Results from the Search for eV-Sterile Neutrinos with IceCube

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TEVPA, SEPTEMBER, 2016

Massachusetts Institute of Technology

(arXiv:1605.01990)

Today

- Neutrino oscillations and matter effects
- IceCube
- The IceCube sterile neutrino search

Today

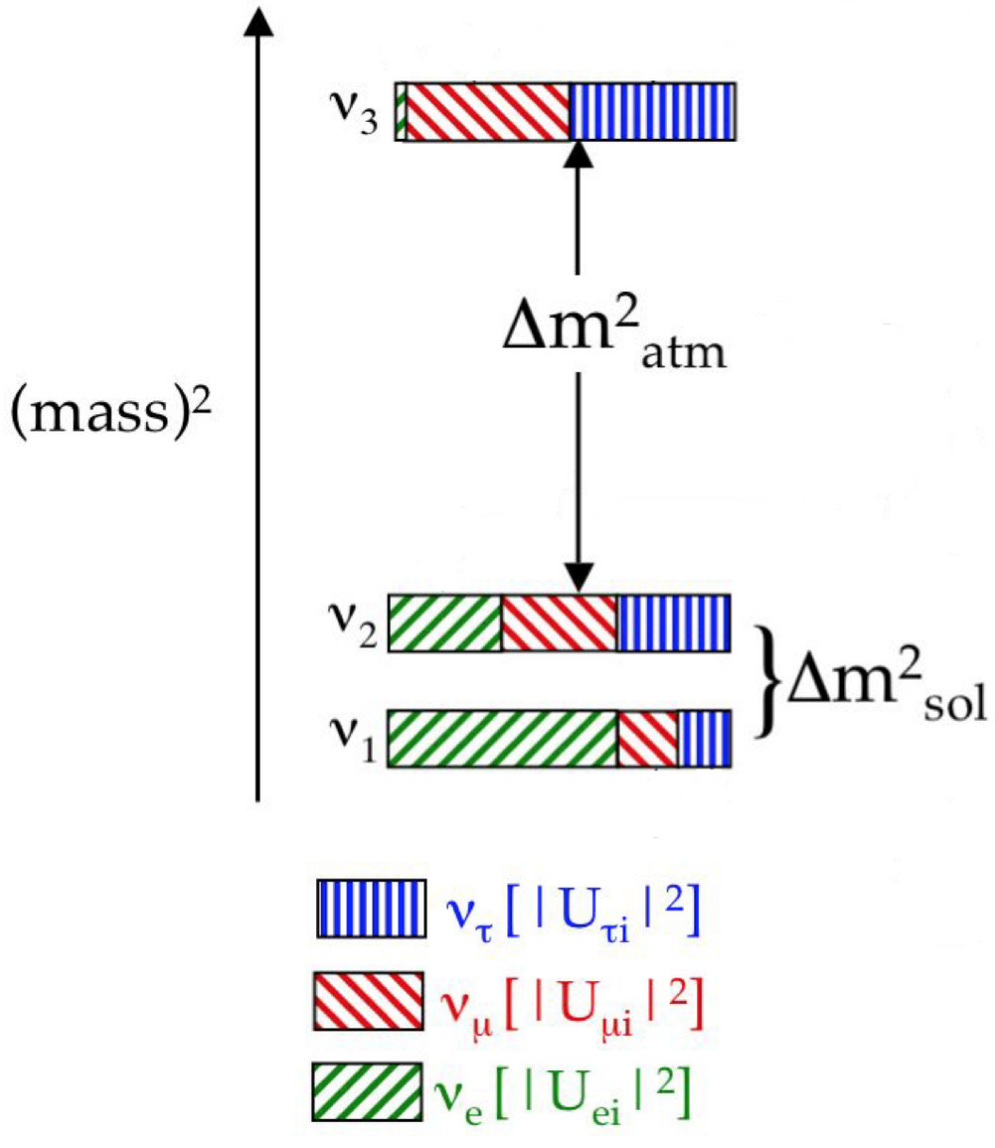
➡**Neutrino oscillations and matter effects**

➡IceCube

➡The IceCube sterile neutrino search

Our current picture

Neutrino oscillations : mass eigenstates (ν_i; $i = 1, 2, 3$) and flavor eigenstates (ν_α; $\alpha = e, \mu, \tau$) are not the same.



$$\Delta m^2_{\rm sol} = 7.5 \times 10^{-5} {\rm eV}^2$$
$$|\Delta m^2_{\rm atm}| = 2.4 \times 10^{-3} {\rm eV}^2$$

$$\nu_i = \sum_\beta U_{\beta i} \nu_\beta$$

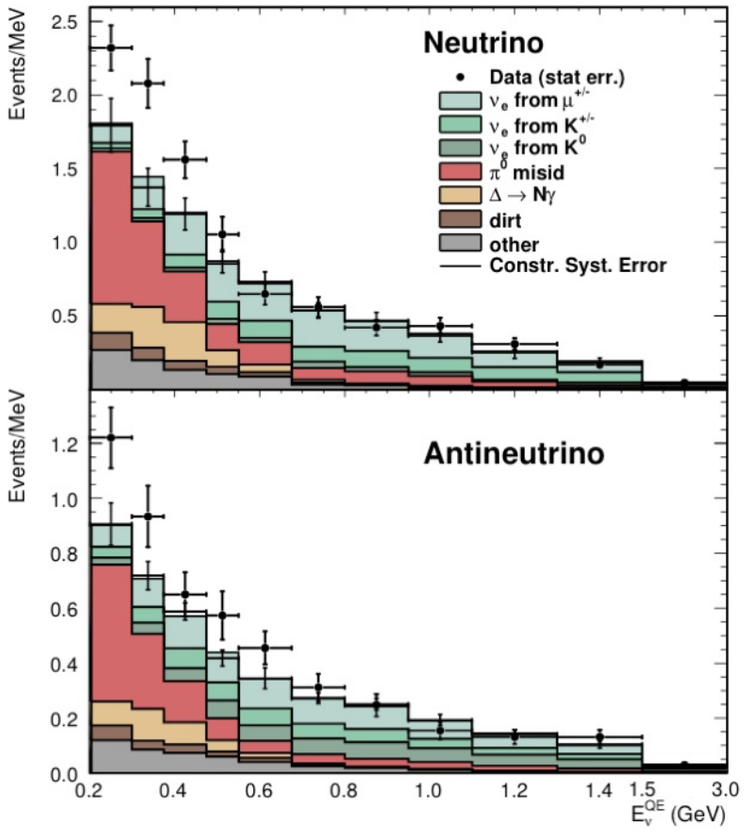
$$U = {\rm U}(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})$$

$$|{\rm U}| \simeq \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix}$$

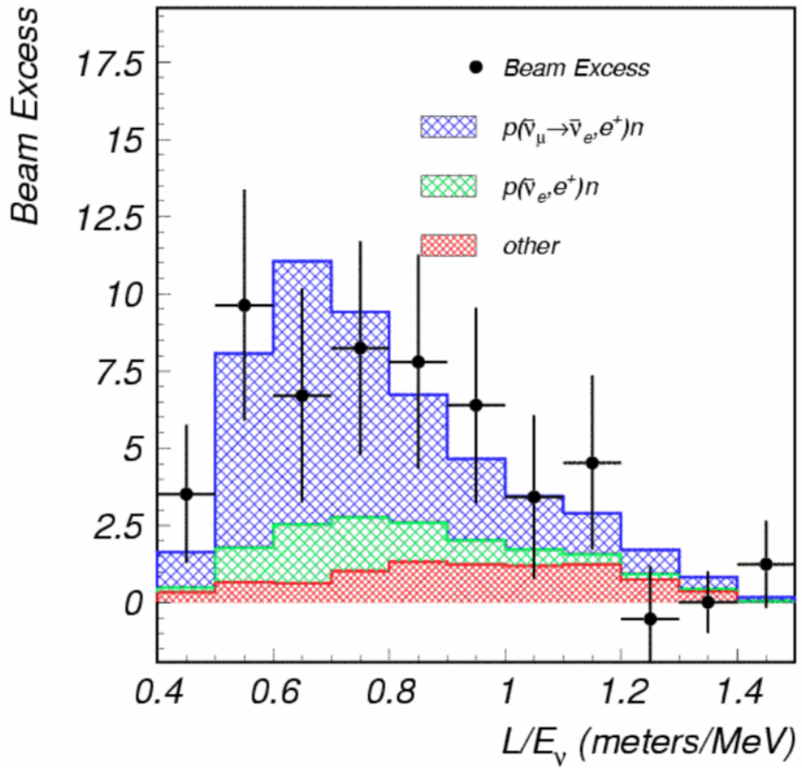
[B. Kayser, hep-ph/0506165 (2004)]

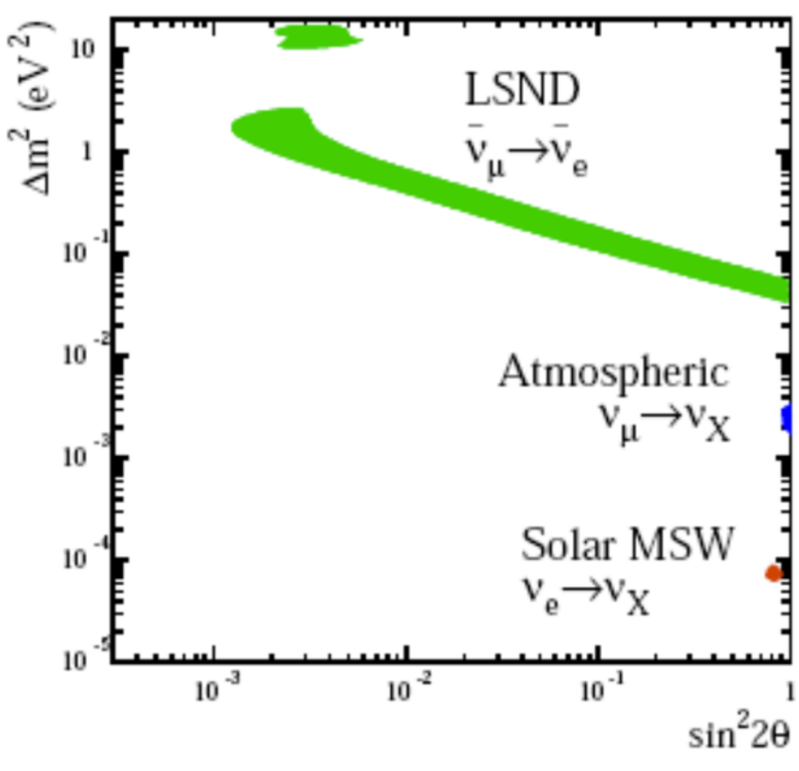
[C. Gonzalez-Garcia et al., JHEP 12 (2012)]

The pieces that do not fit …



Oscillation Channel	Class	Experiments	Oscillation amplitude
ν_e disappearance $P(\nu_e \rightarrow \nu_e)$	Reactor Experiments	GALLEX ($\bar{\nu}$) SAGE ($\bar{\nu}$) {Global Reactors}	$4\|U_{e4}\|^2 (1-\|U_{e4}\|^2)$
ν_μ disappearance $P(\nu_\mu \rightarrow \nu_\mu)$	Long/Short Baseline Experiments	Anomalous-less	$4\|U_{\mu 4}\|^2 (1-\|U_{\mu 4}\|^2)$
ν_e appearance $P(\nu_\mu \rightarrow \nu_e)$	Short Baseline Experiments	LSND ($\bar{\nu}$) MiniBooNe ($\bar{\nu}$, ν)	$4\|U_{\mu 4}\|^2 \|U_{e4}\|^2$

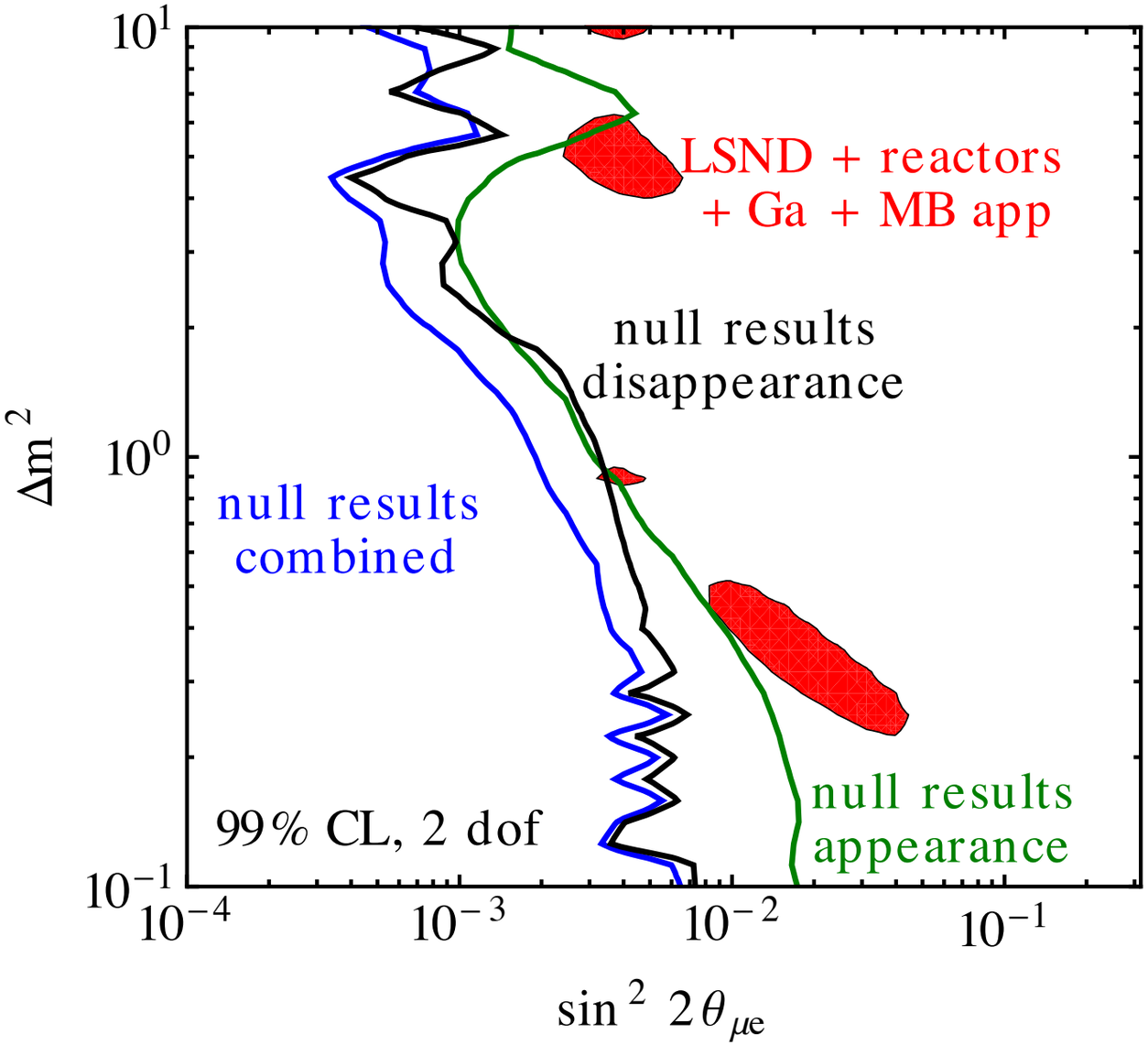




$$\Delta m^2 \sim 1\mathrm{eV}^2$$

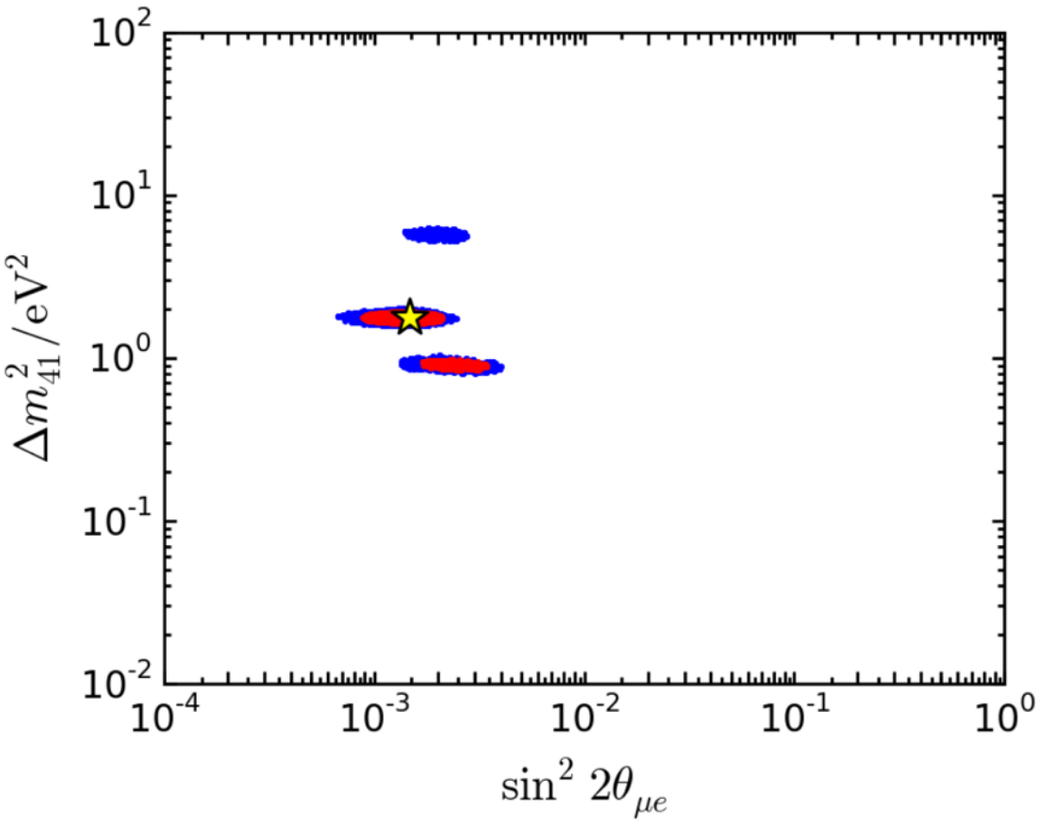
What does the World data say?

