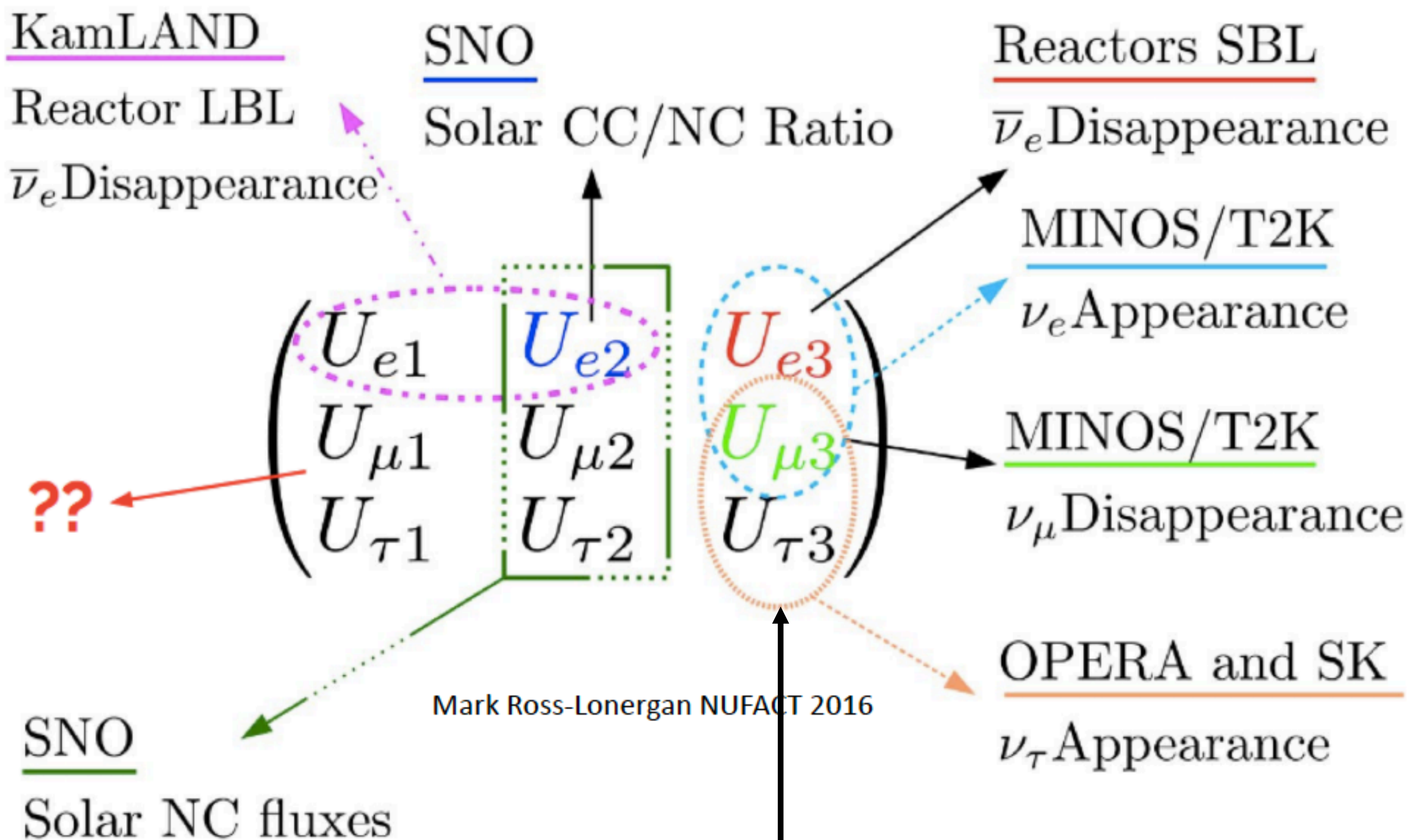
Neutrino Astroparticle Physics

Francis Halzen

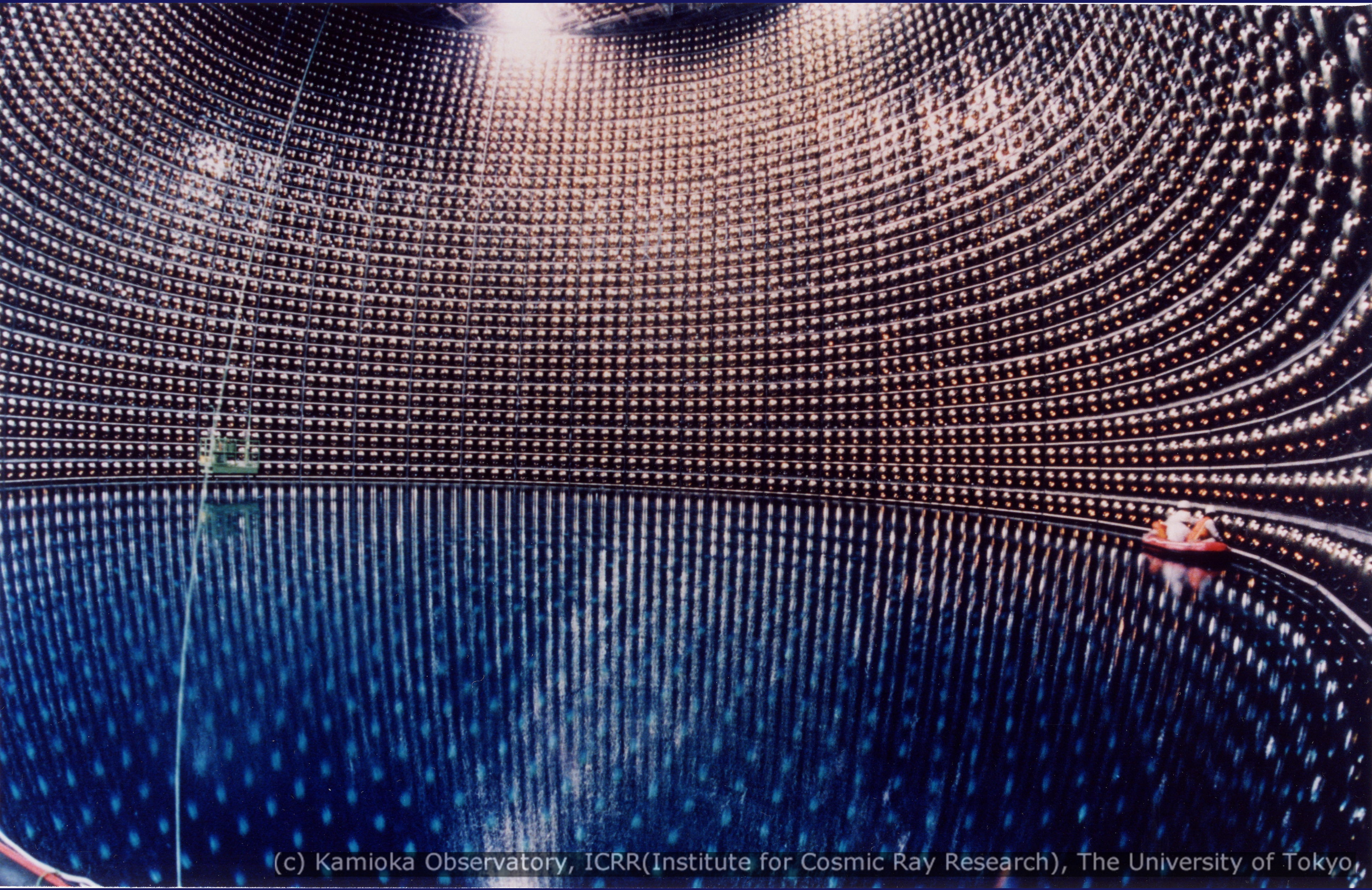
- Physics with neutrino “telescopes” using the atmospheric neutrino beam, also sterile neutrinos.
- The cosmic neutrino beam and neutrino physics using the cosmic neutrino beam.
- BSM neutrino physics using atmospheric and cosmic neutrinos.
- Neutrino physics with a Galactic neutrino explosion.

access to tau neutrinos in the atmospheric and cosmic beam

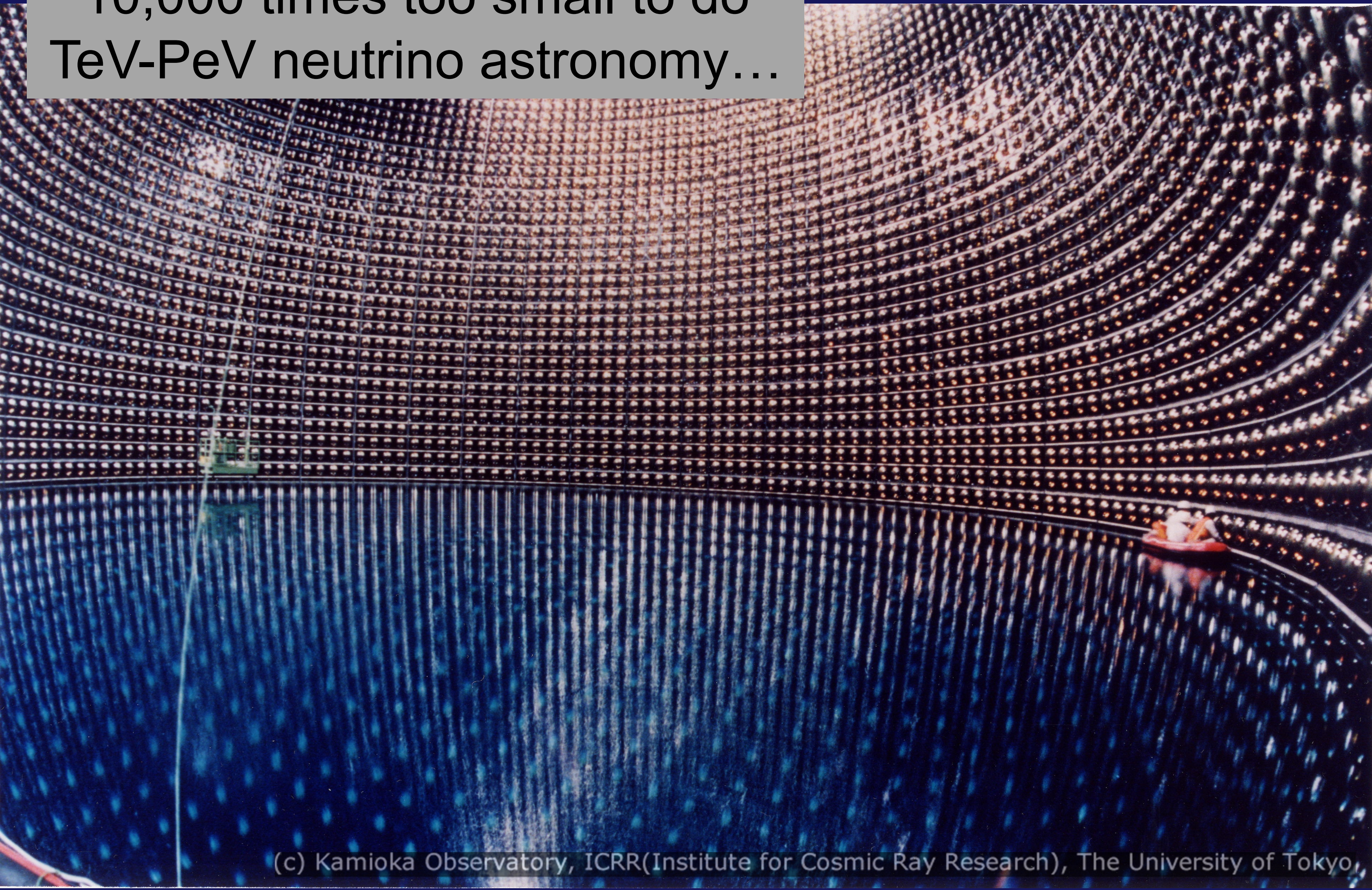
The PMNS mixing matrix



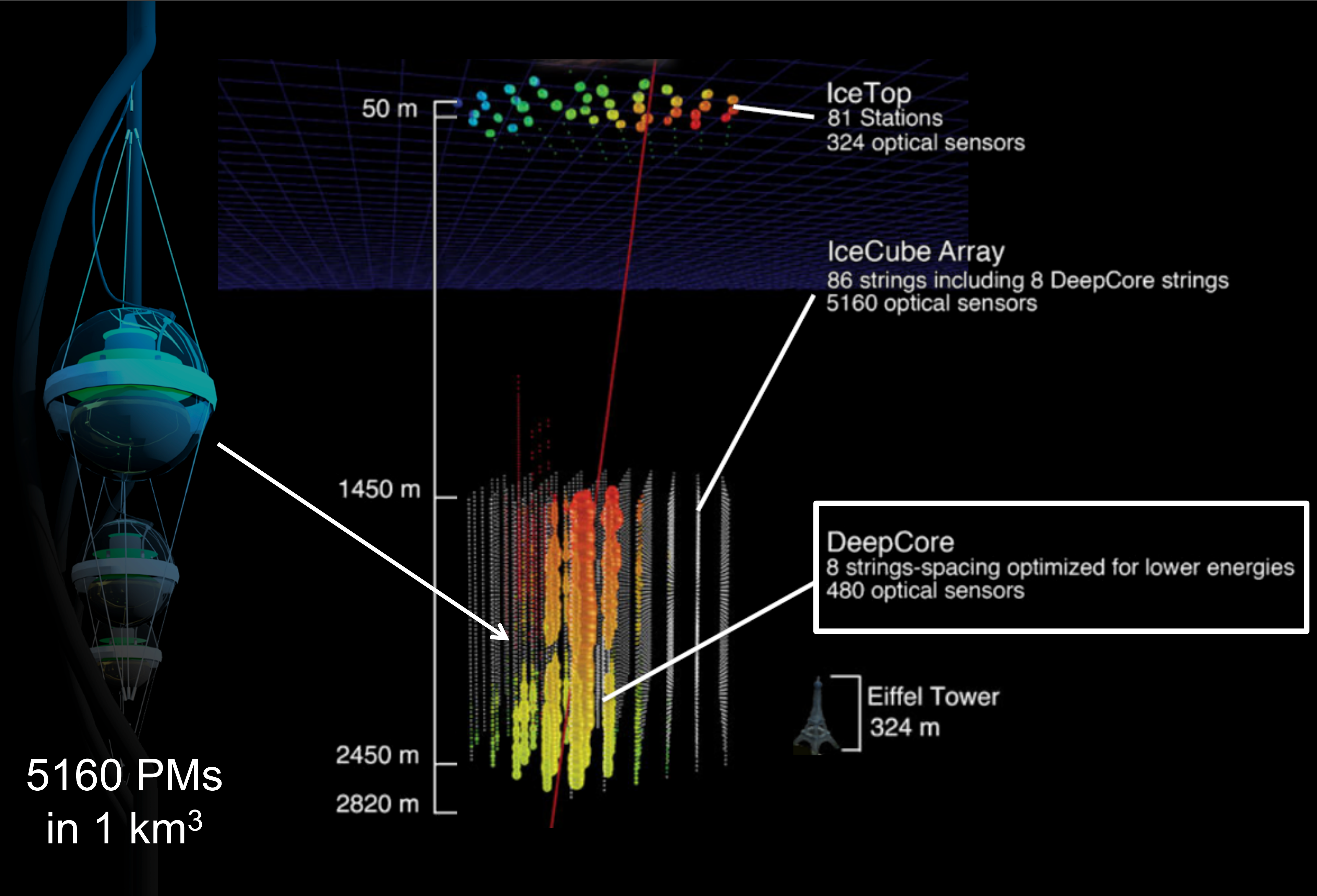
neutrino “telescopes”


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

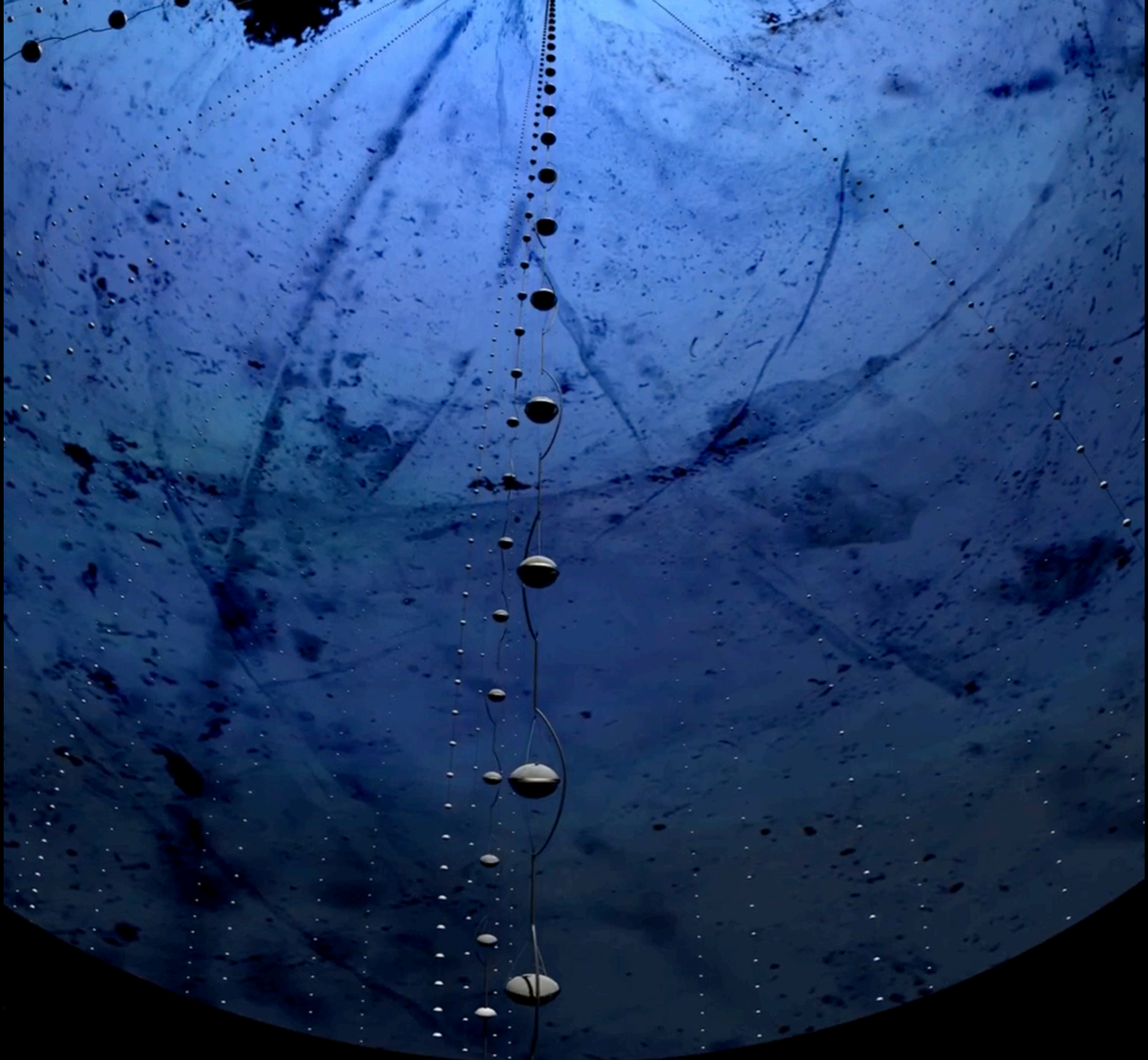
10,000 times too small to do TeV-PeV neutrino astronomy…



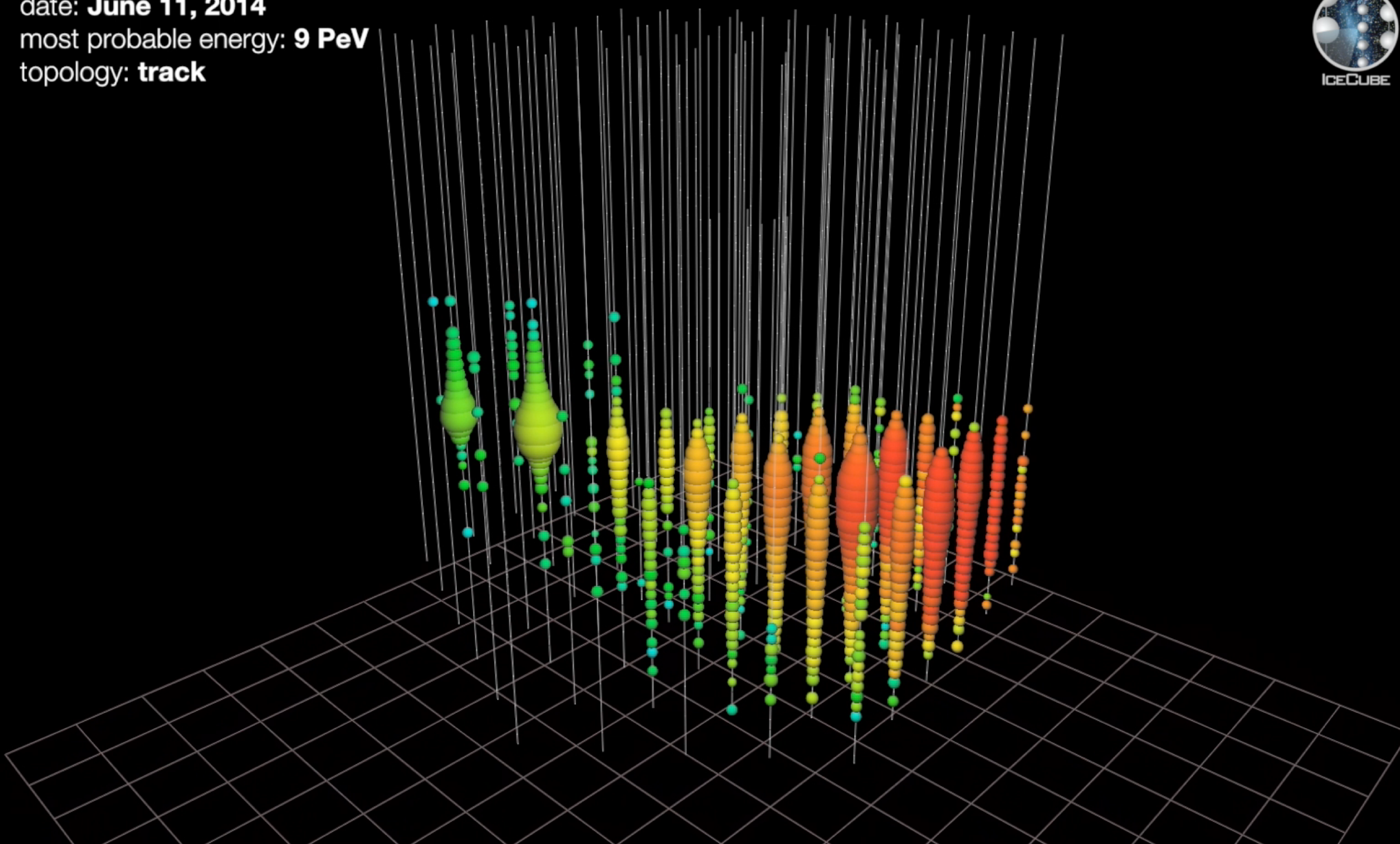
the IceCube neutrino observatory



5160 PMs
in 1 km^3



date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**



ICECUBE

separating signal and “background”

muons detected per year:

