All-sky view of high-energy neutrinos with IceCube, Baikal-GVD and KM3NeT

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HEACOSS-2024, Yerevan, 10.10.2024

Thank you!

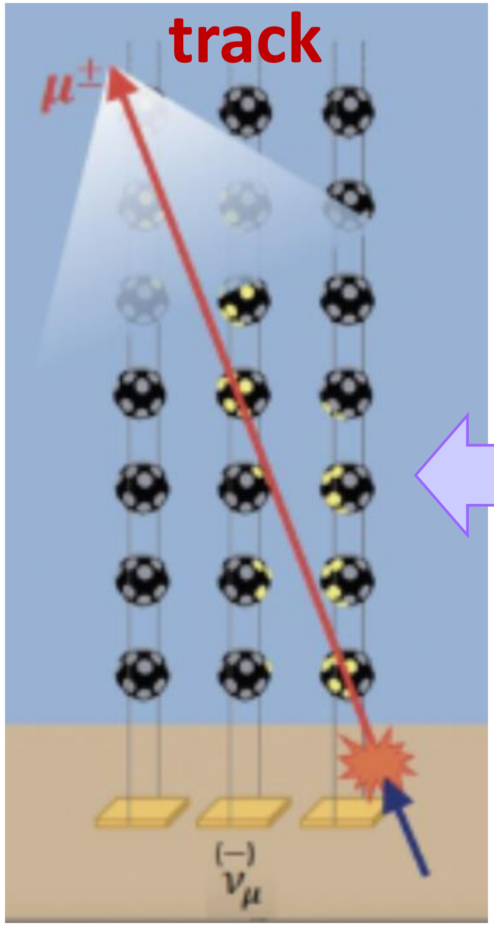
- the organizers of HEACOSS-2024 for invitation and tremendous work for running the conference in the very nice place!

- these studies and my participation in the conference are supported by the "Science" project of the Ministry of Higher Education and Science of Russia, project 075-15-2024-541

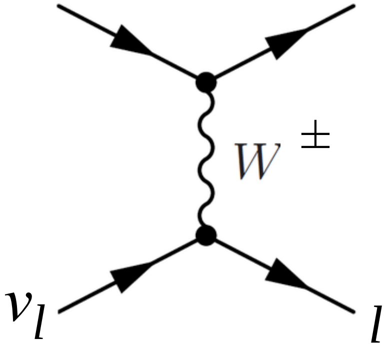
- Baikal-GVD collaboration, Yu. Kovalev, A. Plavin and D. Semikoz, who kindly allowed to show some new results for the first time (slides 18-21)

Baikal-GVD et al.
preliminary

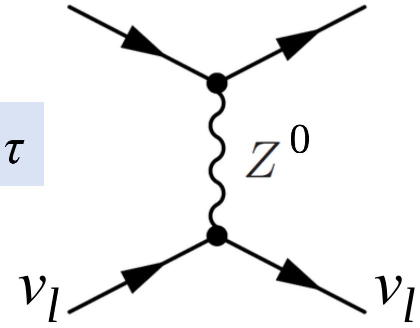
High-energy neutrino detection: tracks and cascades

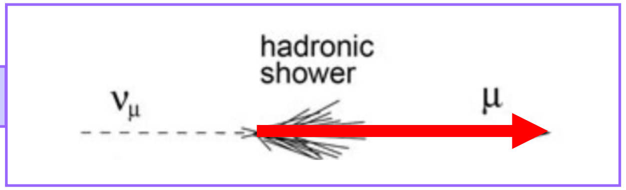


KM3NeT, RICAP2024

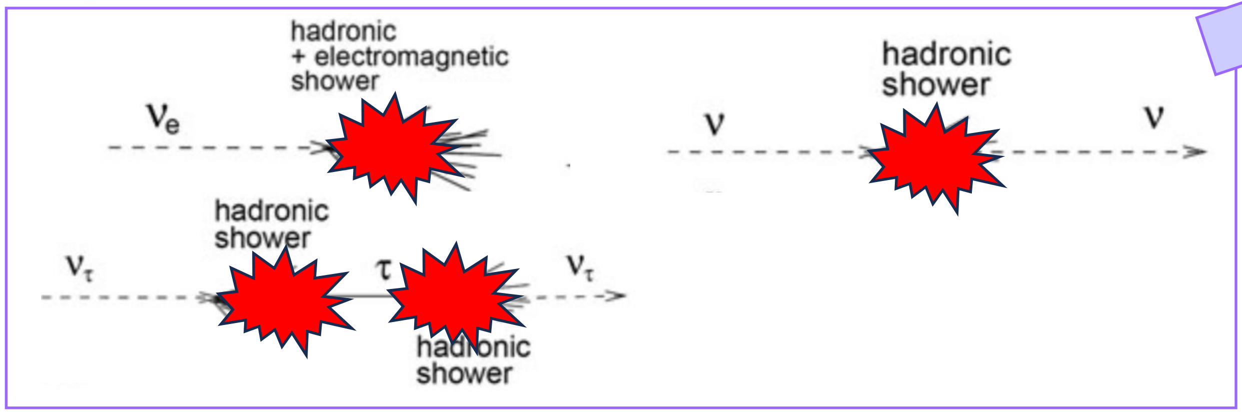


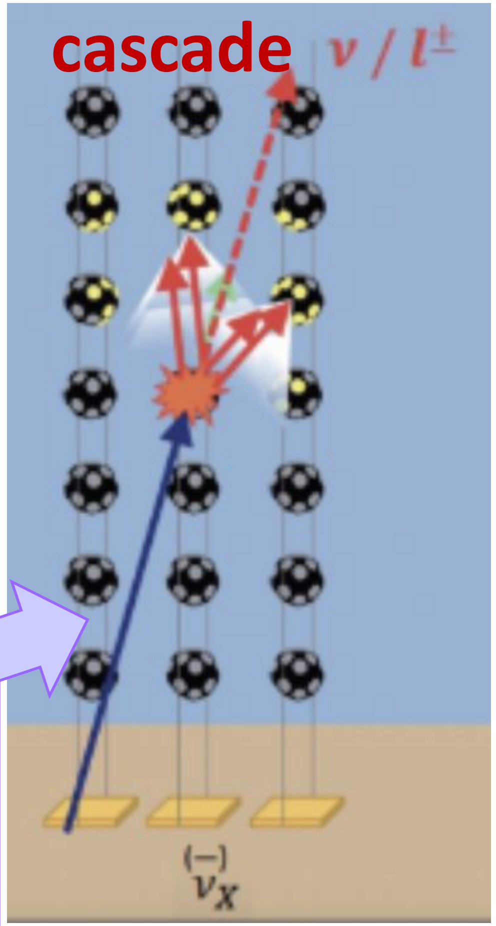
$l = e, \mu, \tau$





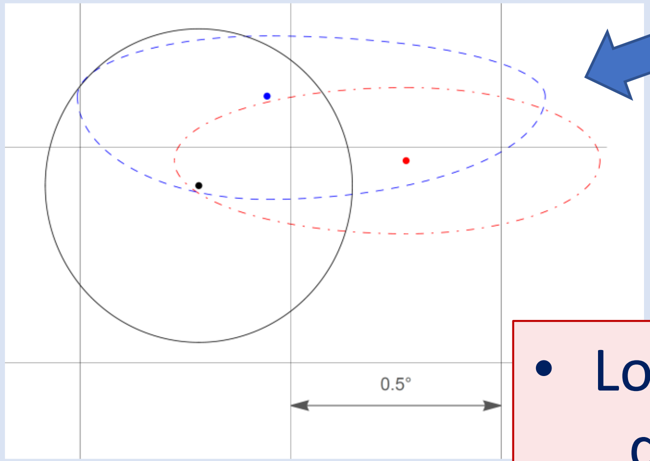
Capone, Lipari, Vissani 2018





KM3NeT, RICAP2024

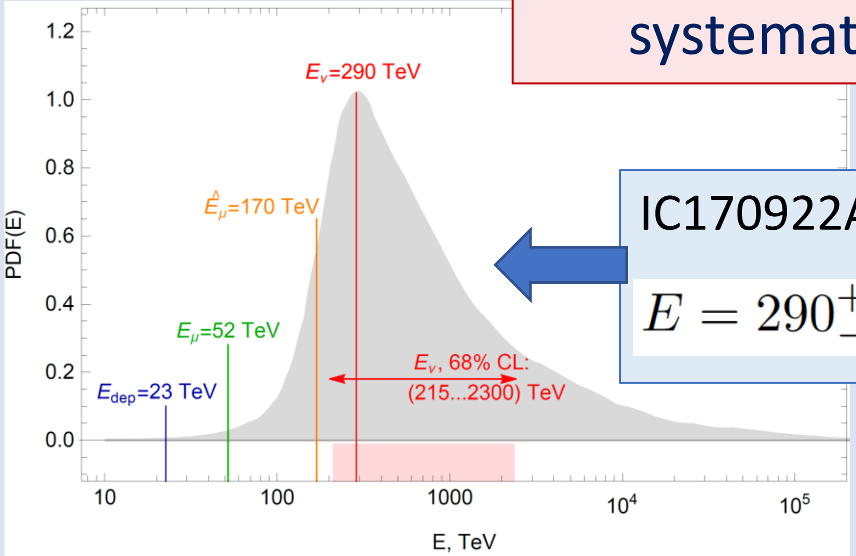
Neutrino astronomy: some troubles



one E>4 PeV track: direction in three published reconstructions

IceCube **tracks**

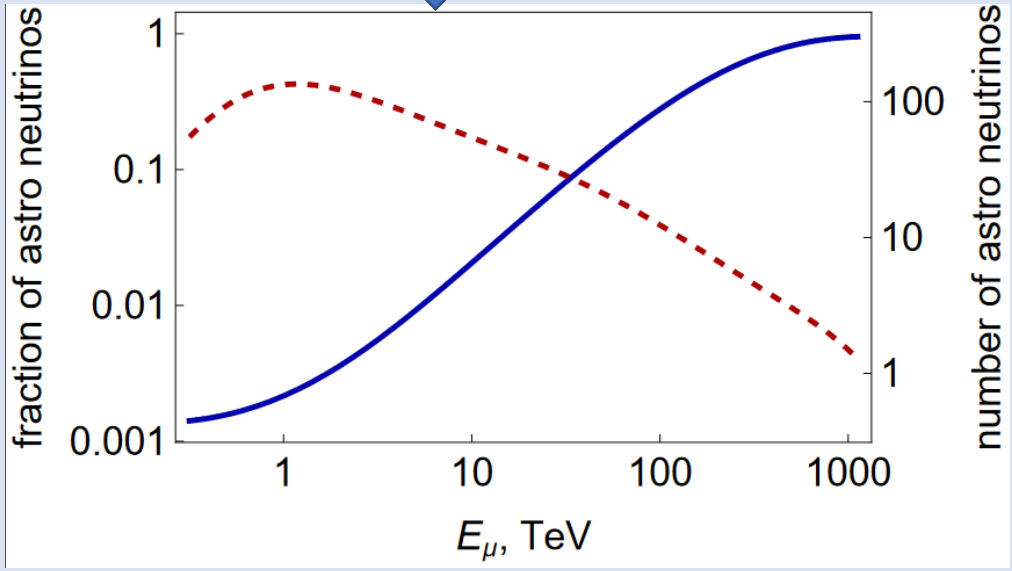
- Low precision of directions and energies, large systematic errors



IC170922A track:

