Hunting neutrinos under the sea

with the KM3NeT neutrino telescope

Alessandro Veutro

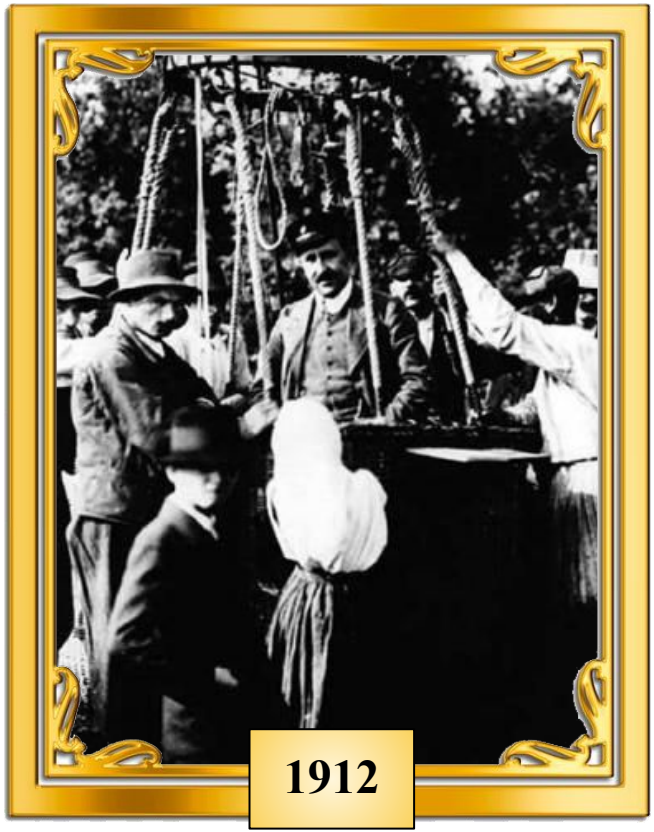
Supervisor: Irene Di Palma

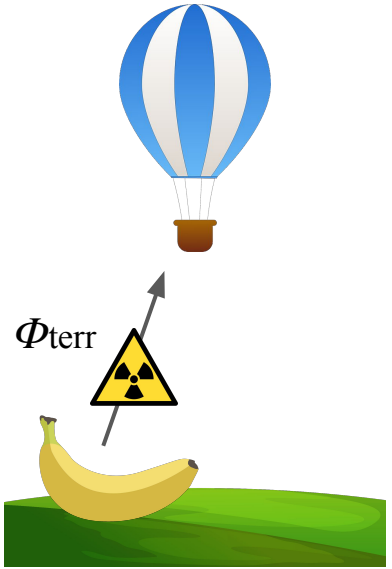
PhD Seminars, 8th November 2023

Once upon a time …

Once upon a time …

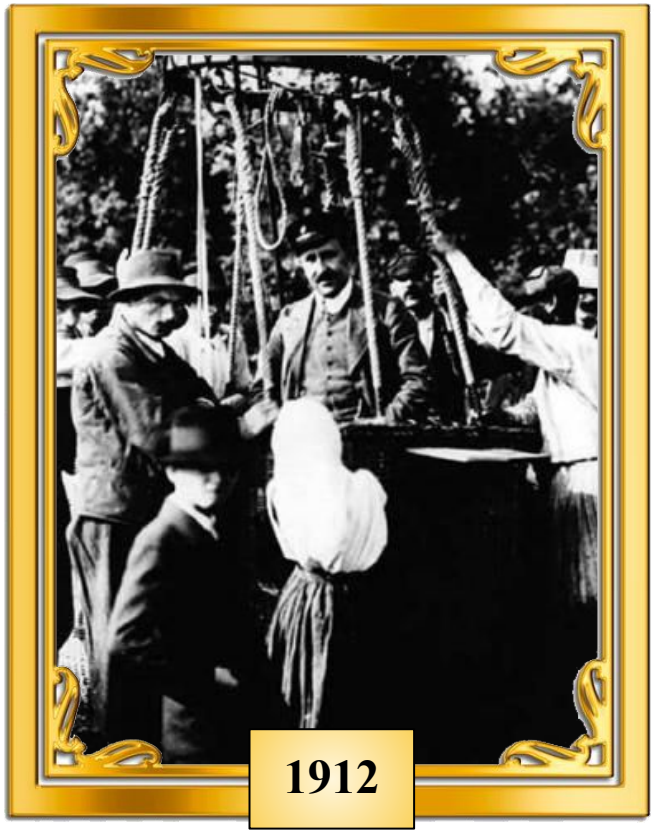
Victor Franz Hess
won the Nobel Prize in
Physics in **1936**

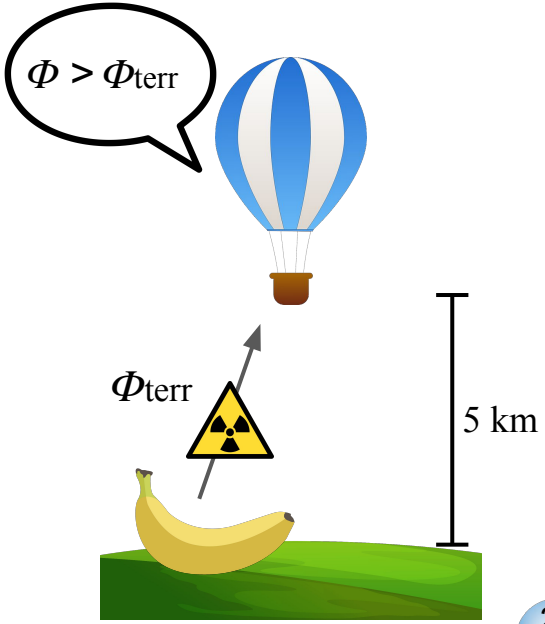




Once upon a time …

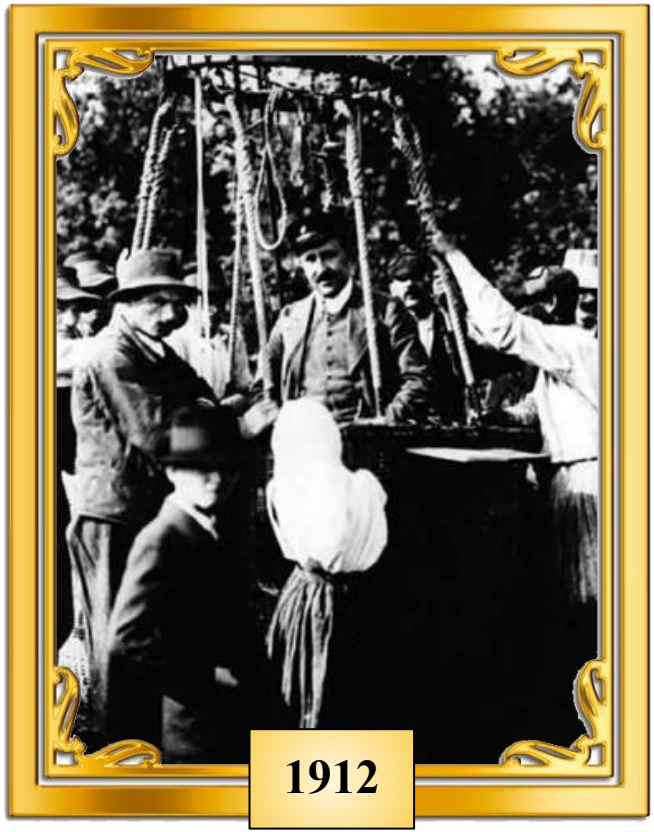
Victor Franz Hess
won the Nobel Prize in
Physics in **1936**

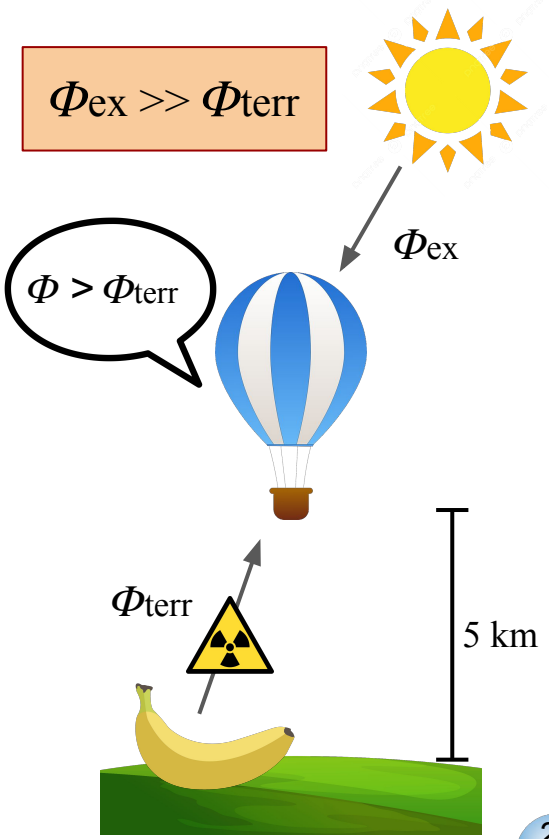




Once upon a time …

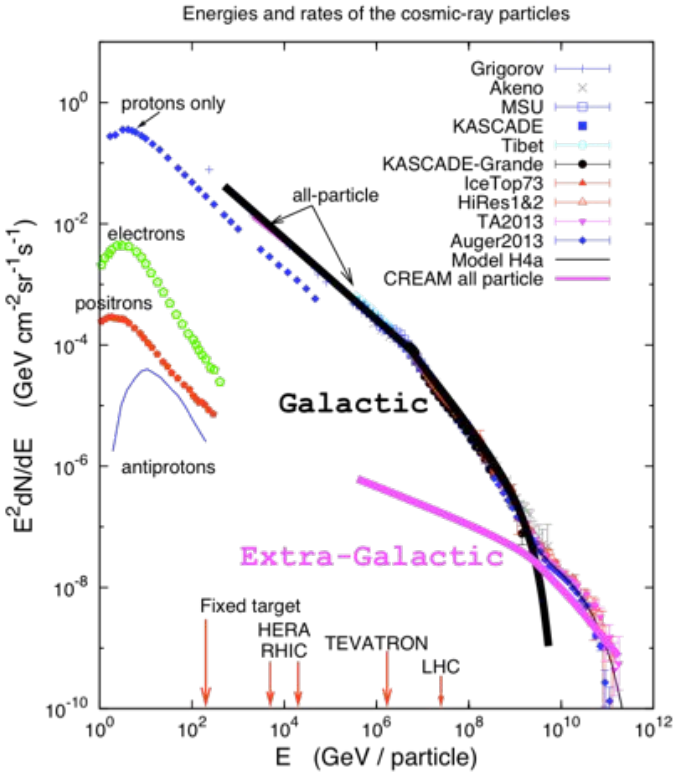
Victor Franz Hess
won the Nobel Prize in
Physics in **1936**



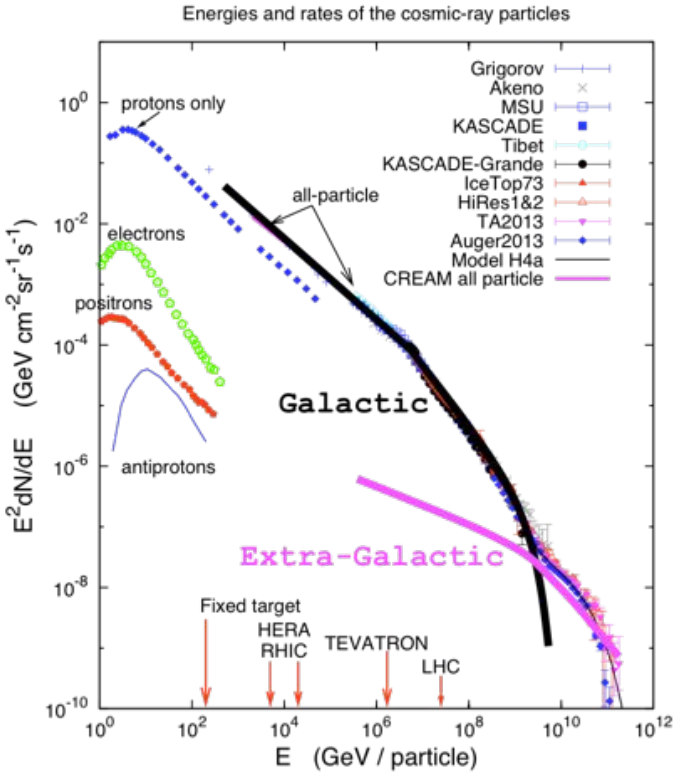


State-of-the-art

Cosmic rays are charged particles coming from outside of the Solar System



State-of-the-art

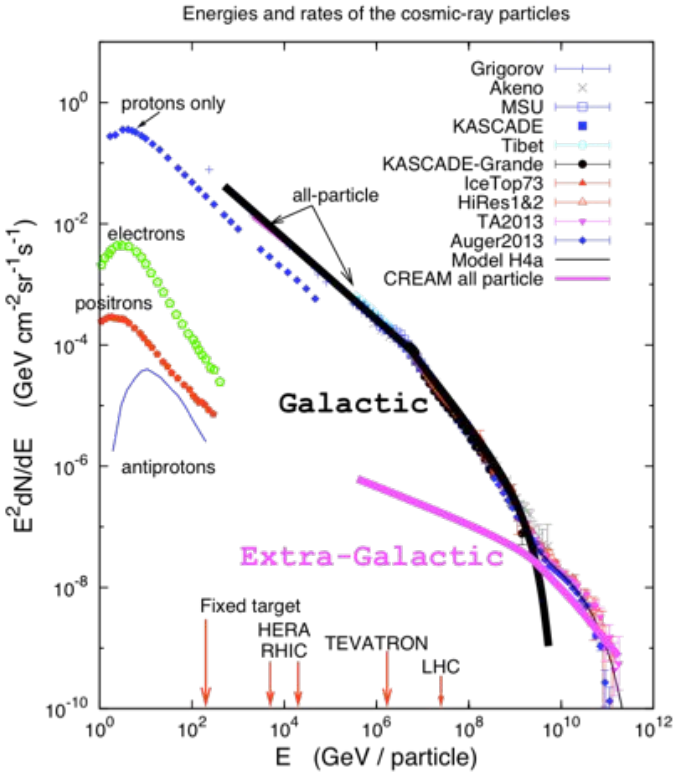


Cosmic rays are charged particles coming from outside of the Solar System

Cosmic rays are made up of:

- 89 % of protons
- 10 % of α particles
- 1 % of electrons and heavy nuclei

State-of-the-art



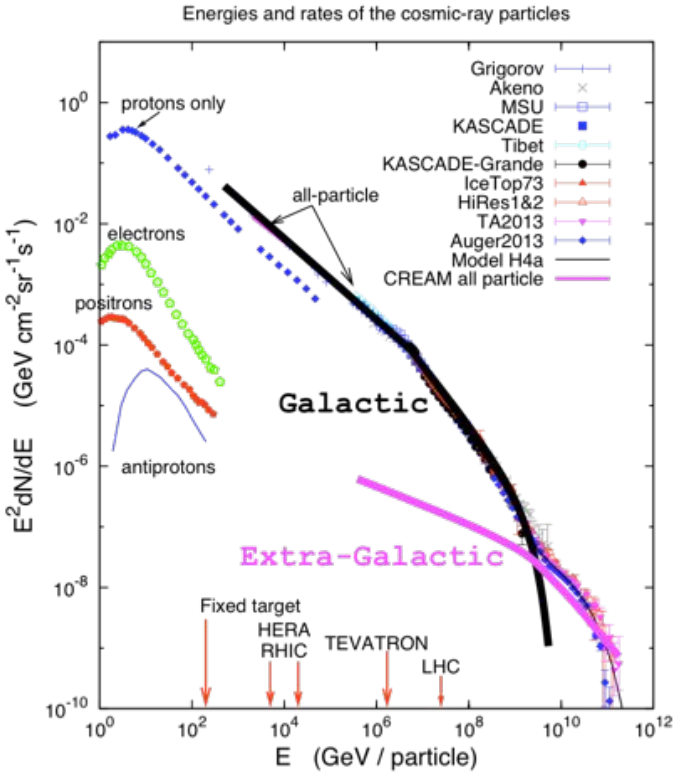
Cosmic rays are charged particles coming from outside of the Solar System

Cosmic rays are made up of:

- 89 % of protons
- 10 % of α particles
- 1 % of electrons and heavy nuclei

At high energy (around 10^9 GeV) the Extra-Galactic component should start dominating the arrival flux.

