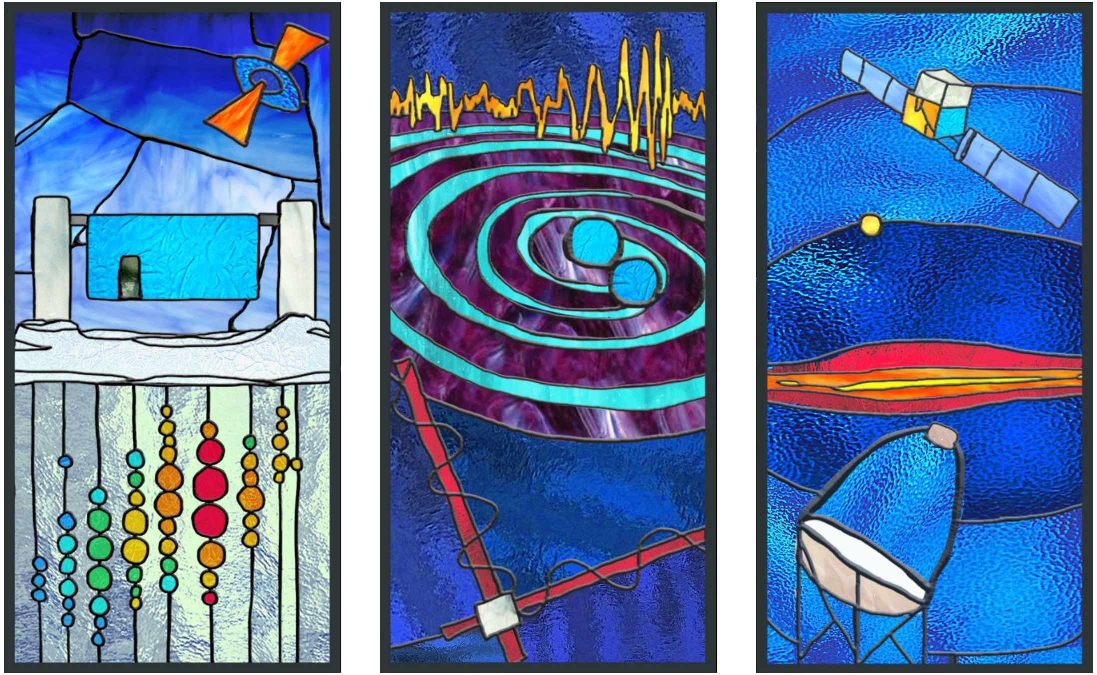
Developing a platform for public neutrino cluster alerts with events from the IceCube Neutrino Observatory

Sarah Mancina

UC Louvain Seminar
September 2nd, 2025

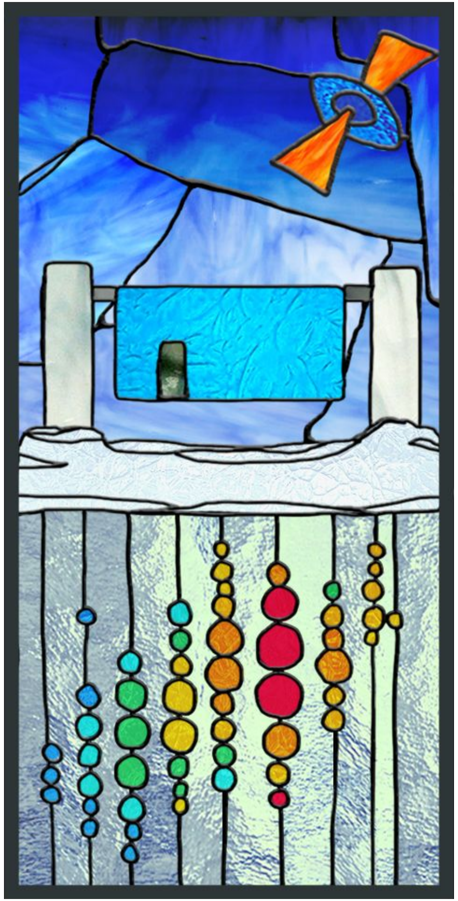


Source: IceCube/NSF

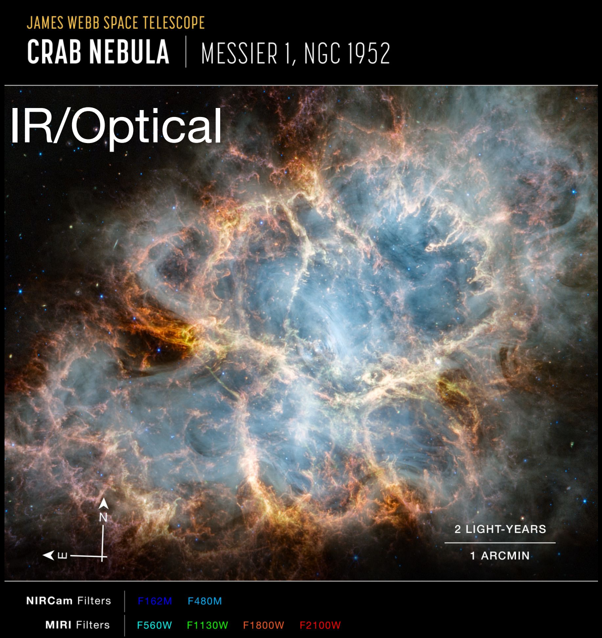
Neutrino astronomy

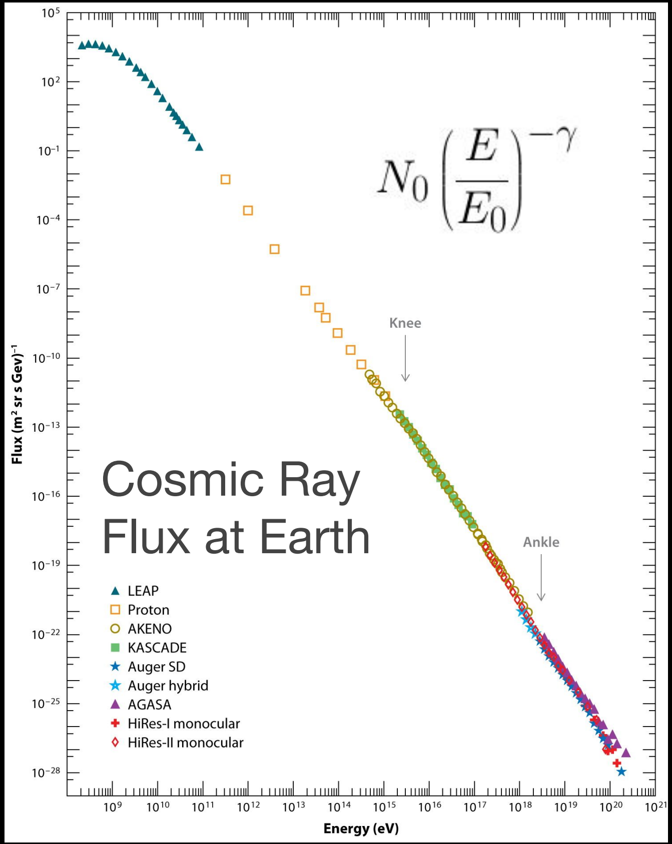
Current IceCube realtime alerts

Next generation cluster alerts

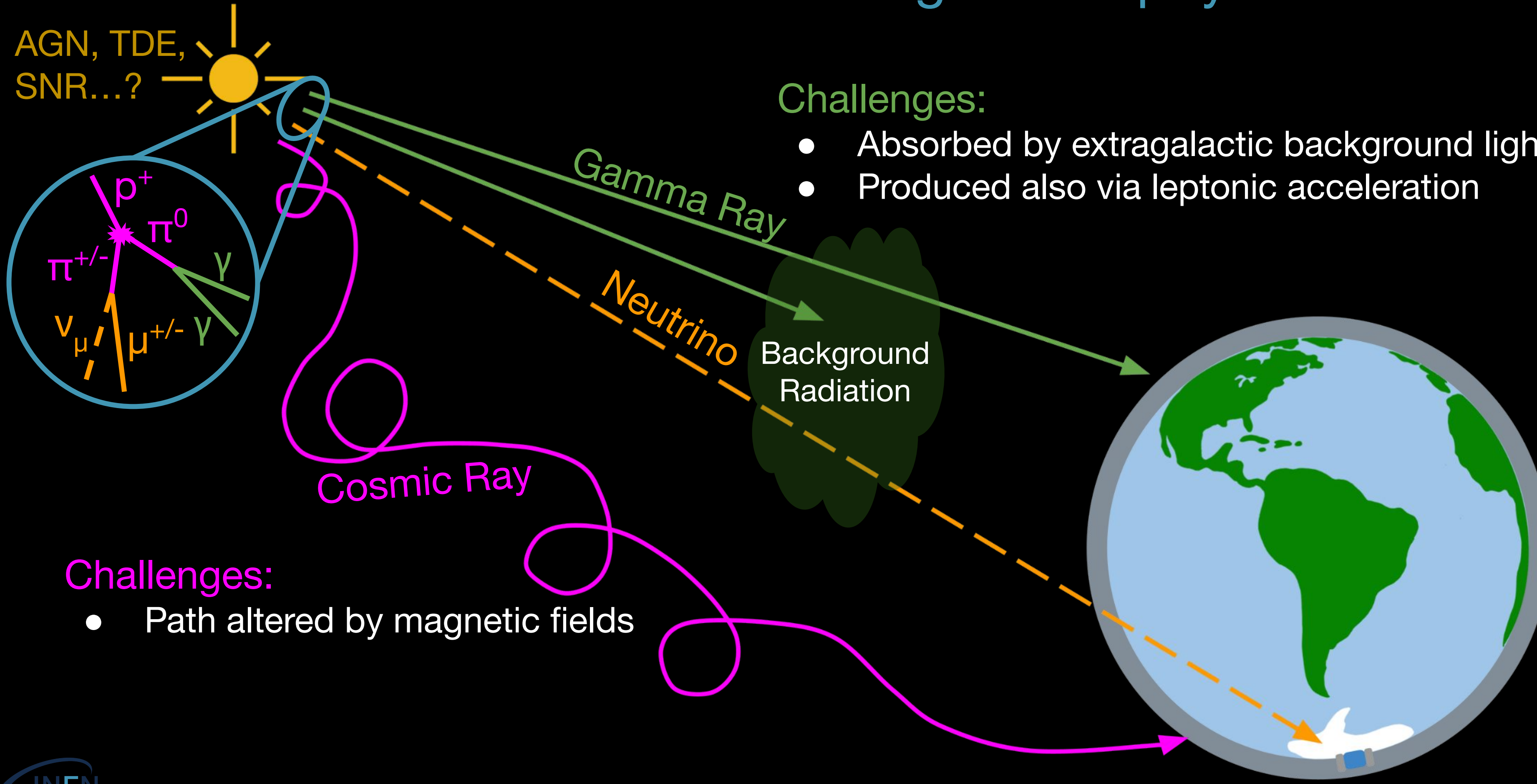


Exploring the universe through different messengers can expose new astrophysical processes





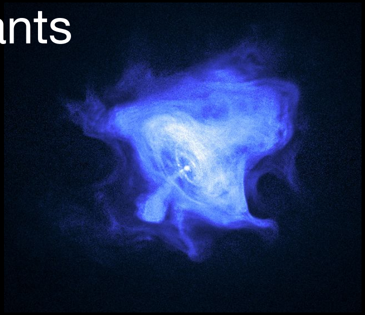
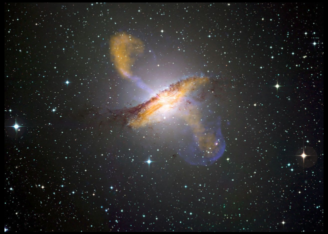
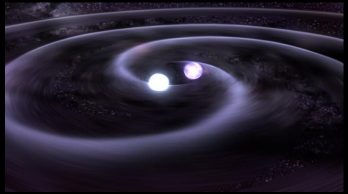
Neutrinos in TeV-scale multi-messenger astrophysics



Challenges:
- Absorbed by extragalactic background light
- Produced also via leptonic acceleration

Challenges:
- Path altered by magnetic fields

Some neutrino source candidates

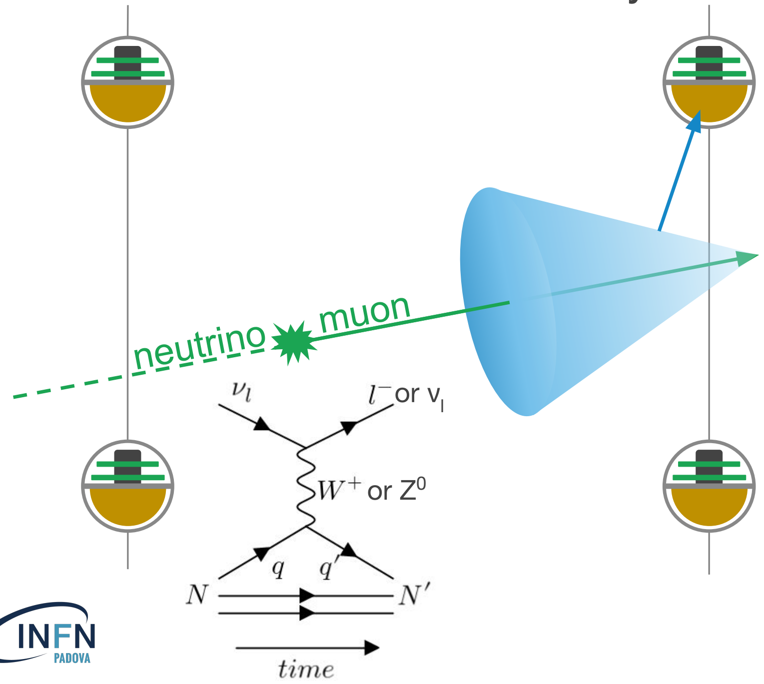
	Steady, Time-Independent	Transient, Time-Dependent
Galactic	Pulsar Wind Nebulae Supernova Remnants 	Microquasars Tidal disruption events (TDE) Core-collapse supernovae Pulsar Wind Nebulae? 
Extragalactic	Active Galactic Nuclei Starburst Galaxies  	AGN flares Kilonovas Gamma ray bursts (GRB) 

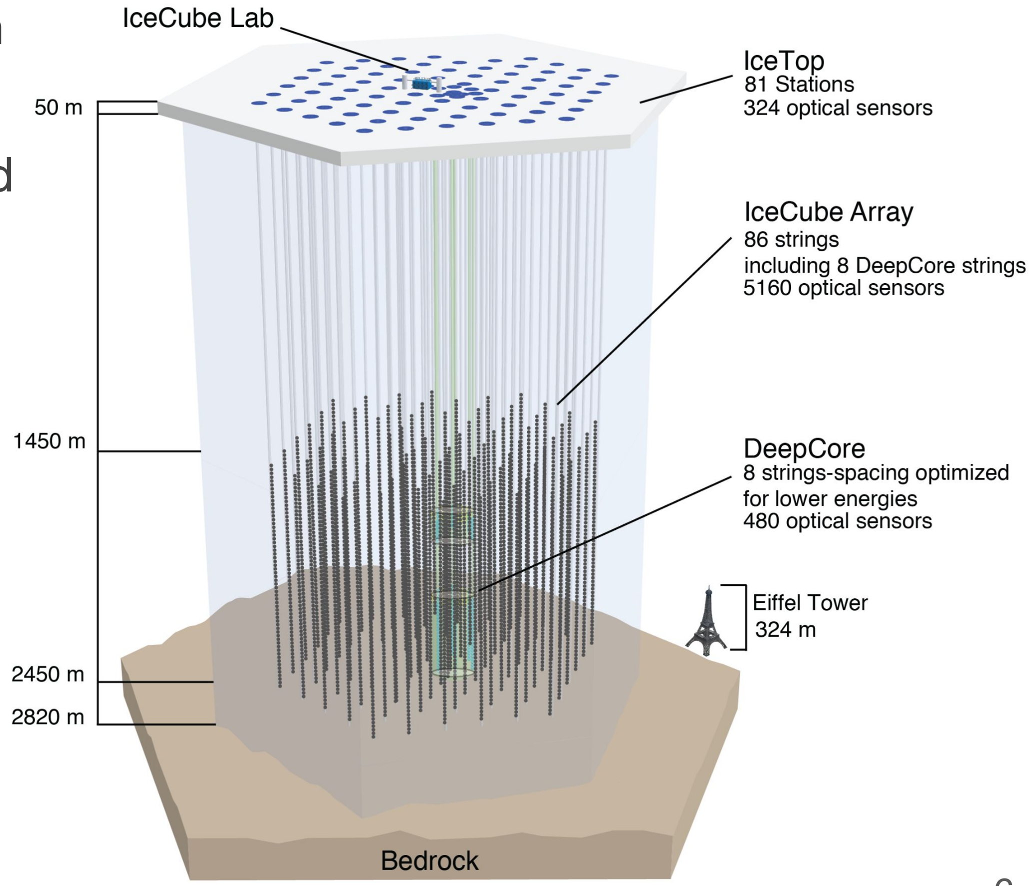
… even more sources including unknown sources also possible!!!