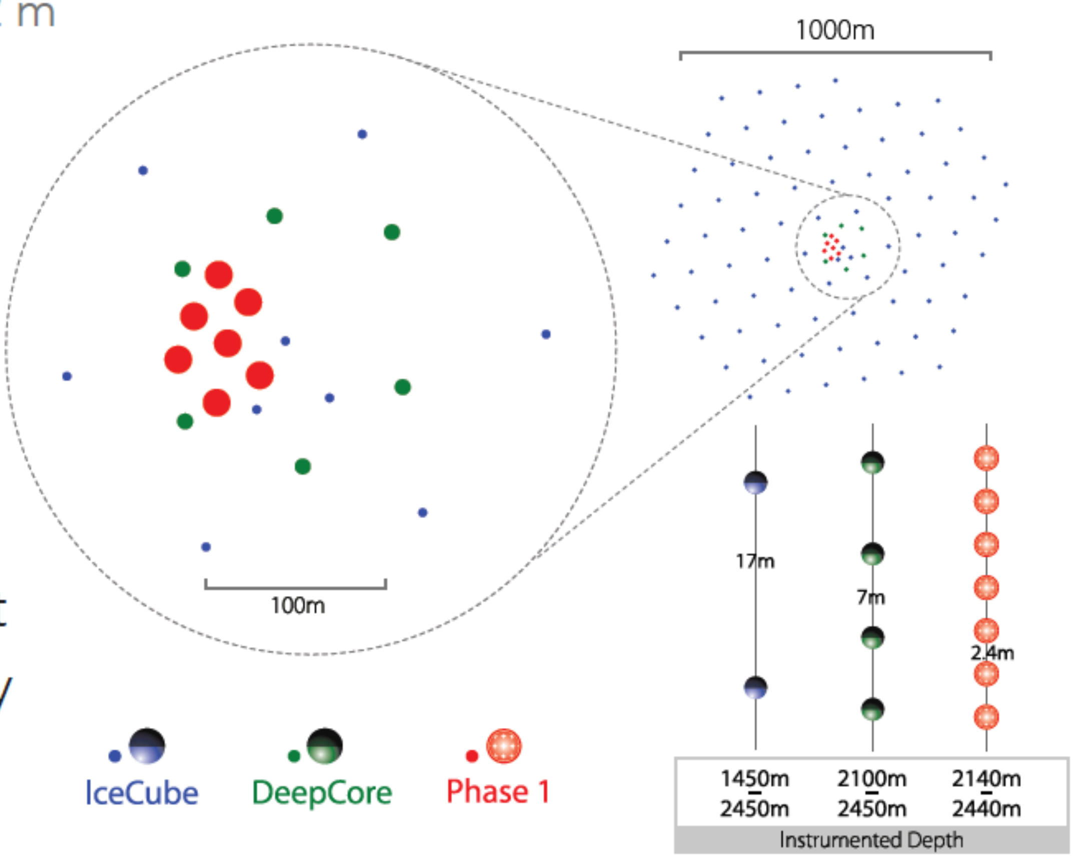
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$> 10^5$
• cosmic	$\nu \rightarrow \mu$	~ 120

* 3000 per second

** 1 every 5 minutes

Next Step: the IceCube Upgrade (2022)

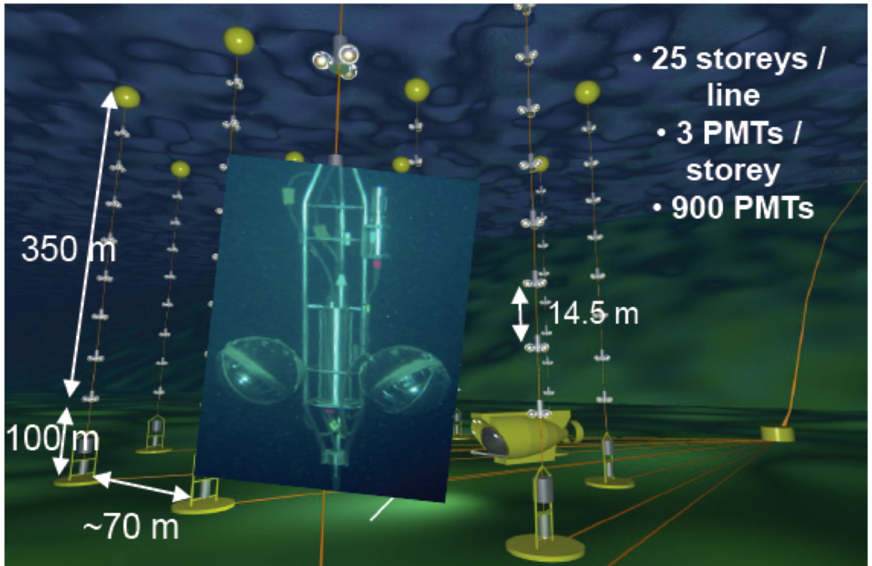
- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



→ soon ORCA with 110 highly instrumented strings

Mediterranean Detectors

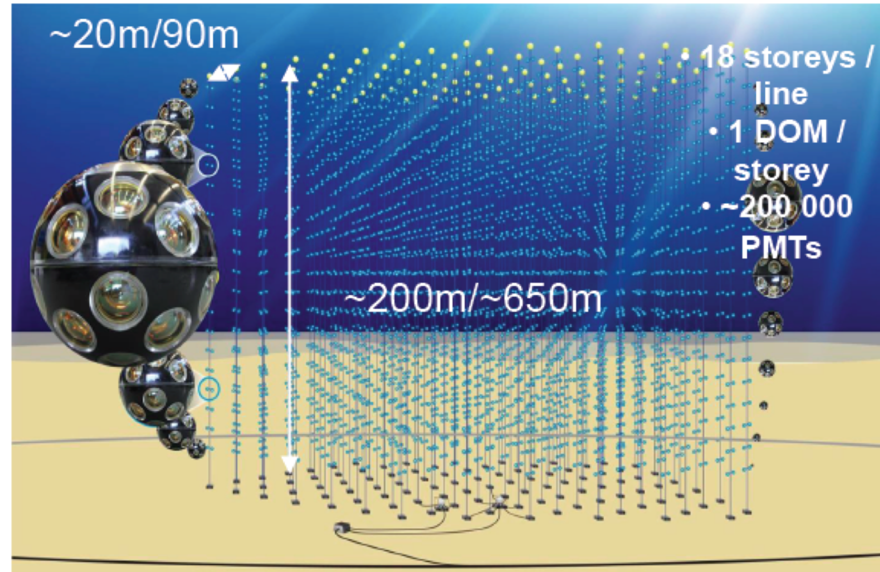
ANTARES Complete since 2008



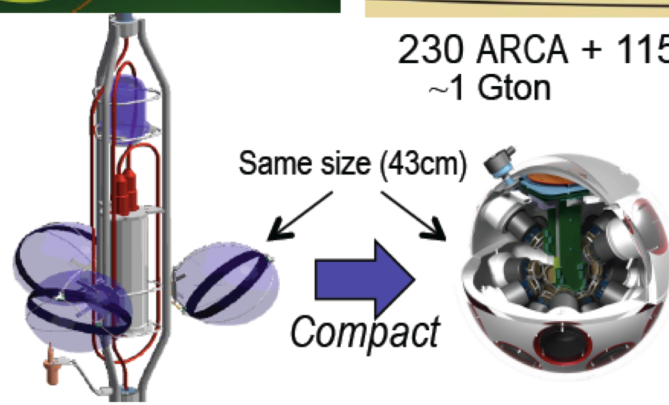
~10 Mton

12 lines
First Generation
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton



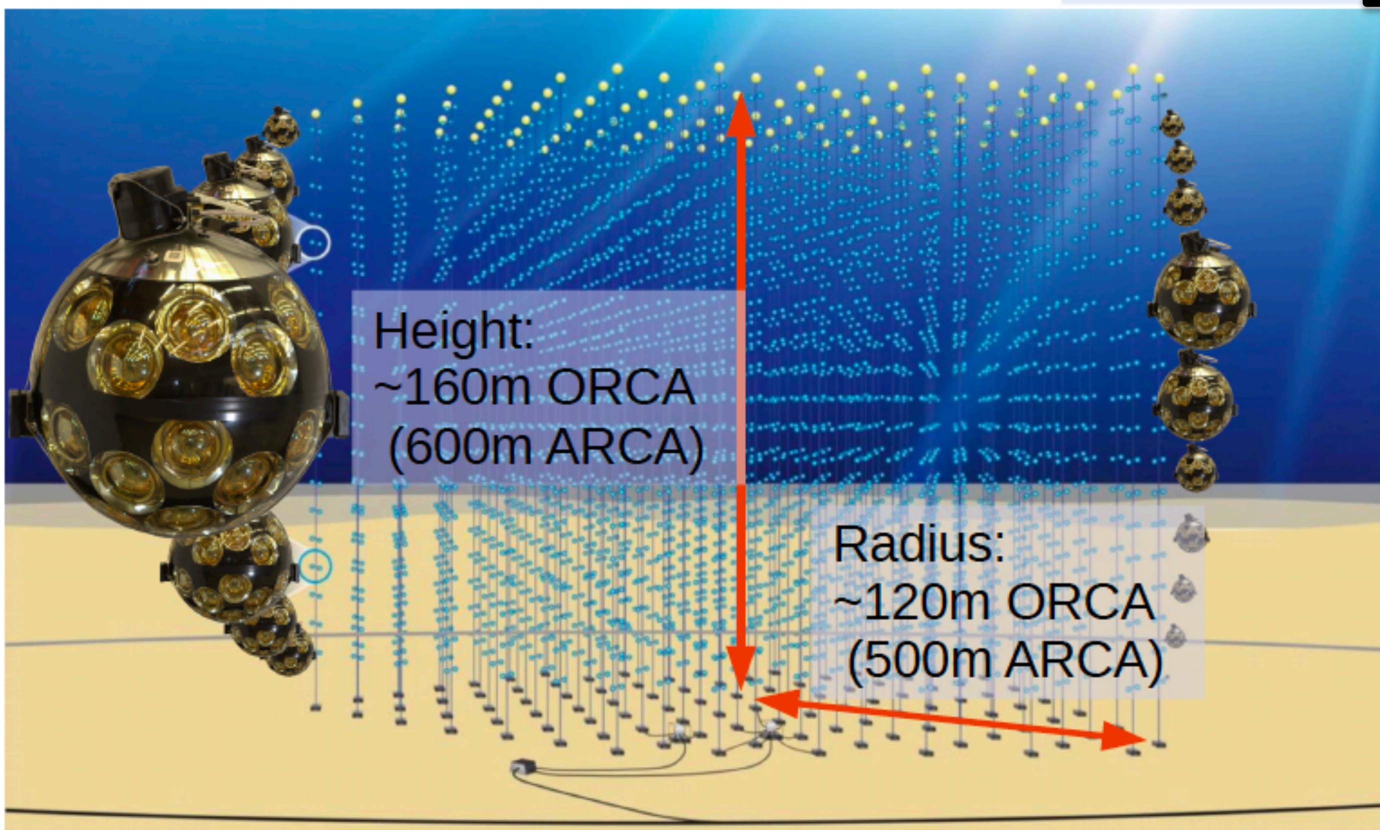
• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

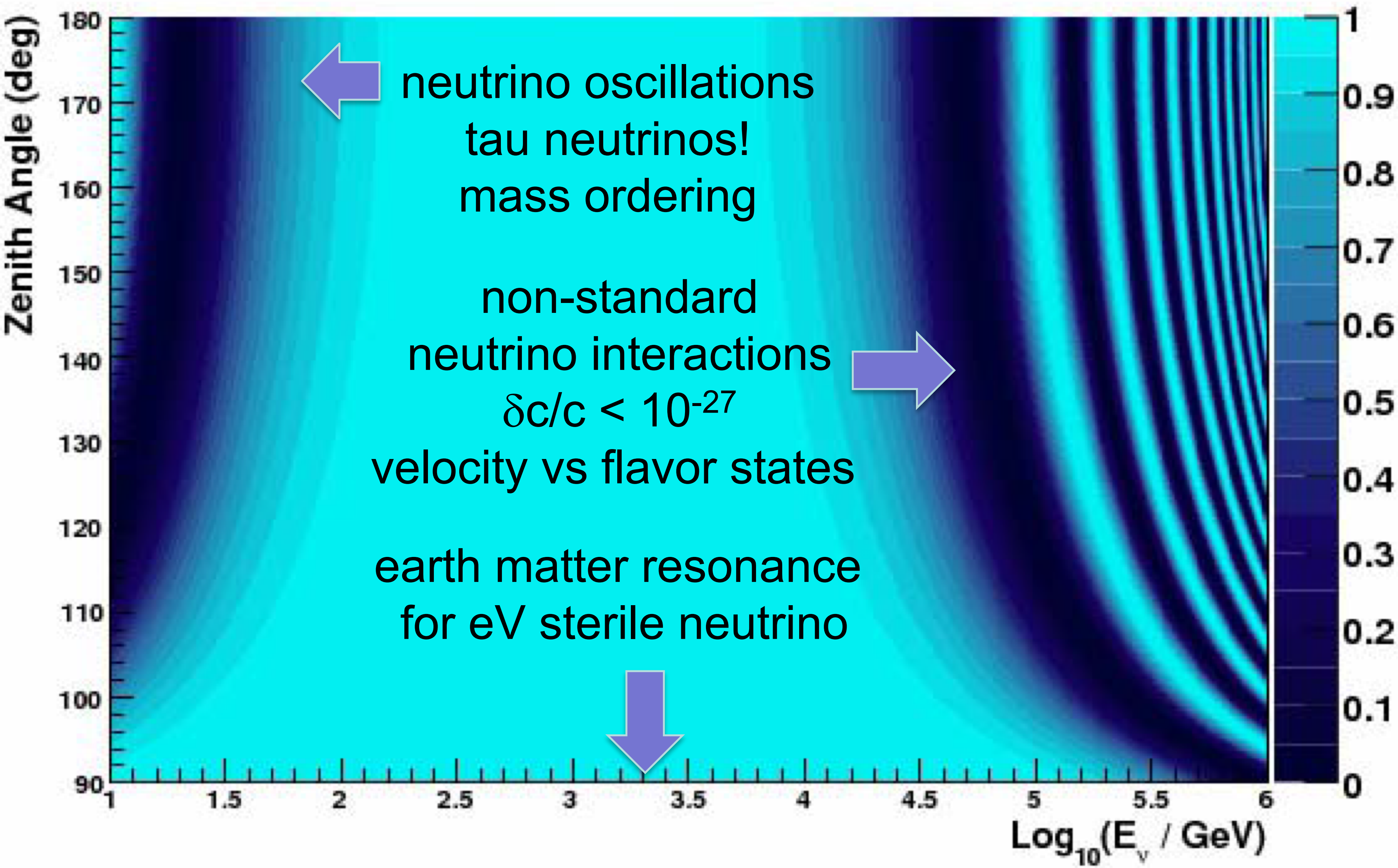
ORCA will consist of one dense
KM3NeT Building Block:

115 detection lines
Total: 64k * 3" PMTs

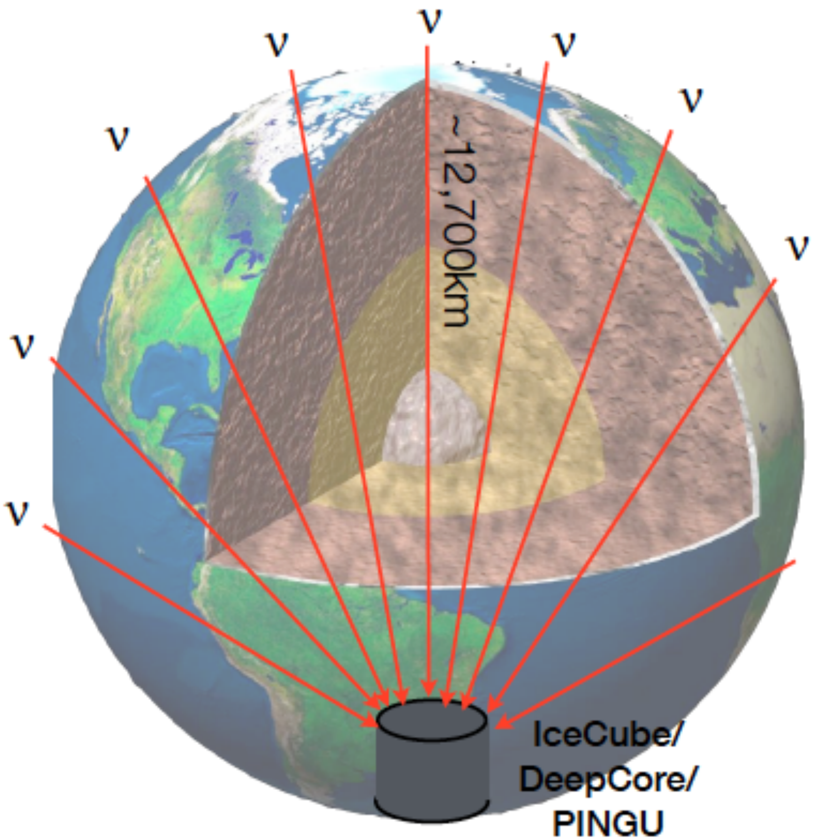
	ORCA	ARCA
String spacing	23 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	1x 8 Mton	2x 0.6 Gton

