Neutrinos with IceCube

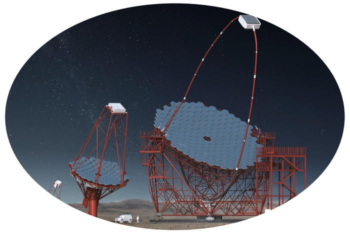
Anna Franckowiak on behalf of
the IceCube Collaboration

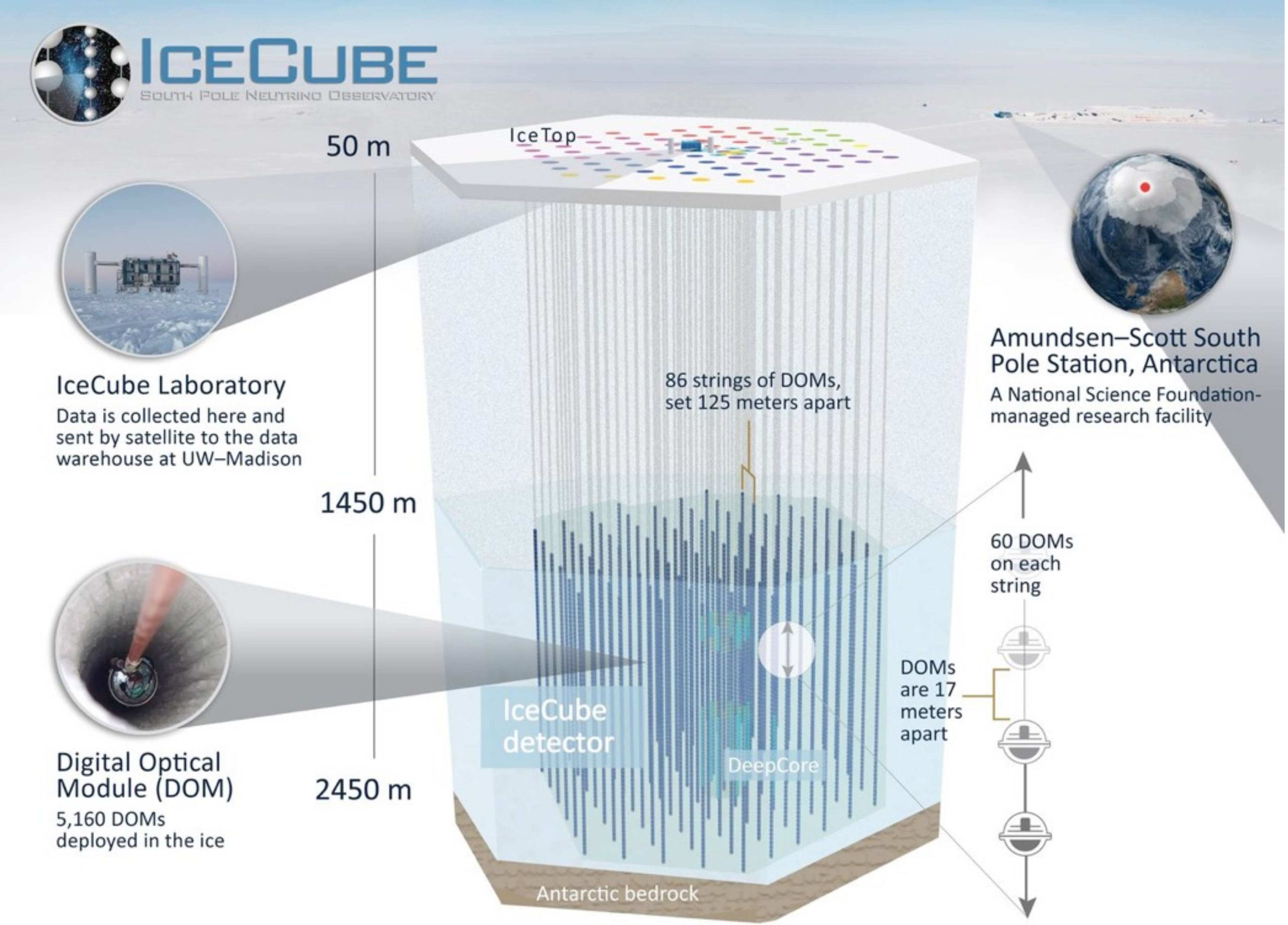
RUHR UNIVERSITÄT BOCHUM RUB

SFB1491

Data Analysis for Multi-Messenger Data Analysis, Oct. 22, 2024

Multi-messenger Astronomy



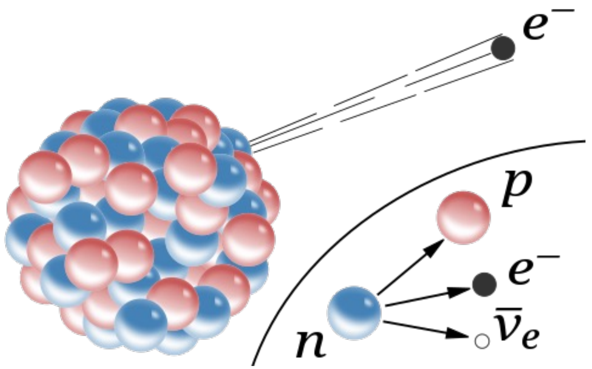


Volume: 1km^3

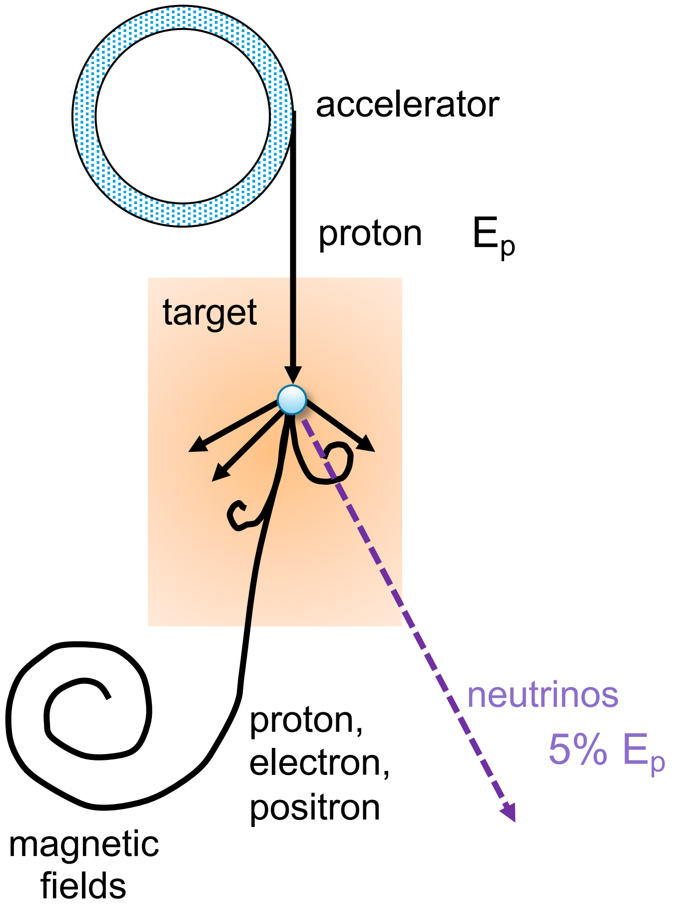
Completed and taking data since Dec 2010

How are neutrinos produced?

MeV neutrinos from nuclear processes, (inverse) beta decay



TeV-PeV neutrinos from cosmic-ray "beam dumps"

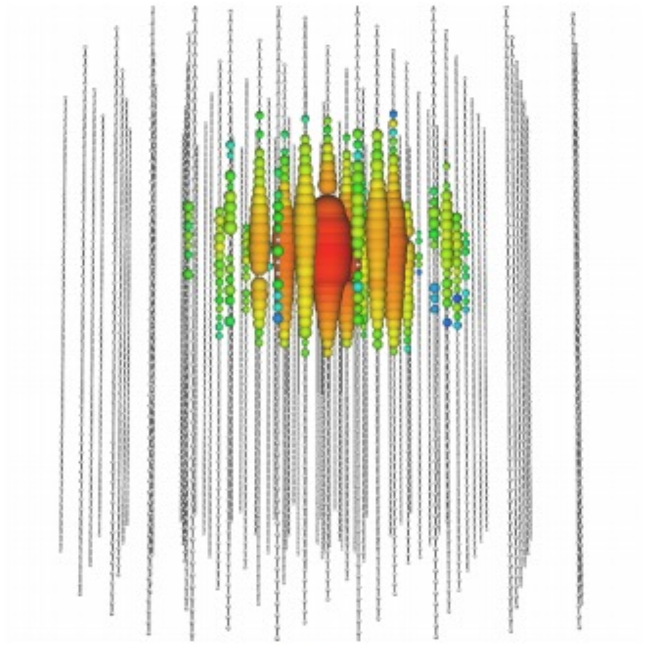


Two ingredients:

- Proton acceleration
- Target for interaction

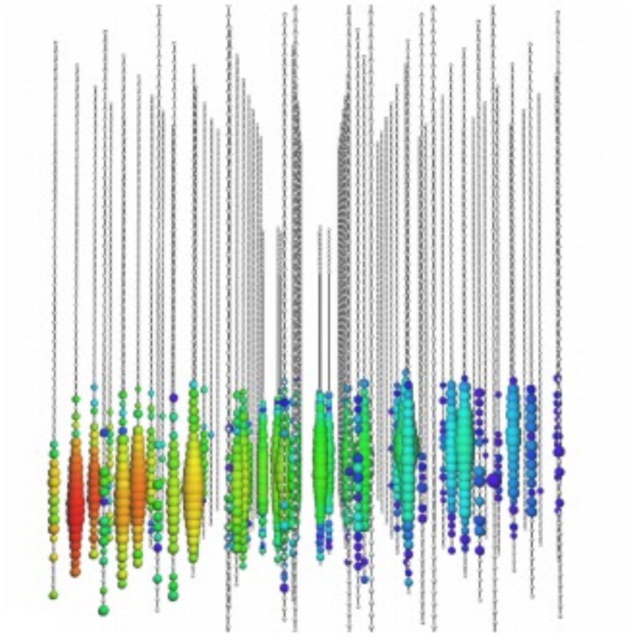
Event Signatures

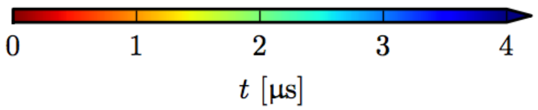
“shower“ events: neutrinos interacting inside the detector



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

“track“ events: muon neutrinos filtered by the Earth





astronomy: angular resolution superior (<1.0º)

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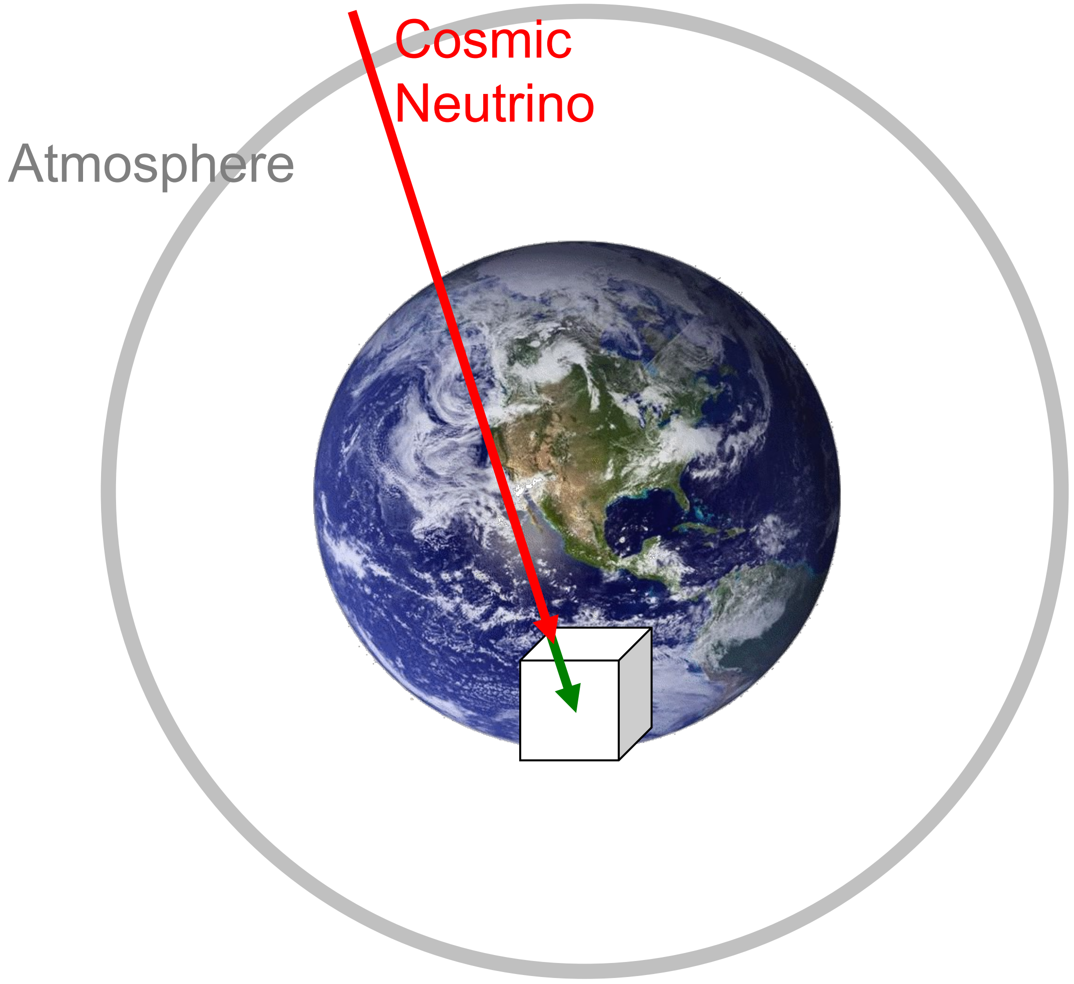
Background in Search for Cosmic Neutrinos



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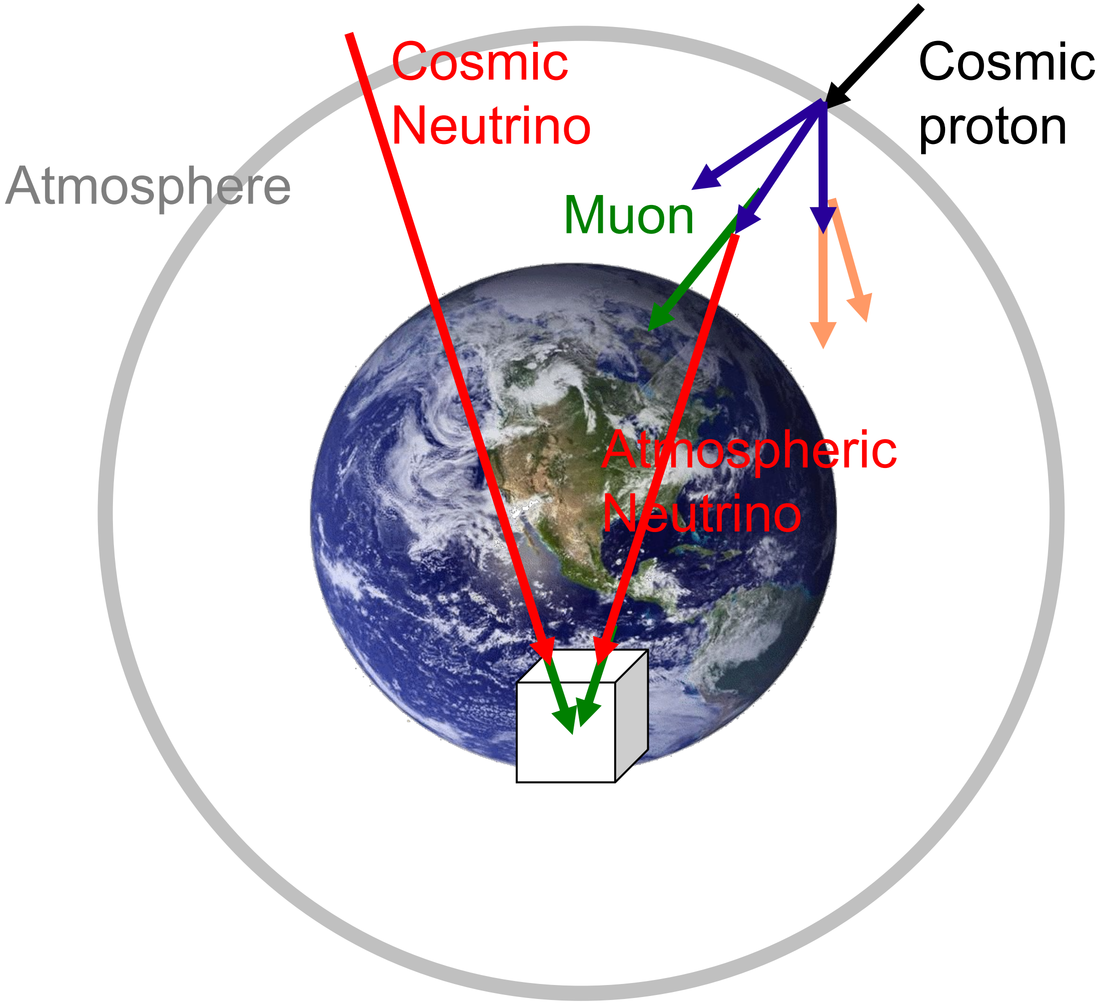

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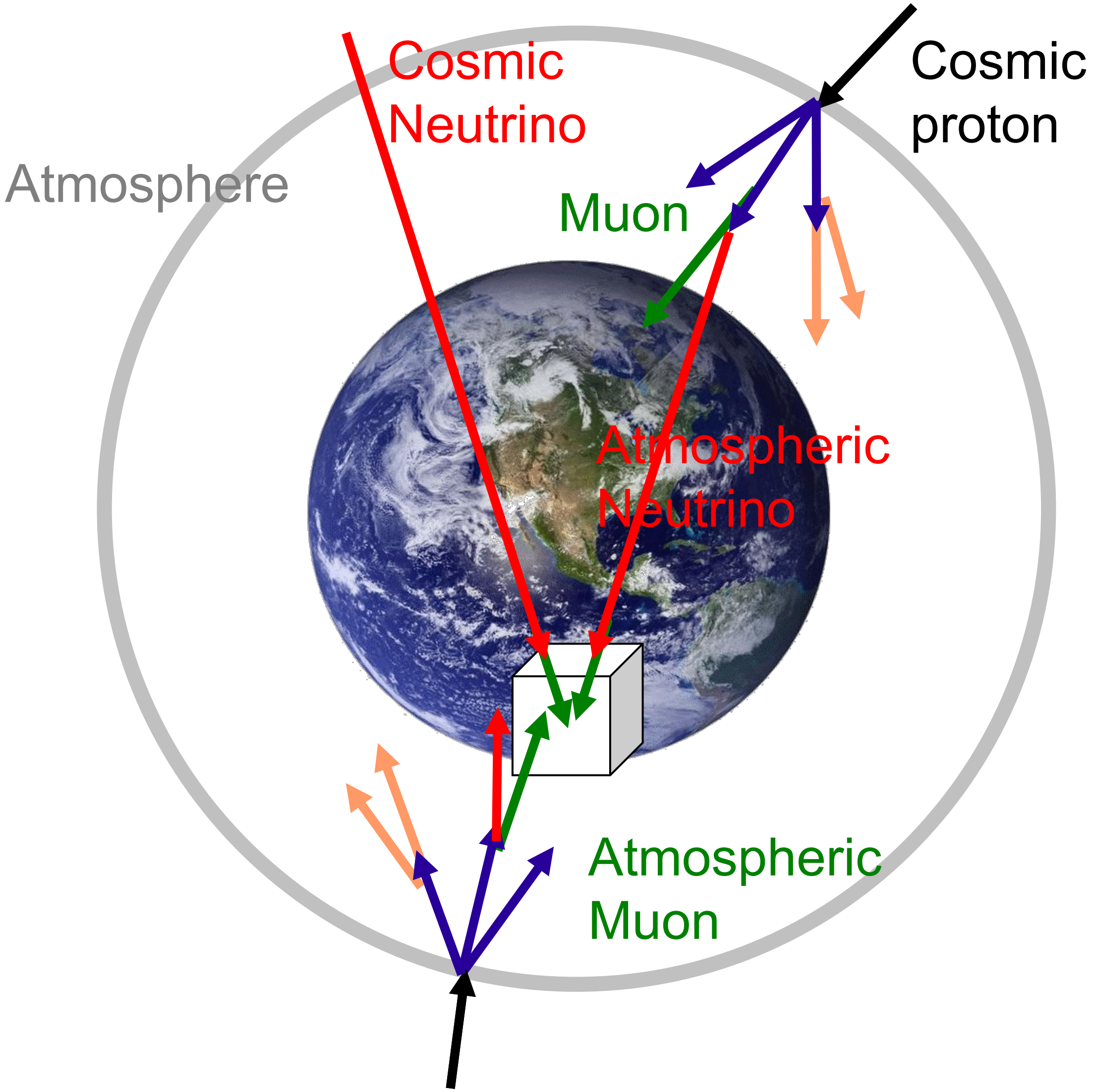

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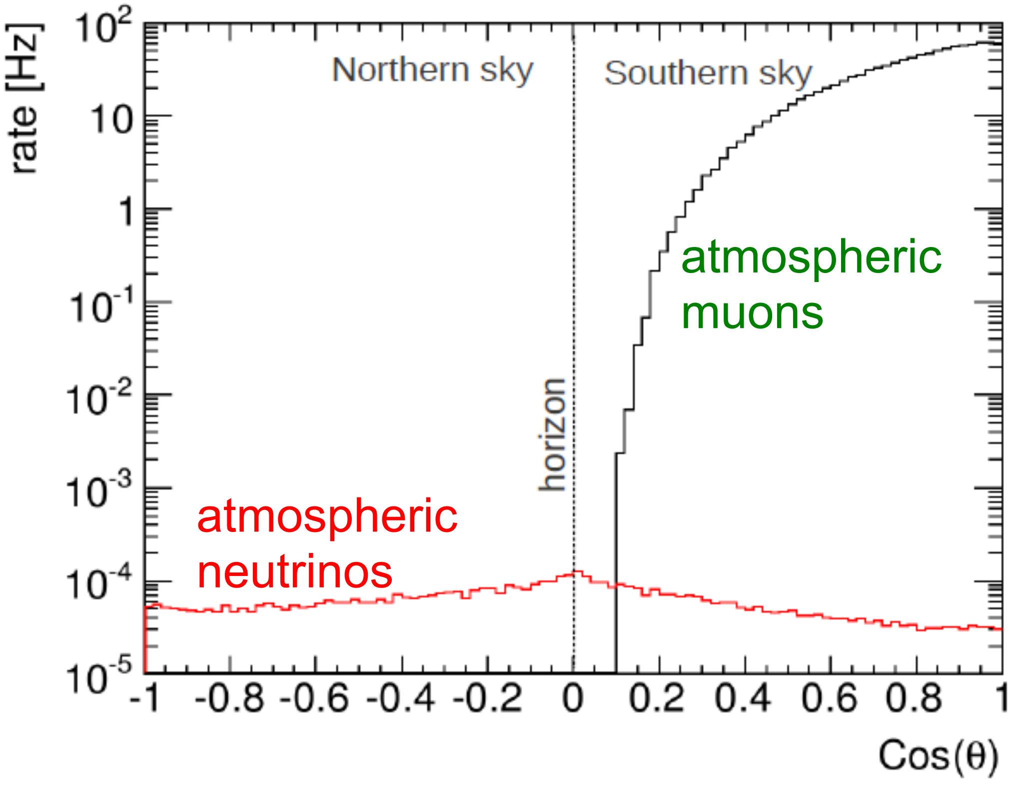

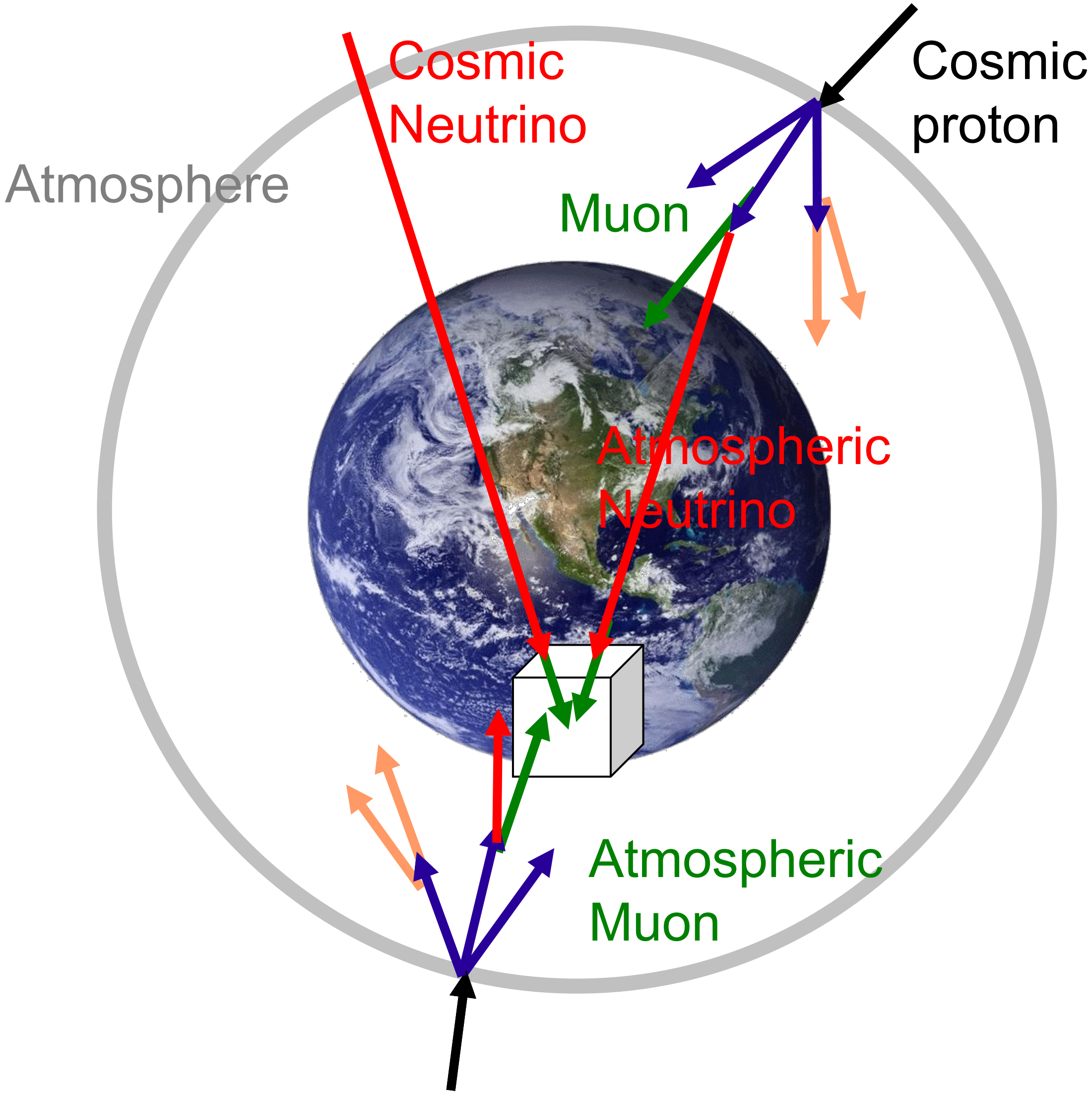

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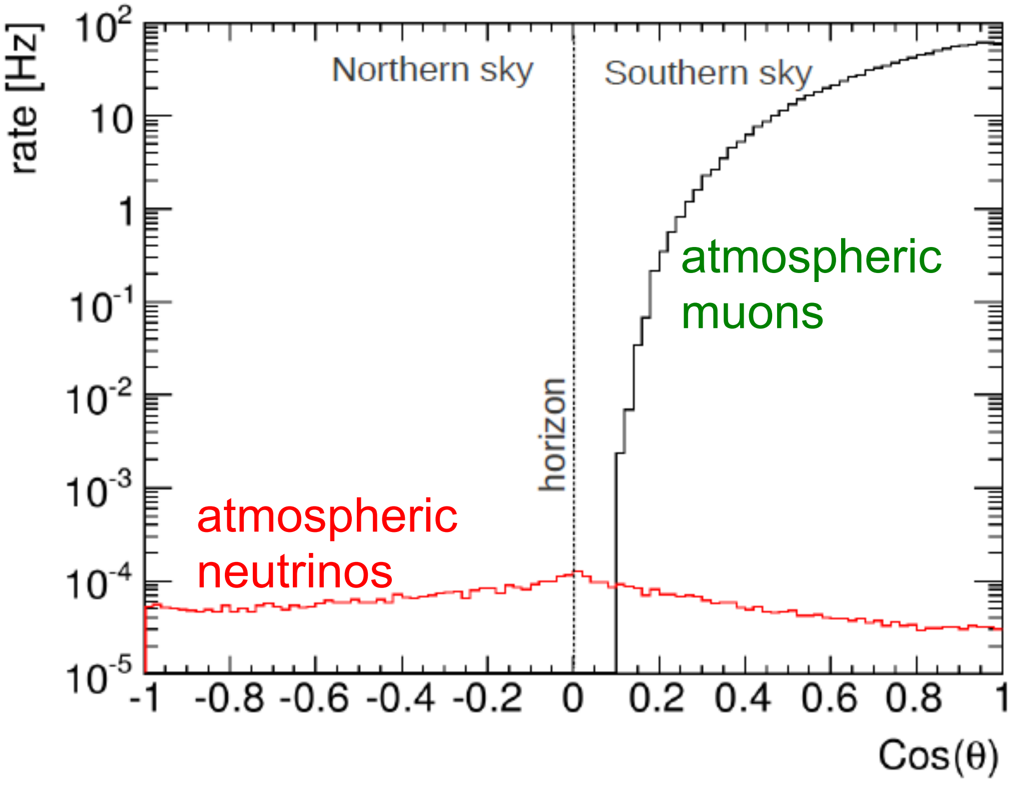
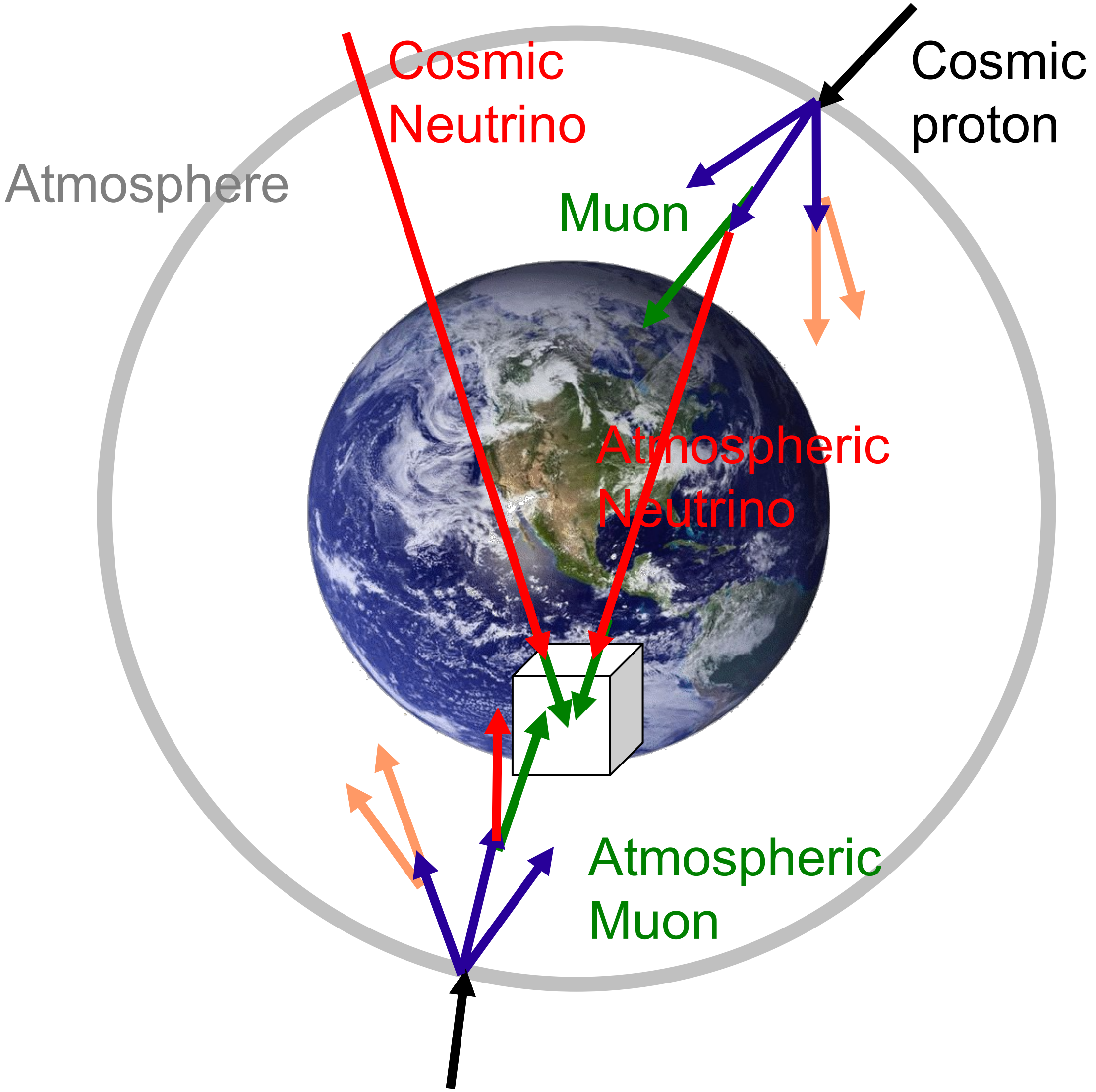
Background in Search for Cosmic Neutrinos