Detecting neutrinos with Cherenkov light

Want to detect **TeV-PeV neutrinos from astrophysical sources**

Use naturally occurring water/ice to build **cubic-kilometer** detector arrays





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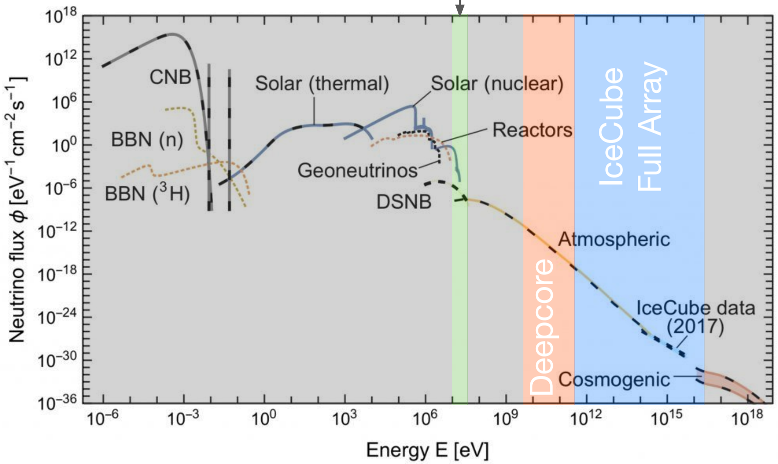
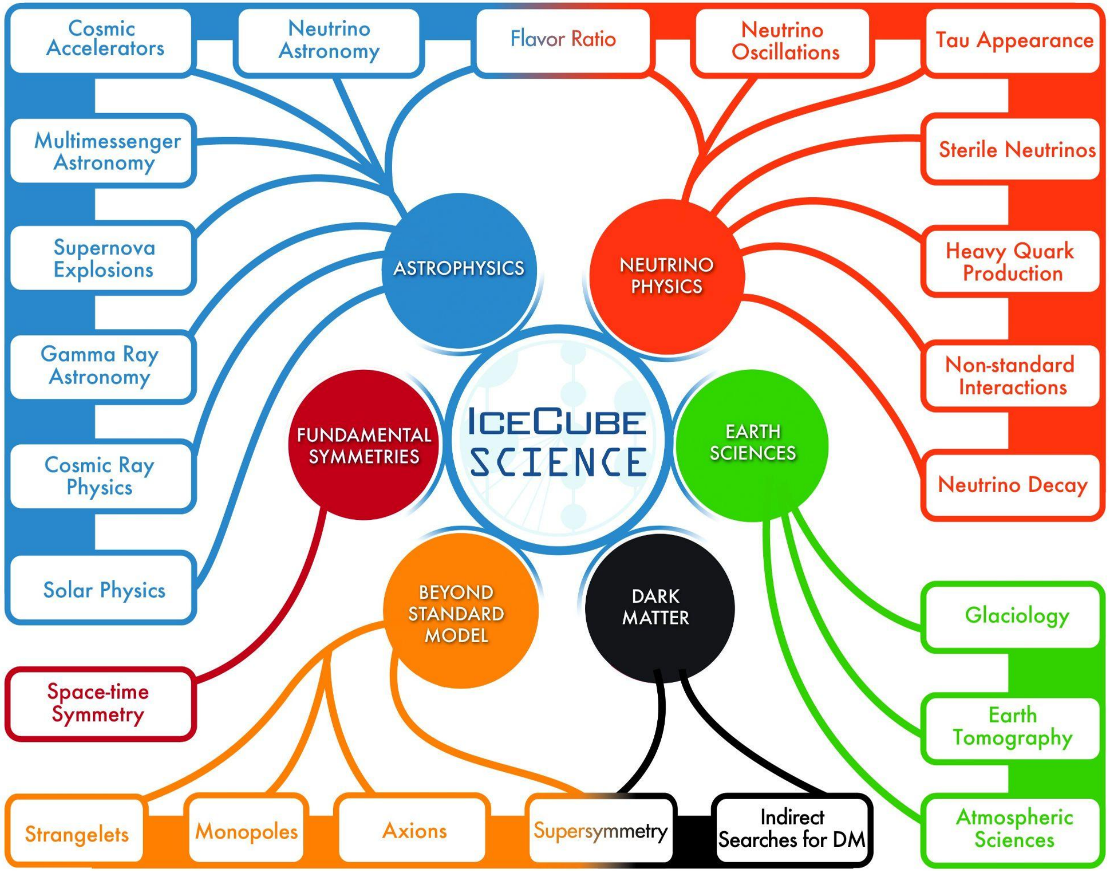
IceCube science covers a broad range of physics topics



Neutrino fluxes across decades of energy
[Rev. Mod. Phys. 92, 45006 (2020)]



IceCube/NSF

Main TeV particle morphology classifications within IceCube

Muon Track

Angular Resolution: 0.6°

Log Energy Resolution: 20% of muon energy at detector entry

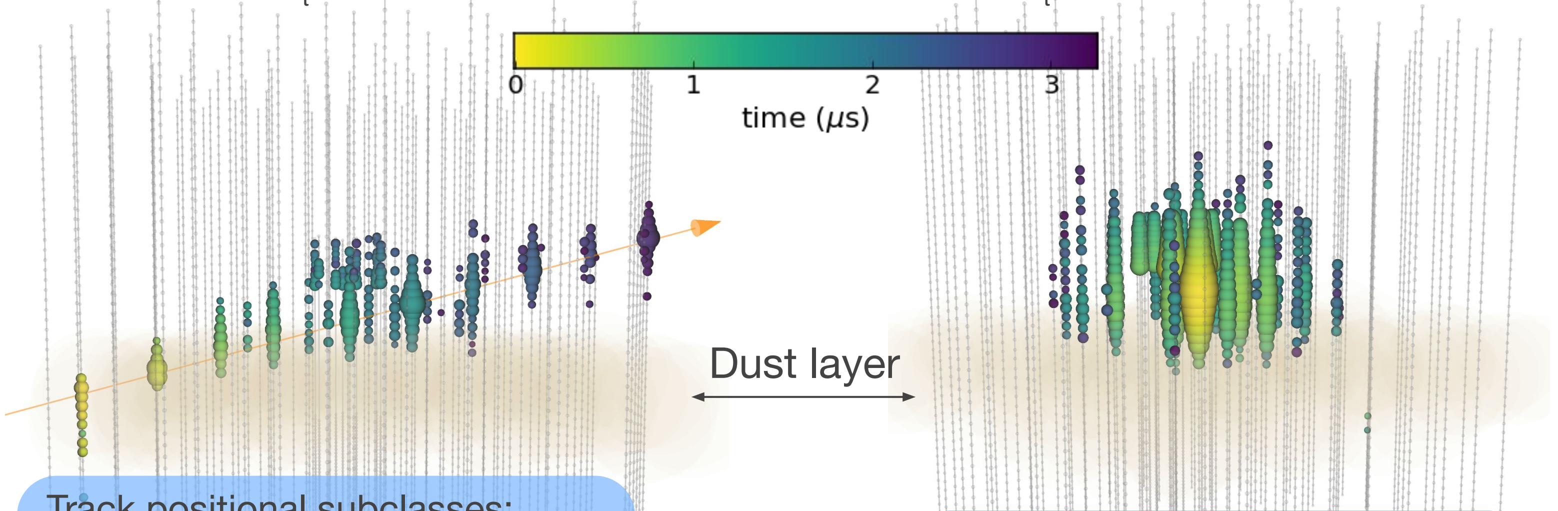
Atmospheric muons, charged current ν_μ and ν_τ ($\tau \rightarrow \mu + \nu$'s)

Electromagnetic/Hadronic Cascade

Angular Resolution: 5°-15°

Log Energy Resolution: 15% of neutrino energy

Neutral current ν, charged current ν_e and ν_τ ($\tau \rightarrow$ e/hadrons + ν's)



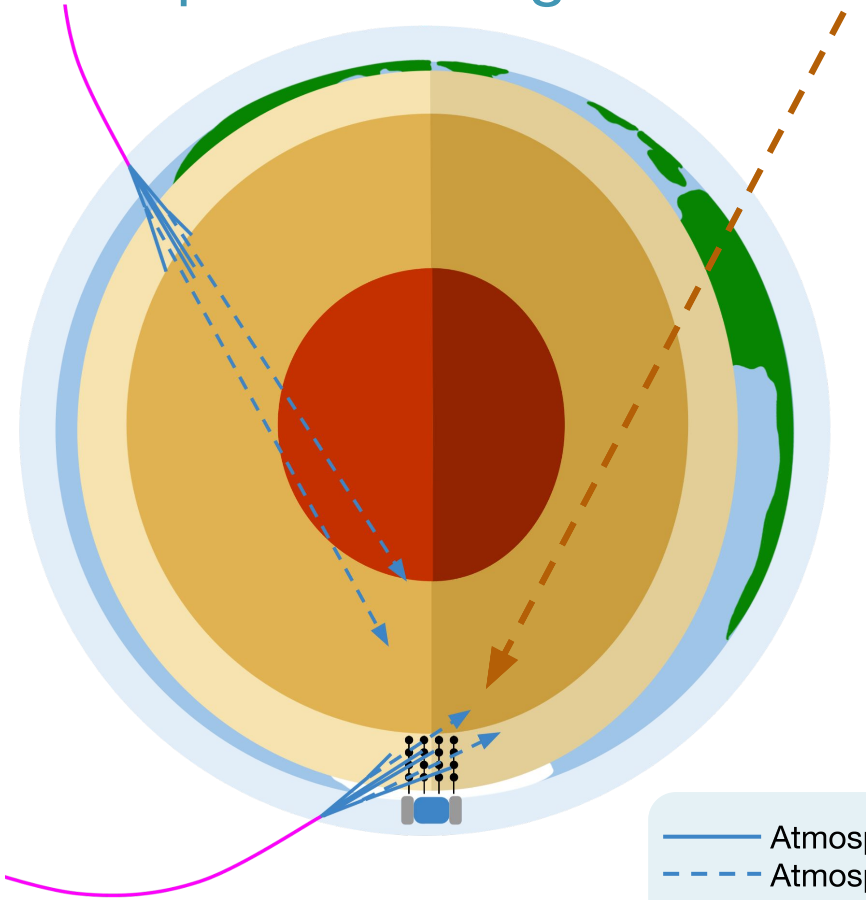
Track positional subclasses:

- Through-going
- Starting
- Stopping
- Skimming

Cascade positional subclasses:

- Contained
- Partially contained

Atmospheric background dominates astrophysical signal

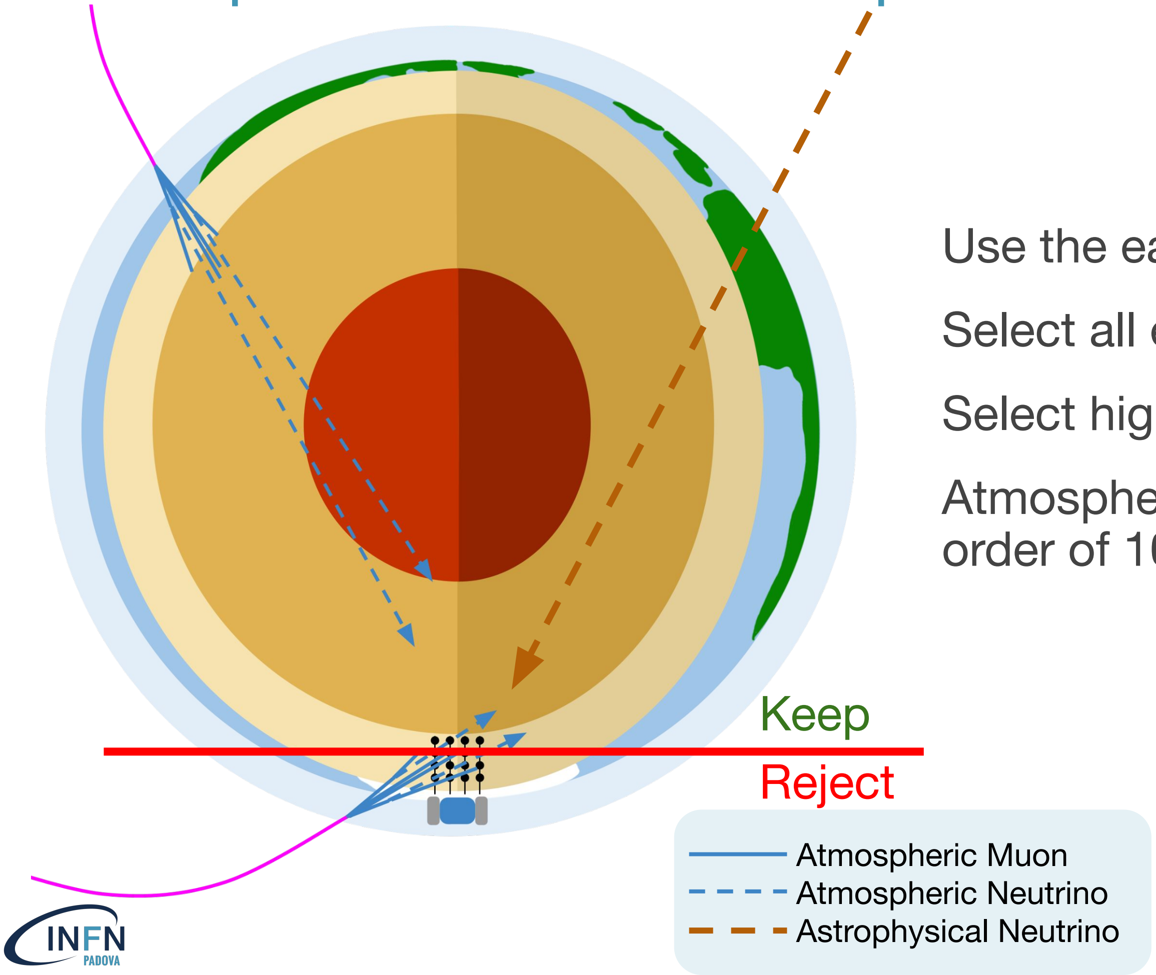


For a 1 km^3 detector

Atmospheric Muons	3000 per second
Atmospheric Neutrinos	~1 per second
Astrophysical Neutrinos	~1 per day

