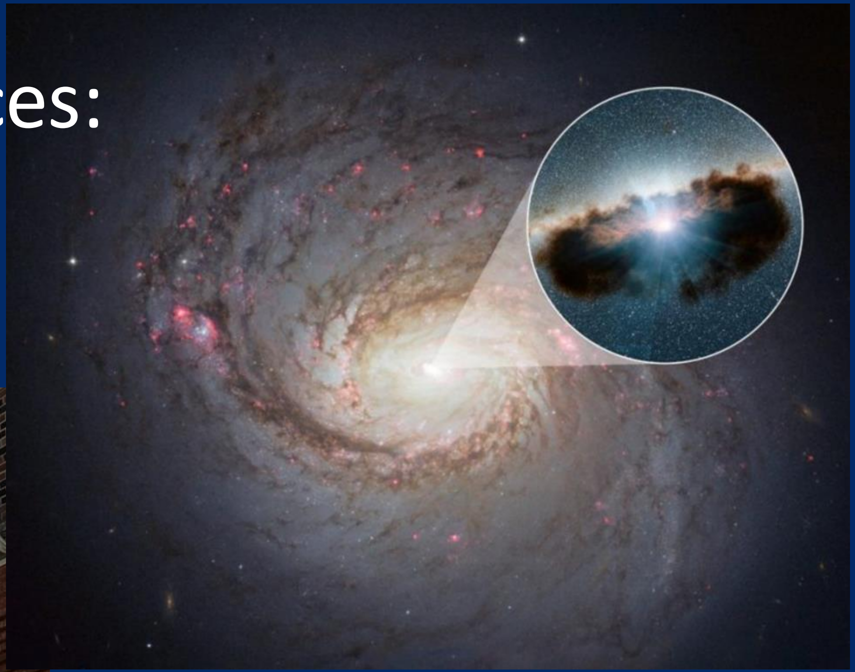
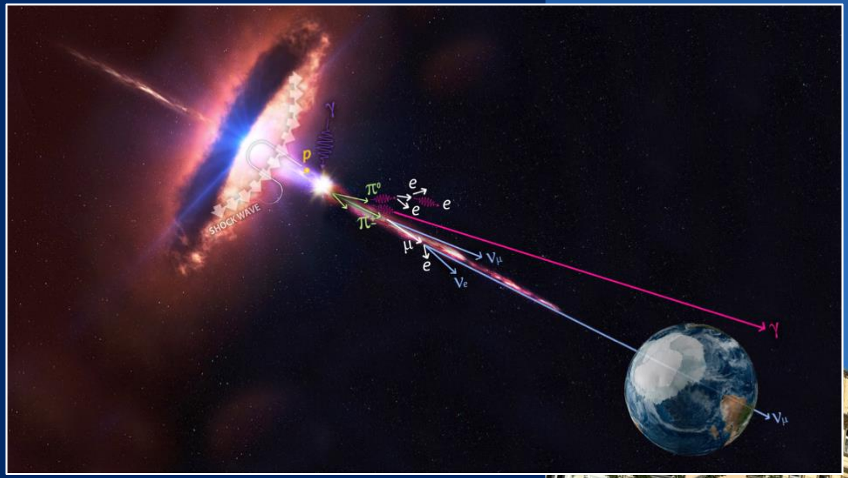
High Energy Neutrinos & Sources: Experimental Results



Joanna Kiryluk

Stony Brook University

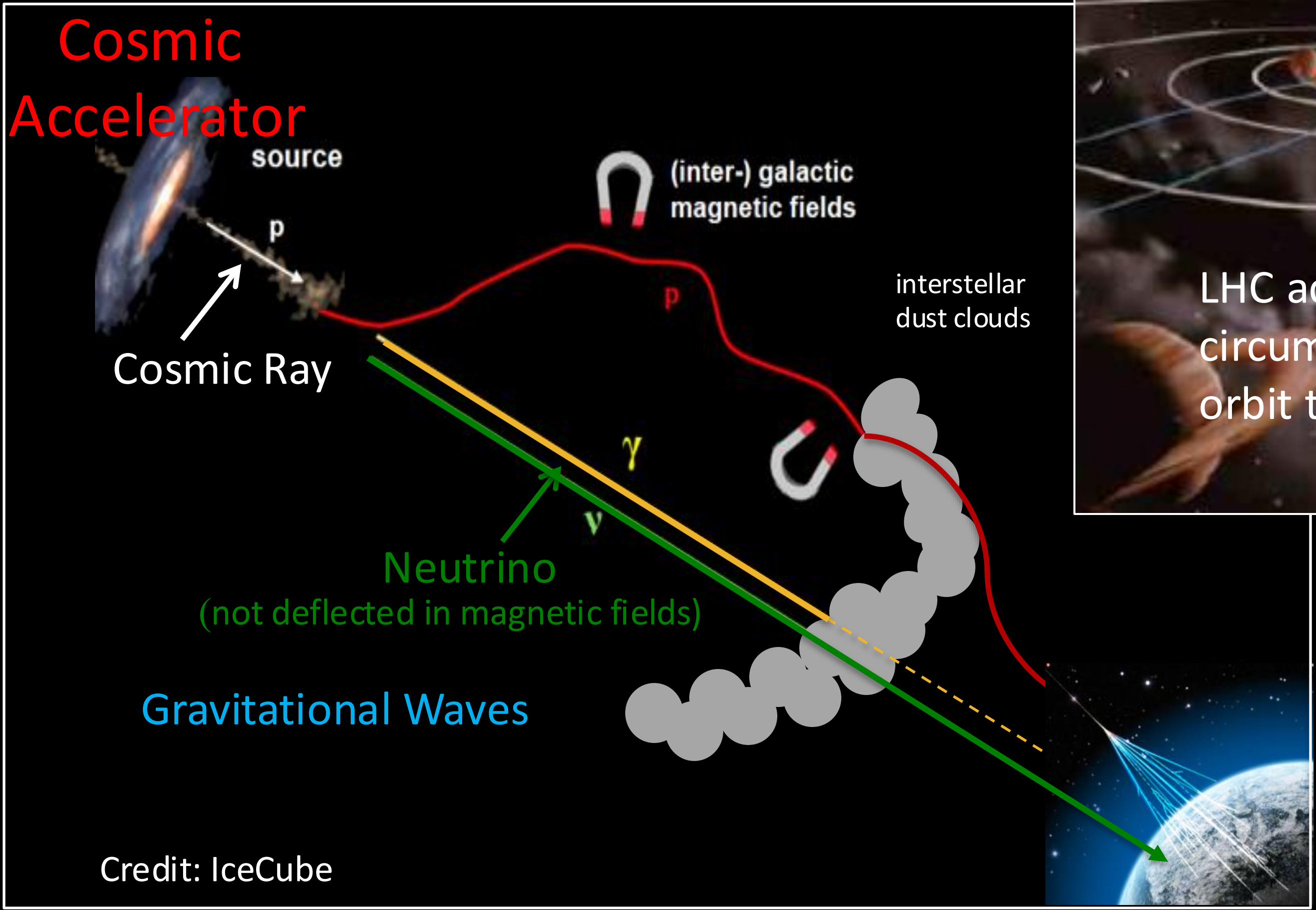


II EU Workshop on Water Cherenkov Experiments on Precision Physics

September 17-19, Cracow, Poland

Why?

Neutrinos as Astronomical Messengers
To Search for Cosmic Accelerator Sources



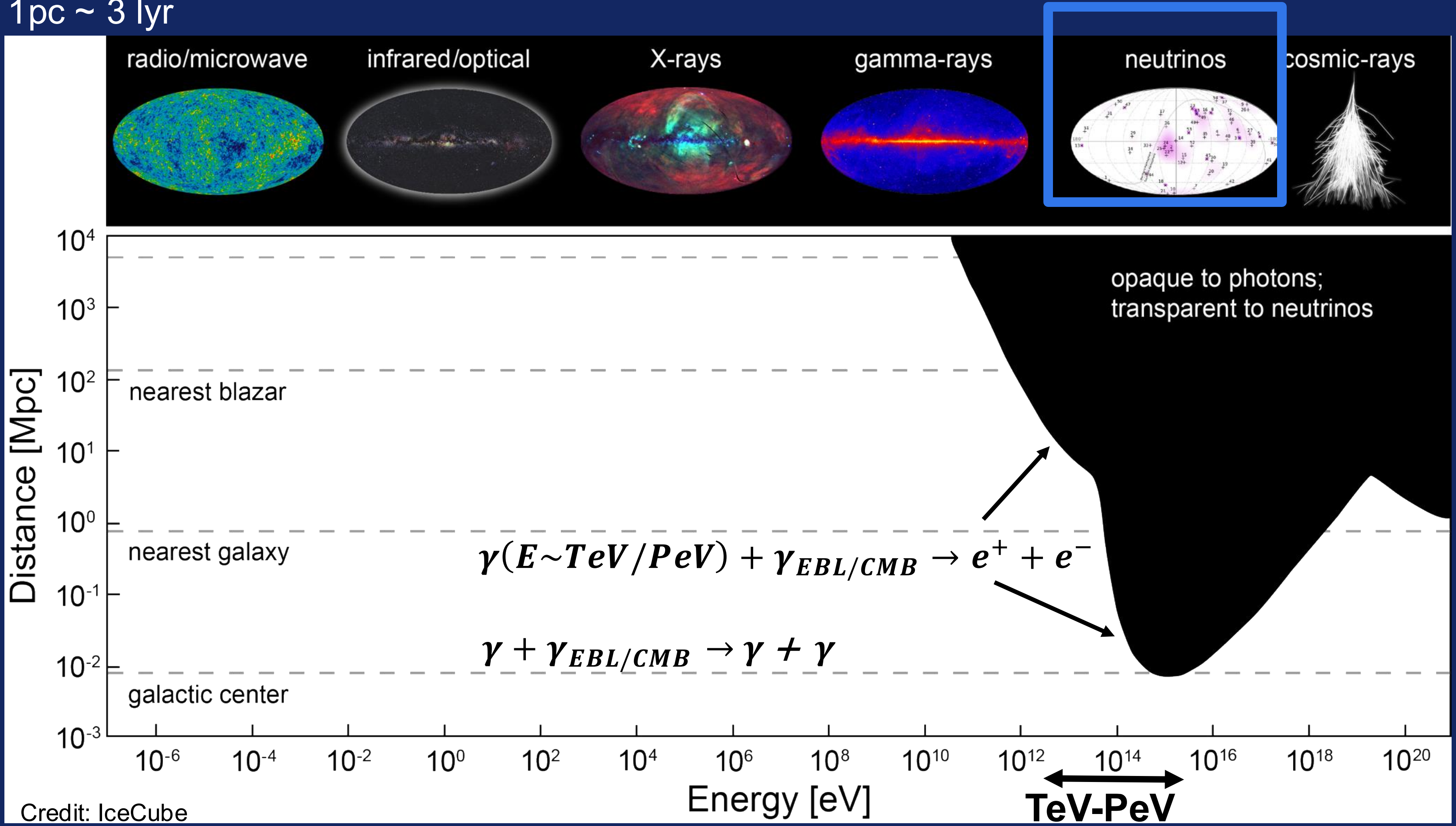
They will help us understand the most extreme physics processes in the Universe

HE Neutrino Astronomy

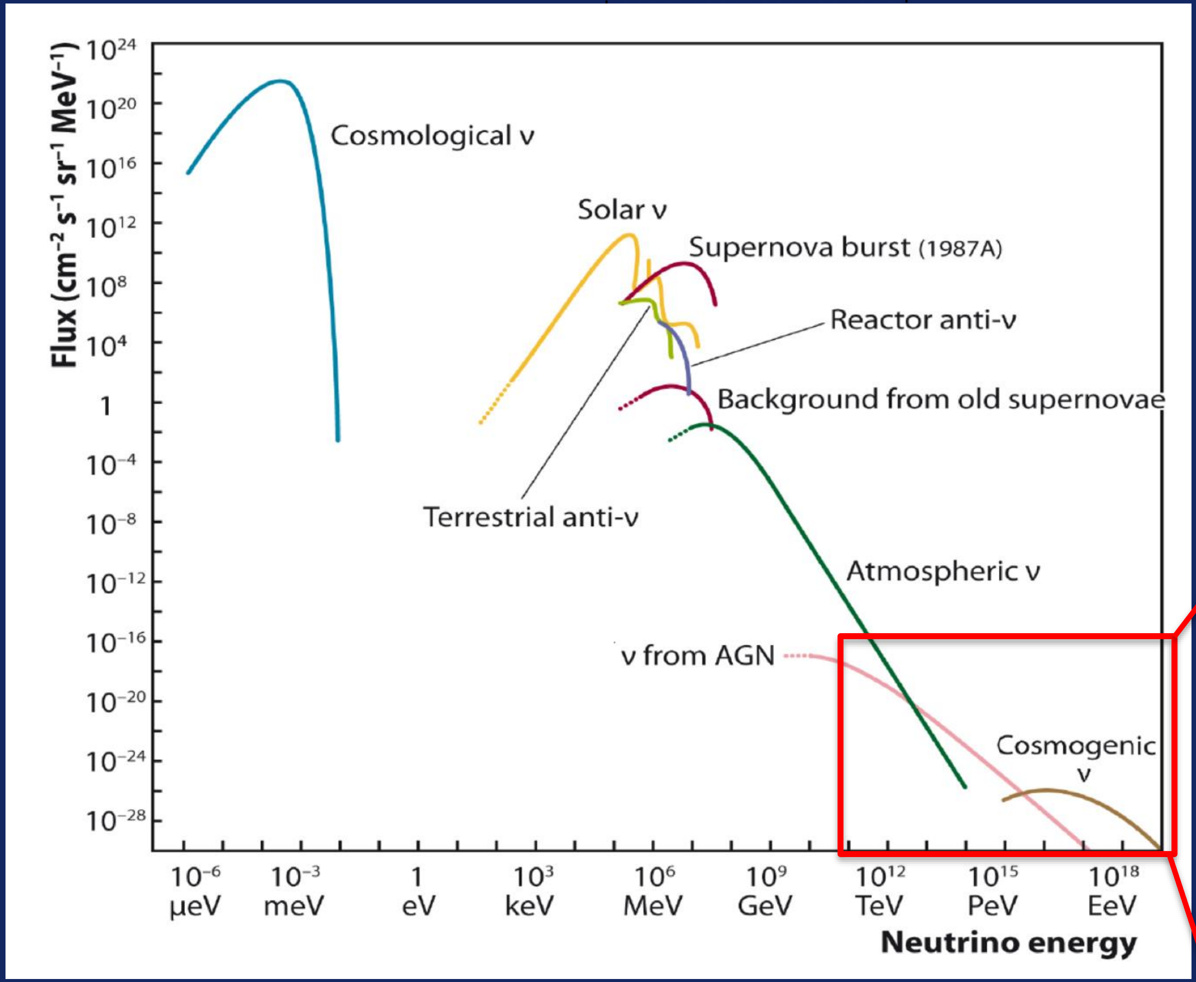
opening a new window to the Universe

+ gravitational waves

1pc ~ 3 lyr



The Expected Neutrinos Fluxes



U. Katz, C. Spiering, Progress In Particle and Nuclear Physics 67.3 (2012) 651

Early estimates: large detection volumes of ~ 1 km^3 or more required to discover astrophysical ν's

- CR spectrum formation
- CR acceleration
  - Fermi mechanism: γ_{CR} ~ 2
- CR propagation γ_{CR} ~ 2.7
- ν benchmark model: γ_ν ~ 2

$\Phi_{CR} \sim E_{CR}^{-\gamma_{CR}}$

$\Phi_{\nu} \sim E_{\nu}^{-\gamma_{\nu}}$

[Fermi acceleration at shock fronts]

- Waxman-Bahcall bound

$$E_\nu^2 \Phi_{\rm WB} \approx 3.4 \times 10^{-8}\ {\rm GeV/cm^2 sr\ s}$$

Two neutrino production mechanisms at source:

- pp (hadro-production)

$$p + p \to \pi + \ldots \to \nu + \ldots$$

hadro production

- pγ (photo-production)

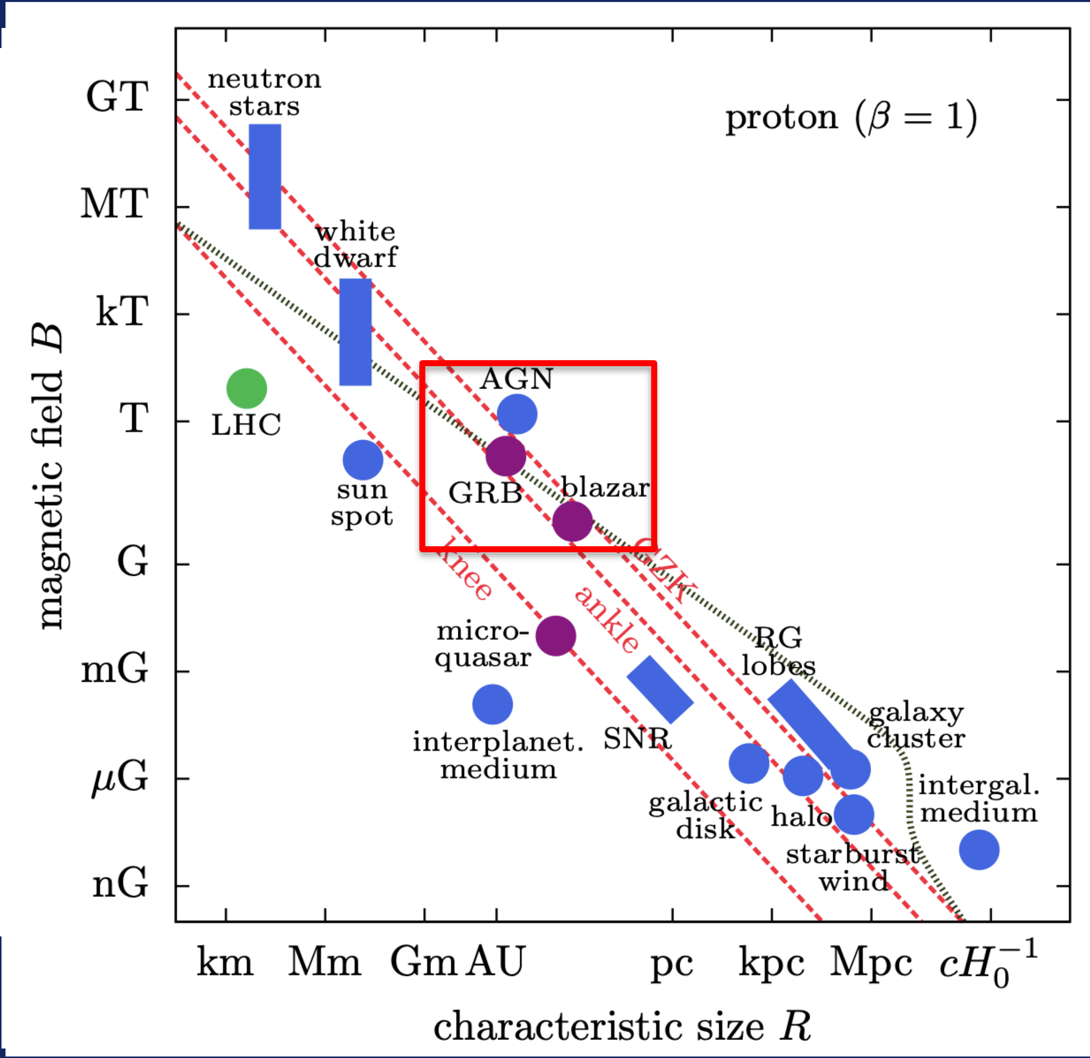
$$p + \gamma \to \Delta \to (p + \pi \to p + \gamma\gamma)$$
$$\to n + \pi \to n + \nu + \ldots$$

photo production

$E_\nu \sim E_p/20 \sim E_\gamma/2$

$$\pi^+ \to \mu^+ + \nu_\mu \to (e^+ + \nu_e + \overline{\nu_\mu}) + \nu_\mu$$

Possible Sources of Accelerated Cosmic Rays: “Hillas Plot”



IceCube: Advances in Space Research 62 (2018) 2902

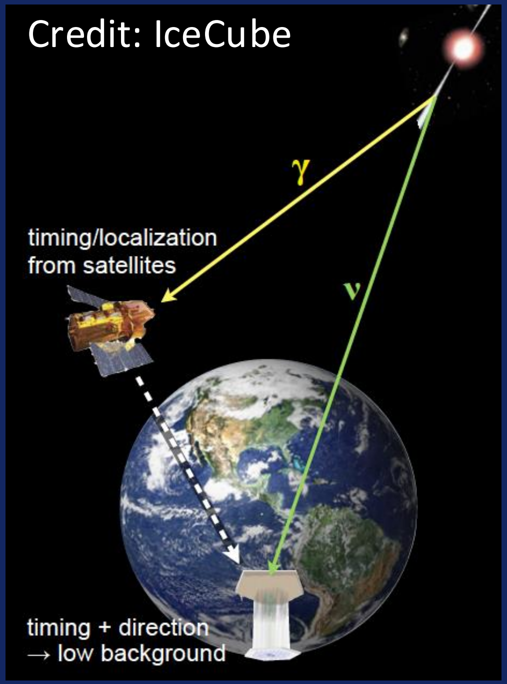
$$E^{CR} < Ze\beta c \left({}^{R}/_{[kpc]} \right) \left({}^{B}/_{[\mu G]} \right)$$

