Systematic uncertainties for atmospheric neutrino measurements

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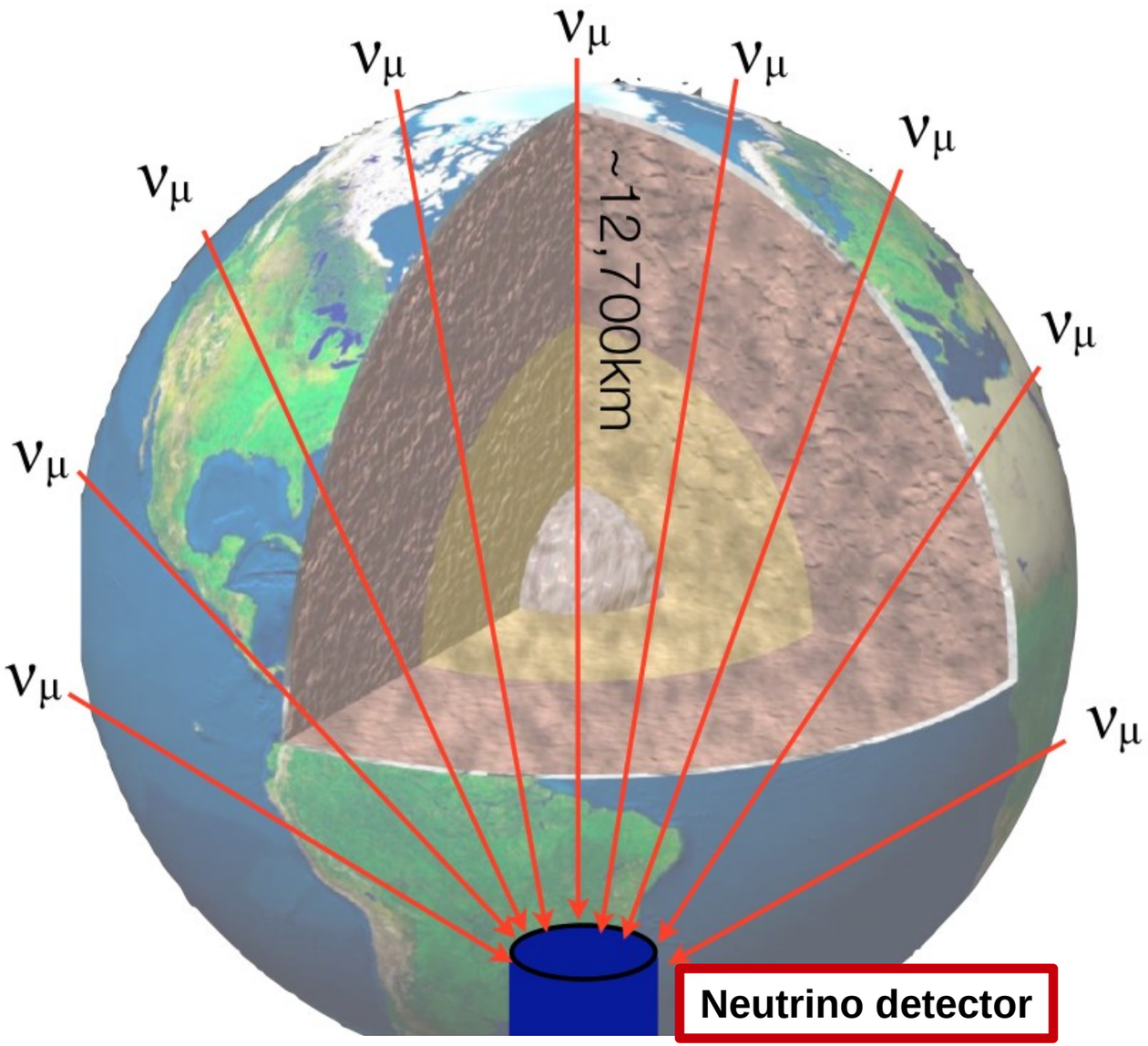
some motivation

why atmospherics?



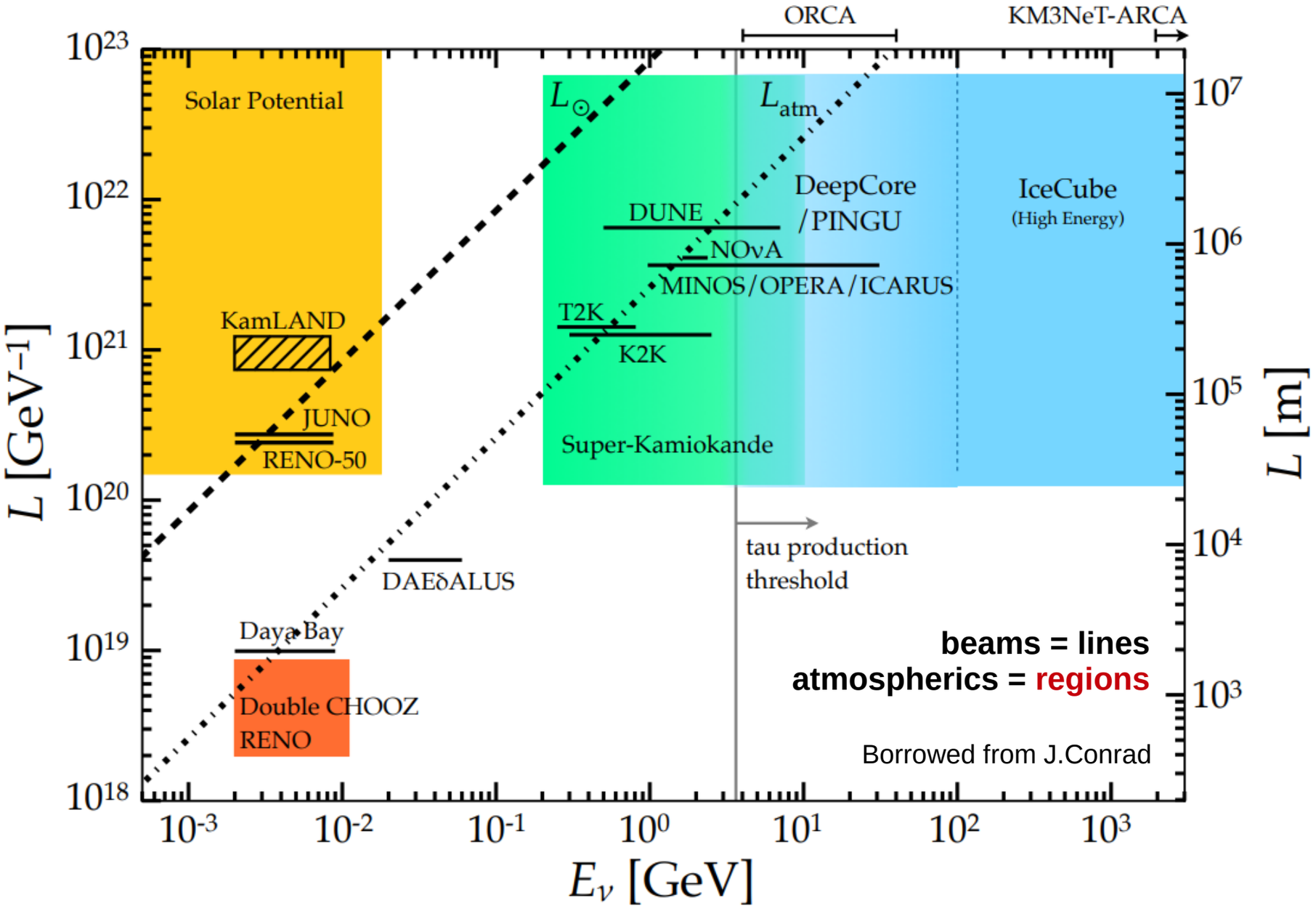
Borrowed from T. DeYoung

direction → baseline

~10km - ~12,700km

different e^- density along paths

wide baseline, energy range



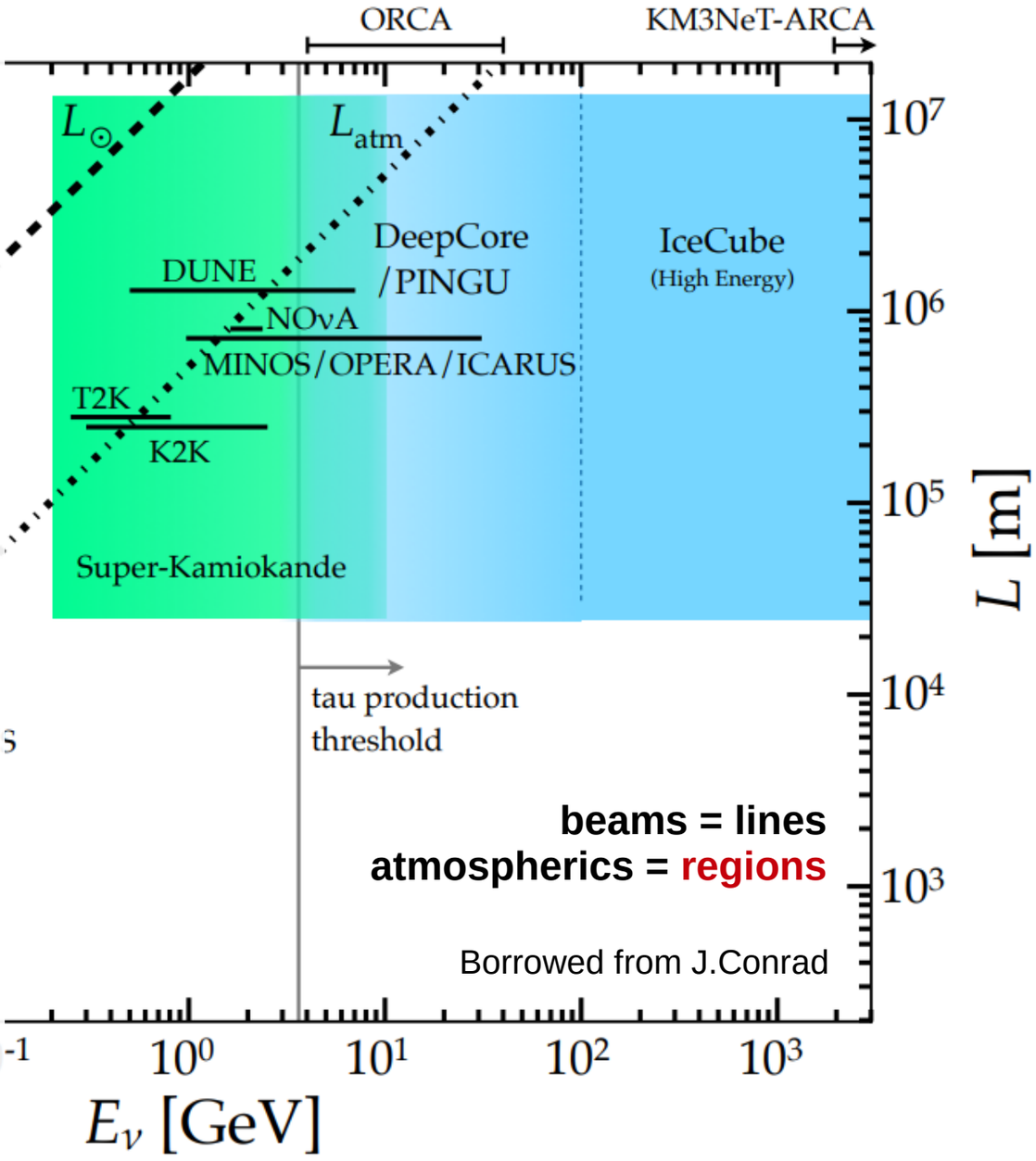
wide baseline, energy range

-large L&E regions of phase space

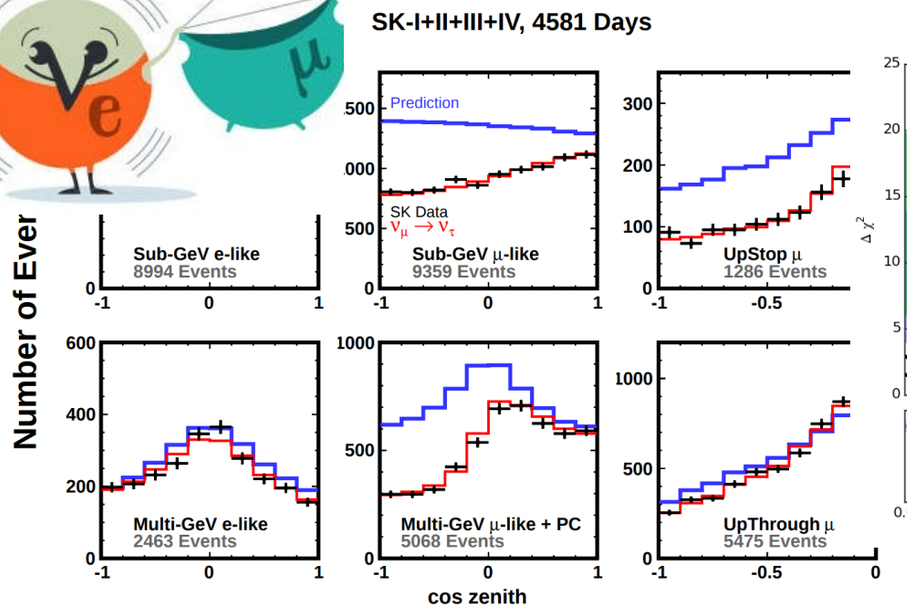
-2 ν, anti-ν flavors in "beam"

