Full-sky searches for very-high-energy neutrinos

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HEACOSS-2026, Yerevan

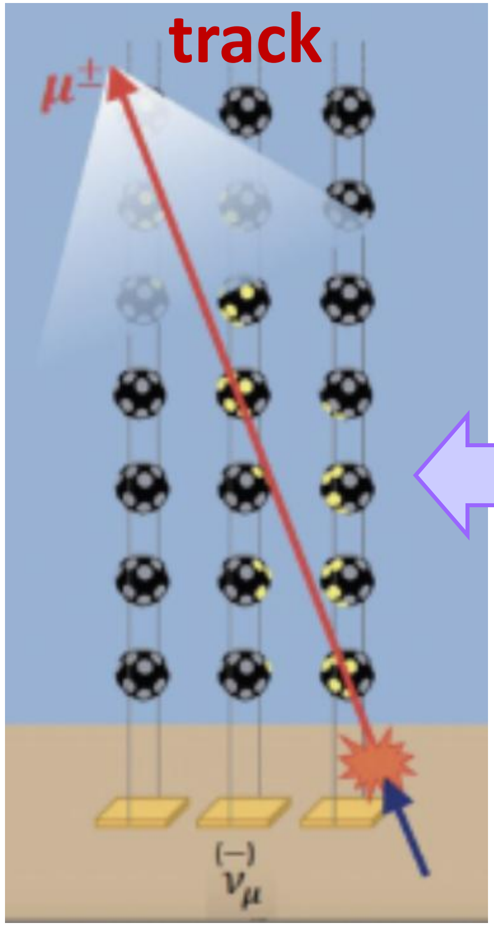
Disclaimer

How high is the energy of 100 TeV?

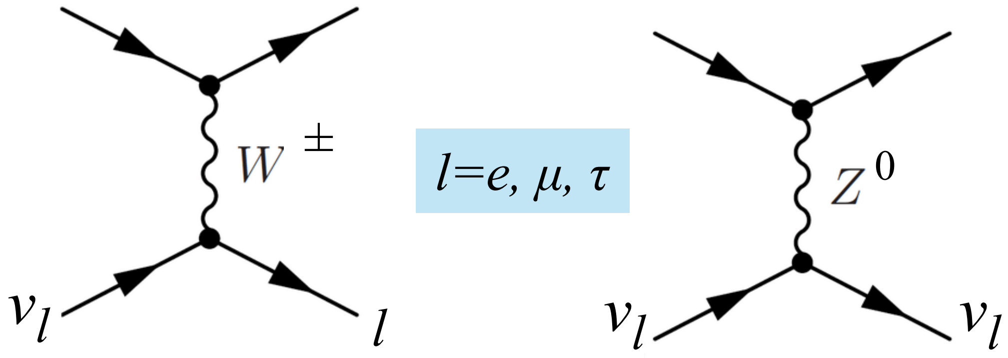
- Gamma rays: "ultra-high-energy"
  - UHE γ means E>100 TeV
- Neutrinos: "high energy"
  - UHE ν means E>100 PeV
- Cosmic rays: "moderate energy"
  - UHECR means E>10^{19} eV

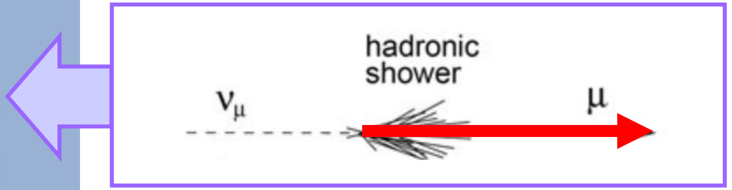
this talk:
VHE neutrinos
E>10 PeV

High-energy neutrino detection: tracks and cascades

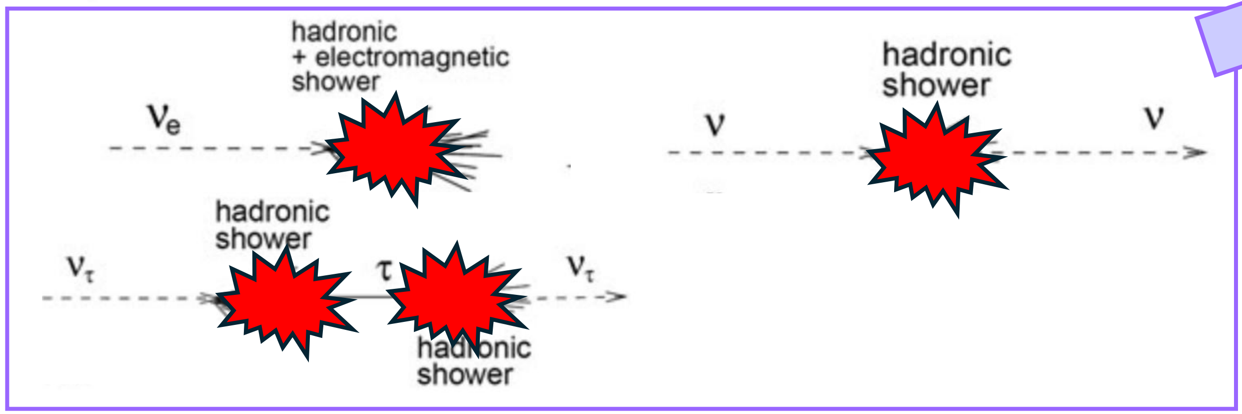


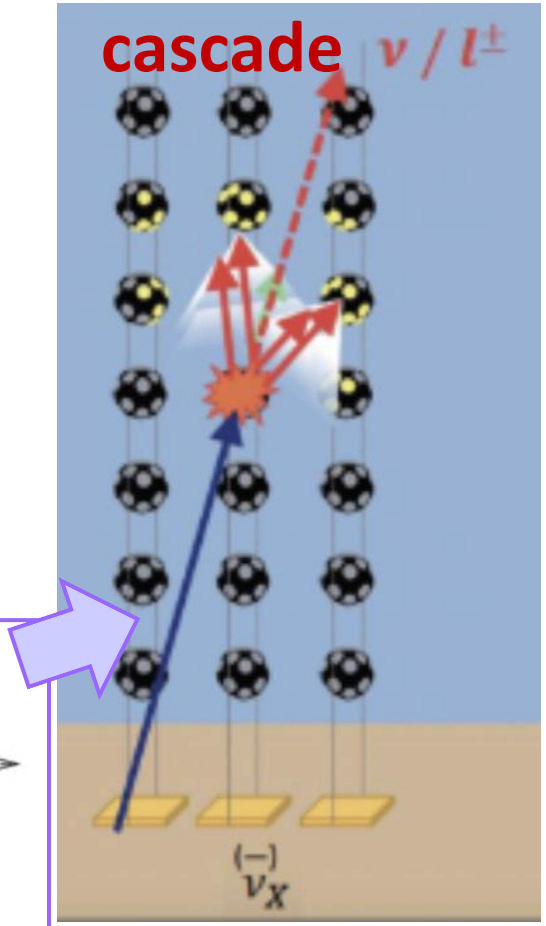
KM3NeT, RICAP2024





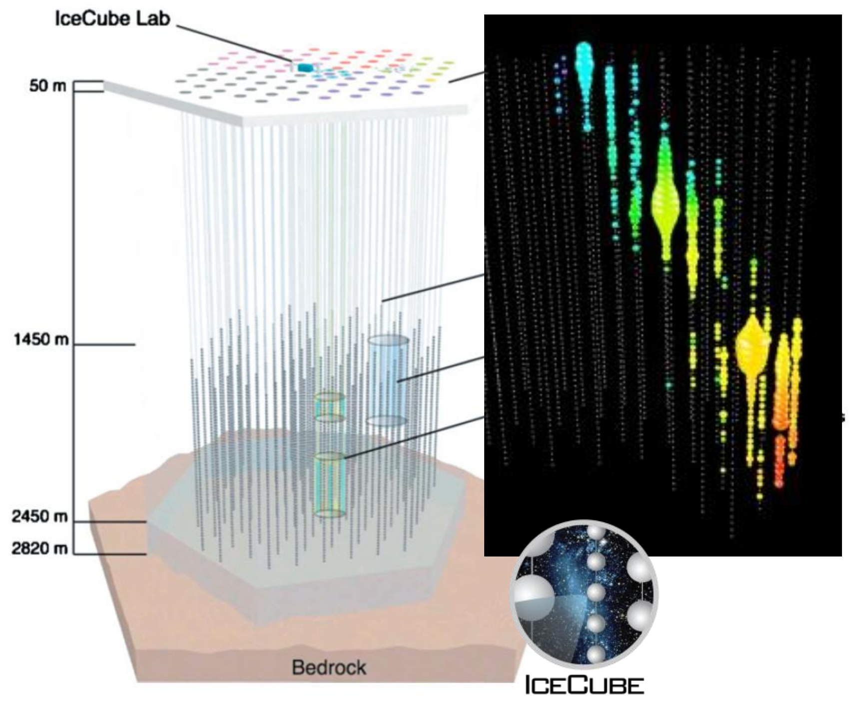
Capone, Lipari, Vissani 2018

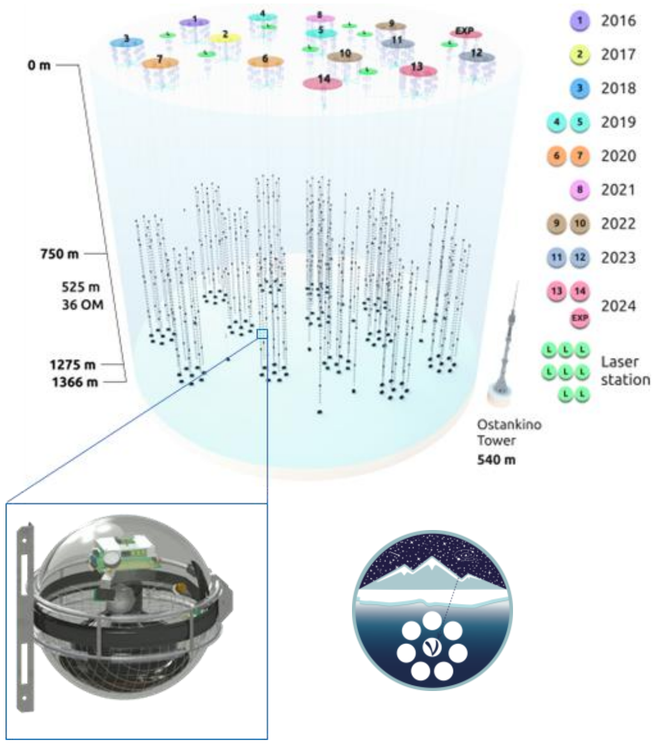


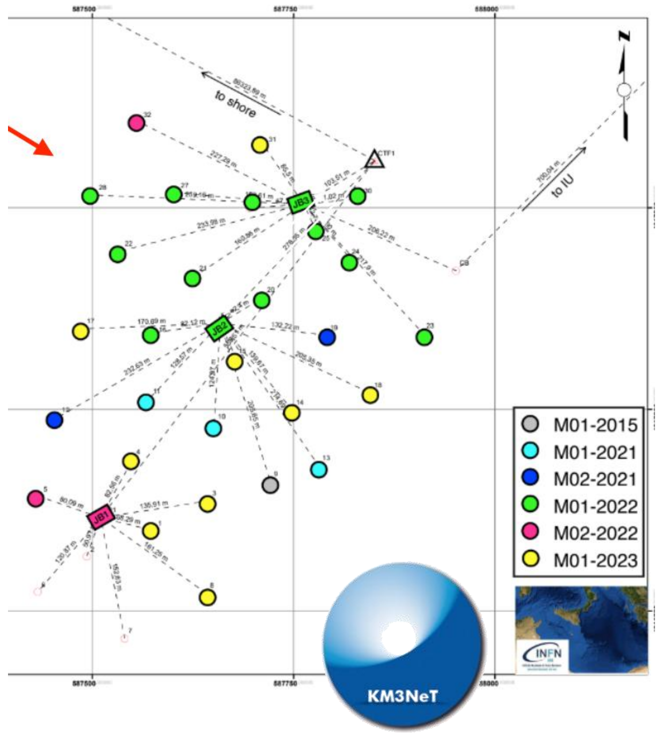


KM3NeT, RICAP2024

Neutrino water Cerenkov telescopes: target TeV to PeV







IceCube:

- South Pole (ice), works since 2008, in the full configuration since 2011
- maximal exposure – the principal source of data
- now: ~ 1 km^3, plan: ~ 1 km^3

Baikal-GVD:

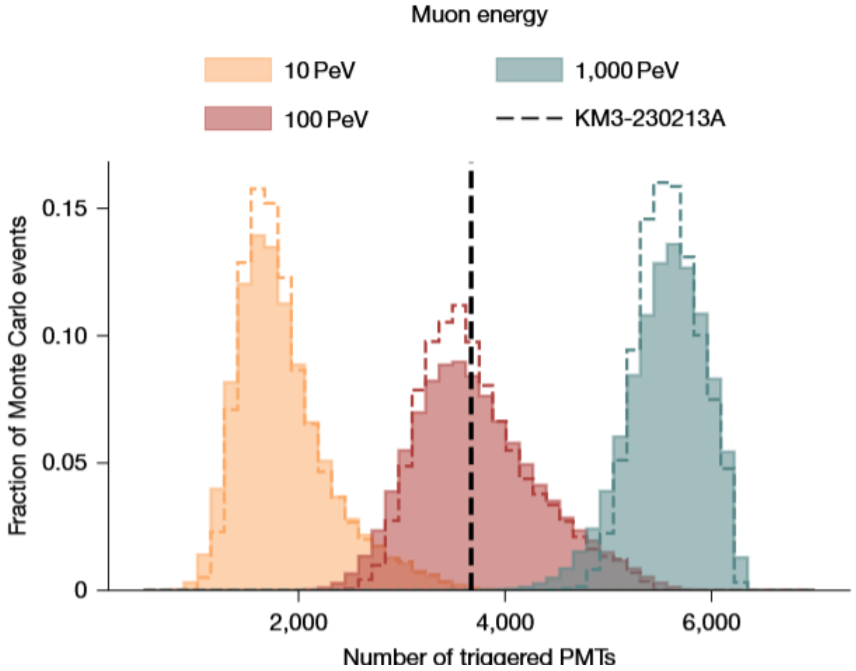
- Lake Baikal (fresh water), works since 2018, growing volume
- now : ~ 0.8 km^3, plan: ~ 2 km^3

KM3NeT:

- Mediterranean (saline water), works since 2018, growing volume
- now : ~ 0.12 km^3, plan: ~ 2 km^3

Accuracy of determination of neutrino arrival directions is about 4 times better in liquid water compared to ice (16 times difference in the uncertainty area in the sky)