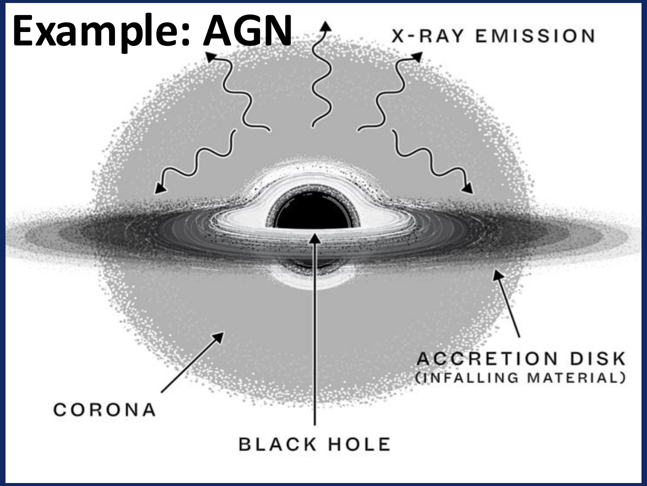
Gyro-radius in the accelerator: $r_L < R$

Source classes as function of

- the magnetic field strength B &
- characteristic size R

Possible Sources of Accelerated Cosmic Rays and secondary γ-rays and ν's





C.A.Argüelles et al, *Phys.Rev.X* 15 (2025) 3, 030501

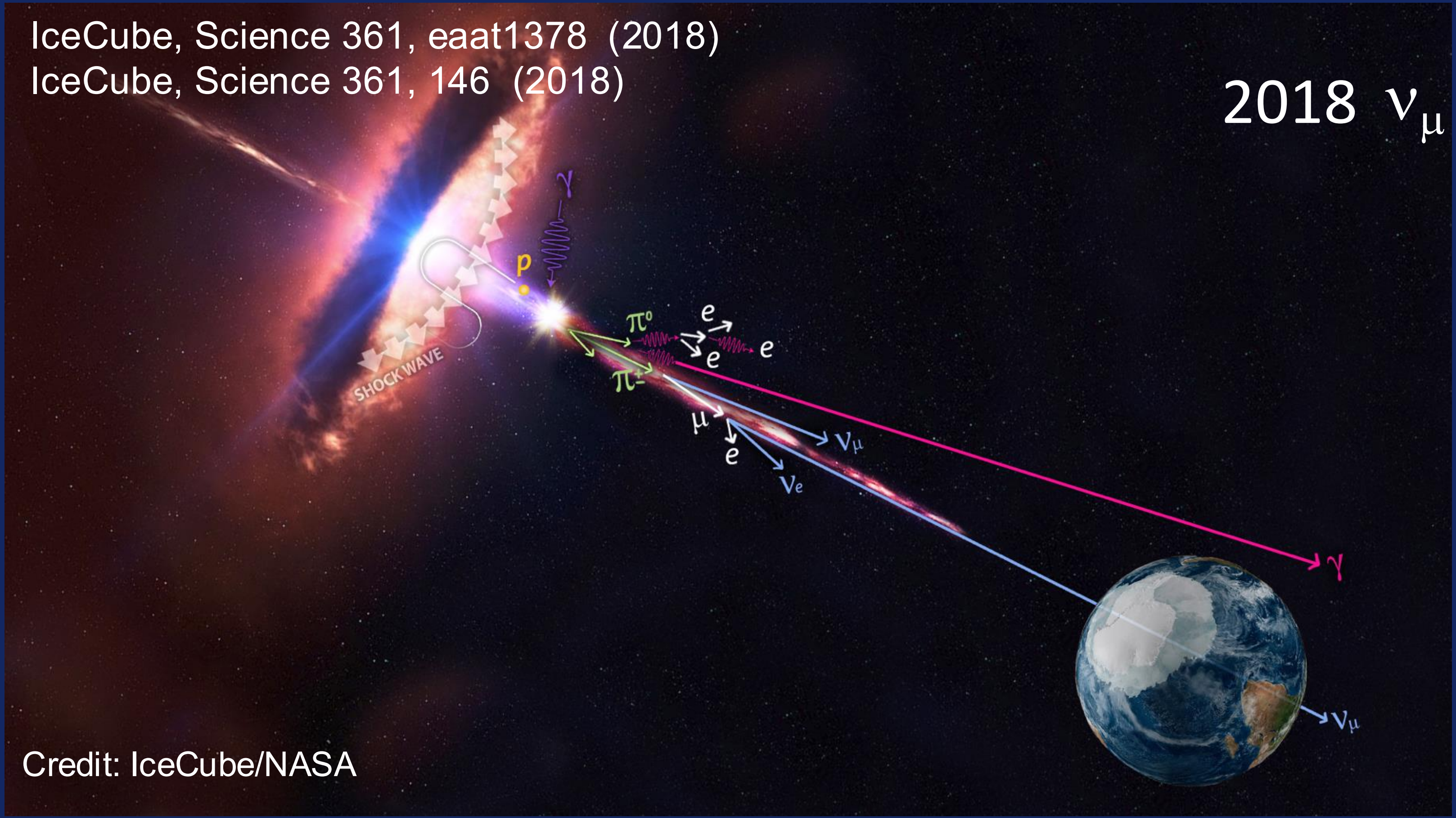
Neutrinos	γ-rays	Galactic / Extra-galactic Source type
Yes		**Hadron progenitor**
	Yes	Low γ-ray absorption
	No	**High γ-ray absorption**

Hadron progenitor:

- $\mathrm{p} + \gamma \rightarrow N + \pi$
- $\mathrm{p} + \mathrm{p} \rightarrow p + N + \pi$

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+ + \nu_e + \bar{\nu}_\mu) + \nu_\mu$$
$$\pi^0 \rightarrow \gamma + \gamma$$

Breakthrough in HE Neutrino Astronomy:
IceCube Neutrinos Point to Long-Sought Cosmic Ray Accelerator

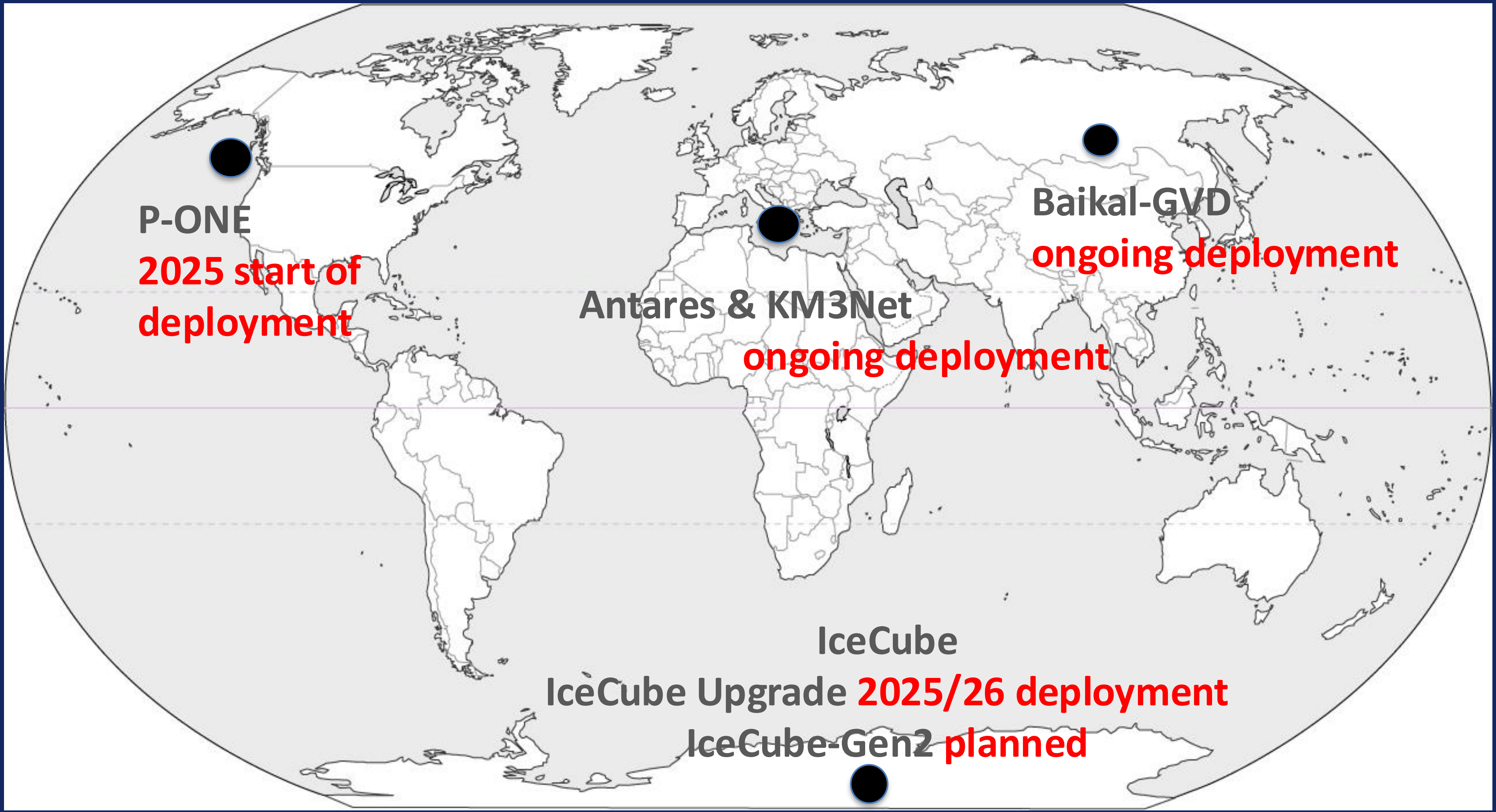


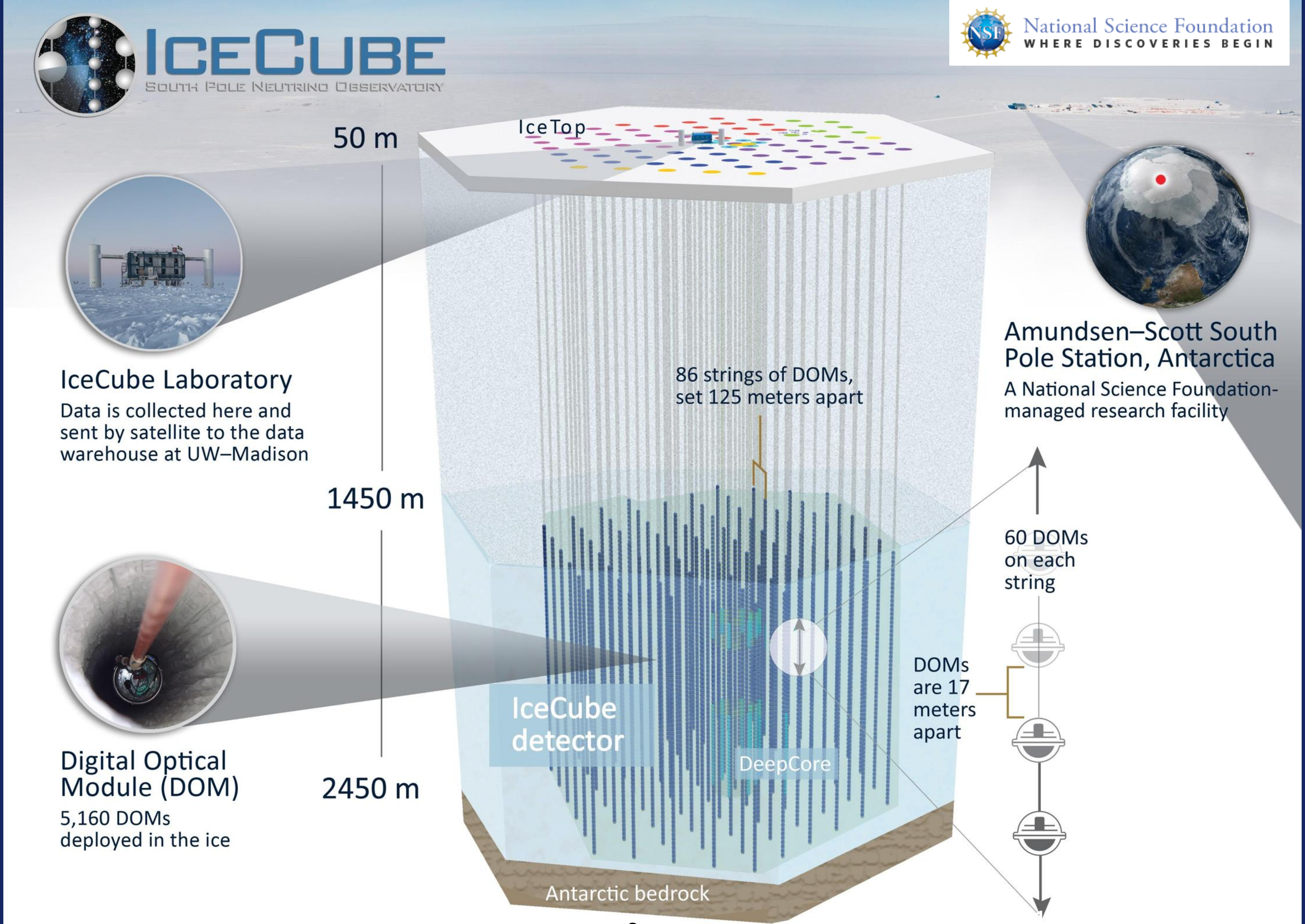
A blazar TXS 0506+056 emitting
very high energy neutrinos and γ-rays

Breakthrough in HE Neutrino Astronomy:
IceCube Neutrinos Point to Long-Sought Cosmic Ray Accelerator

A Galaxy NGC 1068 emitting high energy neutrinos and no γ- rays

Optical High Energy Neutrino Observatories





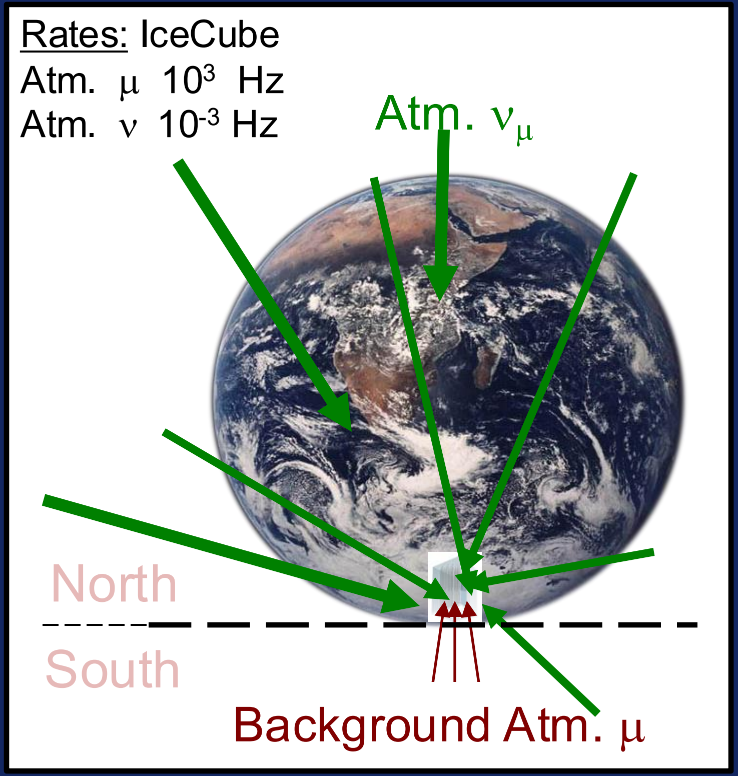
Credit: IceCube/NSF

Data taking with 1km^3 detector, since 2011

Neutrino rates

$$\frac{dR}{dE_\nu} = \mathrm{A_{eff}}(\mathrm{E_\nu}, \theta) \times \frac{dN_\nu}{dE_\nu}(E_\nu, \theta)$$

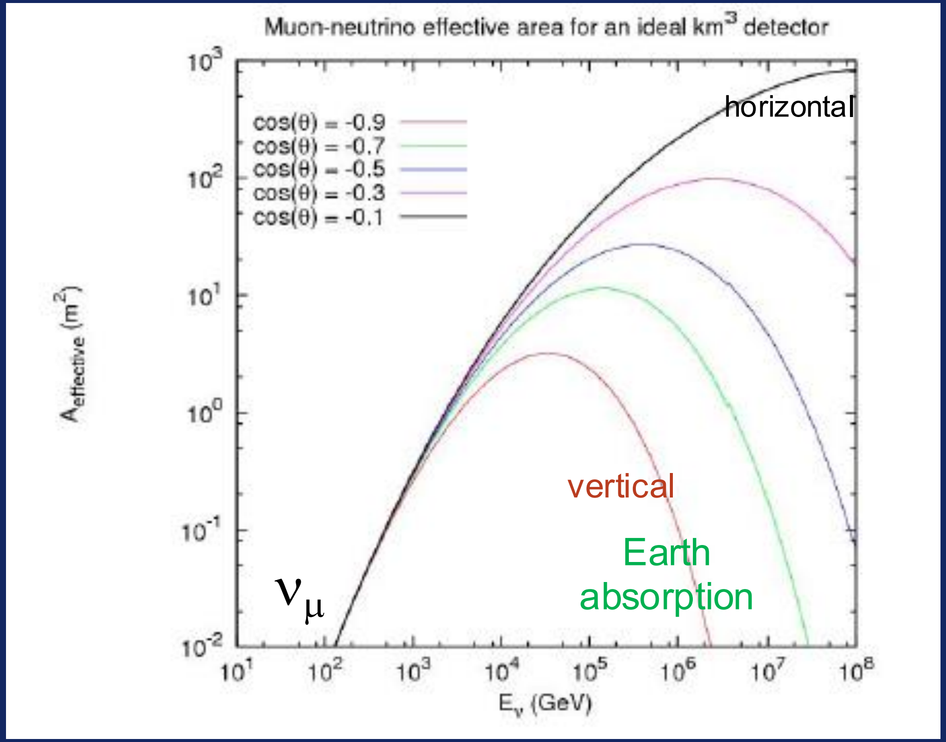
ν flux (energy spectrum)



Example: muon neutrino

$$\mathrm{A_{eff}}(\mathrm{E_\nu}, \theta) = \epsilon(E_{th}, \theta) \cdot \mathrm{A}(\theta) \cdot P(E_\nu, E_{th}) \cdot e^{-\sigma_\nu(E_\nu) N_A X(\theta)}$$

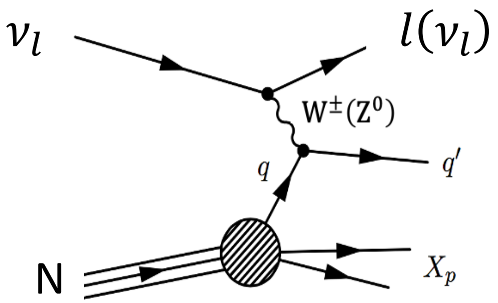
ν interaction Earth absorption



High Energy Neutrino and anti-neutrino interactions

Deep Inelastic Scattering

- $\nu_l + p/A \rightarrow l^- + X$
- $\bar{\nu}_l + p/A \rightarrow l^+ + X$



$$Q^2 = -q^2$$

$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E_\nu}$$

$$x = \frac{Q^2}{2q \cdot p} = \frac{Q^2}{2M_N y E_\nu}$$

$$W^2 = (p+q)^2 = M_N^2 + Q^2\left(\frac{1}{x} - 1\right)$$

$$s = (k+q)^2 = M_N^2 + 2M_N E_\nu$$

$\nu_l + p$

$$\sigma_{CC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[q + (1-y)^2 \bar{q}\right]$$

$$\sigma_{NC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_Z^2}{Q^2 + M_Z^2}\right)^2 \left[q^0 + (1-y)^2 \bar{q}^0\right]$$

Extrapolation to small x

Small at $Q^2 \gg M_{W,Z}^2$

Small at small Q^2

$$q^0 = \frac{u+d}{2}\left(L_u^2 + L_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(R_u^2 + R_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$$\bar{q}^0 = \frac{u+d}{2}\left(R_u^2 + R_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(L_u^2 + L_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$L_u = 1 - 4/3 \cdot x_W$, $L_d = -1 + 2/3 \cdot x_W$, $R_u = -4/3 \cdot x_W$

$R_d = 2/3 \cdot x_W$ where $x_W = \sin^2\theta_W = 0.226$.

$G_F = 1.17 \times 10^{-5}\,\mathrm{GeV}^{-2}$ GeV $M_N = 0.938$ GeV $M_W = 80.398$ GeV $M_Z = 91.187$ GeV

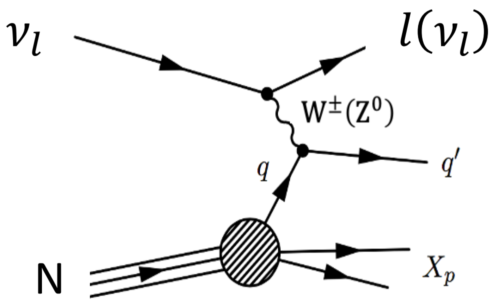
Beyond LO, at ultra HE a change of cross section expected, e.g.

