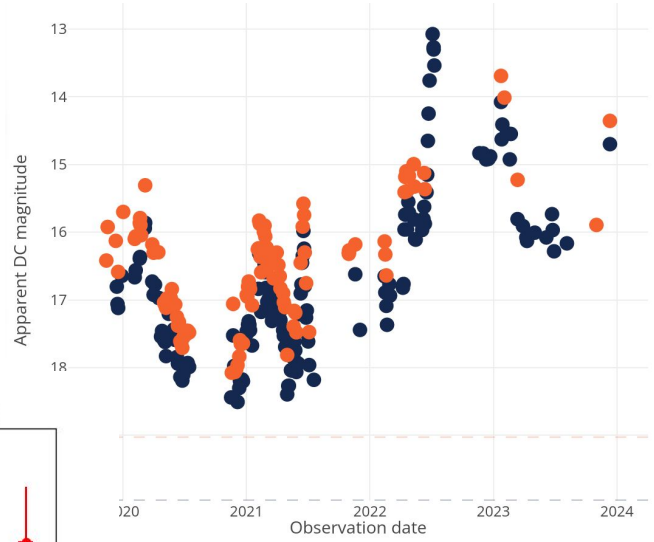
Optical
Use of Fink
For current night data, subscription to Blazar and BLLac livestream and storage in a temporary database
Otherwise search through API

One example: cone search for 70.66, -0.30, 1°

4FGL	raj2000	dej2000	ef100
J0442.6-0017	70.6612	-0.2961	3.89554e-11
4FGL	**raj2000**	**dej2000**	**ef100**







How to compute a score from all of this?

Outlook

Short term
Offline toy experiments
– Download locally catalogs and archival temporal data from Fermi and ZTF
– Repeat N searches to retrieve the different properties and plot the obtained distributions
– Play with every score function to build the best score to discriminate “interesting” sources

During 2024
First KM3NeT public alerts (system ready, but more work is needed for angular error estimation), hopefully optimum multi-wavelength follow-up

What else for the future?
Full combination of KM3NeT neutrino stream with Rubin stream? (like IC and AMPEL)
Other ideas?

If you have ressources, advices, ideas, feel free to share them!