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

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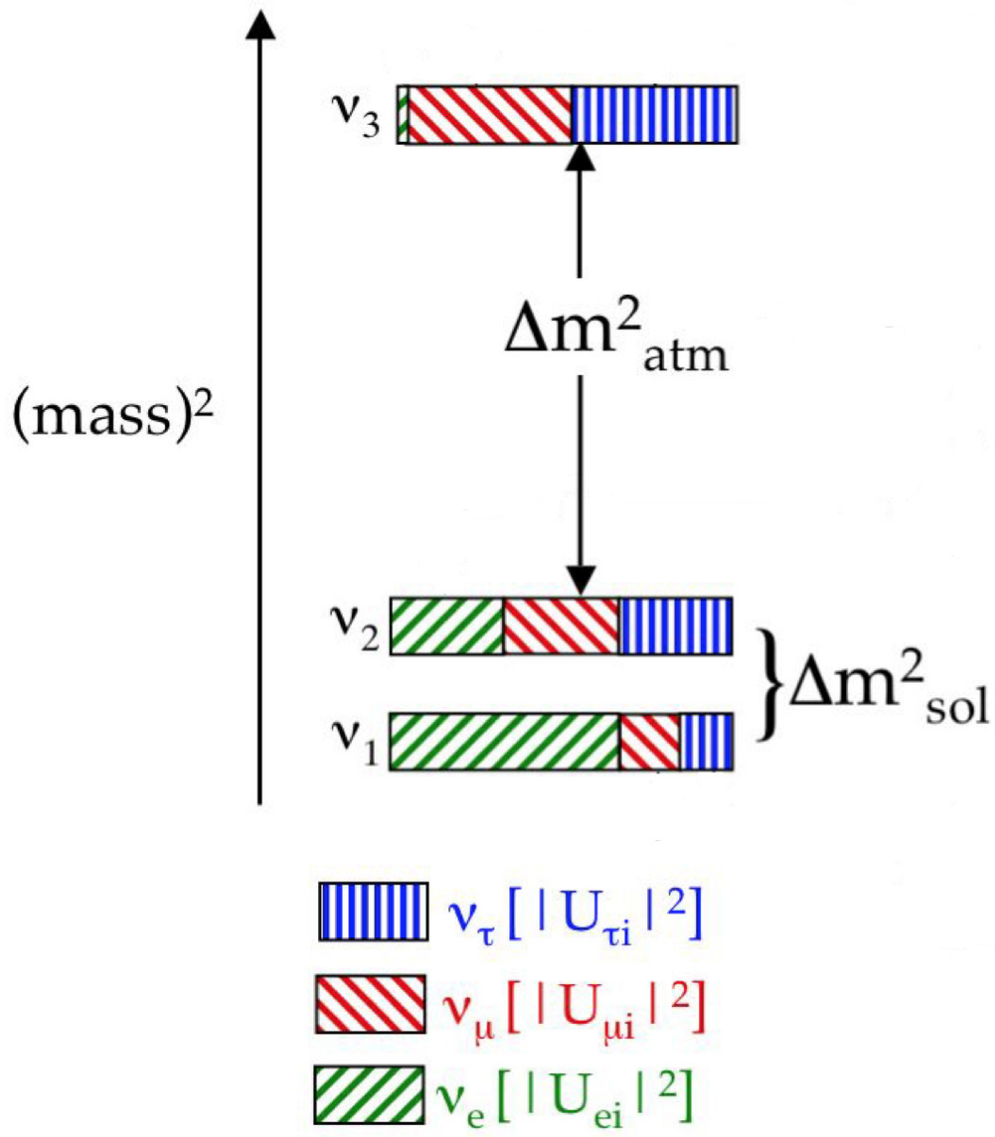
- **Neutrino oscillations and matter effects**
- IceCube
- The IceCube sterile neutrino search

Our current picture

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



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

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

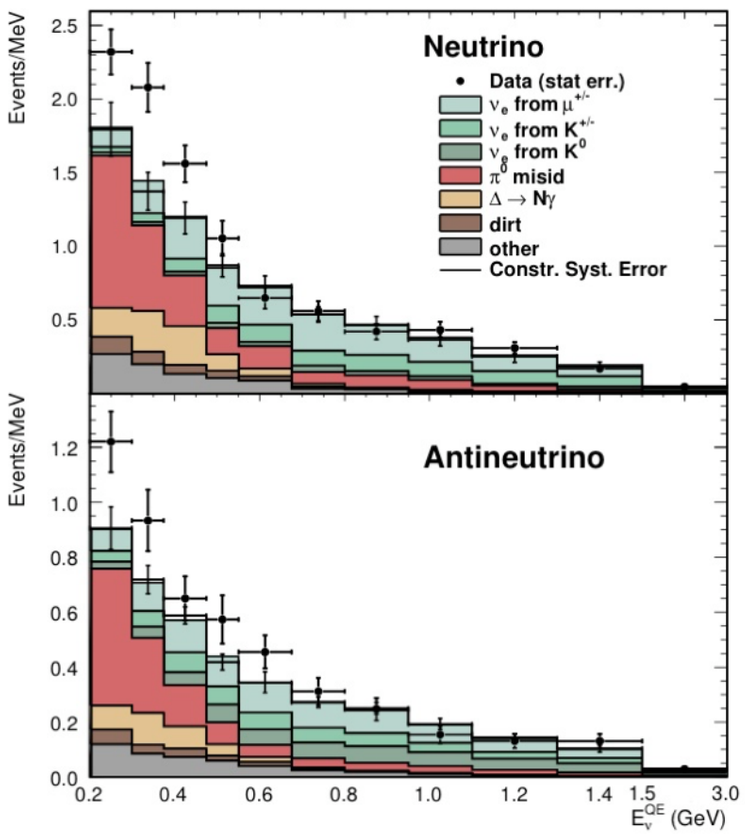
$$U = {\rm U}(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})$$

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

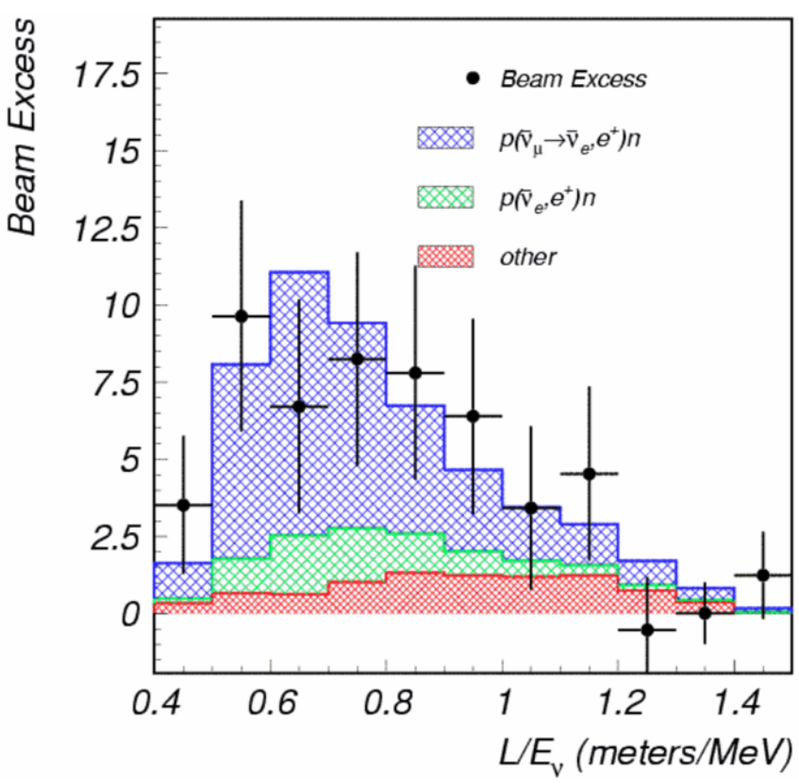
[B. Kayser, hep-ph/0506165 (2004)]

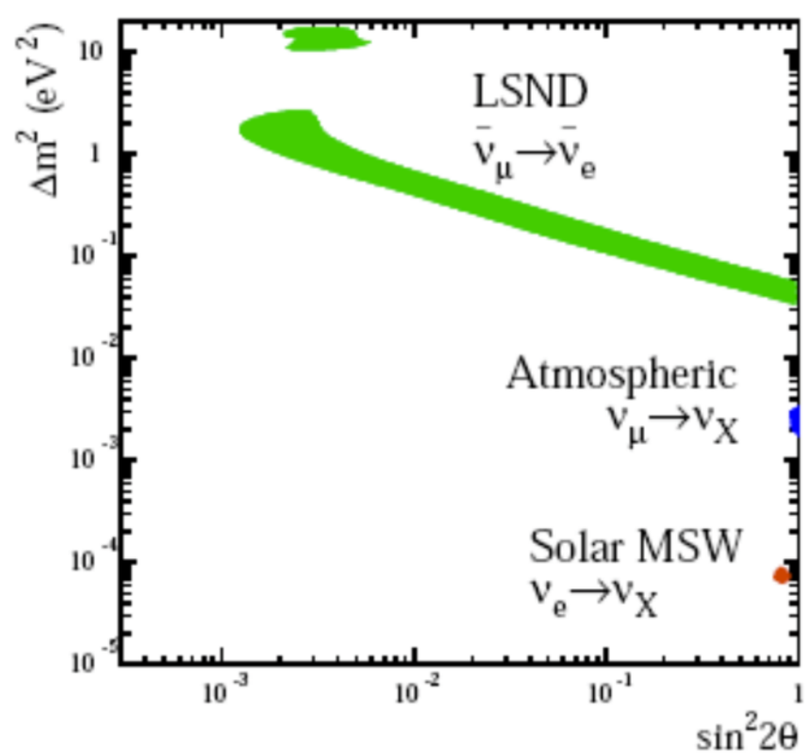
[C. Gonzalez-Garcia et al., JHEP 12 (2012)]

