Large Volume Neutrino Telescopes

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Lecture 2

Data analysis principles

LVNT development history

Selected results

Data analysis principles

Detector positioning and calibration

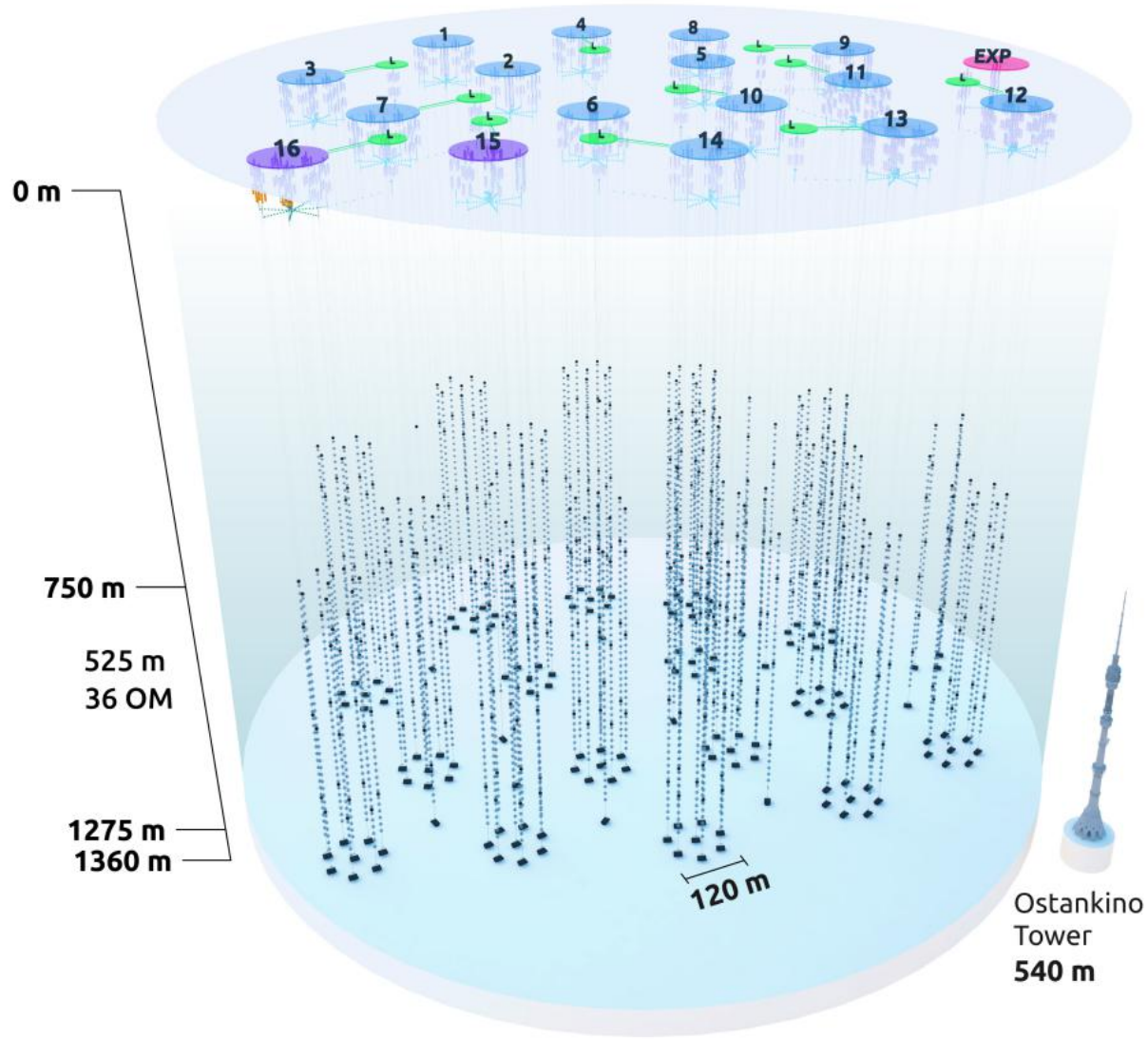
Reconstruction deals with

- Coordinates of each channel
- Pulse charge
- Pulse time

To run the reconstruction we must

- Know coordinates of each channel
- Convert ADC counts to photoelectrons
- Synchronise measurement channels to ns precision

Baikal-GVD detector



16 clusters

135 strings

4896 optical modules

Detection channel positioning

Strings of water-based detectors experience tilts due to water currents

For Baikal-GVD deviations of up to 50m for topmost modules

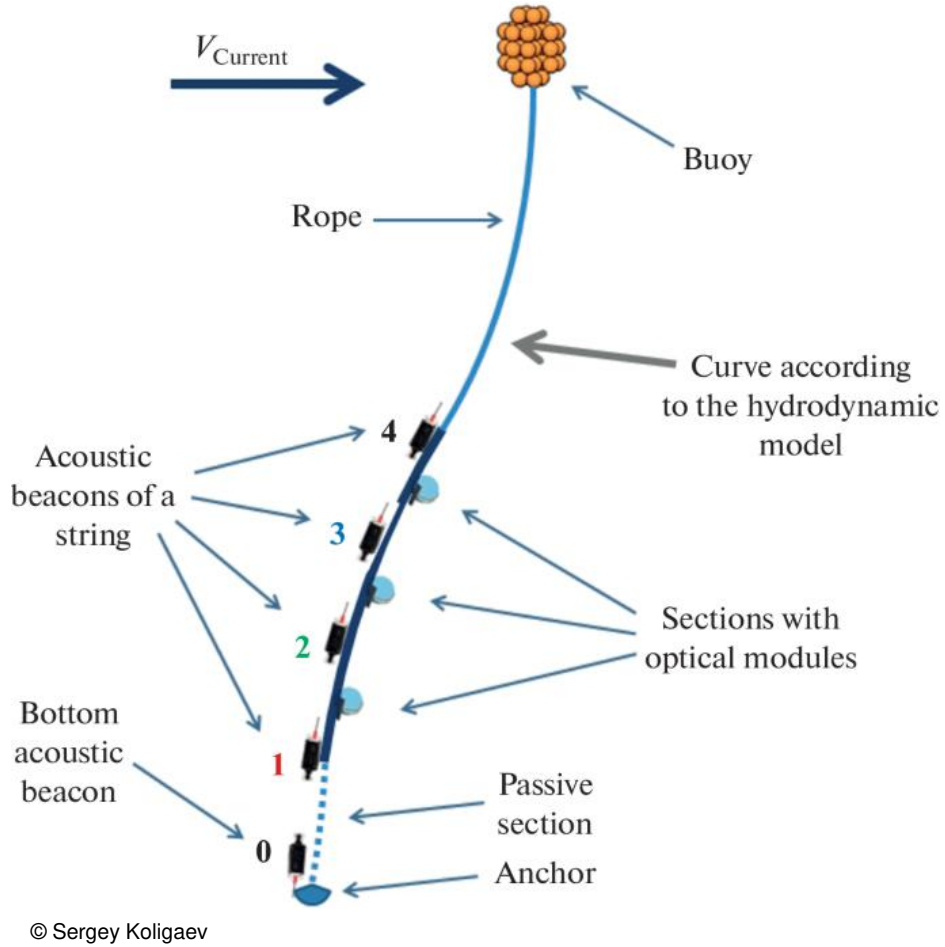


System of acoustic beacons at each string

- Regular acoustic poll
- Coordinates are measured by the time of acoustic signal propagation
- Position is reconstructed online for each measurement
- **The precision of OM position measurement ~40 cm**

Positioning precision corresponds to ~1.8 ns time uncertainty

Baikal-GVD string acoustic instrumentation



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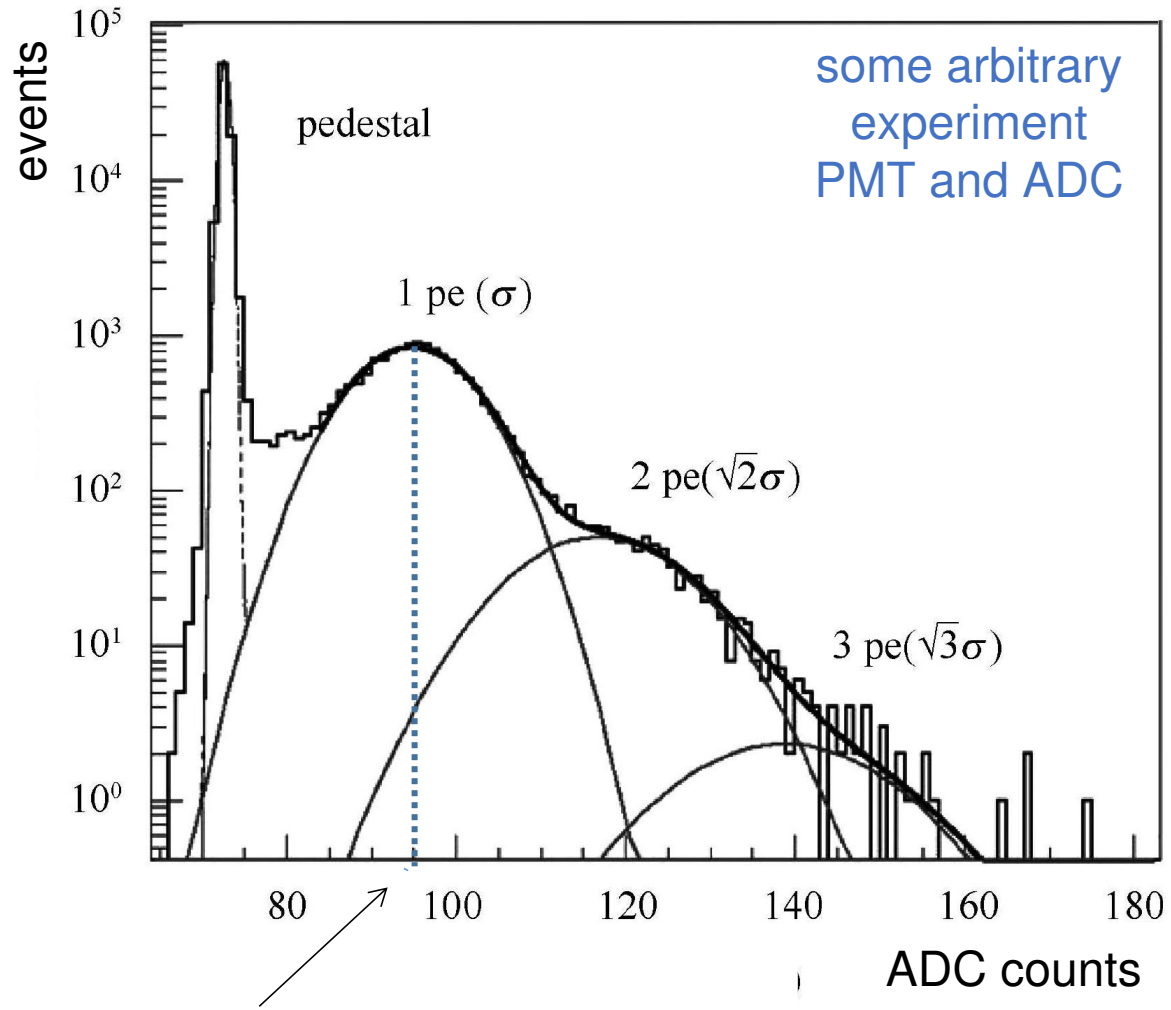
Charge calibration

ADC channels charge per count differ from each other

One need to set the uniform charge scale across the detector

Charge calibration is done by fitting the single photoelectron peak

Classical procedure used in experiments with PMTs involved



Single photoelectron calibration coefficient, C_i

$Q_i = ADC_i / C_i$

Time calibration

Time measurement precision:

$$\sim \sigma_{TTS} \oplus \sigma_{unsync}$$

σ_{TTS} irreducible pulse time uncertainty

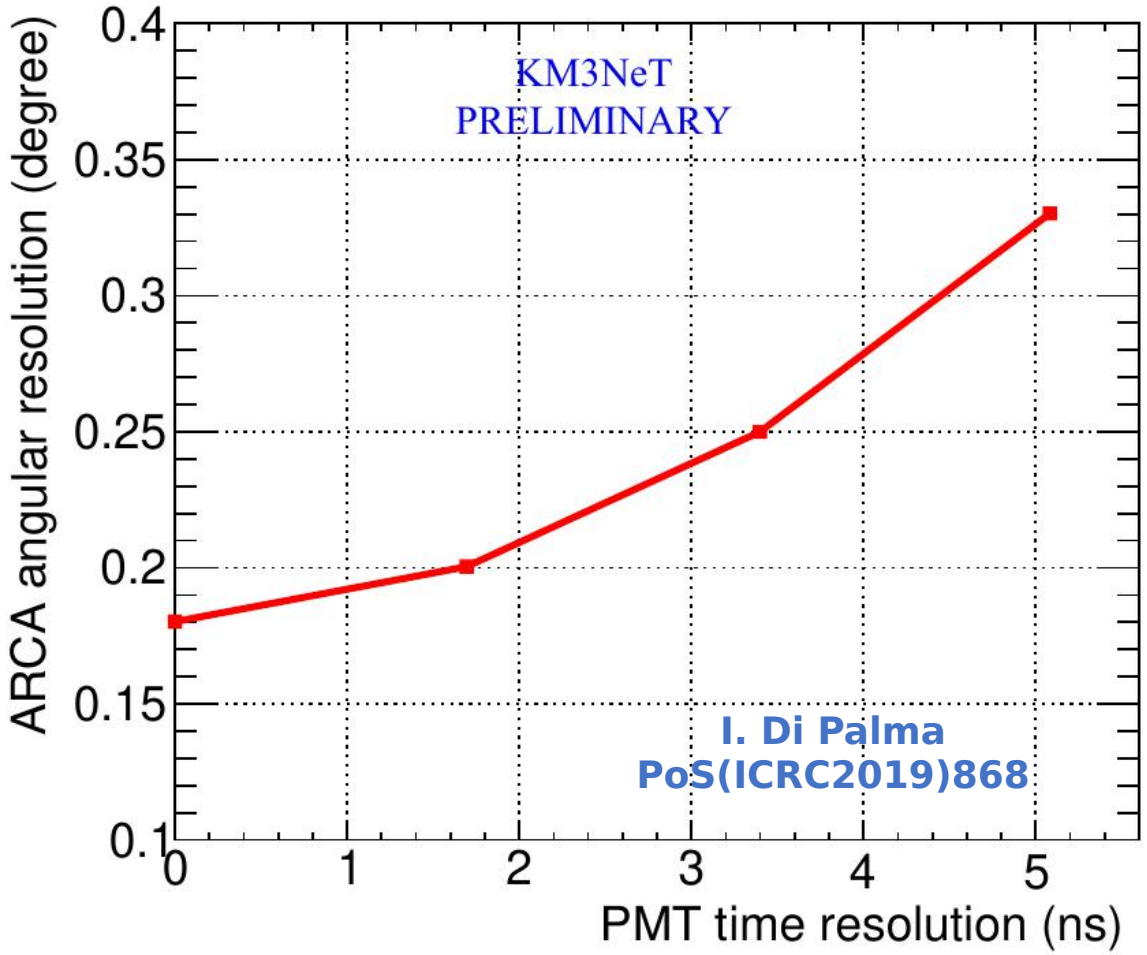
- PMT signal development fluctuations: ~1.4ns for Baikal-GVD R7081-100

σ_{unsync} is minimised by calibration procedures

One should synchronise scales of photon arrival at the PMT photocathode to the 1-2ns level

PMT signal delays are caused by PMT channel transit time, different cable lengths, any possible delays in electronics

Angular resolution dependence on time measurement precision



Detector is calibrated with artificial light sources (LED, Lasers)

Background pulses

PMTs and detection medium always produce some background pulses

In LVNT rate of background PMT pulses is larger than atmospheric muon Cerenkov signal rate
10's Hz vs. up to 10's kHz

Most of the data at LVNT is produced by the background noise

PMT and electronics -generated background

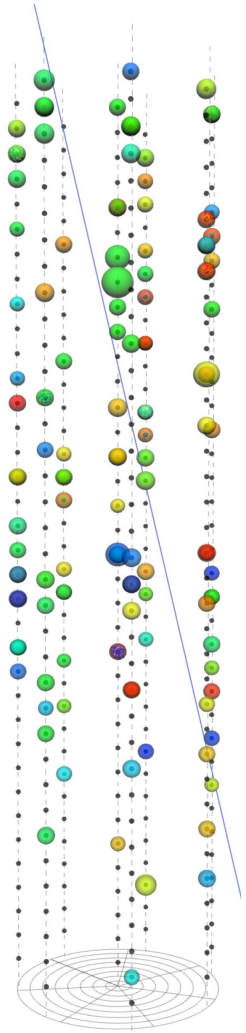
- OM dark current: O(kHz)
- PMT afterpulses, low rate but large pulse amplitude

Water background glow

- Seawater: ^{40}K decays, bioluminiscense
- Baikal Lake: Chemiluminiscense
- **Reach up to hundreds of kHz per optical module**

No chemiluminiscence, bioluminiscence or ^{40}K decays in Antarctic Ice Shield
IceCube background is only due to dark current: "background-free" detector

Background pulses in Baikal-GVD



typical event in Baikal-GVD

Sinking remains of algae or living organisms cause chemiluminiscence

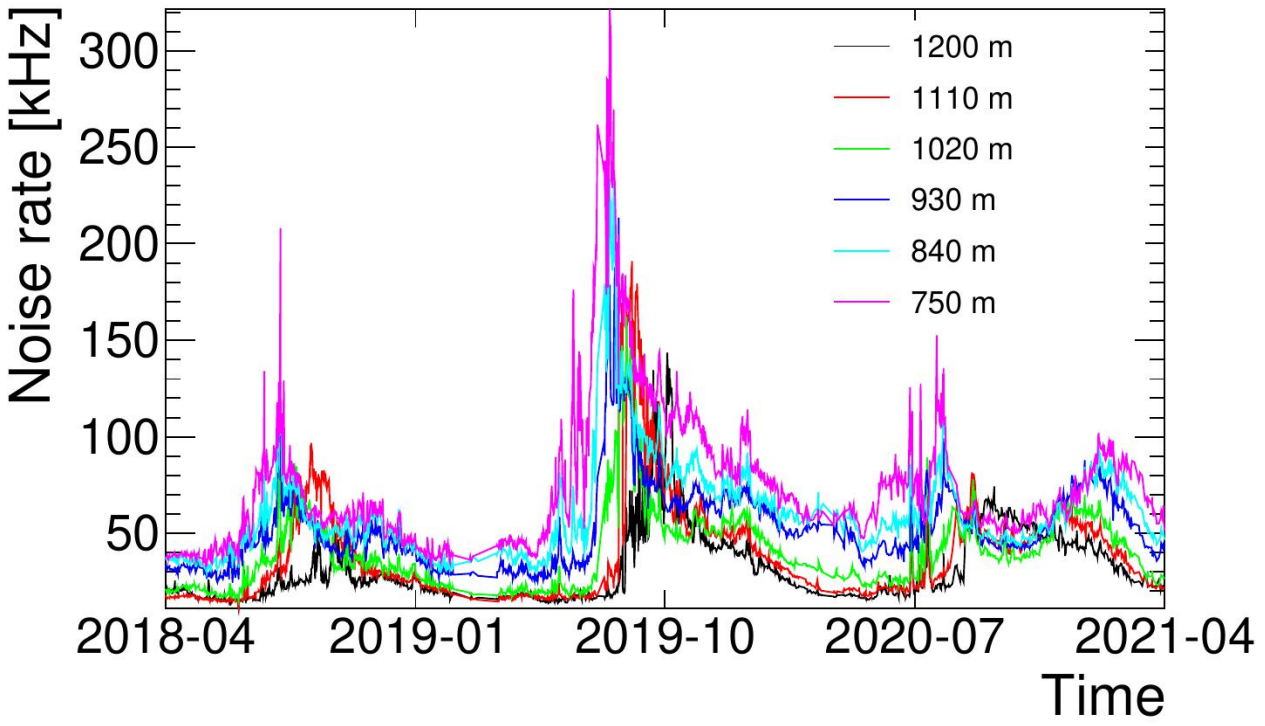
Single p.e. -level signal with rate up to few hunderds of kHz

Substantially non-uniform rate vs. depth

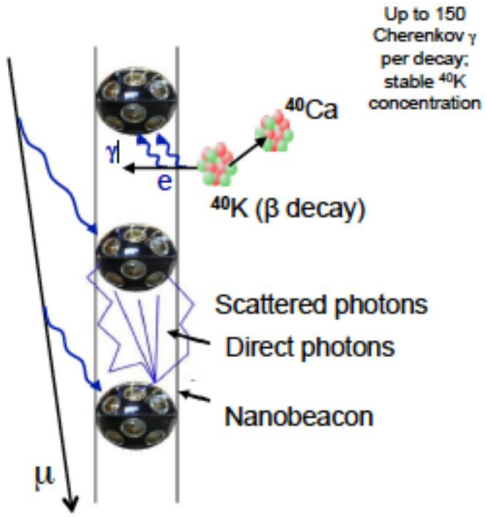
Seasonal variations

- Low noise in winter and spring
- Peak of noise in mid-summer
- Slow decrease towards winter

Up to hundreds of kHz for topmost OMs

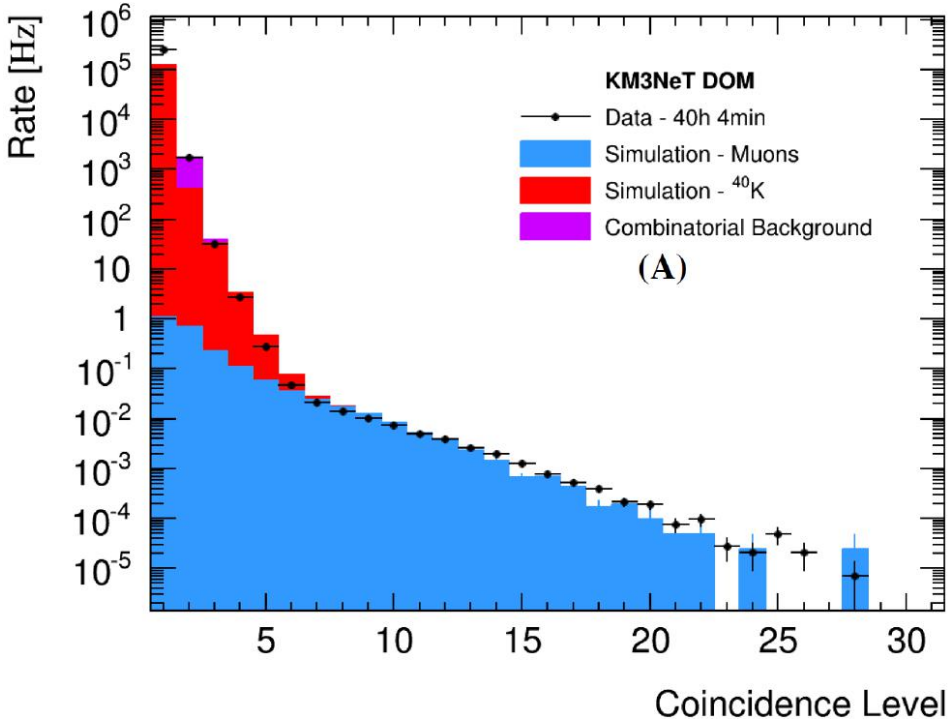


Background pulses in Mediterranean



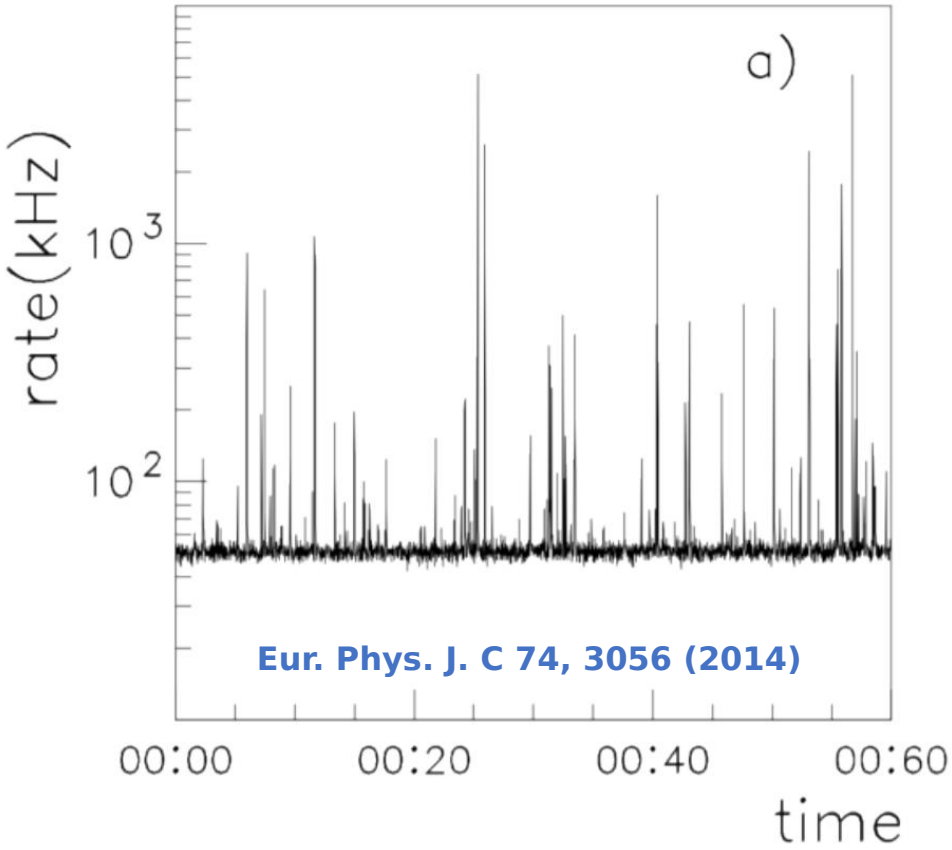
Deep sea backgrounds:

- ^{40}K decay - constant background at the level of hundreds of photons per cm^2
- Bioluminiscence - very high intensity flashes
- Average rate: 7kHz per 3” PMT



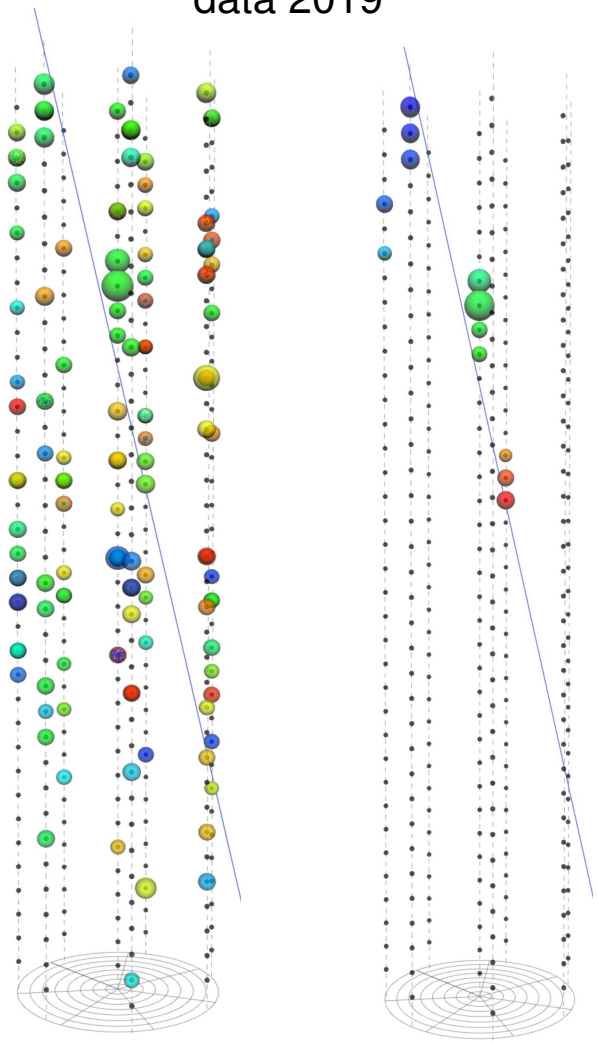
Suppressed with the coincidence counting

10-inch PMT rate near Cape Passasero at ARCA site



Noise suppression algorithms in Baikal-GVD

track-like event,
data 2019



full event with noise

event after the hit selection

From previuous lecture, rough estimate of response to 10 TeV muon

distance (m)	light field (γ/cm²)	photoelectron yield	non-zero p.e. prob. (%)
10	0.35	28.3	~100
22	0.019	1.54	78.5
30	0.012	0.97	62.1

Response at lower energies is sparse, low-charge and fluctuating

- Noise suppression may affect signal hits as well

Suppress noise hits at the minimum cost for Cerenkov hits

- Scanning algorithm **[PoS(ICRC2021)1063]**
- Deep learning -based algorithms **[I. Kharuk et al 2023 JINST 18 P09026]**

ML-based hit finding improves efficiency for low energies

Event reconstruction and analysis

Events are read-out and built
Detector is positioned and calibrated
We identified collection of Cherenkov hits

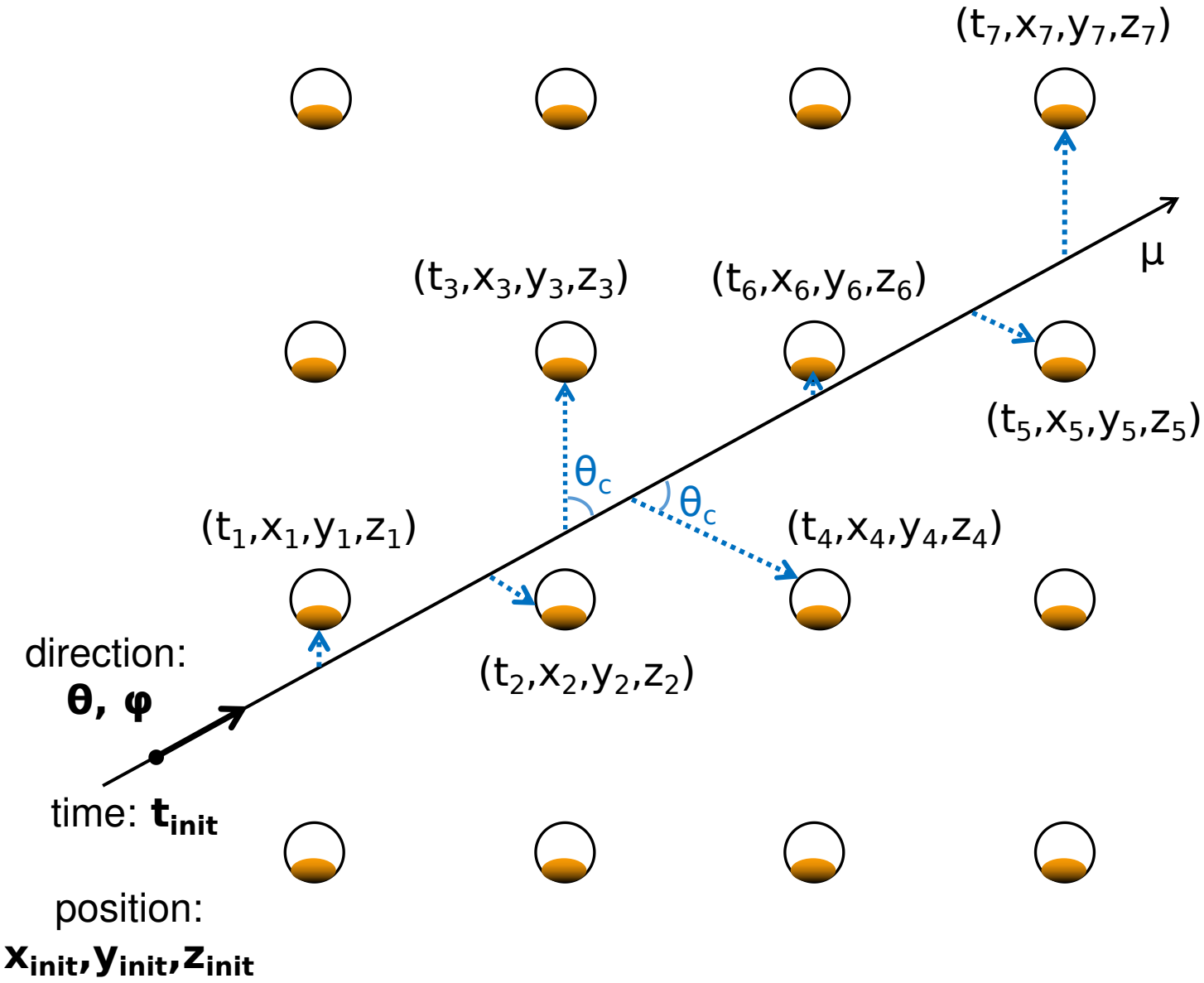
We can associate OM pulses (**hits**) in different sections of the detector with some event hypothesis

Focus on tracks here

Simplest MIP track hypothesis has 5 free parameters

Time of each hit can be unambigously calculated using track hypothesis

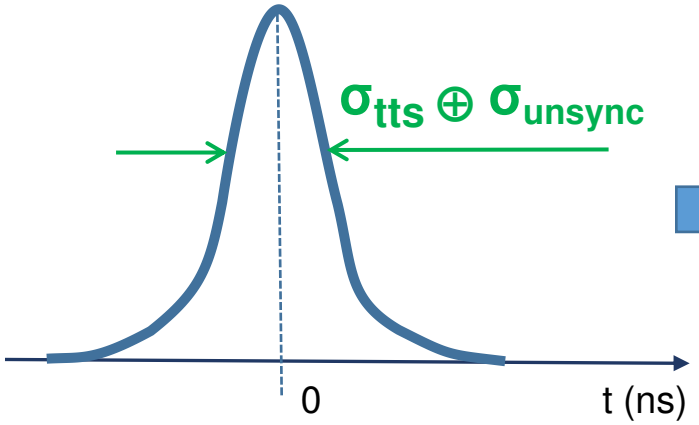
Fit the data to the track hypothesis



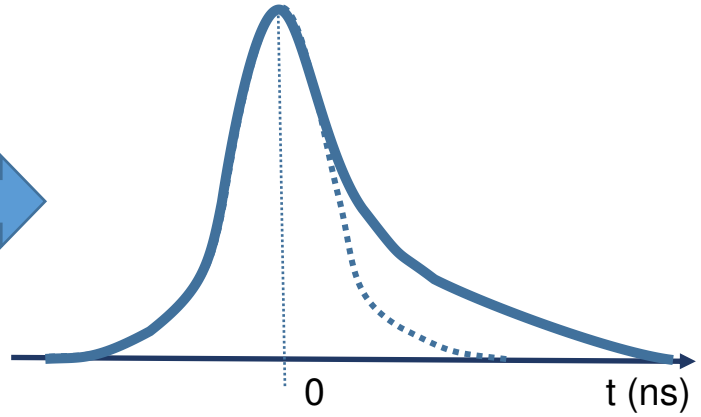
Track models

Different track models can be used depending on importance of effects

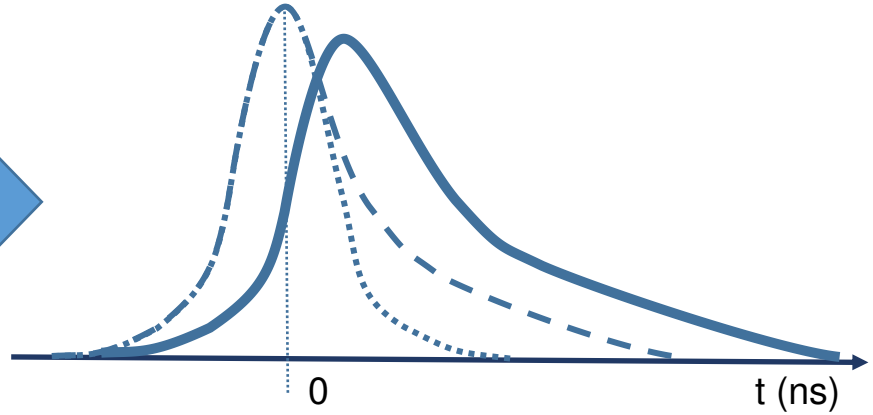
MIP muon



MIP muon + showers



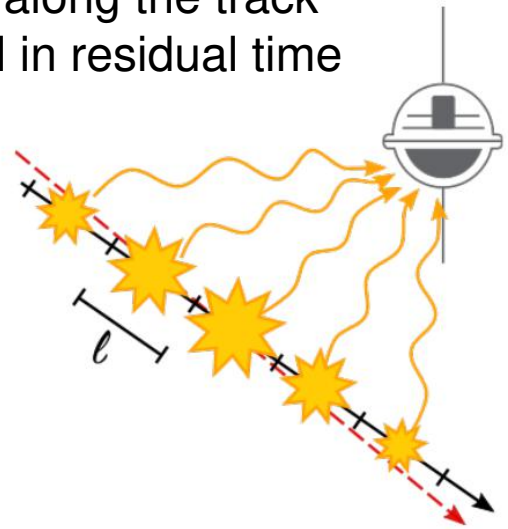
MIP muon + showers + scattering



Mun Cherenkov t

Simplest model:
Time chi2 fit with sigma defined by the time measurement precision

