The IceCube Realtime Program: Science and Infrastructure

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on behalf of the IceCube collaboration.

Astronomy Institute
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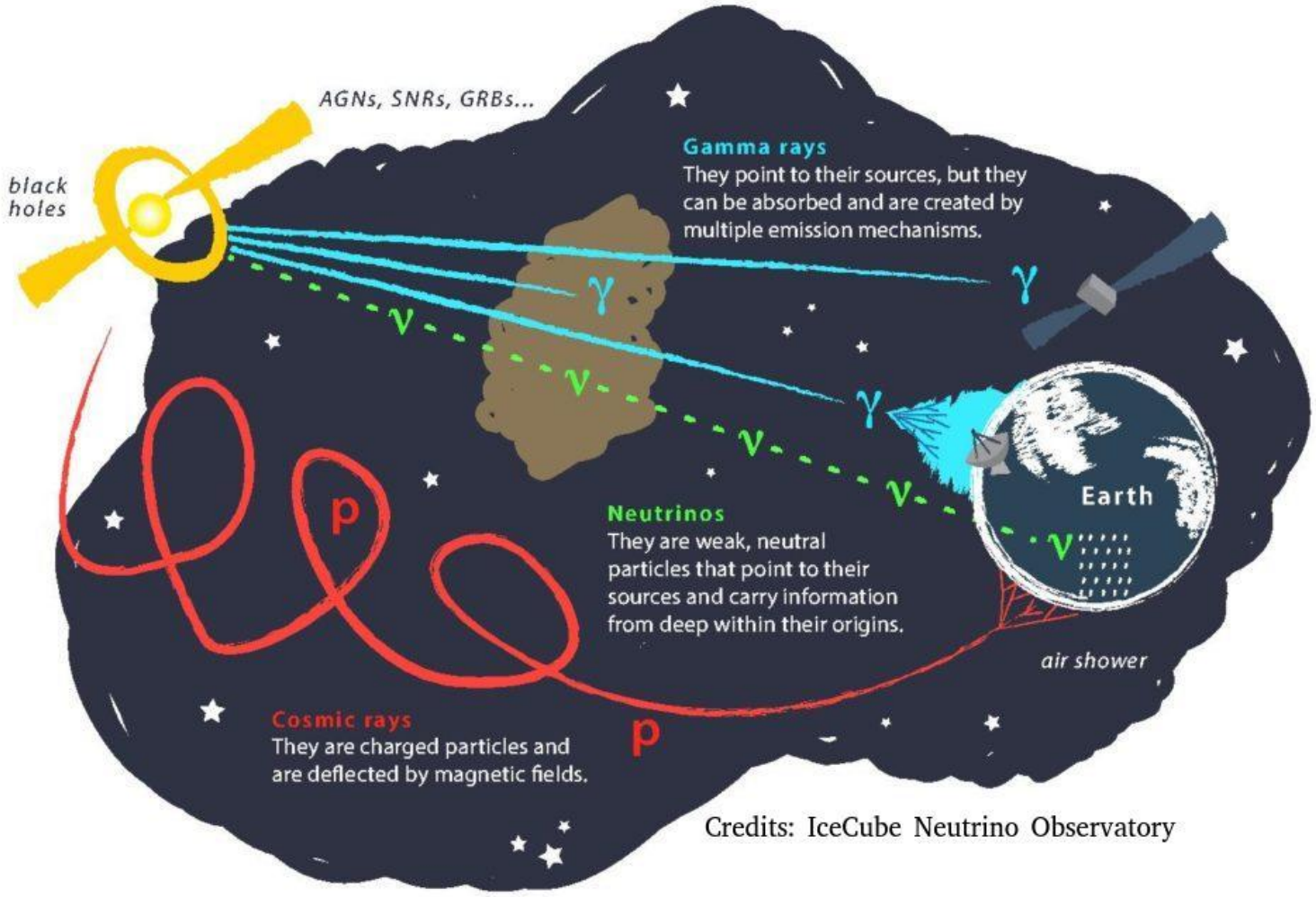
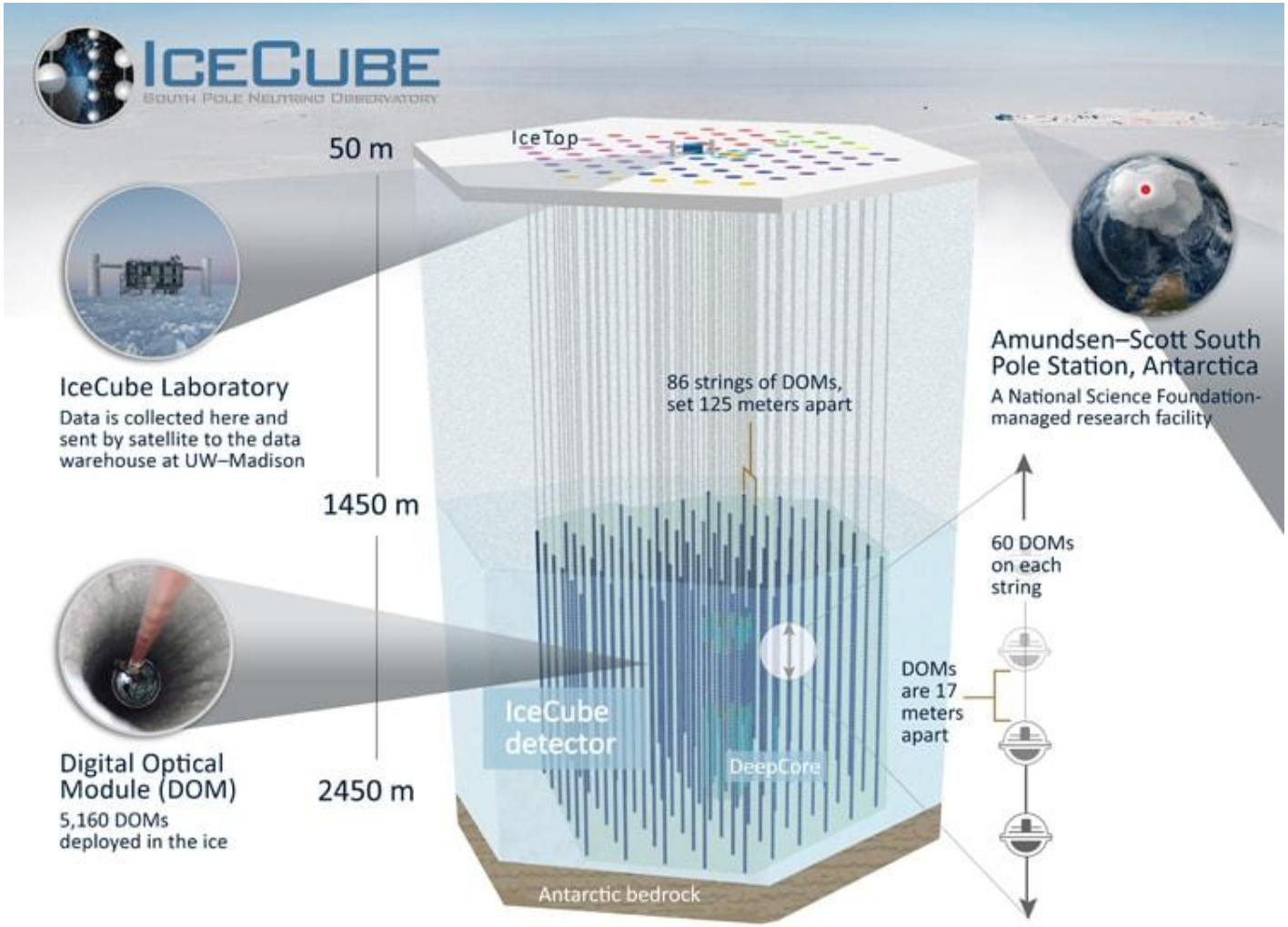
2nd Astro-COLIBRI Workshop
Saclay, 20-24/11/23

