High-energy astronomy with the Baikal-GVD neutrino telescope

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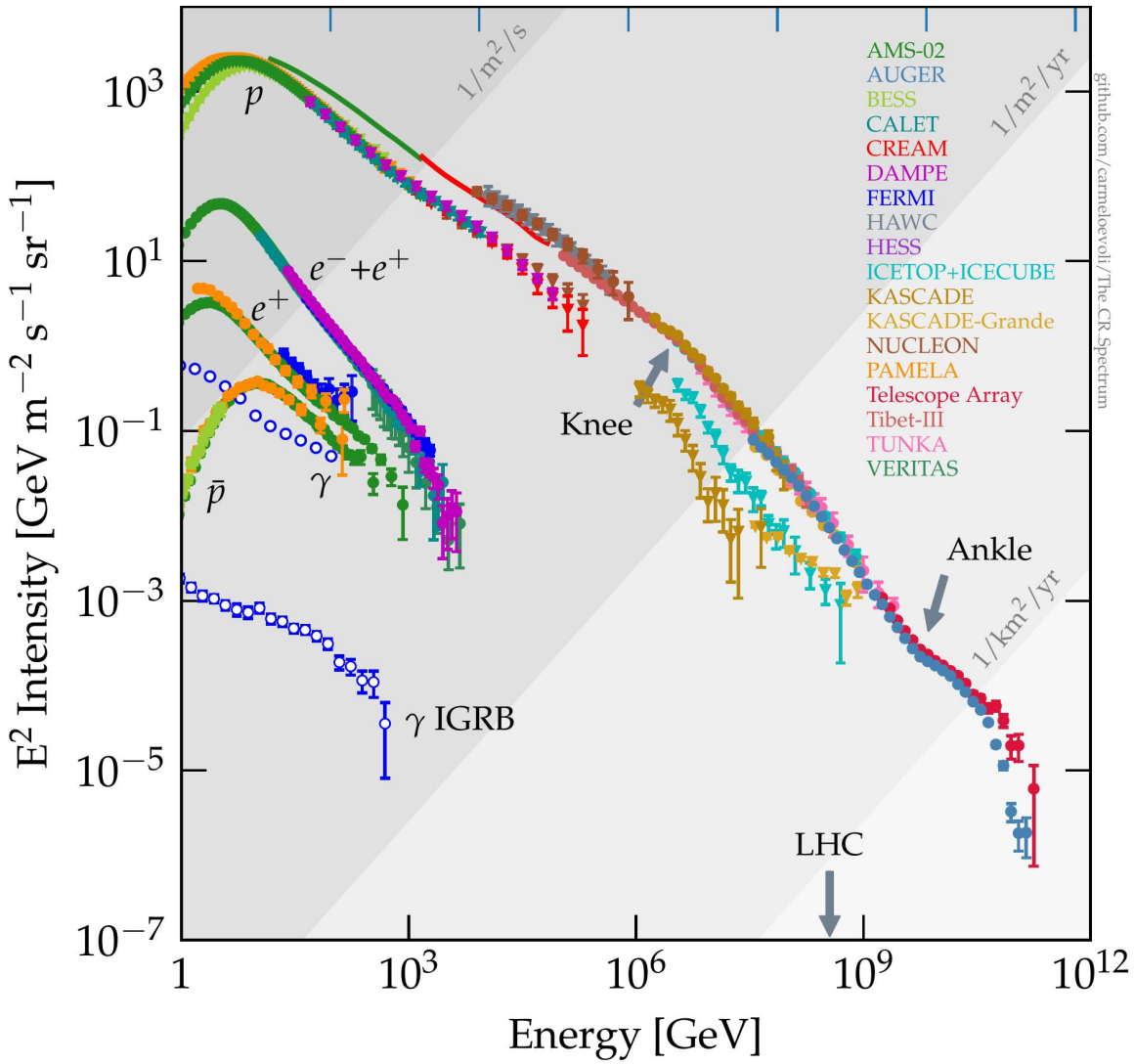
for the Baikal-GVD collaboration

ICPPA 2022, Nov. 29 - Dec. 2, Moscow, Russia

Introduction

Diffuse cosmic ray flux

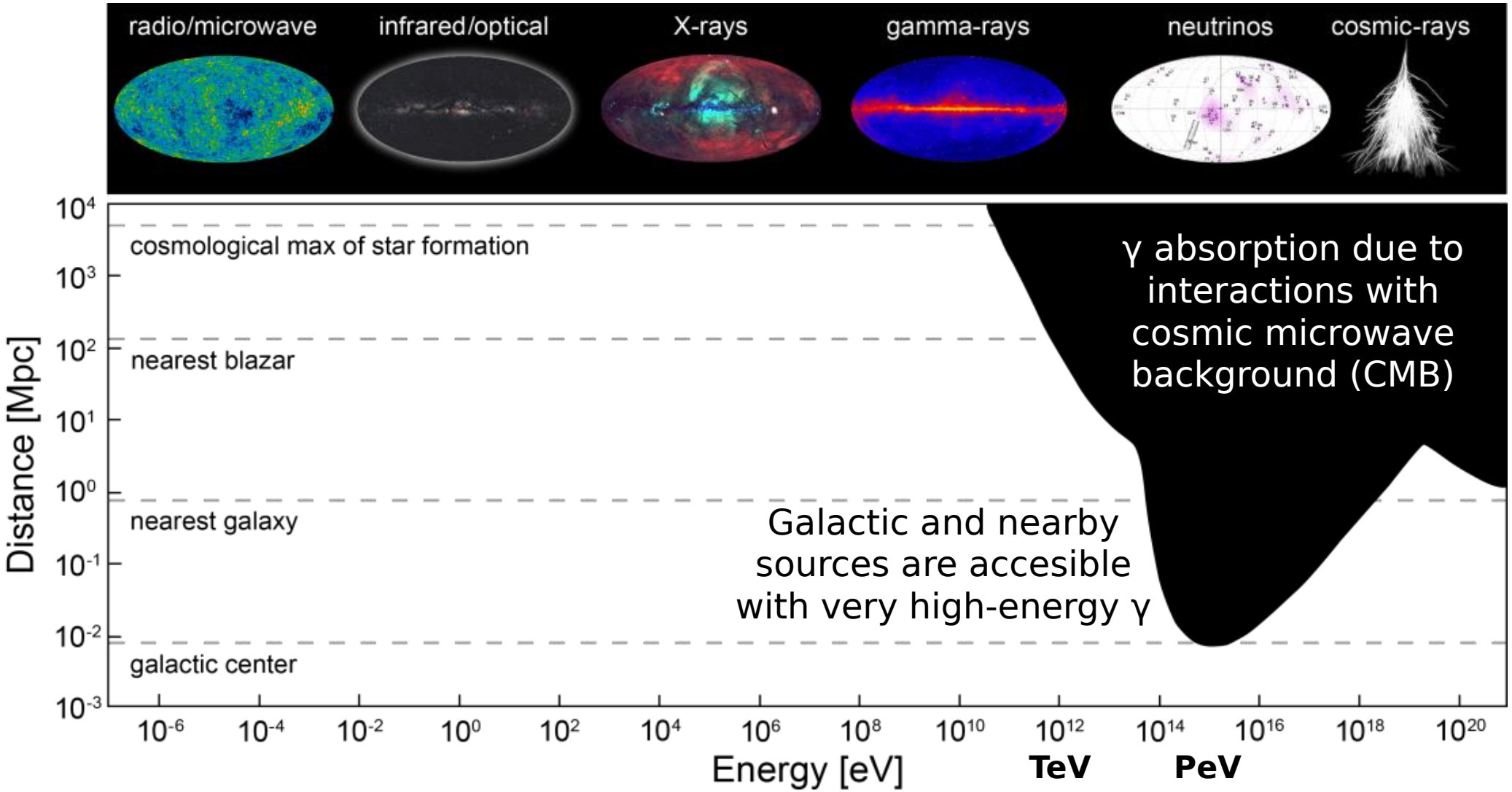


The range of measured charged cosmic ray (CR) particle energies extends up to 10^{11} GeV [10^{20} eV]

Charged CR particles cannot be associated with the source due to interstellar magnetic fields (except for E> ~10^{10} GeV)

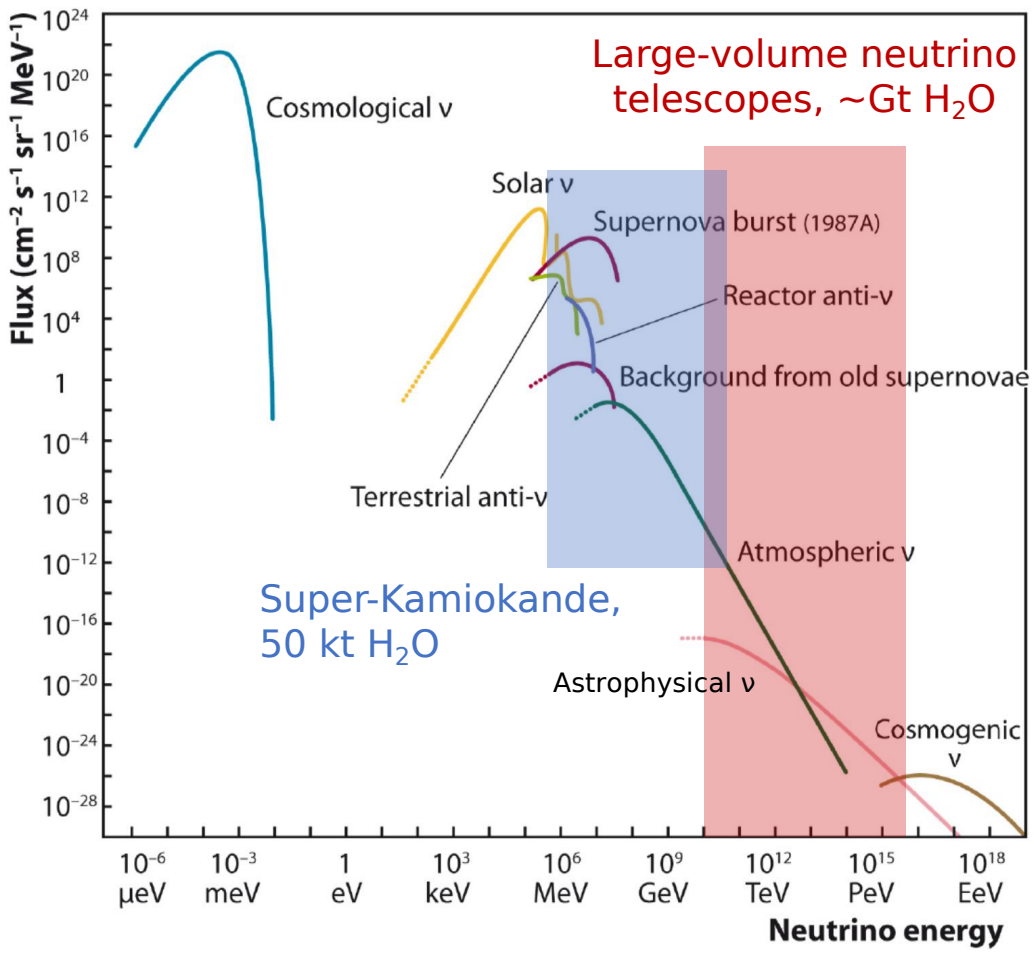
Neutrino produced in distant powerful CR accelerators once detected could sched light on their nature

Neutrino as cosmic messenger



Neutrino propagates to cosmological distances and points to its origin

Neutrino energies at Earth



Low-energy neutrino astronomy: neutrino from thermal processes

- Sun
- Supernova burst 1987A

High-energy neutrino astronomy: study of non-thermal processes (relativistic particles interactions)

High-energy neutrino are produced in CR interactions

- In Earth atmosphere
- In high-energy cosmic sources
- With CMB

High-energy (HE) neutrino flux study is the primary goal of large-volume neutrino telescopes like **Baikal-GVD**

High-energy neutrino production

Accelerated protons interact in the vicinity of the source

Leading processes:

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu \\ \pi^- \rightarrow \mu^-\nu_\mu \rightarrow e^-\bar{\nu}_e\bar{\nu}_\mu\nu_\mu \end{cases} \qquad p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0 \rightarrow p\gamma\gamma \\ n\pi^+ \rightarrow n\mu^+\nu_\mu \rightarrow ne^+\nu_e\bar{\nu}_\mu\nu_\mu \end{cases}$$

Flavour content:

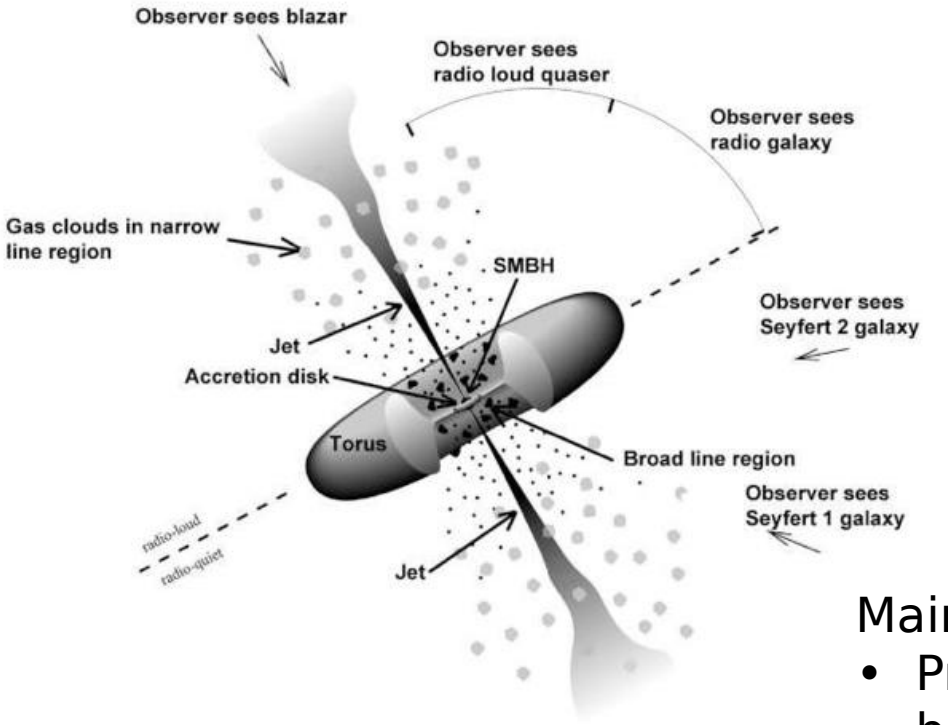
At the source $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ At the Earth $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

While γ are produced both in leptonic and hadronic processes,
Neutrino is the marker of hadronic processes in the source

