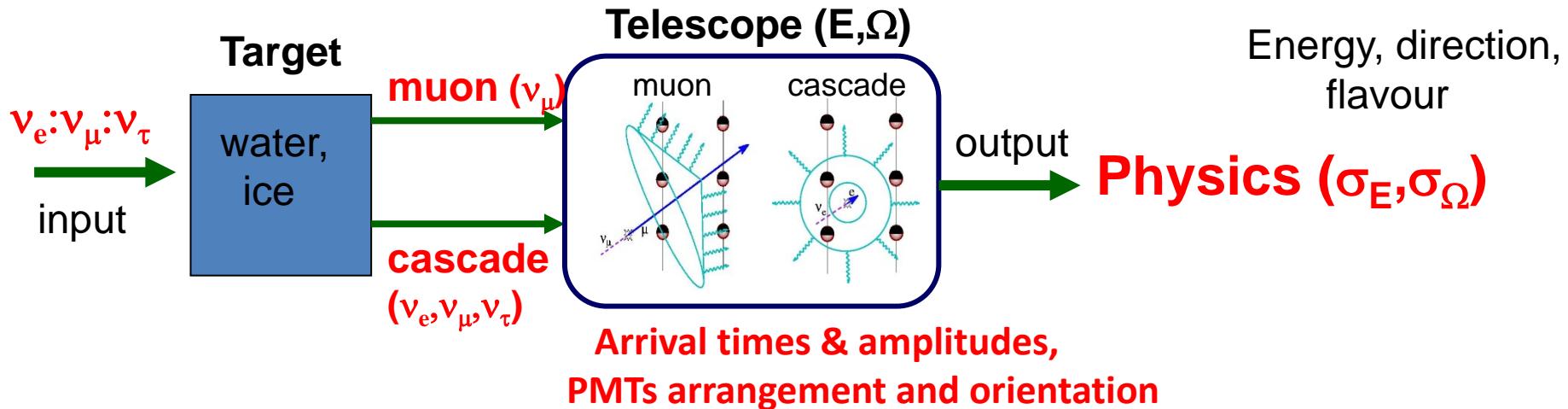


Using cascades for neutrino astronomy

**Zh.-A. Dzhilkibaev, INR (Moscow),
Cosmic Rays and Neutrinos in the Multi-Messenger Era
December 08, 2020**

Detection Principle – M. Markov 1960

Flux	Detection modes	Environment properties	Background
From local sources, diffuse flux	muons, cascades	absorption, scattering, light background – K^{40} , bioluminescence	downward going atm. muons, atm. neutrinos

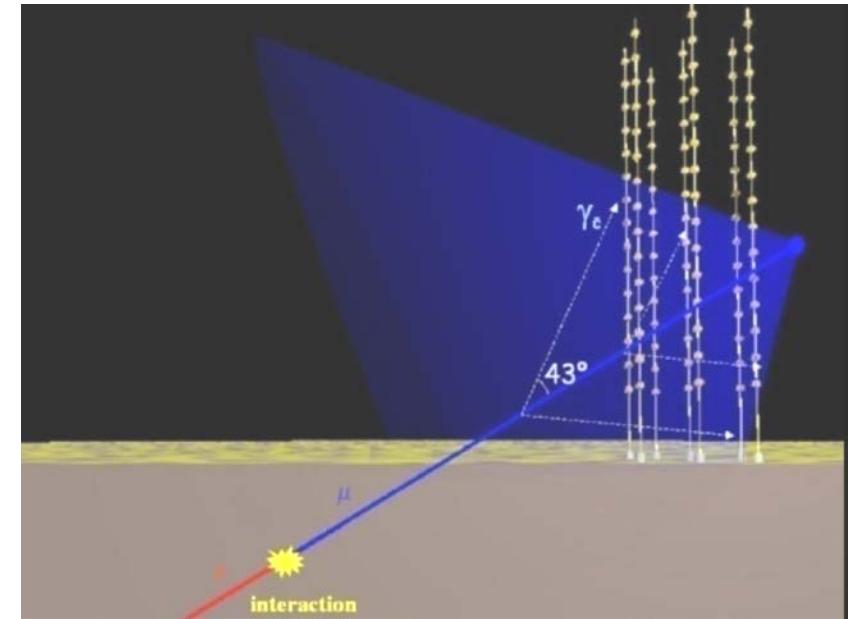


- Detection Modes – cascads&muons

$$\nu_l + N \xrightarrow{CC} \begin{cases} e^- + X \rightarrow \text{cascades} \\ \tau^- + X \rightarrow \text{cascades} \\ \mu^- + X \rightarrow \text{track + cascade} \end{cases}$$

$$\nu_l + N \xrightarrow{NC} \nu_l + \text{cascade}$$

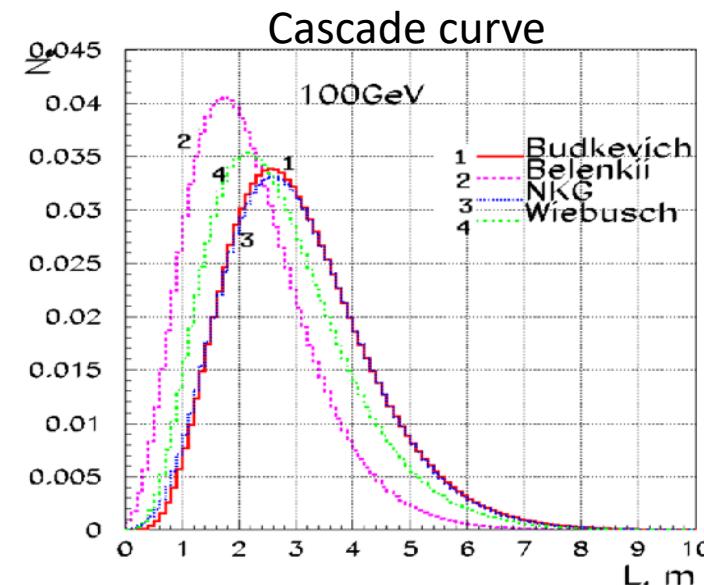
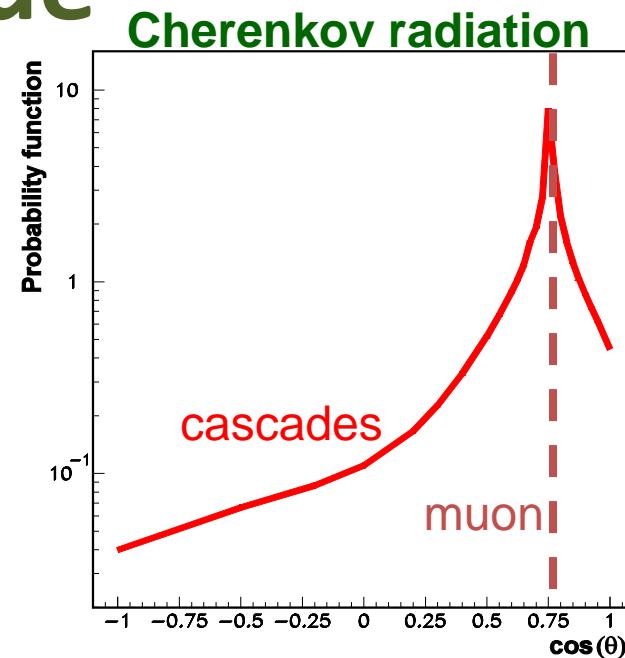
$\mu/\text{casc.} \sim 1/3$ for 1:1:1



• Cascades Detection Mode

✓ Cascades from $\nu_{e,\tau}$ & ν_μ (NC):

- Point-like, strongly anisotropic light-source
 - cascade size proportional to $\sim \ln E_\nu$ (but LPM-effect for $> 20\text{PeV}!$)
- Light intensity proportional to neutrino energy $\sim E_\nu \cdot 10^8 \gamma/\text{TeV}$
- Detection efficiency strongly depend on environment properties (water/ice).
- Angular resolution $\sim 2^\circ - 15^\circ$
- High energy resolution $\sim 10-20\%$



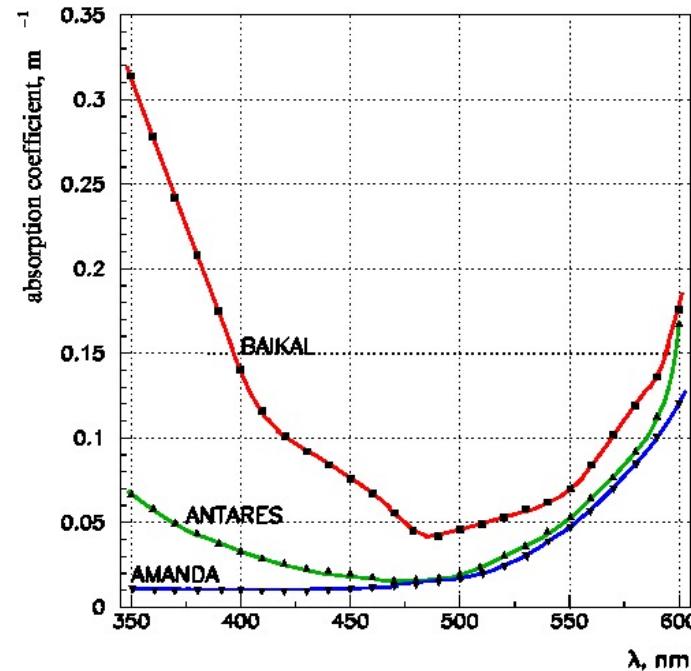
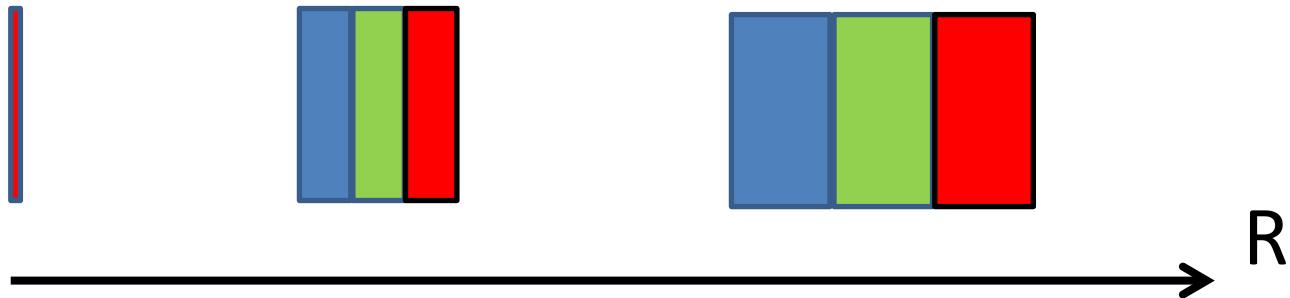
• Environment properties

➤ Light absorption:

$$L_{abs} \sim 20 - 100 \text{ m}$$

$$N \sim \frac{\exp\left(-\frac{r}{L_{abs}}\right)}{r^2}$$

- Density of light-sensor arrangement
- Keeps angular distribution of light flux
- Keeps time distribution of light flux, but filtering for case with deep minimum



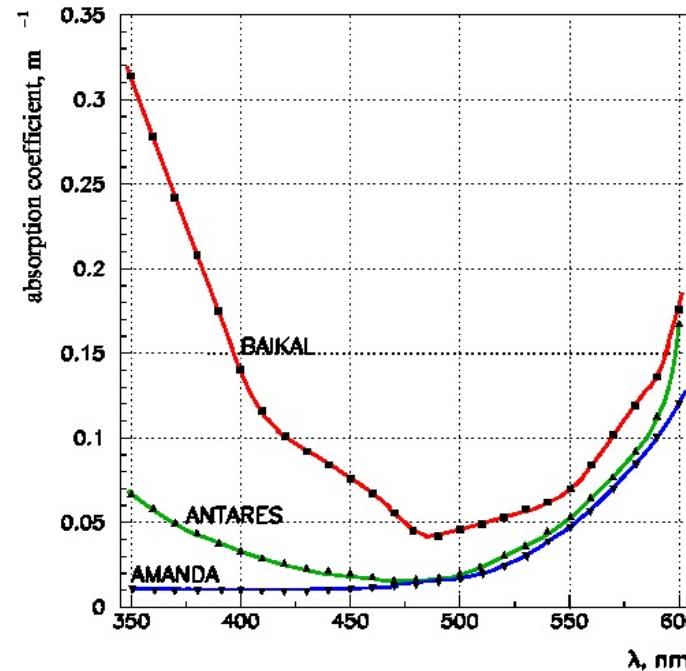
• Environment properties

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- Density of light-sensor arrangement
- Keeps angular distribution of light flux
- Keeps time distribution of light flux, but filtering for case with deep minimum



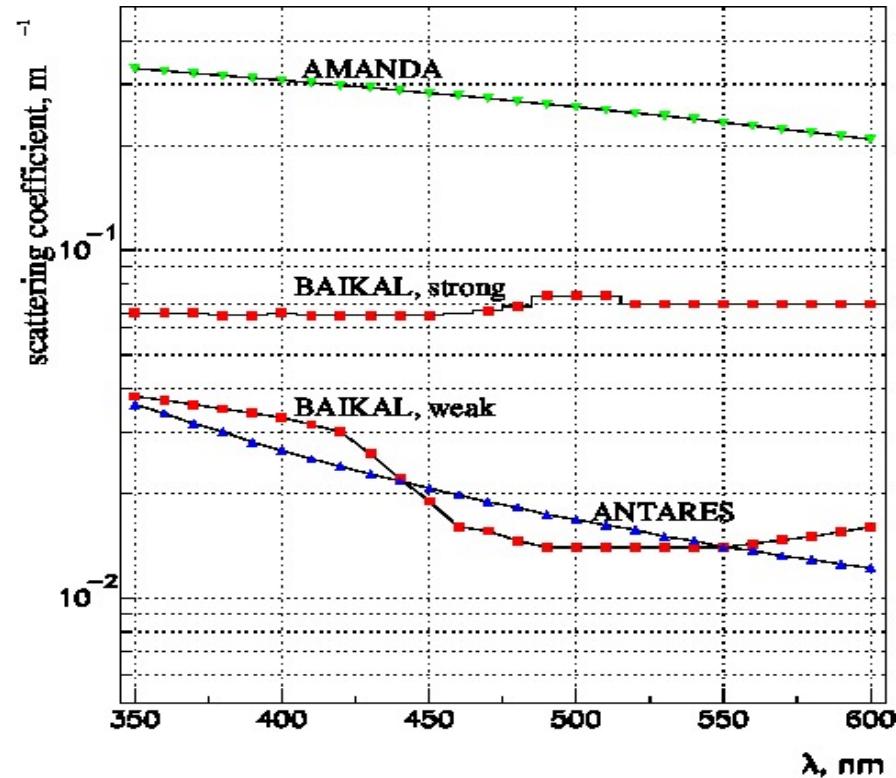
• Environment properties

➤ Light scattering:

$$L_s \sim 1 - 70 \text{ m}$$

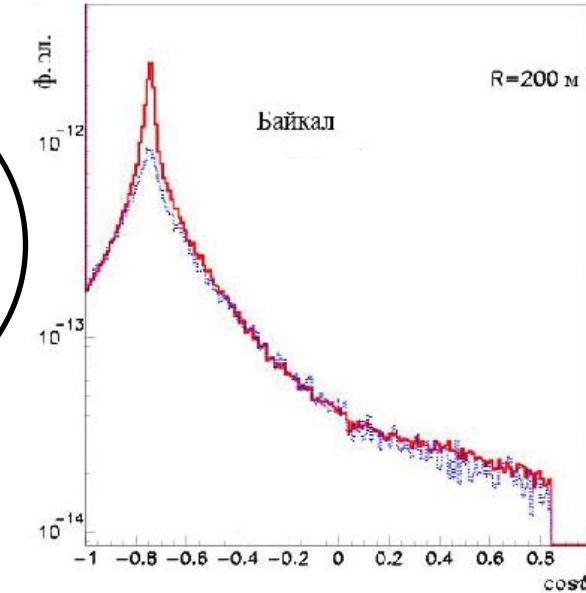
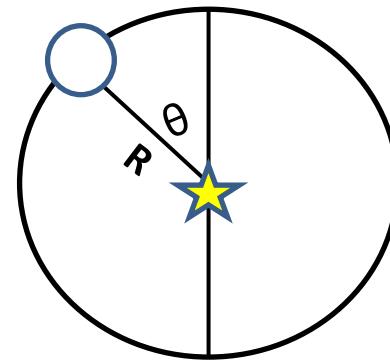
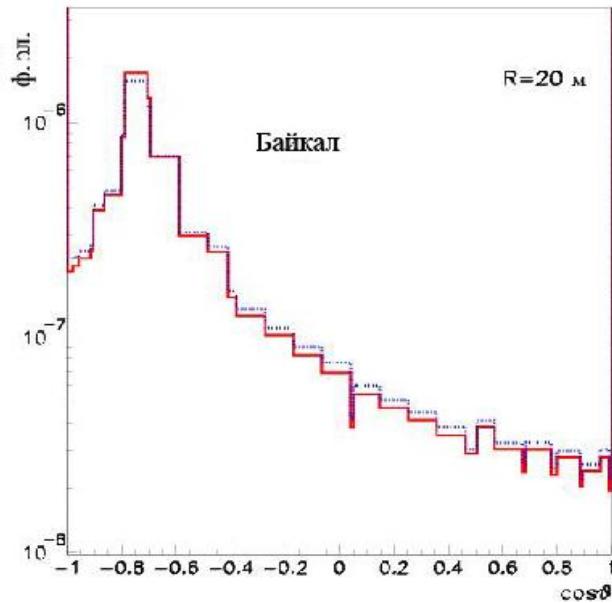
$$L_{ef} = \frac{L_s}{(1 - \cos \theta)}, \quad L_{as} = \sqrt{\frac{L_a L_{ef}}{3}}$$

$$N \sim \frac{\exp\left(-\frac{r}{L_{as}}\right)}{r}$$

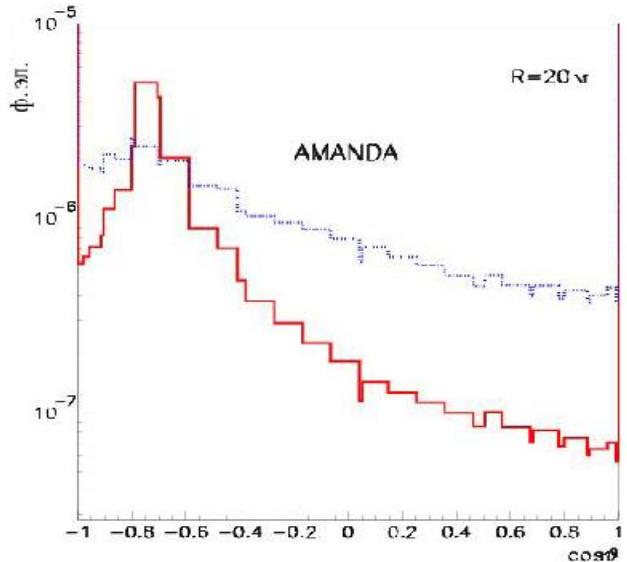


- Additional effective absorption
- Distortion of light arrival time distribution
- Distortion of angular distribution