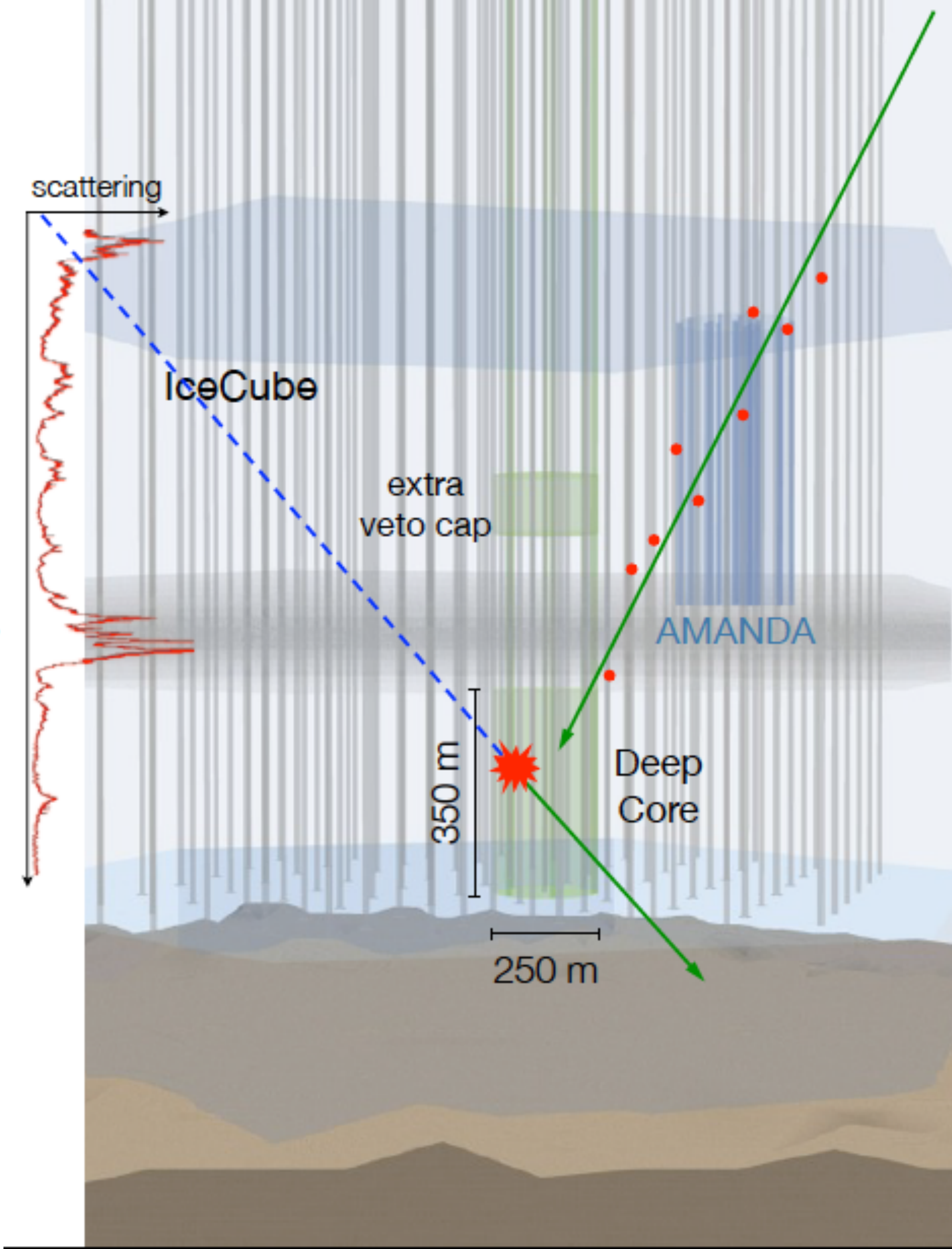


old and new physics with atmospheric neutrinos…

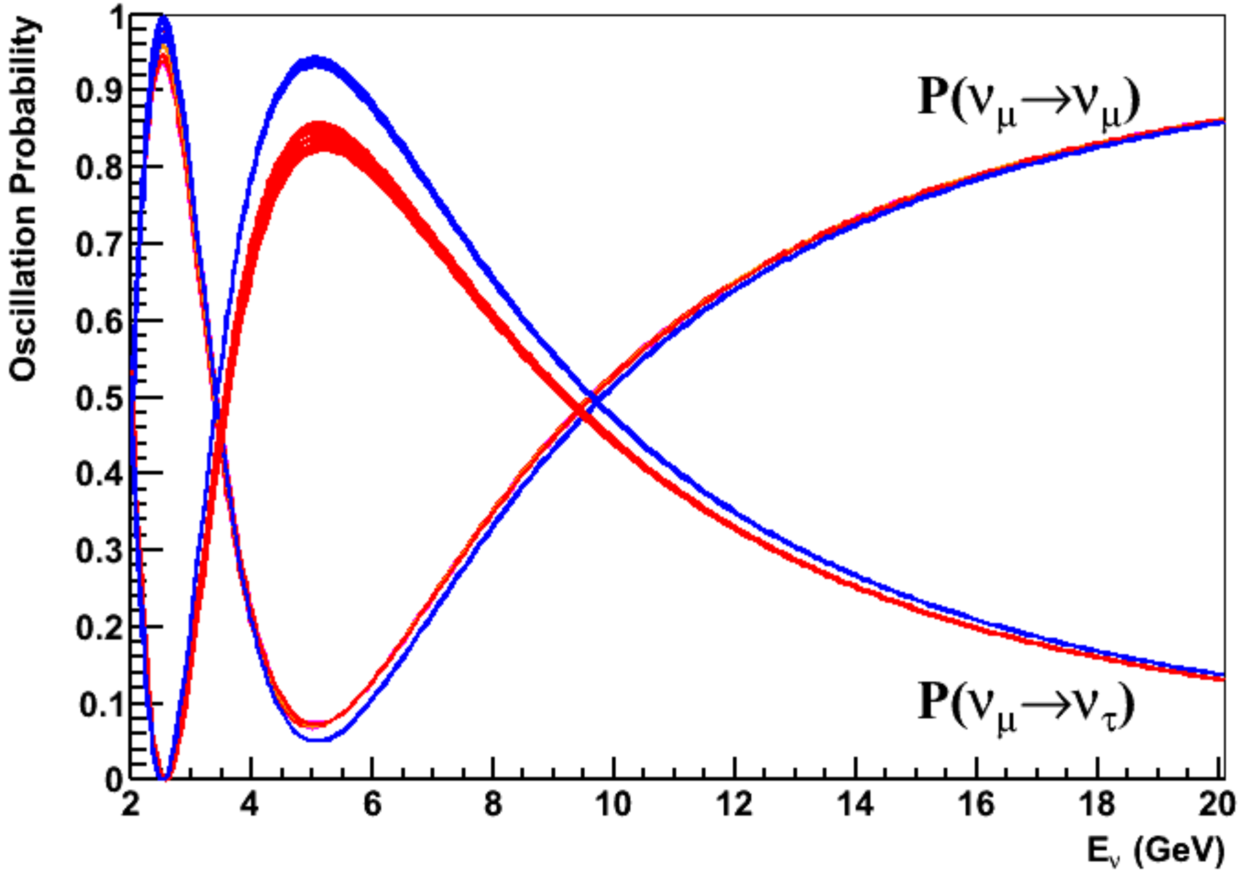


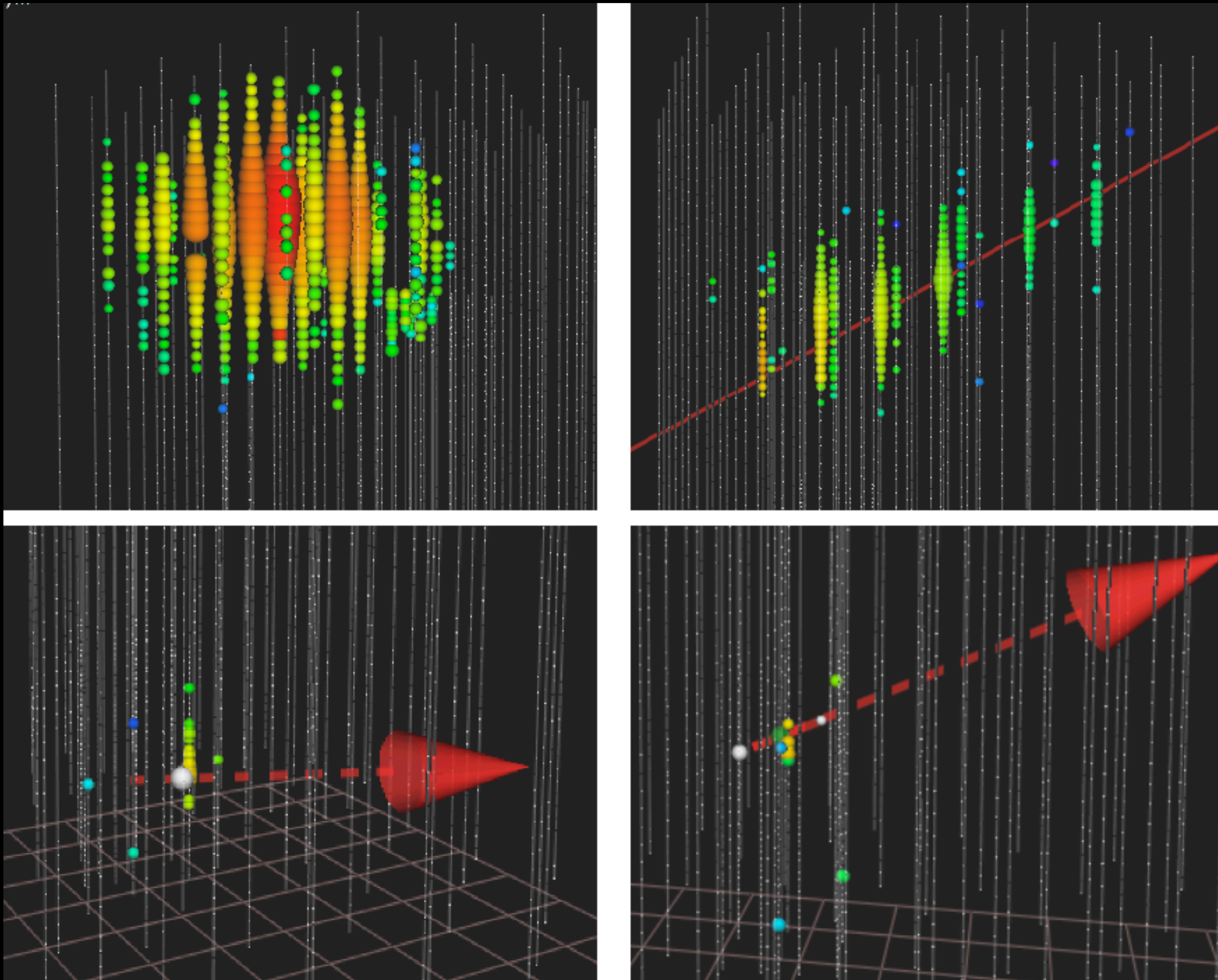
one million atmospheric neutrinos…



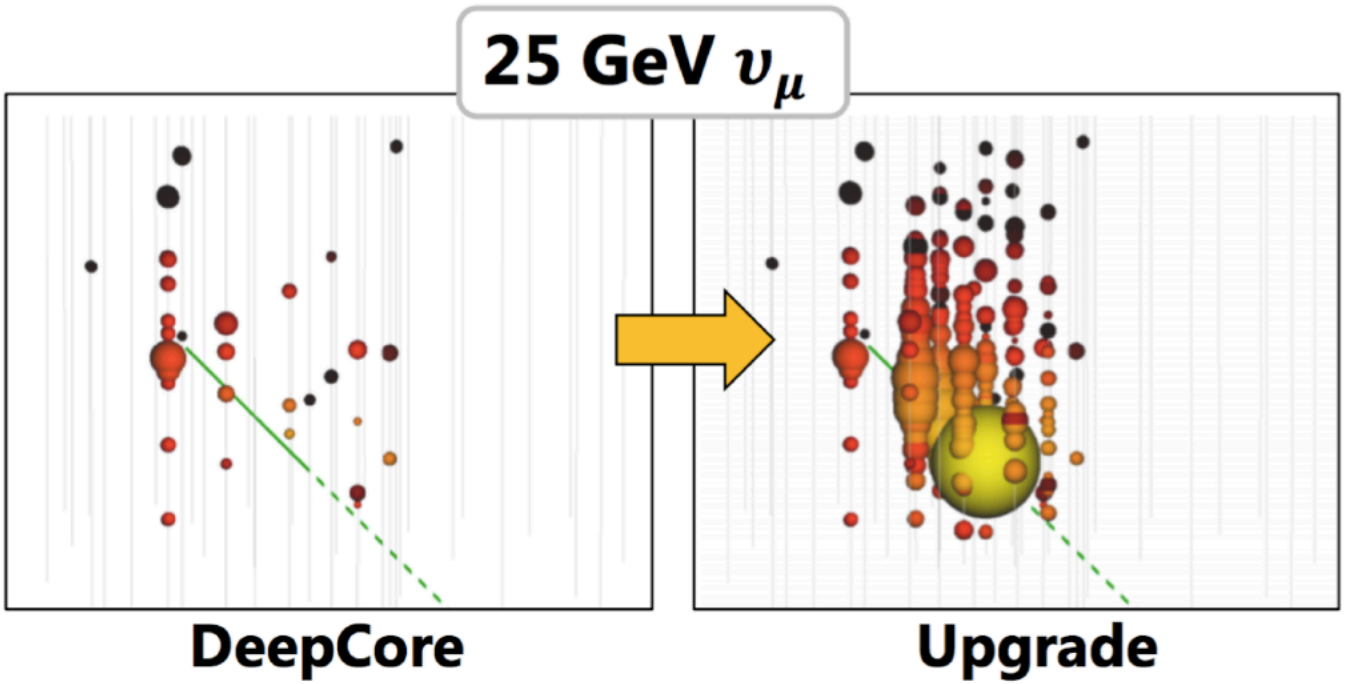


- oscillations at 5-55 GeV energy
- same oscillation parameters measured in a new energy range (BSM neutrino physics?)

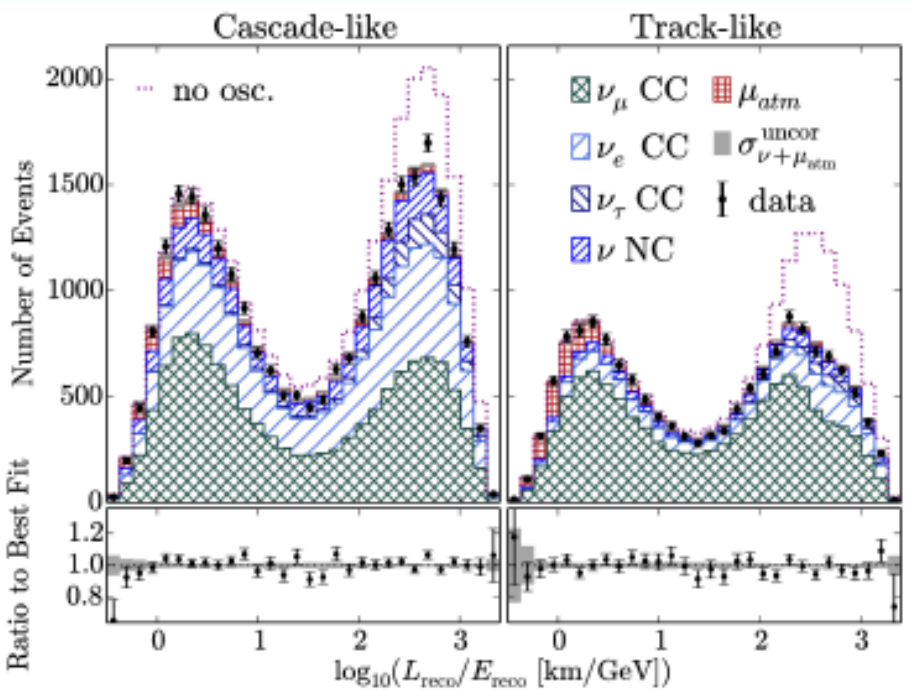




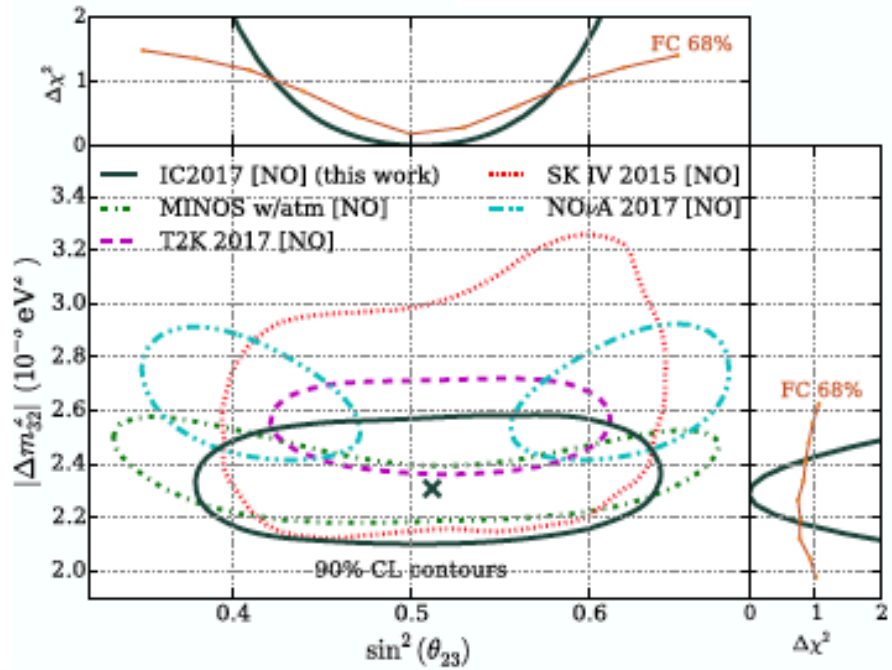
Low energy neutrinos in the Upgrade



Neutrino Oscillation



IceCube, PRL 2018



- 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

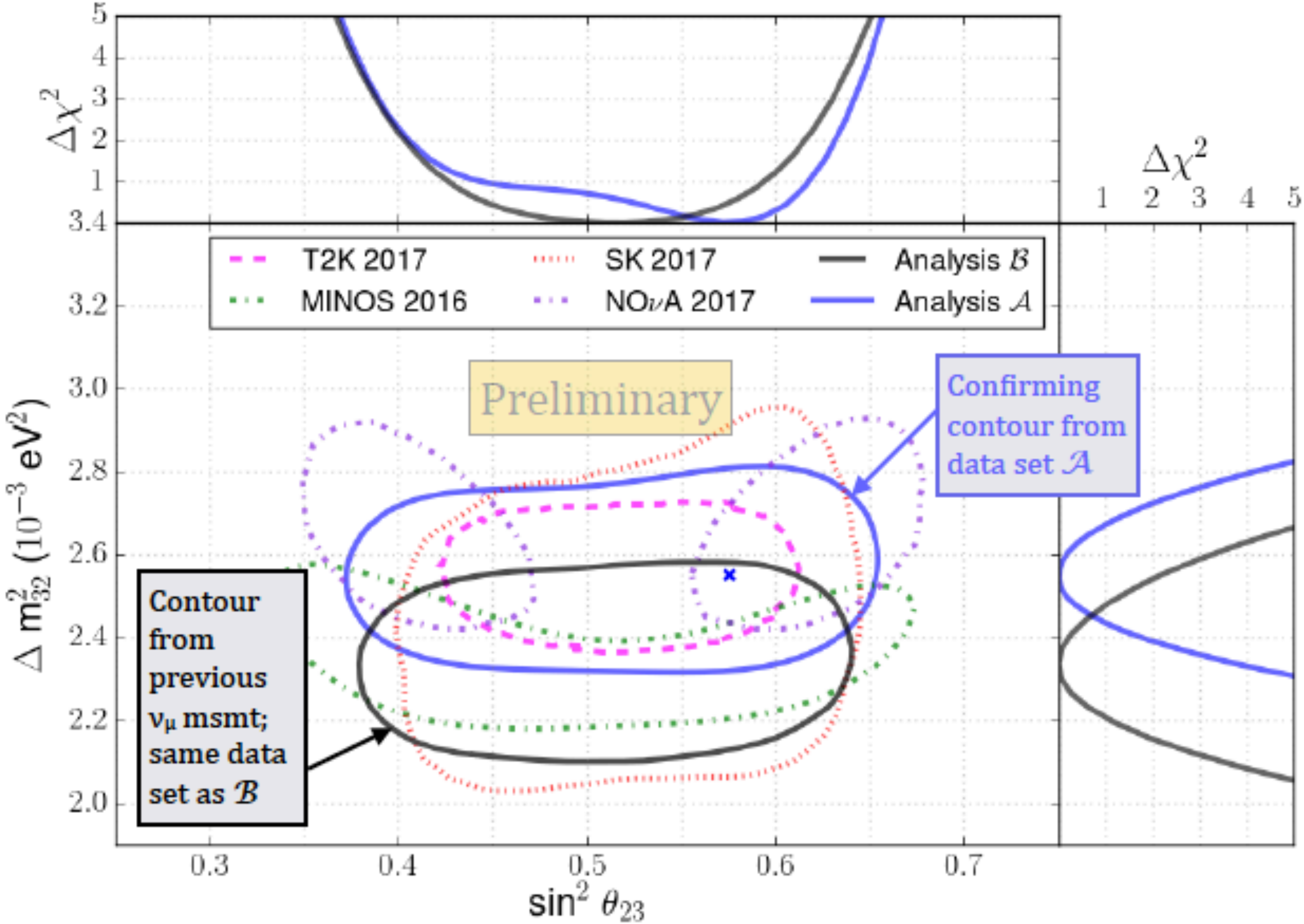
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\mathrm{eV}^2$$

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

IceCube

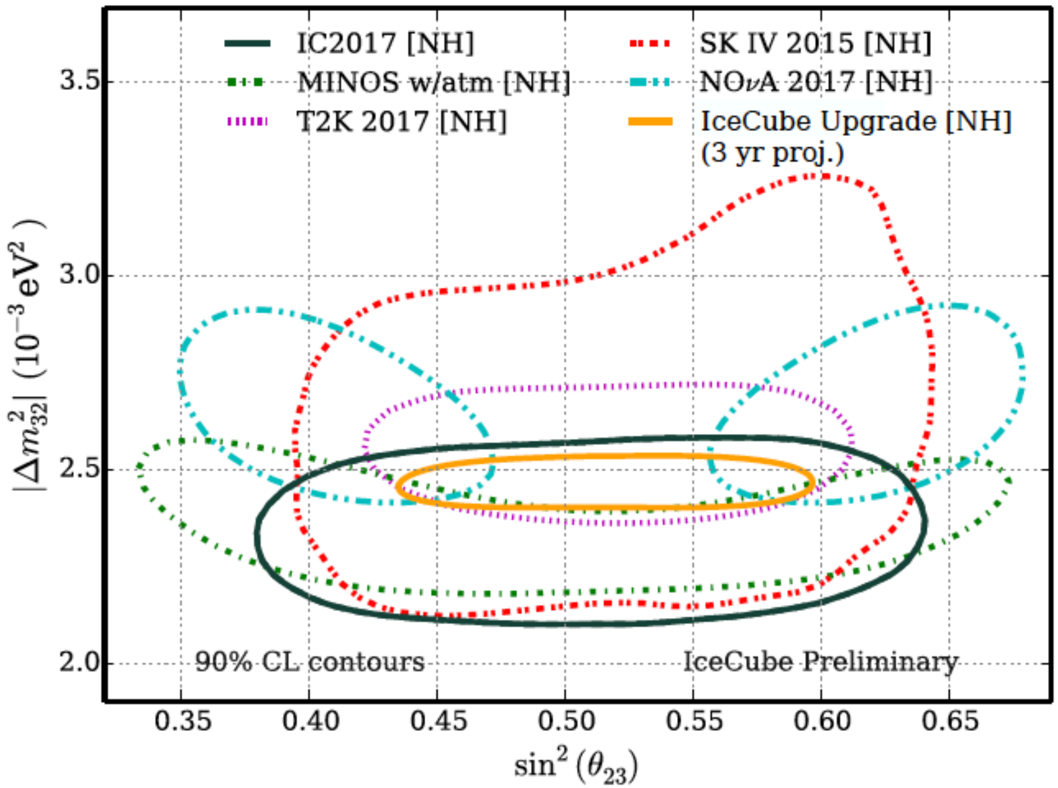
- two independent analyses
- one emphasizing quality of events
- one maximizing statistics
- both blind

		Analysis A GRECO “High statistics sample”	Analysis B DRAGON “High purity sample”
Simulation	Neutrino Simulation	1. Neutrino interactions / lepton generation: GENIE 2. Lepton propagation / photon generation: PROPOSAL & GEANT4 3. Photon propagation: CLSim (GPU-based software) 4. Noise addition 5. PMT response & readout elections	
	Muon Background Simulation	CORSIKA + MuonGun • Uses H4a Cosmic Ray flux model to directly predict muon background. Run through standard simulation chain.	CORSIKA + Data-Driven • Any muon that would have made it to final level had it not been for a hit in the corridor region is considered a background muon
Selection	Goal	High signal acceptance “High statistics sample”	High signal purity “High purity sample”
	Trigger	At least 3 pairs of locally coincident DeepCore DOMs detect hits in a 2.5 microsecond time window	
	Level 2 “Filter”	Veto events with hits in “veto region” consistent with a muon travelling from there to interaction vertex at $v=c$	
	Level 3	Eliminates events with more than 7 hits in veto region, too many noise hits, too many hits in outer region of DeepCore (i.e. not fully contained),	
	Other low-level cuts	Removes events with too many non-isolated hits in veto region and/or too few non-isolated hits in DeepCore fiducial volume	Fast reconstruction to insure enough DOMs to be consistent with either track or shower signature
	Level 4	BDT to remove atmospheric muons (6 variables) • Charge measured by PMTs (3 vars.) • Simple vertex estimator • Event speed simulator • Calculation of event shape	Straight Cuts • Number of photoelectrons deposited in largest cluster of hits • Event vertex in fiducial volume (contained) • No more than 5 p.e. in veto region total • No more than 2 p.e. in veto region consistent with speed-of-light travel from hit to vertex • Minimum number of non-isolated hits • Space-time interval between 1^{st} and 4^{th} hits consistent with $v \leq c$.
	Level 5	Another BDT to remove atmospheric muons (6 variables) • Time to accumulate charge • Vertex estimator • Center-of-gravity information (2 var.) • Causal hit identifier • Zenith angle estimation	BDT (11 variables) • Charge, time, and location of hit DOMs (multiple variables) • Reconstructed zenith angle & event speed using fast construction
	Level 6	Straight cuts • Inconsistent with intrinsic PMT noise • Spatially compact • Require likelihood-based vertex estimator to be well contained in DeepCore fiducial volume • Reject events with hits along “corridors” in surrounding IceCube volume	Straight cuts • Events with reconstructed paths through corridor region • Starting & stopping position in or near DeepCore (contain)
	Level 7	Reconstruction (better & more accurate than fast reconstruction information above) & reconstructed energy must be 5.6-56 GeV	Reconstruction & no cuts on L7 ?