Selected HE neutrino source candidates I

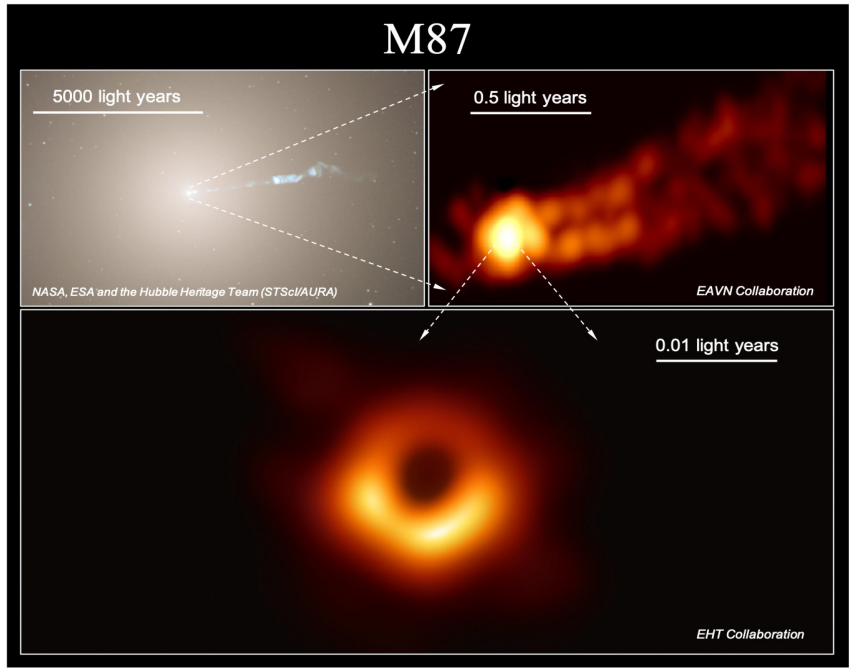
Active galactic nuclei (AGN)

Considered as neutrino sources since the early days of neutrino astronomy



https://fermi.gsfc.nasa.gov/science/eteu/agn/

E.g. nearby supergiant galaxy M87
distance: 16.4 Mpc



Mainly pγ mechanism expected

- Protons are accelerated in shock-waves or black hole (BH) magnetosphere
- Interactions with the EM radiation of the accretion disk

Selected HE neutrino source candidates II

Starburst galaxies (SBG)

Galaxies with very active star formation in the starburst nucleus (SBN)

CR reservoir
- High-energy protons are confined in SBN
- Accelerated by supernovae explosions shockwaves
- Interact with each other
- Main ν production mechanism: pp

Reference SBG M82, distance: 3.7 Mpc

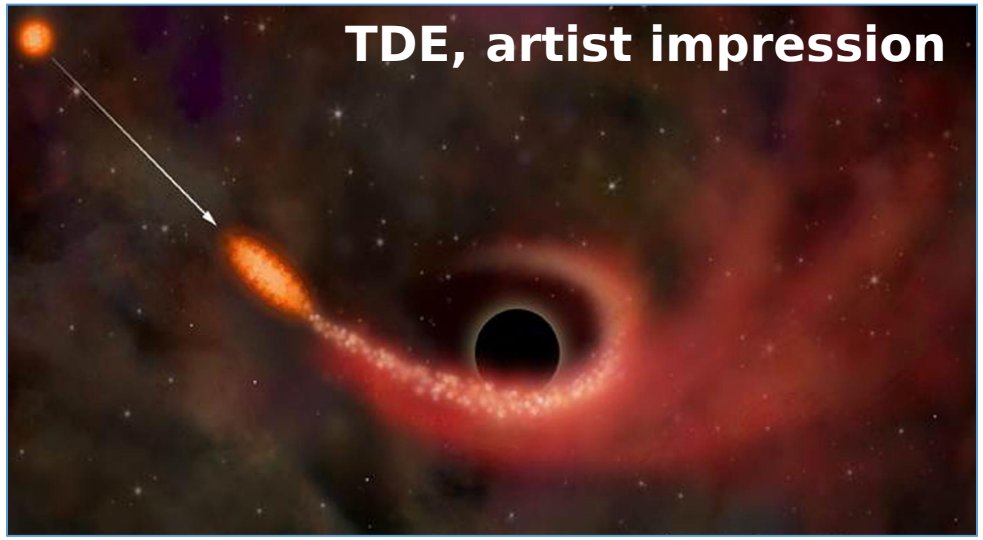
https://chandra.harvard.edu/photo/2006/m82/

Selected HE neutrino source candidates III

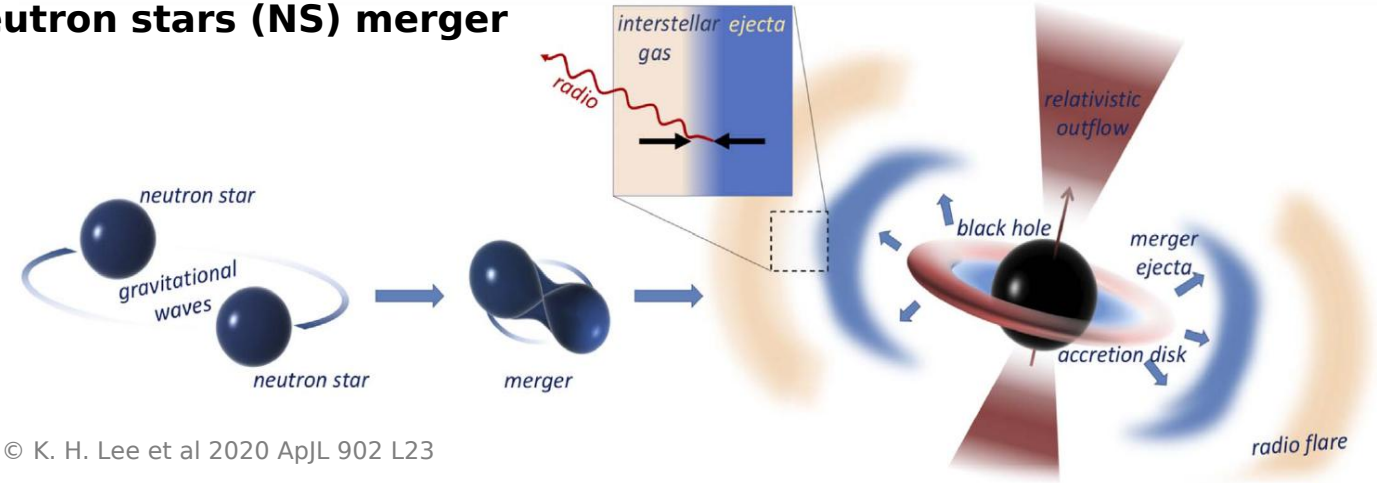
Merger events

Tidal disruption events (TDE):

- Supermassive BH consumes a star
- Short-living accretion disk is formed, pγ process similar to AGN
- pp processes for the star remnants
- Few months - years scale



neutron stars (NS) merger



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Gravitational waves domain:

- BH-BH mergers
- BH-NS (neutron star) mergers
- NS-NS mergers: best candidate

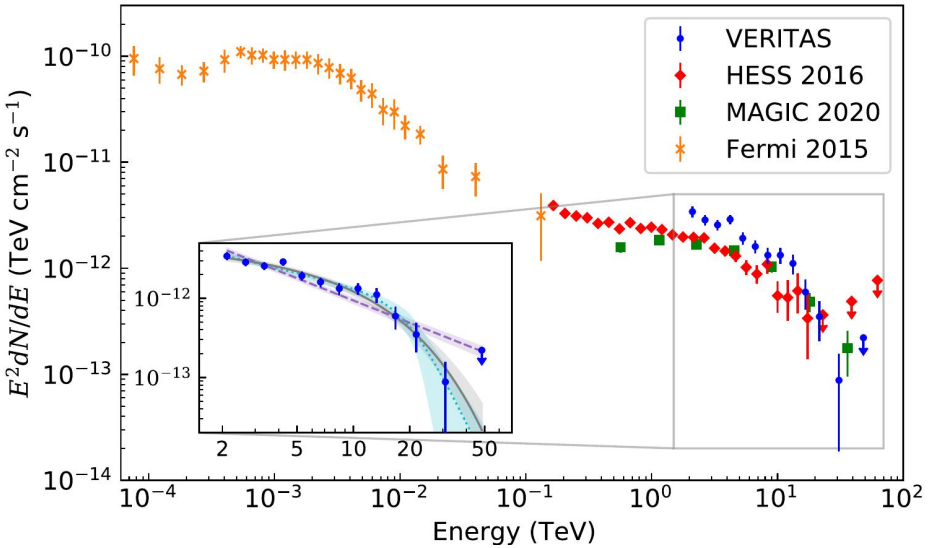
LIGO/VIRGO/KAGRA event set:
90 mergers (mainly BH-BH)
[LIGO-P2000318, arXiv:2111.03606]

Galactic source candidates

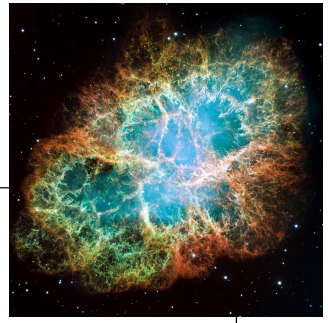
High-energy galactic γ sources: huge progress in last decade

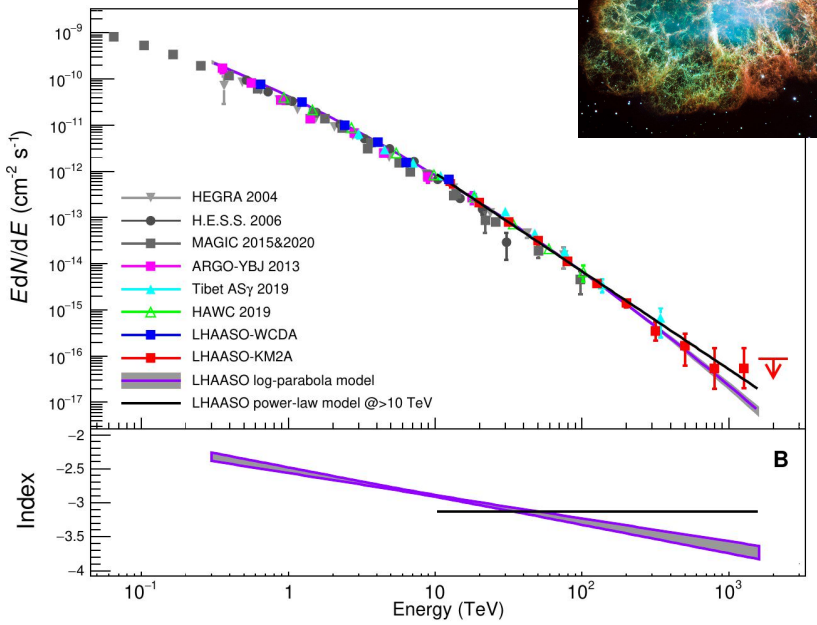
- TeV - scale observations by ground-based γ telescopes: MAGIC, HESS, VERITAS, LHAASO
- LHAASO: set of 12 PeVatrons
  [Nature 594, 33–36 (2021)]

VERITAS: up to 40 TeV γ from the galactic center
[C. B. Adams et al (2021) ApJ 913 115]



LHAASO:
PeV γ from Crab nebula
(supernovae remnant)

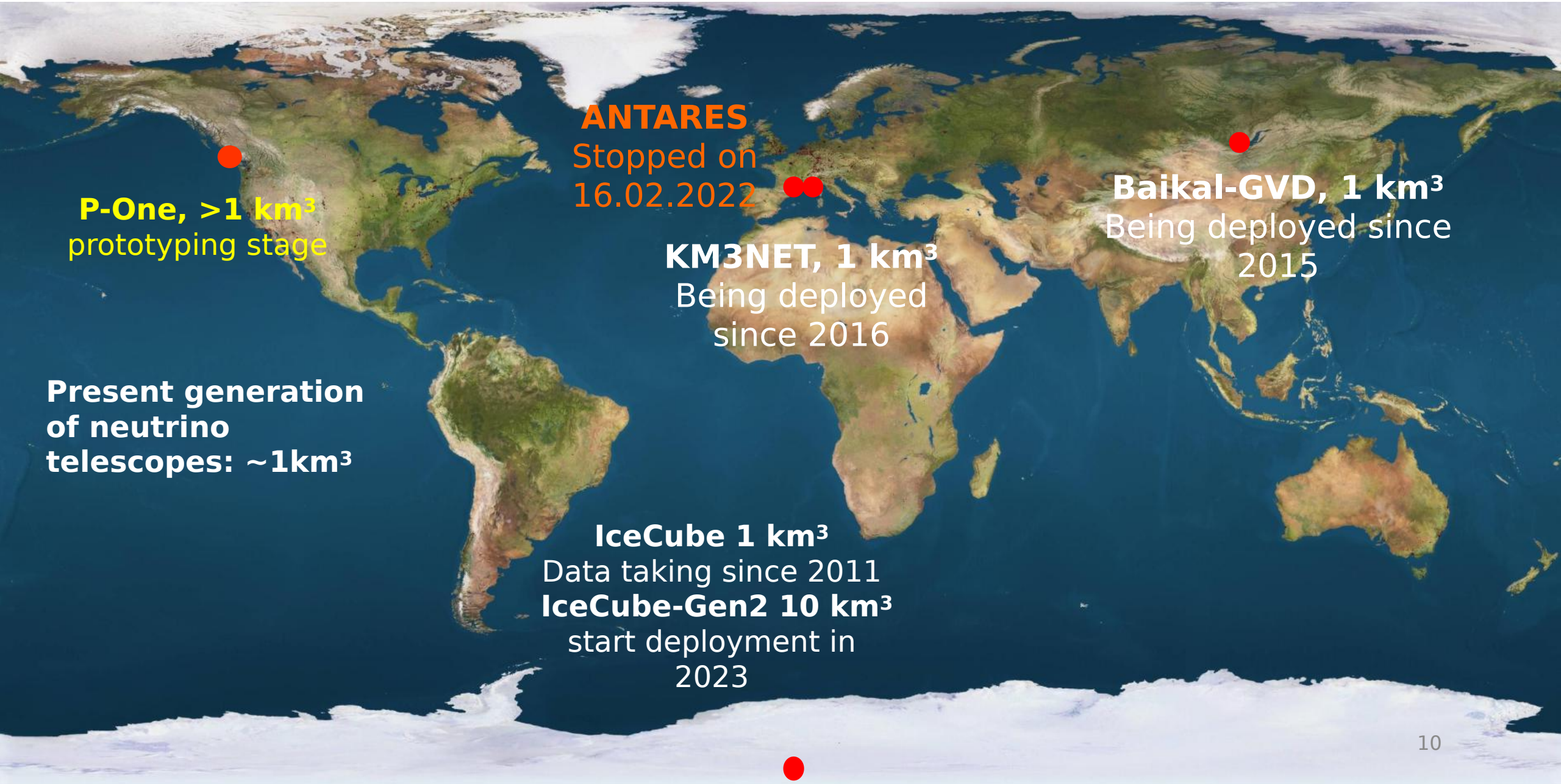




[Science, 2021, Vol 373, Issue 6553, pp. 425-430]

Neutrino (non)detection can sched light on whether galactic TeV-scale γ are produced in hadronic or leptonic processes