State-of-the-art



Cosmic rays are charged particles coming from outside of the Solar System

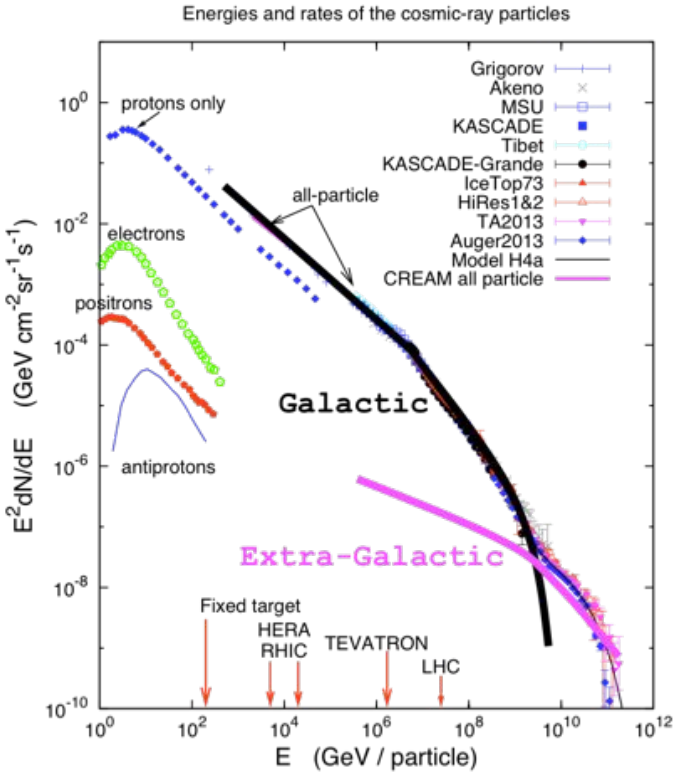
Cosmic rays are made up of:

- 89 % of protons
- 10 % of α particles
- 1 % of electrons and heavy nuclei

At high energy (around 10^9 GeV) the Extra-Galactic component should start dominating the arrival flux.

$$r_L = \frac{E}{ZeB} >$$ Galaxy disk width for a proton with an energy of 10^9 GeV

State-of-the-art



Cosmic rays are charged particles coming from outside of the Solar System

Cosmic rays are made up of:

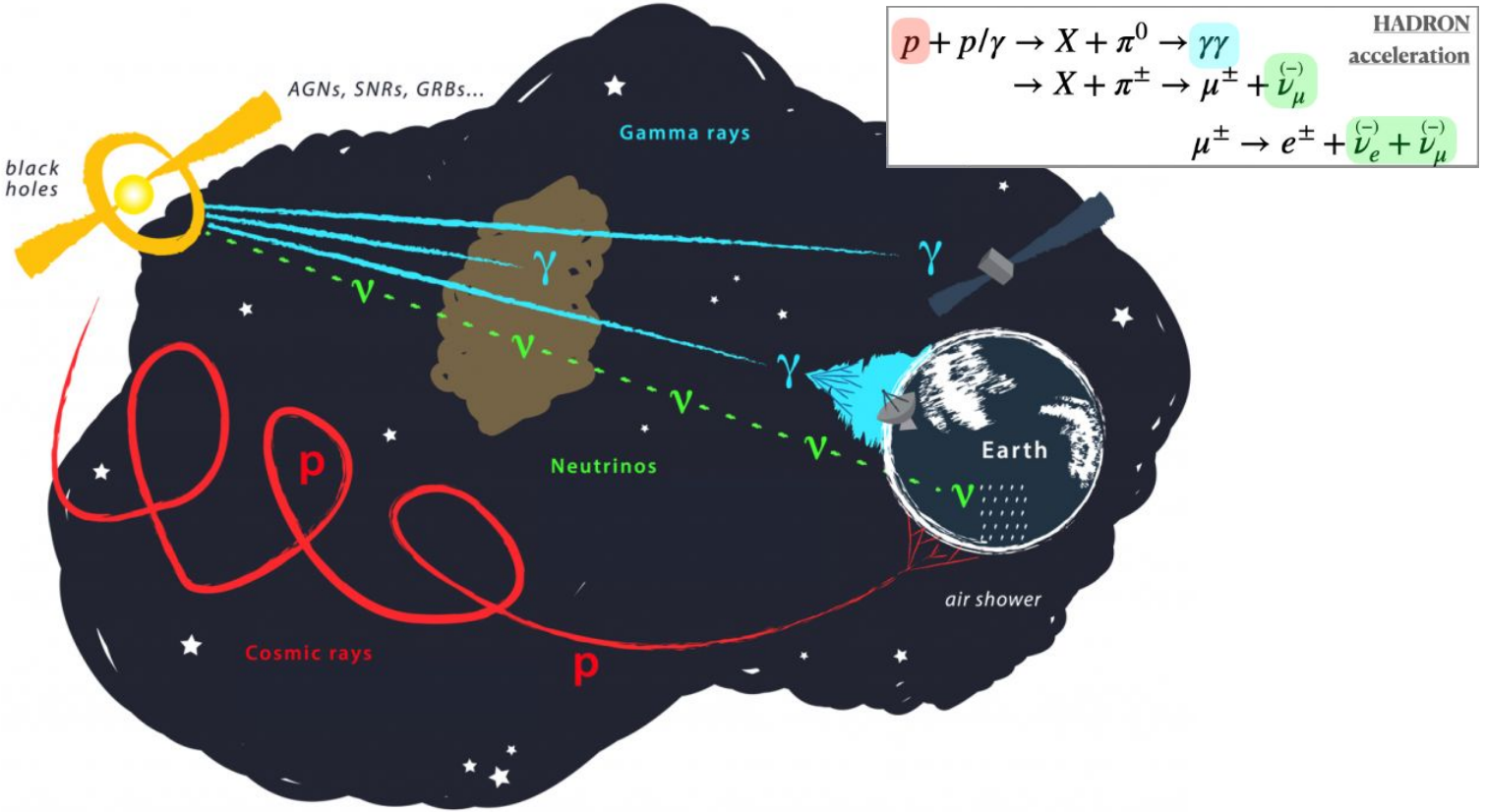
- 89 % of protons
- 10 % of α particles
- 1 % of electrons and heavy nuclei

At high energy (around 10^9 GeV) the Extra-Galactic component should start dominating the arrival flux.

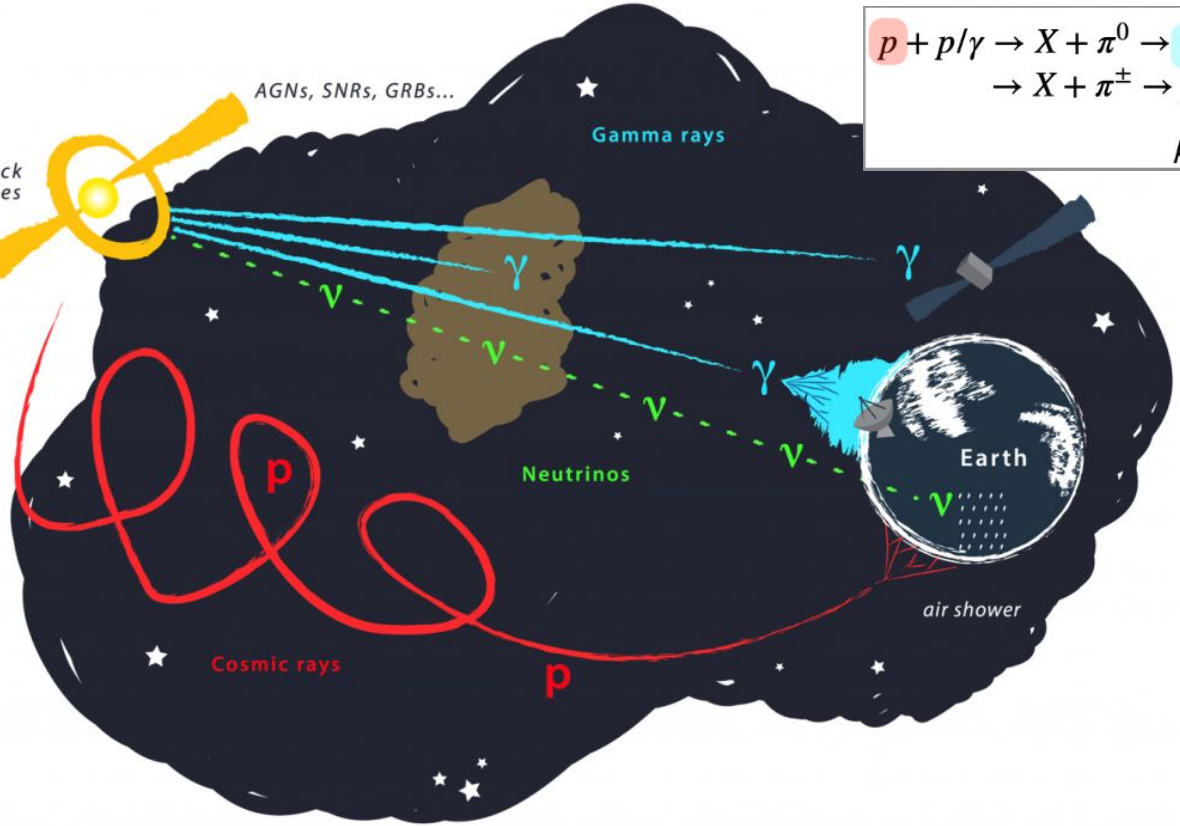
$$r_L = \frac{E}{ZeB} >$$ Galaxy disk width for a proton with an energy of 10^9 GeV

The origin of the highest energy cosmic rays is still unknown!!!

How can we detect Extra-Galactic sources?



How can we detect Extra-Galactic sources?

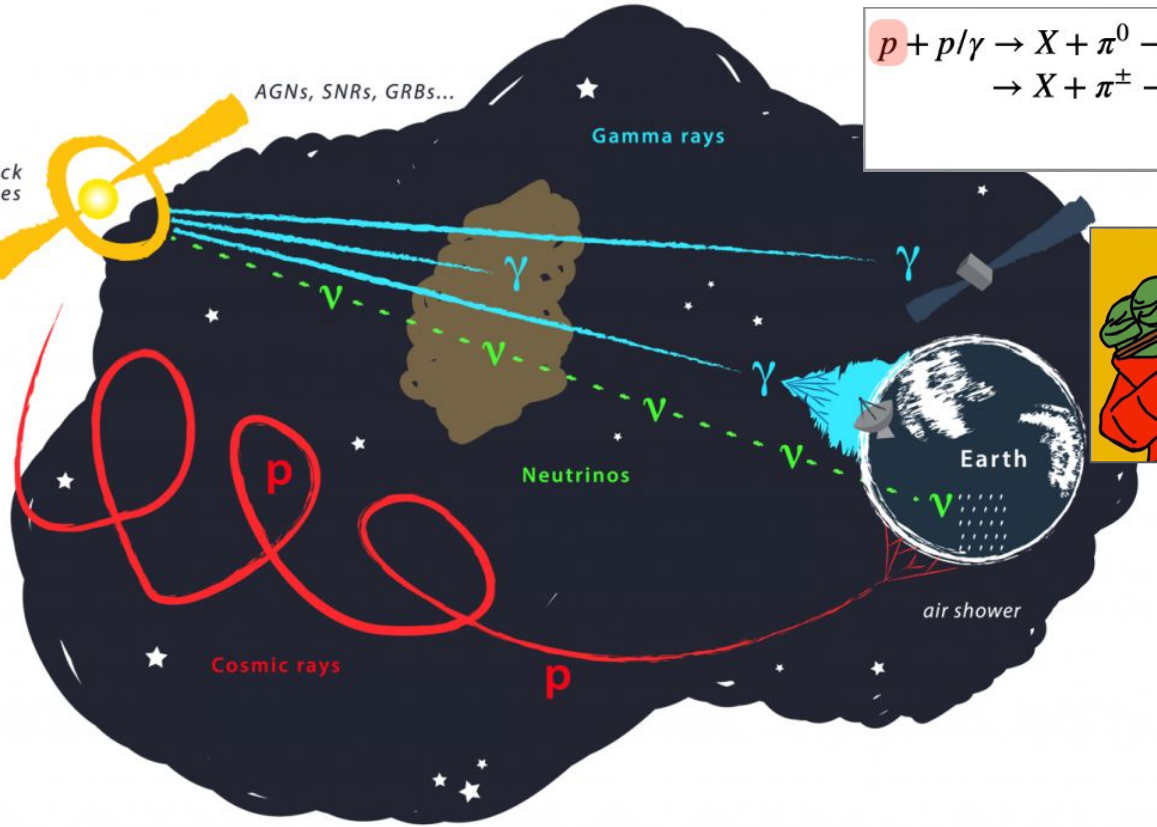


$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

Cosmic rays are deflected by magnetic fields

How can we detect Extra-Galactic sources?



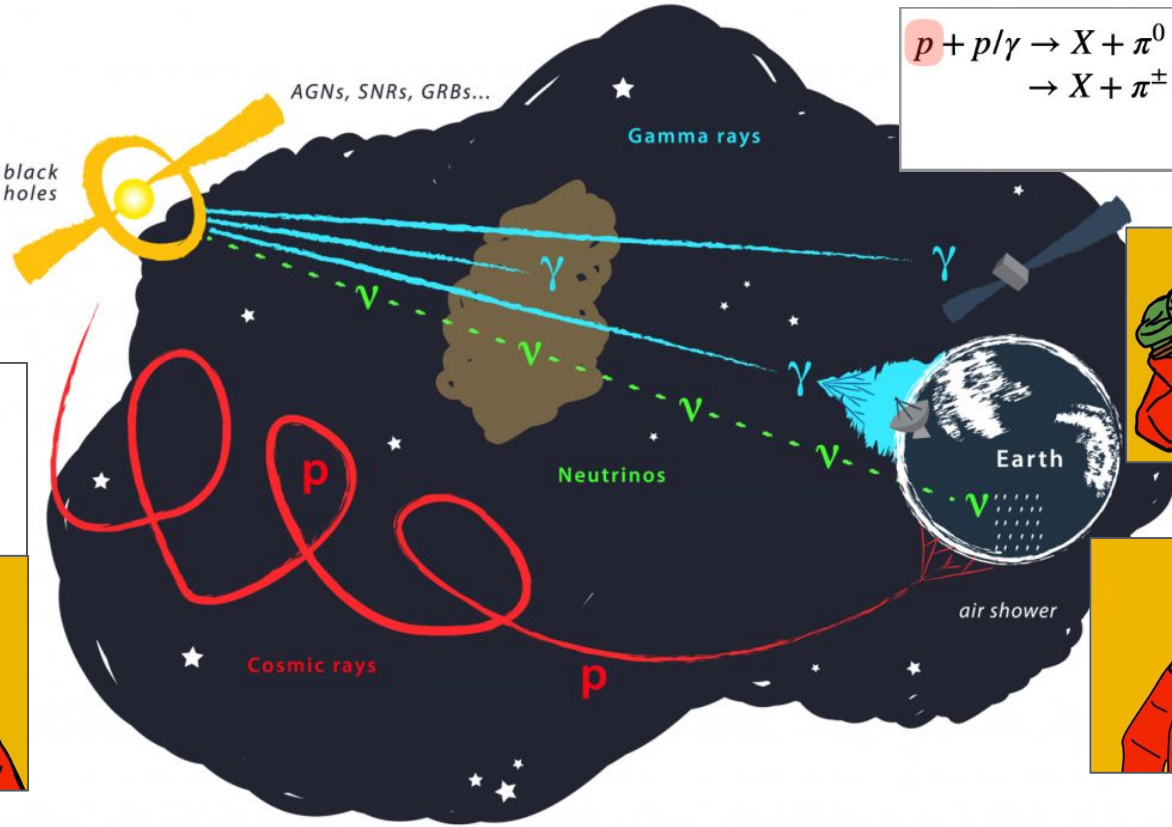
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

HADRON acceleration

Cosmic rays are deflected by magnetic fields

Gamma rays can be absorbed and are produced by multiple emission mechanisms

How can we detect Extra-Galactic sources?



HADRON acceleration

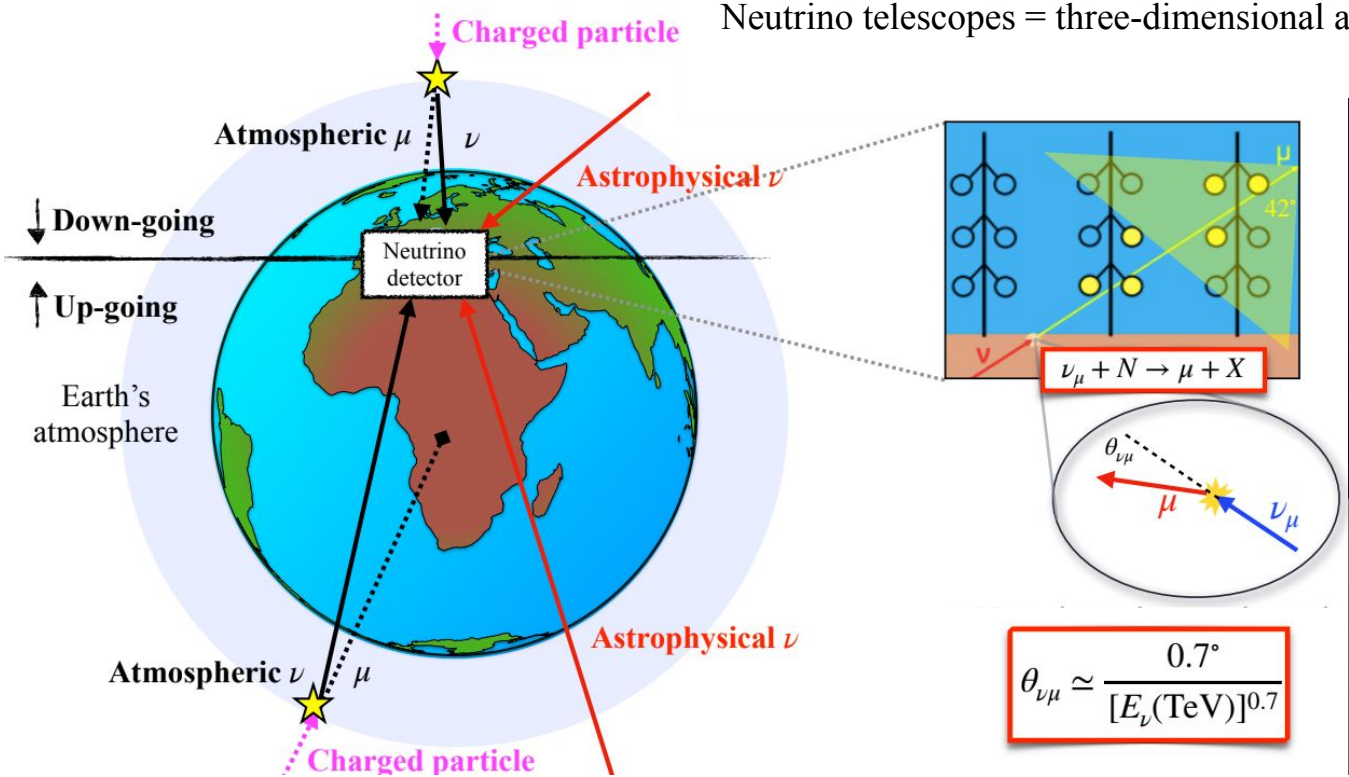
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

