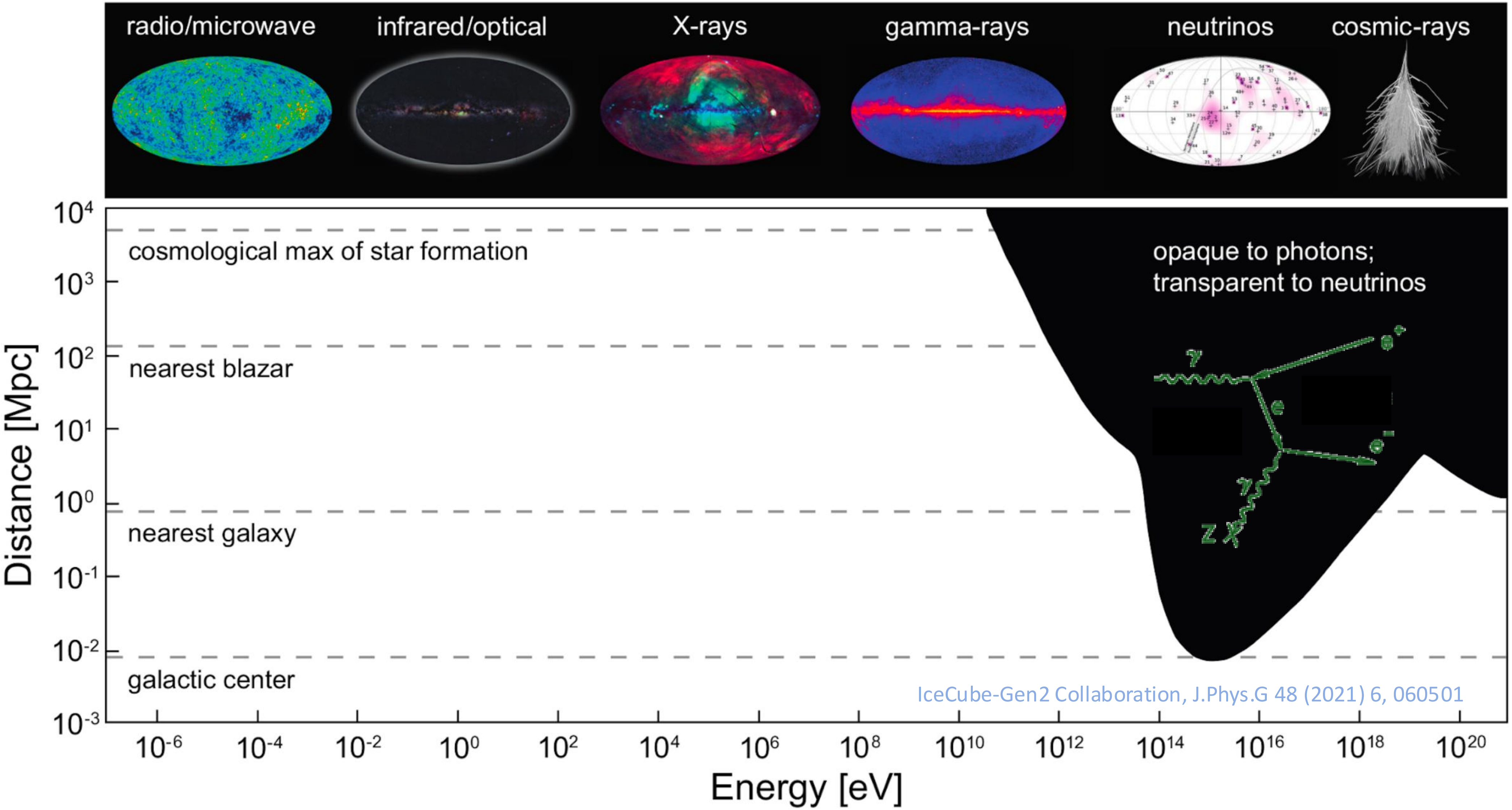
Special session on high energy astrophysics with neutrino detectors

Lu Lu

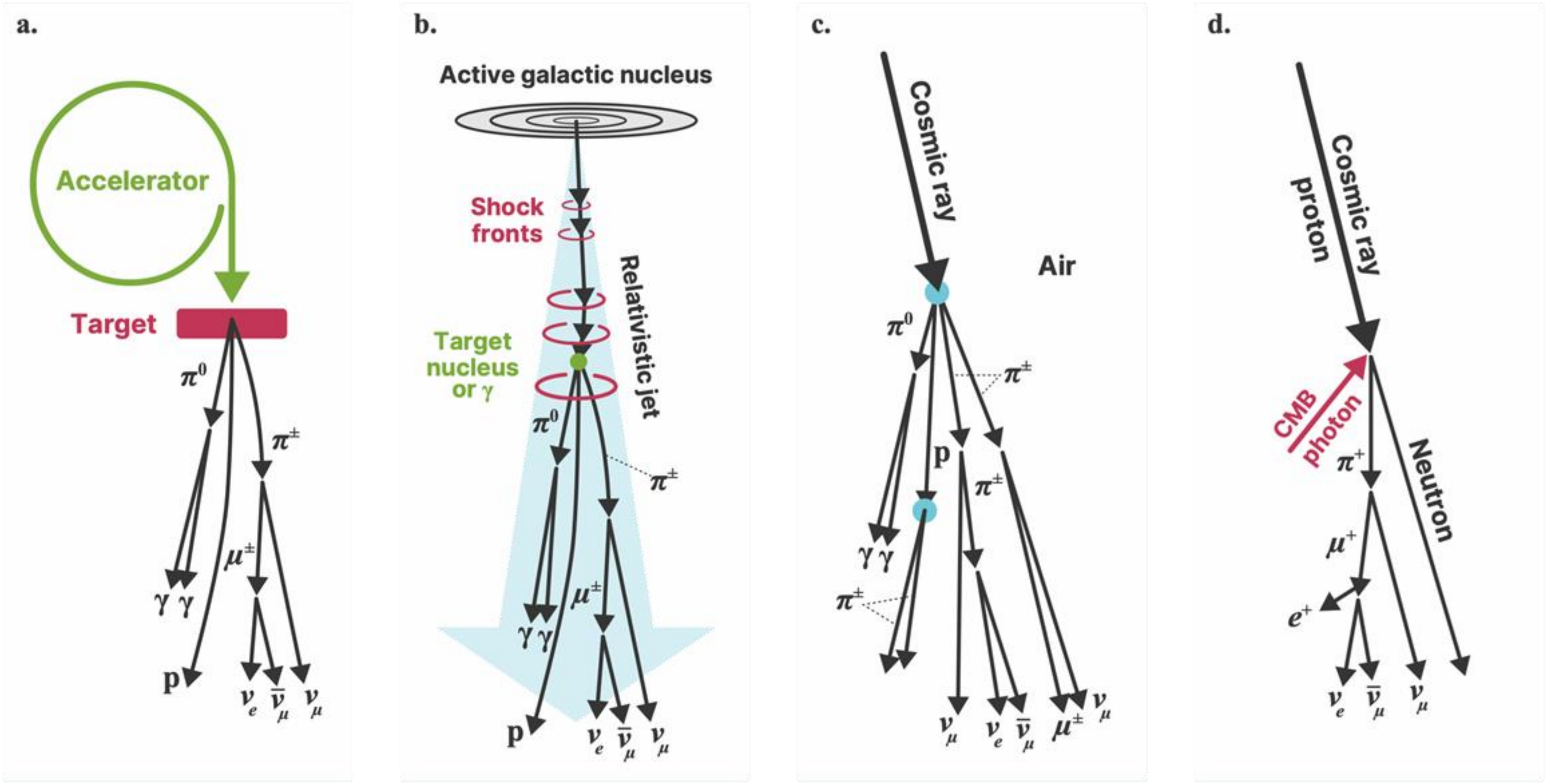
University of Wisconsin-Madison

High Energy Astrophysics

Neutrinos: energy frontier, tracing back to first interactions, cosmological baseline

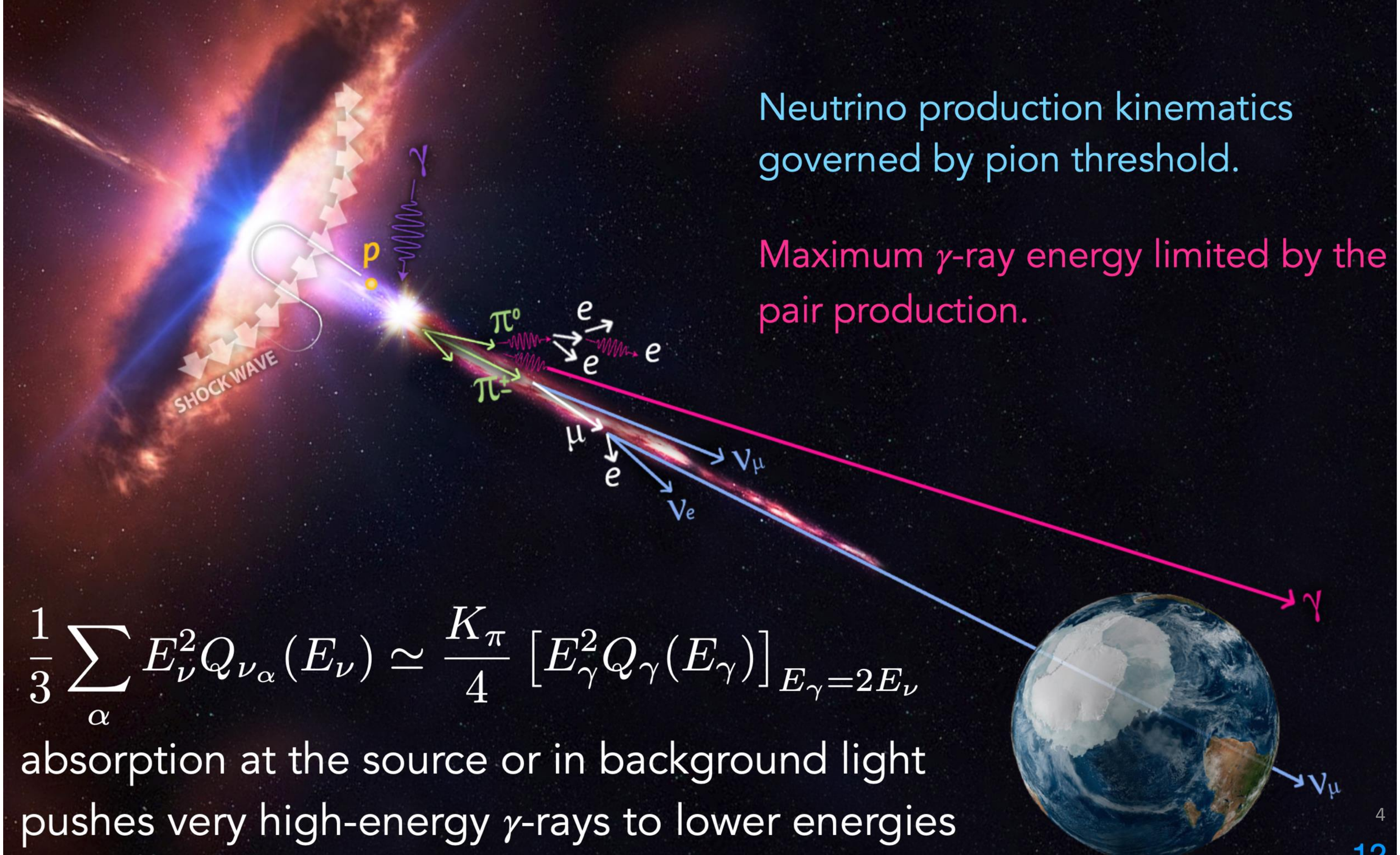


IceCube-Gen2 Collaboration, J.Phys.G 48 (2021) 6, 060501



Particle astrophysics: studying particle showers created by nature

Ali Kheirandish



Neutrino production kinematics governed by pion threshold.

Maximum γ-ray energy limited by the pair production.

