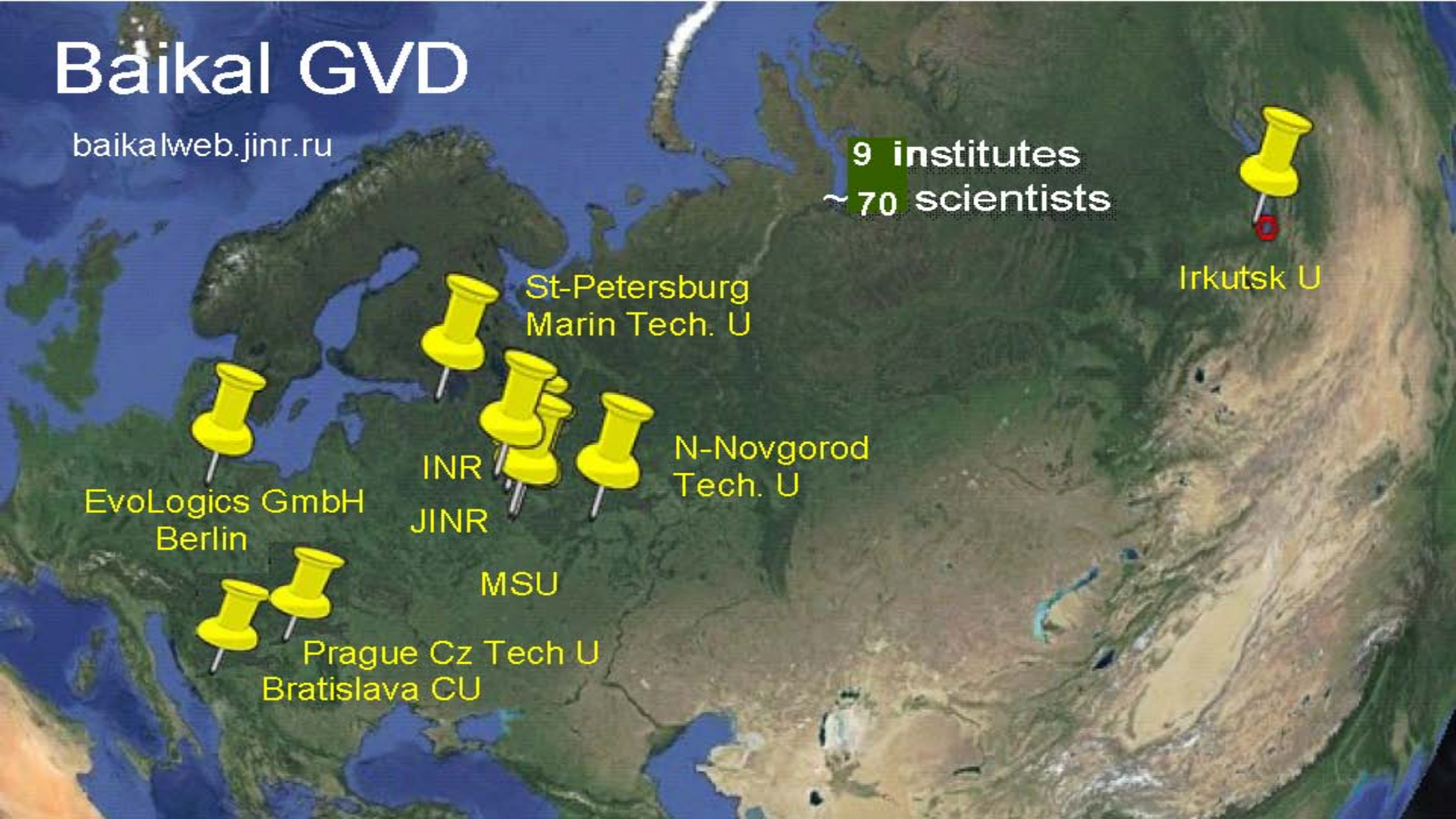
The Baikal-GVD: first results

Zh.-A. Dzhilkibaev,
for the Baikal Collaboration
APC Paris-December, 11-14, 2018


Baikal GVD
baikalweb.jinr.ru
9 institutes
~70 scientists
Irkutsk U
St-Petersburg
Marin Tech. U
N-Novgorod
Tech. U
INR
JINR
EvoLogics GmbH
Berlin
MSU
Prague Cz Tech U
Bratislava CU

Gigaton Volume Detector (GVD) in Lake Baikal

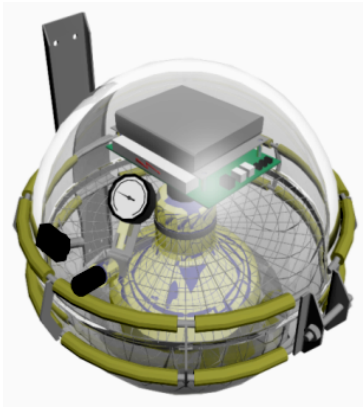
Objectives:

- km3-scale 3D-array of photo sensors
- flexible structure allowing an upgrade and/or a rearrangement of the main building blocks (clusters)
- high sensitivity and resolution of neutrino energy, direction and flavor content

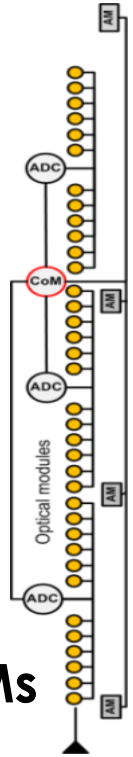
Central Physics Goals:

- Investigate Galactic and extragalactic neutrino "point sources" in energy range > TeV
- Diffuse neutrino flux – energy spectrum, local and global anisotropy, flavor content
- Transient sources (GRB, …)
- Dark matter – indirect search
- Exotic particles – monopoles, Q-balls, nuclearites, …

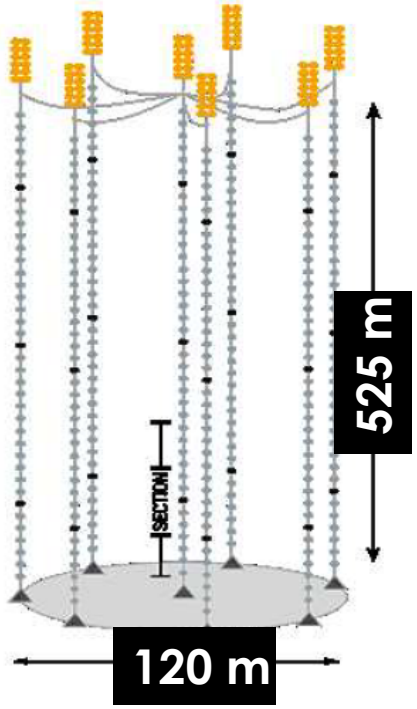
Baikal-GVD : phase 1 (up to 2021)



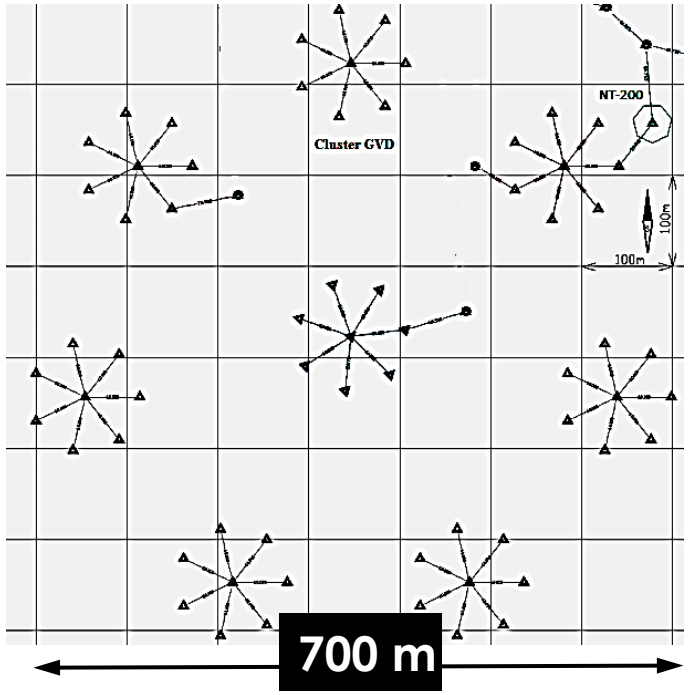
Optical module



String: 36 OMs



Cluster: 8 strings



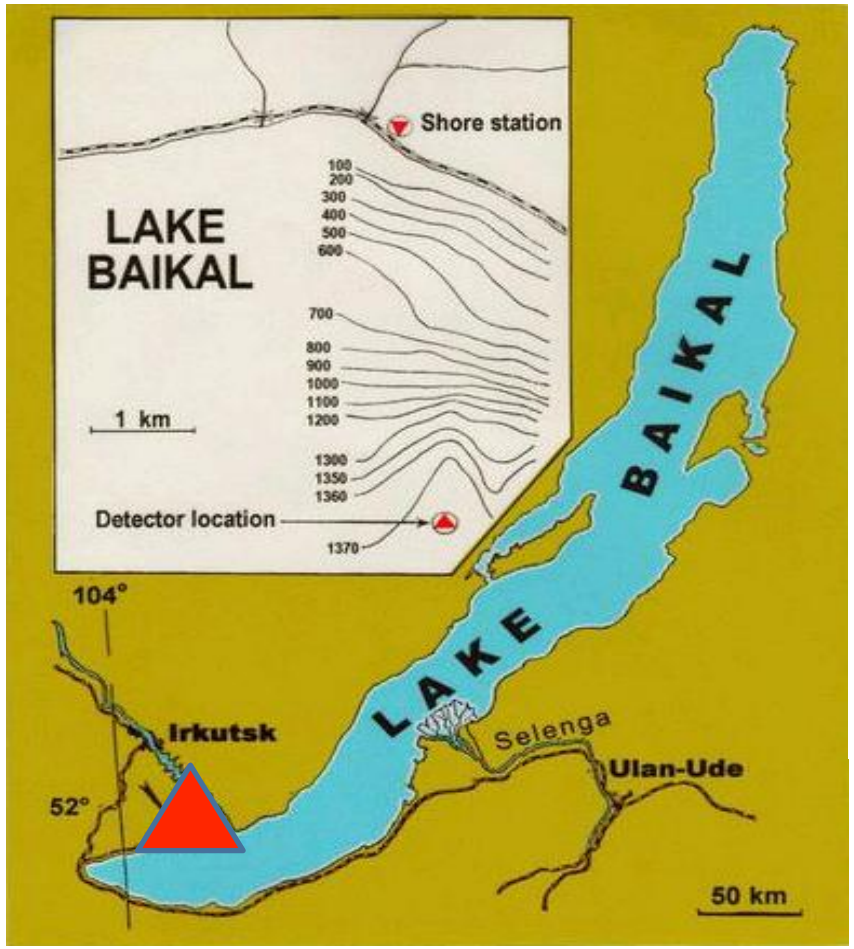
GVD-1: 8 clusters

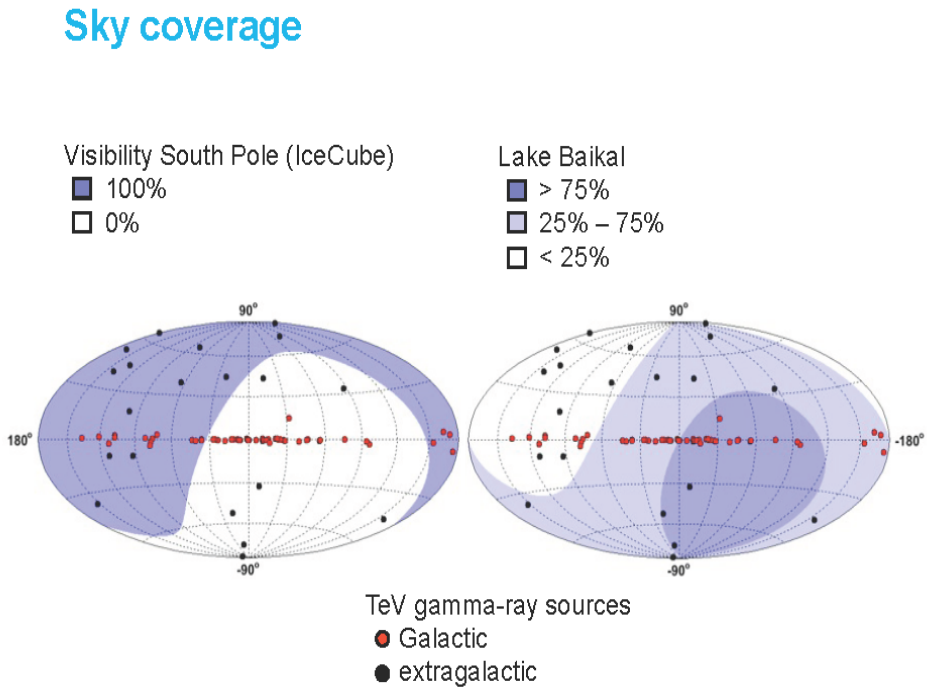
	GVD-1
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume (E_{SH} > 100 TeV)	0.4 km^3

Directional resolution	Energy resolution
Cascades: ~3°	δ (E/Esh) ~ 0.15
Muons: 0.25° - 0.5°	δ (lgE) ~ 0.4

- **Location: 104º25’ E; 51º46’ N**

Northern hemisphere– GC (~18h/day) and Galactic plane survey





The site

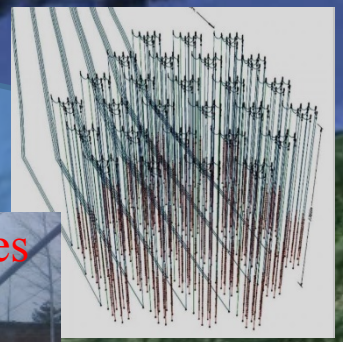
Location: 104°25’ E; 51°46’ N

Shore station

36 km

Baika’lsk

Workshop&Storage facilities



Site:

- 1370 m maximum depth
- Distance to shore ~4 km
- No high luminosity bursts from biology.
- No K^{40} background.

Baikal water

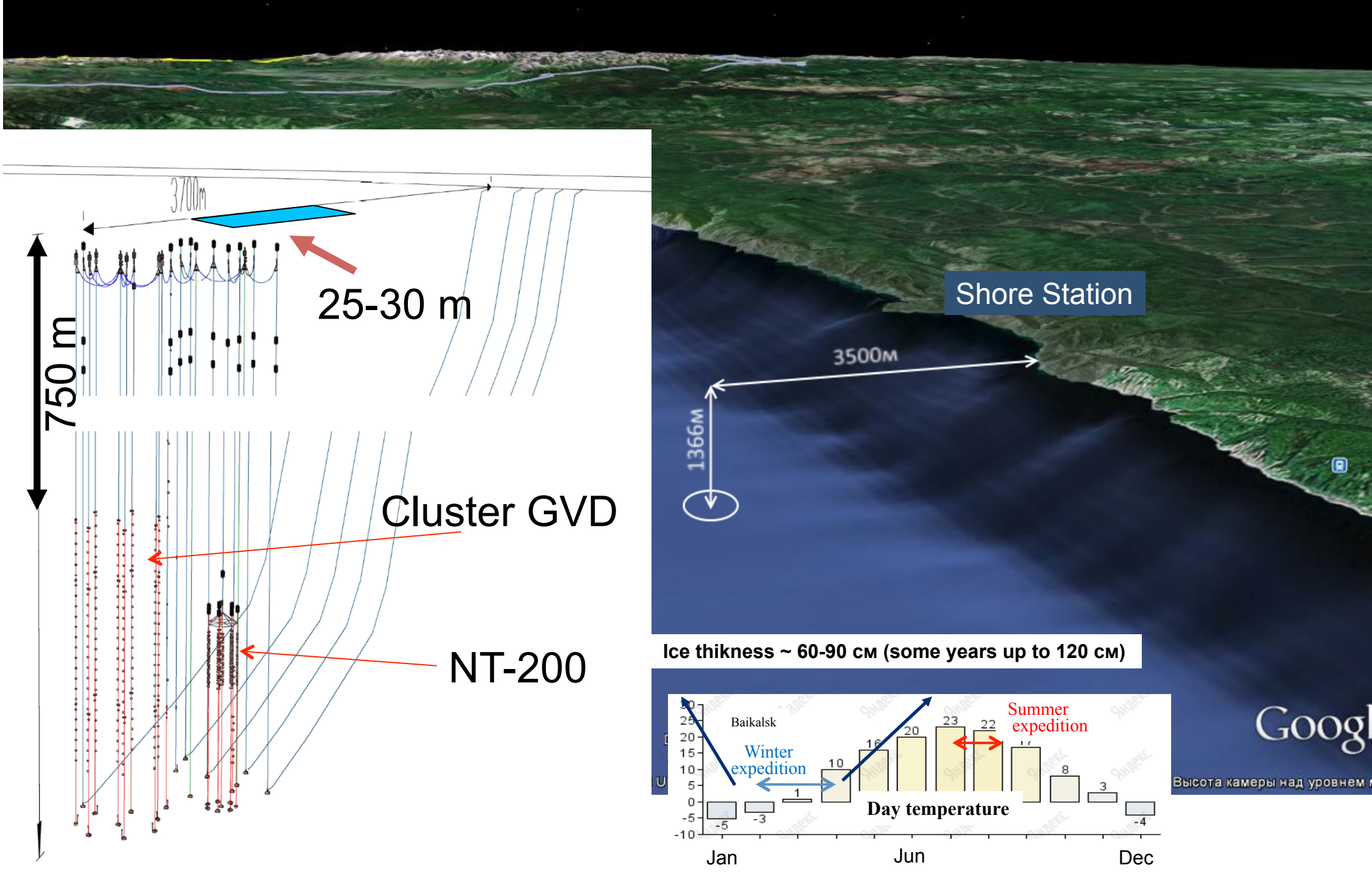
Abs.Length: 22 ± 2 m

Scatt.Length: 30-50 m

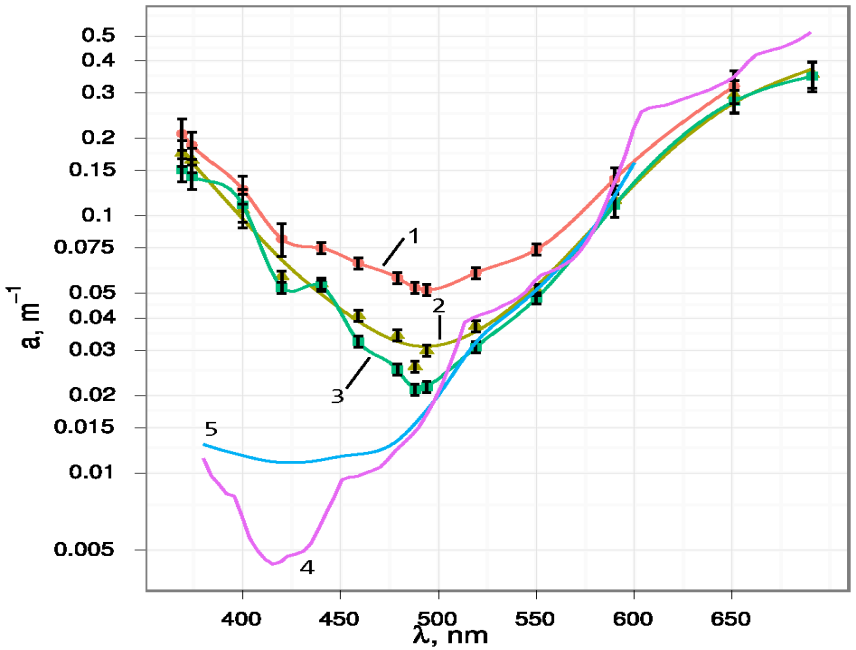
Data INTAS Project 99-1669

Image Landsat

Google earth

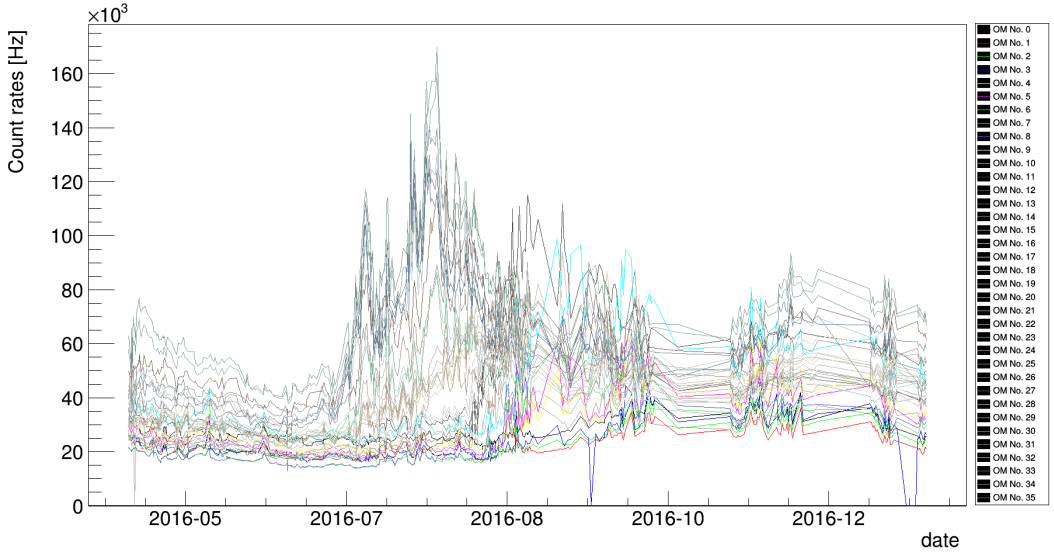

3700m
25-30 m
750 m
Cluster GVD
NT-200
Shore Station
3500м
1366м
Ice thikness ~ 60-90 см (some years up to 120 см)
Baikalsk
Winter expedition
Summer expedition
Day temperature
Jan
Jun
Dec
Высота камеры над уровнем

Water properties



- **Absorption length: ~ 22-24 m**
- **Scattering length: L_s ~ 30-50 m**
  $L_{eff} = L_s /(1- \langle\cos\theta\rangle)$ ~ 300-500 m
- **Strongly anisotropic phase function: $\langle\cos\theta\rangle \sim 0.9$**

Count rates versus time for string No. 1



- **Moderately low background in fresh water:**

  15 – 40 kHz (R7081HQE)
  absence of high luminosity bursts from biology and K^{40} background.

