5th International Conference on Particle Physics and Astrophysics
5-9 October 2020

High-energy neutrino astronomy and the Baikal-GVD neutrino telescope

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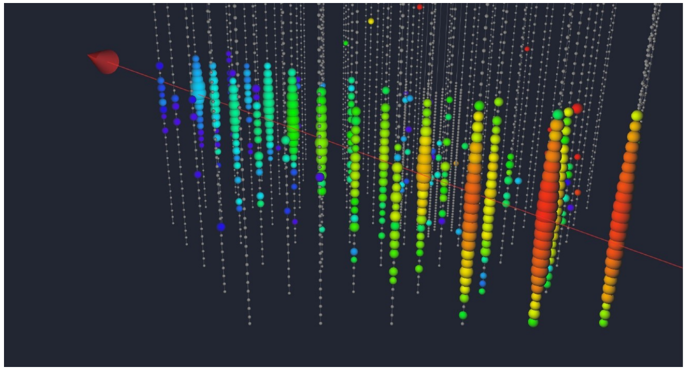
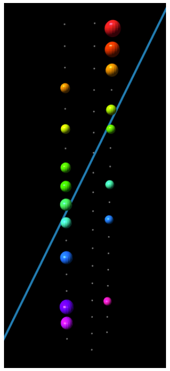
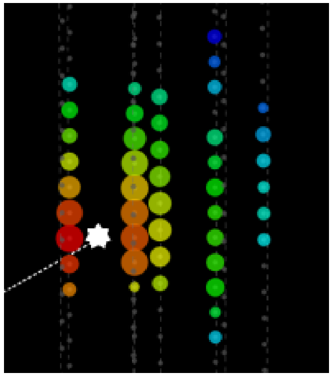
for the Baikal-GVD collaboration







Neutrino as astrophysical messenger

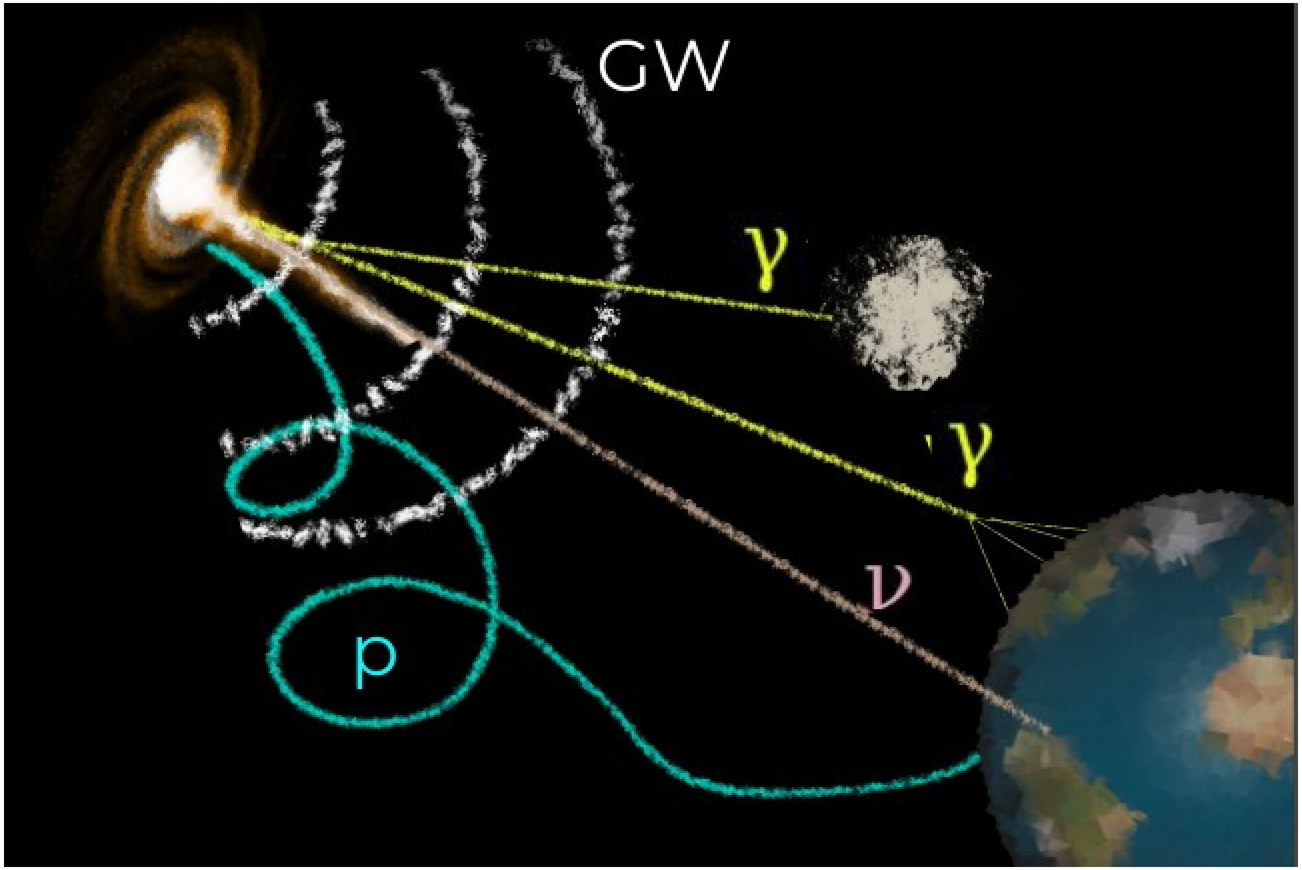
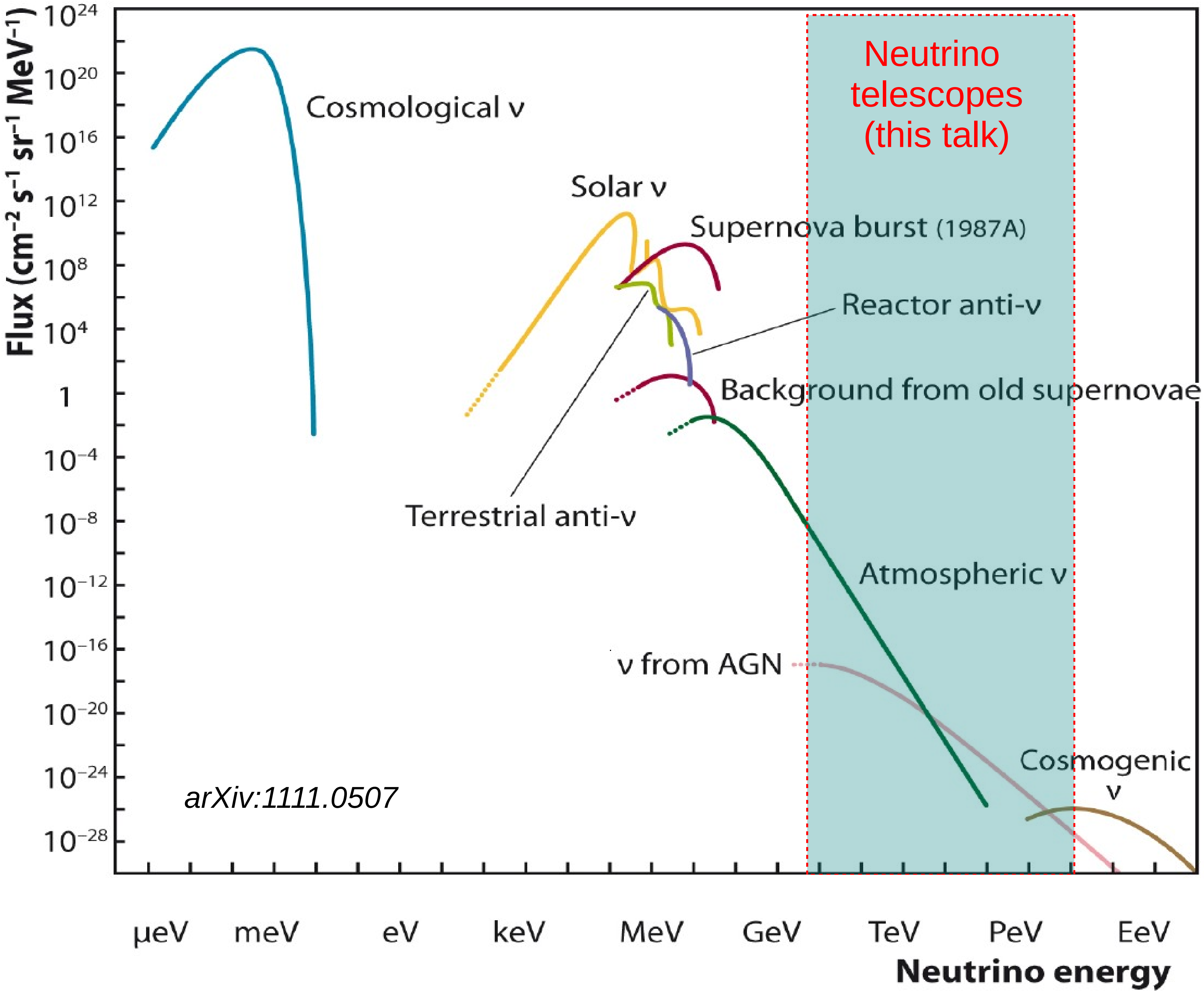


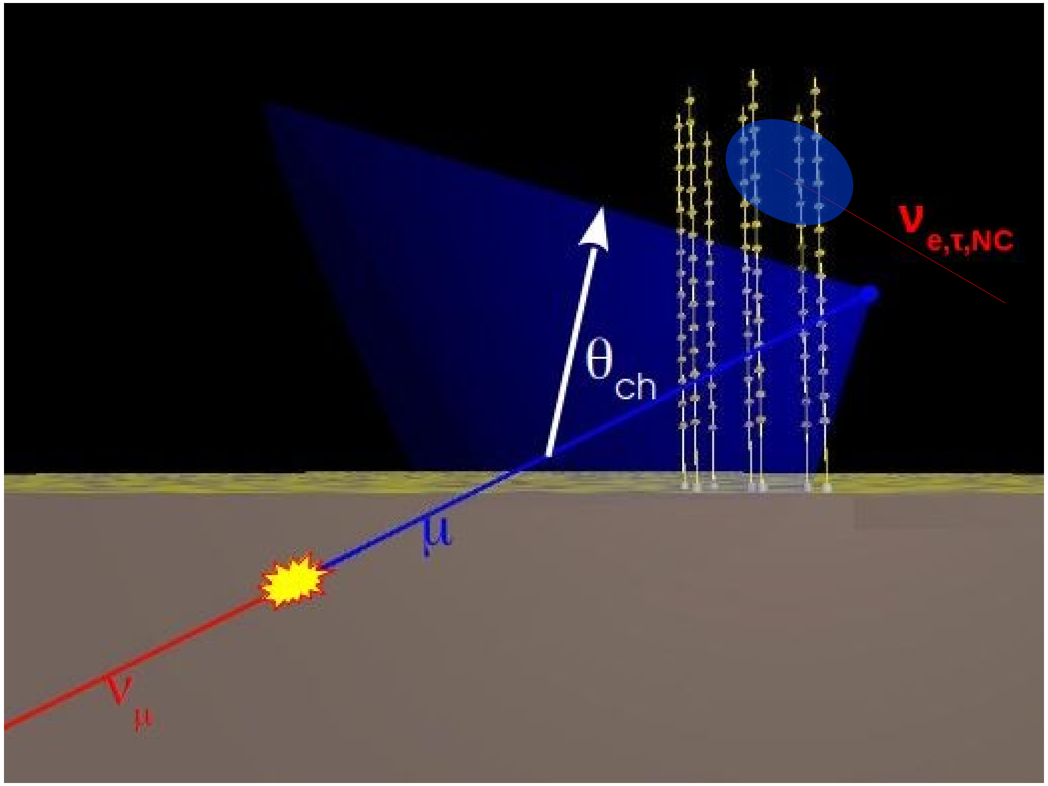
Image borrowed from talk by R. Ruiz

- Can escape from dense environments
- Travels unimpeded through gas and dust
- Does not interact with CMB and infrared background
- Stable (does not decay)
- Not affected by magnetic fields; arrival direction points to the source
- High-energy neutrinos trace production and acceleration sites of cosmic rays

Natural and artificial neutrino fluxes



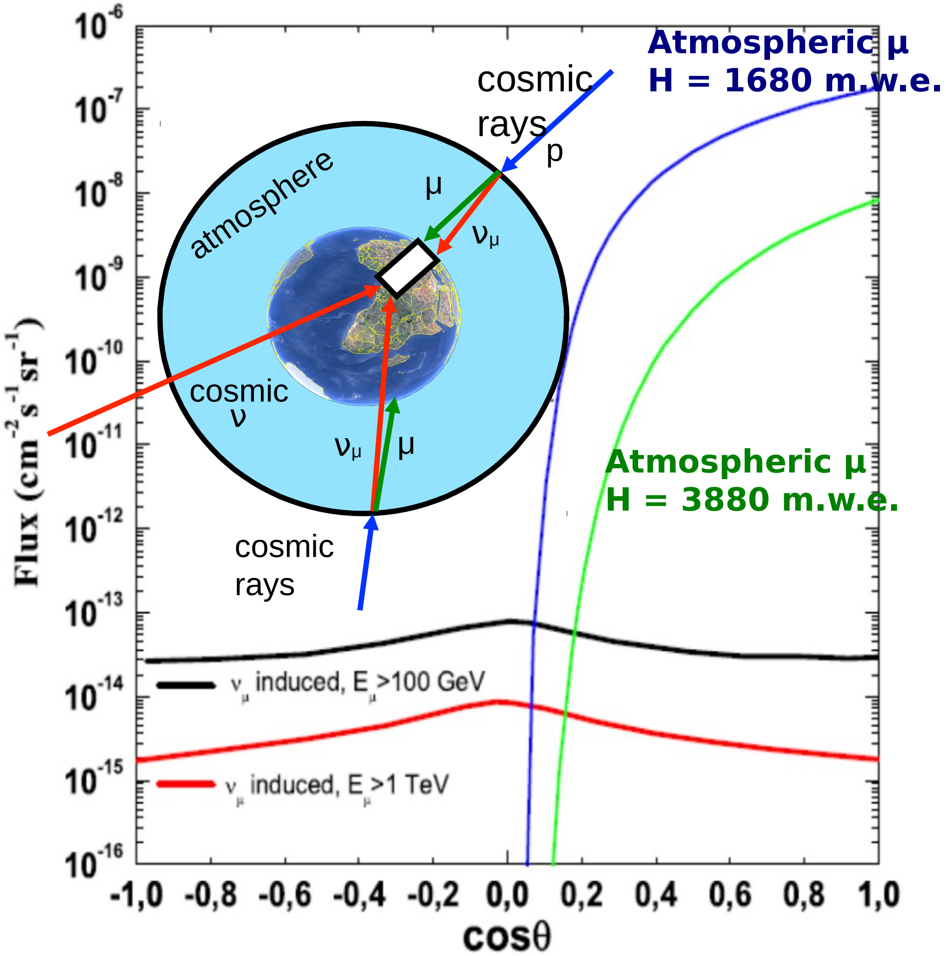
Neutrino telescopes : how they work



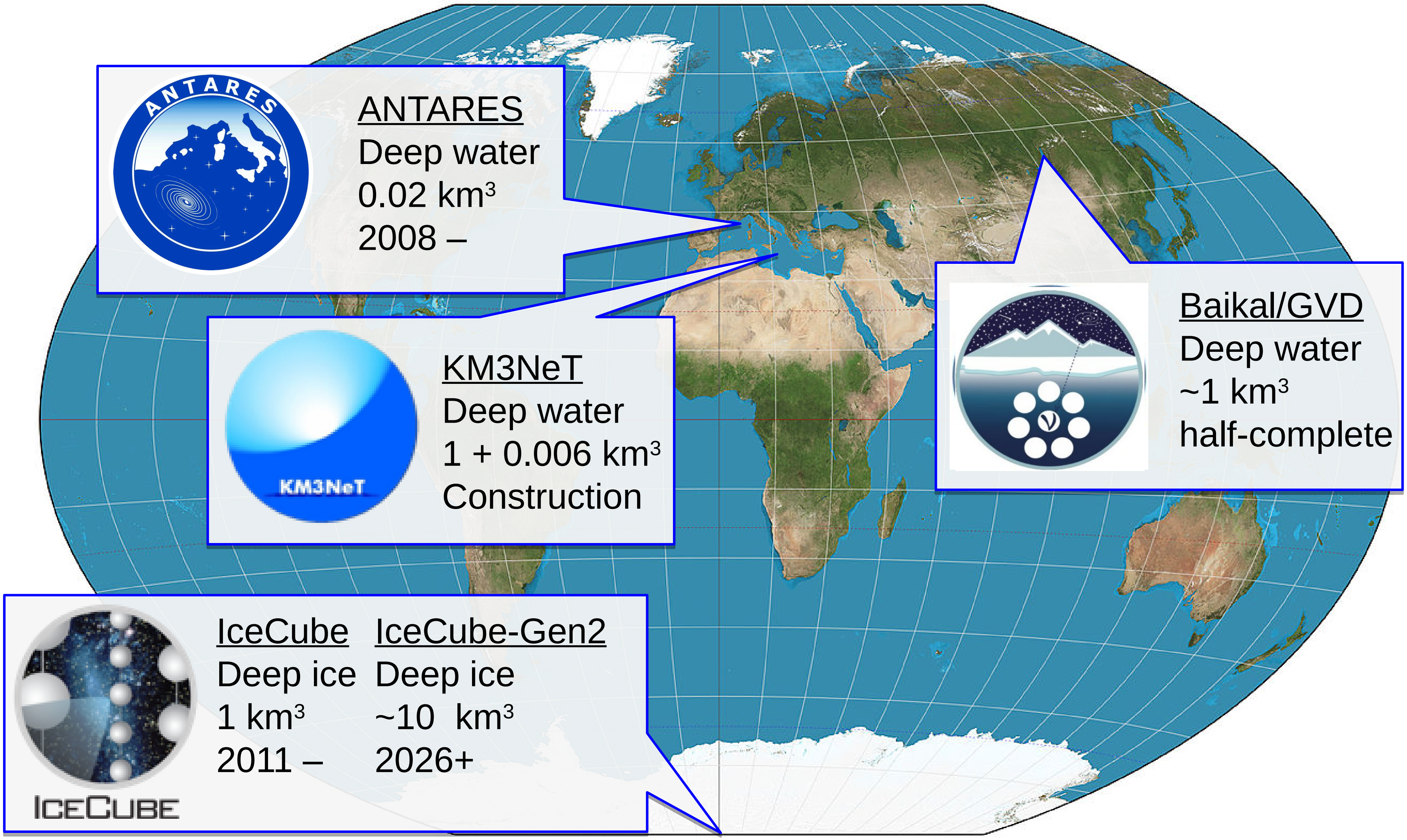
- Large arrays of PMTs in water or ice
- Light produces “hits” on the PMTs
- ν_μ CC → “Tracks”
- ν_e, ν_τ, all-flavour NC → “Showers” a.k.a. “Cascades”
- Hit positions and times → direction
- Hit charge → energy

Backgrounds

- Atmospheric neutrinos
  - quasi-irreducible background
    (for downgoing events, sibling atmospheric muons can be used as veto)
- Atmospheric muons
  - Downgoing only
    (Earth acts as filter)
- Environmental background light:
  natural radioactivity (^{40}K), bioluminescence, chemiluminescence
  - Limits low energy sensitivity

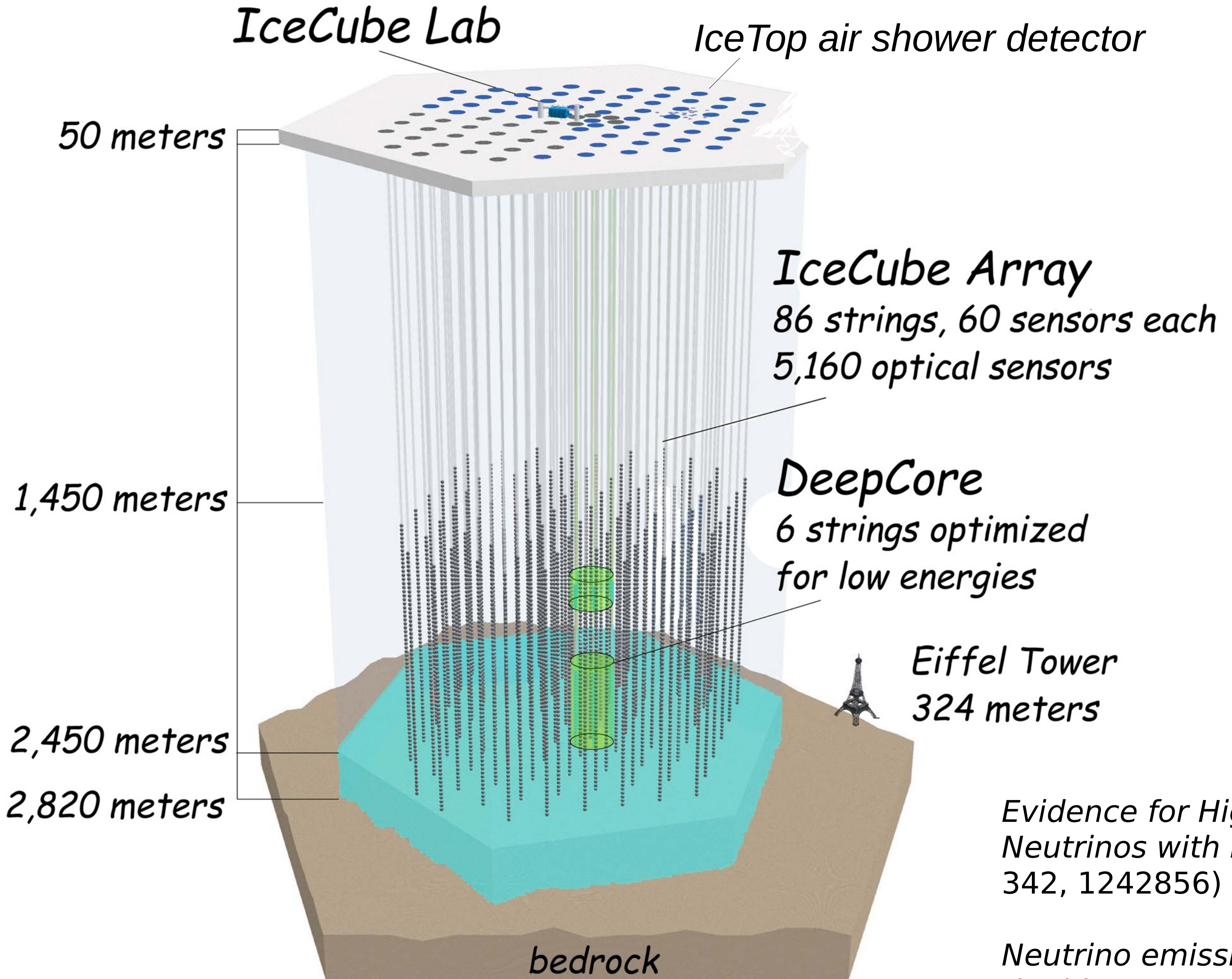


The neutrino telescope world map 2020



These neutrino telescopes form Global Neutrino Network - see talk by Christian Spiering at yesterday's neutrino session

