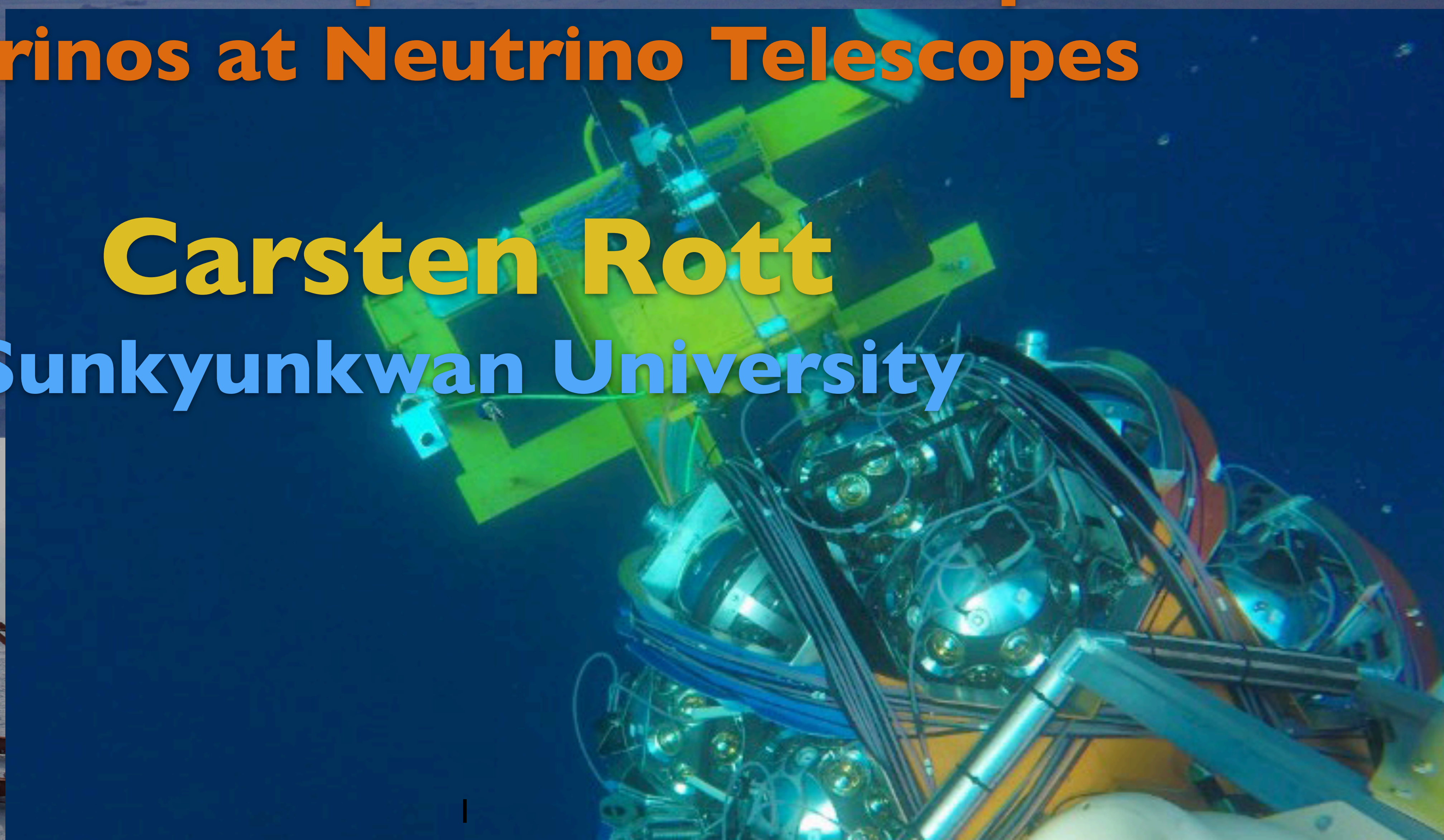
Results and Prospects for Atmospheric Neutrinos at Neutrino Telescopes

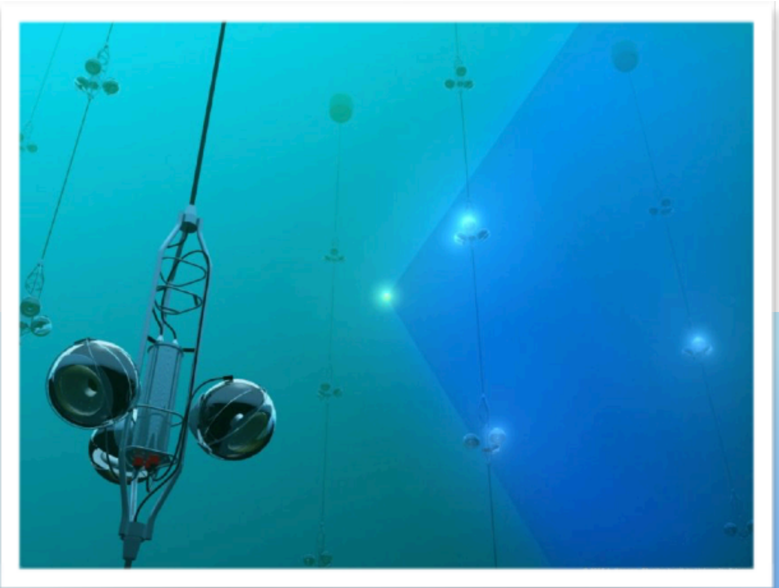


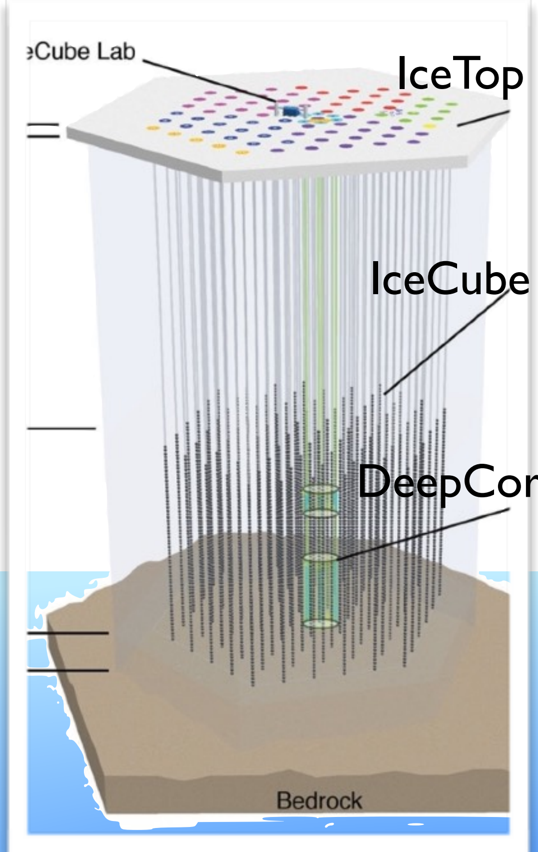
Carsten Rott

Sunkyunkwan University

Overview

- Neutrino Telescope Landscape
- A revolution in the making
- Review of selected (atmospheric) results
- Astrophysical Neutrinos / Multi-messenger Science
- Next generation detectors
- Summary and Outlook





Neutrino Telescope Landscape

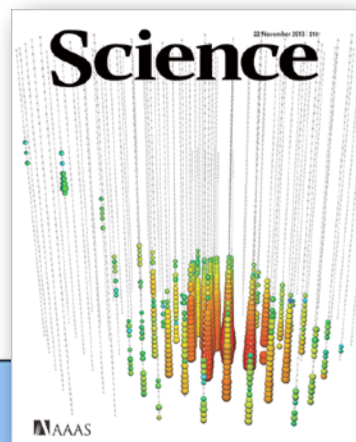
New Window to the Universe !

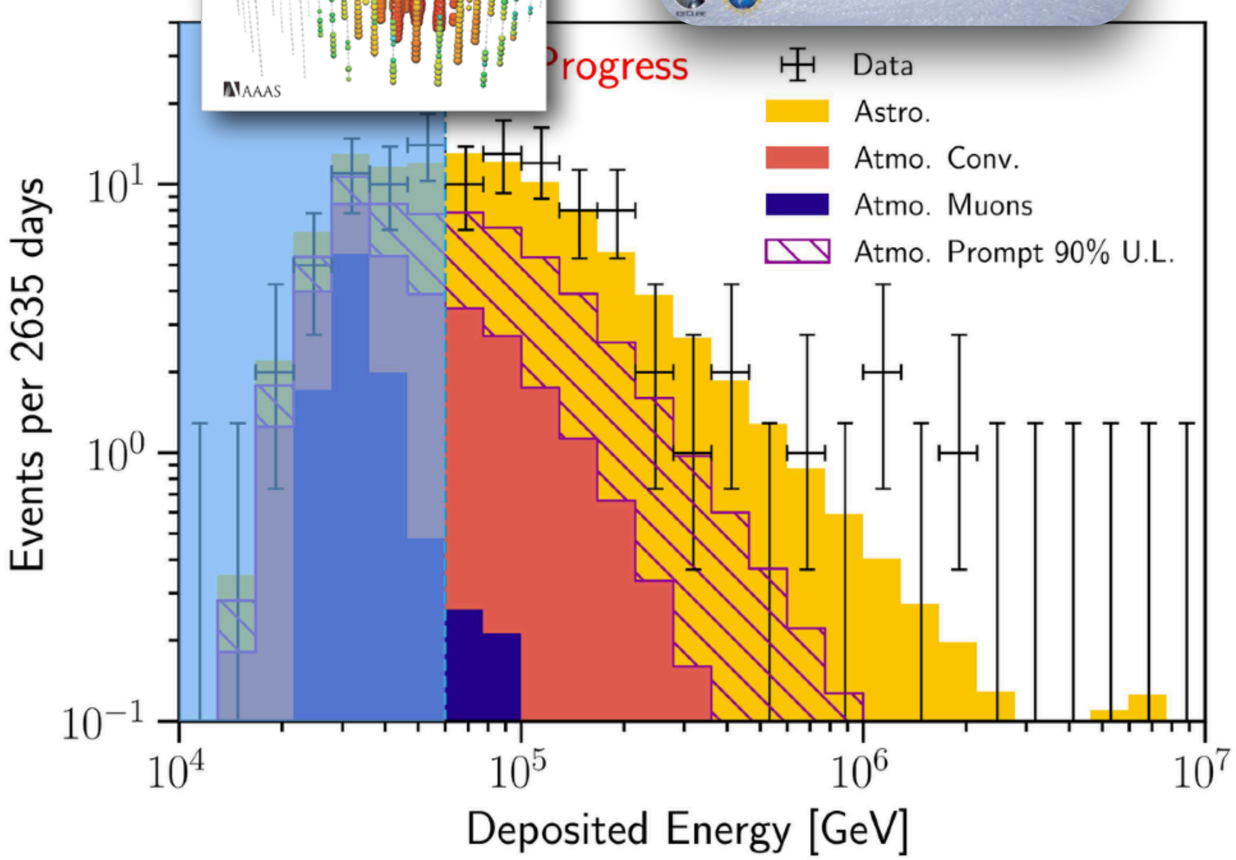
2002

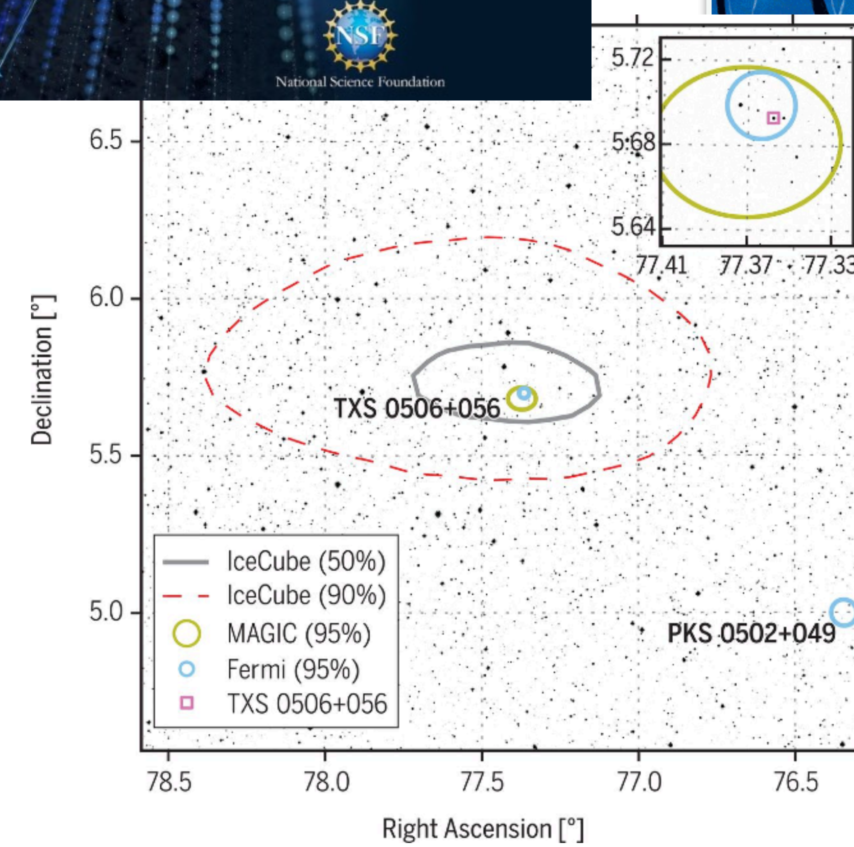
Following the observation of supernova burst neutrinos in 1987*, neutrino astronomy is becoming a reality quickly now …*

2013 Discovery of diffuse astrophysical neutrino flux

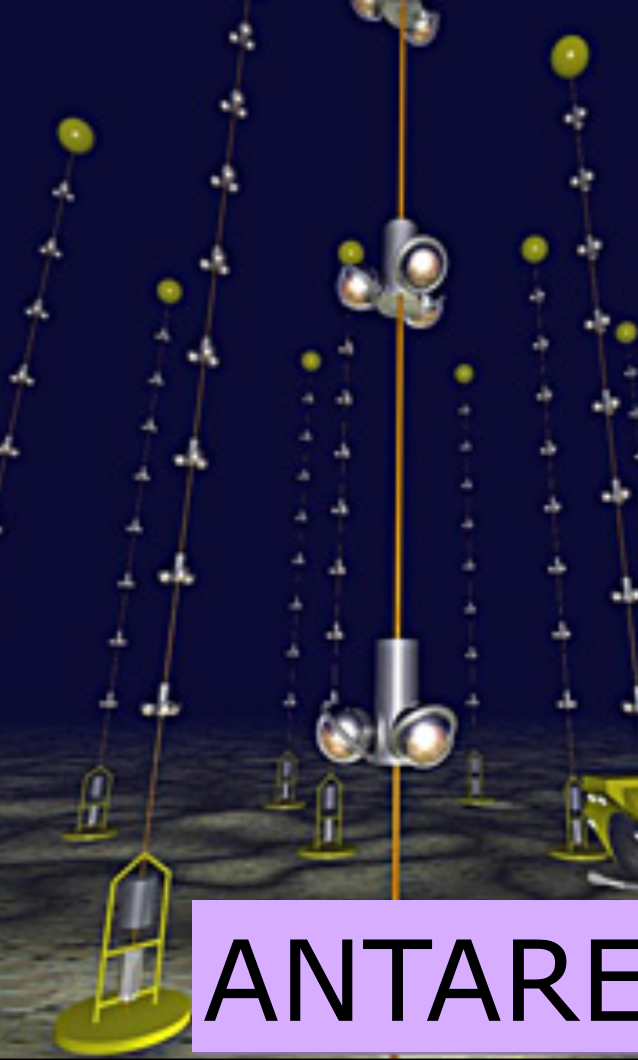
2018 Neutrino multi-messenger astronomy







Neutrino Telescopes



ANTARES

KM3NeT
ORCA

Lake Baikal

GVD

IceCube

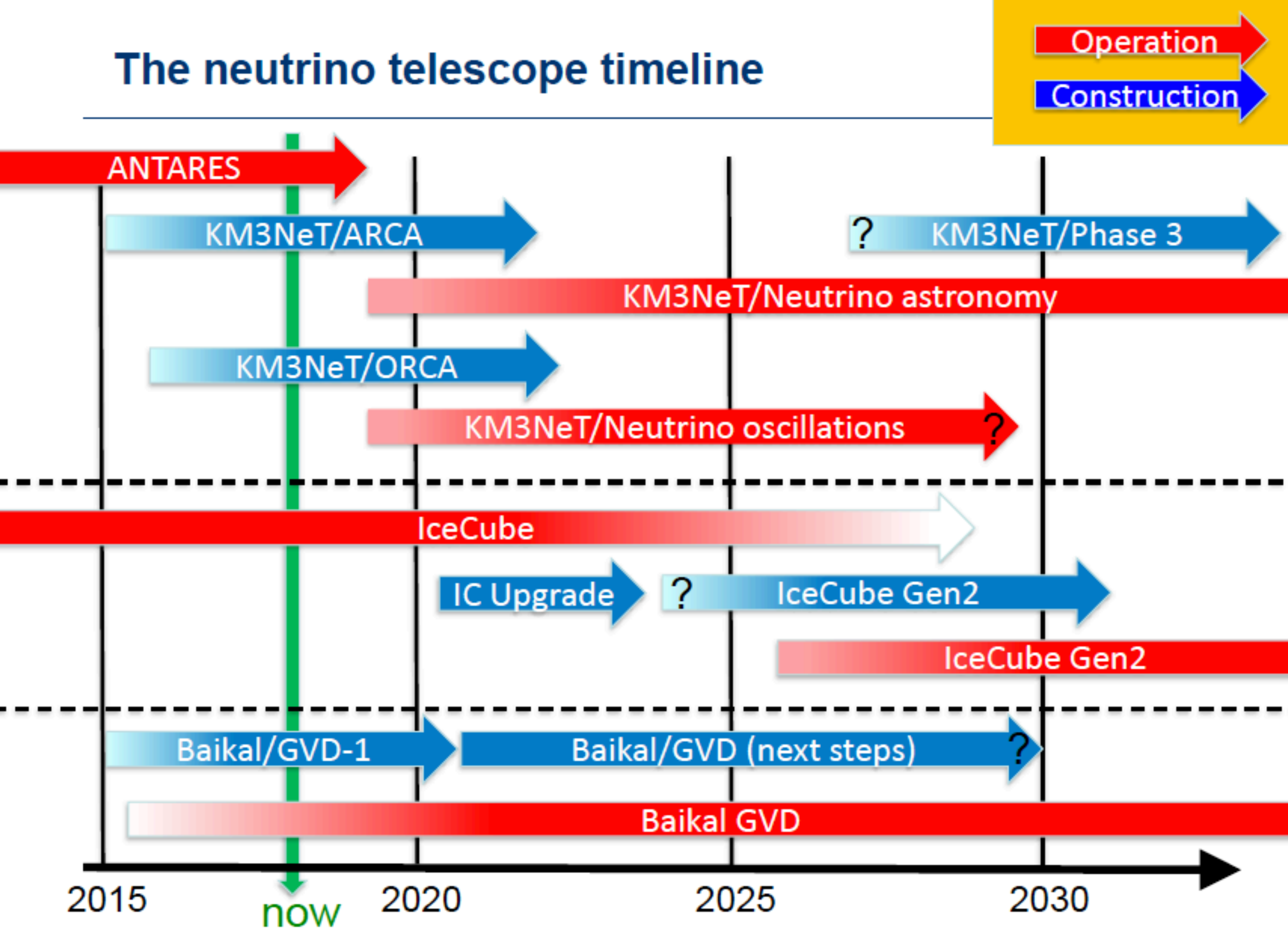
Upgrade/Gen2/PINGU

Active

Construction

Planned

The neutrino telescope timeline

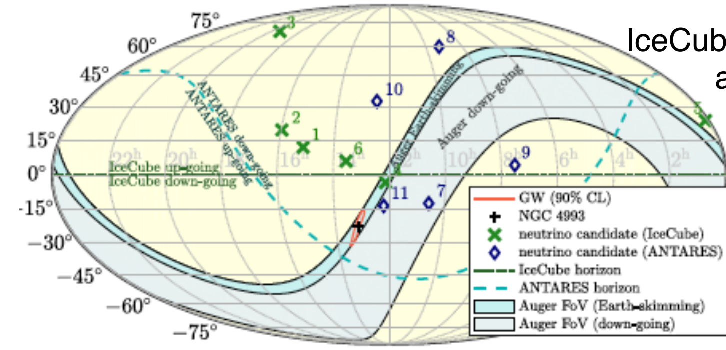


Very Broad Scientific Scope

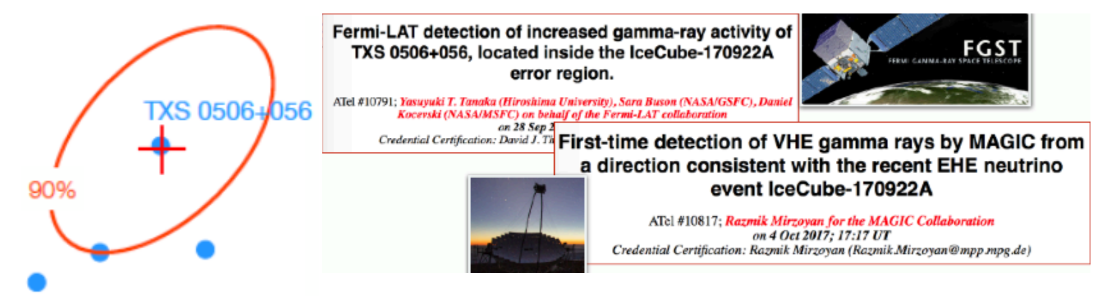
- ASTROPHYSICS
  - point sources of ν's (SNR, AGN …), extended sources
  - transients (GRBs, AGN flares …)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- COSMIC RAY PHYSICS
  - energy spectrum around "knee", composition, anisotropy
- DARK MATTER
  - Dark matter self-annihilation, decay, scattering, …
- BSM PHYSICS
  - magnetic monopoles
  - violation of Lorentz invariance
- PARTICLE PHYSICS
  - ν oscillations, sterile ν's
  - charm in CR interactions
- SUPERNOVAE (galactic/LMC)
- GLACIOLOGY & MARINE SCIENCE & EARTH SCIENCE

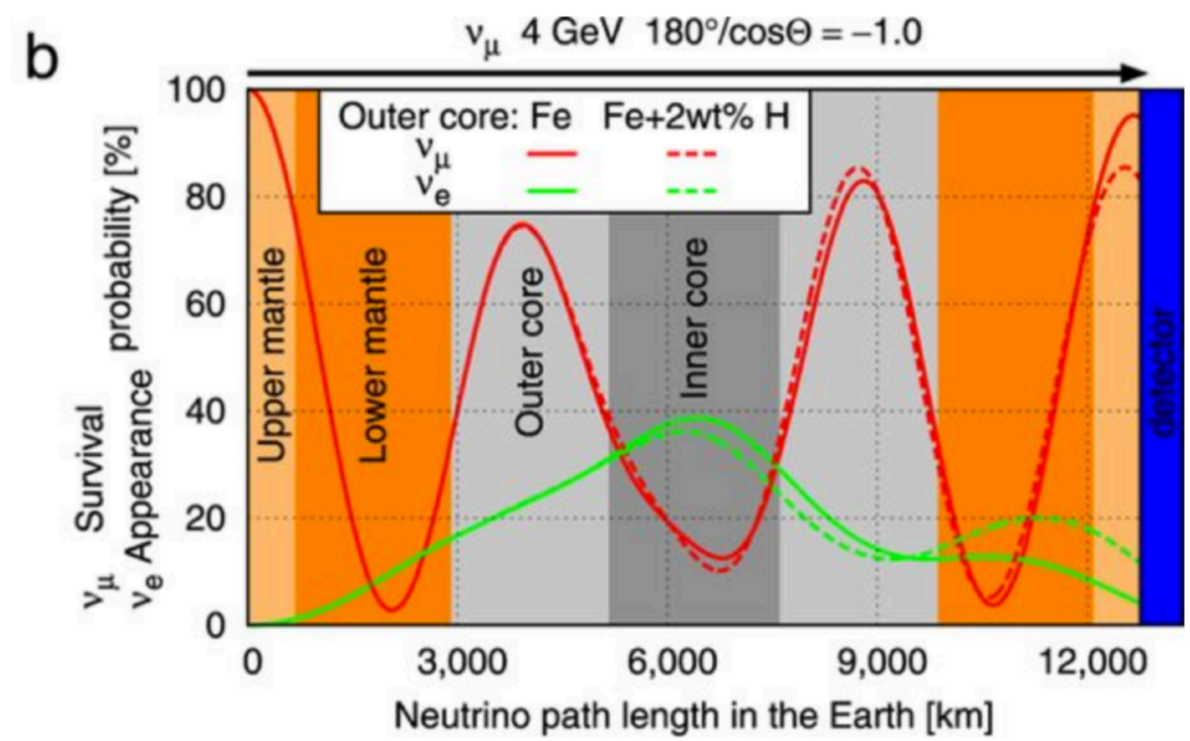
Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

Multi-messenger Observations



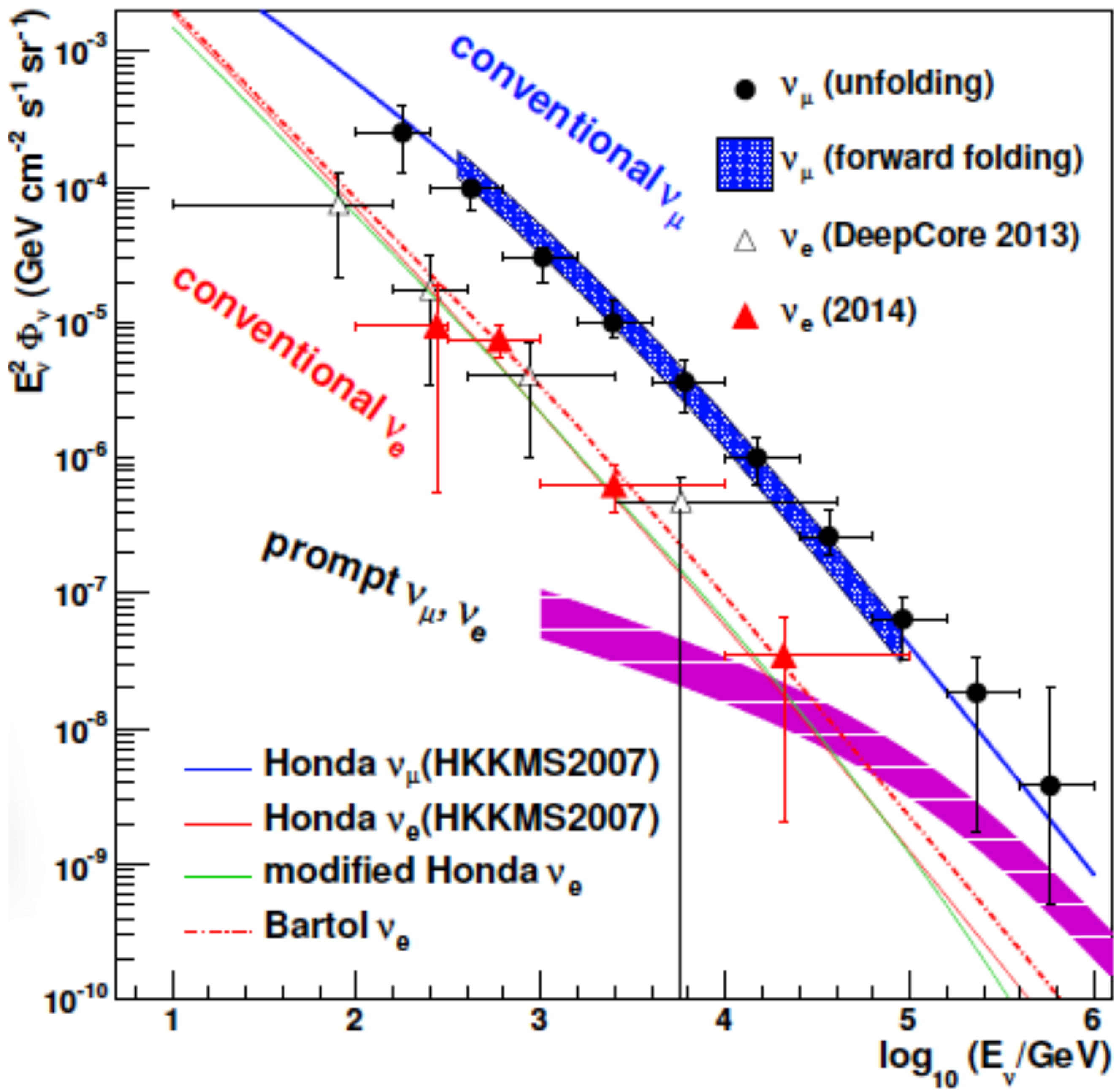
IceCube/ANTARES/Auger/LIGO
arXiv:1710.05839



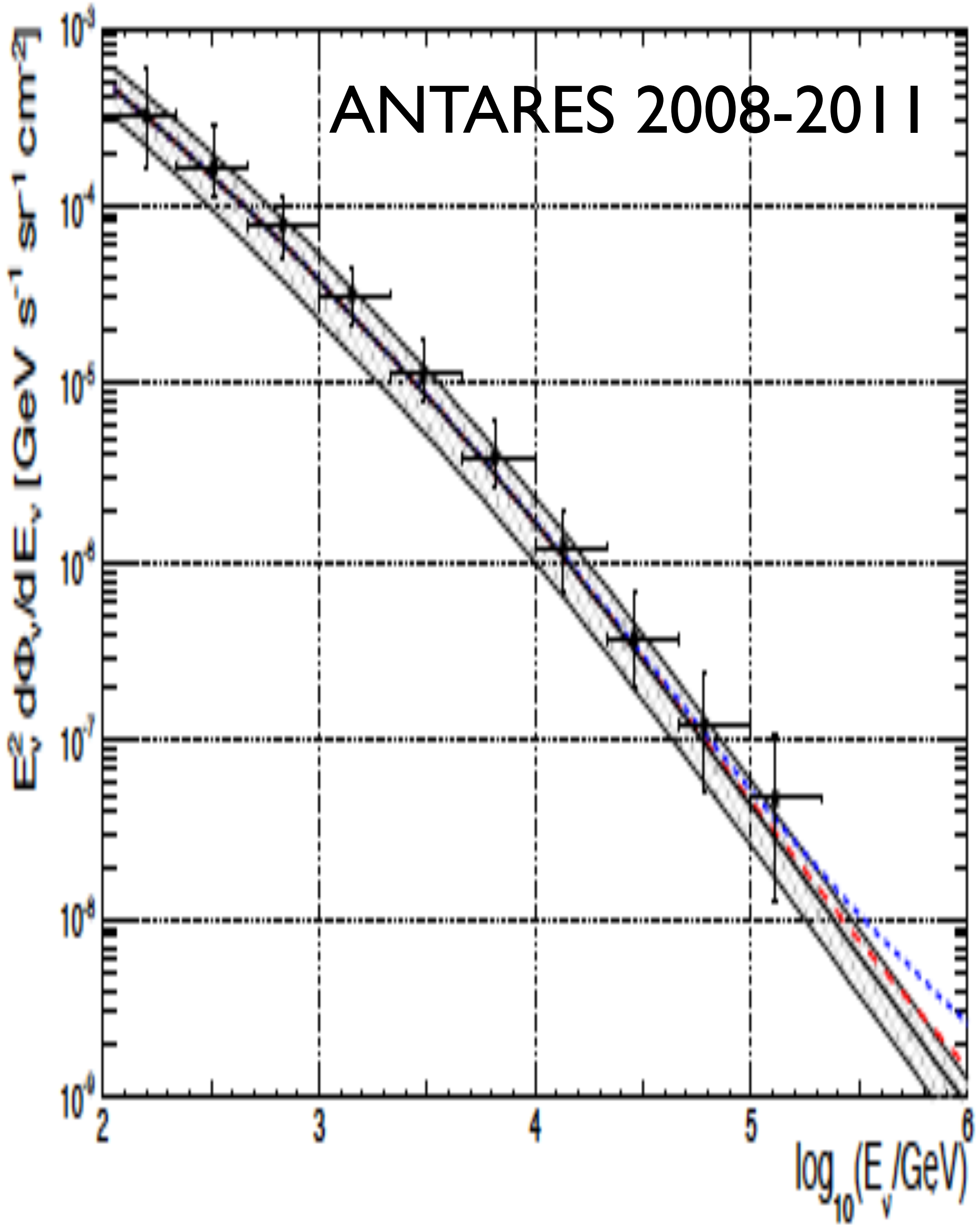


Atmospheric Neutrino Spectra

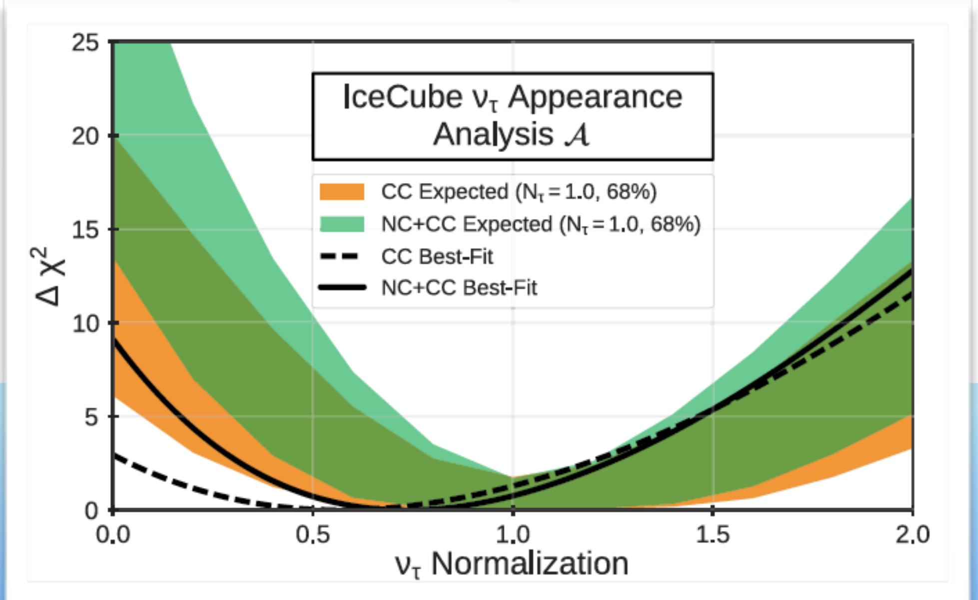
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



ANTARES Eur.Phys.J. C73 (2013) no.10, 2606, Eur.Phys.J. C73 (2013) 2606



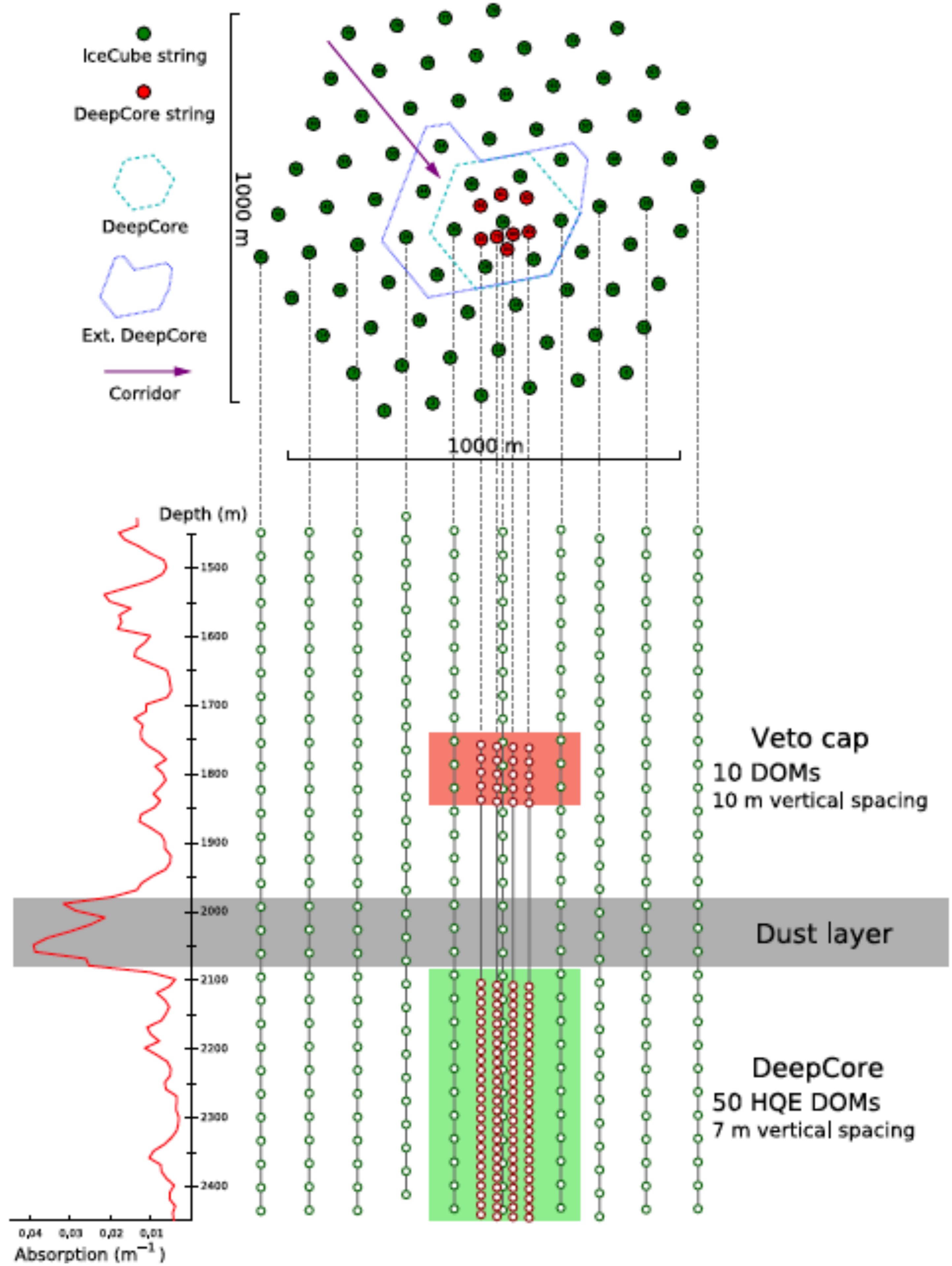
- Very high statistics atmospheric neutrino samples
  - ~100,000 atmospheric neutrinos per year