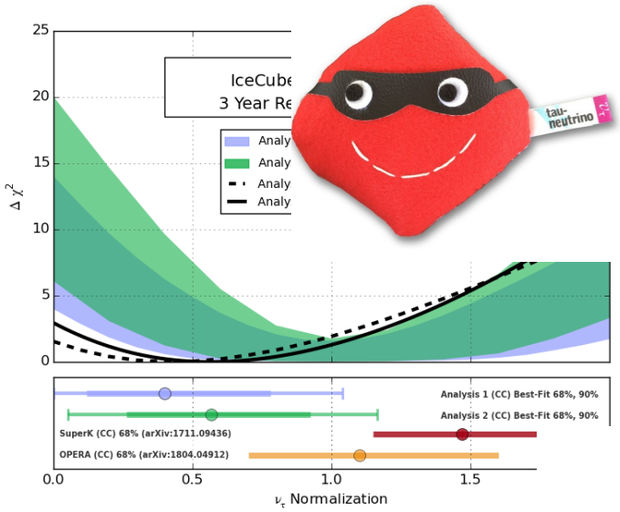
-on/off signal regions

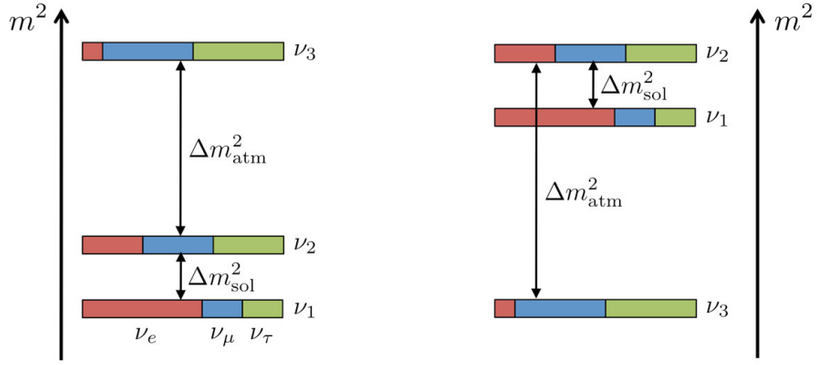
-E > τ threshold

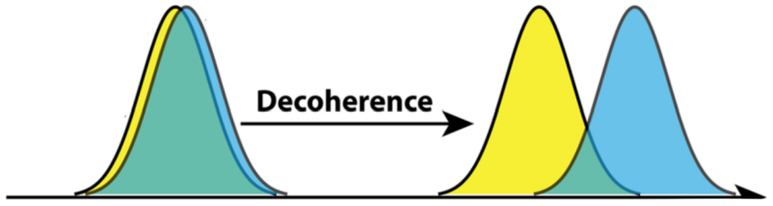


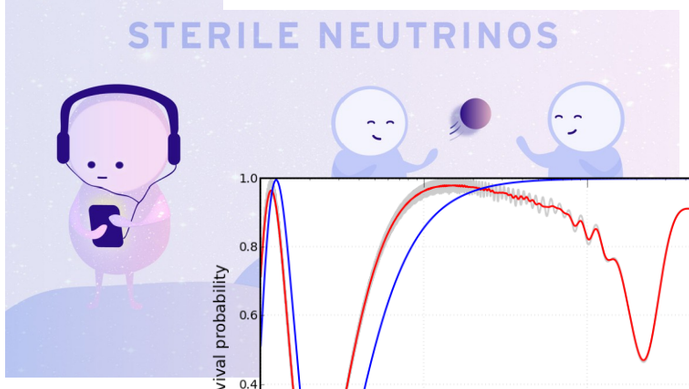
multiple physics topics to study

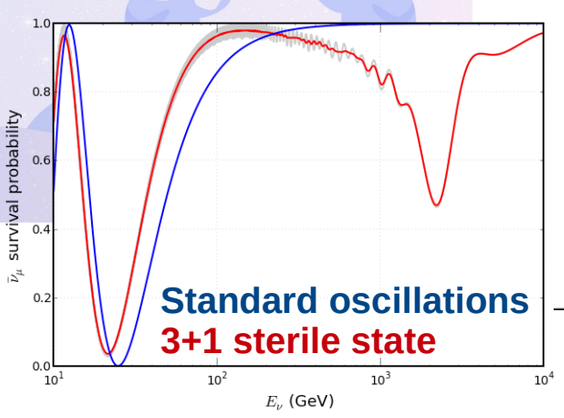


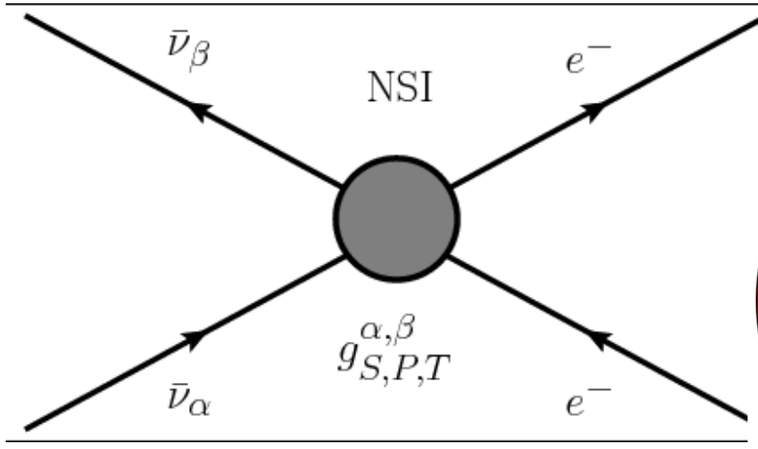


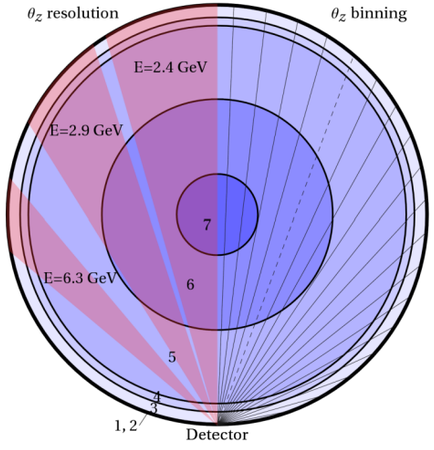


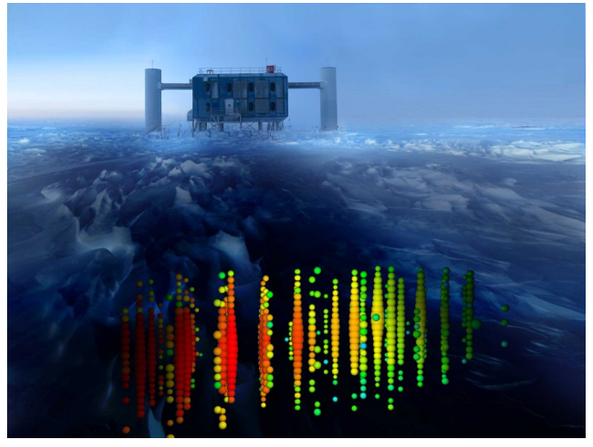




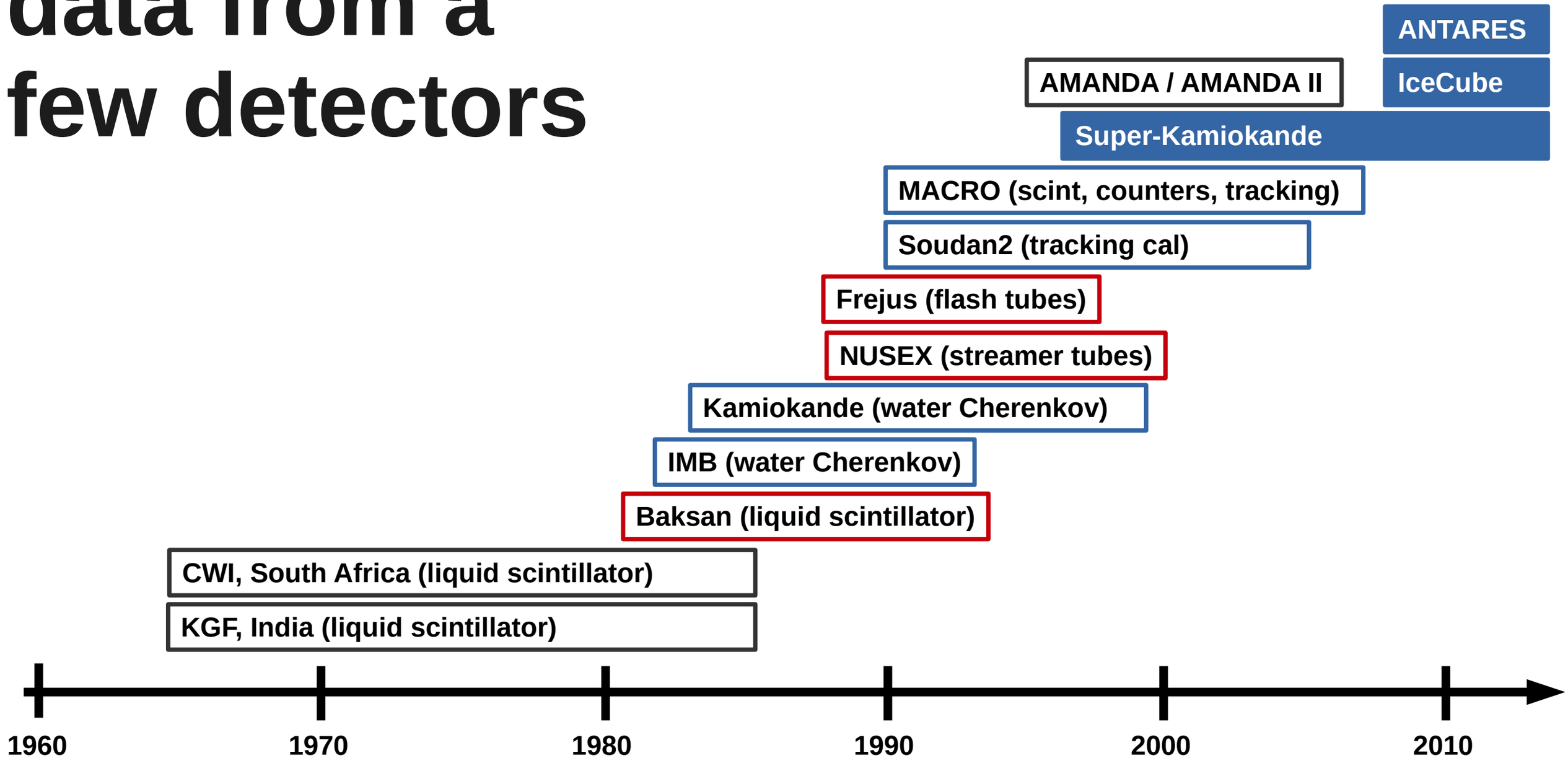








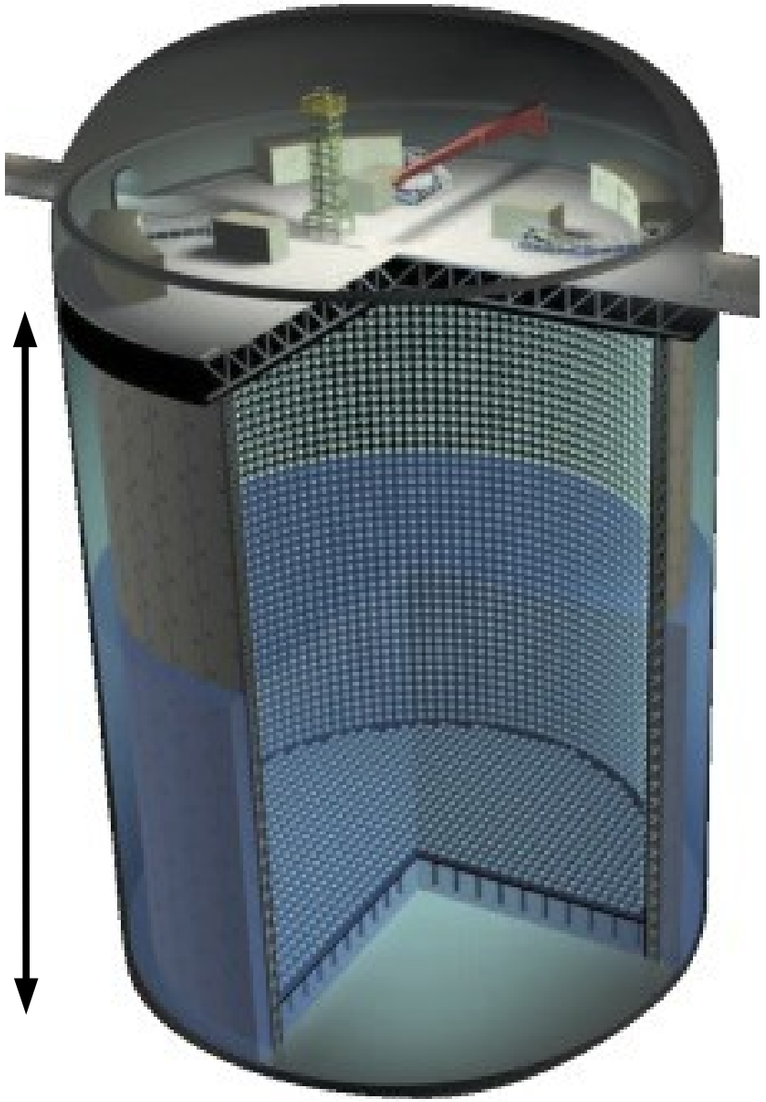
data from a few detectors

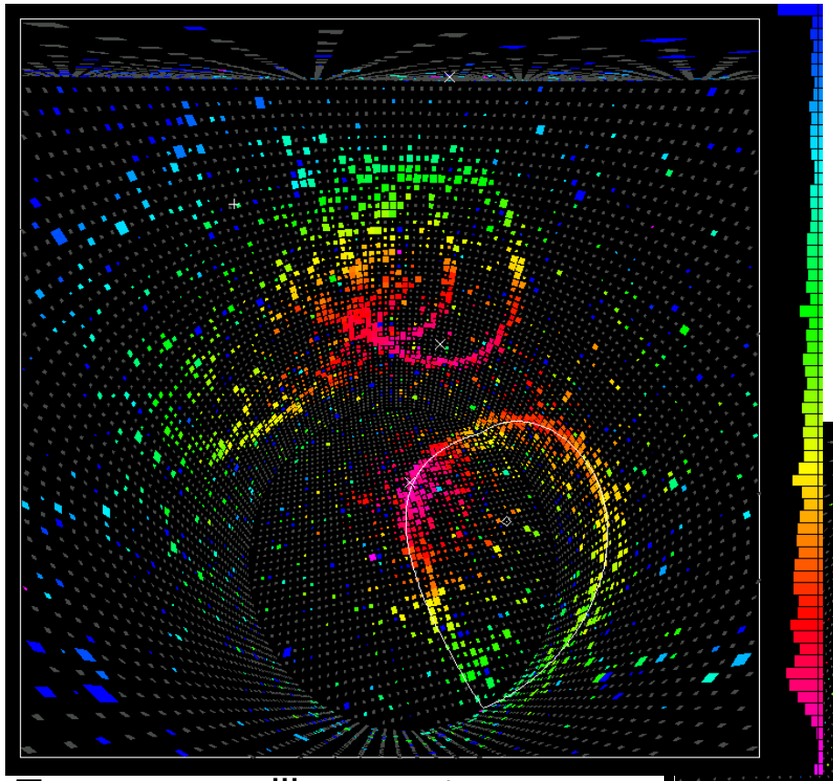


*take dates with caution – list is incomplete

recent atmospheric neutrino measurements

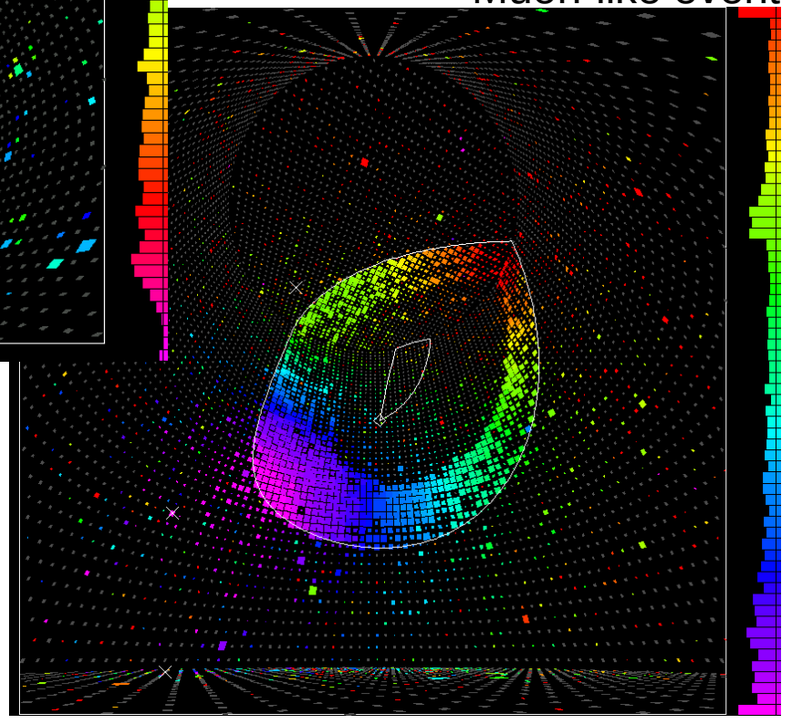
Super-Kamiokande





Two-gamma-like event

Muon-like event

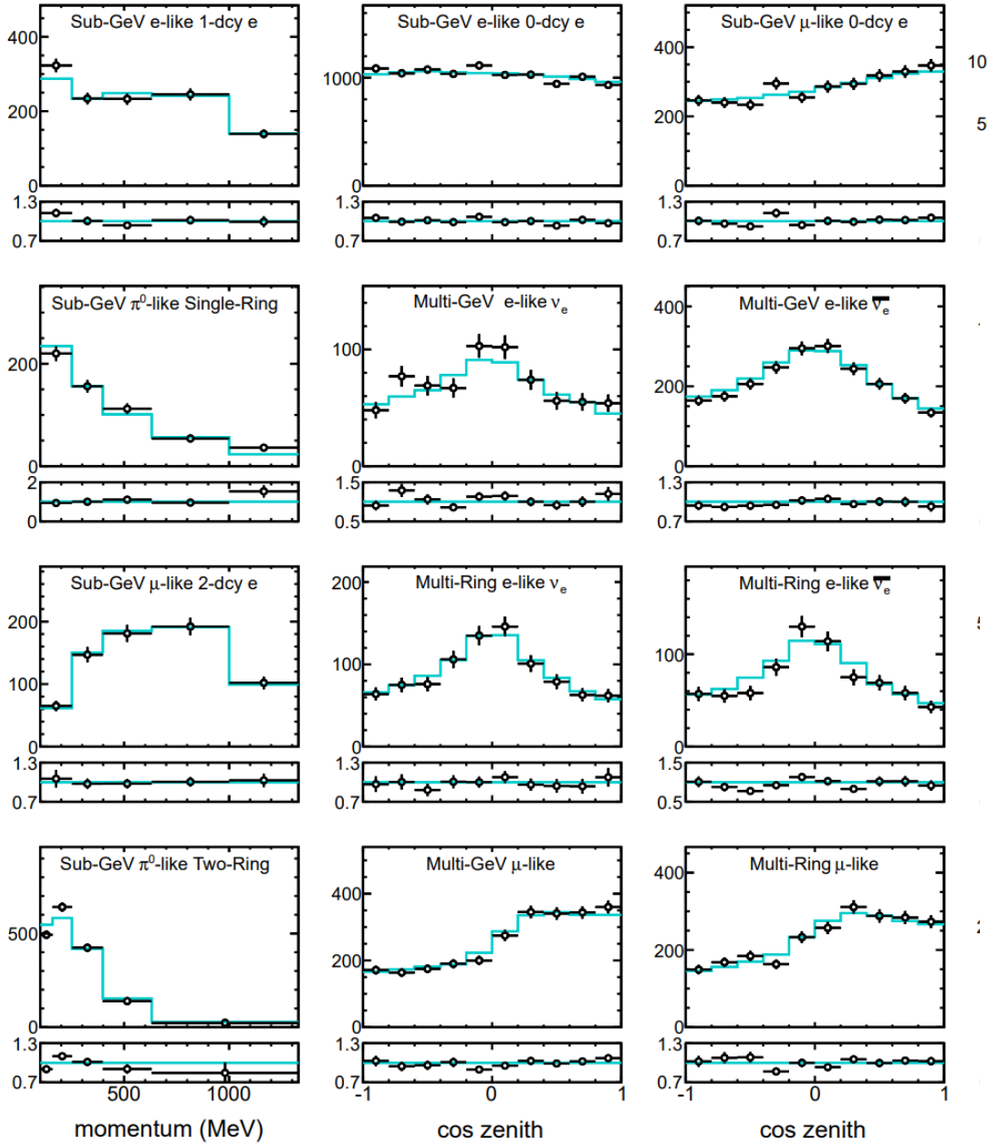


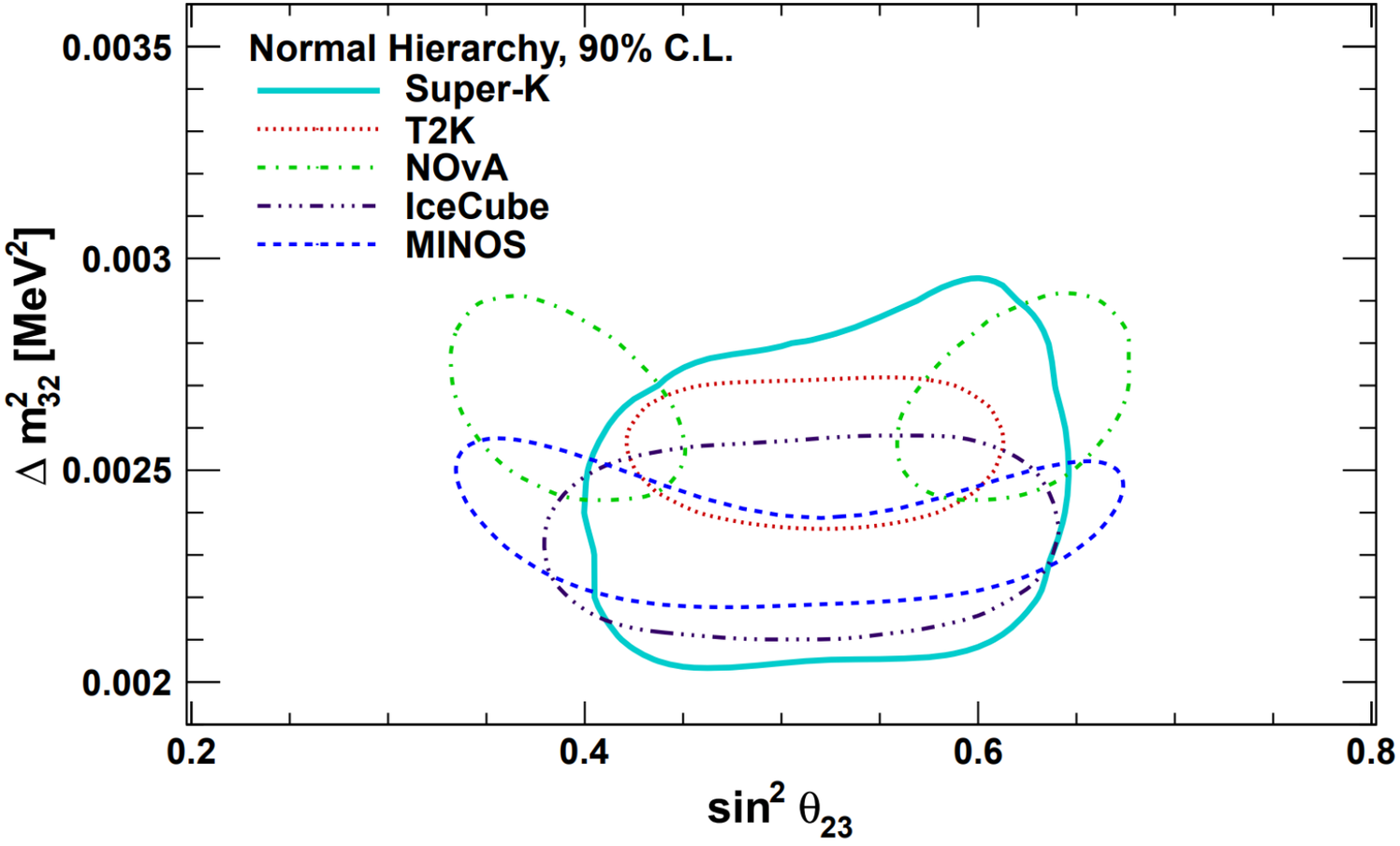
http://www.ps.uci.edu/~tomba/sk/tscan/pictures.html

Super-Kamiokande

Standard oscillations

Phys. Rev. D 97, 072001 (2018)





Systematic Error			Fit Value (%)	σ (%)
Flux normalization	$E_\nu < 1$ GeV[a]		14.3	25
	$E_\nu > 1$ GeV[b]		7.8	15
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$	$E_\nu < 1$ GeV		0.08	2
	$1 < E_\nu < 10$ GeV		−1.1	3
	$E_\nu > 10$ GeV[c]		1.6	5
$\bar{\nu}_e/\nu_e$	$E_\nu < 1$ GeV		1.6	5
	$1 < E_\nu < 10$ GeV		3.3	5
	$E_\nu > 10$ GeV[d]		−1.6	8
$\bar{\nu}_\mu/\nu_\mu$	$E_\nu < 1$ GeV		0.24	2
	$1 < E_\nu < 10$ GeV		2.9	6
	$E_\nu > 10$ GeV[e]		−2.9	15
Up/down ratio	< 400 MeV	e-like	−0.026	0.1
		μ-like	−0.078	0.3
		0-decay μ-like	−0.286	1.1
	> 400 MeV	e-like	−0.208	0.8
		μ-like	−0.130	0.5
		0-decay μ-like	−0.442	1.7
	Multi-GeV	e-like	−0.182	0.7
		μ-like	−0.052	0.2
	Multi-ring Sub-GeV	e-like	−0.104	0.4
		μ-like	−0.052	0.2
	Multi-ring Multi-GeV	e-like	−0.078	0.3
		μ-like	−0.052	0.2
	PC		−0.052	0.2
Horizontal/vertical ratio	< 400 MeV	e-like	0.018	0.1
		μ-like	0.018	0.1
		0-decay μ-like	0.054	0.3
	> 400 MeV	e-like	0.252	1.4
		μ-like	0.341	1.9
		0-decay μ-like	0.252	1.4
	Multi-GeV	e-like	0.576	3.2
		μ-like	0.414	2.3
	Multi-ring Sub-GeV	e-like	0.252	1.4
		μ-like	0.234	1.3
	Multi-ring Multi-GeV	e-like	0.504	2.8
		μ-like	0.270	1.5
	PC		0.306	1.7
K/π ratio in flux calculation[f]			−9.3	10
Neutrino path length			−2.13	10
Sample-by-sample	FC Multi-GeV		−6.6	5
	PC + Stopping UP-μ		0.22	5
Matter effects			0.52	6.8

Super-Kamiokande

Standard oscillations

Phys. Rev. D 97, 072001 (2018)

- relevance of uncertainties not given

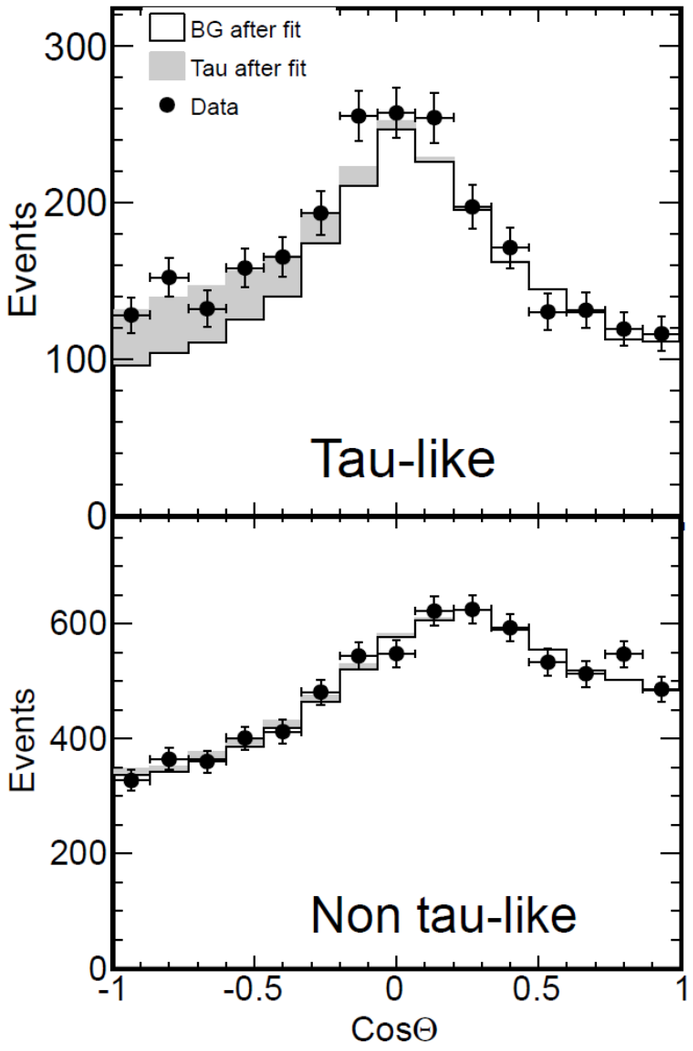
- atmospheric parameters fit in study

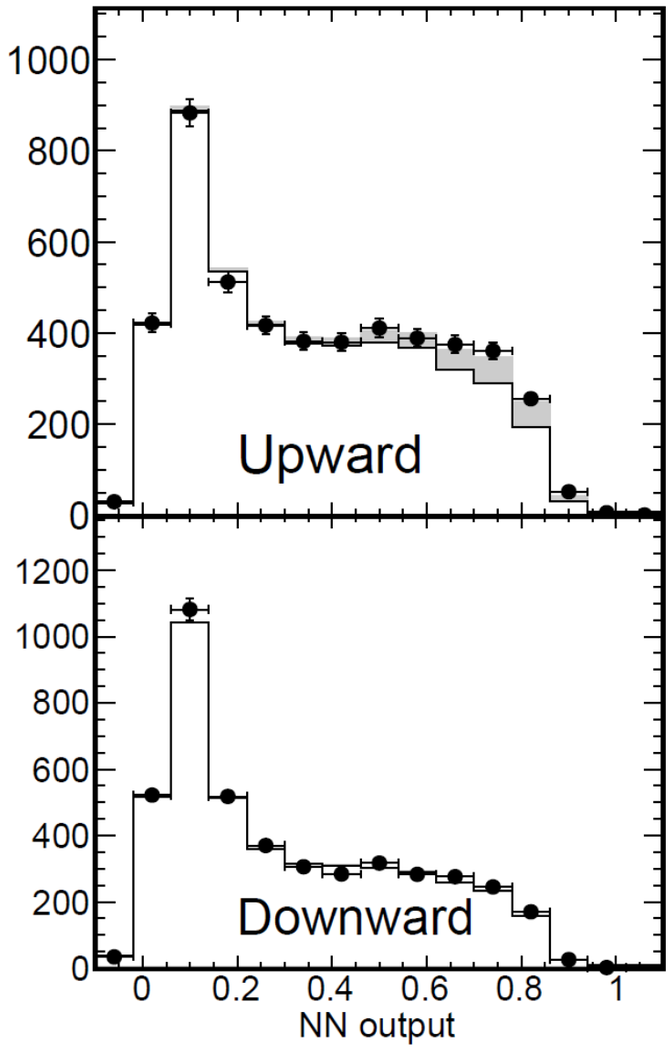
- some values found in 0.5-1σ uncertainty range

Super-Kamiokande

NuTau appearance

Phys. Rev. D 98, 052006 (2018)





4.6σ evidence for NuTau appearance

Super-Kamiokande

NuTau appearance

Phys. Rev. D 98, 052006 (2018)

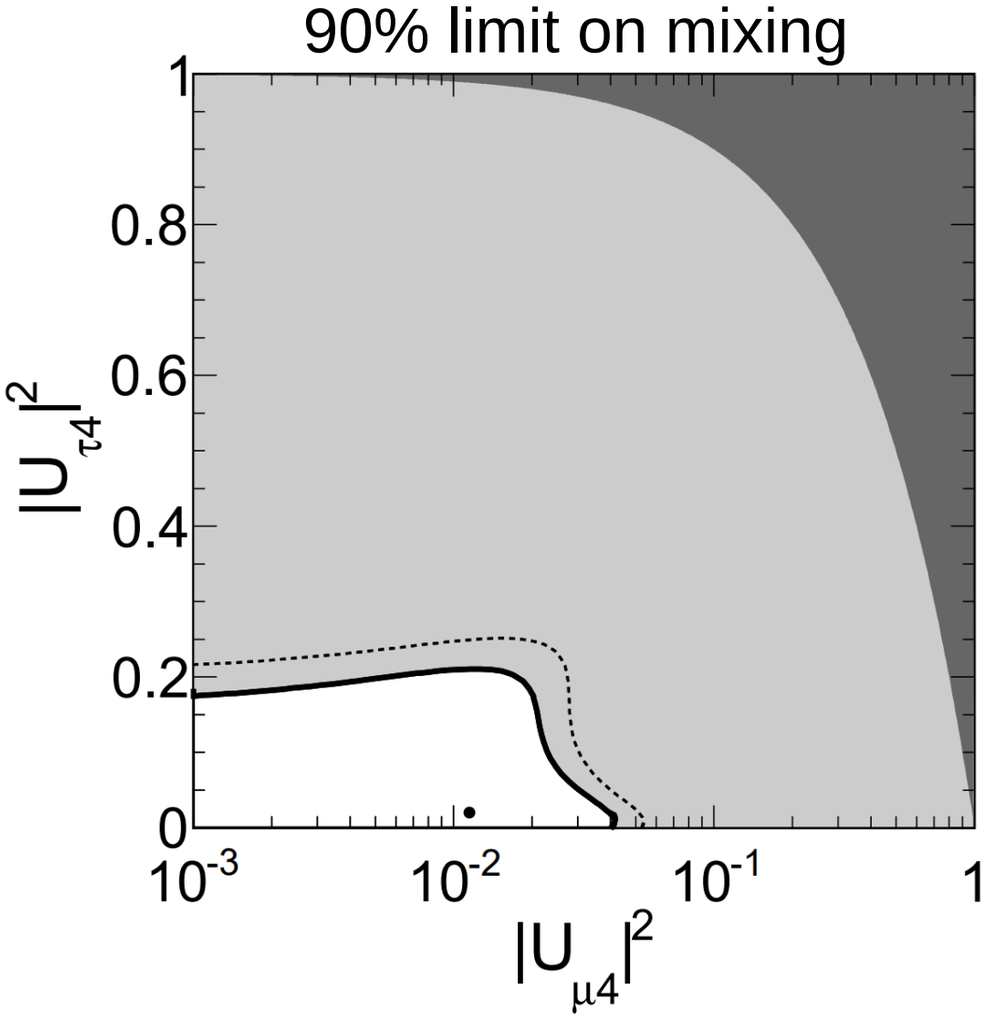
Systematic error	σ (%)
NC/CC ratio	20
DIS q^2 dependence for low W	10
Meson exchange current	10
1π axial coupling	10
DIS q^2 dependence for high W	10
Coherent π cross section	100
Flux normalization ($E_\nu > 1$GeV)	15
1π background scale factor	10
1π axial form factor	10
CCQE cross section	10
Single pion $\pi^0/\pi^\pm$ ratio	40
$\bar{\nu}_\mu/\nu_\mu$ ratio ($E_\nu > 10$ GeV)	15
$\nu/\bar{\nu}$ ratio ($E_\nu > 10$ GeV)	5
DIS cross section ($E_\nu < 10$ GeV)	10
FC multi-GeV normalization	5
$\bar{\nu}_e/\nu_e$ ratio ($E_\nu > 10$GeV)	8
K/π ratio	10
Single meson cross section	20
Single-pion $\bar{\nu}/\nu$ ratio	10
Horizontal/vertical ratio	1
CCQE $\nu/\bar{\nu}$ ratio	10
DIS cross section	5
Matter effect	6.8
Neutrino path length	10

- sources of uncertainty ranked by impact
- only relevant ones here
- flux uncertainties right behind cross sections

Super-Kamiokande

Sterile neutrinos

Phys. Rev. D 91, 052019 (2015)



- search for spectral distortions due to steriles

- sensitive to mu-tau mix

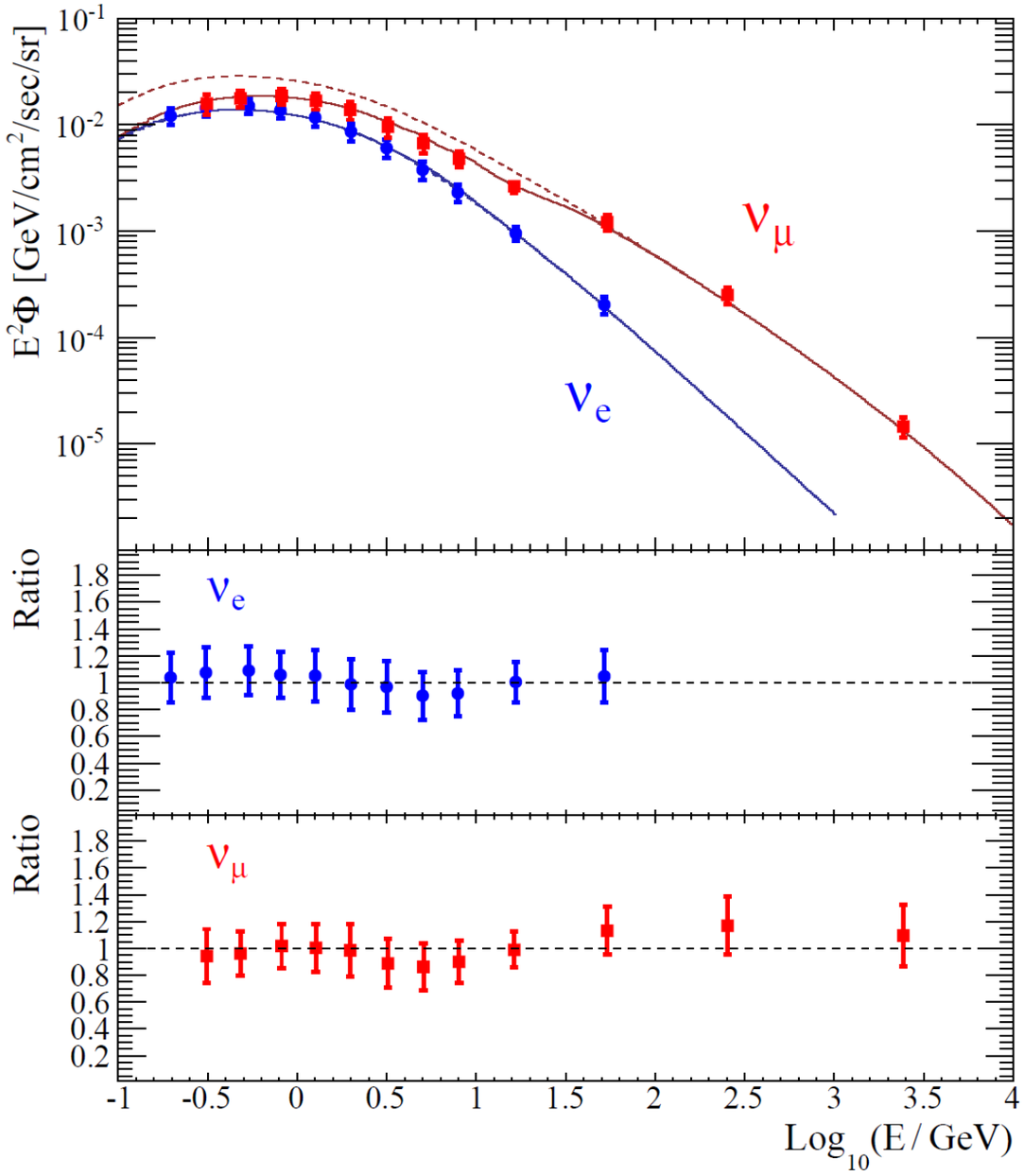
- flux uncertainties show largest pulls in fit

Systematic Uncertainty	No steriles (σ)	Best fit (σ)
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e), < 1$ GeV	-0.49	-0.13
$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e), 1 - 10$ GeV	-0.50	-0.09
CCQE ν_μ/ ν_e	0.36	0.01