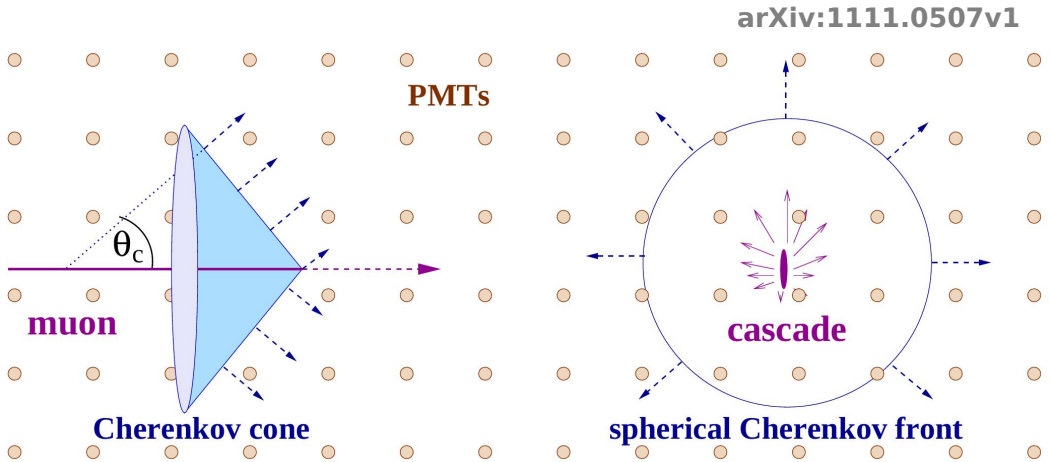
Neutrino telescope network



Neutrino detection principle

Sparse array of photodetectors in natural water (ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected



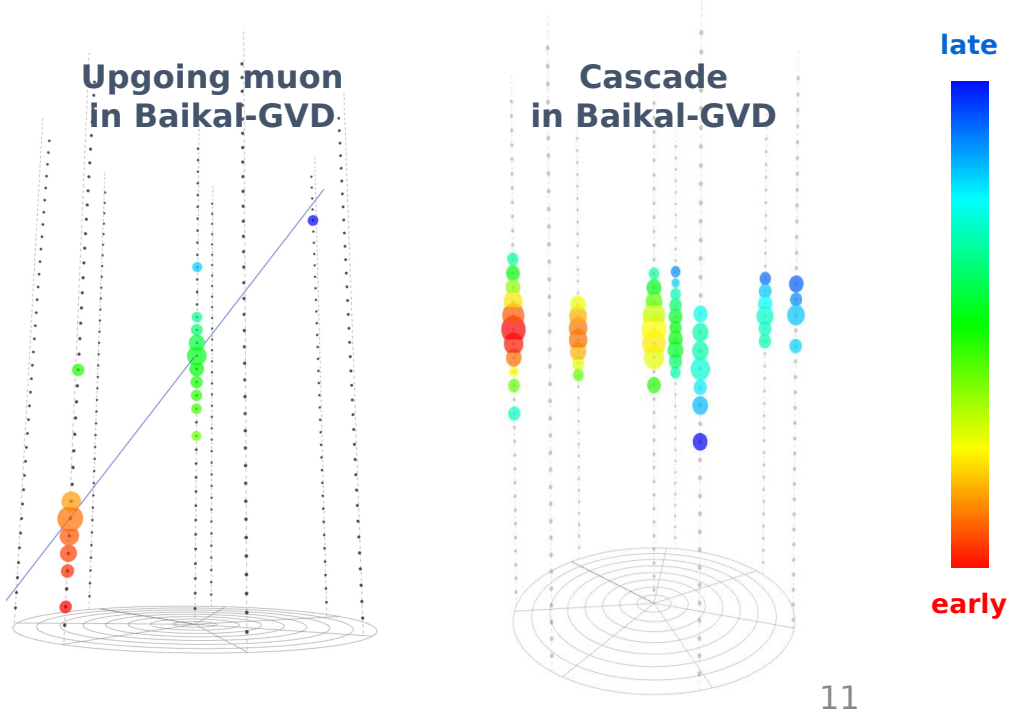
Neutrino event types:

Tracks (CC, ν_μ ν_τ):

- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200-300%
- Increased sensitive volume due to muon propagation range

Cascades (CC ν_e ν_τ, NC):

- Moderate angular resolution 3°-10°
- Good energy resolution: 5-30%



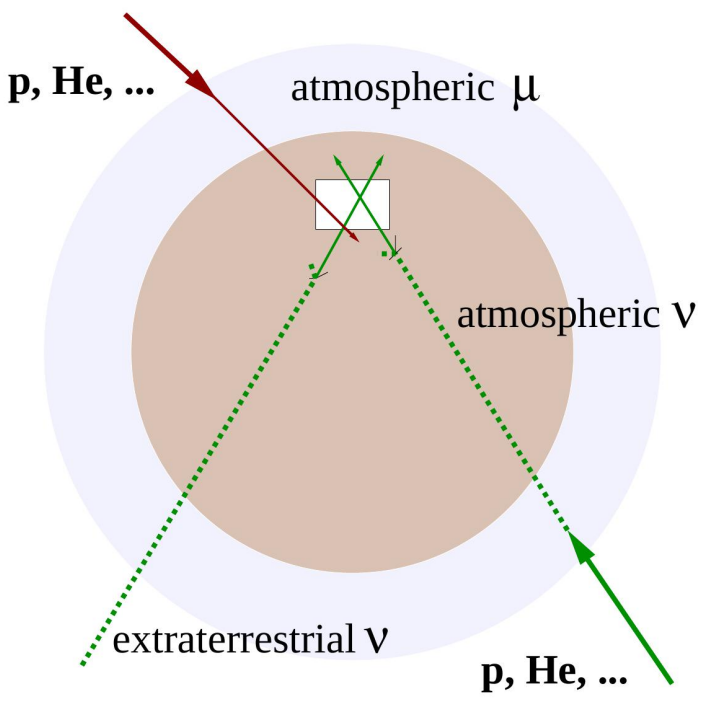
Backgrounds

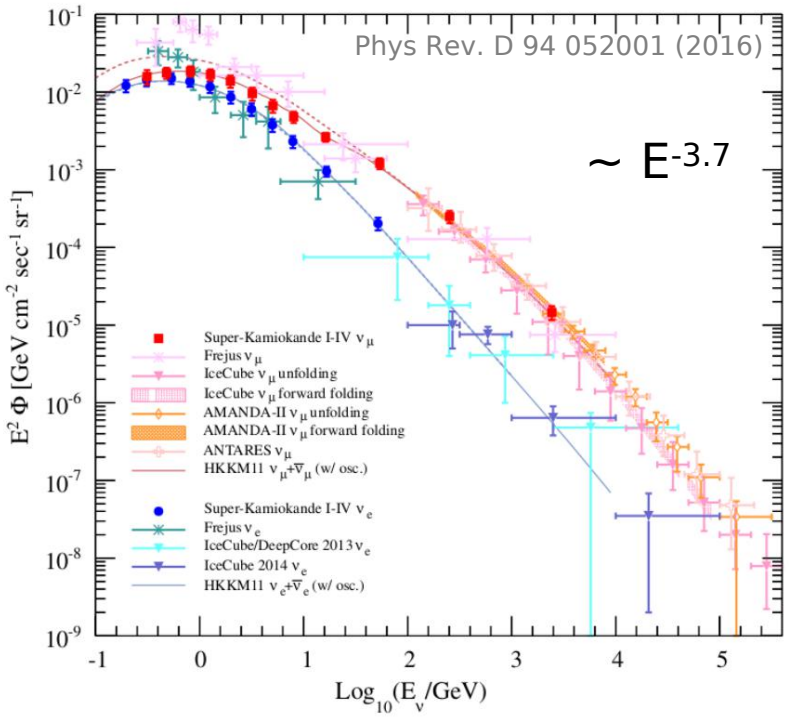
Atmospheric muons: bundle of downgoing muons from CR interaction

- Background to all neutrino events
- Reduced by zenith angle cut

Atmospheric neutrino: neutrino from CR interaction

- “Standard candle” for neutrino telescope performance
- Background to astrophysical searches





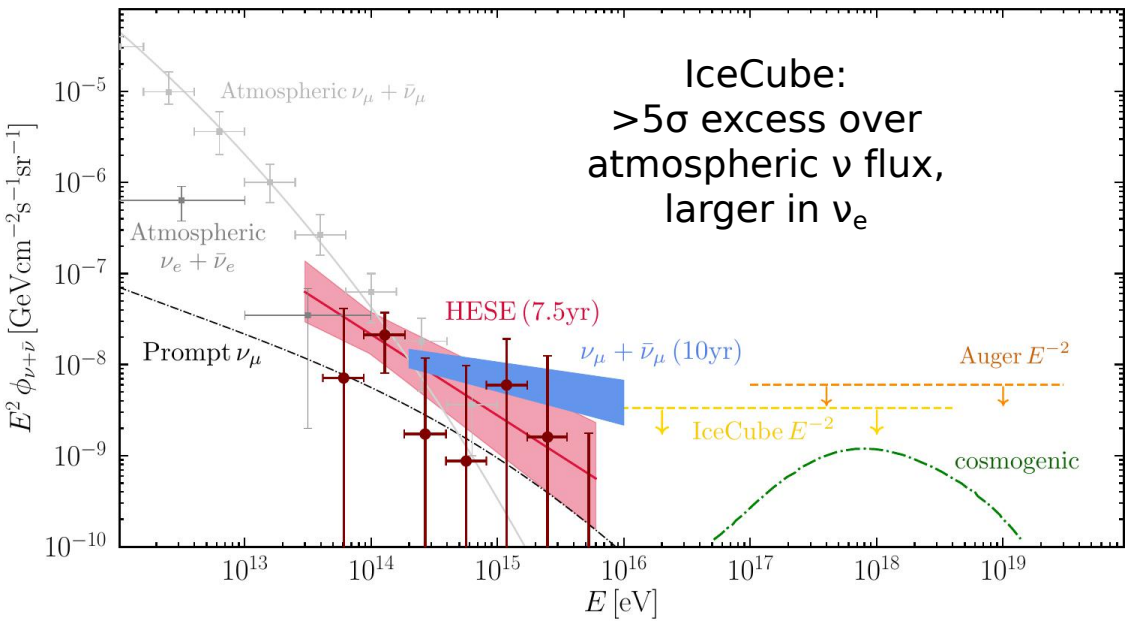
Atmospheric neutrino are dominated by ν_μ for E_ν > ~10 GeV

Astrophysical neutrino diffuse flux:
An excess in neutrino events over atmospheric neutrino spectrum

Diffuse neutrino flux

The presence of TeV - PeV diffuse astrophysical neutrino flux is established by the IceCube telescope with significance well above 5σ (e.g. [Astrophys.J. 928 (2022) 50])

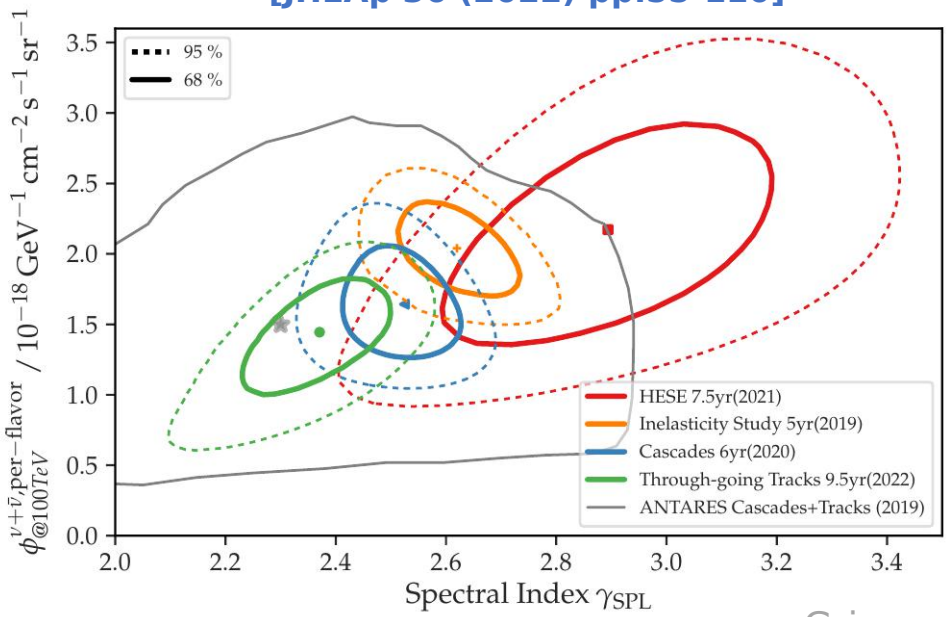
[JHEAp 36 (2022) pp.55-110]



Neutrino energy spectrum is usually fitted as one-component power law:

$$\phi_{\nu+\bar{\nu}} = \phi_0 (E/E_0)^{-\gamma_{SPL}}$$

[JHEAp 36 (2022) pp.55-110]



Different powers for different IC analyses and event sets: **~2.3 <** γ_{SPL} **< ~2.9**

ANTARES data: excess significance 1.8σ
[PoS(ICRC2019)891]

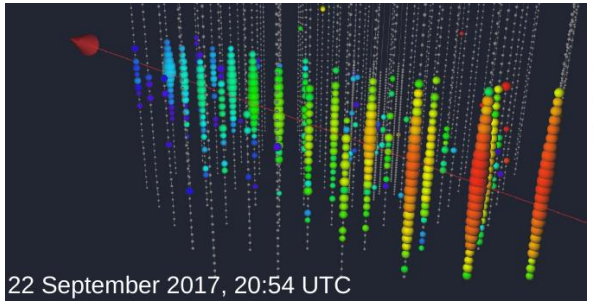
Identified source candidates I

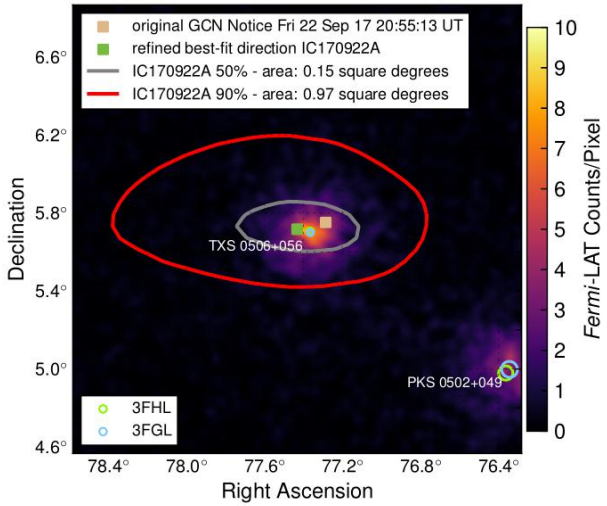
TXS 0506+056: high-energy blazar at 1.75 Gpc

IceCube alert event IC170922A (22.09.2017)

- ~290 TeV muon track in the direction of TXS 0506+056 blazar
- FERMI follow-up (28.09.2017): TXS0506+056 in the flaring state
- Observations followed and confirmed by MAGIC and other ground-based and space telescopes

[Science 361, eaat1378 (2018)]

