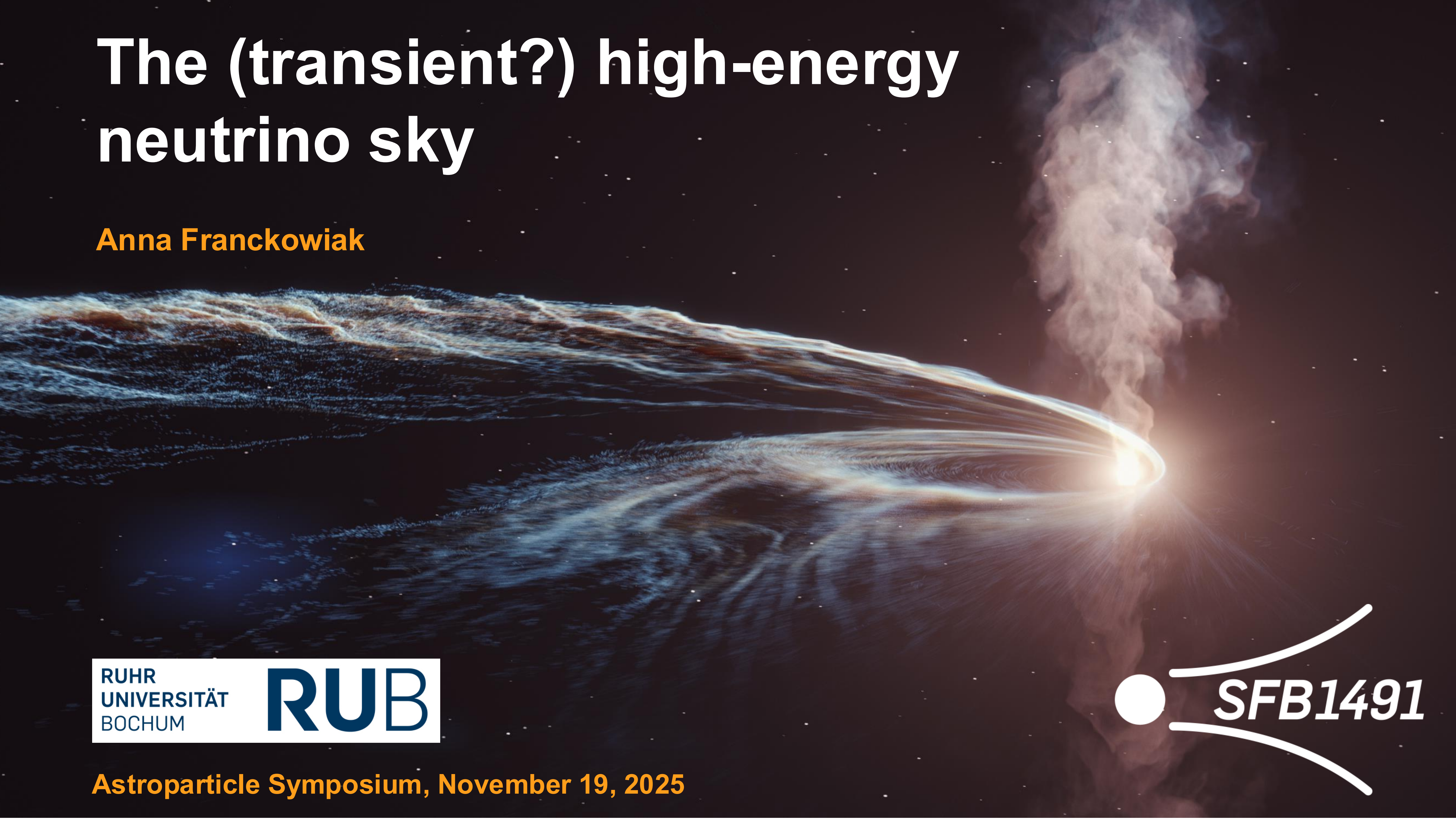


The (transient?) high-energy neutrino sky

Anna Franckowiak

RUHR UNIVERSITÄT BOCHUM RUB

SFB1491

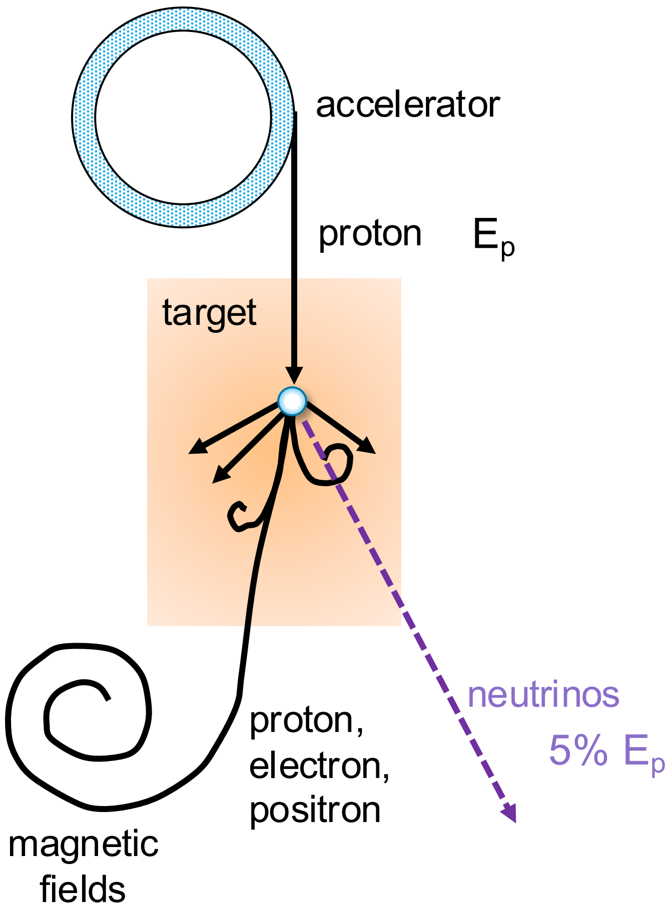
Astroparticle Symposium, November 19, 2025

This Talk

- Why high-energy neutrinos?
- First results
- Realtime search for transient / variable sources
- Future improvements

Why high-energy Neutrinos?

High-energy neutrino sources



Cosmic-ray “beam dumps” produce TeV-PeV neutrinos

Two ingredients:
- Proton acceleration
- Target for interaction

Neutrino Production Processes

Cosmic ray

$$\left.\begin{matrix} pp \\ p\gamma \end{matrix}\right. \rightarrow \begin{cases} \ldots + \pi^+ \\ \ldots + \pi^- \\ \ldots + \pi^0 \end{cases}$$

target

Neutrino Production Processes

Cosmic ray

target

$$pp \atop p\gamma \quad \rightarrow \quad \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \ldots + \pi^- \\ \ldots + \pi^0 \end{cases}$$

Neutrino Production Processes

Cosmic ray

target

$$pp \atop p\gamma \quad \rightarrow \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \\ \ldots + \pi^0 \end{cases}$$

Neutrino Production Processes

$$\begin{matrix} \text{Cosmic ray} & & \\ pp & & \\ & \rightarrow & \\ p\gamma & & \\ \text{target} & & \end{matrix} \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \ldots + \pi^0 \end{cases}$$

Neutrino Production Processes

$$\begin{array}{r} \text{Cosmic ray} \\ pp \\ p\gamma \\ \text{target} \end{array} \rightarrow \left[\begin{array}{l} \ldots + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu} \\ \ldots + \pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu} \\ \ldots + \pi^{0} \rightarrow \gamma\gamma \end{array} \right.$$

Neutrino Production Processes

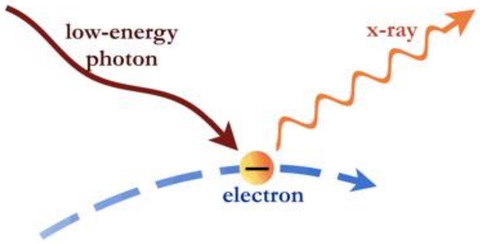
Cosmic ray

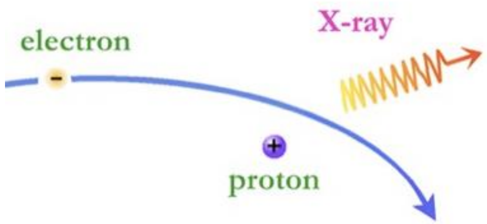
$$pp \atop p\gamma$$

target

$$\rightarrow \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \ldots + \pi^0 \rightarrow \gamma\gamma \end{cases}$$

Gamma-rays are not exclusively produced in hadronic processes





RUB

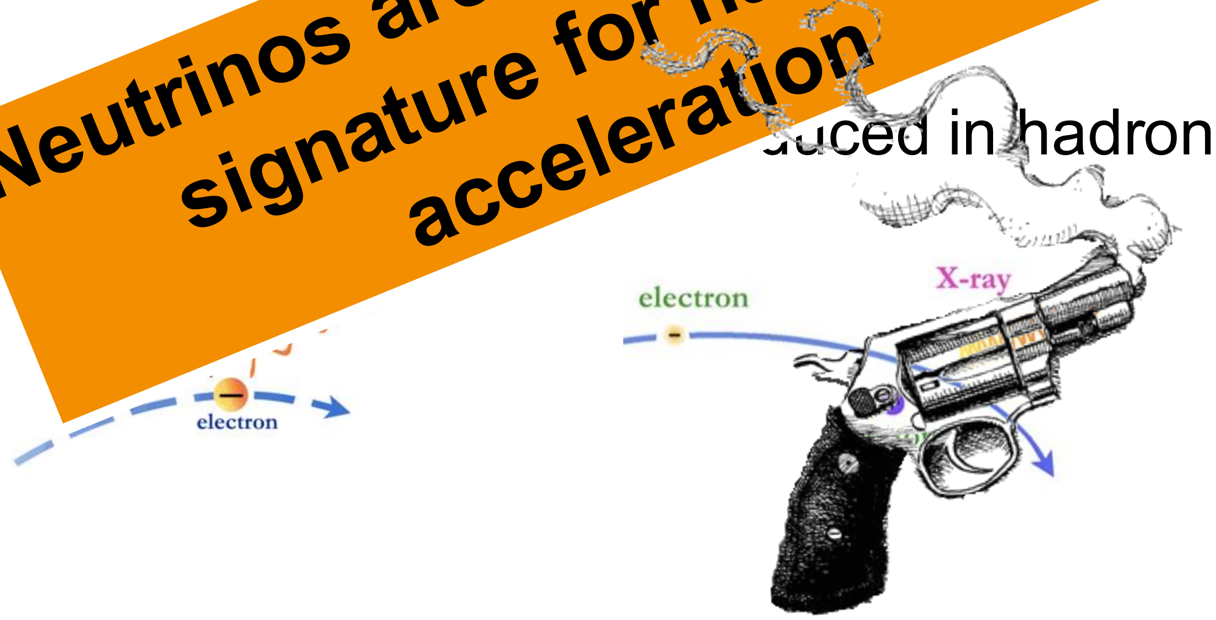
Neutrino Production Processes

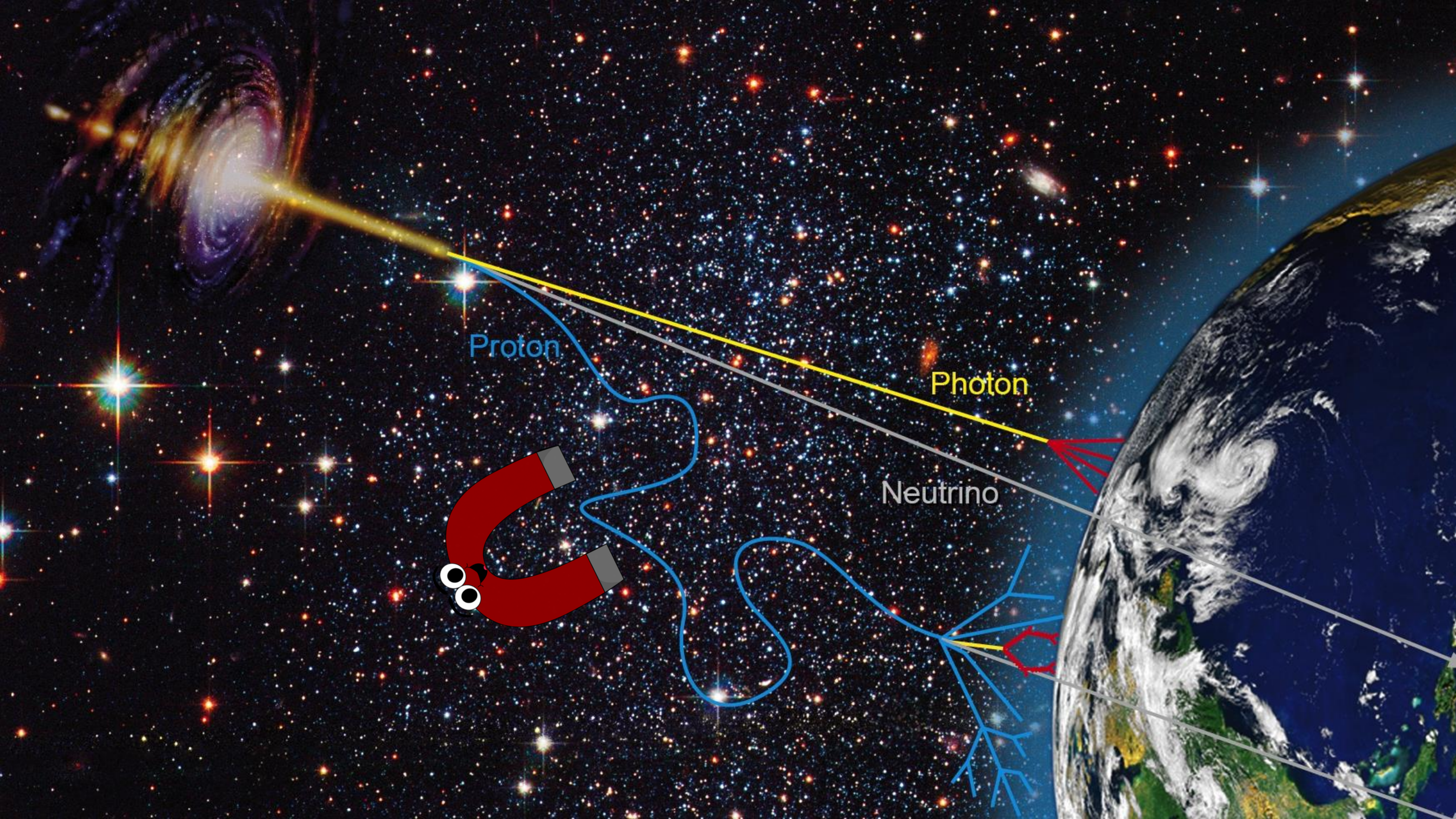
Cosmic ray

$$pp \quad p\gamma \quad \text{target} \rightarrow \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \quad \bar{\nu}_\mu \\ \ldots + \pi^0 \rightarrow \gamma\gamma \end{cases}$$

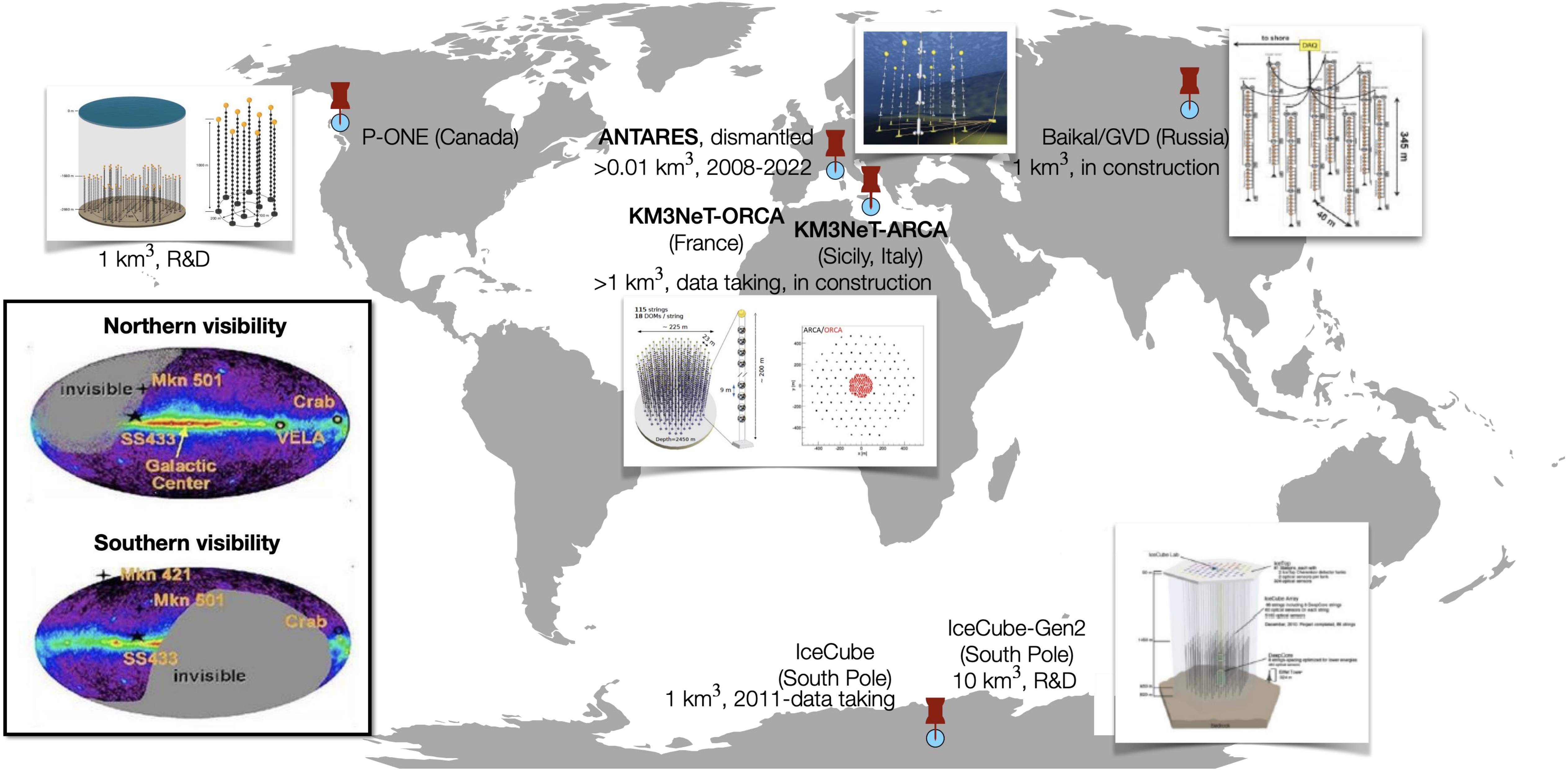
Neutrinos are the smoking gun signature for hadronic acceleration

Gamma duced in hadronic processes

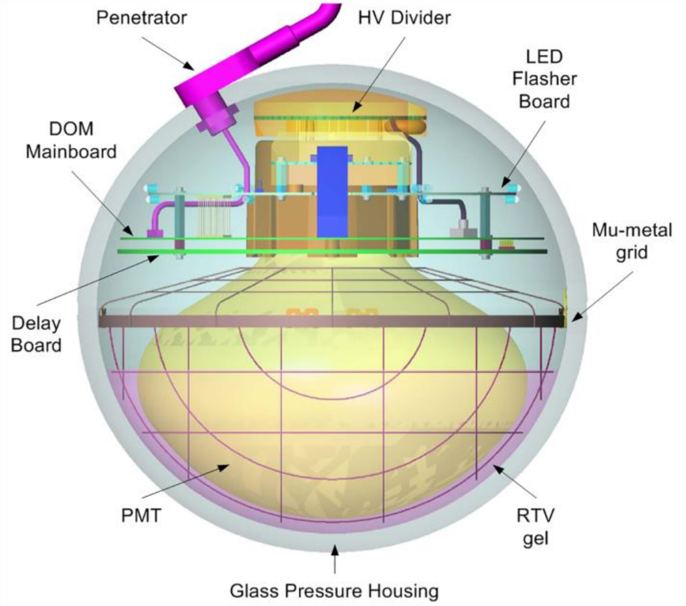


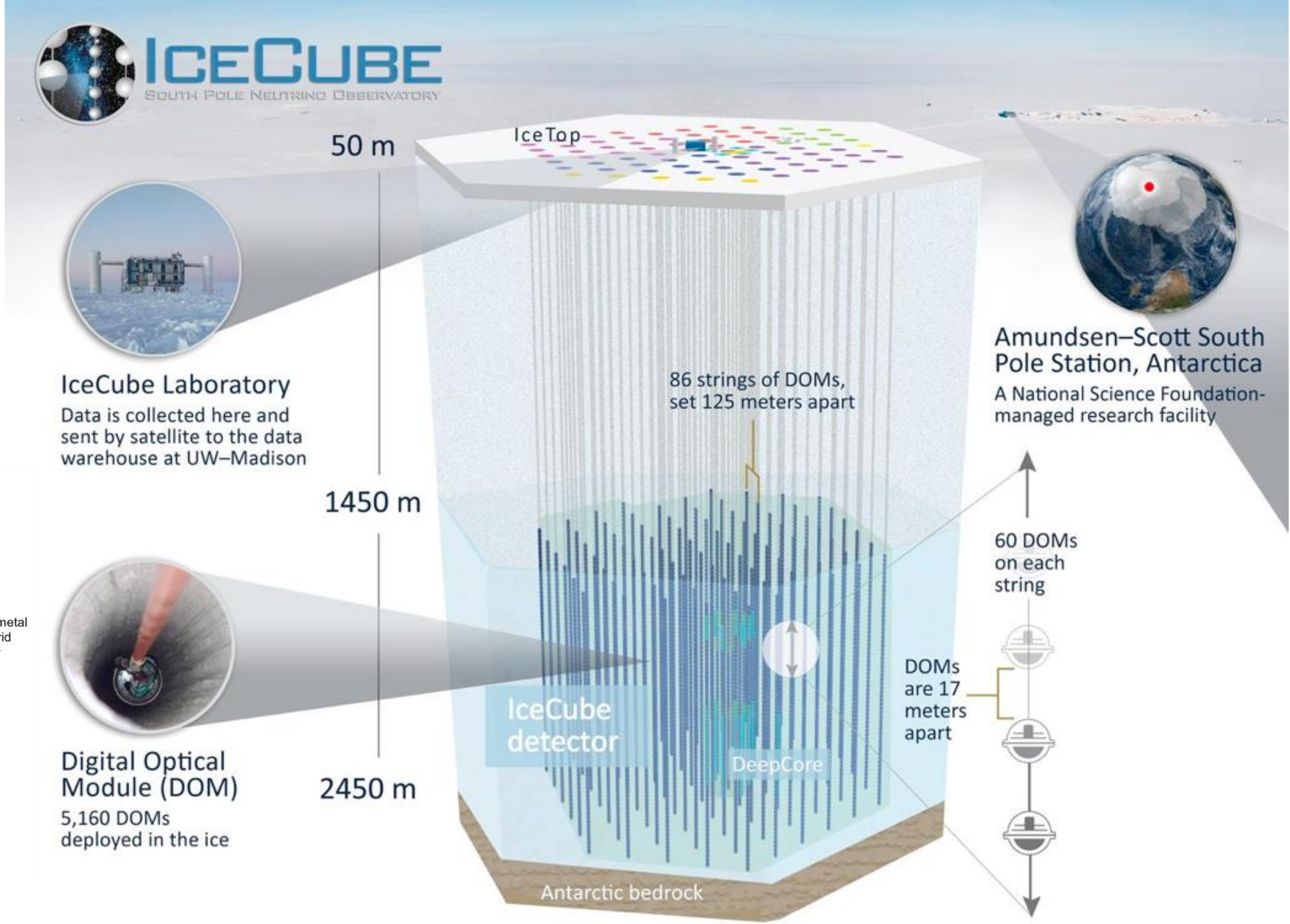

Proton
Photon
Neutrino

How can we detect those neutrinos?



1 km^3, R&D
P-ONE (Canada)
ANTARES, dismantled
>0.01 km^3, 2008-2022
Baikal/GVD (Russia)
1 km^3, in construction
to shore
DAQ
345 m
40 m
KM3NeT-ORCA
(France)
KM3NeT-ARCA
(Sicily, Italy)
>1 km^3, data taking, in construction
115 strings
18 DOMs / string
~ 225 m
23 m
9 m
~ 200 m
Depth=2450 m
ARCA/ORCA
Northern visibility
invisible
Mkn 501
Crab
SS433
VELA
Galactic Center
Southern visibility
Mkn 421
Mkn 501
Crab
SS433
invisible
IceCube
(South Pole)
1 km^3, 2011-data taking
IceCube-Gen2
(South Pole)
10 km^3, R&D


Penetrator
HV Divider
LED Flasher Board
DOM Mainboard
Mu-metal grid
Delay Board
PMT
RTV gel
Glass Pressure Housing

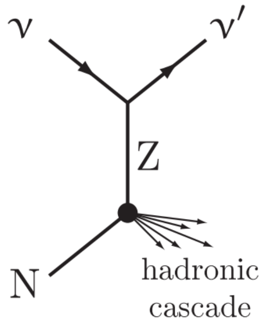

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

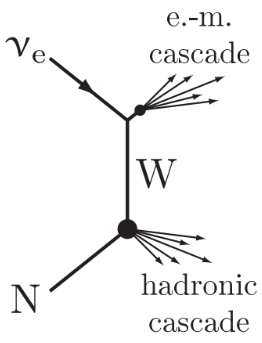
RUB

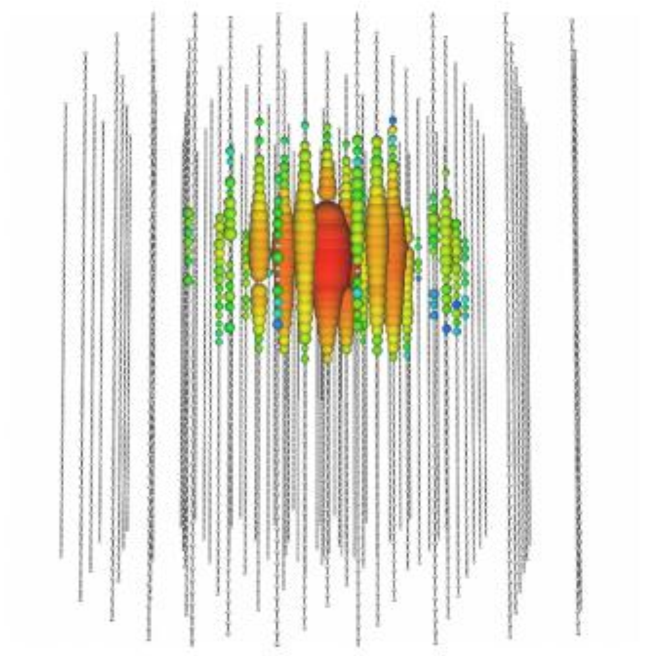
Event Signatures

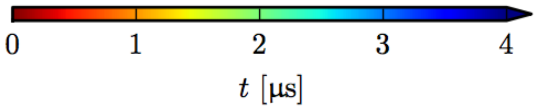
"shower" events: neutrinos interacting inside the detector

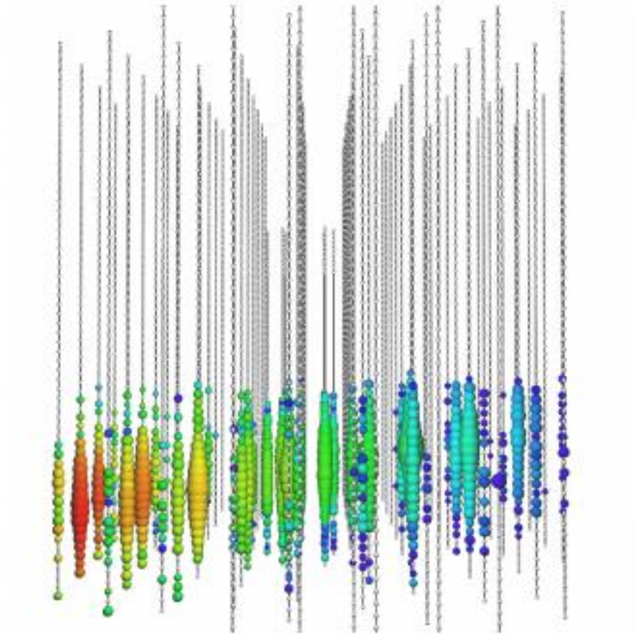
"track" events: muon neutrinos filtered by the Earth

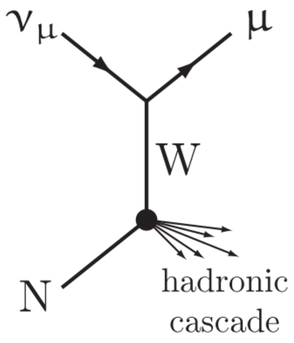








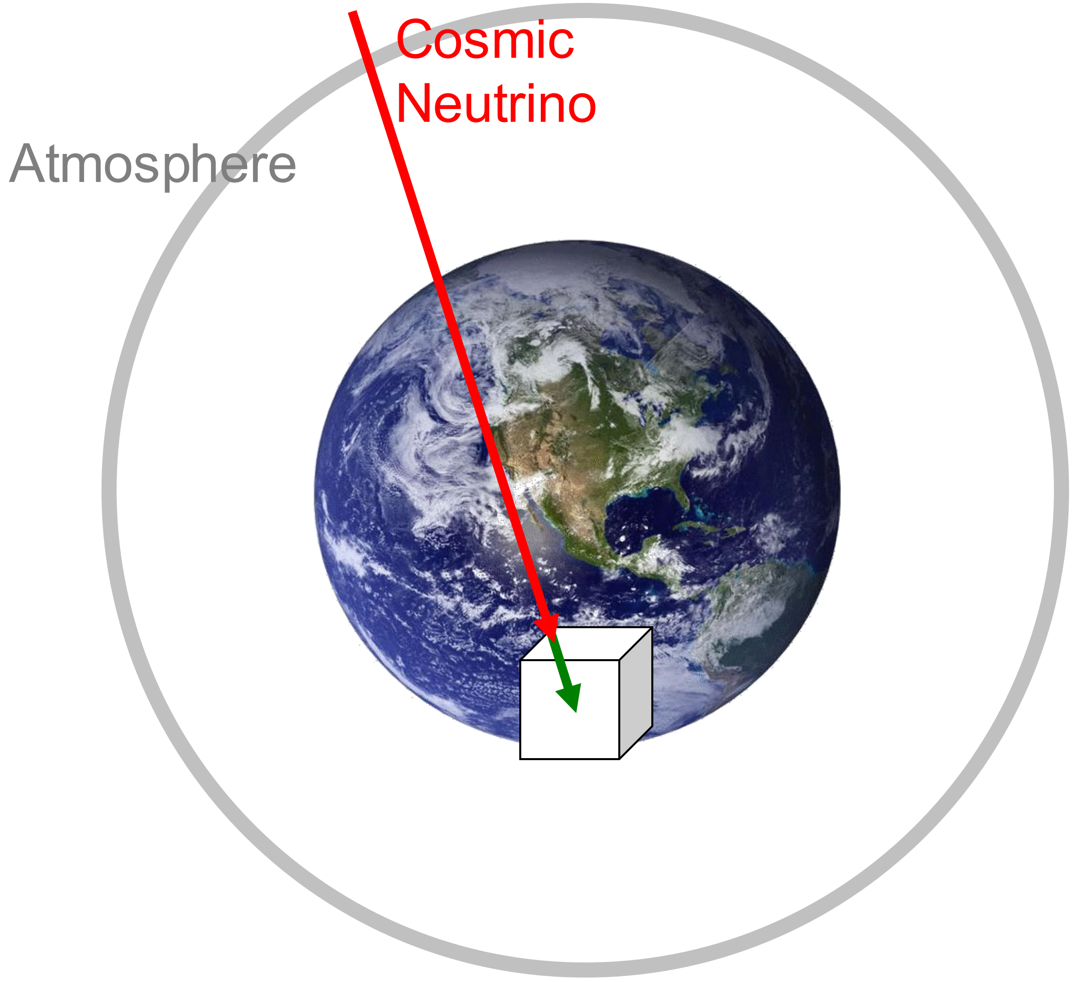




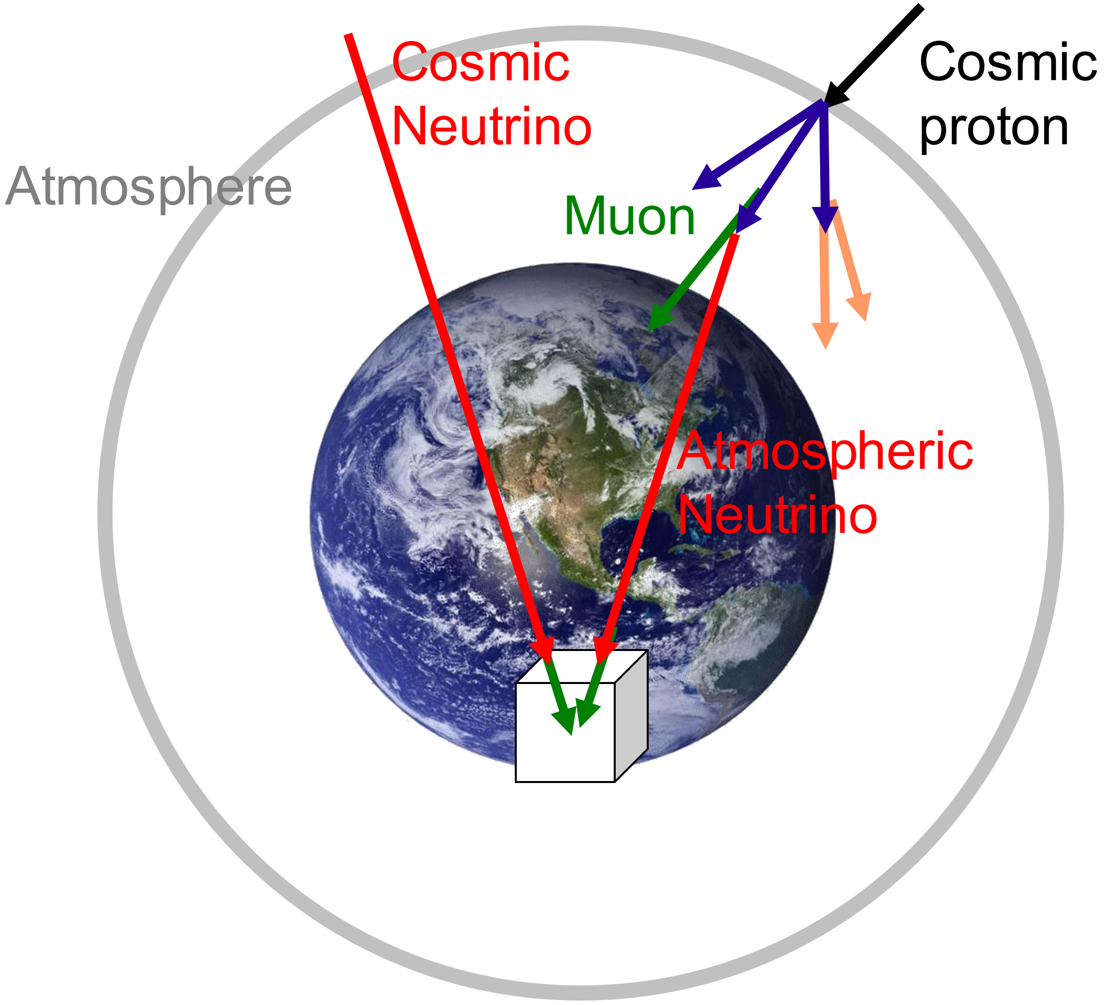
total energy measurement to 10%, all flavors, all sky

astronomy: angular resolution superior (0.2º~0.4º)

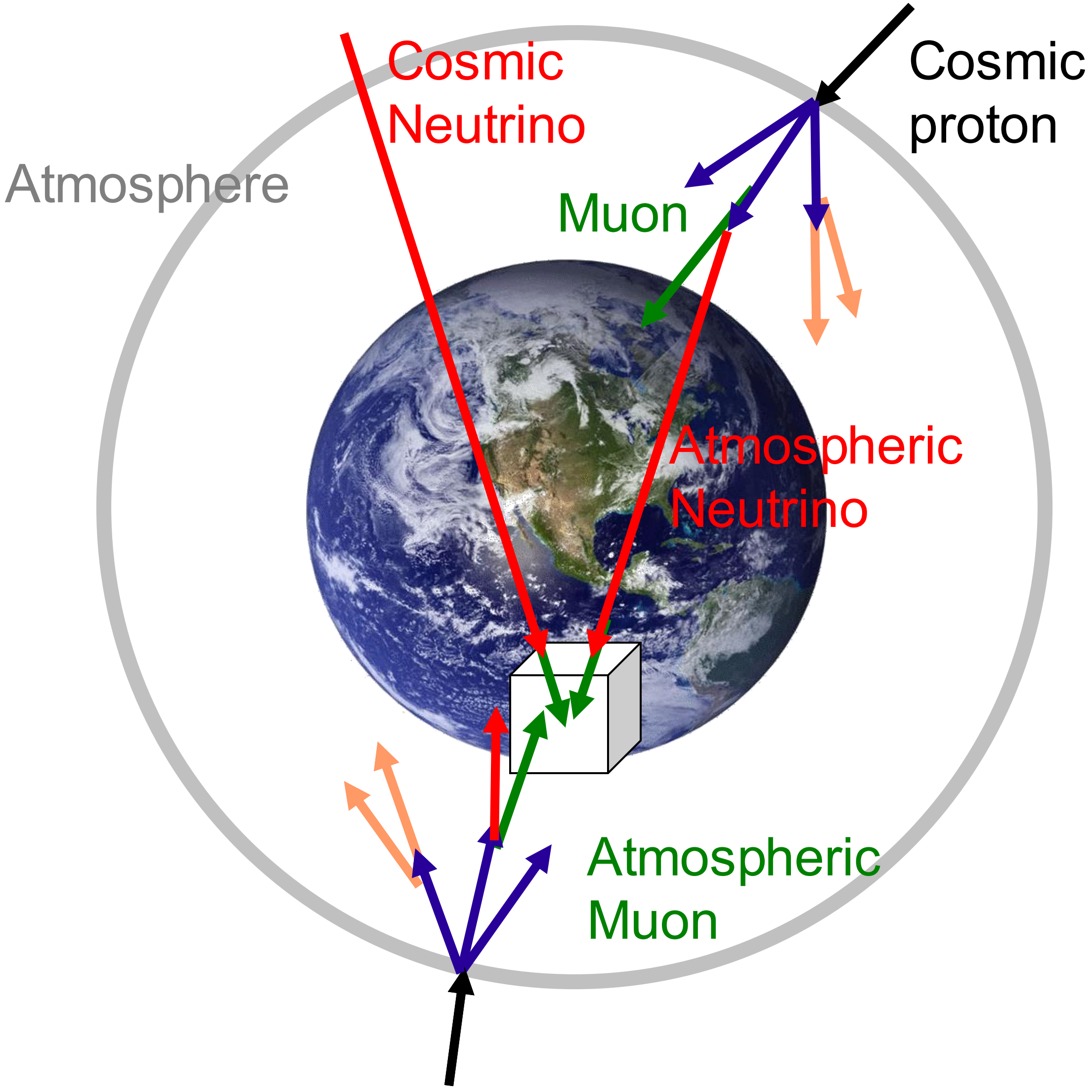
Background in Search for Cosmic Neutrinos



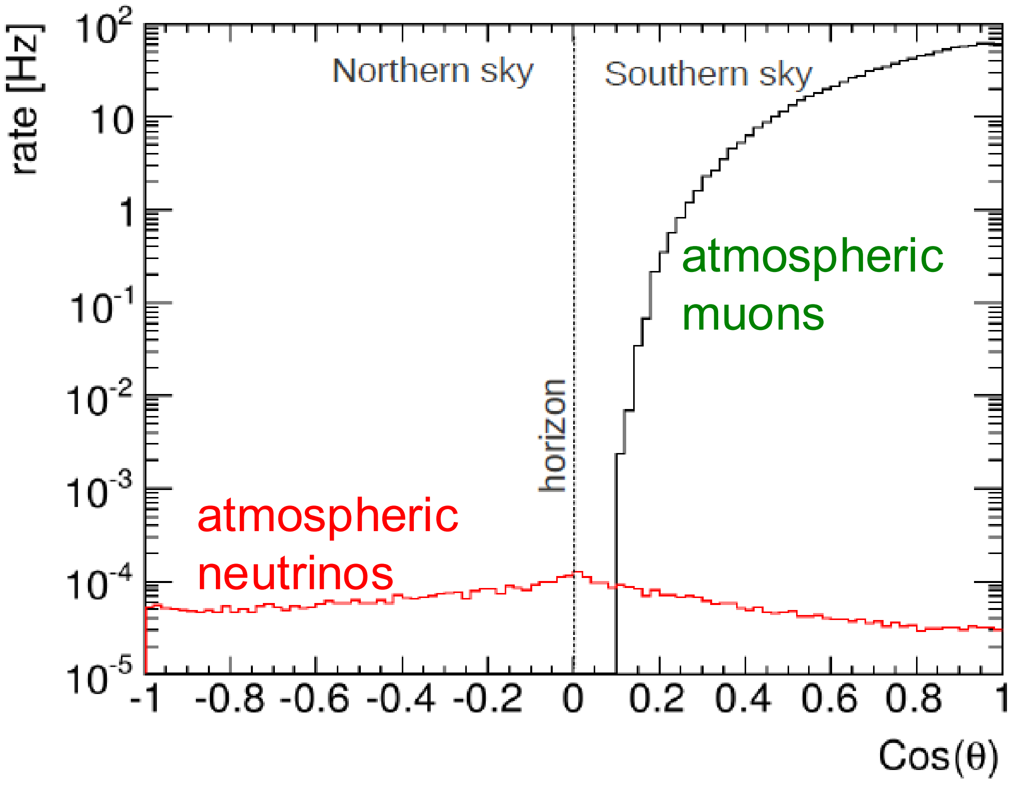
Background in Search for Cosmic Neutrinos