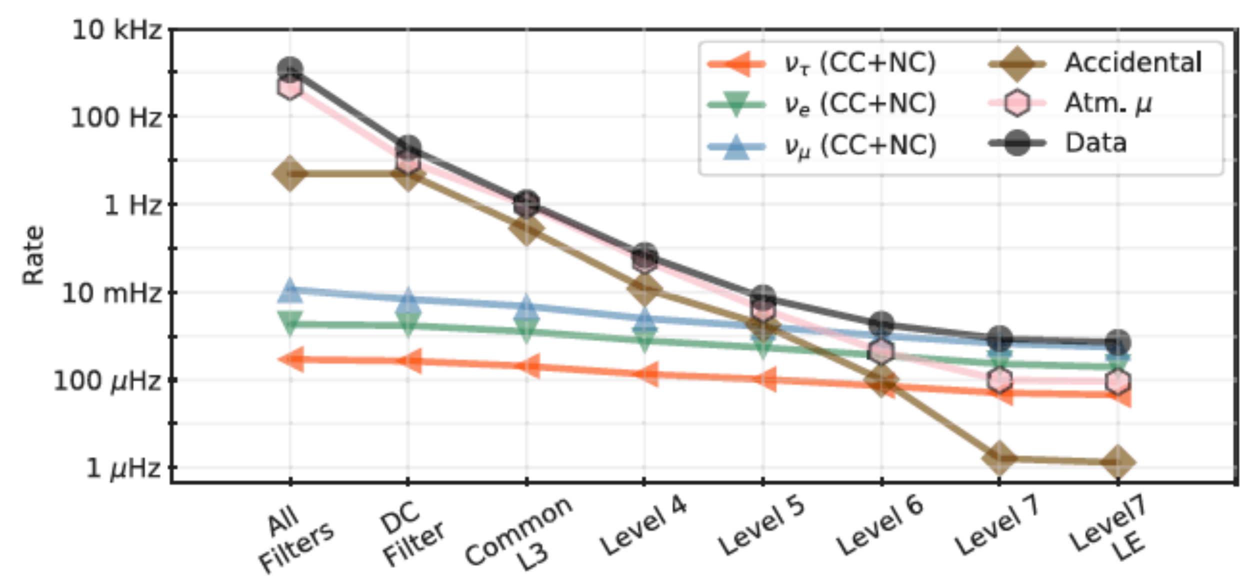
Tau Neutrino Appearance

IceCube Collaboration - Phys.Rev. D99 (2019) no.3, 032007

Detector and Data



- Dataset: April 2012 - May 2015
- Two independent analyses
  - Analysis $\mathcal{A}$: Optimize for high efficiency to select neutrino events in DeepCore (1006days)
  - Analysis $\mathcal{B}$: Designed to effectively reject atm. muon backgrounds (1022days)



IceCube PHYS. REV. D 99, 032007 (2019)

Low-energy neutrinos in IceCube

Expected charge $q_i(t)$ at i^{th} DOM

noise

$$q_i(t) = \Lambda_i^{\mathrm{cscd}}(t) \cdot E_{\mathrm{cscd}}/\mathrm{GeV} + \sum_{\mathrm{segments} \in L_\mu} \Lambda_i^{trck}(t) + n_i$$

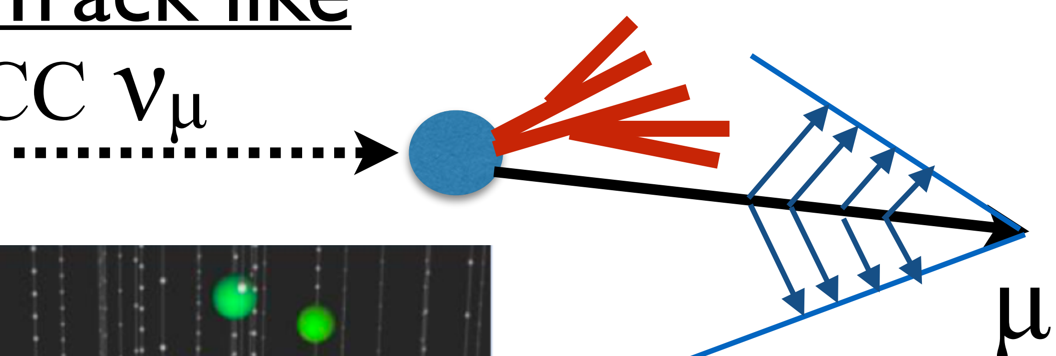
charge expectation
for a 1GeV cascade

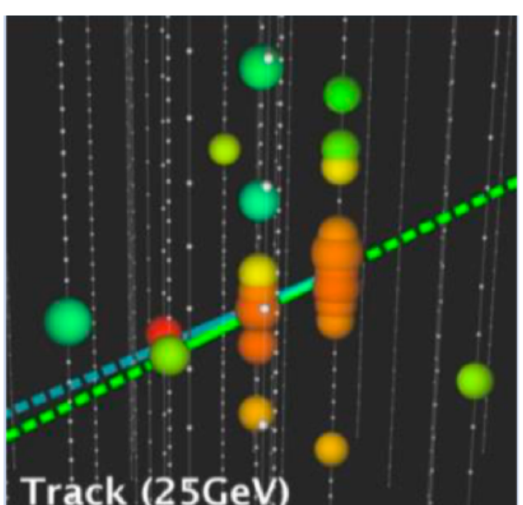
expected charge for
one track segment
of the MIP muon

- Λ^{cscd} and Λ^{trck} obtained from photon propagation look-up tables
- Find best-fit hypothesis using MultiNest

Track like

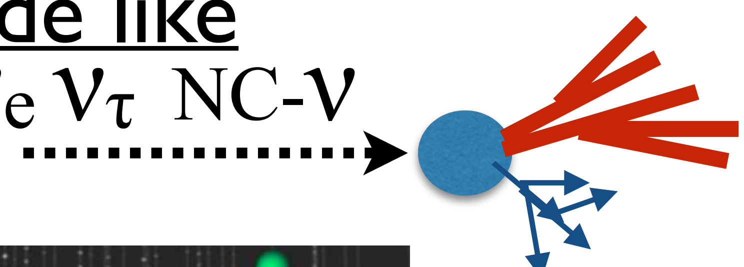
CC ν_μ

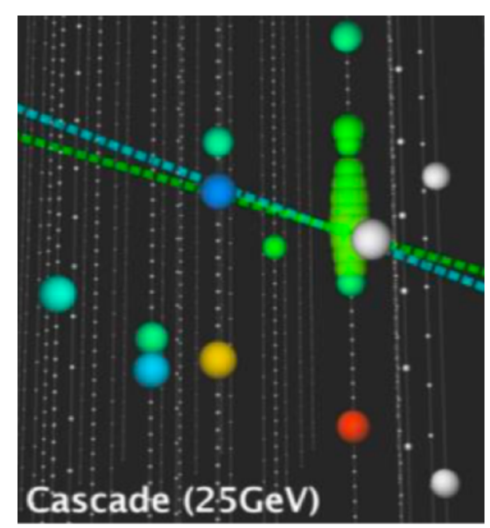




Cascade like

CCν_e ν_τ NC-ν





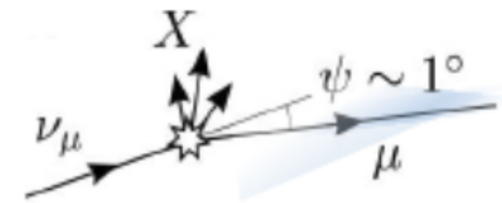
ν_τ appearance analysis IceCube

- Event identification

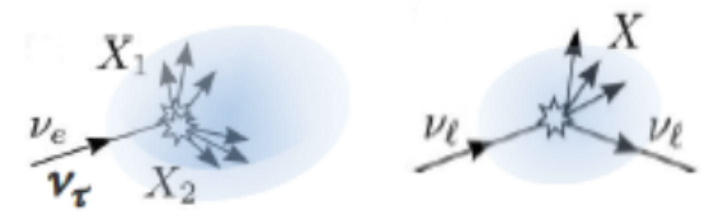
$$\boxed{\Delta\mathrm{LLH}_{reco} = \ln\mathscr{L}_{cascade+track} - \ln\mathscr{L}_{cascade}}$$

Classification	
tracklike	$\Delta\mathrm{LLH}_{reco} > 2$
cascadelike	$-3 < \Delta\mathrm{LLH}_{reco} < 2$

Track - muon neutrino



Cascade - electron/tau neutrino or NC interaction



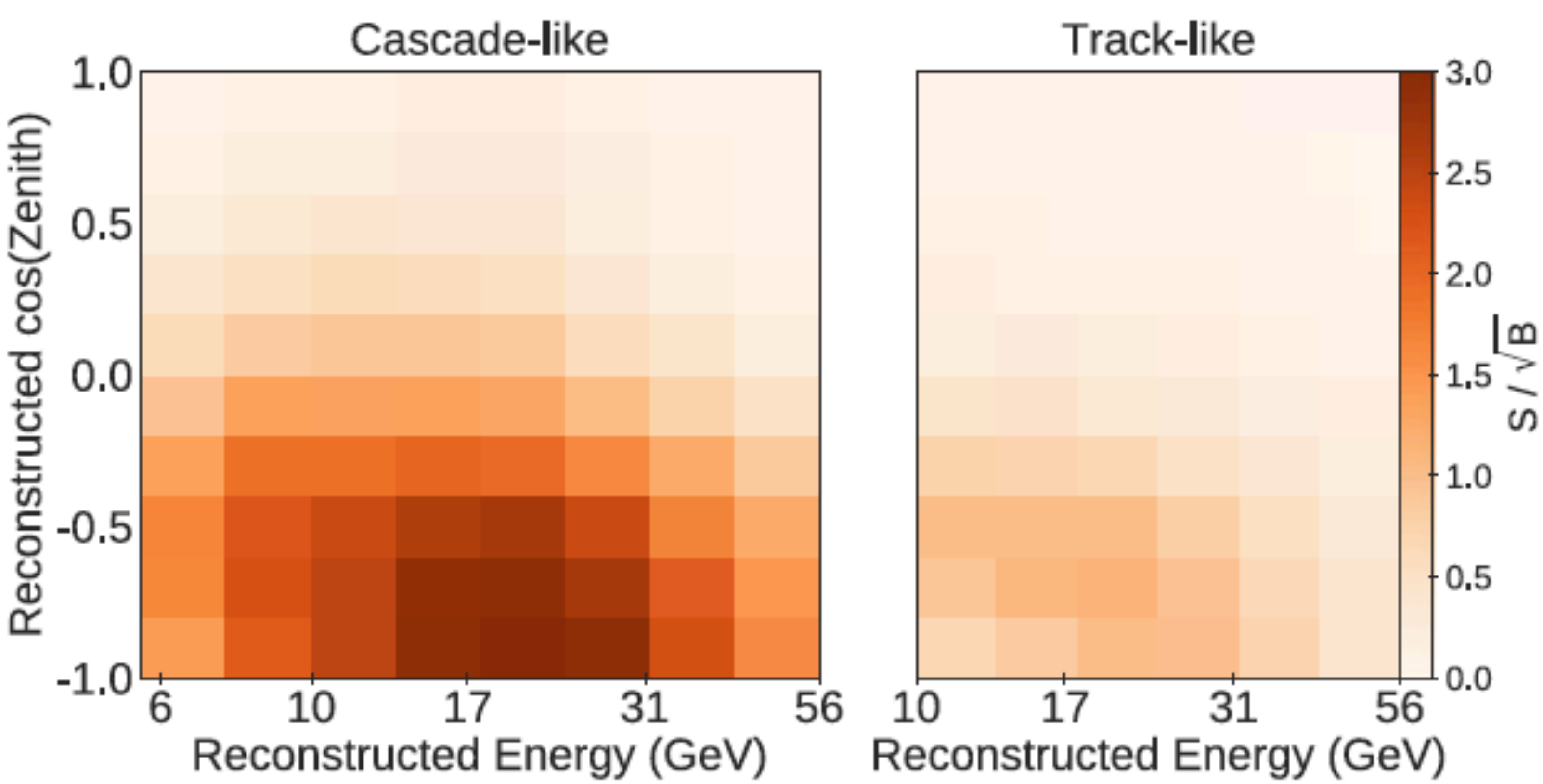
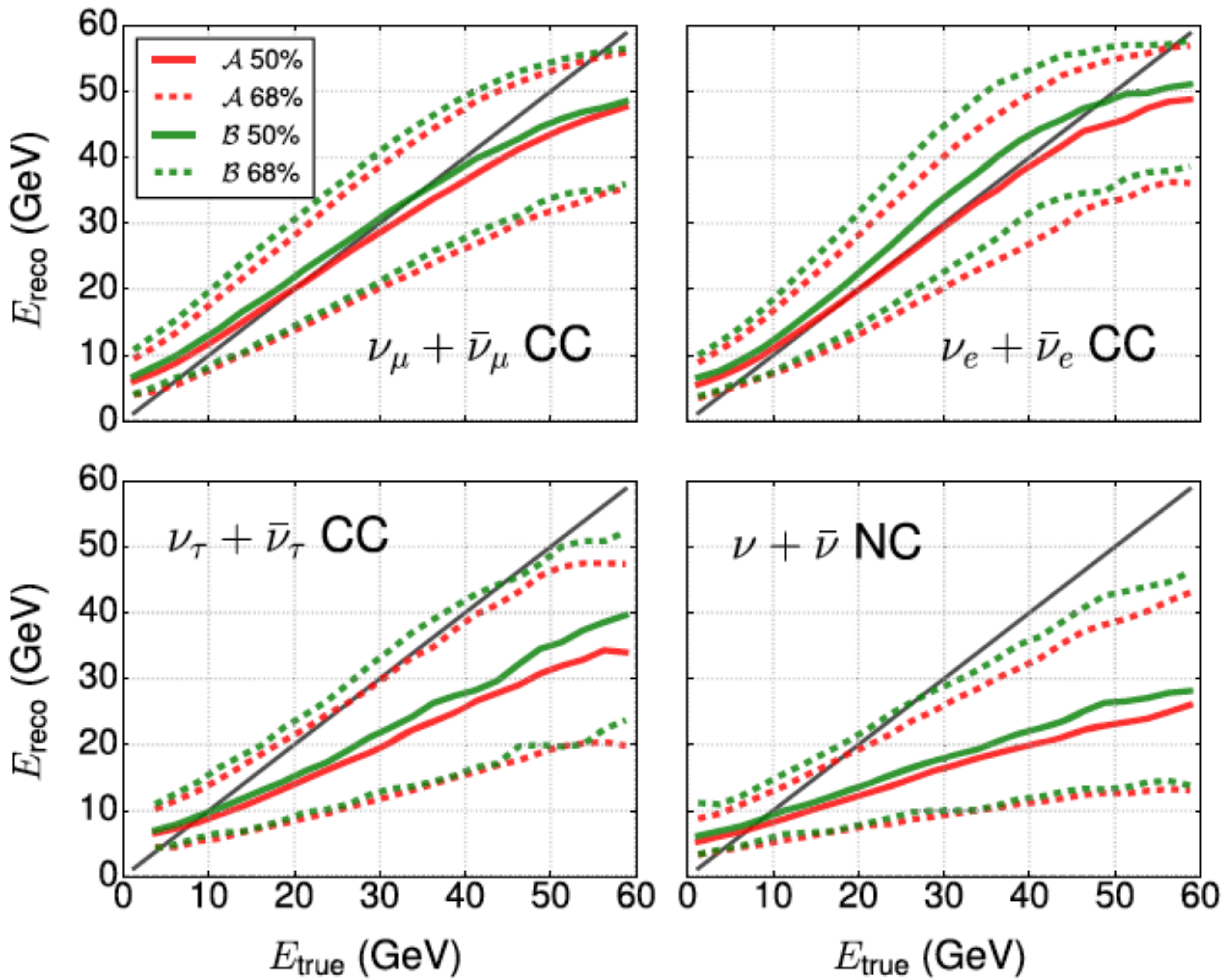
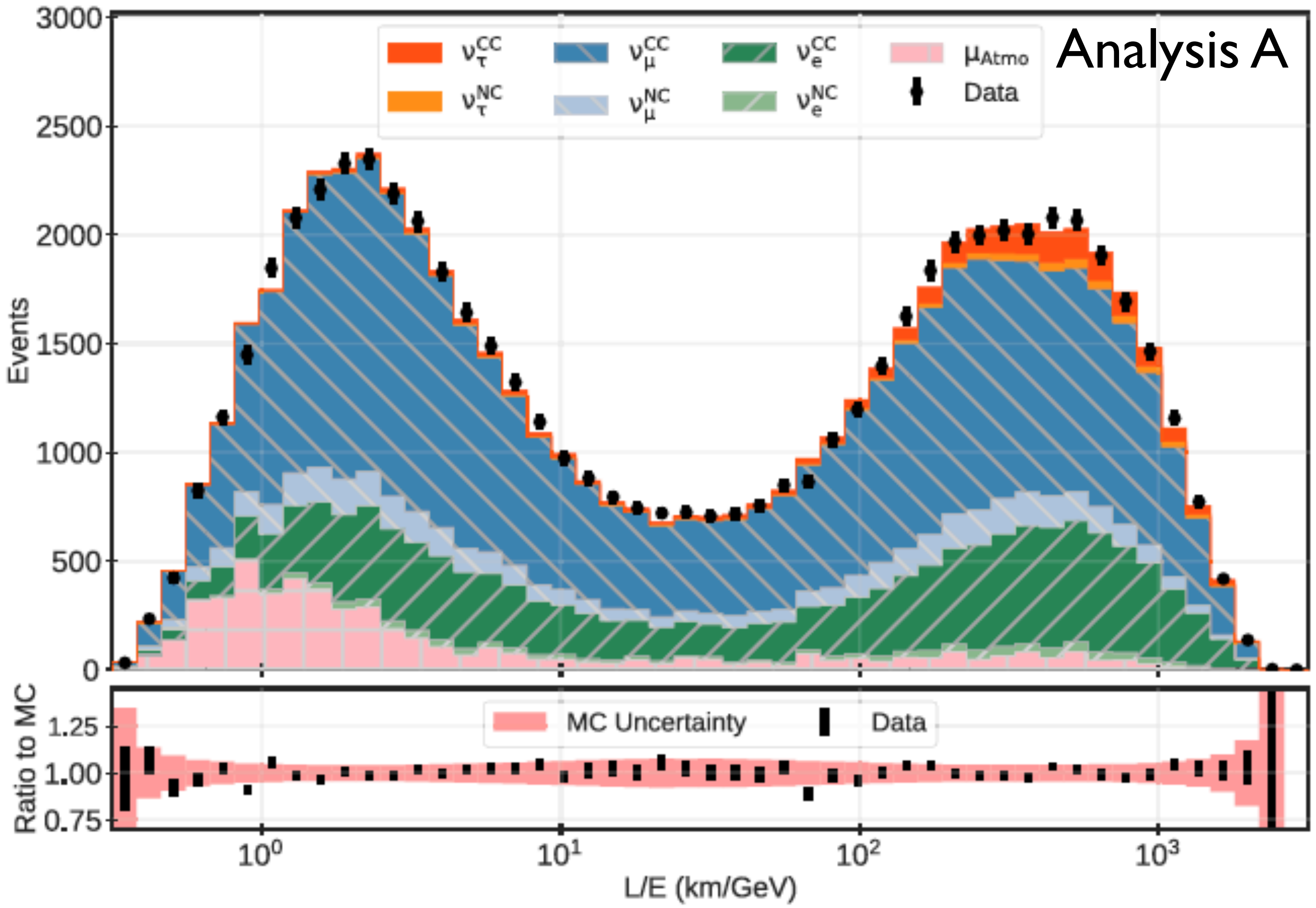


FIG. 8. Expected signal ν_τ (CC + NC) divided by the square-root of the expected background (ν_e, ν_μ, atmospheric μ, and noise-triggered) events as a function of reconstructed cosine of the zenith angle and reconstructed energy. Cascadelike events are shown on the left and tracklike events on the right. The plots include both neutrinos and anti-neutrinos.

Neutrino Energy Reconstruction



ν_τ appearance analysis IceCube

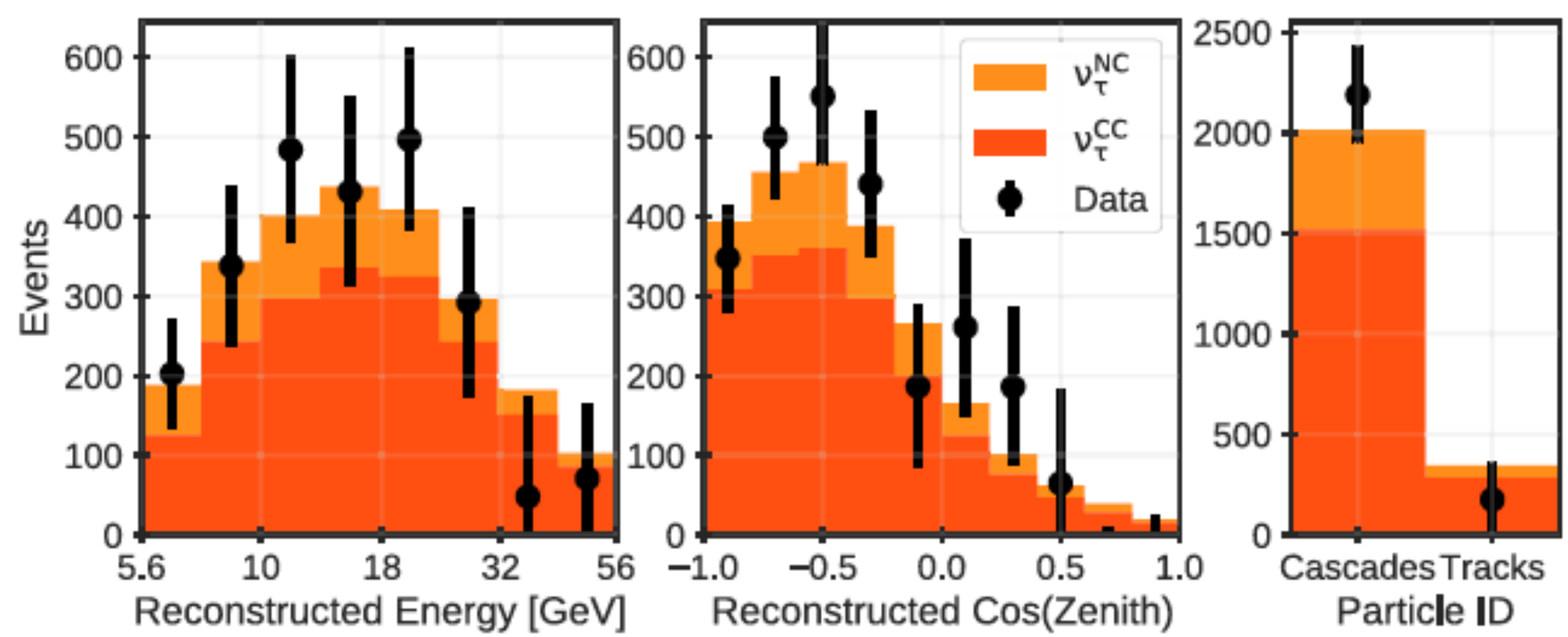


- **Binned analysis** (Energy, reconstructed angle, PID (ΔLLH_{reco}))
- **χ^2 - minimization** as function of ν_τ normalization and nuisance parameters associated with the relevant systematic uncertainties

$$\chi^2 = \sum_{i\in\{\mathrm{bins}\}} \frac{(N_i^{\mathrm{exp}} - N_i^{\mathrm{obs}})^2}{N_i^{\mathrm{exp}} + (\sigma_i^{\mathrm{exp}})^2} + \sum_{j\in\{\mathrm{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\sigma_{s_j}^2}$$

Subtract the best-fit non-ν_τ background

Best fit tau events:
- CC 1804 events
- NC 556 events

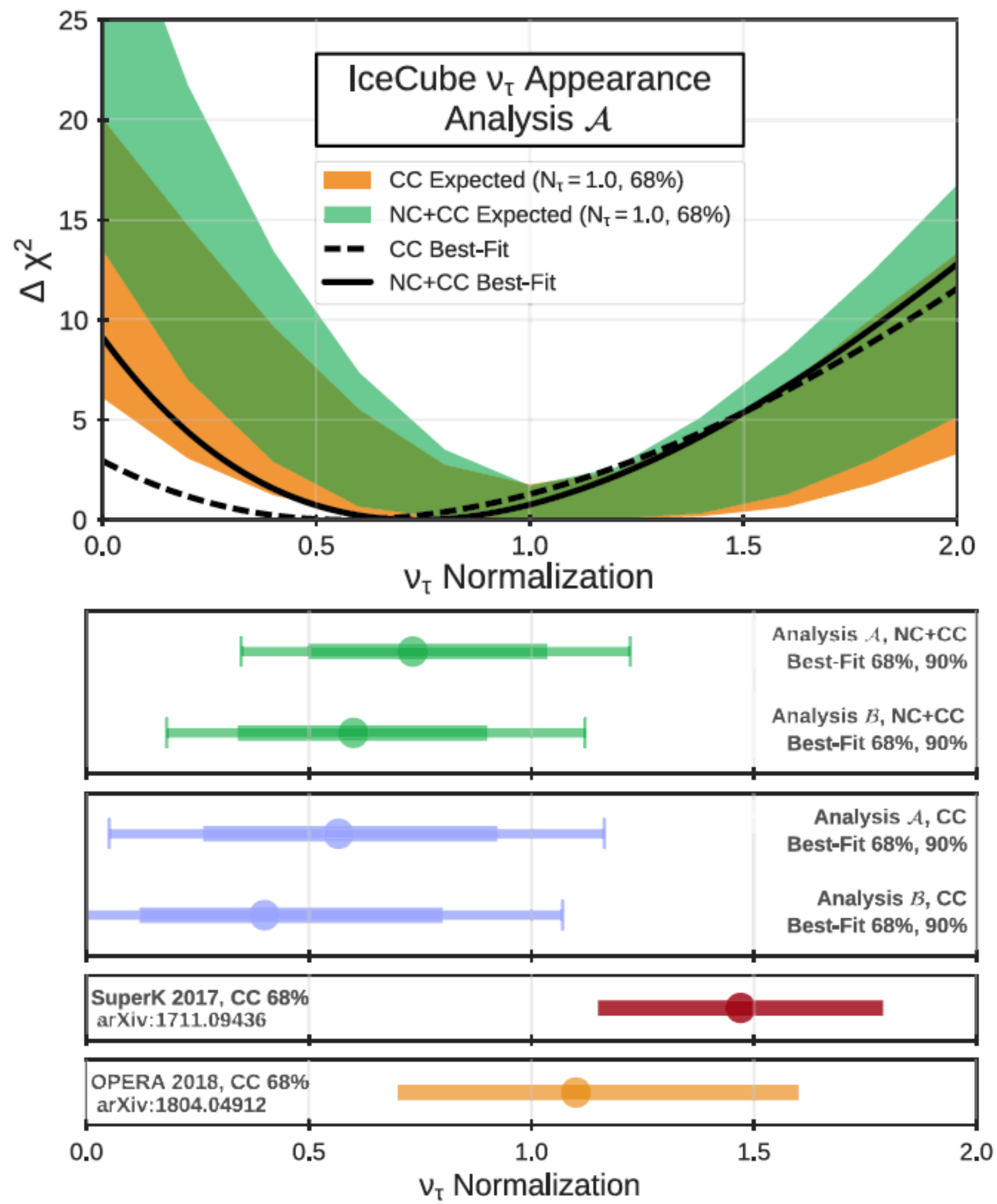


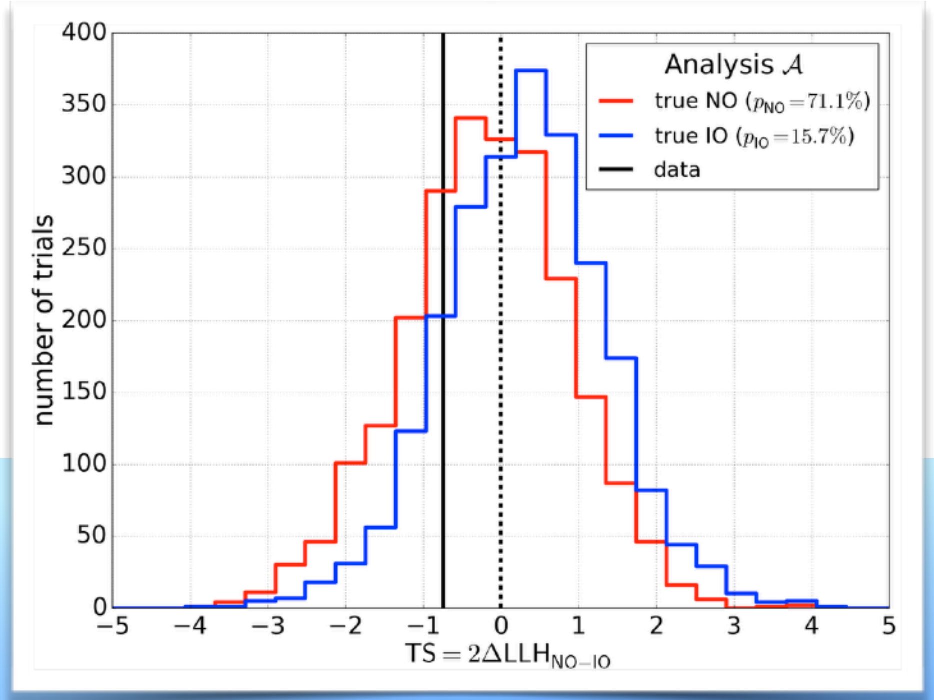
ν_τ appearance analysis IceCube

τ sector is the least well-constrained

Most important test of the unitarity of the PMNS matrix

ν_τ appearance rate consistent with standard neutrino oscillations





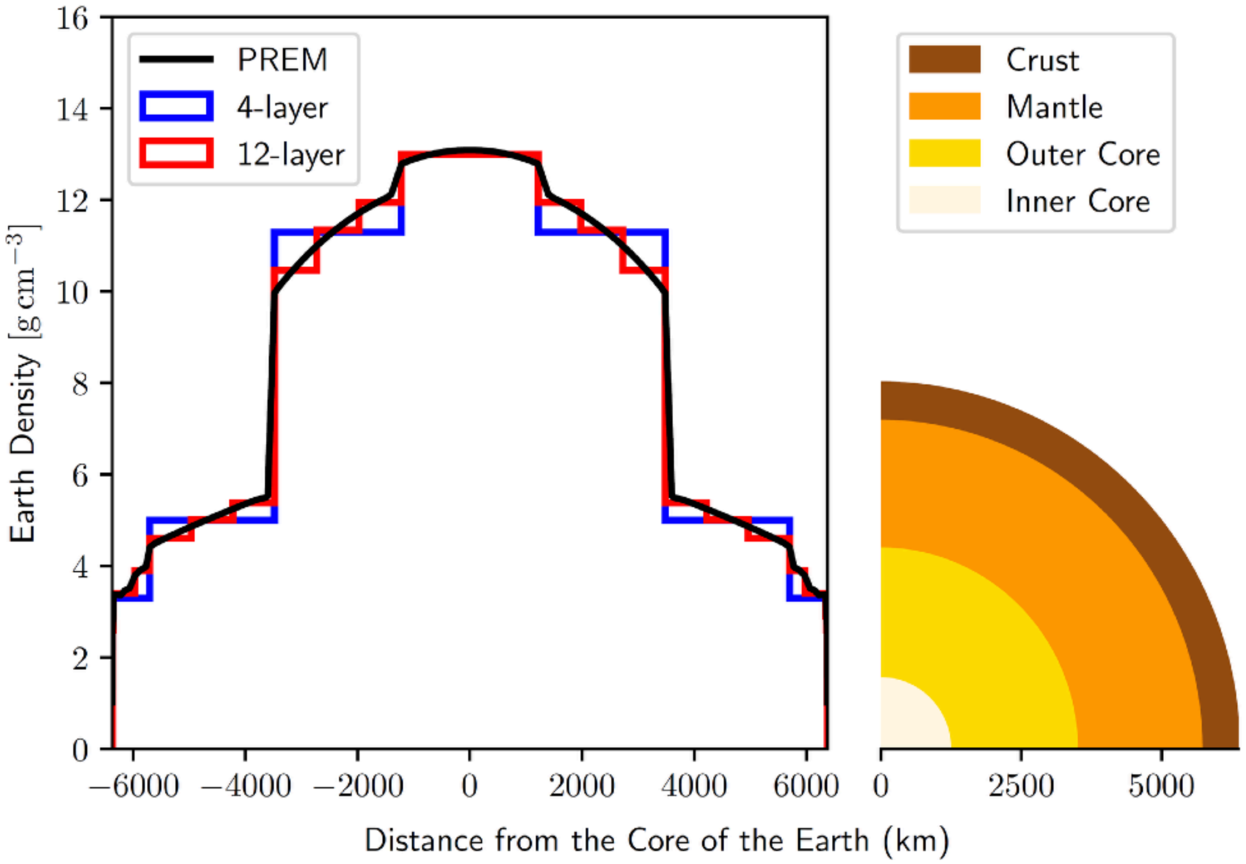
IceCube Neutrino Mass Ordering

IceCube Collaboration arXiv:1902.07771

Neutrino Mass Ordering

- **Basic idea:**
  - Neutrino Oscillation effects enhanced for NO. For the case of IO oscillation effects of anti-neutrinos enhanced
  - Neutrino / anti-neutrino cross-sections differ ! Atm. neutrino fluxes differ between neutrinos and anti-neutrinos

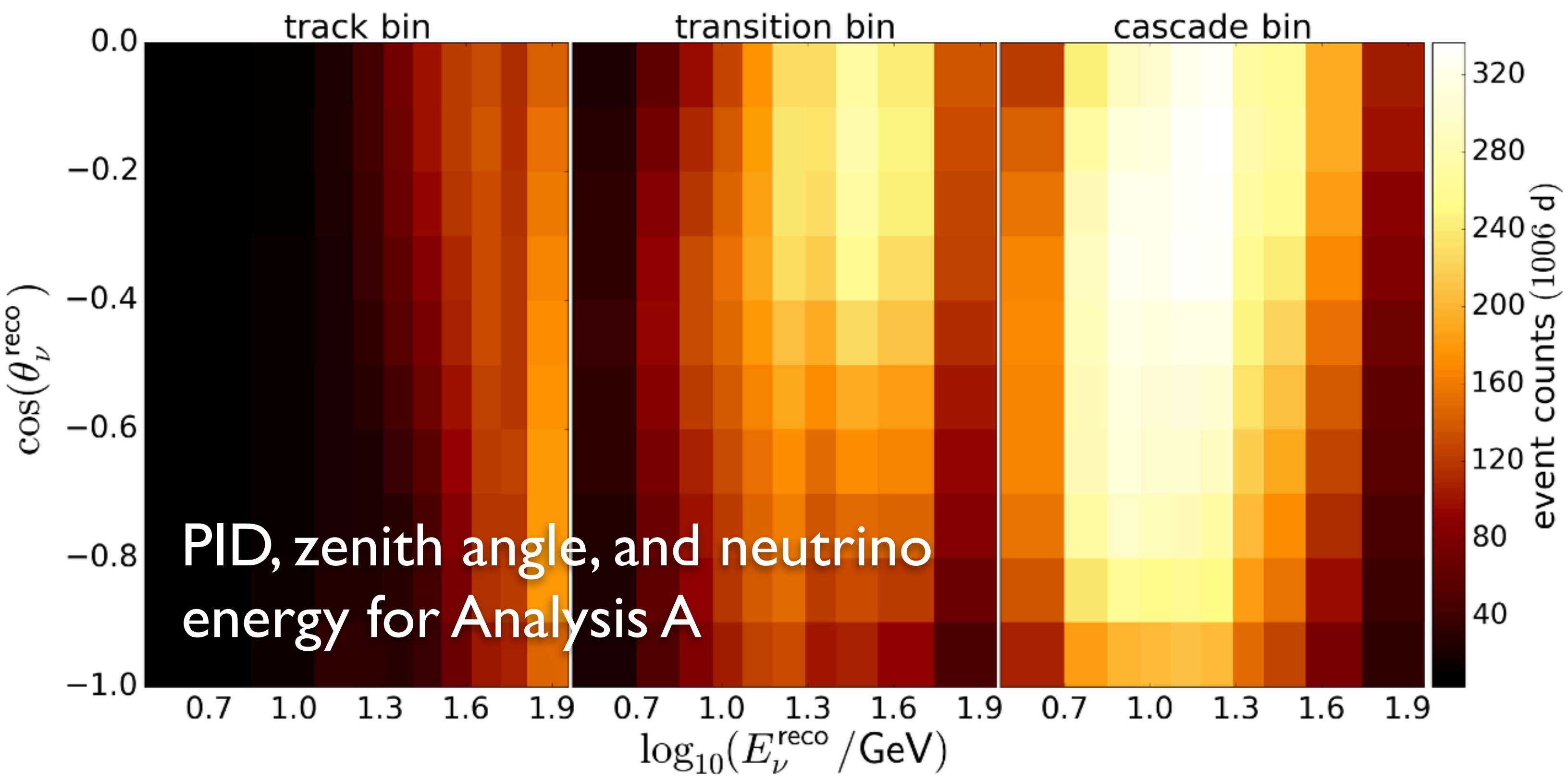
- Three years of data collected with IceCube - DeepCore (May 2012 and April 2014)
- Two independent likelihood analyses
  - Analysis $\mathcal{A}$: Optimize the sensitivity to the NMO with DeepCore
  - Analysis $\mathcal{B}$: Designed to resemble the proposed PINGU analysis