Why neutrino astronomy?



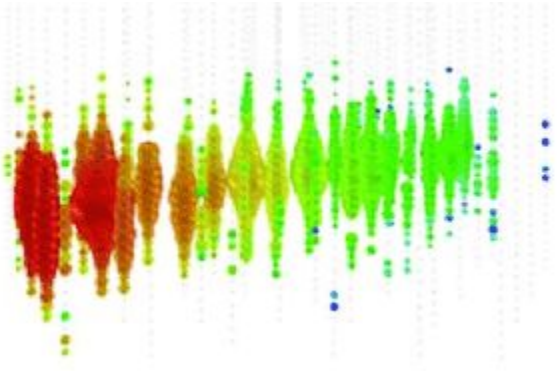
Credits: IceCube Neutrino Observatory

The IceCube Neutrino Observatory



High-energy neutrinos in IceCube

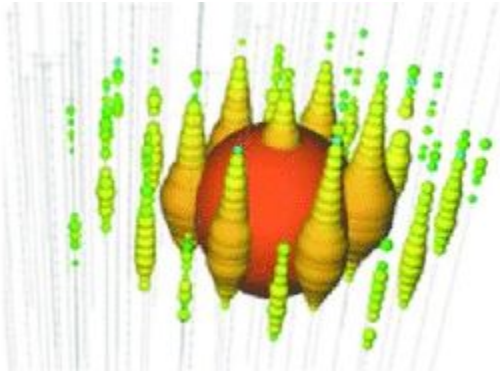
Tracks ($\nu_\mu + \bar{\nu}_\mu$)



~ 0.1-1.0 deg resolution

point sources

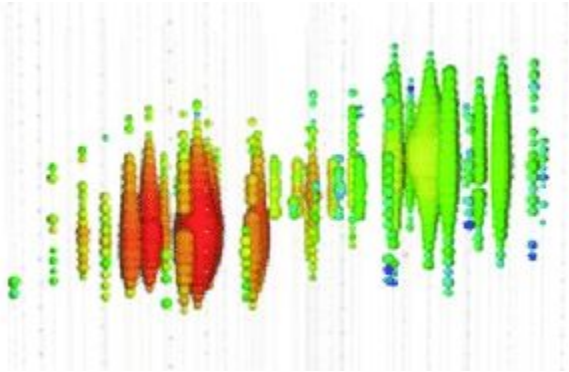
Cascades (all flavour)



~ 10 deg resolution

very good energy resolution

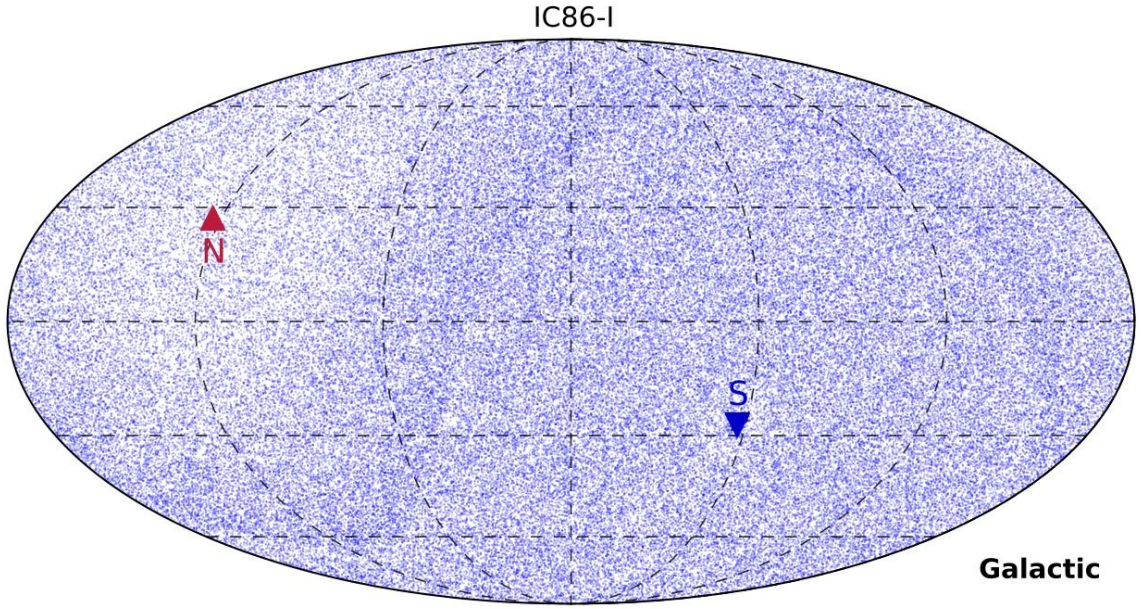
Double bang (ν_τ)



too rare for astronomy

A signal in a haystack

How to identify a signal of O(200) cosmic neutrinos on top of ~ 140000 atmospheric background events?



