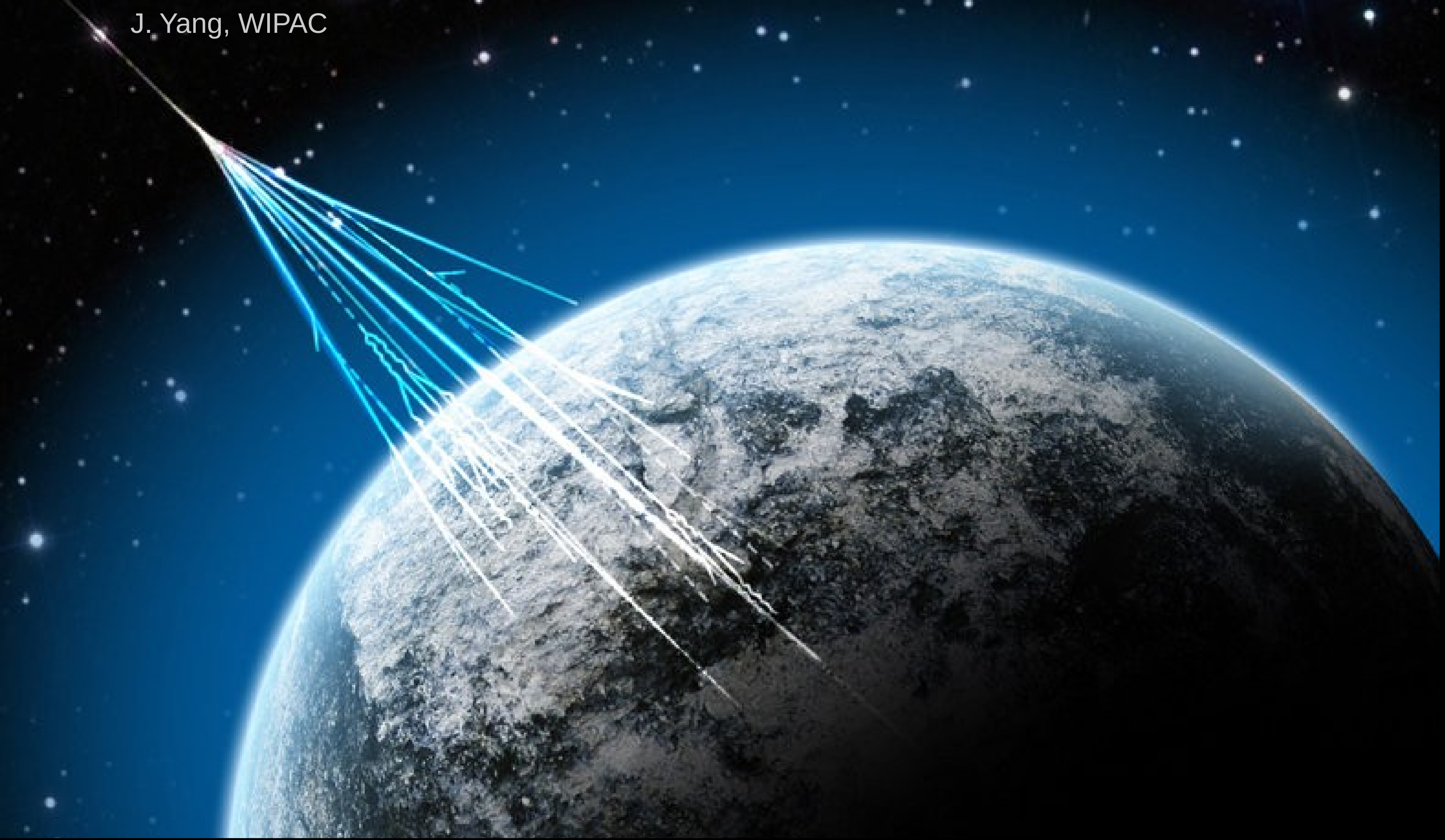


UNIVERSITY OF ALBERTA

Borexino workshop

“Recent developments in neutrino physics and astrophysics”

LNGS & GSSI

September 2017

New determinations of mixing parameters with atmospheric neutrinos

Juan-Pablo Yáñez

j.p.yanez@ualberta.ca

outline

-modeling atmospheric neutrinos

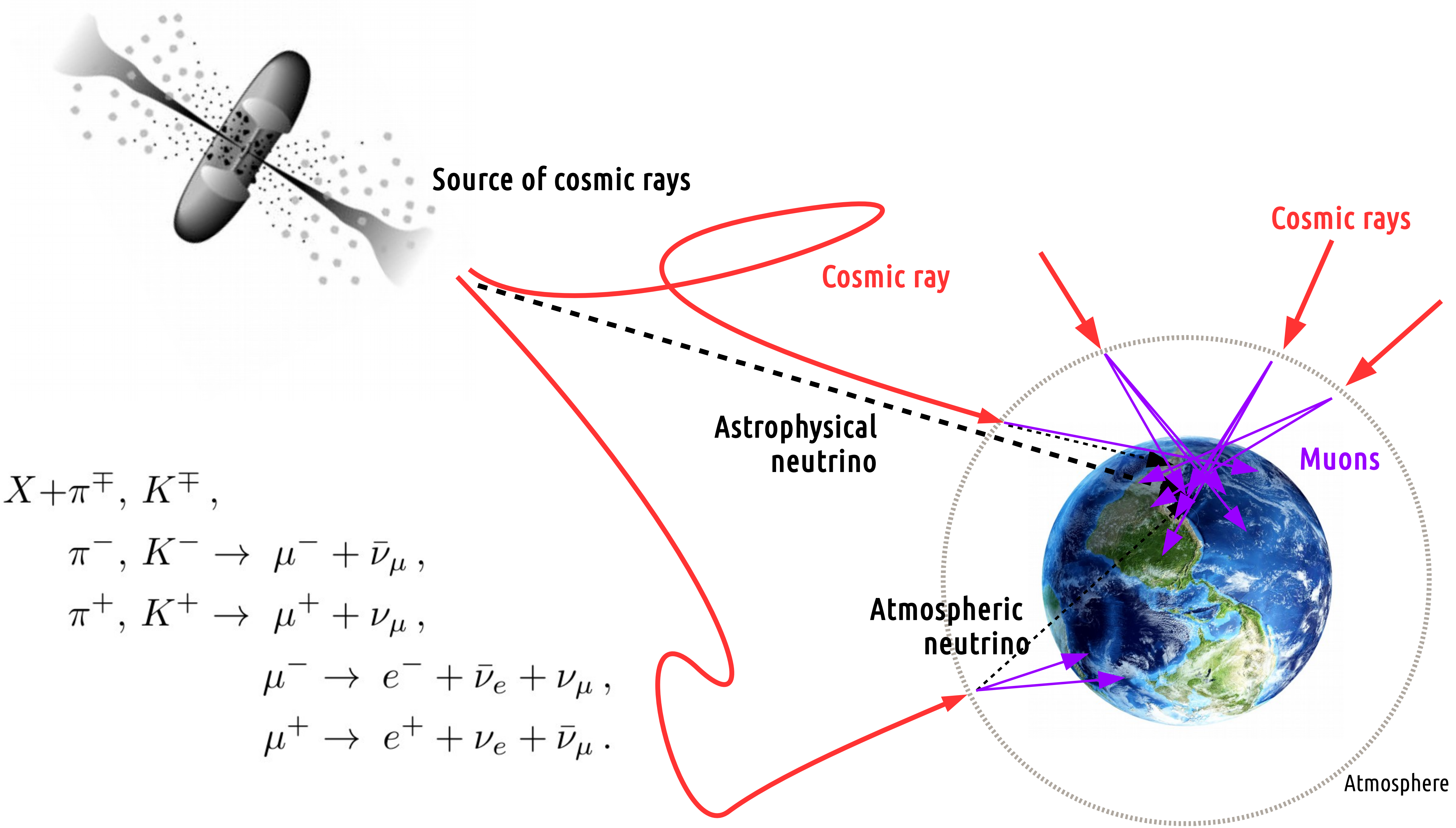
-oscillations in atmospheric nu's

-recent experimental results

-future experiments

modeling atmospheric neutrinos: what's new?

from cosmic rays to neutrinos



$$CR + N \to X + \pi^{\mp},\, K^{\mp}\,,$$

$$\pi^{-},\, K^{-} \to \mu^{-} + \bar{\nu}_{\mu}\,,$$

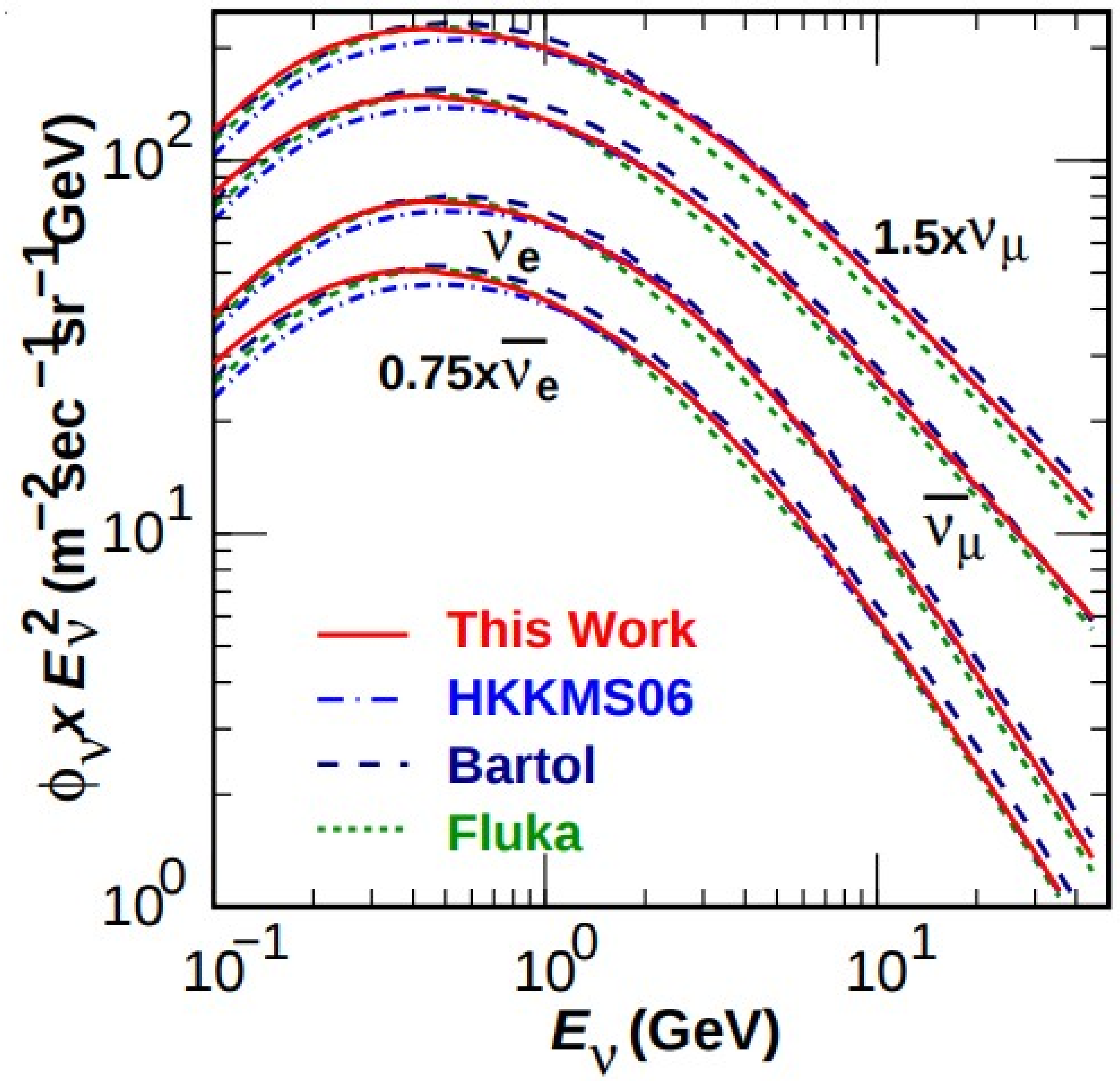
$$\pi^{+},\, K^{+} \to \mu^{+} + \nu_{\mu}\,,$$

$$\mu^{-} \to e^{-} + \bar{\nu}_{e} + \nu_{\mu}\,,$$

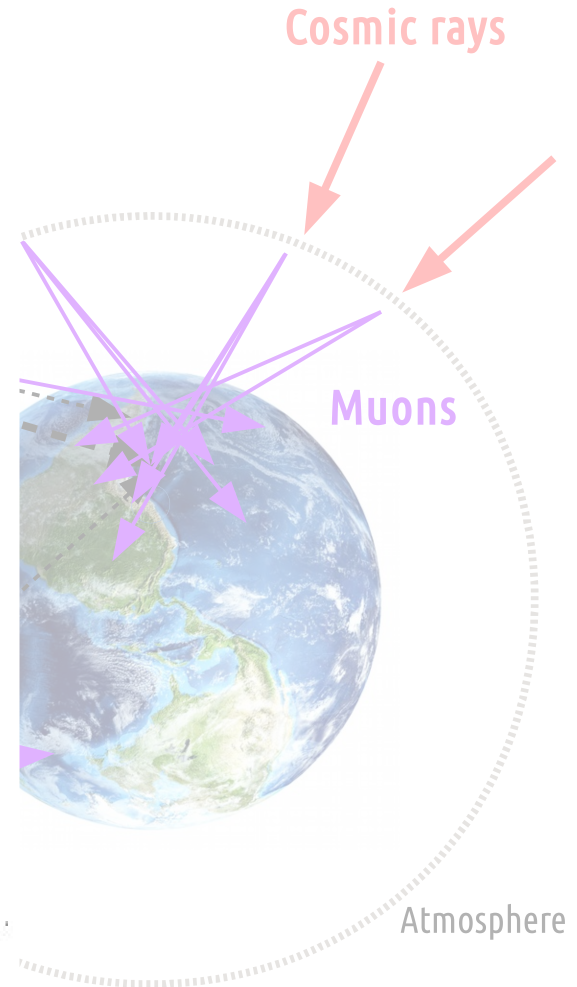
$$\mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}\,.$$

from cosmic rays to neutrinos

$$CR + N \rightarrow X + \pi^{\mp},\, K^{\mp}$$
$$\pi^{-},\, K^{-}$$
$$\pi^{+},\, K^{+}$$



Phys.Rev.D83:123001,2011

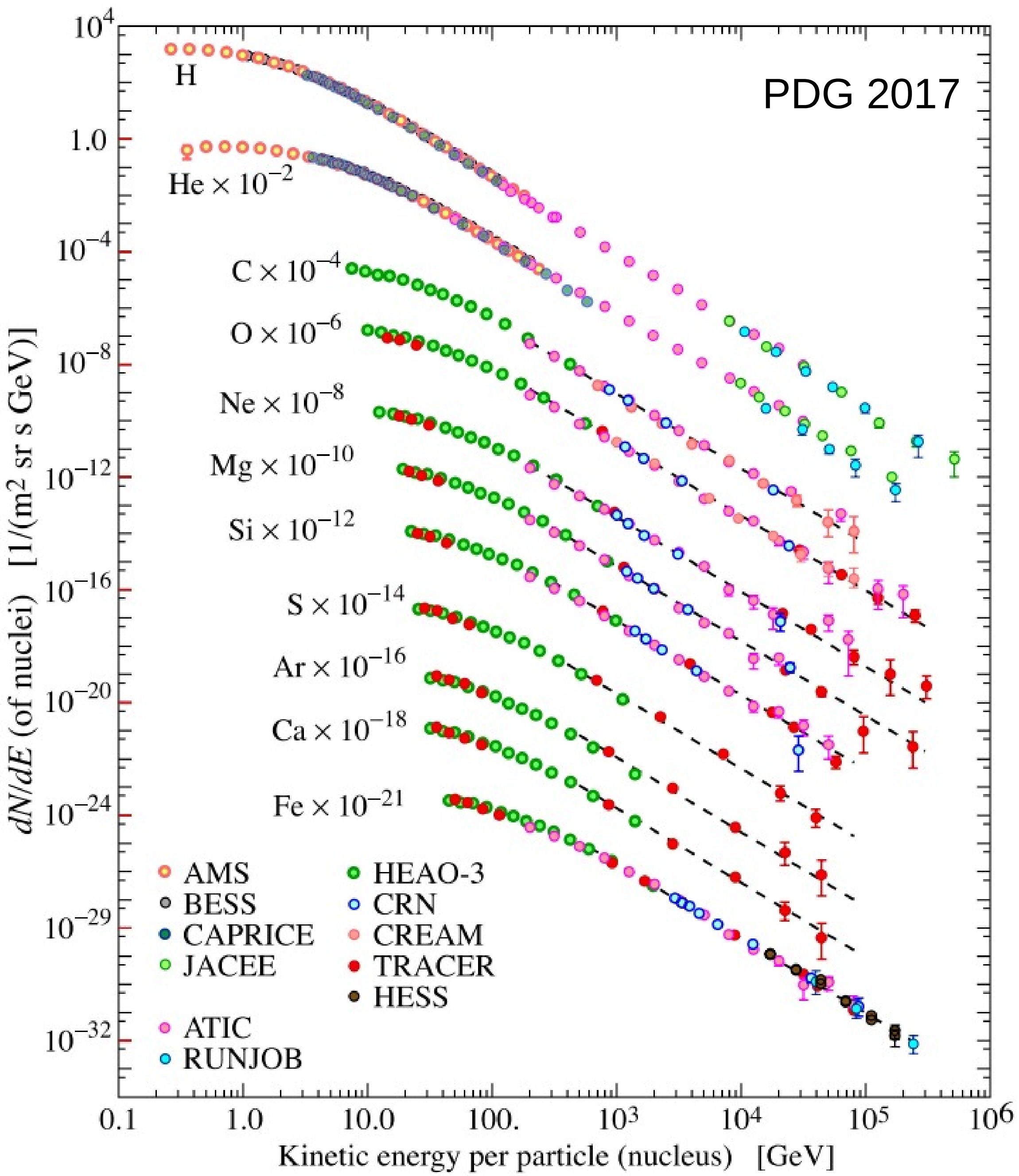


flux basic inputs

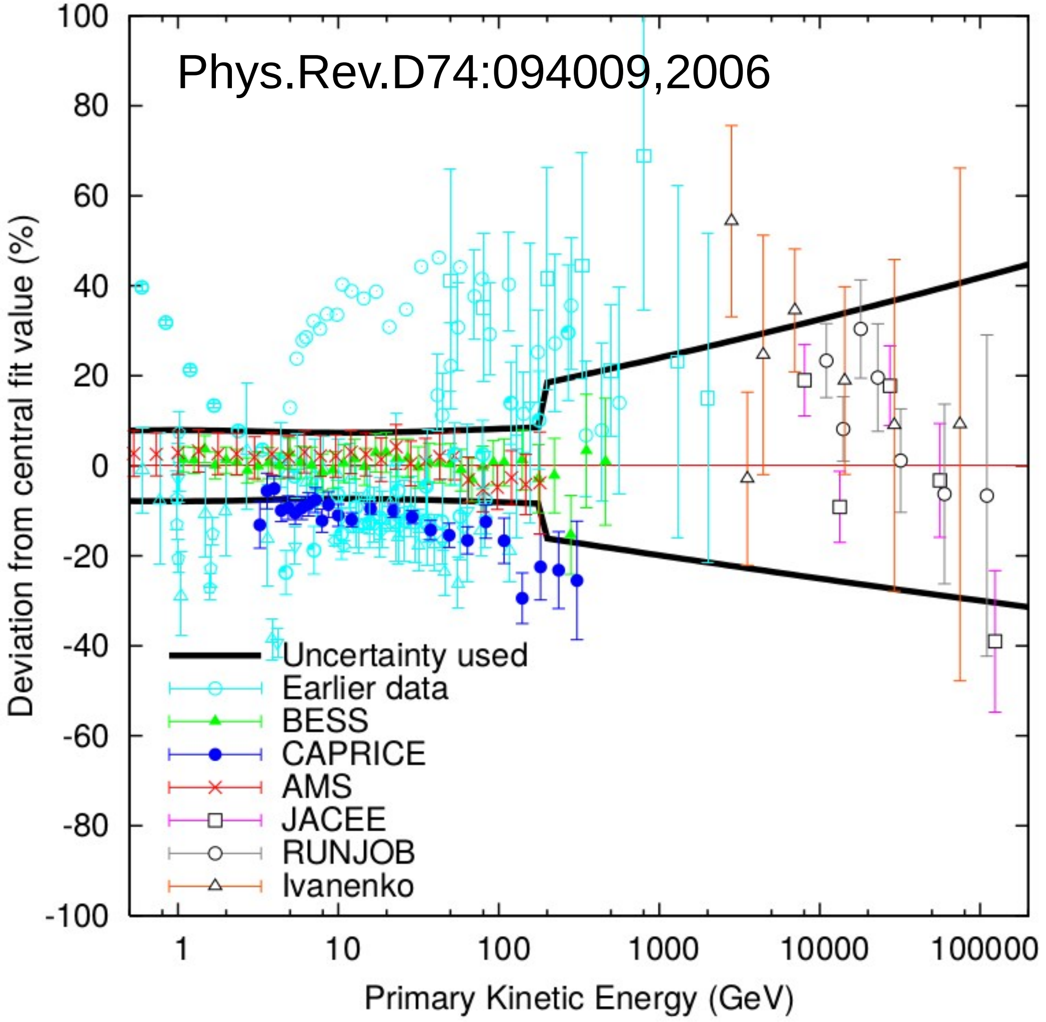
-cosmic ray flux

-4 new measurements in last ~10 years (AMS-II, PAMELA, Cream, BESS)

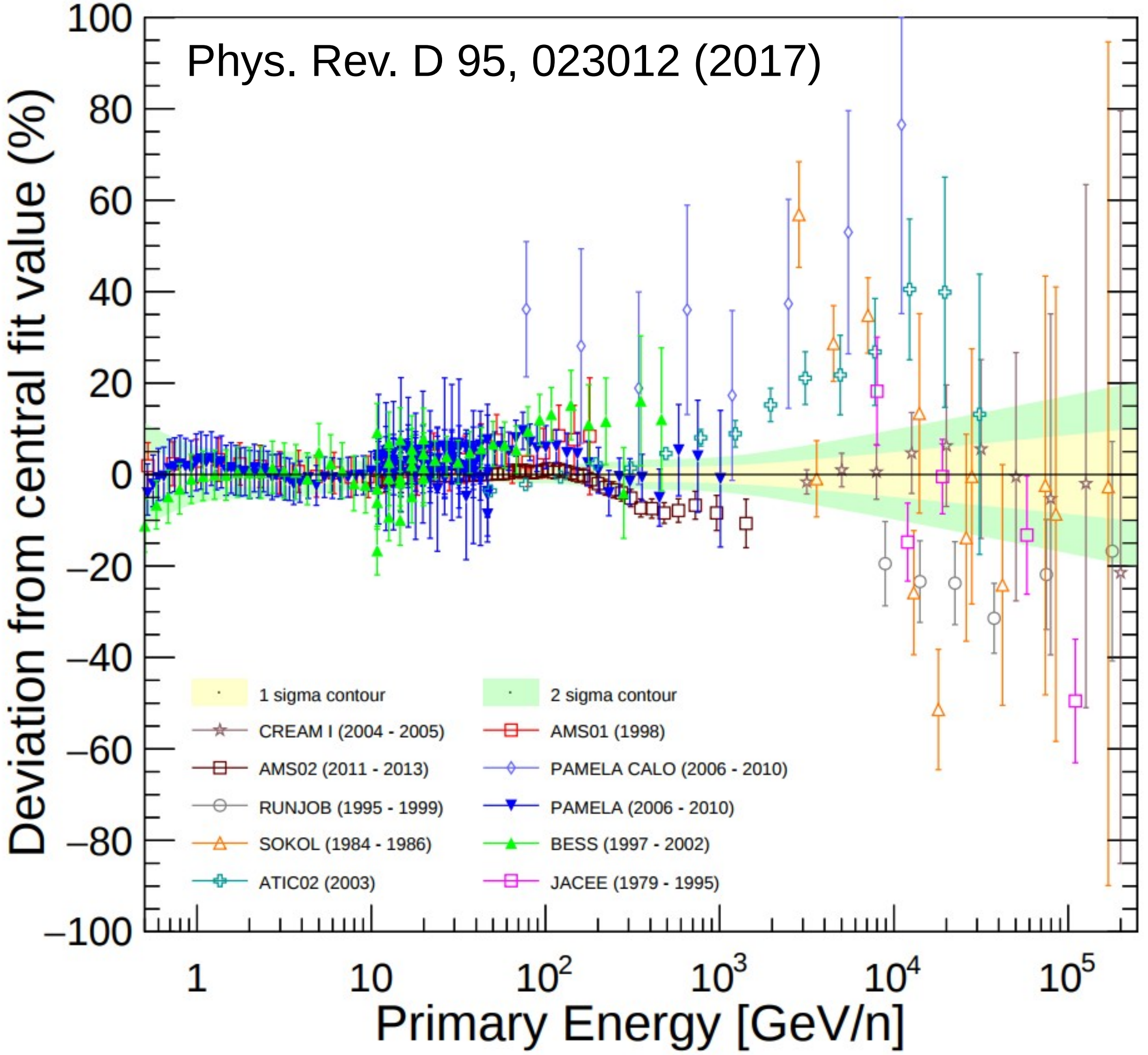
-more detailed flux characterization



-cosmic ray flux



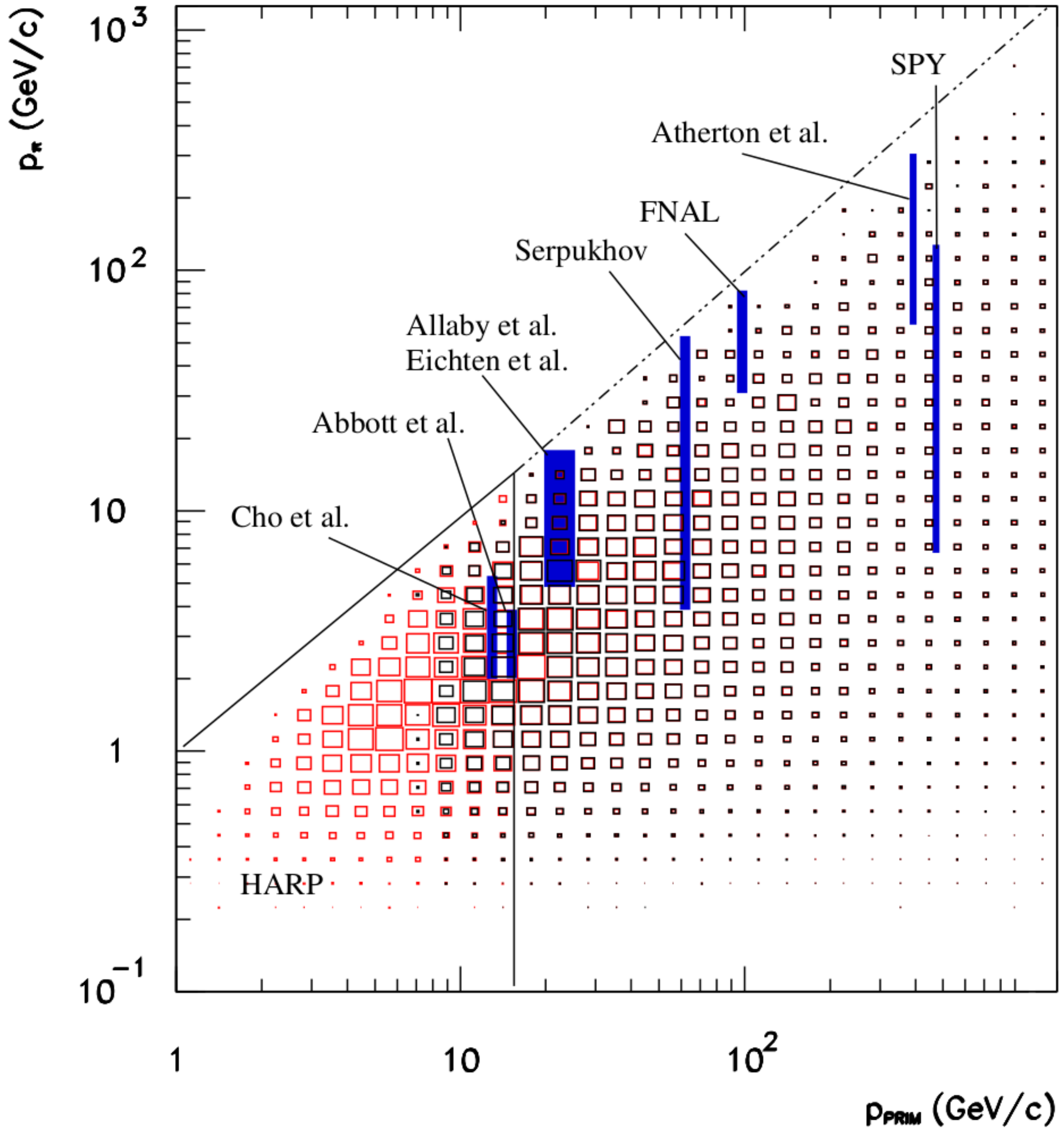
→10 years→



flux basic inputs

-hadronic interactions

Regions measured in **color**
Boxes correspond to phase space relevant to atomspheric neutrinos that could be measured (MC)
Red/black are geomagnetic effects

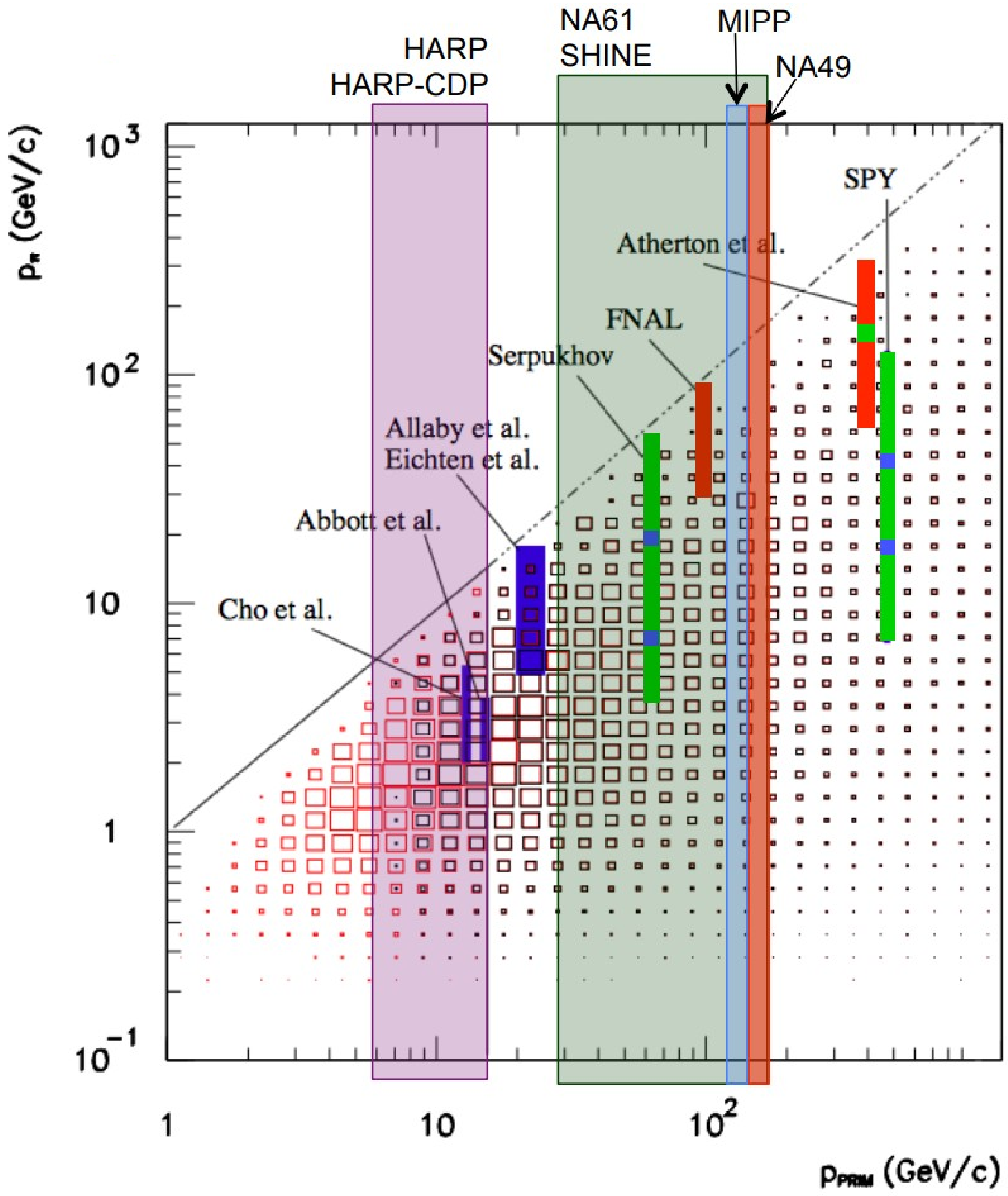


Phys.Rev.D74:094009,2006

flux basic inputs

-hadronic interactions

Regions measured in **color**
Boxes correspond to phase space relevant to atomspheric neutrinos that could be measured (MC)



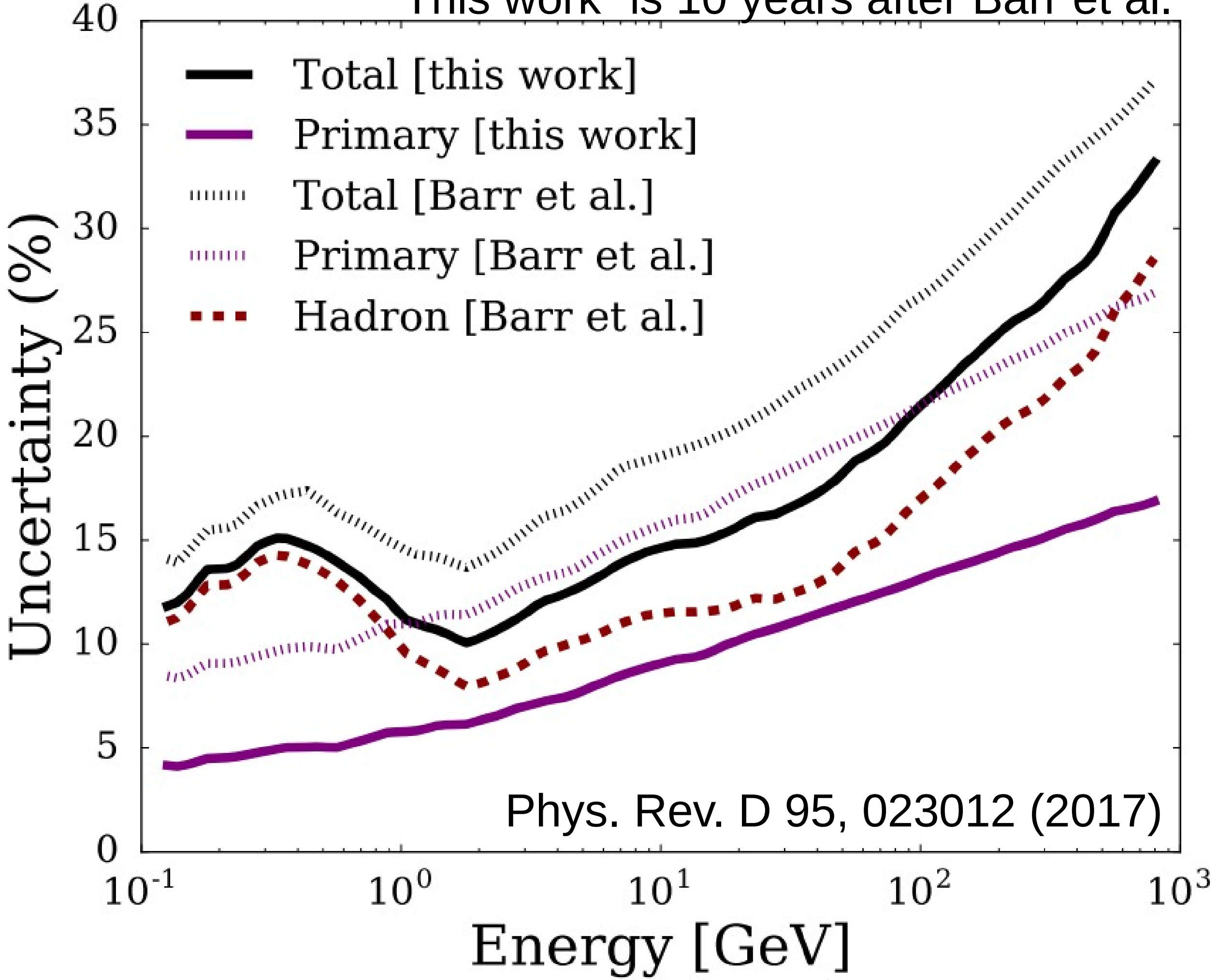
Updated from
Phys.Rev.D74:094009,2006

Barr, AtmNuWorkshop16

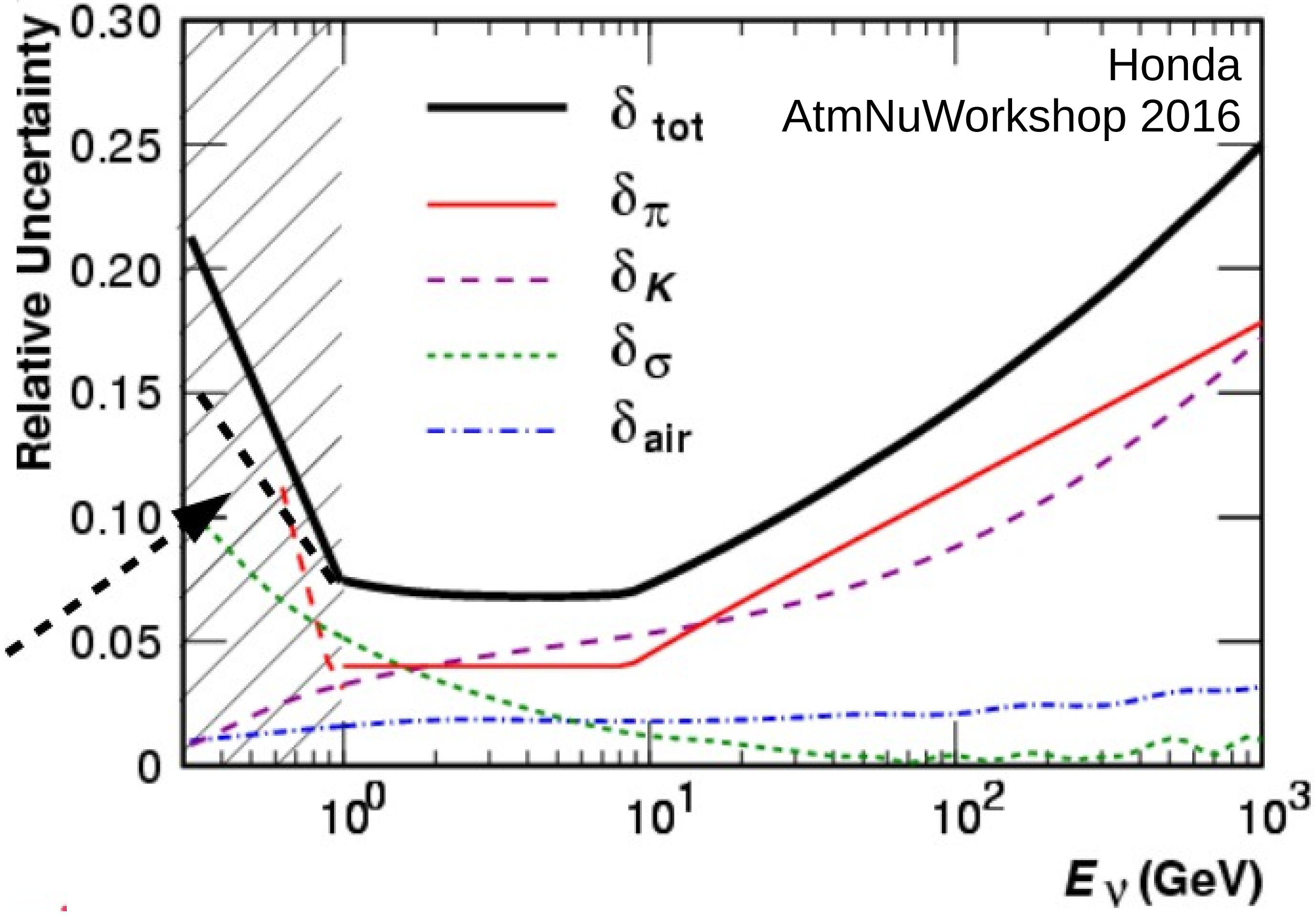
atmospheric neutrino flux

-estimated uncertainties

“This work” is 10 years after Barr et al.