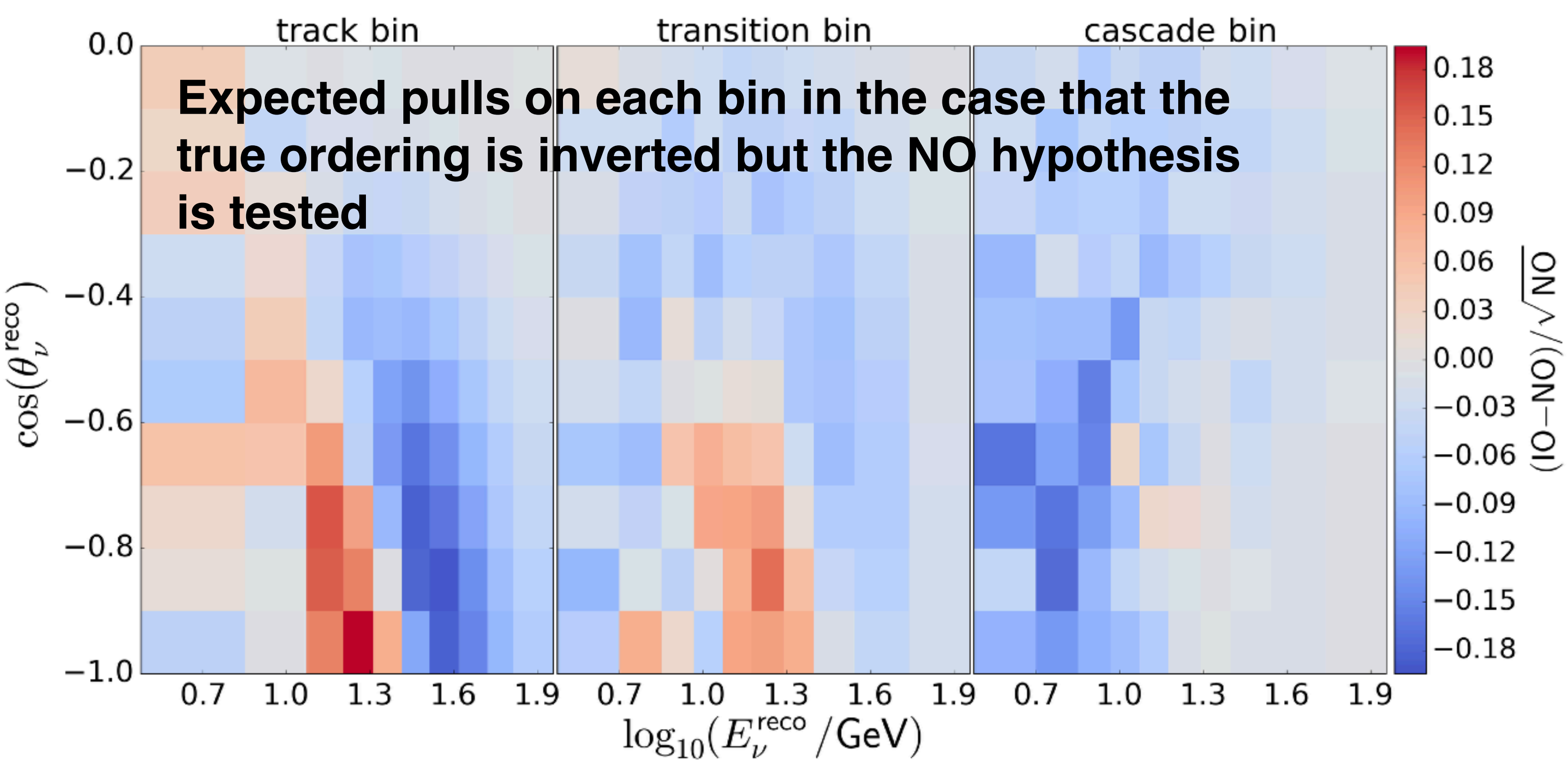


	Data Events	Selection Strategy	Recon. Likelihood	Energy Range	Analysis Binning	Background Description	Template Generation	Estimated Contributions [%] CCν_e/CCν_μ/CCν_τ/NC/μ/noise
$\mathcal{A}$	43 214	high statistics	hit-based	4 – 90 GeV	10, 10, 3	simulation	KDEs	21.7 / 58.4 / 6.2 / 8.8 / 4.8 / 0.1
$\mathcal{B}$	23 053	quality events	charge-based	5 – 80 GeV	10, 5, 2	data	histograms	29.4 / 58.0 / 2.0 / 10.4 / 0.2 / –

IceCube Collaboration arXiv:1902.07771

Analysis A





- Adaptive Kernel Density Estimation (KDE) used to the reduced impact of limited MC statistics
- MC used to generate templates in reconstructed neutrino energy, zenith angle, and Particle ID.
  - Uniform binning in

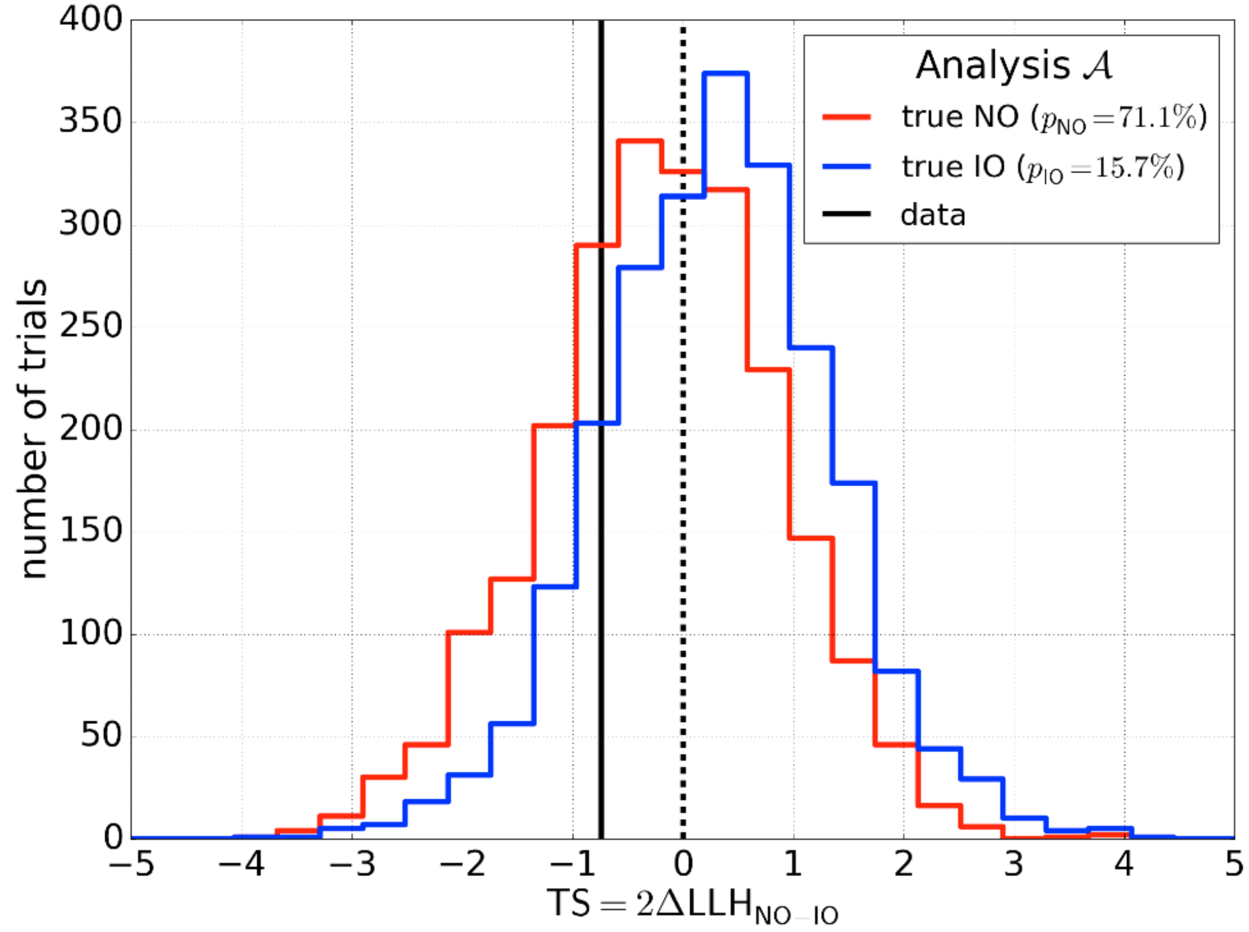
$$\log_{10}(E_\nu^{\rm reco}), \cos(\theta_\nu^{\rm reco})$$

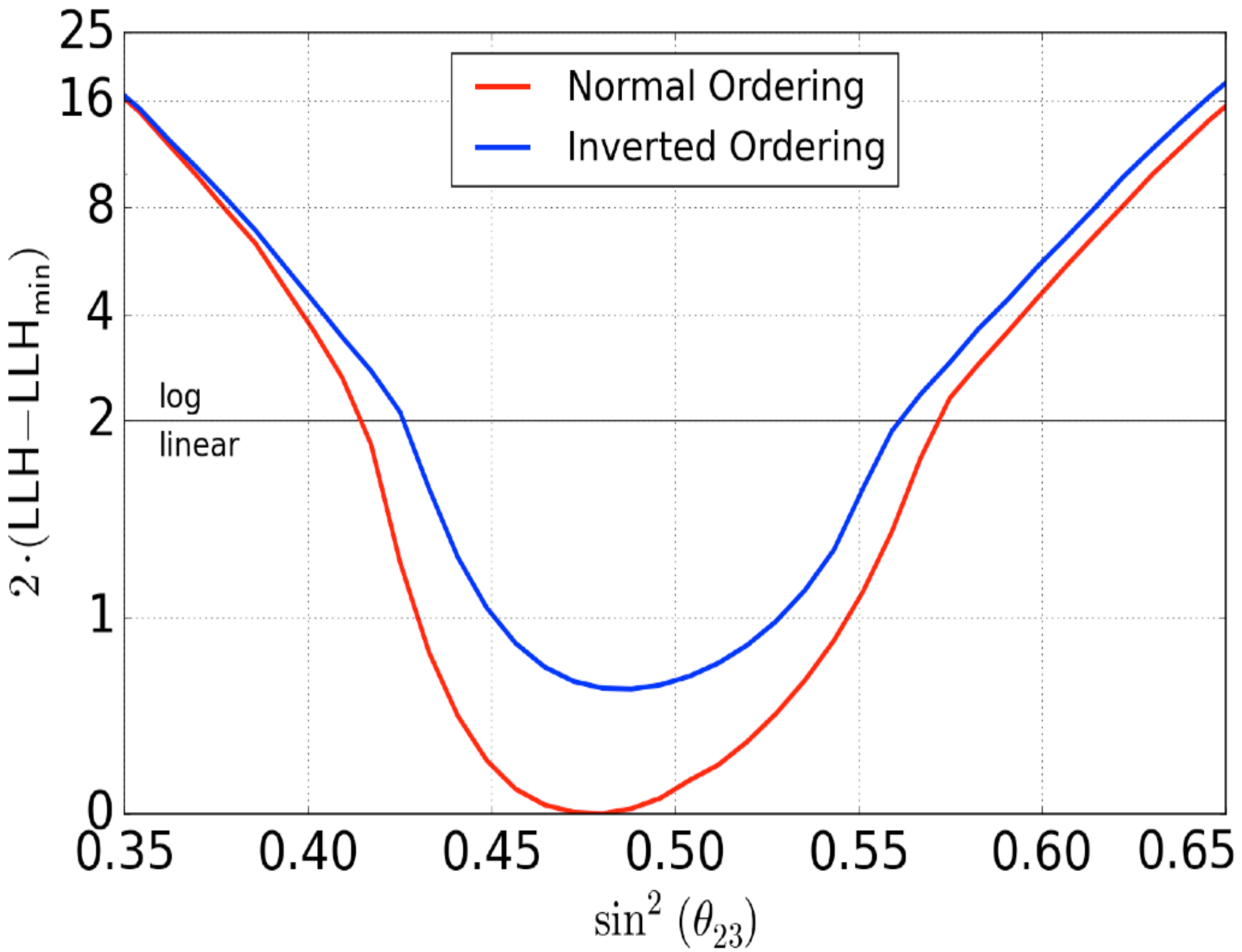
$$\mathrm{LLH} = \left[-\sum_{i\in\{\mathrm{bins}\}} \ln\left(\frac{p_i^{\rm tot}(N_i^{\mathcal{A}}, \mu_i^{\mathcal{A}}, \sigma_{\mu_i}^{\mathcal{A}})}{p_i^{\rm tot}(N_i^{\mathcal{A}}, N_i^{\mathcal{A}}, \sigma_{\mu_i}^{\mathcal{A}})} \right) \right] + \frac{1}{2} S,$$

$$S = \sum_{s\in\{\mathrm{sys}\}} \left(\frac{s - s_0}{\sigma_s} \right)^2$$

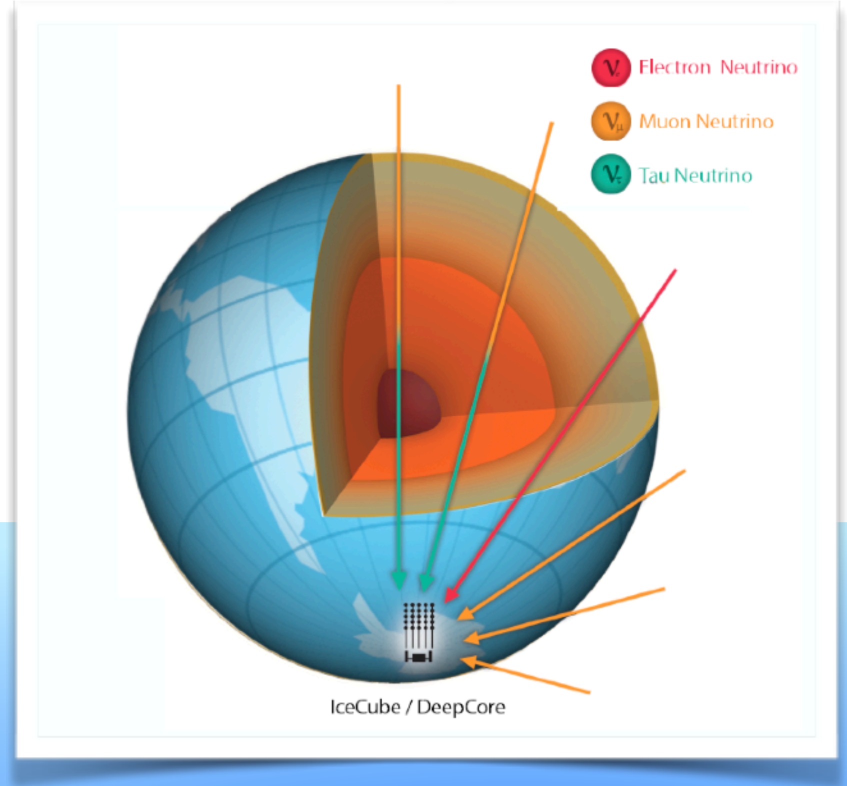
- Gaussian priors are included in the likelihood
- Same priors used for both analyses

Neutrino Mass Ordering IceCube





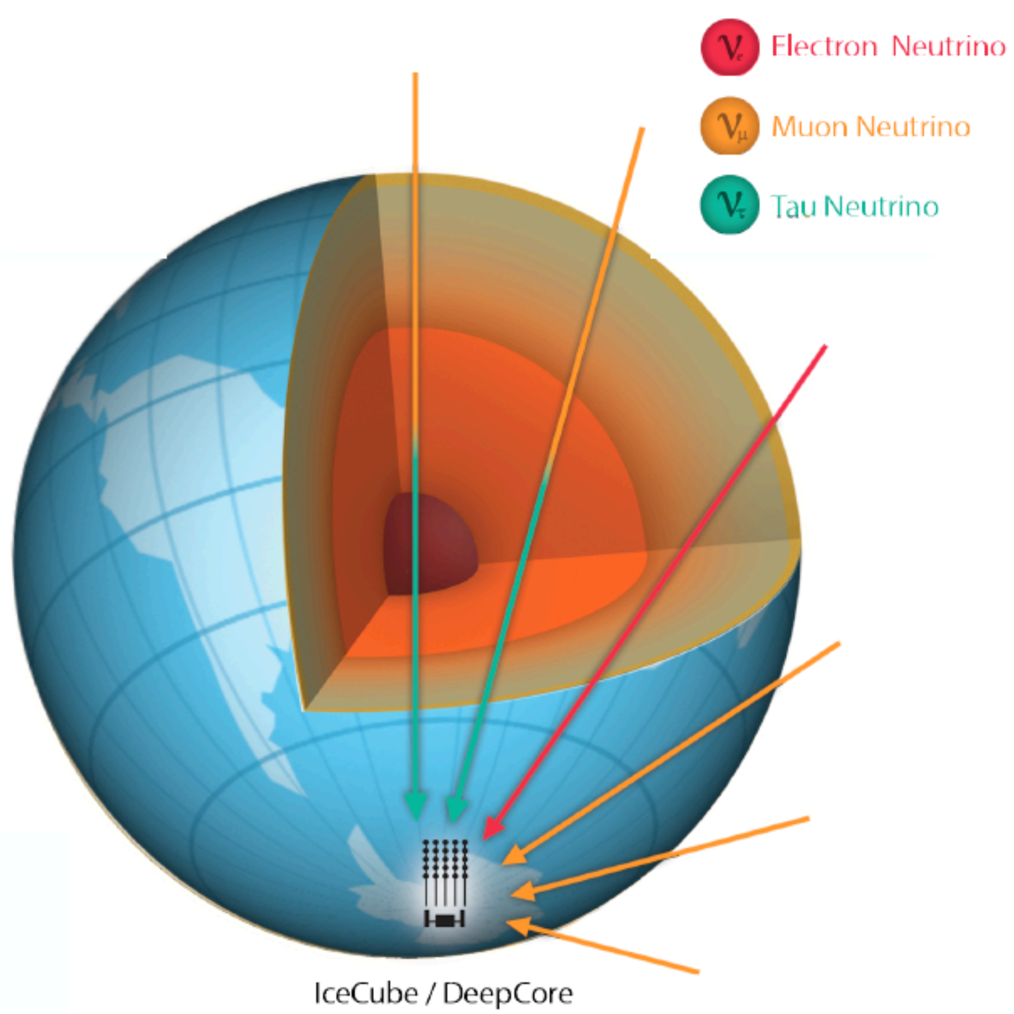
- Slight preference for normal ordering (NO)
  - $2\Delta LLH_{NO\text{-}IO} = 0.738$
  - p-value of inverted ordering is 15.7%

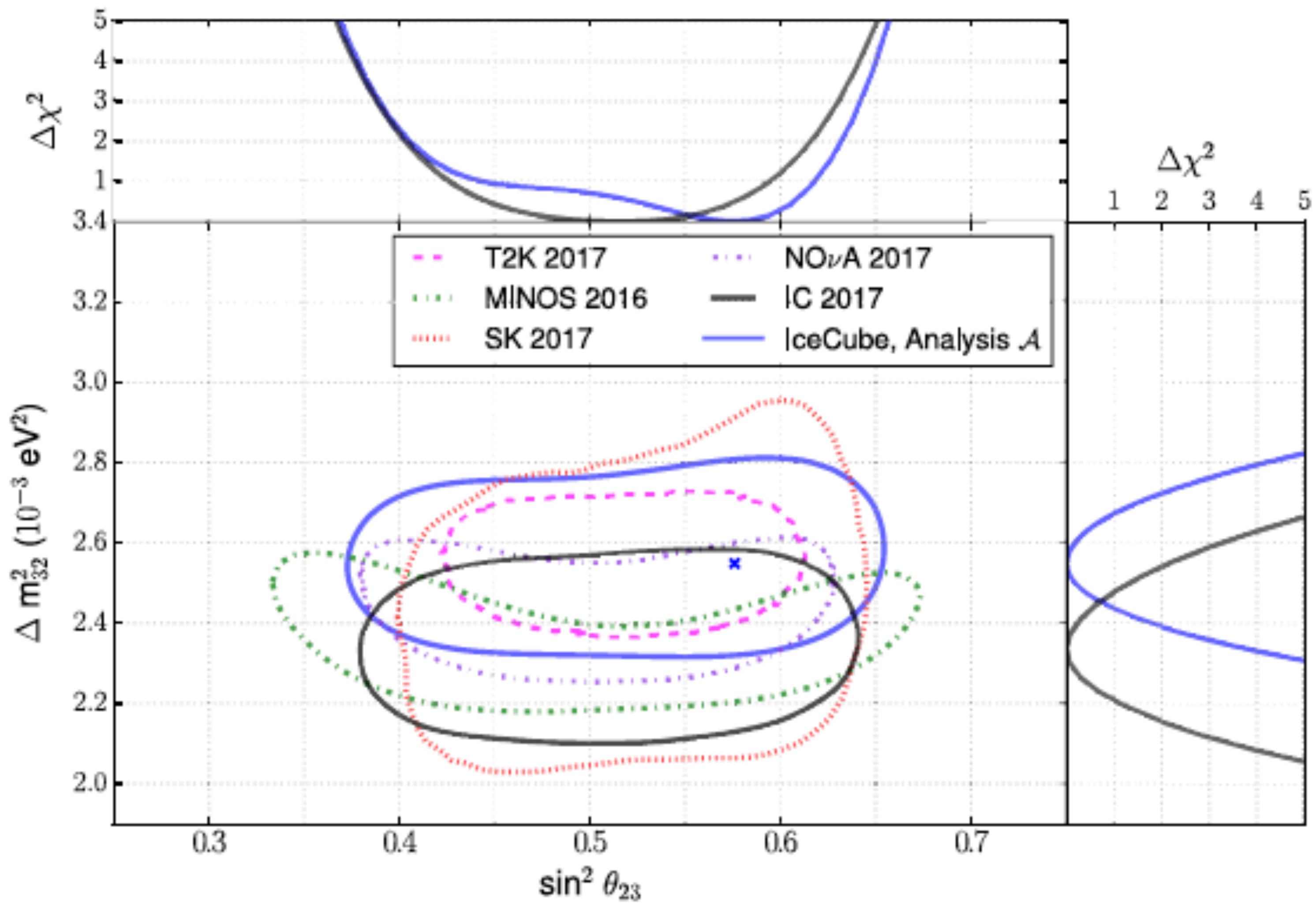


Other Particle Physics Highlights with atm. neutrinos

IceCube Coll. PHYS. REV. D 99, 032007 (2019)
(see also ANTARES Coll. arXiv:1812.08650v1)

Neutrino Oscillations





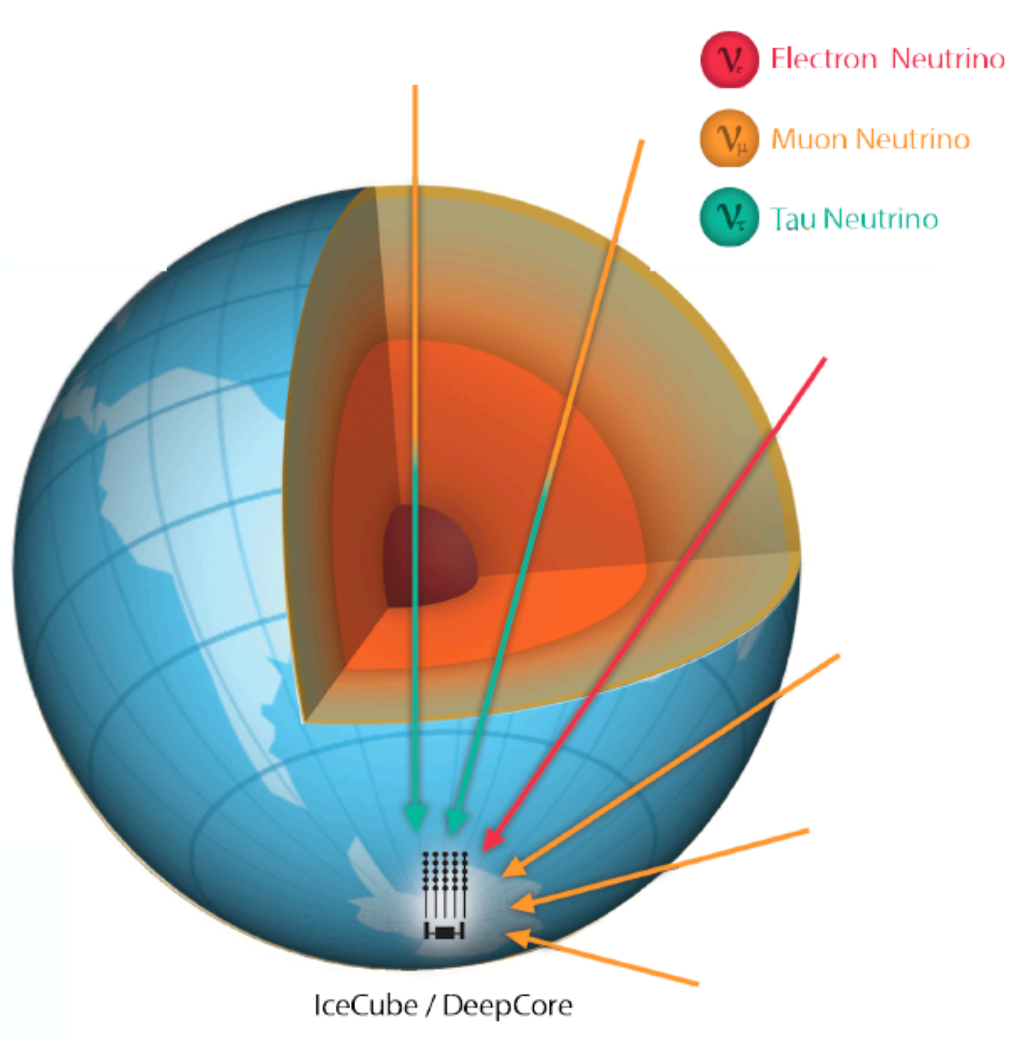
- 3 years of IceCube Deep Core data
- Measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

Normal ordering best fits

$$\Delta m^2_{32} = 2.55^{+0.12}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.58^{+0.04}_{-0.13}$$

Neutrino Oscillations



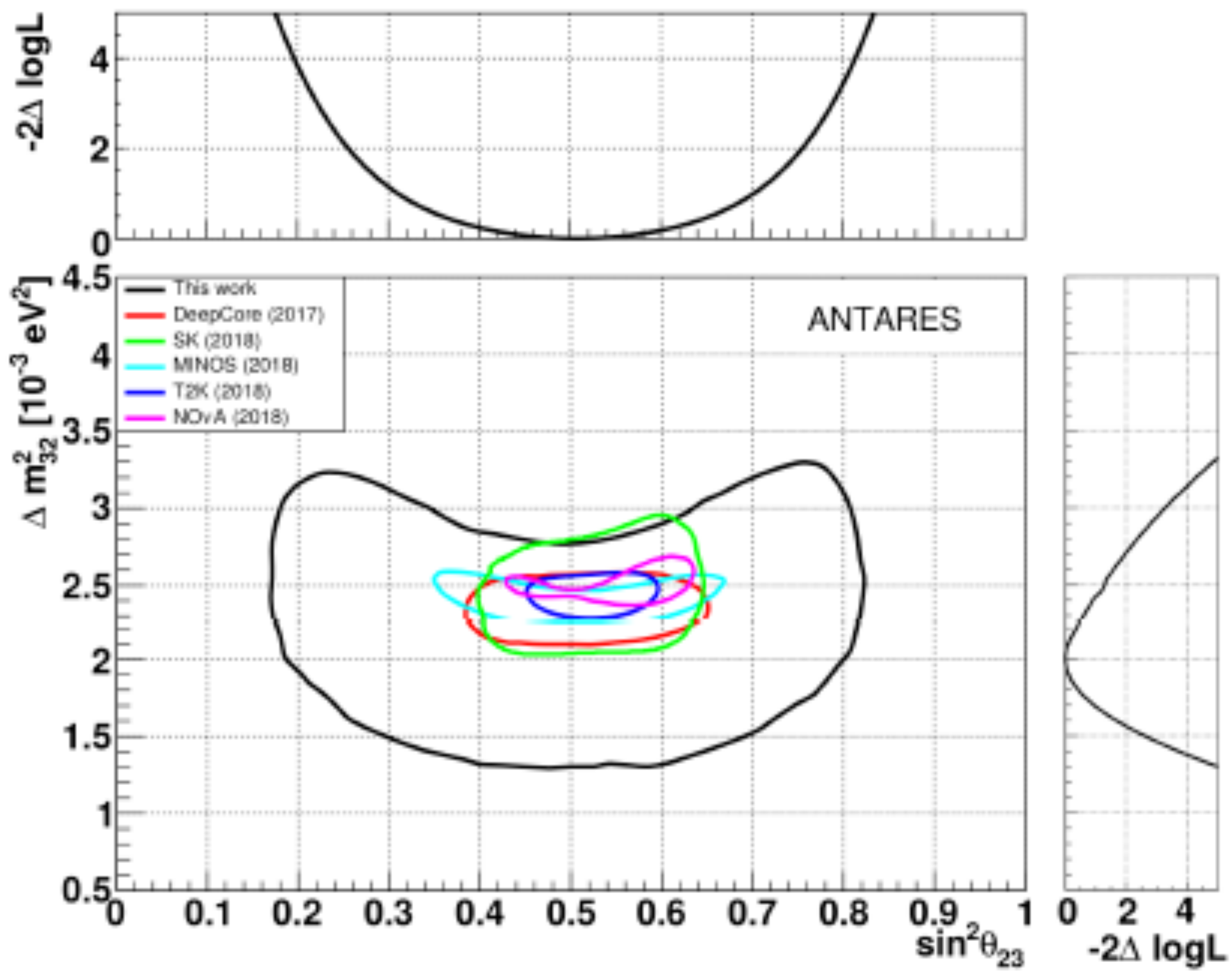
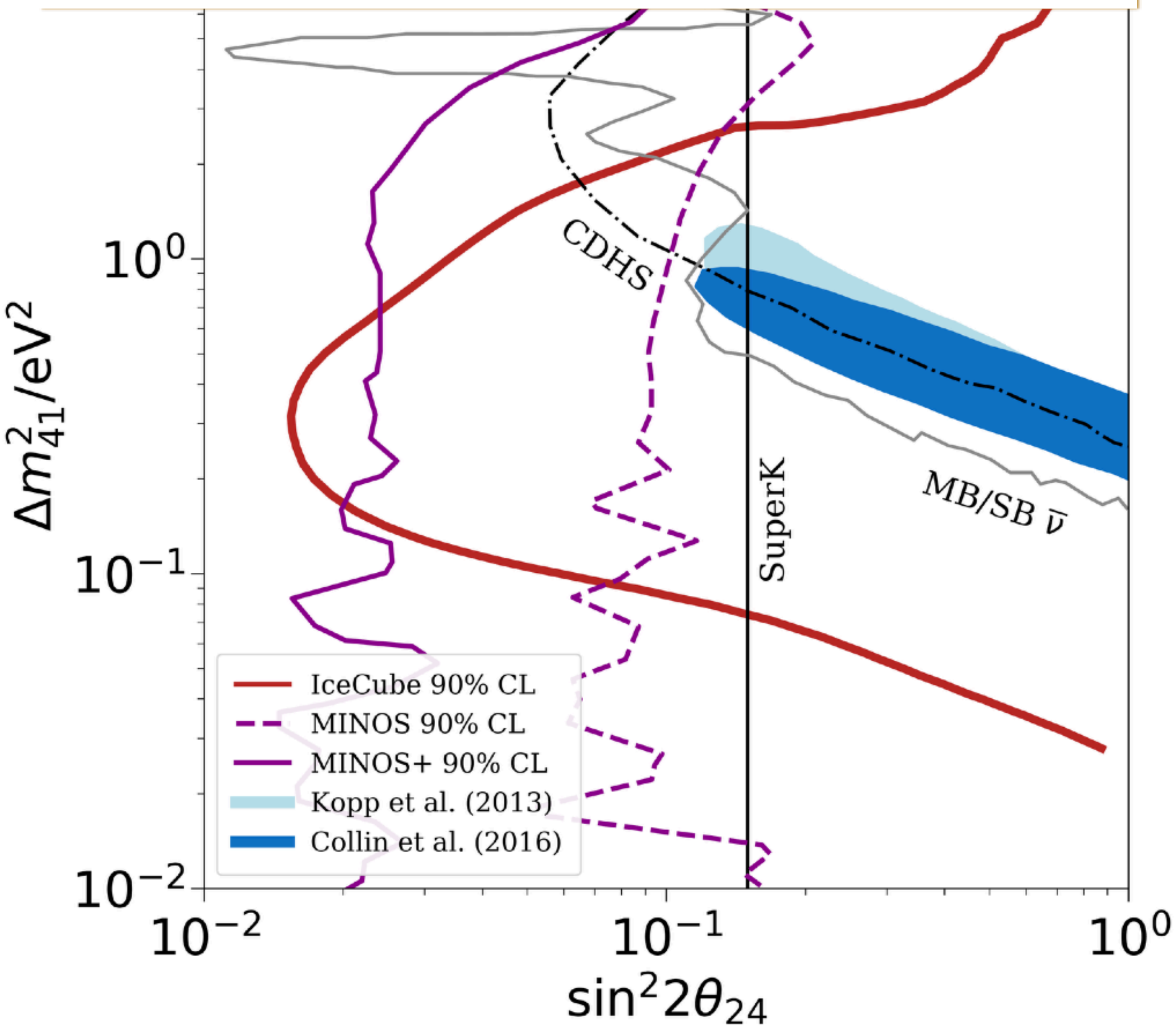


Figure 7: Contour at 90% CL in the plane of $\sin^2\theta_{23}$ and Δm^2_{32} obtained in this work (black line) and compared to the results by other experiments: IceCube/DeepCore (red) [7], Super-Kamiokande (green) [42], NOνA (purple) [43], T2K (blue) [44], and MINOS (light blue) [45]. The lateral plots show the 1D projections on the plane of the two oscillation parameters under study.