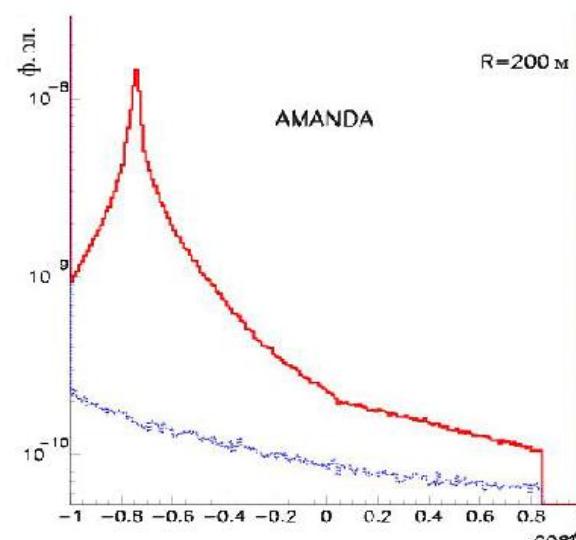
Water (Baikal): Light Scattering - 30 – 50 m



Antarctic Ice: Light Scattering - 1 – 4 m



- absorption only
- with scattering



• Background

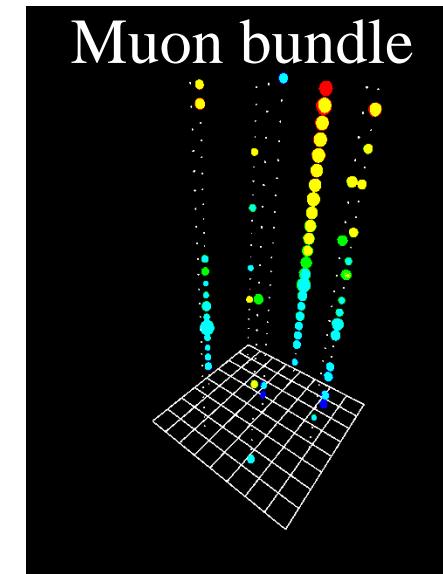
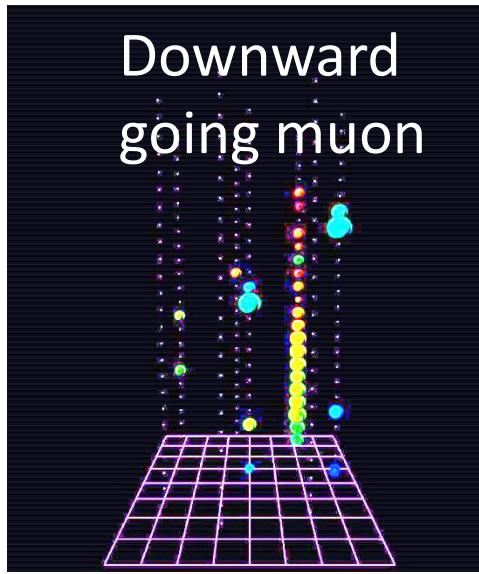
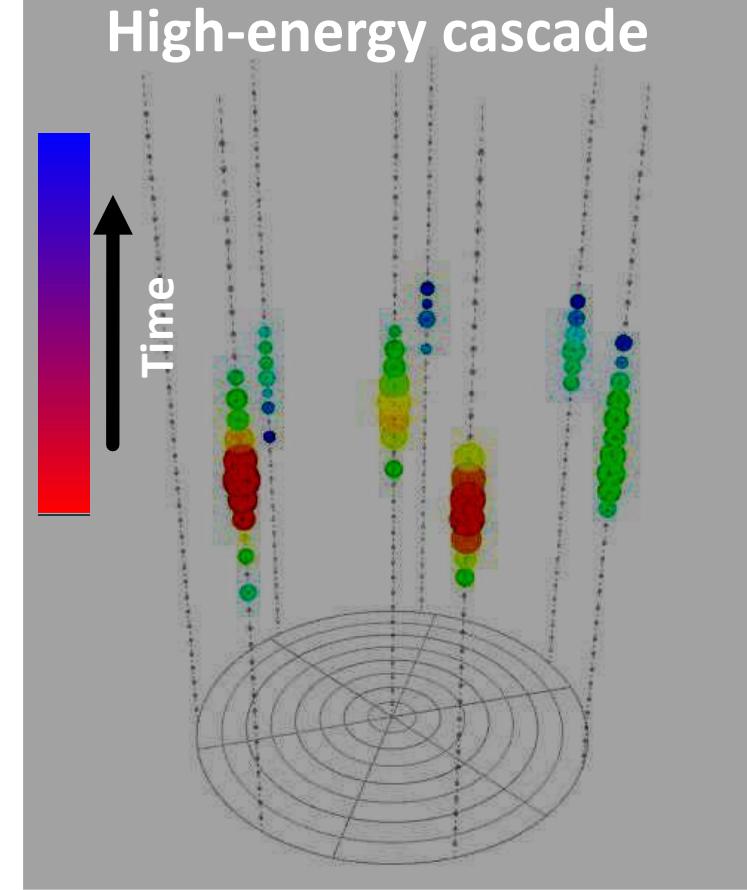
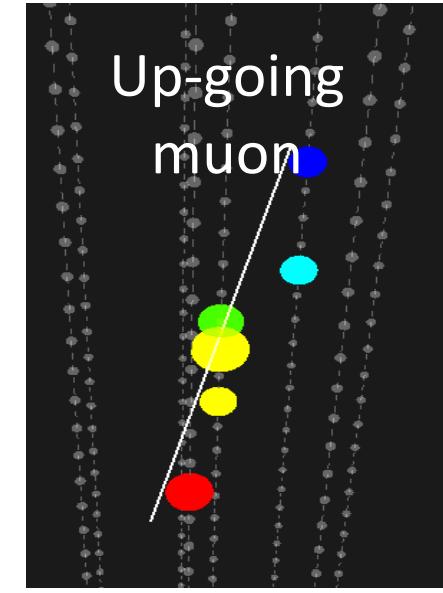
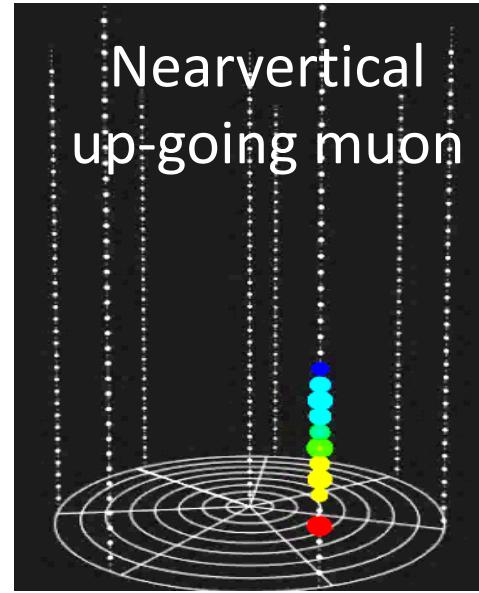
- Cascades from atm. Muons
- Multiple muons of atm. muon bundles
- Atm. muon neutrinos
- Atm. electron neutrinos
 $(\nu_e/\nu_\mu \sim 1/20)$

Search strategy – looking for upward going muons



Detector response

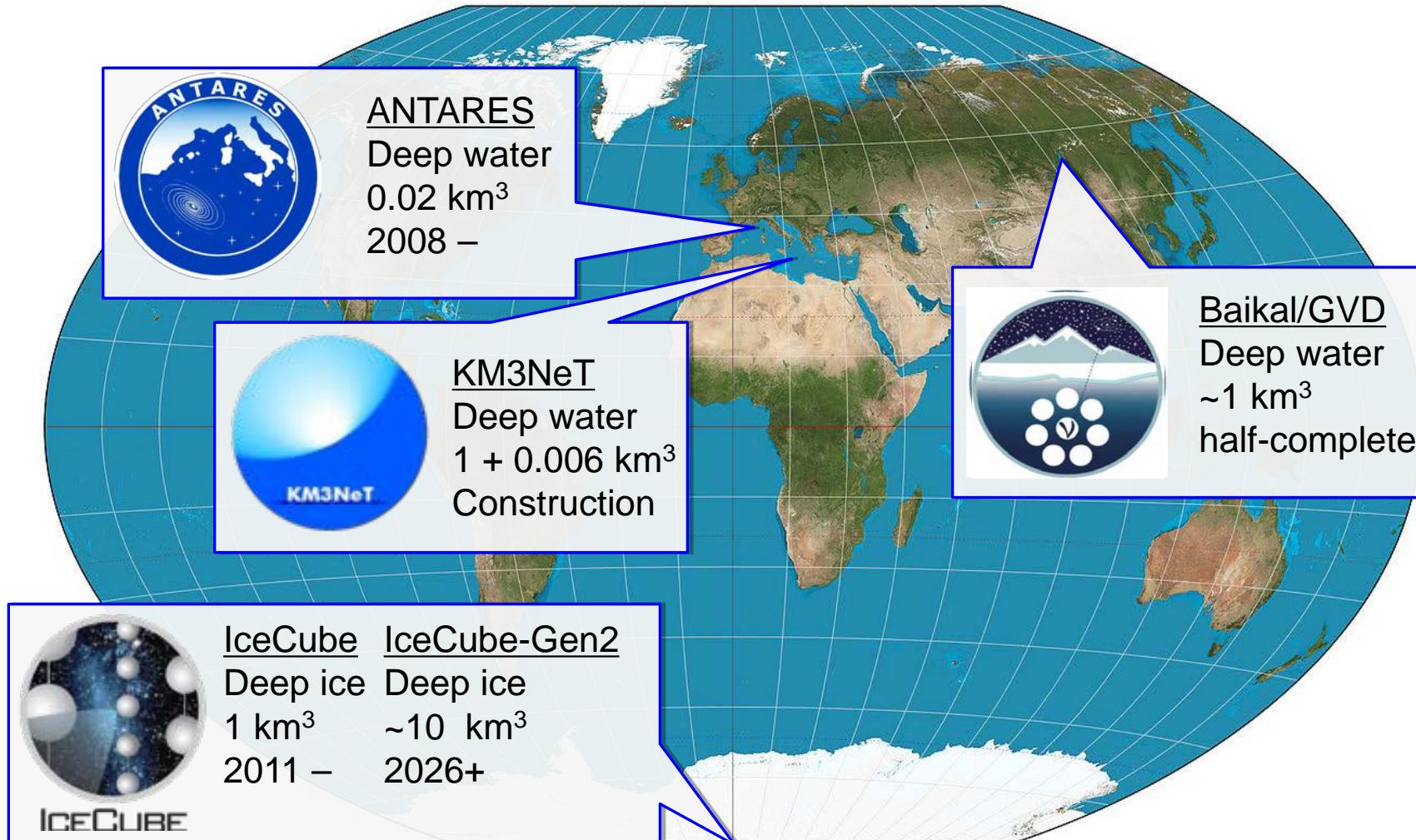
Background Neutrino signals



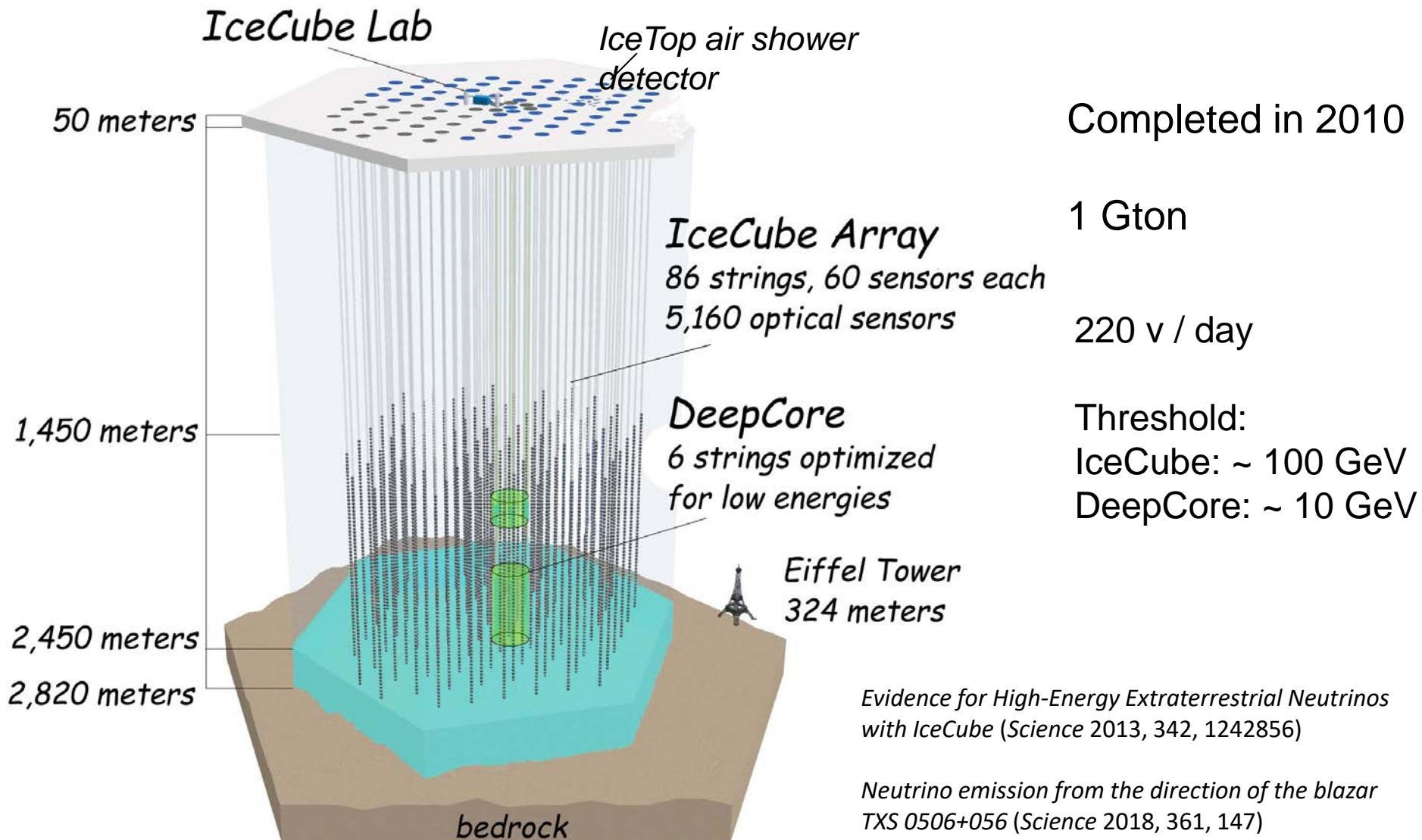
Studies with cascade detection mode

- Diffuse neutrino flux
- Search for local sources
- Search for neutrino flavor composition
- Neutrino cross-sections
- Multi-Messenger studies

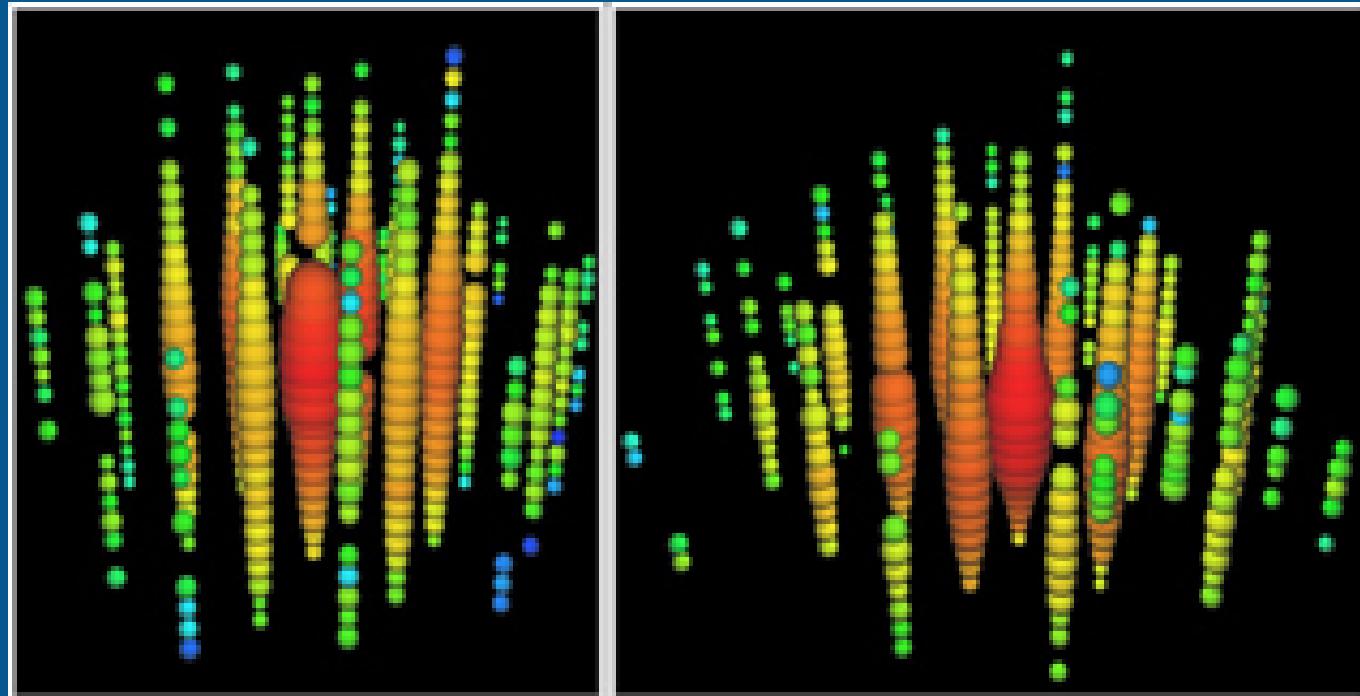
The neutrino telescope world map 2020



IceCube



ERNIE AND BERT



"Bert"
1.04 PeV
Aug. 2011



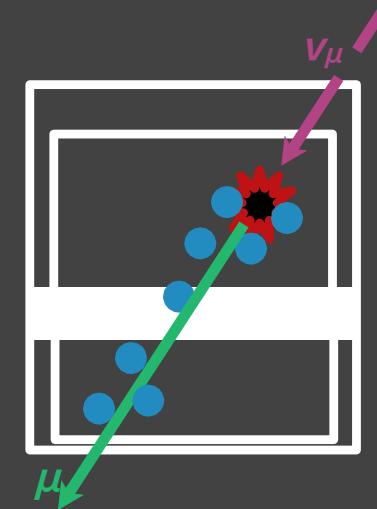
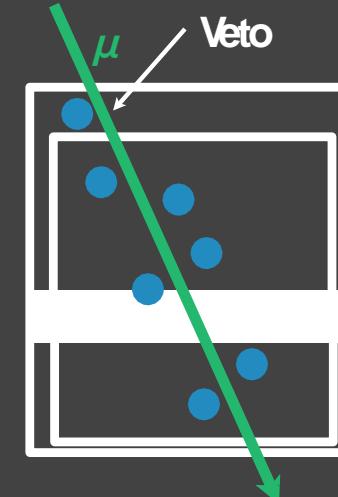
"Ernie"
1.14 PeV
Jan. 2012

Follow-up Analysis (HESE - High Energy Starting Events analysis)