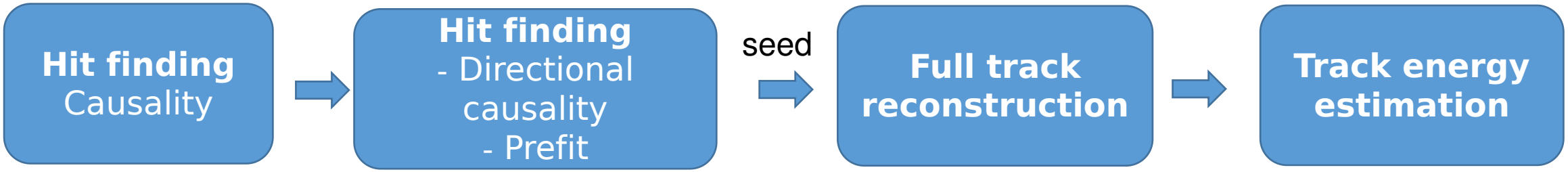
Showers along the track cause tail in residual time



Showers and scattering require complex likelihood functions derived from MC

Track angular resolution

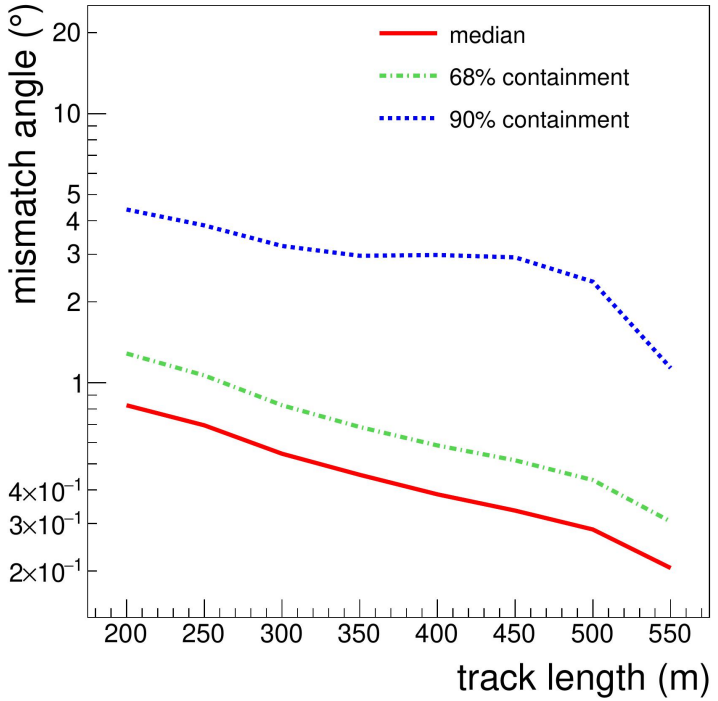
Track reconstruction chain in in Baikal-GVD



Track angular resolution

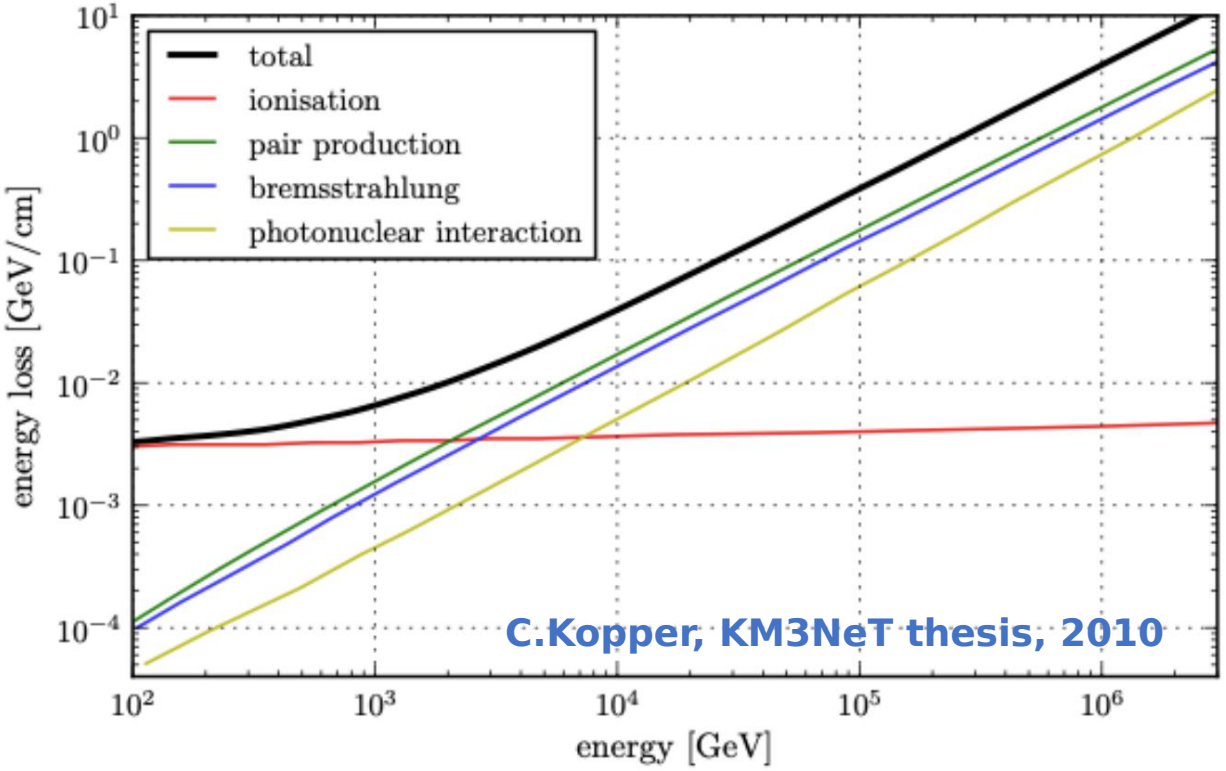
Angular resolution is defined by

- Time measurement precision
- Length of the track
- Number of hits



Muon energy reconstruction

Energy losses for $E_\mu > 1$ TeV are linear on energy



Only part of the muon trajectory is observed in the detector

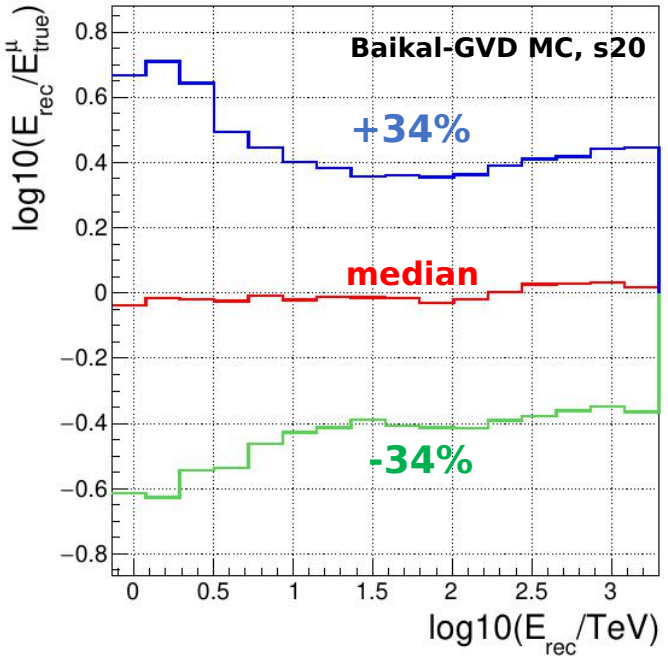
Muon energy can be estimated using energy losses (or light deposition) along the track

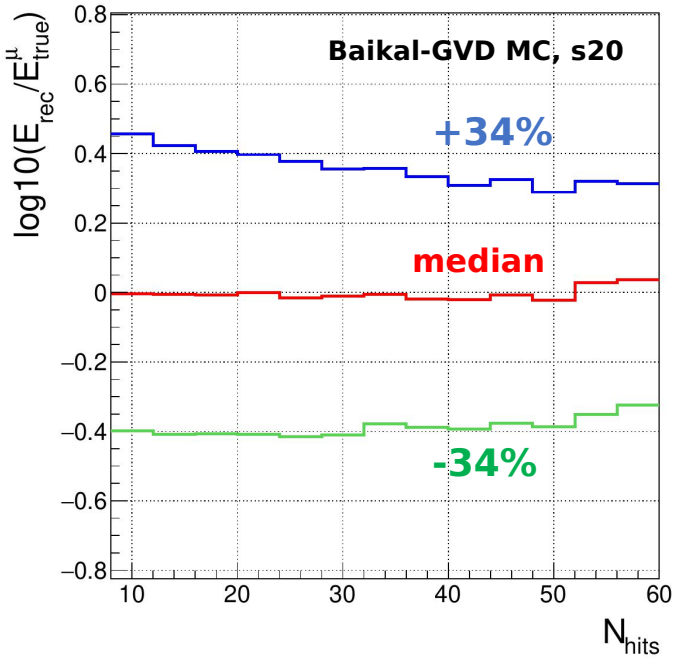
- 200-300% precision

Baikal-GVD muon energy resolution

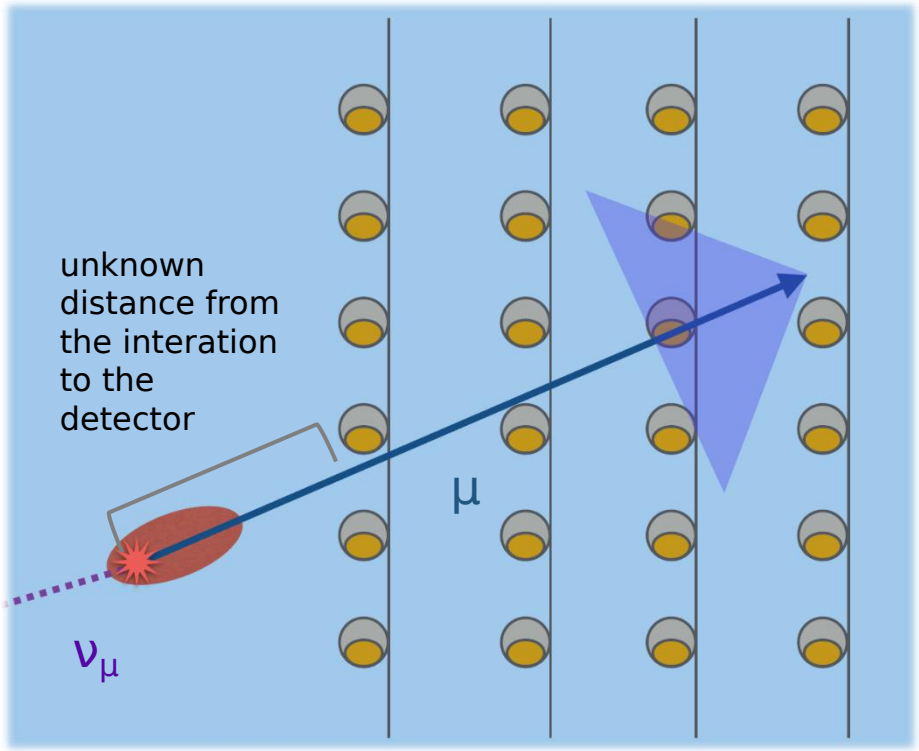
68% confidence interval for E^{μ}_{true} :

- ~ **(E_{rec}/2.5, 2.5×E_{rec})** in the range $10<E_{rec}<1000$ (TeV)
- Resolution improves with N_{hits} increase





Neutrino energy reconstruction

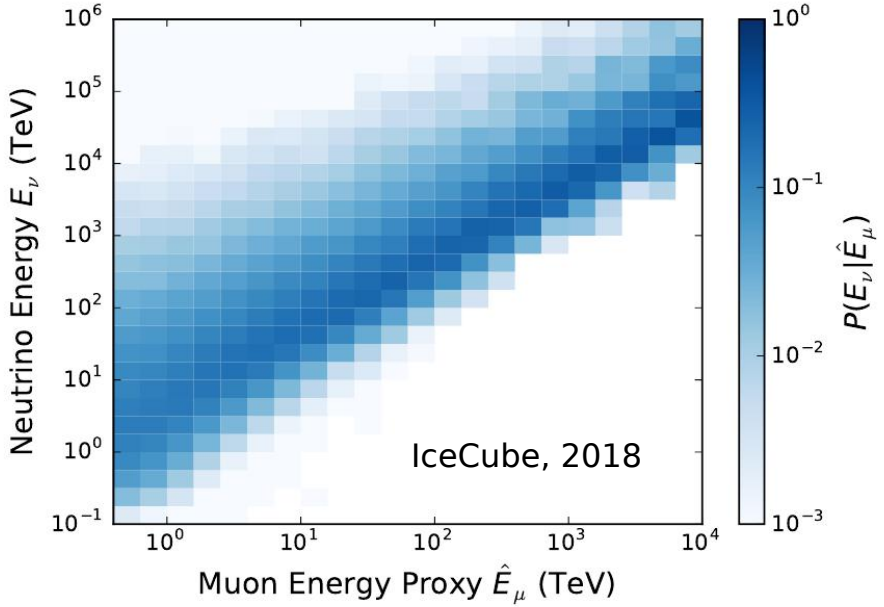


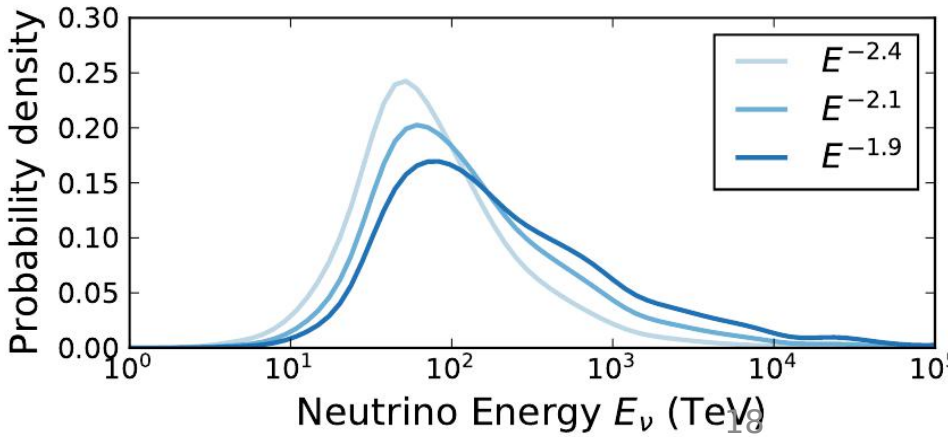
Energy losses before muon has entered the detector are not known

Derived from MC simulation:

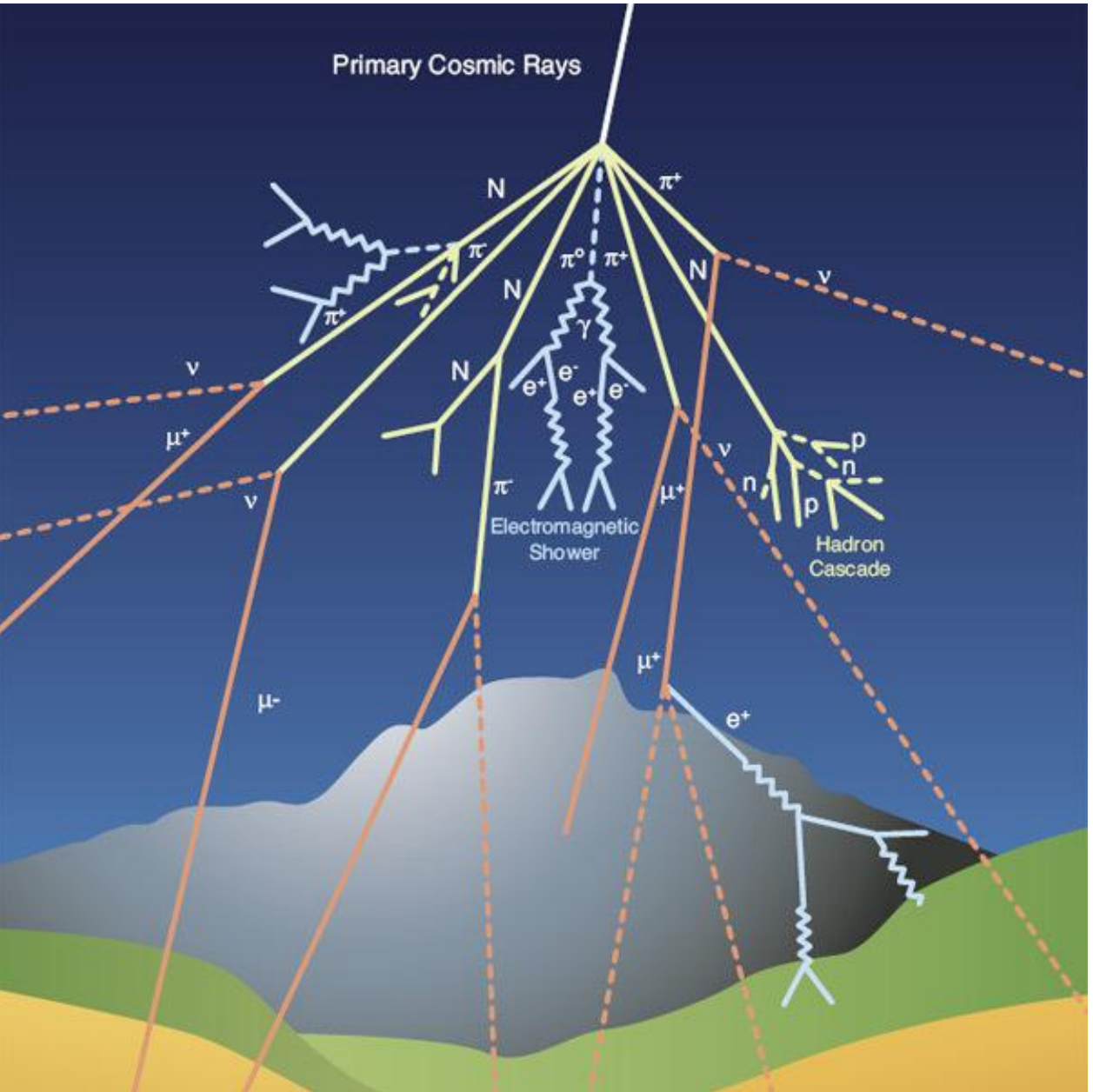
Lower bound on neutrino energy is available

Neutrino most probable energy is often quoted



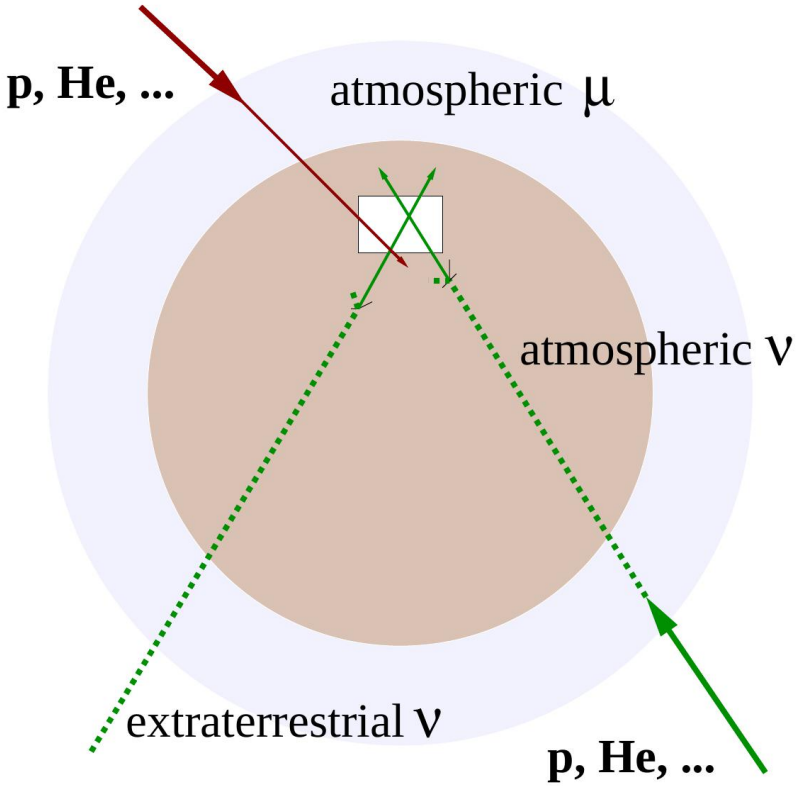


Background events



Muon and neutrino reach Earth surface

- Muons reach the detector from above
- Neutrios arrive from all directions



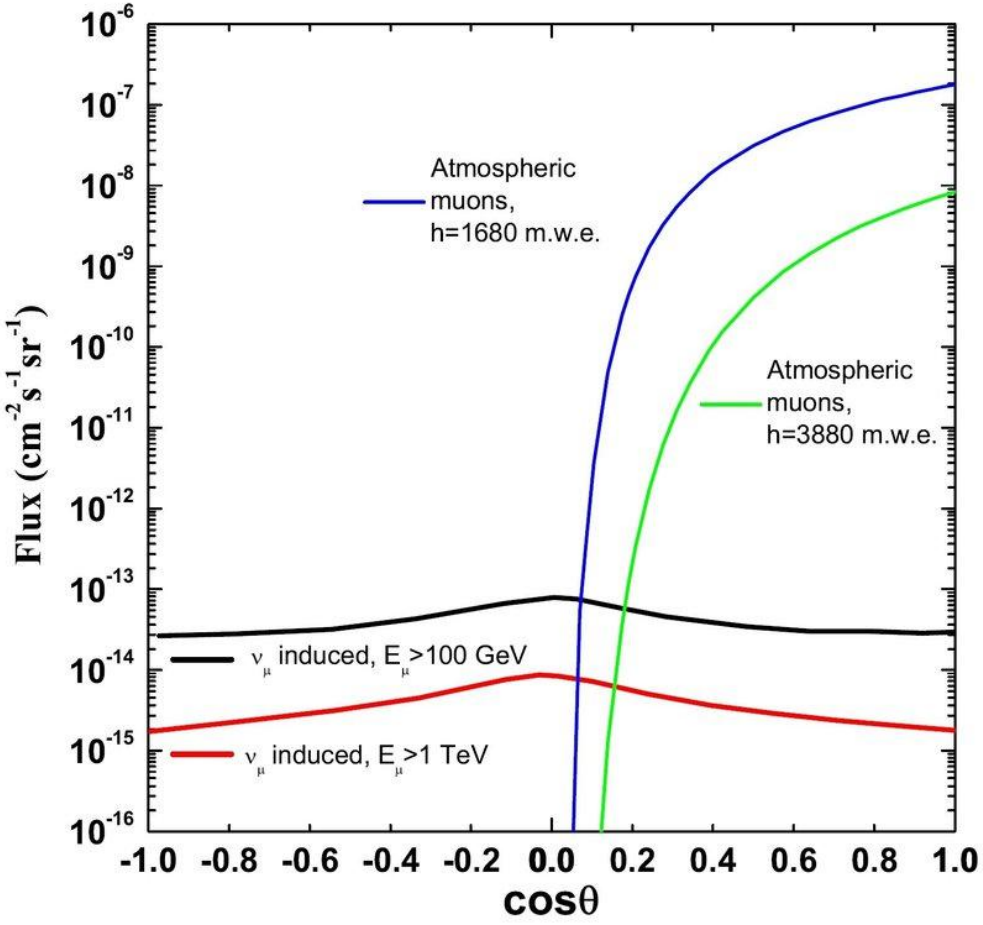
Backgrounds

Atmospheric muon background is many orders of magnitude larger than neutrino-induced event rate

Muon background can be minimized with a cut on zenith angle, by looking at “upgoing events”

One of reasons PMTs are oriented downwards - maximise the sensitivity to upgoing events

True zenith angle distribution



upgoing **downgoing**

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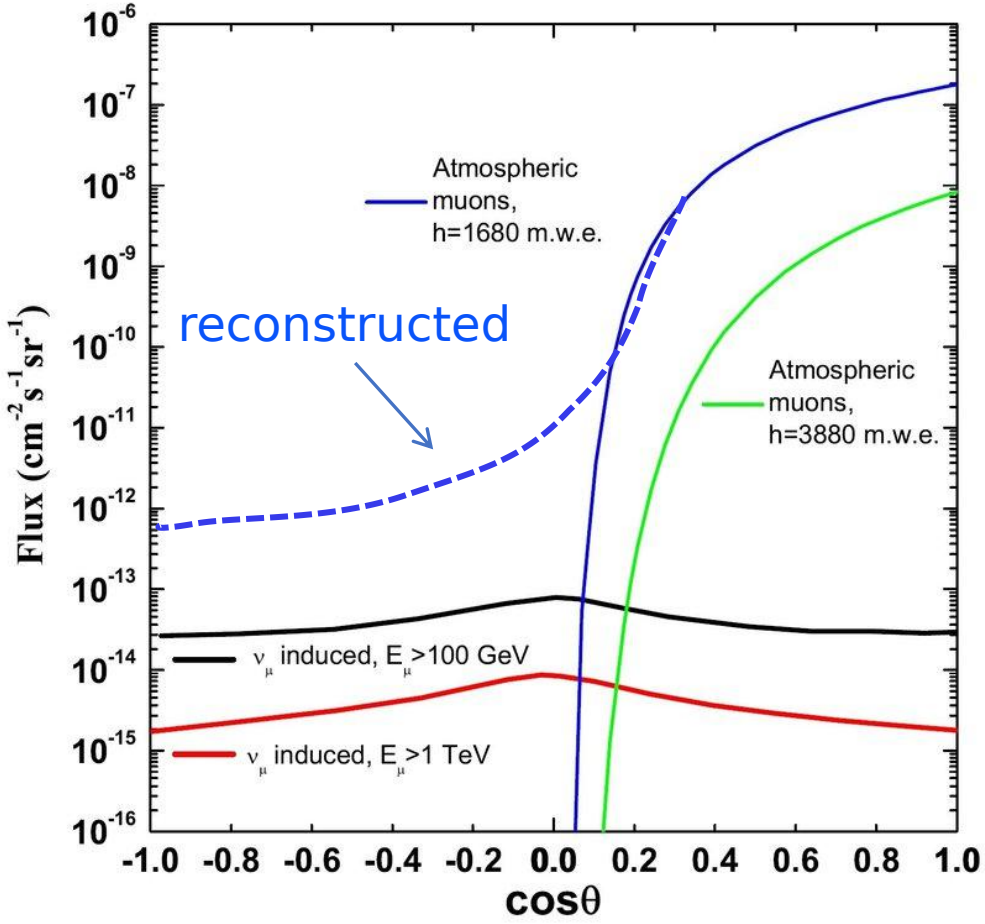
One of reasons PMTs are oriented downwards - maximise the sensitivity to upgoing events

Due to reconstruction uncertainties (downgoing reconstructed as upgoing) atmospheric muons contribute to the background for the upgoing events as well

True zenith angle distribution



upgoing **downgoing**

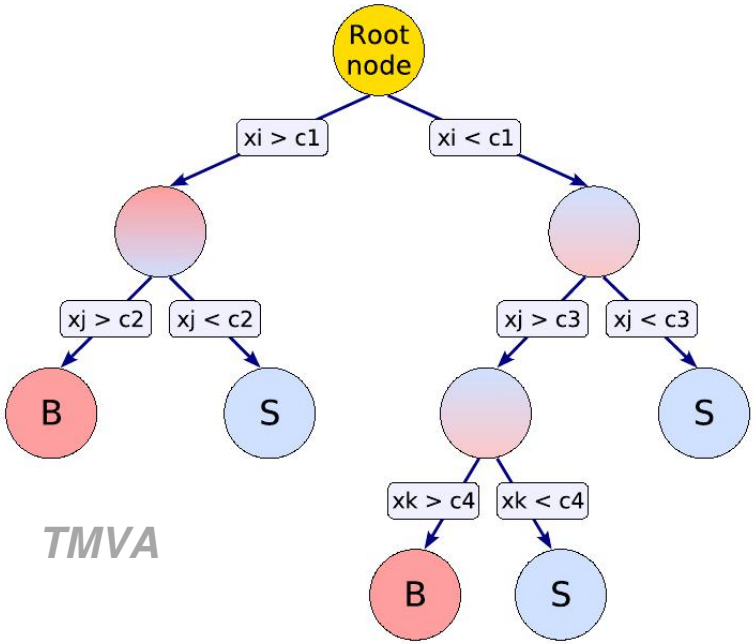
Background suppression: boosted decision trees (BDT)

Active usage in HEP since mid-2000s

- Icreased signal/background (S/B) separation wrt usual cuts analysis
- Very good out-of-the box performance

Elementary decision tree

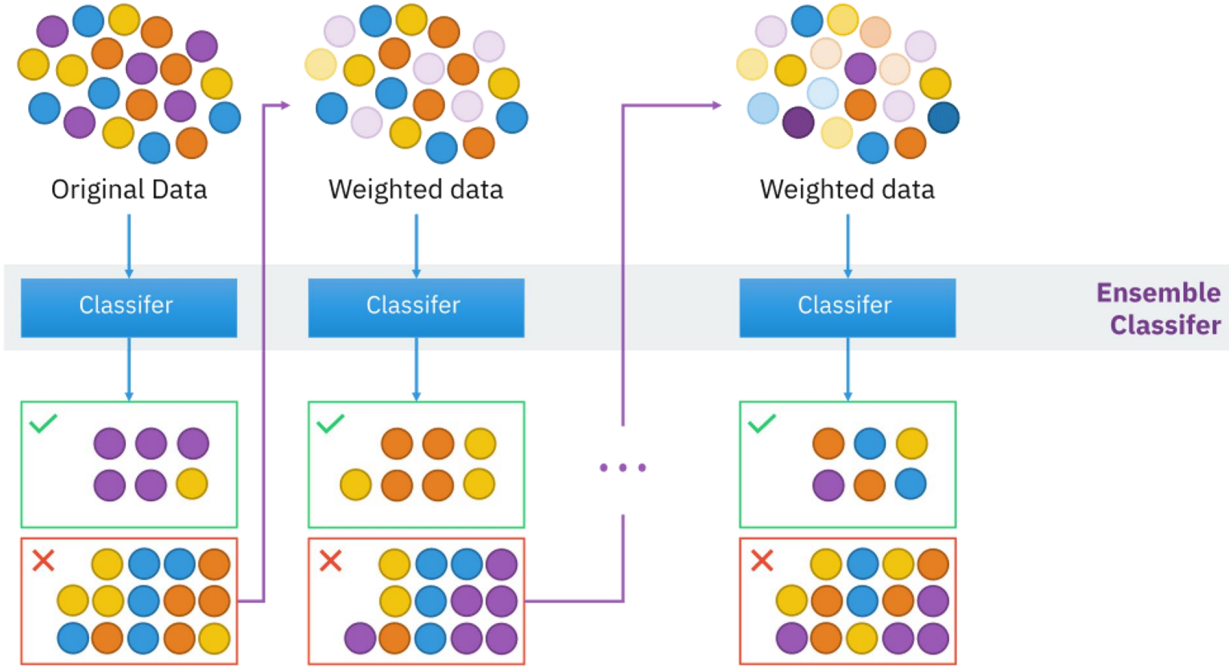
Variable x* at each step is chosen to give the best S/B separation power



Decision tree response:
-1 for bckg.; +1 for noise

Boosting: build sequental set of weighted trees trained on weighted event samples

- Events missclassified on previous step gain increased weight
- BDT response (score): normalised sum of weighted resposes



www.almabetter.com

Suggested reading on BDTs in HEP: **Yann Cadou, arXiv:2206.09645**

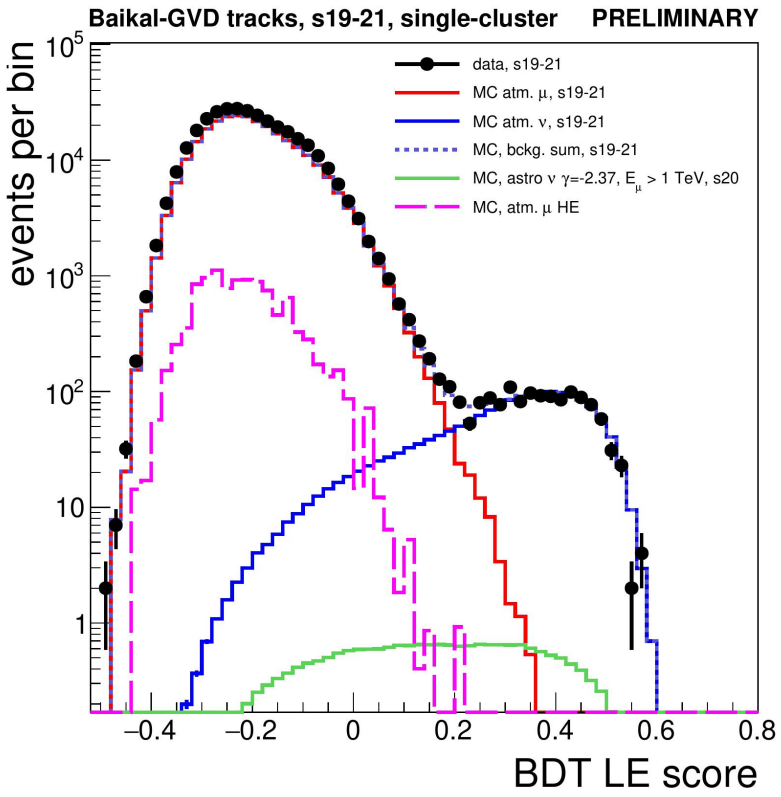
Muon background suppression

Boosted decision trees are commonly used for event classification in traditional analysis

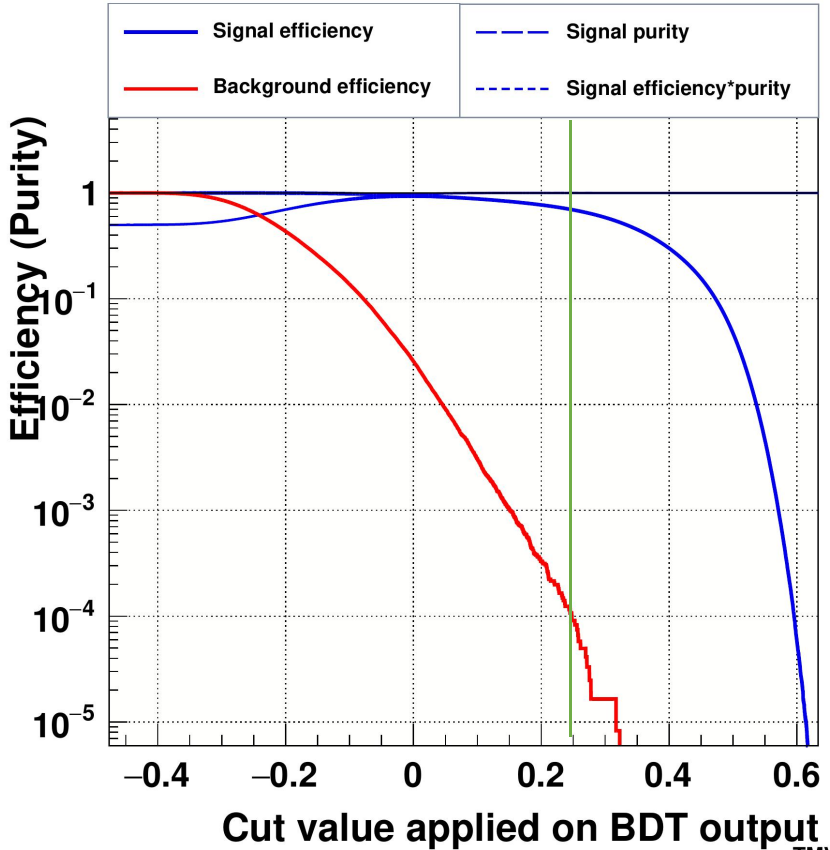
Training datasets
- Background dataset: Atmospheric muons
- Signal dataset: Atmospheric and astrophysical neutrino