Muons from cosmic-ray air showers can penetrate several kilometers underground

Techniques to remove atmospheric background



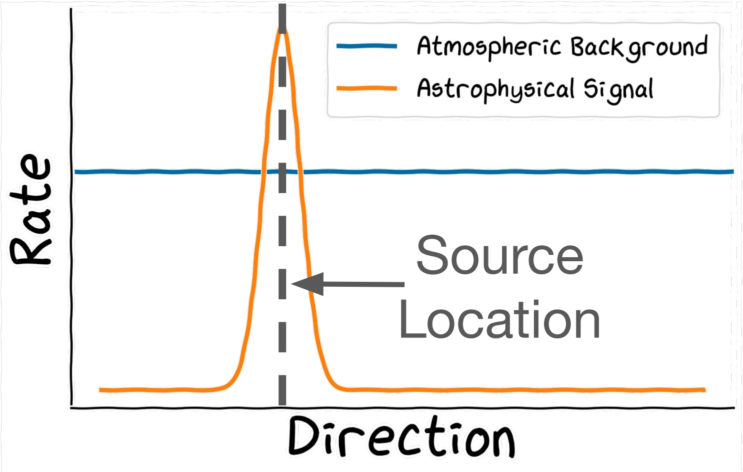
Use the earth as a muon veto

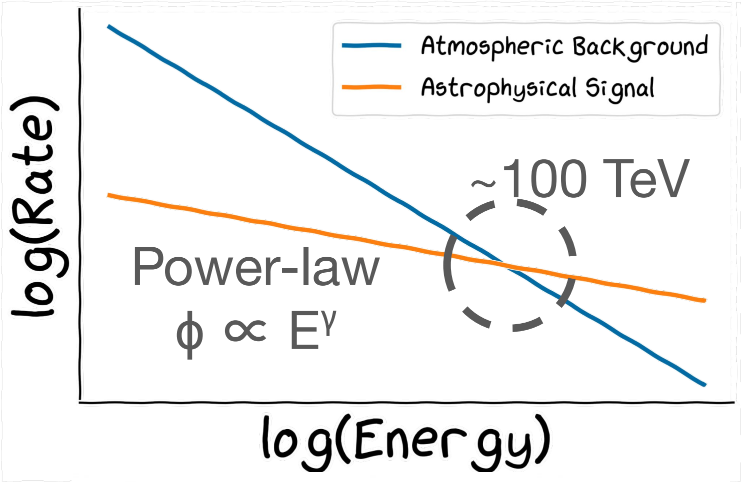
Select all earth-through-going events

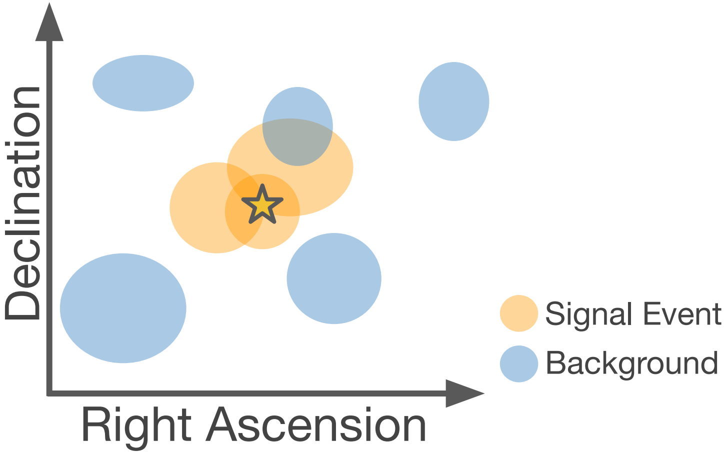
Select high-energy southern sky events

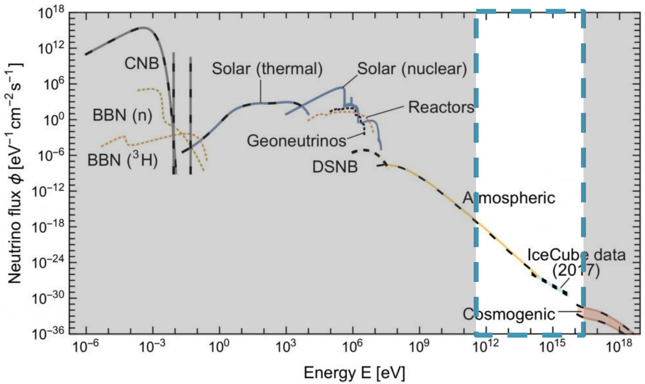
Atmospheric backgrounds still exist on order of 1000x signal rate

Techniques to distinguish astrophysical neutrino signatures



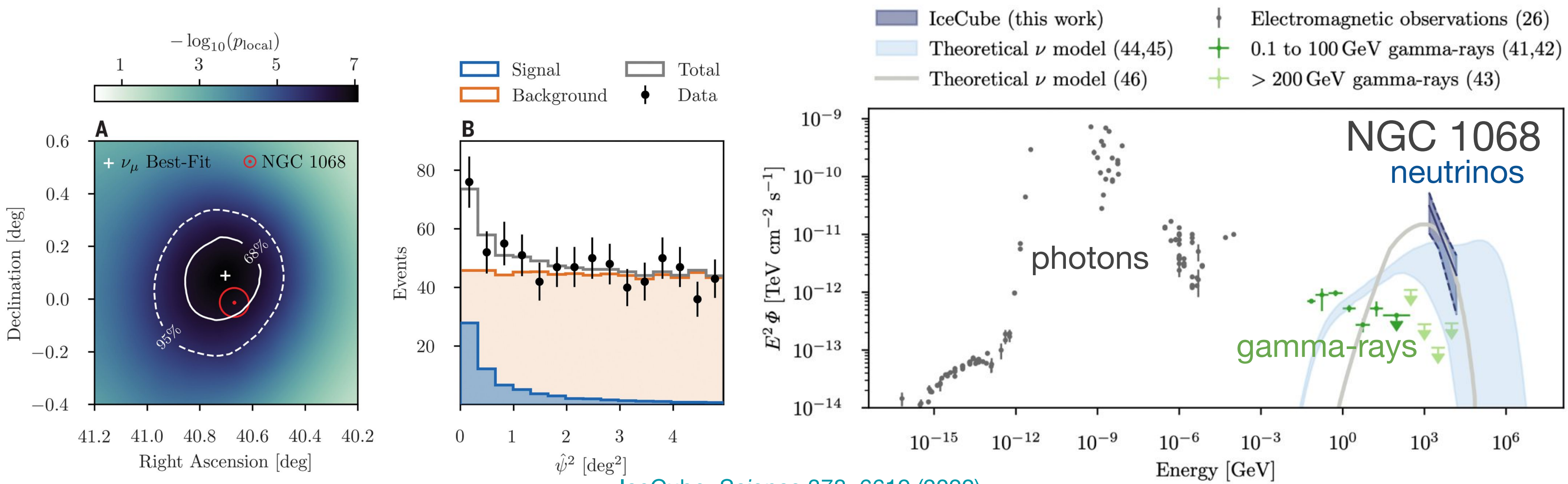






Neutrino fluxes across decades of energy
[Rev. Mod. Phys. 92, 45006 (2020)]

Example of techniques: NGC 1068



[IceCube, *Science* 378, 6619 (2022)](#)

NGC 1068 part of a GeV gamma-ray bright catalog

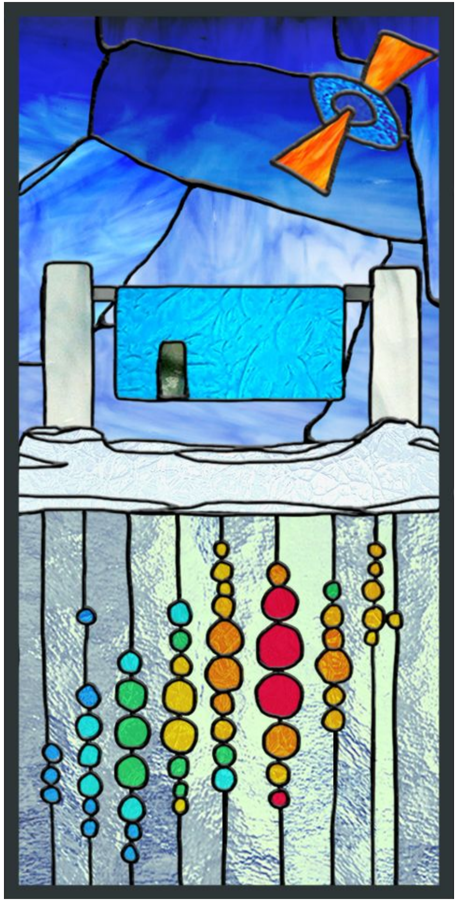
Check for neutrino excesses around locations of sources in the catalog

IceCube observes neutrino emission from NGC 1068 with global significance of 4.2σ

Neutrino astronomy

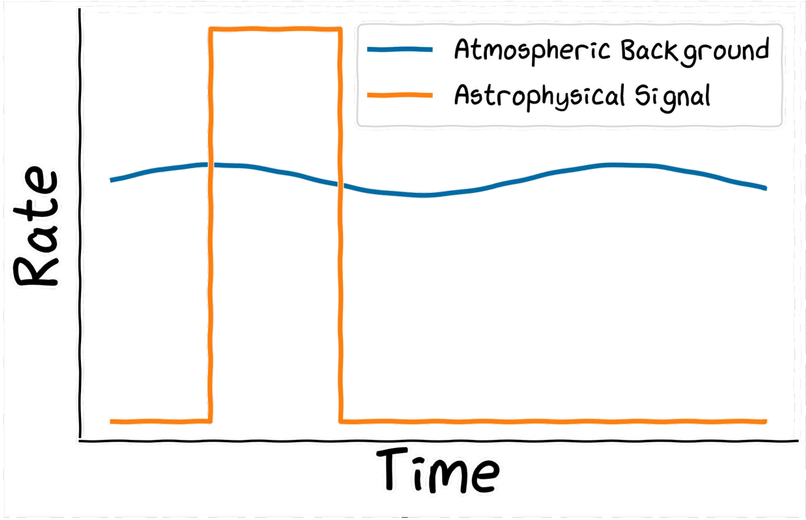
Current IceCube realtime alerts

Next generation cluster alerts



Using realtime neutrino alerts to find astrophysical sources

Transient/Flaring Sources



+

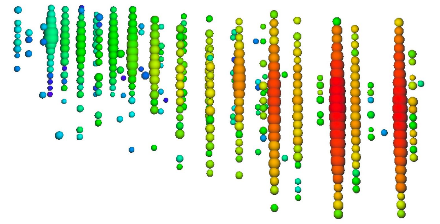
Multimessenger Data

Add time component to analyses to look for time-dependent neutrino emission

IceCube: near 100% uptime and view of full sky

Send neutrino targets of opportunity to telescopes

Tested in the case of TXS 0506+056



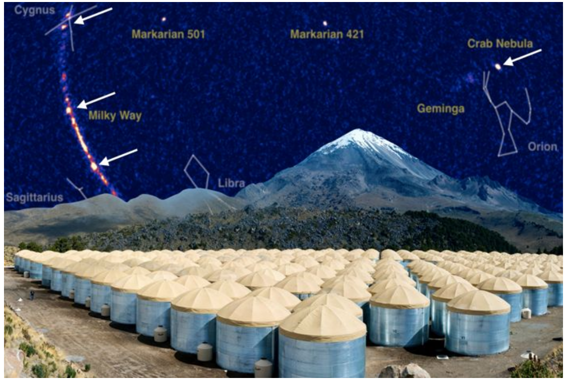
[IceCube, *et. al*, *Science* 361, 6398 (2018)](#)

Gamma-ray detector technologies

Satellite

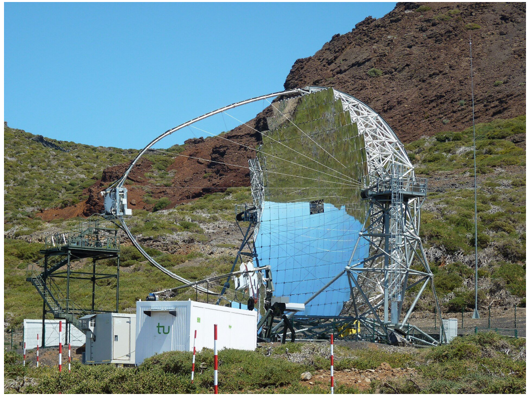
Fermi

Water Cherenkov Tanks



HAWC

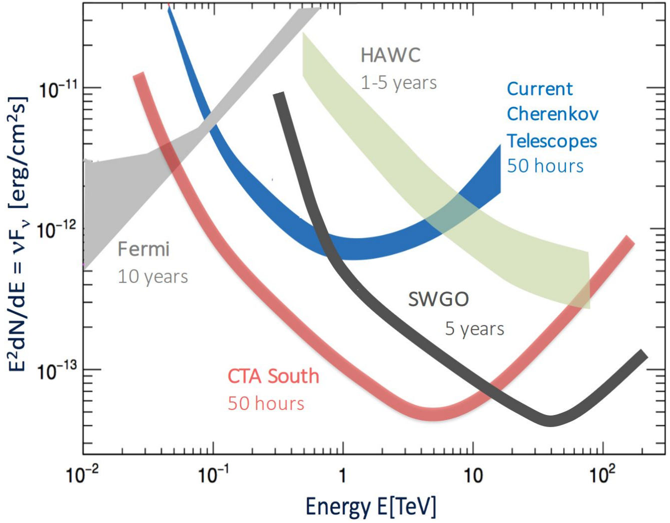
Imaging Air Cherenkov Telescopes (IACTs)