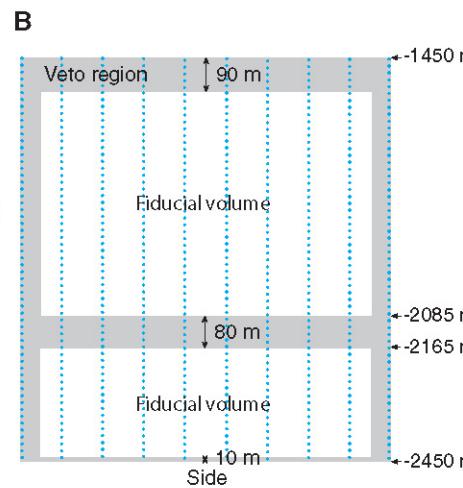
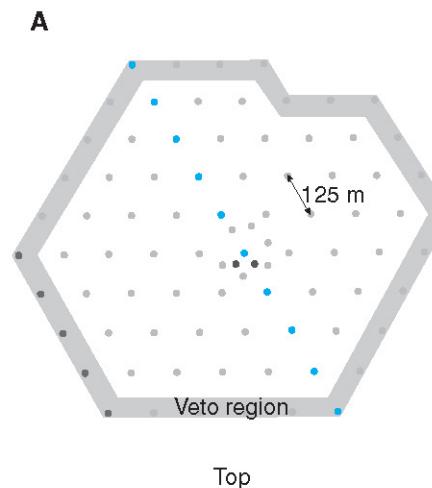
Specifically designed to find these contained events

Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

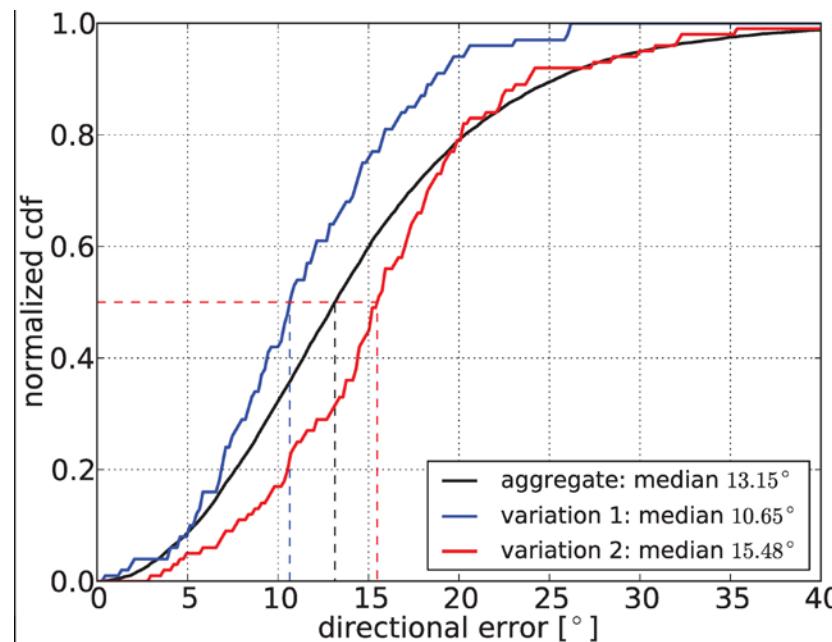
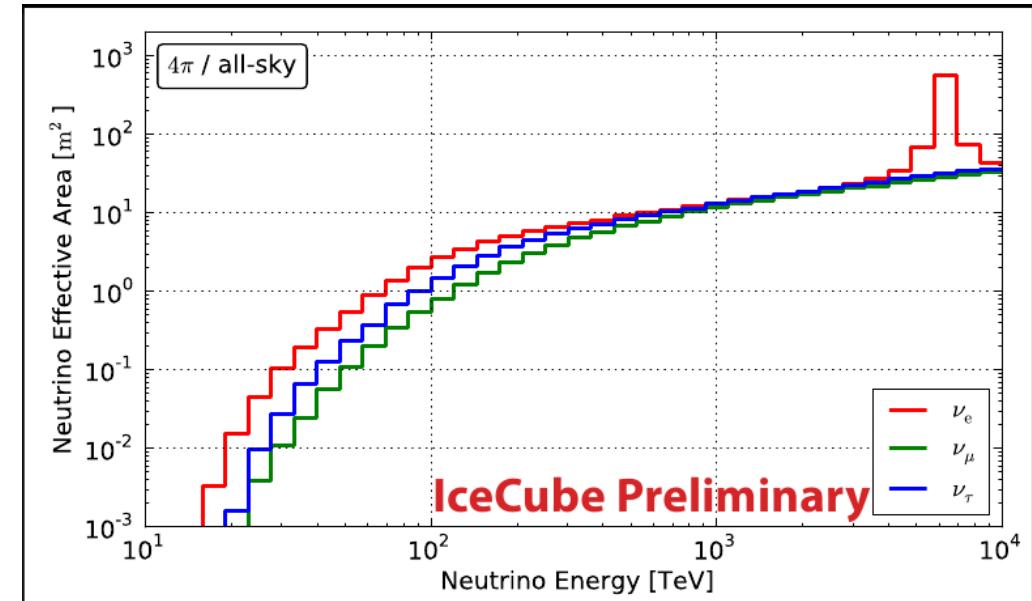
- ▶ Explicit contained search at high energies (cut: $Q_{\text{tot}} > 6000$)
- ▶ 400 Mton effective fiducial mass
- ▶ Use atmospheric muon veto
- ▶ Sensitive to all flavors in region above 60 TeV
- ▶ Three times as sensitive at 1 PeV
- ▶ Estimate background from data



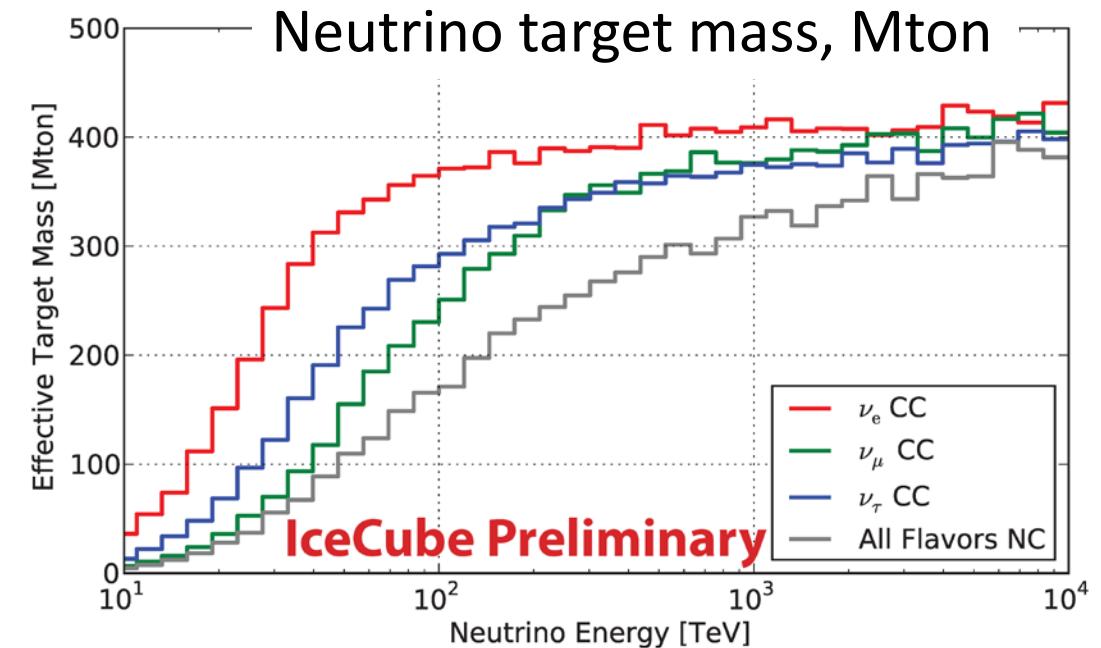
400 Mton fiducial mass



Cascade angular resolution

Neutrino effective area m^2 

Neutrino target mass, Mton

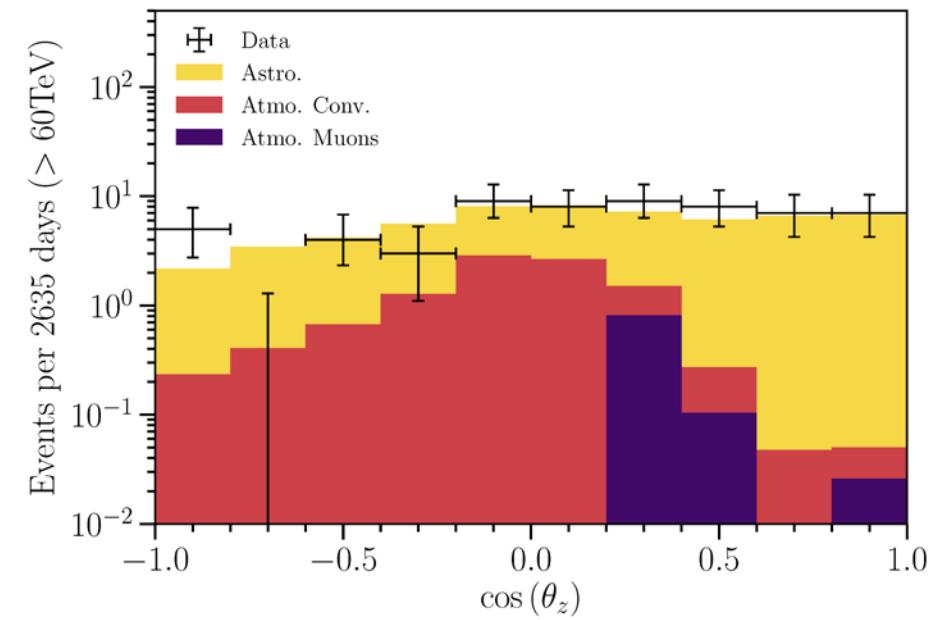
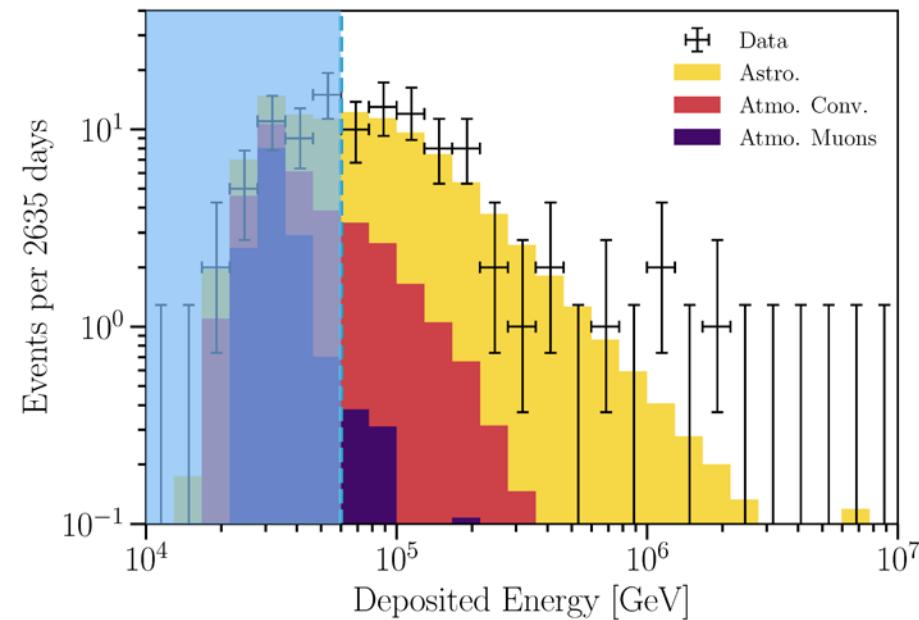


Diffuse neutrino flux observed by IceCube (HESE 7.5 years)

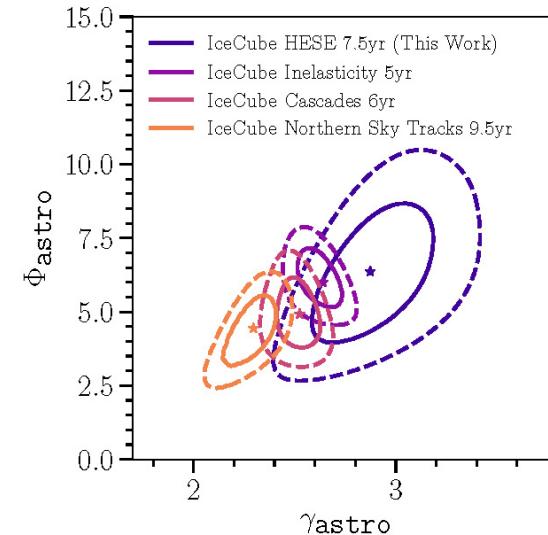
arXiv:2011.03545

Median zenith
resolution 6.3 ° !!!

Deposited energy and reconstructed $\cos \theta_z$ distributions



Category	E<60 TeV	E>60 TeV	Total
Total events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double cascade	2	2	4



Astrophysical flux is well described by single power law:

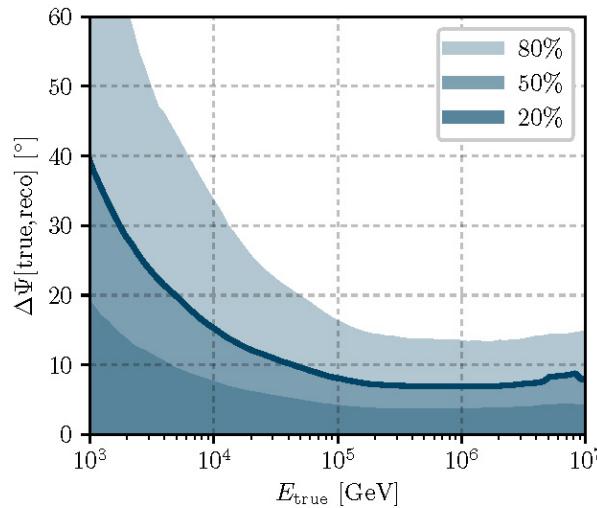
$$\gamma_{\text{astro}} = 2.87^{+0.20}_{-0.19}$$

Search for Neutrino Sources Using Cascade Data

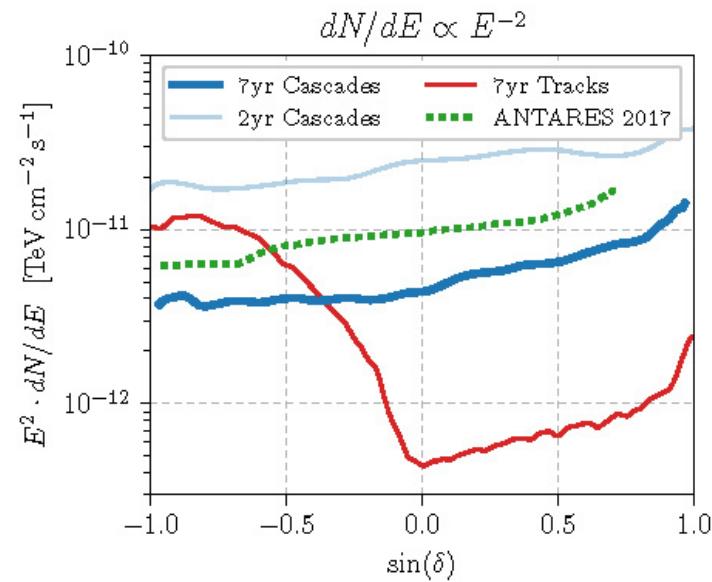
arXiv:1907.06714

Contained cascades $E > 1\text{TeV}$
All sky scan &
Selected Sources

Angular resolution



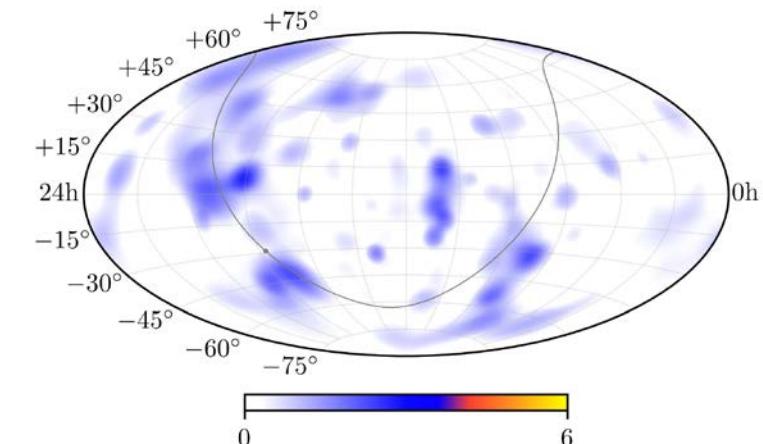
Sensitivity to
Point sources



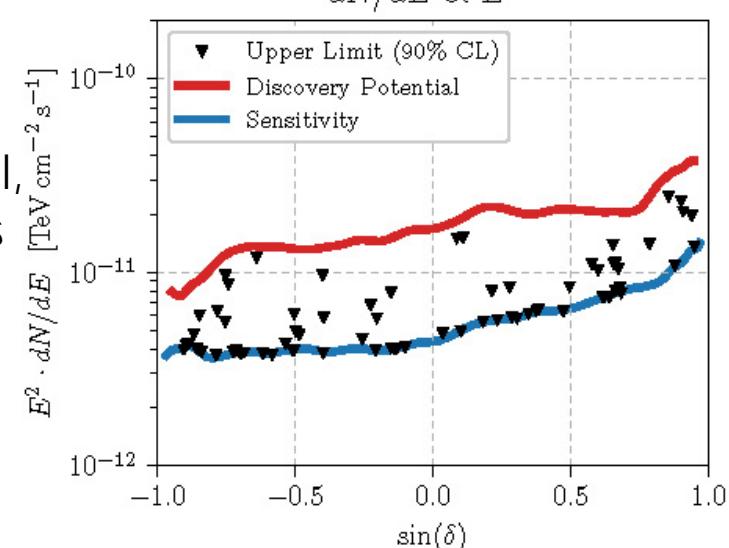
Sensitivity,
discovery potential,
source candidates
upper limits