Find the optimal cut value
- Suppress background
- Keep most signal
- Specific for each analysis

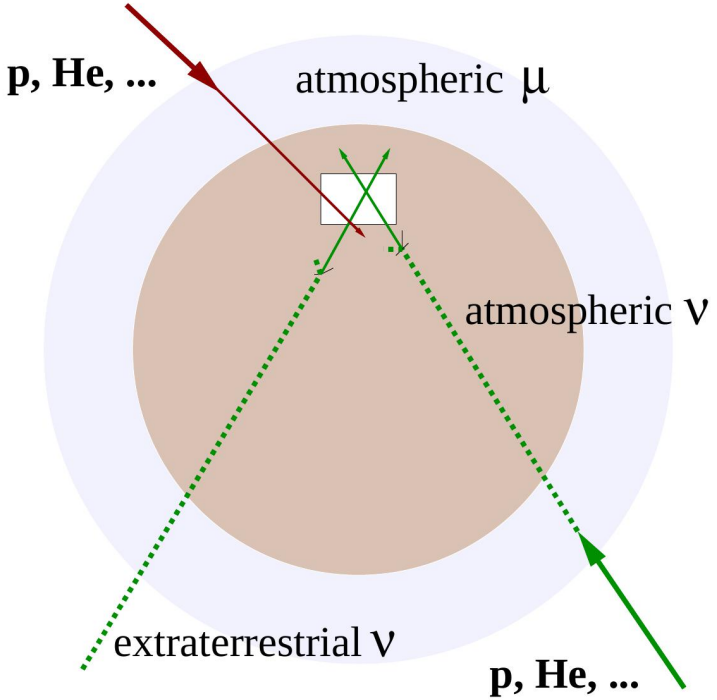
Classifier output distribution



Cut at 0.25:
Background reduction by the factor 10^4,
signal efficiency: ~70%

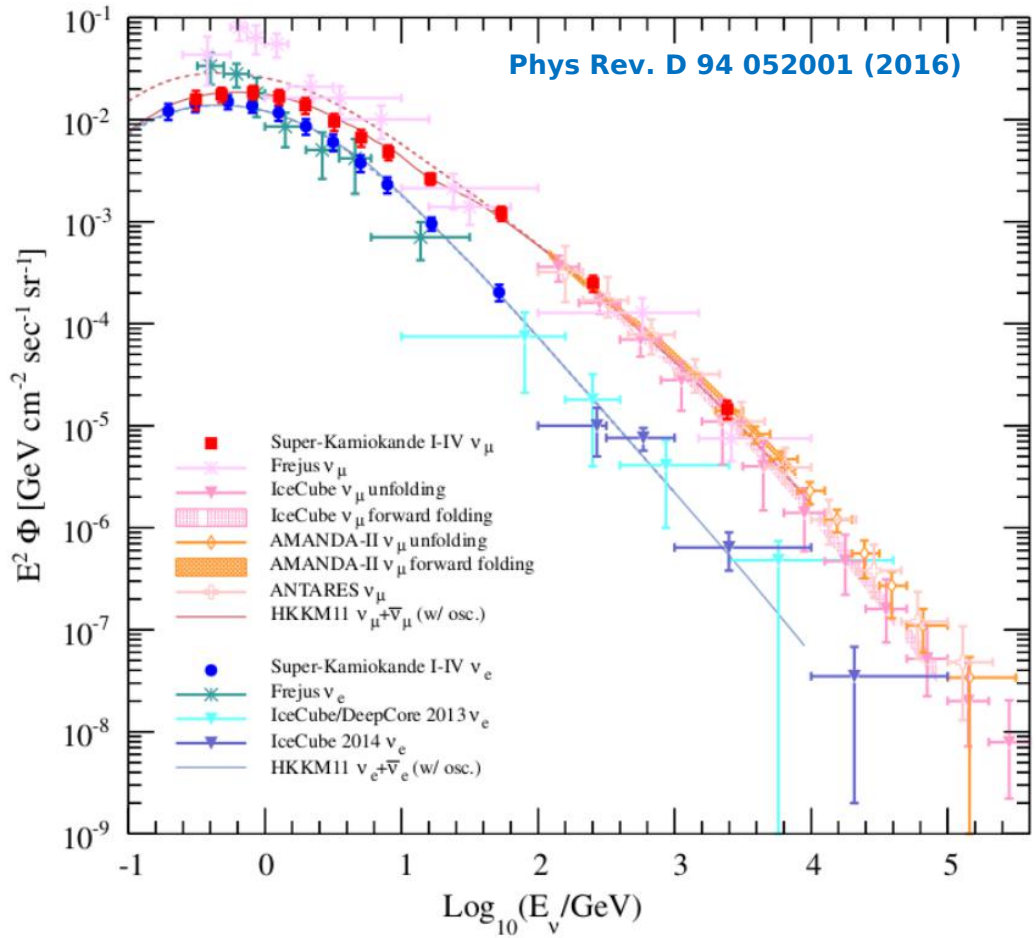


Atmospheric neutrino background



Atmospheric neutrino:

Irreducible background to astrophysics searches



Muon neutrino dominate in atmospheric neutrino flux

- By more than factor ~10 at > TeV energies
- Thus atmospheric background is larger for track channel

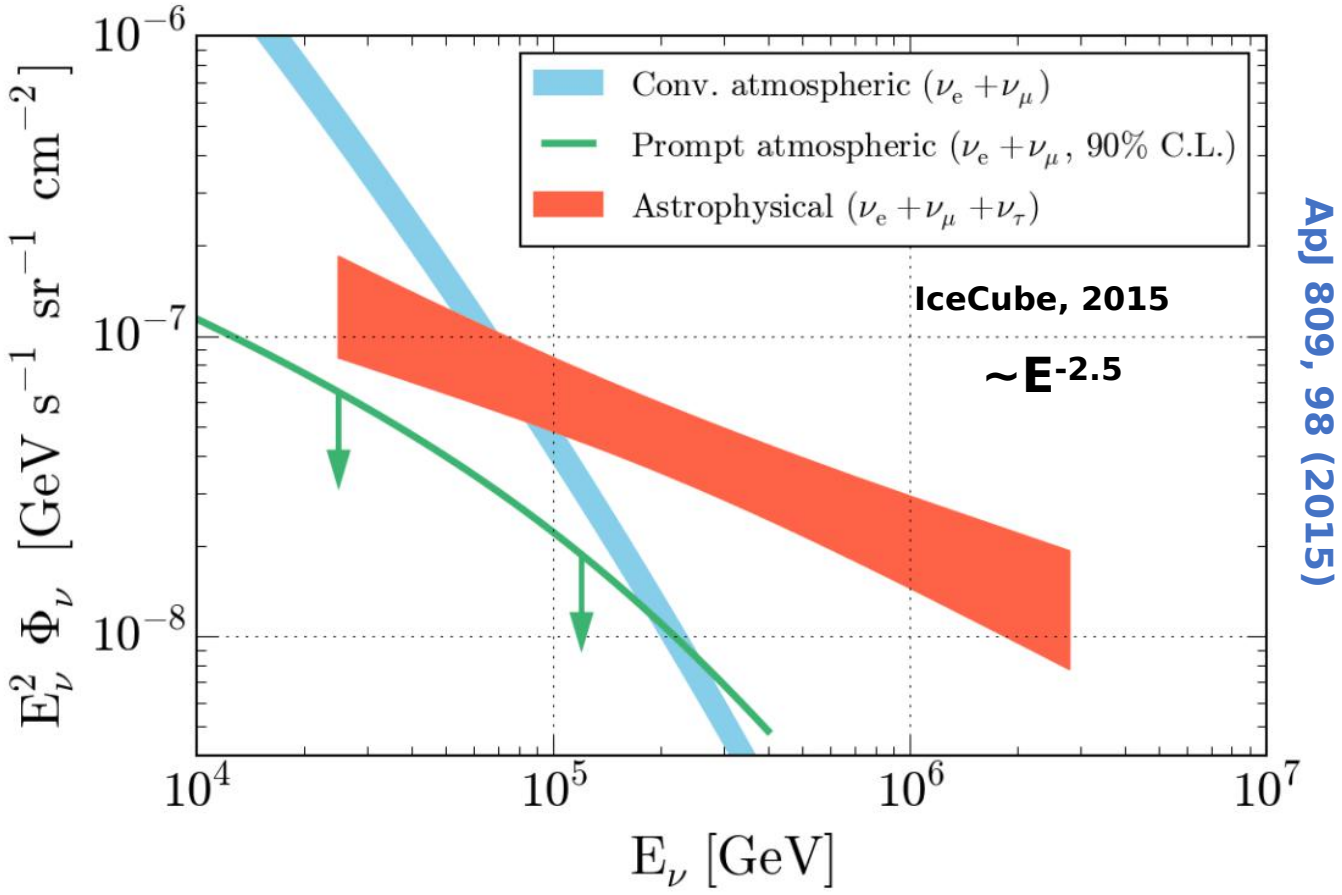
Atmospheric neutrino - “standard candle” for neutrino telescope

- Atmospheric neutrino flux measurement is the first measurement performed at LVNT

Backgrounds

Spectrum slope of atmospheric neutrino ~$E^{-3.7}$ while that of astrophysical neutrino ~$E^{-2.5}$

- Background can be reduced by a cut on event energy
- Or use energy distribution likelihoods
- Optimised for each analysis



ApJ 809, 98 (2015)

Detector effective area

LVNT effective area defines the neutrino event rate

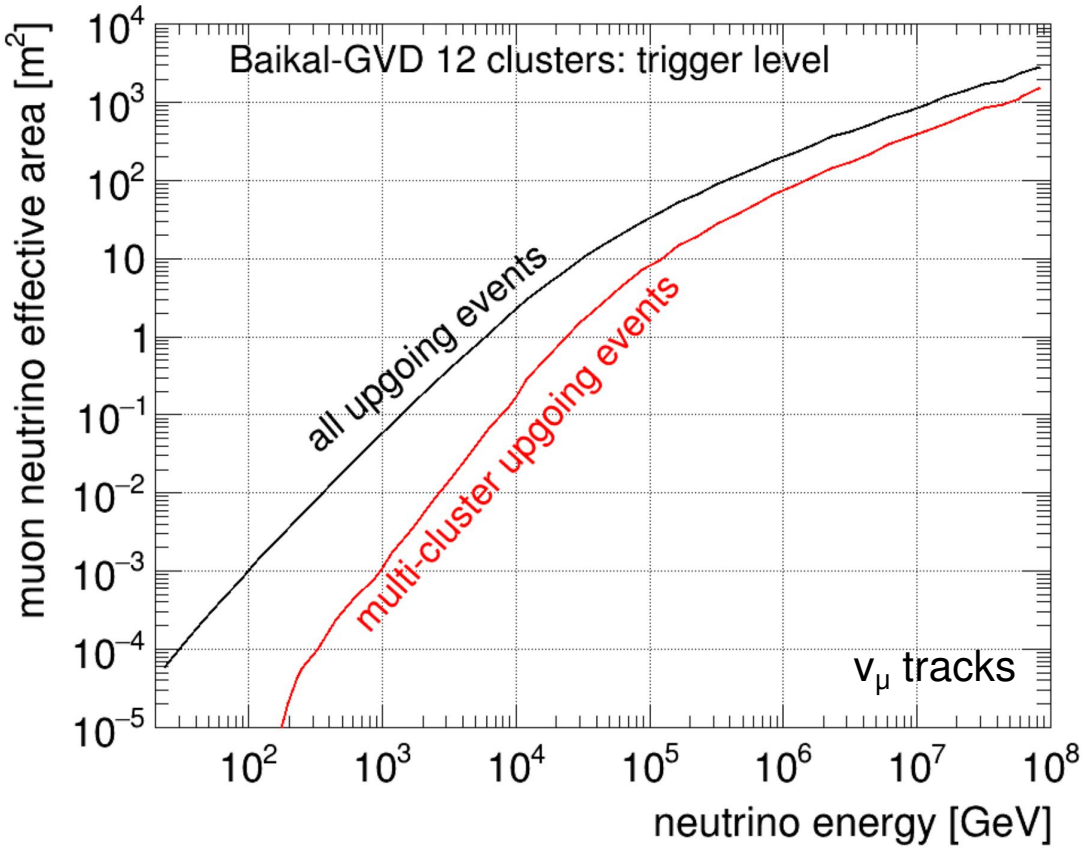
Effective area: an equvalent area of the telescope which detects 100% of incoming particle flux

Neutrino
event counting rate: $R(s^{-1}) = \Phi_\nu A_{eff}$

neutrino flux — **effective area**

Effective area depends on
- Detection channel
- Instrumented volume of the telescope
- OM sensitivity
- Water transparency
- Density of optical modules
- Event selection requirements

ν_μ trigger-level effective area of Baikal-GVD



Detector effective area

Muon neutrino effective area is larger due to muon propagation range

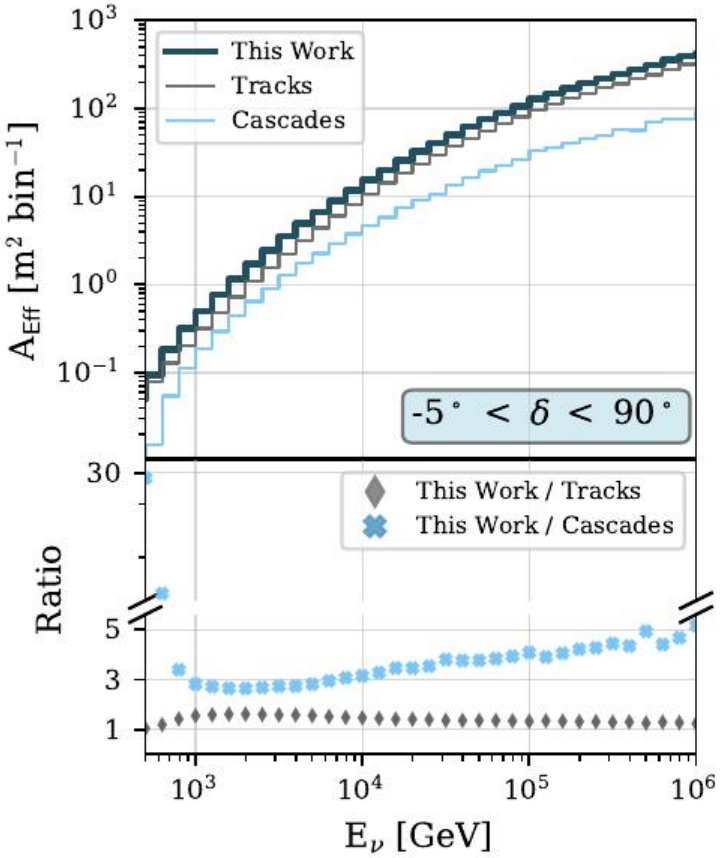
- Problematic detection of downgoing events due to muon background

Full sky can be observed in cascades as starting events inside the detector

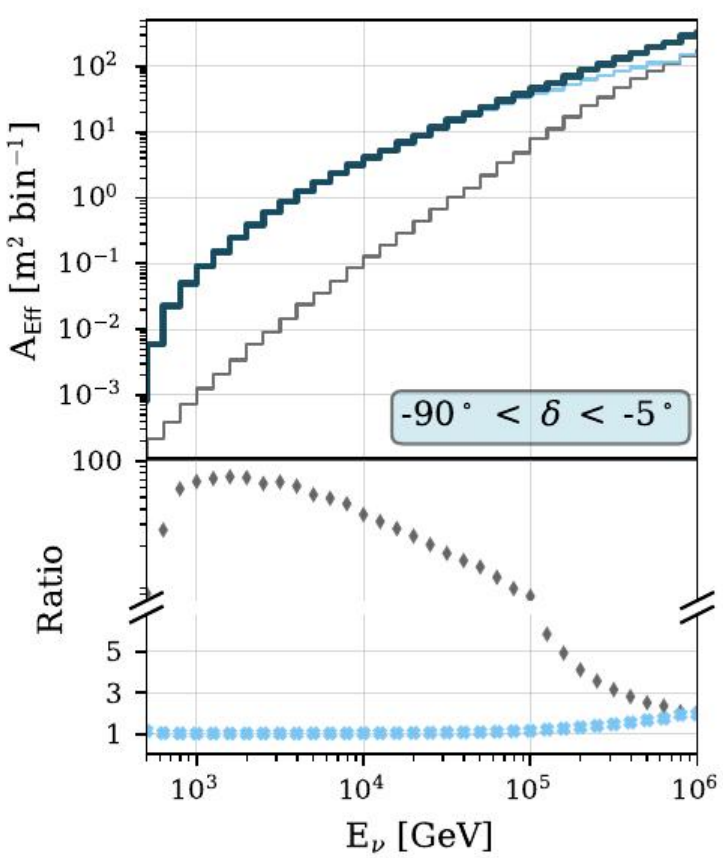
- Veto on through-going downgoing muons

IceCube effective area for various event types

upgoing events



downgoing events



Detector effective area

Experiments develop so-called “event selections” defined by

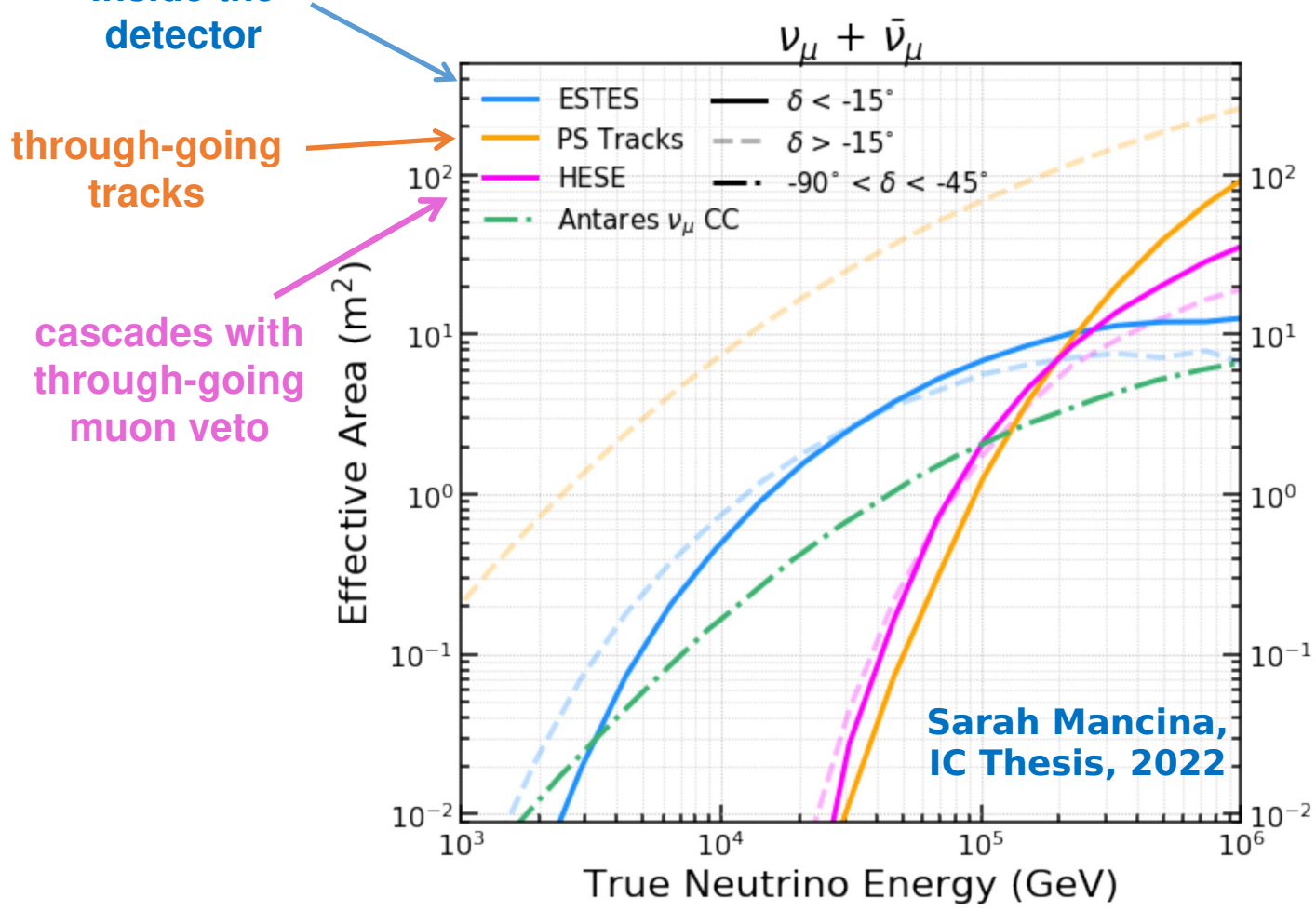
- Detection channel
- Reconstruction algorithms
- Selection algorithms and cuts

Each step in applied data reduction algorithms reduce the effective area

Each event selection is characterised by its own effective area

Further analysis can further reduce the effective area

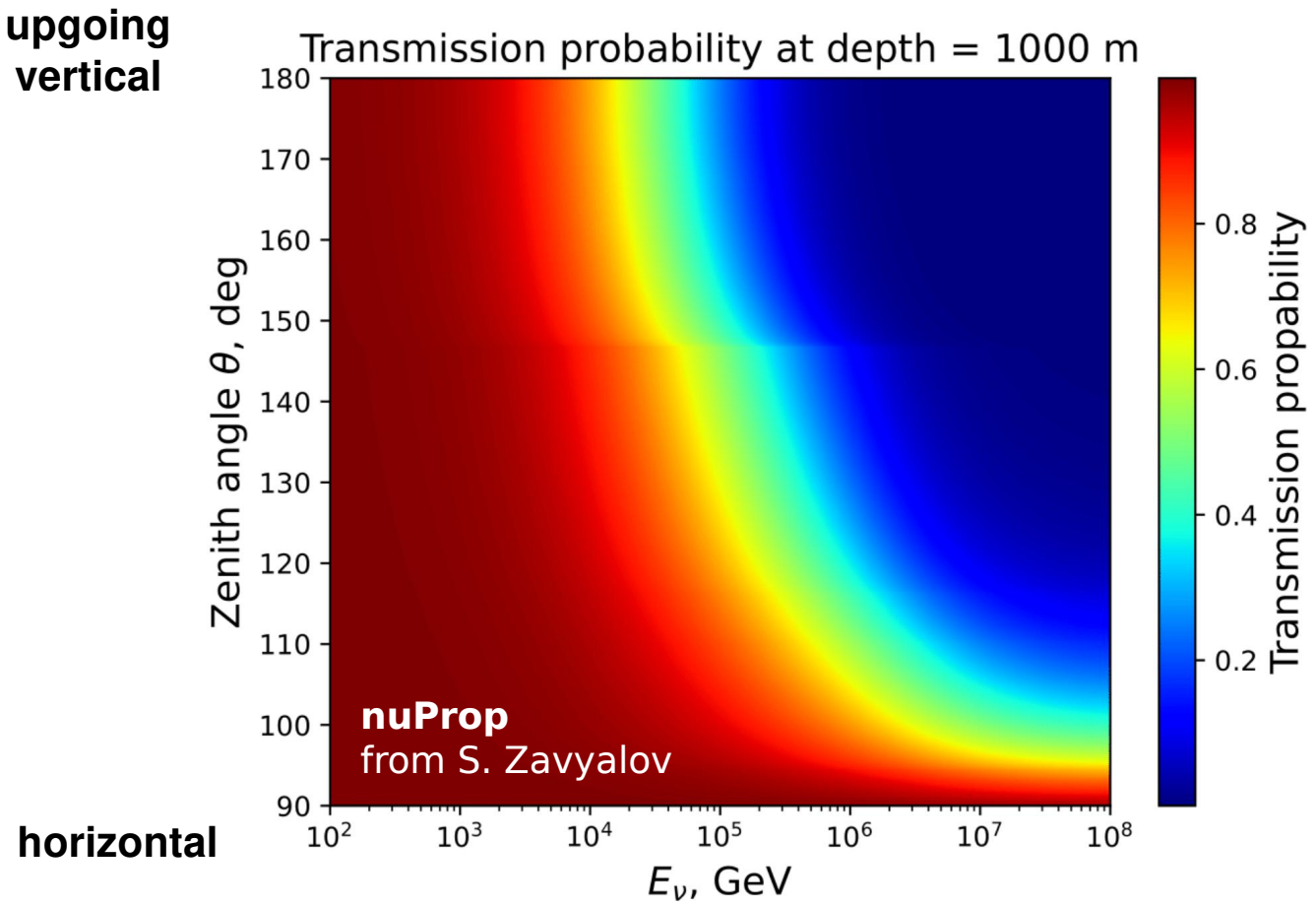
ν_μ effective area for some IceCube event selections



Neutrino propagation through Earth

Earth is not fully transparent
for high-energy neutrino

E > 100's TeV neutrino are downgoing or
nearly-horizontal

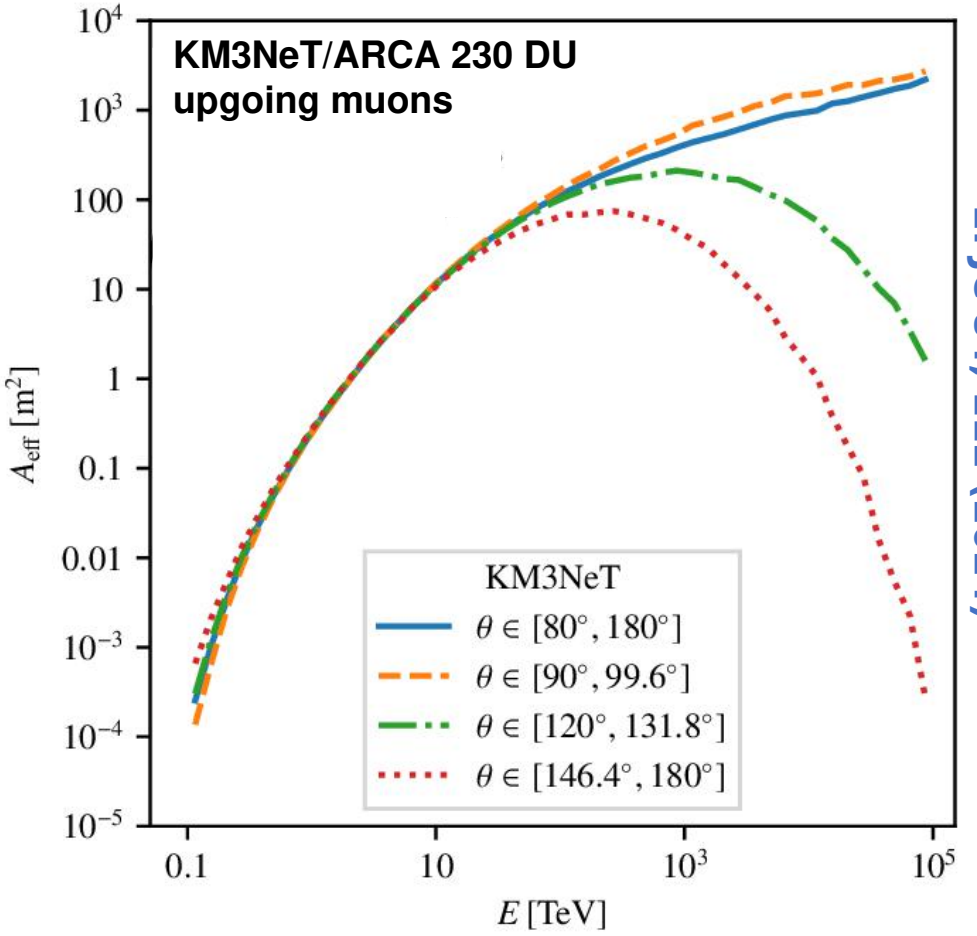


Earth as a part of the neutrino telescope

Absorption in Earth should be taken into account for realistic effective area estimation

Impact on effective area at highest energies

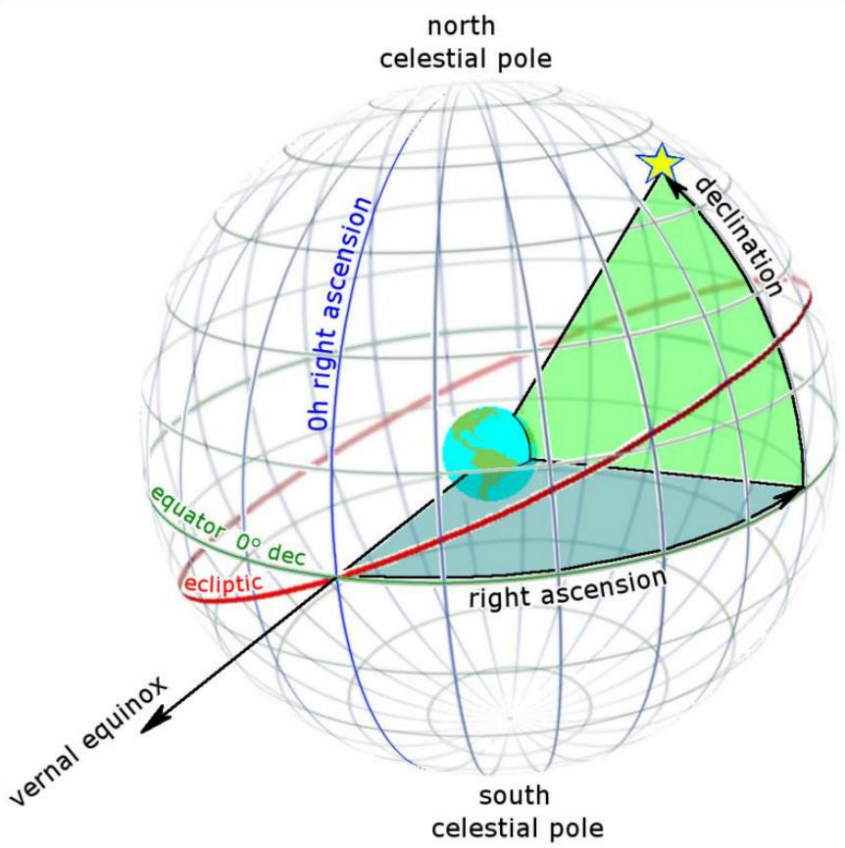
Best 100's TeV - PeV muon detection: nearly-horizontal tracks

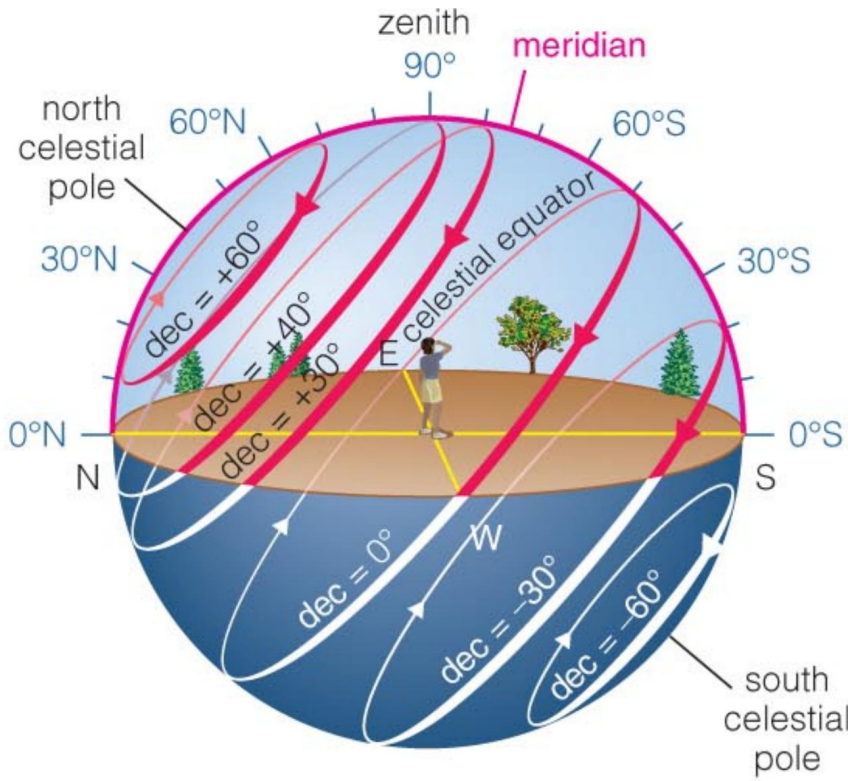


EPJC 84, 112 (2024)

Equatorial coordinate system

Right Ascension (RA) and declination (dec) are defined wrt. the Earth equator plane





- **RA:** angle wrt the vernal equinox direction in equatorial plane (0-24h)
- **dec (δ):** angle between equatorial plane and direction to the star

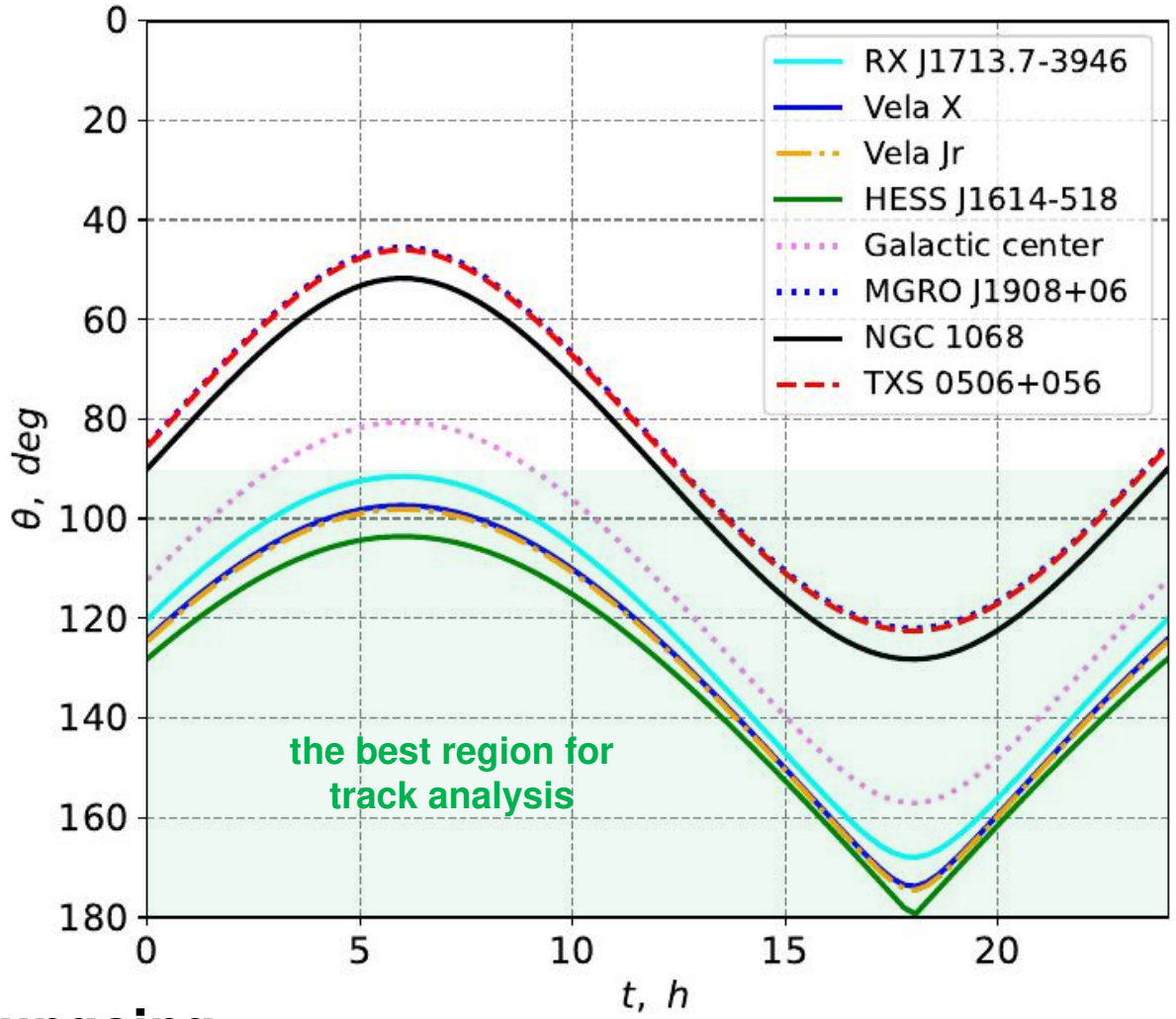
Stars revolve daily around celestial poles
Daily trajectory in zenith angle is defined by declination