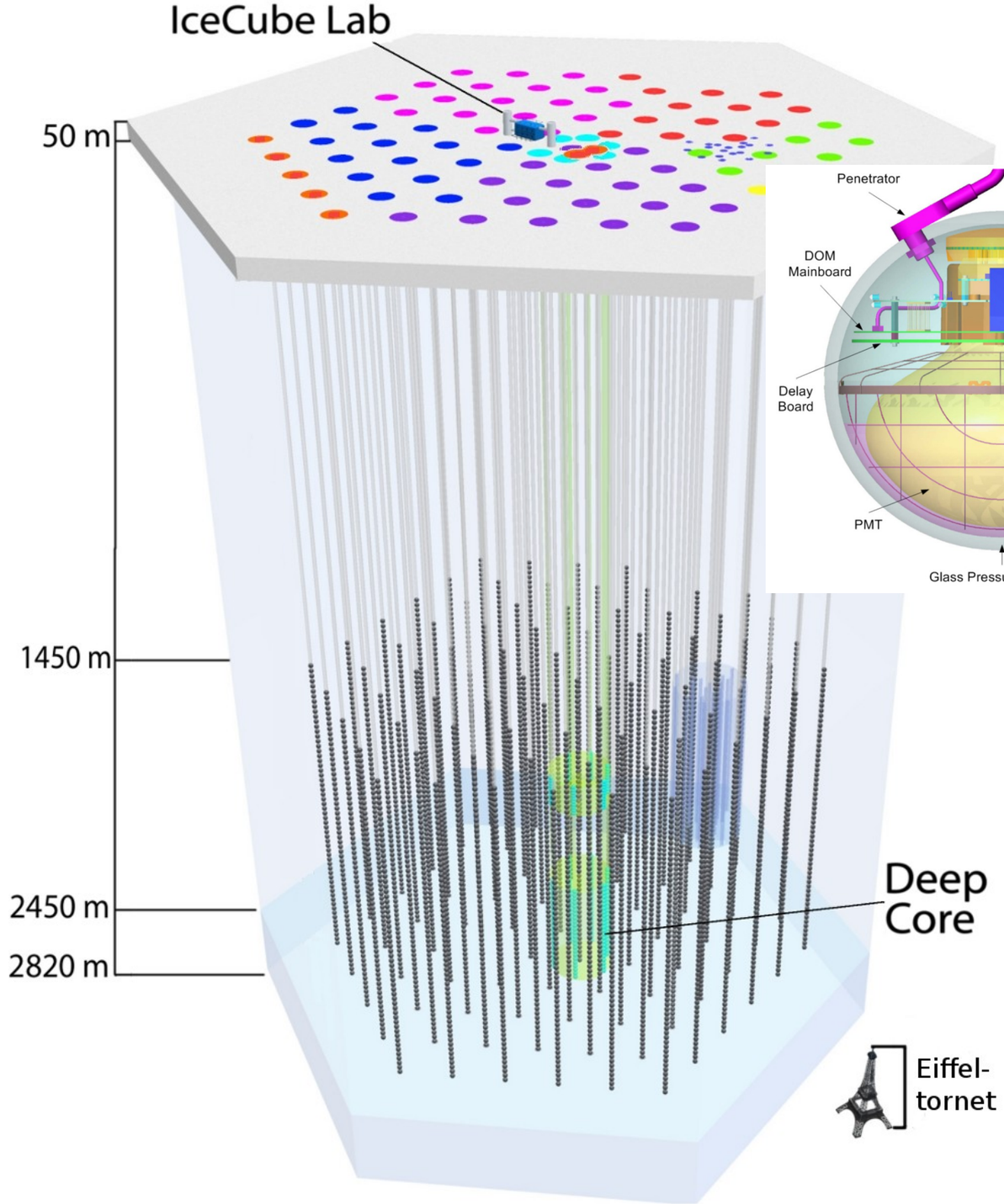
Super-Kamiokande

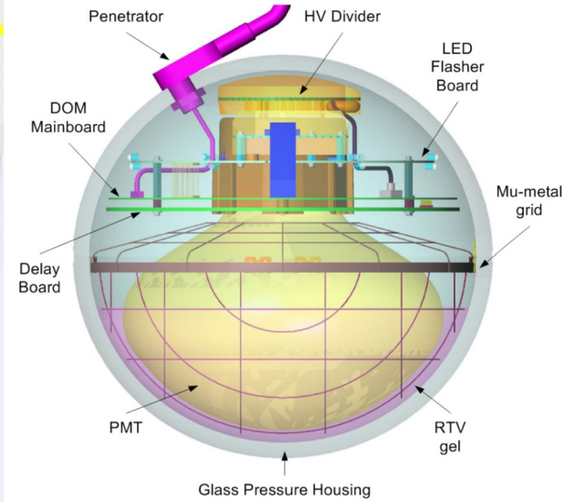
Flux unfolding
Phys. Rev. D 94, 052001 (2016)

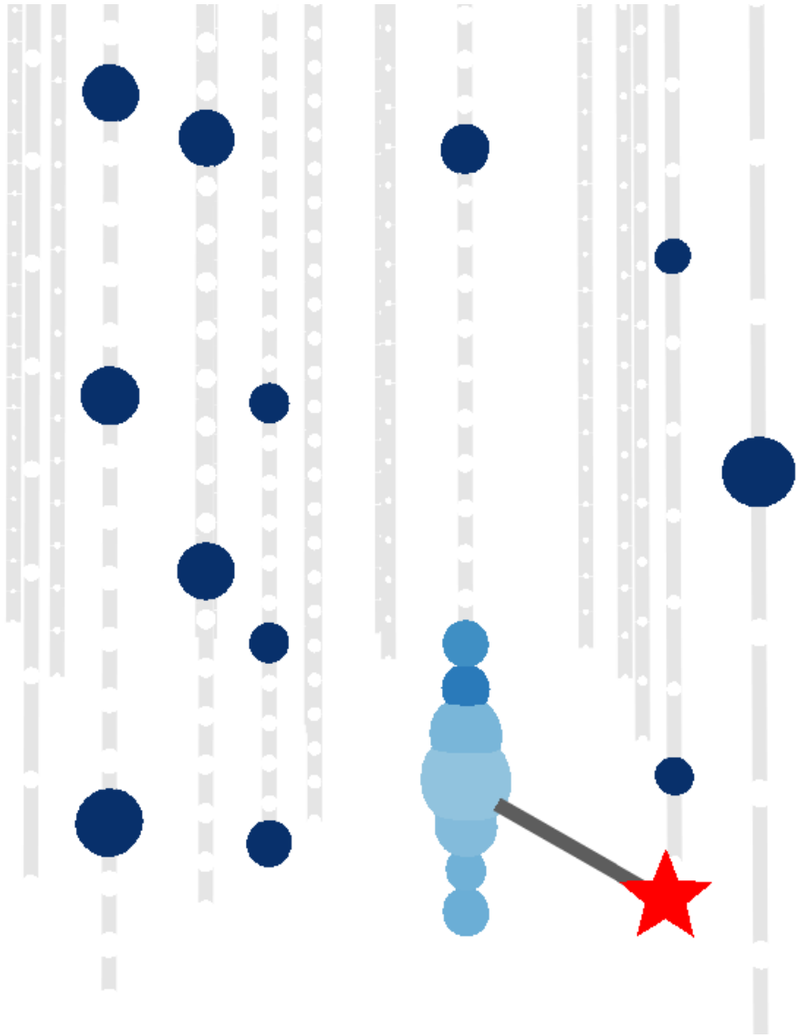
- direct measurement of total fluxes
- unfolding with special attention to low-energies



IceCube DeepCore







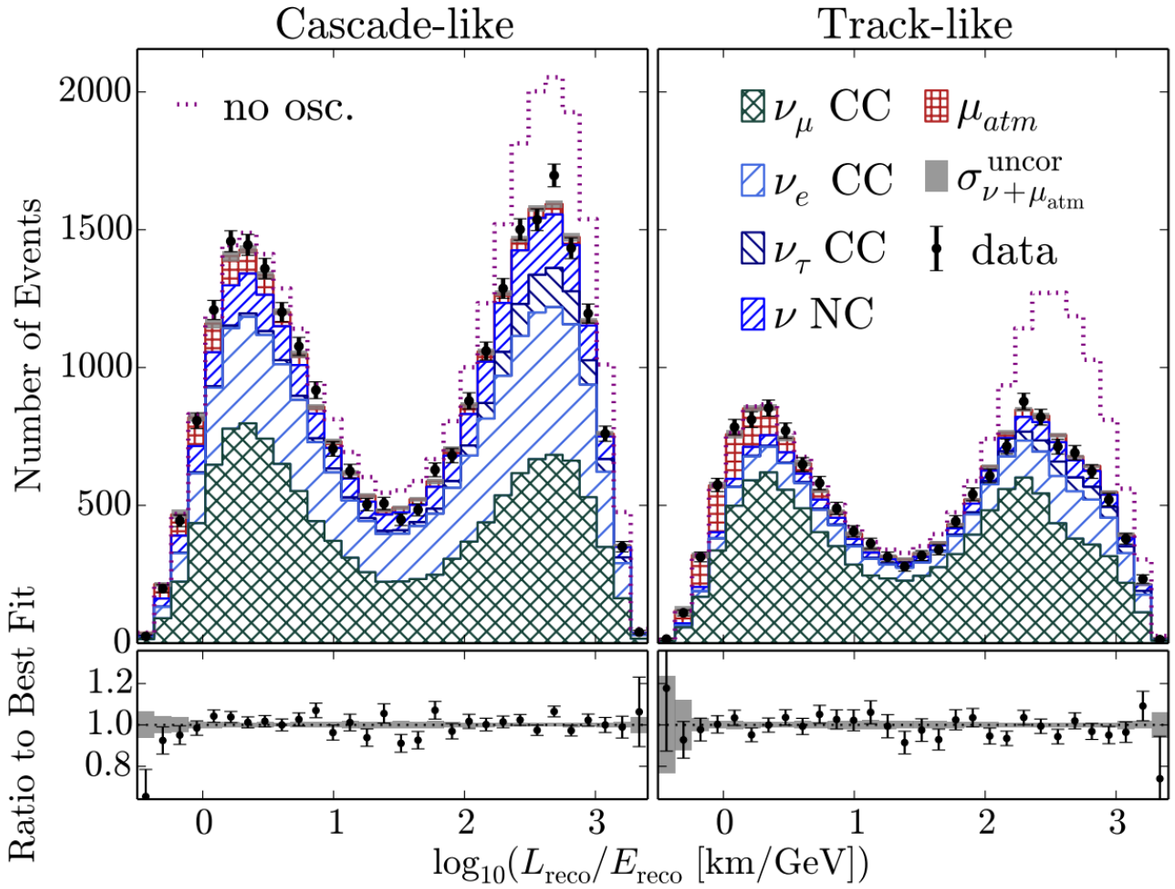
12 GeV ν_μ interaction

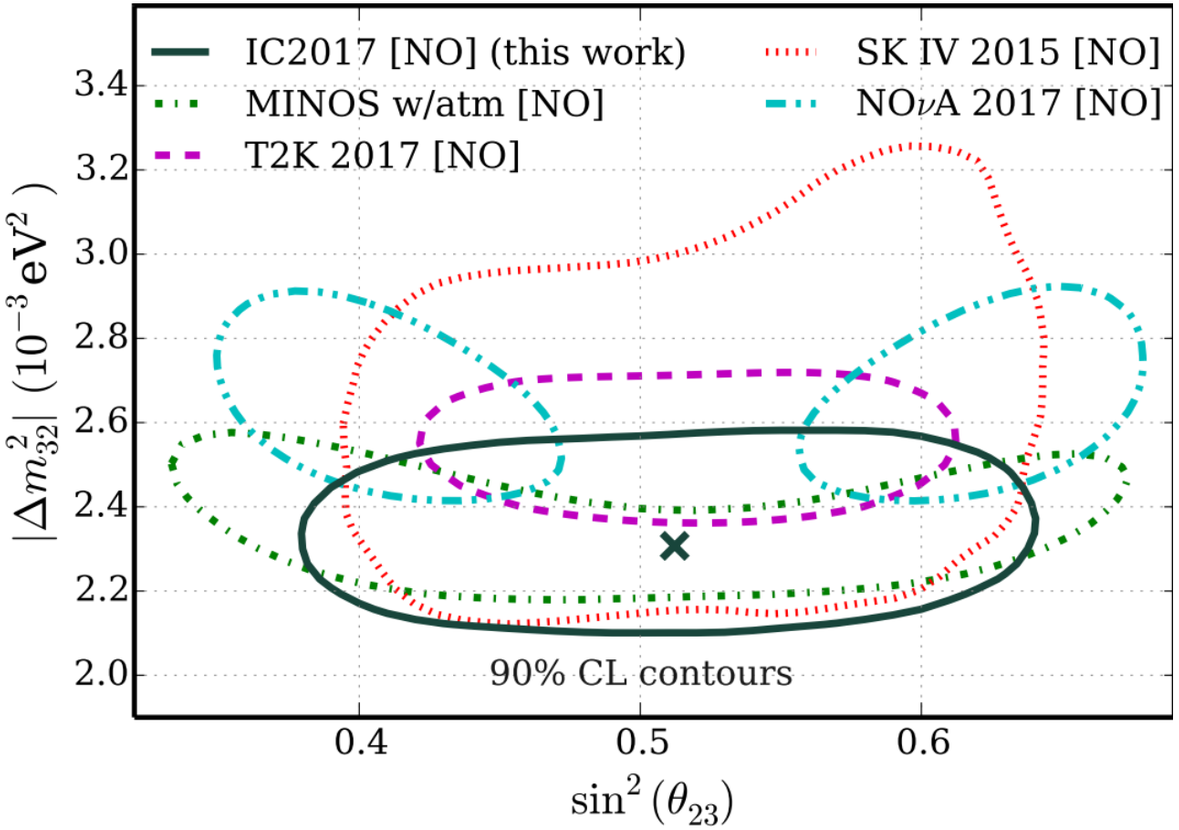
8 GeV track (R~40m) + 4 GeV cascade

IceCube DeepCore

Standard oscillations

Phys. Rev. Lett. 120, 071801 (2018)





IceCube DeepCore

Standard oscillations

Phys. Rev. Lett. 120, 071801 (2018)

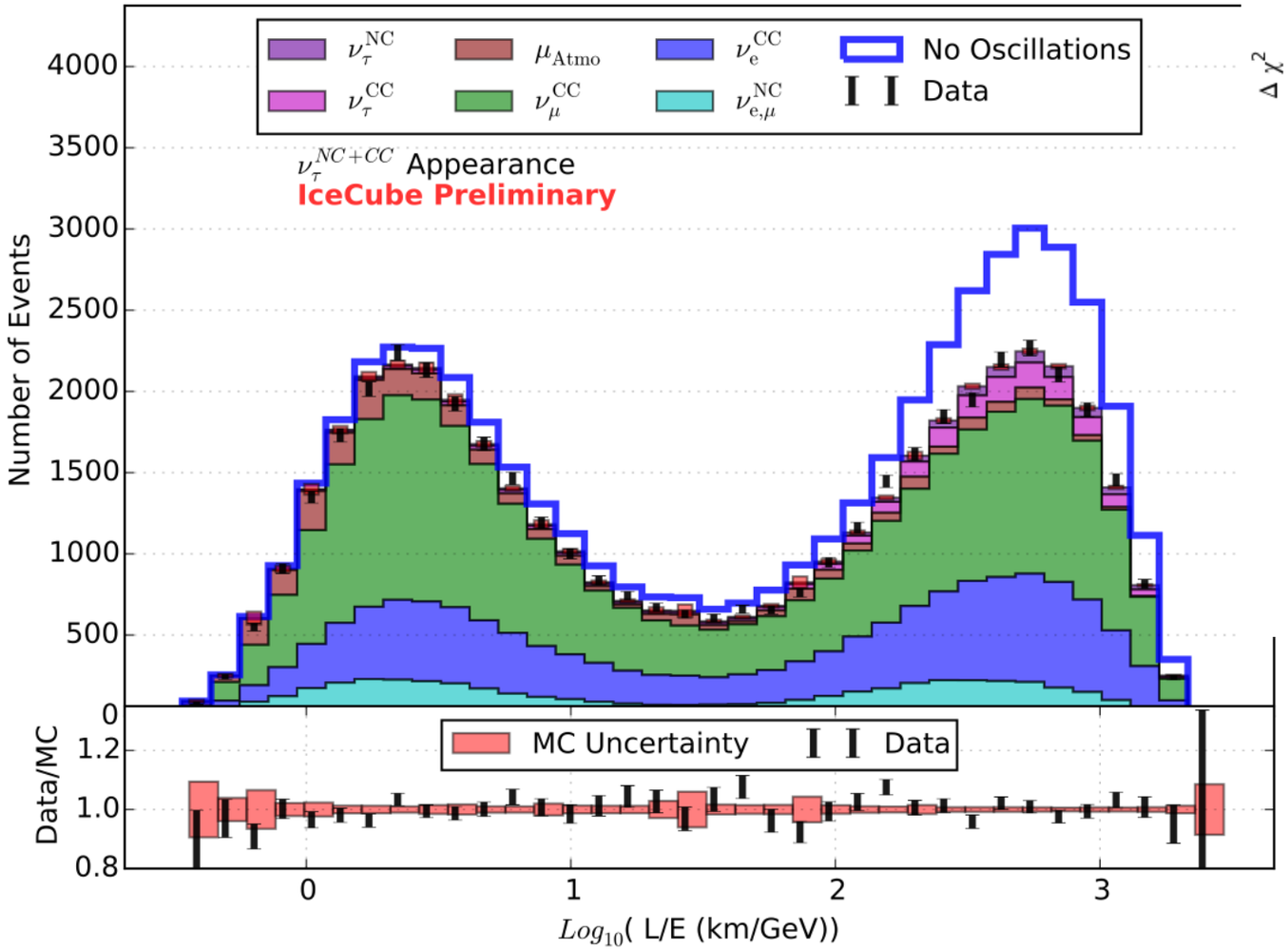
Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
Hadronic flux, energy dependent [σ]	0.00±1.00	-0.56	-0.59
Hadronic flux, zenith dependent [σ]	0.00±1.00	-0.55	-0.57
Detector parameters			
overall optical eff. [%]	100±10	102	102
relative optical eff., lateral [σ]	0.0±1.0	0.2	0.2
relative optical eff., head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

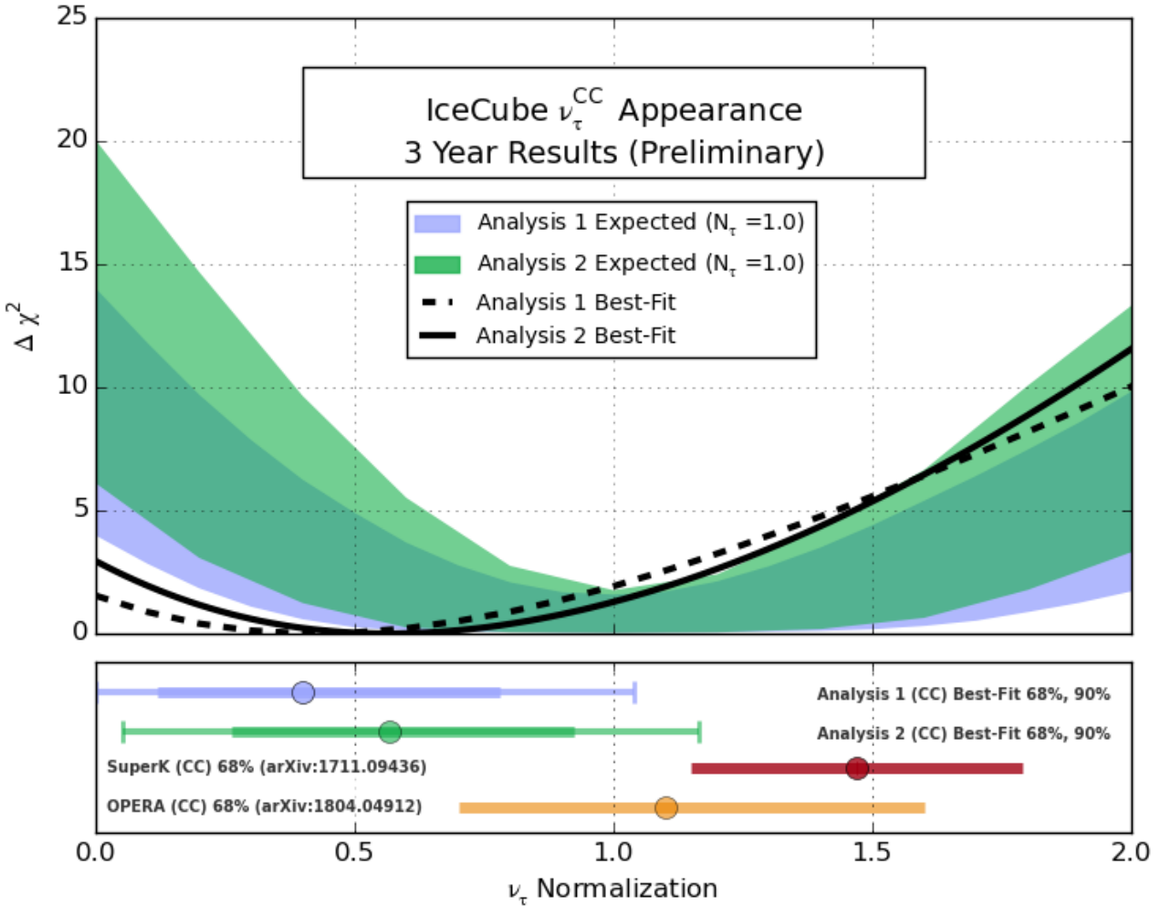
- no uncertainty relevance given
- atmospheric parameters fit in study
- all flux values found in 0.5-1σ uncertainty range

IceCube DeepCore

NuTau appearance

In preparation



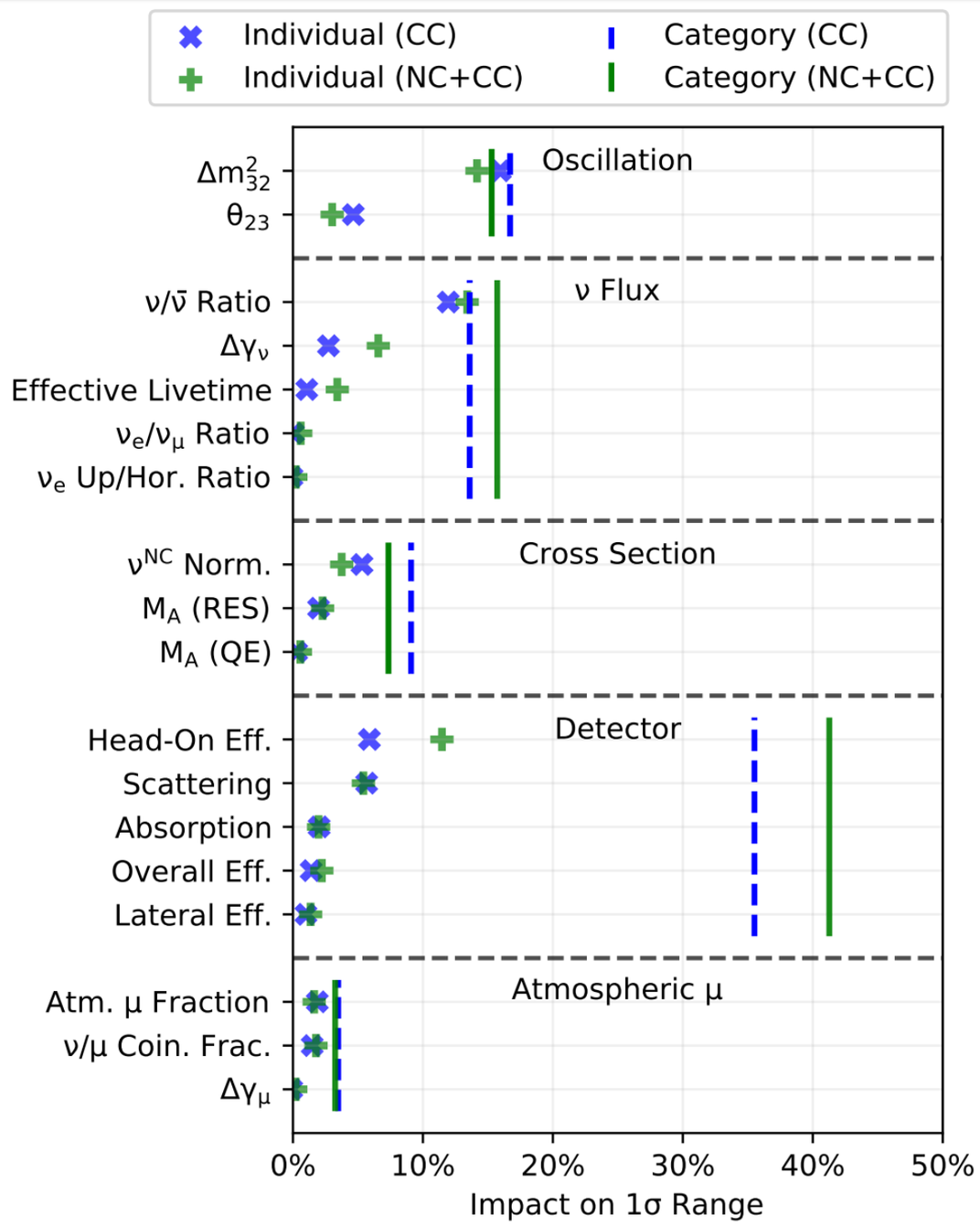


IceCube DeepCore

NuTau appearance
In preparation

- **nu-flux uncertainty as important as oscillation parameters**

- **still second to detector effects**

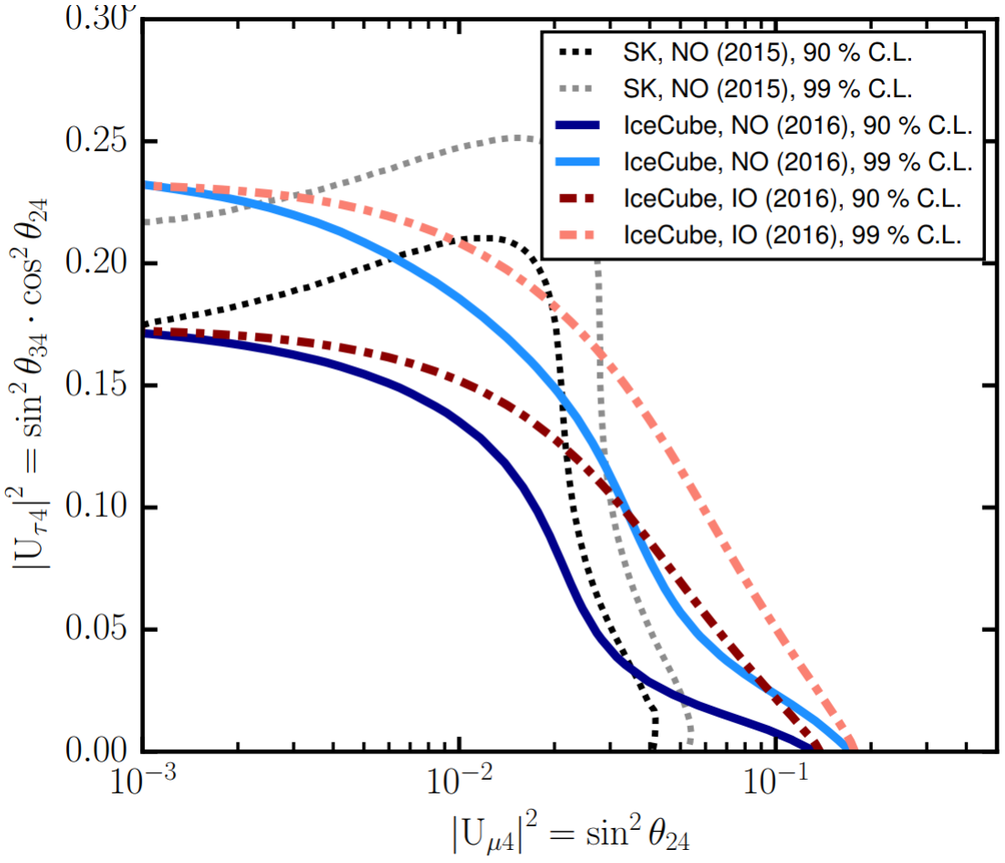


IceCube DeepCore

Sterile neutrinos

Phys. Rev. D 95, 112002 (2017)

- flux has little impact on this study (so far)