All sky scan

No significant clustering was observed



$dN/dE \propto E^{-2}$

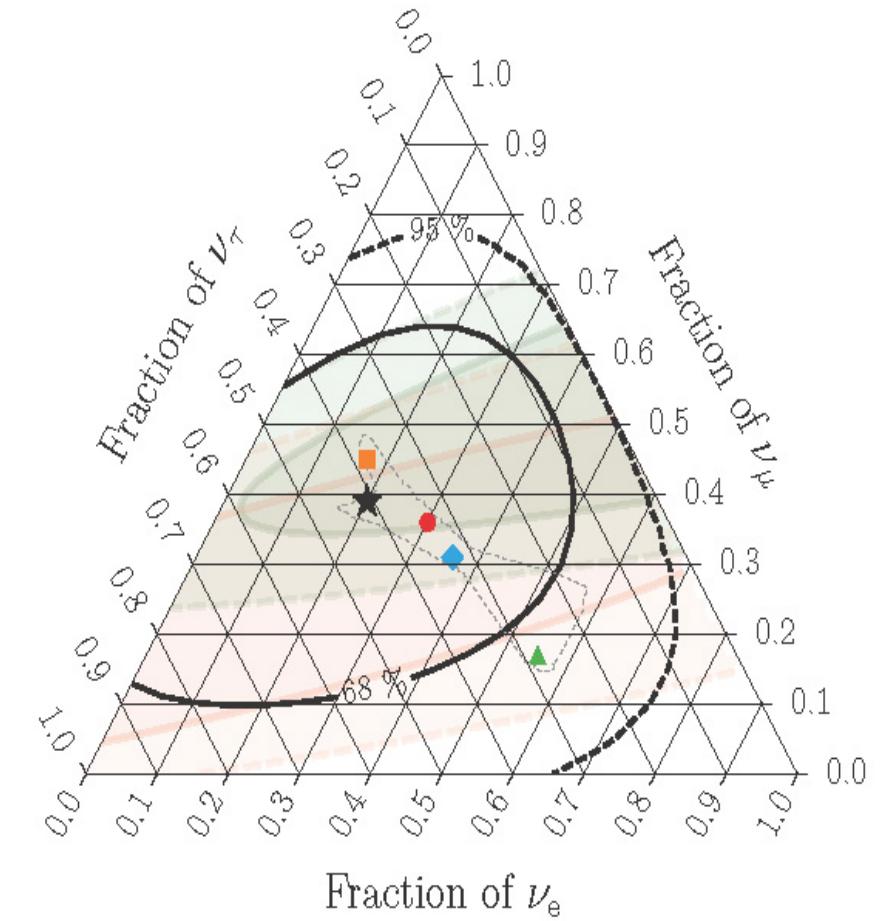
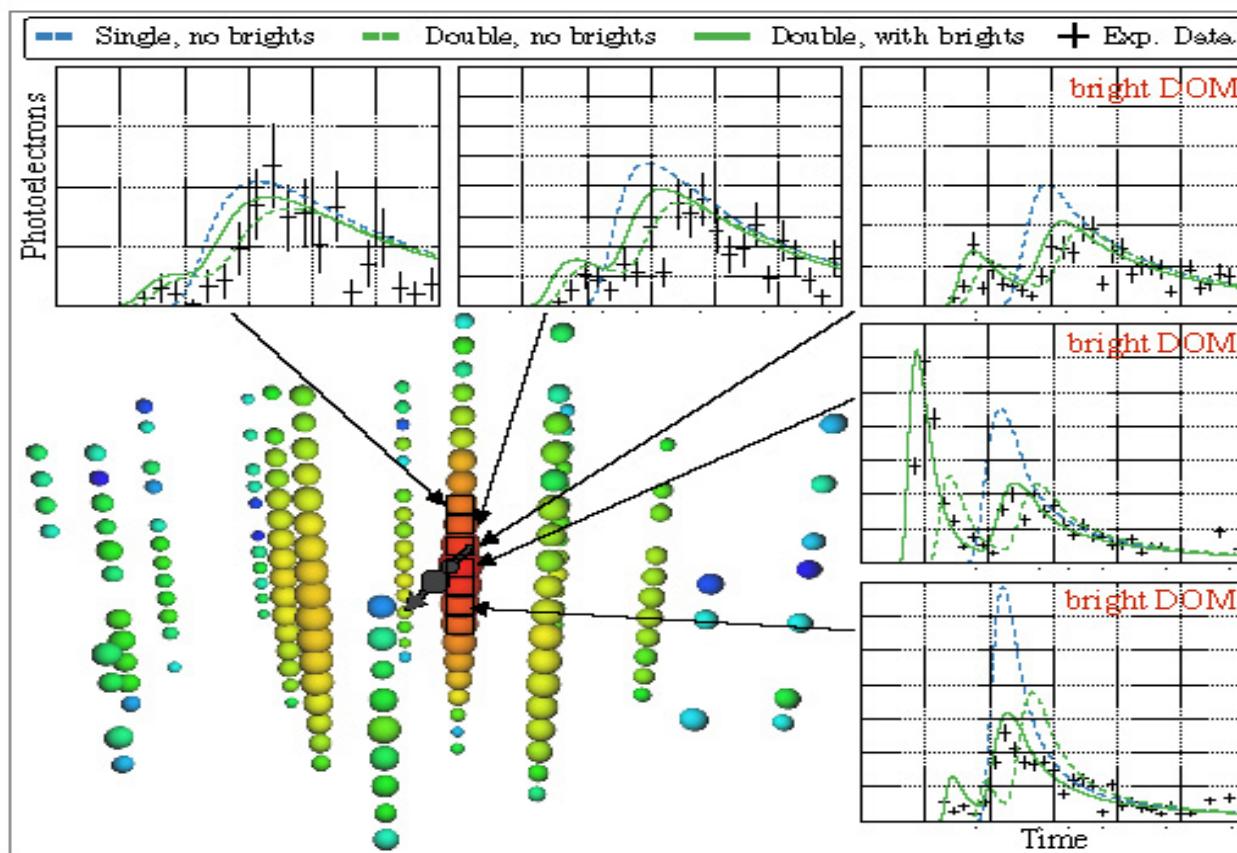


Tau neutrino searchers

HESE 7.5 yr. sample

Tau decay length
 $L_\tau \sim 50\text{m} \times E/\text{PeV}$

Two events are selected

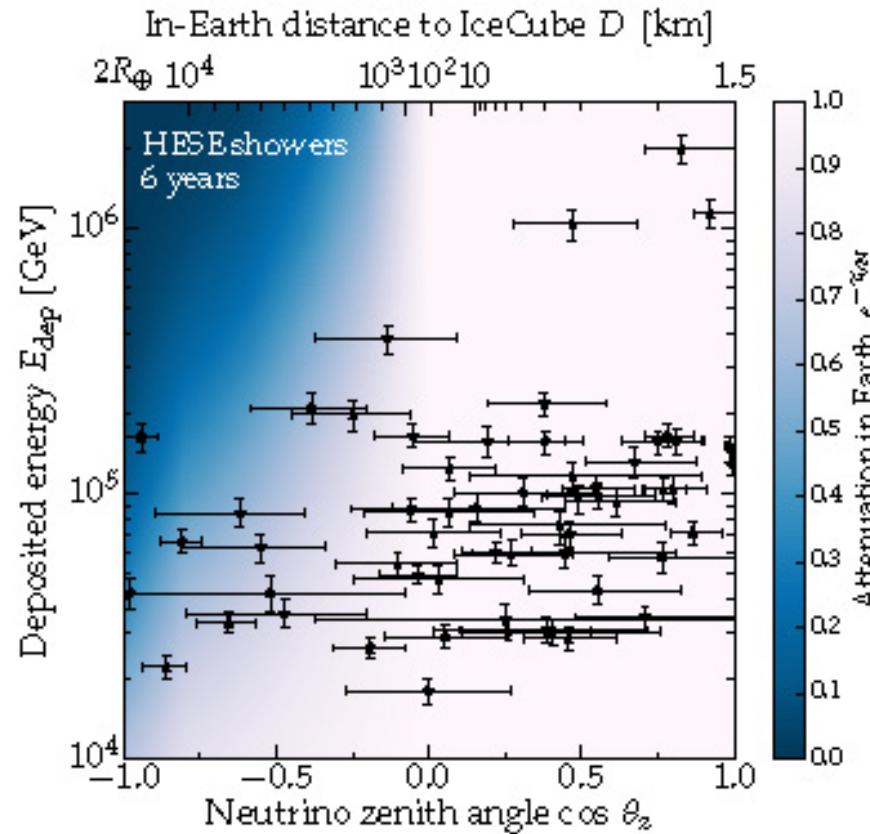


- HESE with ternary topology ID
 - ★ Best fit: $0.20 : 0.39 : 0.42$
 - Global Fit (IceCube, APJ 2015)
 - Inelasticity (IceCube, PRD 2019)
 - 3ν -mixing 3σ allowed region
- $\nu_e : \nu_\mu : \nu_\tau$ at source \rightarrow on Earth:
- | |
|--|
| ■ 0:1:0 \rightarrow 0.17 : 0.45 : 0.37 |
| ● 1:2:0 \rightarrow 0.30 : 0.36 : 0.34 |
| ▲ 1:0:0 \rightarrow 0.55 : 0.17 : 0.28 |
| ◆ 1:1:0 \rightarrow 0.36 : 0.31 : 0.33 |

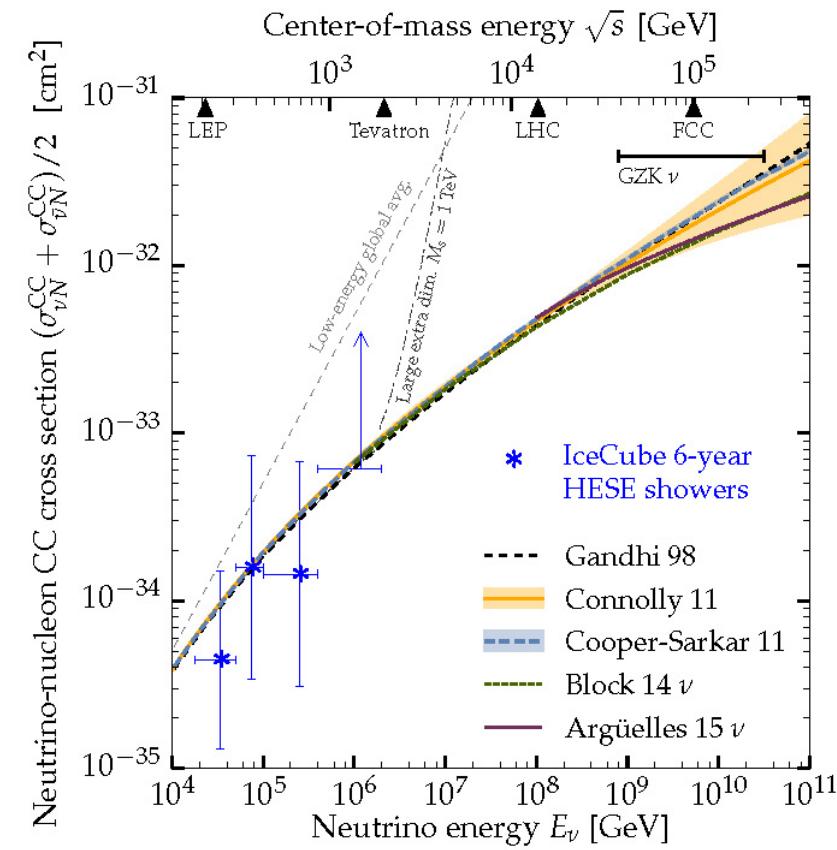
Extracting the Neutrino-Nucleon Cross Section using IC showers

Laboratory measurements up to 350 GeV.
6 yr. HESE sample with 58 cascades
with energies (18TeV – 2 PeV)

Neutrino-induced showers

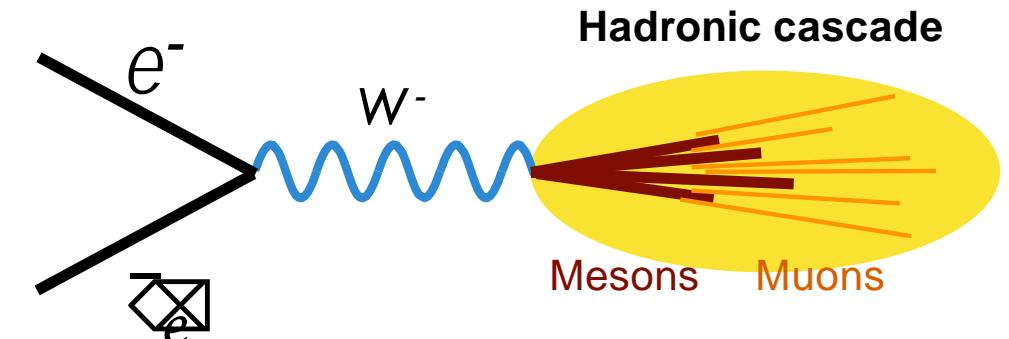
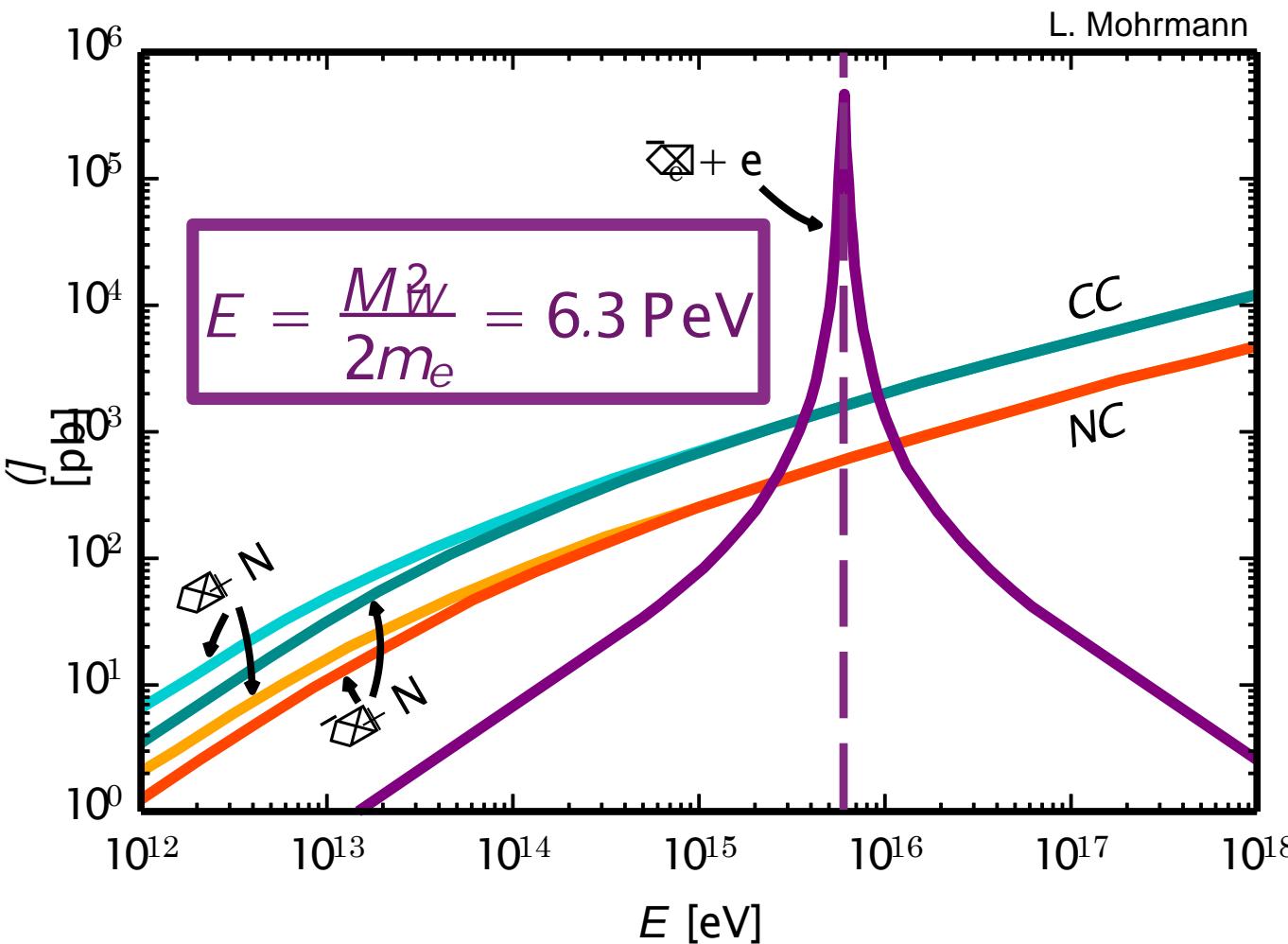


Neutrino-Nucleon CC cross section





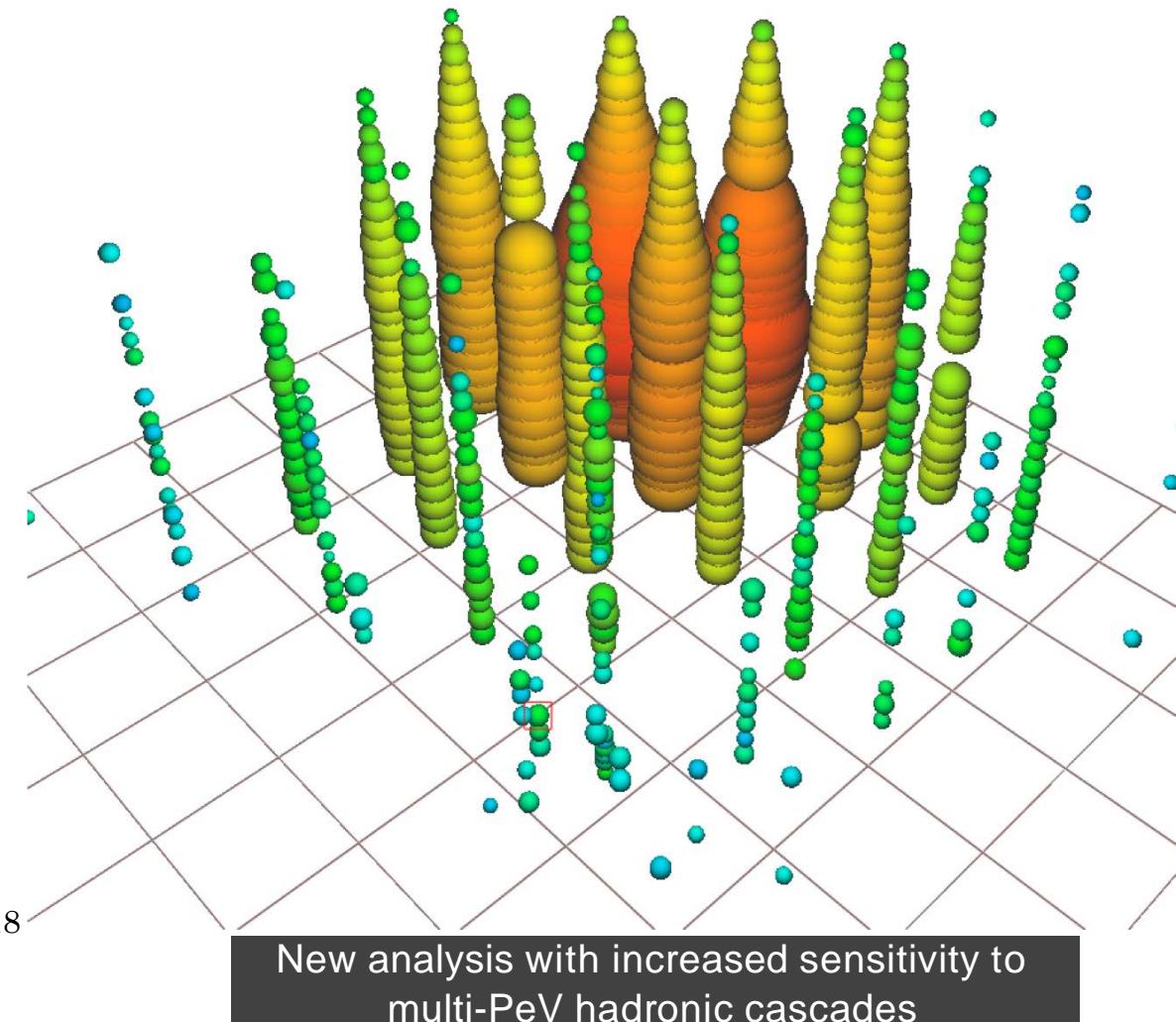
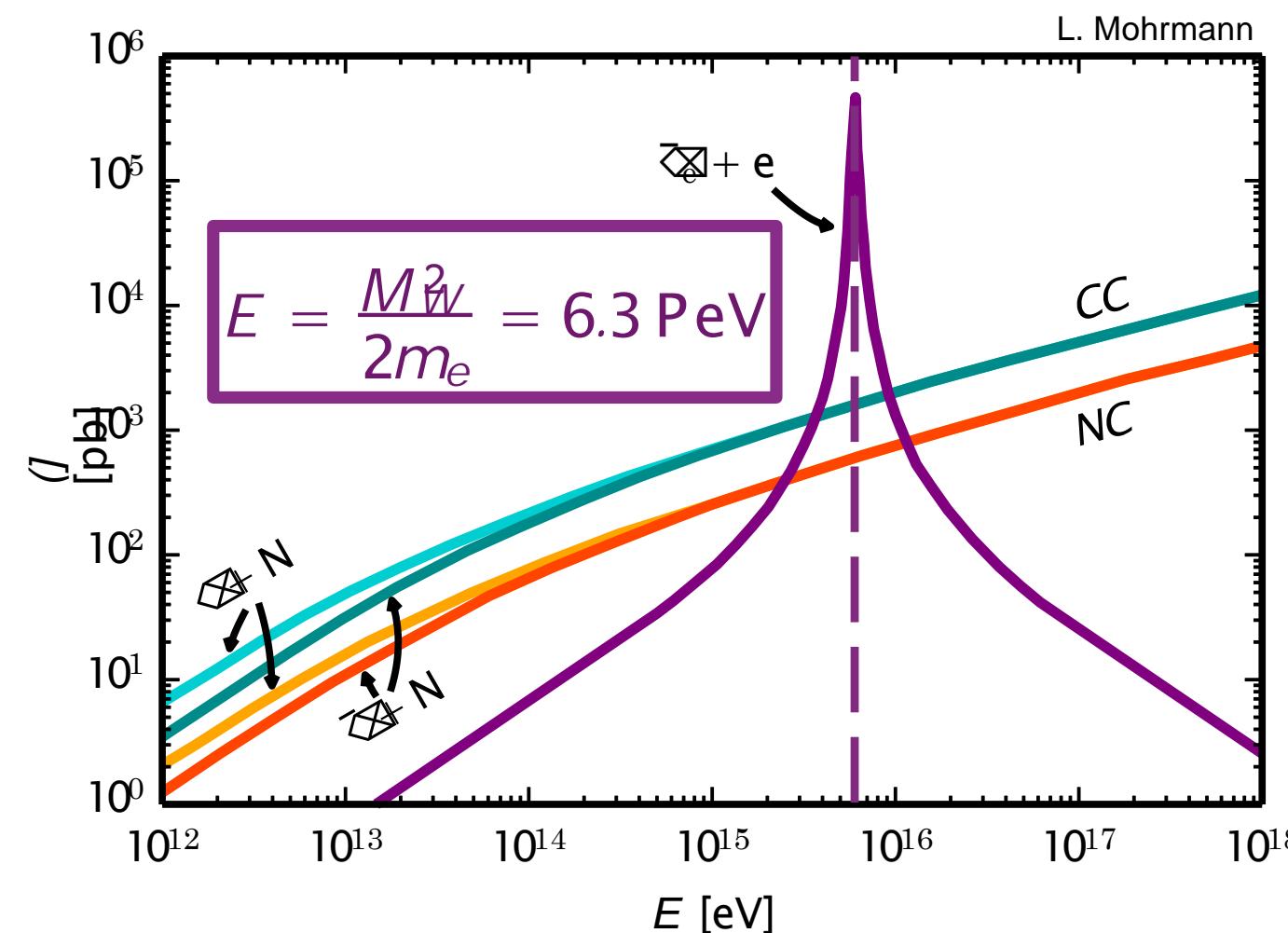
Partially-contained cascades