Daily movement of sources

Due to daily movement sources are visible just fraction of time for particular detection channel

downgoing

Baikal-GVD location

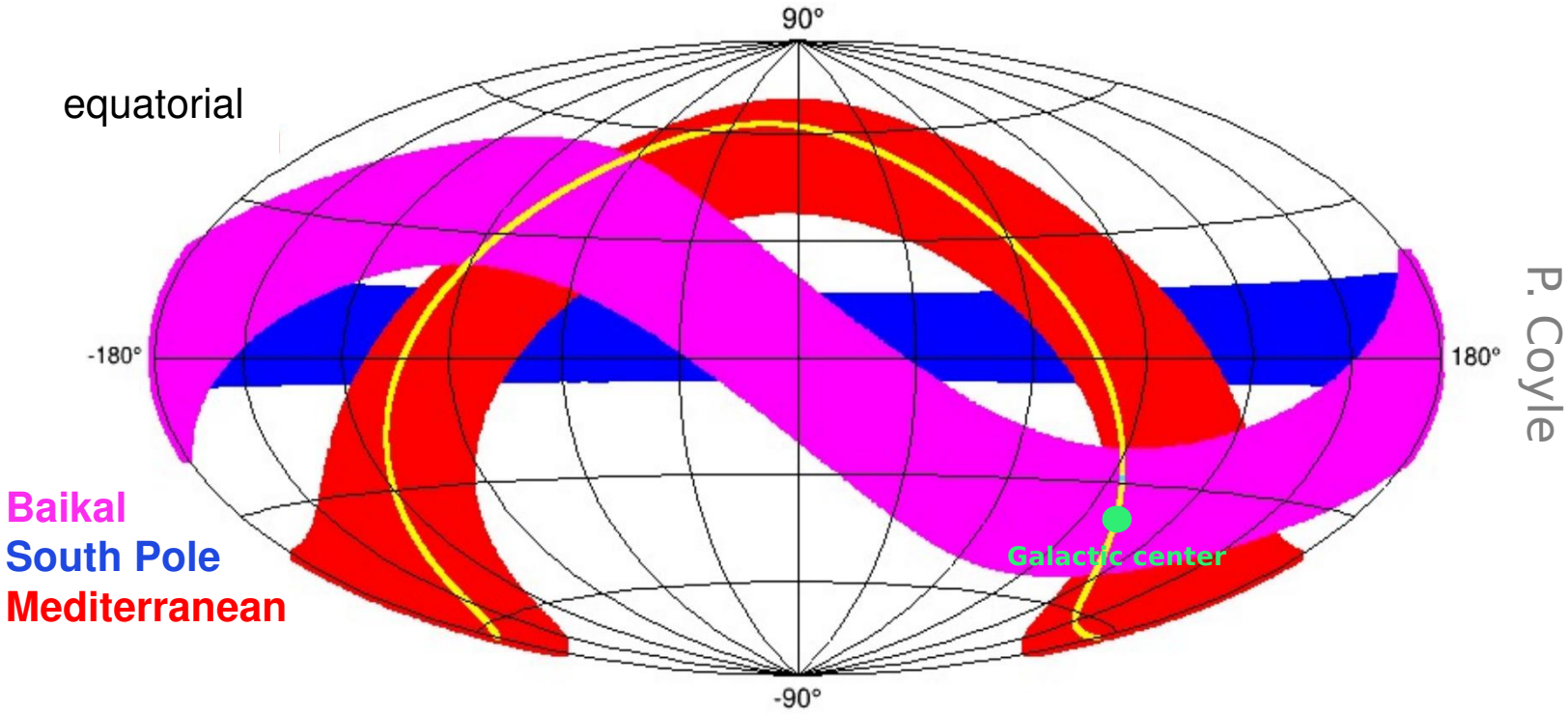


upgoing

Neutrino telescope sensitivity areas

Best sensitivity areas of different telescopes compliment each other

Instantaneous best sensitivity area in nearly-horizontal tracks:



Bands rotates with the Earth’s rotation (excepth for the South Pole)

Neutrino telescopes development timeline

Baikal
South pole
Mediterranean
Pacific, Canada
South China

megaton -scale detectors

gigaton -scale detectors

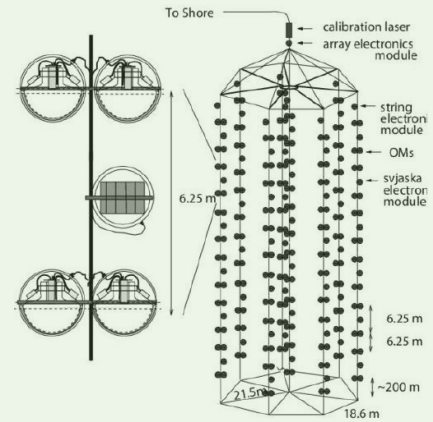
Future
O(10km³)
generation

Baikal-HUNT

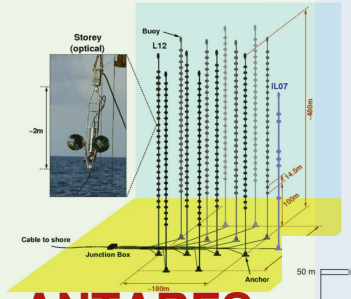
IceCube-Gen2

TRIDENT

First
expeditions at
the
Baikal Lake

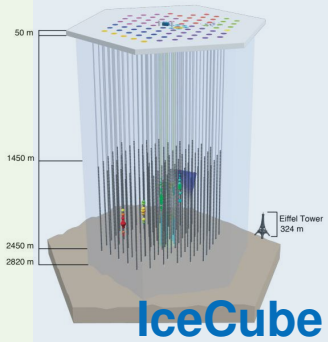


NT-200

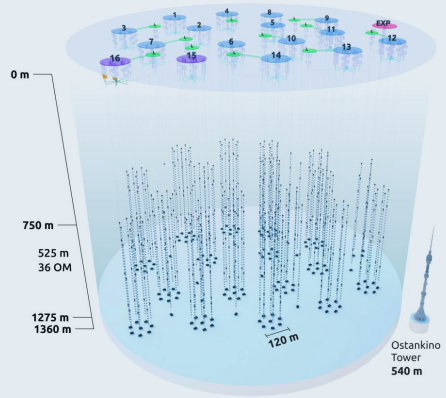


ANTARES

AMANDA



IceCube



Baikal-GVD

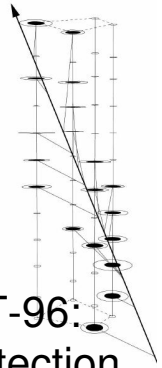
KM3NeT

P-ONE

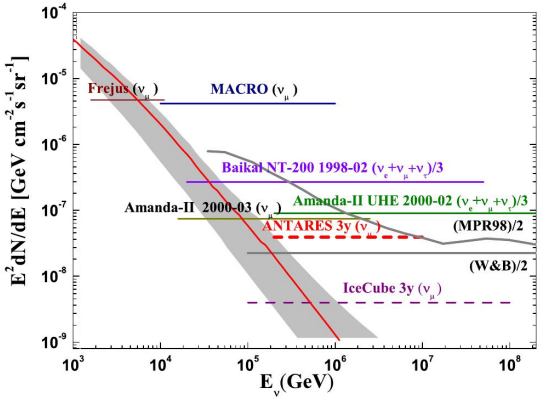
1980 1990 2000 2010 2020 2030

DUMAND

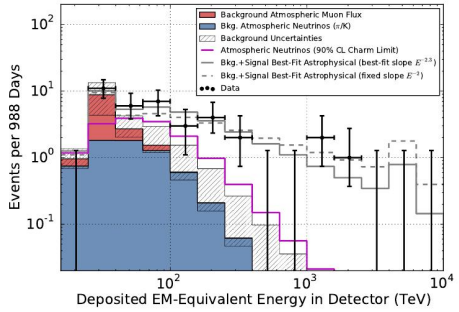
Prototype tests



Baikal, NT-96:
first ever detection
of neutrino event,
proof of principle



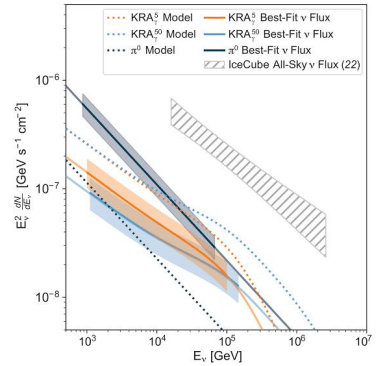
First astrophysical
diffuse flux limits



IceCube, 2013:
discovery of diffuse flux

IceCube ν
sources:
TXS 0506
NGC 1068

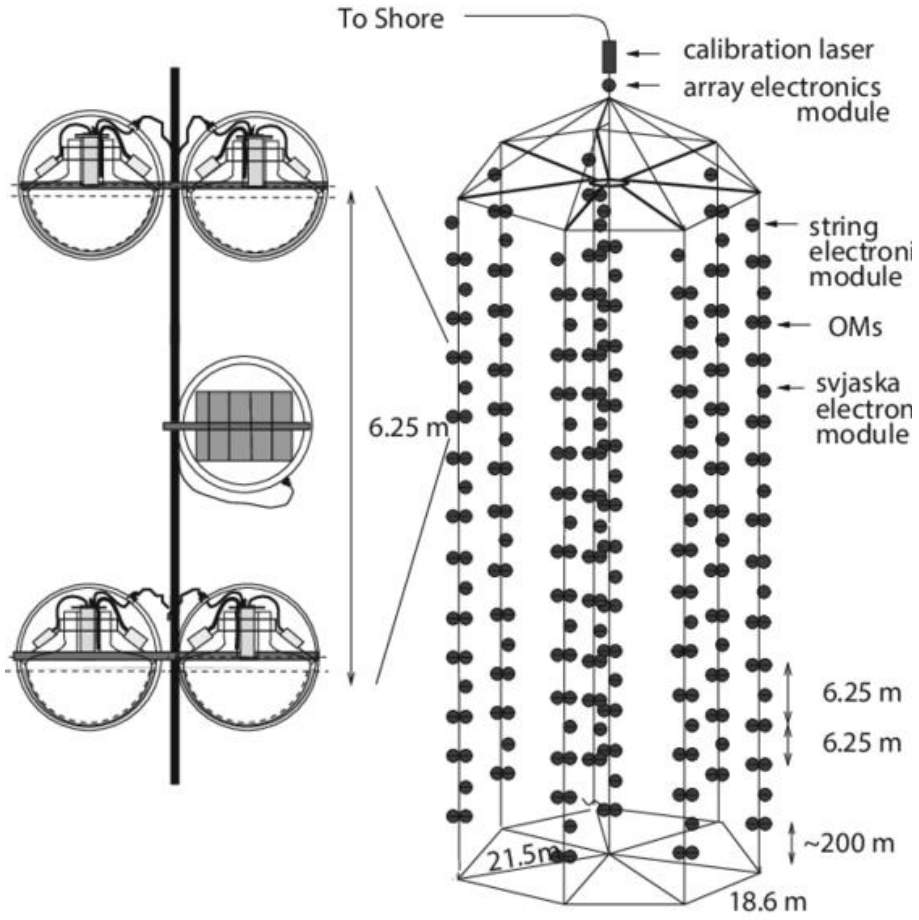
IceCube, 2023:
evidence of galactic
diffuse flux



NT-200 at Lake Baikal

NT-200: first full-scale large-volume neutrino telescope

Fully-deployed in 1998, later upgraded to NT-200+ with additional strings



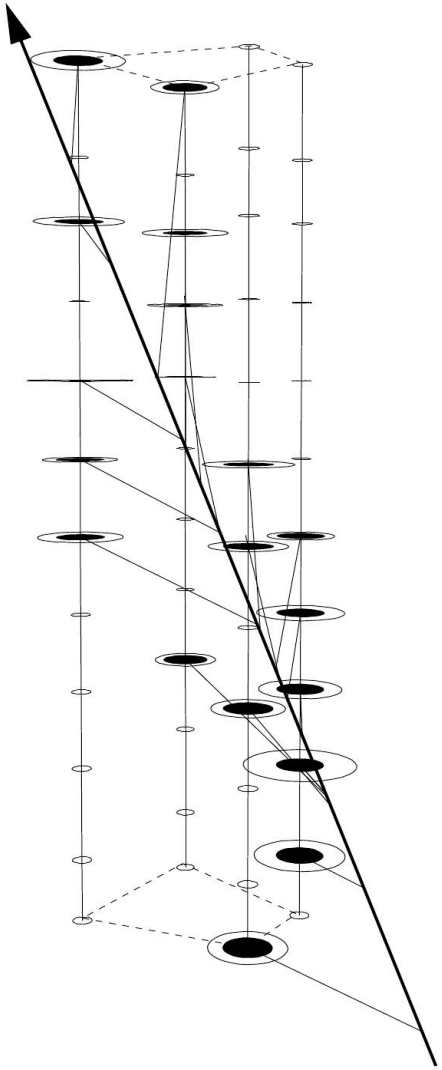
First-ever upgoing muon events detected by unaccomplished 3-string detector in mid 1990-s (NT-36, 96)

- Succesfull proof of principle

Rather small detector

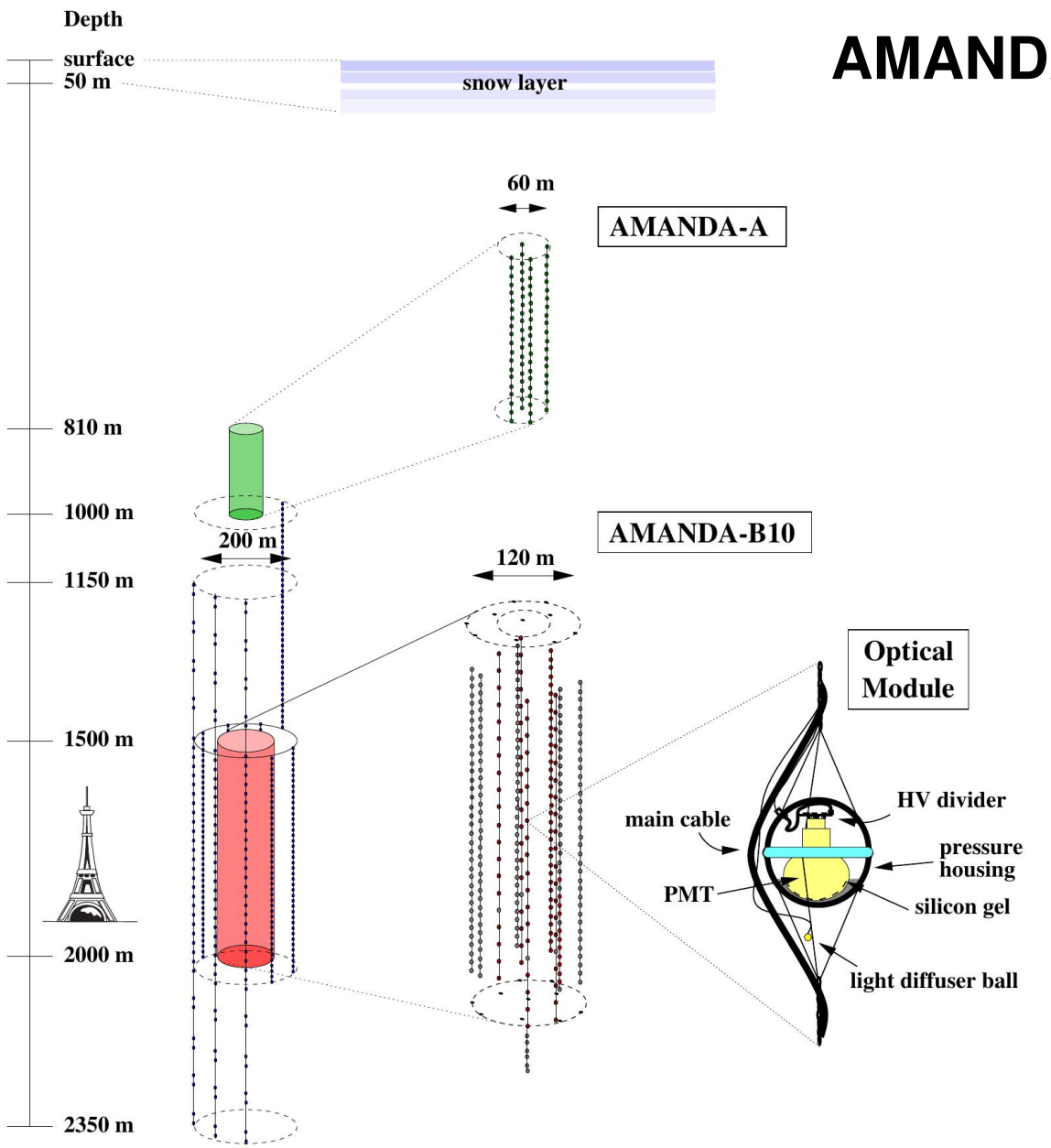
- Height: 72m
- Diameter: 43m

Instrumented volume: ~100 kt



One of the first neutrino candidate events
NT-96, 1996
[arXiv:astro-ph/9705244]

AMANDA at South Pole



AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

End of 1980: idea to build
telescope in Antarctic Ice Shield
F. Halzen and J.G. Learned "High energy neutrino detection in deep polar ice" (1988)

First tests of PMTs in polar ice in 1991

First array at 800-1000m depth in 1993/94: AMANDA-A
- Discovered too strong light scattering

Array at 1500-2000m gradually contructed until 2000

Instrumented volume: ~6 Mt

Basis for the IceCube neutrino telescope

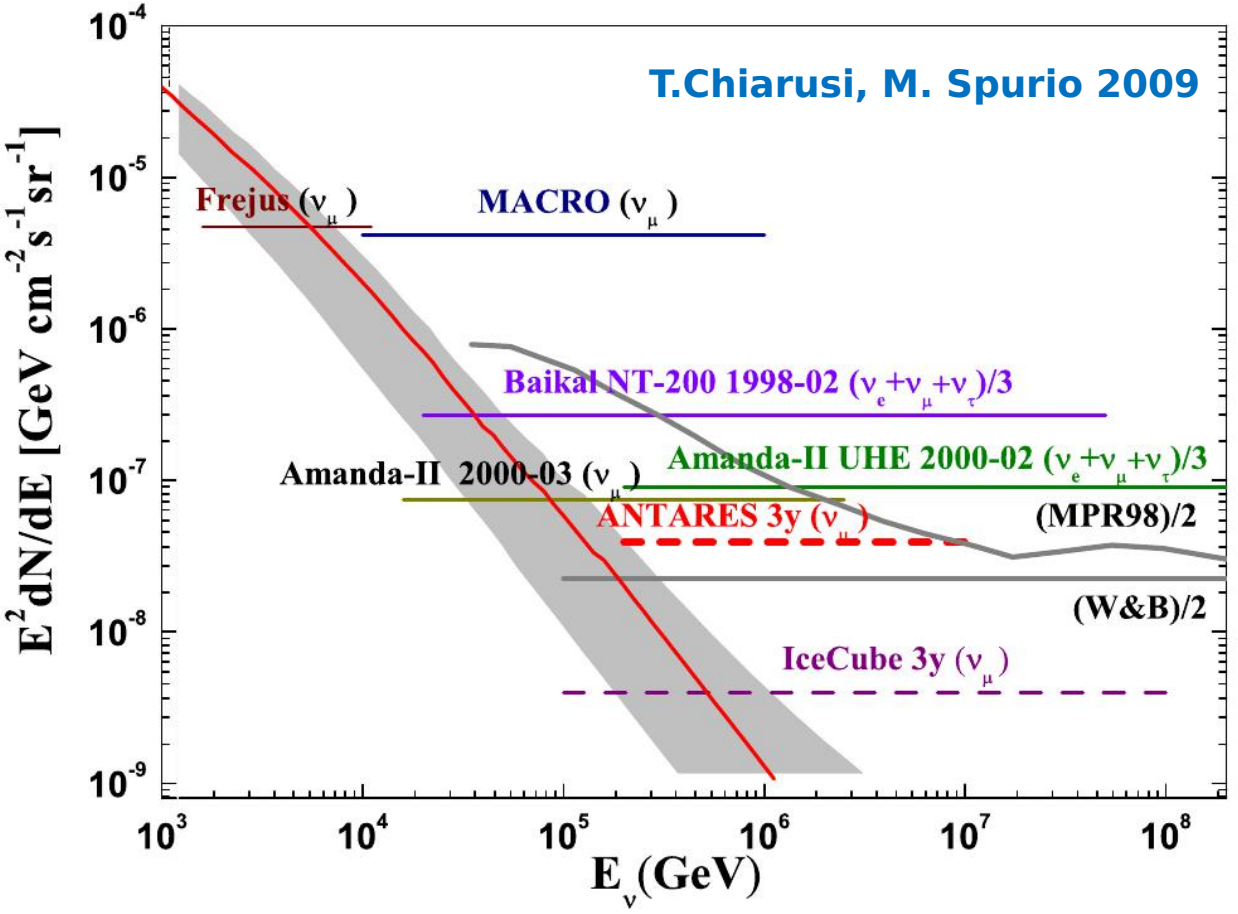
Useful fictional reading:
Mark Bowen "The telescope in the ice" (available in Russian)

Approaching the neutrino diffuse flux

First constraints on diffuse neutrino flux from NT-200

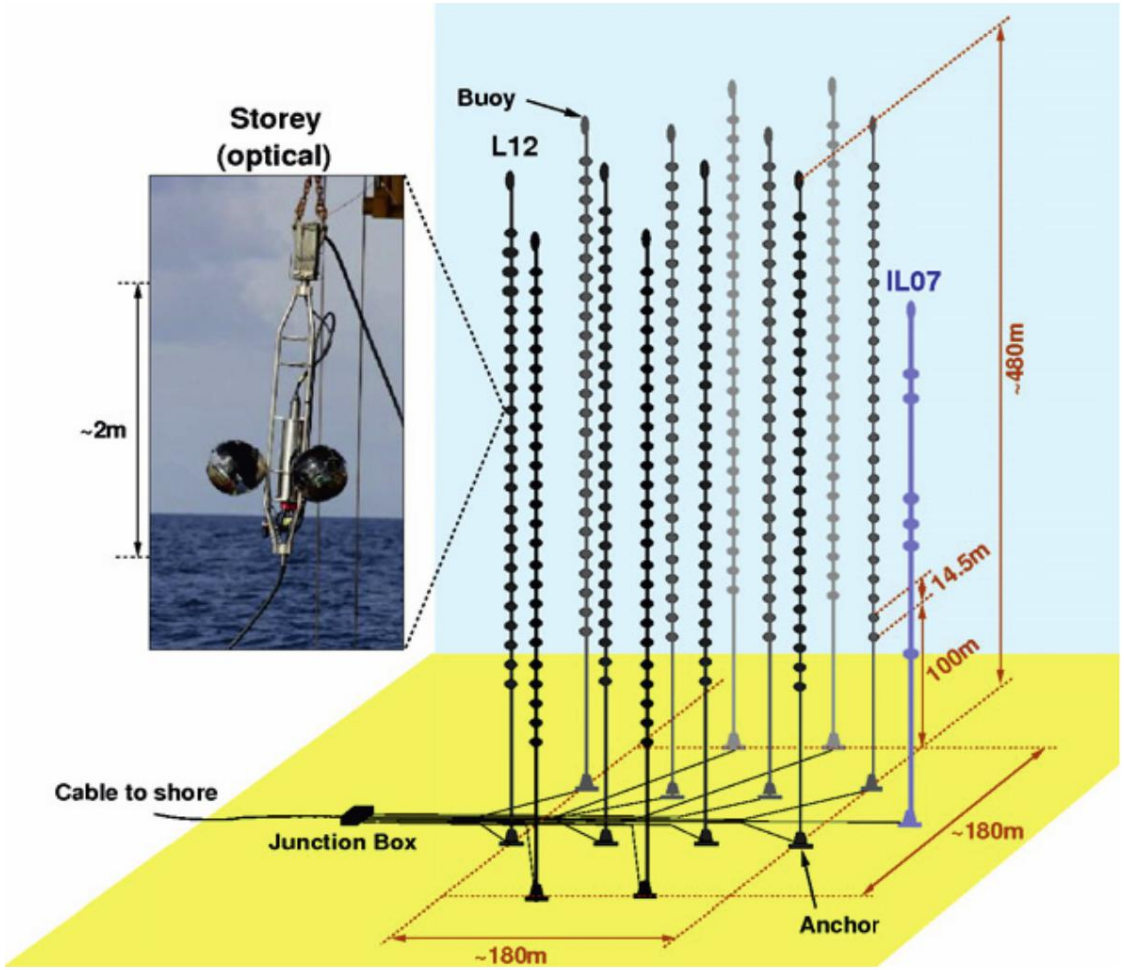
Followed by AMANDA

Early diffuse flux constraints



Sensitivities from ANTARES and IceCube are shown in dashed lines

ANTARES



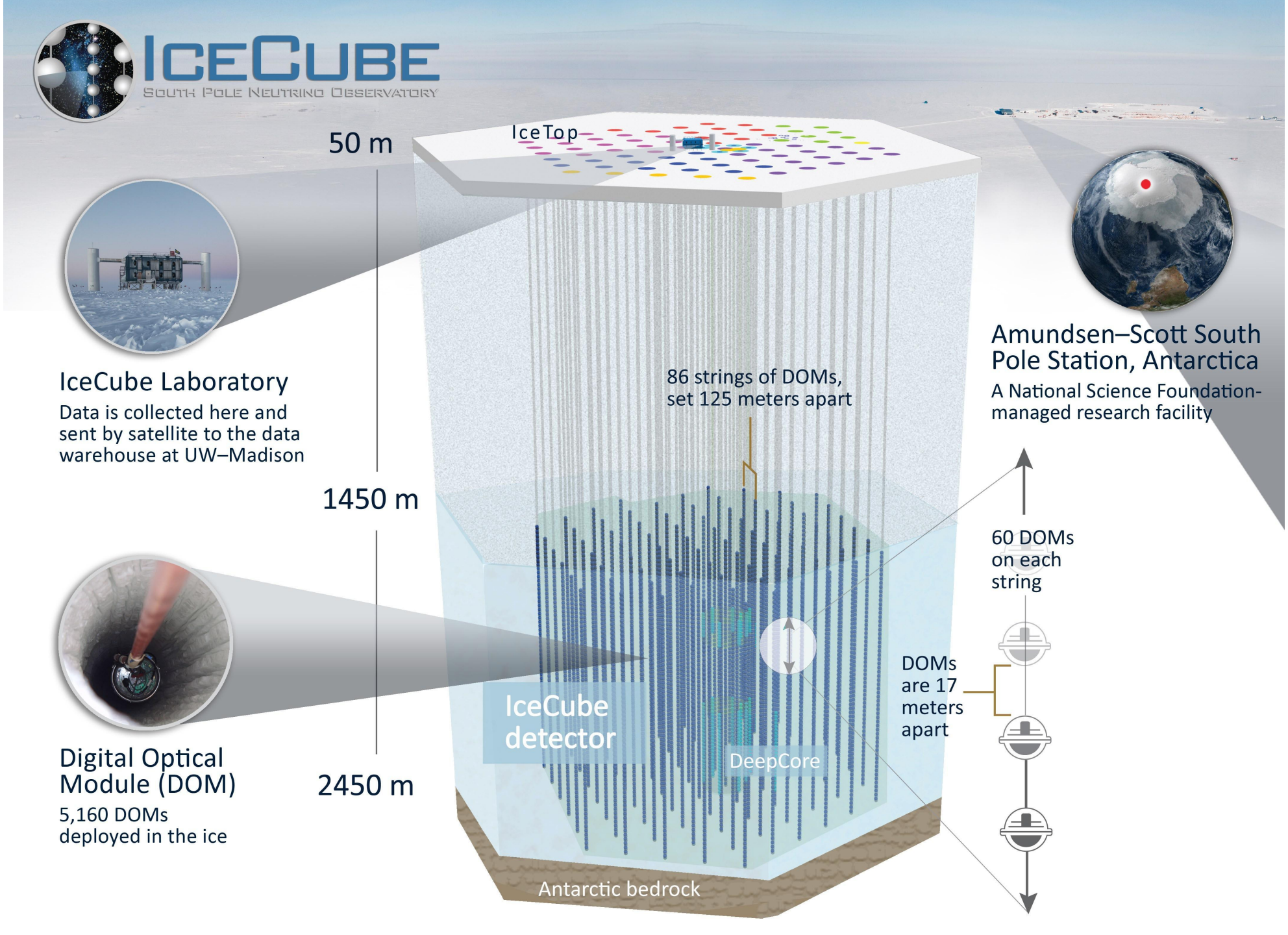
depth: 2475m

Proposal in 1999
Started full-scale operation in 2008
Shut down in 2022

12 strings with 25 “storeys”
Each storey holds 3 PMTs

Instrumented volume: ~12 Mt

ANTARES was a succesfull project although not reaching volume required for astrophysical neutrino detection

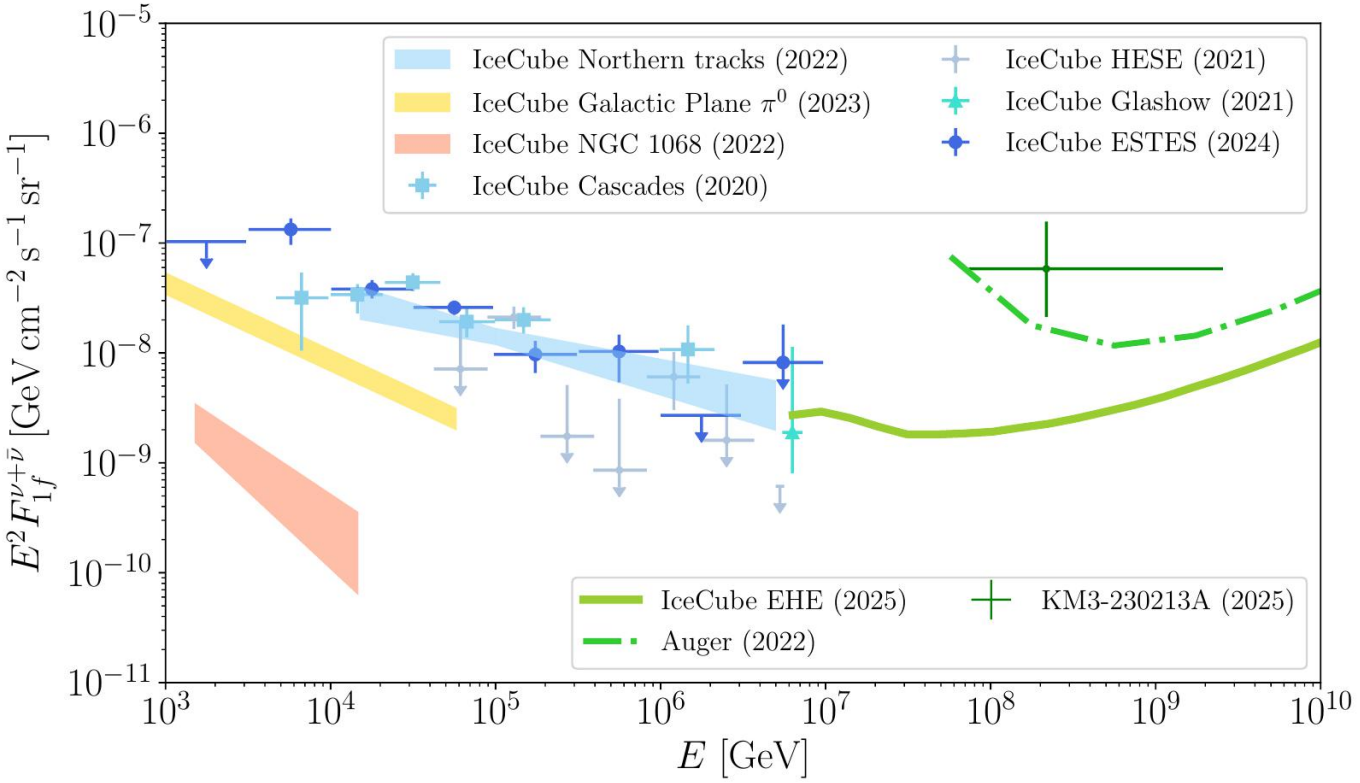

IceCube
South Pole Neutrino Observatory
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

Selected neutrino astrophysics results

What we know from IceCube

IceCube results: first steps in high-energy neutrino astronomy

- Diffuse atsrophysical neutrino flux exists!
- Evidence that ~10% of the flux comes from our galaxy
- <1% of the flux comes from few potential extragalactic sources
- Most of the flux remains unexplained



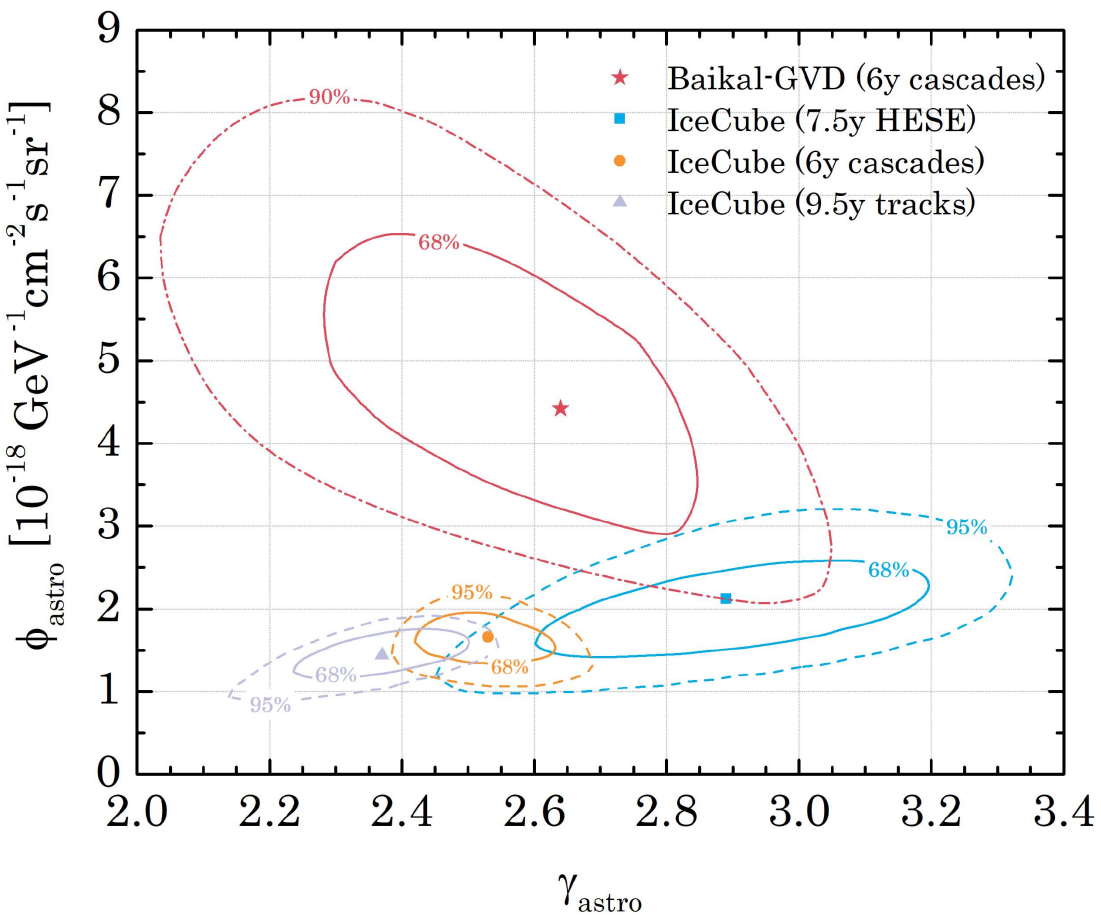
Most significant sources to date

IceCube:

- NGC1068: 4.8σ
- Milky Way Galaxy: 4.8σ
- TXS0506+056: 3.5σ

Many of these results are about to be verified and refined with new detectors entering the game such as Baikal-GVD and KM3NeT!