- at large gluon densities, the saturation region,
- due to non-perturbative QCD effects such as topological charge transitions

High Energy Neutrino and anti-neutrino interactions

Deep Inelastic Scattering

- $\nu_l + p/A \rightarrow l^- + X$
- $\bar{\nu_l} + p/A \rightarrow l^+ + X$



$$Q^2 = -q^2$$

$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E_\nu}$$

$$x = \frac{Q^2}{2q \cdot p} = \frac{Q^2}{2M_N y E_\nu}$$

$$W^2 = (p+q)^2 = M_N^2 + Q^2\left(\frac{1}{x} - 1\right)$$

$$s = (k+q)^2 = M_N^2 + 2M_N\, E_\nu$$

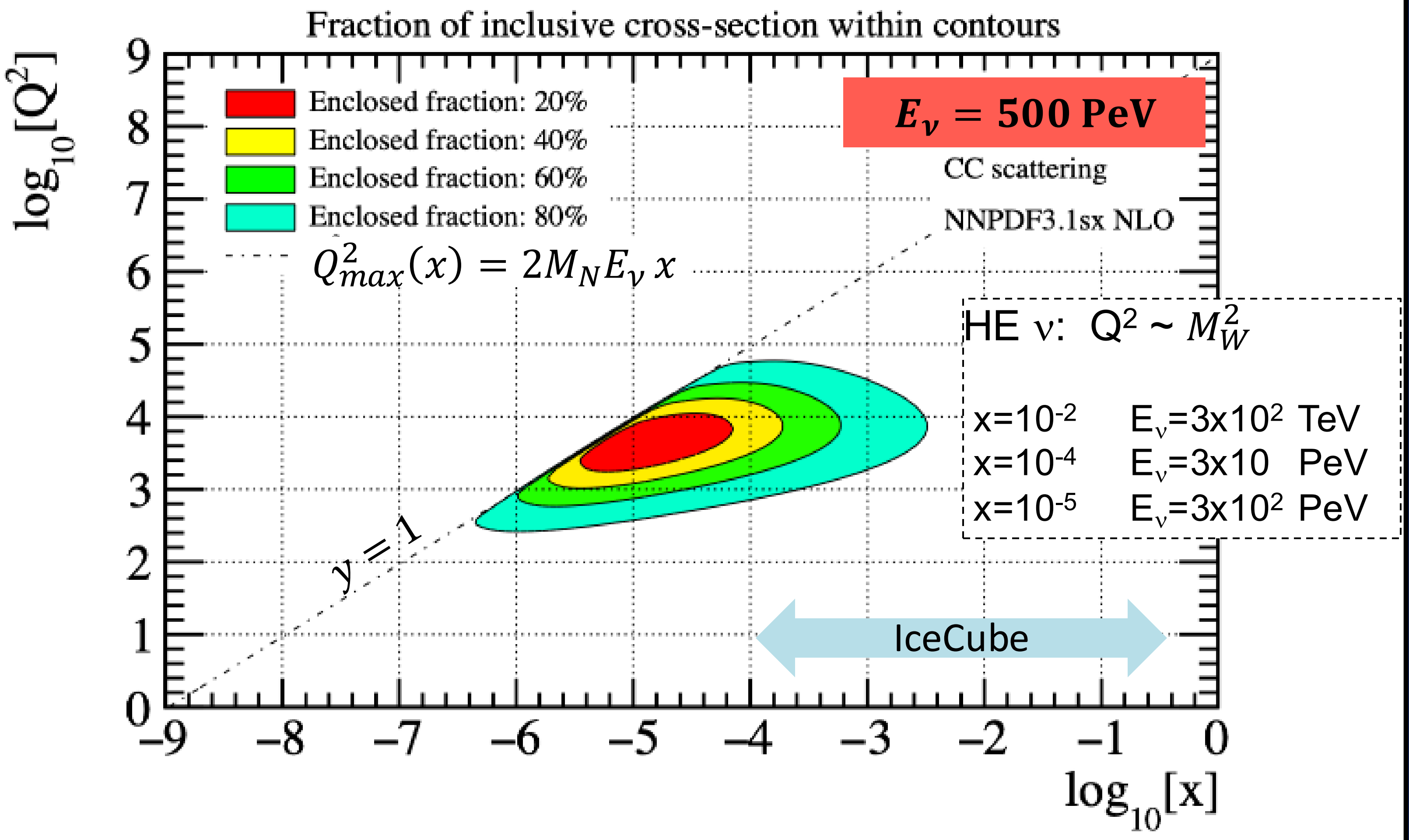
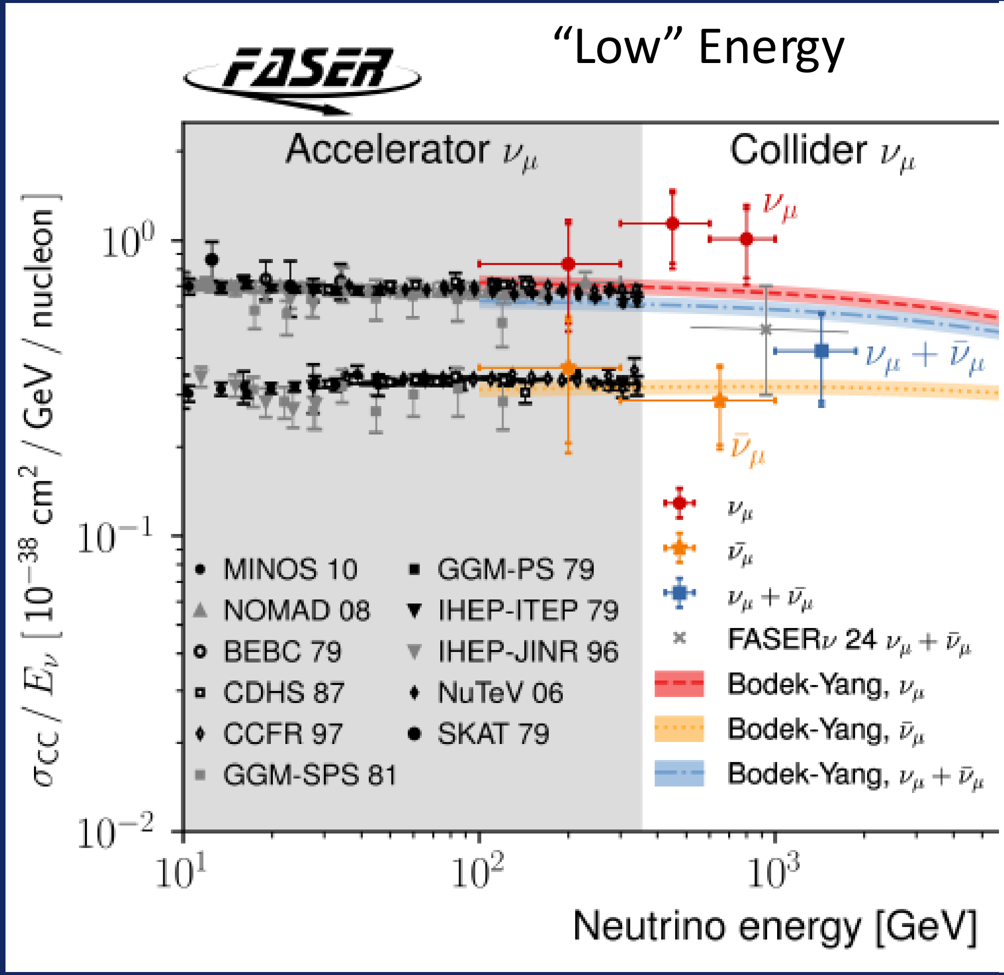
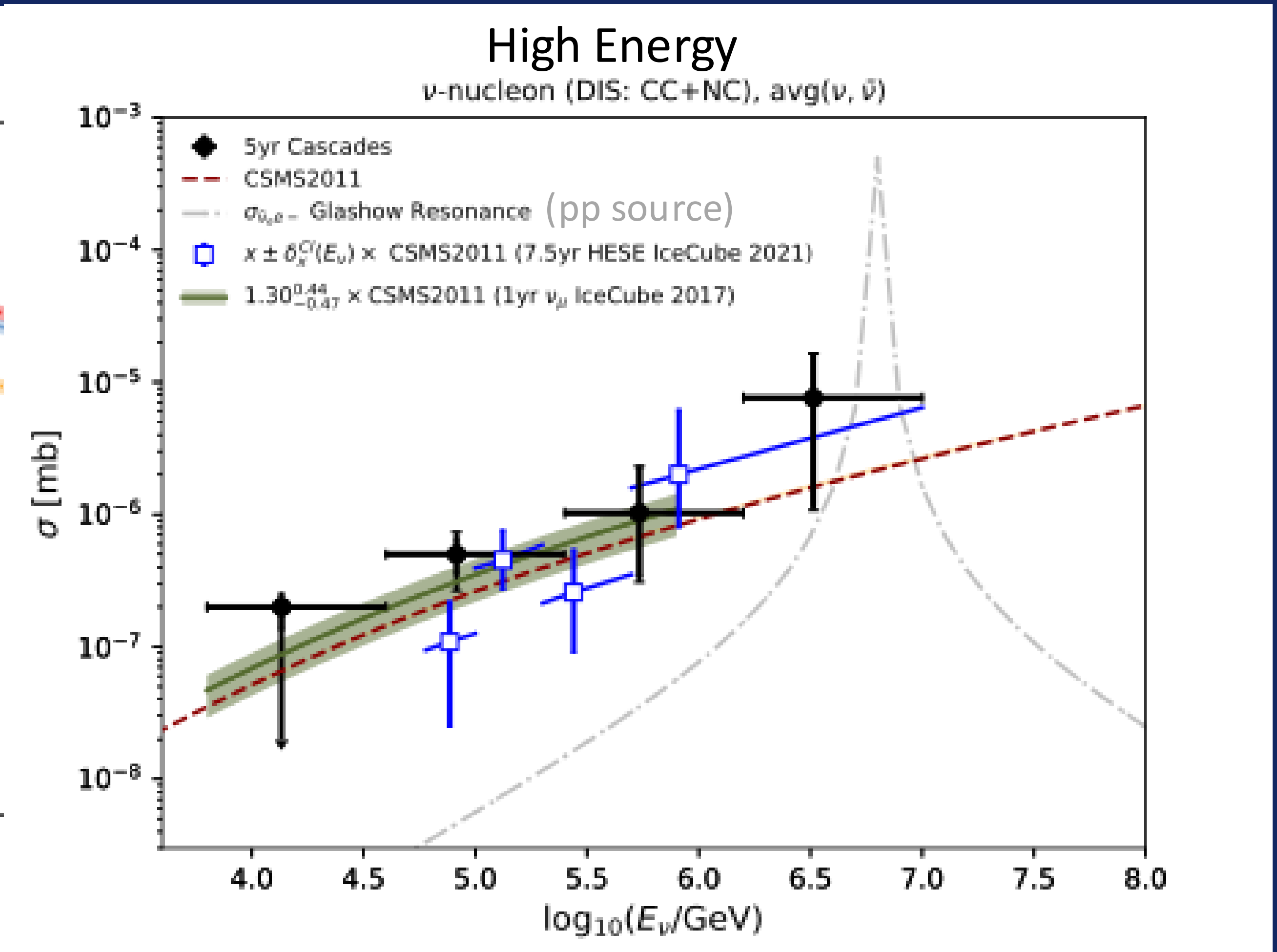


Fig. from: V. Bertone et.al., JHEP01, 217 (2019)

Neutrino-Nucleon Cross Section Results for 10 GeV < E_ν < 10 PeV





FASER, Phys.Rev.Lett. 133 (2024) 2, 021802

1y ν_μ: IceCube: Nature 551 (2017) 596
5y Cscd: Y. Xu PhD thesis Stony Brook U. (2019); arXiv:1809.06782 [hep-ex]
7.5y HESE: IceCube, Phys. Rev. D104, 022001 (2020)

Results consistent with Standard Model within current precision.

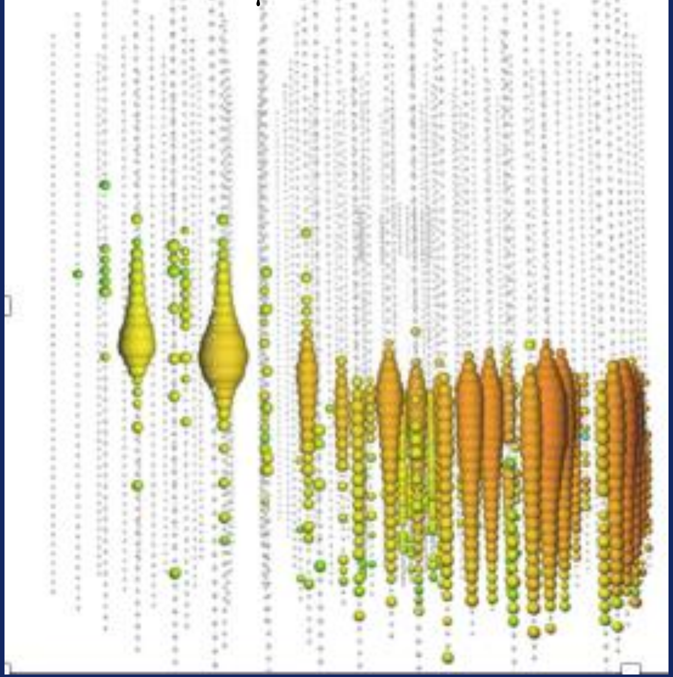
IceCube High Energy Neutrinos (observed)

2014

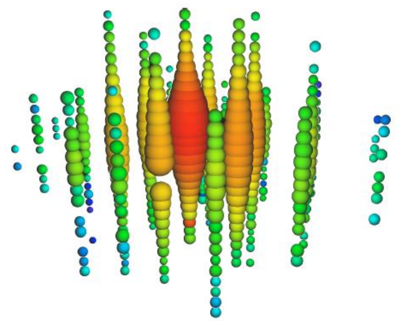
deposited energy:
2.6 ± 0.3 PeV
DEC=11.42° RA=110.63°

Median muon energy: 4.5 ± 1.2 PeV
Median ν energy: 8.7 PeV

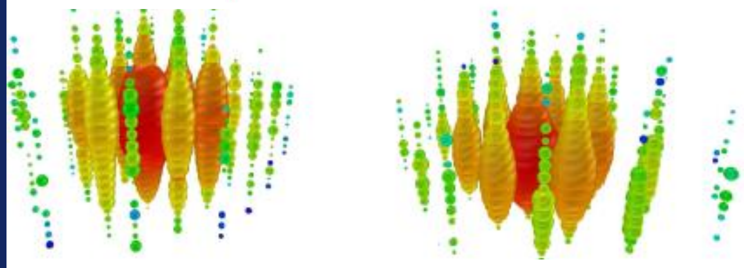
Muon track, ν_μ candidate (p= 87.7%)



IceCube: Astrophys.J. 833 (2016) 1, 3

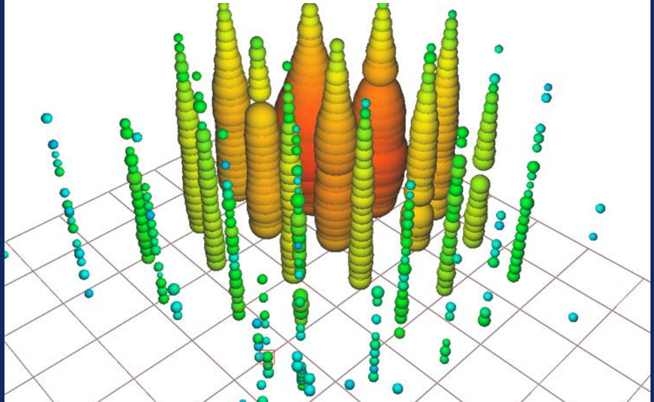


Discovery
E_ν ~ PeV
2011-2012
cascades



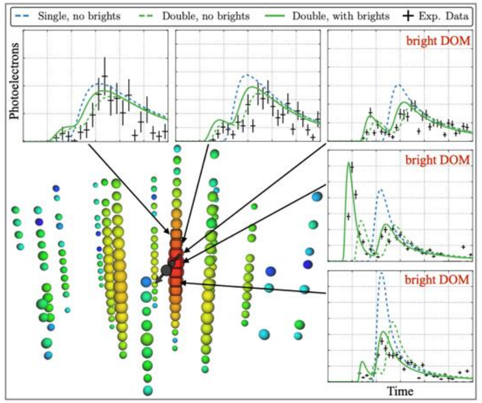
IceCube, Phys.Rev.Lett. 111 (2013) 021103
IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)

$\overline{\nu}_e$ candidate
partially contained cascade
deposited energy: 5.9±0.18 PeV



IceCube: Nature 591 (2021) 7849, 220;
Nature 592 (2021) 7855, E11 (erratum)

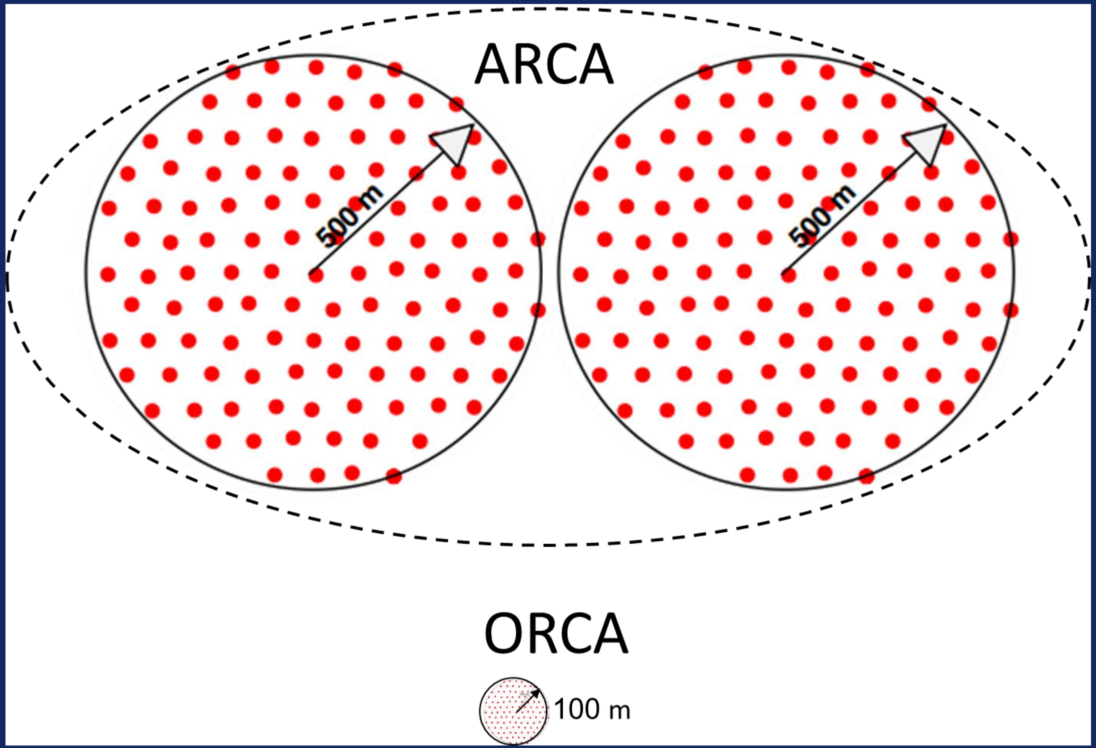
Double cascade & double pulse, ν_τ **candidate**



deposited energy 90 TeV

IceCube,Eur. Phys. J. C (2022) 82:1031
Phys.Rev.Lett. 132 (2024) 15, 151001

KM3Net Detector: ARCA
for TeV – PeV neutrino detection



Location: Mediterranean Sea

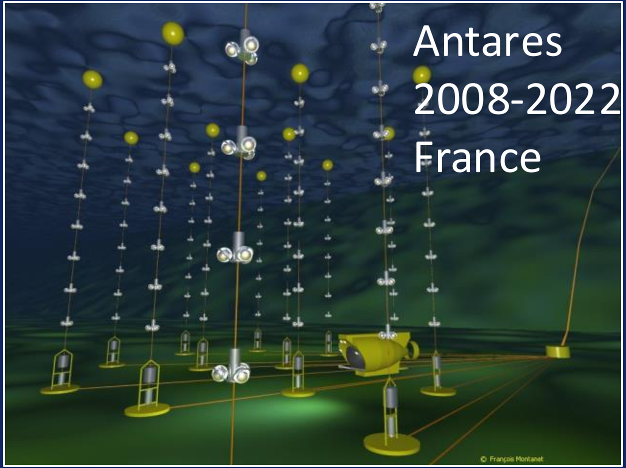
Source: https://www.km3net.org/research/detector/arca-and-orca-detector/

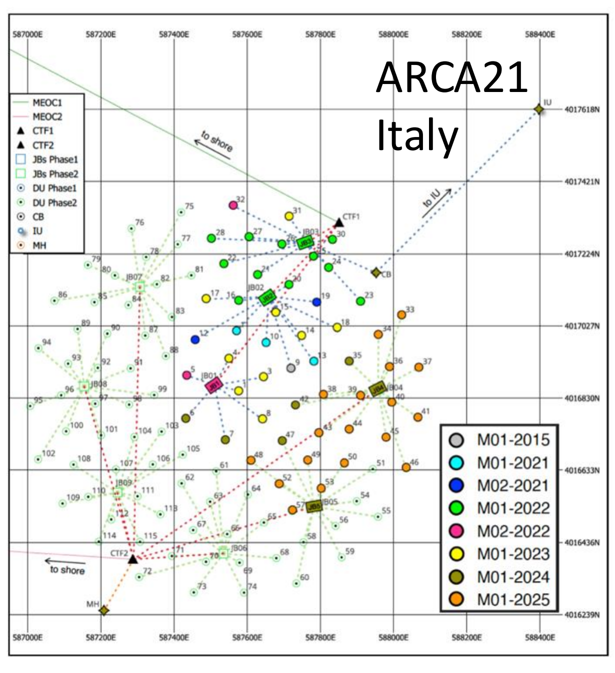
Goal:
- 230 Detection Units (DU)
- 4140 optical modules
- 128340 PMTs
- > 5 km^3 volume