South Baikal in Feb and Apr

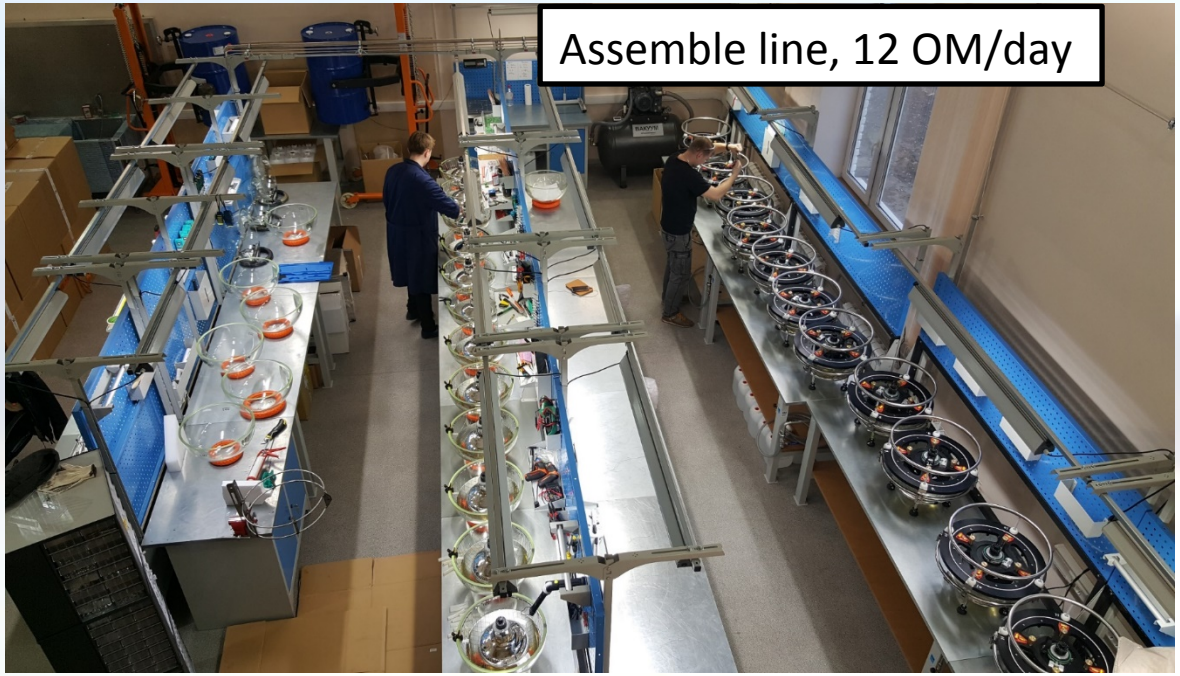
Ice thikness ~ 60-90 см (some years up to 120 см)

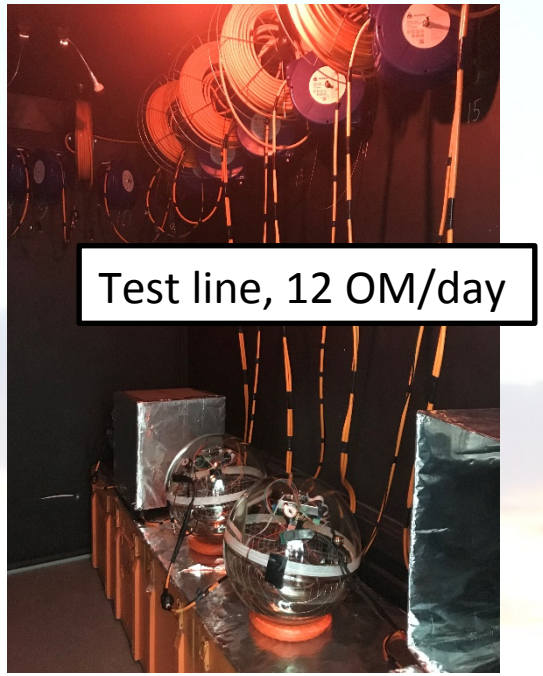
Infrastructure (site)

Status:

- ✓ The DUBNA cluster installed on April 2015 has been upgraded to a final state one with 288 optical modules in 2016 spring . The second cluster started to operate on April 2017 and the third one in April 2018.
- ✓ The new data taking center at the array site has been installed.
- ✓ The new shore lab was installed on the site during summer 2017.
- ✓ The building in Baikalsk is prepared for a local lab and a temporary storage for optical modules of the next stages of the detector.

JINR FACILITIES FOR THE OPTICAL MODULES PRODUCTION





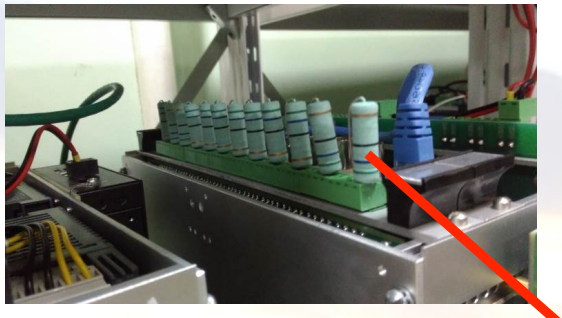
Now we have 450 OMs ready to use: ~1.5 clusters

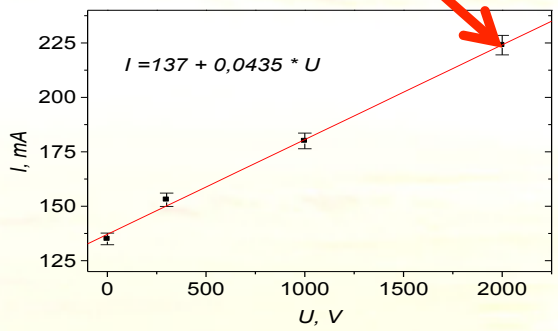
Equipment allows to assemble and test up to 12 OMs per day

INR TEST FACILITIES FOR THE DAQ ELECTRONICS

Facility is designed for long-term tests of all cluster components with full power load.

String electronics:
3 Section modules and String module (36 ADC channels).





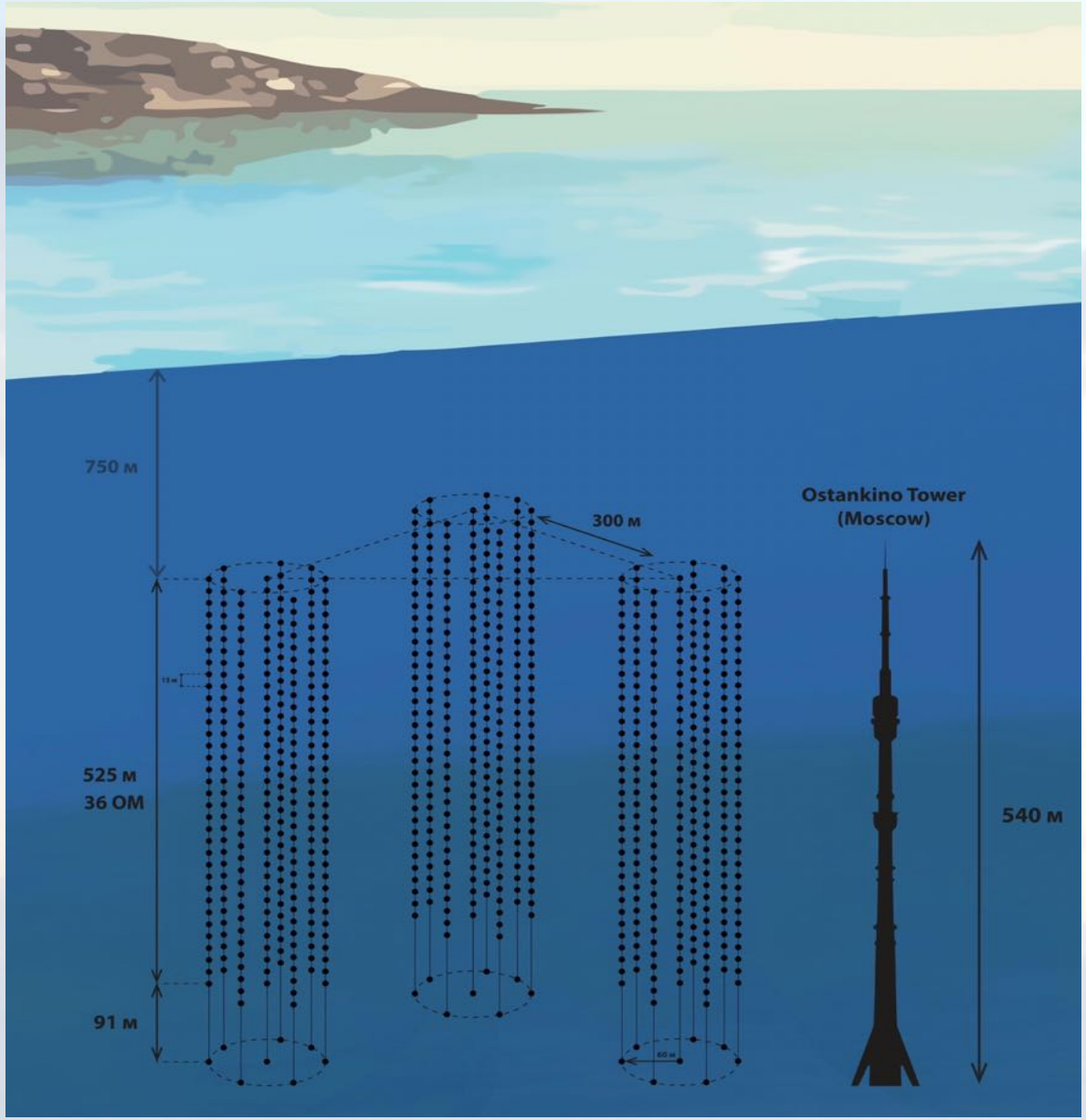
6 strings (216 ADC channels) is under testing now

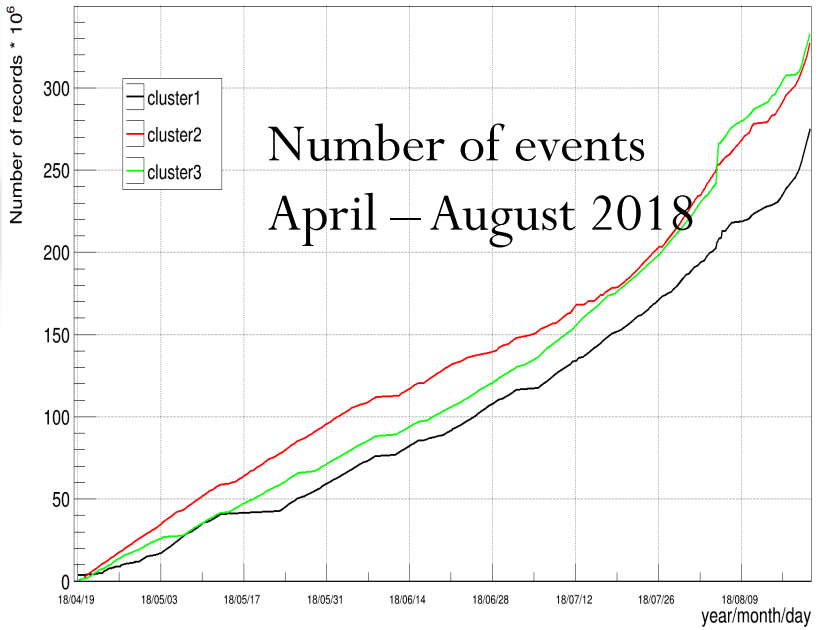
- Signals on the ADC are simulated by generators with an adjustable frequency.
- Software for data acquisition is the same as for real telescope.

Stages of deployment of the Baikal-GVD

Configuration	2015	2016	2017	2018
The number of OMs	192 (8str×24)	288 (8str×36)	576	864
Geometric sizes	∅80m×345m	∅120m×525m	2×∅120m×525m	3×∅120m×525m
Eff. Vol. (E > 100TeV)	0.03 km^3	0.05 km^3	0.1 km^3	0.15 km^3