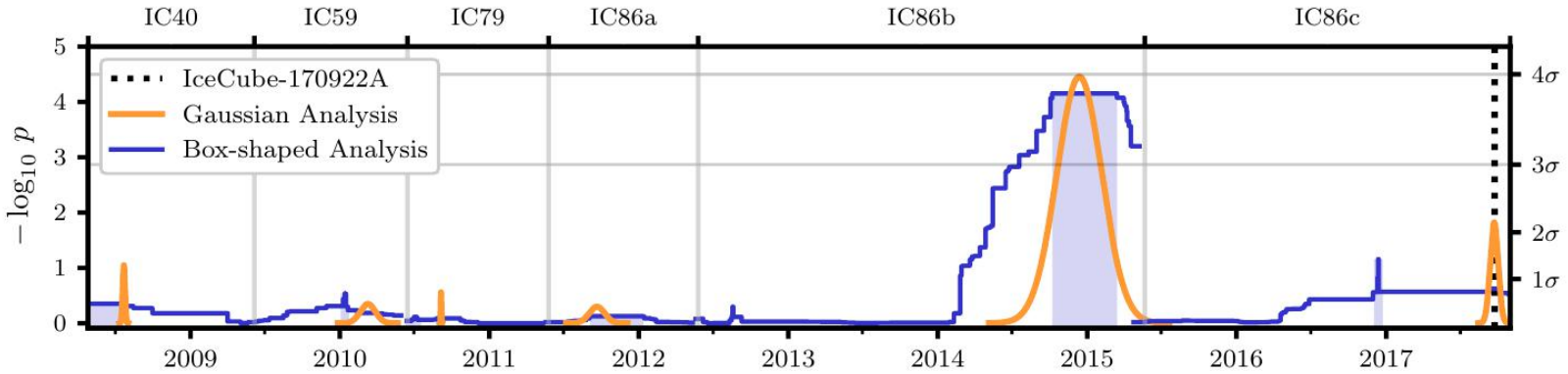




Search of events associated with TXS0506 in pre-alert data

3.5σ post-trial significance

[Science 361, 147-151 (2018)]



TXS0506+056 is considered as the first ever high-energy neutrino source

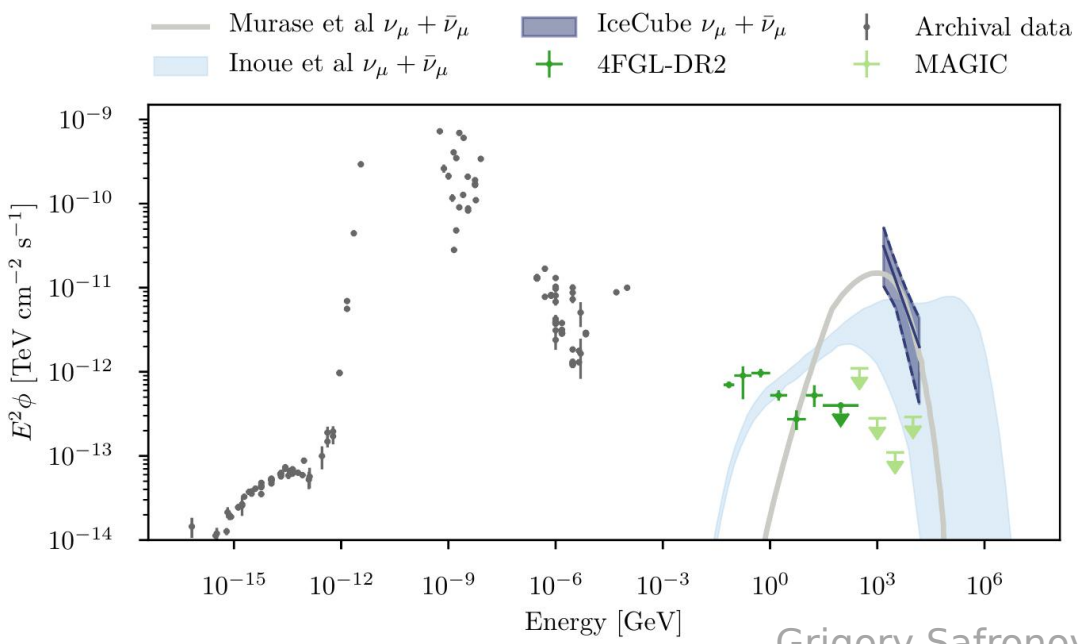
Identified source candidates II

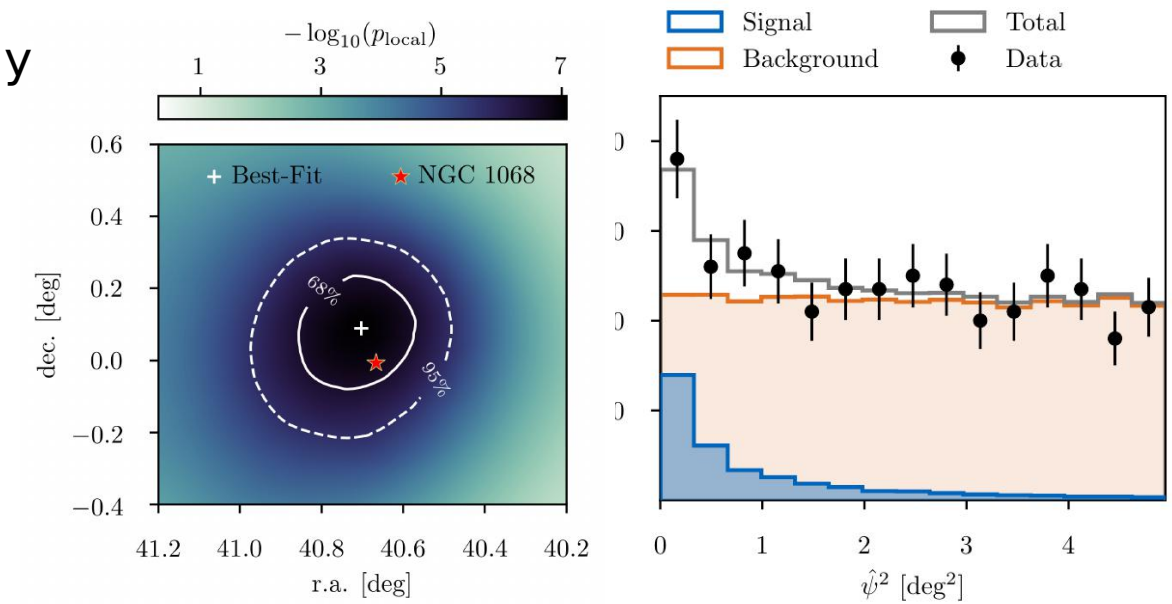
NGC 1068: Seyfert II galaxy, 14.4 Mpc away

Recent IC point source search with muon trackss:
NGC 1068 significance: 2.9σ
[Phys. Rev. Lett. 124, 051103 (2020)]

New analysis, published month ago

- 2011 - 2020: 3186 days of data-taking
- Refined reconstruction and calibrations
- E_ν > 100 GeV, 670000 events after cuts





[Science 378, 6619, 538-543 (2022)]

79^{+22}_{-20} events above background

4.2σ significance

- Main contribution from E_ν ~ 1.5 - 15 (TeV)

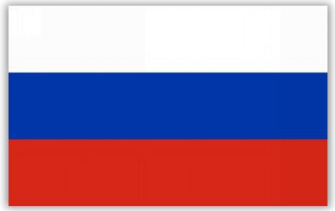
Second high-energy neutrino source candidate

Spectrum measurement in agreement with:
[Phys.Rev.Lett. 125 (2020) 011101]

Baikal-GVD neutrino telescope

Baikal-GVD (Gigaton Volume Detector) is a cubic-kilometer scale underwater neutrino detector being constructed in lake Baikal

10 organisations from 5 countries, ~70 collaboration members



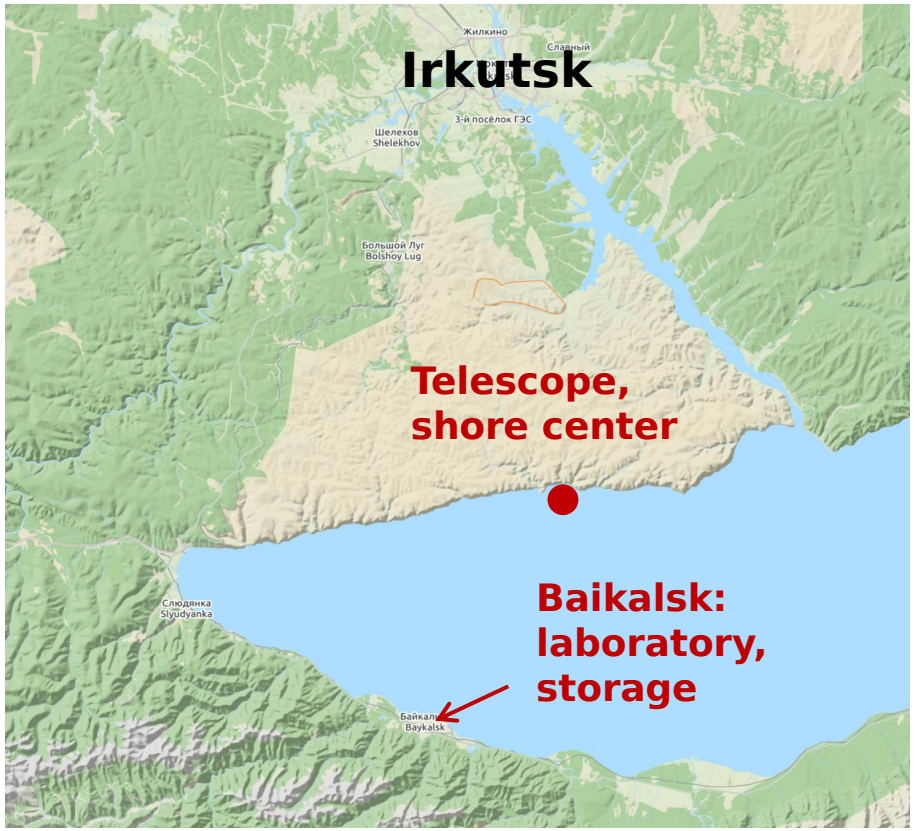


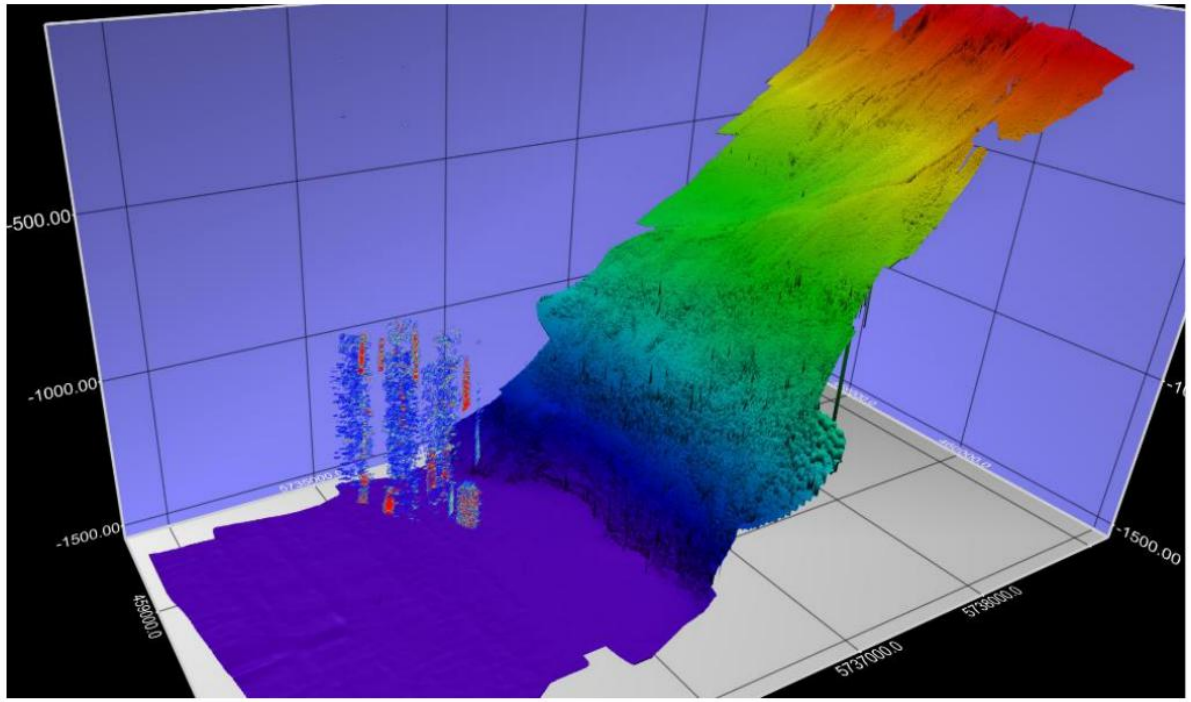
- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- EvoLogics (Berlin, Germany)
- Comenius University (Bratislava, Slovakia)
- Institute of Nuclear Physics ME RK (Almaty, Kazakhstan)

Experiment location

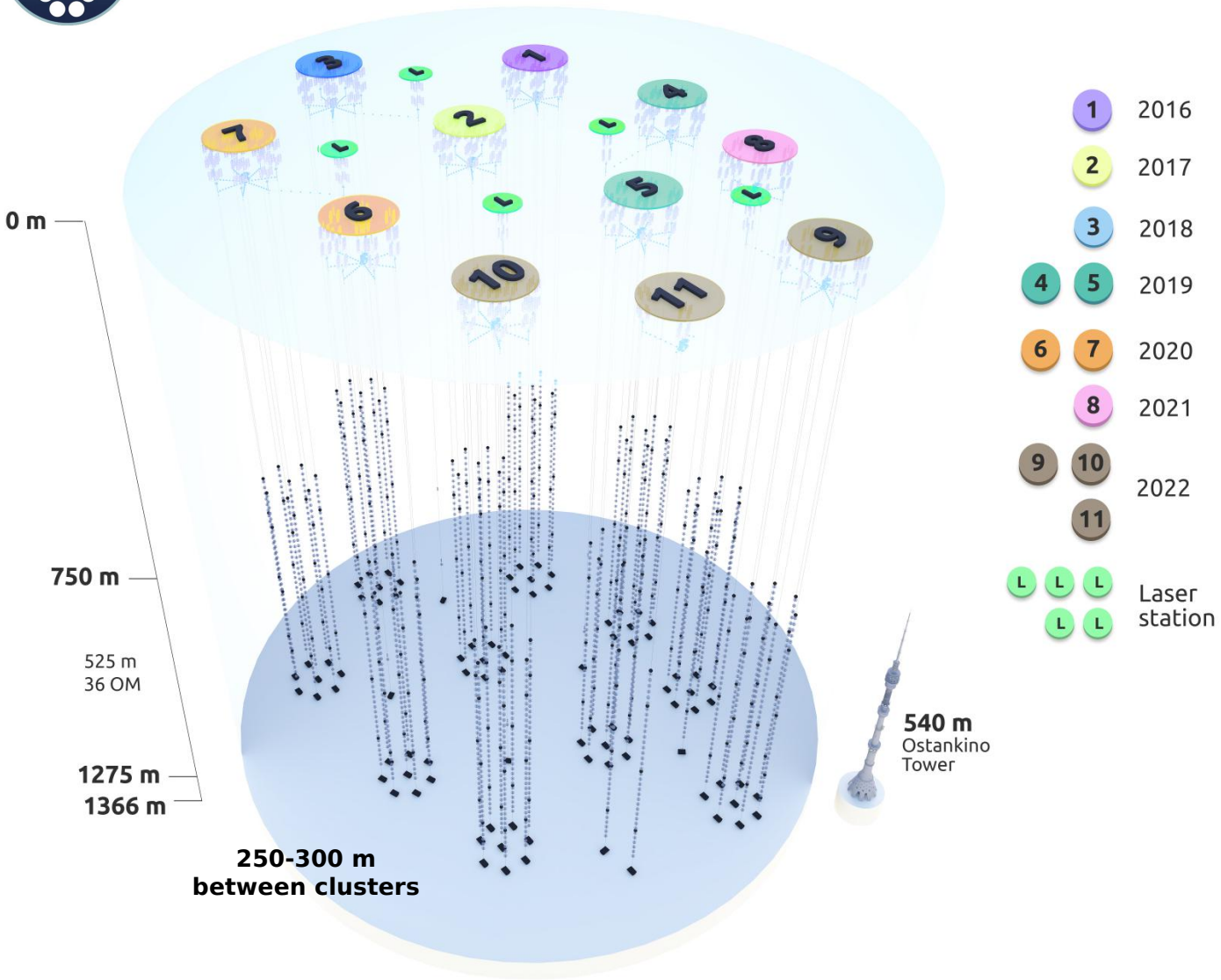
- Platform “106 km” of Circum-Baikal railway
- Telescope is located 3.6 km away from shore
- Constant lake depth: 1366 - 1367 [m]