IceCube



Completed in 2010

1 Gton

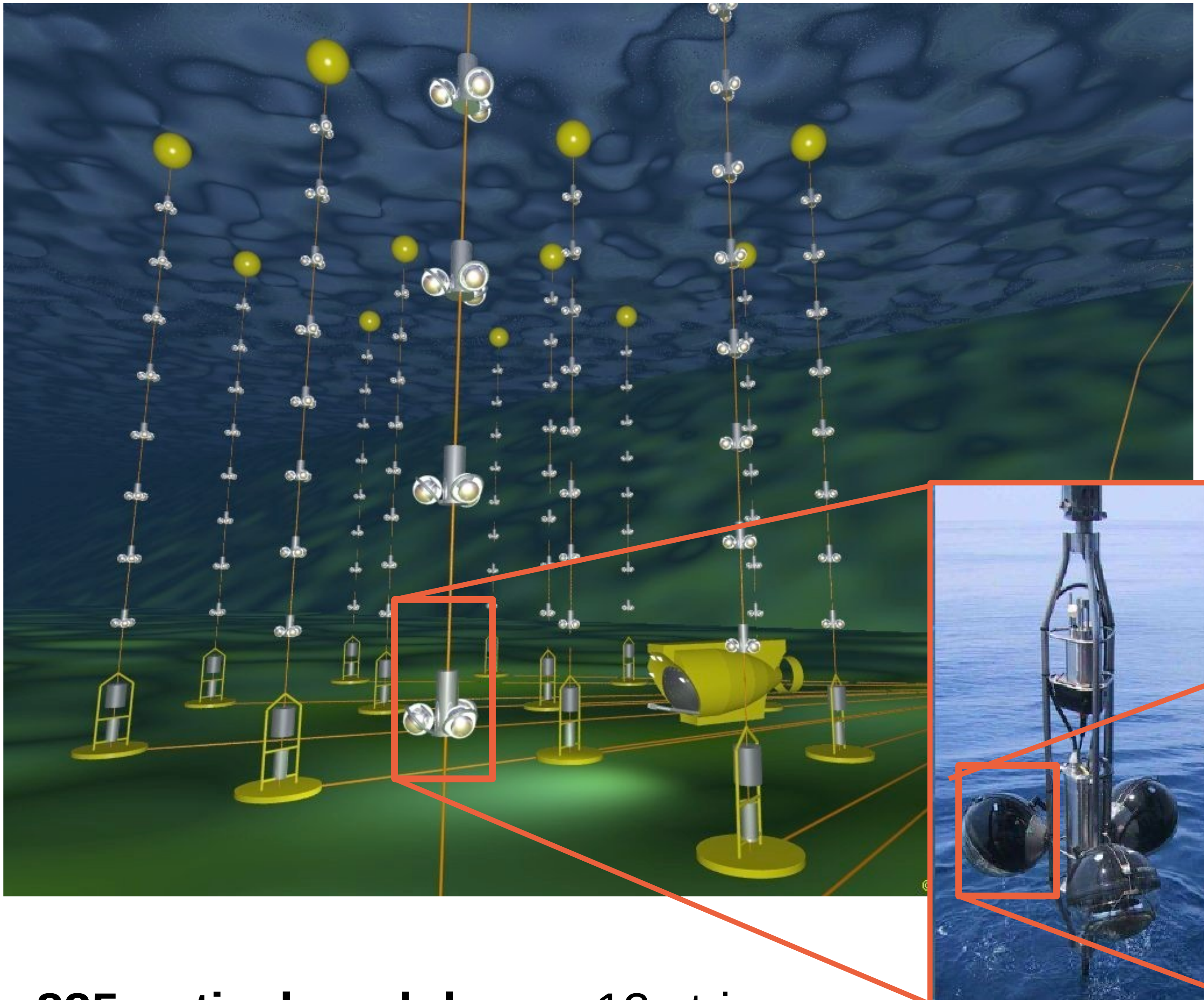
220 ν / day

Threshold:
IceCube: ~ 100 GeV
DeepCore: ~ 10 GeV

Evidence for High-Energy Extraterrestrial Neutrinos with IceCube (*Science* 2013, 342, 1242856)

Neutrino emission from the direction of the blazar TXS 0506+056 (*Science* 2018, 361, 147)

ANTARES



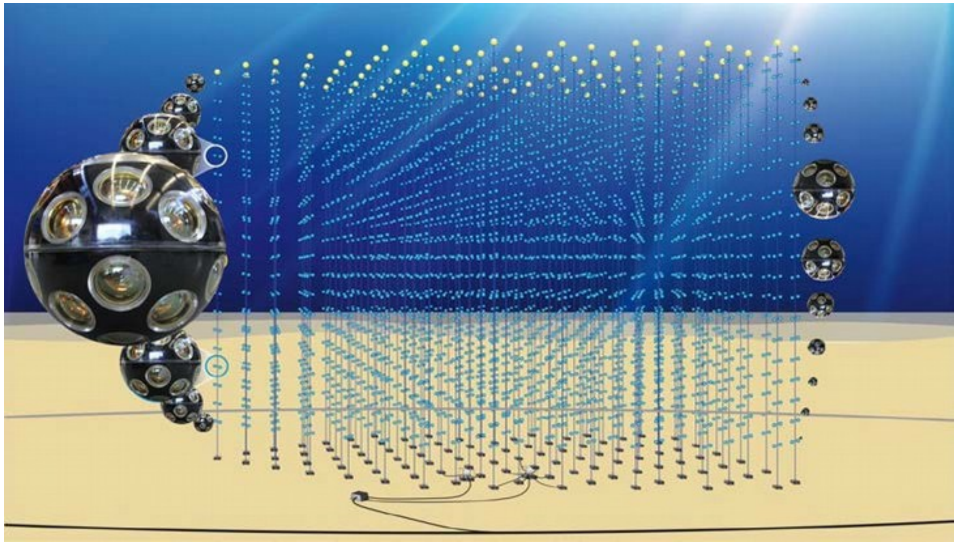
- Completed in 2008
- 12 strings
- 25 storeys per string
- 3 optical modules per storey
- ~ 12 Mton instrumented volume

885 optical modules on 12 strings
Operating for **12 yr** now

ANTARES OM:
10” Hamamatsu PMT

KM3NeT - ARCA

Construction started

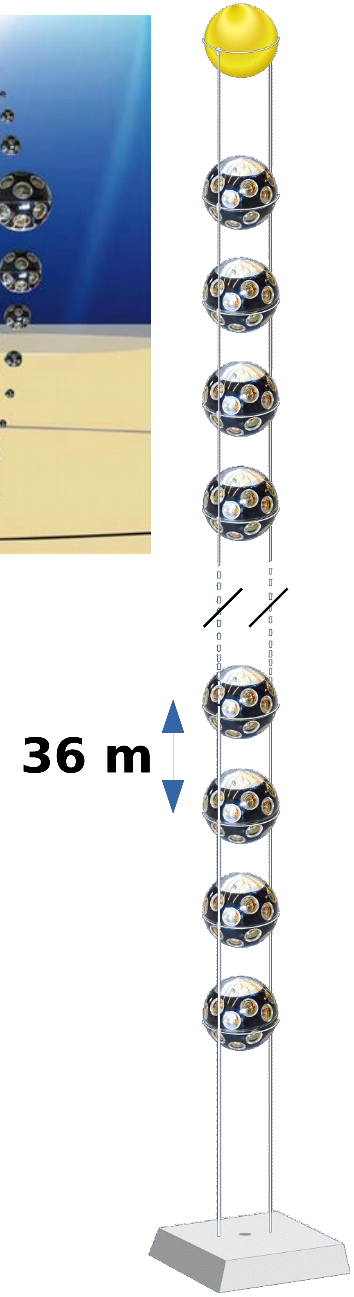


100 km offshore Sicily
Depth: 3400 m

2 x 115 strings
18 DOMs / string
31 PMTs / DOM
Total: **128 000 PMTs (3")**

Vertical spacing: 36 m
Horizontal spacing: 90 m

Volume : 1 km^3



Digital Optical Module

- 31 x 3" PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

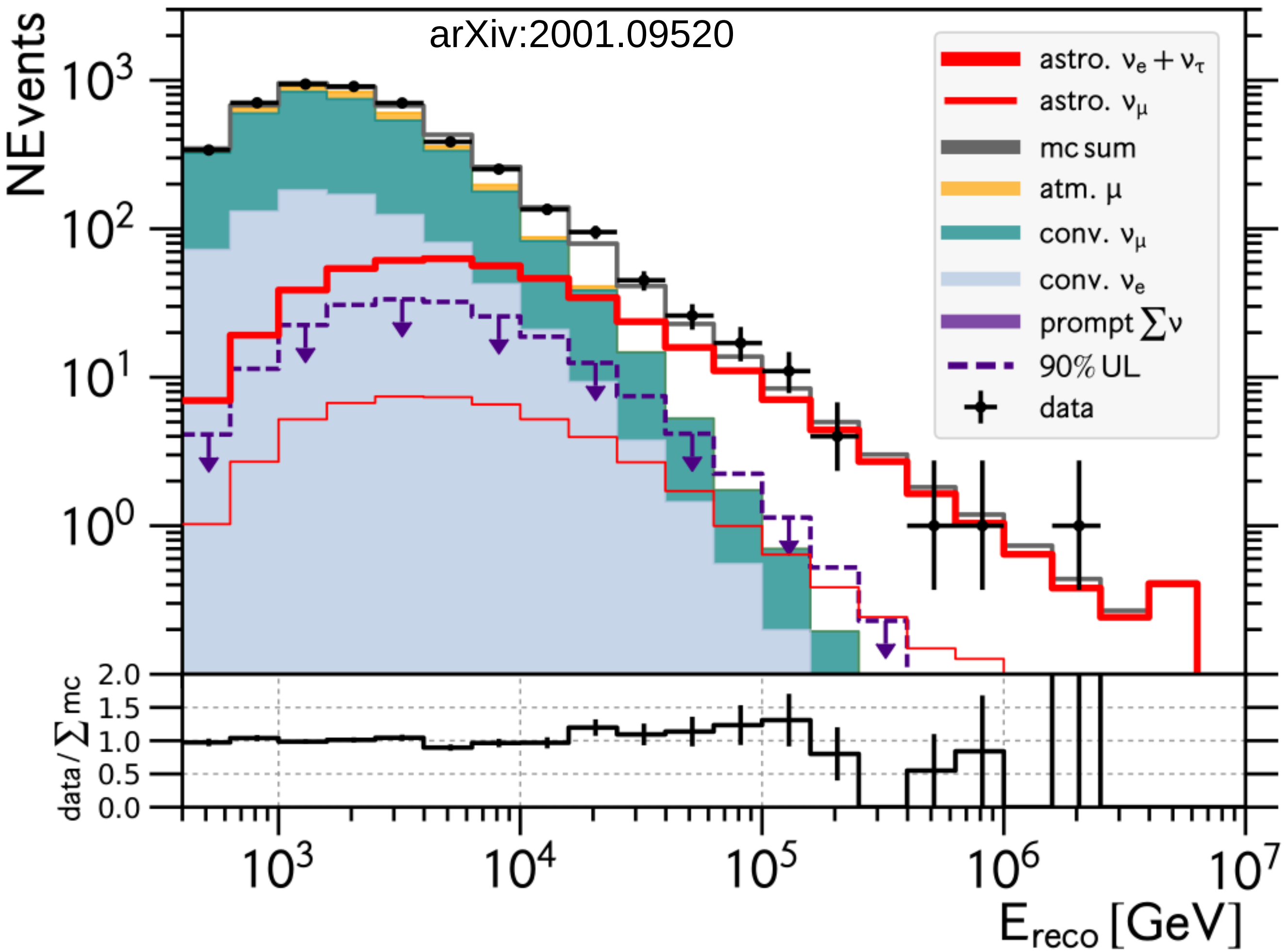
✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

photocathode area similar to a 17" PMT

Optical background (mainly ^{40}K): 5-10 kHz/PMT

Diffuse neutrino flux observed by IceCube

Cascade analysis



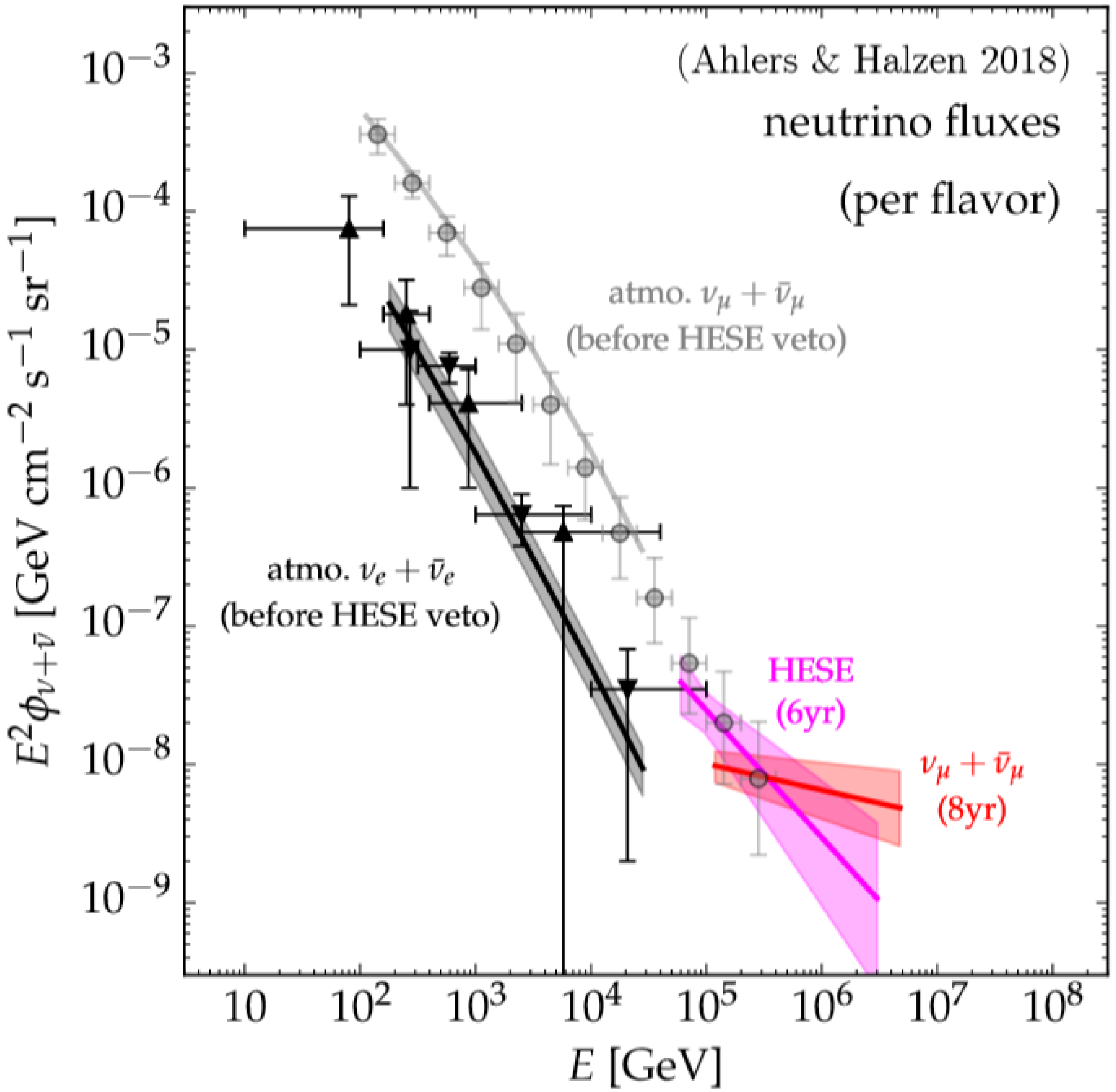
2 yrs data, 4.1 σ
Science 342 (2013)

3 yrs data, 5.9 σ
Phys.Rev.Lett. 113:101101 (2014)

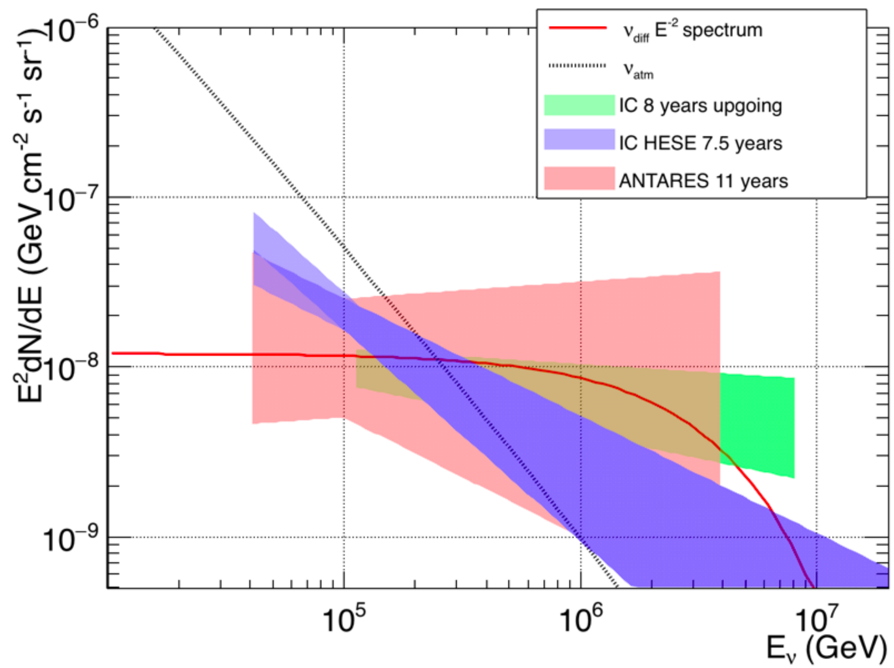
4+2 yrs data, ~10 σ
Phys.Rev.Lett. 125:121104 (2020)

Threshold ~ 30 TeV

Diffuse neutrino flux : IceCube + ANTARES



Adding ANTARES
Total: 50 events, simulation: 36.1 ± 8.7
→ 1.8 σ excess
Best fit $\Phi = 1.5 \pm 1\ 10^{-8}$ GeV^{-1} cm^{-2} sr^{-1} s^{-1}
$\gamma = 2.3 \pm 0.4$

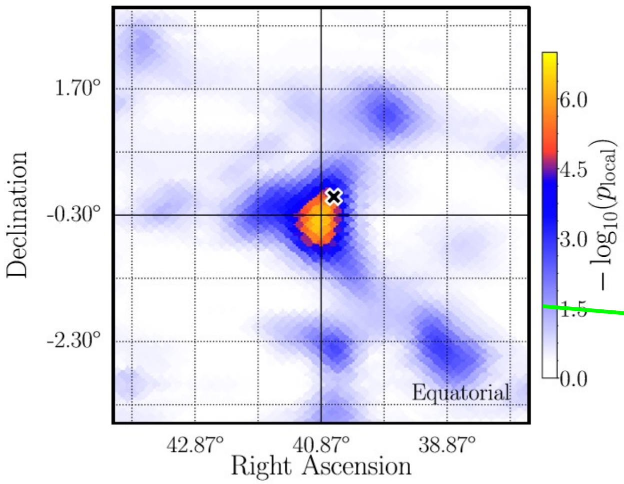


(D. Samtleben Neutrino 2020)

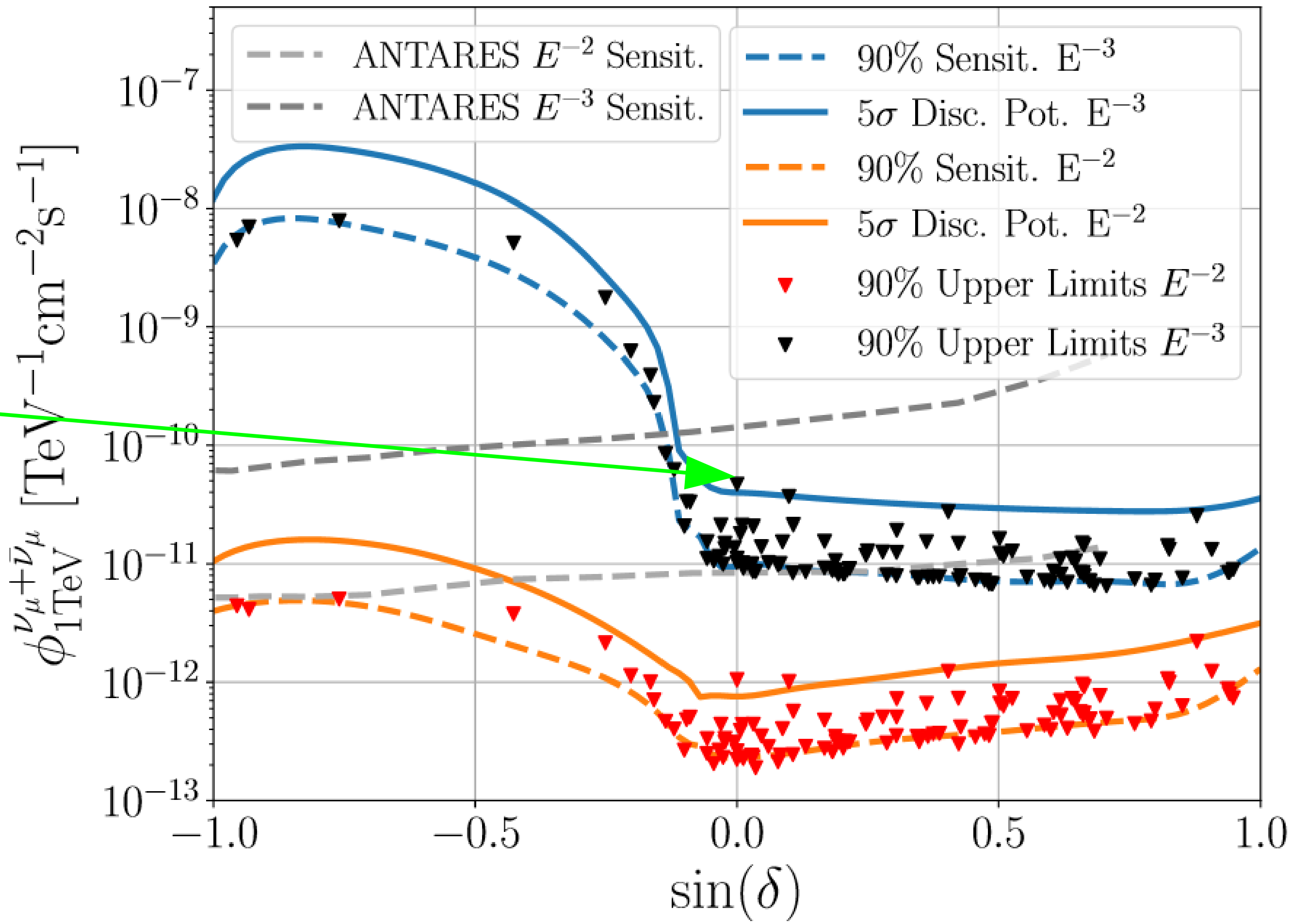
ApJ 853 (2018) L7
arXiv:1711.07212

Point-source searches

Some evidence for non-uniform skymap in 10 years of IceCube data (3.3σ). Mostly resulting from 4 extragalactic source candidates.
No indications for galactic sources

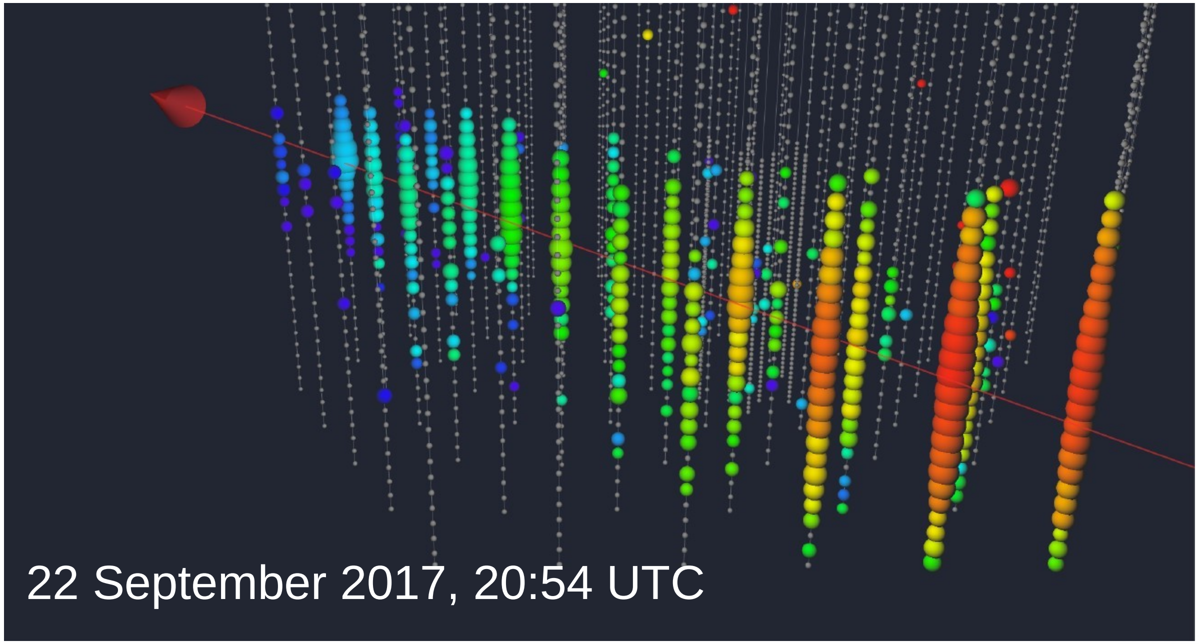


Strongest excess
(2.6 σ post trial) close to
galaxy NGC 1068 (cross)