Spacing:
- 36m vertical spacing
- 90 m horizontal spacing

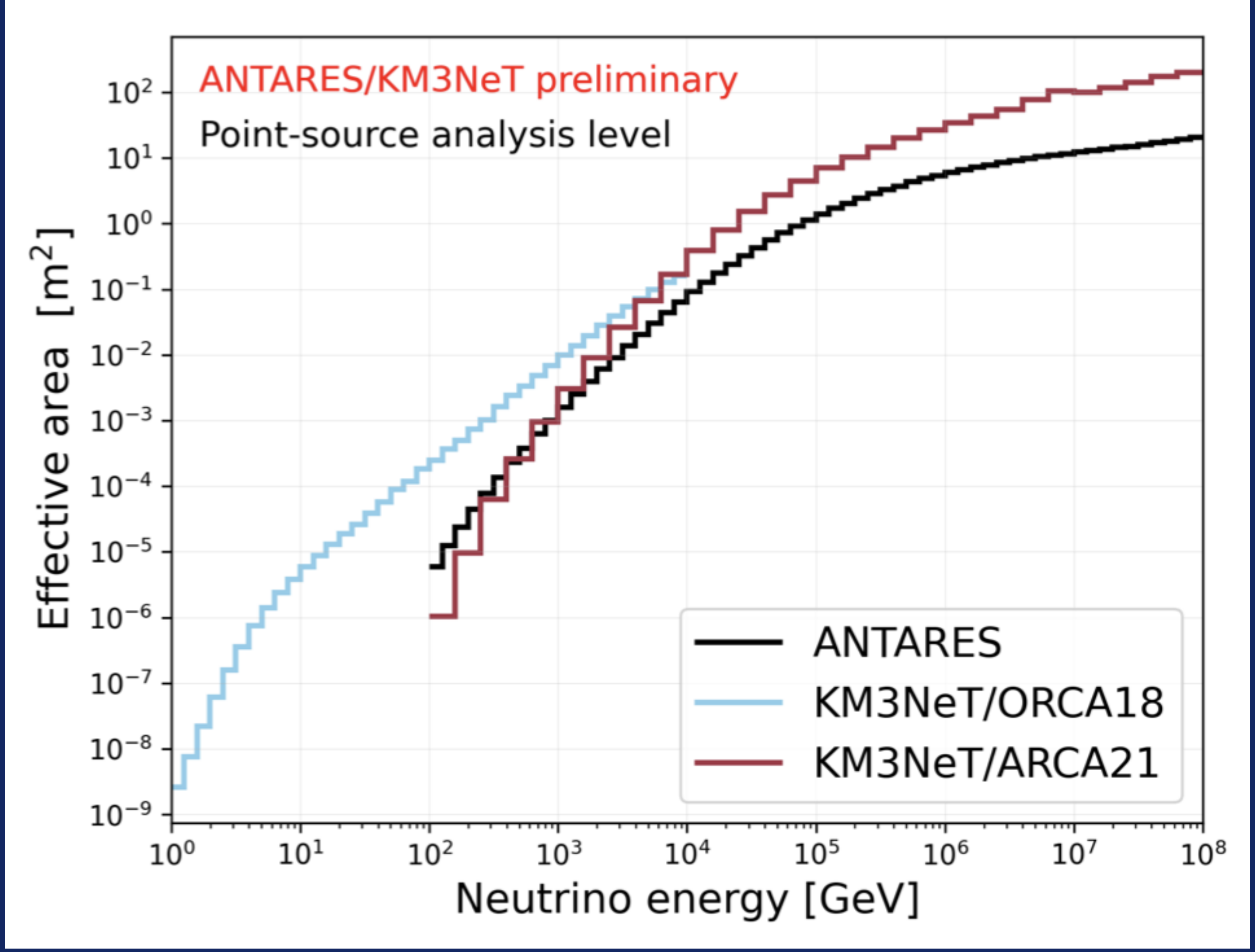
Construction status:
- 51 DU deployed
- 44% of the 1st building block

KM3Net Detector: ARCA
for TeV – PeV neutrino detection



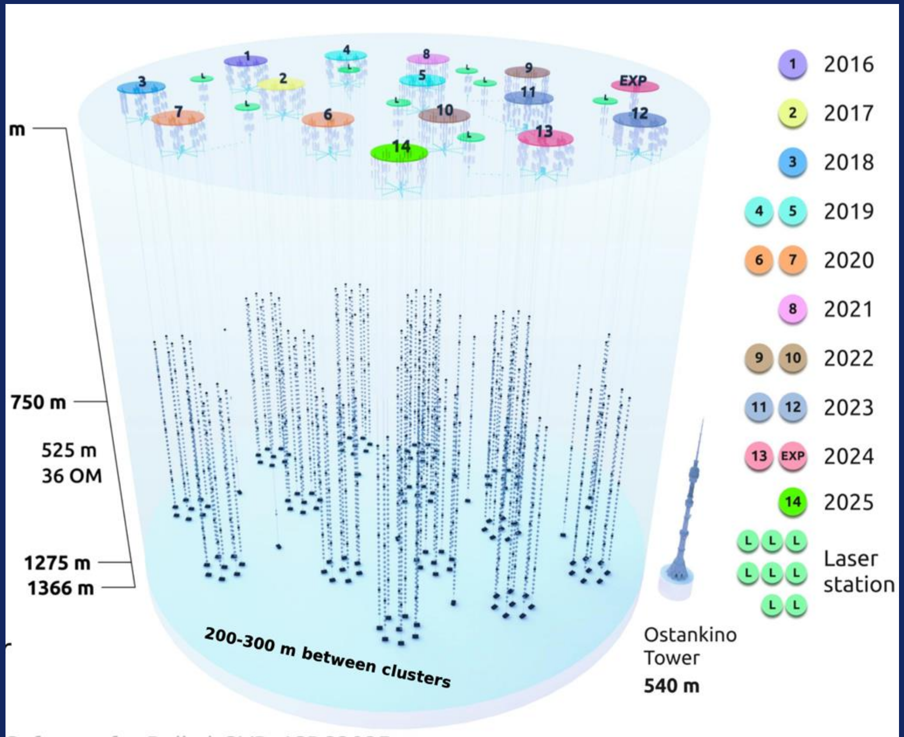


Current layout of the 1st building block



KM3Net, D. Dornic, ICRC2025

Baikal-GVD Detector
for TeV – PeV neutrino detection



Safronov for Baikal-GVD, ICRC2025

Location: Lake Baikal

1998: NT-200 (192 modules)
2004/5: NT200+
>2016 Baikal-GVD/NT-1000

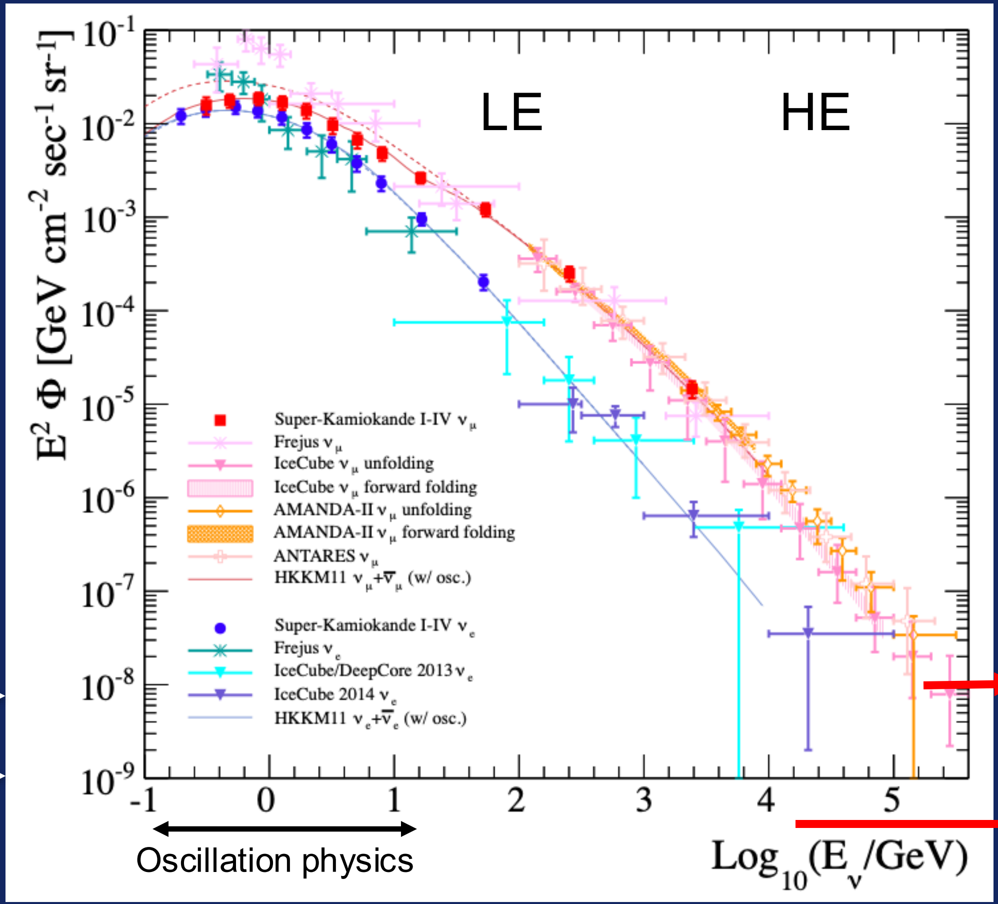
Goal:
- 6000 optical modules
- 1 km^3 volume

Water transparency:
- 21-23 m absorption length
- 60-80 m scattering length

Spacing:
- 15 m vertical spacing
- 200-300 m between clusters

Construction status:
- 14 clusters deployed, 117 strings
- 1 cluster = 8 strings, arranged in 60 m radius
- 1 string = 10 optical modules
- 4212 optical modules
- 0.7 km^3

Atmospheric Neutrino Fluxes
Summary of world measurements



Super-Kamiokande, Phys. Rev. D **94**, 052001

10—100 events per year for fully efficient 1 km^3 detector

$$E_\nu^2 \Phi_{WB} = 3.4 \times 10^{-8}$$

astrophysical ν's

Conventional ν's

- ν_μ and ν_e from π/K decays
- flux peaked at horizon; temp. variations
- sensitive to CR composition

Prompt ν's

- from D/B decays
- short lifetime: interact/lose energy before decay ($\tau \sim 10^{-12}$s)
- ν flux isotropic
- equal parts ν_μ and ν_e , ν_τ negligible (D_s decays)
- spectrum approx. $E^{-2.8}$

- At HE ν measured fluxes consistent with conventional neutrino fluxes.
- No prompt component has been observed yet.
- Atm. ν's are background to astrophysical neutrinos.

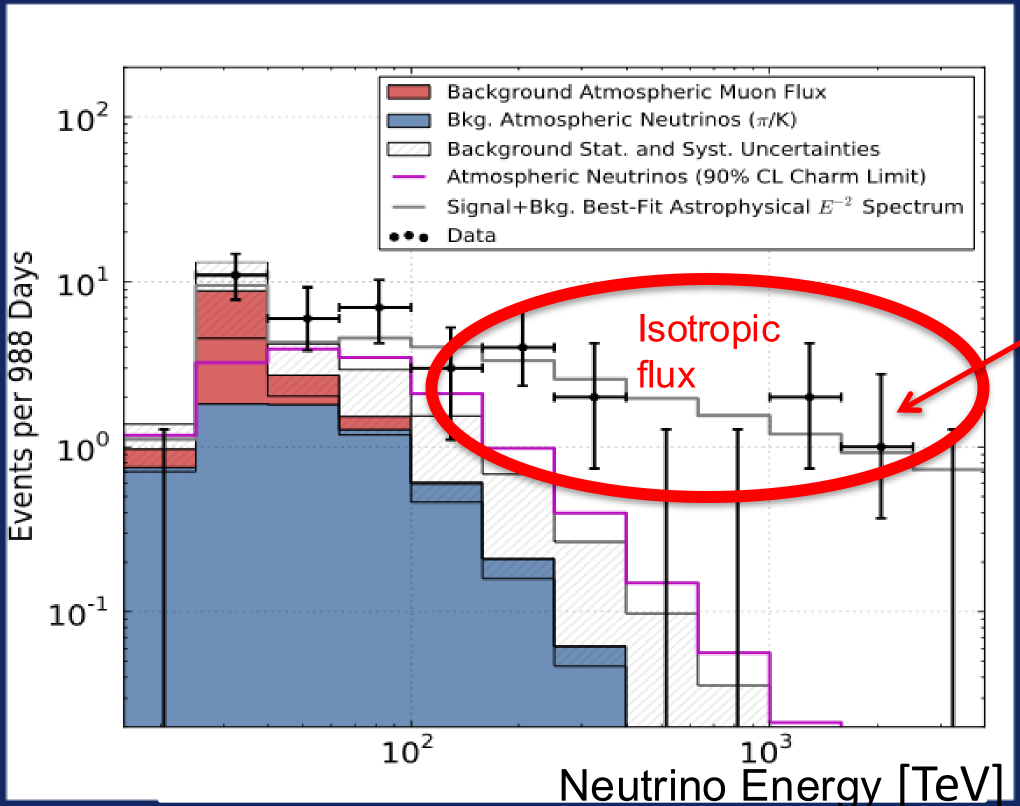
Diffuse ν Flux
Single Power Law

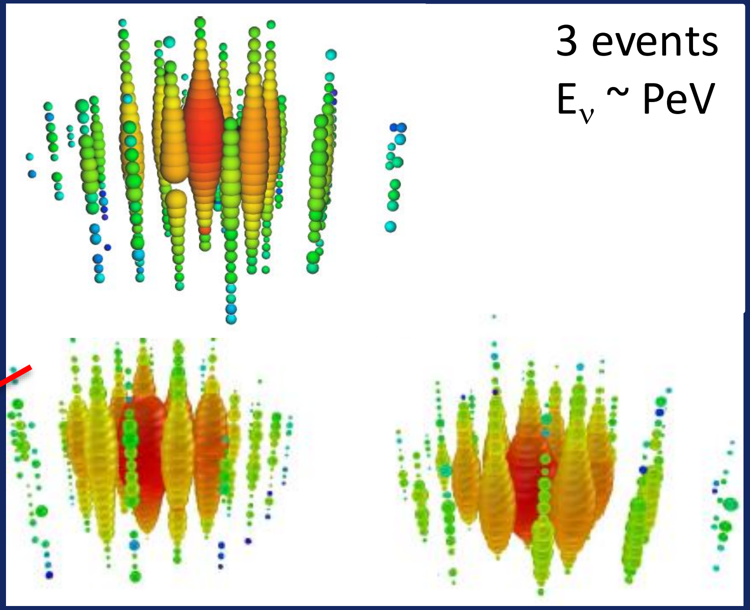
$$\Phi_\nu = \phi \times \left(E_\nu / 100\,\mathrm{TeV}\right)^{-\gamma}$$

and Beyond

IceCube's discovery of PeV ν of astrophysical origin (2013)

- HESE: High Energy Starting Events (tracks + cascades)
- all neutrino flavors, all sky
- Veto-based event selection method





IceCube, Phys.Rev.Lett. 111 (2013) 021103
IceCube, Science 342, 1242856 (2013)
IceCube, Phys. Rev. Lett. (2015)
IceCube, Phys. Rev. D 104 (2021) 022002

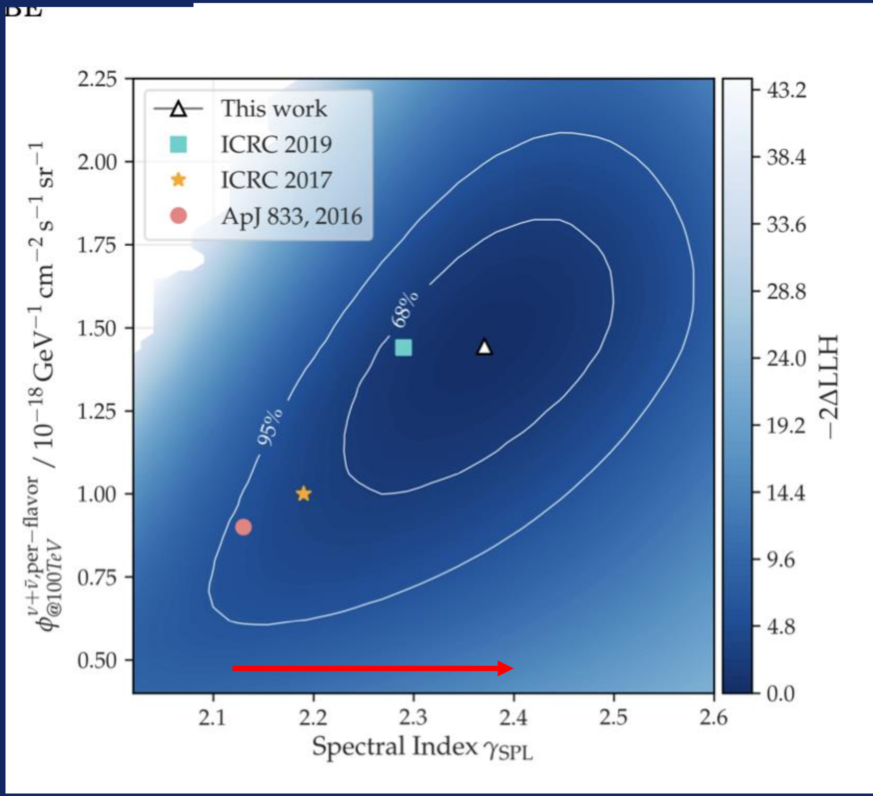
- Likelihood fit analysis method, performed for E > 60 TeV
- Flux isotropic (extragalactic)
- Single power law fit 7.5 yrs results: soft best-fit spectral index $\gamma = 2.9 \pm 0.2$

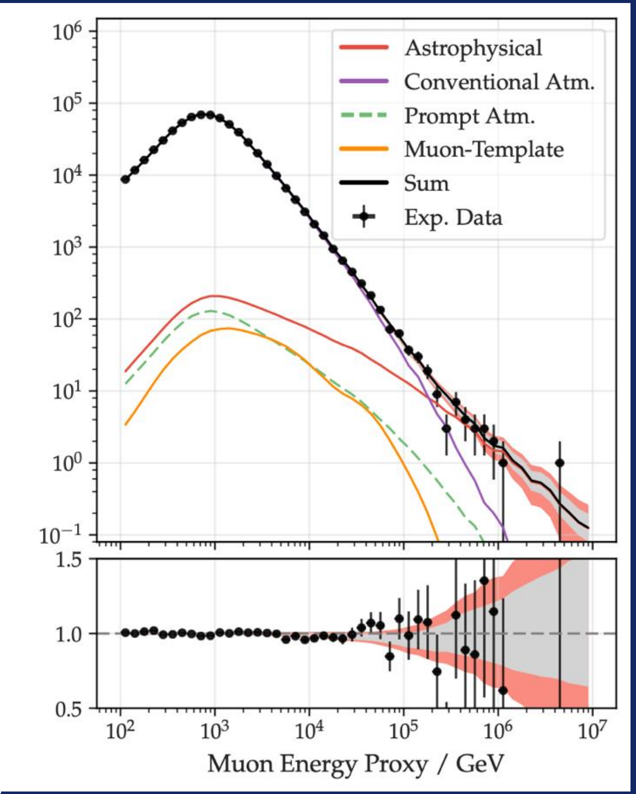
$$\Phi_\nu = \phi \times (E_\nu / 100\,\mathrm{TeV})^{-\gamma}$$

Astrophysical Muon-Neutrino Flux with 9.5 Years of IceCube Data

- Through-going muon tracks
- Muon neutrino flavor, Northern sky

IceCube, Astrophys. J. 928 (2022)





- Likelihood fit analysis method, excess of events E > 100 TeV
- Single power law fit: soft best-fit spectral index γ =2.37±0.09

$$\Phi_\nu = \phi \times (E_\nu / 100\,\mathrm{TeV})^{-\gamma}$$

Diffuse astrophysical electron and tau neutrino flux with 6 years of IceCube high energy cascade data

IceCube, Phys. Rev. Lett. 125 (2020) 121104

Standard maximum likelihood-based template method
matching observed deposited energy distribution (data) in zenith bins to prediction (MC simulation)

$$\log L(\boldsymbol{\theta_r}\boldsymbol{\theta_s}|\boldsymbol{n})=\sum_{i=1}^{3}\sum_{j=1}^{N}\log L^{ij}_{Poisson}\left(\boldsymbol{\theta_r}\boldsymbol{\theta_s}|n_{ij}\right)+\frac{1}{2}\left[\sum_{k=1}^{4}\left(\frac{\varepsilon_k-\widehat{\varepsilon_k}}{\sigma_k}\right)^2\right]+\frac{1}{2}\left(\varepsilon^{BI}-\widehat{\varepsilon^{BI}}\right)^T\Sigma_{BI}^{-1}\left(\varepsilon^{BI}-\widehat{\varepsilon^{BI}}\right)$$