J. Kopp et al., JHEP 1305 (2013) 050



tension between experiments

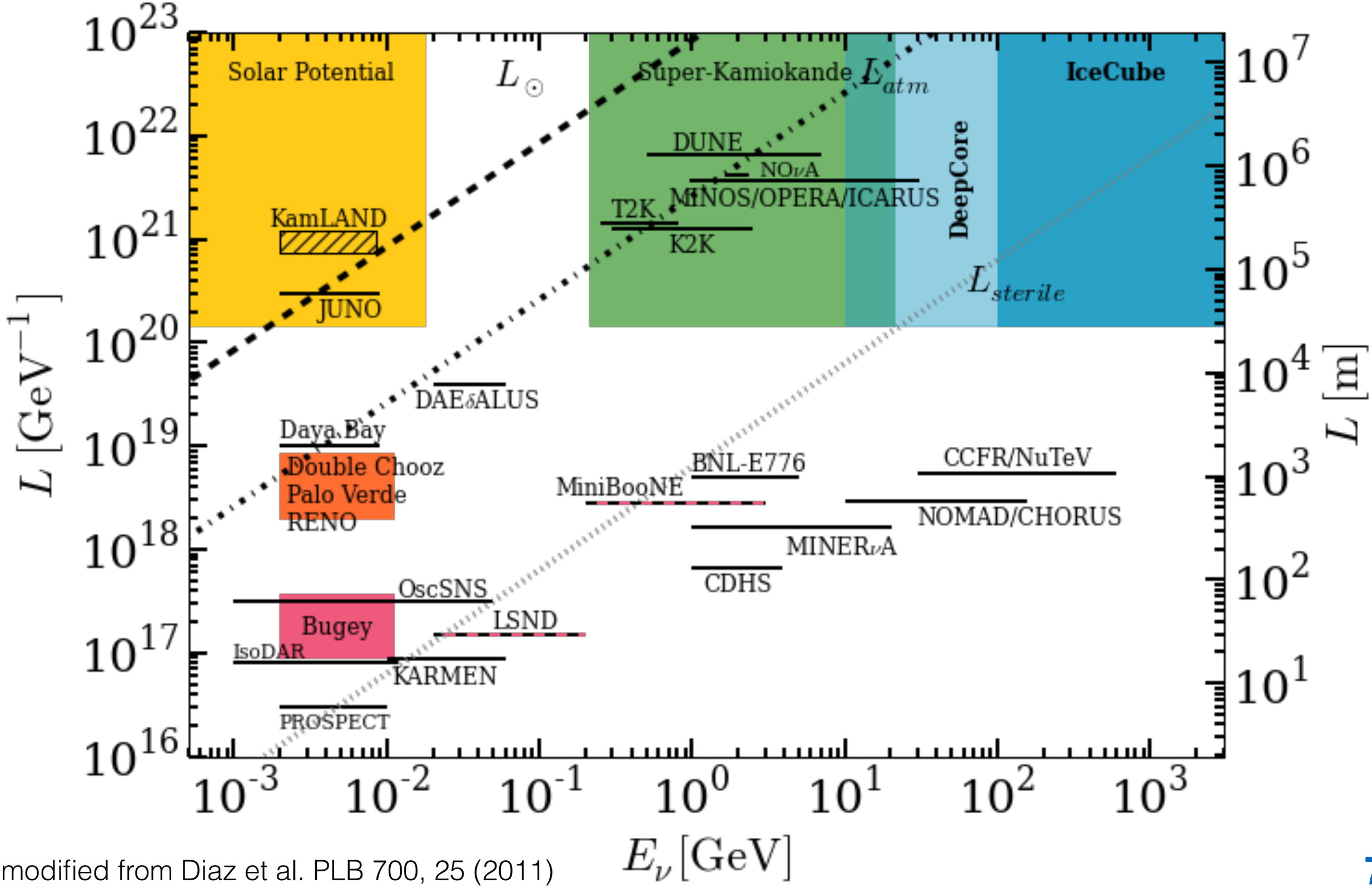
G. Collins et al., arXiv: 1602.00671



On updated fits solutions remain…

We need new measurements!

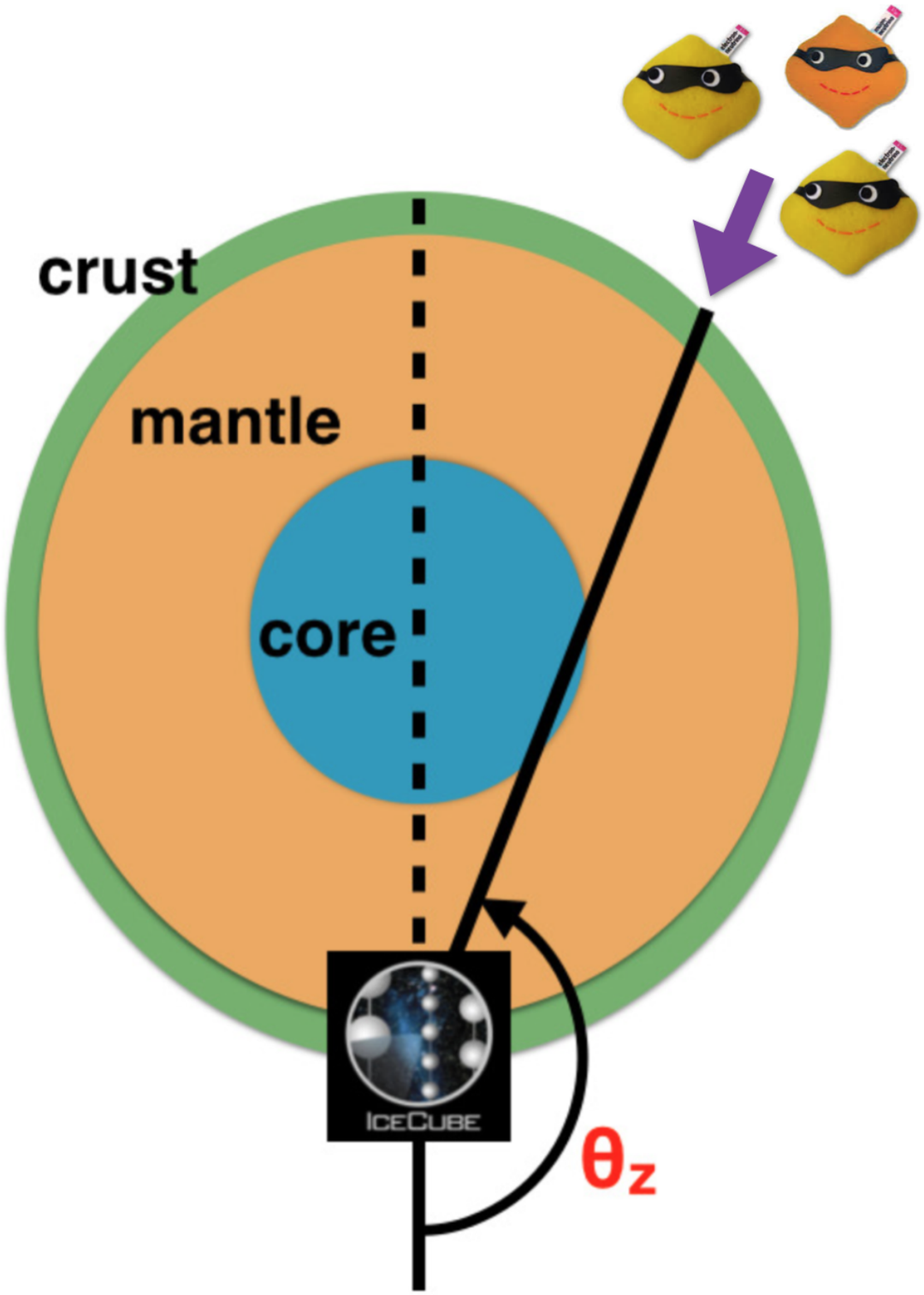
A global view: the IceCube-ShortBaseline connection



modified from Diaz et al. PLB 700, 25 (2011)

A closer look at atmospheric neutrinos oscillation

The neutrinos come from different zenith angles (θ_z) traversing different layers of the Earth



core :

$\cos\theta_z \sim [-1, -0.8]$

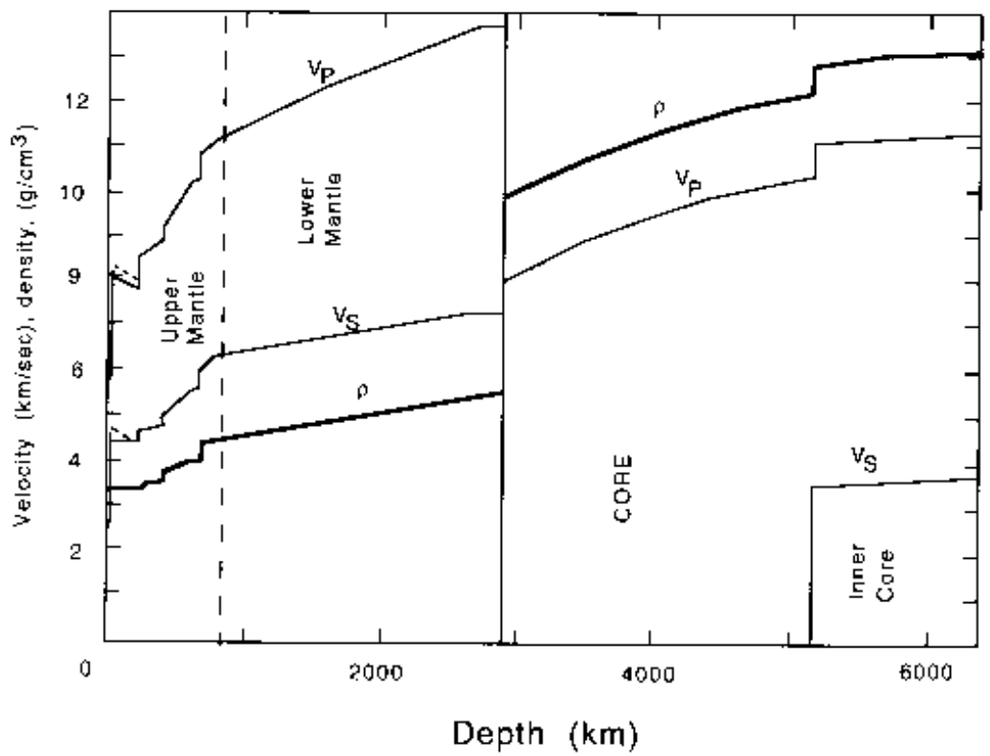
mantle :

$\cos\theta_z \sim [-0.8, -0.1]$

crust :

$\cos\theta_z > -0.1$

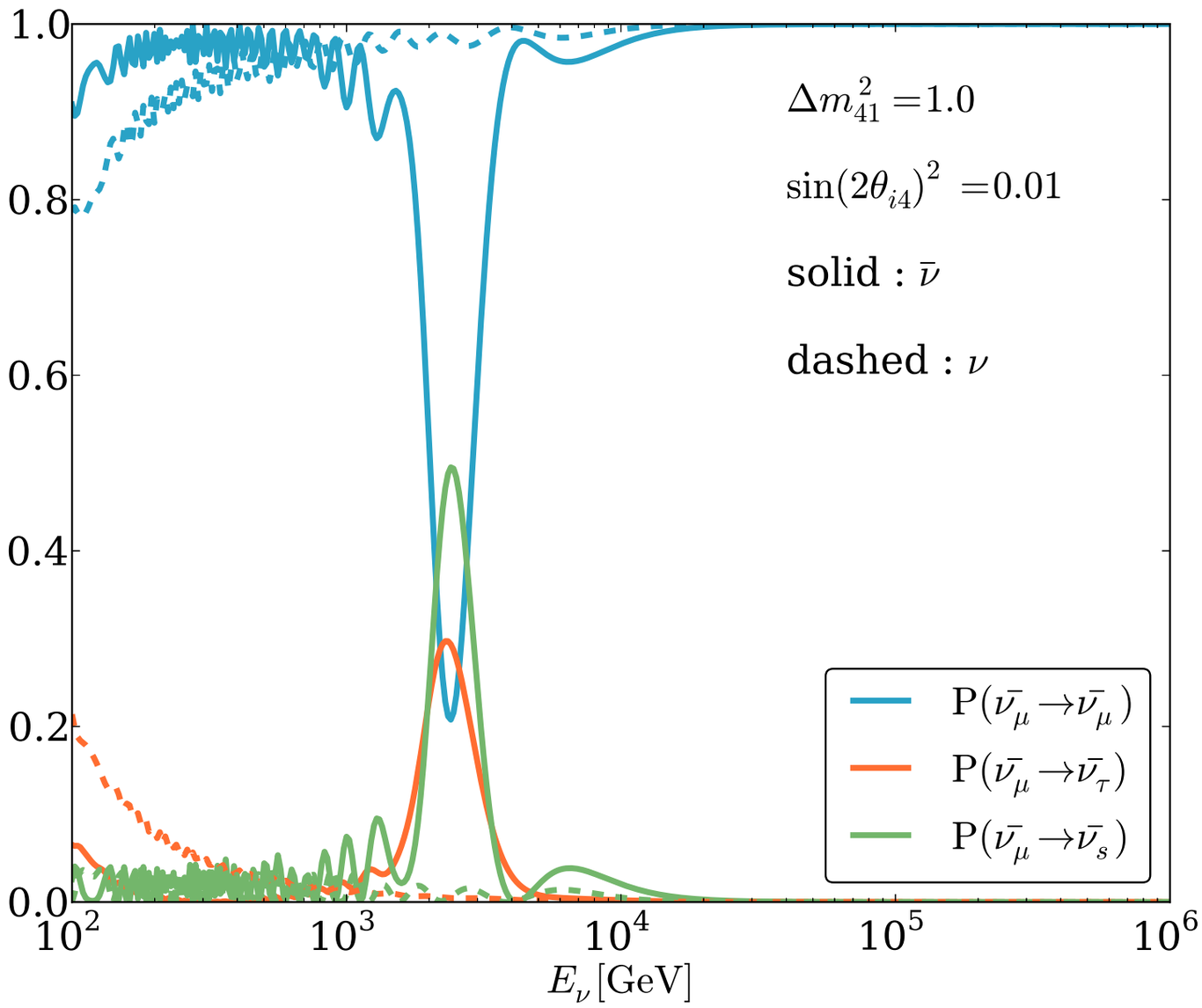
PREM, Dziewonski et al. (1981)



Stroke of luck...

In the **Earth**, for sterile neutrino of $\Delta m^2 = O(1eV^2)$ there is a matter resonant effect when

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



Nunokawa et al. PLB, B562, 279 (2003). arXiv:hep-ph/0302039

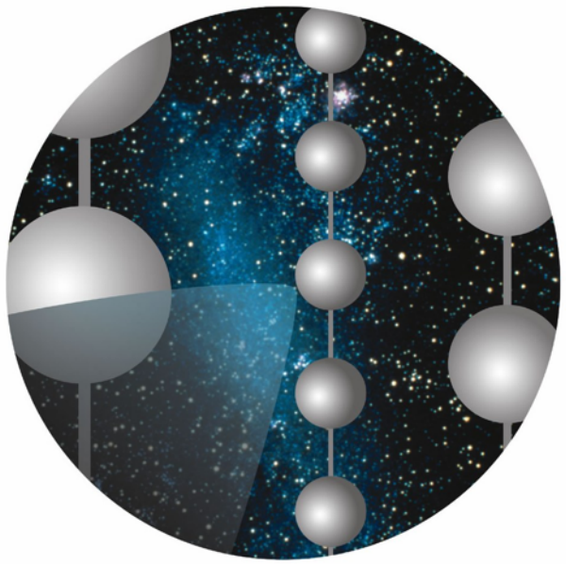
Today

➡Neutrino oscillations and the MSW effect

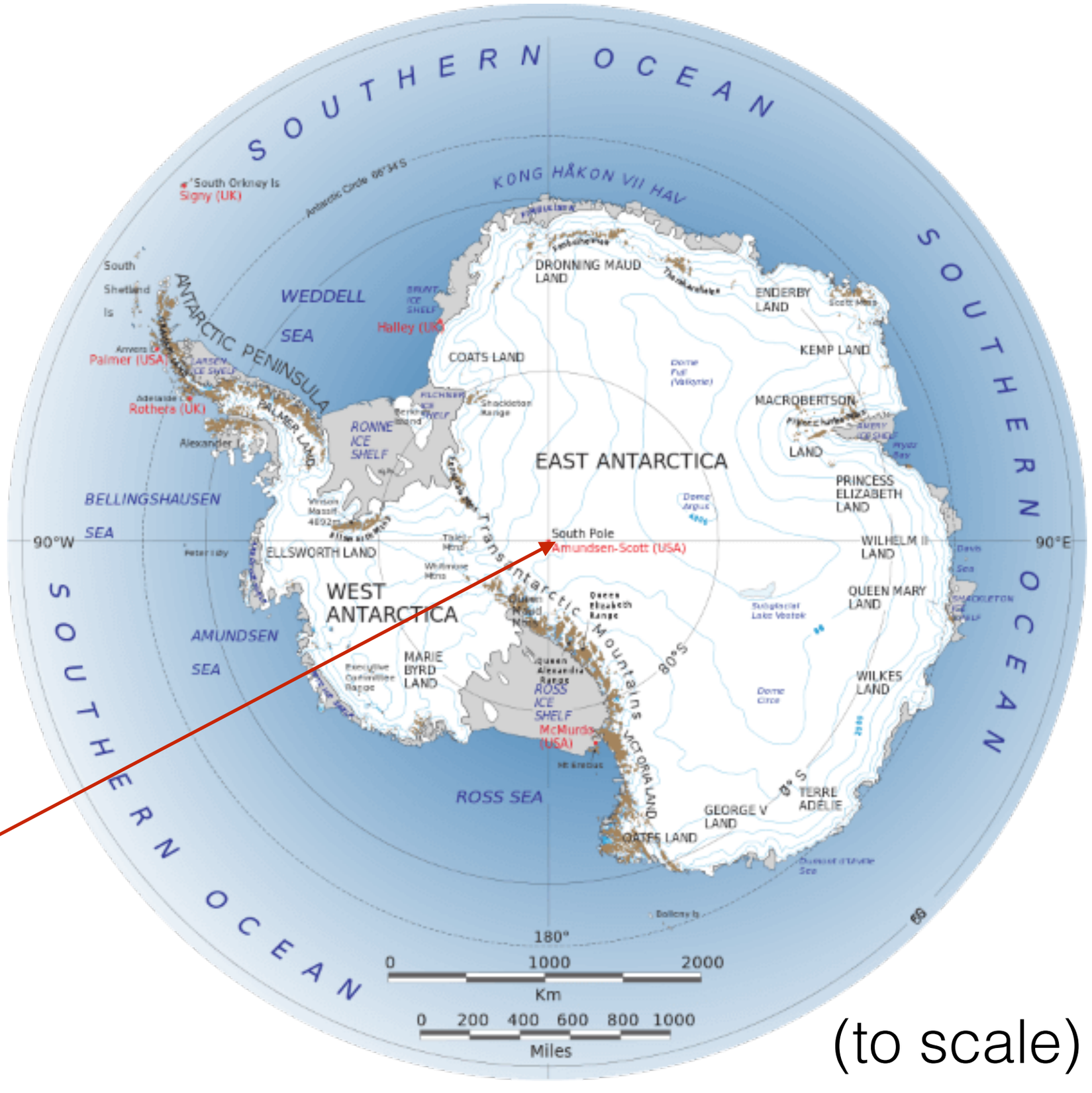
➡**IceCube**

➡The IceCube sterile neutrino search

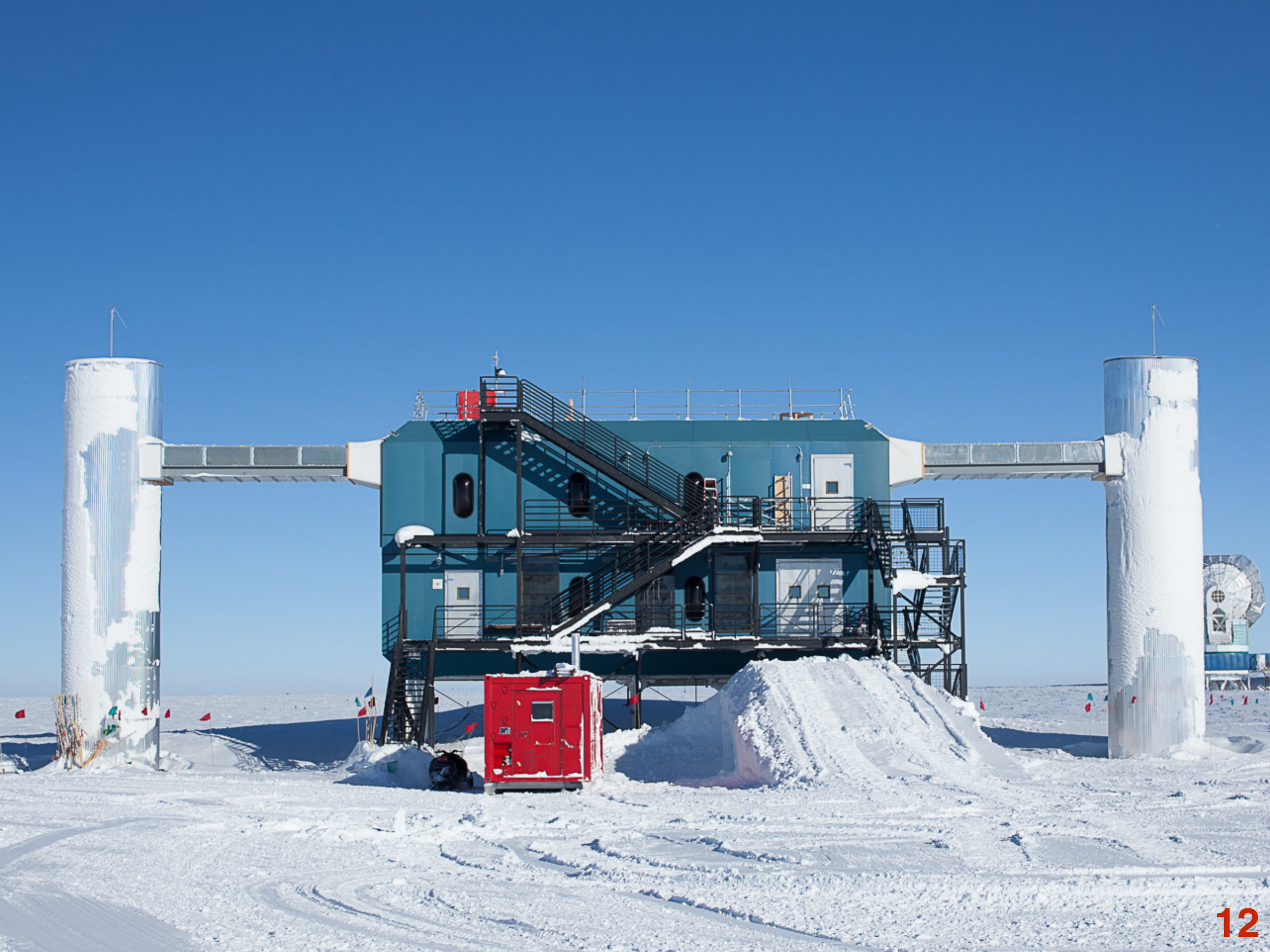
The IceCube experiment



We are here!



