CRIS 2022

12th Cosmic Ray International Seminar
Naples, Italy, September 12 -16, 2022

Yury Malyshkin
Joint Institute for Nuclear Research (Dubna)

on behalf of the Baikal-GVD collaboration

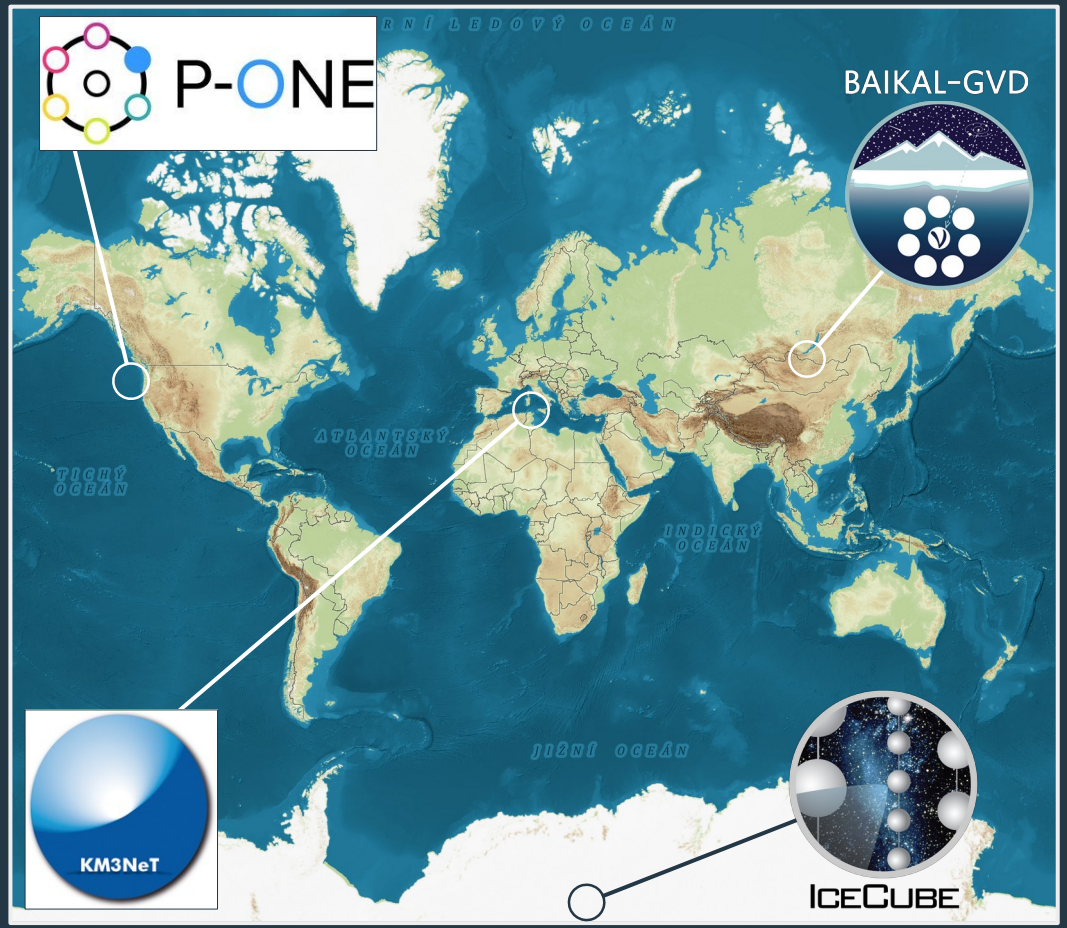
Baikal-GVD Neutrino Telescope

INTRODUCTION

Neutrino Astronomy

- In 1960 Moisey Markov proposed to detect high-energy neutrino, E ~O(TeV-PeV), in a large natural reservoir equipped with a grid of photo-sensors
- In 1996 NT-200 neutrino telescope in Baikal Lake detected first neutrino underwater (produced in Earth's atmosphere)
- Important contributions from DUMAND, AMANDA, and ANTARES
- In 2013 IceCube discovered neutrinos from outside the Solar System
- In 2017 IceCube observed a neutrino coming from blazar TXS 0506+056
- Sources of astrophysical neutrino are yet to be established
- New telescopes: Baikal-GVD, KM3NET/ACRA, and P-ONE are being deployed

Neutrino Telescopes



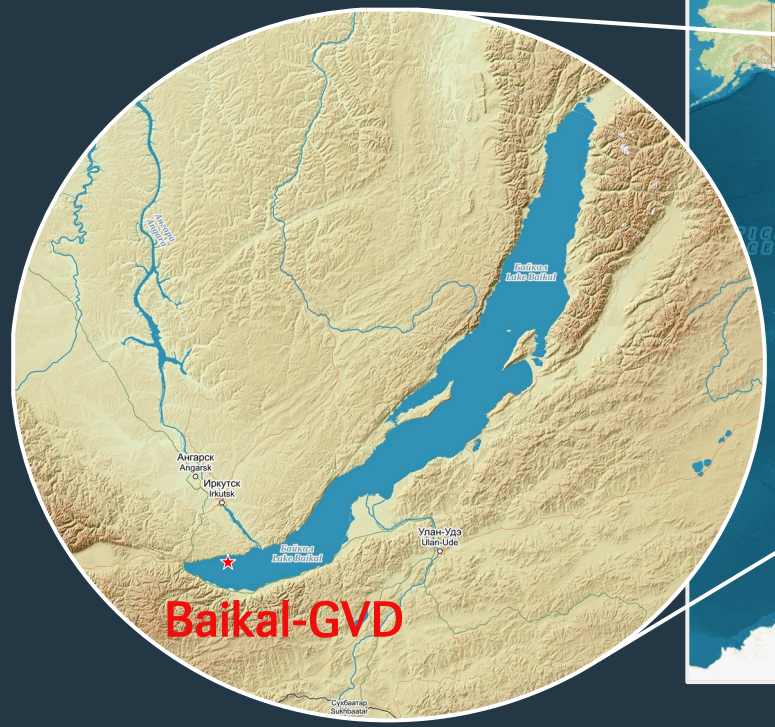
As of 2022 4 telescopes in operation and/or under construction

Baikal-GVD


SEVERNÍ LEDOVÝ OCEÁN
ATLANTSKÝ OCEÁN
INDICKÝ OCEÁN
JIŽNÍ OCEÁN
Байкал
Lake Baikal
Ангарск
Angarsk
Иркутск
Irkutsk
Улан-Удэ
Ulan-Ude
Baikal-GVD