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}	$4\lvert U_{e4}\rvert^2 (1-\lvert U_{e4}\rvert^2)$
ν_μ disappearance $P(\nu_\mu \rightarrow \nu_\mu)$	Long/Short Baseline Experiments	Anomalous-less	$4\lvert U_{\mu 4}\rvert^2 (1-\lvert U_{\mu 4}\rvert^2)$
ν_e appearance $P(\nu_\mu \rightarrow \nu_e)$	Short Baseline Experiments	LSND ($\bar{\nu}$) MiniBooNe ($\bar{\nu}$, ν)	$4\lvert U_{\mu 4}\rvert^2 \lvert U_{e4}\rvert^2$

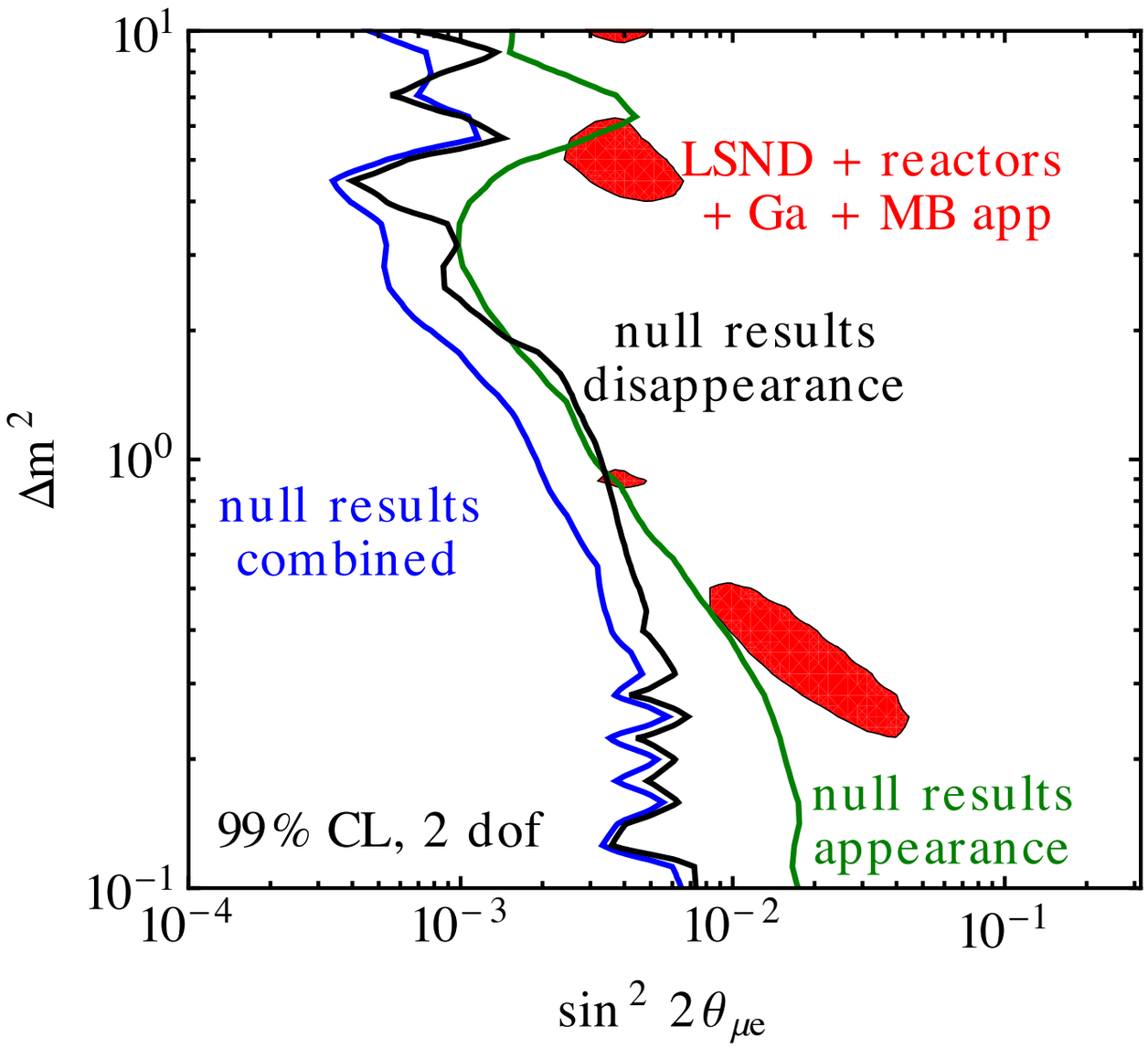




$$\Delta m^2 \sim 1\mathrm{eV}^2$$

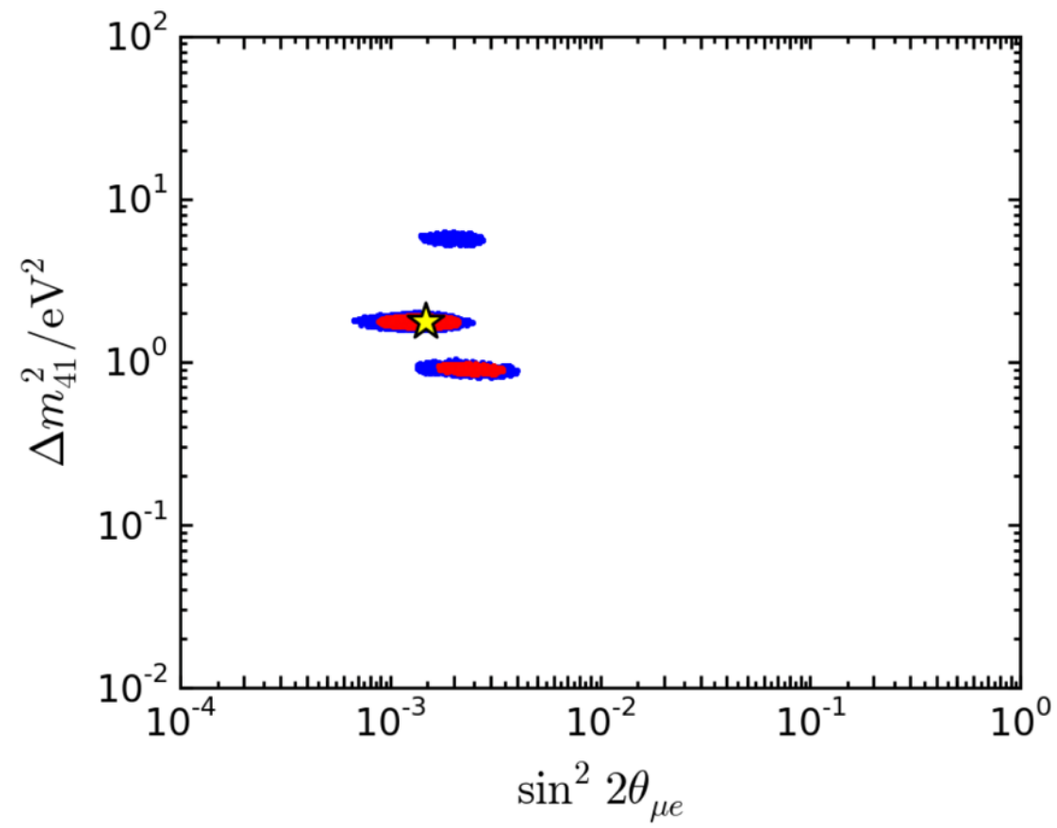
What does the World data say?