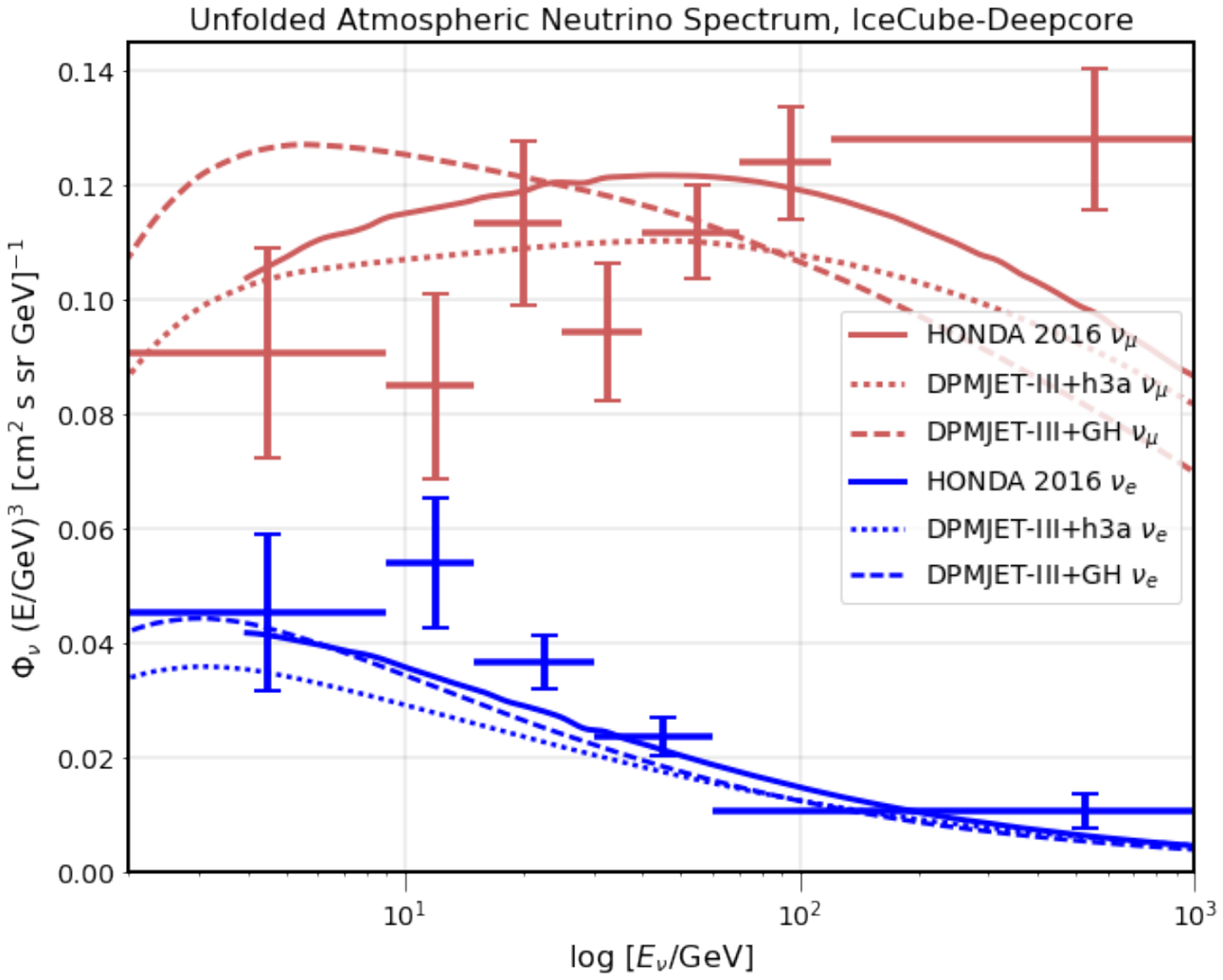


Parameter	Priors	Best fit (NO)	Best fit (IO)
Sterile mixing parameters			
$\|U_{\mu 4}\|^2$	no prior	0.00	0.00
$\|U_{\tau 4}\|^2$	no prior	0.08	0.06
Standard mixing parameters			
Δm^2_{32} [10^{-3}eV^2]	no prior	2.52	−2.61
$\sin^2\theta_{23}$	no prior	0.541	0.473
Flux parameters			
γ	no prior	−2.55	−2.55
ν_e normalization	1 ± 0.05	0.996	0.997
$\Delta(\nu/\bar{\nu})$, energy dependent	$0 \pm 1\sigma$	0.19σ	0.21σ
$\Delta(\nu/\bar{\nu})$, zenith dependent	$0 \pm 1\sigma$	0.19σ	0.16σ

IceCube DeepCore

Flux unfolding

In preparation



fit of total fluxes per flavor

NuMu excess at high energies

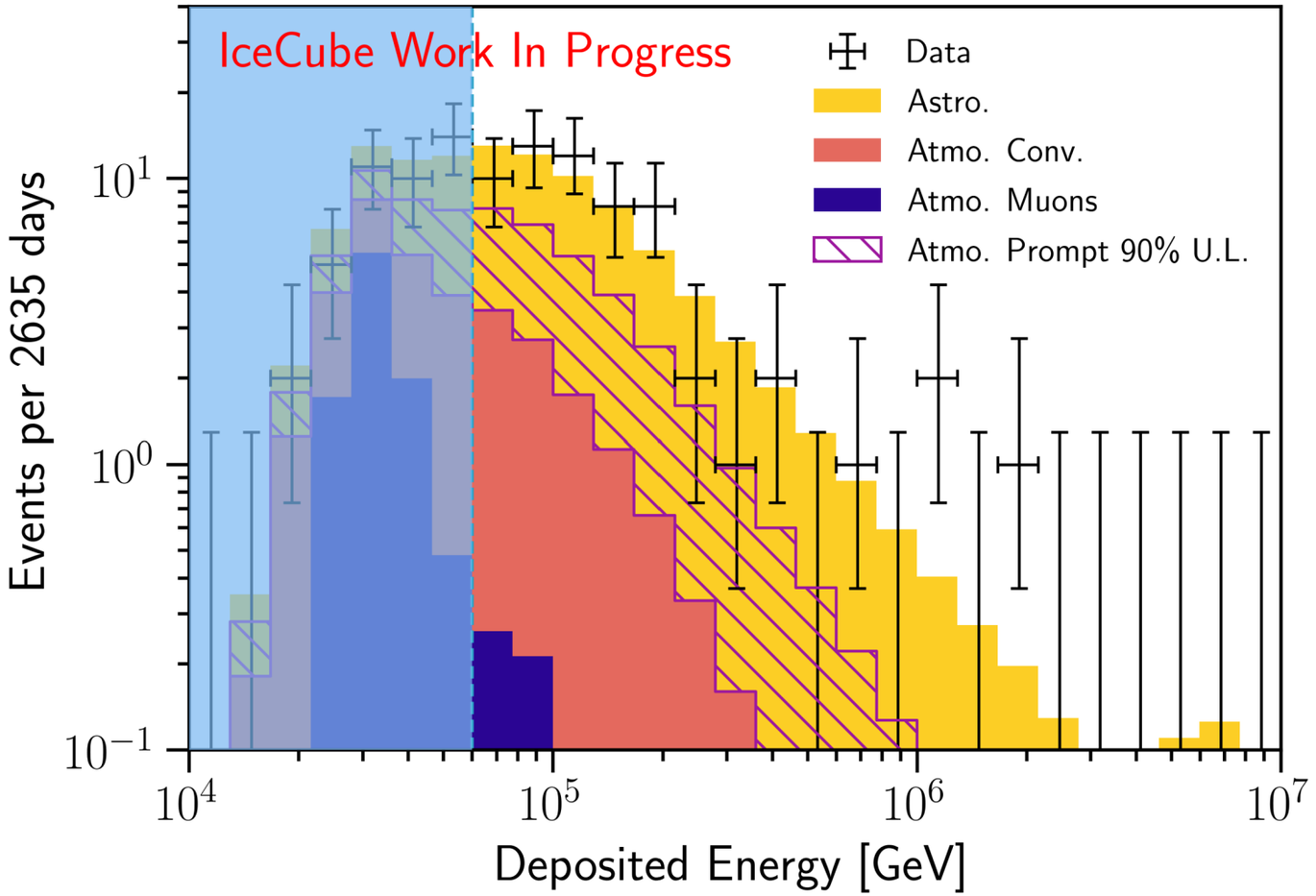
tensions with fixed models

cosmic neutrinos in telescopes

See results from IceCube, ANTARES and future projections

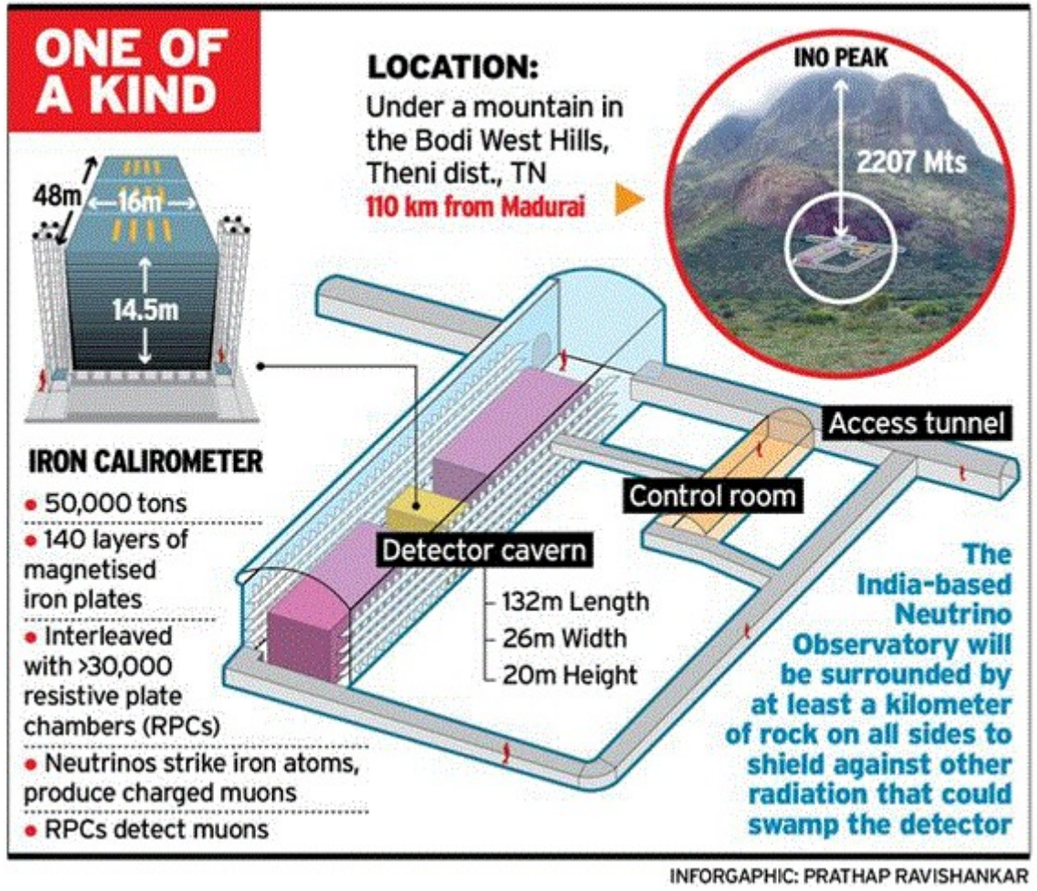
atmospherics are background for cosmic searches

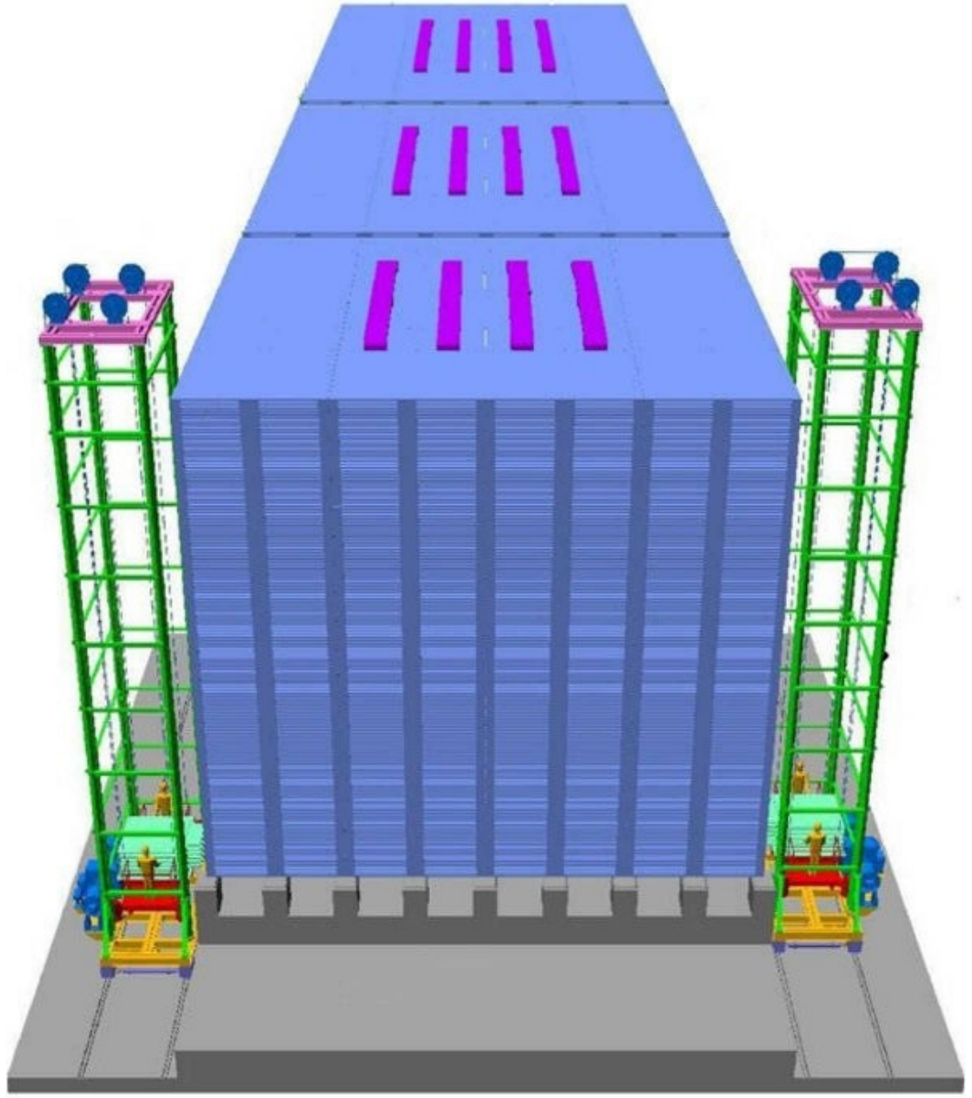
neutrinos from charmed mesons very uncertain