Baikal-GVD

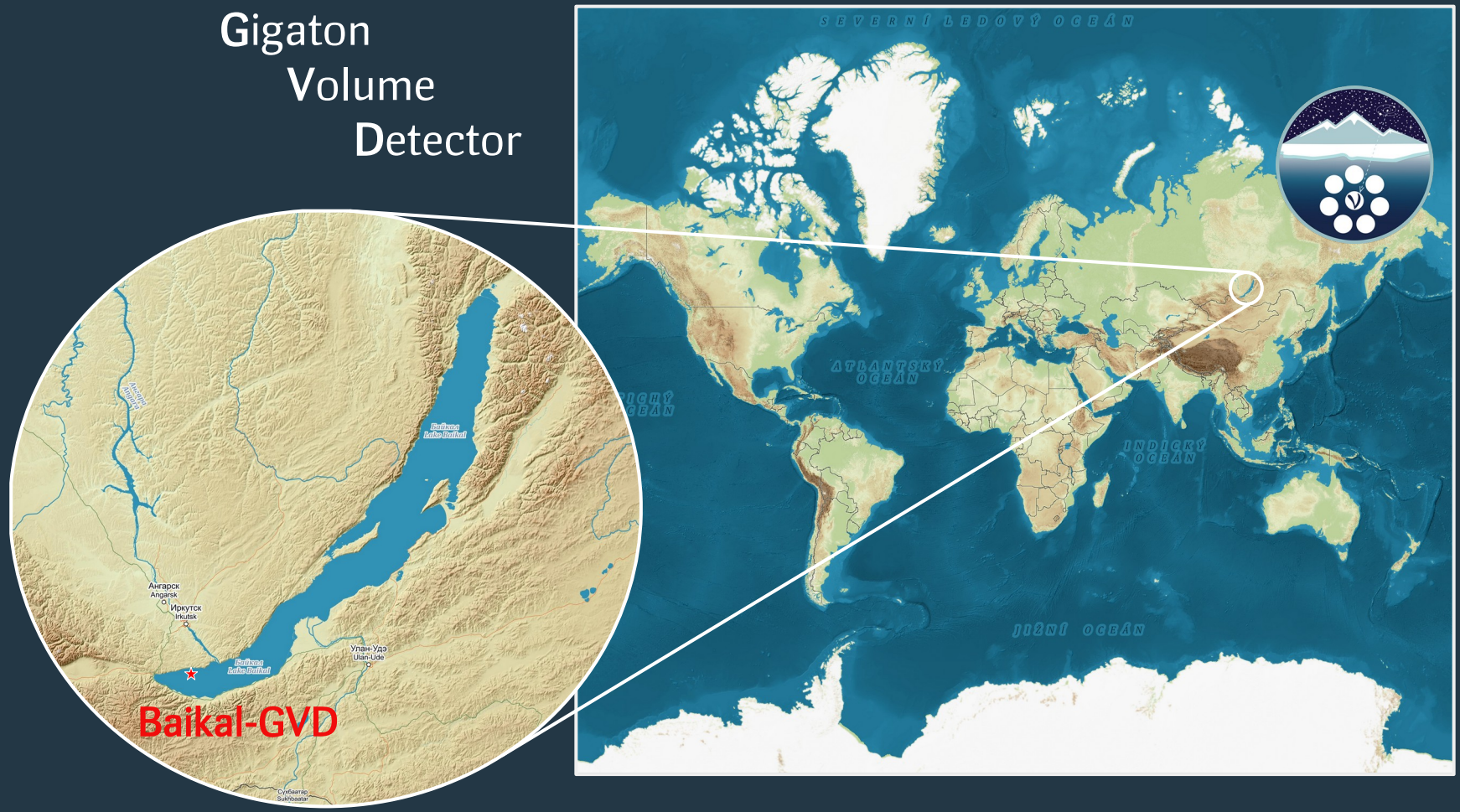
Gigaton
Volume
Detector



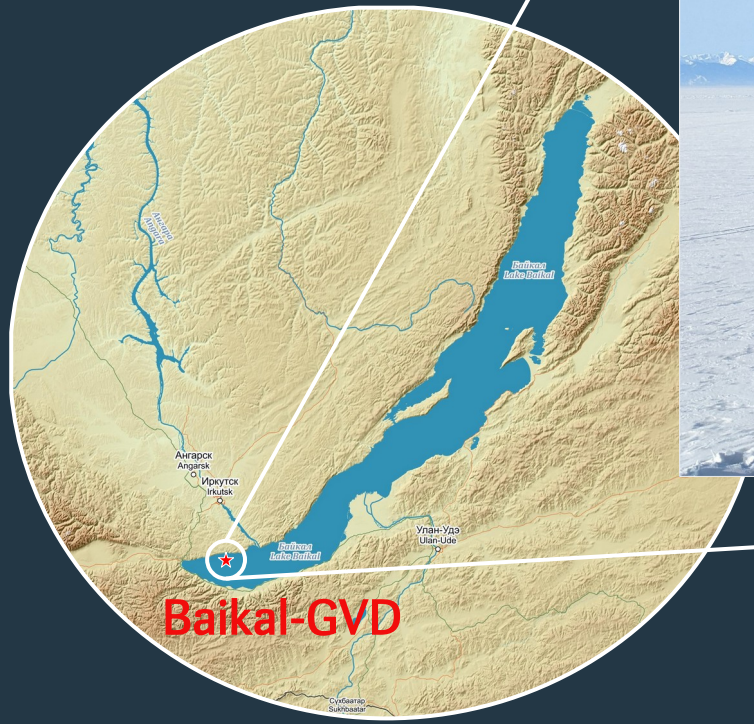
Baikal-GVD

Gigaton
Volume
Detector

1 km^3 – planned detector volume by 2026



Baikal-GVD



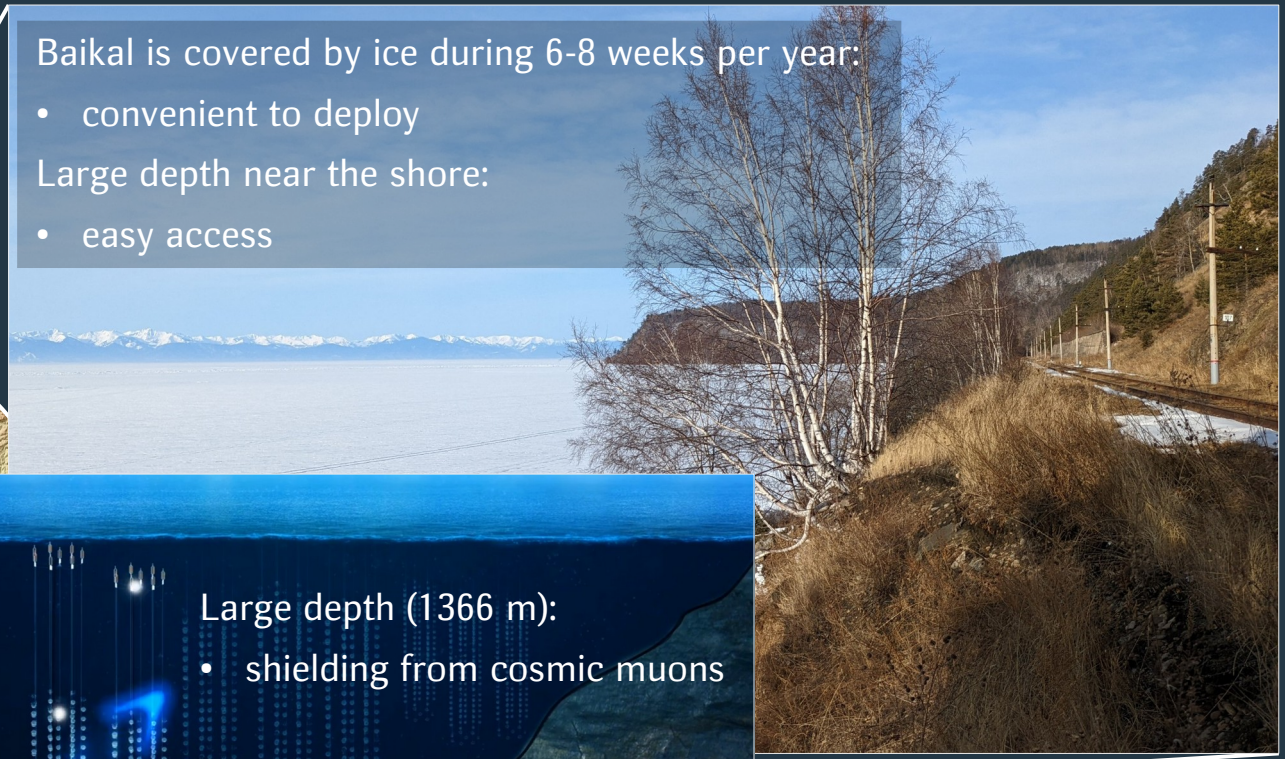
Baikal is covered by ice during 6-8 weeks per year:

- convenient to deploy

Large depth near the shore:

- easy access

Baikal-GVD

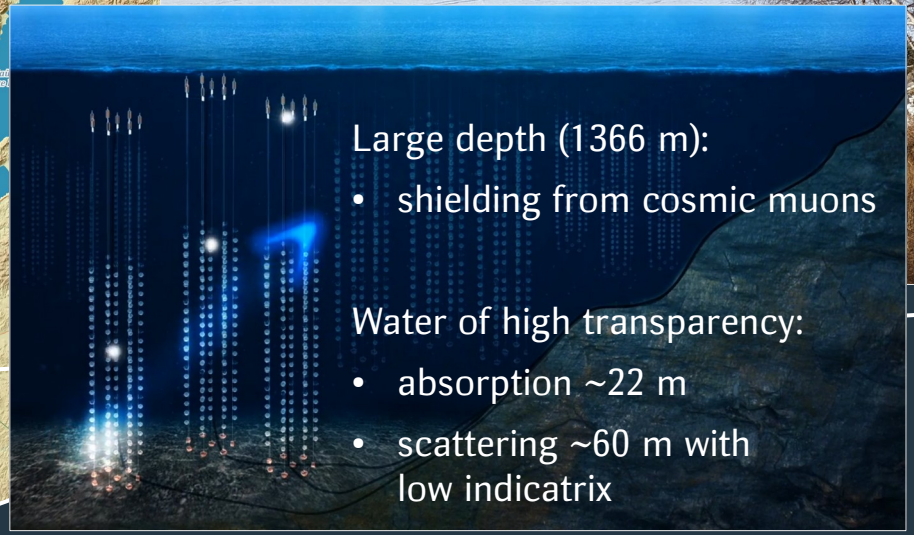


Baikal is covered by ice during 6-8 weeks per year:

- convenient to deploy

Large depth near the shore:

- easy access



Large depth (1366 m):

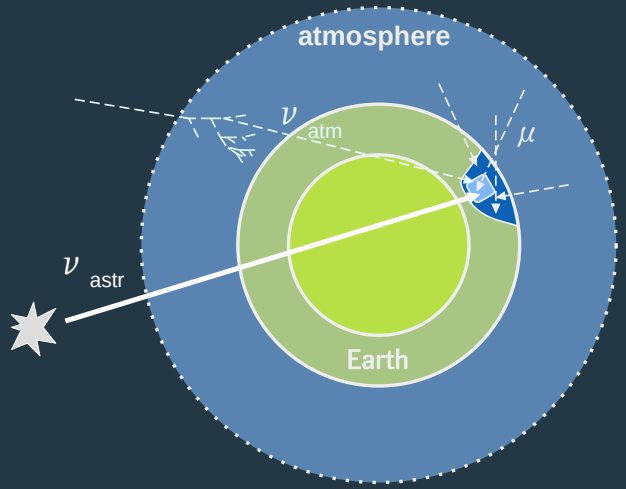
- shielding from cosmic muons

Water of high transparency:

- absorption ~22 m
- scattering ~60 m with low indicatrix

Principle of astrophysical ν detection

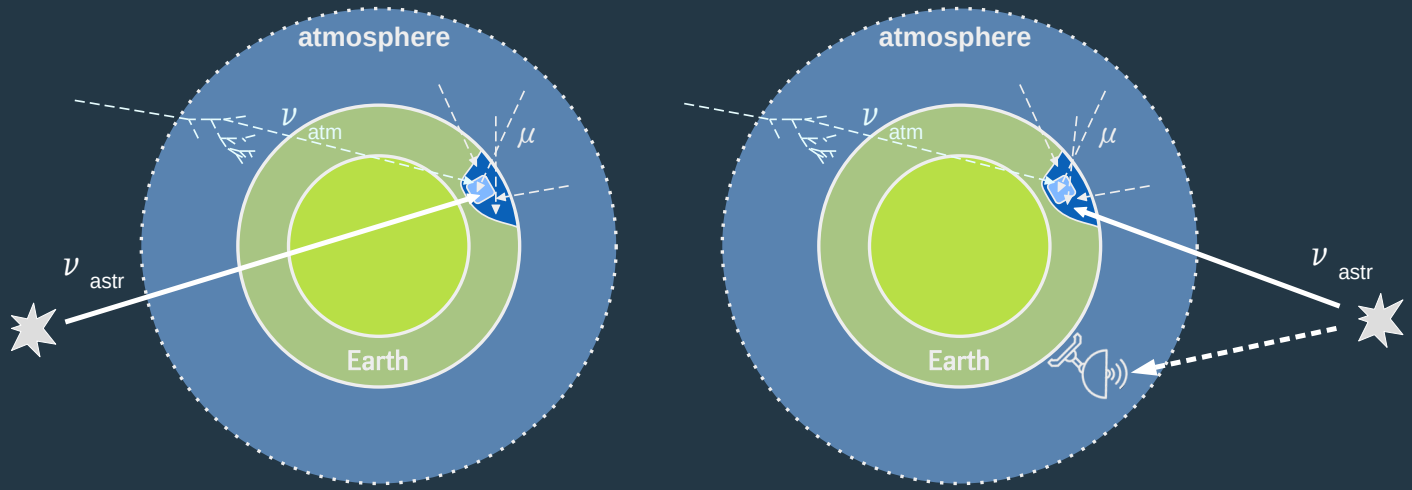
E ~ O(TeV) - O(PeV)



1. Select only upper-going events to ensure suppression of non-neutrino particles and **subtract atmospheric neutrino spectrum**

Principle of astrophysical ν detection

E ~ O(TeV) - O(PeV)

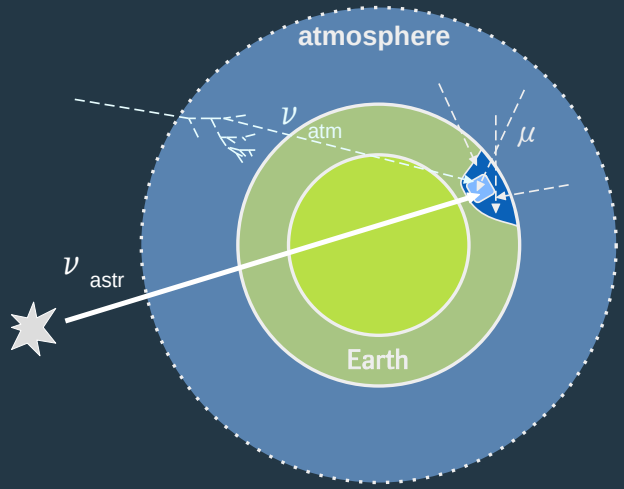


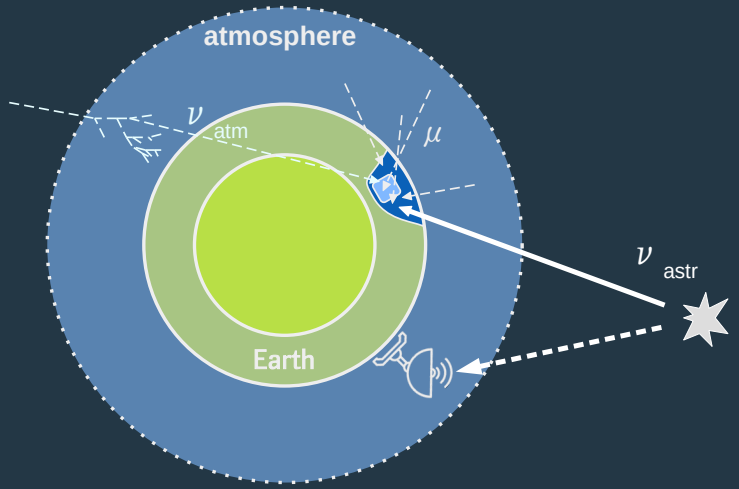
1. Select only upper-going events to ensure suppression of non-neutrino particles and **subtract atmospheric neutrino spectrum**

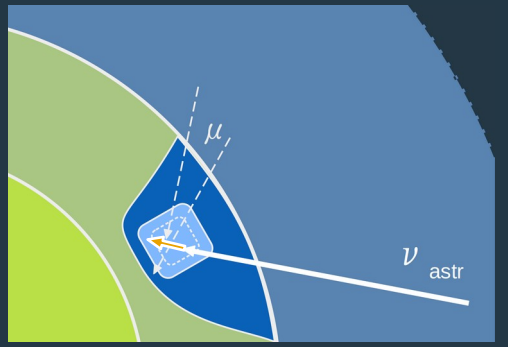
2. Look for correlations with other observations (gamma, radio, gravitational waves, other neutrino telescope) **in all sky**.