Δχ²
T2K 2017
SK 2017
Analysis ℬ
MINOS 2016
NOνA 2017
Analysis 𝒜
Preliminary
Confirming contour from data set 𝒜
Contour from previous ν_μ msmt; same data set as ℬ
Δm^2_{32} (10^{-3} eV²)
$\sin^2\theta_{23}$
Δχ²

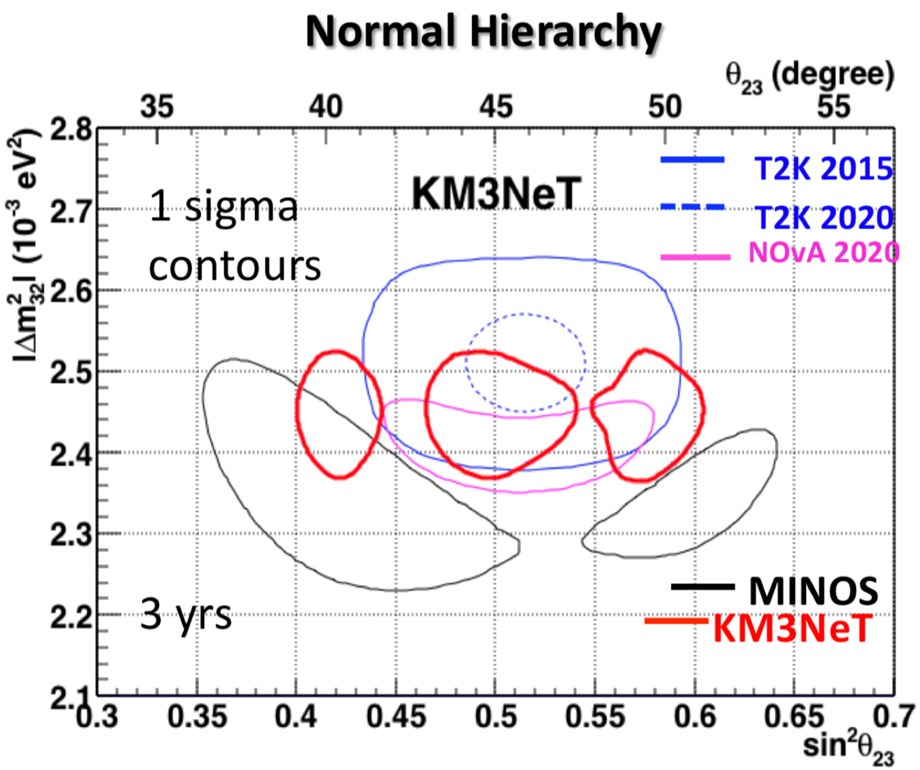
atmospheric oscillation parameters: IceCube upgrade

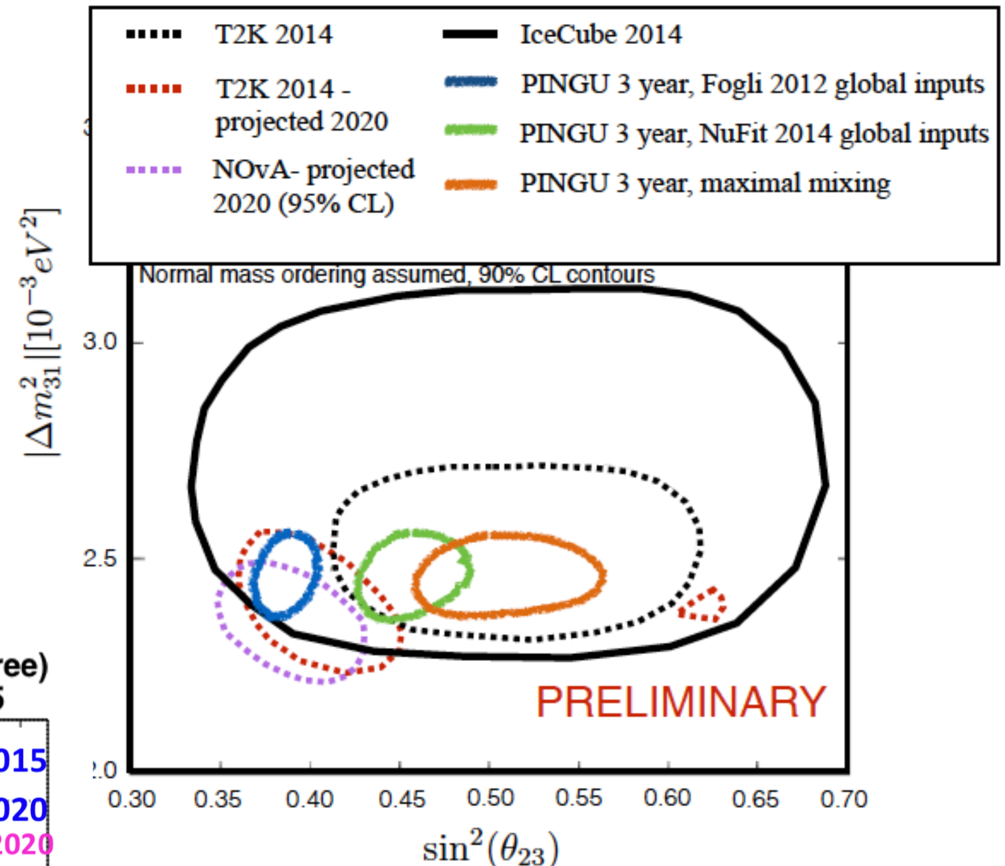
- Currently unclear whether $\sin^2\theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)

and with ORCA/PINGU





tau appearance: IceCube atmospheric neutrinos

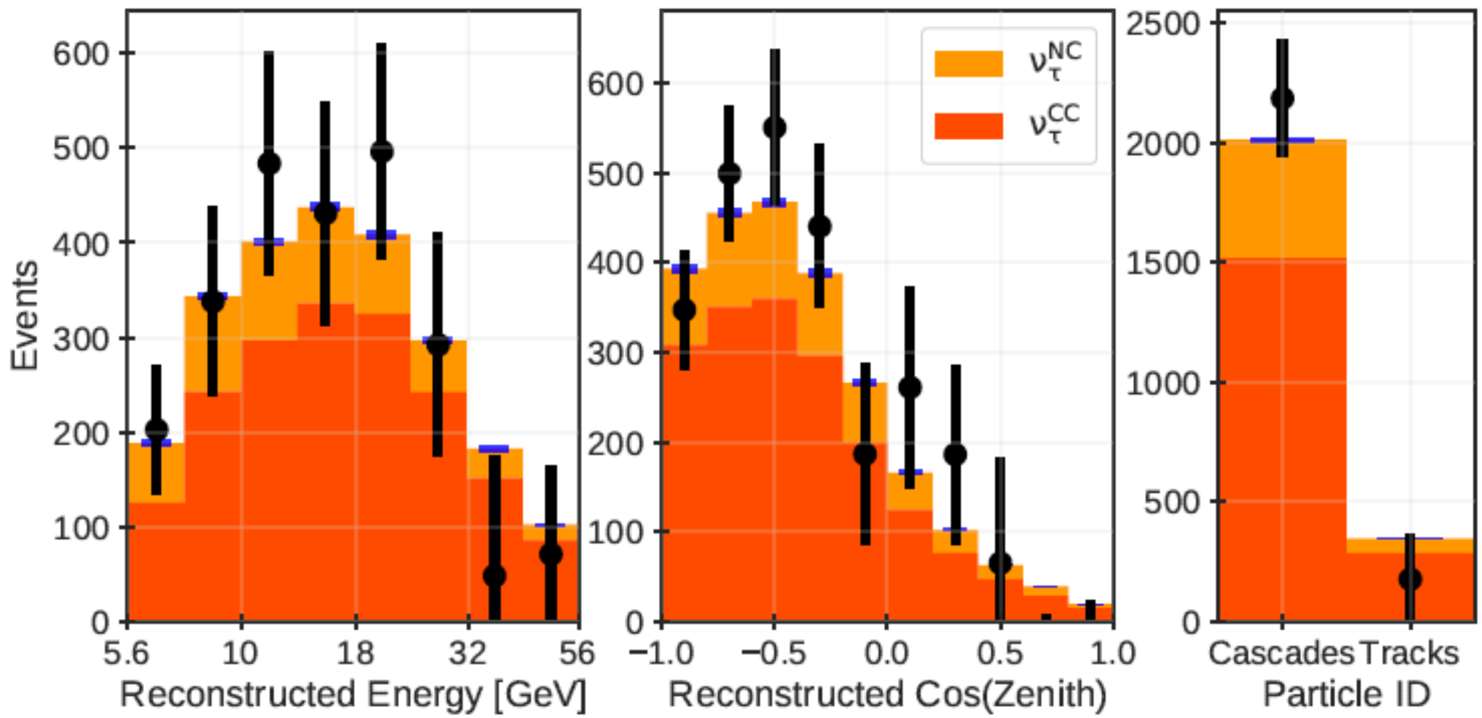
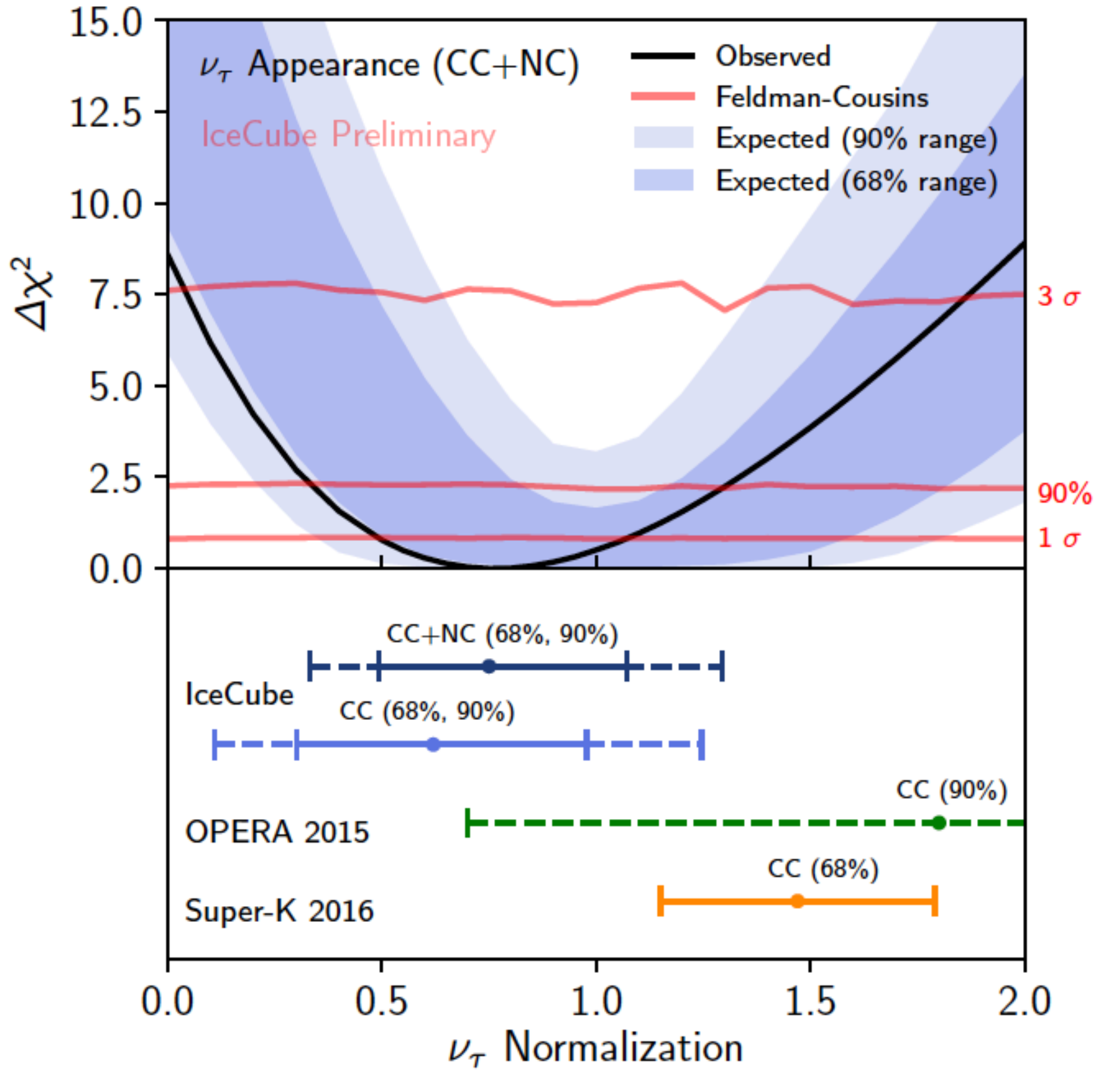


FIG. 14. Distributions of the data with best-fit neutrino and muon backgrounds subtracted, overlaid with the best fit ν_τ hypothesis projected onto the reconstructed energy axis (left), the cosine of the reconstructed zenith angle (middle) and PID categories (right), for Analysis $\mathcal{A}$. Error bars are statistical only.

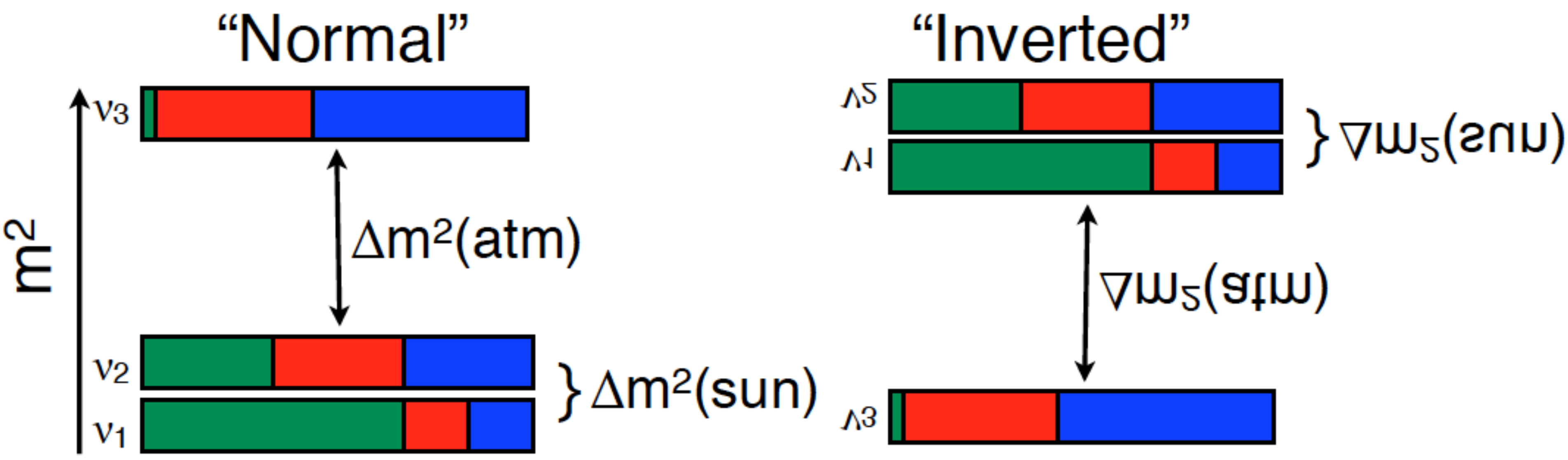
Phys.Rev. D99 (2019) no.3, 032007

Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix



neutrino mass ordering ?



~ 8 GeV : hierarchy revealed by "large" matter effects in the Earth

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2} G_F n_e}{\Delta_{13}}\right]}$$

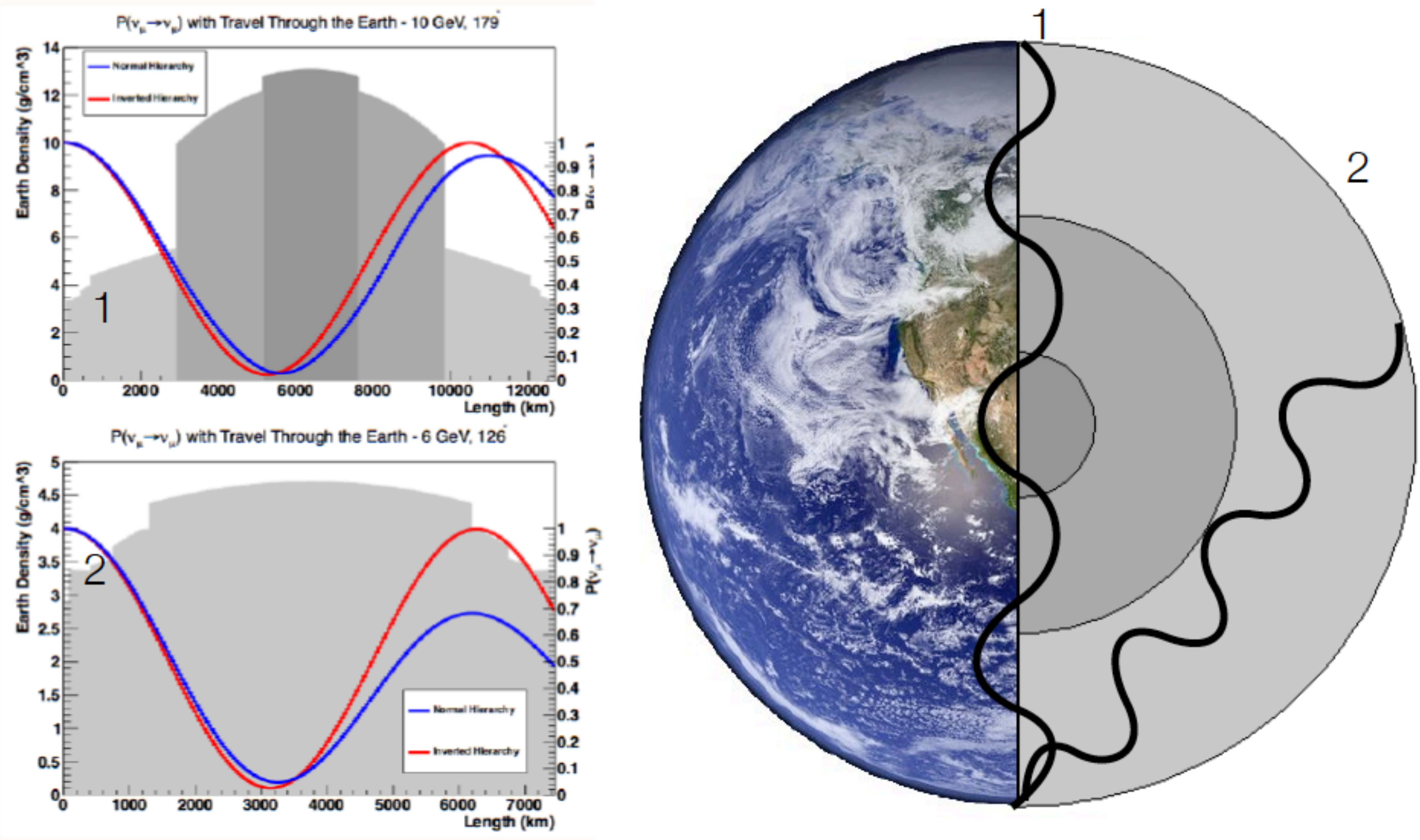
(mostly) neutrino + antineutrino -

$$\Delta m_{31}^2 = m_3^2 - m_1^2$$

sign Δ_{13} : hierarchy !

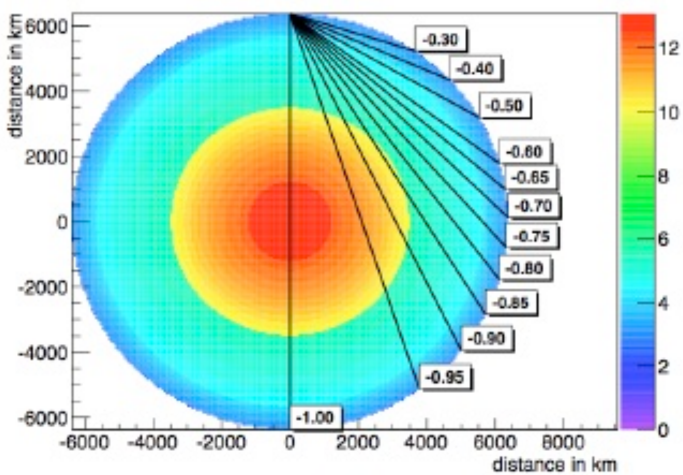
Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy

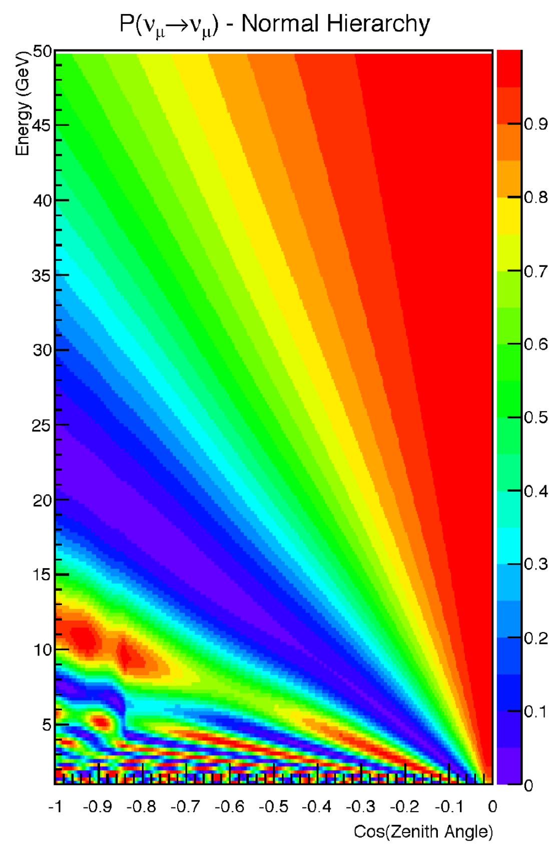


$P(\nu_\mu \rightarrow \nu_\mu)$

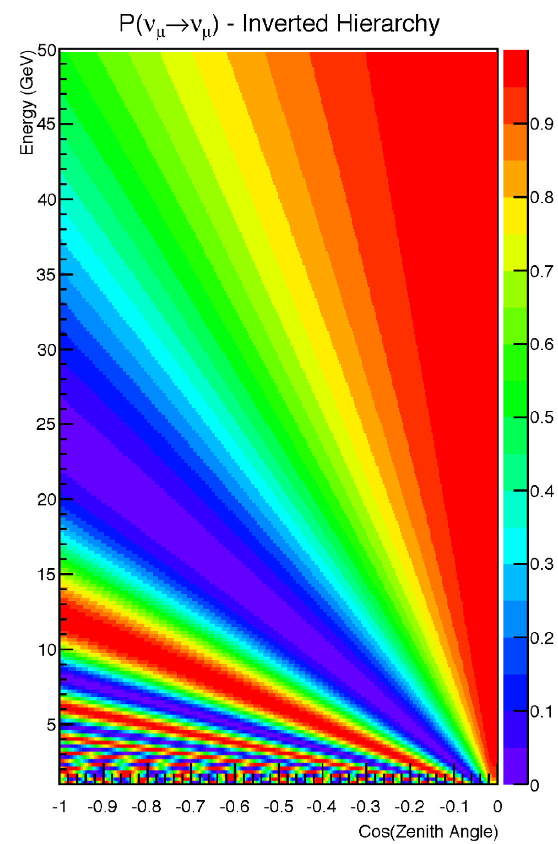
- Map upward ν flux in bins of (E,cosθ);
- cosθ= -1 L~12000 Km;