(to scale)



IceCube

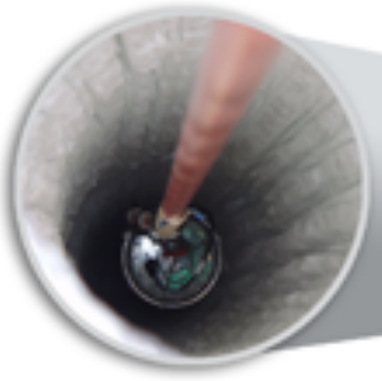
South Pole Neutrino Observatory

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

50 m

1450 m



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

86 strings of DOMs, set 125 meters apart

IceCube detector

DeepCore

Antarctic bedrock

Amundsen–Scott South Pole Station, Antarctica

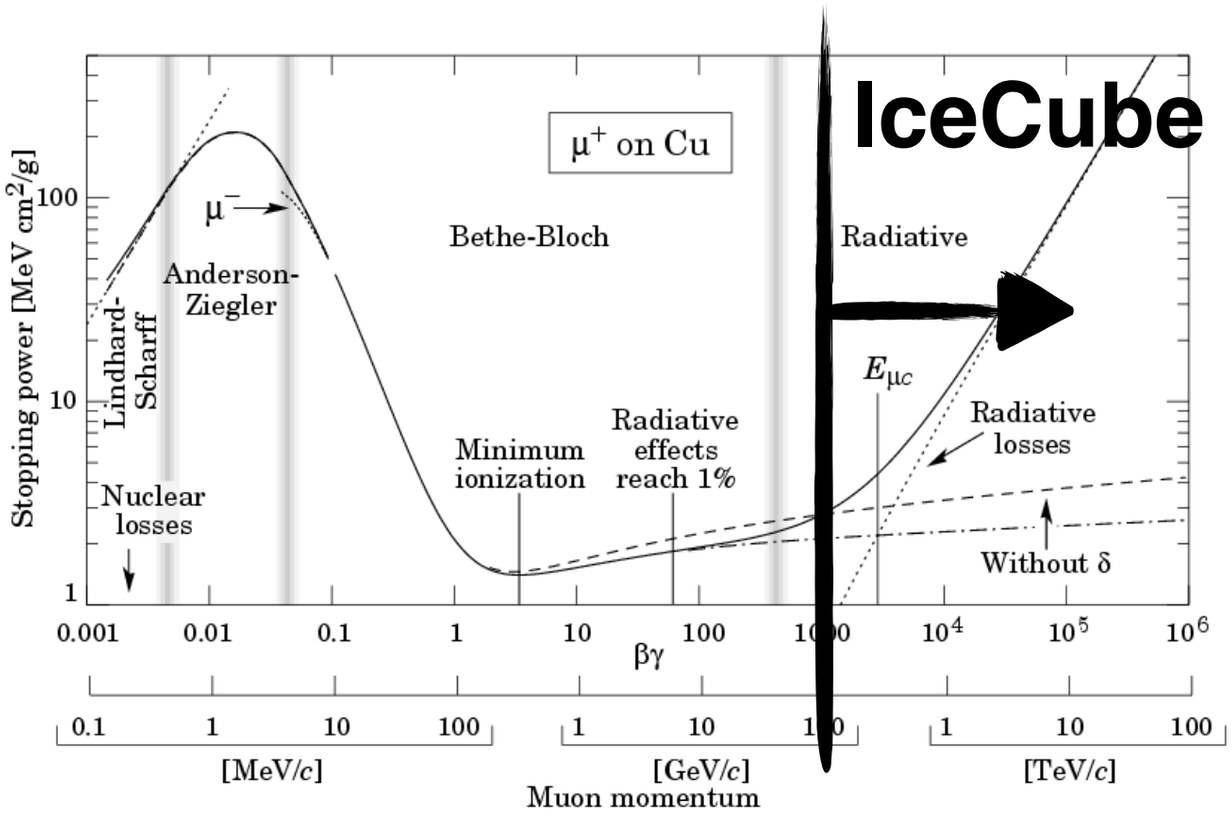
A National Science Foundation-managed research facility

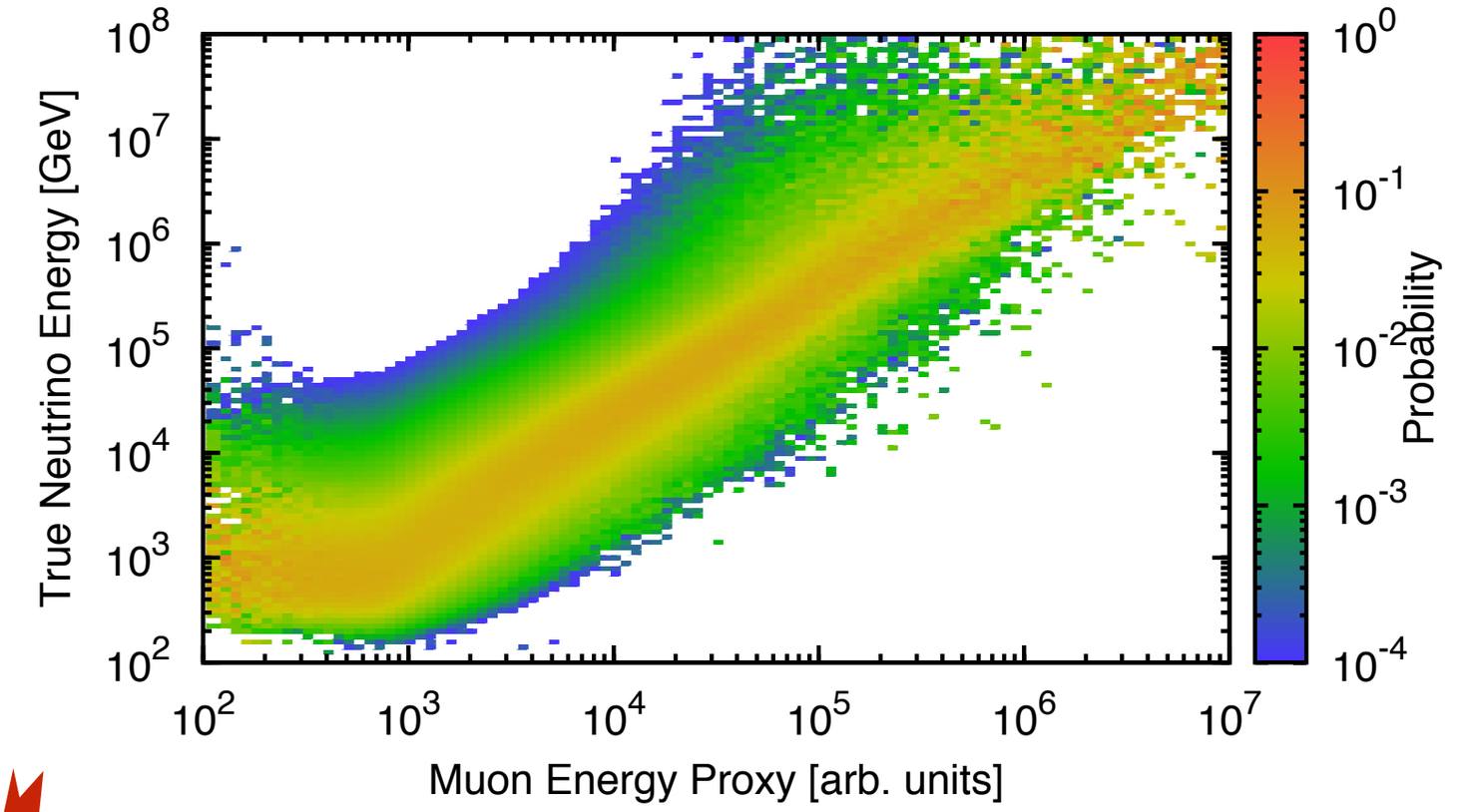
60 DOMs on each string

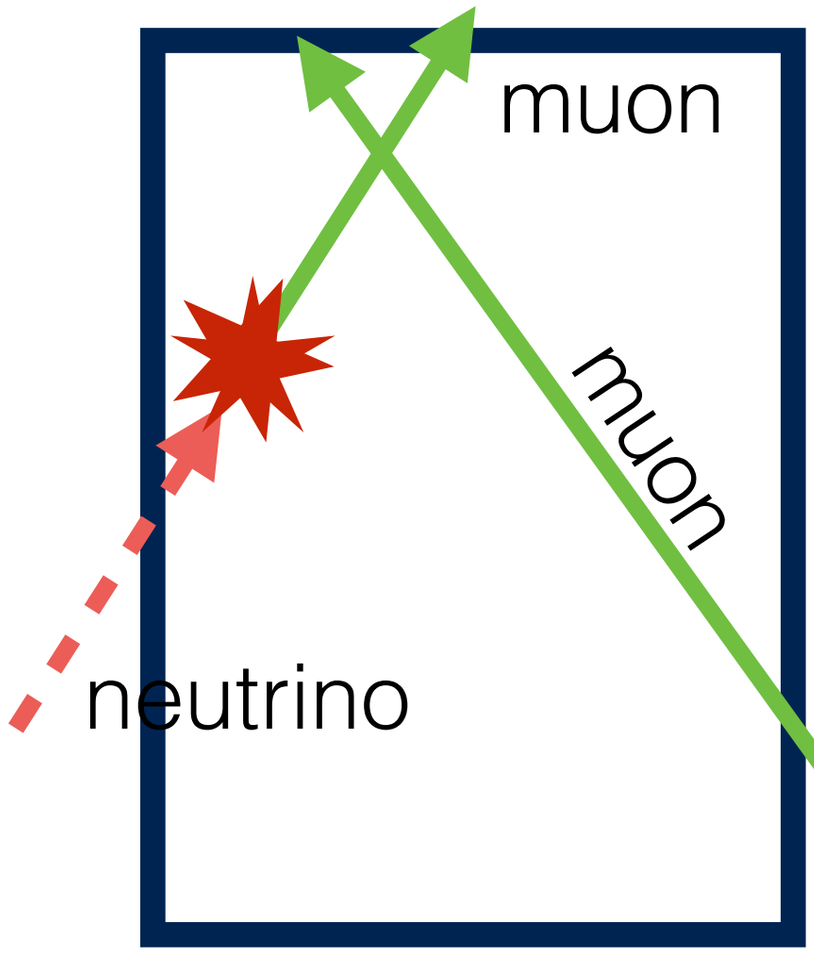
DOMs are 17 meters apart

Through-going muons in IceCube

$$\Delta\theta \sim 1^{o}$$

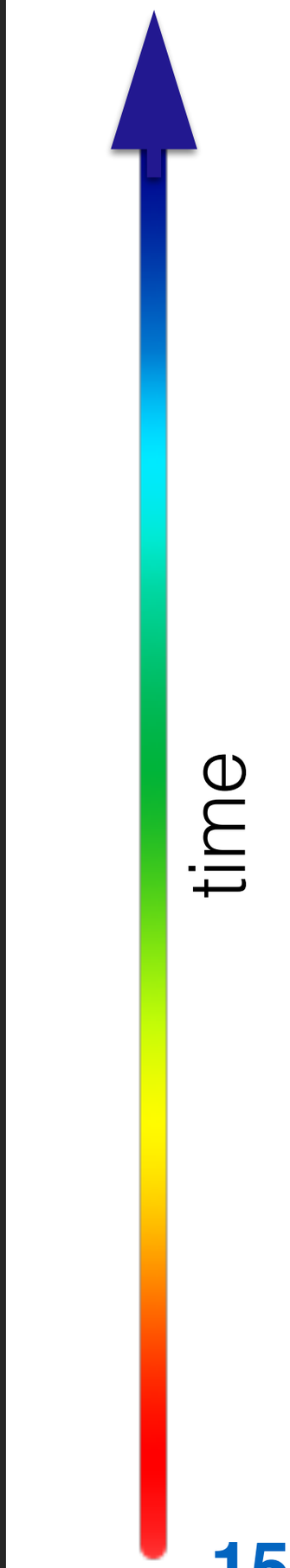




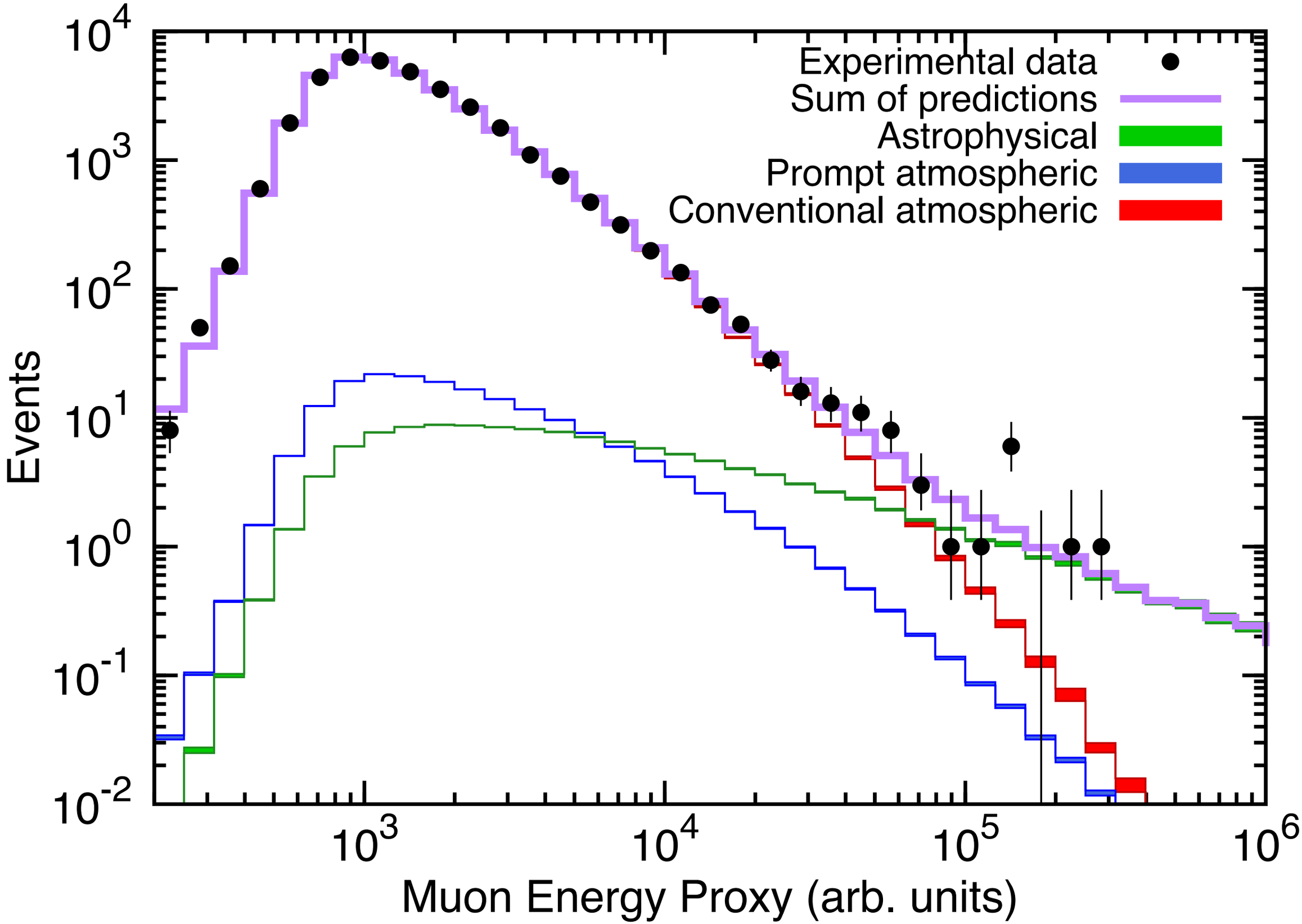


(not to scale)

What do they look like?