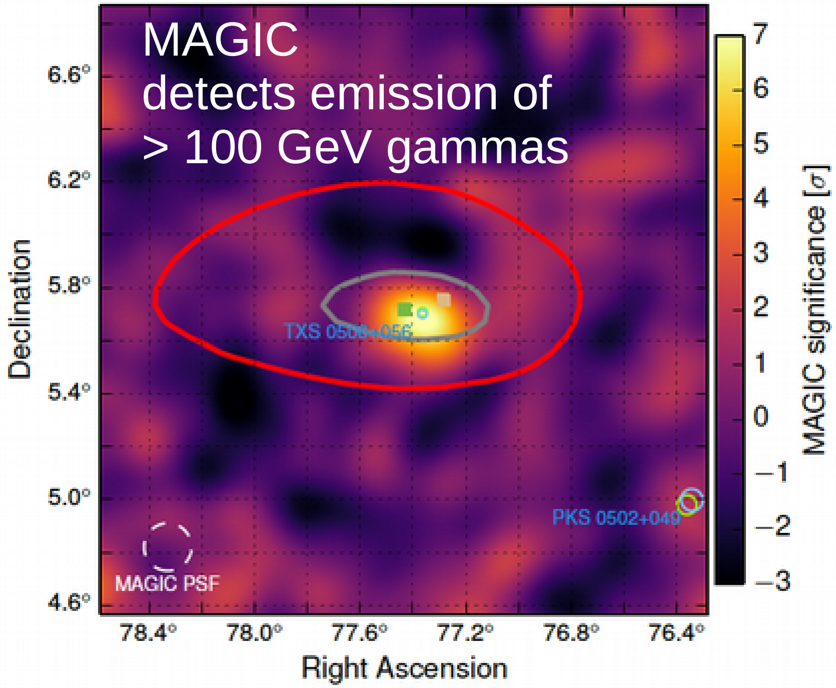
PRL 124, 051103 (2020), arXiv:1910.08488

IceCube 170922 / TXS 0506+056

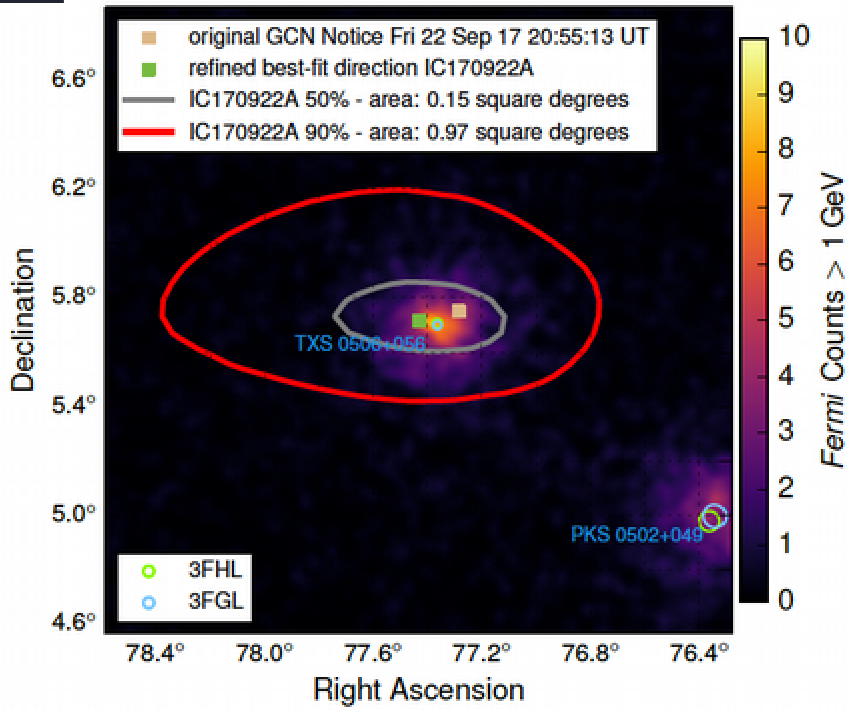


0.1° off the position of the known γ-ray blazar TXS 0506+056

Most probable energy of the neutrino ~290 TeV



Fermi detects a flaring blazar within 0.06°

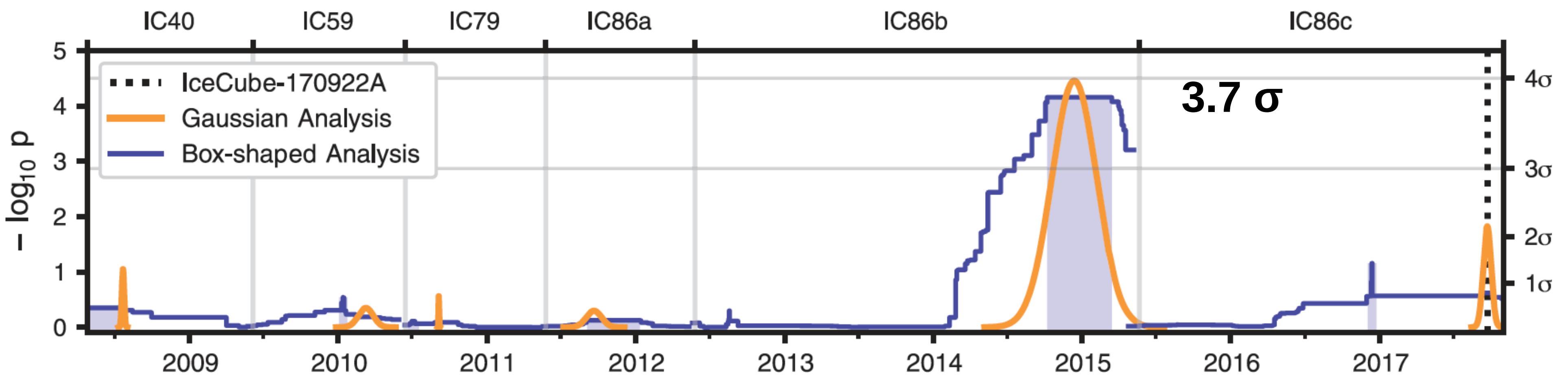


TXS 0506+056

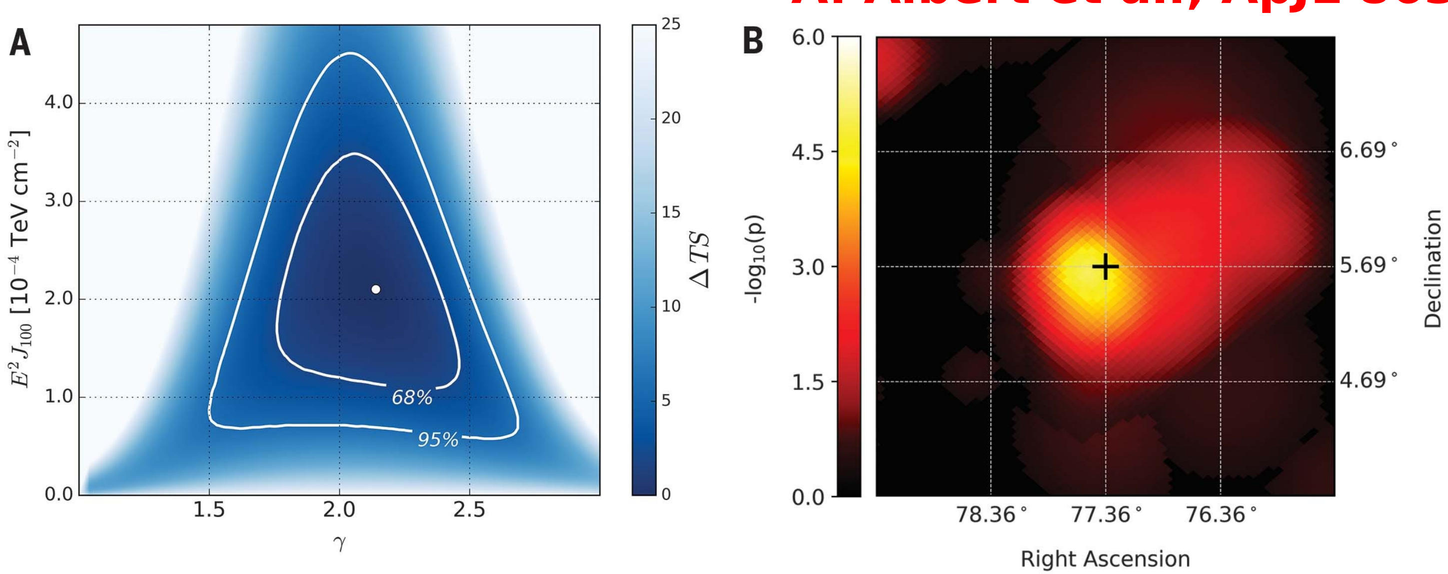
the first known source of high energy neutrinos

High-energy IceCube ν coincident with a γ-ray flare from the blazar TXS 0506+056 (22/9/17)

IceCube Collaboration, Science 361,147–151 (2018)



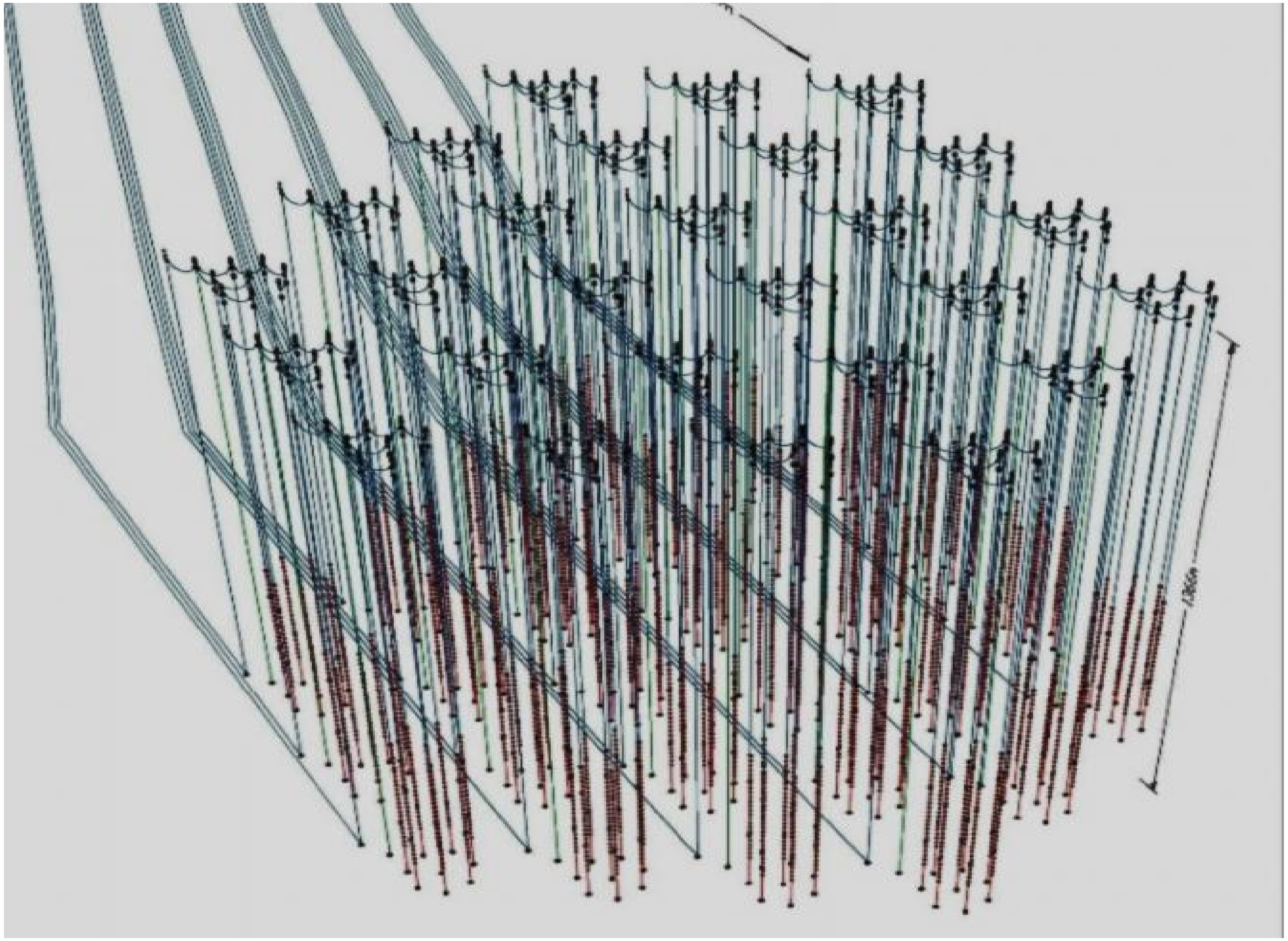
A. Albert et al., ApJL 863, L30 (2018)

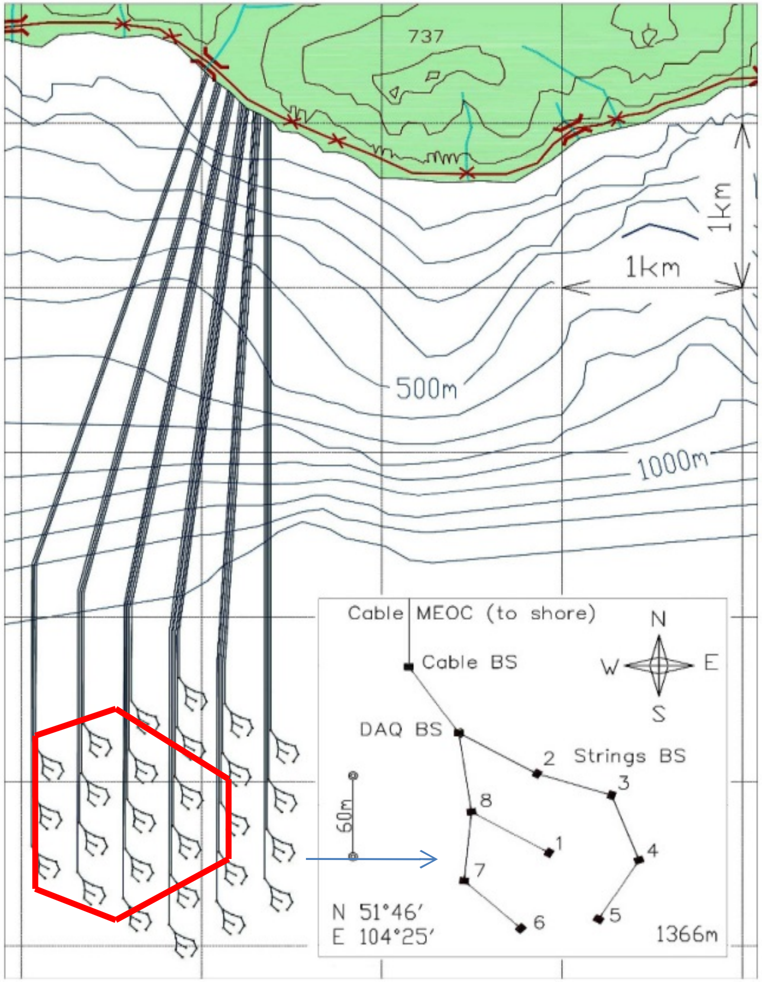


z = 0.34

Gigaton Volume Detector at Lake Baikal

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





Baikal-GVD collaboration

10 organisations from 5 countries, ~70 collaboration members

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

Baikal-GVD site

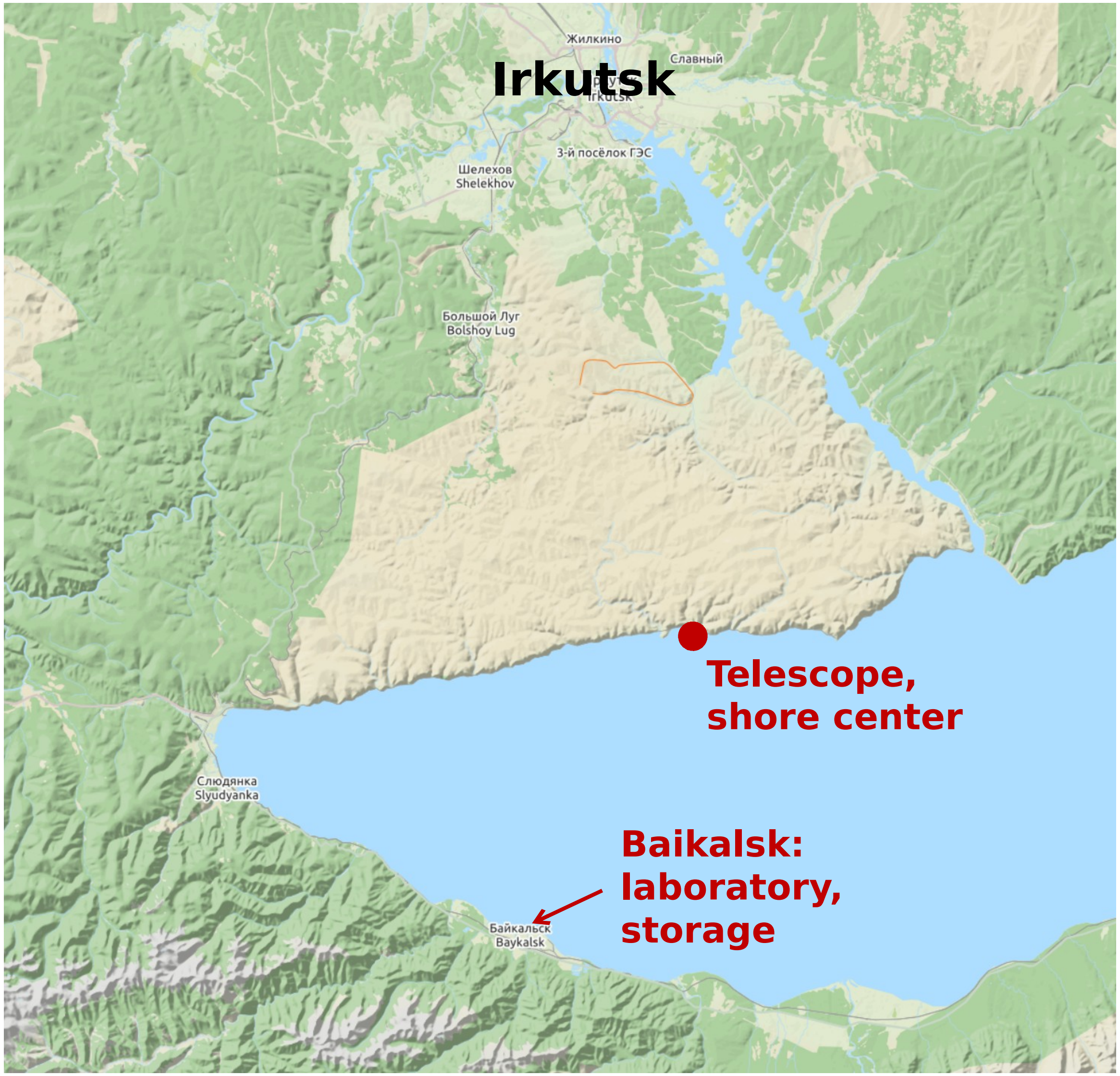
Railway stop "106 km" of Circum-Baikal railway

Telescope is located 3.6 km away from shore

Constant lake depth:
- 1366 - 1367 [m]

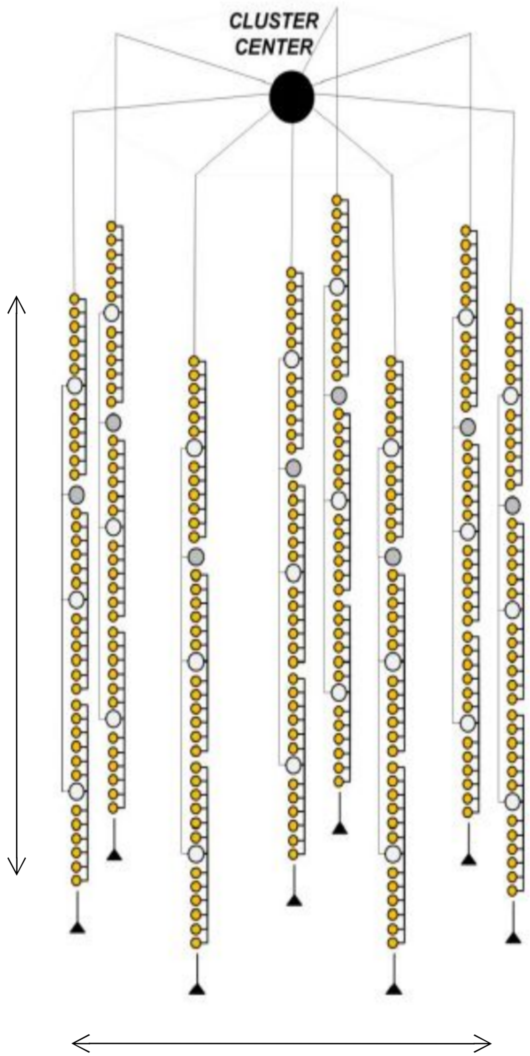
Water transparency:
- Absorption length: 22 m
- Scattering length: 30 - 50 m

Stable ice cover for 6-8 weeks in February - April
- Detector deployment
- Maintenance



Baikal-GVD detector layout

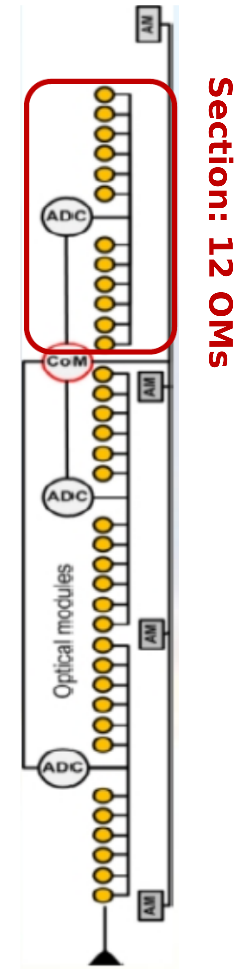
CLUSTER:
8 strings



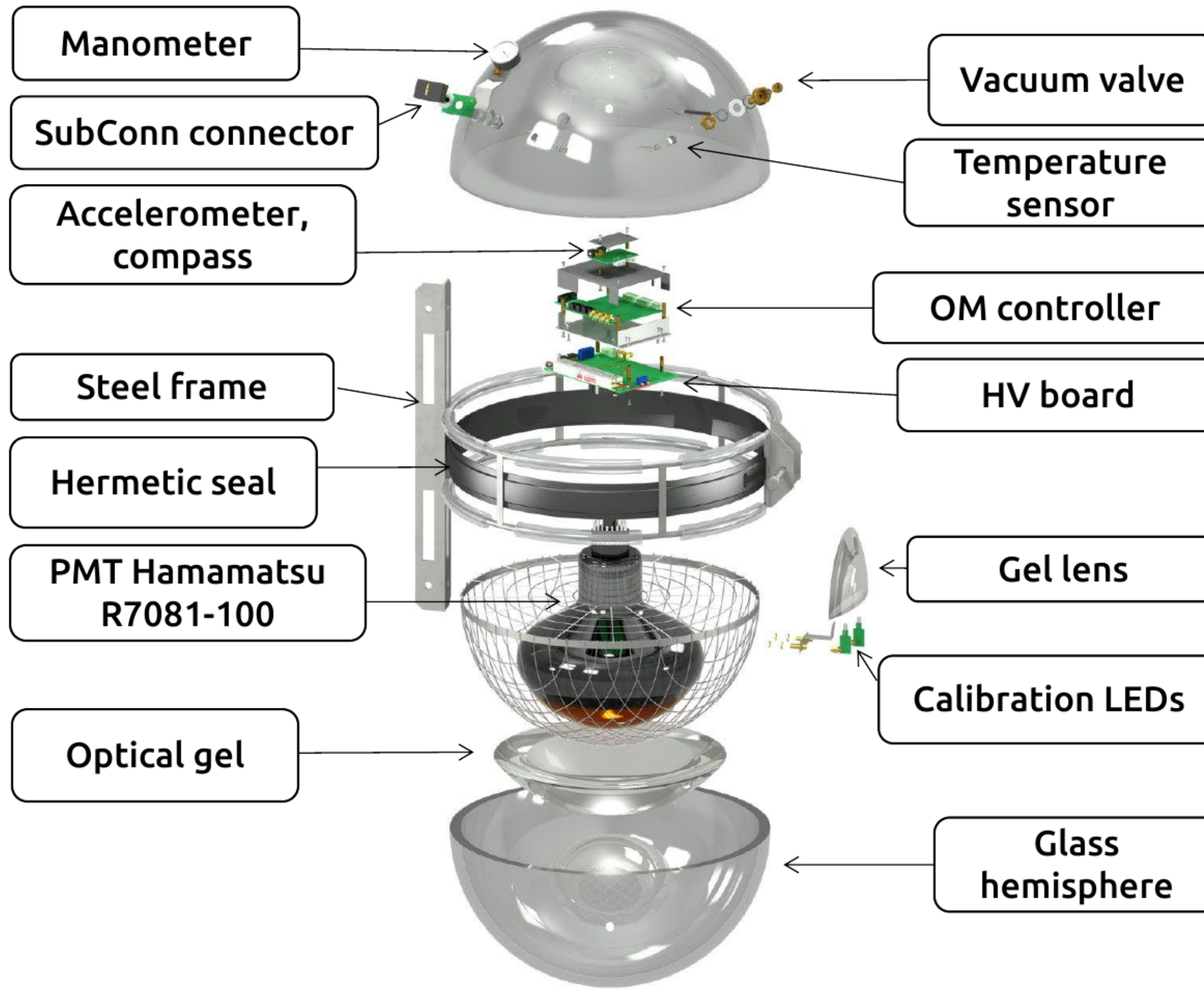
Cluster
- Consists of 8 strings
- 60 m step between strings
- Acts as independent detection unit
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger:
  4.5 p.e. + 1.5 p.e. on adjacent OMs in 100 ns window