future atmospheric neutrino measurements

INO





-individual particle tracking

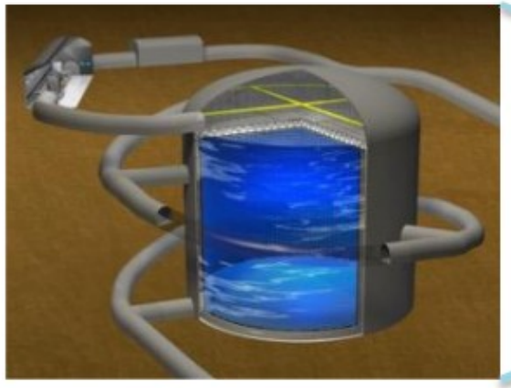
-charge identification

Hyper-Kamiokande

-8x Super-Kamiokande's FV / tank

-260kt mass / tank

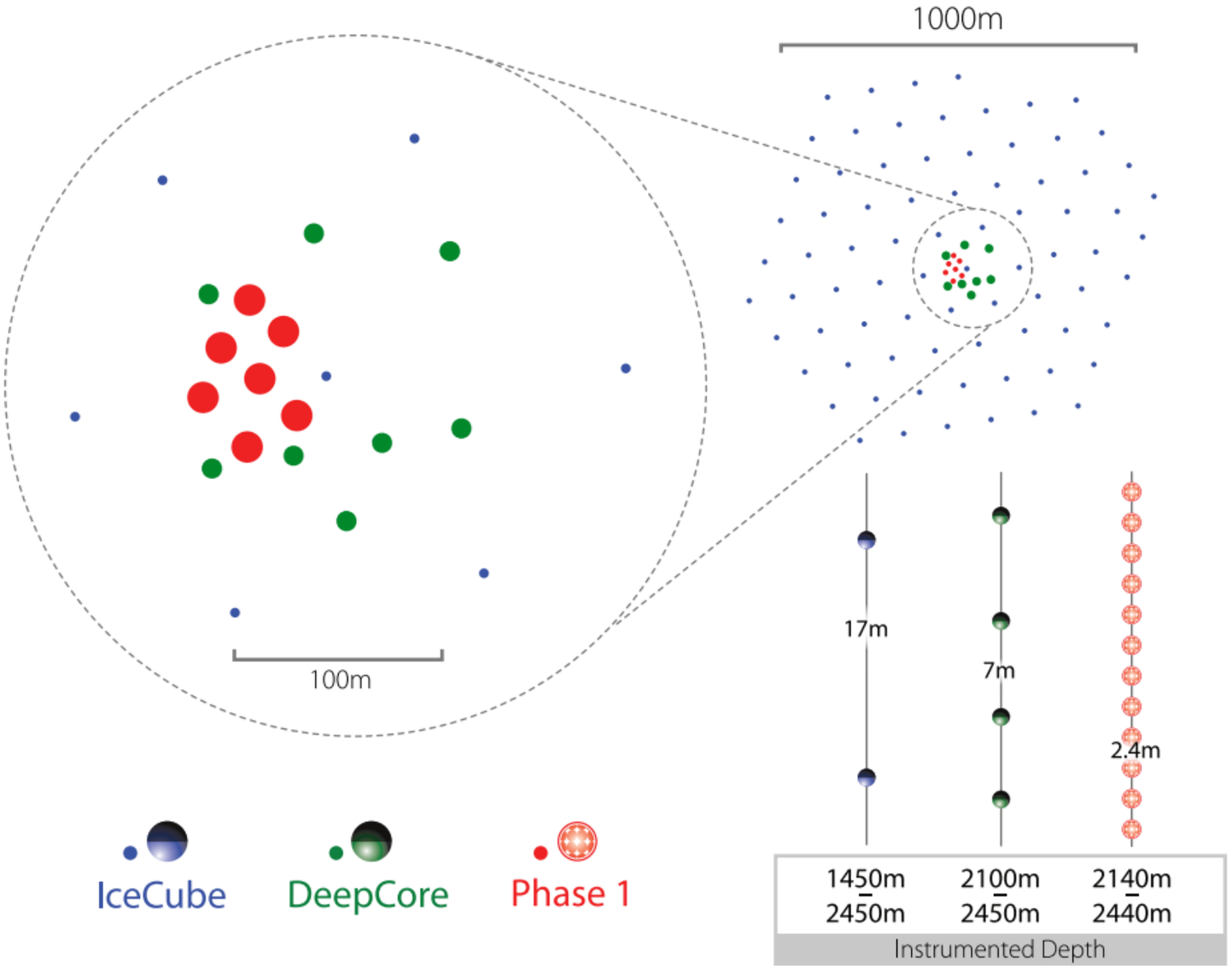
-atmospheric+beam nus



Hyper-K

J-PARC

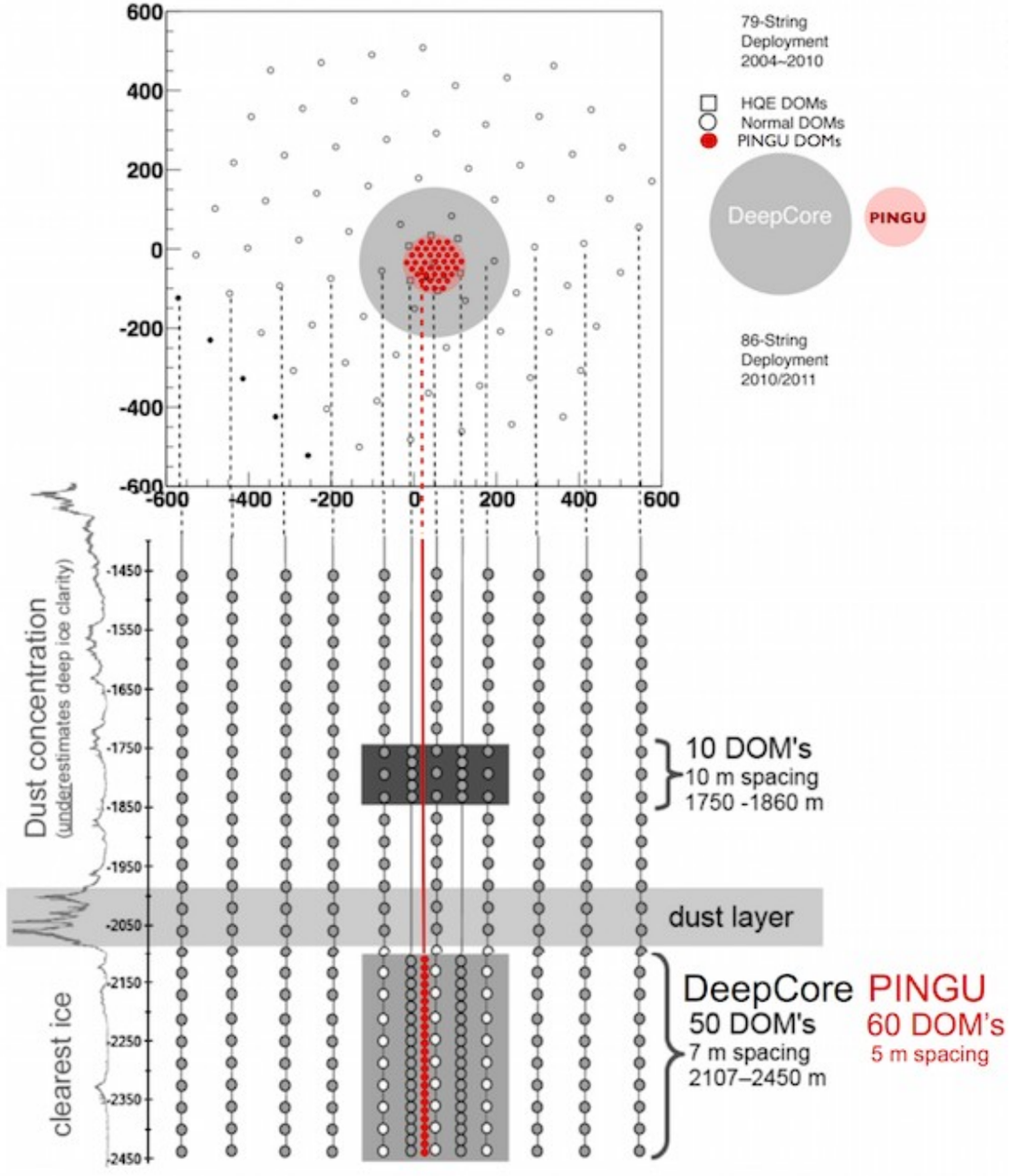
The IceCube upgrade

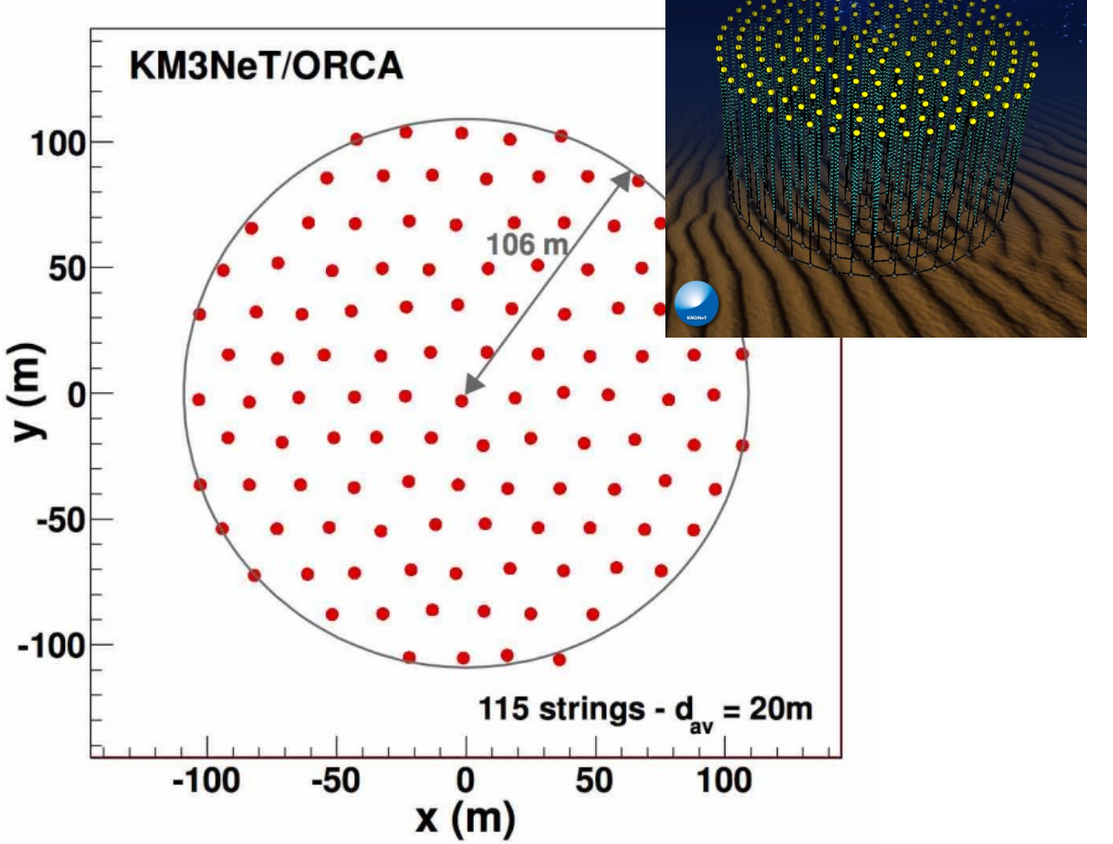


-DeepCore infill

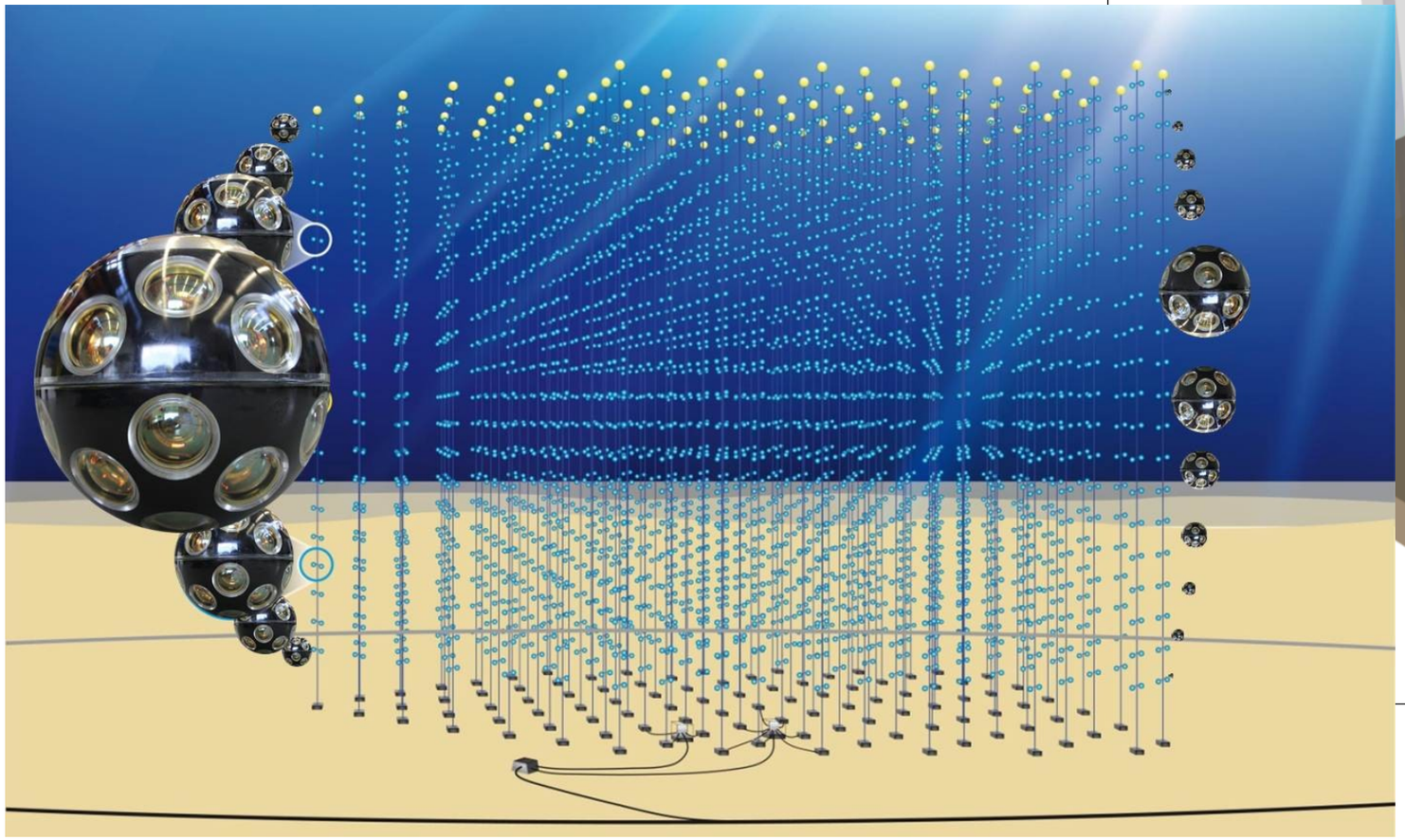
-lower energy threshold

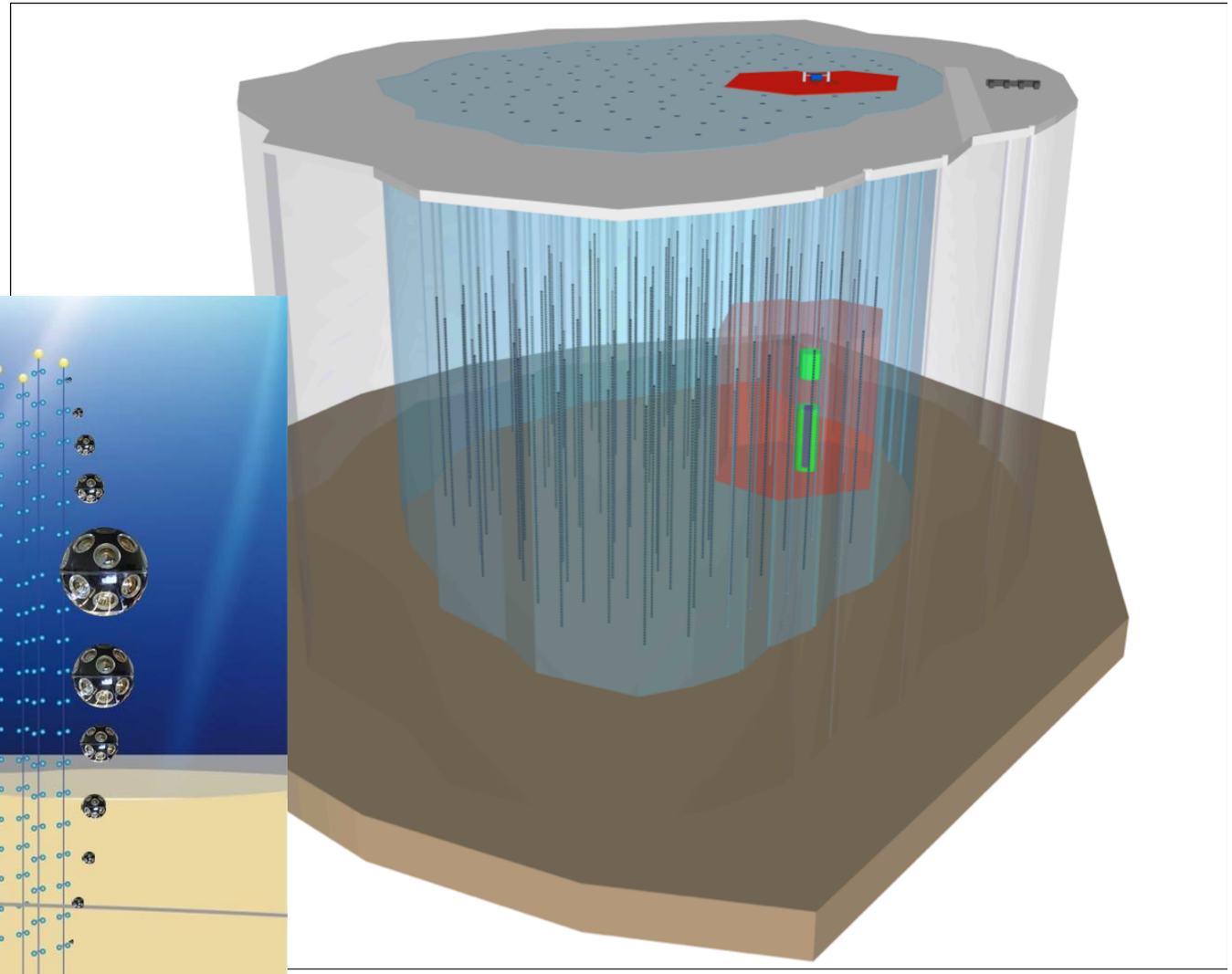
PINGU & ORCA


79-String
Deployment
2004–2010
HQE DOMs
Normal DOMs
PINGU DOMs
DeepCore
PINGU
86-String
Deployment
2010/2011
Dust concentration
(underestimates deep ice clarity)
clearest ice
10 DOM's
10 m spacing
1750 -1860 m
dust layer
DeepCore
50 DOM's
7 m spacing
2107–2450 m
PINGU
60 DOM's
5 m spacing


KM3NeT/ORCA
106 m
115 strings - d_av = 20m
y (m)
x (m)

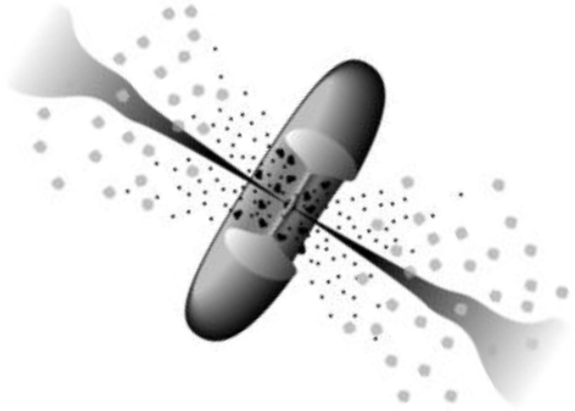
Km3NeT & IceCube Gen2





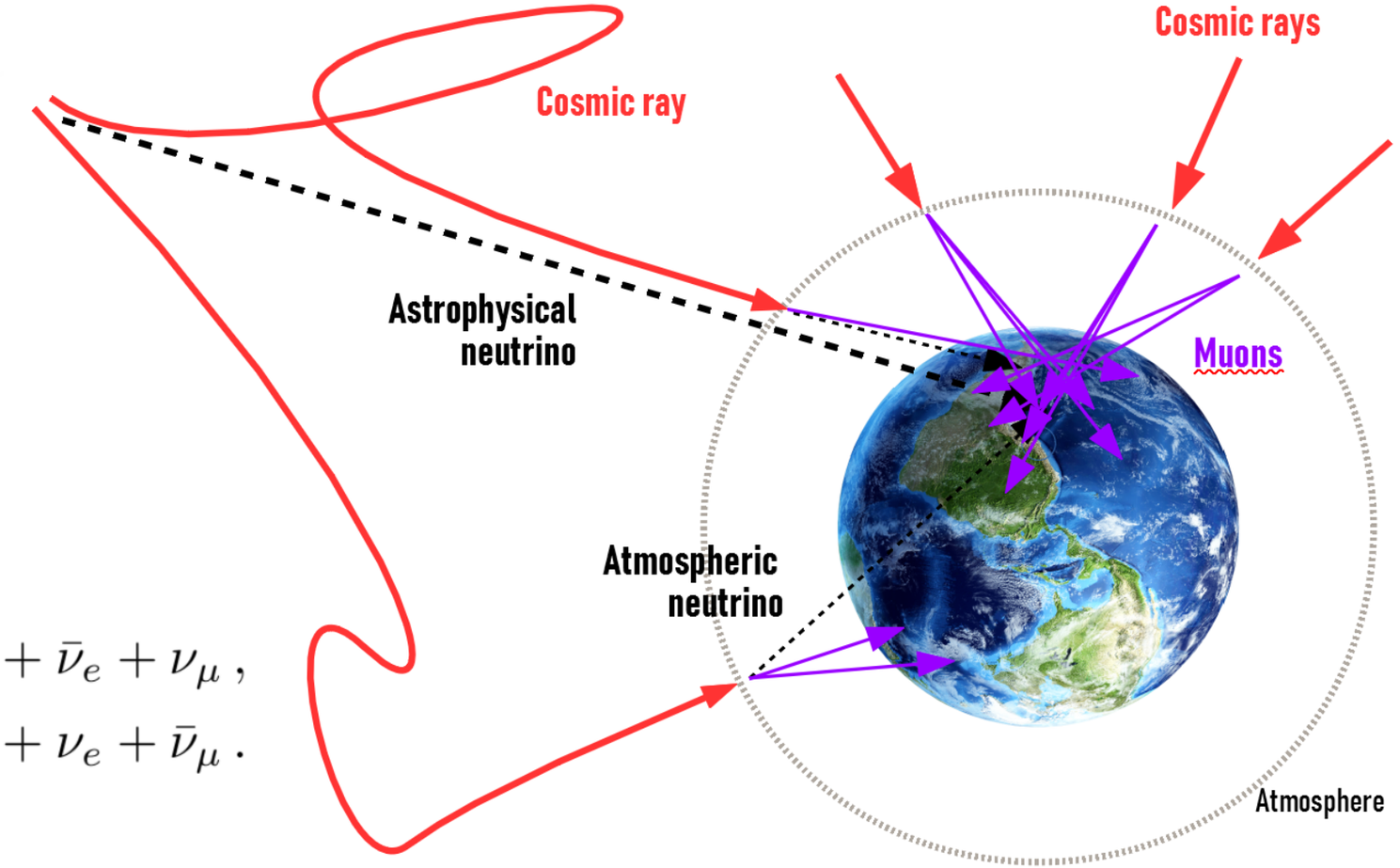
modeling atmospheric neutrinos: what's new?

from cosmic rays to neutrinos



Source of cosmic rays

$$CR + N \rightarrow X + \pi^{\mp}, K^{\mp},$$
$$\pi^{-}, K^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu},$$
$$\pi^{+}, K^{+} \rightarrow \mu^{+} + \nu_{\mu},$$
$$\mu^{-} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu},$$
$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}.$$

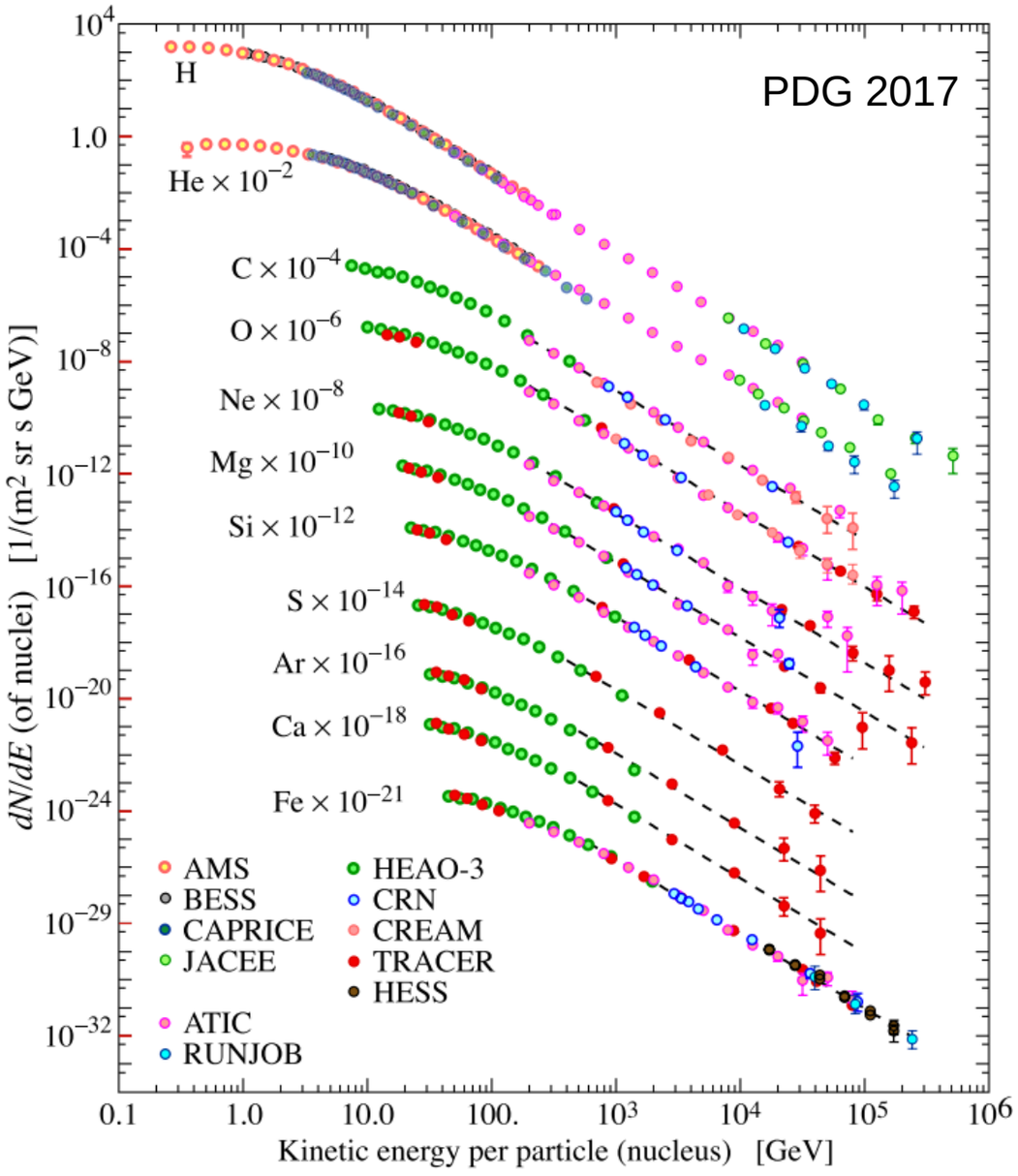


cosmic ray flux

- particle spectra

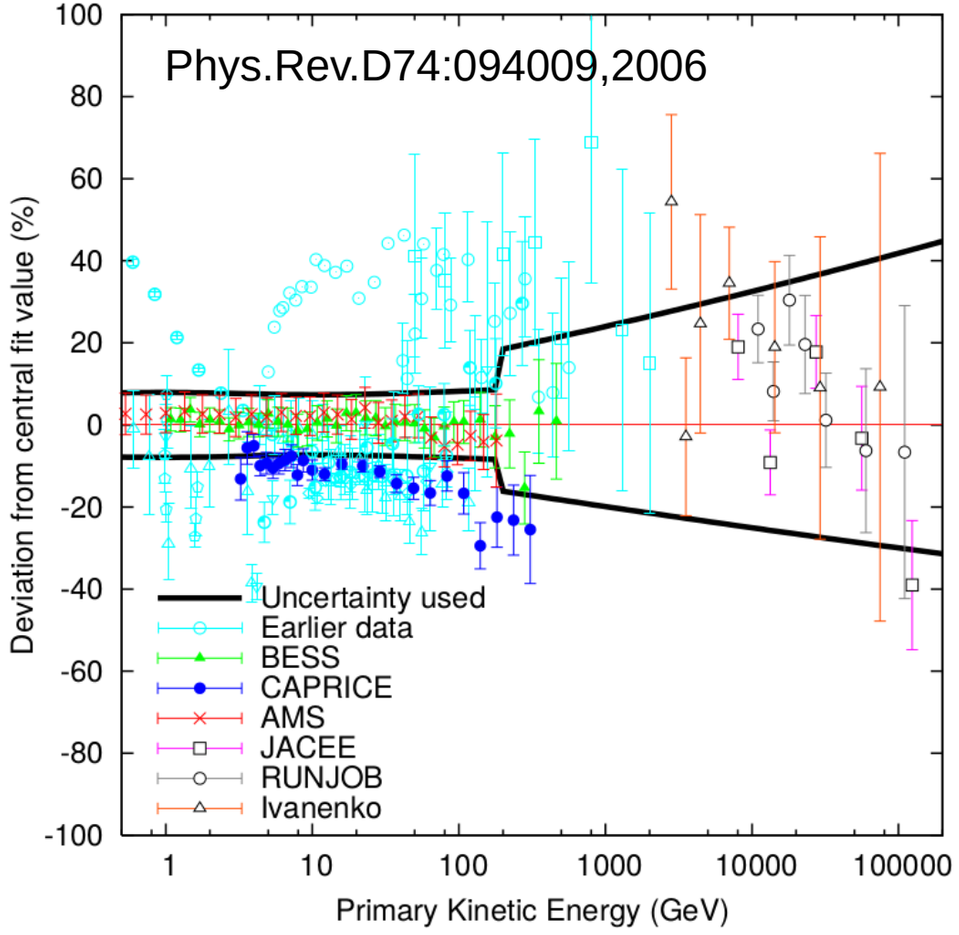
-4 **new measurements** in last ~10 years (AMS-II, PAMELA, Cream, BESS)

-more **detailed** flux characterization

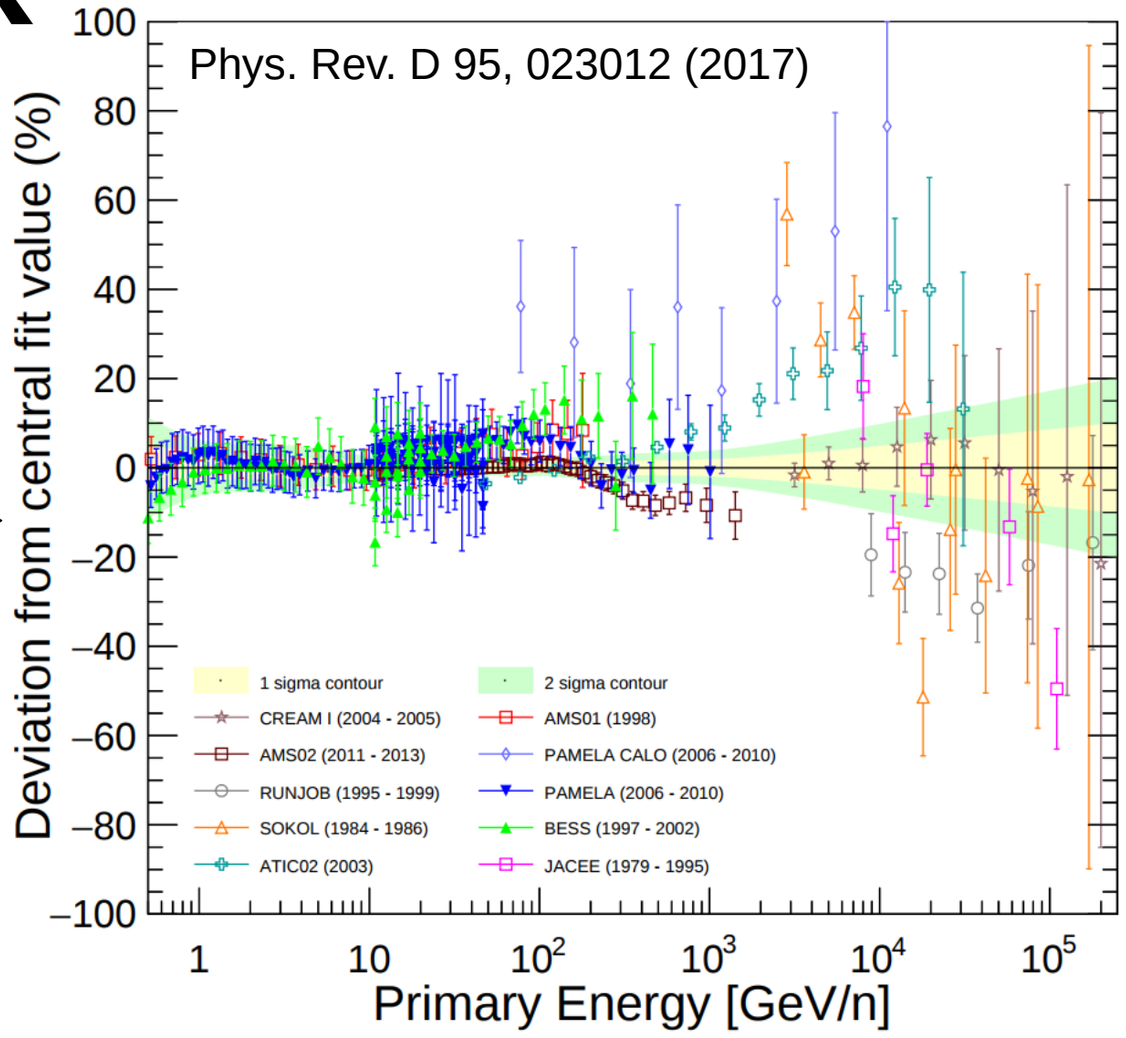


cosmic ray flux

- modeling the flux

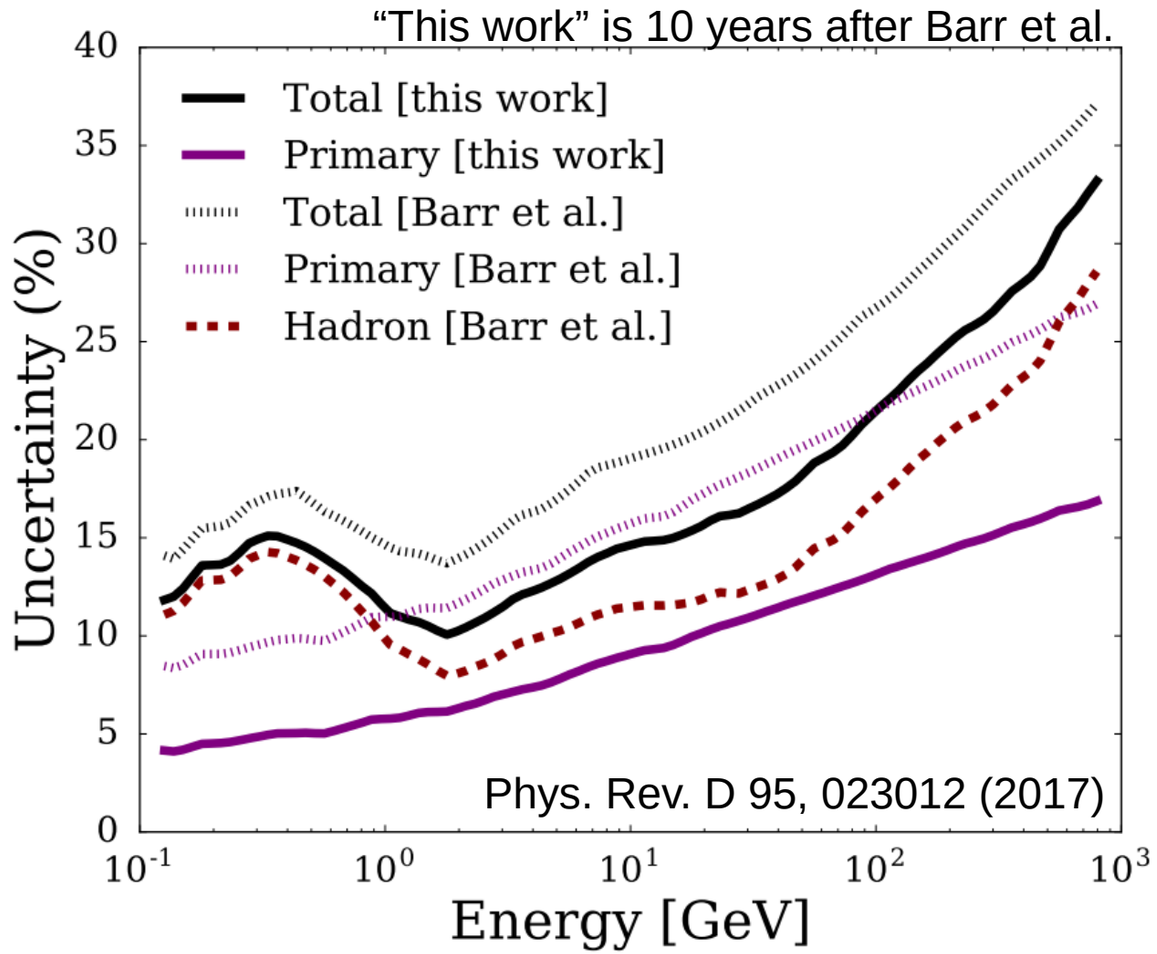


→ **10 years** →



cosmic ray flux

- uncertainties → neutrino impact



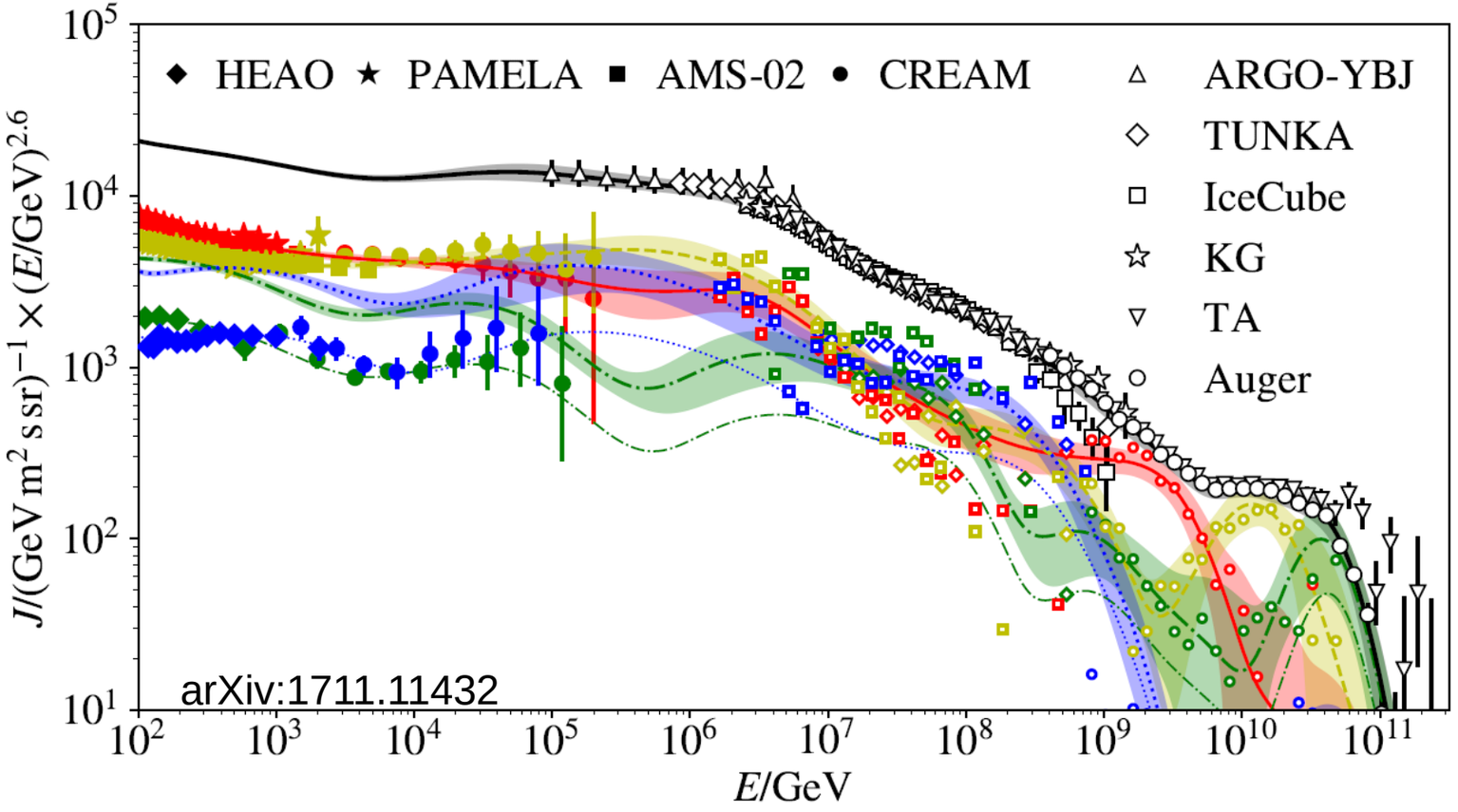
cosmic ray flux

- a new way to model

-standard model: power law primary fluxes

-new approach:

global fit to data

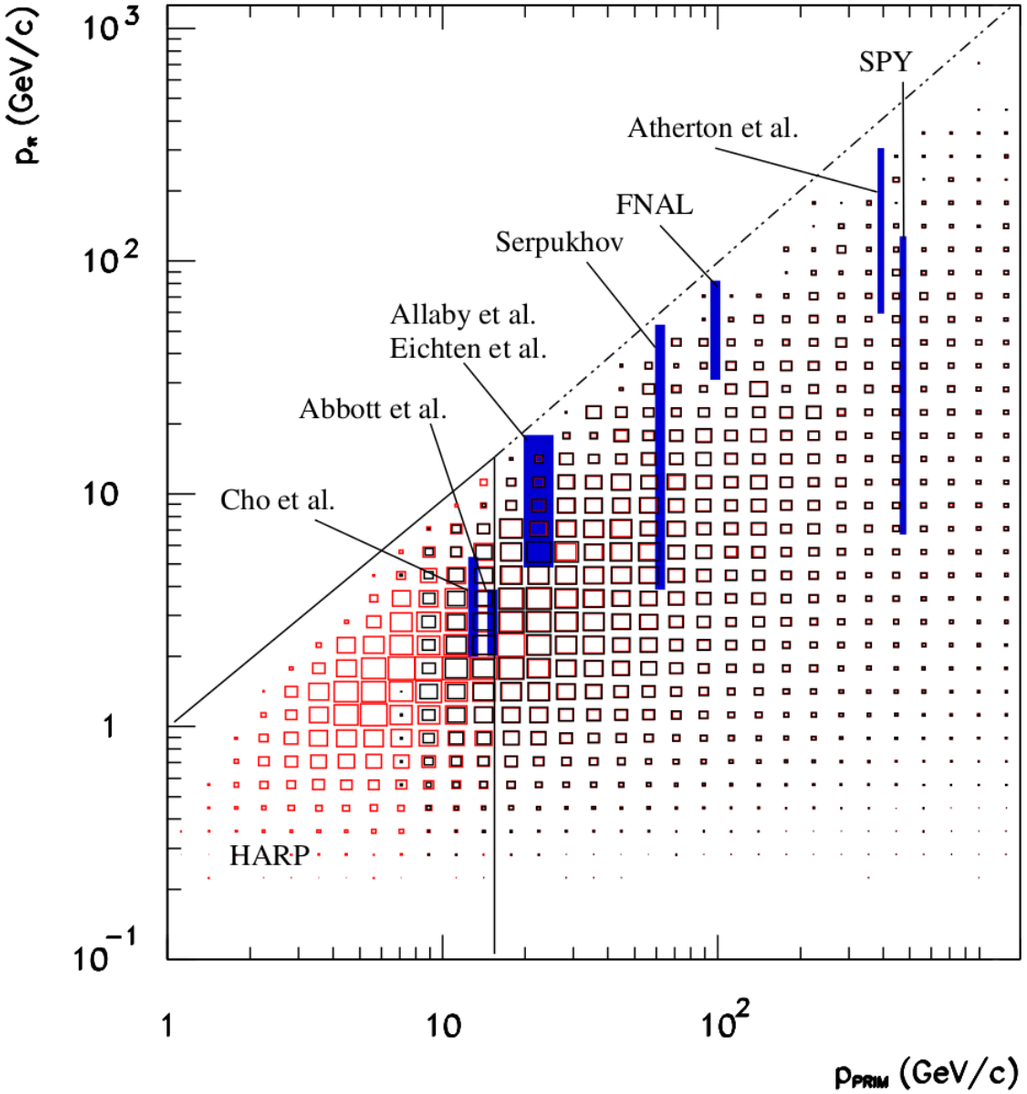


hadronic interactions

- meson yields from showers

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



hadronic interactions

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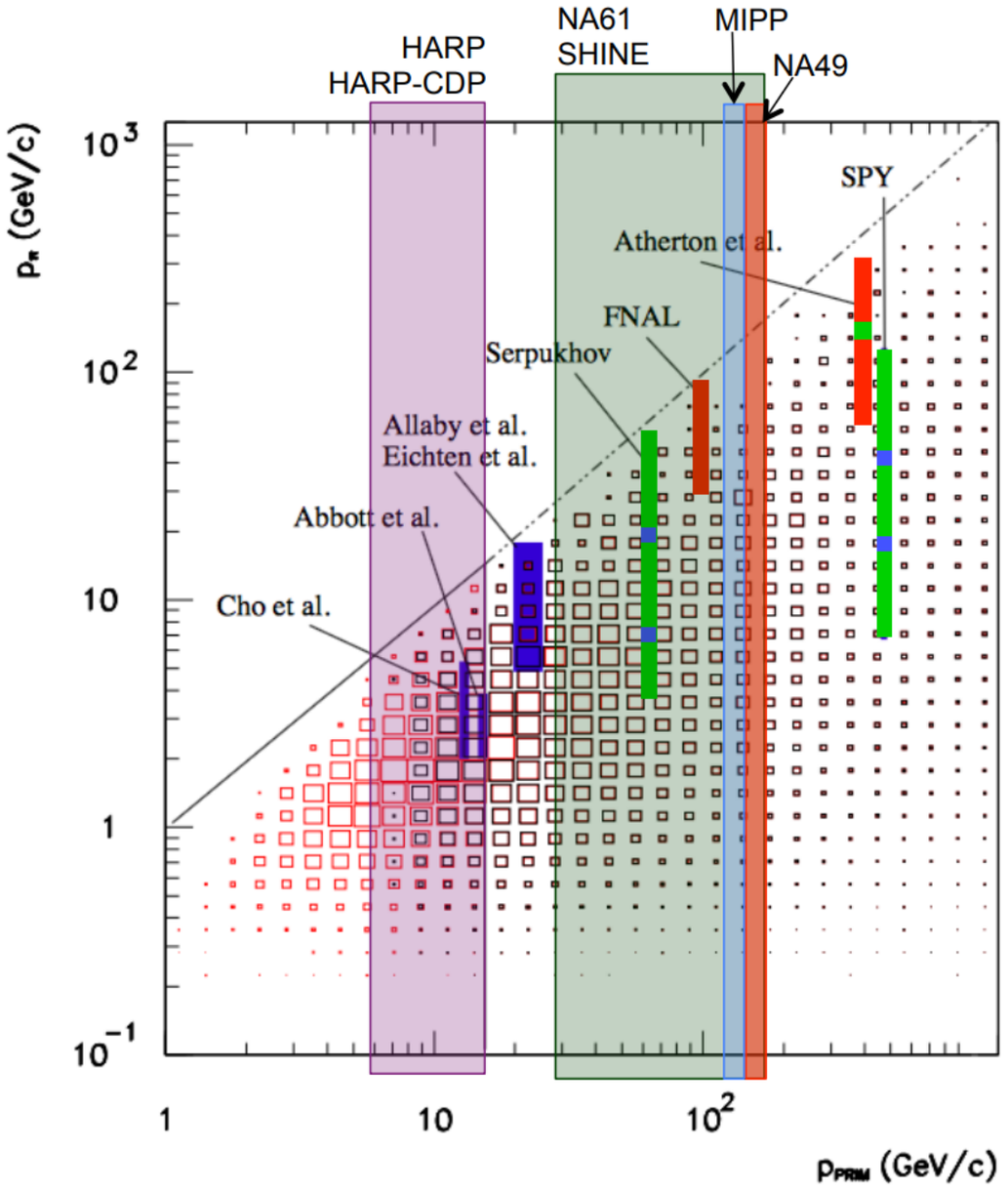
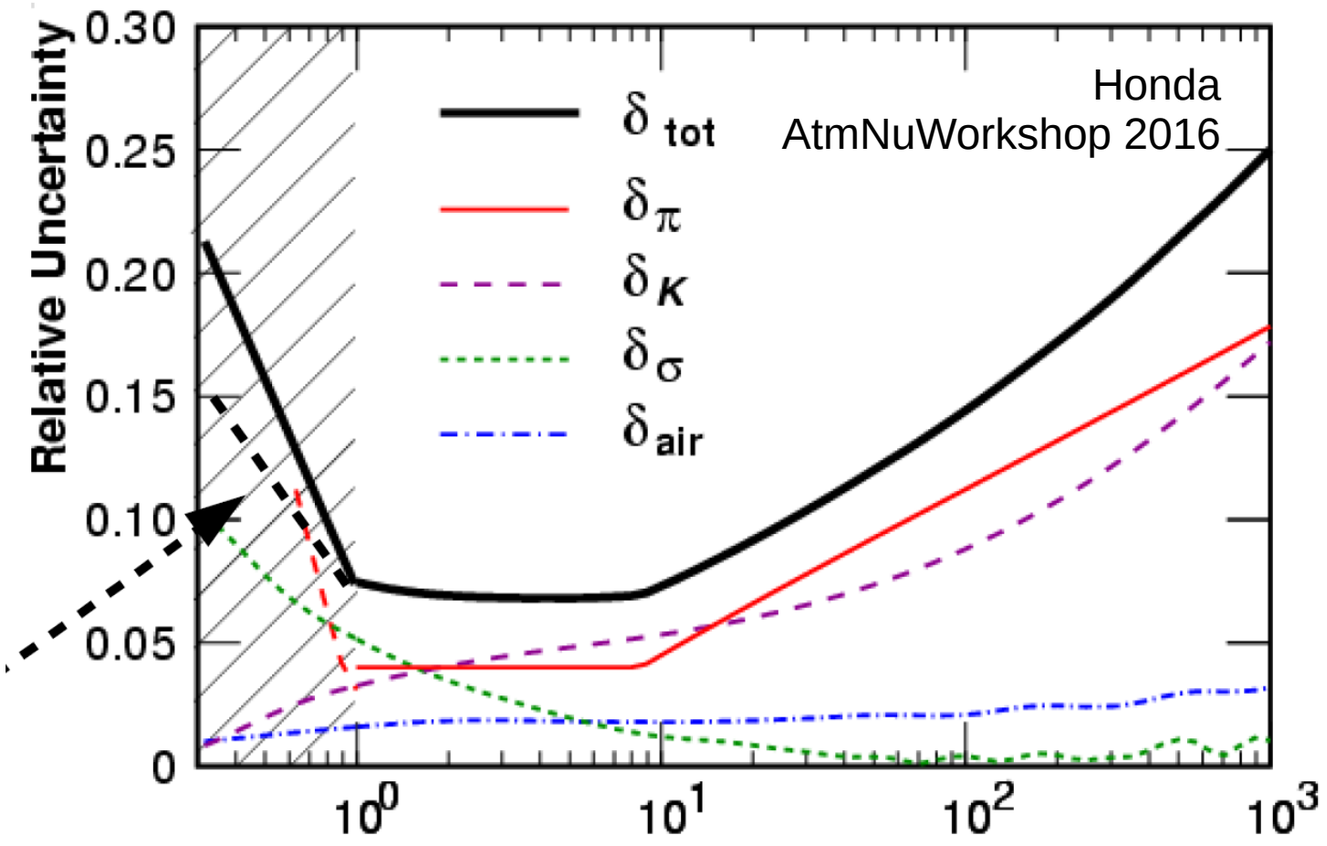


Updated from
Phys.Rev.D74:094009,2006

Barr, AtmNuWorkshop16

hadronic interactions

-estimated uncertainties



MCEq: a new tool

-solving transport equations numerically

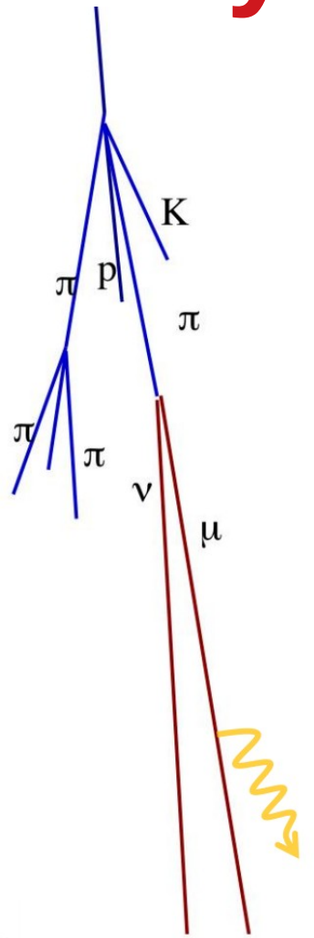
$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)}$$ Interactions with air

$$-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)}$$ Decays

$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X))$$ Continuous losses

$$+\sum_k \int_E^\infty \mathrm{d}E_k \, \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)}$$ Re-injection from interactions

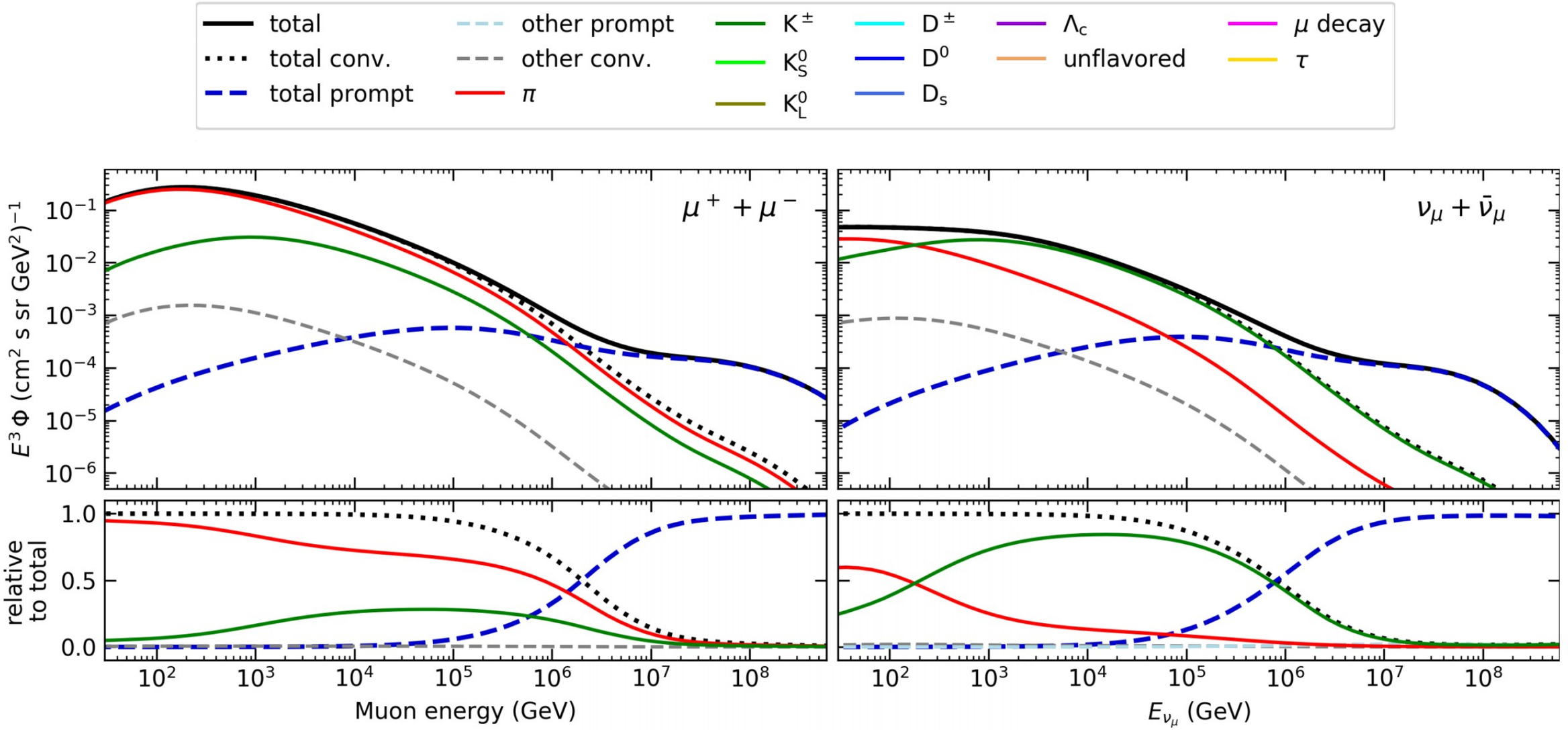
$$+\sum_k \int_E^\infty \mathrm{d}E_k \, \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$ Re-injection from decays