Phys. Rev. D 95, 023012 (2017)



Honda
AtmNuWorkshop 2016

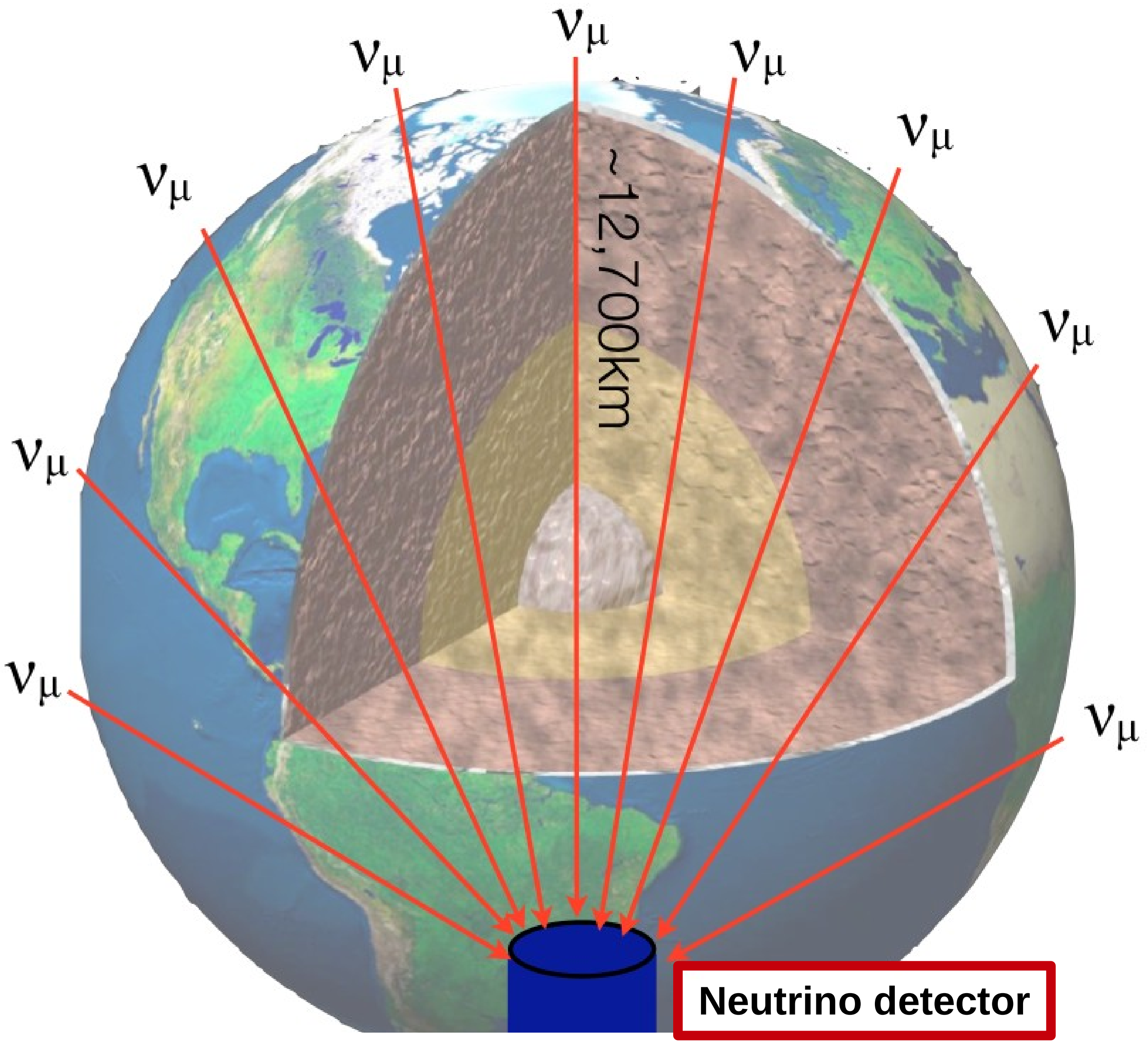
atmospheric neutrino flux

improvements from last decade

- **-better input measurements**
  - **-CR and had. int. errors reduced**
- **-uncertainties under scrutiny**
  - **-renewed efforts & tools**

oscillations in atmospheric ν

wide baseline, energy range



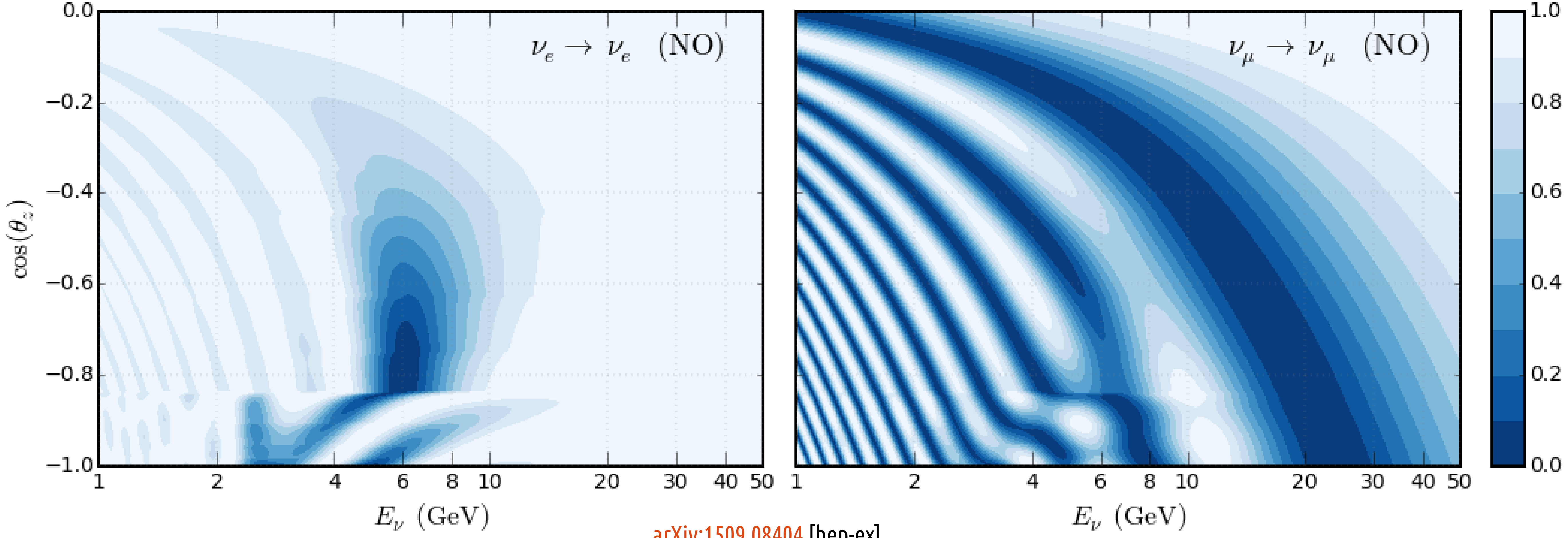
Borrowed from T. DeYoung

direction → baseline

~10km - ~12,700km

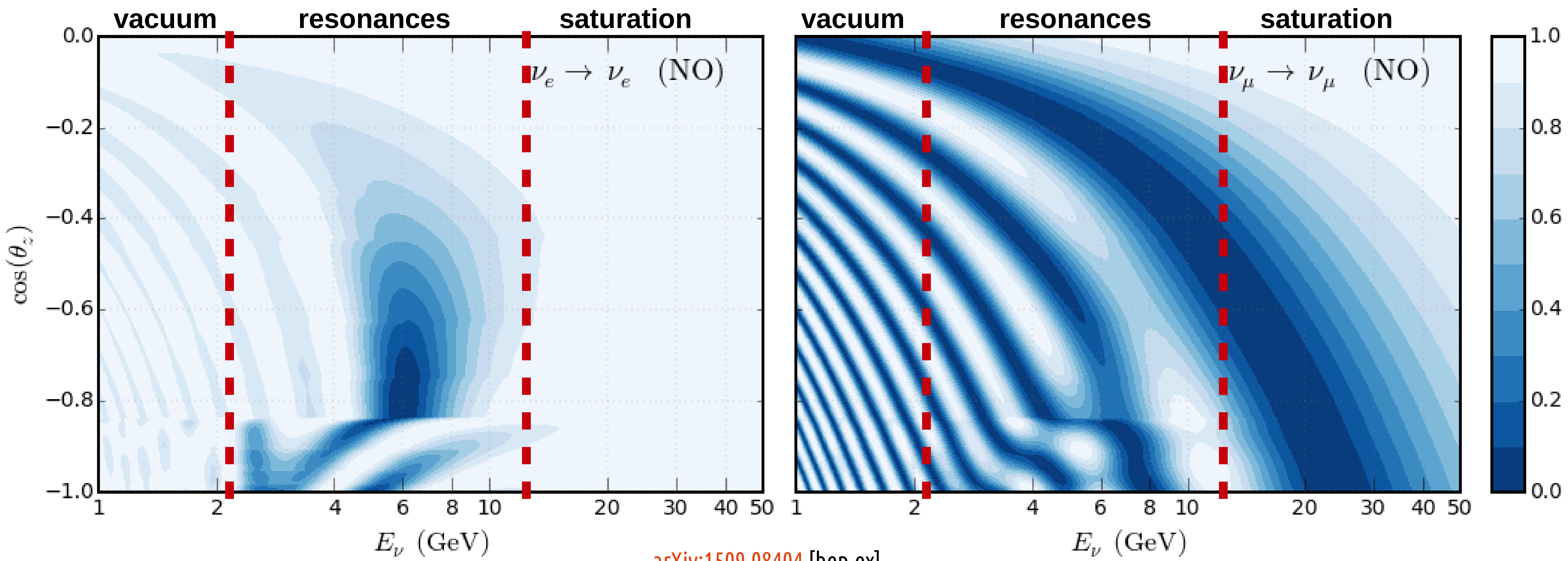
different e^- density along paths

survival probabilities



arXiv:1509.08404 [hep-ex]

survival probabilities



arXiv:1509.08404 [hep-ex]

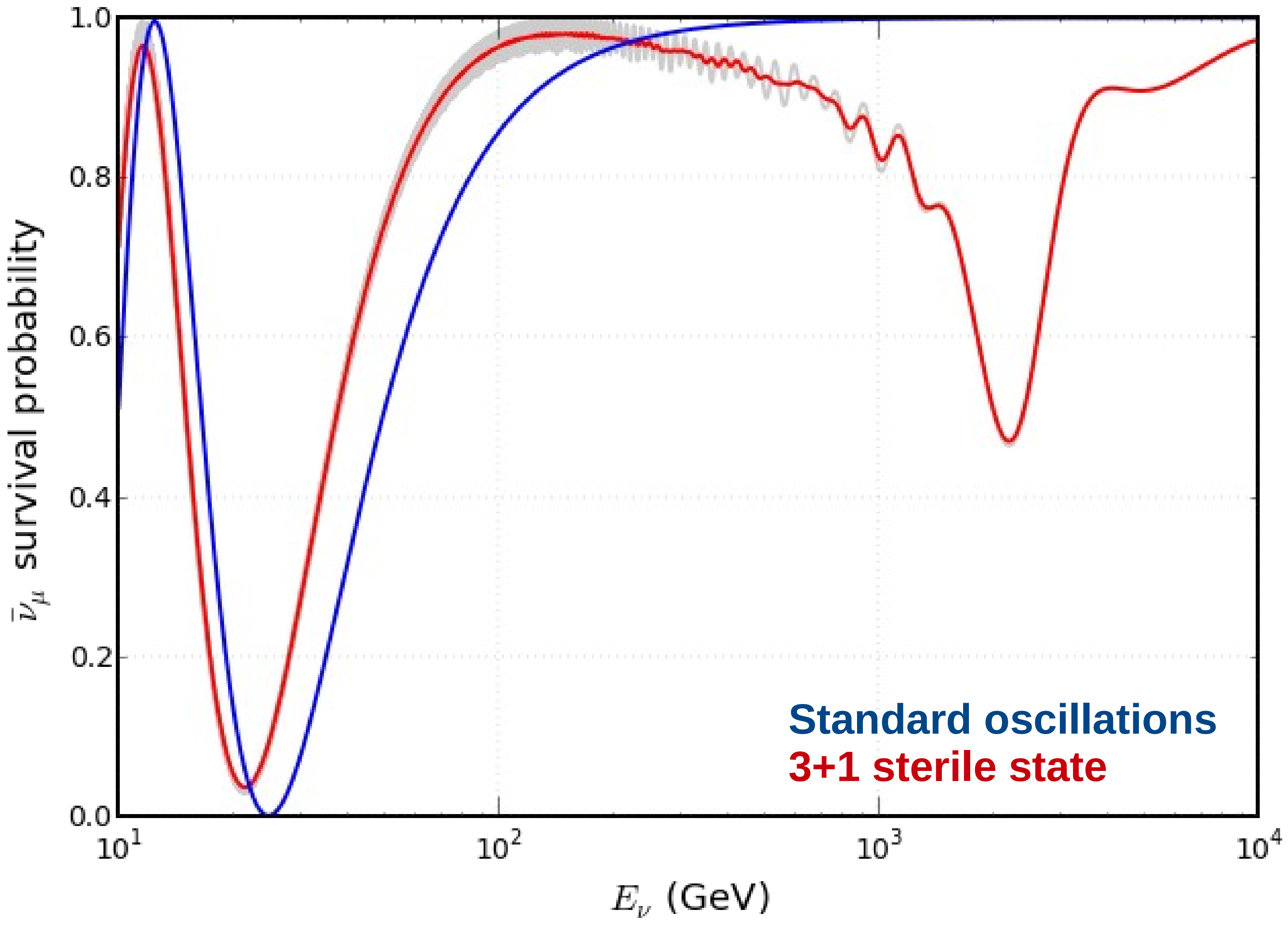
vacuum: $|\Delta m^2_{32}|$ θ_{23} θ_{13}

resonance: Δm^2_{32}

saturation: $|\Delta m^2_{32}|$ θ_{23}

ν_τ appearance

exotic possibilities



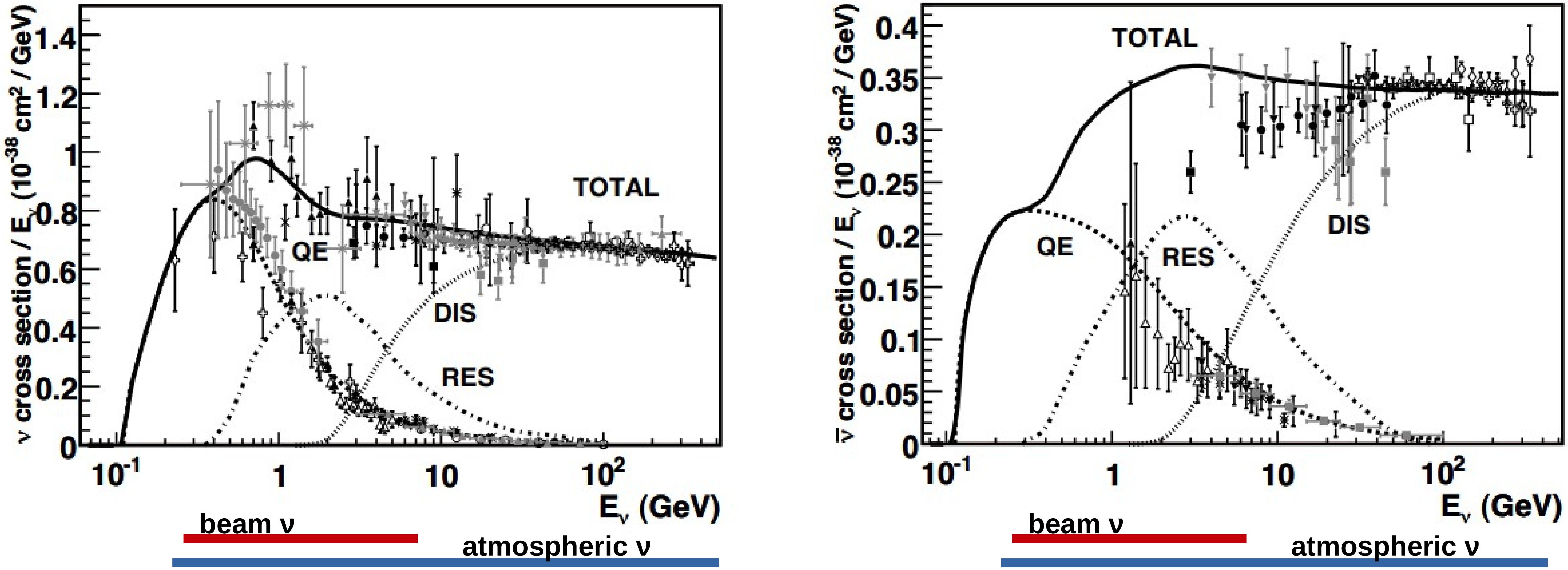
for cosθ = -1 (crossing all of the Earth)

sterile neutrinos

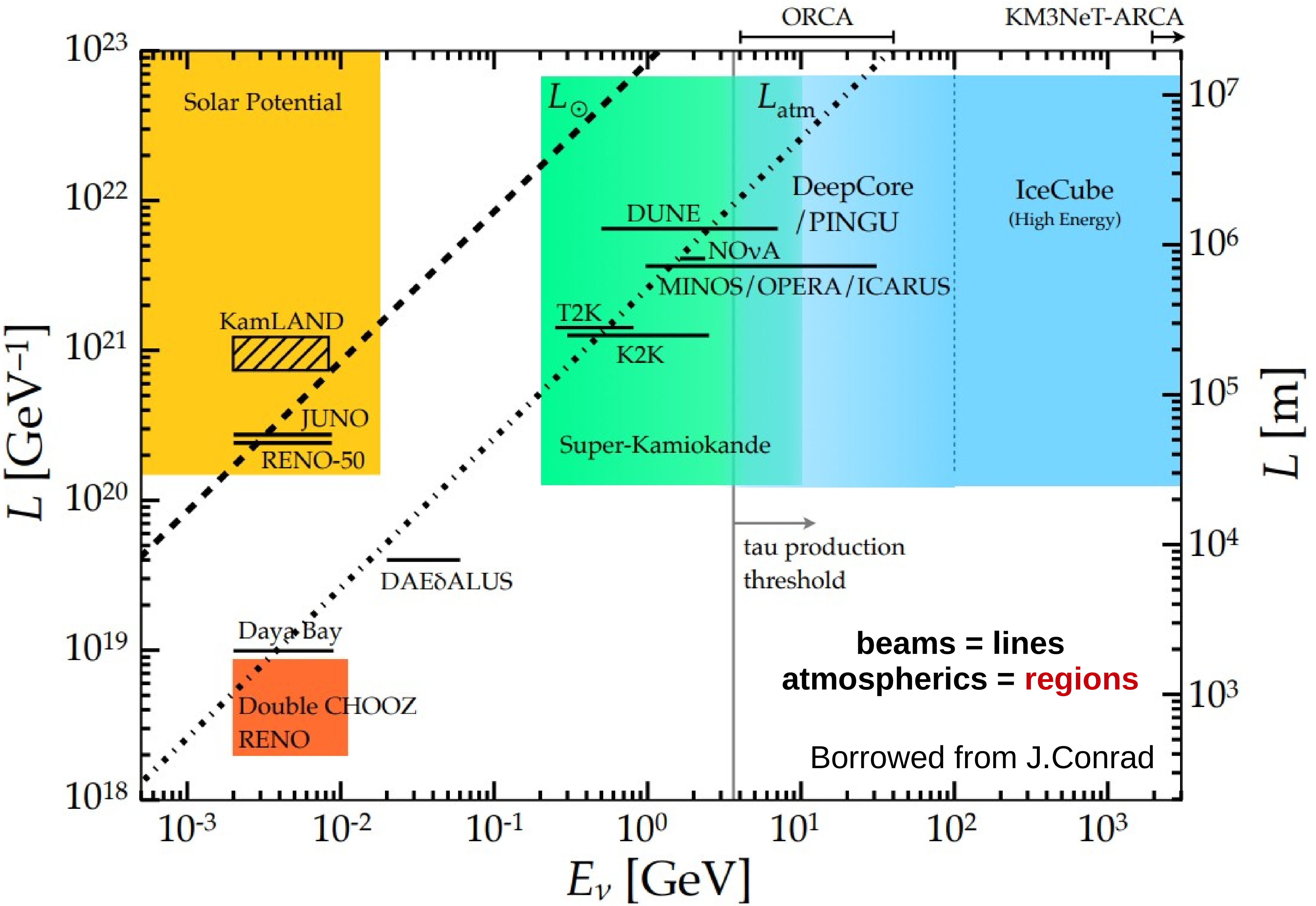
- **modify** std. oscillations effect
- **add** modulation at TeV energies
- modify probs. **μ → τ & μ → μ**

relevant interactions

Rev. Mod. Phys. 84, 1307 (2012)



multi-dimensional constrains



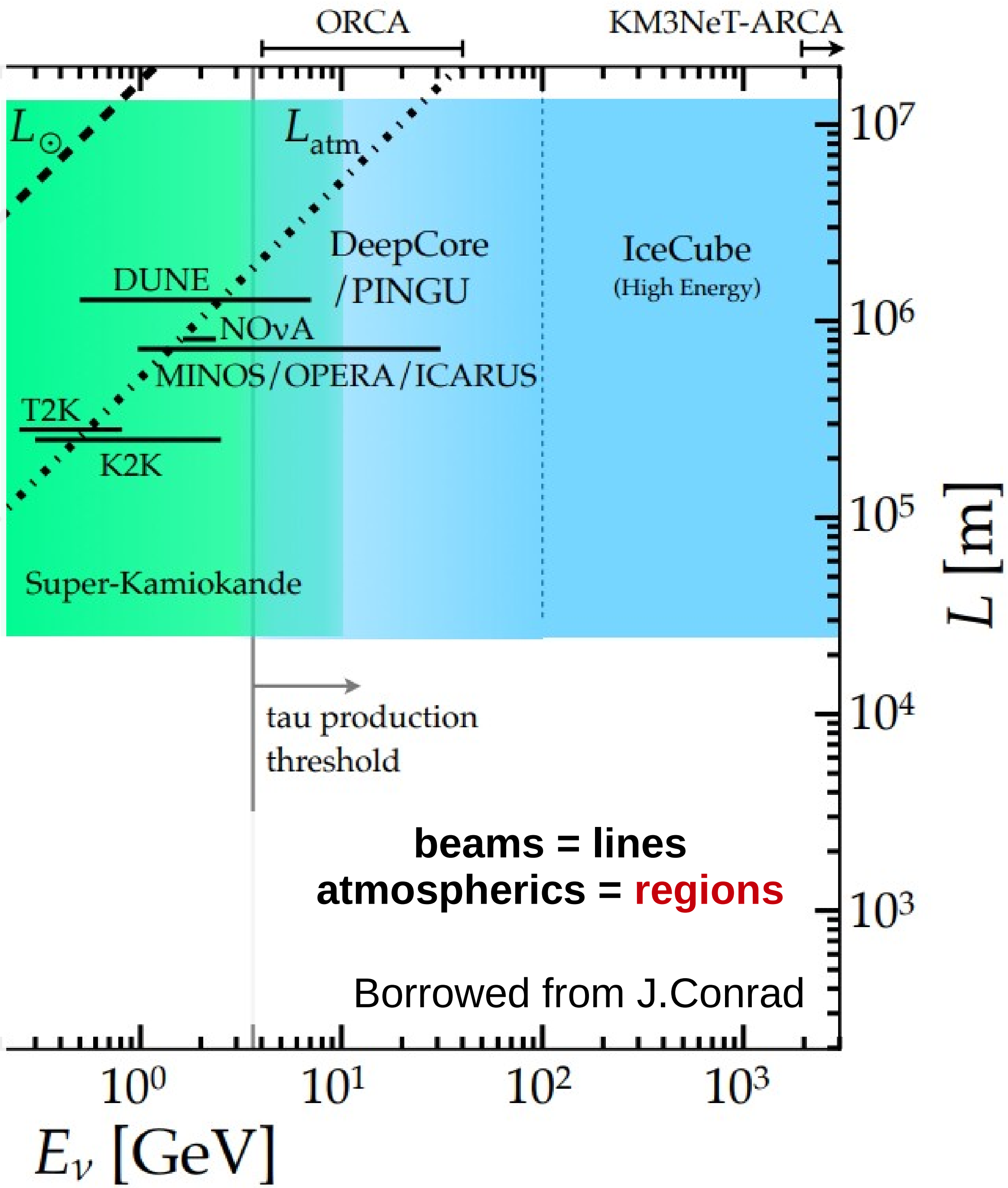
multi-dimensional constrains

-large **L&E** regions of phase space

-2 **ν, anti-ν** flavors in “beam”