String
- 36 OMs, depths from 750 m to 1275 m
- 15 m step between OMs
- All OMs look downward
- Acoustic and LED calibration devices
- Anchored at the lake bottom

STRING

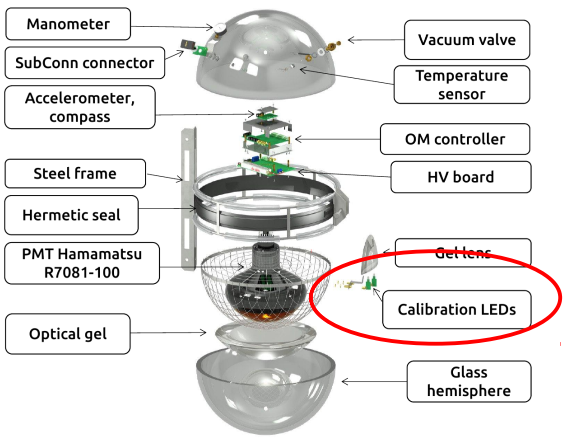


Baikal-GVD optical module

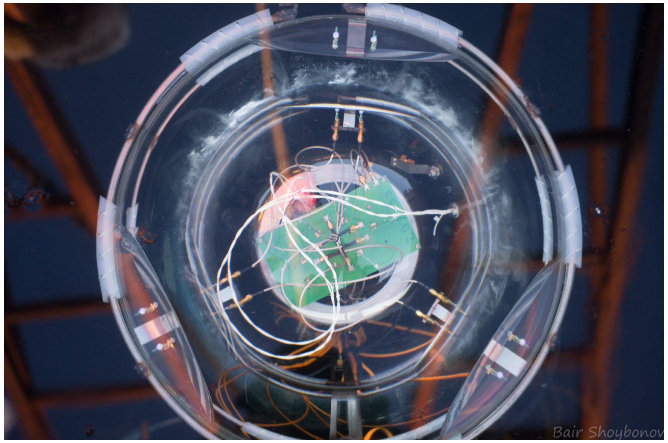


Calibration devices

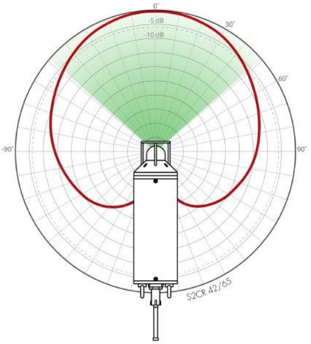
Calibration LEDs in each OM



LED beacons for time calibration (2 per string, 2 ns precision)

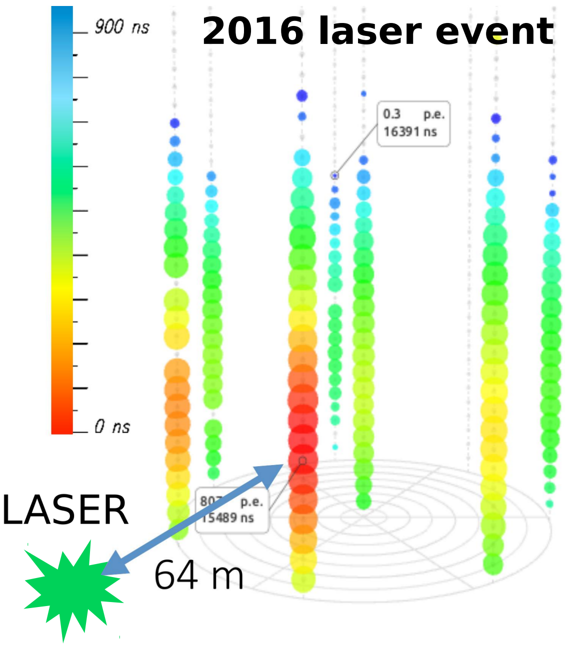


Hydrophones for acoustic positioning (4 per string, ~ 20 cm precision)



Laser 532 nm, 0.37 mJ, 1 ns

Baikal-GVD 2020 top view

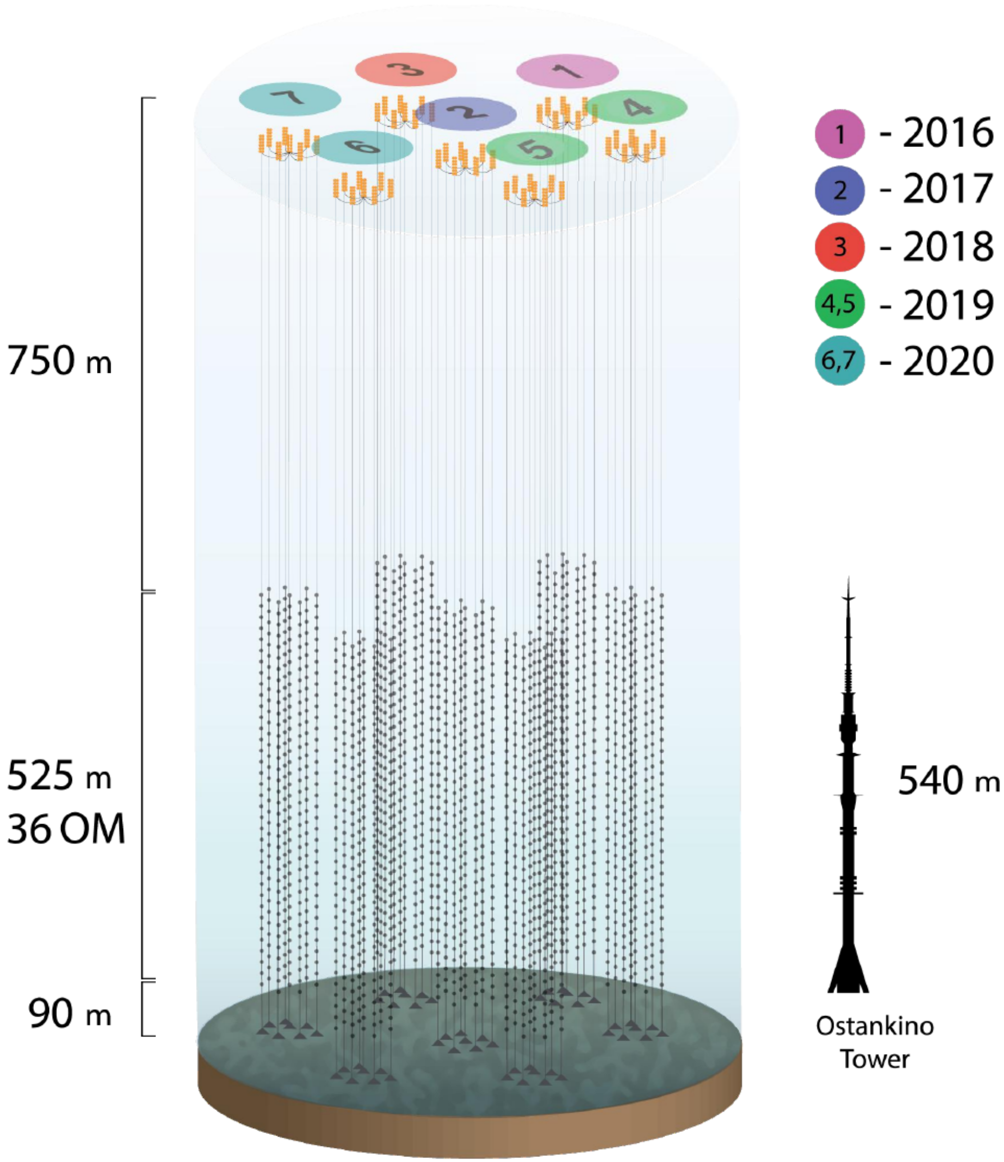


Winter expedition 2020

Despite harsh ice conditions this winter

two new clusters were deployed (596 OMs)

Baikal-GVD construction status and schedule



300 m step between clusters

Deployment schedule

Year	Total number of clusters	Total number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	**7**	**56**	**2016**
2021	9	72	2592
2022	11	88	3168
2023	13	104	3744
2024	15	120	4320

Effective volume 2020: 0.35 km^3

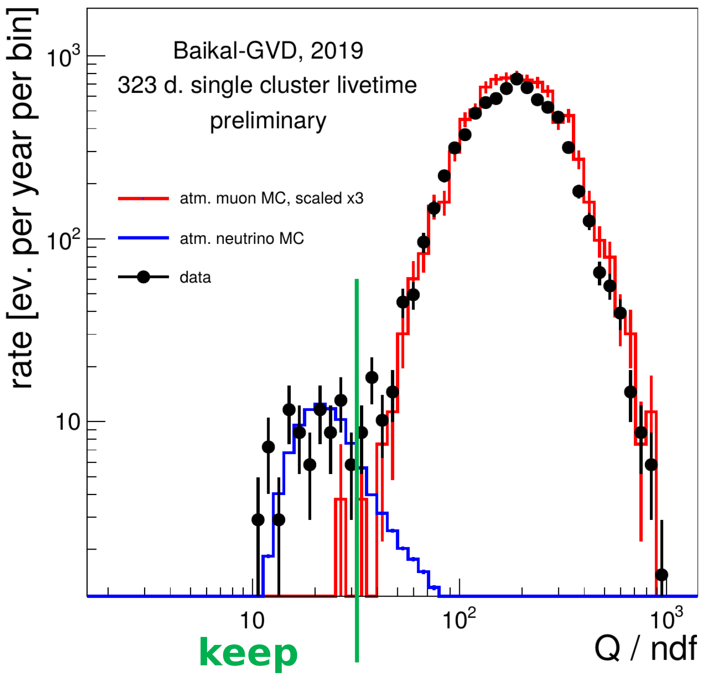
Track analysis

Fit track with quality function

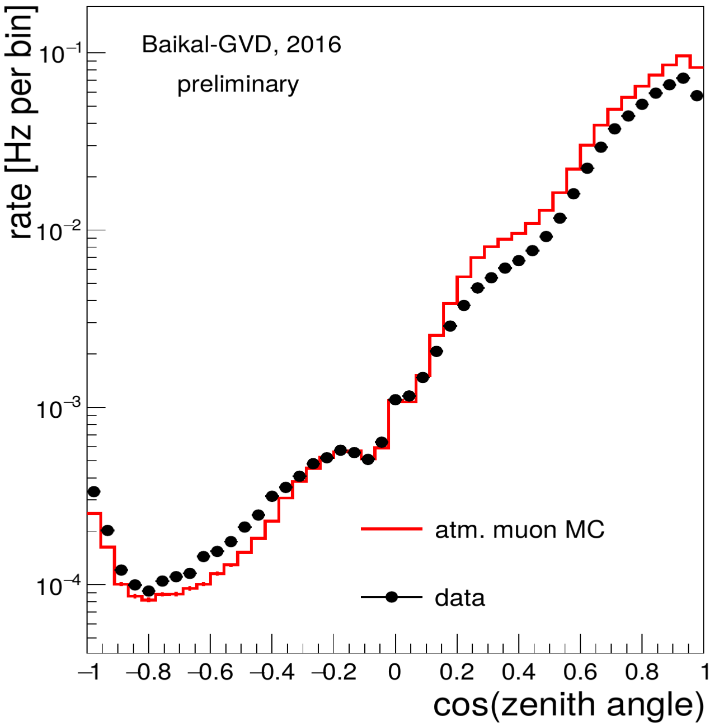
$$Q = \chi^2(t) + f(q, r)$$

Neutrino selection:
- cut on zenith angle
- cut on fit quality

upgoing: θ_{zenith} > 120 deg.



event rate before quality cuts (dominated by muon bundles)

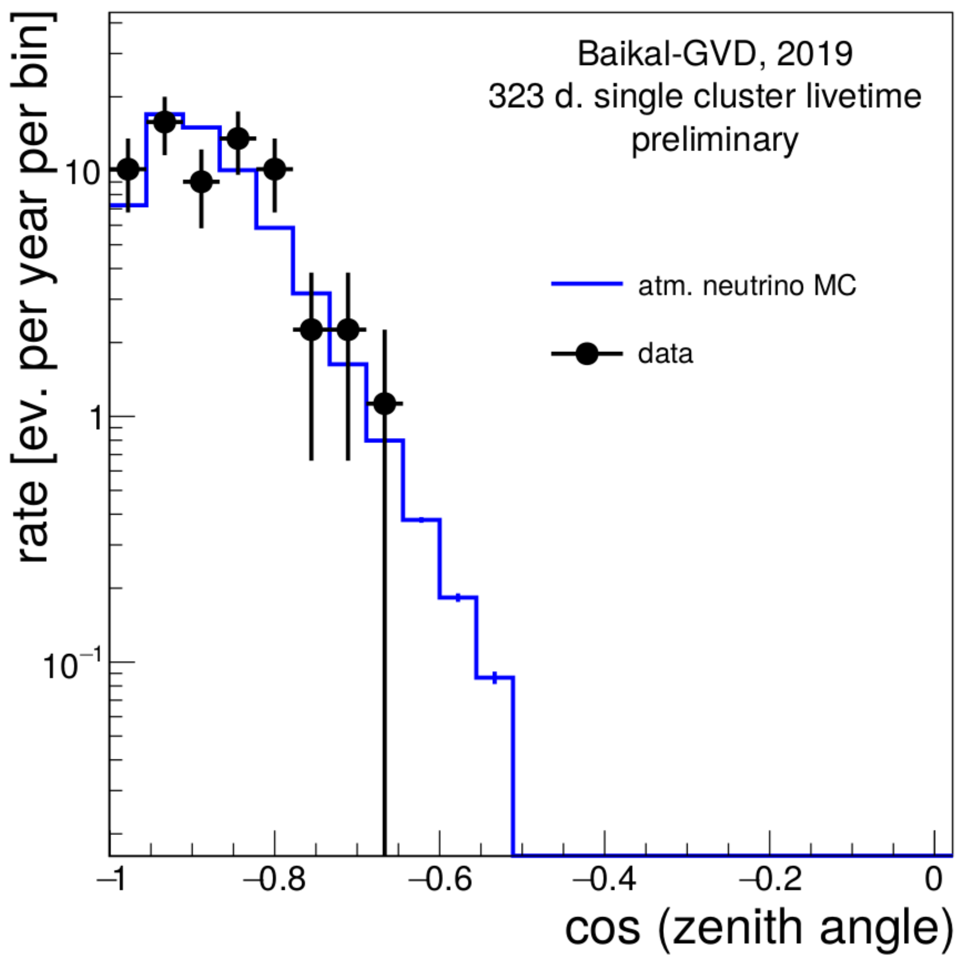


Fair agreement with MC predictions
Neutrino selection works as expected

A likelihood-based reconstruction is in development

Muon neutrino : single-cluster analysis

- Data taken between Apr 1 and Jun 30, 2019
- Live time: 323 days (single-cluster equivalent live time)



MC expected: 54.3
- atm. neutrino : 54.3
- atm. muon: < 1

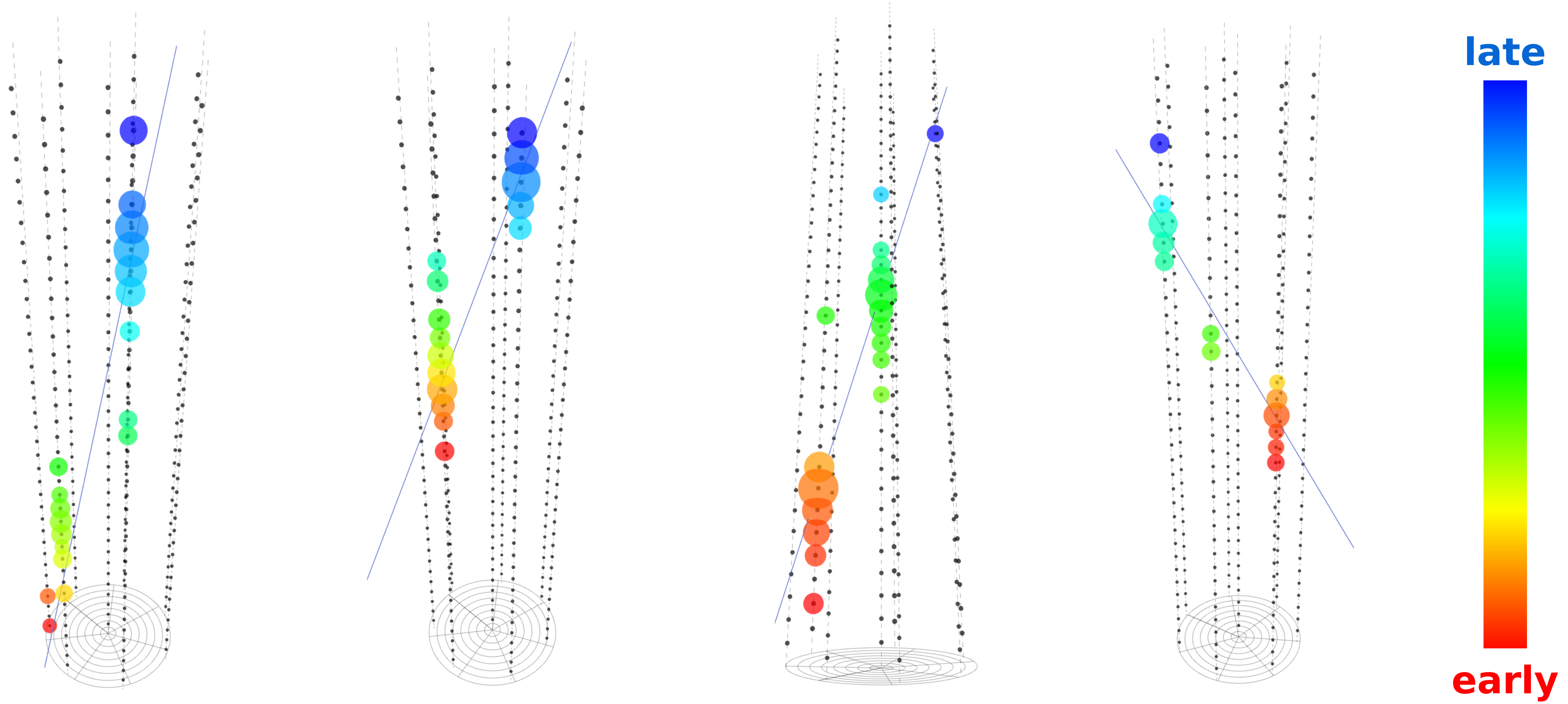
Observed: 57

Fair agreement with MC prediction for atmospheric neutrino

Angular resolution ~ 1° or better (single cluster)

Multi-cluster analysis is in preparation

Muon neutrino candidates



cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
$N_{strings}$ = 19

cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
$N_{strings}$ = 15

cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

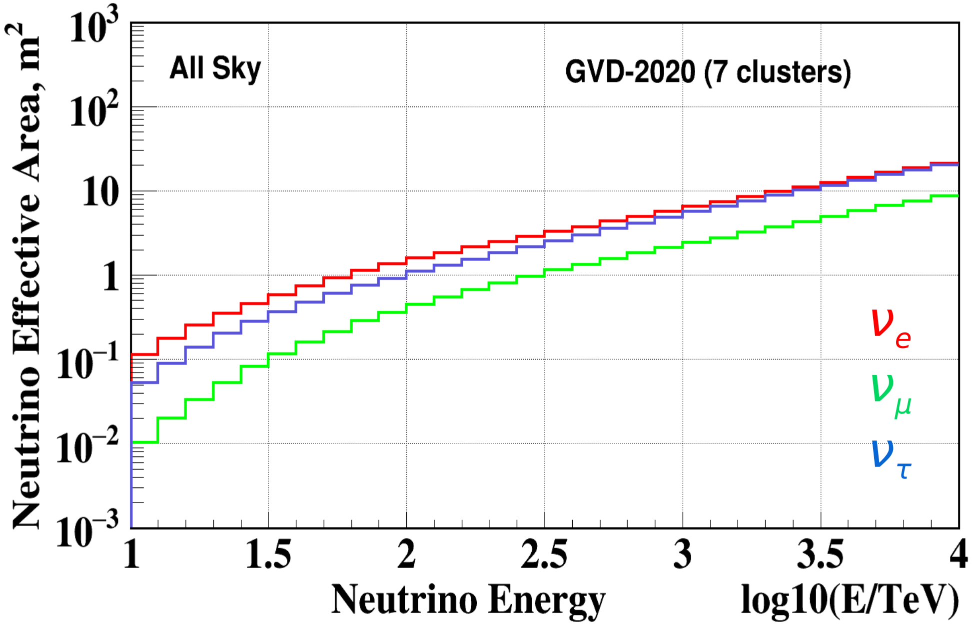
cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13

High energy cascades (expectations)

Analysis sensitive to all-flavour CC and NC interactions over the whole sky

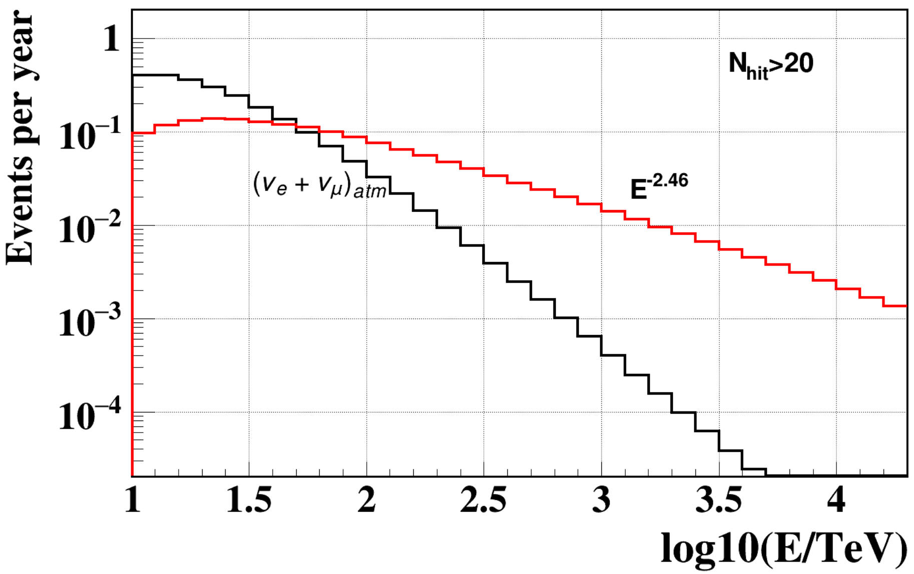
Assumption for astrophysical neutrino energy spectrum (IceCube fit):
$4.1 \cdot 10^{-6}\ E^{-2.46}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$

neutrino effective area for cascade detection



Glashow resonance not included

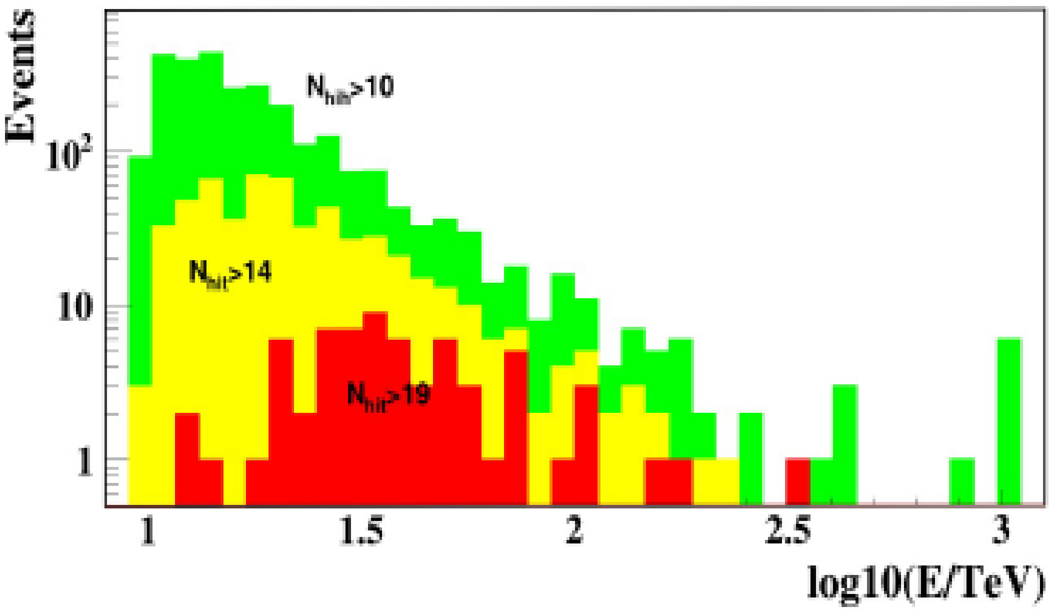
Expected number of cascade events per year per Baikal-GVD cluster



Effective volume for > 100 TeV cascade detection has reached **0.35 km³** !