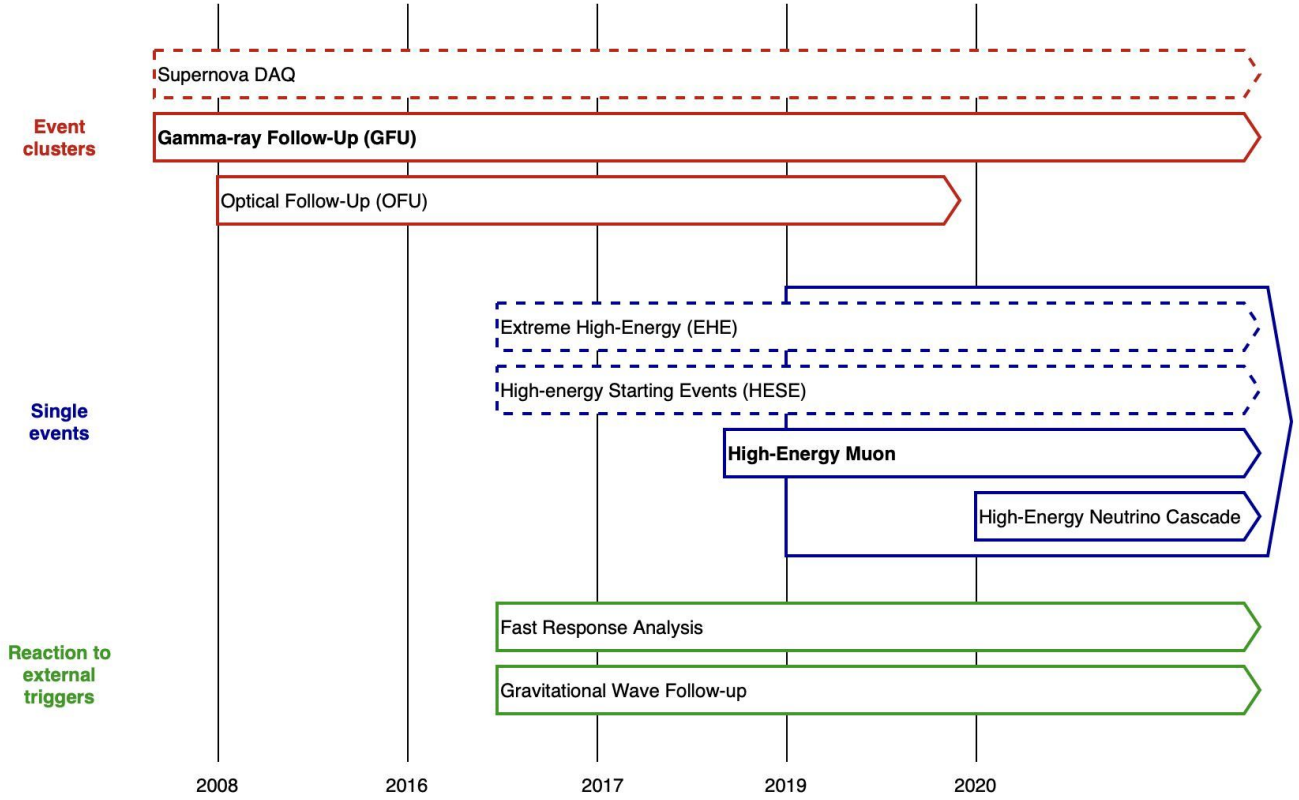
138322 neutrino candidates in one year

Spatial clustering

Spatial and temporal coincidences with astrophysical messengers

The IceCube realtime program

Find transient counterparts to IceCube neutrinos.