Baikal-GVD diffuse flux constraints



Diffuse flux was measured in upgoing cascades

- Significance: 5.1σ
- First non-IceCube diffuse flux observation

Best-fit parameters:

$\gamma_{astro} = 2.64$

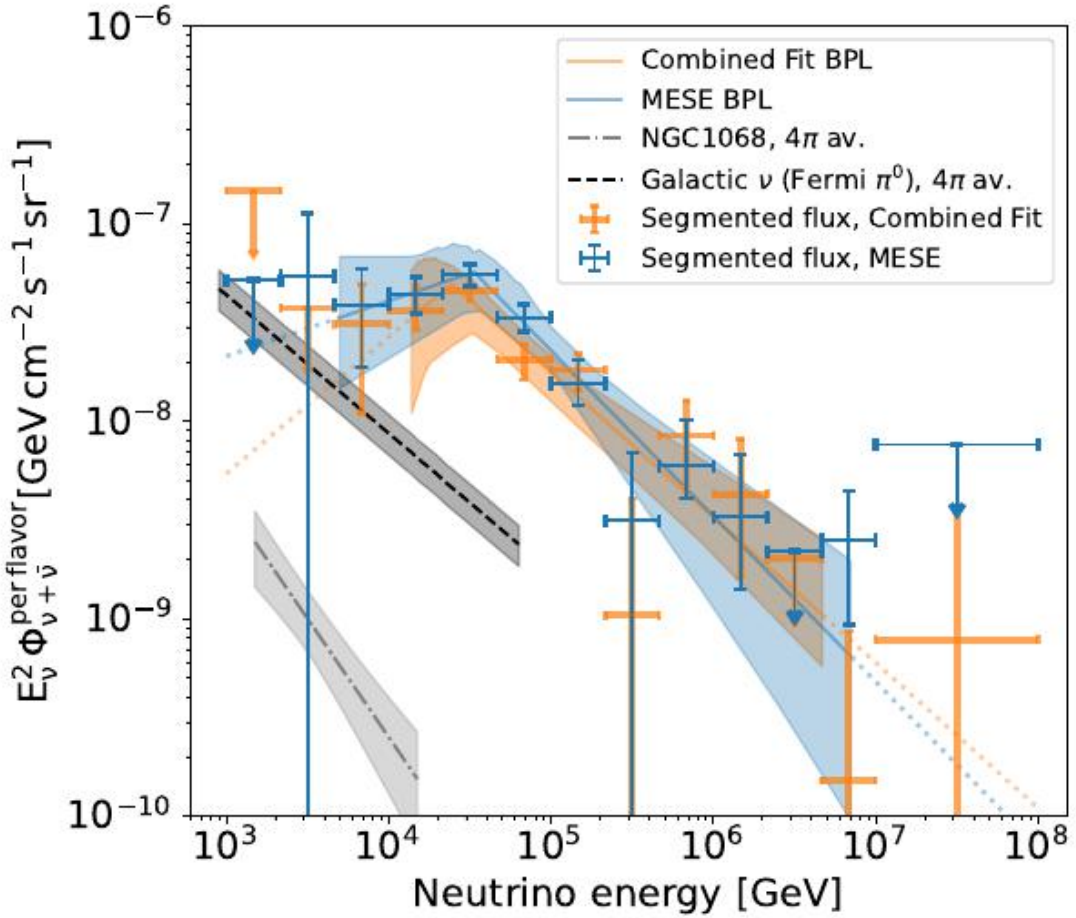
$\varphi_{astro} = 4.42$ (10^{-18} GeV^{-1} cm^{-2} s^{-1}sr^{-1})

The spectrum index is in agreement with IceCube measurements

Spectrum normalisation is in general larger than IceCube

IceCube evidence for spectral break

Evidence for a spectral break in diffuse flux **Phys. Rev. Lett. 136, 121002 (2026)**



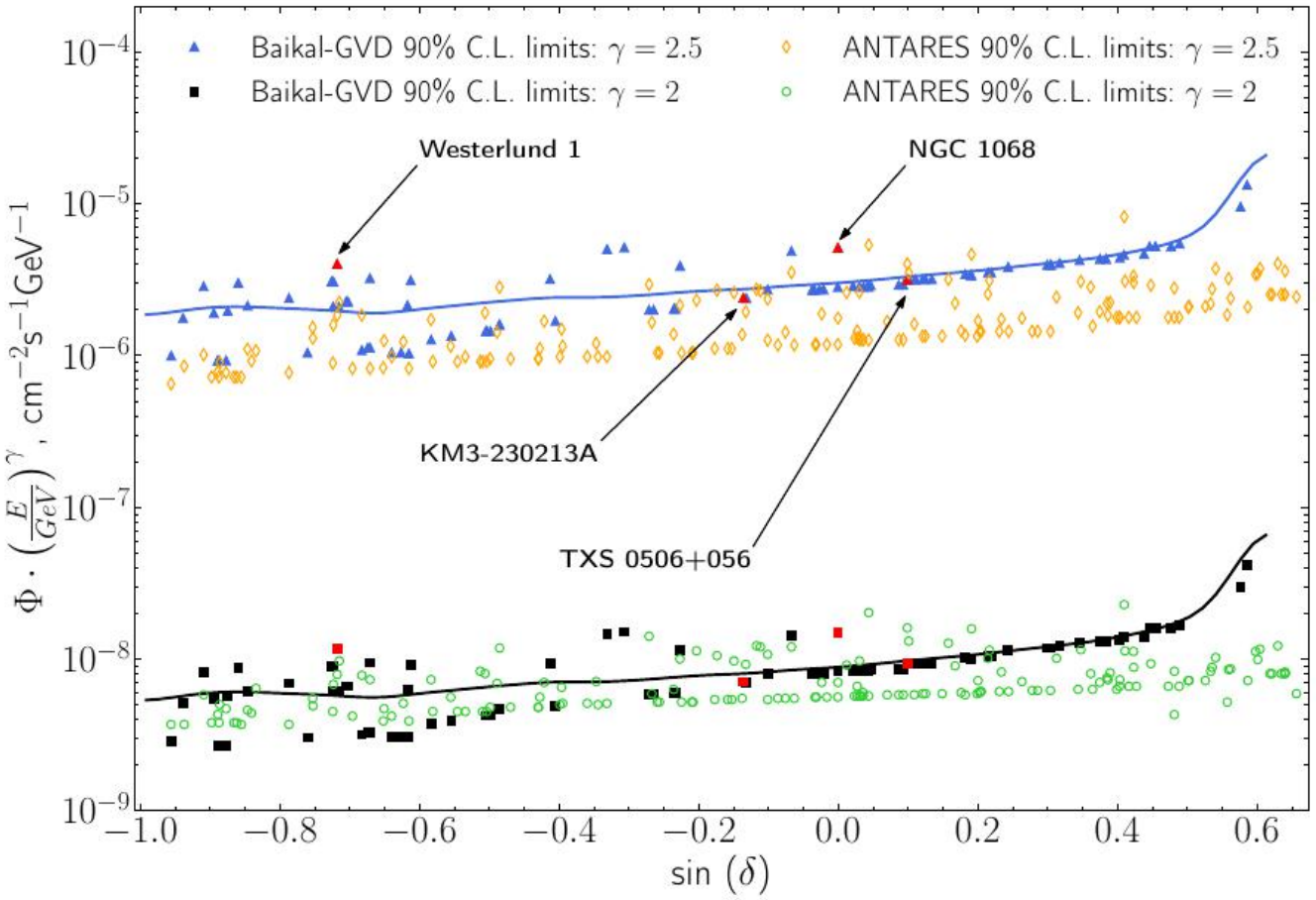
Fit using
- Track+cascade sample (CF)
- Medium Energy Starting Events sample (MESE)

Evidence at the level of
- 4.7σ for CF
- 4.4σ for MESE

		BPL $\left[\phi_{0,\text{broken}}\left(\frac{E_\nu}{E_{\text{break}}}\right)^{-\gamma_{\text{BPL}}}\right]$
		$\phi_0 = 2.28^{+0.22}_{-0.20}$
	CF	$\gamma_1 = 1.72^{+0.26}_{-0.35}$
		$\gamma_2 = 2.84^{+0.11}_{-0.09}$
		$\log_{10}\left(\frac{E_{\text{break}}}{\text{GeV}}\right) = 4.52^{+0.11}_{-0.09}$
4.7σ	$-2\Delta\ln\mathcal{L}$	$= 27.3$
		$\phi_0 = 1.77^{+0.15}_{-0.11}$
	MESE	$\gamma_1 = 1.31^{+0.50}_{-1.21}$
		$\gamma_2 = 2.74^{+0.06}_{-0.07}$
		$\log_{10}\left(\frac{E_{\text{break}}}{\text{GeV}}\right) = 4.39^{+0.09}_{-0.08}$
4.4σ	$-2\Delta\ln\mathcal{L}$	$= 24.7$

First evidence for harder spectrum diffuse neutrino spectrum at < ~30 TeV

Baikal-GVD point source search



Flux limits are comparable to ANTARES 15-year results

Search for point sources using track sample of Apr.2019 - Mar.2024

Point source catalogue of 92 sources

Search cone: 2°

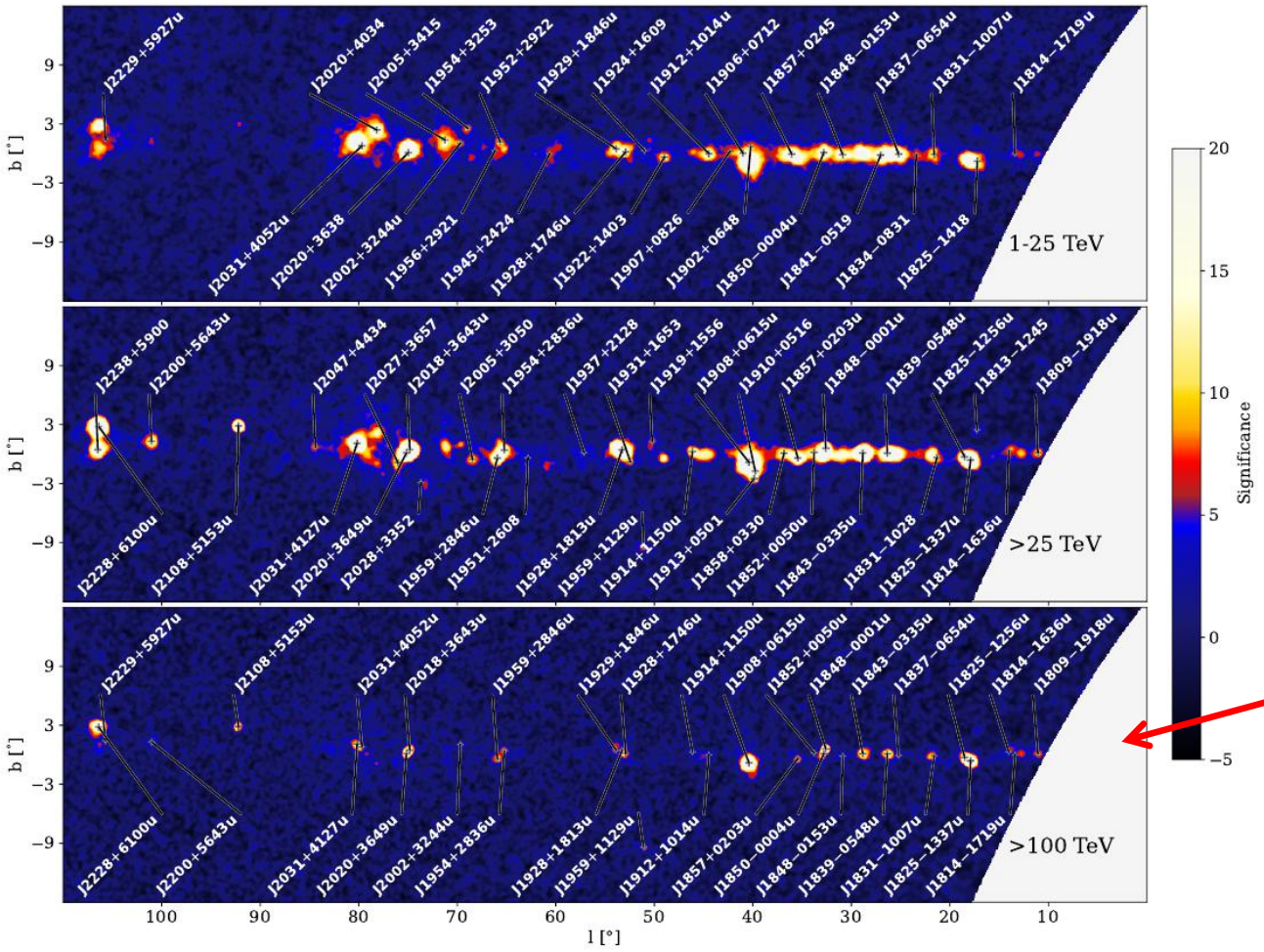
No statistically significant source found

3 coincidences for Westerlund 1 star cluster



13 kpc
from Earth

Galactic neutrinos



Galaxy plane can be studied in VHE gamma-rays

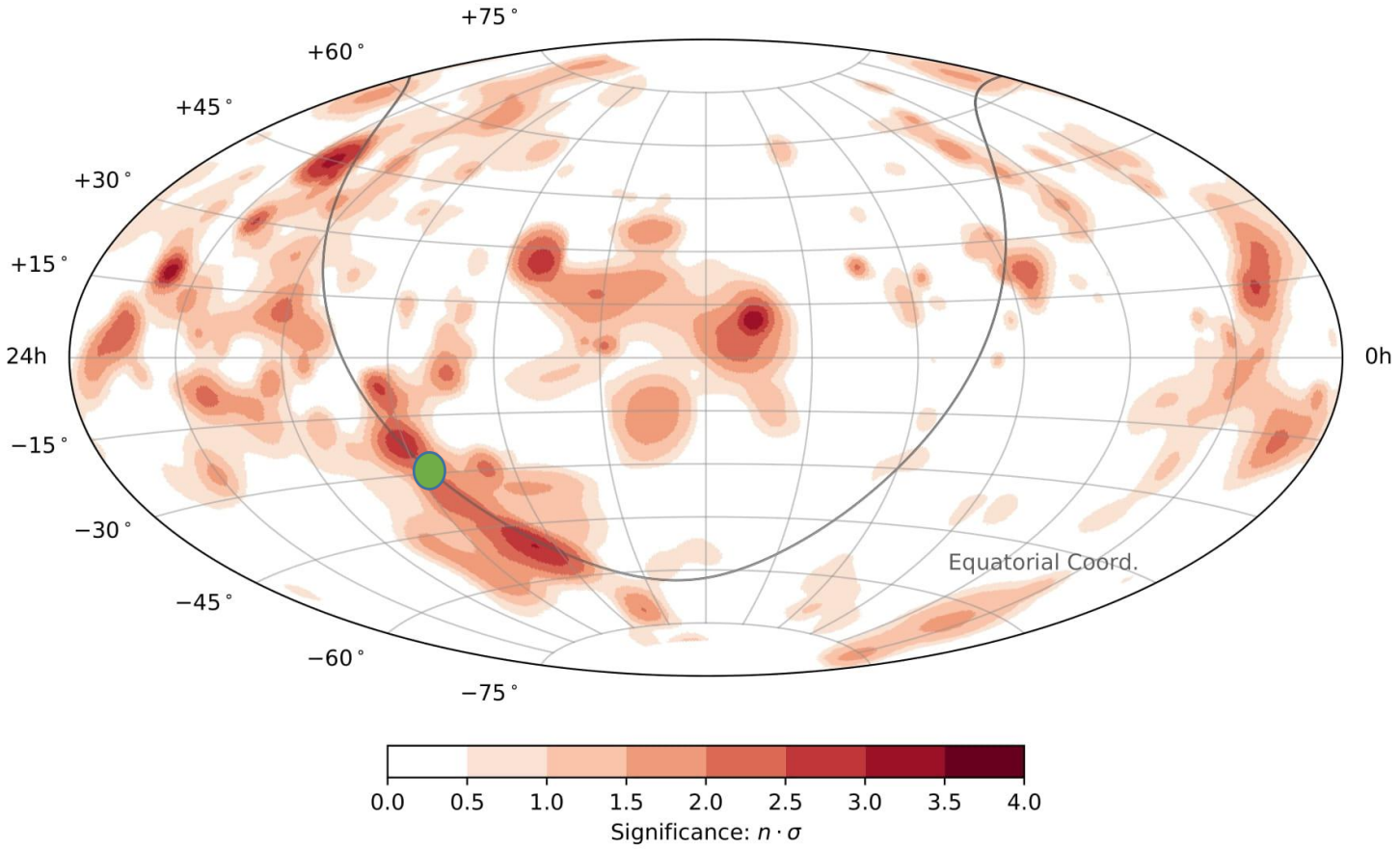
LHAASO catalogue of 2023 includes
43 gamma-ray sources above 100 TeV and 4σ significance

> PeV CR accelerators

Galaxy is full of CR PeVatrons, and neutrino astronomy is a key to understainding their nature

IceCube diffuse galactic flux

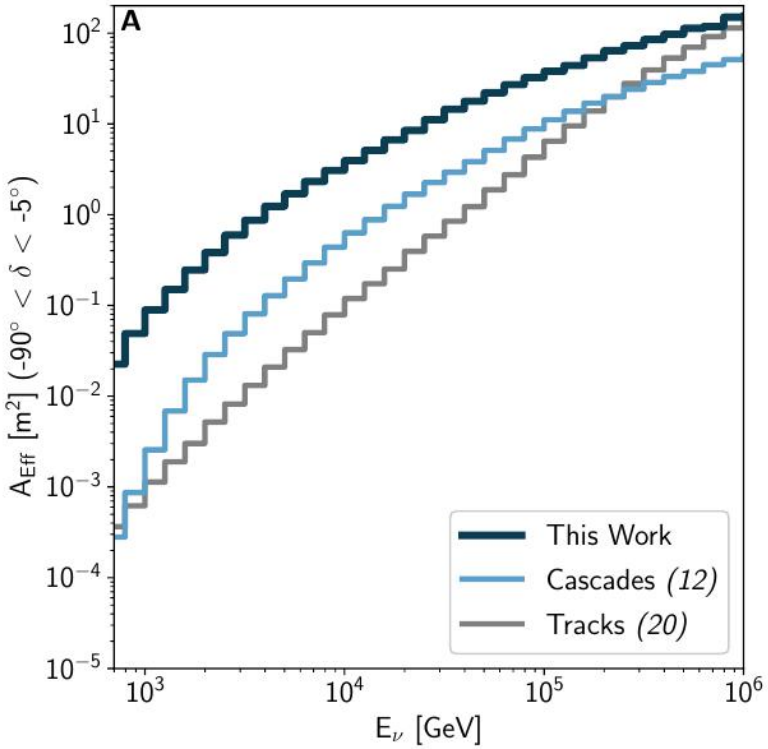
Most of the galactic plane is located in southern sky



For IceCube it can be studied in downgoing events

IceCube galactic neutrino

Impressive effective area improvement



Science 380, 6652, 1338-1343 (2023), arXiv:2307.04427

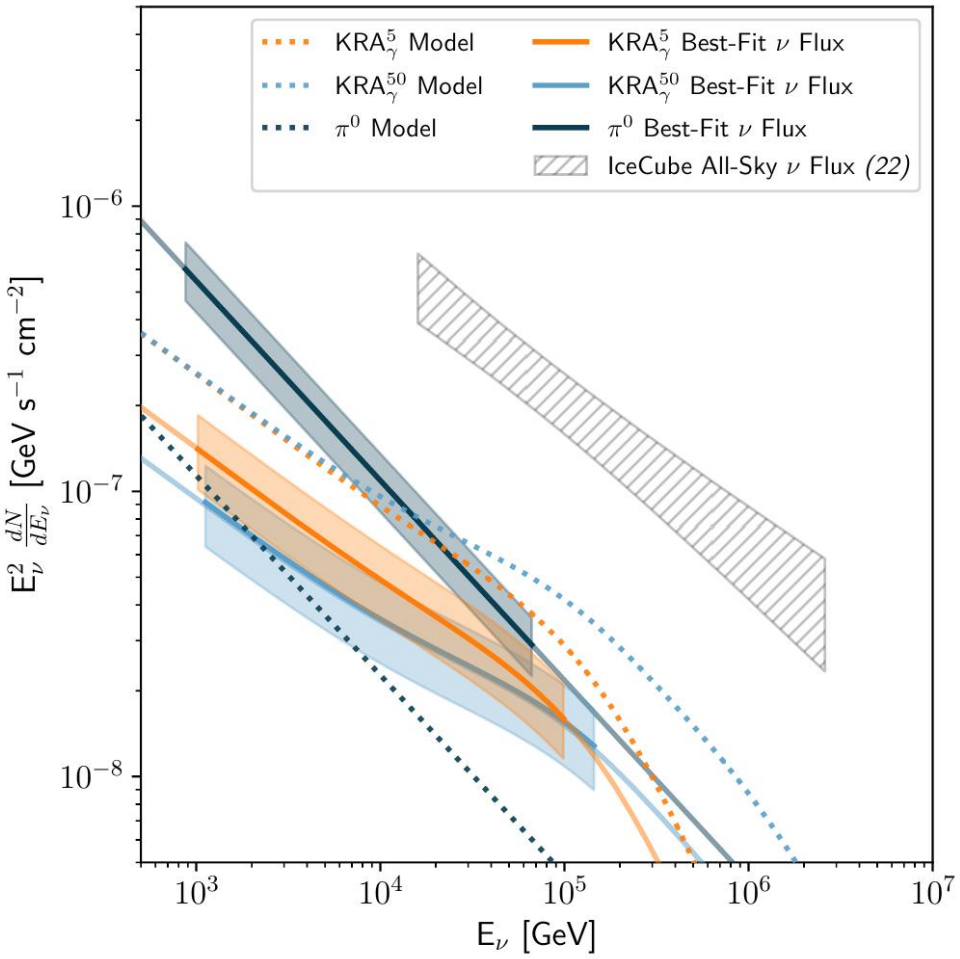
IC search for galactic neutrino in downgoing cascade events

- 10 years, 500 GeV - multi-PeV events
- Active use of machine learning methods
- 20 times improvement in statistics wrt. the previous cascade statistics

With these events test three predefined emission models:

π^0, KRA_γ^5, and KRA_γ^{50}

IceCube diffuse galactic neutrino



Test the significance of spatial templates: emission model covolved with detector acceptance and spatial resolution

Significance 4.71σ, 4.37σ and 3.96σ for π^0, KRA_γ^5, and KRA_γ^{50}

The most significant (π_0): 4.48σ

Galactic point source catalogue search gave no significant results

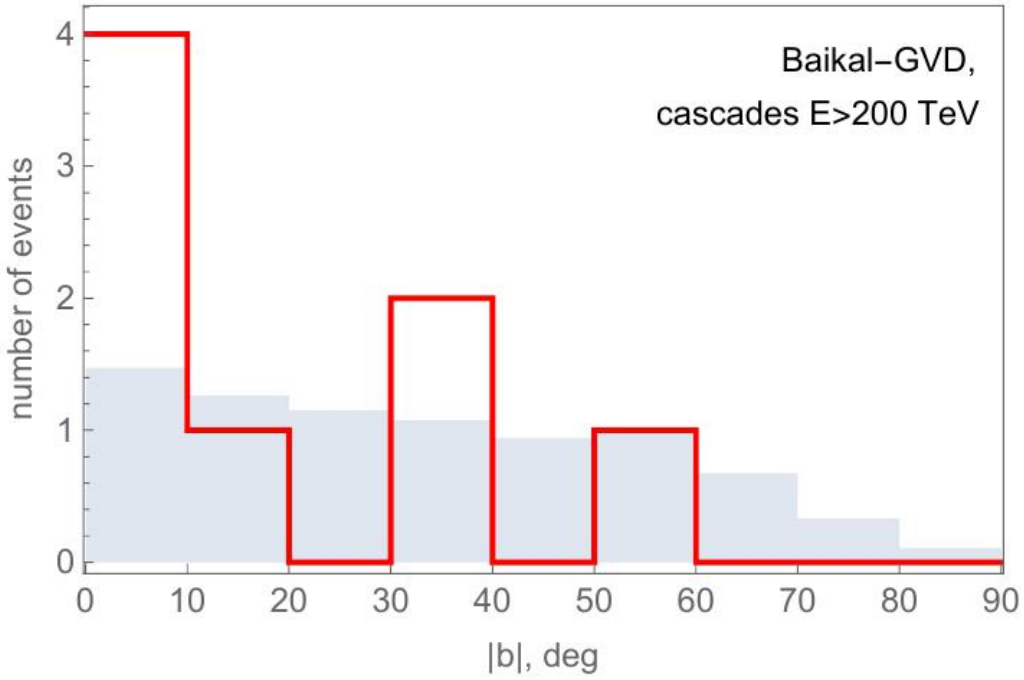
Galactic flux: less than 6-13% contribution to total neutrino flux at 30 TeV

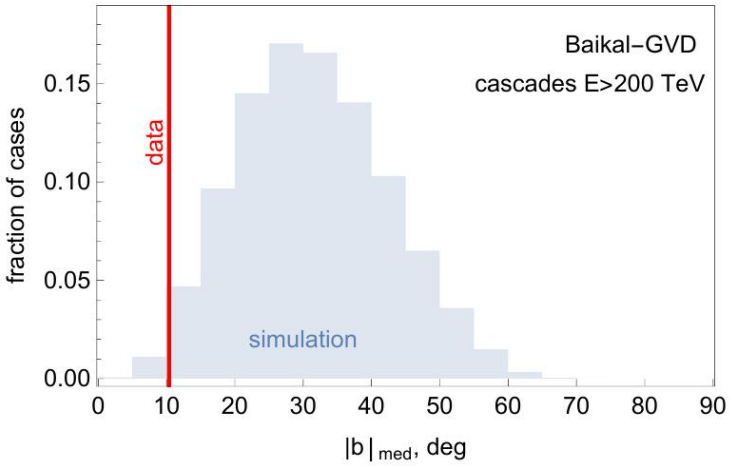
Science 380, 6652, 1338-1343 (2023), arXiv:2307.04427

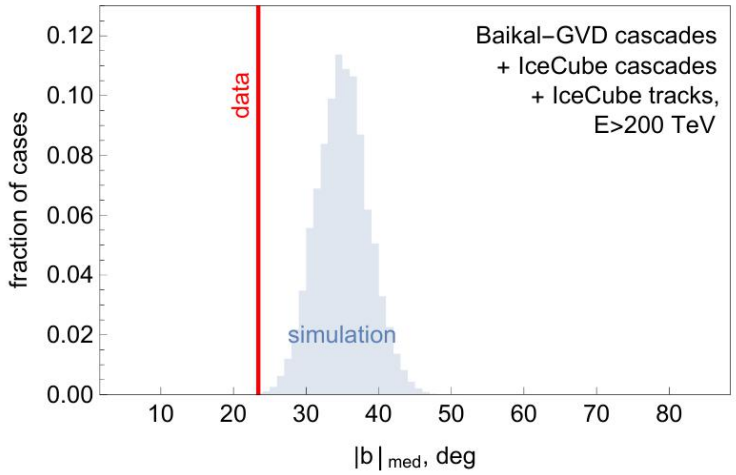
Baikal-GVD galactic plane

ApJ, 982:73 (6pp), 2025

- High-energy cascades April 2018 - March 2024 (6 years)
- Test the Galactic excess at E>200 TeV (8 events, 64% of astrophysical origin)
- Test using median of galactic latitude $|b|_{med}$
- Galactic component is visible with a significance of 2.5σ
- Significance in the combined with IC dataset: 3.6σ
- Fraction of Galactic events reaches several tens of percent at E>200 TeV





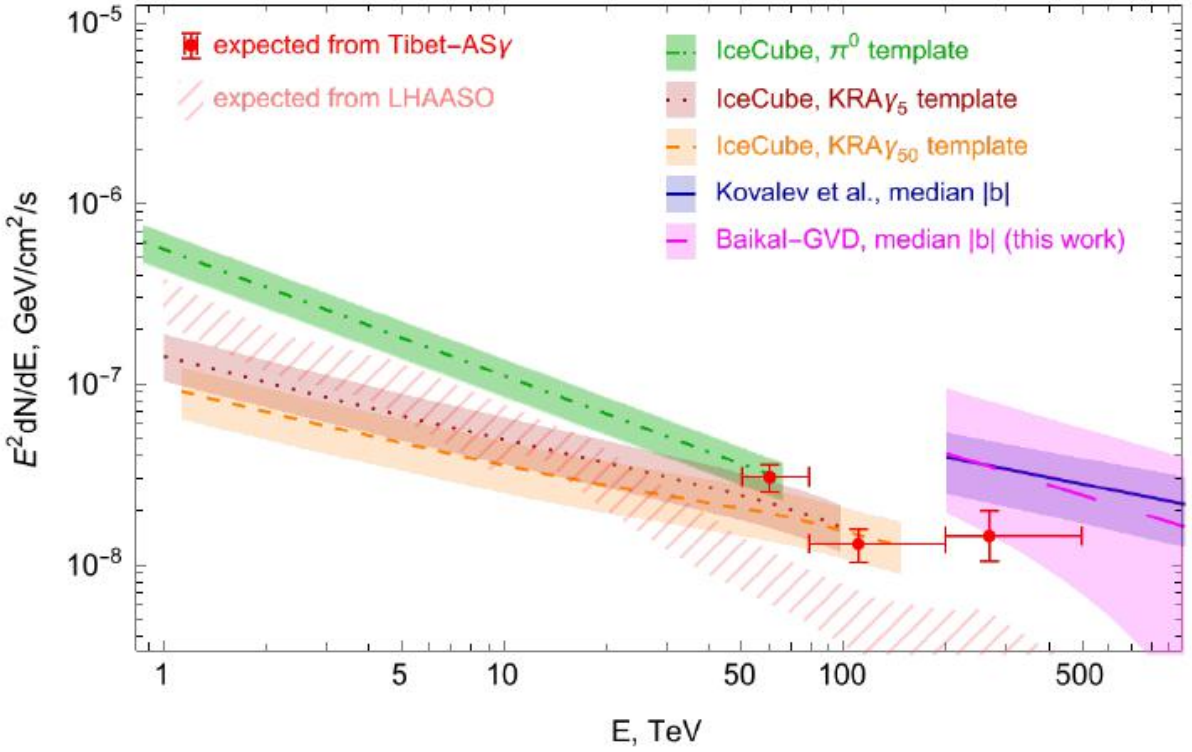


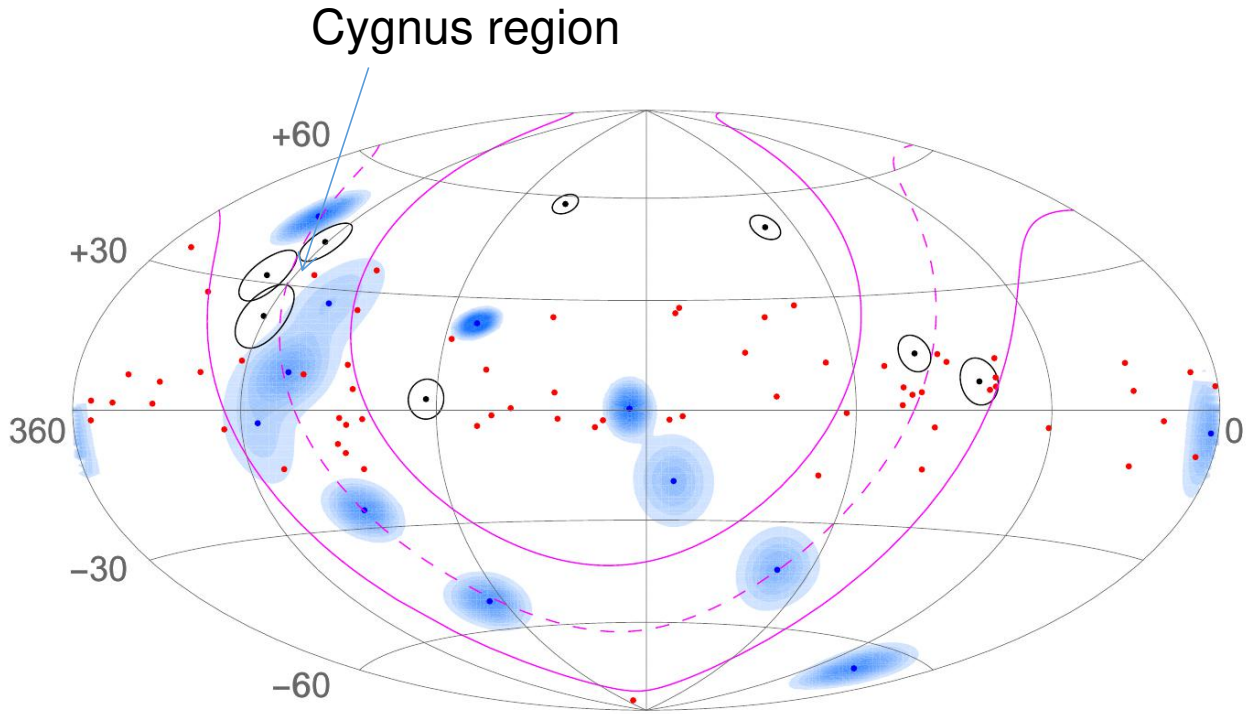
Sample	$\|b\|_{\rm med}$ observed	$\langle\|b\|_{\rm med}\rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4 \cdot 10^{-2}$ (2.5σ)
IceCube cascades	12.4°	31.9°	$8.7 \cdot 10^{-3}$ (2.6σ)
combined cascades	12.4°	31.5°	$1.7 \cdot 10^{-3}$ (3.1σ)
IceCube tracks	24.7°	36.0°	$1.8 \cdot 10^{-3}$ (3.1σ)
all cascades+tracks	23.4°	35.0°	$3.4 \cdot 10^{-4}$ (3.6σ)