- 0.6 cascade events with E>100 TeV and N_{hit} > 20 are expected per year per cluster
- **4.2 events per year for 7 clusters**

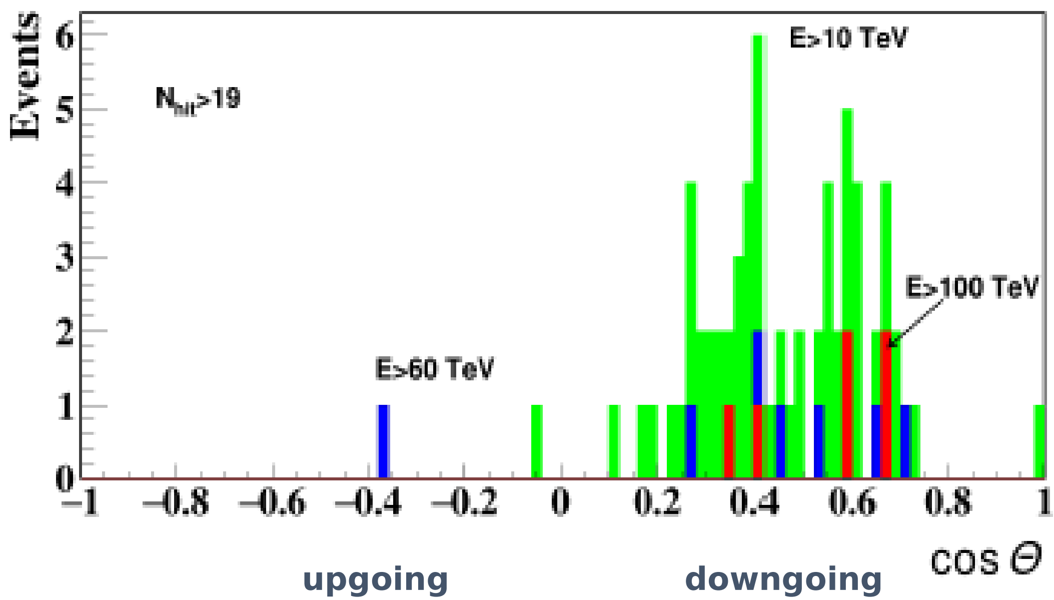
High energy cascades (data)

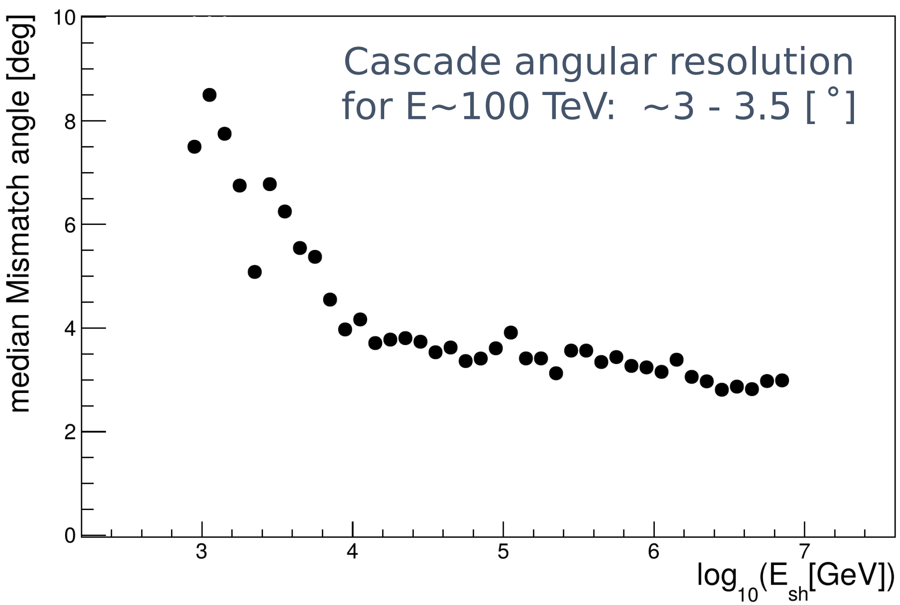


Data from 2016, 2018 and 2019 (4 months), **exposition: 1364 days**

7 candidates with E > 100 TeV and Nhit >19 (+ 5 more events found in later 2019 data)

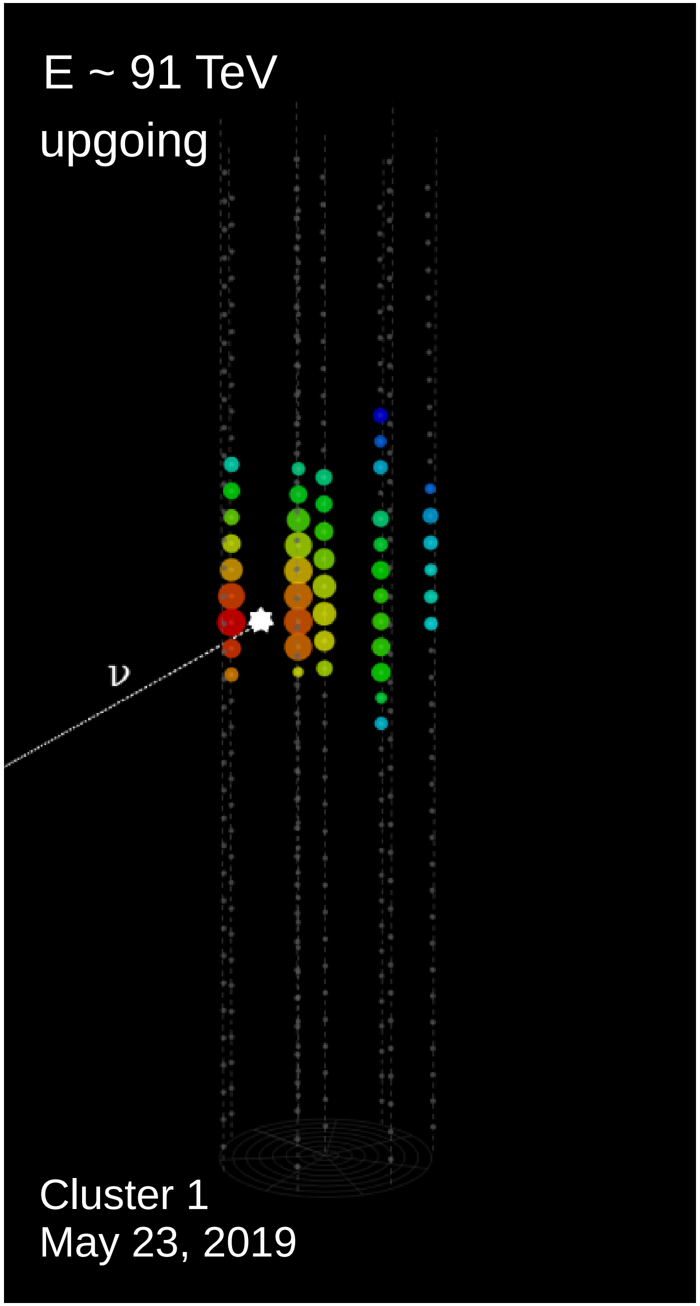
2 upgoing cascades: E ≈ 91 TeV and E ≈ 23 TeV





NB: Contribution of atmospheric muon & neutrino backgrounds is under evaluation

A neutrino candidate



Cascade event
well contained
within a GVD cluster
(50 m off central string)

Reconstructed as
upgoing with a shallow
zenith angle
(19° below horizon)

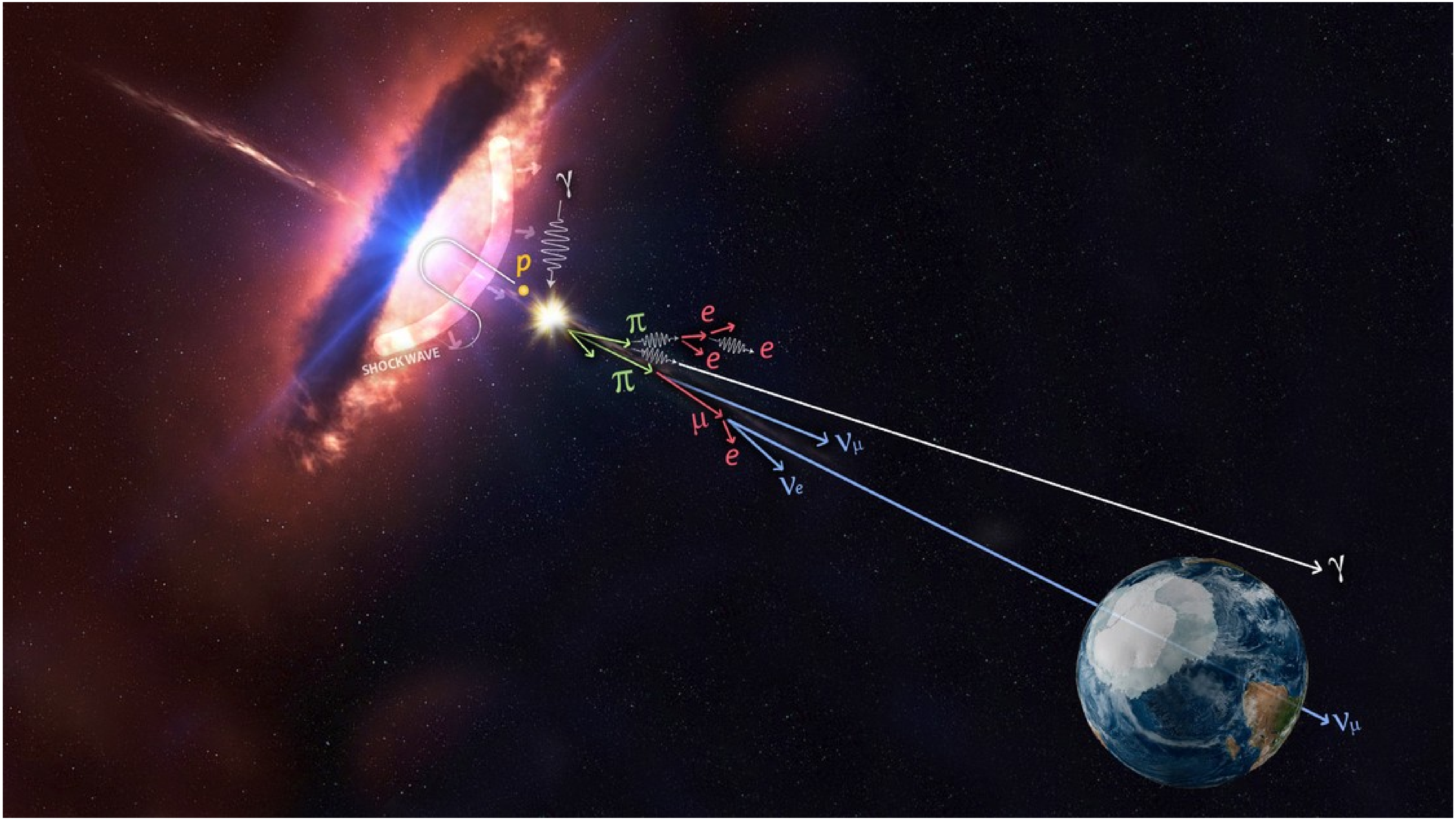
Excellent candidate for
a neutrino event of
astrophysical origin

Conclusion

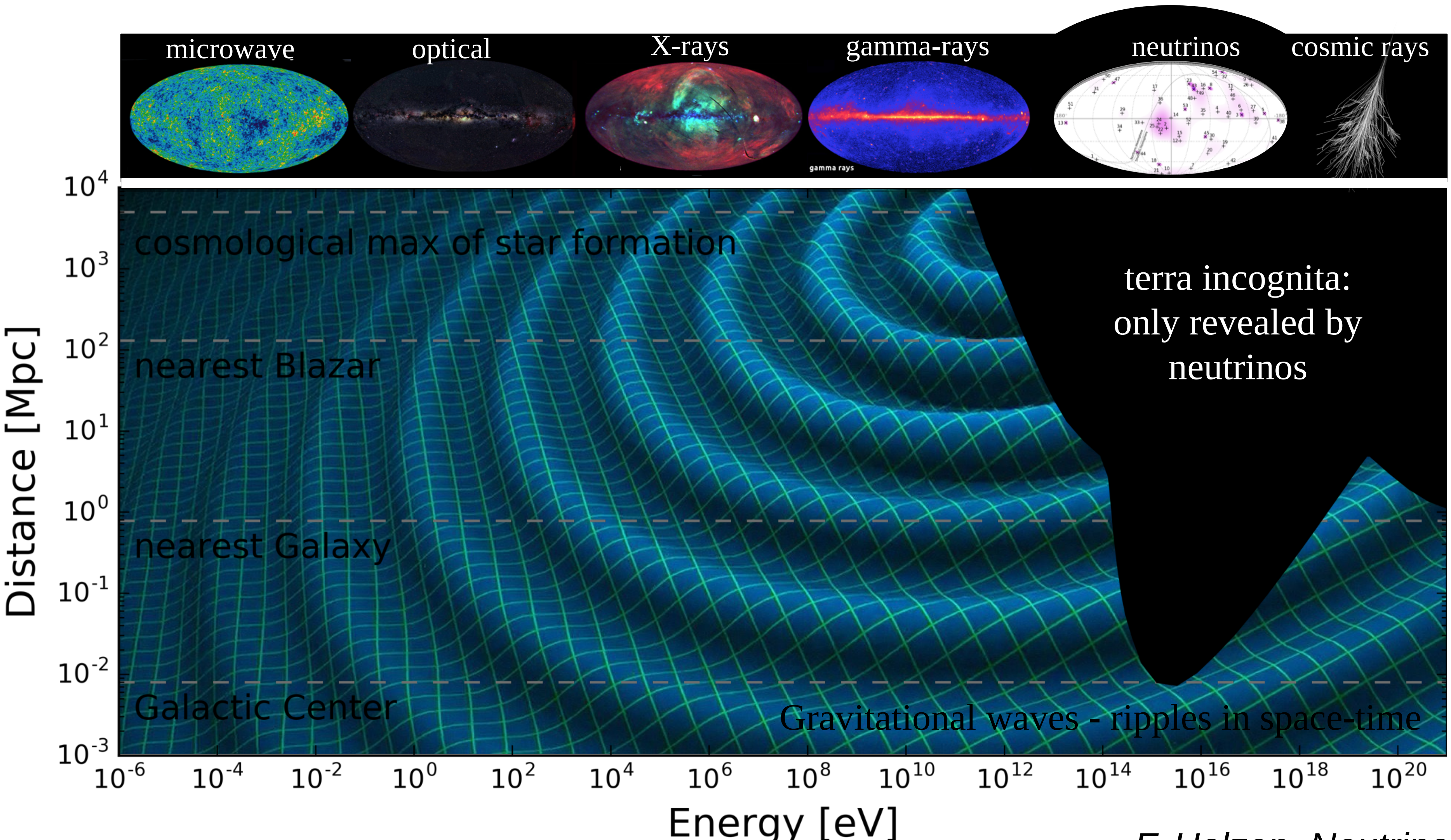
- First discoveries by IceCube lead to further questions
  - The origin of the diffuse neutrino flux remains unknown
  - Physics mechanisms of neutrino production in TXS 0506 remain uncertain
- Baikal-GVD and ANTARES/KM3NeT complement IceCube, providing for a full sky coverage, improved angular resolution and point-source sensitivity
- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere: 0.35 km^3 and growing
- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations; some first astrophysics neutrino candidate events have been shown

Backup slides

A neutrino production scenario



Highest energy radiation in the Universe



F. Halzen, Neutrino 2020

Universe is opaque to photons above ~100 TeV energy

(due to interactions on CMB and EBL photons)

AGN origin of the diffuse neutrino flux?

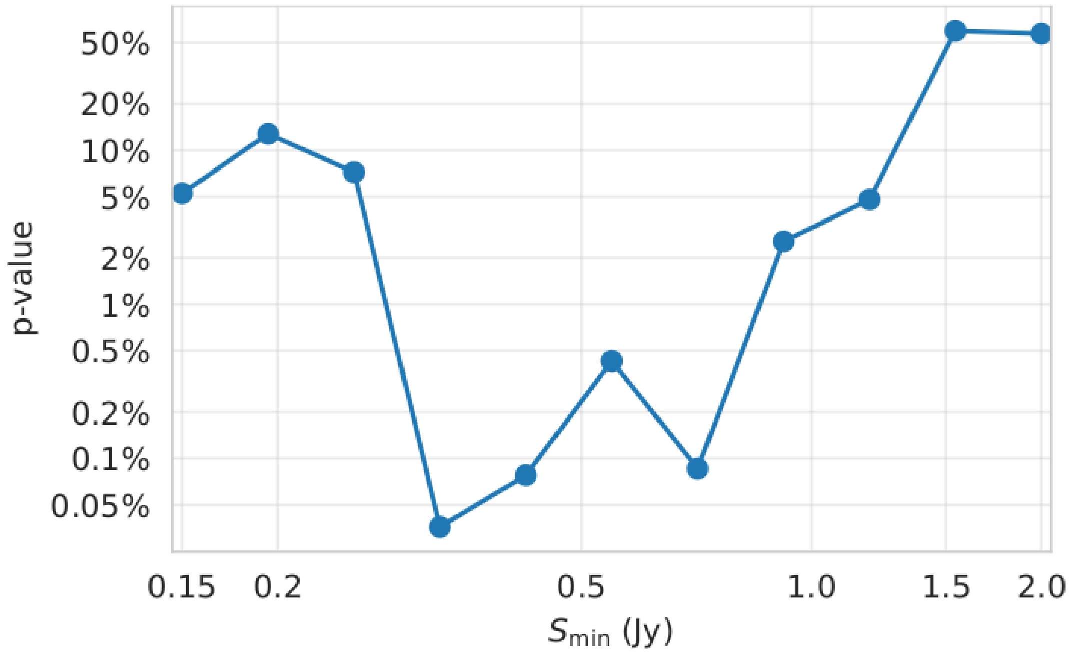


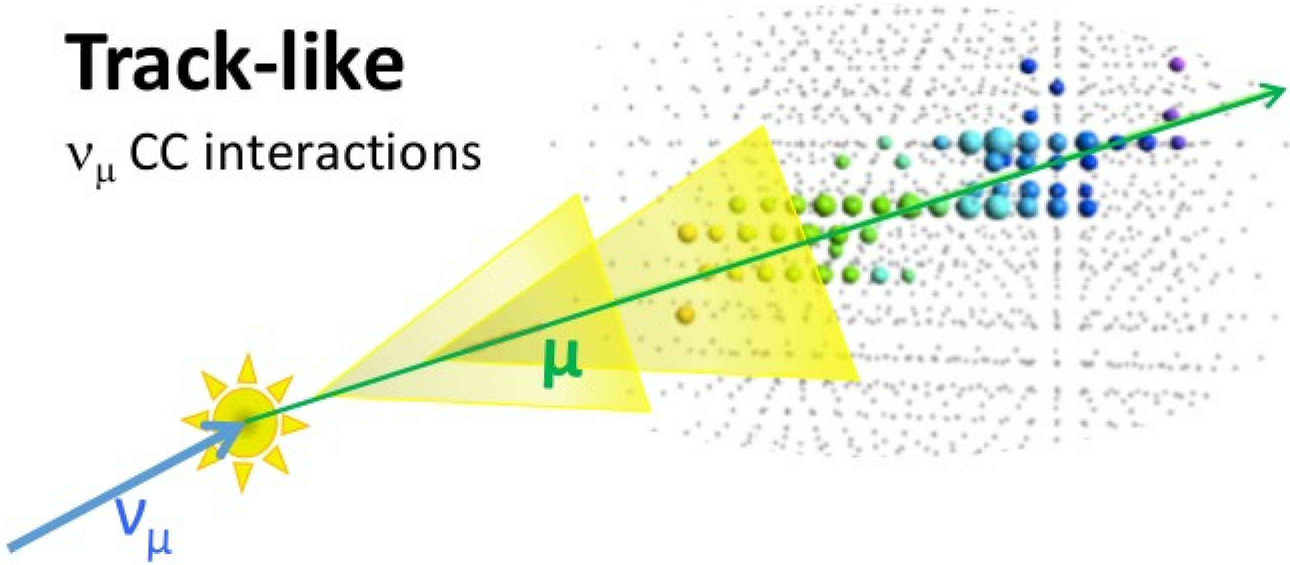
Figure 2. Pre-trial p-values for a range of VLBI flux density cutoffs. The threshold values $S_{\rm min}$ split the interval 0.15-2 Jy into ten parts uniformly in log-scale. The lowest p-value of $4 \cdot 10^{-4}$ is attained for the threshold of 0.33 Jy.