Status-2018 of Baikal-GVD



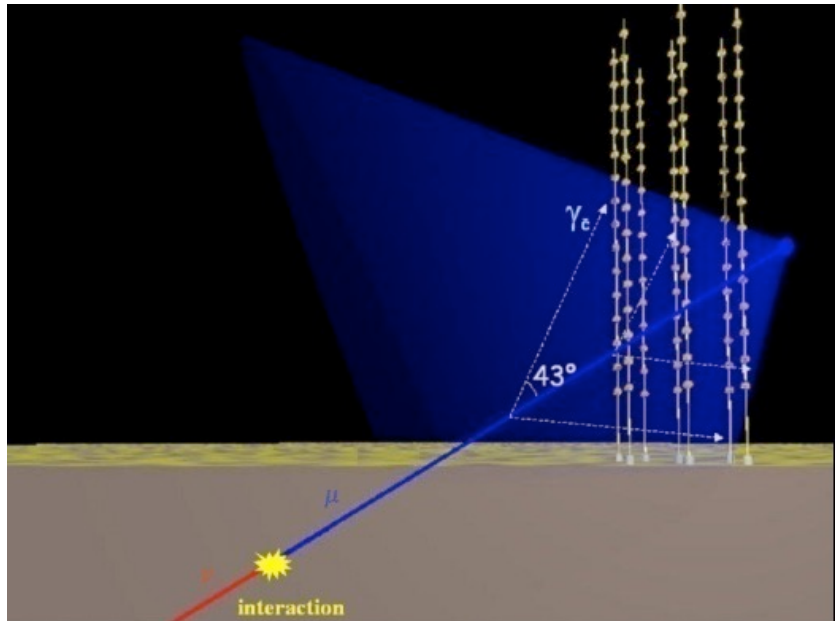


Data transmission

- 40 Gb per cluster per day to shore
- 5 Mb/s 40 km radio channel to Baikalsk

Detection Modes – cascades&muons

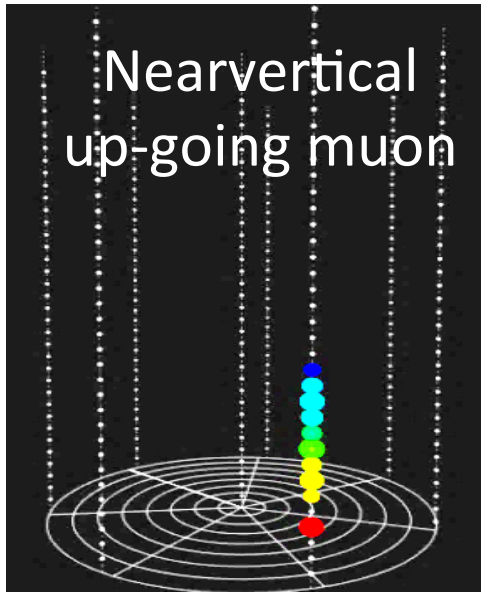
μ/casc. ~ 1/3 for 1:1:1

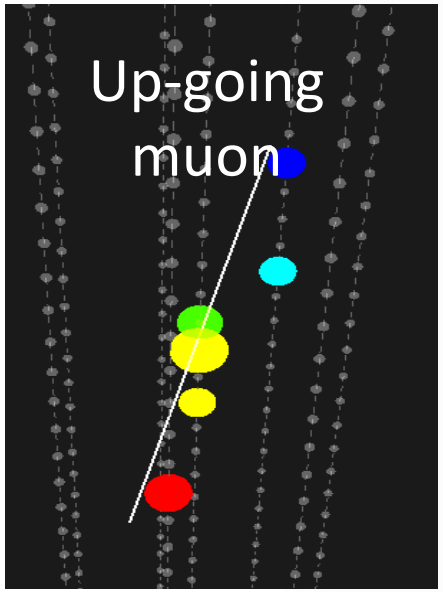


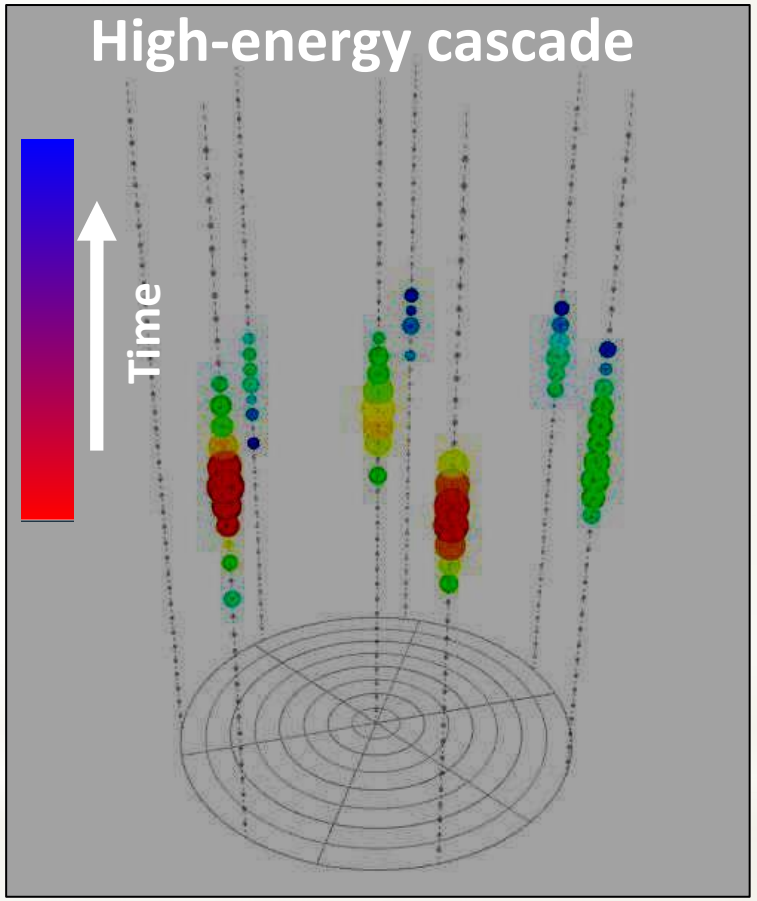
Detector response

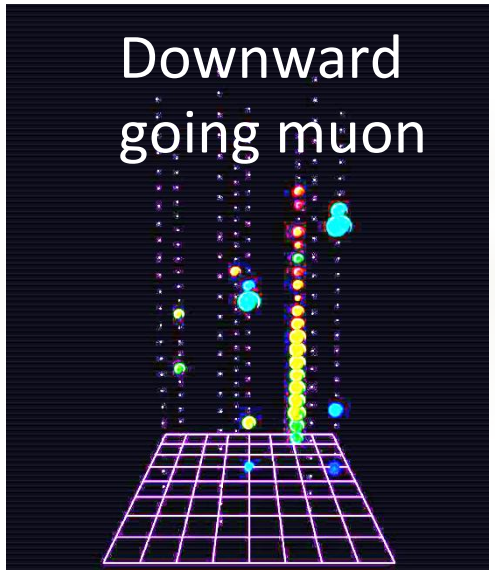
Neutrino signals

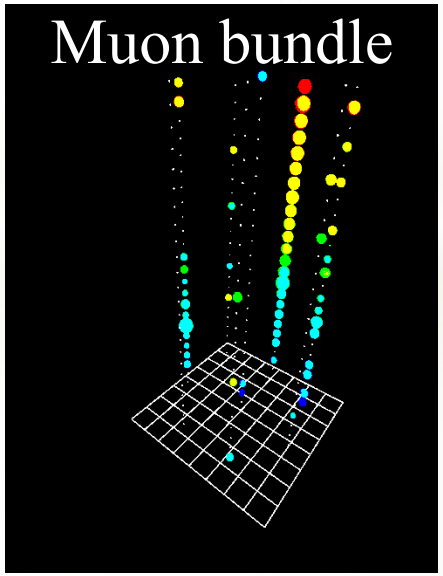
Background



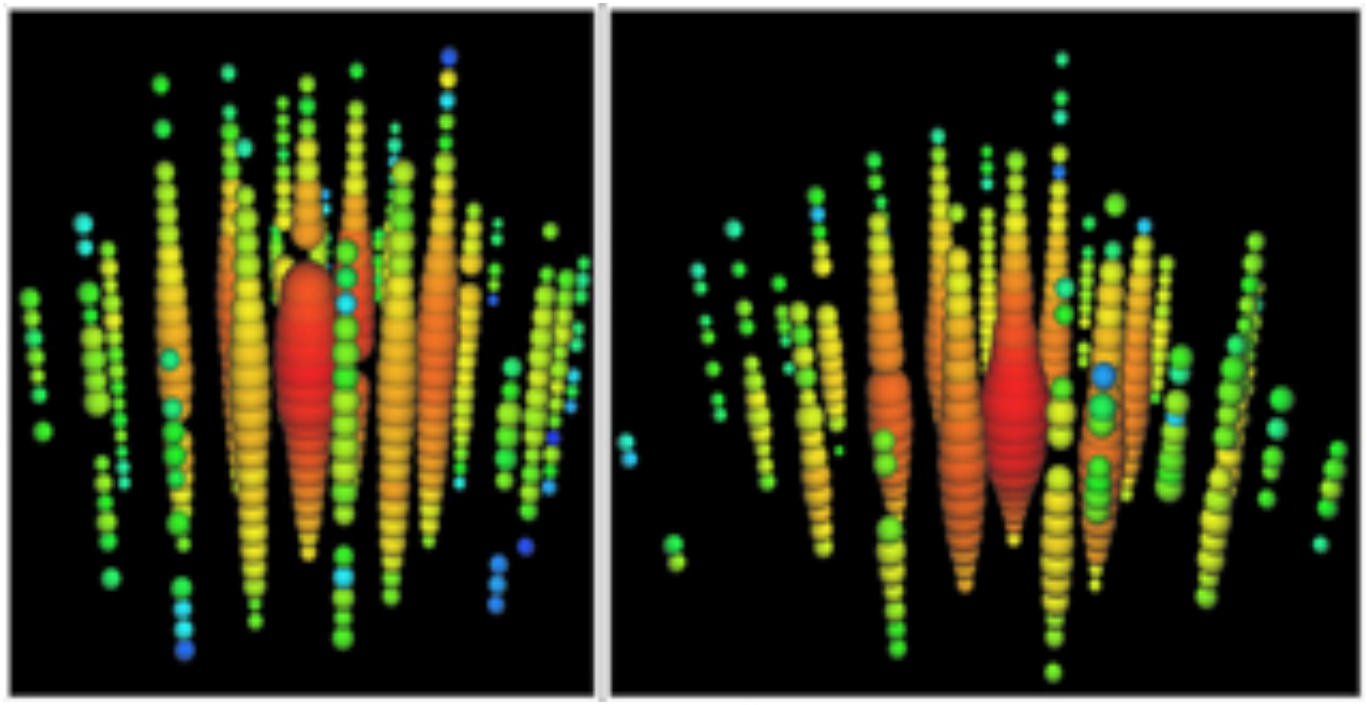








Ernie and Bert

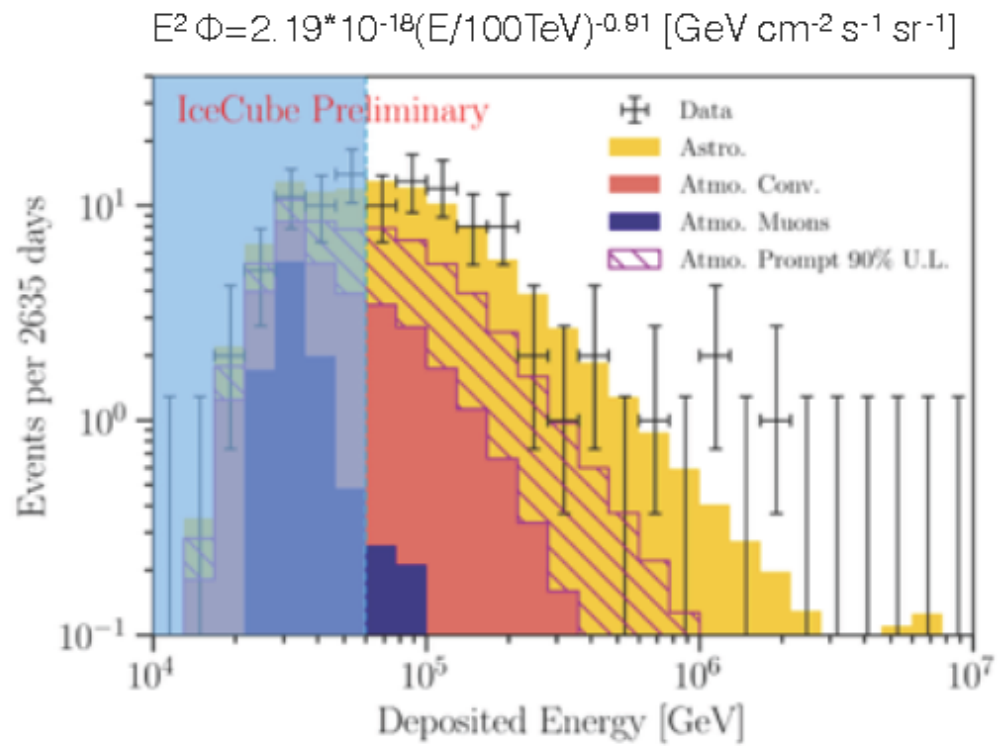


”Bert”
1.04 PeV
Aug. 2011

”Ernie”
1.14 PeV
Jan. 2012

Diffuse Astrophysical Neutrino Flux

- Best fit single powerlaw $2.19^{+1.10}_{-0.55} \times E^{-2.91(+0.33,-0.22)}$
- Prompt 90% upper limit 12.3× BERSS model
- Fit performed for events above 60TeV
- Compatible with results from 6 year analysis



All energies – 102 events

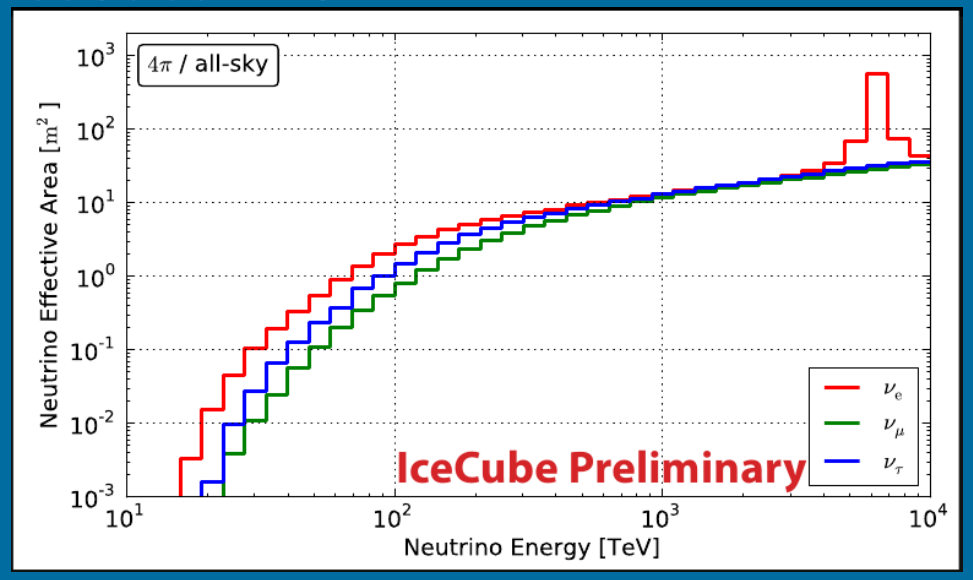
> 60 TeV - 60 events

Honda, Kasahara, Midorikawa, Sanuki
Phys.Rev. D75 (2007) 043006
Bhattacharya, Enberg, Reno, Sarcevic, Stasto
JHEP 1506 (2015) 110

Cascades detection with GVD Cluster

Neutrino Effective Area

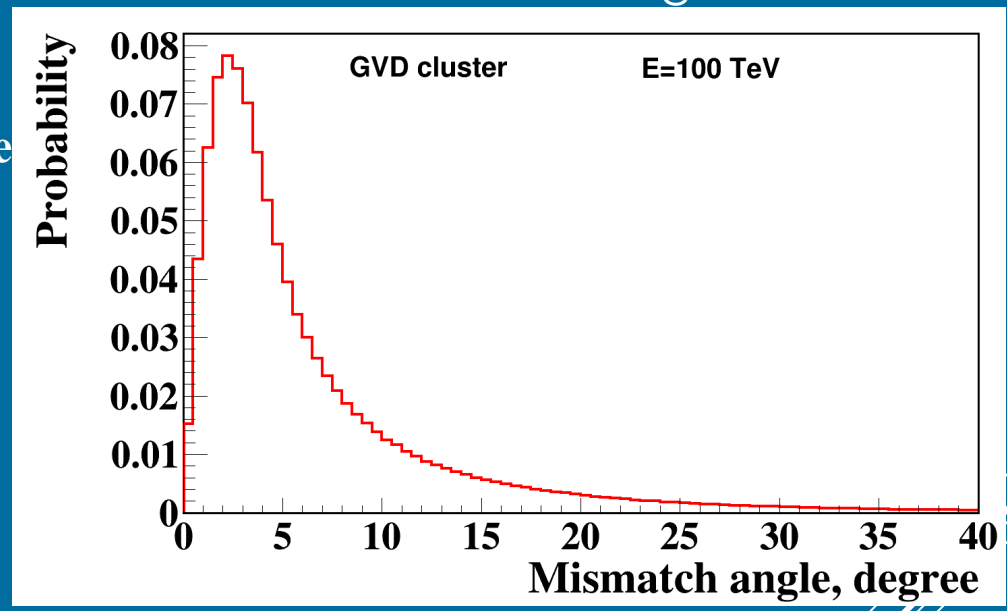
IceCube HESE



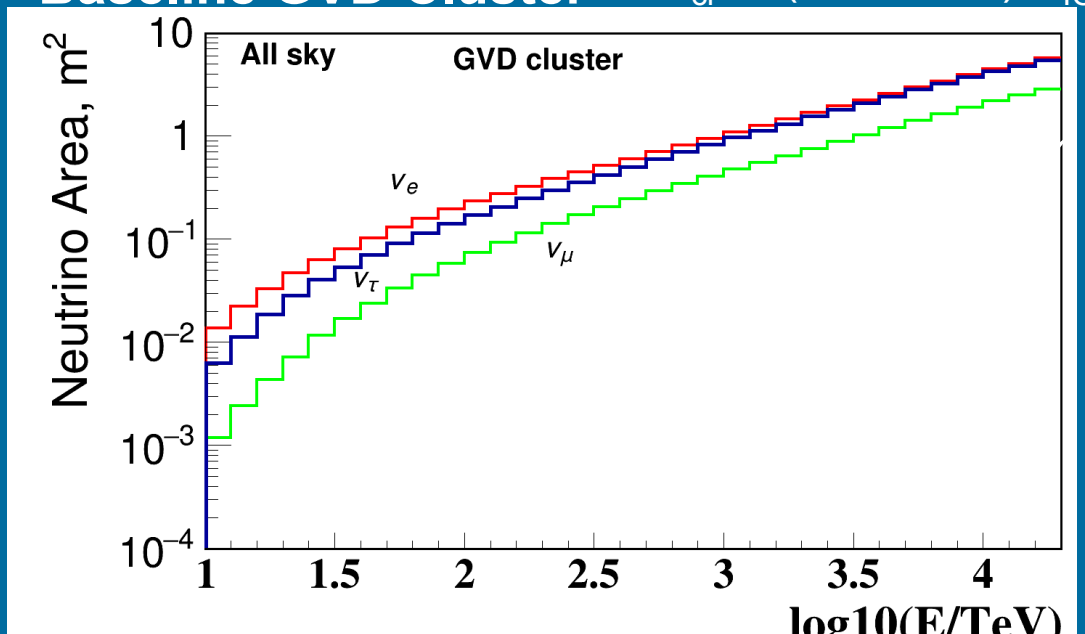
Directional resolution for cascades:

~ 3°- 4° - median value of mismatch angles

Distribution of mismatch angles



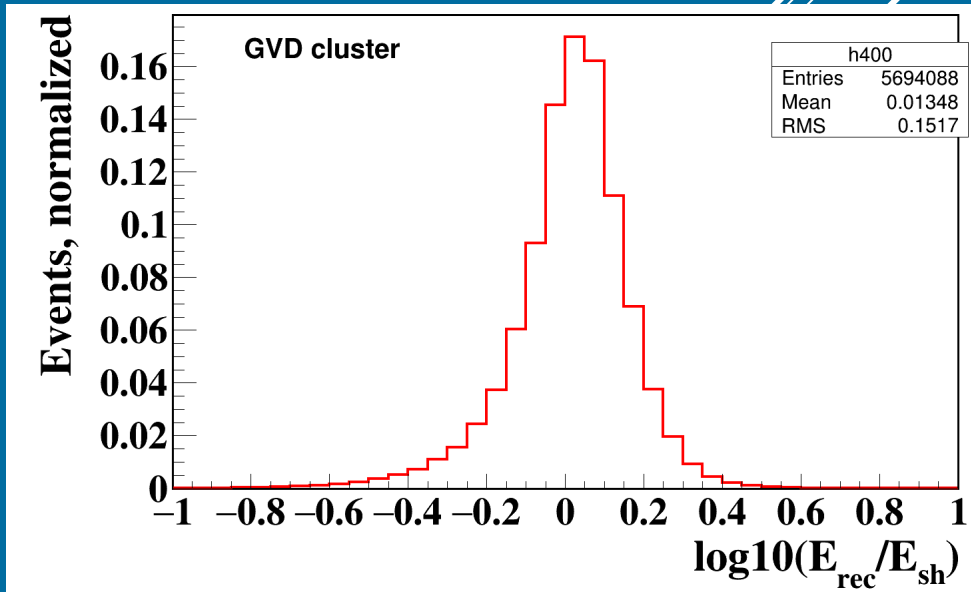
Baseline GVD Cluster S_{cl} ~ (0.05 - 0.1) S_{IC}



Energy resolution :

δE/E ~ 30%

averaged by E^{-2} ν_e spectrum



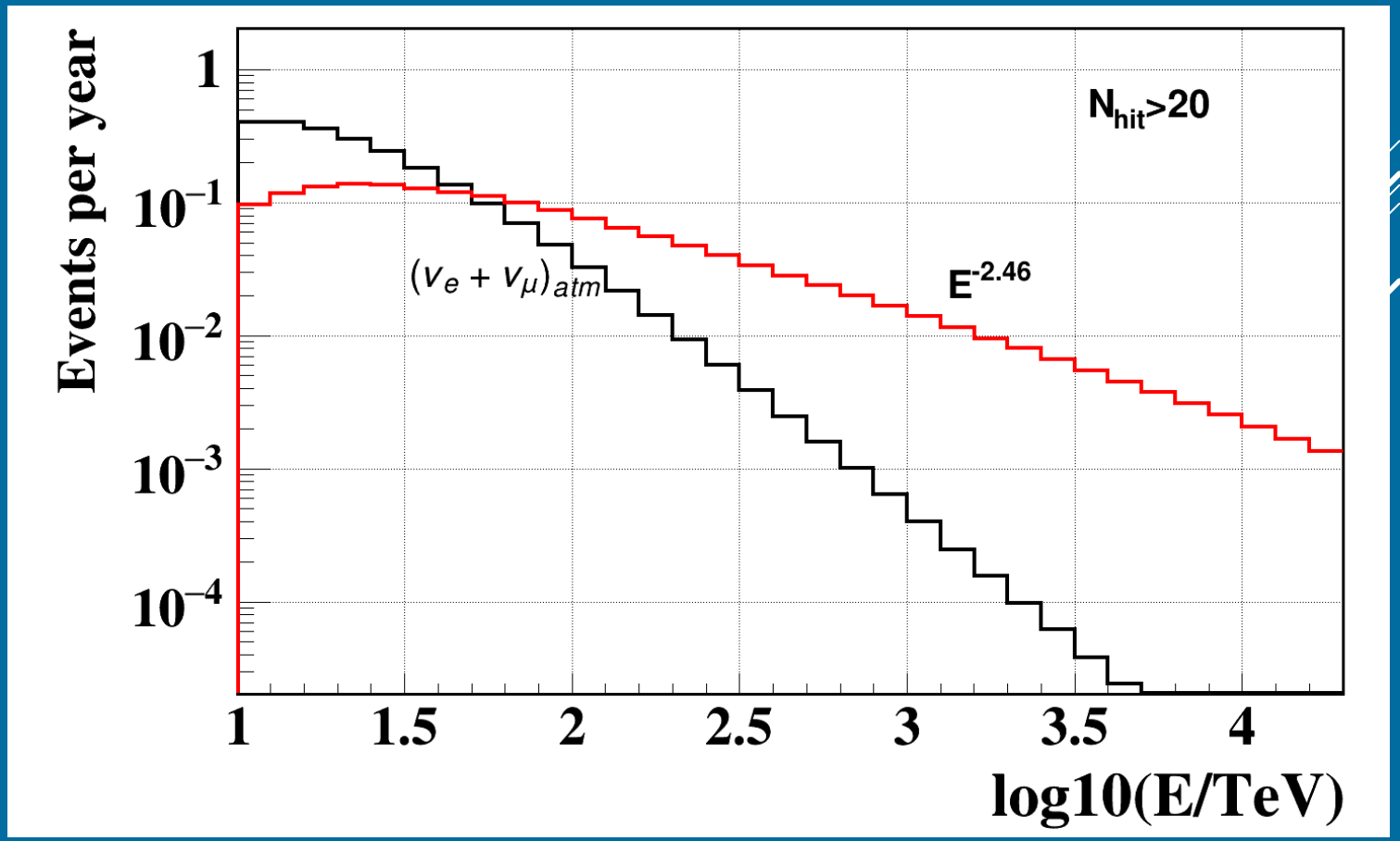
Energy spectrum of astrophysical neutrinos measured by IceCube:

$4.1 \cdot 10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

Event selection criteria (E_{sh} >100 TeV, N_{hit} >20):

~0.6 events/yr are expected

Expected number of detected events in GVD Cluster from astrophysical neutrinos for 1 yr. observation



A search for cascades induced by astrophysical neutrinos

(analysis of 2015 data – ***PRELIMINARY!***)

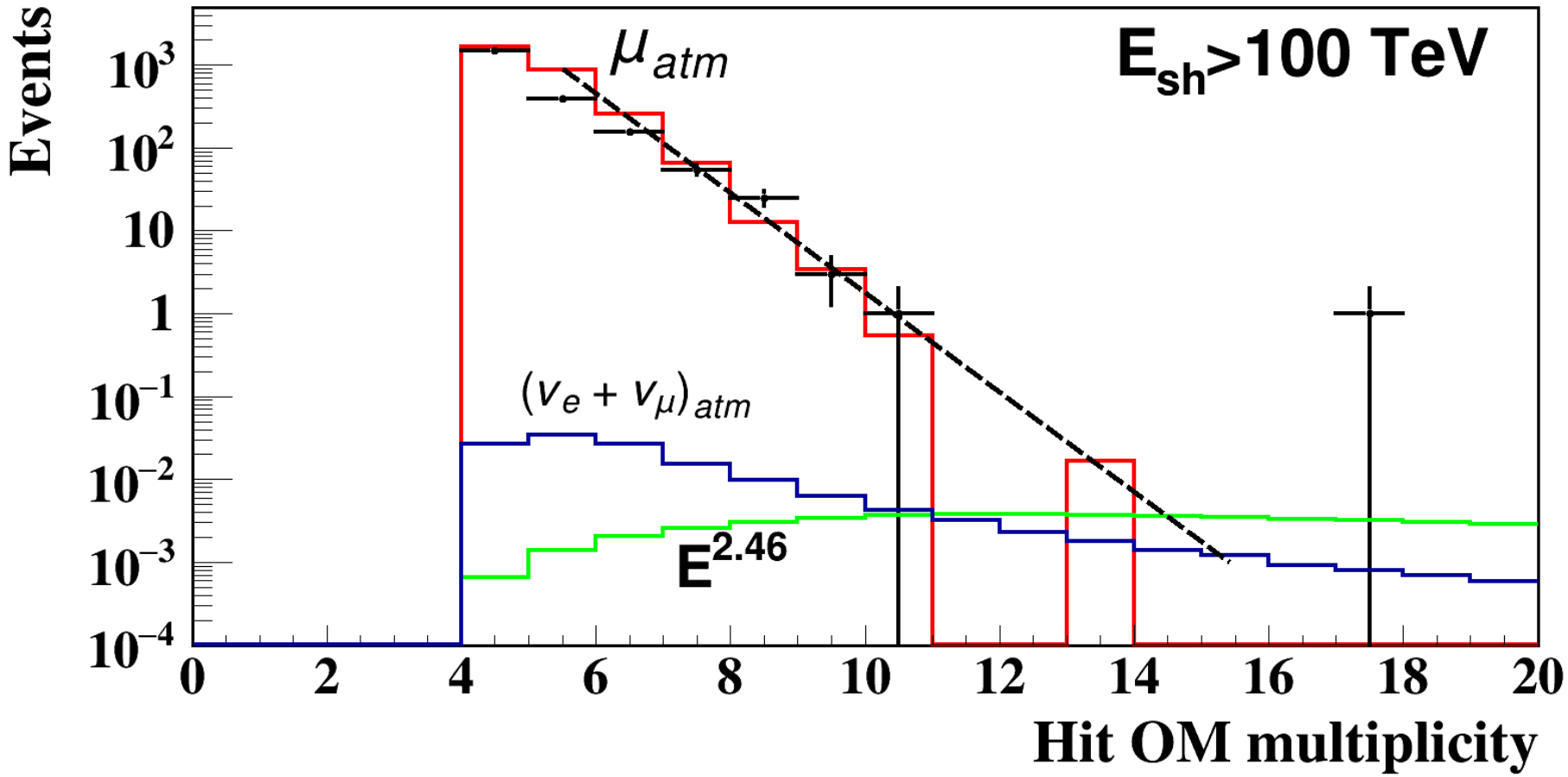
- Total number of accumulated events – 437 970 024 events
  (thresholds: low/high = 1.5/4 ph.el.)