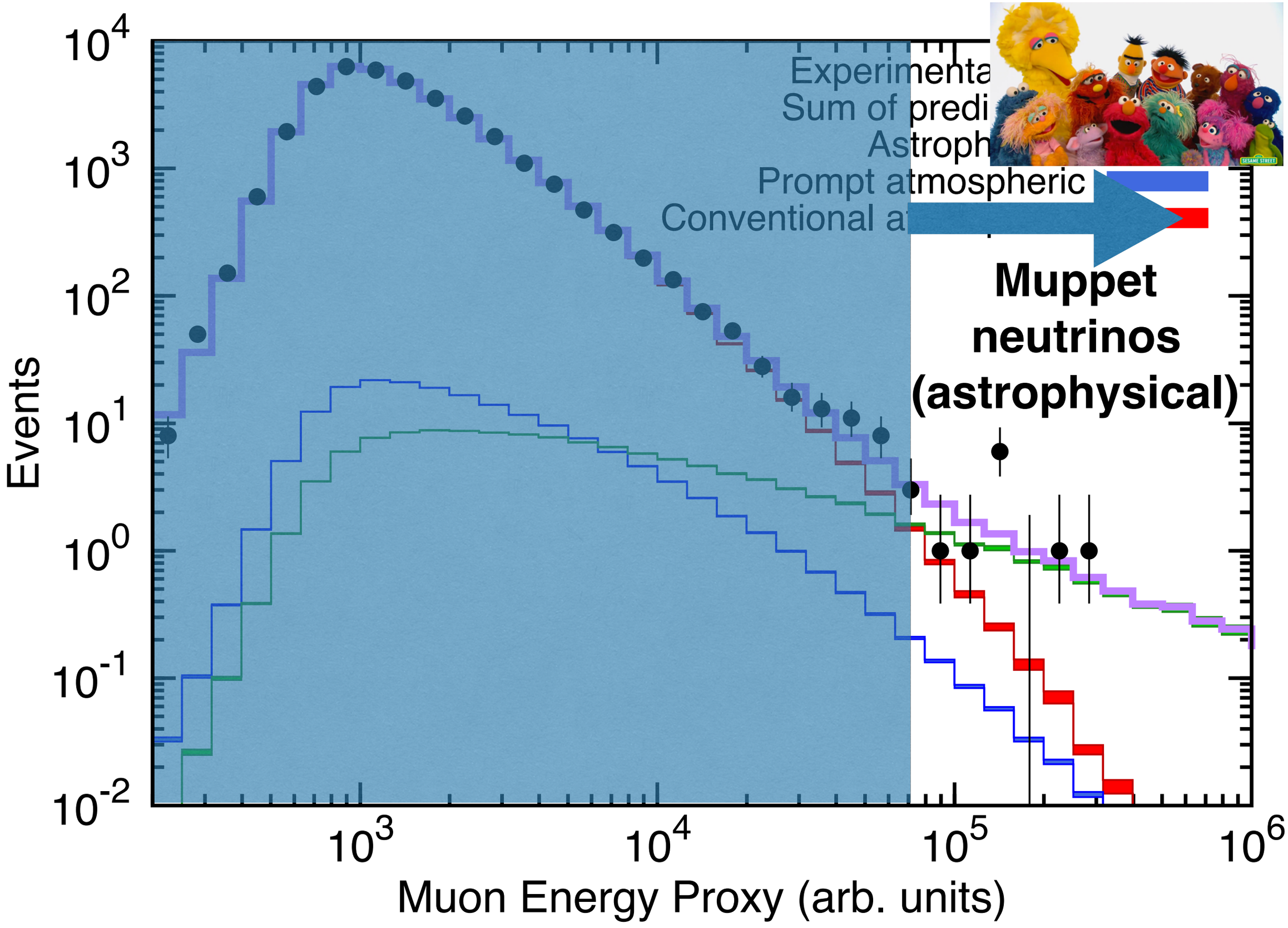


Through-going nu-mu energy distribution



Phys. Rev. Lett. 115, 081102 (2015)

Through-going nu-mu energy distribution



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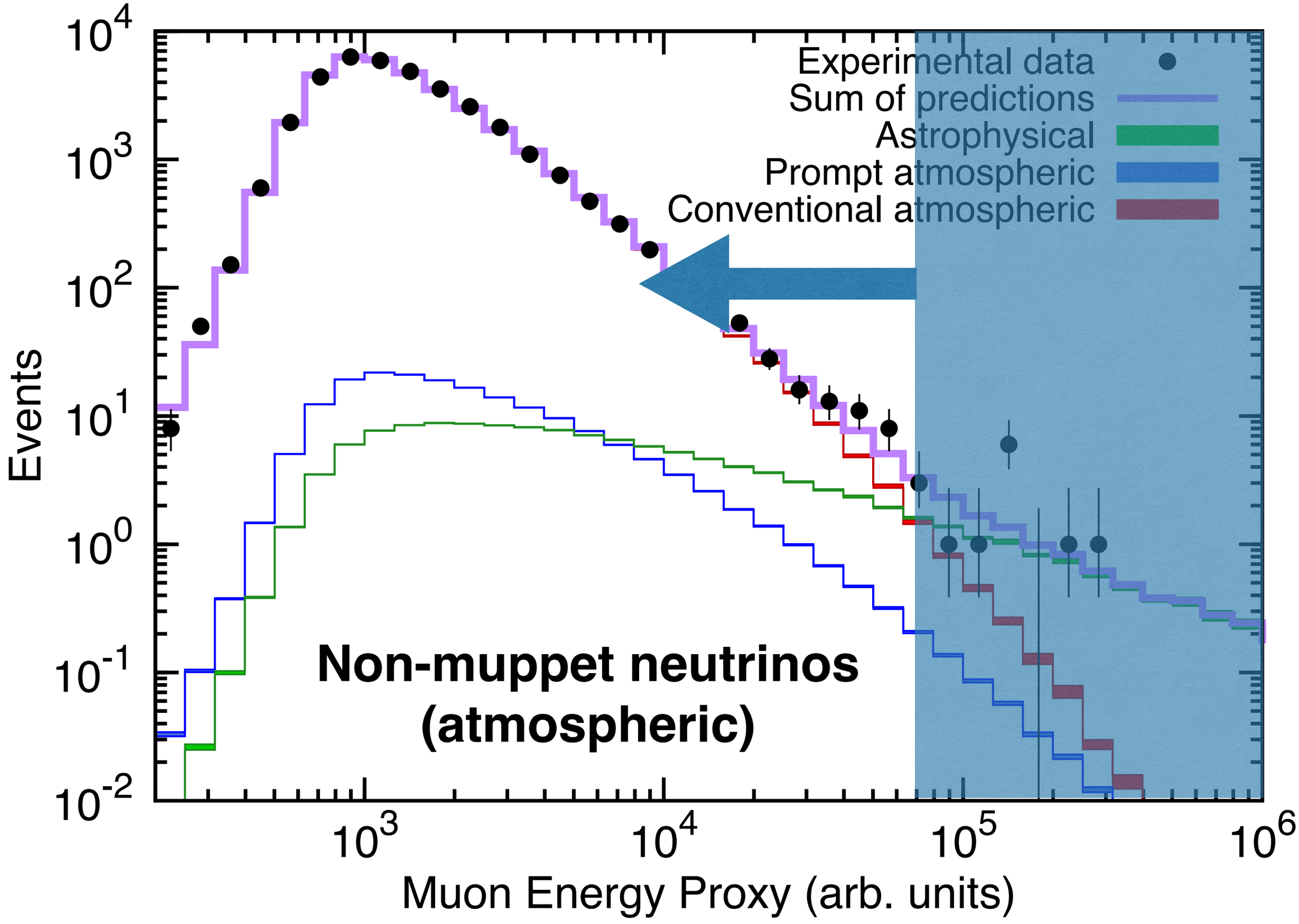
Through-going nu-mu energy distribution



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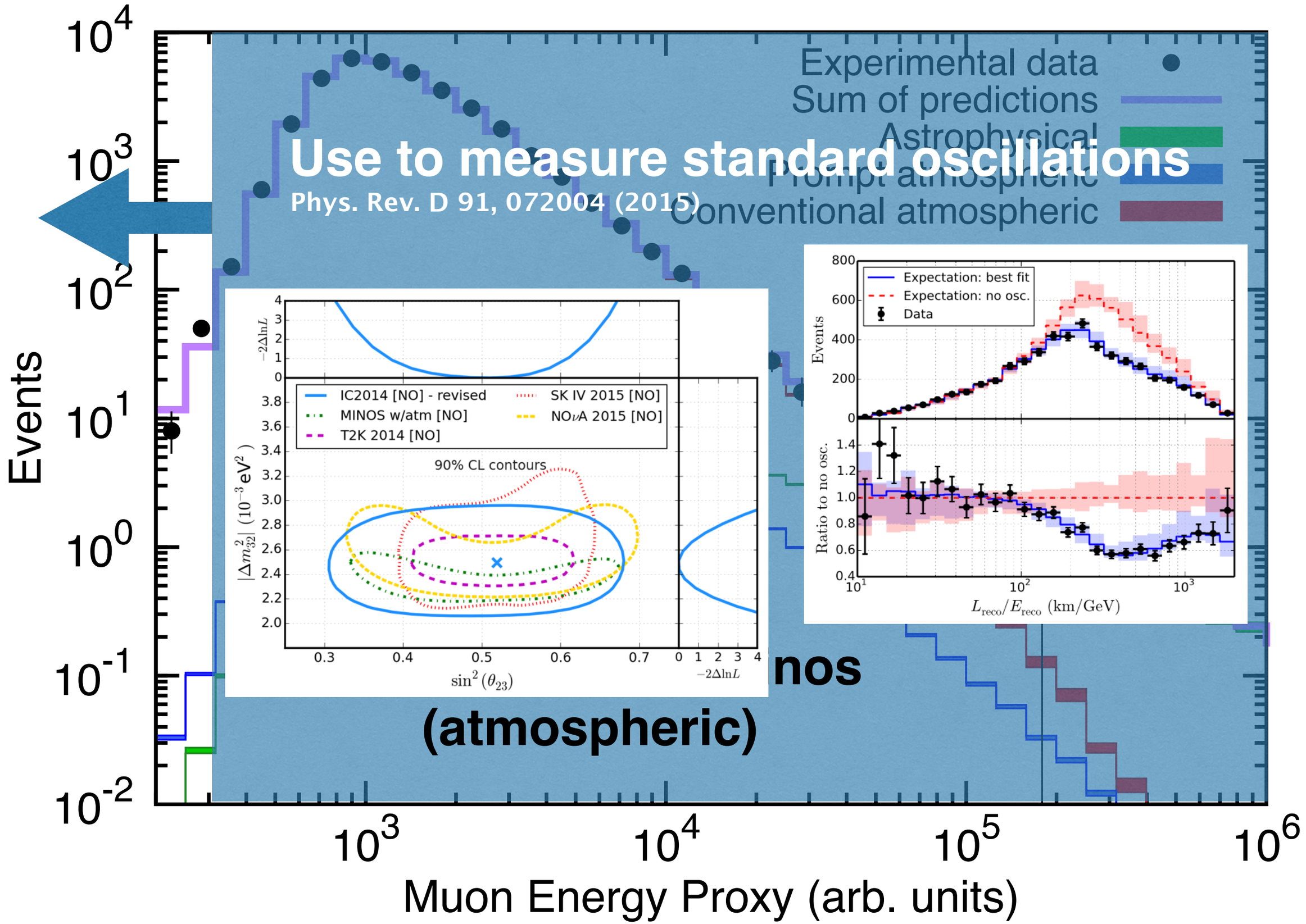
Through-going nu-mu energy distribution



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Today

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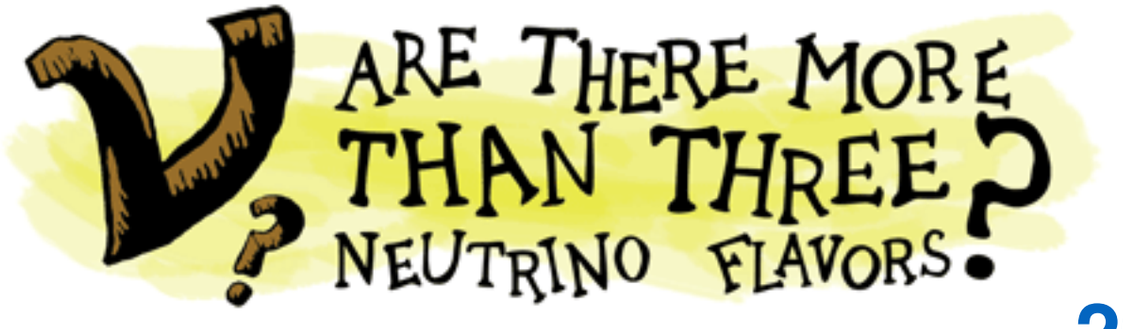
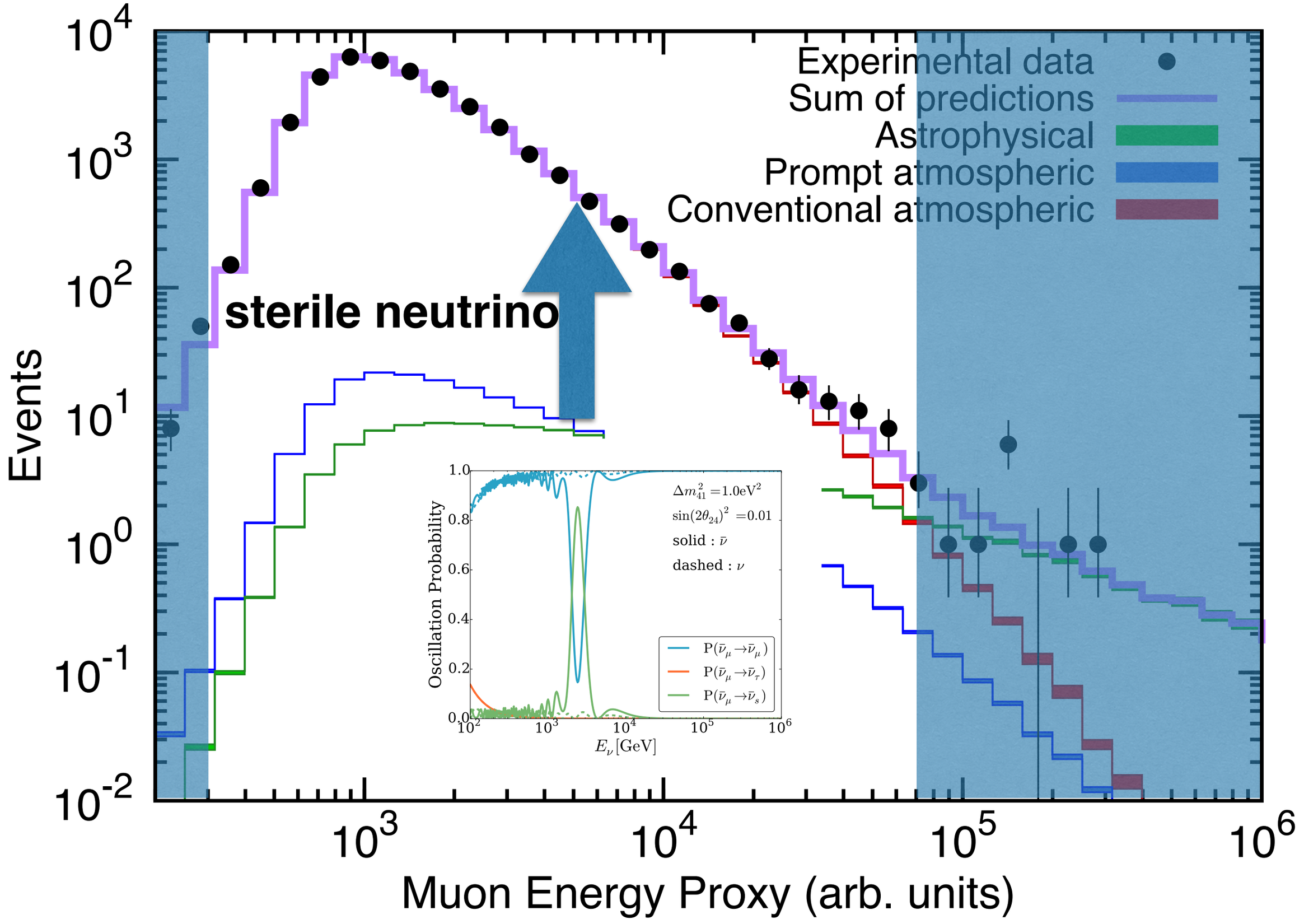
➡IceCube

➡**The IceCube sterile neutrino search**

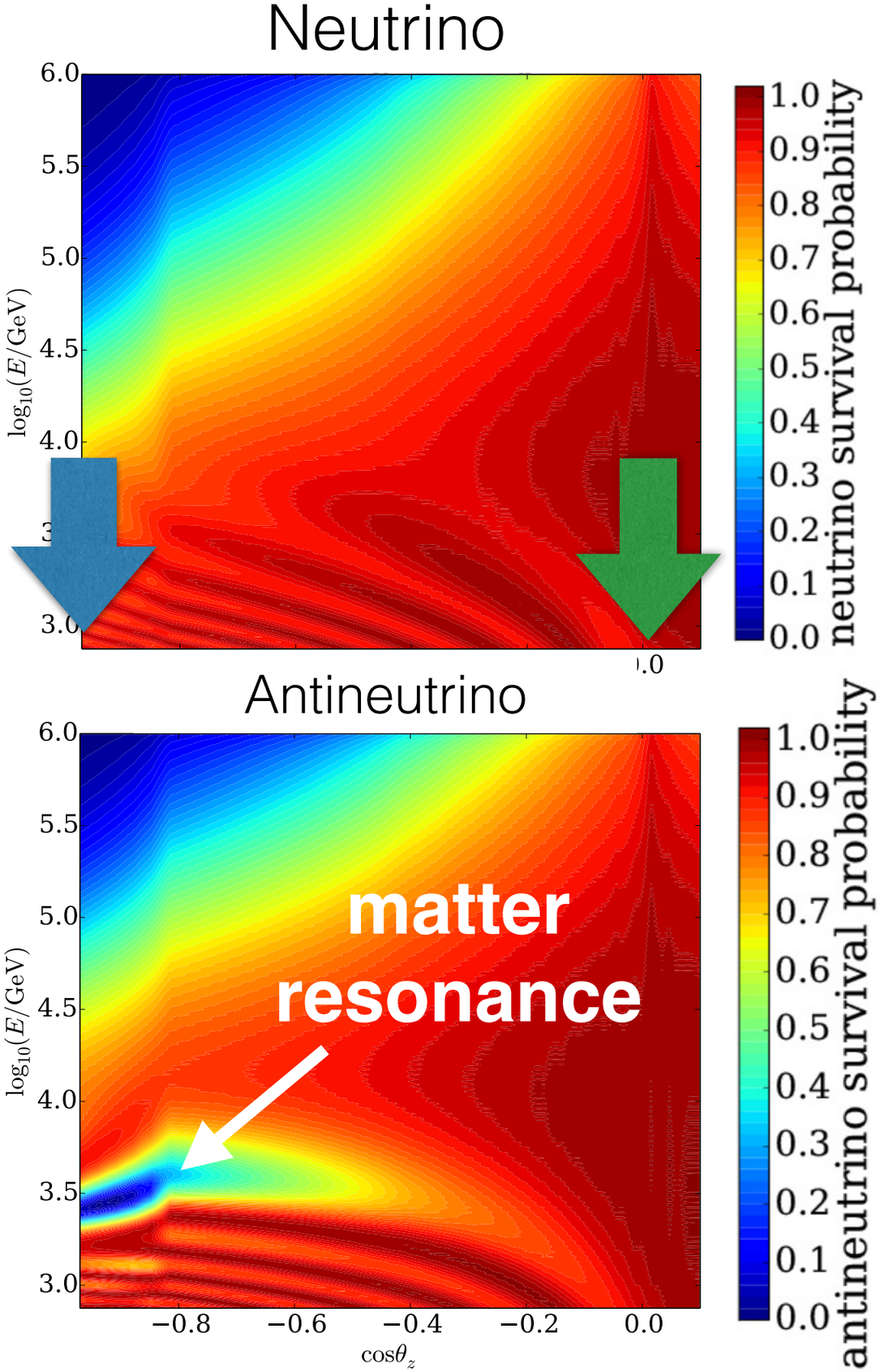


Through-going nu-mu energy distribution



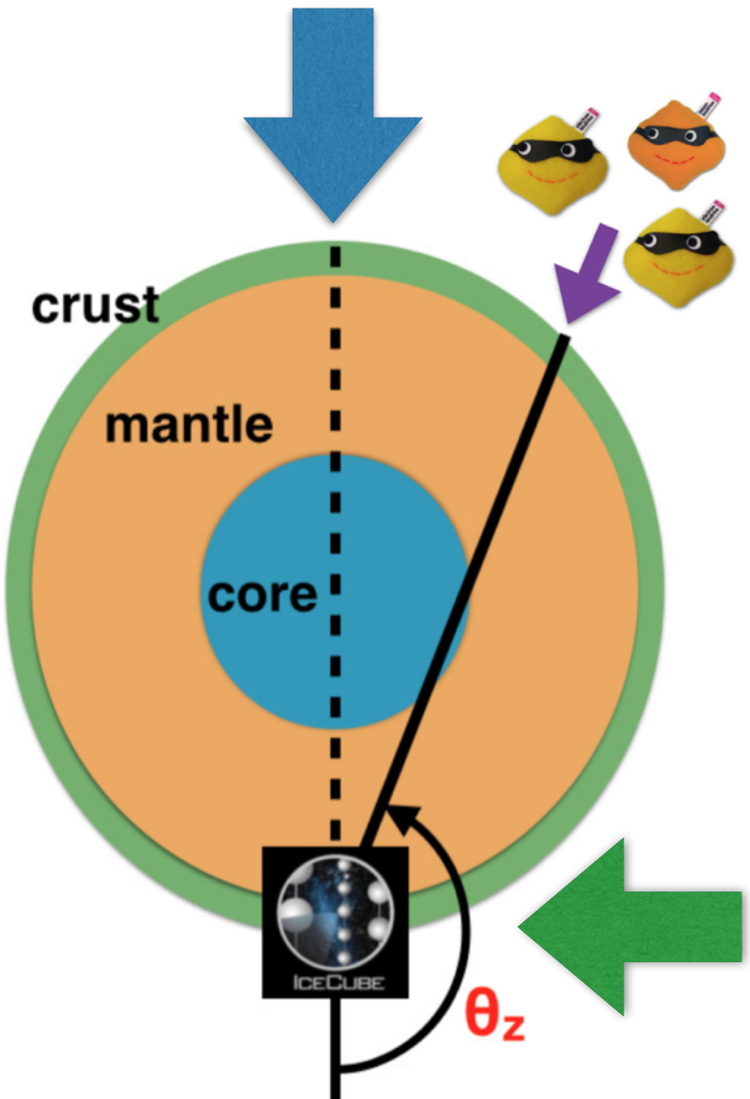
Phys. Rev. Lett. 115, 081102 (2015)