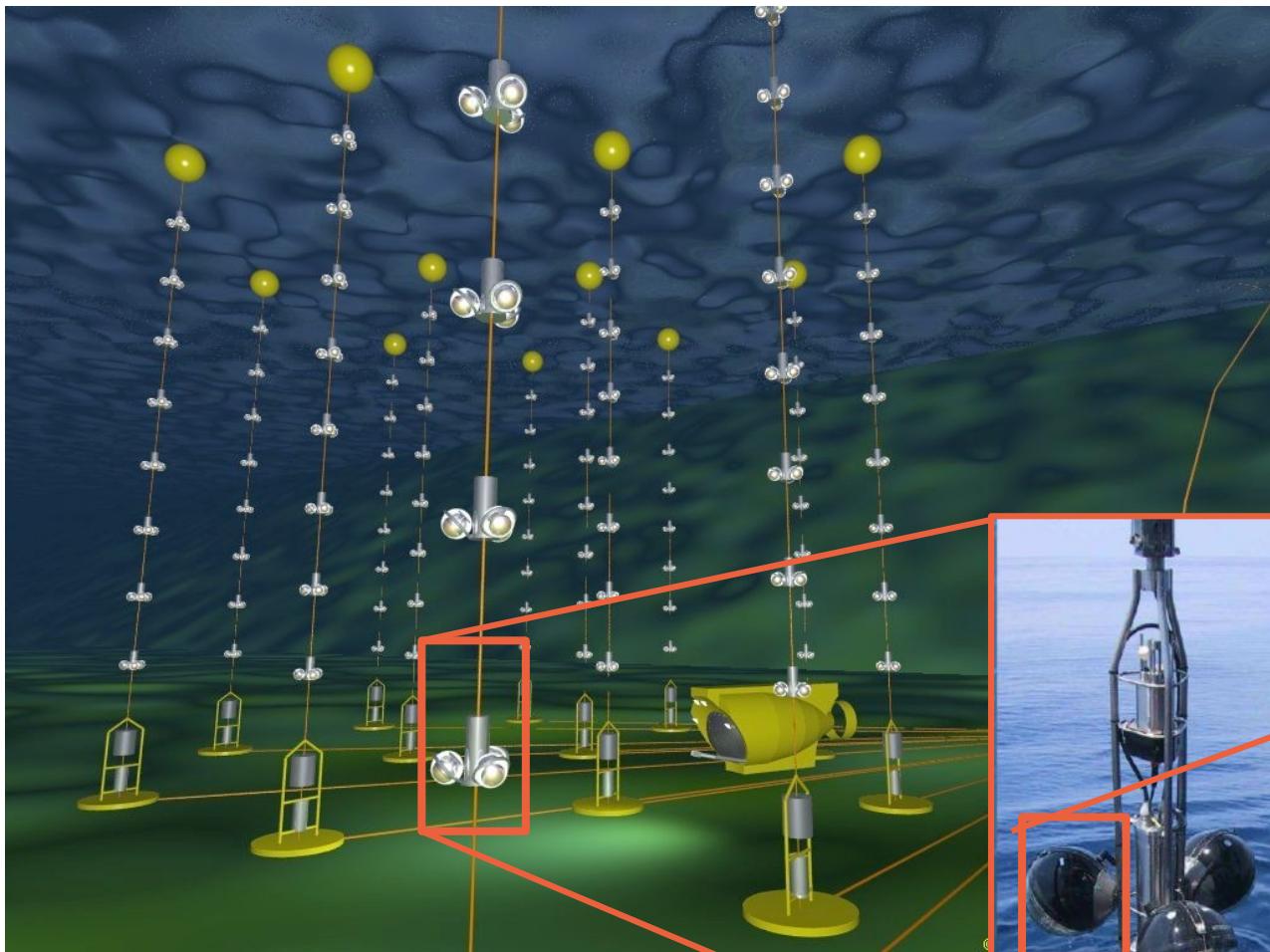


Partially-contained cascades

First Glashow candidate event ~6 PeV
Paper coming soon



ANTARES



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



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

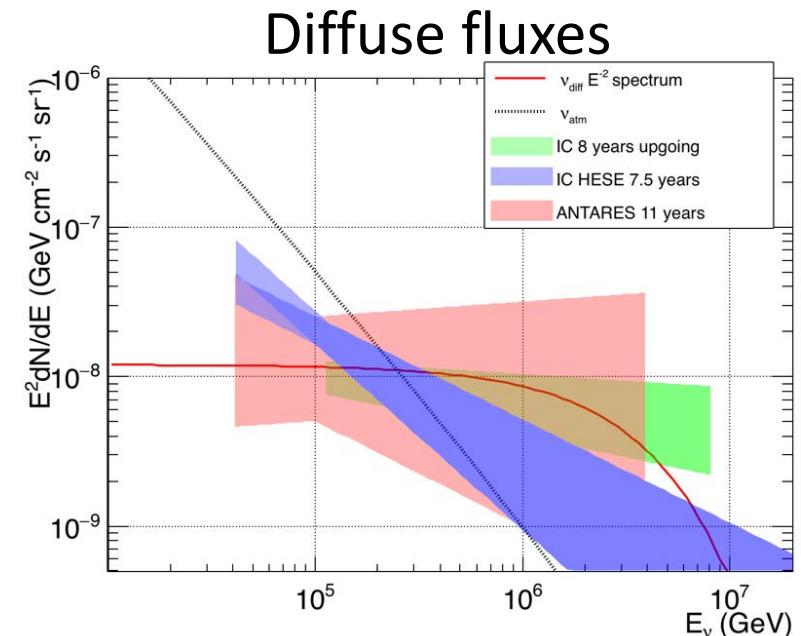
ANTARES OM:
10" Hamamatsu
PMT



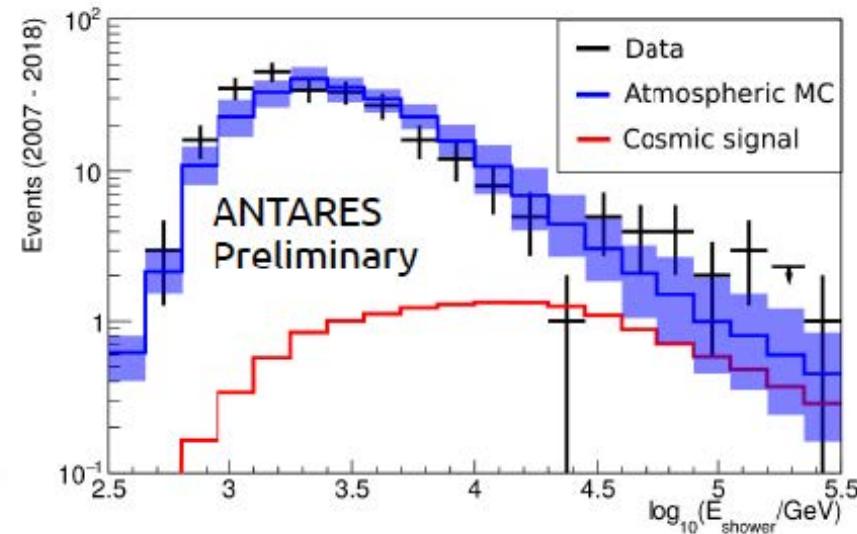
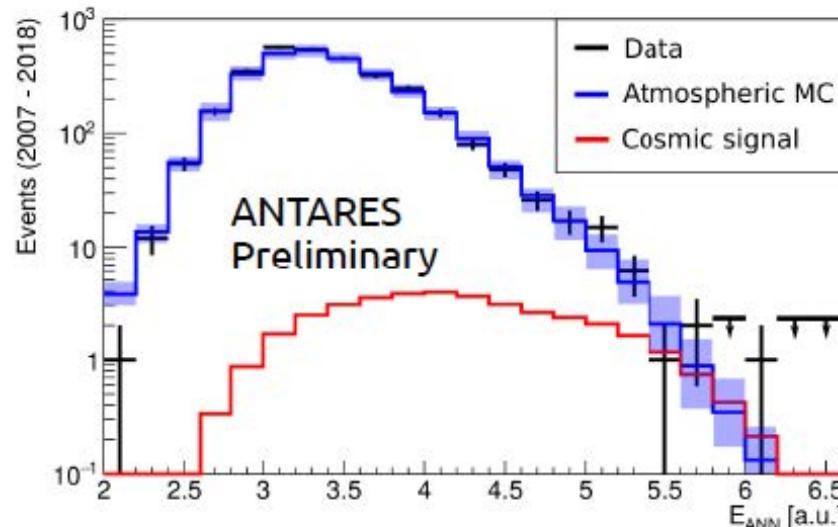
Diffuse neutrino flux

Track and shower data sample.

50 events has been selected (27 track-like and 23 shower-like events) as cosmic neutrino candidates. The observed excess has a significance of 1.8σ . For the cosmic flux The best fit parameters obtained for an unbroken power law spectrum are: $\Gamma = 2.3 (+0.4 -0.4)$ and $\Phi_0(100 \text{ TeV}) = (1.5 \pm 1.0) 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$



Energy distributions of tracks and cascades



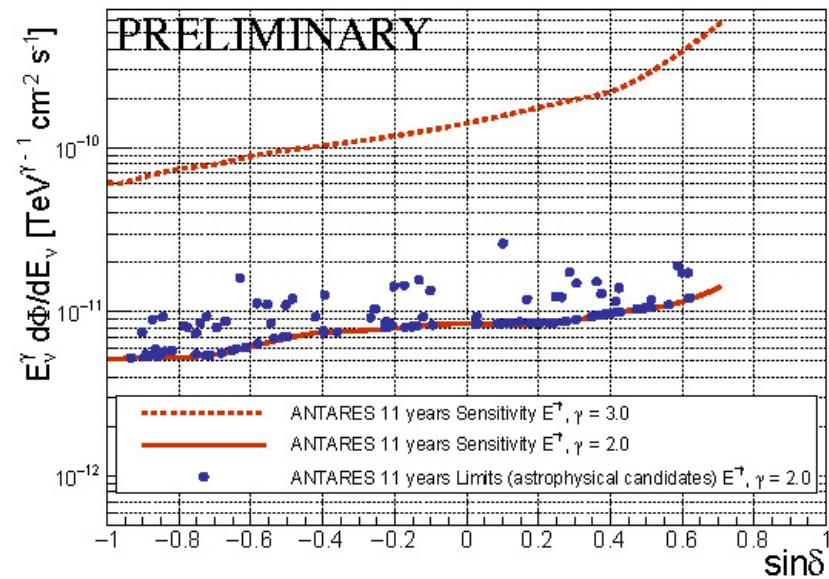
Blue - IceCube HESE analysis.
Green - IceCube up-going track.
Red - ANTARES 11 years.

Searches for point-like sources with 11 years of ANTARES data

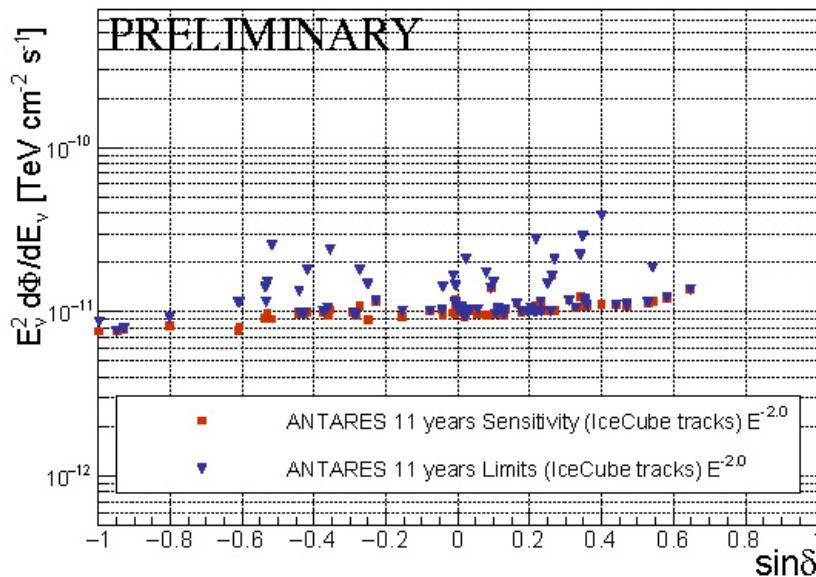
ANTARES Coll. PoS(ICRC2019)920.

Combined analysis of track and cascade events!

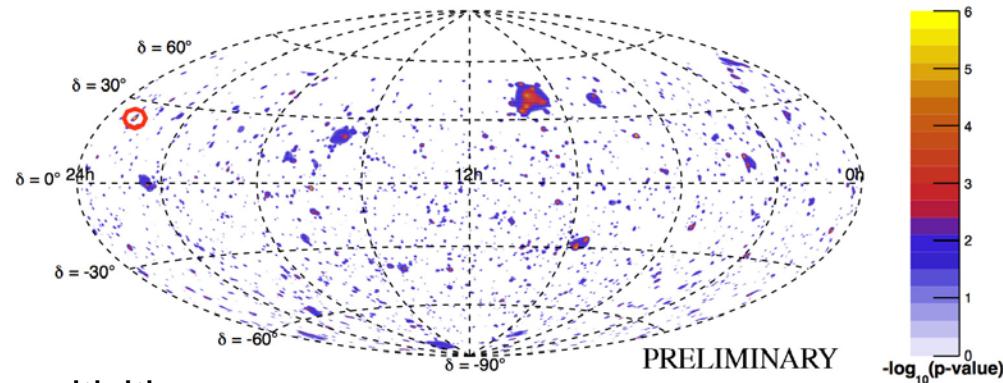
90 % C.L. upper limits on the fluxes from the investigated astrophysical candidates(blue dots) as a function of the source declination.



90 % C.L. upper limits and sensitivities for the investigated IceCube tracks.



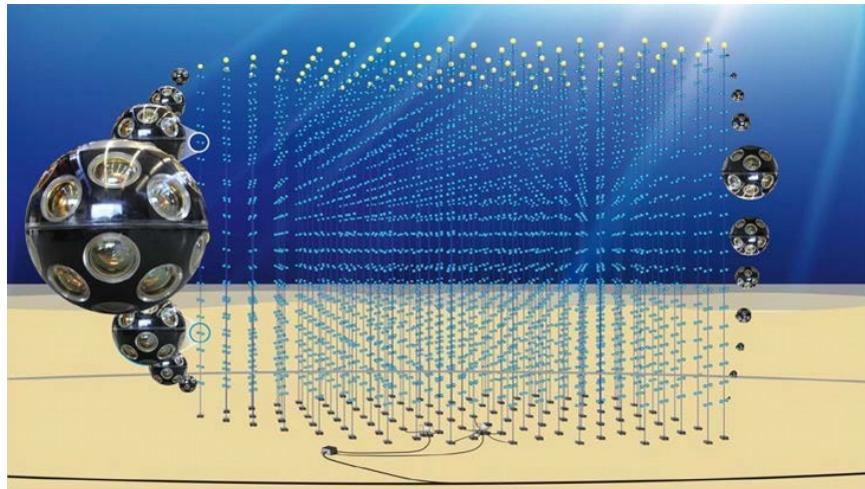
Full-Sky Search



Sky map in equatorial coordinates of pre-trial p-values. The red contour indicates the location of the most significant cluster of the full-sky search. The post-trial significance is 23 % 90 % C.L. upper limits (blue triangles) and sensitivities (orange squares) for the investigated IceCube tracks as a function of the source declination for aE-2.0 spectrum. (1.2σ).