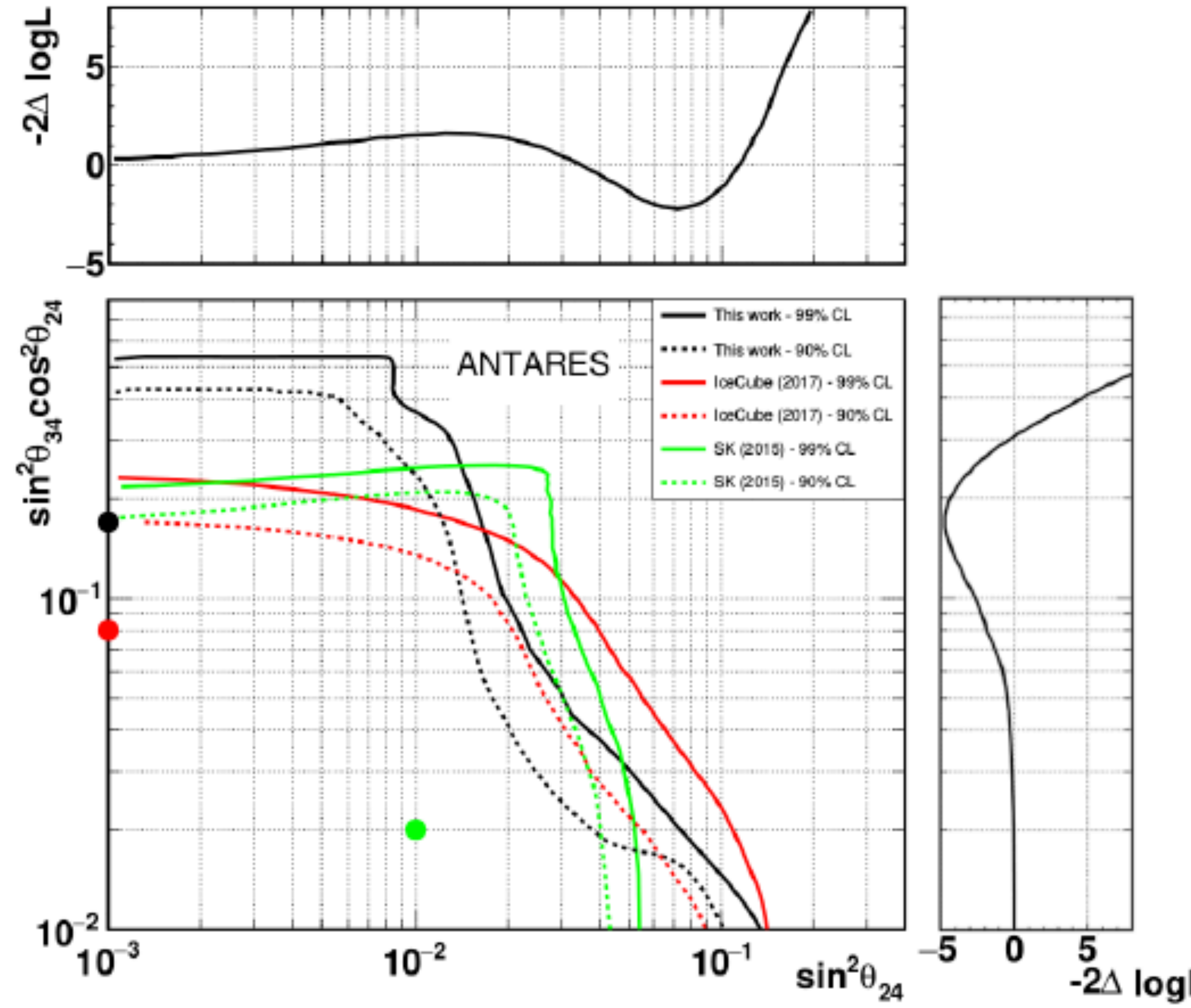
- 3 years of IceCube Deep Core da
- Measurements of muon neutrino disappearance, over a range of ba to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6

Sterile Neutrinos

M.G. Aartsen et al. (IceCube), Phys. Rev. Lett. 117, 071801 (2016), 1605.01990



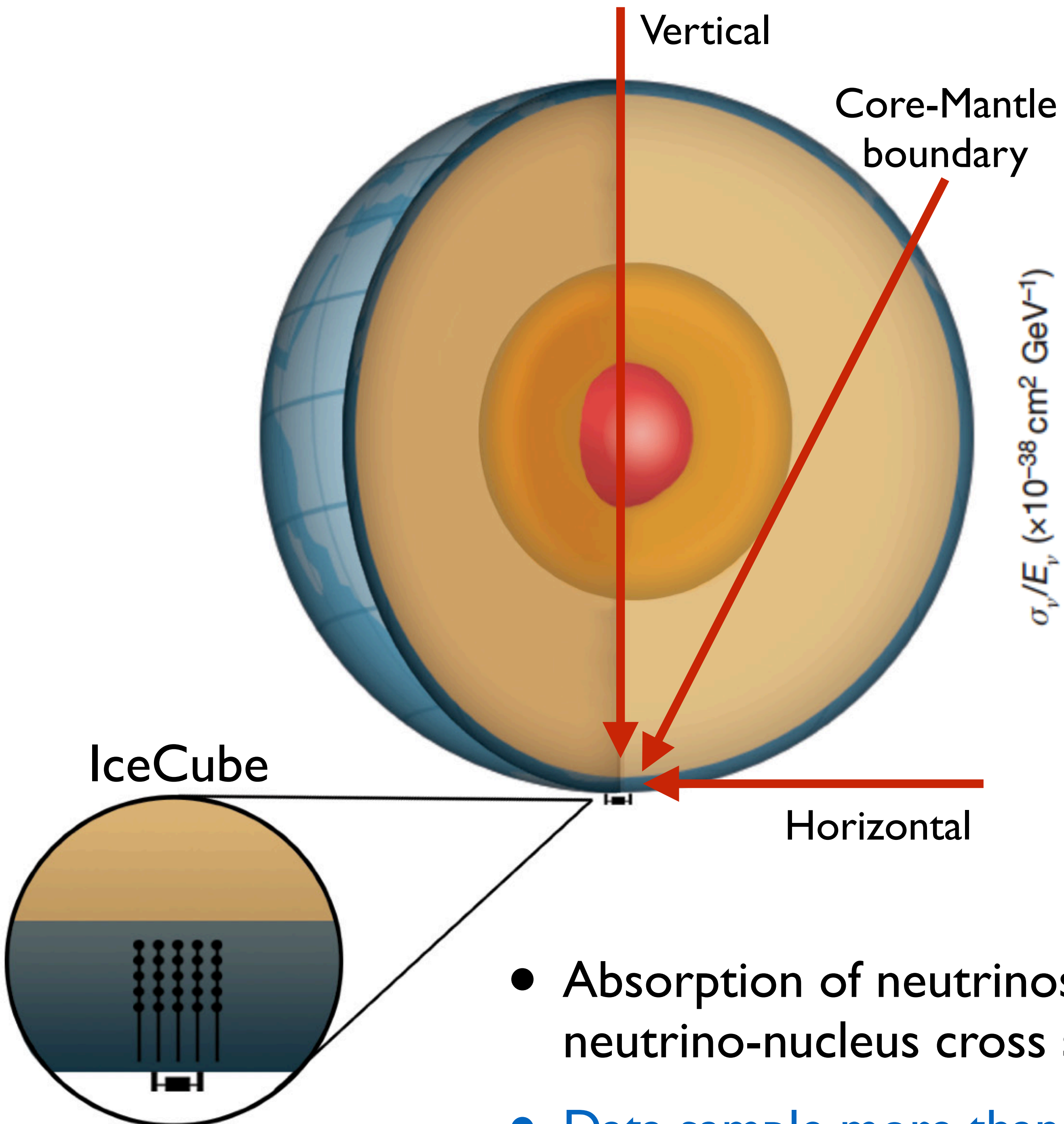
ANTARES arXiv:1812.08650v1



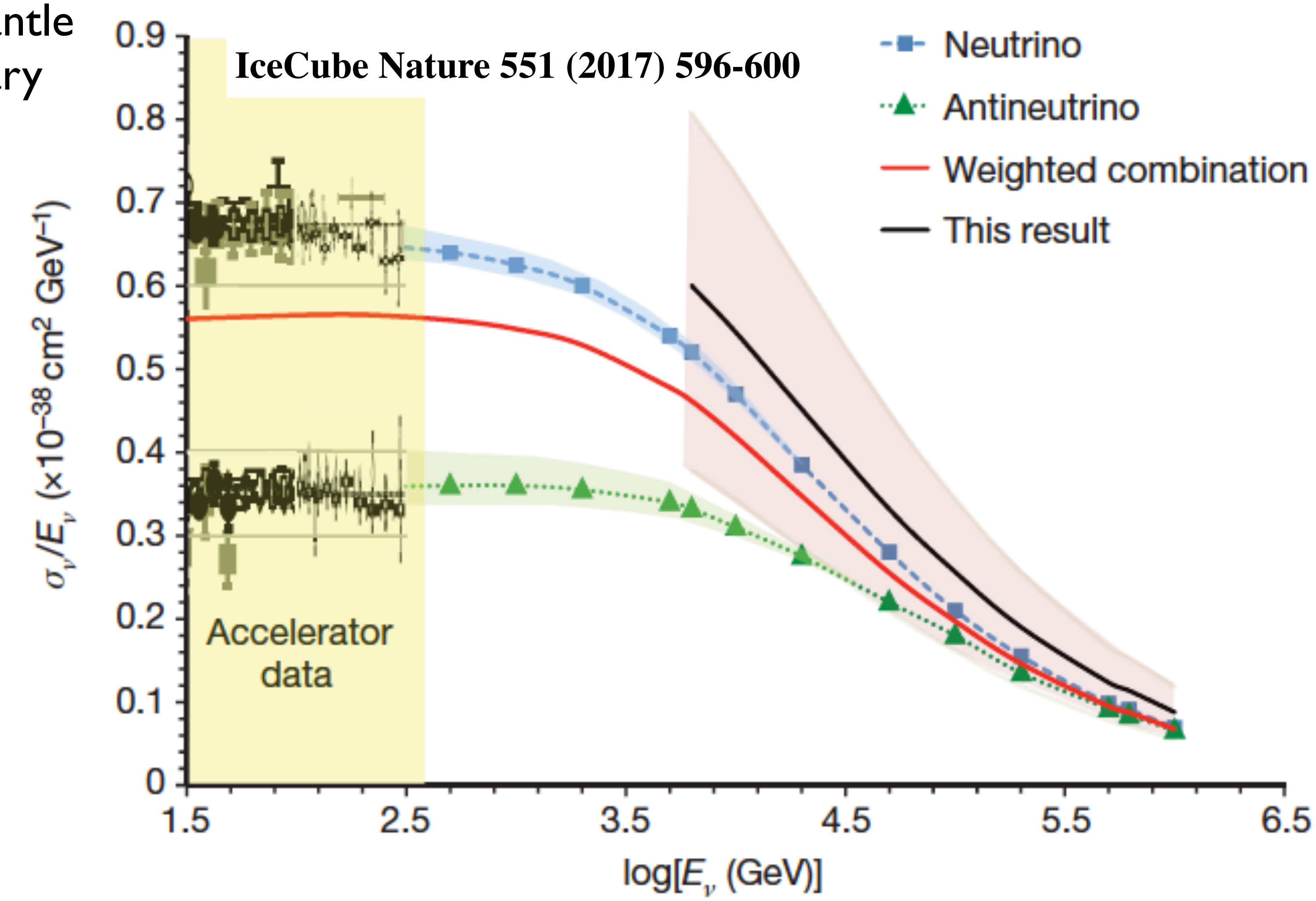
- Anomalies in short baseline experiments have been interpreted as evidence for additional neutrino mass states with large mass splittings
- No evidence for sterile neutrinos observed. Data consistent with 3 active neutrinos

IceCube Nature 551 (2017) 596-600

Neutrino Absorption in the Earth



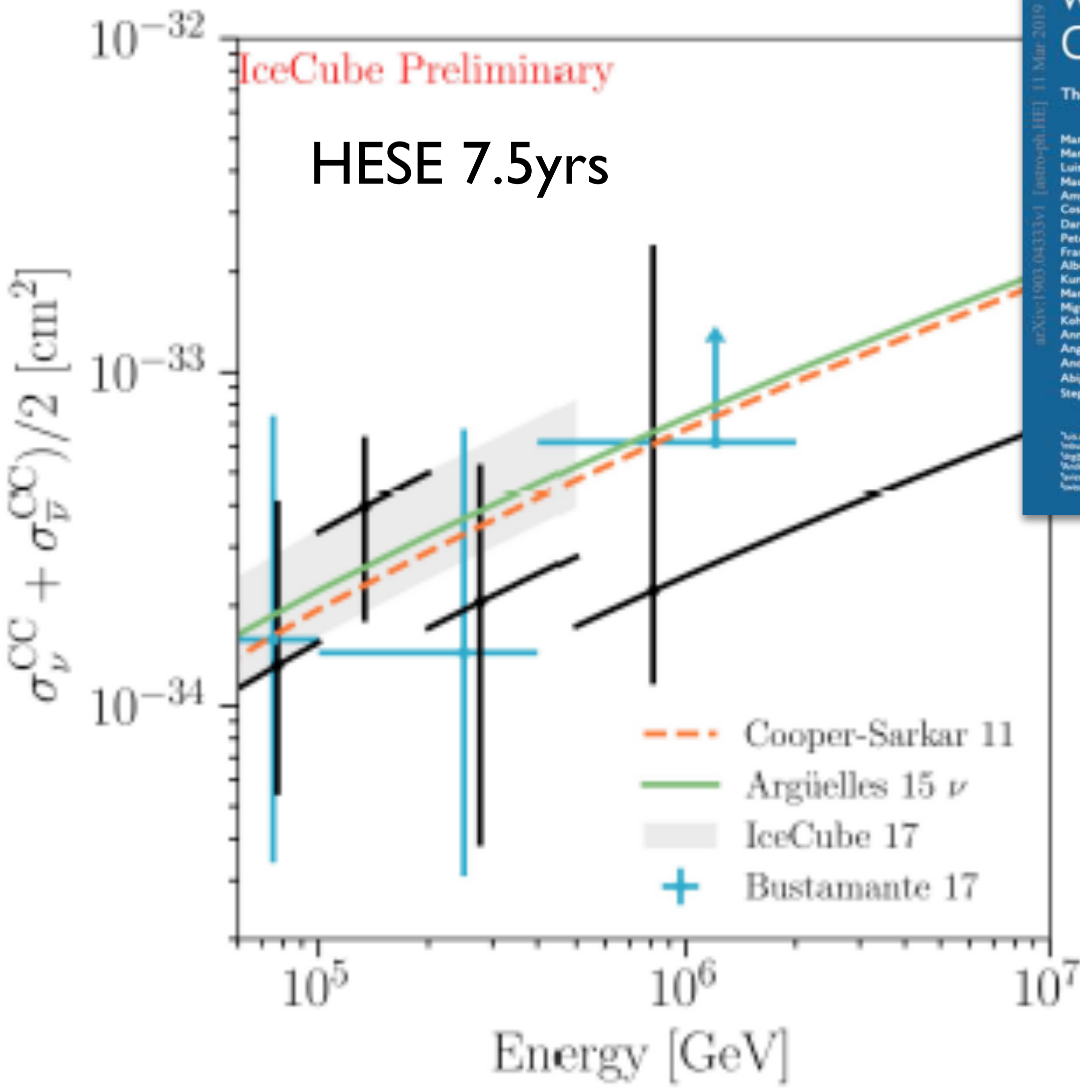
Neutrino-Nucleus Cross Section

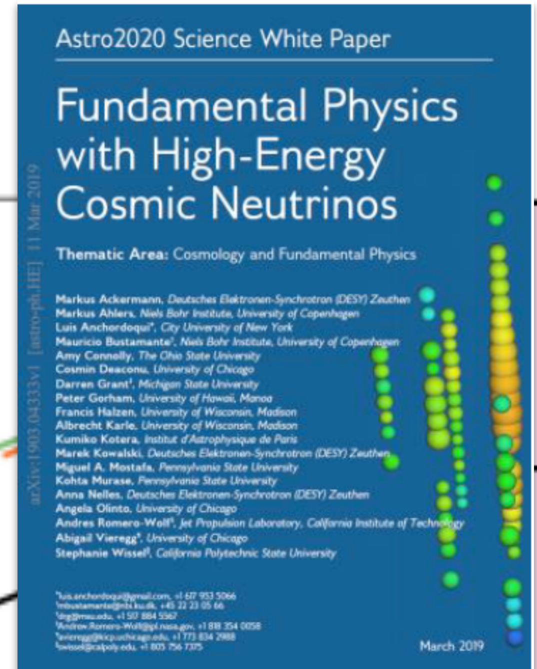


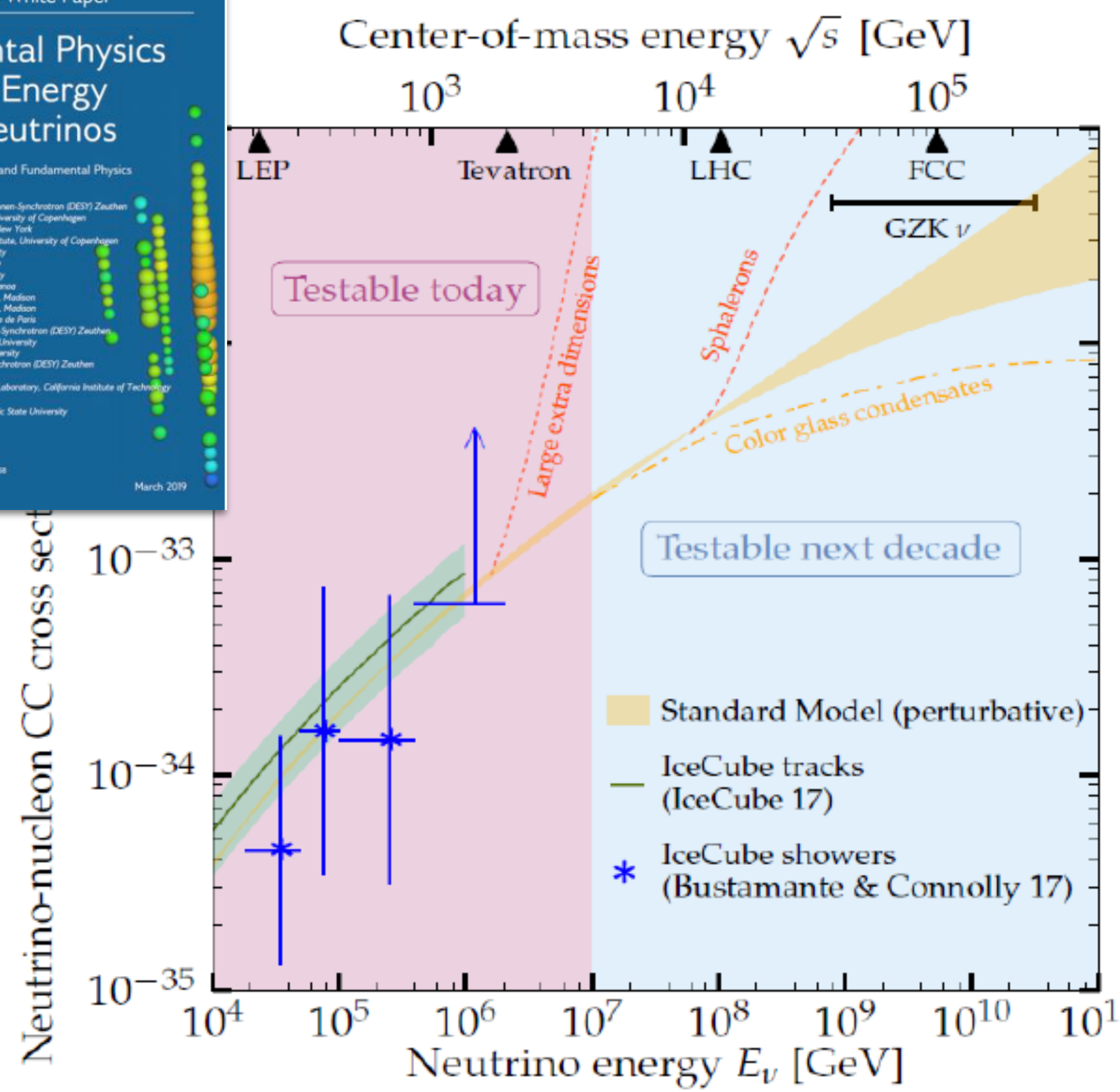
- Absorption of neutrinos in the Earth can be a powerful tool to measure neutrino-nucleus cross section
- Data sample more than 10,000 muon neutrino in one year of data
- Measured cross section between 6.3-980 TeV (extents previous measurements by more than an order of magnitude

Neutrino Absorption in the Earth

IceCube Neutrino 2018







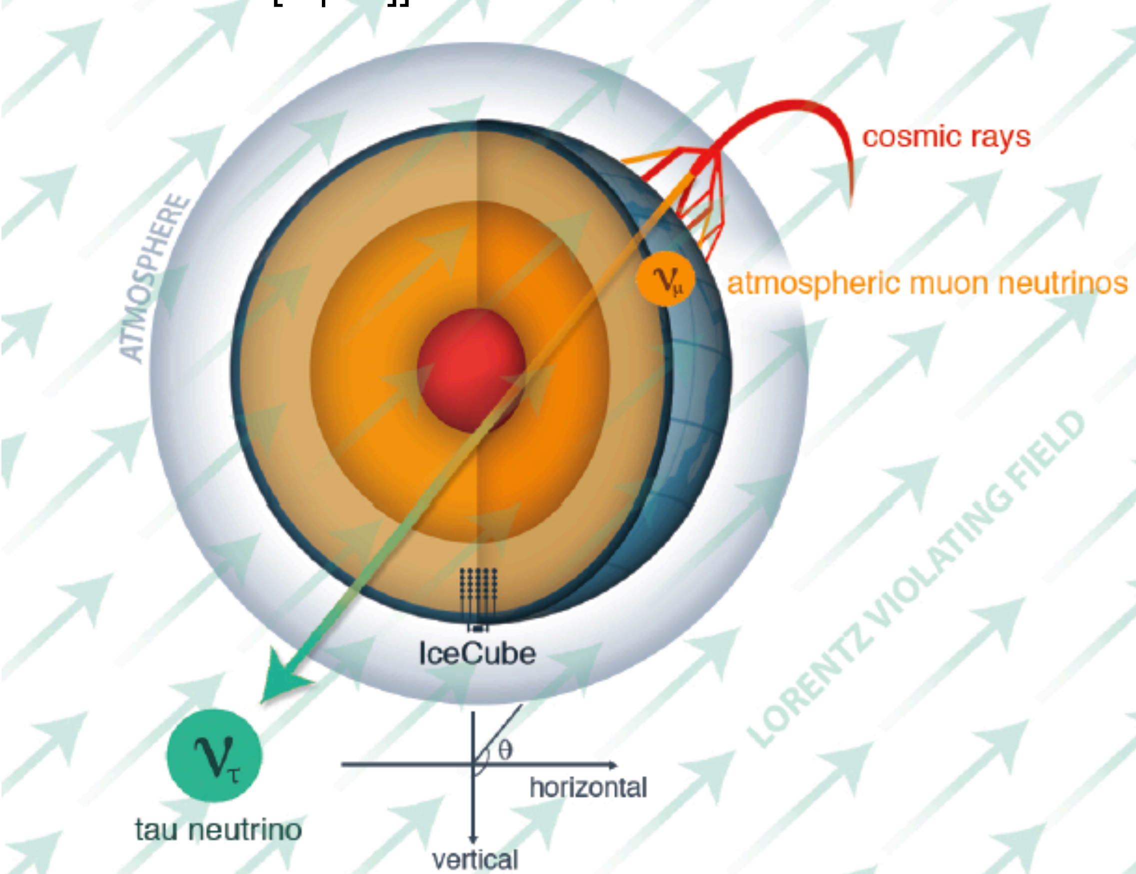
See also tomography:

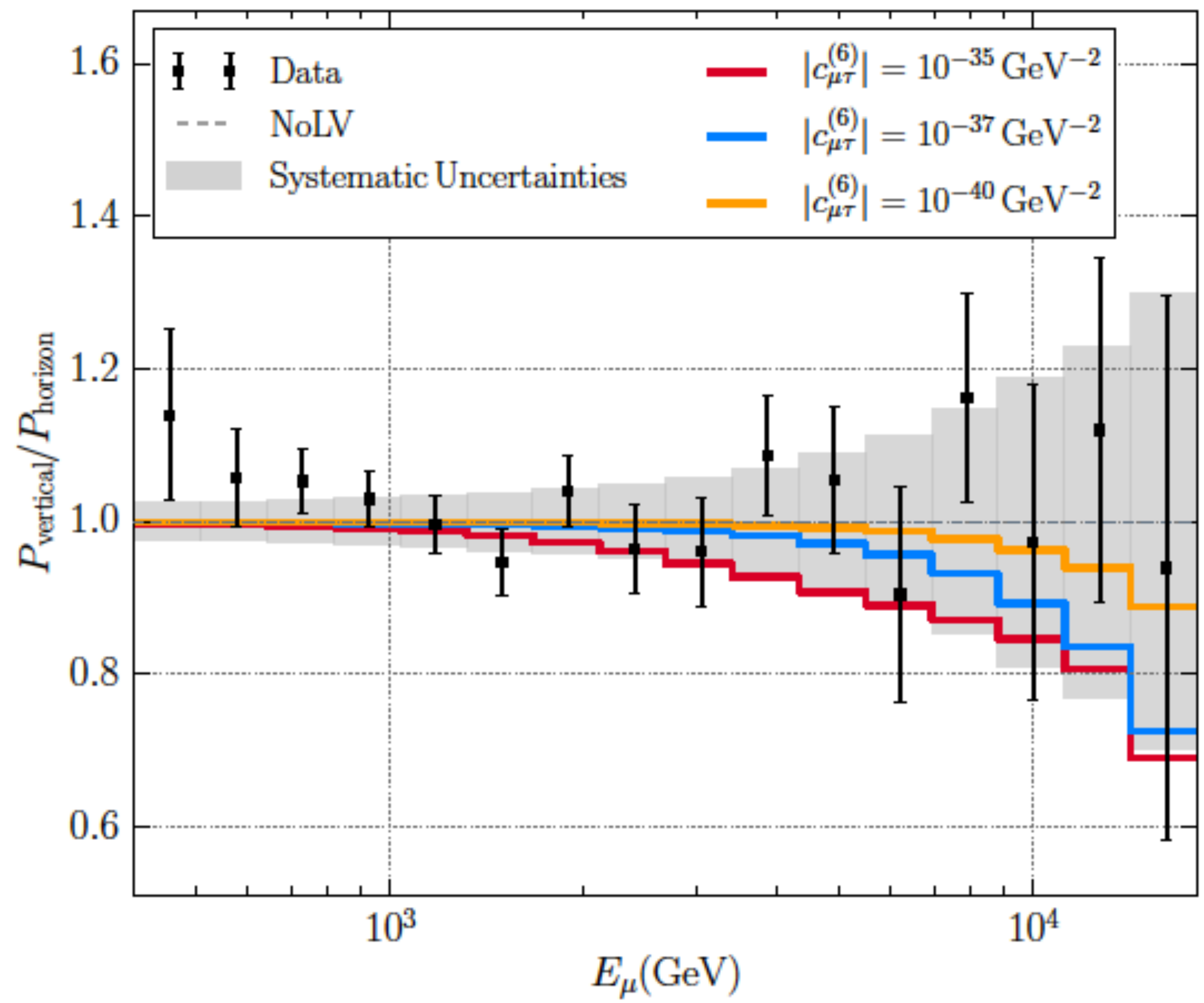
- Gonzalez−Garcia, Halzen, Maltoni, Tanaka, Phys. Rev. Let. 100 (2008)
- Rott, Taketa, Bose, 2015; Winter, 2016; Bourret, Coelho, van Elewyck, 2017
- A. Donini, S. Palomares-Ruiz, and J. Salvado, Nature Phys. 15, 37 (2019)

Tests of Lorentz Symmetry

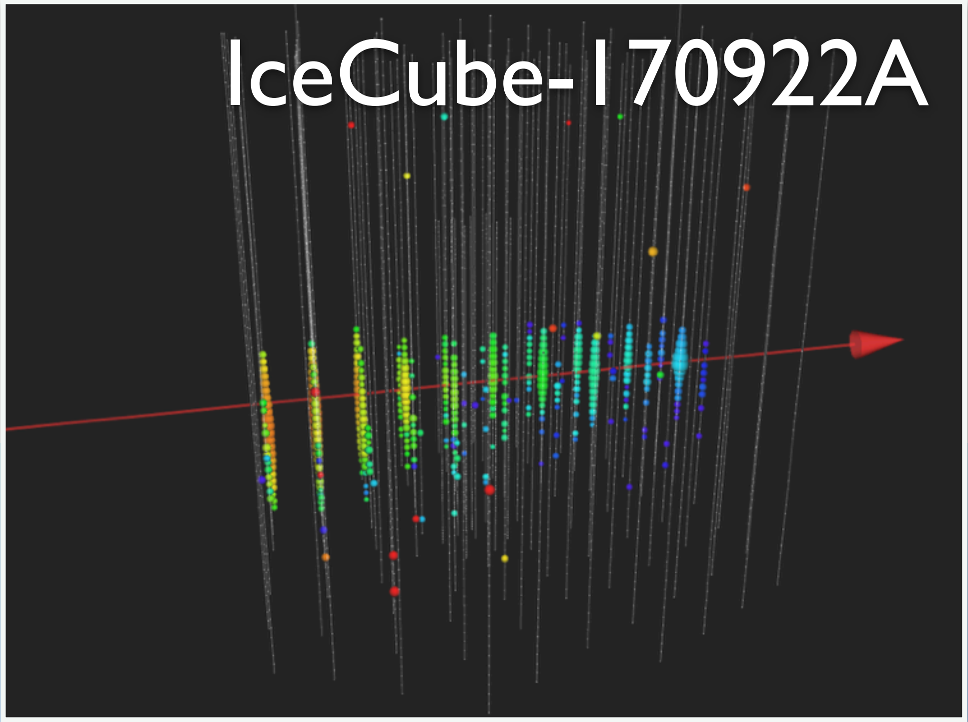
Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

IceCube Coll. **Nature Phys. (2018),** doi:10.1038/s41567-018-0172-2,
[arXiv:1709.03434 [hep-ex]].





- Most precise test of space-time symmetry in the neutrino sector to date
- Search for anomalous neutrino oscillations in IceCube's high energy neutrino sample
  - No evidence for such phenomena

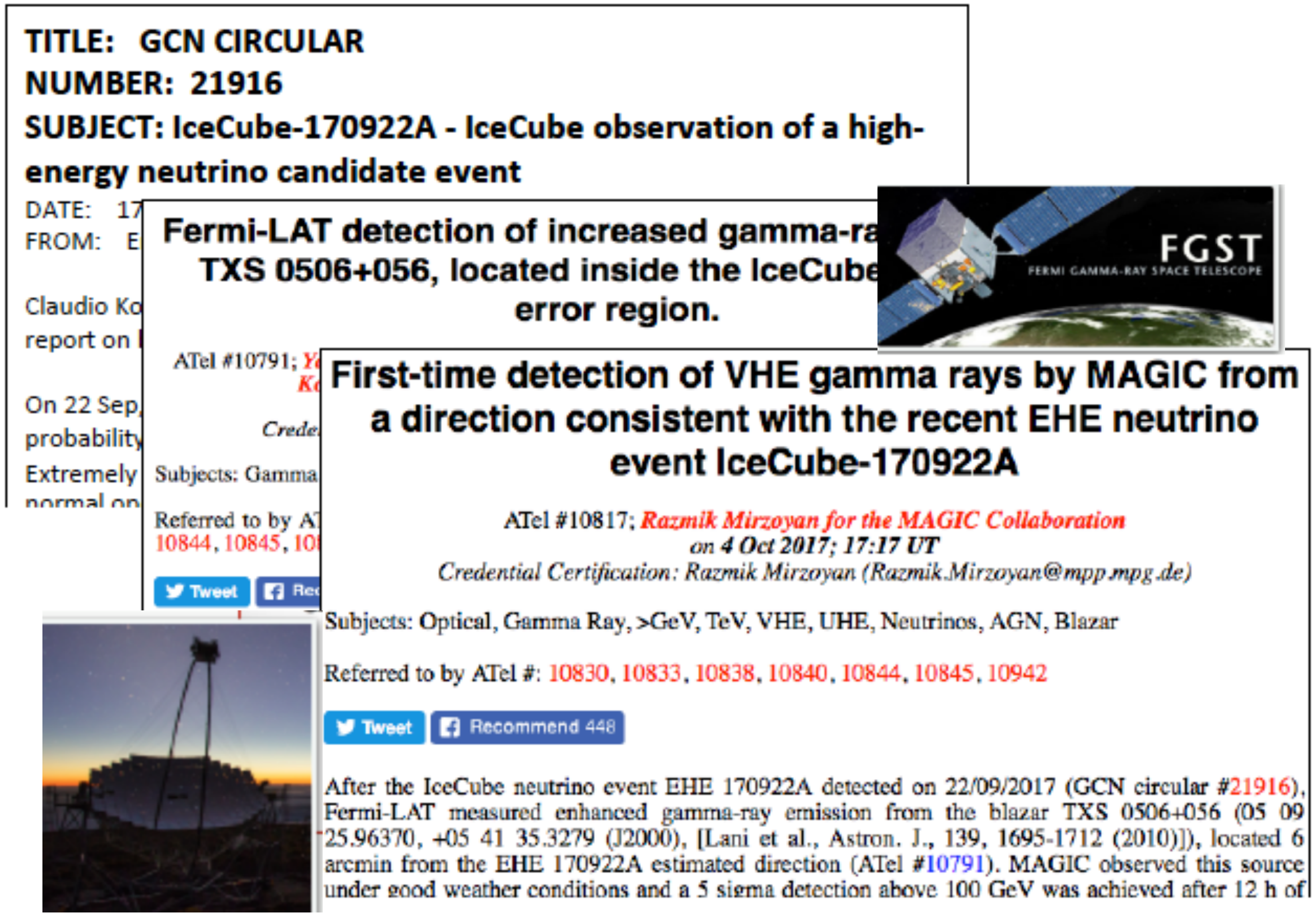


Astrophysical Neutrinos

Astropart. Phys. 92 (2017) 30

A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056



TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event

Fermi-LAT detection of increased gamma-ra… TXS 0506+056, located inside the IceCube error region.

FGST FERMI GAMMA-RAY SPACE TELESCOPE

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

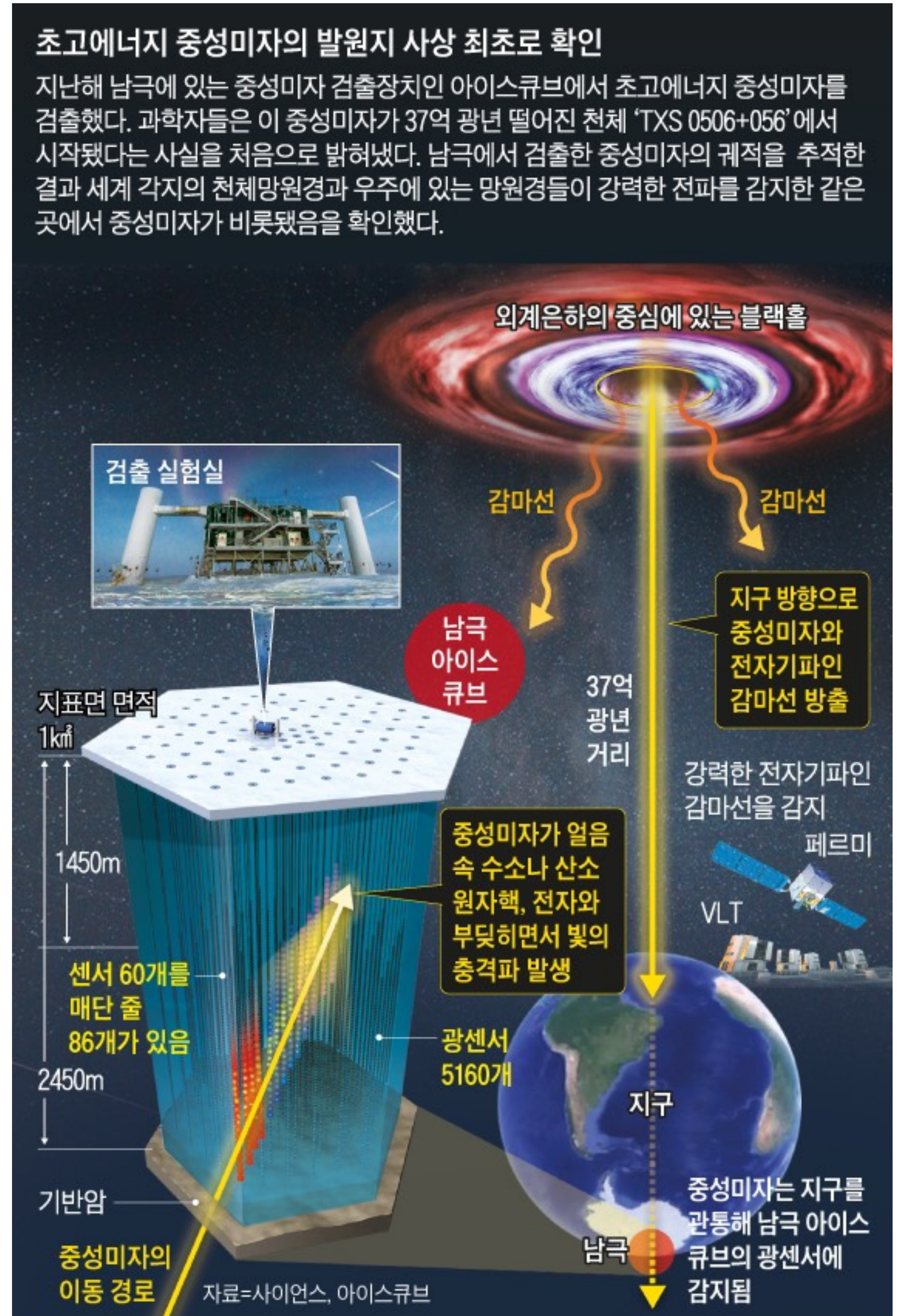
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

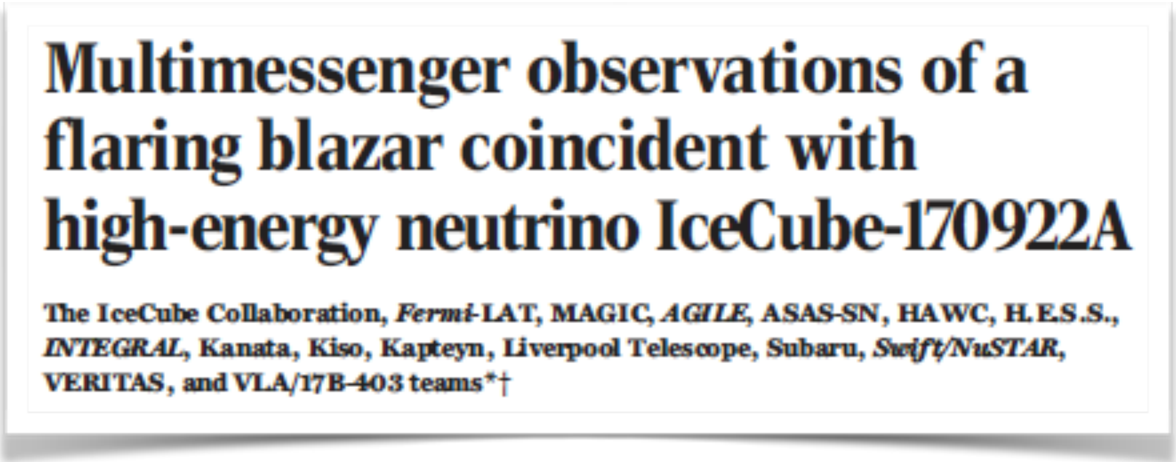
Tweet Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

- September 22, 2017: a neutrino alert issued by IceCube
- Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
- Very active multi-messenger follow-up from radio to γ-rays