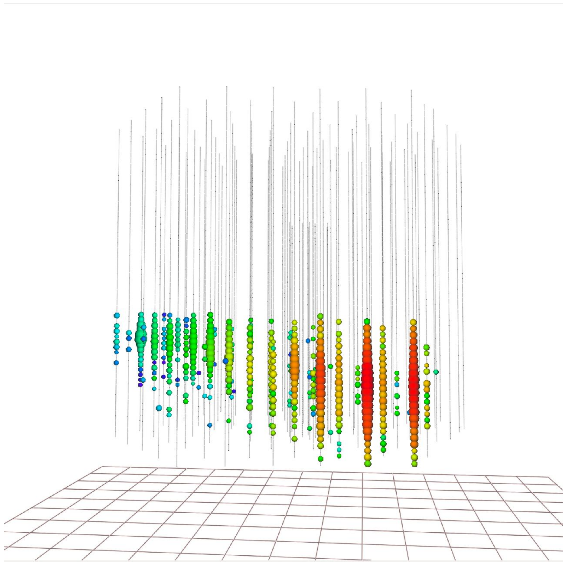
MAGIC

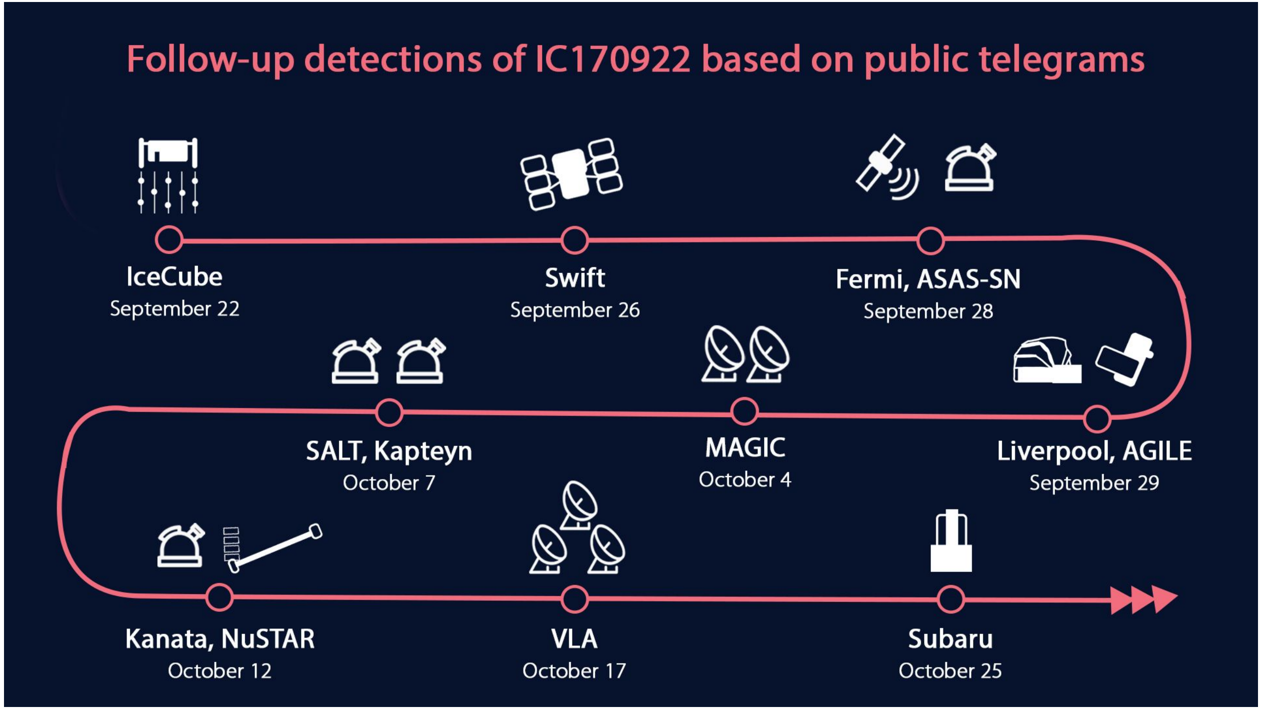
IACTs most sensitive but small FoV: 3°-5°

DOI:10.1088/1742-6596/1468/1/012096



First example of neutrinos in MMA: TXS 0506+056





DOI: 10.1126/science.aat2890

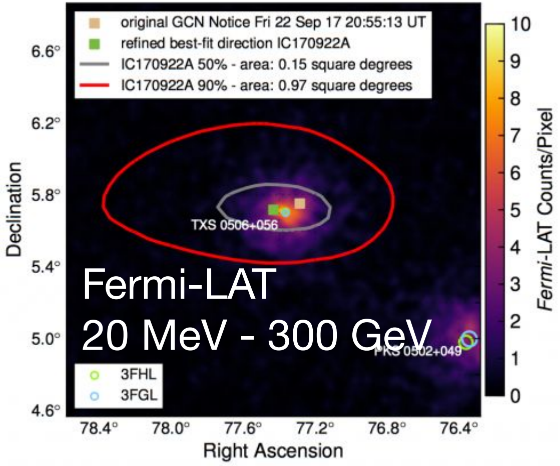
First example of neutrinos in MMA: TXS 0506+056

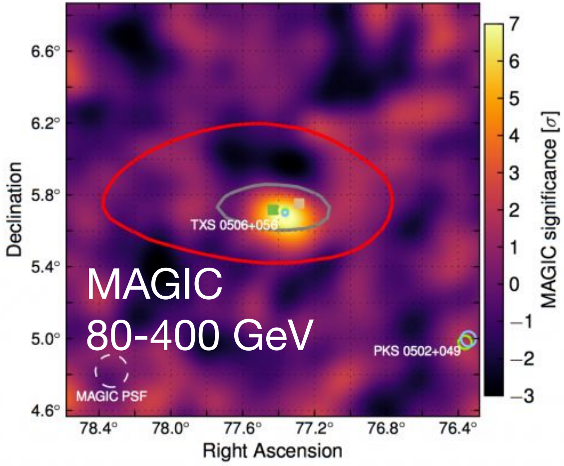
(2017) **high energy neutrino** coincided with **flare from blazar TXS 0506+056** (3σ significance)

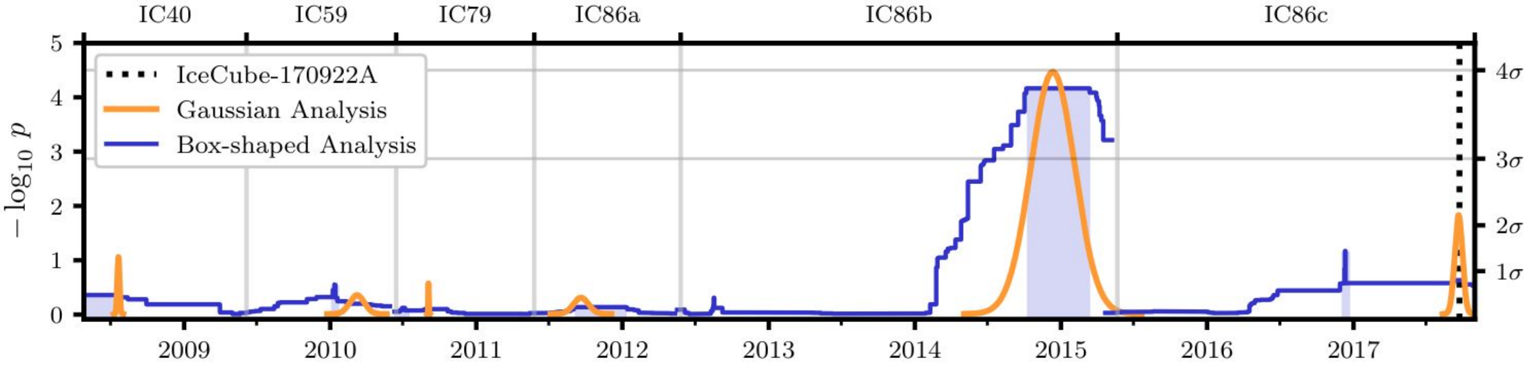
Flare observed across electromagnetic spectrum

Archival neutrino flare also found by IceCube (also at 3σ)

[DOI: 10.1126/science.aat1378](https://doi.org/10.1126/science.aat1378)

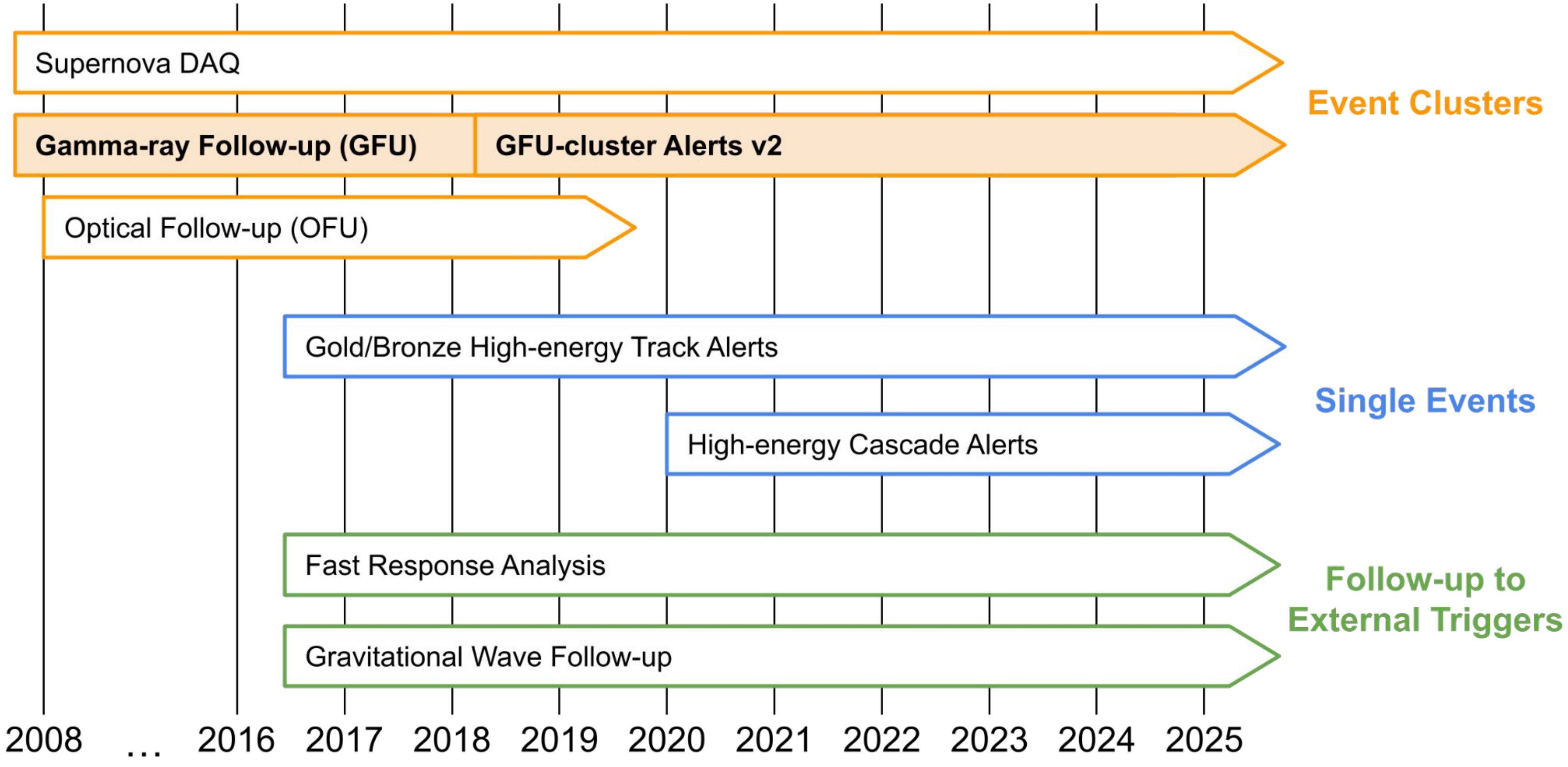




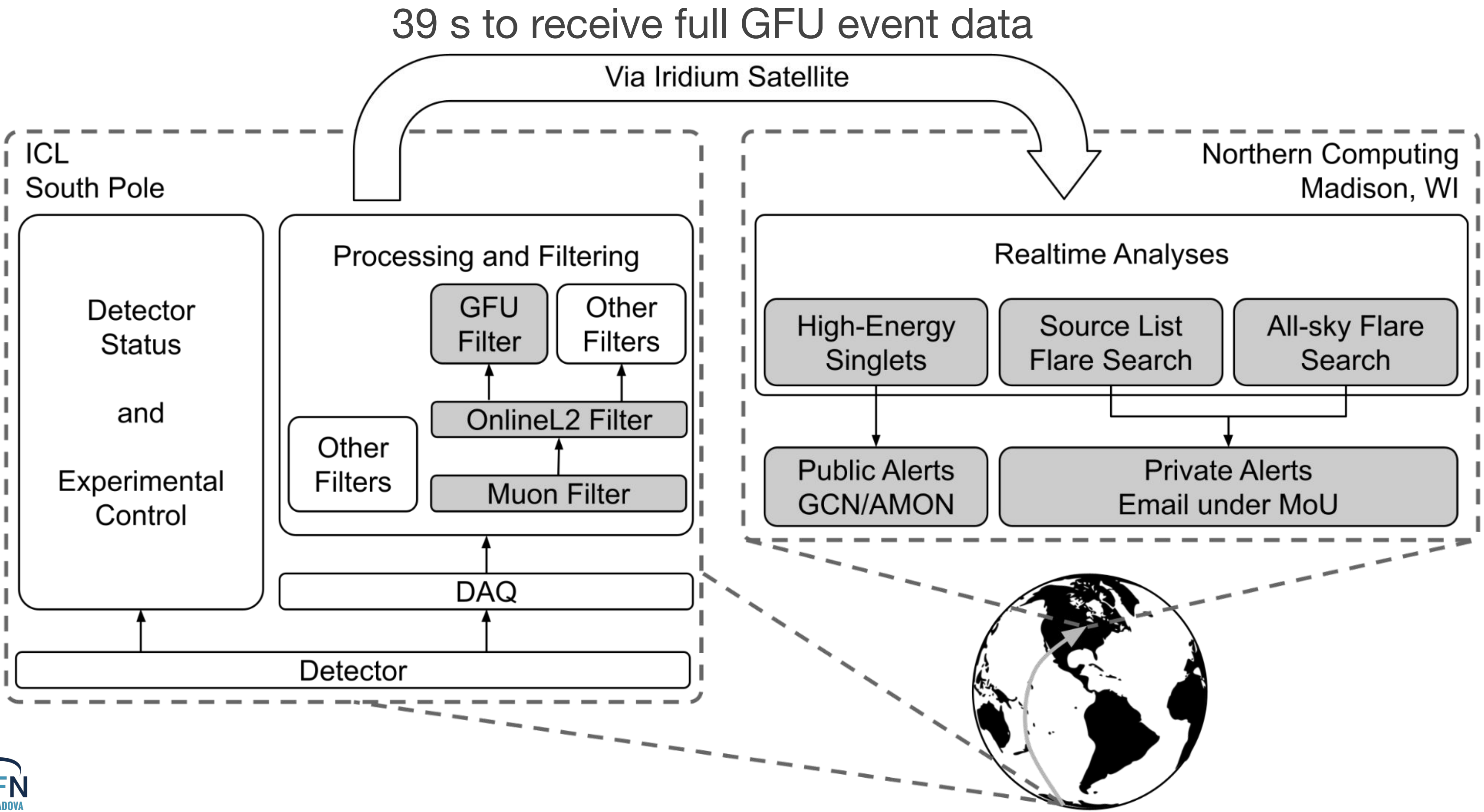


[DOI: 10.1126/science.aat2890](https://doi.org/10.1126/science.aat2890)