KM3NeT - ARCA

Construction started

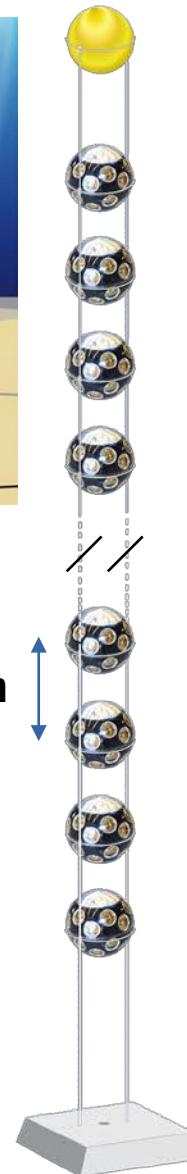


100 km offshore Sicily
Depth: 3400 m

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

Vertical spacing: 36 m
Horizontal spacing: 90 m

³
Volume : 1 km



Digital Optical Module



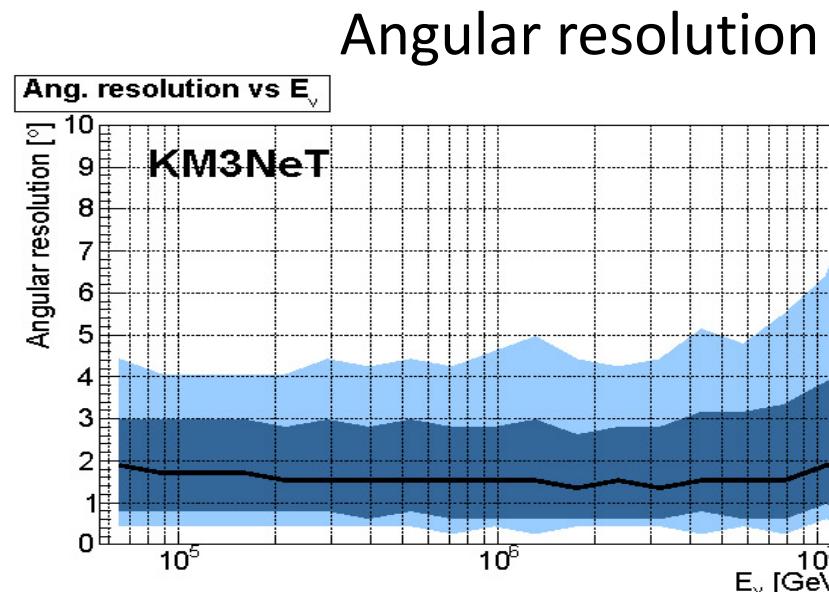
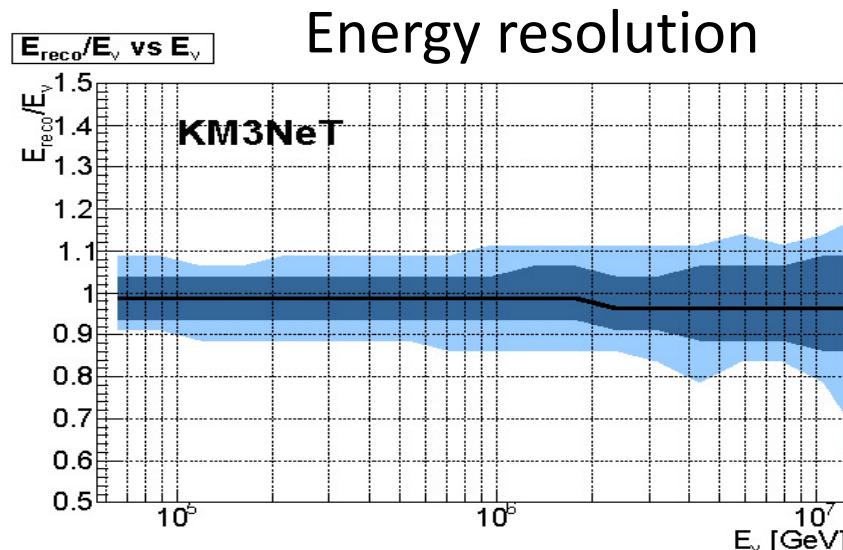
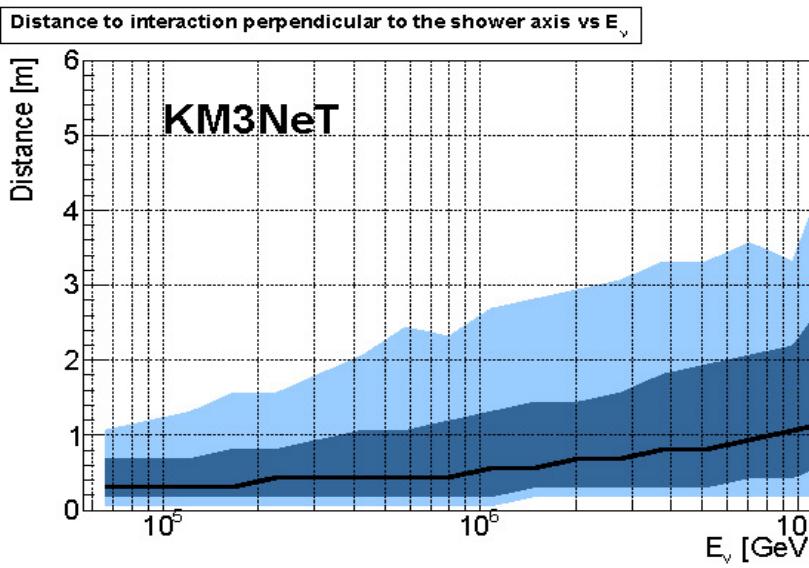
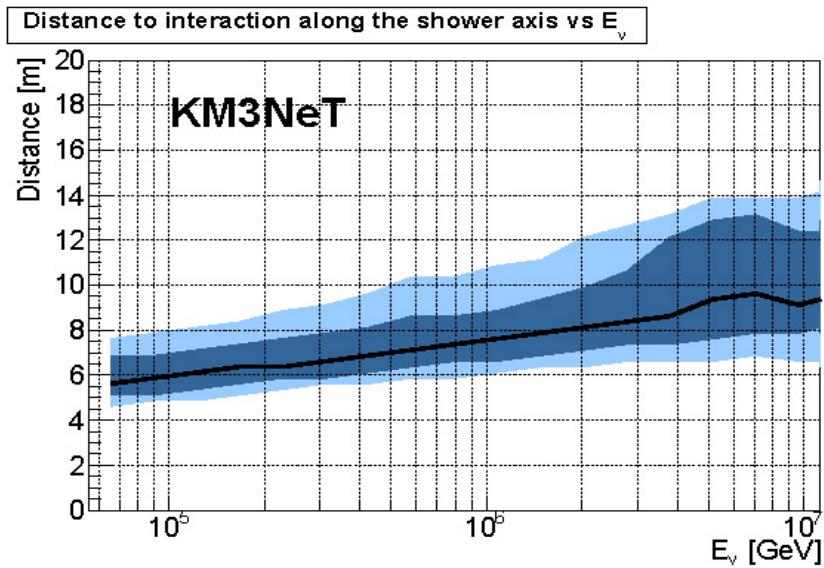
← 17" →

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

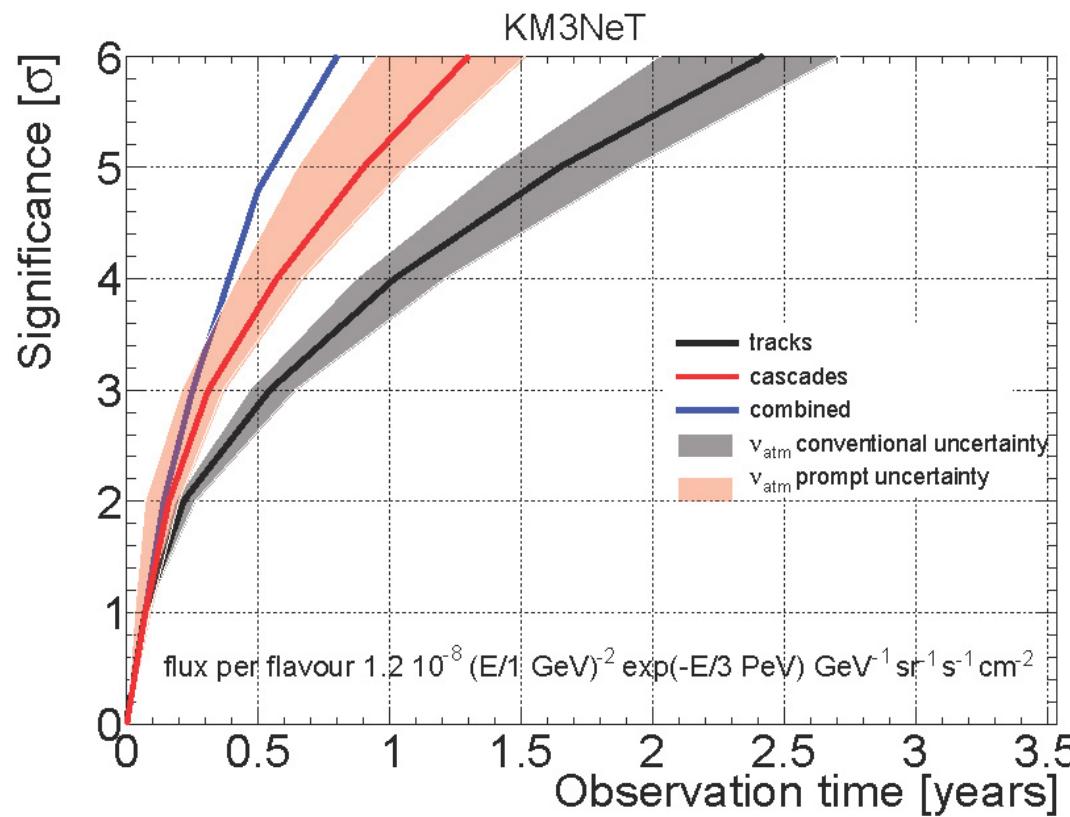
photocathode
area similar to
a 17" PMT

Optical background (mainly
K): 5-10 kHz/PMT

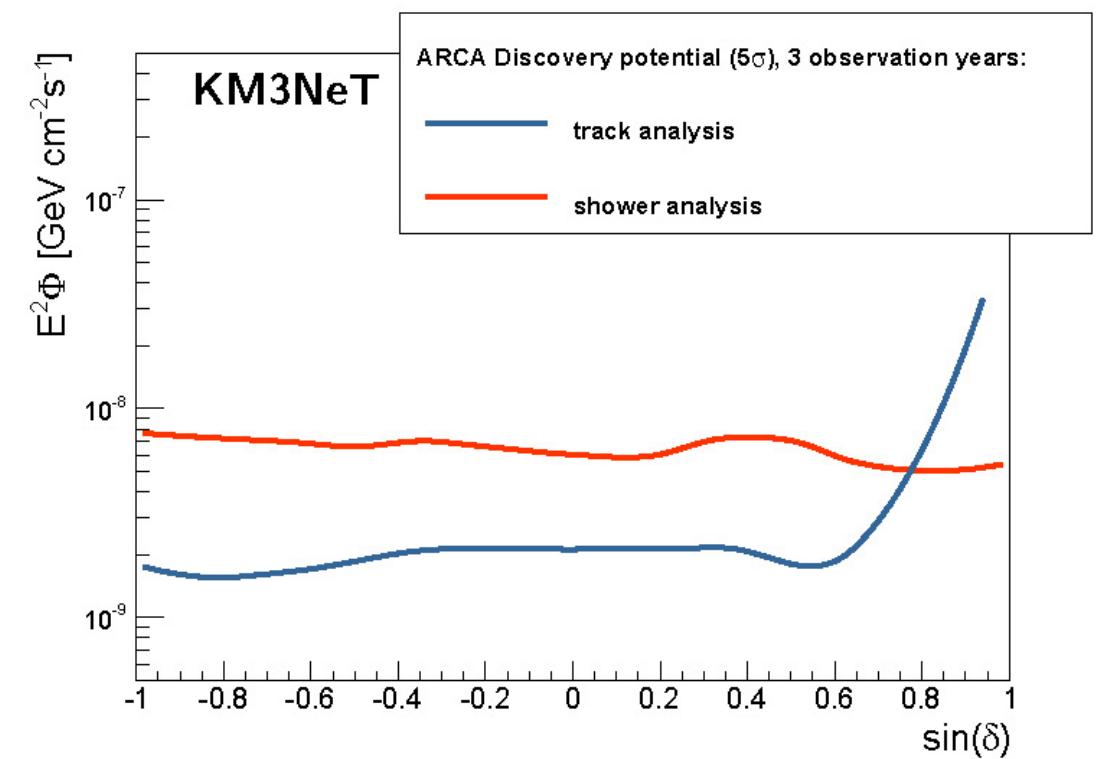
ARCA vertex resolutions for contained ν_e events

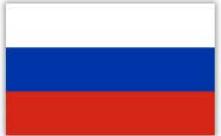


Significance as a function of KM3NeT/ARCA (2 building blocks) observation time for the detection of a diffuse flux of neutrinos. corresponding to the signal reported by IceCube



The discovery flux at the 5σ level as a function of the declination (red line) for 3 years of observation time, and is compared with the discovery flux obtained for the track analysis.



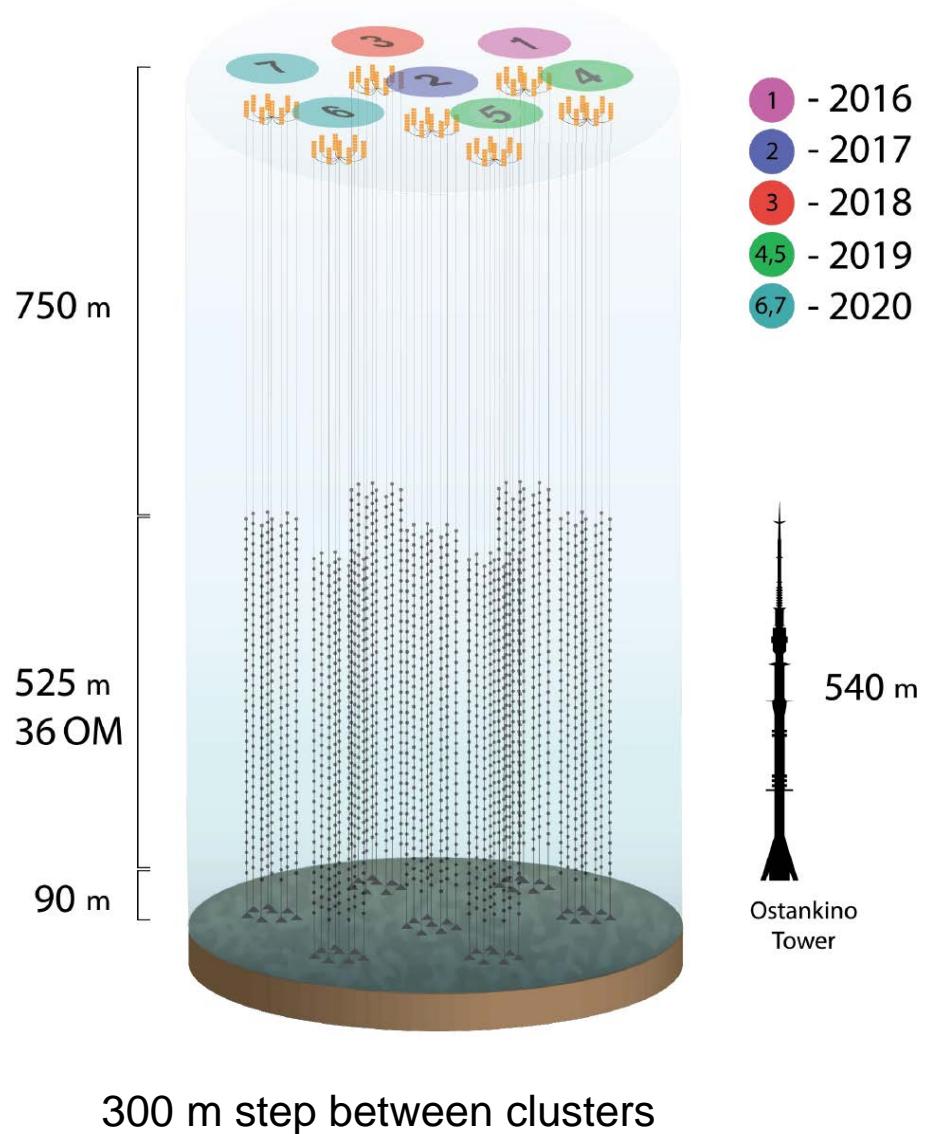


**10 institutes
~ 70 members**





Baikal-GVD construction status and schedule



Deployment schedule

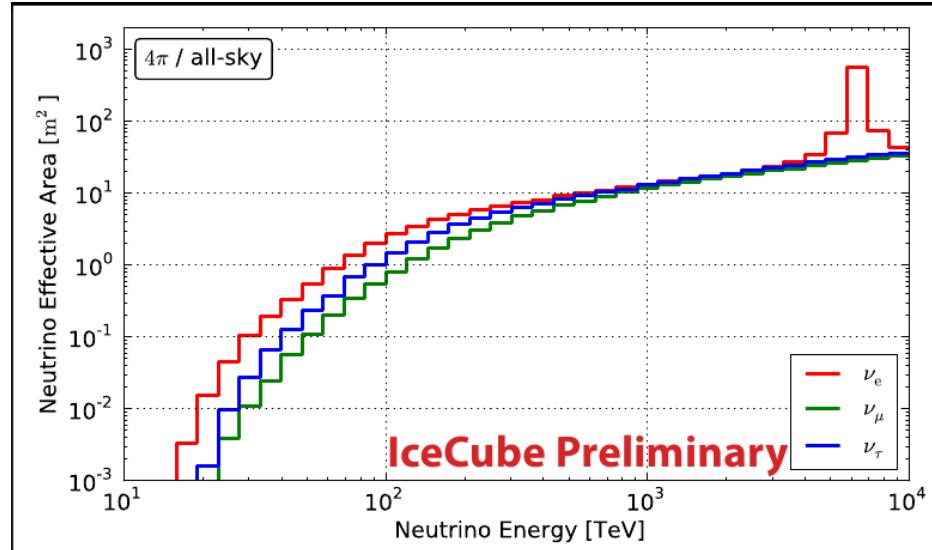
Year	Total number of clusters	Total number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	7	56	2016
2021	9	72	2592
2022	11	88	3168
2023	13	104	3744
2024	15	120	4320