The most energetic particle (muon) directly detected by humankind: KM3 230213A



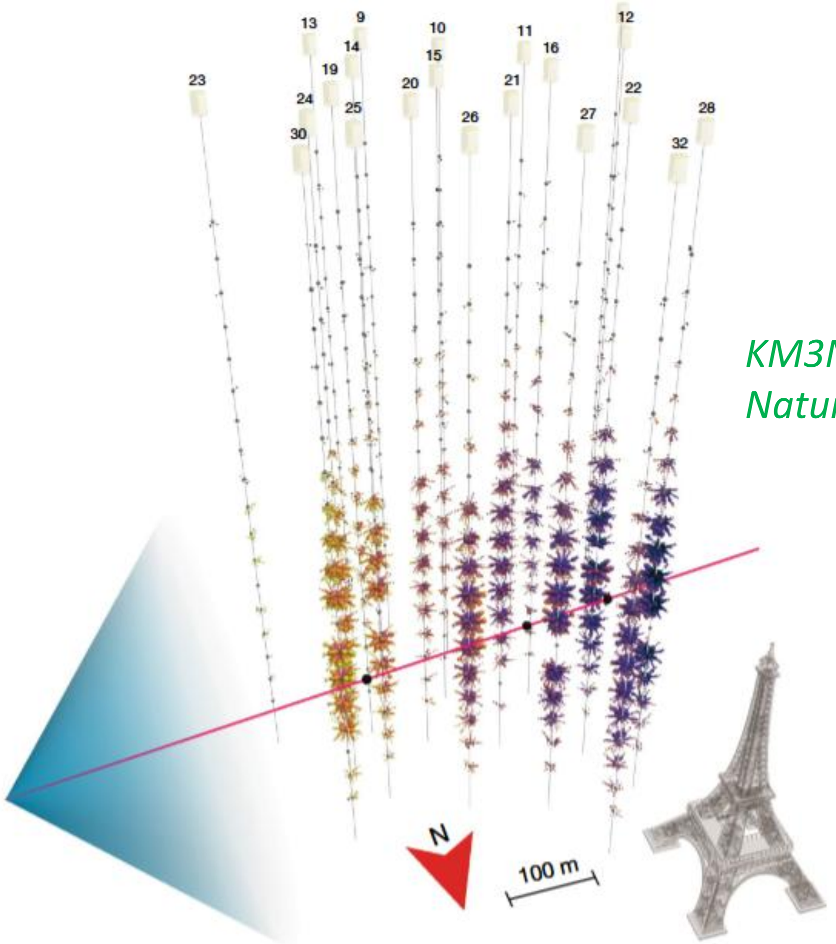
<u>muon energy:</u>

120 PeV best-fit
(60-230) PeV 68%CL
(35-380) PeV 90%CL

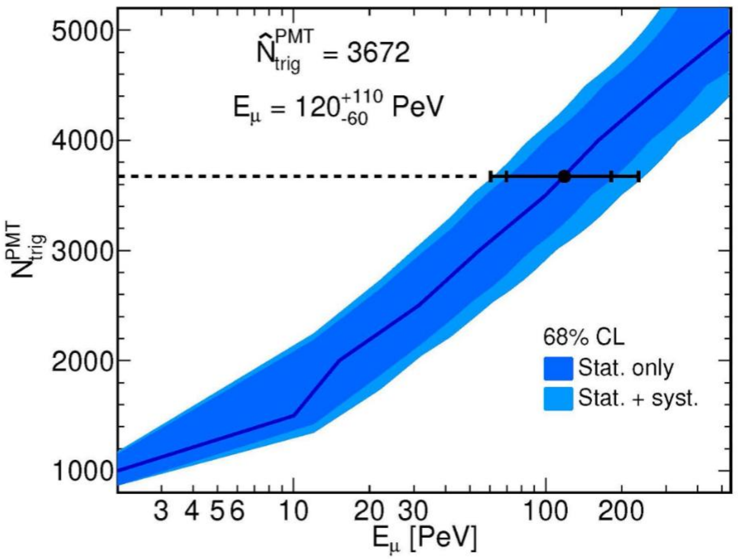
<u>neutrino energy:</u>

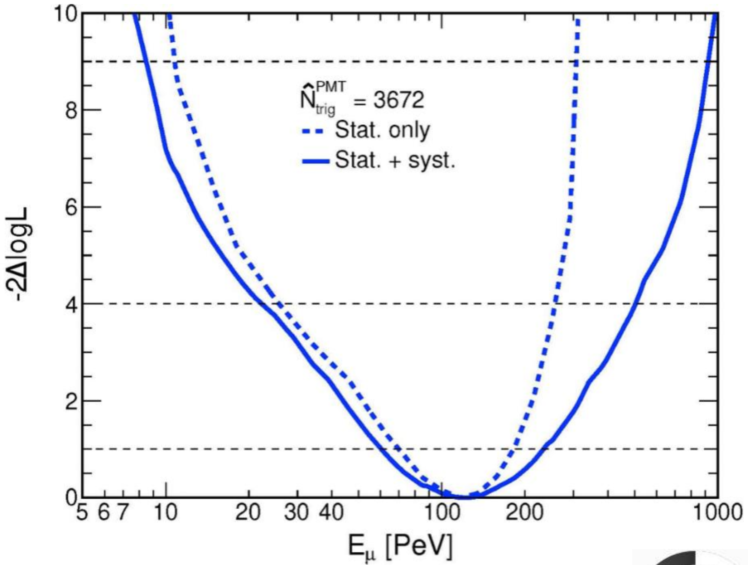
220 PeV best-fit
(110-790) PeV 68%CL
(72-2600) PeV 90%CL

KM3NeT Nature 2025



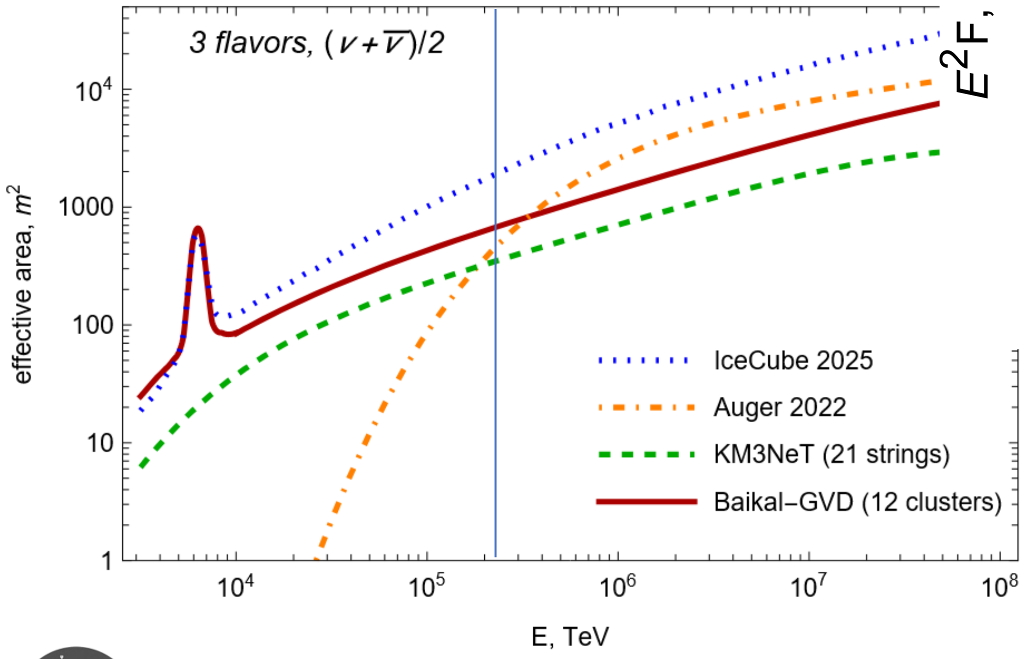
21 string of 230: ~0.1 km^3

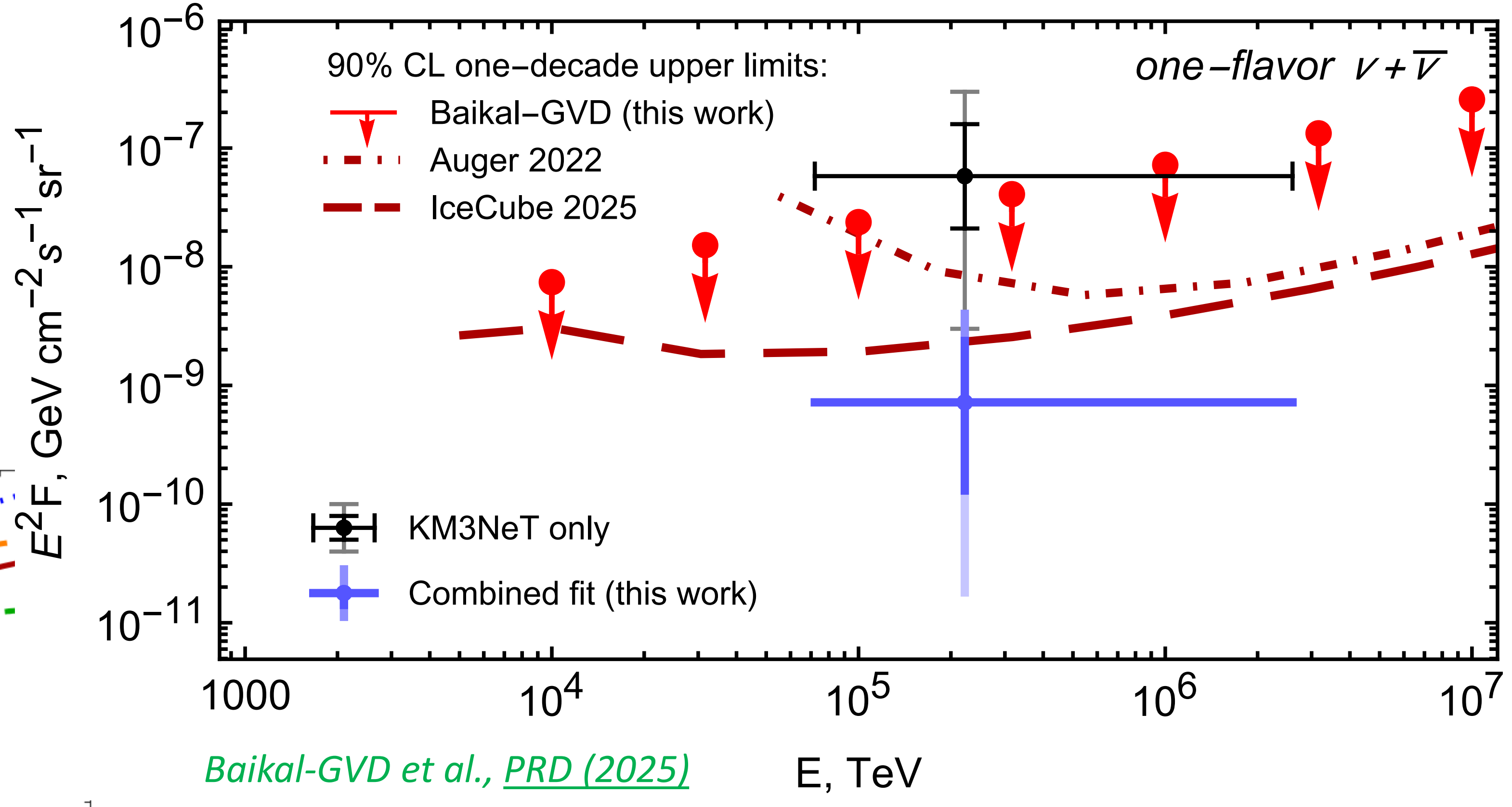




KM3NeT + IceCube + Auger + Baikal-GVD

larger experiments do not see events with that high energies



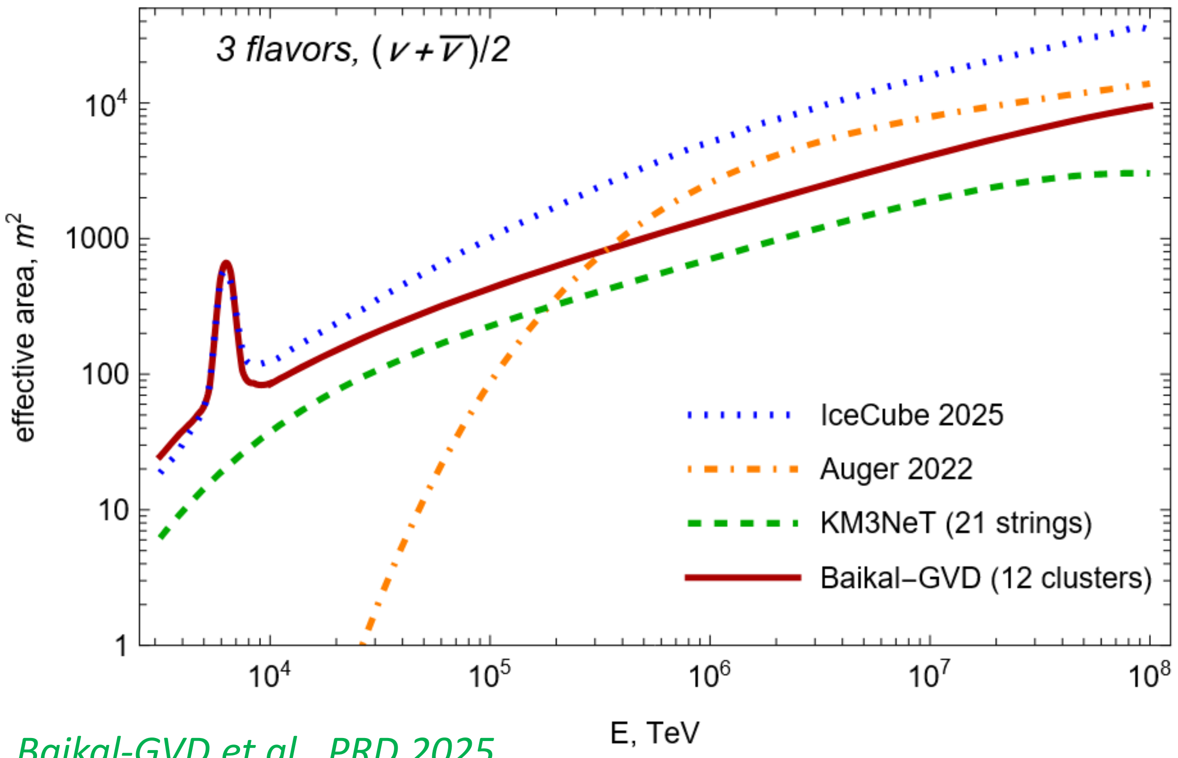


Baikal-GVD et al., PRD (2025)

assuming that KM3-230213A comes from the isotropic diffuse flux:

N[IceCube+Auger+Baikal-GVD]=0 & *N*[KM3NeT]=1: *p*=1.2%

KM3 230213A and point sources



Baikal-GVD et al., PRD 2025

A point-source flare (naively) makes the observations "more consistent"

$$\mathcal{F}_\nu = \frac{E_\nu^2 N}{\Delta E_\nu \Delta t A}$$

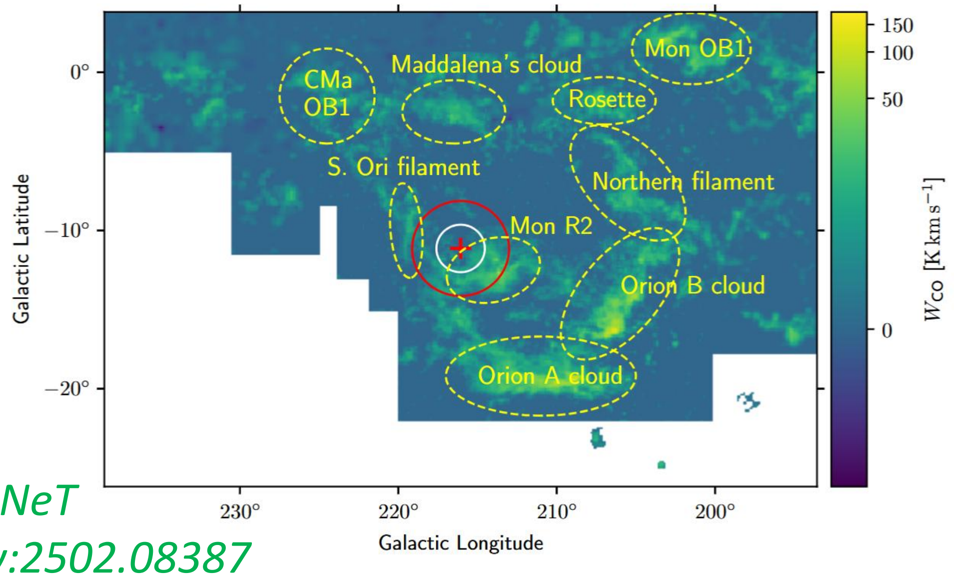
$$A = A_{\rm KM3} + A_{\rm IC} + A_{\rm GVD} \approx (400 + 6000 + 1300)\ \rm m^2$$

$$\mathcal{F}_\nu = \left(\frac{\Delta t}{\rm yr}\right) \left(1.3^{+1.8}_{-0.8}\right) \times 10^{-11}\ \frac{\rm erg}{\rm cm^2\, s}.$$