Oscillation probability as a function of energy and zenith



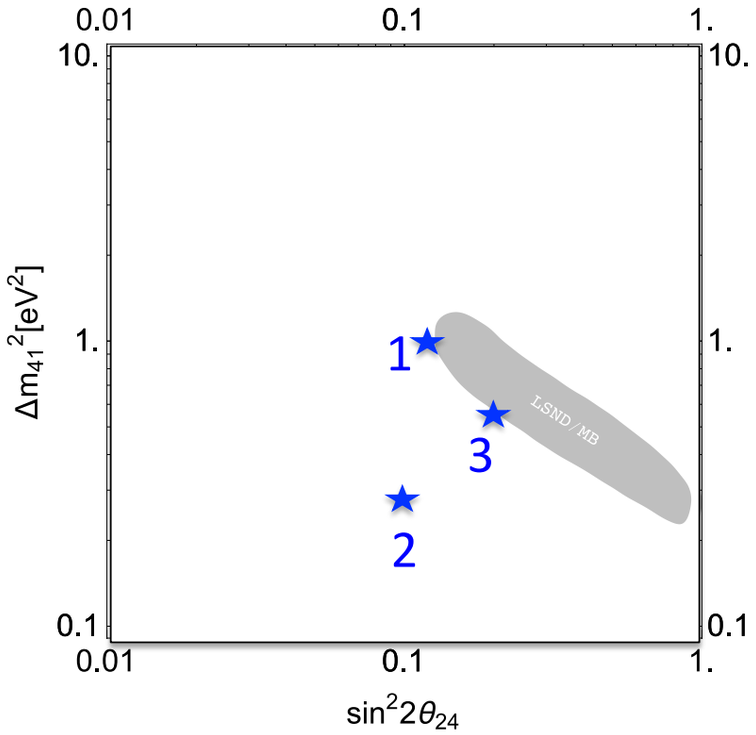
$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$

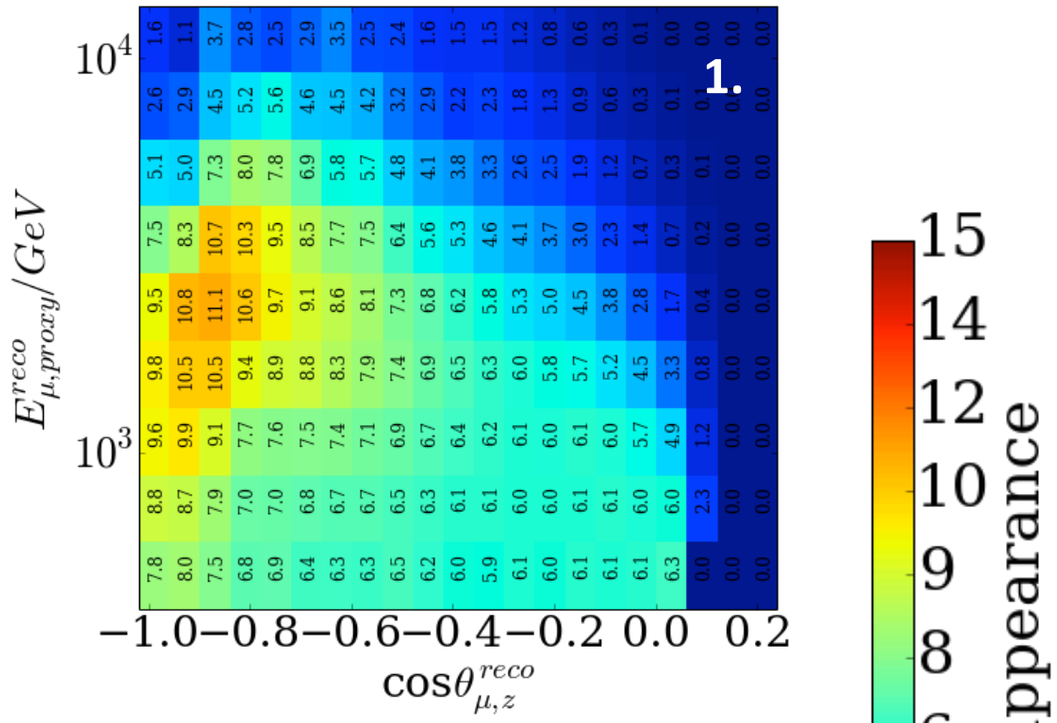
$$\left.\begin{aligned} \sin^2(2\theta) &= 0.1 \\ \Delta m^2 &= 1\mathrm{eV}^2 \end{aligned}\right\} \text{LSND/MB like}$$

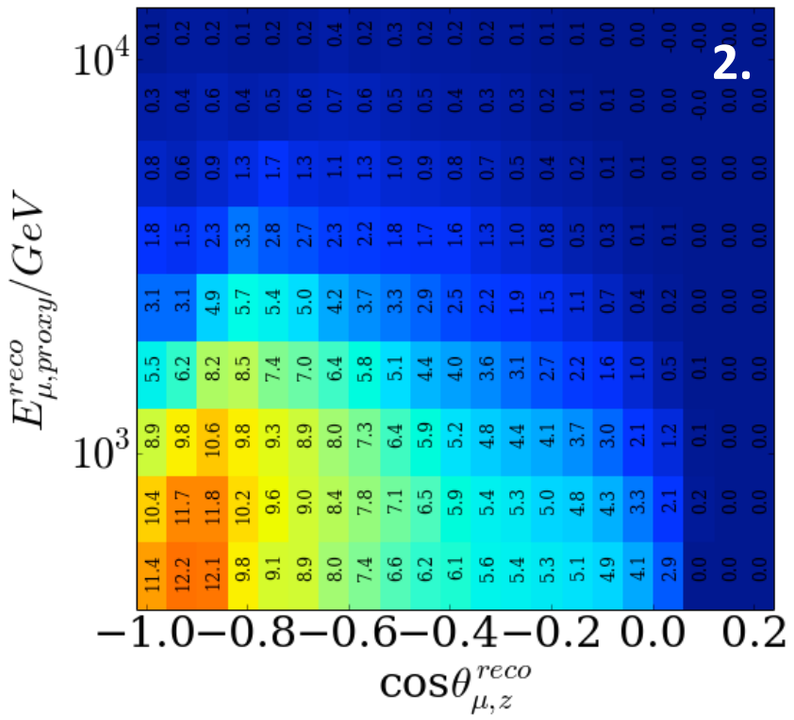


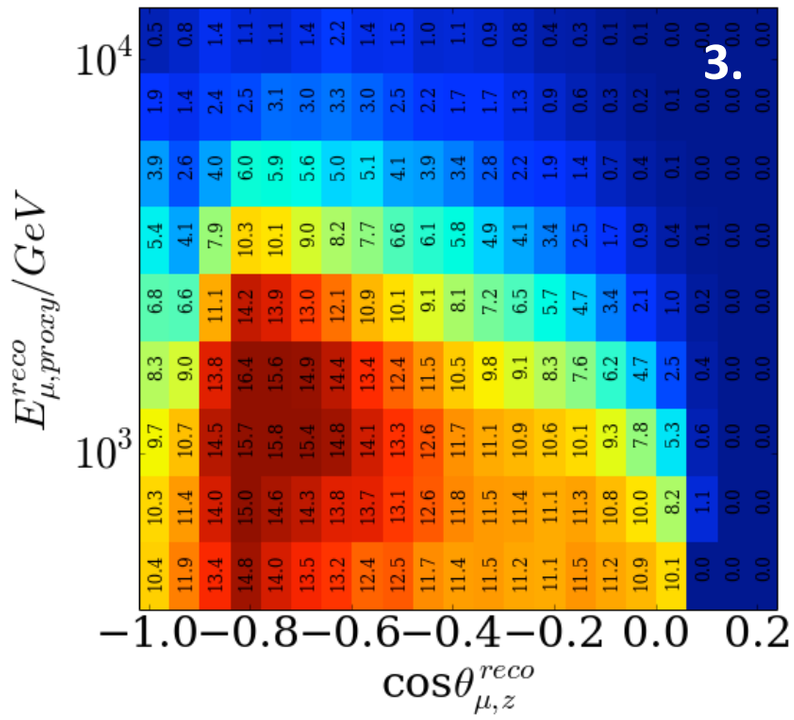
The Signal!

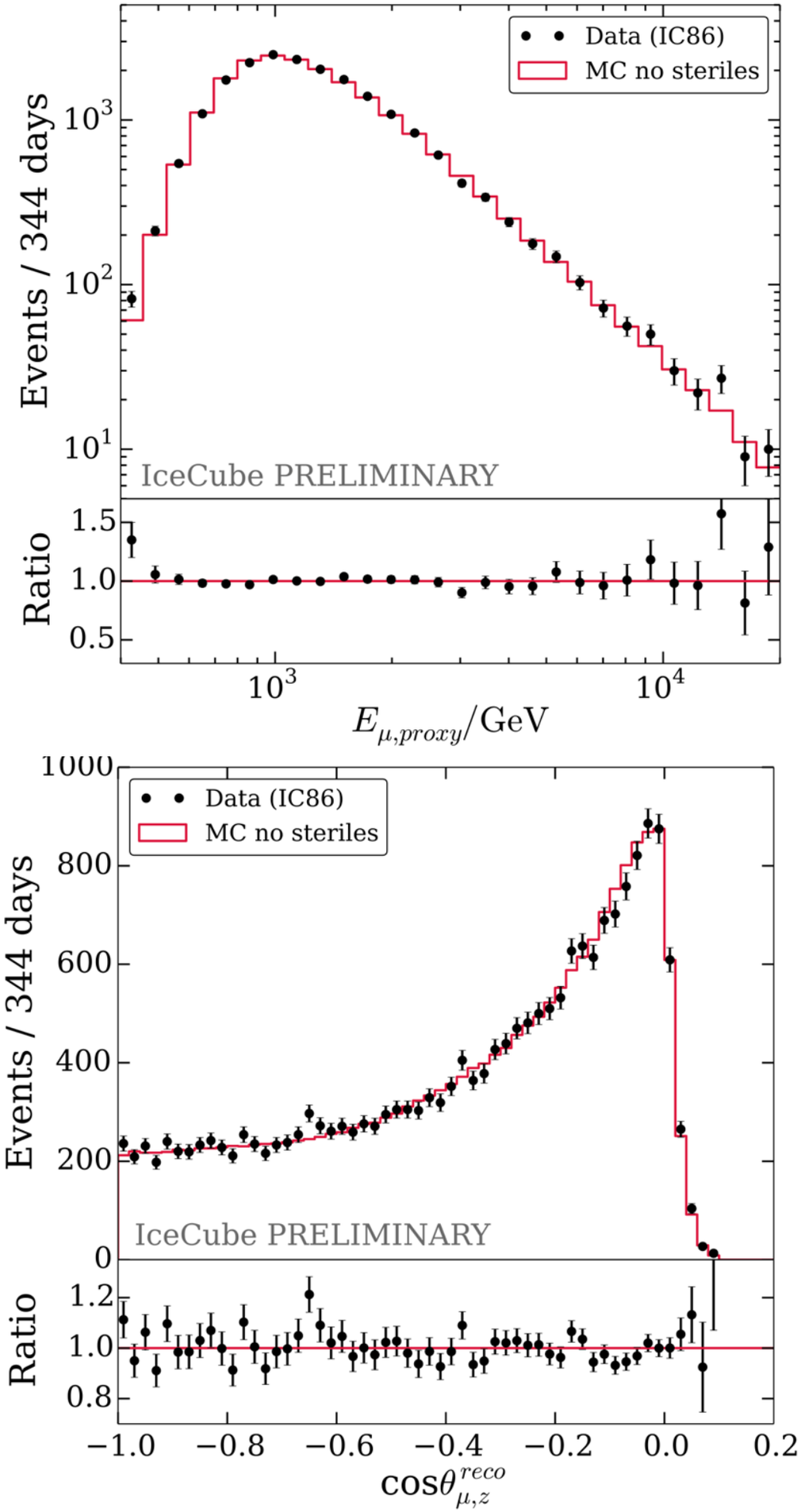
Signal in reconstructed quantities for three points in the parameter space.





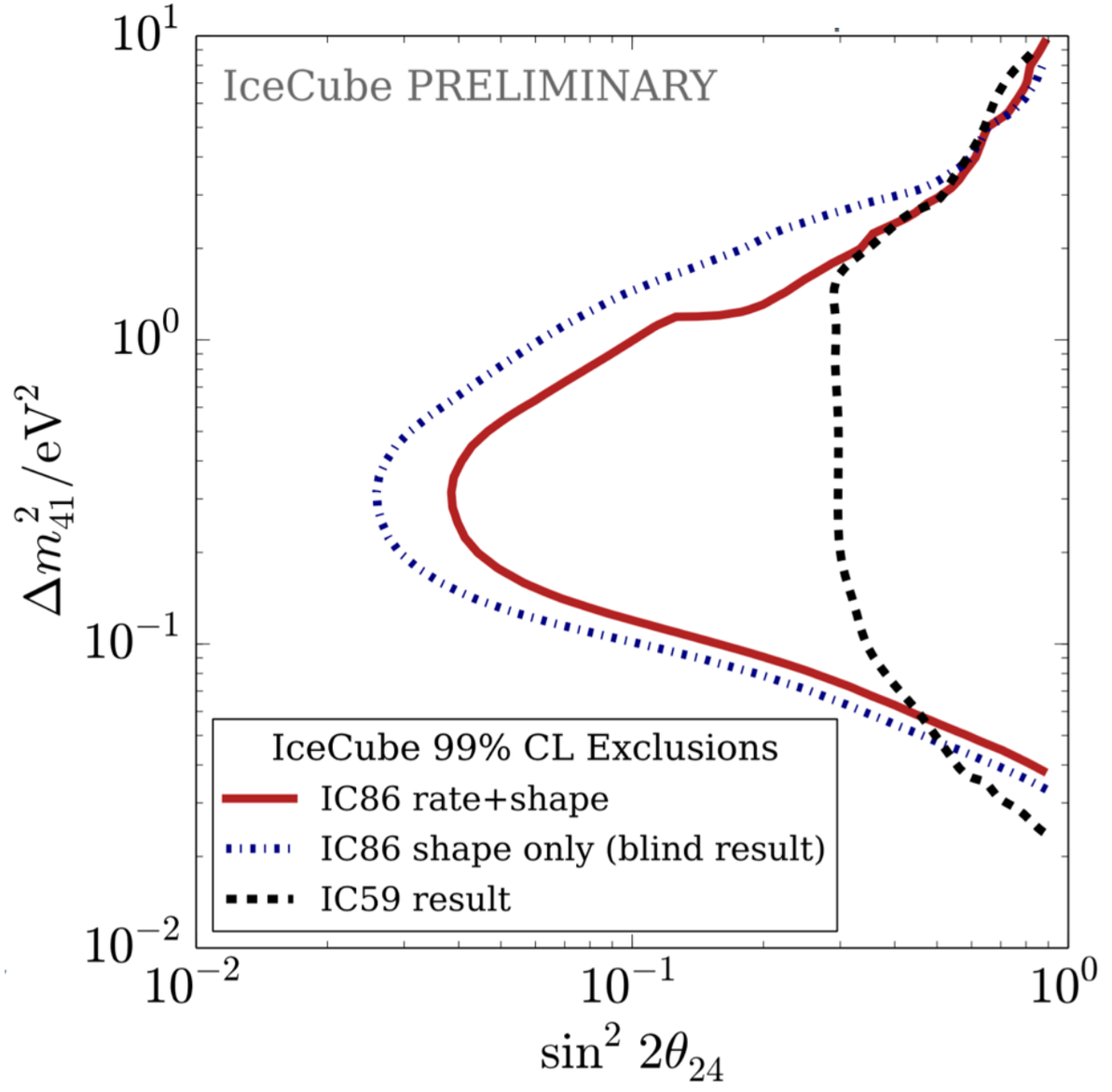




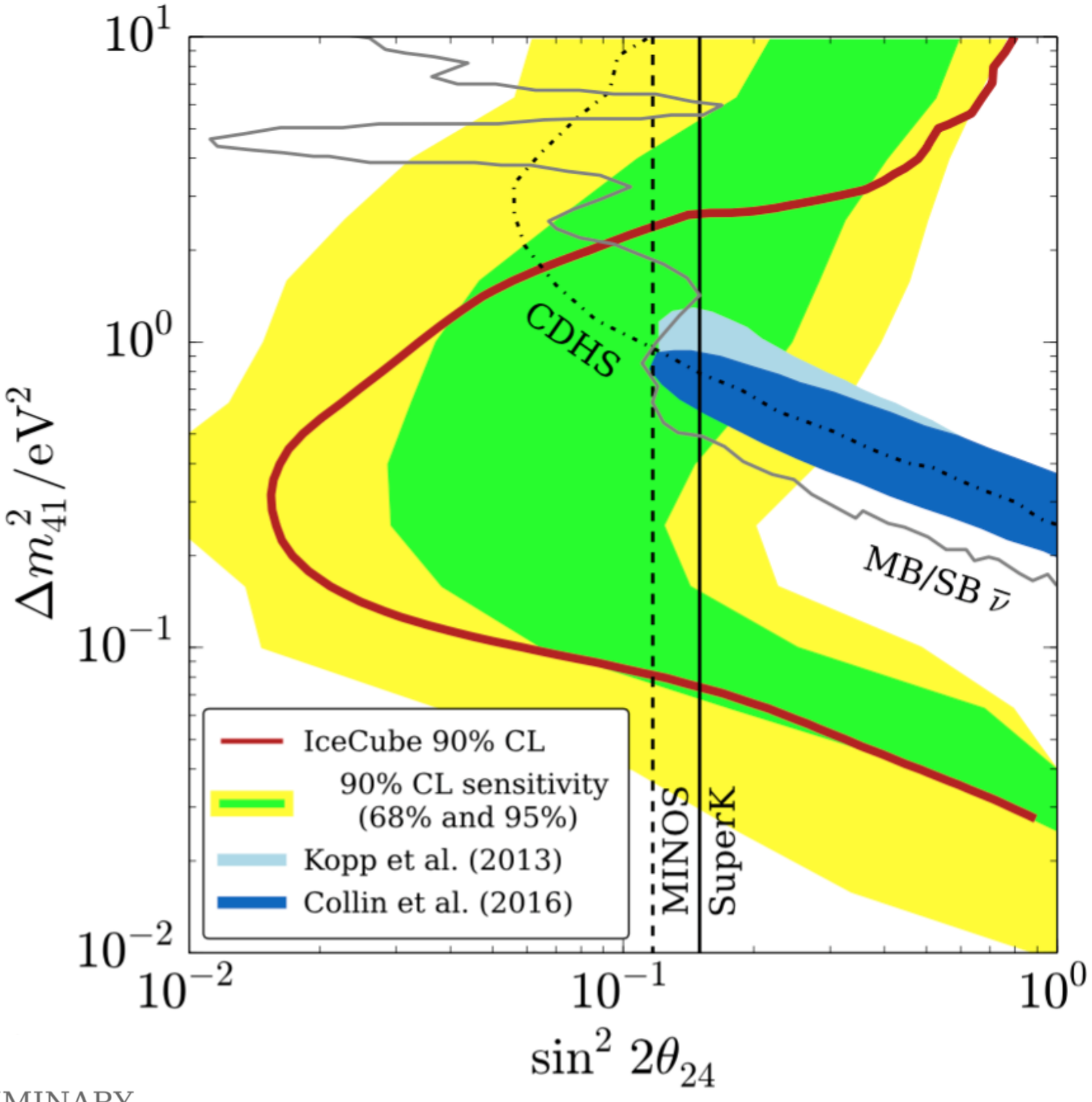


- We unblinded one year of data which had ~ 20 000 neutrino events.
- **Distributions compatible with the no sterile hypothesis.**