- Water transparency:
  - Absorption length: 21 - 23 m
  - Scattering length: 60 - 80 m
- Stable ice cover over 7 - 8 weeks in February - April: detector deployment and maintenance





Detector status



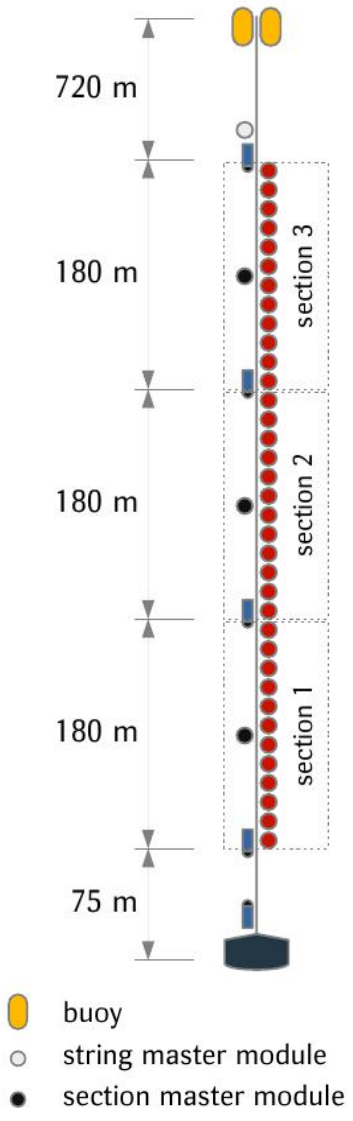
Deployment schedule

Year	Total number of clusters	Total number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	7	56	2016
2021	8	64	2304
2022	**10**	**80+3**	**2988**
2023	12	96	3456
2024	14	112	4032

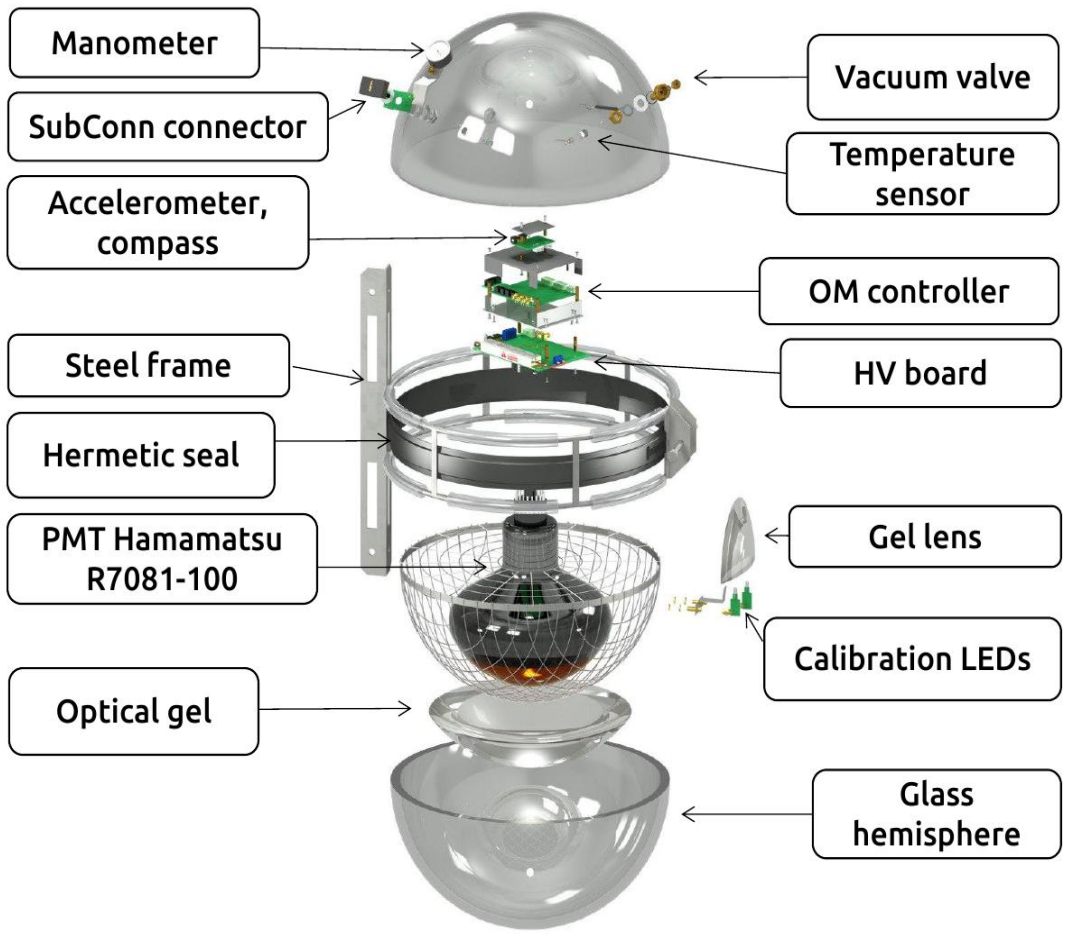
experimental cluster 11: new high-bandwidth DAQ

Detector components

String:



Optical module (OM):

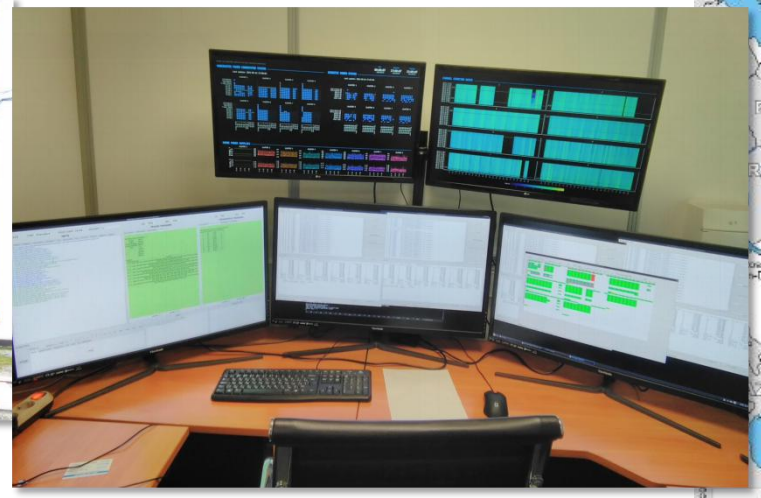


Each string carries 36 OMs
- 10-inch high Q eff. PMT
- 15 m vertical step
- OM facing the lake bottom
- 60 m between strings

Time calibration systems
- LED photodiodes in each OM
- LED beacons at each string
- Isotropic lasers between clusters
- Calibration precision ~2 ns

Geometry calibration system
- Acoustic modems on each string
- Acoustic polling each 1-6 minutes
- OM positioning precision ~ 20cm

Data stream



Baikal shore center
- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Fast reconstruction and alert production (to be deployed in 2023)

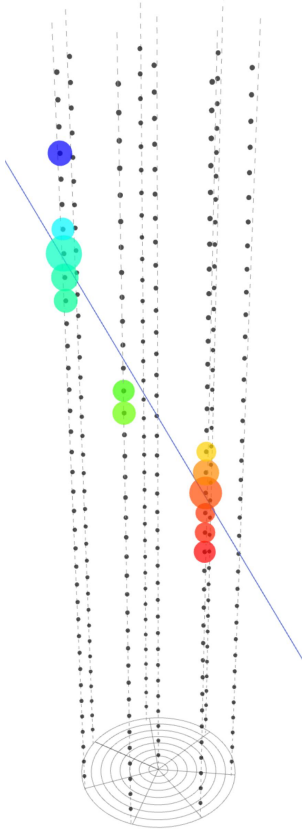
Data are transferred from Shore center to JINR
- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data volume ~40GB per day
- Delay due to shore → JINR data tranfer: < 1 min.
- At JINR data are stored using EOS service

Track-like events

Two modes of analysis

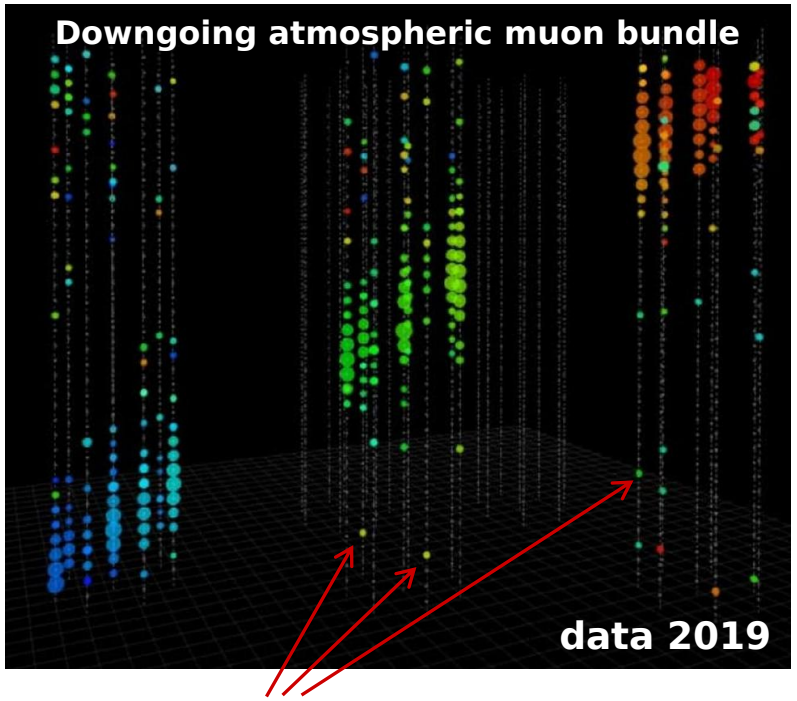
- Single-cluster: each cluster is treated as an independent detector
- Multi-cluster: common reconstruction for simultaneously triggered single-cluster events (in development)

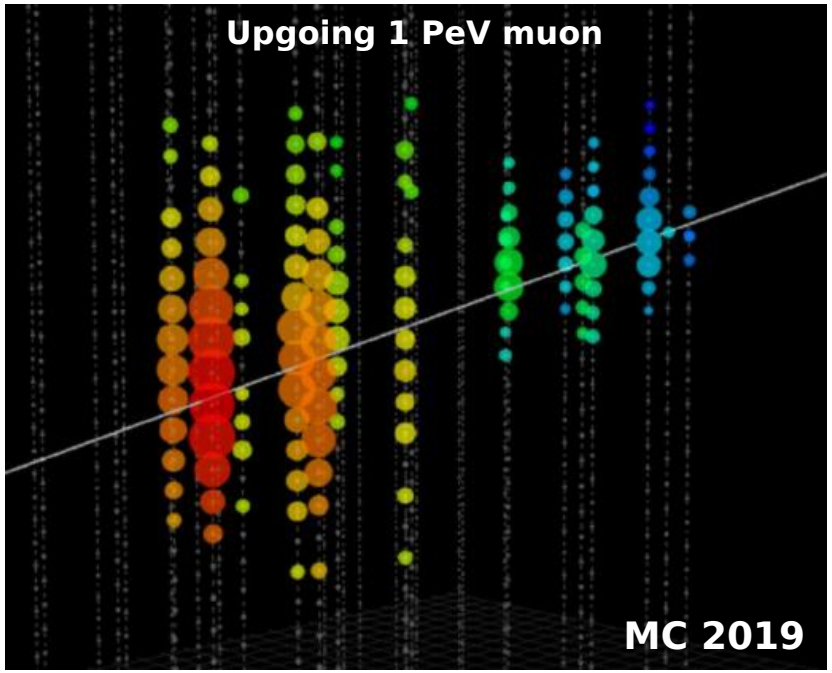
Single-cluster upgoing event:

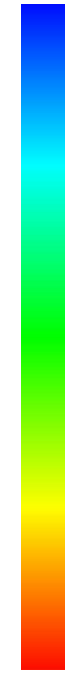


data 2019

Multi-cluster events:



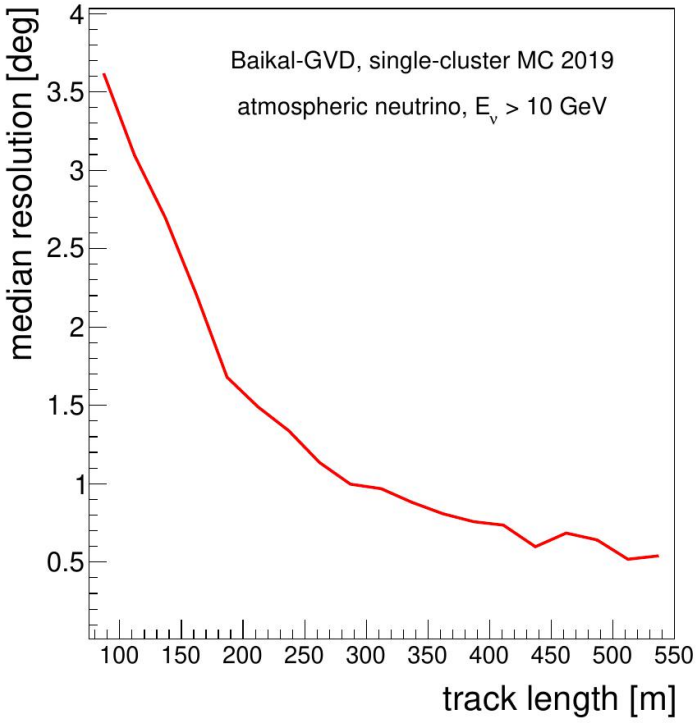




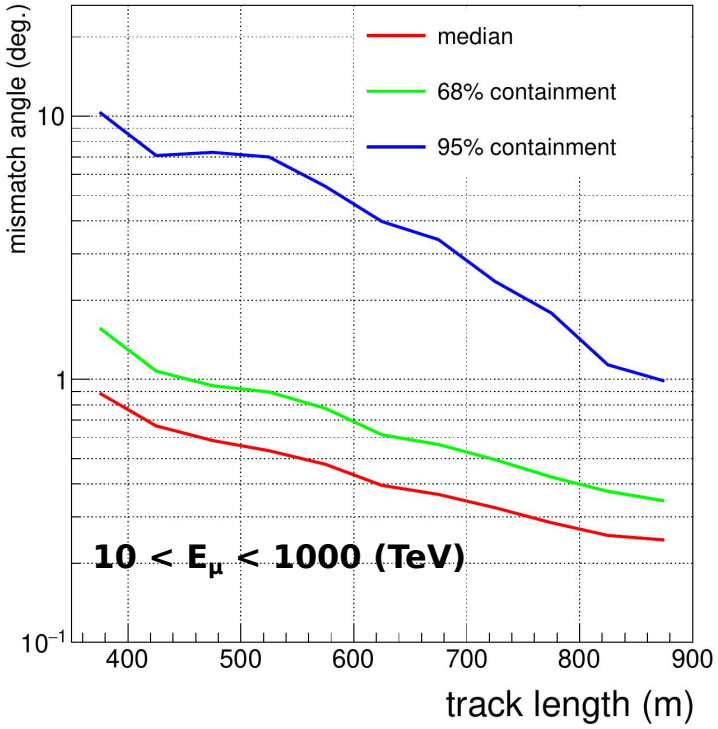
Lake and PMT noise hits

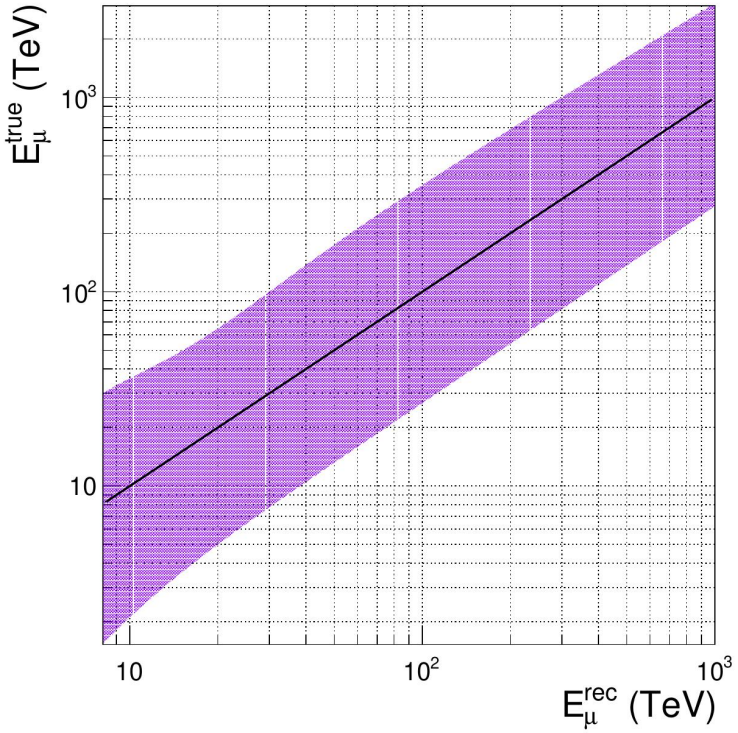
Muon track reconstruction precision

Single-cluster reconstruction



Multi-cluster reconstruction





Better than 0.5° resolution for tracks with length > ~500 m

Multi-cluster event reconstruction allows to reach the best angular precision

Factor 3 - 3.5 energy resolution in 8 TeV - 1 PeV range

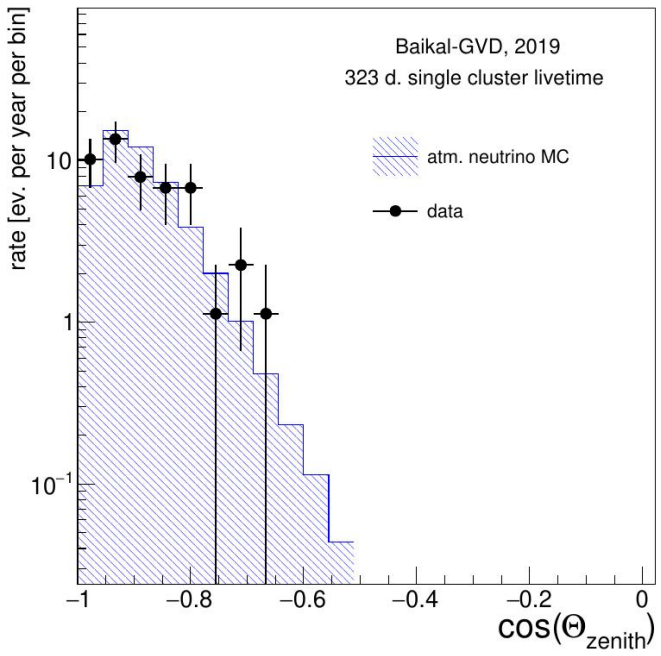
First neutrino candidate event sample

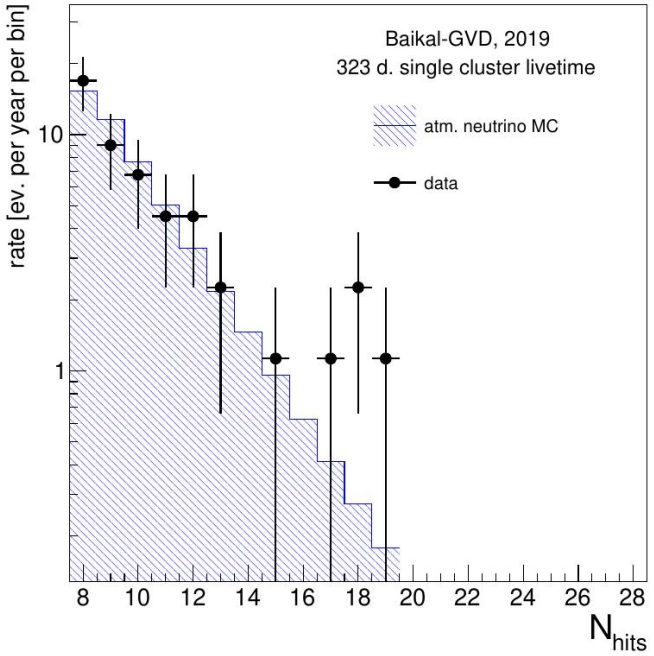
First set of single-cluster muon neutrino candidates is based on 2019 data

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, $\langle E_\nu \rangle \sim 500$ GeV
- Runs from April 1st until June 30th
- Results are compared to atmospheric neutrino simulation

MC expected: 43.6
- atm. neutrino :43.6
- atm. muon: 0

Observed: 44





Excellent agreement of MC expectation and data

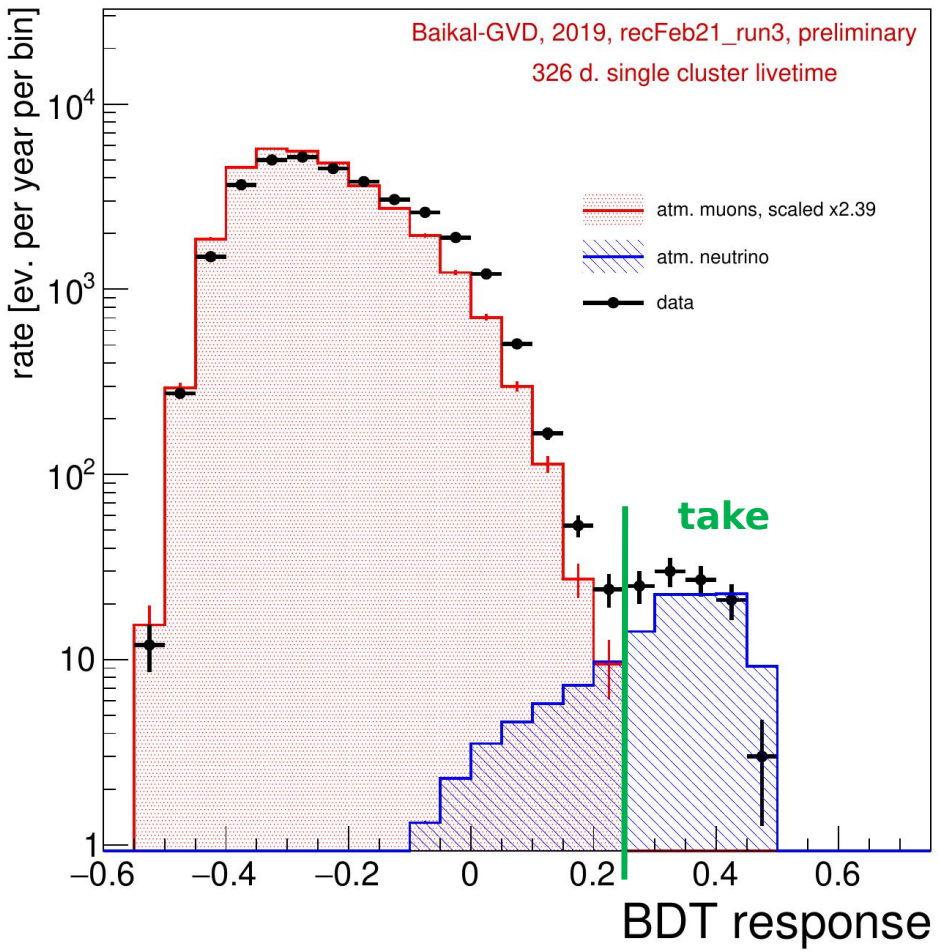
Single upgoing muon angular resolution for single-cluster analysis ~ 1°

[Eur. Phys. J. C 81, 1025 (2021)]

Sucessful Baikal-GVD performance validation

Track-like events analysis progress

Upgoing events: θ_{zenith} > 120°



Track-like reconstruction and neutrino selection techniques are being refined

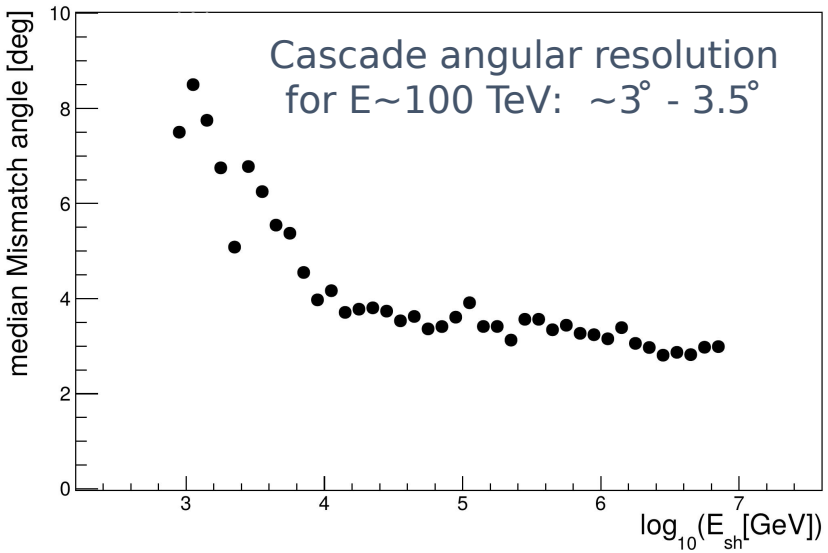
An improvement in sensitivity by a factor of 2 with recent developments
[PoS(ICRC2021)1063, PoS(ICRC2021)1080]

- Improvement in noise suppression techniques
- More efficient neutrino selection using boosted decision trees (BDT)

Machine learning application for Baikal water noise suppression: **[arXiv:2210.04653]**

Massive data reprocessing is ongoing these days, stay tuned for new results!

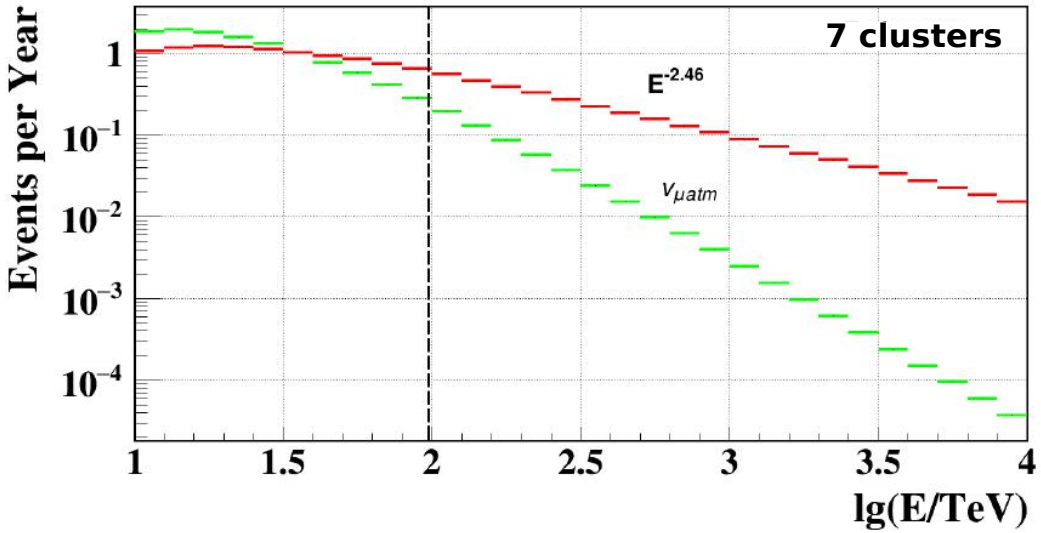
Reconstruction: high energy cascades



Cascade reconstruction
- Time χ^2 fit for the position reconstruction
- Likelihood minimisation for direction and energy

Angular resolution: 3-3.5° depending on energy (in E_{sh} > 10 TeV range)

Energy resolution: $\delta E/E \sim 10\% - 30\%$



~0.4-0.6 astrophysical neutrino per year for one cluster are expected
- In assumption of astrophysical neutrino spectrum $\sim E^{-2.46}$ (one of IceCube fits)