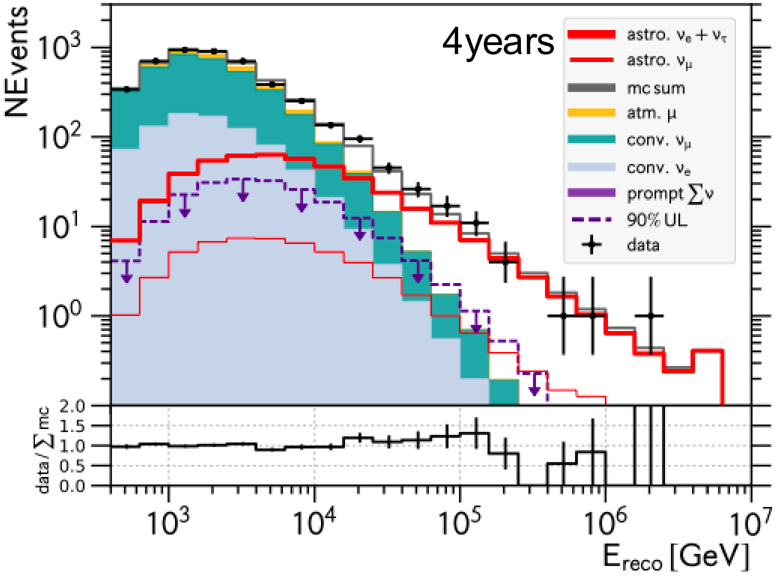
Systematics

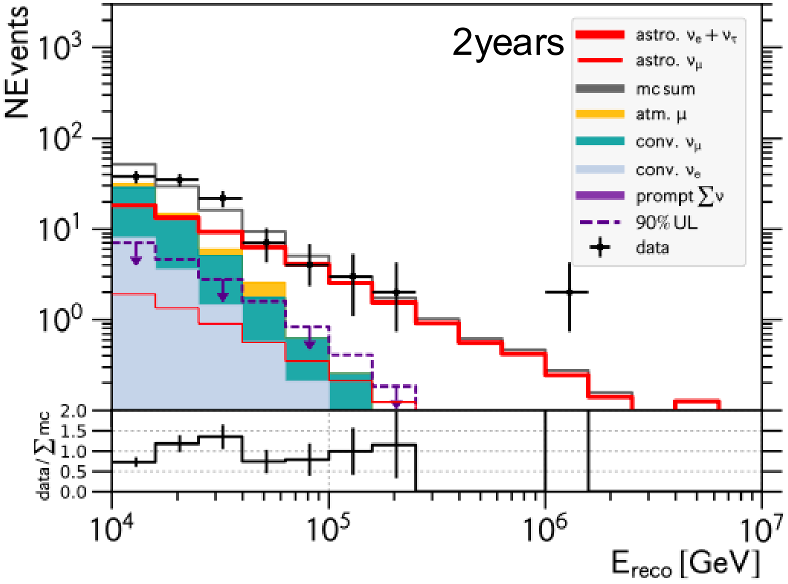
$$L^{ij}_{Poisson}\left(\boldsymbol{\theta_r}\boldsymbol{\theta_s}|n_{ij}\right)=\frac{\mu_{ij}\left(\boldsymbol{\theta_r}\boldsymbol{\theta_s}\right)^{nij}}{n_{ij}!}e^{-\mu_{ij}\left(\boldsymbol{\theta_r}\boldsymbol{\theta_s}\right)}$$

$$\mu_{ij}\left(\boldsymbol{\theta_r},\boldsymbol{\theta_s}\right)=\mu_{ij}^{atm.\mu}+\mu_{ij}^{atm.\nu}+\boxed{\mu_{ij}^{astro.\nu}}$$

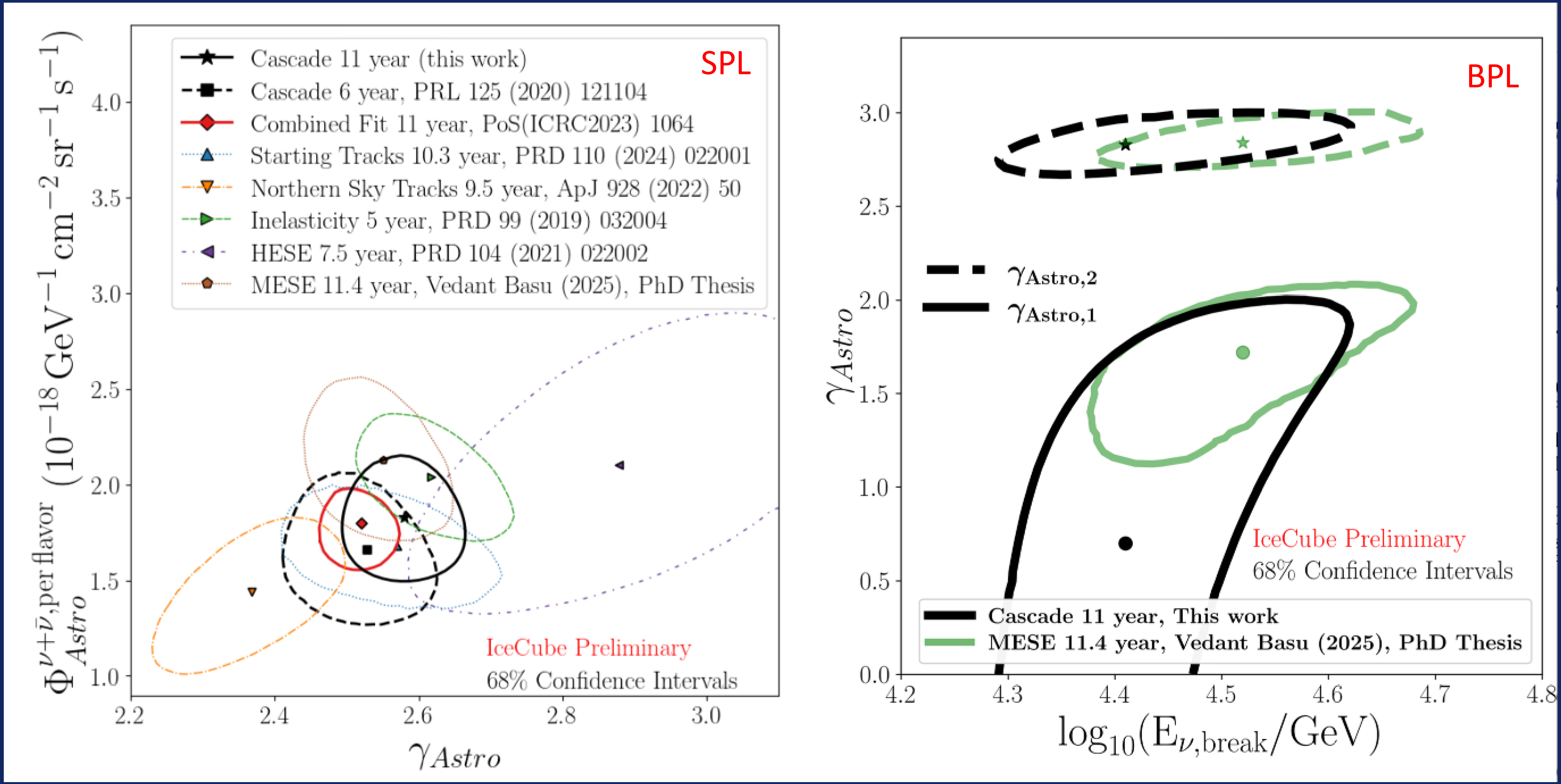
$$\Phi_\nu=\phi\times\left(E_\nu/100\,\mathrm{TeV}\right)^{-\gamma}$$

SPL fit:
soft best-fit spectral index γ =2.53±0.07





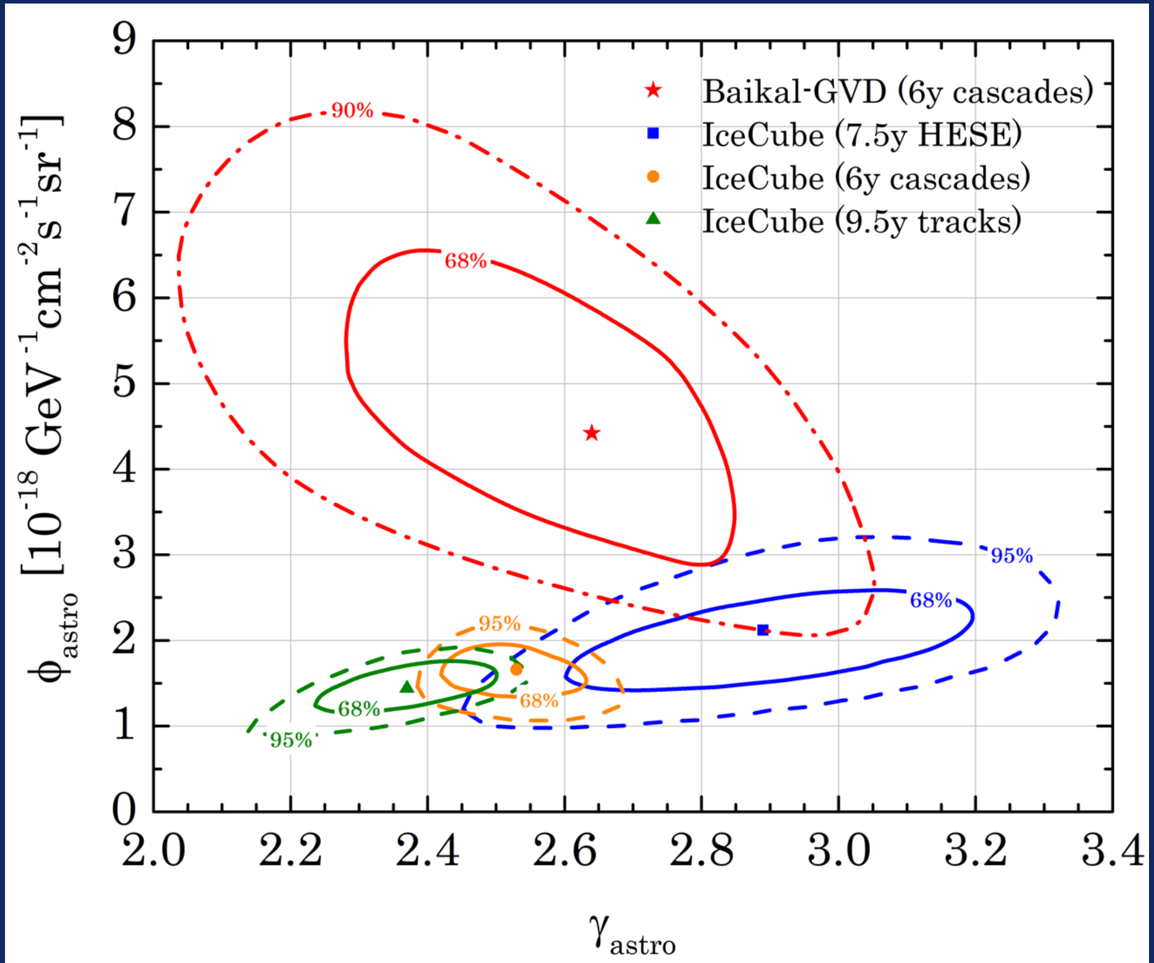
Summary of IceCube Diffuse Flux Results



IceCube, ICRC2025

First observation of the spectral break

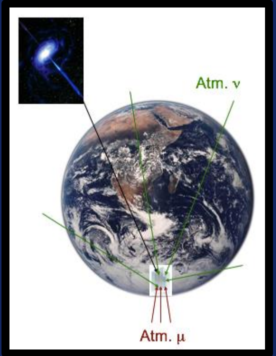
Baikal-GVD Diffuse SPL Flux Result



Baikal-GVD, ICRC2025

Results
consistent with IceCube

Searches for neutrino "Point Sources"
Steady and Transient



Point Source Search: time integrated analysis method

- Un-binned maximum likelihood technique to quantify spatial neutrino clustering in the sky

$$\mathcal{L}(\Phi_{100},\gamma) = \prod_i \left(\frac{n_S(\Phi_{100},\gamma)}{N} \mathcal{S}(\mathbf{x}_S, \mathbf{x}_i, \sigma_i, E_i; \gamma) + \left(1 - \frac{n_S(\Phi_{100},\gamma)}{N}\right) \mathcal{B}(\sin\delta_i, E_i) \right)$$

n_s – number of signal neutrinos for a flux model Φ (E) ~ (E/100 TeV)$^{-\gamma}$
i =1,….,N - total number of data events
S – probability distribution function (PDF) of signal events from a point source
x_S – source position, neutrino: x_i direction, σ_i direction uncertainty , δ_i declination, E_i energy

$$\mathcal{S}(\mathbf{x}_S, \mathbf{x}_i, \sigma_i, E_i; \gamma) = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin\delta_i; \gamma).$$

Spatial term   Energy term

B - PDF of background events (atmospheric neutrinos)

$$\mathcal{B}(\sin\delta_i, E_i) = \mathcal{P}_B(\sin\delta_i) \times \mathcal{E}_B(E_i, \sin\delta_i).$$

Spatial term   Energy term

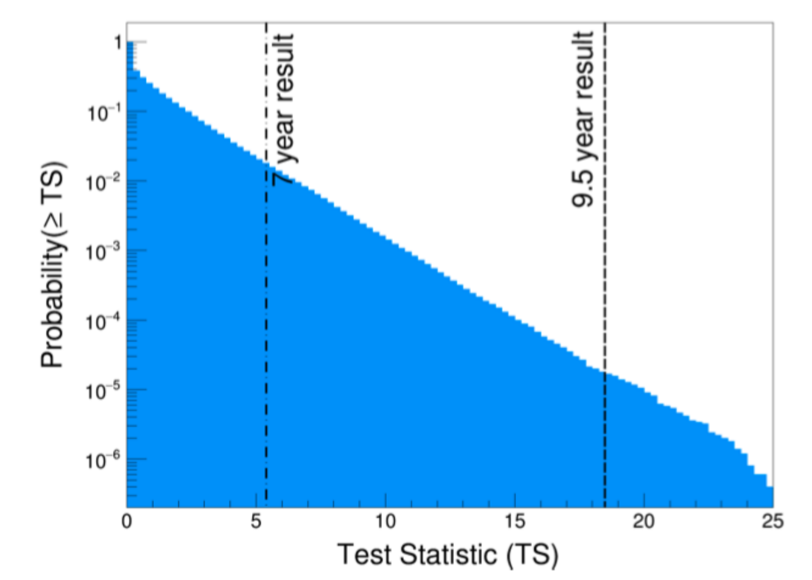
Point Source Search: time integrated analysis method

- Total likelihood L and test statistics TS

$$\mathcal{L}(\Phi_{100}, \gamma) = \prod_j \mathcal{L}_j(\Phi_{100}, \gamma)$$ j – data sample (e.g. year)

$$\mathcal{L}(\Phi_{100} = 0)$$ null hypothesis of no point signal present

$$TS = 2\log(\mathcal{L}(\Phi_{100}, \gamma)/\mathcal{L}(\Phi_{100} = 0))$$ test statistics



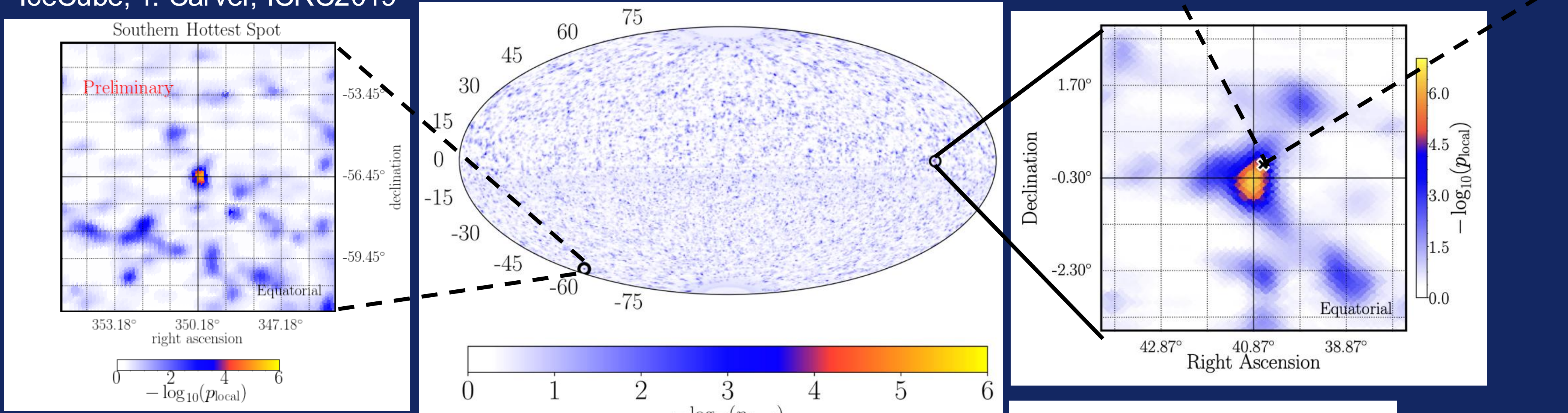
TS from the time-integrated analysis performed on <u>randomized data</u> <u>for a source x_S</u> TXS 0506+056

p-value: fraction of randomized trials with TS > TS_{data} (conservative estimate)

IceCube: All-Sky Point Source Search

- All-Sky search (2008-2018): Search for excess of astro ν from a common direction over bg of atm. ν (Northern Sky) or μ / ν (Southern Sky).
- Assumed time integrated emission of ν and $E^{-\gamma}$ energy spectrum.

IceCube, PRL 124 (2020) 051103
IceCube, T. Carver, ICRC2019



Hottest Point in South : δ< -5°
RA = 350.18° , Dec -56.45°
n_{signal} =17.8, γ = 3.3, TS= 20.0
-log10(pval) =5.37 ⇒ 75% post-trial

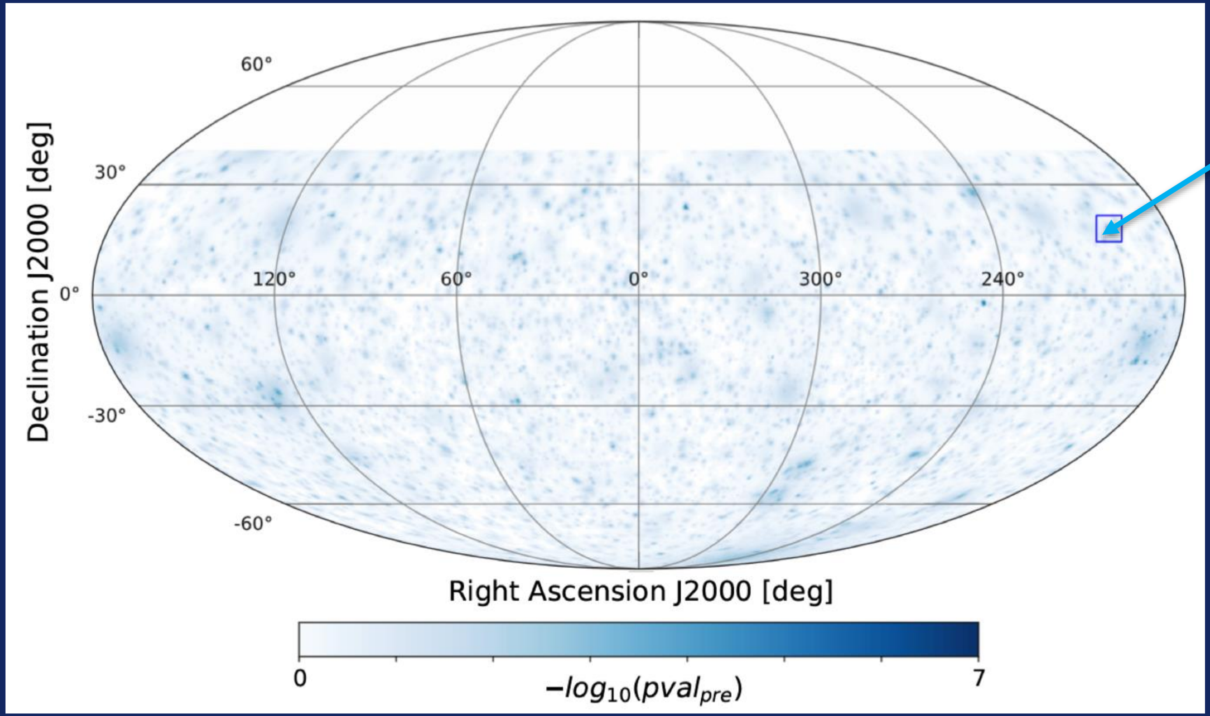
Not significant

Hottest Point in North : δ ≥ -5°
RA = 40.87° , Dec = -0.30°
n_{signal} = 61.5 , γ= 3.4, TS = 25.3
-log10(pval)= 6.45 ⇒ 9.9% post-trial

Not significant

Antares: Point Source Full Sky Search

- Antares data: 2007-2017 (legacy data)