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



tension between experiments

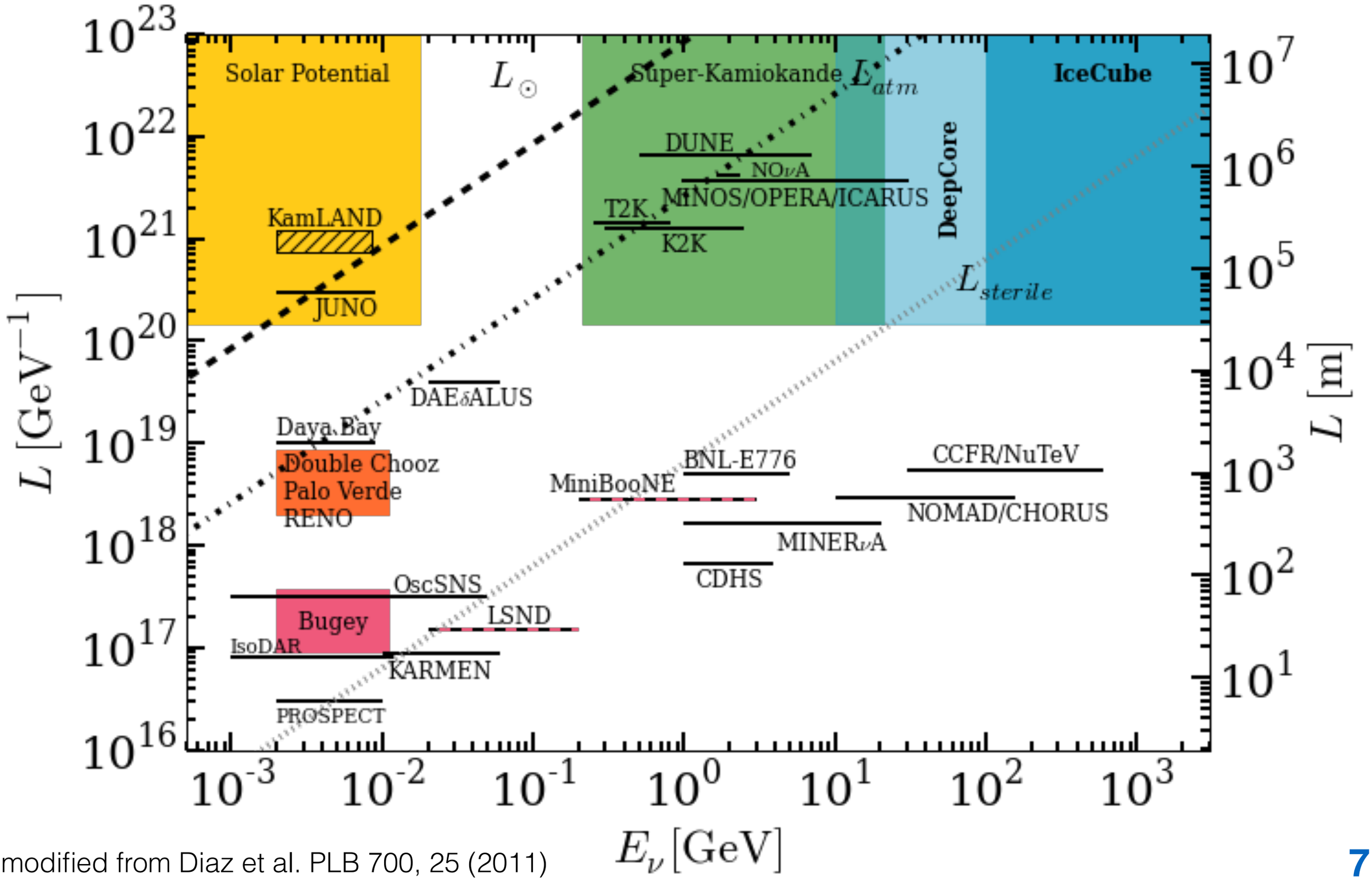
G. Collins et al., arXiv: 1602.00671



On updated fits solutions remain…

We need new measurements!

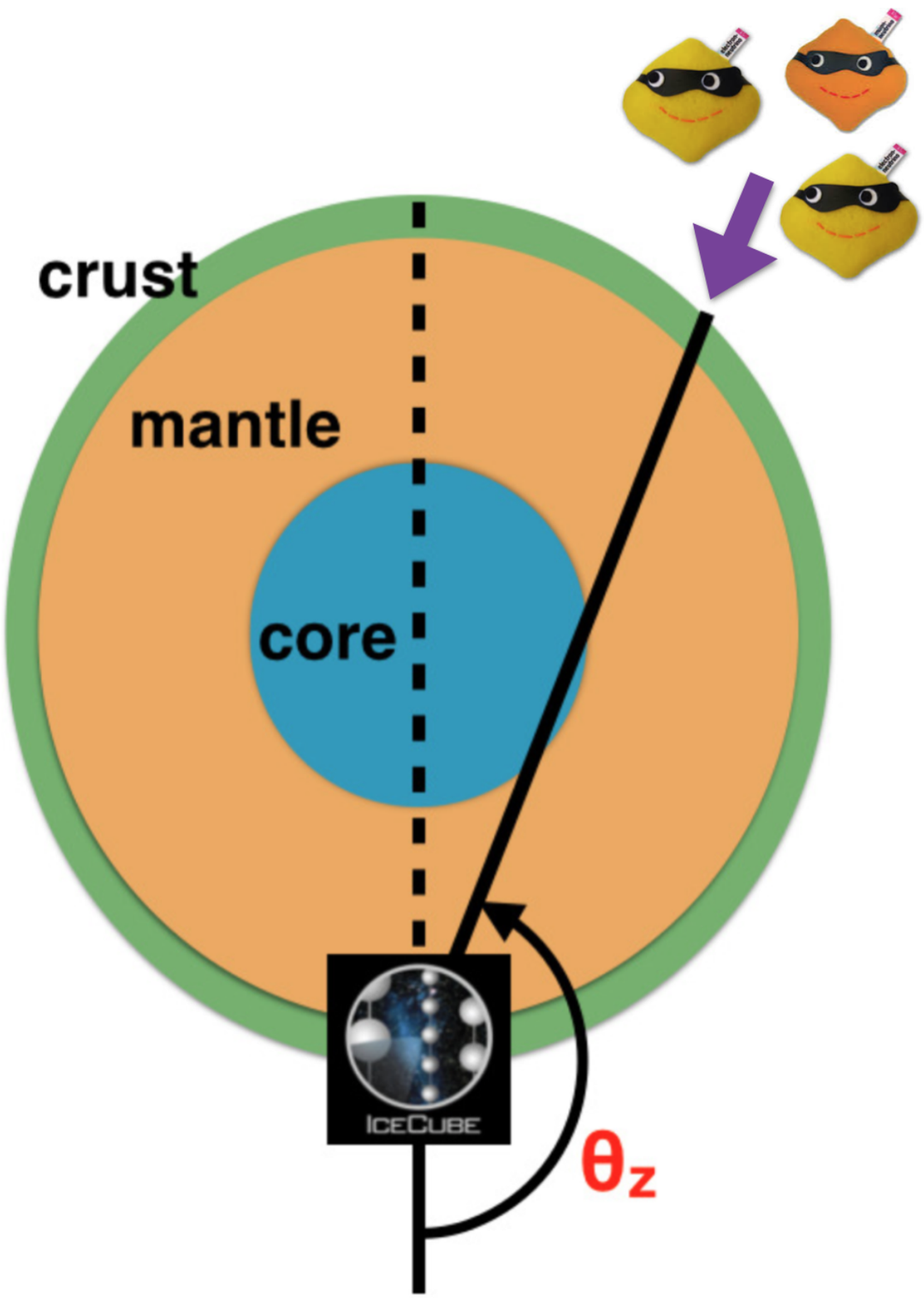
A global view: the IceCube-ShortBaseline connection



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

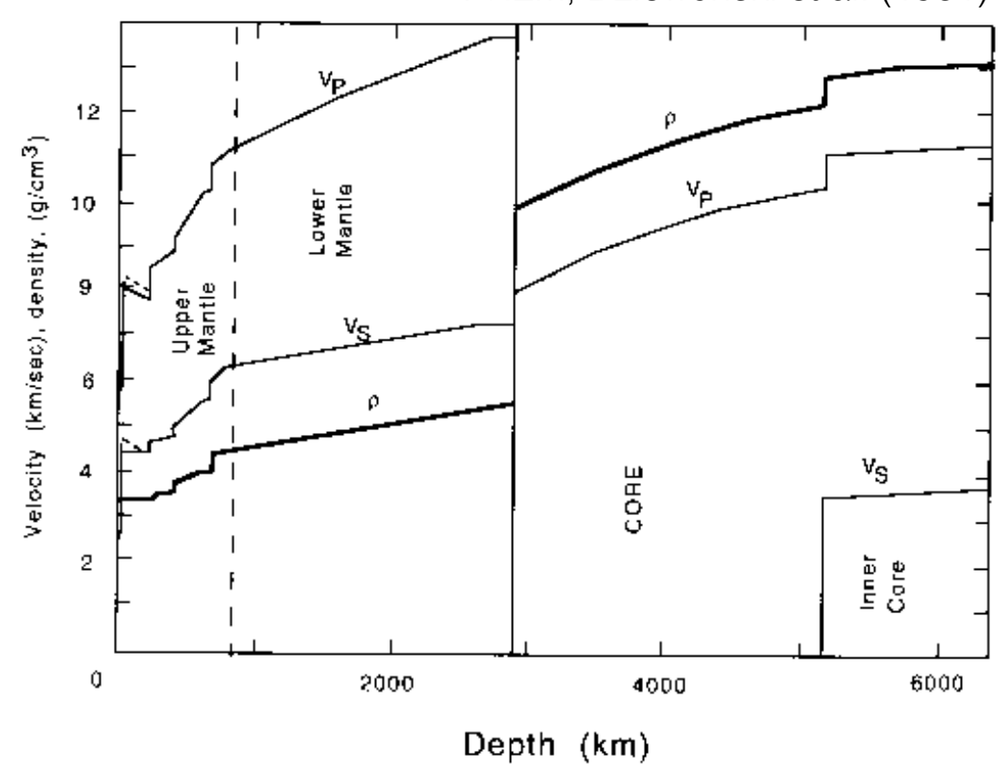
A closer look at atmospheric neutrinos oscillation