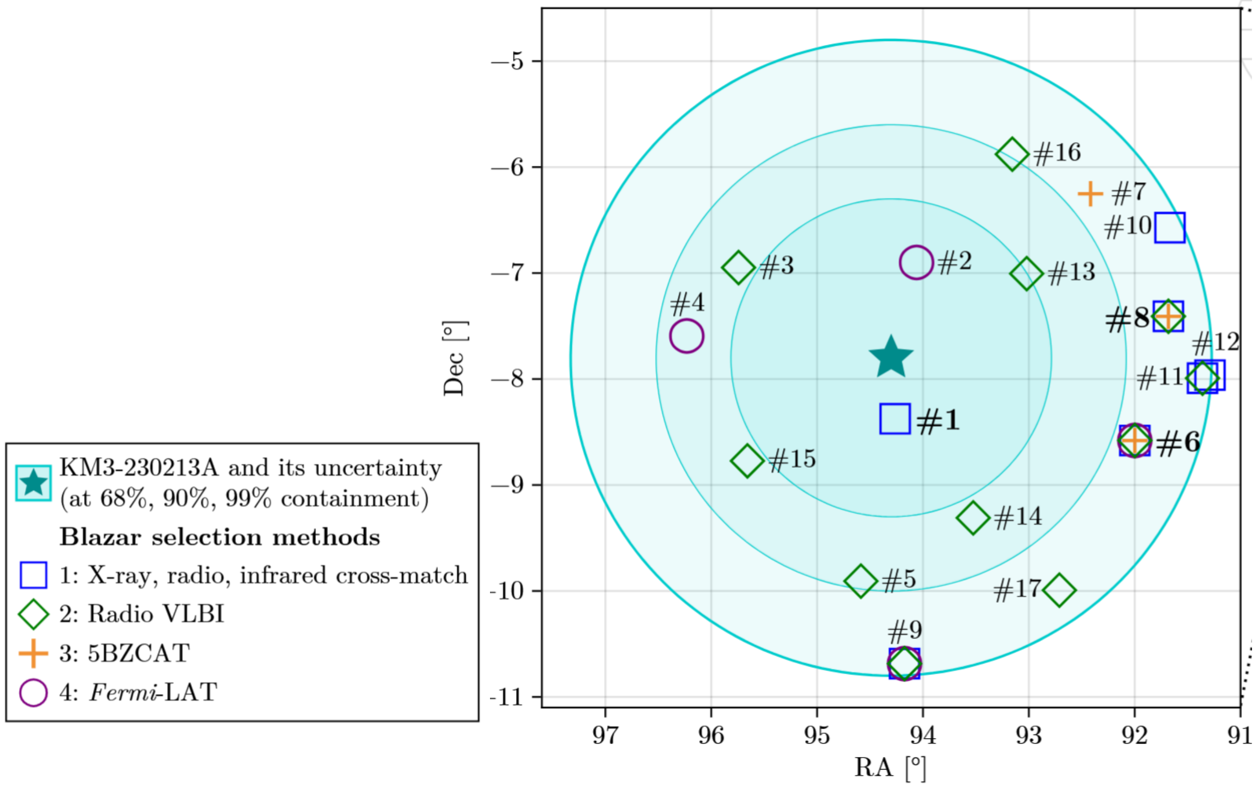
Kivokurtseva, ST, arXiv:2509.10352

(provided a source is observed and Δ*t* fixed)

KM3 230213A and point sources



KM3NeT
arXiv:2502.08387



Galactic:

Monoceros R2 molecular cloud as a target
[830 pc, overdensity ~1000],
star-formation region,
CR source =?

Extragalactic:

blazars

KM3NeT et al.
arXiv:2502.08484

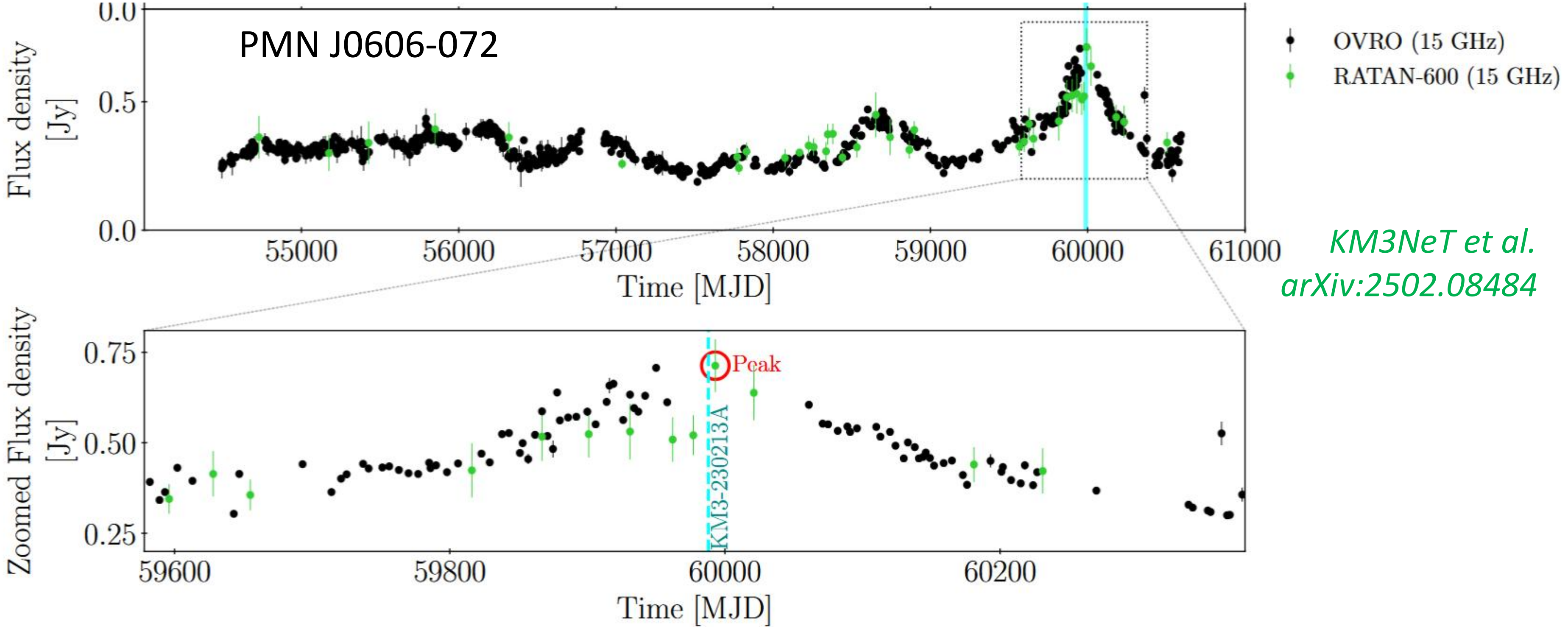
Note:

the angular accuracy much worse than expected…

KM3 230213A and a point-source flare

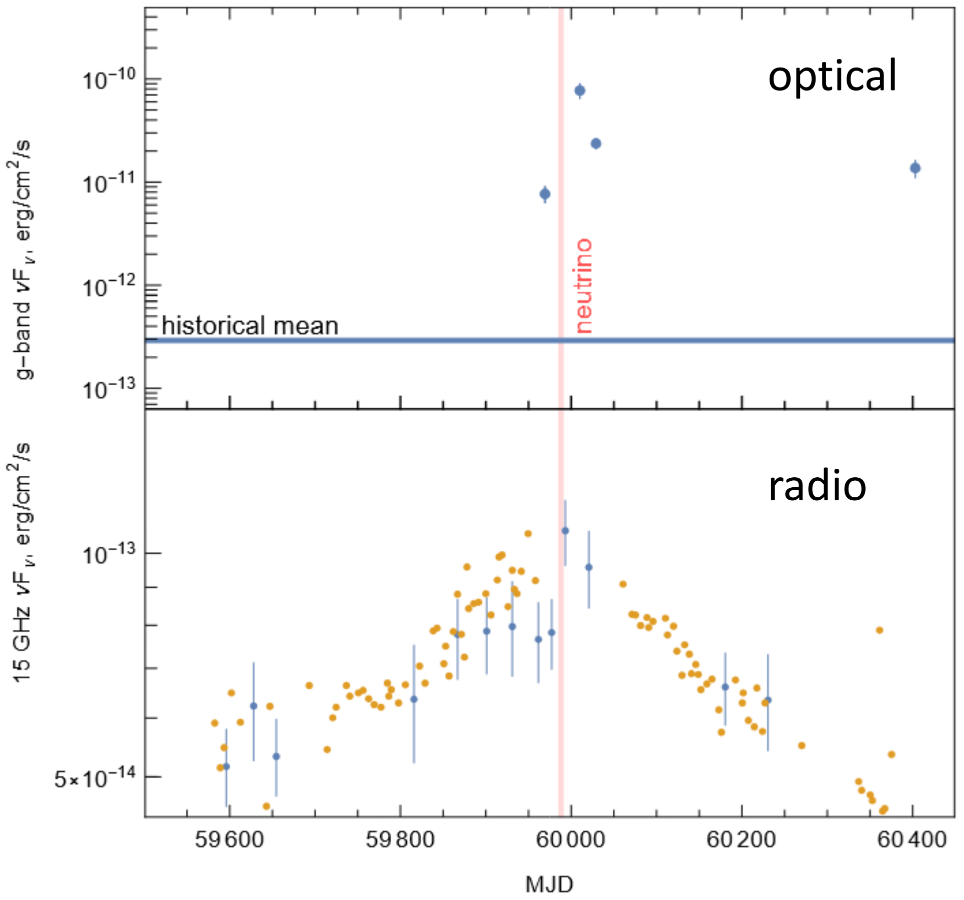
PMN J0606-072 blazar, radio flare from RATAN-600 and OVRO monitoring

gap in **OVRO** observations, only **RATAN** at the time of neutrino arrival

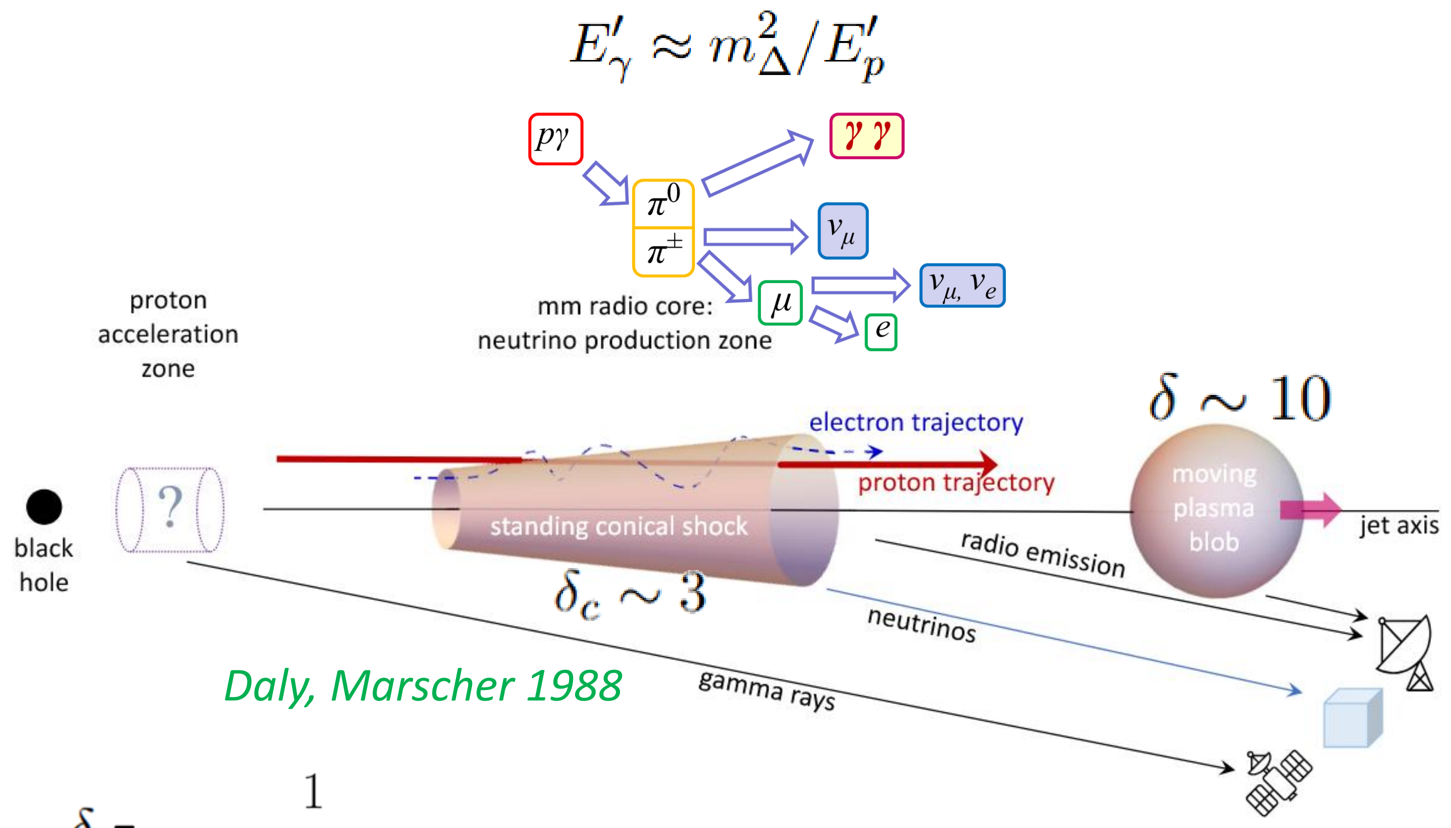


KM3NeT et al. arXiv:2502.08484

KM3 230213A and the flare of PMN J0606-072



Kivokurtseva, ST, arXiv:2509.10352



Daly, Marscher 1988

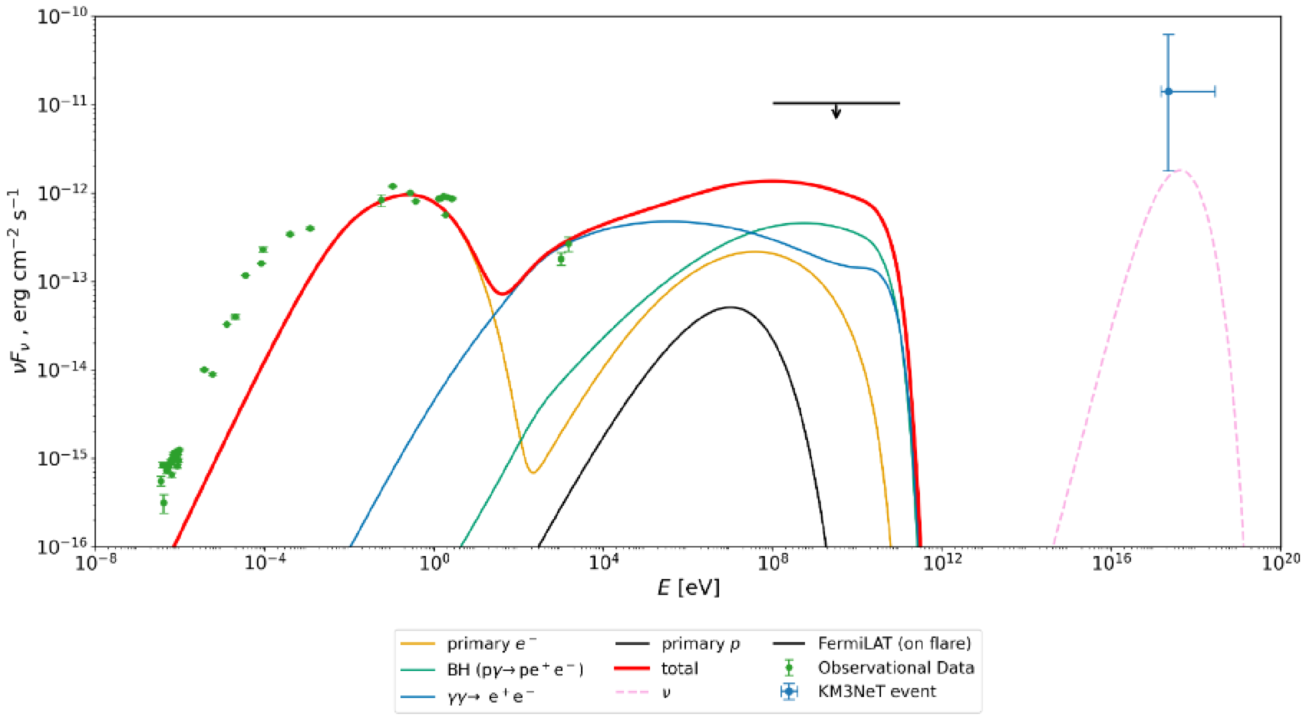
$$\delta = \frac{1}{\gamma(1-\beta\cos\theta)}$$

Kalashev ,Kivokurtseva, ST 2023

(see also the talk by Polina Kivokurtseva after lunch)

KM3 230213A and the flare of PMN J0606-072

Kivokurtseva, ST, arXiv:2509.10352



Parameter	Value	
core length, l'	1.5 pc	
core transverse radius, r'	0.6 pc	
magnetic field, B'	0.05 G	
Doppler factor, δ_c	5	
	Protons:	Electrons:
spectral index	1.0	1.8
minimal energy, $E'_{\rm min}$	1×10^9 eV	1×10^9 eV
maximal energy, $E'_{\rm max}$	2×10^{18} eV	10^{10} eV
total power, L'	5×10^{47} erg/s	5×10^{44} erg/s

Table 1. Parameters used for the SED in Fig. 3.