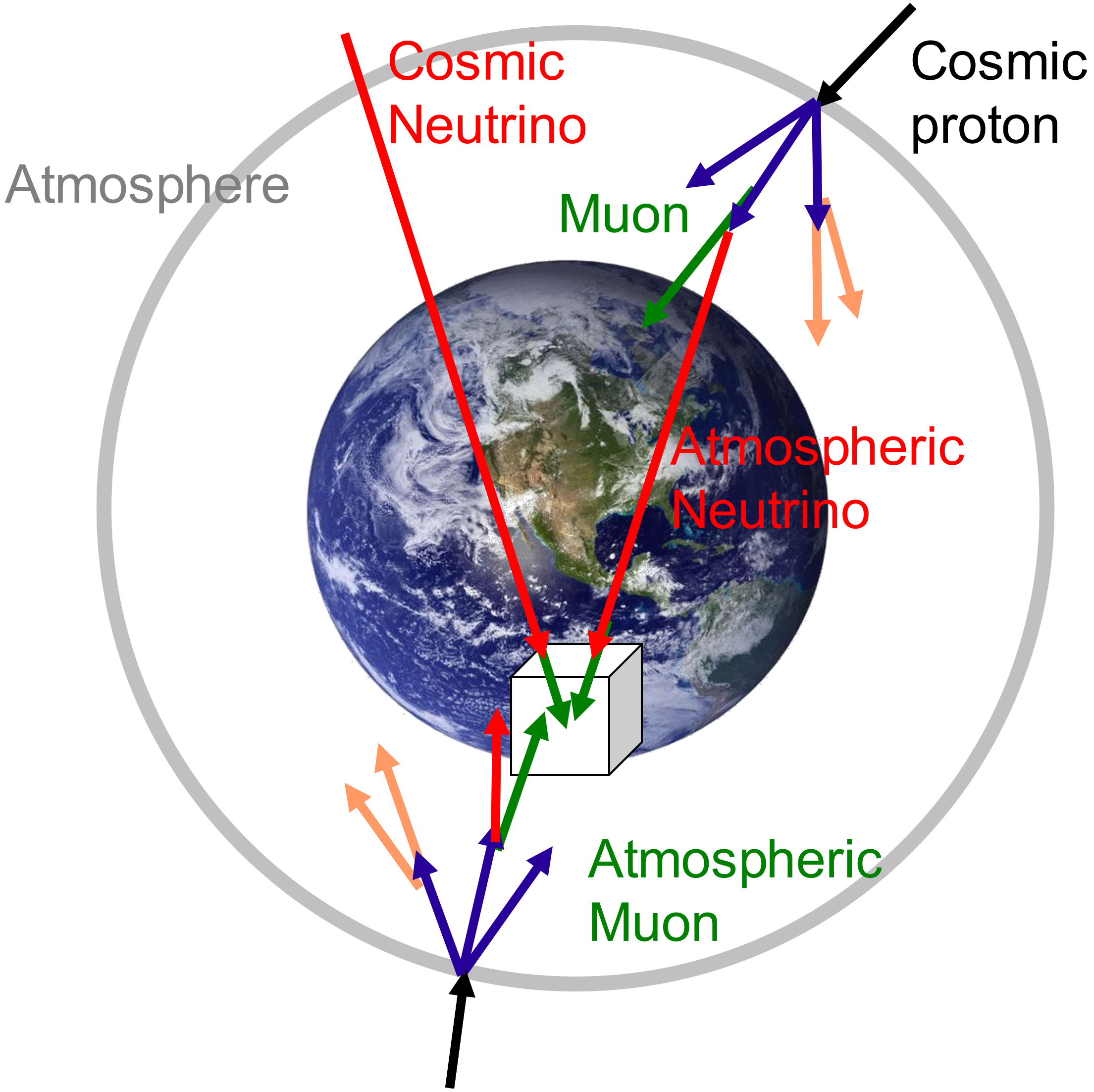


Background in Search for Cosmic Neutrinos



Background in Search for Cosmic Neutrinos



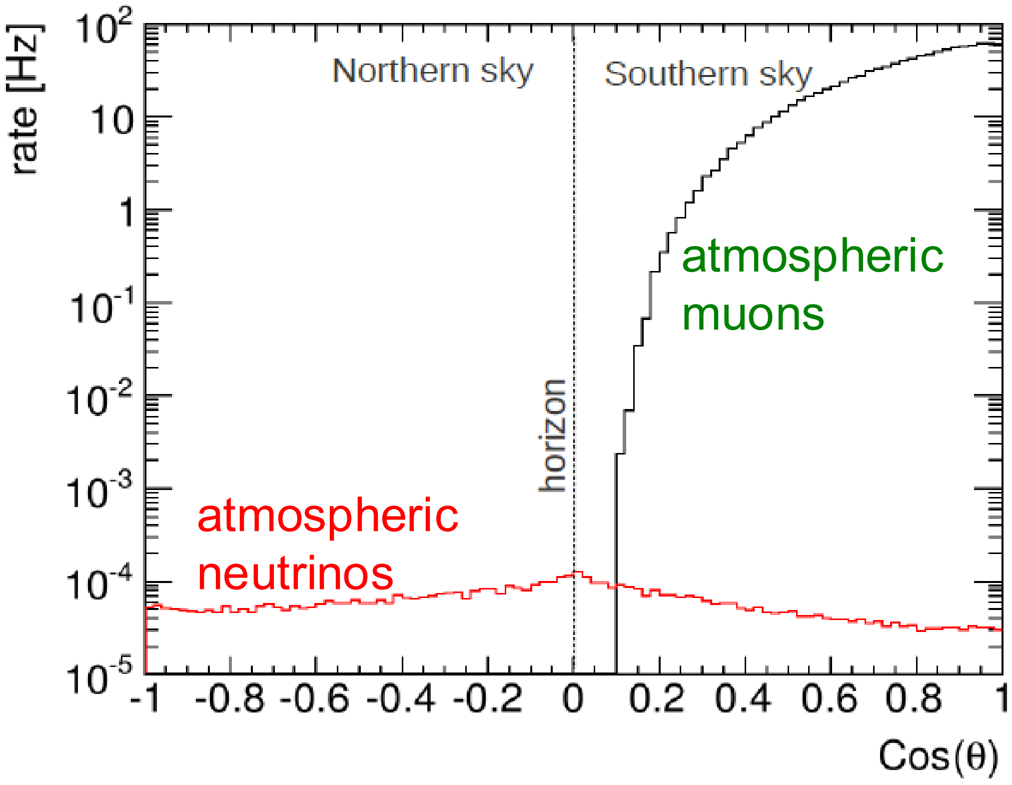


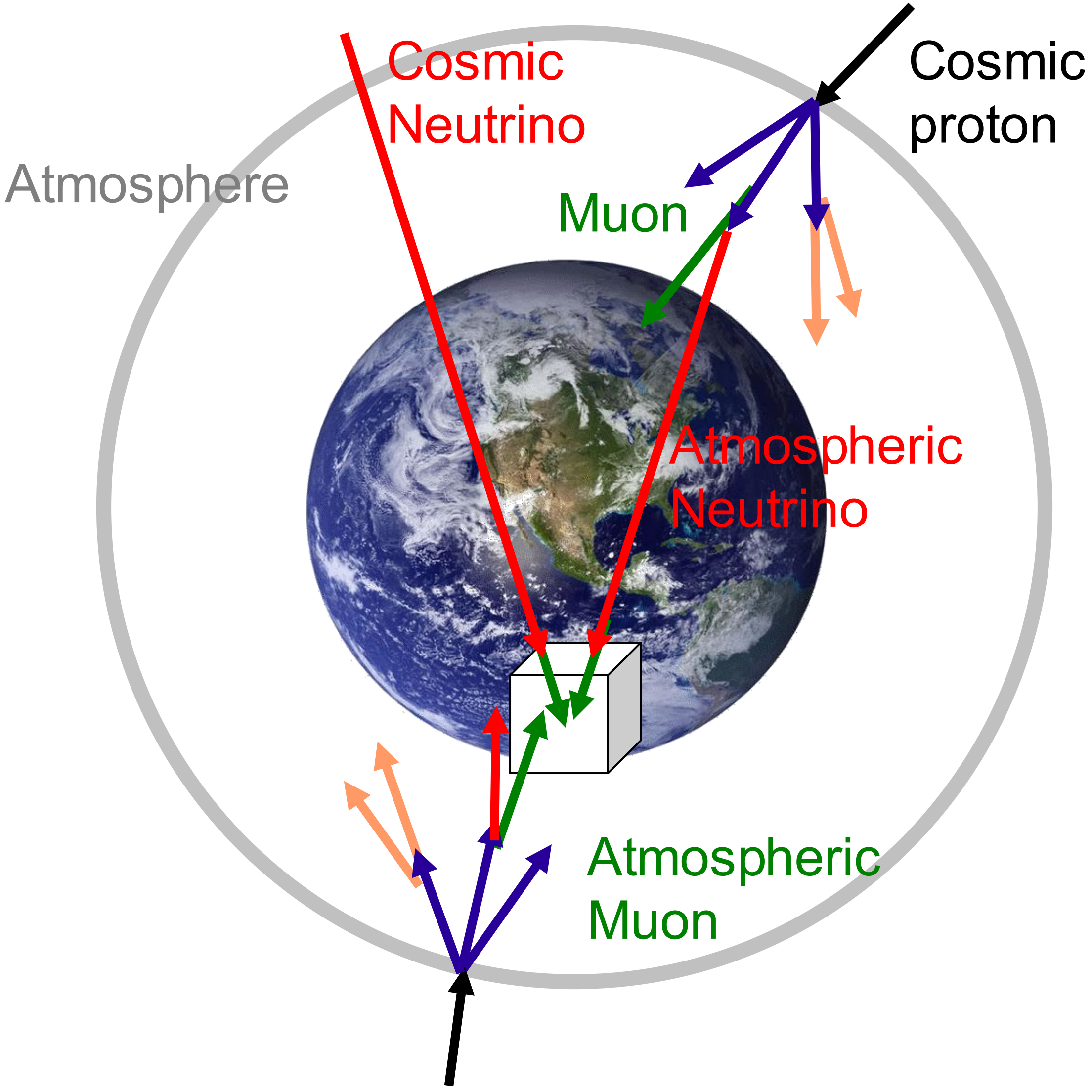
RUB

Background in Search for Cosmic Neutrinos

muons detected per year:

- atmospheric μ ~ 10^{11} (3000/sec)
- atmospheric $\nu \rightarrow \mu$ > 10^5 (1/5min)
- cosmic $\nu \rightarrow \mu$ > 120 / year



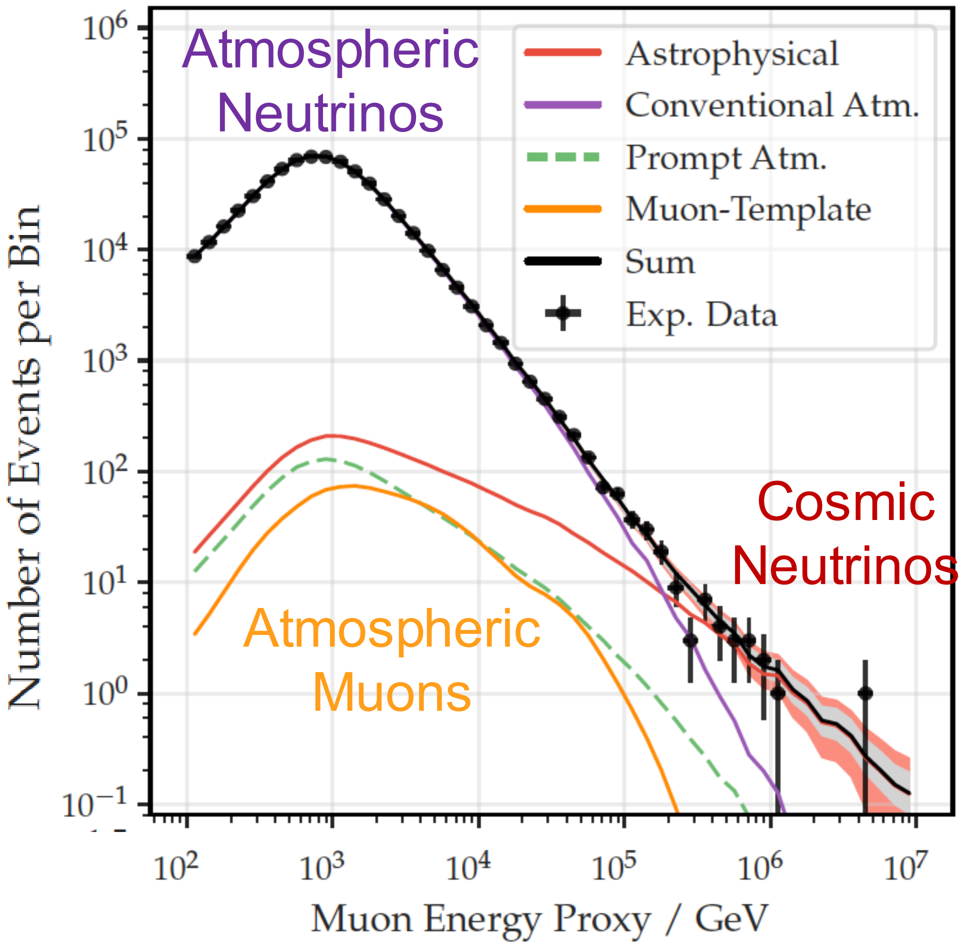


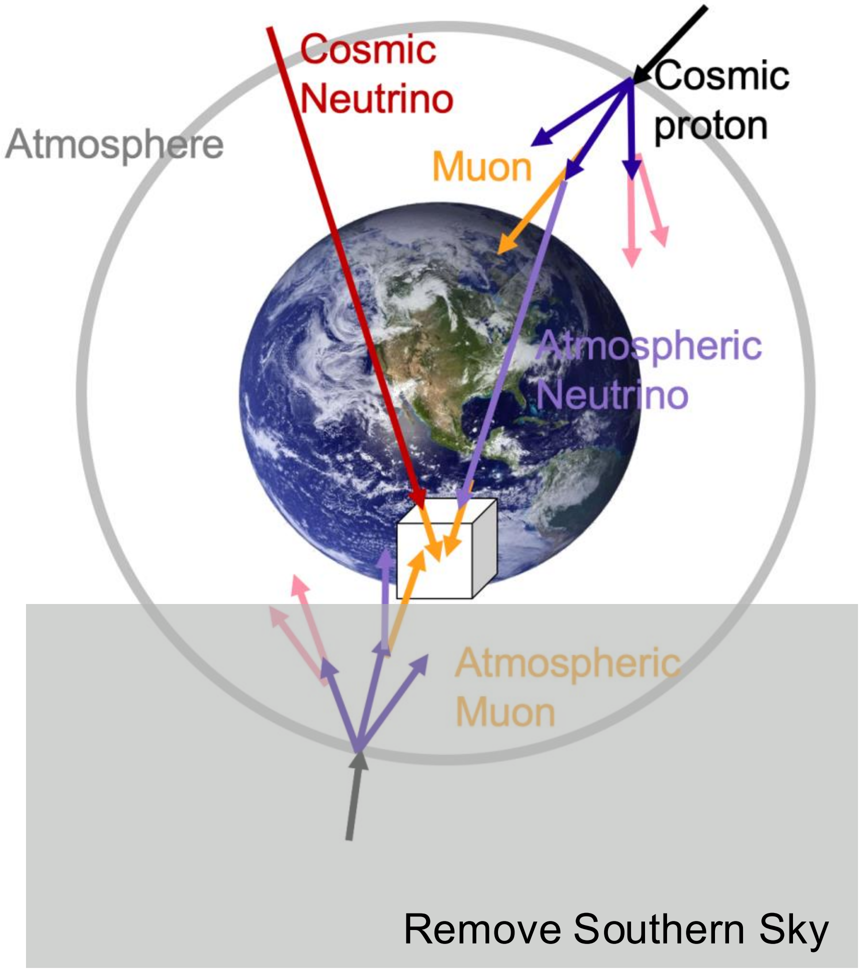
RUB

Key Discoveries

RUB

Diffuse Flux discovered!

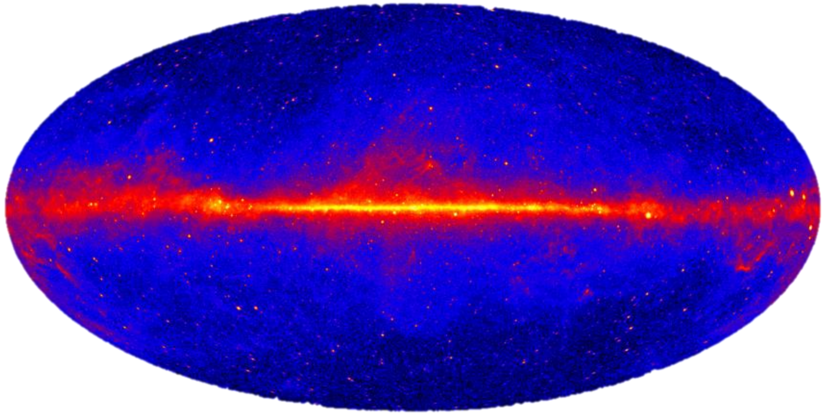




IceCube Coll. ApJ 928 (2022) 50

Galactic Plane

GeV gamma-ray sky by Fermi-LAT

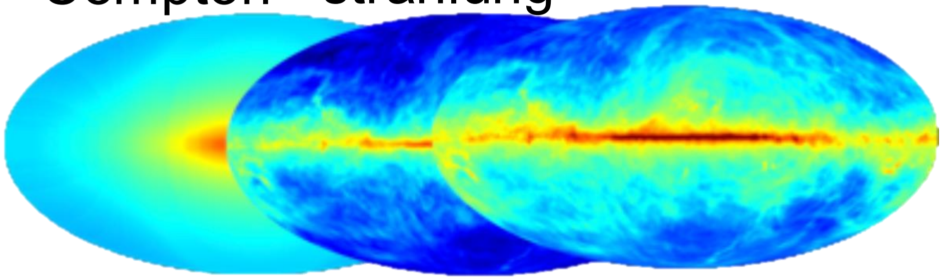


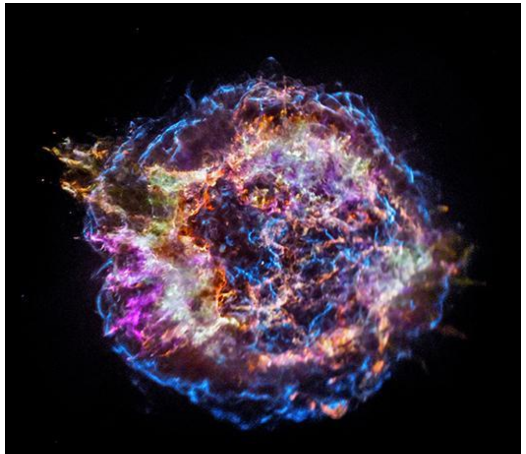
Cosmic rays propagate through the Galaxy and interact with photons and gas

Inverse Compton

Brems-strahlung

π^0 decay

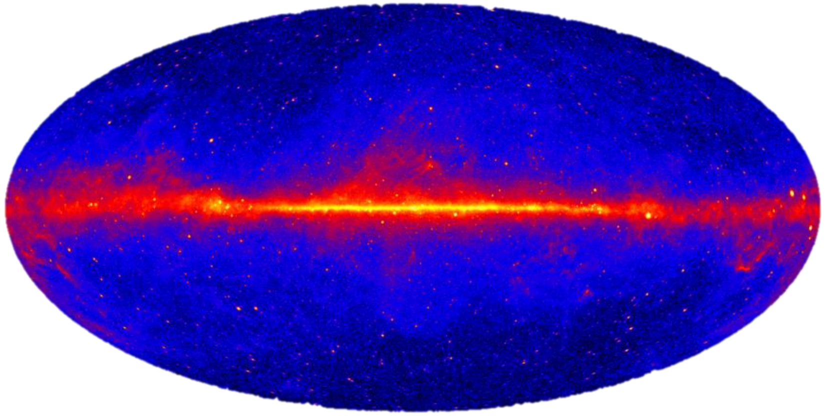




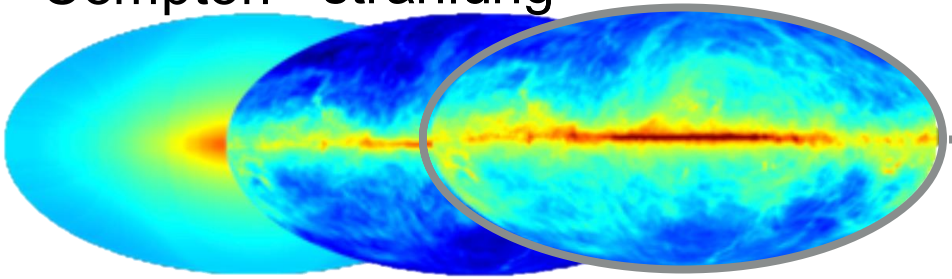
Supernova Remnants

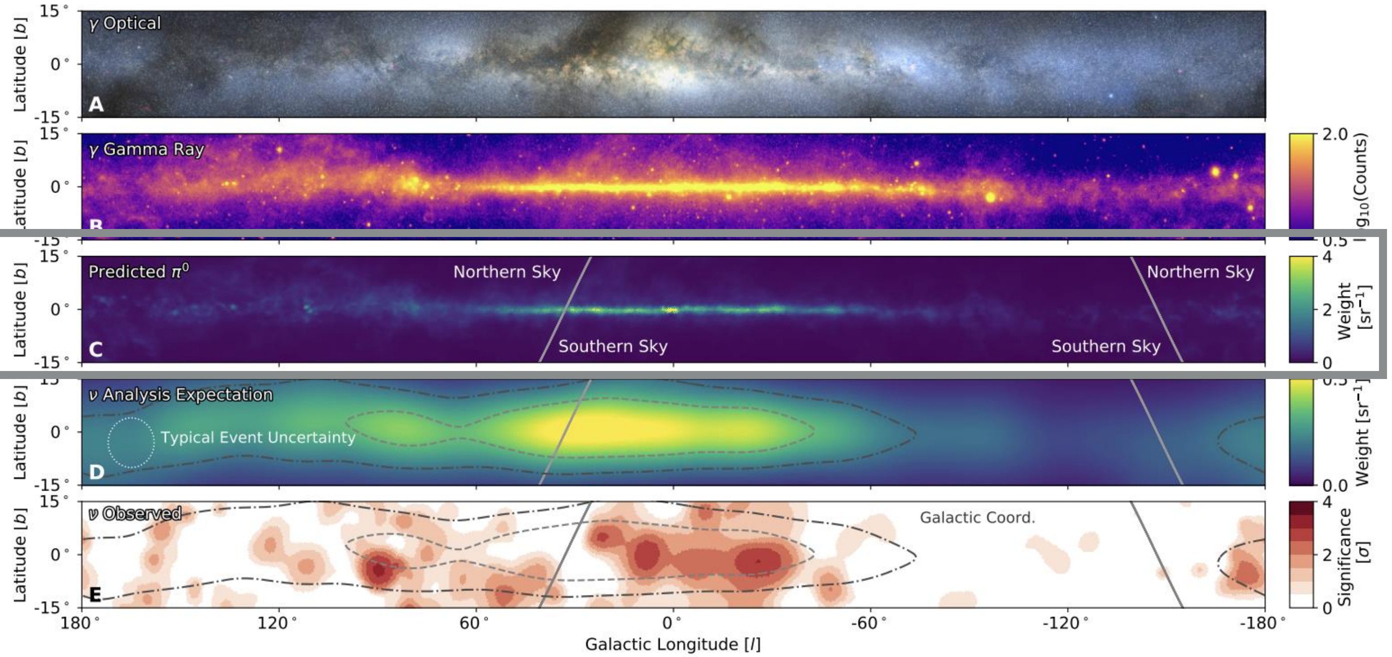
Galactic Plane

GeV gamma-ray sky by Fermi-LAT



Inverse Compton   Brems-strahlung π^0 **decay**

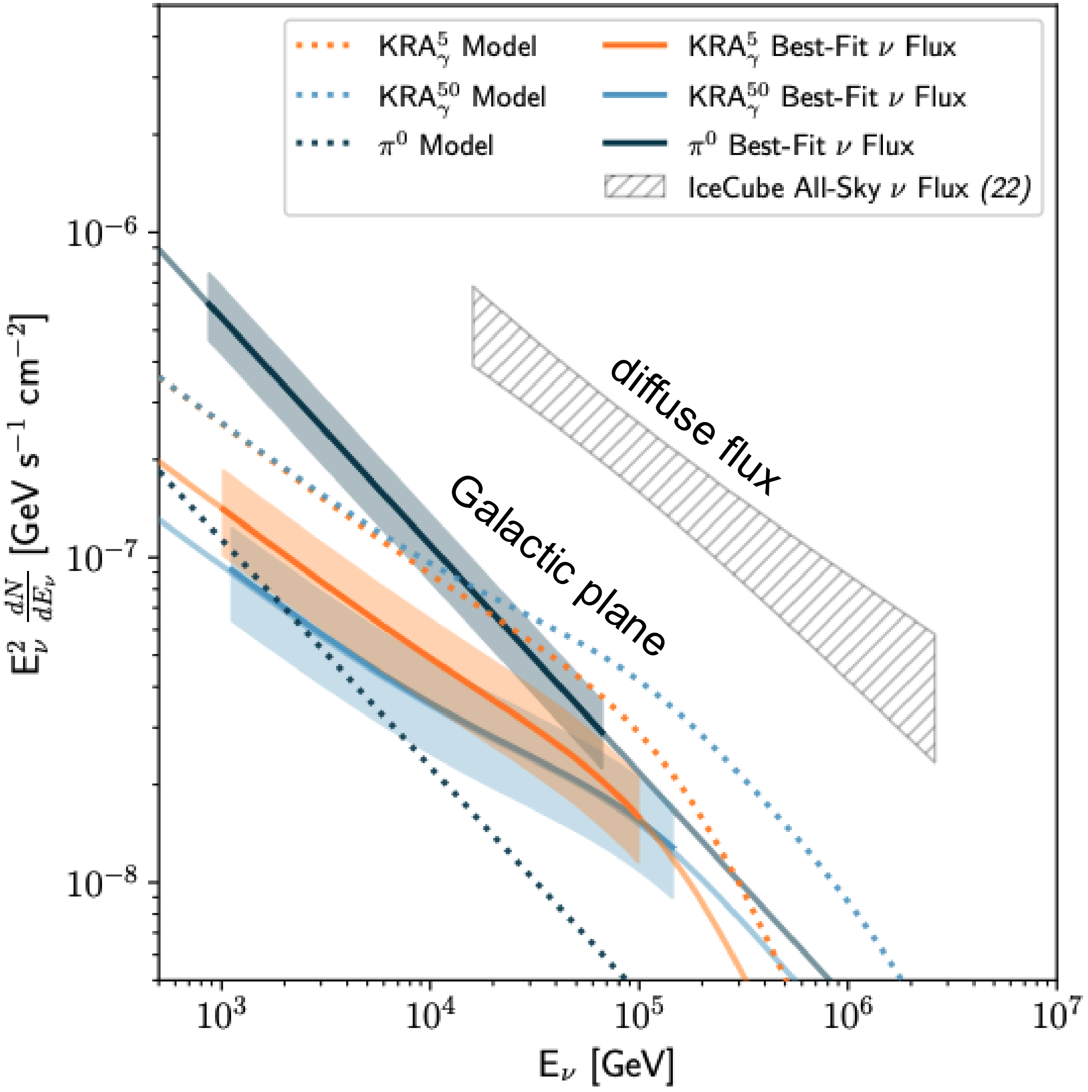




First detection of galactic plane neutrino flux thanks to gamma-ray template fit

IceCube Science 380 (2023)

Galactic Contribution



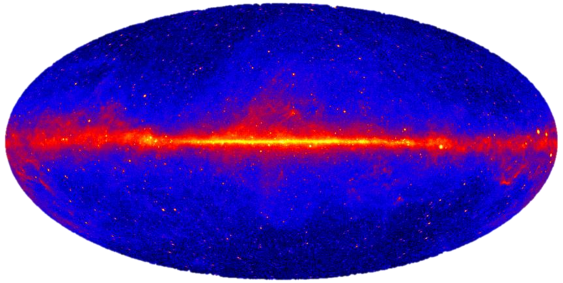
Galactic neutrinos make up ~10% of diffuse neutrinos

IceCube Science 380 (2023), arXiv: 2507.08753

Diffuse flux discovered

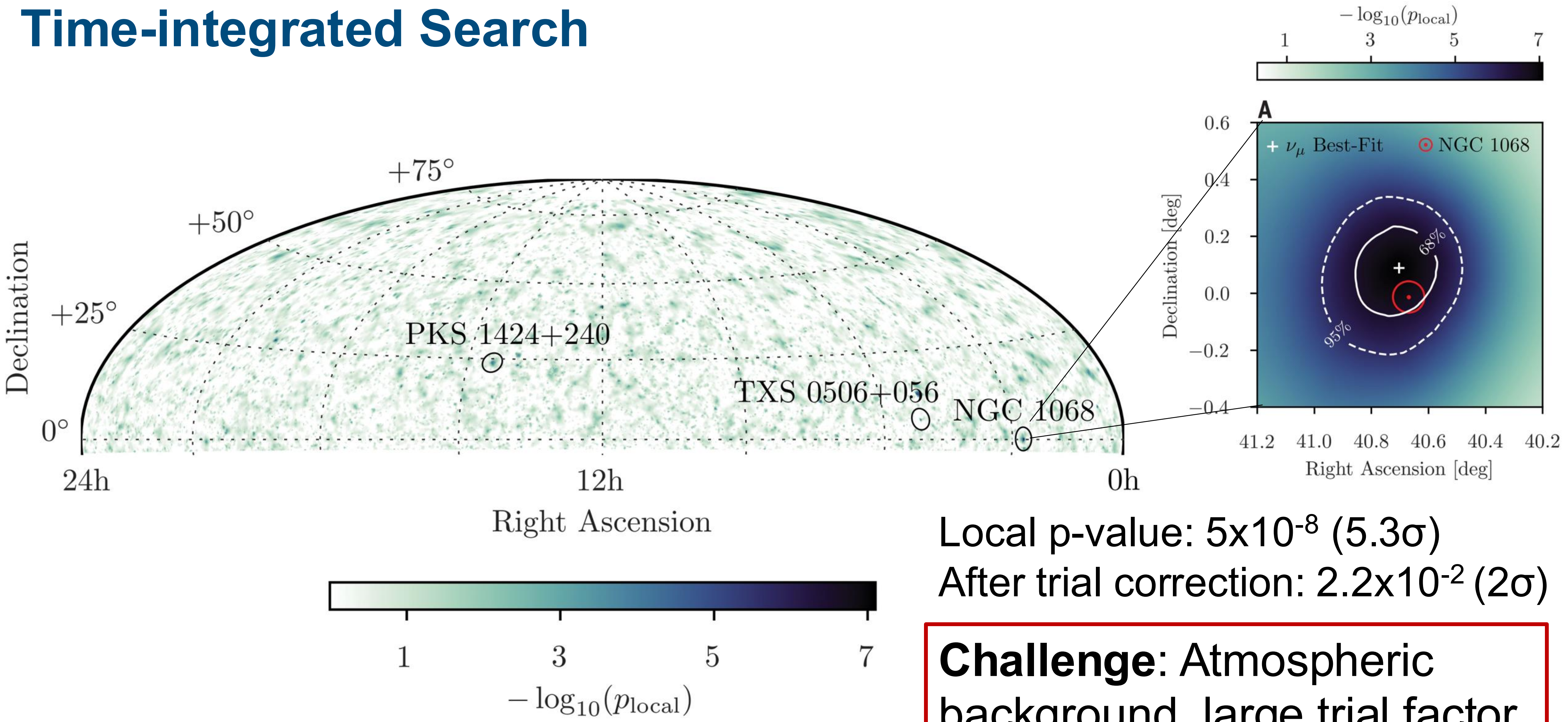
What are the source?

~10%



Remaining ~90%

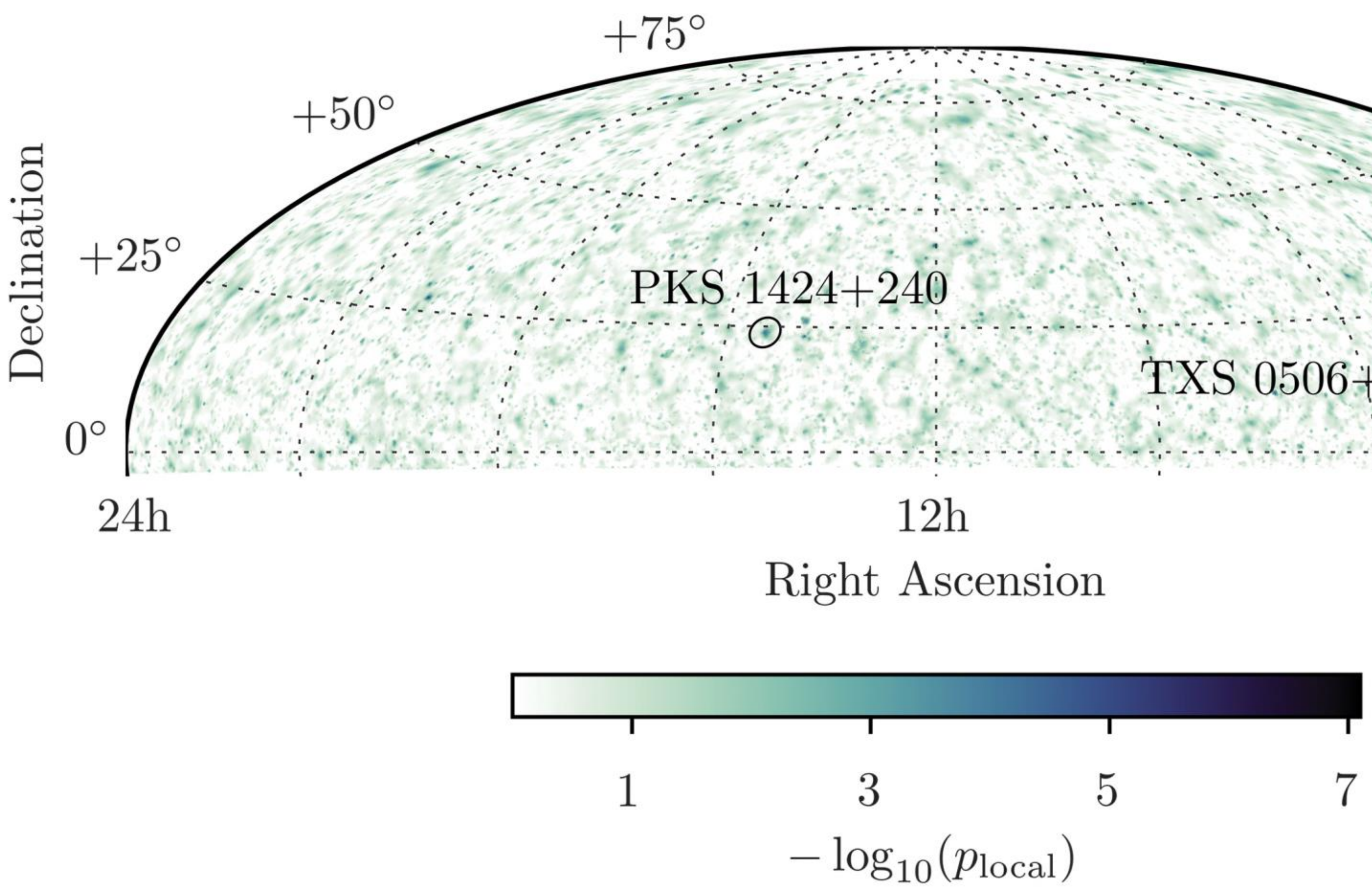
Time-integrated Search

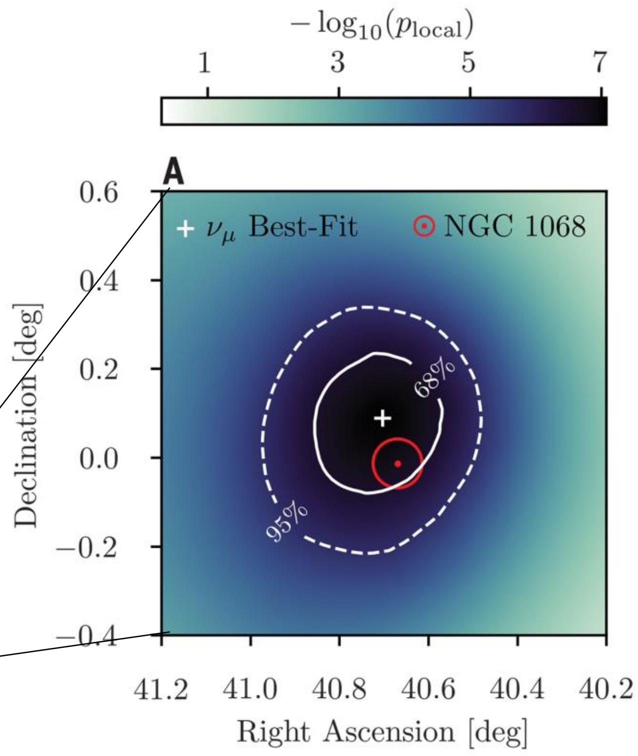


Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

Challenge: Atmospheric background, large trial factor

Time-integrated Search



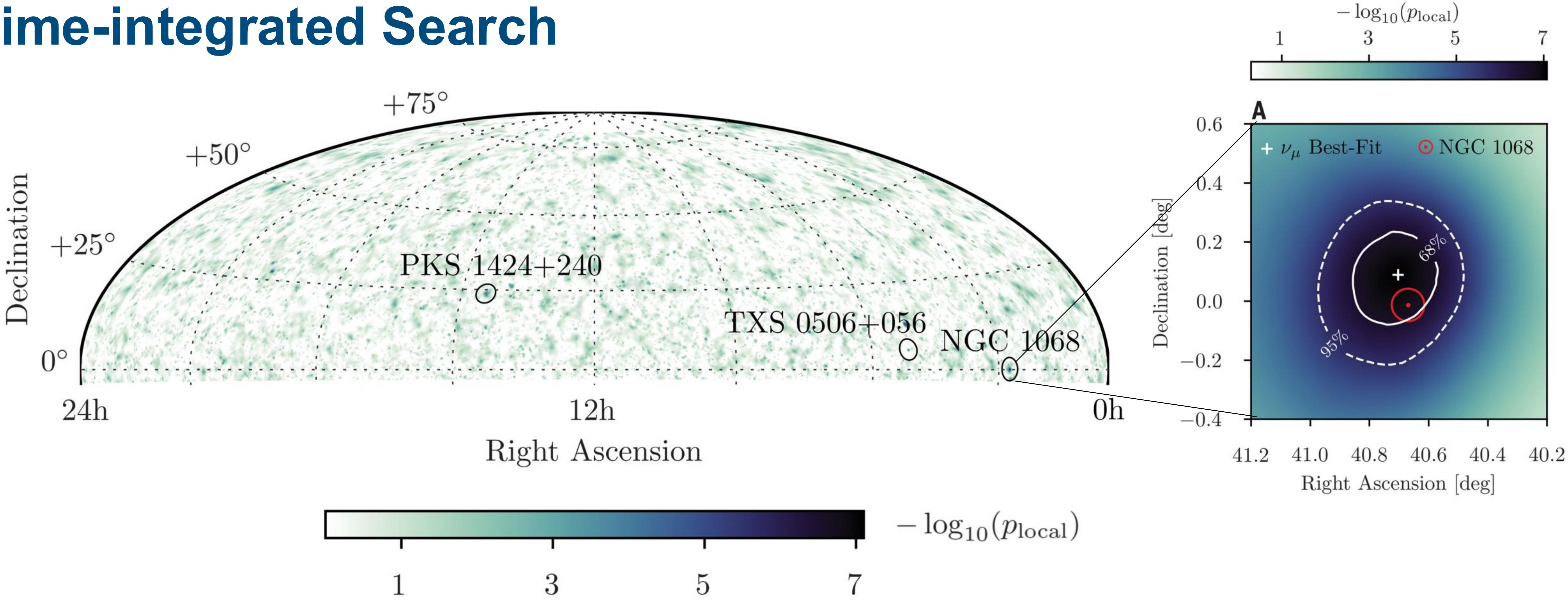


Local p-value: $5\text{x}10^{-8}$ (5.3σ)
After trial correction: $2.2\text{x}10^{-2}$ (2σ)

Solution: Use predefined source lists to reduce trials

IceCube Science 378 (2022)