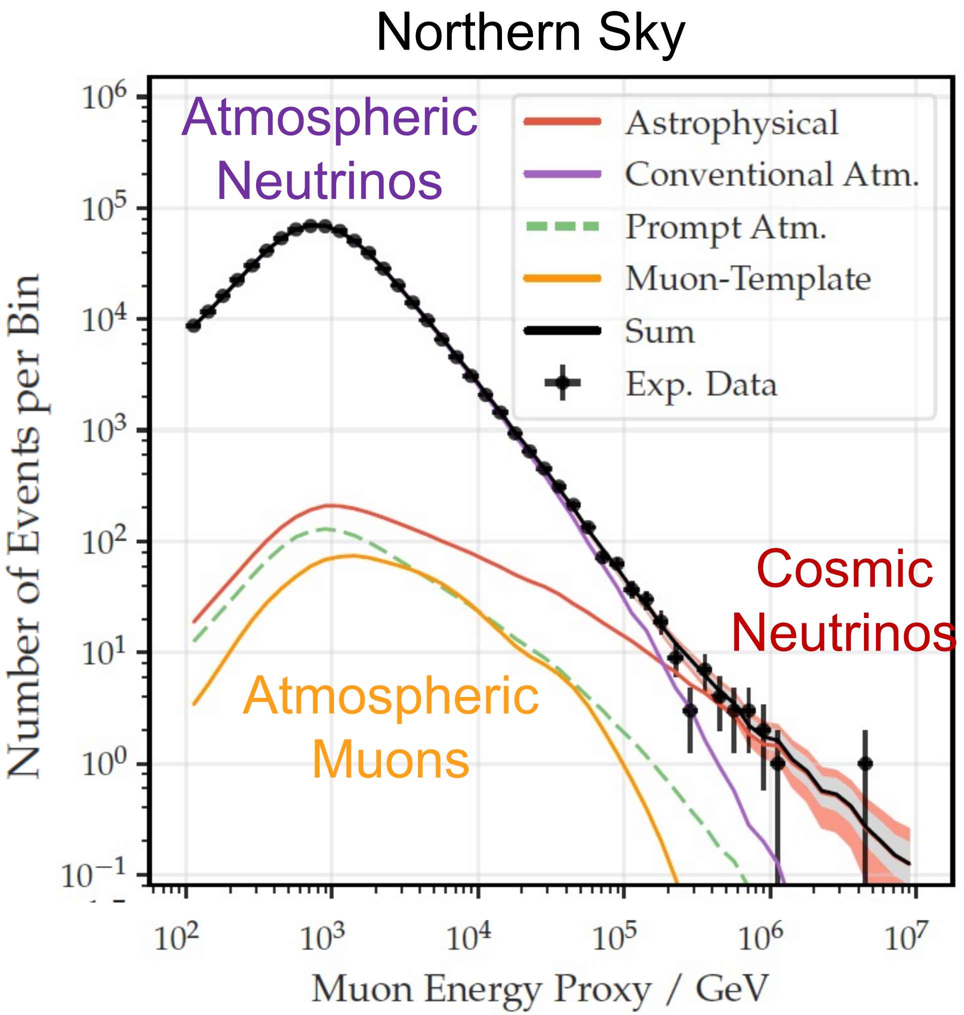
muons detected per year:

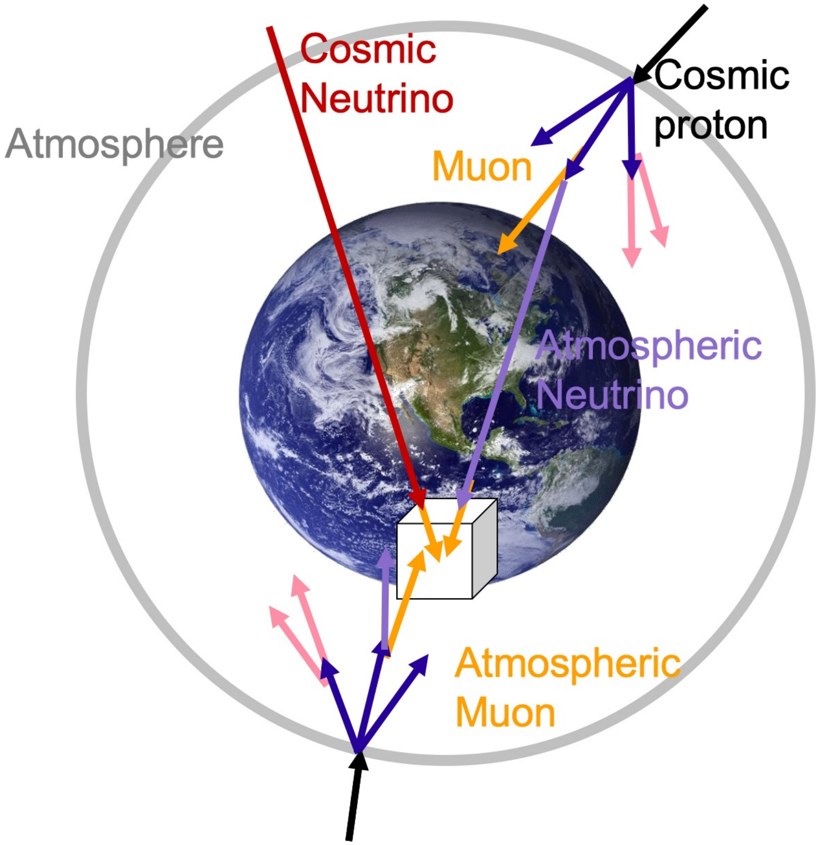
- atmospheric μ $\sim 10^{11}$ (3000/sec)
- atmospheric $\nu \rightarrow \mu$ $> 10^5$ (1/5min)
- cosmic $\nu \rightarrow \mu$ > 120





Diffuse Flux discovered!

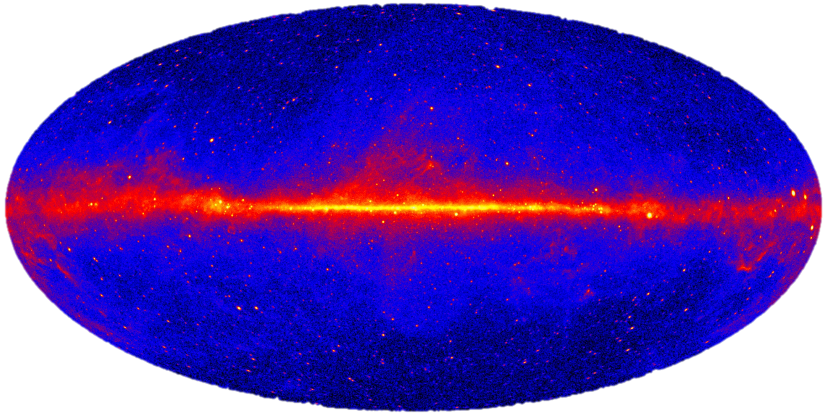




IceCube Coll. ApJ 928 (2022) 50

Galactic Contribution

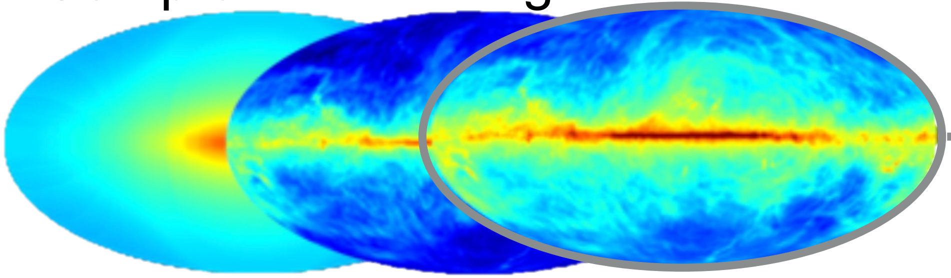
GeV gamma-ray sky by Fermi-LAT

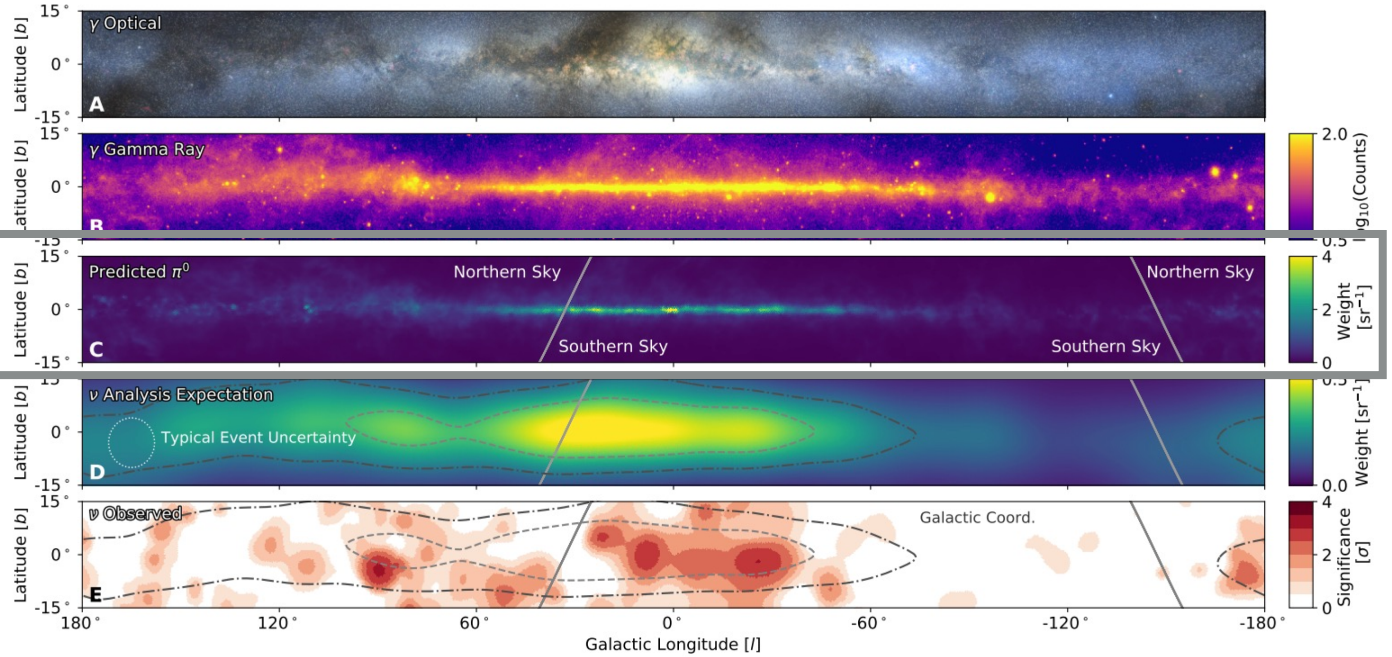


Inverse Compton

Brems-strahlung

π^0 **decay**





IceCube Science 380 (2023)

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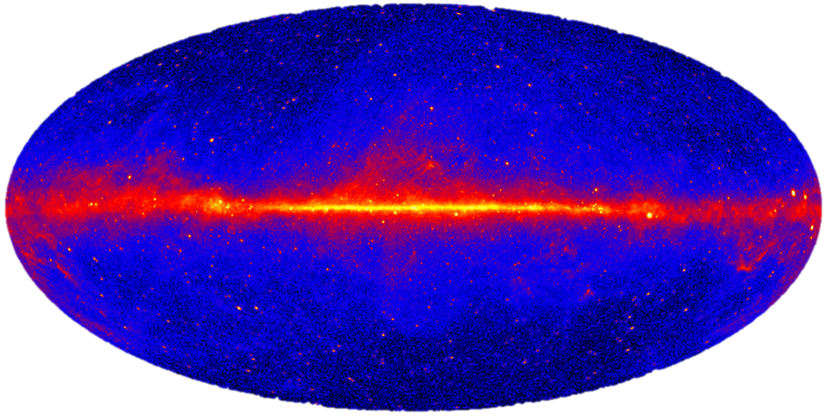

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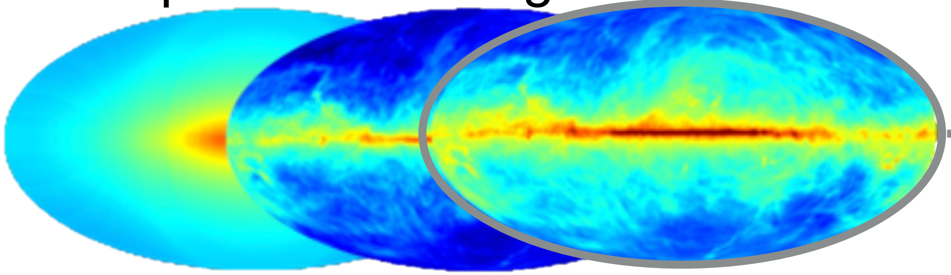

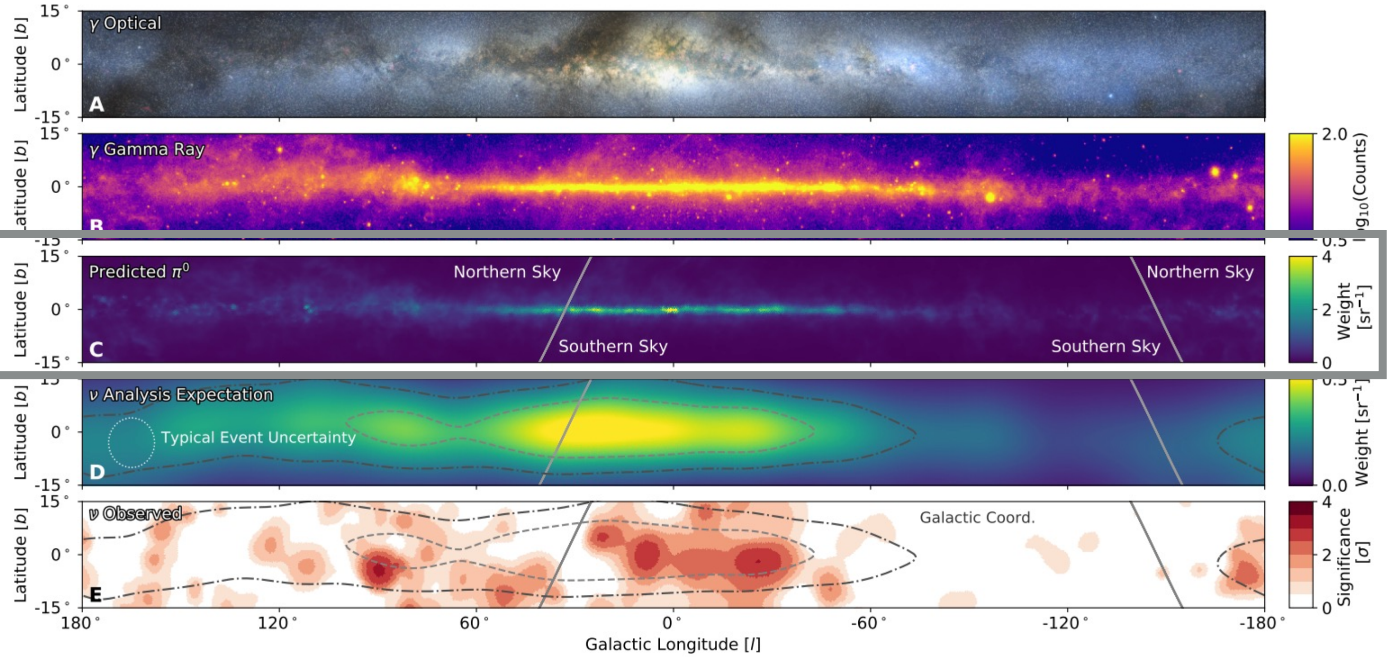

First detection of galactic plane neutrino flux thanks to gamma-ray template fit, ~10% of diffuse flux

IceCube Science 380 (2023)

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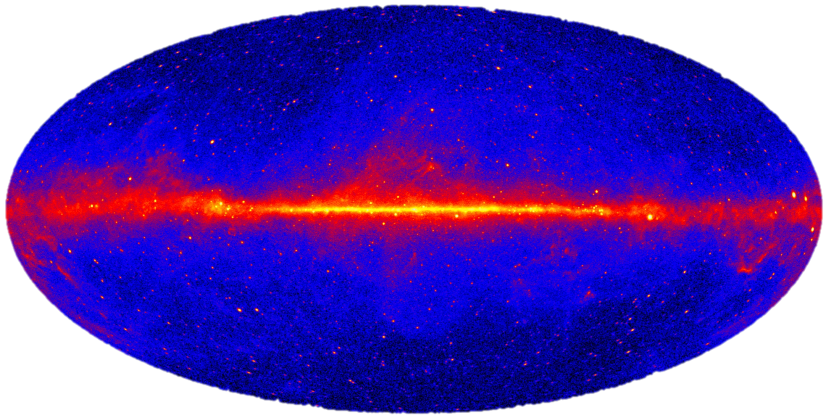
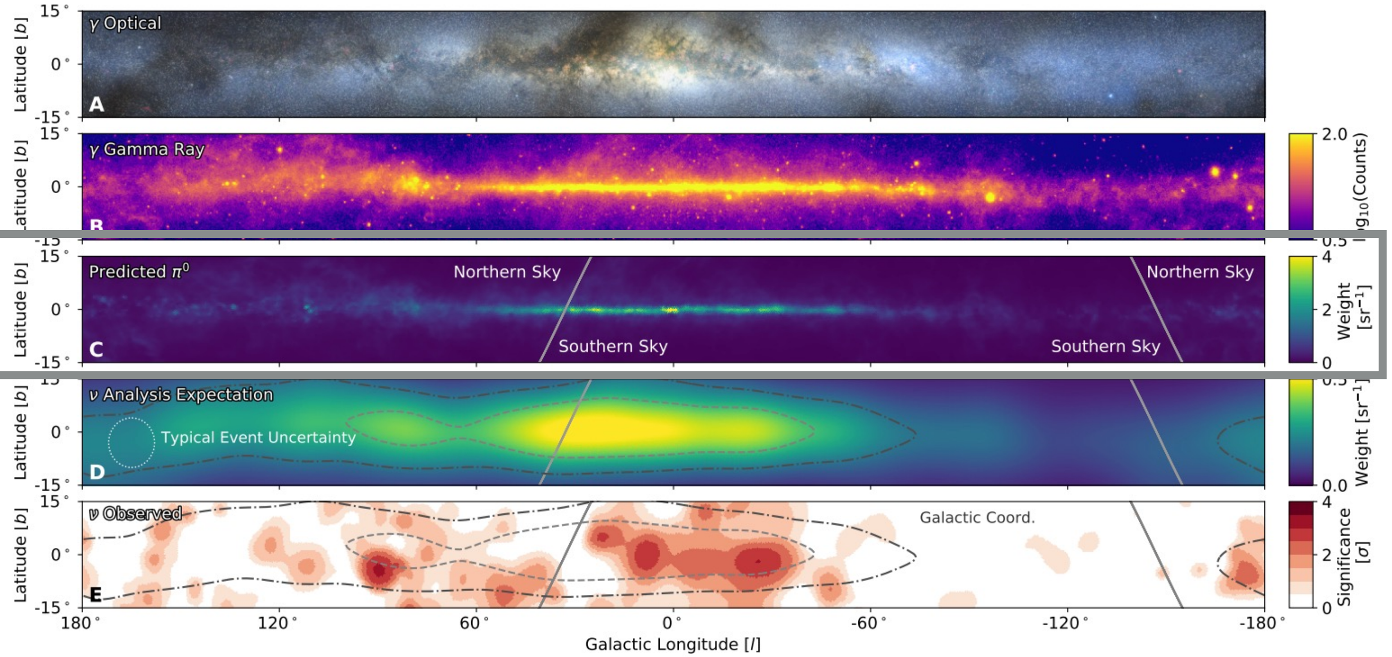
Galactic Contribution

Only possible after application of machine learning algorithms

GeV gamma-ray sky by Fermi-LAT





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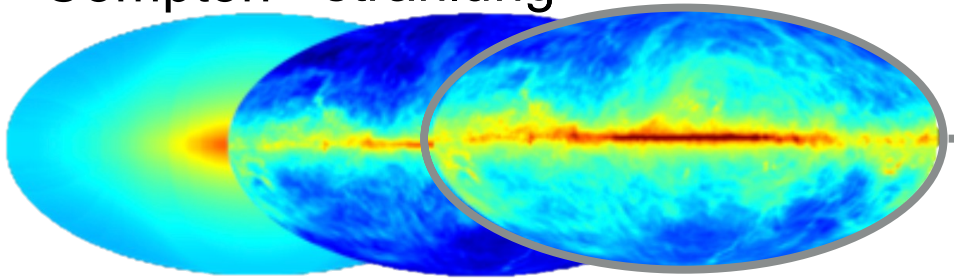

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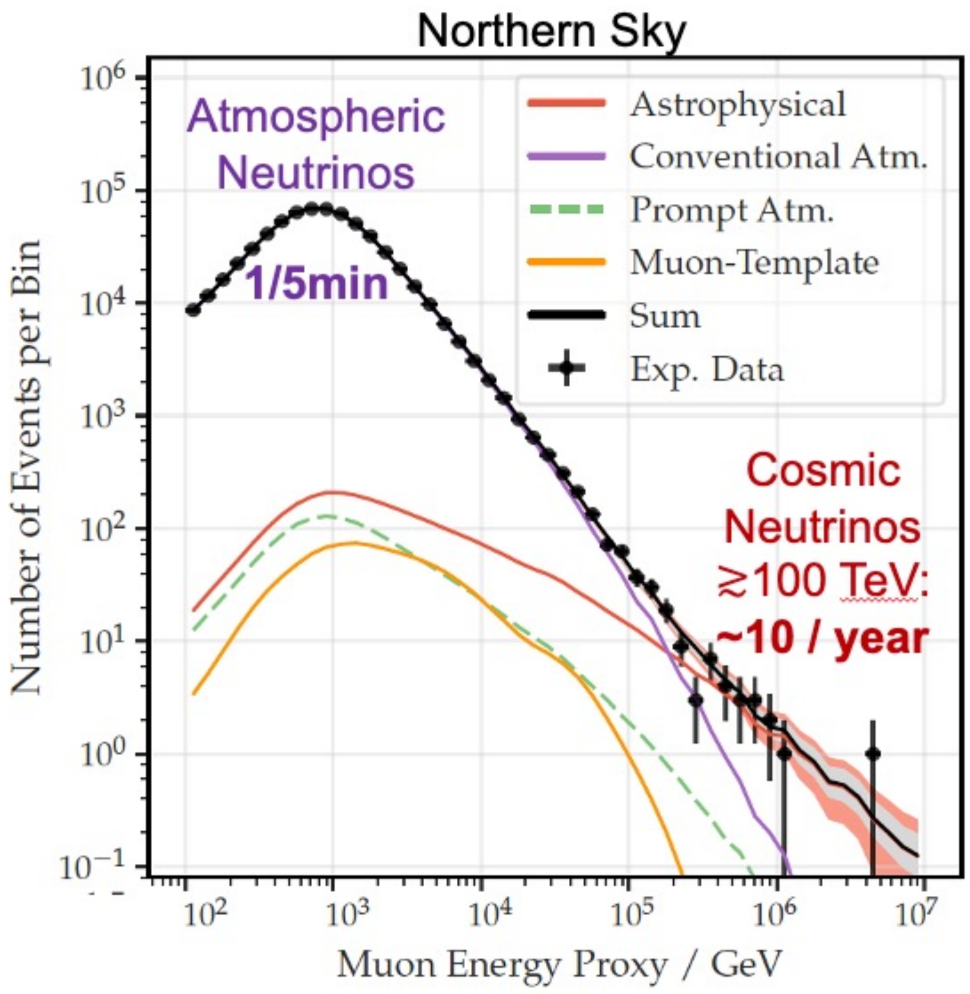
Search for Extragalactic Sources: Strategies



1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

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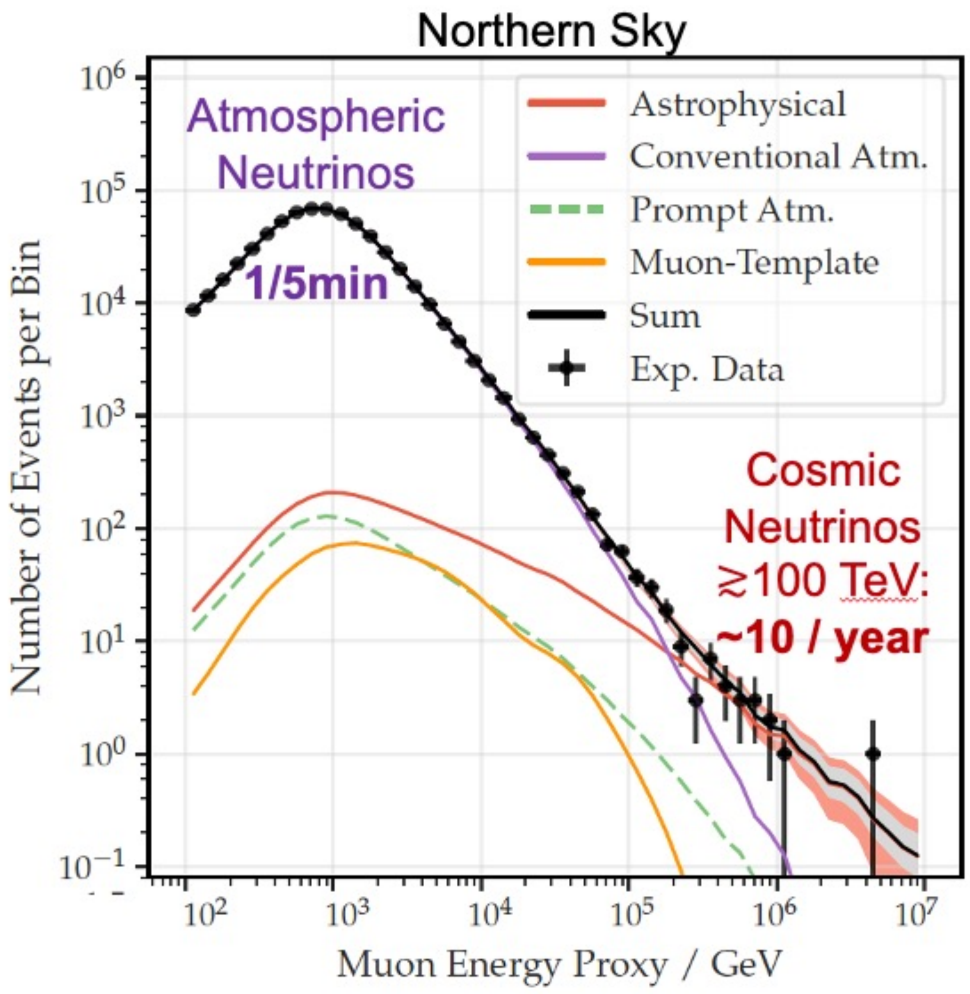