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 :
$\cos\theta_z > -0.1$

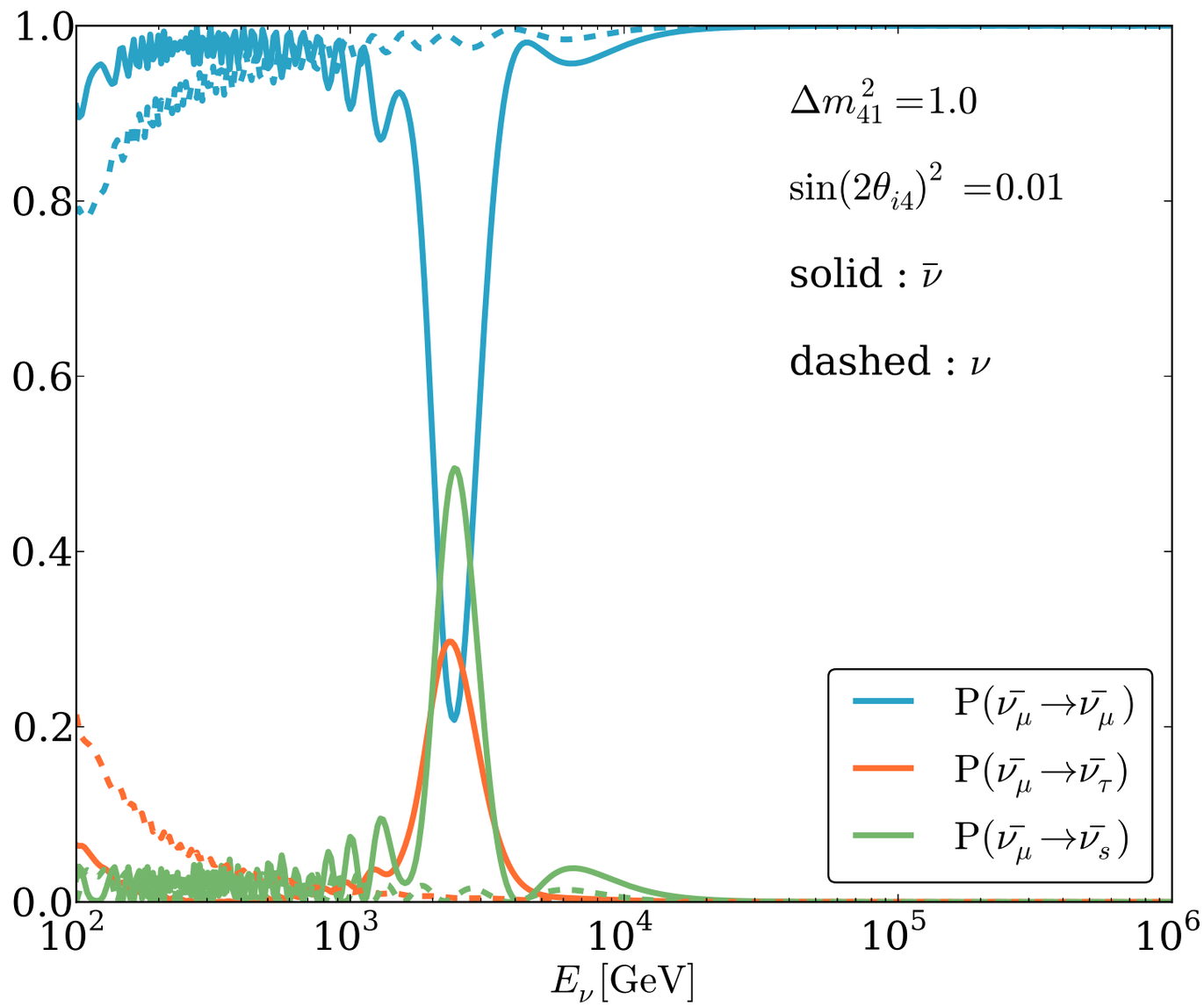
PREM, Dziewonski et al. (1981)



Stroke of luck...

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

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

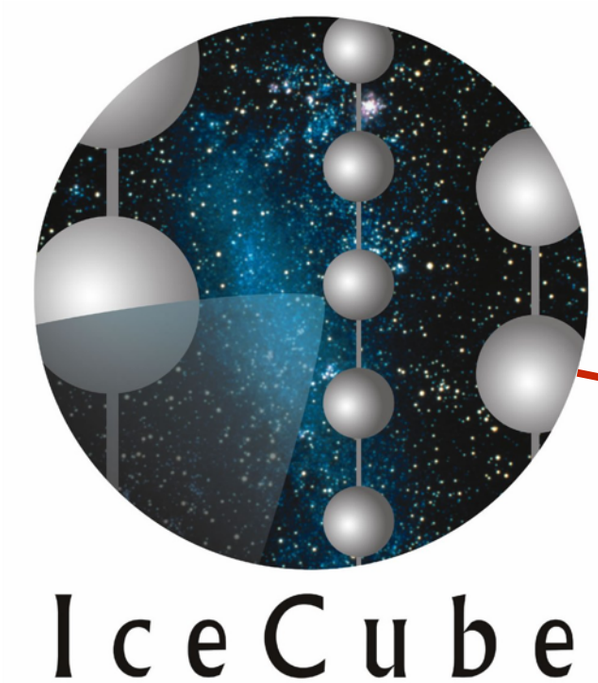


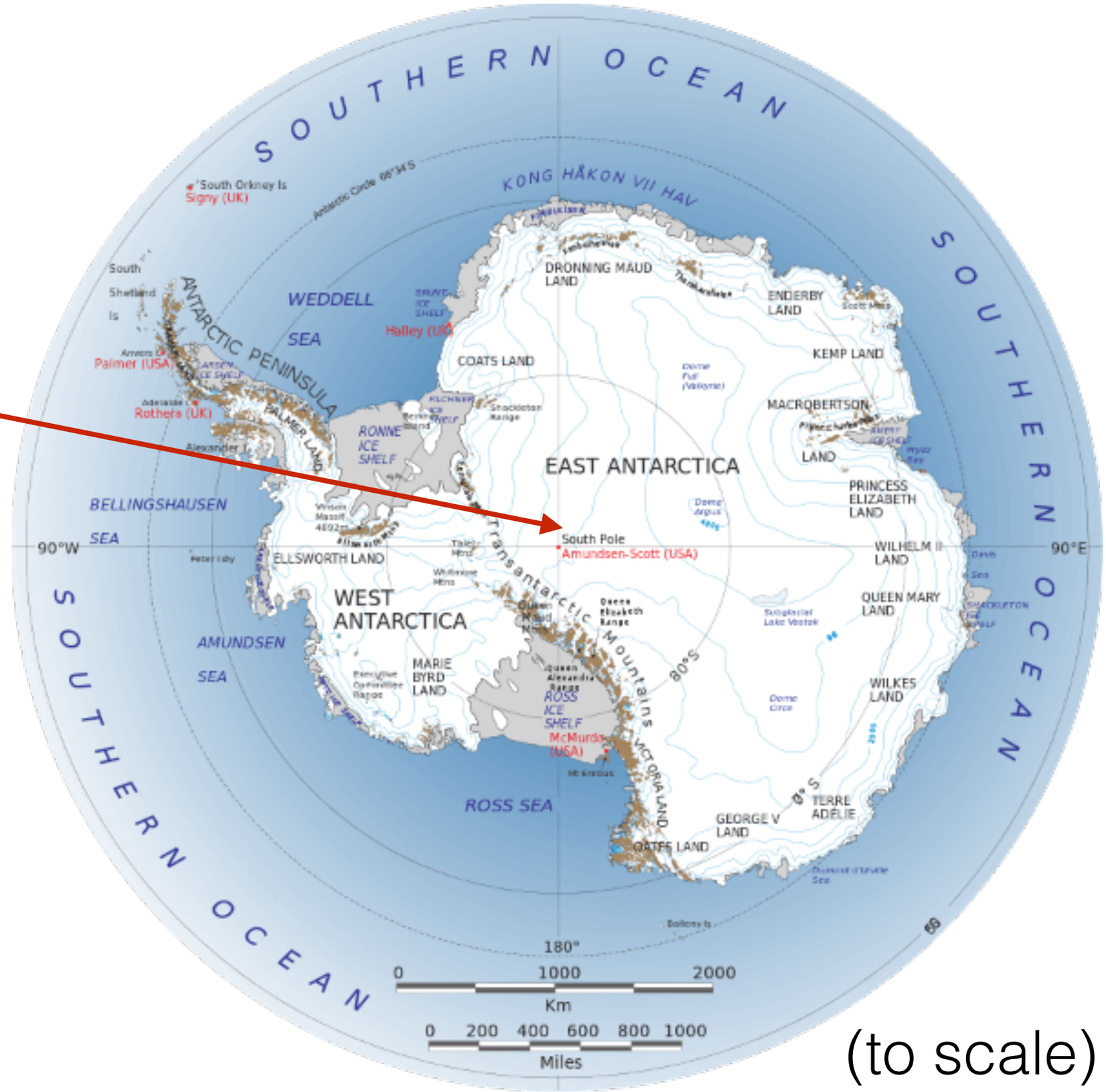
Nunokawa et al. PLB, B562, 279 (2003). arXiv:hep-ph/0302039