Population of similar blazars agrees with 1 event from the full sky:

about 600 sources with same or higher radio flux not in the Fermi catalog,

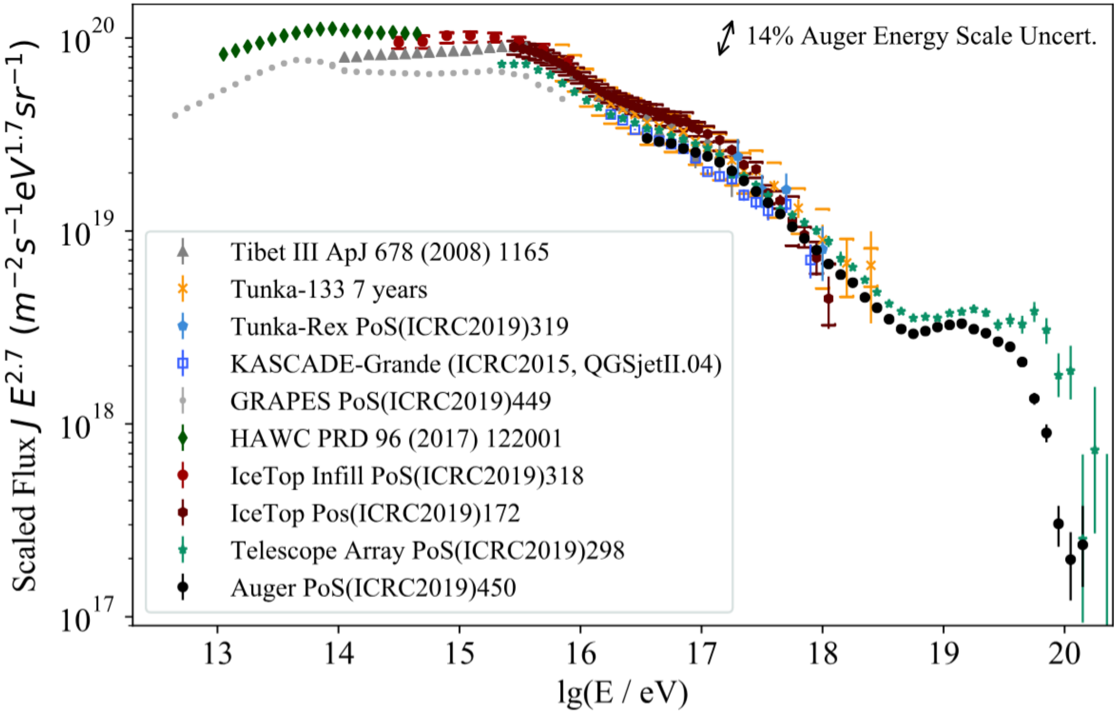
neutrino flux
$$\mathcal{F}_{\rm diff} \sim \frac{1}{4\pi} N_s \eta \mathcal{F}_\nu < 8.4 \times 10^{-9}\ {\rm GeV \cdot cm^{-2}\, s^{-1}\, sr^{-1}}$$

$$\eta \sim \frac{\Delta t}{17\ {\rm yr}} \Rightarrow N_s \lesssim 220^{+310}_{-130}$$

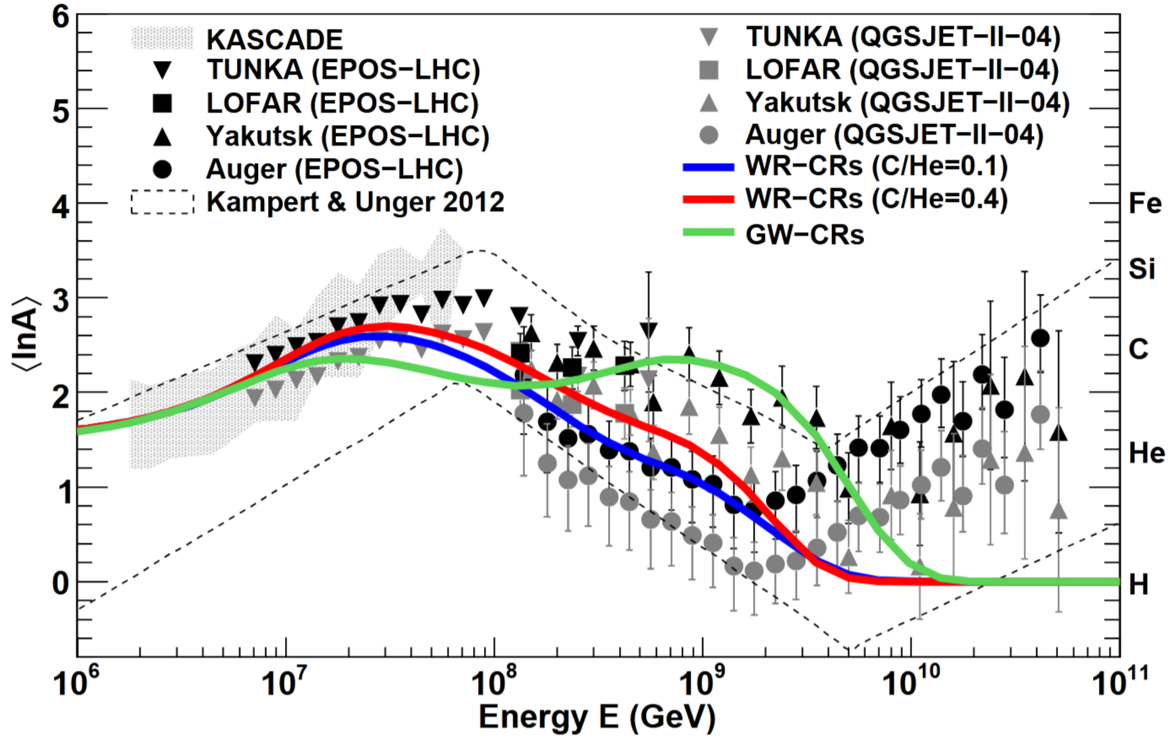
A multimessenger connection: cosmic rays

- **problem:** with indirect detection, primary particle types are hard to determine

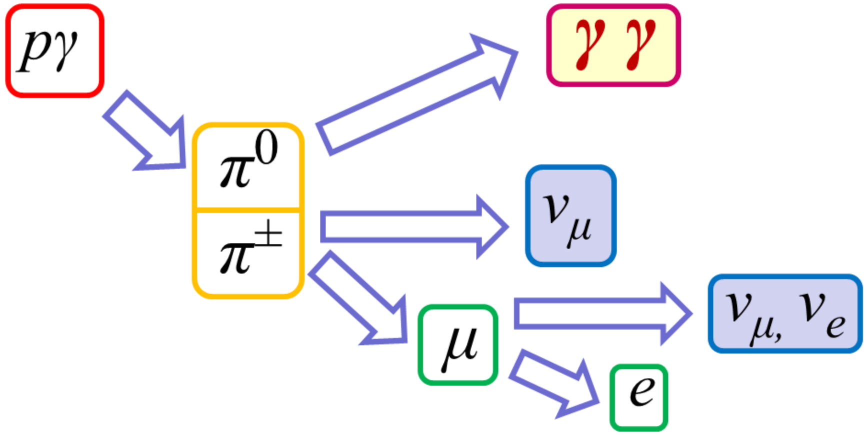
energy



composition



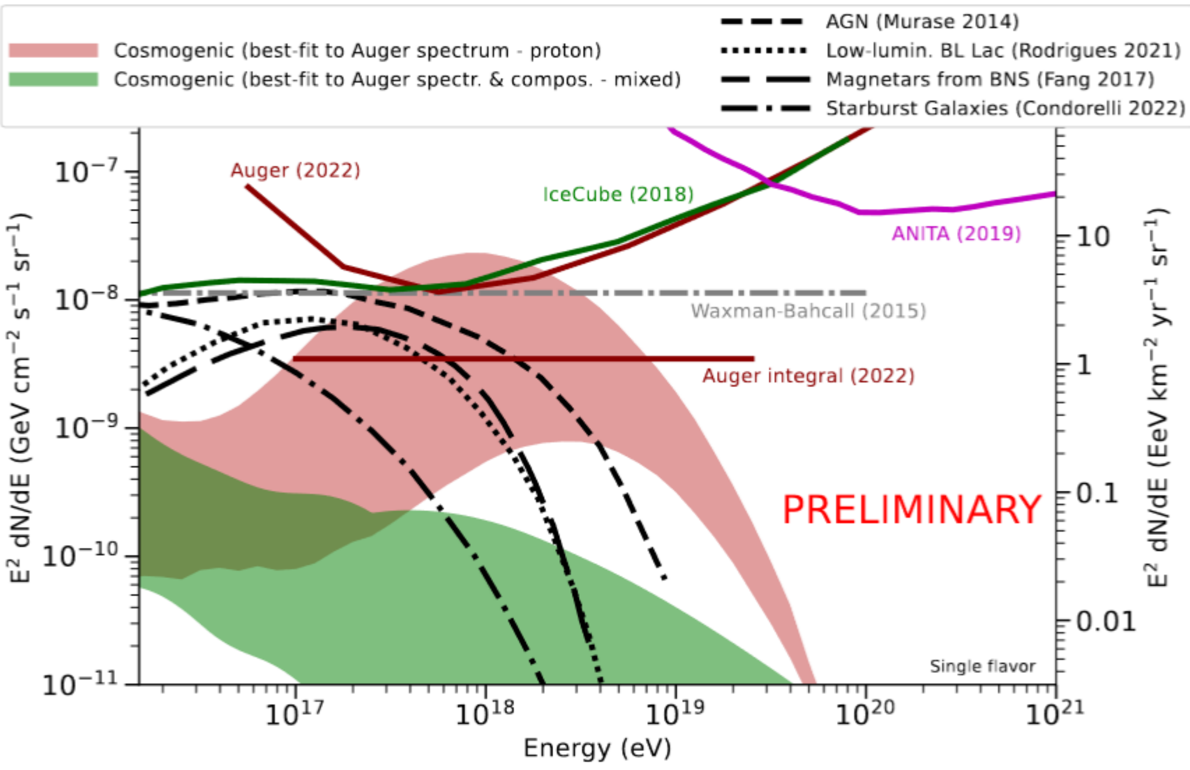
Cosmogenic neutrinos and photons



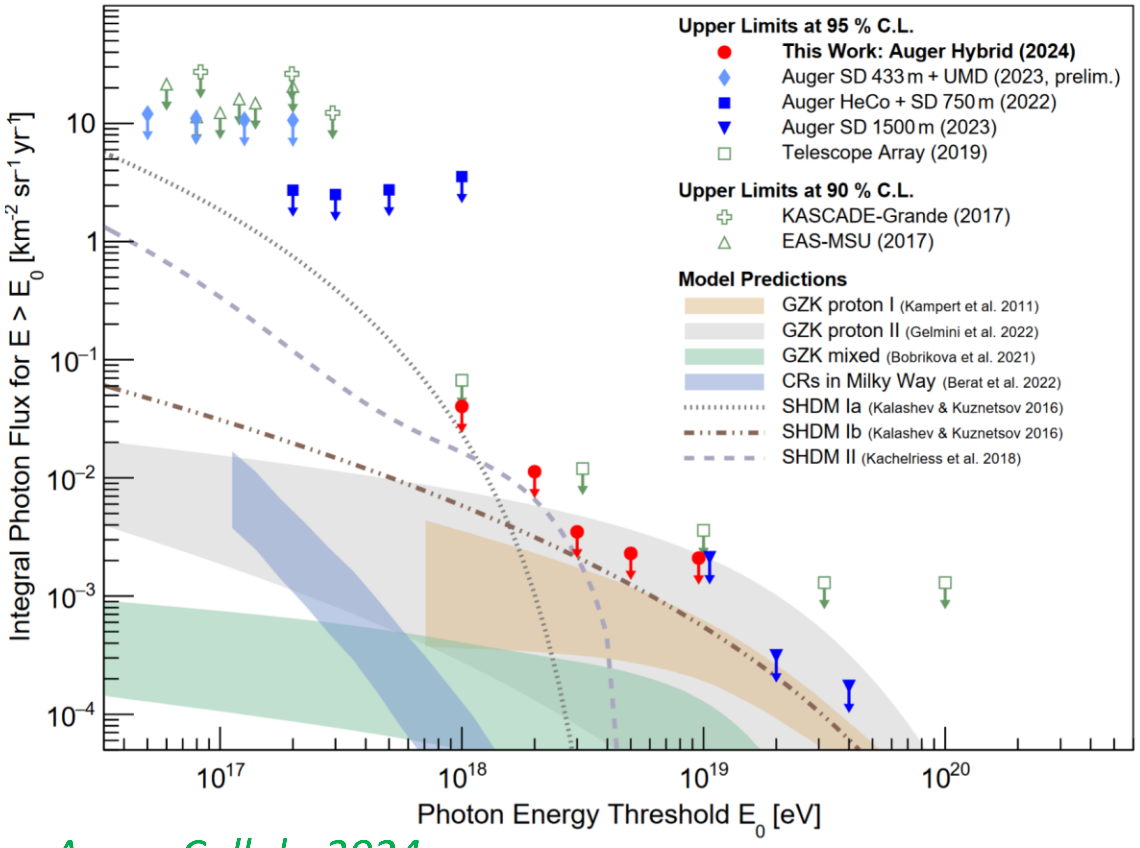
Berezinsky&Zatsepin 1969

- energies of 1/10 (1/20) of proton energy, that is beyond the current IceCube/Baikal GVD range
- predictions very different for nuclei: no Δ resonance, much lower fluxes
- upper limits from cosmic-ray experiments
- future task: to find these photons and neutrinos and to constrain the cosmic-ray composition

Cosmogenic neutrinos and photons: searches and limits (pre-KM3NeT)



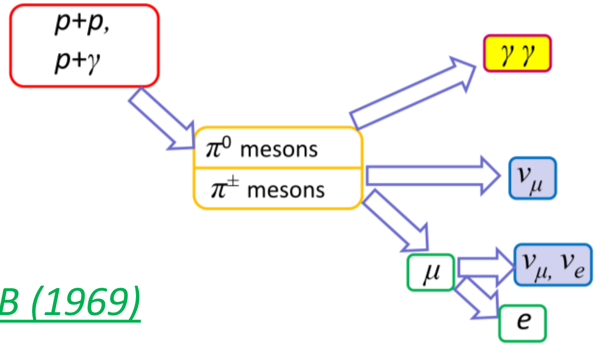
Auger Collab. 2023



Auger Collab. 2024

neutrinos **photons**

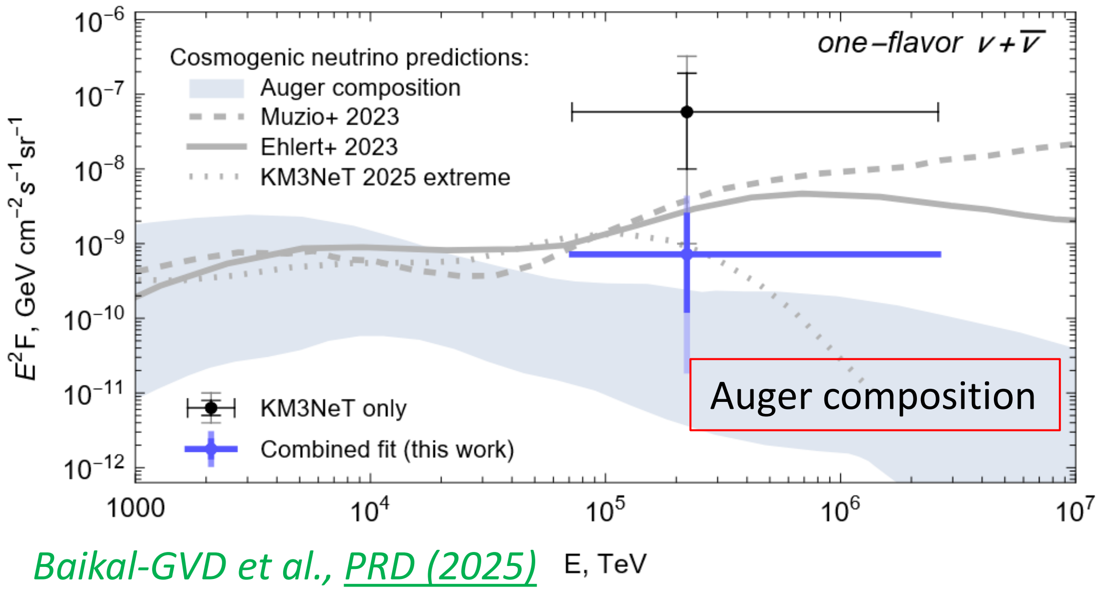
KM3 230213A as a cosmogenic neutrino?