Normal Hierarchy

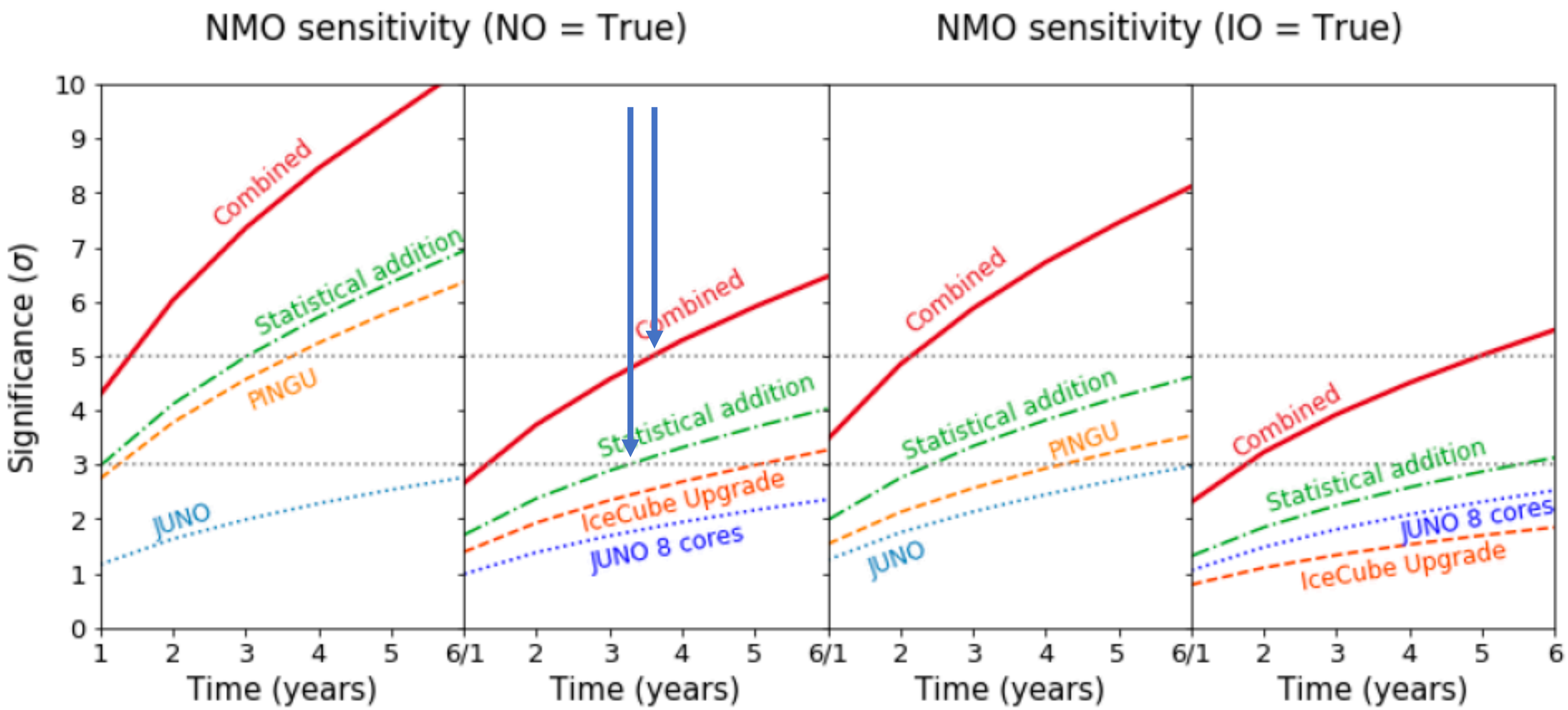


Inverted Hierarchy



Letter of Intent PINGU- arXiV:1401.2046

NMO with JUNO, IceCube upgrade and ORCA/PINGU

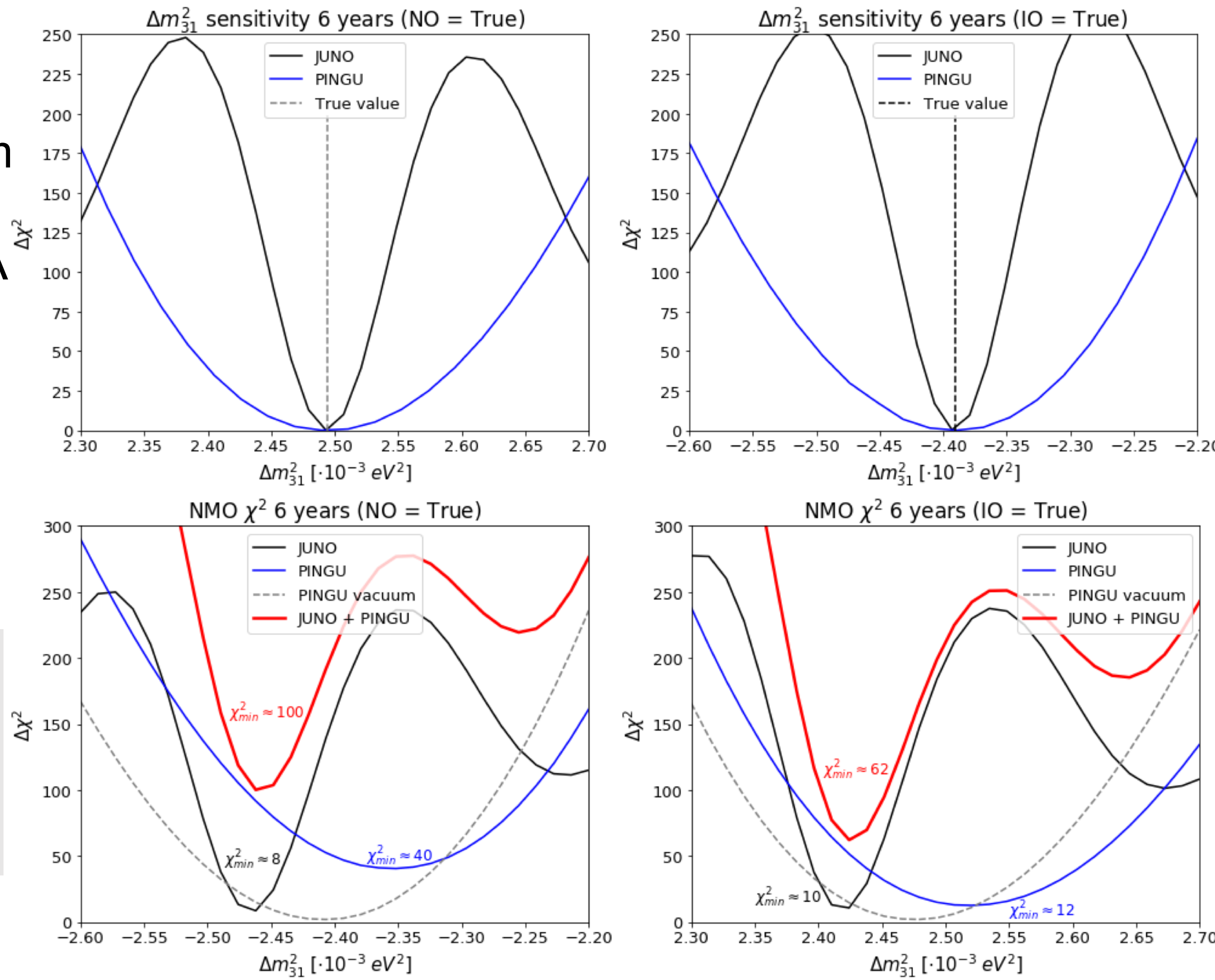


difference between between “statistical combined” and “combined” results from the different tension in the determination of the mass-squared difference of JUNO and Upgrade if one wrongly defines the mass ordering: $\Delta m^2_{31} = m^2_3 - m^2_1$

no synergy effect from combing JUNO+PINGU/ORCA data

fitting the wrong hierarchy →

opposite pull on χ^2_{min}



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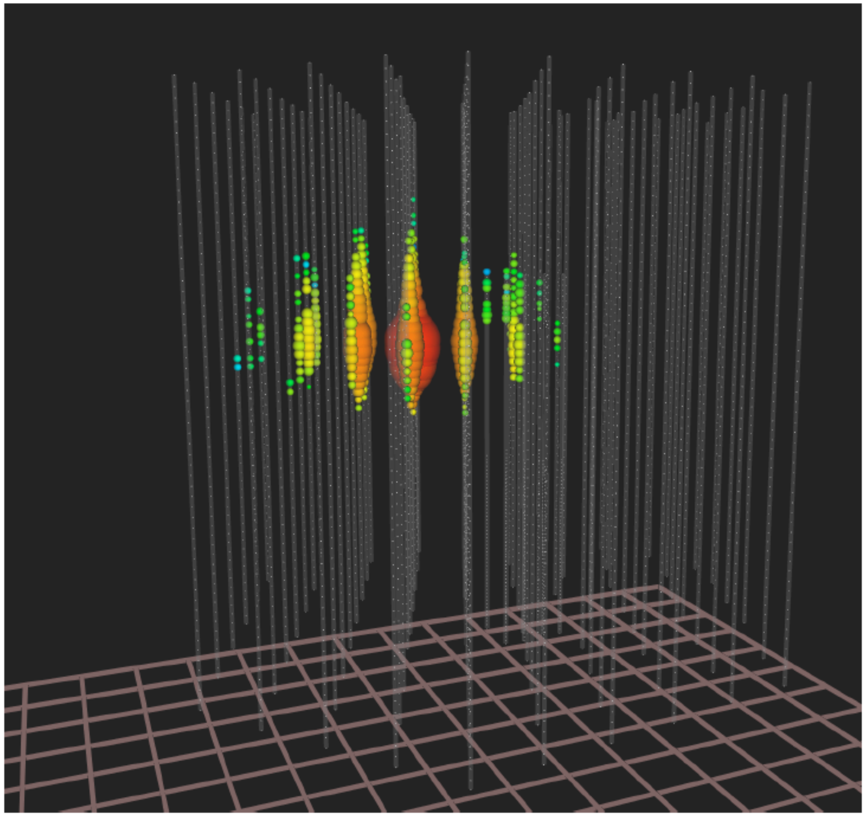
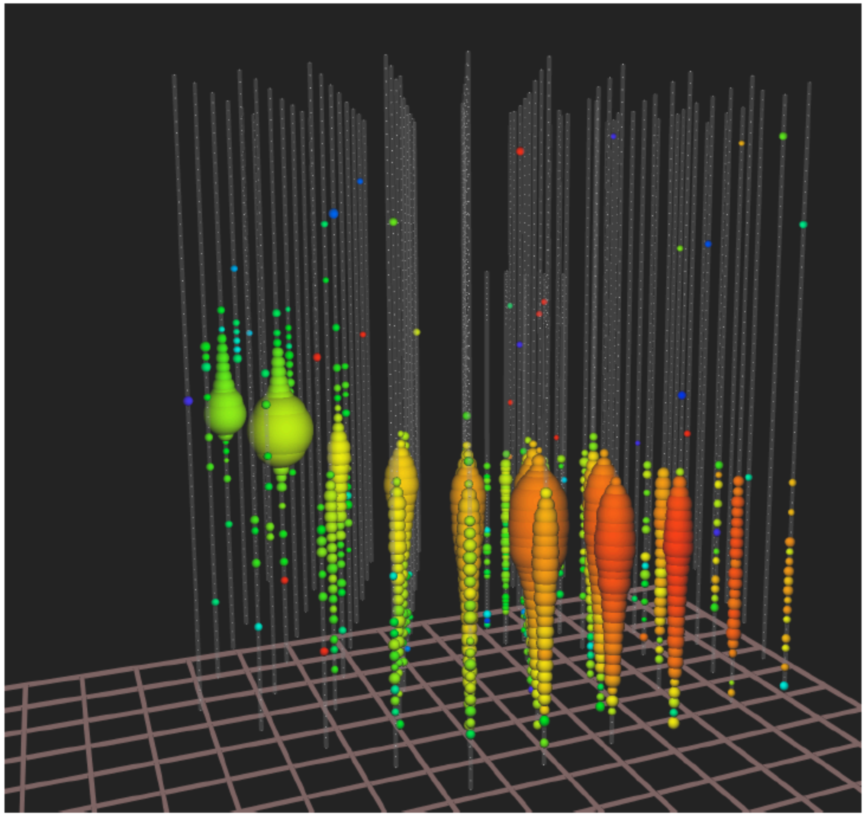
neutrinos interacting inside the detector

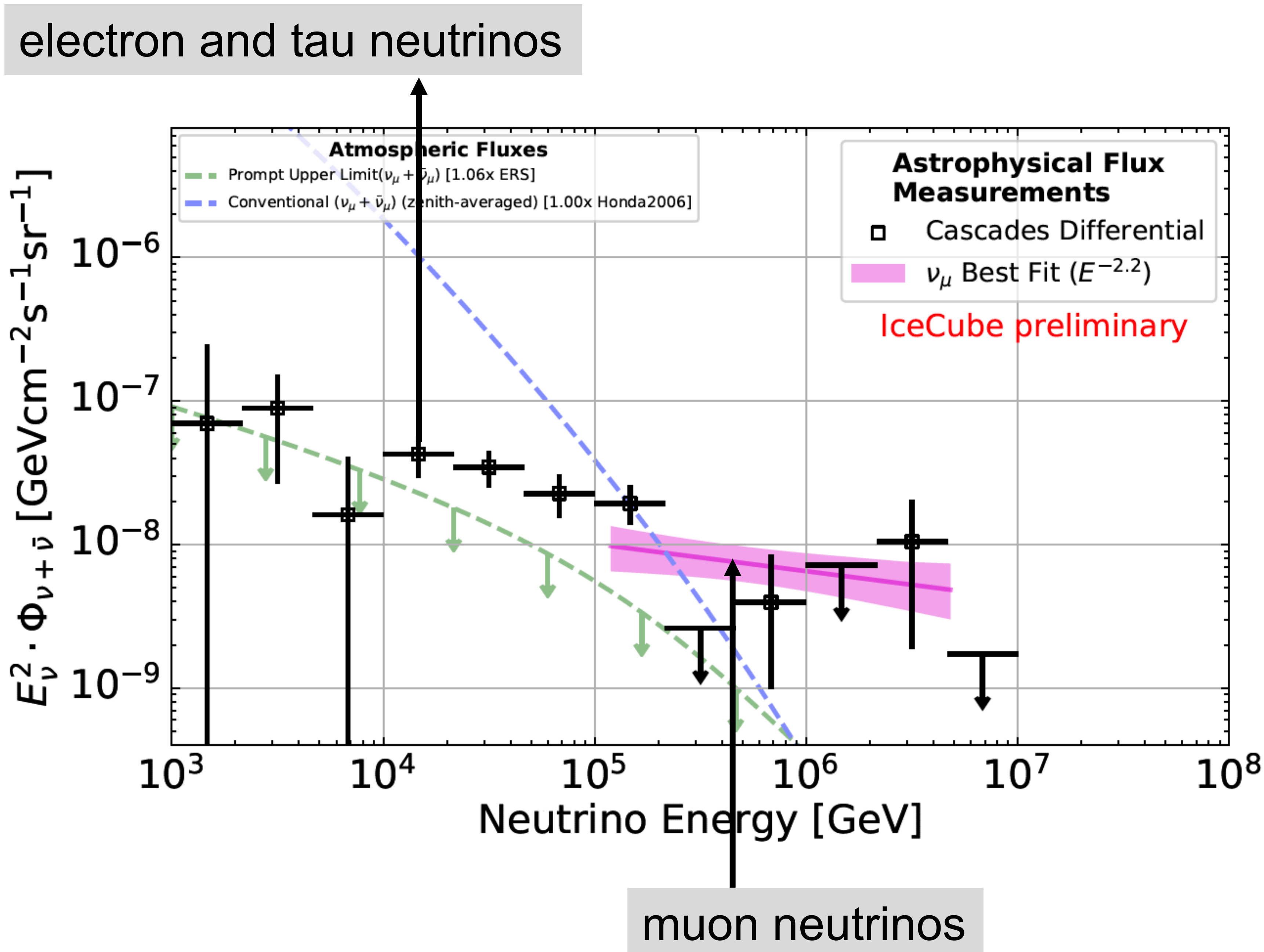
muon neutrinos filtered by the Earth





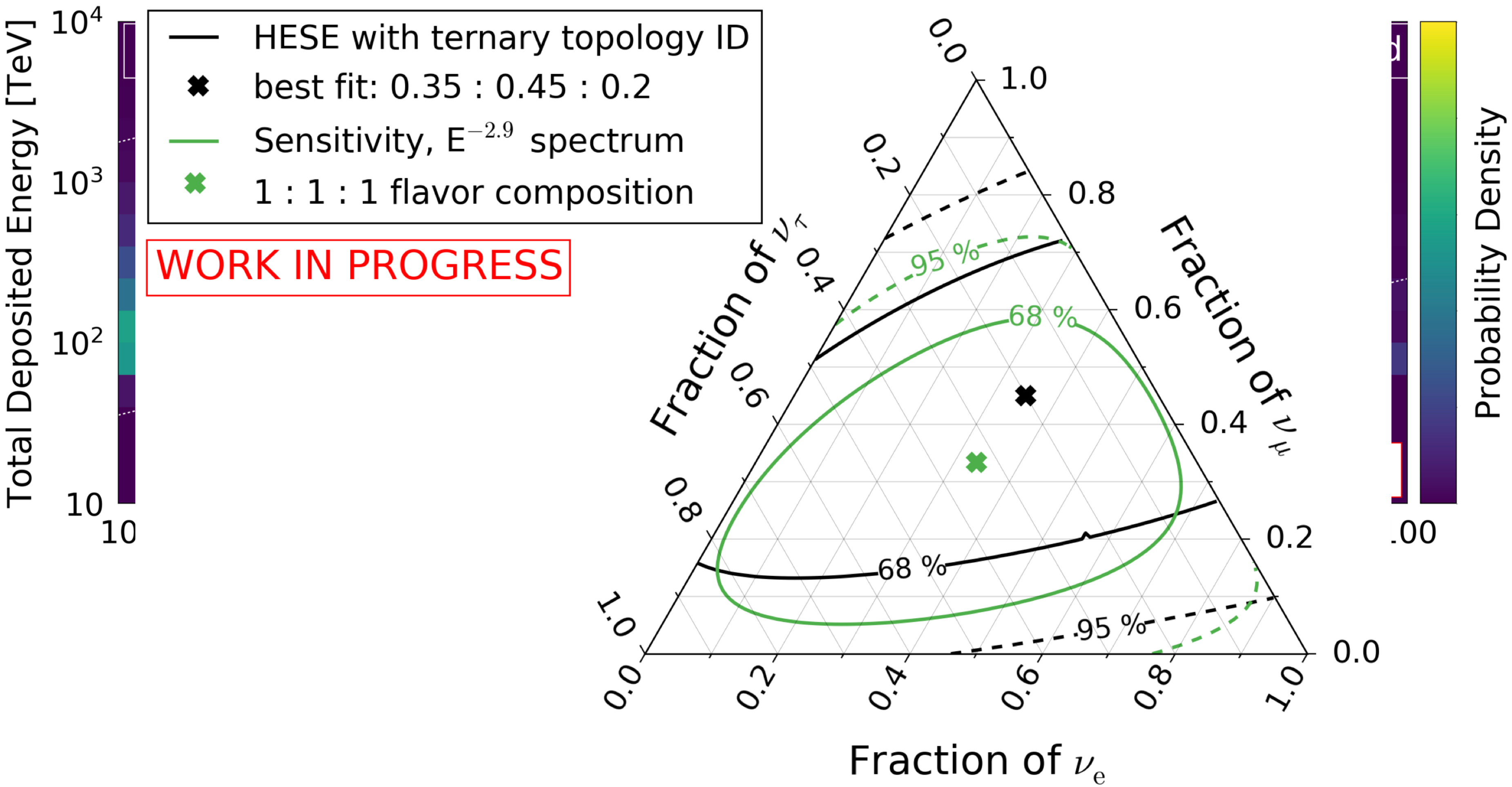
total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.4°)



electron and tau neutrinos
Atmospheric Fluxes
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.06x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]
muon neutrinos