A. Plavin, Y. Kovalev, Yu. Kovalev, S. Troitsky: Directional association of TeV to PeV astrophysical neutrinos with active galaxies hosting compact radio jets, arXiv:2009.08914, subm. to ApJ

Topology of events (track/shower)

Track-like

ν_μ CC interactions

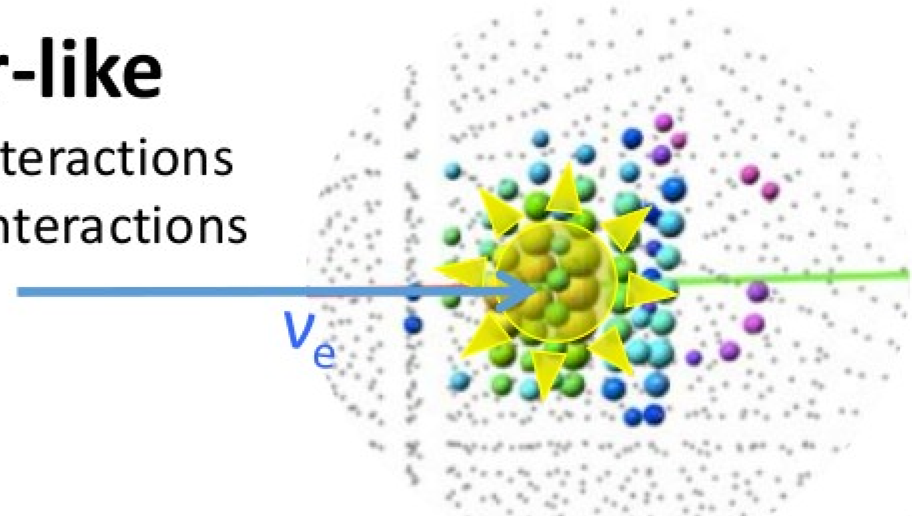


Angular resolution:
~0.1° (full, E>10 TeV)

Energy resolution:
<0.5 (log E_μ)

Shower-like

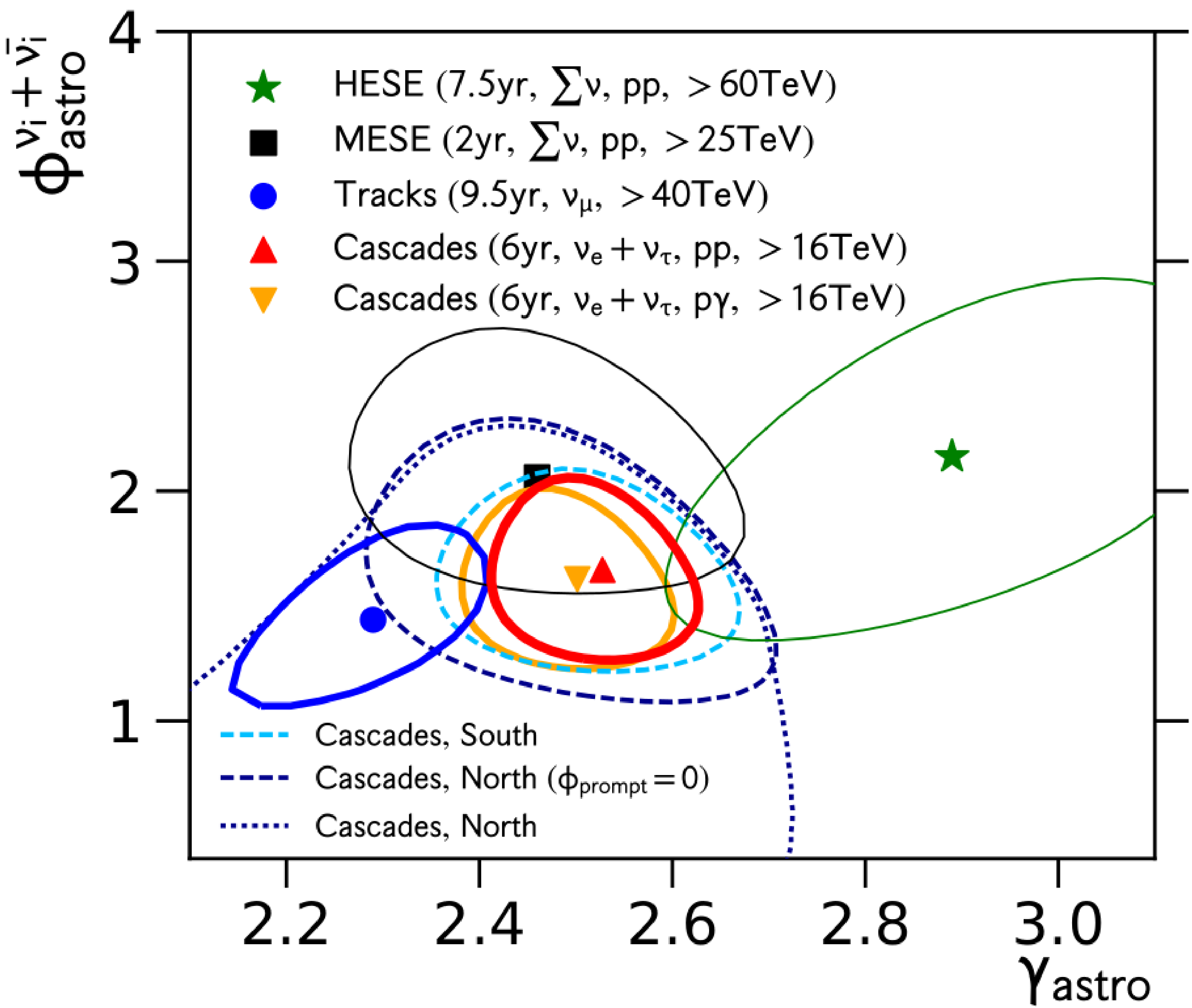
ν_e , ν_τ CC interactions
ν_X NC interactions



Angular resolution:
~3° (full, E>10 TeV)

Energy resolution:
(E_ν) ~25%

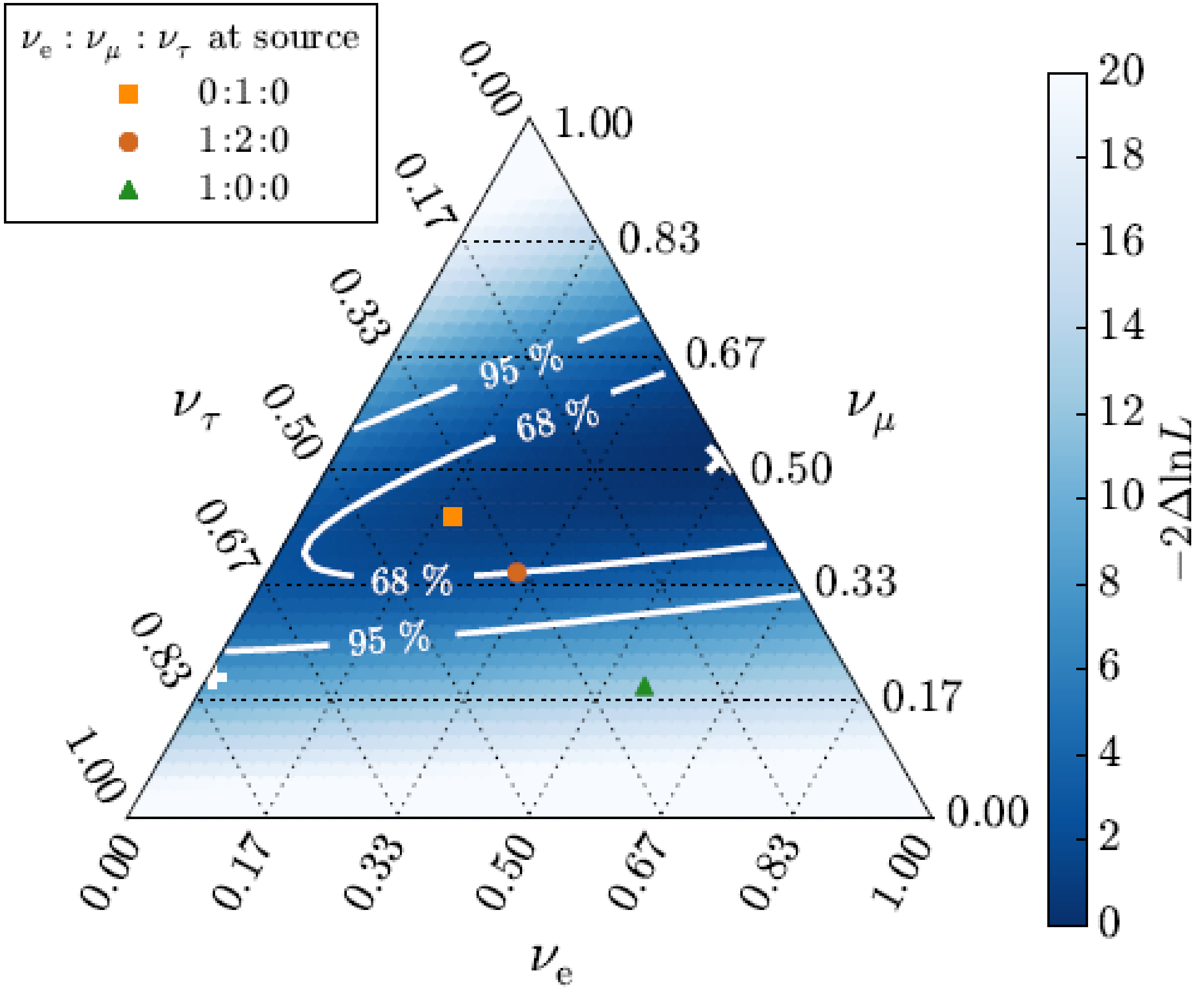
Diffuse neutrino flux



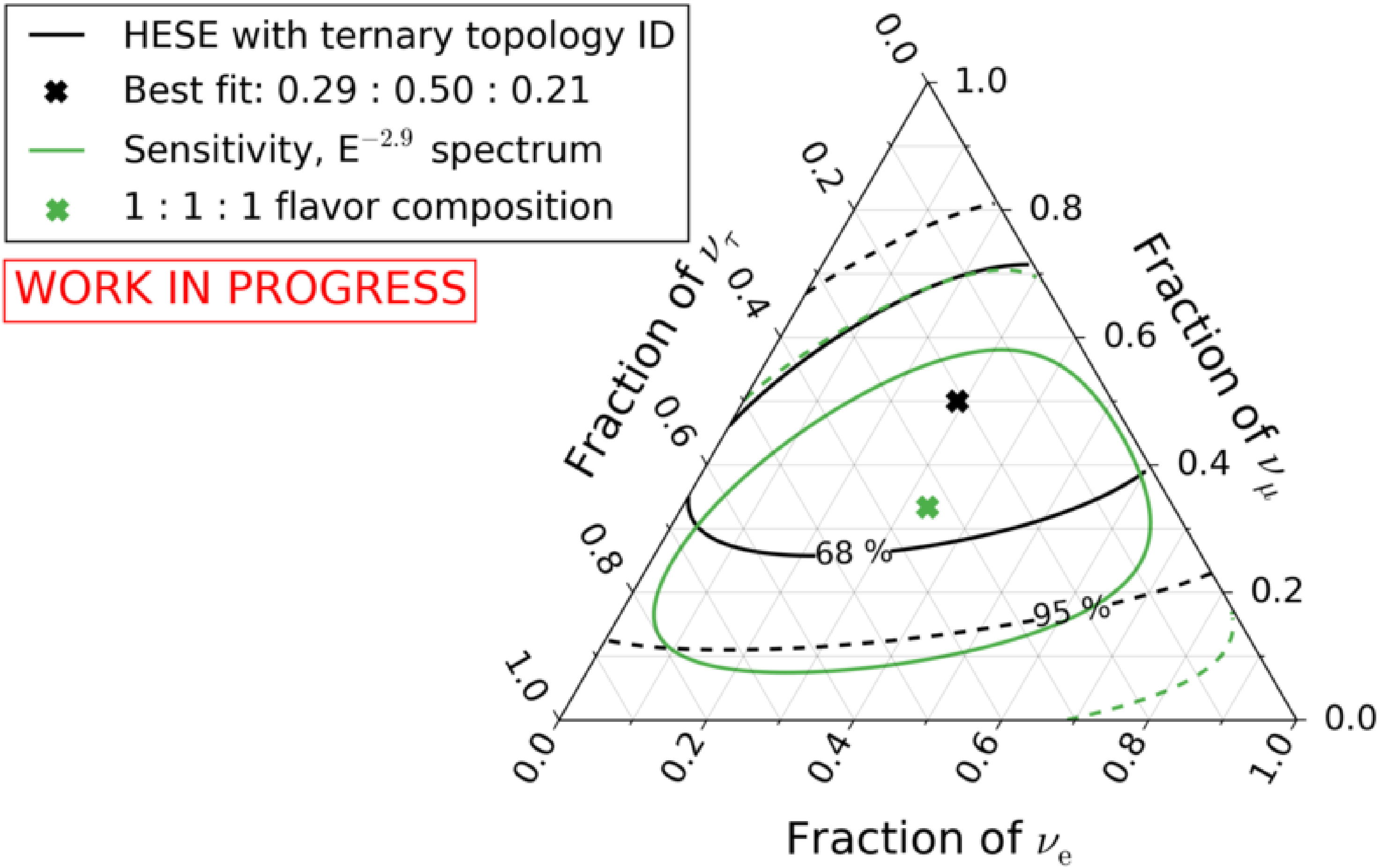
arxiv:2001.09520

Flavour composition of the diffuse flux (IceCube)

the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ



IceCube High energy starting events – 7.5 yr



oscillations of PeV neutrinos over cosmic distances to 1:1:1

ANTARES – diffuse flux

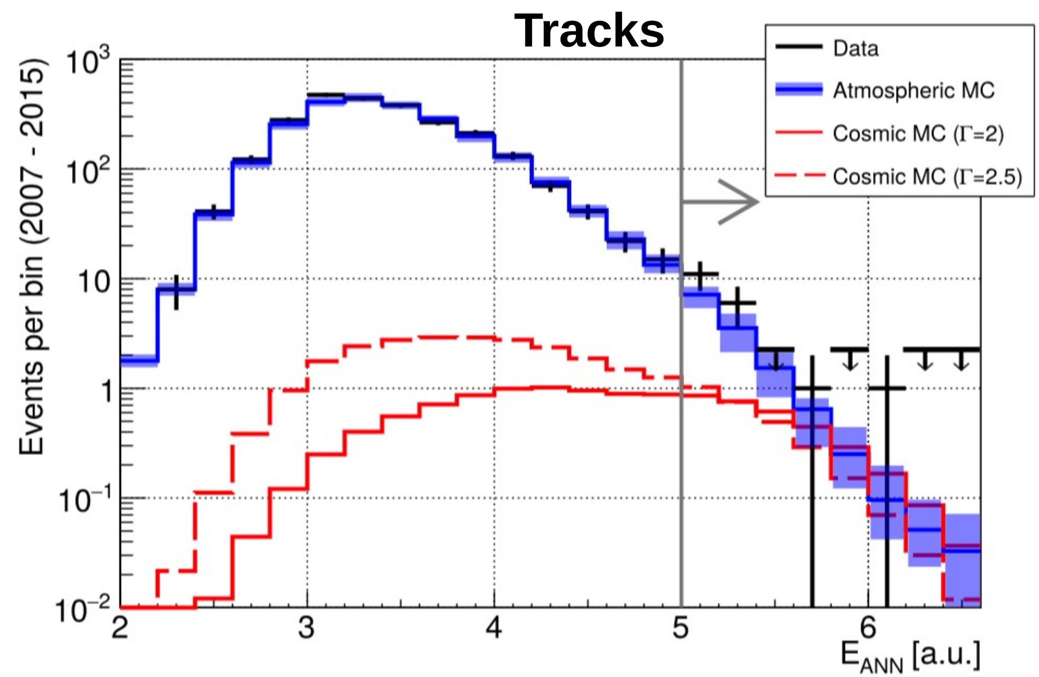
ApJL 853, L7 (2018)

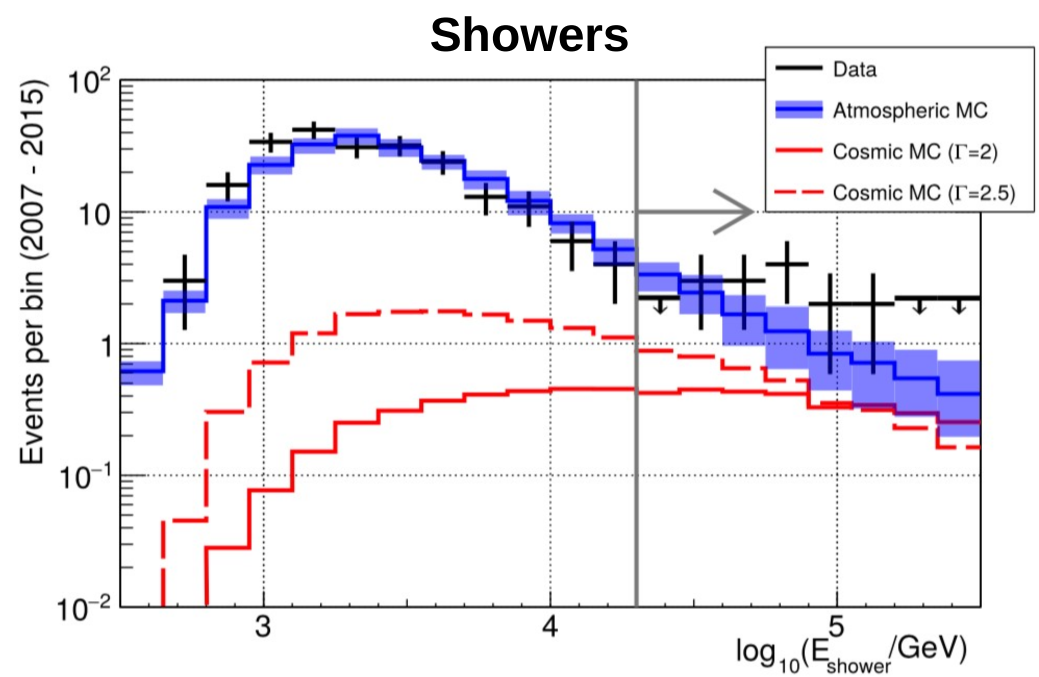
Sample:

- 2007 – 2015
- livetime 2450 days
- All-flavour analysis (track+showers)

	tracks	showers
Expected background	13.5	10.5
Expected signal	3 – 3.5	3 – 3.5
Observed	19	14

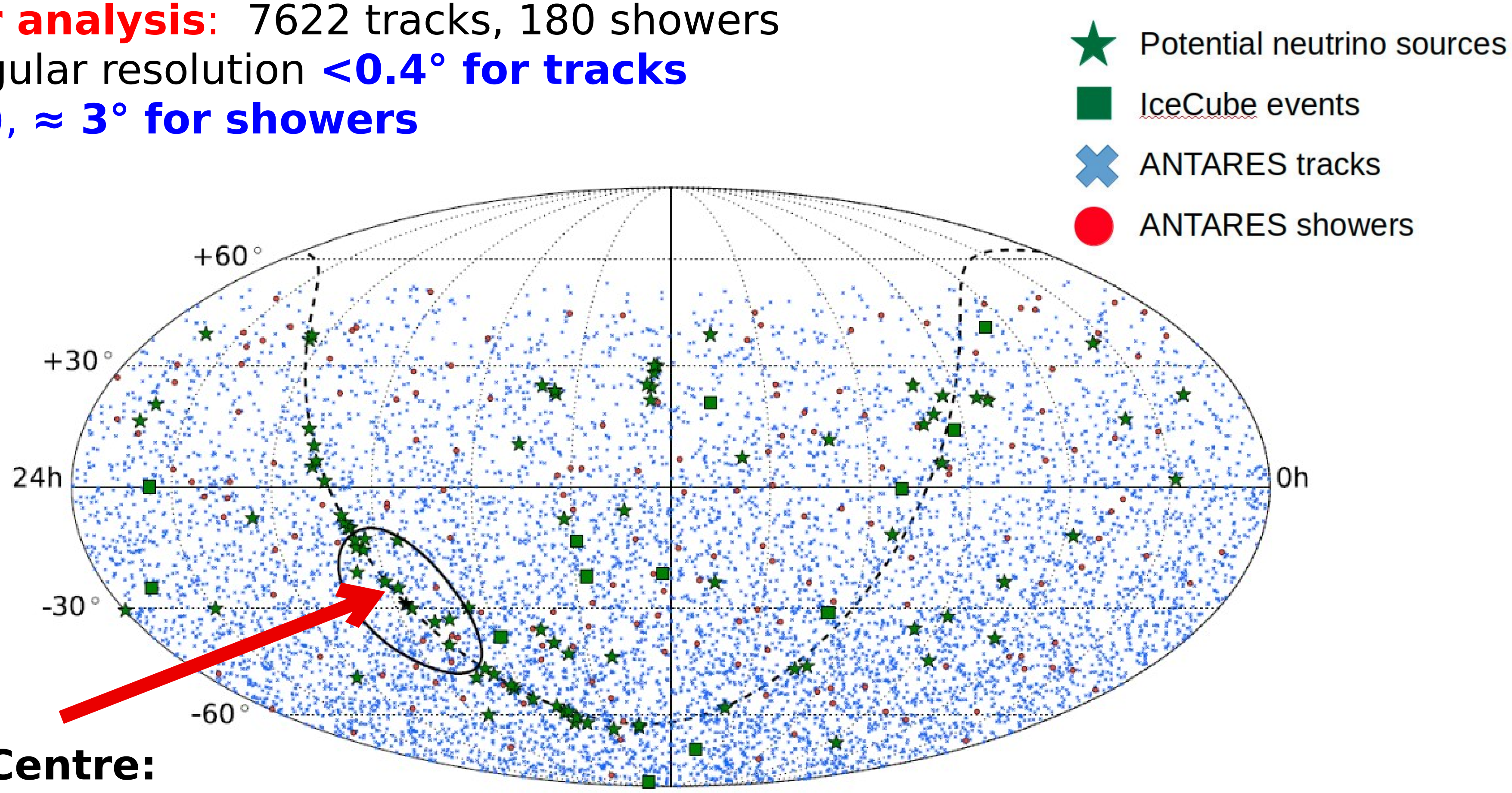
1.6σ excess observed;
null cosmic rejected at 85% CL





Point-like source search with ANTARES

Data sample: 2007 – 2015
Livetime: 2424 days
All-flavour analysis: 7622 tracks, 180 showers
median angular resolution **<0.4° for tracks**
(E_ν>10 TeV), **≈ 3° for showers**



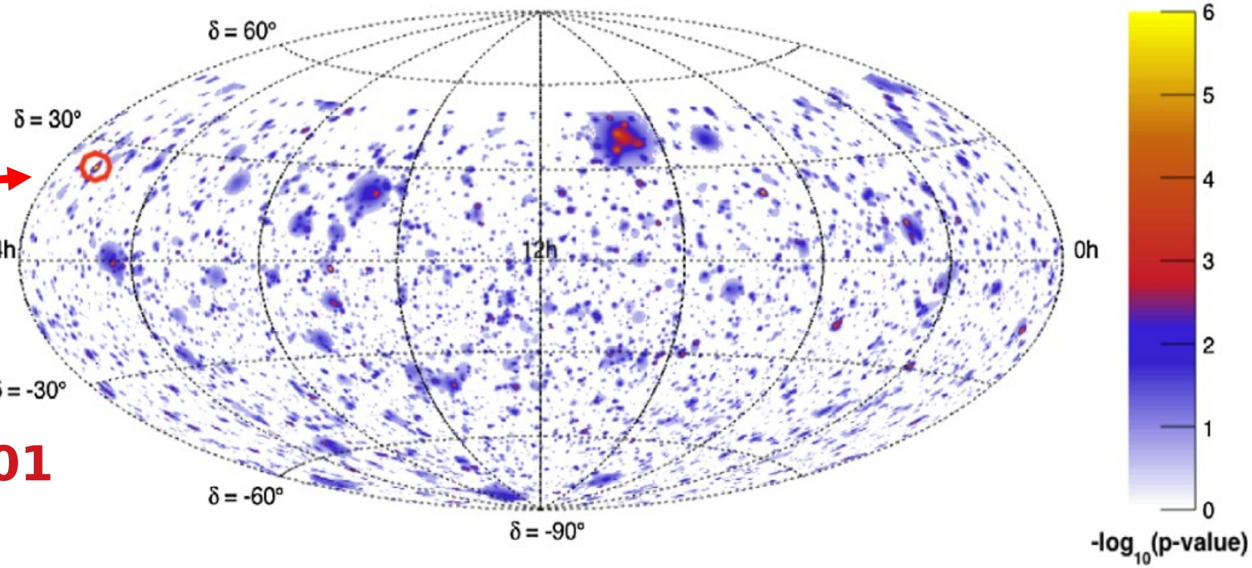
Galactic Centre:
15° x 20° ellipse semiaxes (Gal. lat.x Gal. long.)