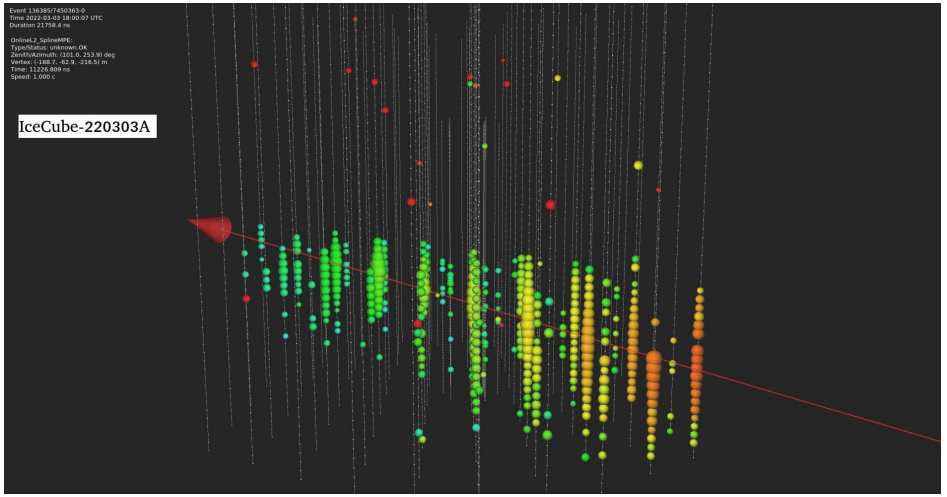


Follow-up interesting events with neutrino data.

IceCube ASTROTRACK alerts

Individual events with **moderate (BRONZE) to high (GOLD)** probability of being astrophysical.

Prompt dissemination via GCN.



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

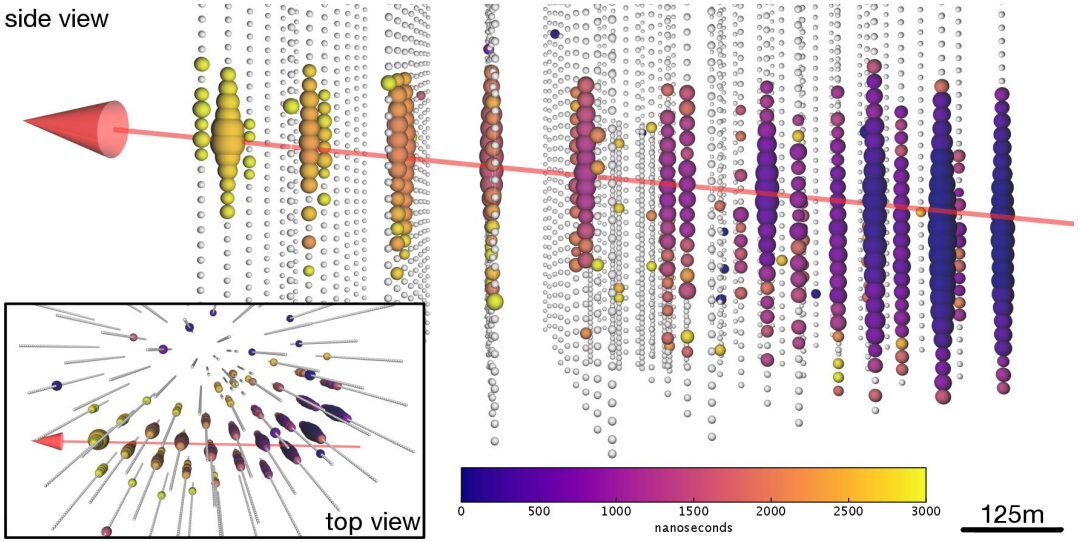
BRONZE: **30-50% signalness (avg.)**

GOLD: >50% signalness (avg.)