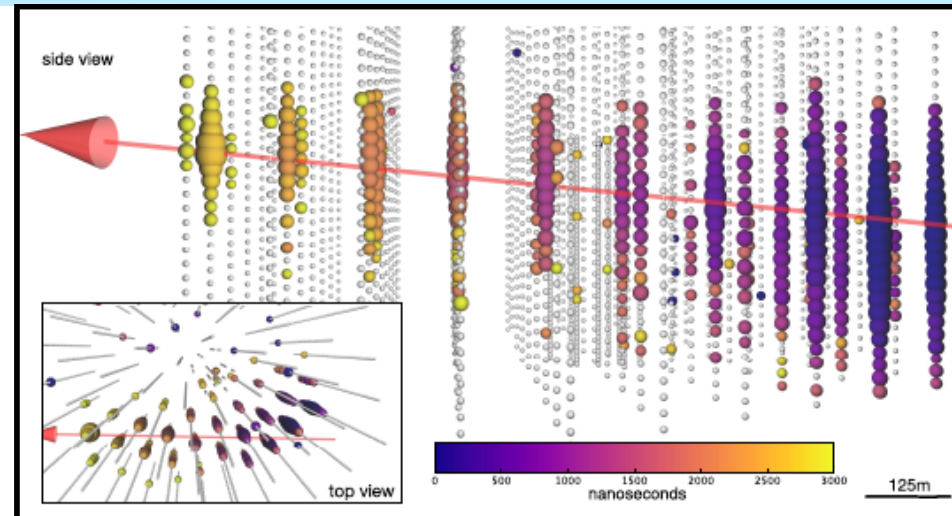
IceCube-170922A

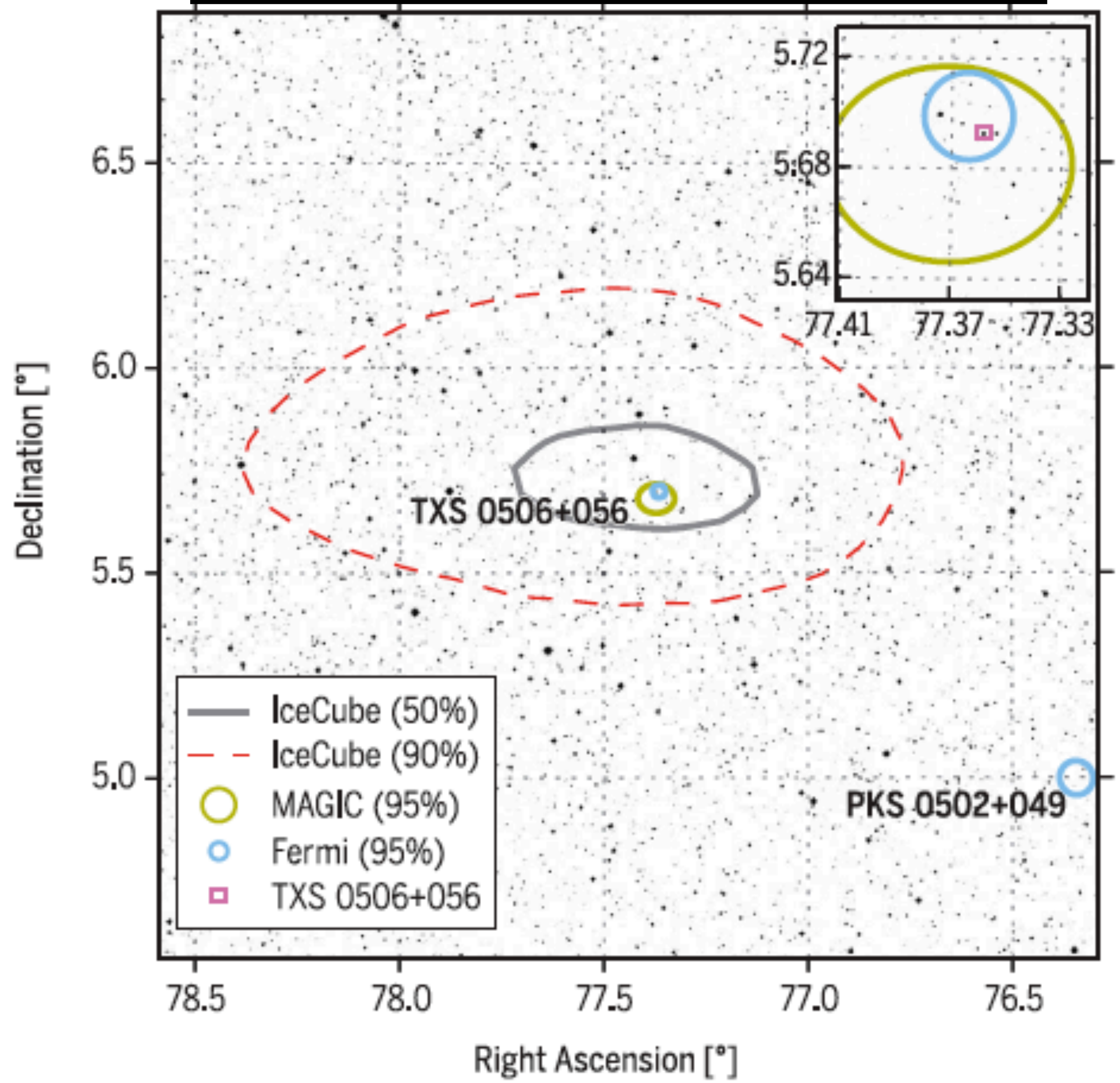


Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: ~**3σ** (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- **TXS 0506+056 redshift determined to be z=0.3365** (S. Paiano et al. ApJL 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605





(Science 361, eaat1378 (2018))

IceCube-170922A

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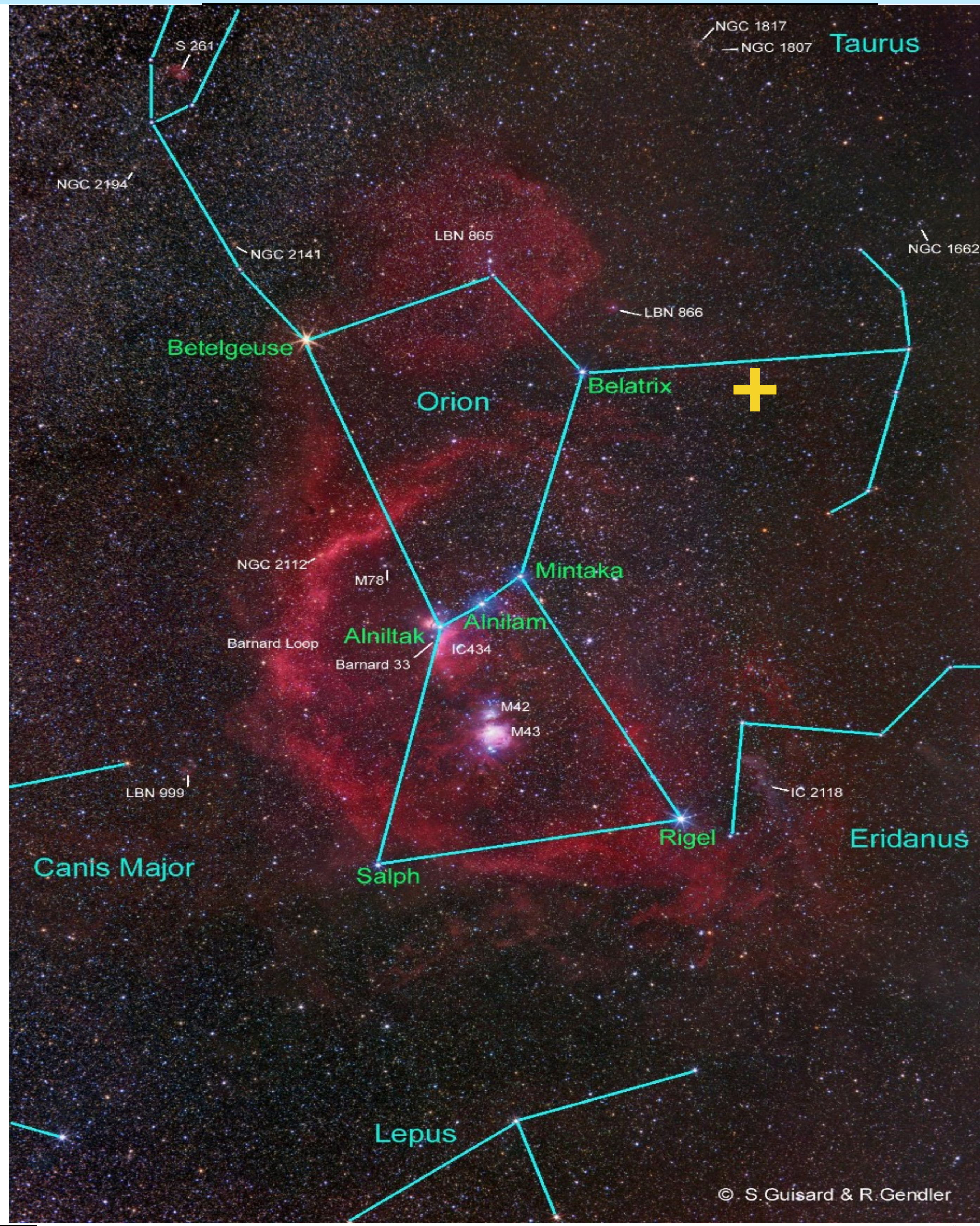
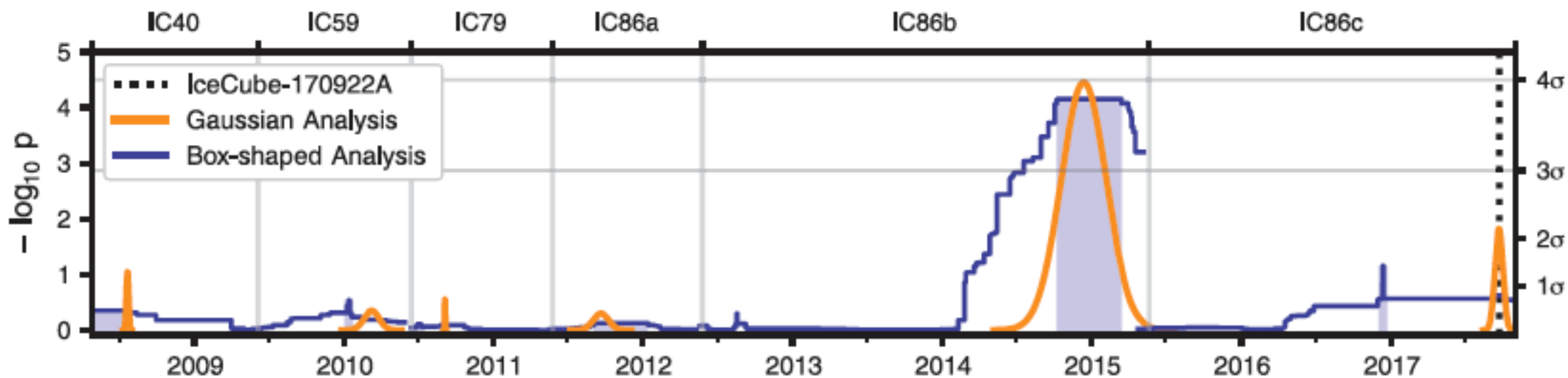
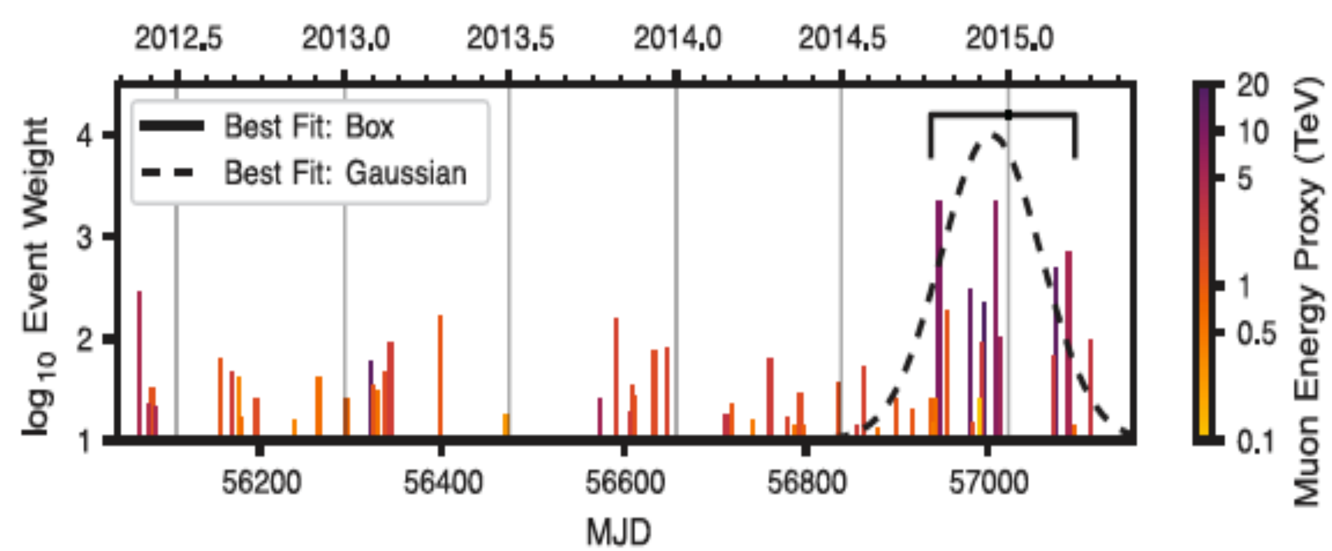


Science 361 (6398), 147-151.

IceCube-170922A

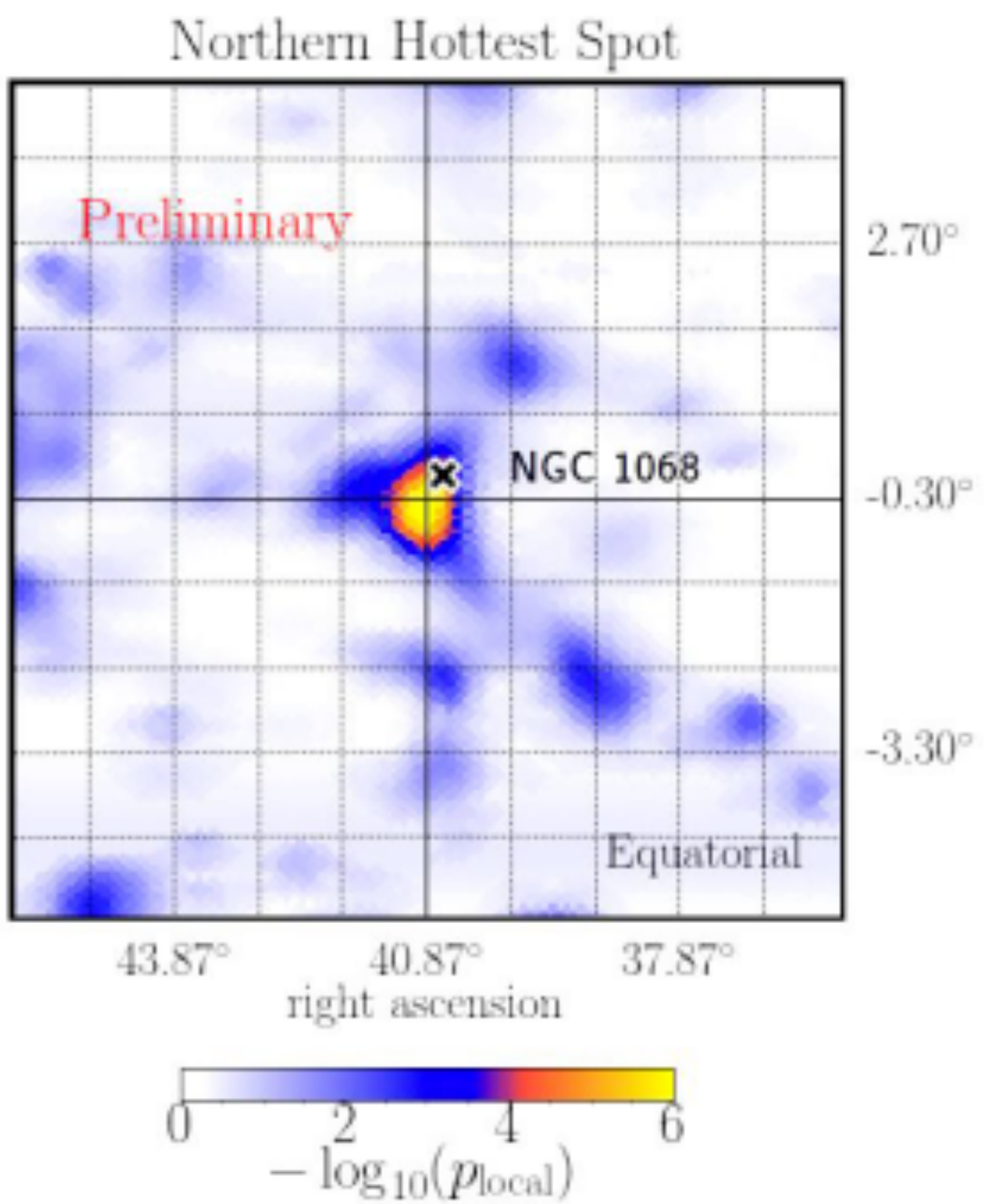


- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)

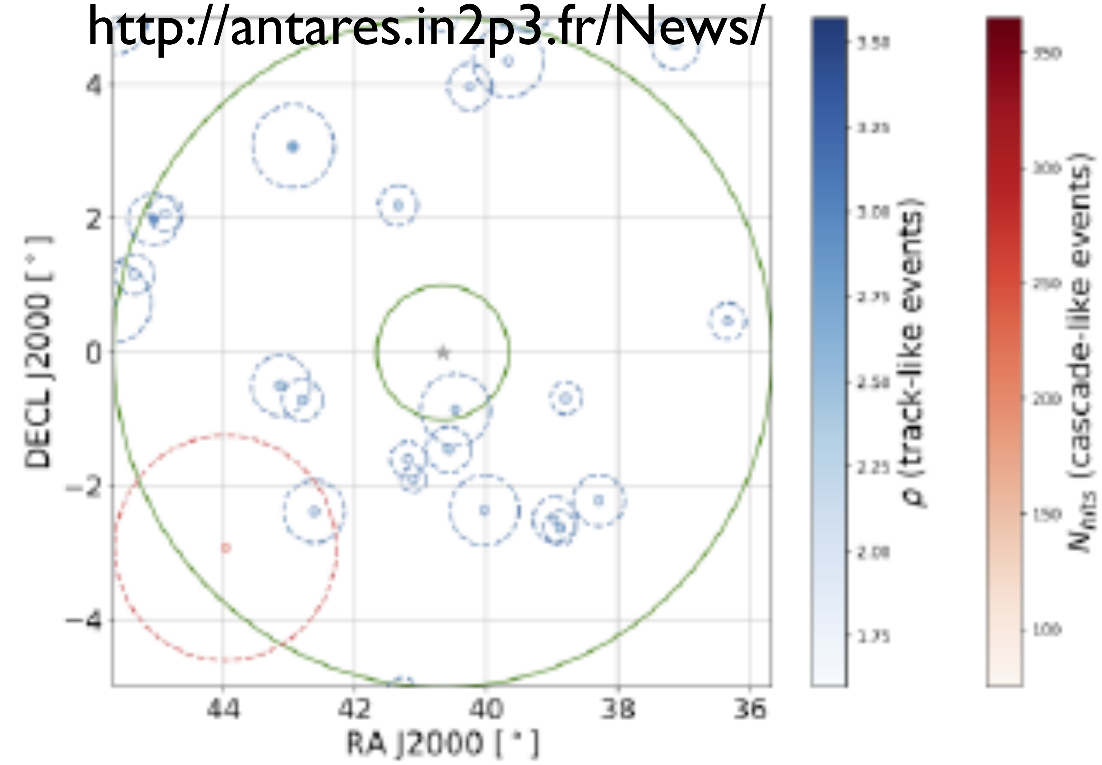


Time-independent weight of individual events during the IC86b period.

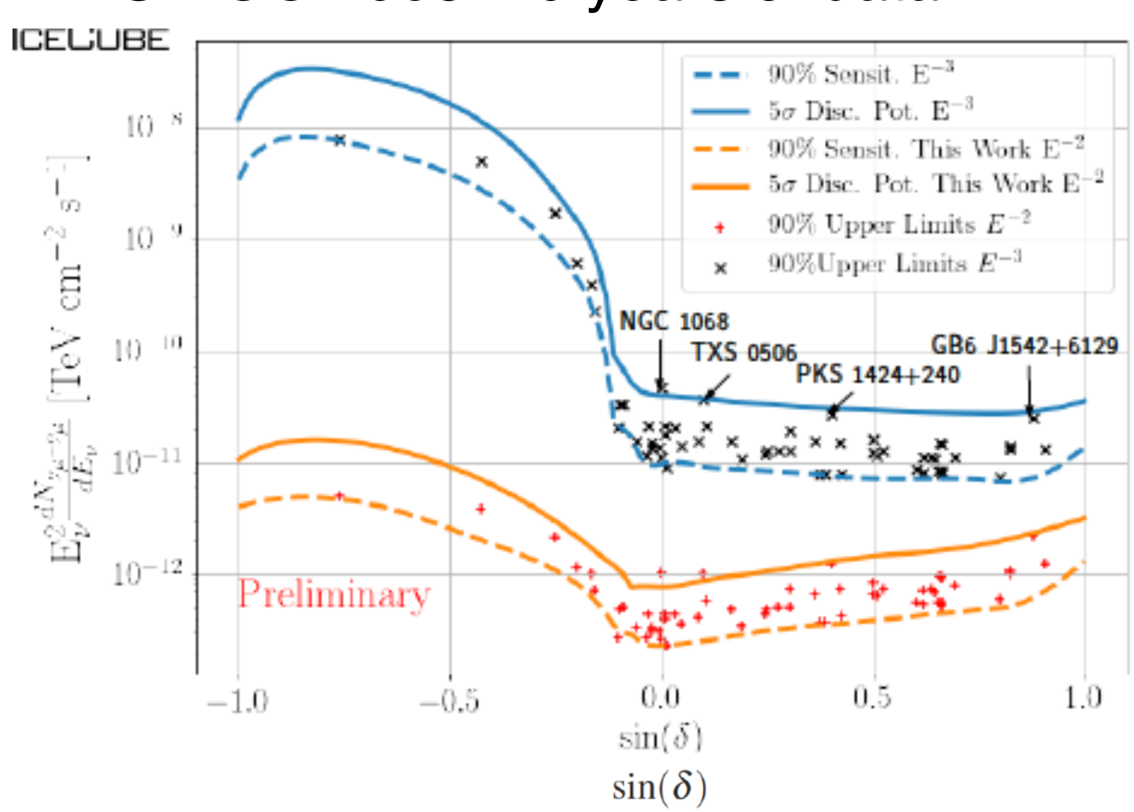
More sources in the future ?



http://antares.in2p3.fr/News/



ANTARES NGC 1068 10 years of data



10 years of IceCube data which recently have been unblinded, unifying the muon diffuse and point source streams

Most significant excess in the Northern Source List.

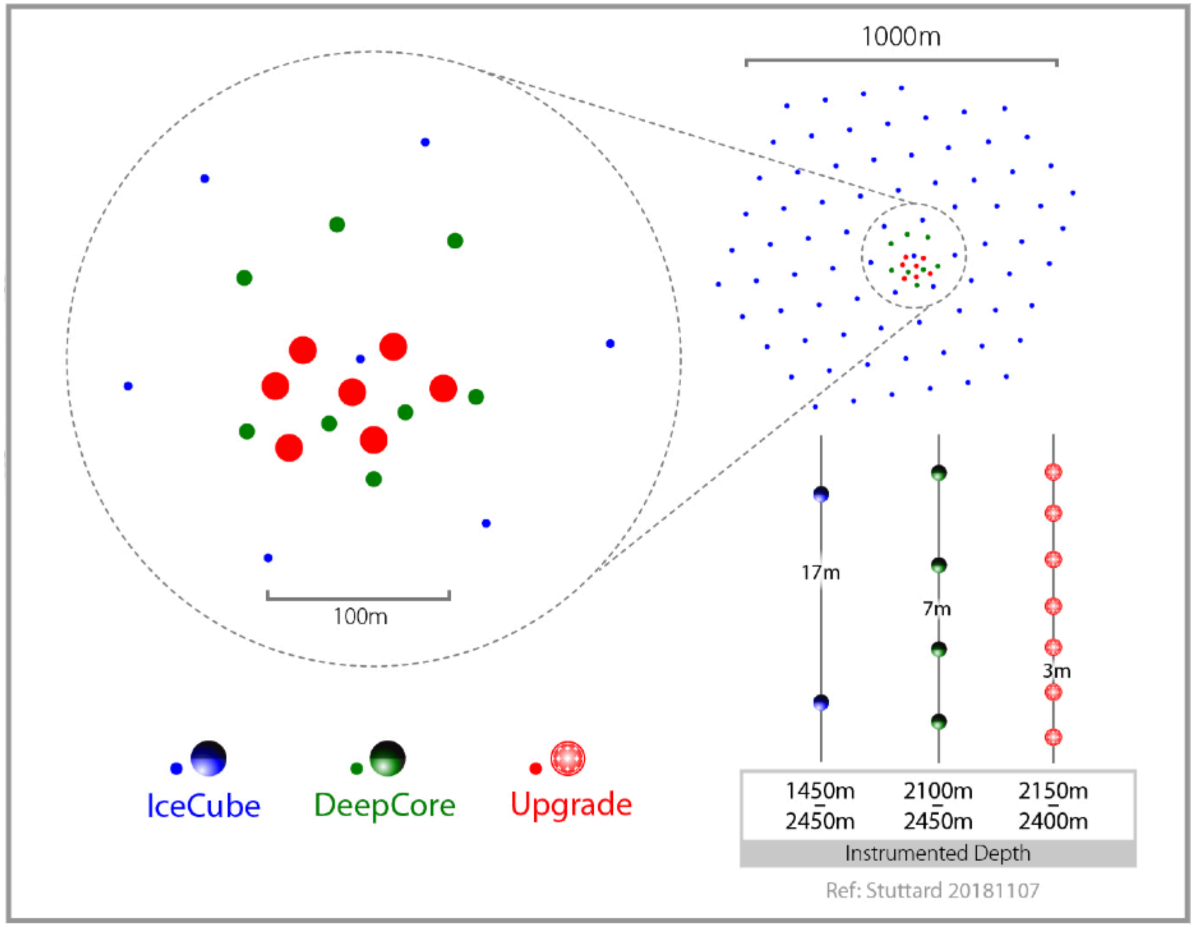
→ 2.9σ post-trial

● 0.35° from the hottest point in the sky.

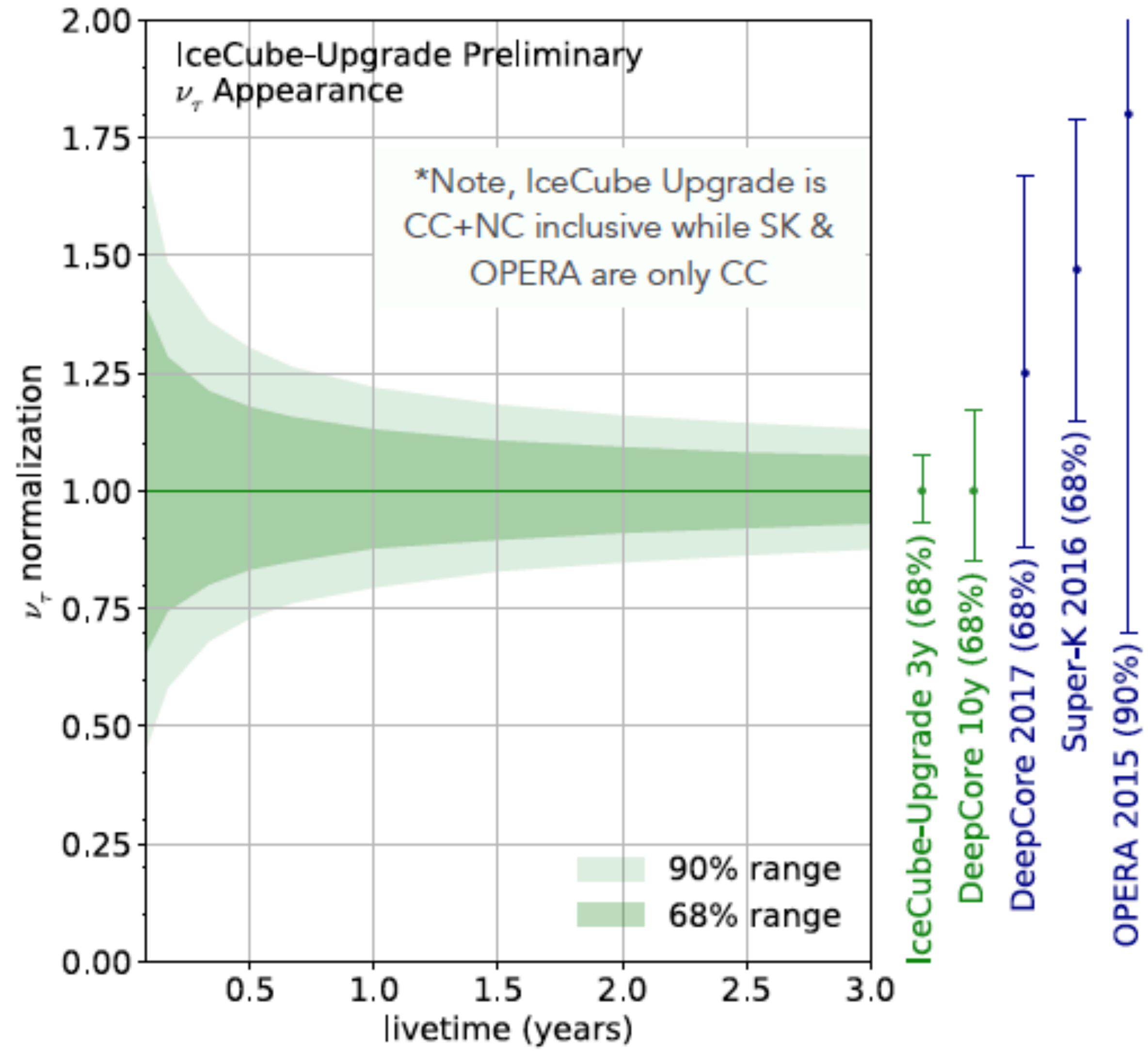
Next generation neutrino telescopes

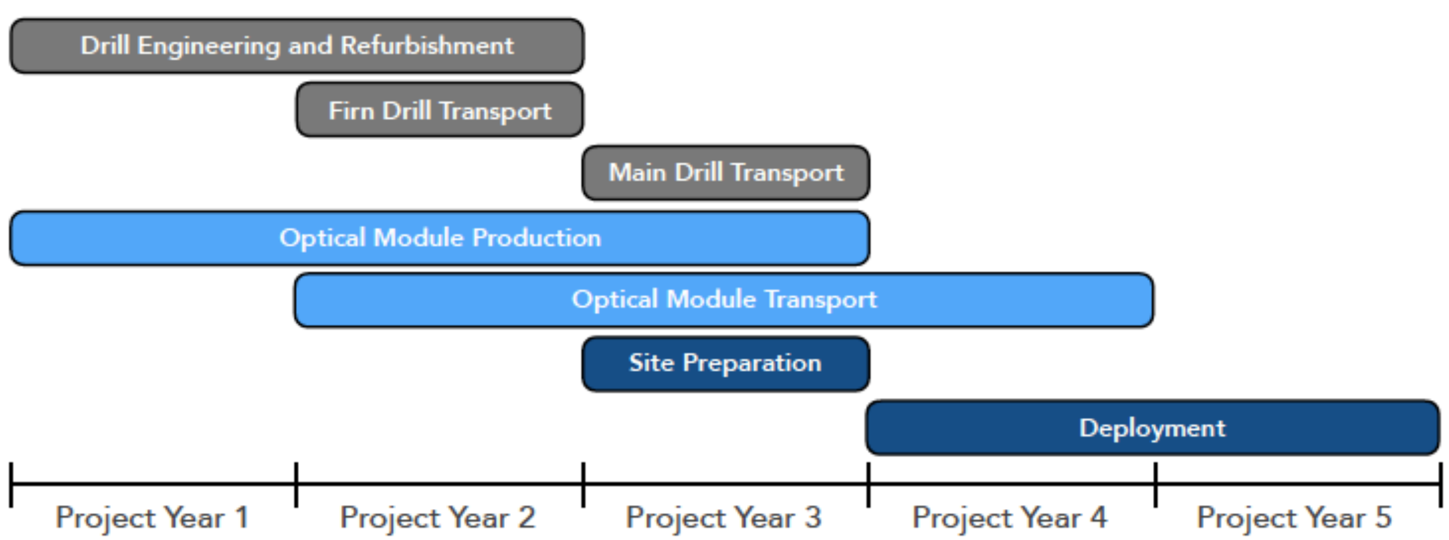
see also:
- PINGU LOI arXiv:1412.5106

The IceCube Upgrade



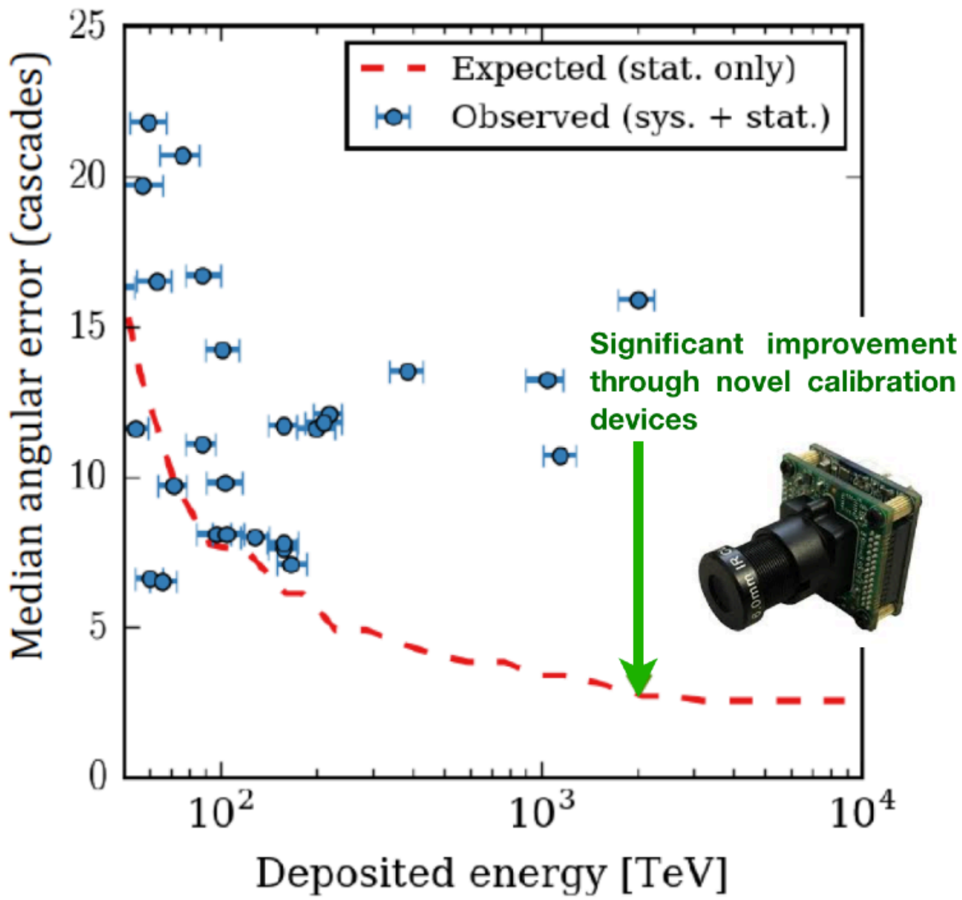
Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125





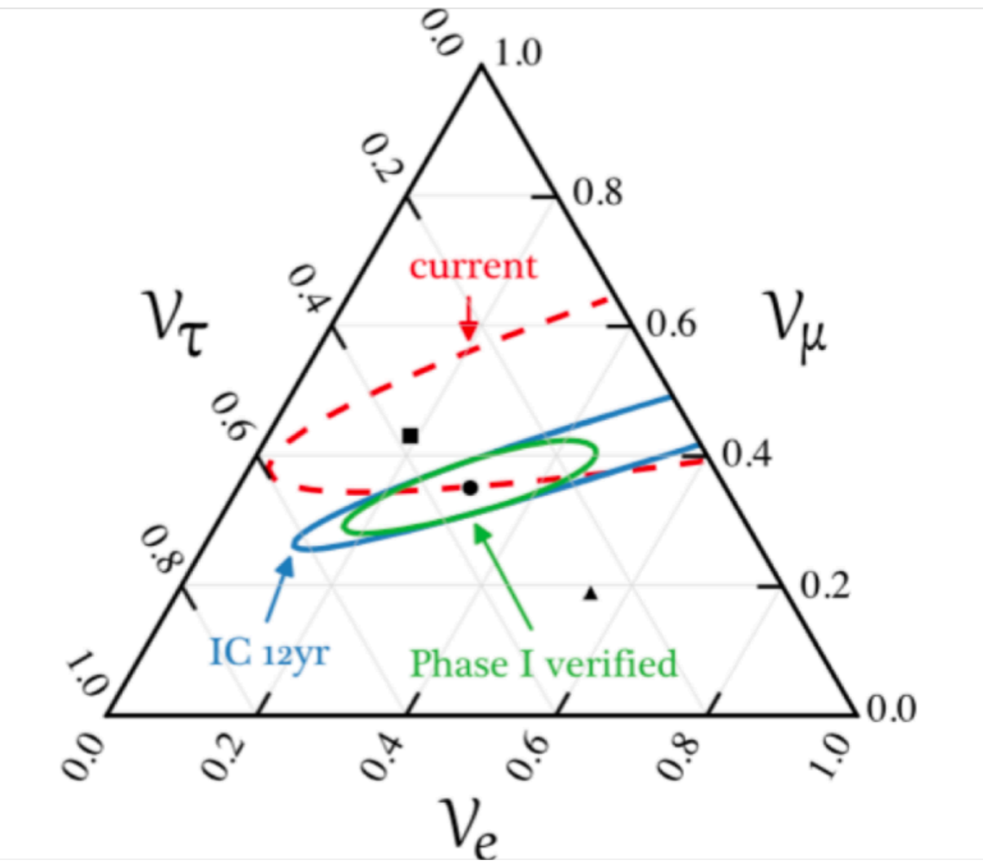
First step to restart South Pole activities
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Calibration devices
- Platform to test new technologies