- Life time – 3 597 921 s = 41.6 days

- After causality cuts – 18 840 822 events

  ($N_{hit} > 3$; $|t_i - t_j| < \Delta r_{ij}/v + \delta t$)

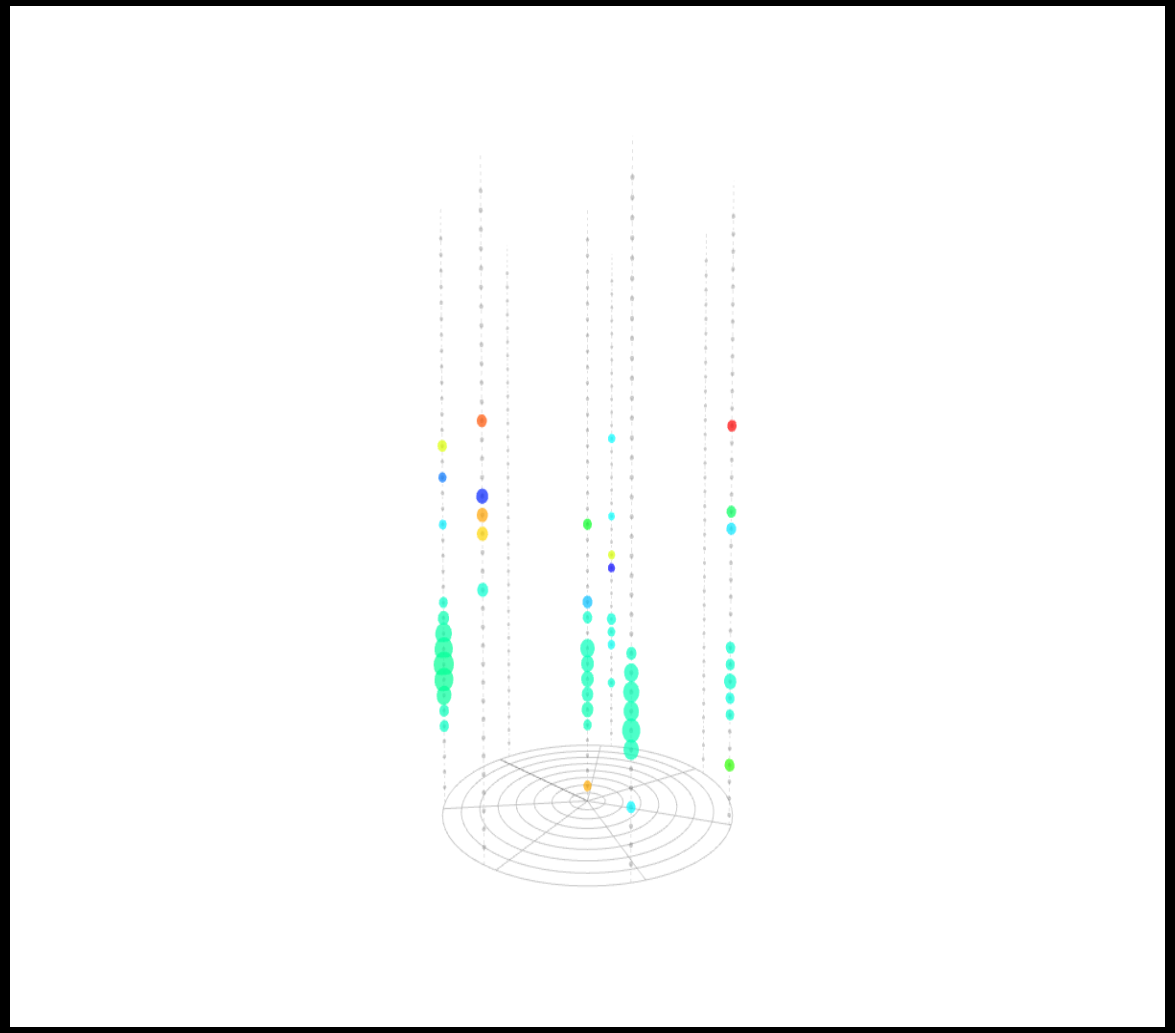
Hit OMs multiplicity after all cuts



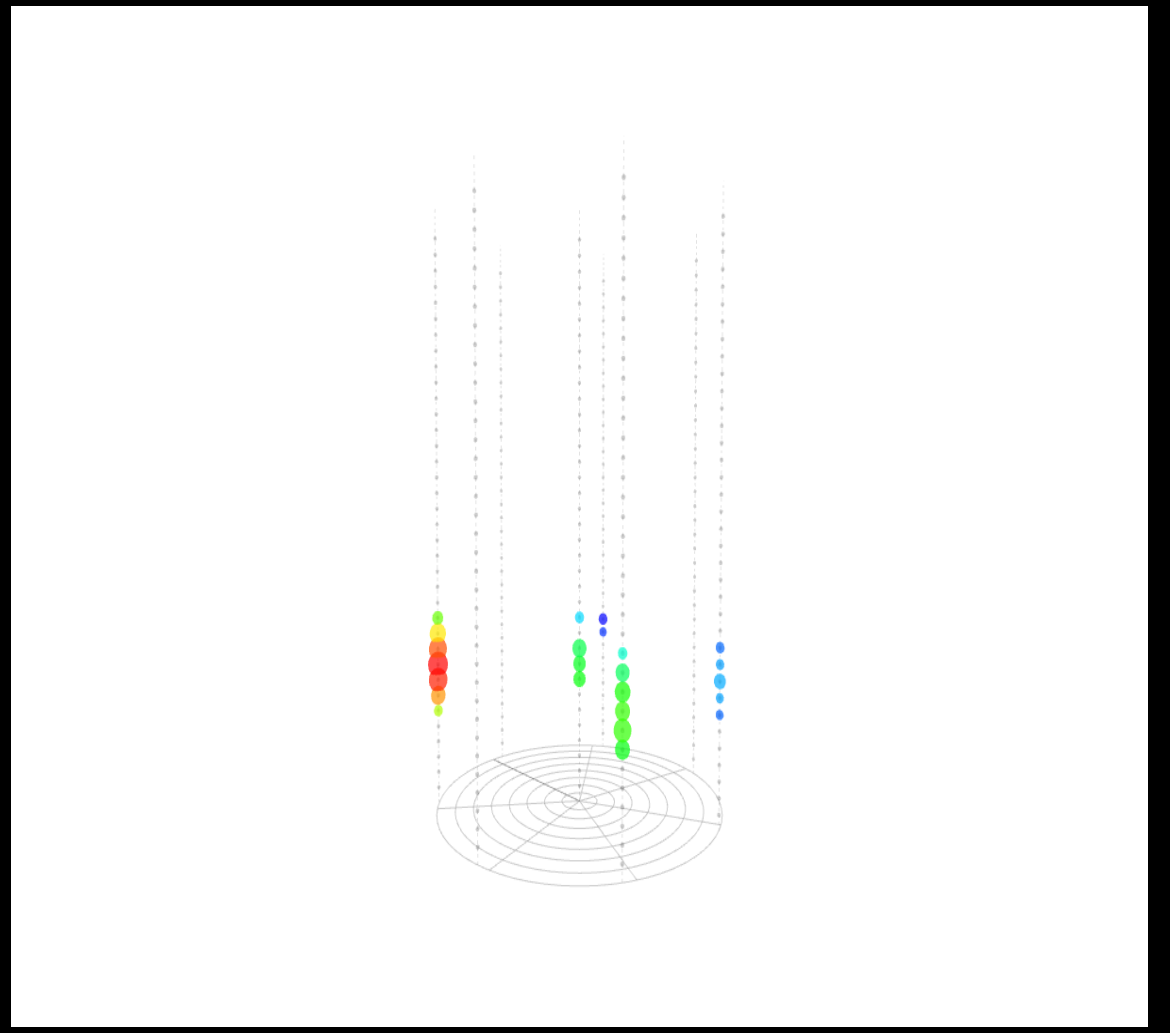
	$E^{-2.46}$	atm. ν_e	atm. ν_μ	atm. ν (total)
Probability of N_{hit} >16 OM:	0.047	0.0015	0.0026	0.0041

Cascade: E=107 TeV, θ = 56.6°, φ = 130.5°
x=-48.5 m, y=47m, z=-59 m, ρ=68 m

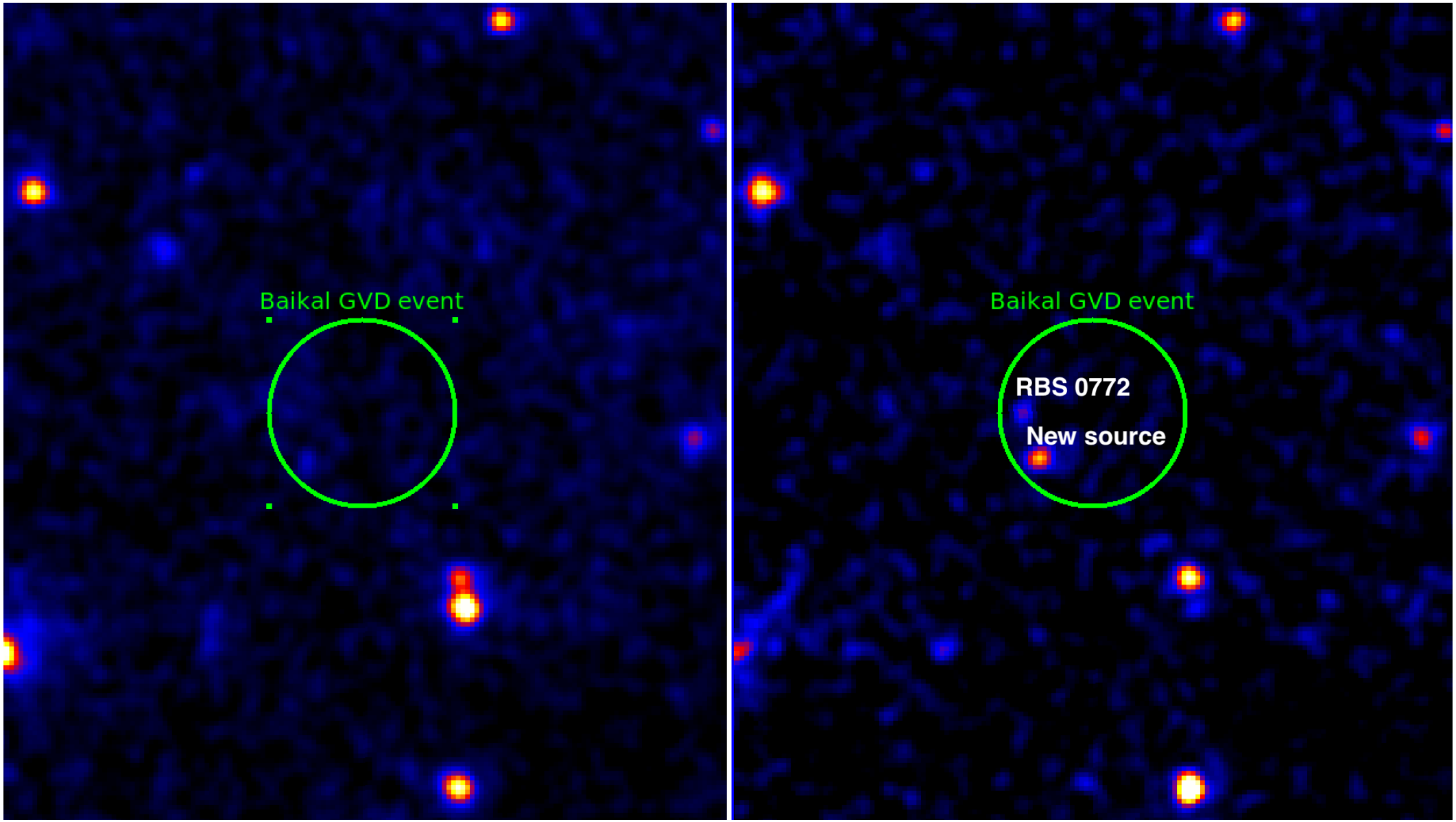
All hit OMs (51 hits)



Selected hits (24 hits)



1. MJD 0.573420552199E+05 RA 139.5° Dec 5.56°



A search for cascades induced in GVD-2016 (*Preliminary)*

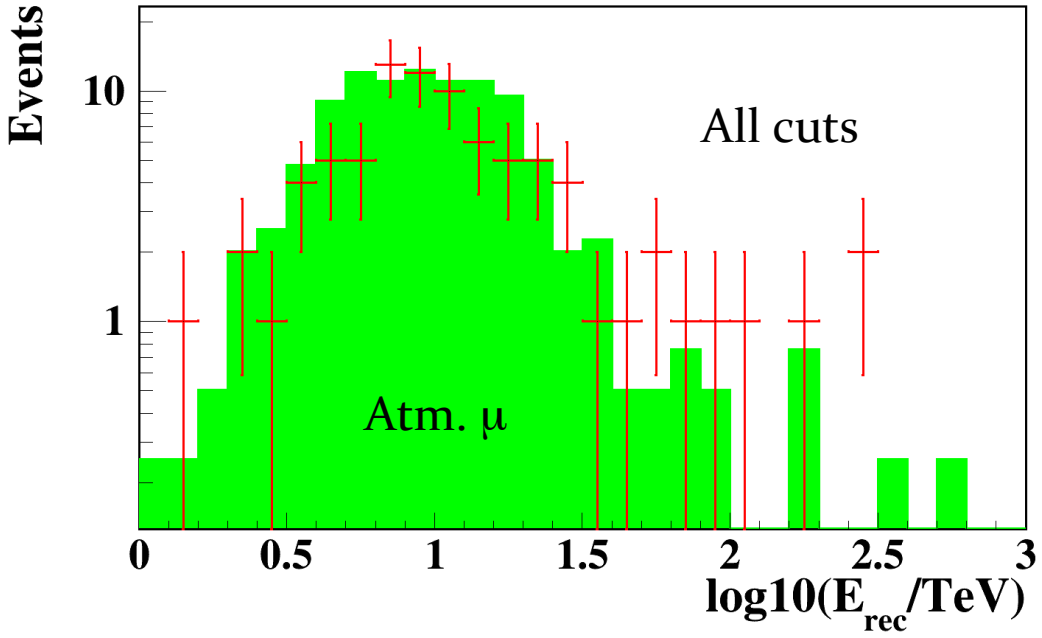
- Life time – 15 693 192 s = 182.0 days

- Total number of accumulated events – 685523932 events
  (thresholds: low/high = 1.5/4 ph.el. & Q >1.5 ph.el.)

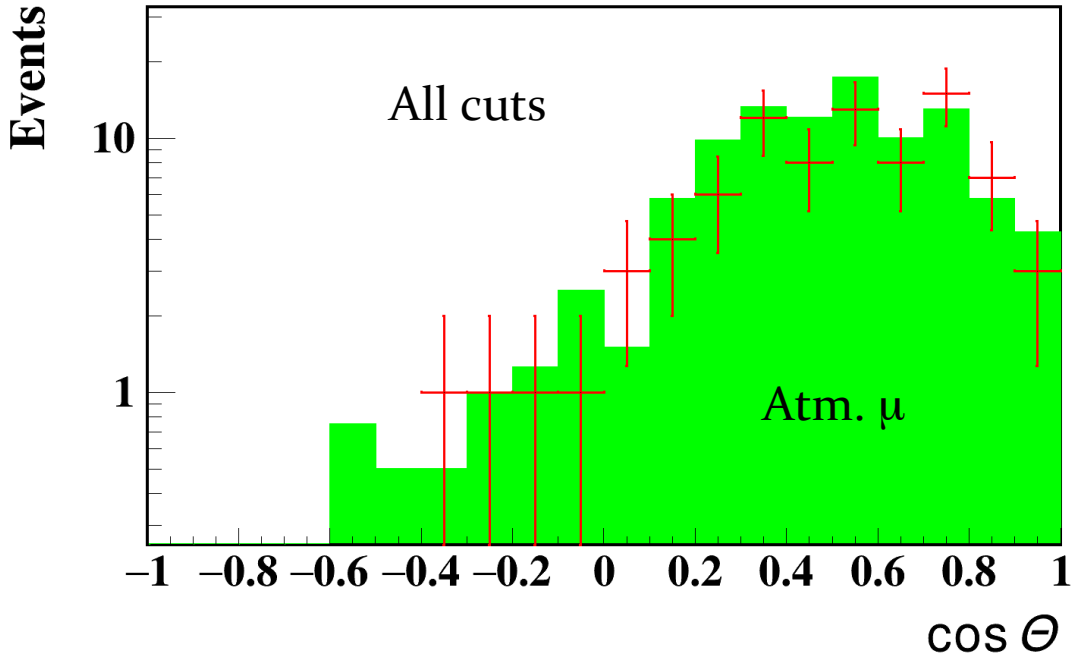
- After causality cuts – 327053415 events

$(N_{hit} > 4;\ |t_i - t_j| < \Delta r_{ij}/v + \delta t)$

Reconstructed cascades energies



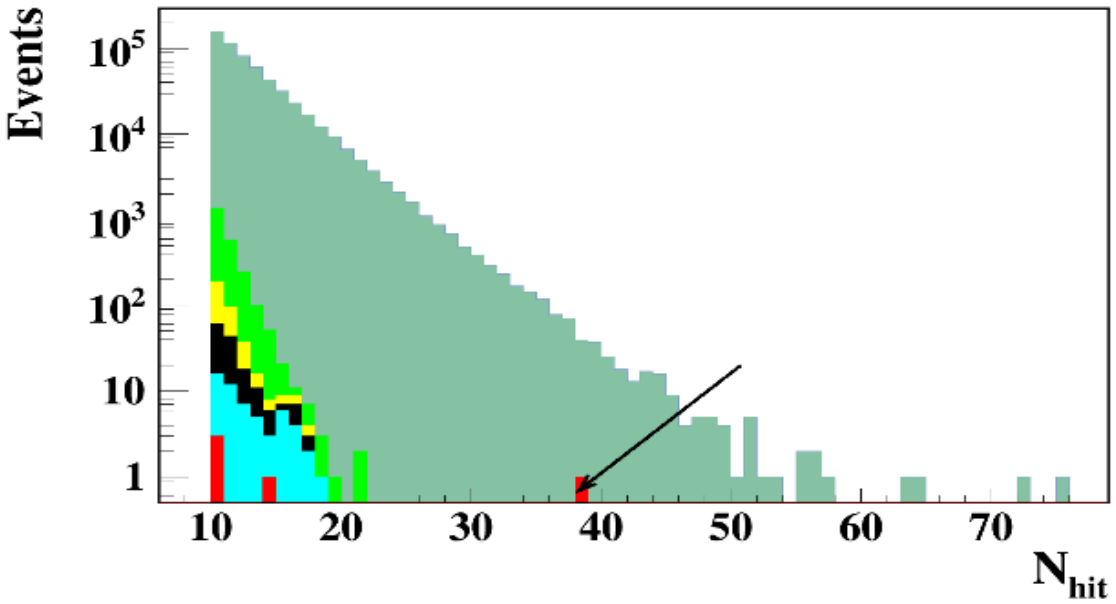
Reconstructed cascade directions



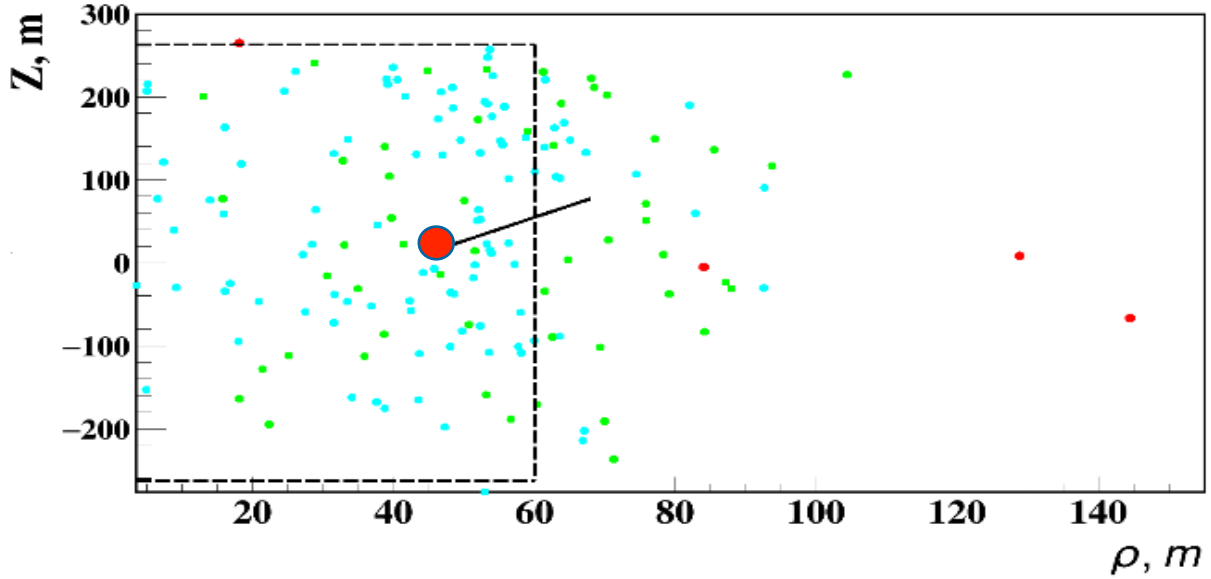
Event selection

Cuts	Events	Rejection
Coordinates reconstruction & N_{hit} >9	577495	1
$\chi^2_t < 4$	2405	1/240
Energy reconstruction		
$L_a < 20$	374	1/6.4
$\eta > 0$	159	1/2.4

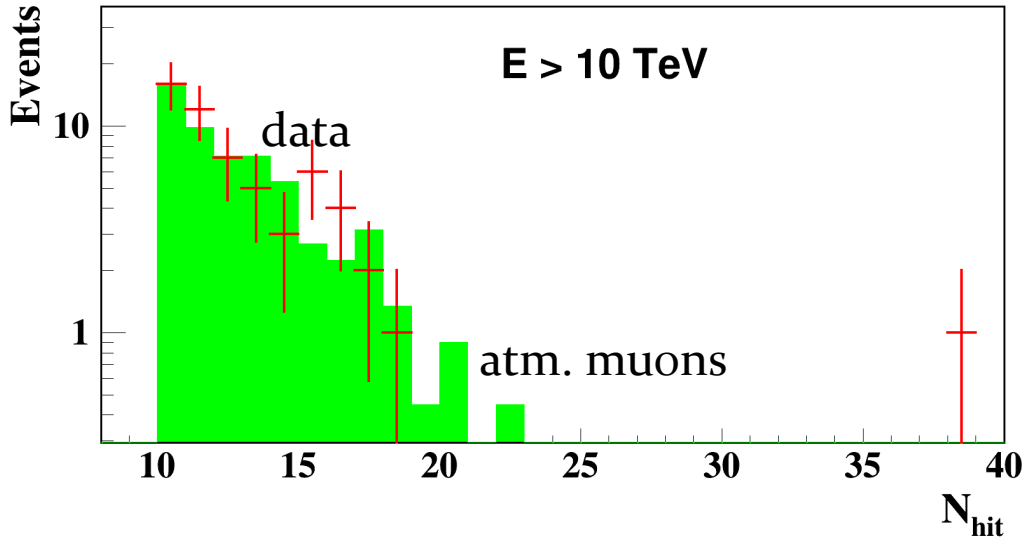
Hit OM multiplicity of events surviving different cuts