-on/off signal regions

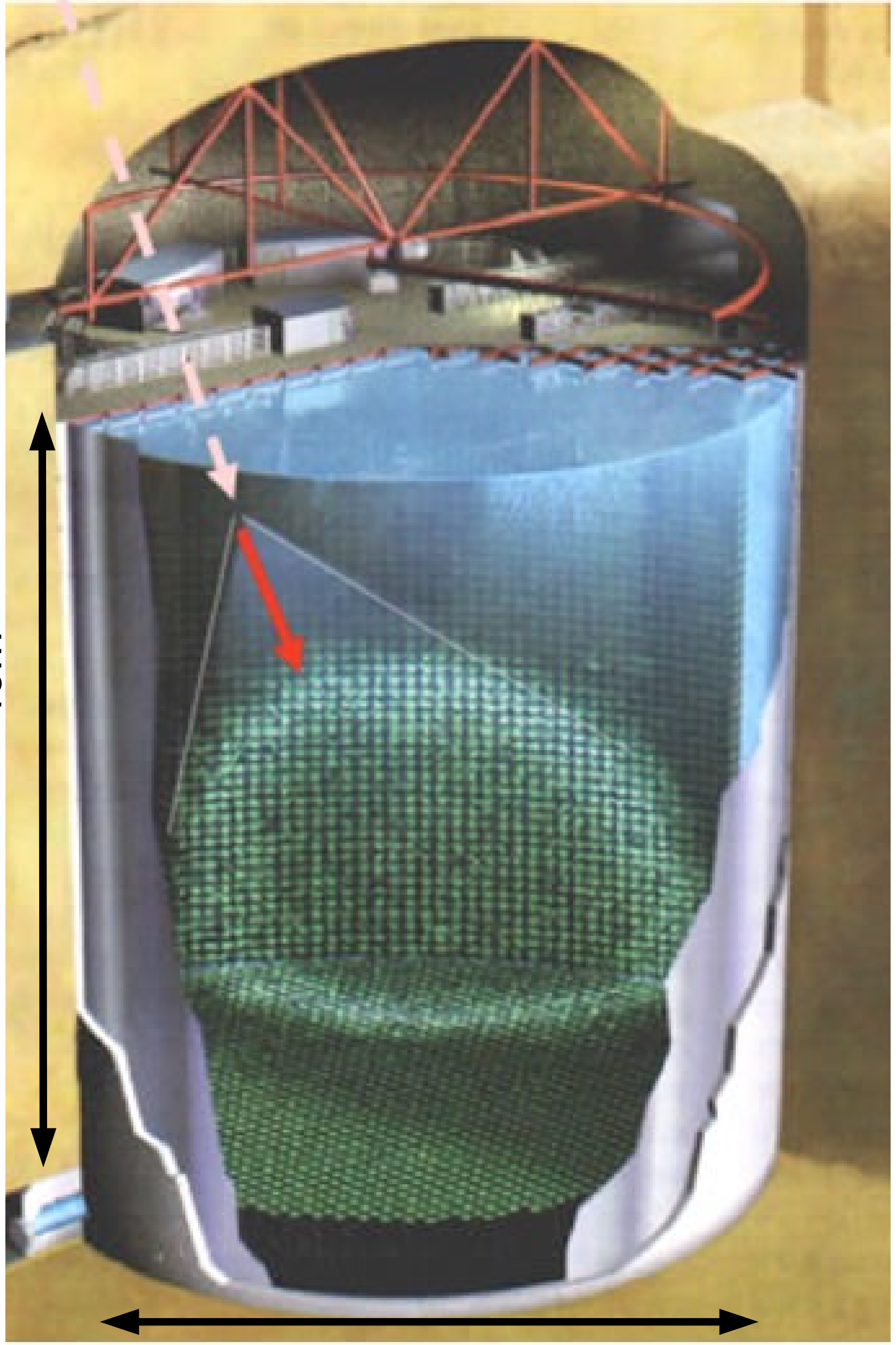
-**E > τ** threshold



recent experimental results

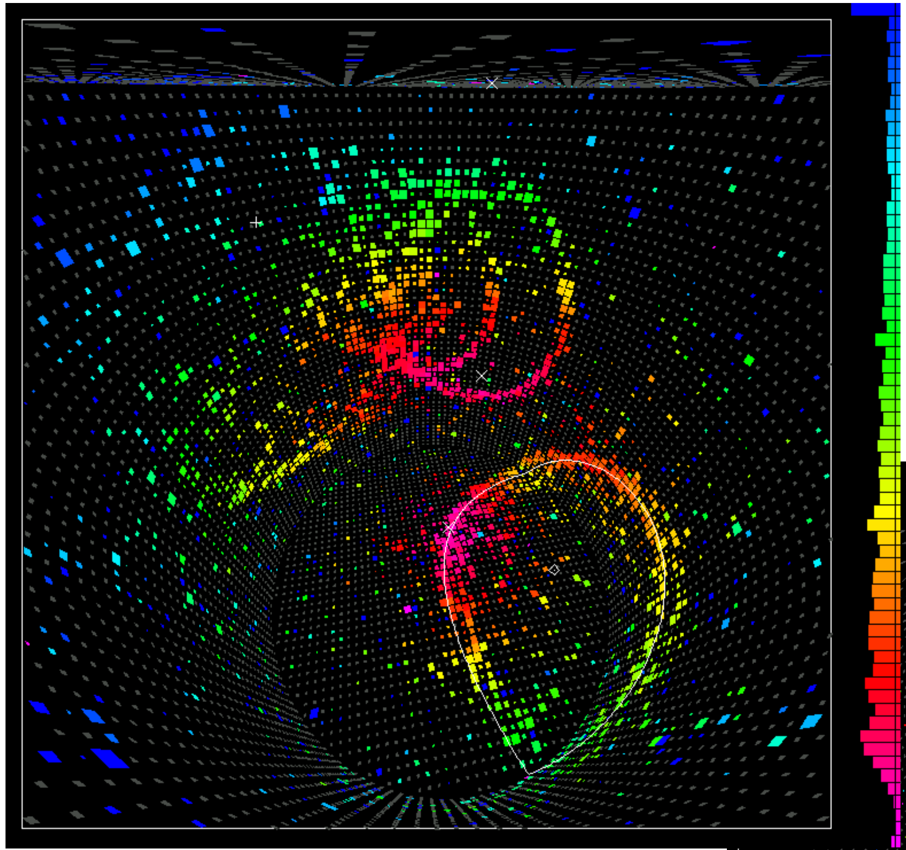
Super-Kamiokande

water Cherenkov



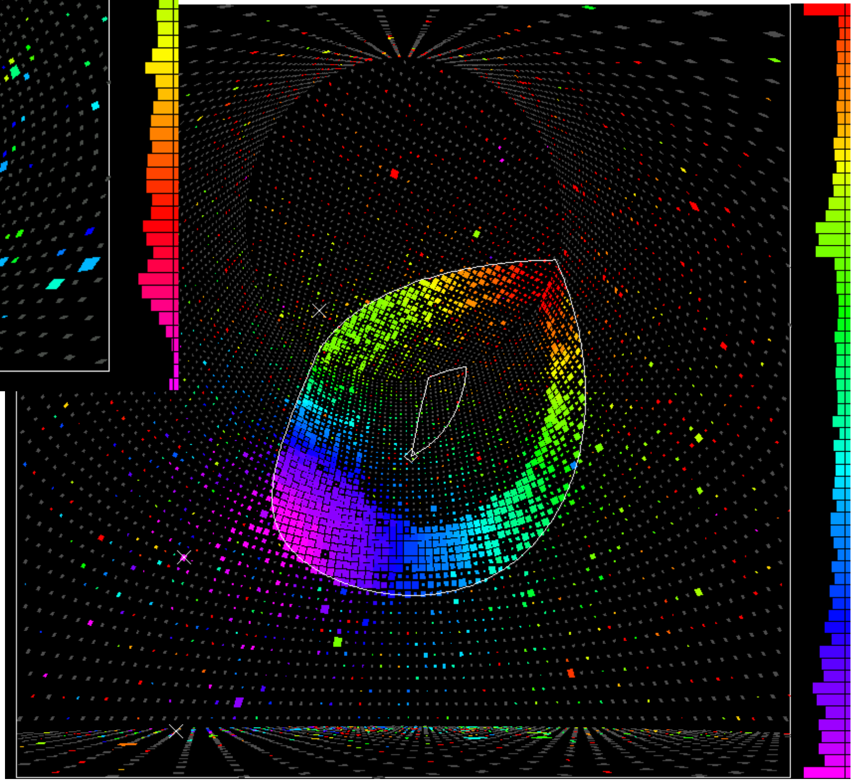
~40m

~40m



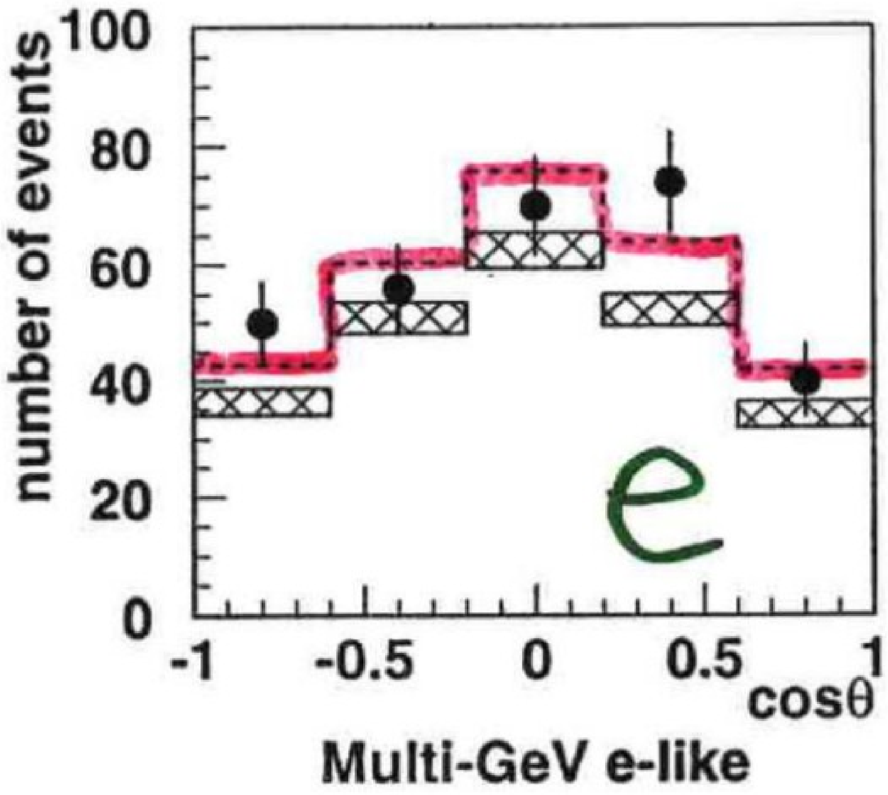
Two-gamma-like event

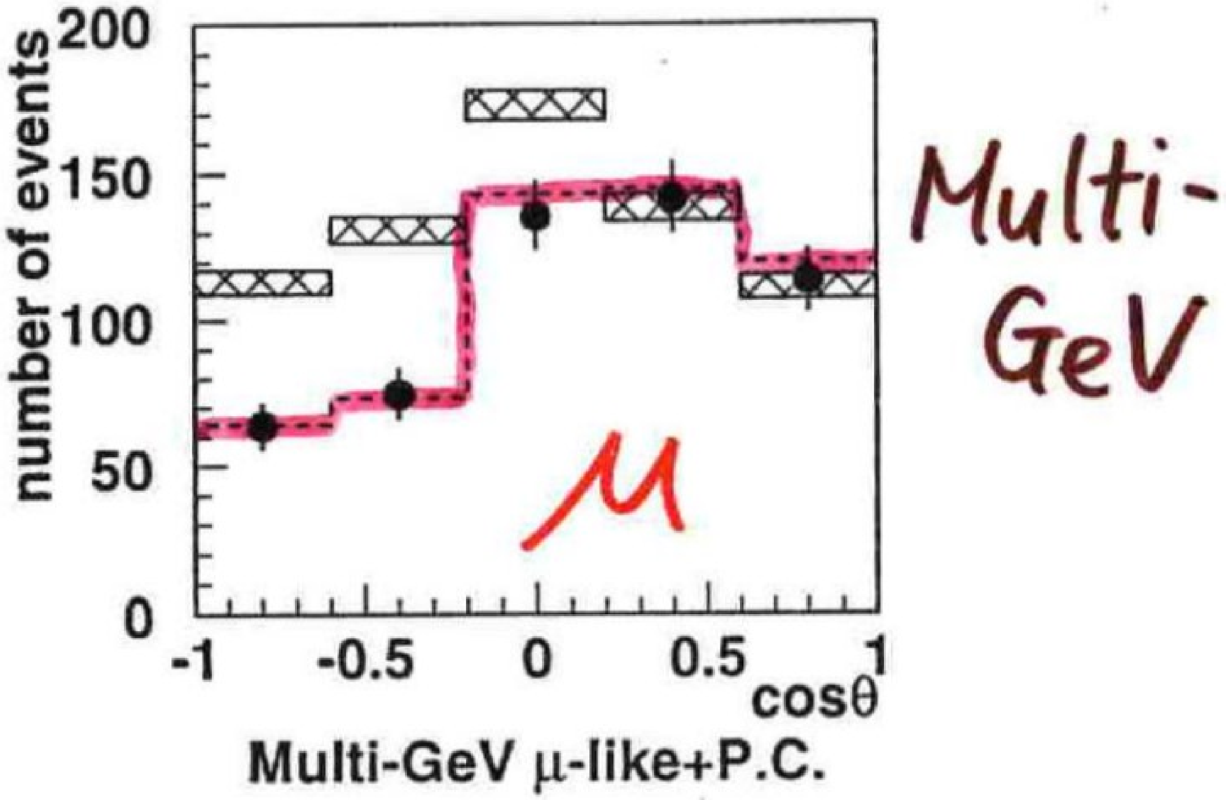
Muon-like event



http://www.ps.uci.edu/~tomba/sk/tscan/pictures.html

Super-Kamiokande

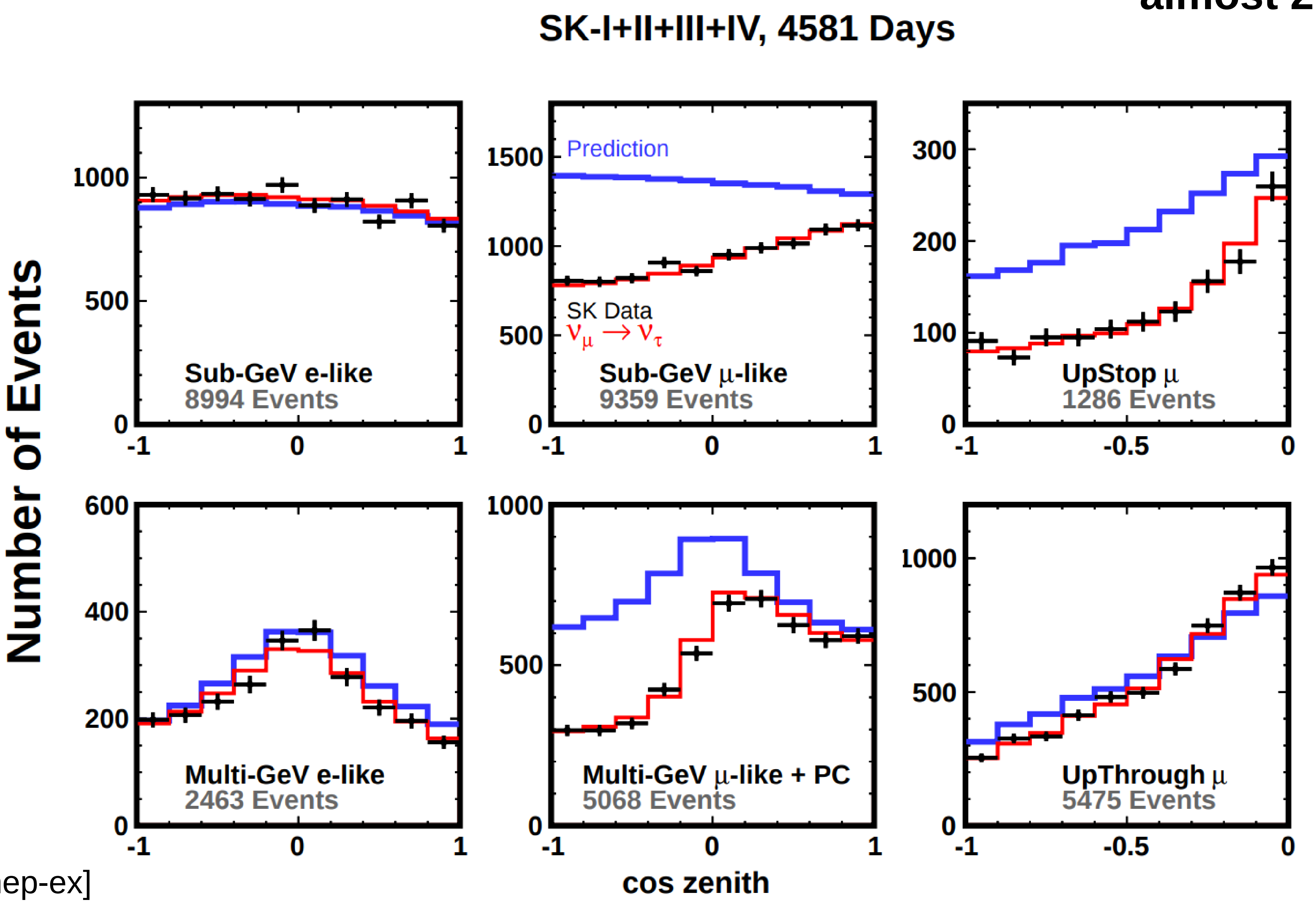




from Neutrino'98 presentation

Super-Kamiokande

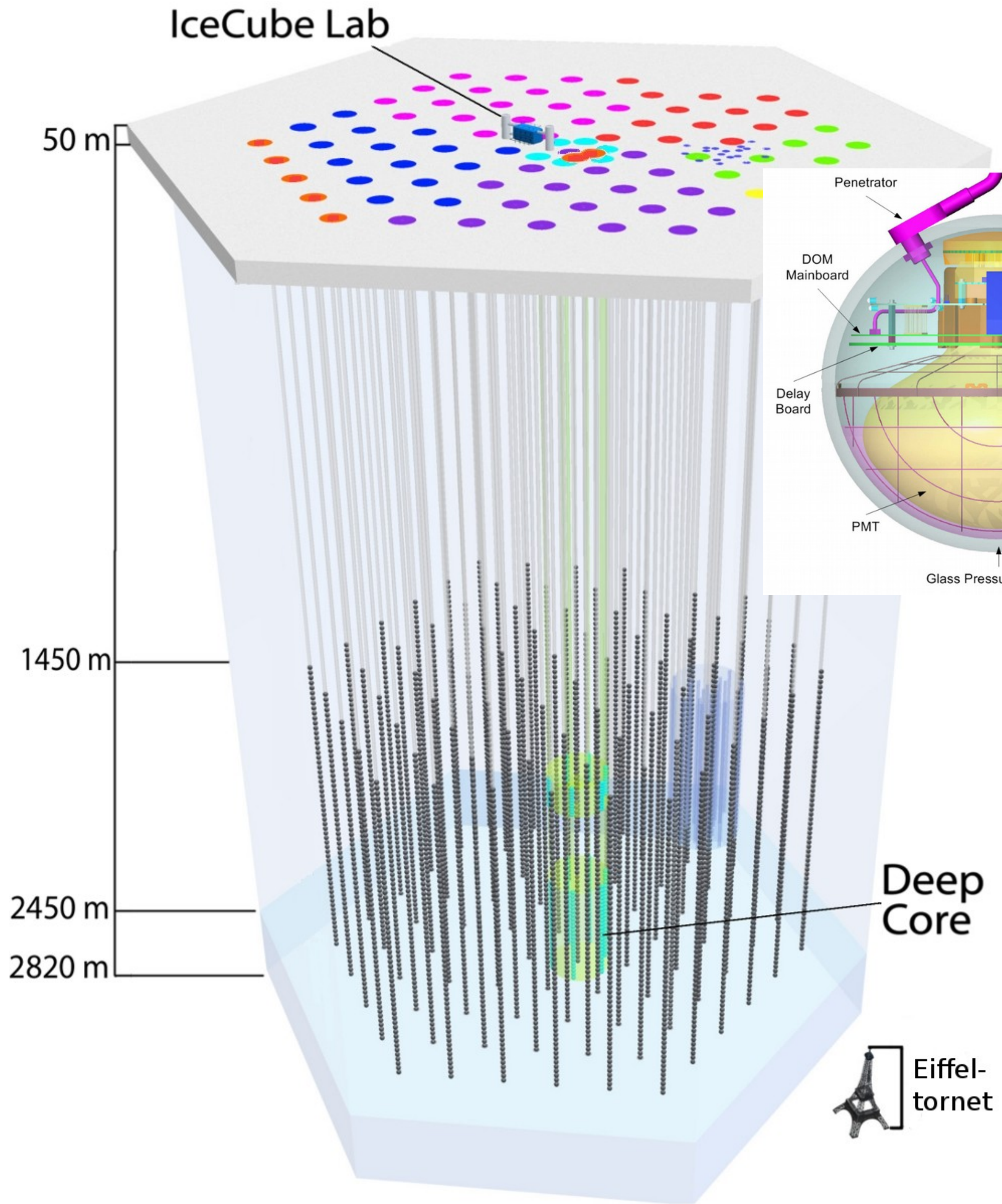
almost 20 years later

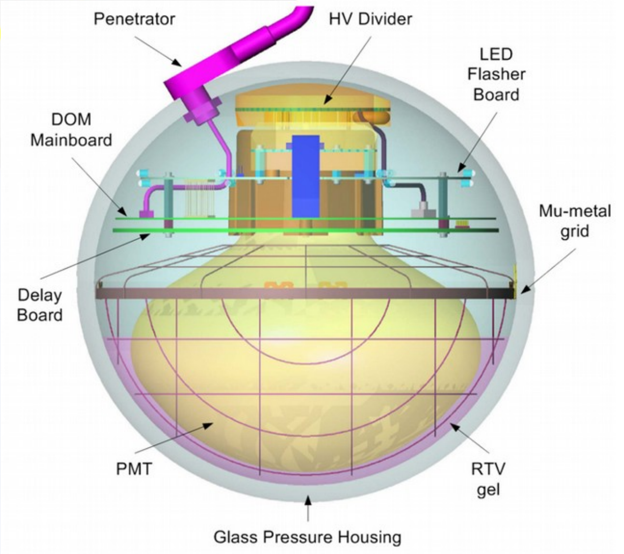


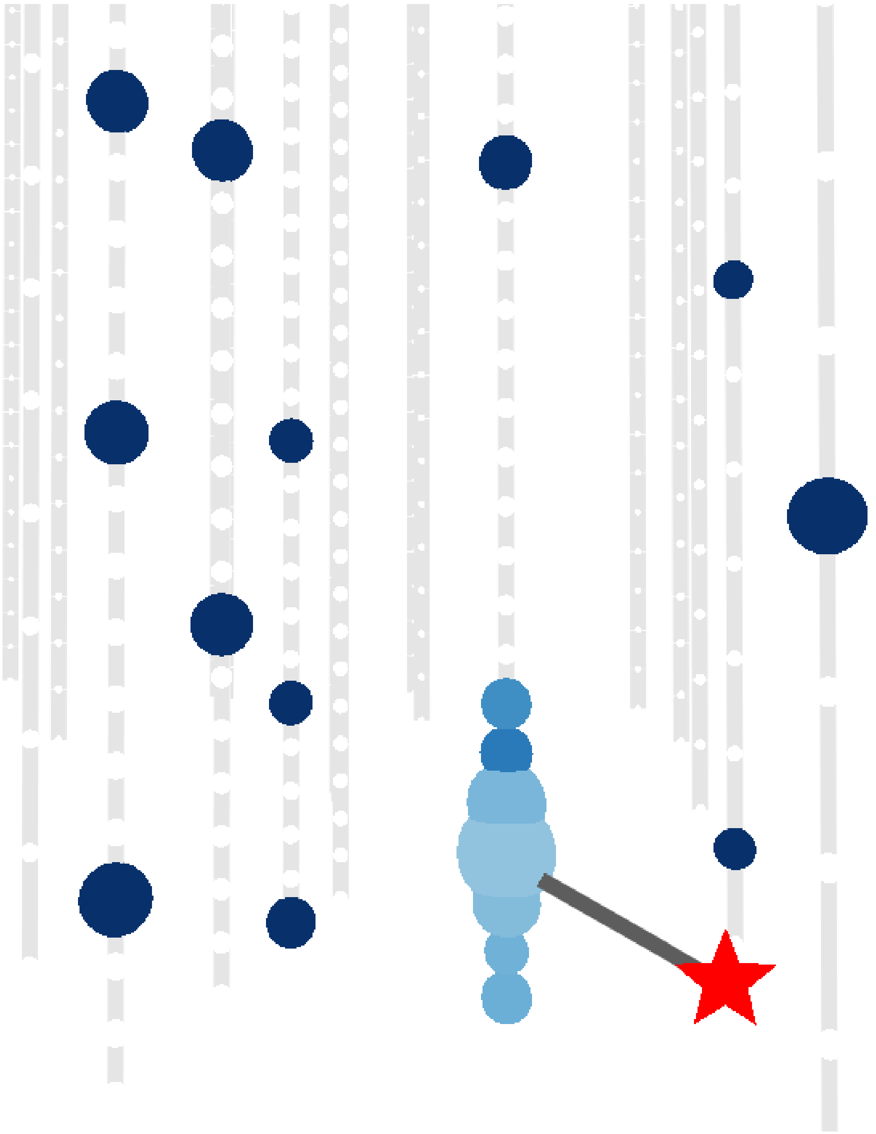
arXiv:1412.5234 [hep-ex]

IceCube DeepCore

ice Cherenkov





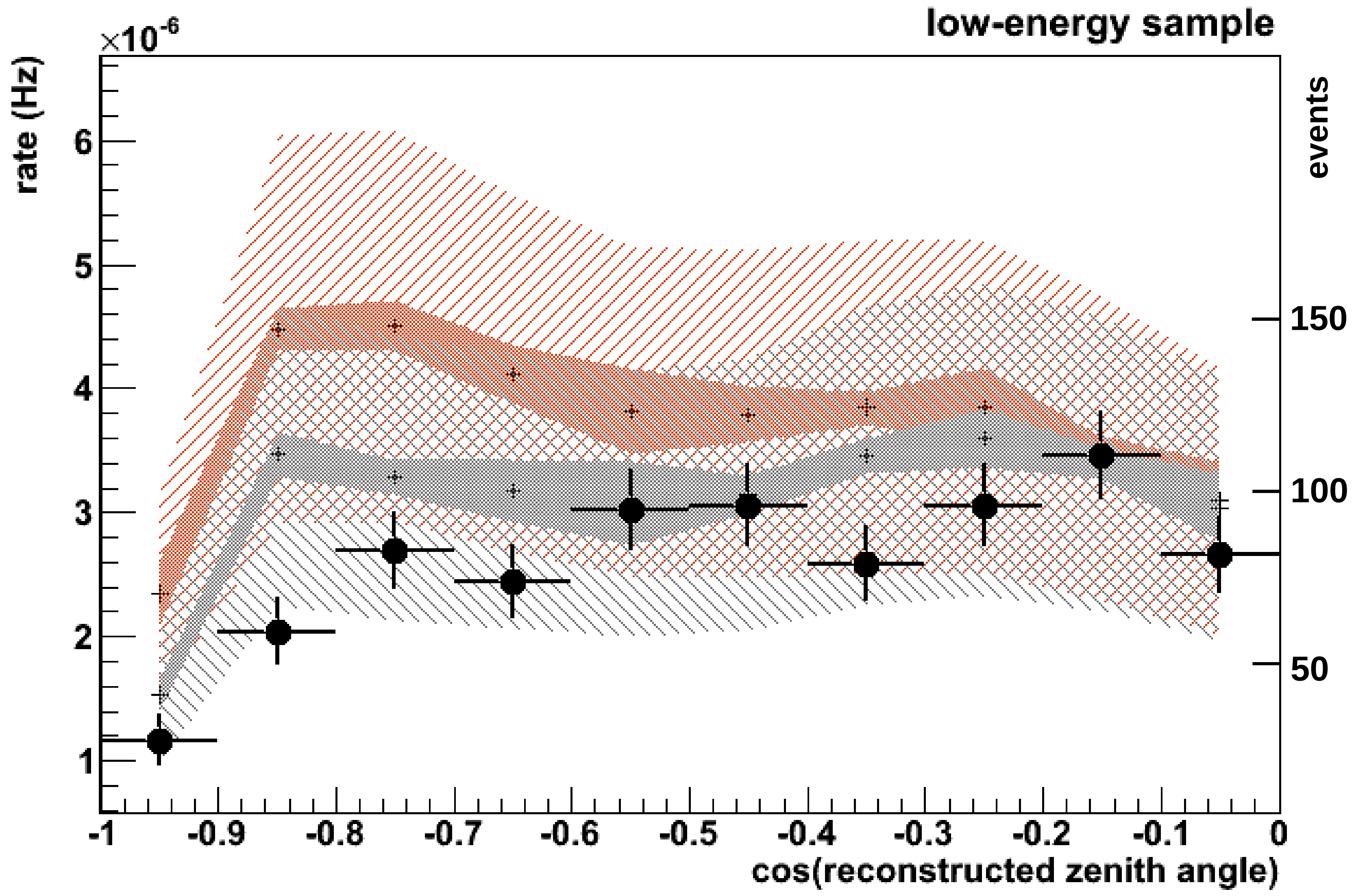


12 GeV ν_μ interaction

8 GeV track (R~40m) + 4 GeV cascade

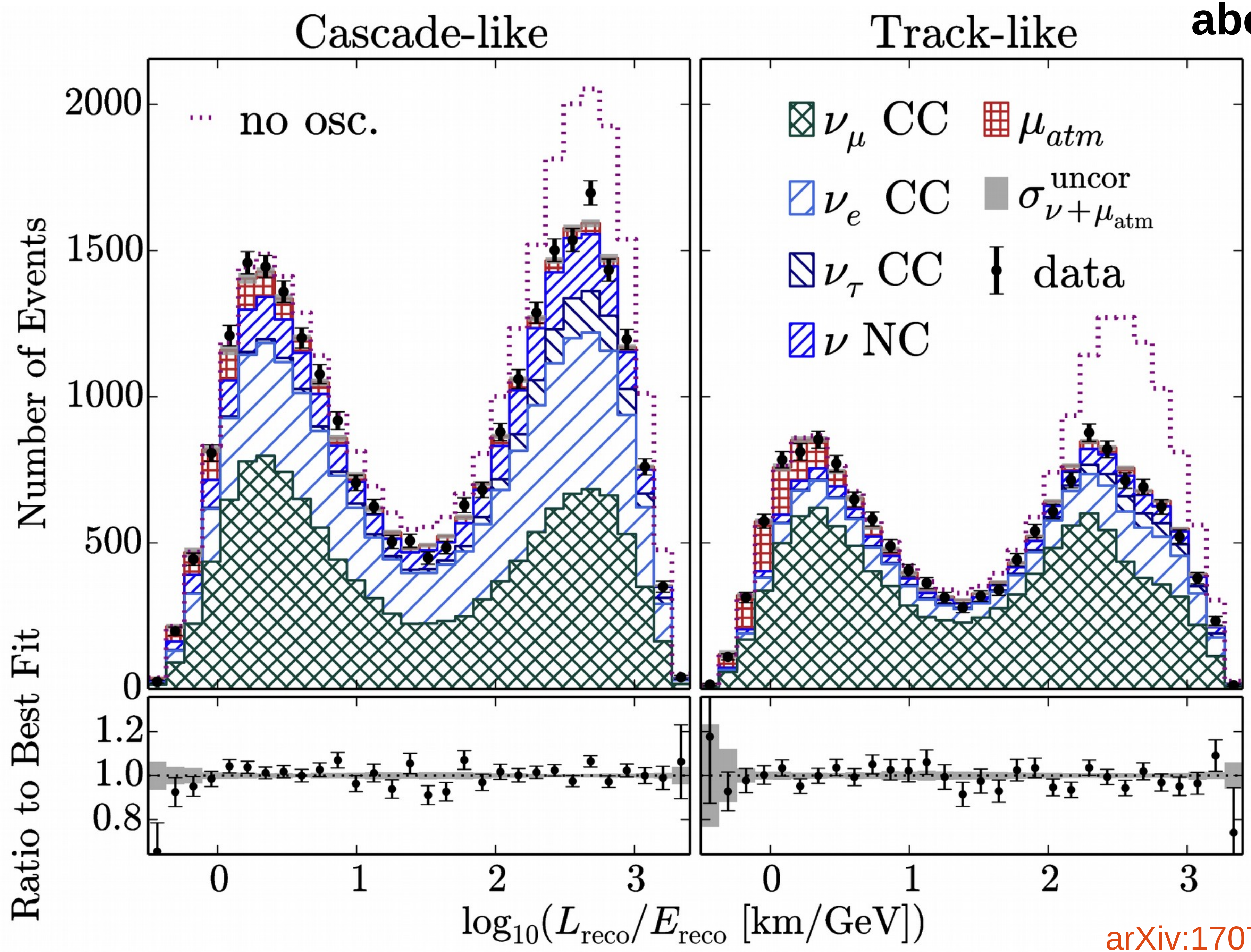
IceCube DeepCore

first publication on oscillations in 2013



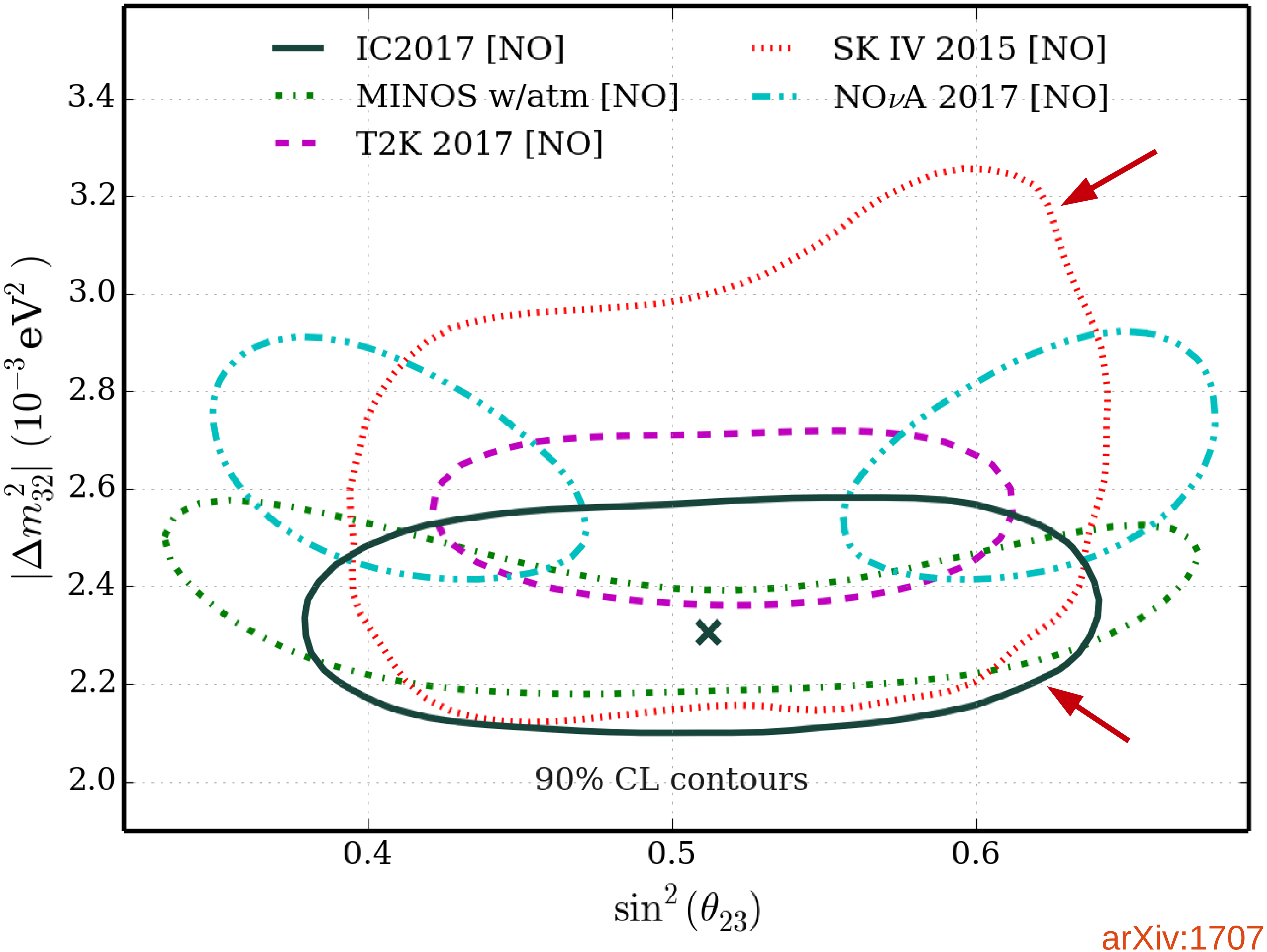
IceCube DeepCore

about 4 years later



arXiv:1707.07081 [hep-ex]

standard oscillations



arXiv:1707.07081 [hep-ex]

ν_τ appearance in Super-Kamiokande

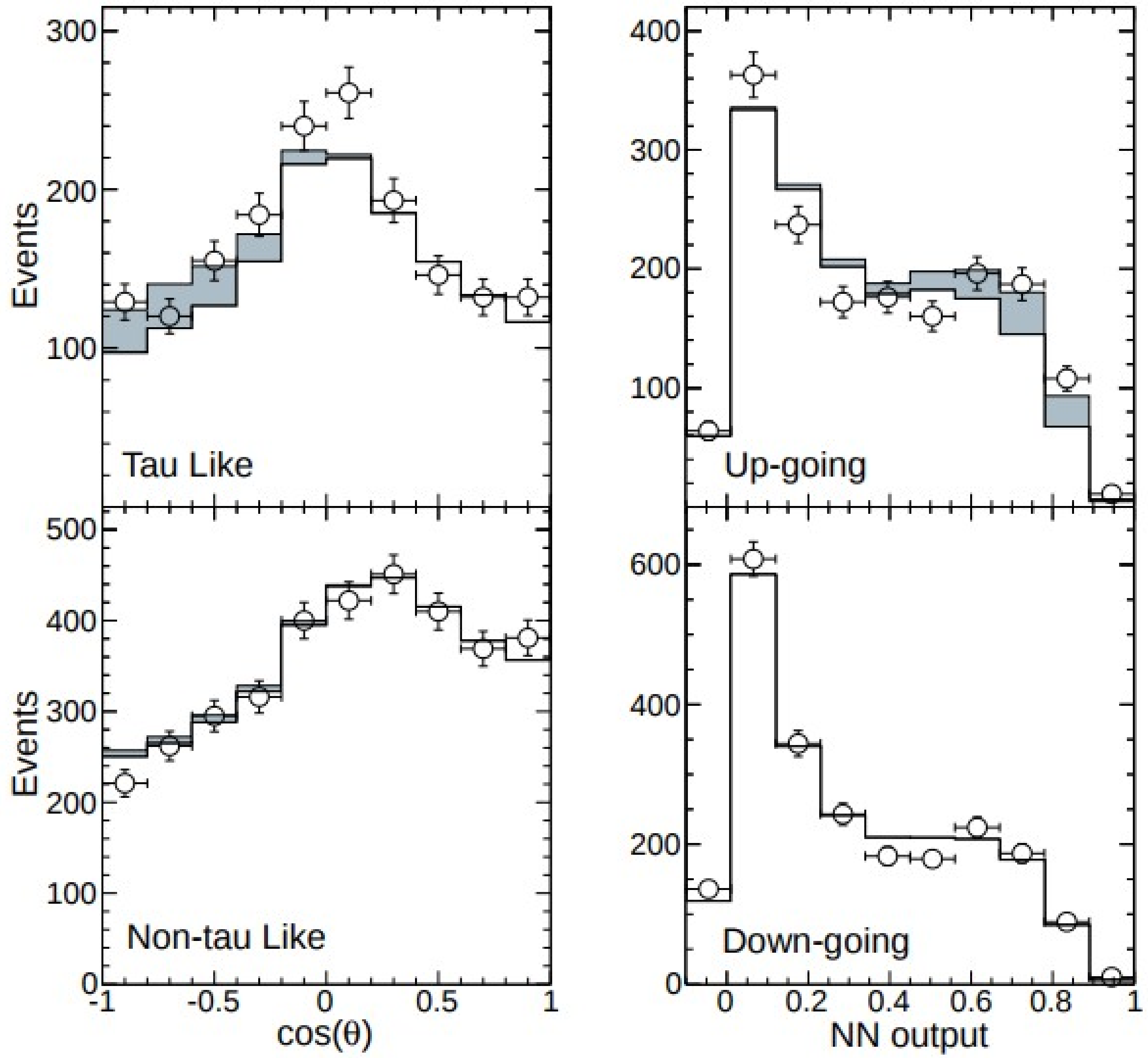


FIG. 3. Fit results showing projections in the NN output and zenith angle distribution for taulike (NN>0.5), upward-going [$\cos(\theta) < -0.2$], nontaulike (NN<0.5), and downward-going [$\cos(\theta) > 0.2$] events for both the two-dimensional PDFs and data. The PDFs and data sets have been combined from SK-I through SK-III in this figure. The fitted tau signal is shown in gray.

NuTau CC scaling

1.42 ± 0.35 (stat)

+0.14 −0.12 (syst).