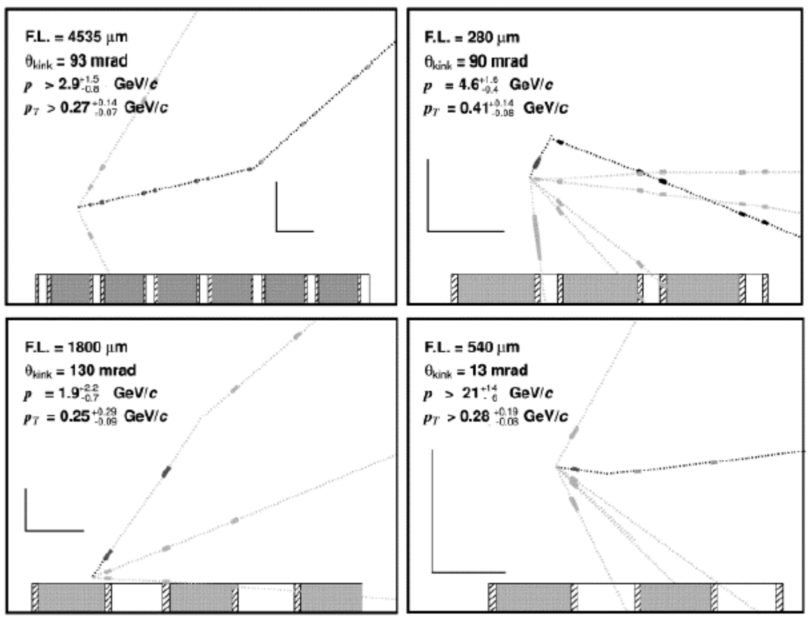
high-energy starting events – 7.5 yr



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

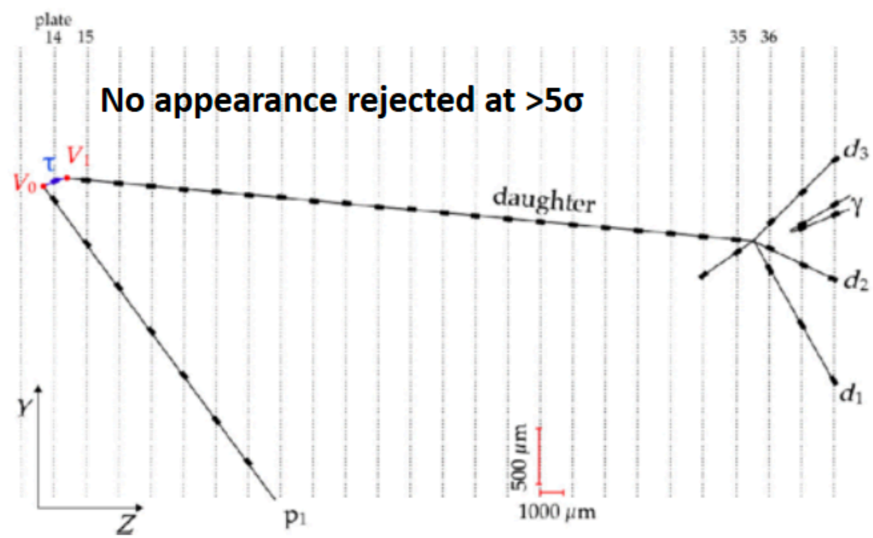
tau neutrinos at Fermilab-- DONUT

DONUT: charmed mesons (no oscillation) and emulsion

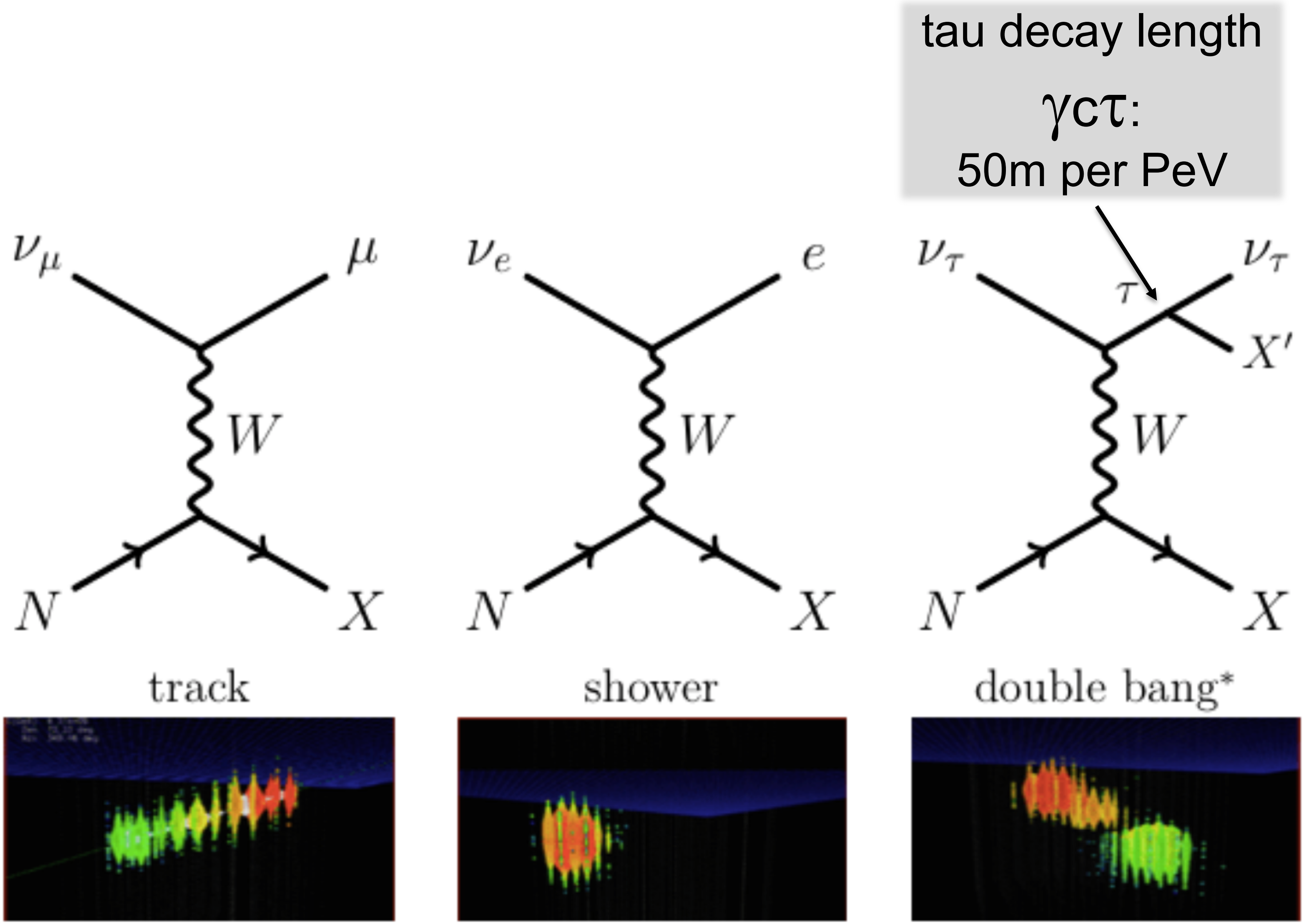


DONUT Phys. Lett. B, Volume 504, Issue 3, 12 April 2001, Pages 218-224

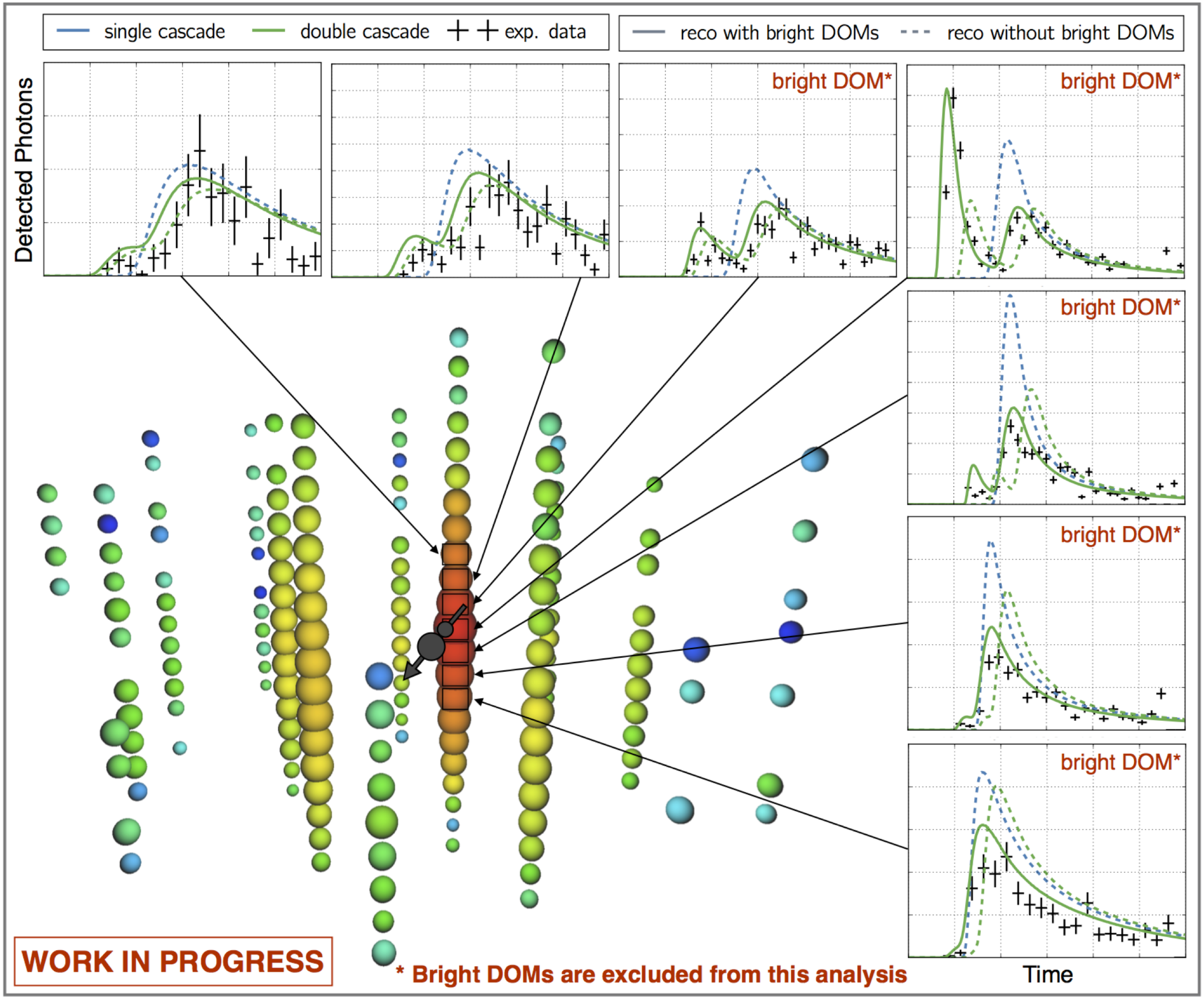
OPERA: oscillation (appearance from CNGS muon neutrino beam) and emulsion



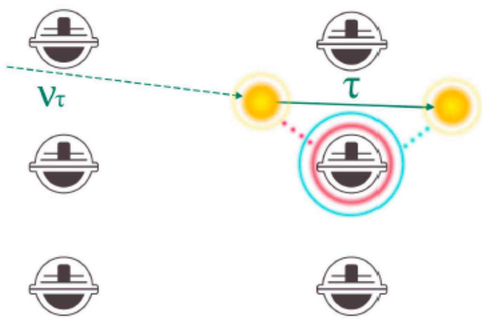
OPERA Phys. Rev. Lett. 115, 121802 (2015)

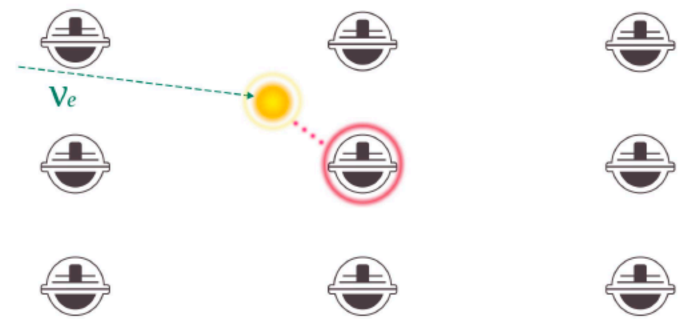

tau decay length
$\gamma c\tau$:
50m per PeV
ν_μ
μ
W
N
X
ν_e
e
W
N
X
ν_τ
τ
ν_τ
X'
W
N
X
track
shower
double bang*

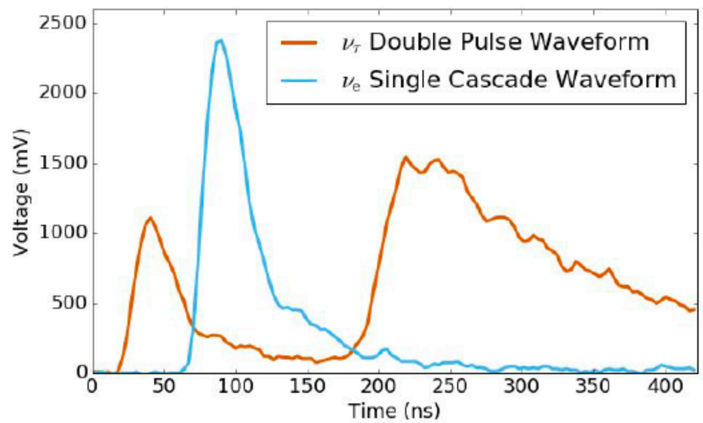
a cosmic tau neutrino: livetime 17m

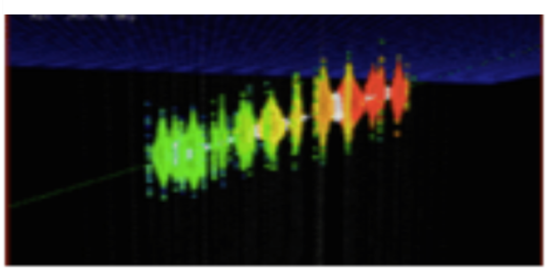


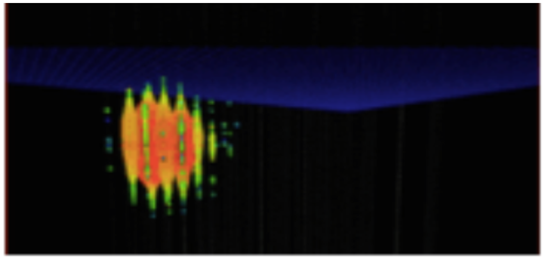
tau decay length:
50m per PeV

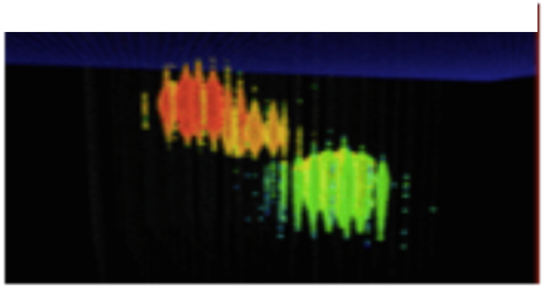




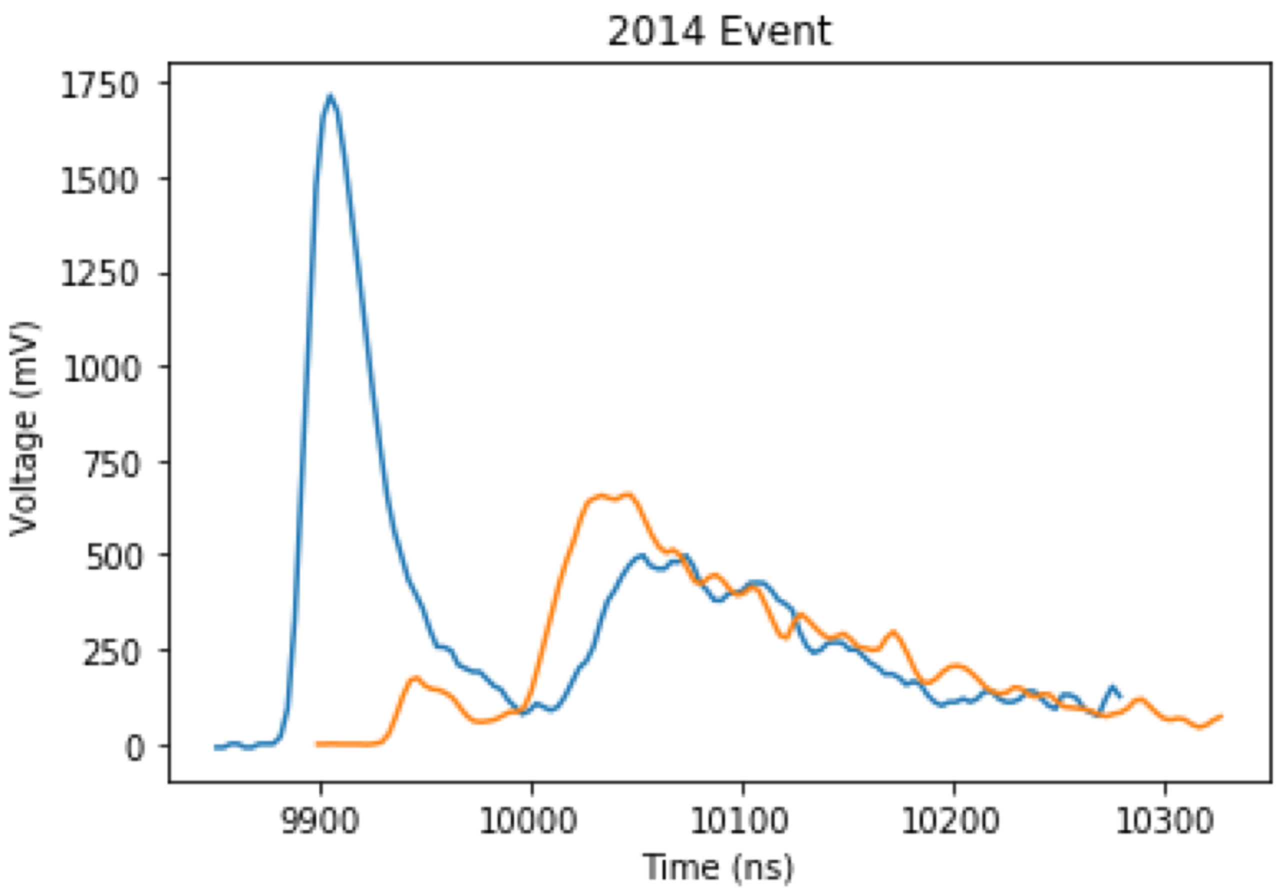








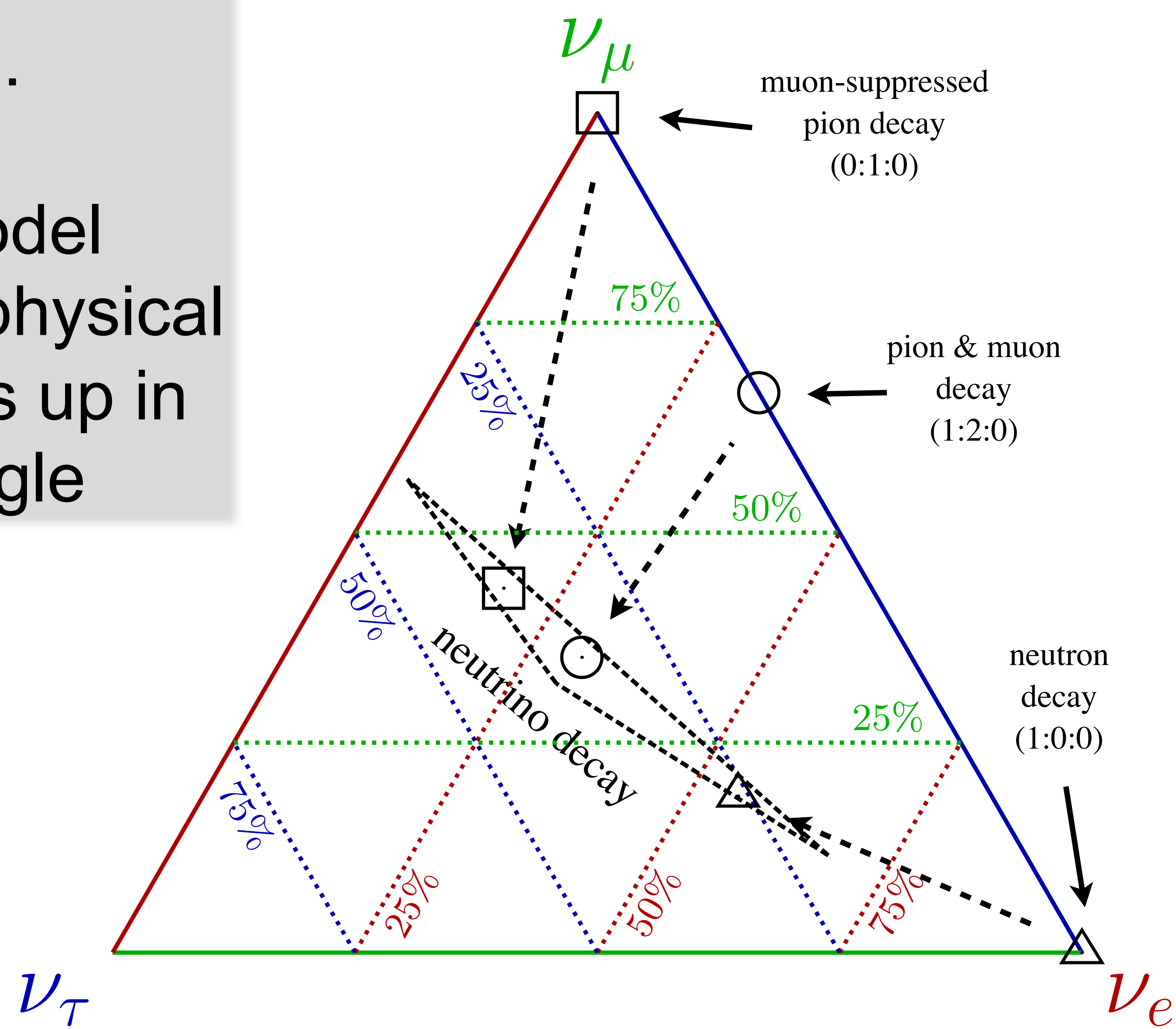
event found in 3 different analyses



new physics ?