The IceCube Upgrade

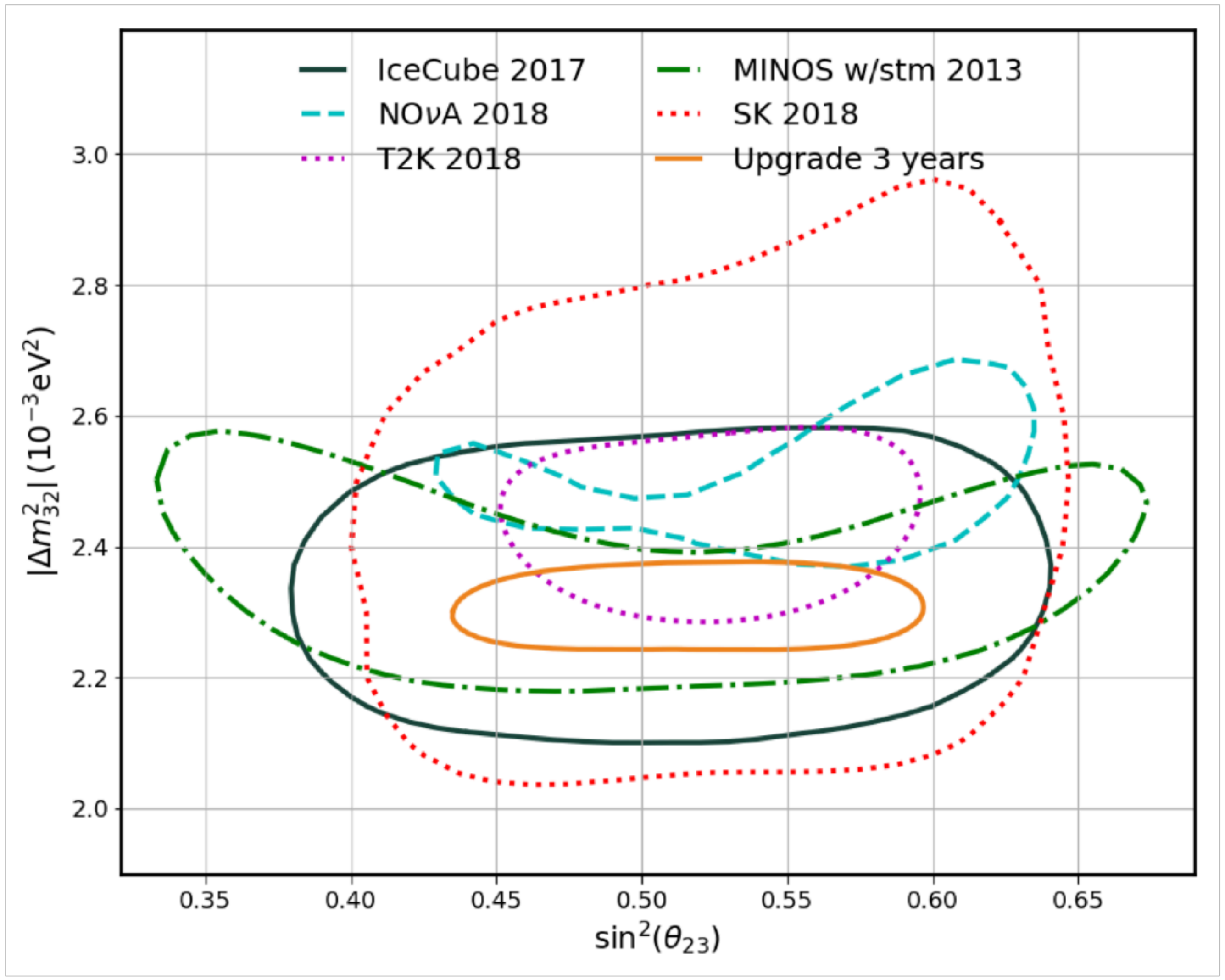


Recalibration campaign

- Improved ice model
- Retroactively apply improved ice-model to archival data
- Precision neutrino physics
- Multi-messenger science with improve pointing

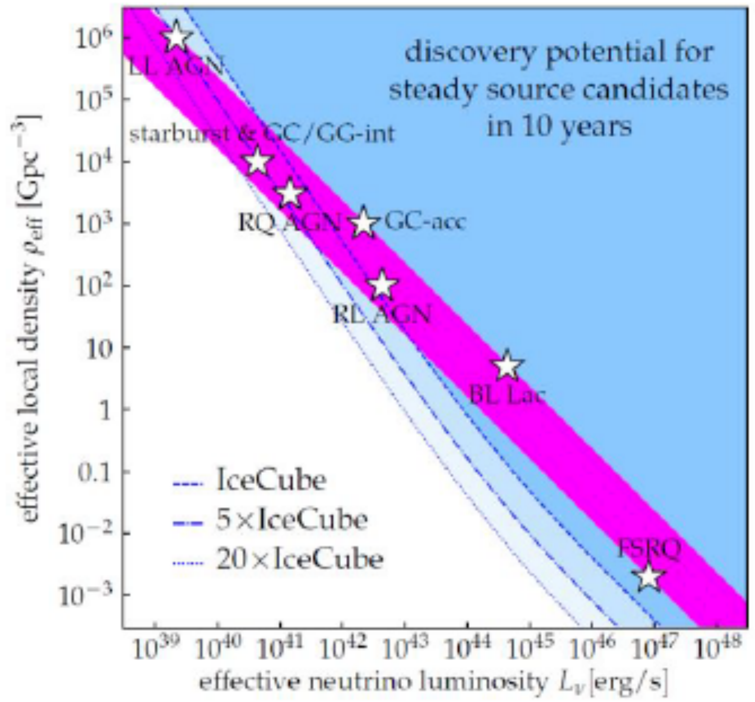


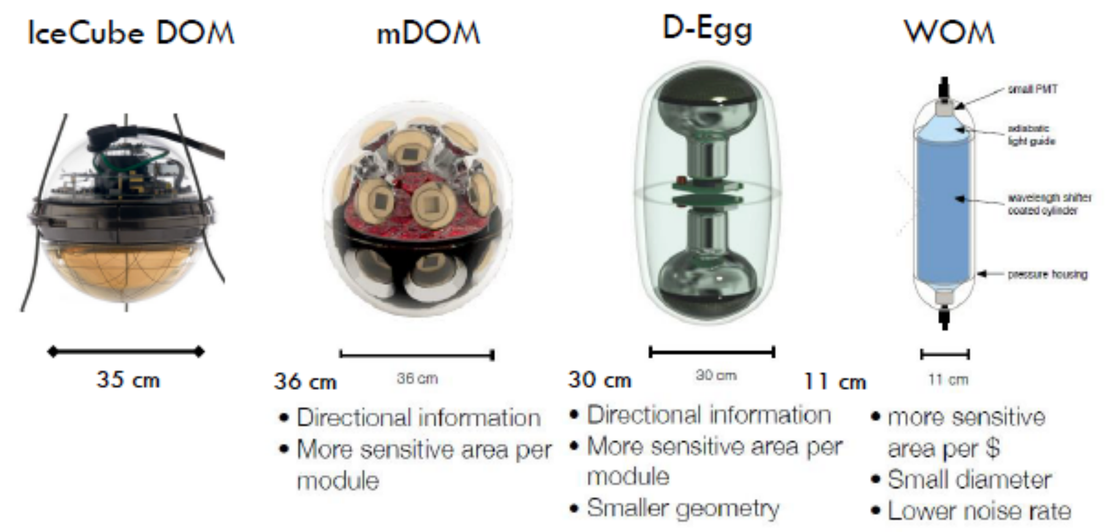
3σ discovery of cosmic tau neutrinos in 12 years of IceCube data, using the new calibration devices

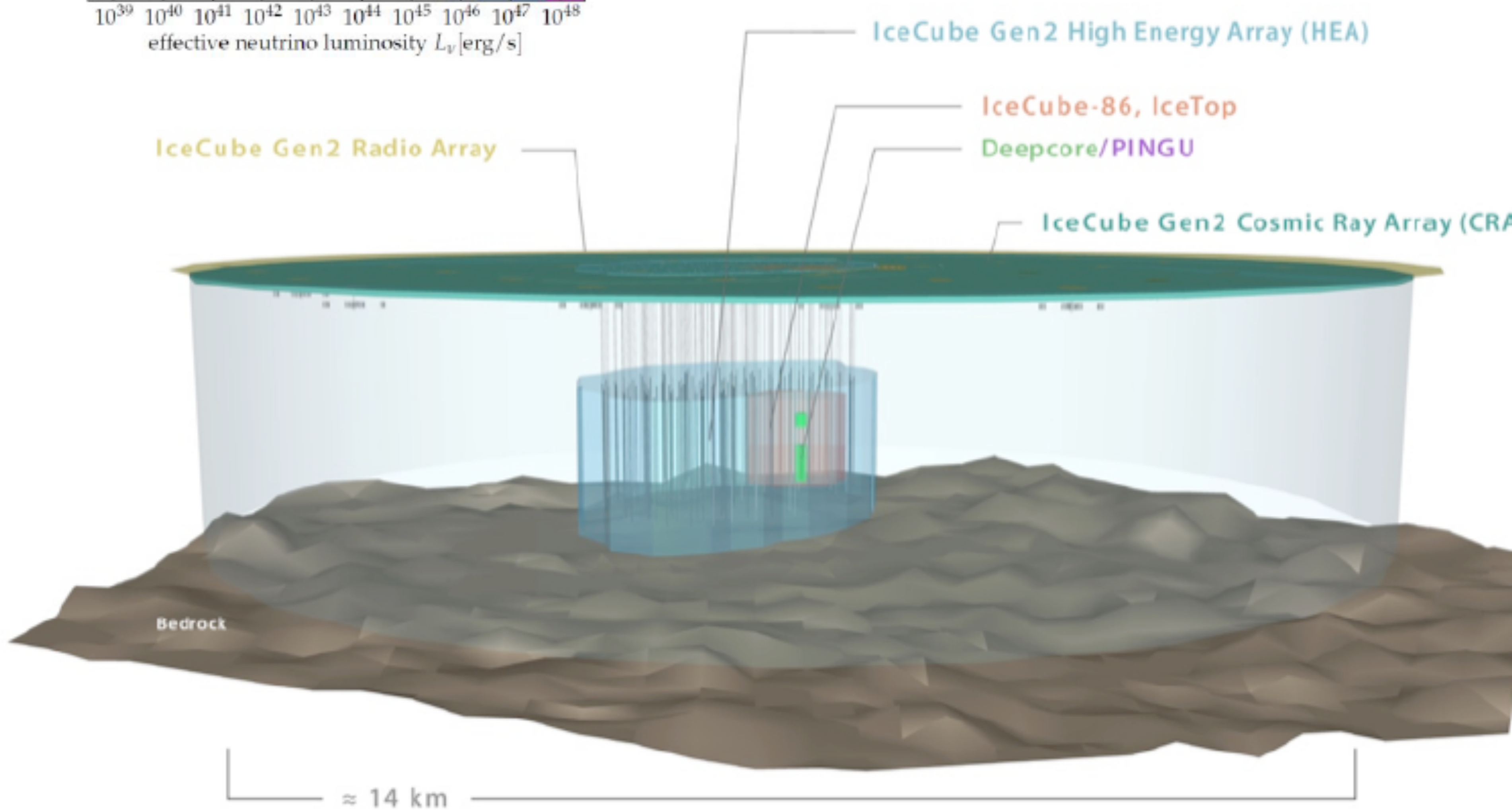


IceCube-Gen2

- IceCube has provided an amazing sample of events, but is still statistics limited
- Observed astrophysical flux is consistent with a isotropic flux of equal amounts of all neutrino flavors
- What is the flavor composition?
- What is the spectrum? Cutoff?
- Transients ?
- Multi-messenger physics?
- GZK neutrinos?
- New physics or something unexpected ?
- …

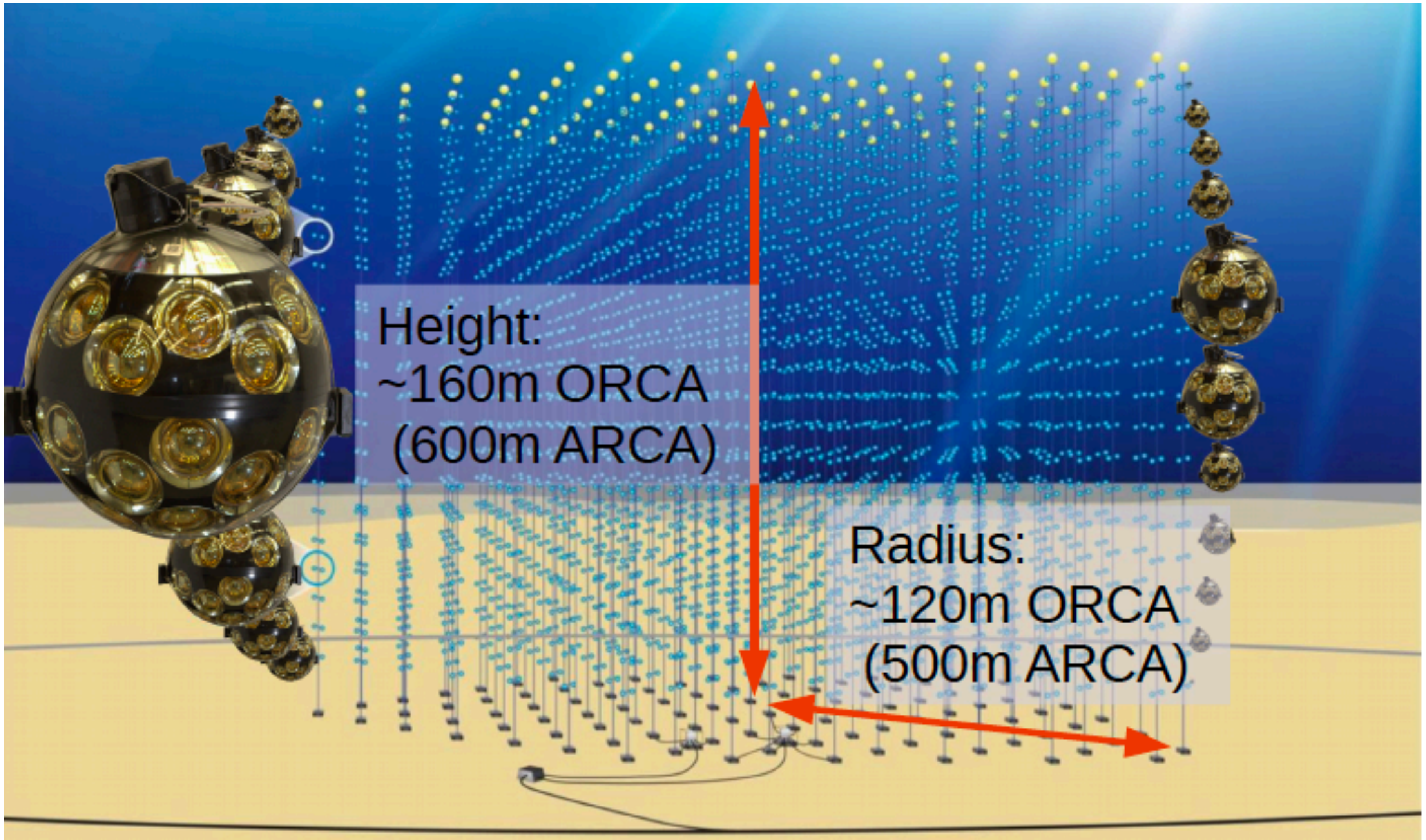






ORCA / KM3NeT see talk by Jannik Hofestaedt on Thursday

ORCA / KM3NeT



	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton

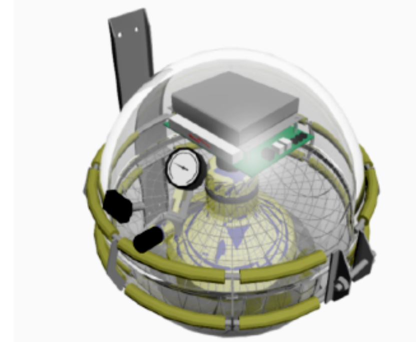
ORCA will consist of one dense KM3NeT Building Block

115 detection lines
Total: 64K * 3" PMTs
ARCA/ORCA construction on-going

Baikal-GVD: first clusters

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March. 2019

- GVD detector construction underway in Lake Baikal
- Currently clusters #2 and #3 are in operation while cluster #1 is subject to maintenance works
- Baikal-GVD expedition on-going (deployments until April 11th) Plan was to deploy and commission two new GVD-clusters (clusters 4 and 5), well underway (and **completed on April 7**)
  - Now reached 0.25 km³ effective volume

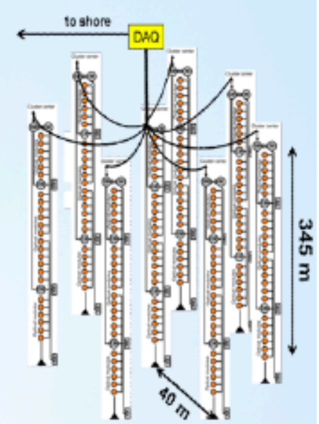


Optical module
PMT: R7081-100

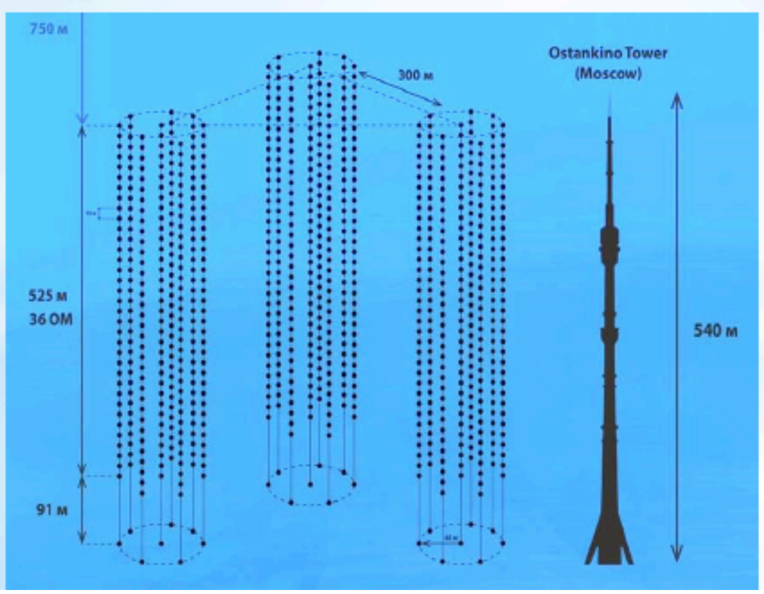
2018: 24 strings (864 OMs) – largest NT in the northern latitudes

Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	Ø80×345	Ø120×525	2×Ø120×525	3×Ø120×525
Eff. Vol	0.03 km³	0.05 km³	0.1 km³	0.15 km³

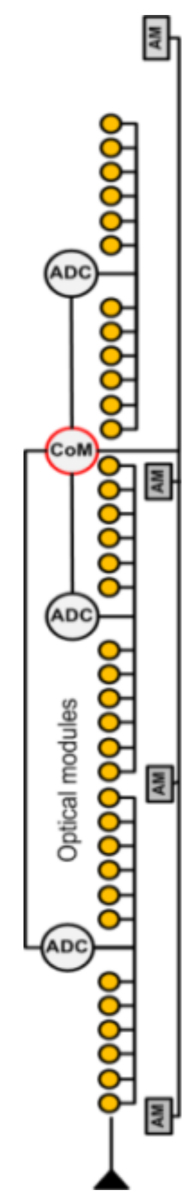
2015: «Dubna»
8 strings (192 OMs)

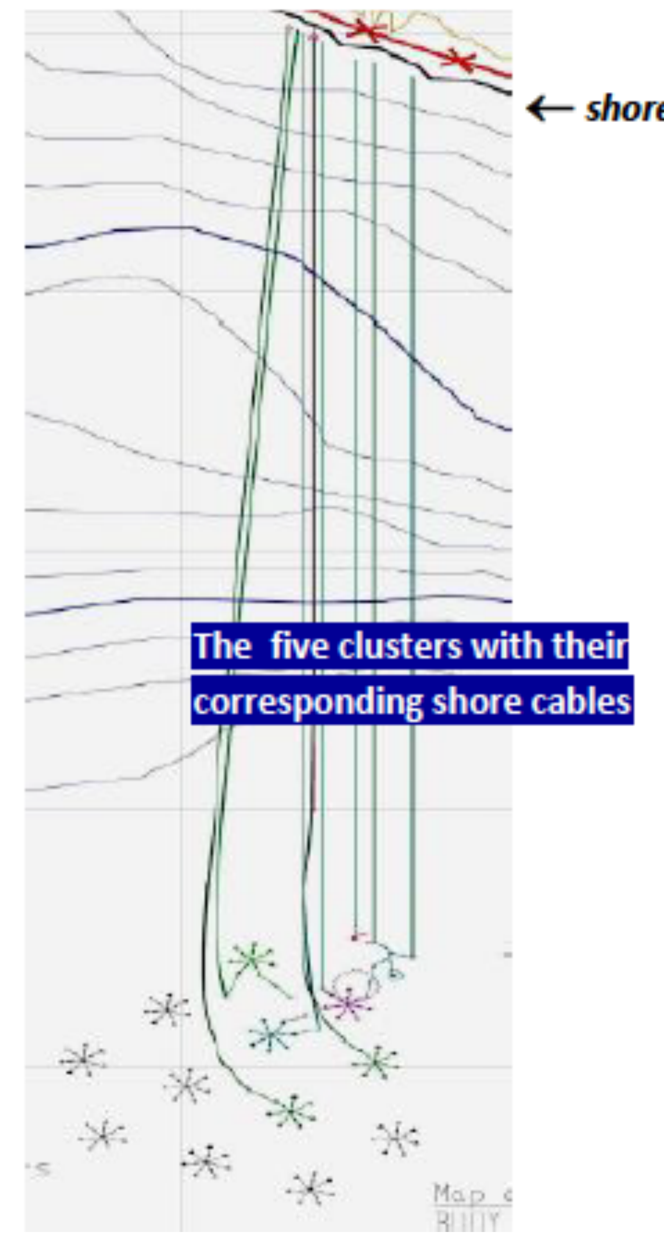


2018: Data taken with three Baikal-GVD clusters



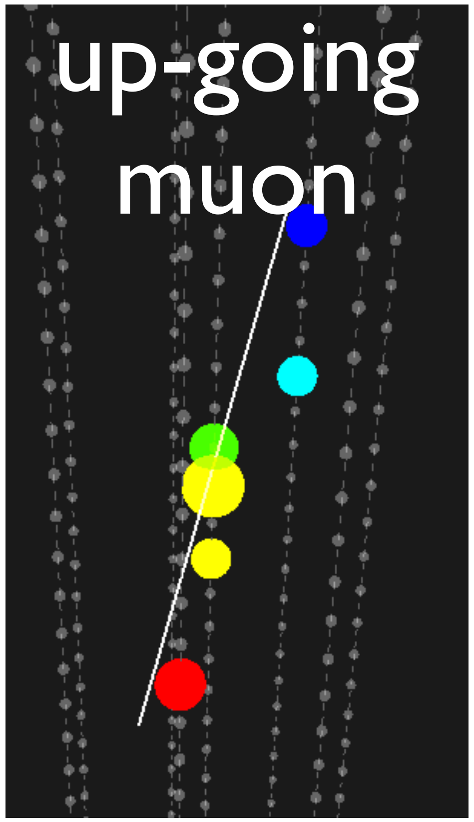
Status in 2018
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

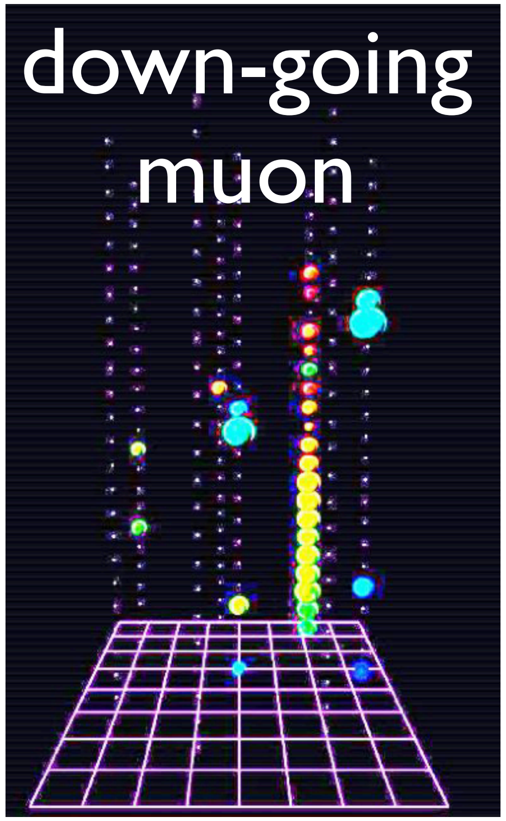


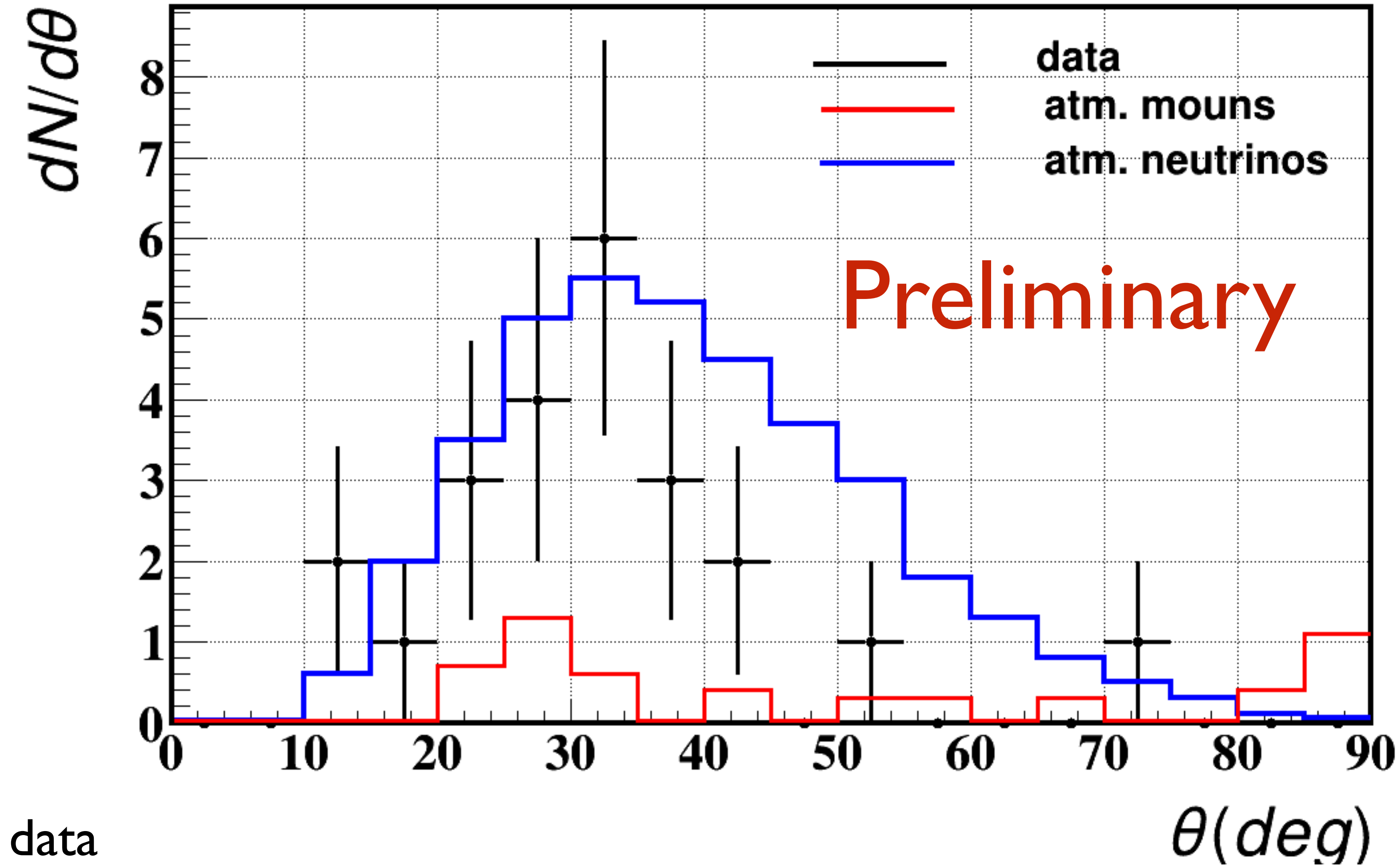


Atmospheric Neutrino Analysis at GVD

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March, 2019







- 33live days were analyzed of the first GVD data
- Event selection via BDT
- Preliminary results:
  - ~ 3 events – estimation of atm. muons background
  - ~36 events – estimation of signal atm. neutrinos
  - 23 events observed in data

Atmospheric Neutrino Physics starting at GVD

GVD-1 to reach 0.4 km³ by 2021 with 9 clusters and 2592 OMs

About 0.6 astrophysical events/year are expected per GVD cluster

Baikal-GVD aims on search for astrophysical neutrinos

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March, 2019

Basic approach in GVD construction:
* Flexible structure allowing an expand, upgrade and rearrange of the detection syste
and
* Simplicity of the basic detector elements

- 1370 m maximum depth
- Distance to shore ~4 km

- Absence of high luminosity from biology and K^{40} background

- Water properties:
  Abs. length: 22 ± 2 m
  Scatt. length: $L_s \sim 30\text{-}50$ m
  $L_s/(1-\langle\cos\theta\rangle) \sim 300\text{-}500$ m

  Strongly anisotropic phase function: $\langle\cos\theta\rangle \sim 0.9$

- Possibility to deploy the detector from the ice of the lake

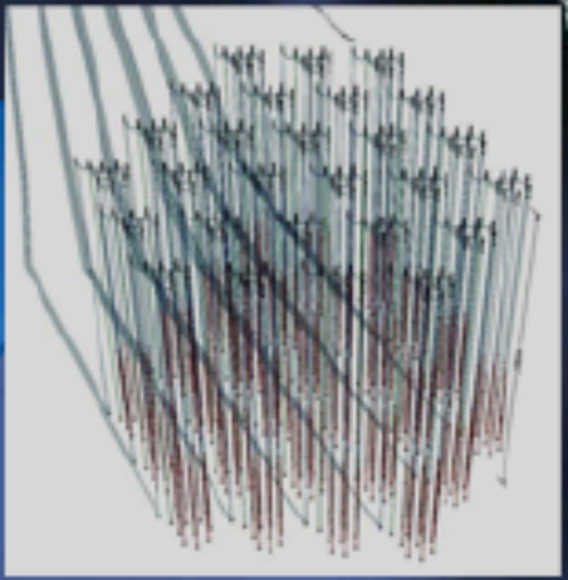
Половинная

3500м

1366м

N 51,76°

E 104,41°



3D array, 10^4 photodetectors

Eff. volume ~1.5 км^3

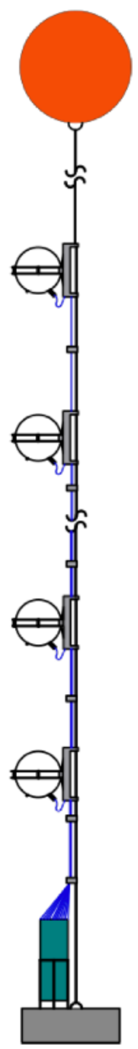
2768 m

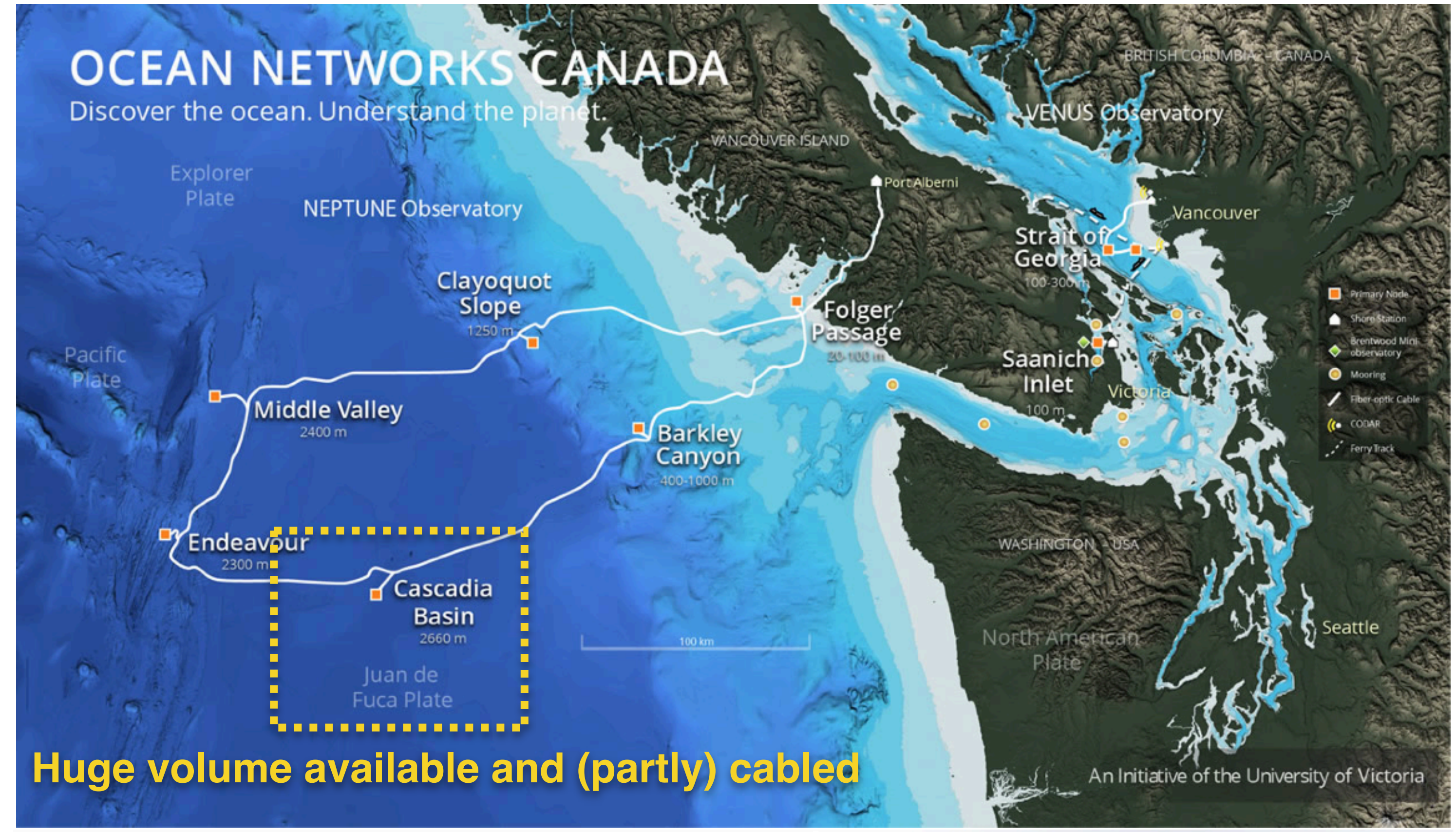
© 2012 GIS
Data INTAS Project 99-1669
Image © 2012 TerraMetrics

Google ea

ONC

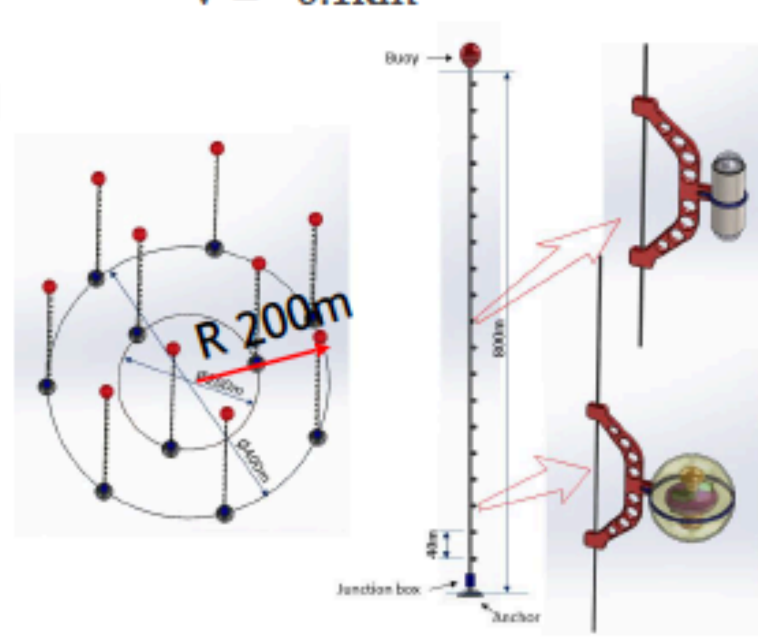
- Ocean Net
  - New idea to build a neutrino telescope in the Pacific Ocean
  - Rely on good infrastructure of the Ocean Network Canada
- Straw Pathfinder Deployed in 2018, data taking on-going
- ONC (U.VICTORIA), U. of Alberta, Queen's U., TU Munich