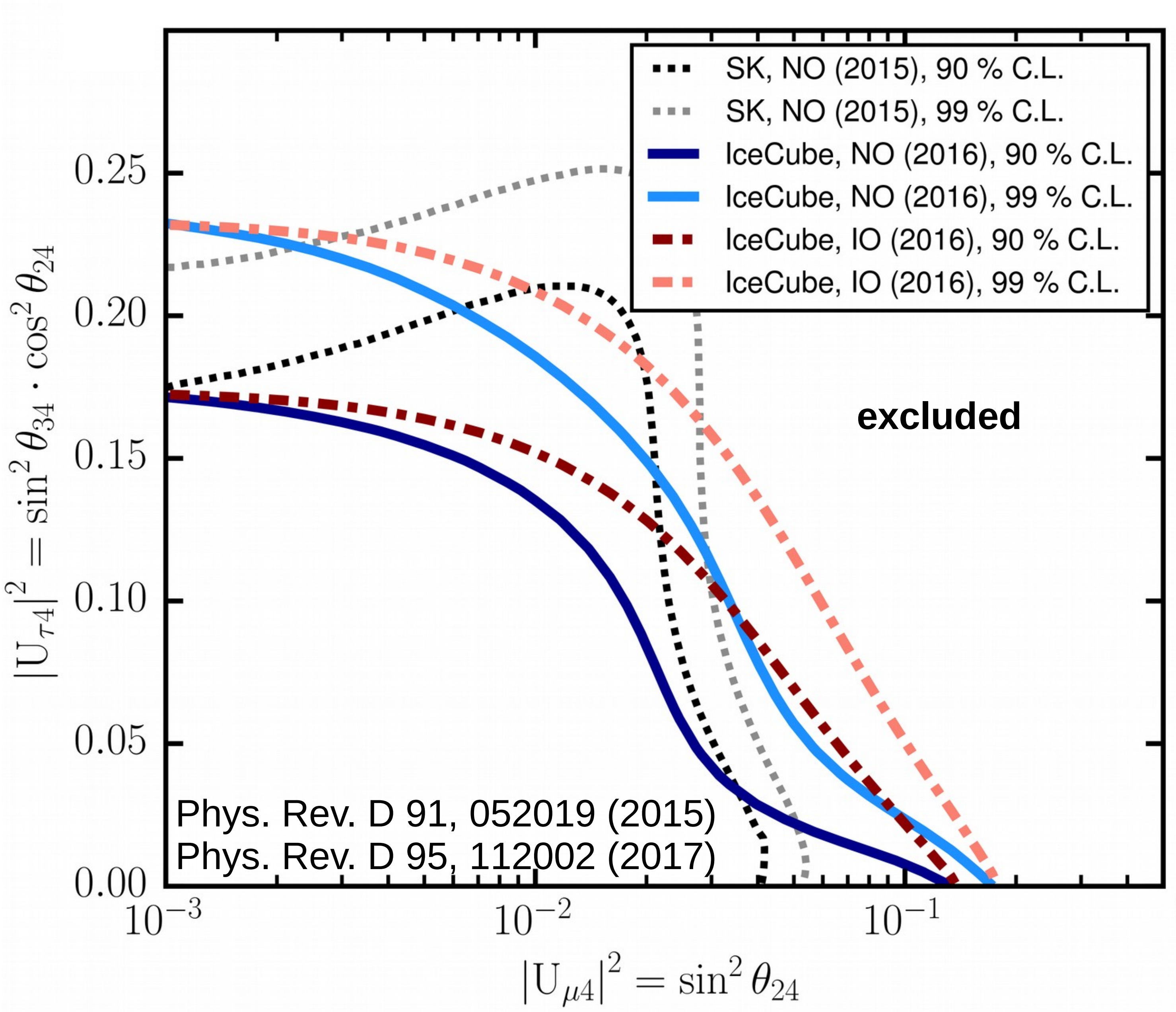
Phys. Rev. Lett. 110, 181802 (2013)

exotic oscillations

E_{nu} ~ GeVs

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$|U_{\mu 4}|^2 = \sin^2\theta_{24},$$
$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}.$$



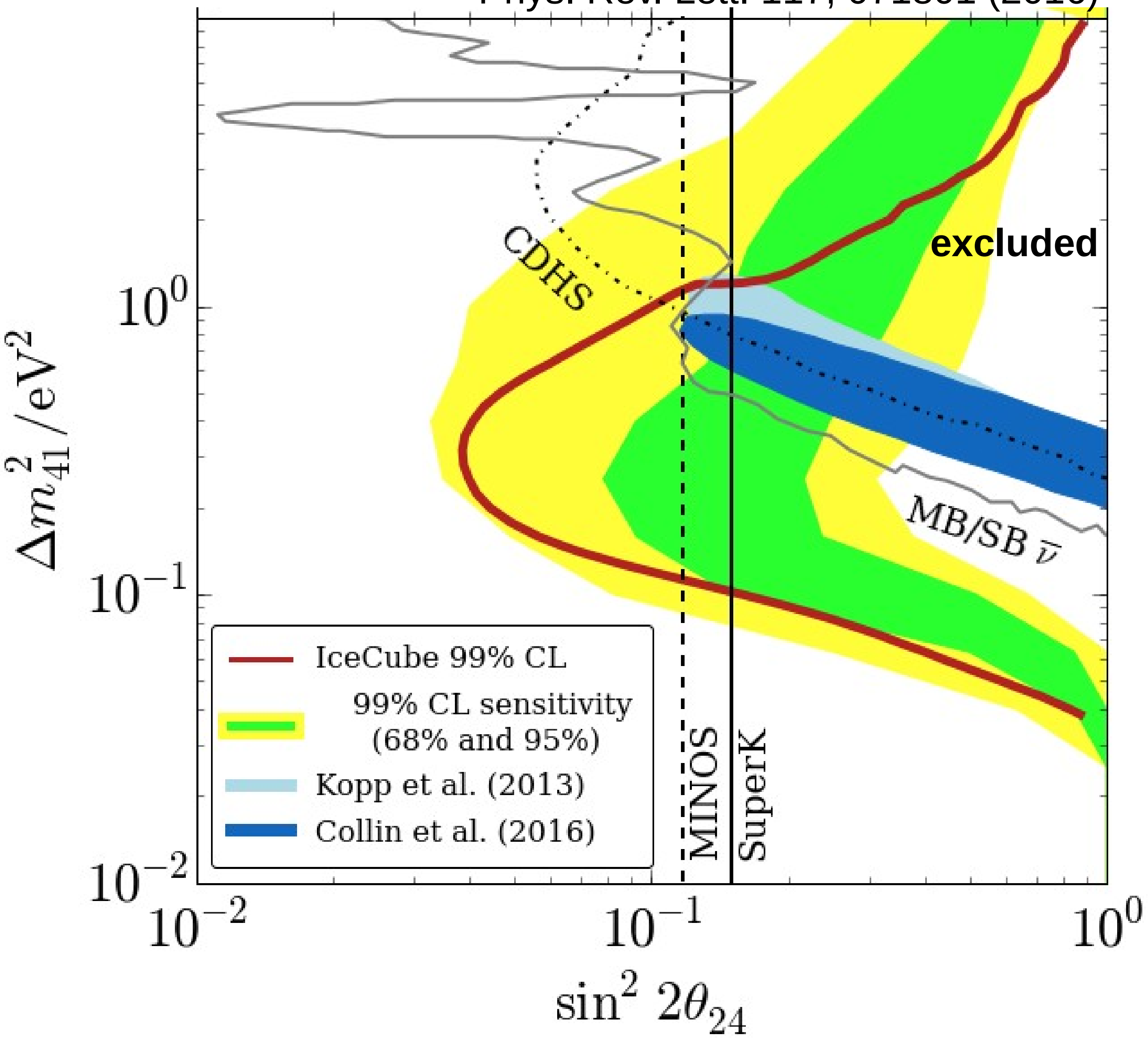
exotic oscillations

E_{nu} ~ TeVs

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

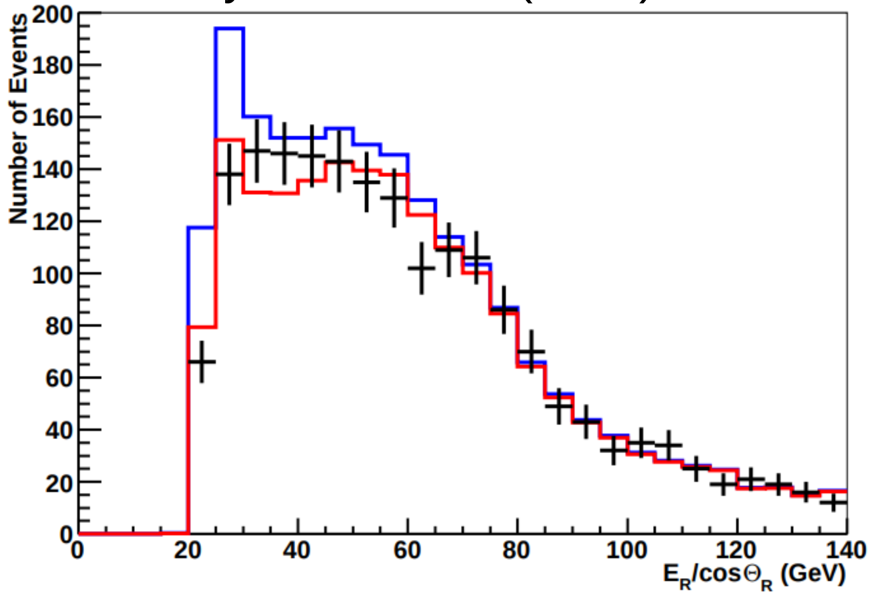
$$|U_{\mu 4}|^2 = \sin^2\theta_{24},$$
$$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}.$$

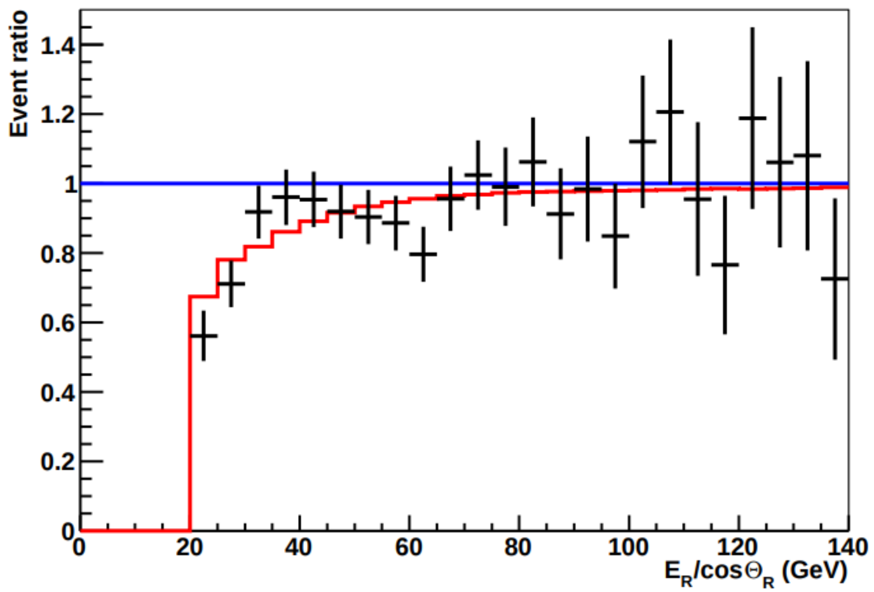
Phys. Rev. Lett. 117, 071801 (2016)

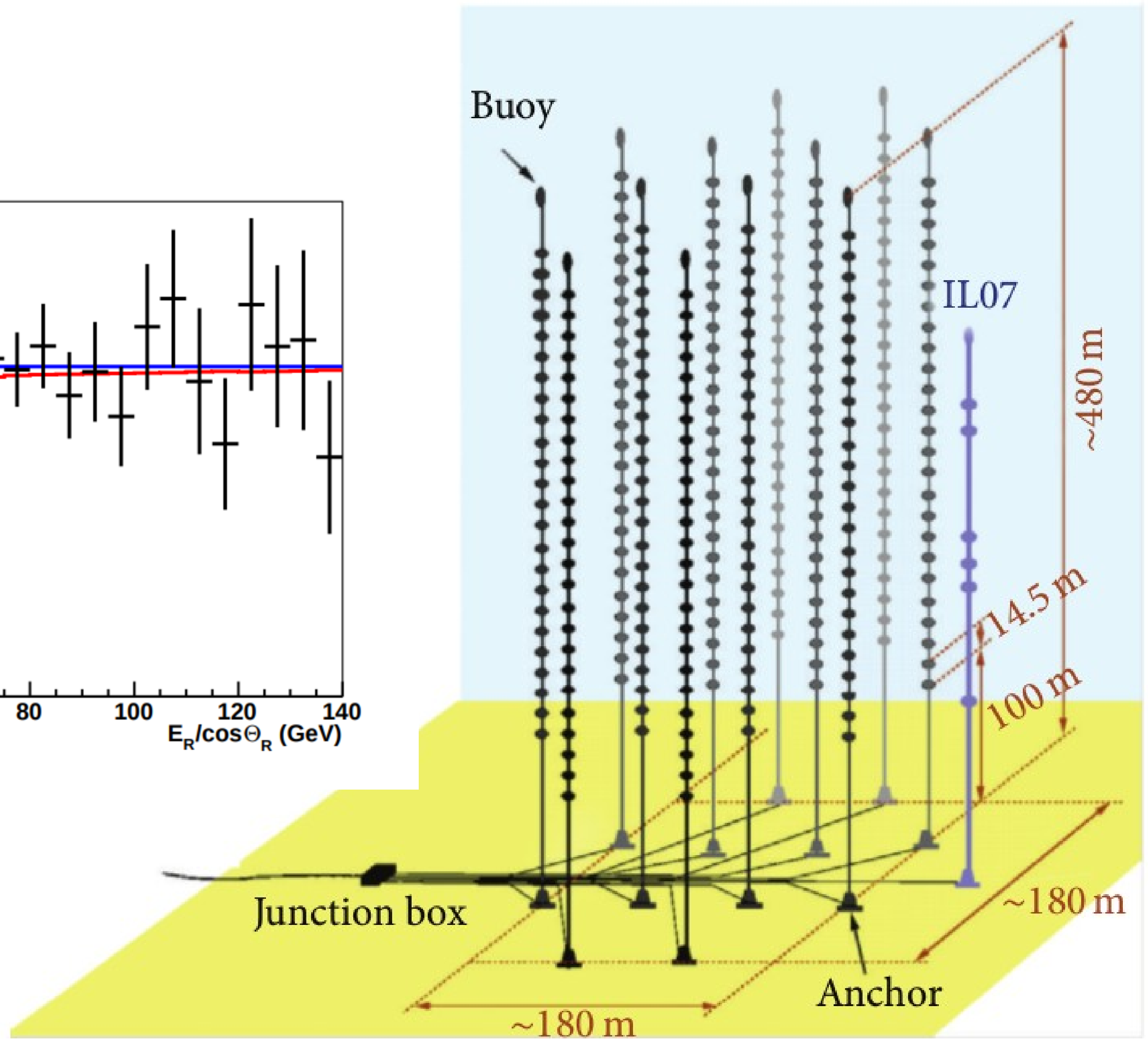


ANTARES
water Cherenkov

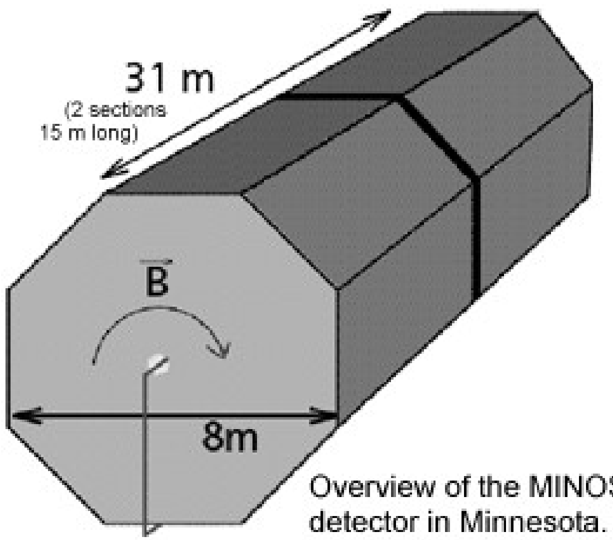
Phys.Lett. B714 (2012)





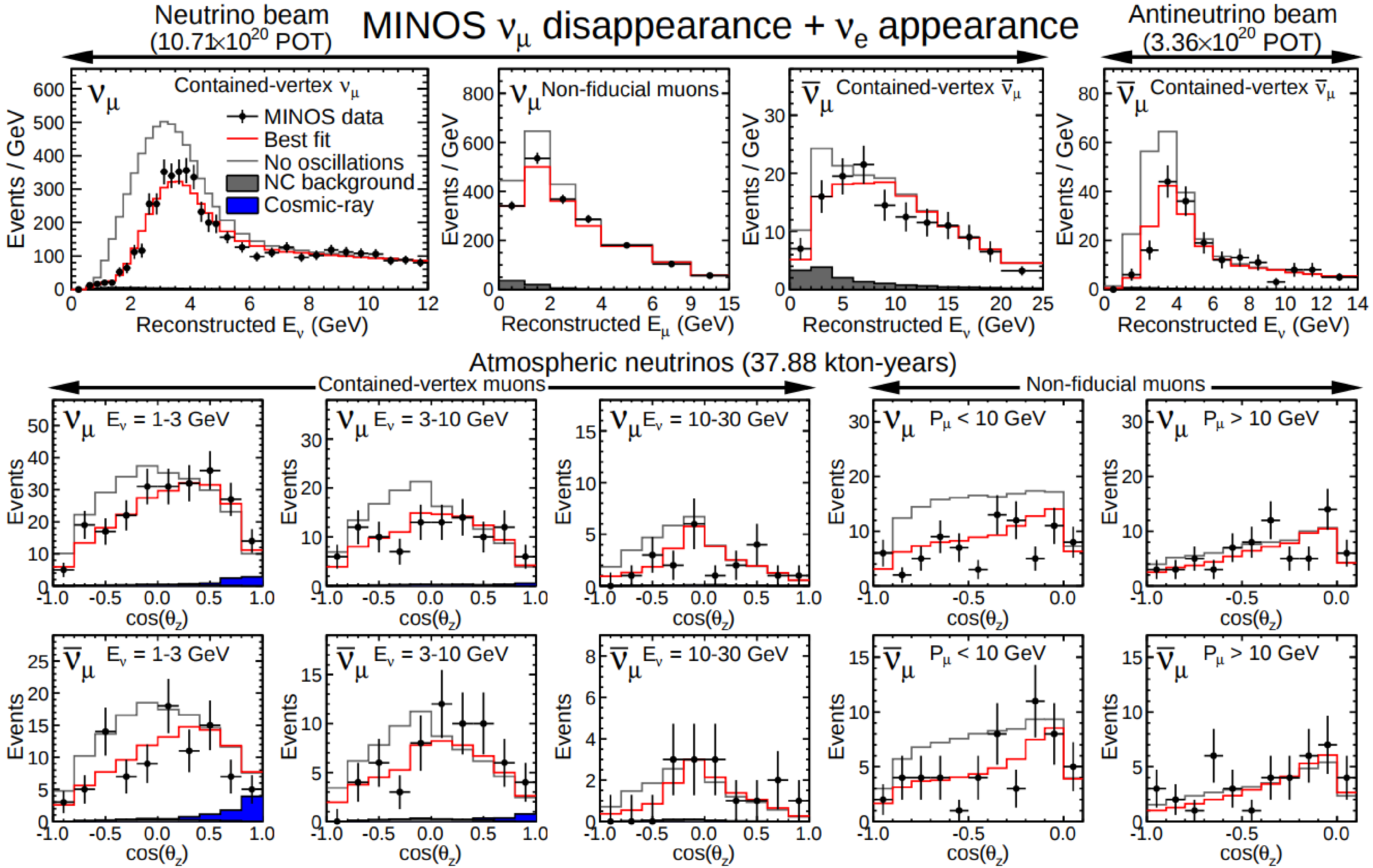


MINOS
magnetized steel & scintillator calorimeter



Overview of the MINOS detector in Minnesota.

Nucl.Phys. B908 (2016) 130-150



***measurement is dominated by beam data**

towards the future

main interests

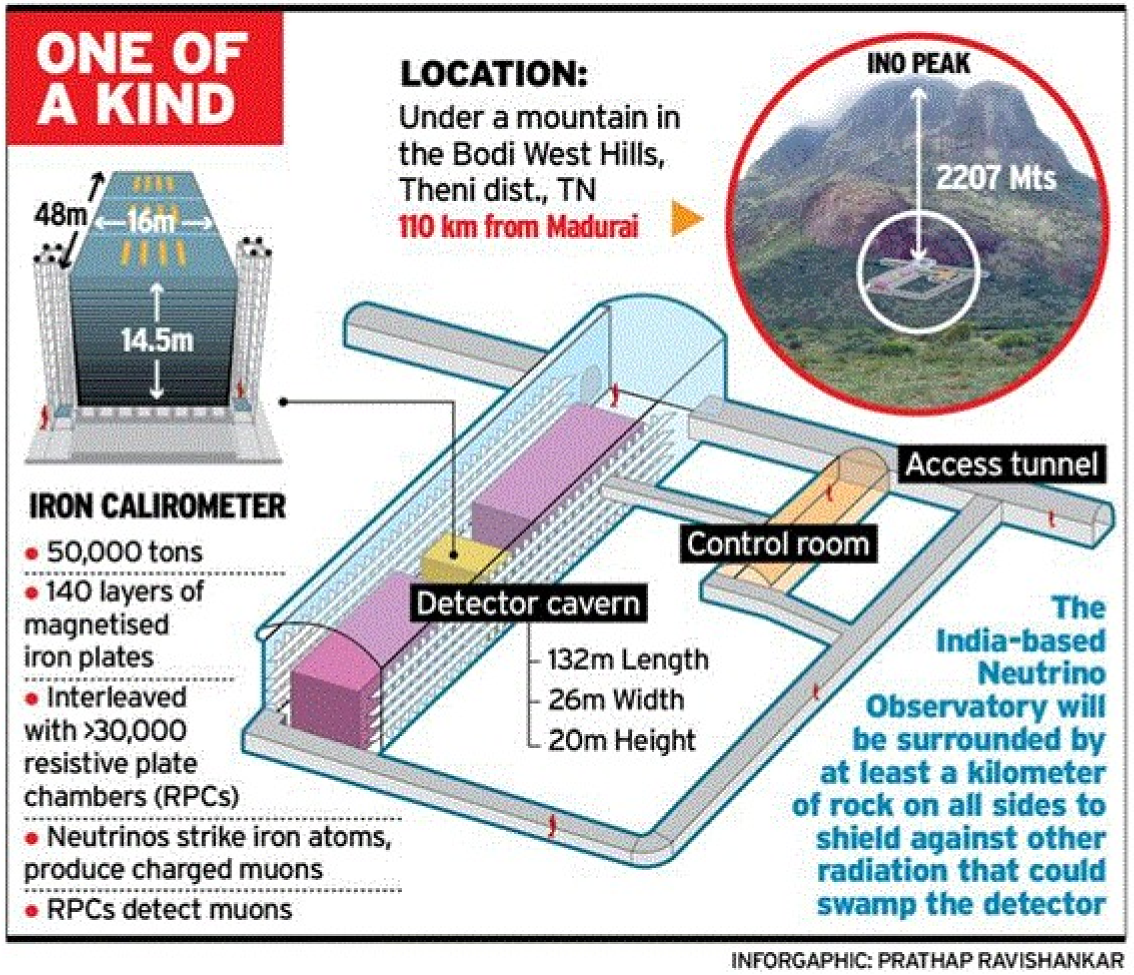
-precision measurements

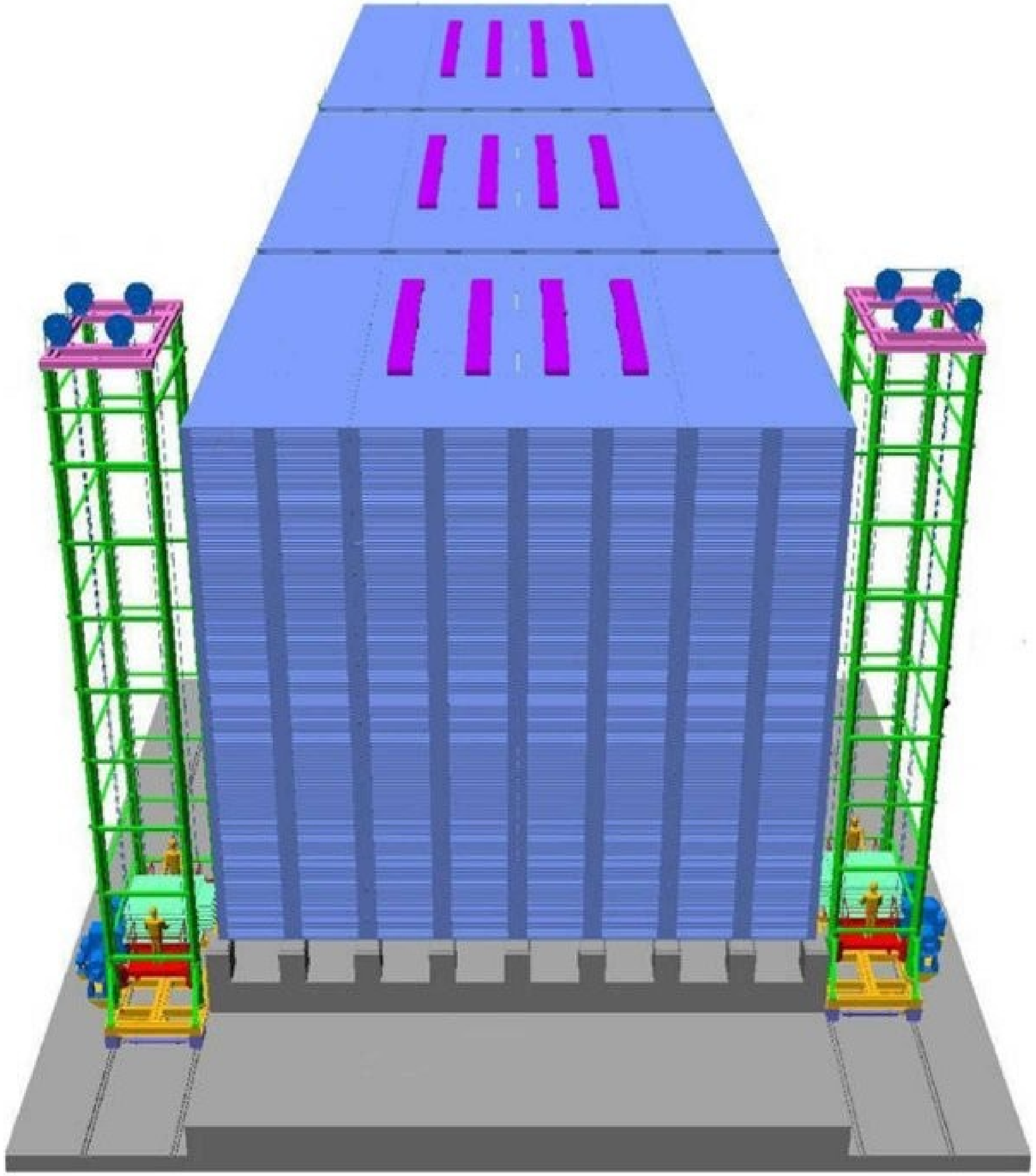
-neutrino mass ordering

-CP-violation in leptons*

… bigger, better, denser experiments

INO

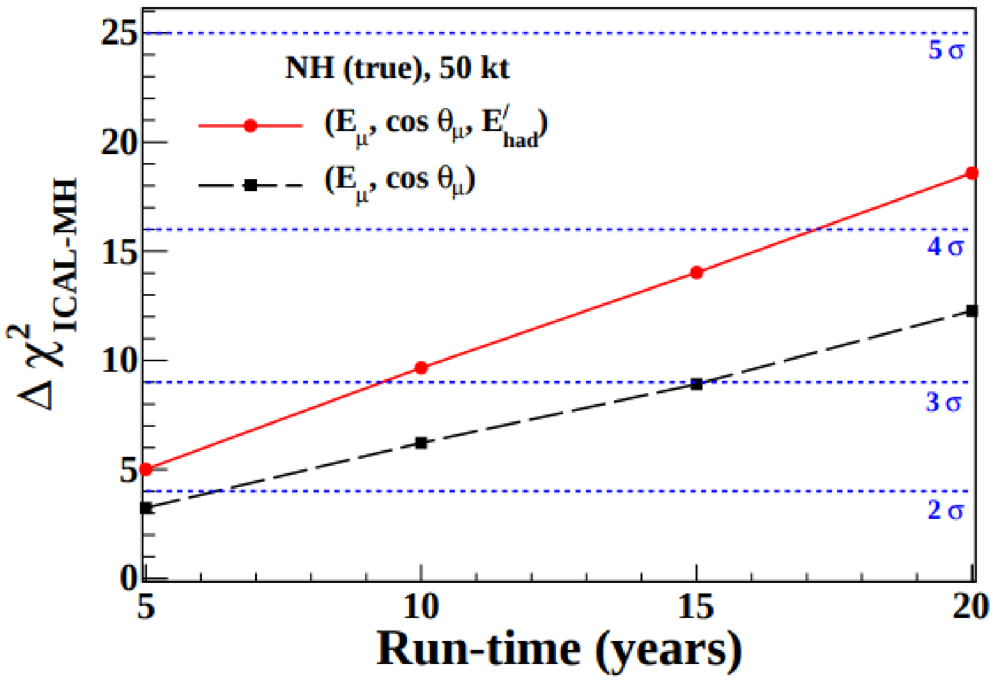


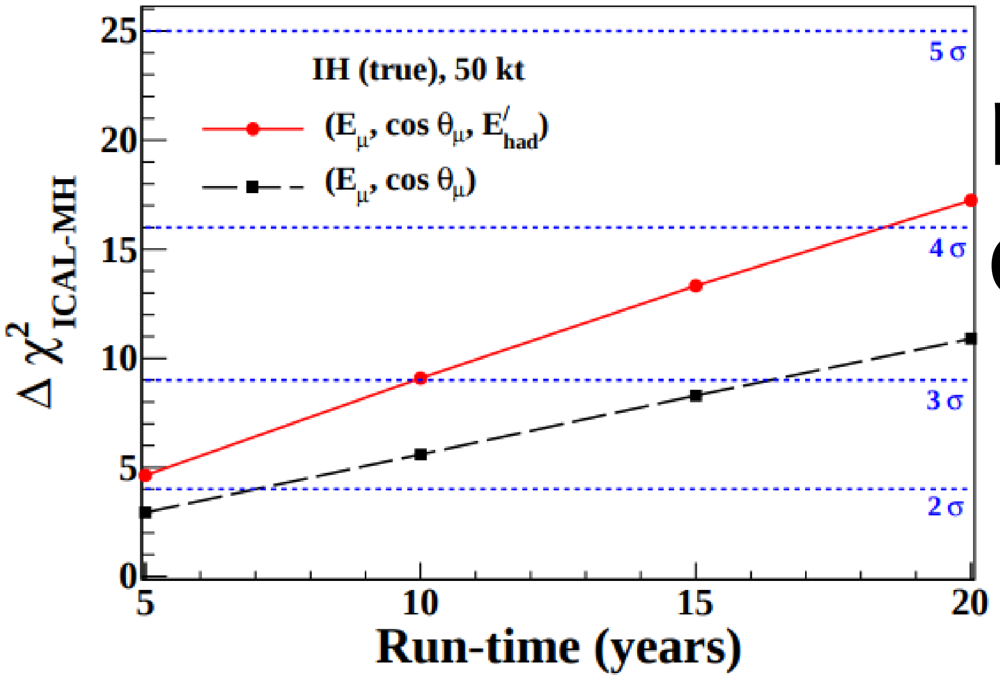


-individual particle **tracking**

-**charge** identification

INO

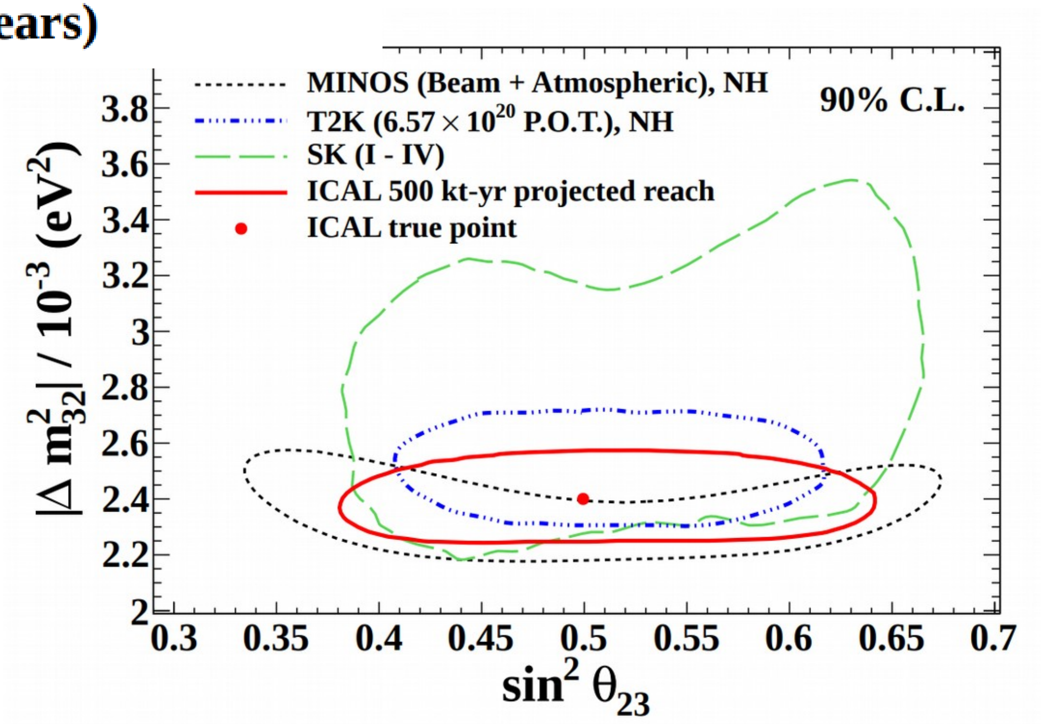




mass ordering

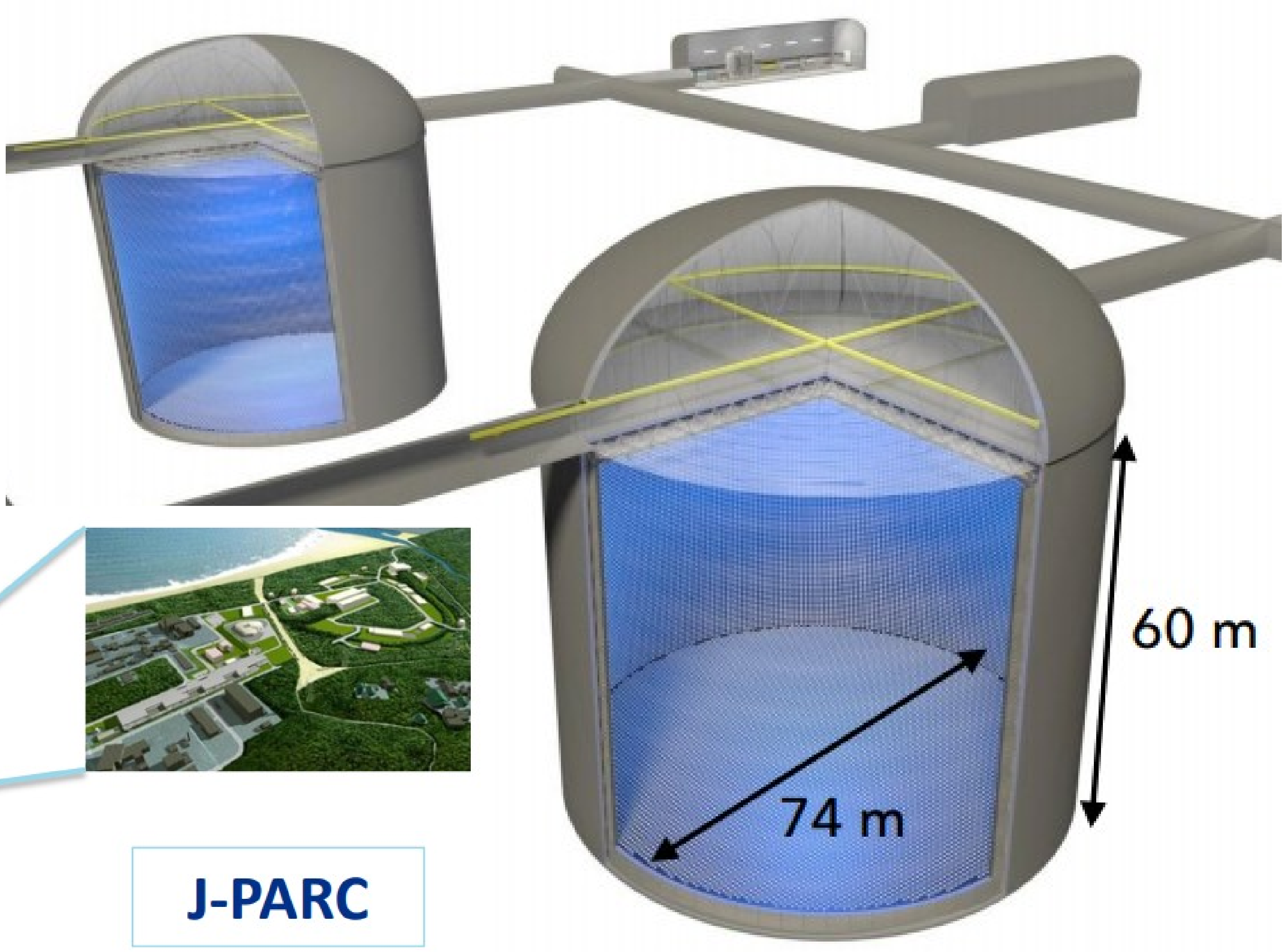
arXiv:1406.3689 [hep-ph]

oscillation parameters after 10 years of run-time



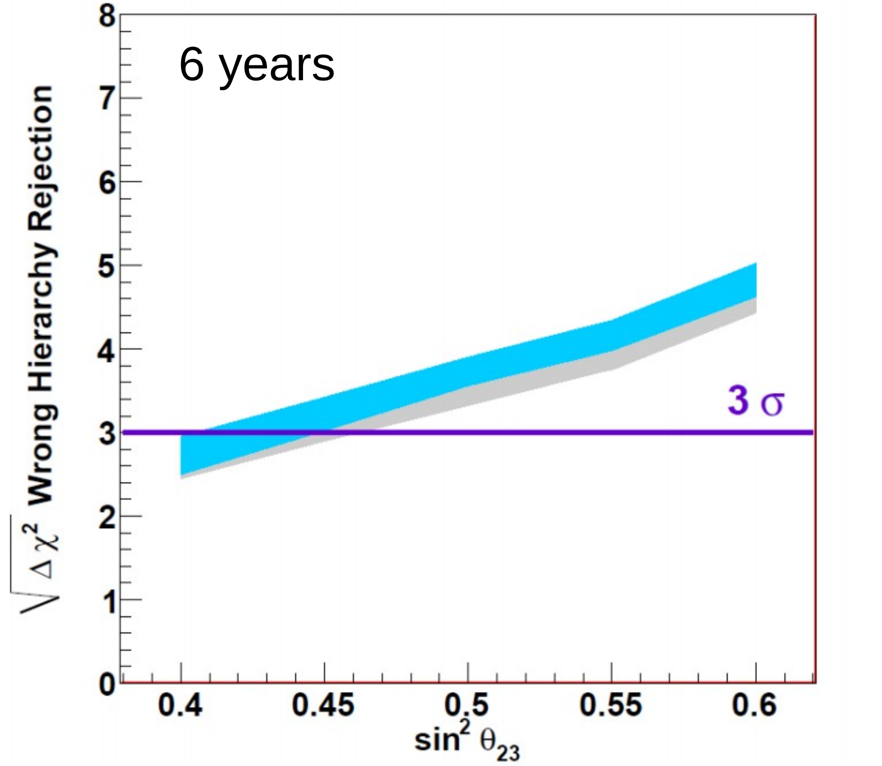
Hyper-Kamiokande

- 8x Super-Kamiokande's FV / tank
- 260kt mass / tank
- atmospheric+beam nus

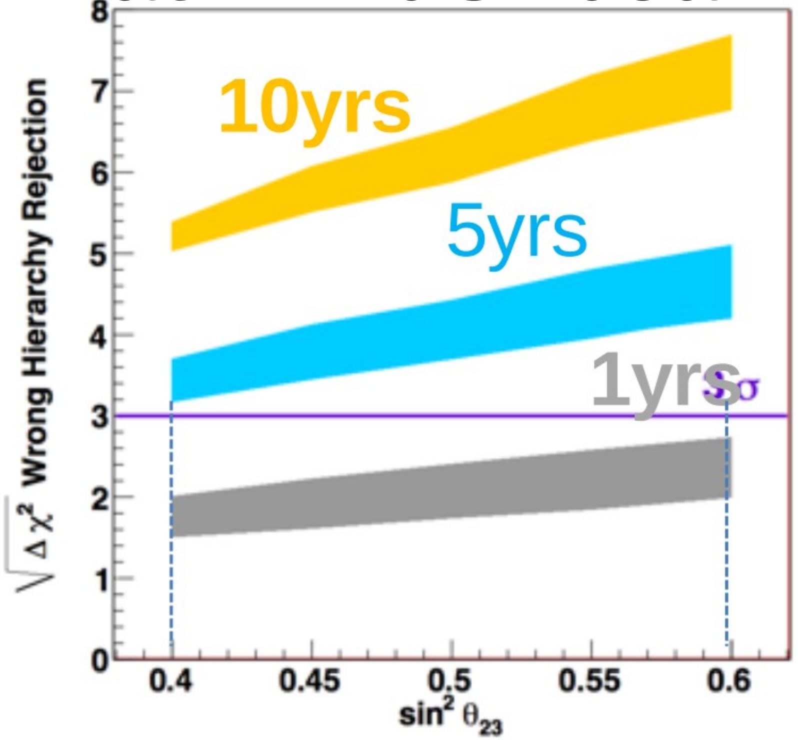


Hyper-Kamiokande (one tank)