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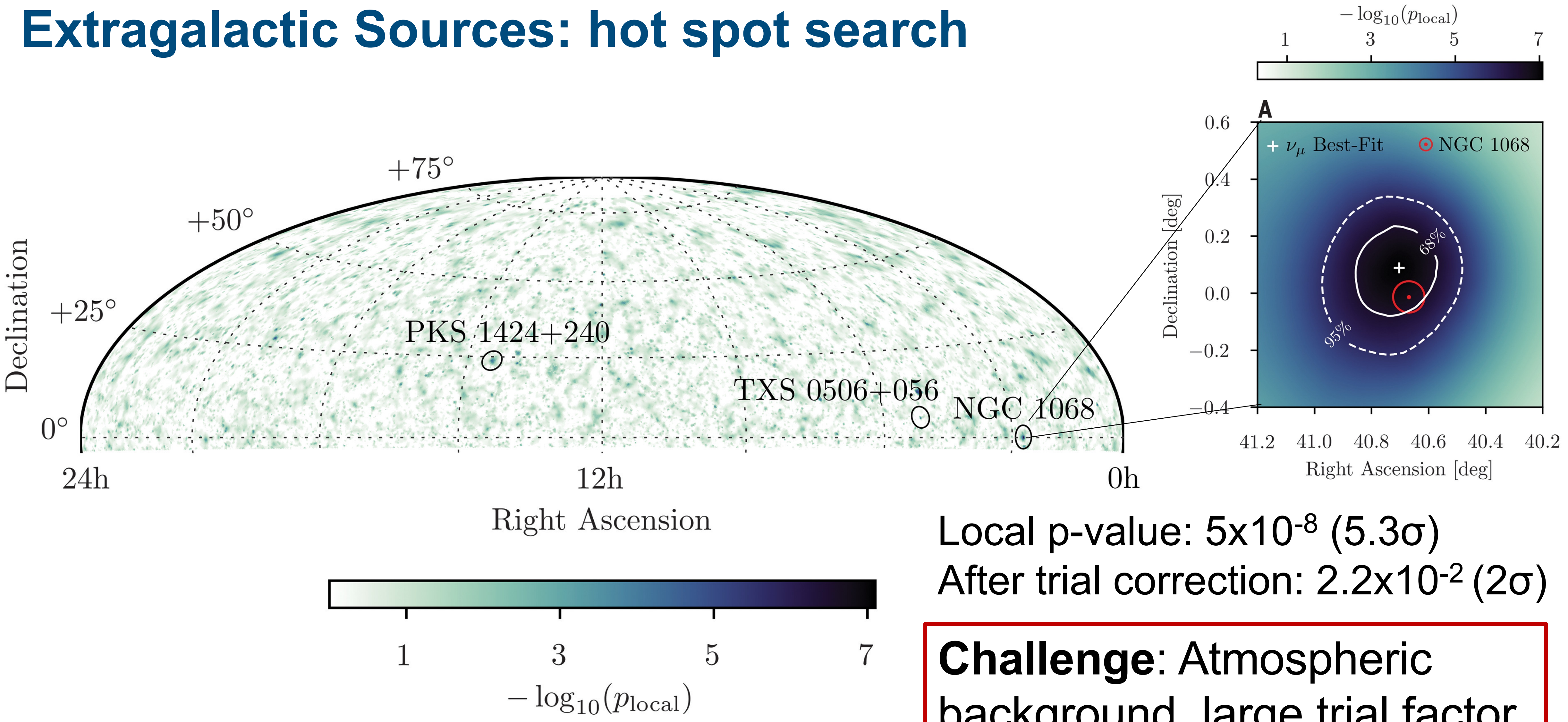
Extragalactic Sources: hot spot search



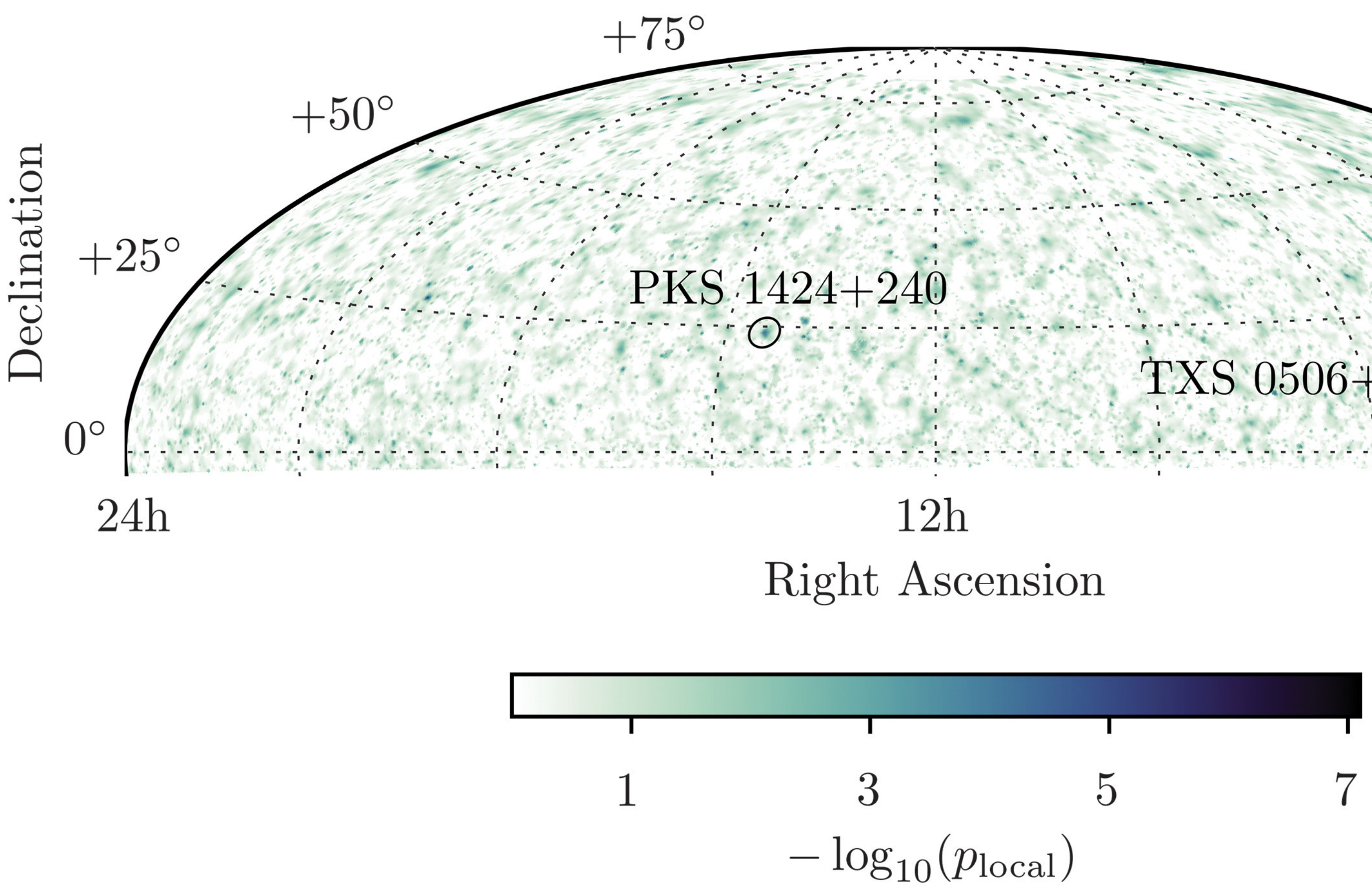
Local p-value: $5\text{x}10^{-8}$ (5.3σ)

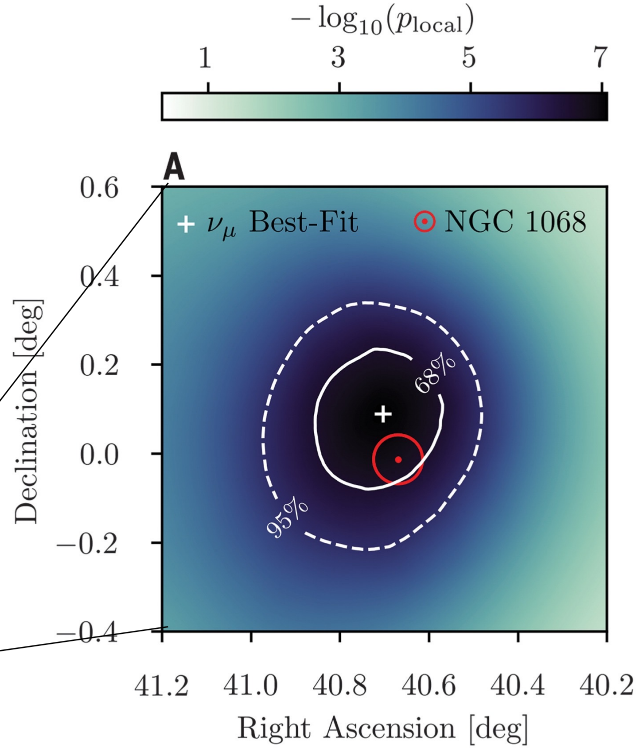
After trial correction: $2.2\text{x}10^{-2}$ (2σ)

Challenge: Atmospheric background, large trial factor

IceCube Science 378 (2022)

Extragalactic Sources: hot spot search





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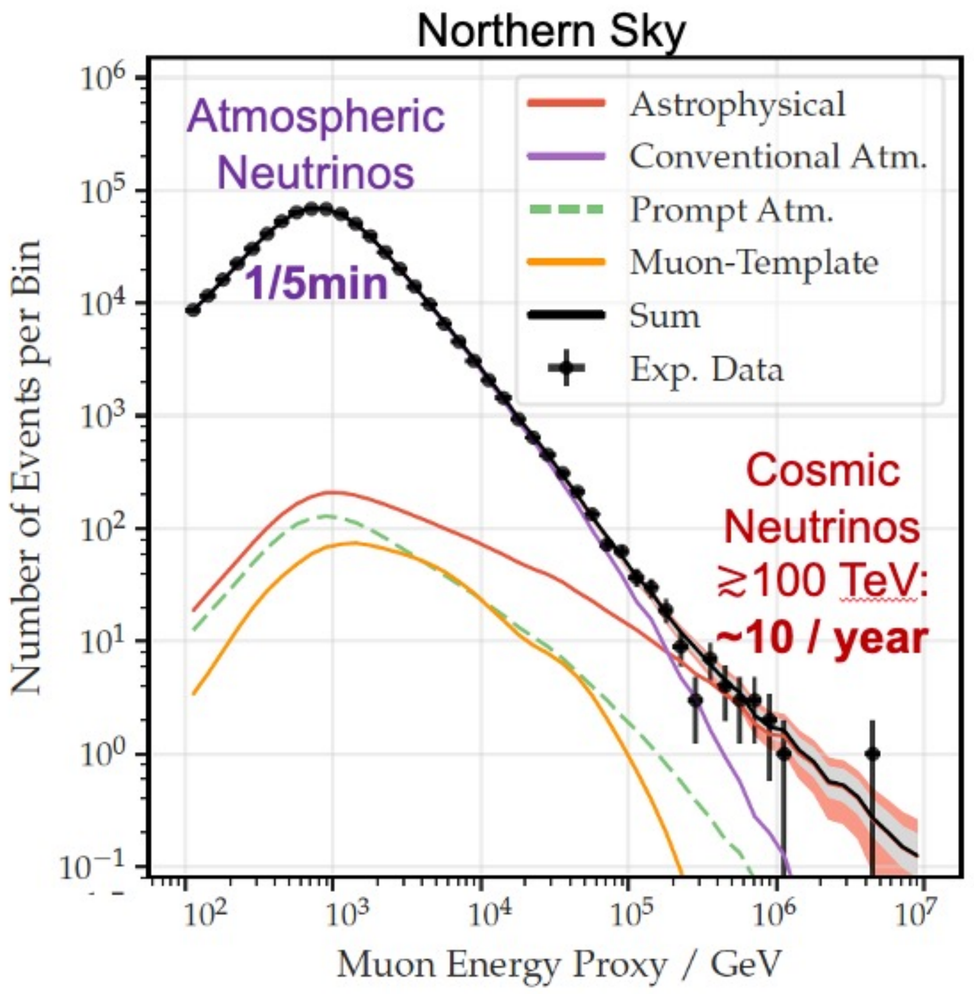
Solution: Use predefined source lists to reduce trials

Search for Extragalactic Sources: Strategies



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Extragalactic Sources

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

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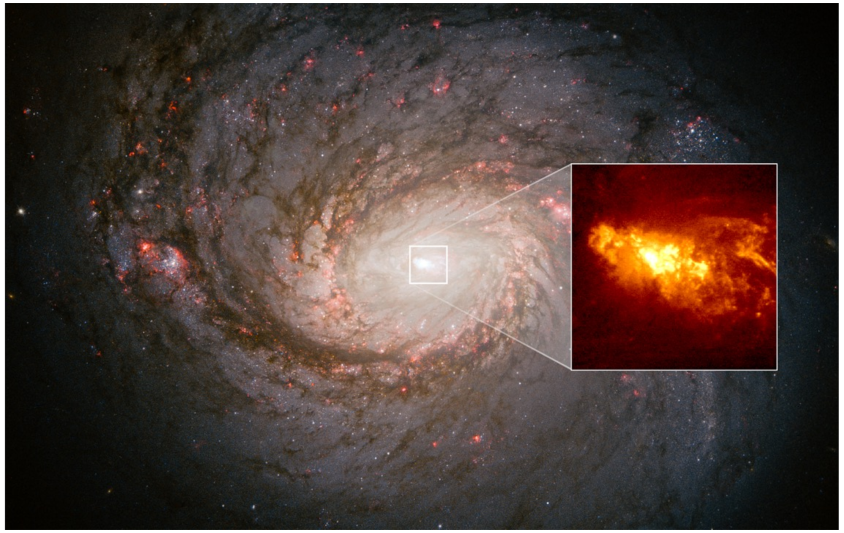


Most significant candidate:

NGC 1068 (M77), 4.2σ

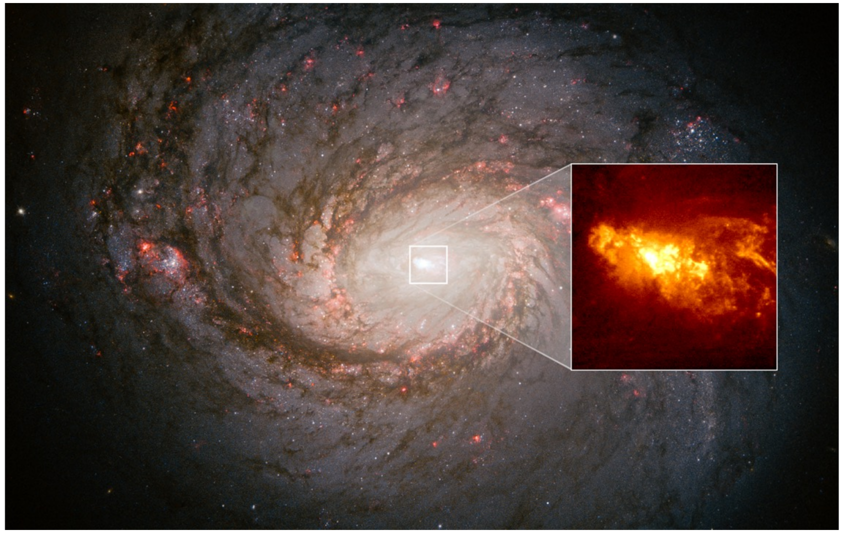
- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

Combining gamma-ray source list with neutrino data allowed neutrino source detection

IceCube Science 378 (2022)

Extragalactic Sources

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity



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Lack of gamma rays places neutrino production site in the heart of the galaxy

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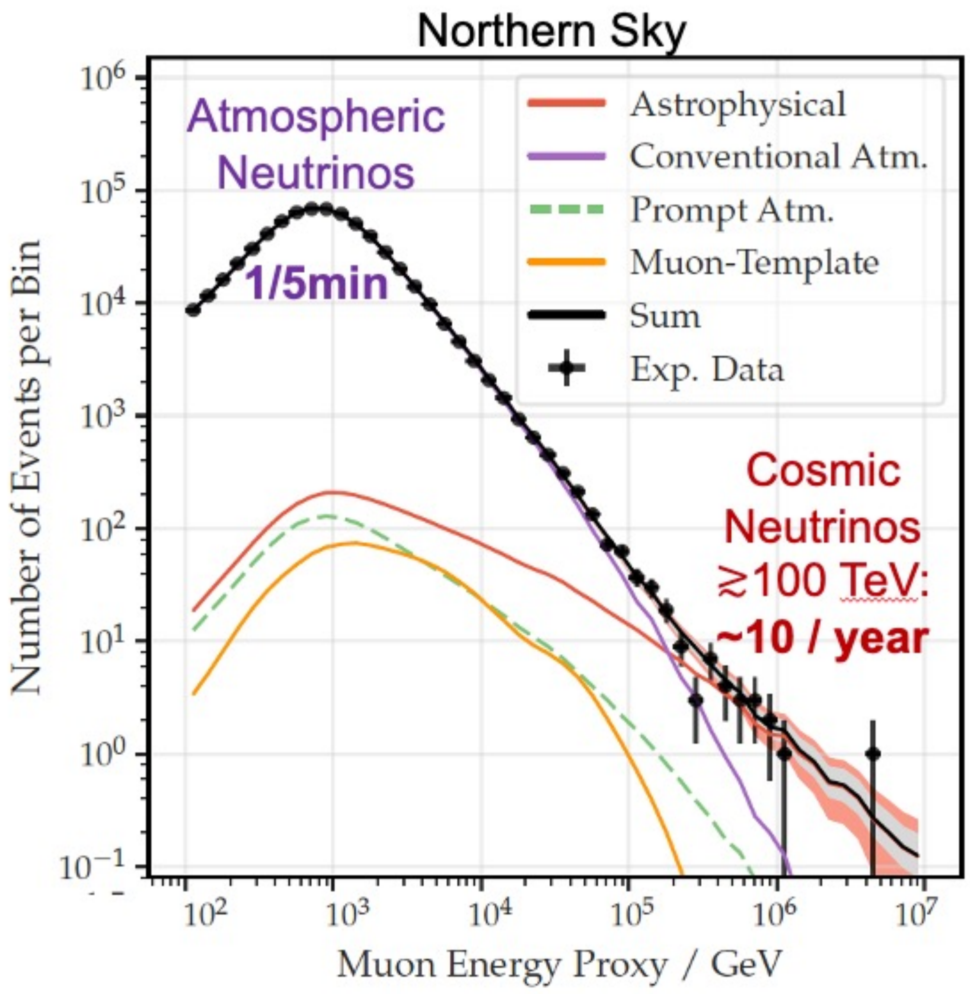
Search for Extragalactic Sources: Strategies



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Neutrinos as Triggers

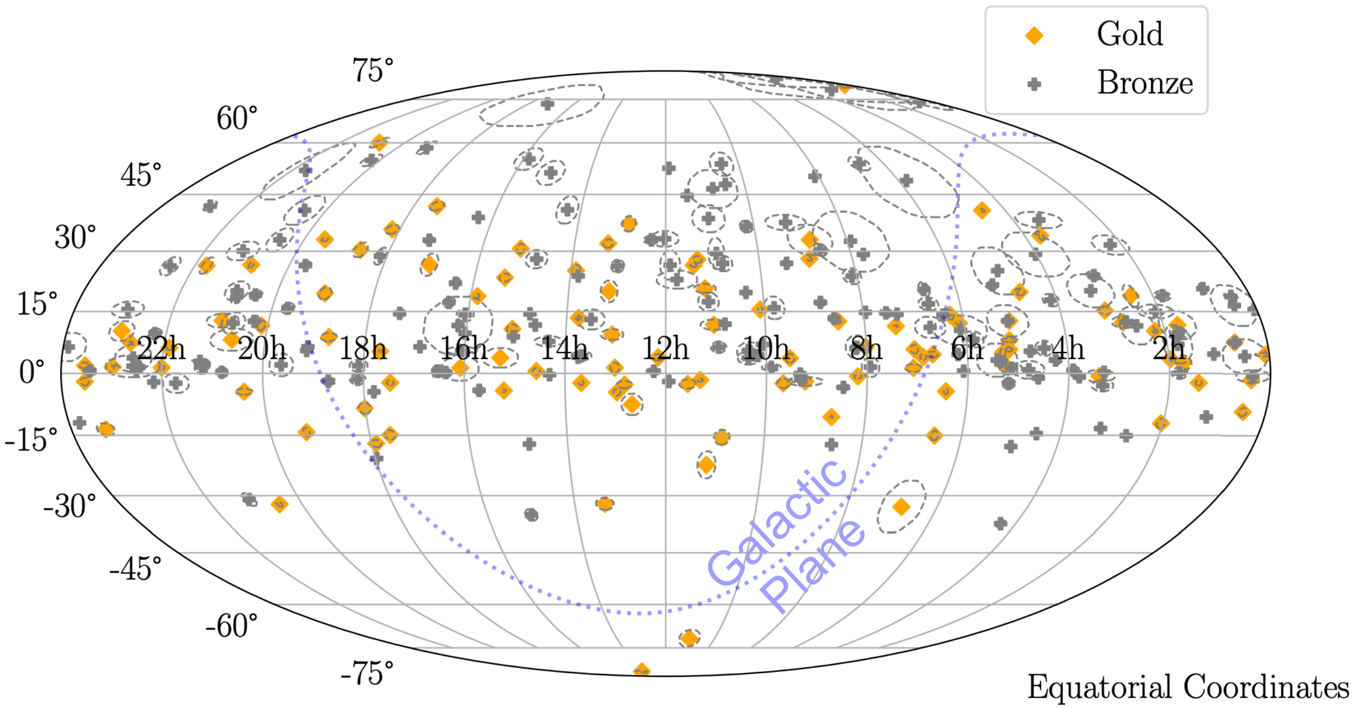
Public alerts since April 2016

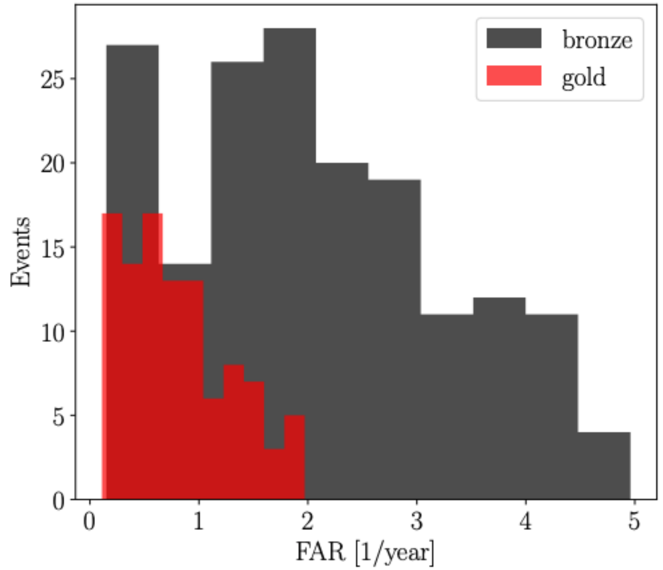
- Single high-energy muon track events (> ~100TeV)
- "Gold" ("Bronze") alert stream 10/yr (30/yr), 50% (30%) "signalness"
- Median latency: 30 sec
- Distributed through GCN

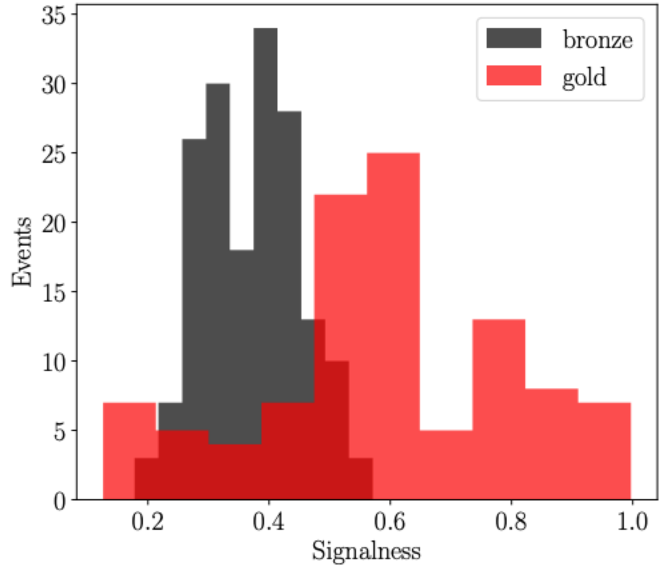
Goal: Find electromagnetic counterpart

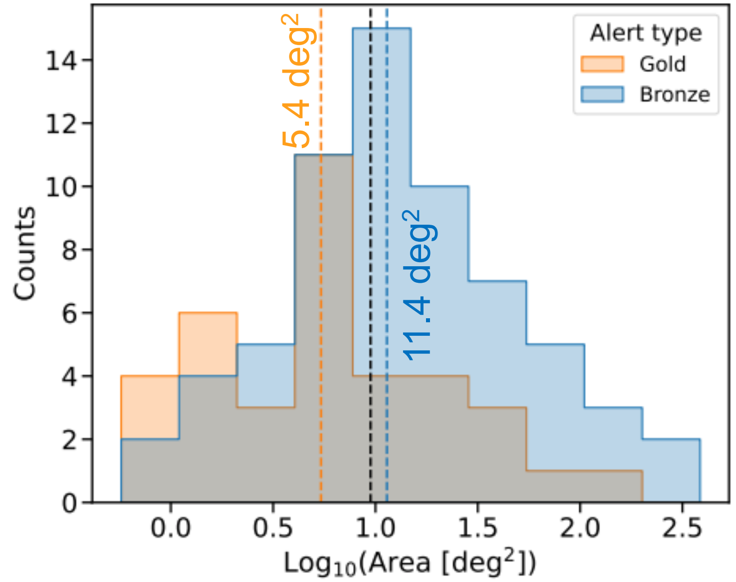
Astropart. Phys., 92, 30 (2017)

IceCat1





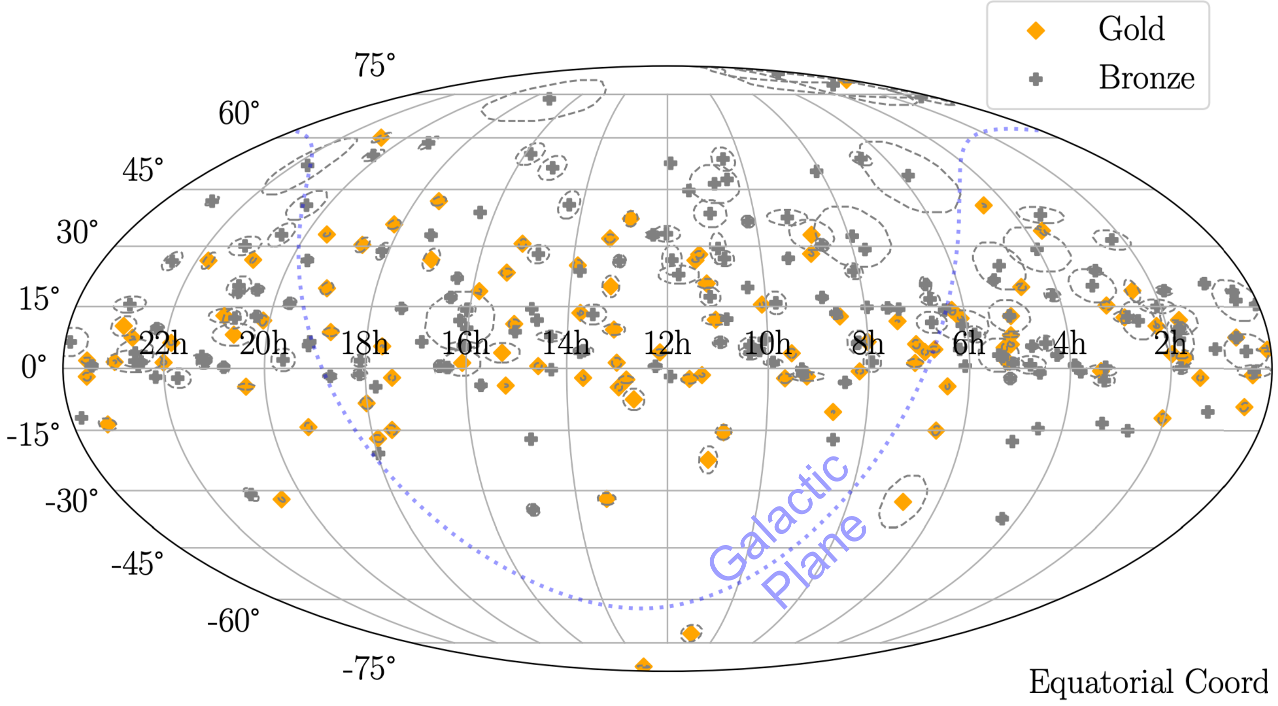




IceCube ApJS 269 (2023)

Garrappa et al. A&A, 687 (2024)

IceCat1

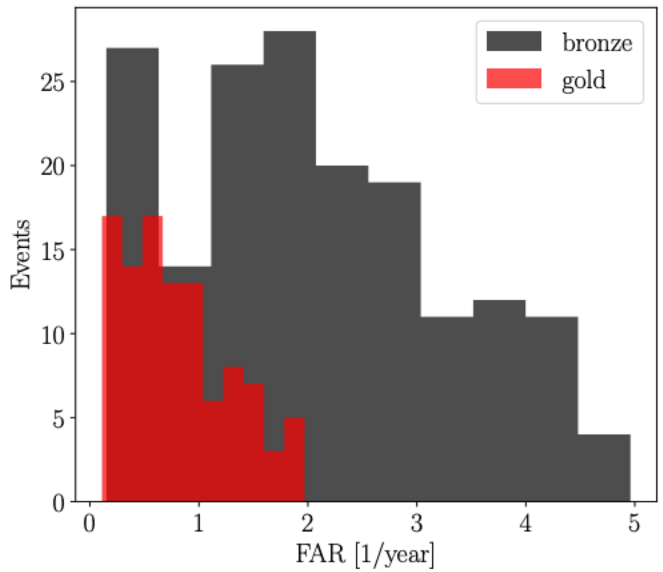


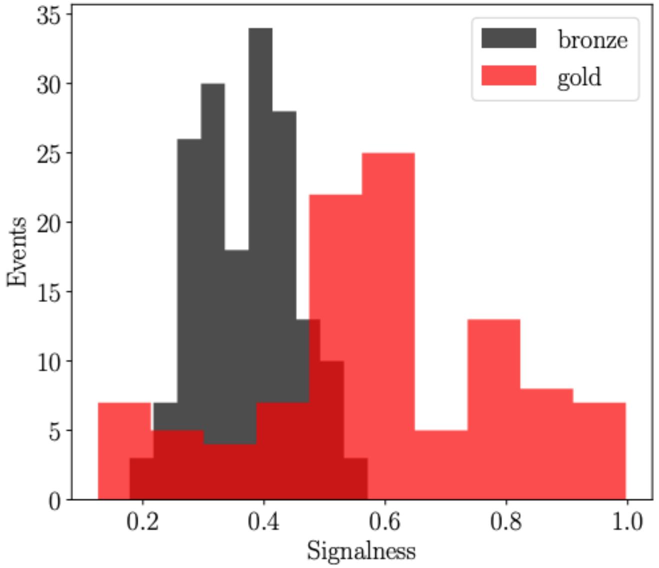
Improved consistency with offline analysis and improved angular reconstruction implemented now