No statistically significant excess

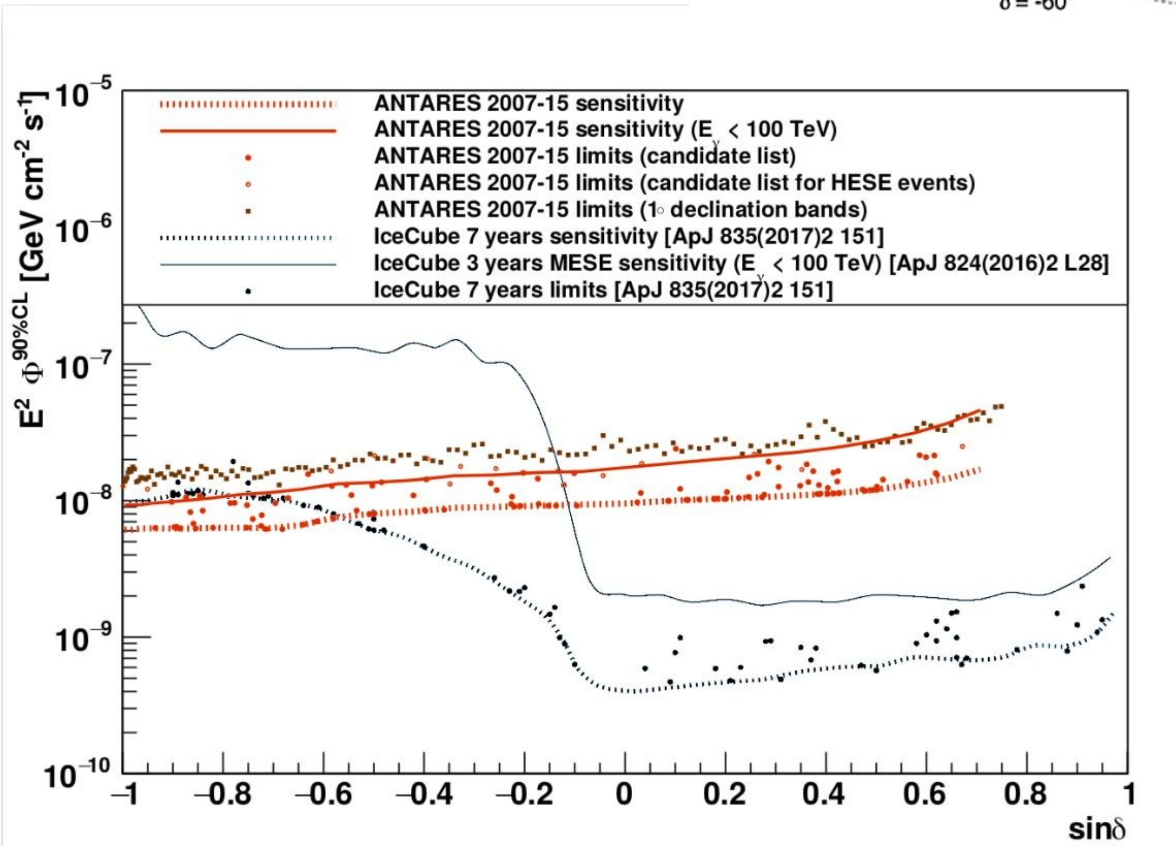
Phys. Rev. D 96, 082001 (2017)

Point-like source search with ANTARES

Most significant cluster of the full-sky search (1.9σ post-trial significance)
α = 343.8° δ = 23.5°



Phys. Rev. D 96 (2017) 082001

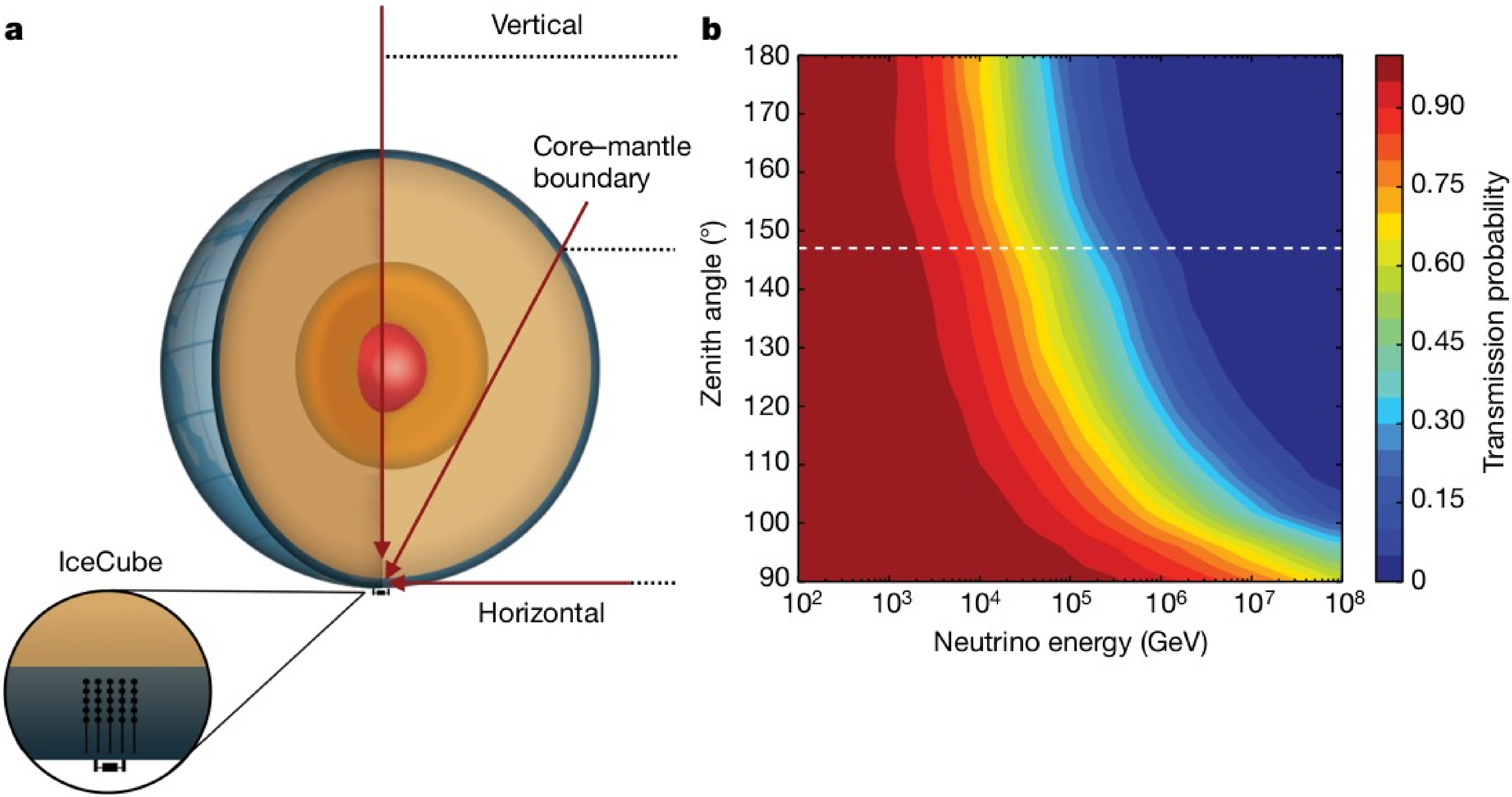


Sensitivities and upper limits at a 90% C.L. on the signal flux from the full-sky and the candidate list searches (Neyman method)

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV

Neutrino absorption in the Earth

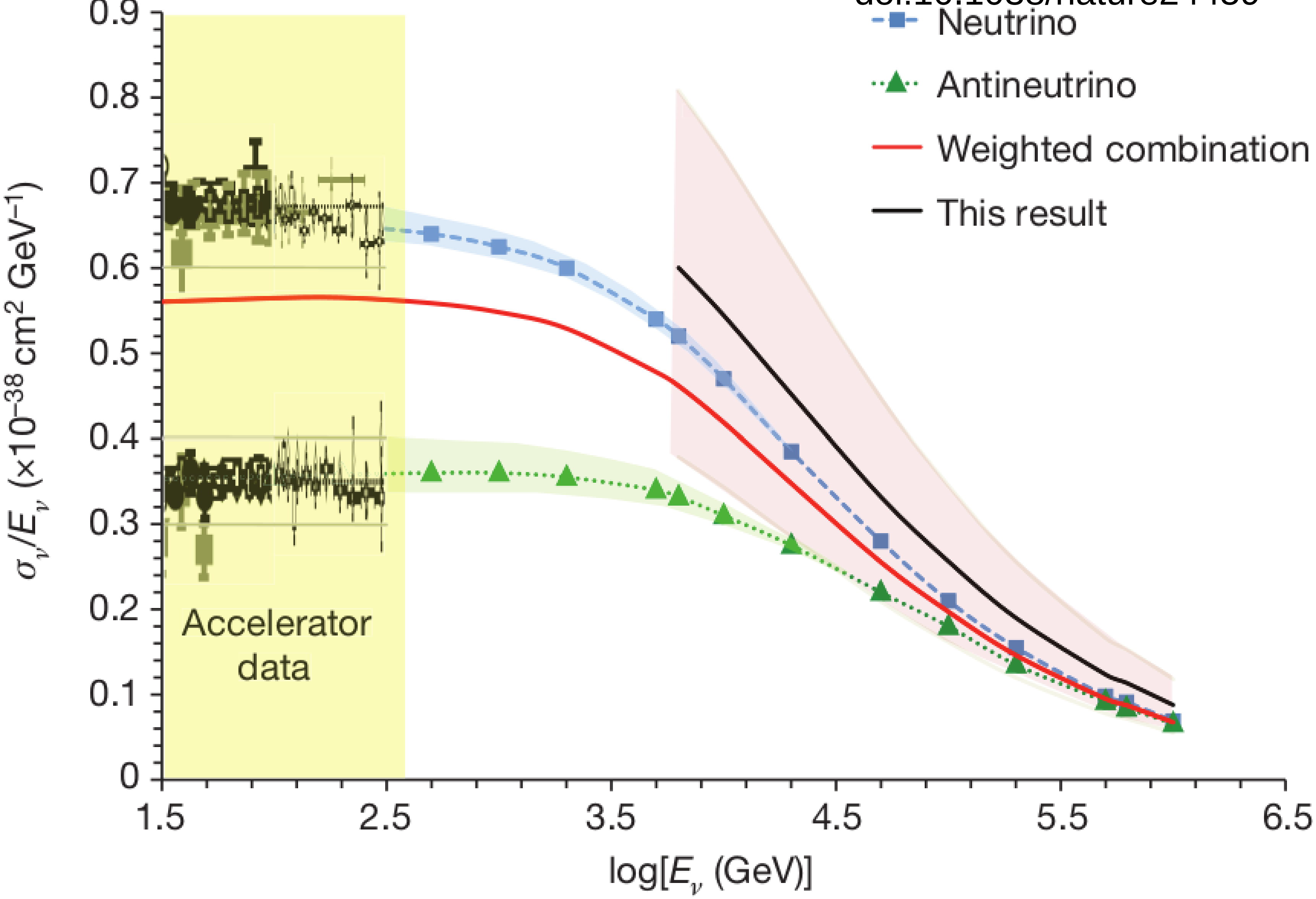
doi:10.1038/nature24459



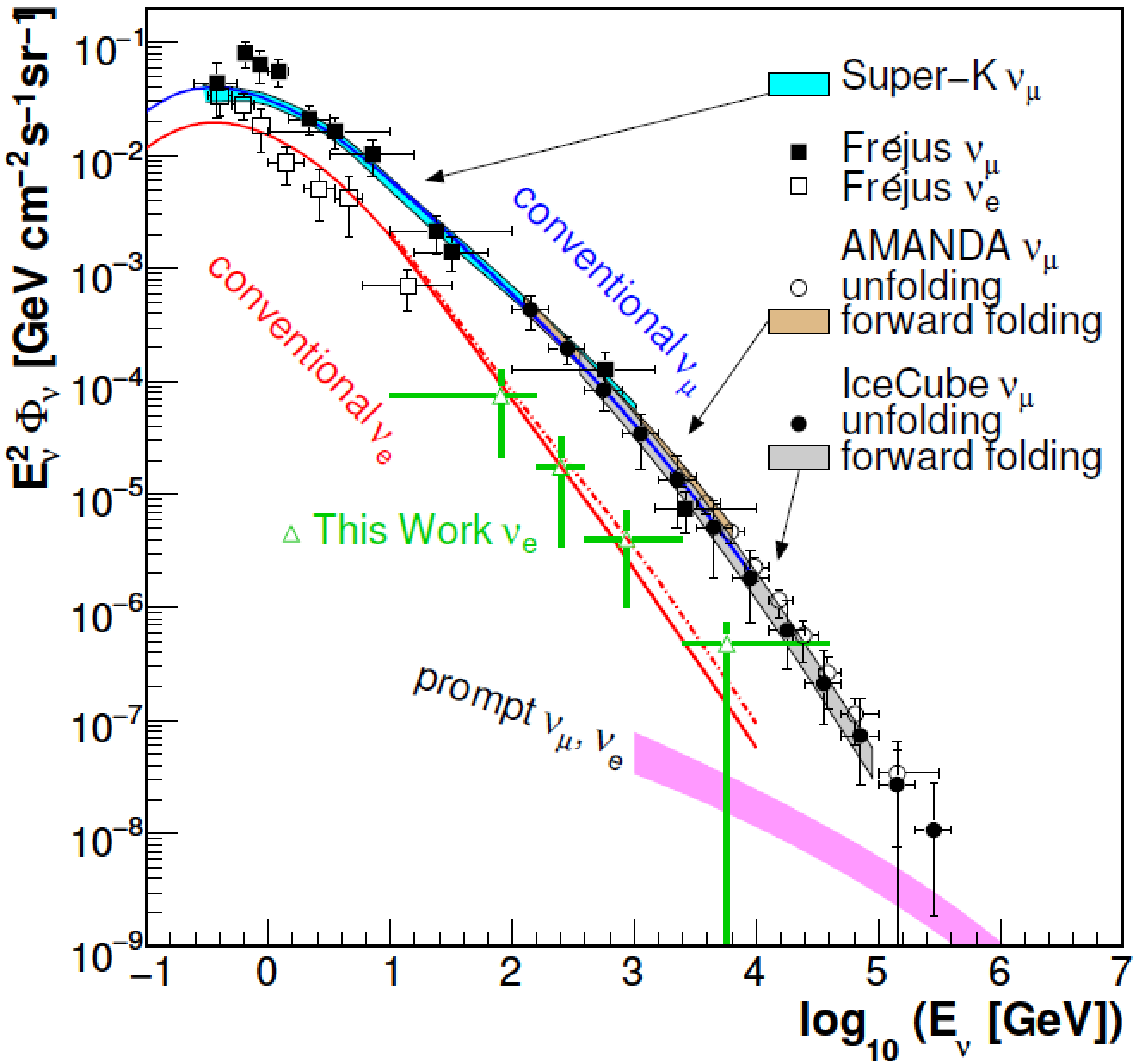
At E > 100 GeV, neutrino absorption limits the telescope's sensitivity for upgoing events (thus limiting field of view)

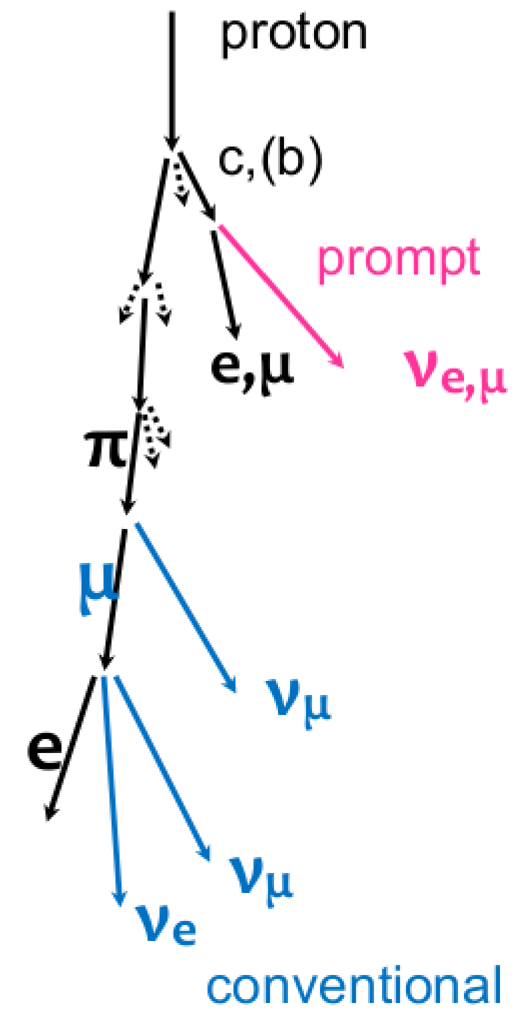
Neutrino cross sections

doi:10.1038/nature24459

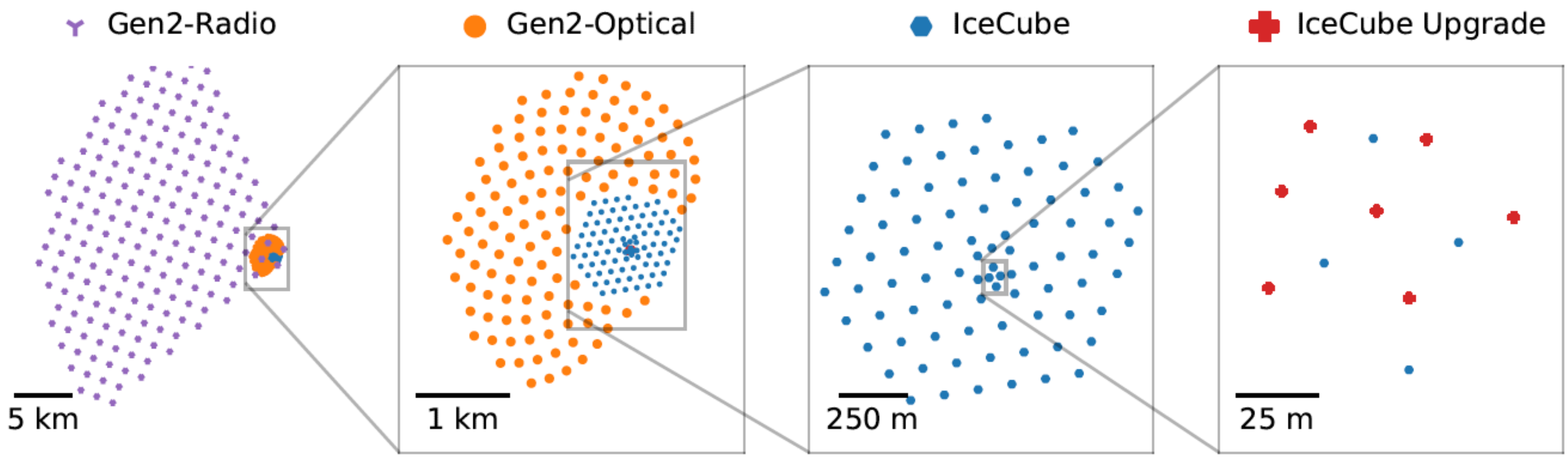


Atmospheric neutrino fluxes





IceCube Gen2 (projected)



10 PeV to >10 EeV

10 TeV – 50 PeV

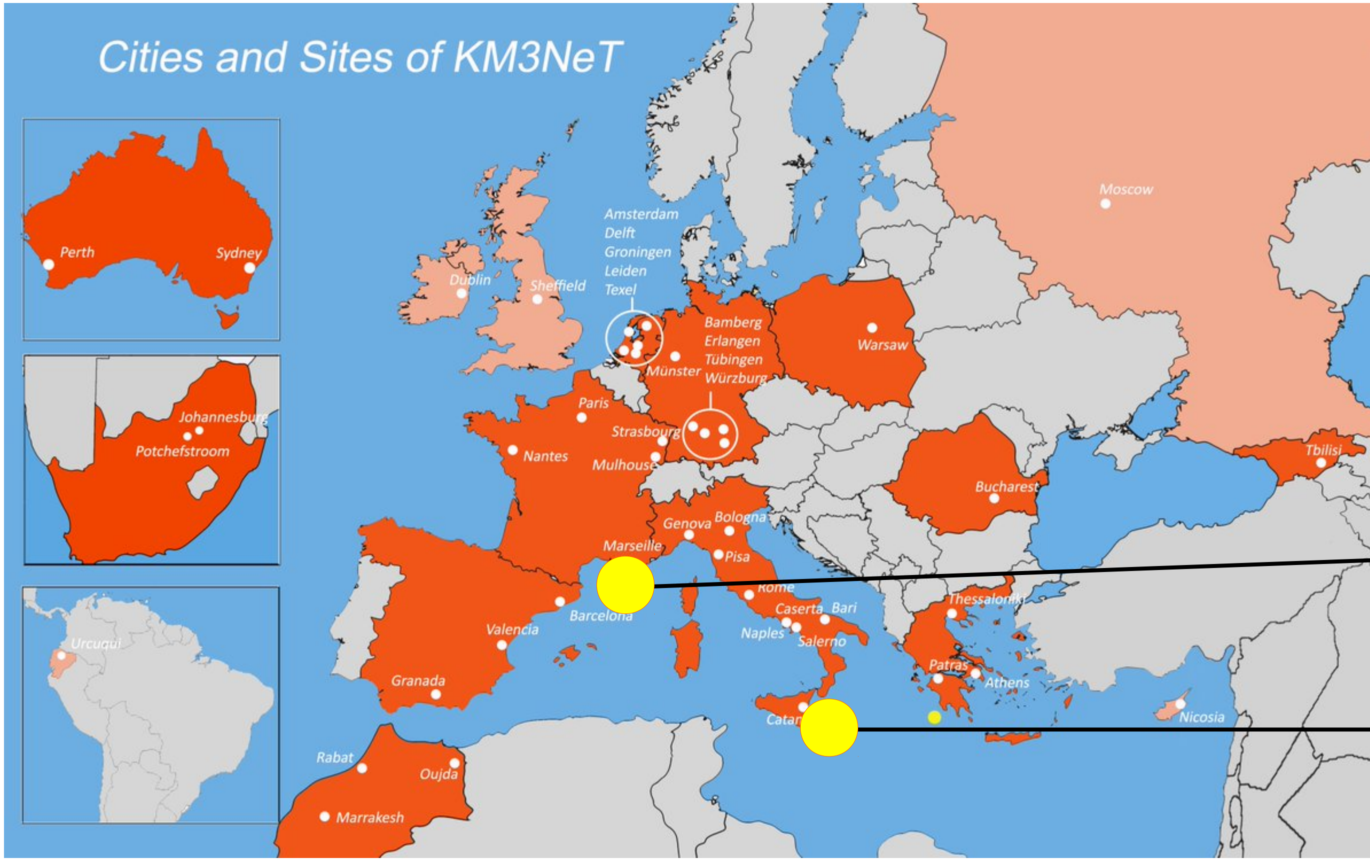
100 GeV – 5 PeV

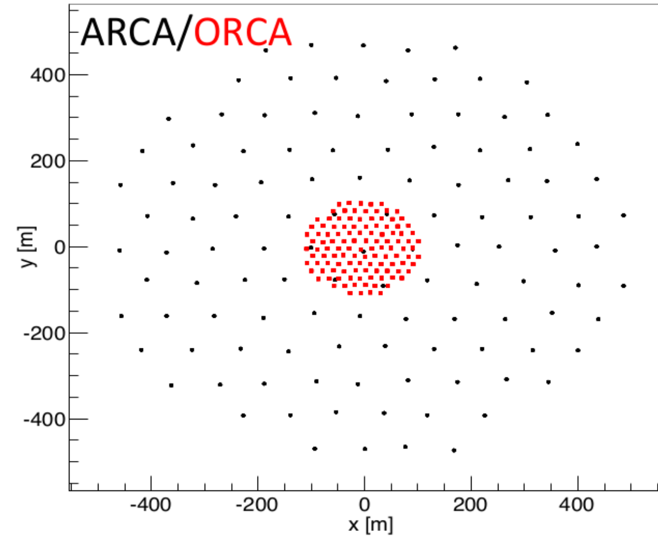
improves DeepCore performance at < 10 GeV

KM3NeT : two detectors at two sites

Construction started

* KM3NeT = **km**^{3} **N**eutrino **T**elescope



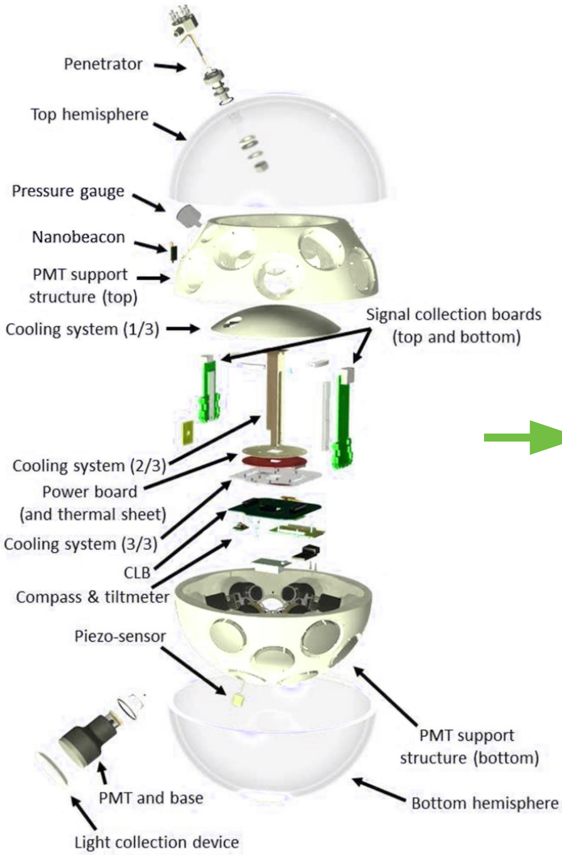


ORCA (**O**scillation **R**esearch with **C**osmics In the **A**byss)

ARCA (**A**stroparticle **R**esearch with **C**osmics In the **A**byss)

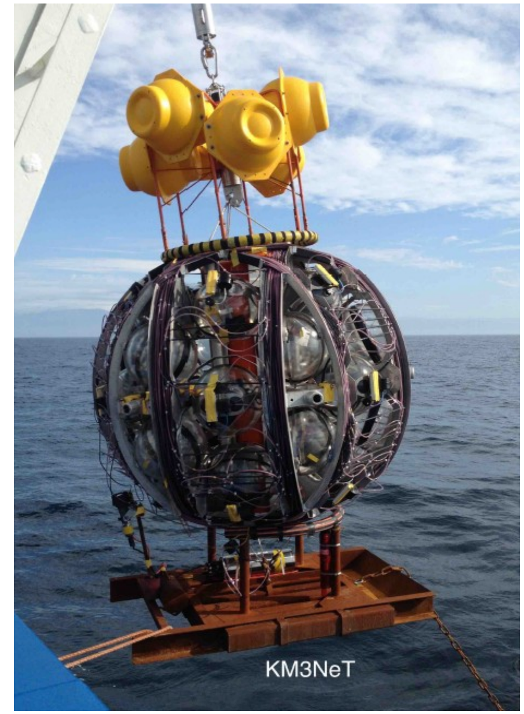
	String spacing	OM spacing	Depth (m)	Instrumented mass (Mt)	Strings	OMs	Science
ORCA	23 m	6 m	2450	8	115	2070	Mass hierarchy
ARCA	90 m	36 m	3400	1000	230	4140	Astrophysics