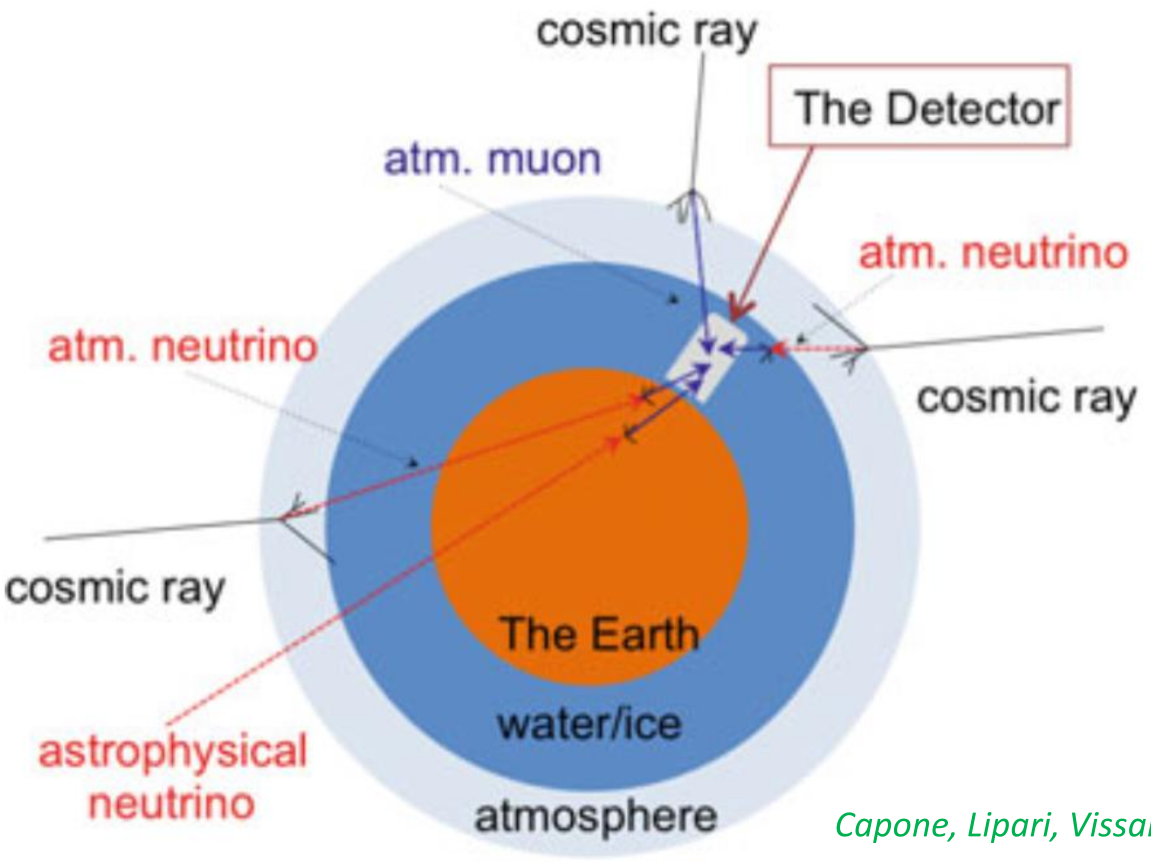
$$E = 290^{+2010}_{-75}\ \text{TeV}$$

- Lots of neutrinos (and muons) are produced in the atmosphere: the astrophysical signal much smaller than the background except for very high energies



All-sky: neutrino come through the Earth, but…

➢ **backgrounds strongly depend on the direction!**



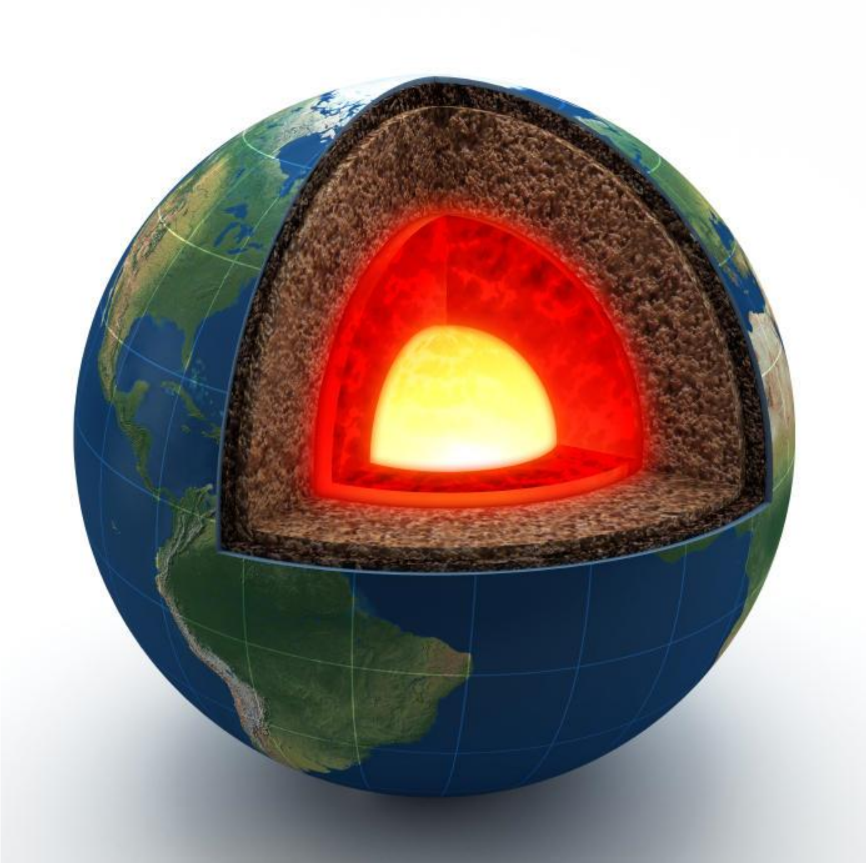
Capone, Lipari, Vissani 2018

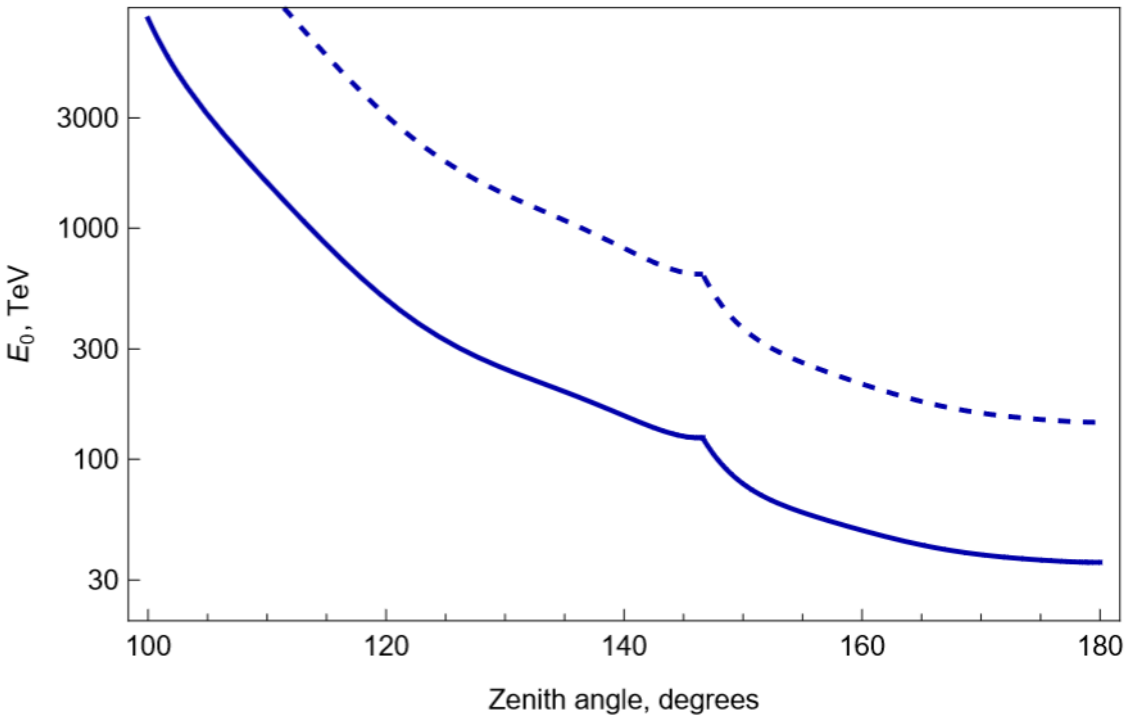
<u>downgoing:</u>
astro neutrino
atmospheric neutrino
atmospheric muons

<u>upgoing:</u>
astro neutrino
atmospheric neutrino
~~atmospheric muons~~

All-sky: neutrino come through the Earth, but…

- not at high energies!

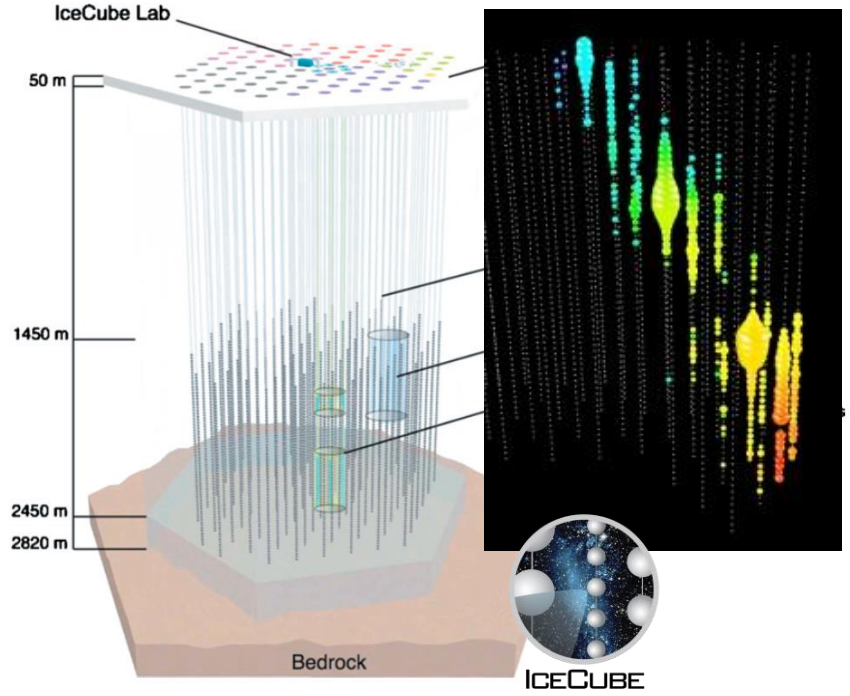


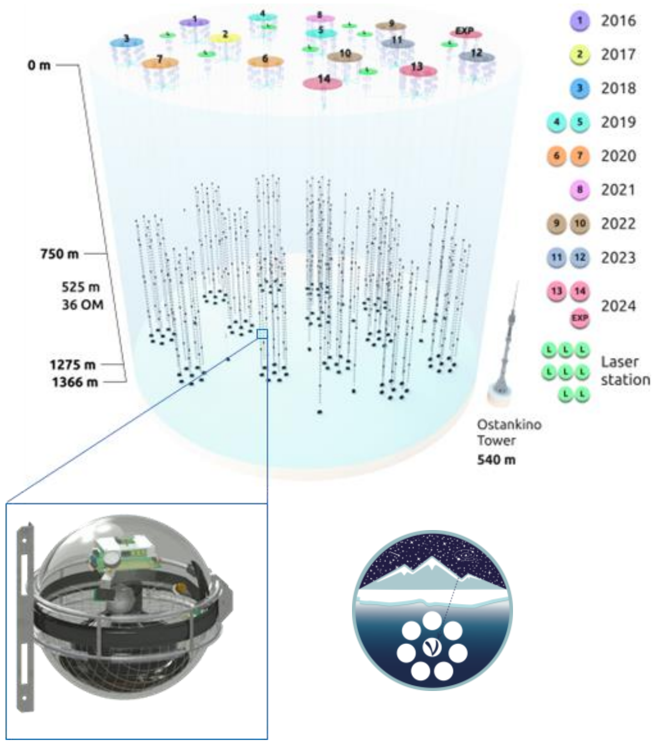


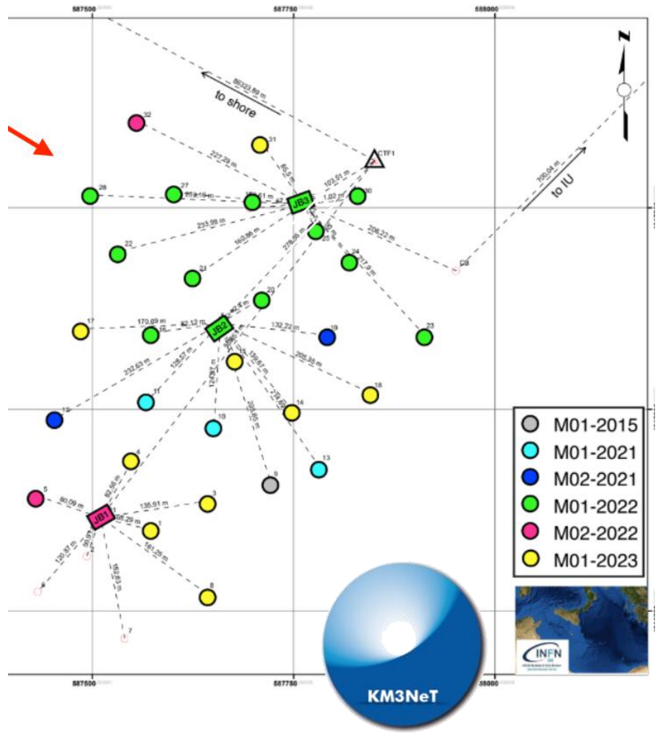
ST 2021

FIG. 4. The critical energy E_0 for which the optical depth for the electron neutrino with respect to its interaction with the Earth's matter is 1 (solid line) or 2.3 (dashed line, 90% of neutrinos interact) as a function of the zenith angle. At energies $\gtrsim E_0$, the Earth gradually becomes opaque to neutrinos coming from this direction.