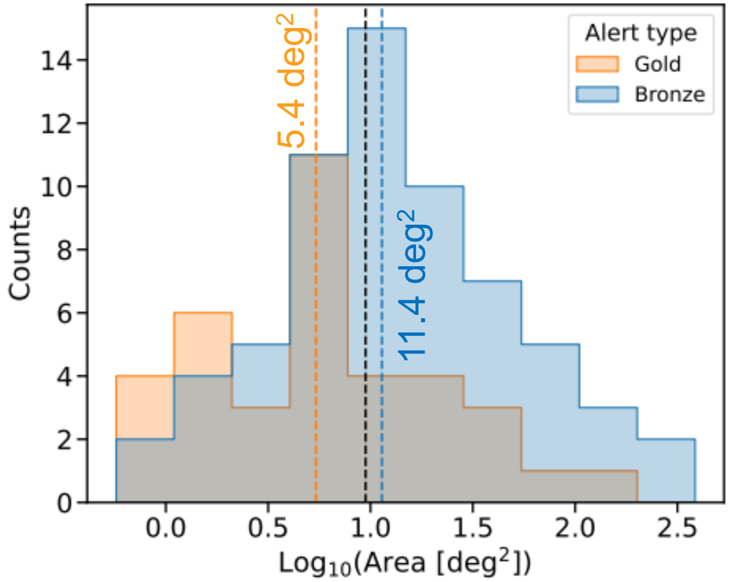
→ areas will be factor of five smaller on average

https://arxiv.org/pdf/2307.13884

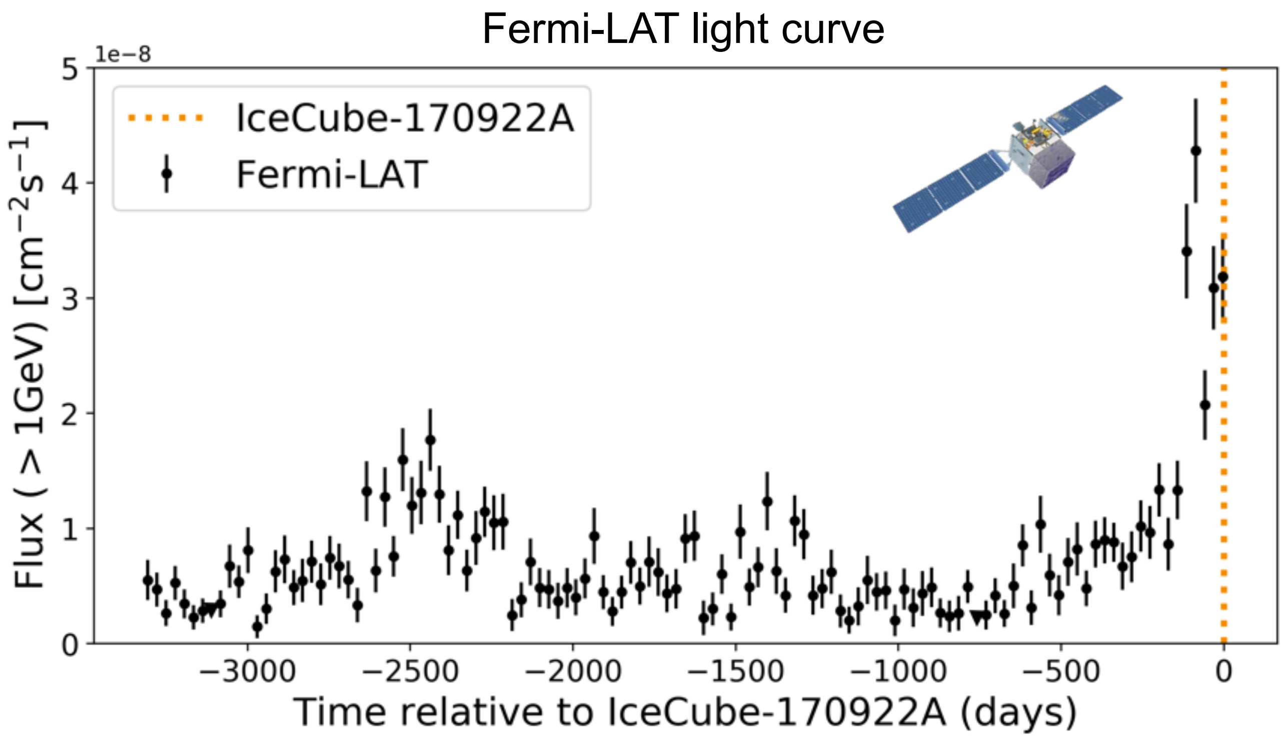
https://arxiv.org/pdf/2307.14069



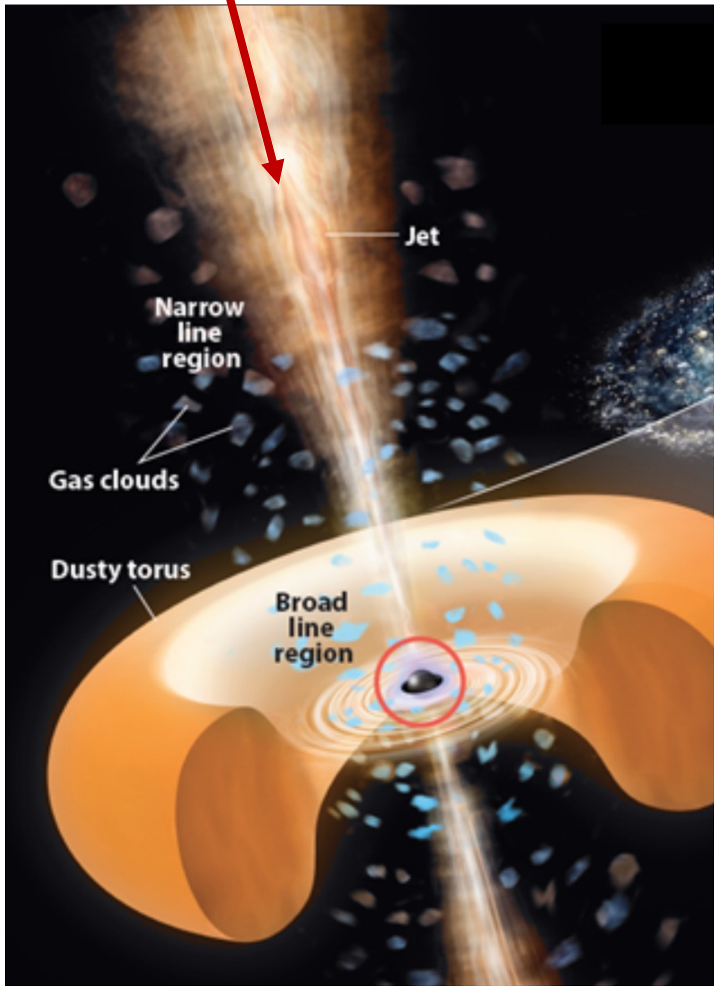




Source Candidates: TXS 0506+056



Blazar

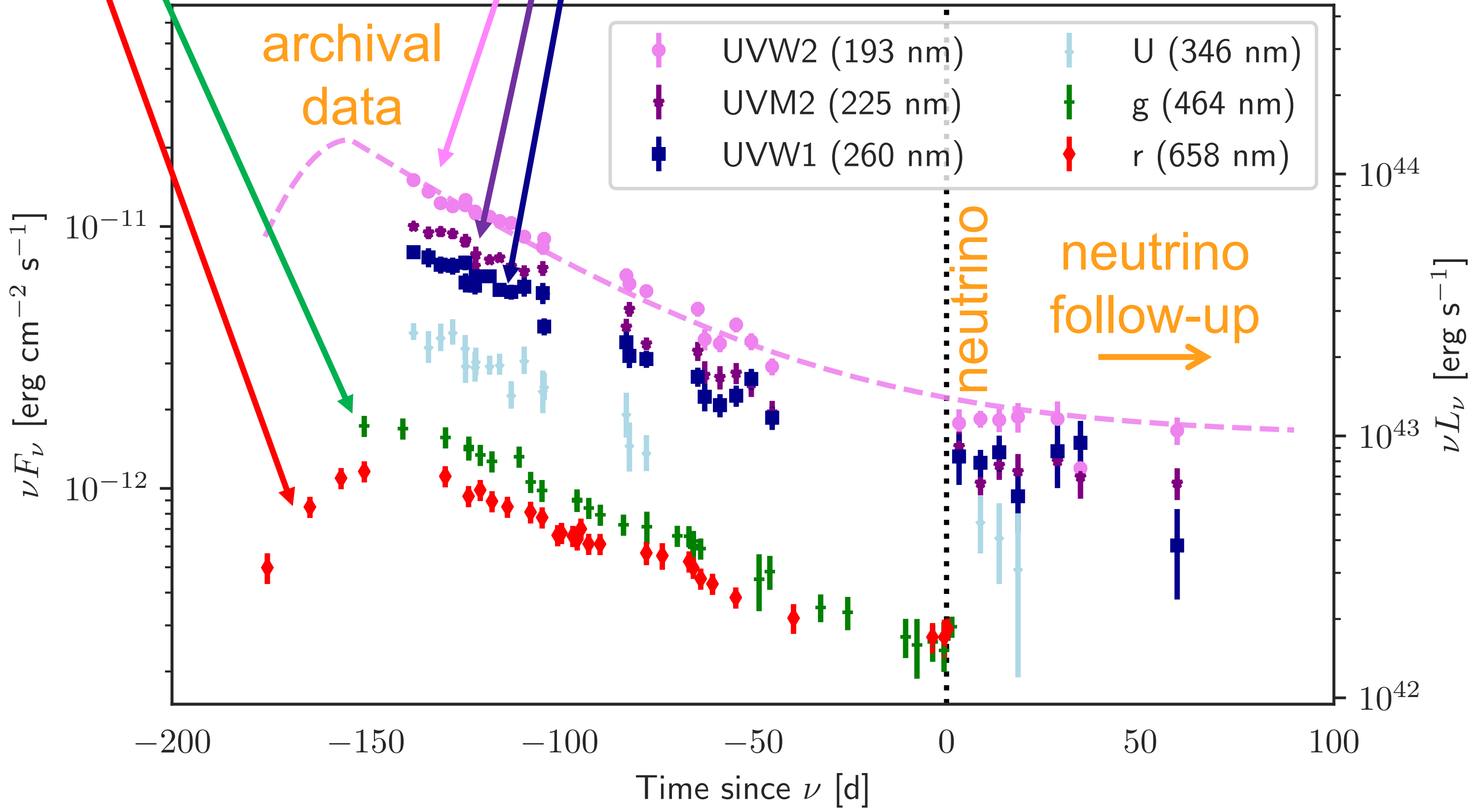


Coincidence with source location and gamma-ray flare increases significance to 3σ

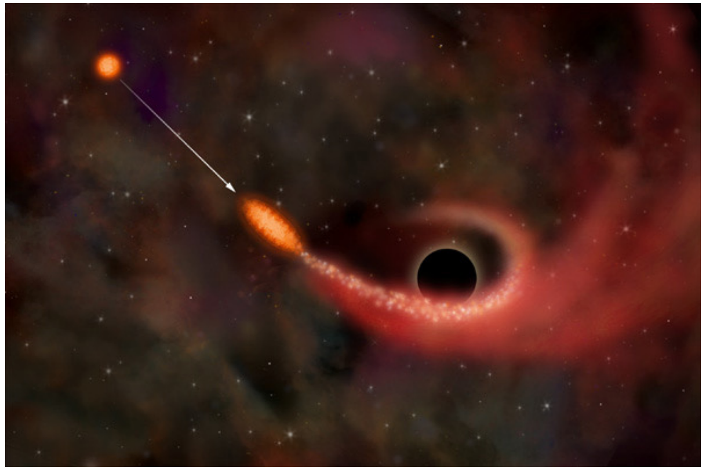
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

RUB

Source Candidates: Tidal Disruption Event AT2019dsg



R. Stein et al., Nature Astronomy 2021

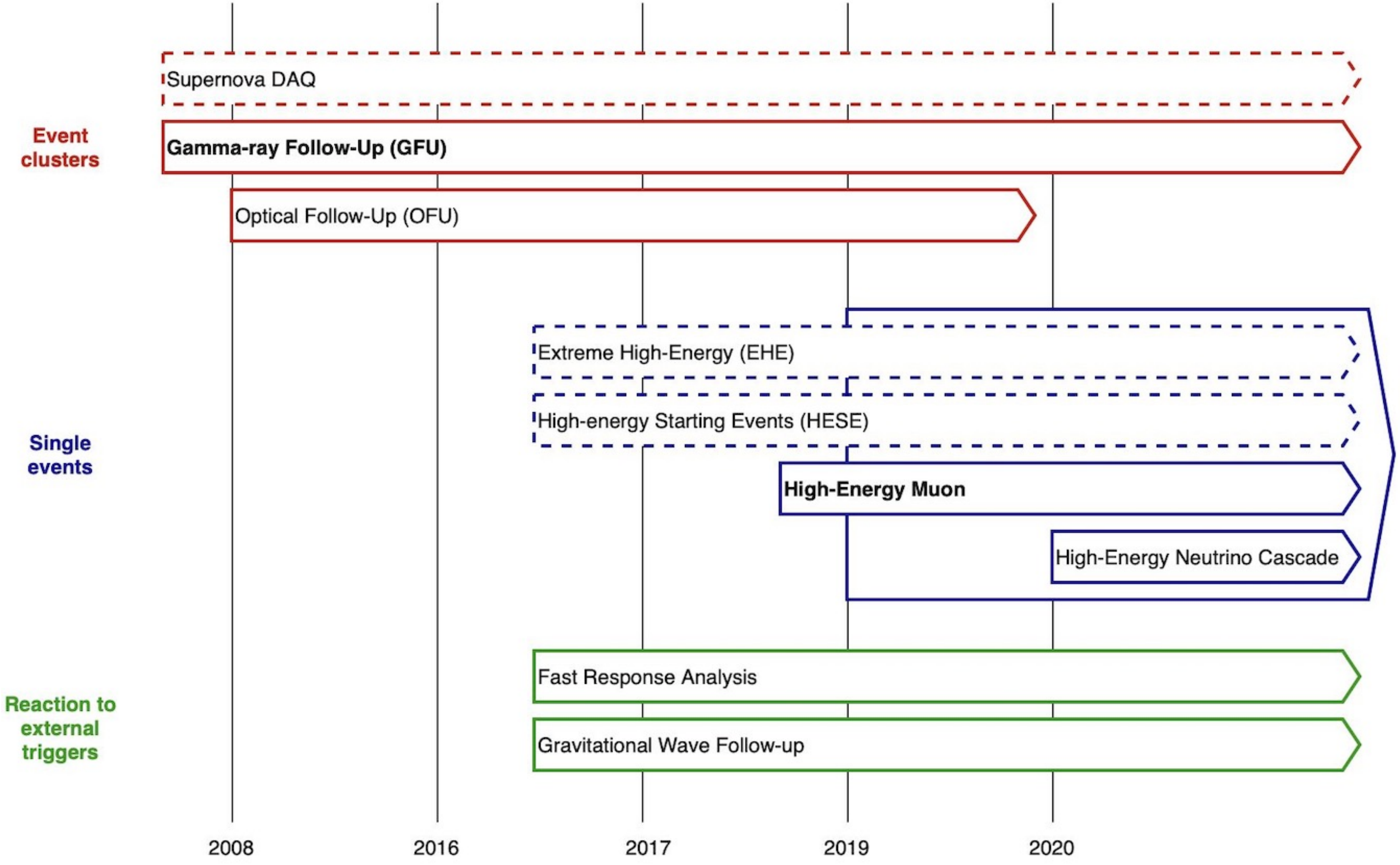


Chance coincidence:
0.2% to find a TDE that bright (including trials)

Two more candidates → 3.7 sigma

S. Reusch et al. PRL 2022, S. Van Velzen et al. MNRAS 529 (2024)

IceCube Realtime System

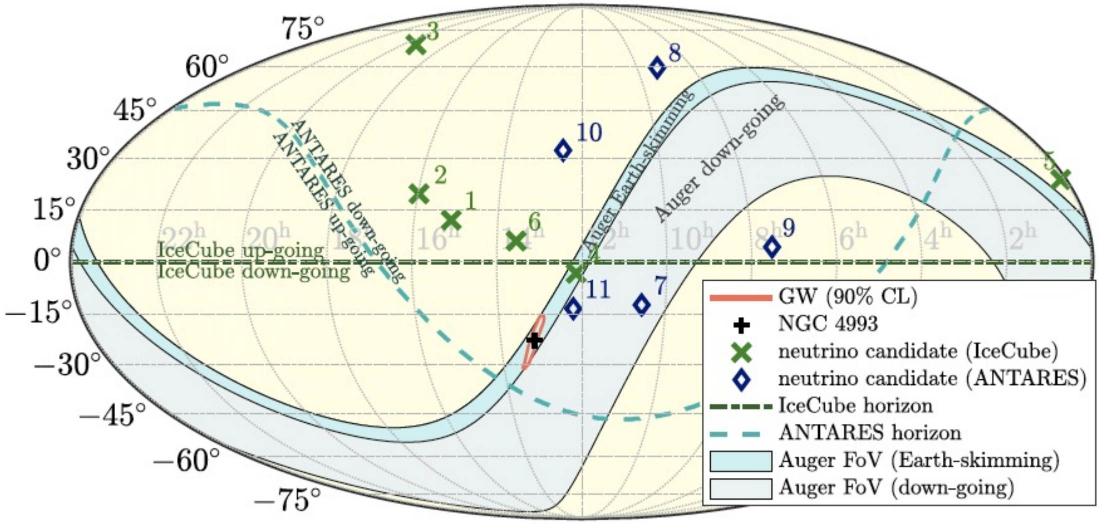


- Alerts coordinate on public alert systems
  - GCN
  - SNEWS
- Collaboration response coordinated by internal Realtime Oversight Committee
  - Ensure rapid response

RUB Credit: Thomas Kintscher & Sarah Mancina

TeV Neutrinos and Gravitational Waves: BNS merger

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



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

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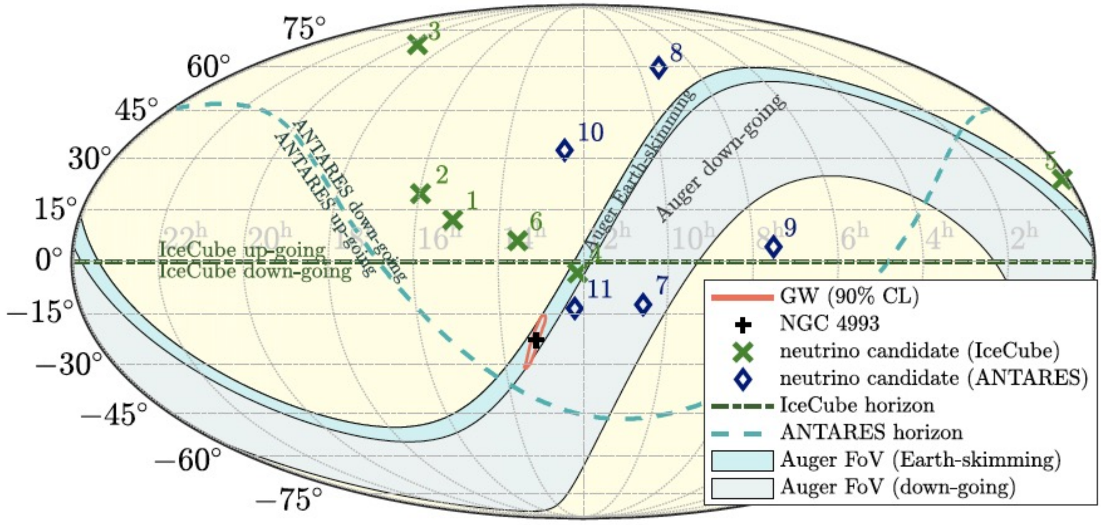
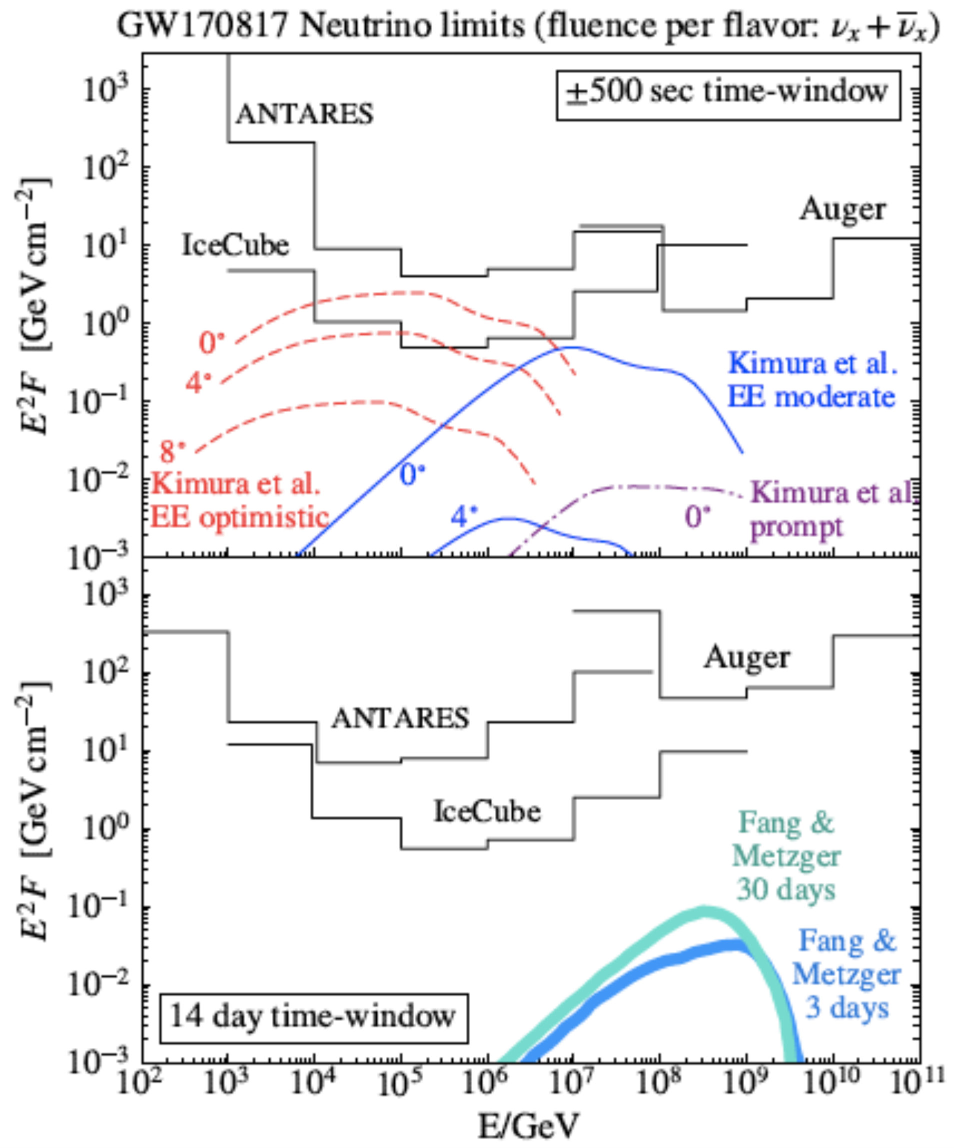


Non-observation is consistent with off-axis short GRB scenario



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

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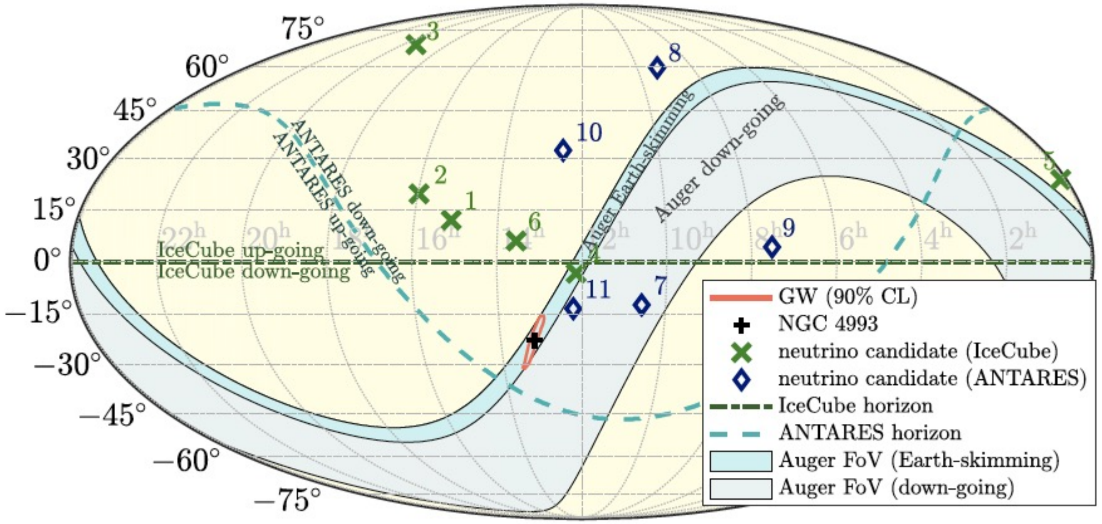
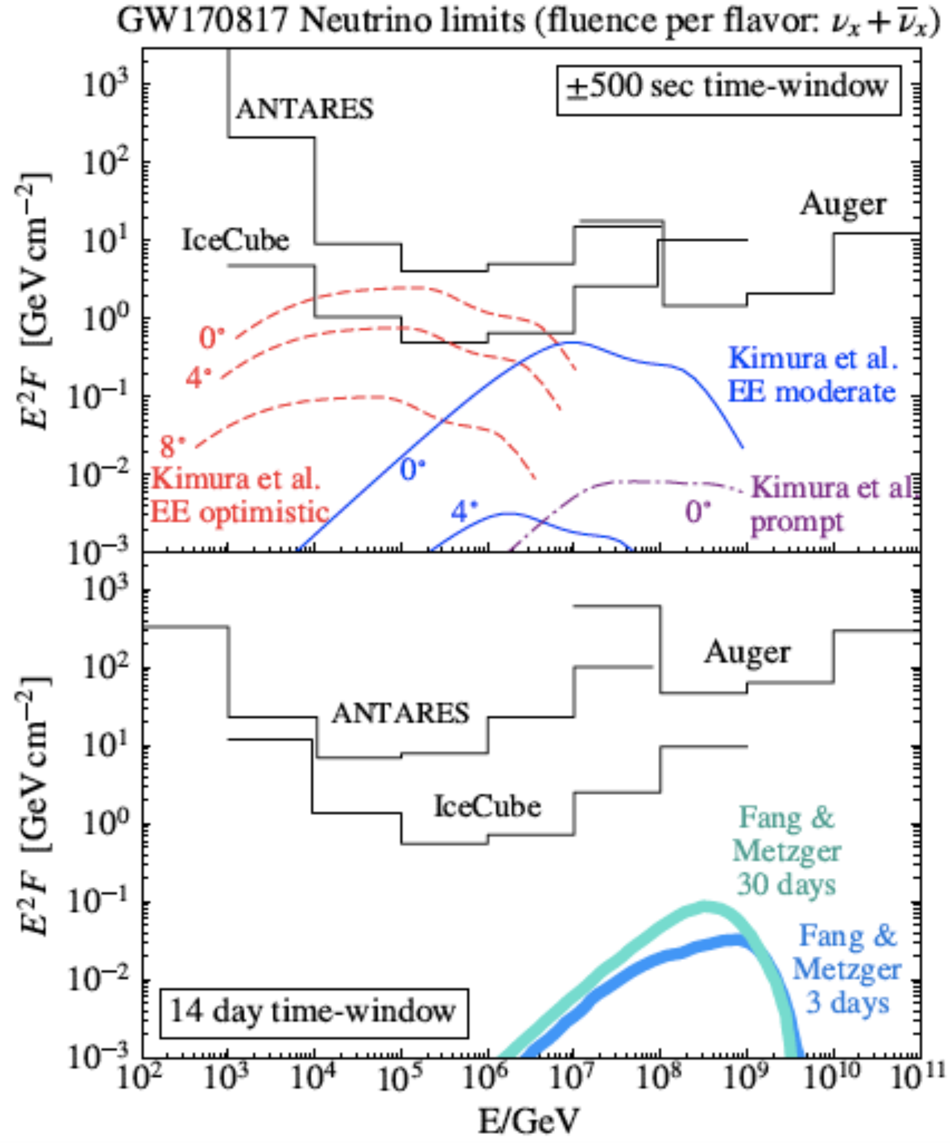




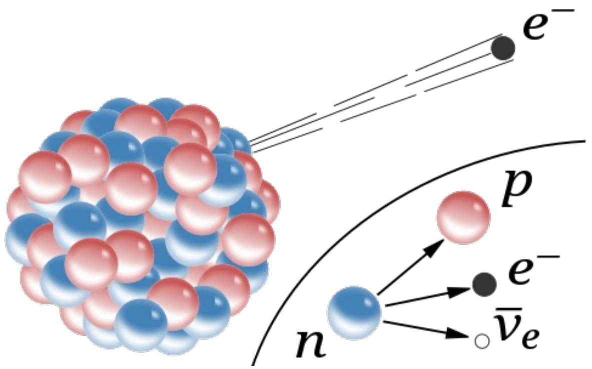
Non-observation is consistent with off-axis short GRB scenario

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

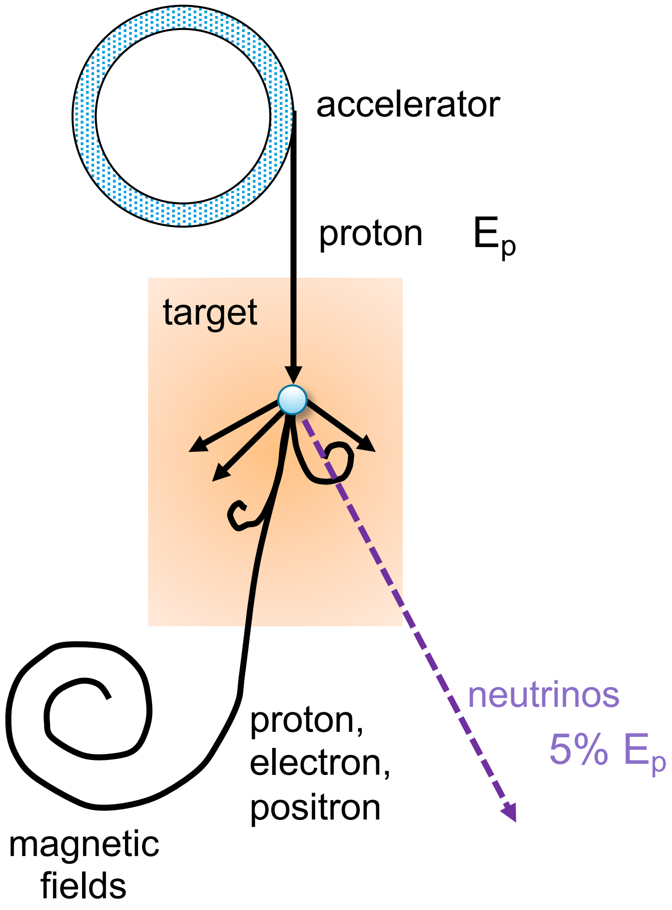
LIGO, Virgo, Auger, ANTARES, IceCube, ApJ 850 (2017)

How are neutrinos produced?