- <u>Hotspot:</u>

(RA, δ) = (200.5◦,17.7◦)
p-val = 3.2×10^{-6} (4.5σ)

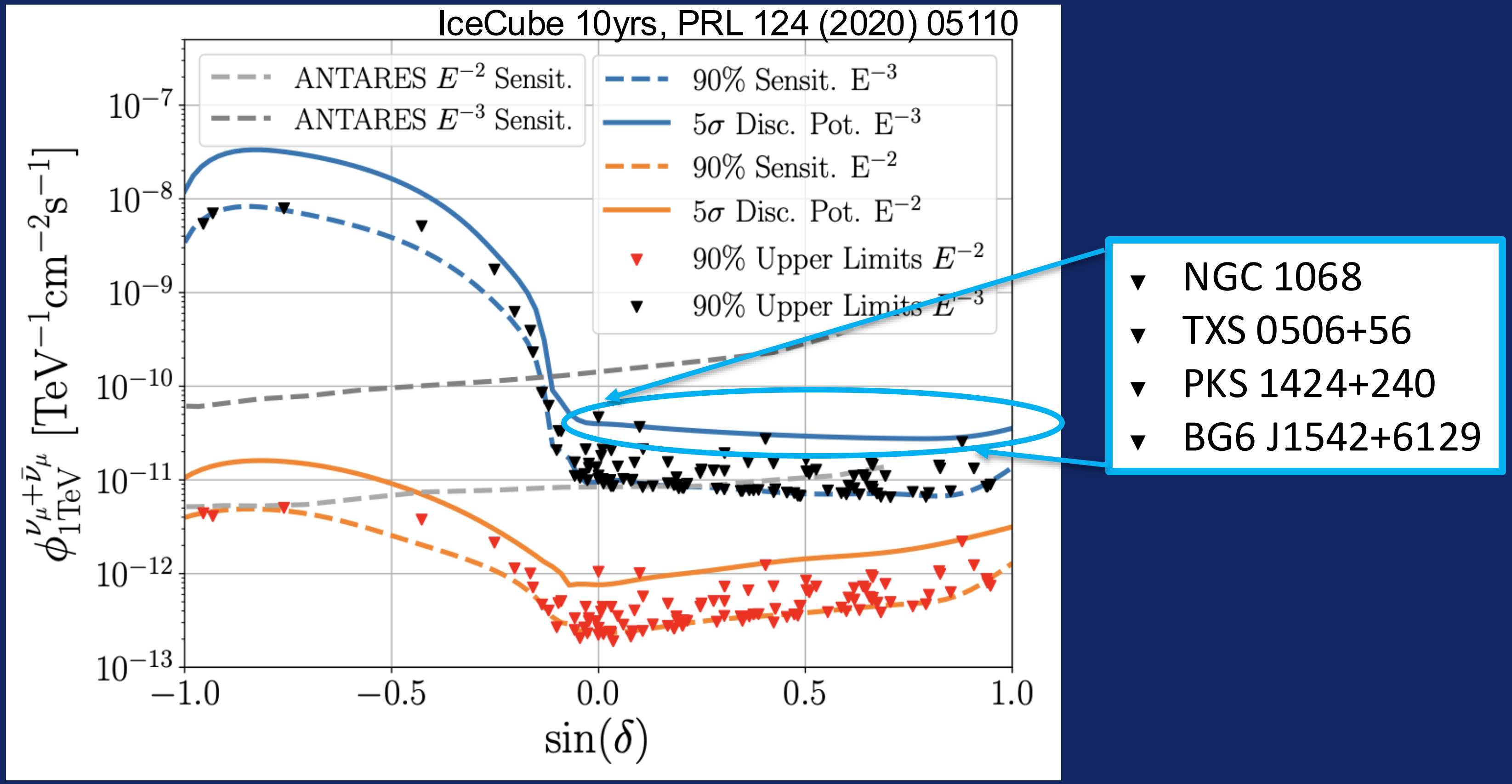
- Compatible with background with 39% probability
- No known source at this location
- The closest source found at 1° distance: the radio blazar J1318+1807

Not significant

Antares, Phys.Rept. 1121 (2025) 1

IceCube: Point Source Catalog Search

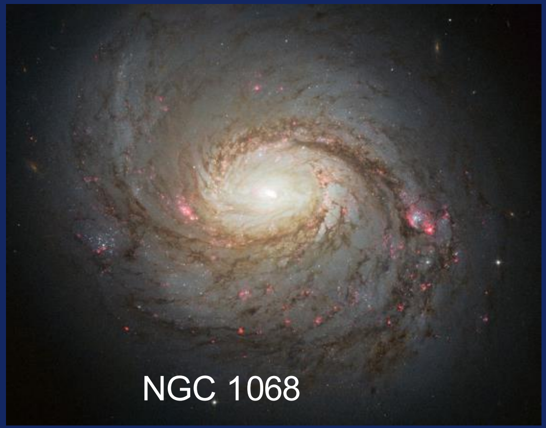
- Source candidates list of 110 Galactic & Extra-galactic sources
  Northern Sources (87 extra-galactic, 10 Galactic), Southern Sources (11 extra-galactic, 2 Galactic)
- IceCube data: 2008-2018

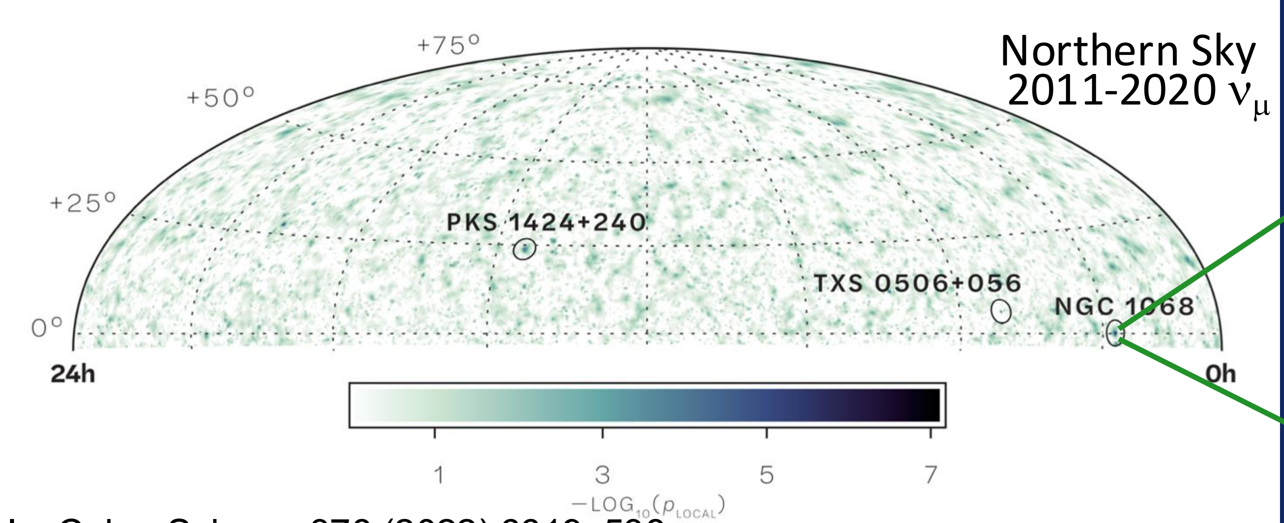


- Most significant source from the list: NGC1068 (2.9σ post trial)
- 4 most significant sources 3.3σ post trial (2.2σ without TXS 0506+056)

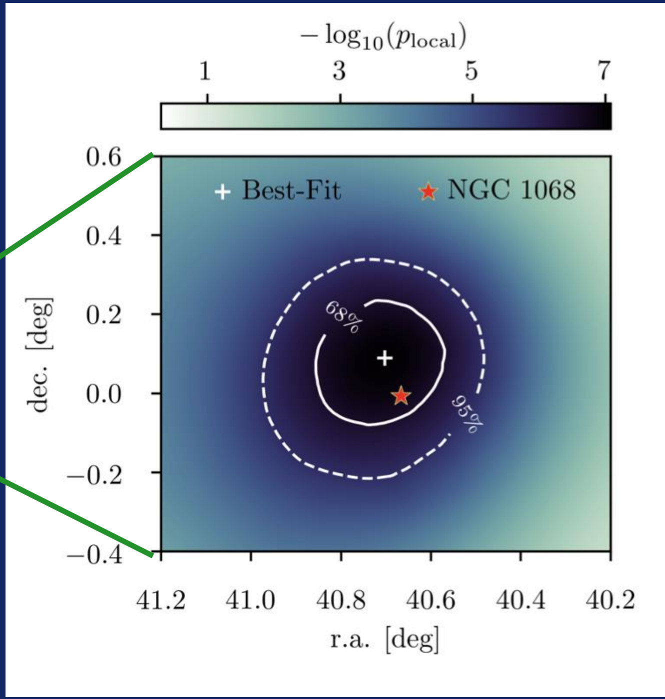
Evidence for TeV neutrino emission from the nearby galaxy NGC 1068

- All-Sky search: Search for excess of astro ν from a common direction over the background of atm. ν (Northern Sky) or μ / ν (Southern Sky).
- Llh method, assumed time integrated emission of ν and $E^{-\gamma}$ spectrum, sky map:



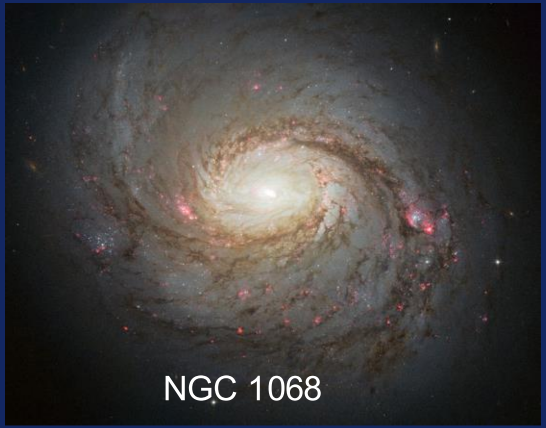


IceCube, Science 378 (2022) 6619, 538

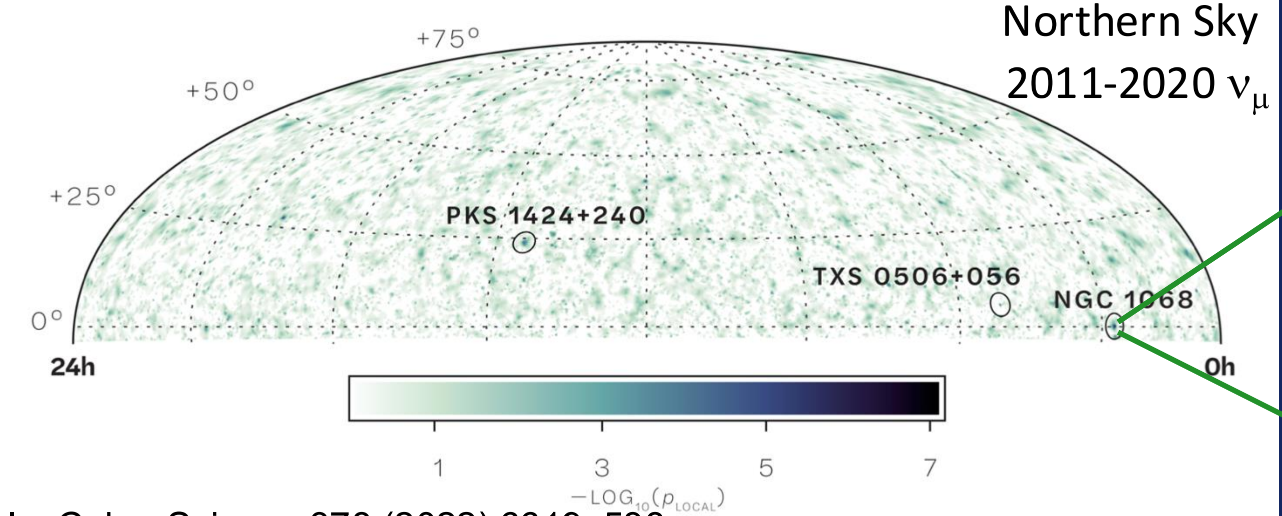


Evidence for TeV neutrino emission from the nearby galaxy NGC 1068

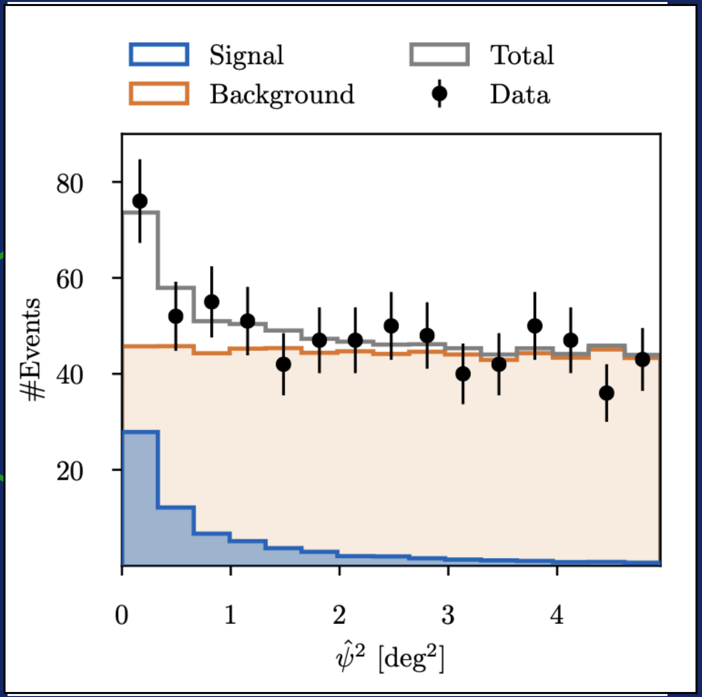
- All-Sky search: Search for excess of astro ν from a common direction over the background of atmospheric ν (Northern Sky) or μ / ν (Southern Sky).
- Llh method, assumed time integrated emission of ν and $E^{-\gamma}$ spectrum, sky map:



Northern Sky
2011-2020 ν_μ



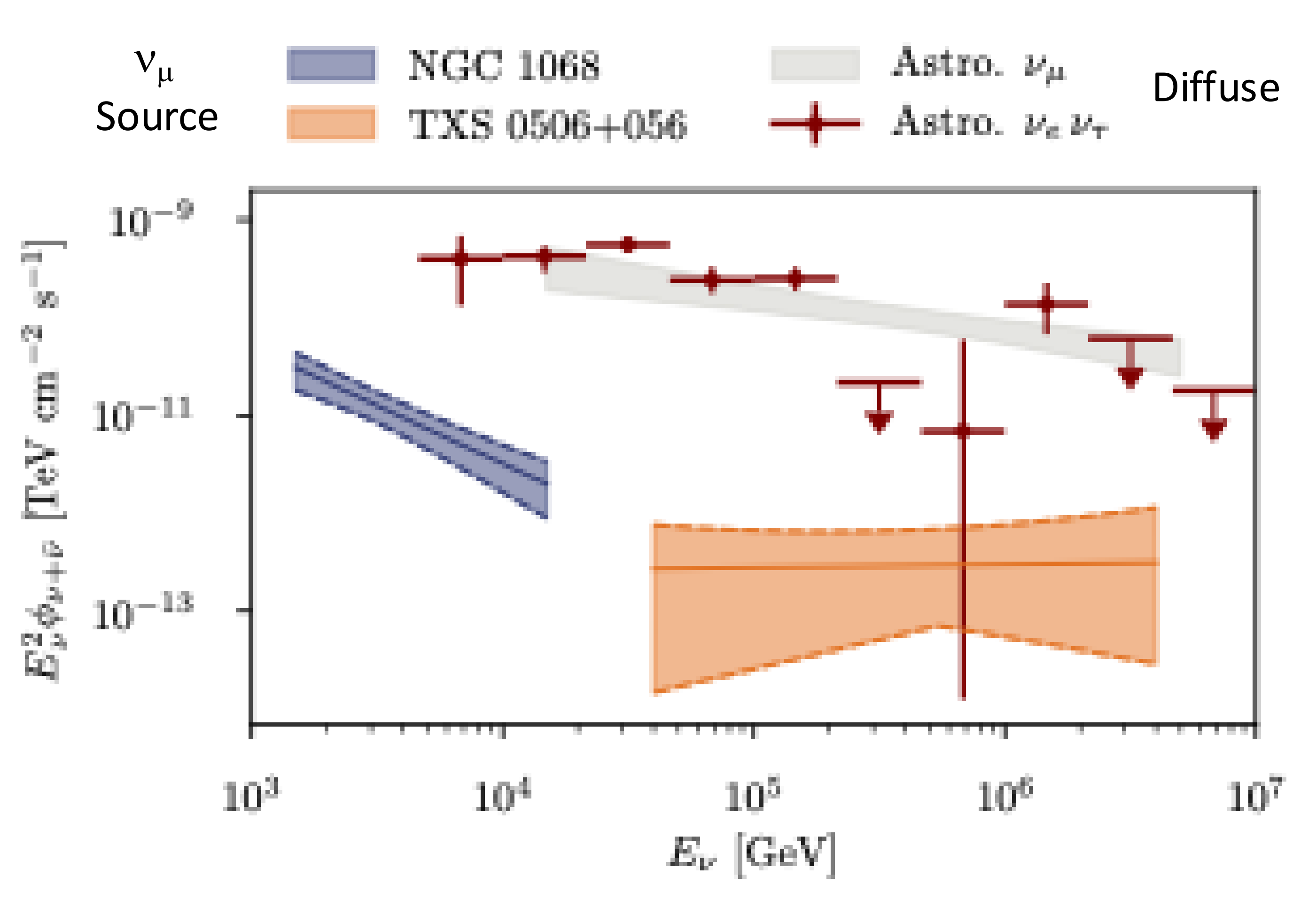
IceCube, Science 378 (2022) 6619, 538



Significance 4σ

IceCube: Astrophysical neutrino flux

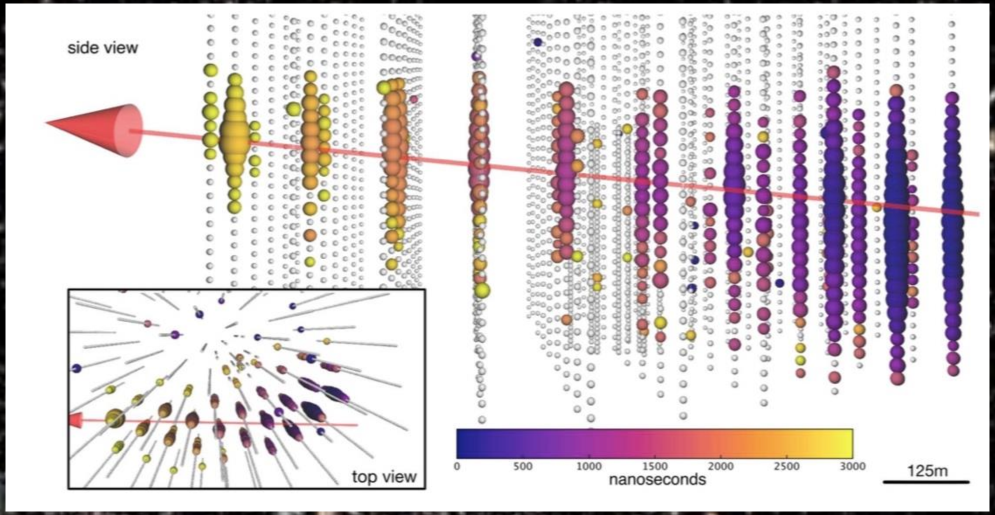
IceCube, Science 378 (2022) 6619, 538-543



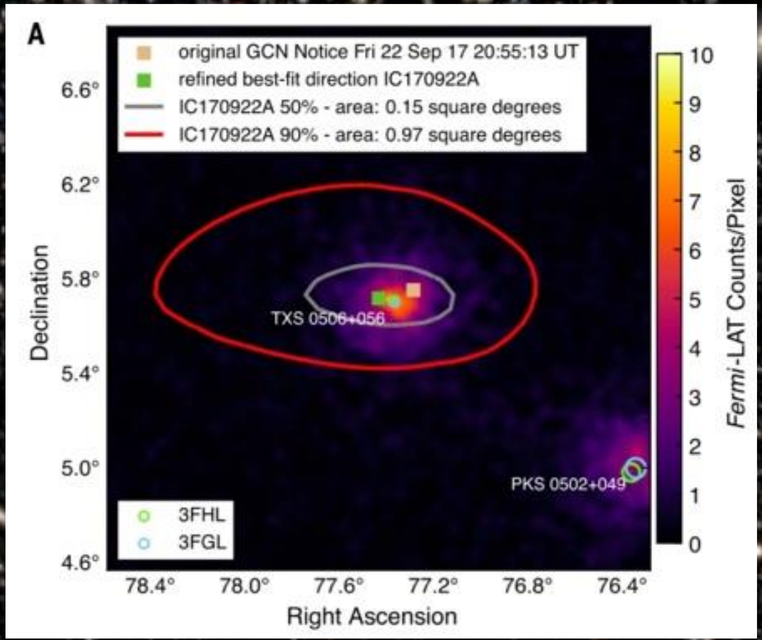
NGC1068 and TXS0506+056 contribute ~1% of the total diffuse flux in their observed energy ranges.