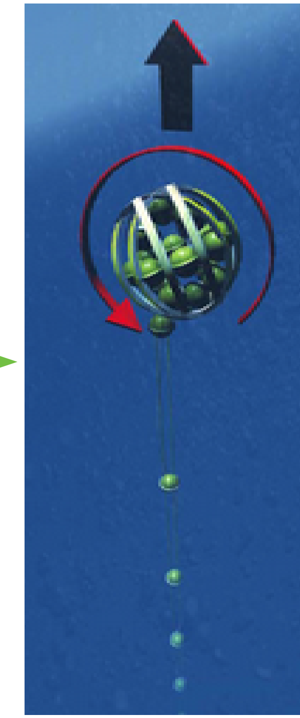
KM3NeT assembly and deployment



DOM

DU





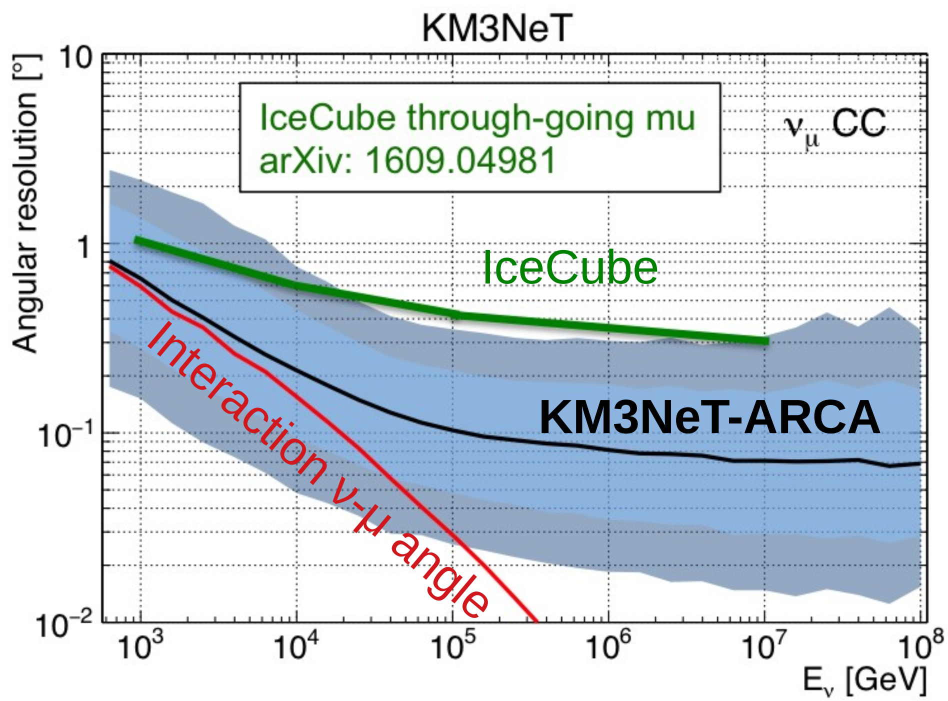
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

https://youtu.be/7HKHW0hLxt4
https://youtu.be/g2Y0KD3kdXs
https://youtu.be/xTj4lLMv1Fw
https://youtu.be/XFPCfCoTfUg

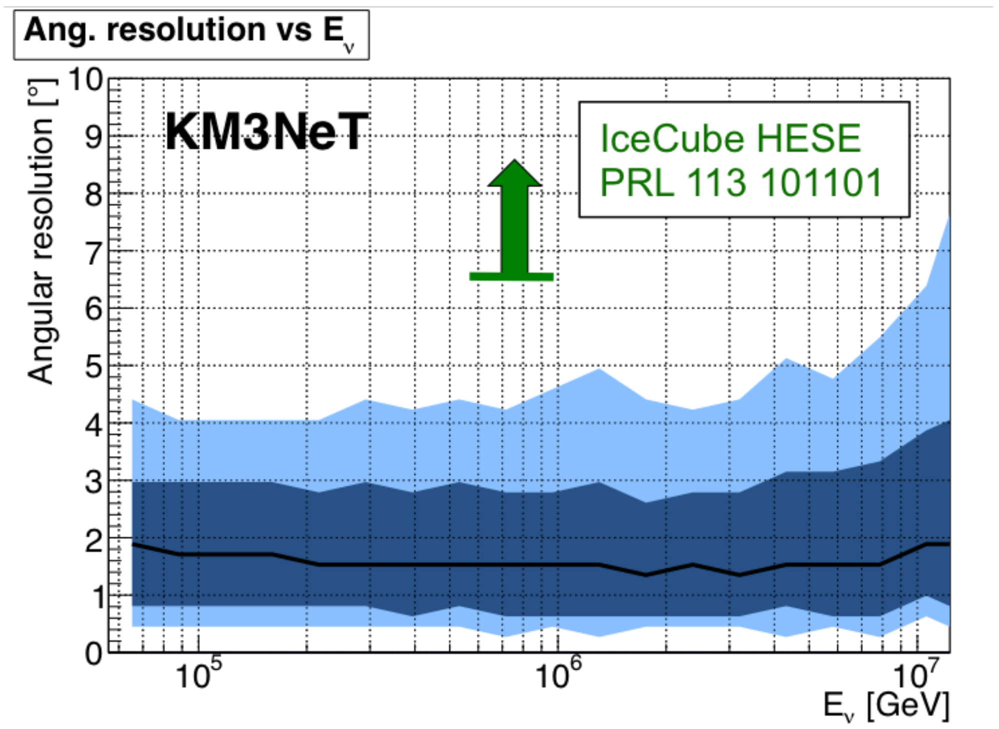
- Rapid deployment
- Autonomous unfurling
- Multiple DUs can be deployed in one sea operation

ARCA - angular resolution

Tracks



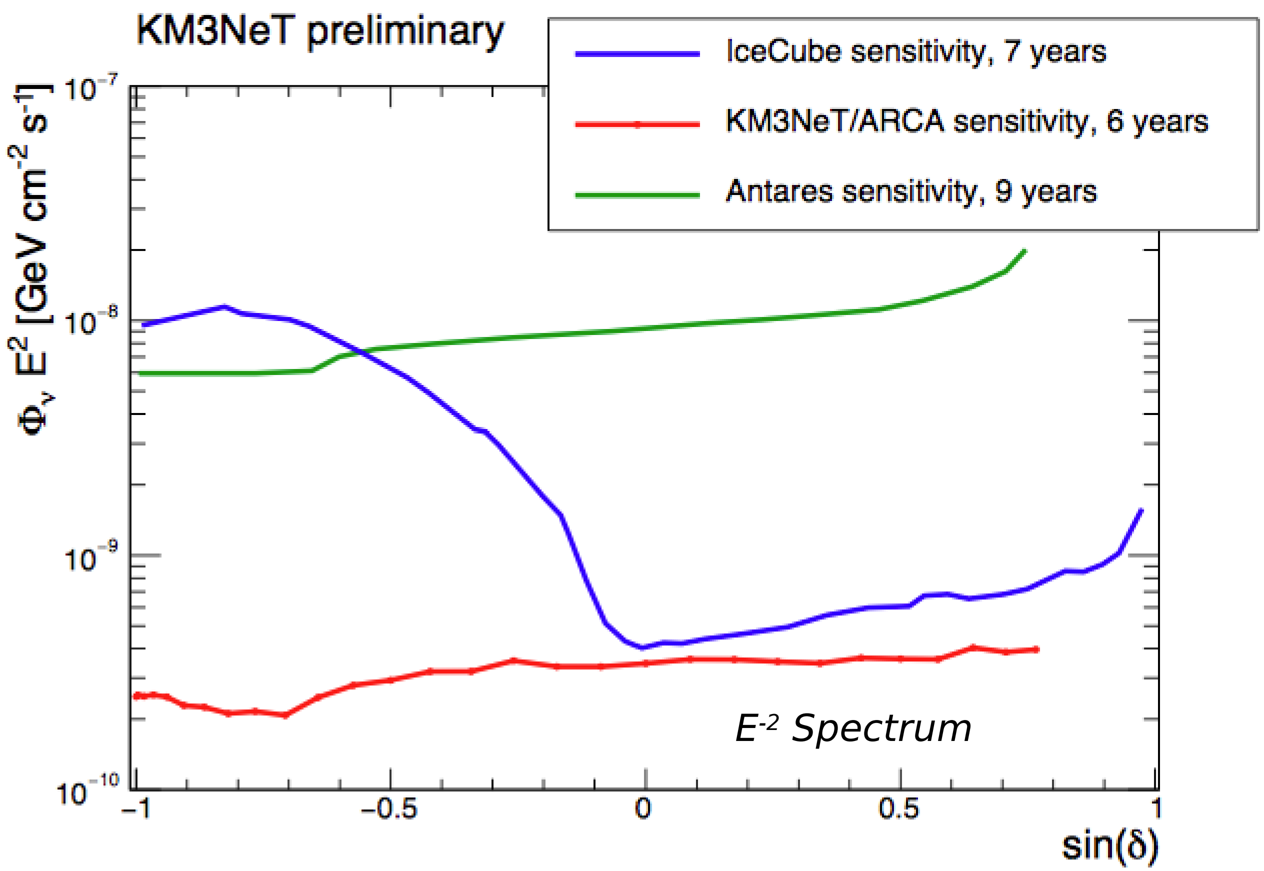
Showers



~ 0.1° angular resolution for tracks (E>100 TeV); ~ 2° for showers

Sensitivity to point-like sources

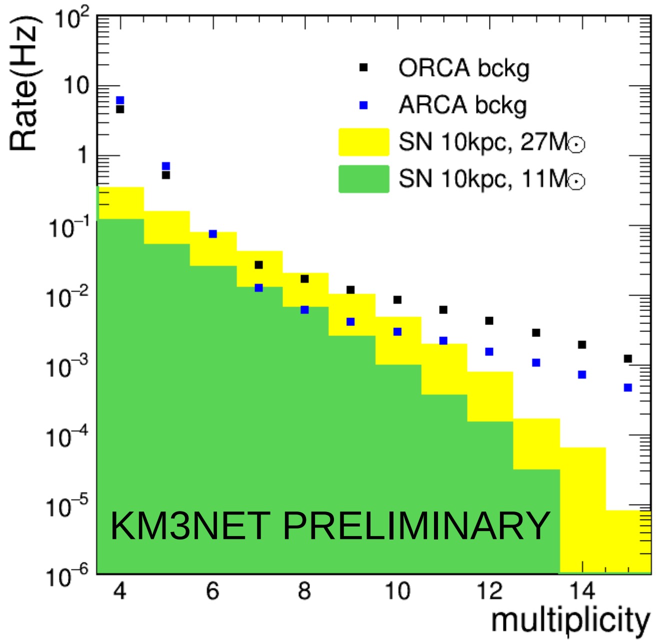
J.Phys. G43 (2016) no.8, 084001

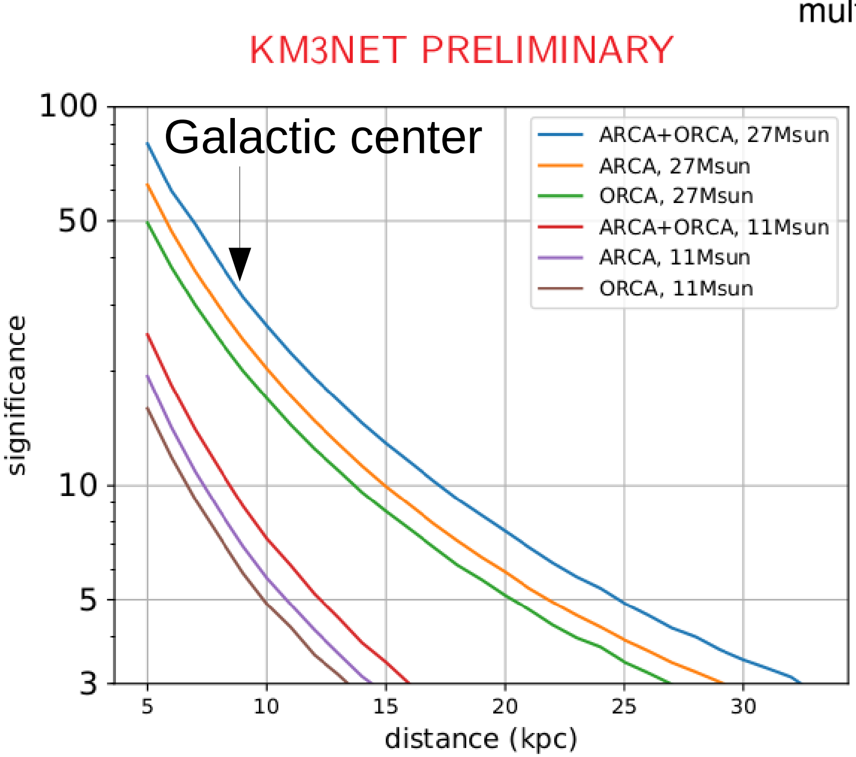


Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

Visibility of Galactic Plane + Galactic Center
Better angular resolution in water will help the source identification

Supernova monitoring with KM3NeT DOMs





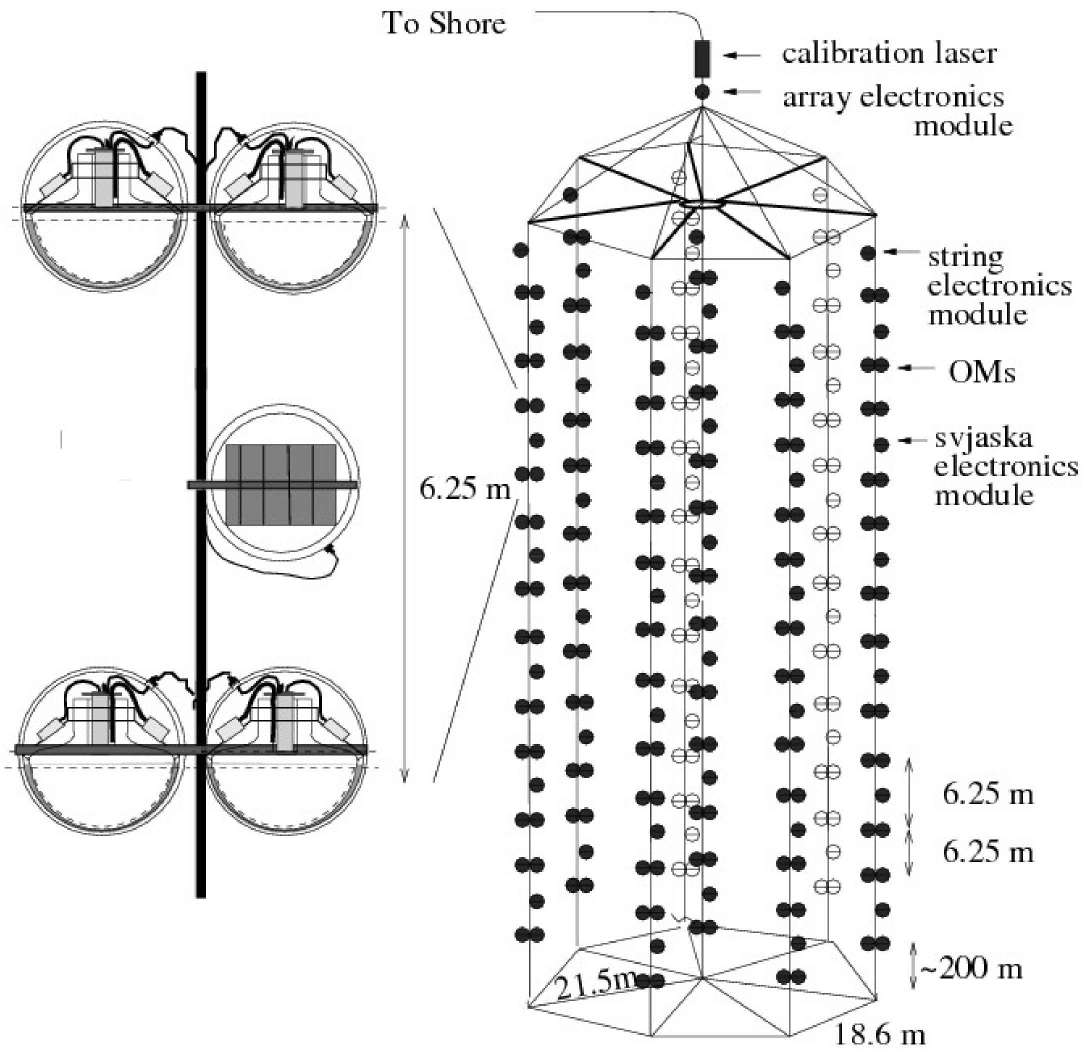
- Count coincidence signals on individual Optical Modules
- Look for a temporary rise of event counts where 6-10 PMTs fire together (~ 100 events in 0.5 s)
- This method is sensitive to ~ 10 MeV anti-neutrinos from core-collapse SN
- Main background are K-40 decays (~ 1 MeV, low multiplicity) and atmospheric muons (~ GeV-TeV, high multiplicity)

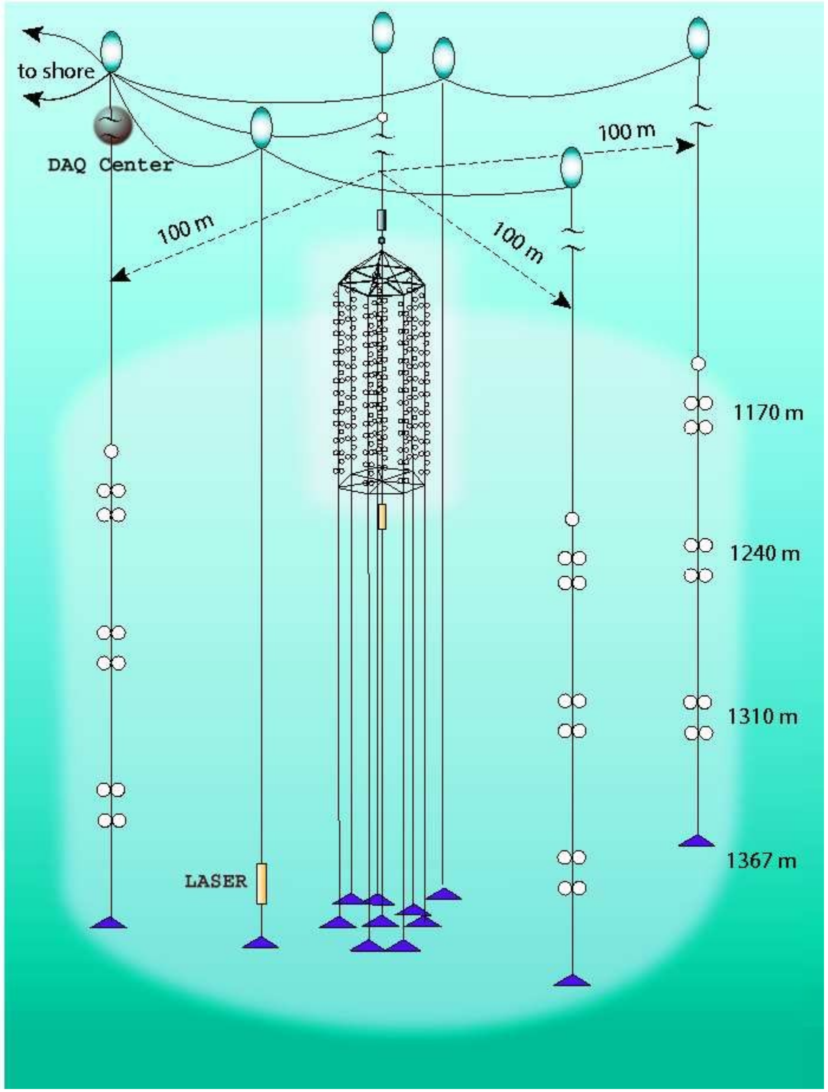
5 σ detection possible
in case of SN explosion
in our Galaxy

M. Lincetto, M. Colomer et al., Neutrino 2018

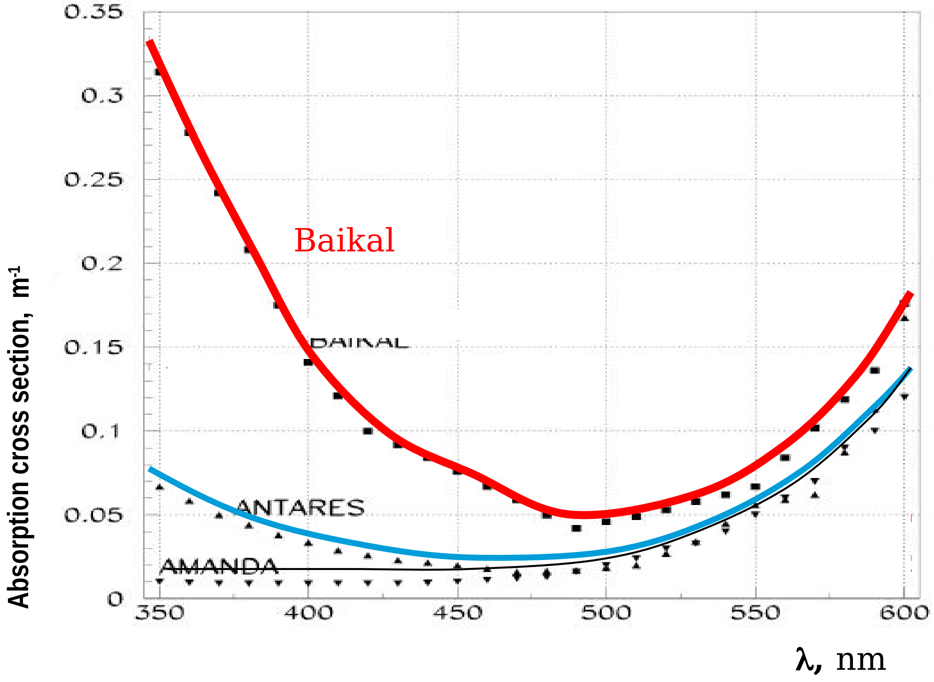
IceCube & Baikal-GVD can do this too

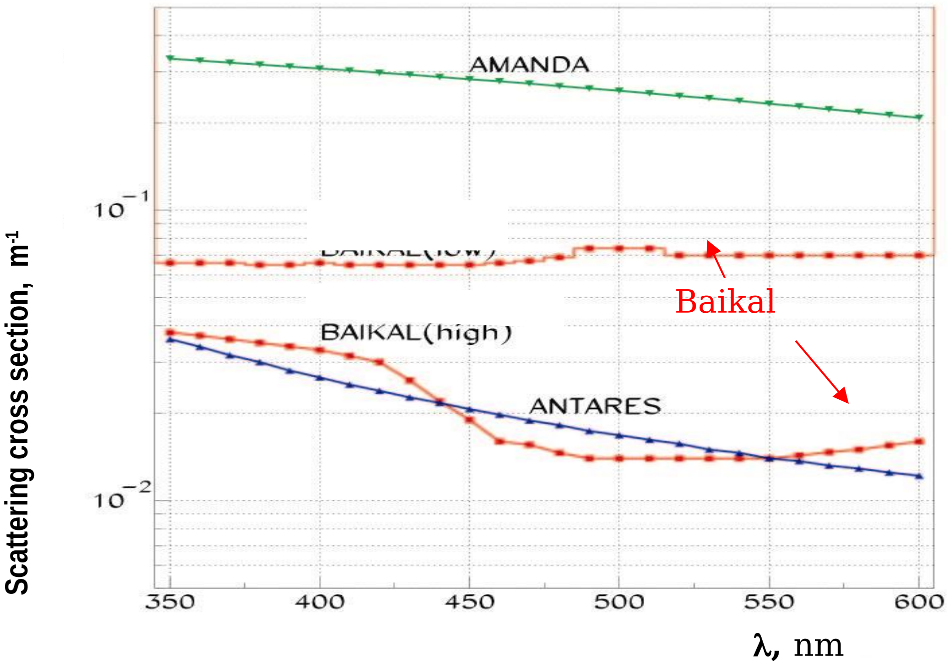
Baikal NT-200 and NT-200+





Water optical properties





GW170817 follow-up

GW170817 - neutron star merger, first gravitational waves detection associated with gamma/optical/radio signal
[Phys. Rev. Lett. 119, 161101]

B. P. Abbott et al., ApJL 848 (2017) L12
A. Albert et al., ApJL 850 (2017) L35

Search for neutrino events with Baikal-GVD in cascade mode

- no events within ± 500 sec window
- no events in 14 days window after the merger

Upper limits on the neutrino flux at 90% CL have been derived assuming E^{-2} spectral behavior and equal flavor flux
[JETP Letters, v.108, issue 12, arXiv:1810.10966]