Reconstructed cascades positions



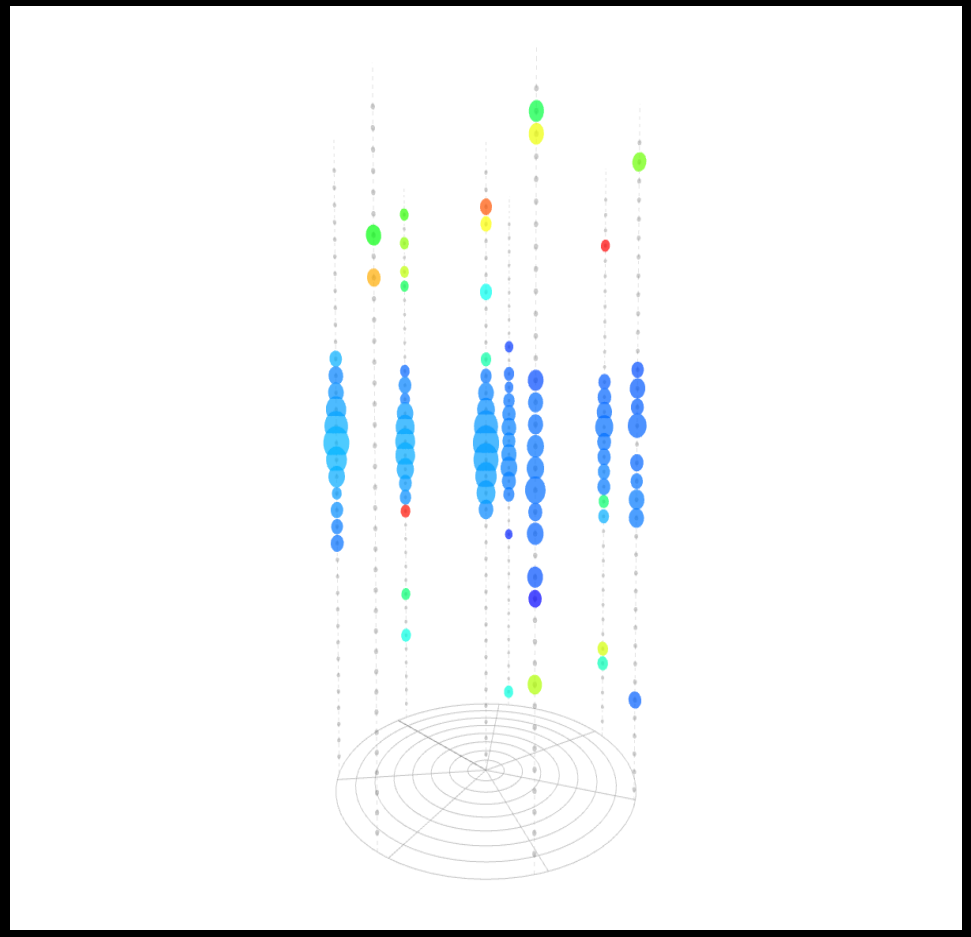
Hit OM multiplicity of events with E > 10 TeV



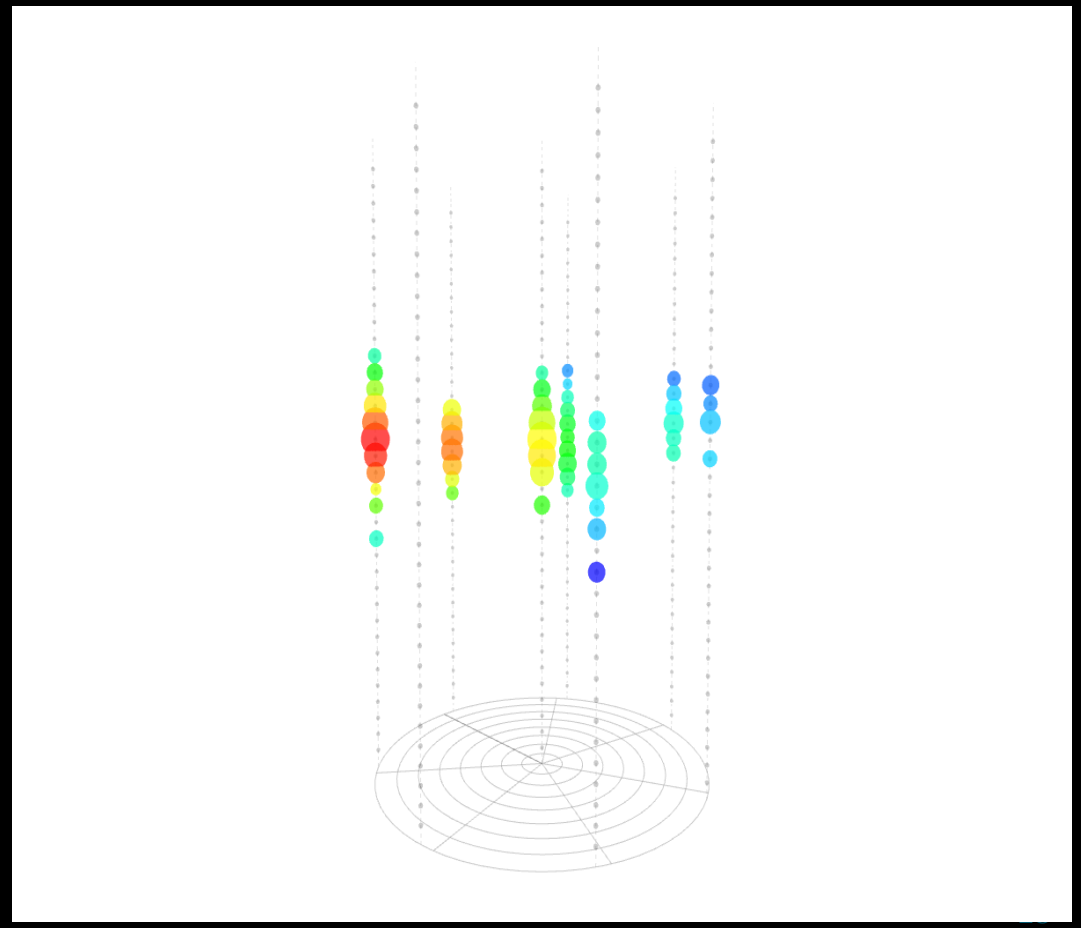
Cuts	Events	Rejection
Coordinates reconstruction & N_{hit} >9	577495	1
$\chi^2 < 4$	2405	1/240
Energy reconstruction		
$L_a < 20$	374	1/6.4
$\eta > 0$	159	1/2.4
E > 10 TeV	57	1/2.8
E > 100 TeV	5	1/11.4
Total rejection factor:		1/115499

Cascade: E=157 TeV, θ = 57°, φ = 249°
x=-25m, y=-37m, z=11m, ρ=44m

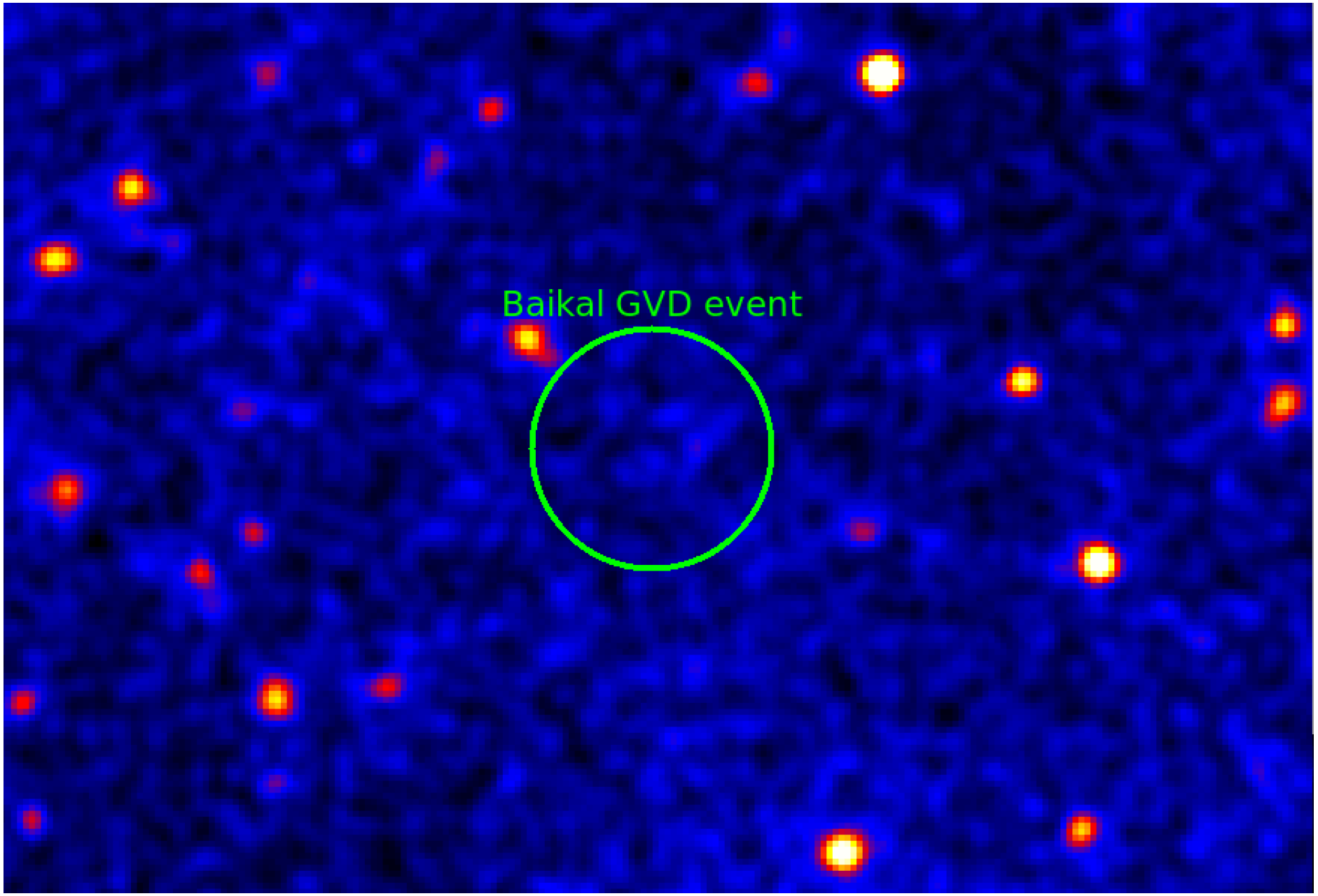
All hit OMs (93 hits)



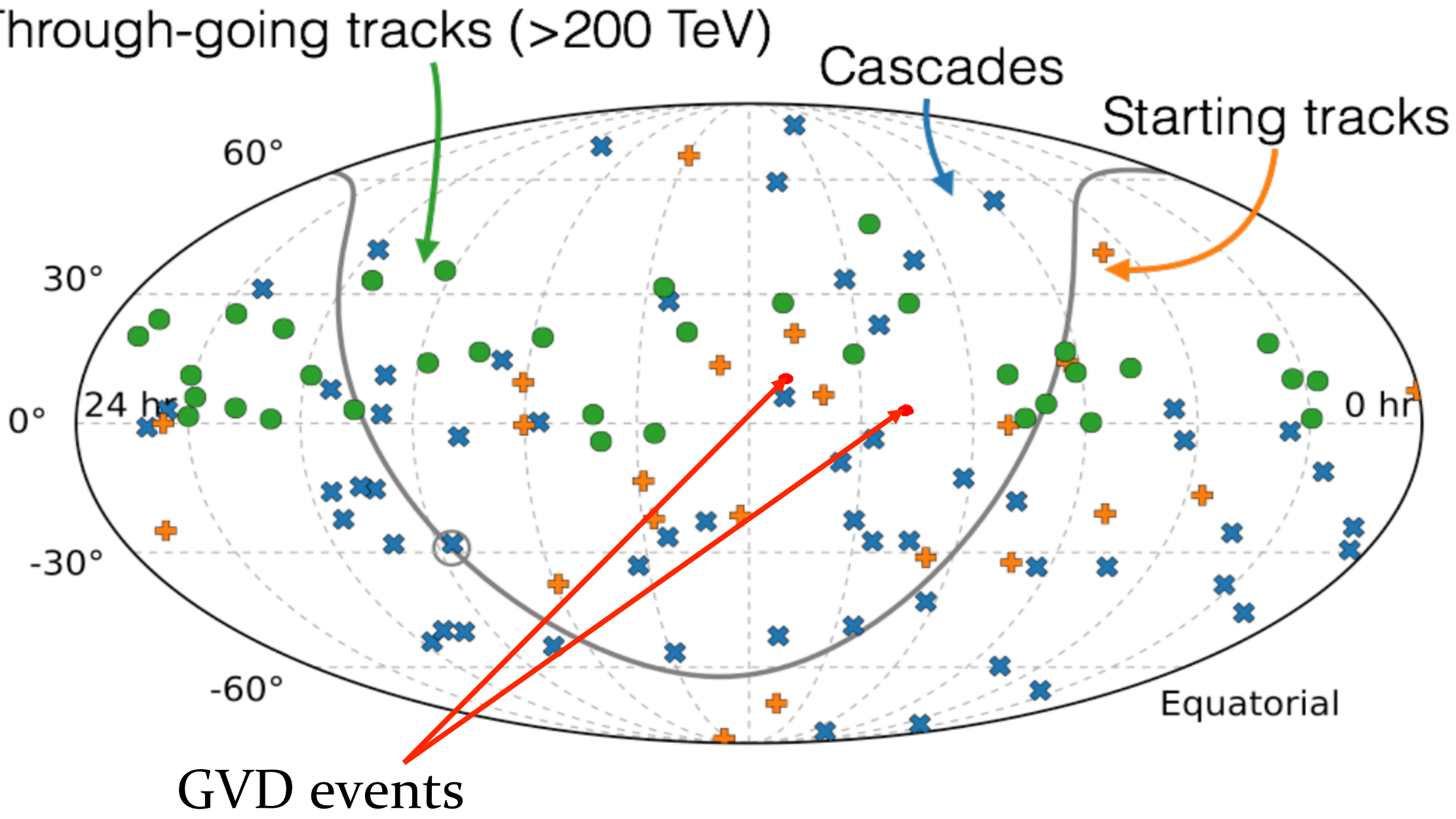
Selected hits (53 hits)



2. MJD 0.575074357292E+05 RA 173.4° Dec 13.95°

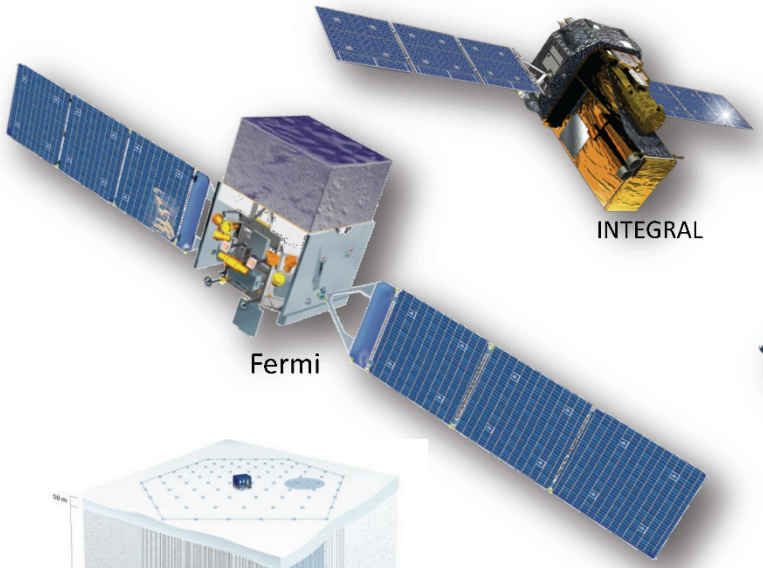


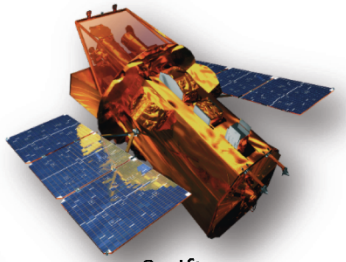
Events from above event selections with energy cut.

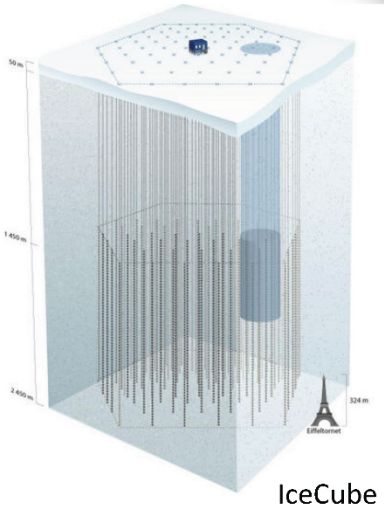


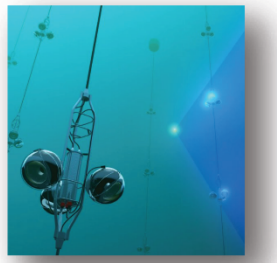
Multi-messenger studies

“all-sky” observatories

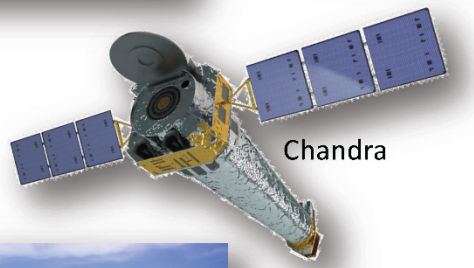






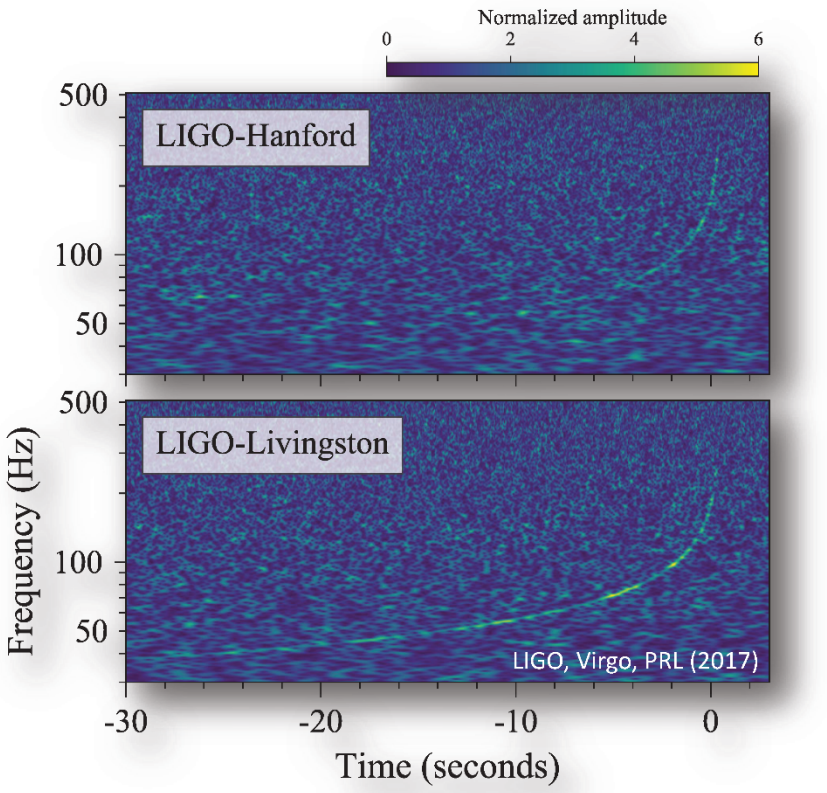


follow-up observatories

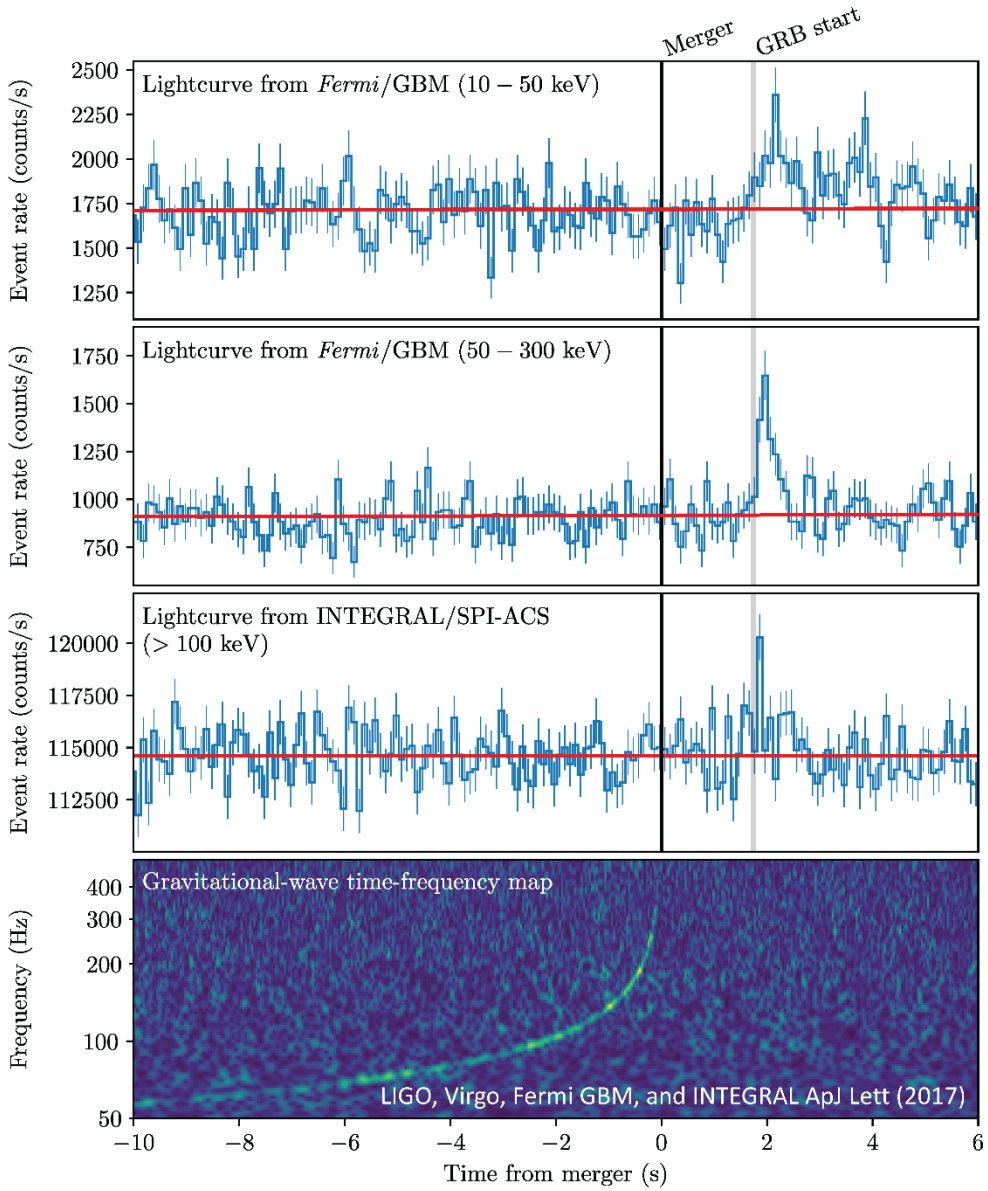


GW170817/GRB170817A from binary neutron star merger

August 17, 2017



- Gravitational-wave trigger in LIGO-Hanford only
- Livingston – noise transient
- No signal in Virgo
- Consistent with BNS merger
- 1.7s later --- GRB alert from Fermi
- Weak GRB (~10^{-7} erg cm^{-2})