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

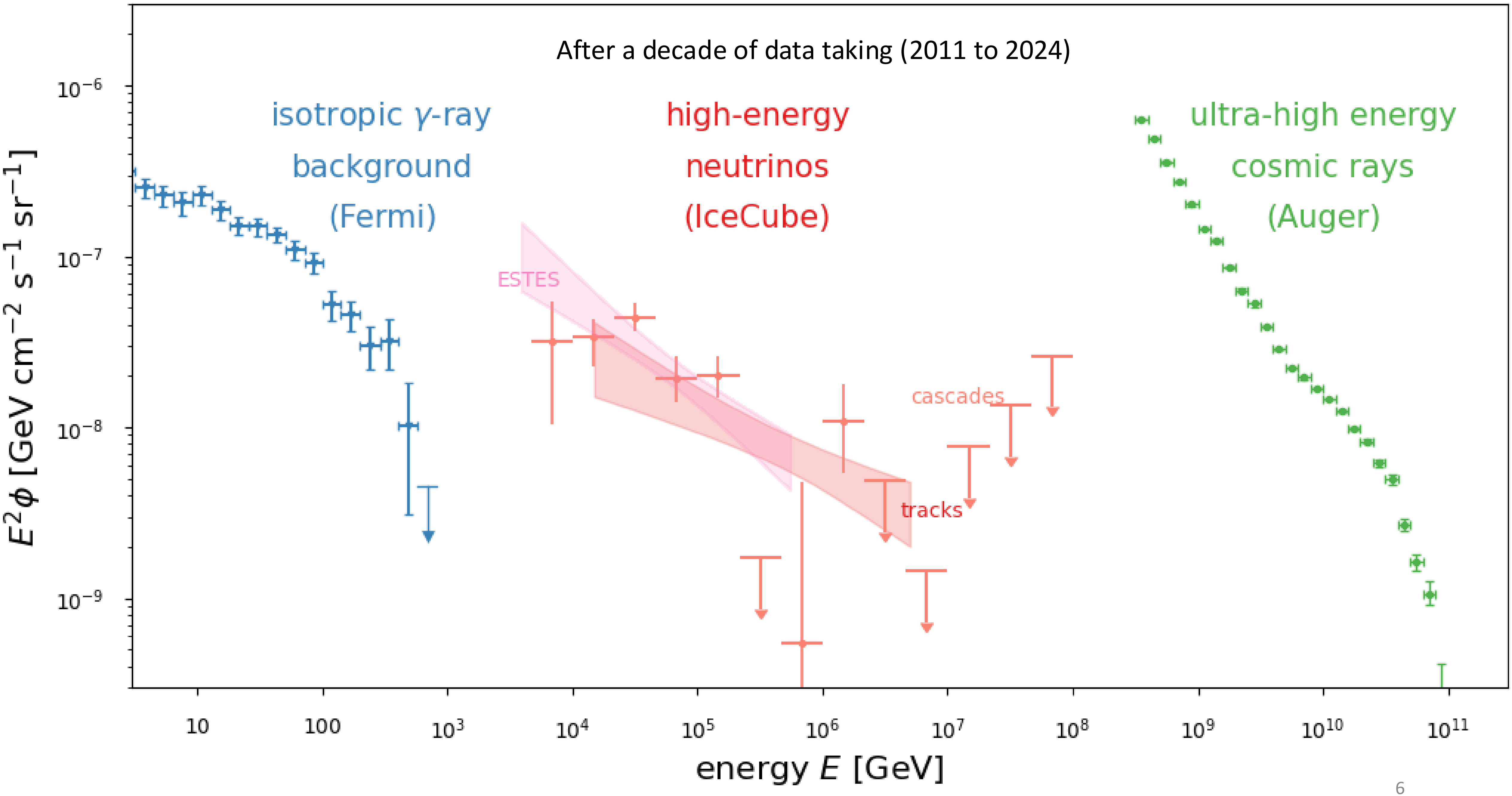
absorption at the source or in background light pushes very high-energy γ-rays to lower energies

Recent Point Source Results from IceCube and Their Implications for the Origin of High-Energy Neutrinos
Ali Kheirandish

Multimessenger Perspectives on High-Energy Cosmic Neutrinos	*Kohta Murase*	
Multicultural Greek		15:50 - 16:10
Hadronic Interaction Models at the Highest Energies	*Dennis Soldin*	
Multicultural Greek		16:10 - 16:30
The Pacific Ocean Neutrino Experiment	*Nathan Whitehorn*	
Multicultural Greek		16:30 - 16:50
LHAASO: Recent Results and Implications on Hadronic PeVatrons.	*Mr Houdun Zeng*	
Multicultural Greek		16:50 - 17:10

IceCube: Recent Results on Diffuse Astrophysical Neutrinos	*Dr Vedant Basu*	
Great Hall		19:00 - 19:20
Latest Results from Super-Kamiokande	*Ed Kearns*	
Great Hall		19:20 - 19:40
Measuring the Neutrino Flavor Ratio from the Galactic Plane with IceCube	*John Hardin*	
Great Hall		19:40 - 20:00
Probing Earth's Core Density with Atmospheric Neutrinos at IceCube Neutrino Observatory	*KOTOYO HOSHINA*	
Great Hall		20:00 - 20:20

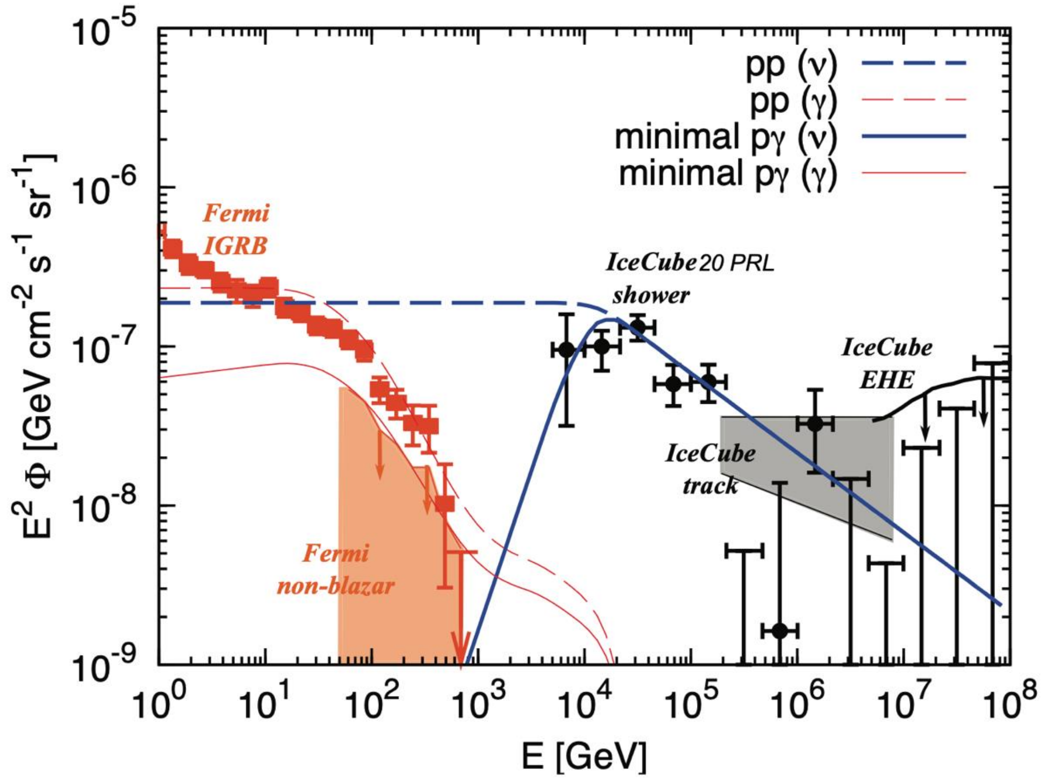
- Locate cosmic beams
- How are particles accelerated, beam properties
- Multi-messenger view with cosmic rays and photons
- Propagation in accelerator environment, CMB…
- Neutrino detections in presence of large atmospheric background



After a decade of data taking (2011 to 2024)
isotropic γ-ray
background
(Fermi)
high-energy
neutrinos
(IceCube)
ultra-high energy
cosmic rays
(Auger)
ESTES
cascades
tracks
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
energy E [GeV]

Extragalactic Multimessenger Connection: Current

- 10-100 TeV shower data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



$$p + p \rightarrow N\pi + X$$

$$p + \gamma \rightarrow N\pi + X$$

$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\text{or } \bar{\nu}_e) + e^{\pm}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

KM, Guetta & Ahlers 16 PRL
see also
KM, Ahlers & Lacki 13 PRDR
Capanema, Esmaili & KM 20 PRD
Capanema, Esmaili & Serpico 21 JCAP
Fang, Gallagher & Halzen 22 ApJL

Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent
→ Requiring hidden (i.e., γ-ray opaque) cosmic-ray accelerators
(ν data above 100 TeV can still be explained by γ-ray transparent sources)

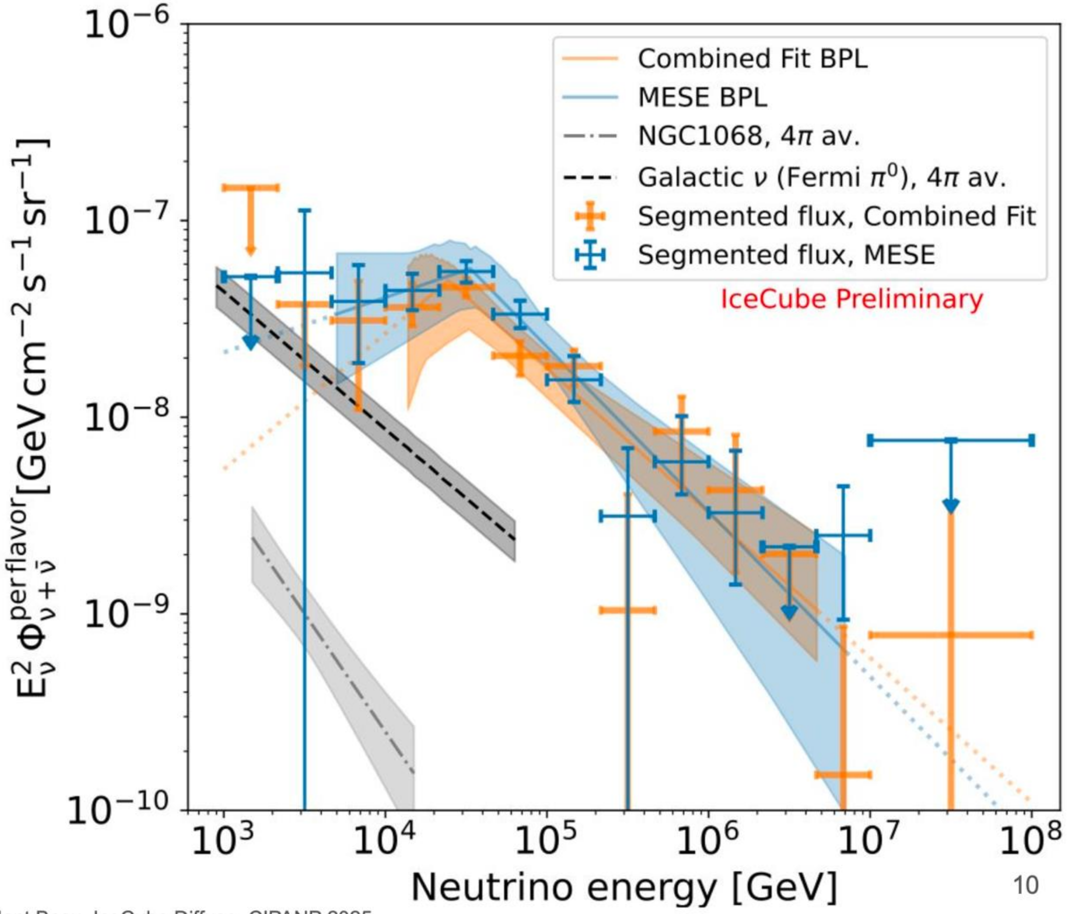
- Neutrino / gamma ray connection key to probe source properties
- Nu results hints obscured gamma ray at source

Kohta Marase

Features in diffuse neutrino flux

Evidence of spectral curvature

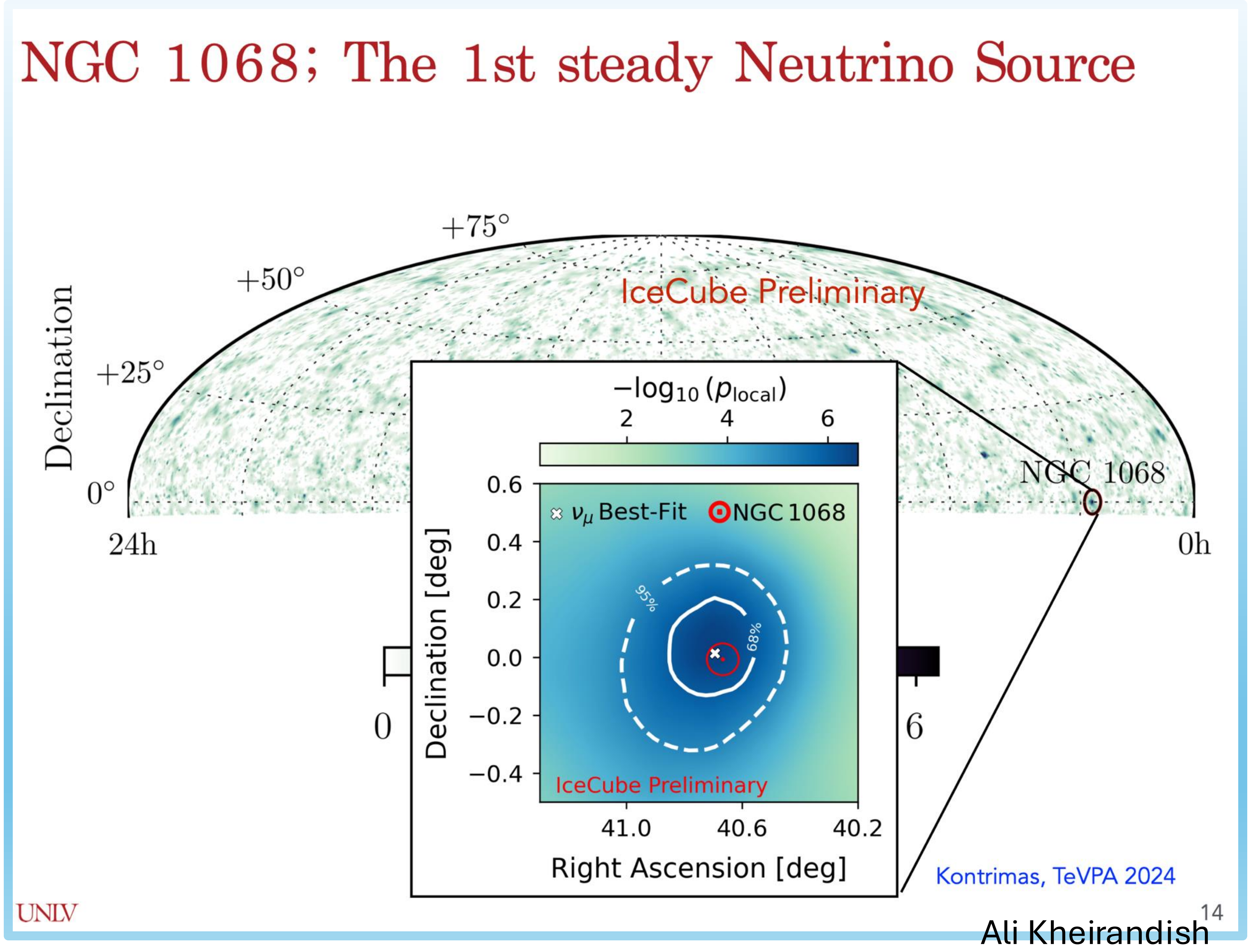
- Two analyses using both cascades and tracks reject SPL model for first time by >4σ
- “Combined Fit” analysis combining Cascades and Northern Tracks dataset
- “Medium Energy Starting Events (MESE)” selection using cascades and starting tracks
- Joint publication underway!