Time-integrated Search



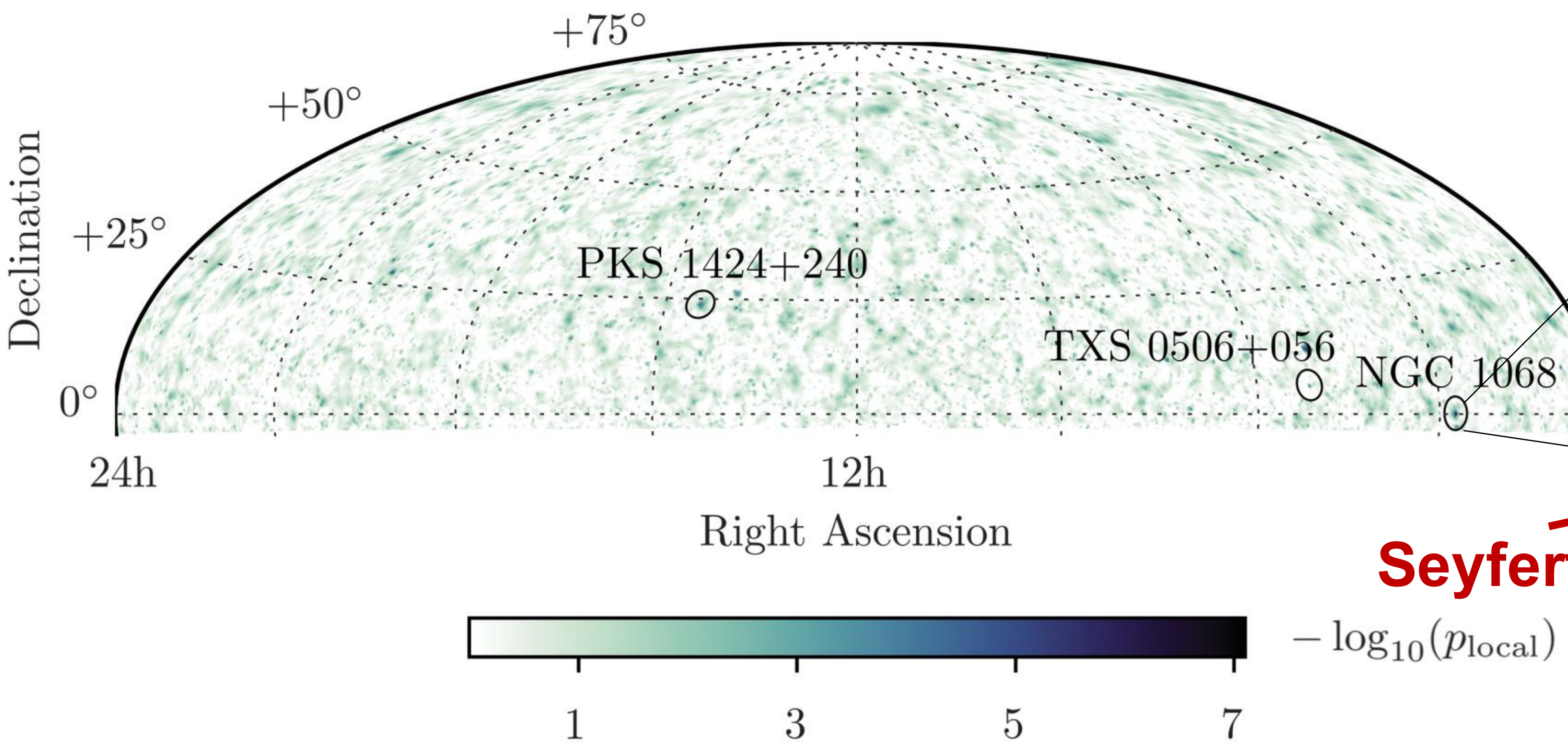
Predefined list of 110 sources → Most significant candidate:

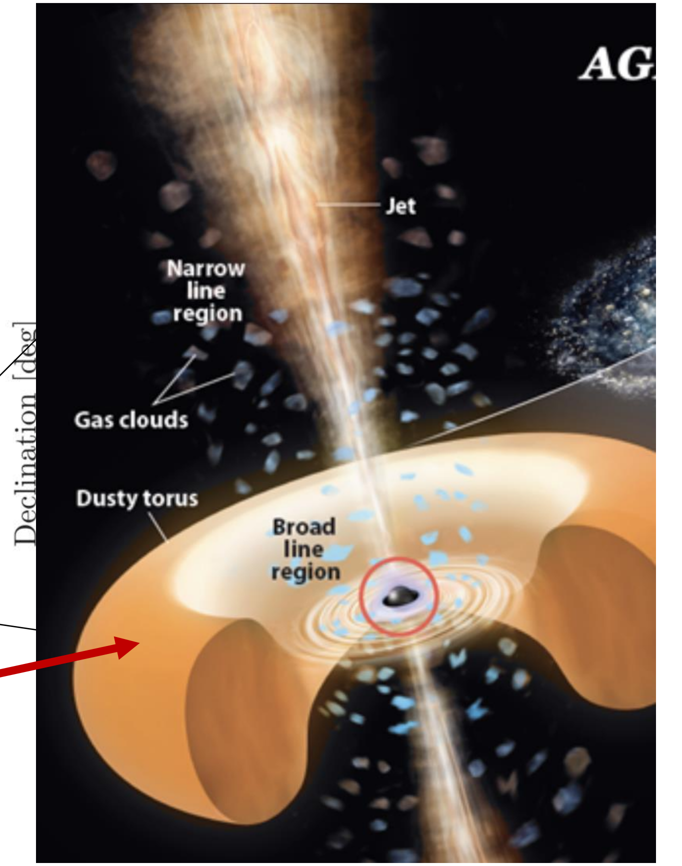
NGC 1068 (M77), ~80 neutrinos (1-10TeV), 4.2σ

- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

RUB

Time-integrated Search





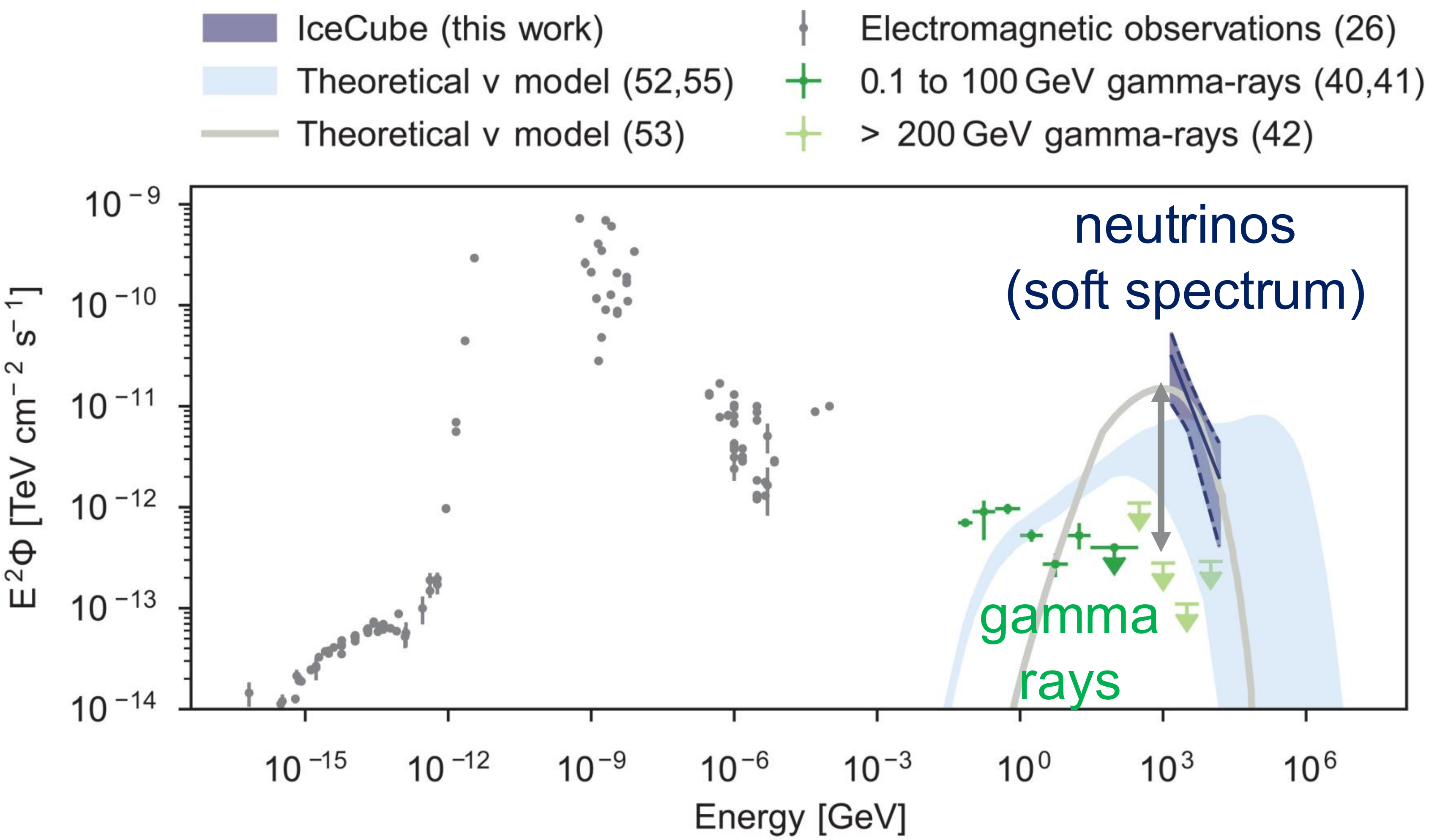
Seyfert 2

Predefined list of 110 sources → Most significant candidate:
NGC 1068 (M77), ~80 neutrinos (1-10TeV), 4.2σ

- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

RUB

Complete Multi-wavelength data of NGC 1068

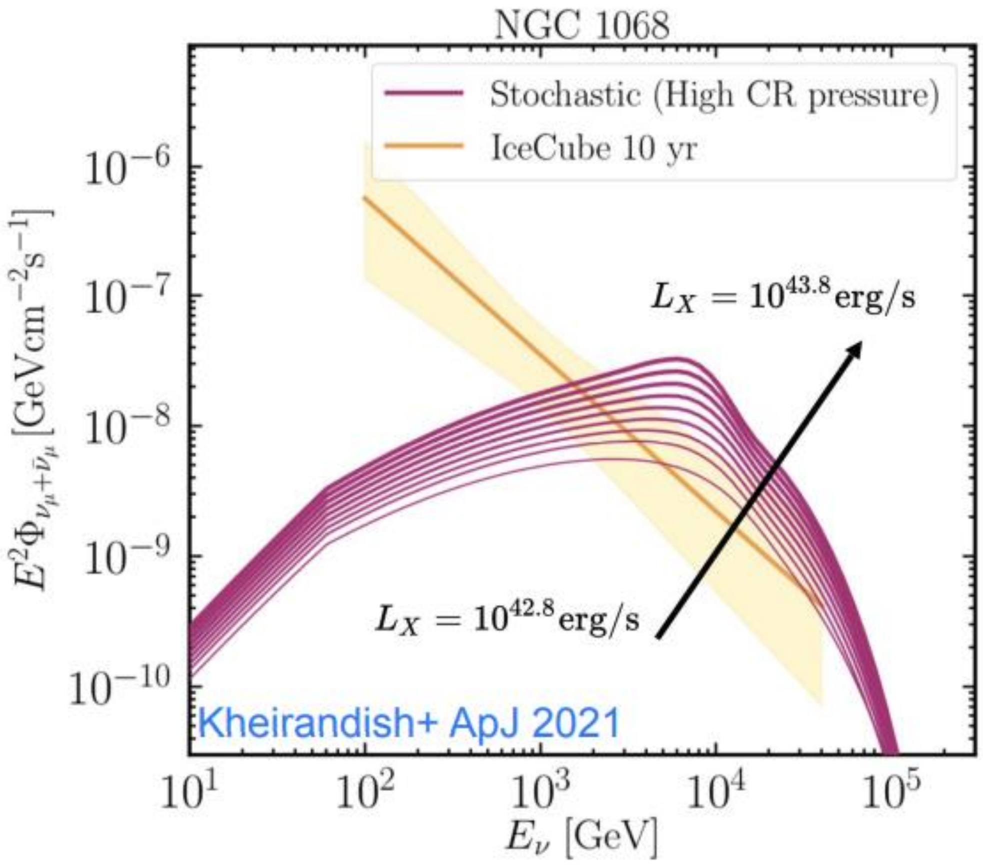


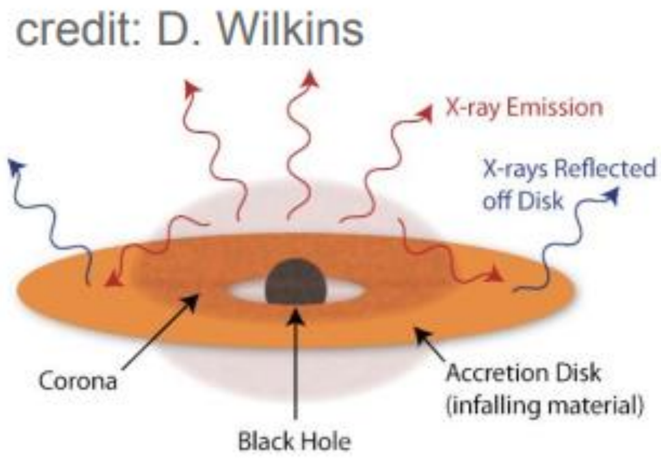
Gamma rays need to be absorbed
→ neutrino production site in the heart of the galaxy

IceCube Science 378 (2022)

Search for Neutrinos from Population of Seyferts

Assumption: Neutrino production in corona, intrinsic X-ray flux (2–10 keV) as proxy for neutrino emission

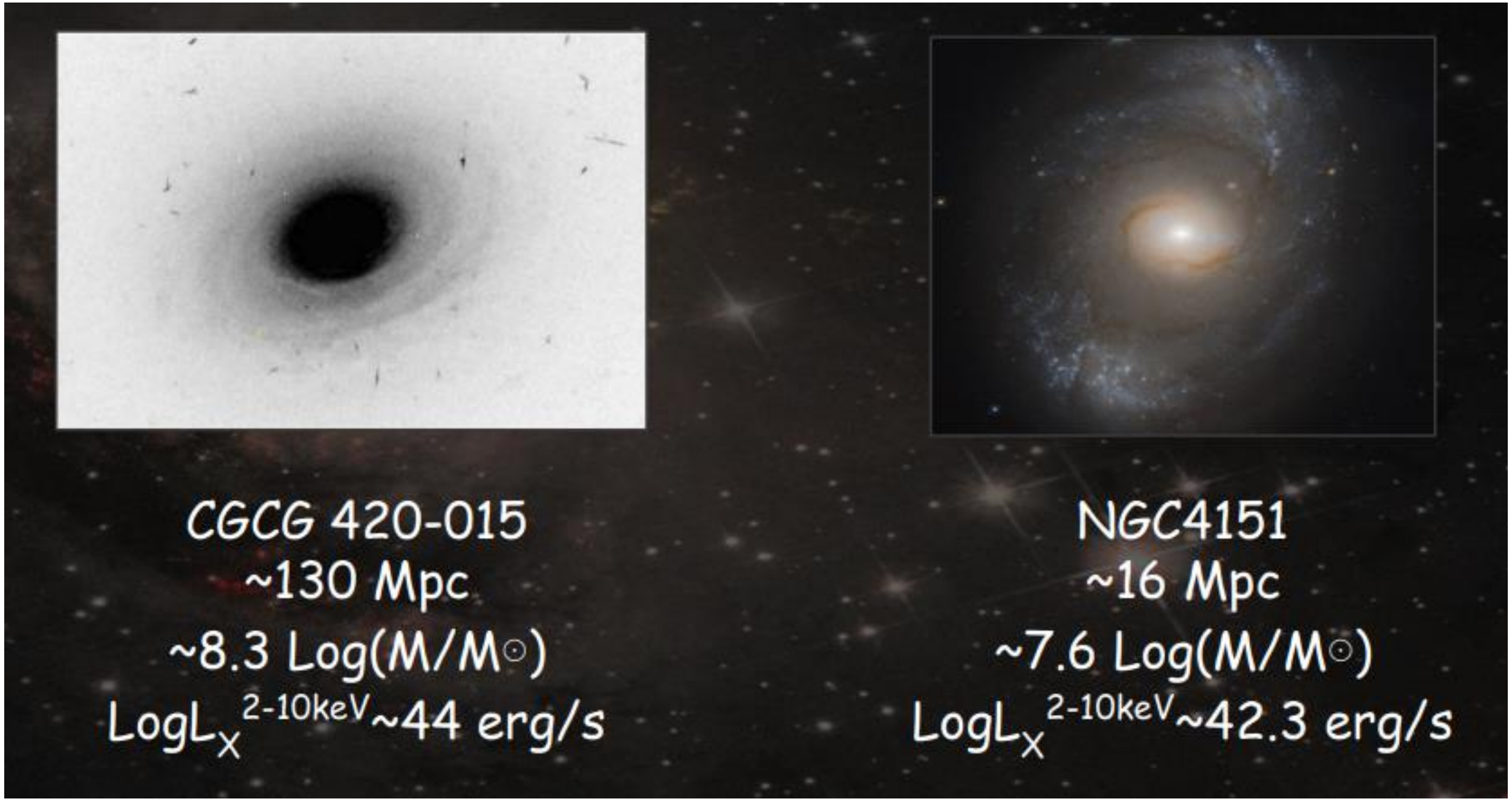




Northern Sky: No significant emission is found in the stacking search excluding NGC 1068.
Southern Sky: 3.0σ excess

Model Independent Search

No assumption about neutrino emission model



Two more source candidates at 2.5σ and 2.1σ level

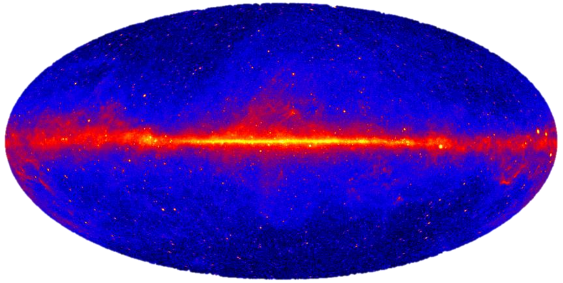
→ Model assumptions in stacking too simplified

IceCube *ApJ* 988 (2025) , see also Neronov et al. PRL 132 (2024) 10, 101002

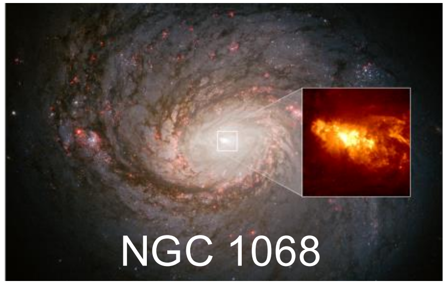
Diffuse flux discovered

What are the source?

~10%



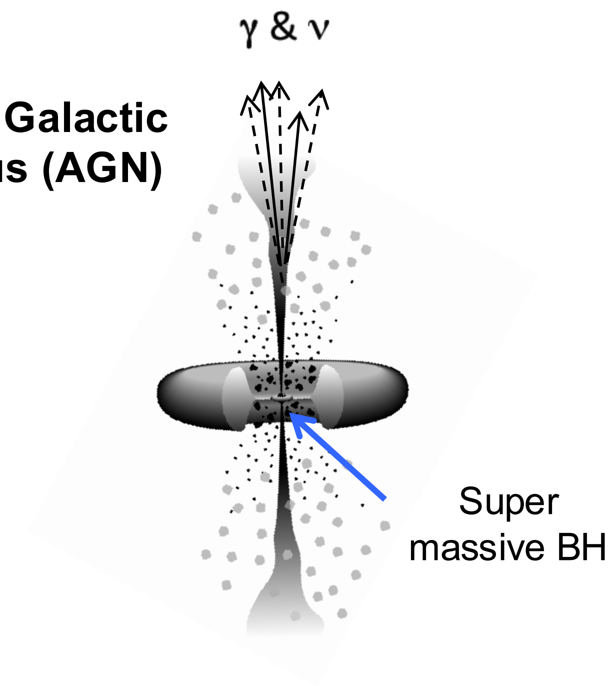
1%



Remaining ~89%

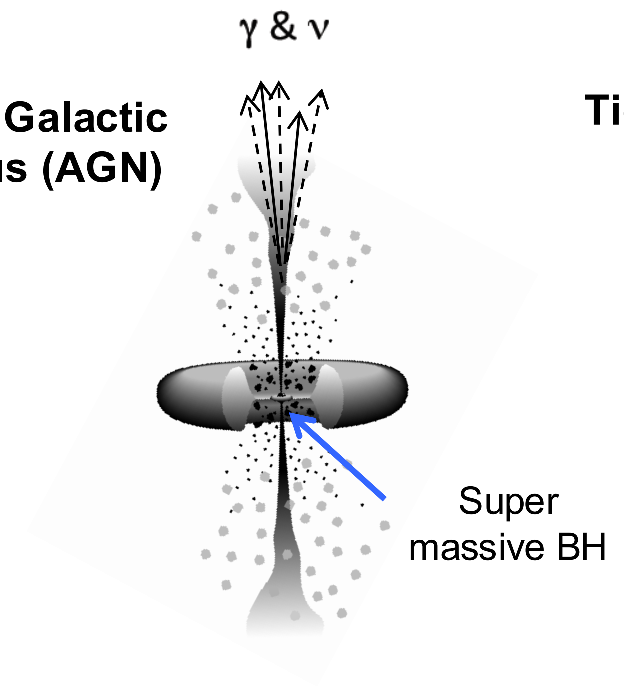
What if sources are variable?

Variable Source Candidates

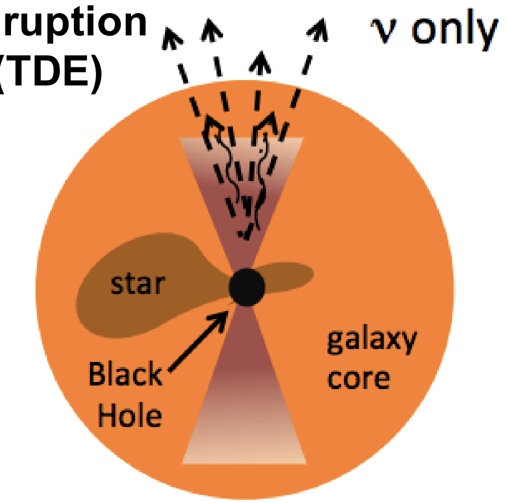


Variable Source Candidates

Active Galactic Nucleus (AGN)

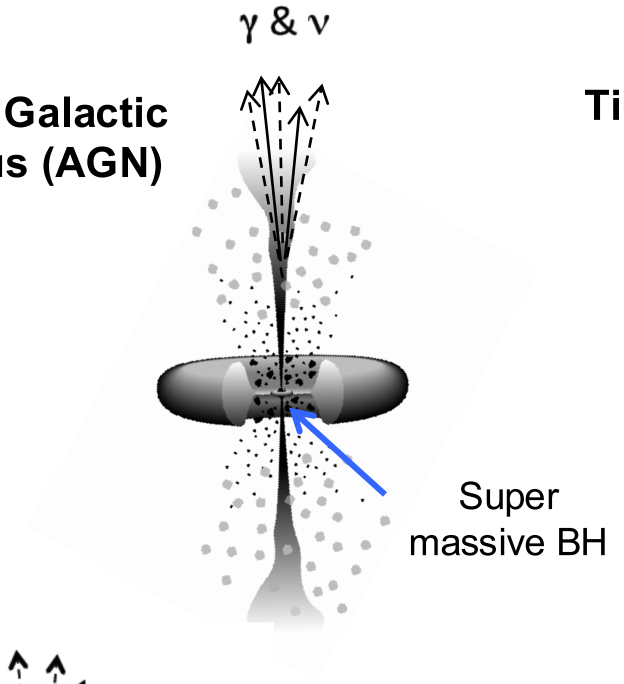


Tidal Disruption event (TDE)

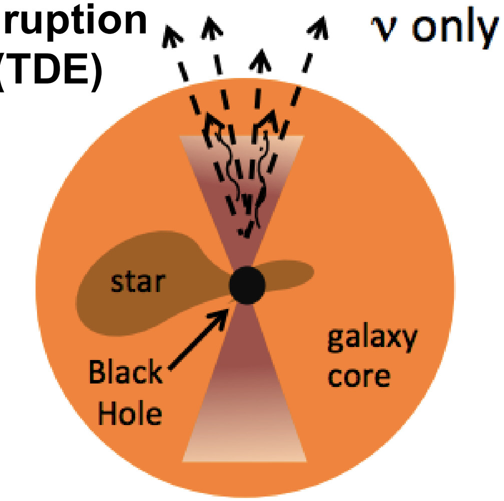


Variable Source Candidates

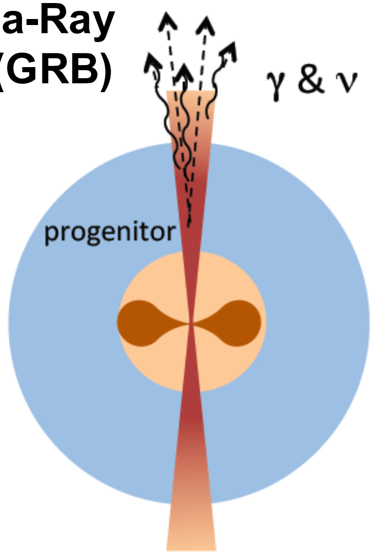
Active Galactic Nucleus (AGN)



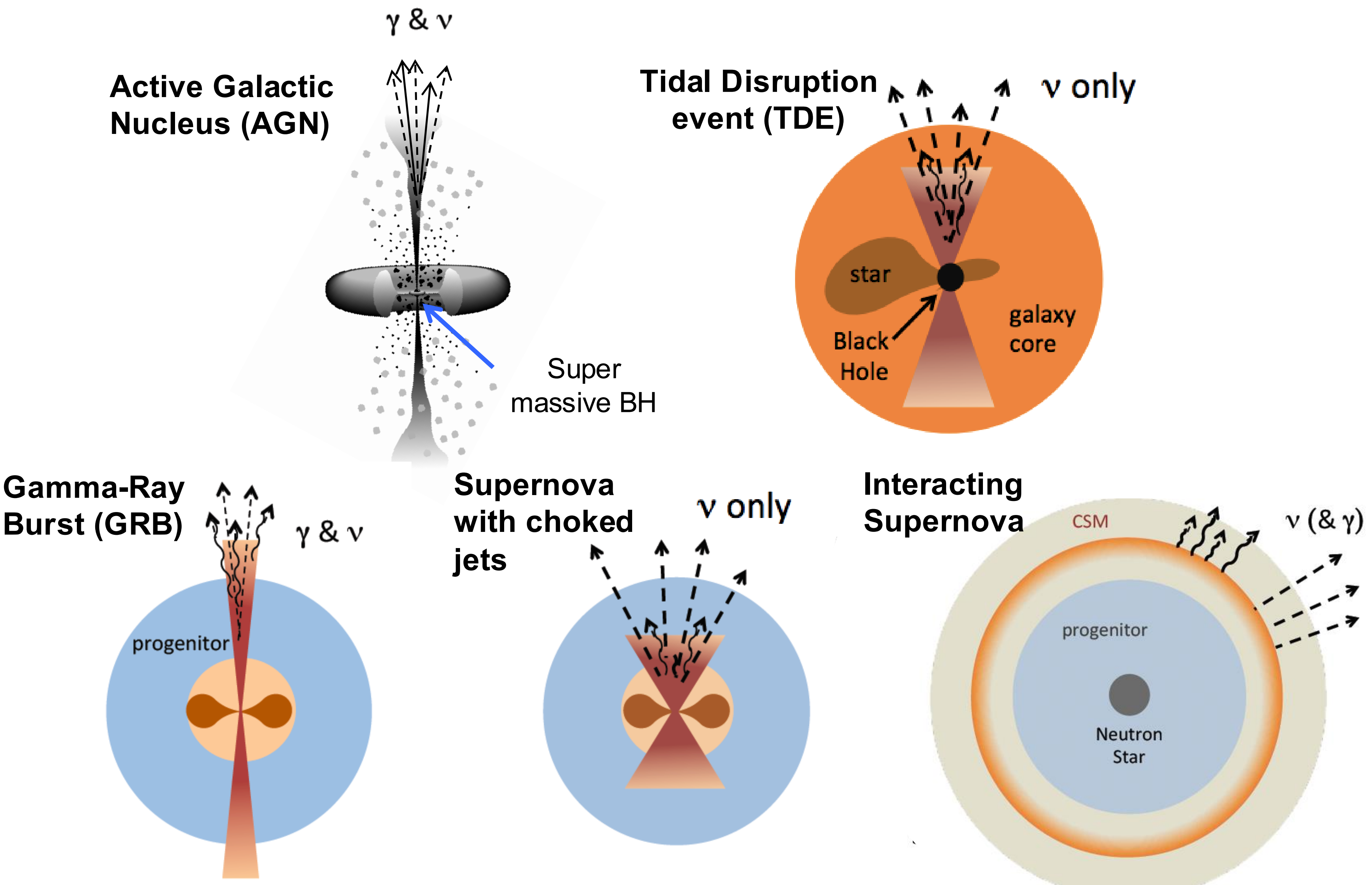
Tidal Disruption event (TDE)



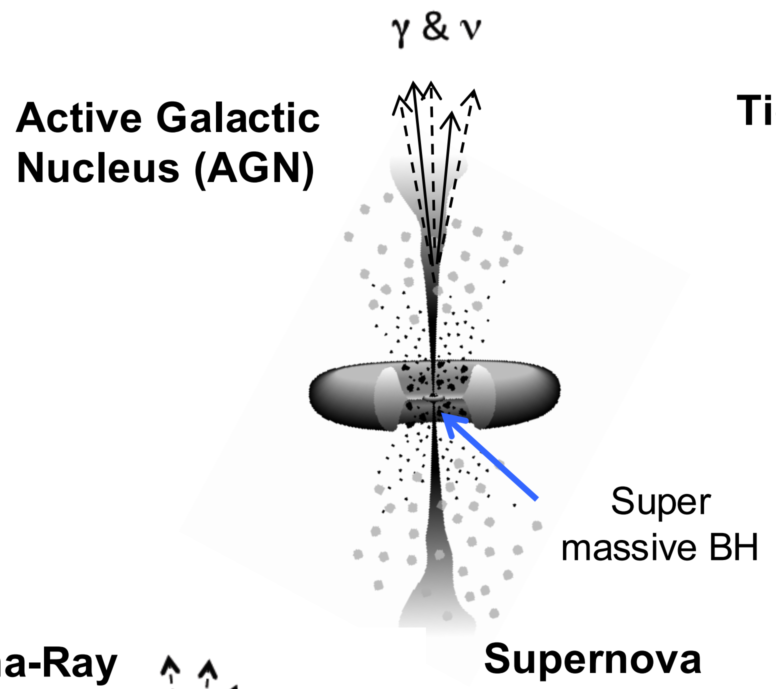
Gamma-Ray Burst (GRB)

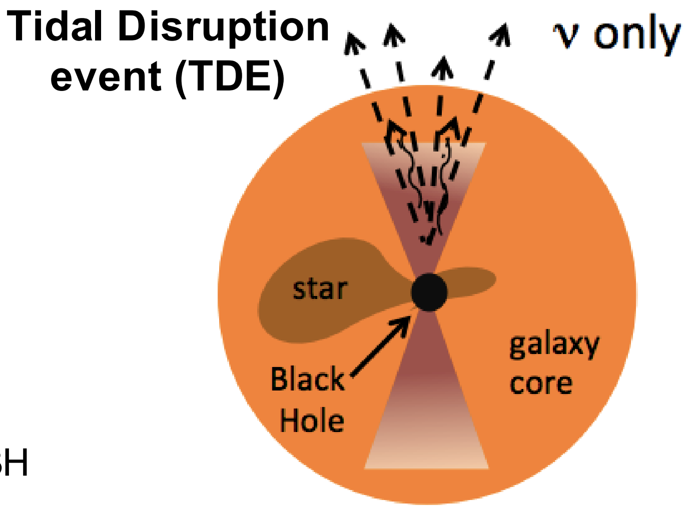


Variable Source Candidates

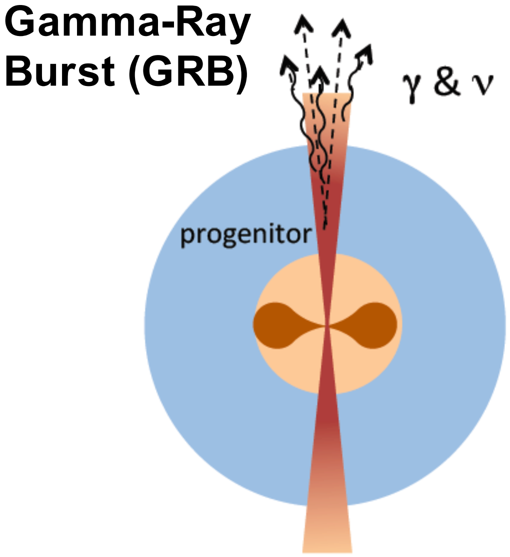


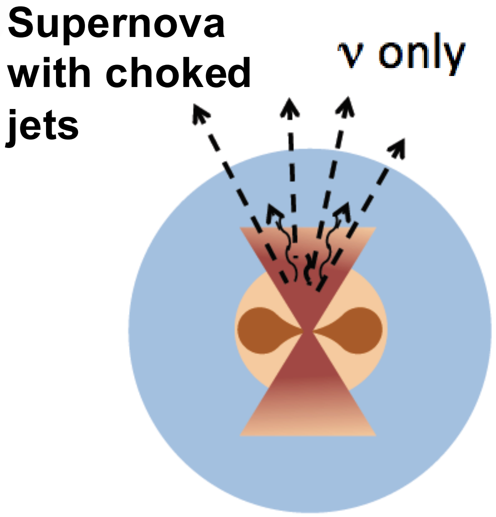
Variable Source Candidates

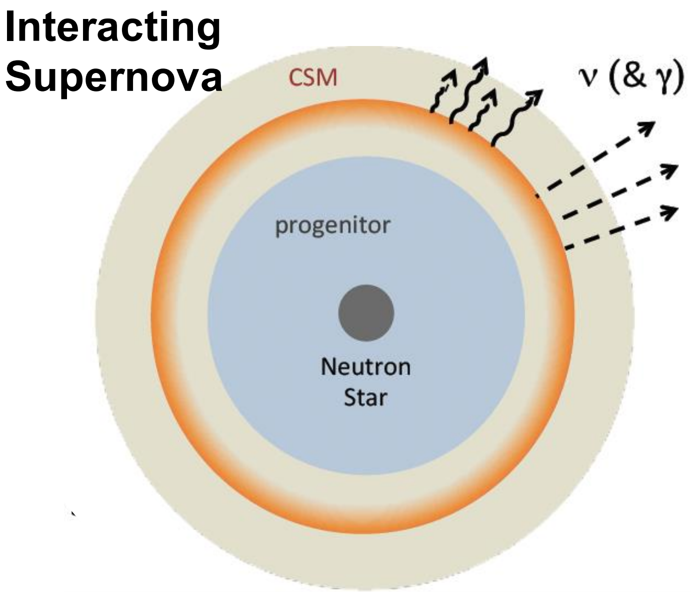




Callenge:
Source class unknown → Different time scales and wavelength





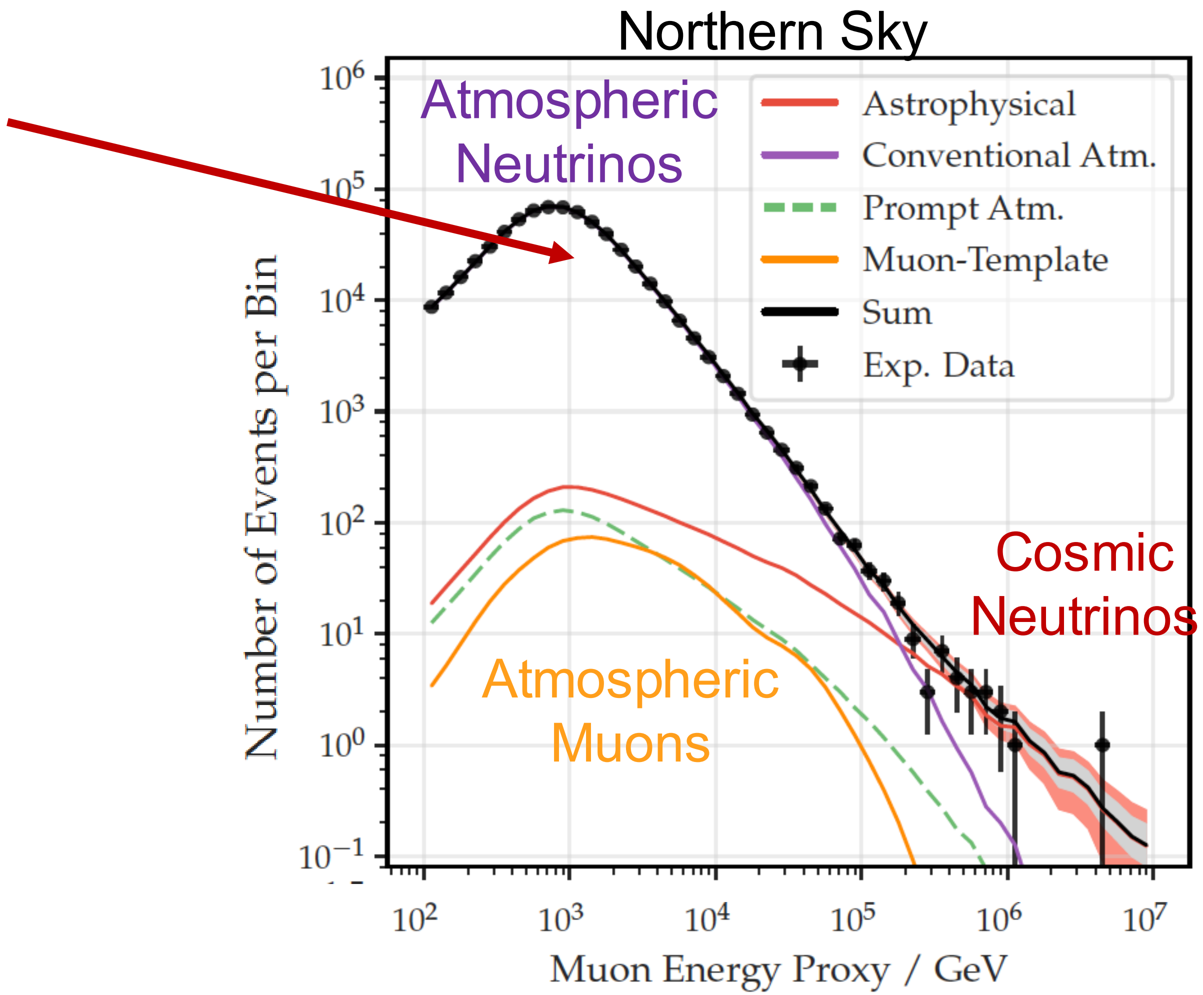


Detection Strategies

- Monitoring of TeV gamma-ray sources → inform IACTs in case of access

Detection Strategies

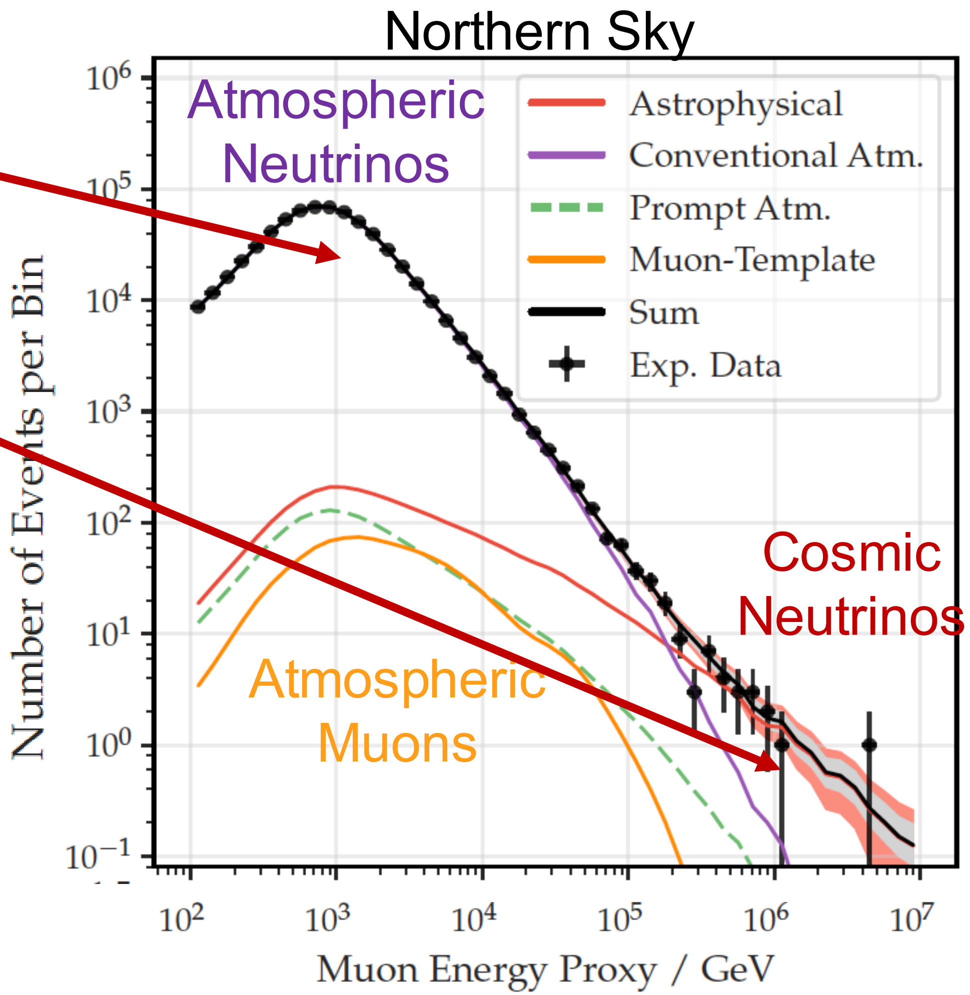
- Monitoring of TeV gamma-ray sources → inform IACTs in case of access
- Search for clusters of 1-10 TeV neutrinos



RUB

Detection Strategies

- Monitoring of TeV gamma-ray sources → inform IACTs in case of access
- Search for clusters of 1-10 TeV neutrinos
- Search for single ~100 TeV events