Search for neutrinos in coincidence with GW170817

Search for neutrinos by muon and cascade detection
in two time-windows: GW ± 500 sec (prompt emission)
GW +14 days (delayed emission)

Horizons of arrays at equatorial coordinates

Zenith angle of the source at detection time:

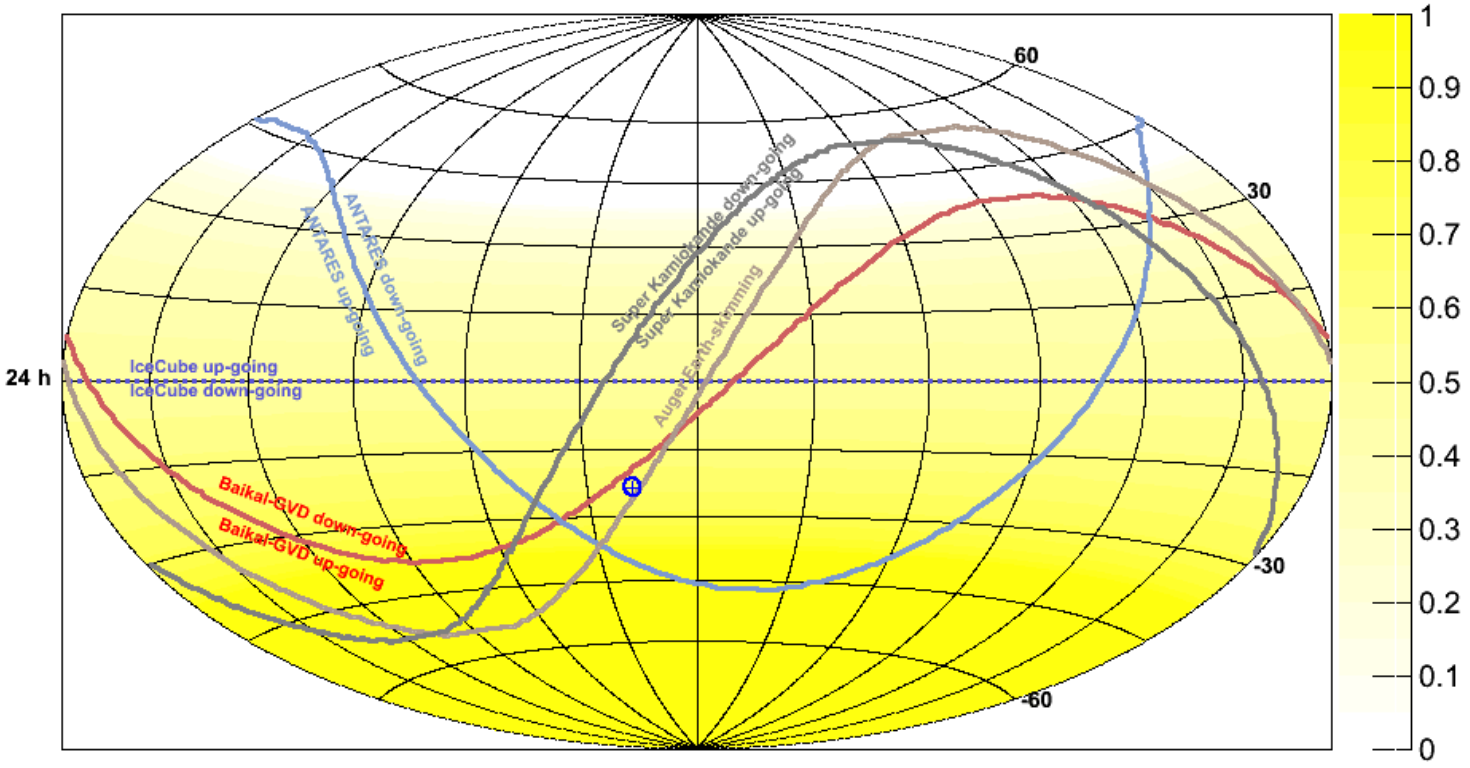
IceCube: 66.6°

ANTARES: 73.8°

Auger: 91.9°

SK: 108°

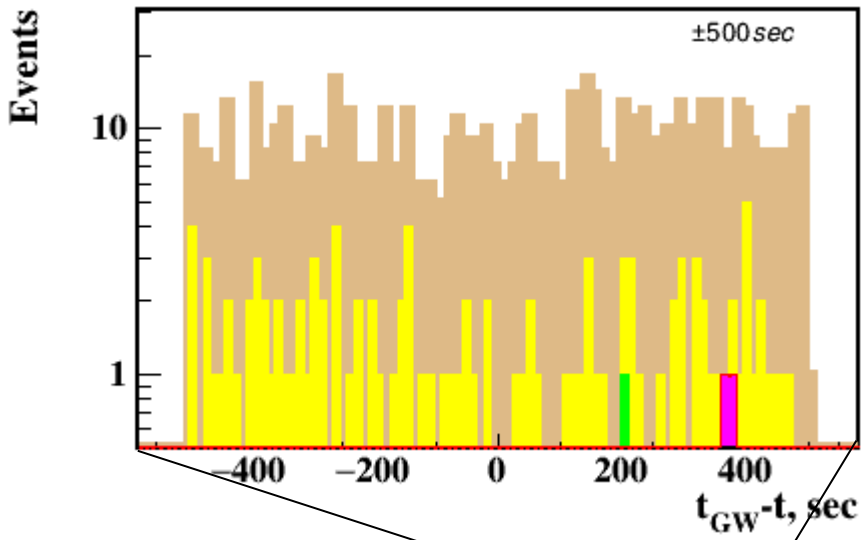
GVD: 93.3°



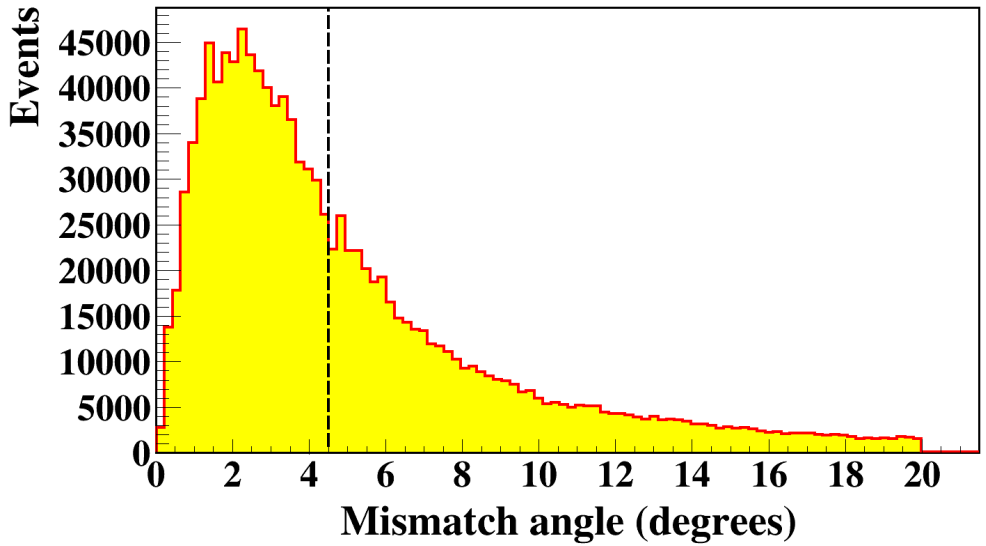
Search for neutrinos within GW ± 500 s time-window by cascade mode

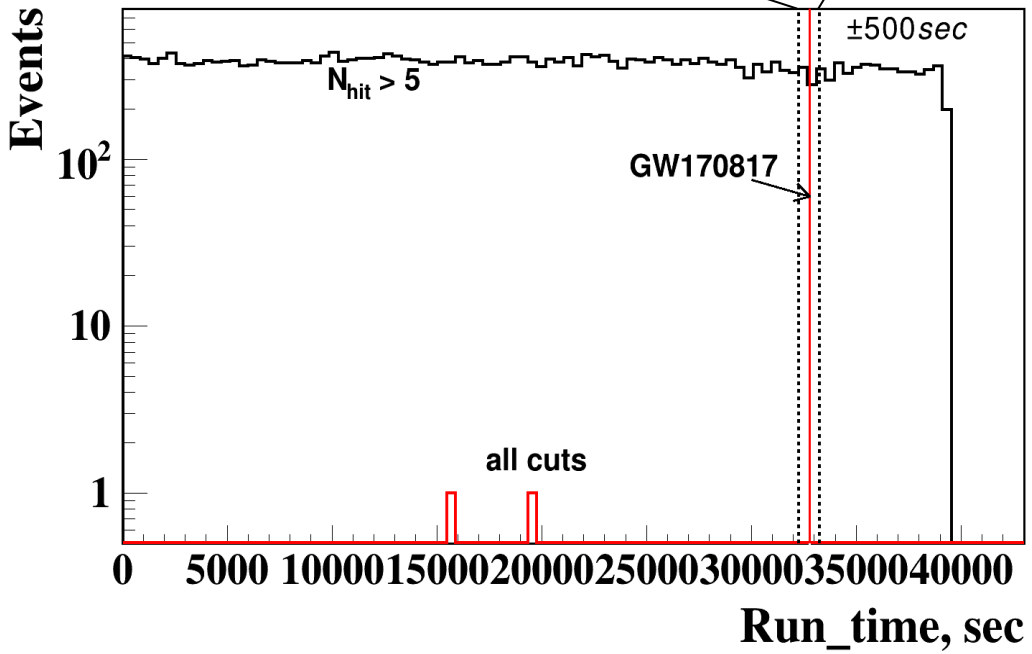
Cl.#1, run g0269; duration 39347 sec; 2463792 ev.

Cut	Events in ± 500 sec window
N_{hit} > 5 OM/3 Str.	731
χ^2_t < 10	108
η > 0	3
L_a < 30	2
ψ < 20°	0 (0.05 events is expected)



Shower direction reconstruction error

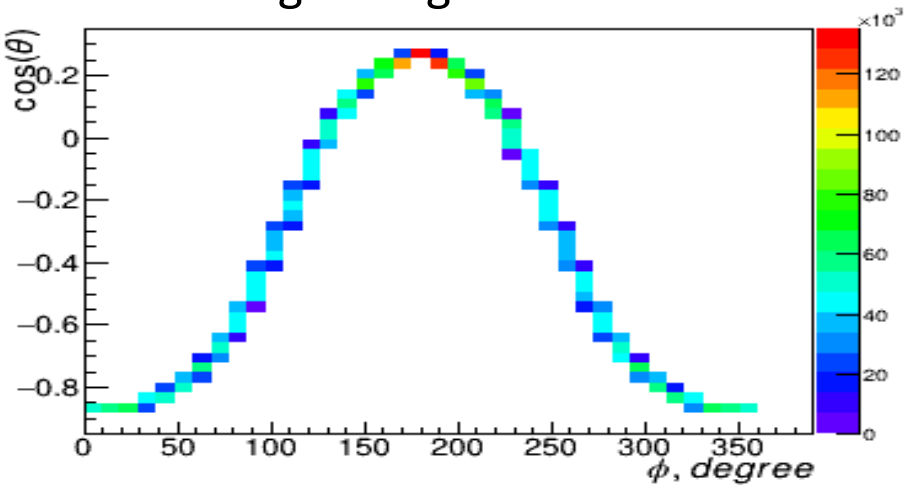




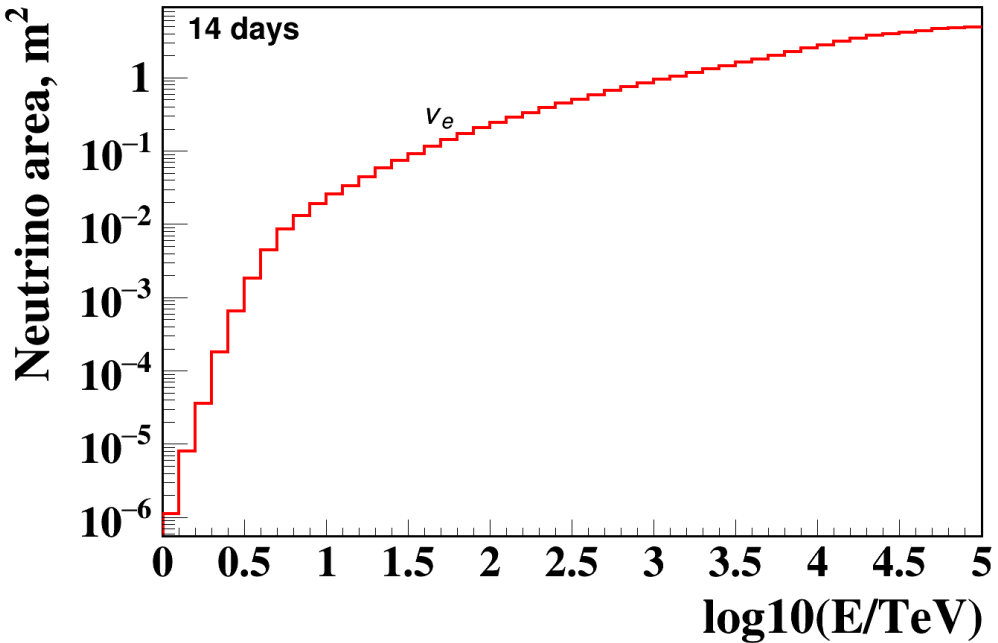
Search for neutrinos in GW170817 following 14 days time-window

Coordinates of NGC4993

zenith angle range 74° < θ <150°



Neutrino detection area



Selection cuts

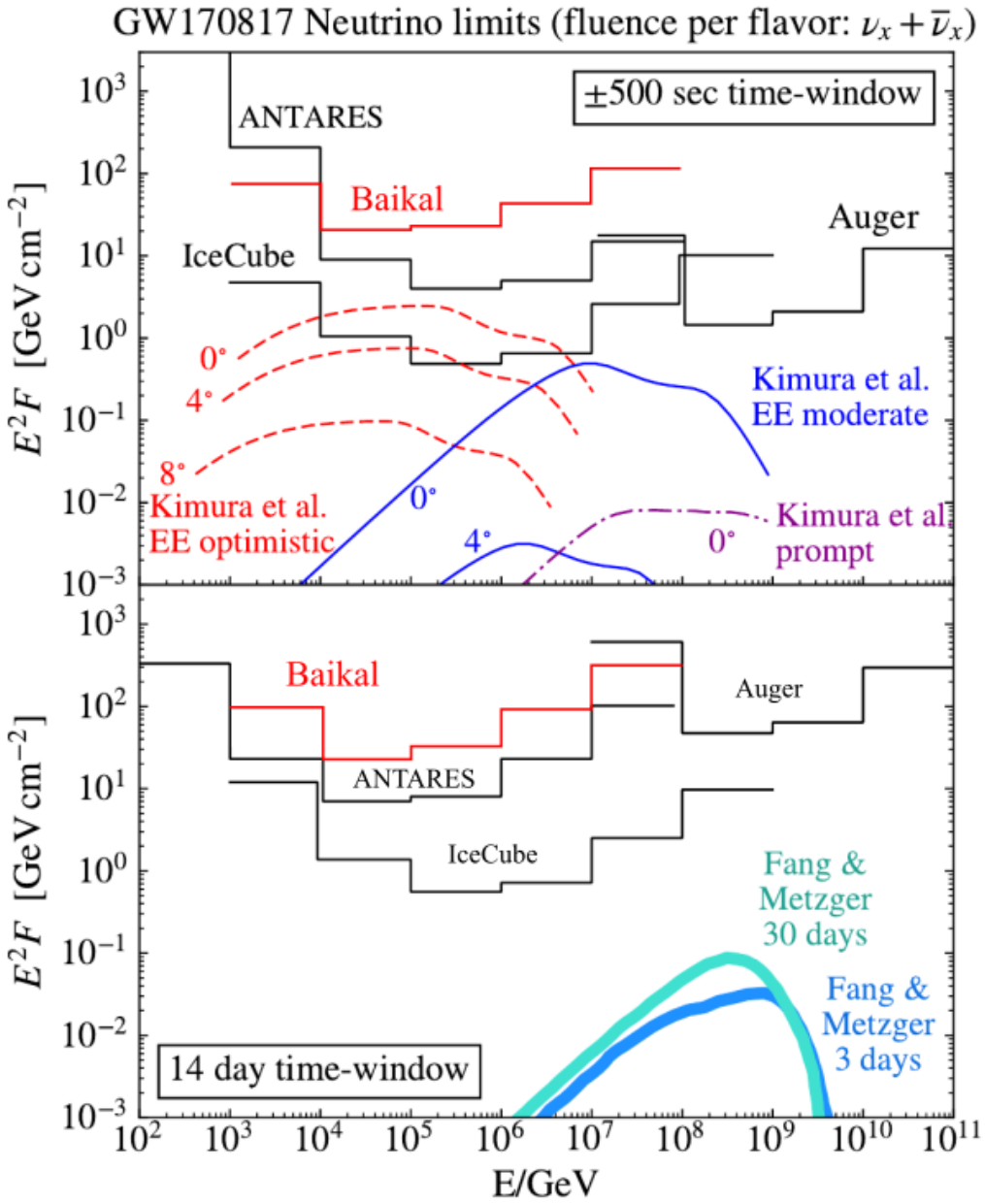
Cut	Events in 14 day window
N_{hit} > 7 OM/3 Str.	384116
χ^2_t < 6	12186
η > 0	445
L_a < 30	372
ψ < 20°	0

Upper limits on fluence of neutrinos associated with GW170817

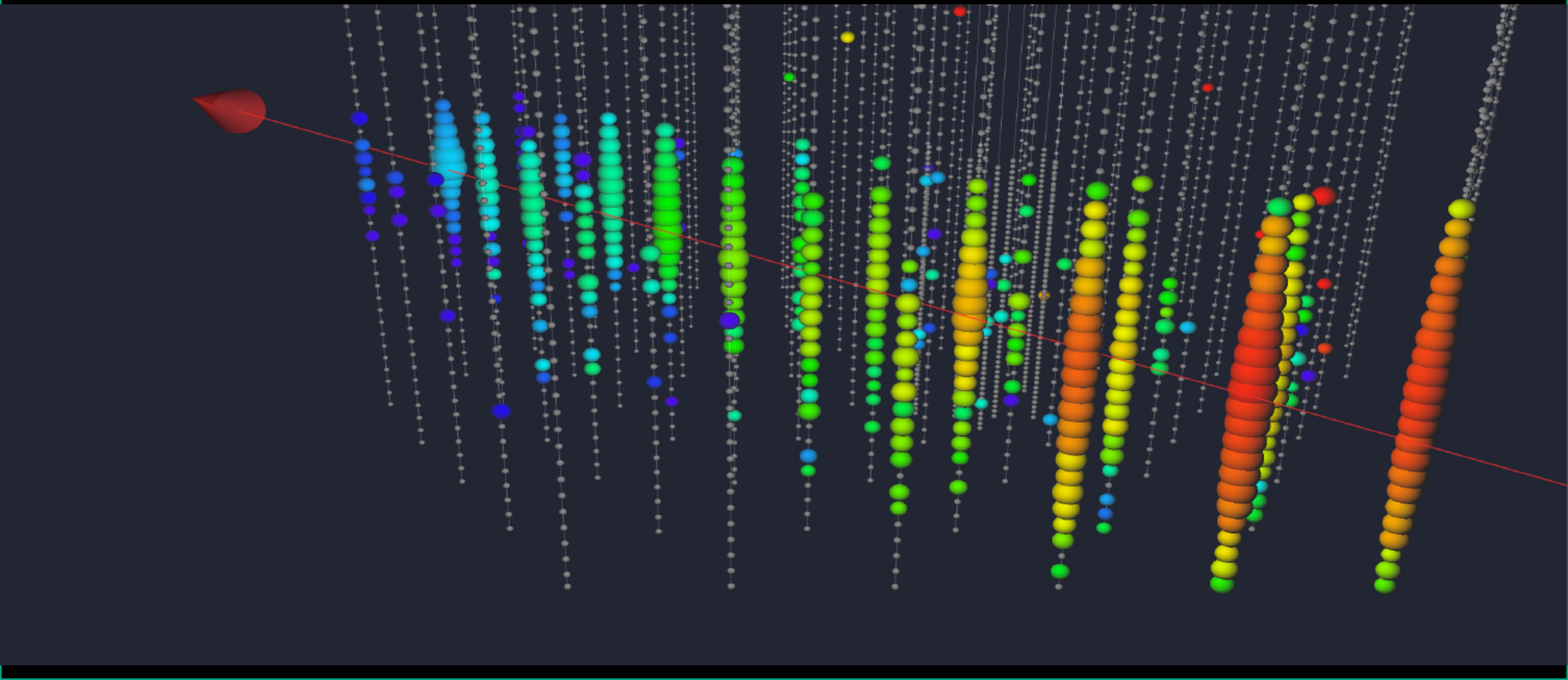
JETP Letters v.108-12 (2018),
arXiv:1810.10966