Vedant Basu, IceCube Diffuse, CIPANP 2025

- New IceCube results
- Electron/tau neutrino driven data samples
- Evidence of spectrum features
- Further supports gamma-ray obscured scenario

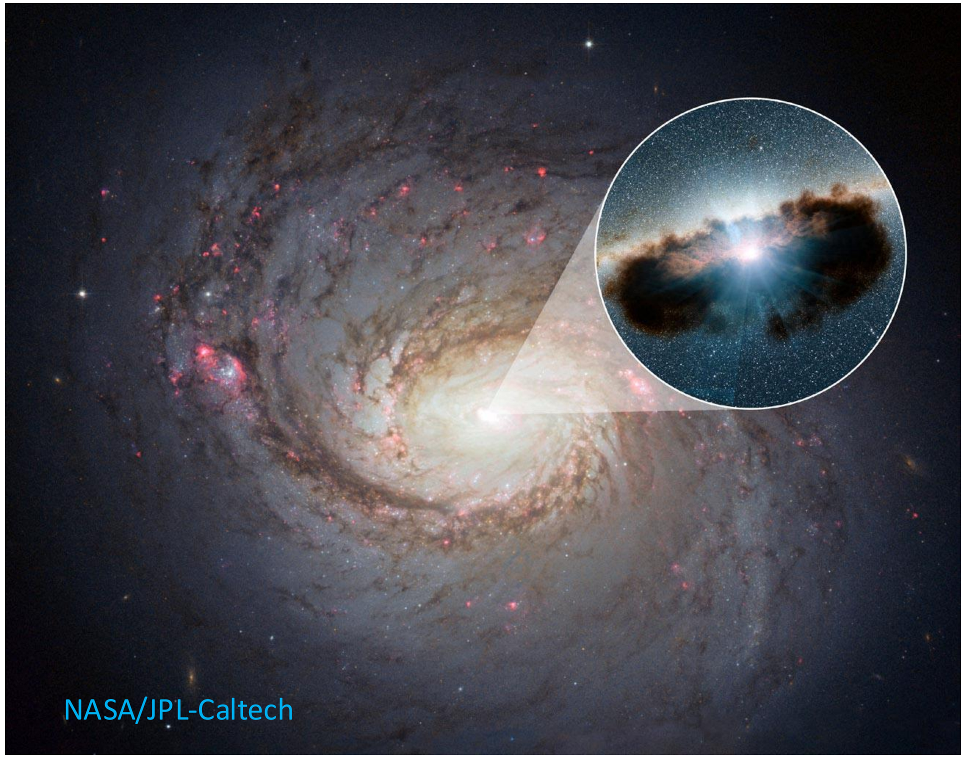
Vedant Basu



- Post trial ~4 sigma
- Bright Seyfert galaxy with hard x-ray flux

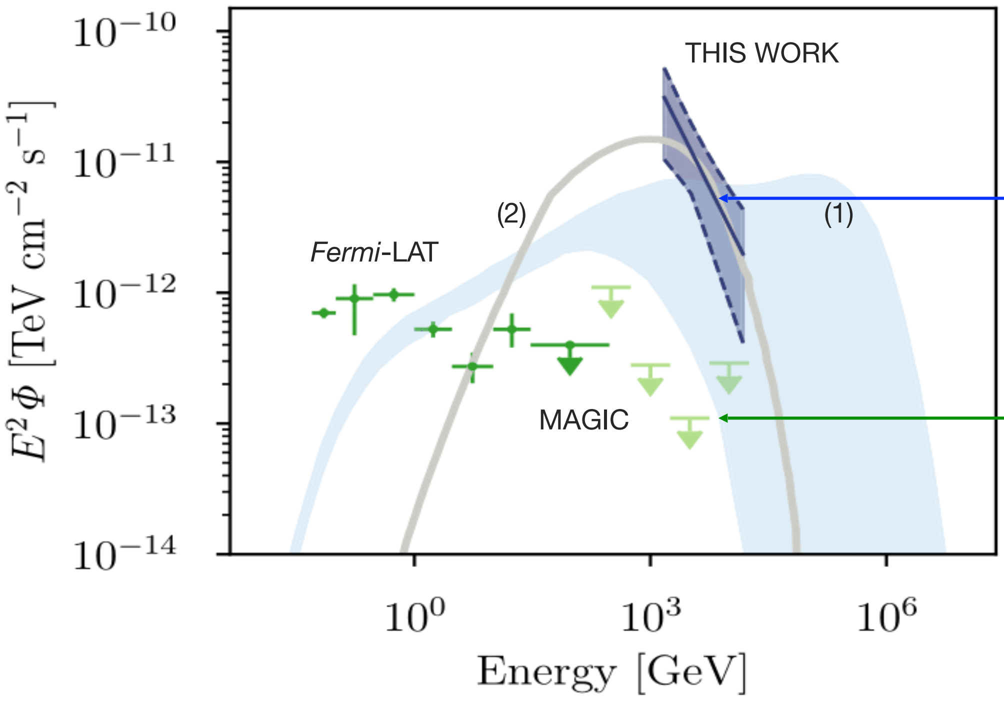
Cosmic obscured accelerators

~14 Mpc, $\mathrm{Log}L_X$ 2-10keV~42.9 erg/s



Gamma Rays (photons) and Neutrinos

We know that neutrinos and gamma rays are produced together



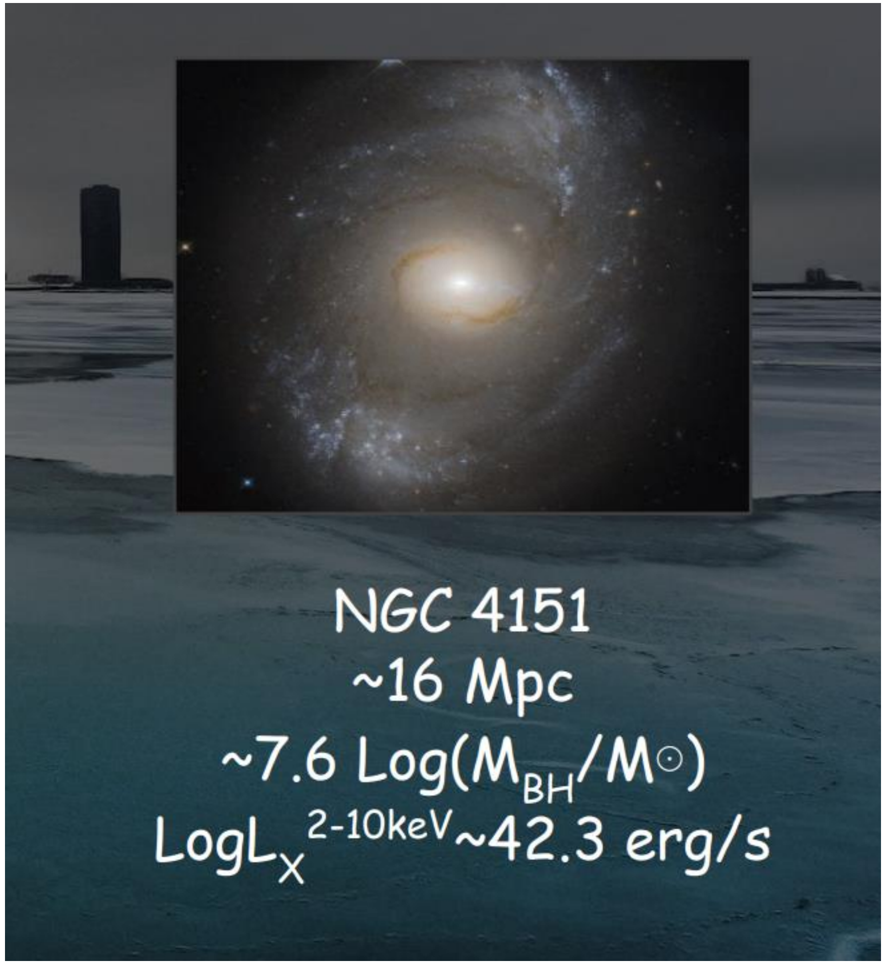
Neutrinos are coming out

Gamma rays are missing
- and it is not a surprise.

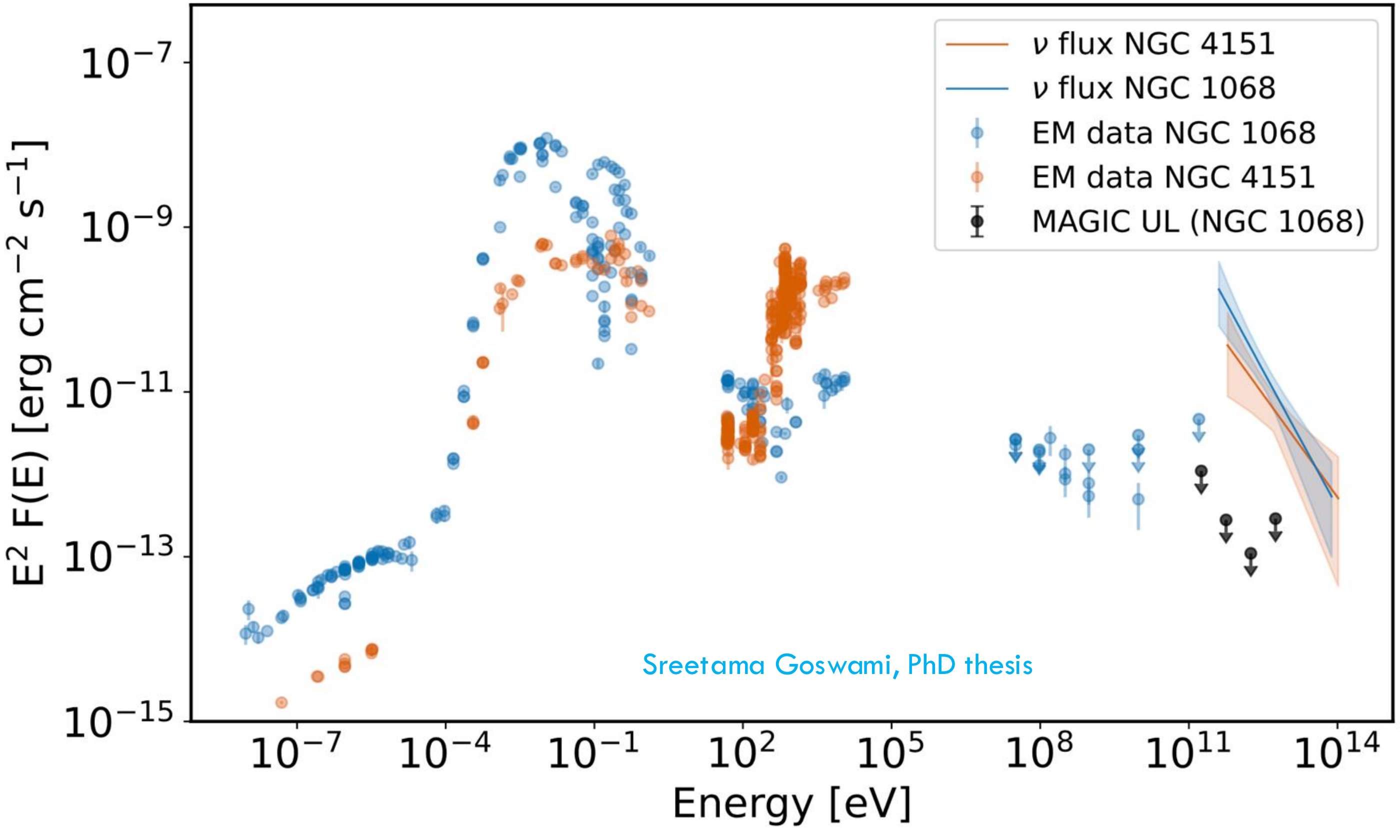
(1) Y. Inoue et al., ApJL'20

(2) K. Murase et al., PRL'20

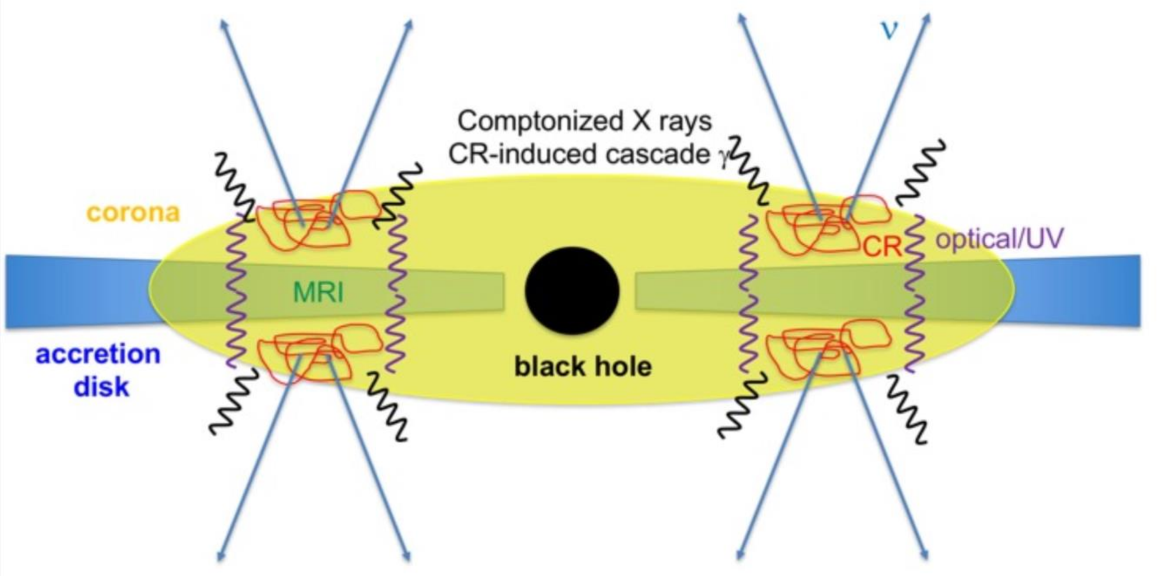
Neutrinos escape dense gas region: excess neutrinos but gamma rays are attenuated / absorbed