Principle of astrophysical ν detection

E ~ O(TeV) - O(PeV)







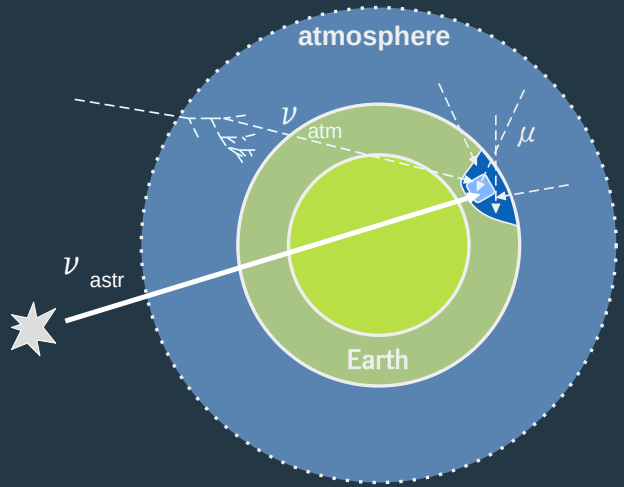
1. Select only upper-going events to ensure suppression of non-neutrino particles and **subtract atmospheric neutrino spectrum**

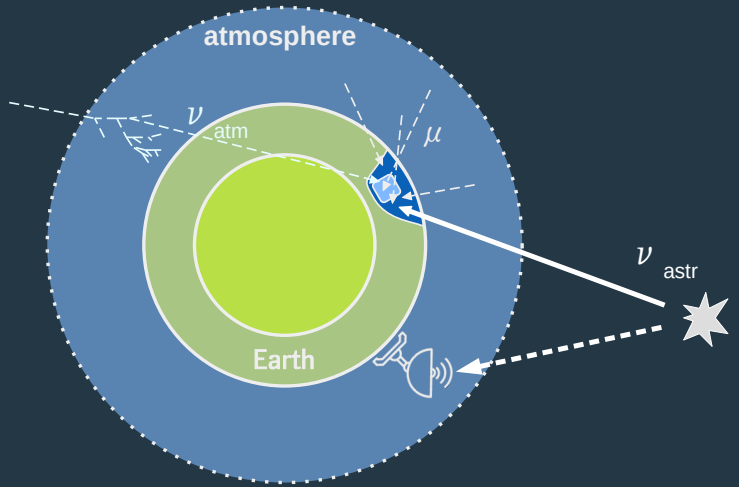
2. Look for correlations with other observations (gamma, radio, gravitational waves, other neutrino telescope) **in all sky**.

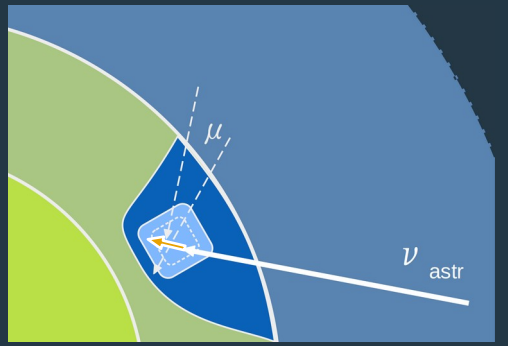
3. High-Energy Starting Events (HESE) – events contained in a fiducial volume

Principle of astrophysical ν detection

E ~ O(TeV) - O(PeV)







1. Select only upper-going events to ensure suppression of non-neutrino particles and **subtract atmospheric neutrino spectrum**

2. Look for correlations with other observations (gamma, radio, gravitational waves, other neutrino telescope) **in all sky**.

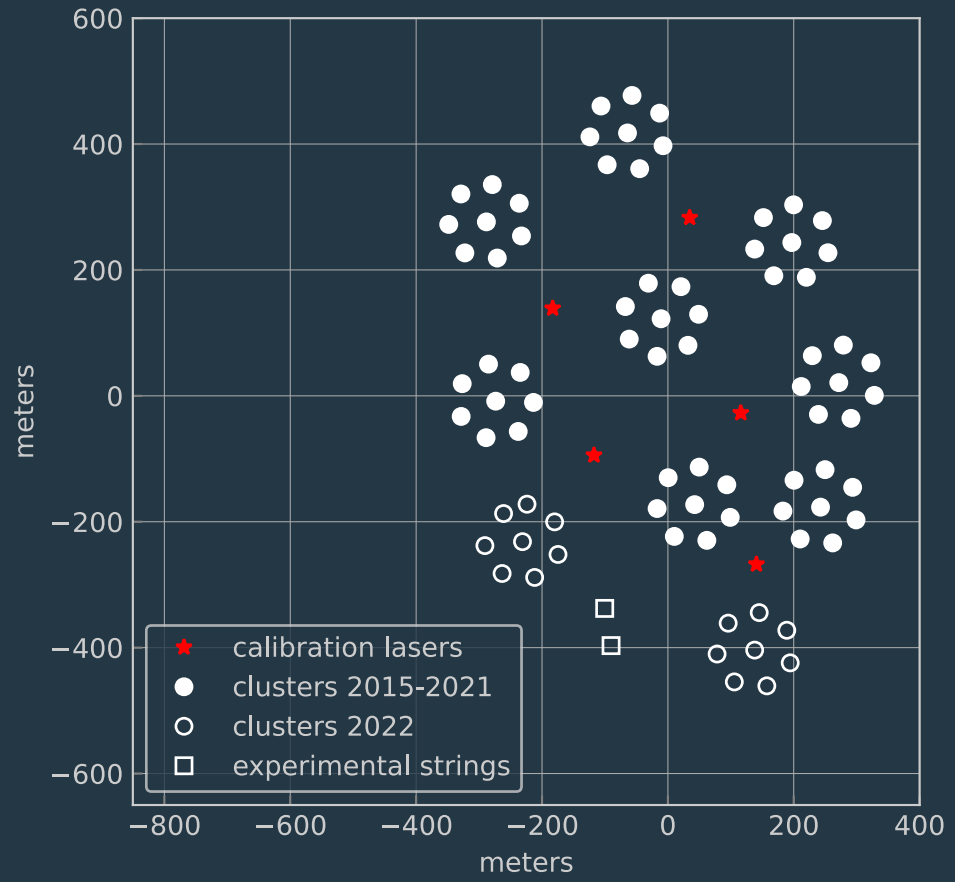
3. High-Energy Starting Events (HESE) – events contained in a fiducial volume

4. Simple all-sky high-energy selection

DETECTOR DESIGN

Baikal-GVD 2022

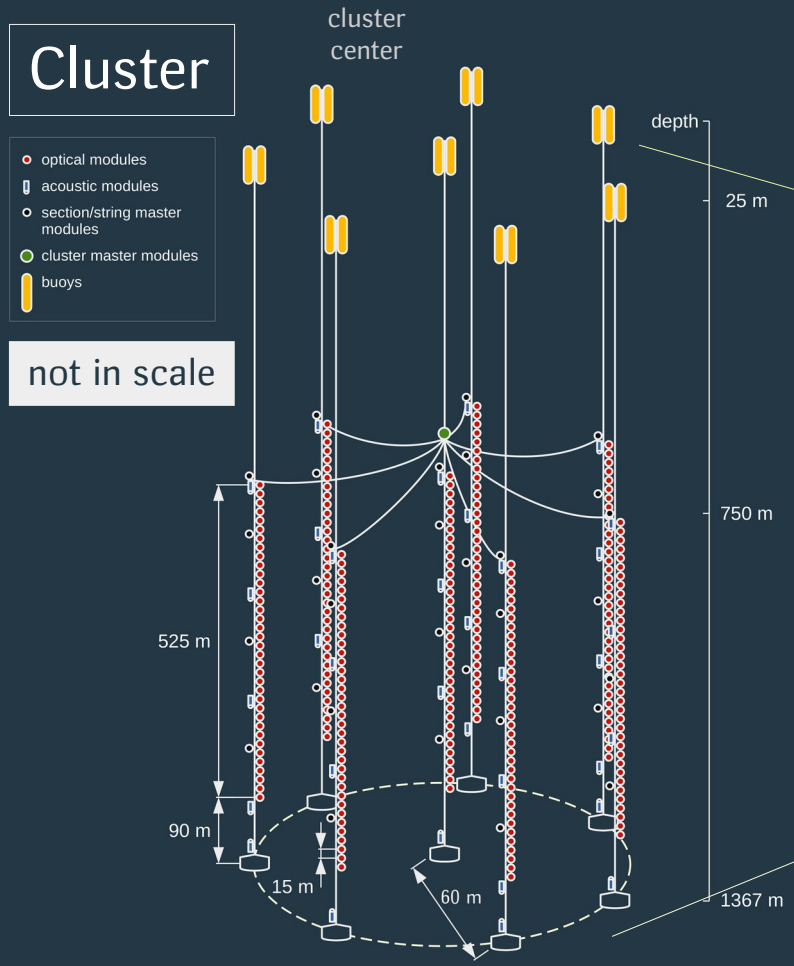
10 clusters (2 deployed in 2022)
8 strings per cluster