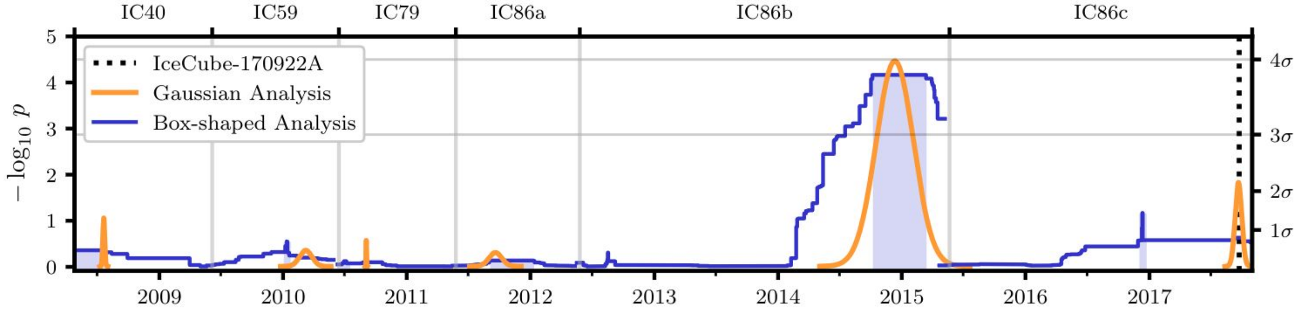
Timeline of IceCube's realtime alerts



Overview of the IceCube realtime stream infrastructure



Gamma-ray Follow-Up (GFU) cluster alerts



Approach: Identify potential neutrino flares in realtime using multiple events

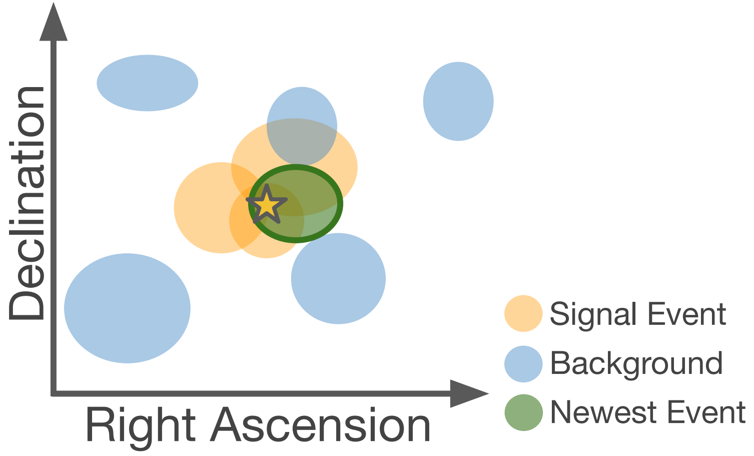
Advantages over single events:

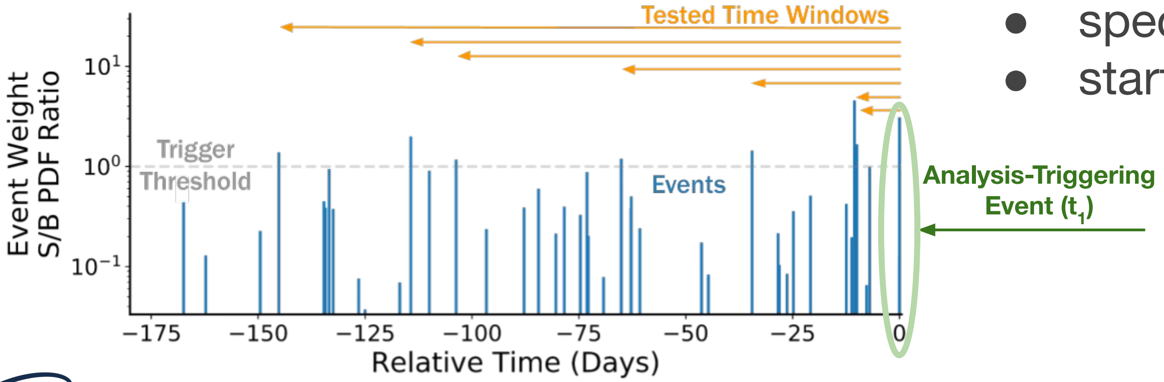
- Biased towards closer sources
- More time window information
- Ability to trigger with <100 TeV events
- Better directional resolution from multiple events (~0.2°)

Challenges:

- Large number of trials performed
- Source-list mode: need to bet on the right sources

How the GFU-cluster algorithm works





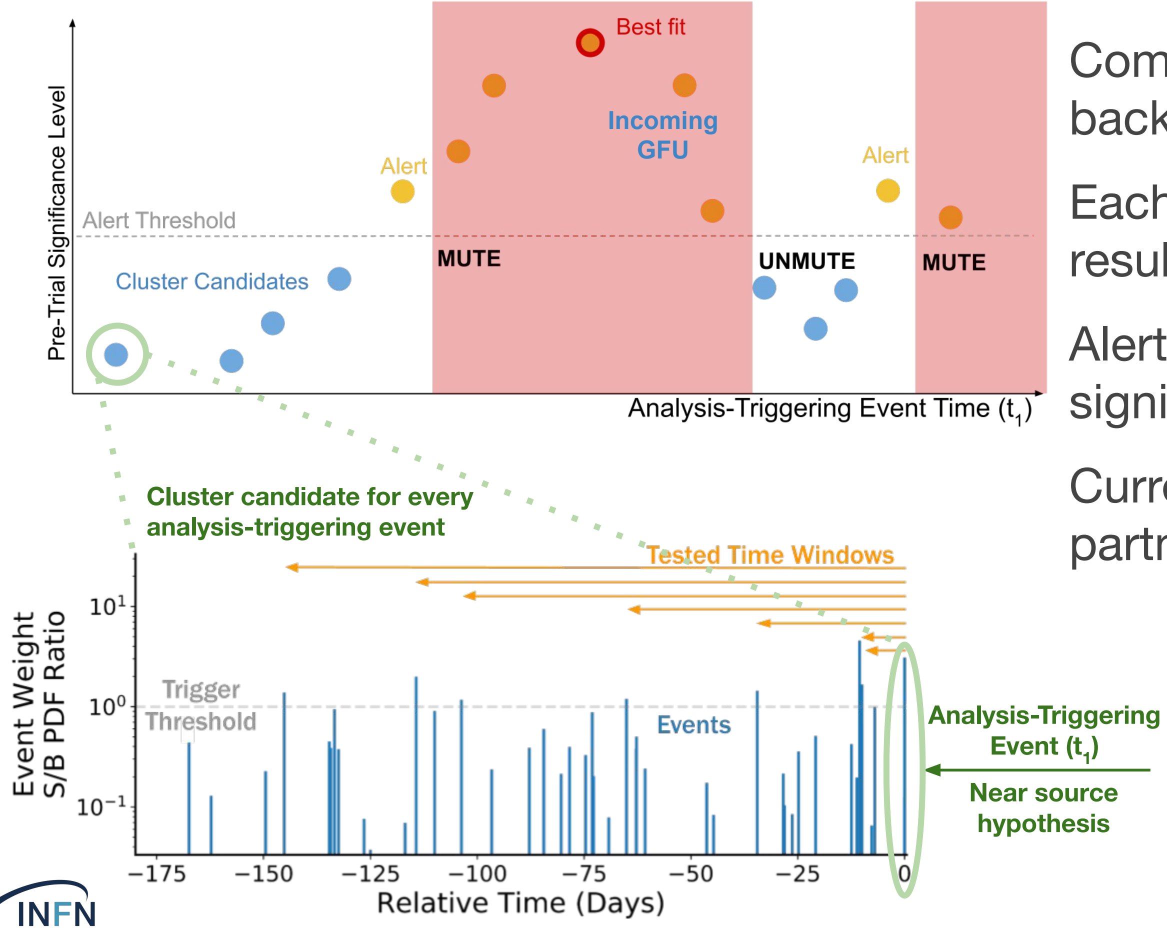
Incoming events in region of source location trigger the analysis pipeline

Likelihood is maximized using all data in the time window

Likelihood maximization estimates:

- number of signal events
- spectral index
- start time of flare candidate

Current GFU-cluster alert algorithm



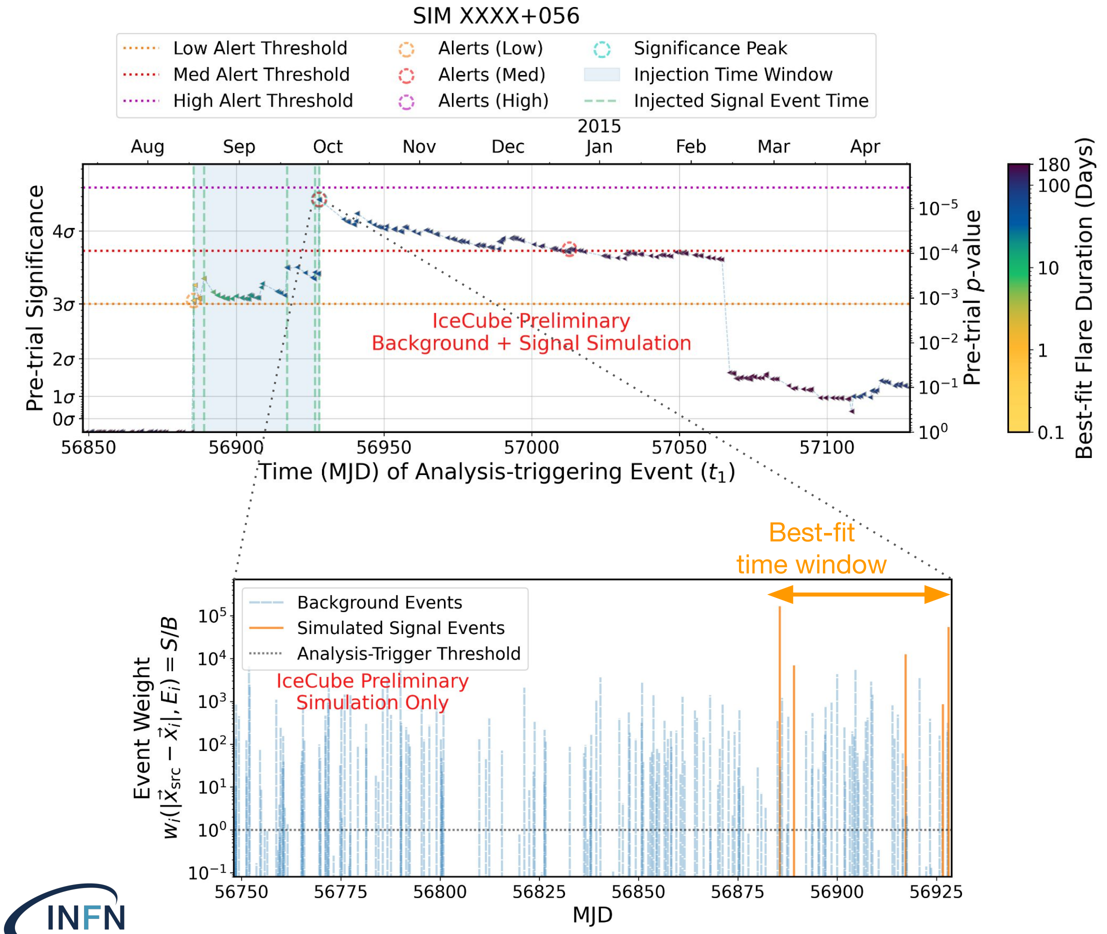
Compare TS from likelihood to background TS distributions

Each analysis-triggering event results in a pre-trial p-value

Alert sent if passes a pre-trial significance threshold

Current: Alerts sent under MoU to partner telescopes

Single example of a simulated source significance curve



Injected source:

- 5 signal events
- 50 day flare duration
- γ = -2

Each point includes data from previous 180 days

Not a light curve, adjacent points use overlapping data

Significance decays over time as no new signal

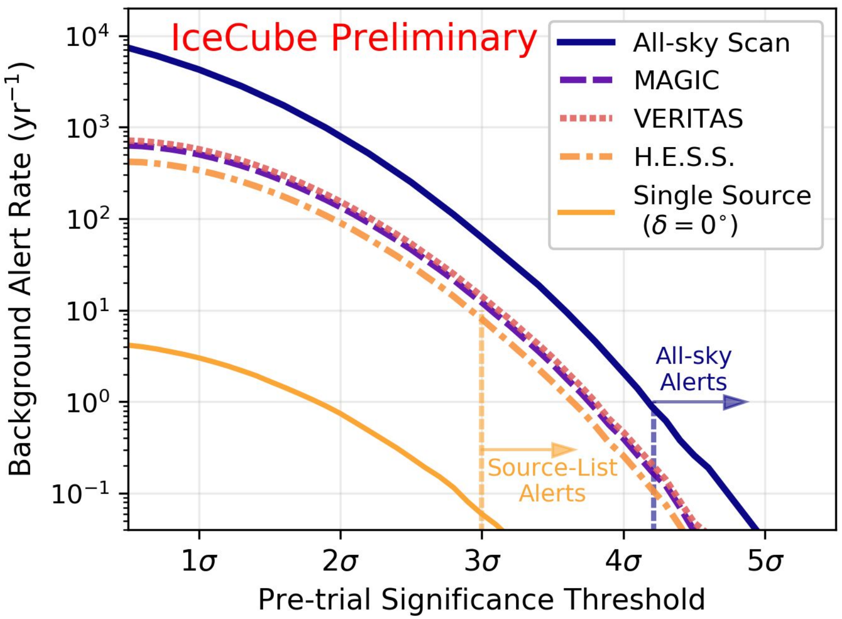
GFU Source list vs. Allsky alerts

GFU alert stream has two different modes: Source list and Allsky

Send out alerts if trigger passes p-value threshold

Source list alerts automatically shared under MoU with IACTs

Allsky alerts shared with human in the loop



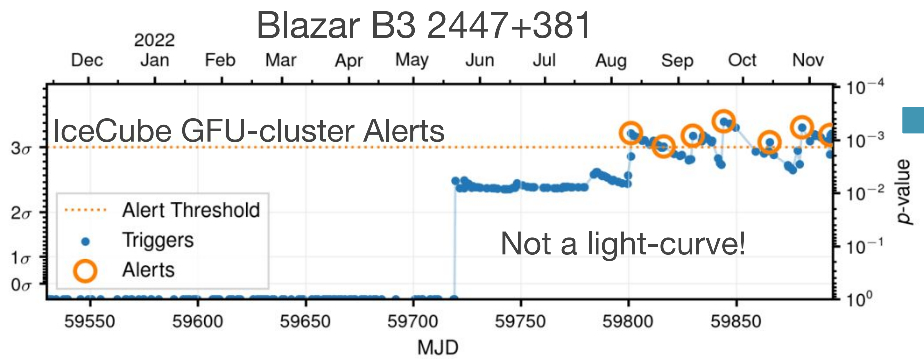
Source list alerts (model dependent)