SED for NGC 1068 and NGC4151

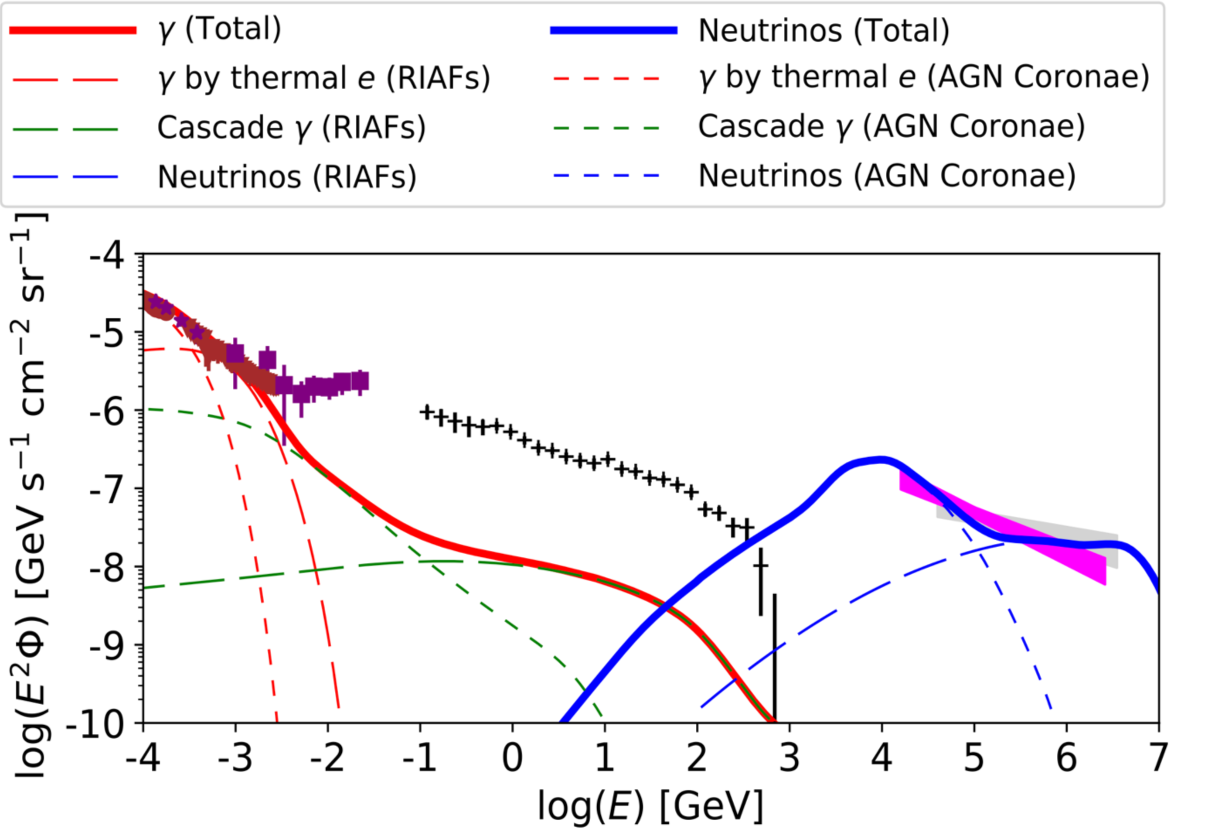


Consistent hints from point source and diffuse



accretion disk + "corona"
opt/UV=multi-temperature blackbody
X-ray=Compton by thermal electrons

KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.

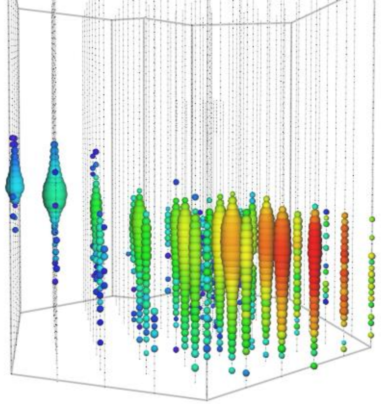


Neutrinos at the highest energies

From both IceCube and KM3NeT observatories

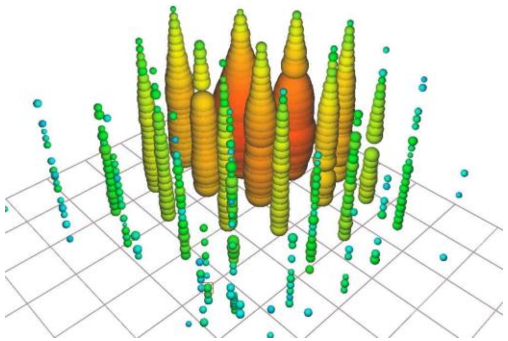
- 3 events with neutrino energy > 5 PeV over a decade of data taking

ApJ **833** 3 (2016)



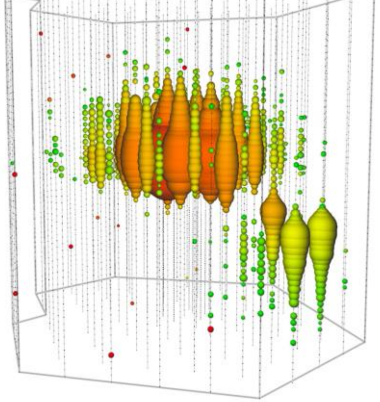
Muon energy: 4.5±1.2 PeV
Nu energy ~ 9 PeV

Nature **591**, 220–224 (2021)



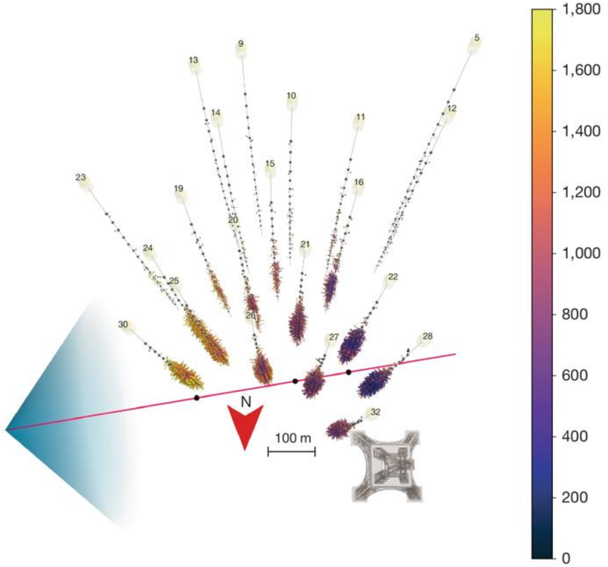
Deposited energy: 6.05 ±0.72 PeV
Nu energy ~6.3 PeV

PoS-ICRC2023-1030 (2023)



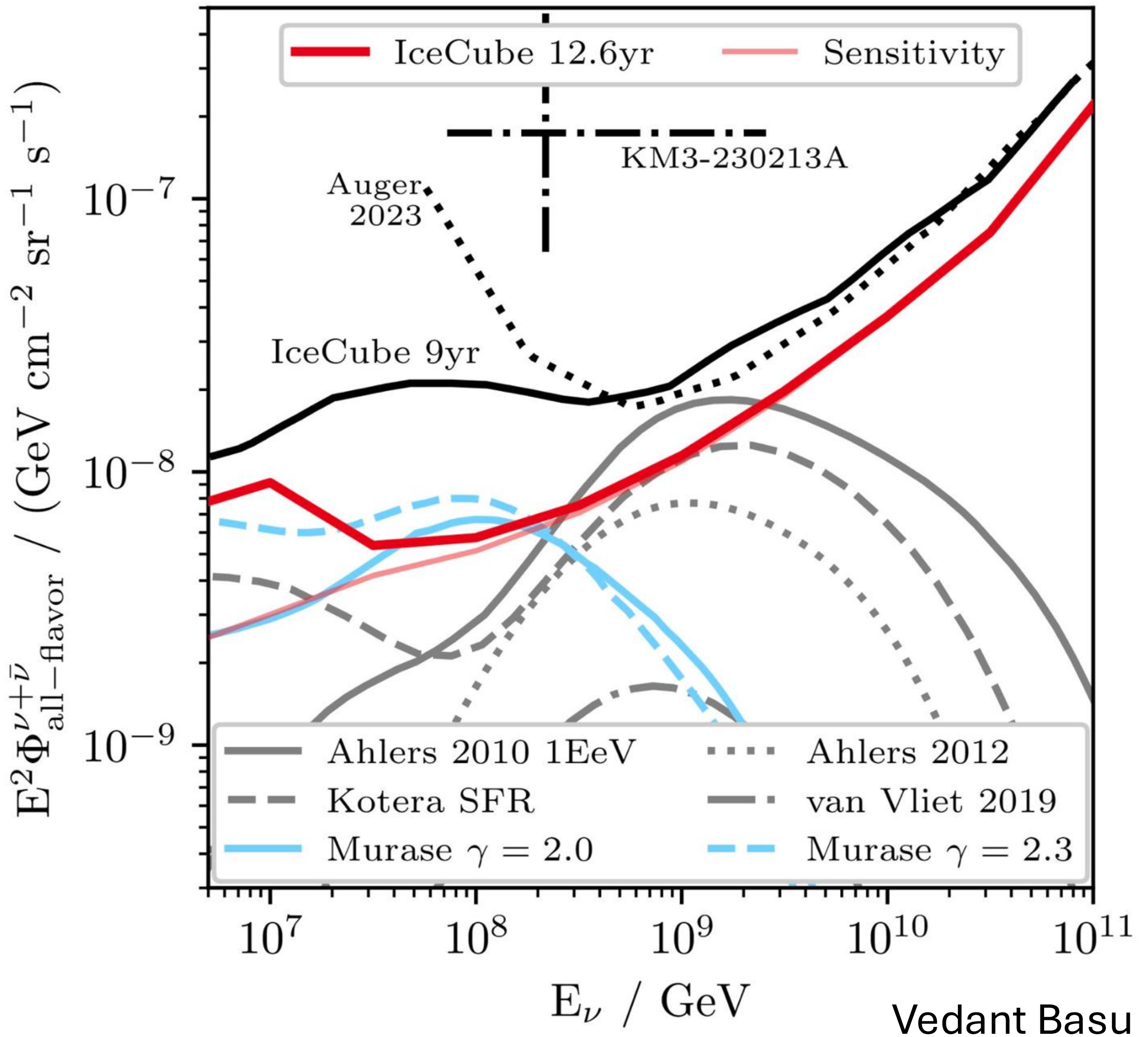
Nu energy ~11.4±2.5 PeV

13



Nu energy 220^{+570}_{-110}PeV

Neutrinos at the highest energies



Vedant Basu

KM3NeT candidate

Assuming E^{-2} spectrum:

→ $E_\nu = 220^{+570}_{-110}$PeV

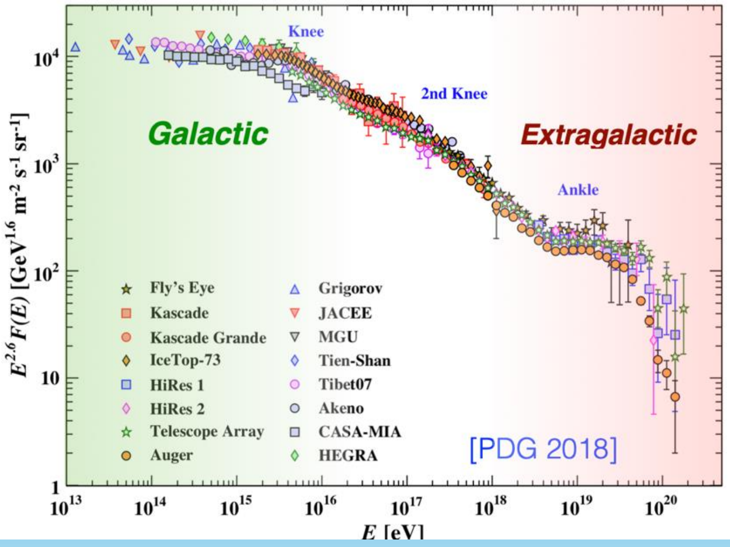
→Strong prior dependence, large energy uncertainty

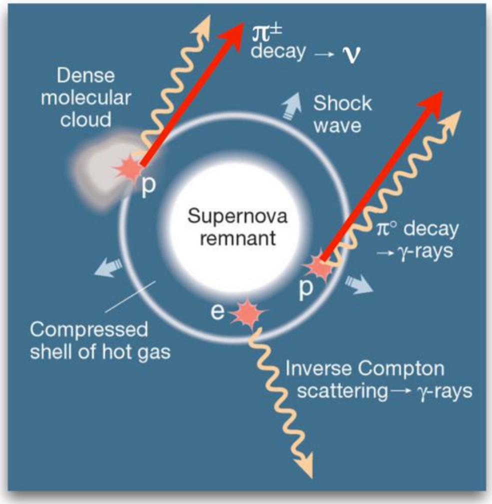
Expect O~70 events from IceCube assuming KM3NeT bestfit