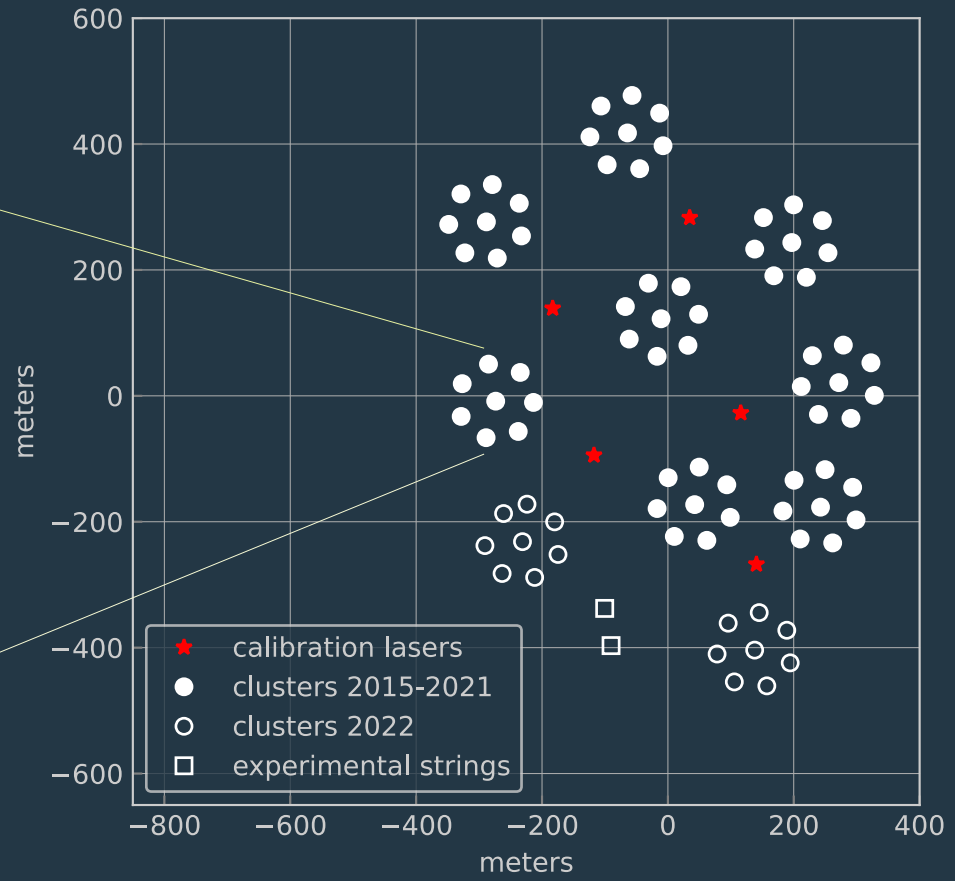


Baikal-GVD 2022

10 clusters (2 deployed in 2022)
8 strings per cluster

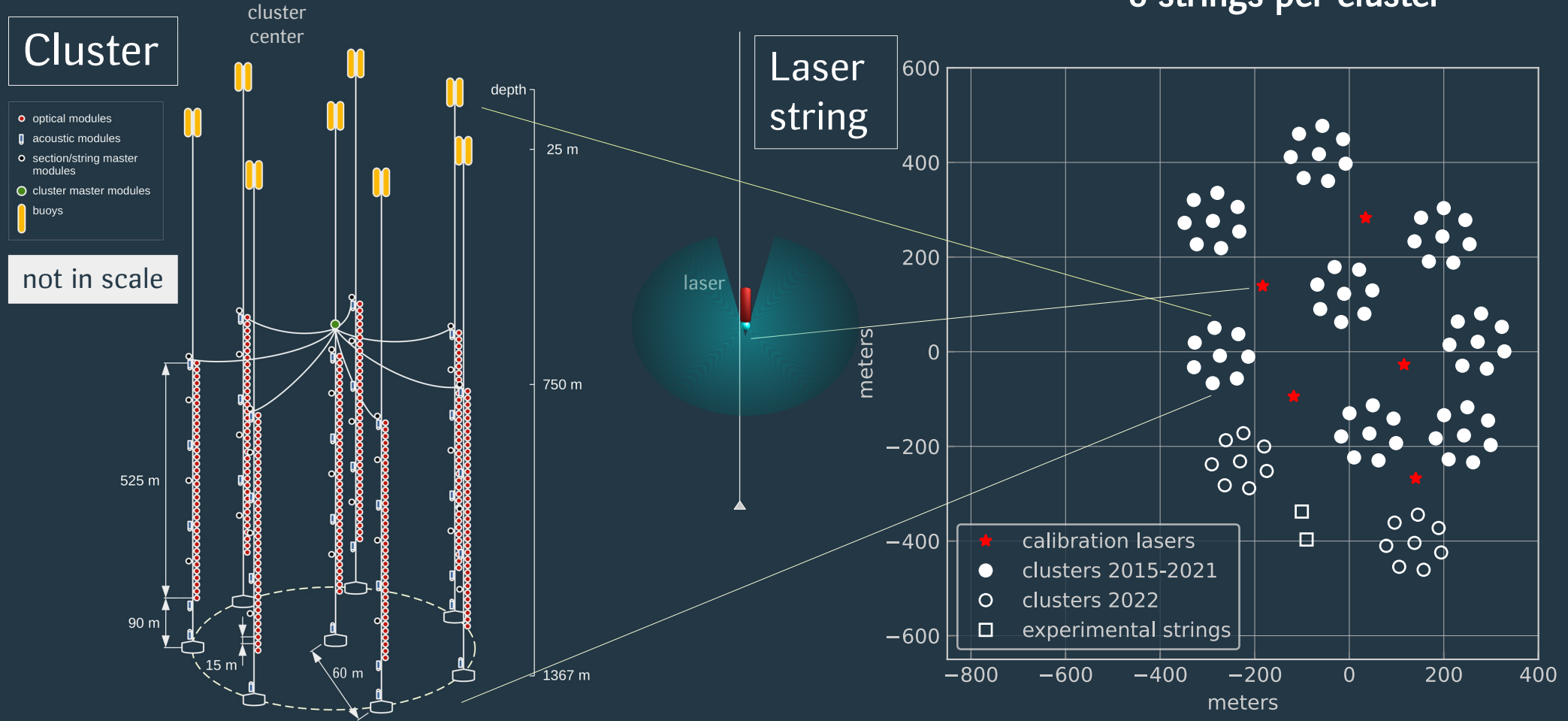
Cluster





Baikal-GVD 2022

10 clusters (2 deployed in 2022)
8 strings per cluster

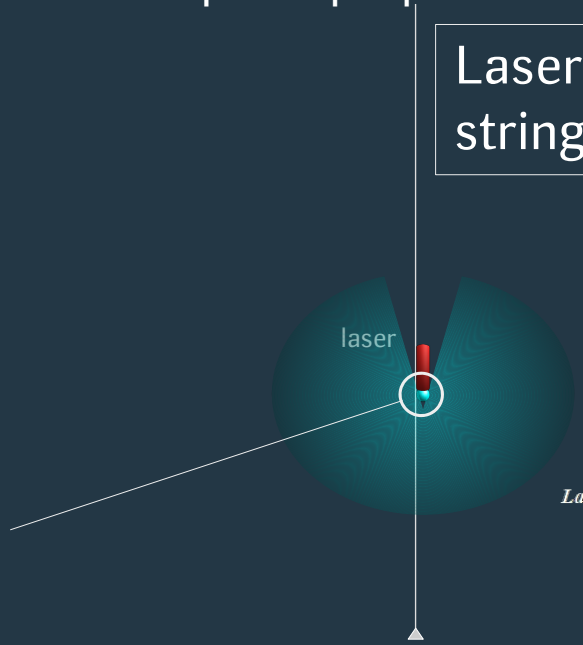


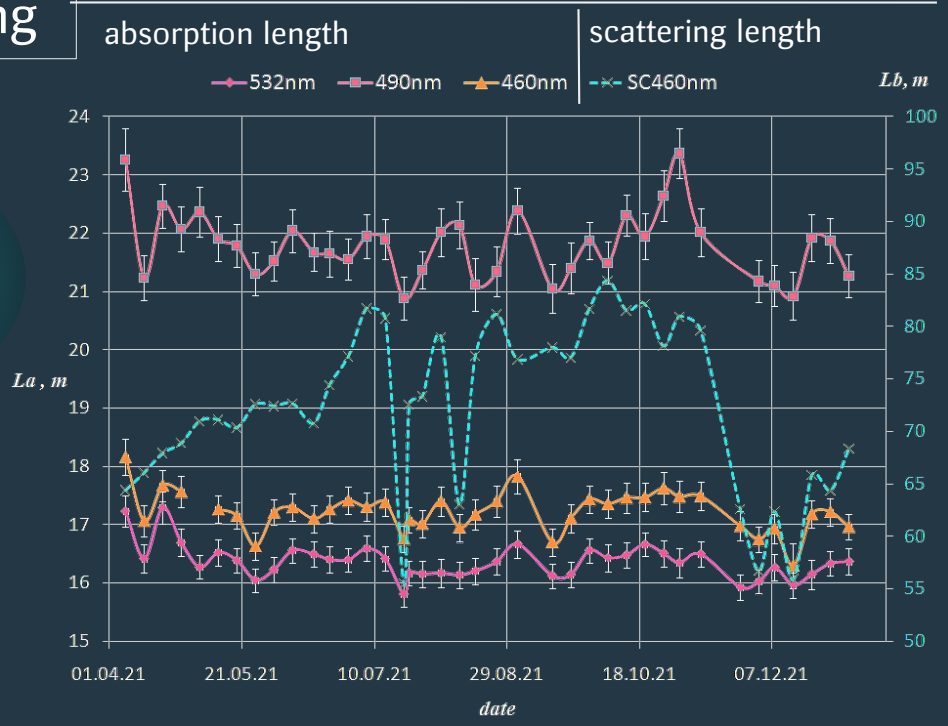
Components: laser

Calibrations and measurement of optical properties of water

[PoS-ICRC2021-1040]

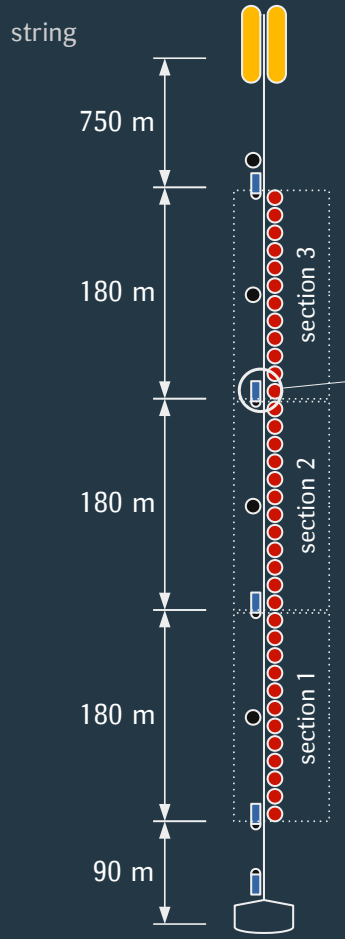
Laser string





Components: acoustic modems [PoS-ICRS2021-1083]

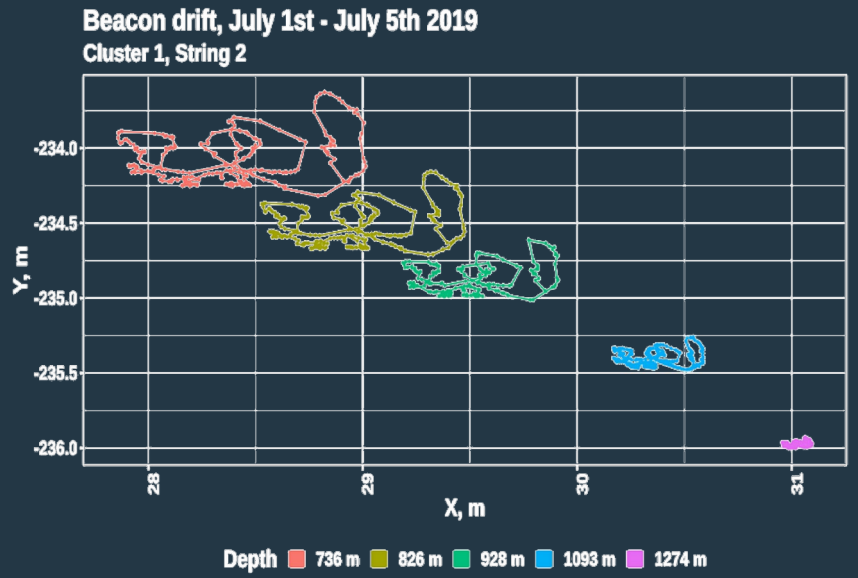
Real-time positioning



4-5 at each string

emitter: the bottom one (on 4 strings per cluster)

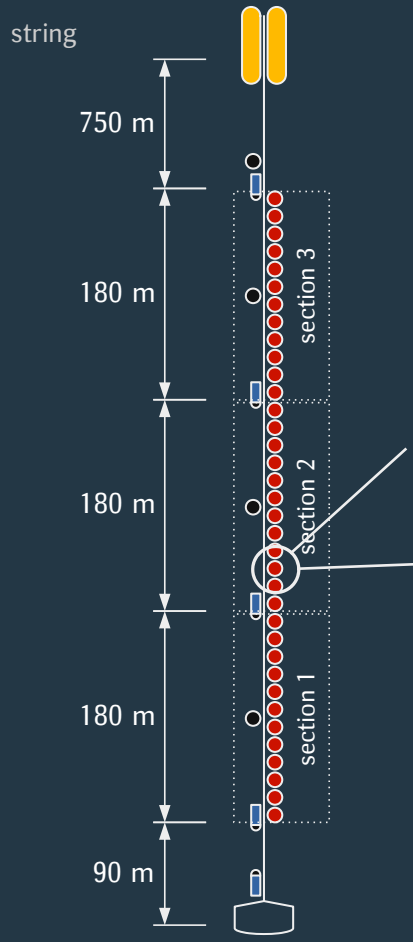
receivers: the 4 others

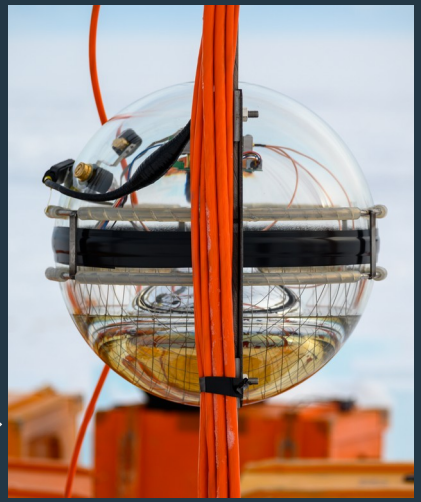


Precision 20-30 cm

Components: optical modules [EPJ WoC 116, 01003 (2016)]