Neutrino telescopes







IceCube:
- South Pole (ice), operates since 2008, complete since 2011
- dominates the world data because of exposure
- current: ~1 km^3, plan: ~1 km^3

Baikal-GVD:
- Lake Baikal (fresh water), operates since 2018, still growing
- current: ~0.65 km^3, plan: ~2 km^3

KM3NeT:
- Mediterranean Sea (saline water), operates since 2024
- current: ~0.12 km^3, plan: ~2 km^3

Neutrino telescopes: a personal look

ICECUBE

• ice: low light absorption (collect light from larger volume)
• ice: high light scattering (low angular resolution)
• ice: unmovable impurities, hard to measure (huge systematic uncertainties)

IceCube:
• South Pole (ice), operates since 2008, complete since 2011
• dominates the world data because of exposure
• current: ~1 km^3, plan: ~1 km^3

• not that deep (background of atmospheric muons)
• water: low light scattering (angular resolution 4 times better than in ice)
• easy water control
• cheap construction and operation

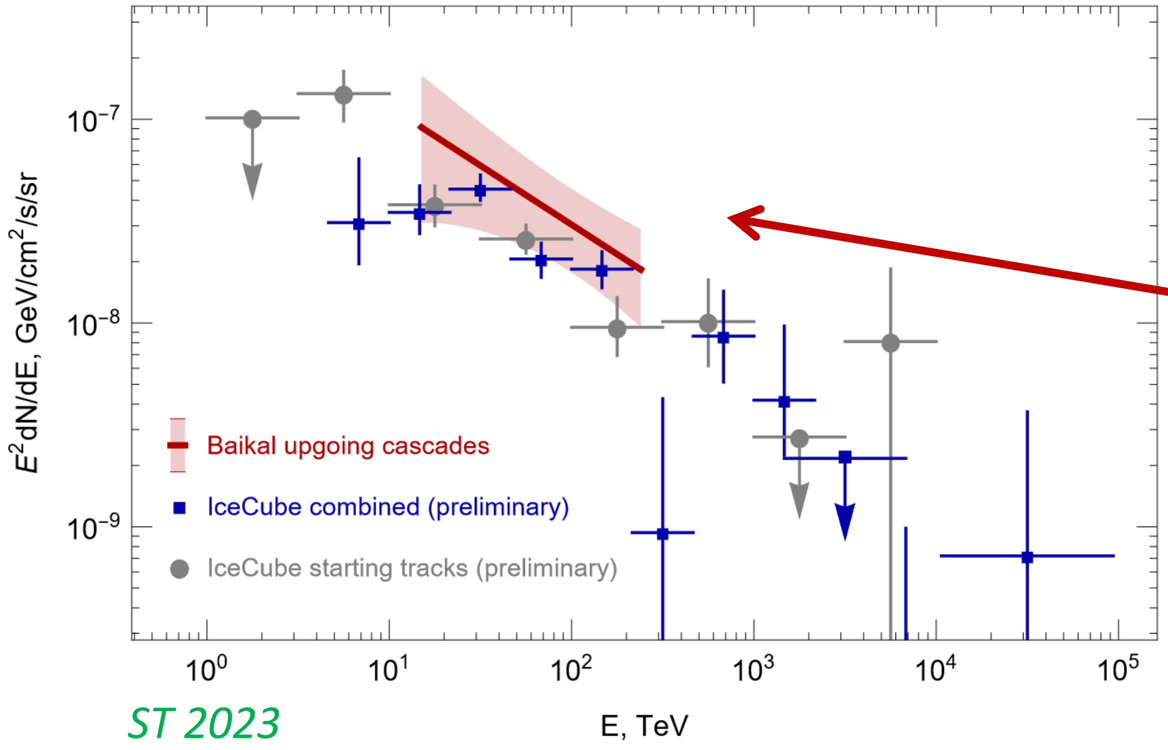
Baikal-GVD:
• Lake Baikal (fresh water), operates since 2018, still growing
• current: ~0.65 km^3, plan: ~2 km^3

KM3NeT

• advanced optical modules
• depth
• low scattering, good resolution
• background at the PMT level (40K, bioluminescence)
• expensive, hence slow

KM3NeT:
• Mediterranean Sea (saline water), operates since 2024
• current: ~0.12 km^3, plan: ~2 km^3

Astrophysical HE neutrinos exist:
the only IceCube result confirmed by an independent experiment!



ST 2023

Baikal-GVD, upgoing cascades:

Seasons	N_{data}	N_{bckg}	P-value	σ(stat.)
18-21	11	3.2	$1.7x10^{-3}$	3.13
18-22	19	5.7	$1.11x10^{-5}$	4.24
18-23	**Stay tuned ☺**			

Baikal-GVD Phys.Rev.D 107 (2023) 4

Baikal-GVD RICAP 2024 preliminary

Many other claims to test

TXS 0506+056

- IceCube track (290 TeV) + gamma-ray flare

  IceCube et al. Science 361 (2018) eaat1378
- IceCube low-energy flare in 2014

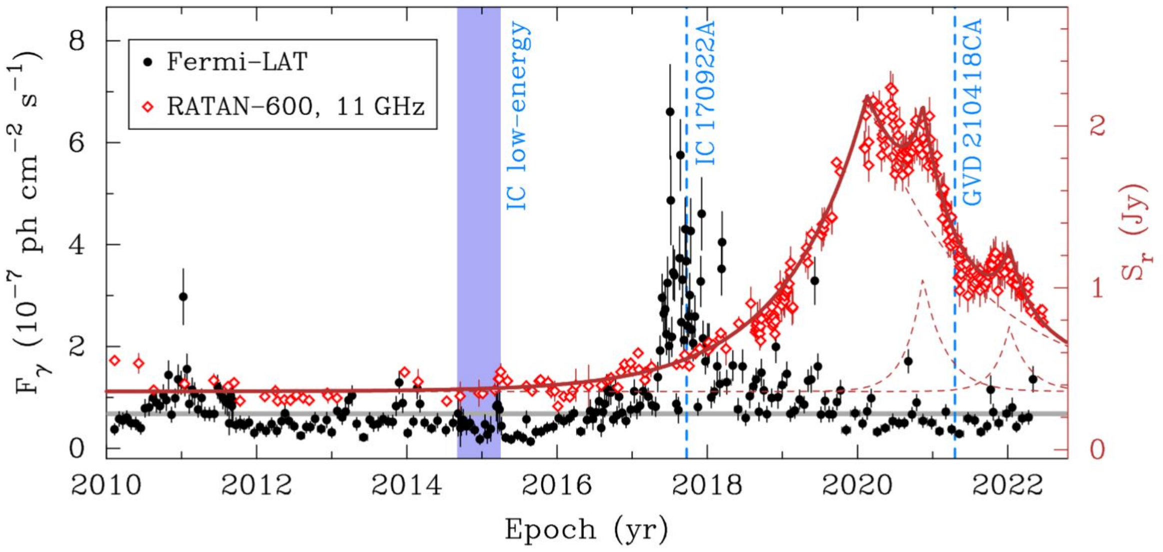
  IceCube Science 361 (2018) 147

(disappeared in the new analysis

IceCube arXiv:2307.14559)

– the highest-energy Baikal upgoing cascade comes from TXS 0506+056

Baikal-GVD et al. MNRAS 527 (2023) 8784



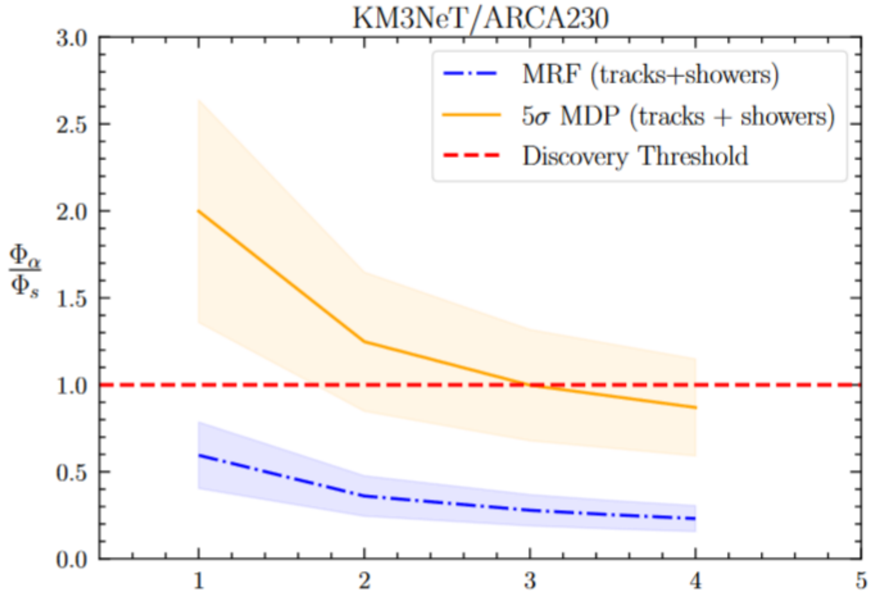
M77 aka NGC 1068

- IceCube “4-sigma” excess
- very soft spectrum (close to atmospheric)
- 2 sigma in full-sky analysis

  IceCube Science 378 (2022) 538

- needs to be tested!

KM3NeT arXiv:2402.09088

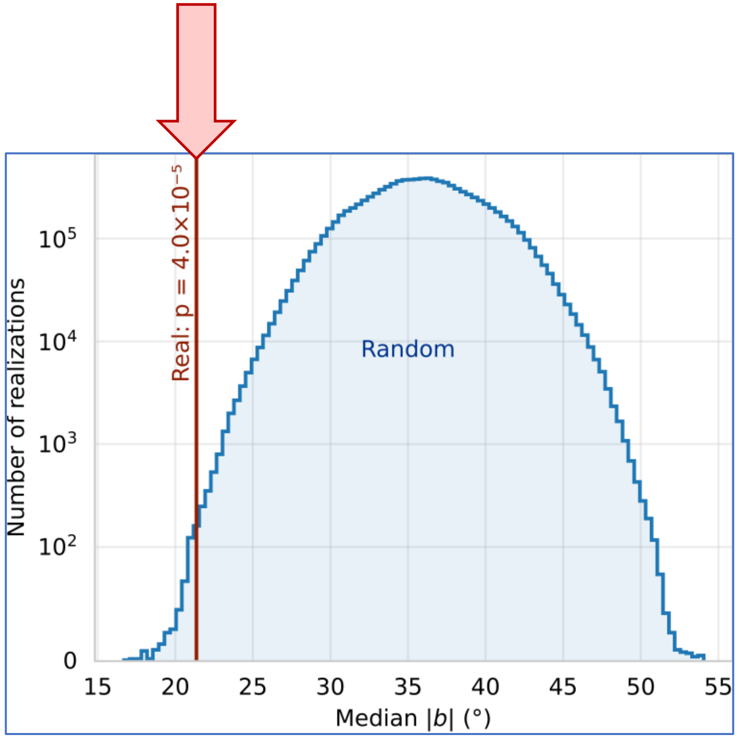


years of full KM3NeT operation

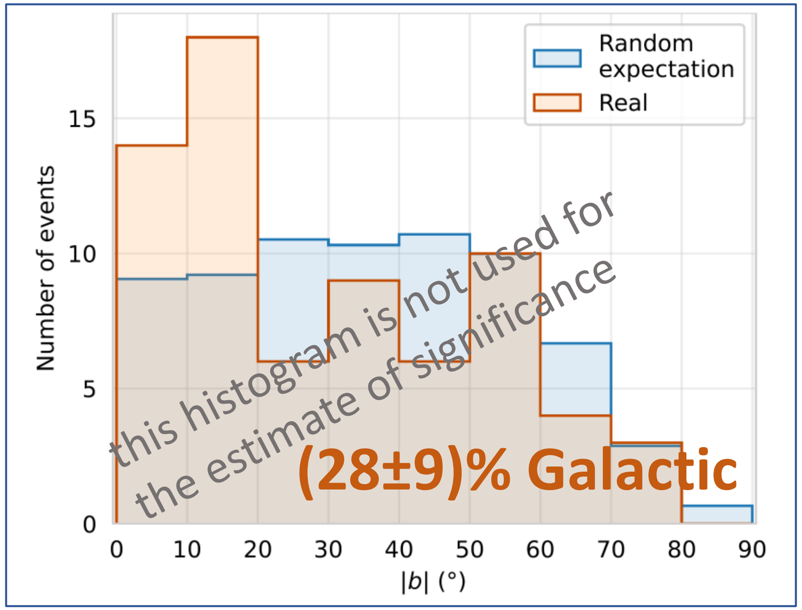
Galactic anisotropy of IceCube tracks above 200 TeV

the simplest observable:
median of the absolute Galactic latitude

- sample of 70 high-quality IceCube events
  - **pre-defined**: selected with the criteria fixed in the radio blazar search (tracks, energy >200 TeV, 90% CL error contour area <10 sq.deg.)