Today

- Neutrino oscillations and the MSW effect
- **IceCube**
- The IceCube sterile neutrino search

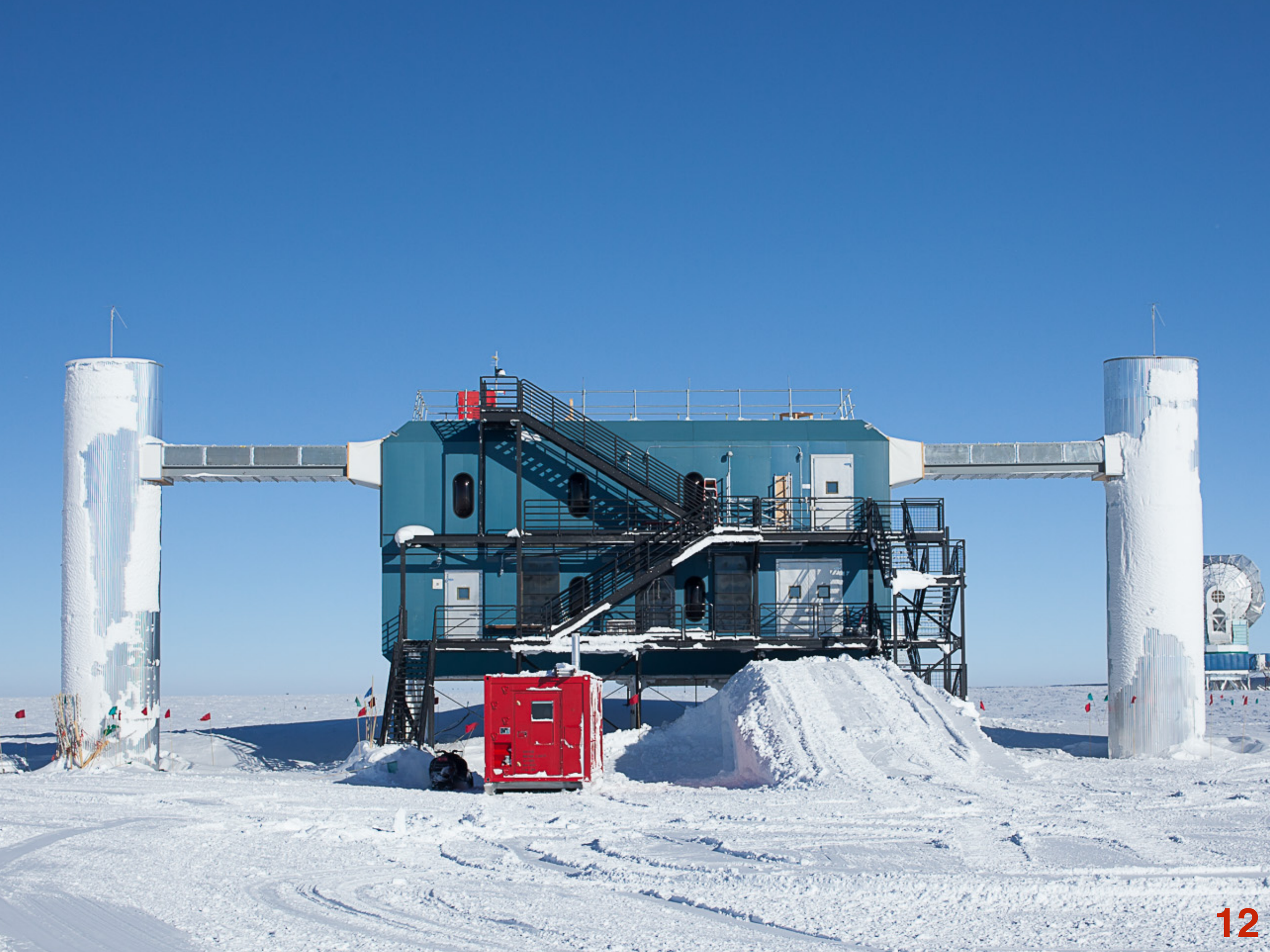
The IceCube experiment

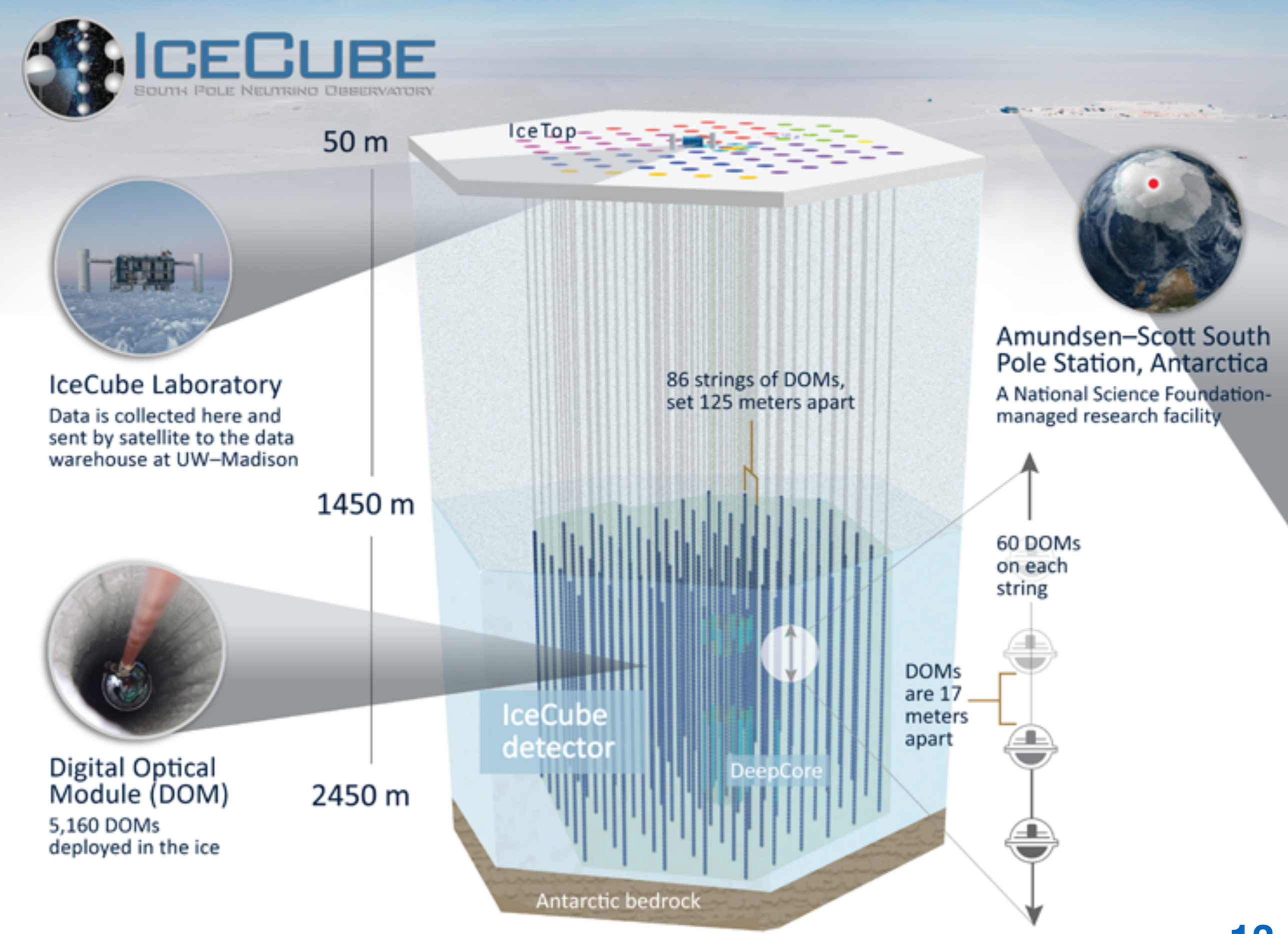




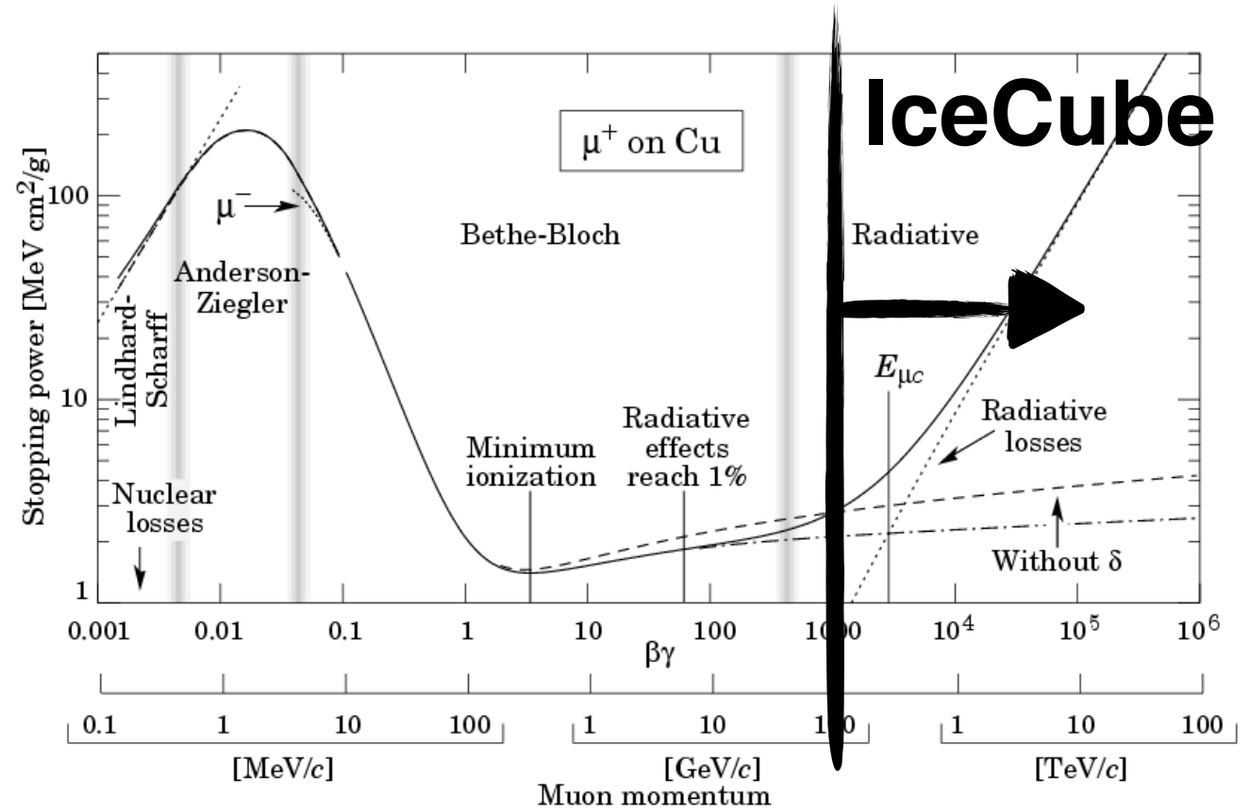
We are here!

(to scale)