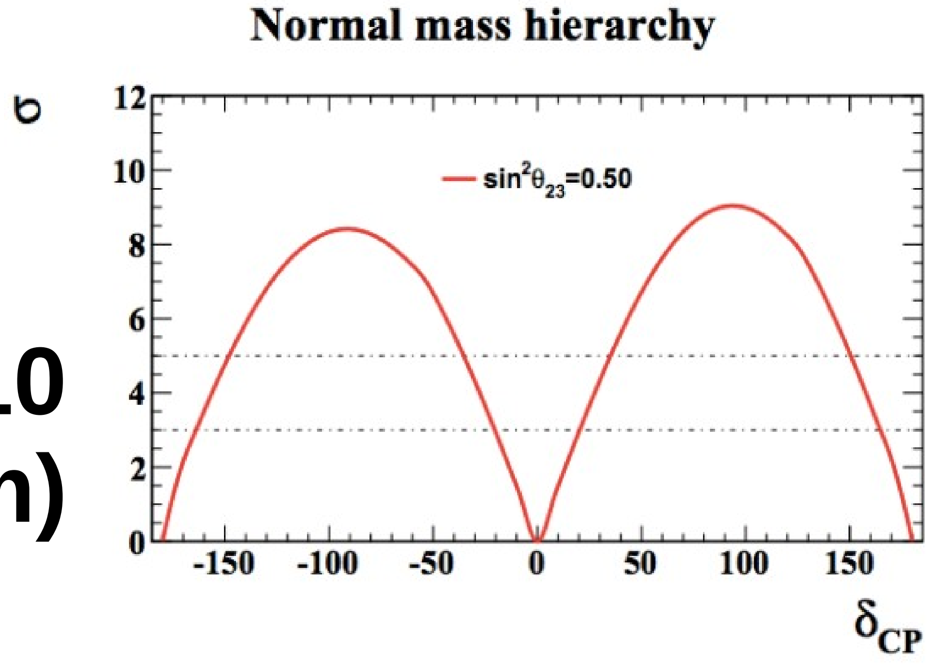
atm. nus



atm. nus+beam

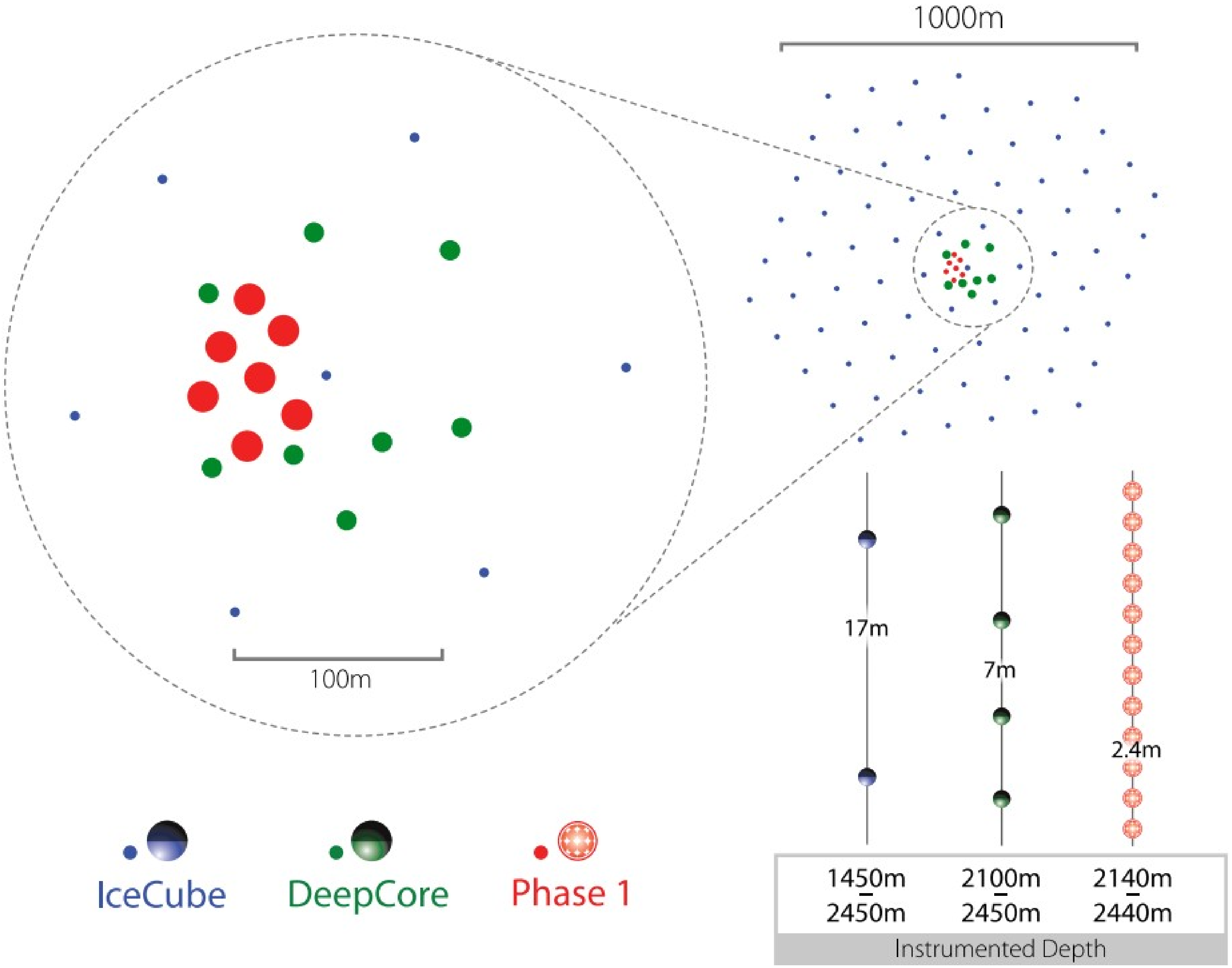


CP-violation after 10 years (beam)



Zsoldos, ICRC2017

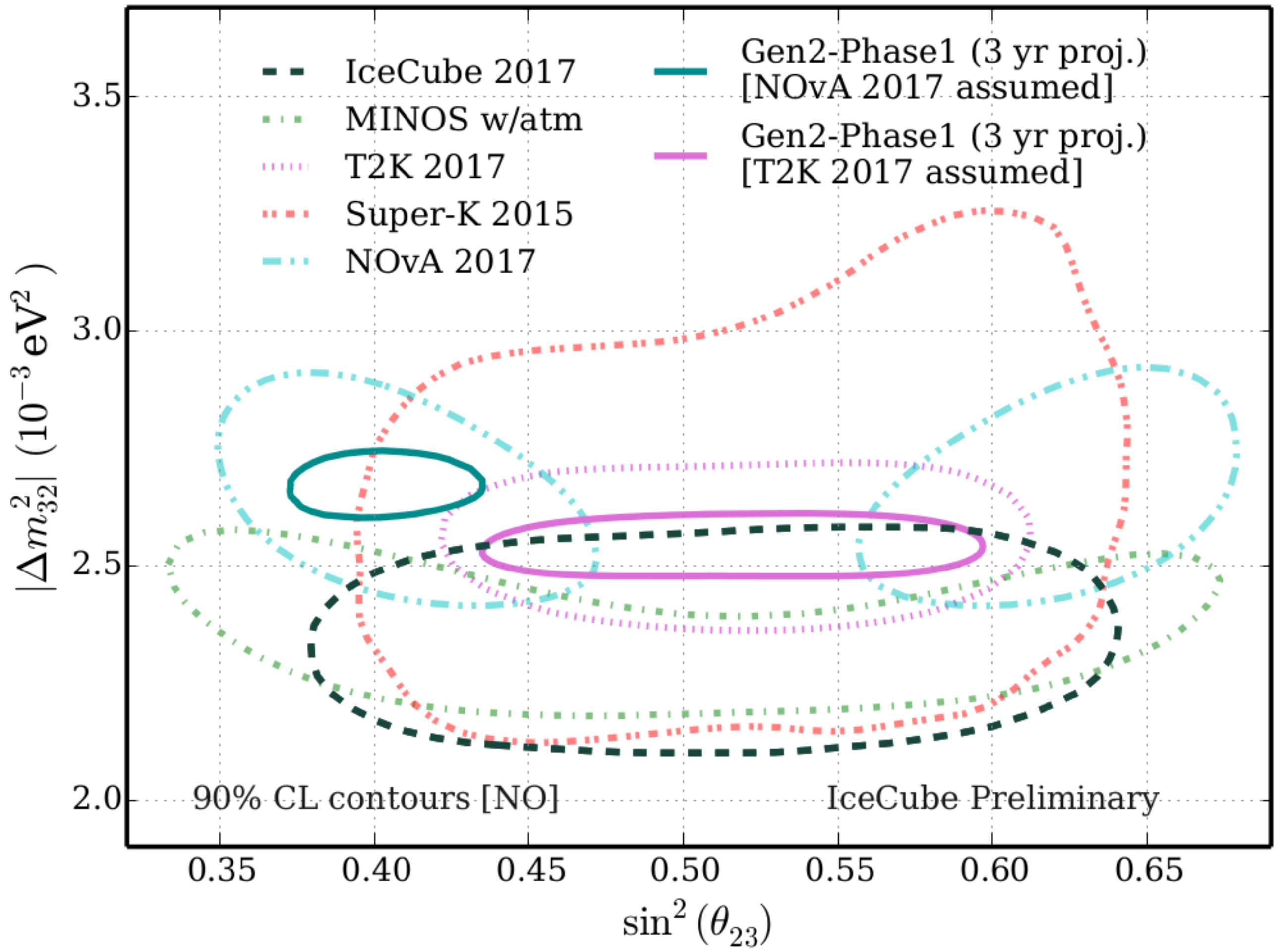
IceCube-Gen2 Phase1



-DeepCore infill

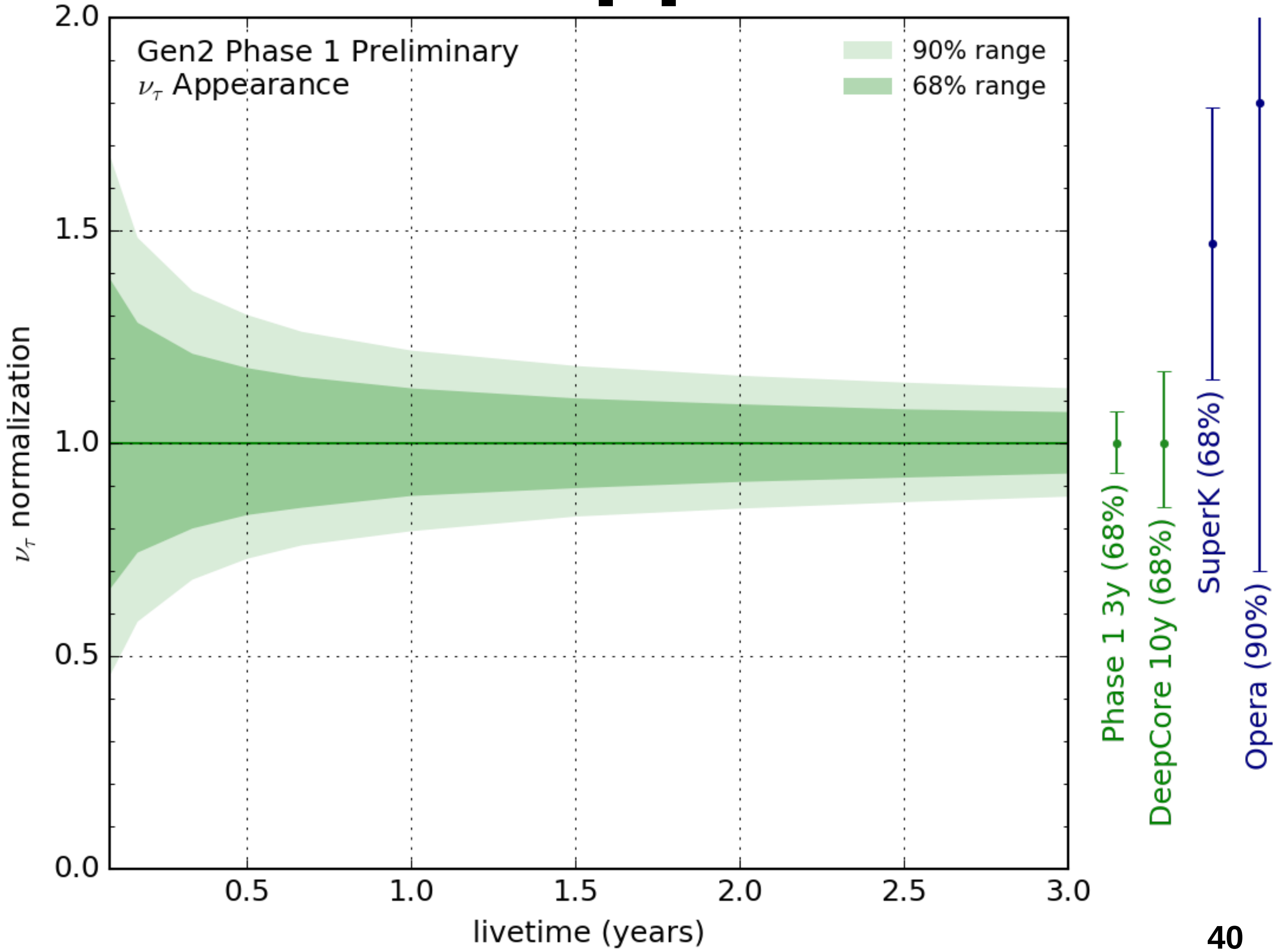
-lower energy threshold

IceCube-Gen2 Phase1

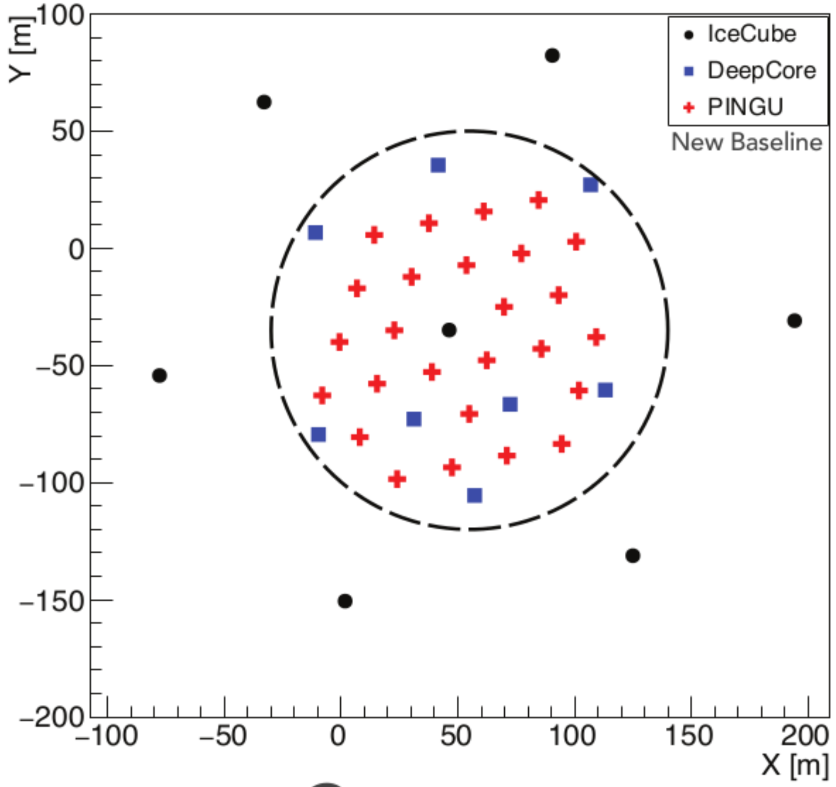


osc. parameters

nutau appearance



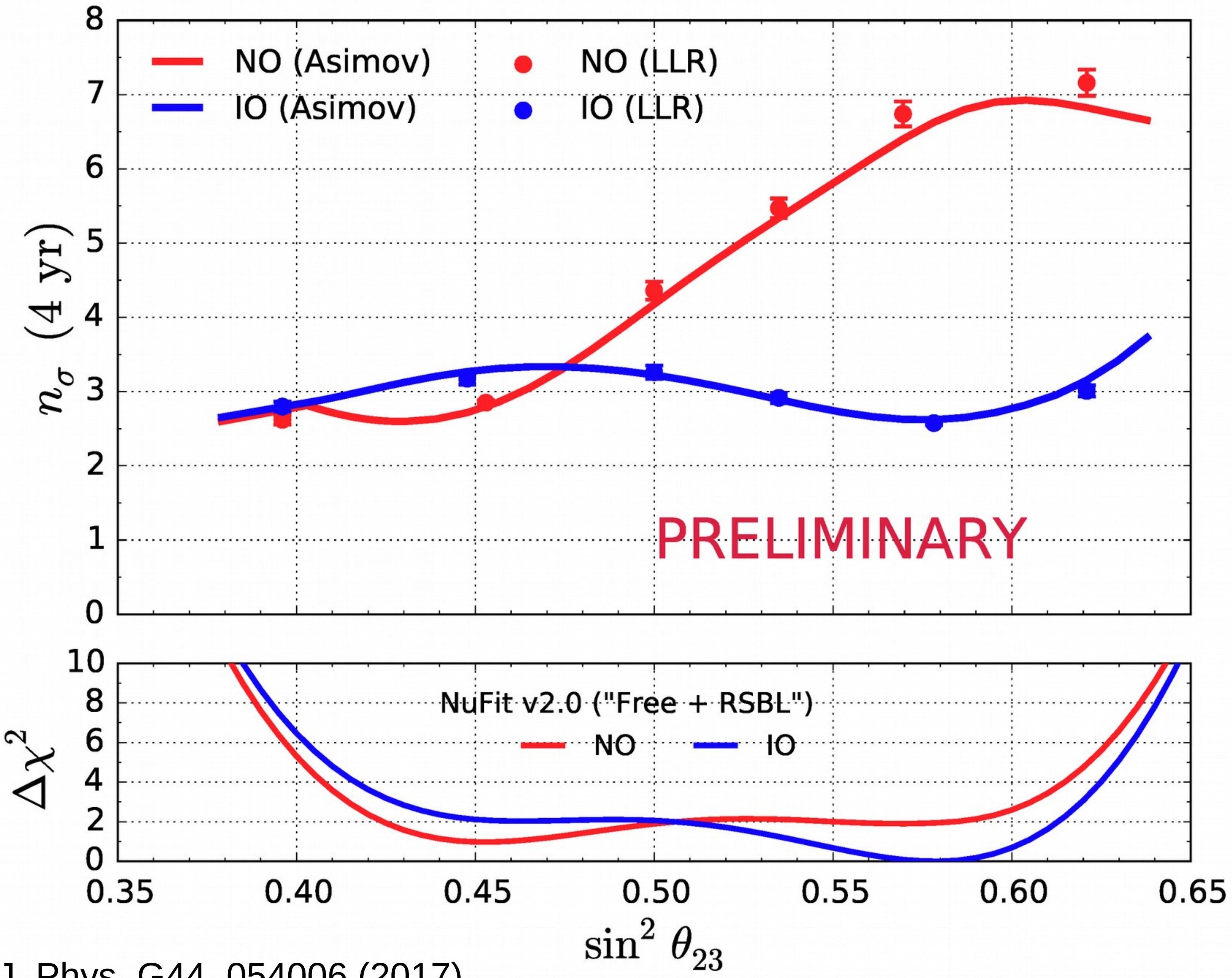
PINGU



Current

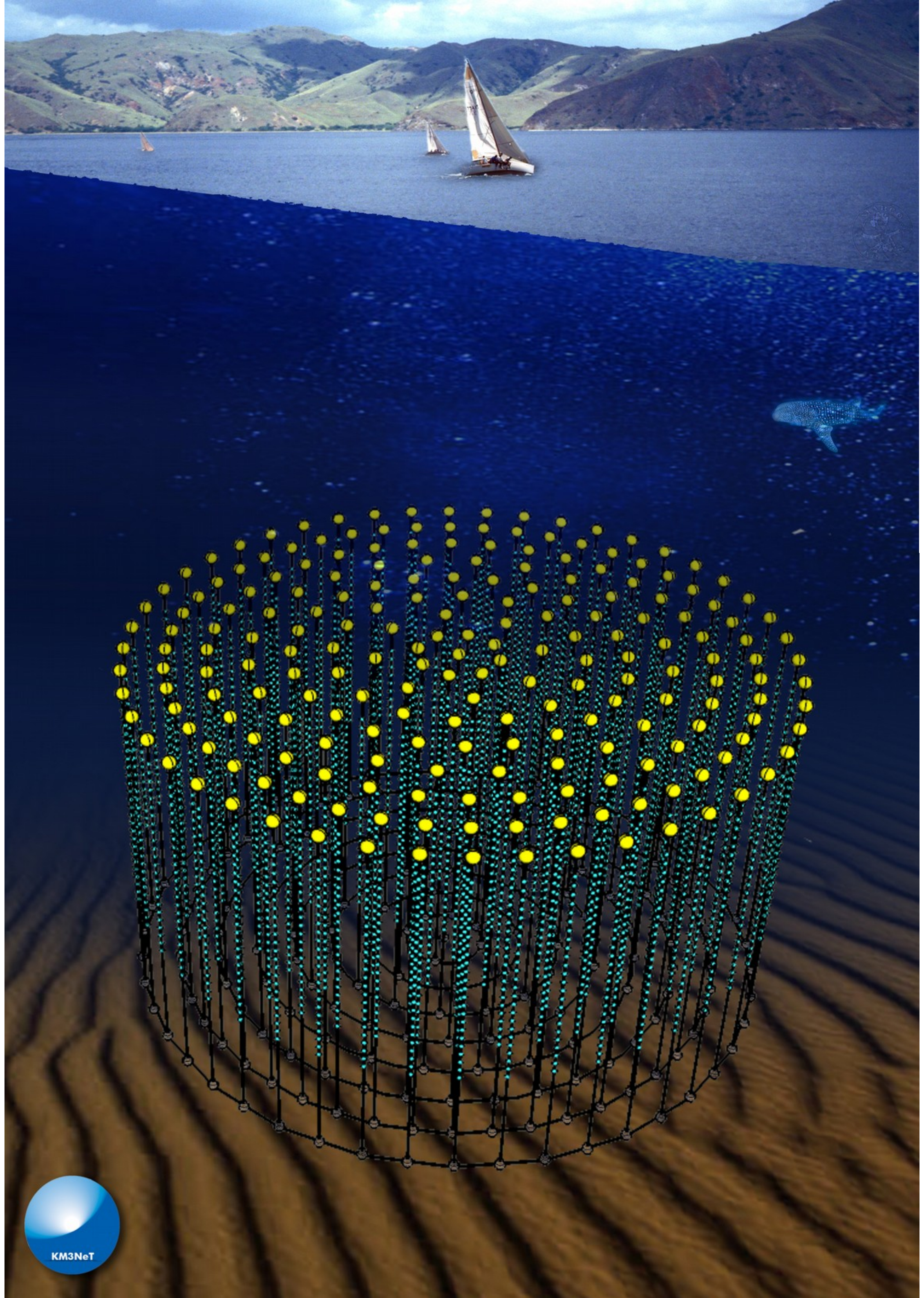
26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

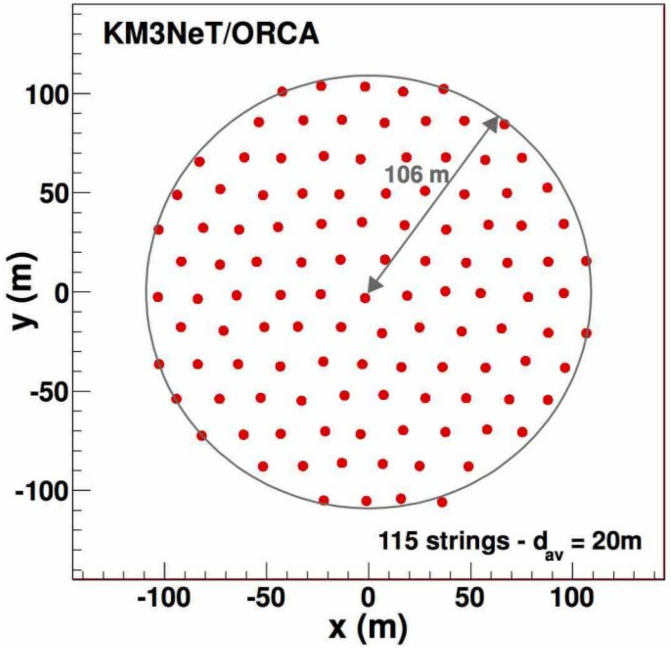
mass ordering



J. Phys. G44, 054006 (2017)

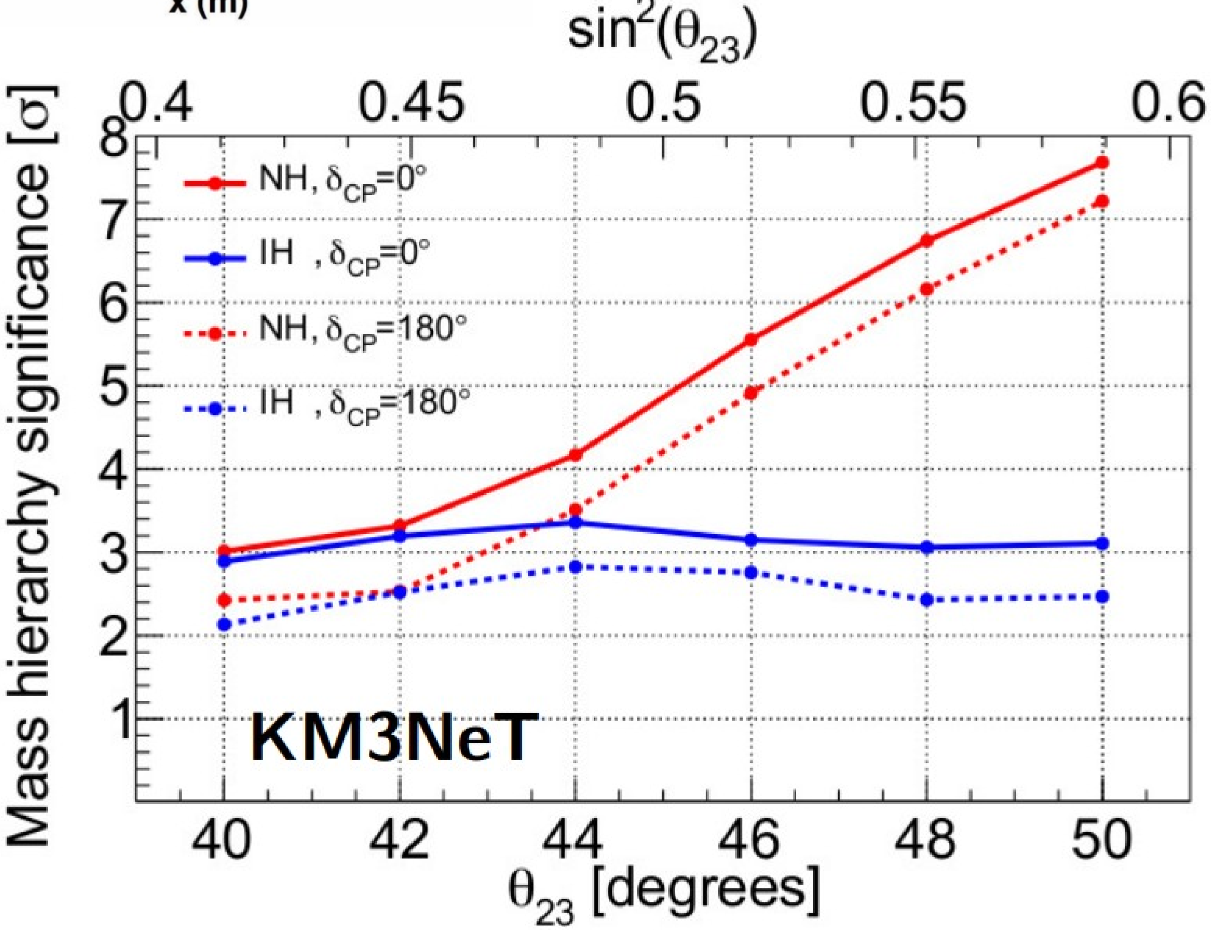
ORCA





mass ordering (3y)

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

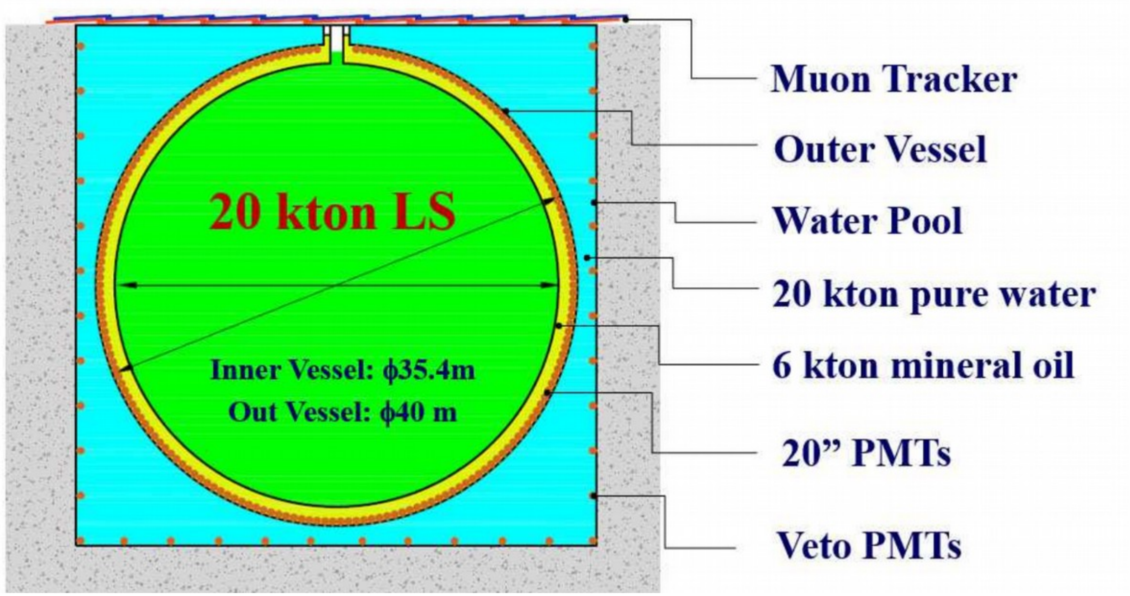


other experiments

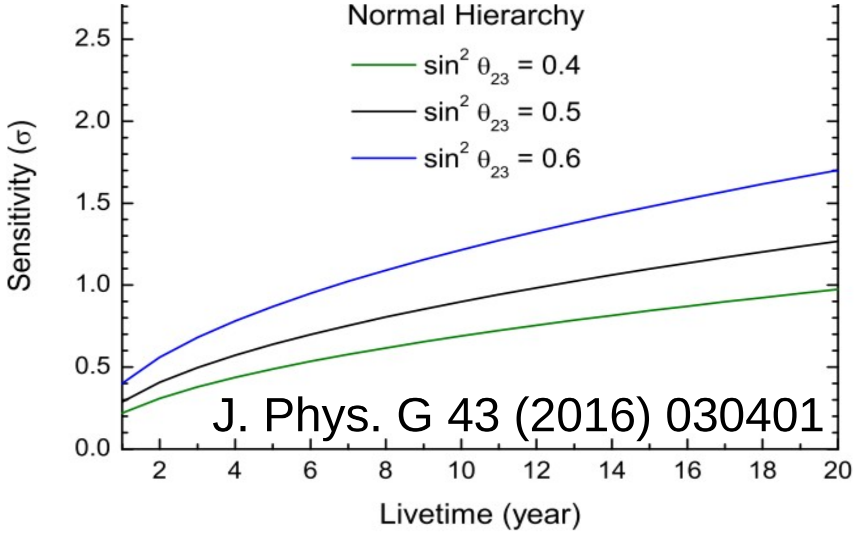
atmospheric ν are a secondary measurement