- MC samples (RA scrambled)
- p-value $p=4\times10^{-5}$ (4.1σ)
- pre-defined sample: no trials
- simplest unbinned test

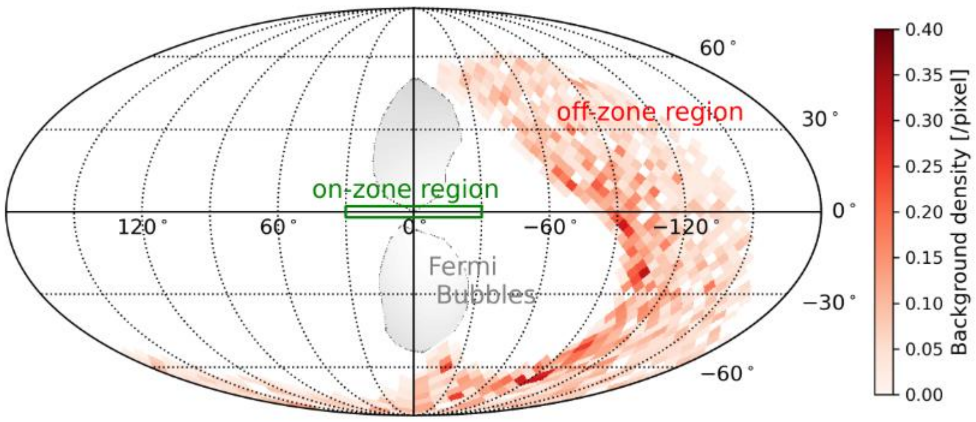


Kovalev, Plavin, ST *ApJL 940 (2022) L41*

ANTARES: Galactic ridge

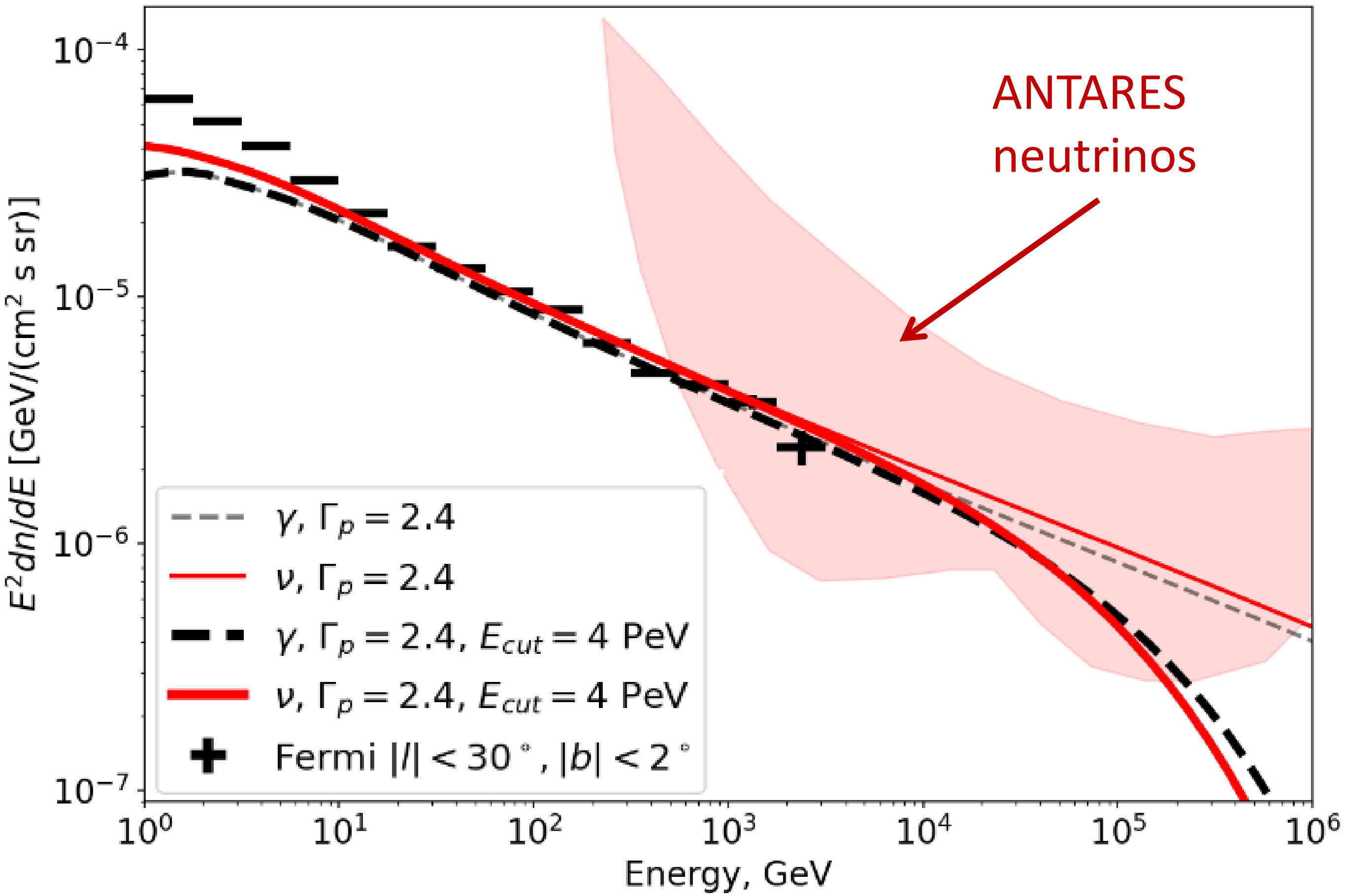
on/off method

on-zone: |l|<30°, |b|<2°



- 2.0σ significance
- consistent with Fermi-LAT spectrum for the same region *Neronov&Semikoz 2019*
- Γ=2.4 for protons (not 2.7)

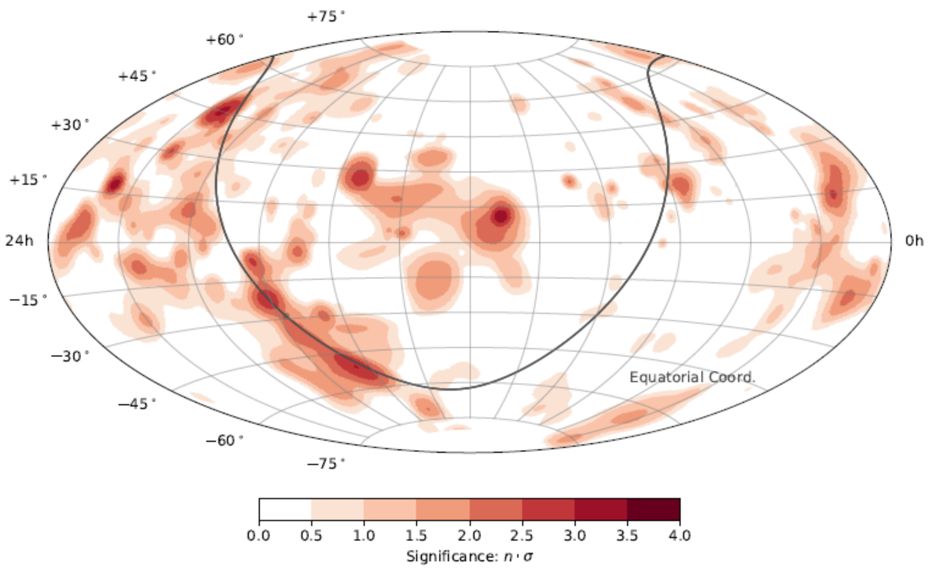
on-zone fluxes:



ANTARES Phys. Lett. B 841 (2023) 137951

IceCube: cascades

- pre-defined spectral and directional shapes (**templates**), free normalizations
- three templates used, all lead to (different) positive signals
- final significance, 4.5σ, includes correction for the 3 trials



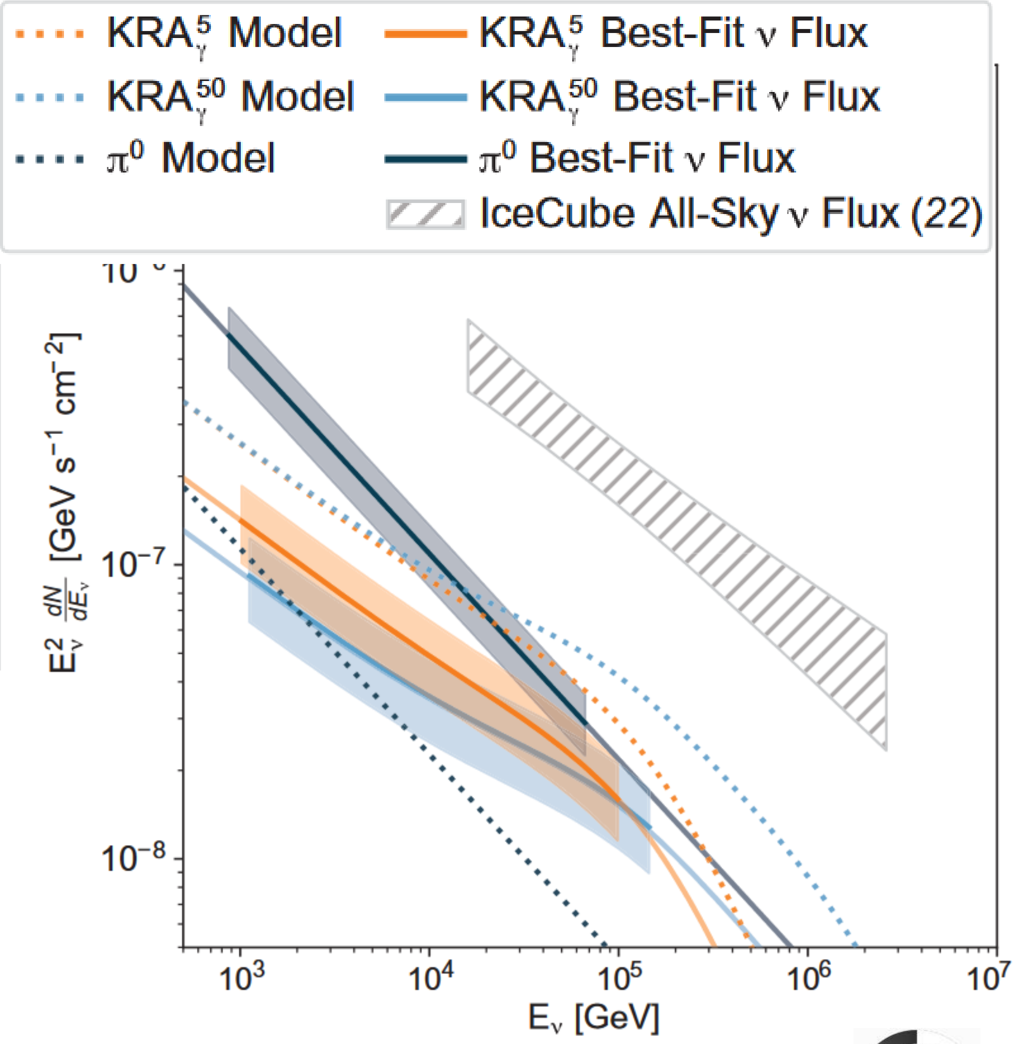
- **π^0 template**
  - assume that Fermi-LAT Galactic photon emission at GeVs comes from π^0 decays. Take the corresponding neutrinos from $\pi^\pm$ decays and extrapolate from GeVs to TeVs with $E^{-2.7}$ spectrum
- **KRAγ^5 template**
  - use the DRAGON model to calculate the expected neutrino flux, assuming model distribution of cosmic rays and gas and the CR spectral cutoff at 5 TeV
- **KRAγ^5 template**
  - the same but fot the CR spectral cutoff at 50 TeV