Neutrinos as Triggers

Public alerts since April 2016

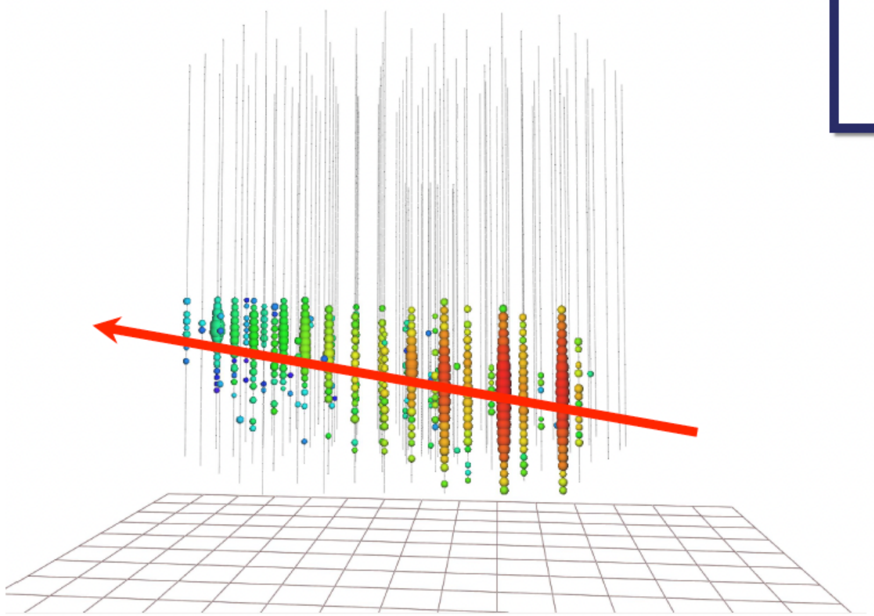
- Single high-energy muon track events (> ~100TeV)
    - “Gold” alert stream 10 / yr, ~5 / yr of cosmic origin
    - “Bronze” alert stream 30 / yr, 10/yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

IceCube Realtime Alert Flow

Gold/Bronze alert



1. General Coordinate Network (GCN) Notice

Results from a fast and simplified reconstruction algorithm (processed at South Pole)

< 1 min

2. GCN Circular + Updated GCN Notice

Updated reconstruction with more sophisticated algorithms (processed at North)

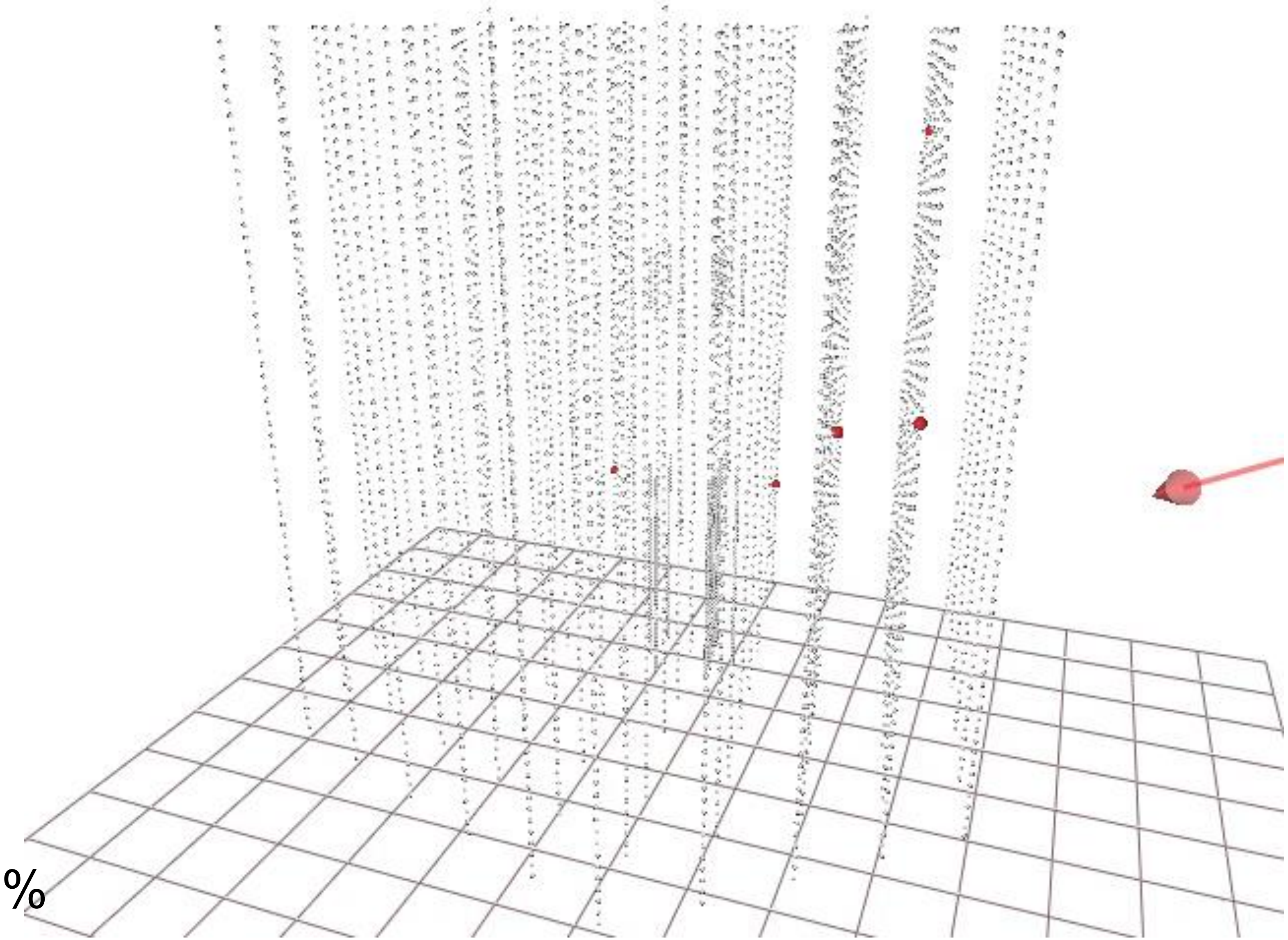
< a few hours

Refined best-fit direction and angular coordinates (rectangular error region)

Realtime Result 1:

Neutrino from gamma-ray flaring blazar

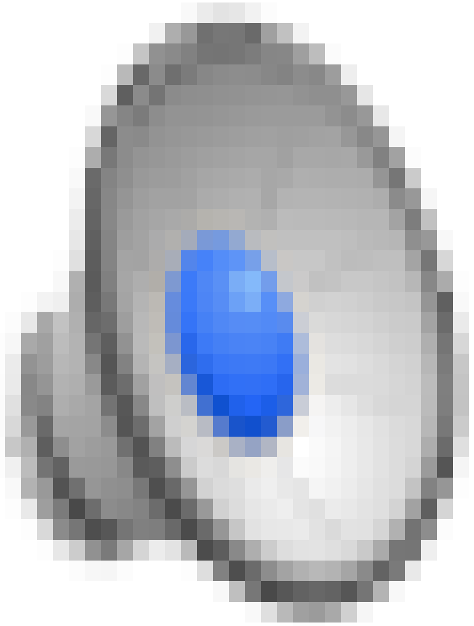
IC-170922A – a 290 TeV Neutrino



Signalness: 56.5%

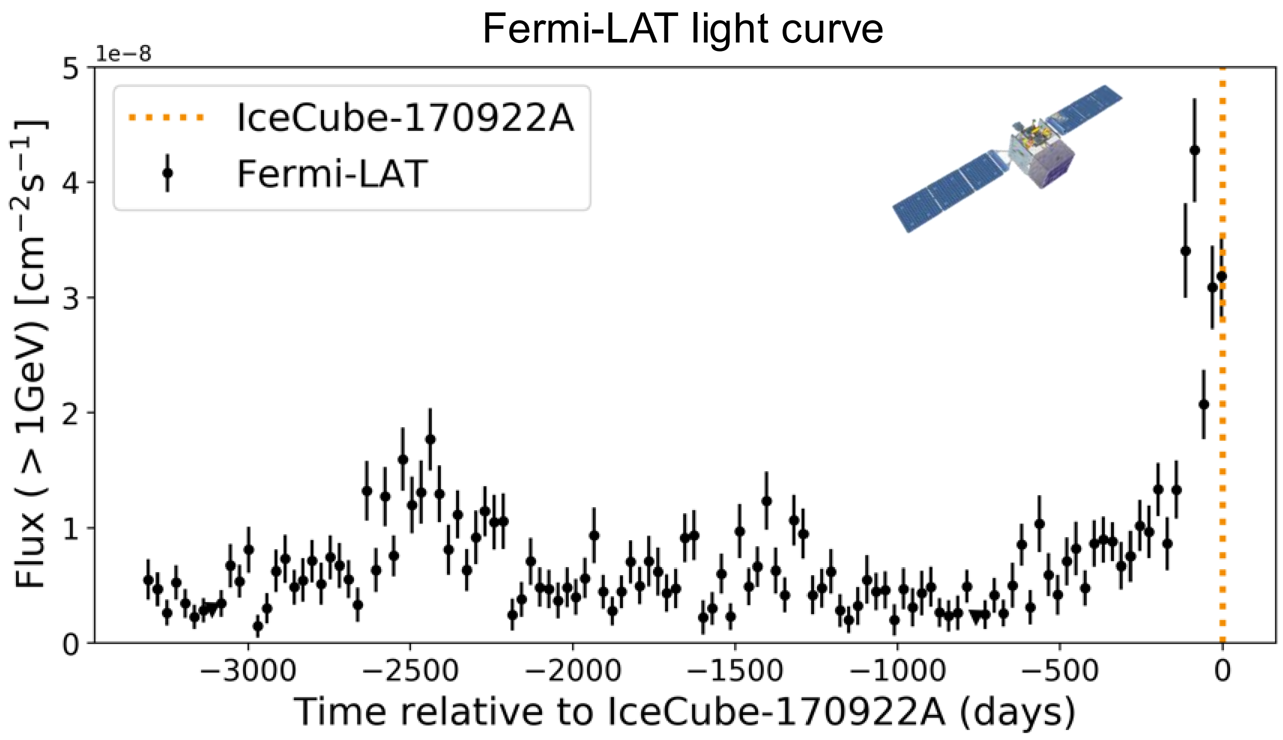
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Fermi-LAT finds Flaring Source

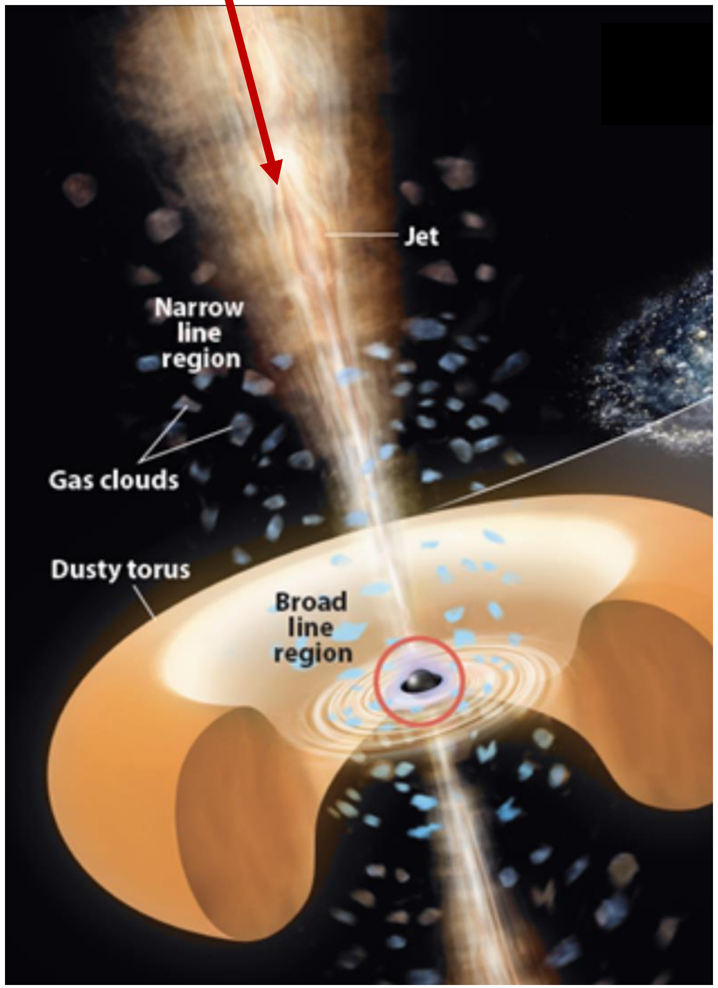


Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Source Candidates: TXS 0506+056



Blazar



Coincidence with source location and gamma-ray flare increases significance to 3σ

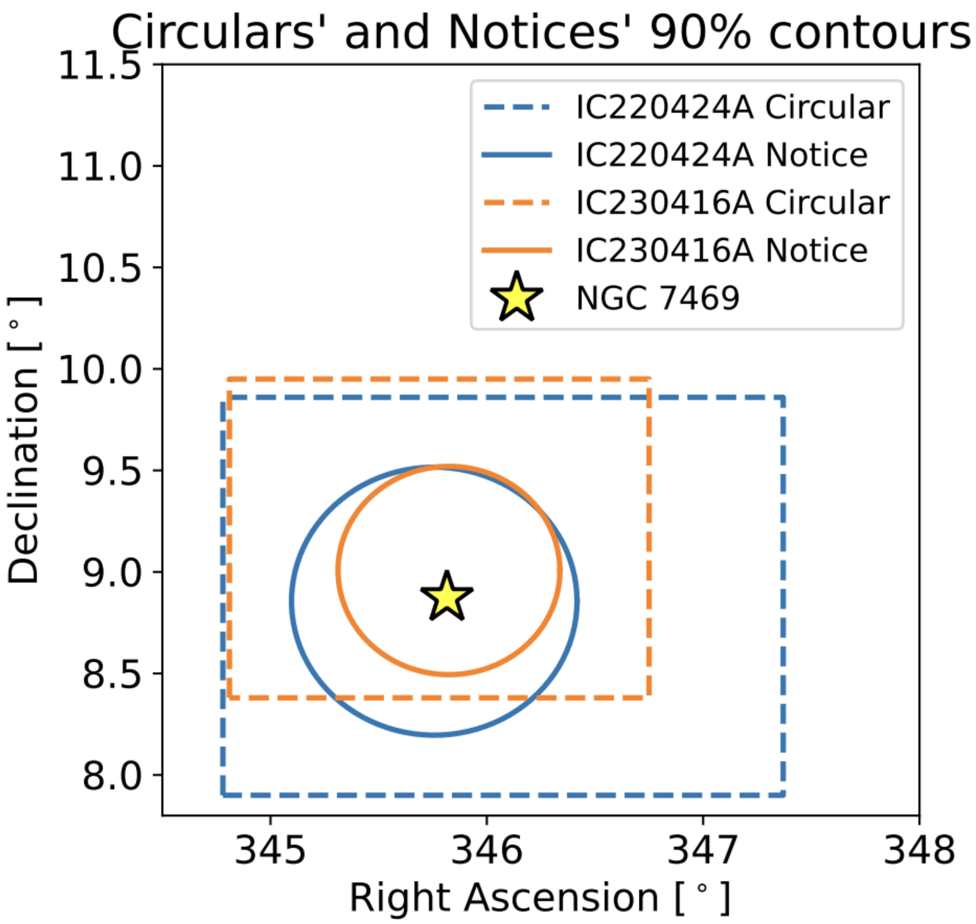
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

RUB

Realtime Result 2:

Two neutrinos from Seyfert galaxy NGC 7469

Two 100 TeV Neutrinos from NGC 7469



3.2 sigma candidate

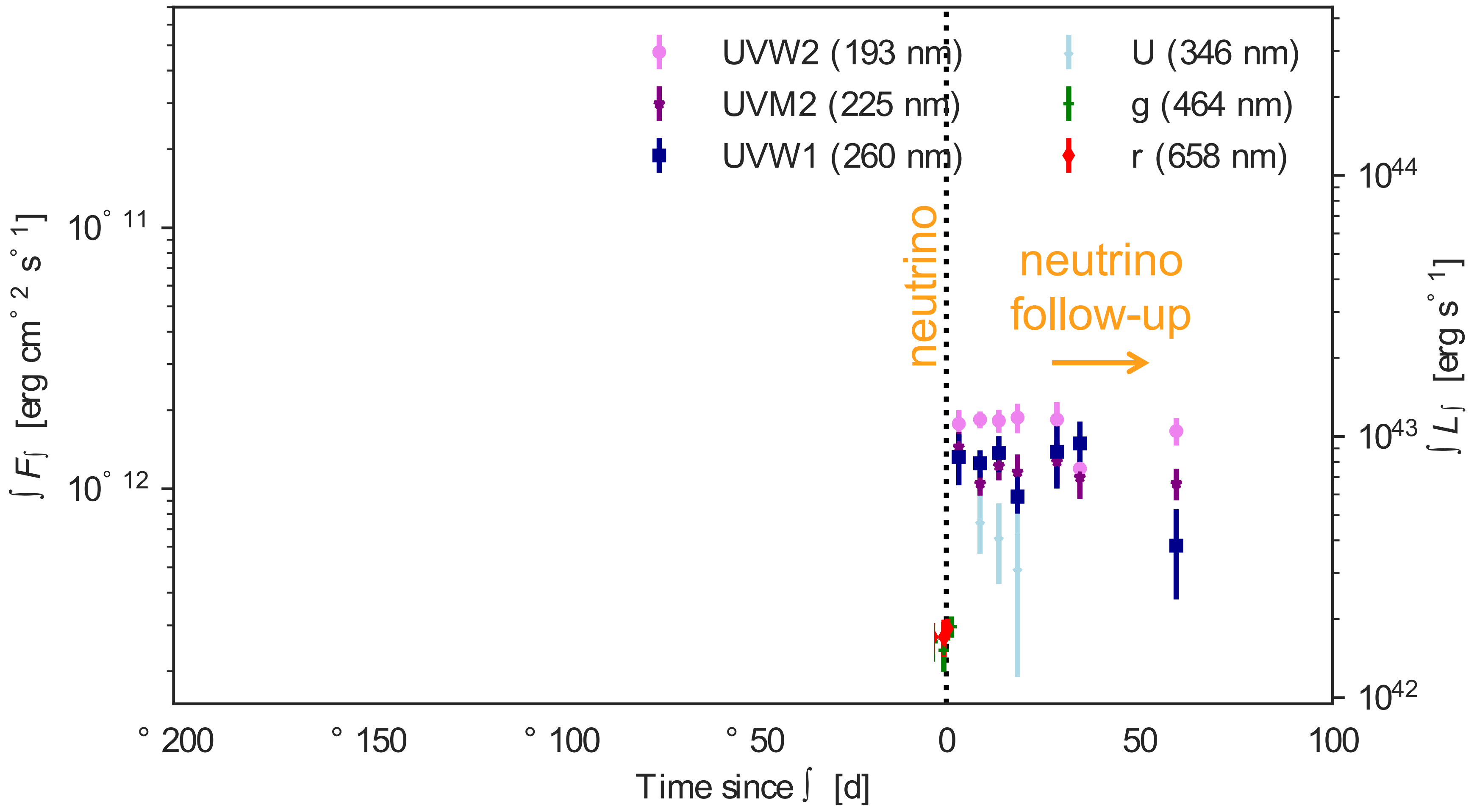
Much harder neutrino spectrum than NGC 1068

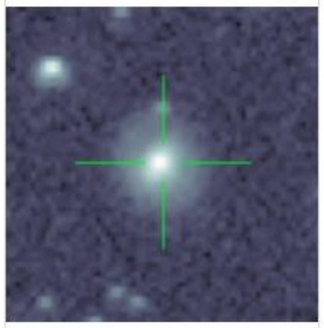
Sommani et al. *Astrophys.J.* 981 (2025)

Realtime Result 3:

Neutrino from Tidal Disruption Event

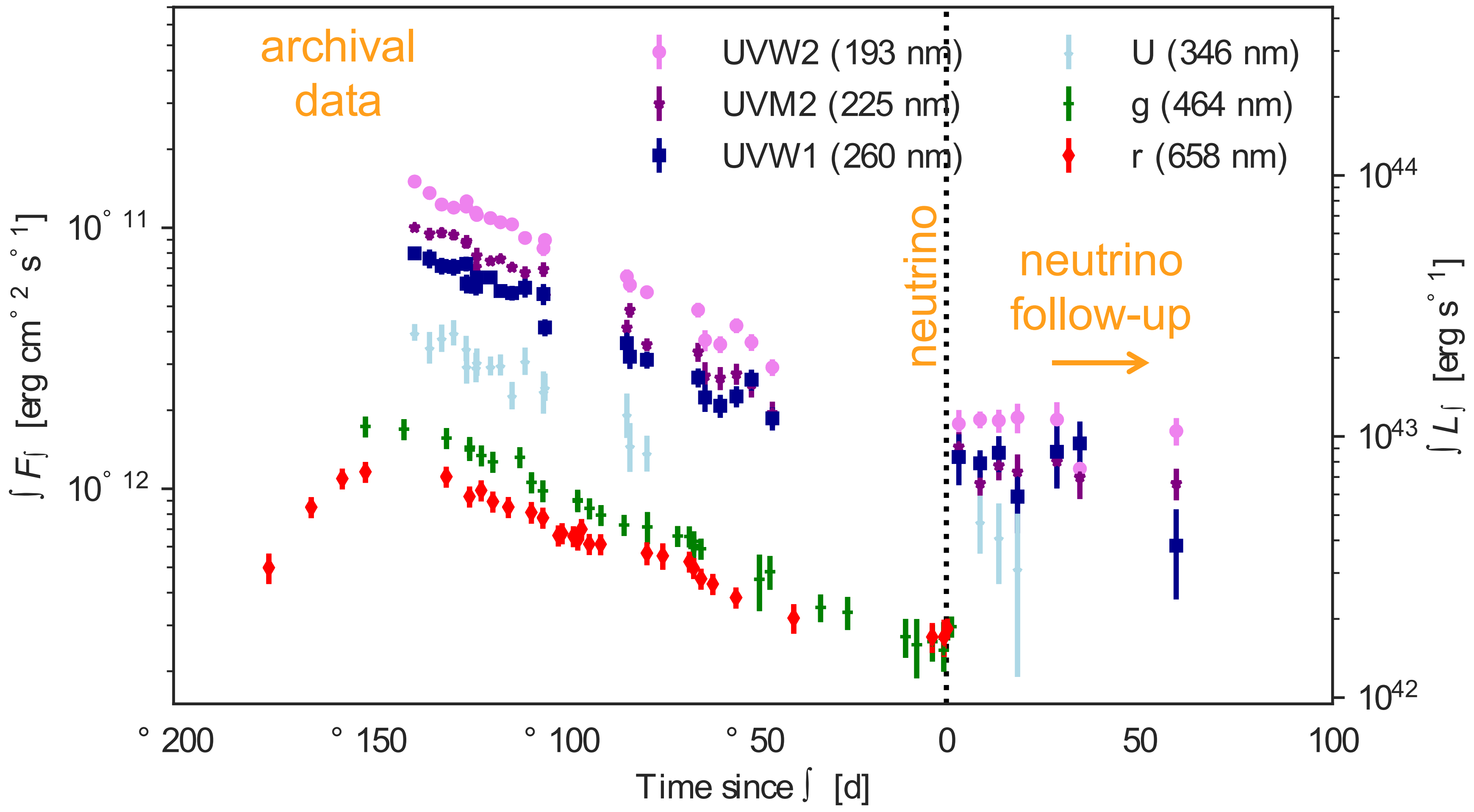
Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg

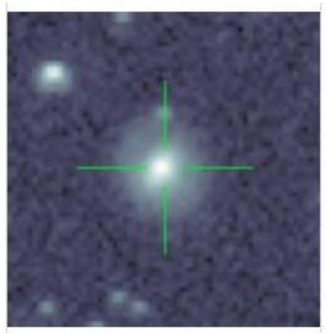




R. Stein et al., Nature Astronomy 2021

Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg

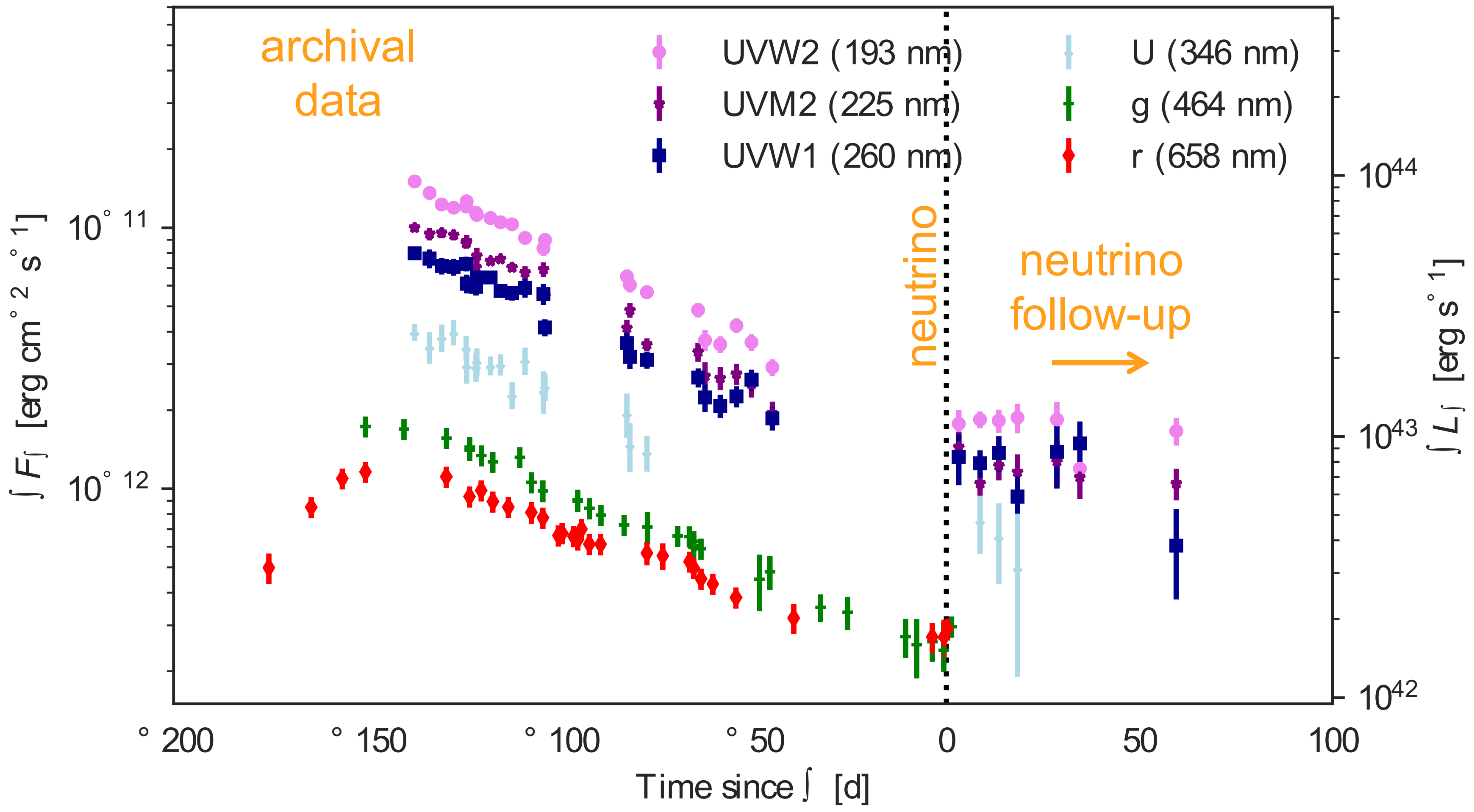


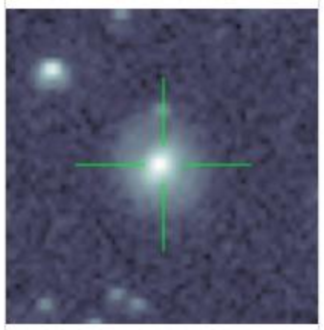


Distance: z = 0.05 (d = 230 Mpc), thermal X-rays, no gamma rays

R. Stein et al., Nature Astronomy 2021

Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg





Distance: z = 0.05 (d = 230 Mpc), thermal X-rays, no gamma rays

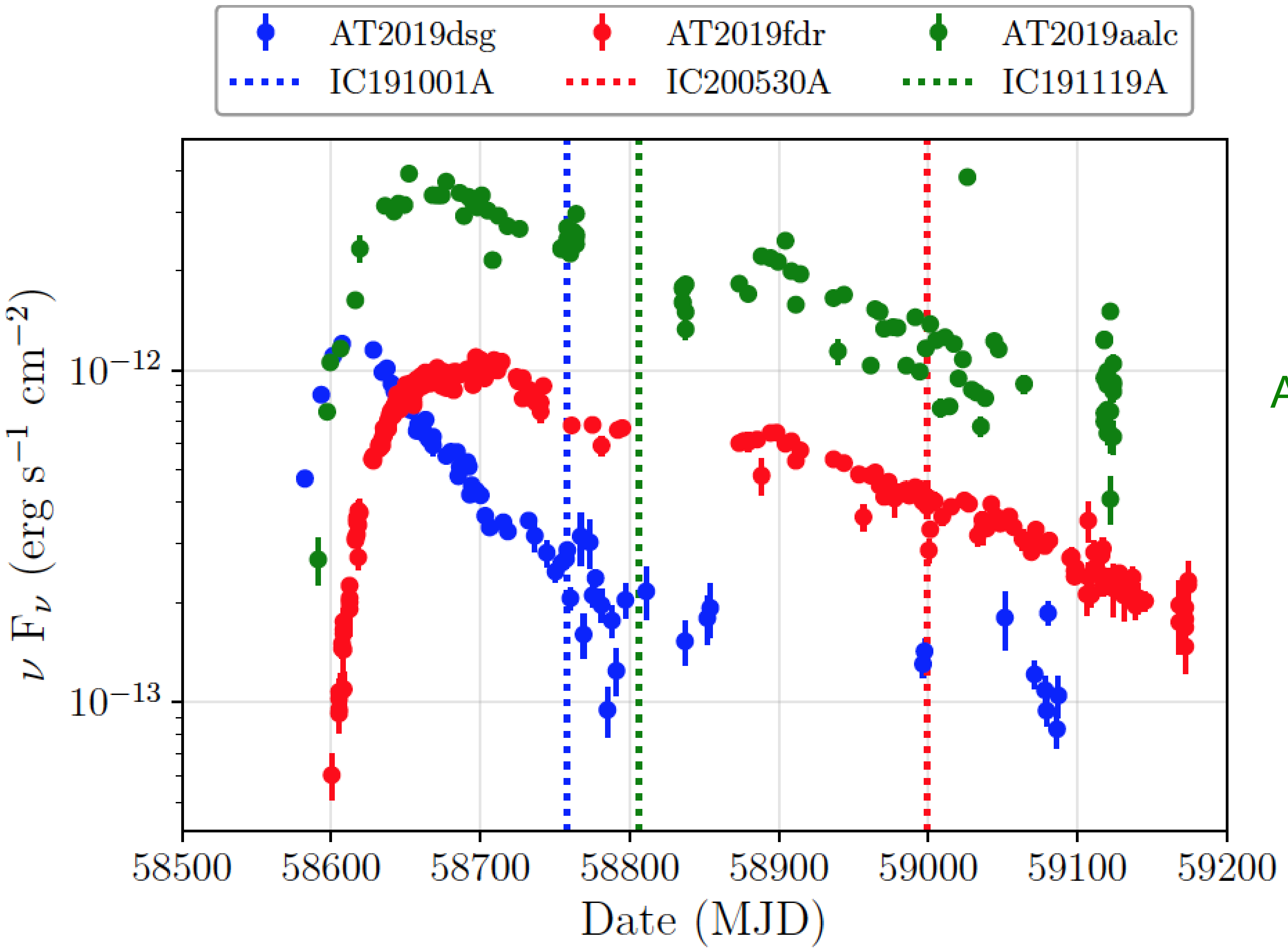
Chance coincidence:
0.2% to find a TDE that bright (including trials)

R. Stein et al., Nature Astronomy 2021

Three TDE neutrino candidates

AT2019dsg coincident with IC191001A

AT2019fdr coincident with IC200530A



AT2019aalc coincident with IC191119A

Significance 3.6σ

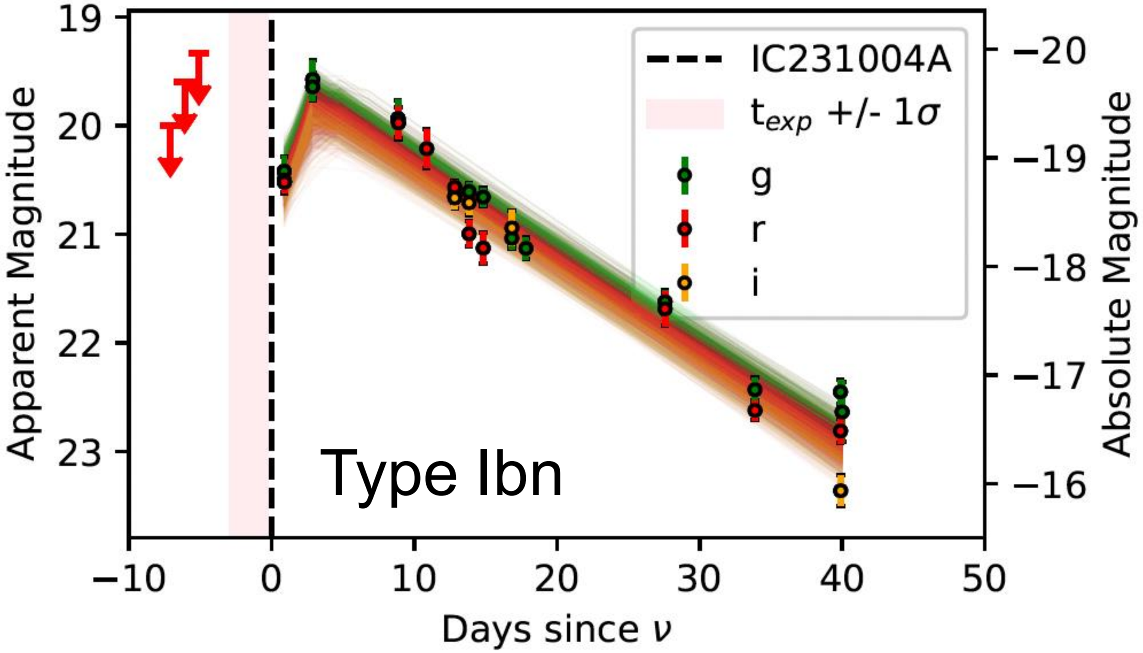
R. Stein et al., Nature Astronomy 2021, S. Reusch et al. PRL 2022, S. Van Velzen et al. MNRAS 529 (2024)

Realtime Result 4:

Neutrino from Interacting Supernova

Optical Counterpart to a high-energy neutrino: SN2023uqf

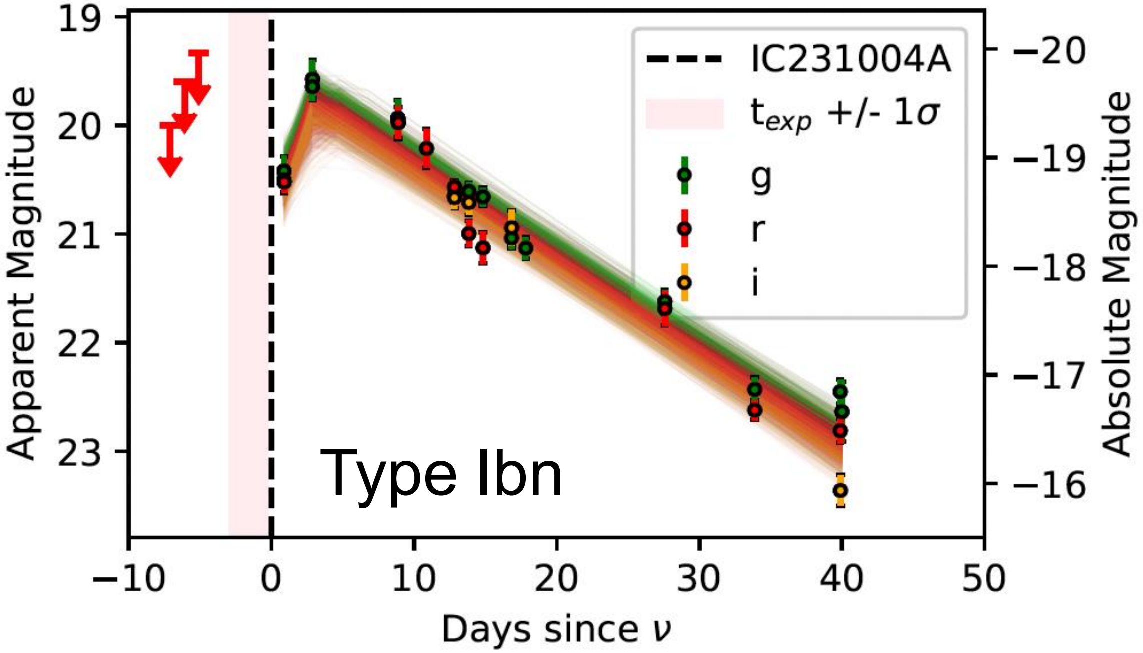
IC-231004A
440 TeV Neutrino
84% signalness
3σ association
Distance: 700 Mpc



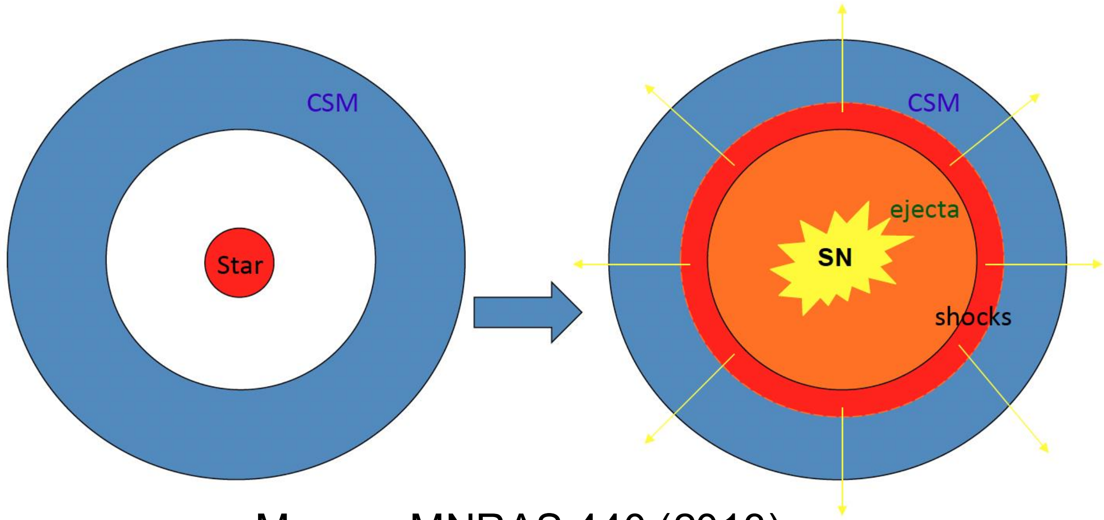
Stein et al. arXiv:2508.08355

Optical Counterpart to a high-energy neutrino: SN2023uqf

IC-231004A
440 TeV Neutrino
84% signalness
3σ association
Distance: 700 Mpc



Stein et al. arXiv:2508.08355



Murase MNRAS 440 (2013)

Evidence for hadronic acceleration in core-collapse supernova explosions

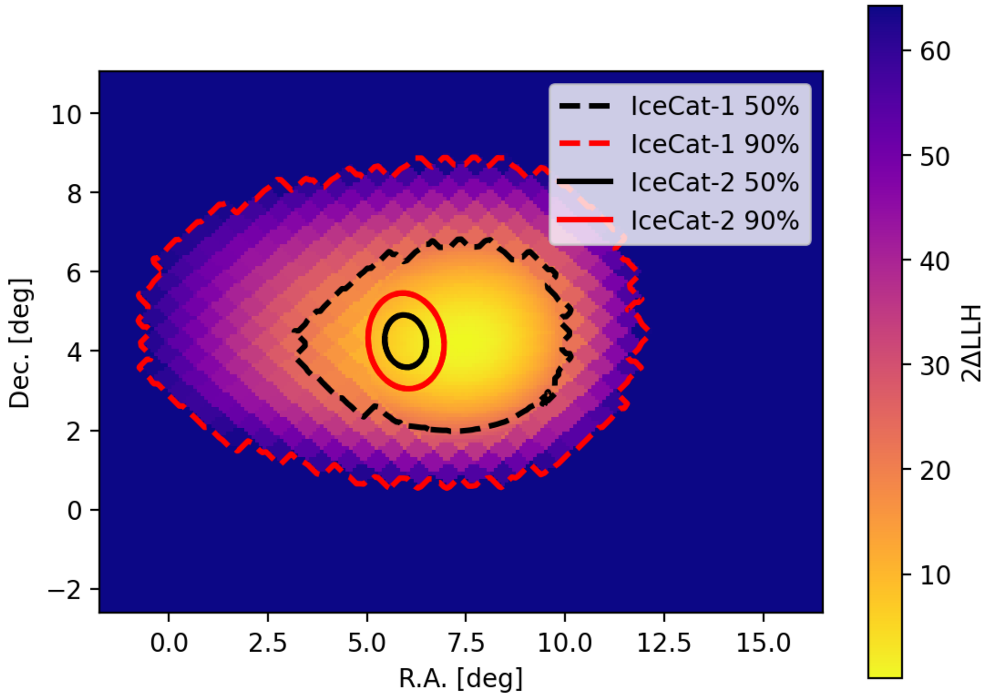
How can we improve our searches for neutrino sources?

How can we improve our searches for neutrino sources?