Detection of Cherenkov light



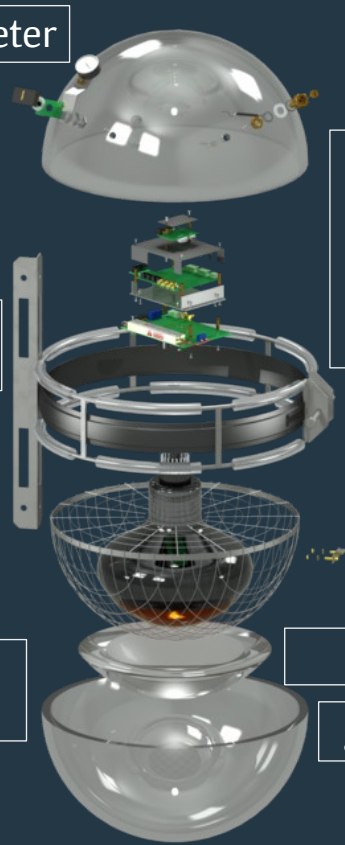


36 at each string,

15 m vertical spacing,

60 m horizontal spacing,

oriented downwards



Inventory and performance 2022

10 clusters:

- 2880 optical modules
- 320 acoustic modules
- 5 lasers

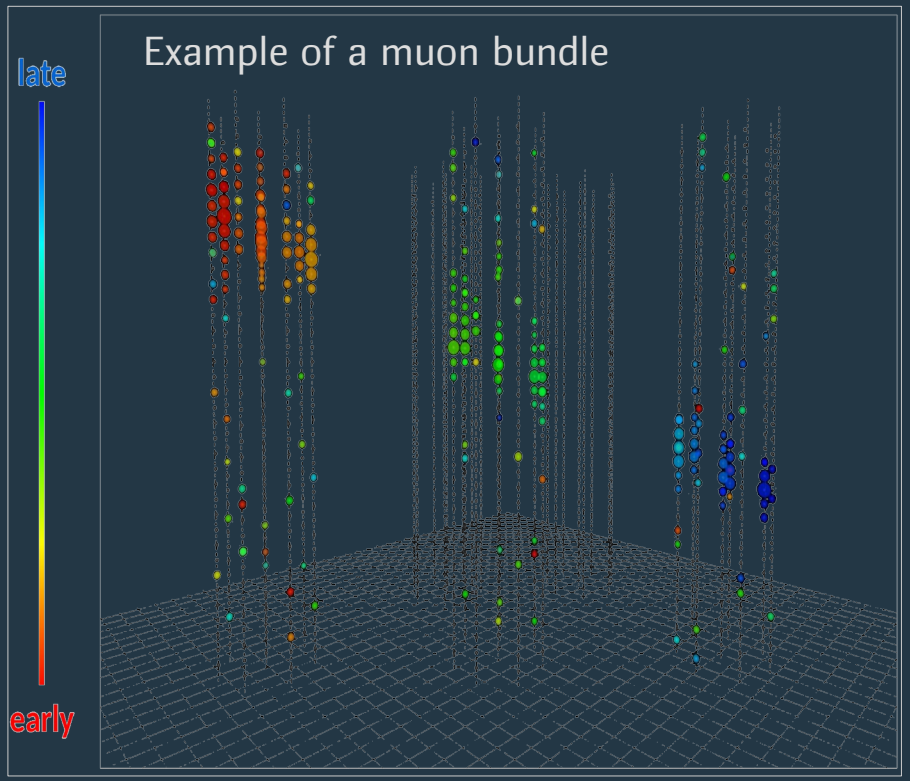
+ 2 experimental strings

2 ns time synchronization between clusters
20-30 cm position precision

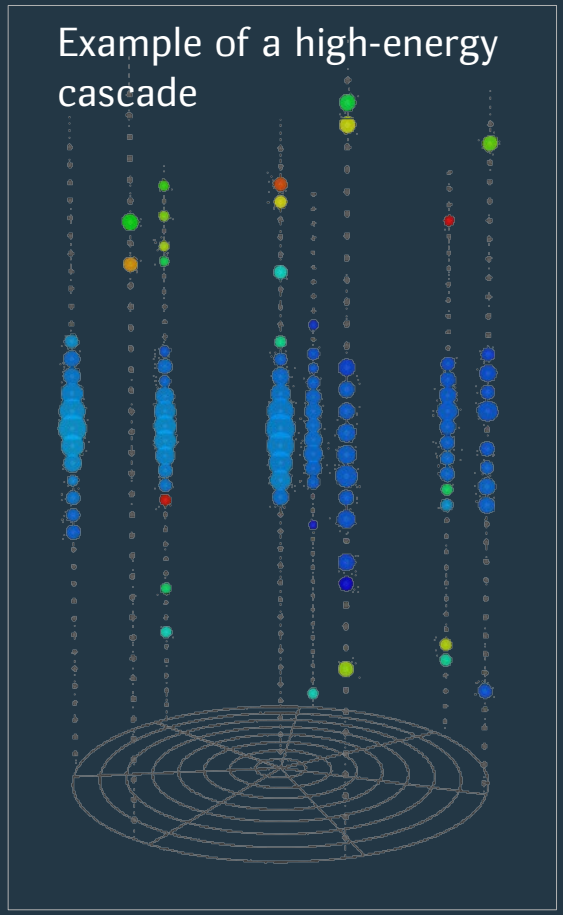
DATA

Event types

1. Track-like

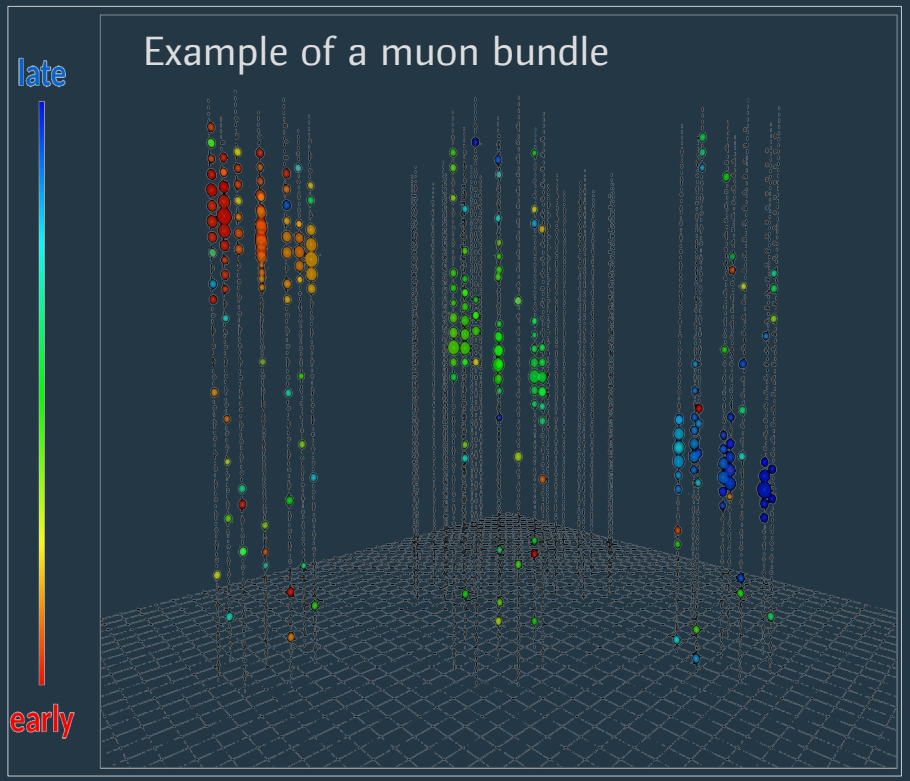


2. Cascades



Event types

1. Track-like



- atmospheric single muons and muon bundles
- muons produced in CC interaction of ν_μ
- muons produced in decay of τ produced in CC interaction of ν_τ

Muons of O(TeV) energy travel hundred meters in water which allows to observe track-like traces.

Directional resolution: up to 0.5°
Energy resolution: poor

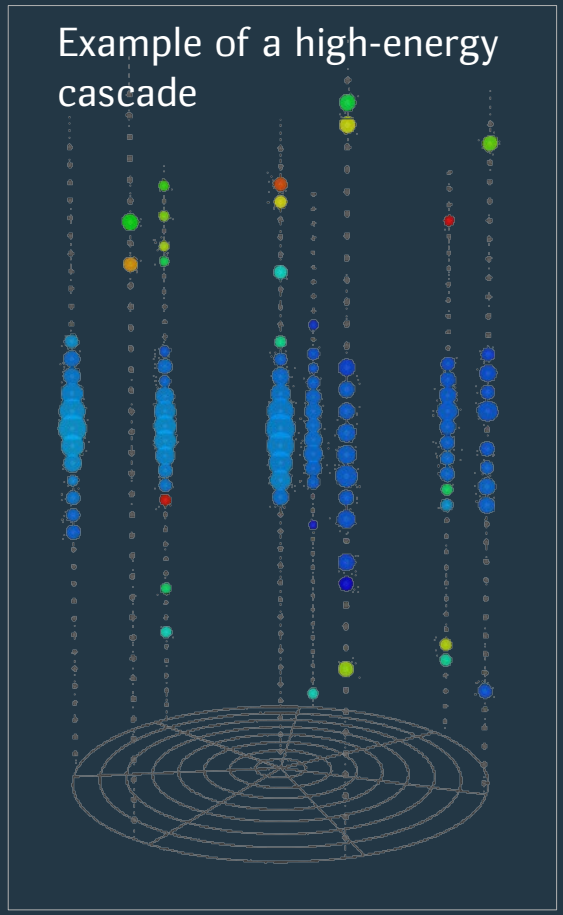
Event types

- electromagnetic and hadronic cascades initiated by neutrino interaction products

Cascade deposits its whole energy locally (within several meters) and their energy can be derived from the amount of collected light