3

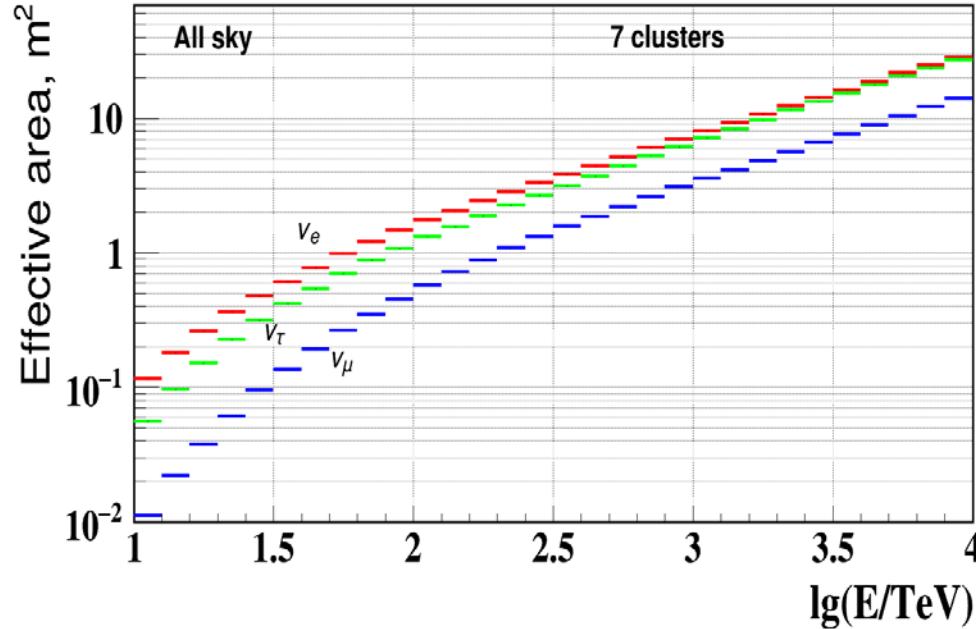
Effective volume 2020: 0.35 km³

Neutrino Effective Area

IceCube HESE

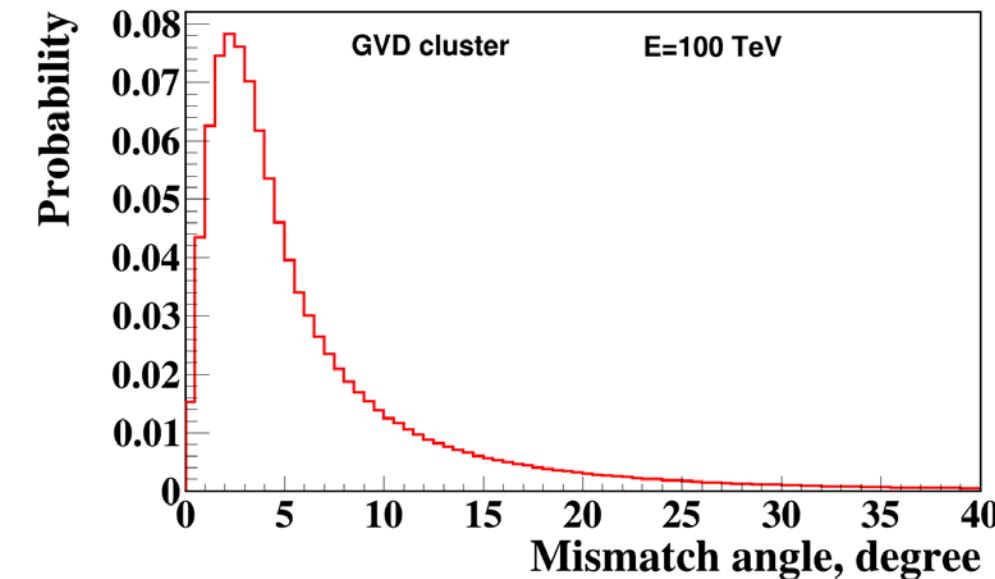


7 GVD Clusters



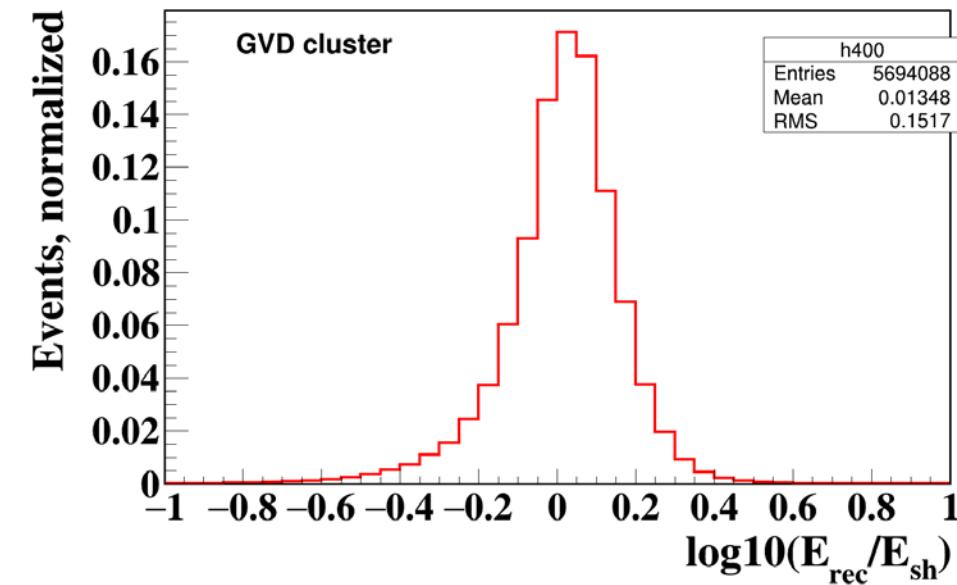
Cascades detection with GVD

Distribution of mismatch angles



Energy resolution :

$\delta E/E \sim 10\%-30\%$



Energy spectrum of astrophysical neutrinos measured by IceCube:

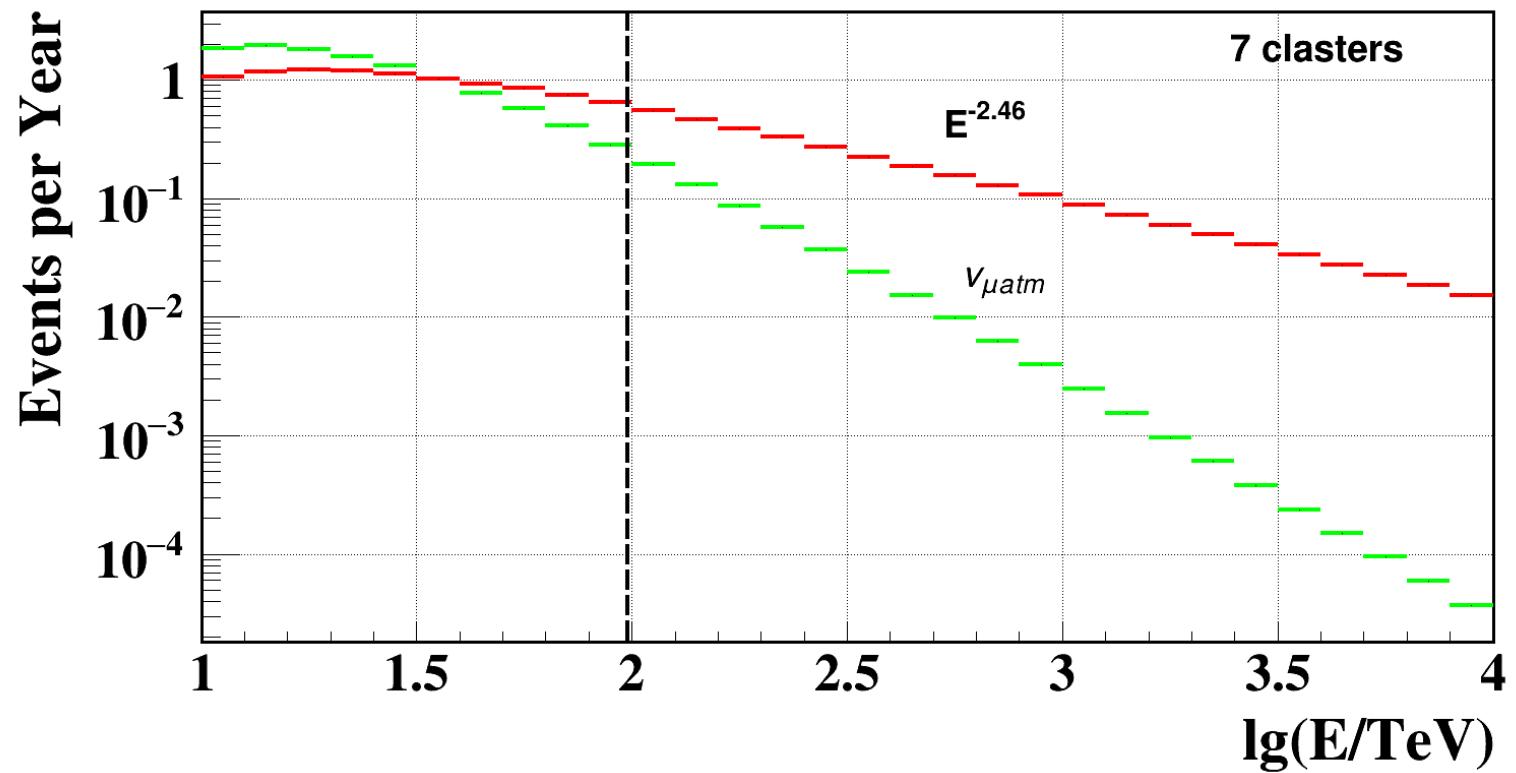
$$4.1 \cdot 10^{-6} E^{-2.46} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

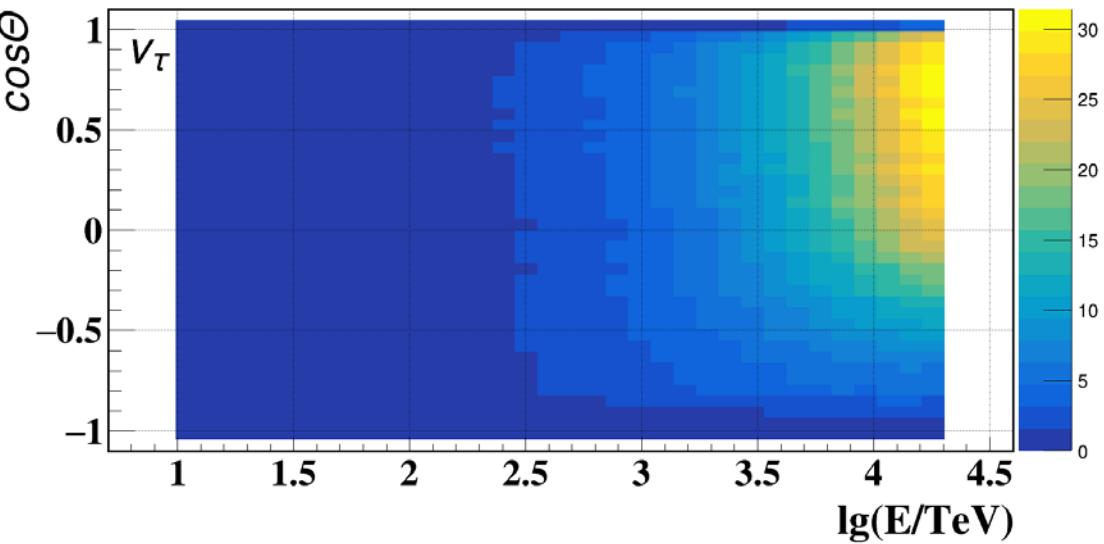
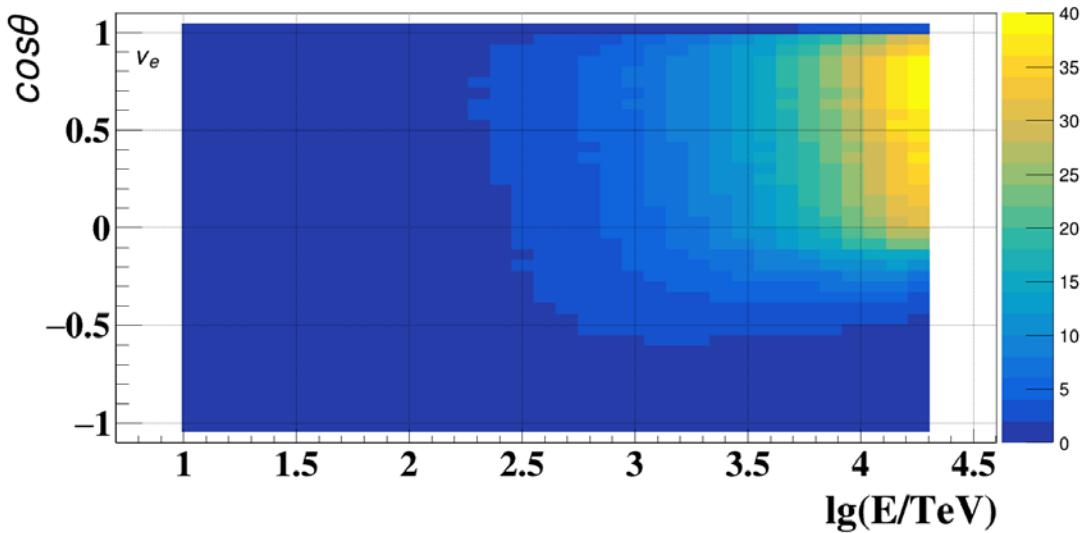
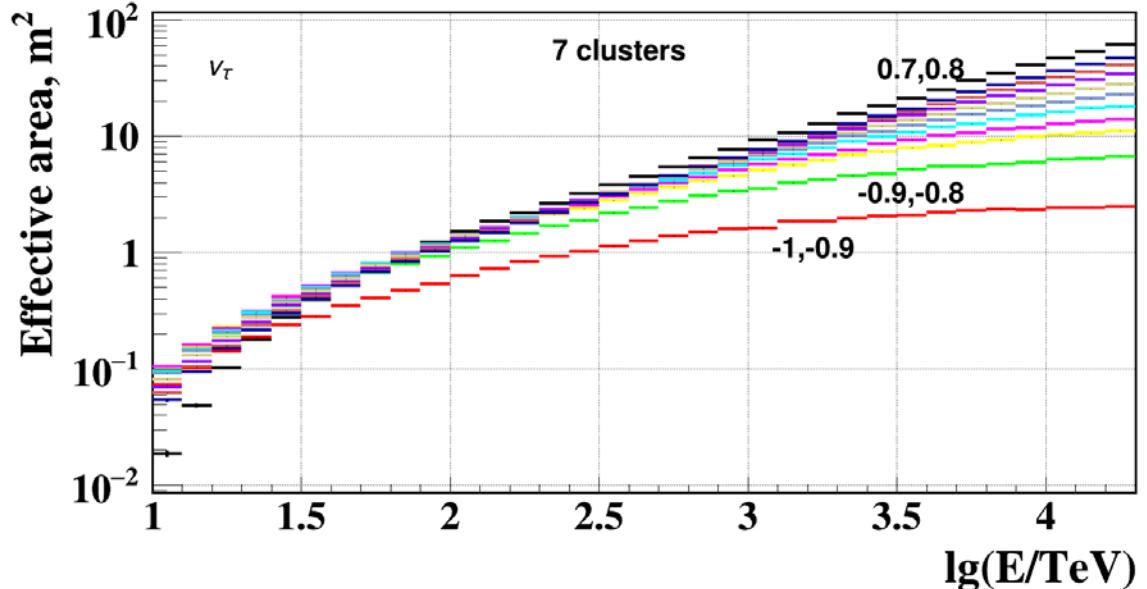
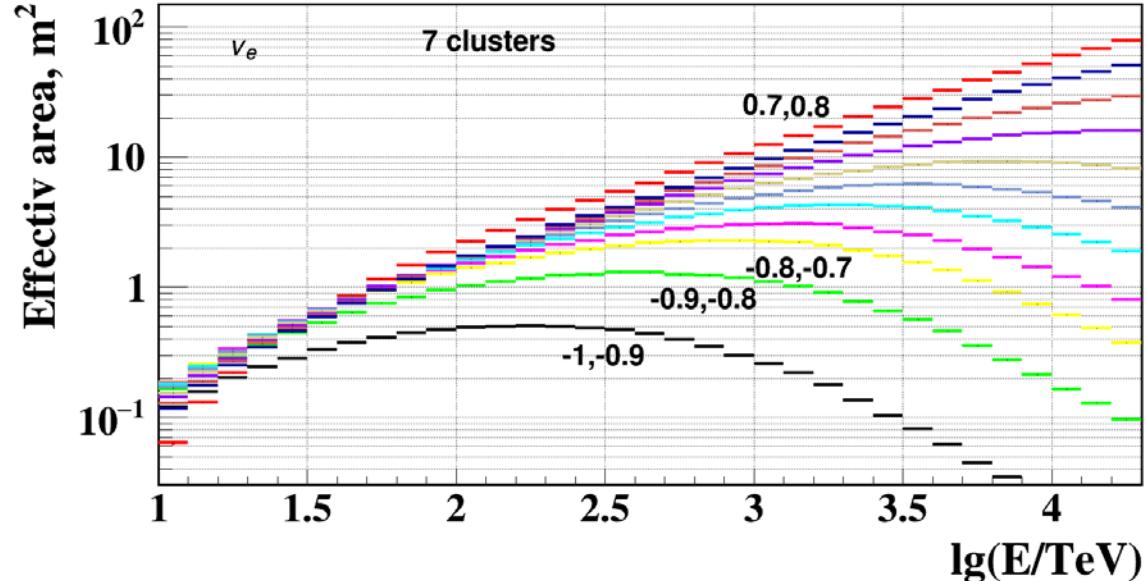
**Event selection criteria
($E_{\text{sh}} > 100 \text{ TeV}$, $N_{\text{hit}} > 20$):**

~0.6 events/yr with 1 cluster

~ 3-4 events/yr with 7 clusters

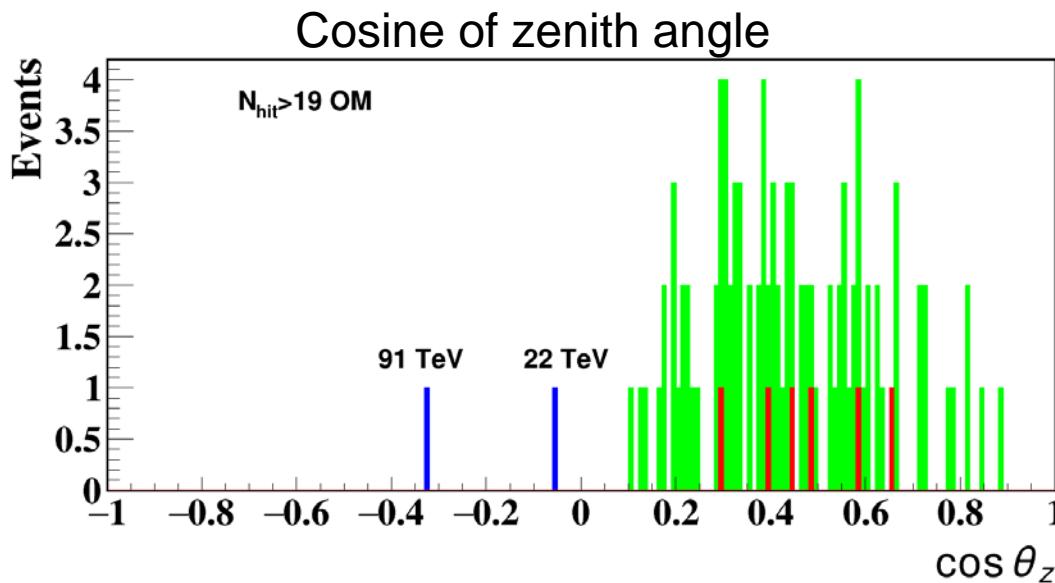
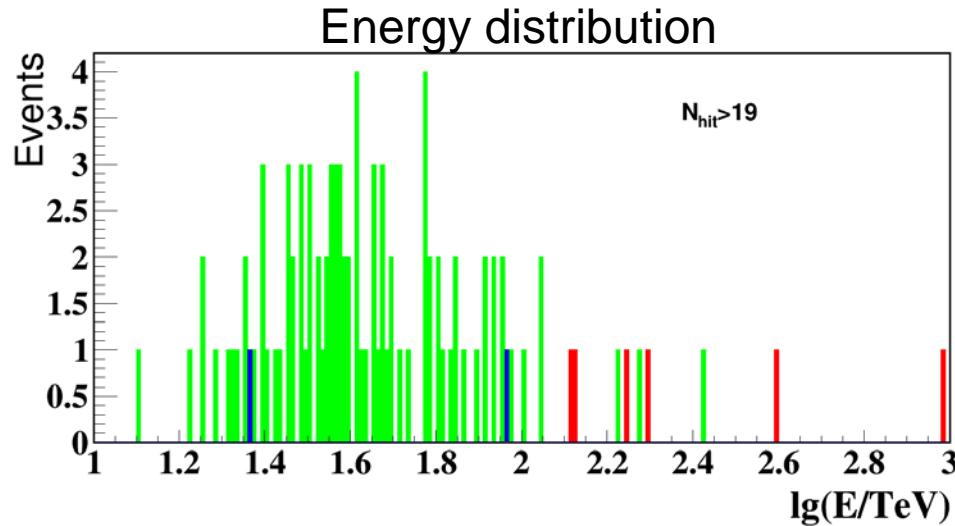
Expected number of detected events in 7 GVD Clusters from astrophysical neutrinos for 1 yr. observation