Time-dependent Sources
Evidence of the first neutrino source
AGN TXS 0506+056

IceCube-170922: IceCube neutrino alert



IceCube, Science 361, eaat1378 (2018)
IceCube, Science 361, 146 (2018)



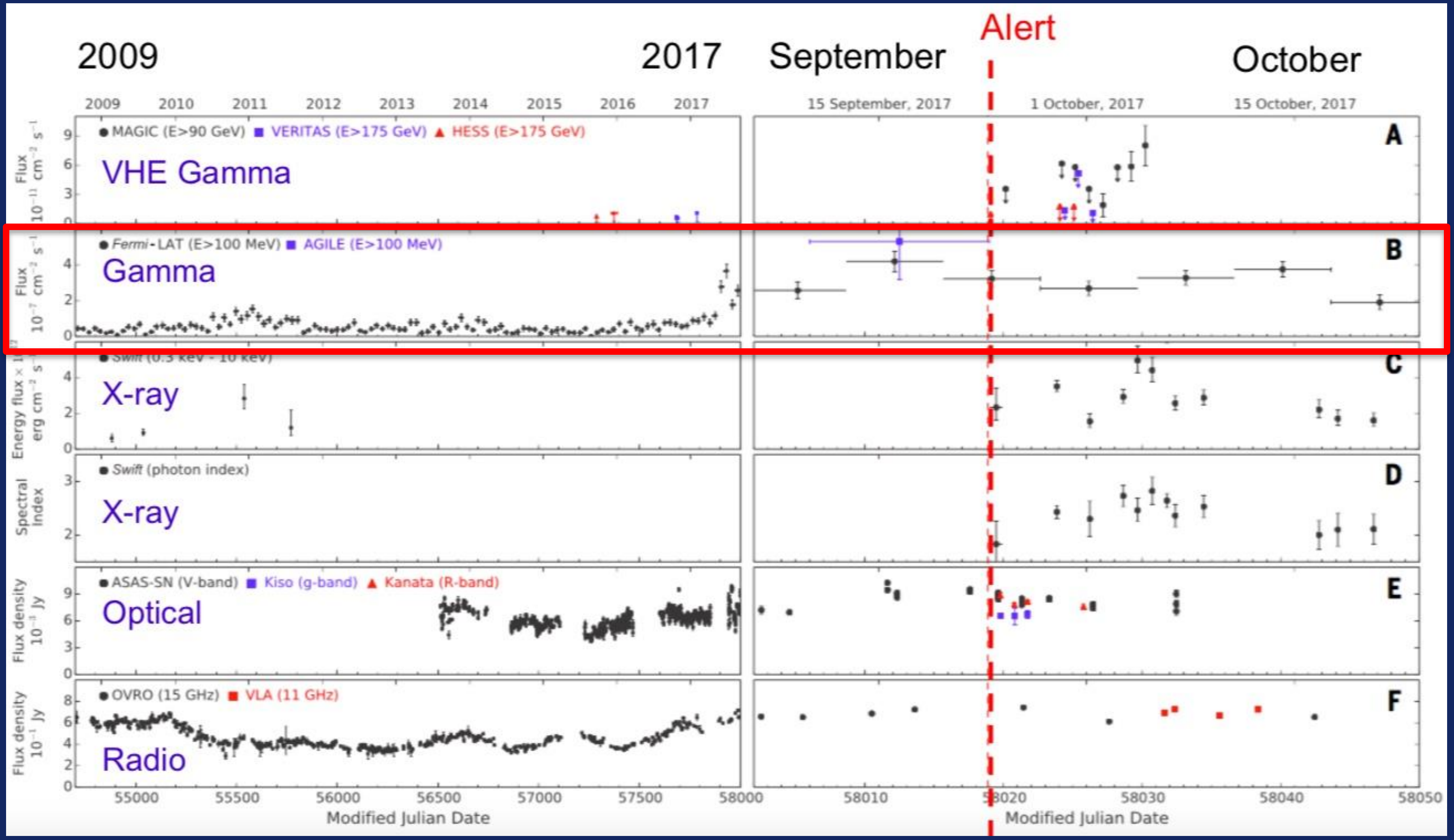
On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction, as reported by Fermi-LAT on September 28, 2017, consistent with the flaring γ-ray AGN TXS 0506+056.

Flaring AGN TXS 0506+056 identification by Fermi & Magic

Evidence of the first ν source: TXS 0506+056

Science 361, eaat1378 (2018)
Science 361, 146 (2018)

IceCube-170922: IceCube neutrino EHE alert



Evidence of the first ν source: TXS 0506+056

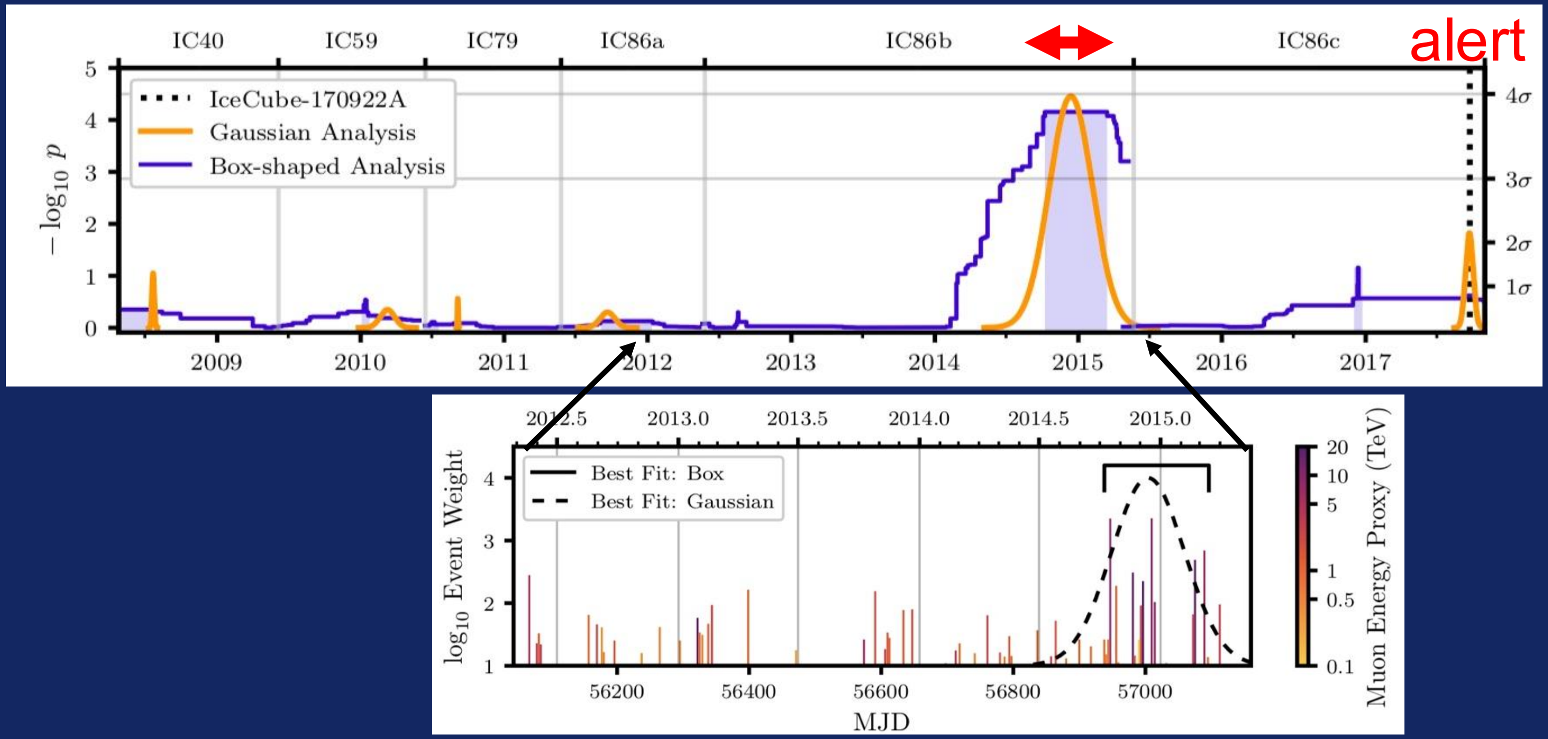
IceCube, Science 361, eaat1378 (2018)
IceCube, Science 361, 146 (2018)

- ν_μ-flare found in archival IceCube data 10/2014- 03/2015 (data dominated by atm. ν_μ)

$$\mathcal{L}(\Phi_{100},\gamma,T_0,T_W) = \prod_i \left(\frac{n_S(\Phi_{100},\gamma)}{N} \mathcal{S} \times \mathcal{T}_S(t_i; T_0, T_W) + \left(1 - \frac{n_S(\Phi_{100},\gamma)}{N}\right) \mathcal{B} \times \mathcal{T}_B \right)$$

$$TS = 2\log\left[\frac{T_W}{\mathrm{T}} \times \frac{\mathcal{L}(\Phi_{100},\gamma,T_0,T_W)}{\mathcal{L}(\Phi_{100}=0)}\right]$$

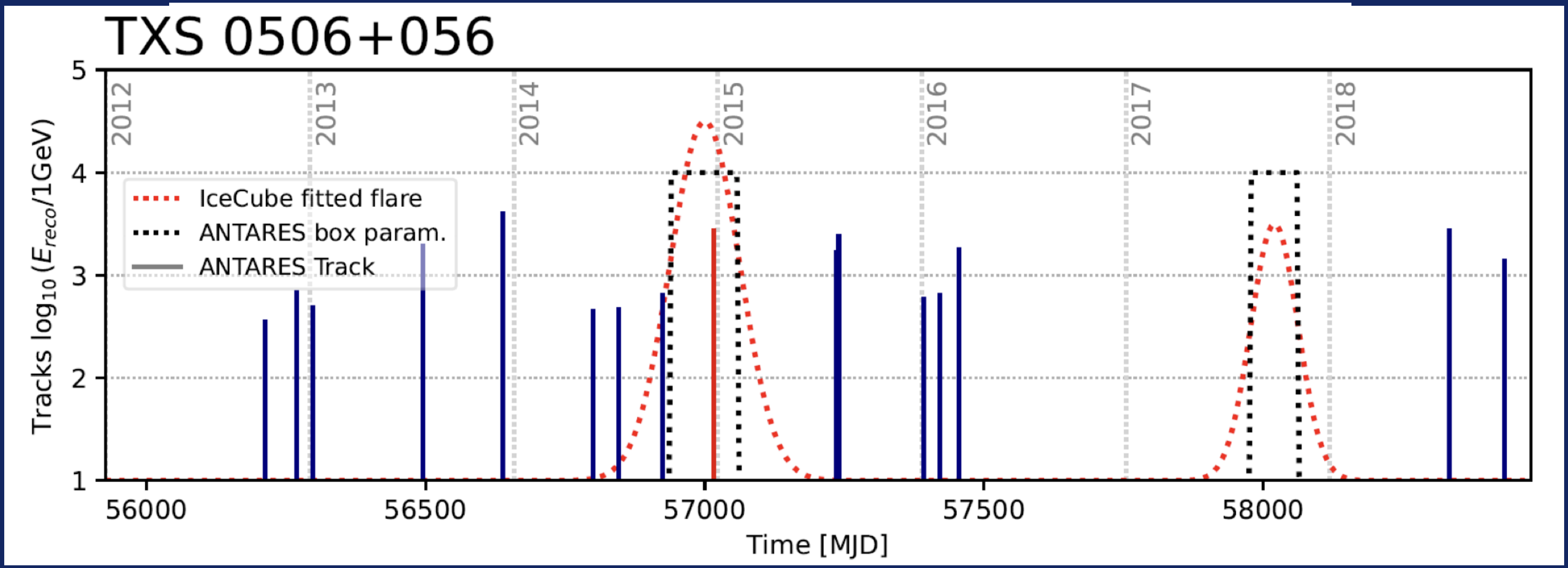
T_B = 1/T where T=total observation time
T_S –function for the temporal distribution of events



- Identification of a blazar TXS 0506+056 as a source of HE ν's and CR's with significance of 3.5σ ($2\ 10^{-4}$)
- Other neutrino alerts & MMA follow ups correlations consistent with background expectation.

Antares follow up on the TXS 0506+056

Antares, Phys.Rept. 1121 (2025) 1

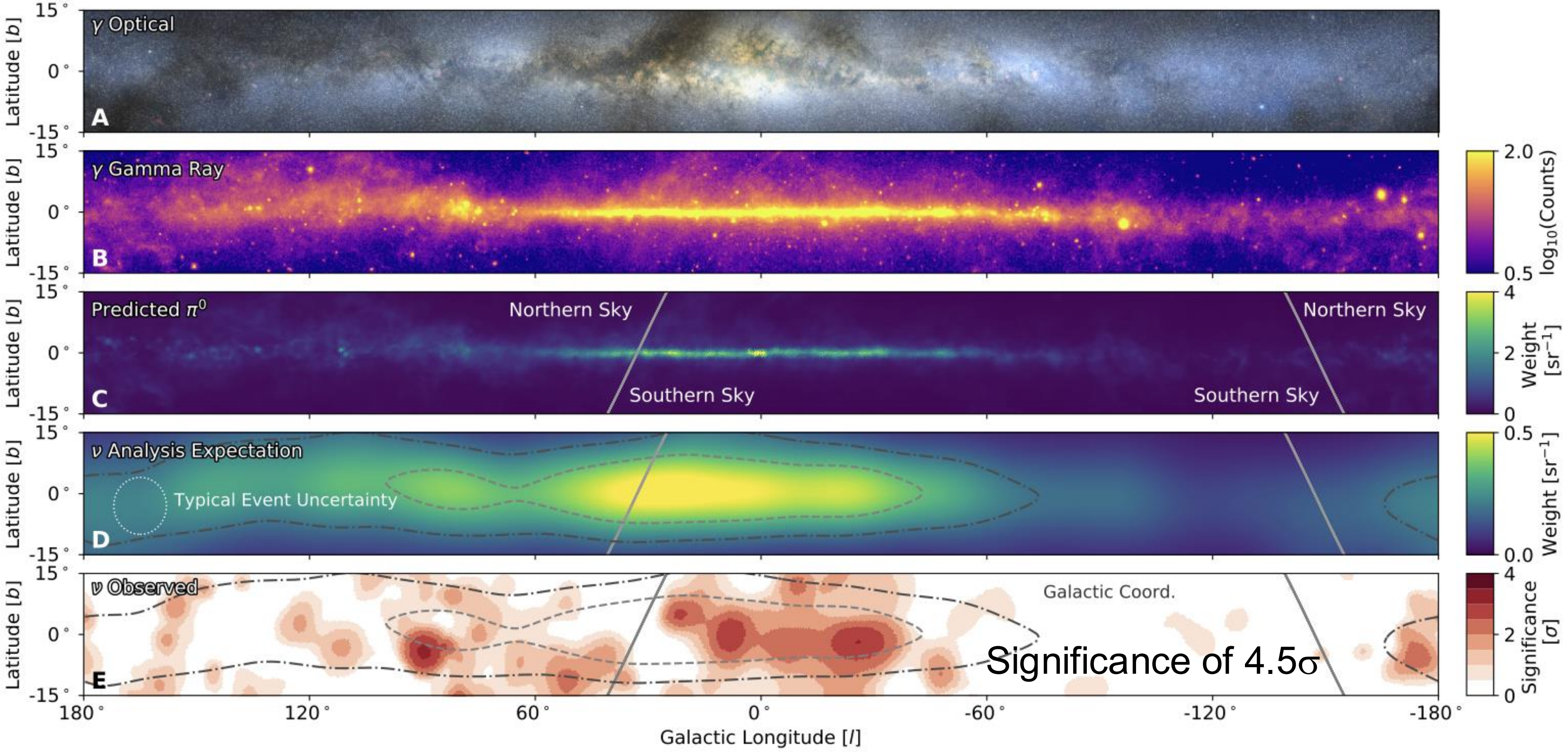


- Arrival time of neutrino candidates found within 5° of the direction of the source.
- Time integrated search, significance of 2.4σ

Diffuse Neutrino Emission from the Galactic Plane

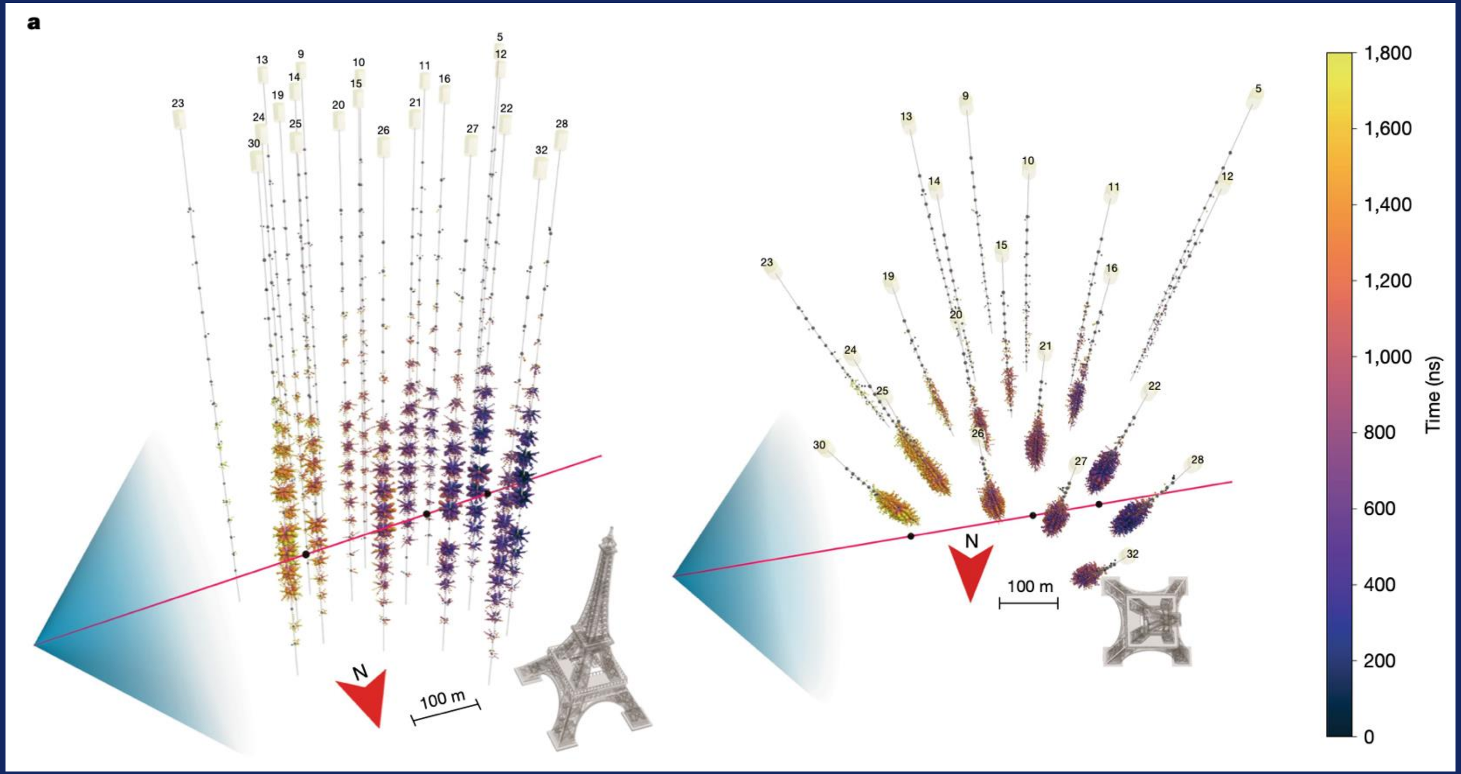
IceCube: Science 380 (2023) 6652

2023



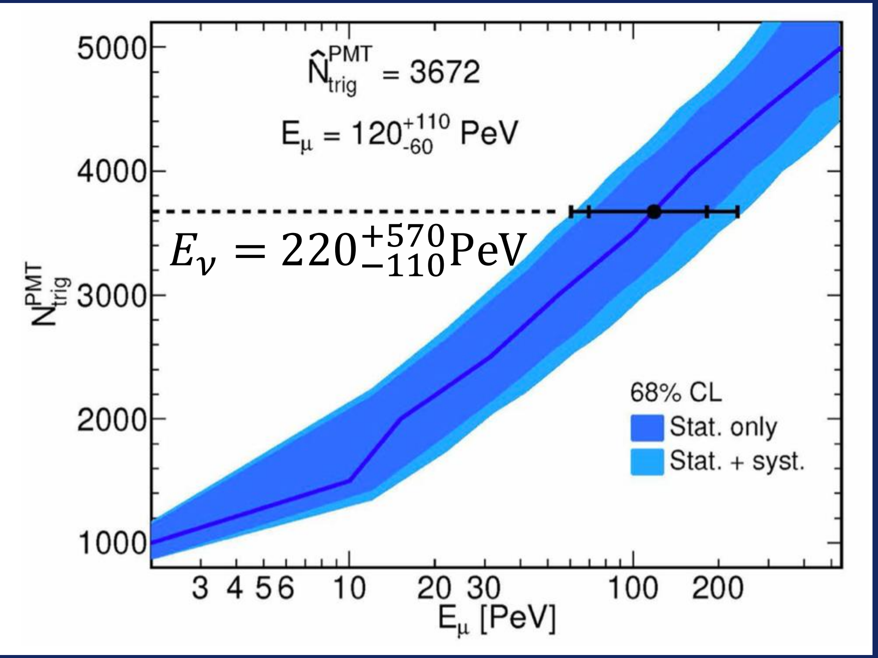
Significance of 4.5σ

KM3-20230213A: UHE ν_μ neutrino event



KM3Net, Nature 638 (2025) 376, Nature 640 (2025) E3 (erratum)