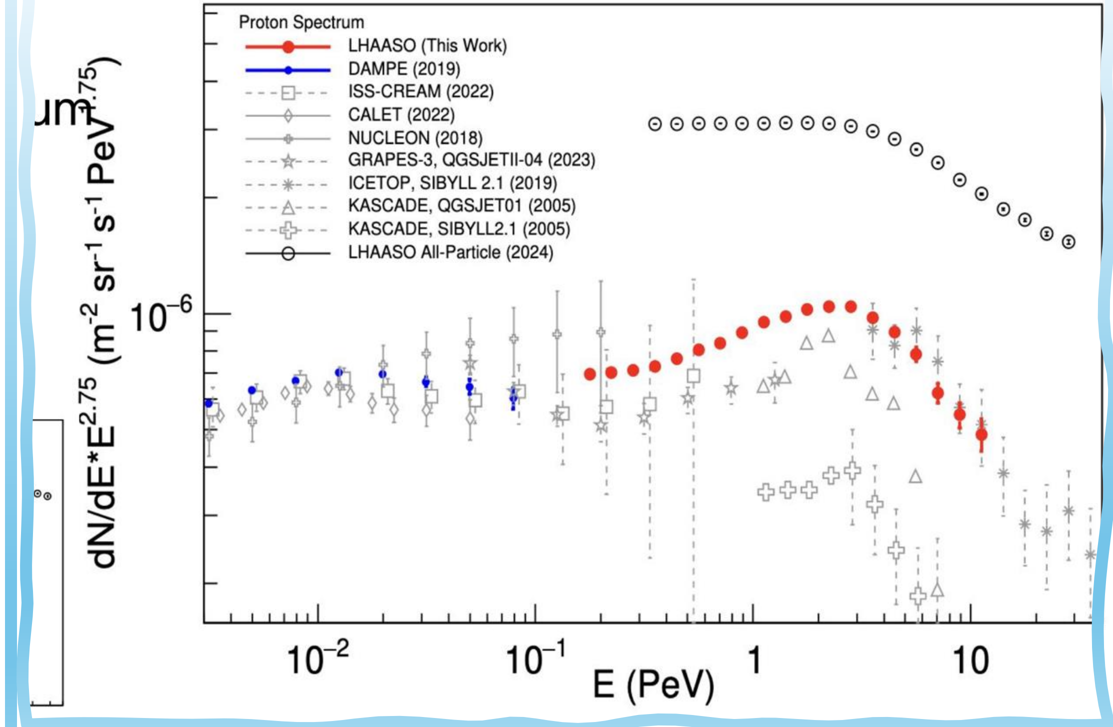
Tension relaxes when doing joint analysis at ~3 sigma

Galactic particle accelerators

- The search for Galactic cosmic neutrino sources concentrates on the search for “Pevatrons” which have the required energetics to produce cosmic rays up to the knee in the spectrum.
- ``Pevatrons” will produce pionic γ-rays whose spectrum extends to several hundred TeV without cut-off.
- Supernova remnant meet such condition.
- TeV γ-rays should be accompanied by TeV neutrinos, observable at IceCube.



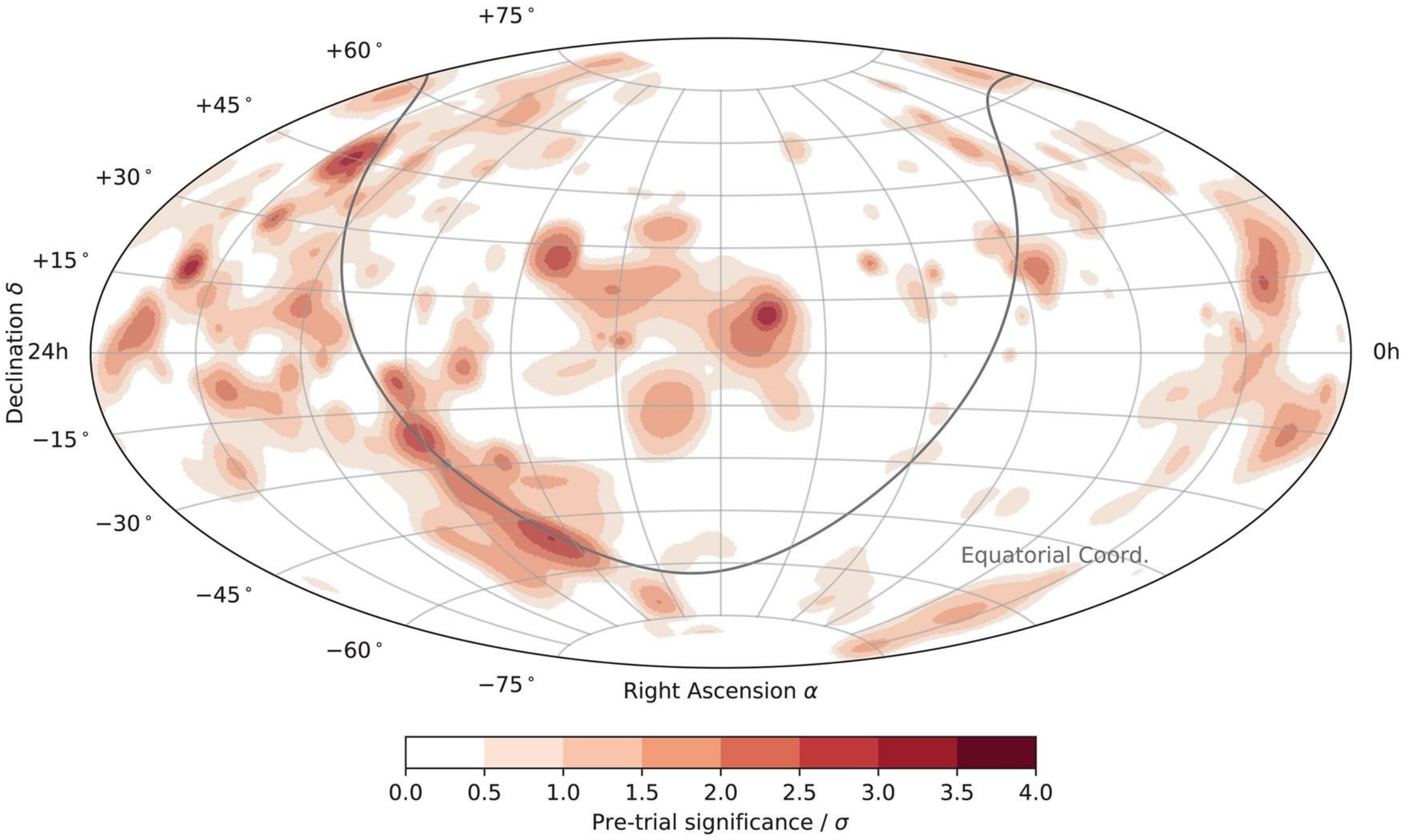




Ali Kheirandish

Houdun Zeng (LHAASO)

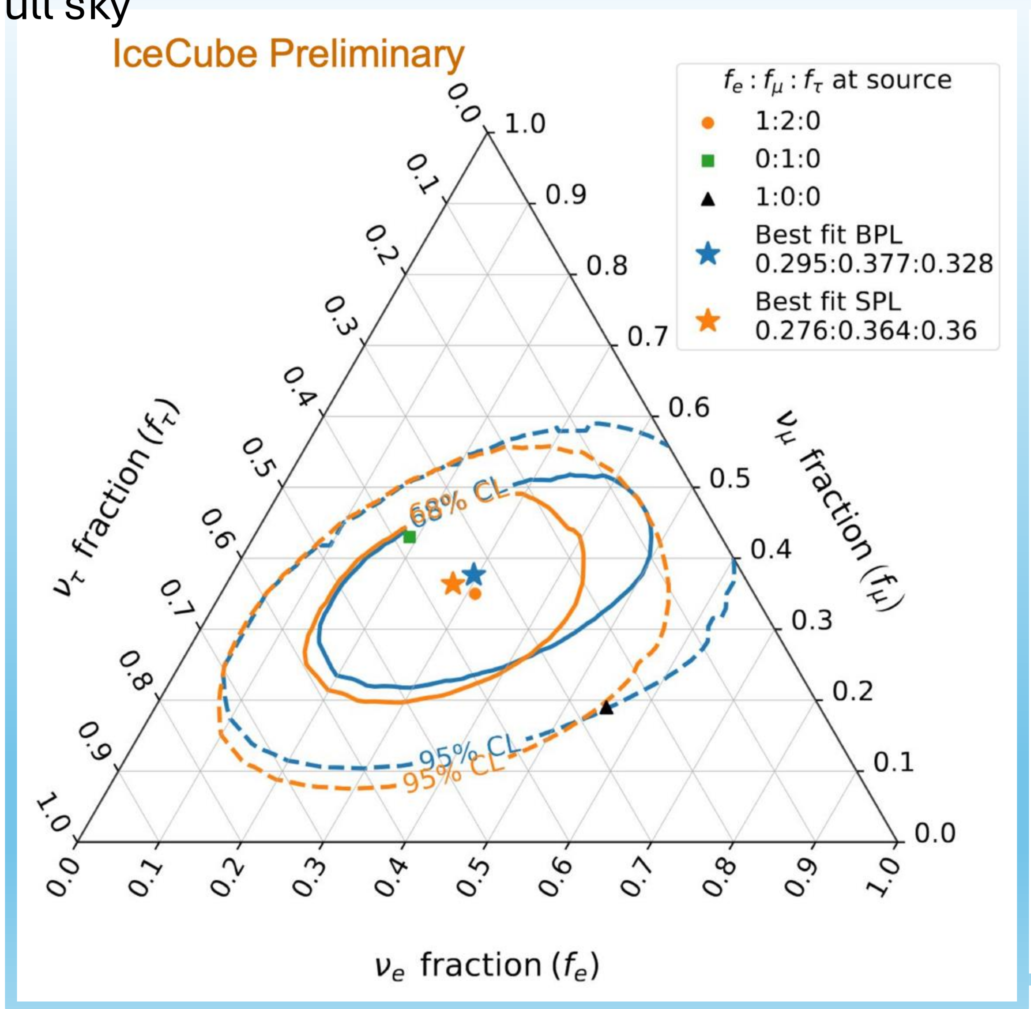
Galactic neutrinos



- 4.5 sigma post trial significance rejecting null galactic emissions
- Observed by electron and tau neutrinos.
- Exciting results coming up with inclusion of muon neutrinos