Cosmic rays are deflected by magnetic fields

Gamma rays can be absorbed and are produced by multiple emission mechanisms

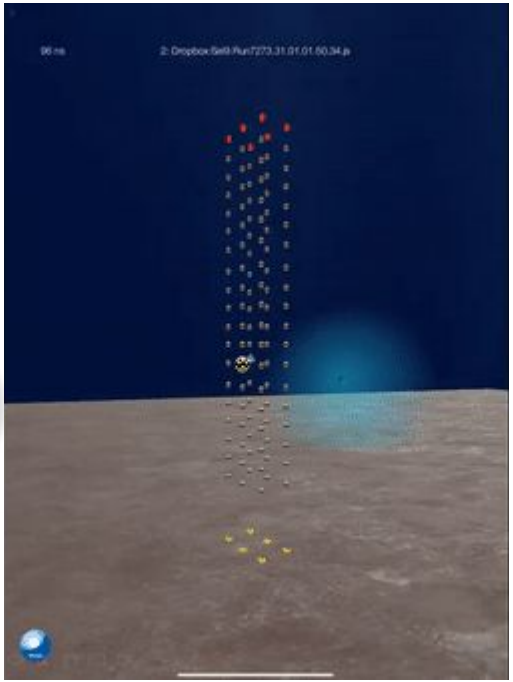
Neutrinos are ideal messenger in the search for distant astrophysical objects

Cherenkov neutrino telescope

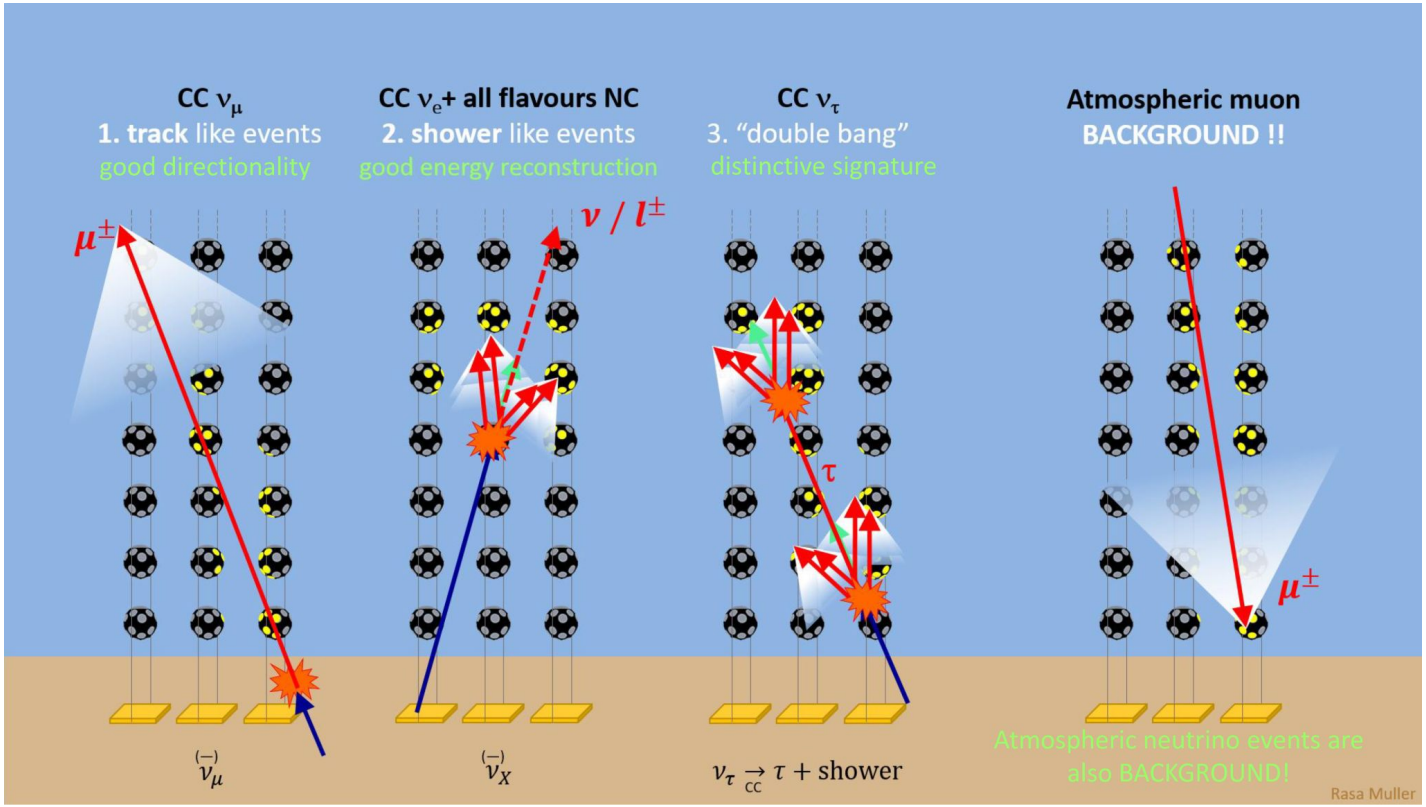


Neutrino telescopes = three-dimensional arrays of photomultiplier tubes (PMTs)

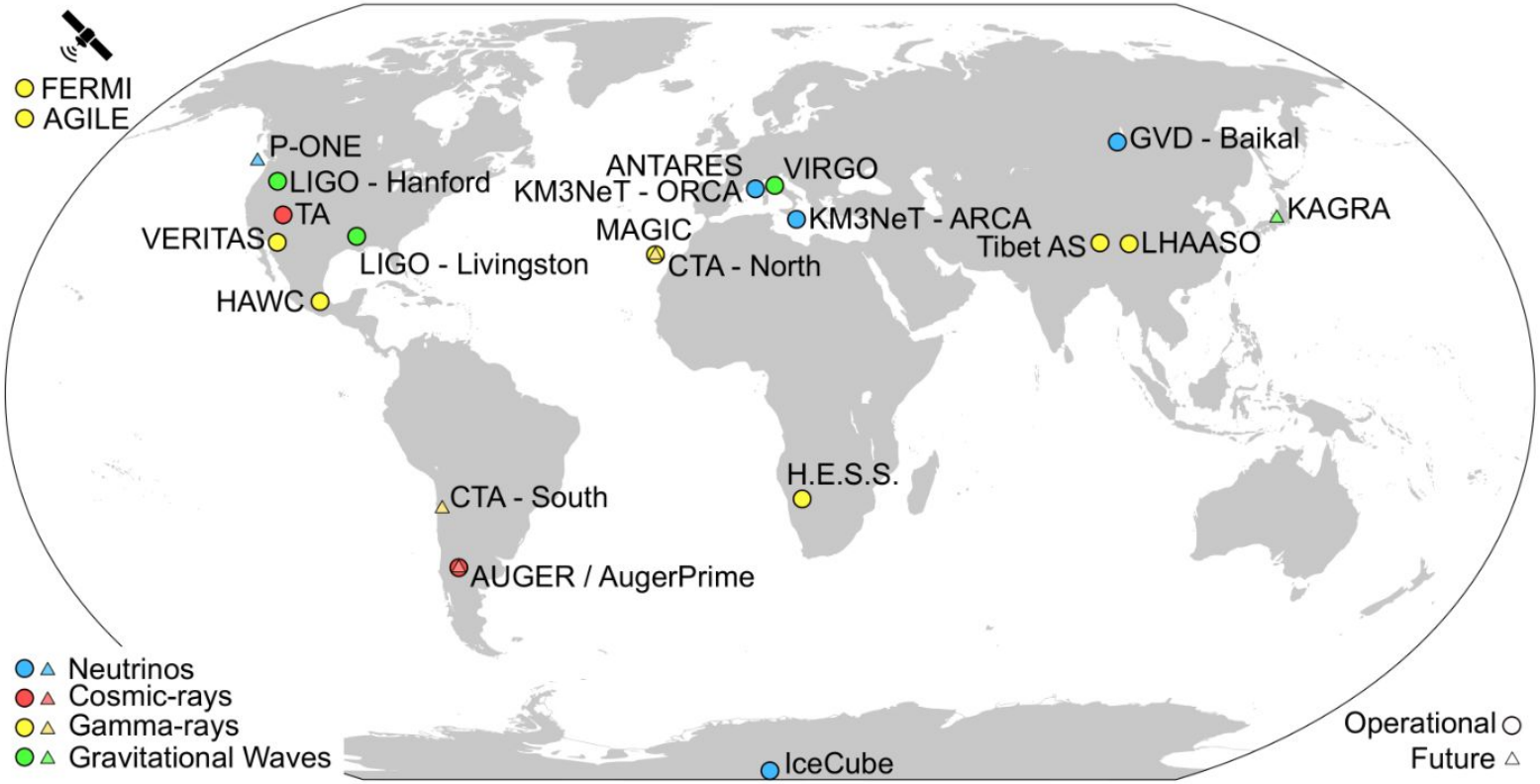
$$\theta_{\nu\mu} \simeq \frac{0.7^\circ}{[E_\nu(\mathrm{TeV})]^{0.7}}$$



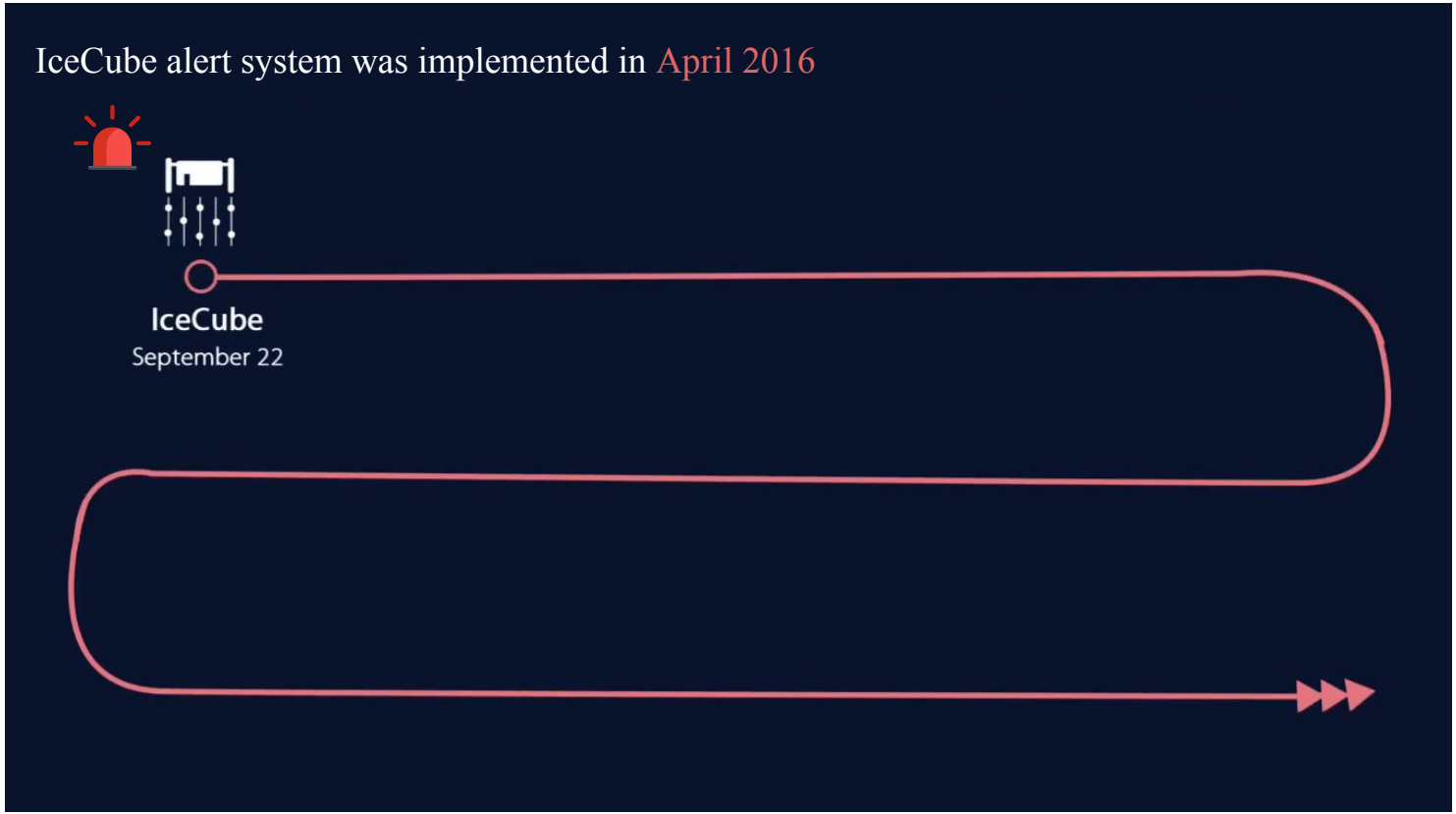
Events topology in cherenkov neutrino telescopes



Multi-messenger community

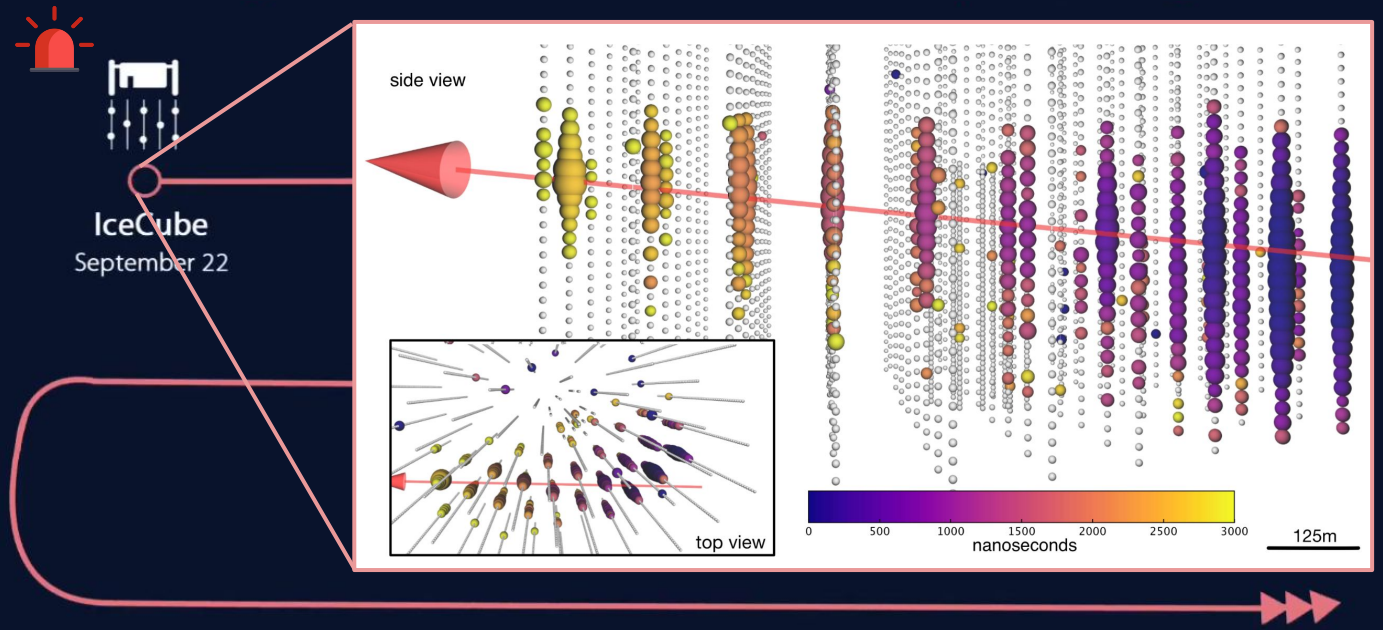


Back to the 22nd September 2017



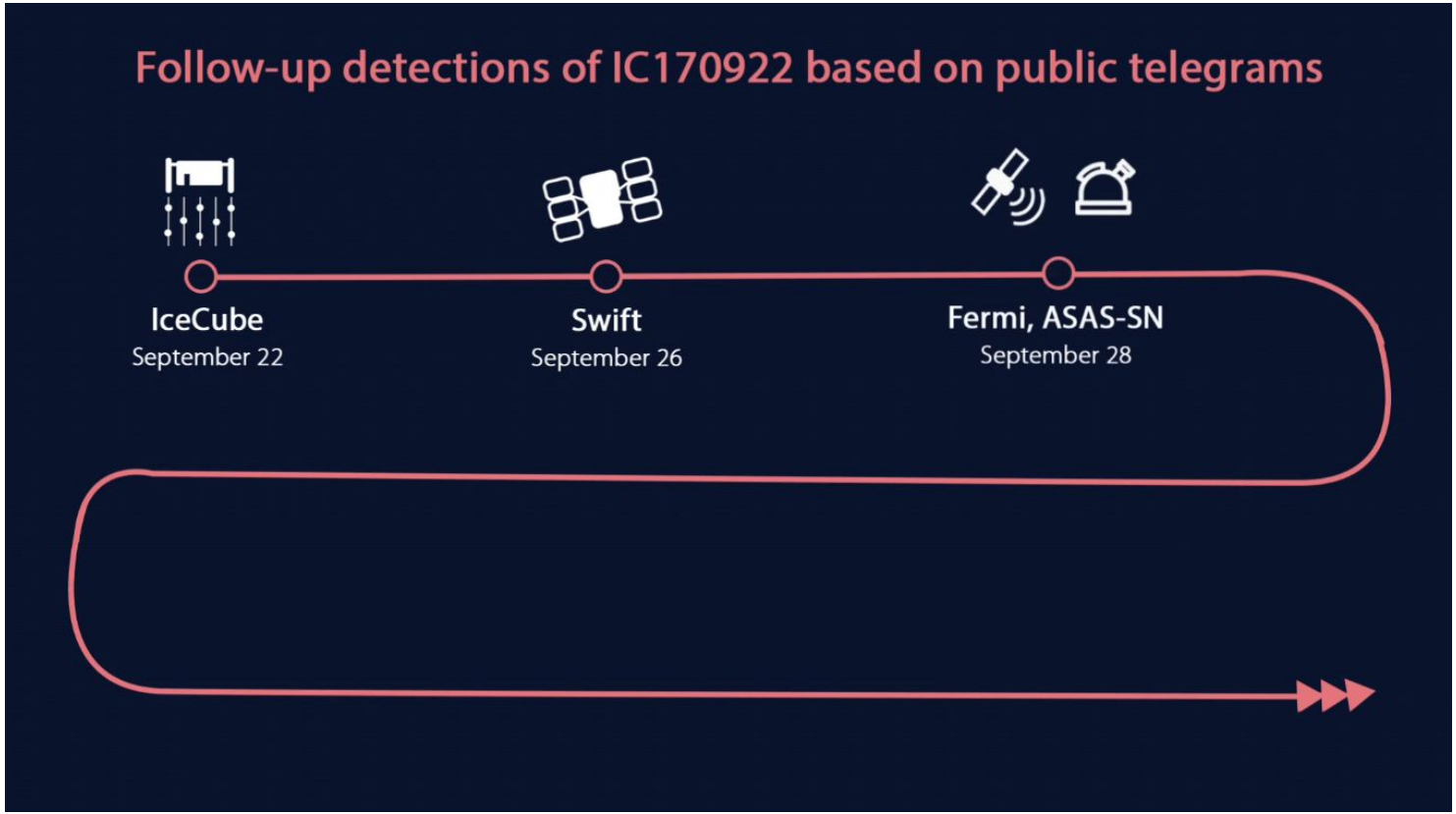
Back to the 22nd September 2017

Notice from IceCube for a 290 TeV neutrino with an astrophysical origin probability of 60 %