MeV neutrinos from nuclear processes, (inverse) beta decay



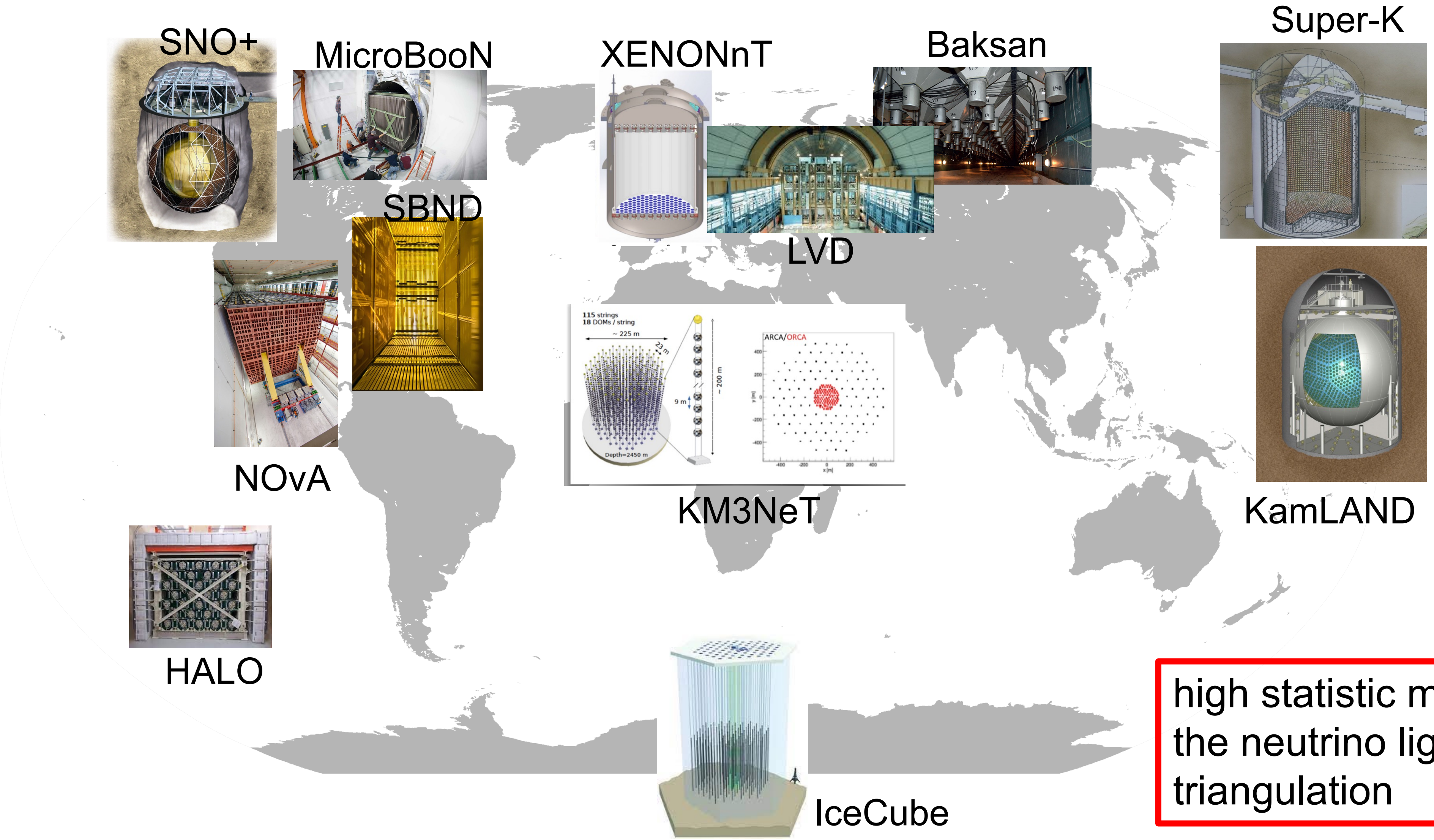
TeV-PeV neutrinos from cosmic-ray "beam dumps"



Two ingredients:

- Proton acceleration
- Target for interaction

Detectors participating in SNEWS



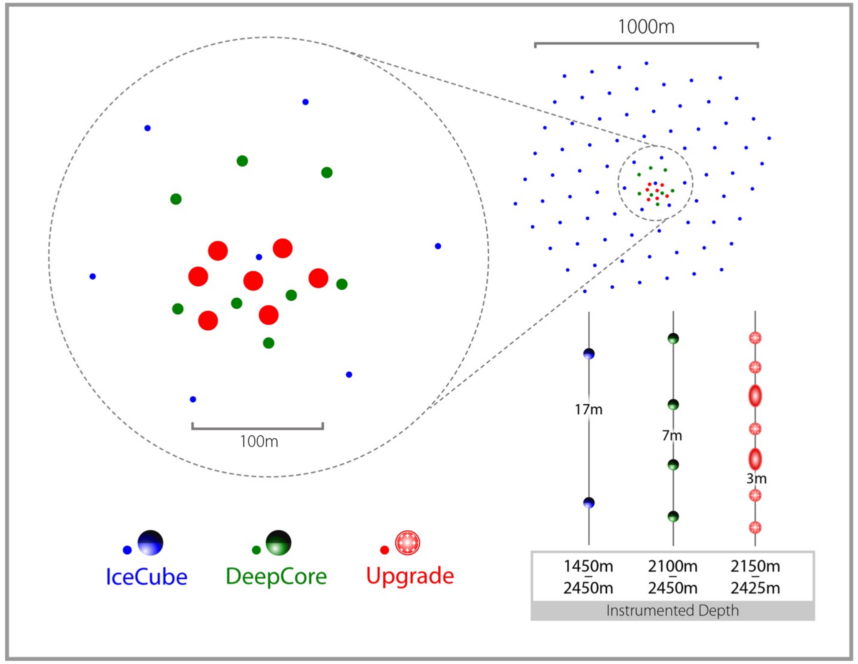
high statistic measurement of the neutrino lightcurve and triangulation

https://snews2.org/

Next Generation at the South Pole – two tier process

IceCube Upgrade – in progress

- Focus on improved calibration and low energy neutrino physics
- Test new technologies
- Deployment in 2025/26 polar season
- Ice is stable → **reprocess decade+ of neutrinos with improved analyses and systematics**



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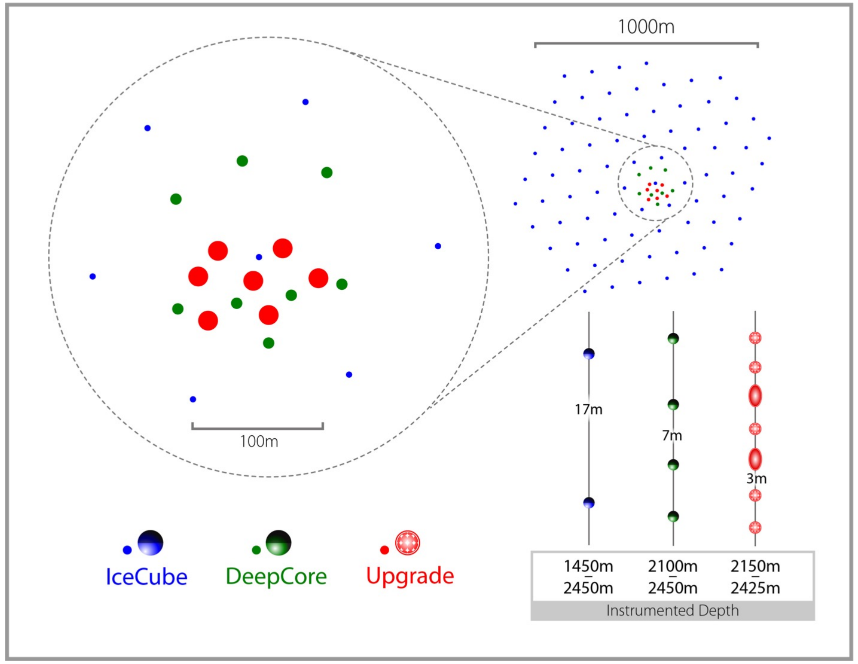
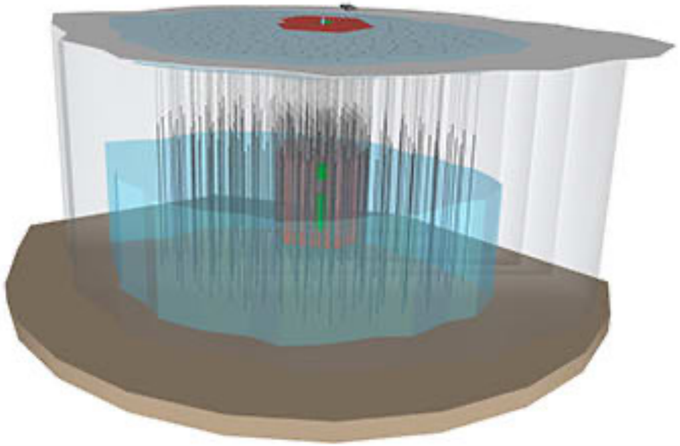


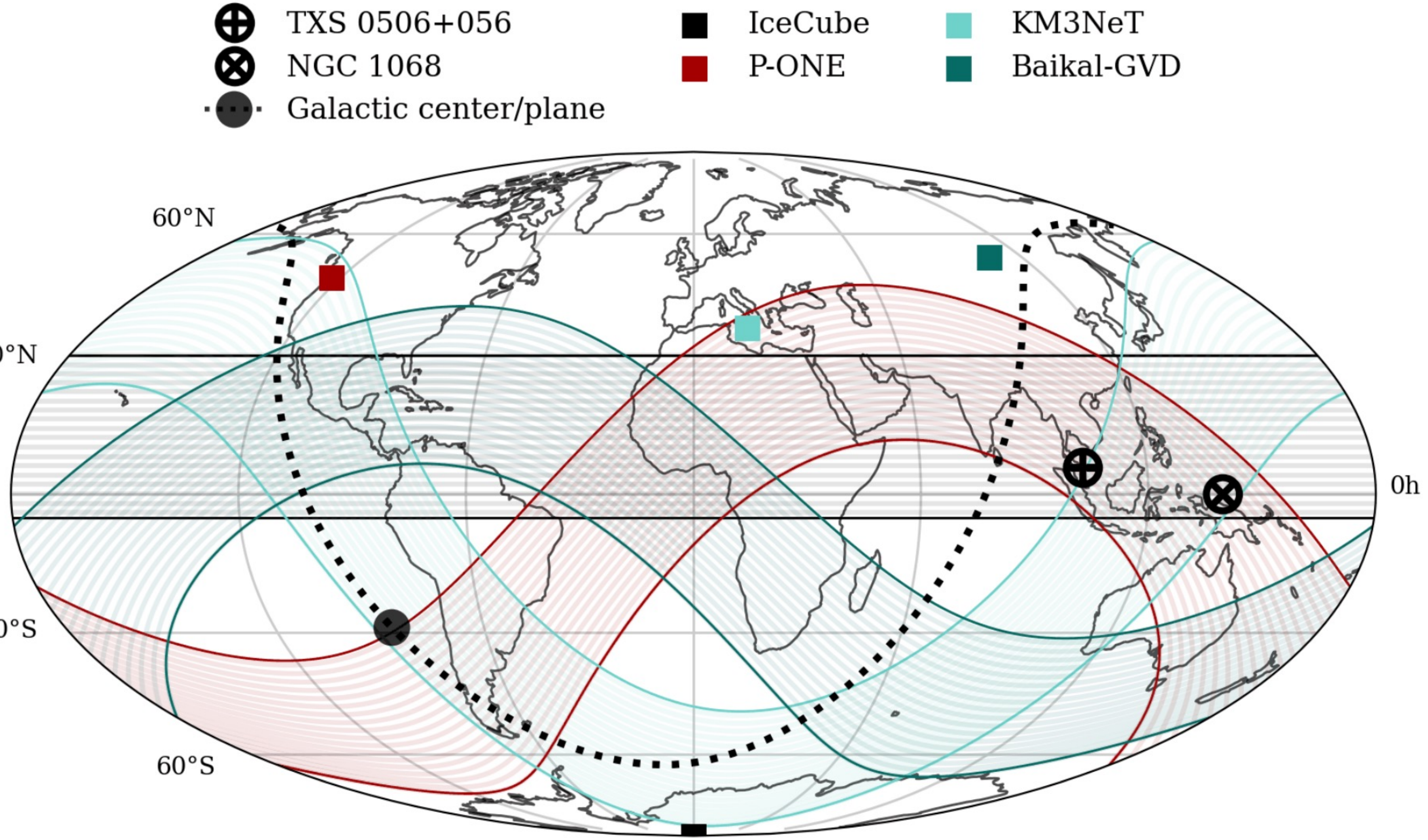
IceCube Gen2

- **8-10 x larger optical Cherenkov detector:** Neutrino astronomy and multimessenger astrophysics
- **Askaryan radio detector array:** Probe neutrinos beyond EeV energies
- **Surface particle detector:** CR physics and veto capabilities

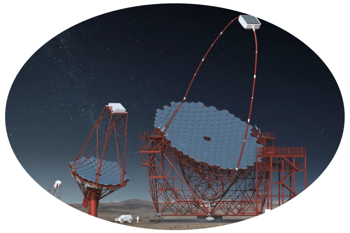


IceCube-Gen2 TDR

Benefit of Multiple Neutrino Detectors



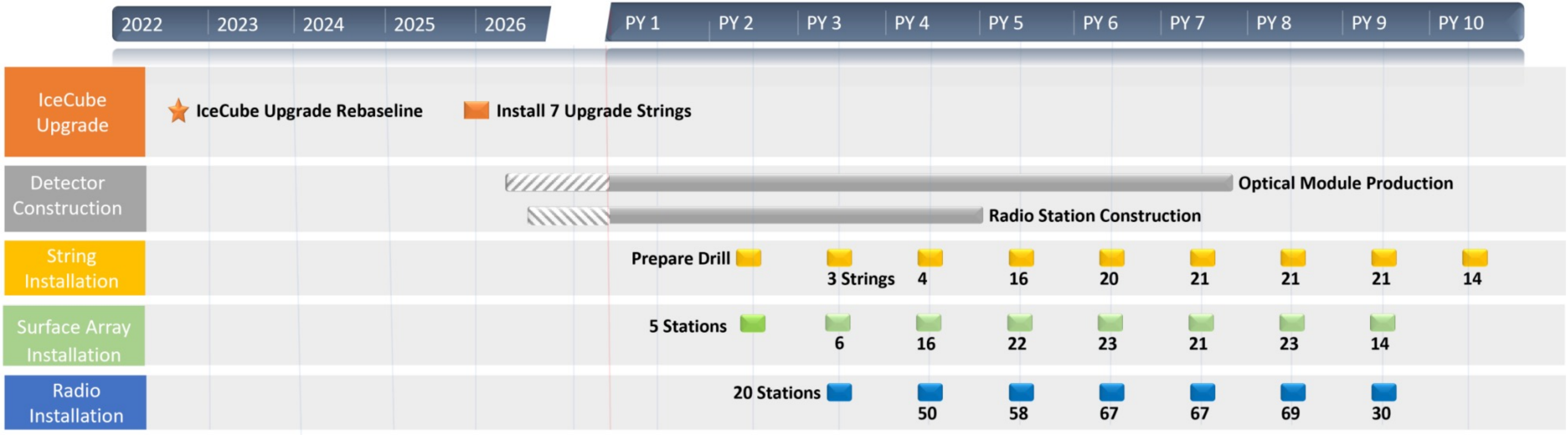
Summary




Stay tuned!

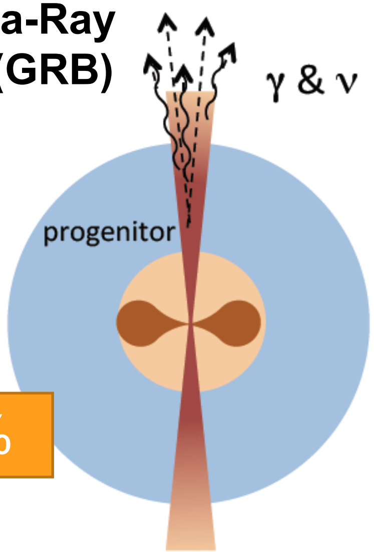
Backup

IceCube-Gen2 time line



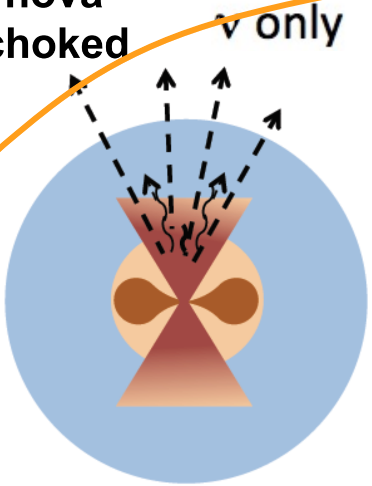
Other neutrino source candidates

Gamma-Ray Burst (GRB)

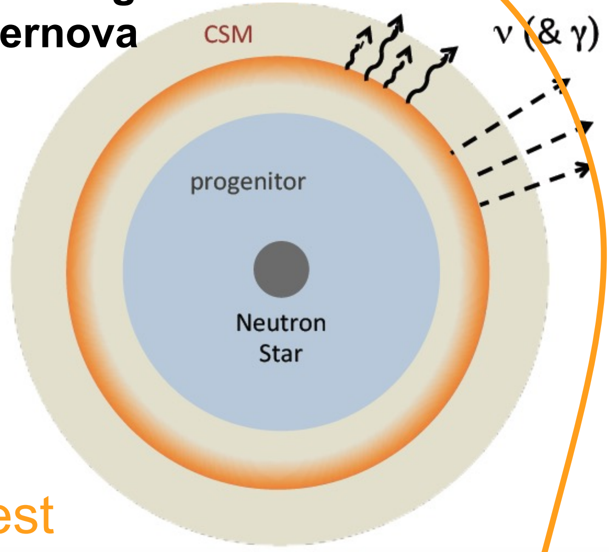


<1%

Supernova with choked jets



Interacting Supernova



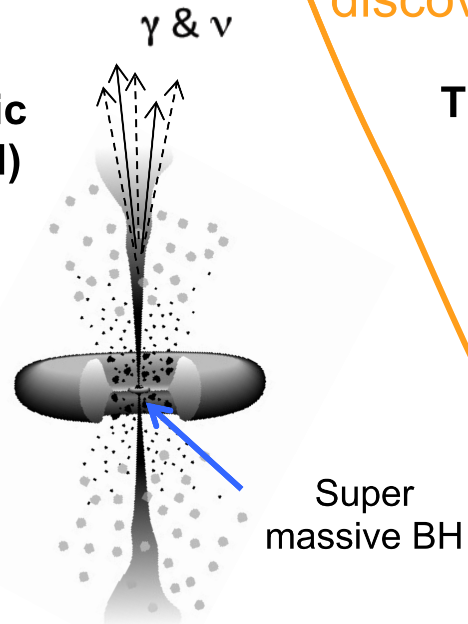
FBOTs

Guarini+ 2022, Fang+ 2019

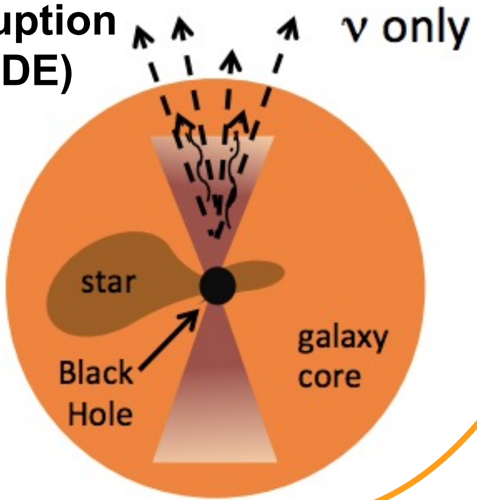
“hidden“ sources, best discovered in the optical

Active Galactic Nucleus (AGN)

γ-ray blazars <30%



Tidal Disruption event (TDE)

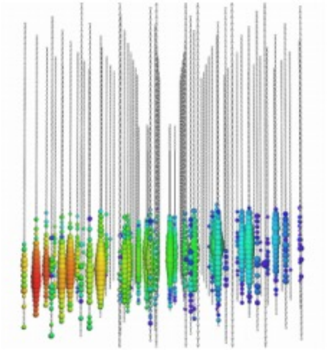


Senno+ 2016; Ando & Beacom 2005; Razzaque+ 2004; Denton & Tamborra 2018

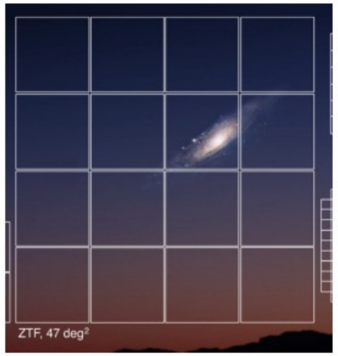
Murase+ 2011; Zirakashvili & Ptuskin 2016; Pitik+ 2022; Sarmah+ 2022

ZTF Follow-up Pipeline

Reject stars, planets, artifacts, asteroids



1. high-energy neutrino alert arrives



2. Observe with ZTF

3. Follow-up with AMPEL

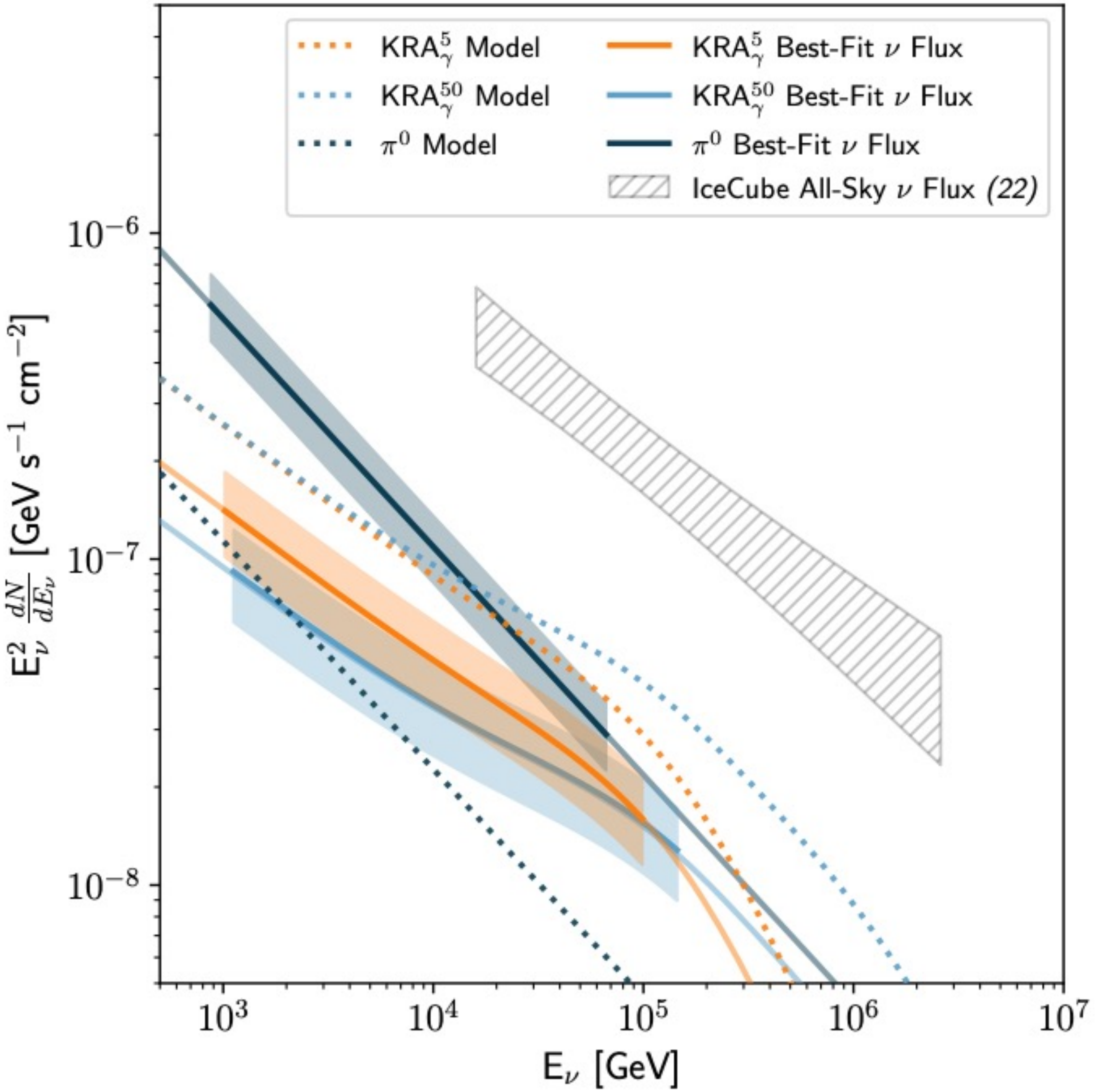
Nordin et al., A&A 631, A147 (2019)

Reject unrelated transients (e.g. Type Ia Supernovae)

4. Trigger further follow-up observations

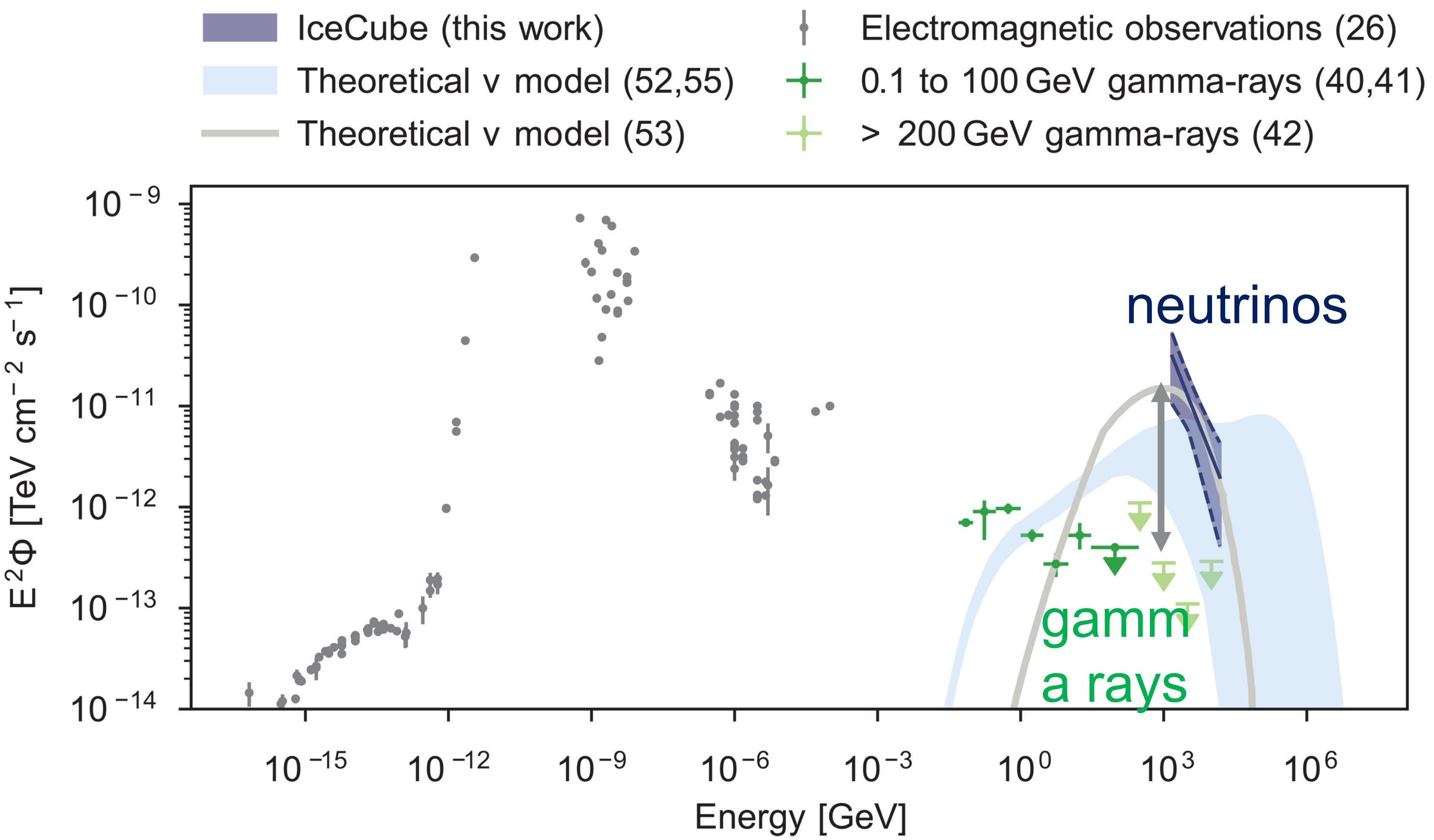
RUB

Galactic Contribution



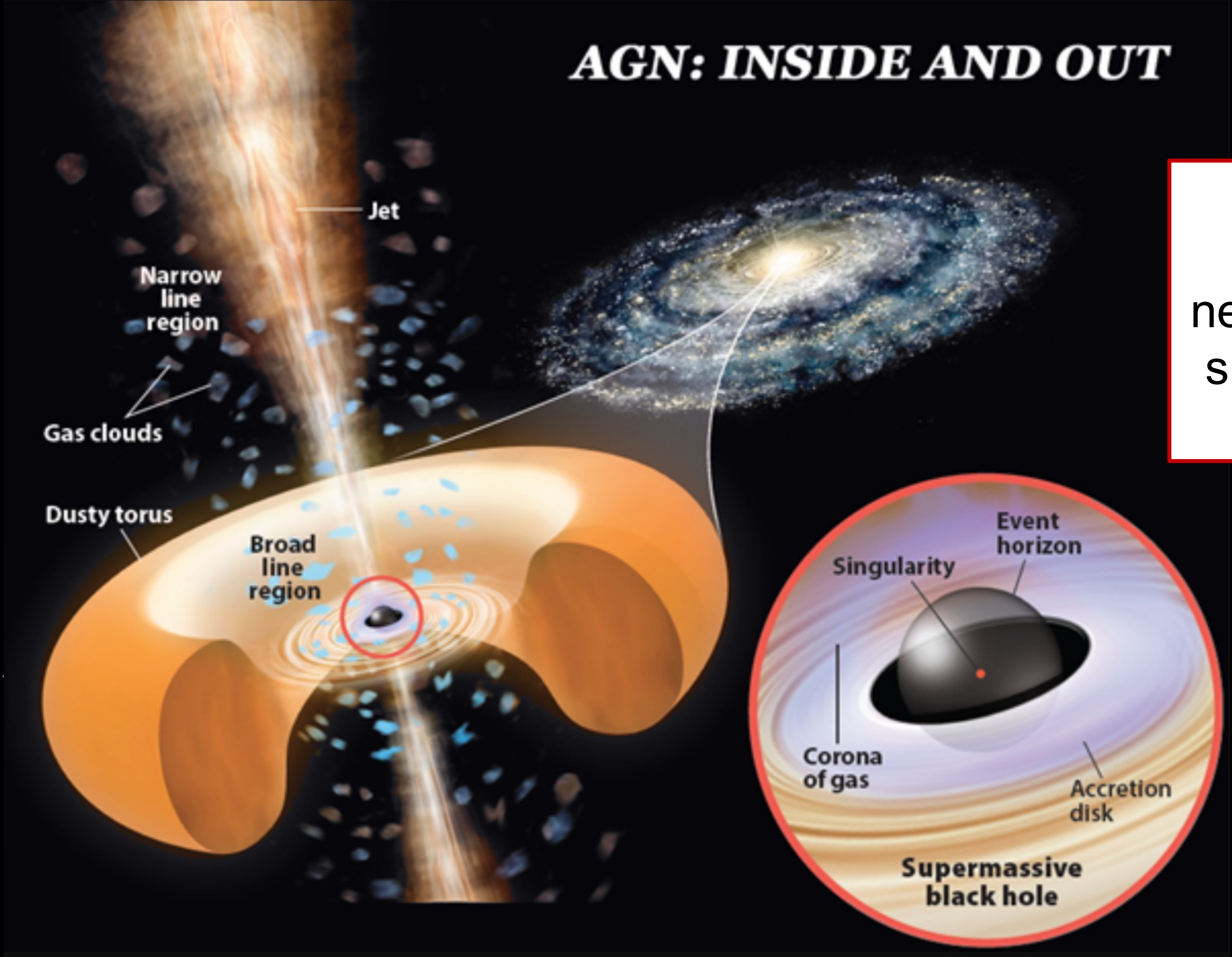
IceCube Science 380 (2023)