IceCube Science 380 (2023) 6652

IceCube: cascades

- pre-defined spectral and directional shapes (**templates**), free normalizations
- three templates used, all lead to (different) positive signals

	Flux sensitivity Φ	P value	Best-fitting flux Φ
Diffuse Galactic plane analysis			
π^0	5.98	1.26×10^{-6} (4.71σ)	$4.9^{+1.2}_{-1.1} \times$ MF
KRA_γ^5	0.16 × MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times$ MF
KRA_γ^{50}	0.11 × MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times$ MF



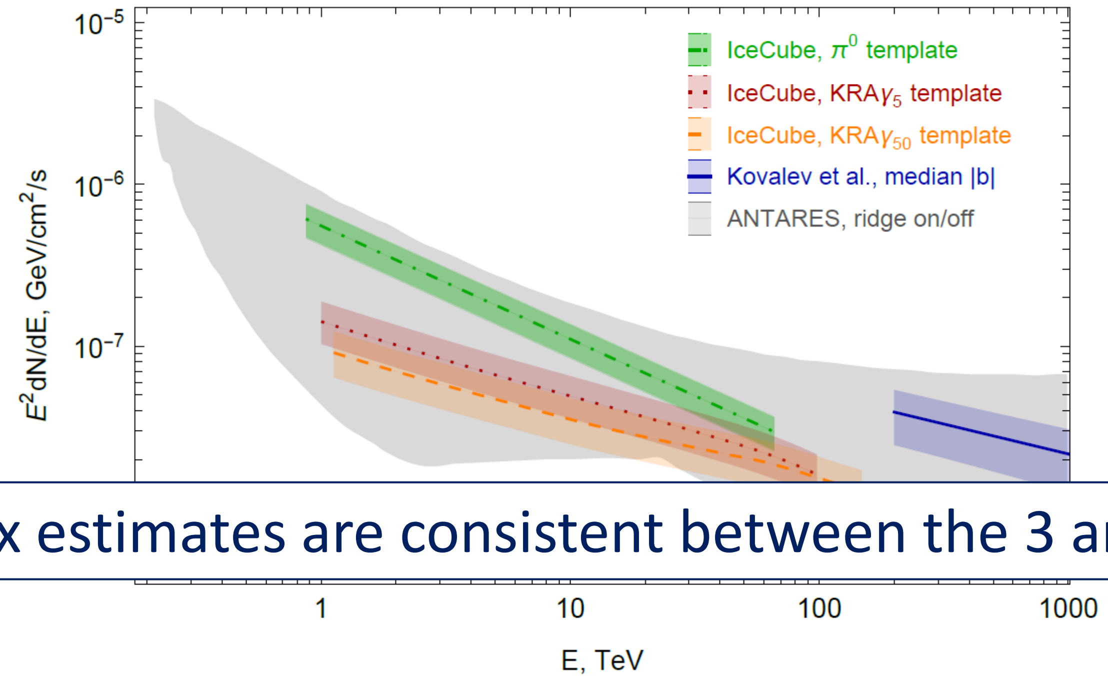
- normalizations do not match models, nor each other

IceCube Science 380 (2023) 6652

Comparison of analyses

*very uncertain because of differences in analyses and sky coverage

Analysis	Energies	Method	Significance
Kovalev et al., 2022 ApJL	$\gtrsim$ 200 ТэВ	median of $\|b\|$ distribution	4.1σ
ANTARES, 2022 PLB	$\sim 1 - 100$ TeV	on/off, ridge	2.0σ
IceCube, 2023 Science	$\sim 1 - 100$ TeV	templates	4.5σ

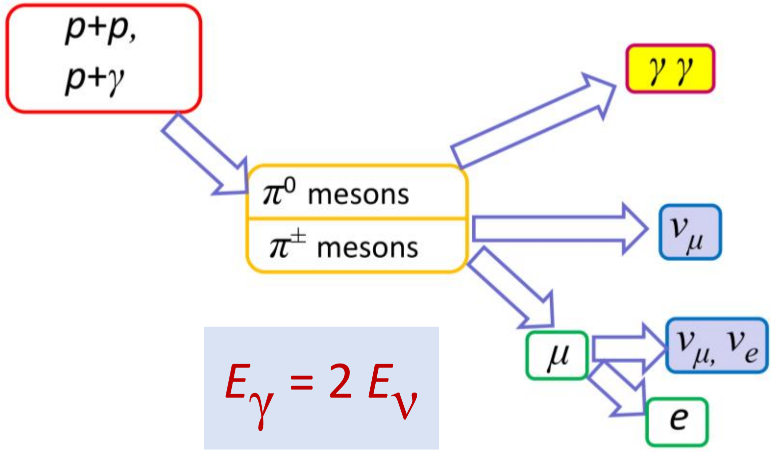


ST 2023

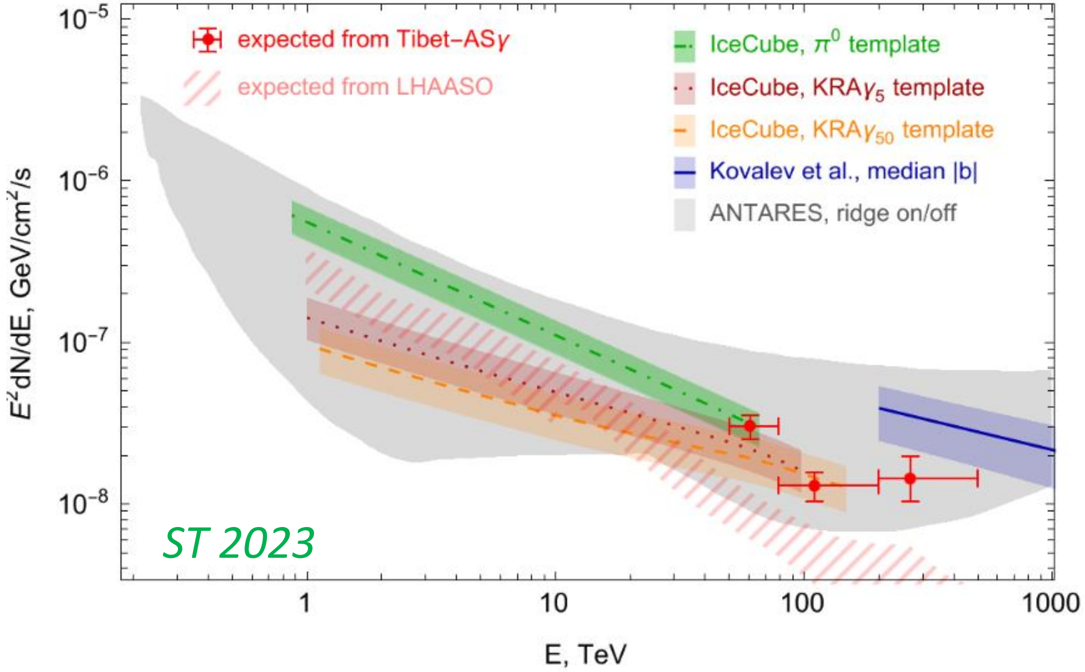
full-sky Galactic flux estimates are consistent between the 3 analyses (assumptions used)

Comparison with diffuse gamma rays

*very uncertain because of differences in analyses and sky coverage



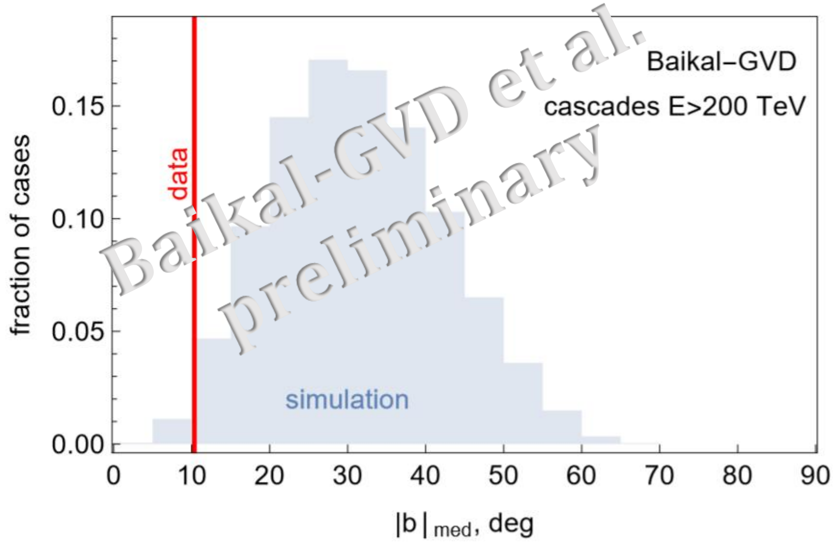
$E_\gamma = 2\, E_\nu$

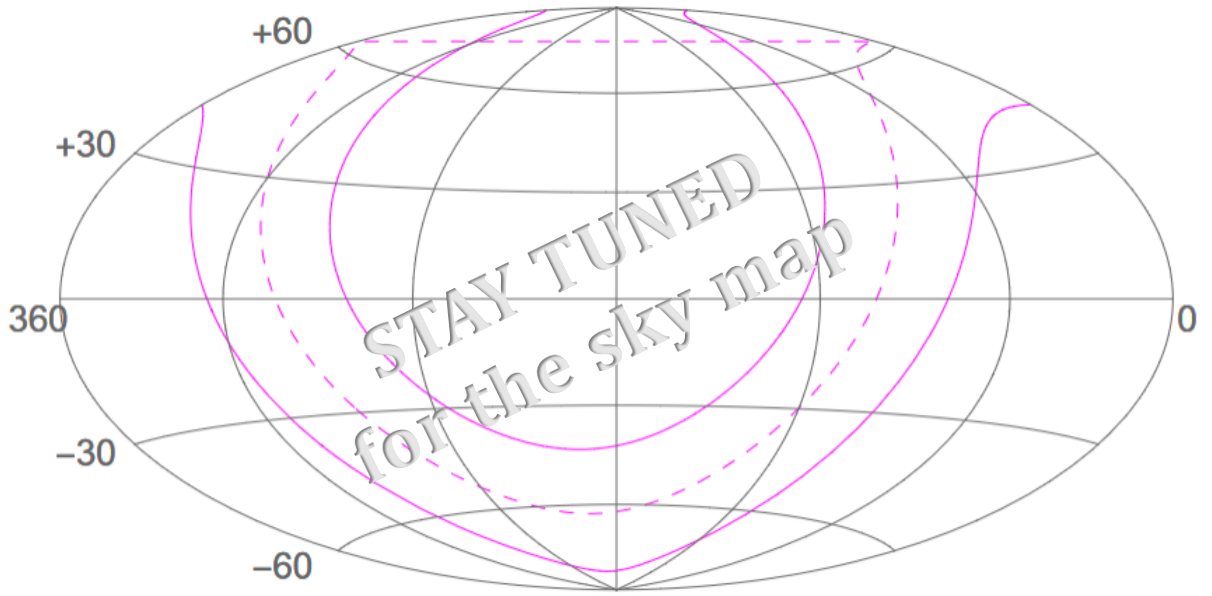


- (model-dependent) recalculation of Tibet-ASγ and LHAASO measurements to the expected corresponding neutrino flux *Fang & Murase 2021, 2023; ST 2023*
- neutrinos and gamma rays match quite well
- note: contribution of point sources to the Galactic neutrino flux is expected (the notion of diffuse flux is uncertain)