High energy cascades (data)



Data from 2016, 2018 and 2019 ,
exposition: 2294 days

12 events with $E > 100 \text{ TeV}$ and $N_{\text{hit}} > 19$:
5 events – cascade events
7 events – cascade events with muon pattern

2 upgoing cascades: $E \approx 91 \text{ TeV}$
and $E \approx 23 \text{ TeV}$

Baikal GVD: examples of first results

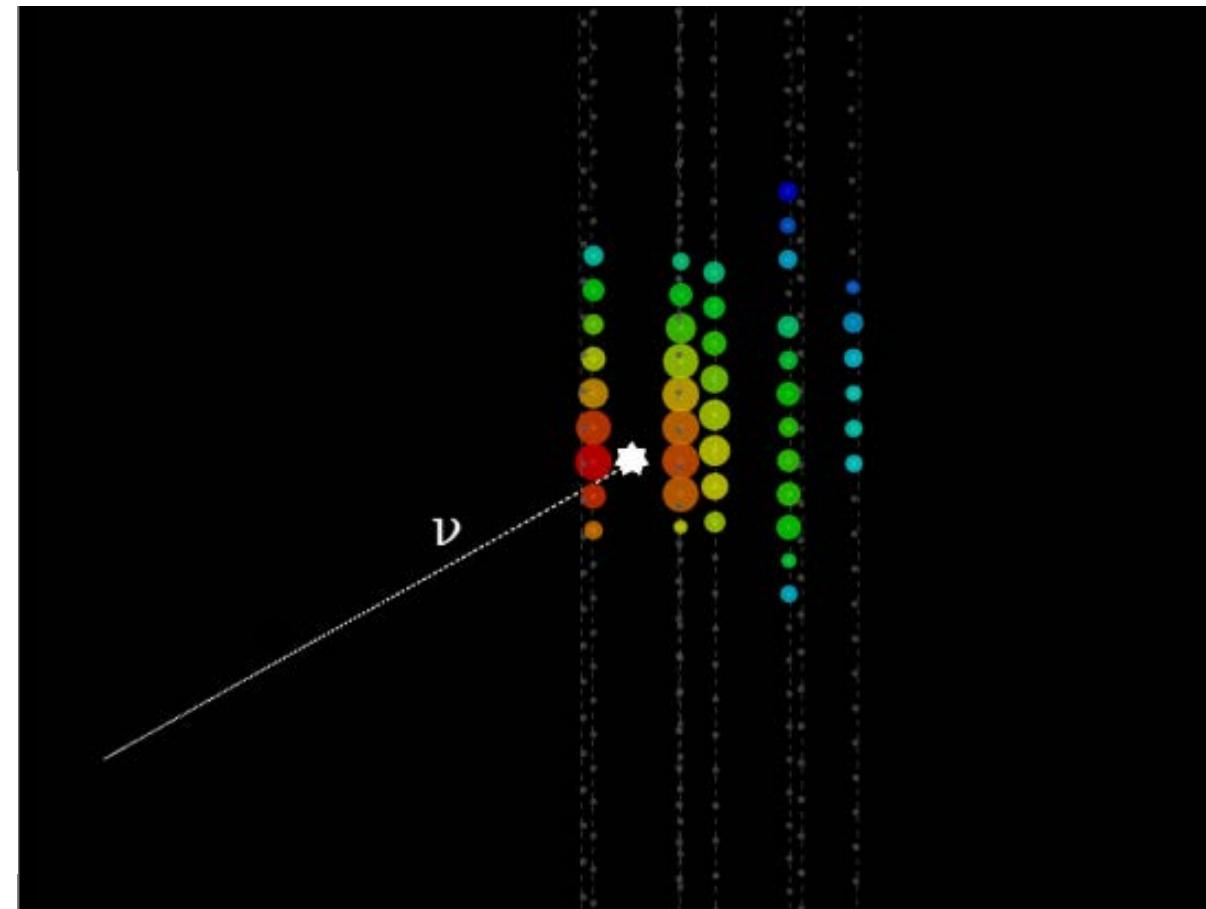
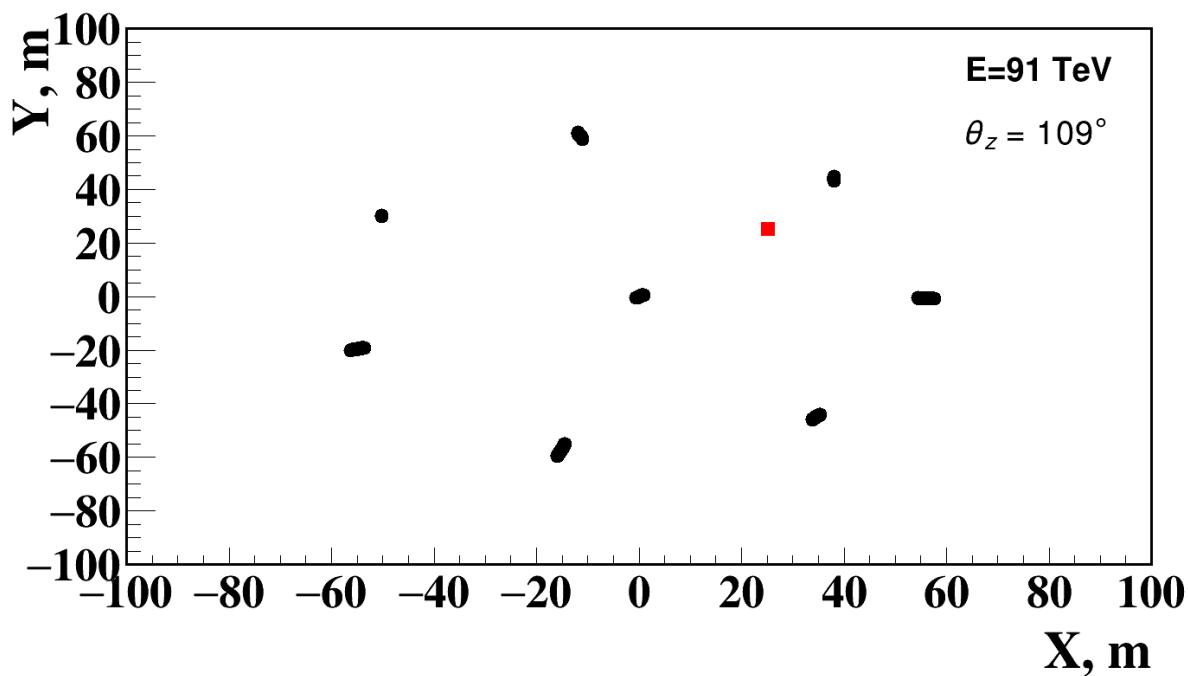
The first clear cascade event from the interaction of an upward moving electron- or tau-neutrino at the 100 TeV scale (91 ± 10) TeV

Preliminary

Contained event

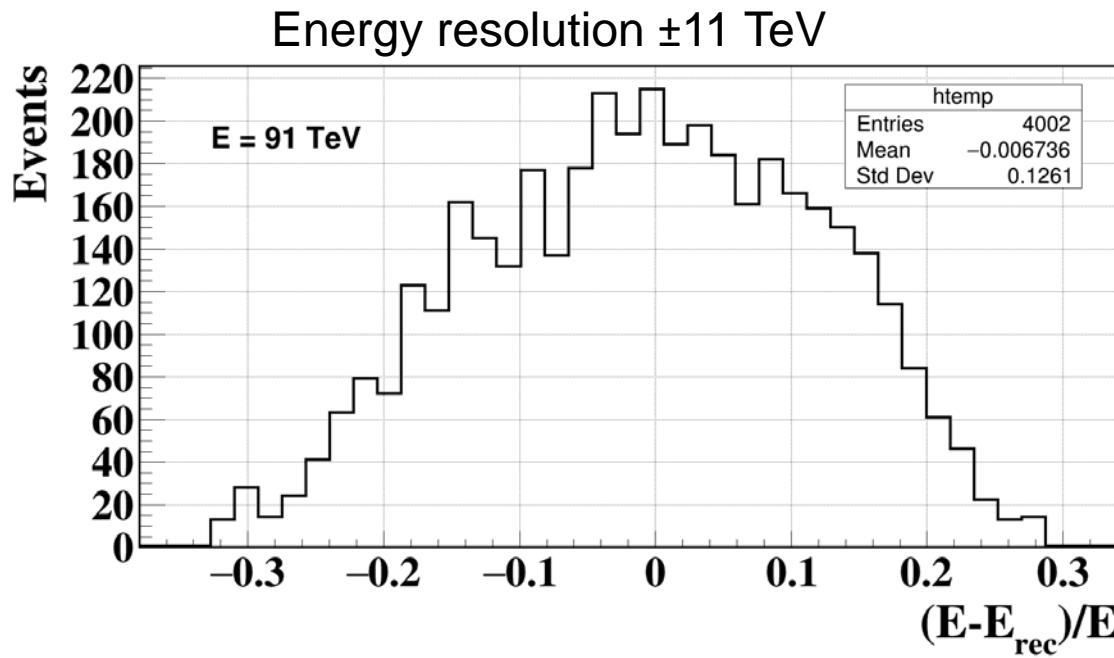
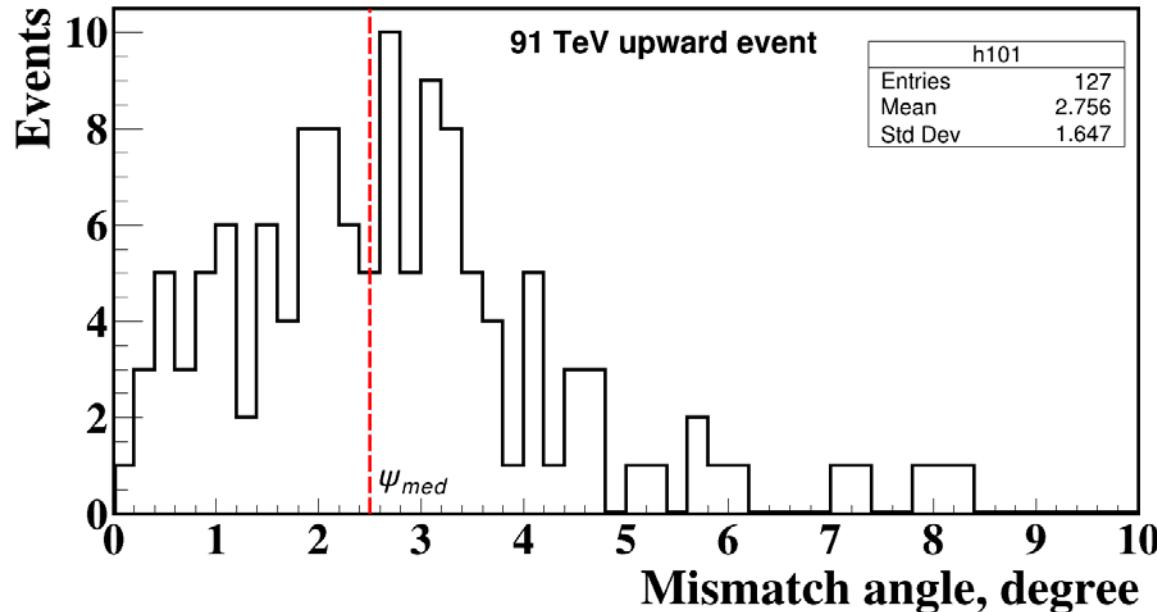
Reconstructed energy $E = (91 \pm 11)$ TeV

Zenith angle $\theta_z = 109^\circ$

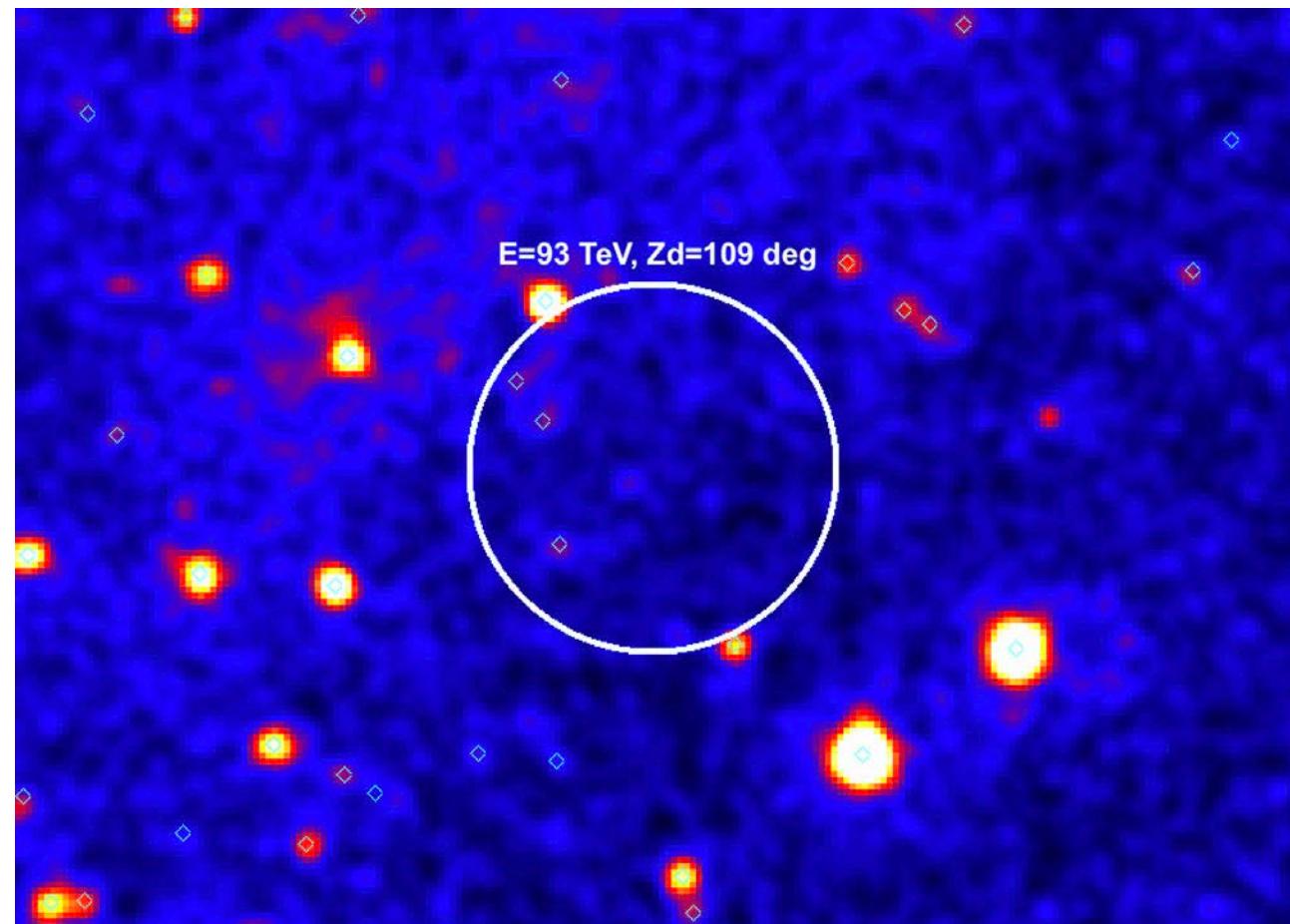


Angular resolution - $\psi_{med} = 2.5^\circ$

Preliminary



Sky map, 2° circle around event direction



Baikal GVD: Multi-Messenger Studies with cascades

Follow up IC and ANTARES alerts:

see Posters

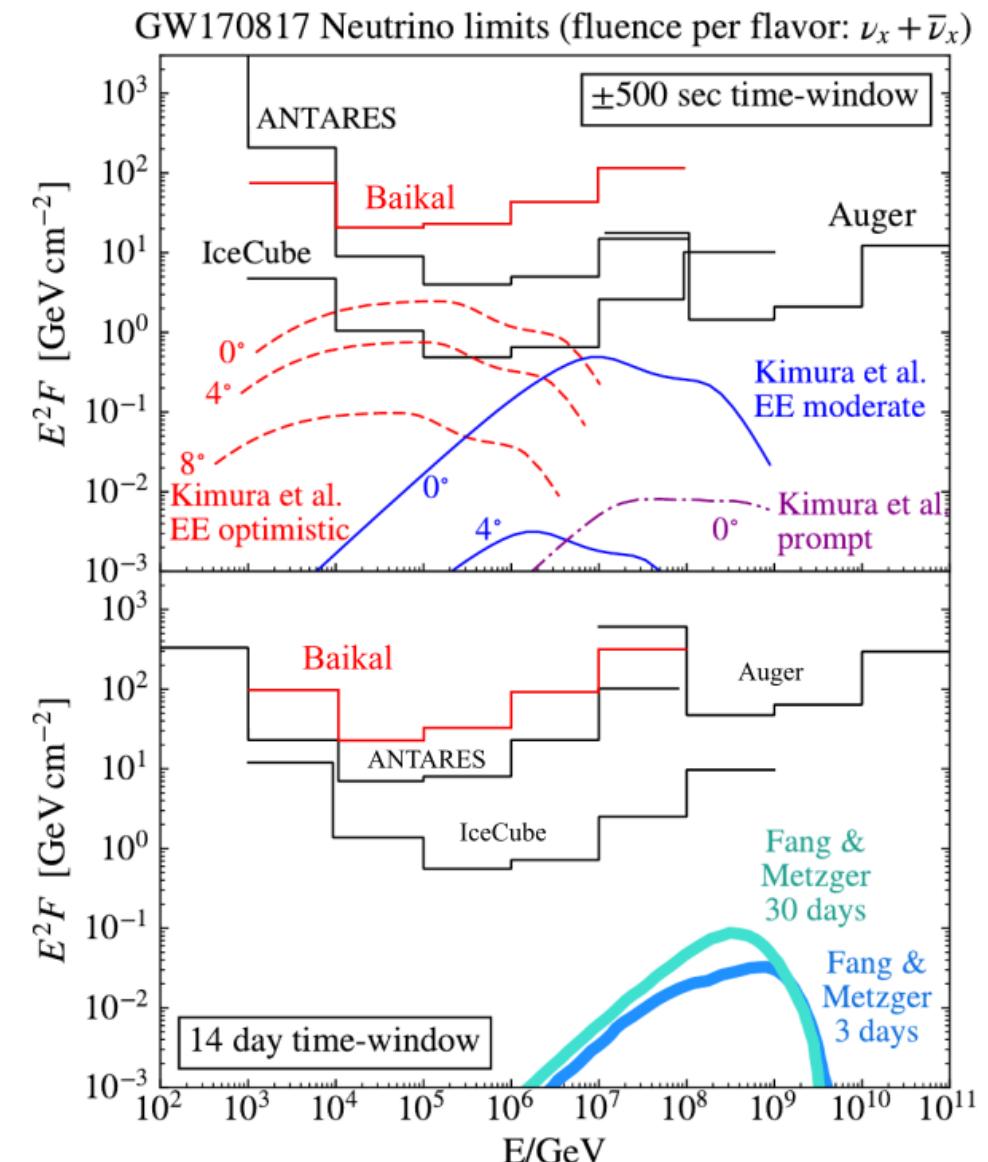
ID=101 - әтө V.Dik et all for Baikal-GVD

ID= 62 - Sergio Alves et al .../ ANTARES+GVD

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.

arXiv:1810.10966





Thank you!