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

A. Fedynitch, PANE2018
https://github.com/afedynitch/MCEq

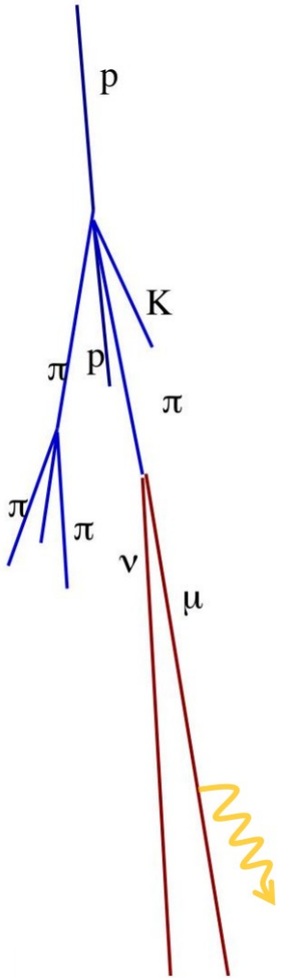
MCEq: a new tool

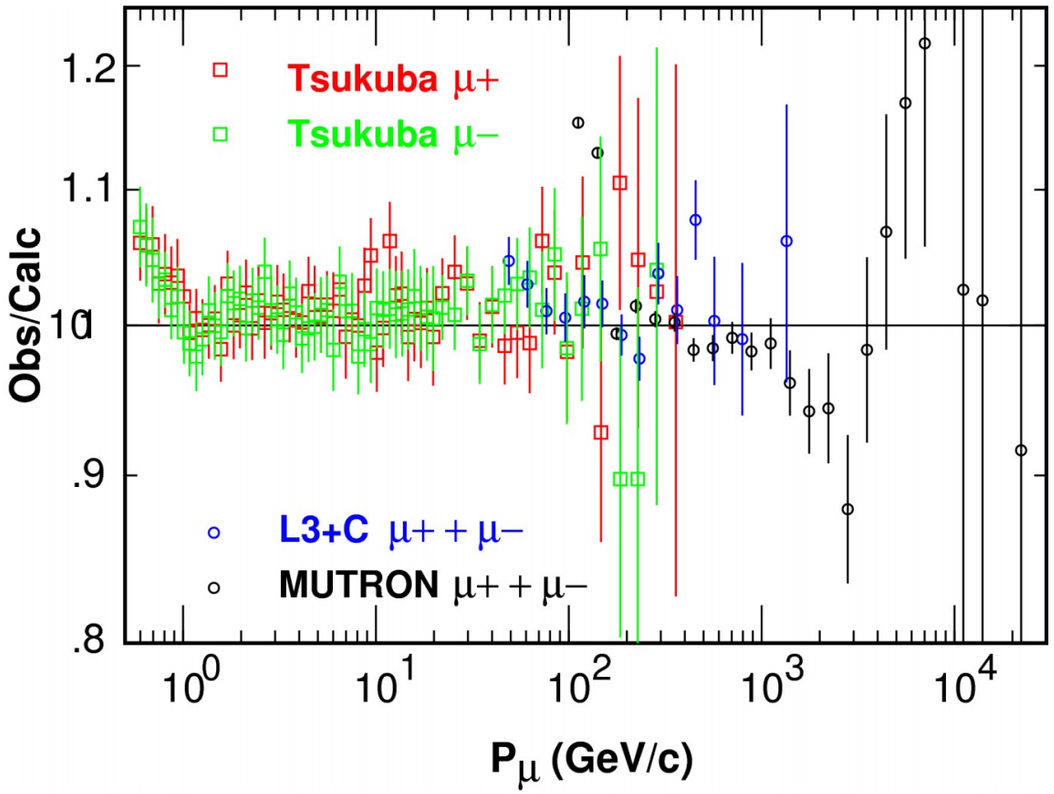


A. Fedynitch, PANE2018
https://github.com/afedynitch/MCEq

calibrating fluxes with muons

-use **cosmic muon** data to calibrate hadronic int. models → **nu flux**

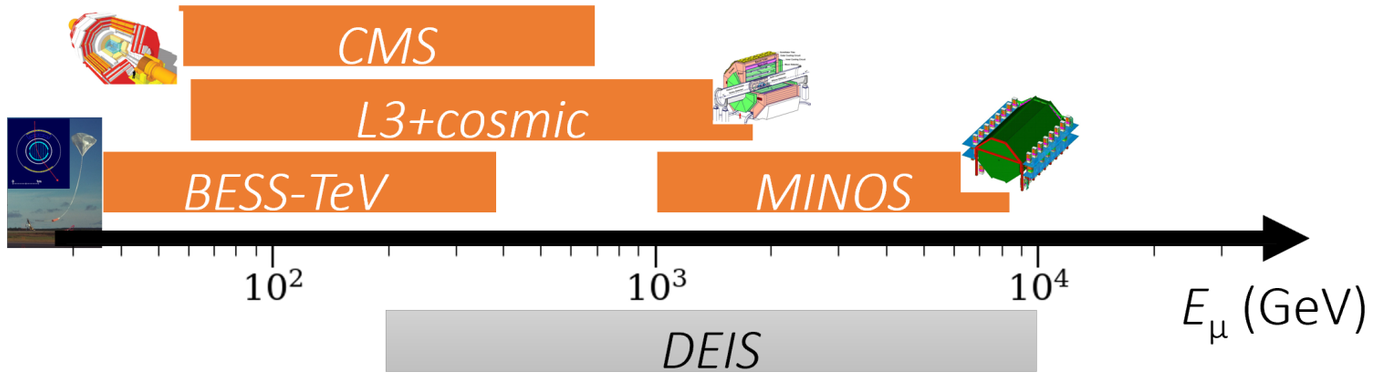


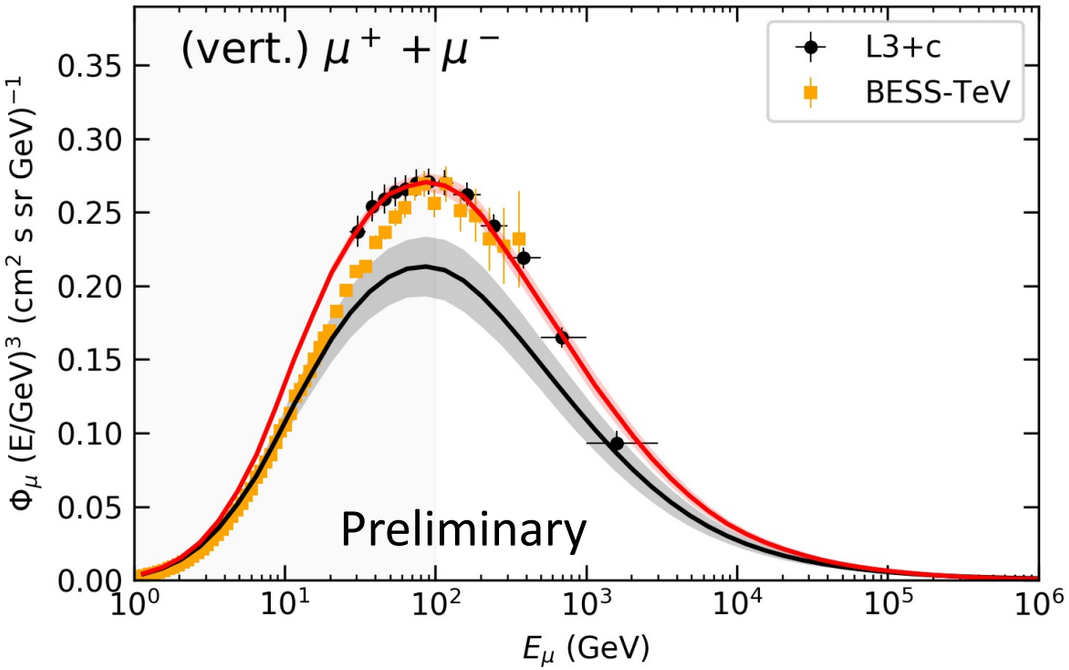


Honda, PANE2018
Muon flux comparison after tuning hadronic interaction models

calibrating fluxes with muons

-use all available cosmic muon data to calibrate hadronic int. models → nu flux

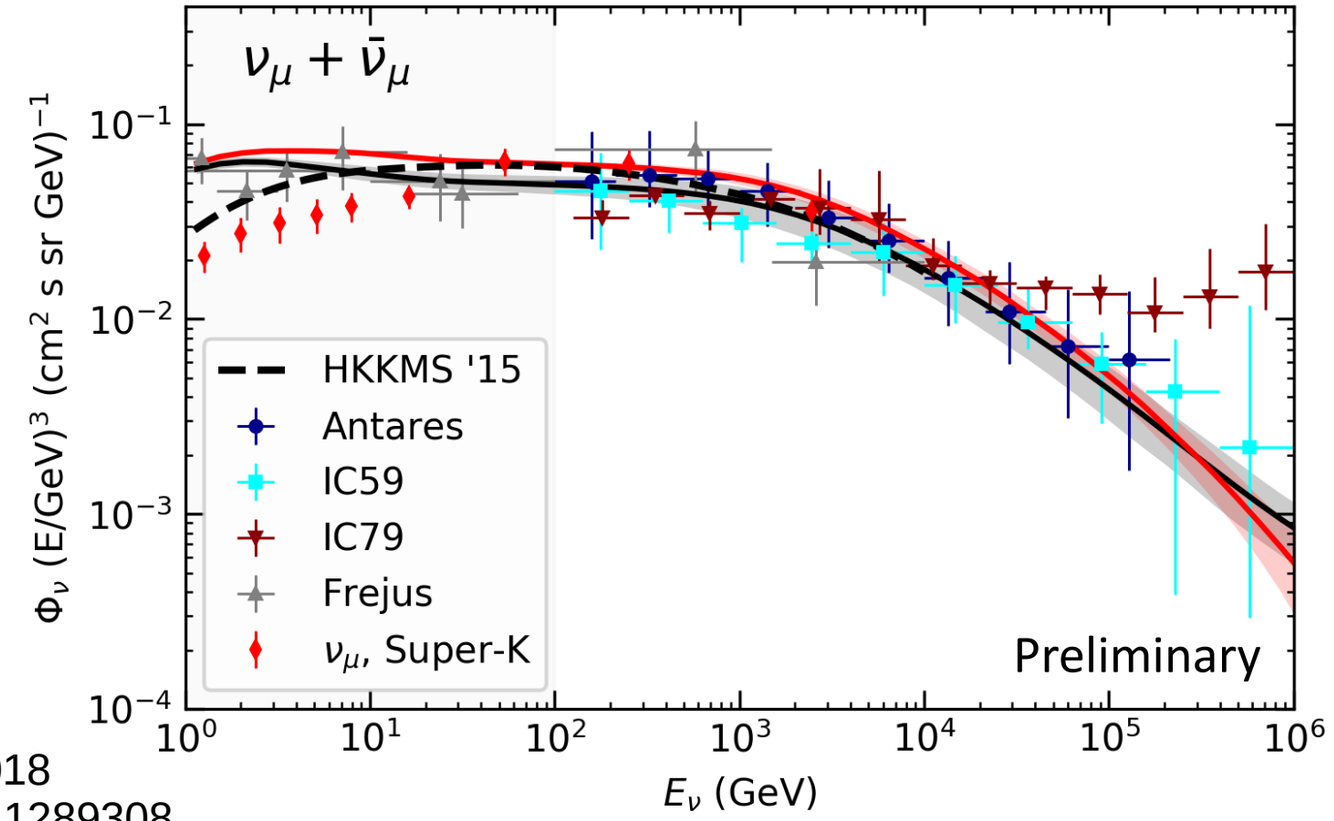




Yanez & Fedynitch, Neutrino2018
https://doi.org/10.5281/zenodo.1289308

calibrating fluxes with muons

-use all available cosmic muon data to calibrate hadronic int. models → nu flux



Yanez & Fedynitch, Neutrino2018
https://doi.org/10.5281/zenodo.1289308

final words

summary & outlook

-atm. nus are an **invaluable tool** for neutrino physics

-very large & unique phase space in **L/E, flavor**

-experiments producing **well understood, reliable** results

-next generation measurements tough, but possible

-neutrino flux unknowns already playing a role

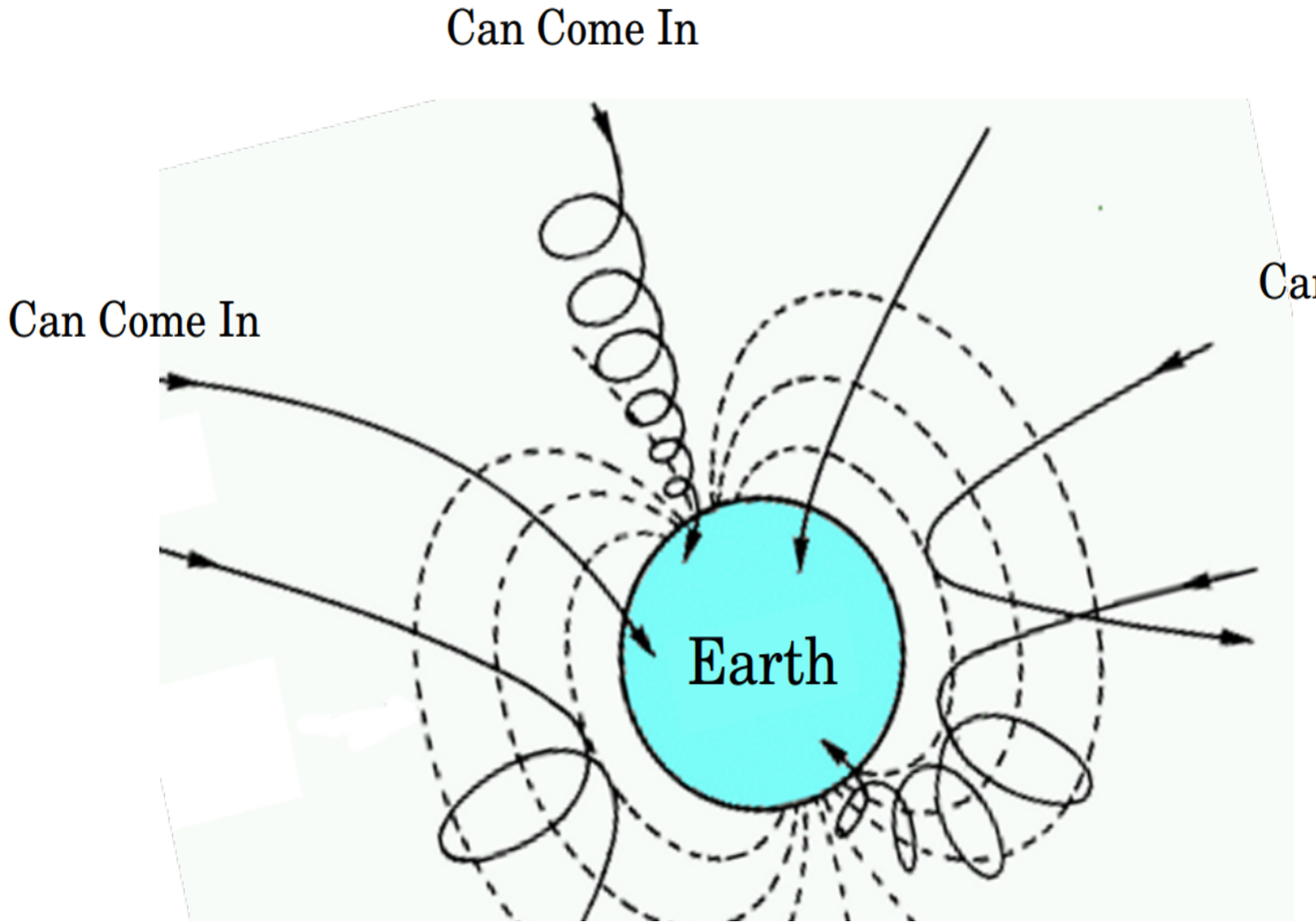
-renewed efforts to **model & understand** atm nus ongoing

-more data, new software, workshops in last years

backup

flux basic inputs

-geomagnetic effects

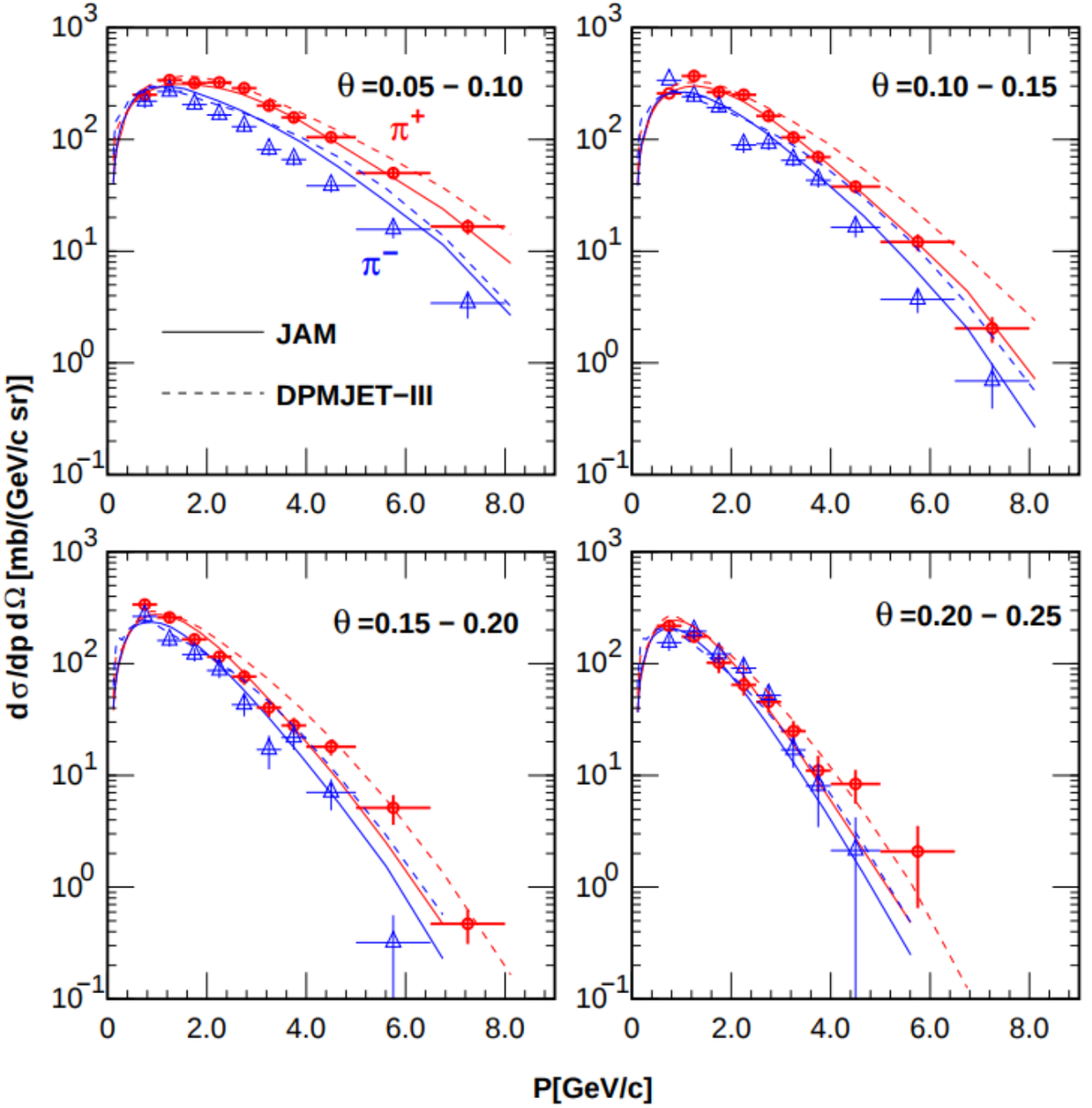


-3D calculations

-site-specific

flux basic inputs

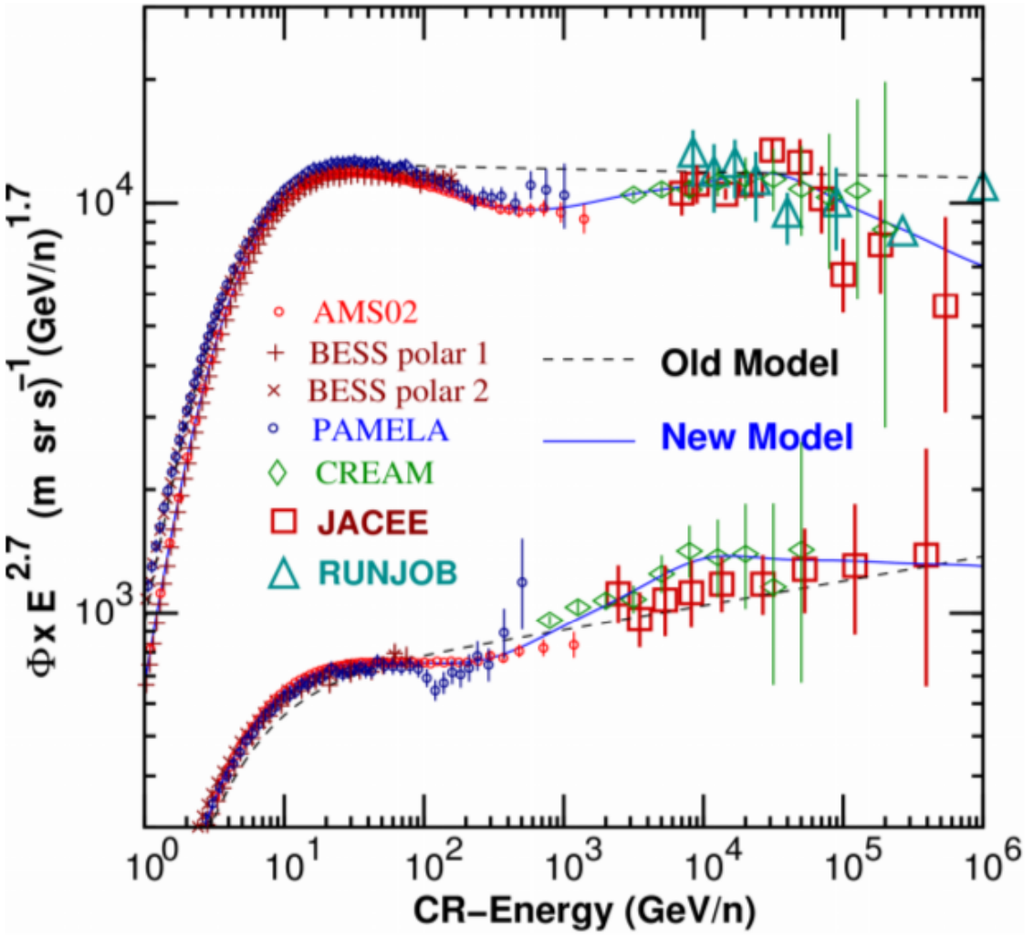
-**hadronic interactions HARP data**



Phys.Rev.D83:123001,2011

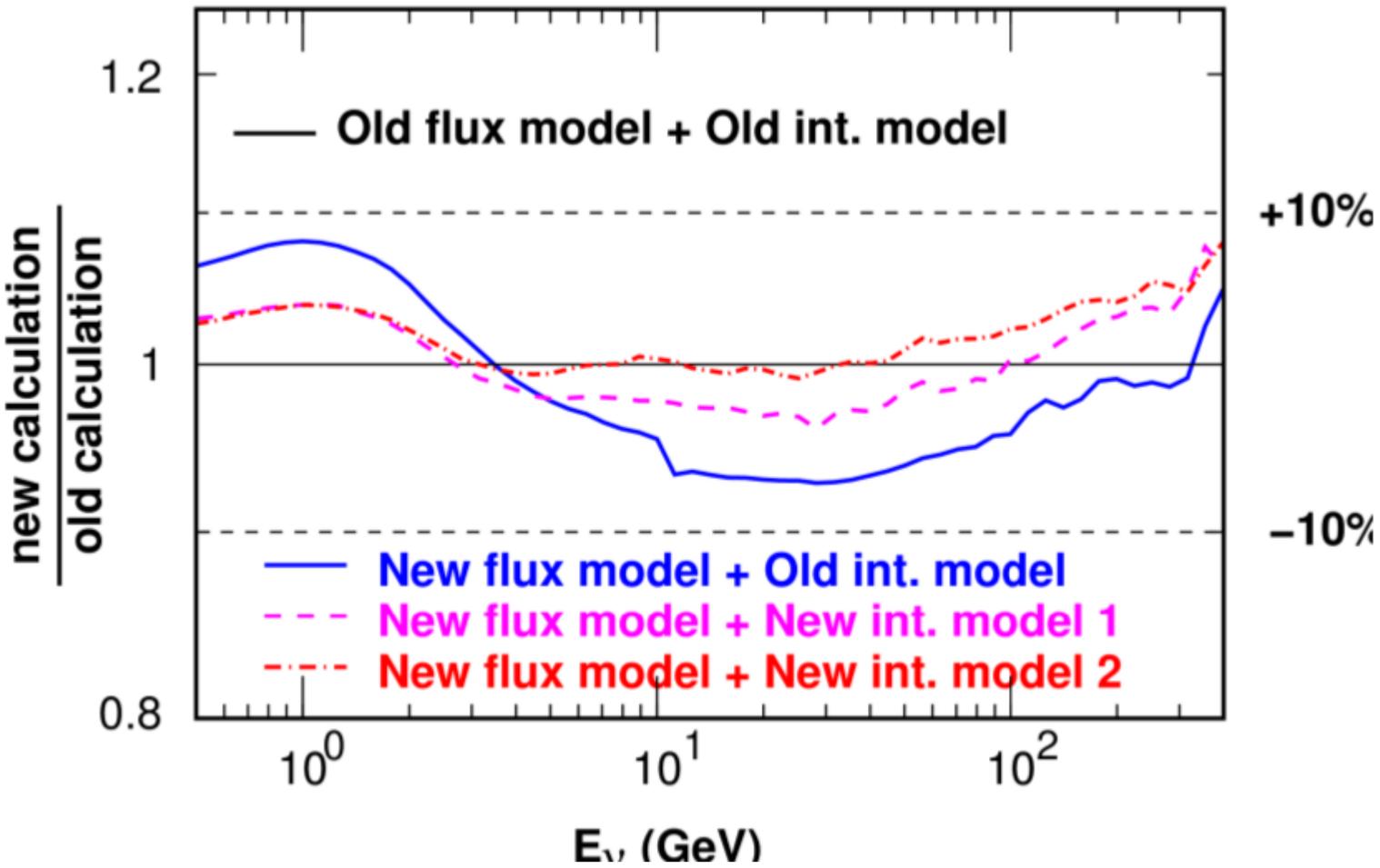
HKKM CR flux

Honda
AtmNuWorkshop 2016



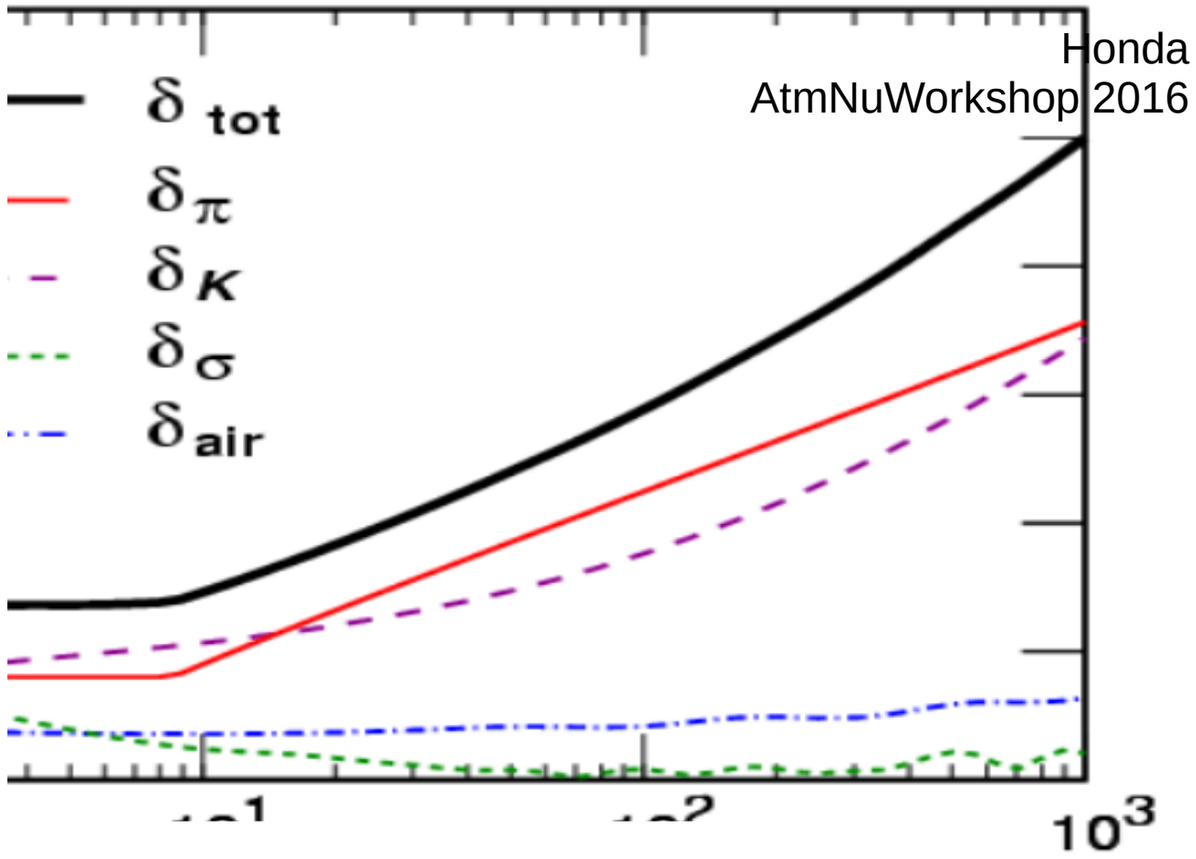
HKKM neutrino flux updates

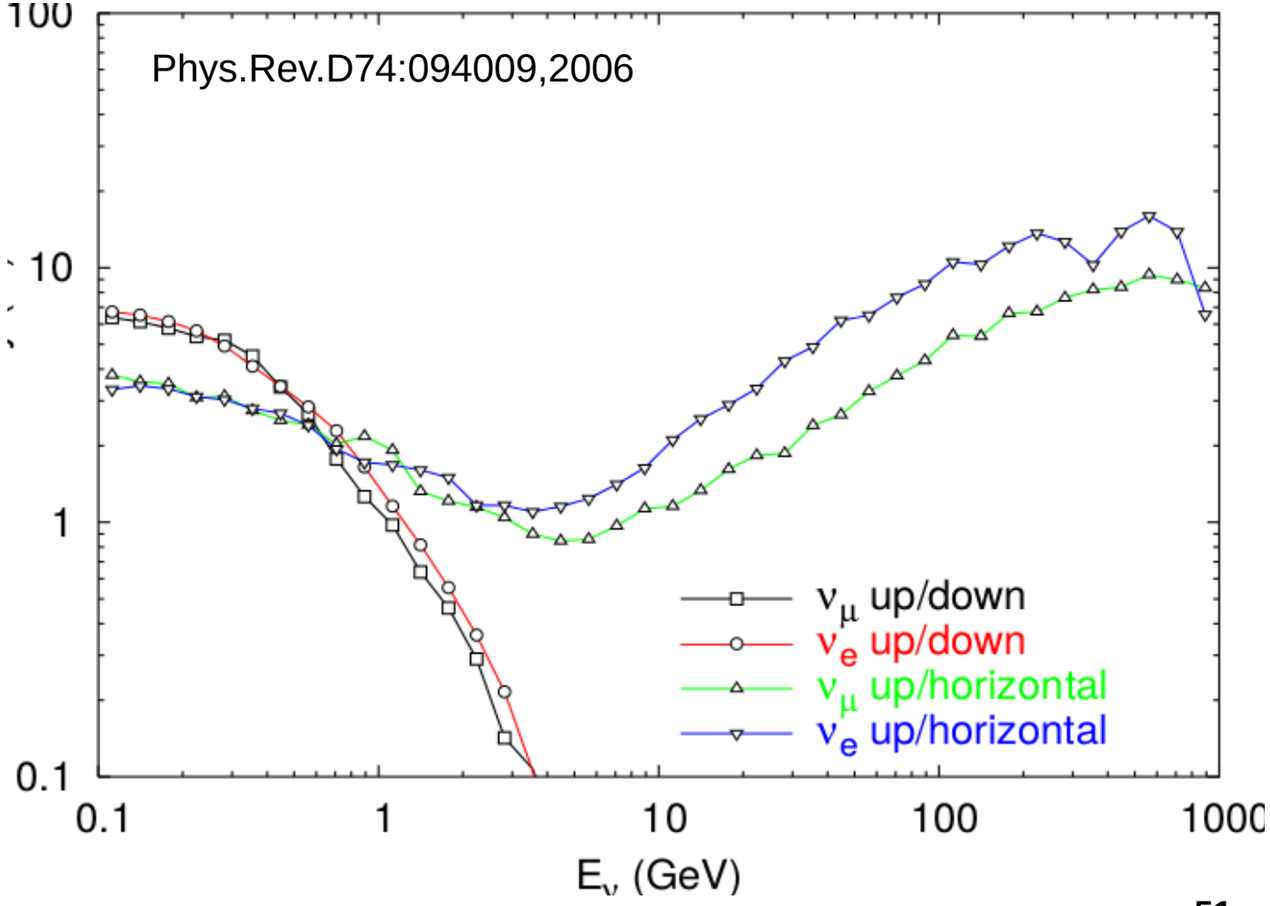
Honda
AtmNuWorkshop 2016



atmospheric neutrino flux

-and its uncertainties





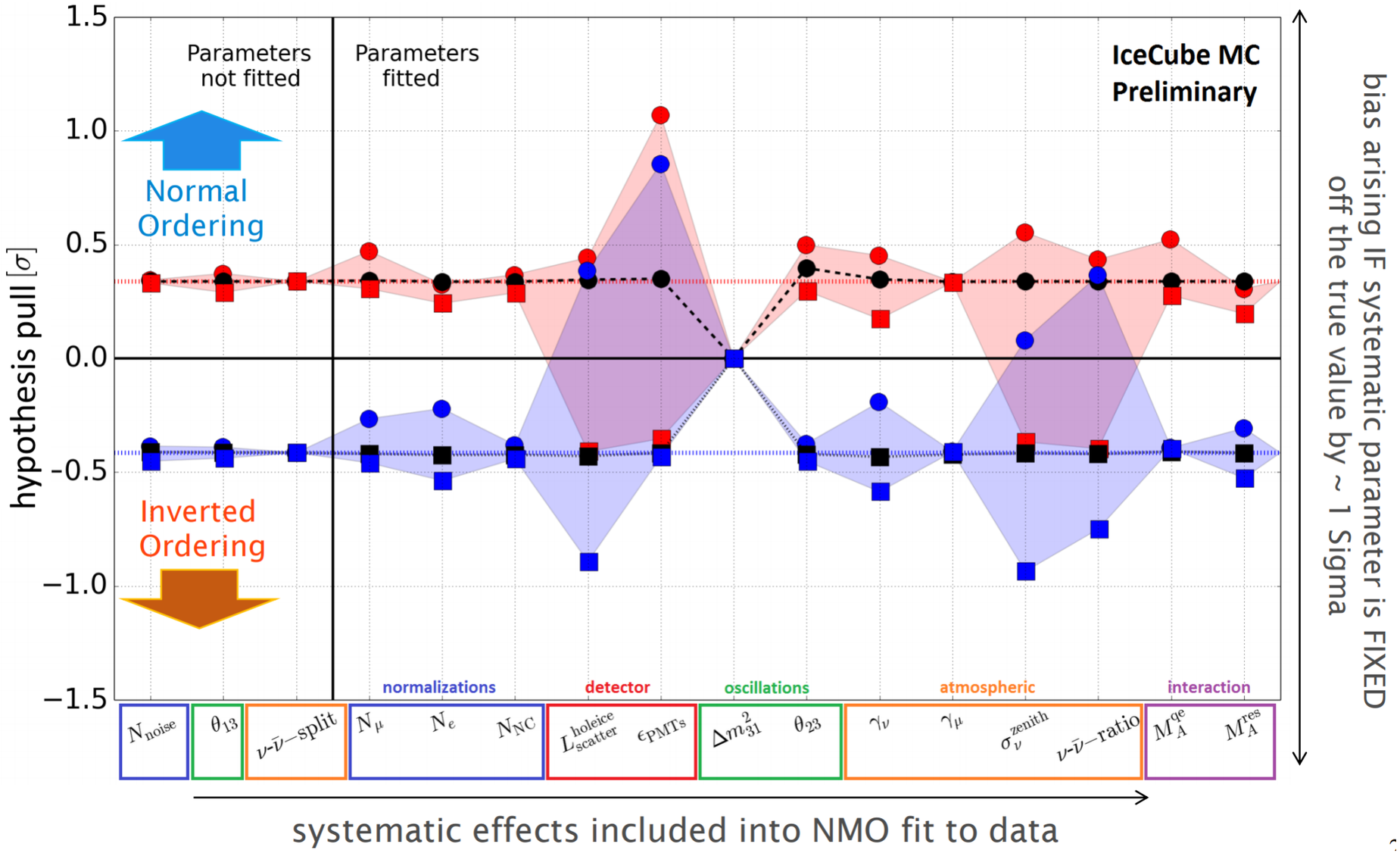
VLVNTs vs beam experiments

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.