Complete Multi-wavelength data of NGC 1068



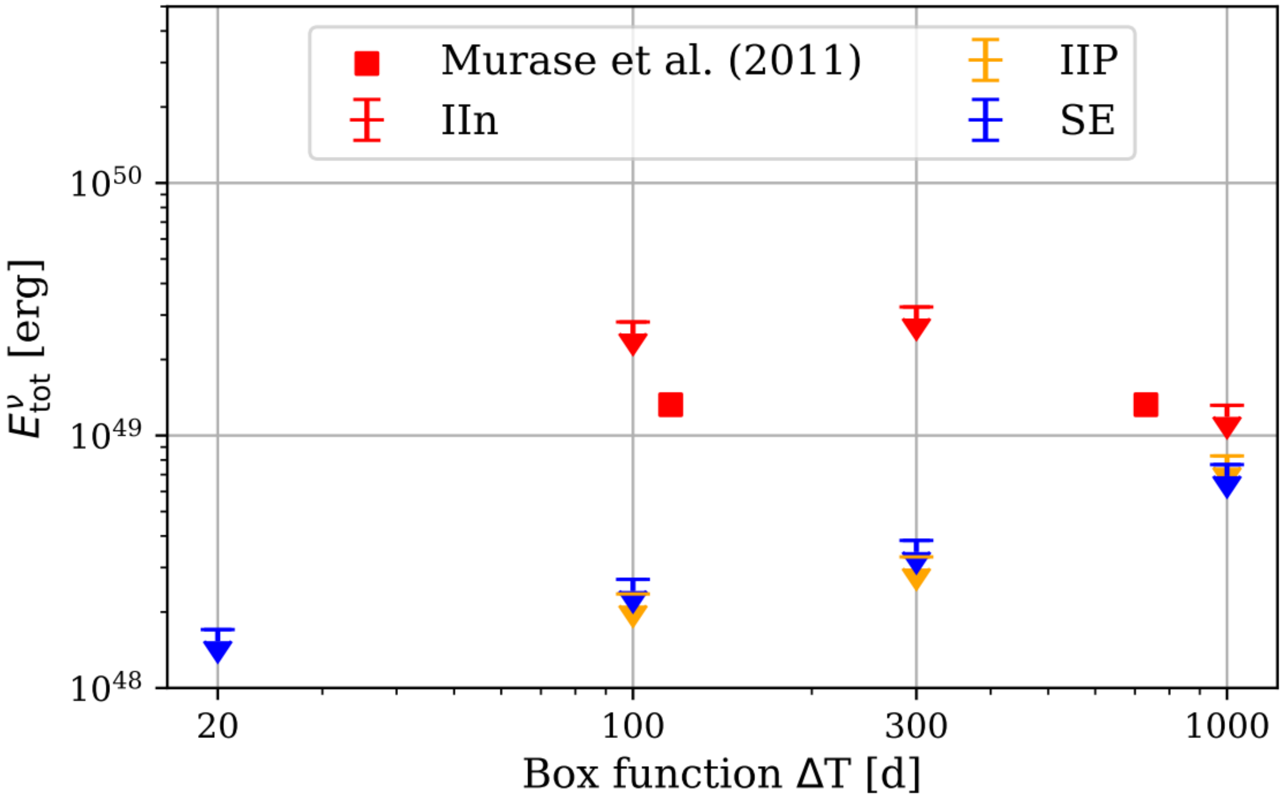
Gamma rays need to be absorbed

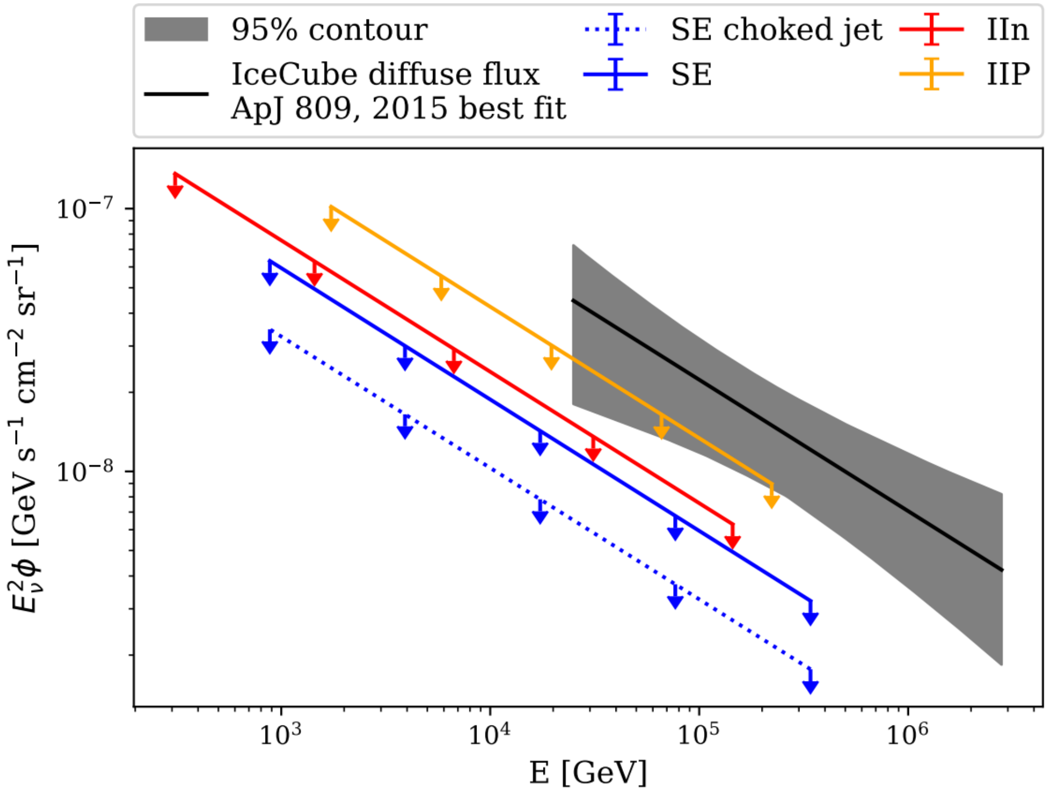
IceCube Science 378 (2022)



Lack of gamma rays places neutrino production site in the heart of the galaxy

Supernova Stacking

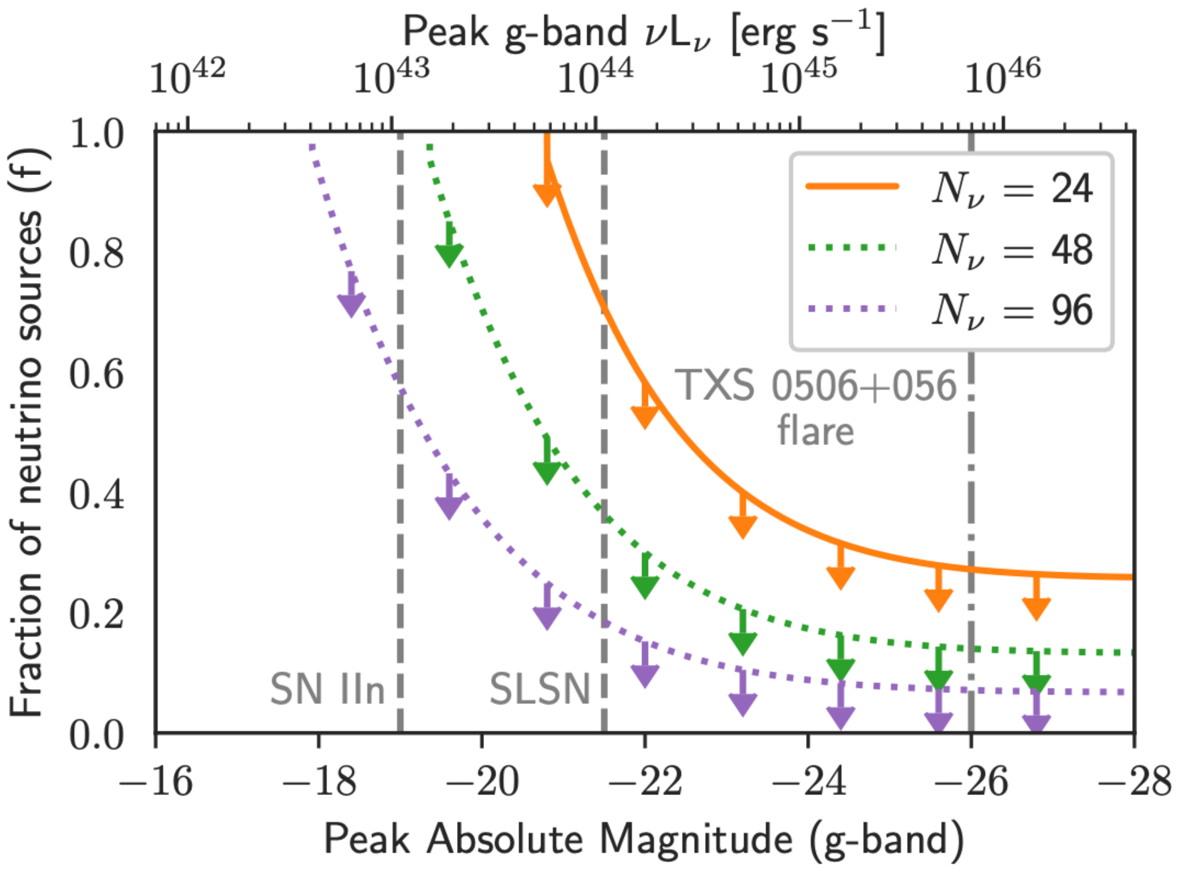


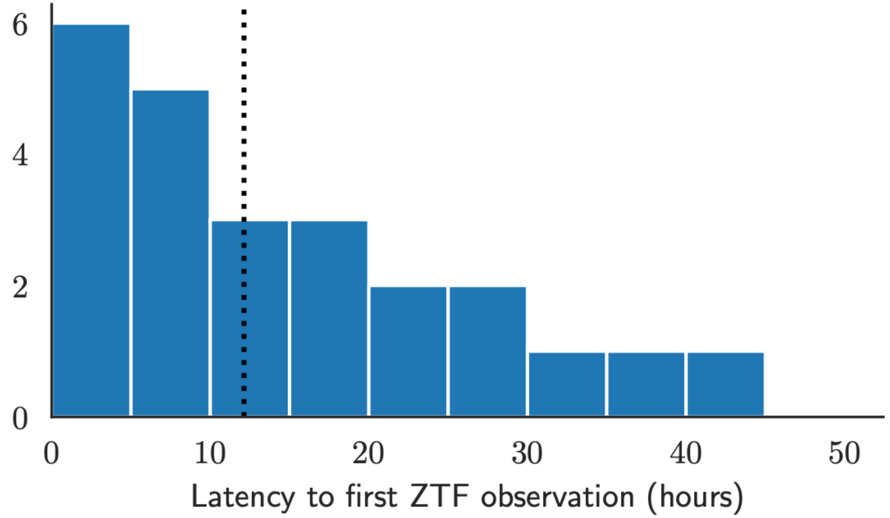


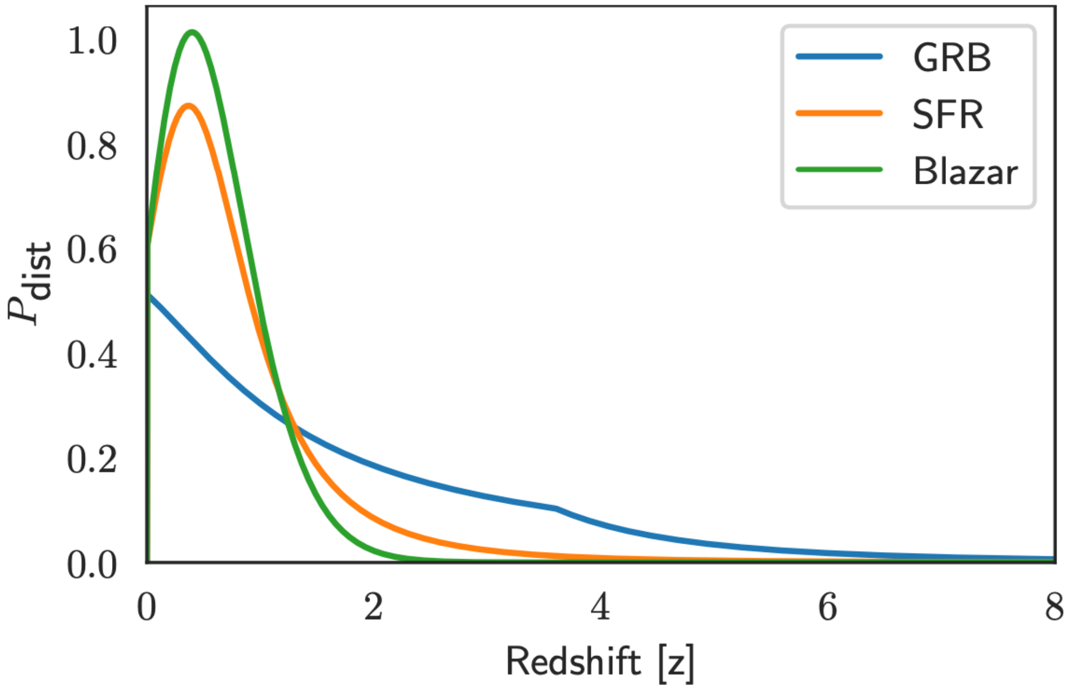
Similar searches planned for FBOTs and other source classes.
Input from theory needed

IceCube ApJL 949 (2023)

Optical Counterpart Search with ZTF

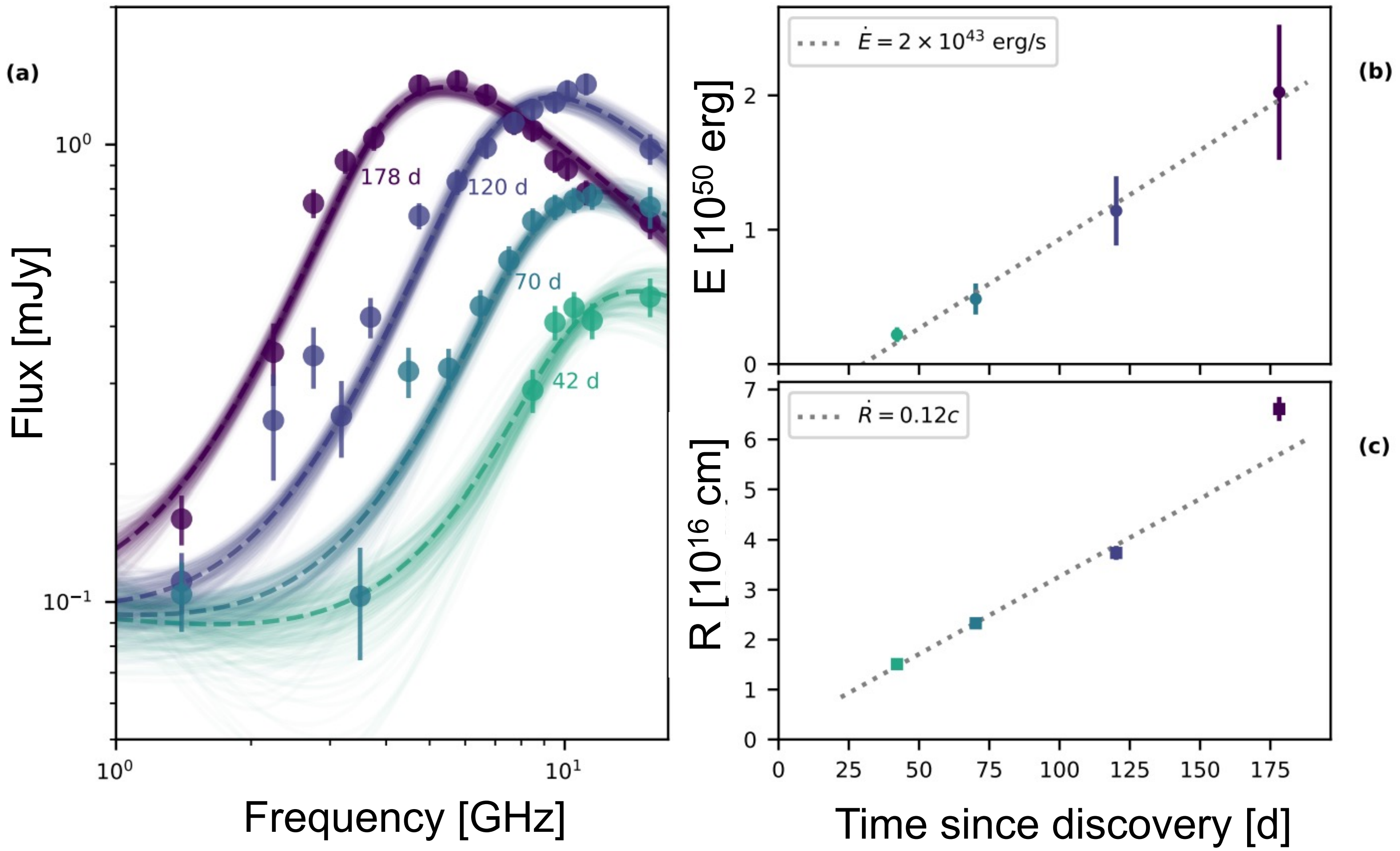






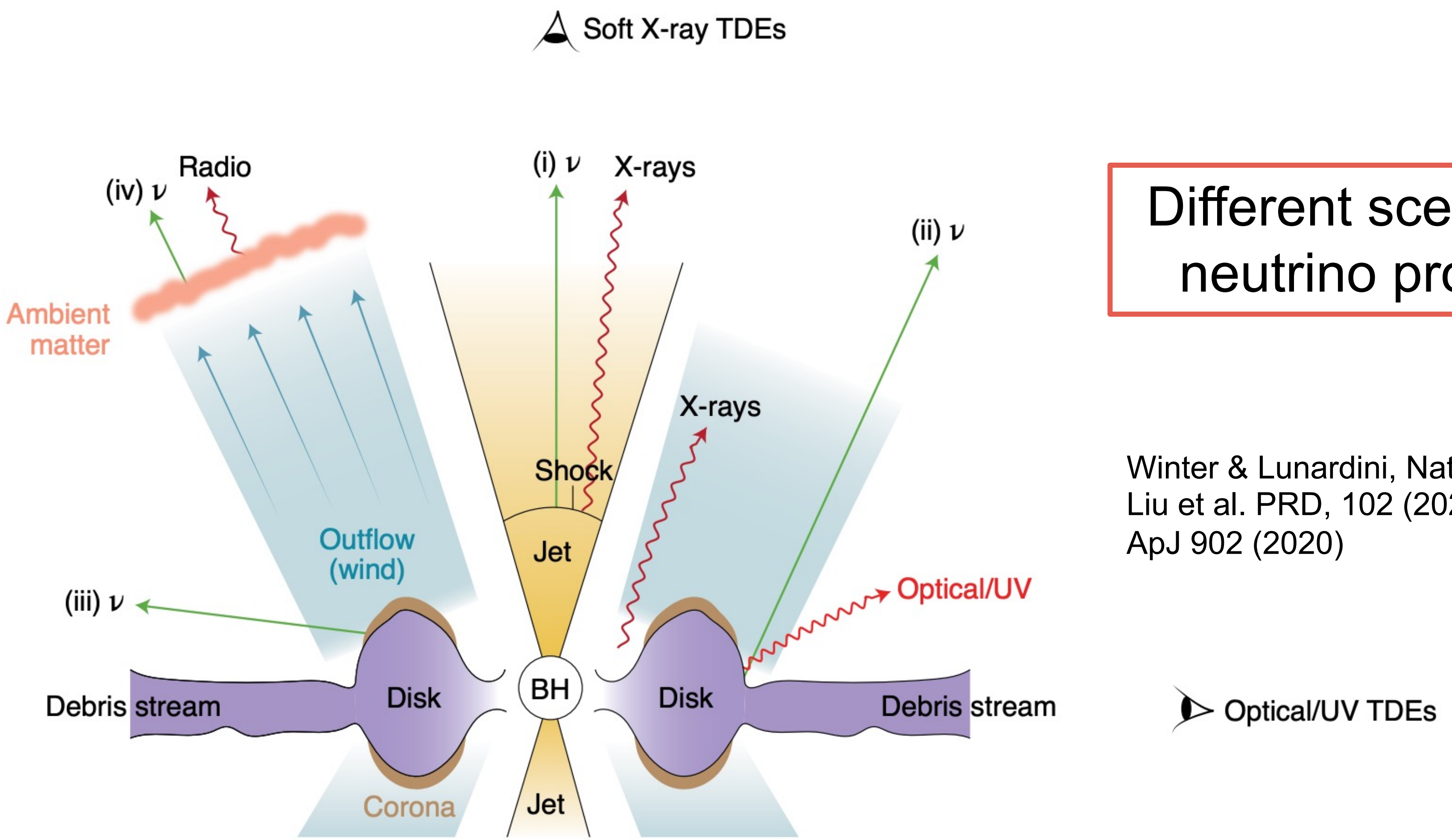
R. Stein, S. Reusch, AF et al. MNRAS 521 (2023)

Radio Data reveal long-lasting activity of central engine



R. Stein et al., Nature Astronomy 2021, see also Y. Cendes *et al* 2021 *ApJ* **919** 127

Neutrino Production in TDEs



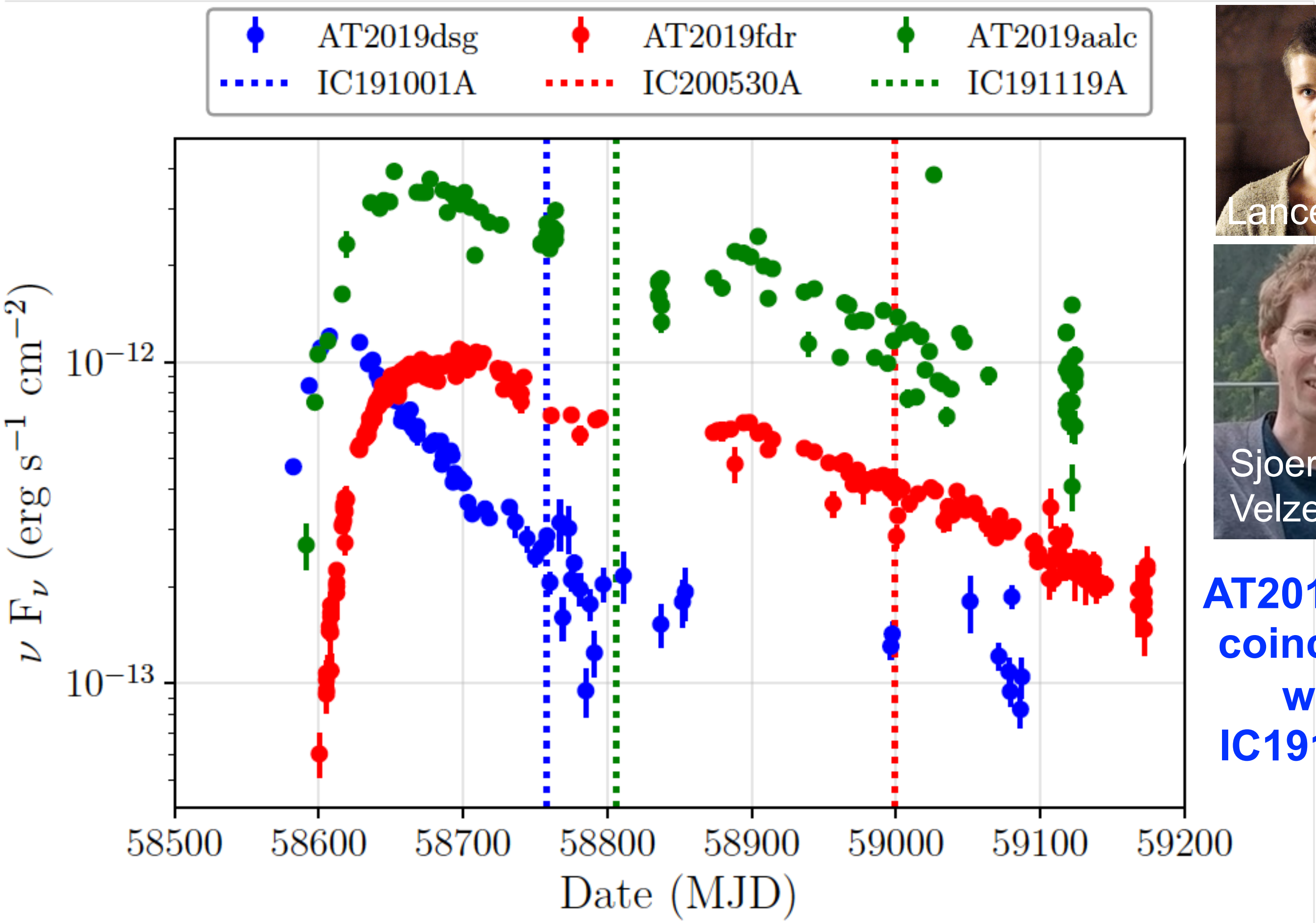
Different scenarios for neutrino production

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

Hayasaki, Nature Astronomy 2021

Two more TDE candidates!

AT2019fdr coincident with IC200530A



AT2019aalc coincident with IC191119A

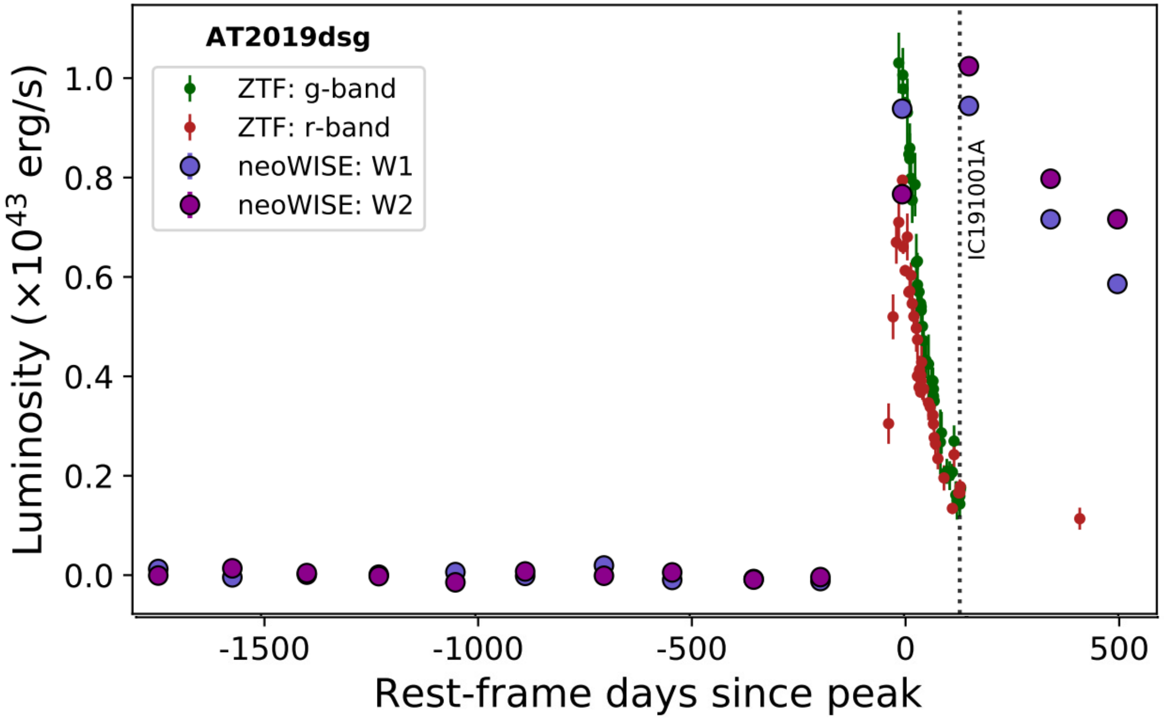
First hint of neutrino production in TDEs

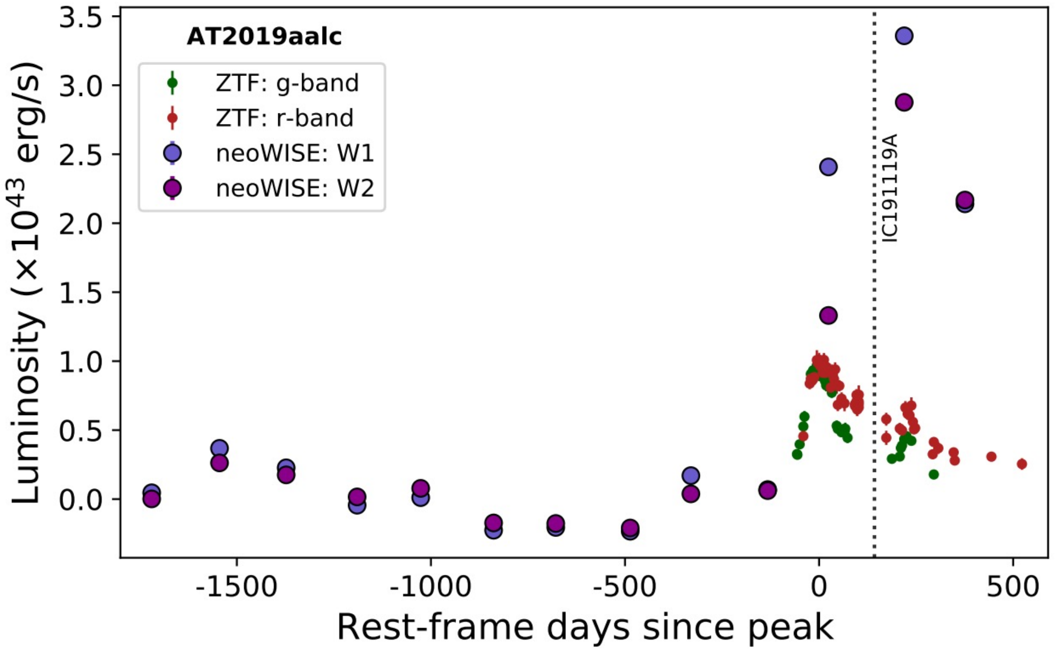
→ **Very efficient neutrino production in TDEs compared to AGN?**