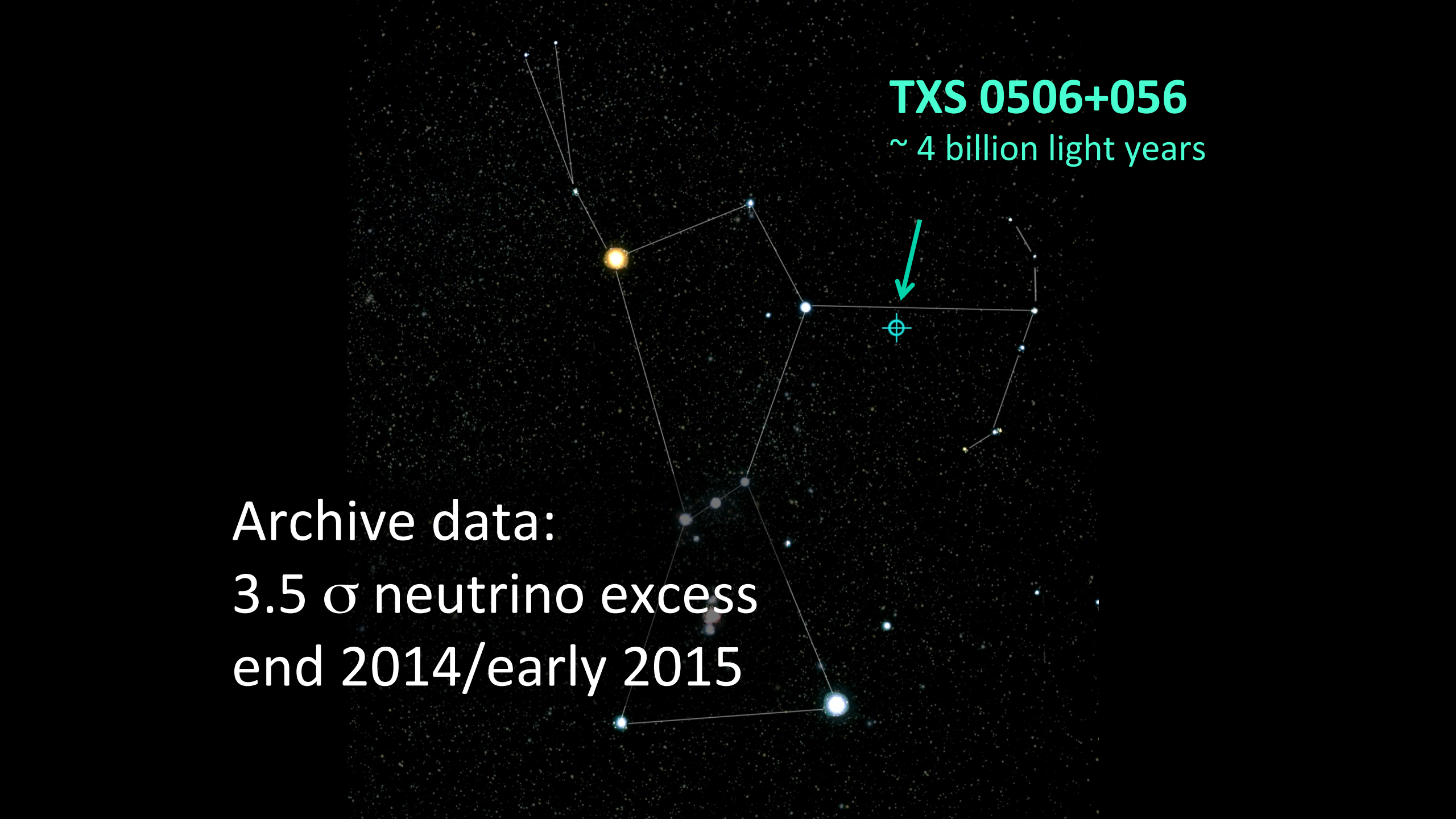
No neutrino events associated with GW170817 have been observed Using cascade mode within ± 500 sec window and 14 days after the neutron star merger.

Assuming E^{-2} spectral behavior and equal fluence in all flavors upper limits at 90% c.l. have been derived on the neutrino fluence from GW170817 for each energy decade.



22. September 2017, 20:54 UTC

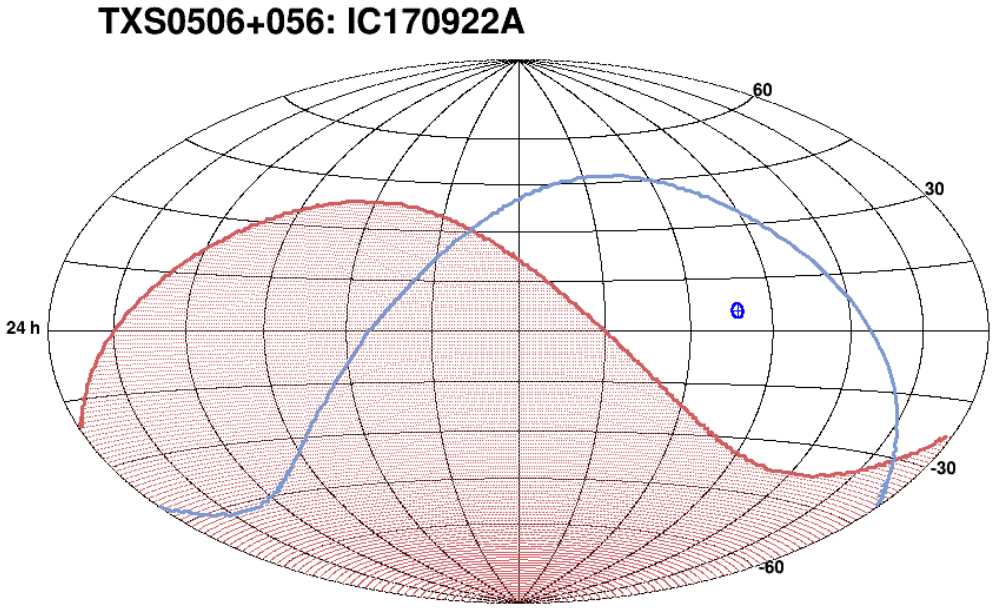




Archive data:
3.5 σ neutrino excess
end 2014/early 2015

Search for neutrinos in coincidence with IC170922A in Baikal-GVD

PRELIMINARY!!!



Baikal-GVD ANTARES

IceCube on 22 September 2017:
HE neutrino from the direction of
BL Lac TXS 0506+056 -
the first evidence for the existence of an astrophysical source of high-energy neutrinos

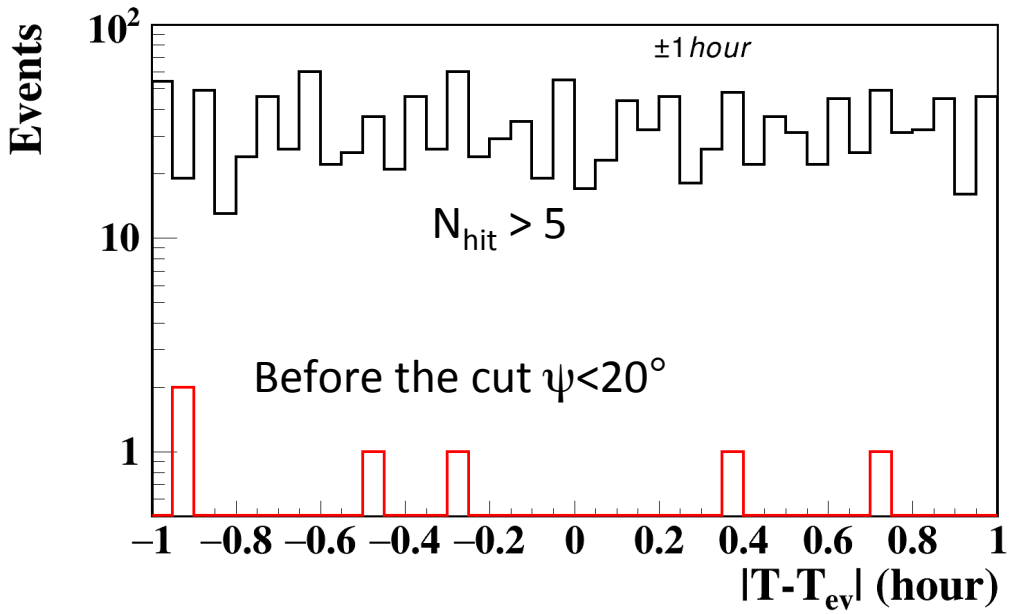
ANTARES - 104.2°

Baikal-GVD - 63° - search by cascade detection mode

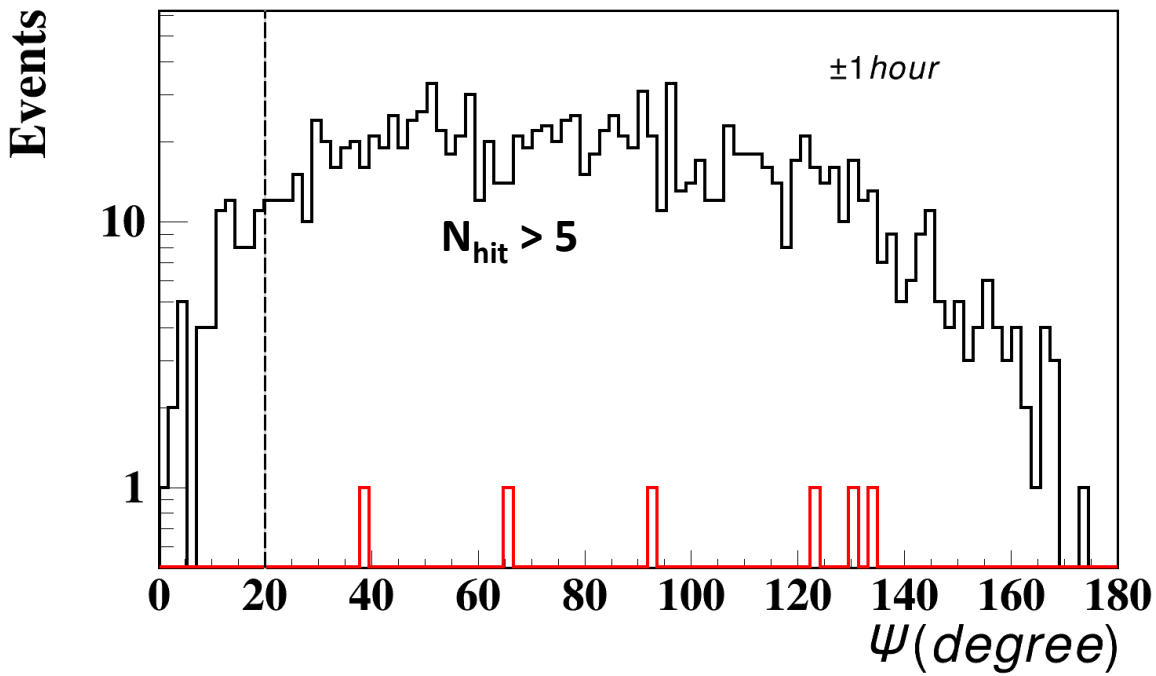
Search for neutrinos within ± 1 hour time-window around IC170922A

Events selection cuts

Cut	Events in ± 1 hour window
N_{hit} > 5 OM/3 Str.	1345
χ^2_t < 10	221
η > 0	11
L_a < 30	9
ψ < 20°	0



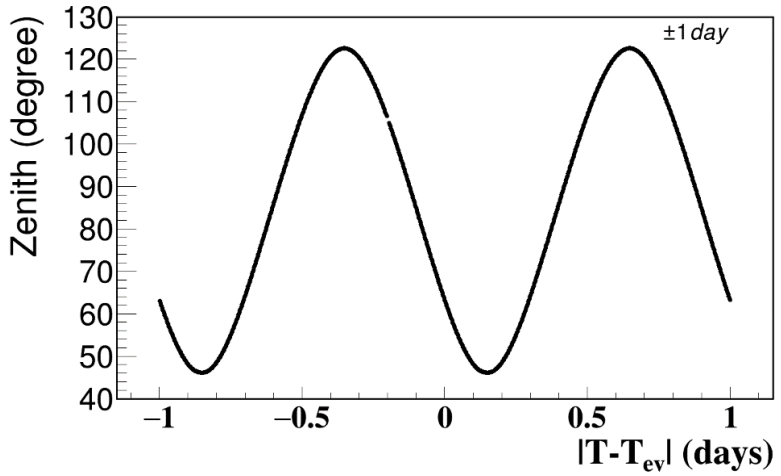
Angular distance around the direction of the source



No neutrino candidate event was recorded within ± 1 hour time window around the IC170922A

Search for neutrinos within ± 1 day time-window around IC170922A

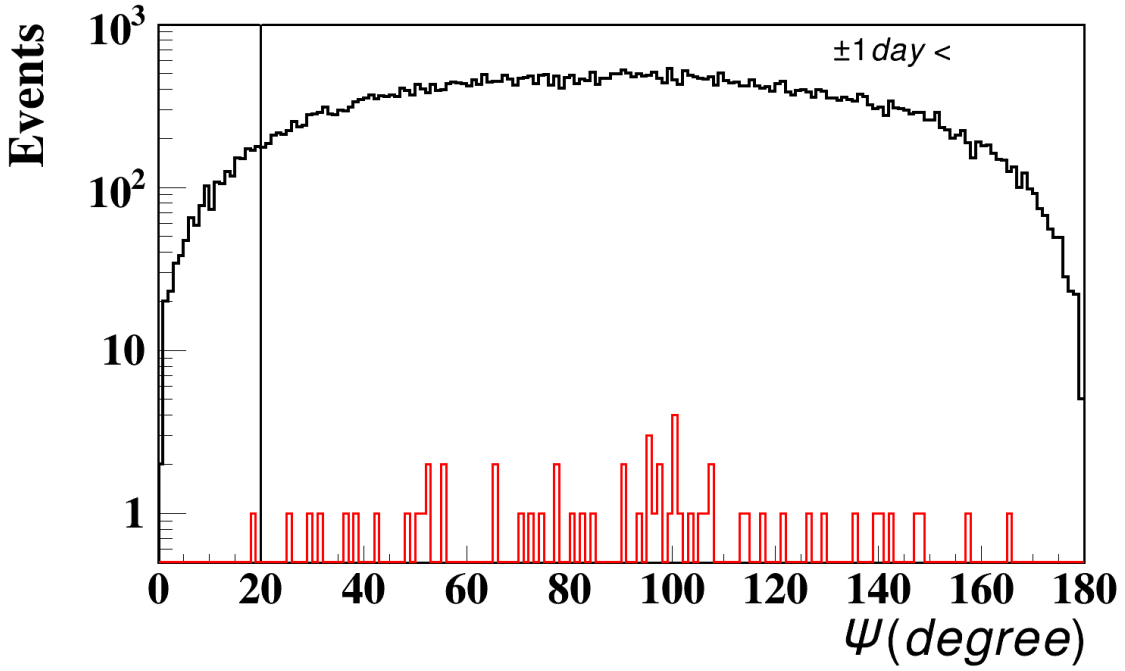
Source direction at GVD site
zenith angle range 45° < θ <126°



Events selection cuts

Cut	Events in ±1 day window
N_{hit} > 7 OM/3 Str.	56822
χ^2_t < 6	1717
η > 0	68
L_a < 30	58
ψ < 20°	1 (ψ = 18°)

Angular distance around the direction of the source



No neutrino events associated with IC170922A have been recorded

GVD plans

Timeline GVD 1

Year	2016	2017	2018	2019	2020	2021
Nb. of clusters	*1*	*2*	*3*	*5*	*7*	*9*
Nb. of OMs	*288*	*576*	*864*	*1440*	*2016*	*2592*

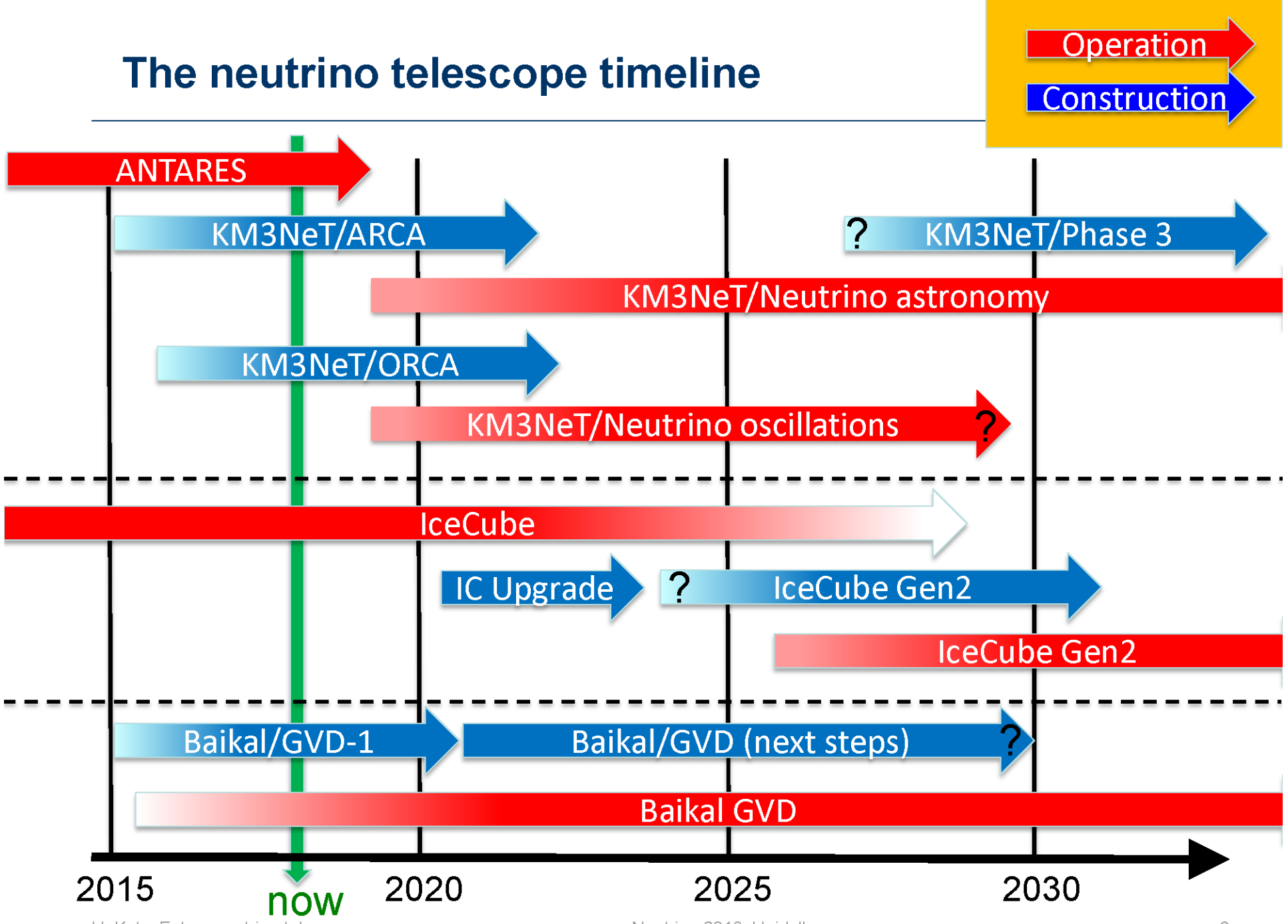
Main tasks 2019

- Two clusters deployment
- Reliability increasing.

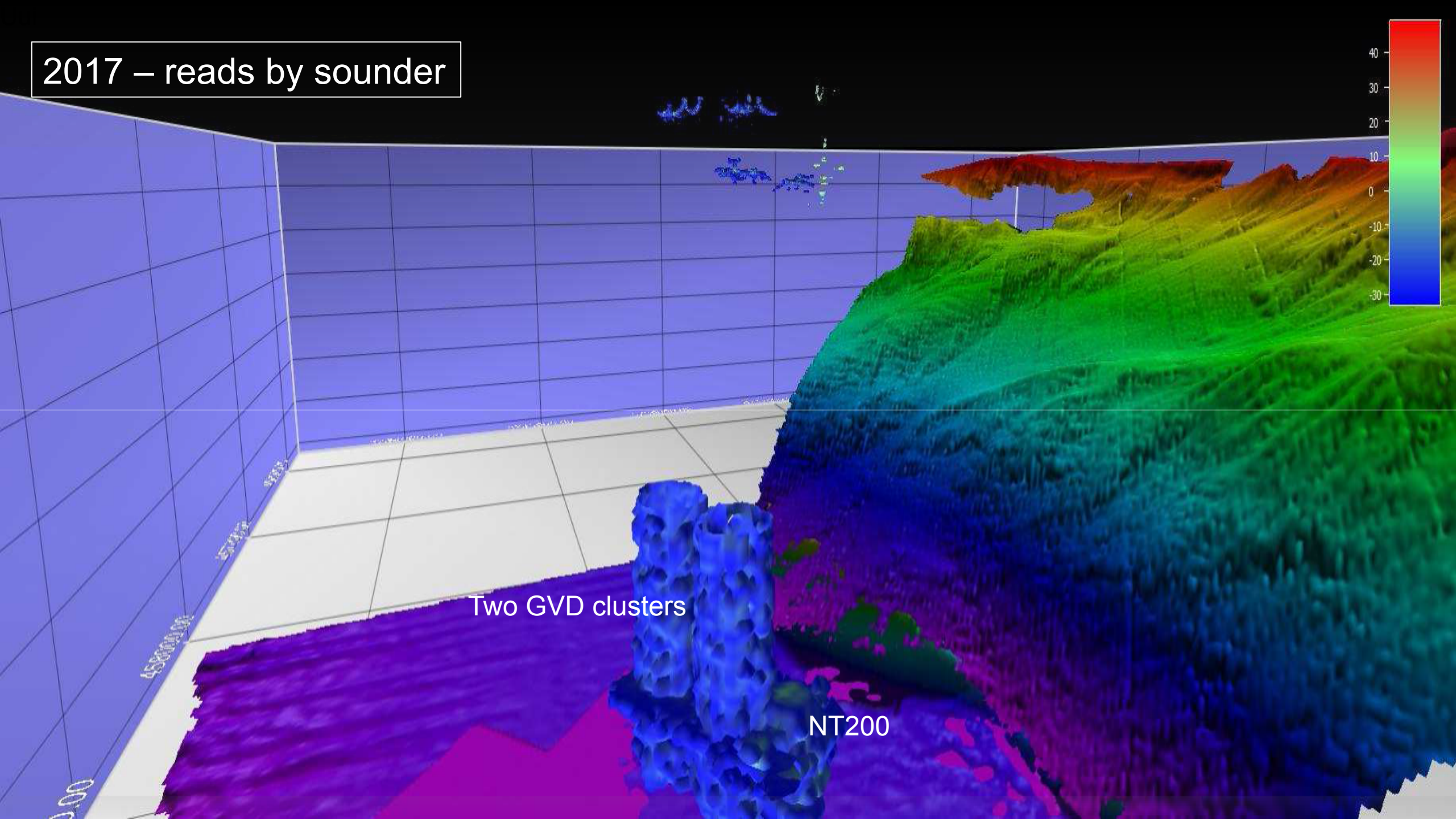
- Additional facilities for long-term tests of electronics are foreseen.
- Created a conditions for the laying of two shore cables during the season.
- The increasing of manpower during the expedition to Baikal is foreseen.