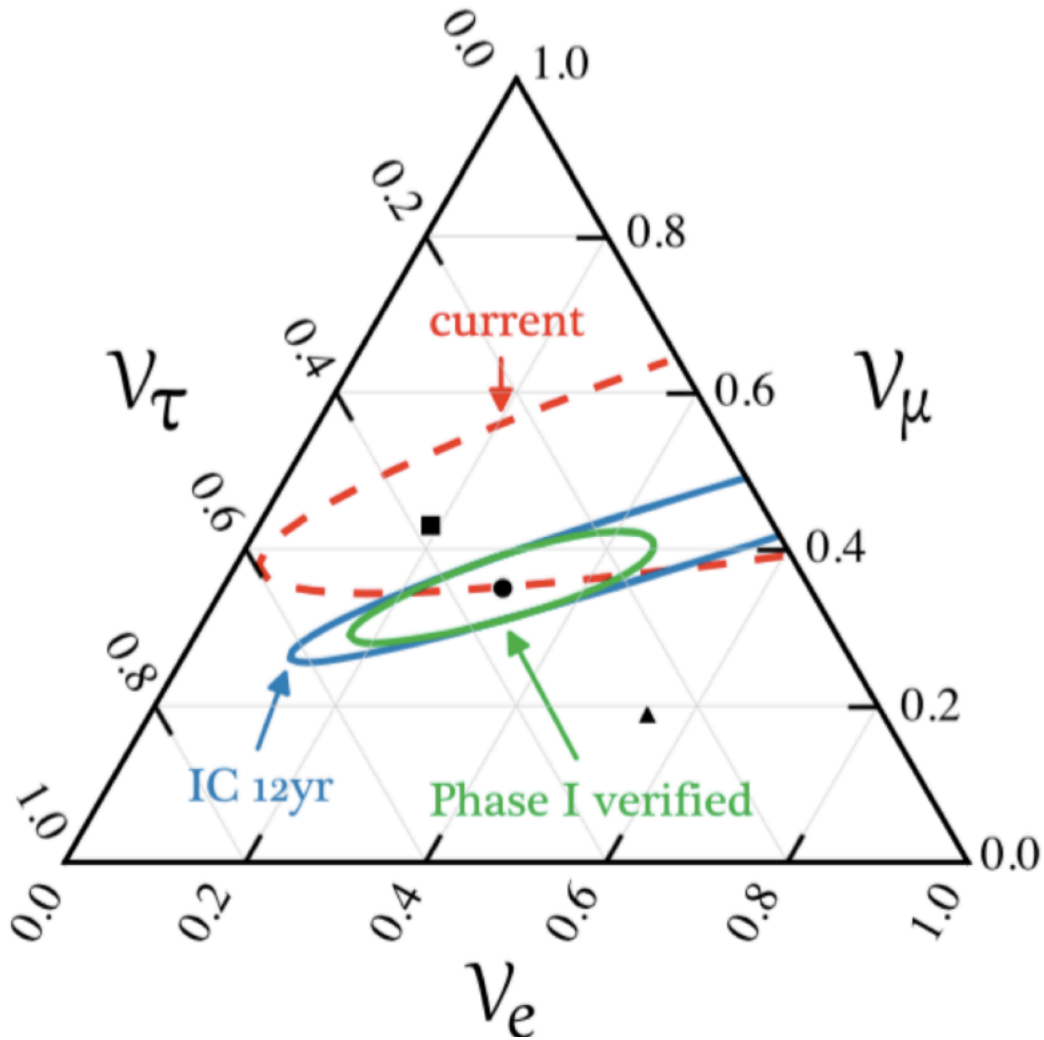
if not…

every model
for the astrophysical
source ends up in
the triangle

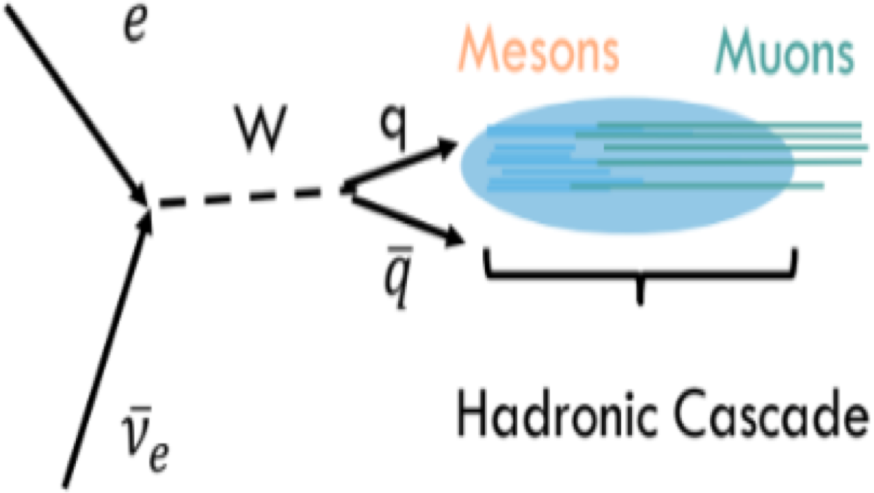


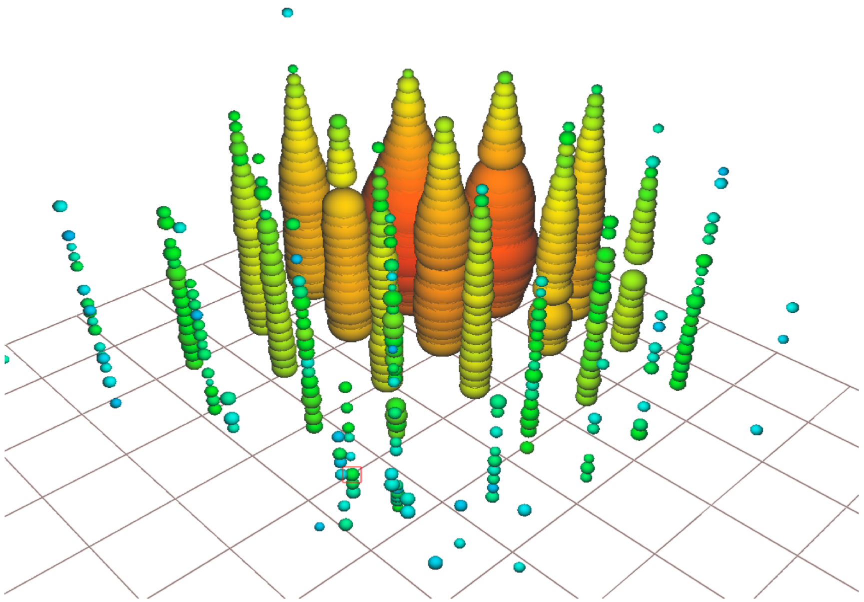
upgrade

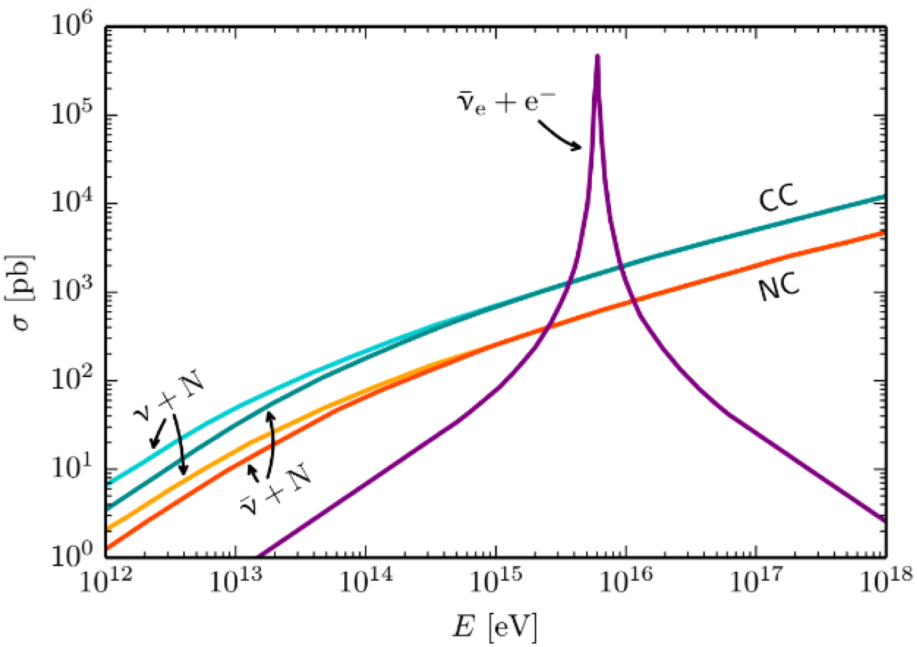
- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM



Glashow resonance: anti-ν_e + atomic electron → real W





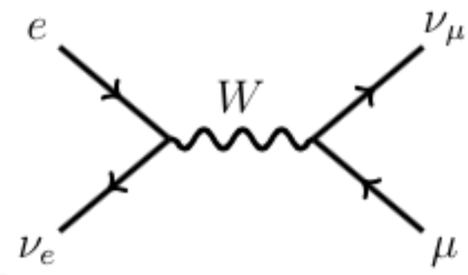


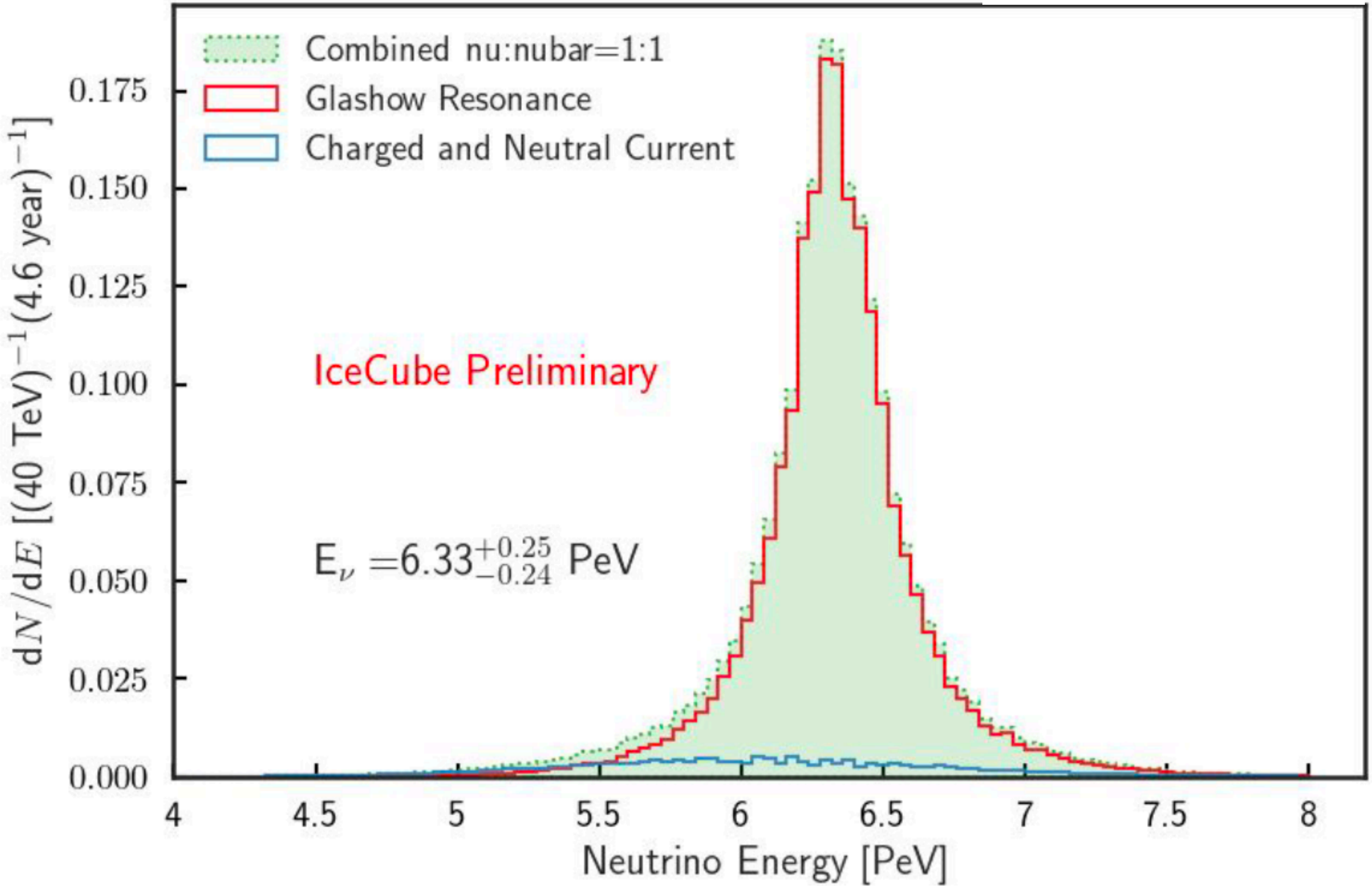
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

- energy measurement understood
- identification of anti-electron neutrinos

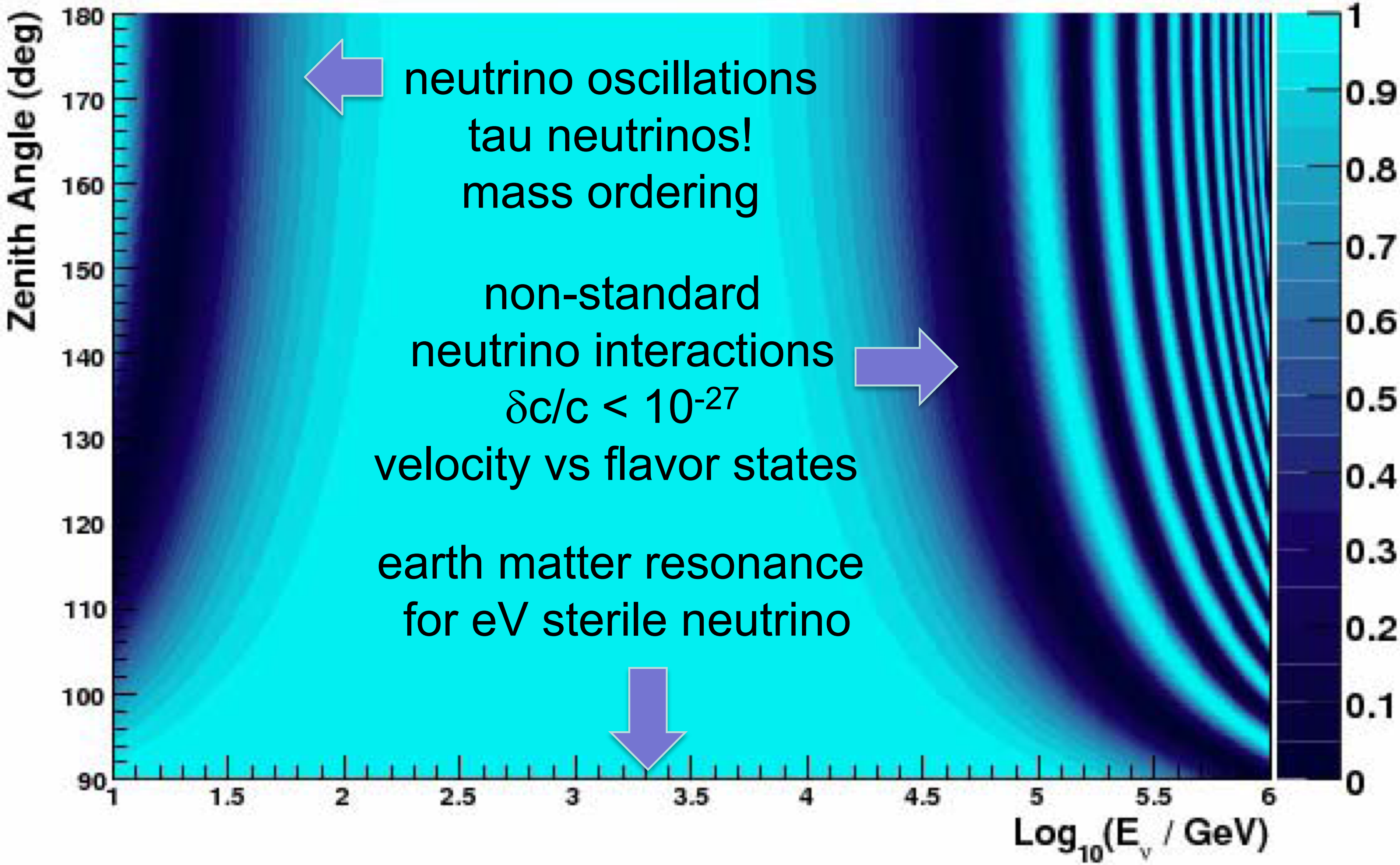




Neutrino Astroparticle Physics
Francis Halzen

- Physics with neutrino “telescopes” using the atmospheric neutrino beam, also sterile neutrinos.
- The cosmic neutrino beam and neutrino physics using the cosmic neutrino beam.
- BSM neutrino physics using atmospheric and cosmic neutrinos.
- Neutrino physics with a Galactic neutrino explosion.

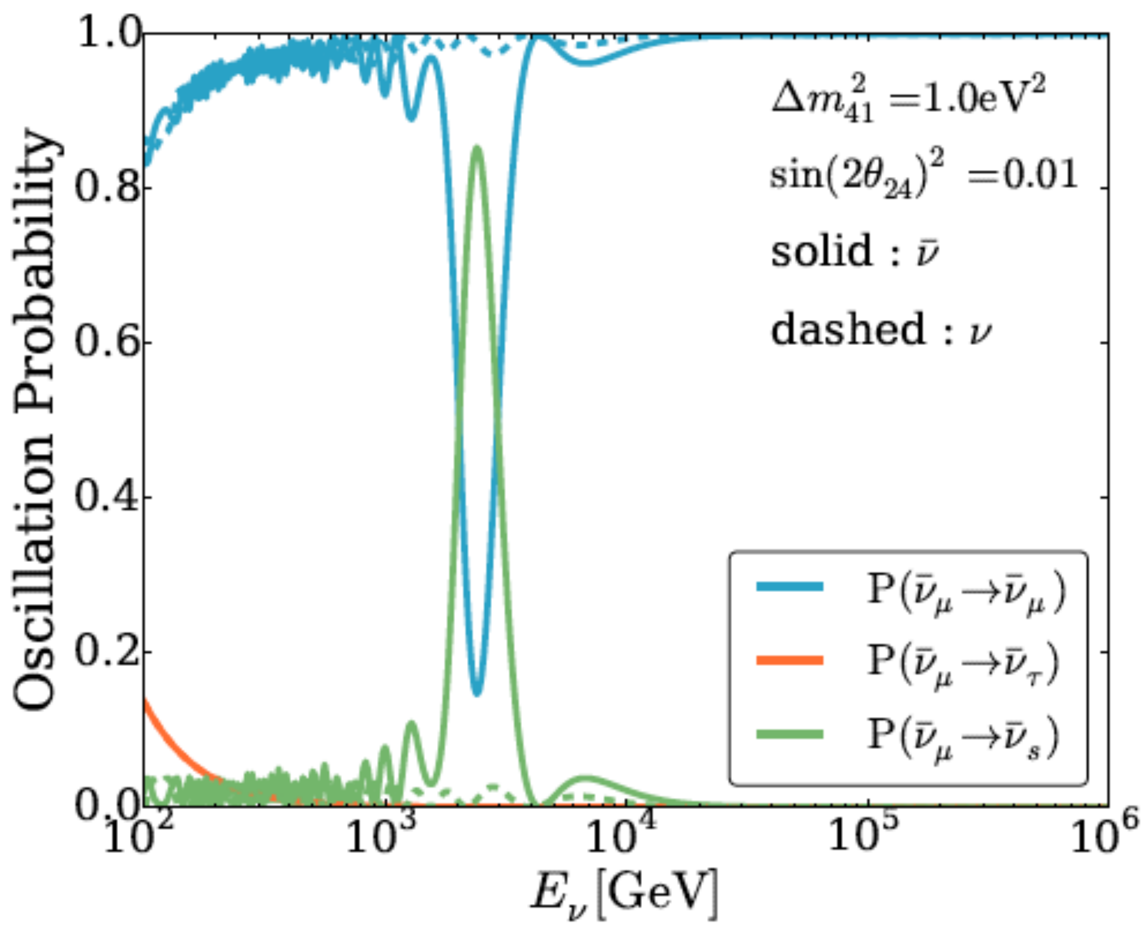
old and new physics with atmospheric neutrinos…

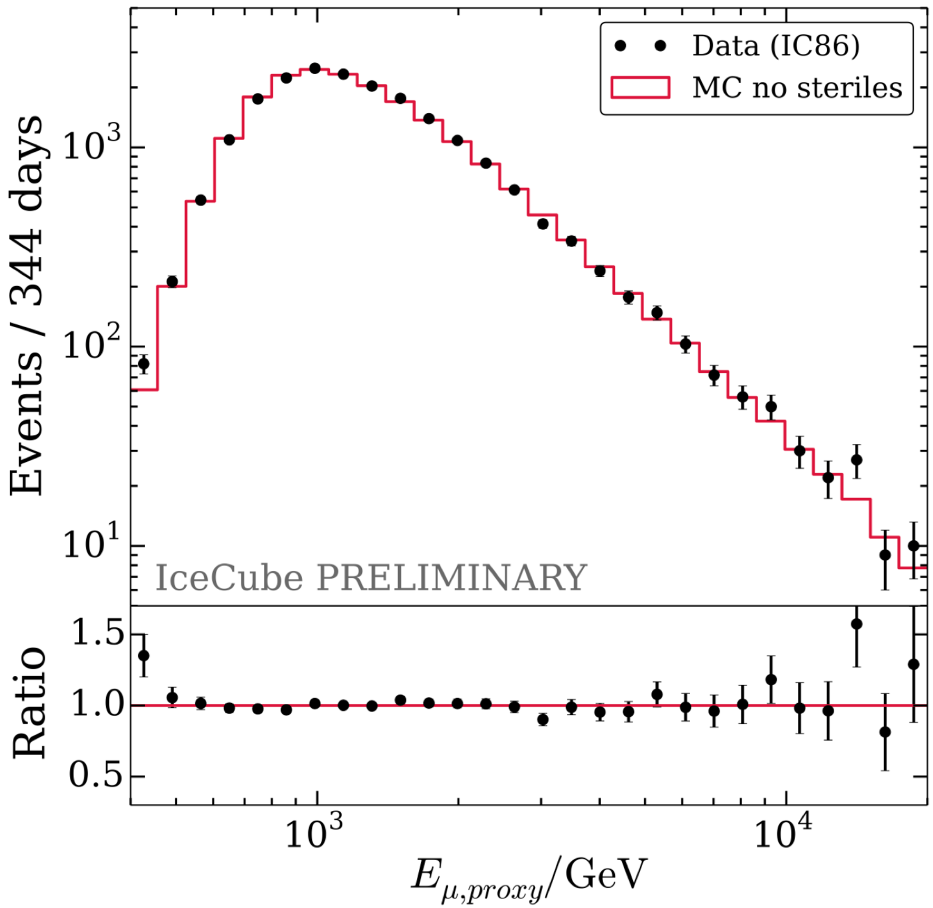


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

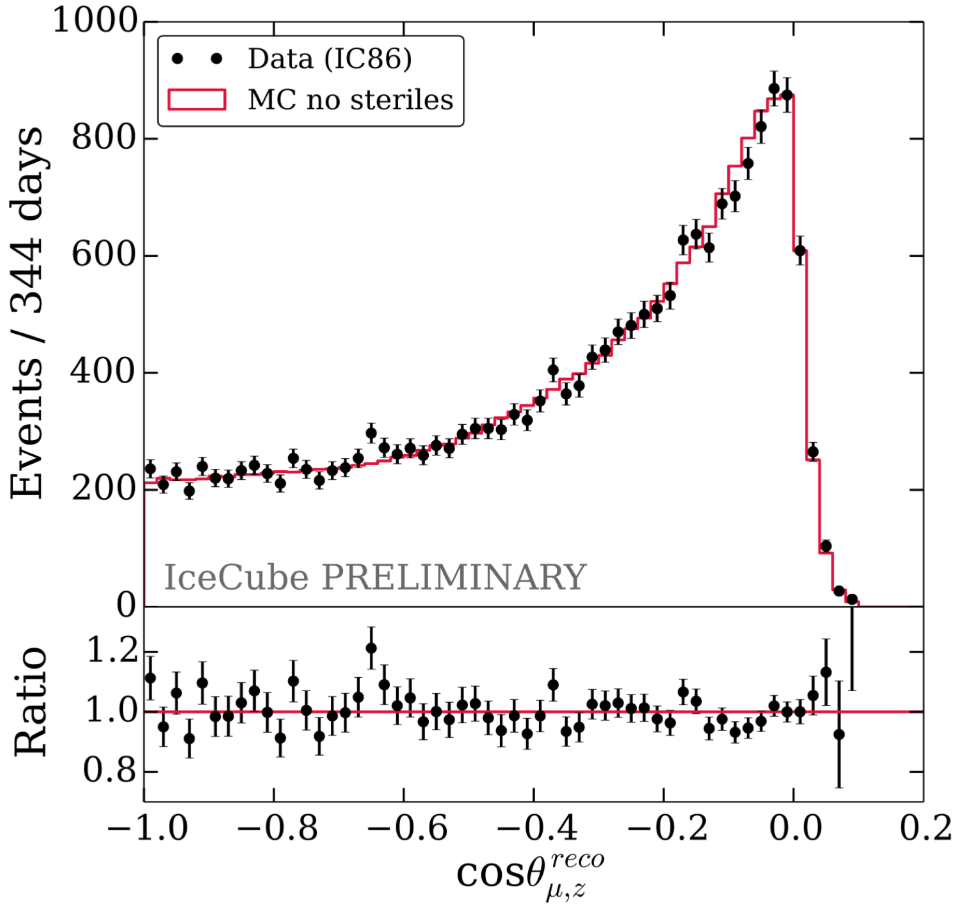
In the **Earth** for sterile neutrino $\Delta m^2 = O(1 eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$