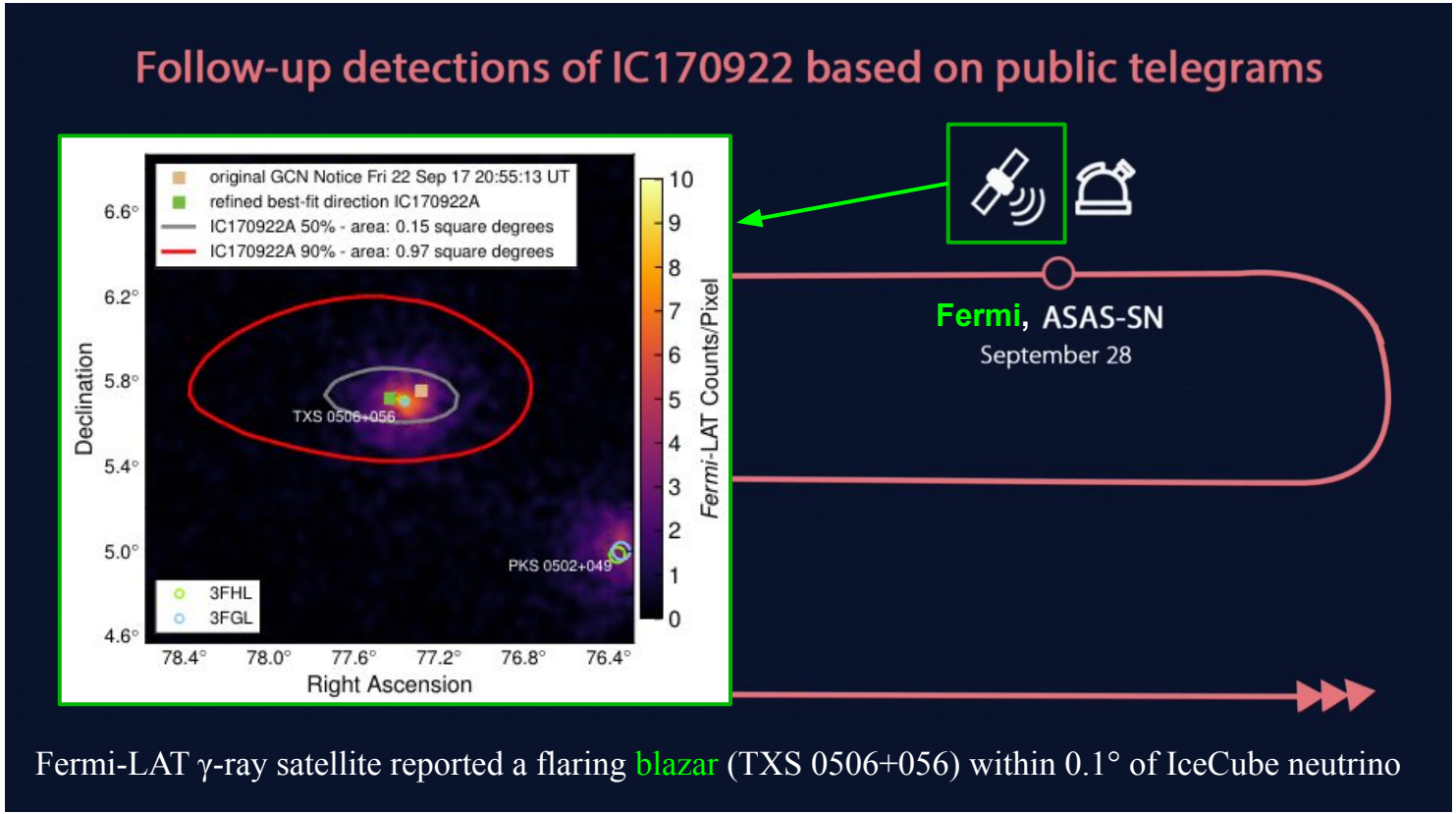


The alert was publicly distributed after 43 s after the trigger, refined direction 4 h later

Back to the 22nd September 2017

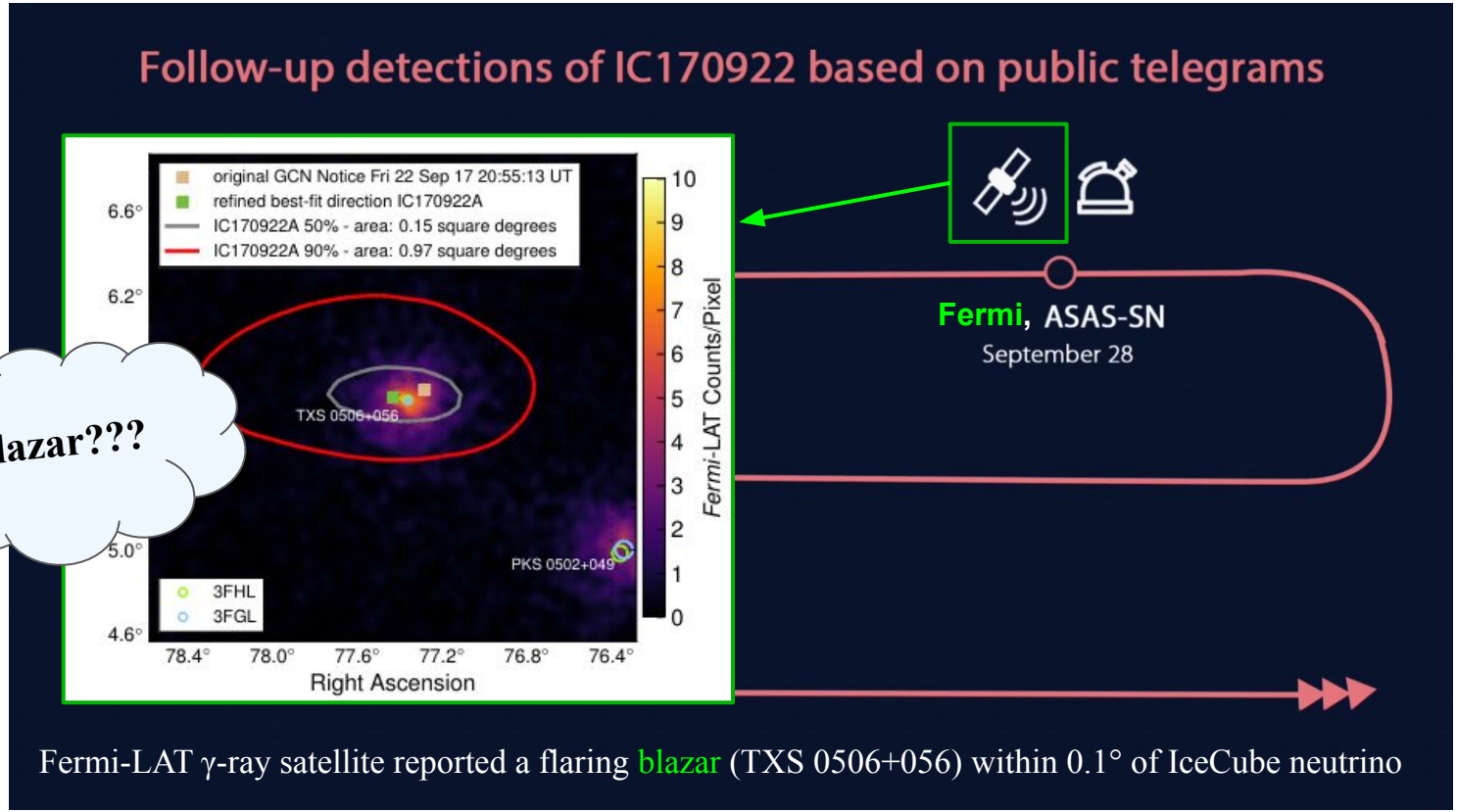


Back to the 22nd September 2017

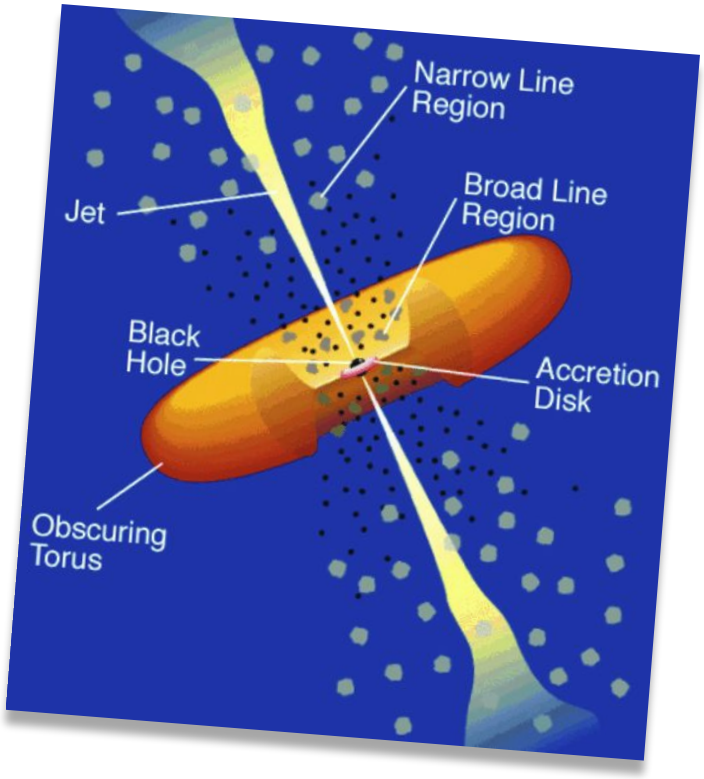


Fermi-LAT γ-ray satellite reported a flaring blazar (TXS 0506+056) within 0.1° of IceCube neutrino

Back to the 22nd September 2017



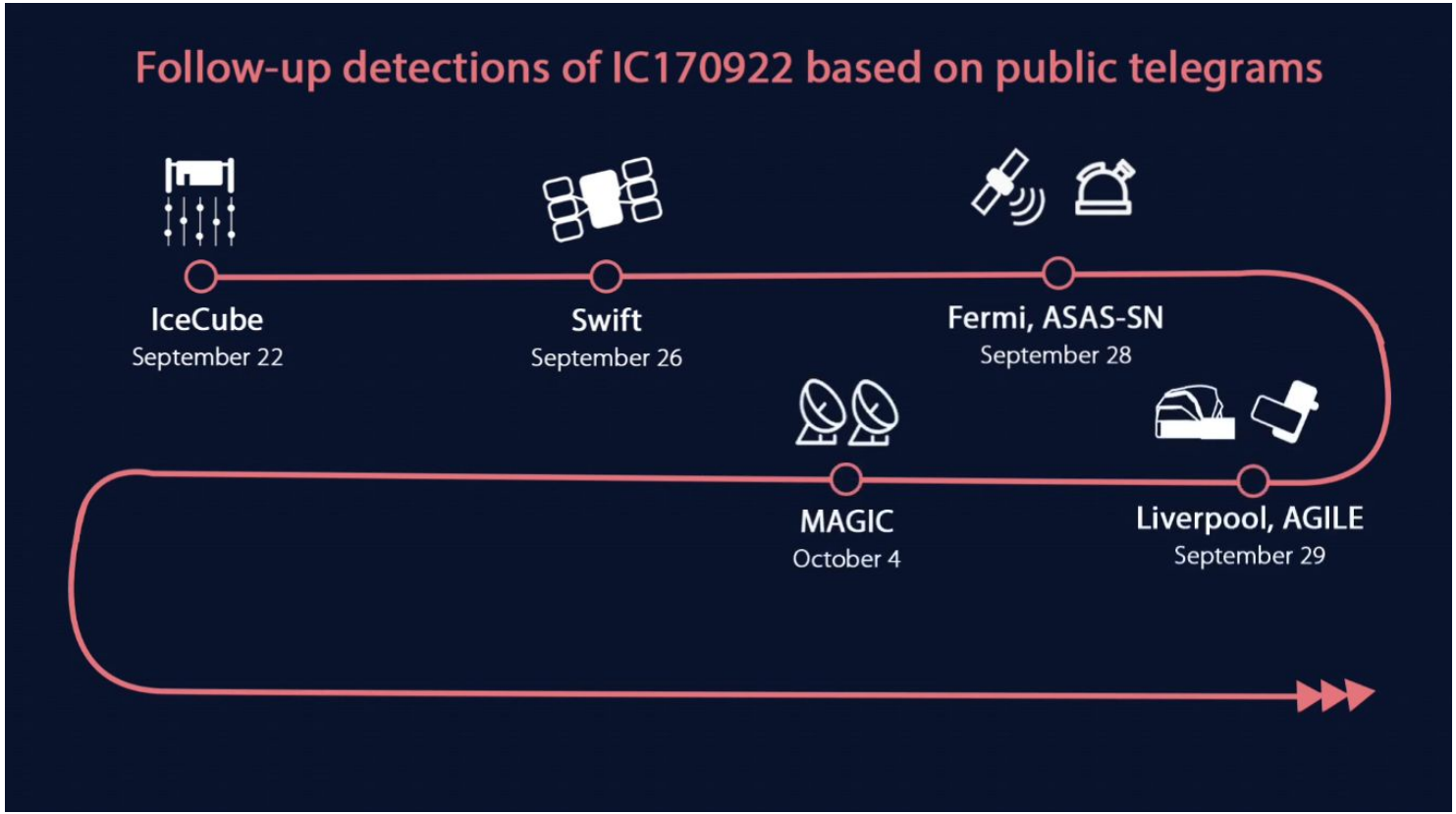
What is a blazar?



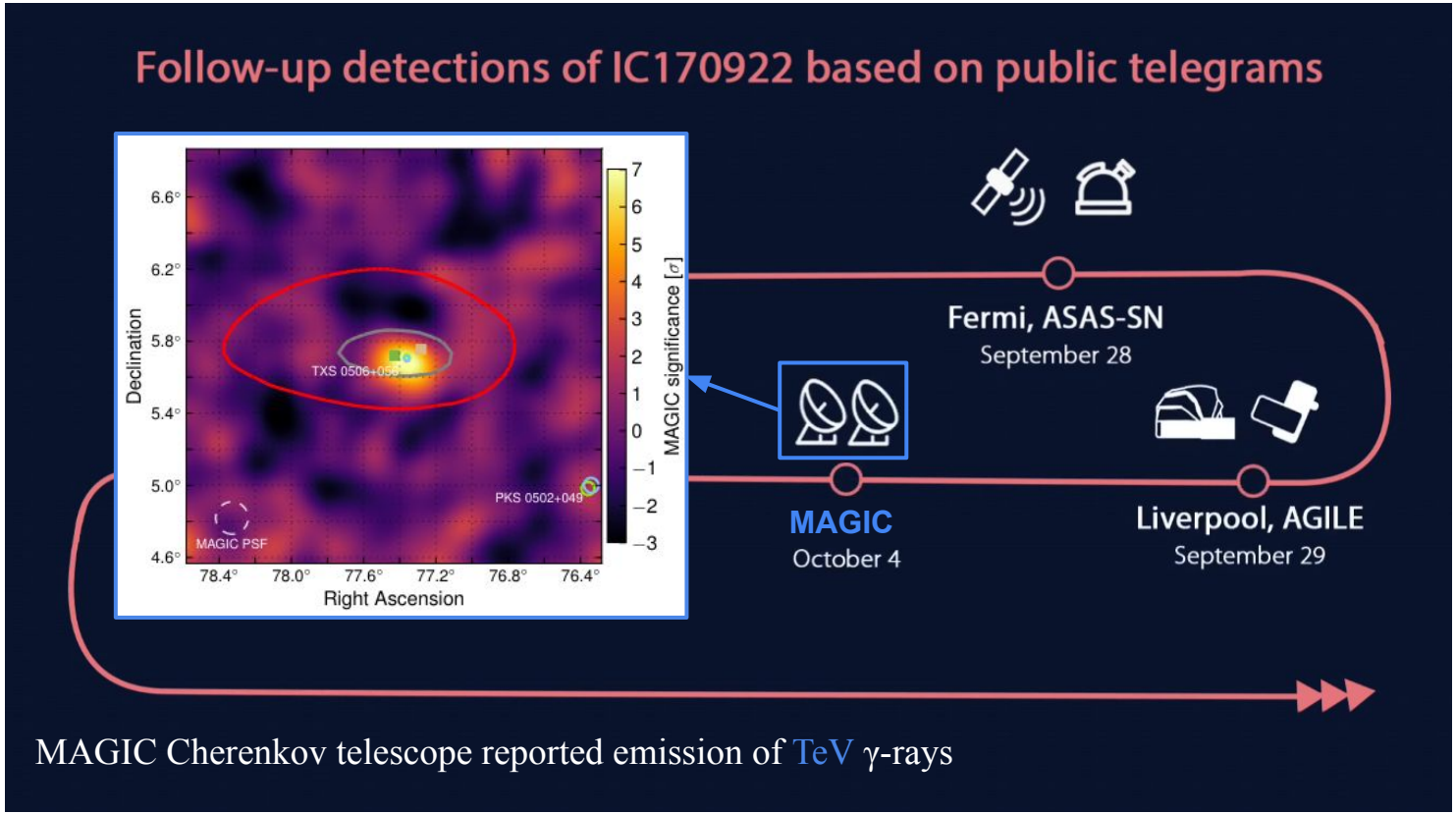
A blazar is an **Active Galactic Nucleus** (AGN), i.e. a supermassive black hole in accretion phase, with relativistic jet pointing toward us.