Blaufuss et al., PoS ICRC2019 (2019), 1021

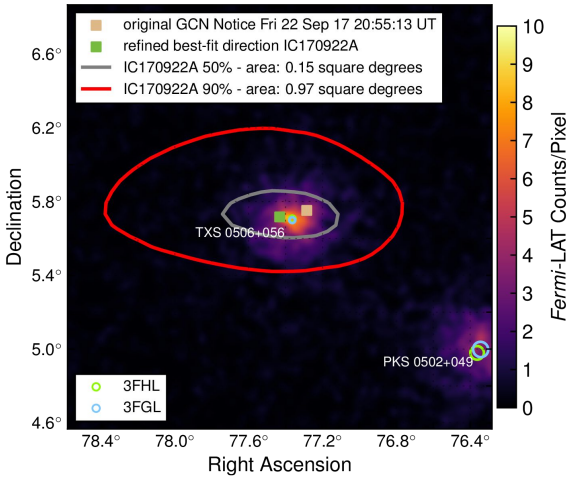
The first transient source: TXS 0506+056

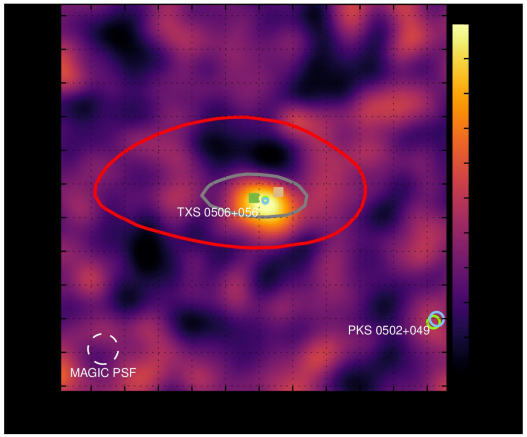
IceCube-170922A 290 TeV neutrino
coincident with the flaring TXS0506+056 blazar.



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 **Science 361, eaat1378 (2018)**

Fermi-LAT γ flare





MAGIC VHE γ detection

Alert distribution

Within ~ 1 min -> **GCN NOTICE**

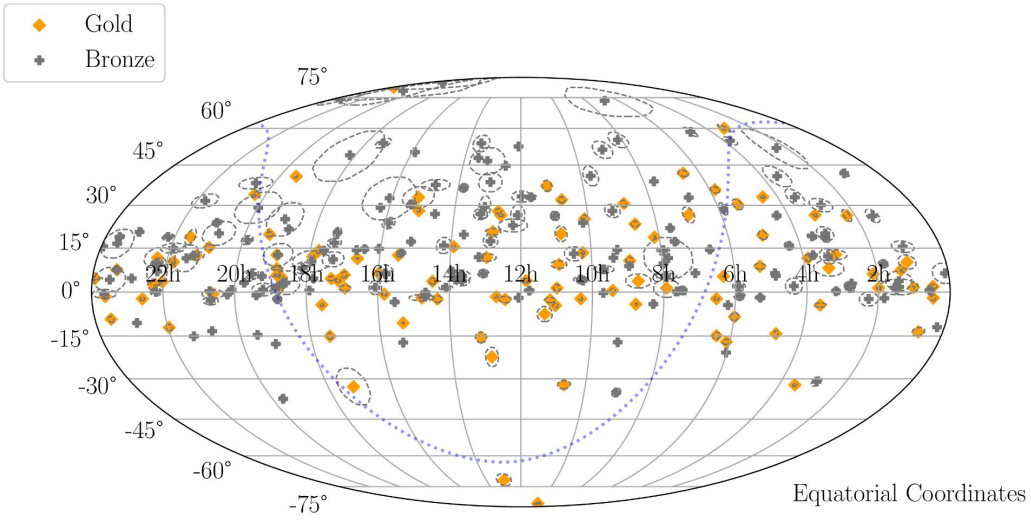
Event date, time, est. energy, FAR, **preliminary reconstruction.**

After a few hours -> **GCN CIRCULAR**

Detailed reconstruction (rectangular region bounding the 90% contour) + comments on associated 4FGL sources.

ICECAT-1: the first catalogue of alert tracks

Archival search for neutrinos matching the ASTROTRACK alert criteria.



Astrophys.J.Suppl. 269 (2023) 1, 25

Public data release on Harvard Dataverse

Also in Astro-COLIBRI!

Alert **angular uncertainty**

Preliminary reconstruction:

- simplified, faster variant of the reco used in IceCube point-source searches;
- may not provide good information on **individual high-energy events** (no accounting for stochastic energy losses).