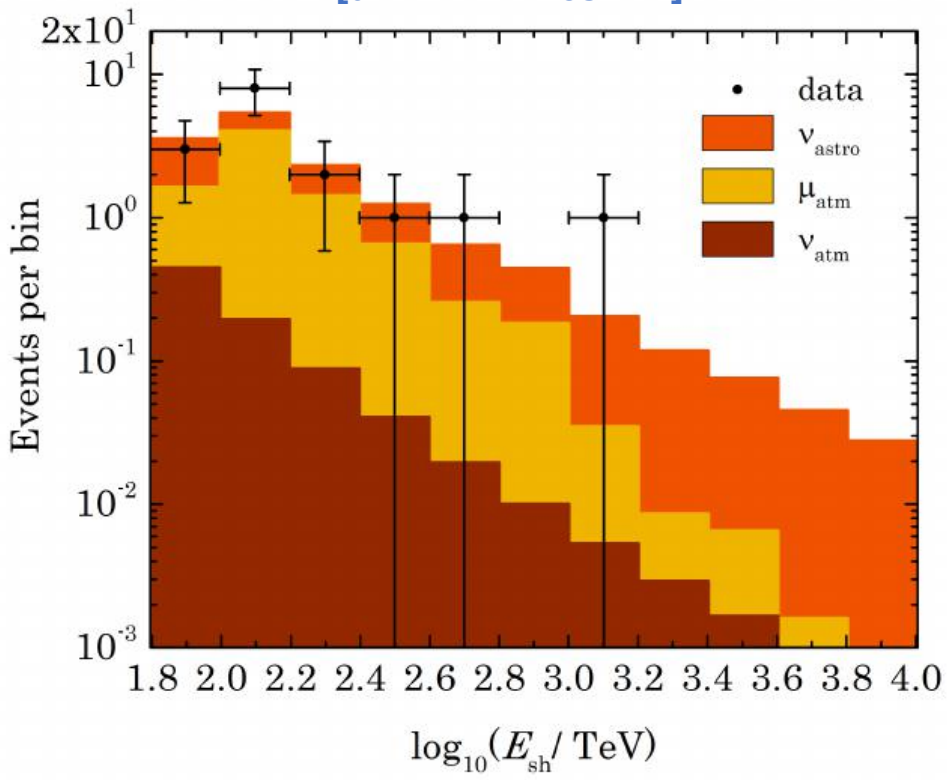
More details on cascade reconstruction and selection: **[PoS(ICRC2021)1144]**

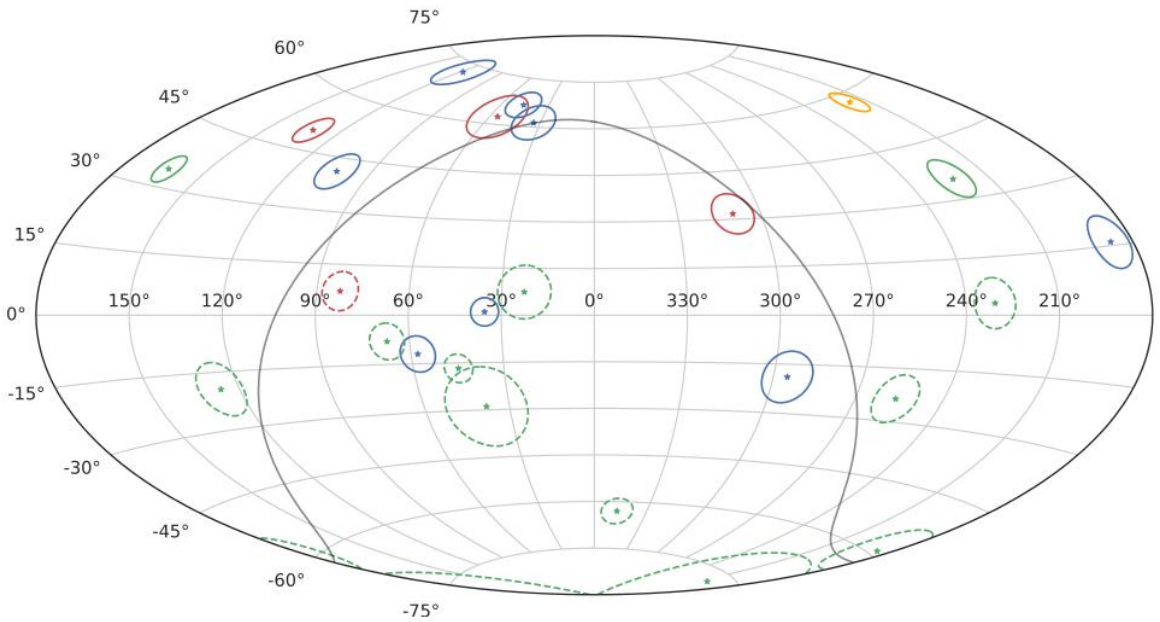
Diffuse flux in cascades I

Four years dataset: 04.2018 - 03.2022

14328 events E_{sh}>10 TeV, N_{hit} > 11 after quality cuts

[arXiv:2211.09447]





All sky analysis:

- E_{sh} > 70 TeV, N_{hit} > 19
- 16 events were selected
- 8.2 background ev. expected
  - 7.4 μ_{atm}, 0.8 ν_{atm}
- 5.8 ν_{astro} ev. expected
- Largest energy event: ~1.2 PeV

All sky diffuse flux significance: 2.22σ

Diffuse flux in cascades II

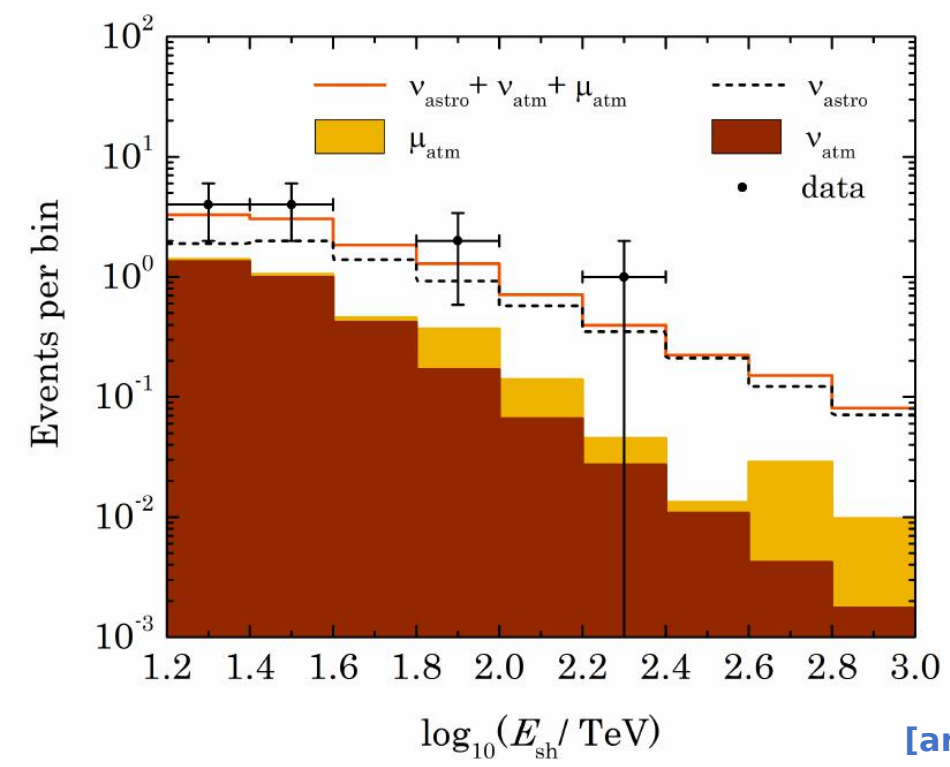
Analysis of upward-going events

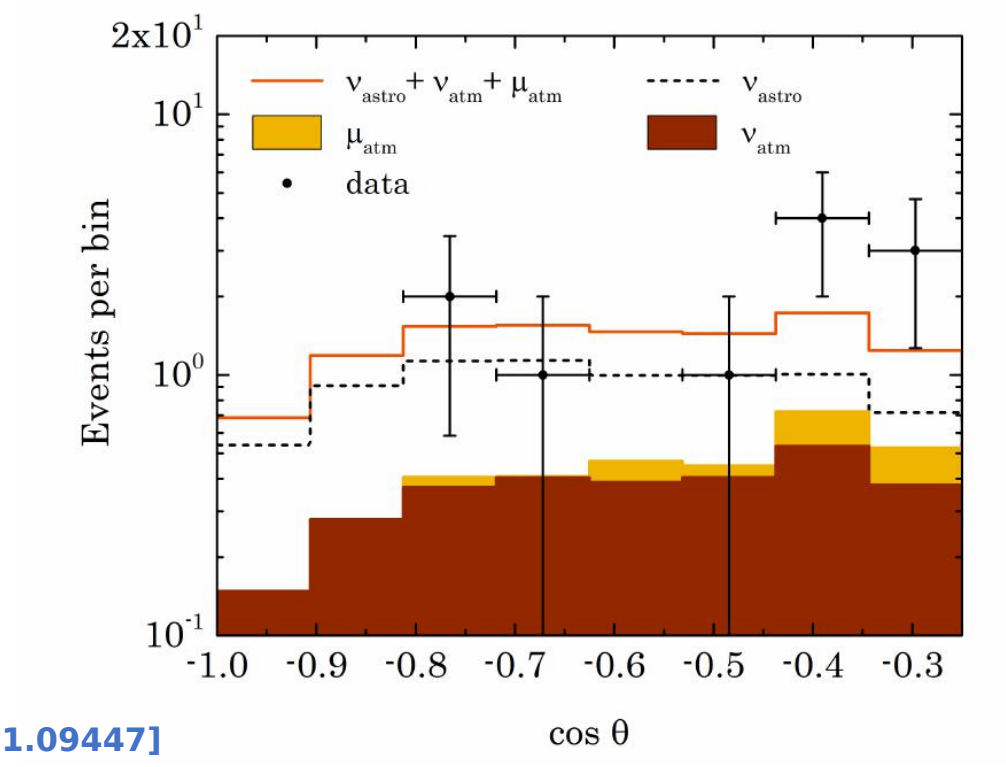
- Zenith angle cut: $\cos(\theta) < -0.25$
- Loosened cuts: $E_{sh} > 15$ TeV, $N_{hit} > 11$
- 11 events selected
- 3.2±1.0 atm. background ev. are expected
  - 0.5 μ_{atm}, 2.7 ν_{atm}
- Highest energy: 224 TeV

Significance of diffuse flux in upward-going events: 3.03σ !

Main uncertainties

- Absorption length ±5%
- OM sensitivity ±10%
- ν_{atm} flux normalisation ±15%



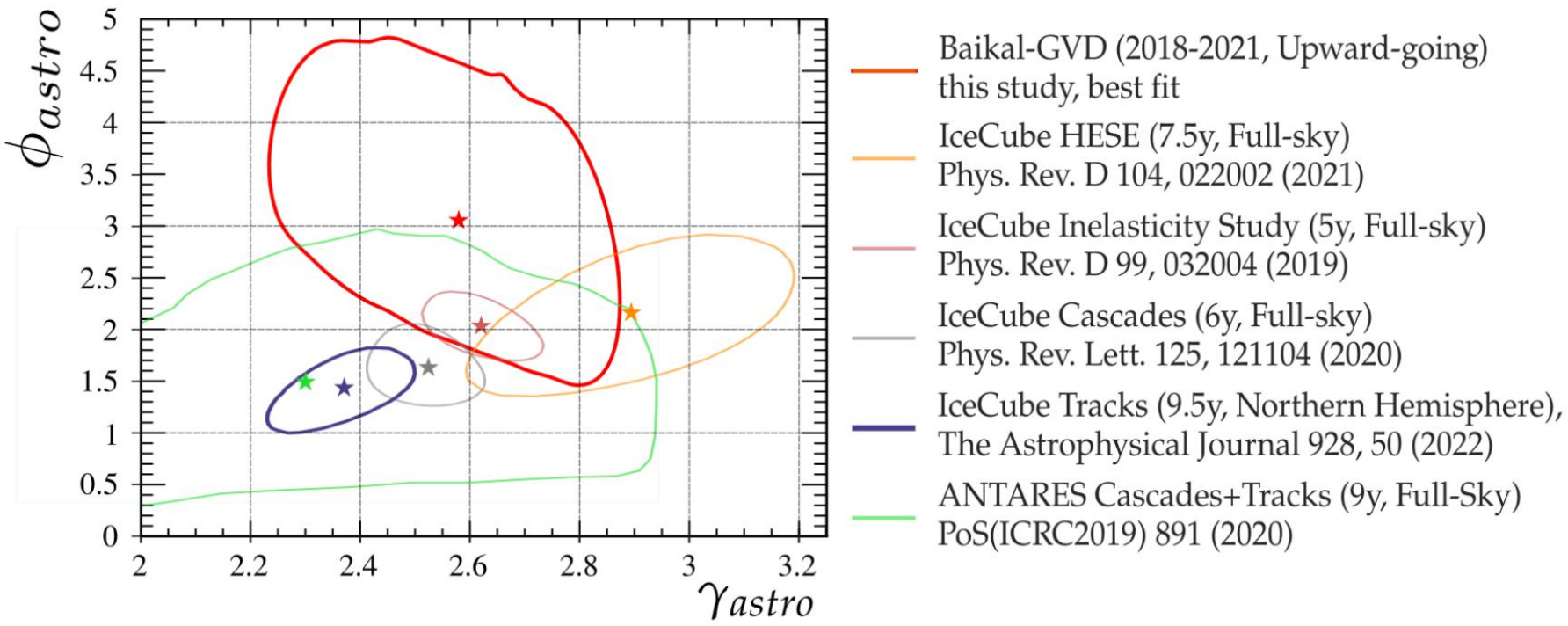


[arXiv:2211.09447]

Diffuse flux in cascades III

Extraction of spectrum power and flux normalisation:

$$\Phi_{astro}^{\nu+\bar{\nu}} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0} \right)^{-\gamma_{astro}}$$



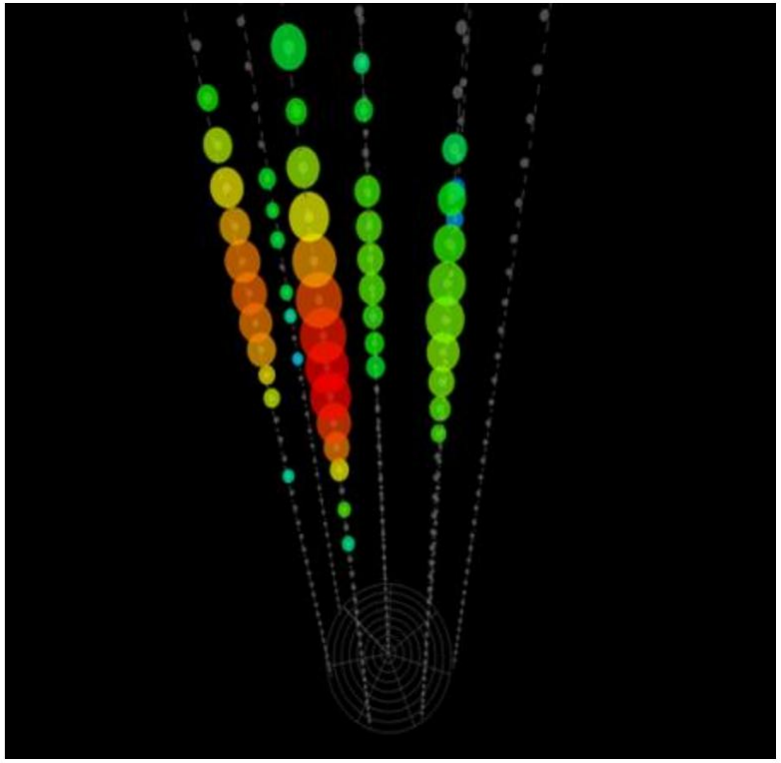
Results are in agreement with previous measurements by IceCube and ANTARES

First "non-IceCube" evidence for diffuse ν_{astro} flux at above 3σ !