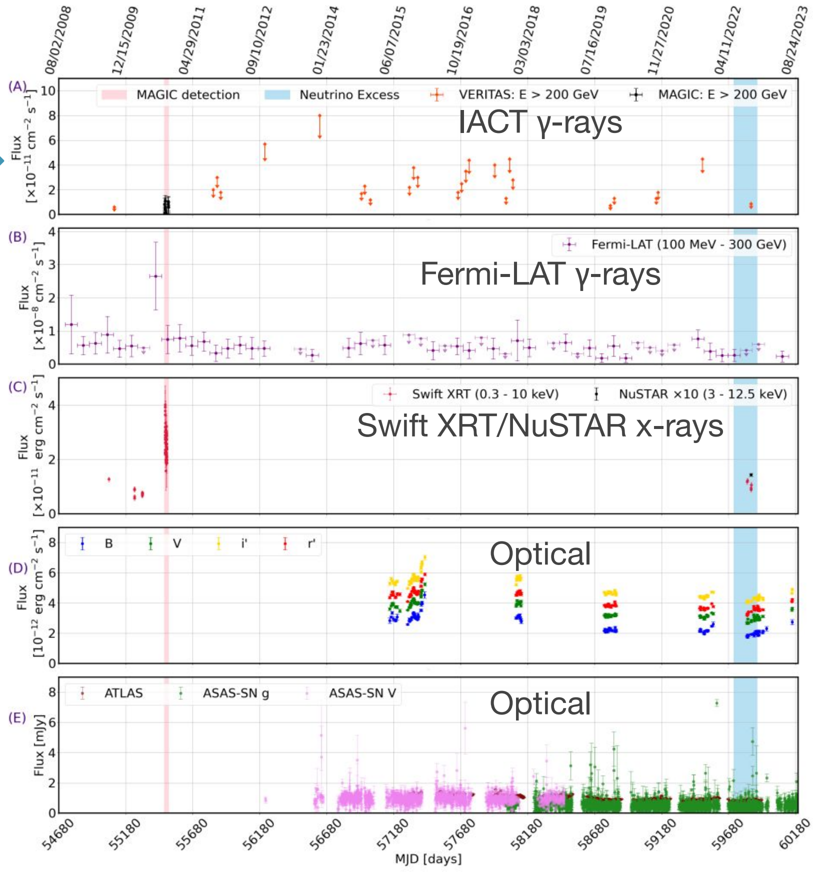
- Test location of nearby AGN that are highly variable in gamma-rays
- Pro: reduces trials factor
- Con: relies on model assumptions
- Con: $z \leq 1$ bias

Allsky alerts (model independent)

- Test pixels around incoming events
- Pro: can identify previously unknown/unexpected sources
- Con: large number of trials

Example of IACT follow-up: VERITAS and B3 2447+381





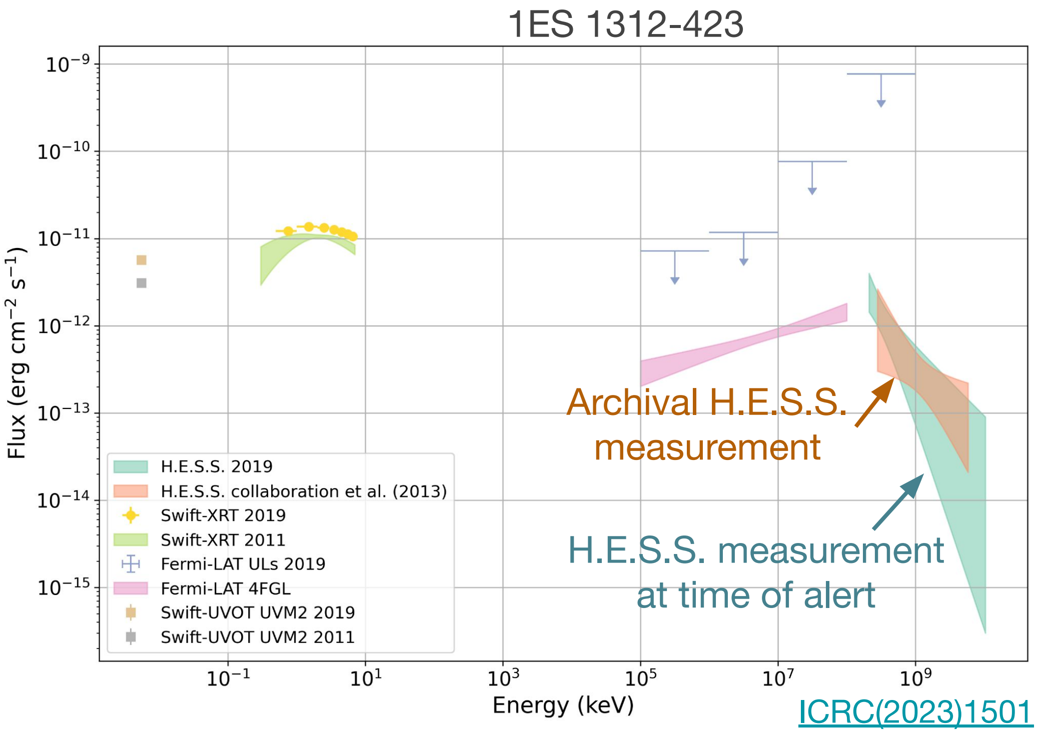
IACT can request a more complete report for GFU-cluster alerts

IACT analysers look at multiwavelength (MW) data for more evidence of transient activity

VERITAS sends ToO to NuSTAR (hard X-ray) for further follow-up

DOI: 10.3847/1538-4357/adb30c

Example of IACT follow-up: H.E.S.S. and 1ES 1312-423



ICRC(2023)1501

GFU-cluster alert from direction of 1ES 1312-423 in 2019

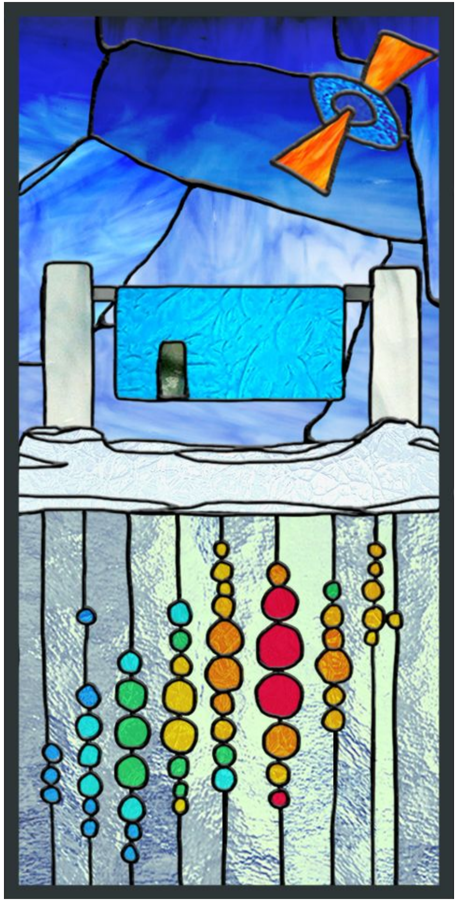
H.E.S.S. 4σ observation can be compared to archival analysis

Besides TXS 0506+056, no TeV γ-ray flares identified by follow-ups of neutrino alerts

Neutrino astronomy

Current IceCube realtime alerts

Next generation cluster alerts



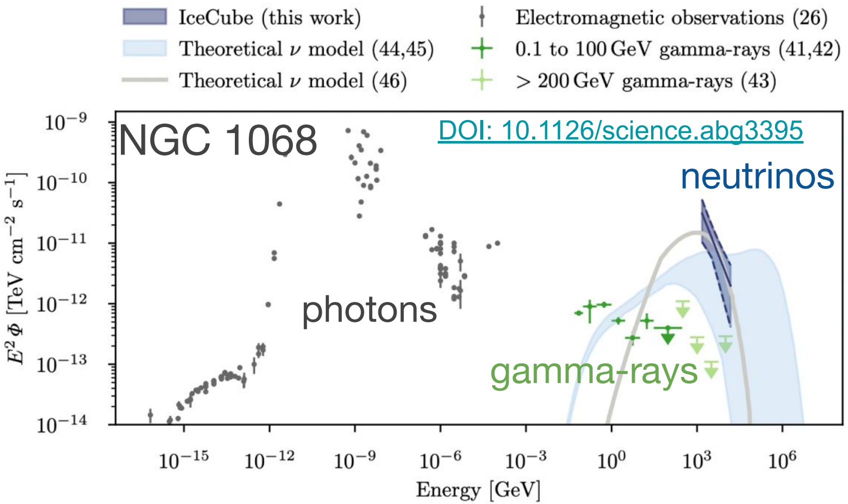
Current work: new public GFU-cluster alerts

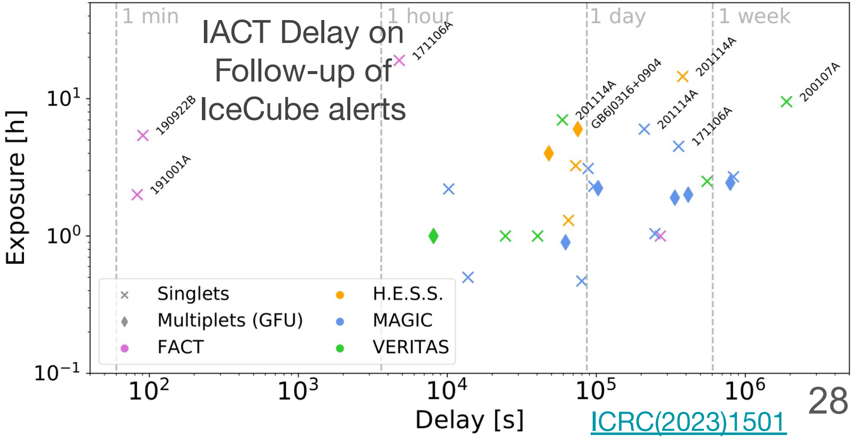
Physics:

- Expand focus beyond just TeV gamma-rays
- **Update source-lists** with improving understanding of potential source classes
- **Automatically provide updates on source status** to communicate if still interesting

Other:

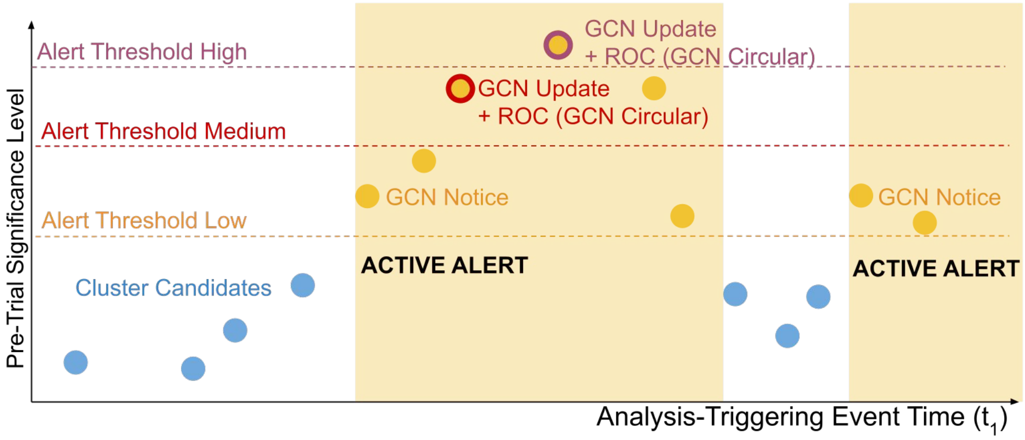
- Shift towards more public sharing of data
- Increase ease in publishing follow-up papers

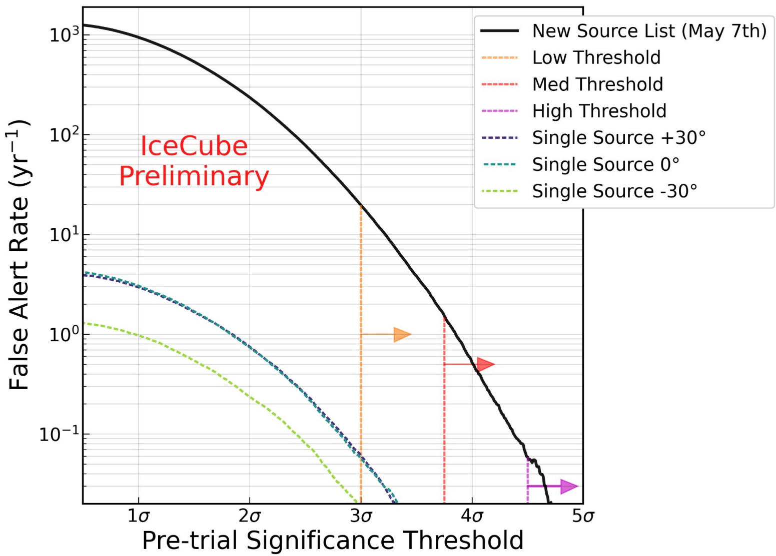




ICRC(2023)1501

Proposed public alerts distribution





NASA GCN: Multi-threshold system to provide updates on interesting activity

FlareWatch Website: Provide updates on sources without notifications

False alarm rate calculated by running simulations of 1 year of scrambled data

Proposed thresholds:

- σ_{pre} = 3.00σ, ~**20** bkg alerts **per year**
- σ_{pre} = 3.75σ, ~**1** bkg alert **per year**
- σ_{pre} = 4.50σ, ~**0.05** bkg alerts **per year**

Neutrino FlareWatch website - archival alerts page

ICECUBE NEUTRINO OBSERVATORY — REALTIME GFU ALERTS

Alerts ▾ Support

IceCube Preliminary

Realtime Gamma-Ray Follow-Up — Archival Alerts

This page provides a table of **historical events** detected by the IceCube Neutrino Observatory, featuring events from the past year where the **significance initially exceeded 3 sigma** but has since dropped below this threshold. These events highlight some of the most significant detections in IceCube's history.

For additional information about these events or the IceCube project, please visit our support page.