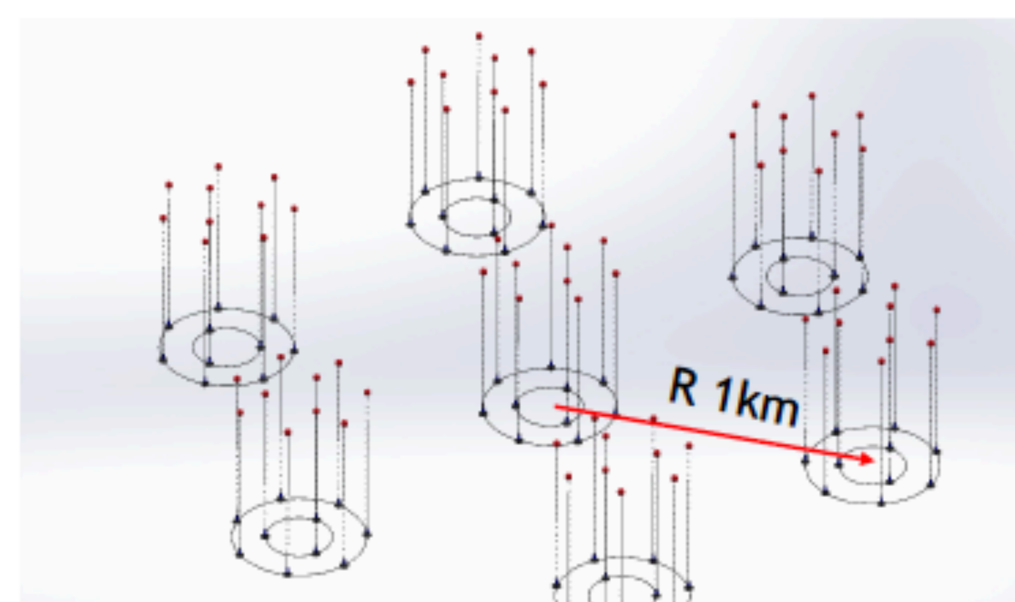


10 strings bundle
$V = \sim 0.1 km^3$

70-100 strings
$V = \sim 2 km^3$



PRELIMINARY geometry



PRELIMINARY geometry

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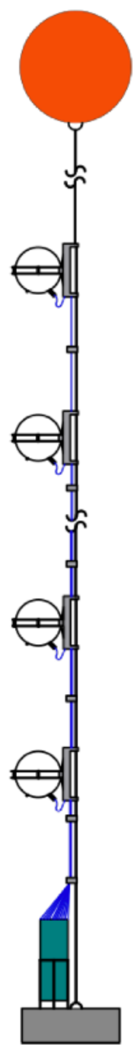
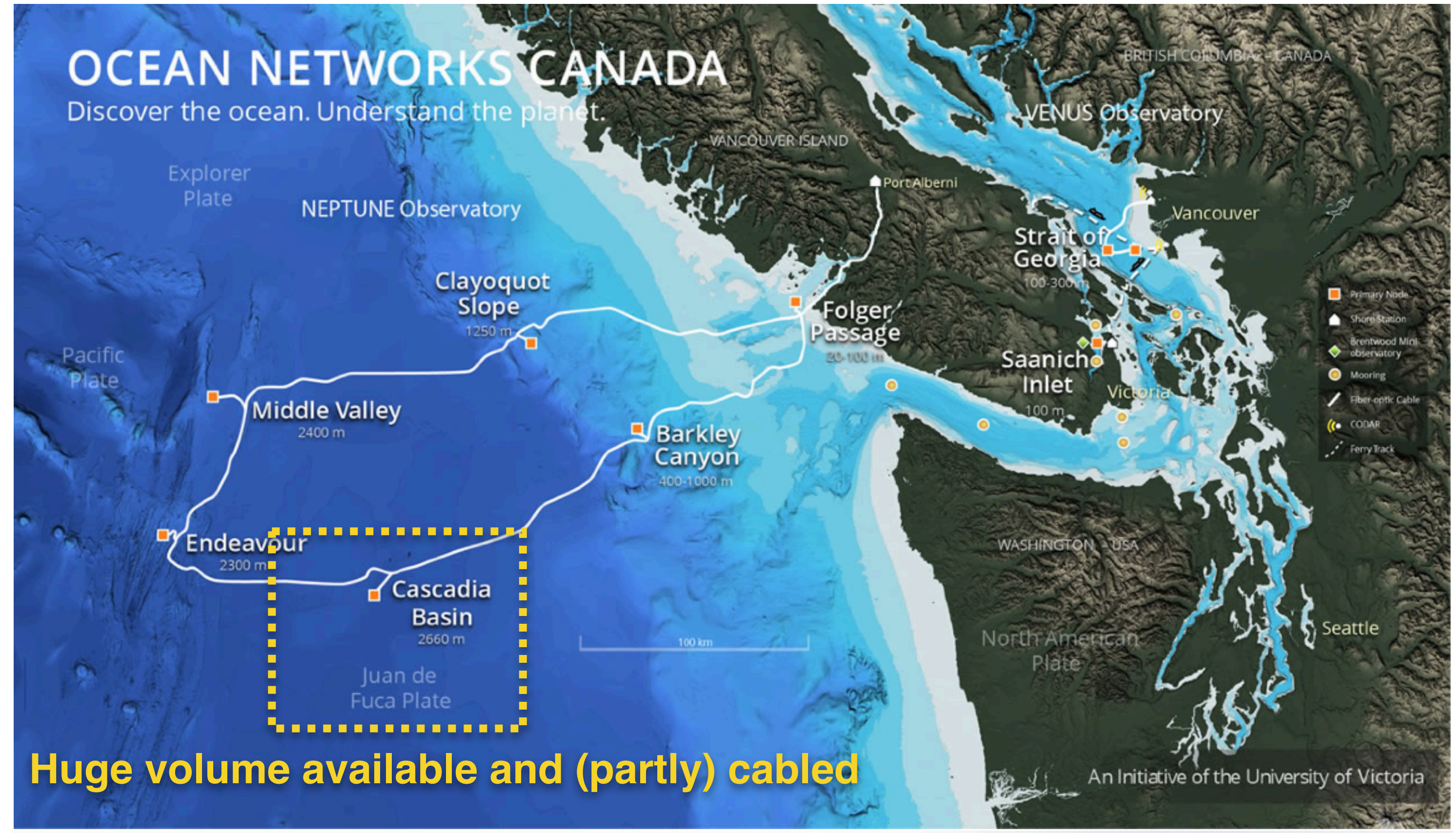
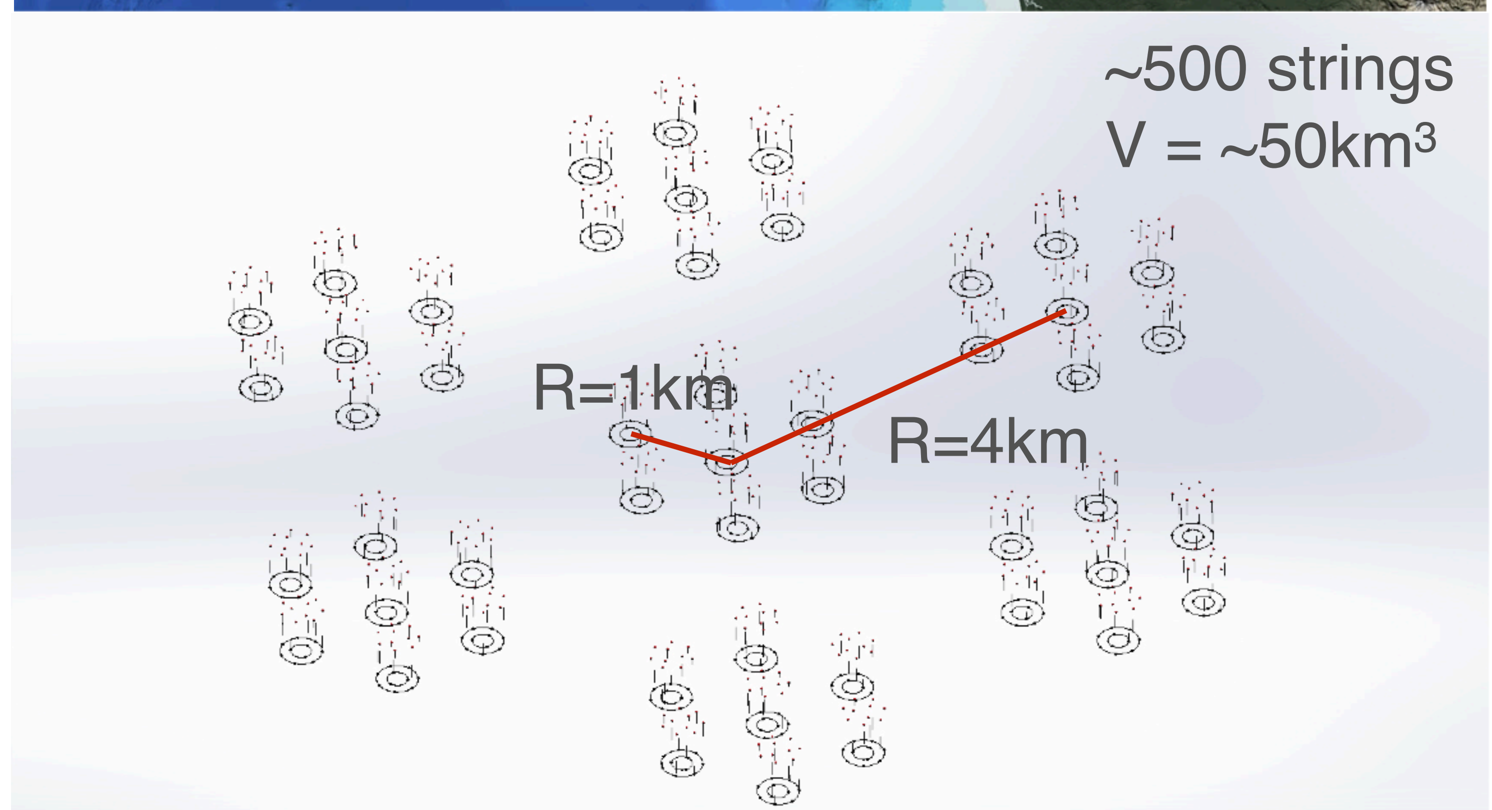




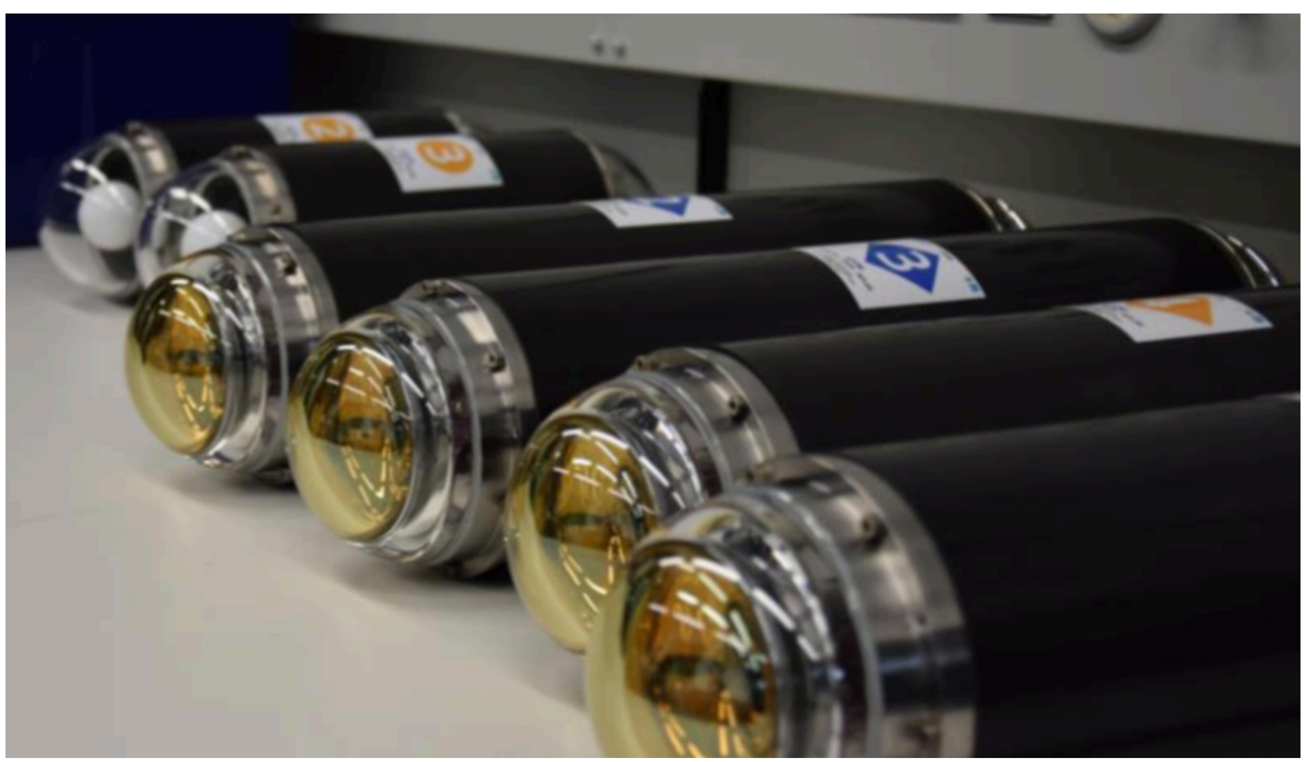


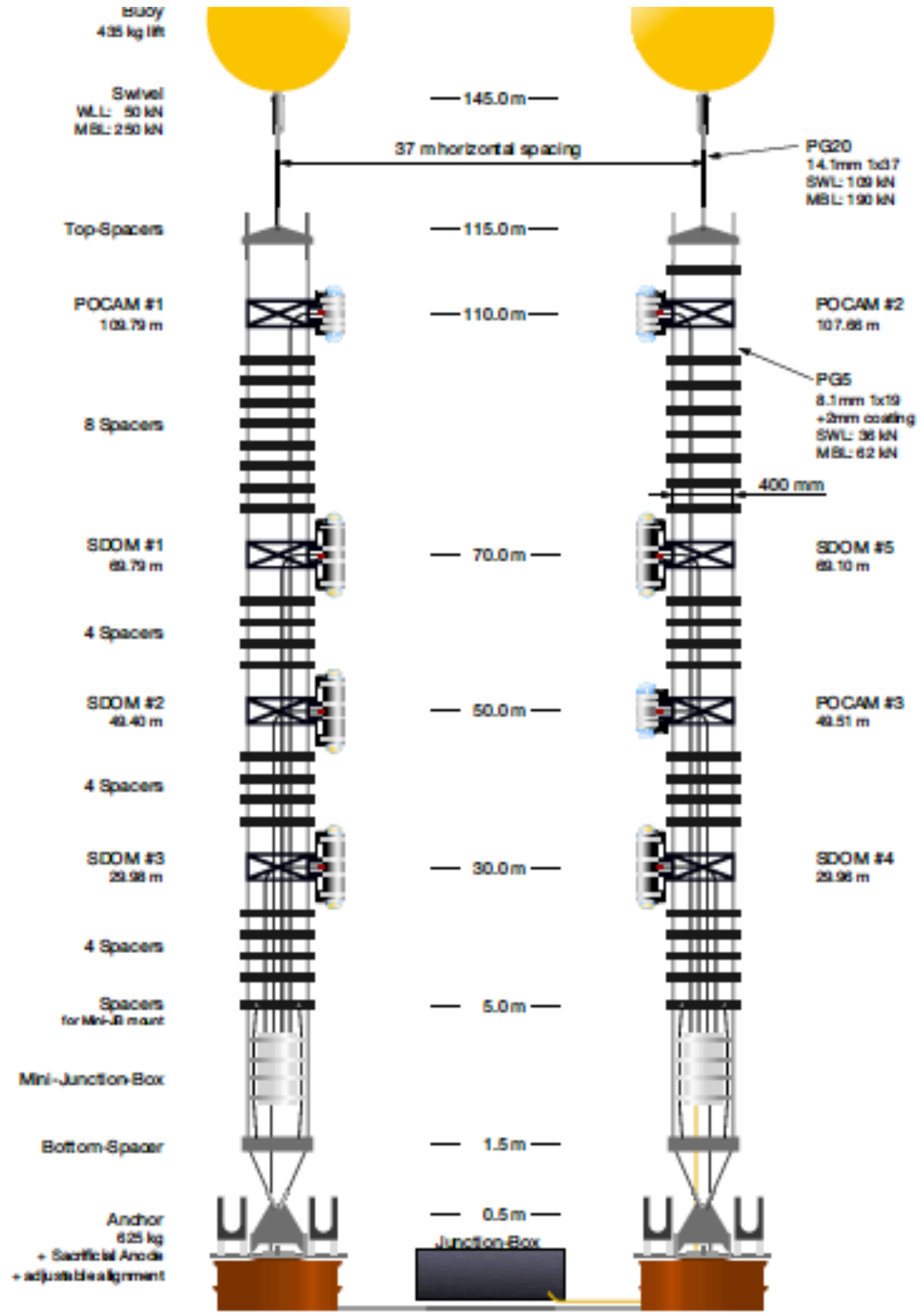
STARTING UP CONCEPTUAL DESIGN

M. Boehmer et al 2019 JINST 14 P02013

STRAW

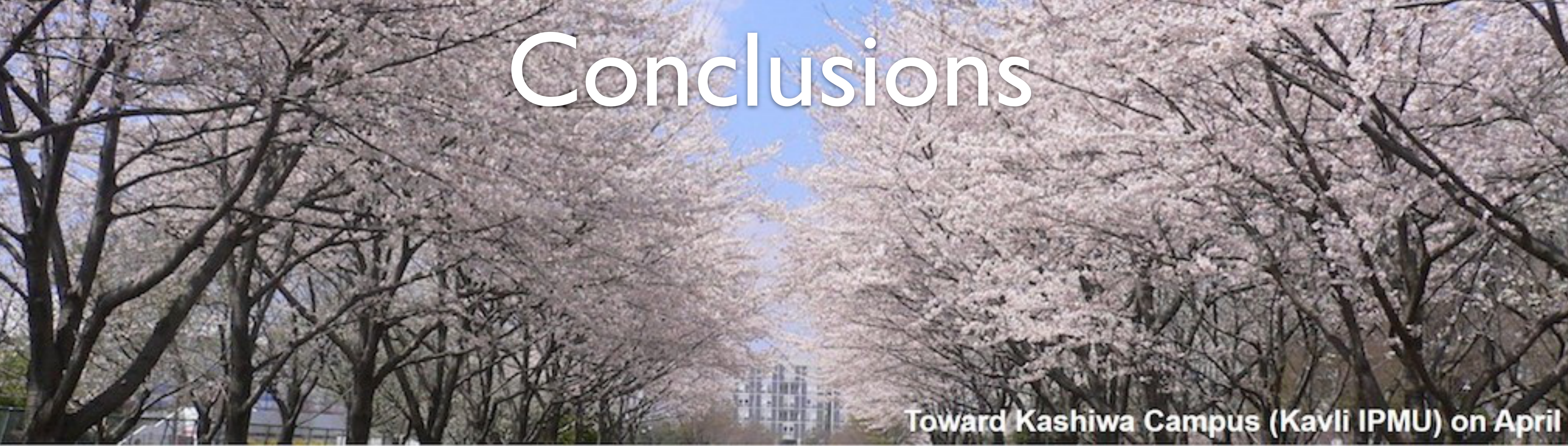
- STRAW - **STR**ings for **A**bsorption length in **W**ater
  - Pathfinder mission towards a possible large scale neutrino telescope
  - Deployed in June 2018 at the Cascadia Basin site operated by Ocean Networks Canada (ONC)
  - Depth of about 2600meters
  - Two STRAW120 meters tall mooring lines
    - instrumented with 3 POCAMs and 5 sDOMs





Conclusions

Conclusions



- We have now entered the era of neutrino astronomy
- Neutrino Telescopes accumulate rich high-statistics dataset of atmospheric neutrinos
  - Competitive oscillation parameter measurements
  - World-leading tau-neutrino appearance measurements
  - First results on neutrino mass ordering
  - Cross-section measurements, Sterile neutrinos, Non-standard interactions, and more…
- Next generation neutrino telescopes is becoming a reality fast
  - Multi-messenger astroparticle physics
  - Tremendous potential for neutrino physics / neutrino property measurements

Bonus materials

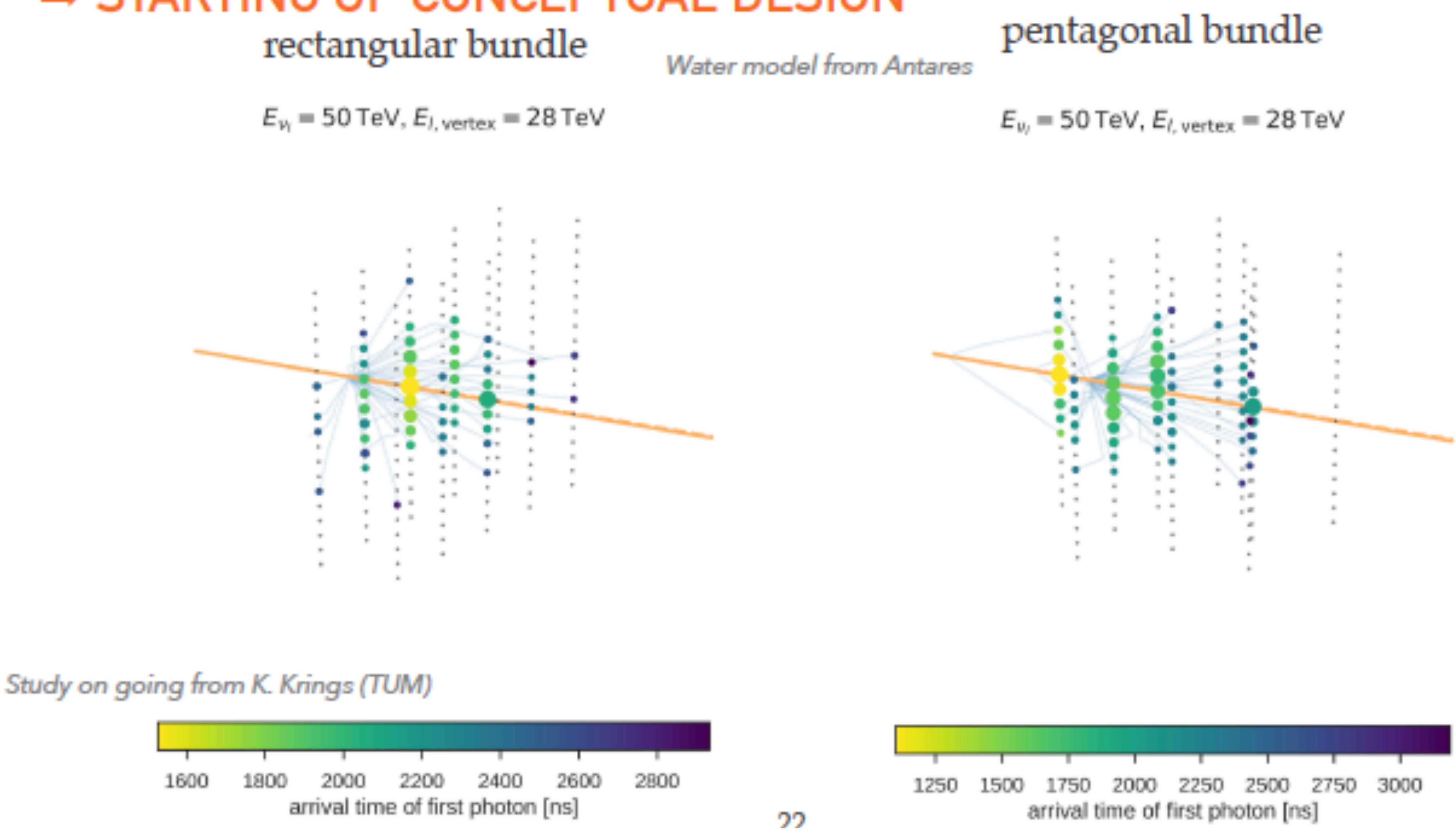
Details see E. Resconi @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March, 2019

ONC

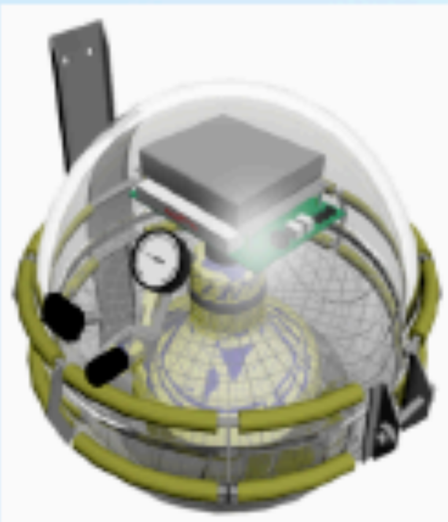
NEW ENTRY ON THE NEUTRINO MAP – @ONC

BRAINSTORMING AROUND A SEGMENTED DETECTOR FOR HE HORIZONTAL TRACKS

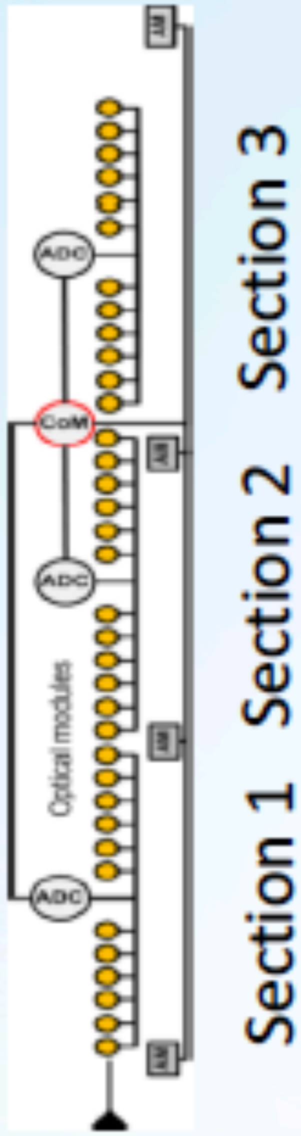
➡ STARTING UP CONCEPTUAL DESIGN

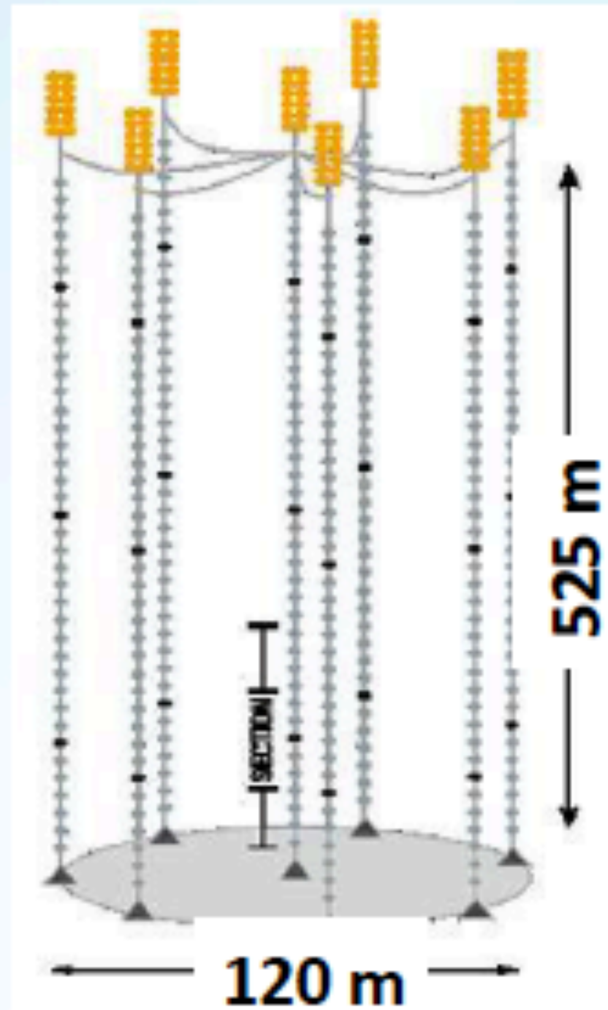


Baikal-GVD: phase 1 (2020-2021)

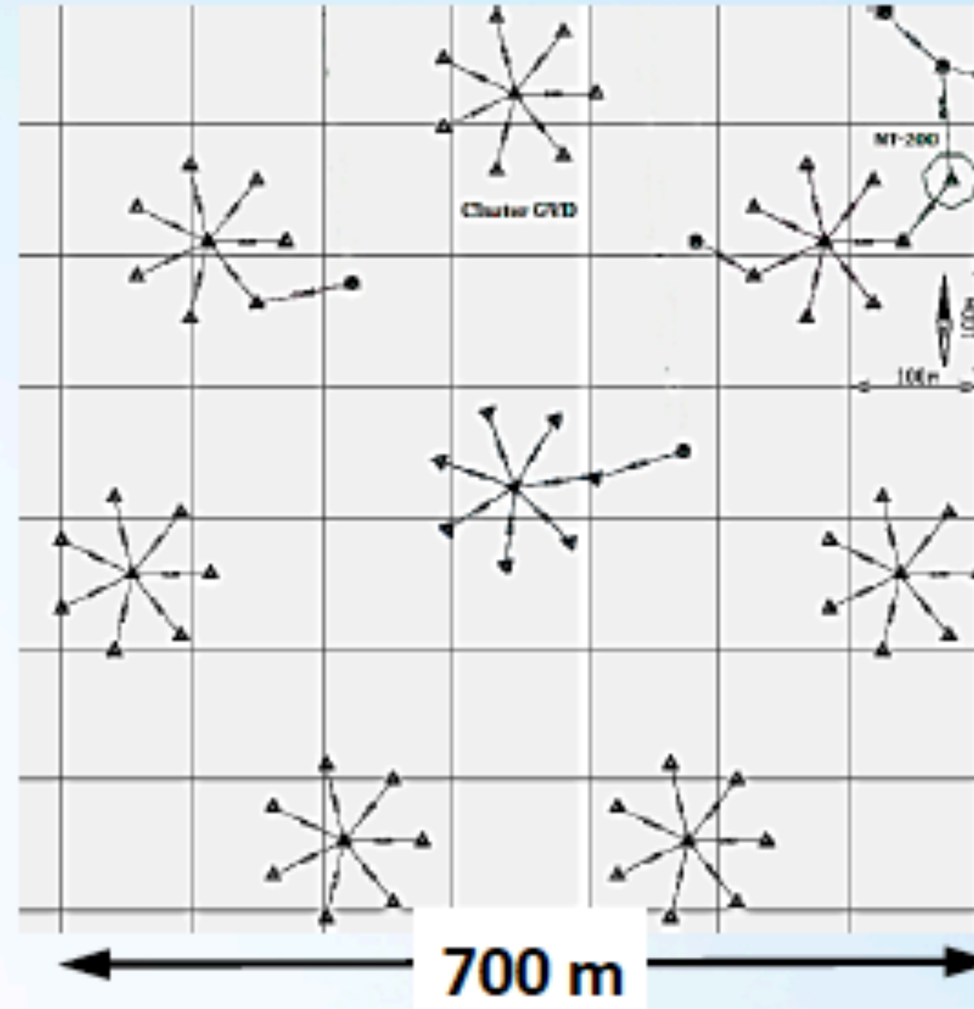


Optical module
PMT: R7081-100





Cluster: 8 strings



GVD-1: 8 clusters

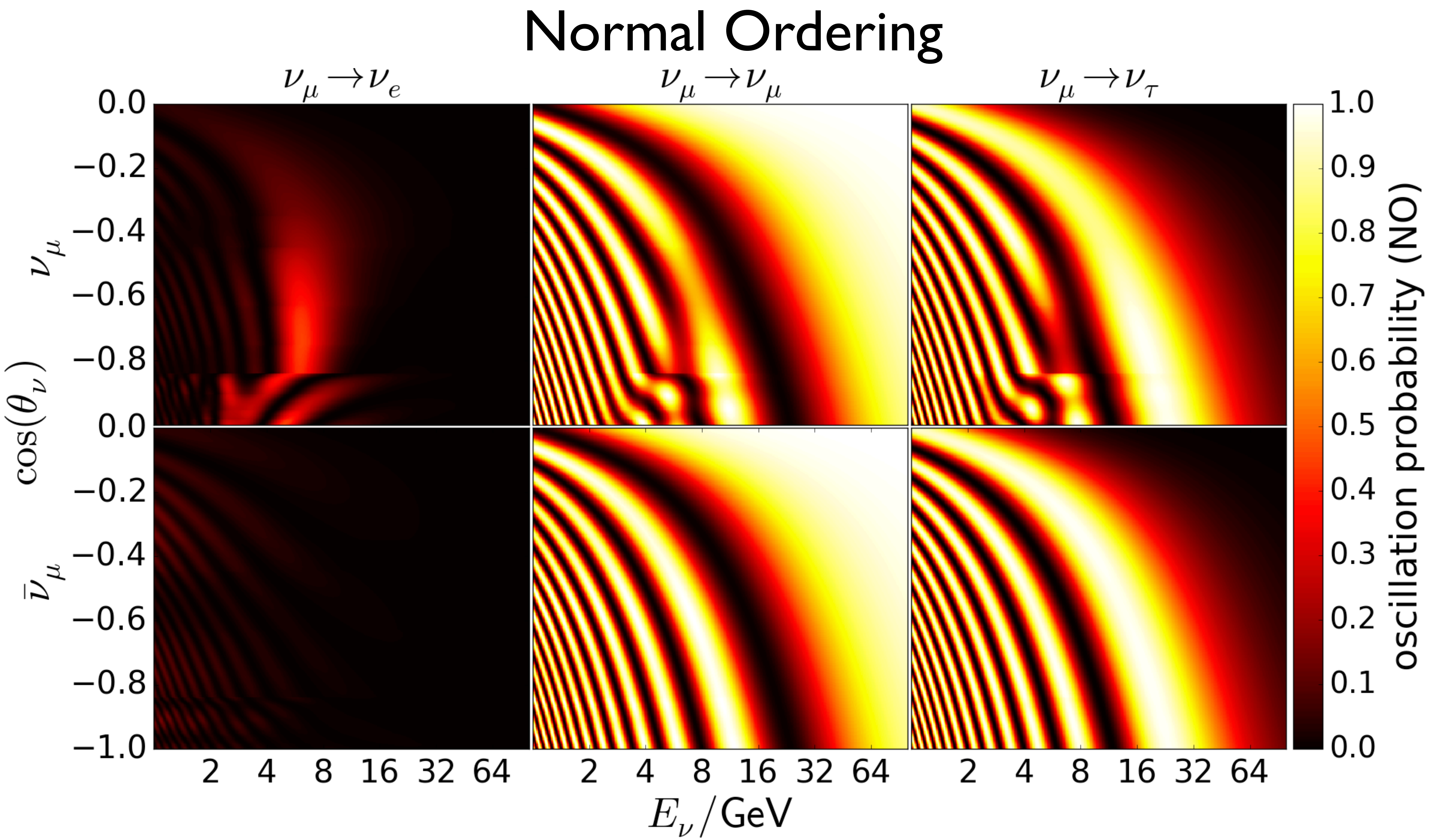
GVD-1	
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume	0.4 km^3

Directional resolution	Energy resolution
Cascades: 3.5° – 5.5°	δ(E/Esh) ~ 0.15
Muons: 0.25° - 0.5°	δ(lgE) ~ 0.4

Details see Olga Suvorova @ XVIII International Workshop on Neutrino Telescopes - Venezia - 18-22 of March, 2019

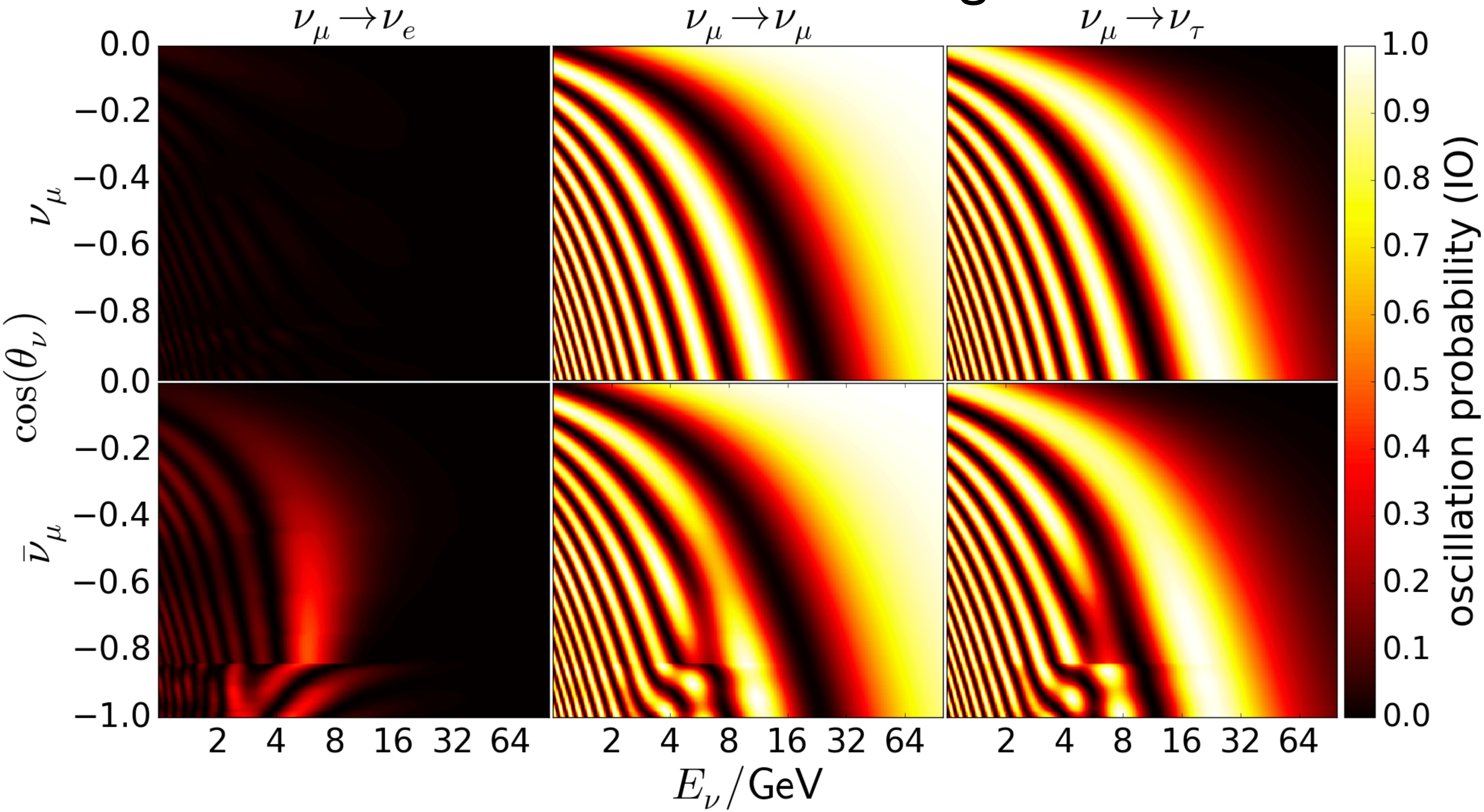
IceCube Collaboration arXiv:1902.07771

Neutrino Mass Ordering



Neutrino Mass Ordering

Inverted Ordering



ANTARES Coll. arXiv:1812.08650v1

Neutrino Oscillations ANTARES

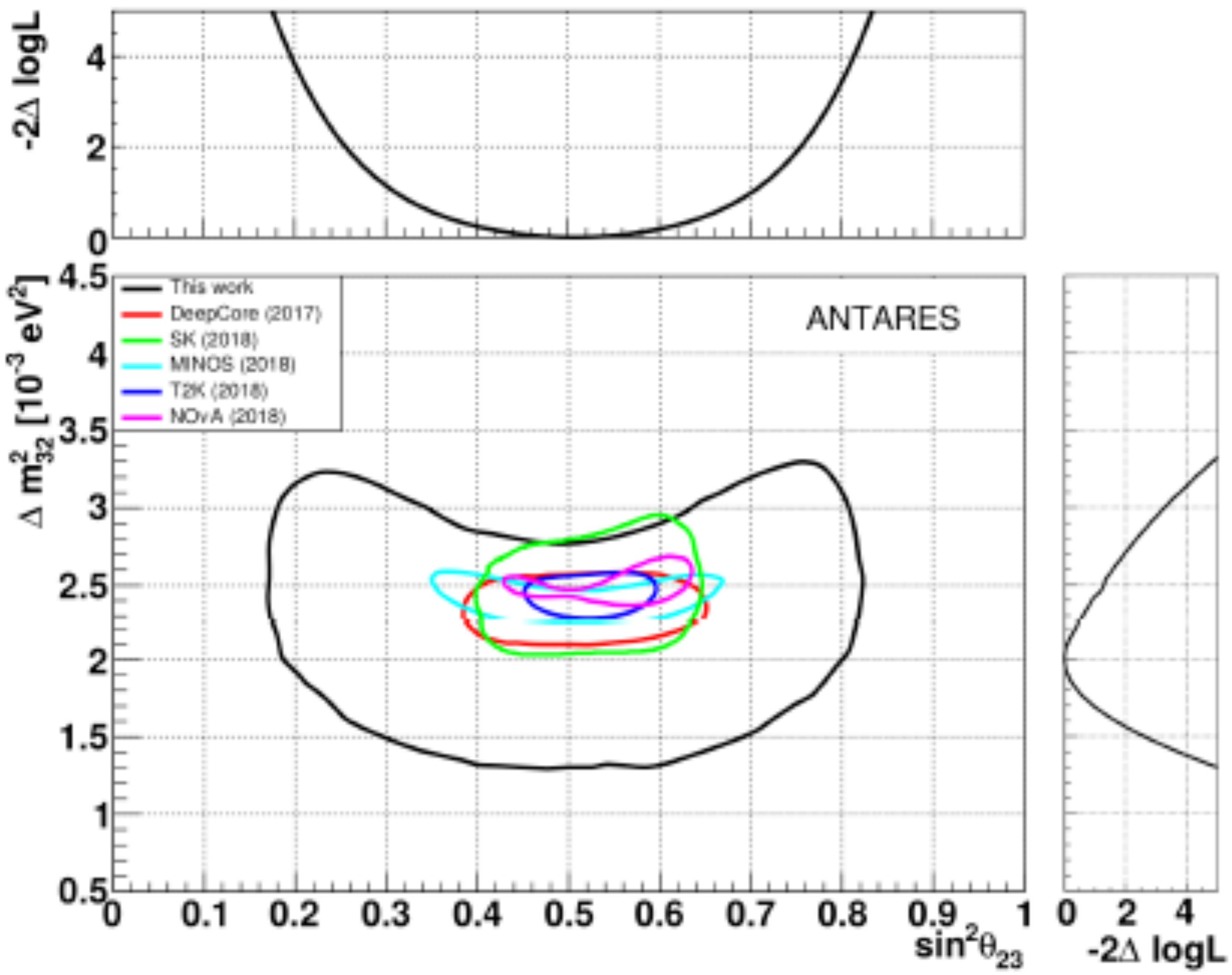


Figure 7: Contour at 90% CL in the plane of $\sin^2\theta_{23}$ and Δm^2_{32} obtained in this work (black line) and compared to the results by other experiments: IceCube/DeepCore (red) [7], Super-Kamiokande (green) [42], NOνA (purple) [43], T2K (blue) [44], and MINOS (light blue) [45]. The lateral plots show the 1D projections on the plane of the two oscillation parameters under study.