Improve neutrino angular uncertainty

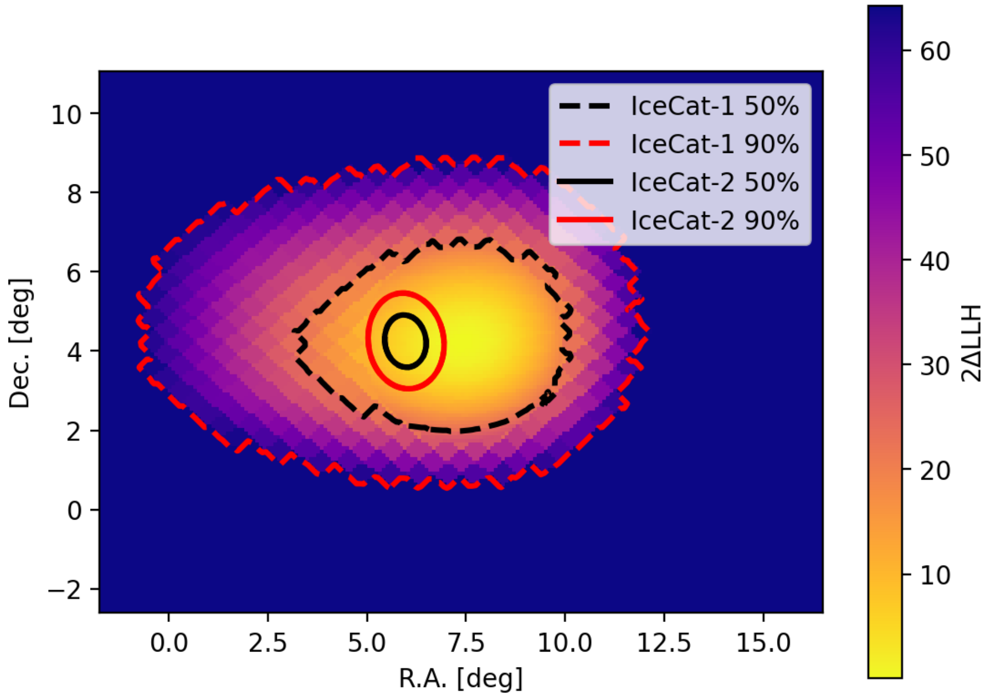
RUB

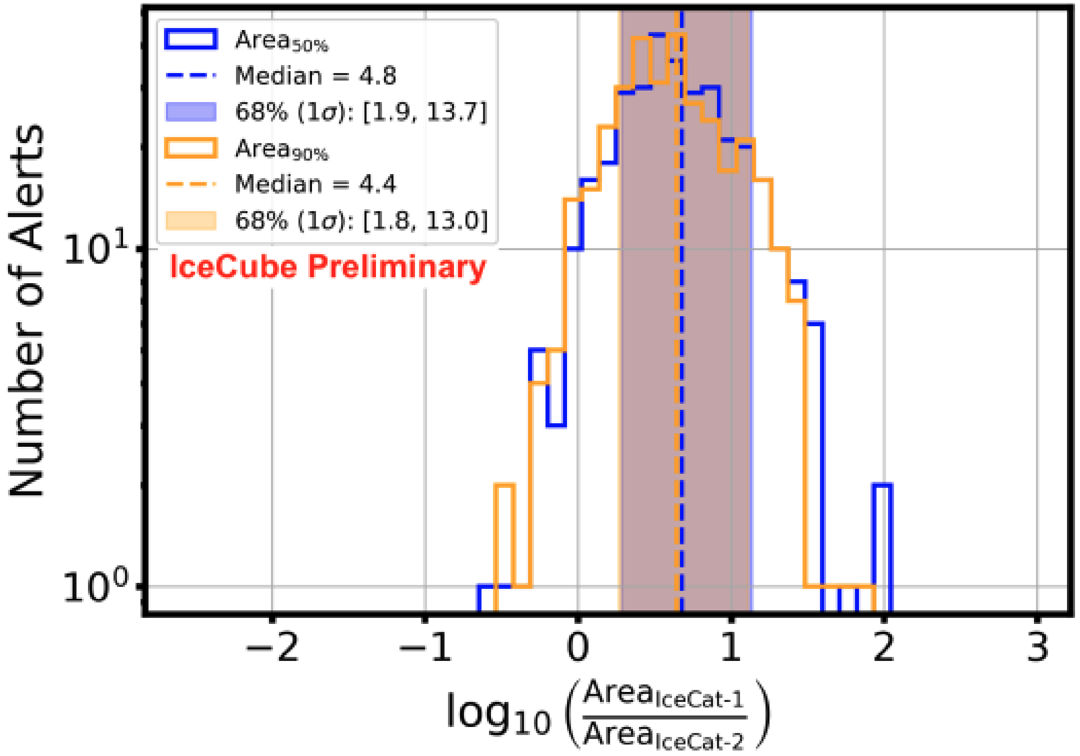
Improved in IceCube Realtime Stream: IceCat-2



A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176,
https://roc.icecube.wisc.edu/public/docs/IceCube_Update_Muon_Alert_Reco.pdf

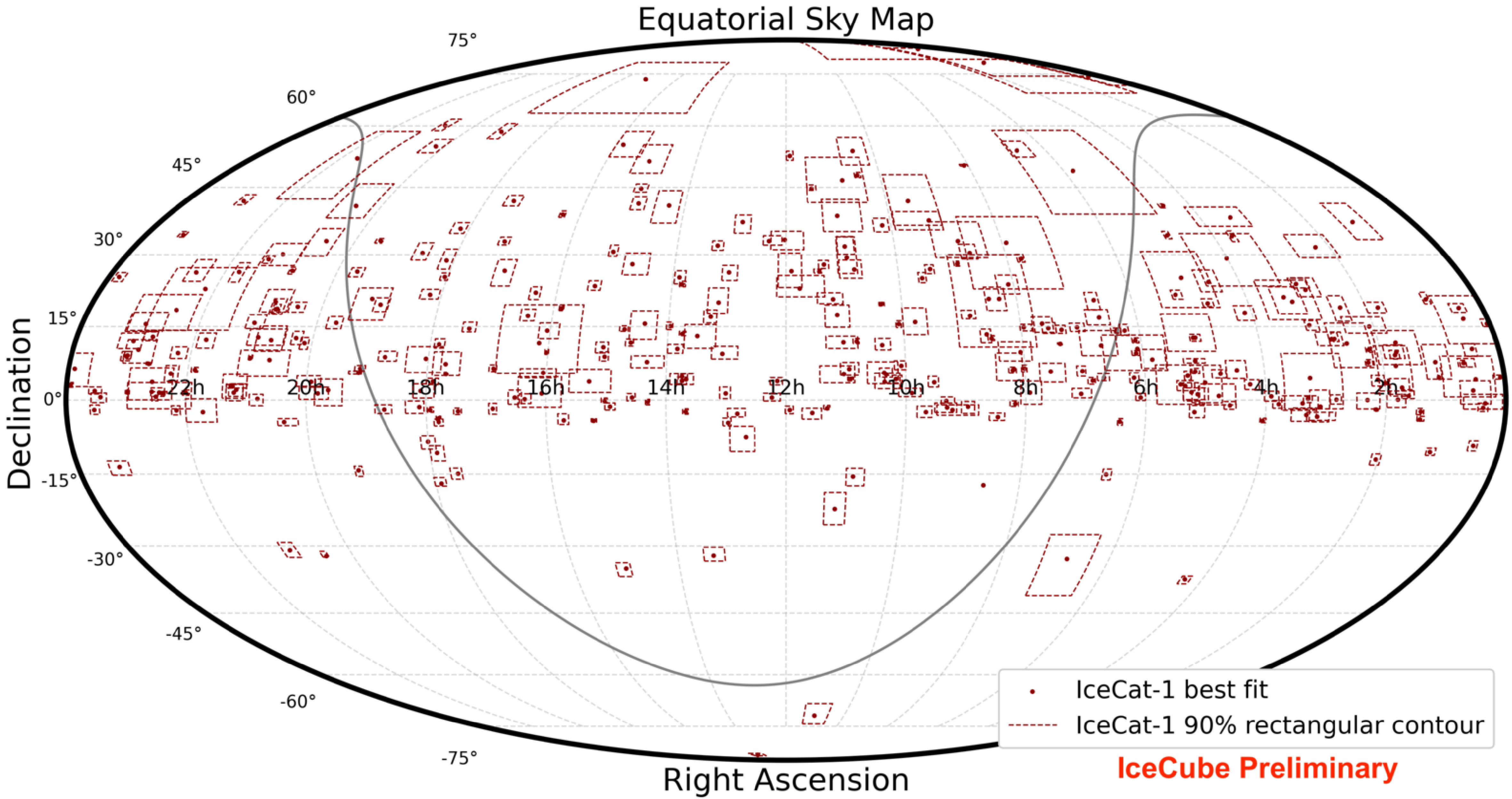
Improved in IceCube Realtime Stream: IceCat-2



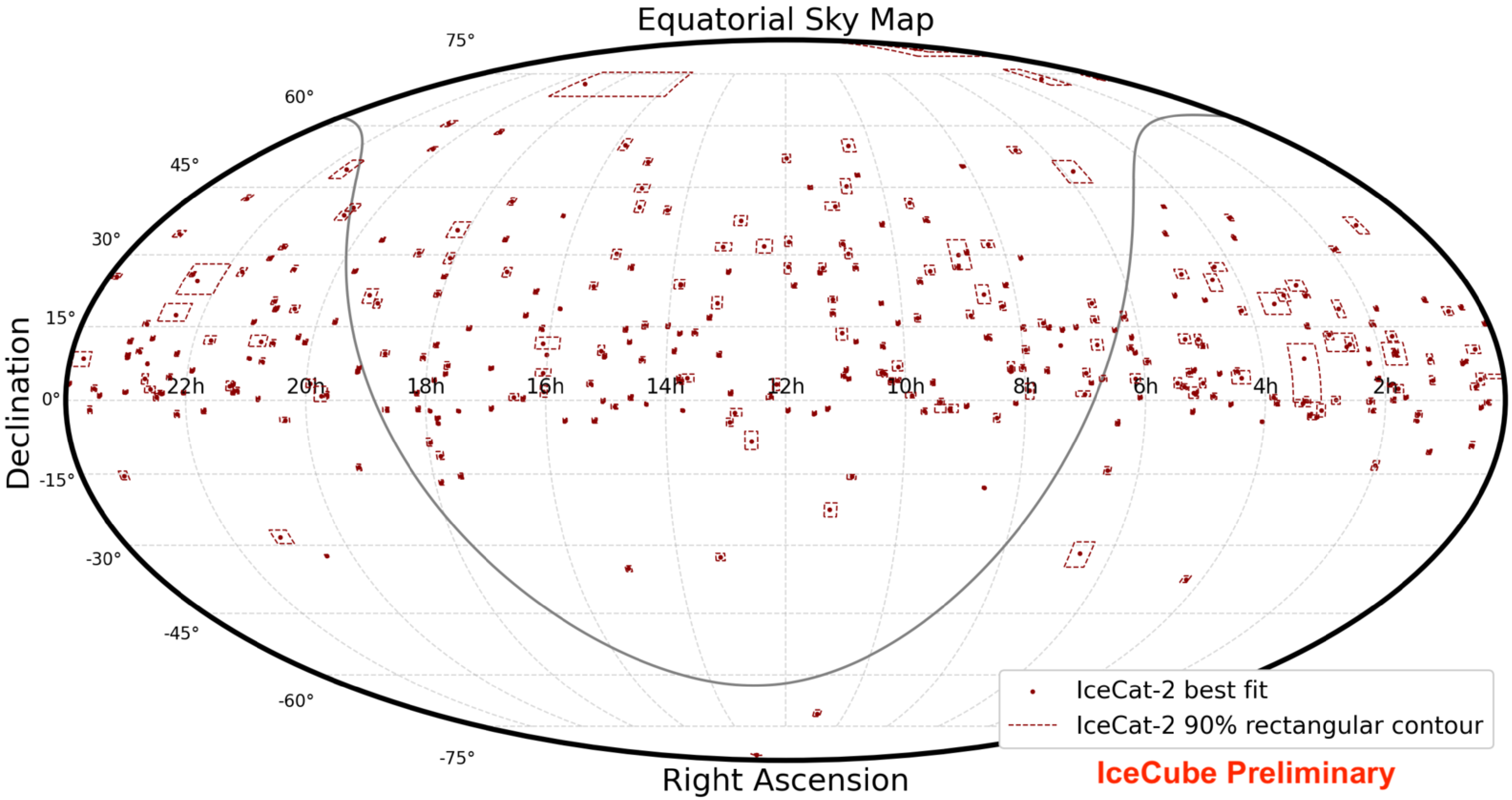


Improvement in 90% uncertainty area of factor 4.4
→ Archival alert catalog (IceCat-2) under development

A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176,
https://roc.icecube.wisc.edu/public/docs/IceCube_Update_Muon_Alert_Reco.pdf


Equatorial Sky Map
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
Declination
Right Ascension
IceCat-1 best fit
IceCat-1 90% rectangular contour
IceCube Preliminary

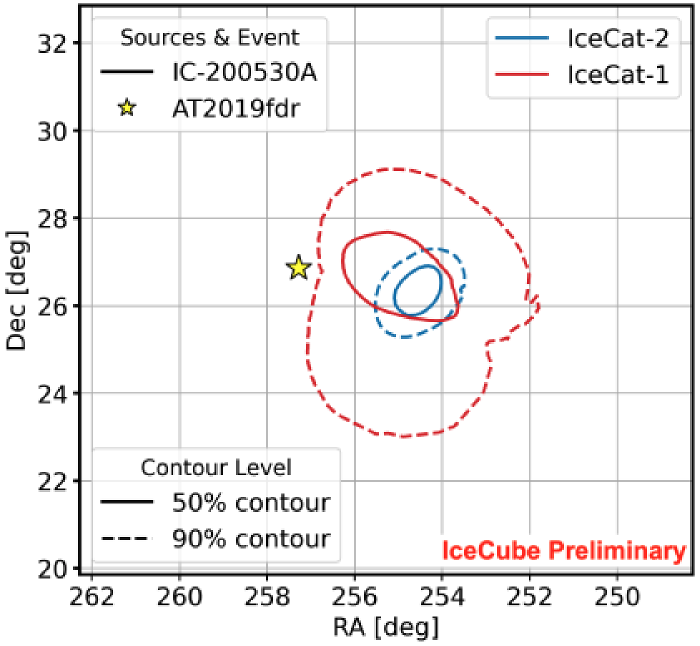
RUB



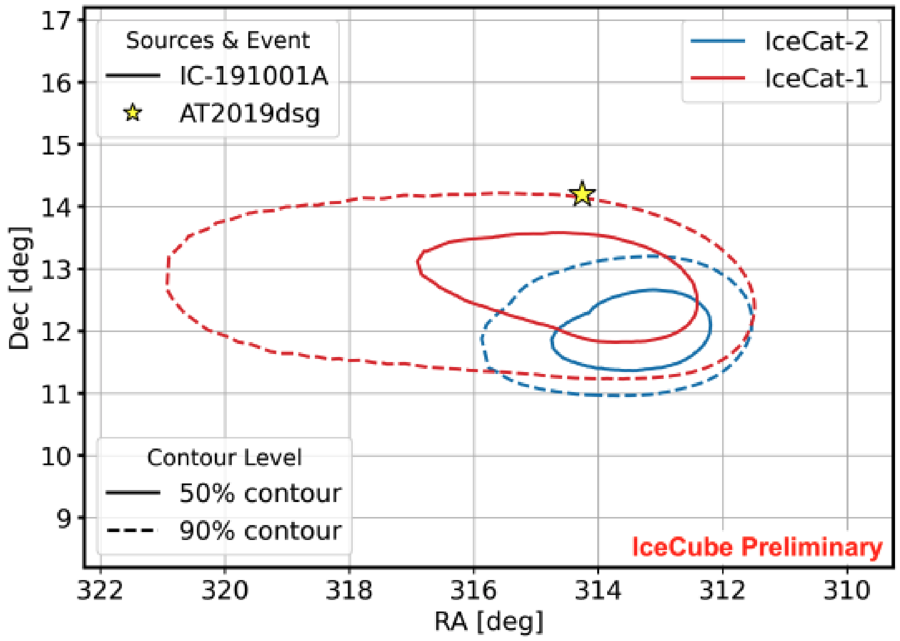
Equatorial Sky Map
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Declination
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
Right Ascension
IceCat-2 best fit
IceCat-2 90% rectangular contour
IceCube Preliminary

RUB

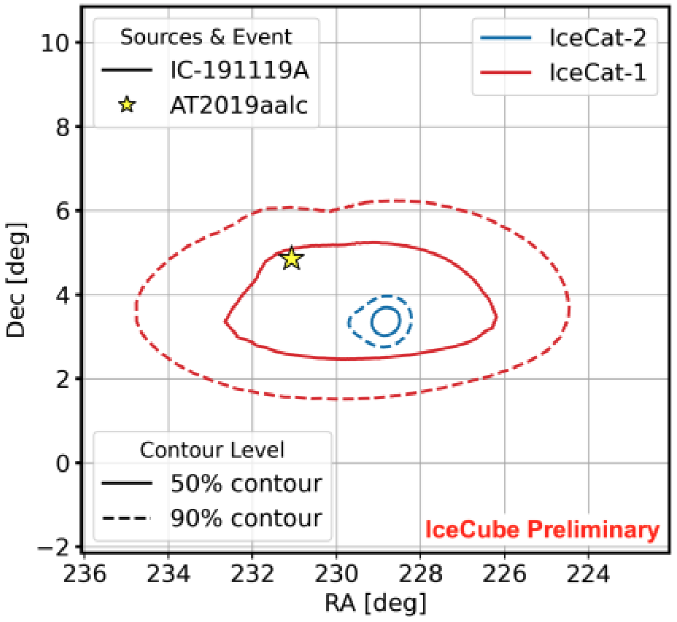
TDEs disfavored by new IceCat-2 Contours



(a) AT2019fdr



(b) AT2019dsg

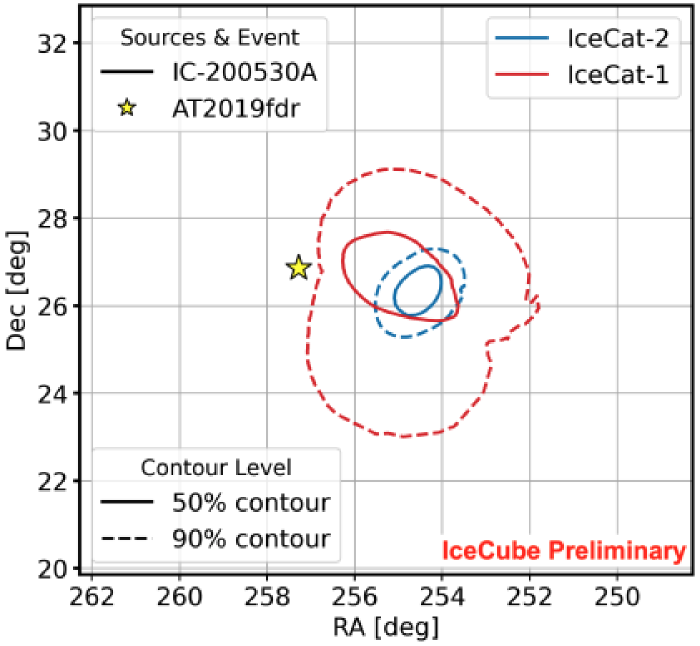


(c) AT2019aalc

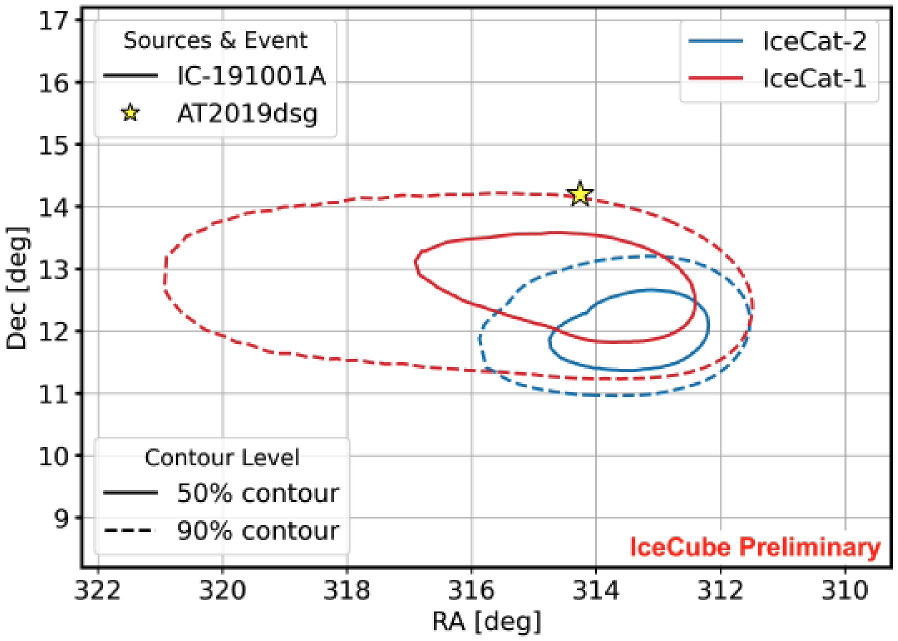
RUB

A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176

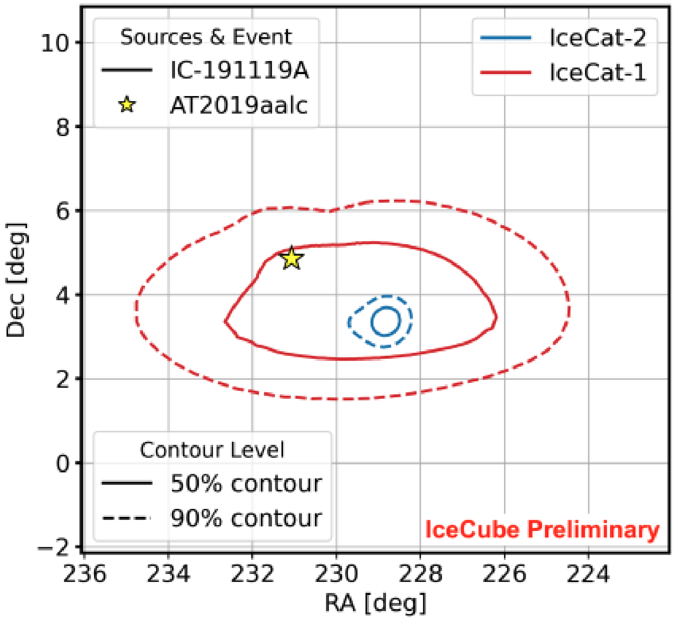
TDEs disfavored by new IceCat-2 Contours



(a) AT2019fdr

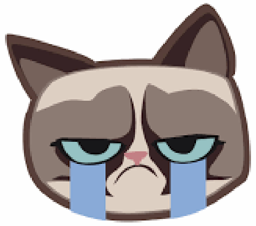


(b) AT2019dsg



(c) AT2019aalc

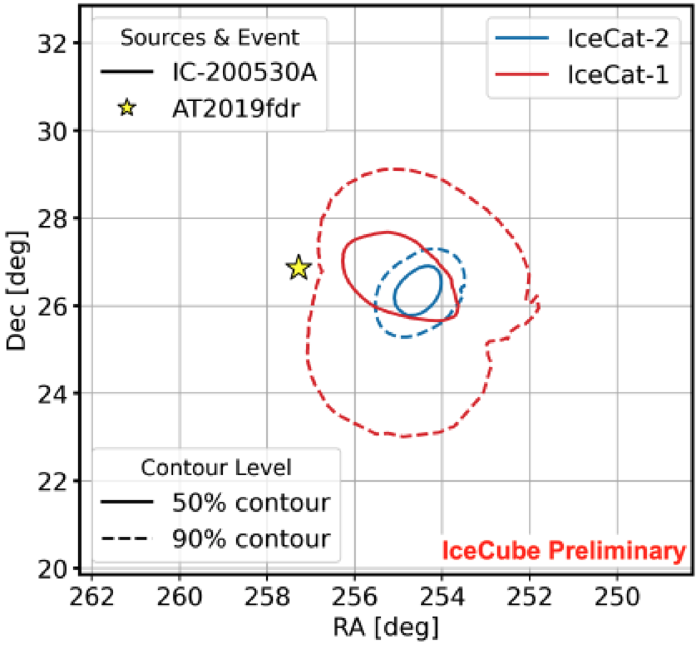
All three TDEs lie outside the new uncertainty contours



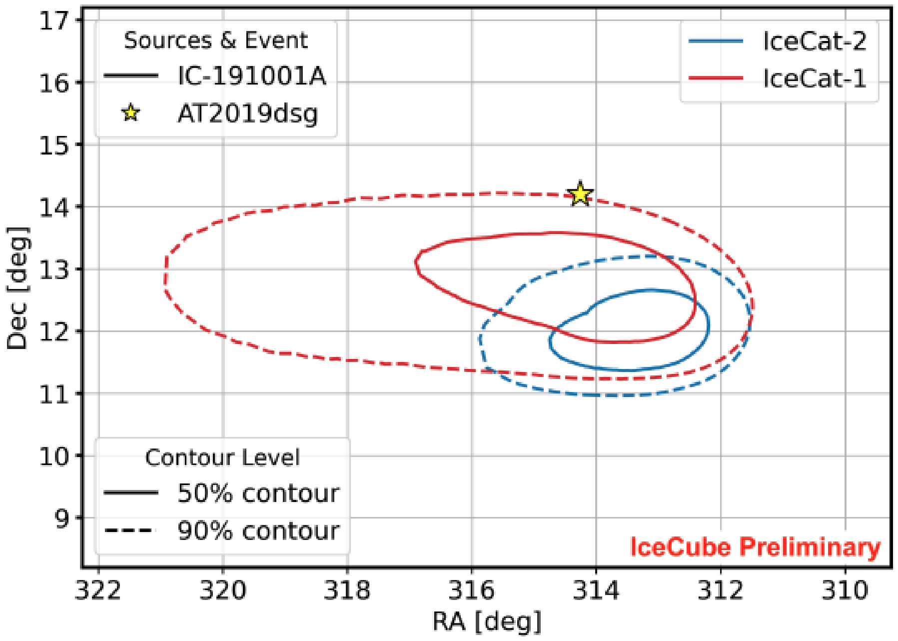
RUB

A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176

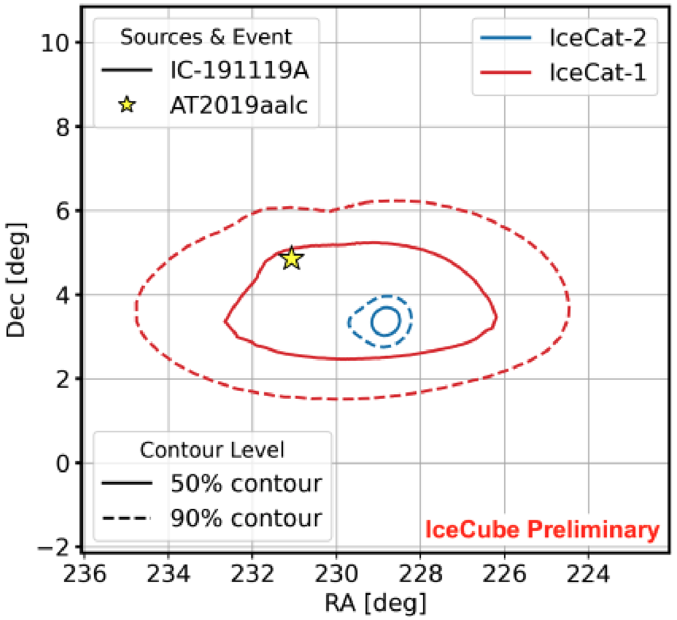
TDEs disfavored by new IceCat-2 Contours



(a) AT2019fdr

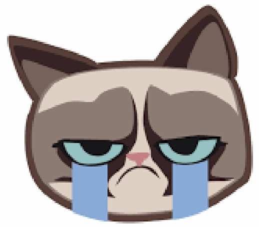


(b) AT2019dsg



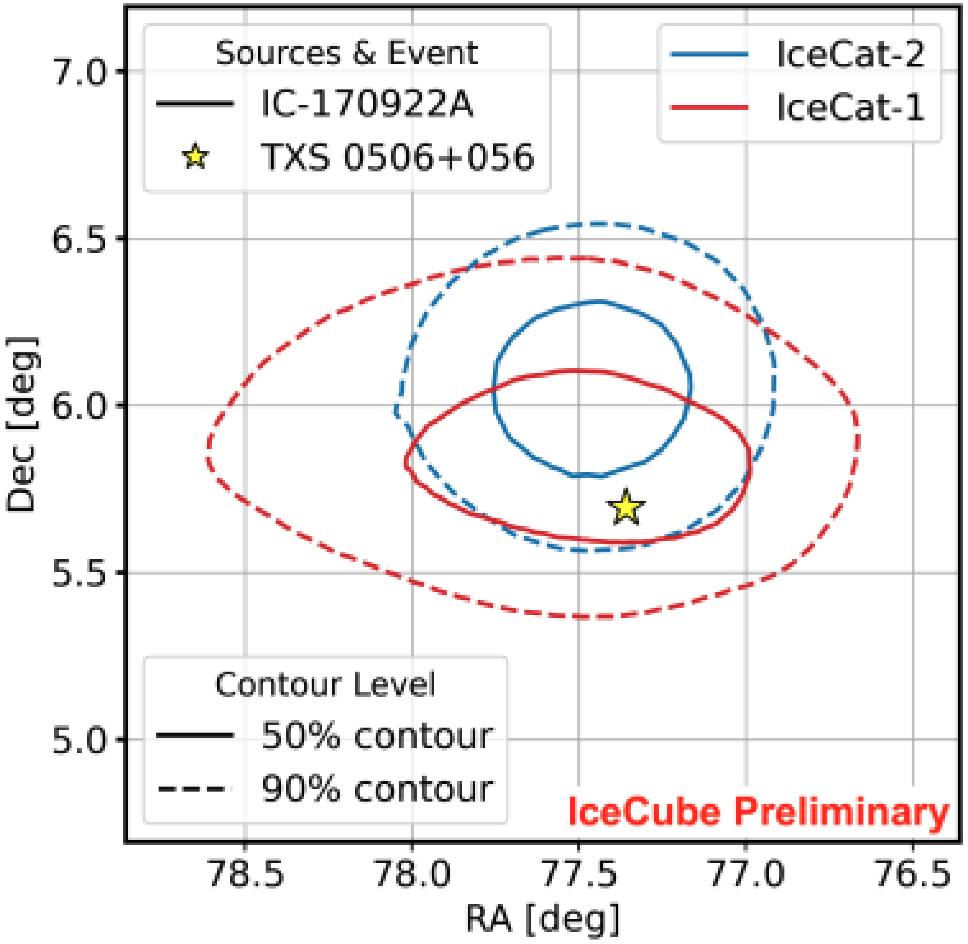
(c) AT2019aalc

Consistent with non-detection of TDE-neutrino correlation in full IceCube dataset
J. Necker et al. PoS-ICRC2023-1478, T. Pernice @ TeVPA 2025



A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176

TXS 0506+056 still within the contour



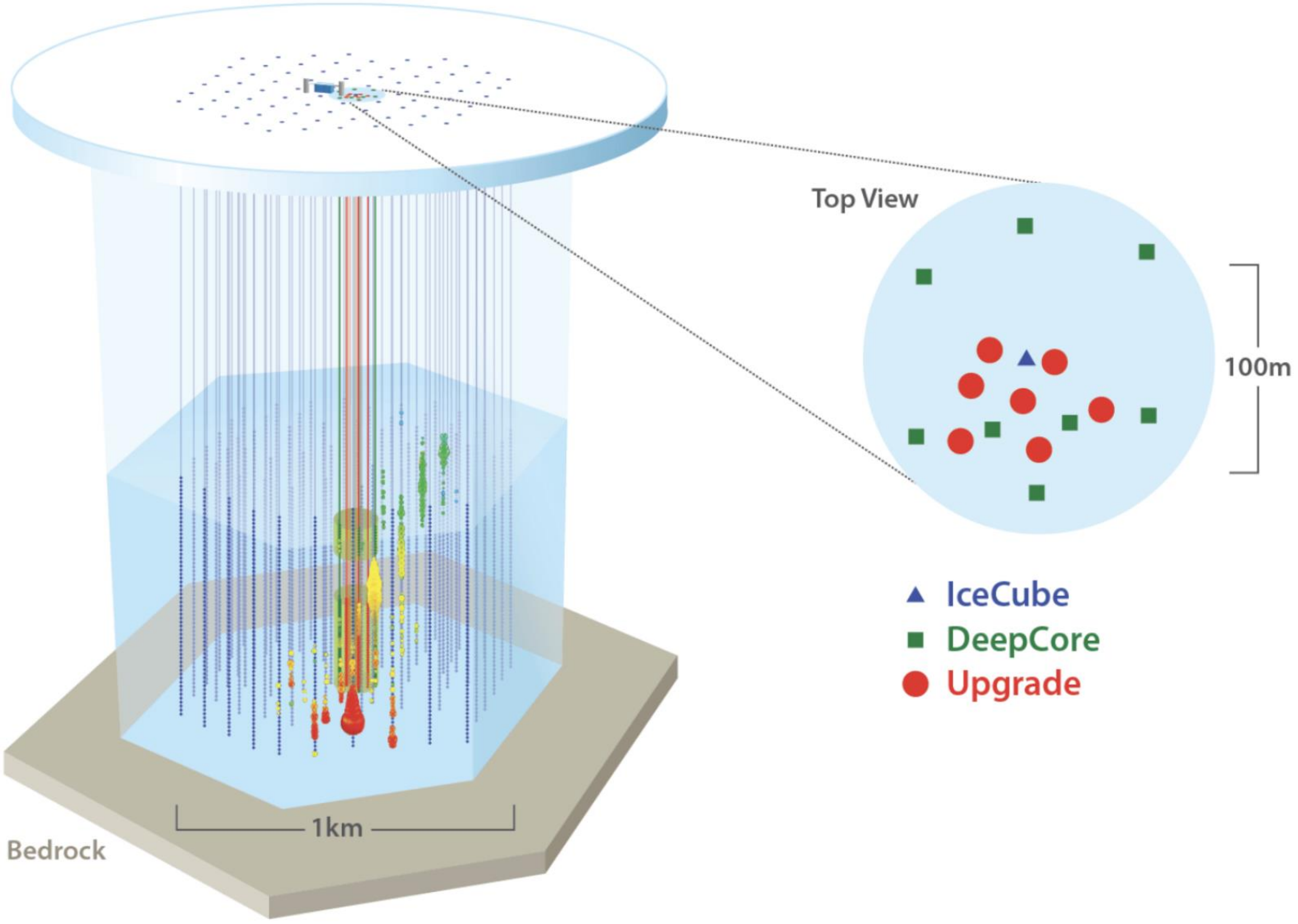
Further improvement expected

New algorithms

- E.g. transformer-encoded normalizing flows

Better understanding of ice with IceCube Upgrade

→ Reduced systematic uncertainties



RUB

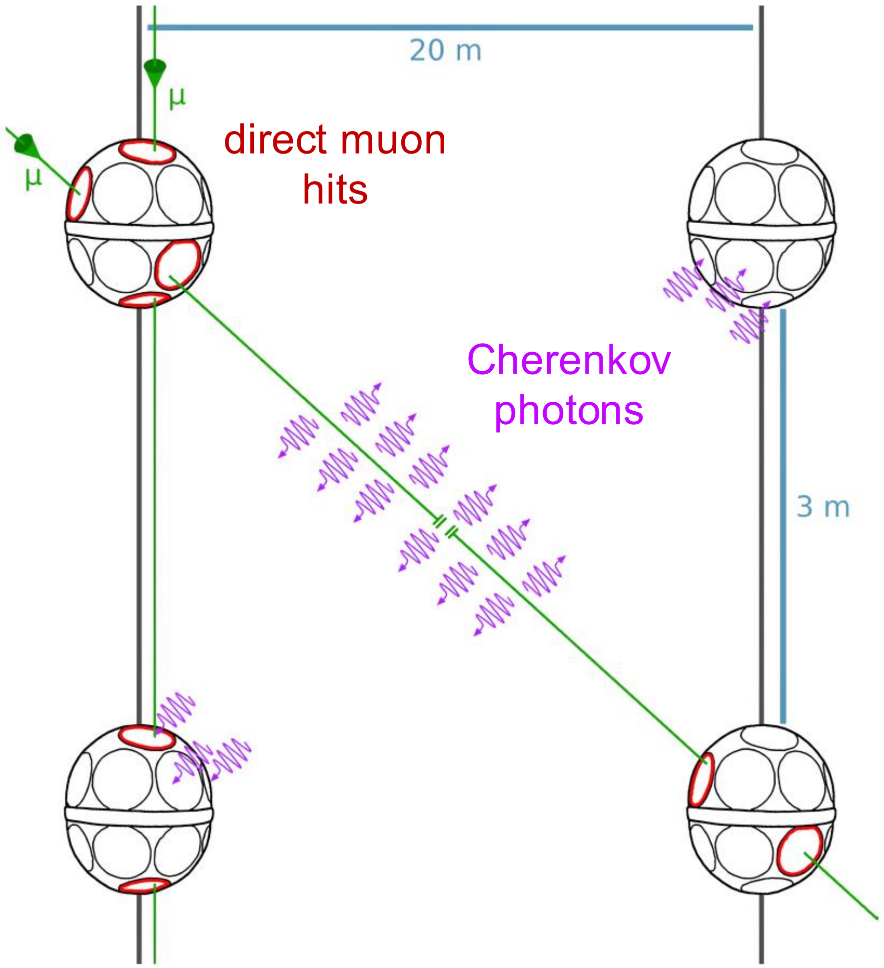
Further improvement expected

New algorithms

- E.g. transformer-encoded normalizing flows

Better understanding of ice with IceCube Upgrade

→ Reduced systematic uncertainties



How can we improve our searches for neutrino sources?

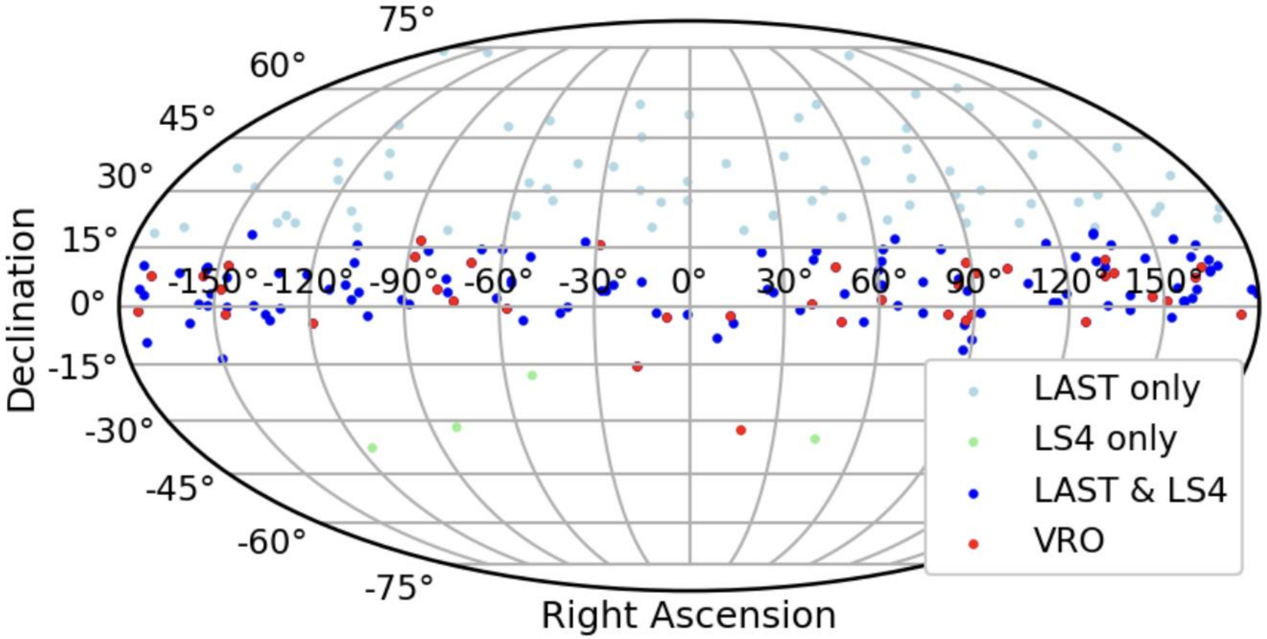
Improve follow-up sky coverage and depth

RUB

Improved sky coverage of optical follow-up

La Silla Schmidt Telescope (LS4): 20 sqr. deg.