New Limit:

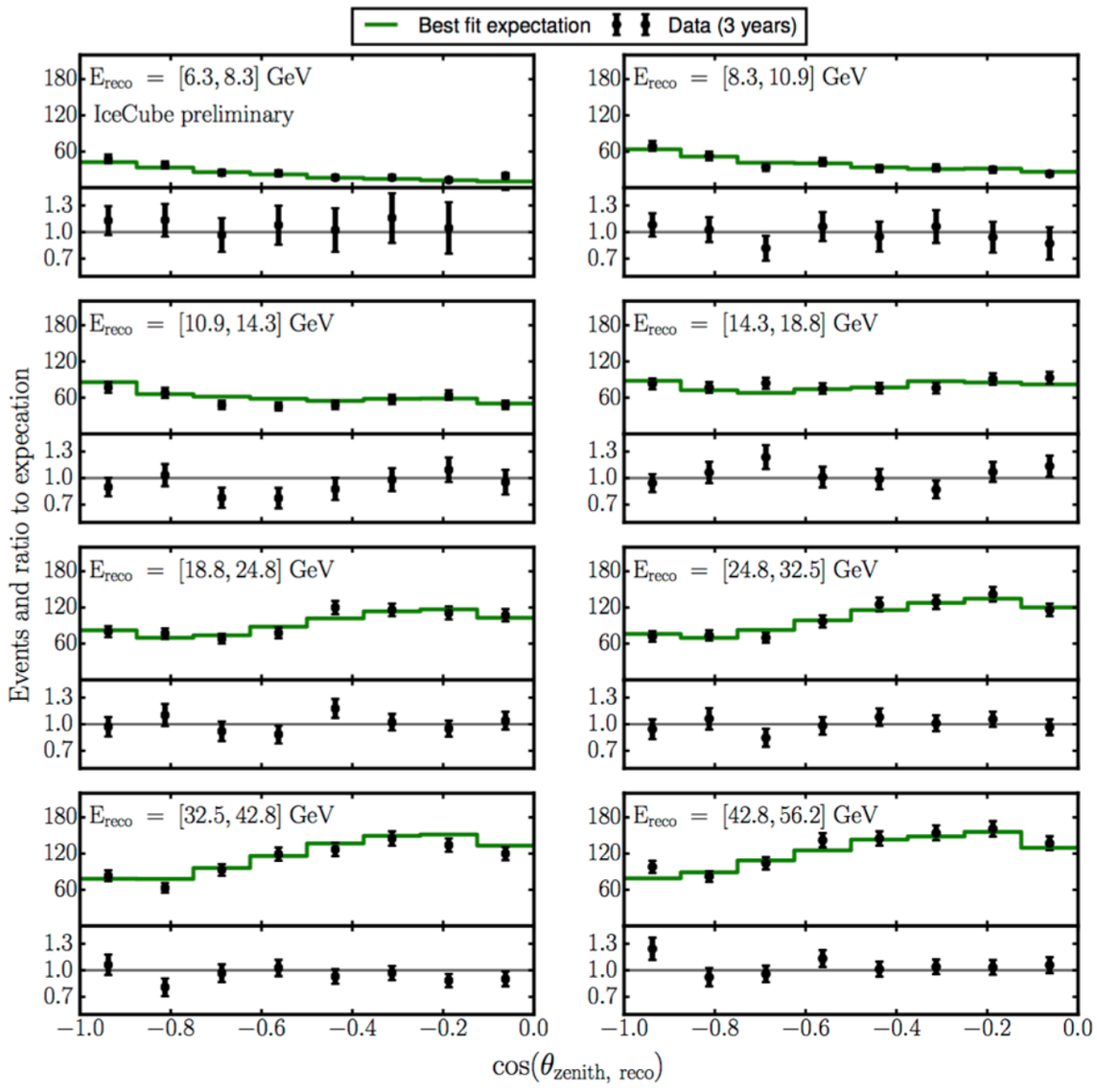


Main result!

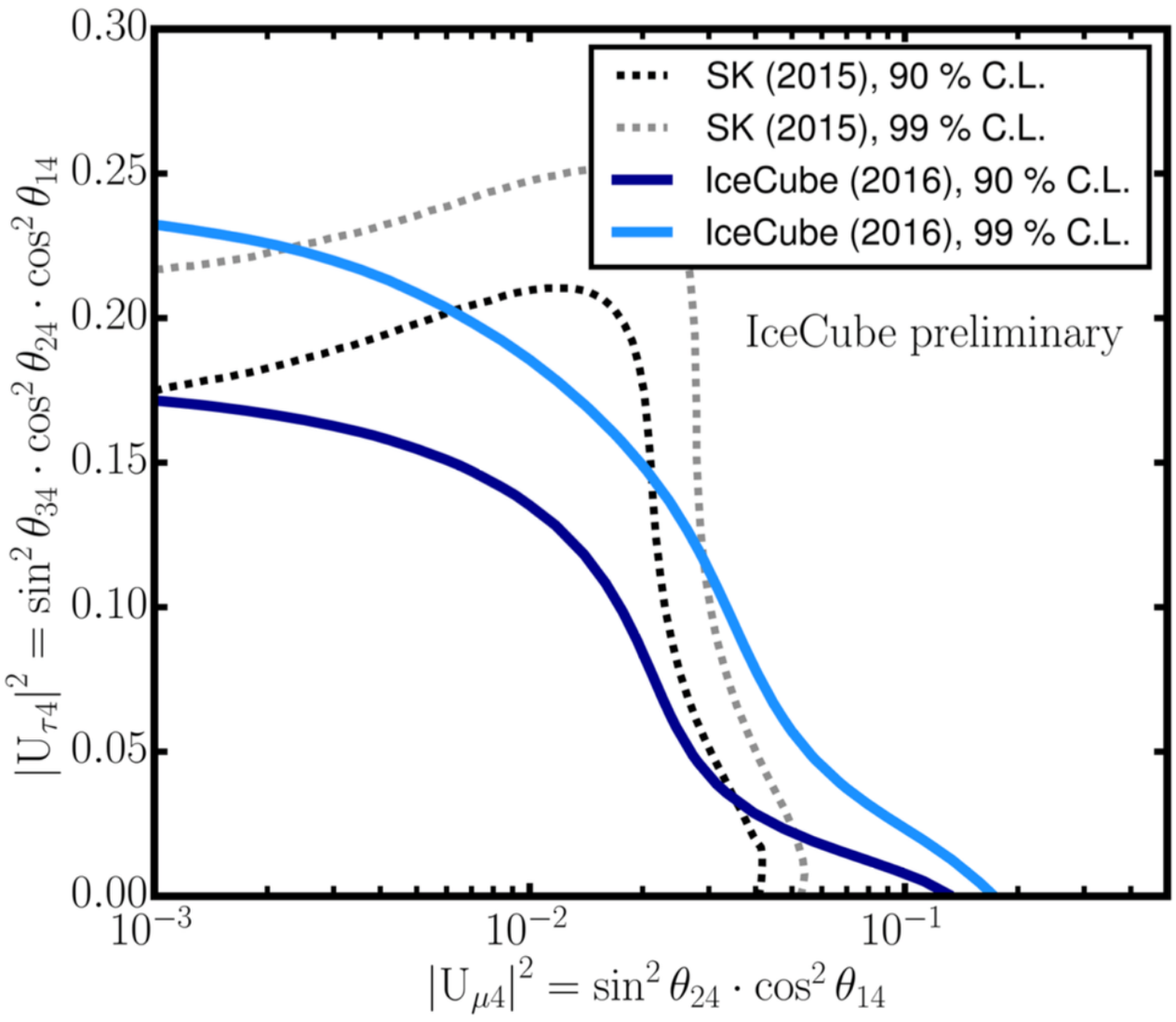


IceCube PRELIMINARY

Also, IceCube + DeepCore analysis



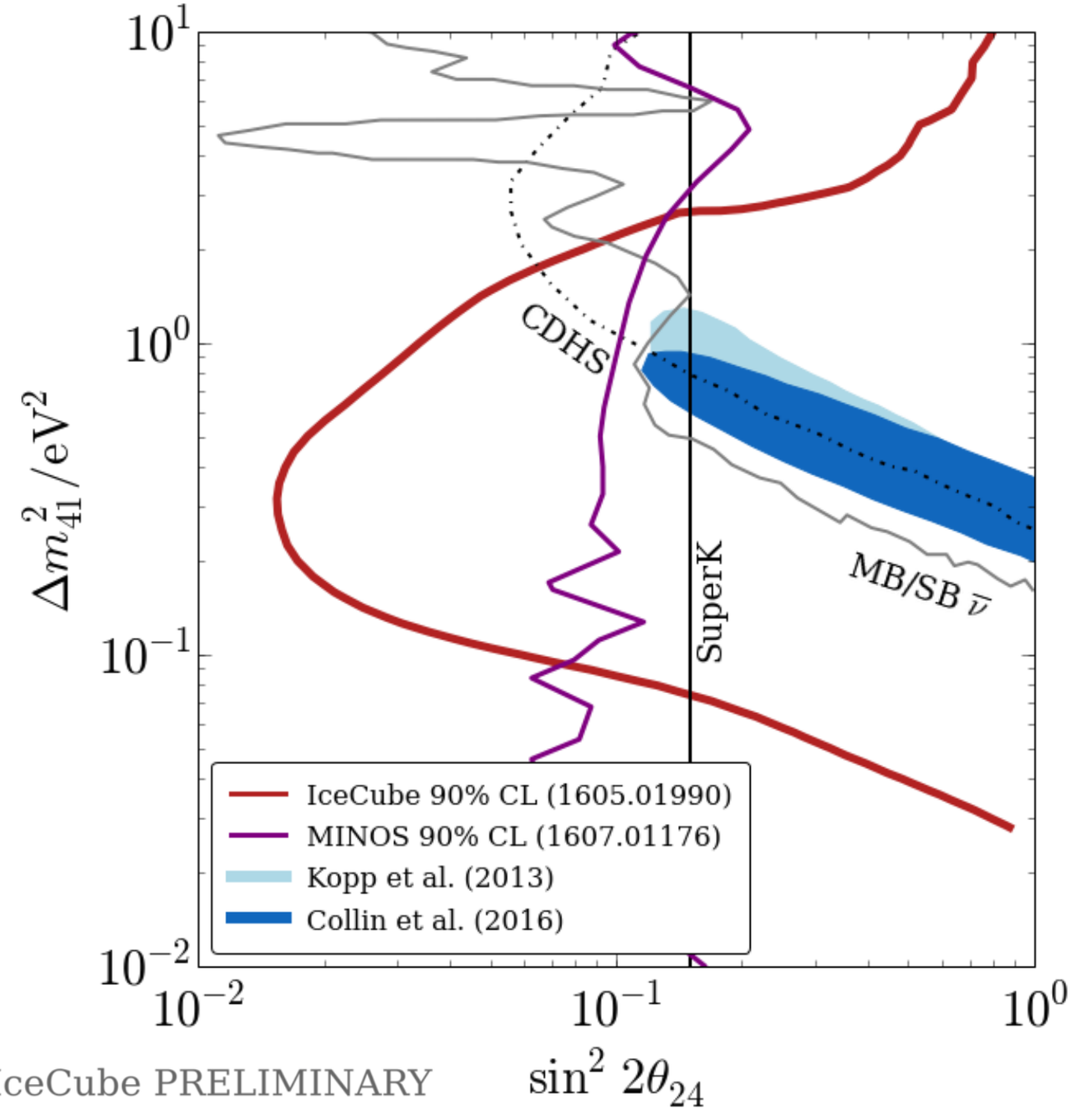
IceCube PRELIMINARY



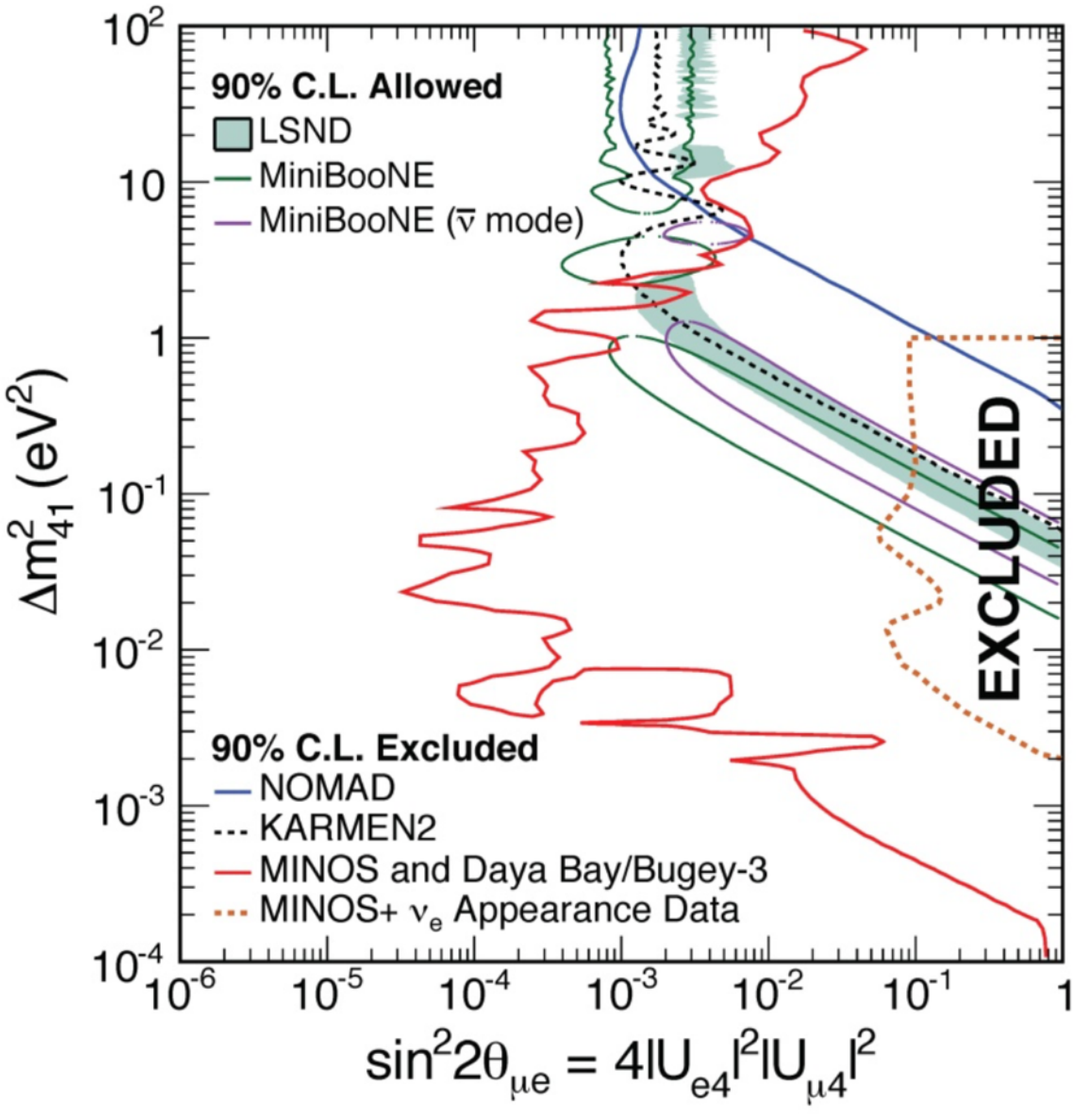
Using events below a 100 GeV we can also obtain constraints on sterile neutrinos by deviations from standard oscillations.