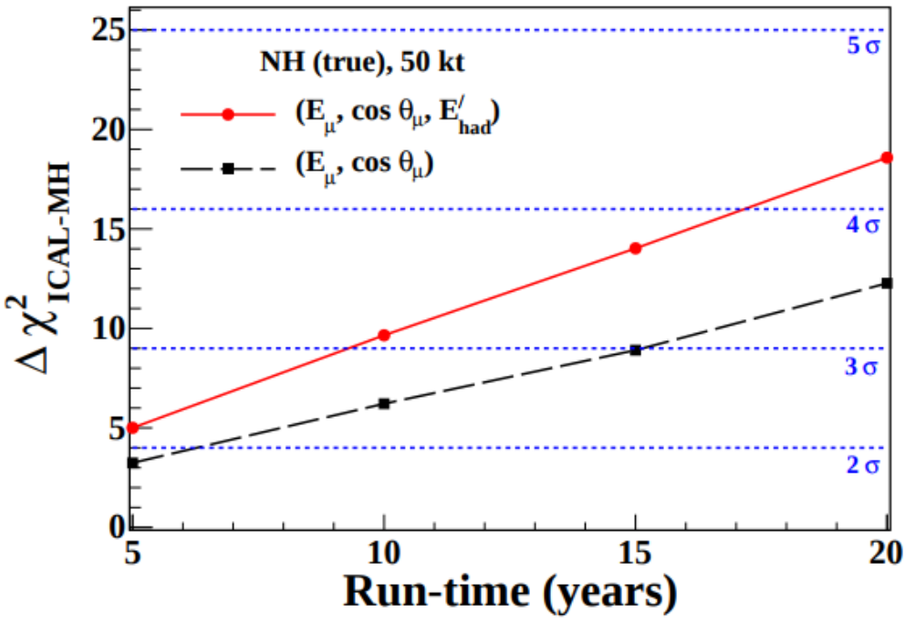
	Parameter	VLVNT		SK	MINOS, T2K, and NOvA
		ANTARES	DeepCore		
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% ± 22%	25% at 20 GeV	3% 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 $\nu_e, \overline{\nu}_e, \nu_\mu$, and $\overline{\nu}_\mu$			Accelerator: $\nu_\mu/\overline{\nu}_\mu$ 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)

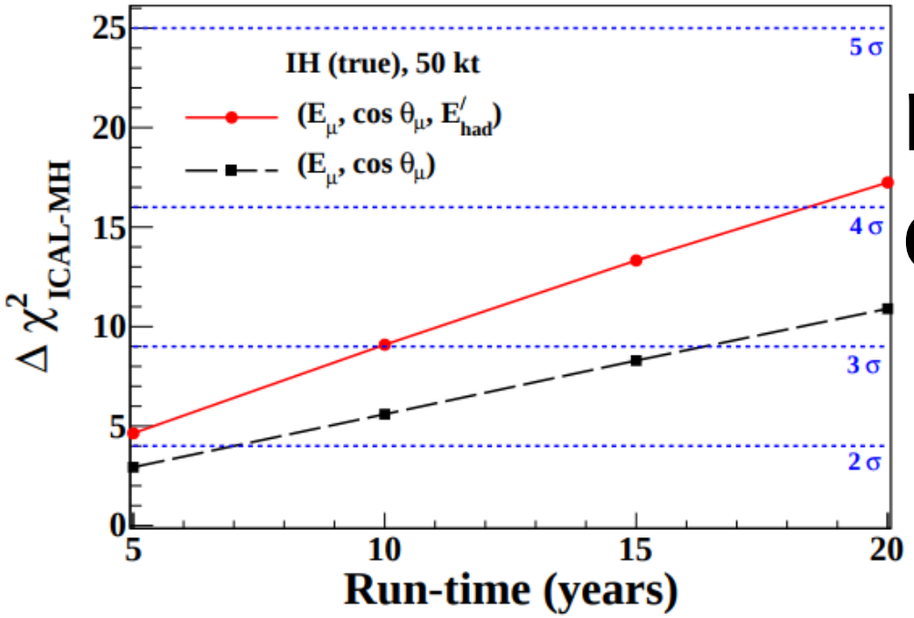
arXiv:1509.08404 [hep-ex]

NMO in IceCube DeepCore



INO

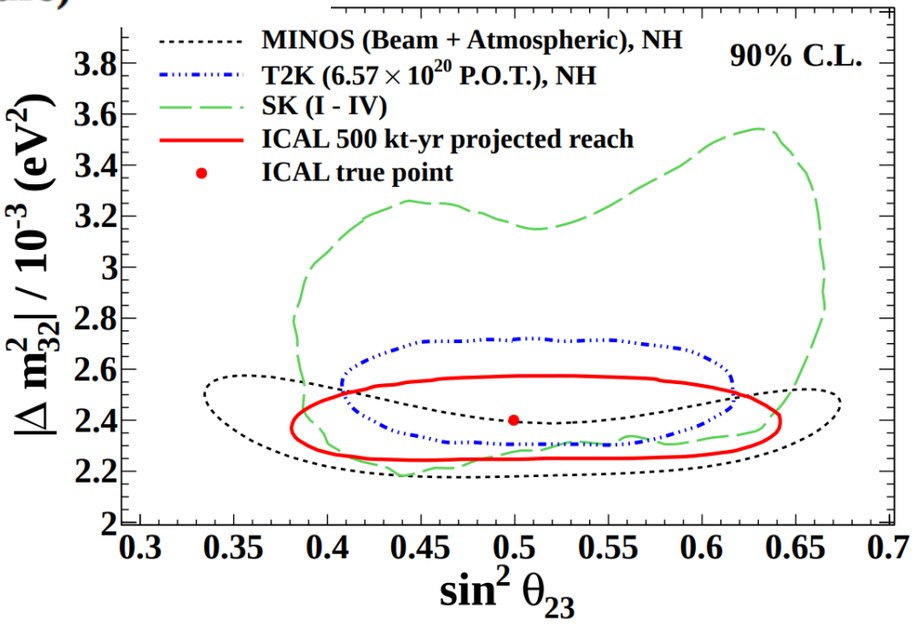




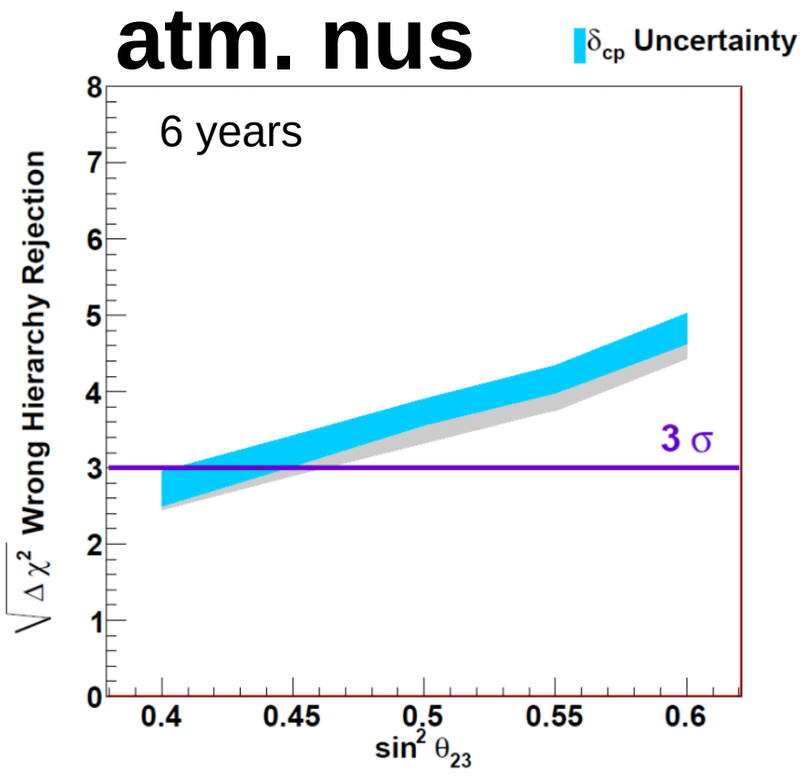
mass ordering

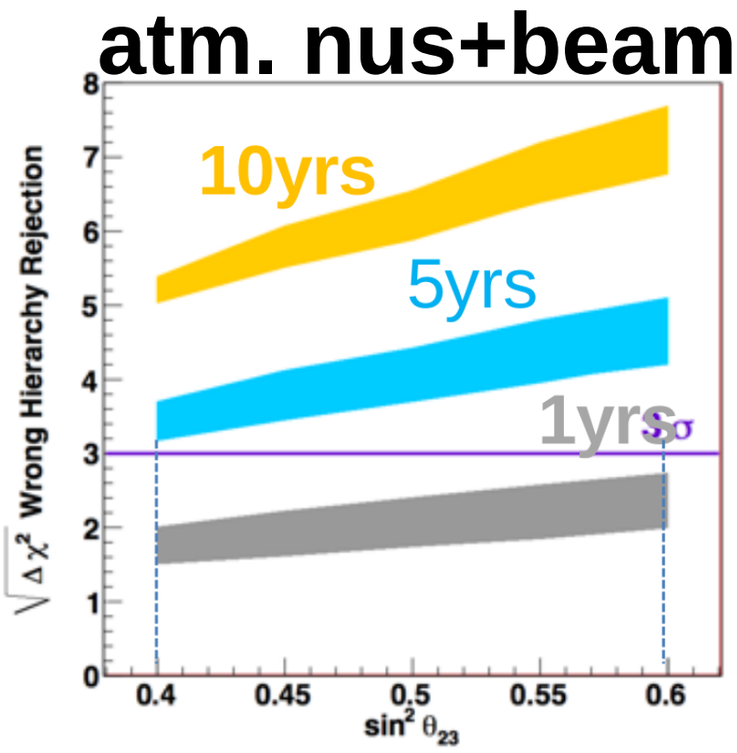
arXiv:1406.3689 [hep-ph]

oscillation parameters after 10 years of run-time



Hyper-Kamiokande (one tank)

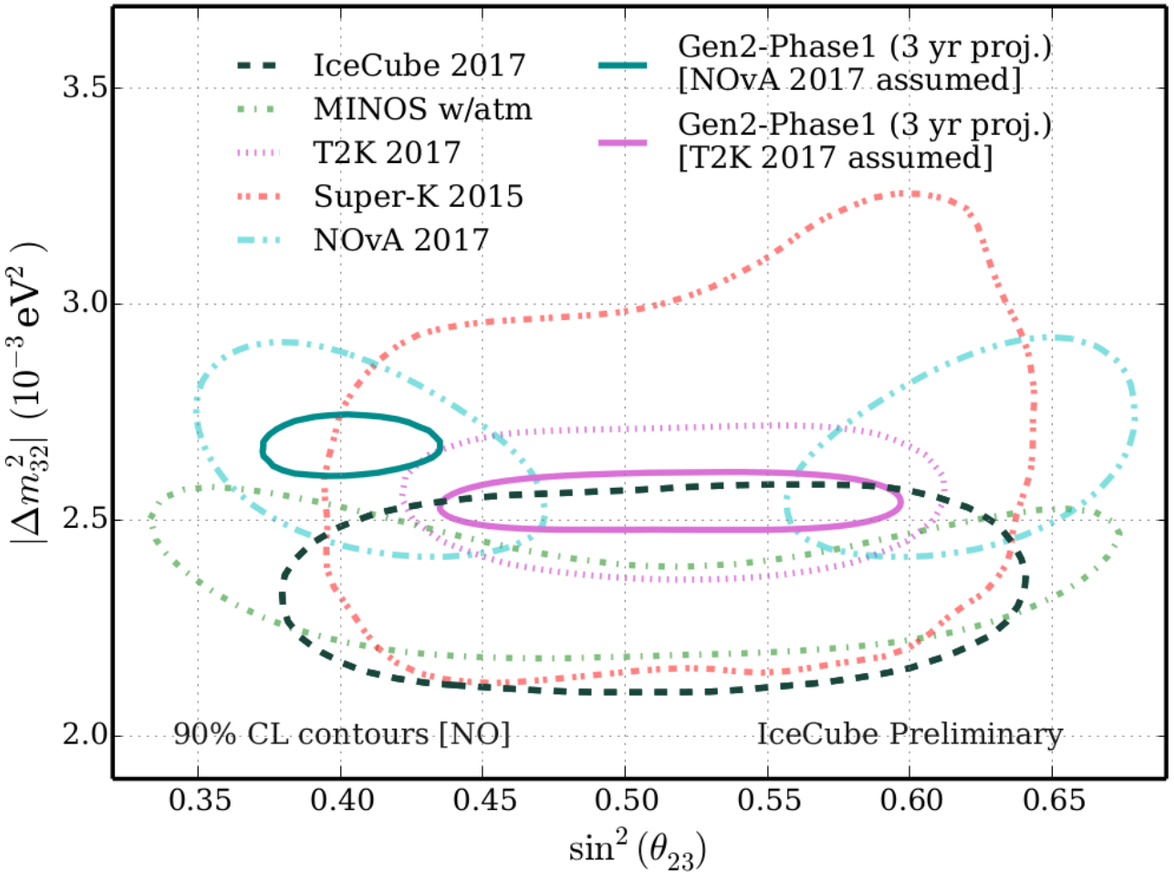




CP-violation after 10 years (beam)

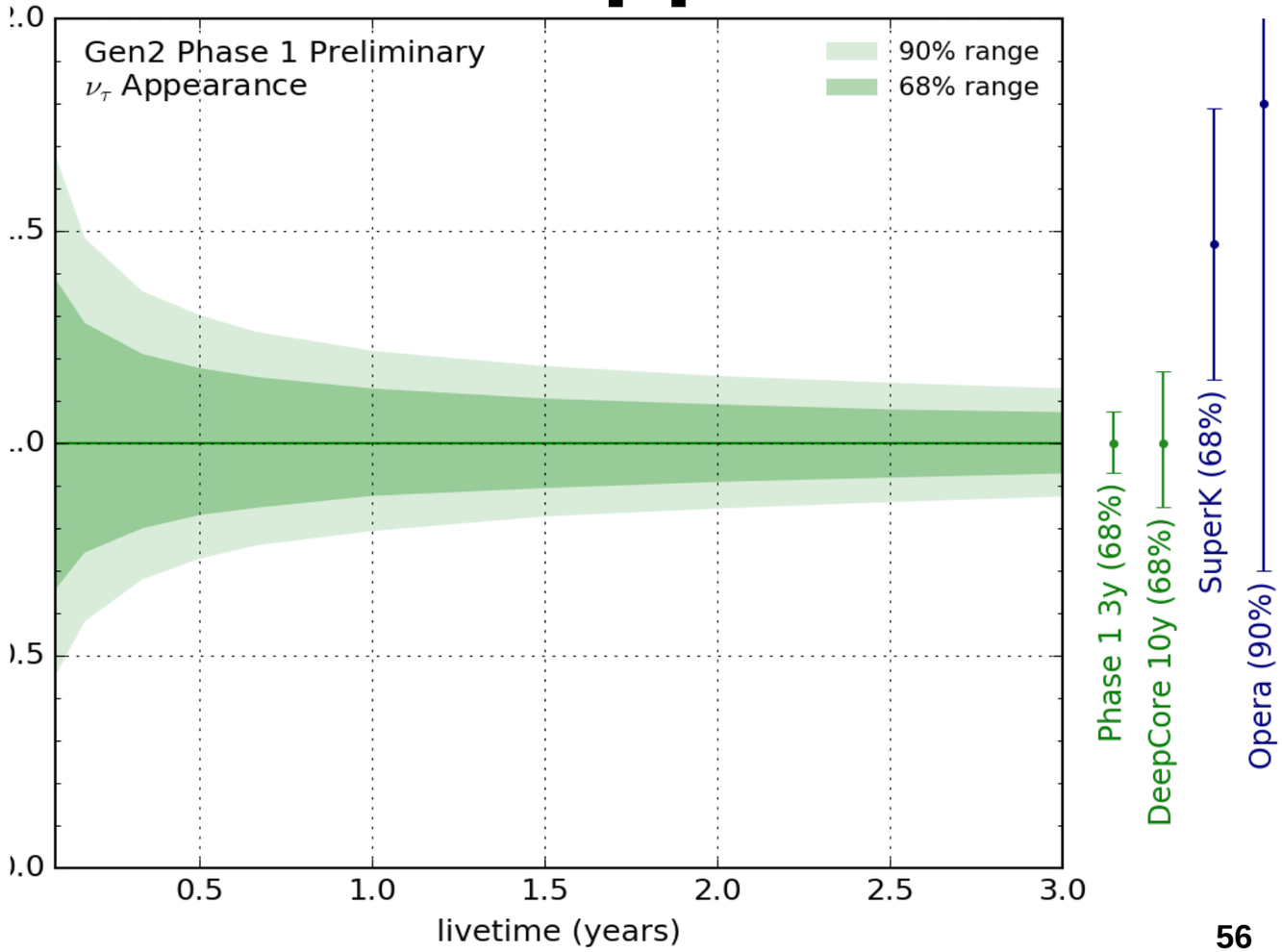
Zsoldos, ICRC2017

IceCube-Gen2 Phase1

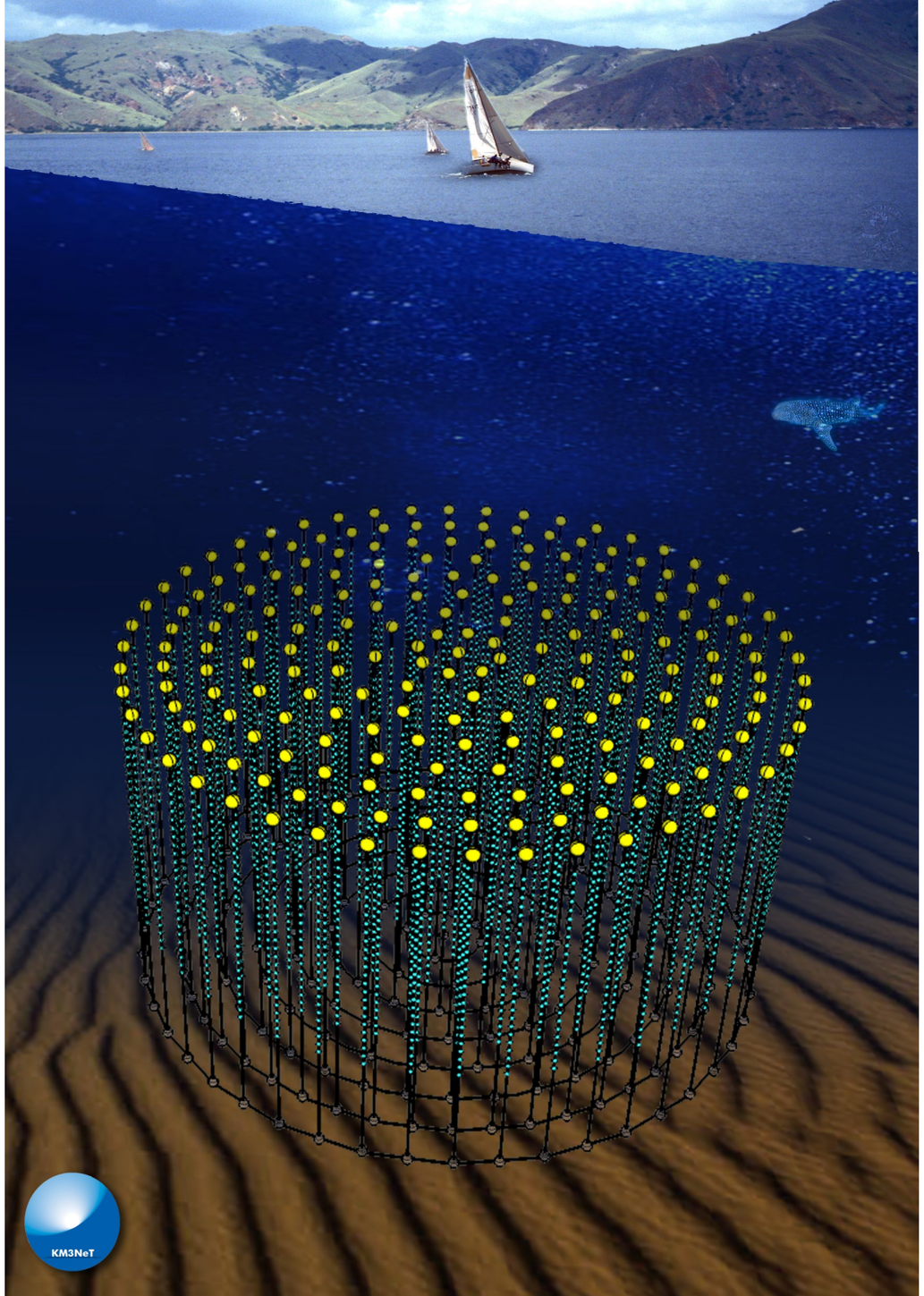


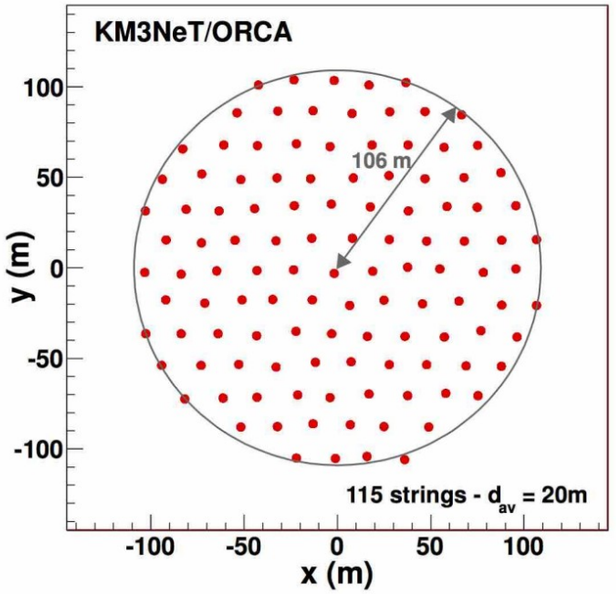
osc. parameters

nutau appearance



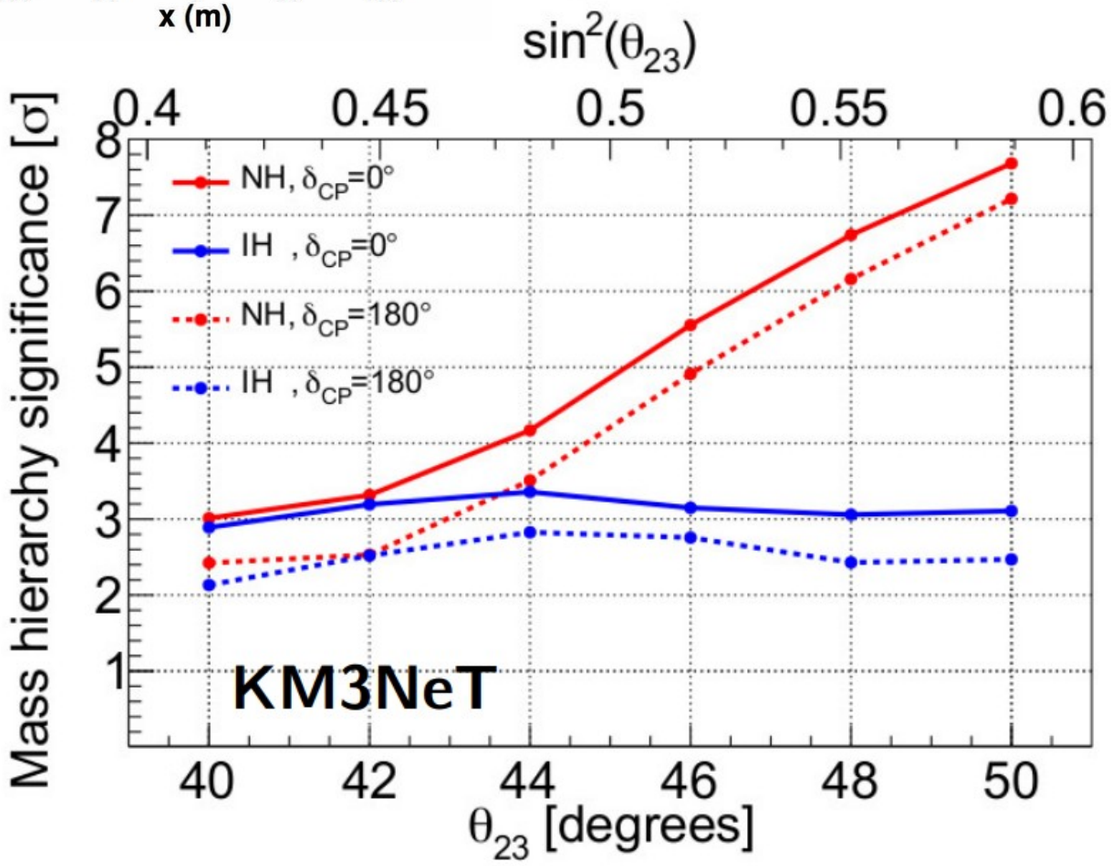
ORCA





mass ordering (3y)

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



NMO

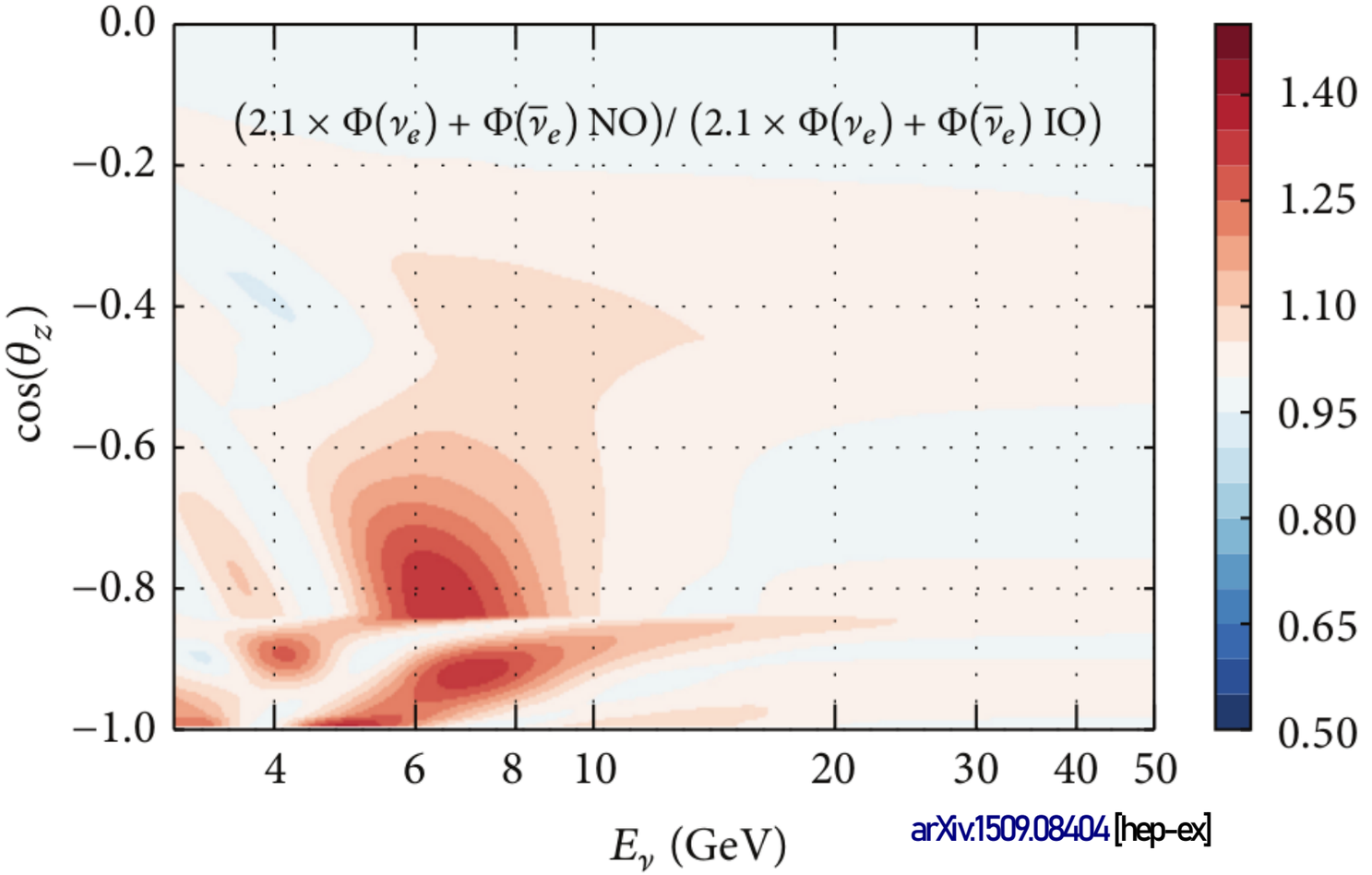


FIGURE 5: Expected interaction rate of electron neutrinos and antineutrinos predicted by a NO over the rate predicted assuming an IO. Using the oscillation parameters in [3]. Because of the flux ratio $\nu_\mu/\bar{\nu}_\mu$ and the cross section difference, estimated to be 2.1 times larger for neutrinos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