Search:

Source name	Right ascension (deg)	Declination (deg)	Duration (days)	Latest event time (UTC)	Signal events	Spectral index	Pre-trial p-value	Level
SIM XXXX+056	77.36	5.69	171.16	2017/11/17 21:57:54	19.99	-3.12	0.00093	⭐
SIM XXXX+056	77.36	5.69	135.11	2017/09/22 20:54:30	17.82	-3.05	0.0007	⭐
SIM XXXX+056	77.36	5.69	176.74	2017/08/28 07:04:56	21.13	-3.08	0.00087	⭐
SIM XXXX+056	77.36	5.69	127.84	2014/12/21 19:47:11	6.53	-2.14	0.000082	⭐⭐
SIM XXXX+056	77.36	5.69	43.07	2014/09/28 01:19:02	8.06	-2.25	0.0000063	⭐⭐
SIM XXXX+056	77.36	5.69	0.57	2014/08/16 13:22:25	1.35	-1.40	0.0011	⭐

Showing 1 to 6 of 6 entries

Previous 1 Next

⭐ Low Threshold (20 bkg per year)
⭐⭐ Medium Threshold (1 bkg per year)
⭐⭐⭐ High Threshold (0.05 bkg per year)

INFN PADOVA

Neutrino FlareWatch website - source detail page

ICECUBE NEUTRINO OBSERVATORY

REALTIME GFU ALERTS

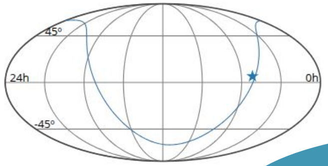
Alerts Support

IceCube Preliminary

← Go back

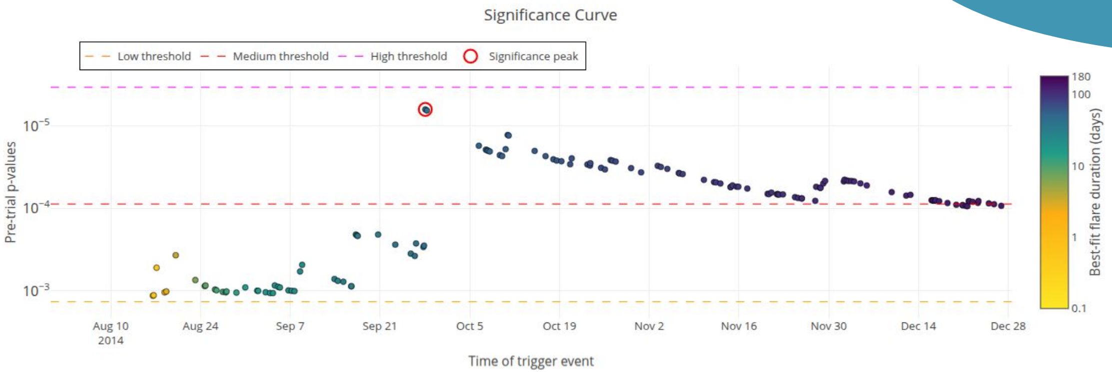
SIM XXXX+056

Name	SIM XXXX+056
Other associations	Simulated Source with 50 Day Flare Injected
Right ascension	77.36 °
Declination	5.69 °

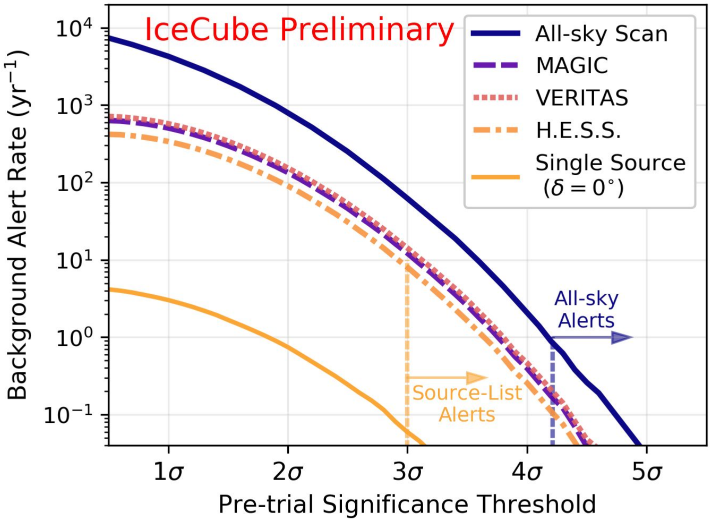


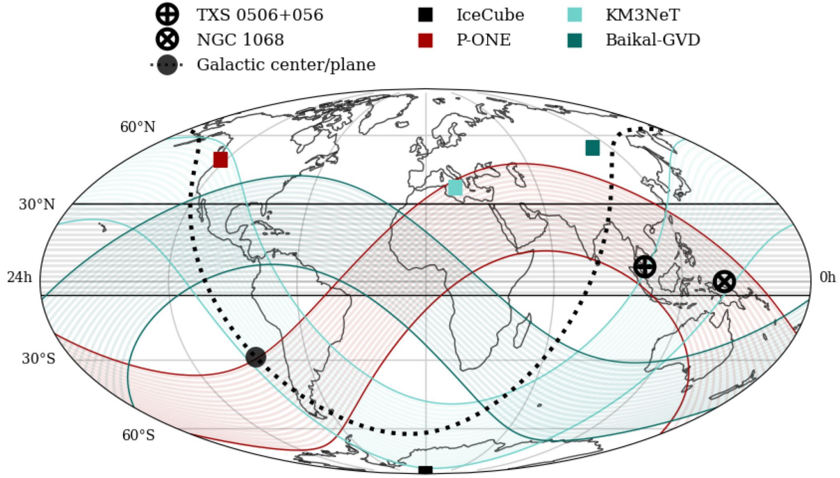
Source-list alerts live by end of 2025

Significance curve Alert history



Future work: Flare searches using multiple instruments





https://doi.org/10.3390/universe10020053

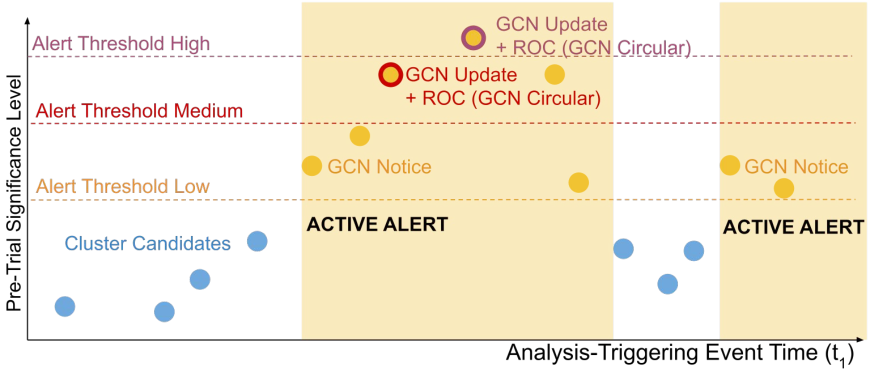
Flaring/Transient sources must be bright to be seen over atmospheric background

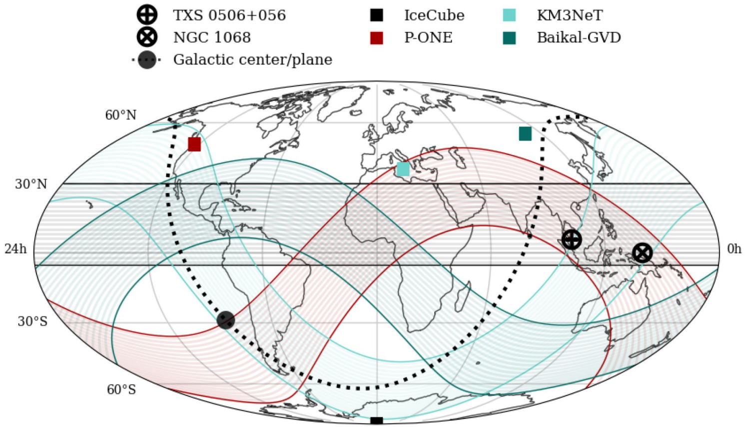
Combining with multiple instruments can increase number of signal events

More instruments also improves sensitivity to different regions of the sky

First steps: begin combining IceCube and KM3NeT data in realtime

Conclusions





P-ONE Collaboration

DOI: 10.3390/universe10020053

IceCube looks for astrophysical neutrino signatures in realtime

GFU-cluster alerts check incoming data for quick evaluation of neutrino flare candidates

Public GFU-cluster alerts by end of 2025

Neutrino FlareWatch website will provide updates on active sources

Future outlook: cluster alerts using multiple neutrino telescopes

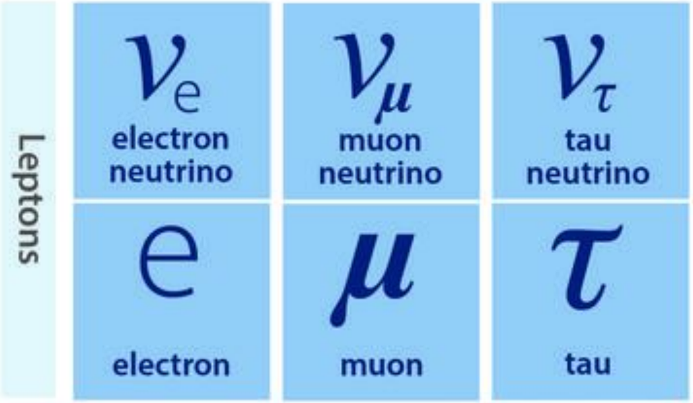
Backup

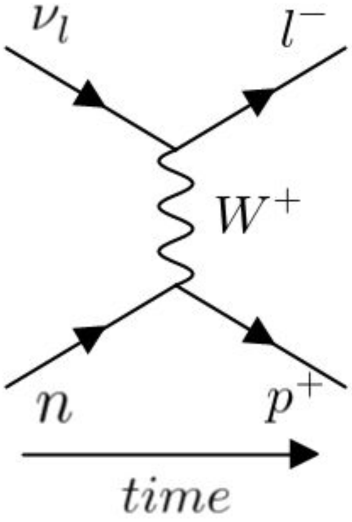
Neutrino Interactions

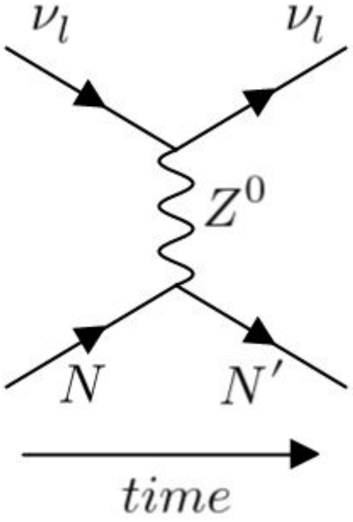
Cannot observe neutrinos directly

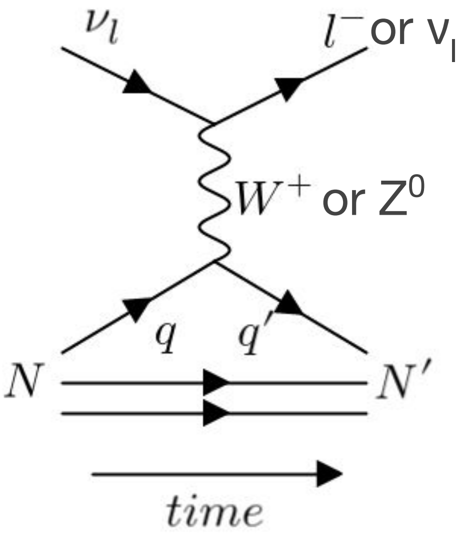
Instead observe the outgoing charged particles from weak neutrino interactions

At IceCube energies, most interactions DIS



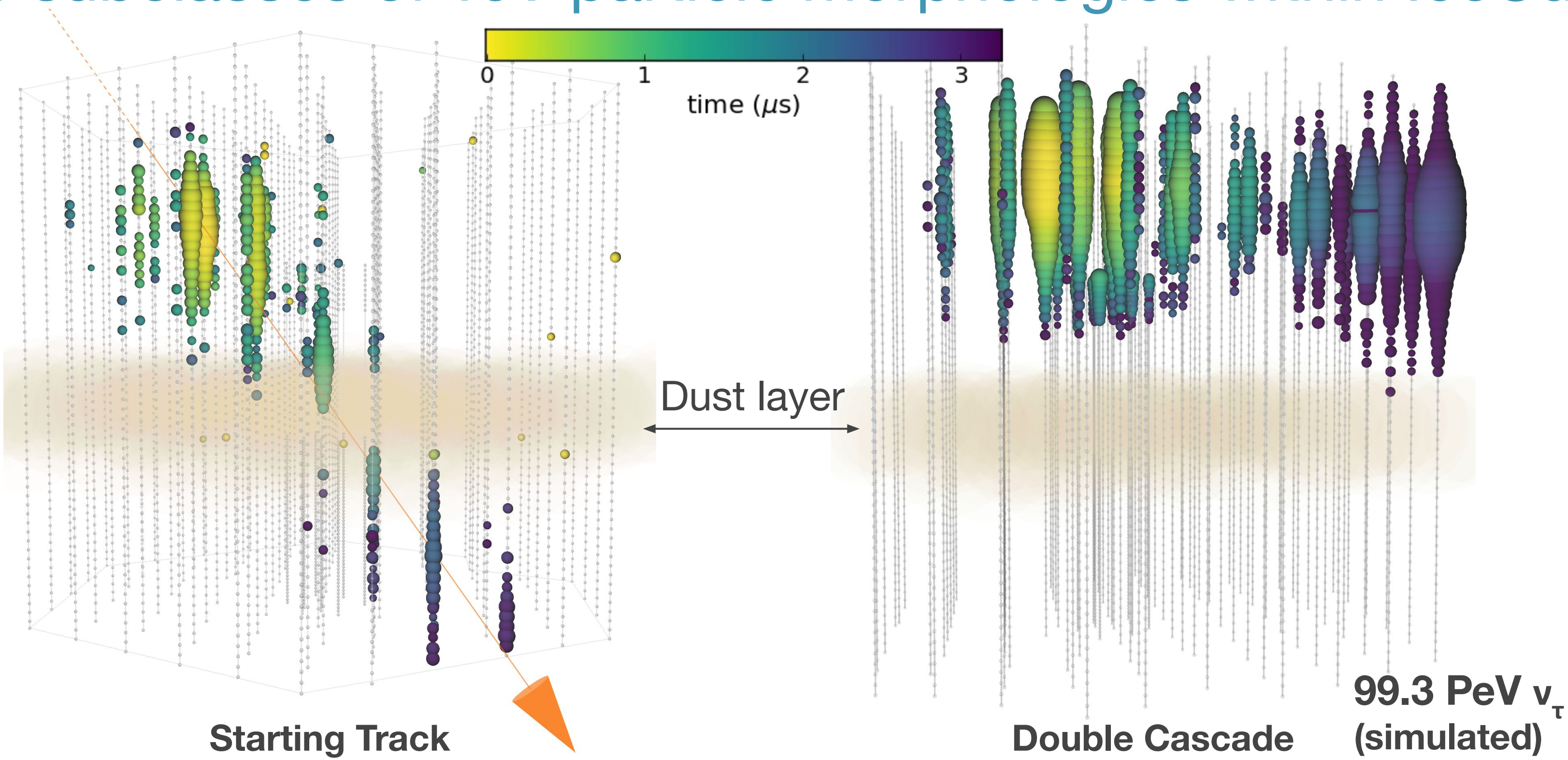






Charged Current (CC) Neutral Current (NC) Deep Inelastic Scattering (DIS)

Some subclasses of TeV particle morphologies within IceCube



Starting Track

Angular Resolution: 1.5°

Log Energy Resolution: .3 x log(E_ν)

Charged current ν_μ and ν_τ ($\tau \rightarrow \mu + \nu$'s)

Double Cascade

ν_τ ($\tau \rightarrow$ e/hadrons + ν's)