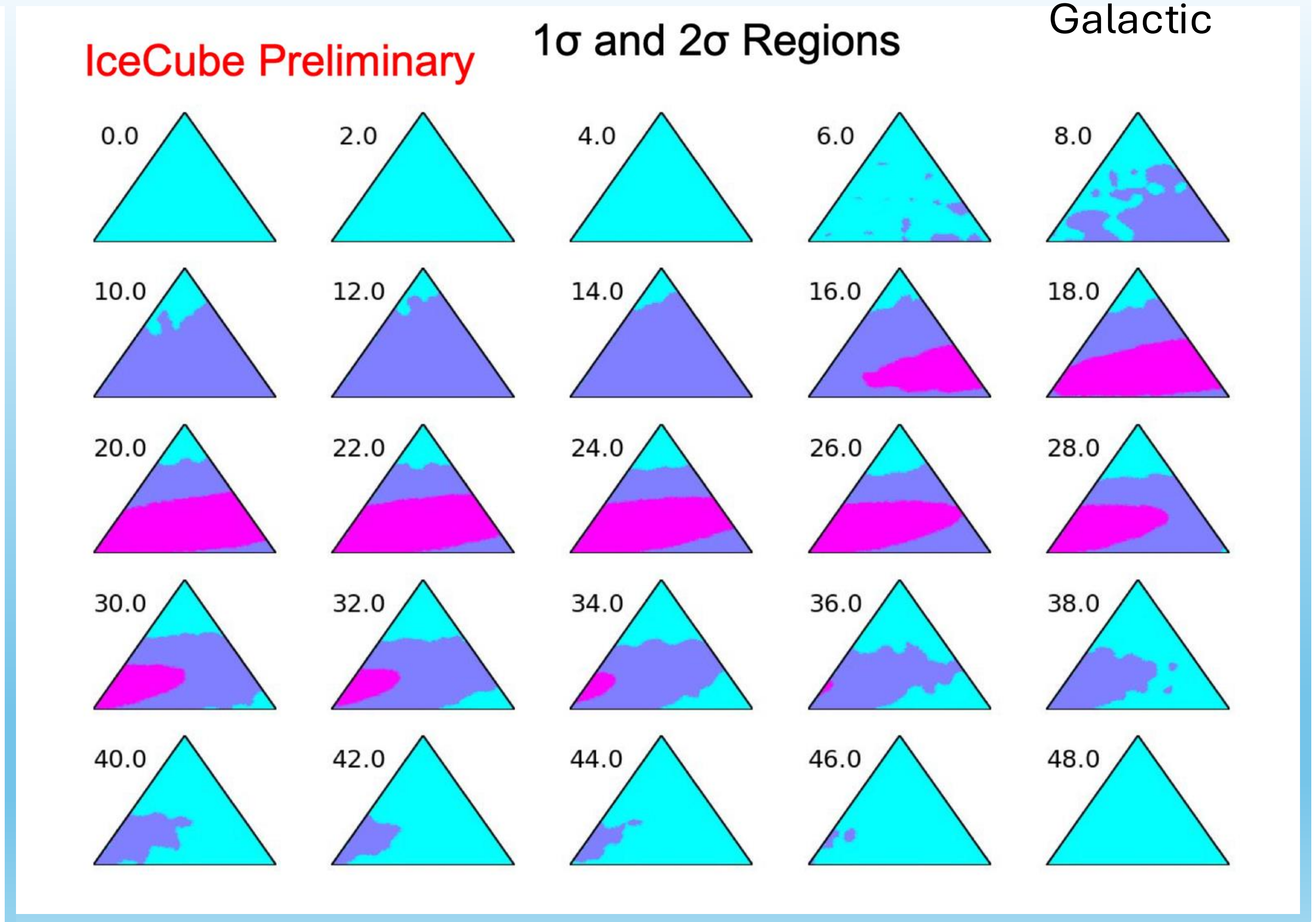
Flavour measurement

Full sky



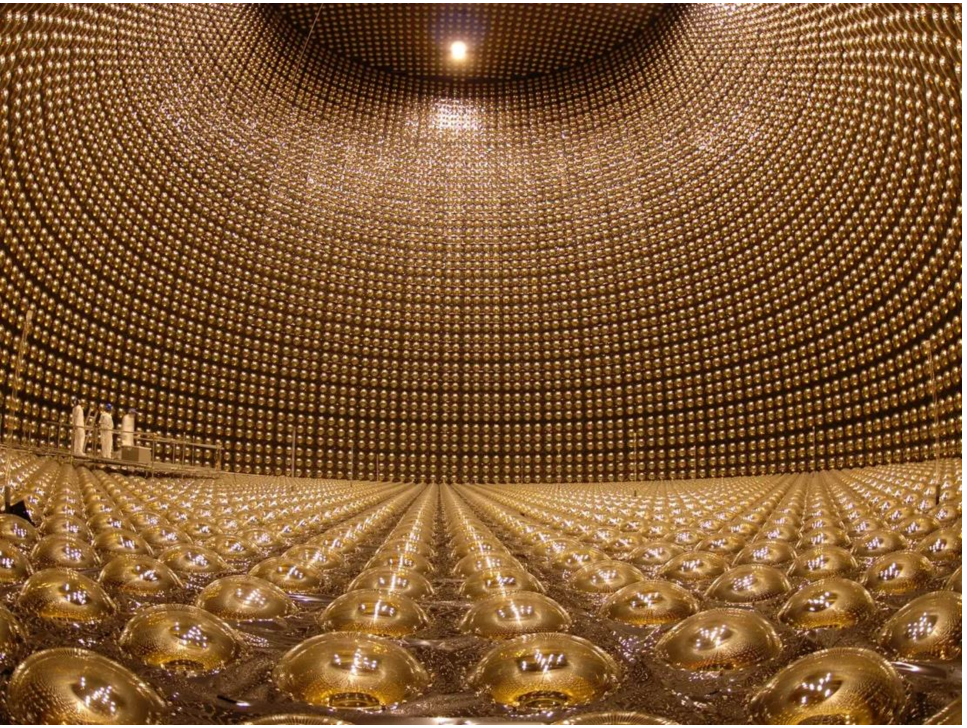
Vedant Basu

Galactic



John Hardin

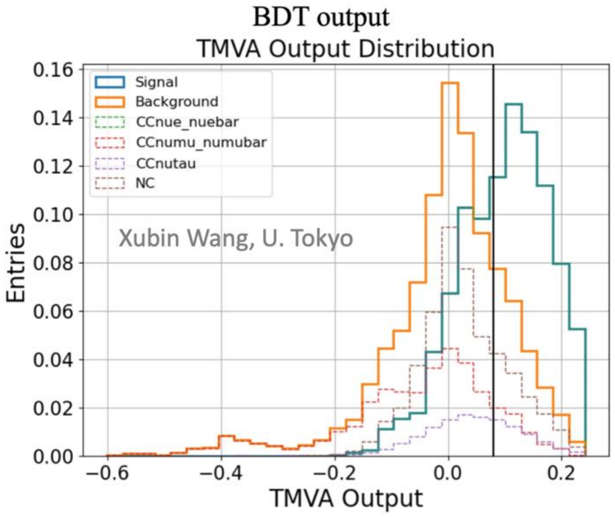
SuperK: eyes on galactic GeV electron neutrinos

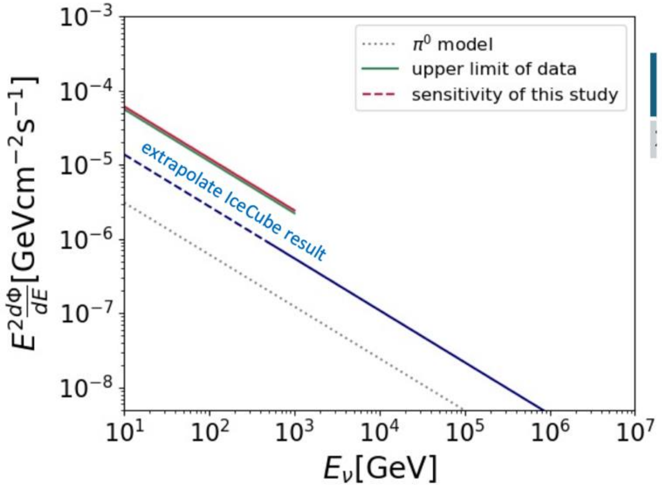


something new… (most of our astrophysical searches have emphasized muon neutrinos, especially upward-going)

Search for Astrophysical Electron Neutrinos in Multi-GeV Sample

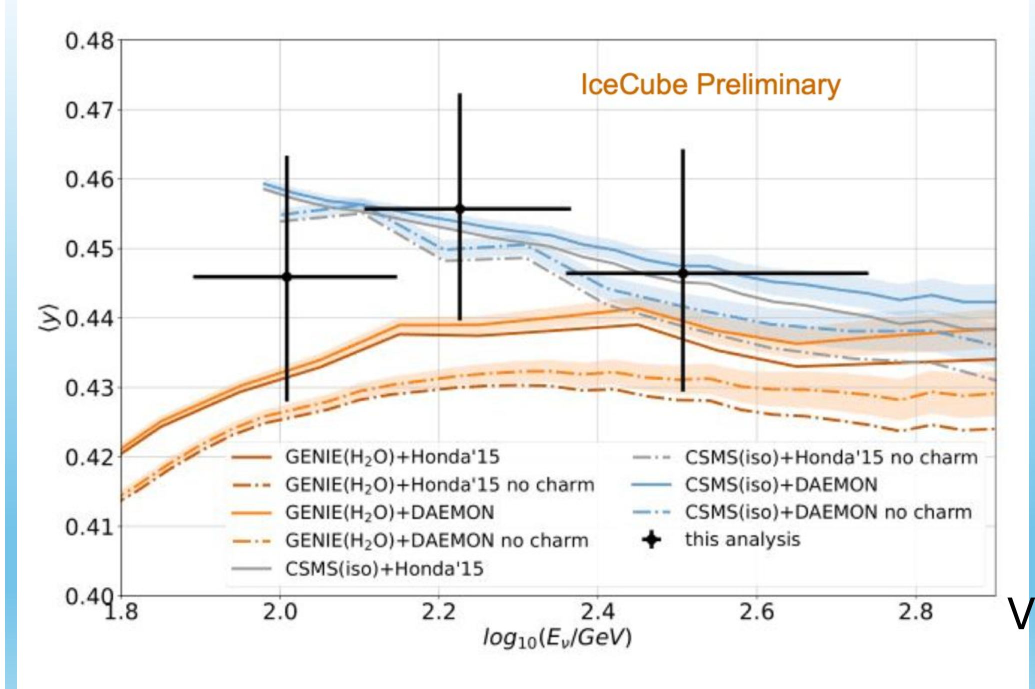
motivated by IceCube evidence for cascade events from galactic plane