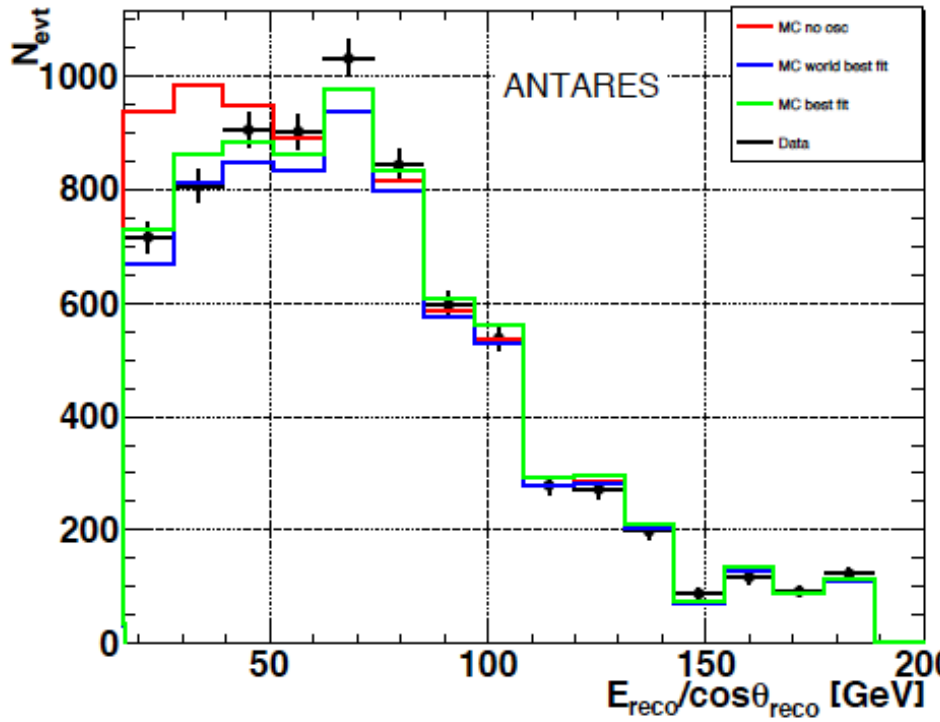
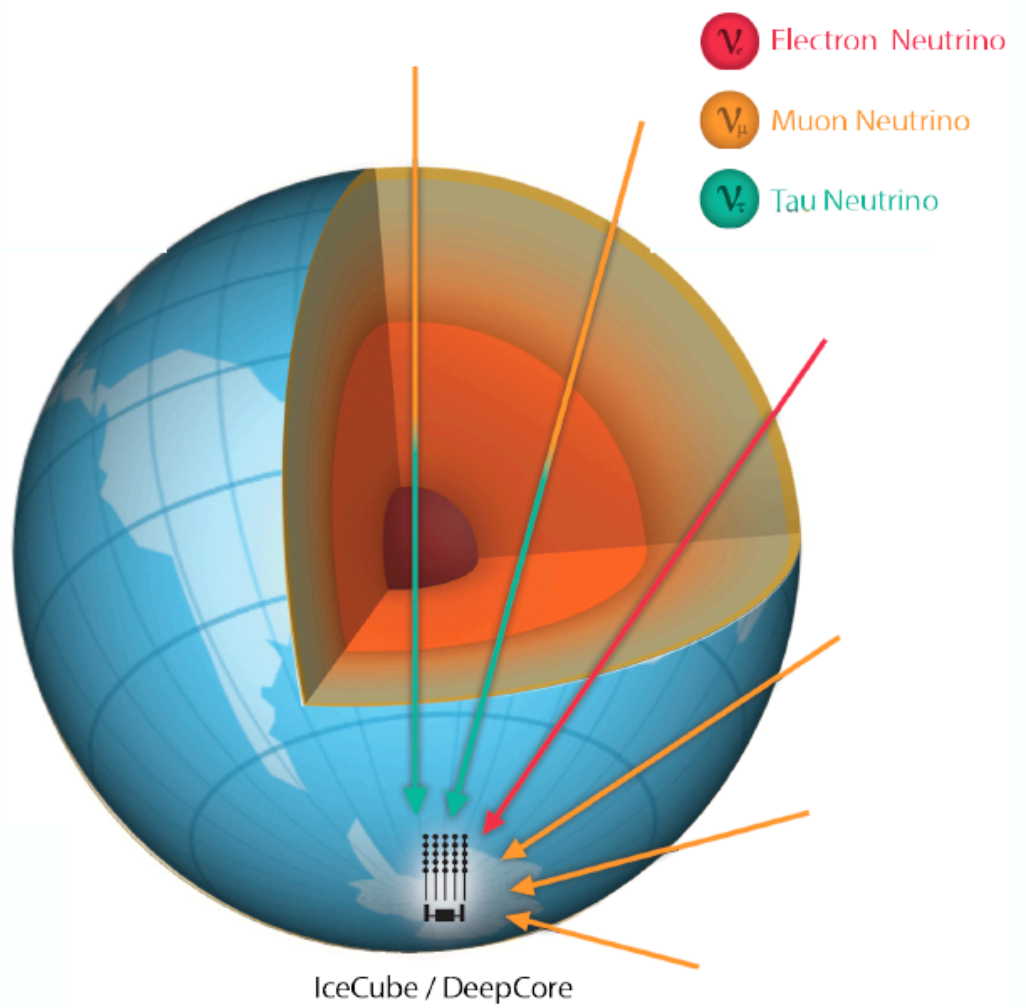
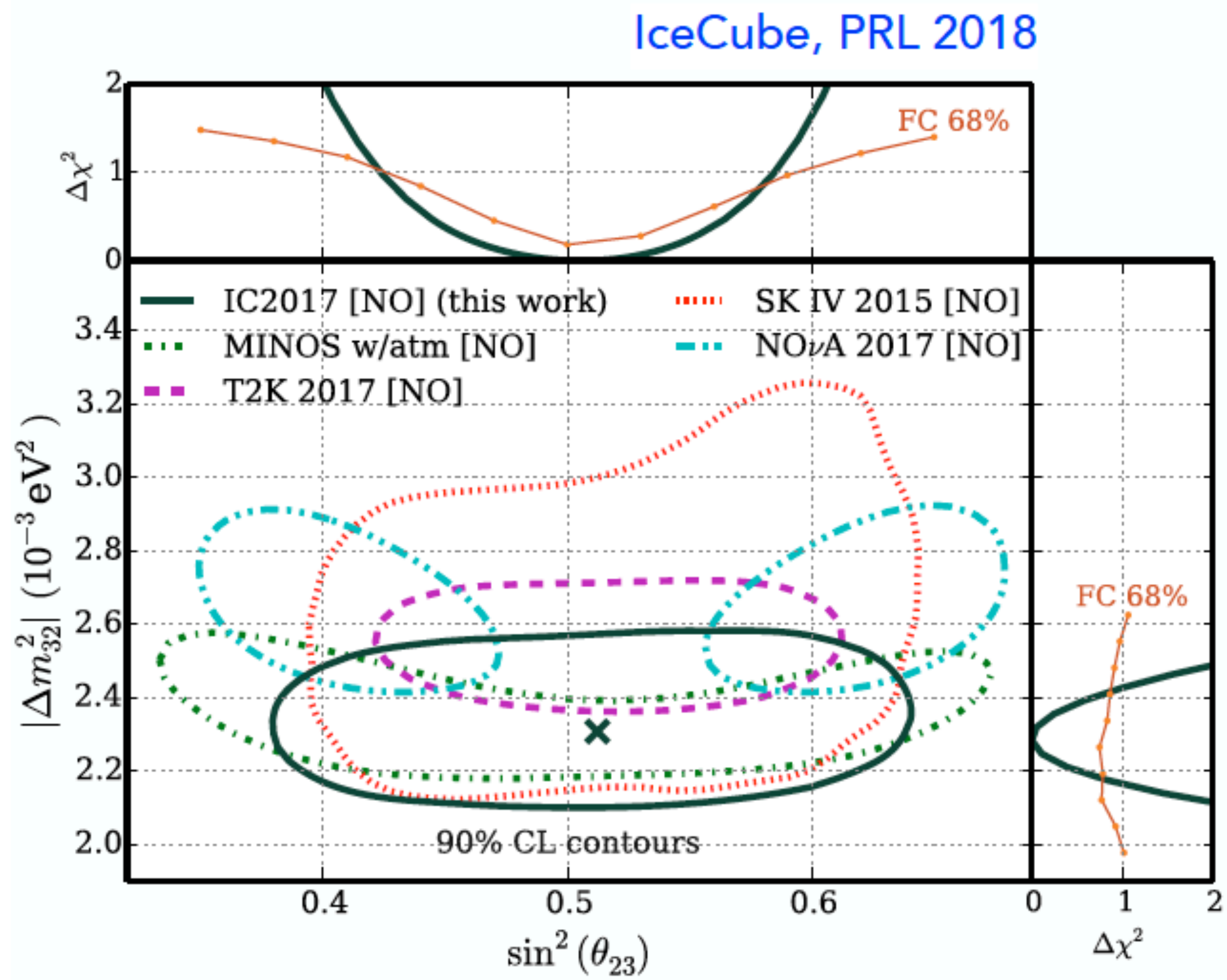


Figure 6: $E_{\text{reco}}/\cos\theta_{\text{reco}}$ distribution for data (black), MC without oscillation (red), MC assuming the world best-fit values (blue) [41] and MC assuming best-fit values of this analysis (green).

Neutrino Oscillations





- 3 years of IceCube Deep Core data
- Measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

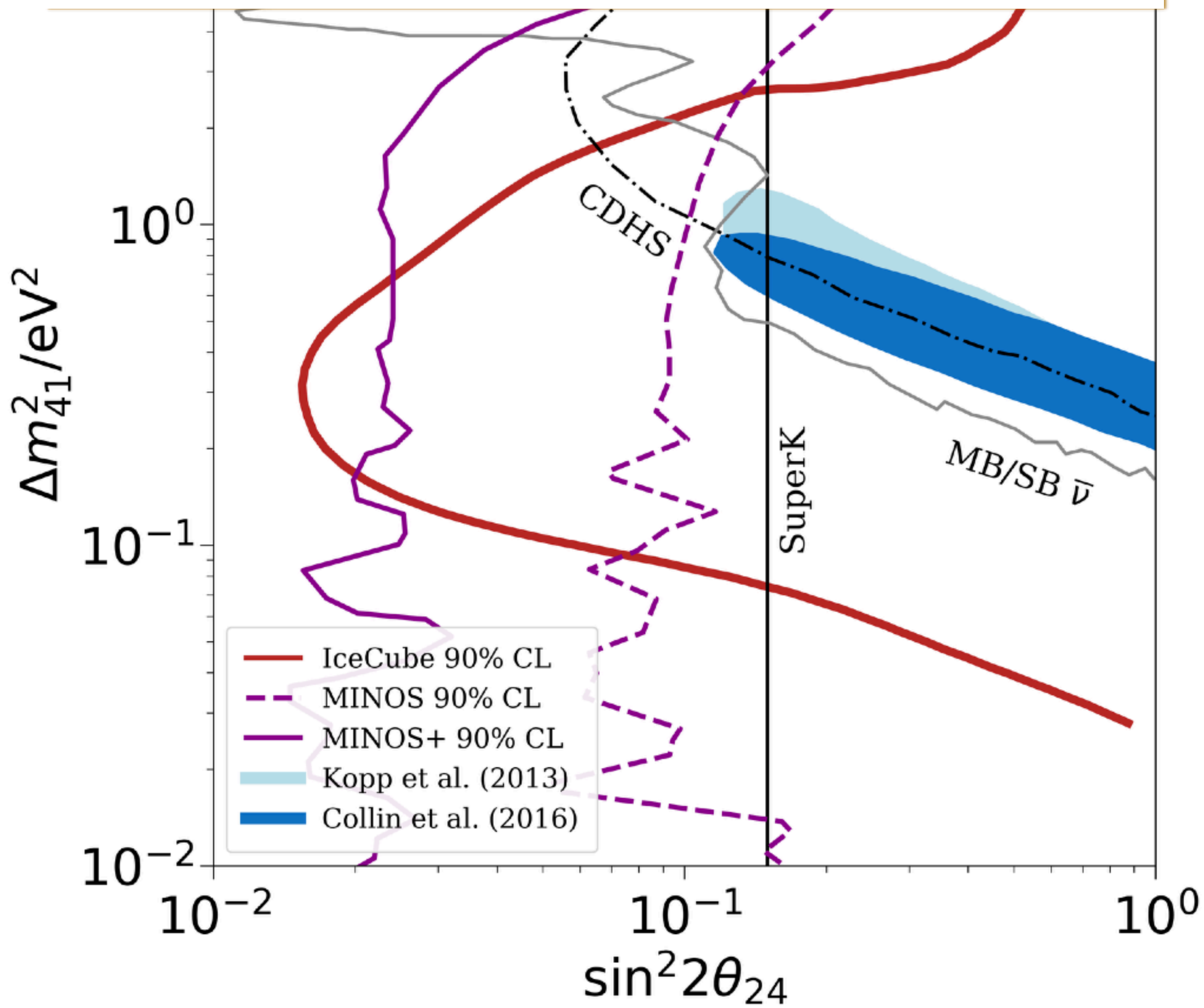
Normal ordering best fits

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\mathrm{eV}^2$$

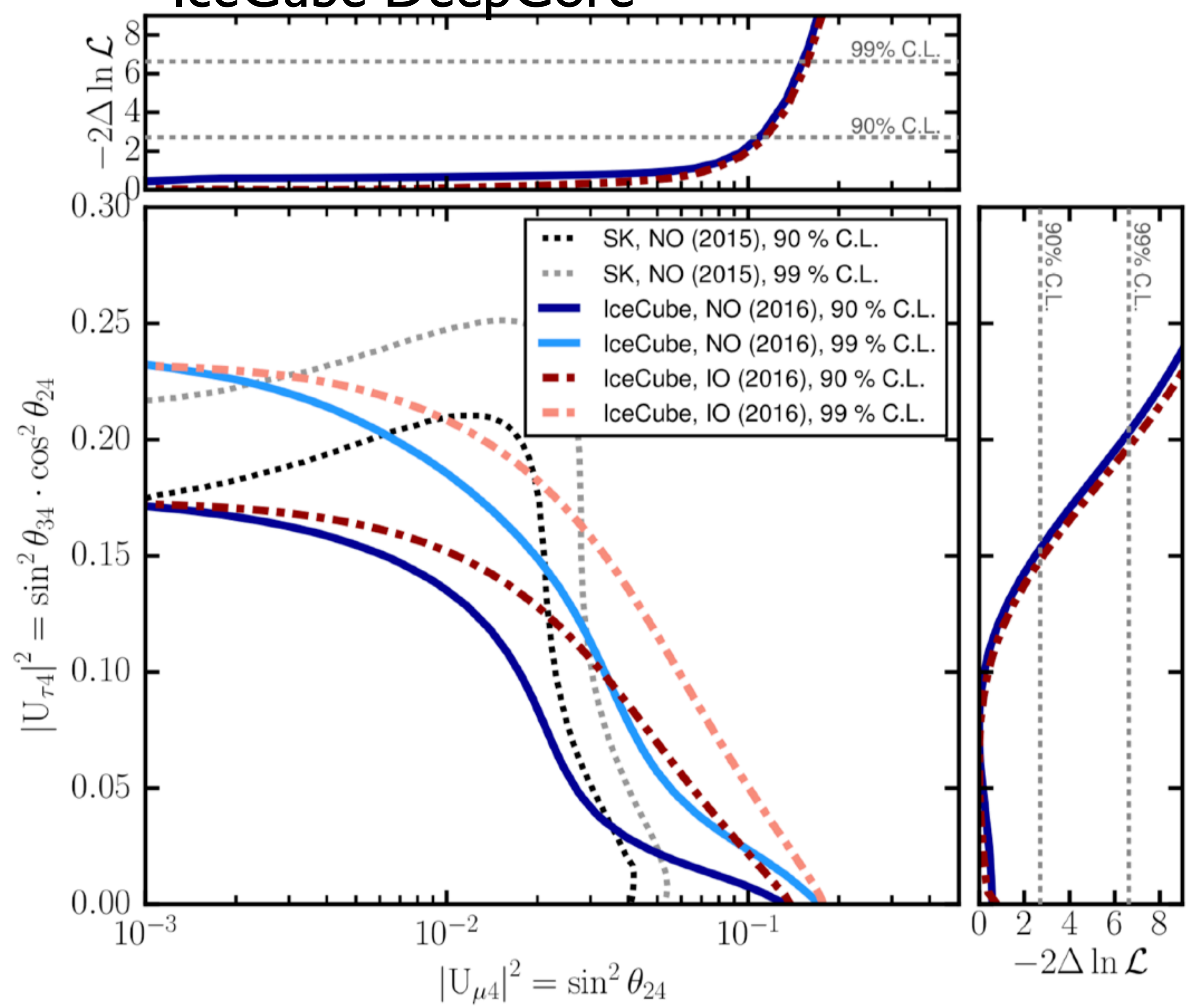
$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Sterile Neutrinos

M.G. Aartsen et al. (IceCube), Phys. Rev. Lett. 117, 071801 (2016), 1605.01990

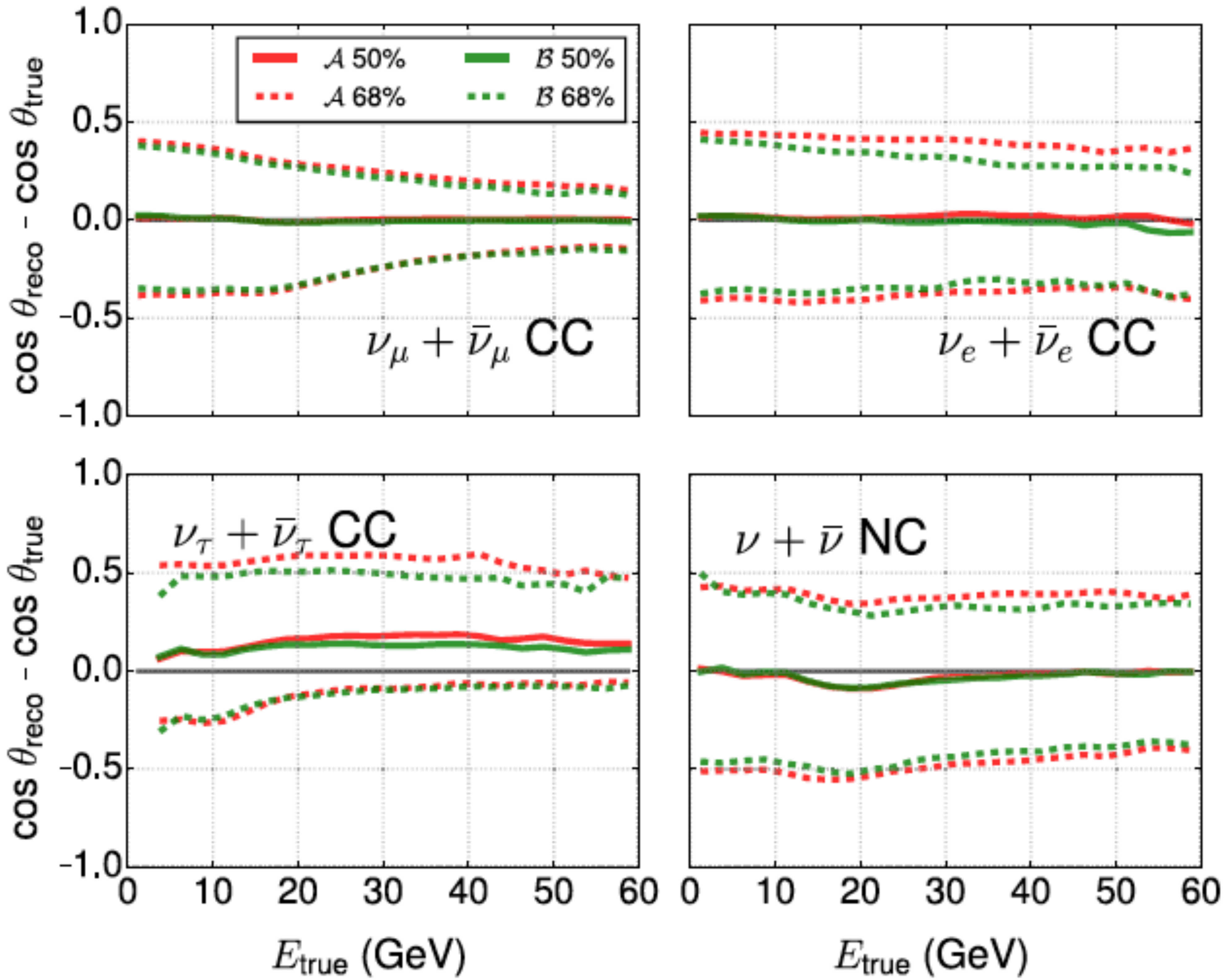


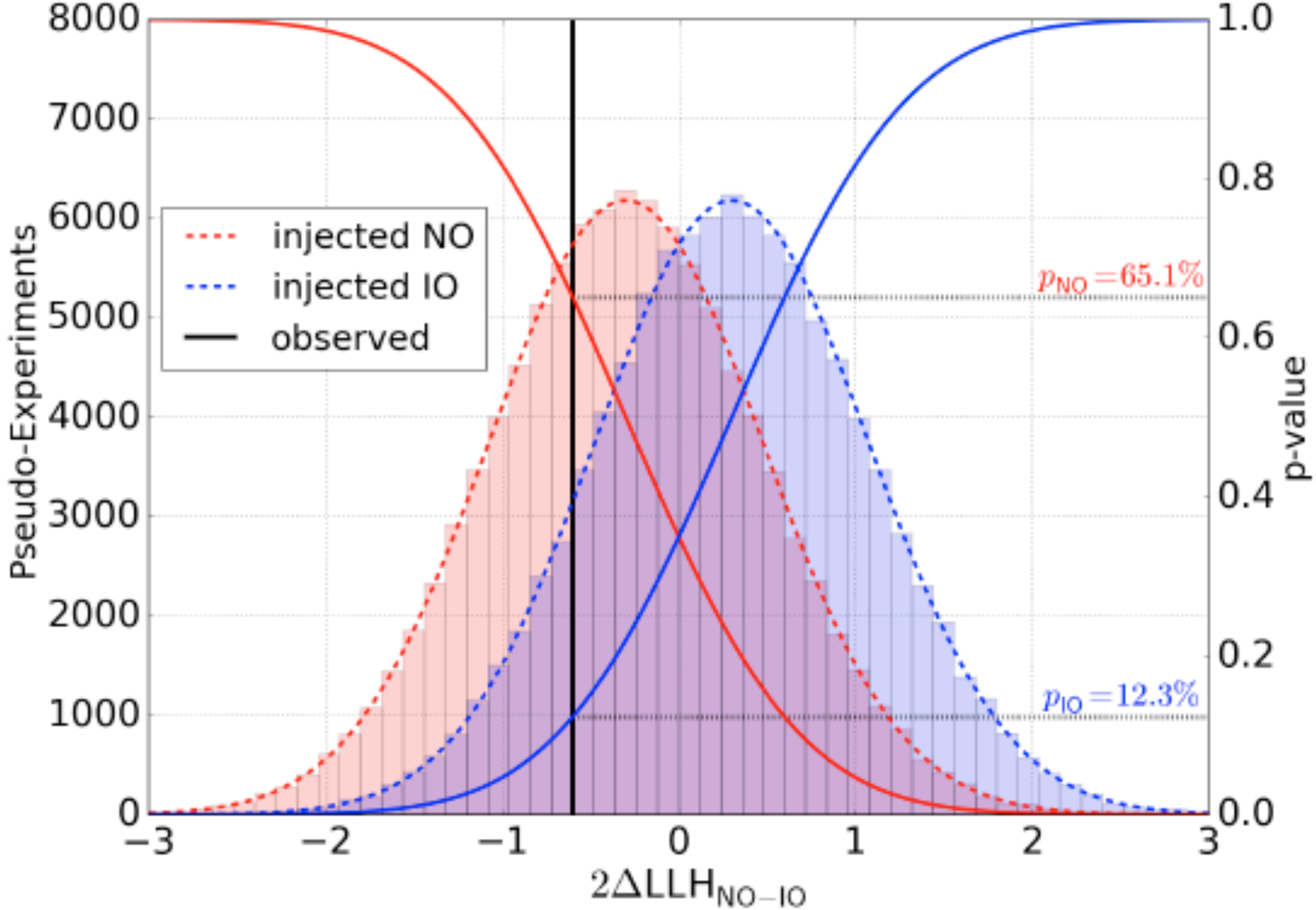
IceCube DeepCore



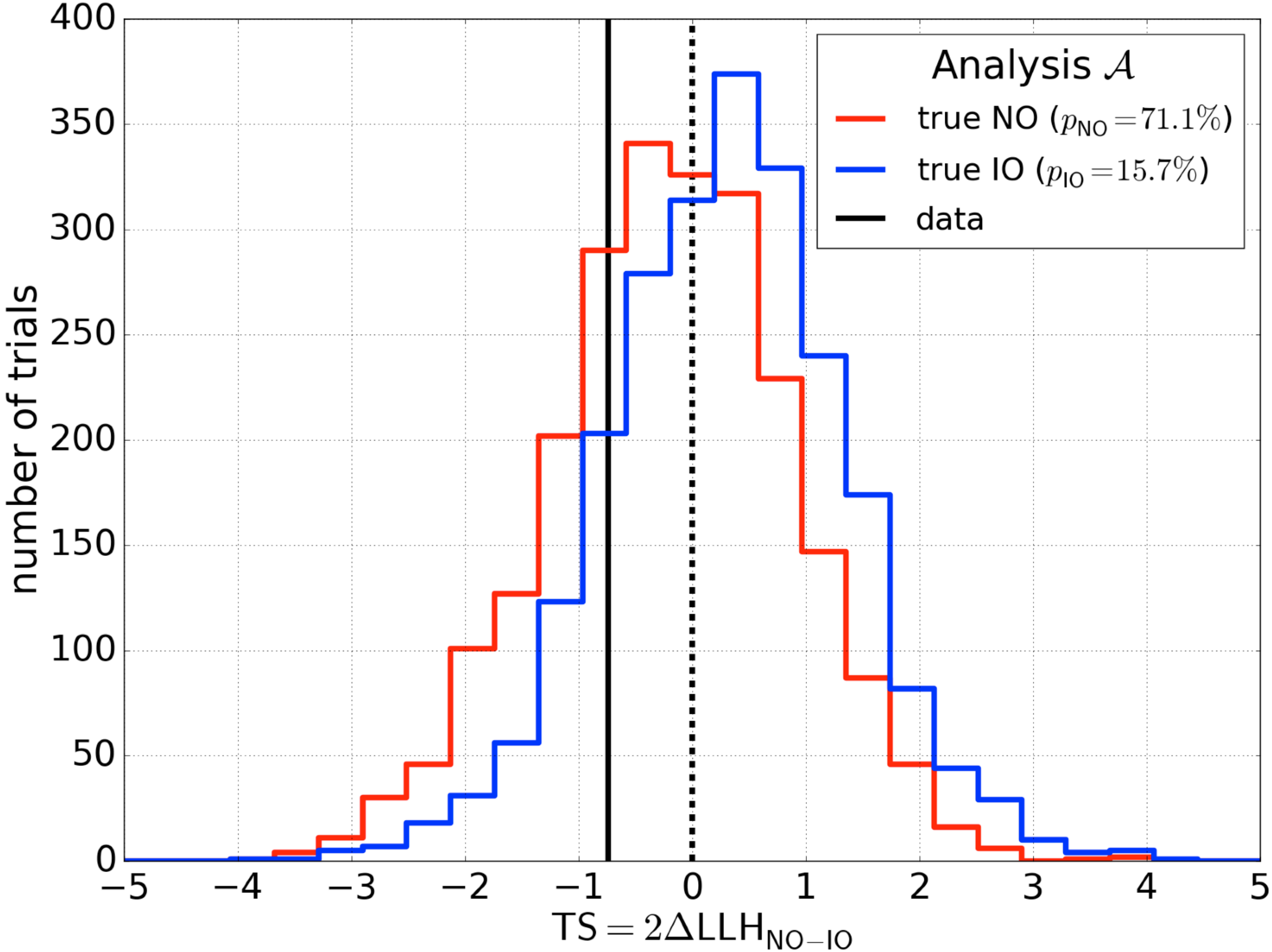
- Anomalies in short baseline experiments have been interpreted as evidence for additional neutrino mass states with large mass splittings
- No evidence for sterile neutrinos observed. Data consistent with 3 active neutrinos

Neutrino Directional Reconstruction

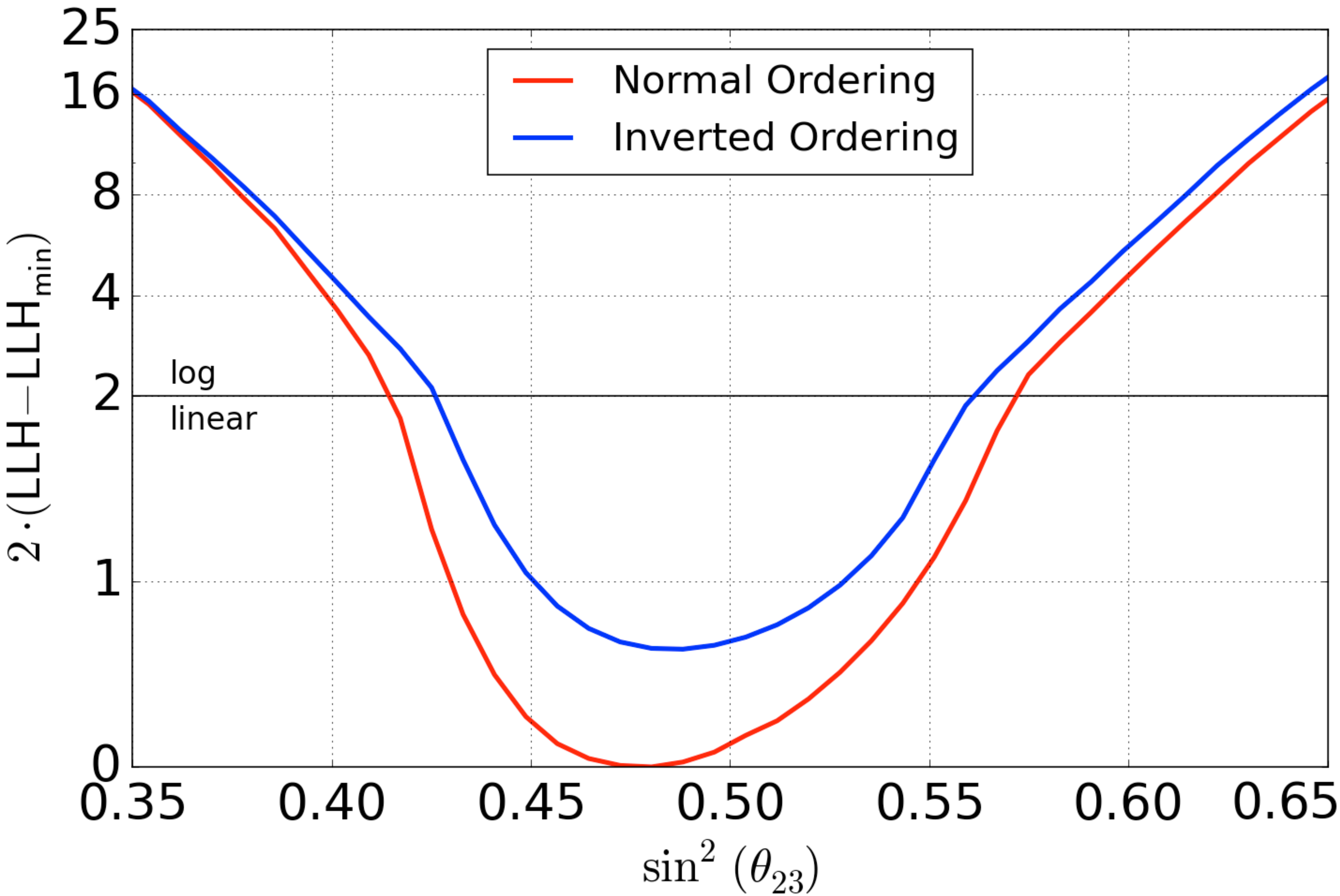




8000
7000
6000
5000
4000
3000
2000
1000
0
Pseudo-Experiments
1.0
0.8
0.6
0.4
0.2
0.0
p-value
−3
−2
−1
0
1
2
3
$2\Delta LLH_{NO-IO}$
injected NO
injected IO
observed
$p_{NO} = 65.1\%$
$p_{IO} = 12.3\%$



Analysis $\mathcal{A}$
true NO ($p_{\mathrm{NO}} = 71.1\%$)
true IO ($p_{\mathrm{IO}} = 15.7\%$)
data
number of trials
400
350
300
250
200
150
100
50
0
−5
−4
−3
−2
−1
0
1
2
3
4
5
$\mathrm{TS} = 2\Delta\mathrm{LLH}_{\mathrm{NO-IO}}$



25
16
8
4
2
1
0
log
linear
Normal Ordering
Inverted Ordering
$2\cdot(\mathrm{LLH}-\mathrm{LLH}_{\mathrm{min}})$
0.35
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2(\theta_{23})$