Other new results from *Neutrino2016*

MINOS



MINOS+Daya Bay

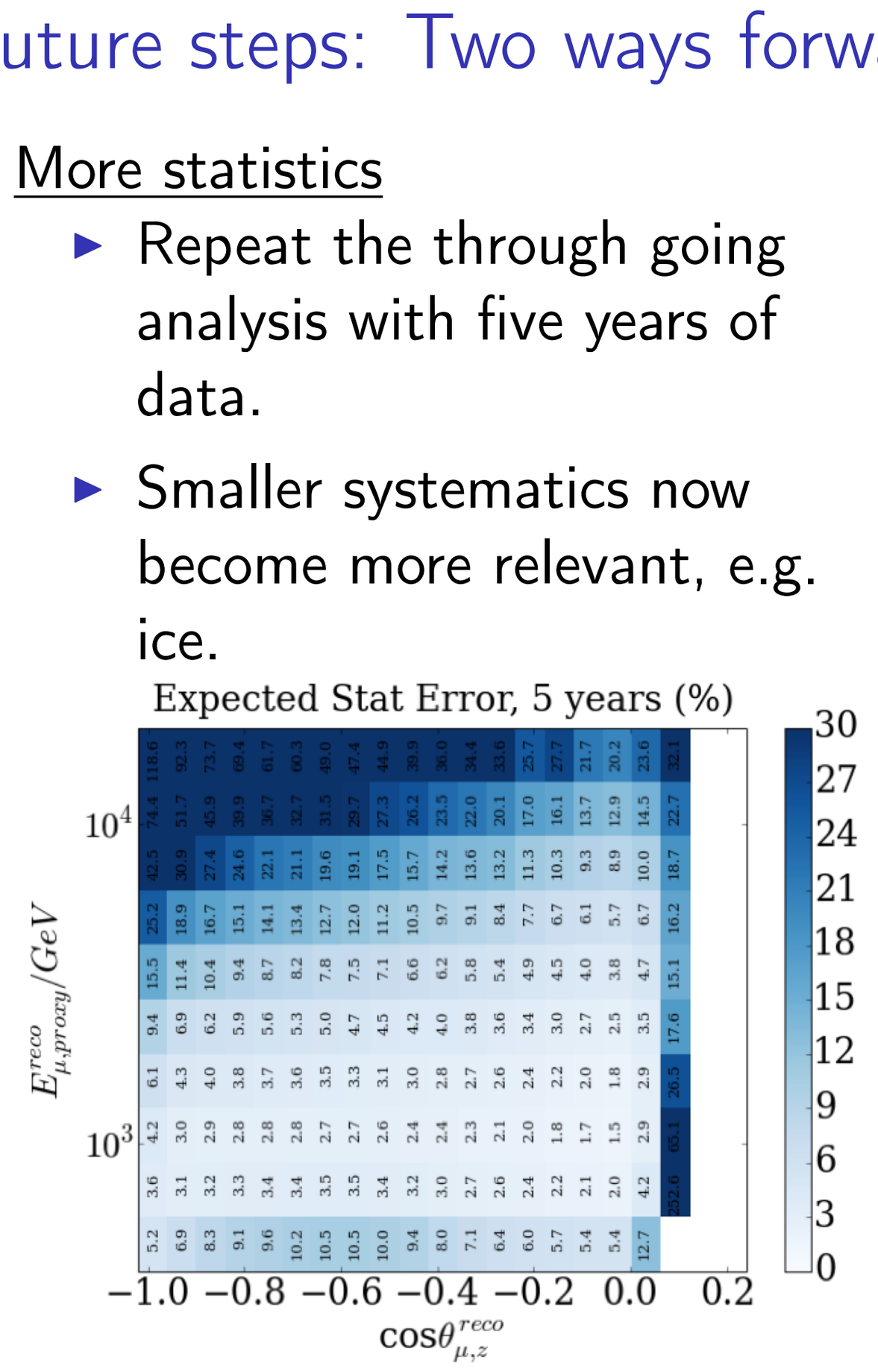


arXiv:1607.01176,1607.01177

Future steps: Two ways forward

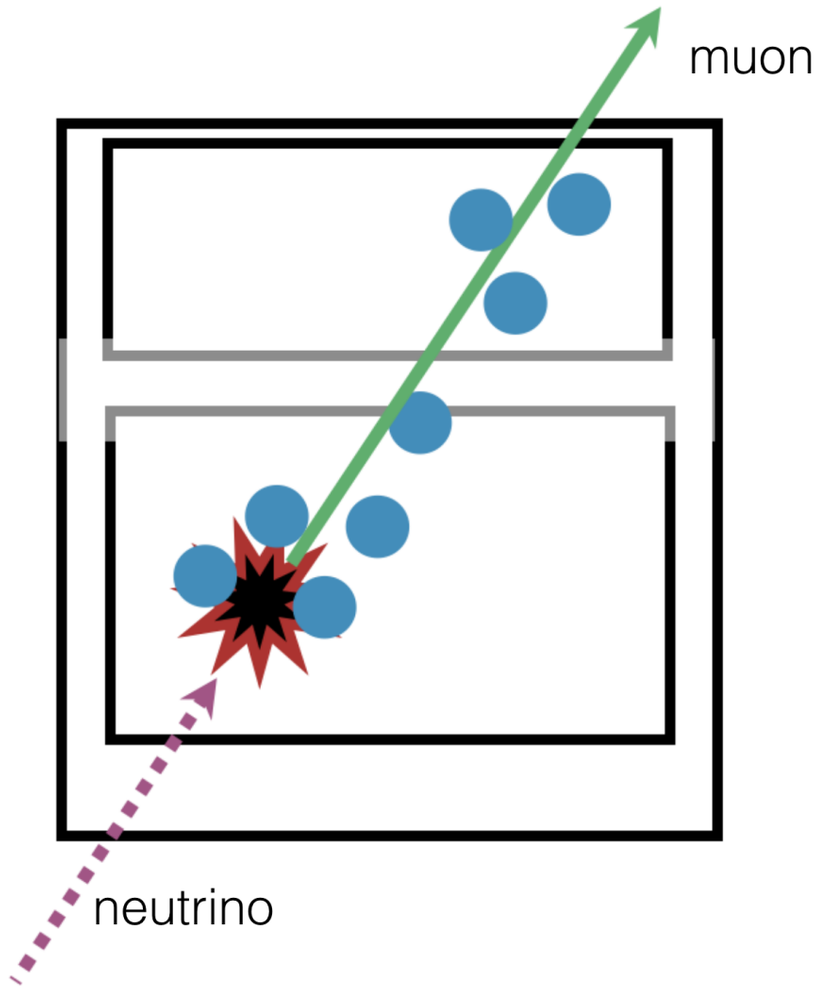
More statistics

- Repeat the through going analysis with five years of data.
- Smaller systematics now become more relevant, e.g. ice.



Better events

- Select only starting events.
- Better neutrino energy reconstruction: track+shower energies.
- Reduced statistics.



Take home message

✤We have performed a search for eV-sterile neutrinos using one year of IceCube data. **No significant signal of sterile neutrinos was found.**

✤**IceCube result is competitive with other limits and the World best at ~ 0.1-1.0 eV².**

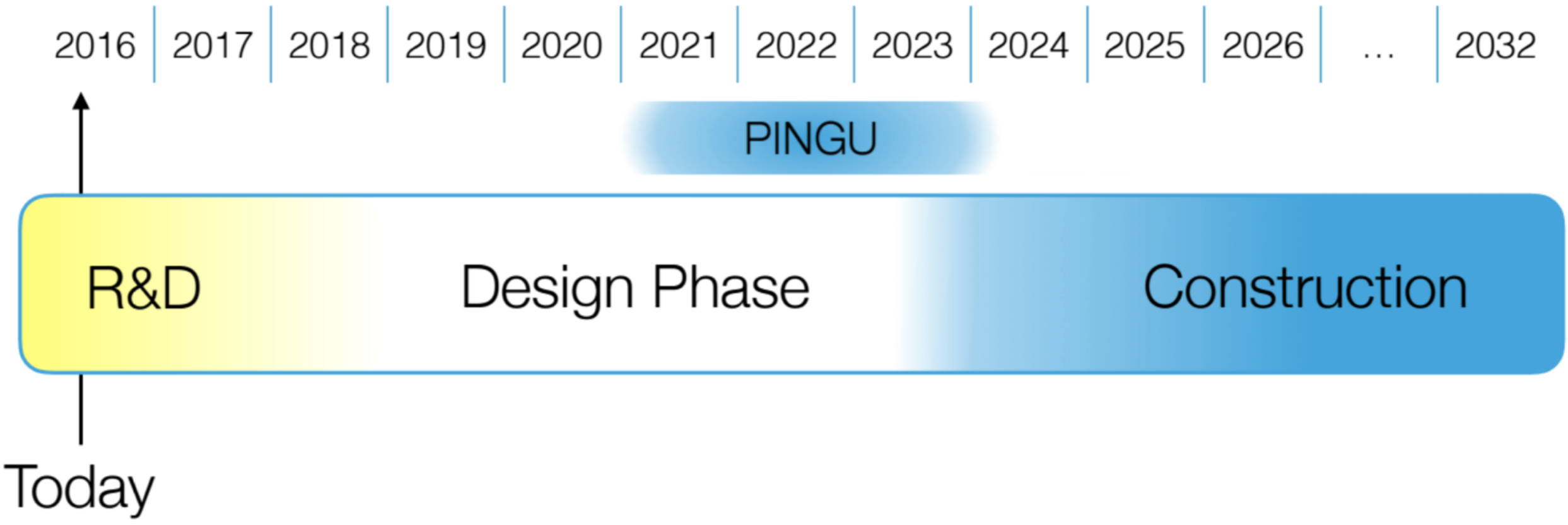
✤ IceCube has several more years of data ready to analyze: We are just getting started!

THANKS!

See arXiv:1605.01990 for more details

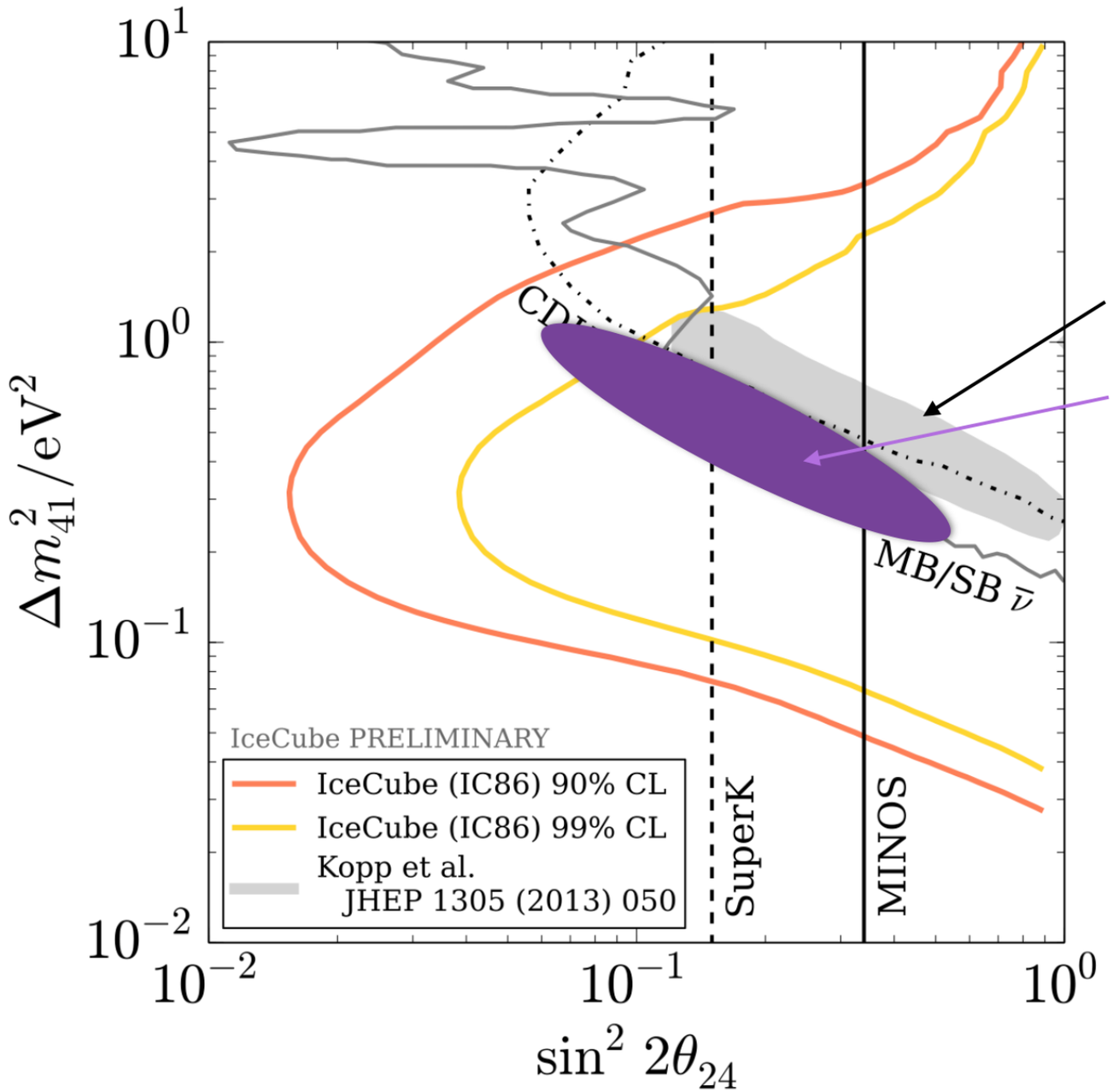
BONUS SLIDES

Gen-2 PRELIMINARY **timeline**

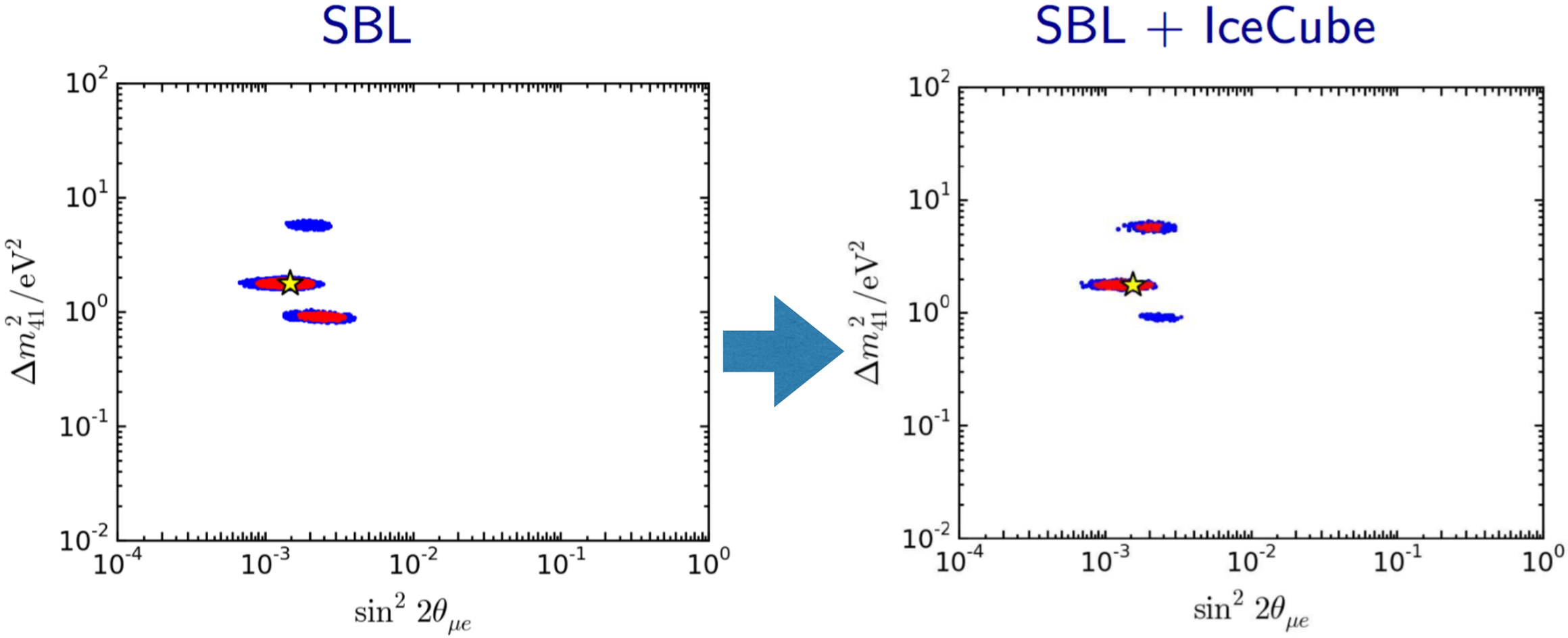


Relationship with other angles

- $\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1-|U_{e4}|^2)$: reactor experiments.
- $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$: MINOS, SK. (**this analysis**)
- $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$: LSND, MB, KARMEN, NOMAD.



A new global fit with IceCube



Red: 90% CL Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	χ^2_{min}	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

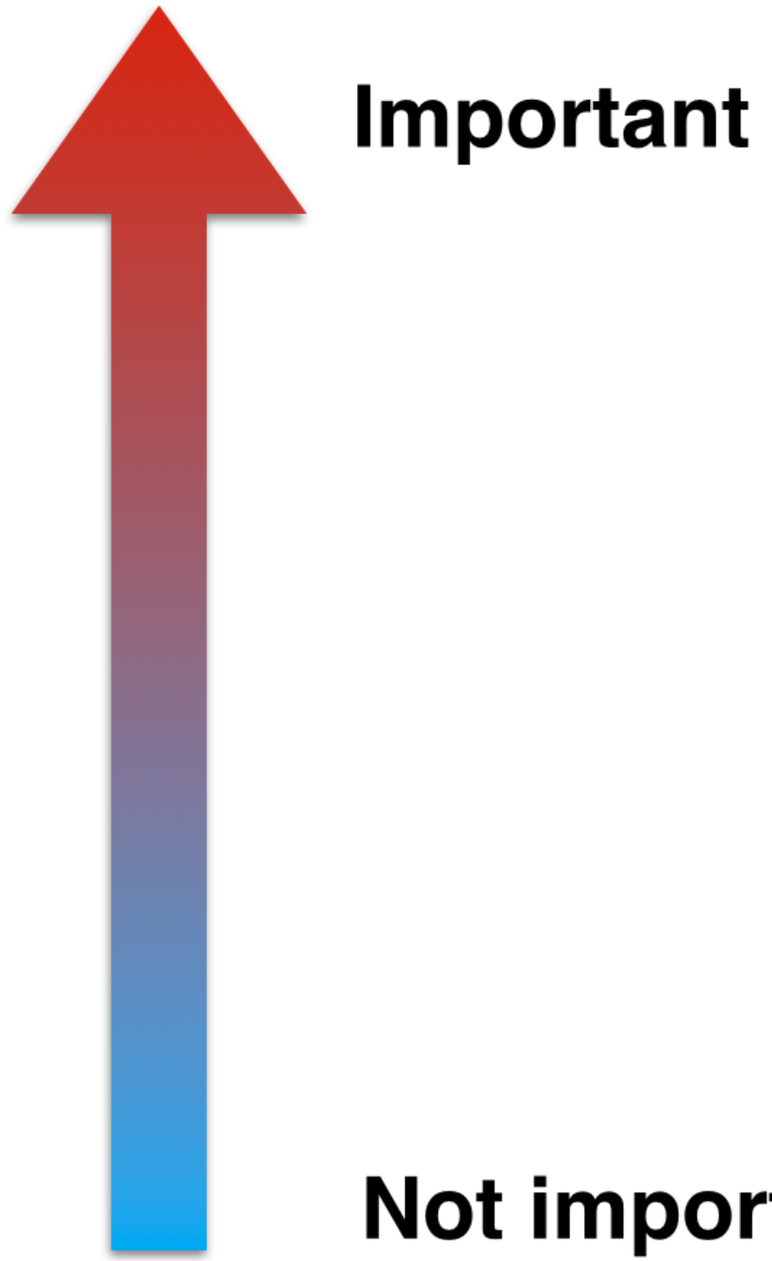
G.Collins, C.A., J. Conrad, M. Shaevitz (arXiv:**1602.00671** and arXiv:**1607.00011**)

Systematics!