Galactic neutrinos with Baikal-GVD

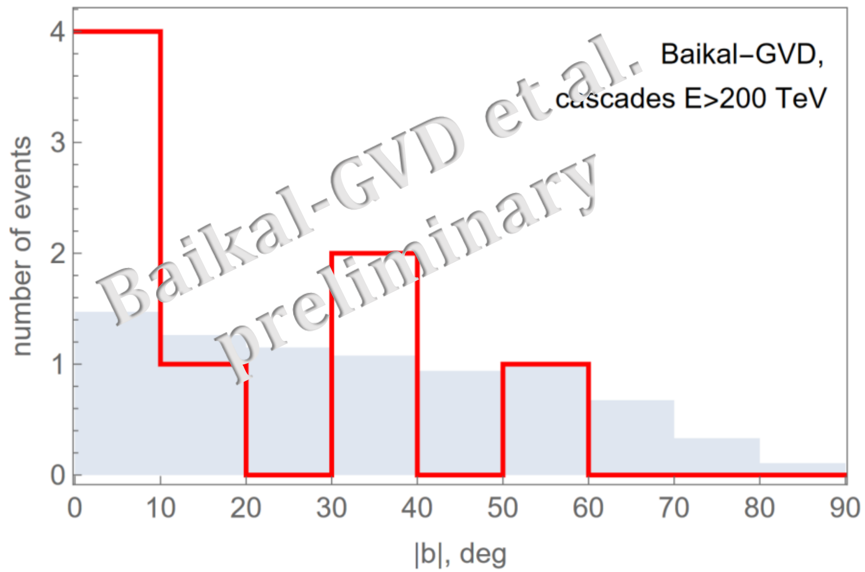
- test the Galactic excess at E>200 TeV
- high-energy cascades 2018-2023
- simplest, model-independent median |b| test like in Kovalev et al. 2022





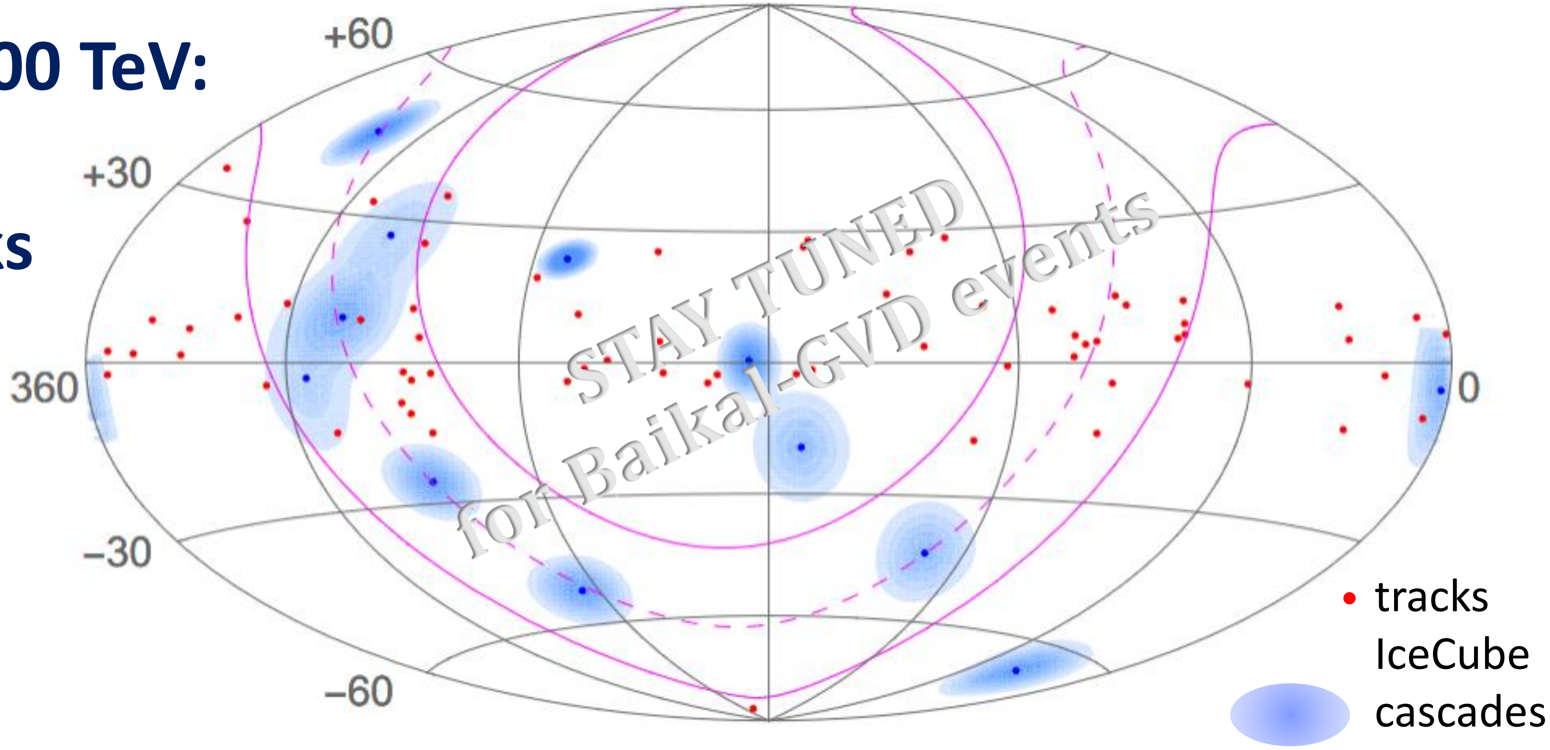
Sample	$\lvert b\rvert_{\rm med}$ observed	$\langle\lvert b\rvert_{\rm med}\rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4\cdot10^{-2}$ (2.5σ)

Baikal-GVD et al. preliminary

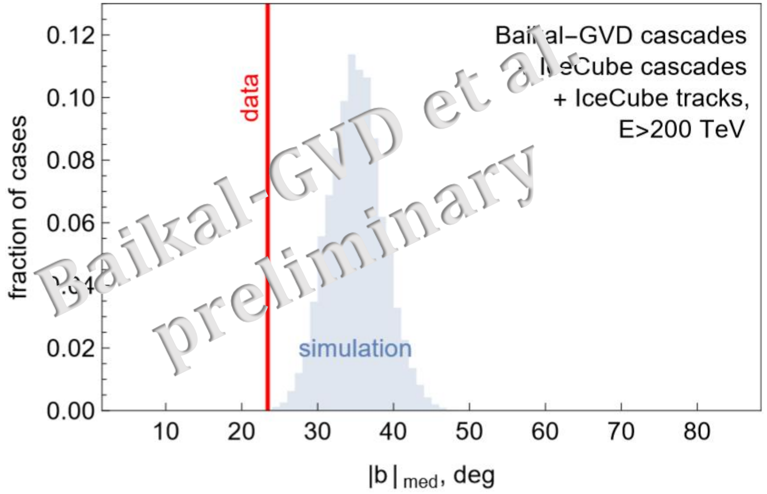


Galactic neutrinos above 200 TeV: Baikal-GVD cascades, IceCube cascades and tracks

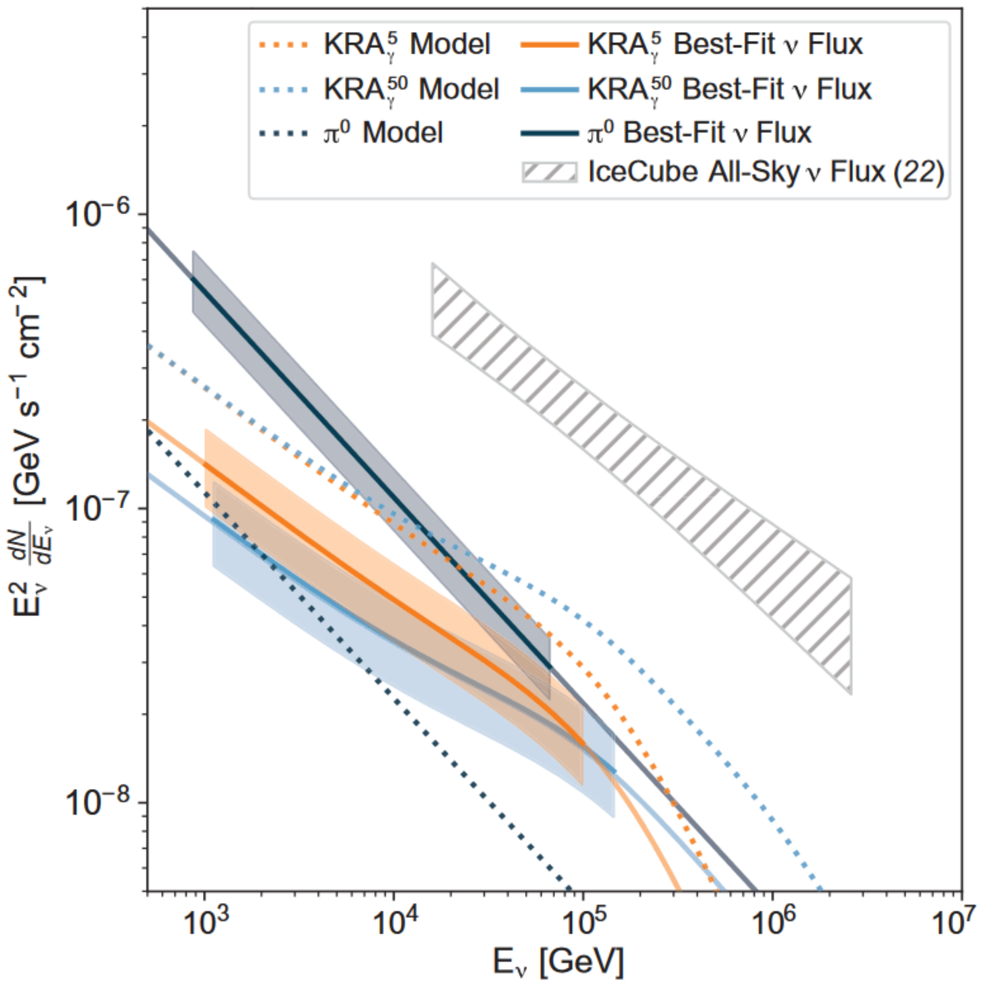
- newest IceCube public data
  - ✓ HESE cascades *IceCube 2023*
  - ✓ ICECAT v2 tracks *IceCube 2024*
- same selection (E>200 TeV)
- same median |b| test
- **same results**



Sample	$\lvert b\rvert_{\rm med}$ observed	$\langle \lvert b\rvert_{\rm med}\rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4 \cdot 10^{-2}$ (2.5σ)
IceCube cascades	12.4°	31.9°	$8.7 \cdot 10^{-3}$ (2.6σ)
IceCube tracks	24.7°	36.0°	$1.8 \cdot 10^{-3}$ (3.1σ)
combined	23.4°	35.0°	$3.4 \cdot 10^{-4}$ (3.6σ)



Say no to templates



200 TeV < E < 1000 TeV, Milky Way:	Flux	Fraction
Predicted by templates:		
KRAγ_5	0.34	–
KRAγ_{50}	0.78	–
π^0	0.077	–
Templates normalized to IceCube [8]:		
KRAγ_5	$0.19^{+0.06}_{-0.05}$	$0.044^{+0.016}_{-0.014}$
KRAγ_{50}	$0.29^{+0.10}_{-0.09}$	$0.067^{+0.026}_{-0.024}$
π^0	$0.37^{+0.09}_{-0.08}$	$0.086^{+0.026}_{-0.025}$
Estimated in Ref. [6]:		
IceCube tracks	1.27 ± 0.49	0.28 ± 0.09
Estimated in the present work:		
Baikal-GVD cascades	$1.20^{+1.59}_{-0.75}$	$0.49^{+0.51}_{-0.24}$
IceCube cascades	$0.96^{+1.14}_{-0.56}$	$0.26^{+0.30}_{-0.12}$
IceCube tracks	$1.72^{+0.91}_{-0.71}$	$0.34^{+0.17}_{-0.12}$