Baikal-GVD galactic plane

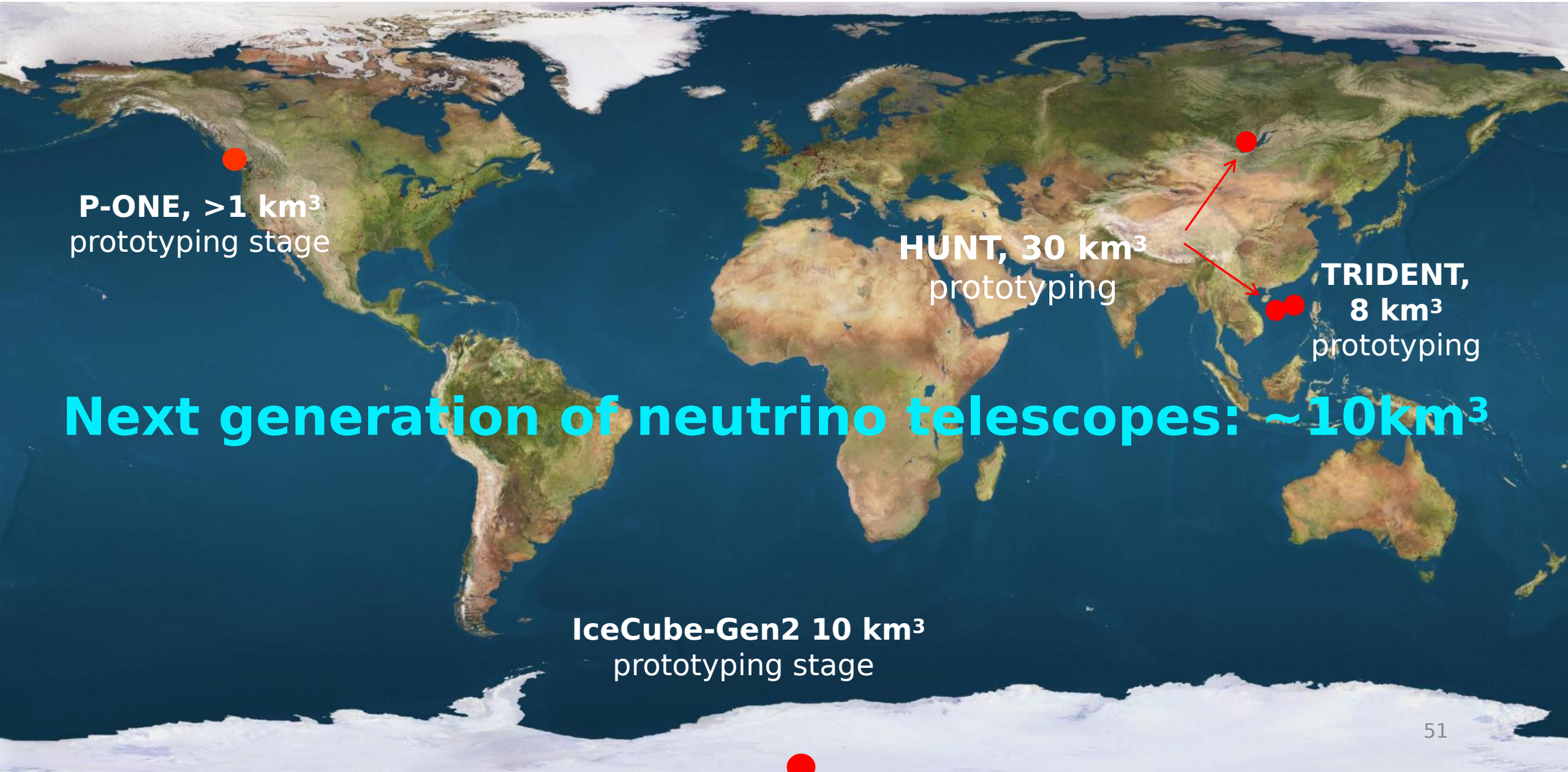
ApJ, 982:73 (6pp), 2025

- Very rough estimate of the Galactic neutrino flux is obtained
- Agrees with Galactic gamma-ray diffuse emission by Tibet-ASγ
- Some event clustering towards the Cygnus region (the brightest region of diffuse γ-ray emission in the northern sky)





Future generation of telescopes



Summary

Neutrino telescopes are challenging detectors to calibrated and analyse the data

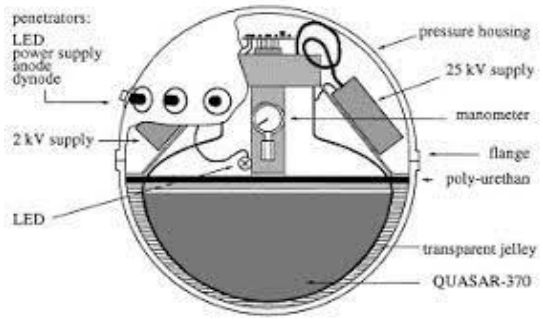
We are watching the first steps of high-energy neutrino astrophysics

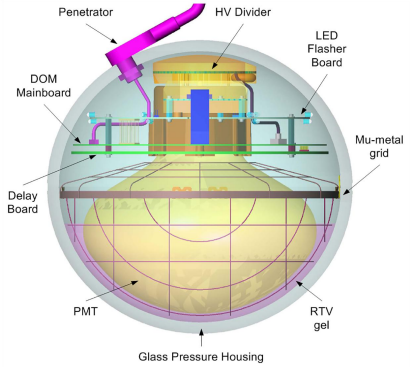
- Discovery of diffuse astrophysical neutrino flux
- Evidence for diffuse galactic neutrino emission
- Increasing evidence for extragalactic neutrino point sources

The next generation of telescopes will be more sensitive in neutrino sources searches

Optical modules (OM)

PMTs are enclosed into the hermetic transparent container
which also contains power and readout electronics







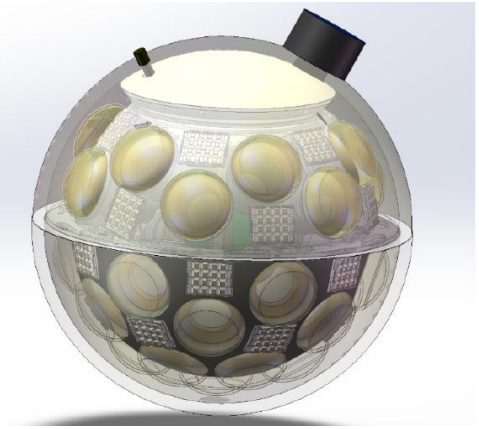


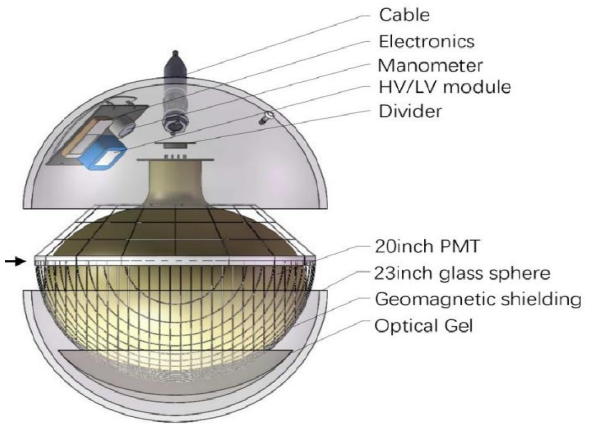






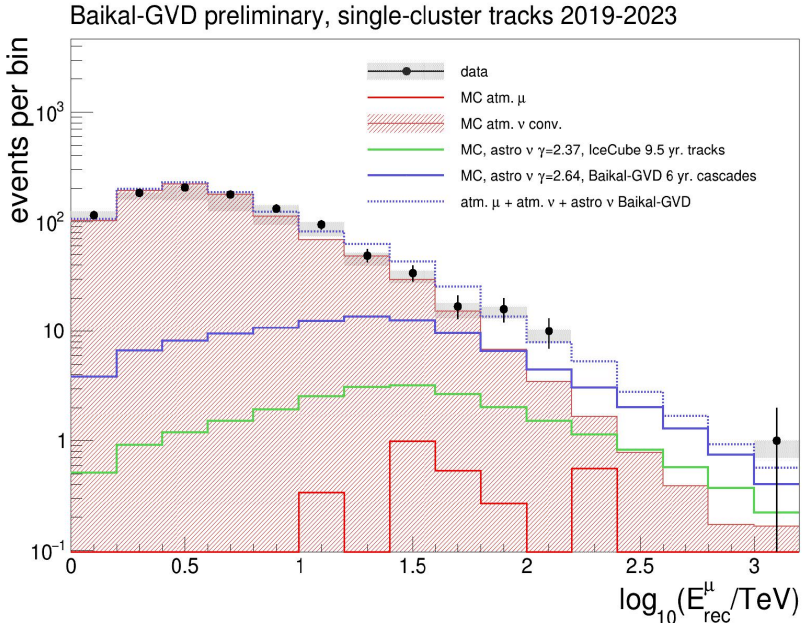


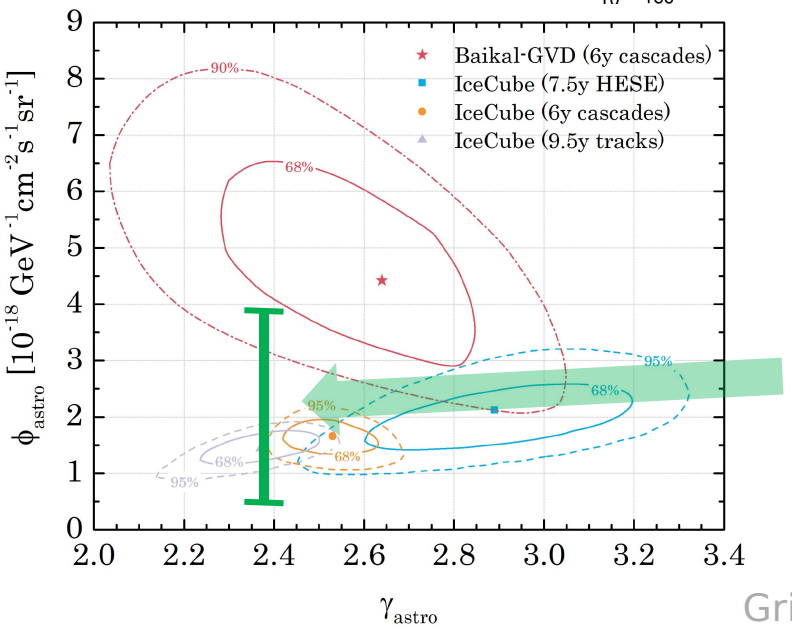




OM design is a key component of LV neutrino telesope

Probe for diffuse flux with tracks





Probe the diffuse flux with cut-based event-counting analysis

Background MC was modified to match the data
- Scaled the flux to match ν normalisation in data
- add 20% to photoelectron yield to match the shape in low-energy region

Optimised E^{μ}_{rec} and BDT cuts for the best sensitivity to single-power-law wihth index 2.37 **ApJ 928, 50 (2022)**
- Results of the optimisation: $E^{\mu}_{rec} > 45$ TeV, BDT_HE > 0.26

MC expectation: 1.4 muon bundle and 23.5 atm. neutrino events
Observed in data: 38 events

P-value of the excess: 0.0087, significance: 2.39σ,
no systematics is taken into account yet

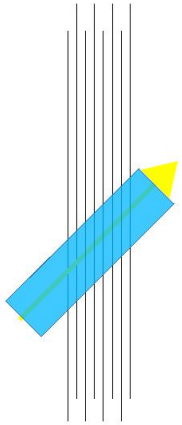
The 90% CL one-flavour flux limits for γ=2.37:
0.59 < φ0 < 3.95 (10^{-18} GeV^{-1} cm^{-2} s^{-1}sr^{-1}) do not contradict IC and Baikal-GVD

PO-2: GS, PoS(ICRC2025)1162

BACKUP

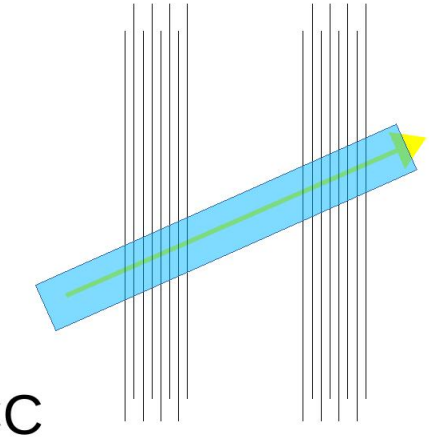
Baikal-GVD analysis pipelines

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

Multi-cluster tracks

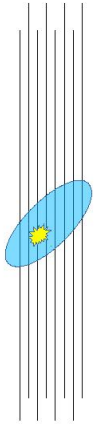


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

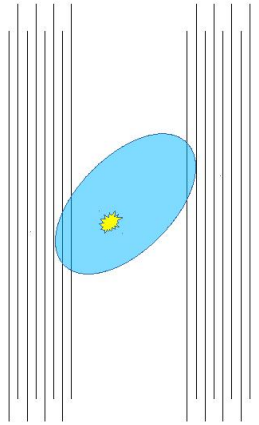
NC, ν_e ν_τ CC

Single-cluster cascades



- High energy threshold
- Good energy resolution
- Relatively rare events

Multi-cluster cascades



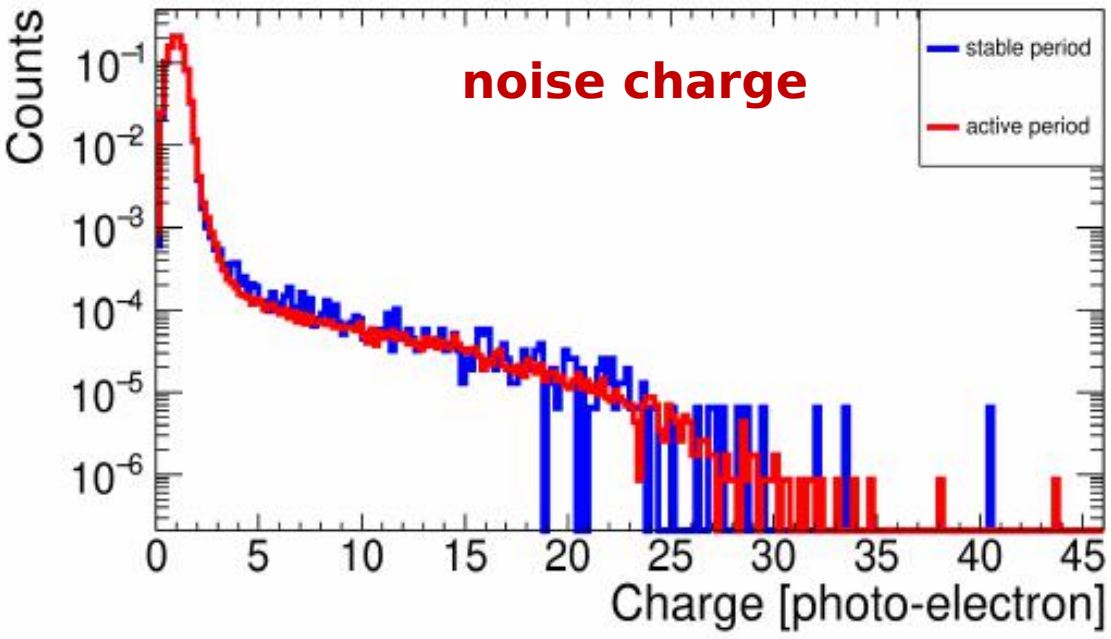
- Very high energy threshold
- Excellent energy resolution
- Very rare events

Hit finding: causality criterium

The noise charge distribution is at the level of 1 p.e.

- Simplest hit selection technique: cut on the hit charge
- Baikal-GVD cascade analysis: q > 1.5 p.e.

Charge cut would affect the efficiency of low-energy (~ 1TeV) track reconstruction



Signal hits are correlated in time while noise hits are not

Causality criterium: $\Delta t_{ij} < \Delta R_{ij} \frac{c}{n} + \delta$

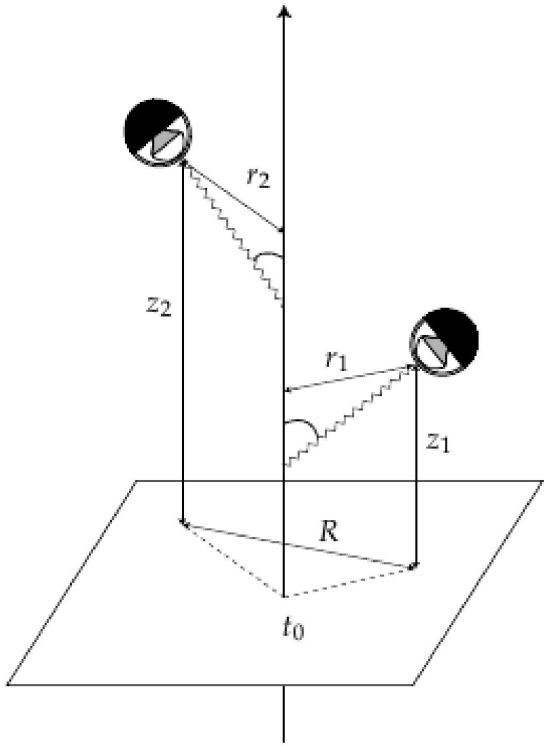
Where δ ~ 10 ns, accounts for time measurement precision

Event purity of ~70-80% is achieved keeping efficiency at >99%

- For atmospheric neutrino spectrum, E_{median} ~ 500 GeV

For good reconstruction precision we need to further purify signal hits

Hit finding: directional causality



$$t_j = t_0 + \frac{1}{c}(z_j + k r_j)$$

$$c(t_j - t_i) - (z_j - z_i) = k(r_j - r_i)$$

$$|r_j - r_i| < R$$

R.Bruijin, 2008, ANTARES

More strict causality condition for predefined track direction

$$|\Delta r_{i,j}| < R \qquad \Delta z_{i,j} - kR - \delta \leq c\Delta t_{i,j} \leq \Delta z_{i,j} + kR + \delta$$

Perform scan on (θ,φ) - find the set of largest cliques of causally-connected hits

- Graph theory algorithms, e.g. Bron-Kerbosch clique search algorithm

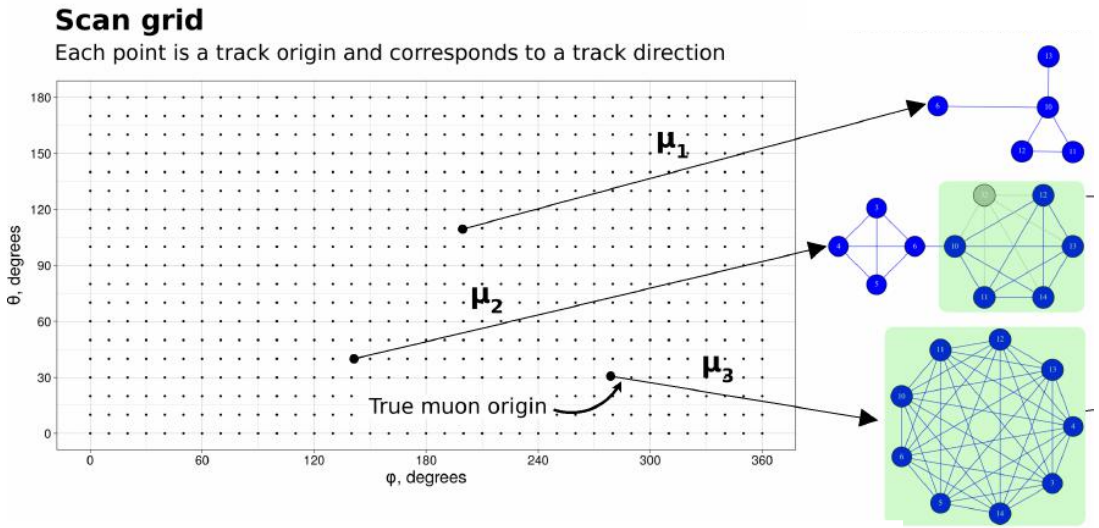
Few largest hit cliques are fit with fixed direction to find optimal track position

For atmospheric neutrino spectrum (E_{median} ~ 500 GeV):

- Purity ~ 95%
- Hit selection efficiency ~95%

Few best hit collections are passed to full-scale muon reconstruction

- At least 8 hits on 2 strings
- Track direction and position are used as seeds



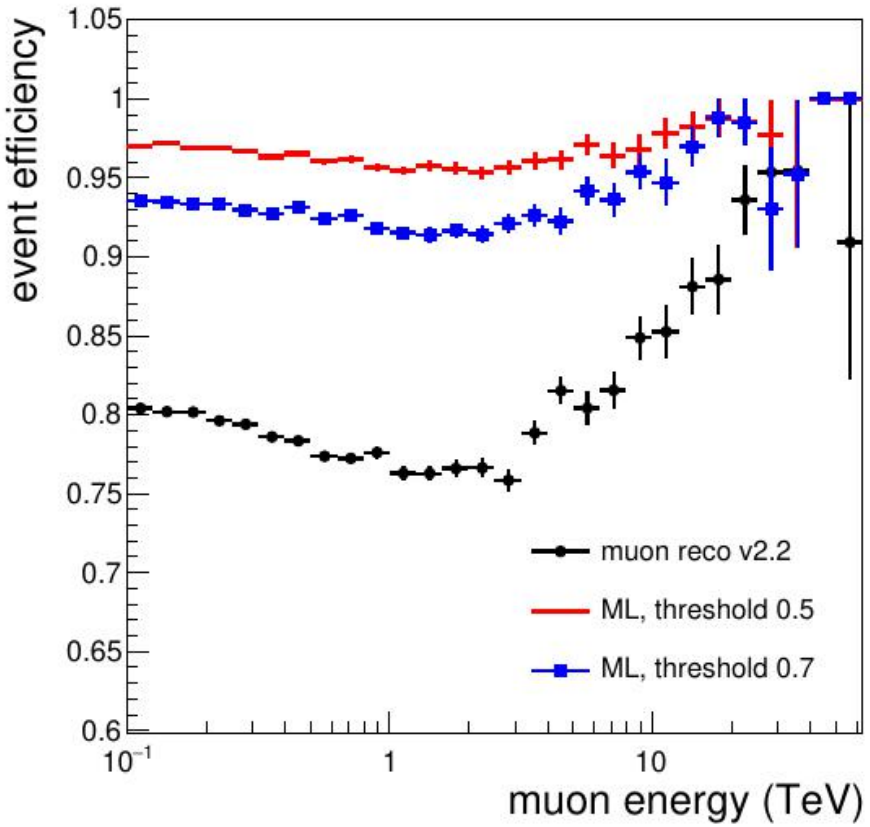
Hit finding with neural networks

Noise suppression algorithm based on deep learning: **I. Kharuk et al 2023 JINST 18 P09026**

Neural networks allow to impove detection efficiency at low energies, when we look for smaller number of low-charge hits hidden in noise

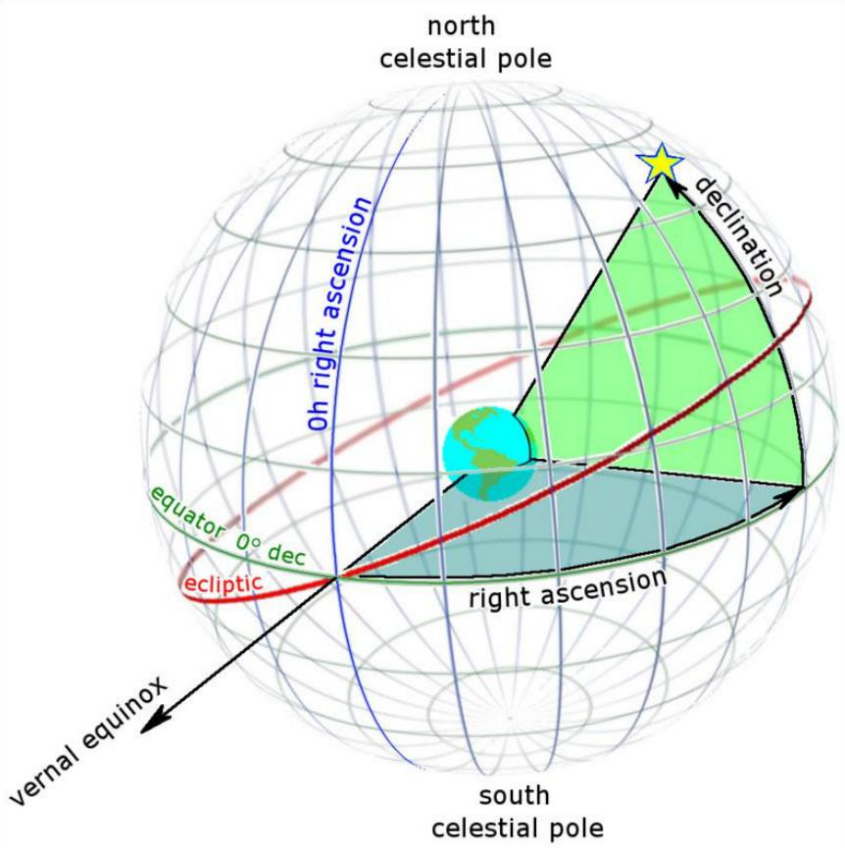
Application of ML in other areas of event reconstruction is being developed

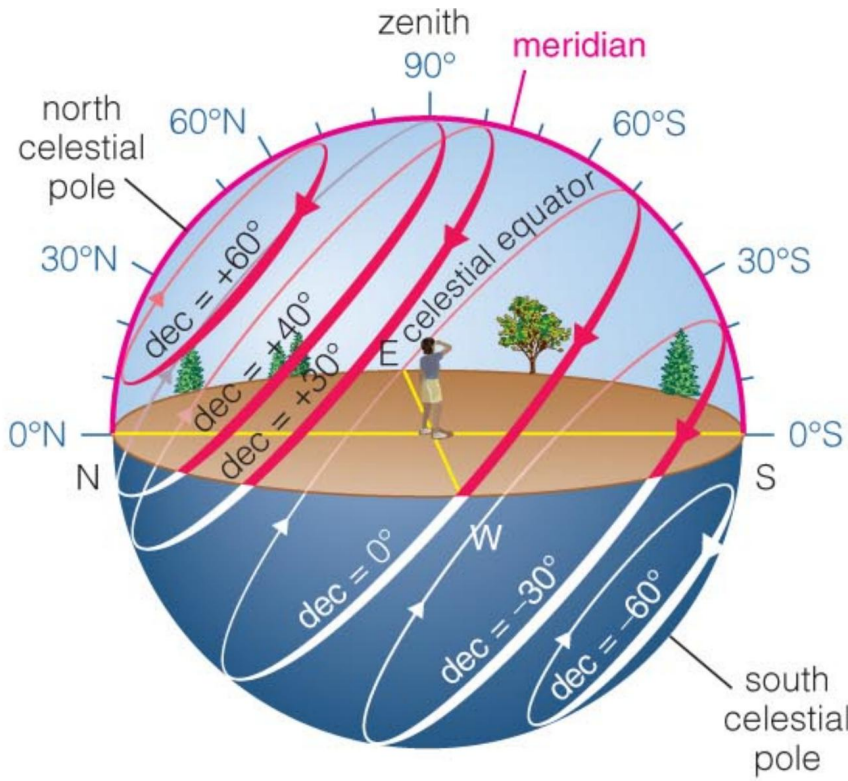
Efficiency of the detection of event with at least 8 signal hits on 2 strings



Equatorial coordinate system

Right Ascension (RA) and declination (dec) are defined wrt. the Earth equator plane





- **RA:** angle wrt the vernal equinox direction in equatorial plane (0-24h)
- **dec:** angle between equatorial plane and direction to the star

Stars revolve daily around celestial poles
Daily trajectory in zenith angle is defined by declination

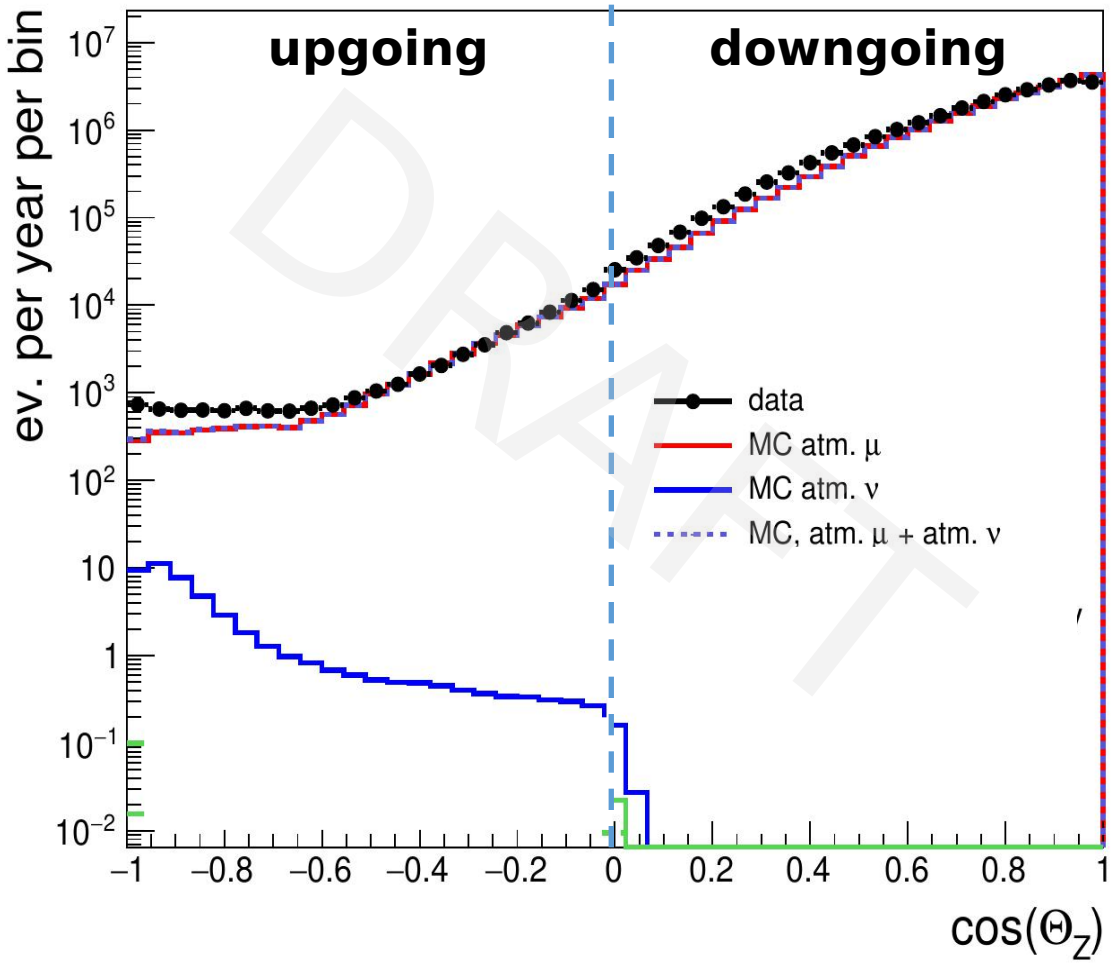
Neutrino event selection

Reconstructed tracks are dominated by atmospheric muon background

On average ~3 events per second

Background rate in the region of upgoing events up to ~10000 times larger than neutrino rate

Zenith angle of reconstructed tracks



DRAFT

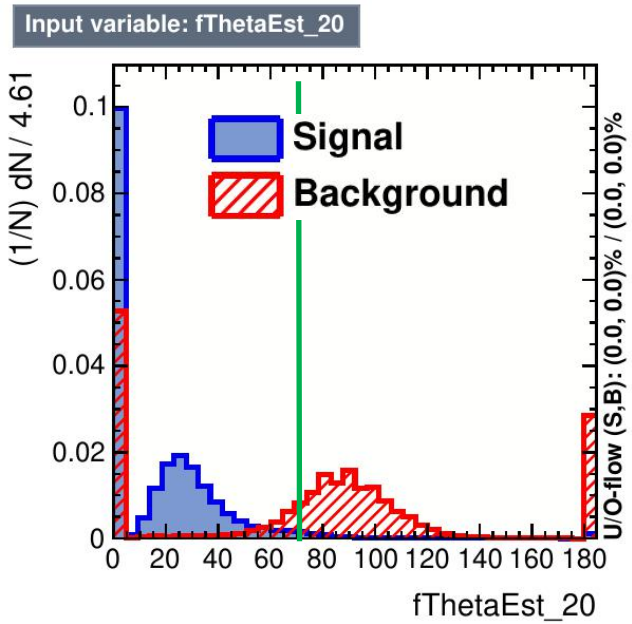
Track-like event selection

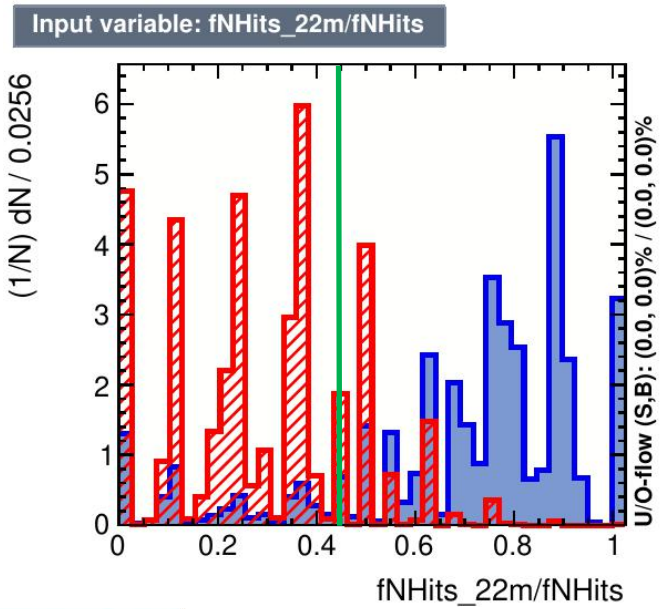
Rejection of badly reconstructed tracks is performed with cuts on various quality variables

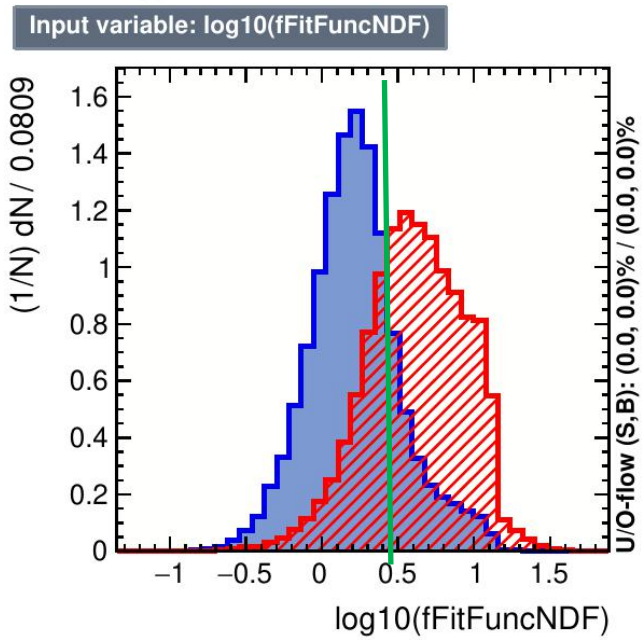
One needs to suppress background 10^3 time larger than signal

Often it is not possible to design cuts on limited set of variables with enough rejection power and high signal efficiency

In this case Boosted Decision Trees (BDT) are used







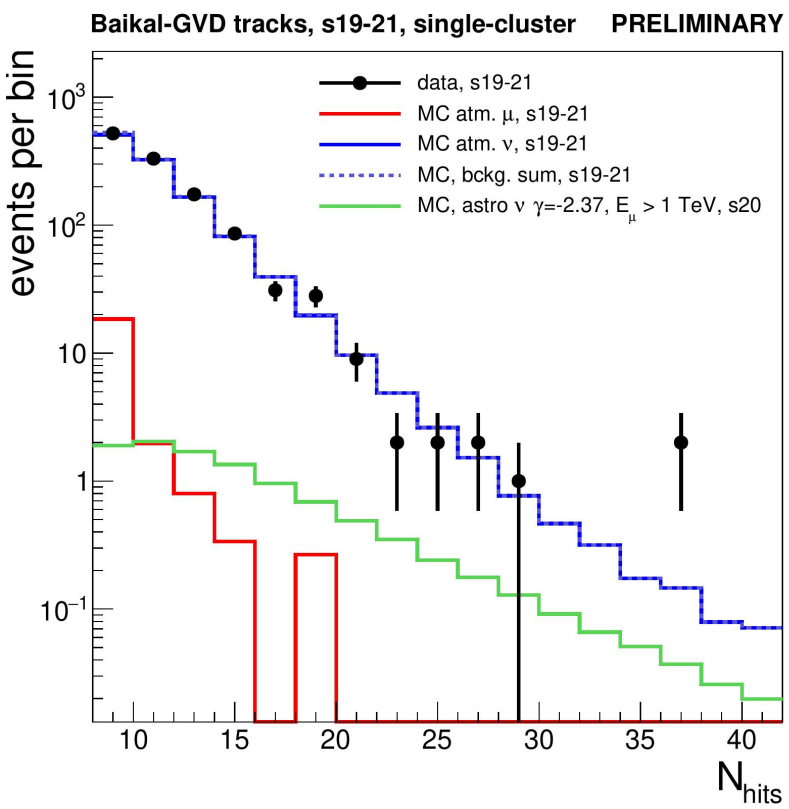
Neutrino candidates

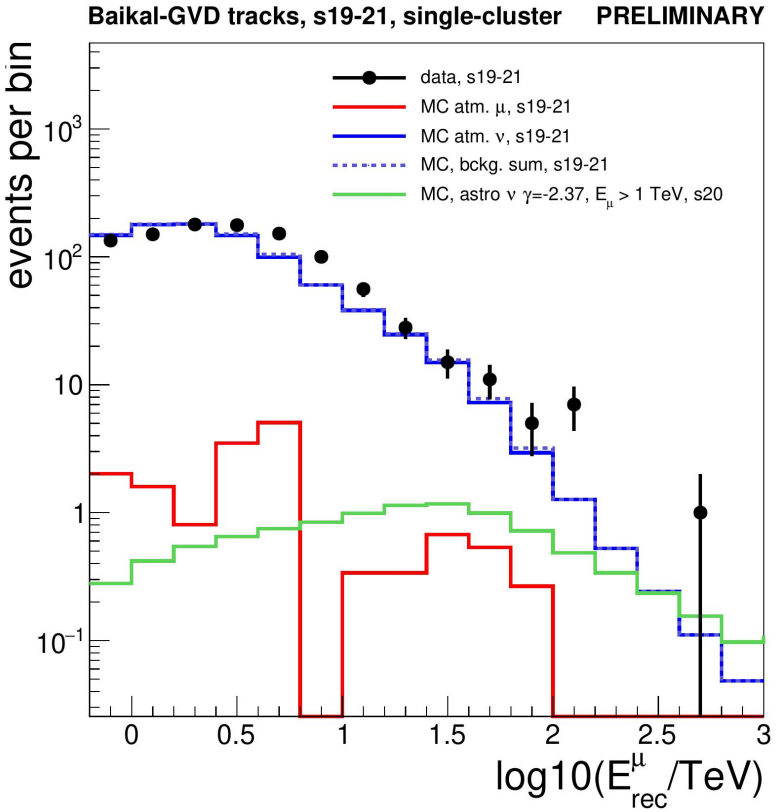
An illustration of cleaned track-like neutrino candidate sample

- A cut on BDT: BDT_LE>0.25|| BDT_HE>0.25
- Cut is not optimized, it could change depending on analysis: time-integrated PS search or time-dependent search, energy threshold etc..