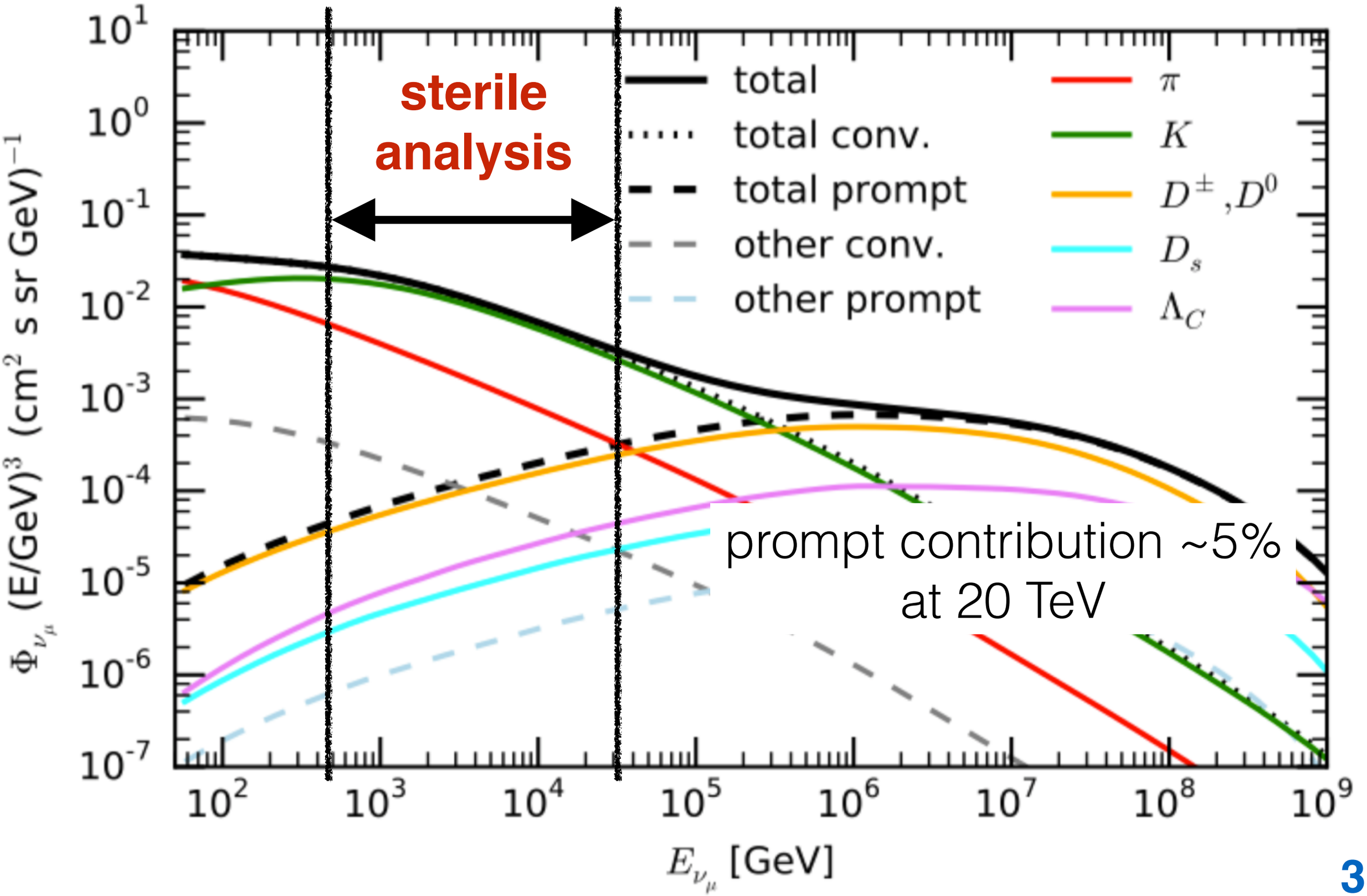
Systematics are super important; *some are more than others*.
These are the systematics we considered:

- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - π/K *ratio*
  - $\nu/\bar{\nu}$ *ratio*
- Air shower hadronic models
- Primary cosmic ray fluxes
- Hole ice
- Neutrino cross sections
- Bulk ice scattering/absorption
- Earth model

continuous systematics
discrete systematic

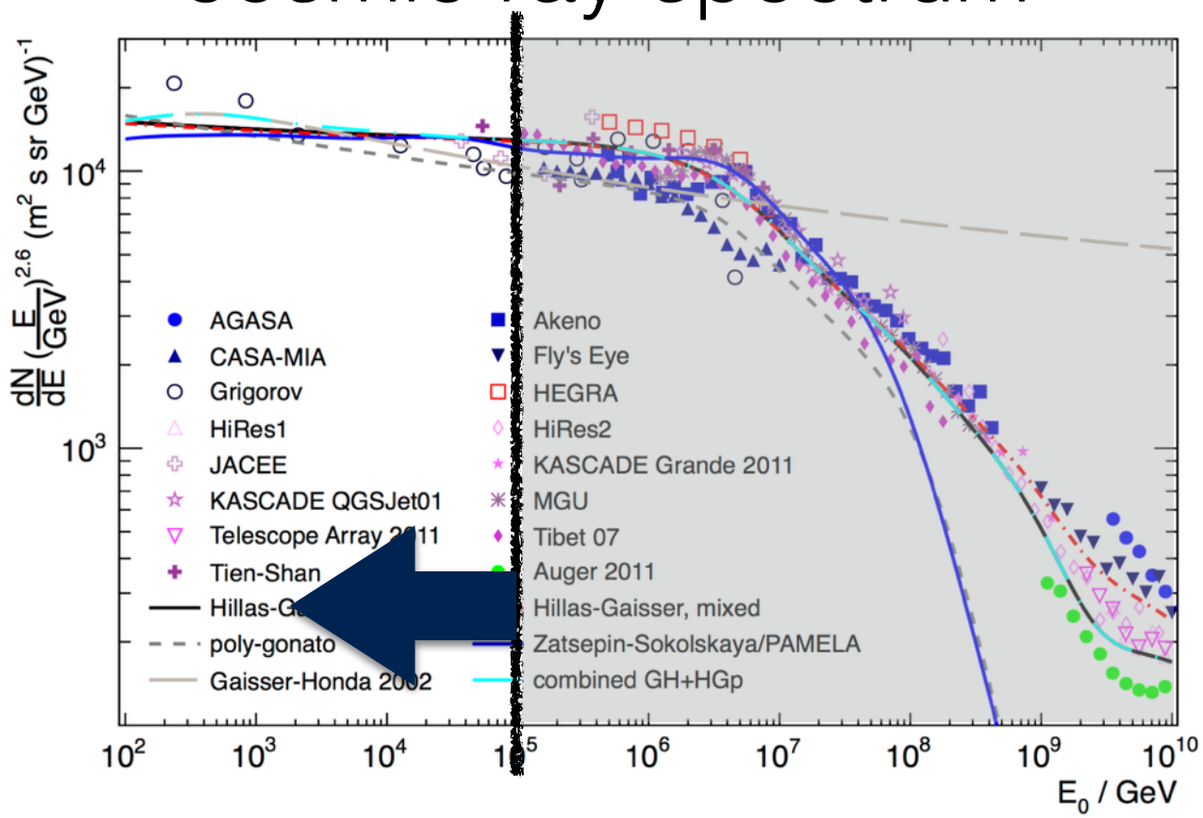


Atmospheric flux decomposed



Atmospheric neutrino flux uncertainties

cosmic ray spectrum



$$\phi_{atm} = N_0\left(\phi_K + R_{\pi/K}\phi_\pi\right) \times E_\nu^{-\Delta\gamma}$$

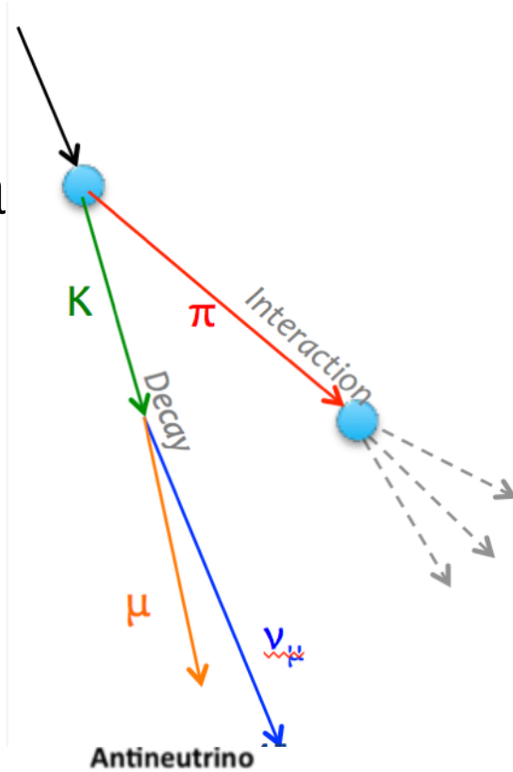
[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]

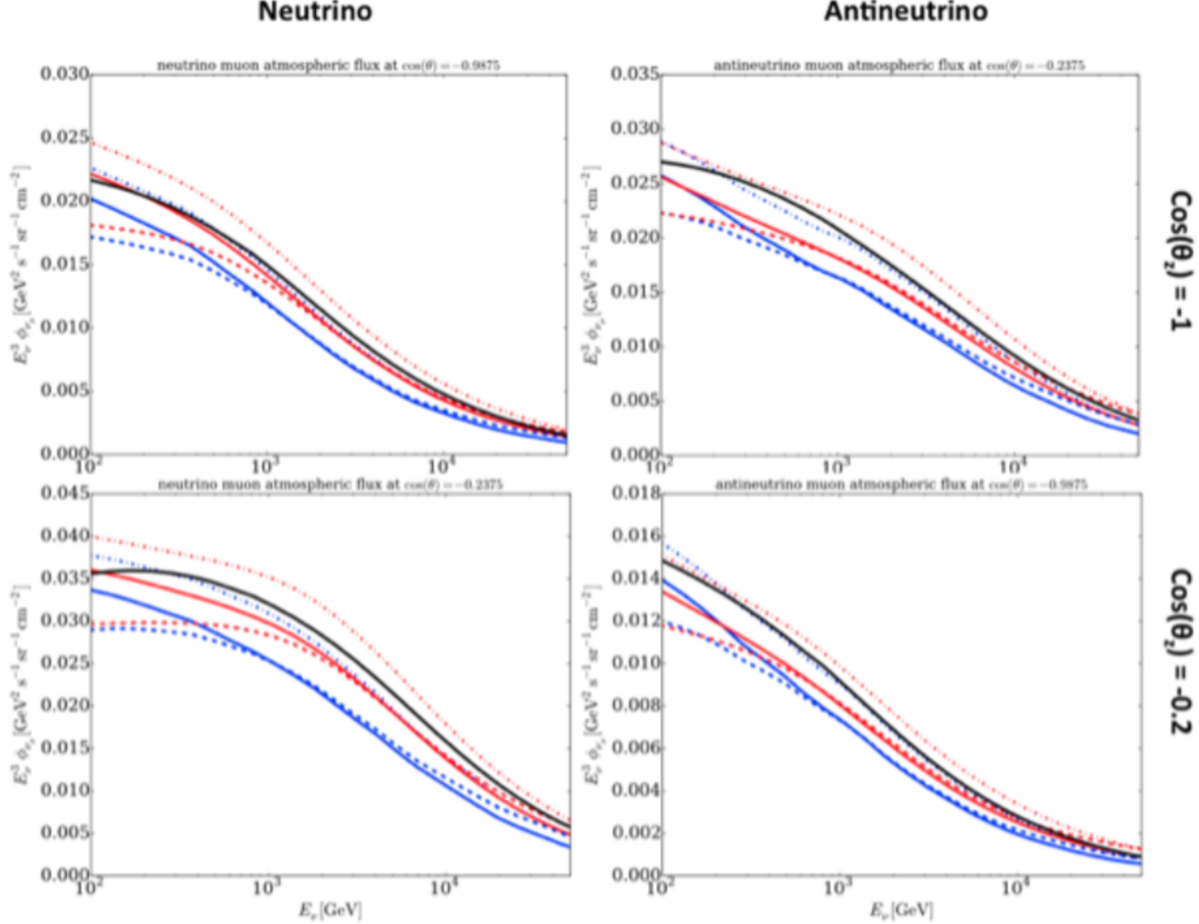
Cosmic ray models:

- Zatsepin-Sokolskaya
- Polygonato
- Gaisser+Honda

Hadronic models:

- Sibyll 2.3
- QGSJET II



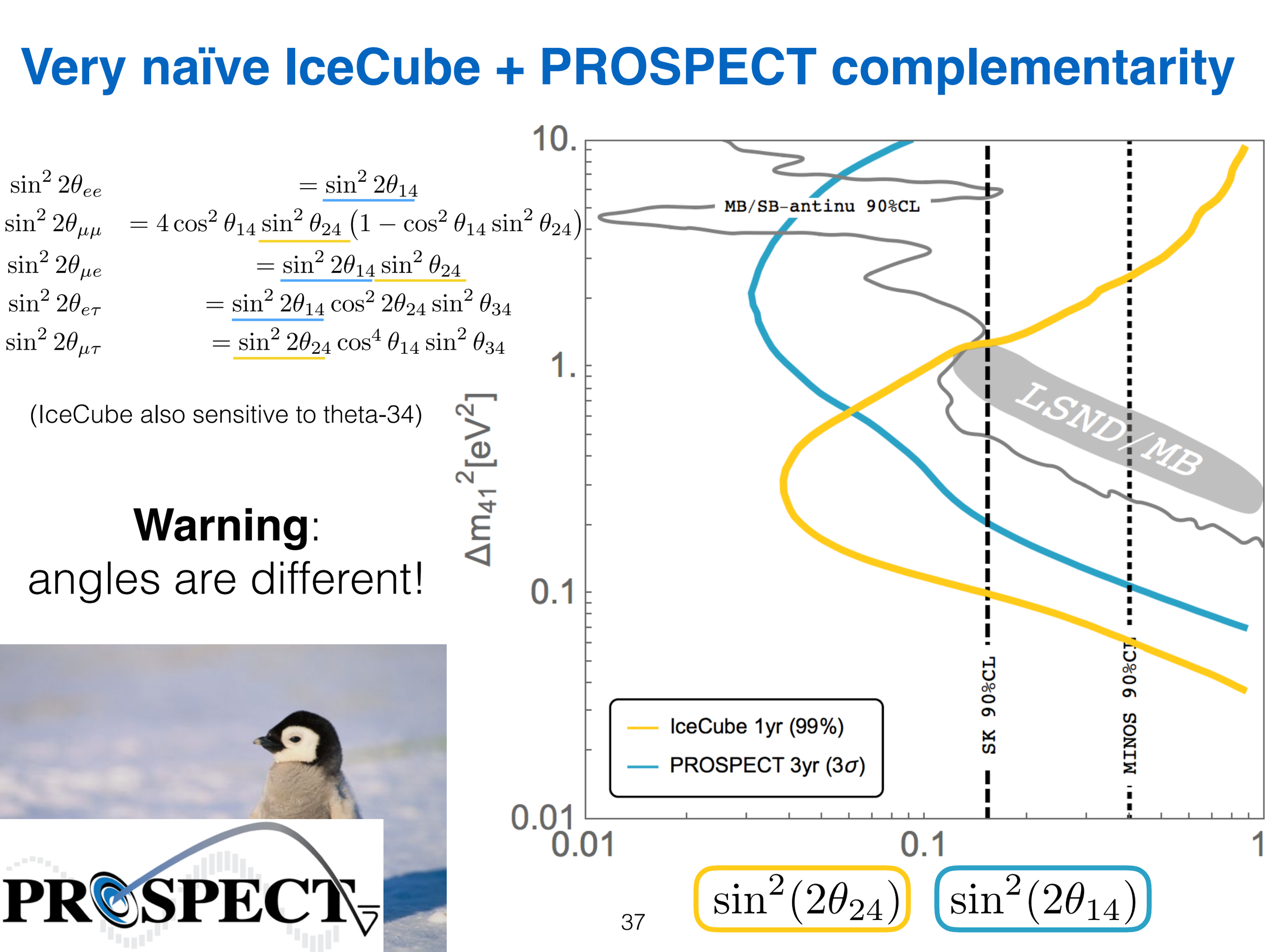


Very naïve IceCube + PROSPECT complementarity

$$
\begin{aligned}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} \\
\sin^2 2\theta_{\mu\mu} &= 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1-\cos^2\theta_{14}\sin^2\theta_{24}\right) \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14}\sin^2\theta_{24} \\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14}\cos^2 2\theta_{24}\sin^2\theta_{34} \\
\sin^2 2\theta_{\mu\tau} &= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34}
\end{aligned}
$$

(IceCube also sensitive to theta-34)

Warning:
angles are different!



PROSPECT

More experiments complementarity…

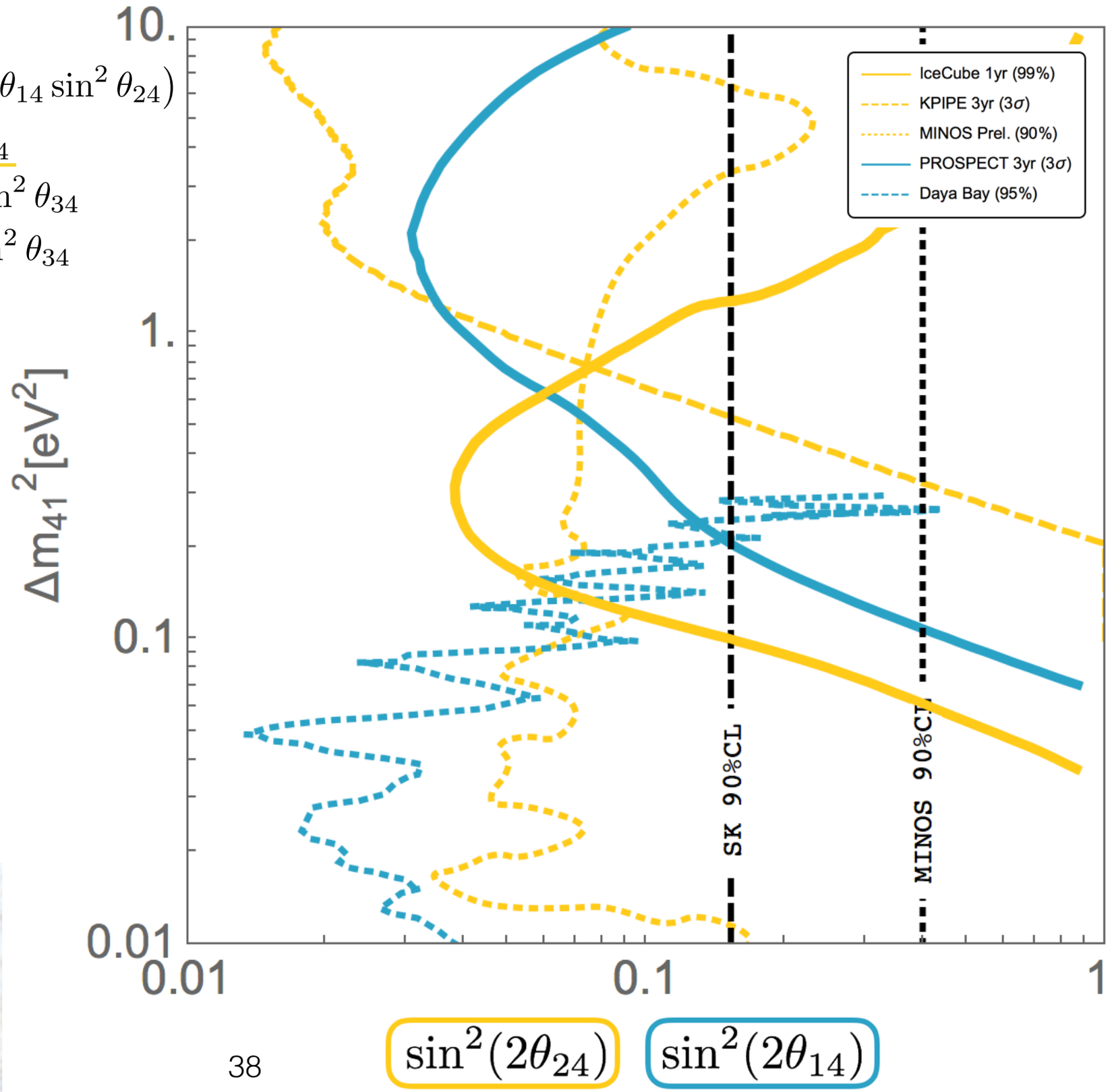
$$
\begin{aligned}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} \\
\sin^2 2\theta_{\mu\mu} &= 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1-\cos^2\theta_{14}\sin^2\theta_{24}\right) \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14}\sin^2\theta_{24} \\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14}\cos^2 2\theta_{24}\sin^2\theta_{34} \\
\sin^2 2\theta_{\mu\tau} &= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34}
\end{aligned}
$$

KPIPE

arXiv:1506.05811

PROSPECT

arXiv:1512.02202



DANSS sensitivity estimation 95%CL with 1 year of data.