JUNO

mass ordering from reactor neutrinos

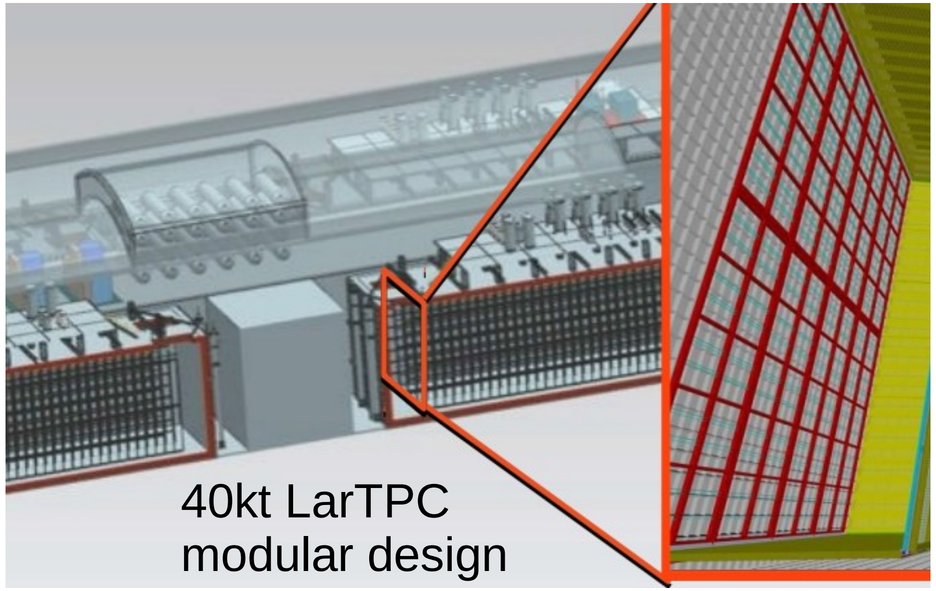


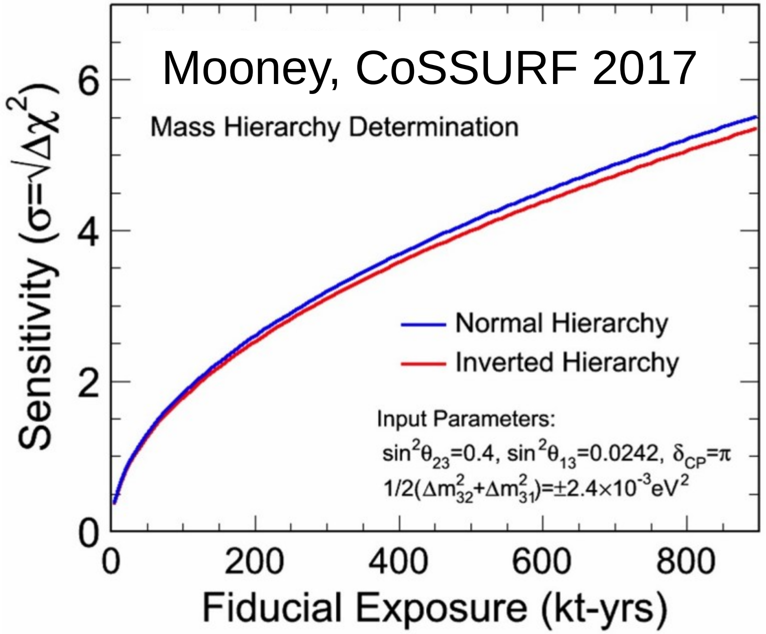
mass ordering sensitivity from atm. ν only



DUNE

CP violation from beam neutrinos





back to the present

summary & outlook

-atm. nus are an invaluable tool for neutrino physics
  -very large & unique phase space in L/E, flavor

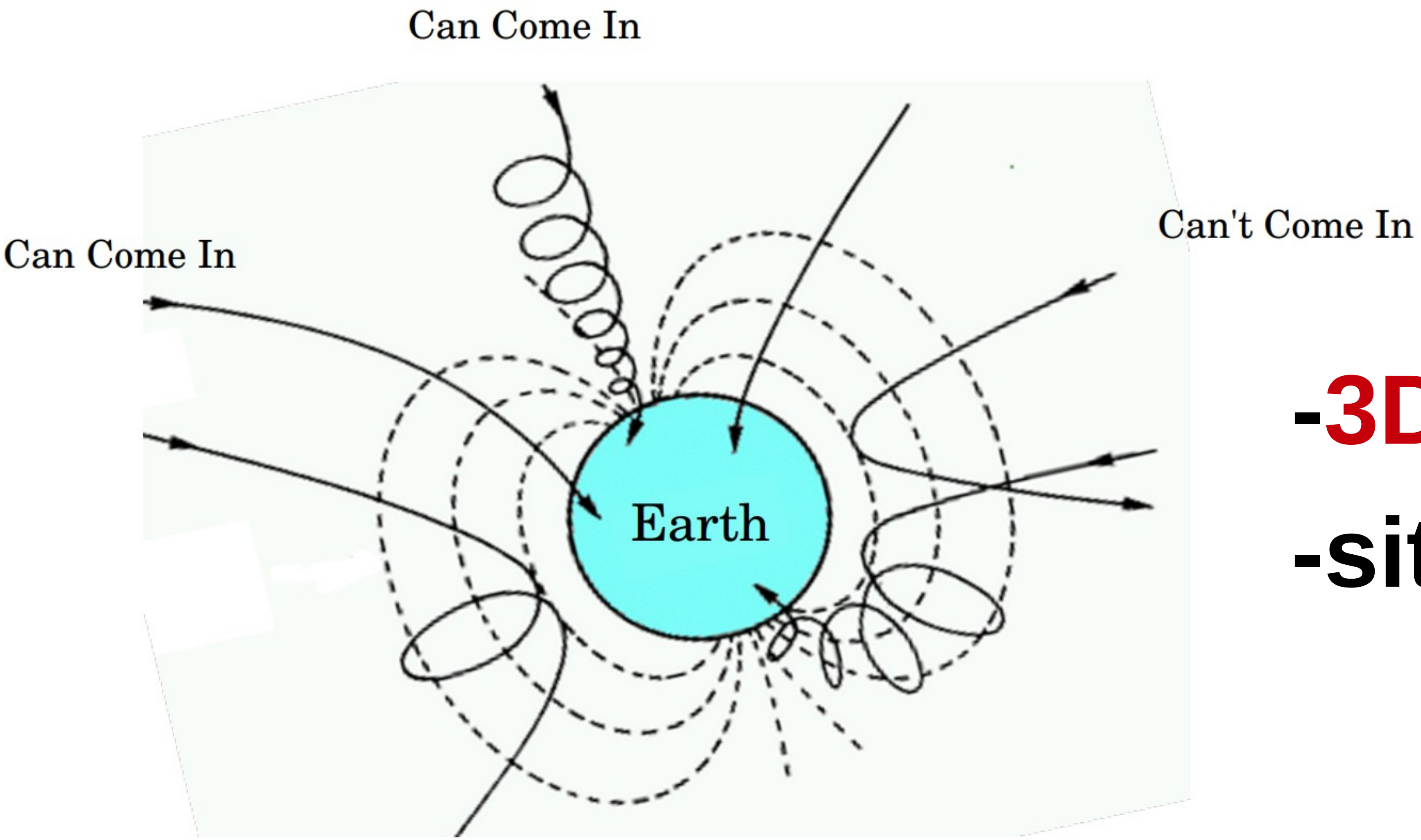
-renewed efforts to model & understand atm nus ongoing
  -more data, new software, workshops in last years

-experiments producing well understood, reliable results
  -next generation measurements tough, but possible

backup

flux basic inputs

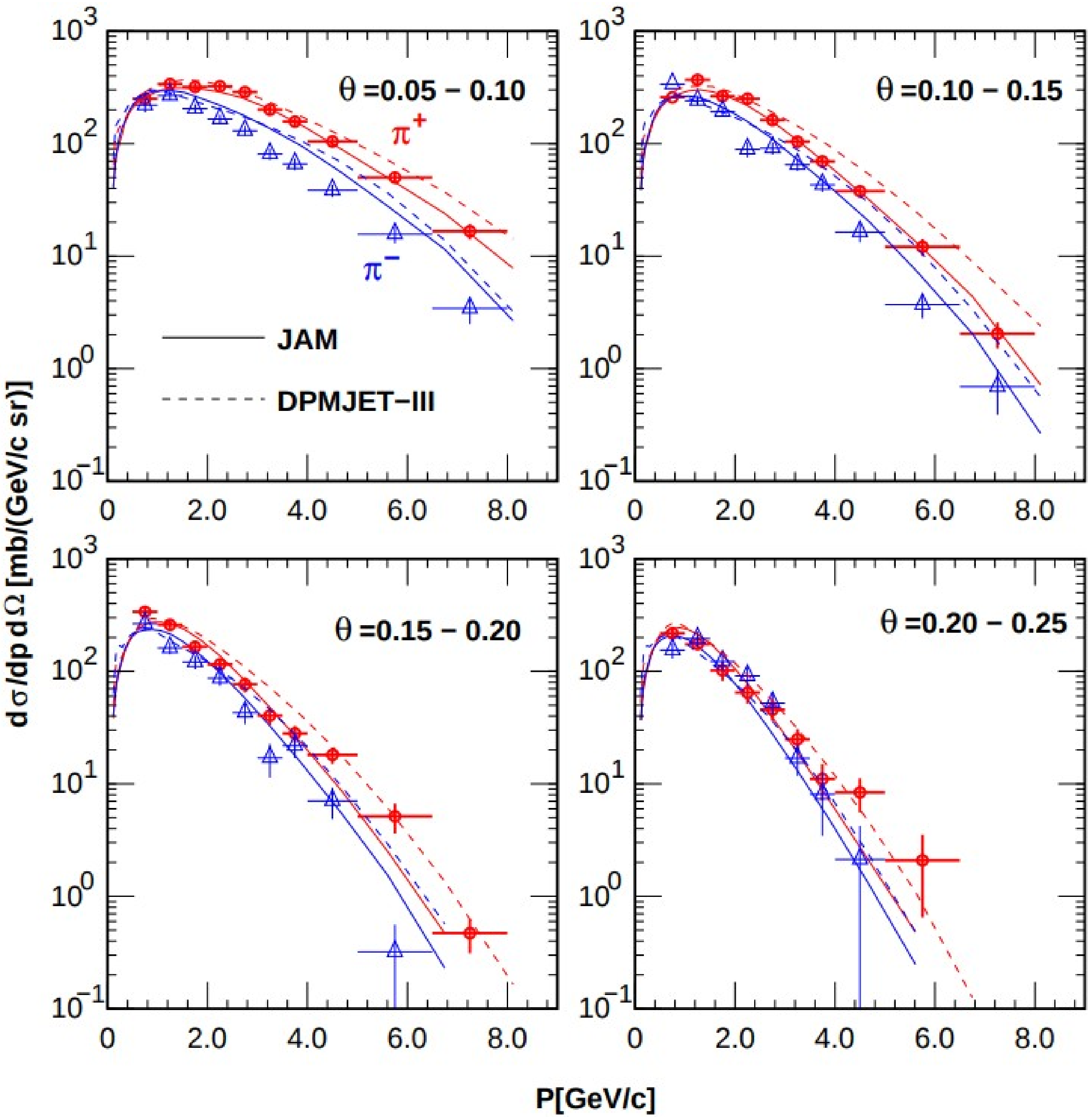
-geomagnetic effects



- **-3D calculations**
- **-site-specific**

flux basic inputs

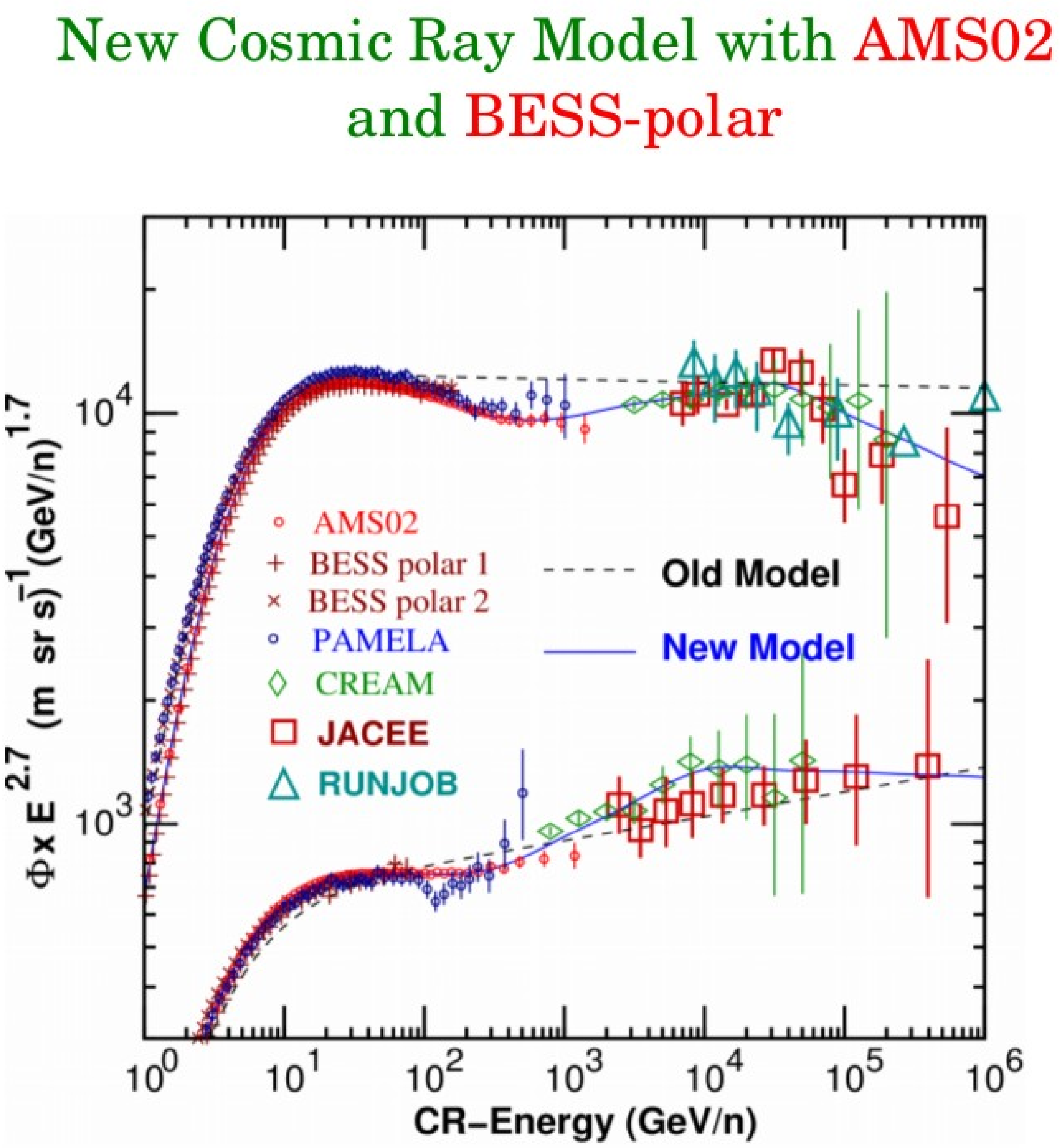
-hadronic interactions HARP data



Phys.Rev.D83:123001,2011

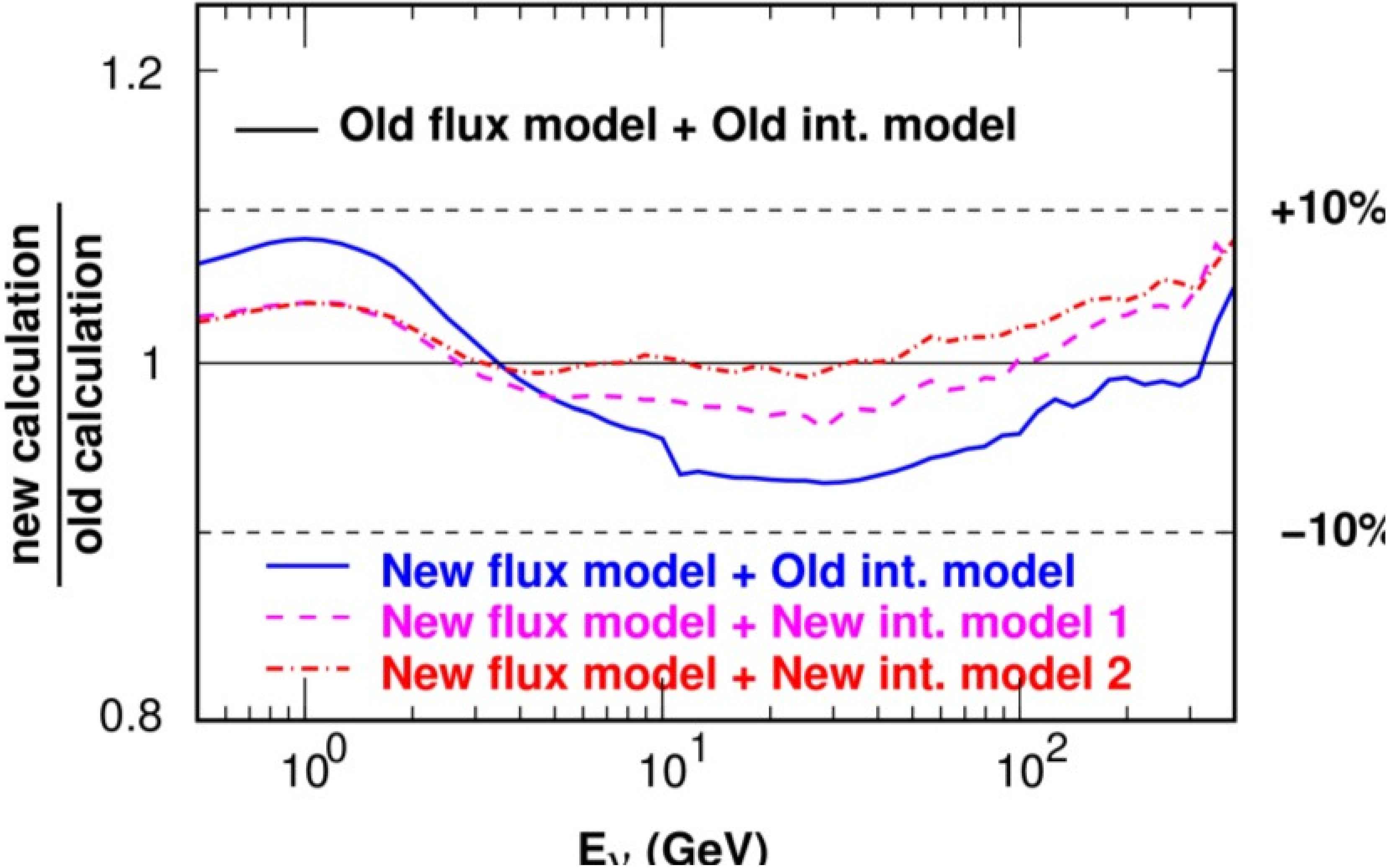
HKKM CR flux

Honda
AtmNuWorkshop 2016



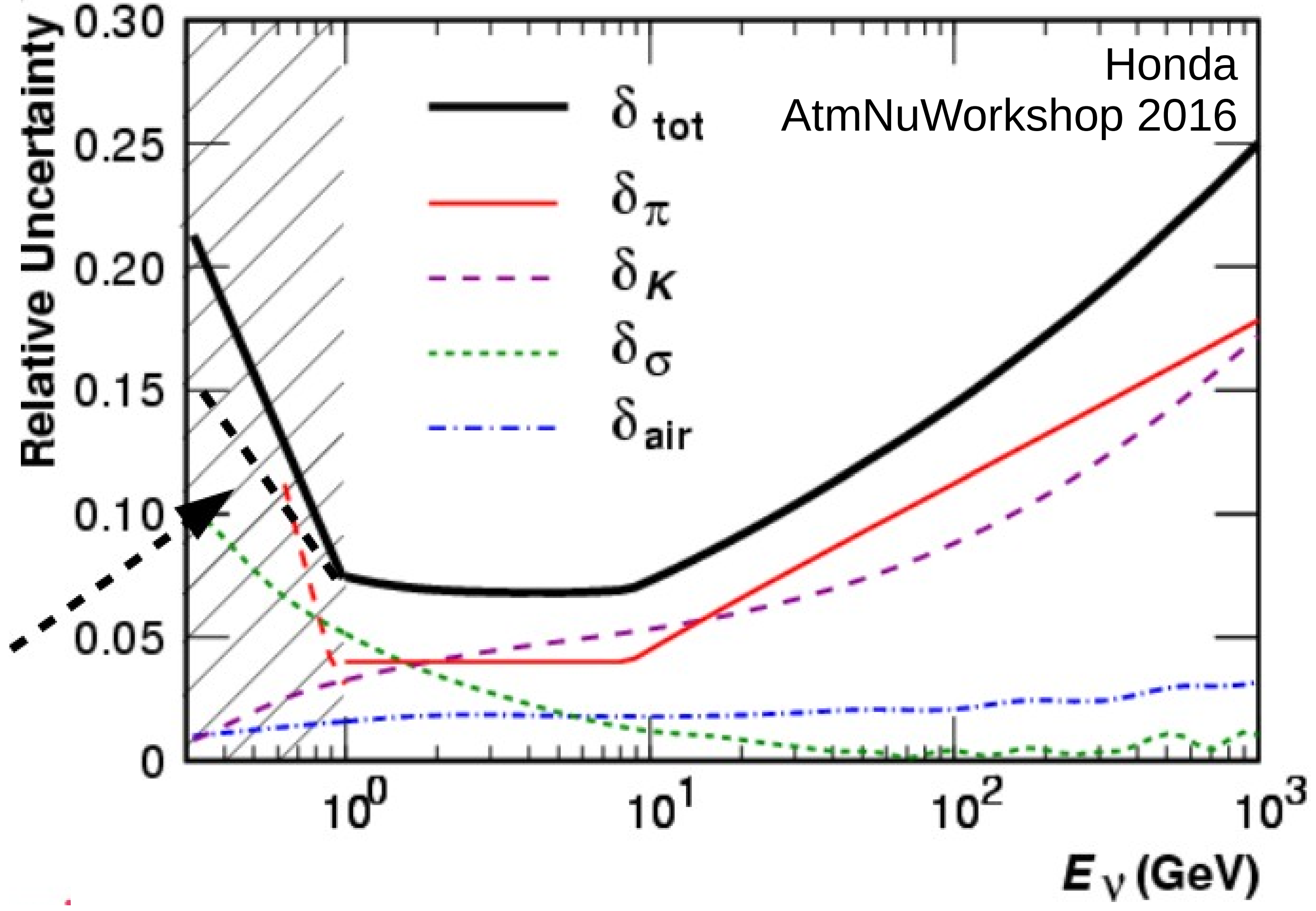
HKKM neutrino flux updates

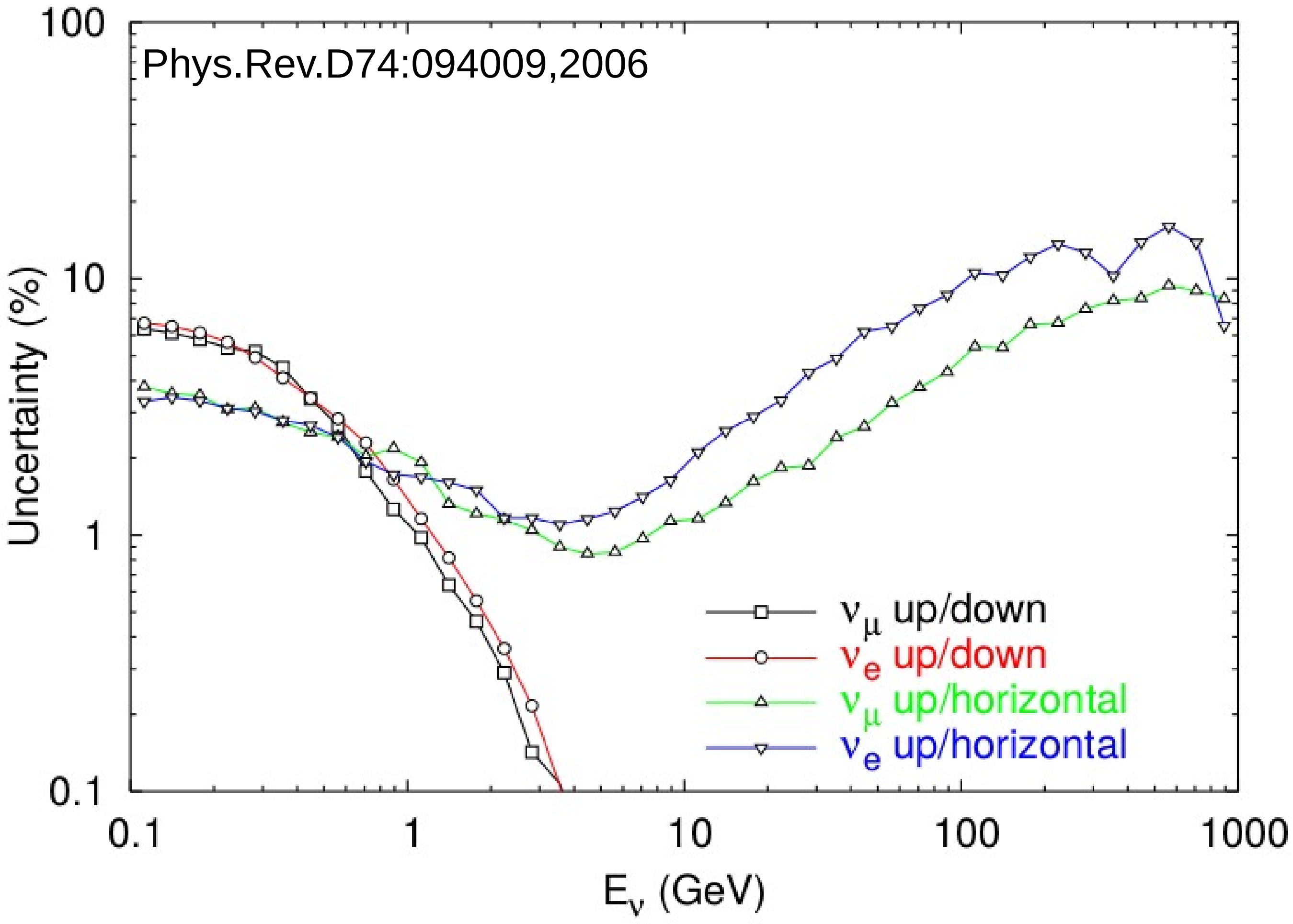
Honda
AtmNuWorkshop 2016



atmospheric neutrino flux

-and its uncertainties





parameters accessible

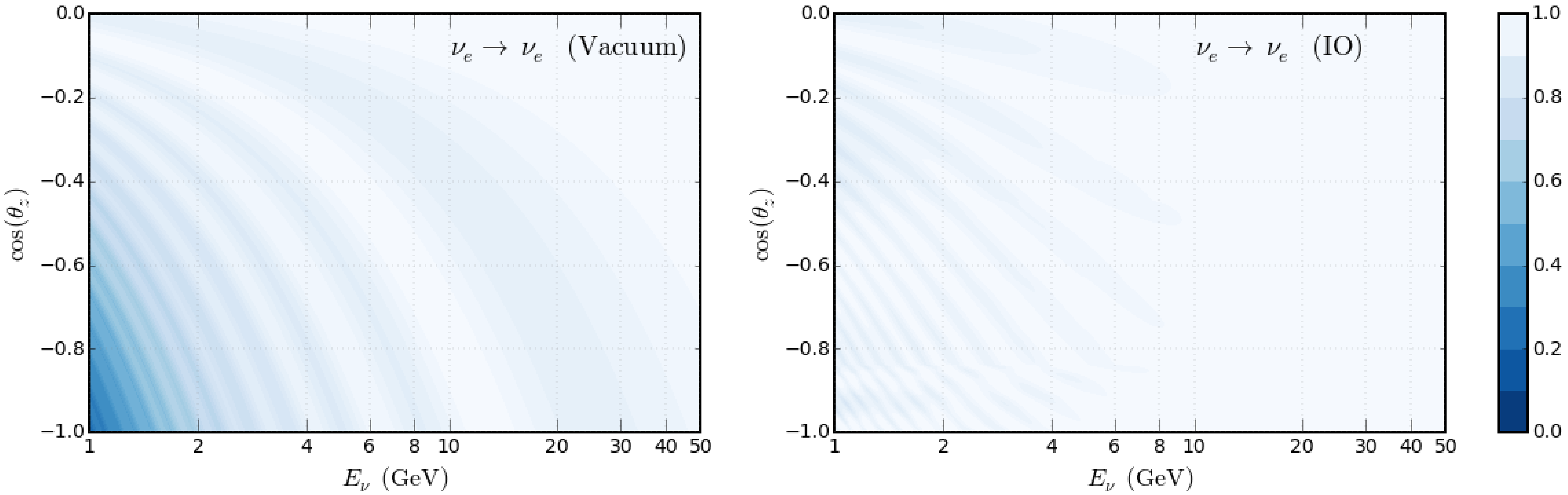
$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

$$|\Delta m^2_{\text{large}}| \gg |\Delta m^2_{\text{small}}|$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

survival probabilities

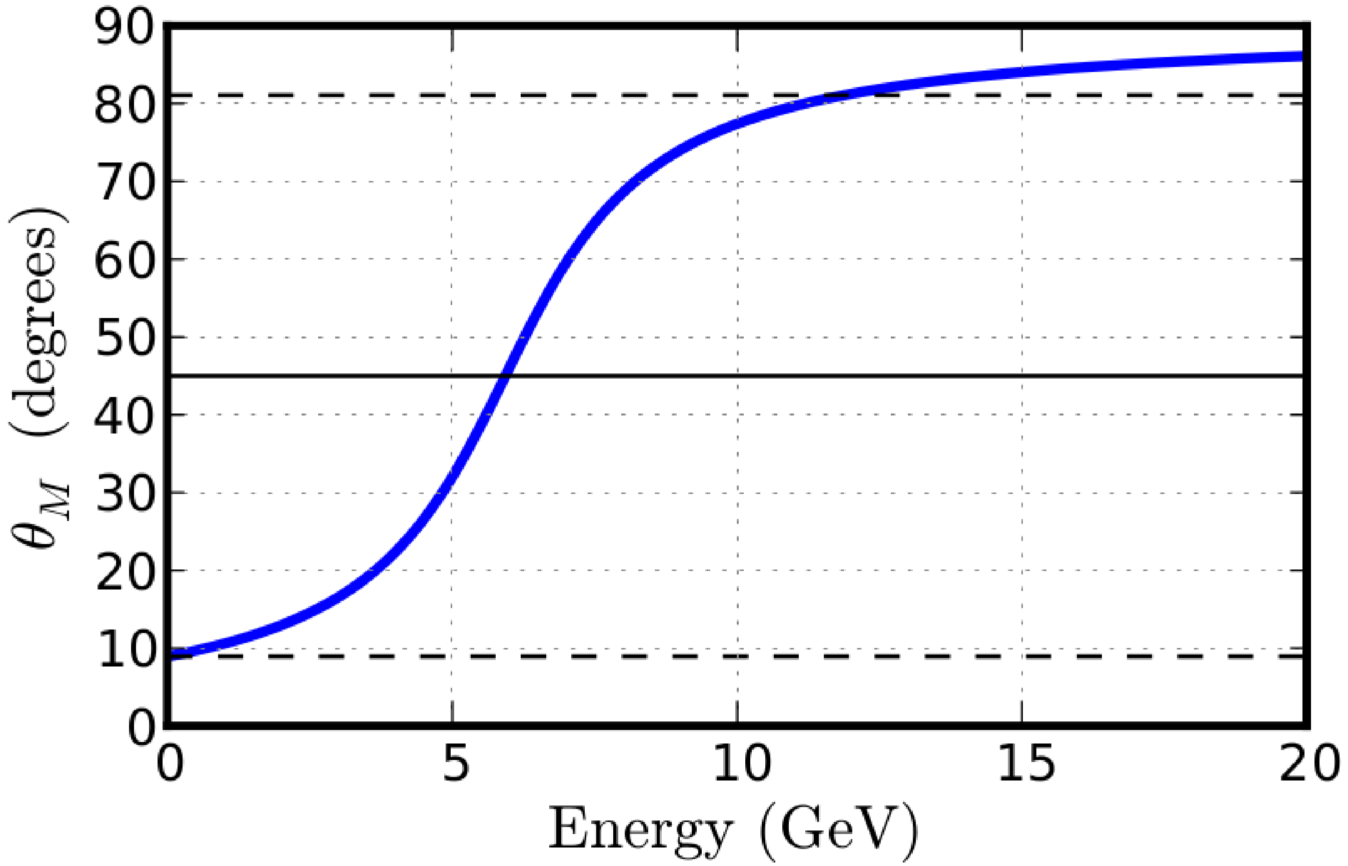
$$P_{\mu e} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left[\Delta^M \frac{L}{4E}\right],$$



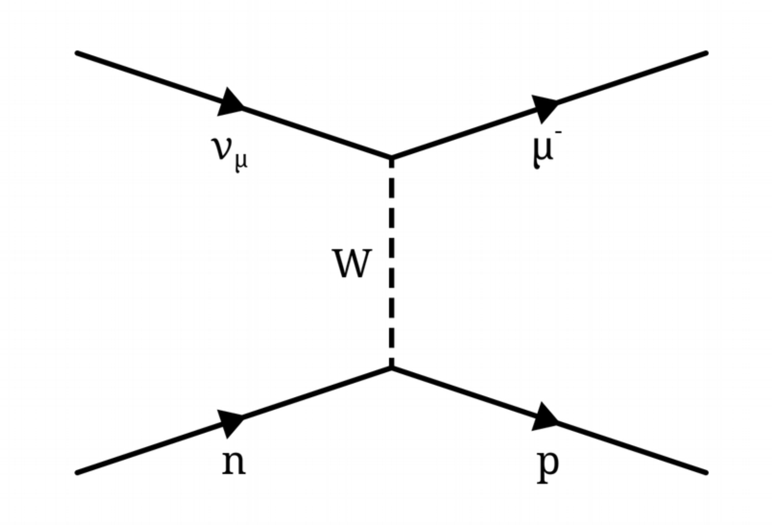
saturation effect

saturation effect on θ_{13}

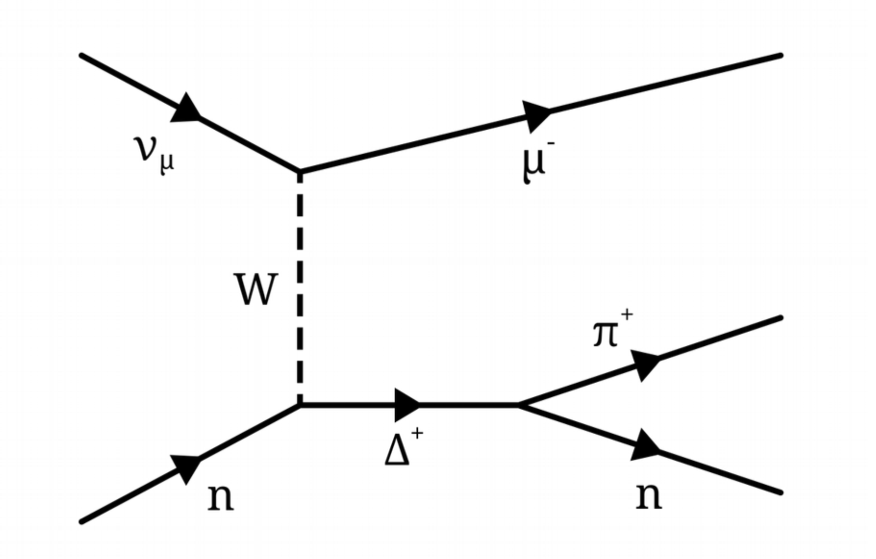
Figure 3.4: Effective θ_{13} as a function of neutrino energy for an electron number density of 2.5 (blue). Dashed black lines show the value of θ_{13} for vacuum, from 4.1, and its complement $(\pi/2 - \theta_{13})$. The solid black line indicates maximal mixing. Calculated using Eq. 3.45.