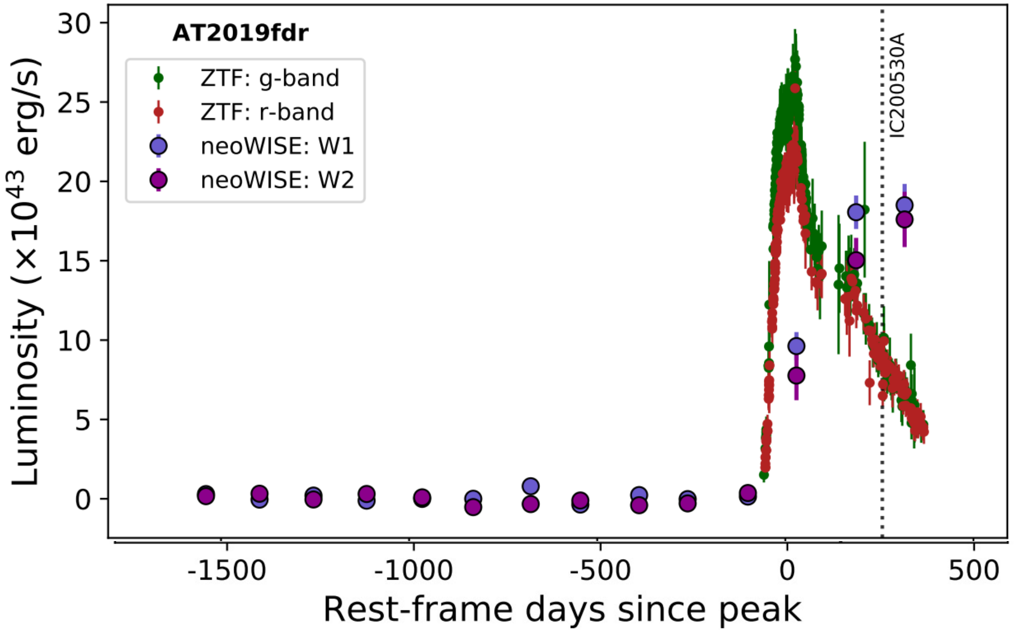
S. Reusch et al. PRL 2022

S. Van Velzen et al. MNRAS 529 (2024)

Dust echos







RUB

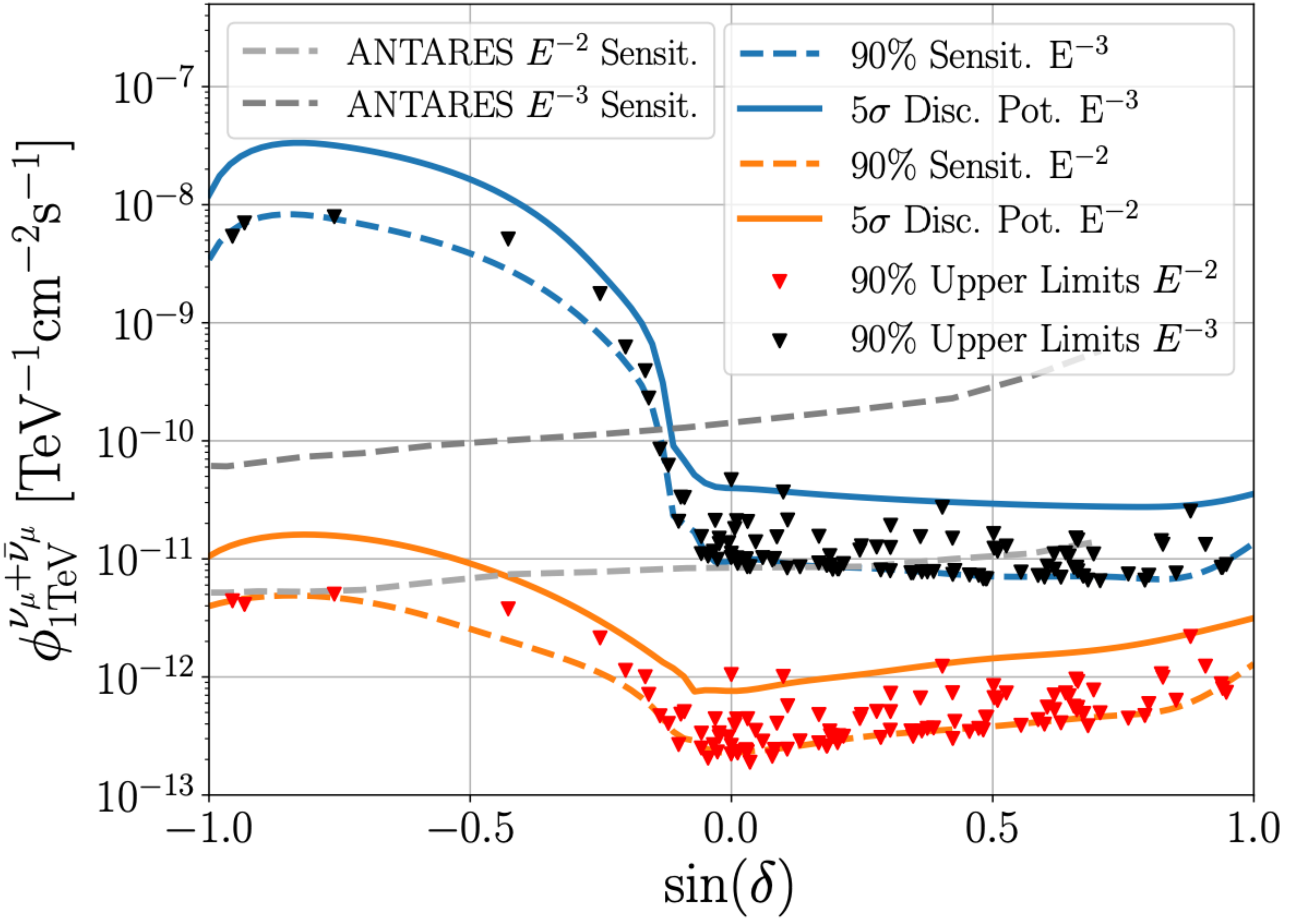
S. Van Velzen et al. MNRAS 529 (2024)

Comparison of Tywin, Bran & Lancel

	AT2019dsg	AT2019fdr	AT2019aalc
TDE	yes	likely	?
Peak Luminosity	3.5×10^{44} erg s^{-1}	1.4×10^{45} erg s^{-1}	?
Radio	evolving	non-evolving	detected
UV	very bright	bright	?
X-ray	early, soft spectrum	late, soft spectrum	soft spectrum
Dust echo	very strong	strong	very strong
Neutrino delay	~ 5 months	~ 10 months	~ 5 months
nu production possible?	yes	yes	?

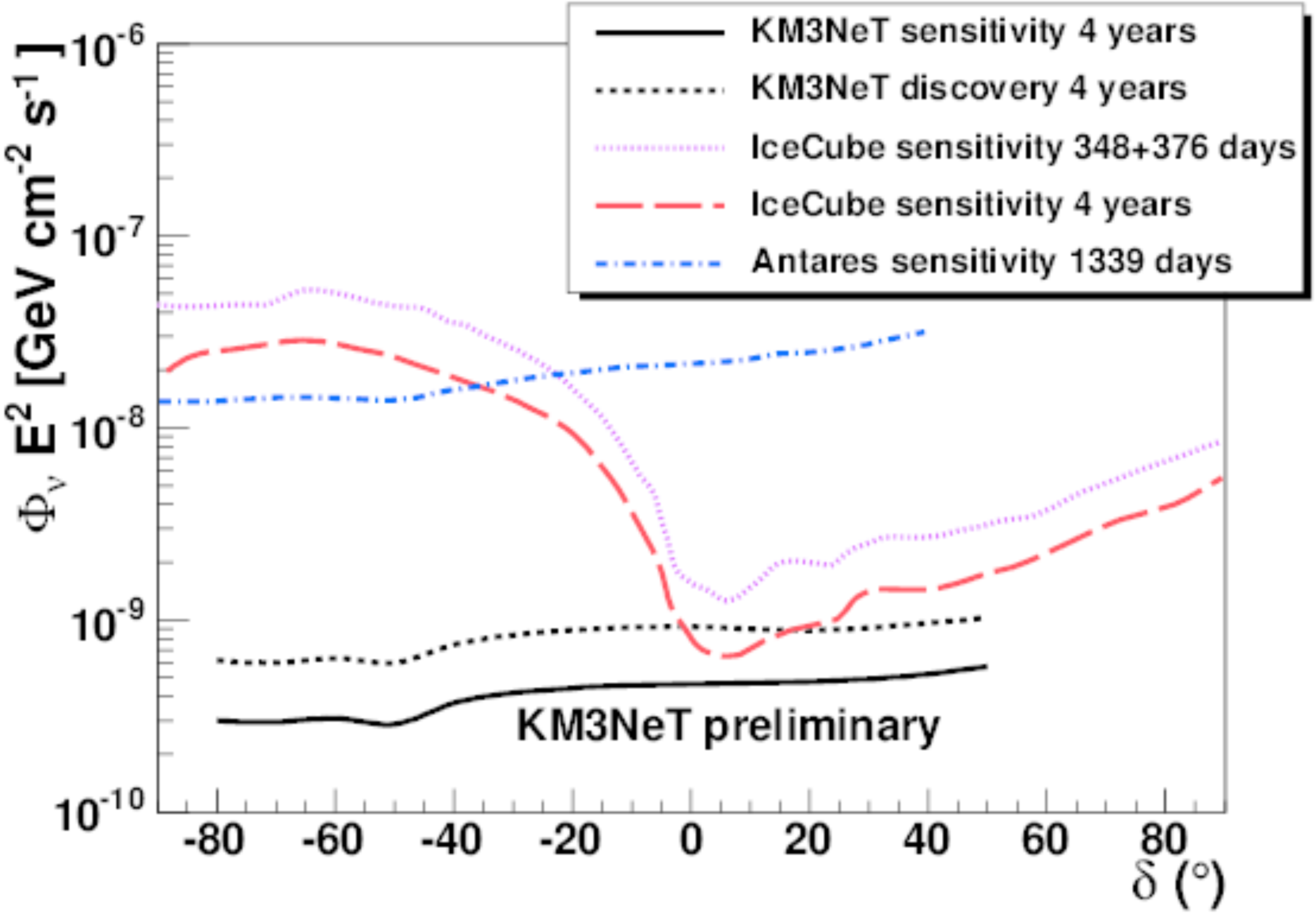
$$p = 2 \times 10^{-4} \; (3.7\,\sigma)$$

S. Van Velzen et al. arXiv:2111.09391



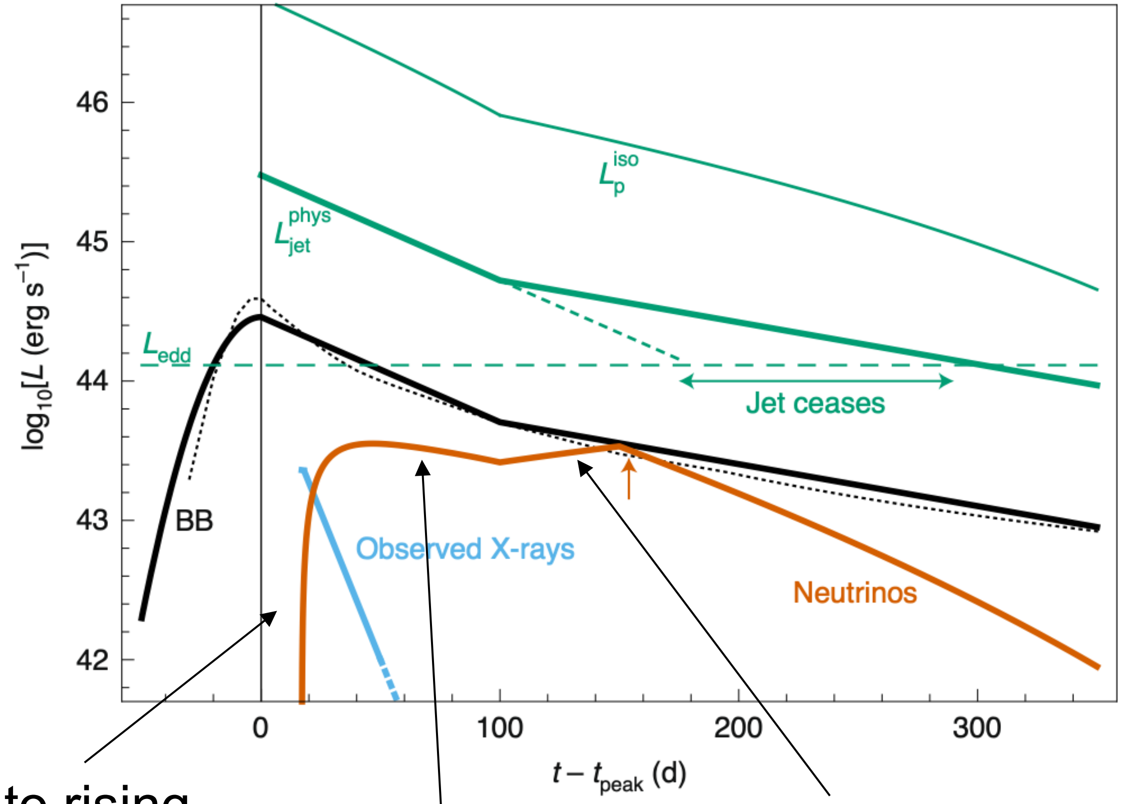
ANTARES E^{-2} Sensit.
ANTARES E^{-3} Sensit.
90% Sensit. E^{-3}
5σ Disc. Pot. E^{-3}
90% Sensit. E^{-2}
5σ Disc. Pot. E^{-2}
90% Upper Limits E^{-2}
90% Upper Limits E^{-3}
$\phi_{1\mathrm{TeV}}^{\nu_\mu+\bar{\nu}_\mu}$ [$\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]
10^{-7}
10^{-8}
10^{-9}
10^{-10}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

TDE AT2019dsg / “Bran Stark” coincident with 200 TeV Neutrino IC191001A



Rise due to rising target X-ray

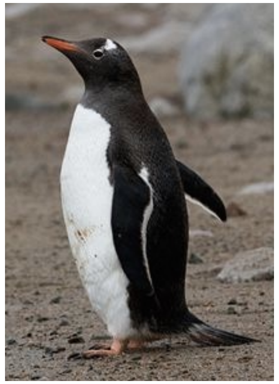
Decreasing proton injection and target photon density

Decreasing production radius → more compact region, enhancing neutrino flux

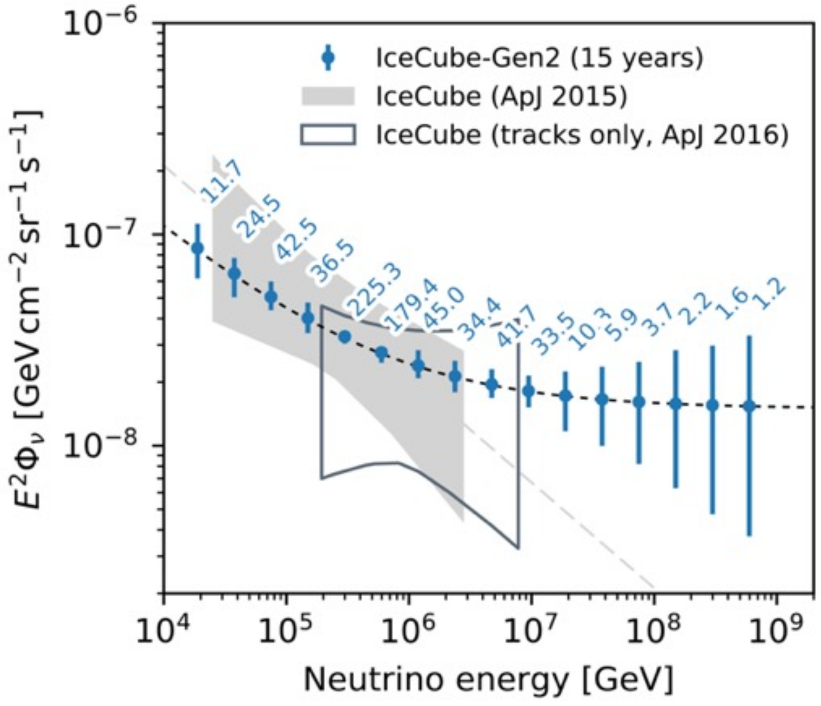
Winter & Lunardini, Nature Astronomy 2021

RUB

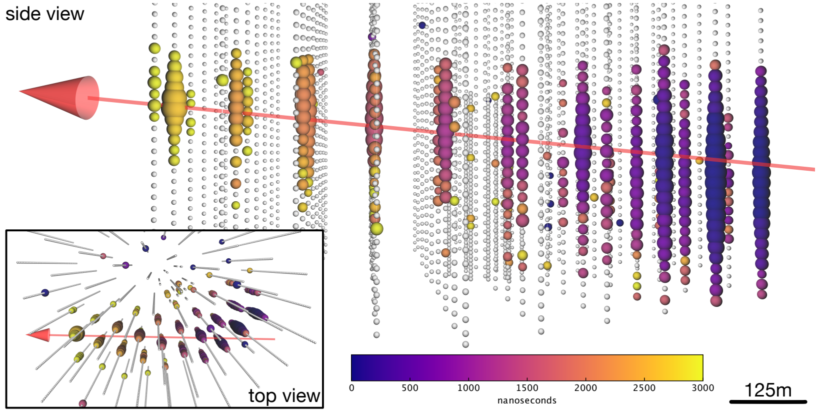
Neutrino Astronomy with IceCube Gen2



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

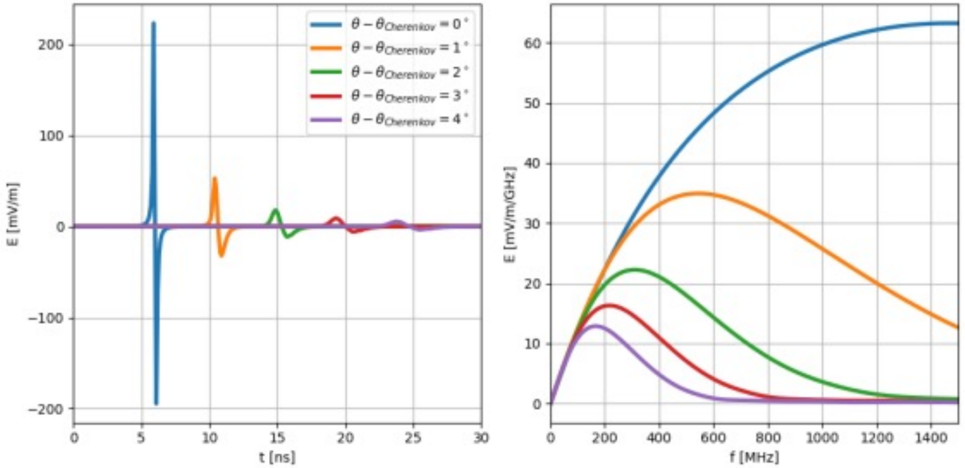


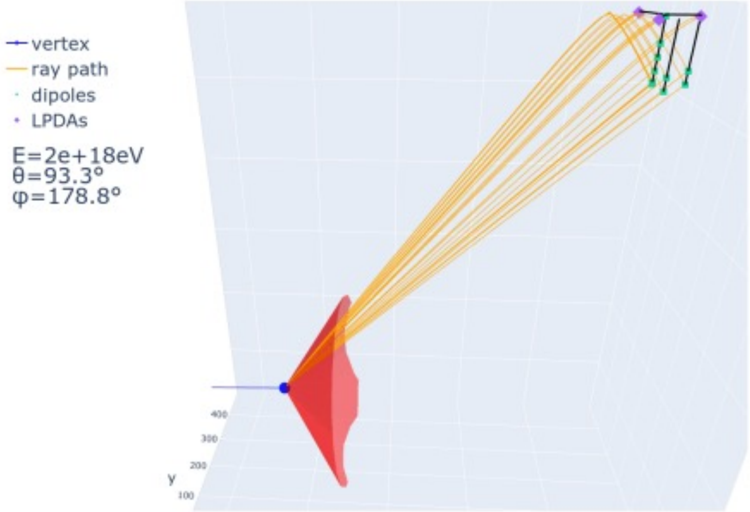
IceCube-Gen2 White Paper, astro-ph:2008.04323

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



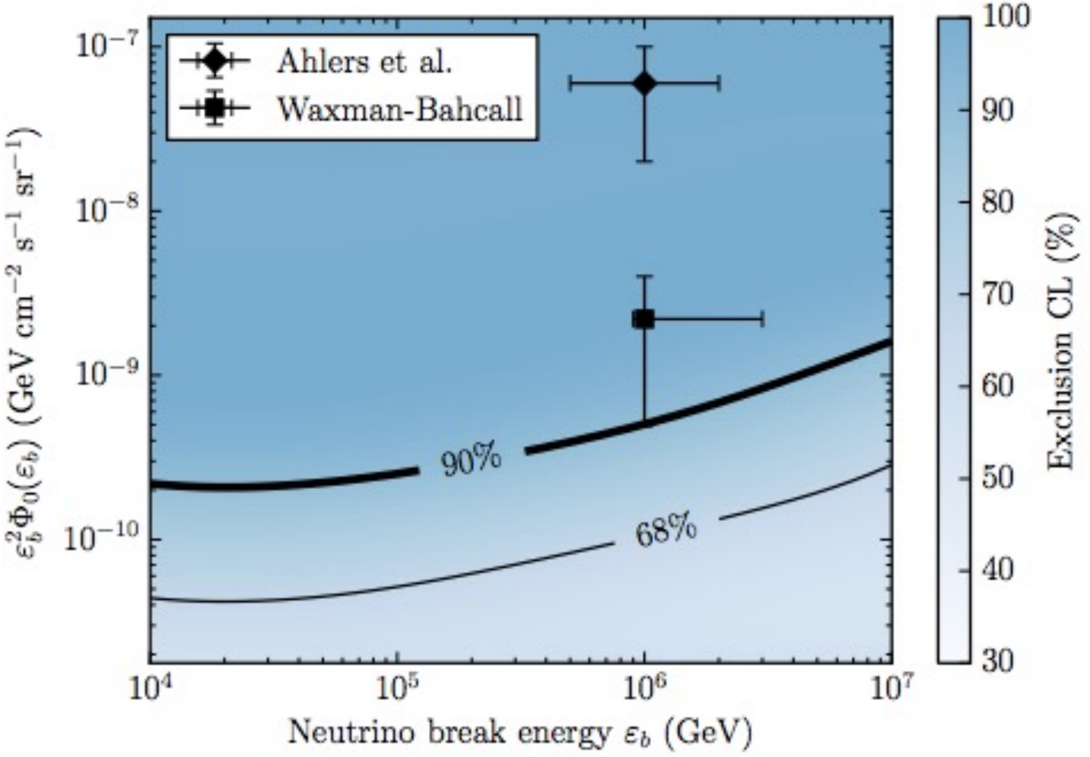


Gamma-Ray Bursts (GRBs)

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

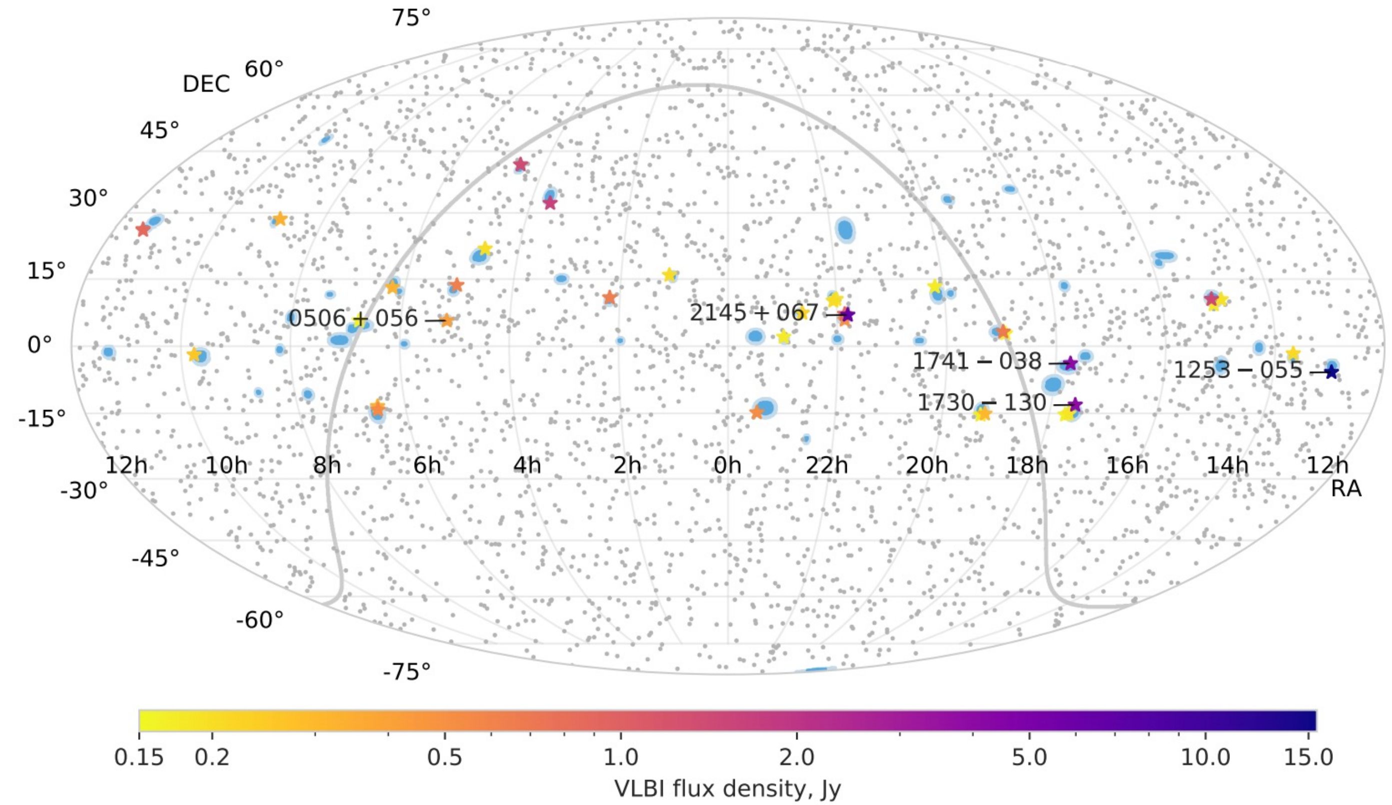


GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained

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

Radio-loud AGN

Correlation with VLBI-flux-density limited sample of AGN

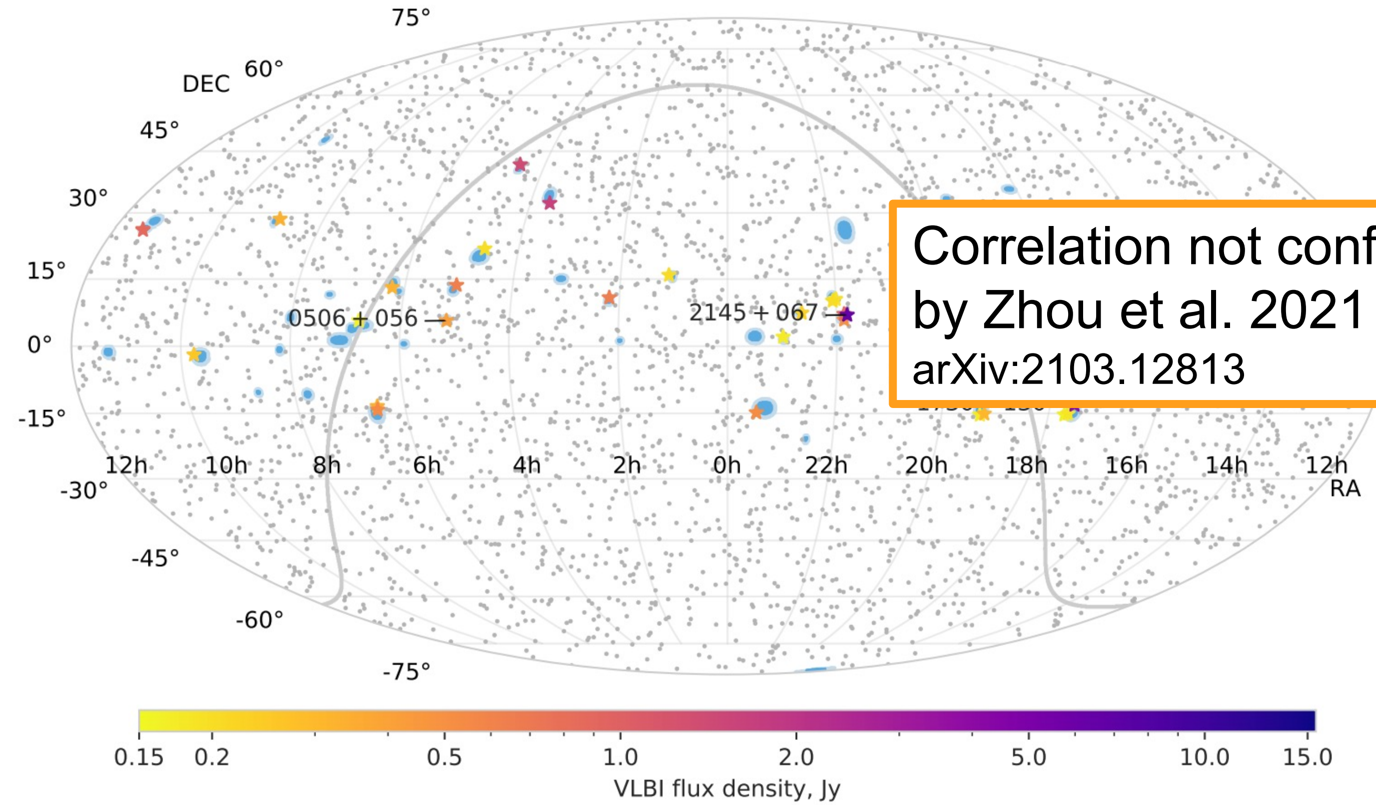


Correlation of radio-bright AGN with IceCube neutrino alerts at chance coincidence of 0.2%