Blazar jets may accelerate cosmic rays and can produce γ-rays and neutrinos in cosmic ras interaction with matter and/or radiation around blazar.

Back to the 22nd September 2017



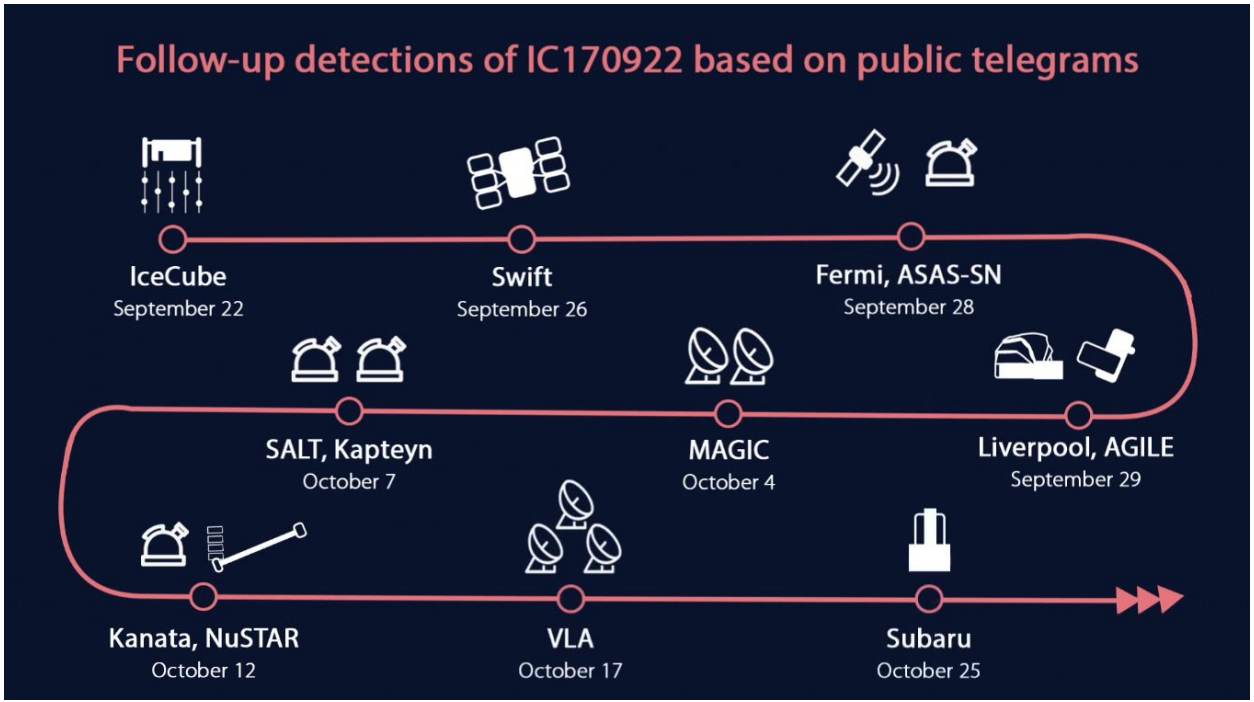
Back to the 22nd September 2017



MAGIC Cherenkov telescope reported emission of TeV γ-rays

Back to the 22nd September 2017

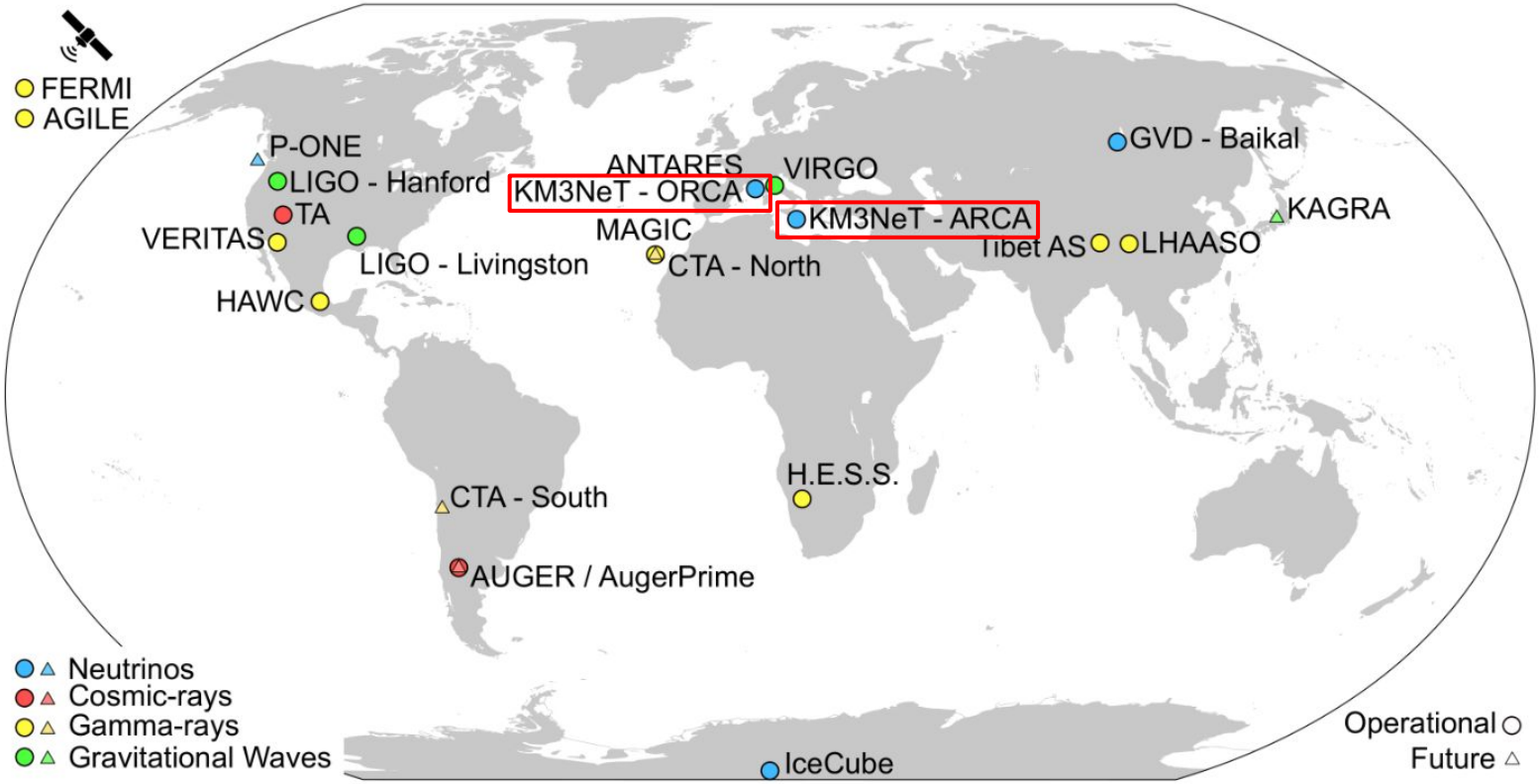
Chance coincidence of the neutrino with the flare of blazar TXS 0506+056 is disfavored at the **3σ** level



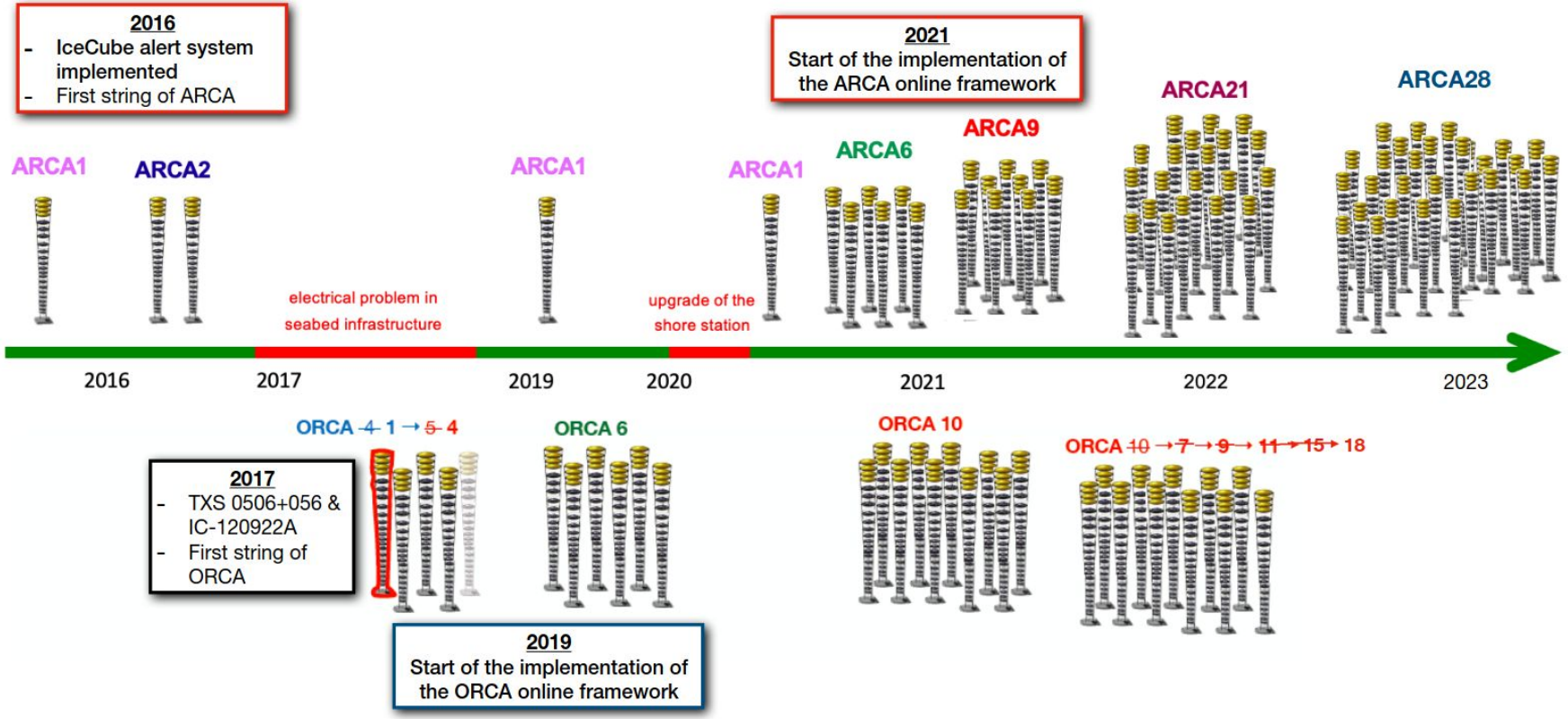
Taken together, these observations provide a mostly complete, contemporaneous picture of the source emissions from 0.3 keV to 400 GeV.

arXiv:1807.08816 (2018)

Multi-messenger community

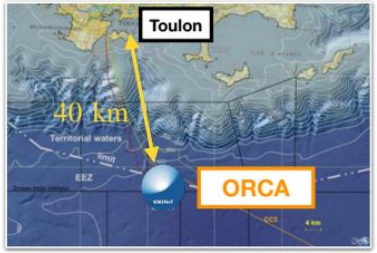


Status of the deployment

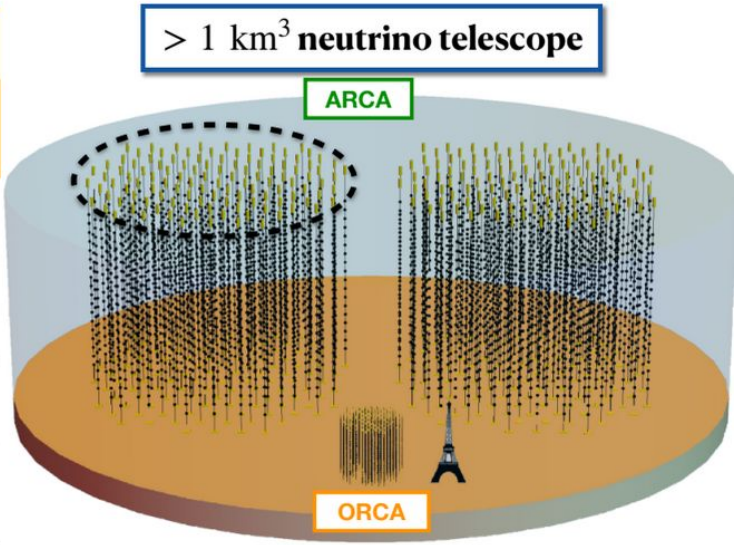


KM3NeT

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy) ⟶ **Same technology** used for both detectors but **different physics**



	Astroparticle **R**esearch with **C**osmics in the **A**byss	**O**scillation **R**esearch with **C**osmics in the **A**byss
Location	Italy (Sicilian coast)	France (coast of Toulon)
Depth	3450 m	2450 m
Number of DUs	**115 x 2 (2 BB)**	**115 (1 BB)**
Instrumented volume	~1 Gton	~7 Mton



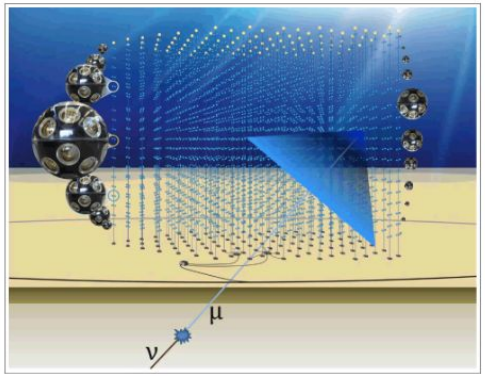
- Construction started in 2015
- Status at 2023: ARCA(ORCA) taking data with 21(18) DUs

1 Building Block = 115 Detection Units
(1 BB = 115 DUs)

Credits: KM3NeT Collaboration

Multi-messenger program in KM3NeT

Data AcQuisition (DAQ) level



KM3NeT ORCA and ARCA

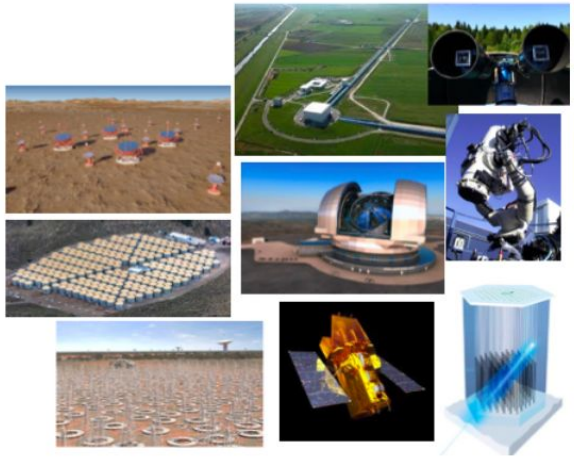
SENDING ALERTS

Send neutrino alerts to external communities for subsequent follow-ups

RECEIVING ALERTS

- Follow-up of EM/GW alerts
- Offline time/space correlation search with catalogues (GRB, AGN, SN, etc.)

EM/MM external communities



Driving factors in multi-messenger detections

ANGULAR RESOLUTION

BACKGROUND REJECTION

RESPONSE TIME

WELL-DEFINED FOLLOW-UP STRATEGY

Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Thanks to the low light dispersion in water, better angular resolution can be achieved wrt IceCube.

Less than 1° for track-like events.