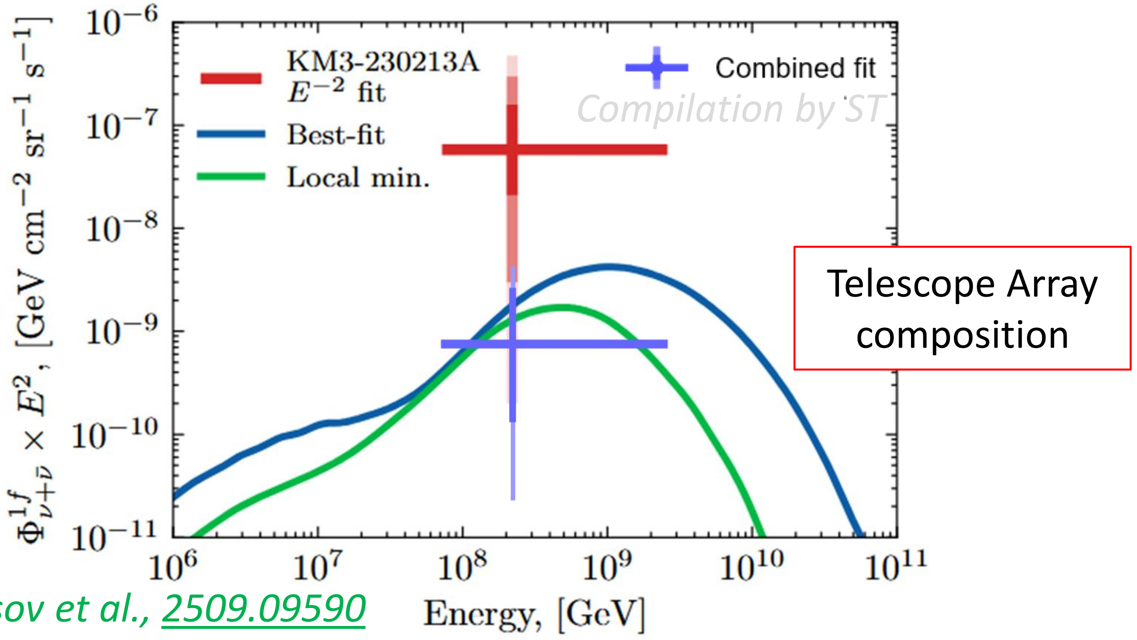
- for the isotropic diffuse flux:
  - *N*[IceCube+Auger+Baikal-GVD]=0 & *N*[KM3NeT]=1: *p*=1.2%
- cosmogenic neutrinos – from **protons**

Berezinsky & Zatsepin, PLB (1969)

IceCube, PRL (2025); KM3NeT, ApJL (2025); Baikal-GVD et al., PRD (2025); Kuznetsov et al., 2509.09590



Baikal-GVD et al., PRD (2025)

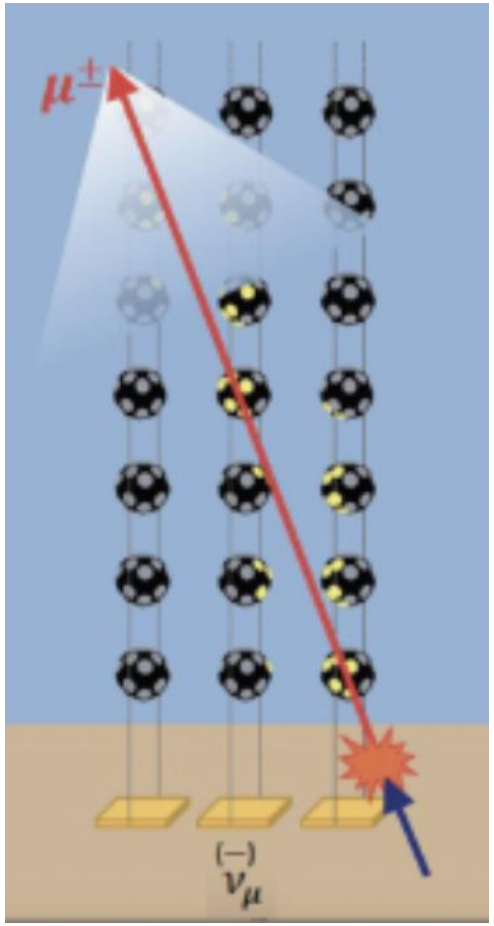


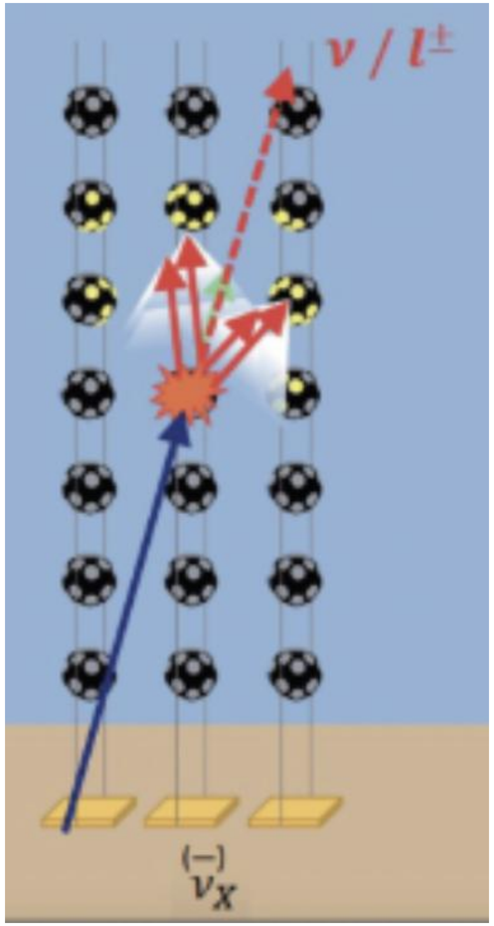
Kuznetsov et al., 2509.09590

- (if cosmogenic!) interesting implications for cosmic-ray composition

Very high energies: neutrinos in neutrino telescopes

- beyond the target energy range, but why not





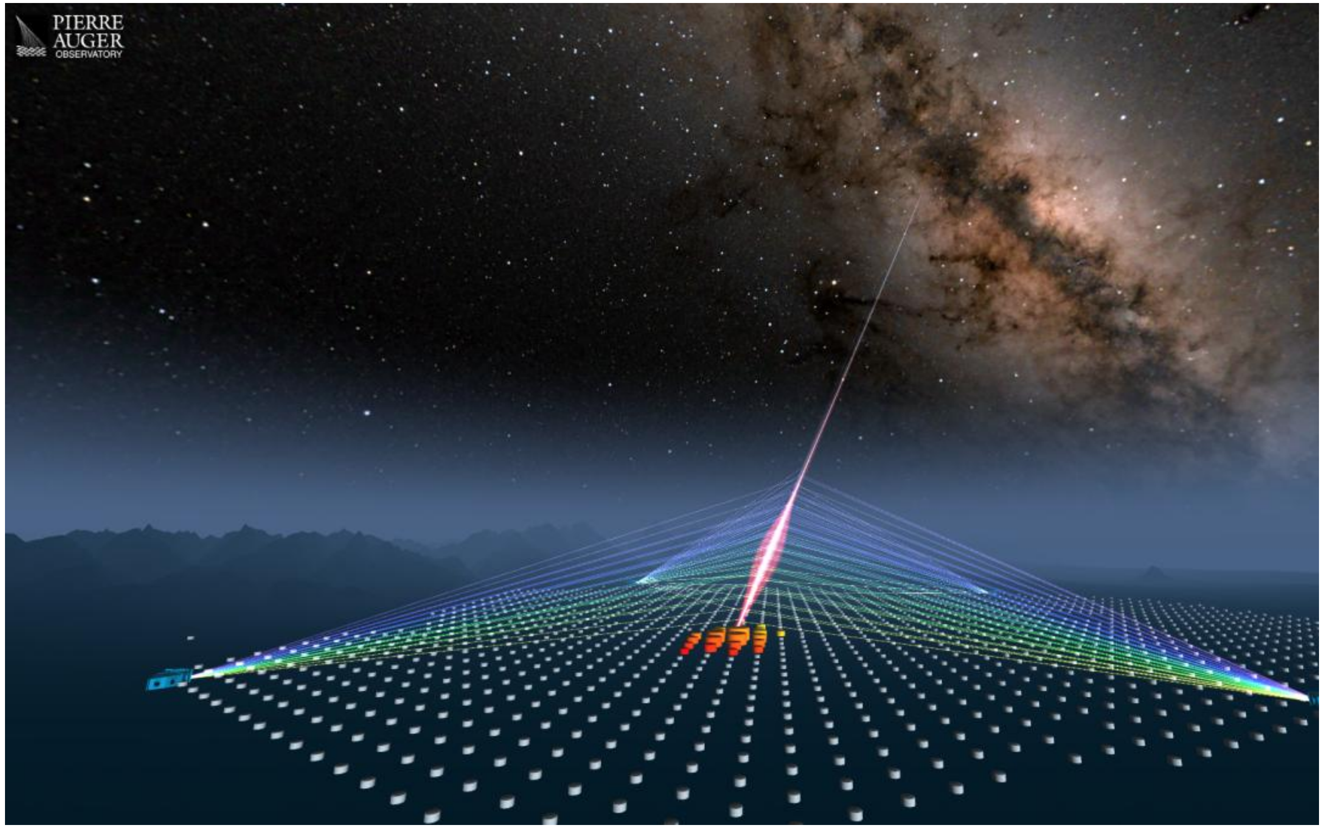
IceCube
Baikal-GVD
KM3NeT

P-ONE
IceCube-Gen2
HUNT
TRIDENT

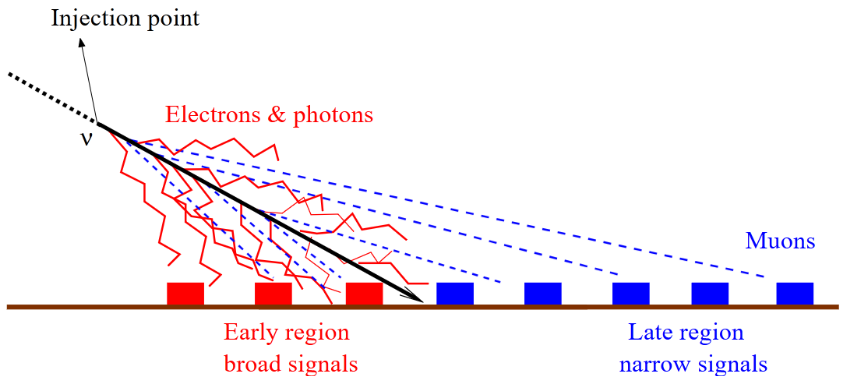
Credit: *KM3NeT Collaboration*

Very high energies: neutrinos in cosmic-ray detectors

- deep air showers



HiRes
Pierre Auger Observatory
Telescope Array

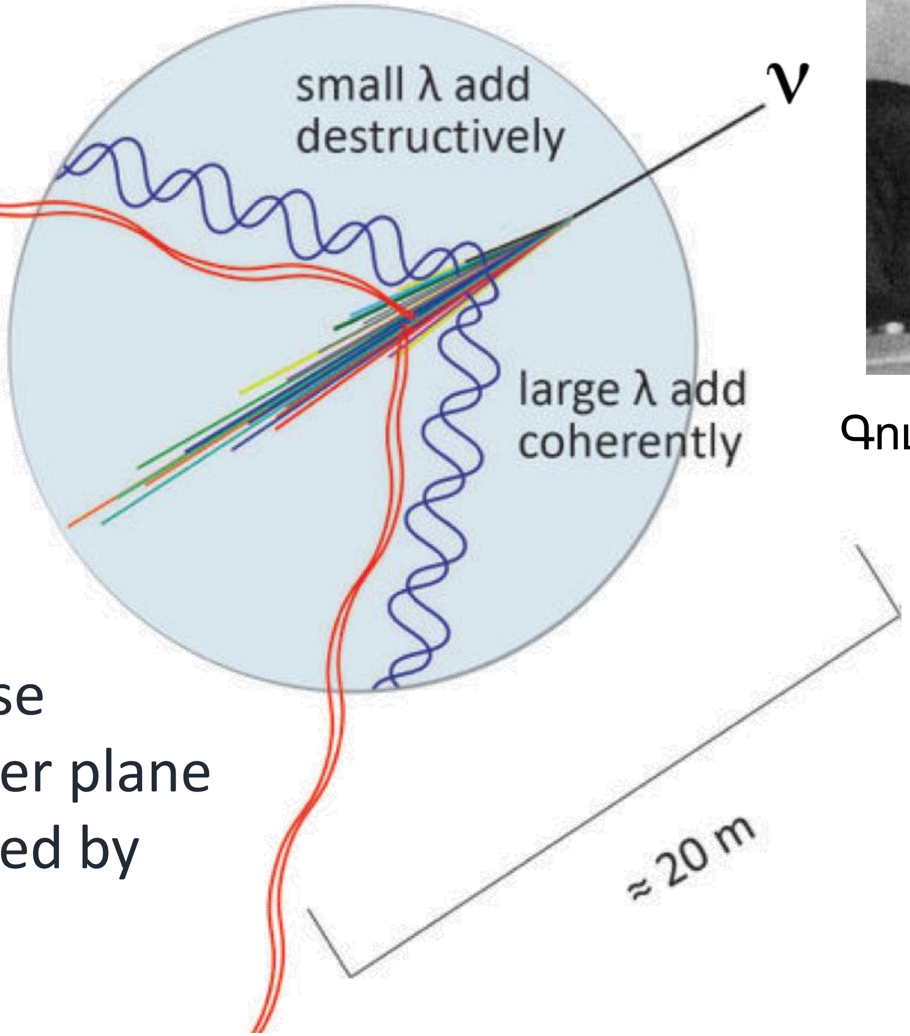


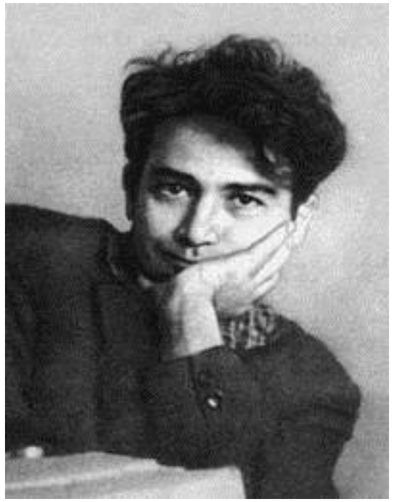
Credit: *Pierre Auger Observatory*

Very high energies: the Askaryan effect

Askaryan 1961

- negative charge excess in an electromagnetic cascade
- Cherenkov radiation of these electrons
- coherent radiation at large wavelengths (entire cascade as a point source)