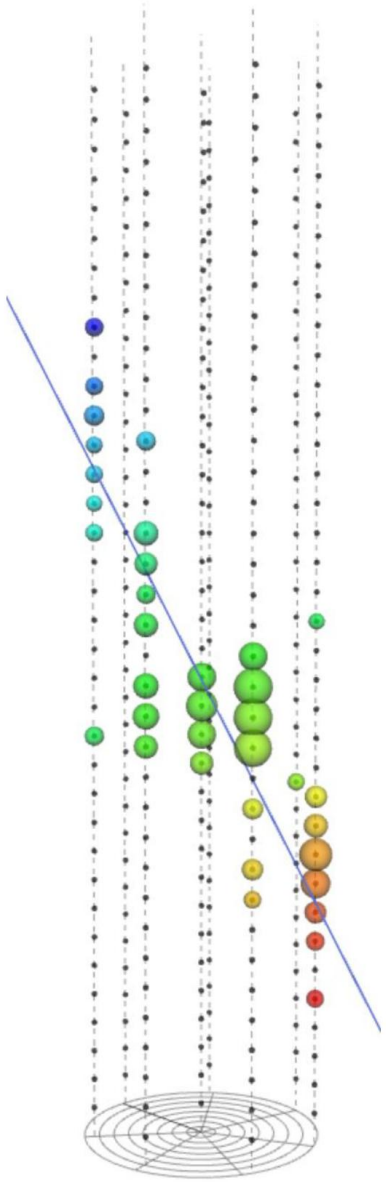
Sample of track-like events selected in data-taking seasons 19-21

- 14.37 years of taking data in single-cluster configuration
- ~Half of processed data





Some interesting events s19-21



Season 2019, December
Cluster 3

N_{hits}	36
E^{μ}_{rec}	62.1 ТэВ
θ_{rec}	153.1°
L_{track}	332.4 м

Angular precision:

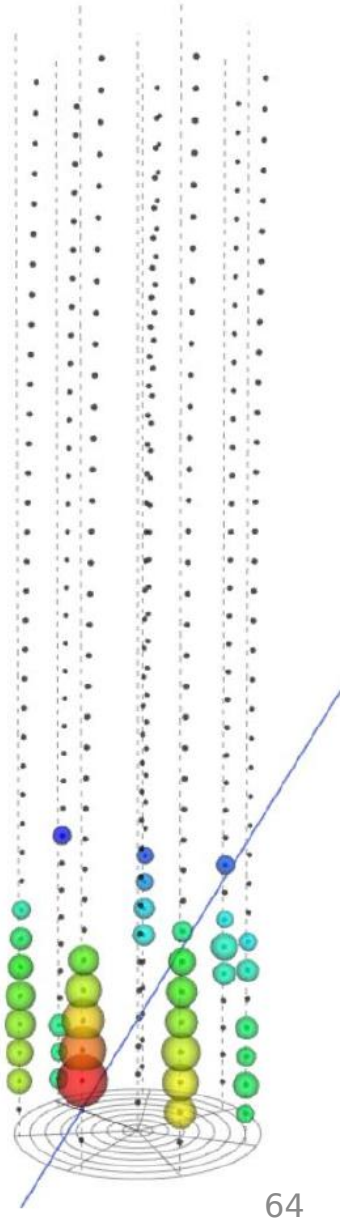
50%:	0.5°
68%:	0.7°
90%:	1.0°

Season 2020, September
Cluster 5

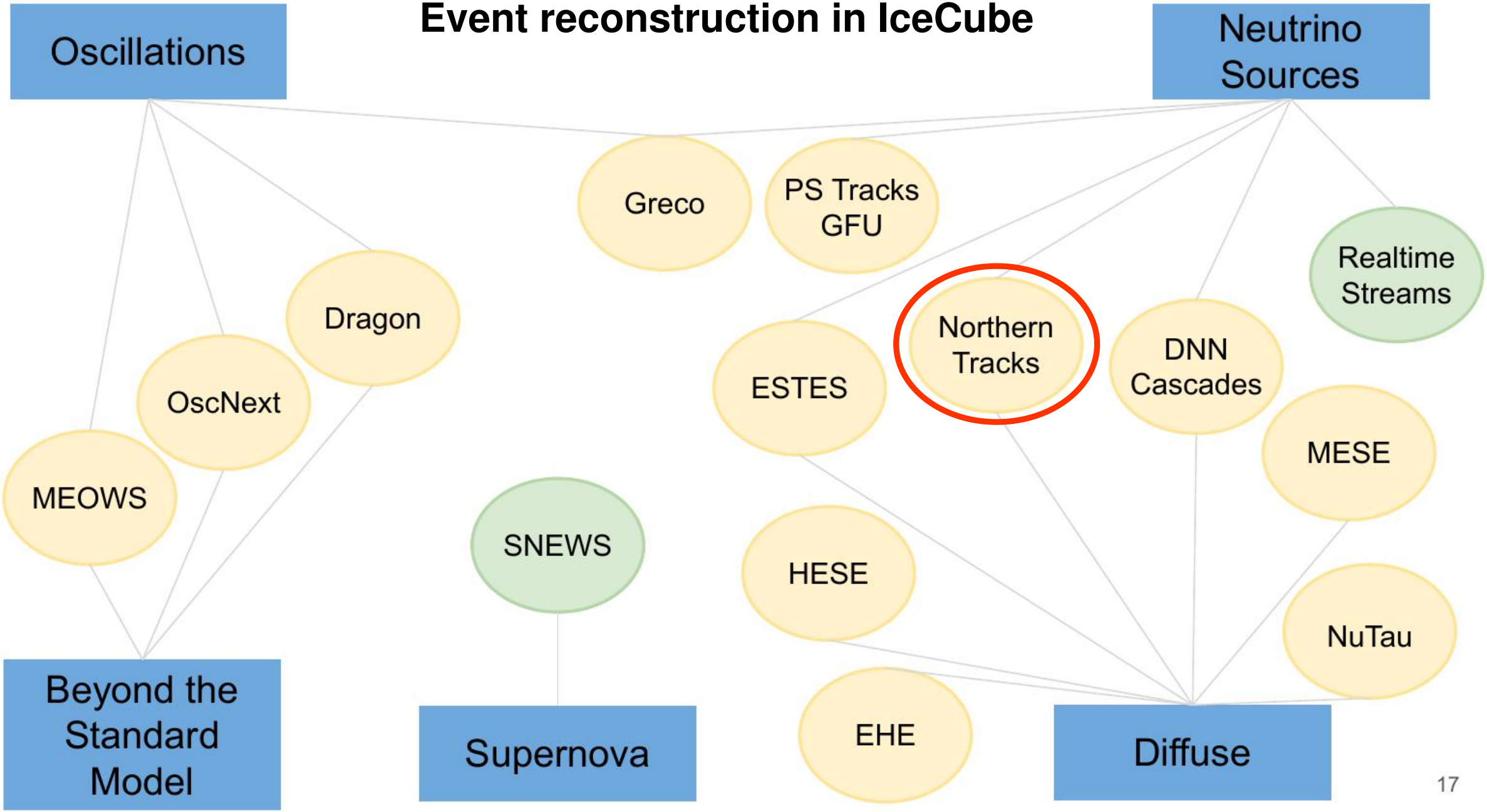
N_{hits}	37
E^{μ}_{rec}	107.2 ТэВ
θ_{rec}	116.7°
L_{track}	140.1 м

Angular precision:

50%:	0.7°
68%:	1.0°
90%:	1.5°



Event reconstruction in IceCube



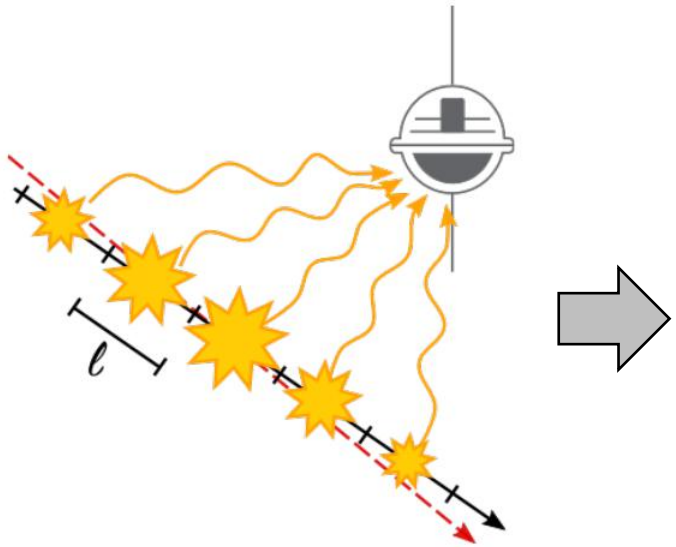
Track event reconstruction in IceCube

Likelihood for all hits at the channel:

$$L(x, y, z, t, \theta, \phi) = \prod_{j=1}^{N_{\mathrm{DOM}}} \prod_{i=1}^{N_{\mathrm{hit}}} [p_j(t_i)]^{q_i}$$

Likelihood for the first photon:

$$L_{1\mathrm{st}}(x, y, z, t, \theta, \phi) = \prod_{j=1}^{N_{DOM}} p_{j,1\mathrm{st}}(t_1)$$



“Plane wave” approximation

Full MIP likelihood with homogenous ice model

First photon MIP likelihood with homogenous ice model

First photon MIP likelihood with realistic ice model

Likelihood with realistic ice model accounting for EM showers at stochastic energy losses

PREVIOUS ALGORITHMS

GAUSSIAN PDF (LEAST-SQUARE)

seed

GAMMA PDF

seed

GAMMA PDF (L_{1st})

seed

B-SPLINE PDF (L_{1st}) (“SPLINERECO”)

seed

COMPOSITE B-SPLINE PDF (“SEGMENTEDSPLINERECO”)

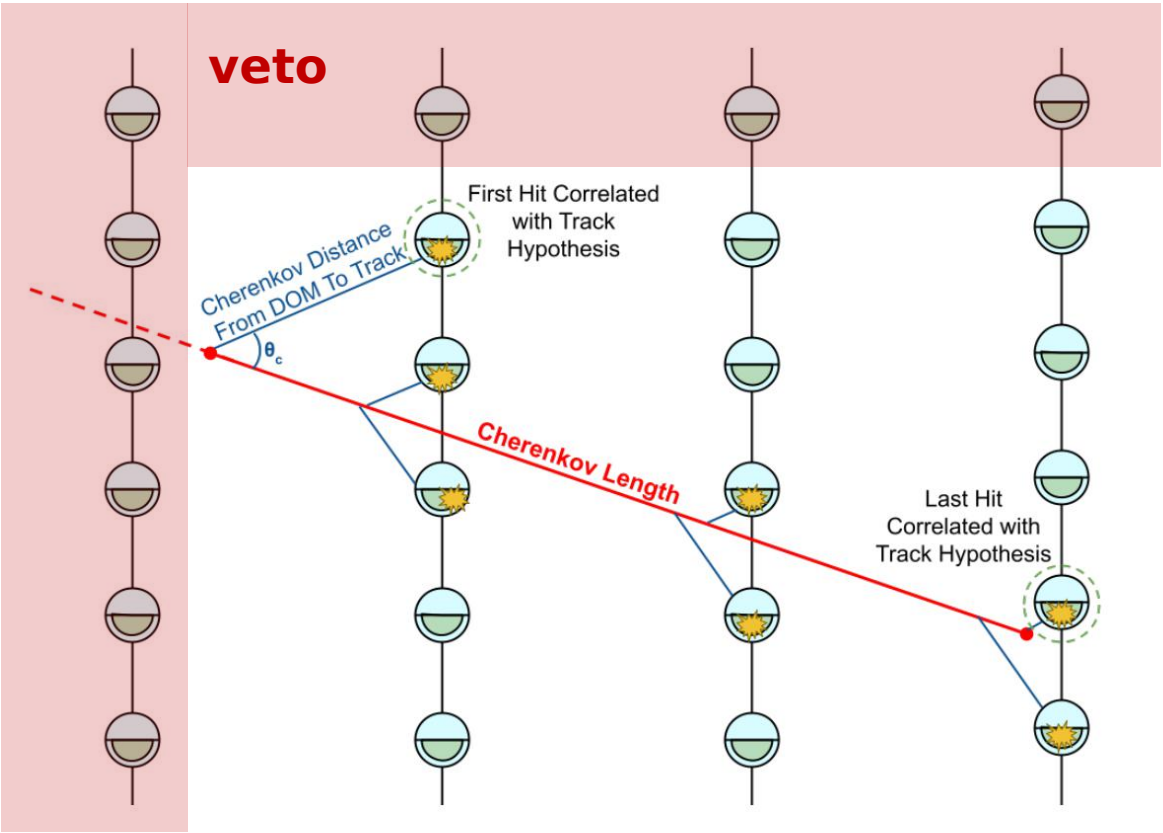
NEW ALGORITHM

JINST 16 P08034

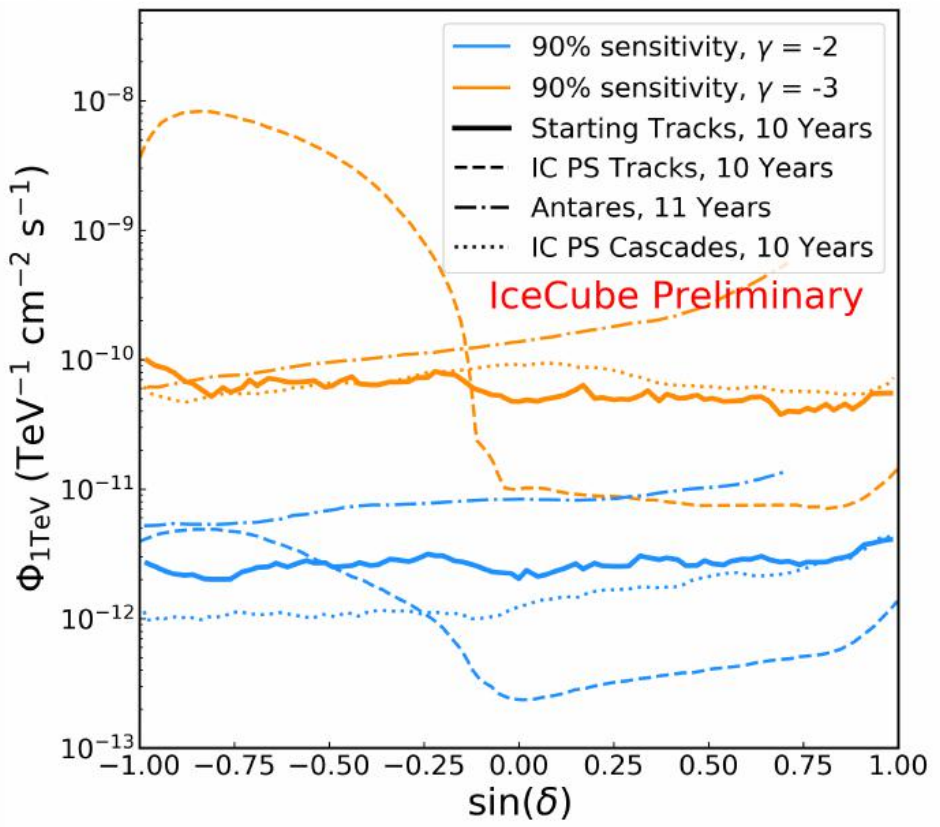
Starting tracks in IceCube

Starting tracks allow to study downgoing numu neutrino flux

- Worse angular resolution
- Higher energy threshold



Sensitivity compared to through-going tracks

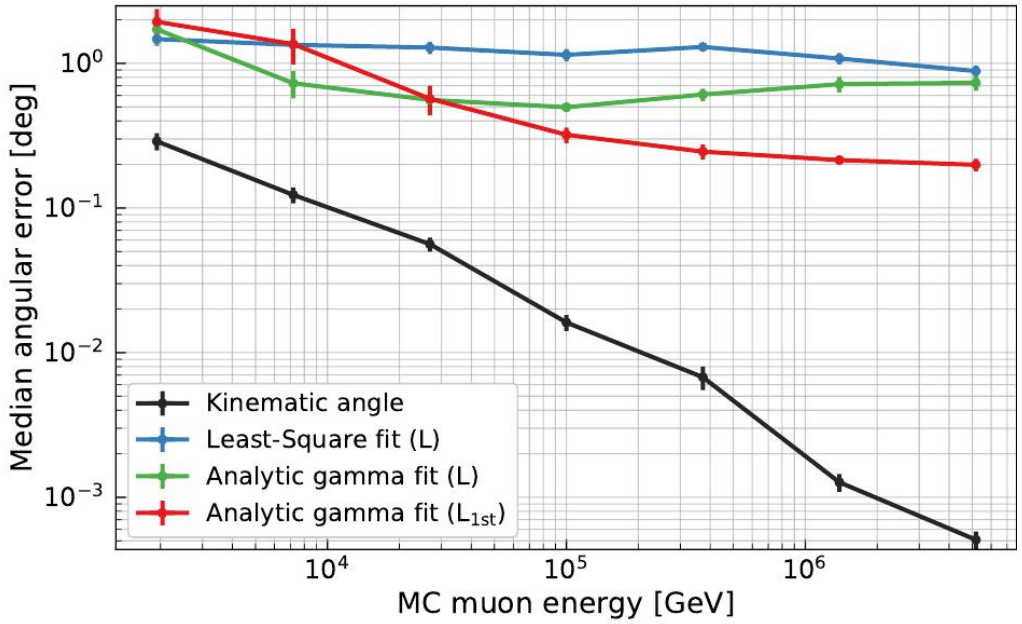


Sarah Mancina, IC thesis, 2022

Track events reconstruction in IceCube

Angular resolutions for different stages of track-like event reconstruction

L > 700m



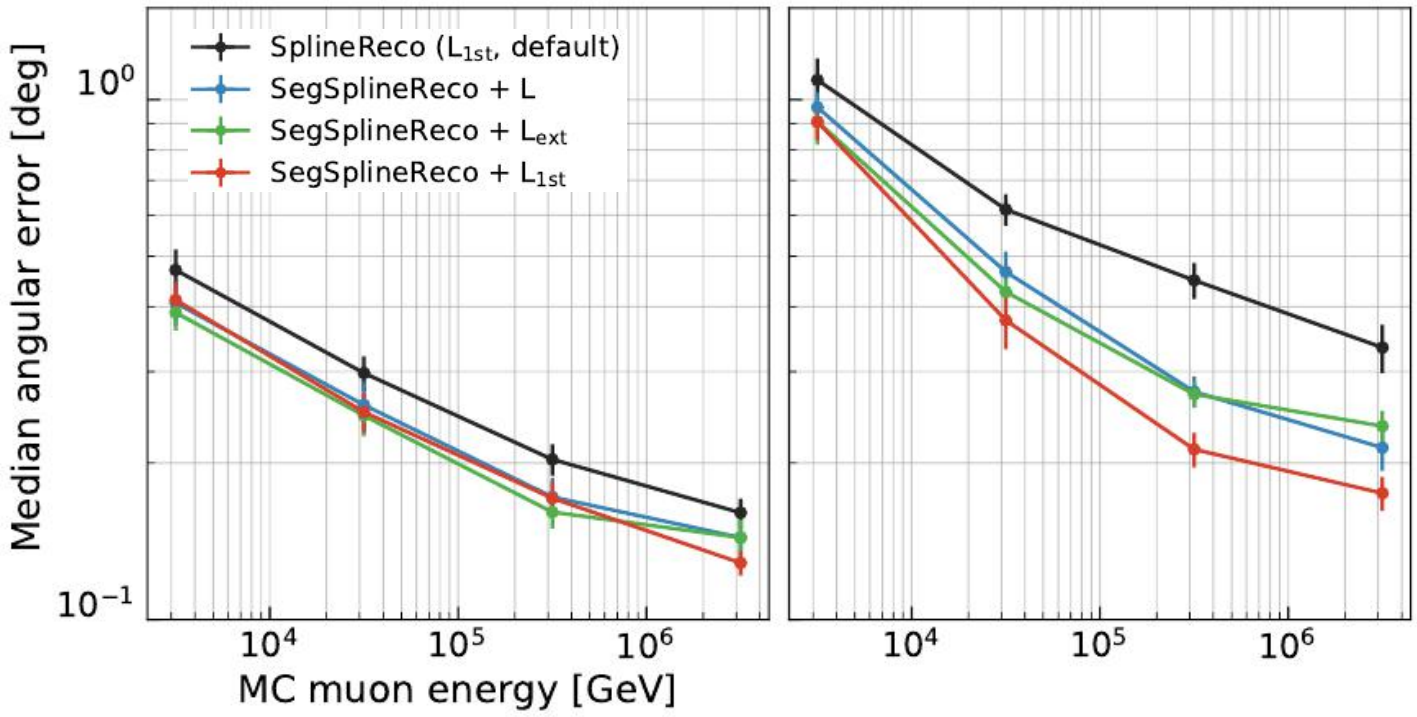
JINST 16 P08034

L > 700m

Through-going events

L > 400m

Starting events



IceCube ice properties

Feature of IceCube: complex ice light propagation properties
Very small absorption and enormous light scattering

Effective scattering length is few times shorter than absorption length

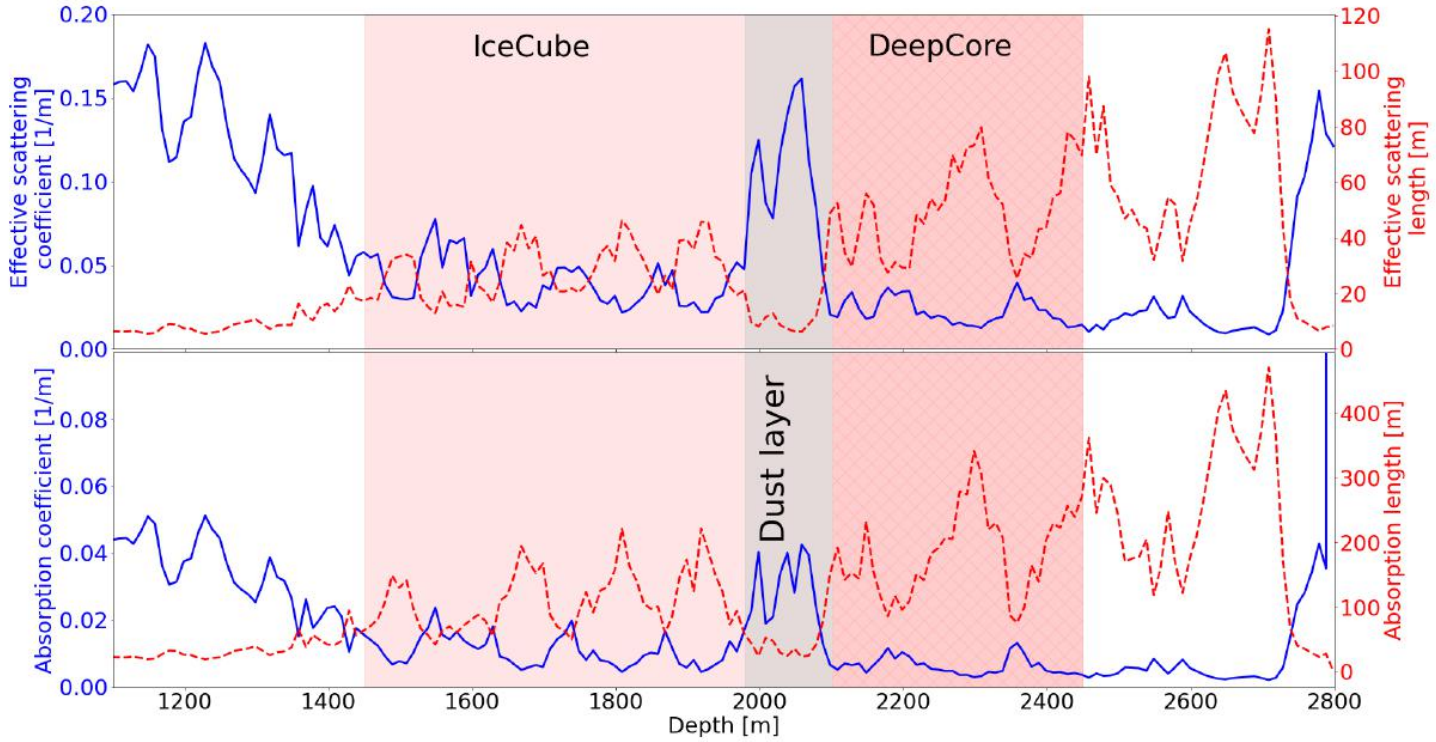
Large dependence on depth of both scattering and absorption

“Dust layer” with both large absorption and scattering

Light propagation anisotropy

Layers with stable ice properties are not at constant depth

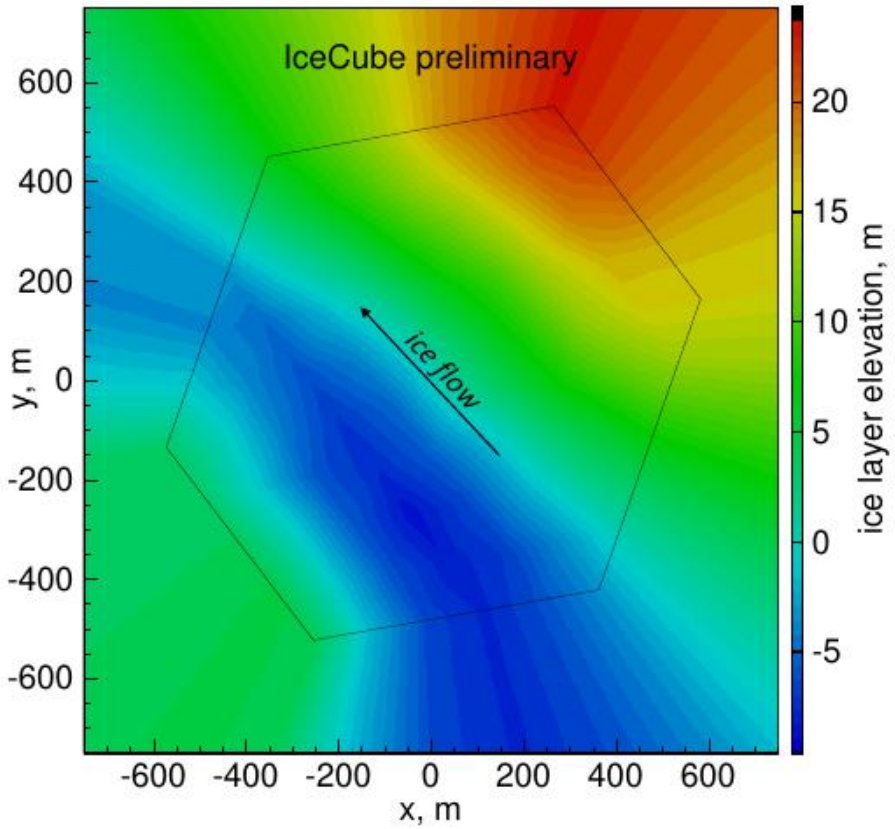
Scattering on bubbles in drill holes



IC, The Cryosphere Discussions 2022 (2022) 1–48

IceCube ice properties

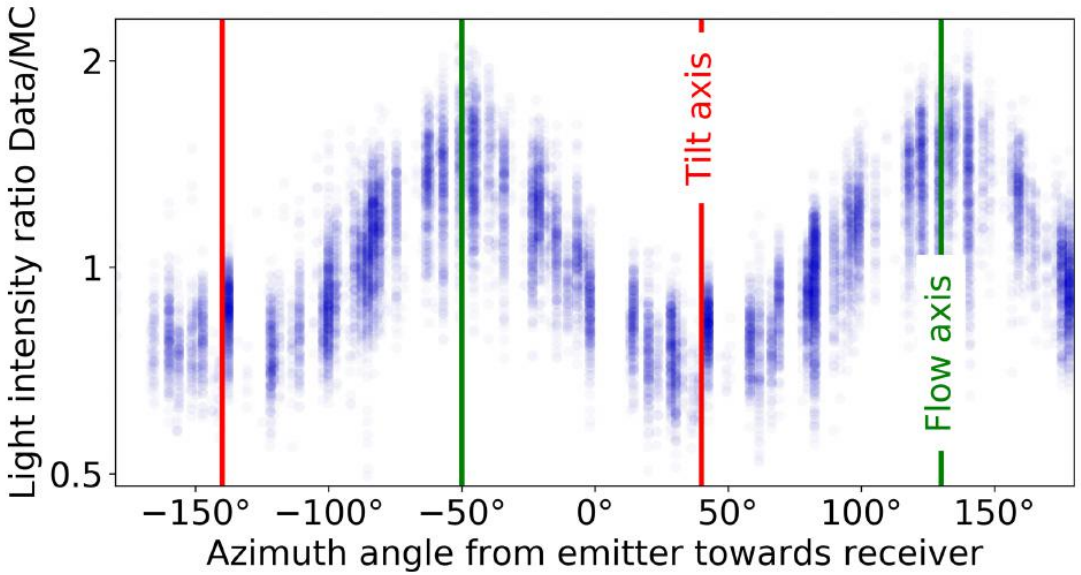
Antarctic Ice Shield flows at
10m/year which defines “flow axis”

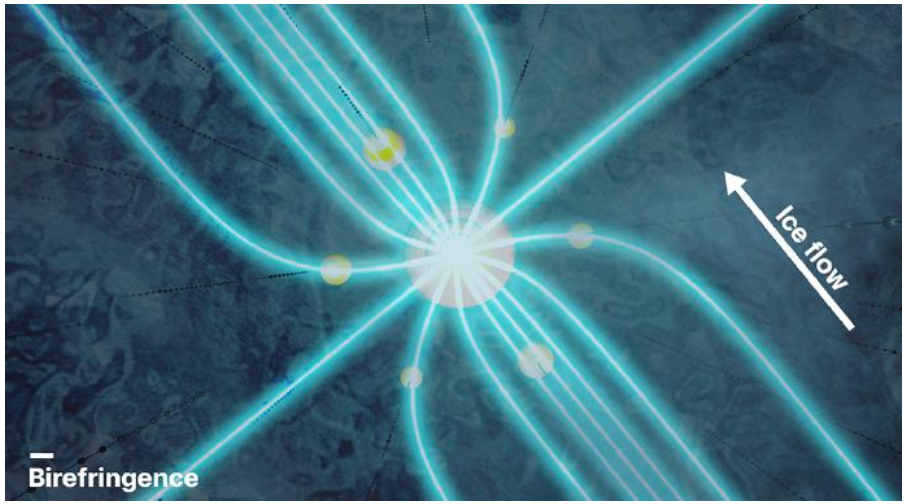


Layer undulations: Ice layers with constant ice properties change their depth

PoS(ICRC2023)975

Light tends to be deflected towards flow axis

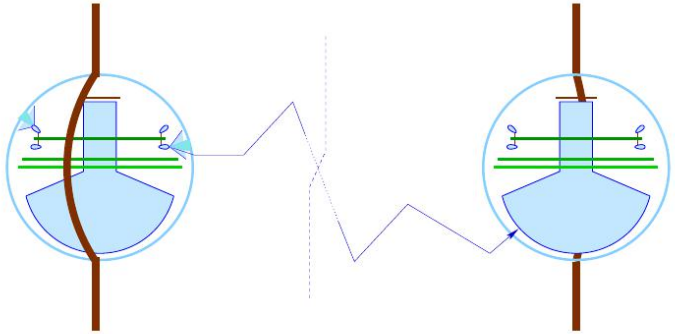


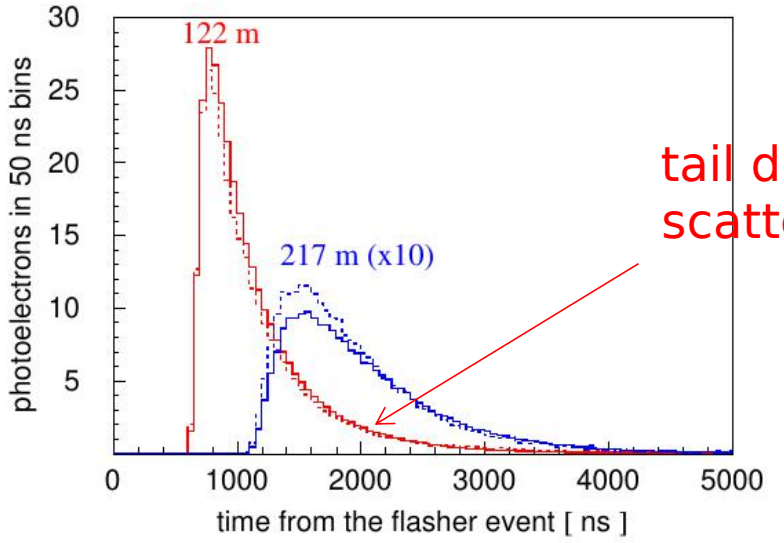


IC, The Cryosphere 18 (2024) 1

IceCube ice properties

Ice models are established by fits to flasher data

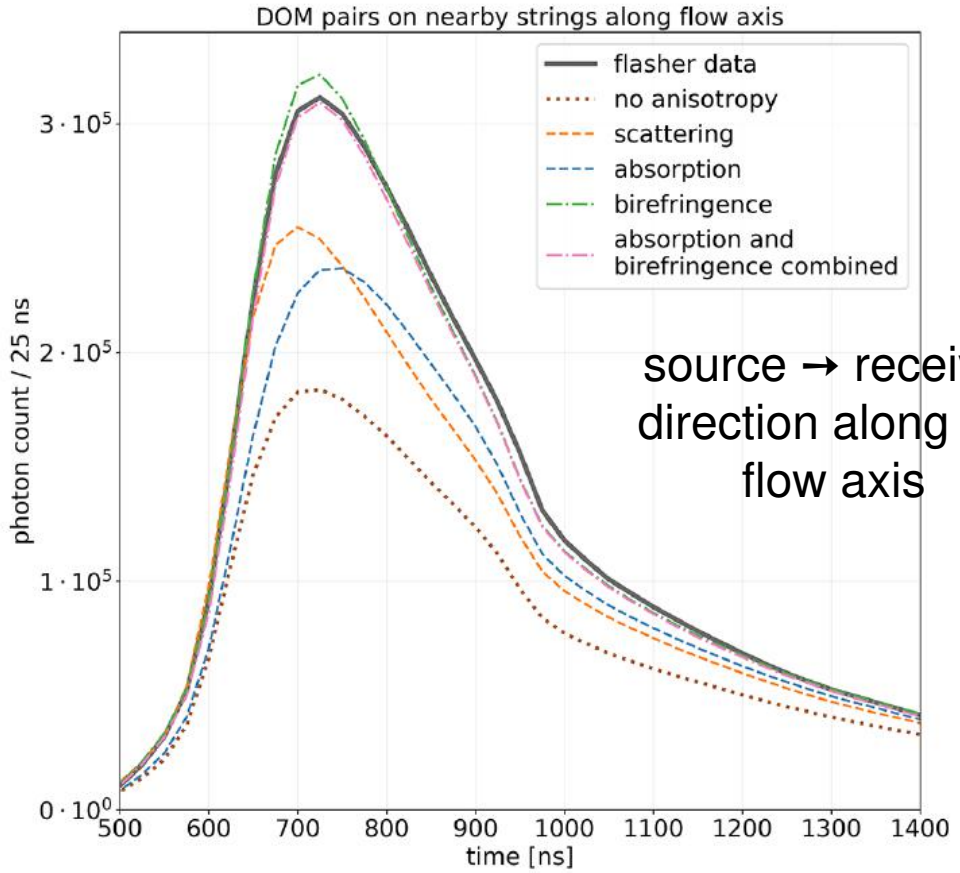




tail due to scattering

NIM A, Volume 711, 21 May 2013, Pages 73-89

Results of fits of models incorporating different effects to flasher data



source → receiver direction along the flow axis

IC, The Cryosphere 18 (2024) 1

IceCube ice properties

Steady progress in ice description models over the years

AMANDA ice models:			model error
bulk, f125, mam, mamint, stdkurt, sudkurt, kgm, …			
millennium (published 2006) → AHA (2007)			55%
IceCube ice models:			
WHAM	(2011)		42%
SPICE 1	(2009)		29%
SPICE 2, 2+, 2x, 2y	(2010)	added ice layer tilt	
SPICE Mie	(2011)	fit to scattering function	29%
SPICE Lea	(2012)	fit to scattering anisotropy	20%
SPICE (Munich)	(2013)	7-string, LED unfolding	17%
SPICE^3 (CUBE)	(2014)	llh fixes, DOM sensitivity fits	11%
SPICE 3.0	(2015)	improved RDE, ang. sens. fits	10%
SPICE 3.1, 3.2	(2016)	85-string, correlated model fit	<10%
SPICE HD, 3.2.2	(2017)	direct HI and DOM sens., cable, DOM tilt	
SPICE EMRM	(2018)	absorption-based anisotropy	*single*
SPICE BFR	(2020)	birefringence-based anisotropy	*LEDs*