Must be high energy to see tau track

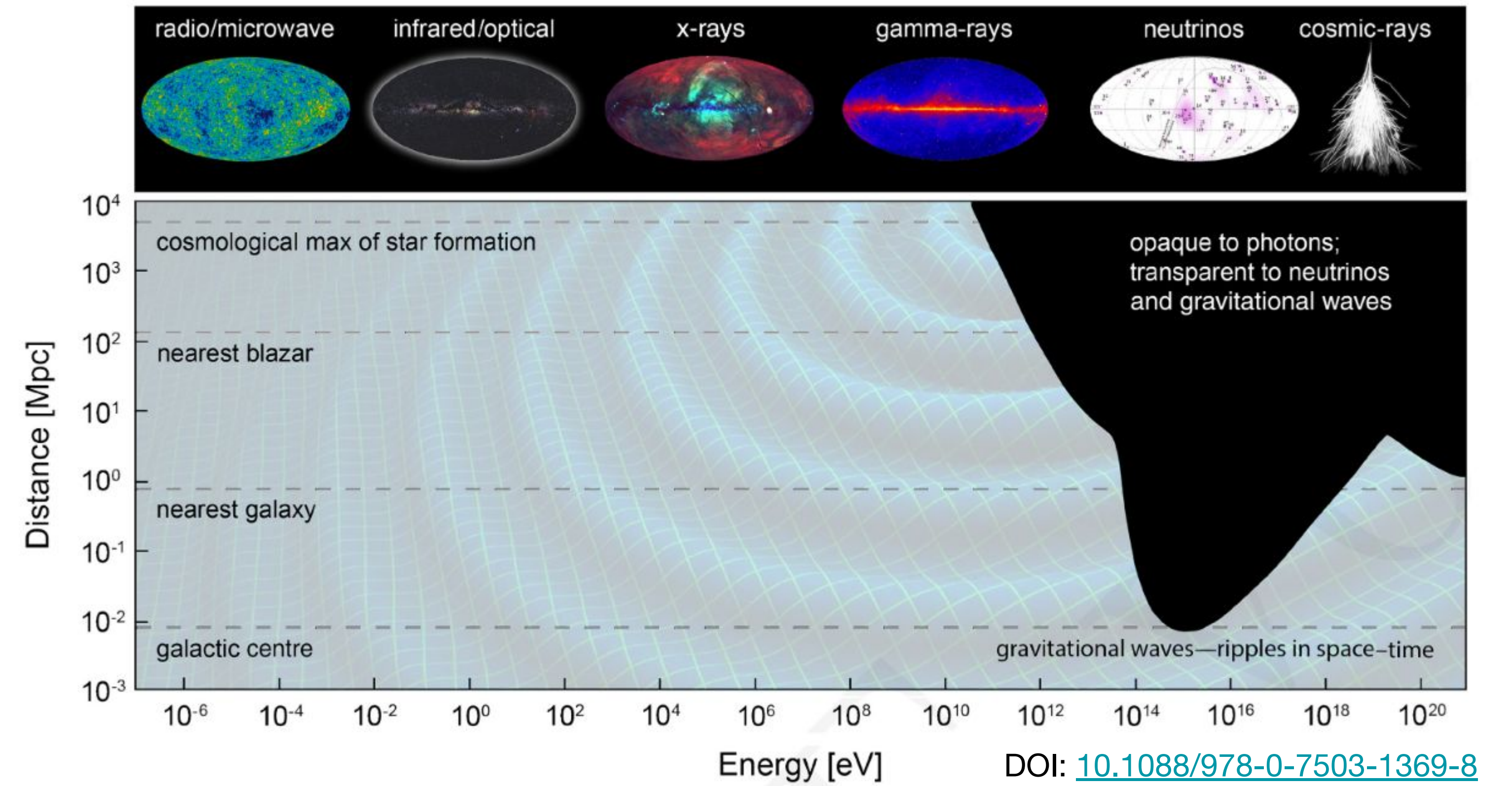
At lower energies look for double pulse structure in PMT waveform

INFN PADOVA

Limitations of gamma-ray astronomy

Gamma rays attenuated by CMB and other background light in the TeV energy ranges

Gamma rays also produced by cosmic ray electron acceleration (**leptonic acceleration**)



DOI: 10.1088/978-0-7503-1369-8

Time-dependent Likelihood Approach

Fitted parameters

Uniform Time PDF

Azimuthal term for short time-windows

$$\mathcal{L}(n_s, \gamma, t_0, t_1) = \prod_{i}^{N\in[t_0,t_1]} \left(\frac{n_s}{N}\mathcal{S}(|\vec{x}_i - \vec{x}_s|, \sigma_i, E_i, \gamma) + (1 - \frac{n_s}{N})\mathcal{B}(\theta_i, \phi_i, E_i) \right)$$

S/B PDF

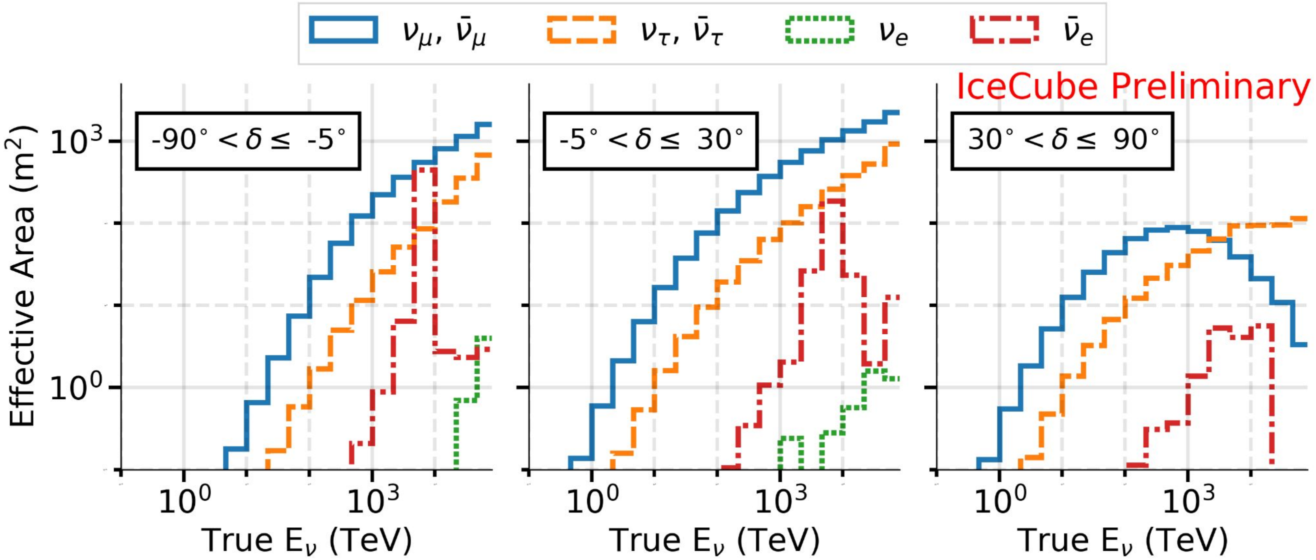
$$\Lambda' = 2\log\left[\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma}, \hat{t}_0, t_1)}{\mathcal{L}(n_s = 0, \hat{t}_0, t_1)}\right] = 2\sum_{i}^{N\in[t_0,t_1]} \log\left[1 + \frac{n_s}{N}(w_i(\hat{\gamma}) - 1)\right]$$

Final Test Statistic (TS)

Penalty factor for small time windows

$$\Lambda = 2\log\left[\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma}, \hat{t}_0, t_1)}{\mathcal{L}(n_s = 0, \hat{t}_0, t_1)}\frac{\mathcal{U}(\hat{t}_0, t_1)}{\mathcal{U}(t_1 - T_{\max}, t_1)}\right] = \Lambda' + 2\log\left[\frac{\mathcal{U}(\hat{t}_0, t_1)}{\mathcal{U}(t_1 - T_{\max}, t_1)}\right]$$

GFU Event Sample Properties

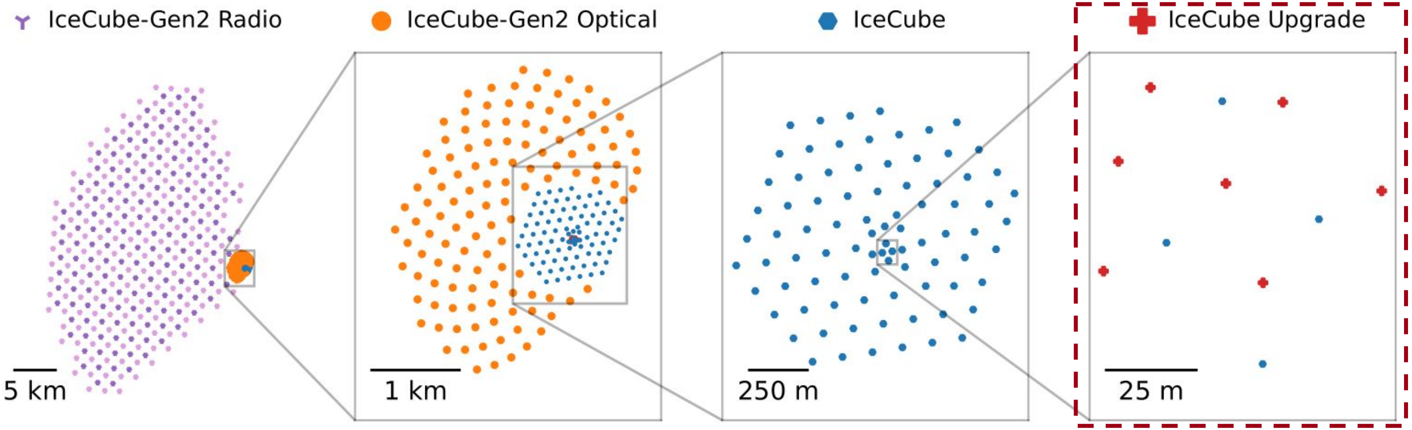


Gamma-ray Follow-Up (GFU) event sample covers full-sky

Harsh energy requirements in southern sky to remove cosmic-ray background

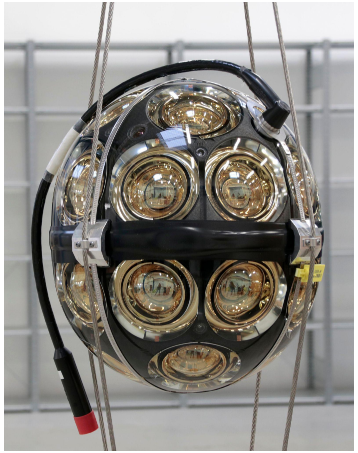
Earth absorption effect seen in northern sky for high energy events

The next generation of IceCube: the IceCube Upgrade

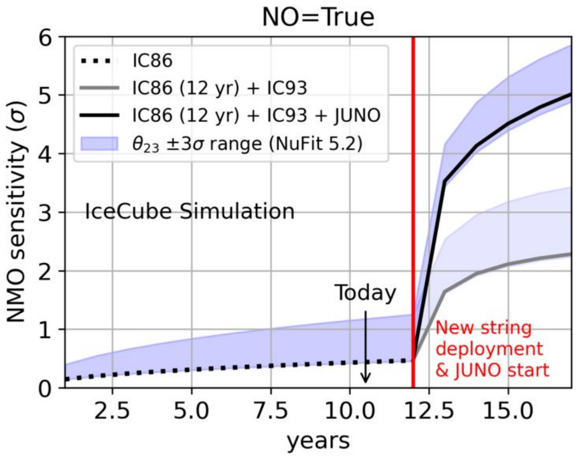


IceCube Upgrade (deployment 2025/26)
- Denser instrumentation
- Lower minimum energy (~1 GeV)

Goals:
- R&D for IceCube-Gen2
- Calibration of detector systematics
- Oscillation physics



Multi-PMT DOM
PoS(ICRC2023)1183



Neutrino Mass Ordering
PoS(ICRC2023)1036

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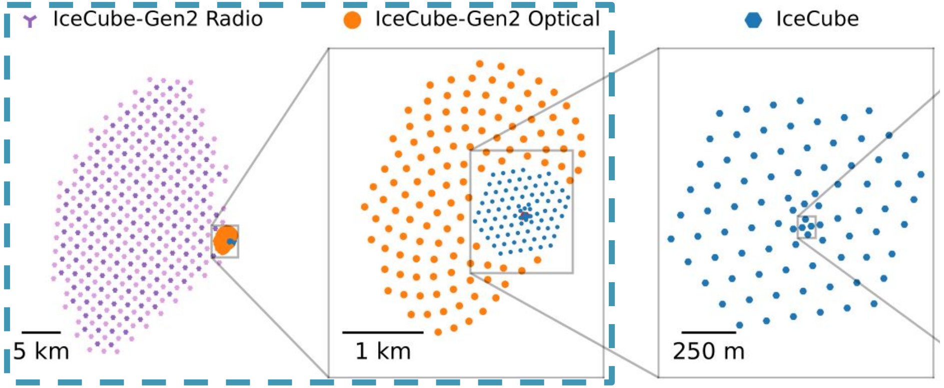
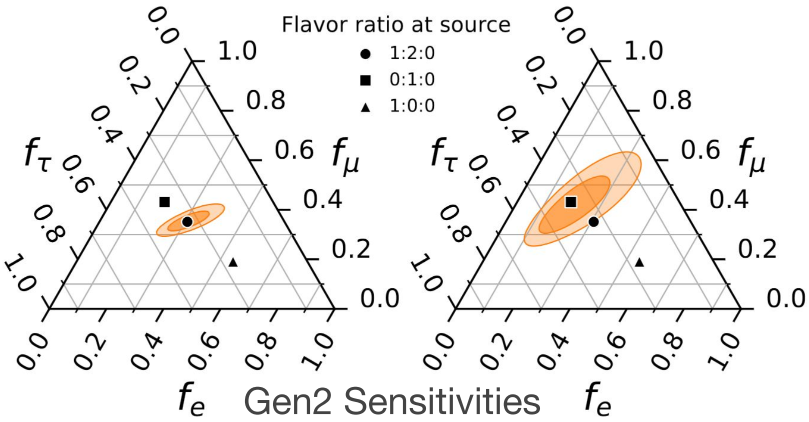
The next generation of IceCube: IceCube-Gen2

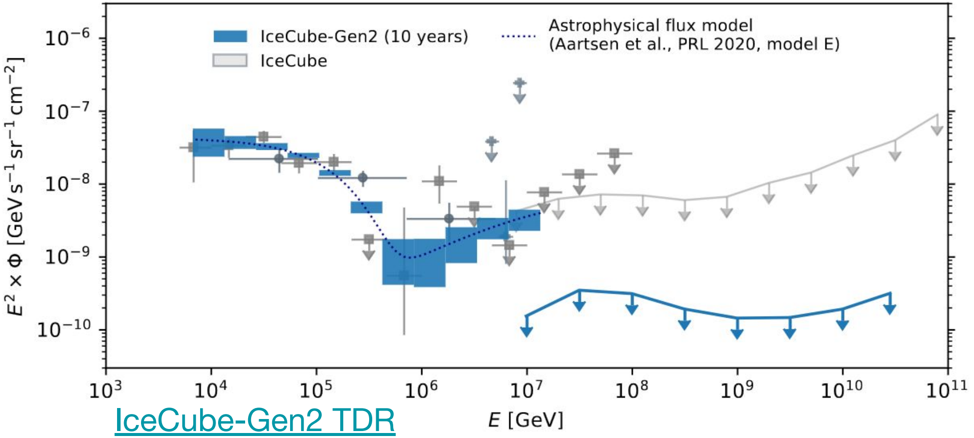




Increase effective volume to 8 km^3

Increase upper energy threshold

Improve sensitivity to astrophysical neutrino sources by factor of ~5



IceCube-Gen2 TDR