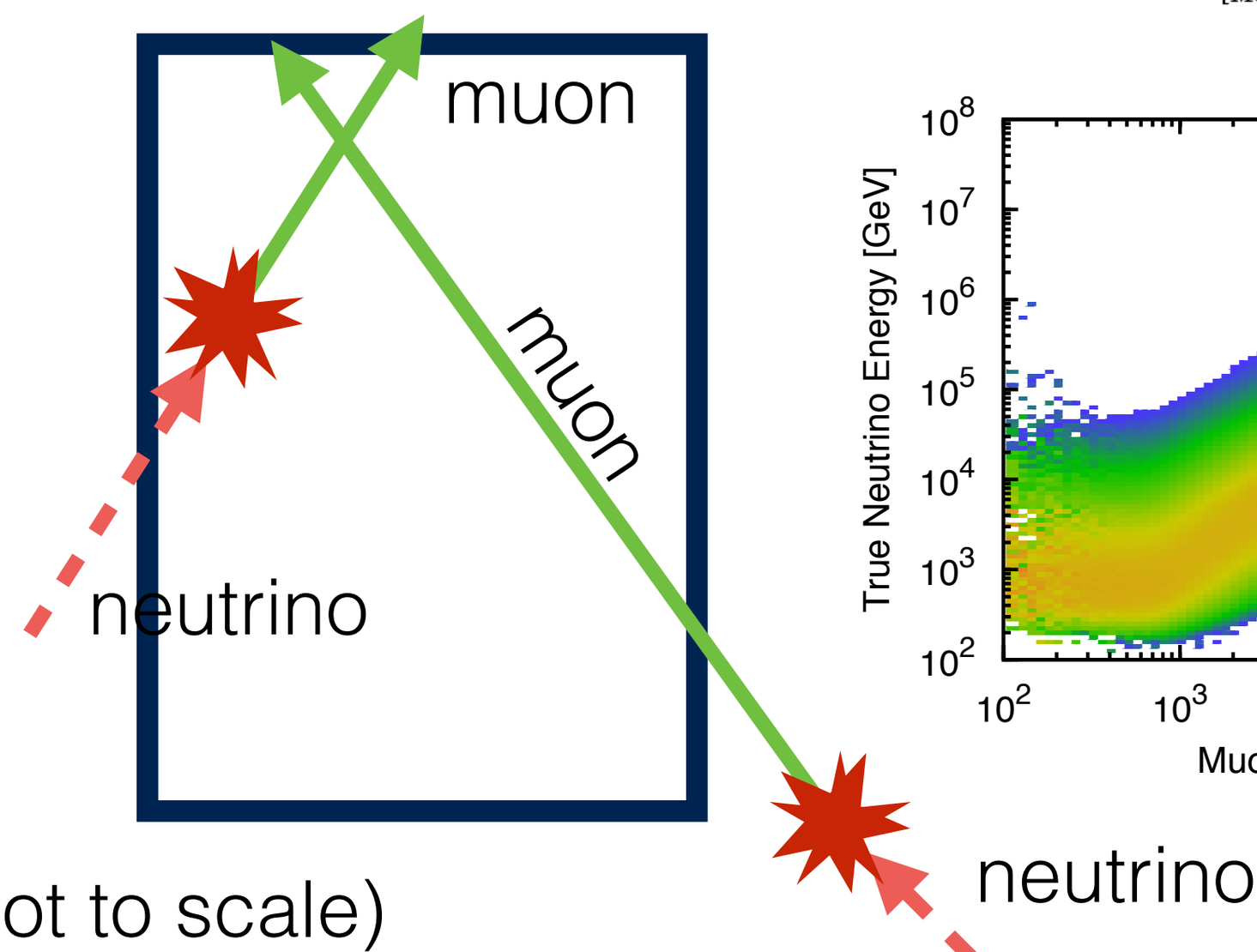



IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

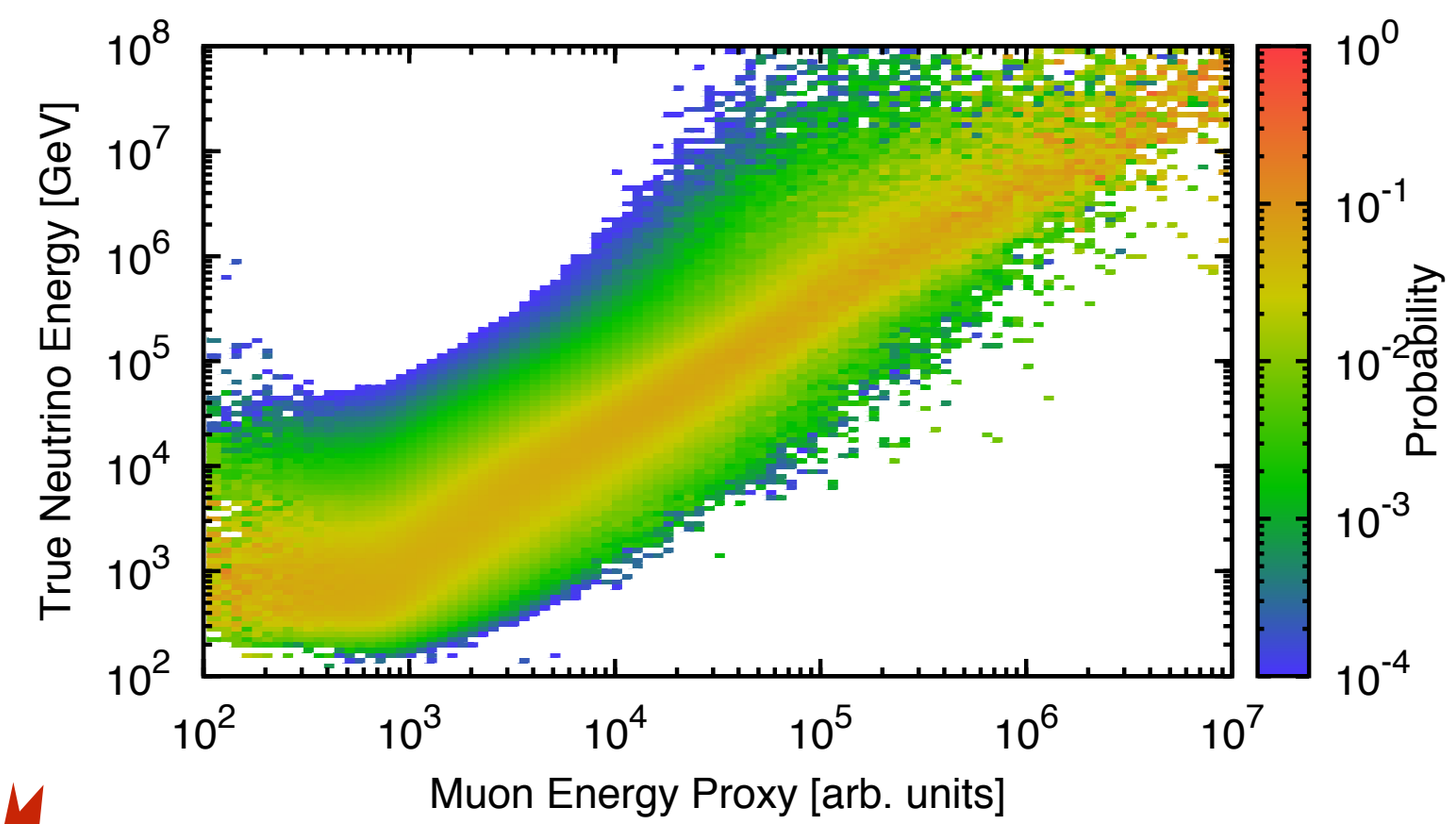
Through-going muons in IceCube



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



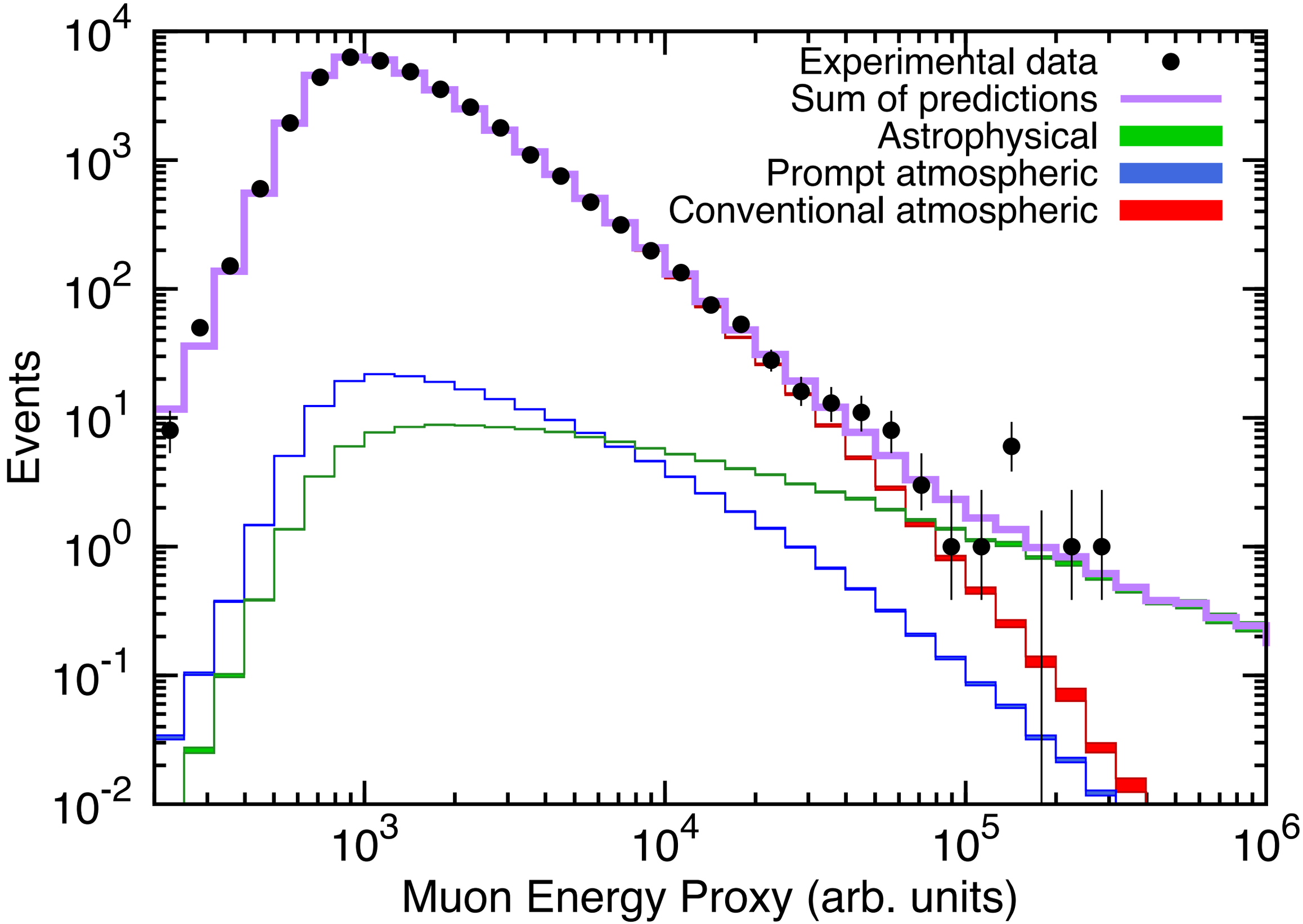
(not to scale)



What do they look like?