Գուրգեն Ասկարյան
1928 - 1997

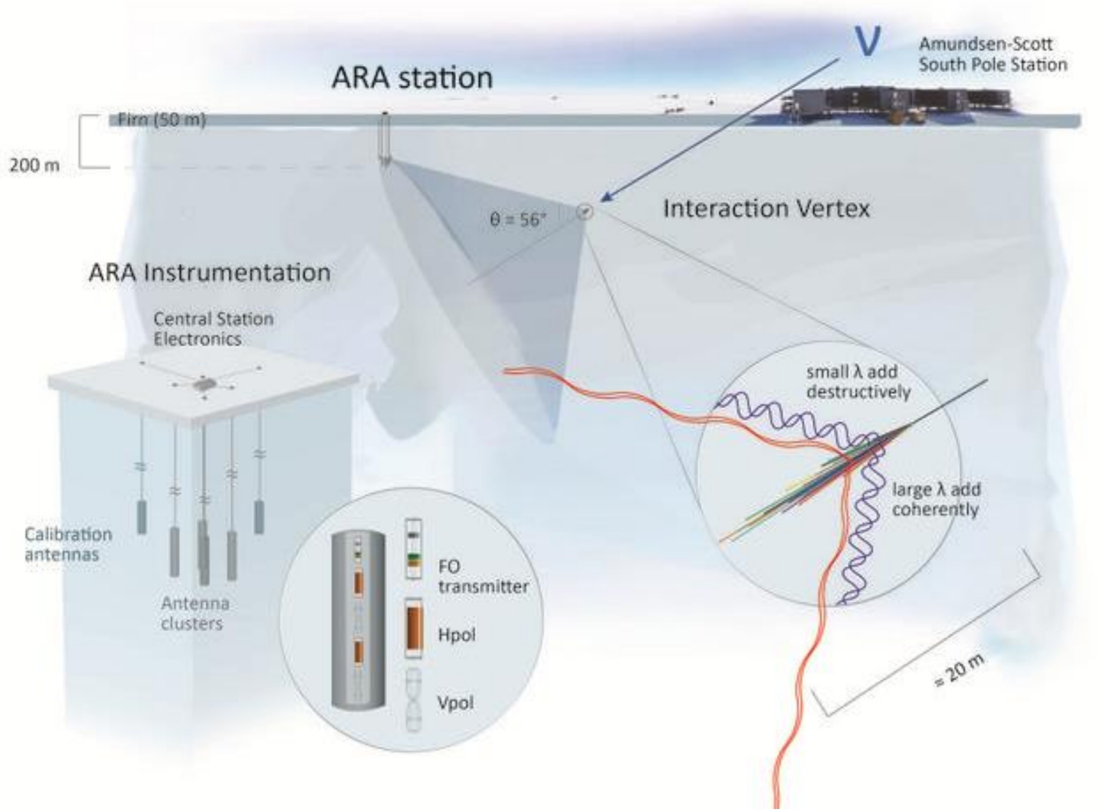
observation:

- broadband, nanosecond-scale radio pulse
- linear polarization in the shower-observer plane
- angular and spectral structure determined by shower geometry and coherence
- long radio attenuation lengths

➡ sparse detectors, large volume (ice, salt, lunar regolith)

Very high energies: the Askaryan effect

- array of antennas in ice



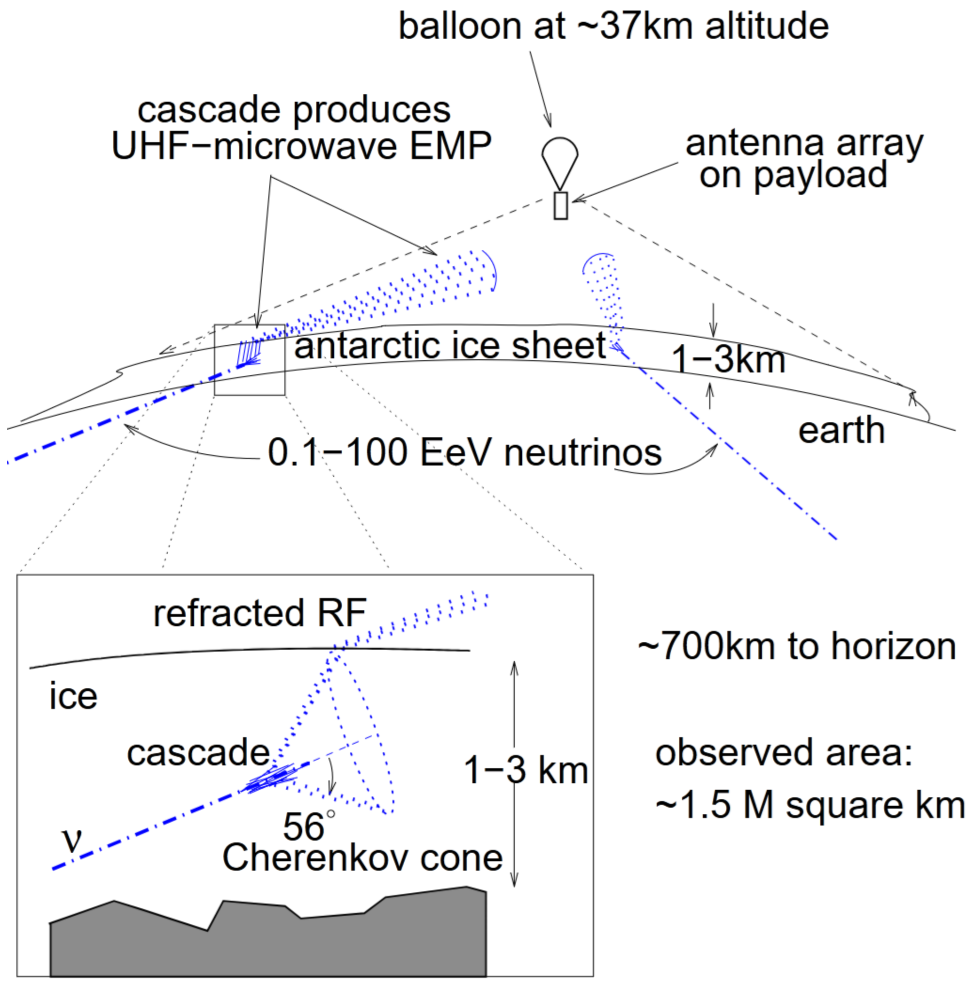
Credit: *Askaryan Radio Array (ARA) / University of Wisconsin–Madison / WIPAC*

RICE
ARIANNA
ARA

ARA
RNO-G
IceCube-Gen2 radio

Very high energies: the Askaryan effect

- observing the ice surface from above



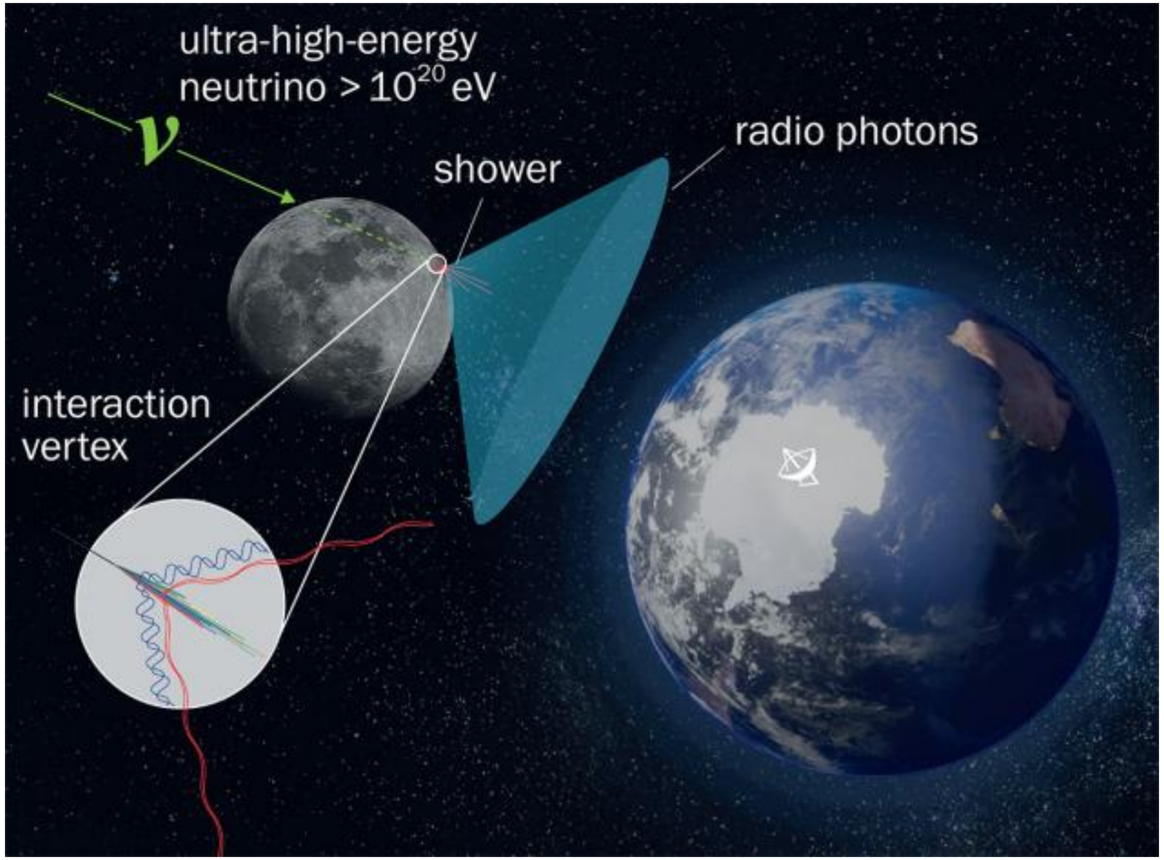
ANITA
FORTE

PUEO
POEMMA

Credit: *ANITA Collaboration,* astro-ph/0503304

Very high energies: the Askaryan effect

- observing the Moon



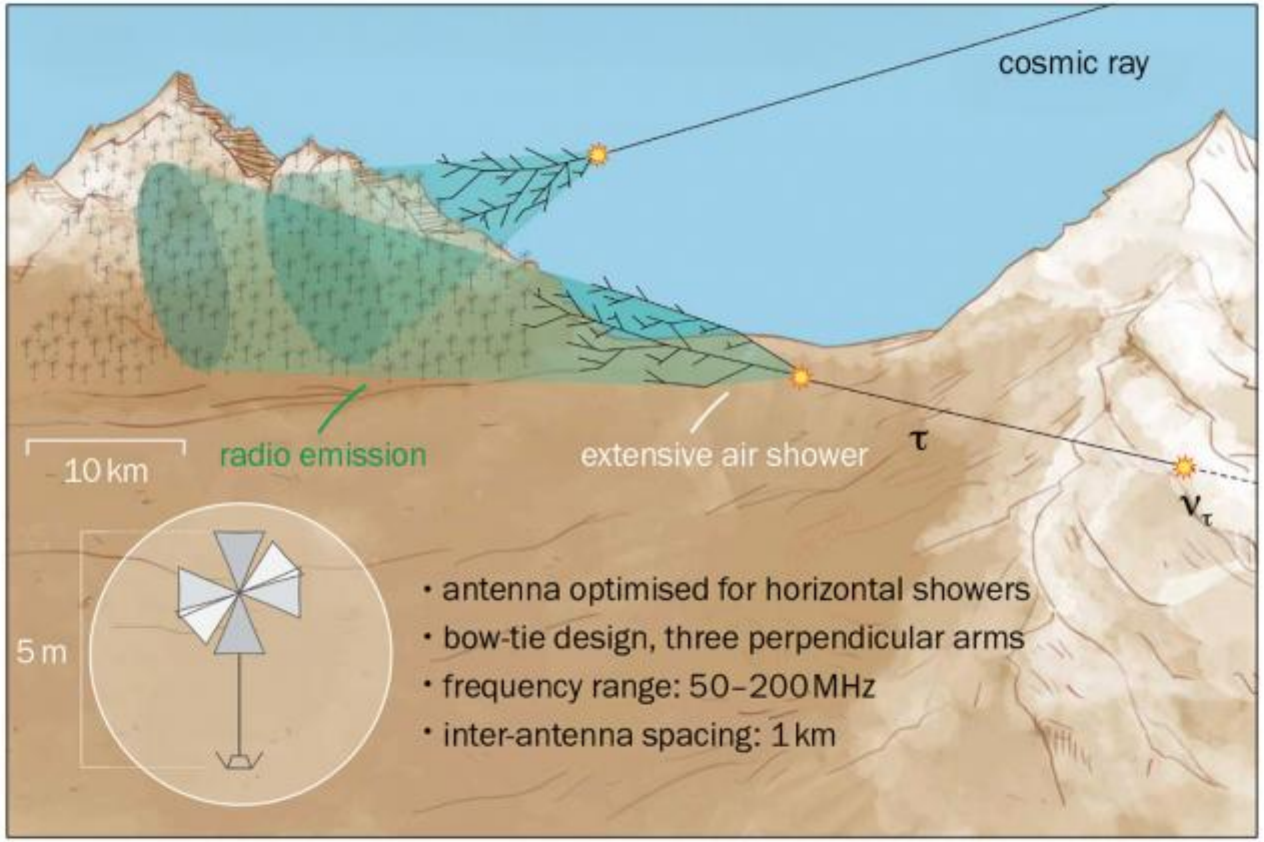
GLUE
RESUN
Kalyazin
LUNASKA
NuMoon

LORD
ULW lunar orbiter
Lunar 2x30m telescope
LOFAR, SKA, …

Credit: *A. Nelson, CERN Courier*

Very high energies: Earth-skimming tau neutrinos

- horizontal air showers

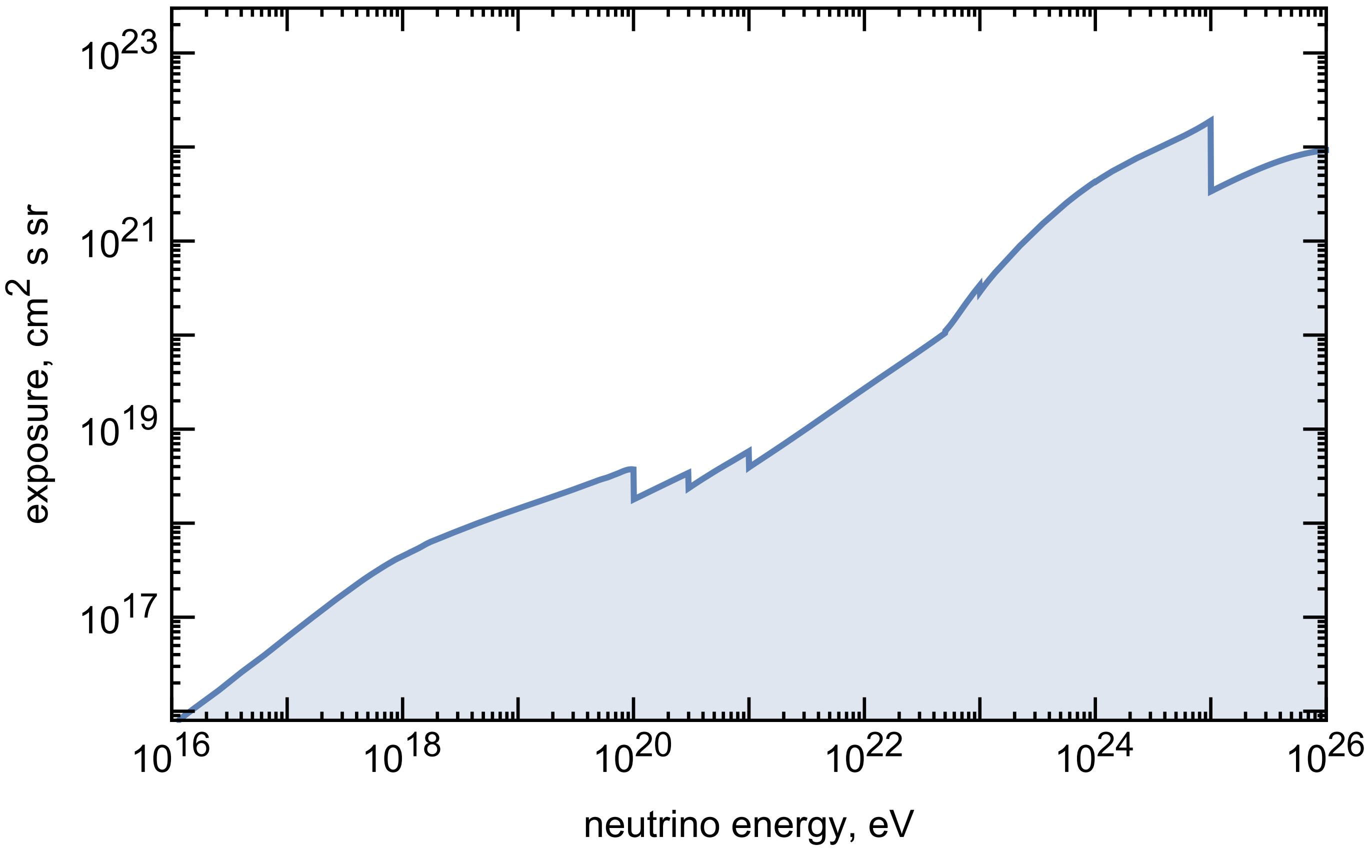


GRAND
Trinity
BEACON
HERON
TAROGE-M
TAMBO

Credit: *GRAND Collaboration, CERN Courier*

Very high energies: combination of all experiments (full sky!)