BACKGROUND REJECTION

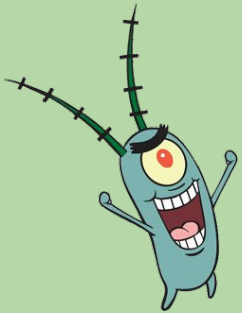
L-DEFINED FOLLOW-UP STRATEGY

Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Less than 1° for track-like events

BACKGROUND REJECTION



bioluminescence

^{40}K

atmospheric muons

RESPONSE TIME

Driving factors in multi-messenger detections

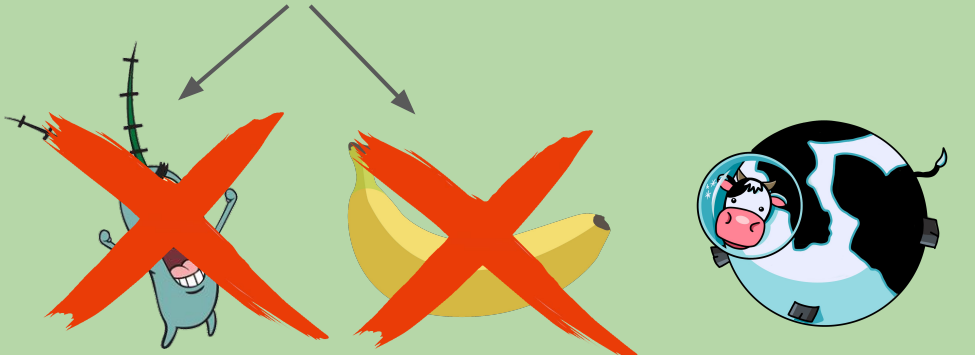
ANGULAR RESOLUTION

Less than 1° for track-like events

RESPONSE TIME

BACKGROUND REJECTION

Time coincidence of hits



bioluminescence ^{40}K atmospheric muons

Driving factors in multi-messenger detections

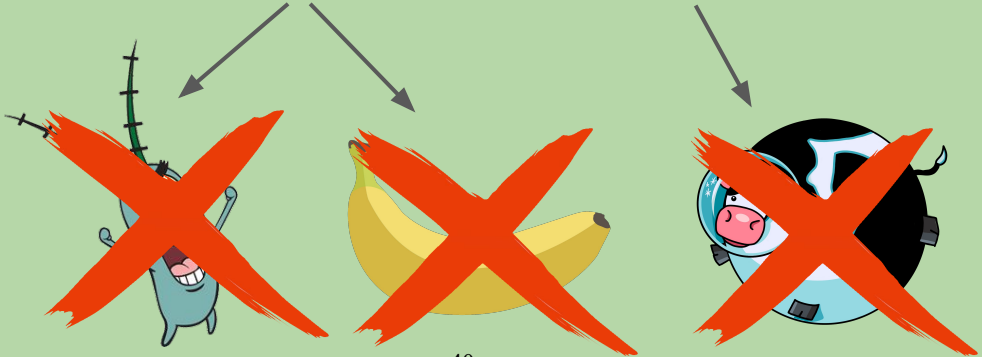
ANGULAR RESOLUTION

Less than 1° for track-like events

RESPONSE TIME

BACKGROUND REJECTION

Time coincidence of hits and up-going events selection



bioluminescence ^{40}K atmospheric muons

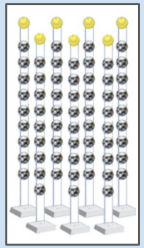
Driving factors in multi-messenger detections

ANGULAR RESOLUTION

BAC

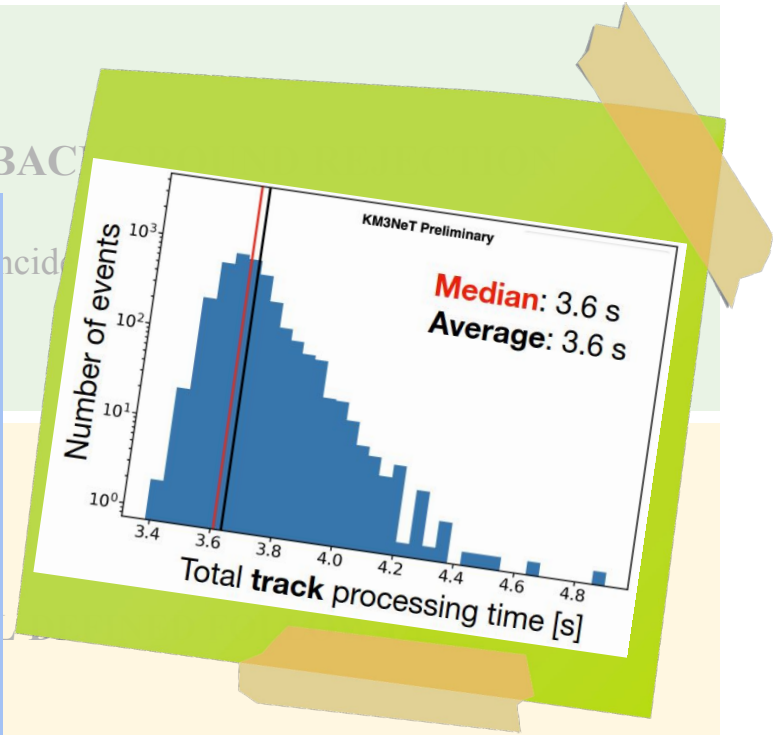
RESPONSE TIME

Triggered events are processed <u>in parallel in less than 4 s</u> (ARCA)



Portopalo di Capopassero (Sicily)

- Track reco
- Shower reco
- Classifier (GNN)



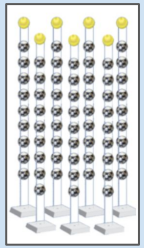
Driving factors in multi-messenger detections

ANGULAR RESOLUTION

BAC

RESPONSE TIME

Triggered events are processed <u>in parallel in less than 4 s</u> (ARCA)



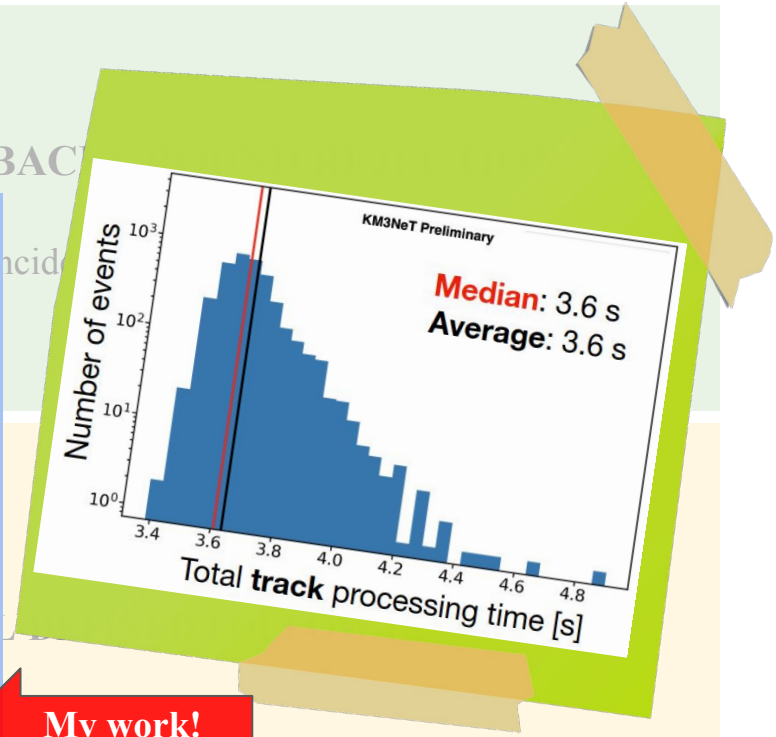
Portopalo di Capopassero (Sicily)

Track reco

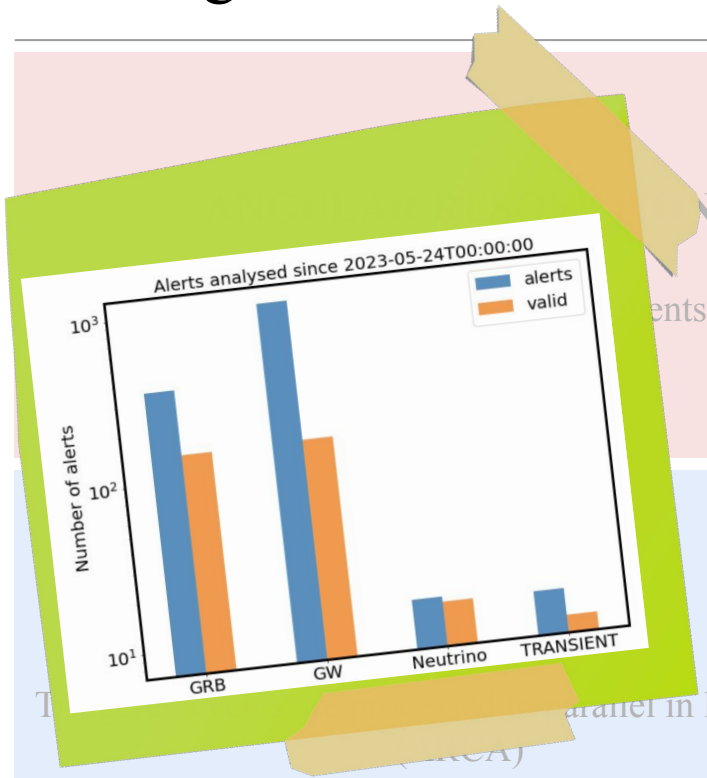
Shower reco

Classifier (GNN)

My work!



Driving factors in multi-messenger detections



BACKGROUND REJECTION

WELL-DEFINED FOLLOW-UP STRATEGY

Follow-up analyses are launched automatically for external triggers selected in the up-going sky of KM3NeT.
Only track-like events are currently used (better angular resolution).

Different analyses performed depending on the source.

Driving factors in multi-messenger detections

ANGULAR RESOLUTION

Less than 1° for track-like events

BACKGROUND REJECTION

Time coincidence of hits and up-going events selection

RESPONSE TIME

Triggered events are processed in parallel in less than 4 s (ARCA)

WELL-DEFINED FOLLOW-UP STRATEGY

Follow-up analyses are launched automatically for external triggers selected in the up-going sky of KM3NeT.

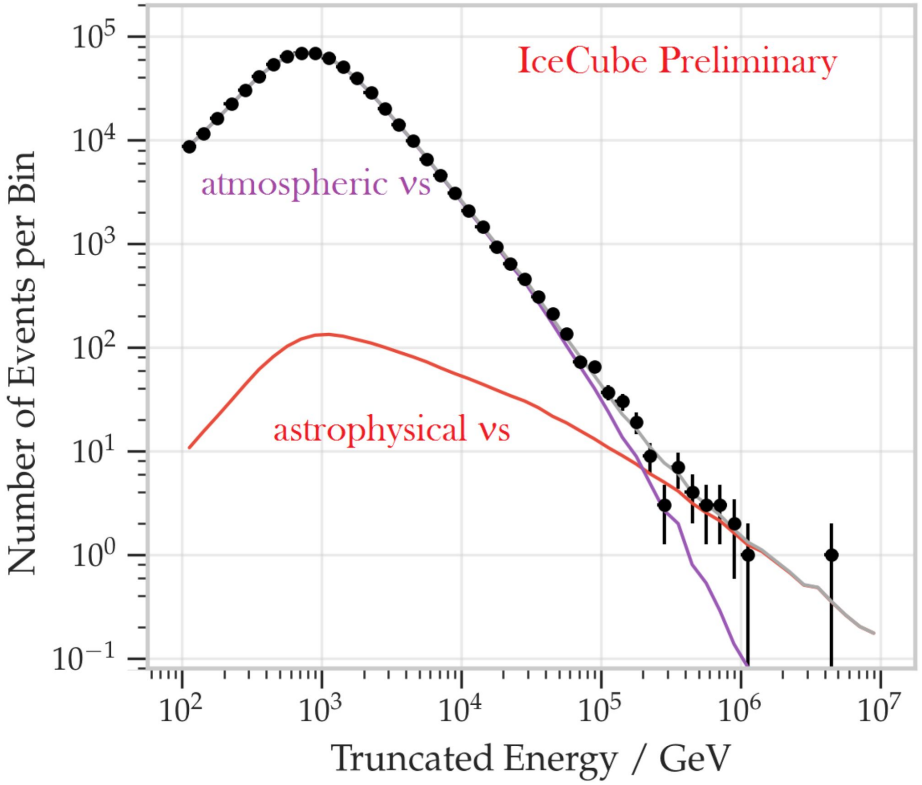
Take-home message!

KM3NeT has started to play its role in the field of the real-time multimessenger astronomy!


Thank you for your attention!


Backup slides

Atmospheric neutrinos background



In IceCube the selection criteria is based on a quantity called *Signalness*.

$$\text{Signalness}(E,\delta) = \frac{N_{\text{signal}}(E,\delta)}{N_{\text{signal}}(E,\delta) + N_{\text{background}}(E,\delta)}.$$

It represents the probability for a given neutrino event to have an astrophysical origin.

arXiv:2304.01174 (2023)

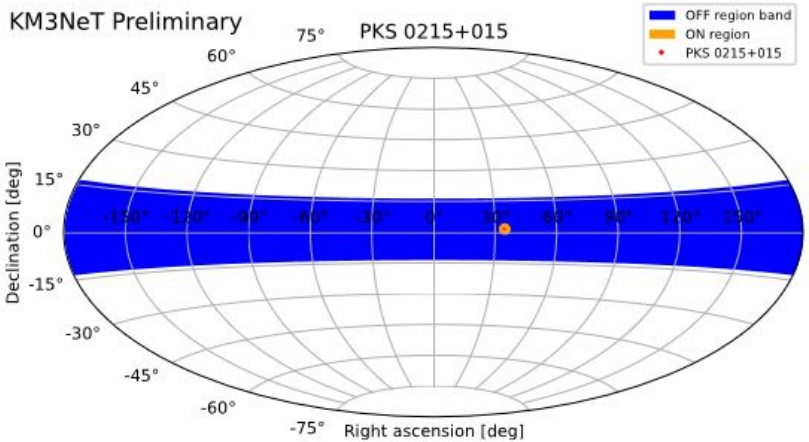
ON/OFF technique

PoS (ICRC2023) 1521

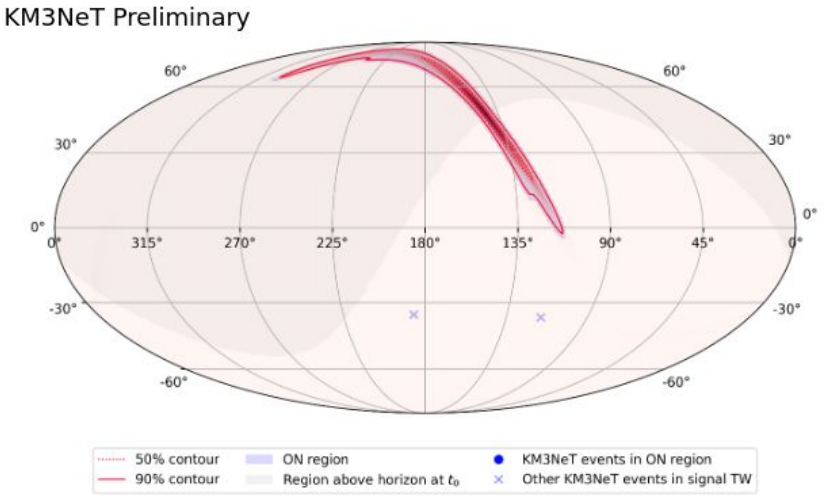
- The **Region of Interest** (RoI) is selected as: max[Source error, 2° for ARCA or 4° for ORCA]. It is, in general, a circular region, except for GWs, which moves in local coordinates to follow the source in time window below the day;
- The expected background is computed from an **OFF region** defined for each alert, using various days before the alert trigger time in a region with similar coverage in local coordinates as the ON region.
- Checks on the stability conditions during the ON and the OFF period ensure a **stable data-taking** flow.

PKS 0215+015

(Potentially correlated with IC-220225A)



GW S230628ax



GRBs/Transients analysis pipeline

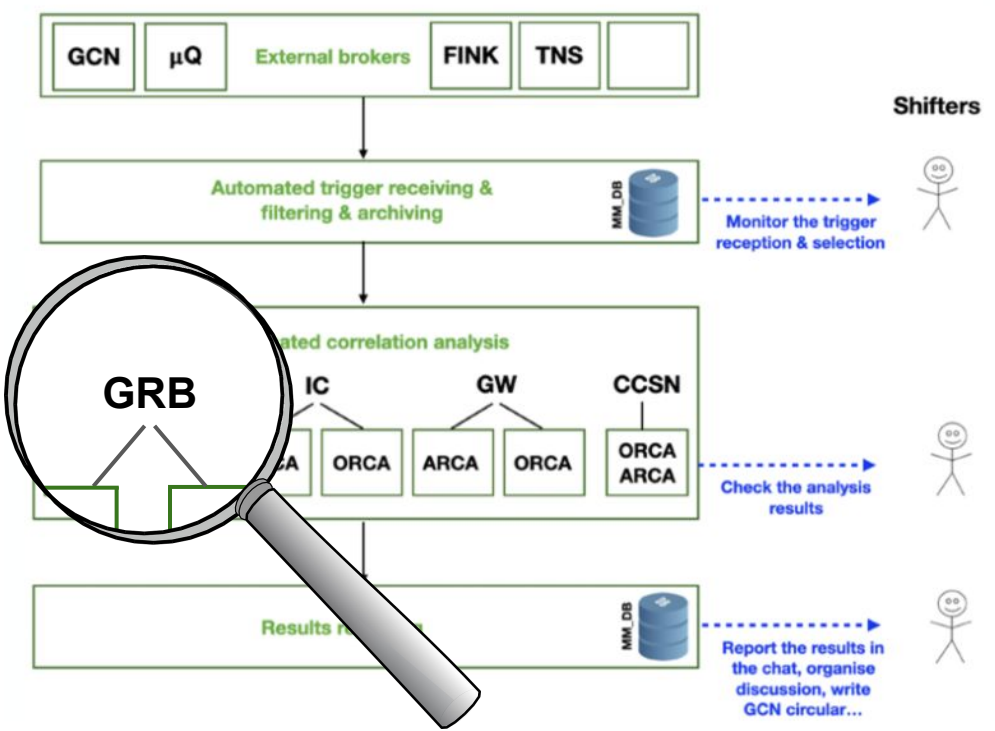
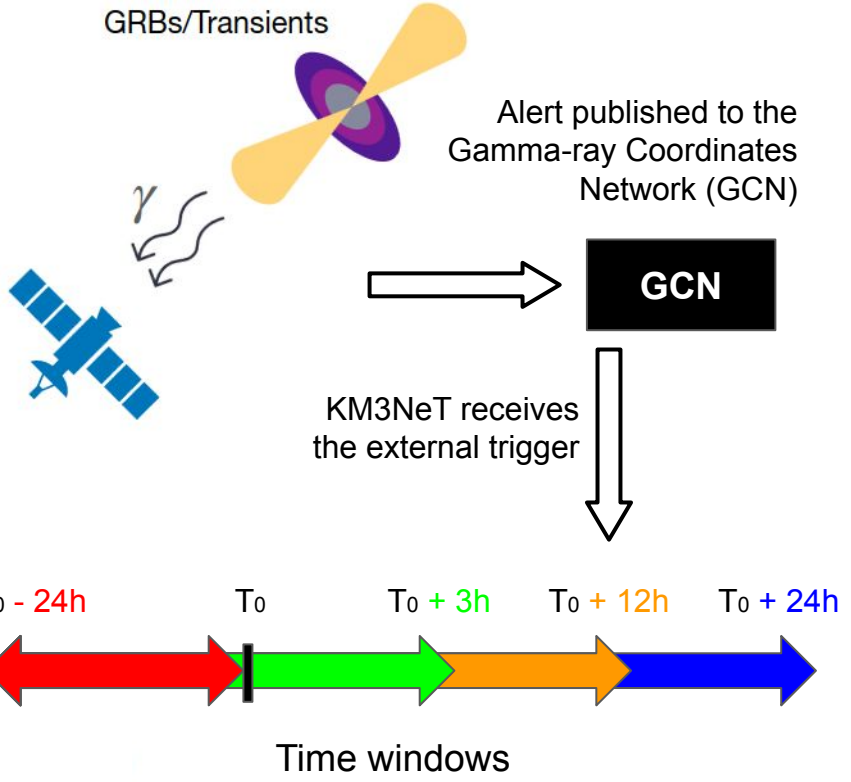