D.Chirkin, M.Rongen
IceCube Polar Science workshop, 2021

IceCube ice properties

Event selections are updated incorporating more data, new reconstructions and improved in ice models

HESE events:
diffuse flux discovery (2013)

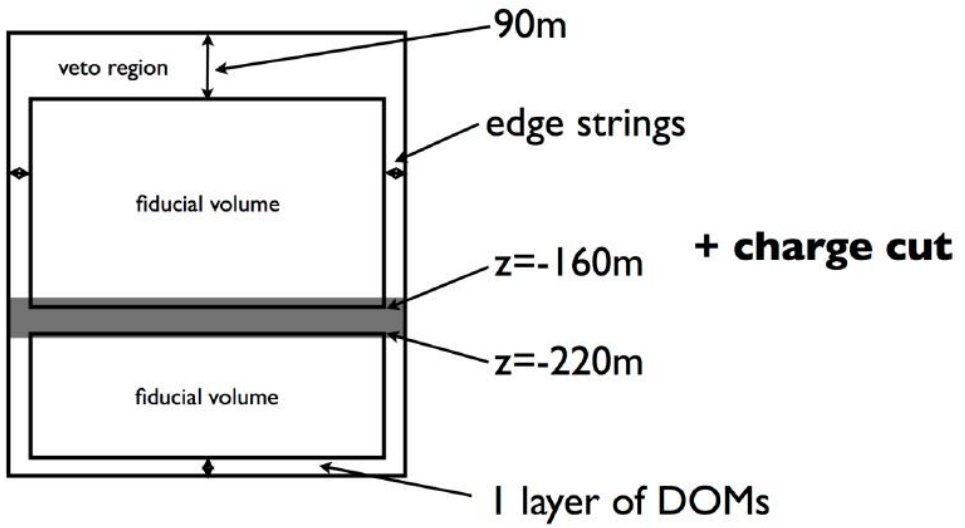
An update of High-Energy Starting Events (HESE) event sample **PoS(ICRC2023)1030**

- Added 4.5 years of data to **[Phys. Rev. D 104, 022002]**
- Ice model with birefringence
- Ice layer undulations
- Reconstruction by re-simulation

102 events before, 62 new events found

Re-simulation: event reconstruction by multiple event simulation finiding event parameters fitted to data

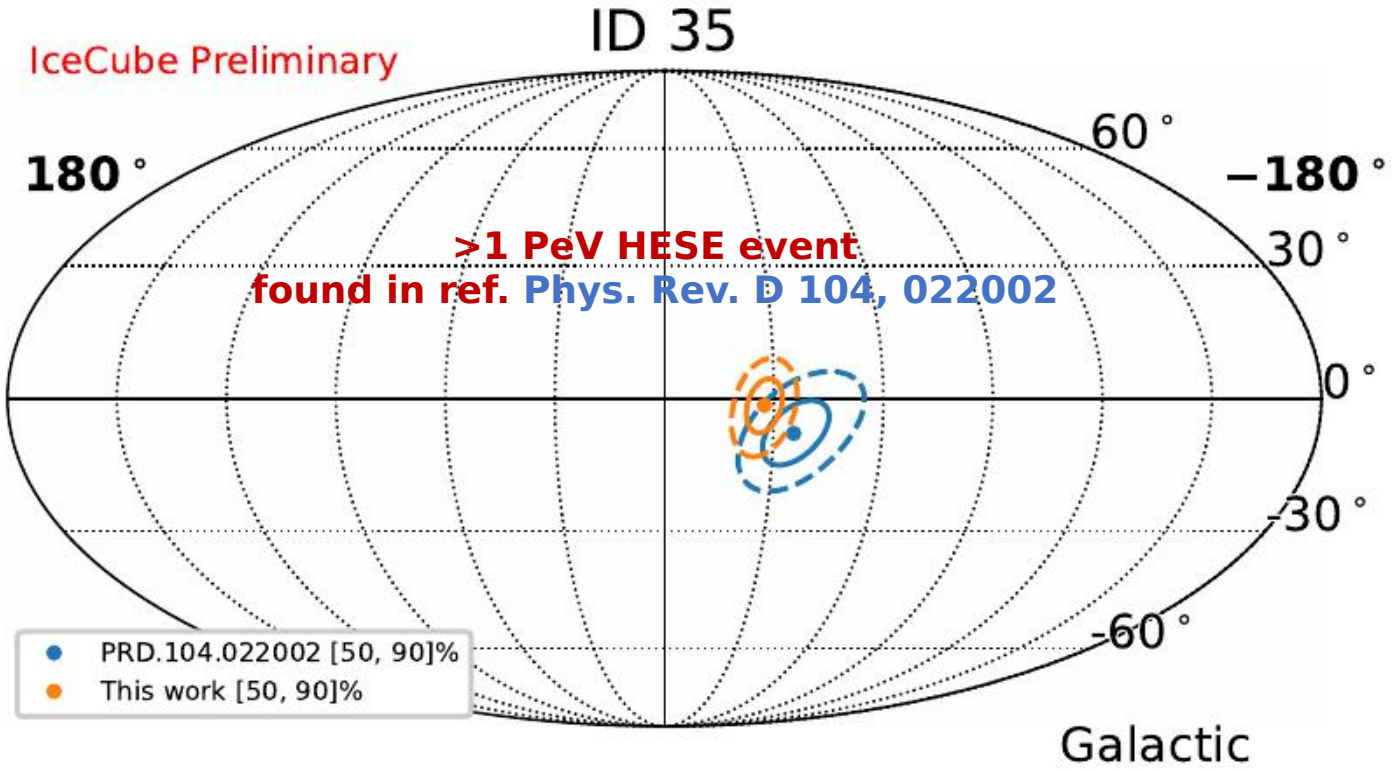
HESE event definition



charge cut: Q_{tot} > 6000 p.e.

IceCube ice properties

Directions of previously found HESE events were updated
Considerable change in direction of some events



Impact on the direction reconstruction:
Main contribution due to improved ice modelling [PoS(ICRC2023)1030]

An update has entered IceCube 12 year data release: https://doi.org/10.7910/DVN/PZNO2T

Systematic uncertainties

Uncertainties in the knowledge of the detector and theoretical calculations affect the measurement results

Main sources of uncertainty in neutrino telescope

- Detection medium properties: Absorption and scattering measurement uncertainties, ice properties
- Sensitivity of optical modules: In-situ optical module sensitivity, module rotations, sedimentations, drill holes (IC)
- Theoretical uncertainties in background fluxes: atmospheric neutrino flux

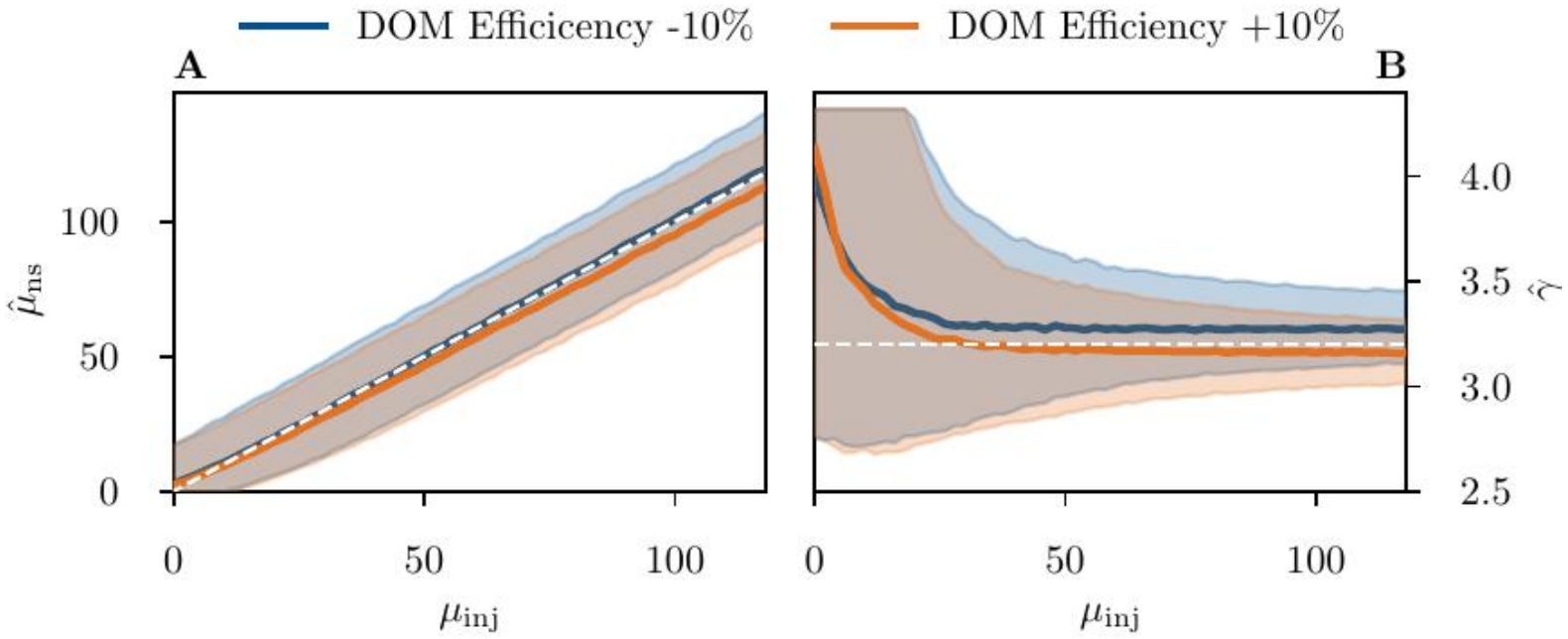
Typically considered systematic uncertainties, e.g. Baikal-GVD diffuse flux **[Phys.Rev.D 107 (2023) 4, 042005]**

- Light absorption +- 5%
- Optical module sensitivity +-10%
- Theoretical: Atmospheric neutrino flux +-15%

Systematic uncertainties

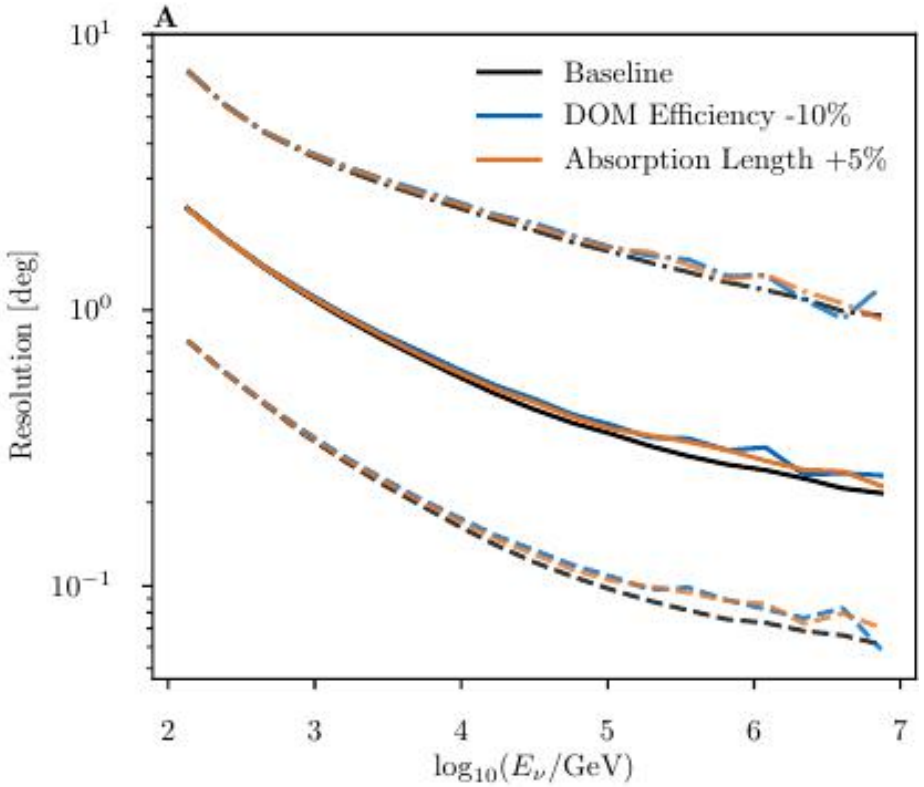
IceCube ν emission from NGC1068 paper, PS tracks
Science 378, 538 (2022)

Considered uncertainties
- Absorption length ±5%
- Scattering length ±5%
- DOM efficiency ±10%
- Angular acceptance due to drill hole: shadowing of head-on photon direction



The largest impact from
- Absorption length +5%
- DOM efficiency -10%

Up to 10% effect on resolution



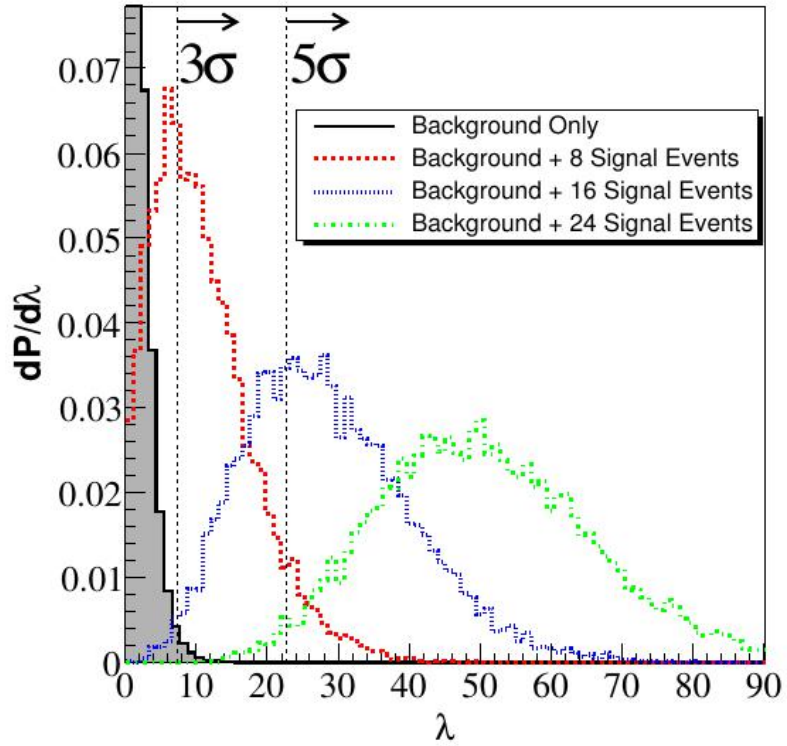
Point source search

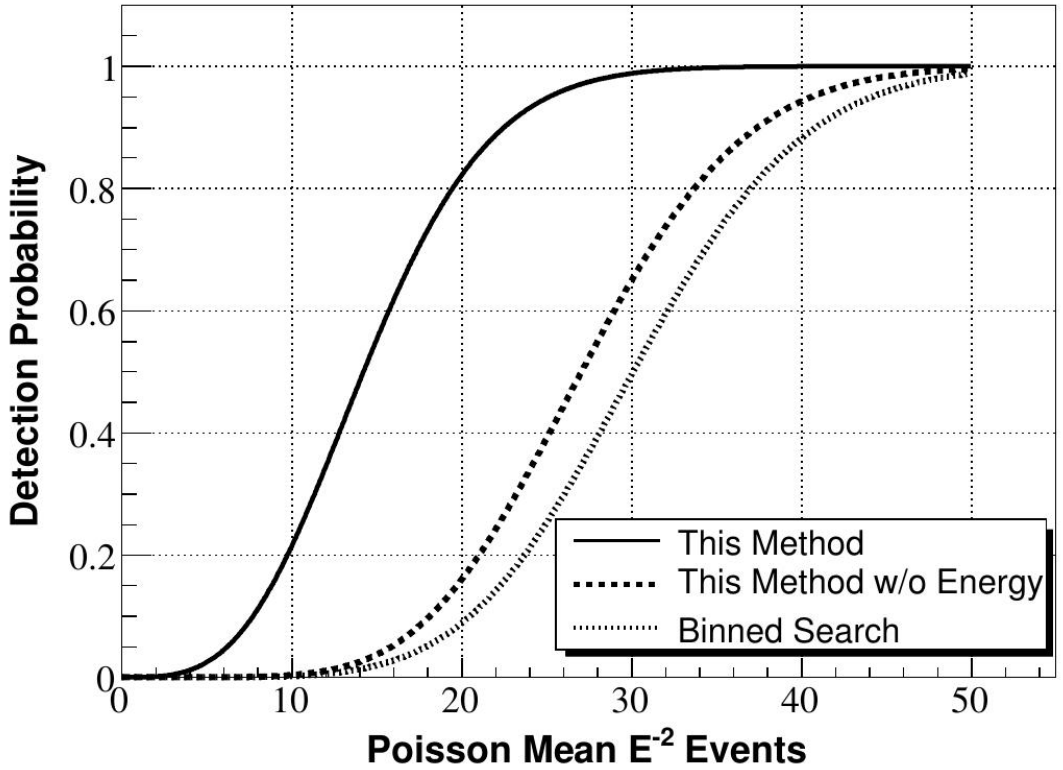
$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_N \left(\frac{n_s}{N} \mathcal{S}_i + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

$$\mathcal{S}_i(\vec{x}_i, \vec{x}_s, E_i, \gamma) = \frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma^2}} P(E_i|\gamma)$$

$$\mathcal{B}_i = P(\vec{x}_i, E_i | \phi_{atm} + \phi_{mu} + \phi_{diffuse})$$

$$\lambda = -2 \cdot sign(\hat{n}_s) \cdot log\left[\frac{\mathcal{L}(\vec{x}_s, 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})} \right]$$





Point source search

Widely used point source unbinned likelihood search approach [J. Braun et. al.,2008]

Fix potential source direction in equatorial coordinates: $\vec{x_s}$

Assume the symmetric detector angular resolution σ

Choose some (RA,dec) region around the source, e.g. 4 σ

Suppose we have a data sample and N events have entered the (RA,dec) region

Evaluate the likelihood function over all data events

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_N \left(\frac{n_s}{N} \mathcal{S}_i + (1 - \frac{n_s}{N}) \mathcal{B}_i \right)$$

Where S_i and B_i are the signal and background probability density functions (PDF)
n_s is the number of signal events, free parameter

Point source search

PDF for signal: $$\mathcal{S}_i(\vec{x}_i, \vec{x}_s, E_i, \gamma) = \frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma^2}} P(E_i|\gamma)$$

data event coordinates

spatial term

spectral term E_i data event energy estimate, **γ is the source spectrum power**

PDF for background: $$\mathcal{B}_i = P(\vec{x}_i, E_i|\phi_{atm} + \phi_{mu} + \phi_{diffuse})$$

Likelihood is maximised with free n_s and γ

- Depending on analysis γ can also be fixed to some value or set of values

The test statistic of the form $$\lambda = -2 \cdot sign(\hat{n}_s) \cdot log\left[\frac{\mathcal{L}(\vec{x}_s, 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})}\right]$$ is used for hypothesis testing

The power of good angular resolution

- The better the angular resolution - the smaller is the (RA, dec) region, the less background enters N
- The test statistic gains larger value for optimal parameters, thus better discovery potential

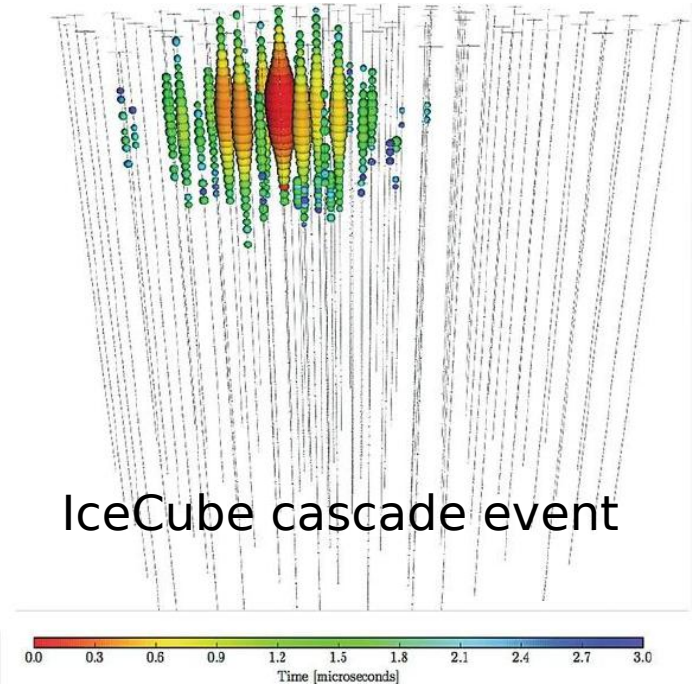
Energy reconstruction

Charge deposited in PMTs is used for cascade or muon energy reconstruction

Cascades:
- Calorimeter-type energy measurement
- Full energy deposition of cascade can be reconstructed

Precision depends on cascade location wrt the detector
- Worse for partially-contanied cascades

Neutrino energy resolution: 10-30%



IceCube cascade event

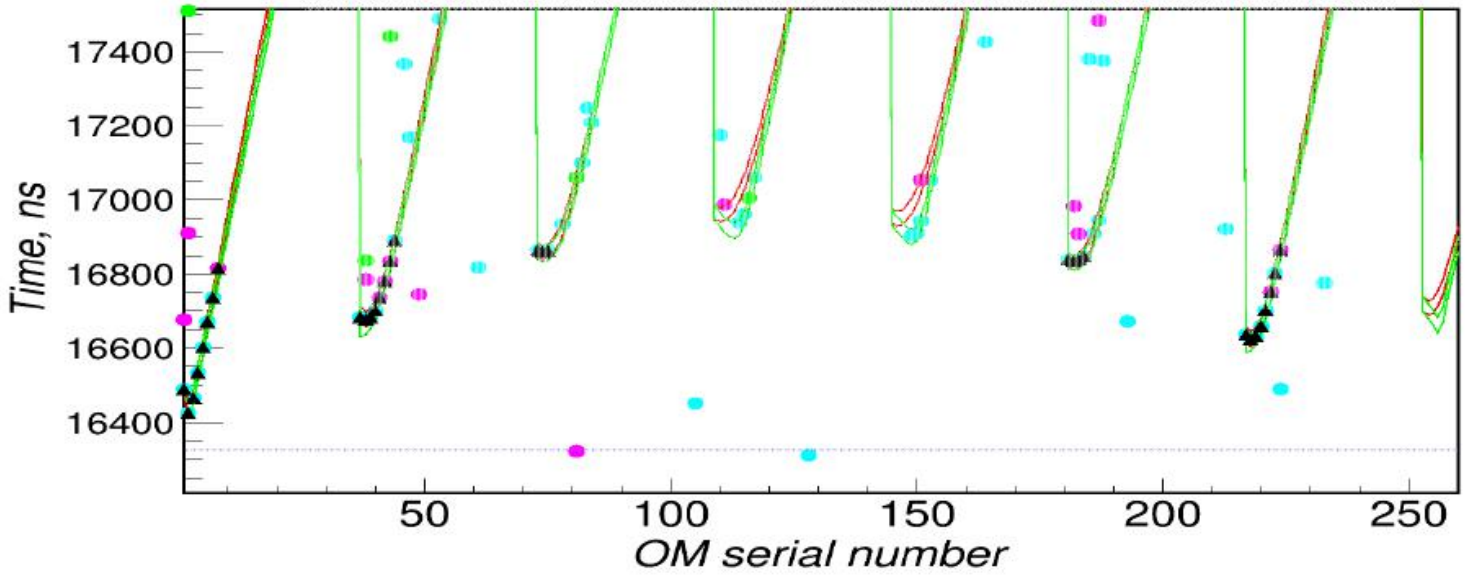
Event GVD200906

Zhan Djilkibaev, Rubakov 70 conference, February 2025

Track reconstruction

Cascade energy – 85 TeV; Zenith angle – 117°

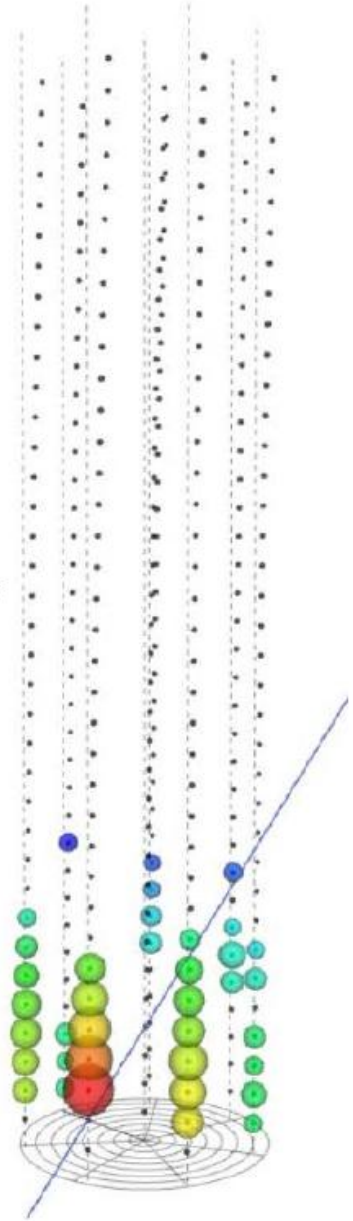
OM hit arrival time



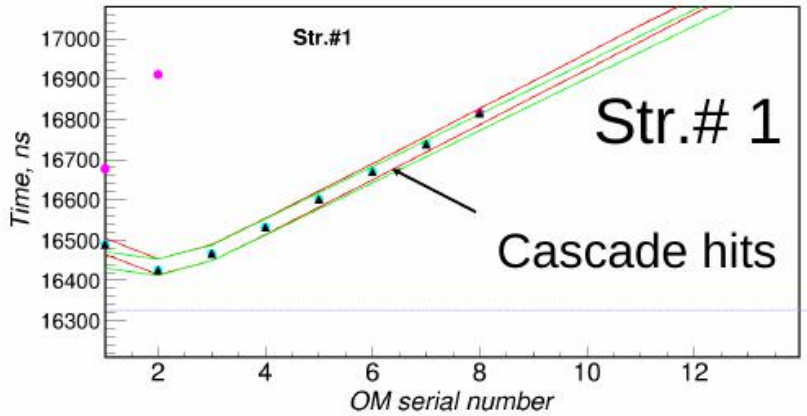
Season 2020,
September
Cluster 5

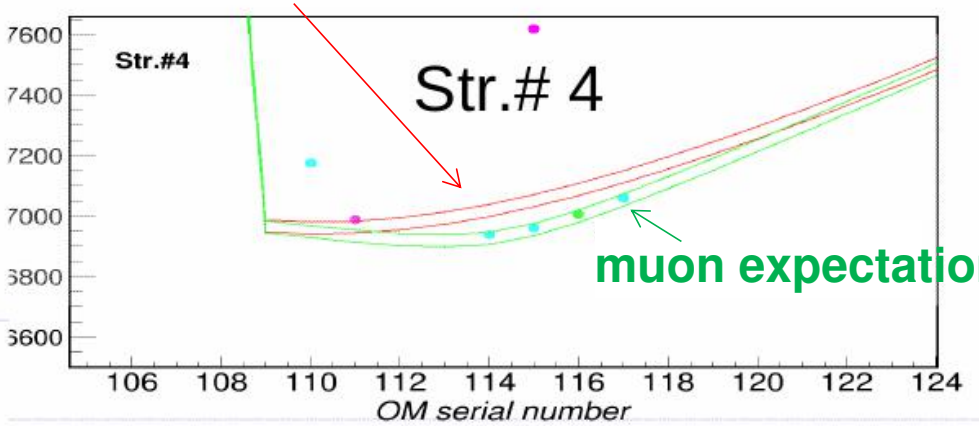
N_{hits} 37
E^{μ}_{rec} 107.2 ТэВ
θ_{rec} 116.7°
L_{track} 140.1 м

Angular precision:
50%: 0.7°
68%: 1.0°
90%: 1.5°

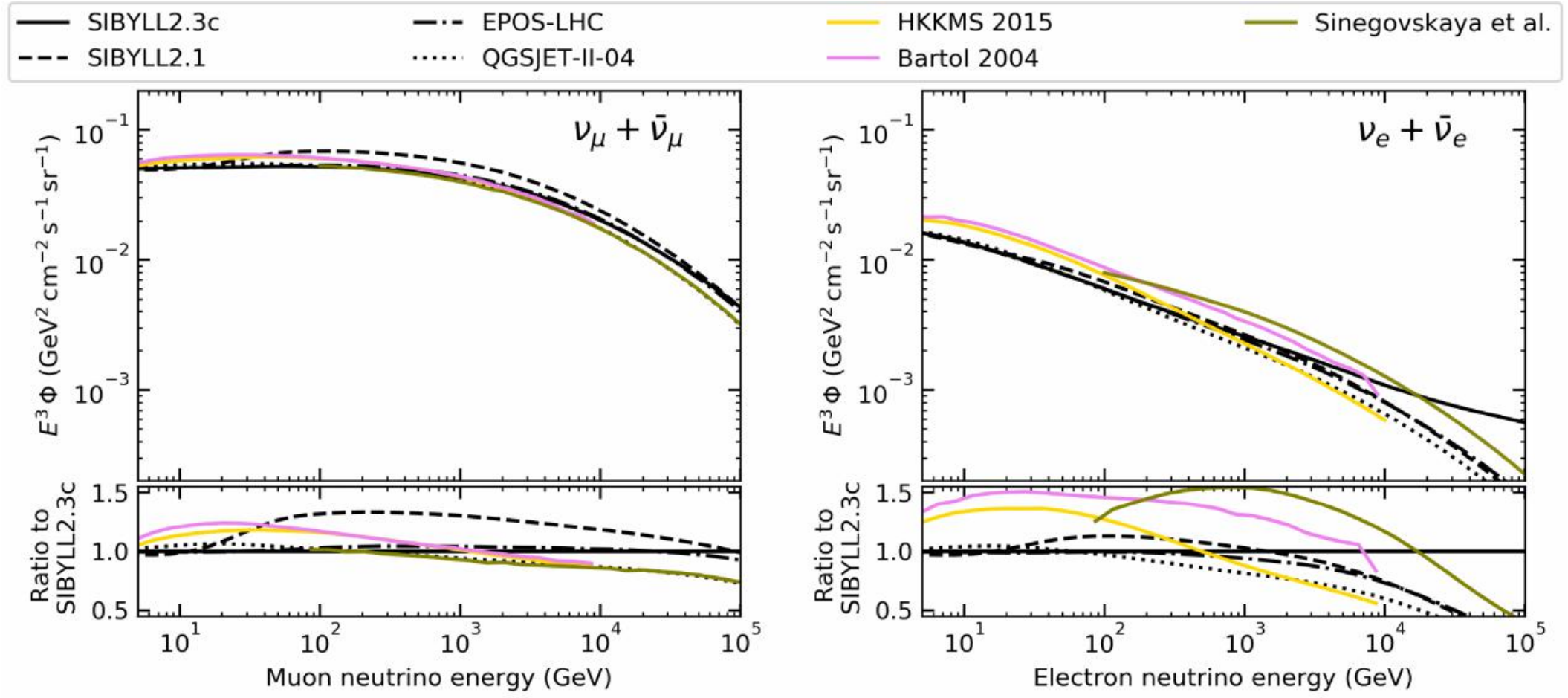


point source expectation





HKKMS: M. Honda et al., PRD 92 (2015)
Bartol: G. Barr et al., PRD 70 (2004)
Sinegovskaya et al. PRD 91 (2015)
MCEq: AF, R. Engel in prep.



A. Fedynich et al. Phys. Rev. D 100, 103018 (2019)

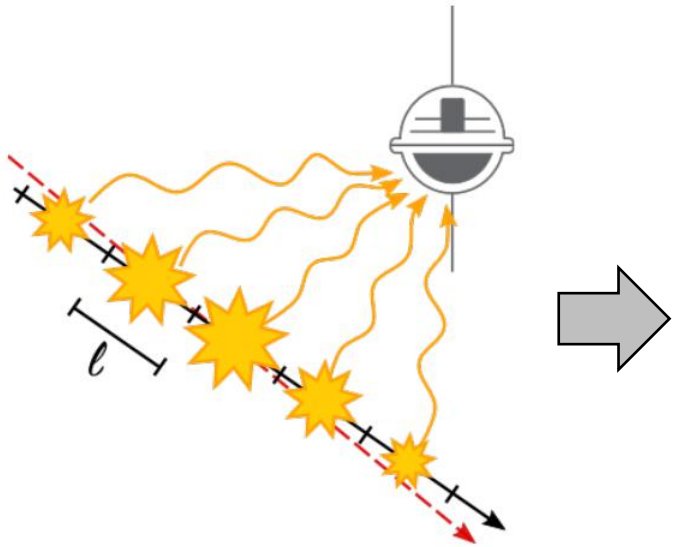
Track event reconstruction in IceCube

Likelihood for all hits at the channel:

$$L(x, y, z, t, \theta, \phi) = \prod_{j=1}^{N_{\mathrm{DOM}}} \prod_{i=1}^{N_{\mathrm{hit}}} [p_j(t_i)]^{q_i}$$

Likelihood for the first photon:

$$L_{1\mathrm{st}}(x, y, z, t, \theta, \phi) = \prod_{j=1}^{N_{DOM}} p_{j,1\mathrm{st}}(t_1)$$



“Plane wave” approximation

Full MIP likelihood with homogenous ice model

First photon MIP likelihood with homogenous ice model

First photon MIP likelihood with realistic ice model

Likelihood with realistic ice model accounting for EM showers at stochastic energy losses

PREVIOUS ALGORITHMS

GAUSSIAN PDF (LEAST-SQUARE)

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GAMMA PDF

seed

GAMMA PDF (L_{1st})

seed

B-SPLINE PDF (L_{1st}) (“SPLINERECO”)

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COMPOSITE B-SPLINE PDF (“SEGMENTEDSPLINERECO”)

NEW ALGORITHM

JINST 16 P08034