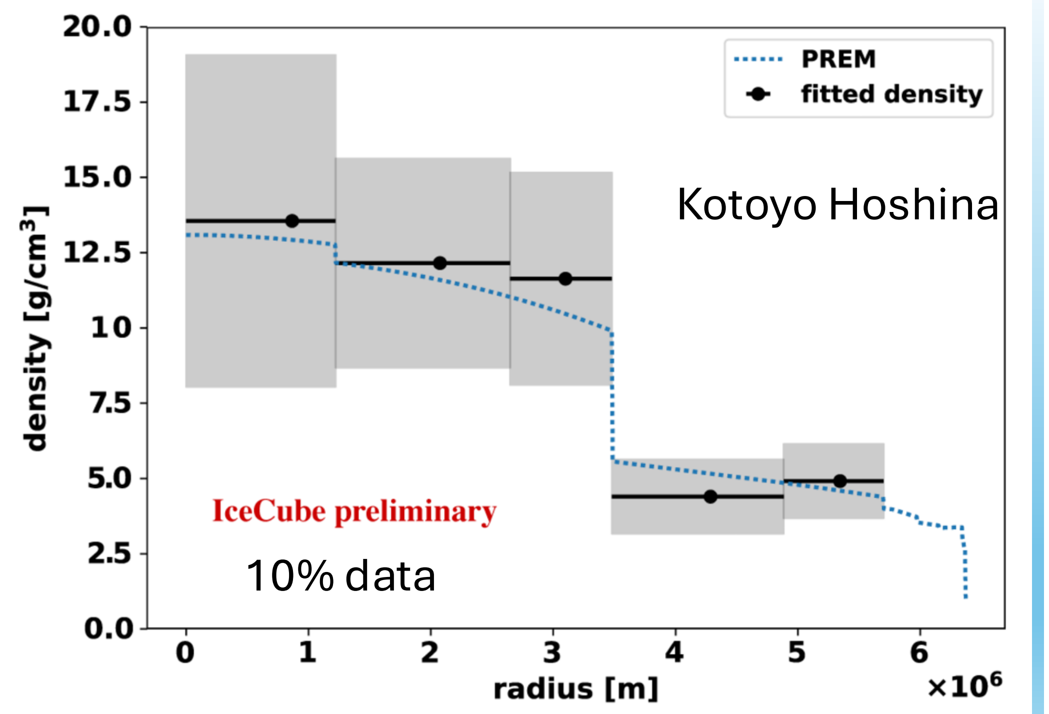


61% efficiency
70% pure CC electron neutrino

Ed Kearns

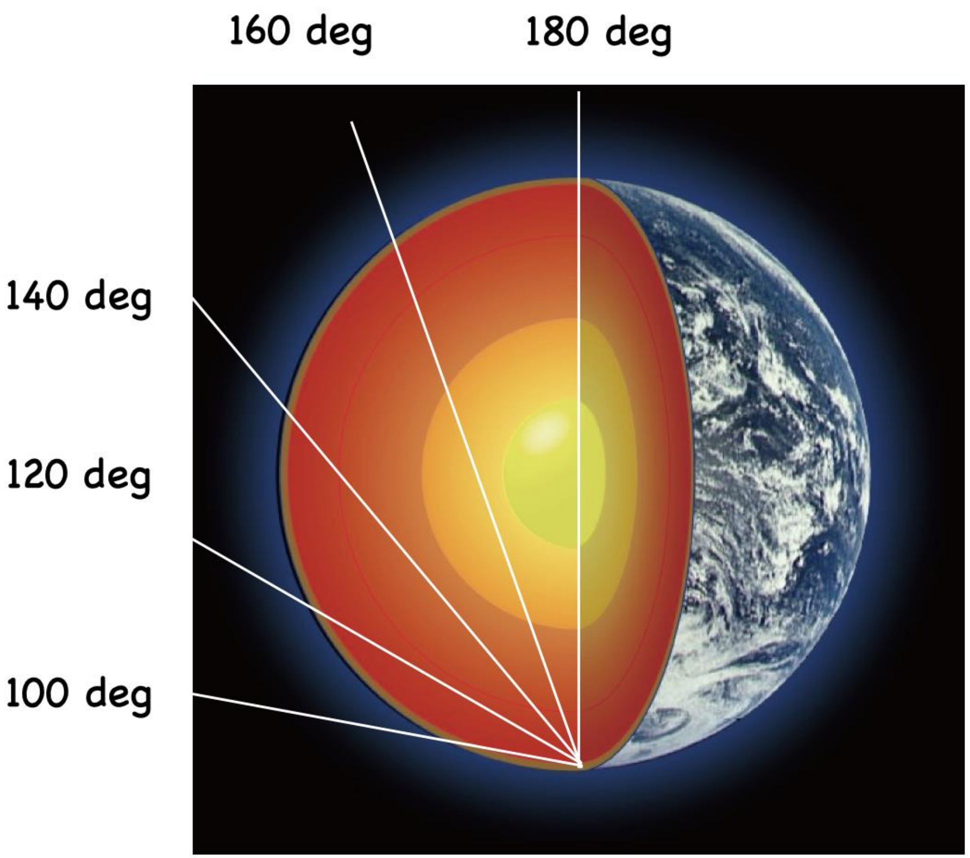


Vedant Basu

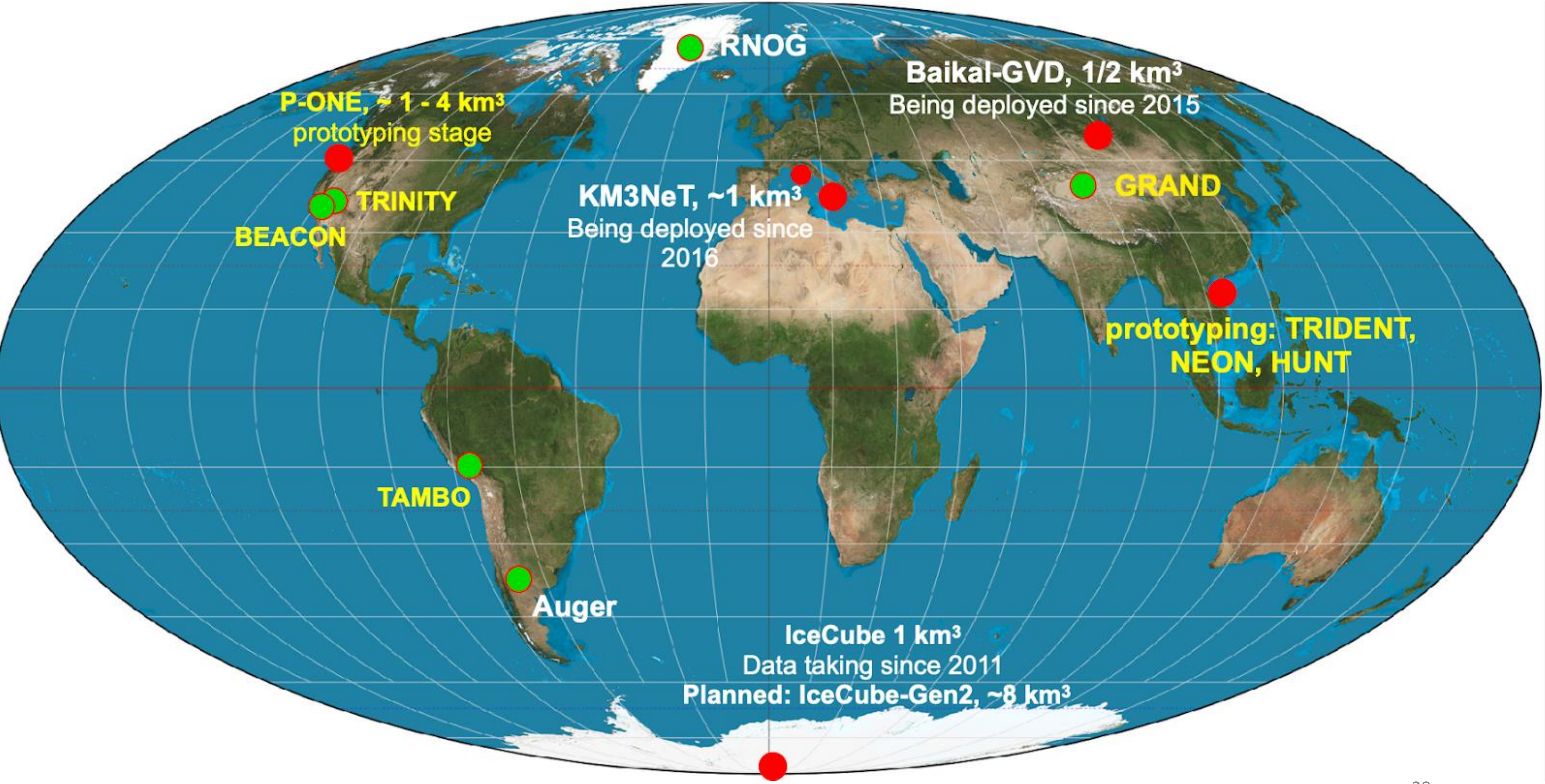


Kotoyo Hoshina

10% data

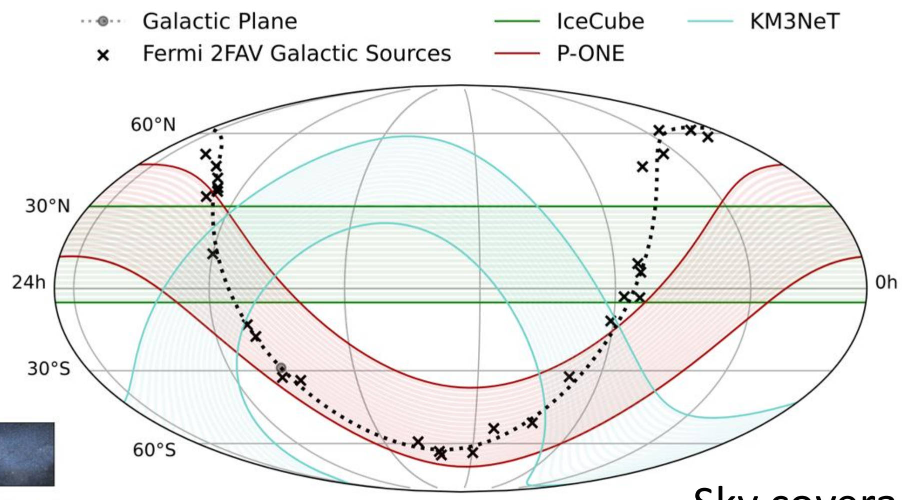


	Energy*
100 deg	2.2 PeV
120 deg	132 TeV
140 deg	51 TeV
160 deg	36 TeV
180 deg	32 TeV

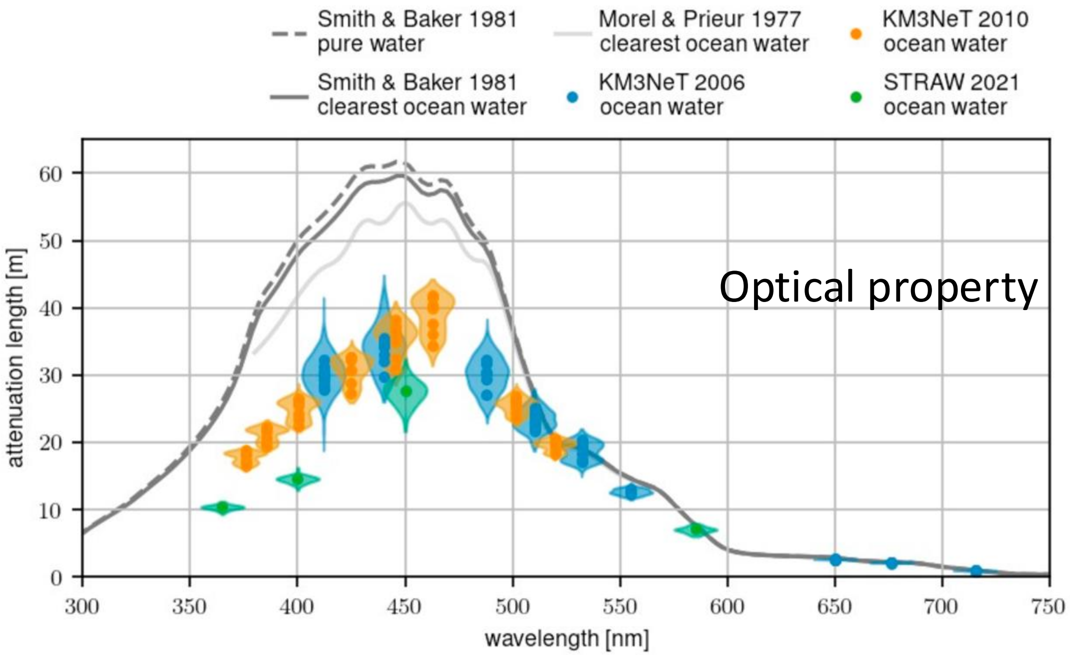

RNOG
Baikal-GVD, 1/2 km³
Being deployed since 2015
P-ONE, ~ 1 - 4 km³
prototyping stage
TRINITY
BEACON
KM3NeT, ~1 km³
Being deployed since 2016
GRAND
prototyping: TRIDENT, NEON, HUNT
TAMBO
Auger
IceCube 1 km³
Data taking since 2011
Planned: IceCube-Gen2, ~8 km³