Directional resolution: 2-4°
Energy resolution: 10-30%

2. Cascades



SELECTED RESULTS

Track-like events

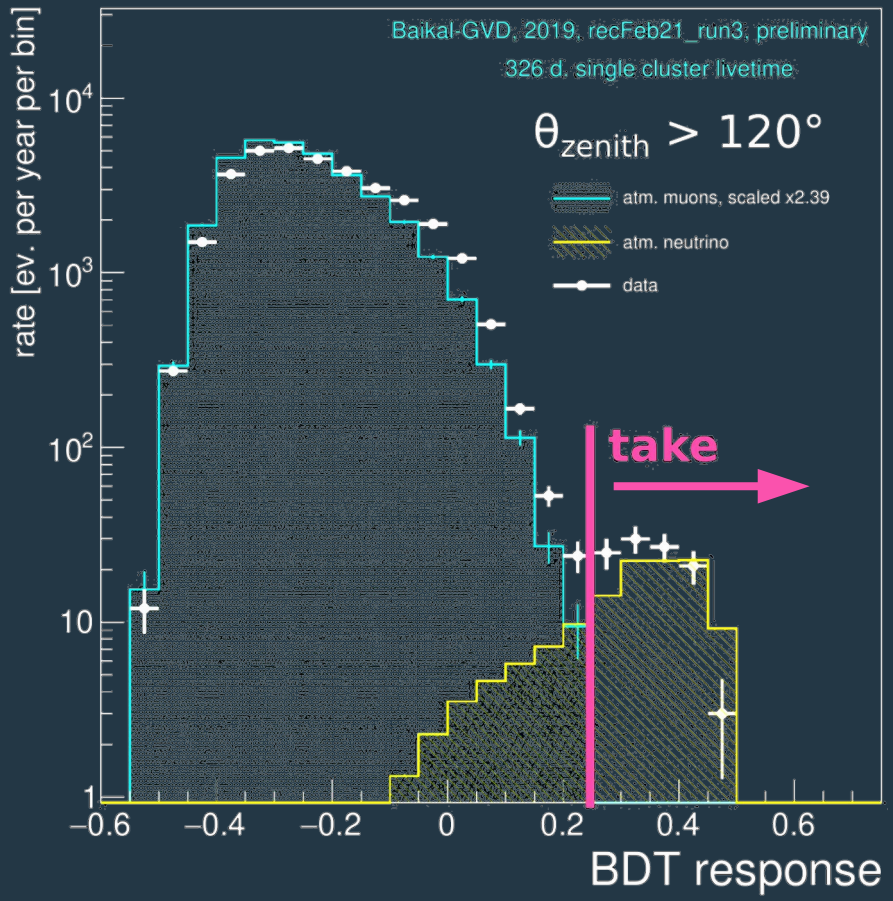
[Neutrino-2022 poster]

Event reconstruction:

- Hit finder: efficient hit-finding algorithm [PoS-ICRC2021-1063]
- Track fit: χ^2 (t) - based fitter
- Energy estimation based on dE/dX proxy
- Neutrino selection based on Bosted Decision Trees classification

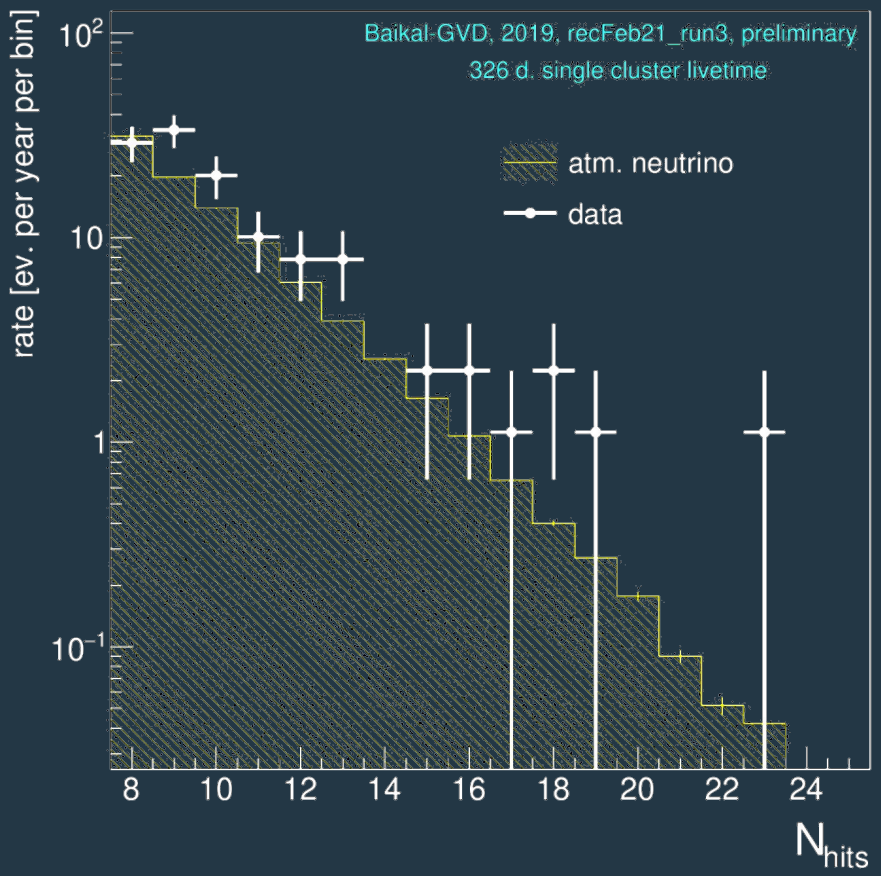
326 cluster x days
→ 106 candidate events (81.2 events expected)

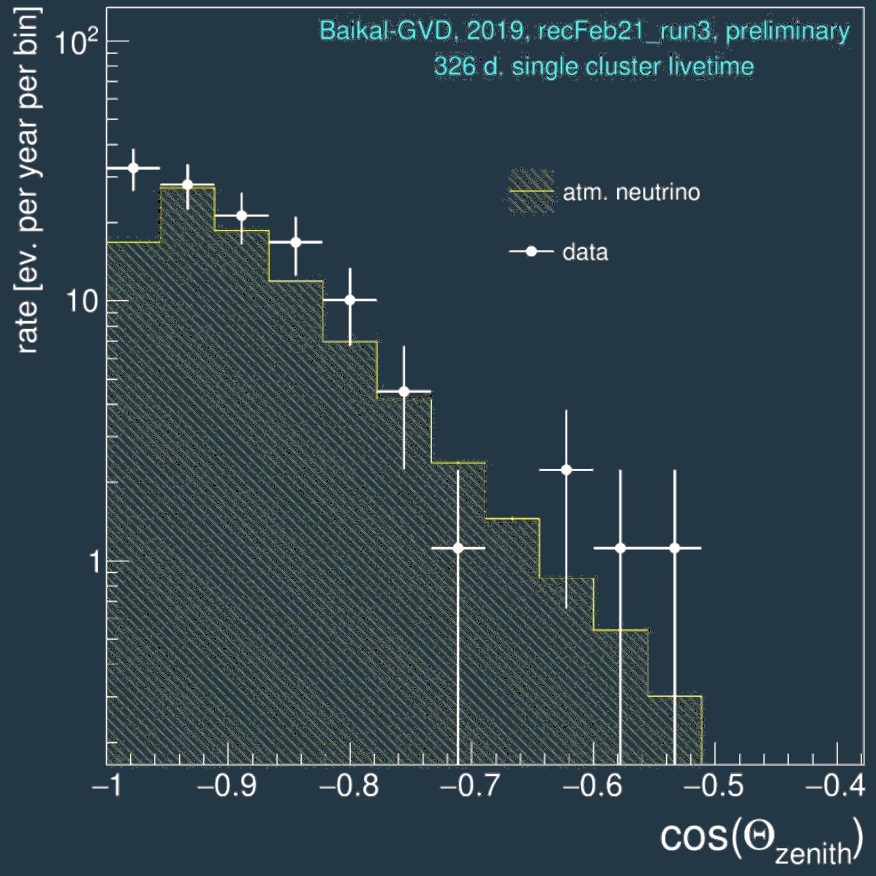
An effort to extend single-cluster analysis to the full dataset is ongoing



Track-like events

[Neutrino-2022 poster]

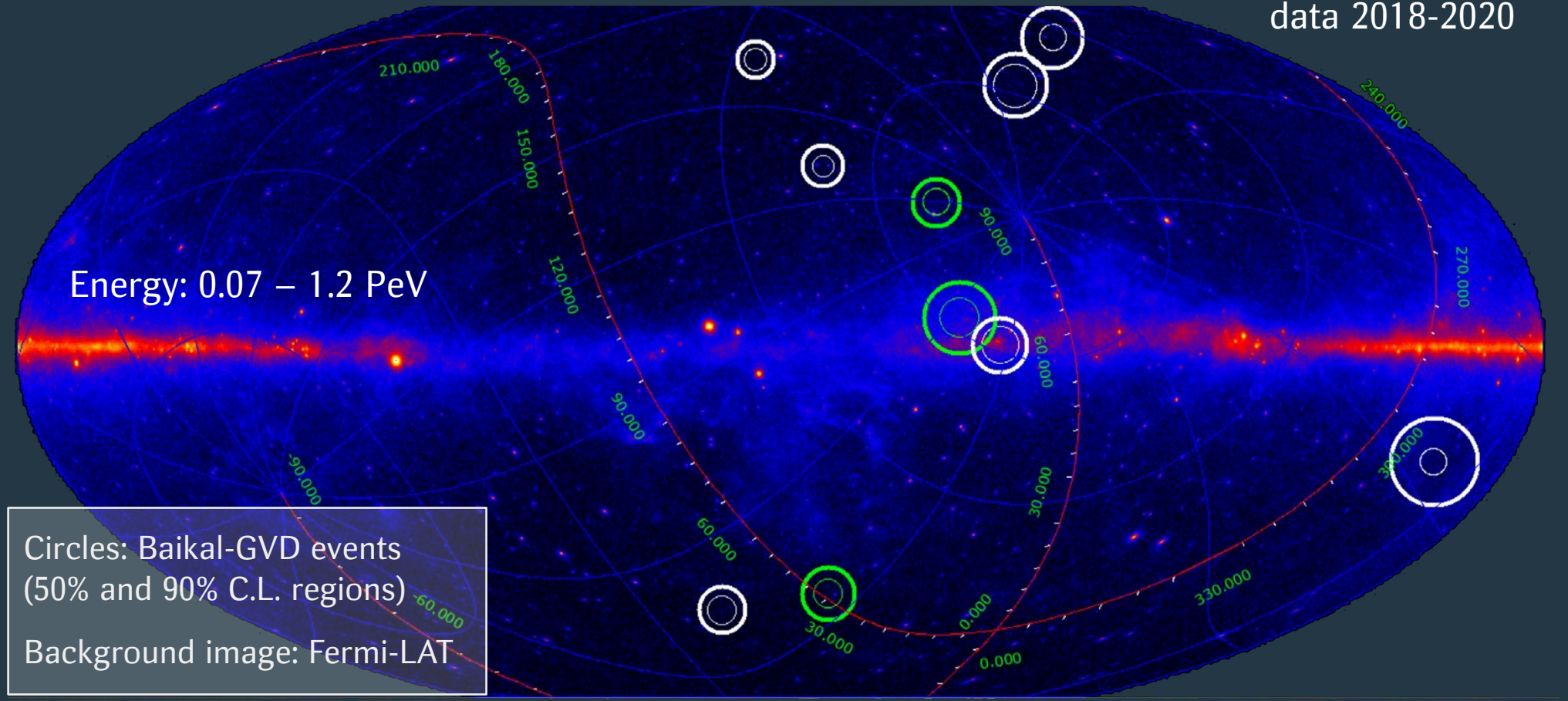




First 10 cascade events

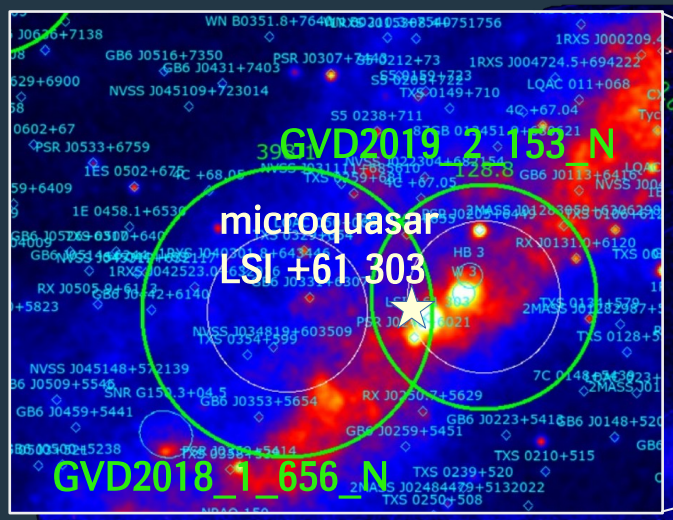
[PoS-ICRC2021-002]

data 2018-2020



Two close cascade events

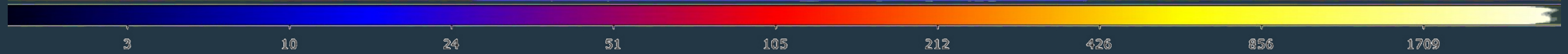
[PoS-ICRC2021-002]



Circles: Baikal-GVD events (50% and 90% C.L. regions)

Background image: Fermi-LAT

Microquasar LSI +61 303 – a double system (Be star + compact invisible object), emitting from radio to TeV range. Only 4 such objects are known in Milky Way.