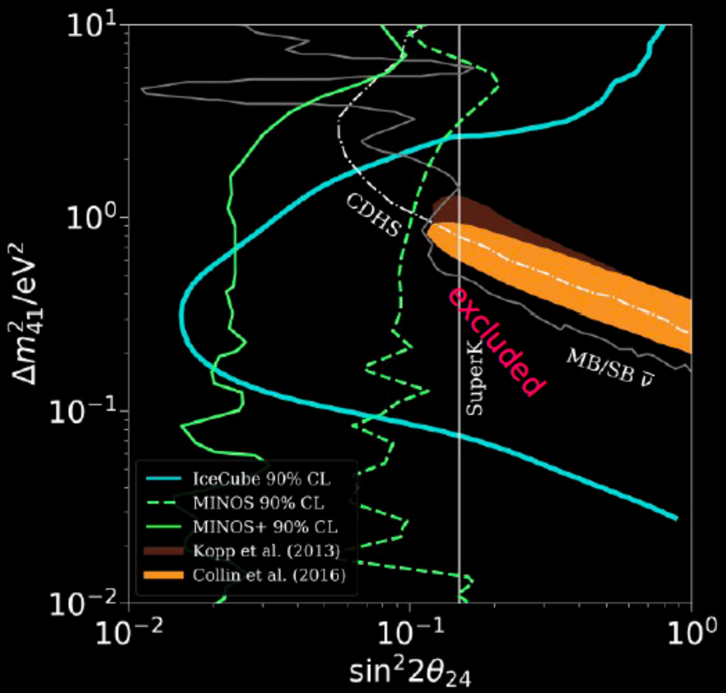




IceCube 86 first year
7 year analysis soon

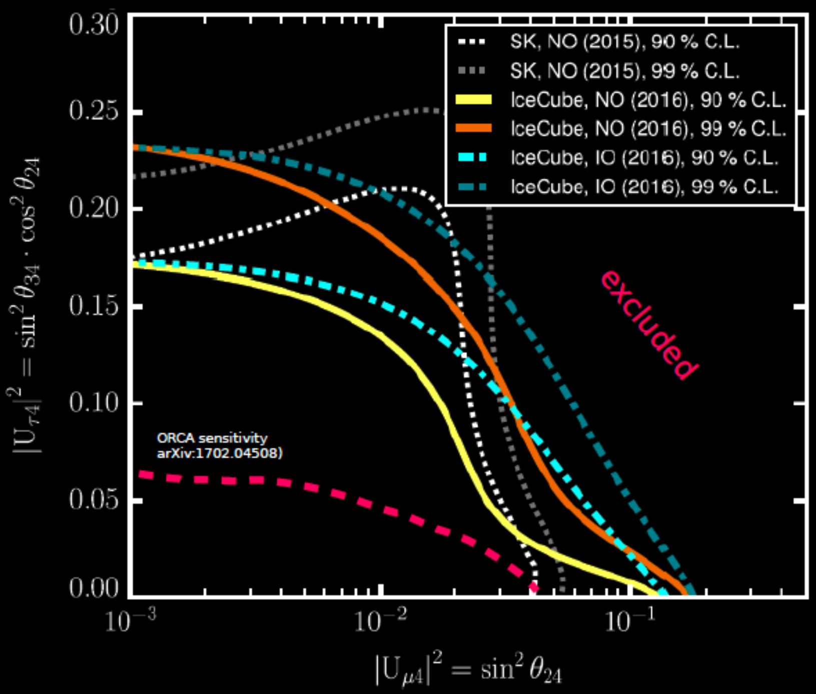


NTs sensitive to disappearance effects in atmospheric neutrinos, ie, mainly to Δm^2_{41} and $\sin 2\theta_{24}$



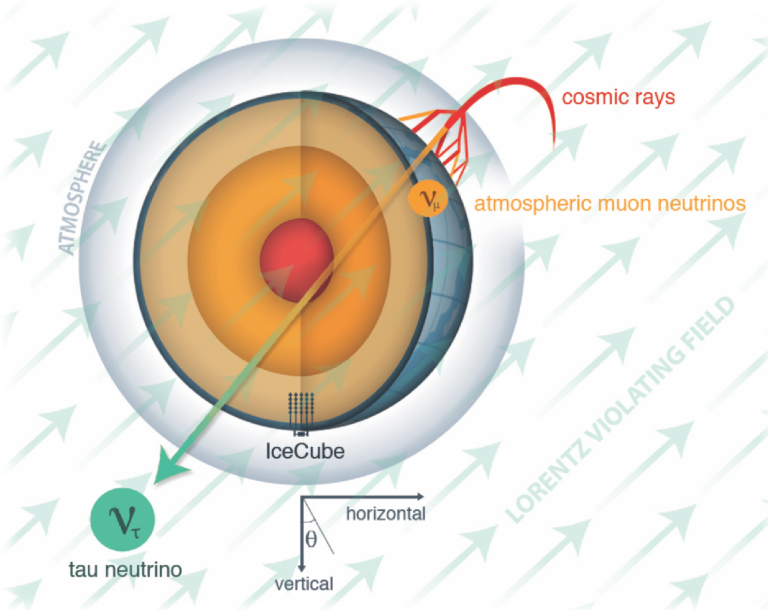
High energy analysis: $E_\nu \gtrsim 300$ GeV

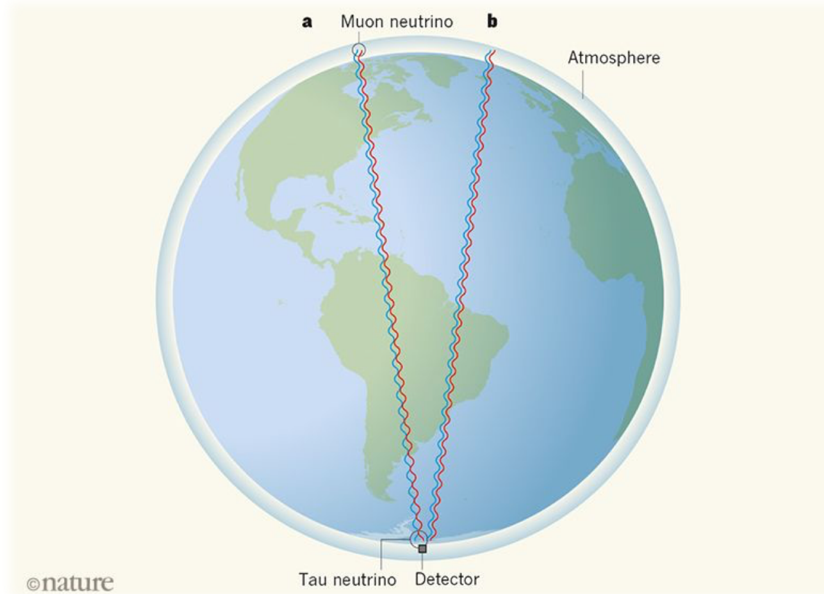
Phys. Rev. D 95, 112002 (2017)



Low energy analysis: $E_\nu \lesssim 60$ GeV

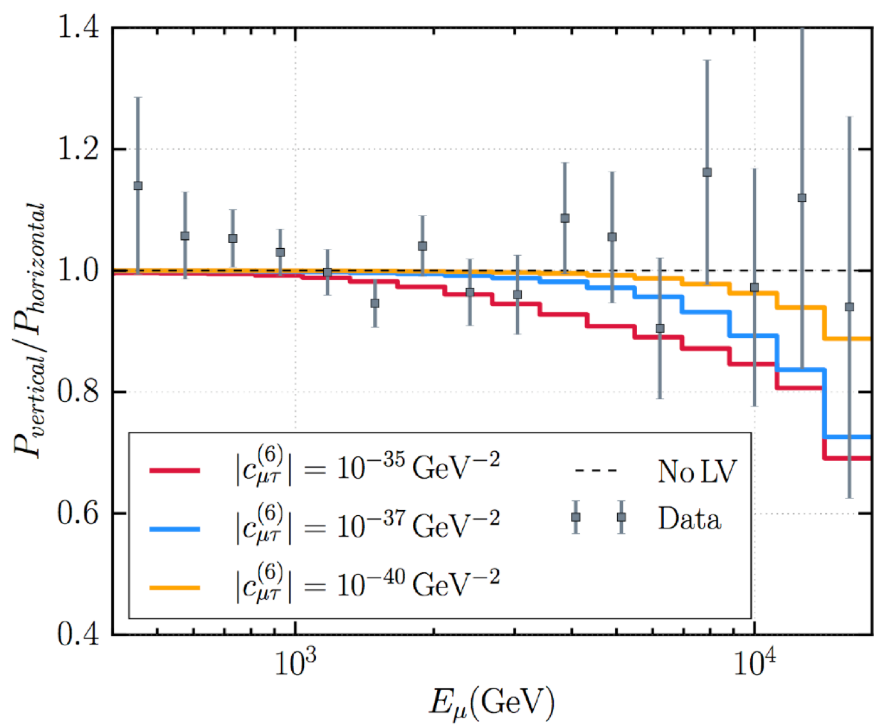
So far, results consistent with the standard three-neutrino hypothesis





neutrino interferometry tests Lorentz symmetry:

- e.g. ratio of the vertical vs horizontal oscillation probability
- result for dimension 6 μ-τ operator shown here

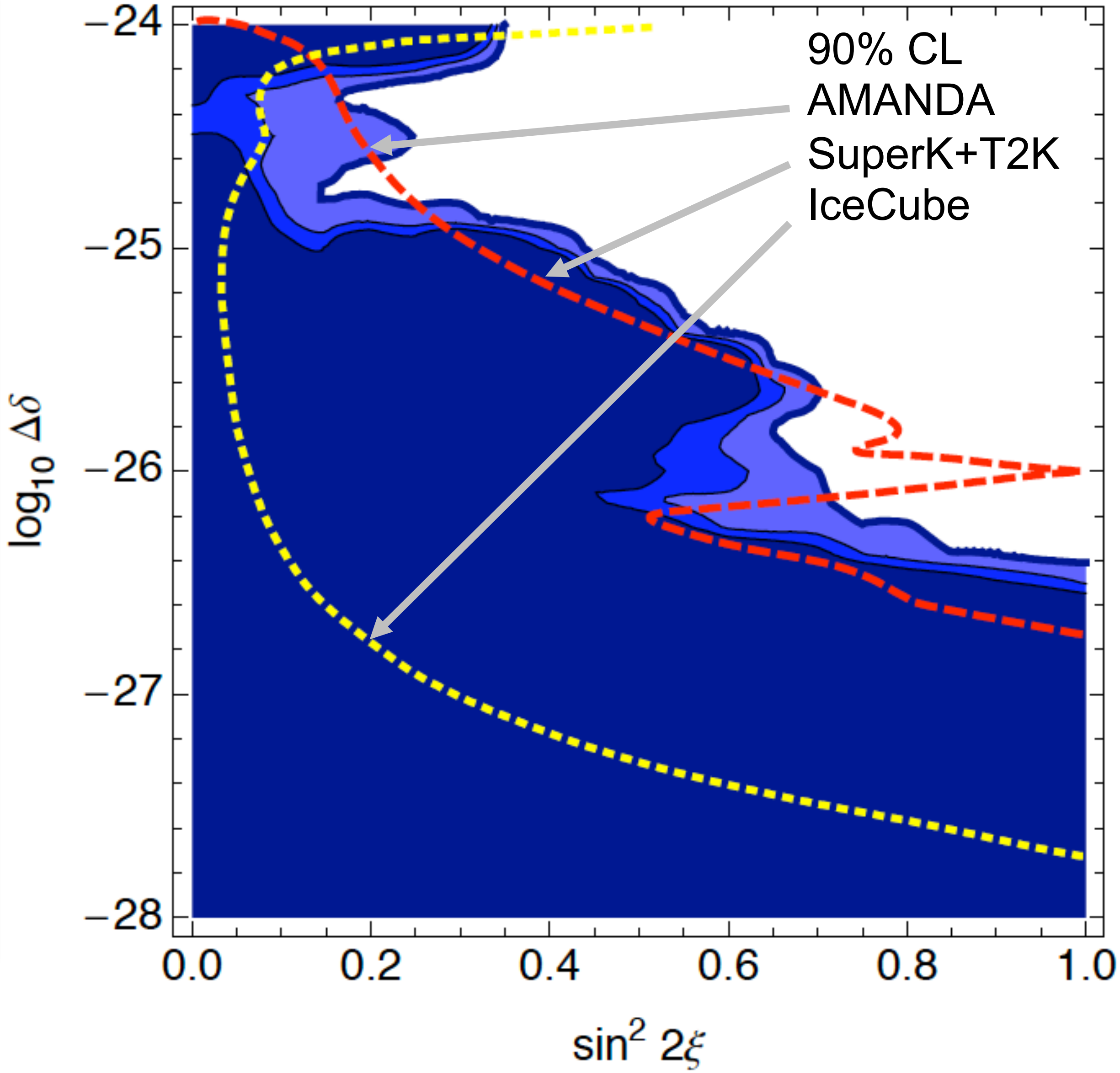


beyond the SM with high energy neutrinos

tests
- equivalence principle
- Lorentz invariance

$\delta c/c \sim 10^{-26}$

also
- dark matter annihilation, decay, interactions
- magnetic monopoles, …



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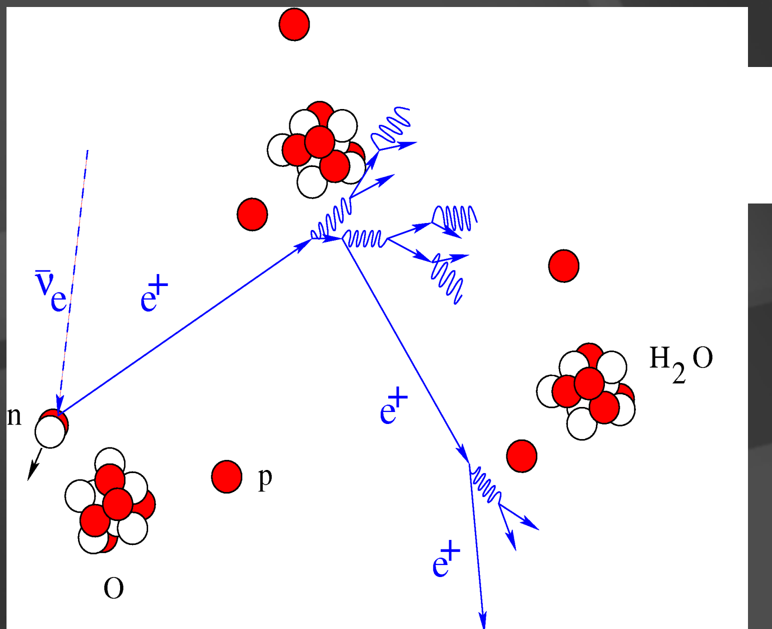
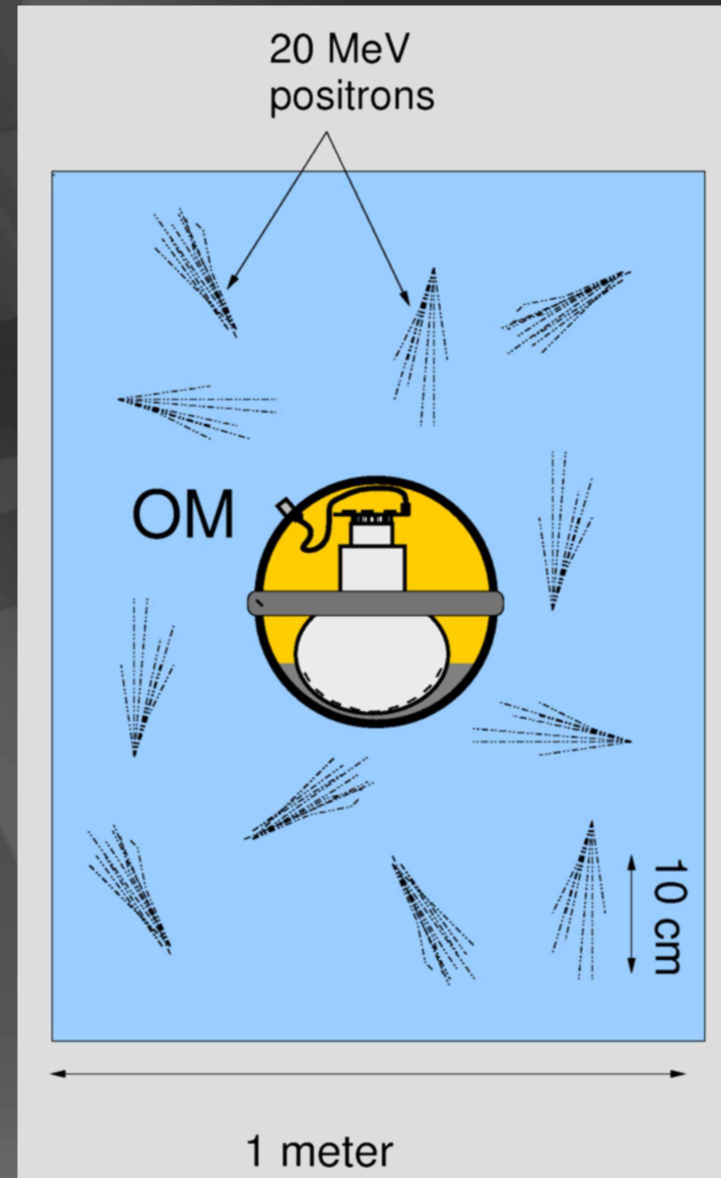
supernova neutrino events from most likely distance

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

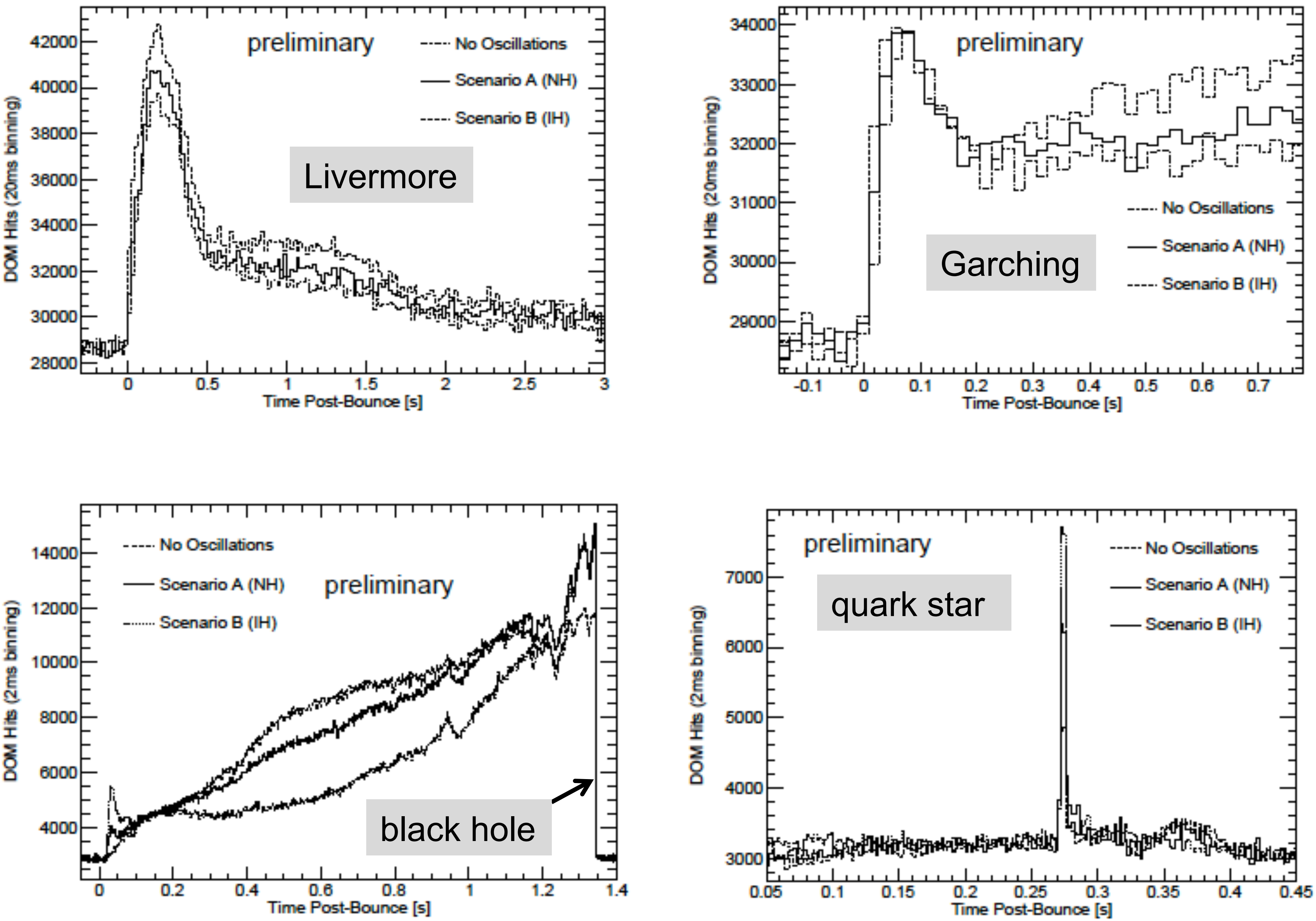
supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$





- ☞ PMT noise low (280 Hz)
- ☞ detect correlated rate increase (DC current) on top of PMT noise when supernova neutrinos pass through the detector

IceCube DOM photoelectron counts vs time: 10^6 for a supernova at 10 kpc



Neutrino Astroparticle Physics

- atmospheric and cosmic beam
- capabilities demonstrated by ANTARES and IceCube
- *complementary* to accelerator beams: higher energy, nutau