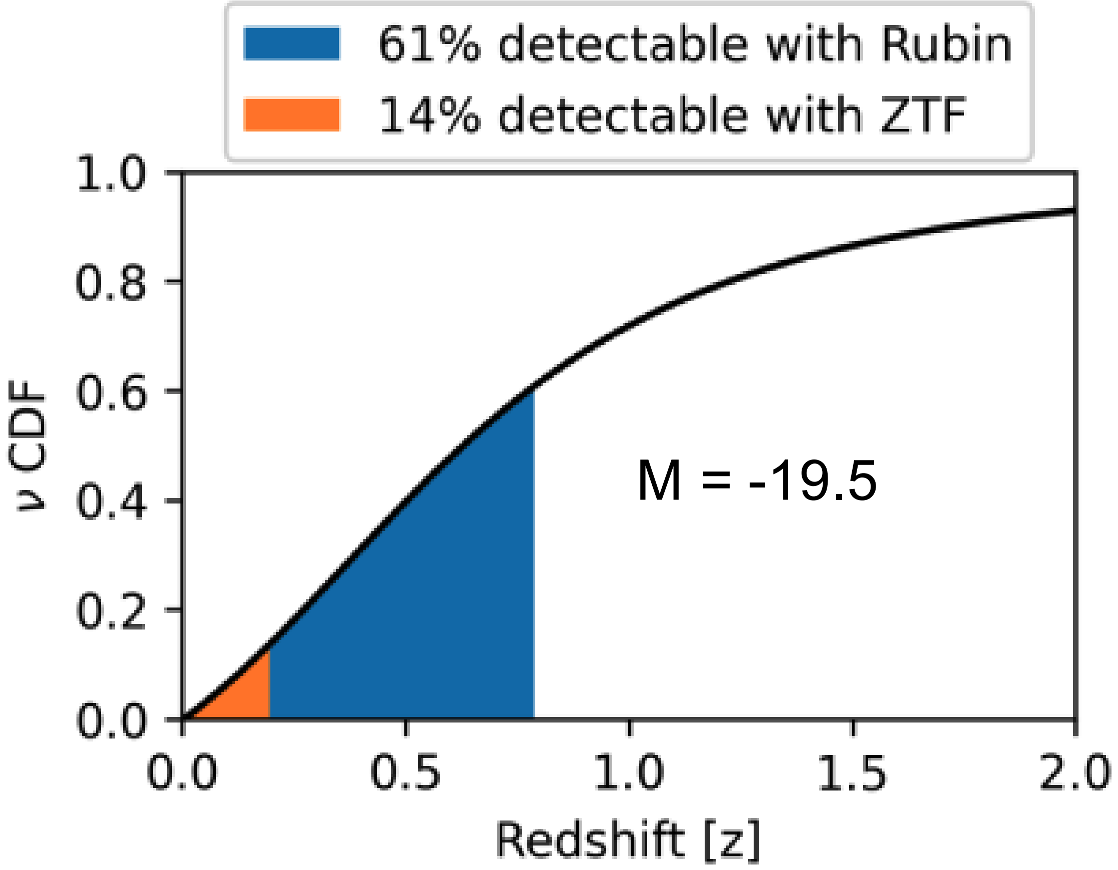
Large Array Survey Telescope (LAST)



 Miller, ... AF, ... et al. PASP 137 (2025)

Ben-Ami, Ofek, Polishook, AF et al. PASP 135 (2023)

Improved optical follow-up in depth



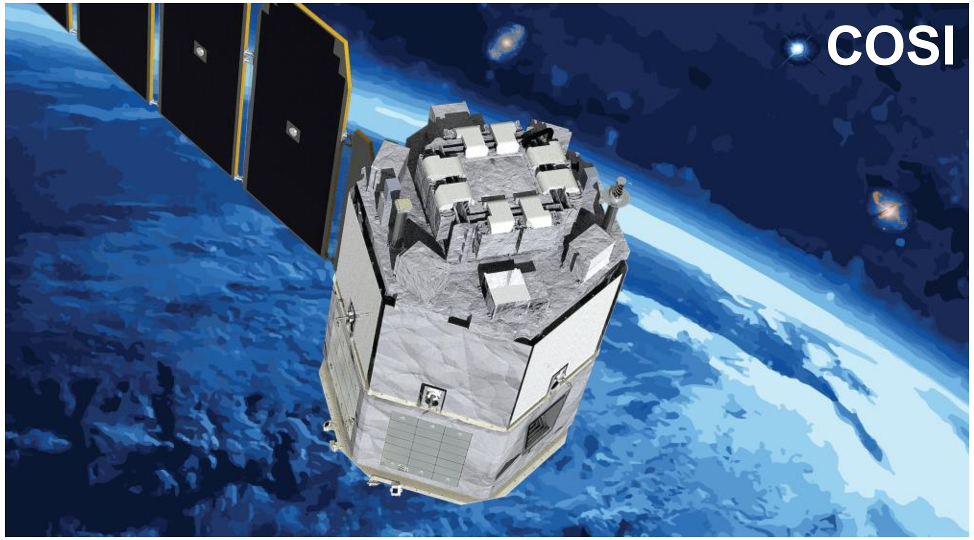
First light: July 2025, Alert stream in preparation
Rubin ToO report: 2-12 triggers/year

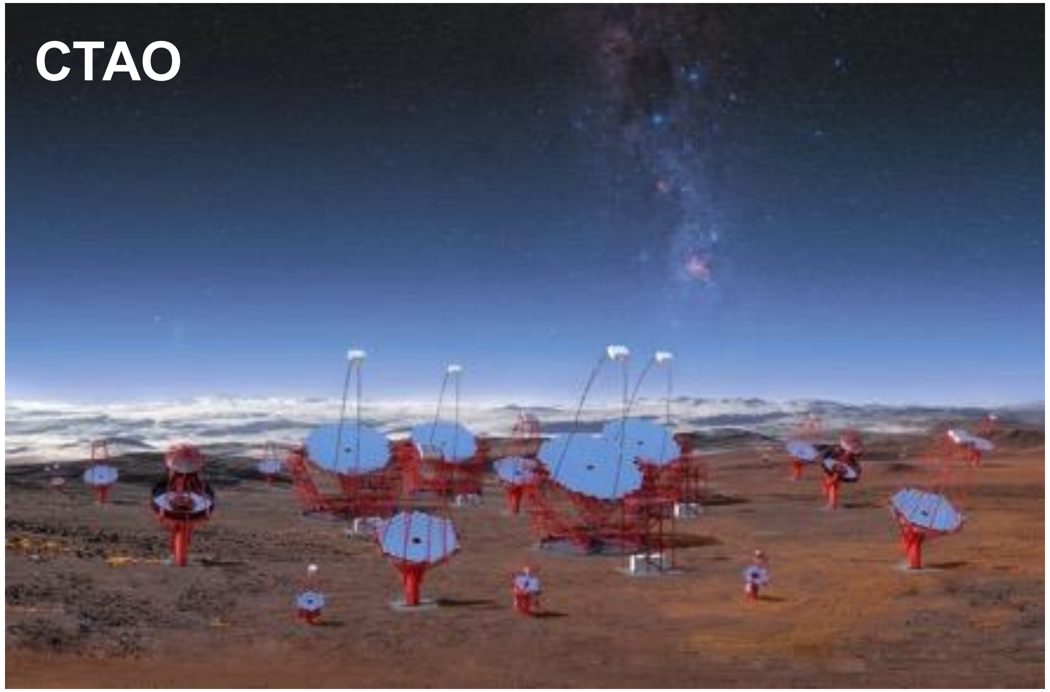
https://arxiv.org/pdf/2411.04793

How can we improve our searches for neutrino sources?

Improve wavelength coverage

Improve Wavelength Coverage

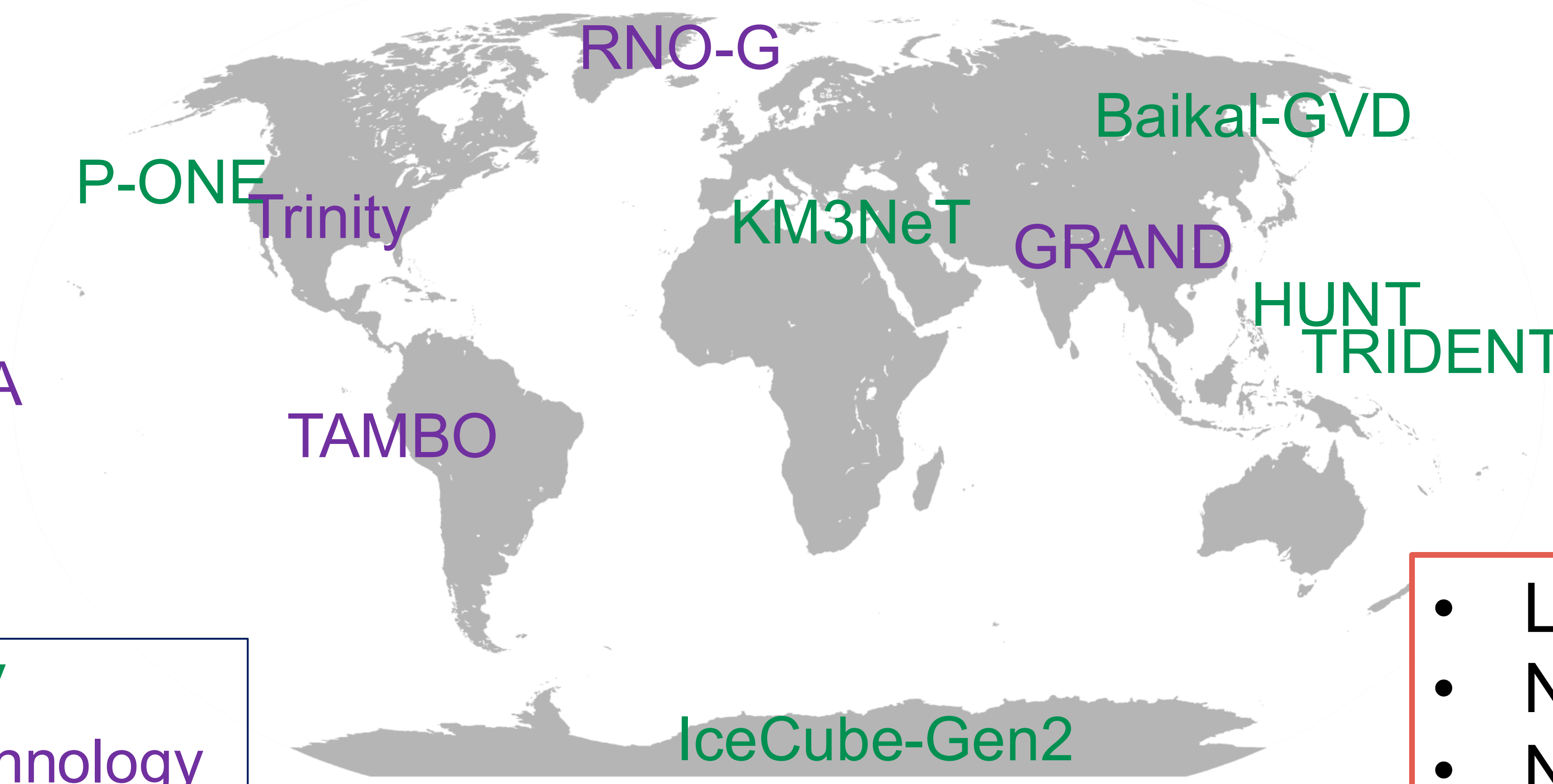




How can we improve our searches for neutrino sources?

Include new neutrino instruments

New Neutrino Detectors



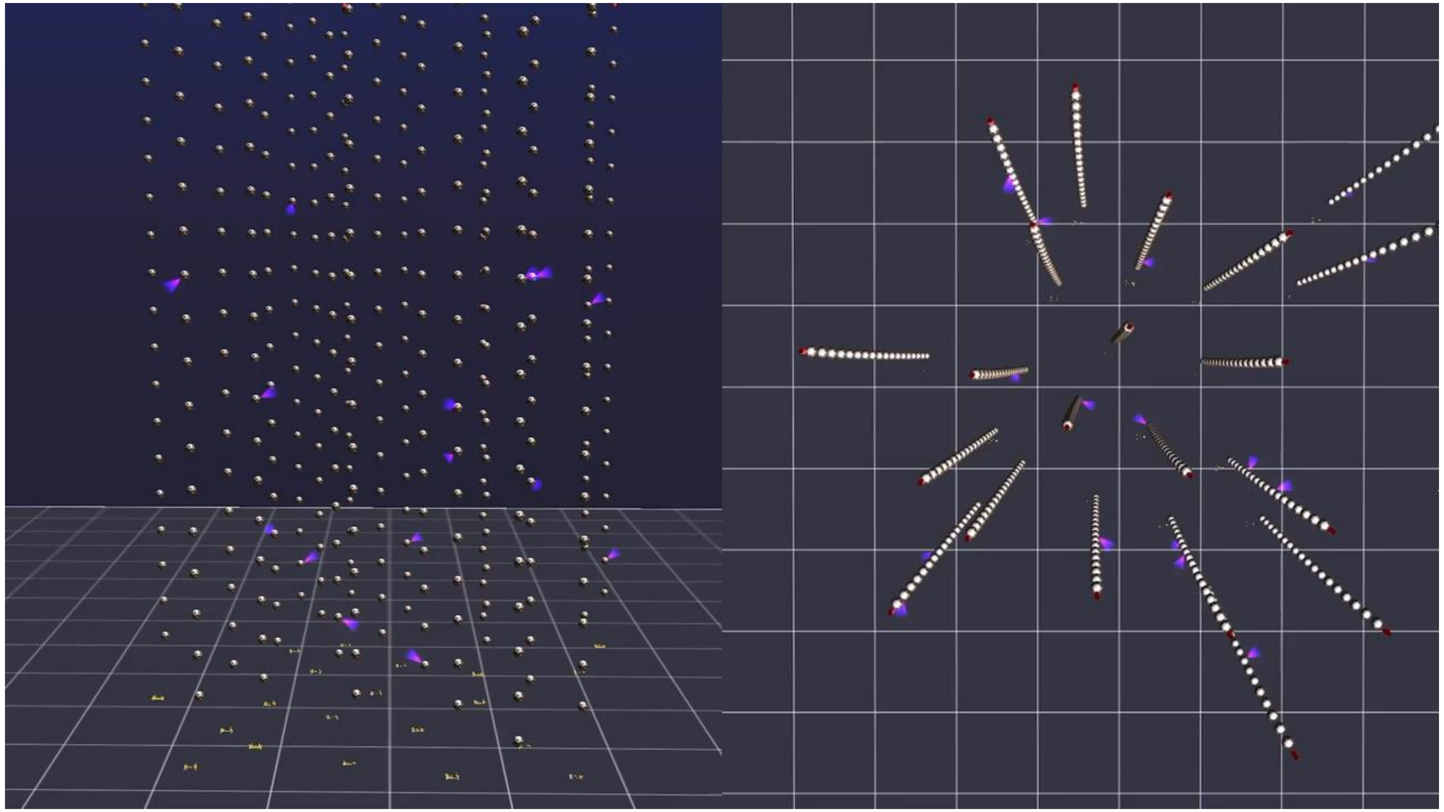
POEMMA
PUEO

TeV-PeV
New technology

- Larger detectors
- New sites
- New technologies

New Instrument enters the game

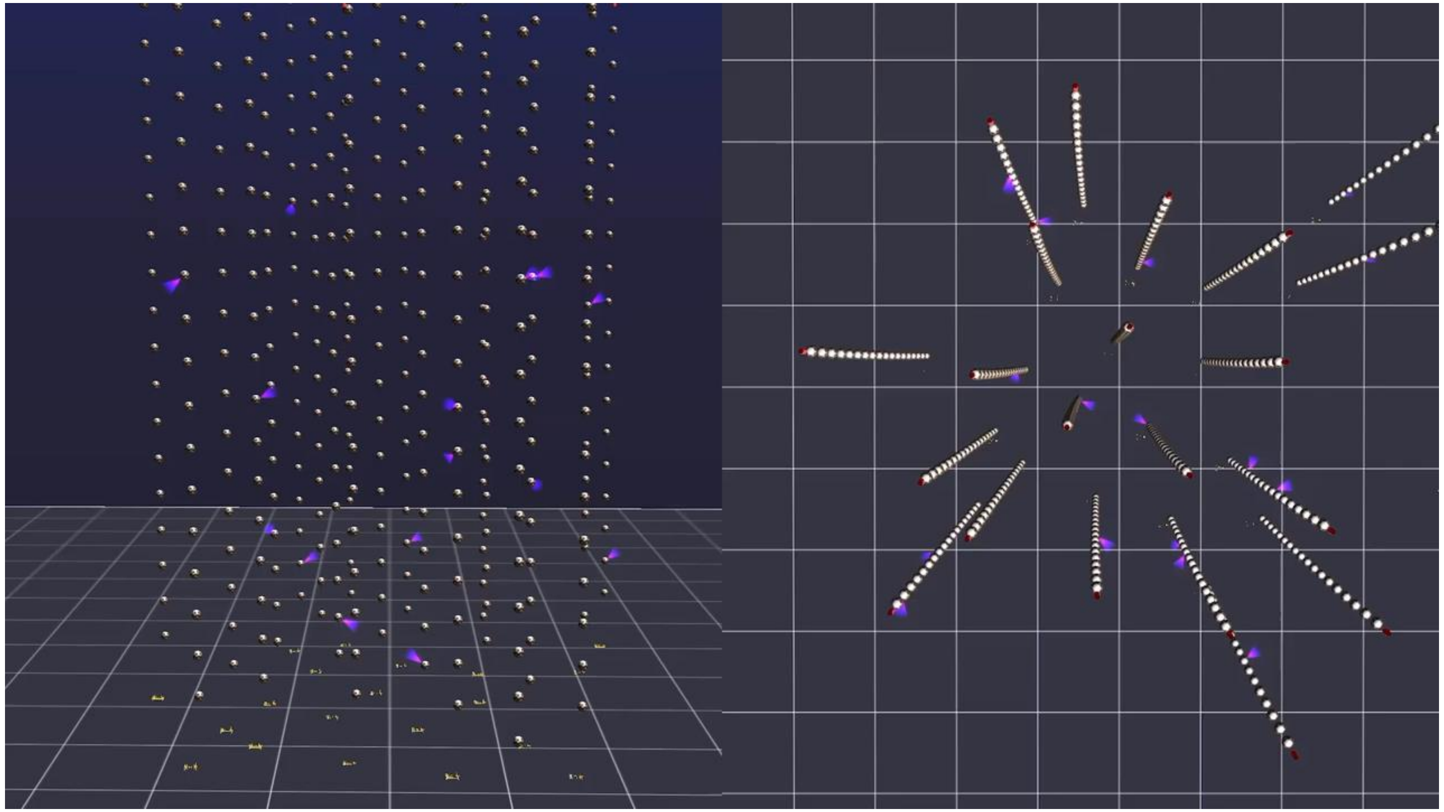
Highest energy neutrino event (220PeV) observed by KM3NeT (with partial detector)

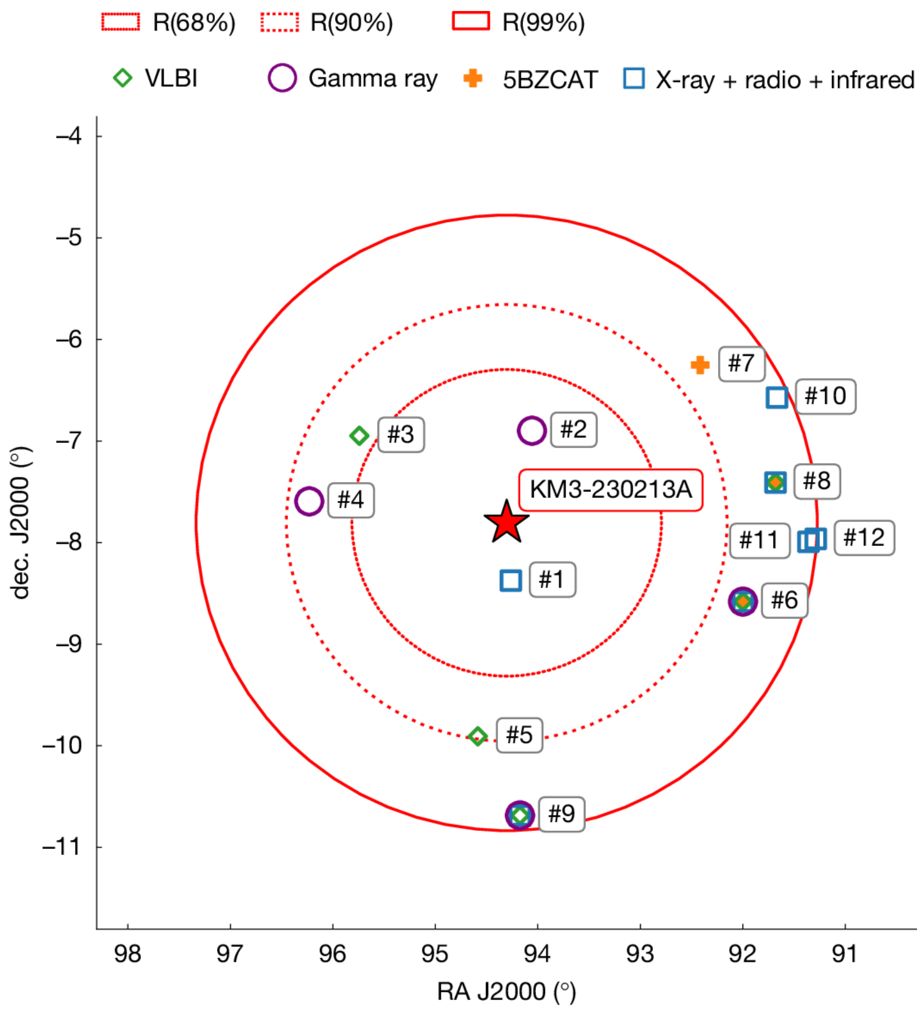


KM3NeT Collaboration, Nature 638 (2025) & arXiv:2502.08484 & arXiv:2502.08387

New Instrument enters the game

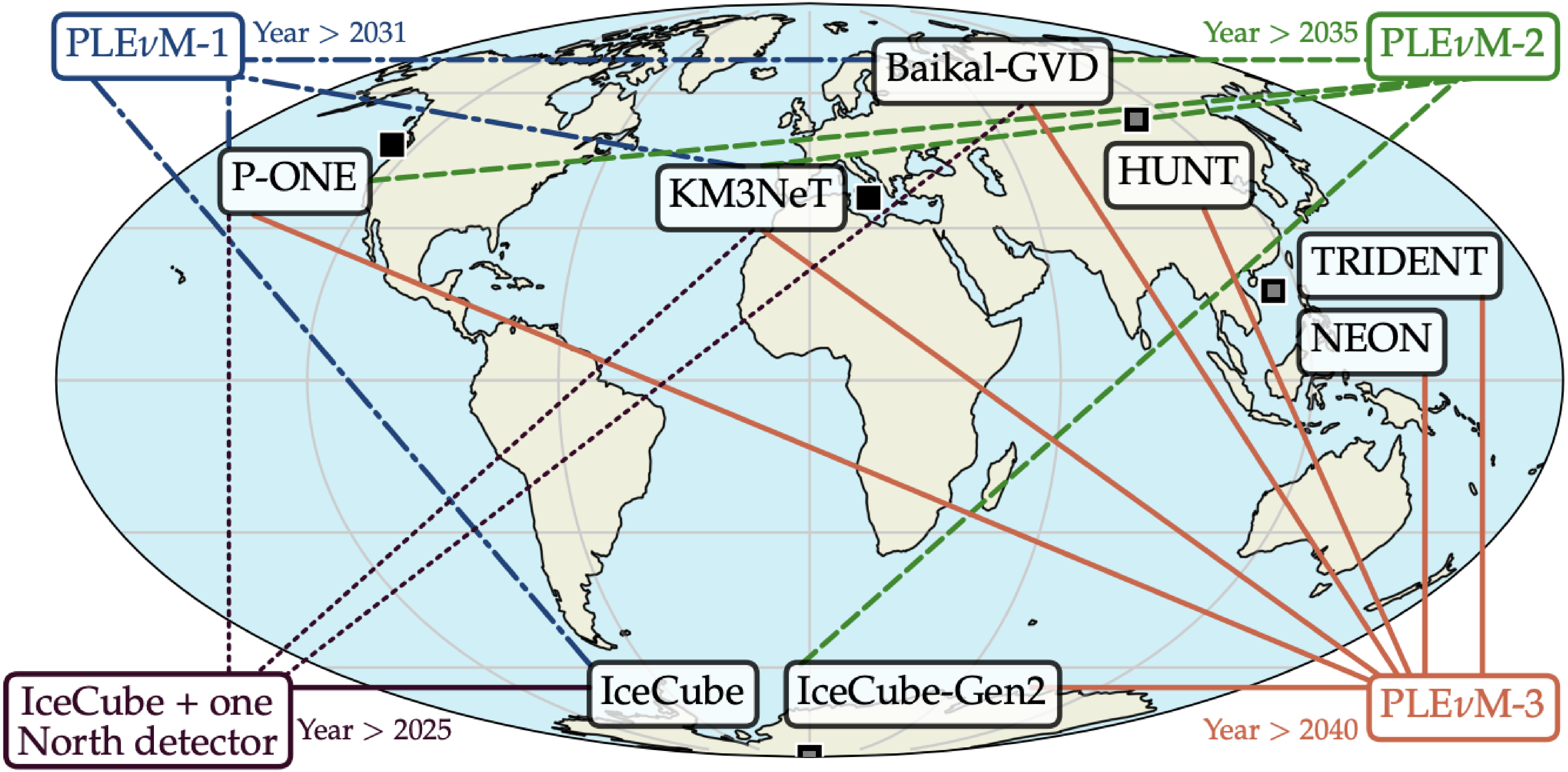
Highest energy neutrino event (220PeV) observed by KM3NeT (with partial detector)



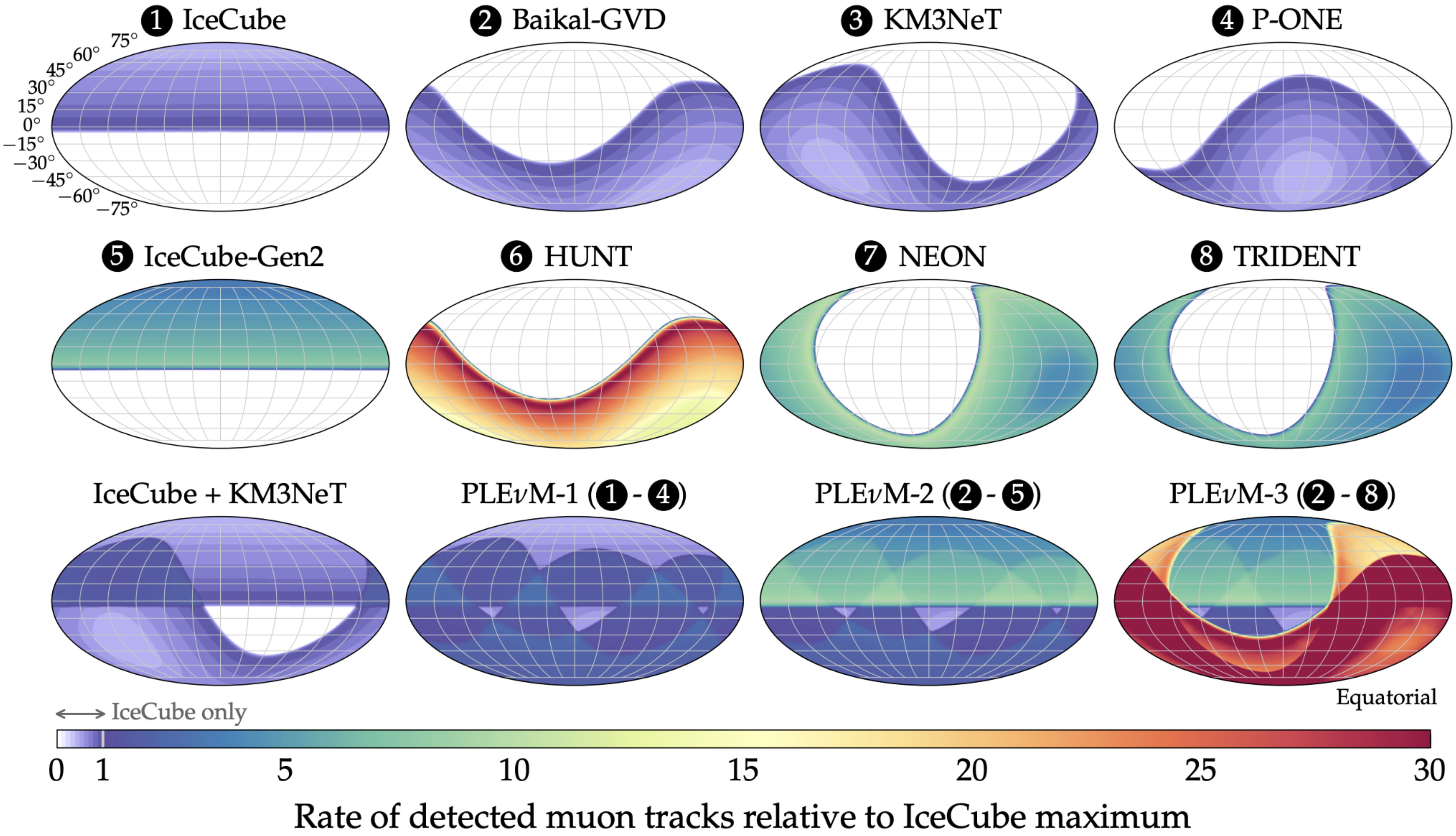


No unique blazar counterpart. Galactic origin unlikely

KM3NeT Collaboration, Nature 638 (2025) & arXiv:2502.08484 & arXiv:2502.08387


PLEνM-1
Year > 2031
Year > 2035
PLEνM-2
Baikal-GVD
P-ONE
KM3NeT
HUNT
TRIDENT
NEON
IceCube + one
North detector
Year > 2025
IceCube
IceCube-Gen2
PLEνM-3
Year > 2040

RUB

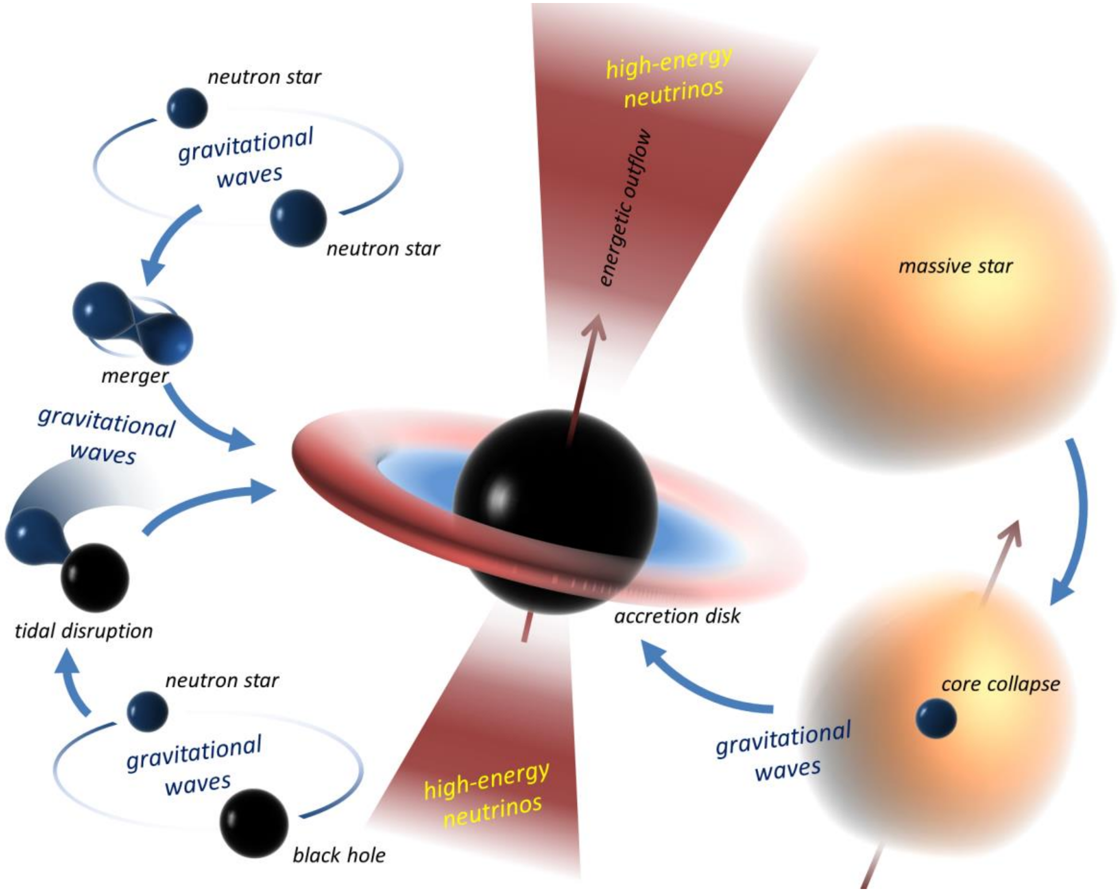


Schumacher et al. Phys.Rev.D 112 (2025)

How can we improve our searches for neutrino sources?

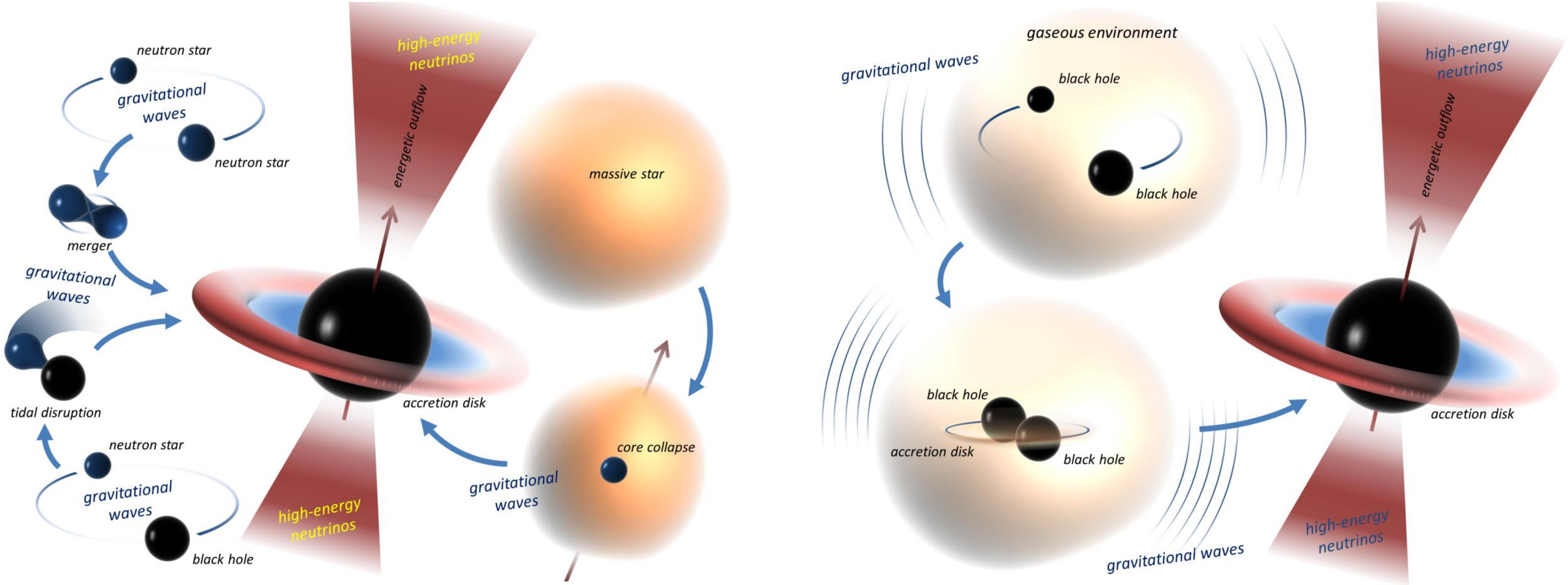
Include new messengers

Neutrinos and Gravitational Waves



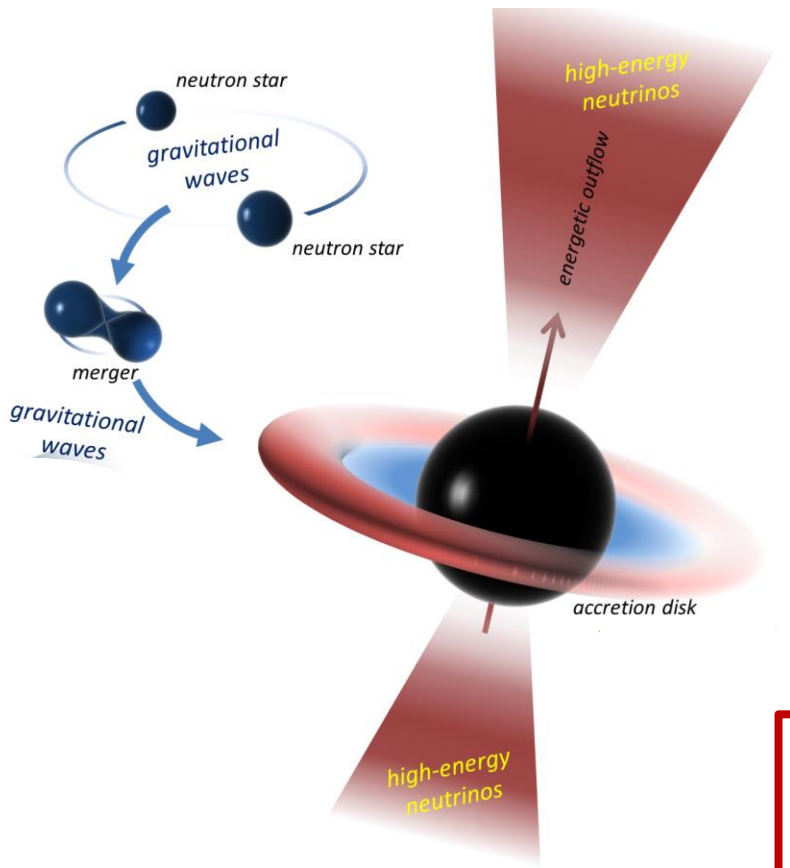
Credit: I. Bartos

Neutrinos and Gravitational Waves

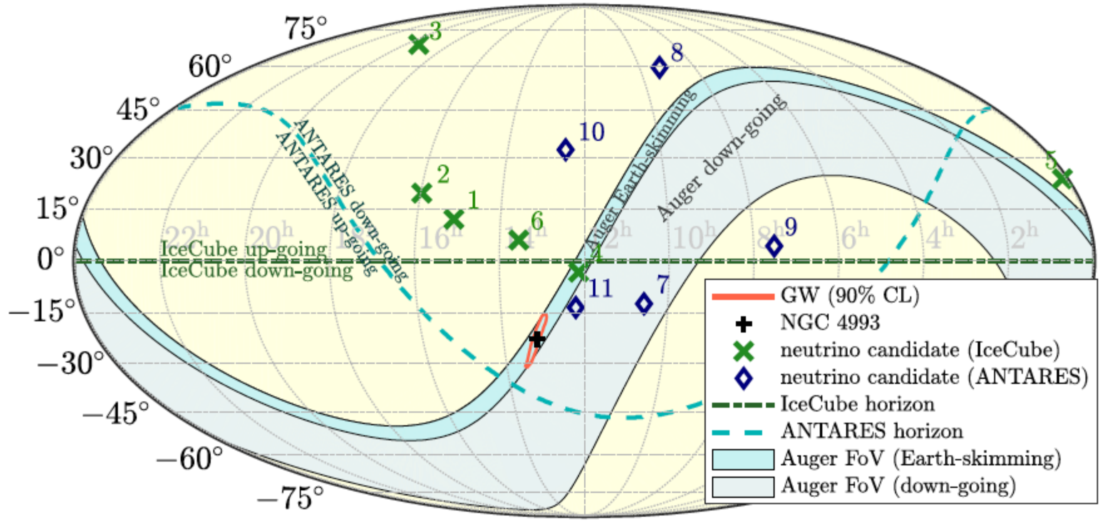


Credit: I. Bartos

TeV Neutrinos and Gravitational Waves: BNS merger



GW170817: Search for neutrinos in ANTARES, Auger and IceCube data in +/-500 sec



Neutrino could help to constrain direction and teach us about the GW source environment

LIGO, Virgo, Auger, ANTARES, IceCube,ApJ 850 (2017)

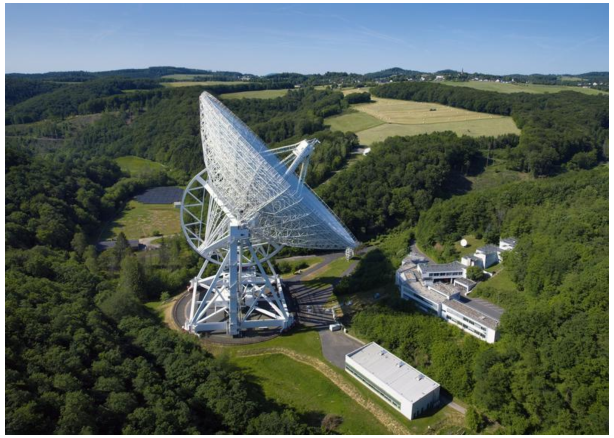
Summary

- Diffuse neutrino flux detected
- Sources mostly unknown
- Promising strategy: Identification of sources through electro-magnetic counterpart
- Realtime program enables counterpart searches for transient and variable sources

Graduate School on Astro-Particle Physics, Jan. 18-23, 2026 in Bad Honnef

We have a fantastic program including lectures on:

- Introduction to Astroparticle physics (Foteini Oikonomou)
- Astrophysical Plasmas and Cosmic Ray Propagation (Daniel Verscharen)
- Cosmic Ray Flux Calculations and Particle Physics Input (Michael Schmelling)
- Radio Astronomy (Laura Spittler)
- Neutrino Astronomy (Dorothea Samtleben)
- Galactic Magnetic Fields (Marijke Haverkorn)
- Multi-Messenger Astronomy (Marek Kowalski)
- Gravitational Waves (Michela Mapelli)
- Introduction to Machine learning with hands-on session