Baikal-GVD et al.
preliminary

Say no to templates

- IceCube template-based results very sensitive to the choice of templates
- KRAγ uses DRAGON (simplified cosmic-ray distribution)
- KRAγ: cosmic-ray cutoff @ 5 or 50 PeV $E_p = 20\ E_\nu$
- Galactic protons observed up to energies an order of magnitude higher, e.g. *Telescope Array Collab. 2020*
- Better cosmic-ray propagation models are needed! *Giacinti & Semikoz 2023*
- Significant local contribution (Local Bubble?) *Andersen et al. 2018, Bouyahiaoui et al. 2020*

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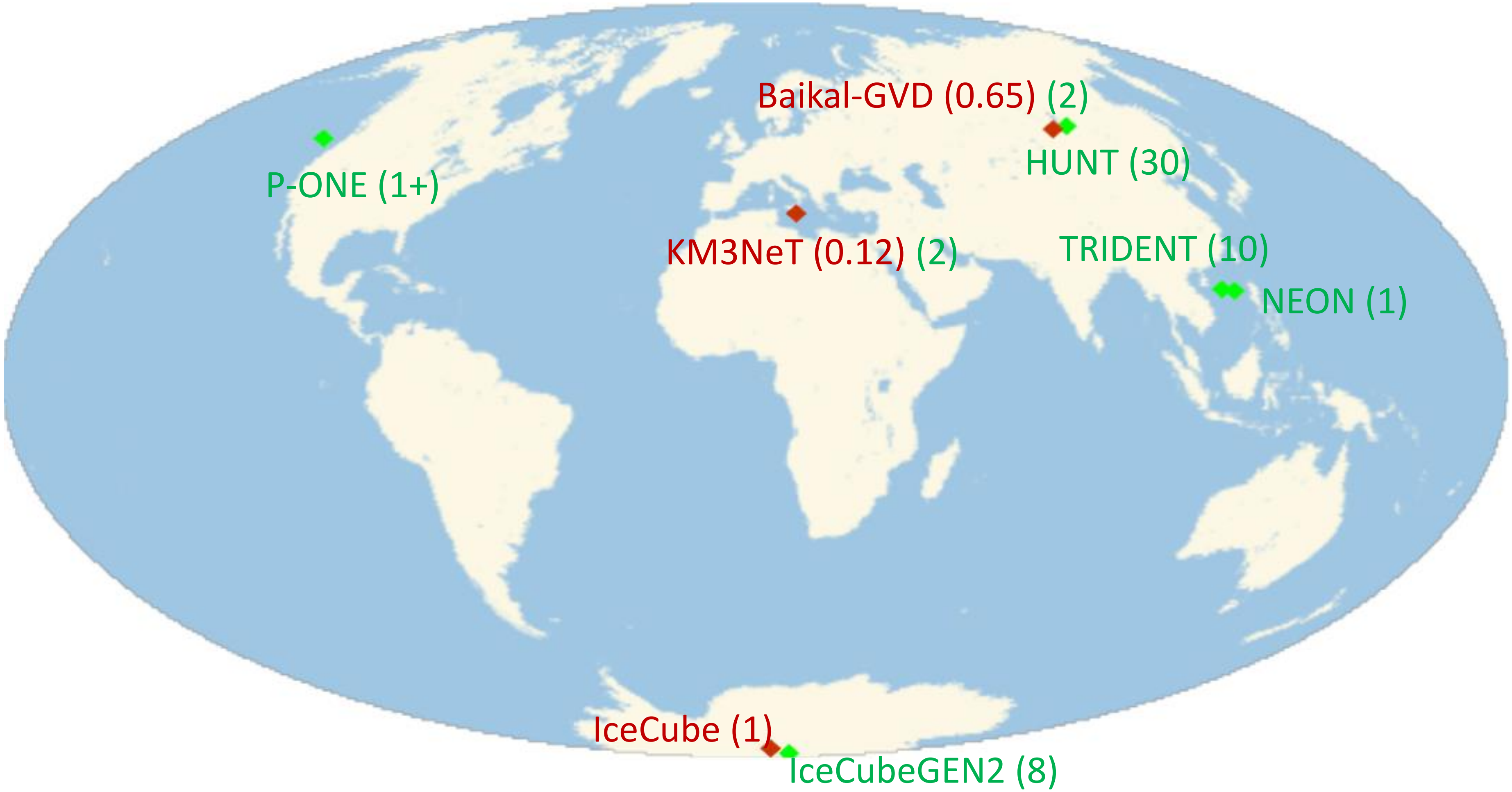
Future of all-sky neutrino surveys

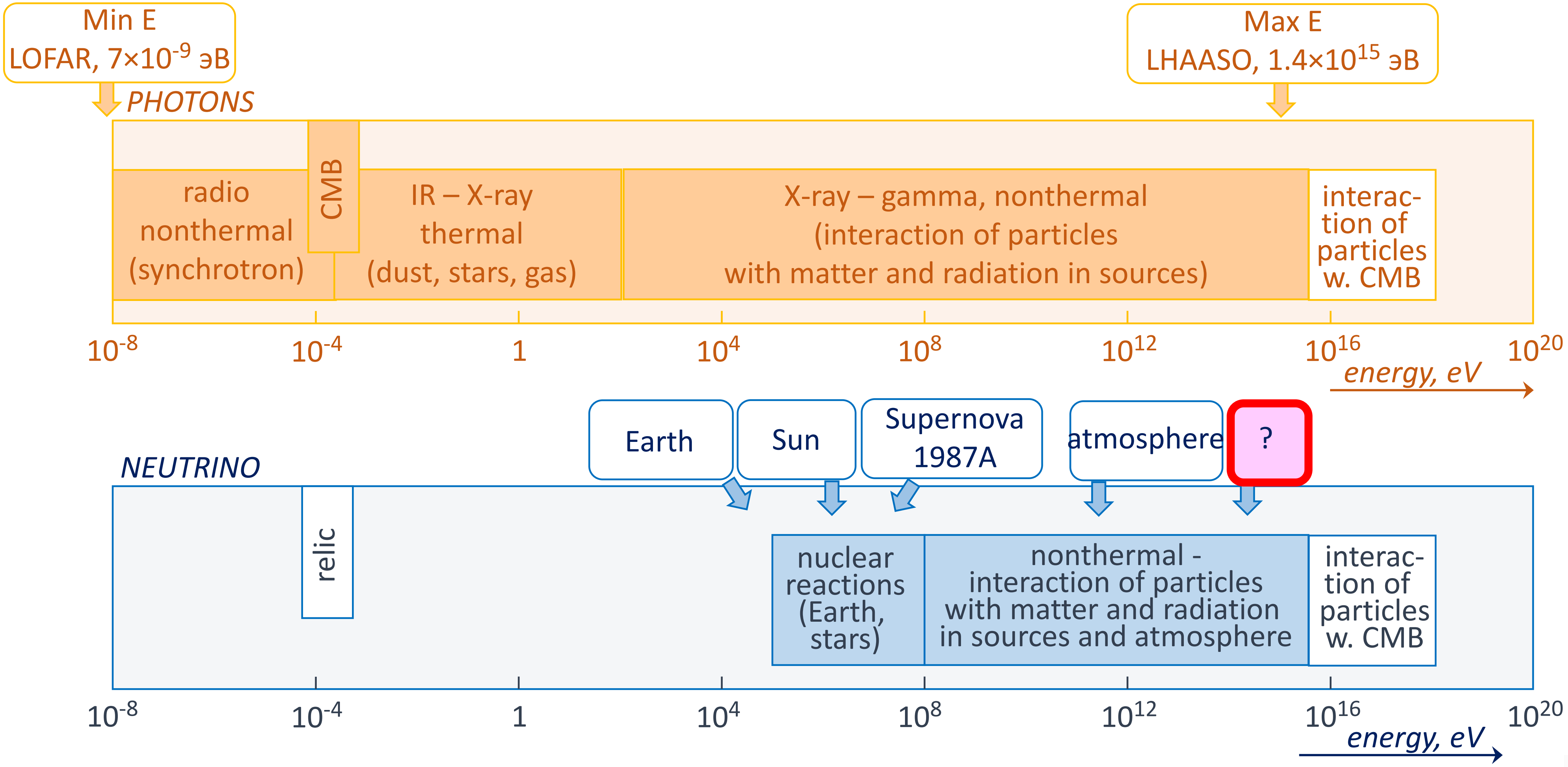


Conclusions

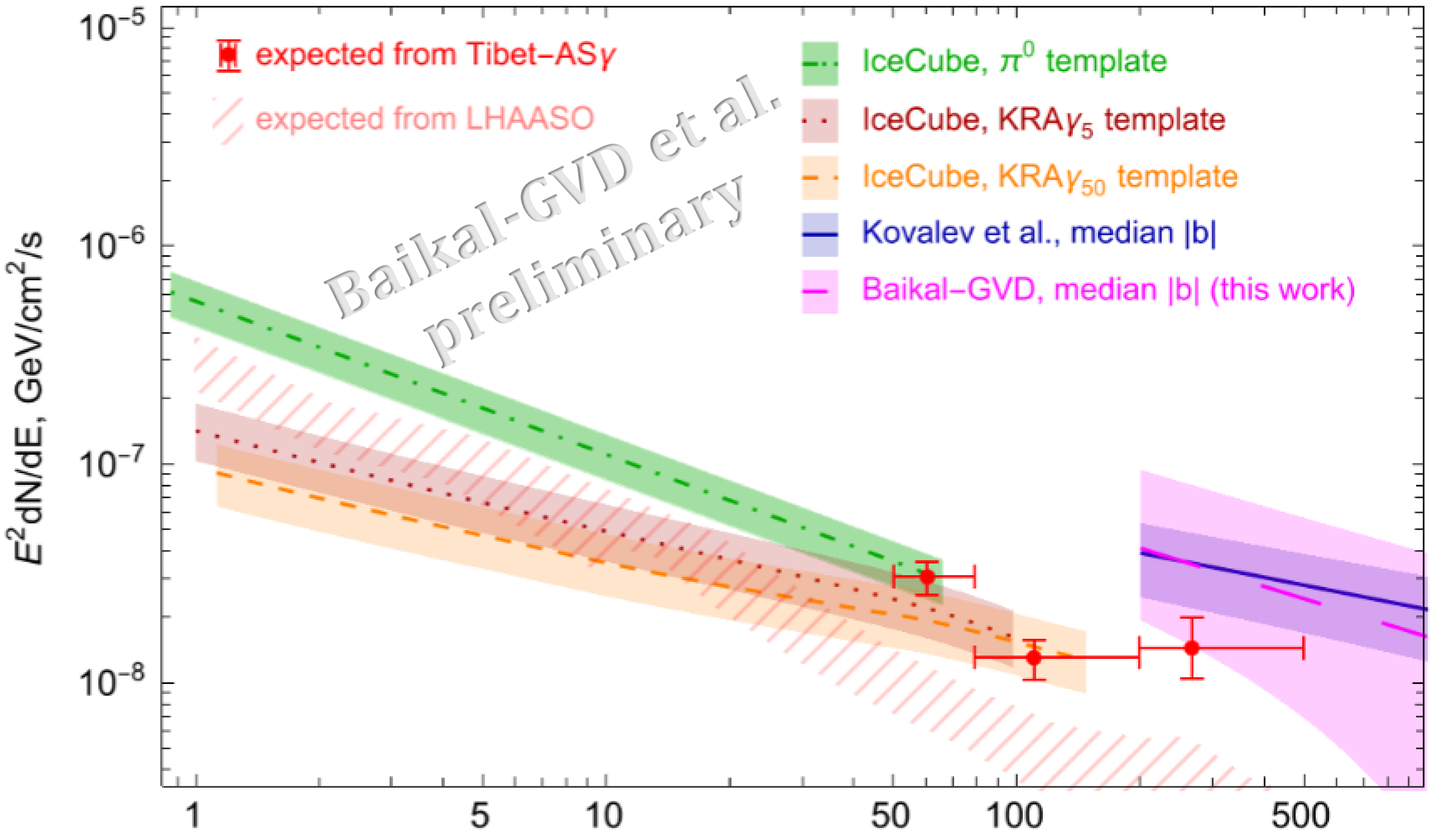
- ✓ Complementarity of neutrino telescopes (North/South, water/ice)
- ✓ Three big telescopes are taking data (IceCube, Baikal-GVD, KM3NeT)
- ✓ Baikal-GVD confirms the astrophysical neutrino flux found by IceCube
- ✓ New preliminary results from Baikal-GVD: Milky Way in E>200 TeV neutrinos, match IceCube
- ✓ Important implications for Galactic cosmic rays
- ✓ Bright all-sky future with many big but realistic projects