Image from Damien



IC neutrinos analysis pipeline

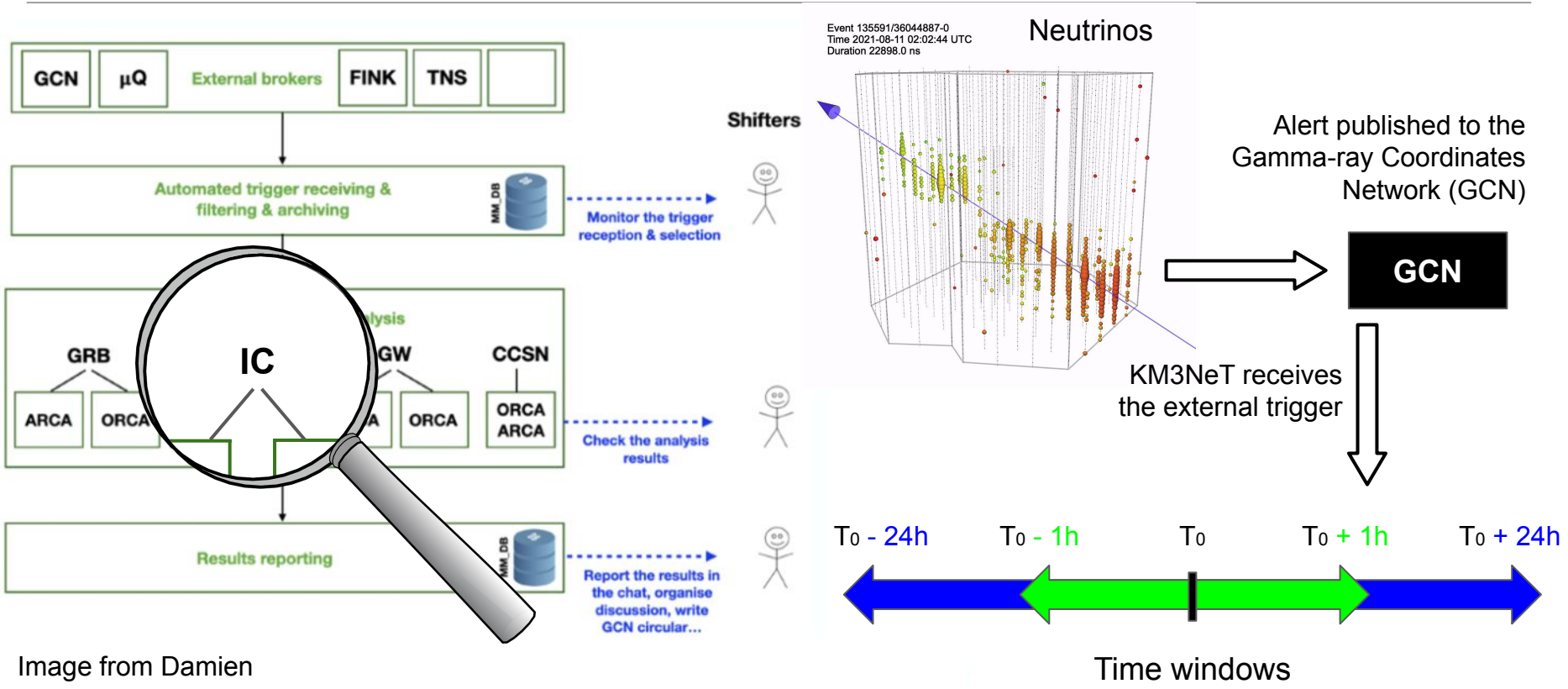
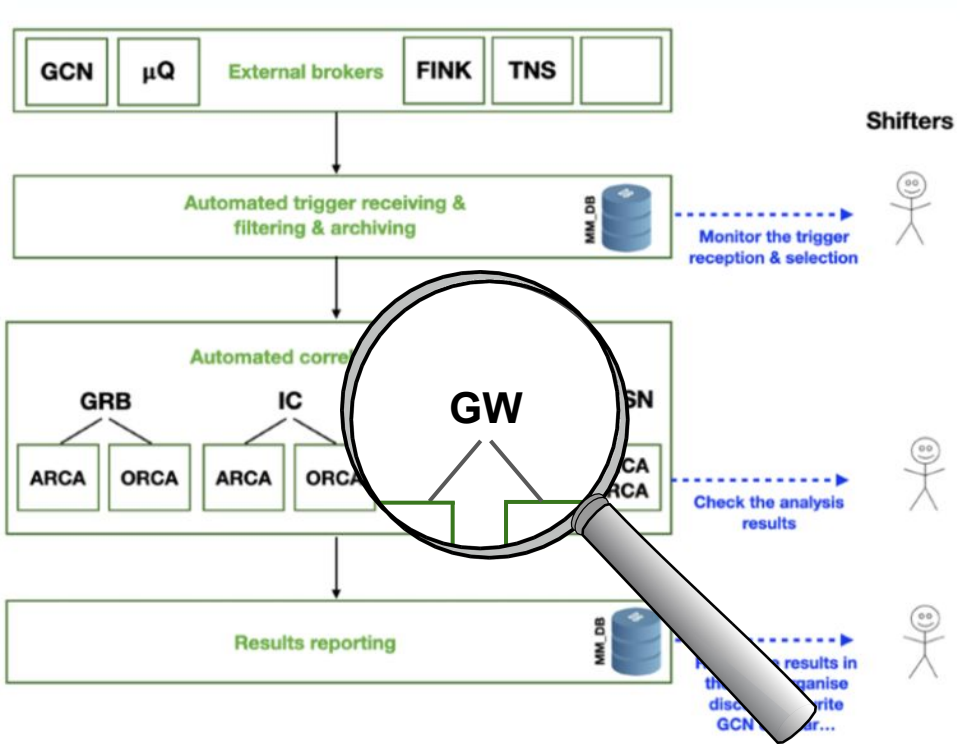
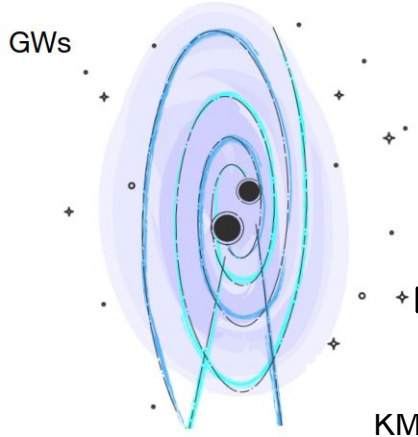


Image from Damien

GWs analysis pipeline

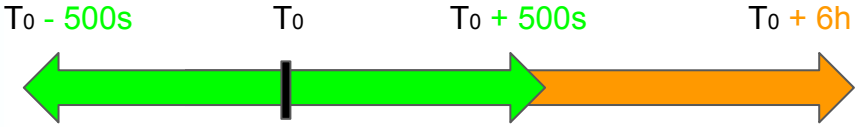




Alert published to the Gamma-ray Coordinates Network (GCN)

GCN

KM3NeT receives the external trigger



Time windows

Image from Damien

CCSNe analysis pipeline

PoS (ICRC2023) 1223

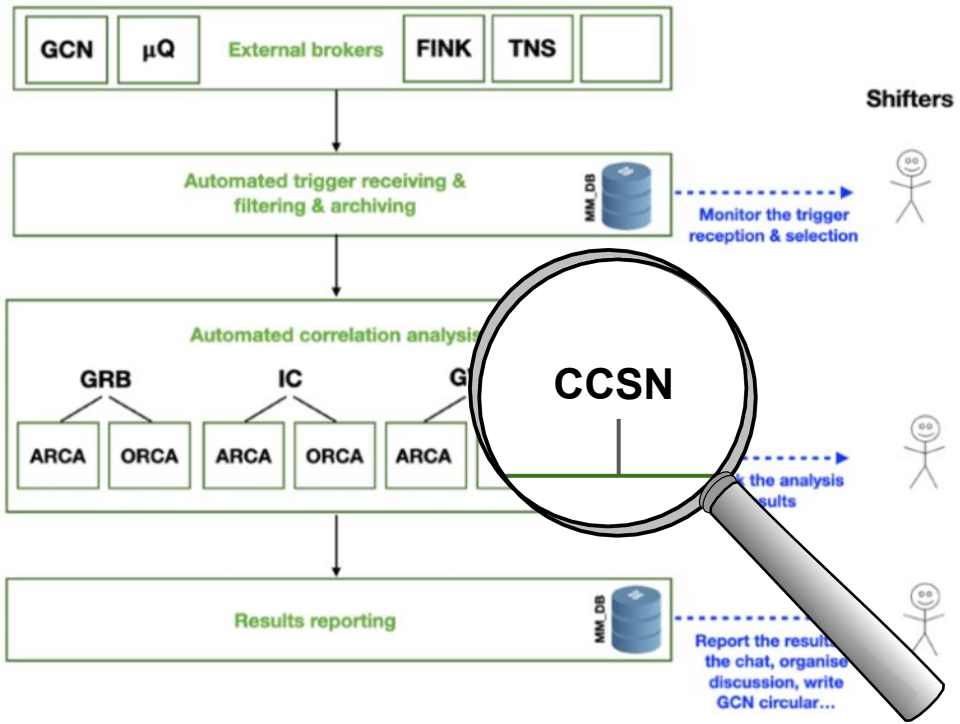


Image from Damien

This pipeline search for the low energy neutrinos (~100 MeV) emitted during a time window of a few hundreds of ms to one second, during the core-collapse of massive star (> 8 $M_{\odot}$).

The strategy adopted is to search for an excess of coincidences between PMTs in single DOMs in a sliding window of 0.5 s.

The online follow-up of GRB 221009A

One year ago, the brightest long GRB ever detected was observed, relatively close to us (z ~ 0.15, corresponding to 2.4 billion light-years away), at 13:16.59 UTC.
This event produced the most energetic GRB photon ever seen by Fermi LAT (ATel #15656), that of 99 GeV.

LHAASO during 2000 sec after the GRB trigger detected photons up to 18 TeV, highest energies ever detected from a GRB (GCN #32677)

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:

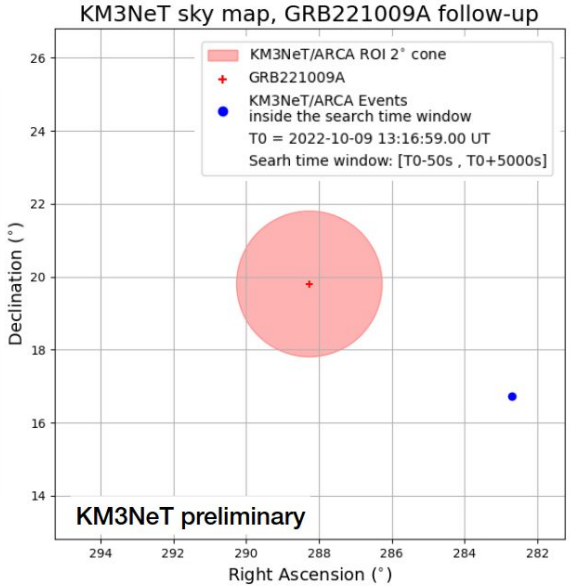
Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], 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.

A parallel search has been performed in the MeV range (Eur.Phys.J.C 82 (2022) 4, 317) without any significant neutrino coincidence.

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 GCN Circular 32741

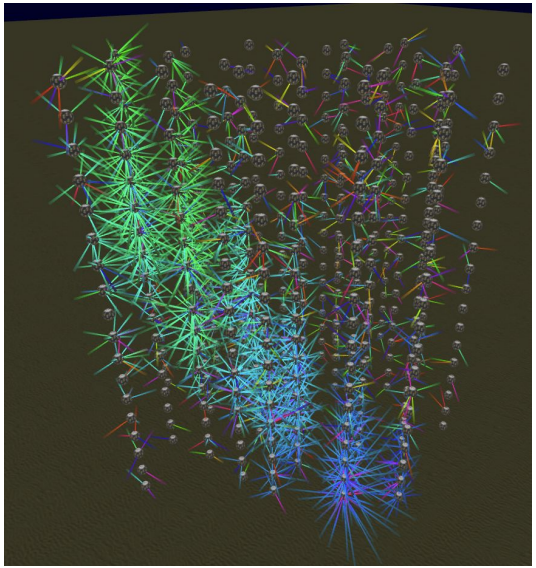
No events found in the signal region!

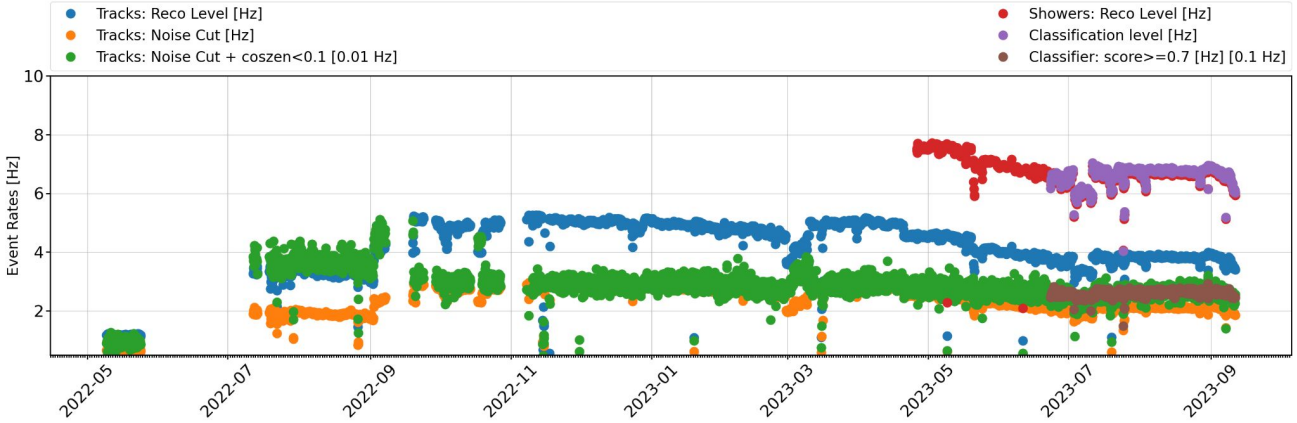


GNN classifier

GNN takes as input graphs, which are unordered sets of nodes and links.
This makes GNN very flexible and suitable for a moving detector such as KM3NeT.

In the following, we will focus on the ***atmospheric muon vs neutrino*** classifier, which has been running in the online pipeline since June 2023 (see below).
The output of the muon vs neutrino classifier is the ***neutrino score***, a number between 0 and 1, that can be interpreted as the probability of a given event to be a neutrino.