Completion of equipment preparation for two clusters is planned for December 2018.

The neutrino telescope timeline



2017 – reads by sounder



Summary

- Prototyping & Early Construction Phase of Baikal-GVD project is concluded with construction and commission of the first GVD Cluster “Dubna” in 2015

- Array “Dubna” was upgraded to baseline configuration of GVD cluster with 288 OMs in 2016.

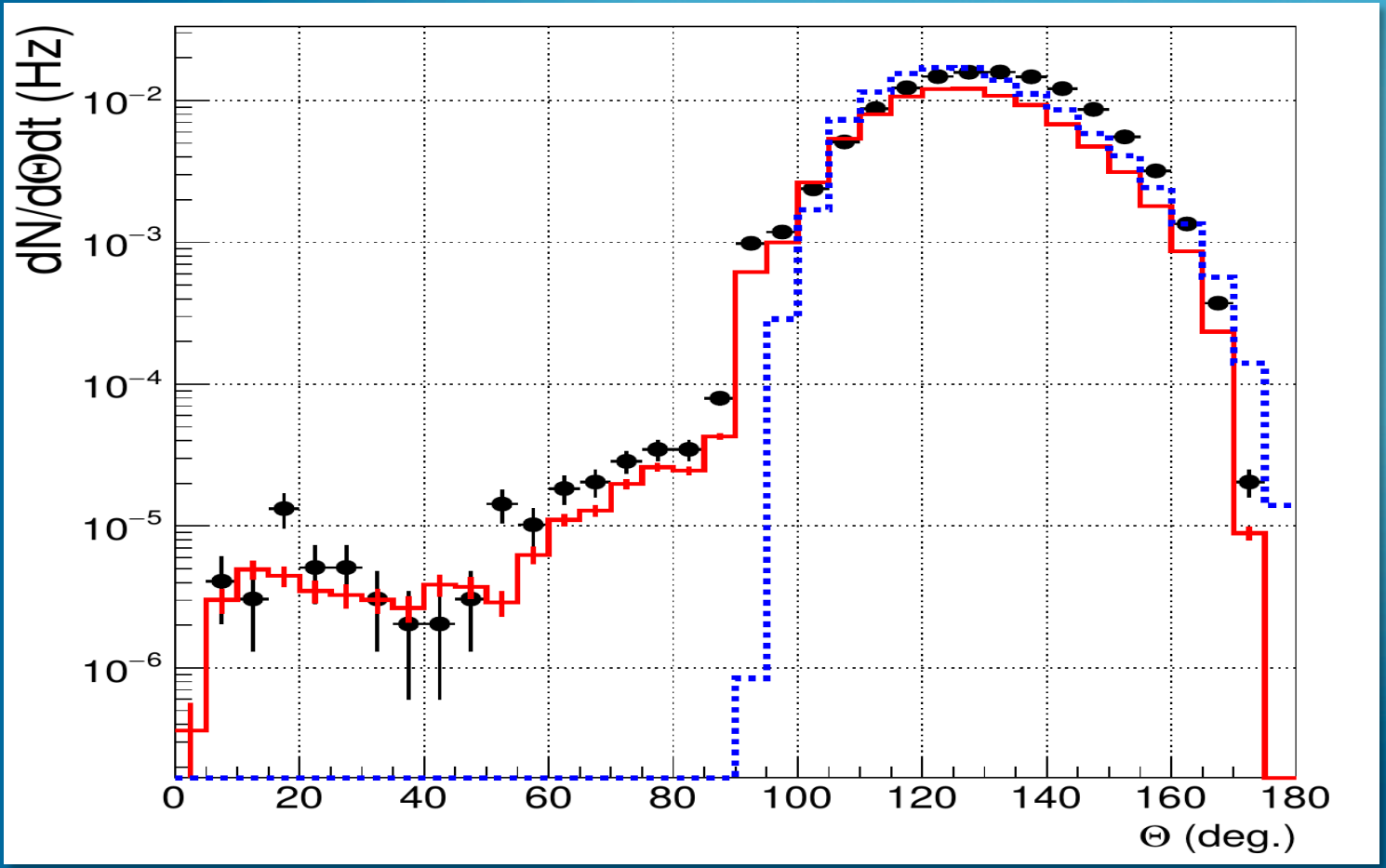
- The second and the third full-scale GVD clusters were installed and commissioned in April 2017 and April 2018. GVD-2018 – the largest Northern neutrino telescope to date.

- Completion of the GVD-1 is expected in 2020-2021.

THANK YOU!!!

Search for muon neutrinos (2016 yr.)

Reconstructed zenith angle distribution with cuts



Polar angle distribution of muons selected with the requirement of at least 6 hit OM's at 3 strings.
Data (black dots) is compared to the atmospheric muon flux generated with CORSIKA (dashed histogram) and passed through the detector simulation (histogram)

Atmospheric background suppression

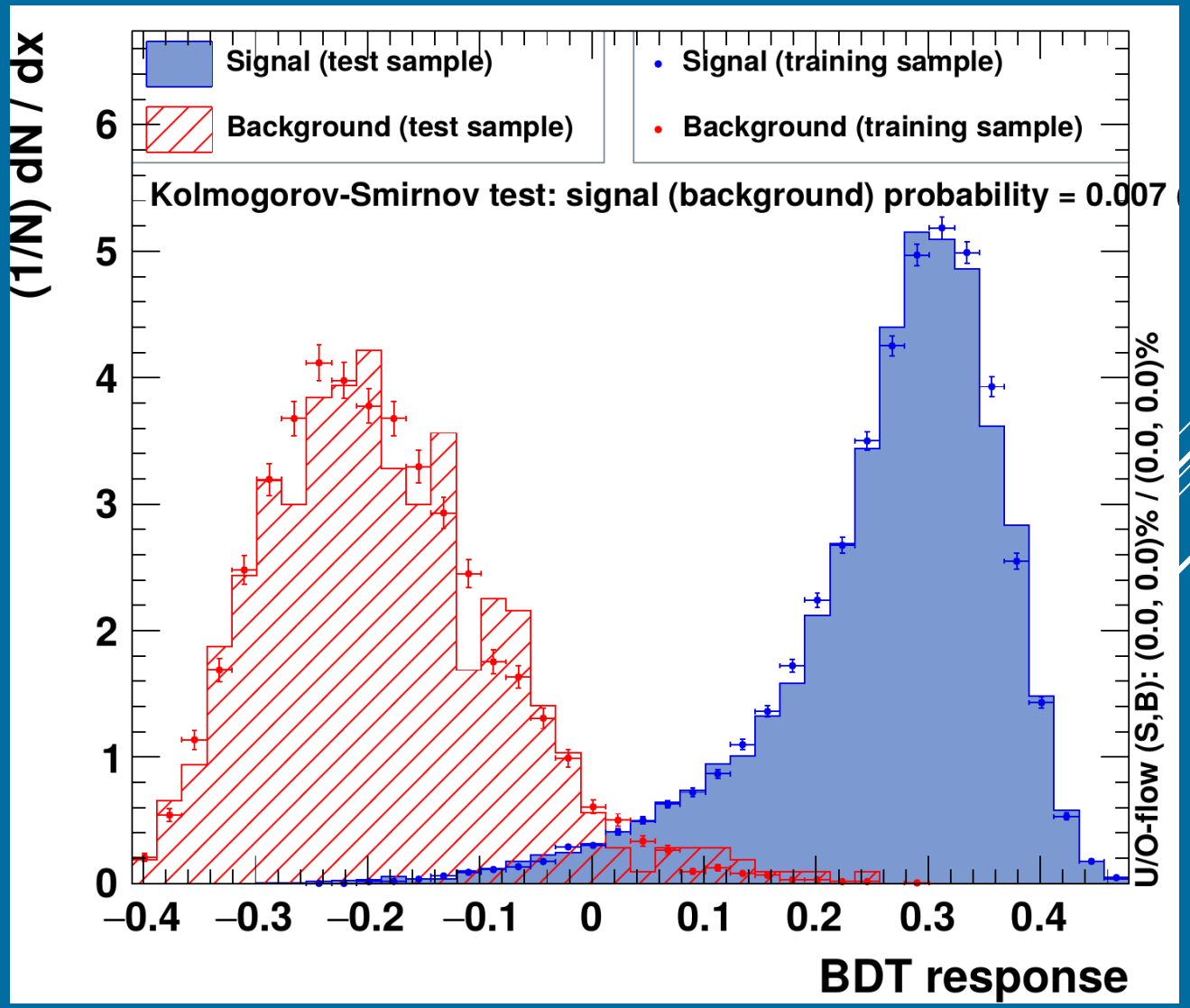
After track reconstruction and cuts on quality variables have been done, Boosted decision tree (BDT) was used.

BDT is trained on events reconstructed as upgoing with $0 < \theta < 80$ deg.

30k signal events
9k background evts.

signal is separated from the background by the BDT classifier value

cut BDT > 0.2 is 80% efficient for signal
> 0.25 -> 65% efficient
> 0.3 -> 40% eff.

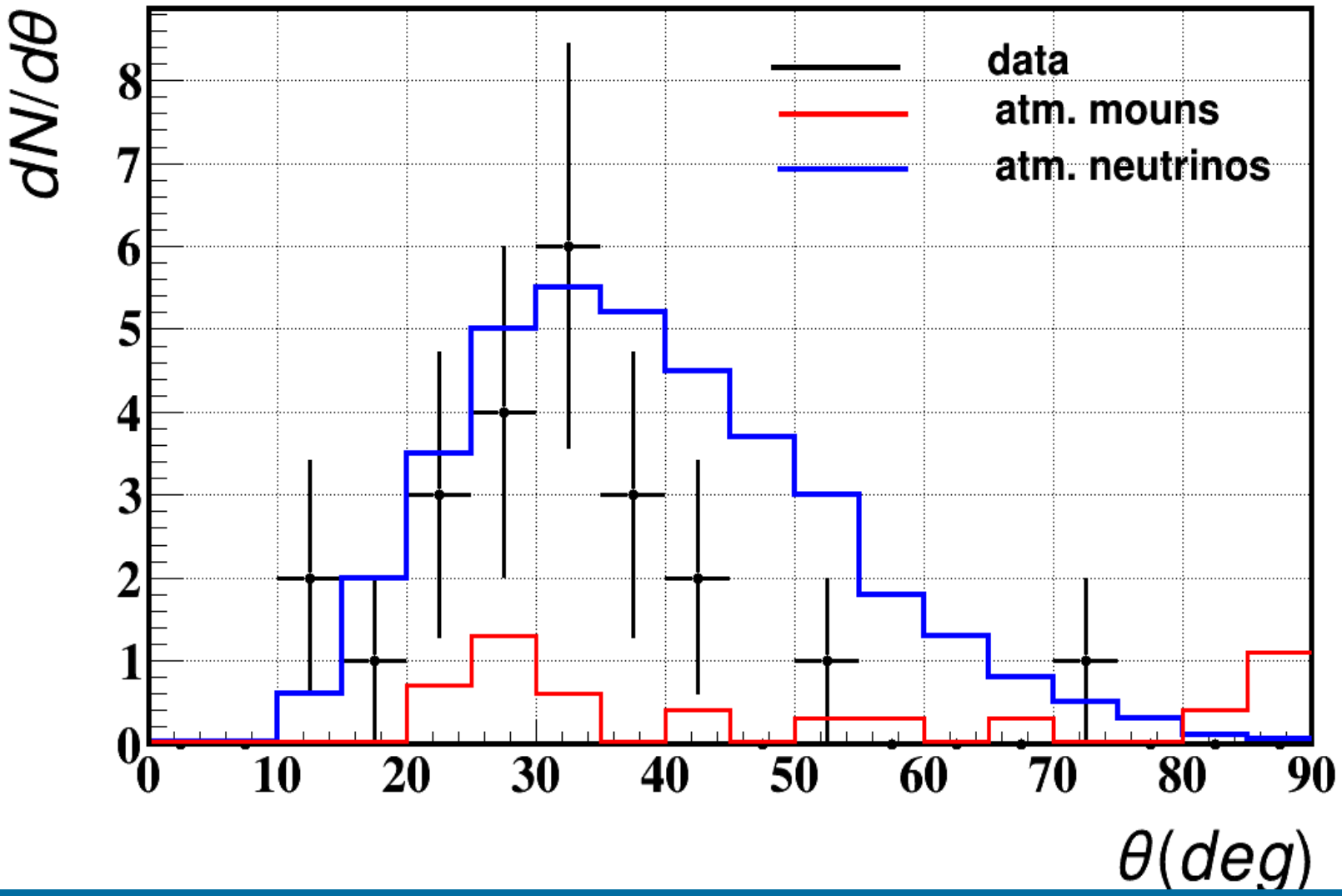


2016: 33 live days

Preliminary

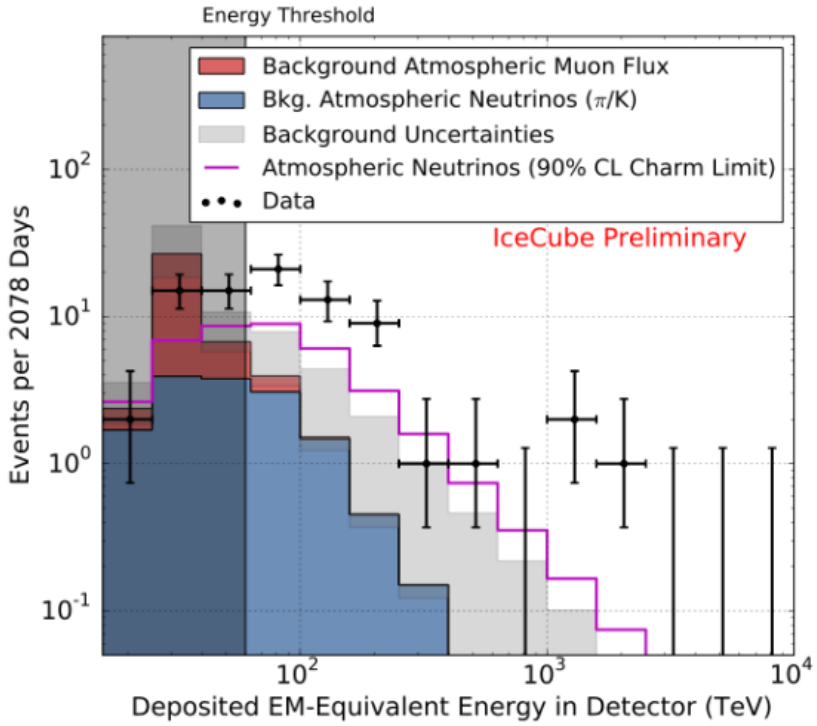
Angular distribution for
BDT > 0.2 cut

- 23 events were selected in the signal region in data
- ~ 3 events – estimation of atm. muons background
- ~36 events – estimation of signal atm. neutrinos

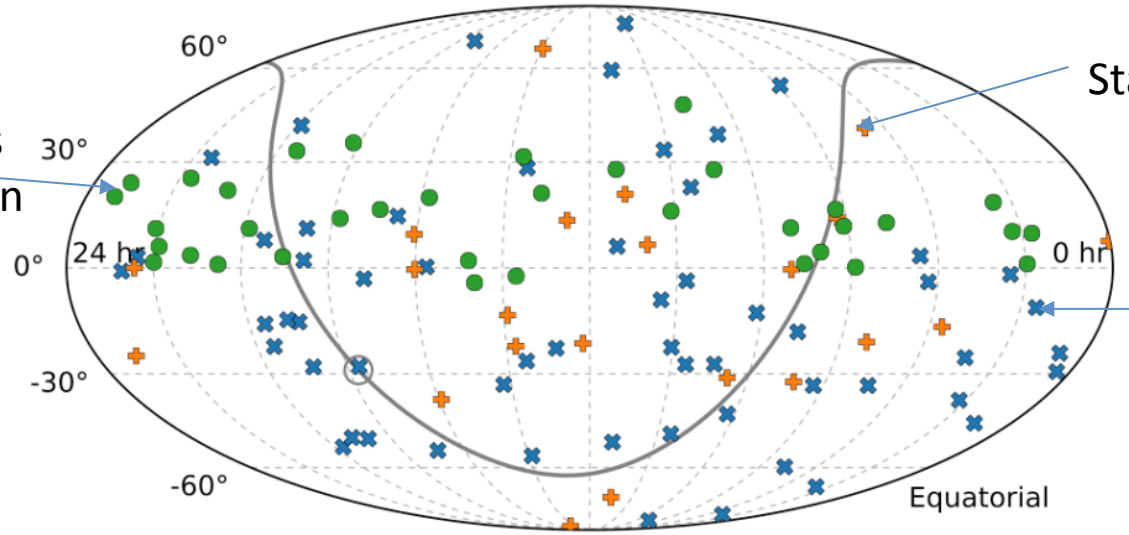


IC astrophysical neutrinos

82 events started
in IC volume in 6 years



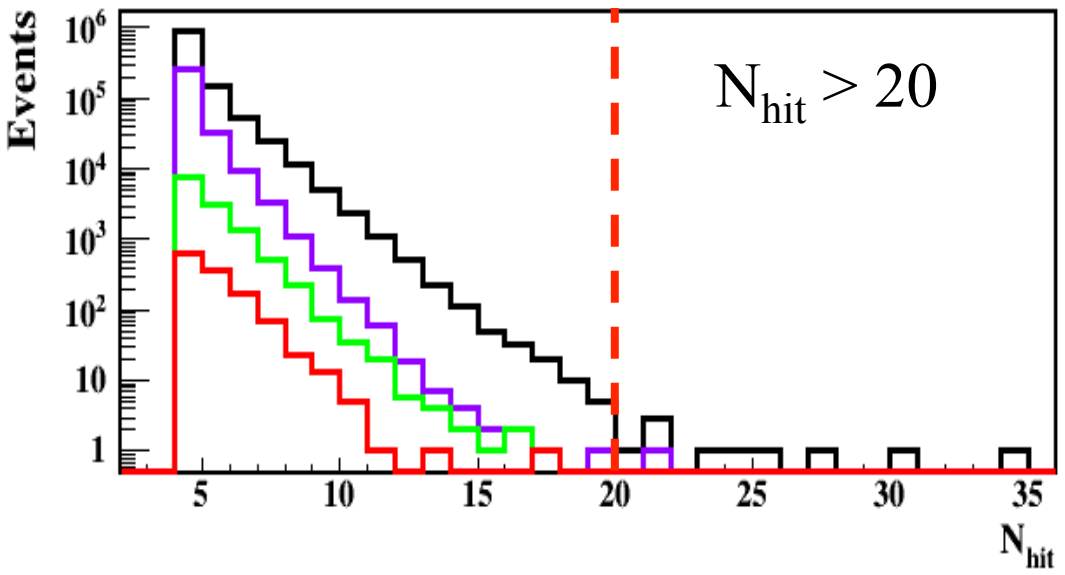
Through-going tracks
E>200 TeV, more than
50% of events are
astrophysical

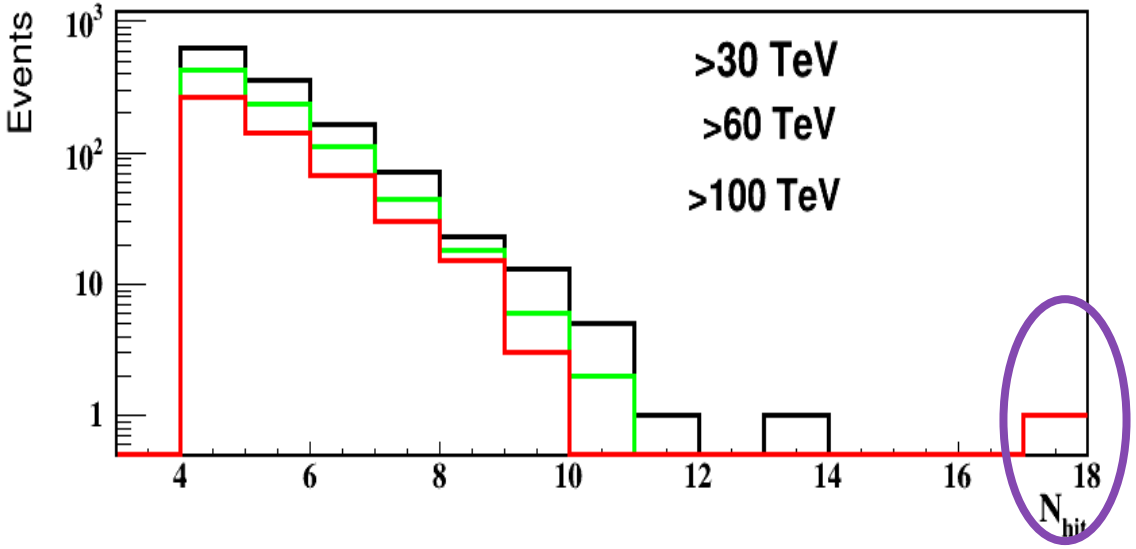


Starting tracks

Cascades

Hit OM multiplicity dependence on cuts





One event with N_{hit} = 17 OMs and E > 100 TeV is delected!

Cuts	Events	Rejection
Reconstruction of coordinates (Q>1.5ph.el.)	1 171 077	1
($\chi^2 < 2$)	316229	1/3.7
($L_a < 10$)&($\eta > 0$)	12931	1/90
E > 30 TeV	1291	1/900

Cuts	Events	Rejection
E > 30 TeV	1291	1/900
E > 60 TeV	859	1/1360
E > 100 TeV	539	1/2000