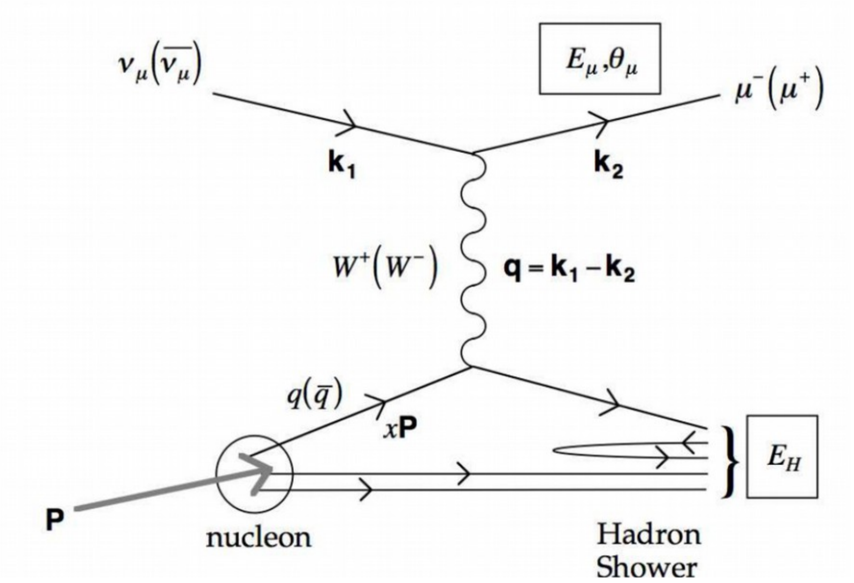
event signature & energy



Quasi-elastic



Resonance single-pion



Deep inelastic

-particle (ring) counting

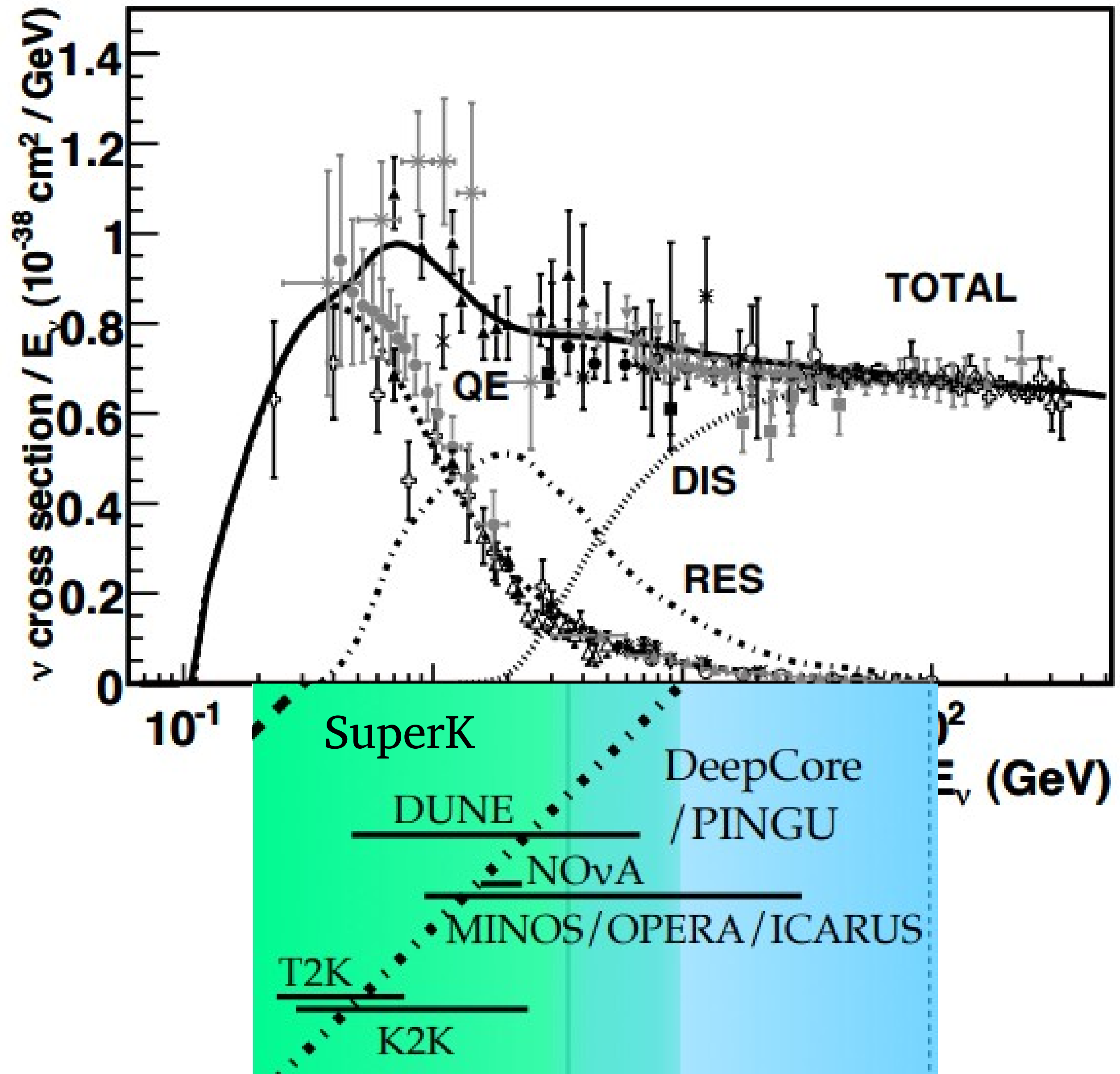
-Cherenkov light emission

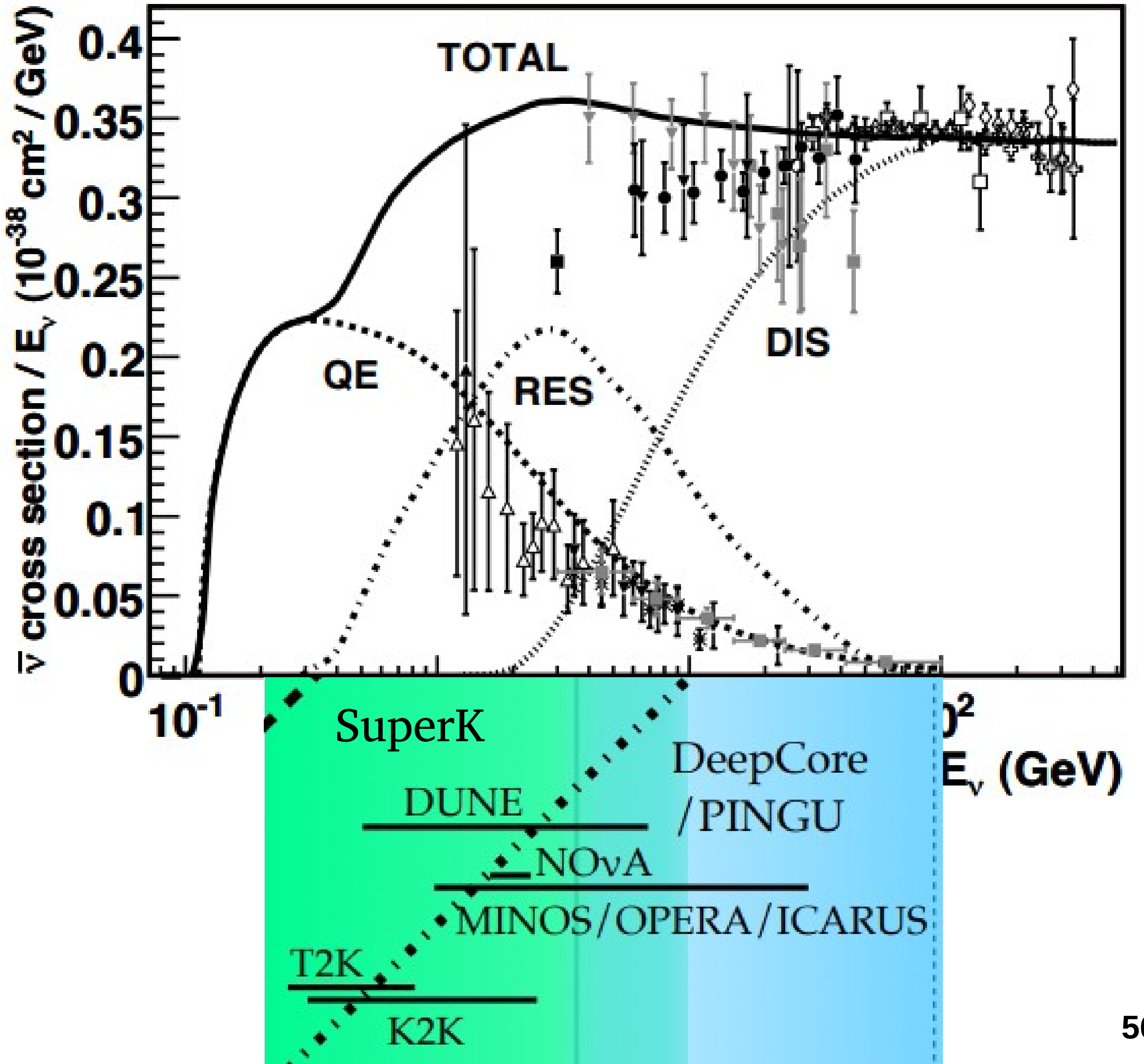
-ionization

Diagrams from
http://danielscully.co.uk/thesis/interactions.html
Rev. Mod. Phys. 70, 1341 (1998)

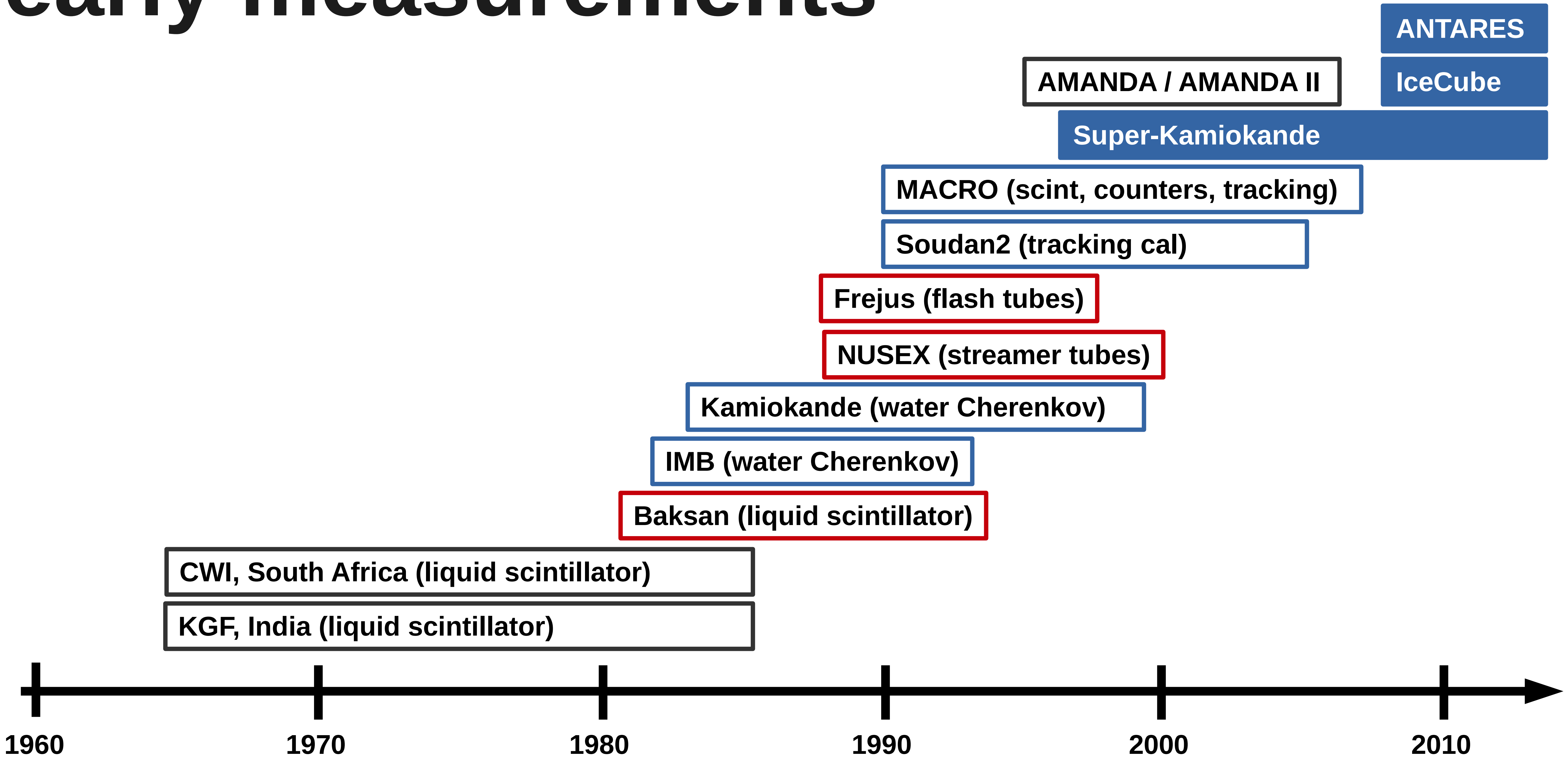
relevant interactions

Rev. Mod. Phys. 84, 1307 (2012)



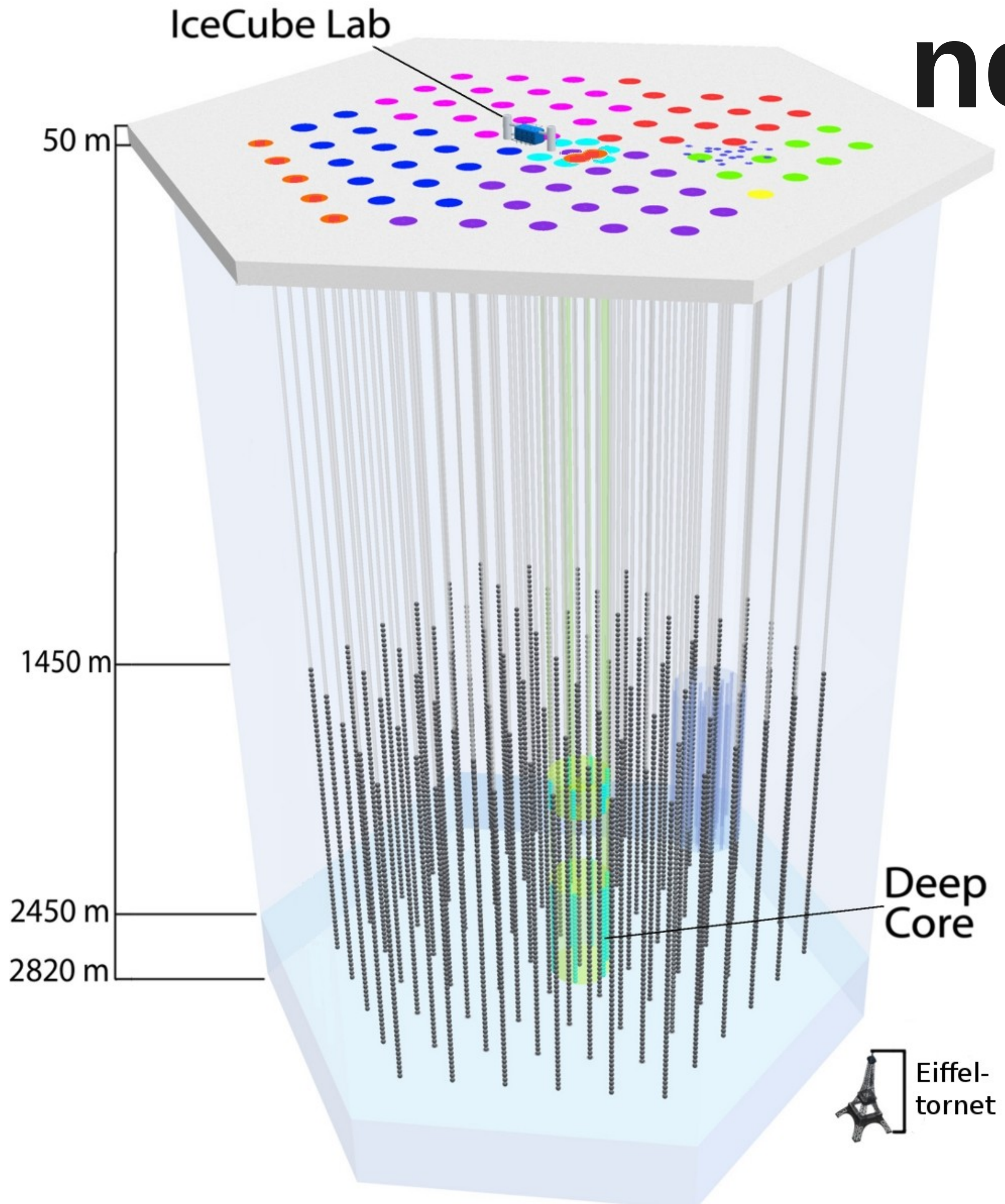


early measurements



*take dates with caution – list is incomplete

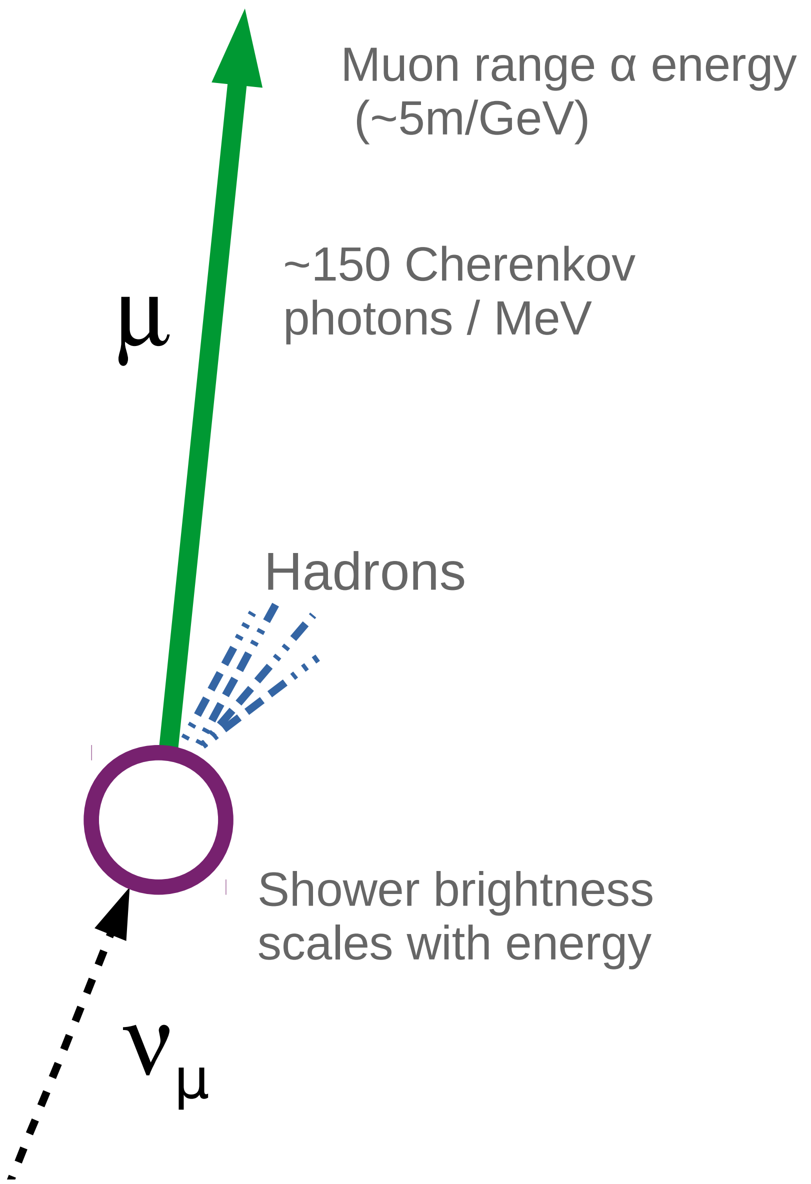
neutrinos in IceCube



signature extension and brightness scales with neutrino energy

The lowest energy neutrinos are seen by the DeepCore sub-array (E >= 10 GeV)

detection principle



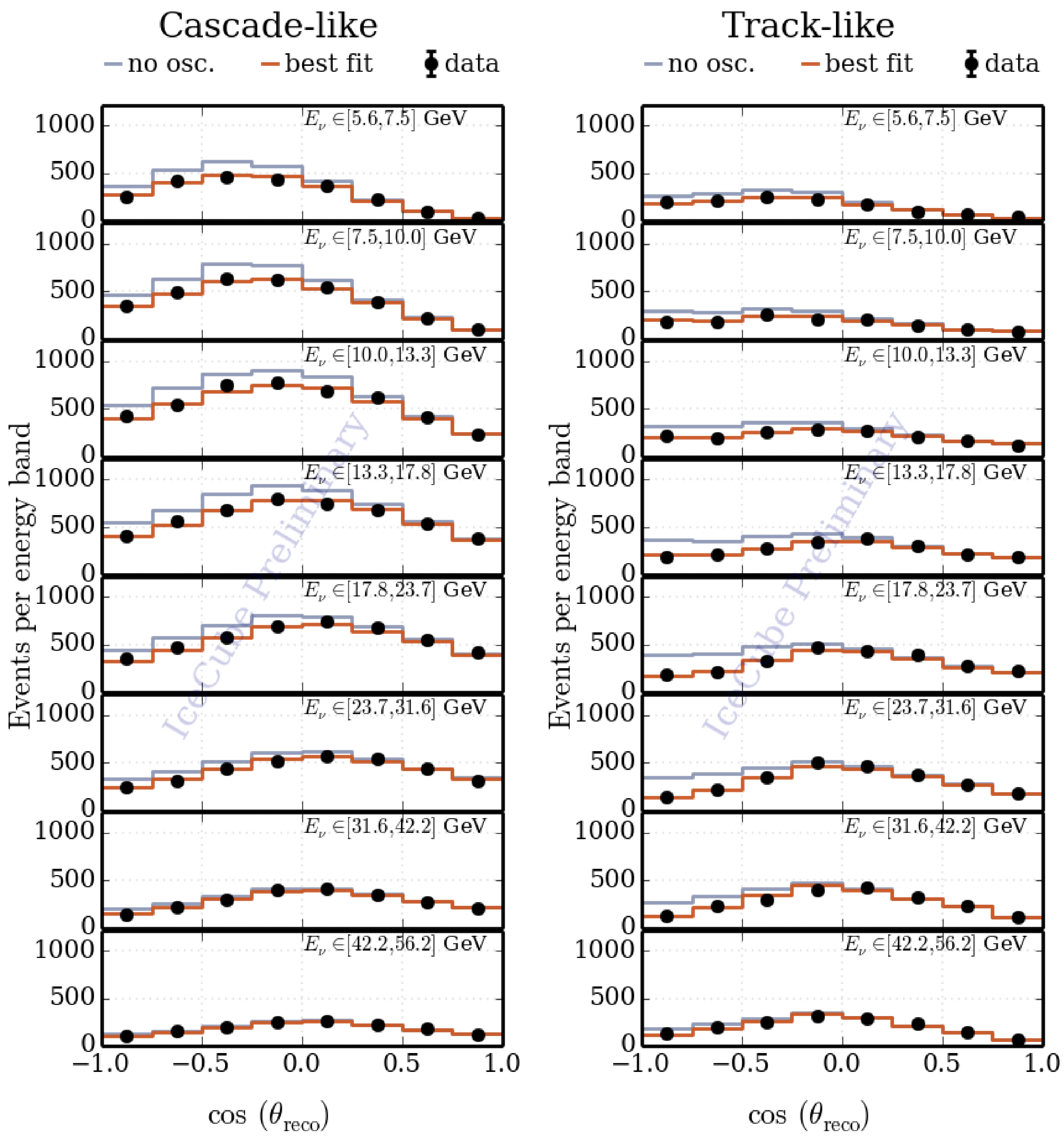
$$\nu_\mu N \to \mu^- X \qquad \overline{\nu}_\mu N \to \mu^+ X$$

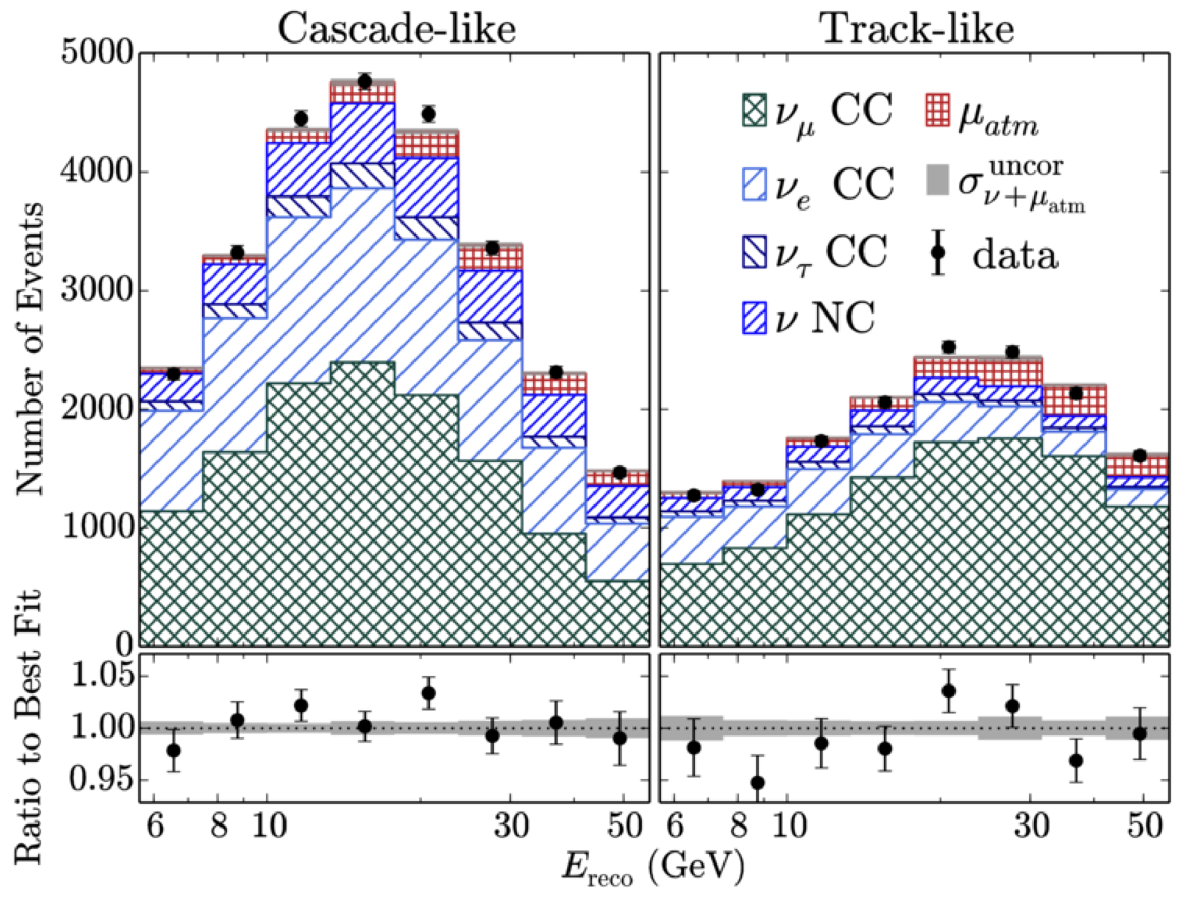
$$\nu_\mu N \to \nu_\mu X \qquad \overline{\nu}_\mu N \to \overline{\nu}_\mu X$$

neutrino interacts with ice nuclei via “deep inelastic scattering”

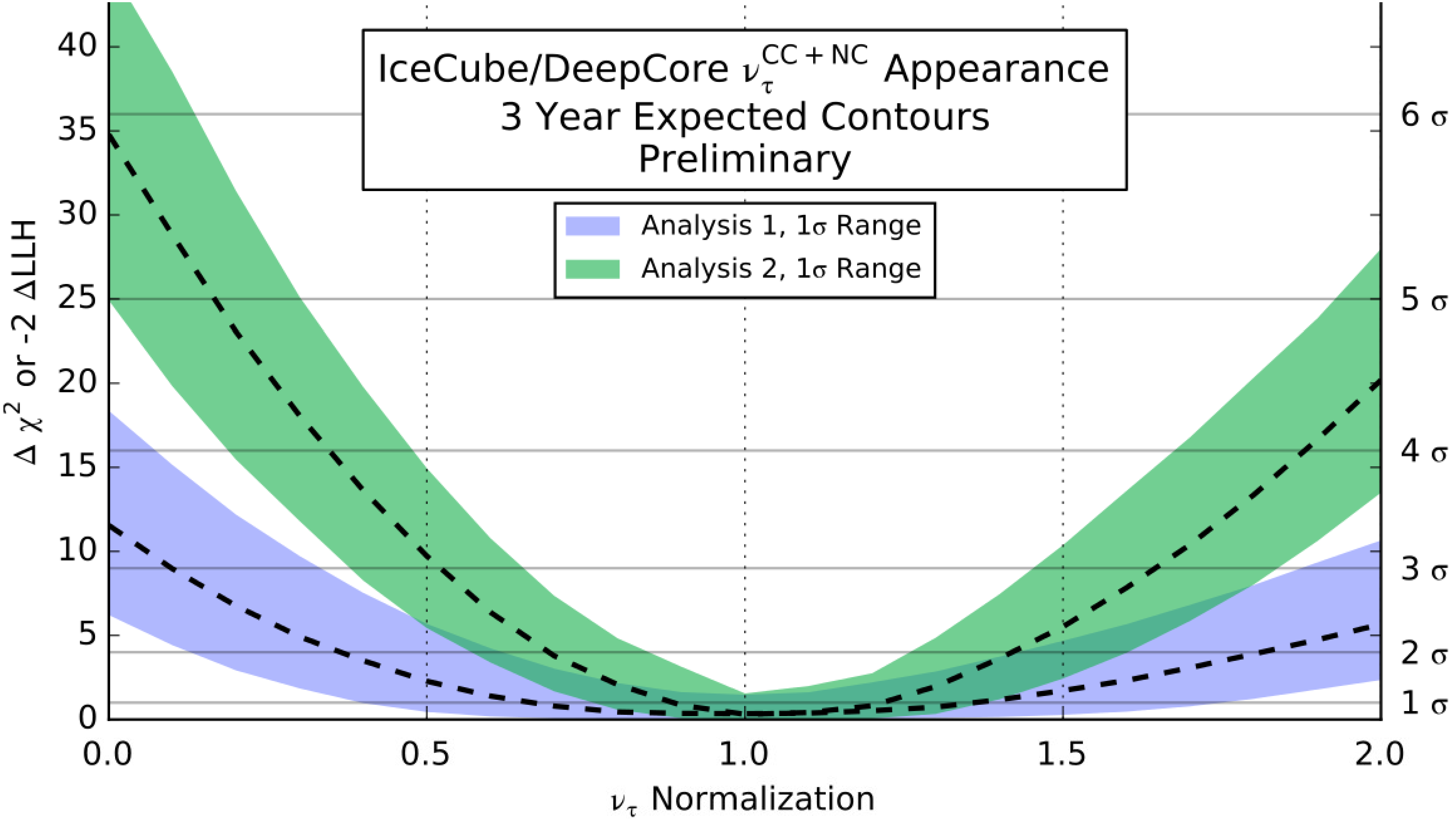
secondary charged particles produced as a result