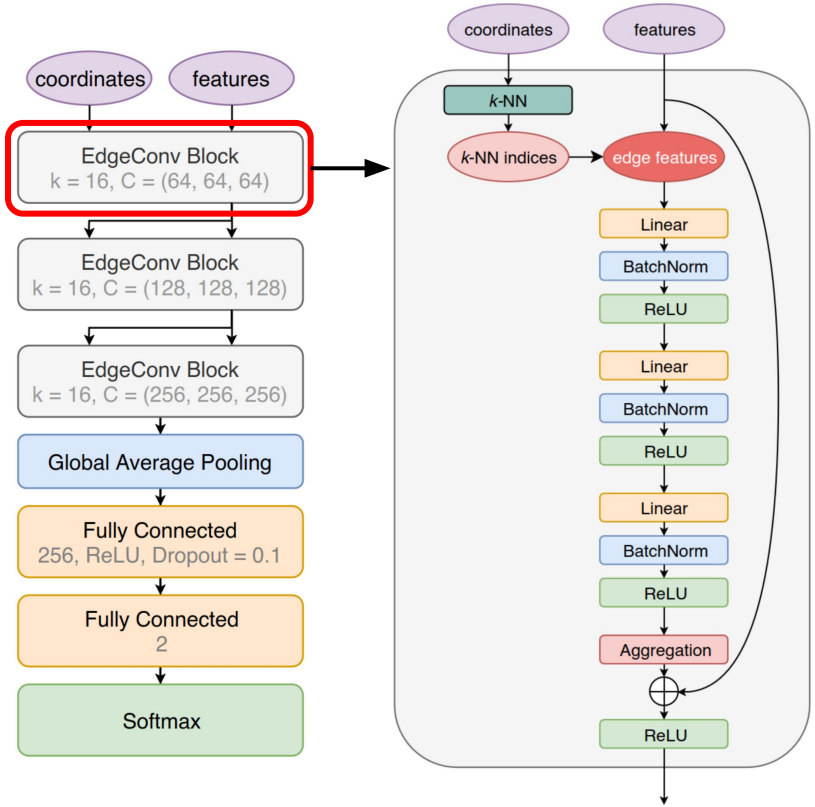




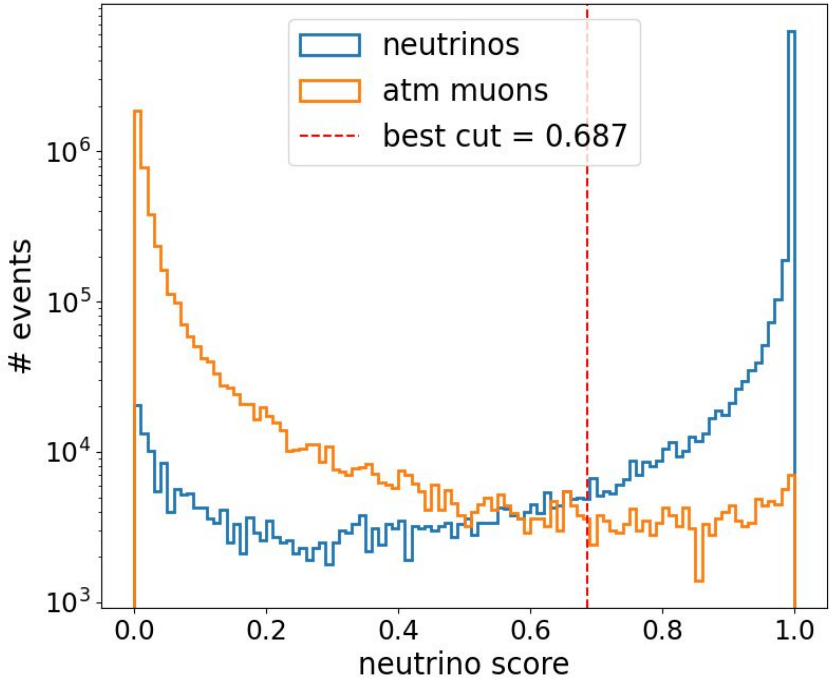
GNN model

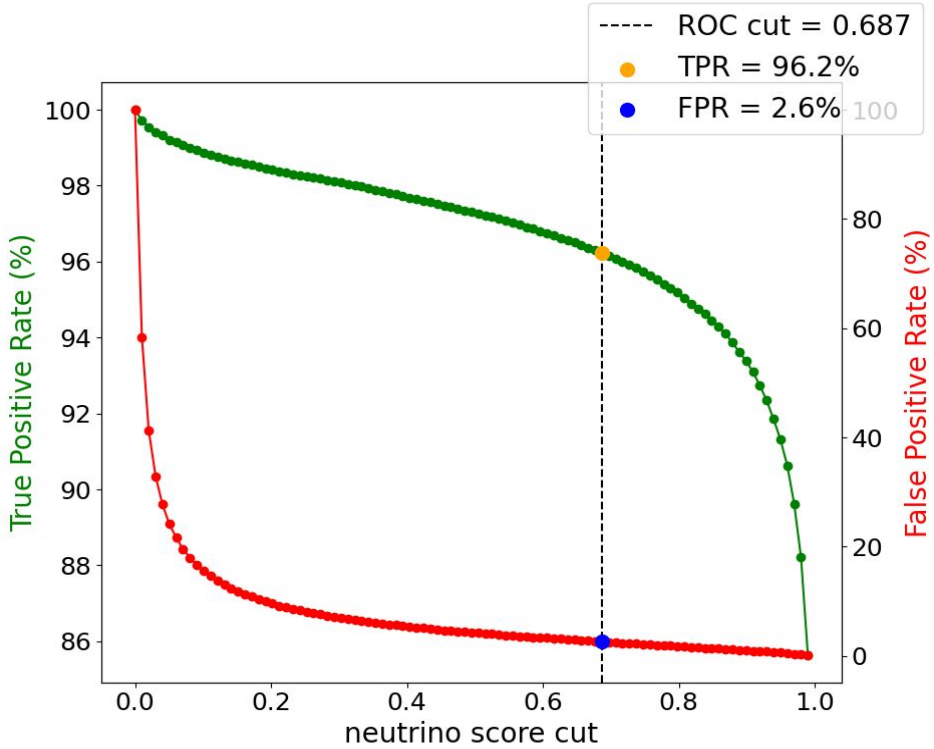
The GNN model implemented in KM3NeT is based on the **ParticleNet** architecture (see here for reference), which makes extensive use of **EdgeConv** (edge convolution) operations and also adopts the dynamic graph update approach.

The EdgeConv block starts with finding the k nearest neighboring particles for each particle, using the "coordinates" input of the EdgeConv block to compute the distances.

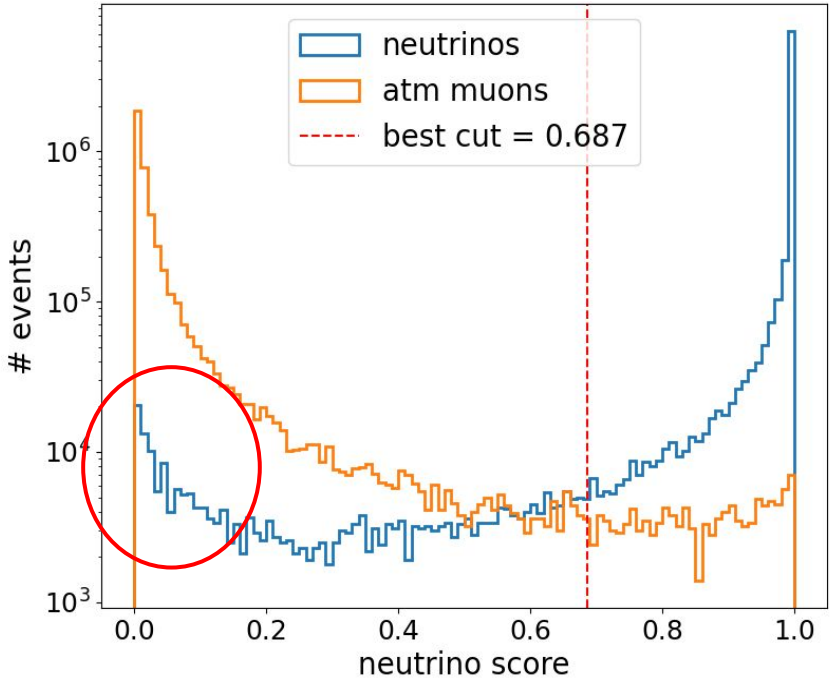


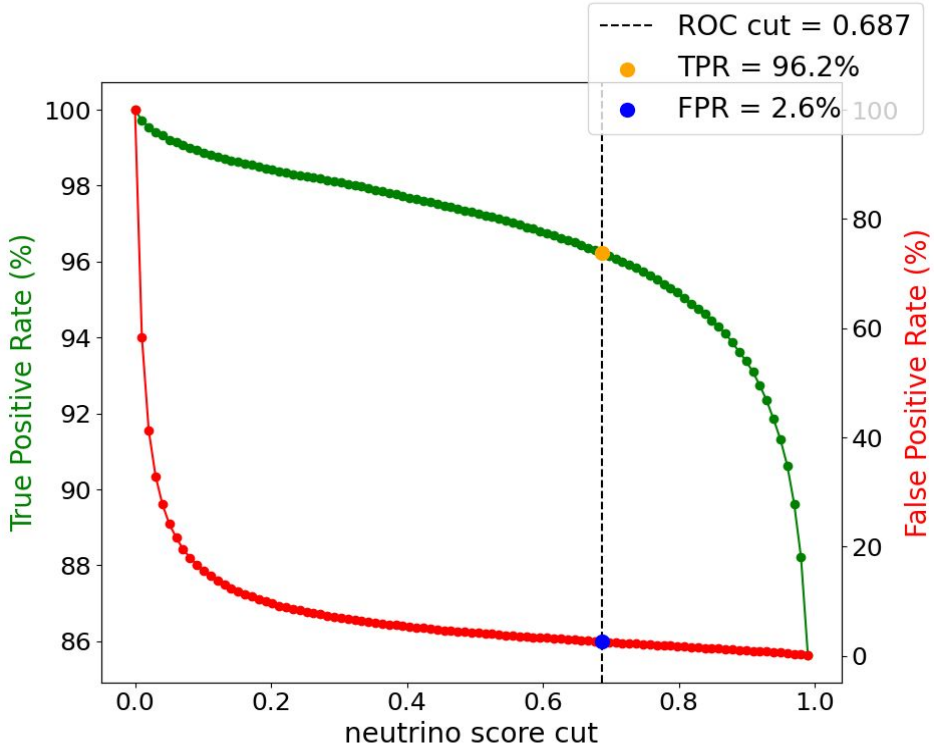
GNN performance



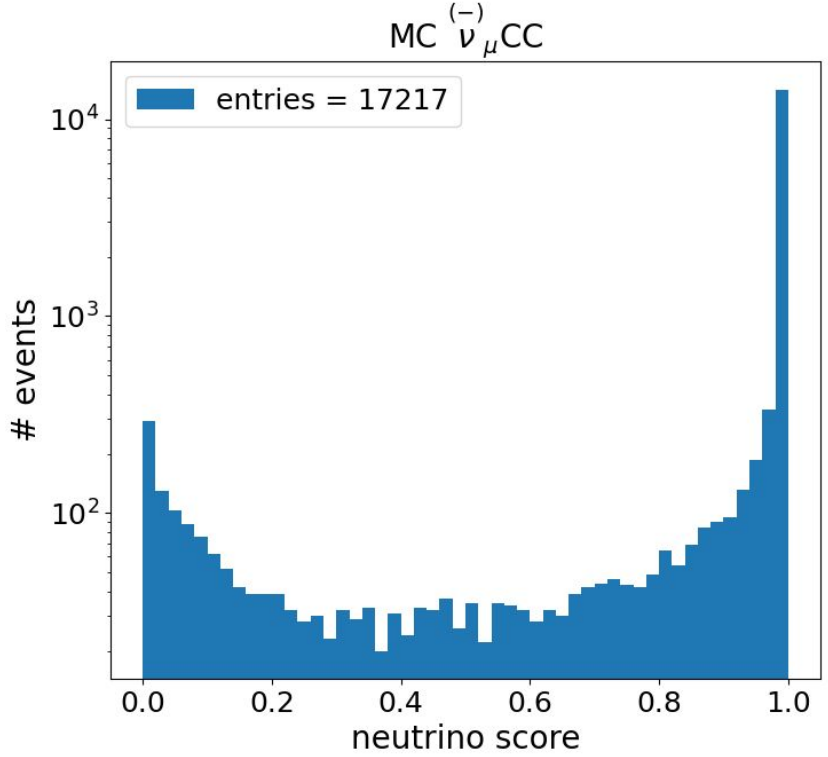


GNN performance



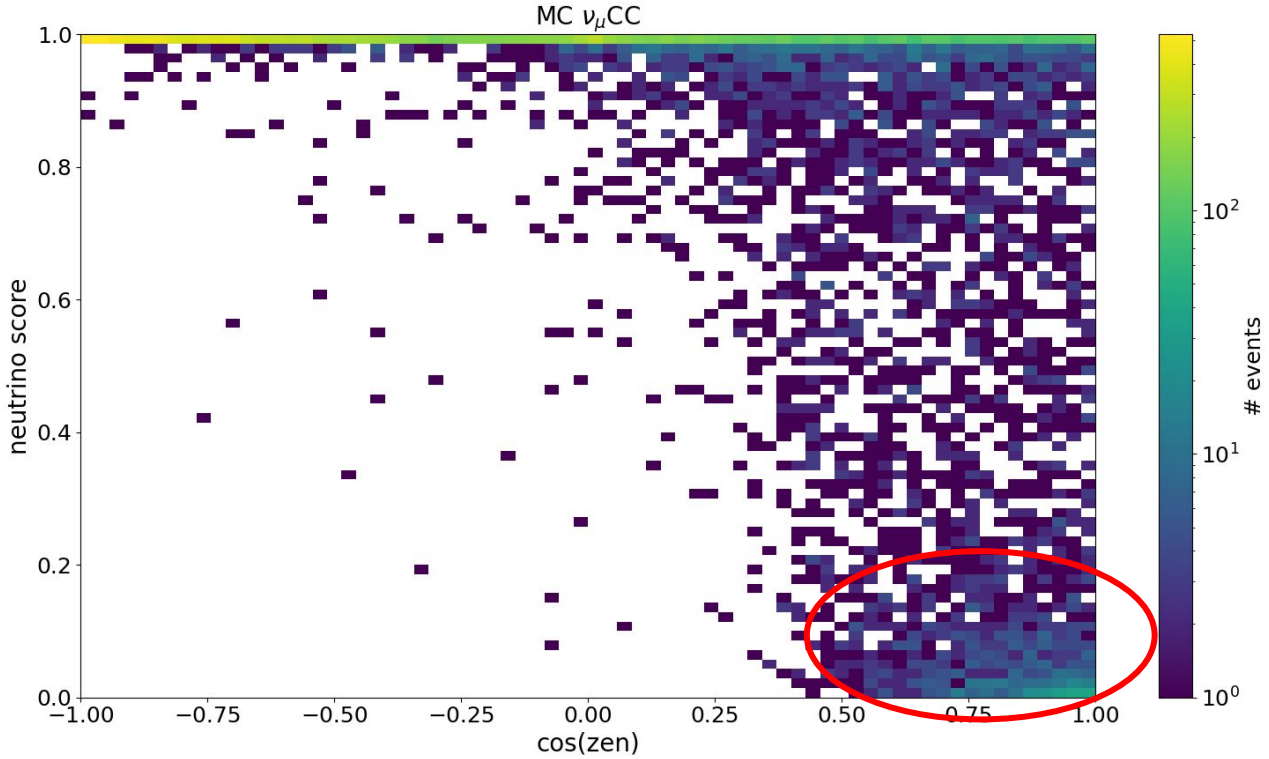


GNN performance on track-like events

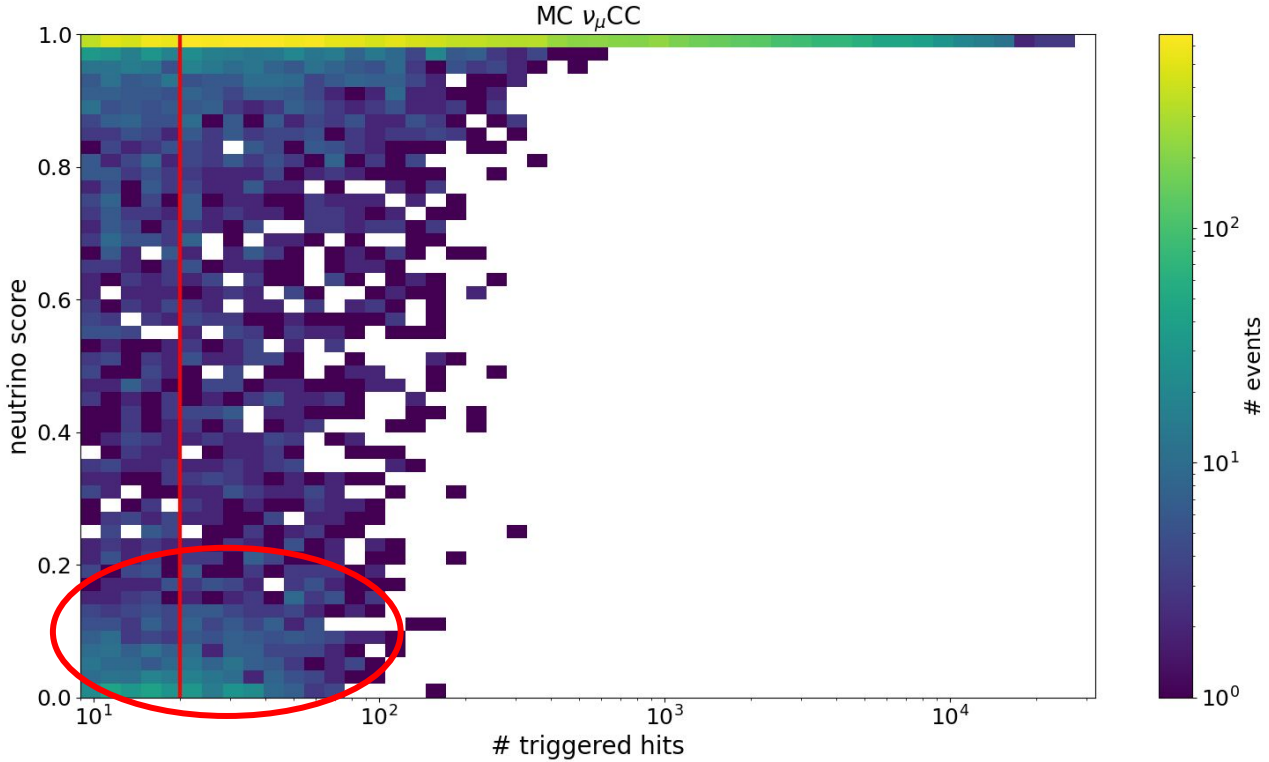


Indistinguishable from an atmospheric muon except for energy and direction

GNN performance on track-like events



GNN performance on track-like events



Low energy down-going ν_μCC are indistinguishable from atmospheric muon