ARCA21: February 13th 2023, 01:16:47 UTC
Detection of KM3-20230213A

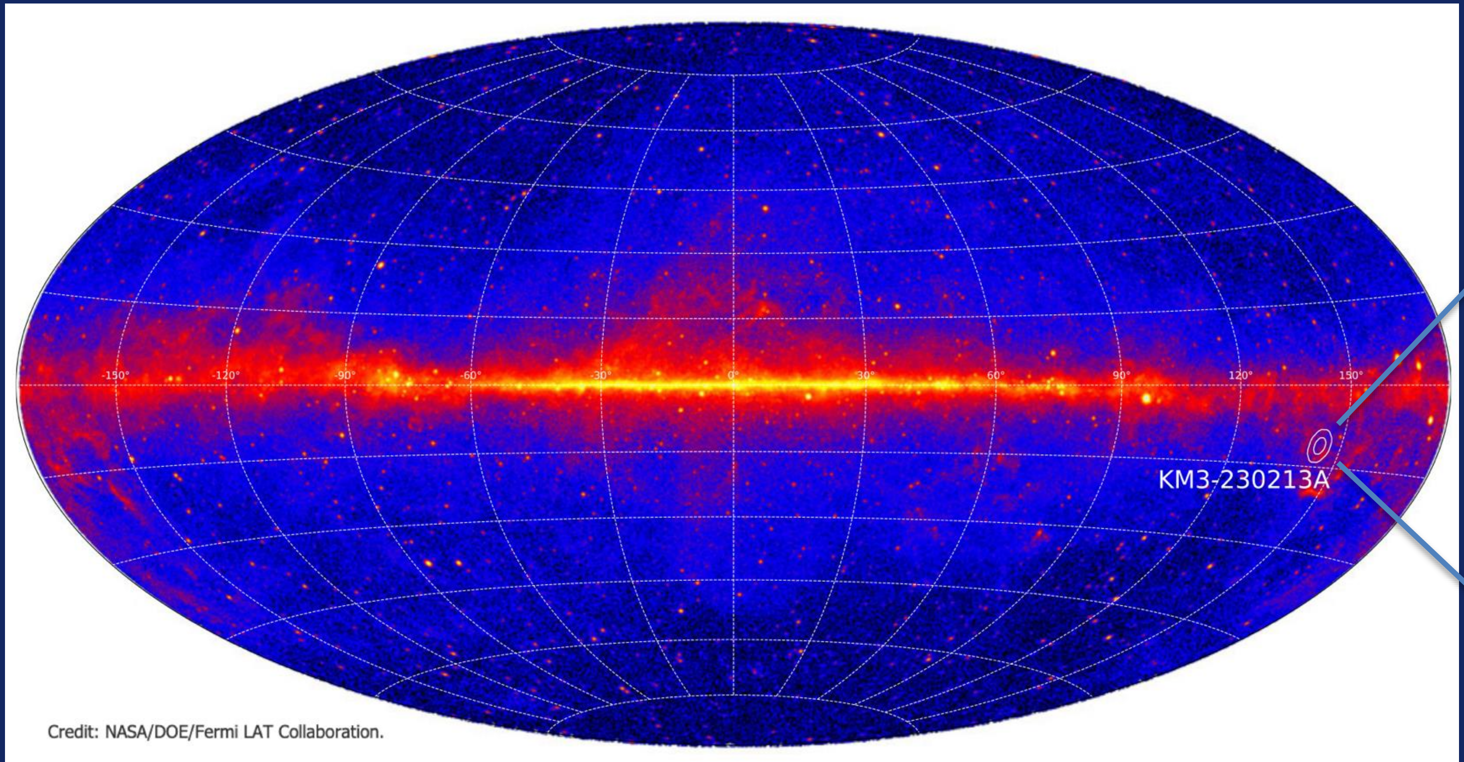


KM3Net, D. Dornic, ICRC2025

High quality horizontal muon track:

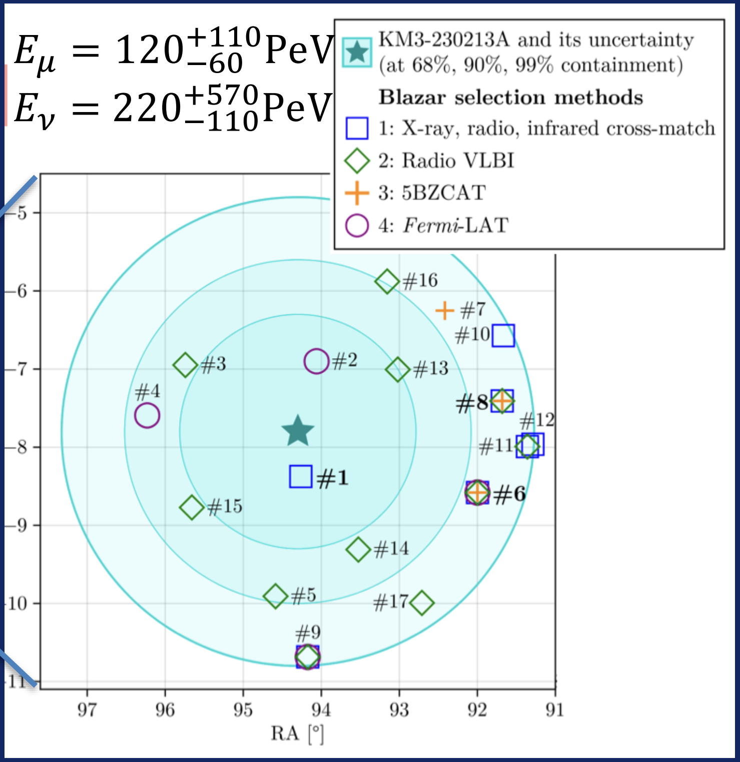
- atm. muon rate << 10^{-10} / yr
- atm. muon bundles 10^{-3} / yr
- atm. neutrino < 10^{-5} / yr

KM3-20230213A: UHE ν_μ neutrino event



KM3Net, Nature 638 (2025) 376, Nature 640 (2025) E3 (erratum)

On-going position recalibration efforts



KM3Net, M. Lincetto, ICRC2025

γ-rays/X-rays/radio catalog search

- 17 blazar candidates identified
- 3 coincidence e-m flares

Origin: Galactic? Extragalactic? First detection of a ν from p+γ_{CMB} interactions?

Summary

1. Diffuse high energy (TeV-PeV) neutrino flux discovered by IceCube (2013) and characterized
   - Single power law spectrum with equal flux per ν flavor assumption describes data well
   - Most precise result by IceCube: soft index $\gamma = -2.54 \pm 0.04$, 2TeV – 6 PeV
   - First indication of "beyond single power law" spectrum by IceCube
   - Experimental results from IceCube / Antares / Baikal-GVD consistent
2. 3 astrophysical TeV neutrino sources discovered by IceCube to date:
   - 2018: TXS 0506+056: source of neutrinos and gamma rays
   - 2022: NGC 1068: source of neutrinos, no gamma rays
   - 2023: Galactic Plane
   - No coincidence with GRB's & GW's
3. Highest energy neutrino event observed in 2023 with Km3Net-Arca
   $E_\nu = 220^{+570}_{-110}\mathrm{PeV}$ Origin uncertain: Galactic? Extragalactic? GZK?

Thank you!

Neutrino astrophysical fluxes to probe sources and non-standard ν interactions

Neutrino Oscillations Over Astronomical Distances

- Oscillation phase:

$$\varphi_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu} = 2.8 \times 10^4 \frac{\Delta m_{ij}^2}{7.4 \times 10^{-5}\mathrm{eV}^2} \frac{100\ \mathrm{TeV}}{E_\nu} \frac{\mathrm{L}}{\mathrm{pc}}$$

L=1-10 kpc for Galactic sources; L > Mpc for extragalactic sources

- For L >> L_{osc} the averaged prob. for a ν flavor to change depends on mixing angles:

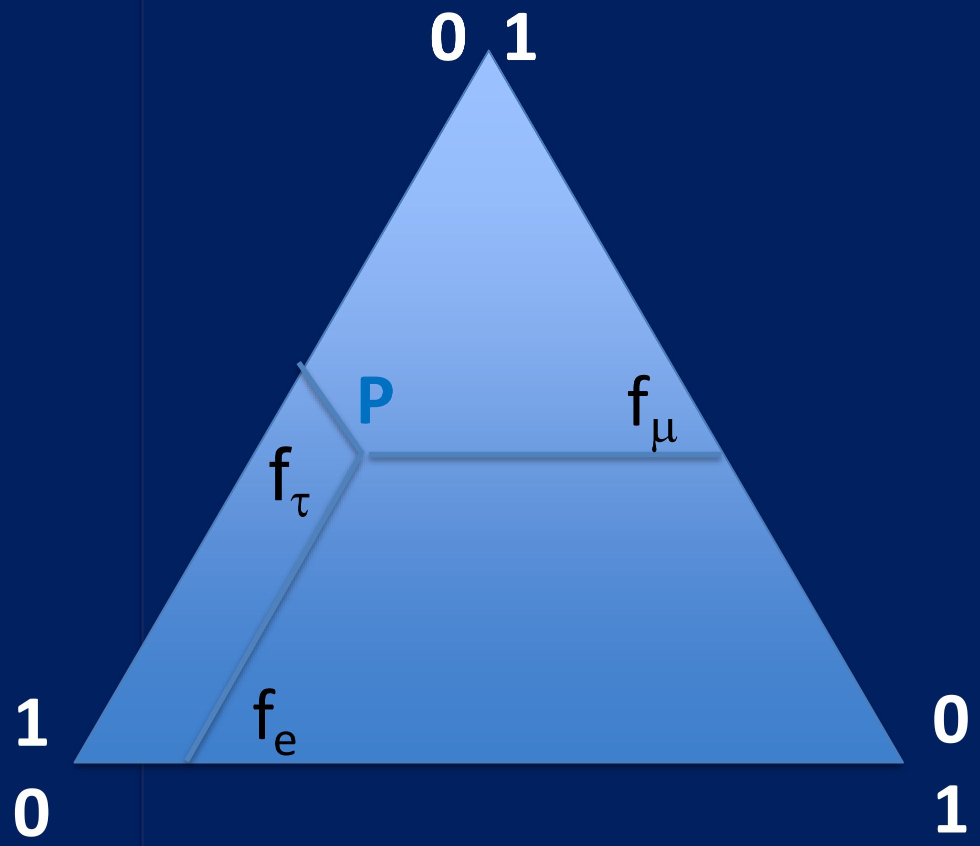
$$\langle P_{l\to l'}\rangle = \sum_{i=1}^{3} |U_{li}^2||U_{l'i}^2| \approx \begin{pmatrix} 0.552 & 0.226 & 0.222 \\ 0.226 & 0.395 & 0.379 \\ 0.222 & 0.379 & 0.399 \end{pmatrix}$$

- ν flavor fraction at Earth given the initial ν flavor fraction at Source:

$$f_l = \sum_{l'=e,\mu,\tau} \langle P_{l\to l'}\rangle \times f_{l'}^0$$

Neutrino Flavor Fractions at Earth

- flavor fraction at Earth given the initial ν flavor fraction at Source



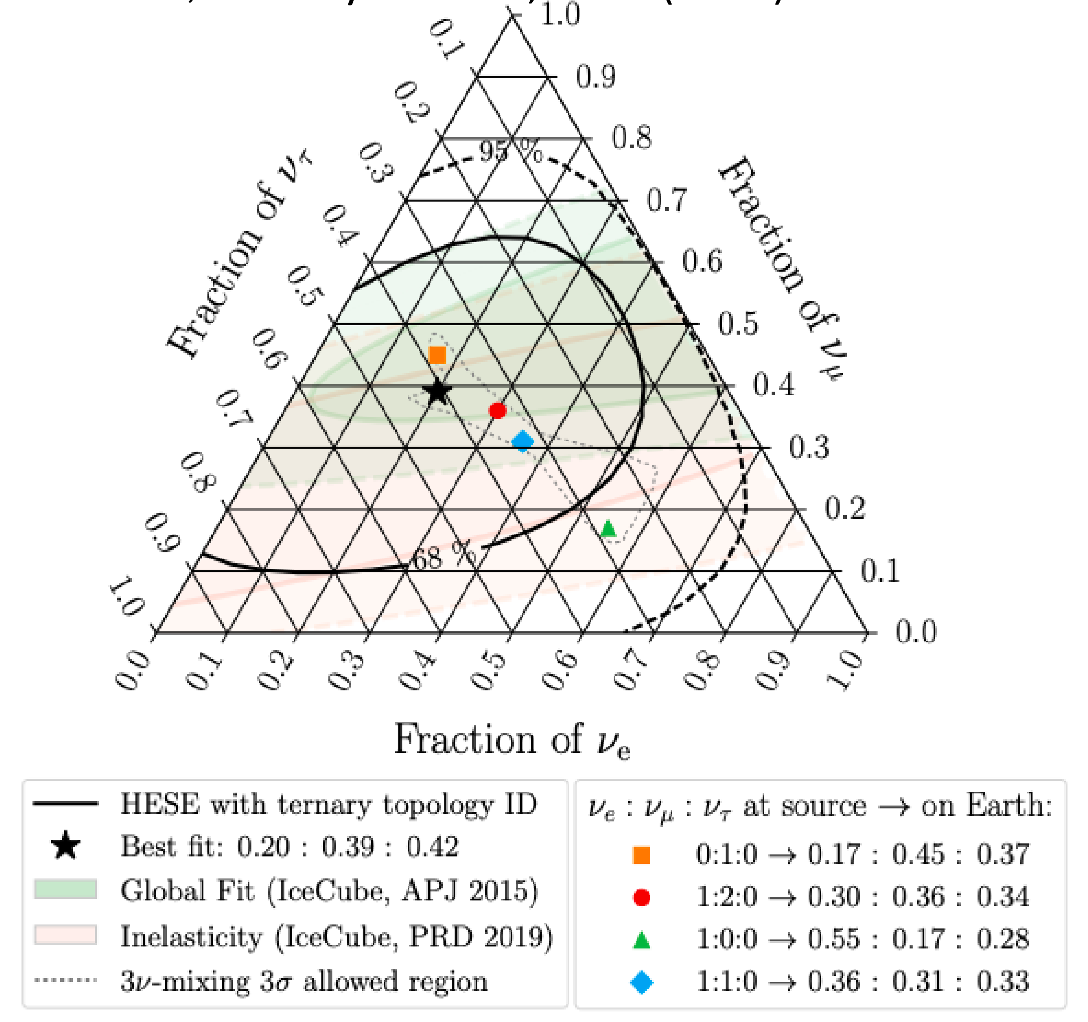
$$f_e + f_\mu + f_\tau = 1$$

$$0 \leq f_l \leq 1$$

From: E. Roulet and F. Vissani "Neutrinos in Physics and Astrophysics"

Neutrino Flavor Fractions

IceCube, Eur. Phys. J. C 82, 1031 (2022)



$$p + \gamma \rightarrow n + \pi^+$$

$$\mathrm{p} + \mathrm{p} \rightarrow p + N + \pi$$

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

Benchmark model $(f_e : f_\mu : f_\tau)_S = (1 : 2 : 0)$

$(f_e : f_\mu : f_\tau)_S = (0 : 1 : 0)$

Synchrotron cooling

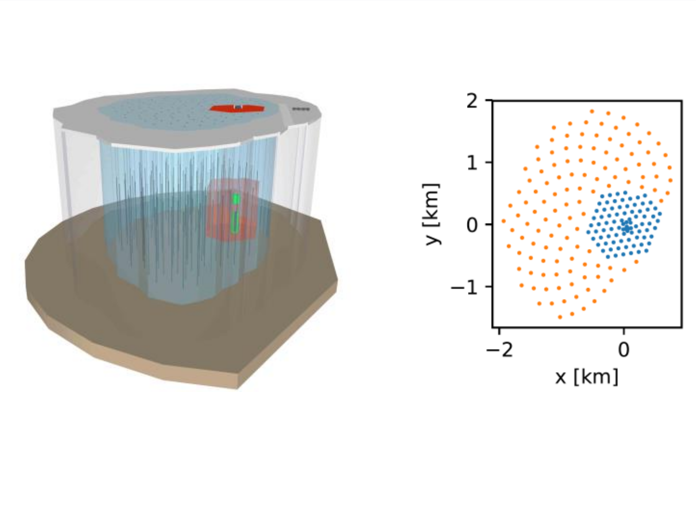
$$n \rightarrow p + e^- + \bar{\nu}_e$$

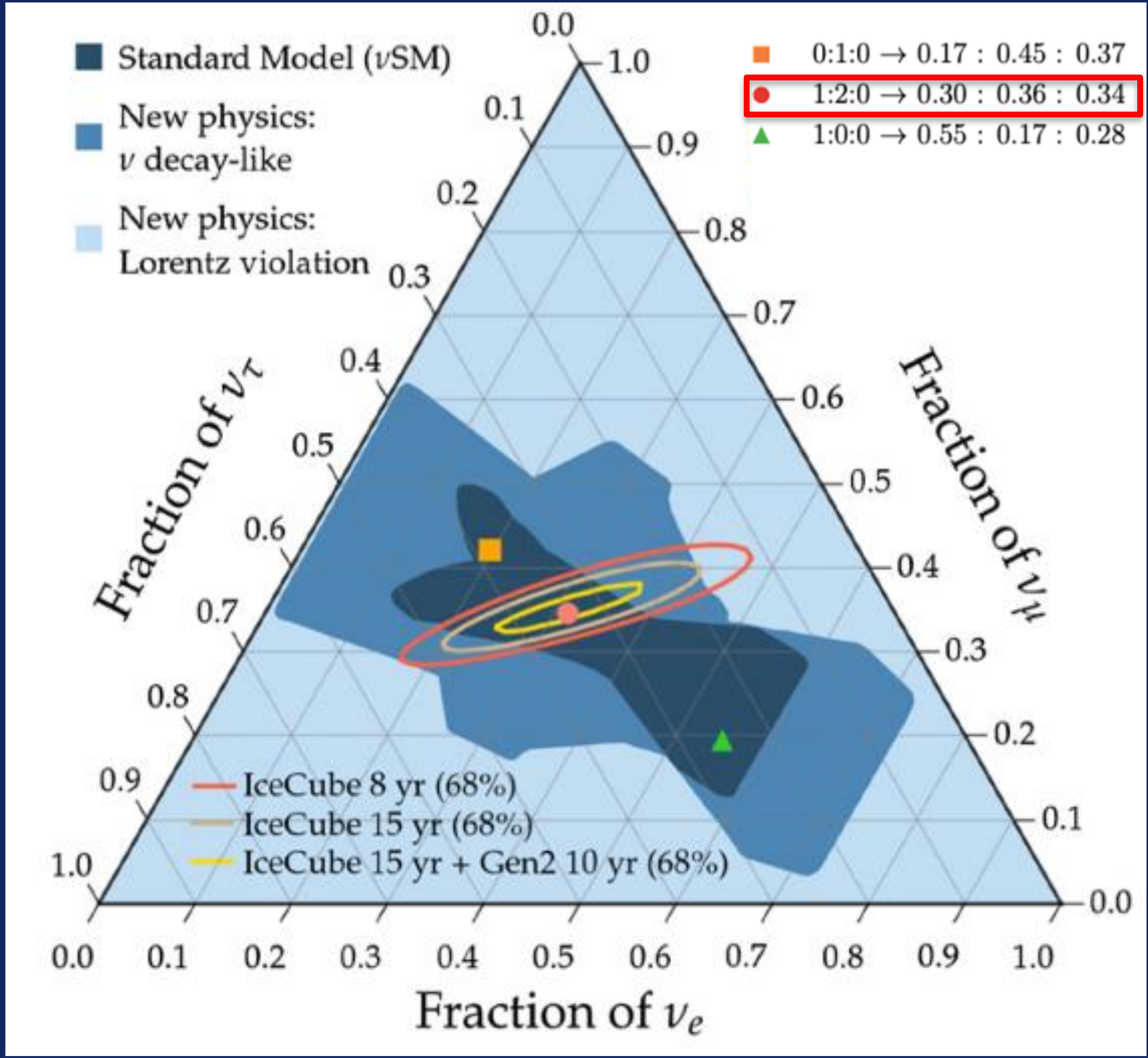
$(f_e : f_\mu : f_\tau)_S = (1 : 0 : 0)$

- Flavor composition likely E dependent, may provide insight into energy losses of π’s and μ’s in the B fields of cosmic accelerators
- New physics in ν propagation may modify flavor composition
- Assumption: flux $\boldsymbol{\nu} \approx \bar{\boldsymbol{\nu}}$ (true for pp only)

Results compatible with standard astrophysical neutrino flavors production assumption $(f_e:f_\mu:f_\tau)=(1:2:0)_S = (1:1:1)_E$. Future: sensitivity to new physics!

IceCube Neutrino Observatory: Future





IceCube: J. Phys. G: Nucl. Part. Phys. 48 (2021) 060501


Thank you!

More than 450 people, 58 institutions in 14 countries (31 U.S. and Canada, 21 Europe and 6 Asia Pacific)