Detailed reconstruction:

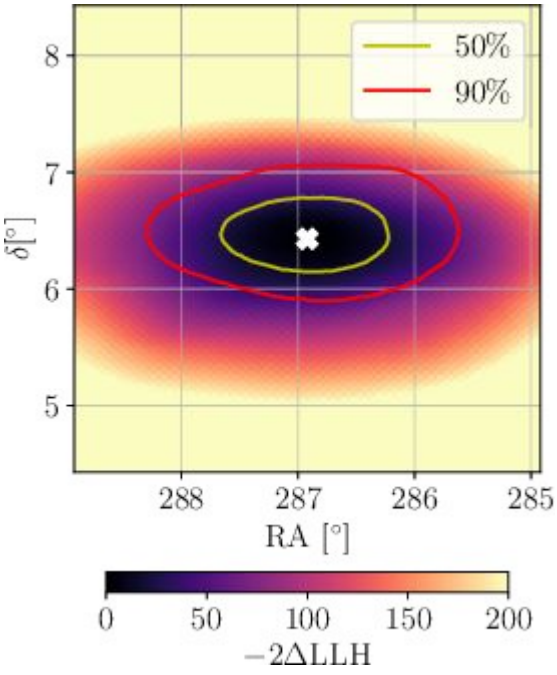
- more sophisticated algorithm accounting for stochastic energy losses;
- **“sky scan” method**: evaluate the likelihood on a fine grid of fixed directions to ensure robustness;
- error contours defined in terms of likelihood critical values.

The **sky scan** reconstruction method

A likelihood function of the **photon arrival times** is evaluated against a grid fixed directions generated with HEALPIX (healpy).

The algorithm starts with on coarse grid, and **iteratively refines** the patch of the sky where the **highest likelihood** is found.

One event requires the evaluation of about O(30000) pixels.



Improving the alert reconstruction

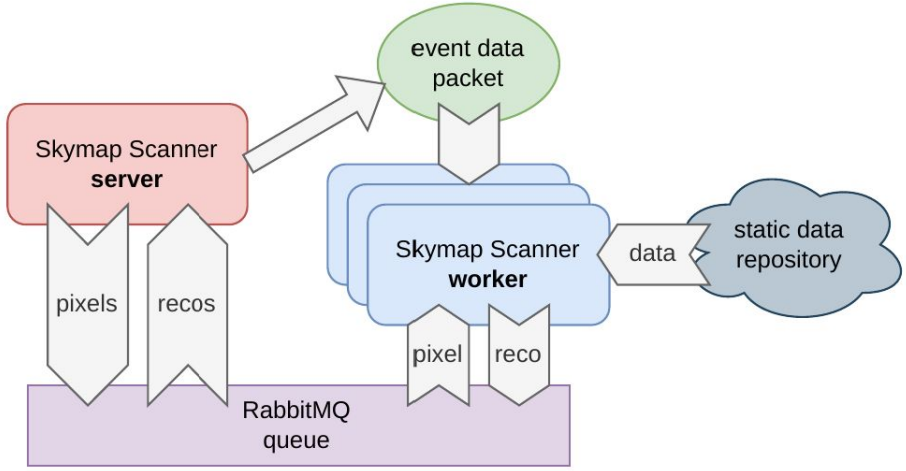
Current directional reconstruction has known limitations due to the impact of systematic uncertainties: **coverage of contours can be improved** (Lagunas Gualda *et al., PoS ICRC2021, 1045*).

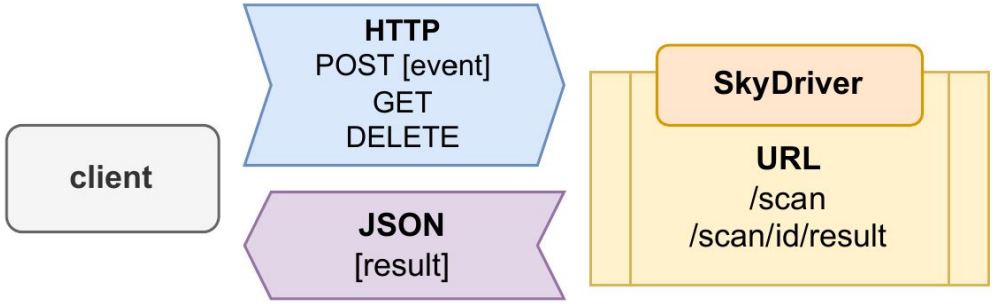
Different algorithms are being evaluated to improve the reconstruction performance (Yuan *et al.*, *PoS ICRC2023*, 1005 – Sommani *et al., PoS ICRC2023, 1186*).