BACKUP SLIDES

Natural sources of neutrinos



Galactic neutrinos

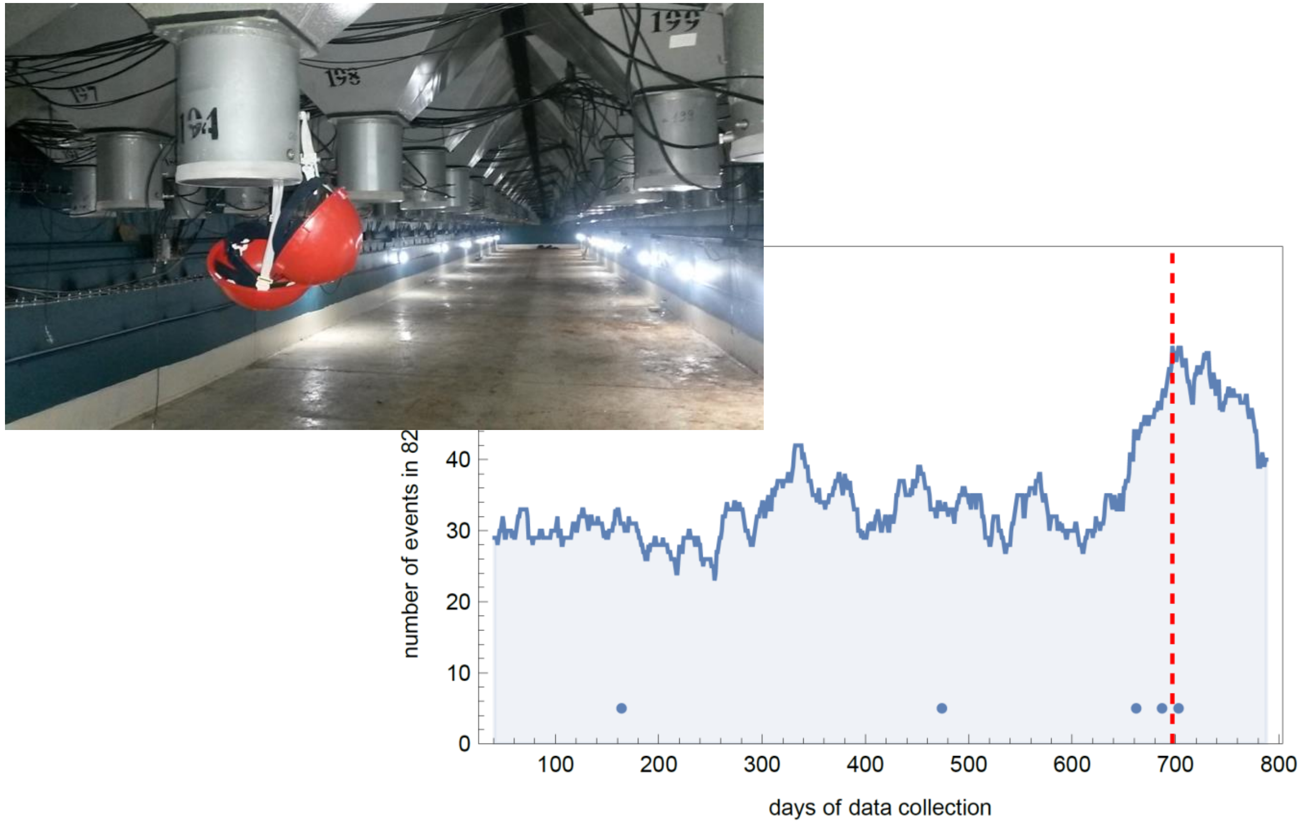


High-energy neutrinos from Galactic point sources?

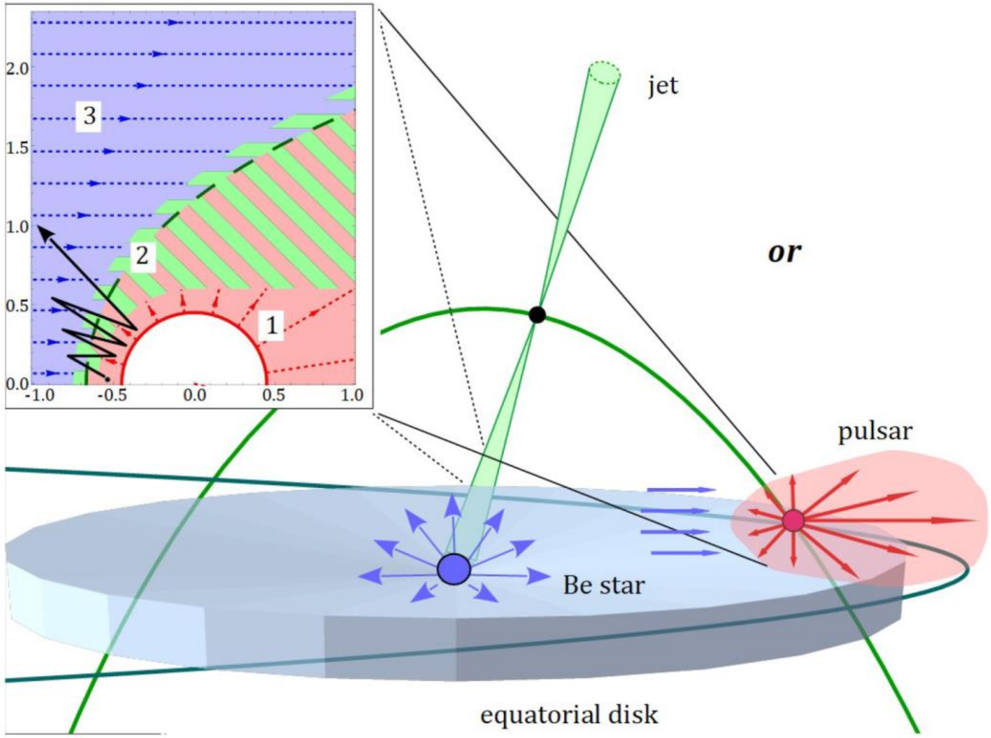
neutrino + VHE photons, one observation

- IceCube: a 150 TeV neutrino alert
- Carpet-2: E>300 TэВ flare of gamma-like events

- Cygnus region: many sources
- theory: binary system PSR J2032+4127?

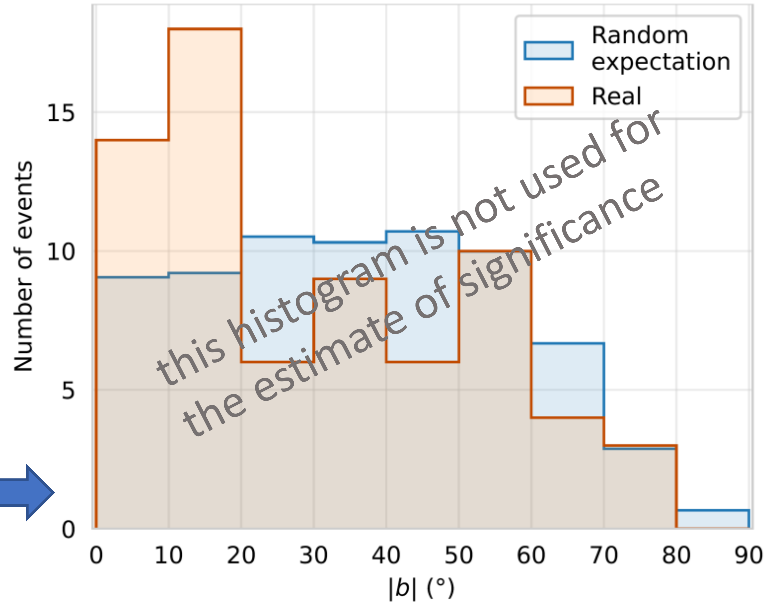


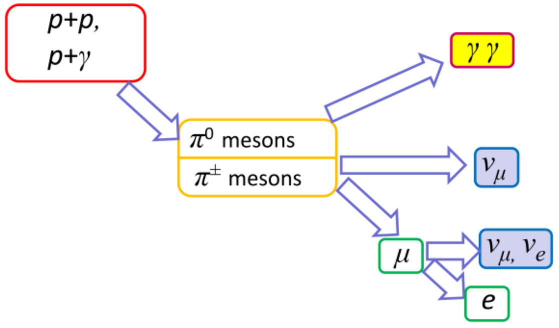
Dzhappuev et al., Astrophys. J. Lett. 916 (2021) L22



Bykov et al., Astrophys. J. Lett. 921 (2021) L10

Discussion: width of the Milky Way

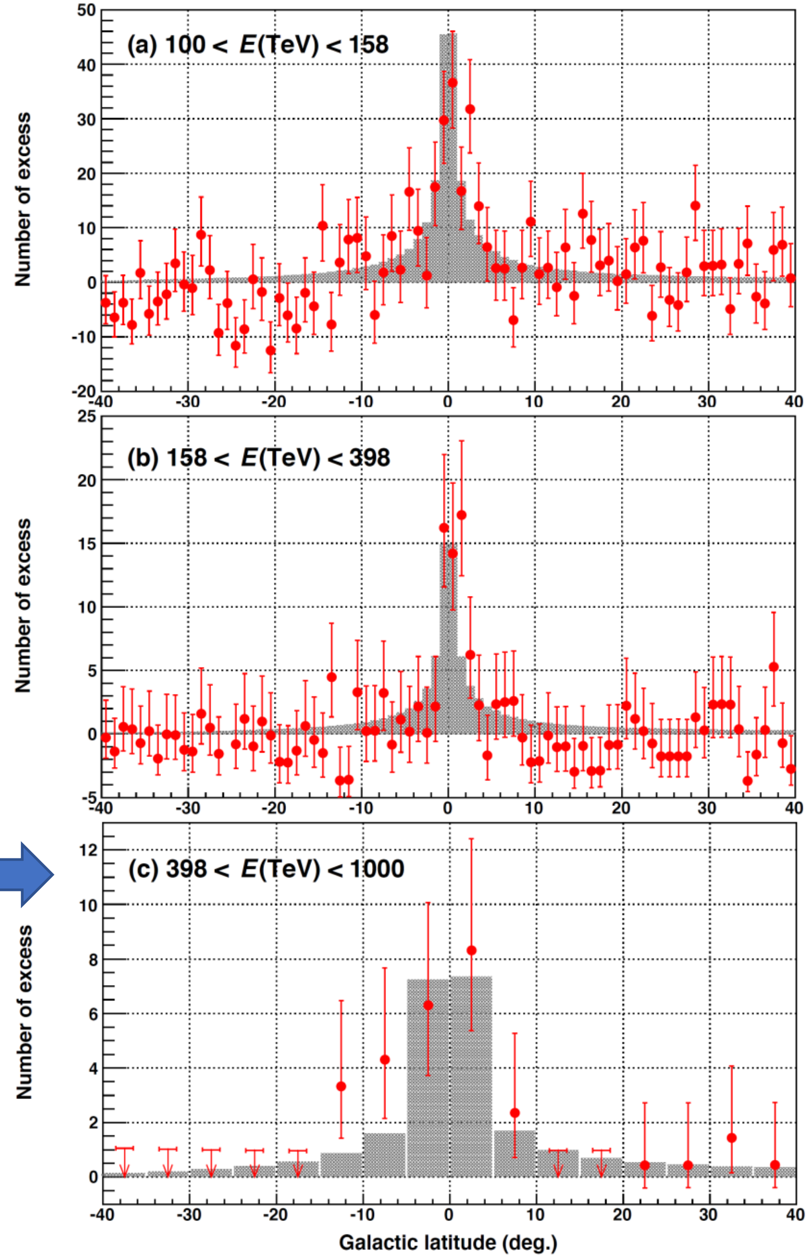




$E_\gamma = 2\, E_\nu$

neutrino >200 TeV *Kovalev+ 2022*

photons *Tibet-ASγ 2021*



- higher CR energy – larger Larmor radius
- still wider than model

similar trends in gamma rays and neutrinos