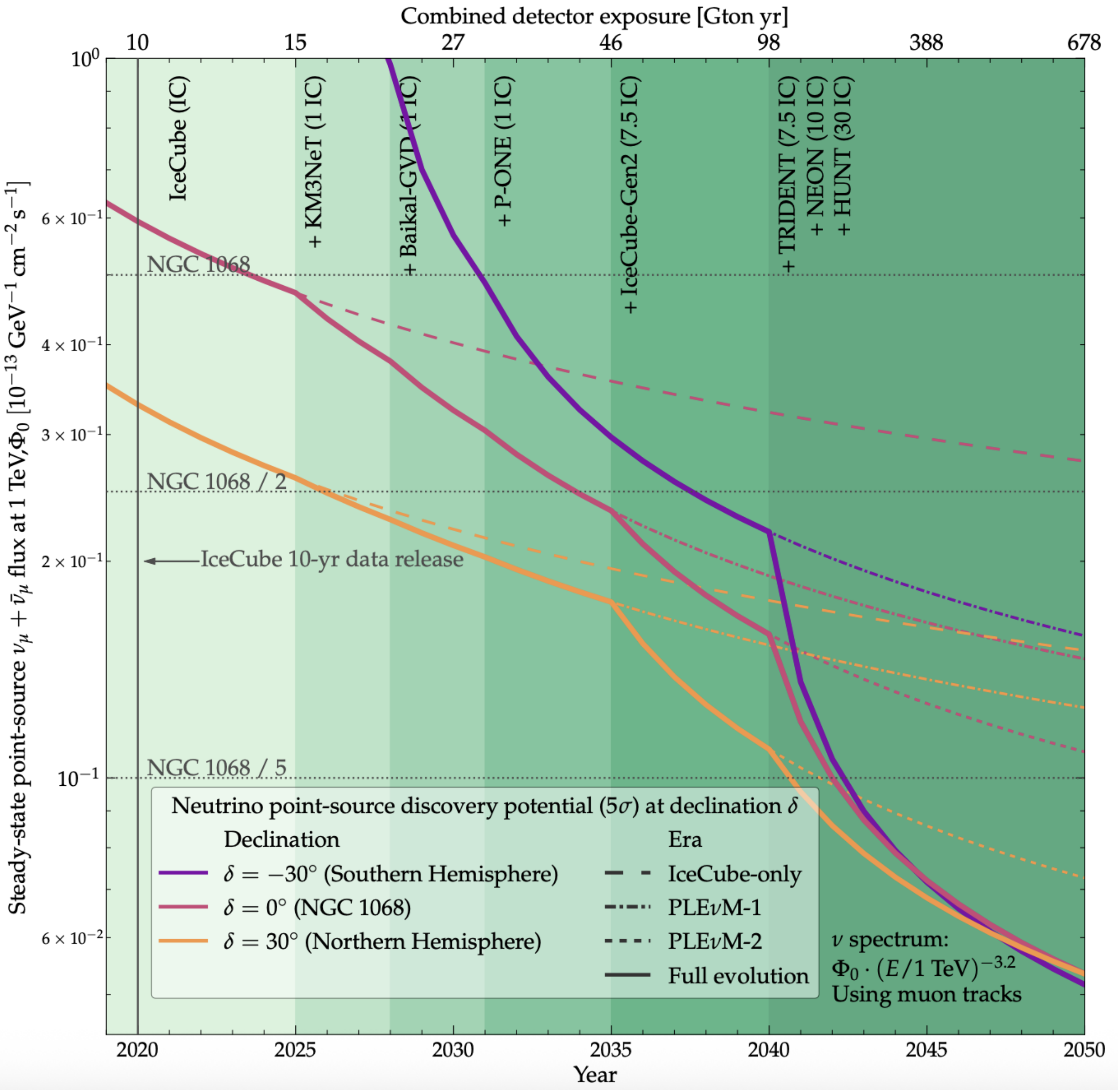


and an **evening lecture by Jocelyn Bell Burnell!**

Costs for one week of full board only 200 Euros (100 Euros for DPG members)

https://indico-sfb1491.epp.physik.tu-dortmund.de/event/87/

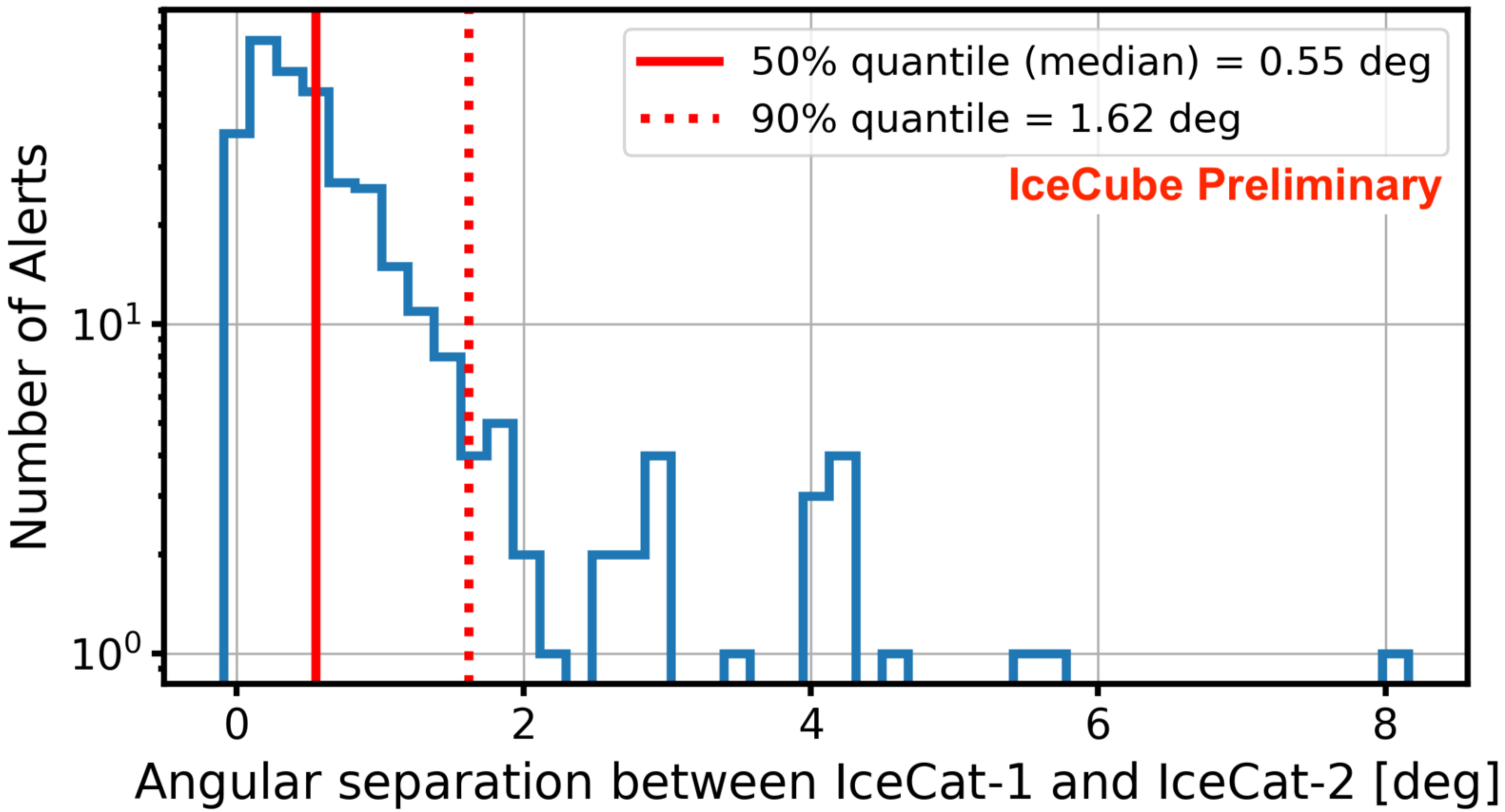
Back up



Combined detector exposure [Gton yr]
10
15
27
46
98
388
678
IceCube (IC)
+ KM3NeT (1 IC)
+ Baikal-GVD (1 IC)
+ P-ONE (1 IC)
+ IceCube-Gen2 (7.5 IC)
+ TRIDENT (7.5 IC)
+ NEON (10 IC)
+ HUNT (30 IC)
NGC 1068
NGC 1068 / 2
NGC 1068 / 5
IceCube 10-yr data release
Steady-state point-source $\nu_\mu + \bar{\nu}_\mu$ flux at 1 TeV, Φ_0 [10^{-13} GeV^{-1} cm^{-2} s^{-1}]
10^0
6×10^{-1}
4×10^{-1}
3×10^{-1}
2×10^{-1}
10^{-1}
6×10^{-2}
Neutrino point-source discovery potential (5σ) at declination δ
Declination
$\delta = -30°$ (Southern Hemisphere)
$\delta = 0°$ (NGC 1068)
$\delta = 30°$ (Northern Hemisphere)
Era
IceCube-only
PLEνM-1
PLEνM-2
Full evolution
ν spectrum:
$\Phi_0 \cdot (E/1\ \text{TeV})^{-3.2}$
Using muon tracks
2020
2025
2030
2035
2040
2045
2050
Year

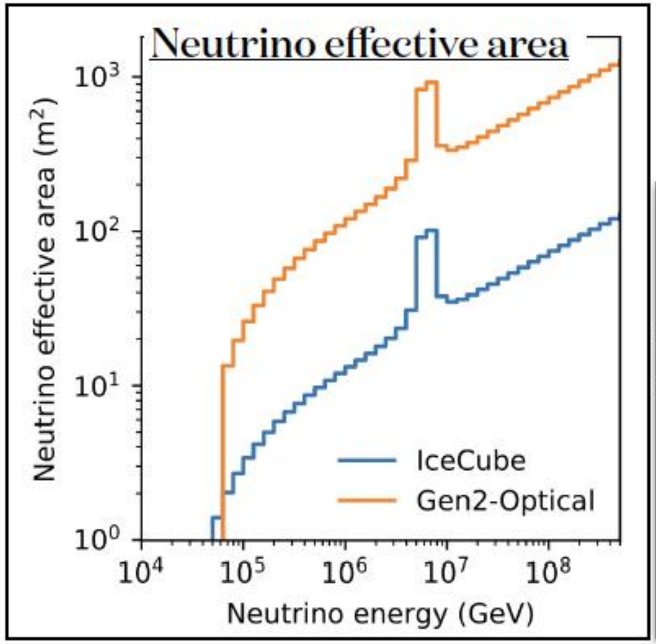
RUB

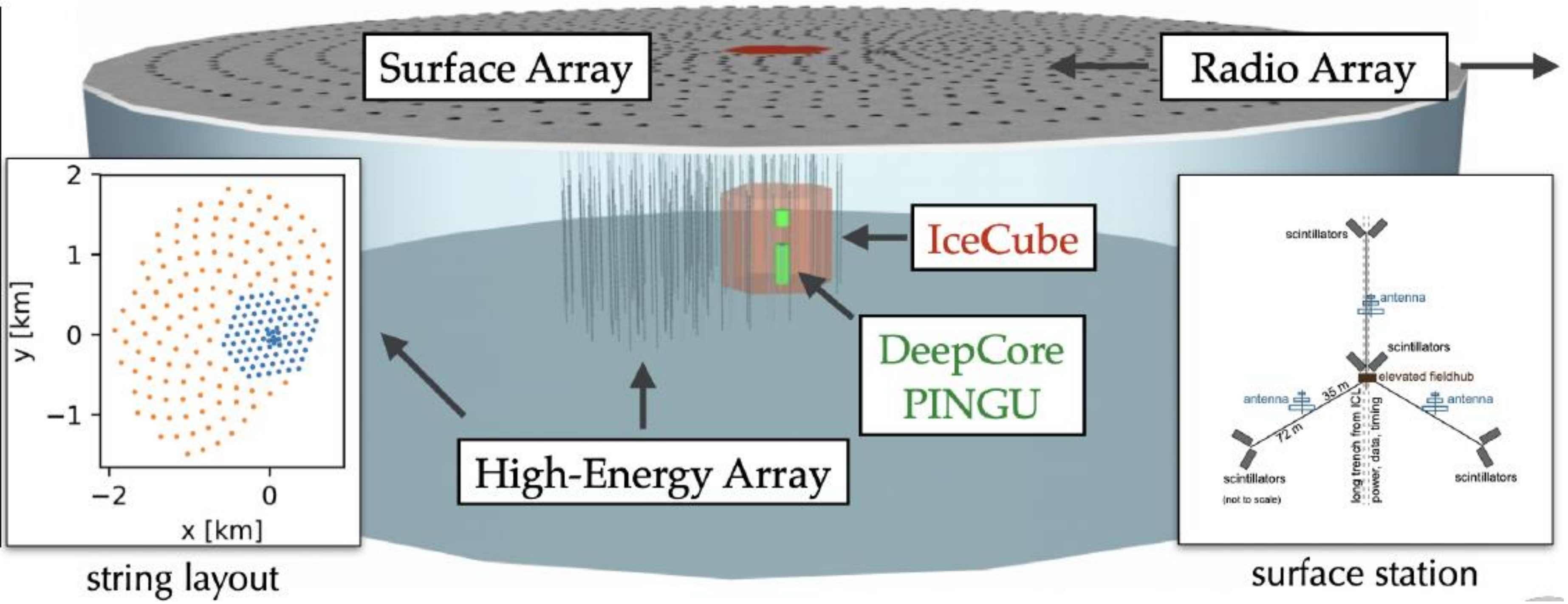
IceCat-1 vs. IceCat-2



IceCube-Gen2

- Multi-component facility (low- and high-energy & multi-messenger)
- In-ice optical Cherenkov array with 120 strings and 240m spacing (~8 cubic-kilometre detector)
- Surface array (scintillators & radio antennas) for PeV-EeV CRs
- Askaryan radio array for >10PeV neutrino detection





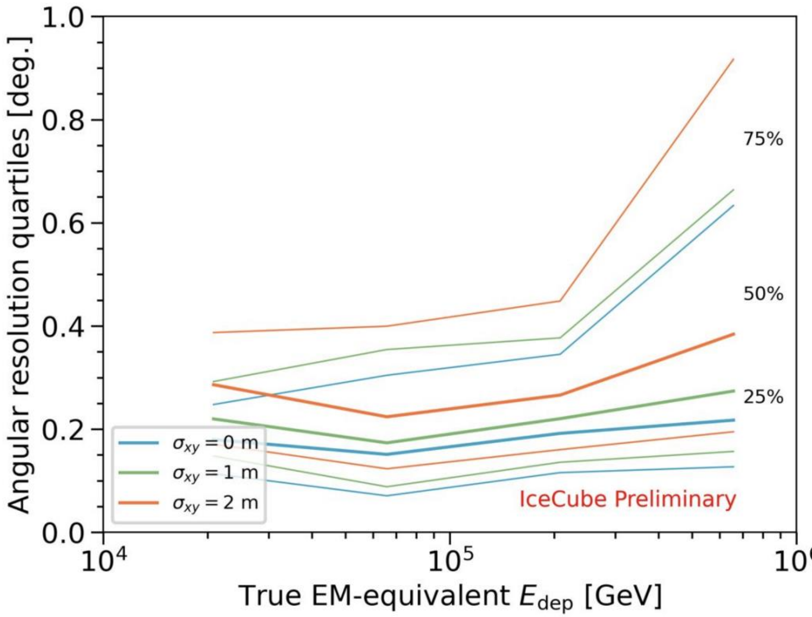
Improved reco algorithms

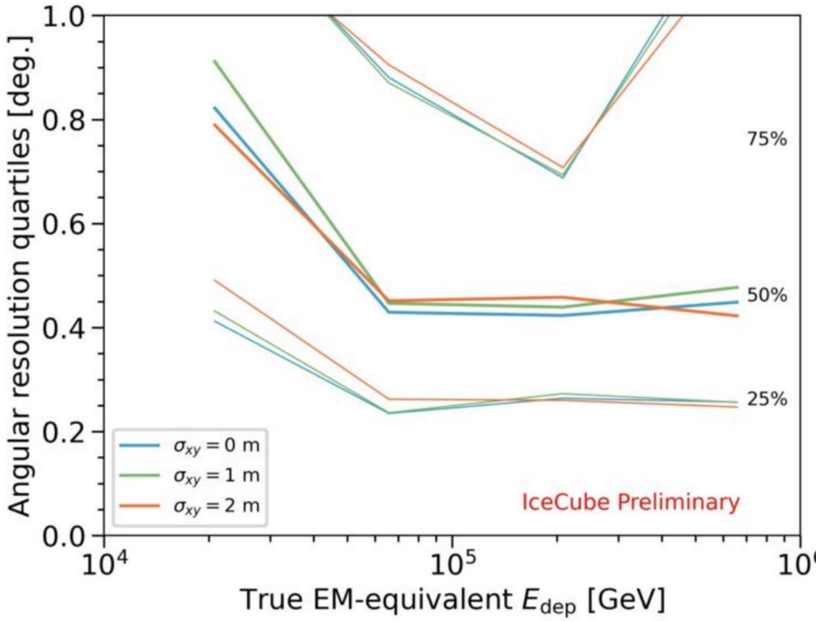
Spline MPE

- Fits continuous light emission along the high-energy muon track → good for the lower muon energies
- Uses only the first-detected photon plus the total number of detected photons per each DOM → simpler method, robust against uncertainties in the ice modeling

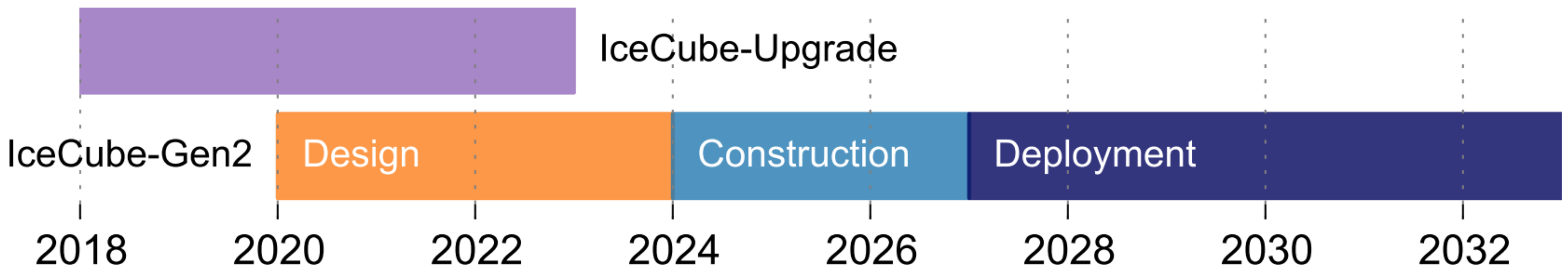
Millipede Wilks

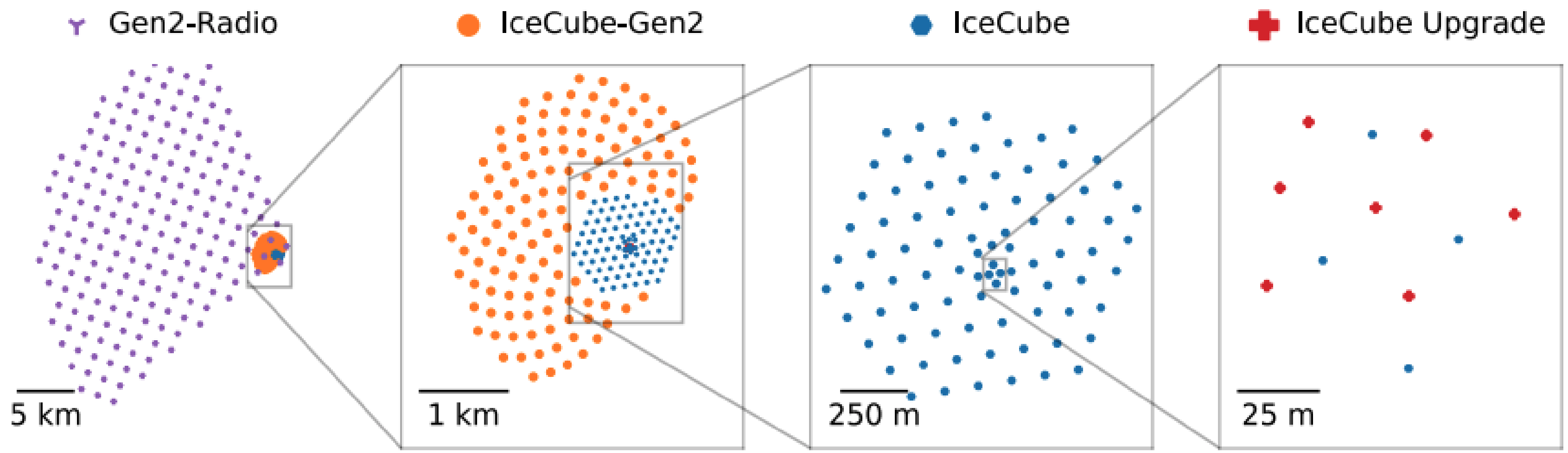
- Fits stochastic energy losses along track → good for the highest muon energies.
- Uses all detected-photons per each digital optical module → very sophisticated, but requires detailed modeling of the ice



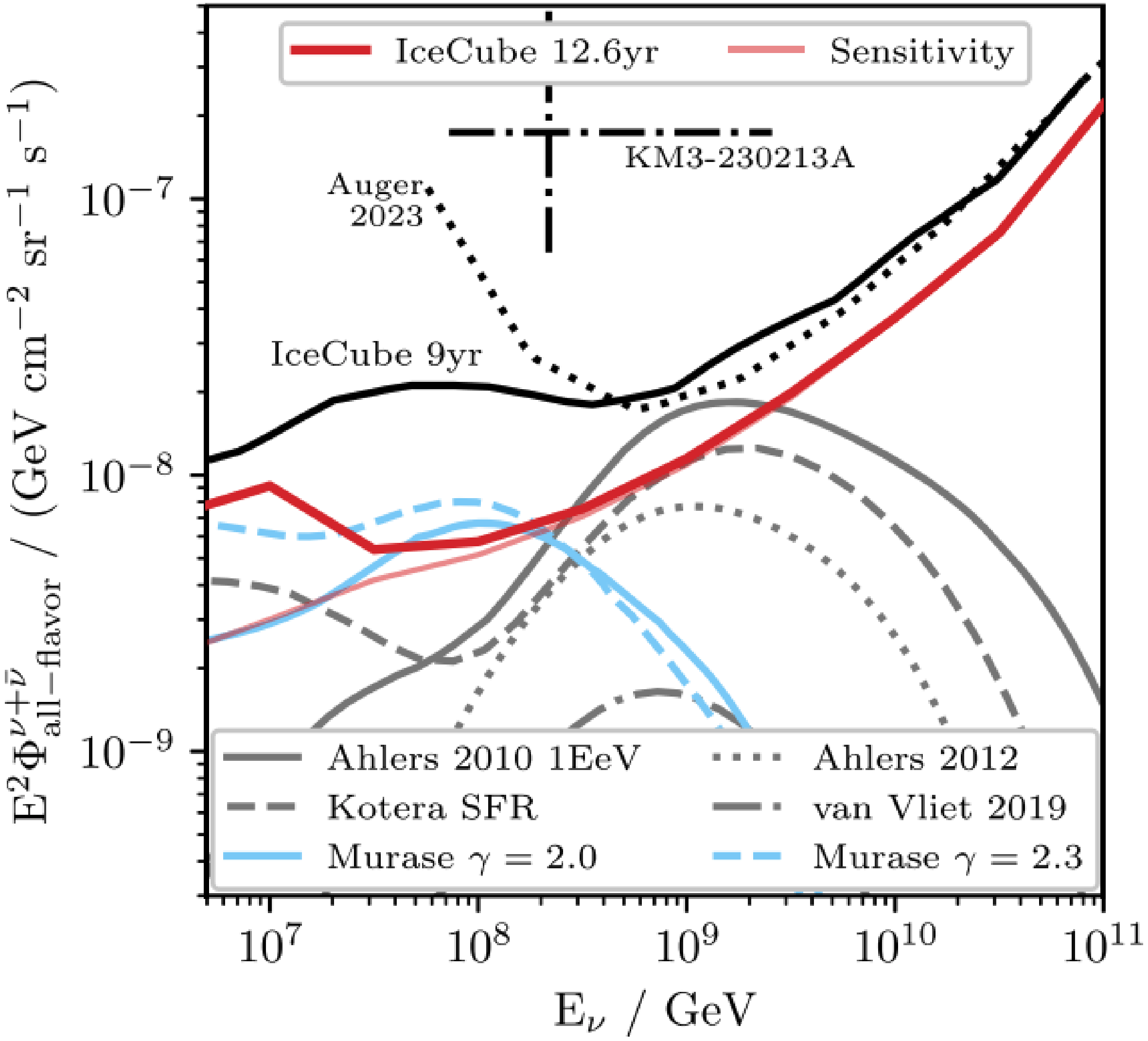


IceCube-Gen2 time line





First cosmogenic neutrino?



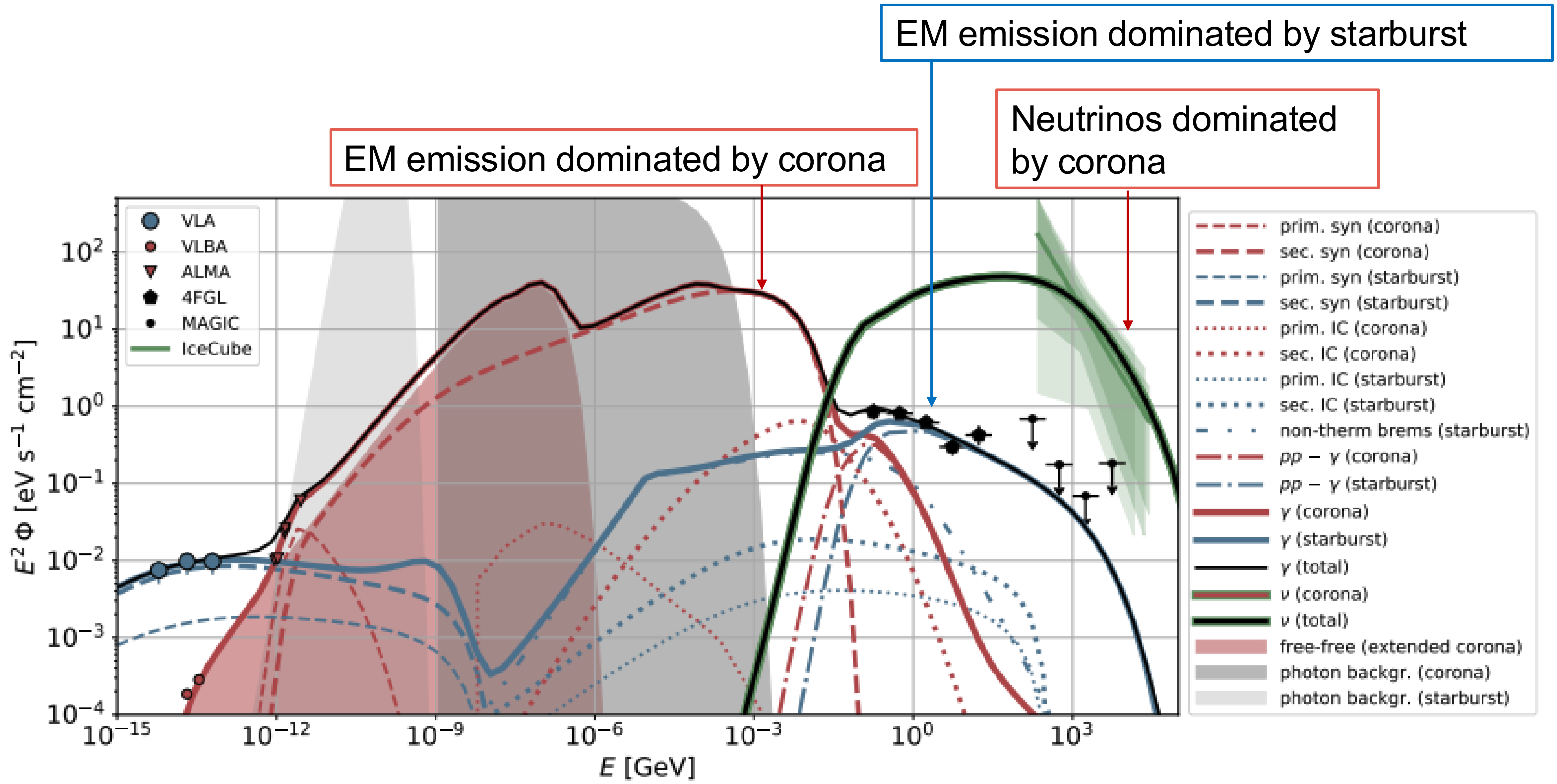
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

Energy Threshold: $5 \cdot 10^{19} eV$

based on a joint-livetime fit (Auger, IceCube, KM3NeT) $\sim 2.9\sigma$ tension

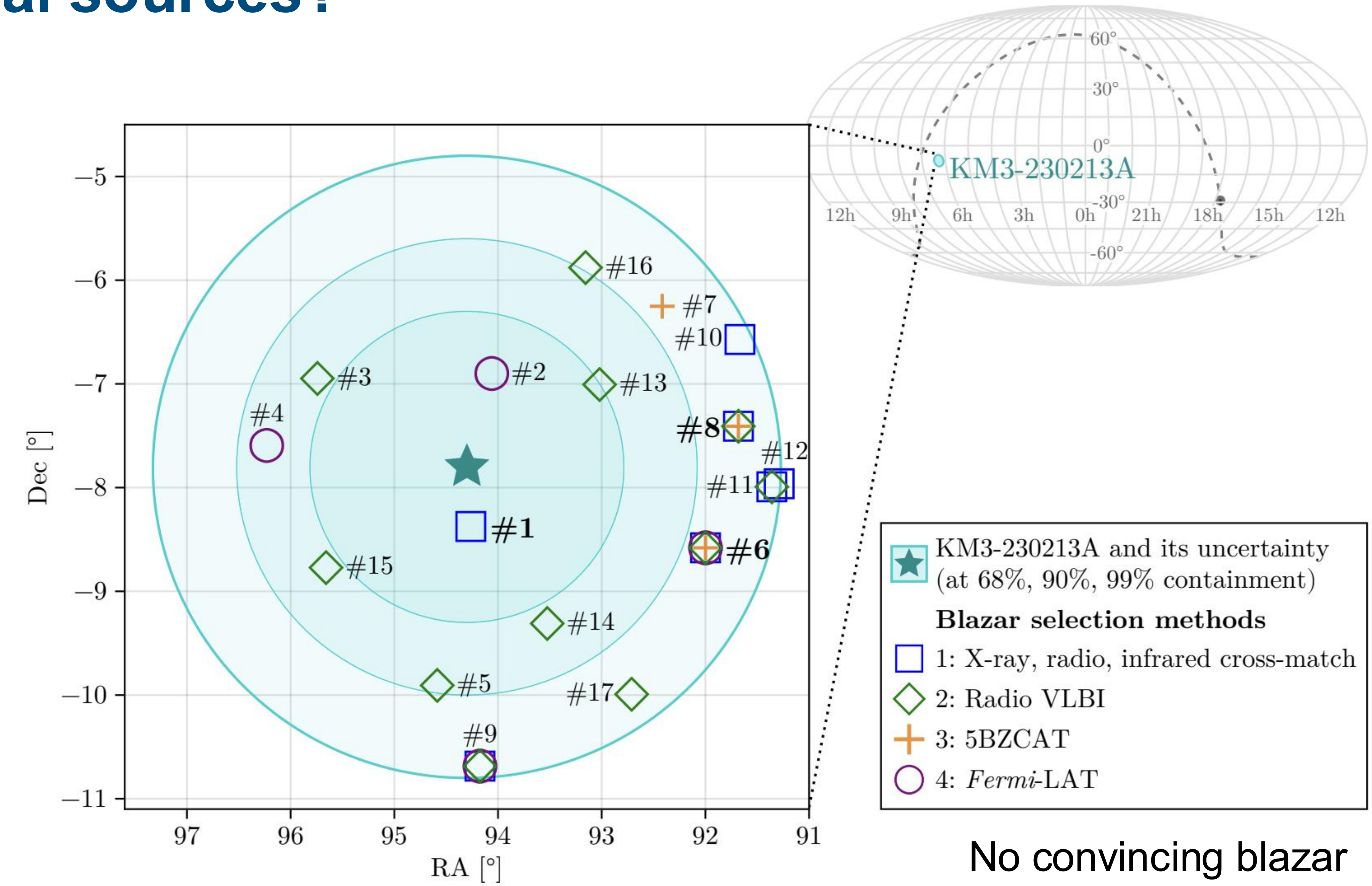
IceCube, 2025, PRL 135

Detailed Modeling of Starburst-AGN Composite



Eichmann ApJ 939 (2022) 43

Potential sources?

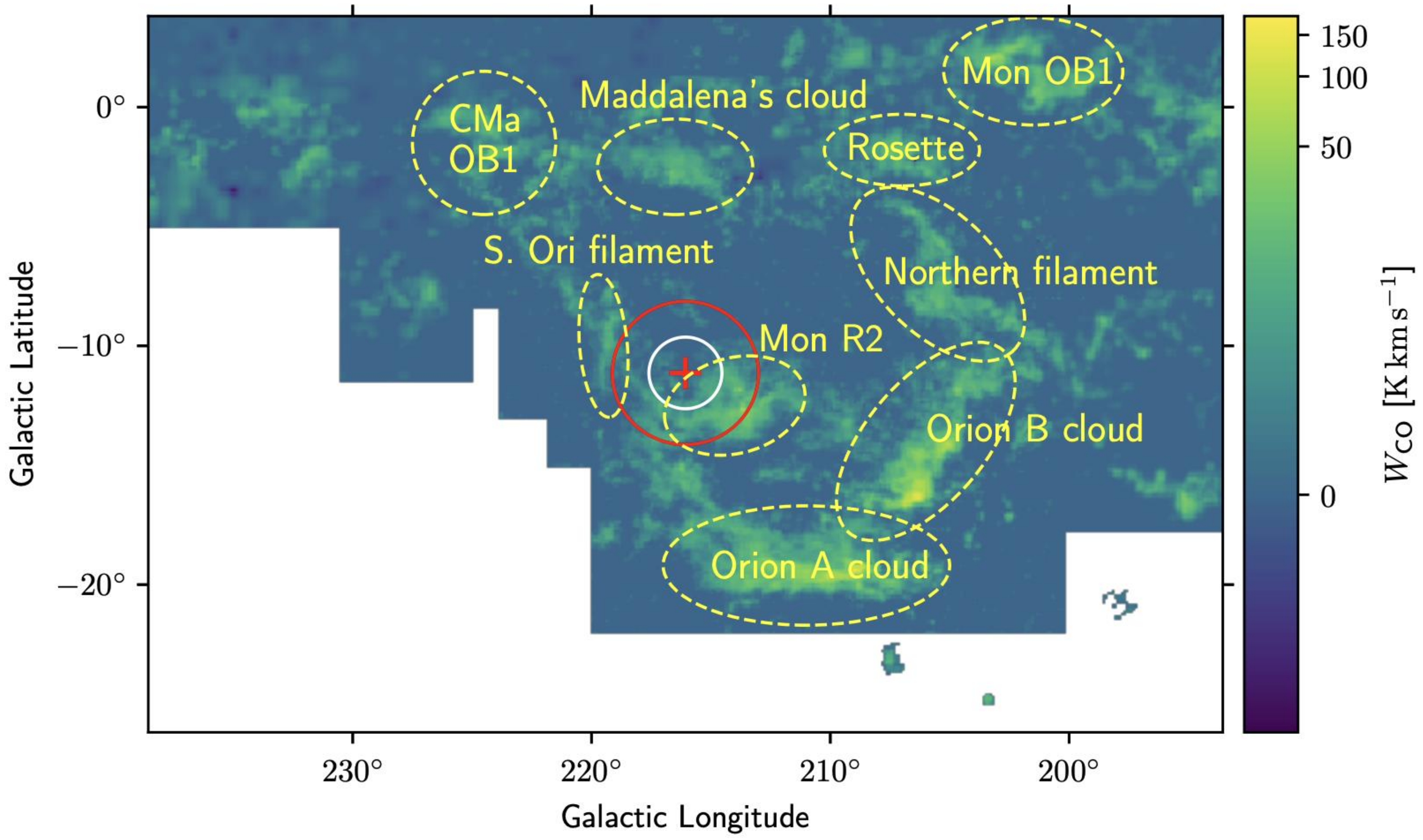


No convincing blazar counterpart found

KM3NeT et al. arXiv, 2502.08484

RUB

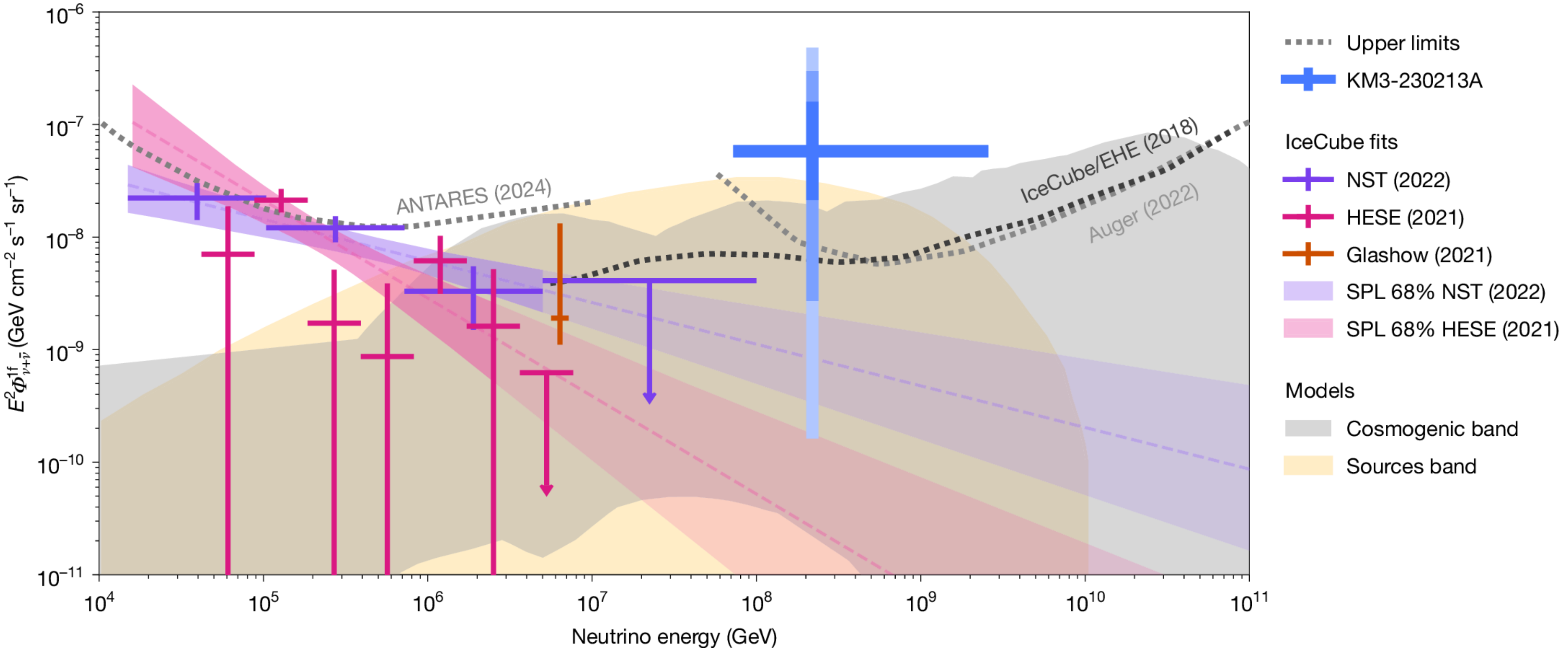
Potential sources?



Galactic origin unlikely

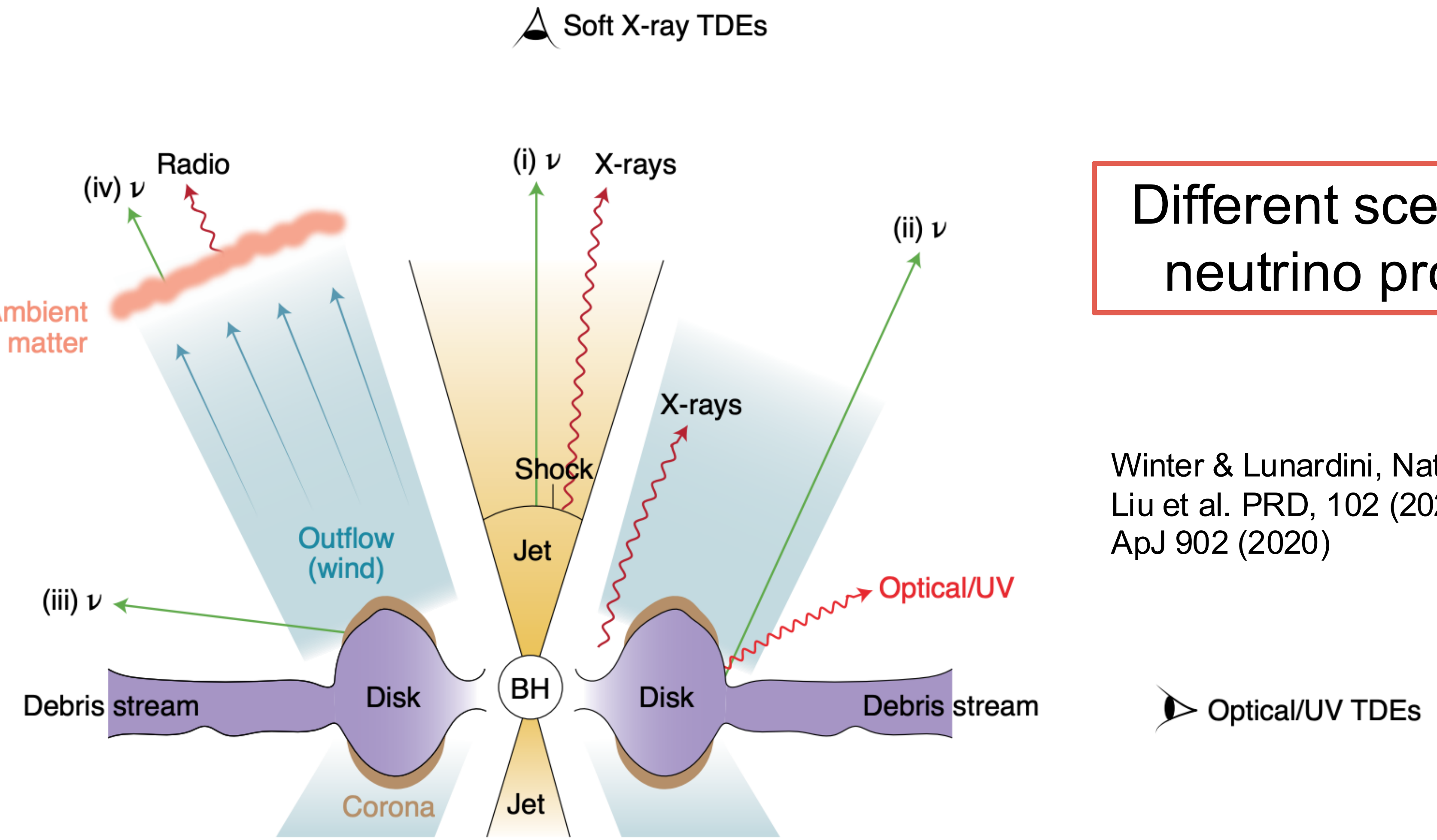
KM3NeT, arXiv:2502.08387

Tension with IceCube and Auger upper limits?