IceCube DeepCore

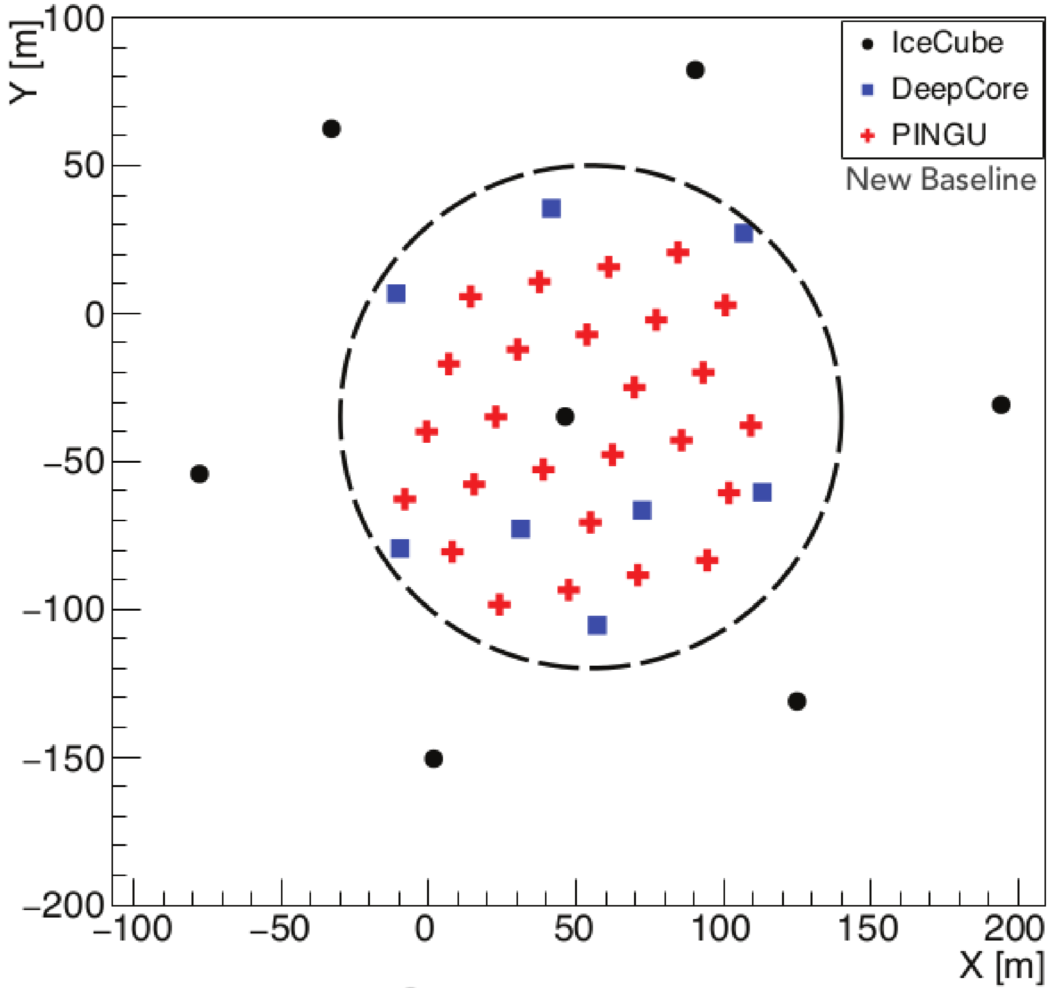




Tau apperance in IceCube



PINGU

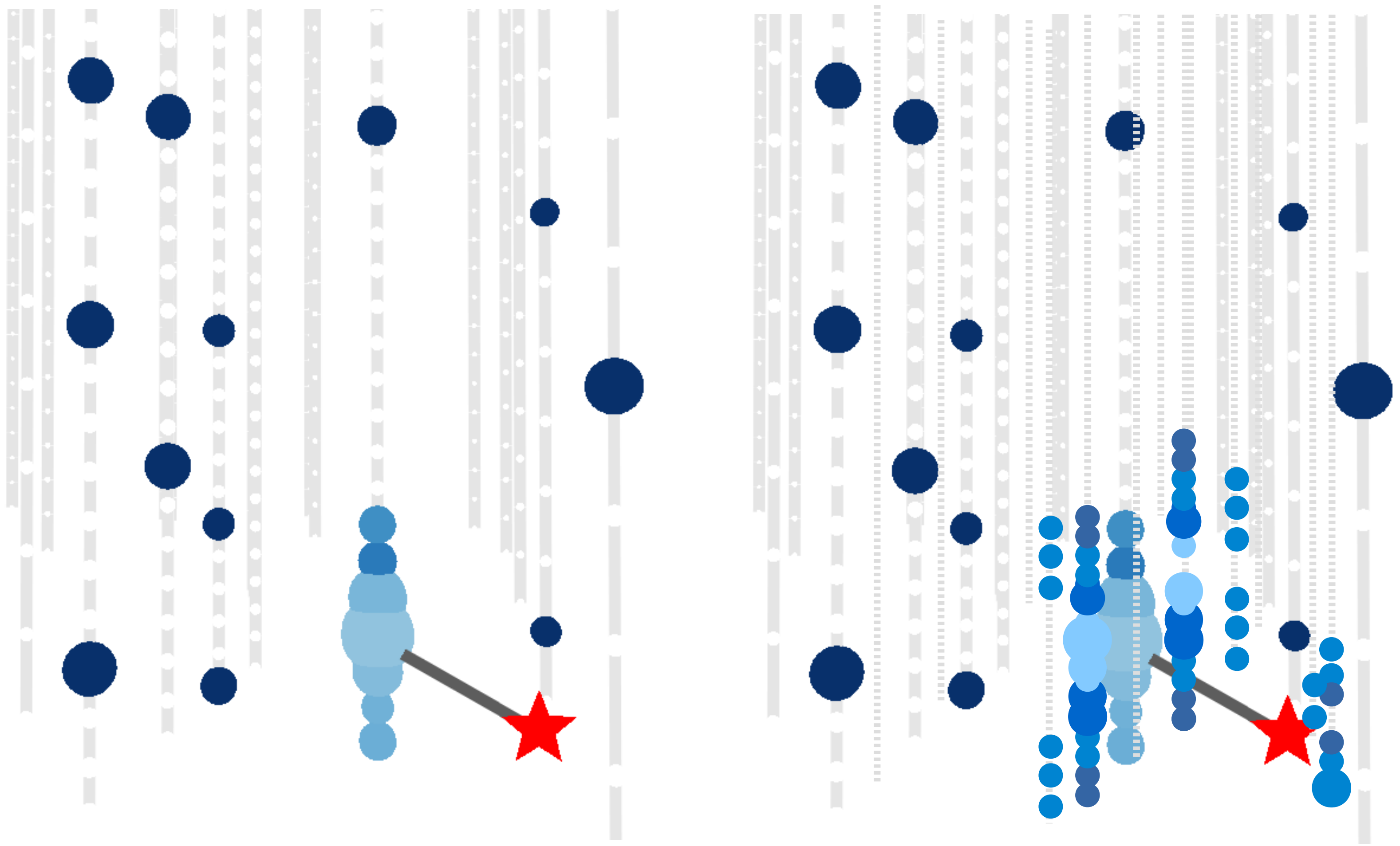


Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

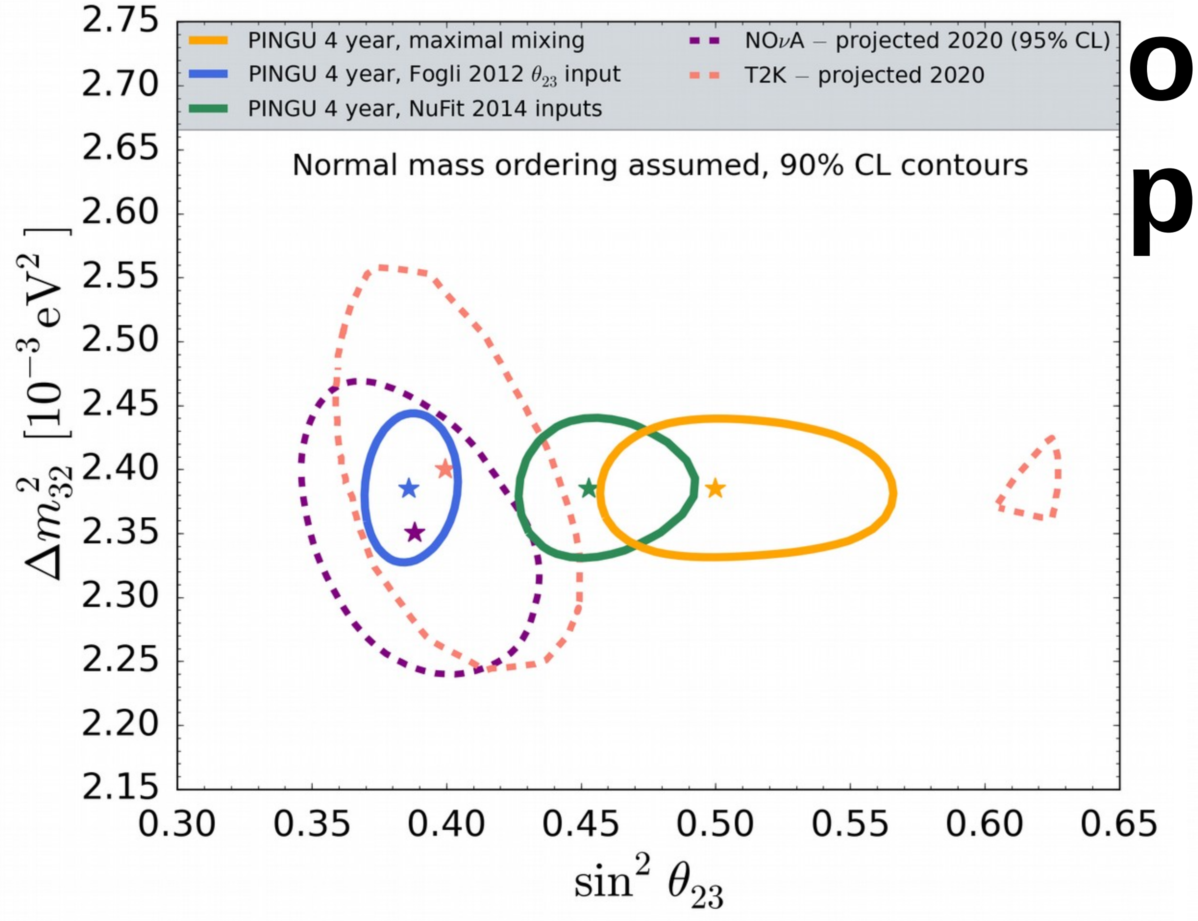
-DeepCore infill

-lower energy threshold

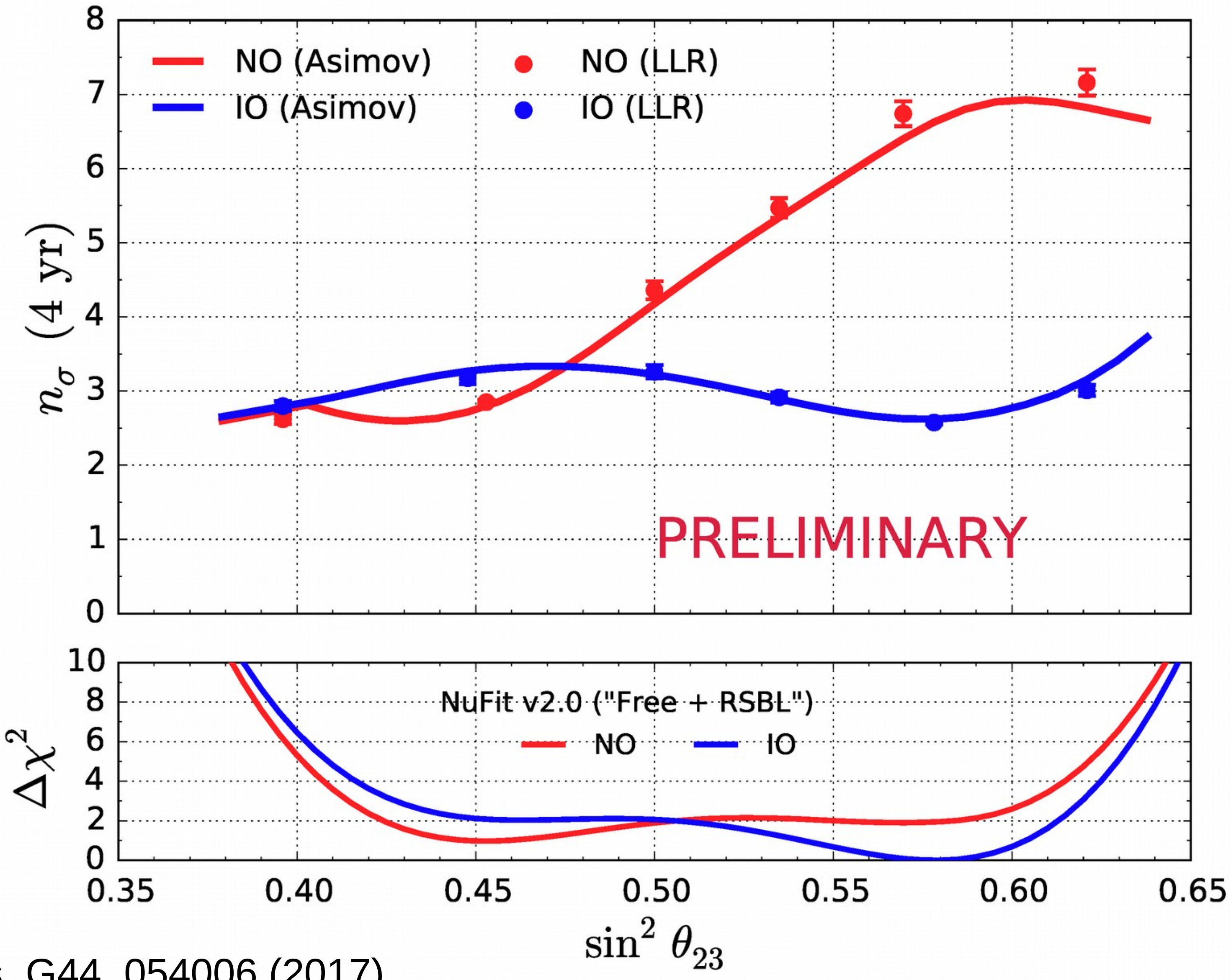


PINGU

oscillation parameters

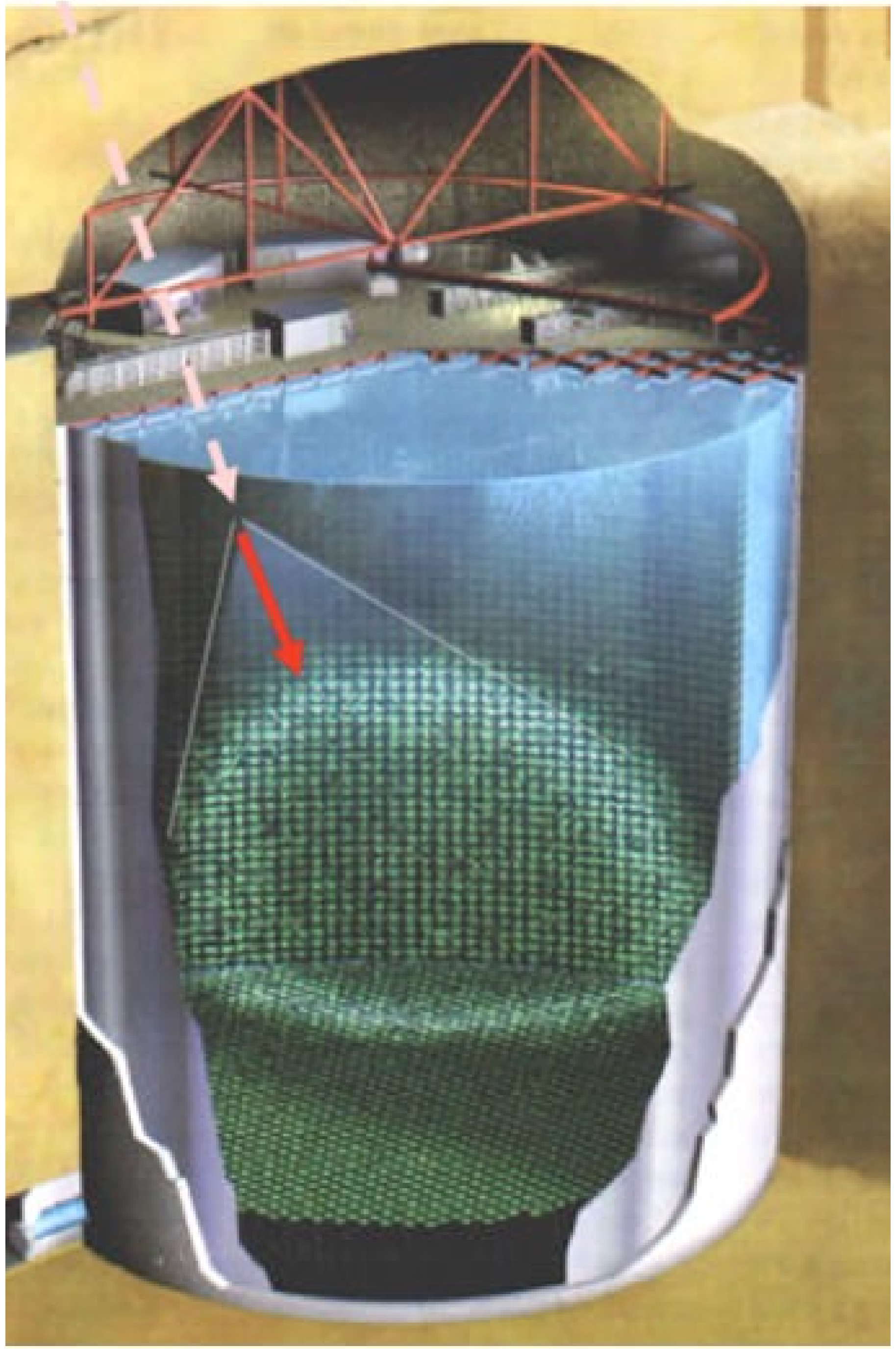


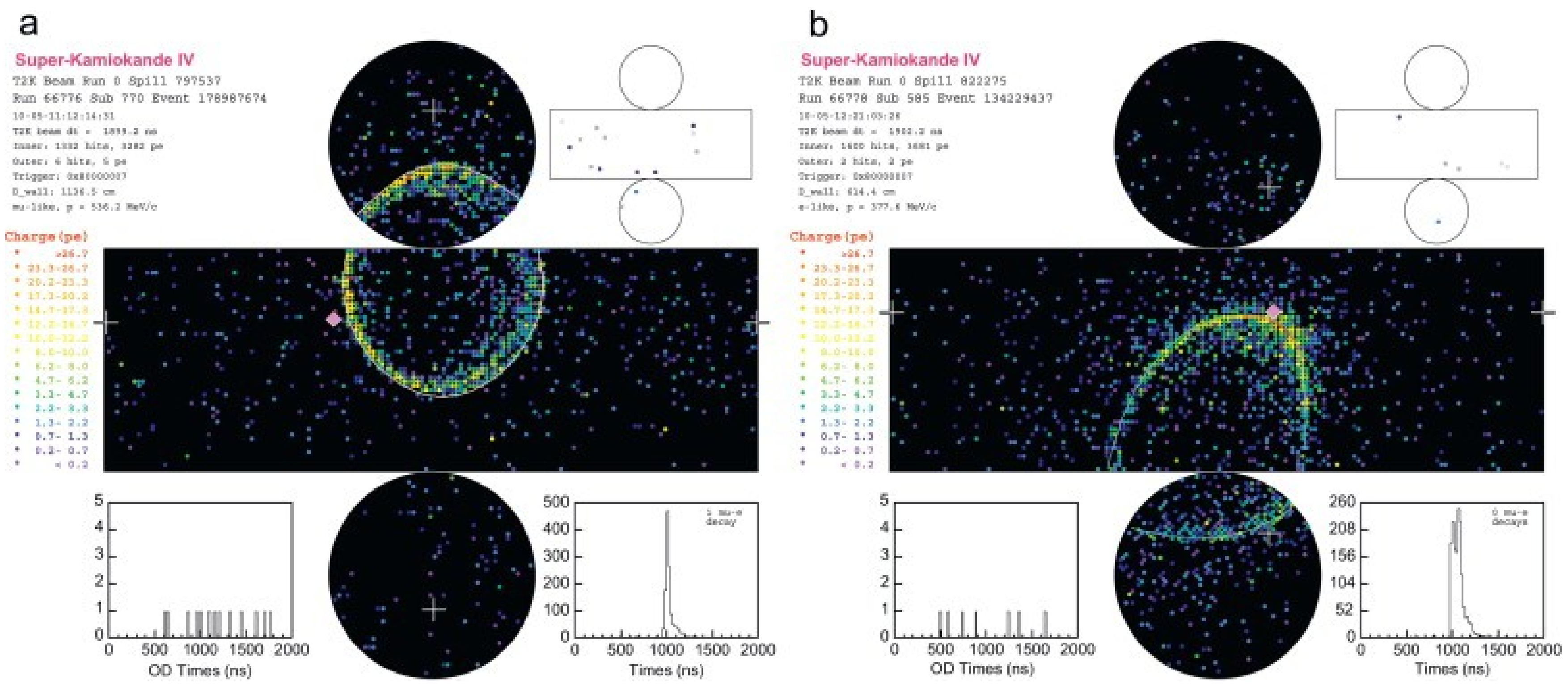
mass ordering



J. Phys. G44, 054006 (2017)

Super-Kamiokande





MINOS far detector

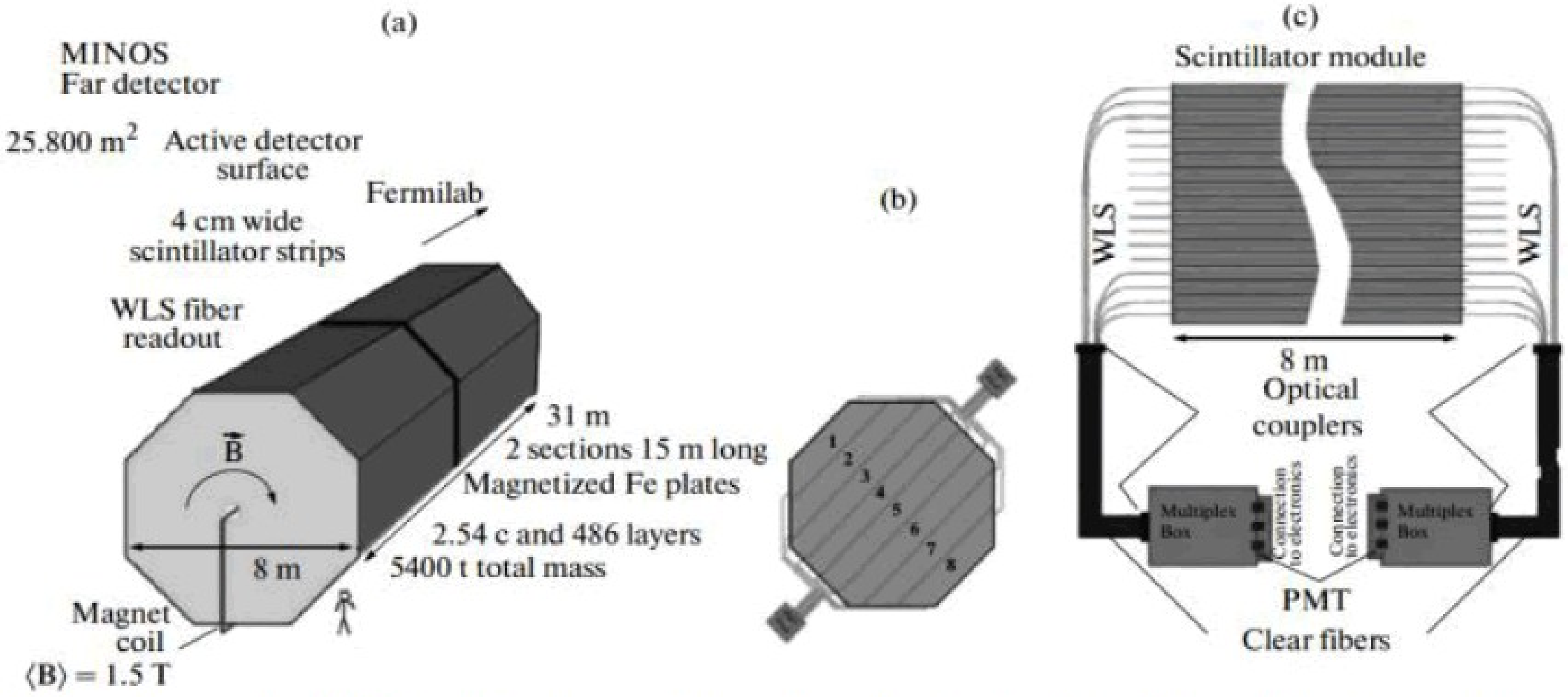
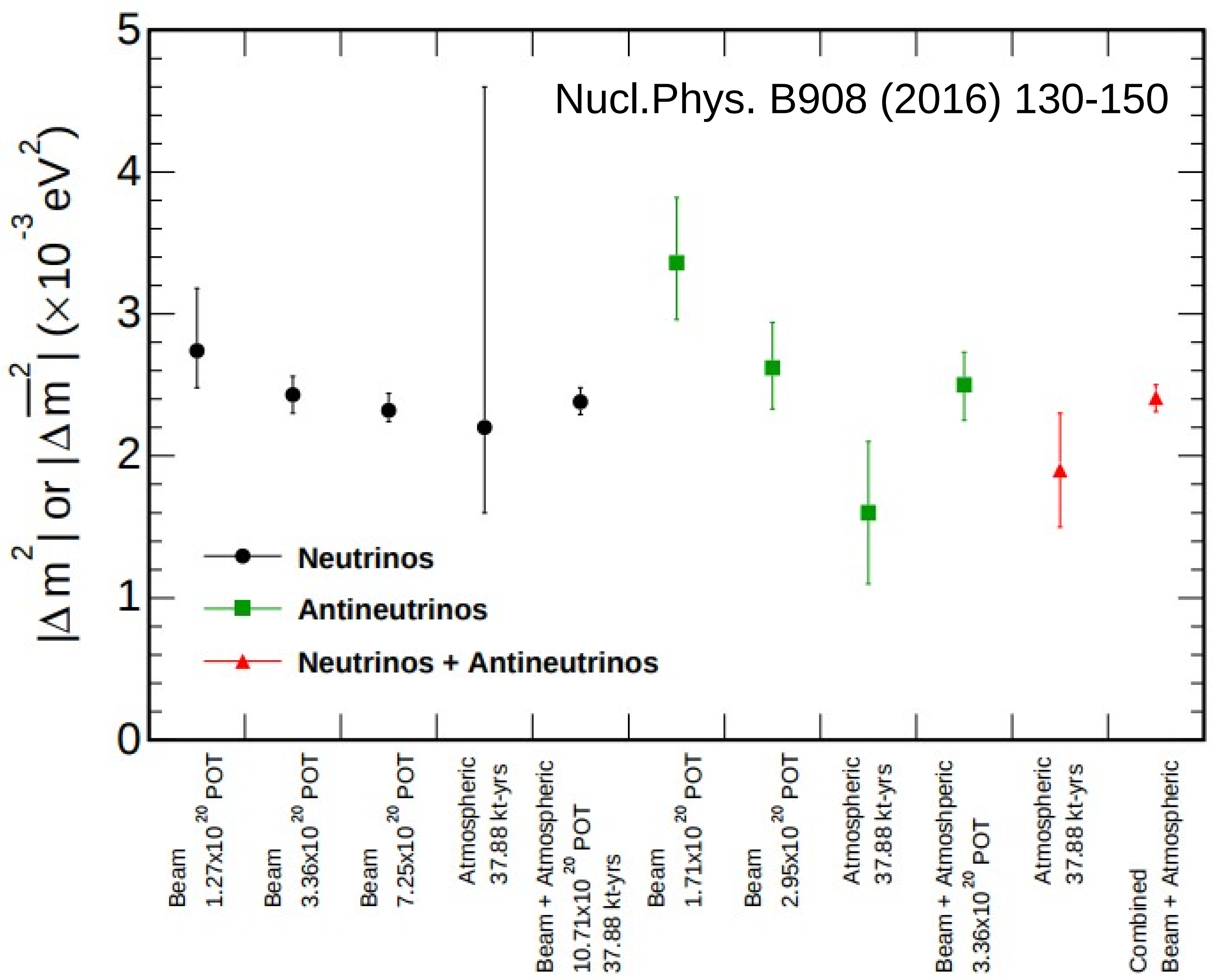


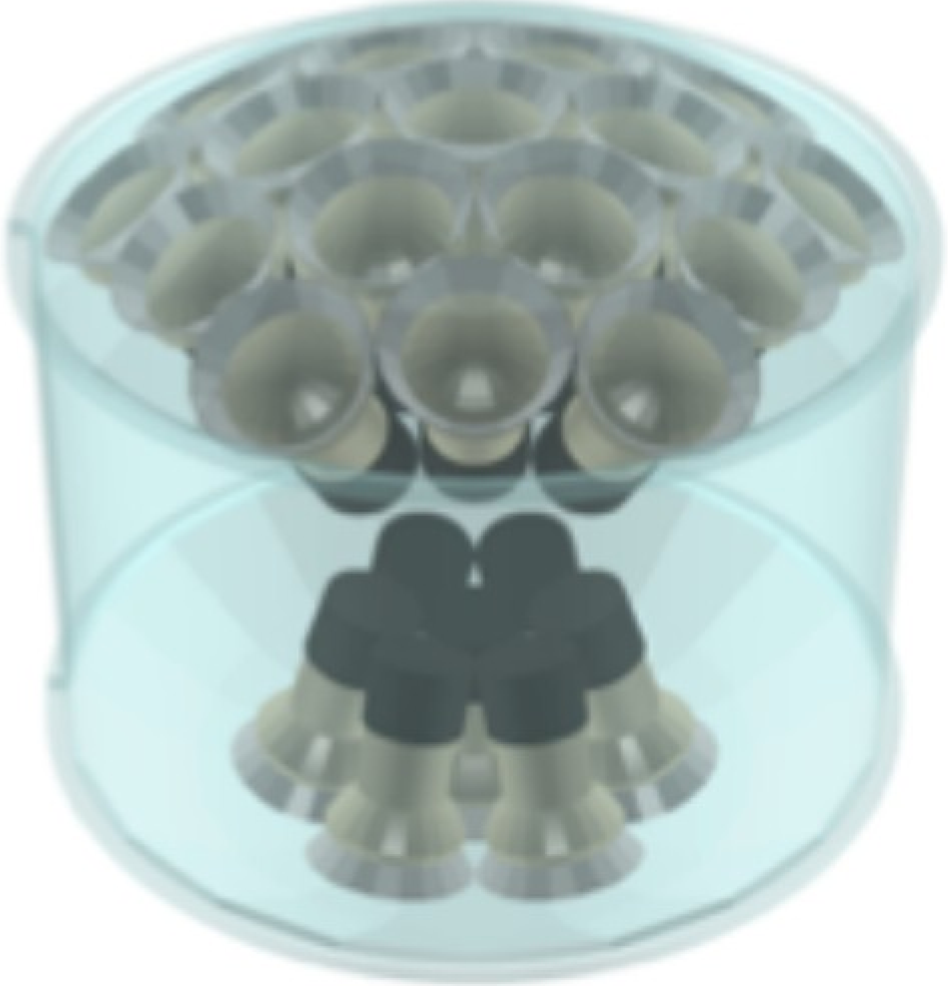
Figure 9: Schematic view of the MINOS far detector (a), a scintillation plane with 8 modules (b), and the scintillation strip readout scheme (c).

MINOS

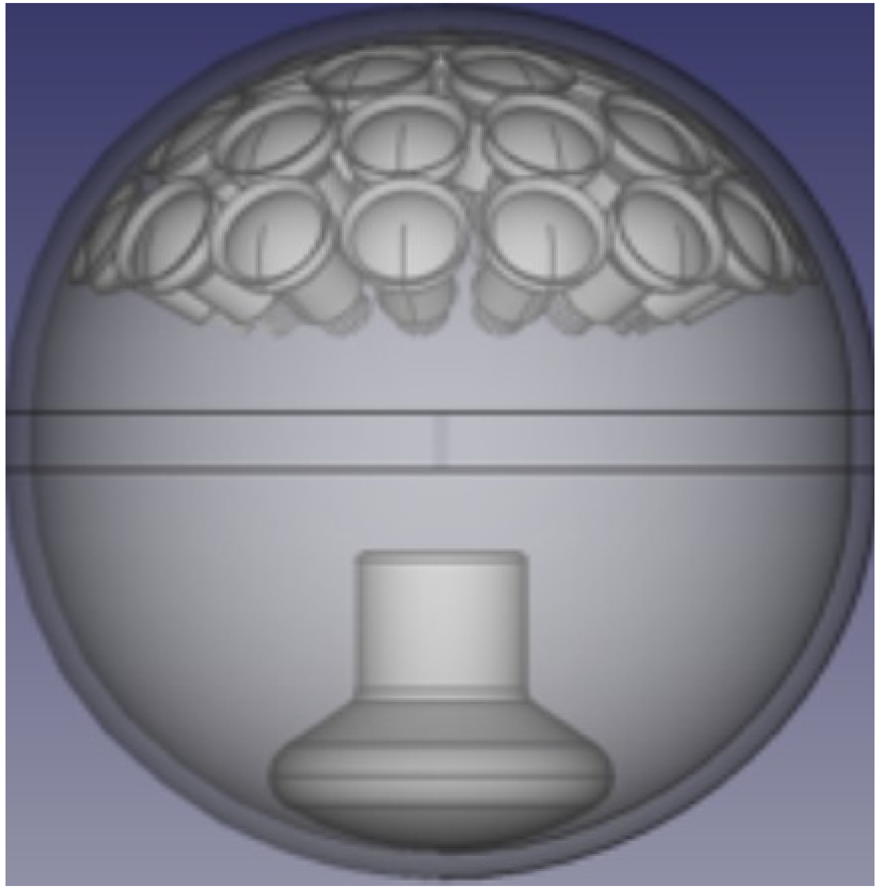

Nucl.Phys. B908 (2016) 130-150
$|\Delta m^2|$ or $|\Delta \overline{m}^2|$ ($\times 10^{-3}$ eV^2)
0
1
2
3
4
5
Neutrinos
Antineutrinos
Neutrinos + Antineutrinos
Beam 1.27x10^{20} POT
Beam 3.36x10^{20} POT
Beam 7.25x10^{20} POT
Atmospheric 37.88 kt-yrs
Beam + Atmospheric 10.71x10^{20} POT 37.88 kt-yrs
Beam 1.71x10^{20} POT
Beam 2.95x10^{20} POT
Atmospheric 37.88 kt-yrs
Beam + Atmoshperic 3.36x10^{20} POT
Atmospheric 37.88 kt-yrs
Combined Beam + Atmospheric

segmented modules proposed

NuPRISM



HyperKamiokande



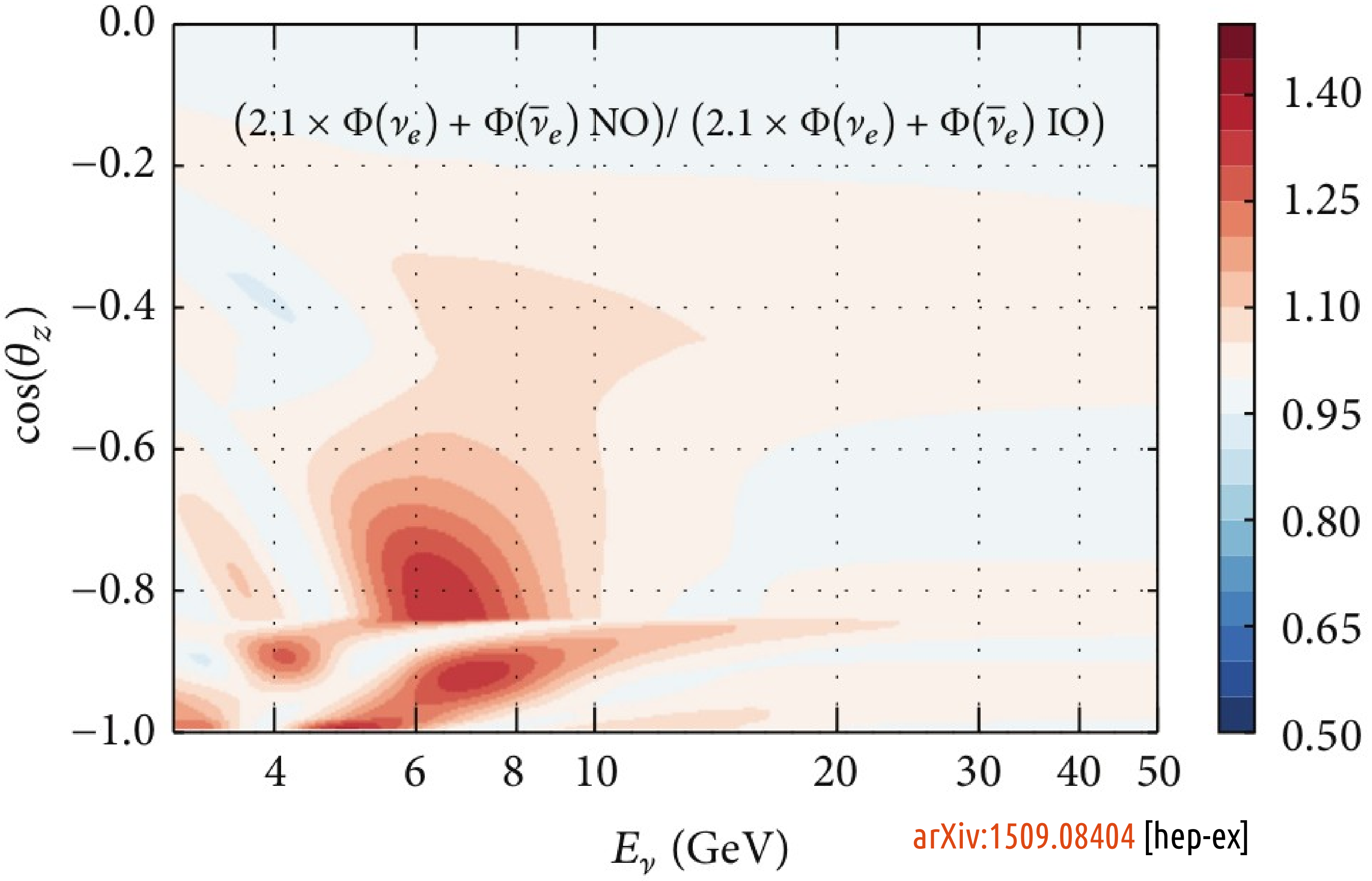
VLVNTs vs beam experiments

Table 1: Qualitative comparison of experiments measuring the atmospheric neutrino oscillation parameters. The table is divided into detector and flux characteristics. Note that the far detector of T2K is Super-Kamiokande but uses accelerator neutrinos. Detector performances taken from [4, 9, 38, 43, 49, 83, 95]. Expected neutrino events quoted from published results of ν_μ disappearance at analysis level (note that for VLVNTs this number can vary significantly depending on the studied range in energy, zenith angle, and topology). COH refers to coherent pion production. For details on the other interaction channels and energy ranges see Figure 8.

	Parameter	VLVNT		SK	MINOS, T2K, and NOvA
		ANTARES	DeepCore		
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% ± 22%	25% at 20 GeV	3% at 1 GeV	10–15% at 10 GeV
	θ_ν resolution	3° at 20 GeV	8° at 20 GeV	2-3°	—
	Particle ID capabilities	Muon/no muon in interaction		e, μ, π (rings)	Individual particles, charge
Neutrino flux	Source of neutrinos	Atmosphere: mix of $\nu_e, \bar{\nu}_e, \nu_\mu$, and $\bar{\nu}_\mu$			Accelerator: $\nu_\mu/\bar{\nu}_\mu$ modes
	Baseline	10–12700 km			300–800 km
	Flux determination	Atm. ν models, self-fit		+top/down ratios	Near/far detector
	Energy range	10–100 GeV		Few MeV–few GeV	Few GeV
	Main interaction channel	DIS		QE	QE, RES, COH, and DIS
	ν events expected with osc.	530	1800	2000	30 (T2K), 900 (MINOS)
	and without osc. (per year)	660	2300	2300	120 (T2K), 1050 (MINOS)

arXiv:1509.08404 [hep-ex]

NMO



arXiv:1509.08404 [hep-ex]

FIGURE 5: Expected interaction rate of electron neutrinos and antineutrinos predicted by a NO over the rate predicted assuming an IO. Using the oscillation parameters in [3]. Because of the flux ratio $\nu_\mu/\bar{\nu}_\mu$ and the cross section difference, estimated to be 2.1 times larger for neutrinos than antineutrinos, more electron neutrino interactions are expected for a NO.