P-One project

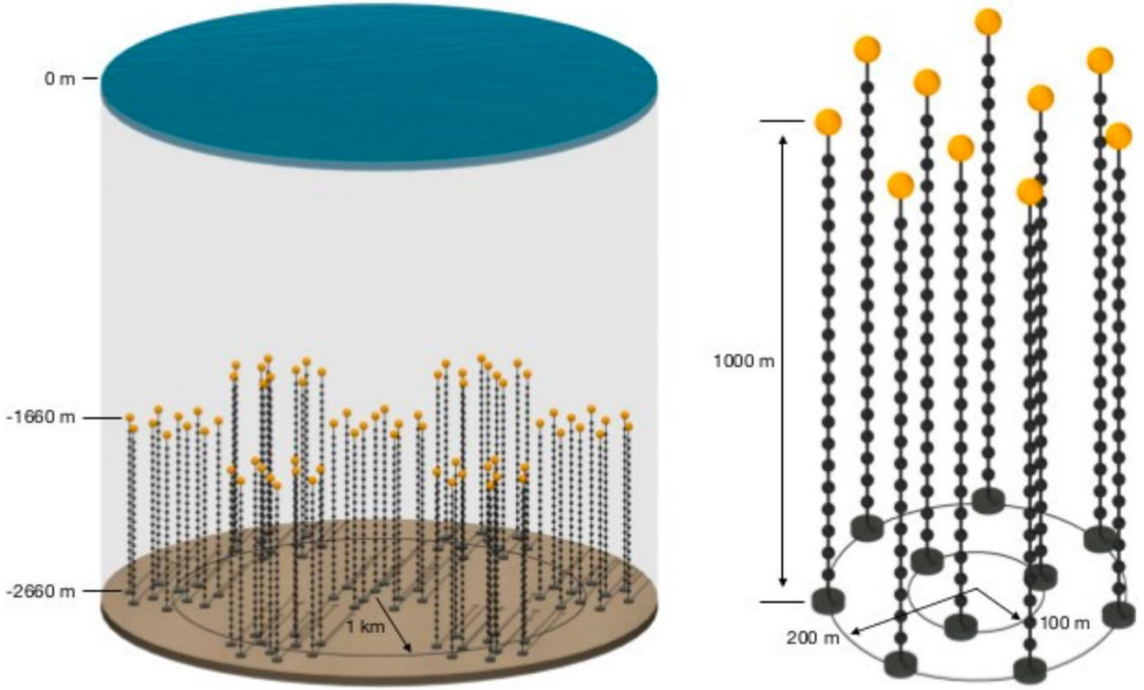
Nathan Whitehorn



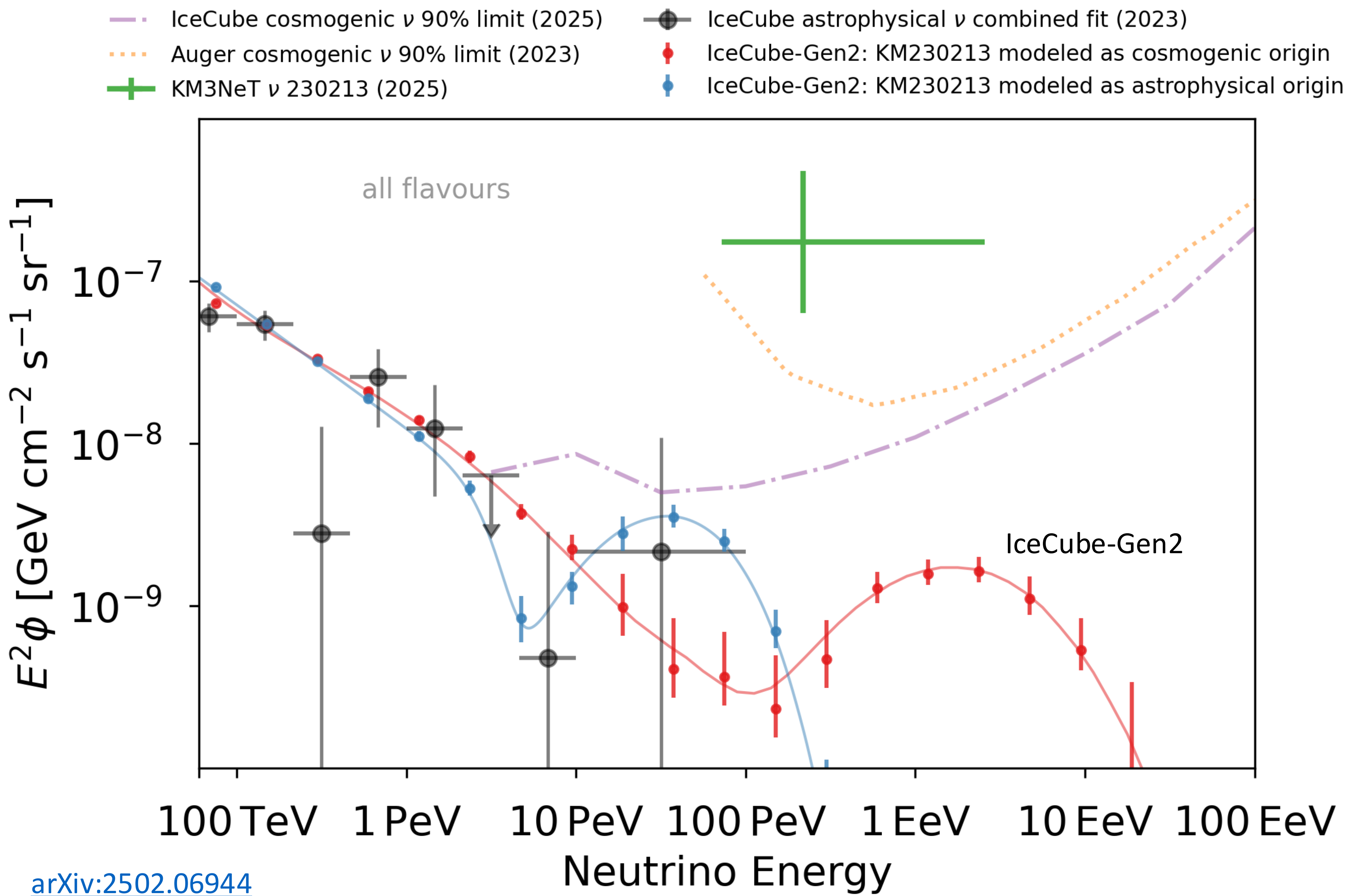
Sky coverage



Optical property



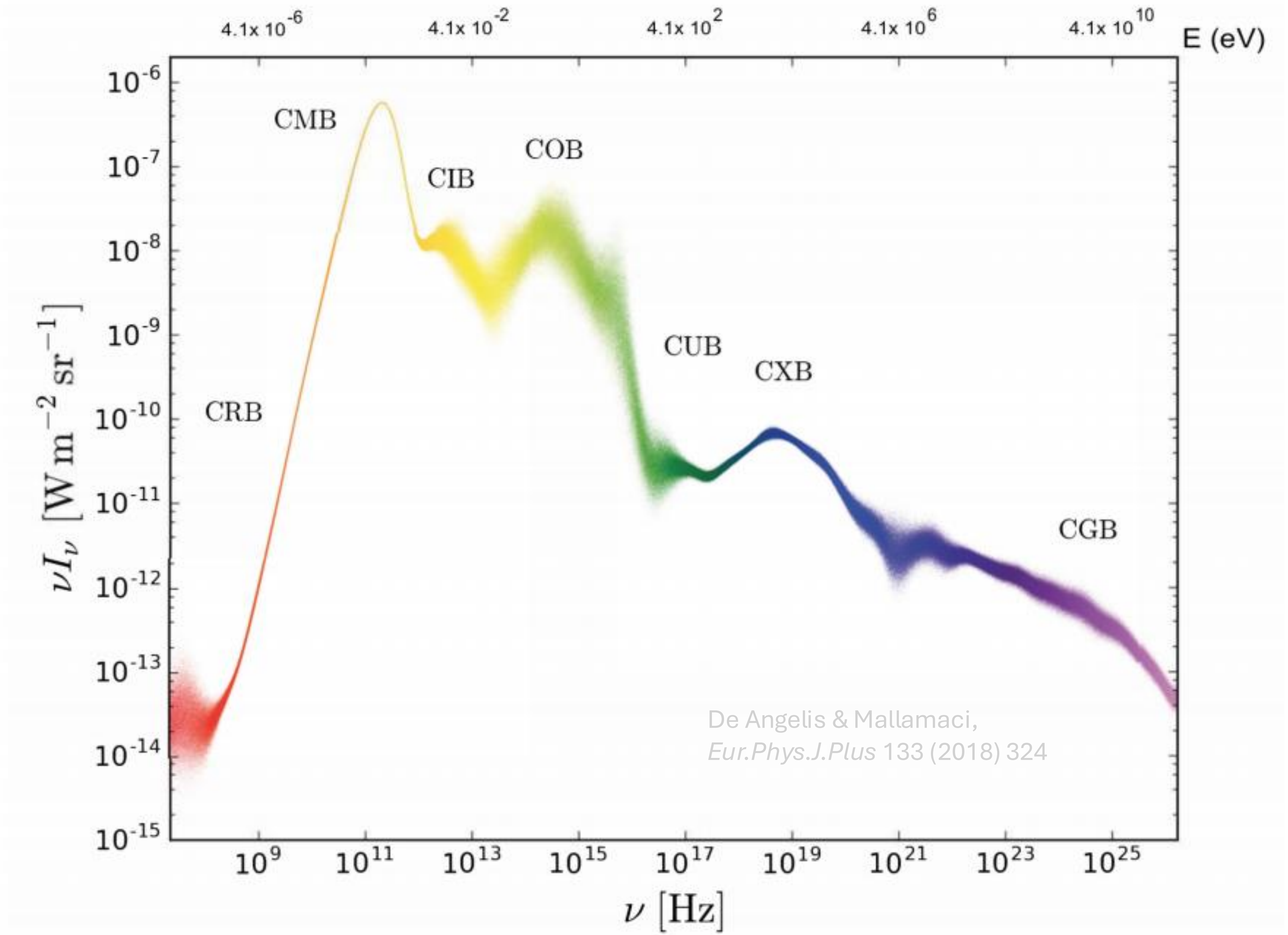
Nature Astronomy 4, 913-915, 2020



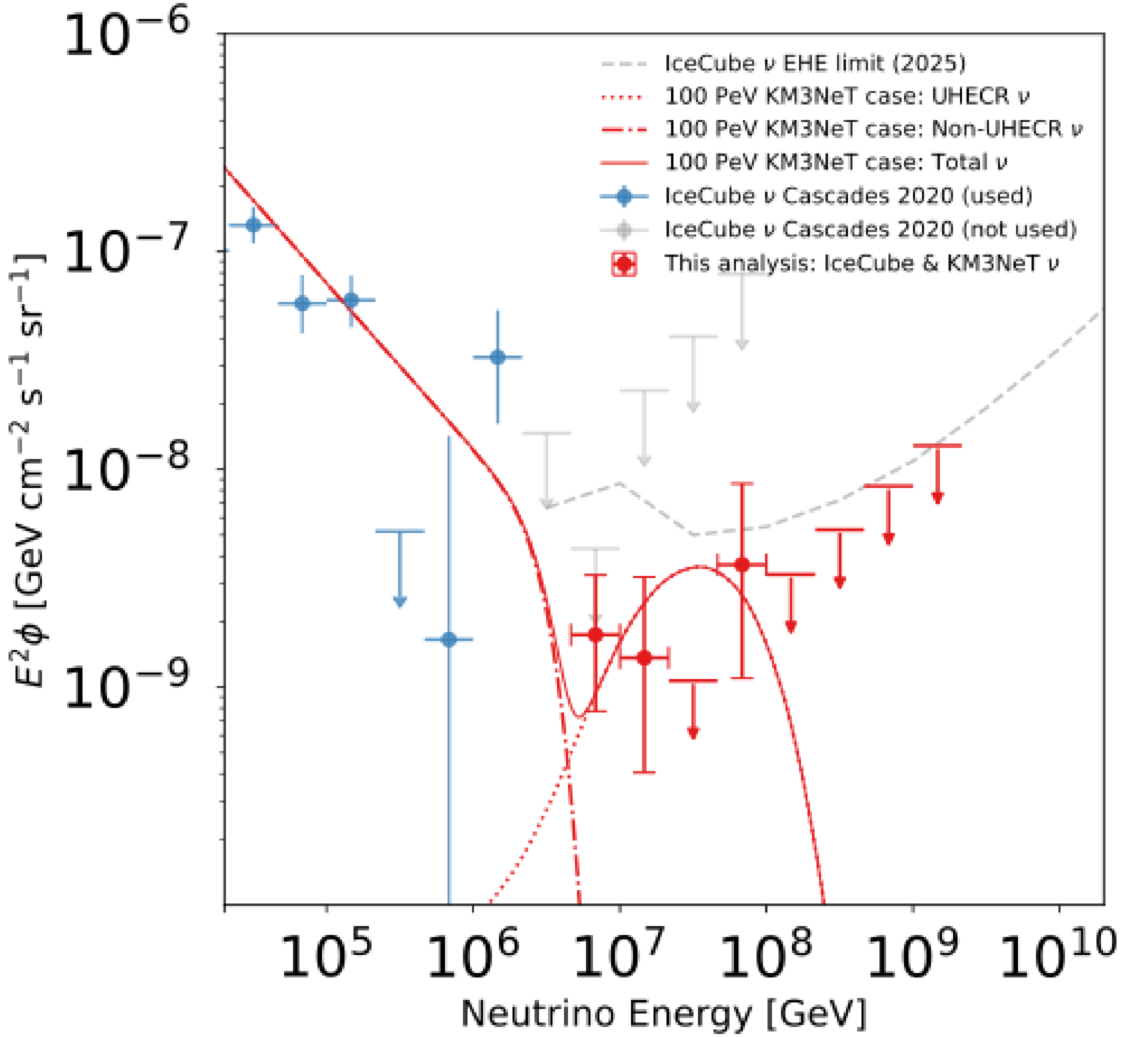
arXiv:2502.06944

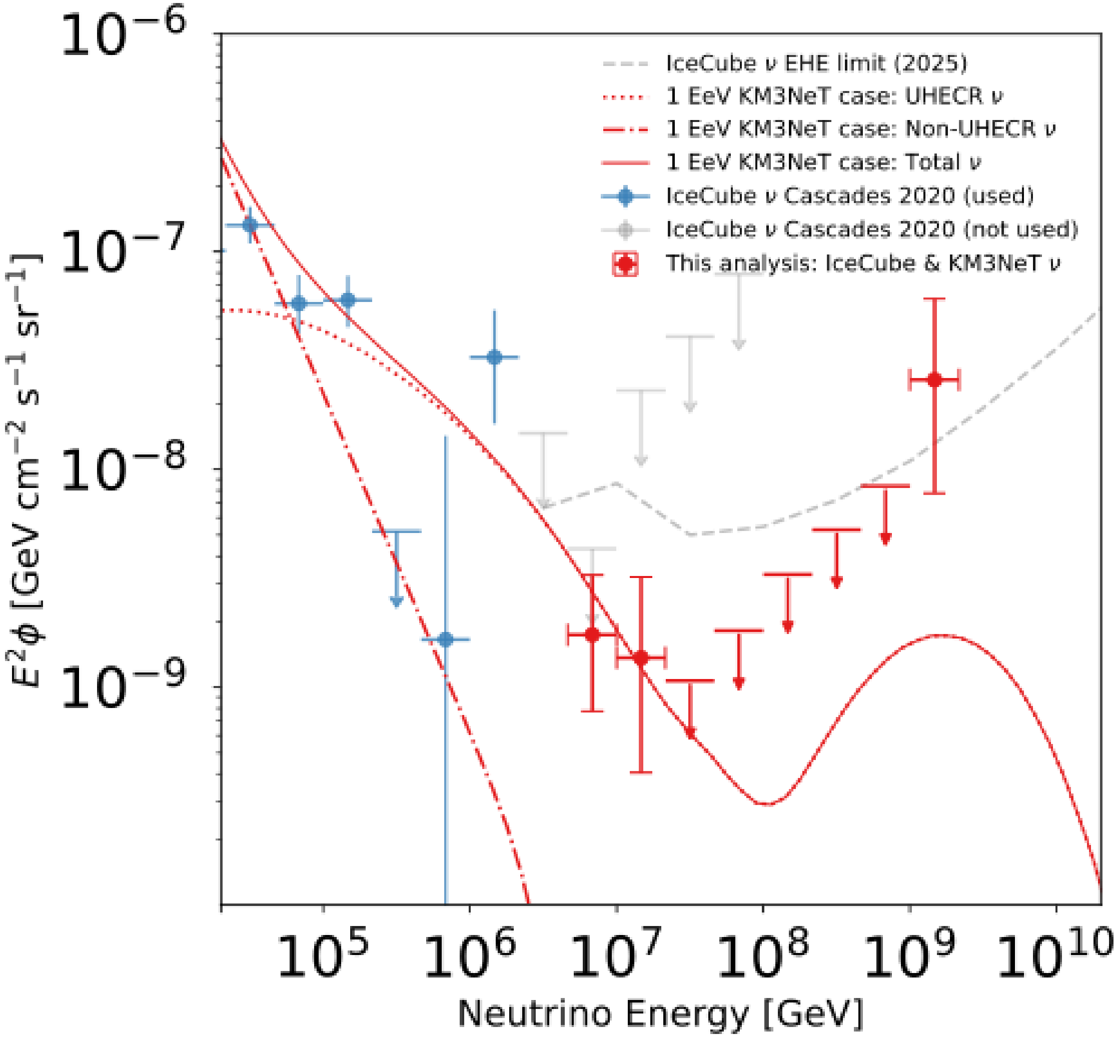
Conclusions

- First extragalactic neutrino source has been identified
- Evidence suggests TeV neutrinos may originate from environments where gamma rays are obscured
- Neutrinos have been detected from our own Galaxy — but their production mechanisms remain uncertain
- Cross-section and inelasticity measurements offer complementary to particle accelerator experiments
- The unexpected ~220 PeV KM3NeT event requires next-generation detectors to resolve tension with IceCube and Auger
- Neutrino observatories support a broad range of interdisciplinary research: Earth tomography, space weather, ocean and glacier science, and more



4.1x 10^-6
4.1x 10^-2
4.1x 10^2
4.1x 10^6
4.1x 10^10
E (eV)
CMB
CIB
COB
CRB
CUB
CXB
CGB
De Angelis & Mallamaci,
Eur.Phys.J.Plus 133 (2018) 324
νI_ν [W m^{-2} sr^{-1}]
ν [Hz]


IceCube ν EHE limit (2025)
100 PeV KM3NeT case: UHECR ν
100 PeV KM3NeT case: Non-UHECR ν
100 PeV KM3NeT case: Total ν
IceCube ν Cascades 2020 (used)
IceCube ν Cascades 2020 (not used)
This analysis: IceCube & KM3NeT ν
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]


IceCube ν EHE limit (2025)
1 EeV KM3NeT case: UHECR ν
1 EeV KM3NeT case: Non-UHECR ν
1 EeV KM3NeT case: Total ν
IceCube ν Cascades 2020 (used)
IceCube ν Cascades 2020 (not used)
This analysis: IceCube & KM3NeT ν
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]

[1]: Nature 638, 376–382 (2025)

KM3-230213A

- From a steady per-flavor isotropic flux of $E^2\Phi = 5.8 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ from $72\,\mathrm{PeV} - 2.6\,\mathrm{EeV}$ ([1]), we expect ~70 events given the analyzed exposure

- The non-observation with IceCube rejects that flux with more than 10σ
- Tension can be reduced for a transient source hypothesis

- Considering a joint fit, the tension for the diffuse hypothesis can be reduced.
- Re-doing the joint fit (described in [1]): Poisson likelihood assuming an E^{-2} spectrum including exposures of IceCube, KM3NeT and Auger, with the observation of $n_{\mathrm{IC}} = 0,\ n_{\mathrm{KM3}} = 1,\ n_{\mathrm{A}} = 0$ gives a best-fit flux of $E^2\Phi = 5.7 \cdot 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ with $\mu_{\mathrm{IC}} = 0.68,\ \mu_{\mathrm{KM3}} = 0.01,\ \mu_{\mathrm{A}} = 0.3$
- The goodness-of-fit p-value using the saturated Poisson likelihood test is 0.4% (2.9σ)