RUB

Neutrino Production in TDEs



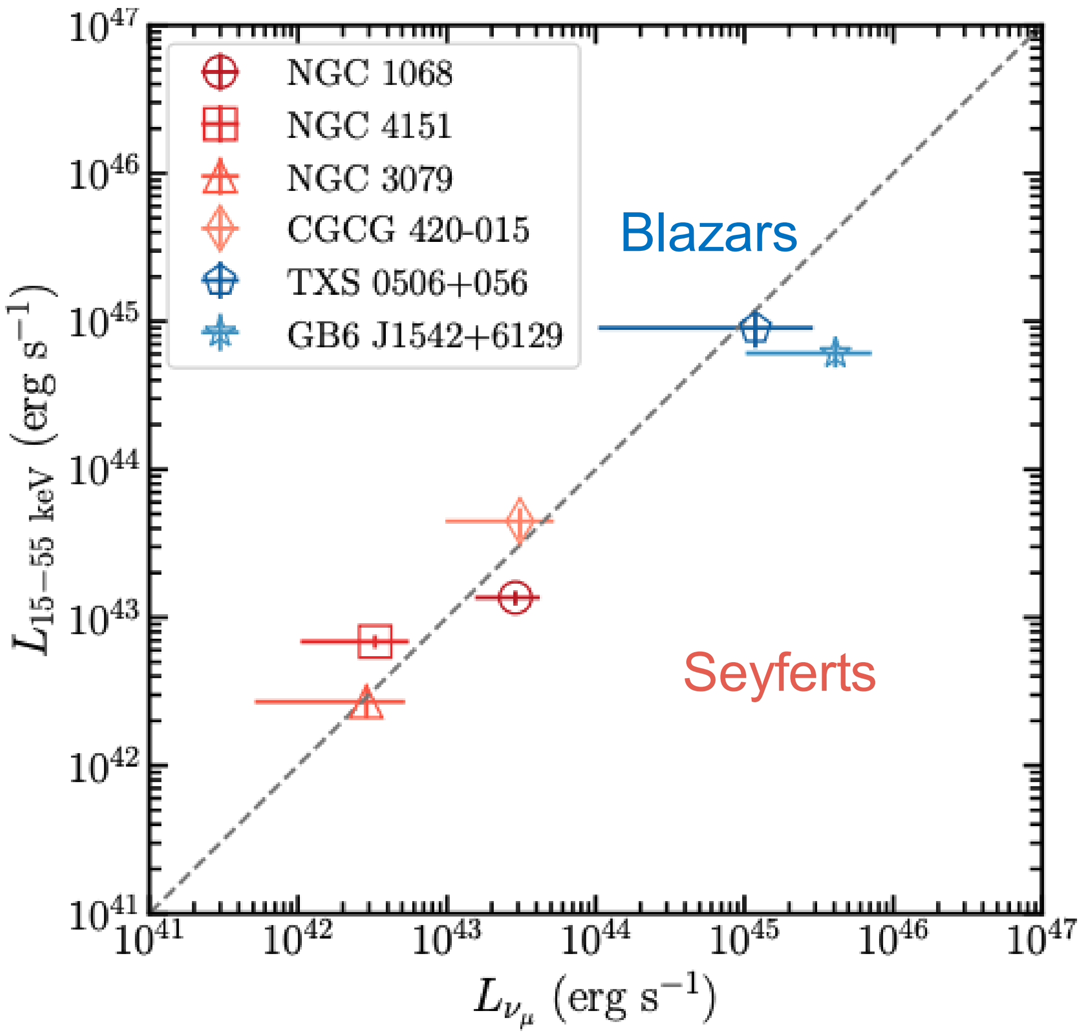
Different scenarios for neutrino production

Winter & Lunardini, Nature Astronomy 2021
Liu et al. PRD, 102 (2020) Murase et al. ApJ 902 (2020)

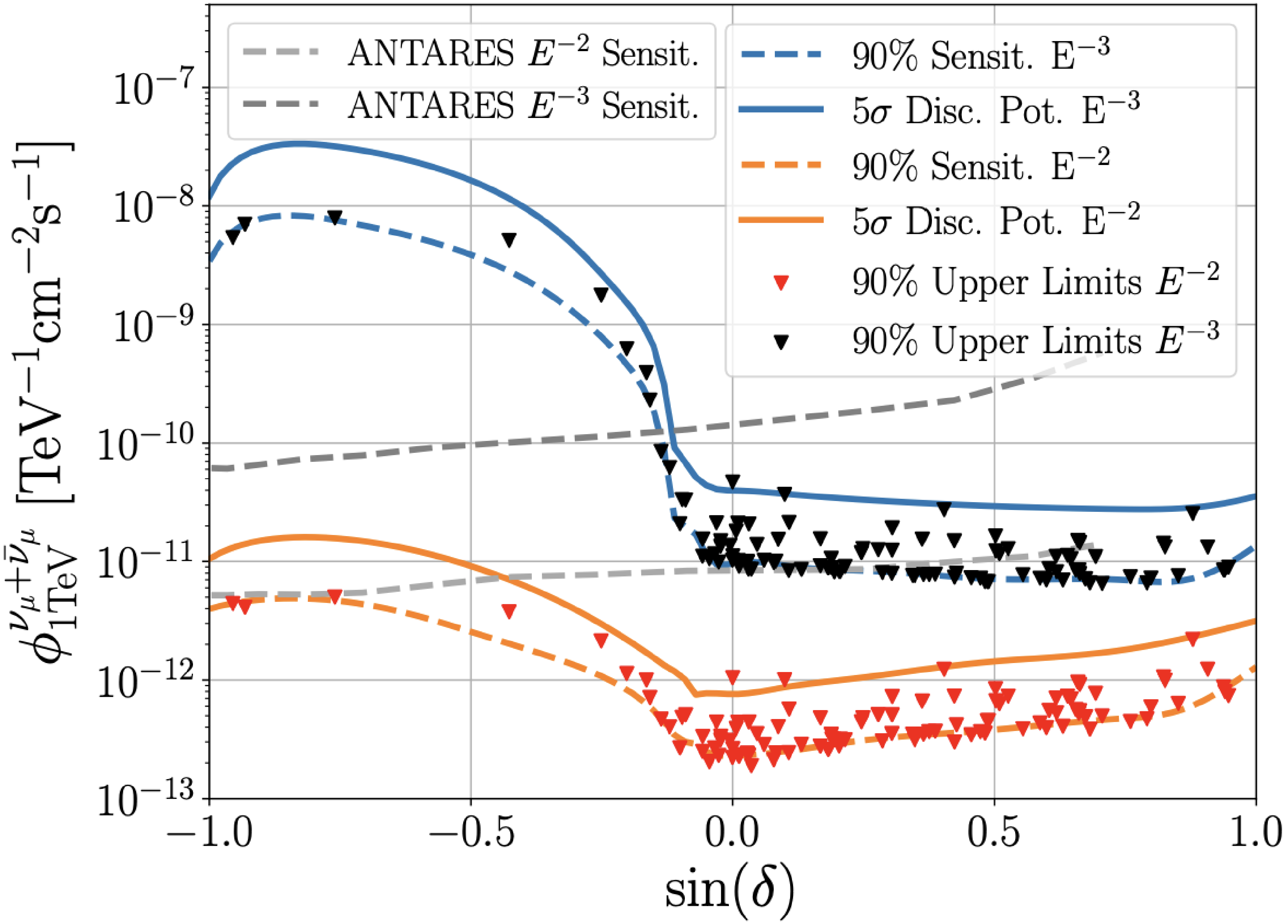
Hayasaki, Nature Astronomy 2021

Connection of Seyferts and Blazar neutrino candidates?

Scaling between neutrinos and intrinsic hard X-ray flux for Seyfert and blazar neutrino source candidates?

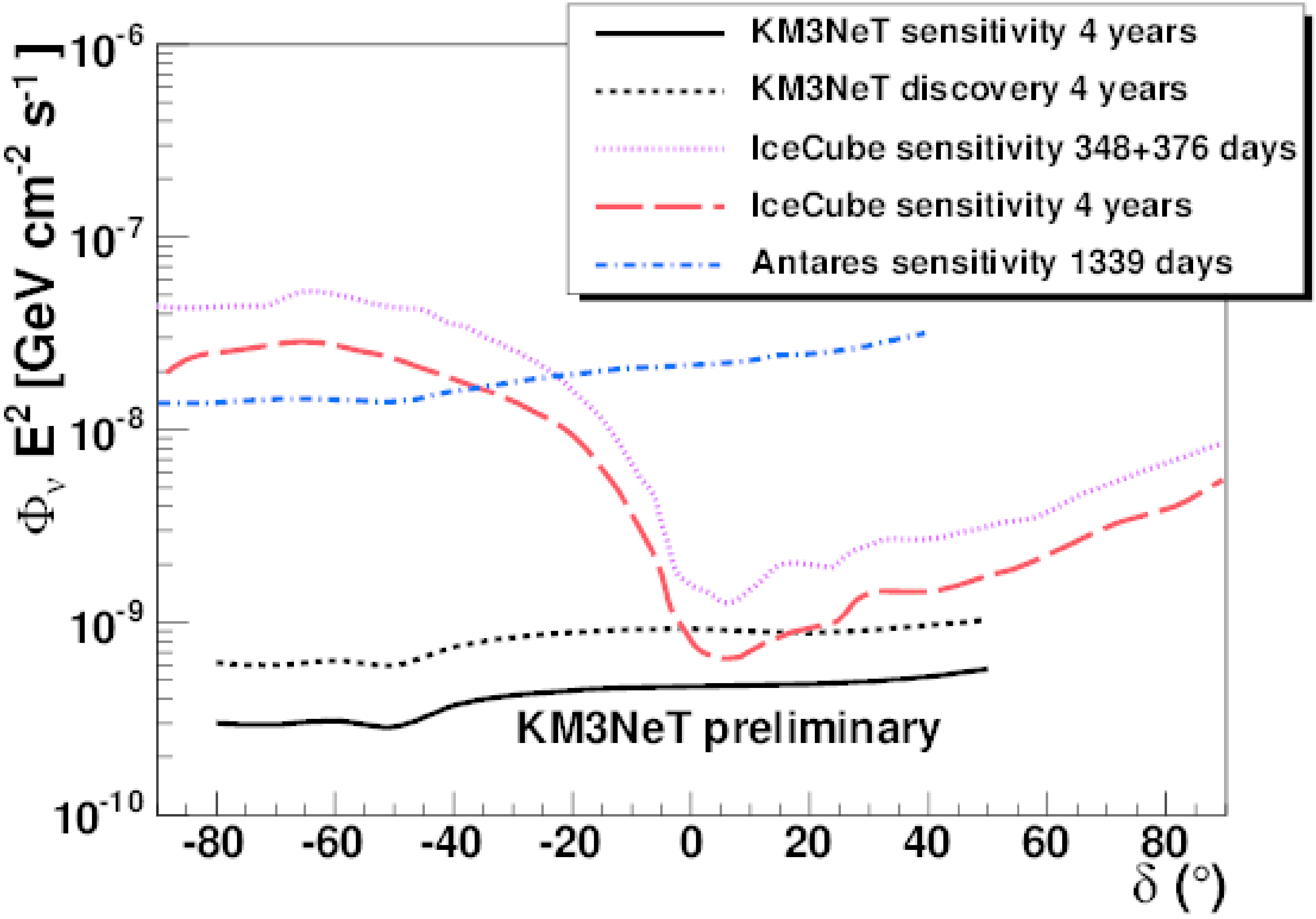


E. Kun et al *PRD* 110 (2024) 12, 123014



ANTARES E^{-2} Sensit.
ANTARES E^{-3} Sensit.
90% Sensit. E^{-3}
5σ Disc. Pot. E^{-3}
90% Sensit. E^{-2}
5σ Disc. Pot. E^{-2}
90% Upper Limits E^{-2}
90% Upper Limits E^{-3}
$\phi_{1\mathrm{TeV}}^{\nu_\mu+\bar{\nu}_\mu}$ [$\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
-1.0
-0.5
0.0
0.5
1.0
$\sin(\delta)$

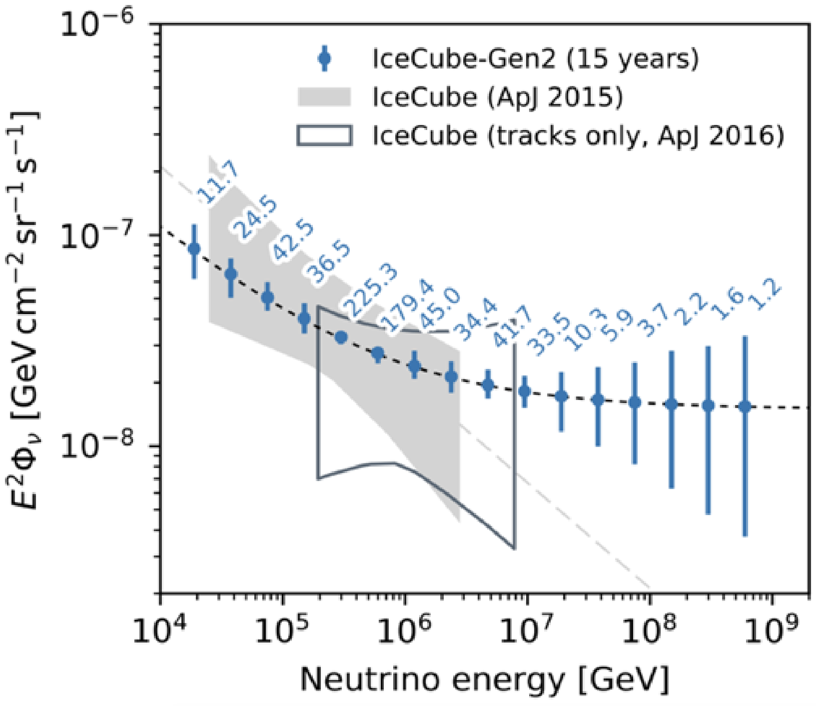
RUB



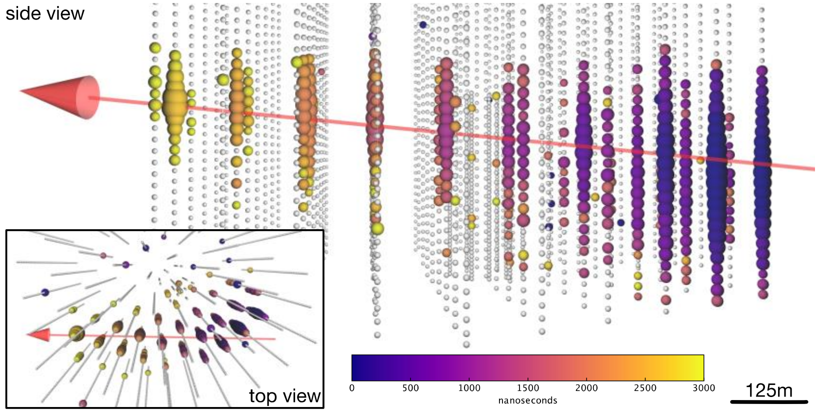
KM3NeT sensitivity 4 years
KM3NeT discovery 4 years
IceCube sensitivity 348+376 days
IceCube sensitivity 4 years
Antares sensitivity 1339 days
KM3NeT preliminary
$\Phi_\nu\ E^2\ [\mathrm{GeV\ cm^{-2}\ s^{-1}}]$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
-80
-60
-40
-20
0
20
40
60
80
δ (°)

Neutrino Astronomy with IceCube Gen2

Precision measurement of the spectrum
from 10 TeV - 100 PeV
(up to 10 EeV with Gen2 Radio)



>1 high-energy neutrino / year
from gamma-ray blazars

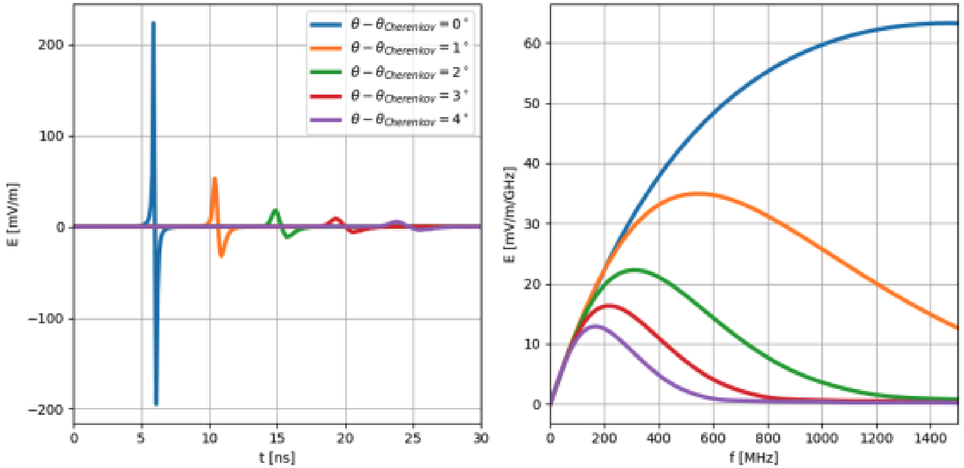


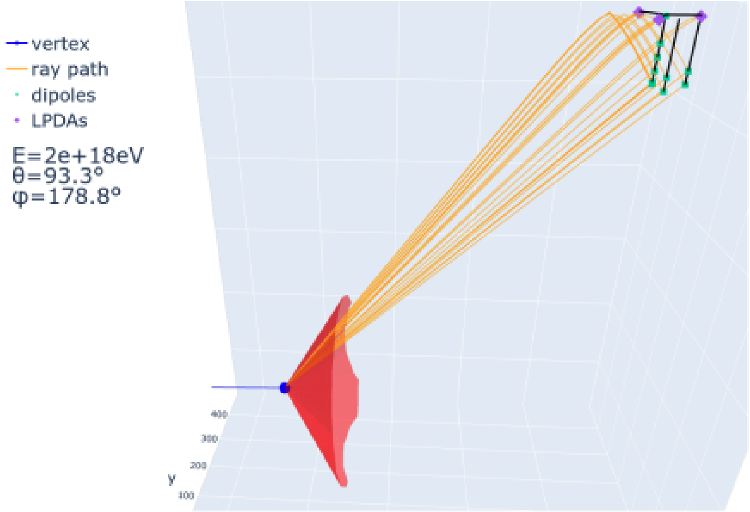
IceCube-Gen2 White Paper, astro-ph:2008.04323

Radio emission of showers in dense media

What are we looking for?

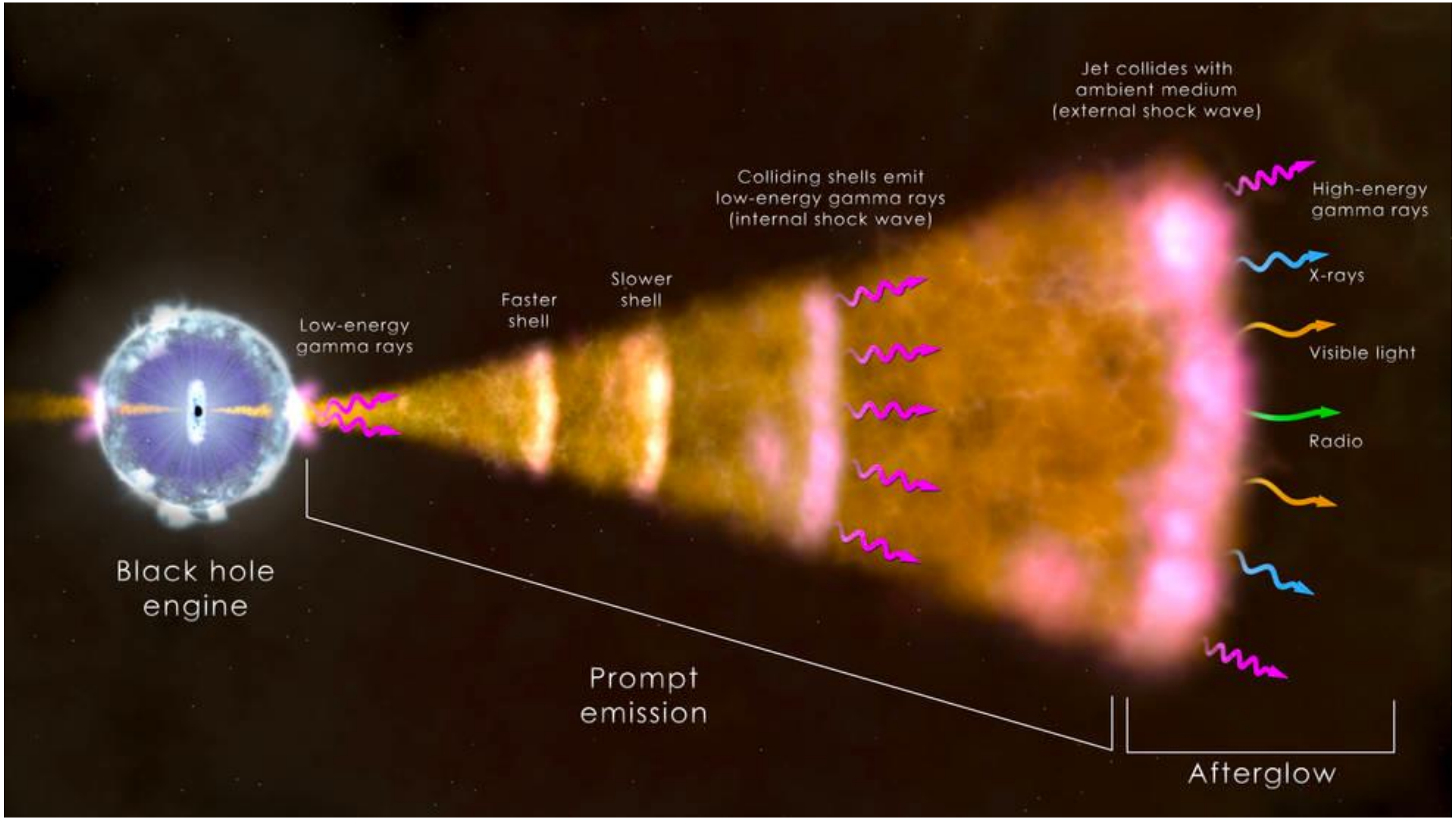
- **Askaryan effect**: Charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower
- Index of refraction >> 1, emission strong on the Cherenkov cone, travel on non-straight lines with changing n
- Signals contain information in amplitude, frequency and polarisation





Gamma-Ray Bursts (GRBs)

Extremely large energy release on the time-scale of 0.1-100 seconds

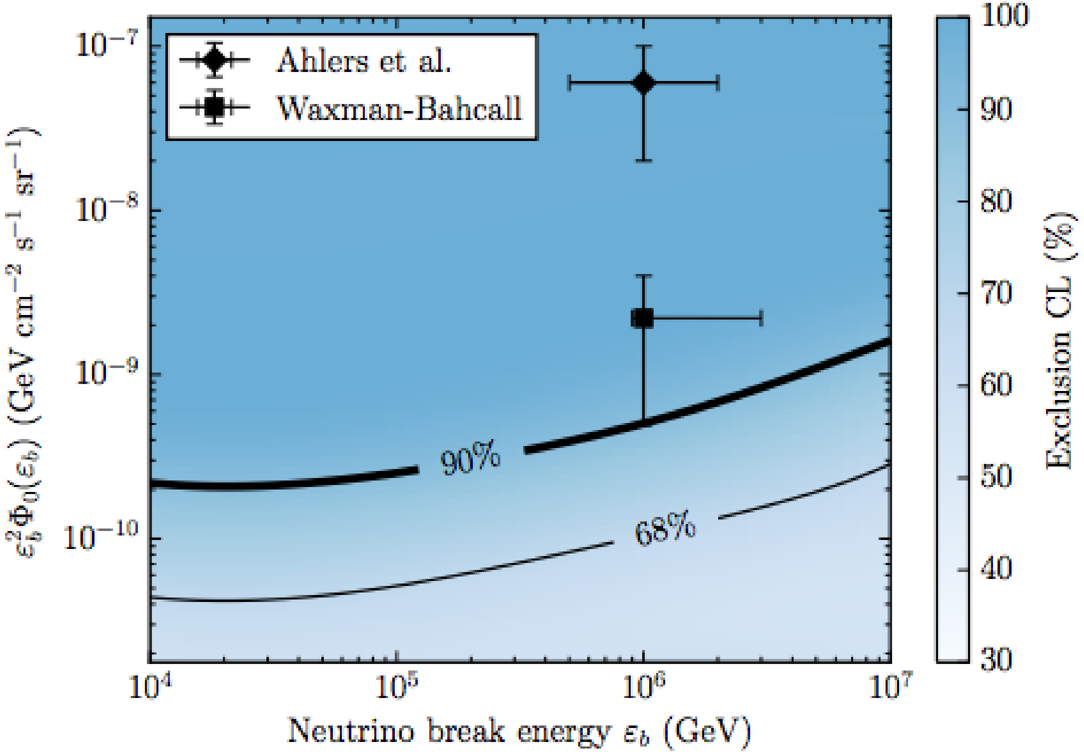


Gamma-Ray Bursts (GRBs)

Gamma rays and X-rays tell us **where** and **when** to look for neutrinos

Prompt emission of
> 800 GRBs correlated
with IceCube data
→ **no excess found**

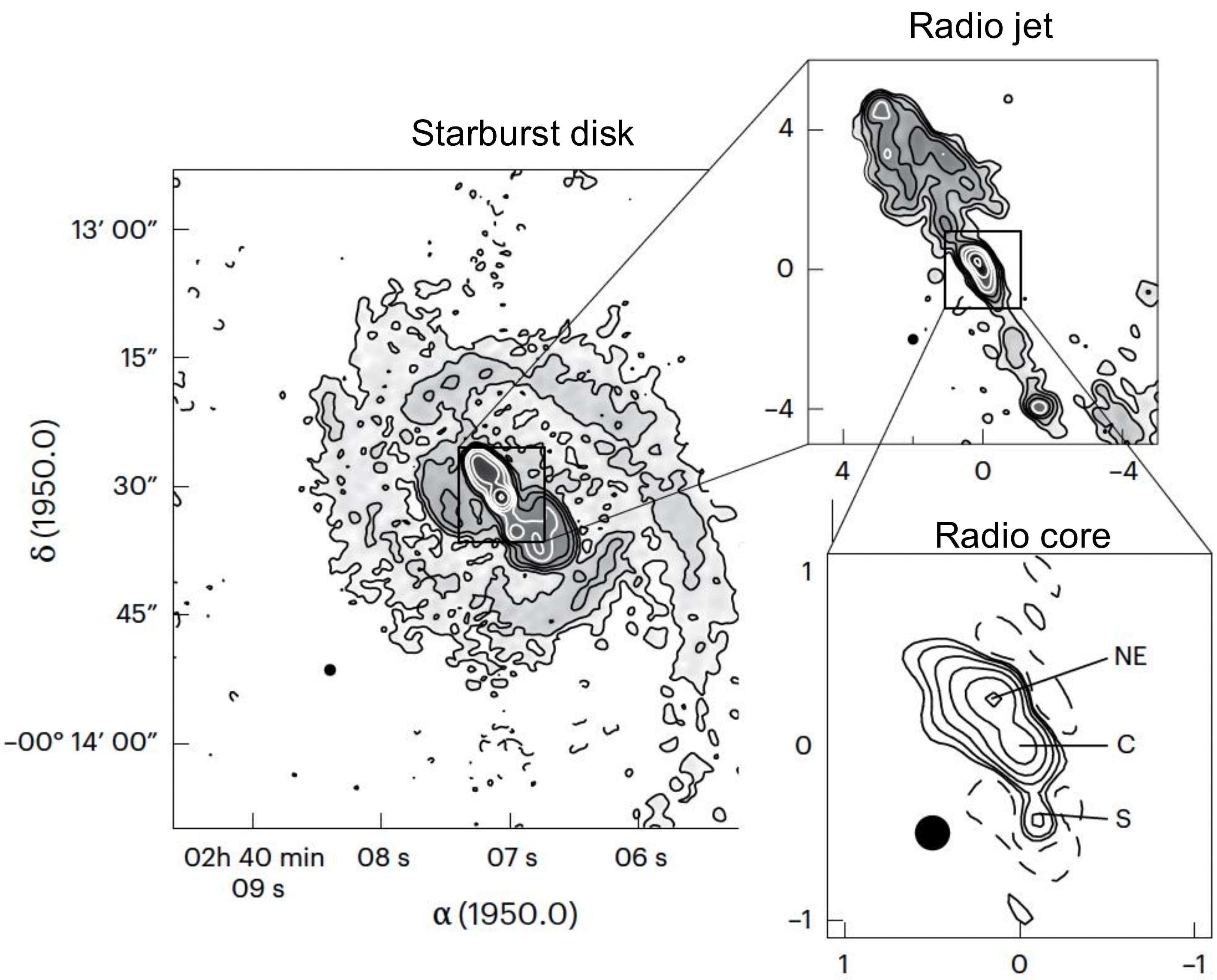
Precursor and
afterglow searches in
preparation



GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained

IceCube Coll., ApJ 805 (2015), ApJ 824 (2016)

1.7 GHz Map



Padovani et al. Nature Astronomy (2024)

Table 1 | Measured powers

L_{radio} (1.4 GHz) (erg s^{-1})	L_{FIR} (8–100 μm) (erg s^{-1})	L_x (2–10 keV) (erg s^{-1})	L_γ (0.1–100 GeV) (erg s^{-1})	L_ν (1.5–15 TeV) (erg s^{-1})	L_{Edd} (erg s^{-1})
$10^{38.9}$	$10^{44.6\pm0.1}$	$10^{43.4\pm0.3}$	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$	$10^{44.9\pm0.3}$[a]

[a]A factor of 2 uncertainty was assumed on M_{BH}.

Table 2 | Derived powers

L_{kin} (erg s^{-1})	L_{jet} (erg s^{-1})	L_{bol} (erg s^{-1})	L_{bol}/L_{Edd}
$10^{41.6\pm1.0}$	$10^{42.9\pm1.0}$	$10^{44.7\pm0.5}$	$10^{-0.3\pm0.6}$

Note that the Eddington ratio is unitless.

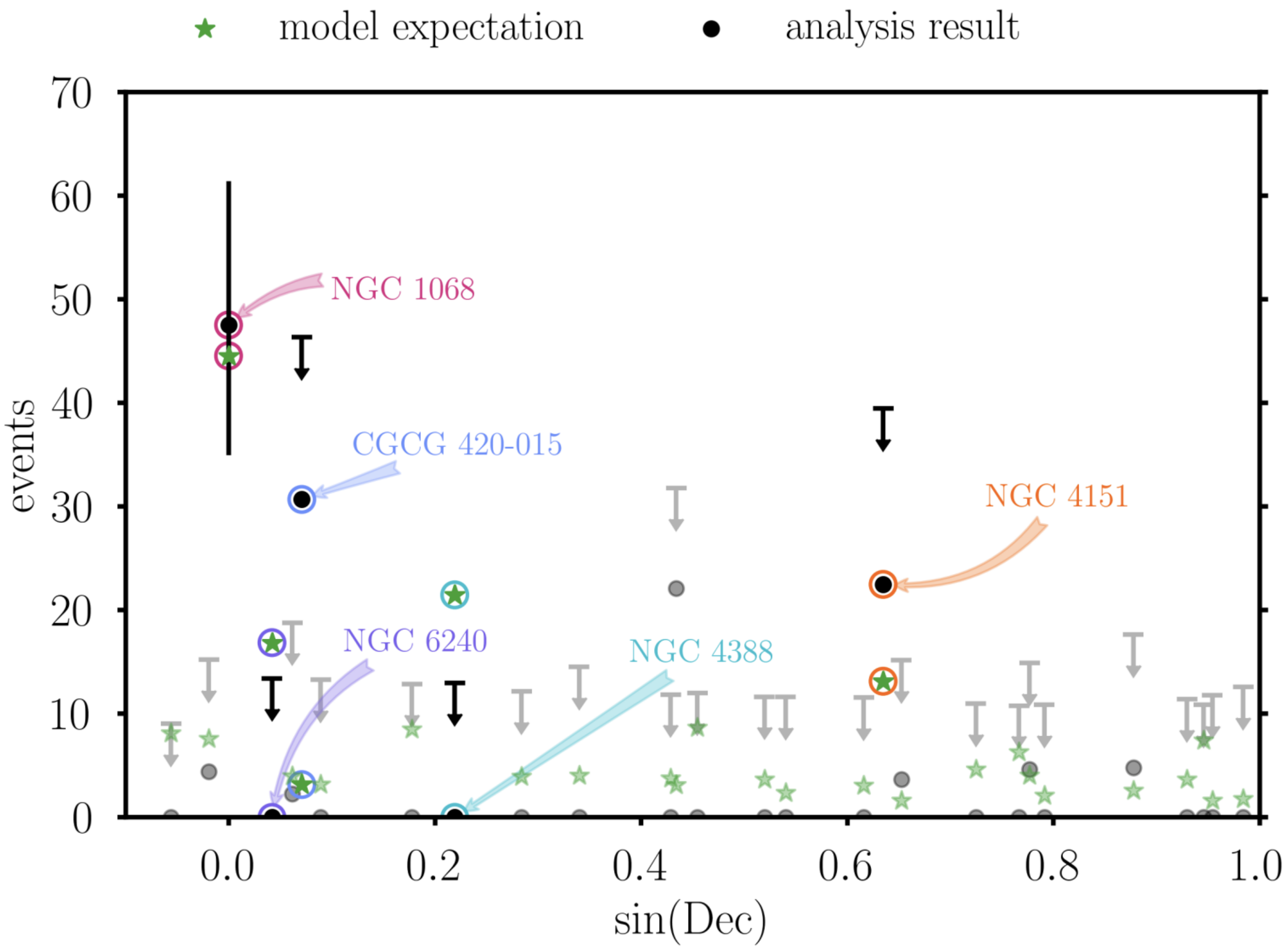
Padovani et al. Nature Astronomy (2024)

Table 3 | Estimated γ-ray and neutrino powers

Component	Scale	L_γ(0.1–100 GeV) (erg s^{-1})	L_ν(1.5–15 TeV) (erg s^{-1})
Star formation	>kiloparsec	$\sim 10^{40.9}$	$\lesssim 10^{40.1}$
Jet	~kiloparsec	$< 10^{41.7}$ (M87-like)	$< 10^{40.9}$
Outflow (UFO)	~parsec	$< 10^{41.2}$	$< 10^{40.4}$
Black hole vicinity	~0.03 mpc (~50 R_s)	?	?
Total		$\lesssim 10^{41.9}$	$\ll 10^{41.1}$
Observed		$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$

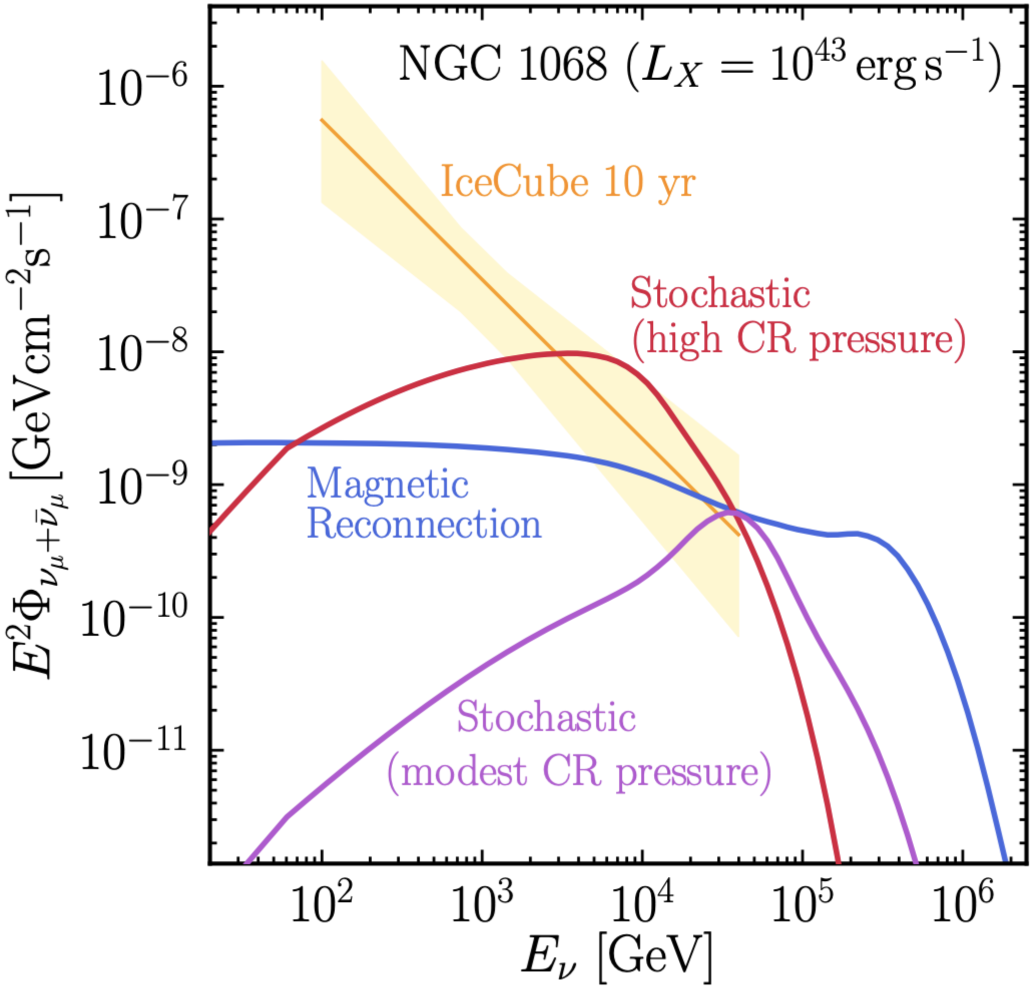
R_s is the Schwarzschild radius. '?' denote unknown values.

Padovani et al. Nature Astronomy (2024)



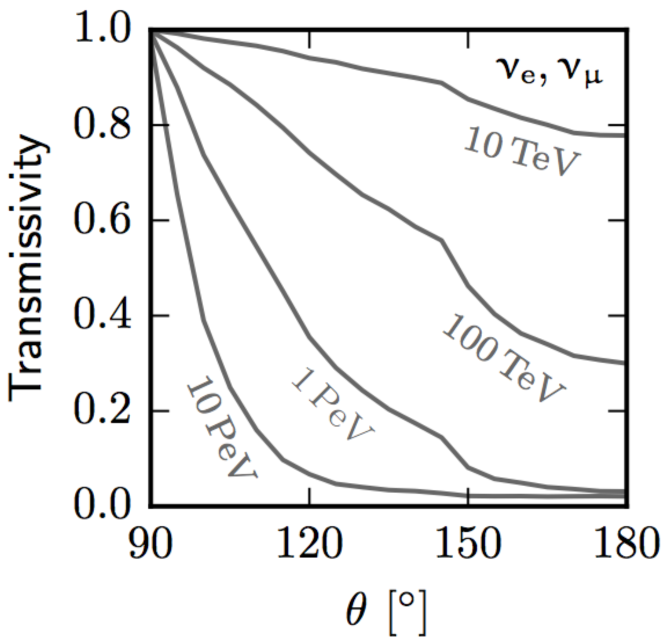
model expectation
analysis result
NGC 1068
CGCG 420-015
NGC 4151
NGC 6240
NGC 4388
events
sin(Dec)
0
10
20
30
40
50
60
70
0.0
0.2
0.4
0.6
0.8
1.0

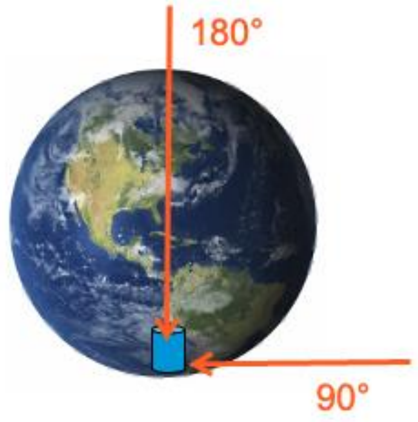
RUB



Model	$P_{\rm CR}/P_{\rm th}$ ($\epsilon_{\rm CR}$)	q	$\eta_{\rm tur}$	s	$\eta_{\rm acc}$	$E_p^{\rm rec}$
Stochastic acceleration with high CR pressure	0.5 (0.03)	5/3	50	-	-	-
Stochastic acceleration with modest CR pressure	0.008 (0.0009)	5/3	10	-	-	-
Magnetic Reconnection	0.5 (0.01)	-	-	2.0	300	5 PeV

For high energies Earth becomes opaque to neutrinos
→ this can be used to infer the neutrino cross section





IceCube, Nature 551, 596–600 (2017)