- combined exposure

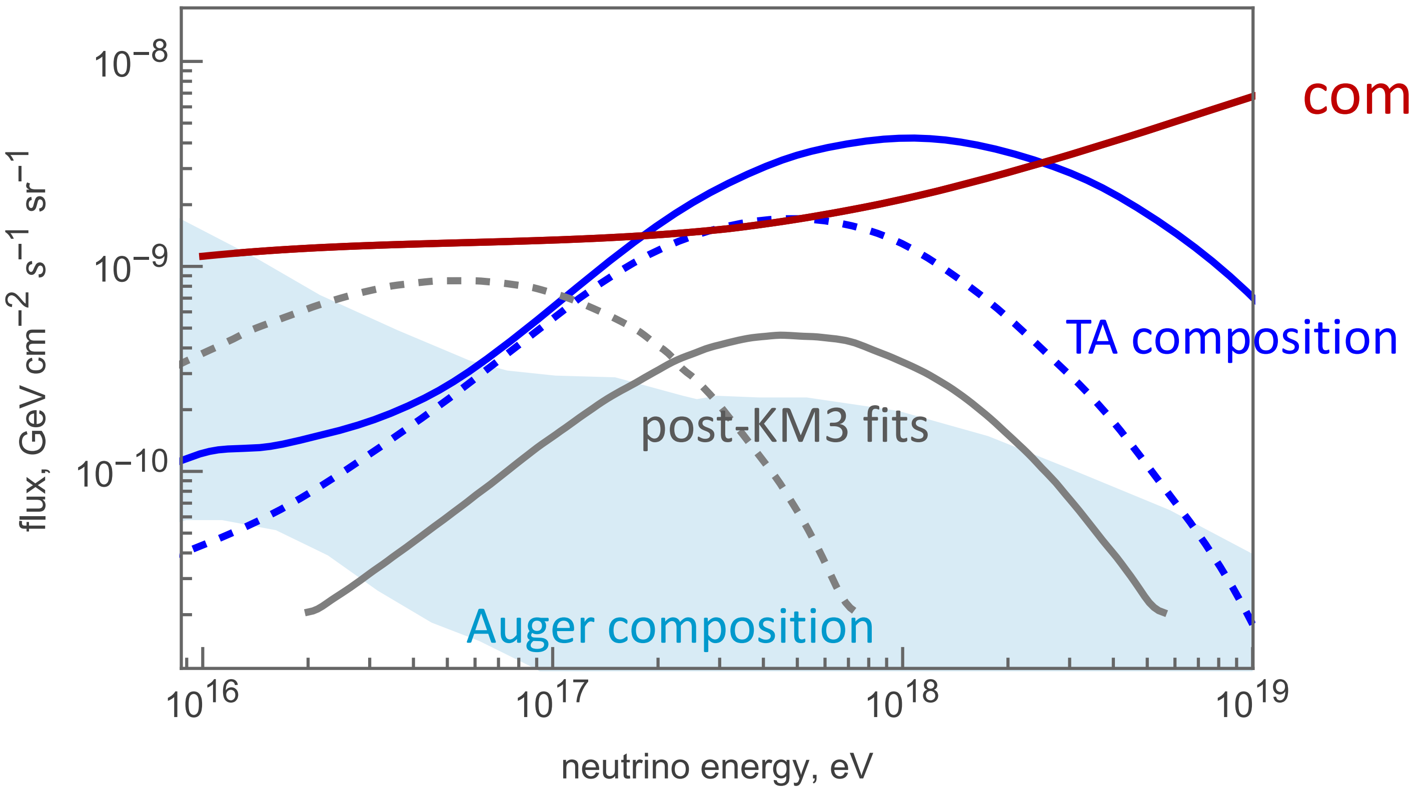


IceCube
Baikal-GVD
KM3NeT
Auger
RICE
ARIANNA
ARA
ANITA
FORTE
GLUE
RESUN
Kalyazin
LUNASKA
NuMoon

ST 2026

Very high energies: combination of all experiments (full sky!)

- cosmogenic neutrinos



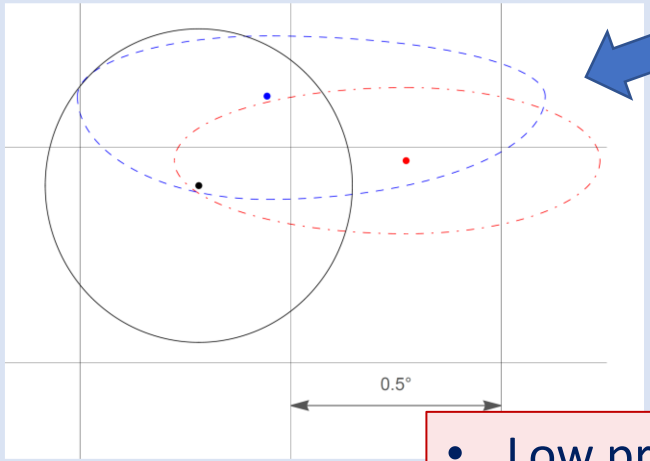
ST 2026

experiments start to touch cosmogenic neutrino predictions!

Very high energy neutrinos: conclusions

- ✓ Firm observation of a >100 PeV by KM3NeT
- ✓ Non-observation by larger experiments: a two-sigma tension
- ✓ Can be associated with a flaring blazar
- ✓ Or can be the first cosmogenic neutrino ever detected, important to solve the composition problem of cosmic rays
- ✓ Combination of experiments already starts to constrain cosmic-ray scenarios
- ✓ Many projects based on Askaryan effect and other approaches

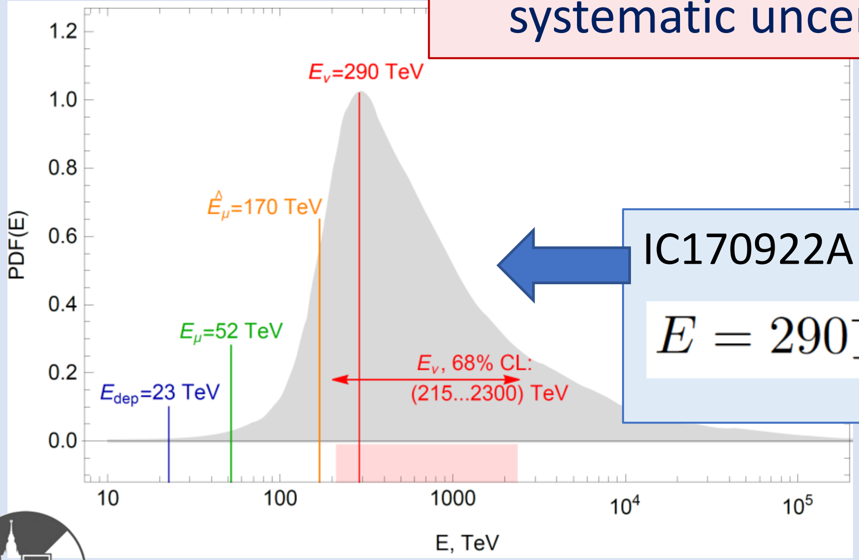
Neutrino astronomy: some difficulties



arrival directions of a single neutrino event with extreme energy in three reconstructions

IceCube **tracks**

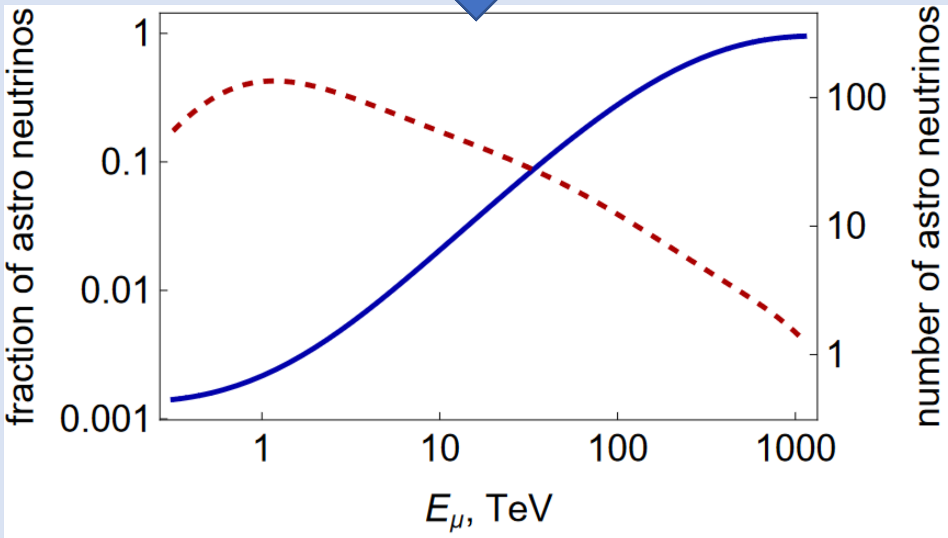
- Low precision of both direction and energy; systematic uncertainties



IC170922A track:

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

- Abundant neutrinos and muons produced in the atmosphere: except the highest energies, the astrophysical signal is much lower than the background



ST, Phys. Usp. 2022

KM3 230213A and the flare of PMN J0606-072

Kivokurtseva, ST, arXiv:2509.10352

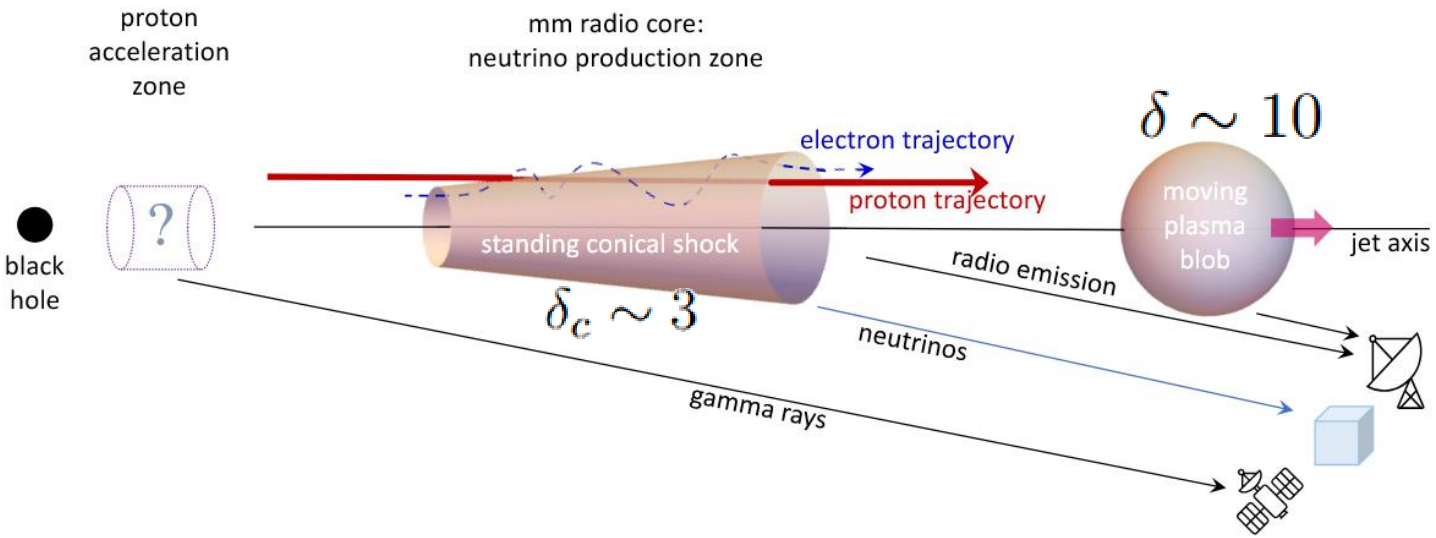
$z = 1.277 \qquad d_{\mathrm{L}} \approx 8.8\ \mathrm{Gpc}$

$$E_p^\star \approx 20 E_\nu (1+z)$$

$$E_p^\star \approx \left(1.0^{+2.6}_{-0.5}\right) \times 10^{19}\ \mathrm{eV}$$

optimal proton power:
proton interacts once

$$E'_\gamma n'_\gamma(E'_\gamma) = \frac{4 d_L^2 \mathcal{F}}{\delta_c^4 E'_\gamma r'^2} \left(\frac{r'}{l'}\right)^{2/3} \Rightarrow \delta_c \approx 2.8$$



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$$z = 1.277 \qquad d_{\mathrm{L}} \approx 8.8\ \mathrm{Gpc}$$

$$E_p^\star \approx 20 E_\nu (1+z)$$

$$E_p^\star \approx \left(1.0^{+2.6}_{-0.5}\right) \times 10^{19}\ \mathrm{eV}$$

$$L_\nu = \left(\frac{2.8}{\delta_c}\right)^4 \left(2.0^{+2.7}_{-1.2}\right) \times 10^{45}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

$$L_p = \left(\frac{2.8}{\delta_c}\right)^4 \left(4.0^{+5.3}_{-2.4}\right) \times 10^{46}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

optimal proton power:
proton interacts once

$$E'_\gamma n'_\gamma(E'_\gamma) = \frac{4 d_L^2 \mathcal{F}}{\delta_c^4 E'_\gamma r'^2} \left(\frac{r'}{l'}\right)^{2/3} \Rightarrow \delta_c \approx 2.8$$

$$L_{\mathrm{bol}} \approx \left(\frac{2.8}{\delta_c}\right)^4 1.5 \times 10^{45}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

$$L_{\mathrm{Edd}} = 1.3 \times 10^{46} \frac{M_{\mathrm{BH}}}{10^8 M_\odot}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

KM3 230213A and the flare of PMN J0606-072

Kivokurtseva, ST, arXiv:2509.10352

$$E_p^\star \approx (1.0^{+2.6}_{-0.5}) \times 10^{19}\ \mathrm{eV}$$

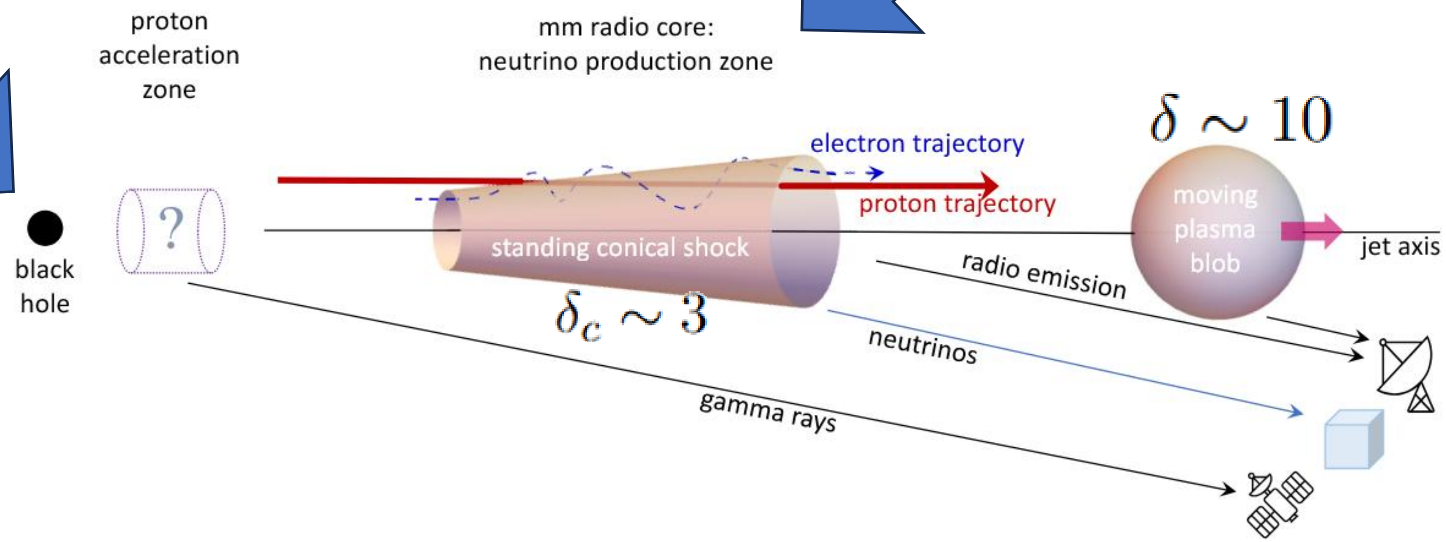
can this source accelerate protons to that high energy?