Plavin et al., ApJ 894 (2020), Plavin et al. 2020 arXiv:2009.08914

Radio-loud AGN

Correlation with VLBI-flux-density limited sample of AGN

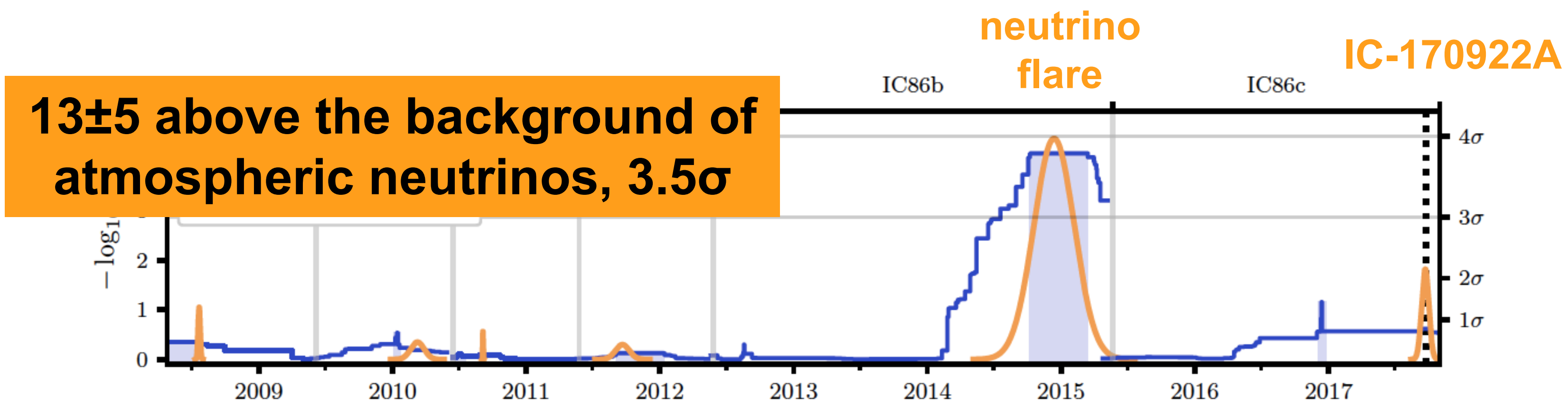


Correlation not confirmed by Zhou et al. 2021
arXiv:2103.12813

Correlation of radio-bright AGN with IceCube neutrino alerts at chance coincidence of 0.2%

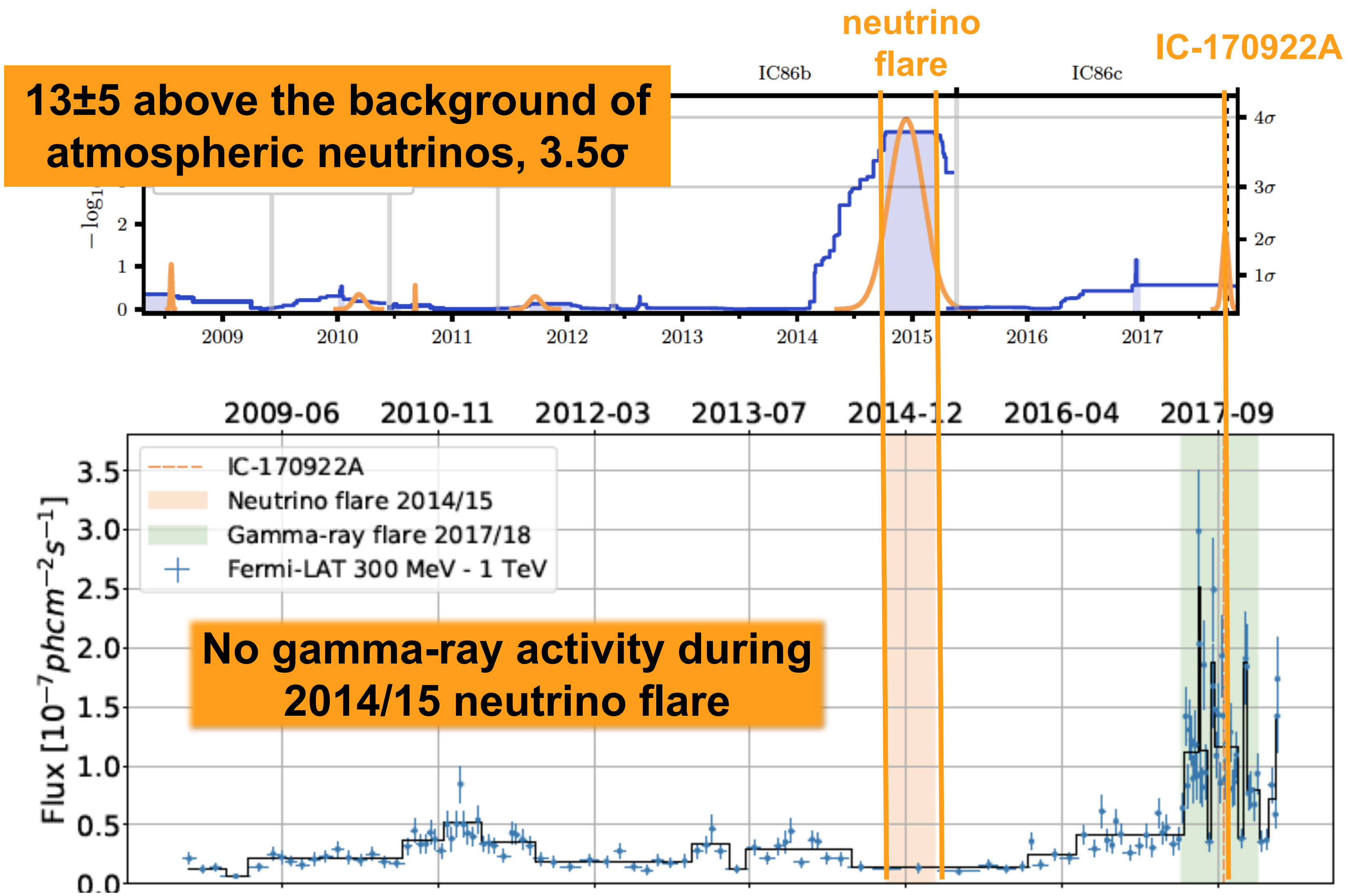
Plavin et al., ApJ 894 (2020), Plavin et al. 2020 arXiv:2009.08914

Are there more Neutrinos from this Source?



IceCube, Science 361, 2018

Is there also a Gamma-ray Flare?

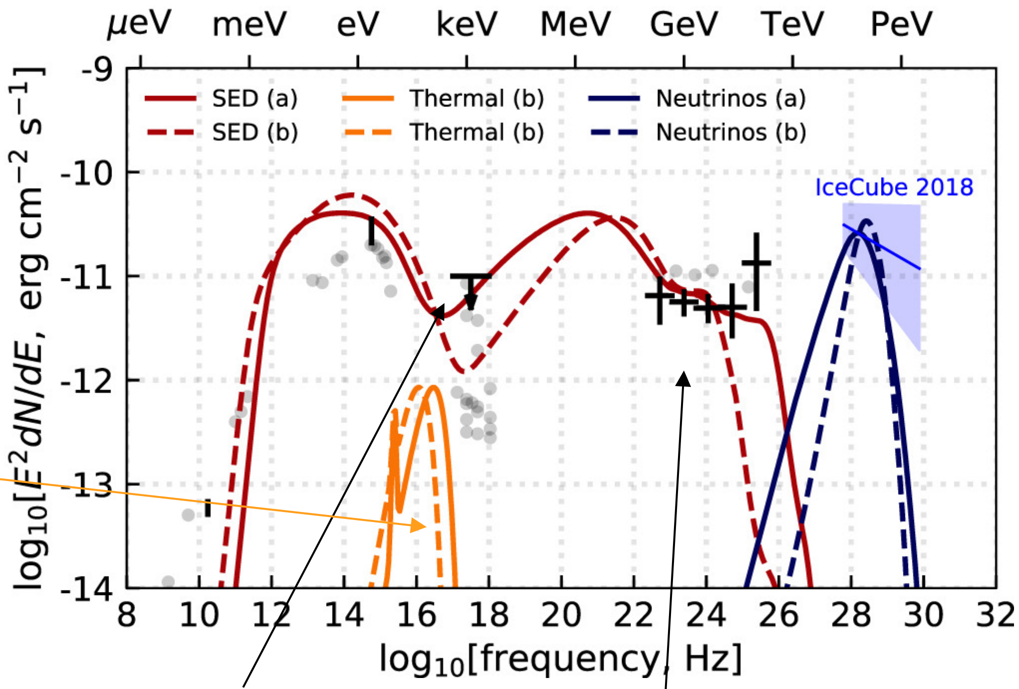


IceCube, Science 361, 2018, Garrappa et al. ApJ 880 2019, Padovani et al. MNRAS 480 2019

Modeling of 2014/15 neutrino flare

neutrino luminosity is ~4 times higher than gamma-ray luminosity
→ **challenge for models**

BLR photons boosted into the jet

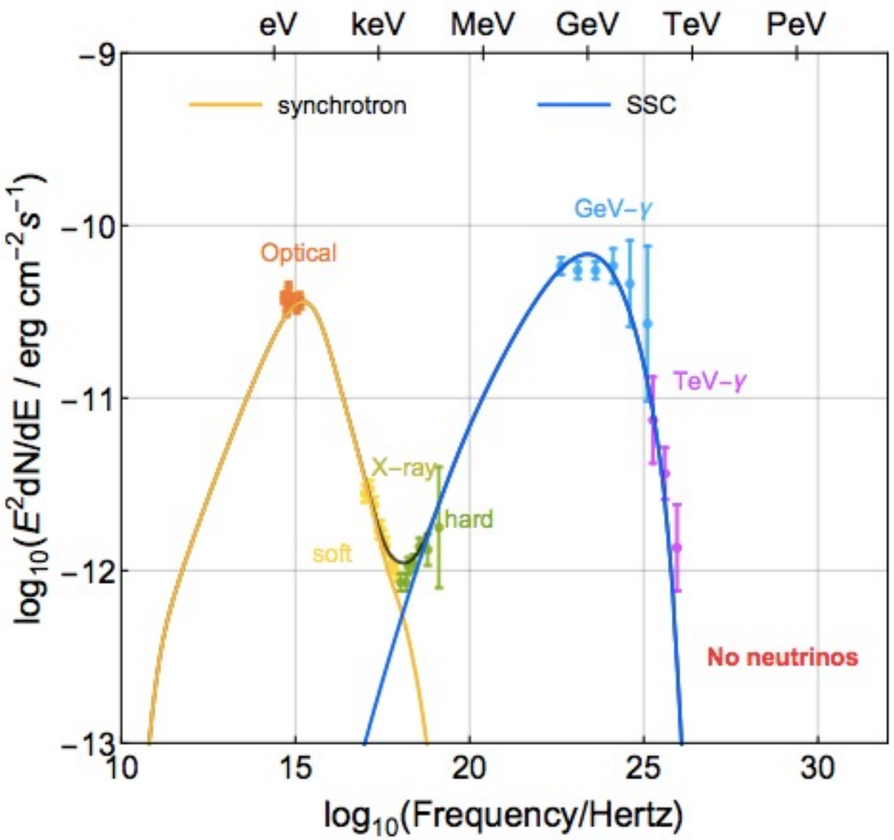


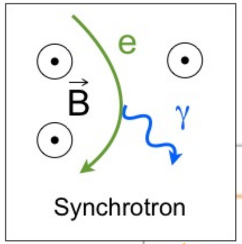
Swift-BAT
upper limit

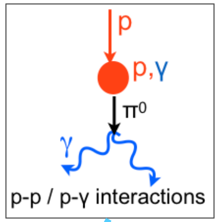
Fermi-LAT

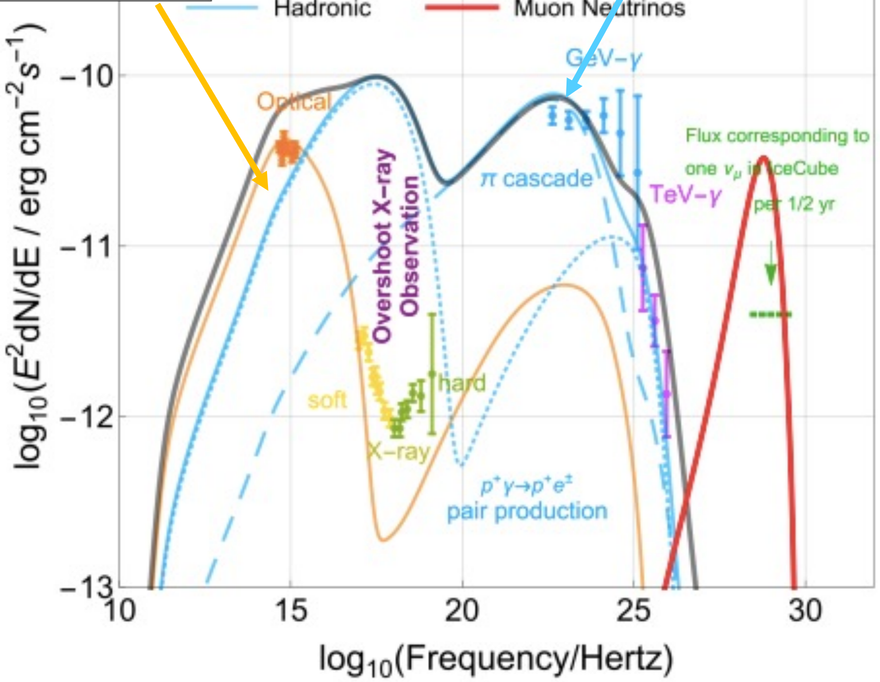
see e.g. Rodrigues et al. ApJL 874 2019, A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019

Modeling – leptonic, hadronic



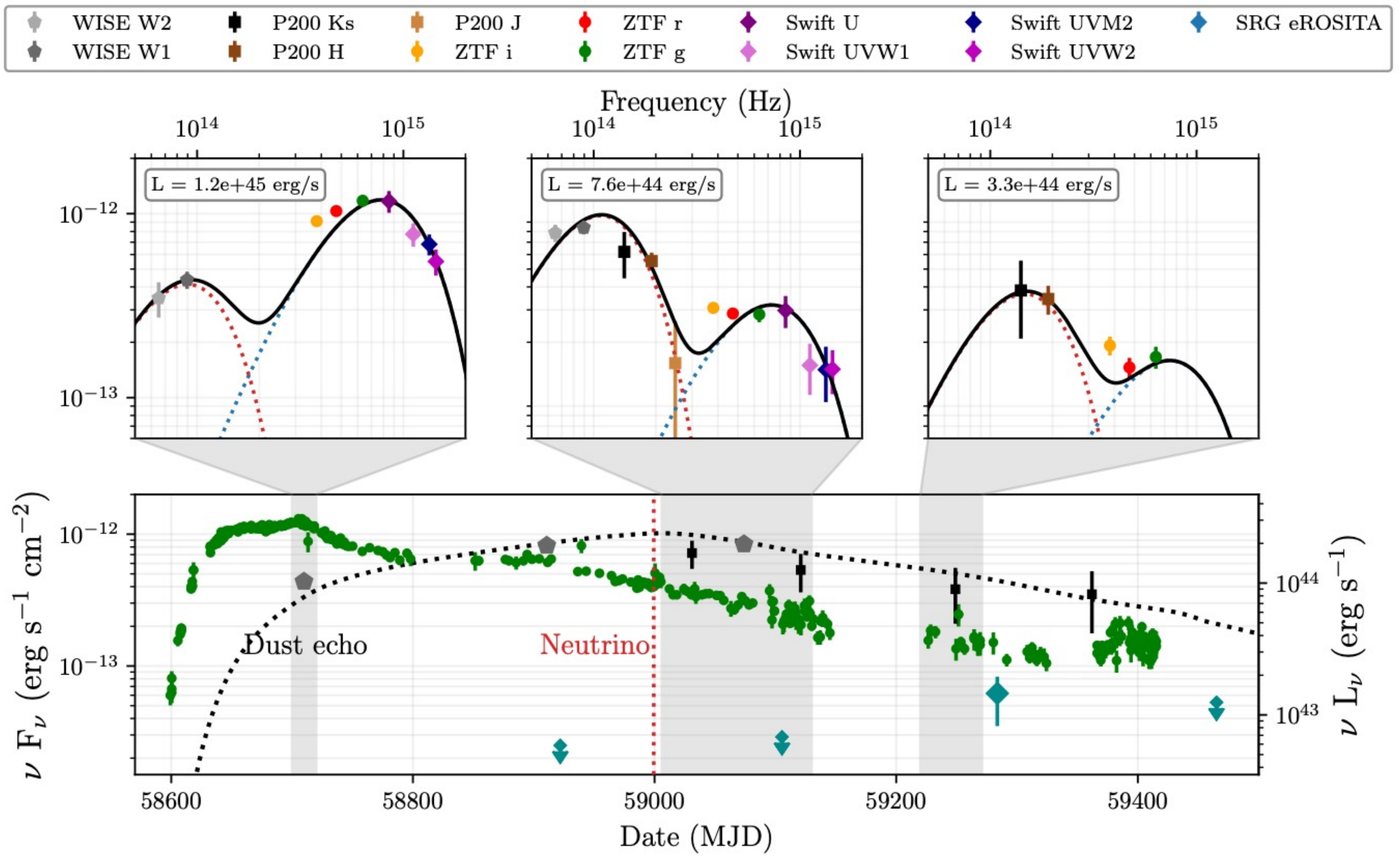






Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

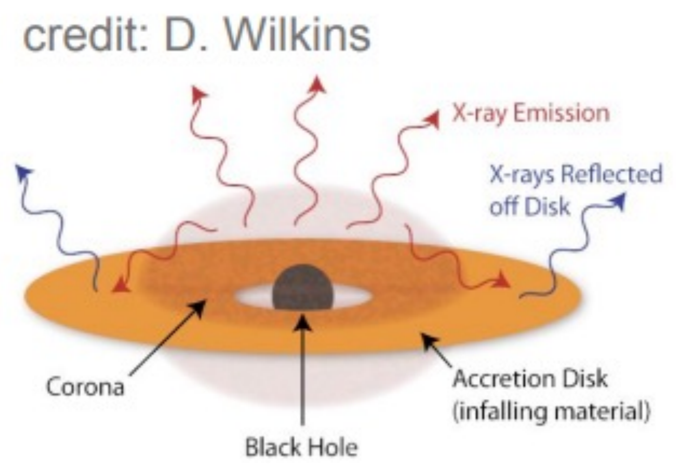


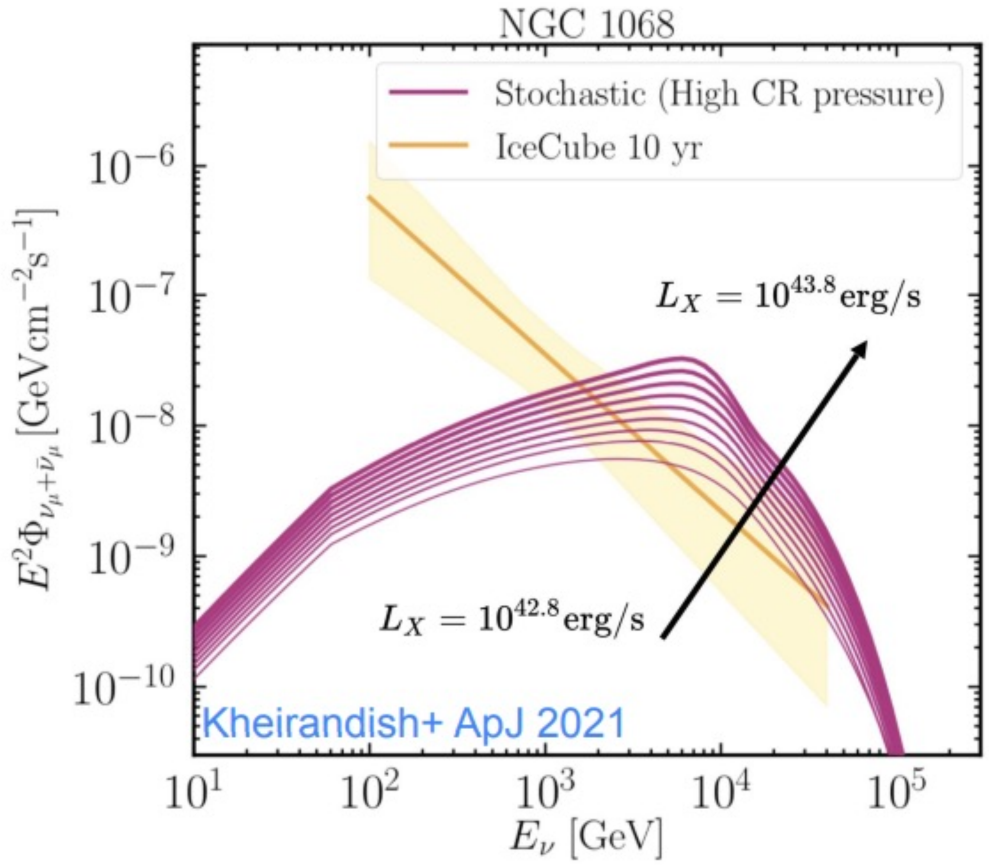
WISE W2
WISE W1
P200 Ks
P200 H
P200 J
ZTF i
ZTF r
ZTF g
Swift U
Swift UVW1
Swift UVM2
Swift UVW2
SRG eROSITA
Frequency (Hz)
L = 1.2e+45 erg/s
L = 7.6e+44 erg/s
L = 3.3e+44 erg/s
Dust echo
Neutrino
νF_ν (erg s^{-1} cm^{-2})
νL_ν (erg s^{-1})
Date (MJD)

Does the population of Seyferts produce Neutrinos?

Seyfert Stacking

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



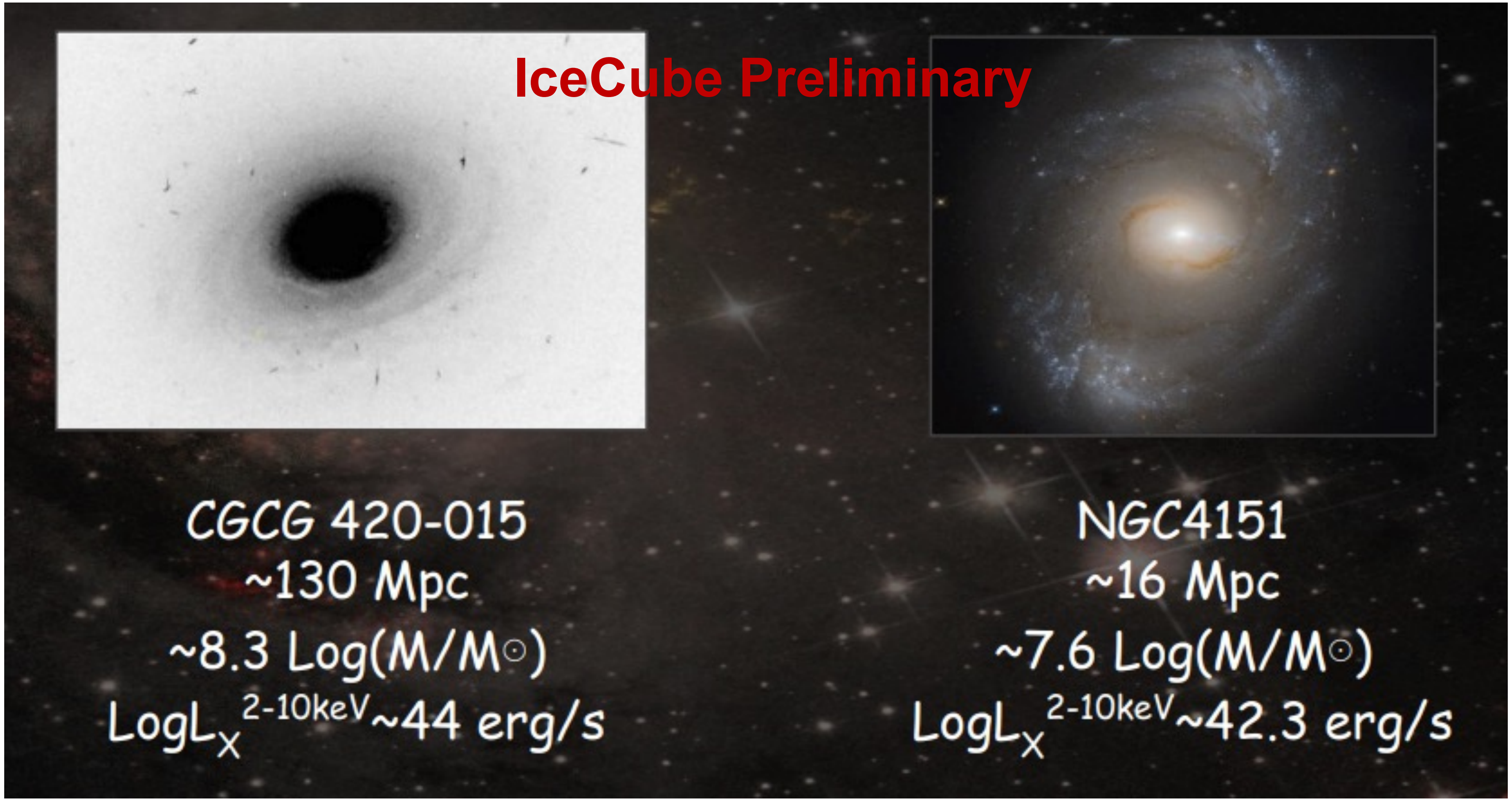


No significant emission is found in the stacking search excluding NGC 1068.

IceCube arXiv:2406.07601

Seyfert Catalog Search

No assumption about neutrino emission model



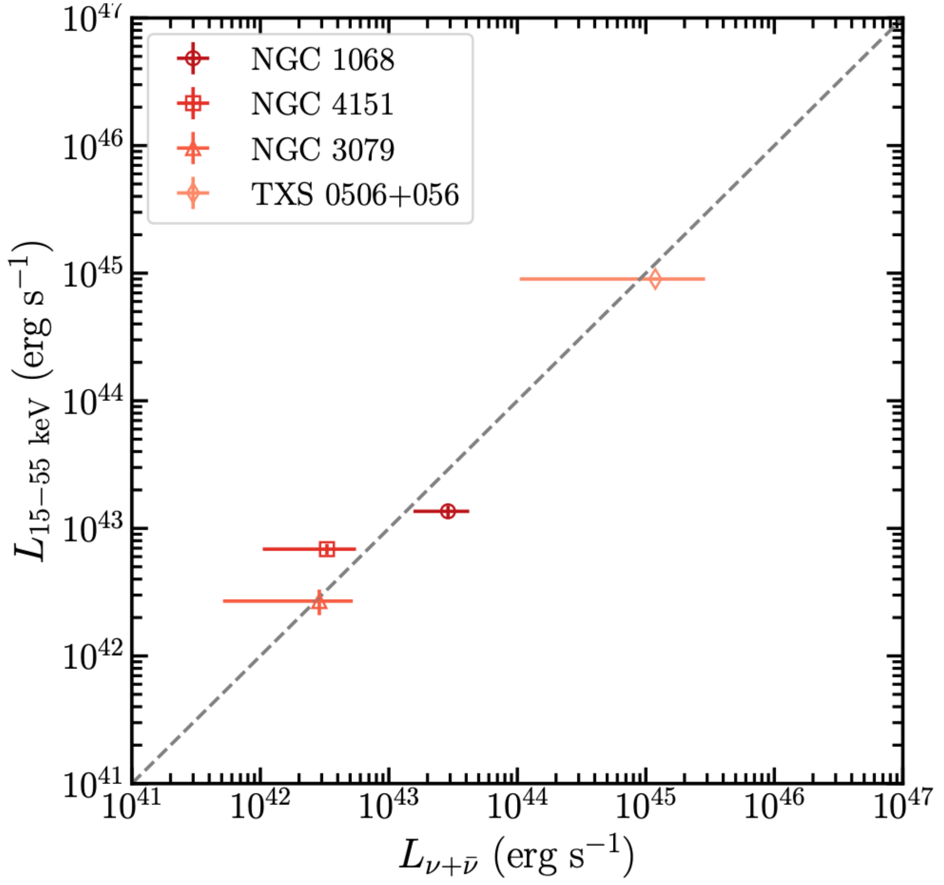
Two more source candidates at 2.5σ and 2.1σ level

IceCube arXiv:2406.07601, see also Neronov et al. PRL 132 (2024) 10, 101002

Connection of Seyferts and Blazar neutrino candidates?

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

Intrinsic (unabsorbed) luminosity

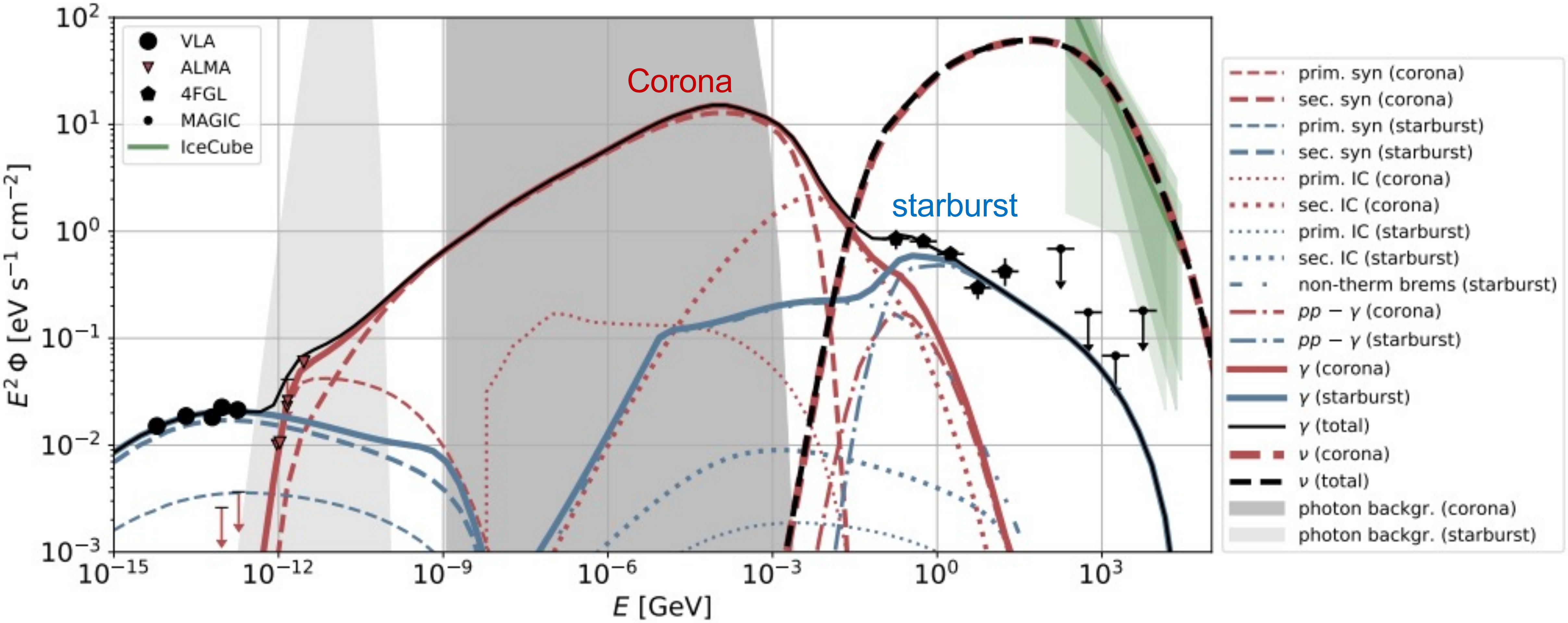


Hard X-rays

0.3-100 TeV neutrinos

E. Kun et al. https://arxiv.org/abs/2404.06867

Model of NGC 1068 (M77)



Neutrinos from corona, gammas from starburst

Eichmann et al. ApJ 939 (2022) 43, Inoue et al. ApJL 891 (2020), Fang et al. ApJ 956 (2023), ...