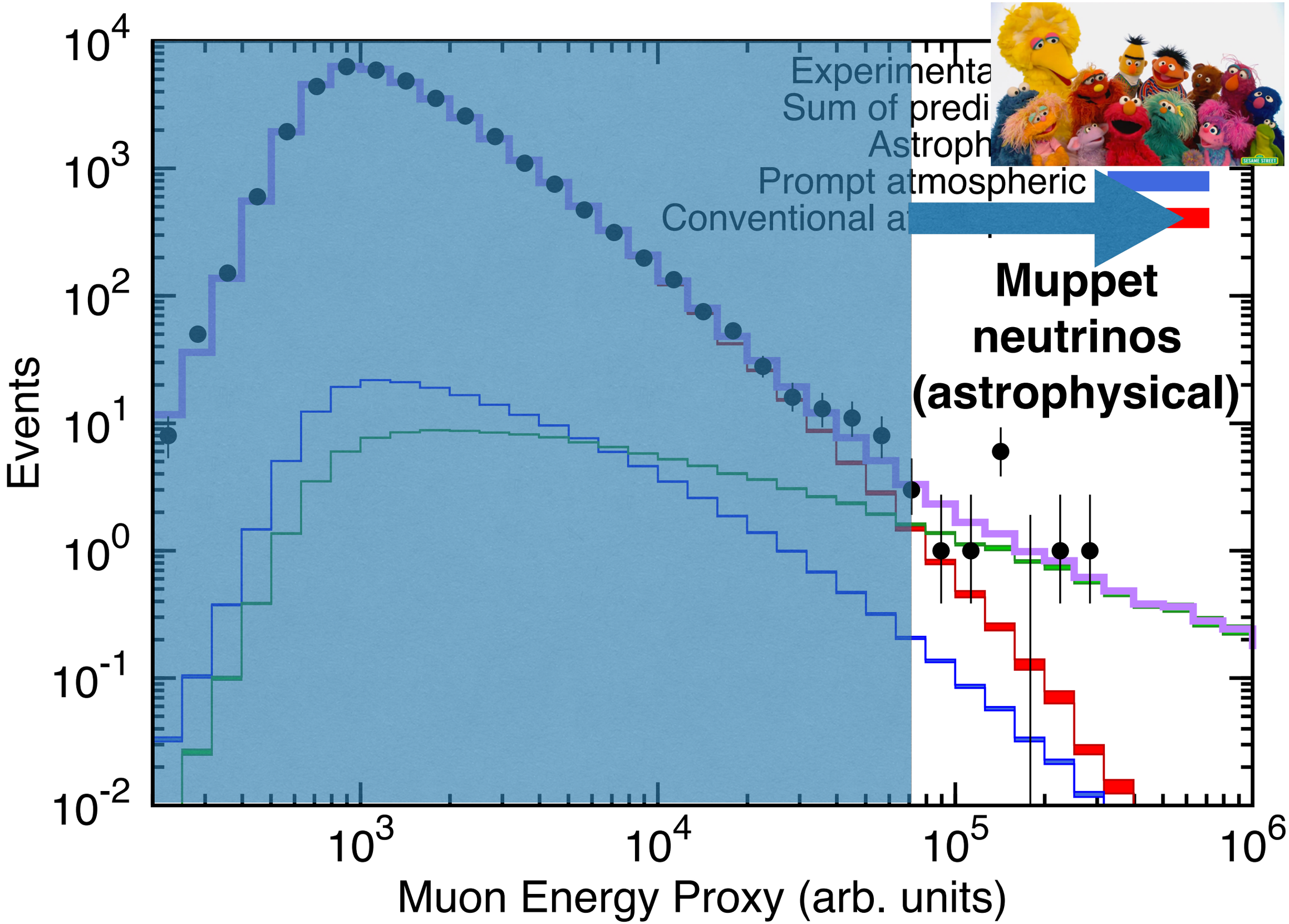
Size of spheres ~ deposited charge

Through-going nu-mu energy distribution



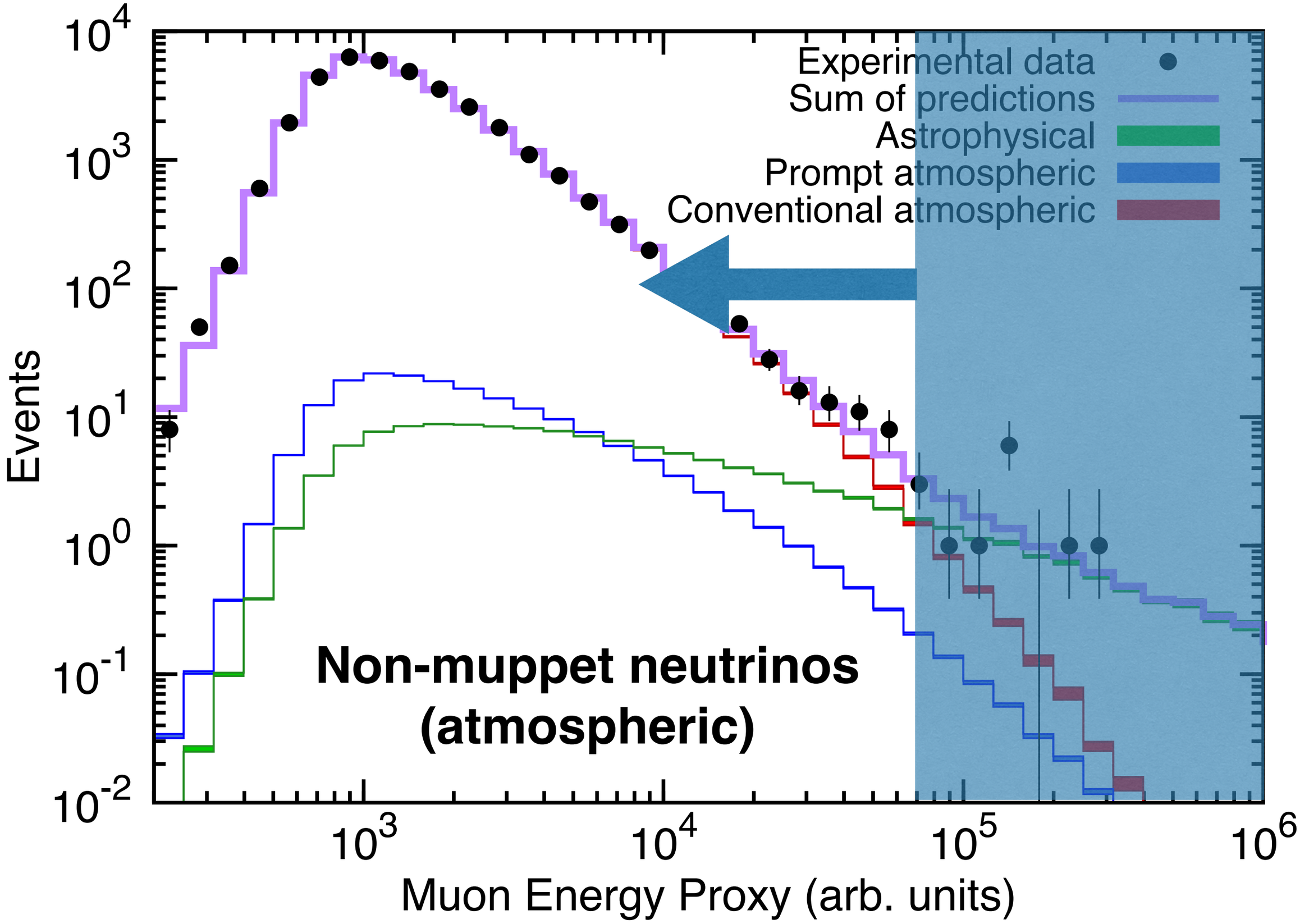
Phys. Rev. Lett. 115, 081102 (2015)

Through-going nu-mu energy distribution