~~in the black-hole magnetosphere?~~

Ptitsyna, Neronov 2018

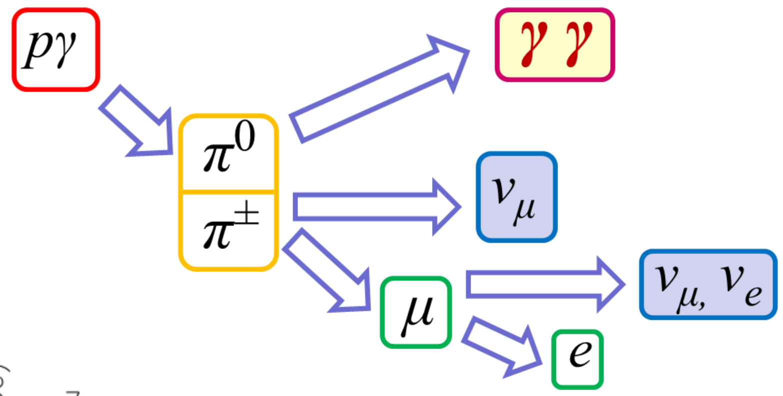
in a moderately relativistic shock?

Bykov et al. 2012



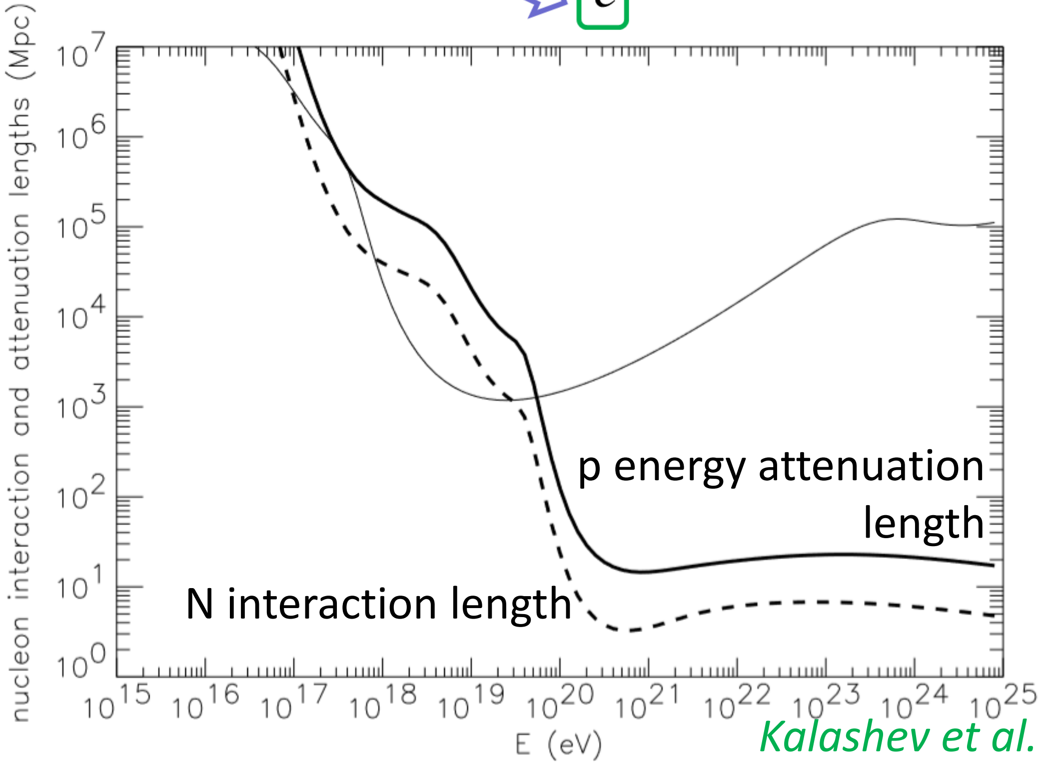
The Greisen-Zatsepin-Kuzmin (GZK) process

$$E_\pi \approx E_p/5$$



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

$$E_p E_{\gamma_B} = m_\Delta^2 \quad \Rightarrow \quad E_{\gamma_B} = \frac{m_\Delta^2}{20 E_\nu} \simeq 750 \text{ eV} \left(\frac{E_\nu}{100 \text{ TeV}}\right)^{-1}$$

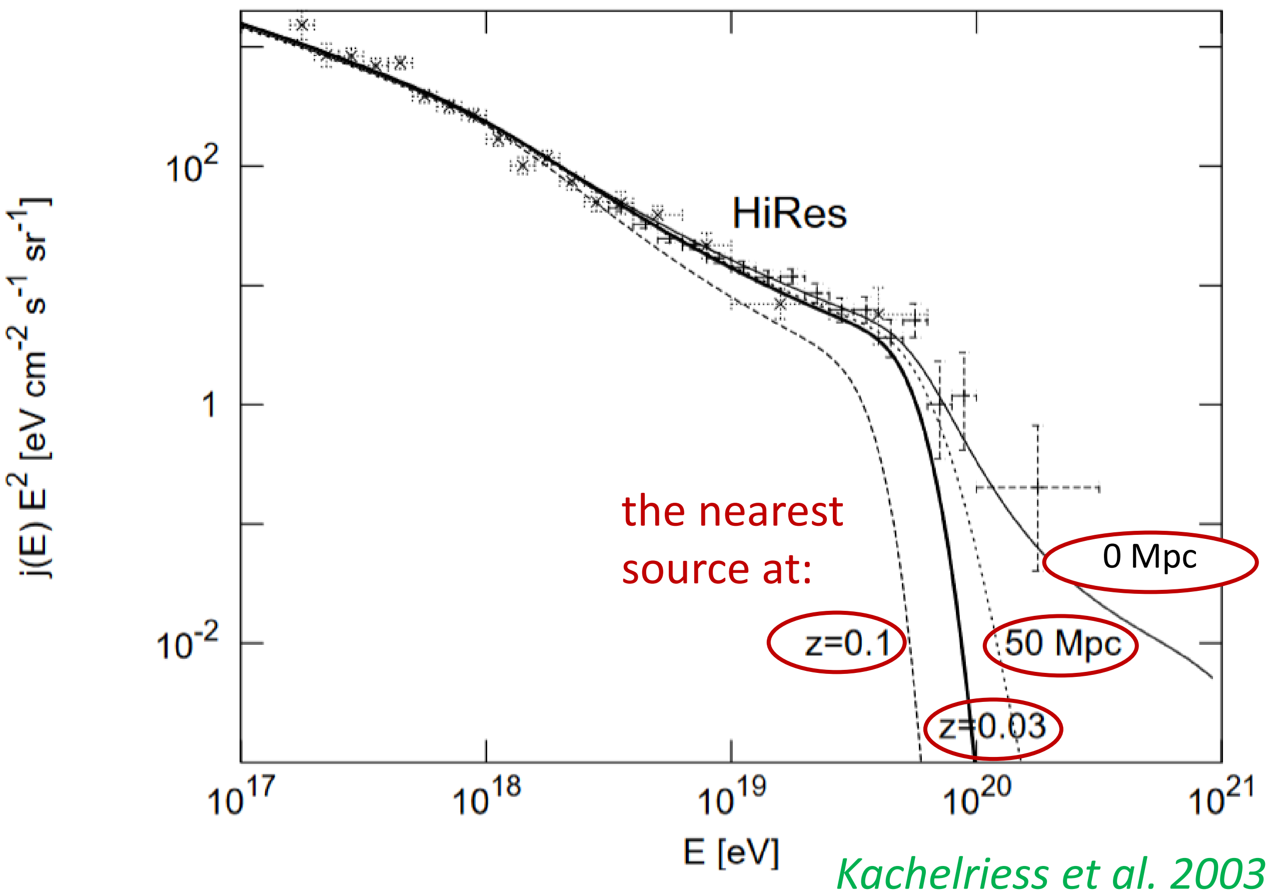


Kalashev et al. 2002

- for $E_p = 4\times10^{19}$ eV, this relation gives the CMB photon energy
- the GZK process limits the 10^{20} eV propagation to ~100 Mpc

[note the difference between the interaction and energy attenuation lengths]

The Greisen-Zatsepin-Kuzmin (GZK) cutoff

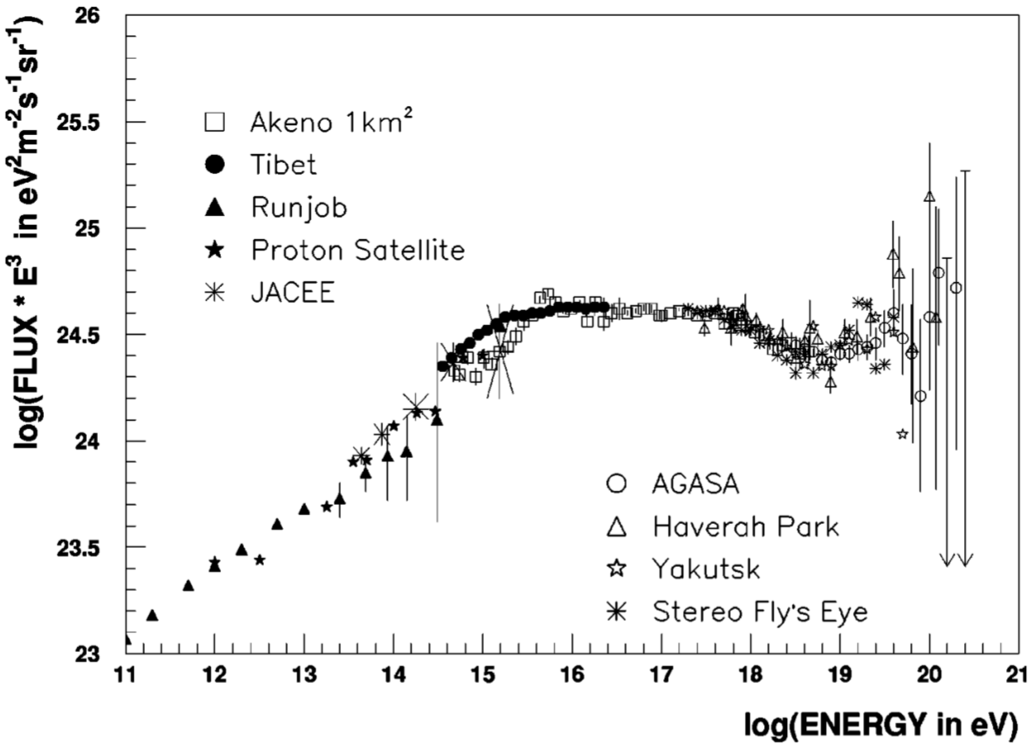


Kachelriess et al. 2003

- the GZK process limits the 10^{20} eV propagation to ~100 Mpc

  Greisen 1964, Zatsepin&Kuzmin 1964
- 100 Mpc is ~1/40 of the size of the Universe
- cosmic rays with higher energies come from $1/(40)^3$ volume of the Universe
- for uniformly distributed sources, this means a **sharp cutoff** in the spectrum
- details depend on the source distribution in the Universe and on injected spectra

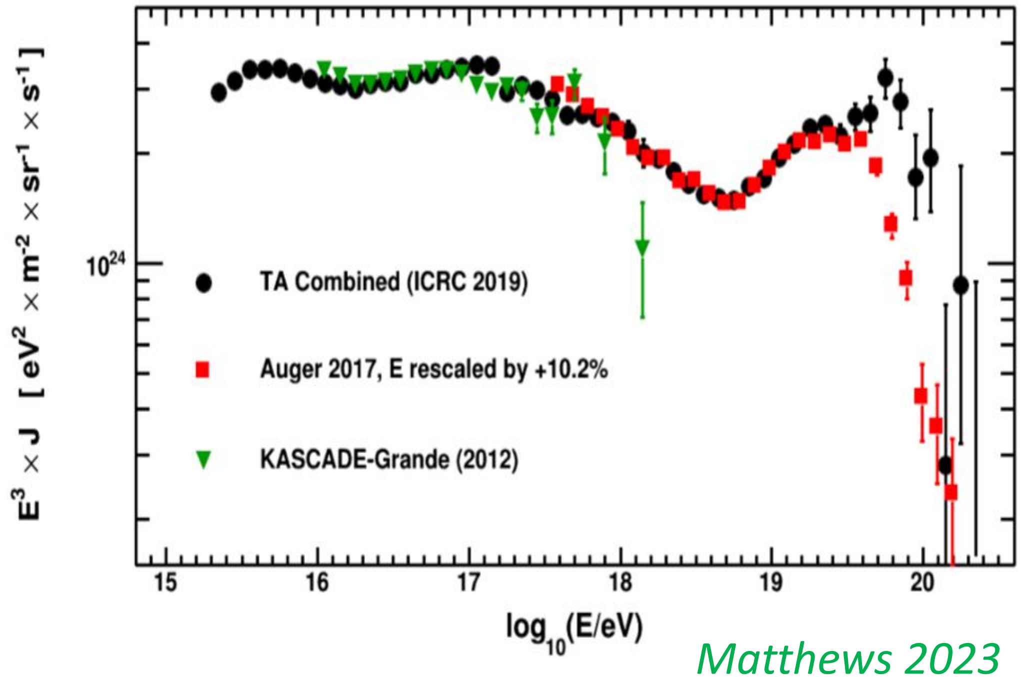
Two faces of the GZK problem: historical versus modern



Nagano & Watson 2000

- early, small-exposure experiments (Volcano Ranch, Haverah Park, SUGAR, Fly's Eye, Yakutsk, AGASA) observed many super-GZK events (one even before the CMB discovery)
- the spectrum continued beyond the GZK energy (no cutoff)
- that meant *either* strong local overdensity of sources *or* exotic particles
- new-physics scenarios were suggested
- the scenarios were killed by observations of GeV diffuse gamma-ray background (electromagnetic cascades!), then by limits on unusual UHECR showers

Two faces of the GZK problem: historical versus modern



Matthews 2023

- the 21st century experiments (HiRes, Pierre Auger Observatory and Telescope Array) measured the spectrum with large statistics, and it is (±) consistent with the GZK cutoff
- many events above the GZK energy were detected
- this means *either* that their sources are within 50 Mpc, *or* that new-physics scenarios are still needed
- no obvious sources capable to accelerate particles to 10^{20} eV are evident in the Local Universe
- in particular, no sources in the directions of events (magnetic deflections are small for these energies)