Aim: release of individual **event likelihood maps** and **contour shapes** in realtime.

The new-generation **sky scan** infrastructure

Parallelized workflow: pixels are distributed from a server to O(100-1000) workers using a **RabbitMQ** message queue.

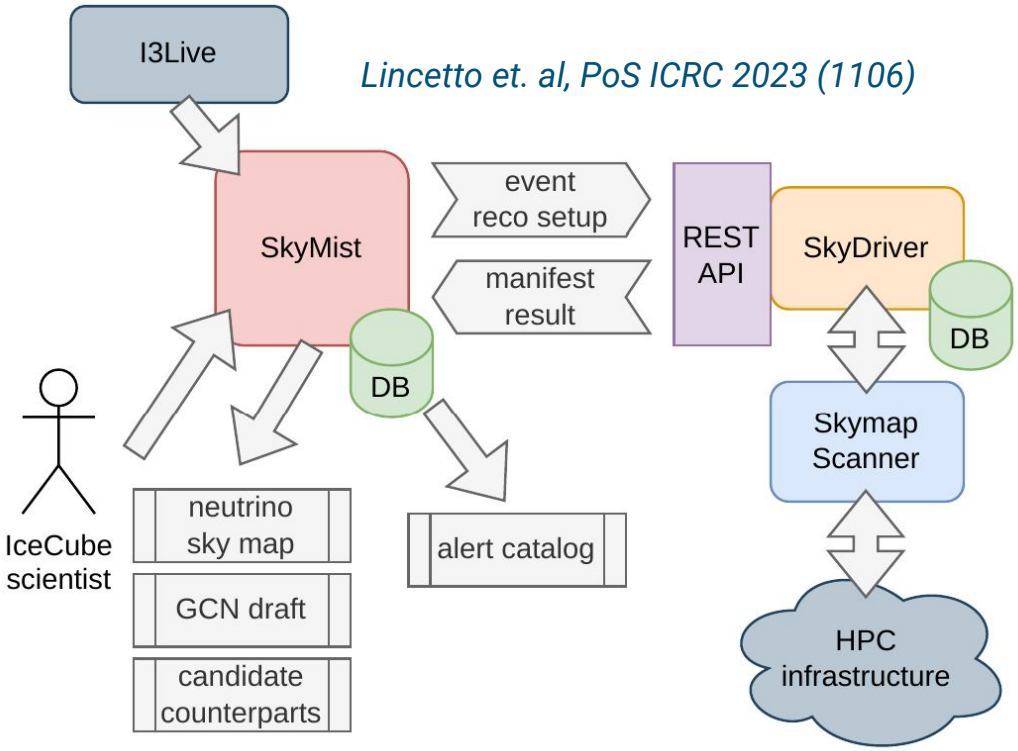




Event reconstruction *as a service* using the **SkyDriver event workflow management system**.

Support for **multiple reconstruction algorithms** allows to develop **improvements to the realtime reconstruction.**

The **SkyMist** orchestration framework



Lincetto et. al, PoS ICRC 2023 (1106)

Monitors the realtime event stream and automates the **scheduling of alert reconstructions** using **SkyDriver.**

Standardizes of **data formats and workflows** for the dissemination of results according to **FAIR data principles**.

Can use **Astro-COLIBRI API** to automate the search of associated sources at the time of alert.

Summary and outlook

The IceCube realtime system has been in operation since 2019, enabling several tens of multi-messenger follow-ups of IceCube neutrinos.

Improvements are ongoing to improve the **alert directional reconstruction**.

These efforts supported by a new-generation **infrastructure for the management of parallel reconstruction workflows.**

Standardization of the **data formats** and **workflows** will enable a more timely and comprehensive dissemination of alert information to the community.