Cascade events

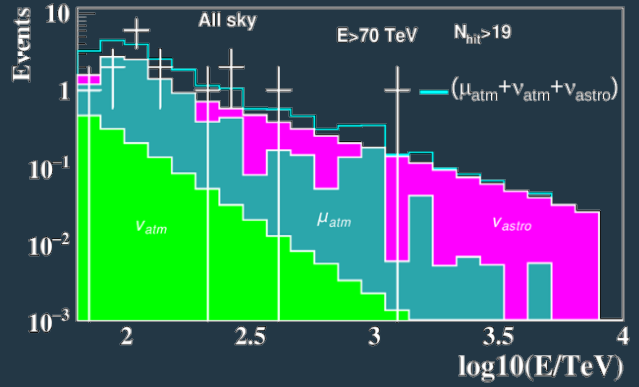
PRELIMINARY

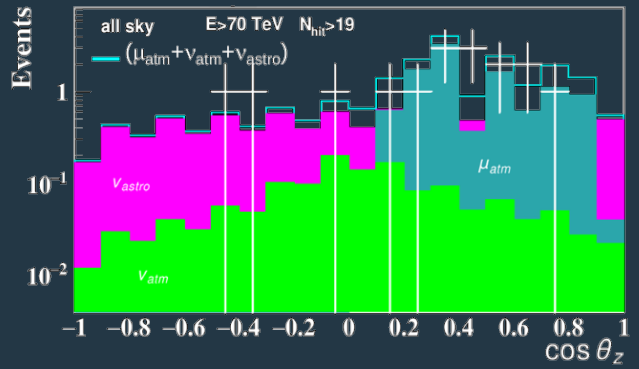
Test background-only hypothesis

New dataset: 5522 cluster x days (2018-2022)

All sky

p-value = 0.033 (2.13σ)





Cascade events

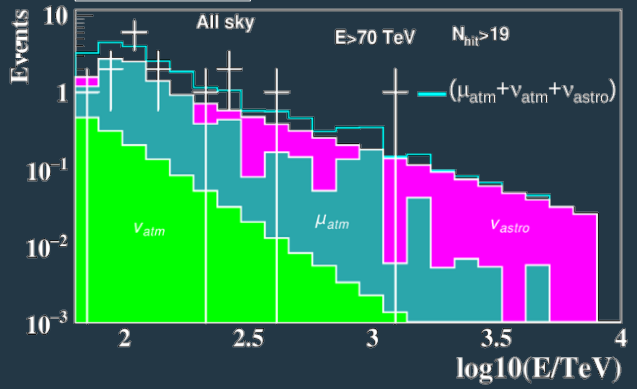
PRELIMINARY

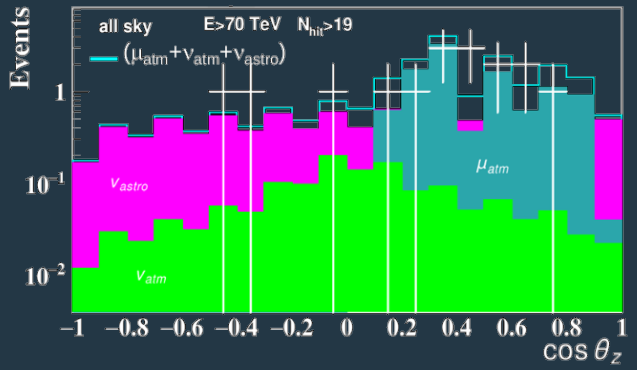
Test background-only hypothesis

New dataset: 5522 cluster x days (2018-2022)

All sky

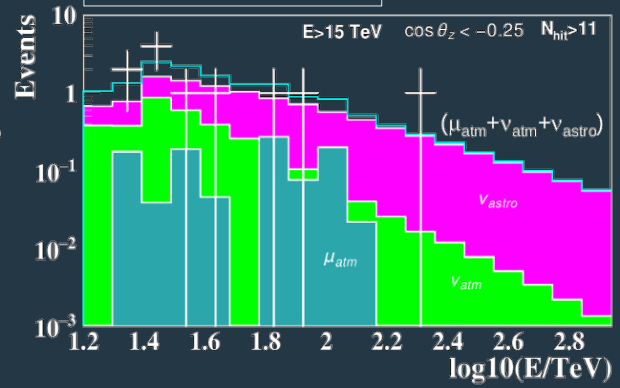
p-value = 0.033 (2.13σ)

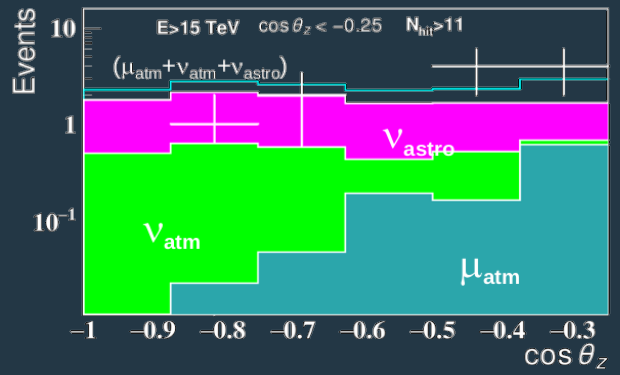




Upper-going

p-value = 0.0027 (3σ)





Cascade events

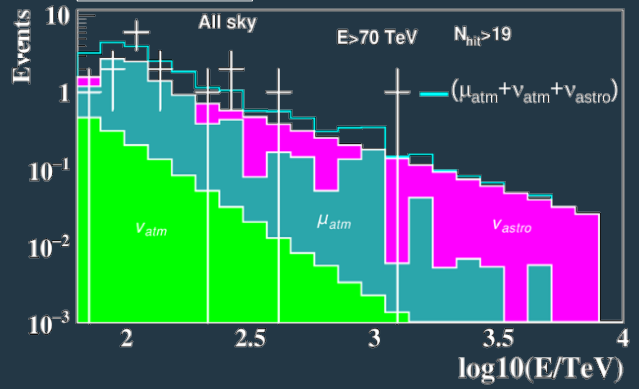
PRELIMINARY

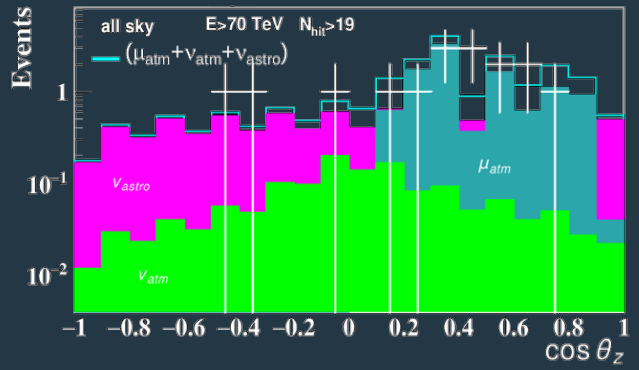
Test background-only hypothesis

New dataset: 5522 cluster x days (2018-2022)

All sky

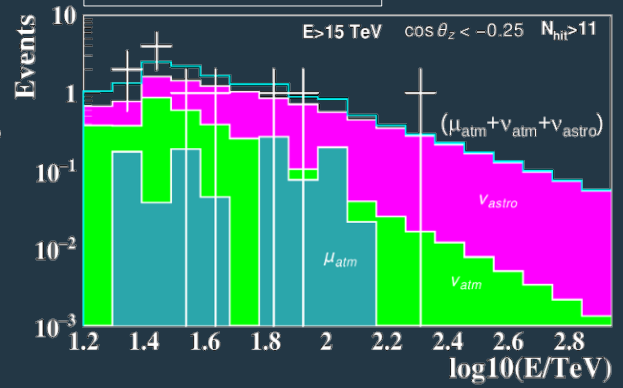
p-value = 0.033 (2.13σ)

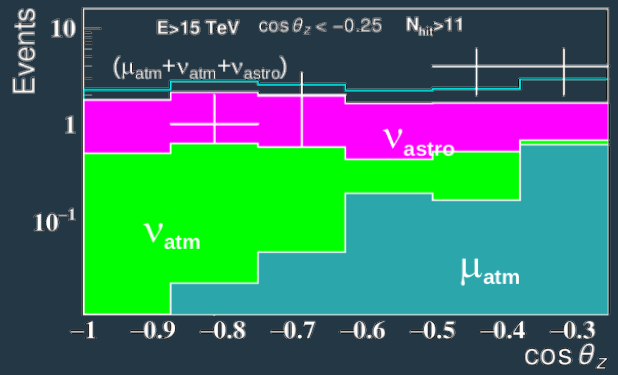




Upper-going

p-value = 0.0027 (3σ)





Upper- and down-going combined

25 events selected / 13.1 background events expected

p-value = 0.0022 (3σ)

Cascade events

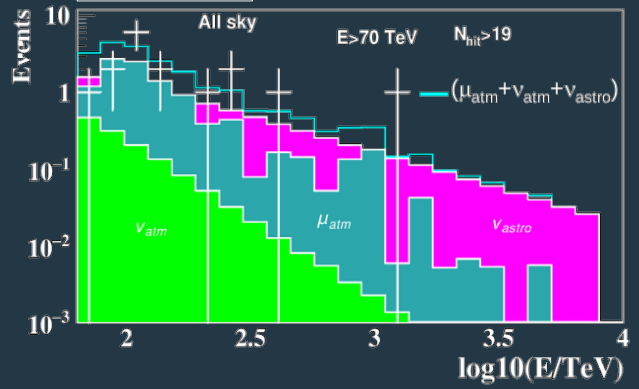
PRELIMINARY

Test background-only hypothesis

New dataset: 5522 cluster x days (2018-2022)

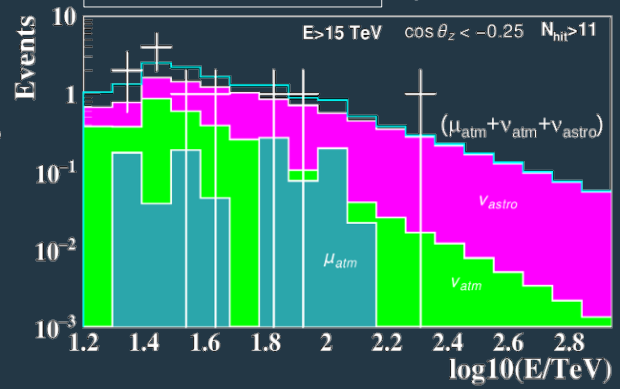
All sky

p-value = 0.033 (2.13σ)