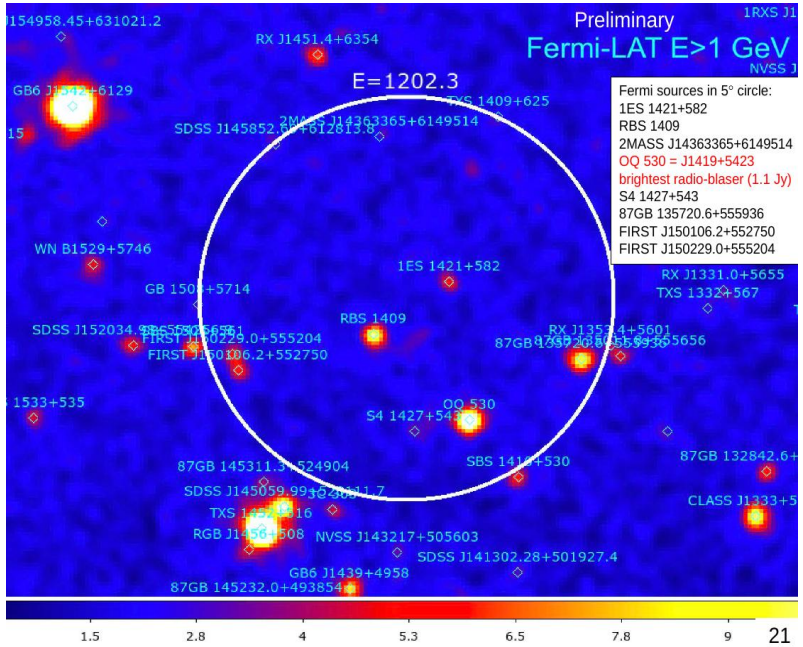
[arXiv:2211.09447]

PeV cascade

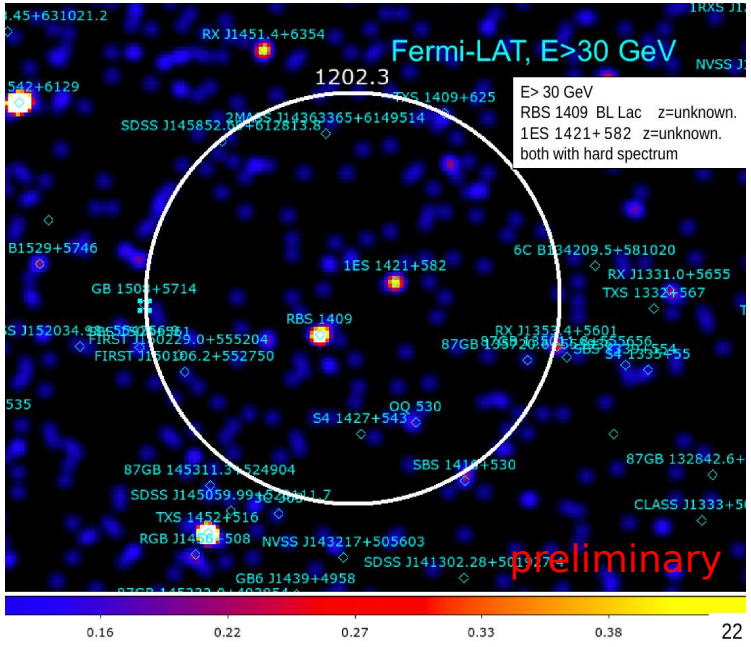
Reconstructed energy: 1.2 PeV
Zenith angle: 61°



$E_\gamma > 1$ GeV



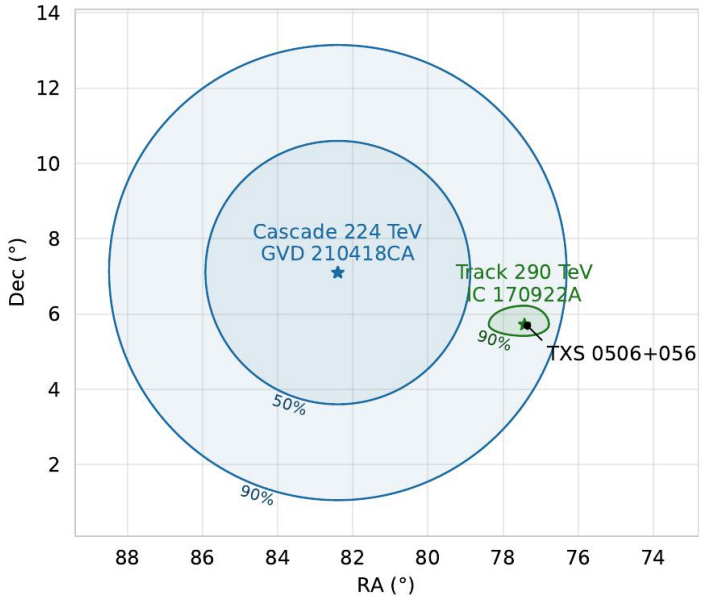
$E_\gamma > 30$ GeV



Two sources with hard γ spectrum within 5° circle:

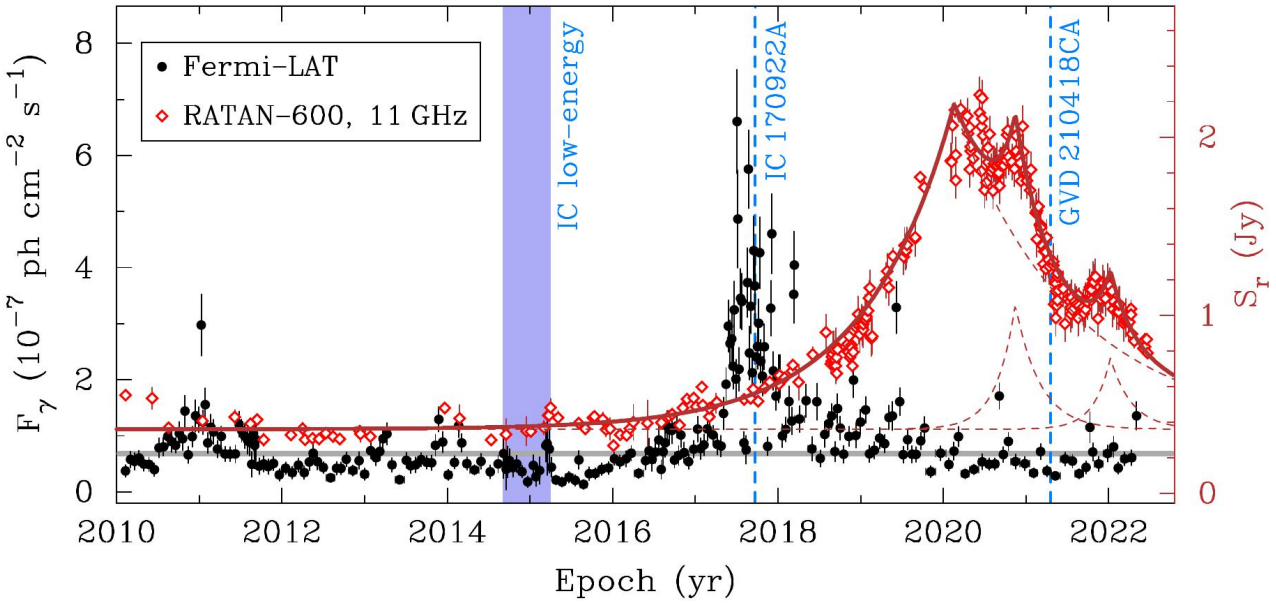
- BL Lac RBS 1409
- 1 ES 1421+582

Cascades: TXS0506



Upgoing cascade analysis, highest energy event (18.04.2021):

- 224 TeV, 24 hits
- Famous TXS 0506+056 is within 90% containment circle
- Signalness: 97.1% (probability of astro origin)
- Chance coincidence probability (E>200 TeV): 0.0074



Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare
- Baikal event during radio activity
- Probability of IC non-observation: 11%

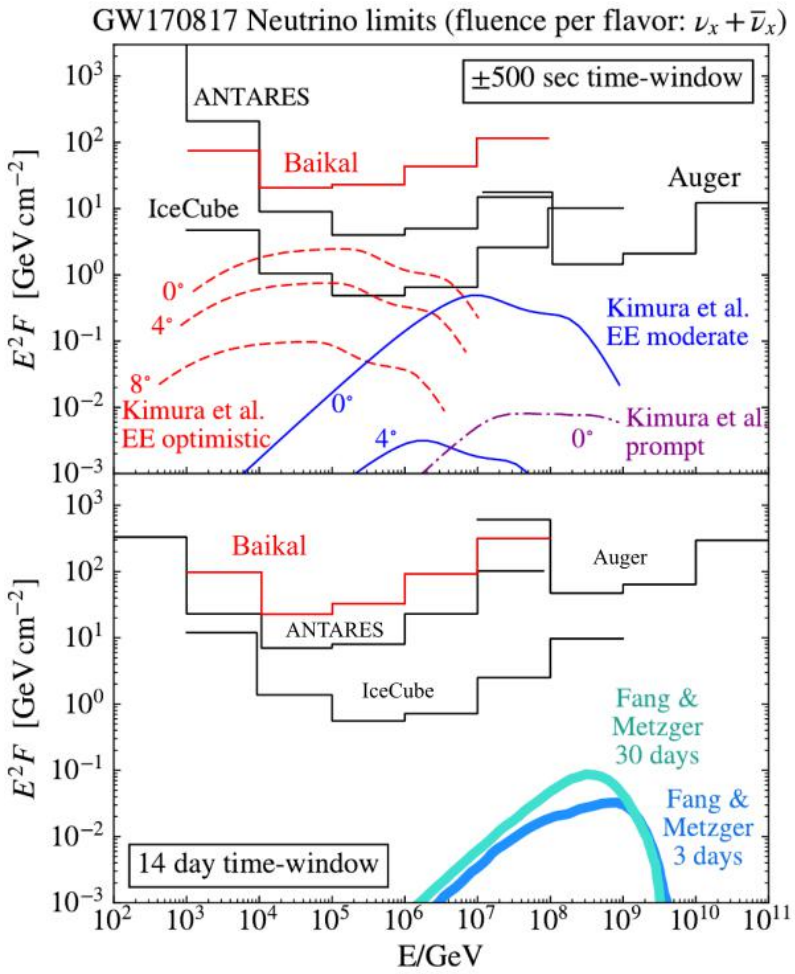
[arXiv:2210.01650]

Follow-up program

Baikal-GVD follows reported multimessenger high-energy events, e.g.:

GW170817 (LIGO/VIRGO) - neutron star merger, first gravitational waves detection associated with γ/optical/radio signal: time-integrated flux (fluence) limit is set

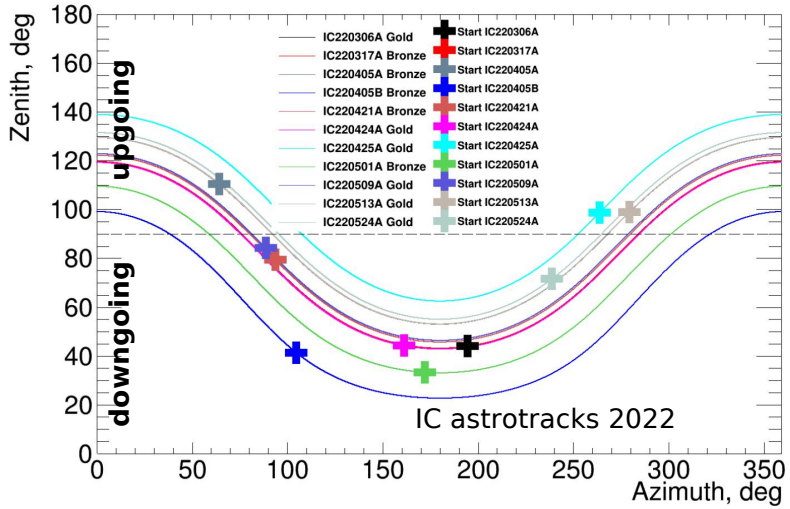
[Phys. ReV. Lett. 119, 161101]
[JETP Letters, v.108, issue 12]



Radio-burst from magnetar **SGR 1935+2154** (28.04.20)

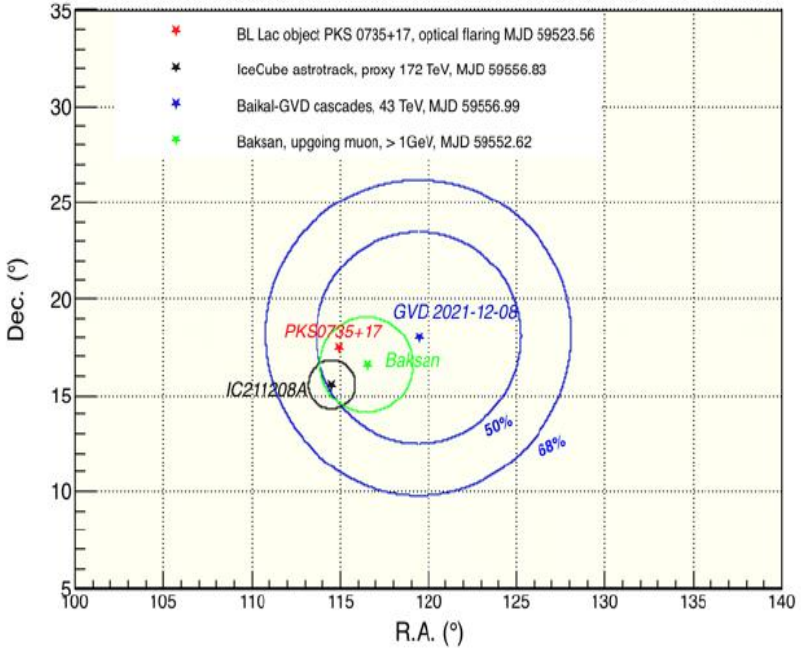
- IceCube fluence limit: $5.2*10^{-2}$ GeV*cm^{-2}
- ANTARES fluence limit: 14 GeV*cm^{-2}
- Baikal-GVD fluence limit: 2 GeV*cm^{-2} **[PoS(ICRC2021)946]**

Neutrino alert exchange



Alerts: events with a high probability
of astrophysical origin distributed between telescopes

Baikal-GVD alert system
- Simplified extrapolated calibrations
- Processing delay 3-10 minutes
- Planned to be deployed at the shore to reduce delay
- Presently internal distribution of alerts



[PoS(ECRS2022)096]

Follow-up of IceCube and ANTARES alerts

60 ANTARES alerts followed, 3 correlated cascades
[PoS(ICRC2021)1121]

Follow-up of IceCube “astrotracks” events (~20 per year)
- On 8.12.2021 detected cascade from the direction of blazar PKS0735+17 in coincidence with IC211208A
- Delay wrt. IC: 3.95 hrs., E ~ 43 TeV
- Pre-trial significance: 2.85σ, later reduced to 1.13σ
- Astrotelegram published:

  https://www.astronomerstelegram.org/?read=15112

Conclusions

High-energy astronomy is an actively developing field with many recent breakthrough observations

Large volume neutrino telescopes are an essential part of high-energy astronomy tool set

Baikal-GVD is joining the astrophysical neutrino origin quest

- Atmospheric neutrino flux measurement is in good agreement with expectations
- First evidence for astrophysical neutrino flux above 3σ !
- Baikal-GVD participates in high-energy alert follow-up and alert exchange