Upper-going

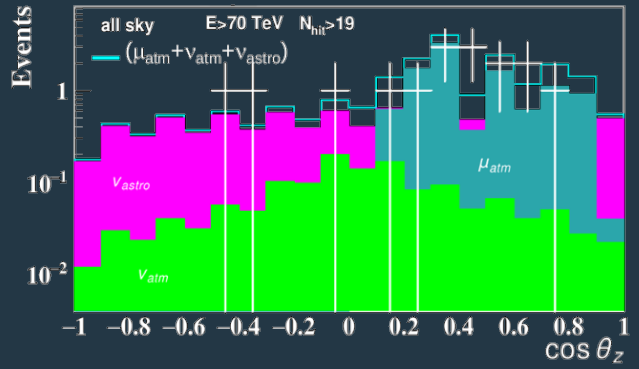
p-value = 0.0027 (3σ)

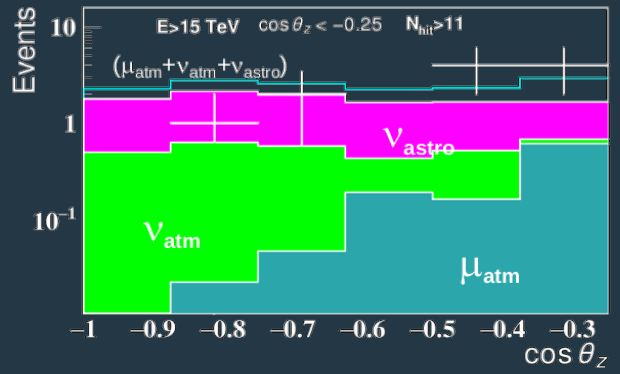


Upper- and down-going combined

25 events selected / 13.1 background events expected

p-value = 0.0022 (3σ)





Baikal-GVD confirms IceCube discovery of astrophysical diffuse neutrino flux at 3σ level

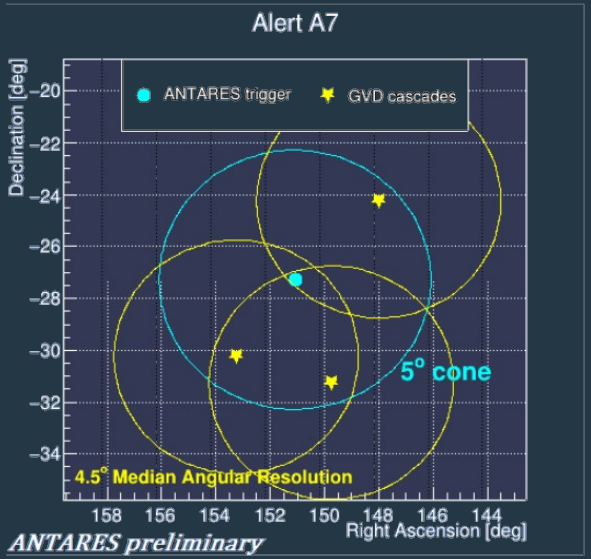
[Neutrino 2022 talk]

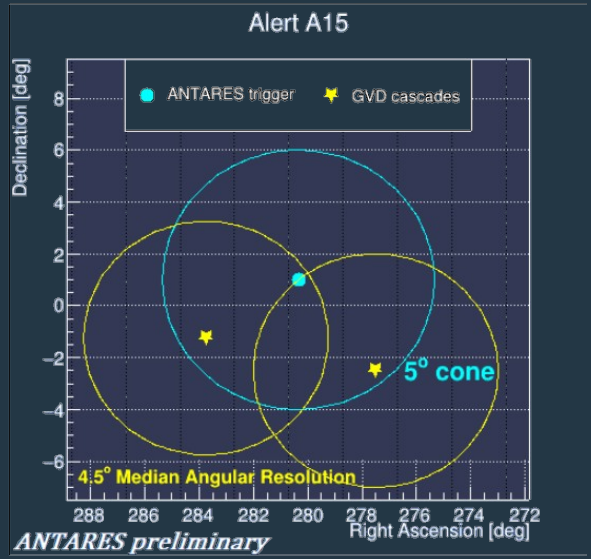
Follow-up of ANTARES alarms [PoS-ICRC2021-1121]

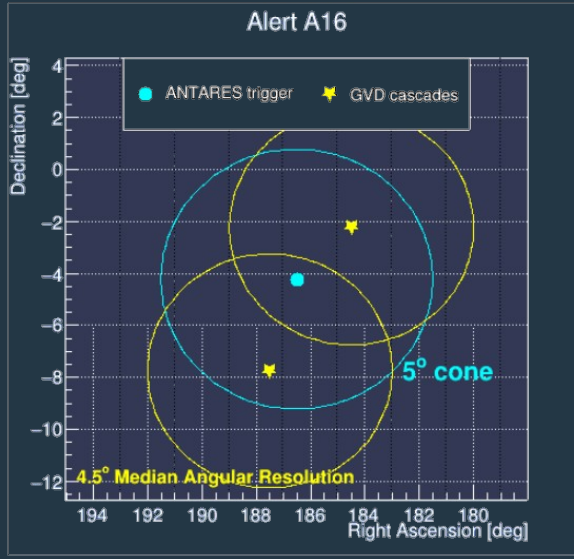
60 alerts since December 2018

±24 hours
5° cone

Coincidences found for 3 cascades





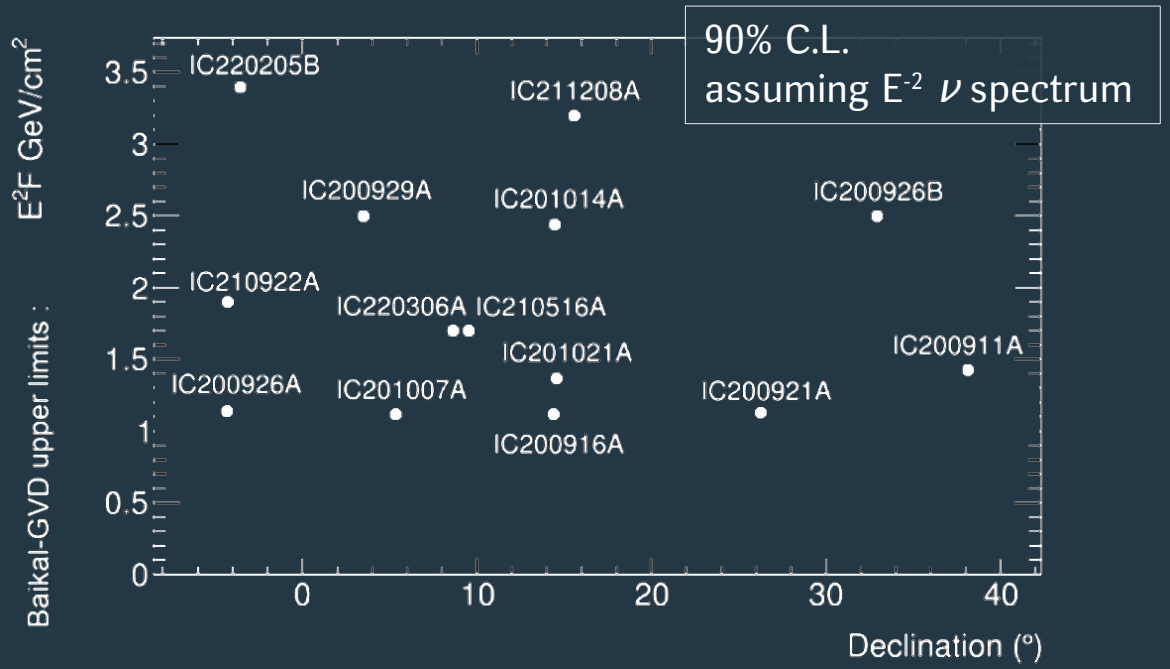


Alert ID	# cas.	$\Delta T_{trigger}$ [h]	Bkg/(clust.·day)	$p_{value}^{pre-trial}$	sig. [σ]
A7	3	+21.7, -3.2, -23.2	0.090	$8.46 \cdot 10^{-4}$	3.1
A15	2	+20.3, -0.6	0.108	$5.2 \cdot 10^{-3}$	2.6
A16	2	-14.8, -18.6	0.090	$3.6 \cdot 10^{-3}$	2.7

Follow-up of IceCube astrotrack events

[Neutrino-2022 poster] 45 alerts since September 2020 (±12 hours, 5° cone, 1 TeV - 10 PeV)

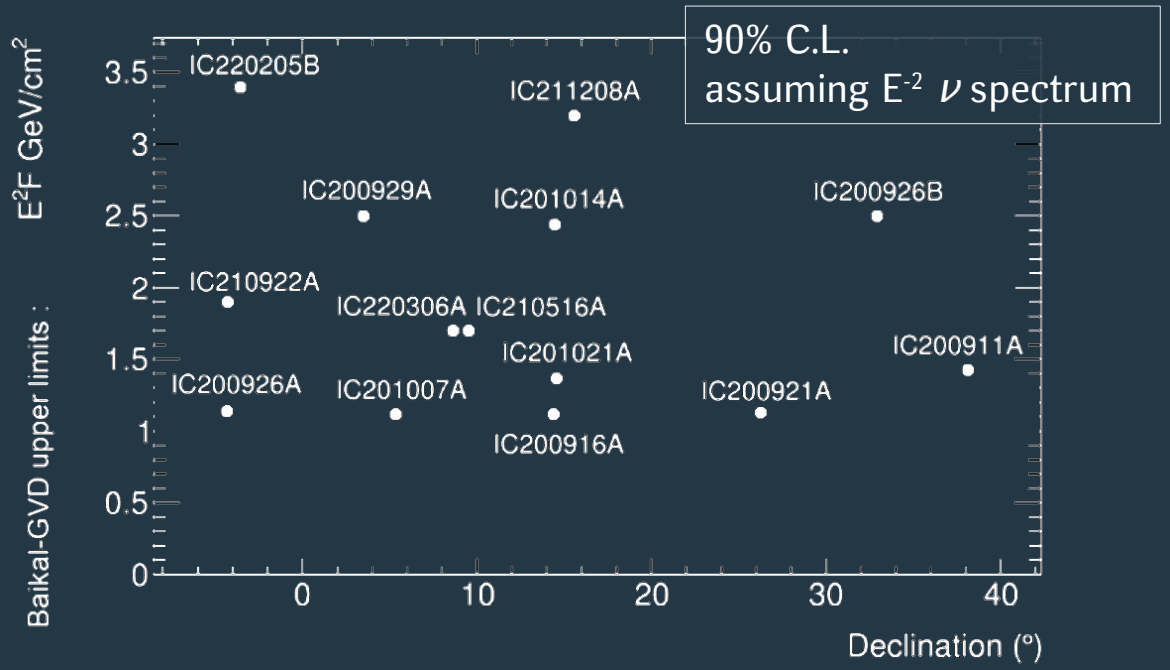
When no correlated events found an upper limit on neutrino flux is derived



Follow-up of IceCube astrotrack events

[Neutrino-2022 poster] 45 alerts since September 2020 (±12 hours, 5° cone, 1 TeV - 10 PeV)

When no correlated events found an upper limit on neutrino flux is derived



5 correlated cascade events selected by online analysis

2 of them passed all offline selections

1 sent to Astrotelegram (15112)

IceCube: **IC211208A**

- Temporal and directional coincidence with a burst of blazar **PKS 0735+17**
- Bursts are observed in gamma, radio and optical waves

Summary and outlook

Baikal-GVD is continuing to be deployed:

- 10 clusters with 2880 optical modules are in operation
- 2 clusters / year until 2026

Analysis of the collected data is ongoing:

- Atmospheric neutrino measurements agree with expectations
- Baikal-GVD follows-up alerts from other detector searching for astrophysical neutrino sources
- First 25 high-energy neutrino candidate events confirms at 3σ level IceCube discovery of diffuse astrophysical flux

Next-generation neutrino telescope is to be designed in 2022-2024


Thank for your attention!