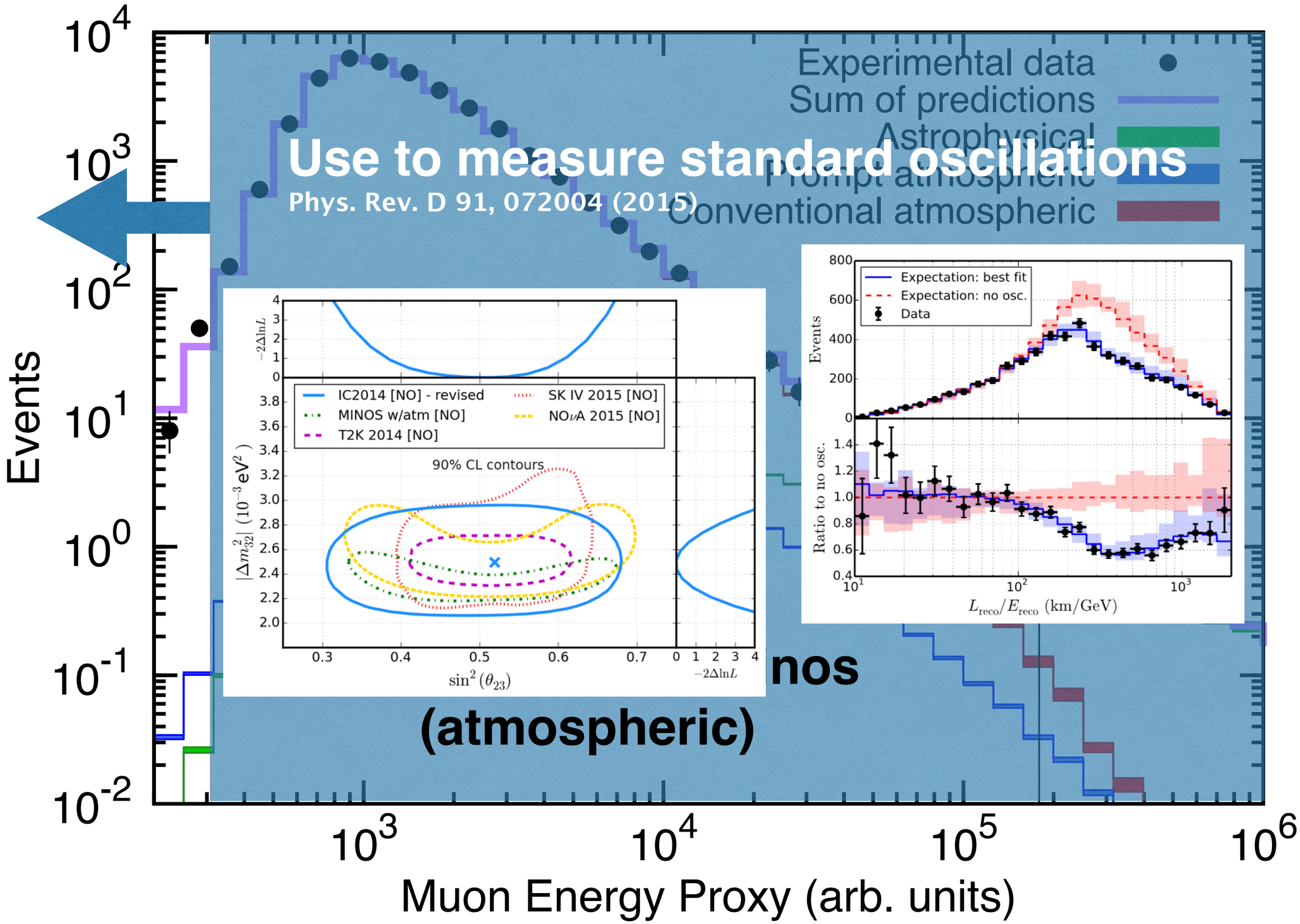
Phys. Rev. Lett. 115, 081102 (2015)

Through-going nu-mu energy distribution



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

Through-going nu-mu energy distribution

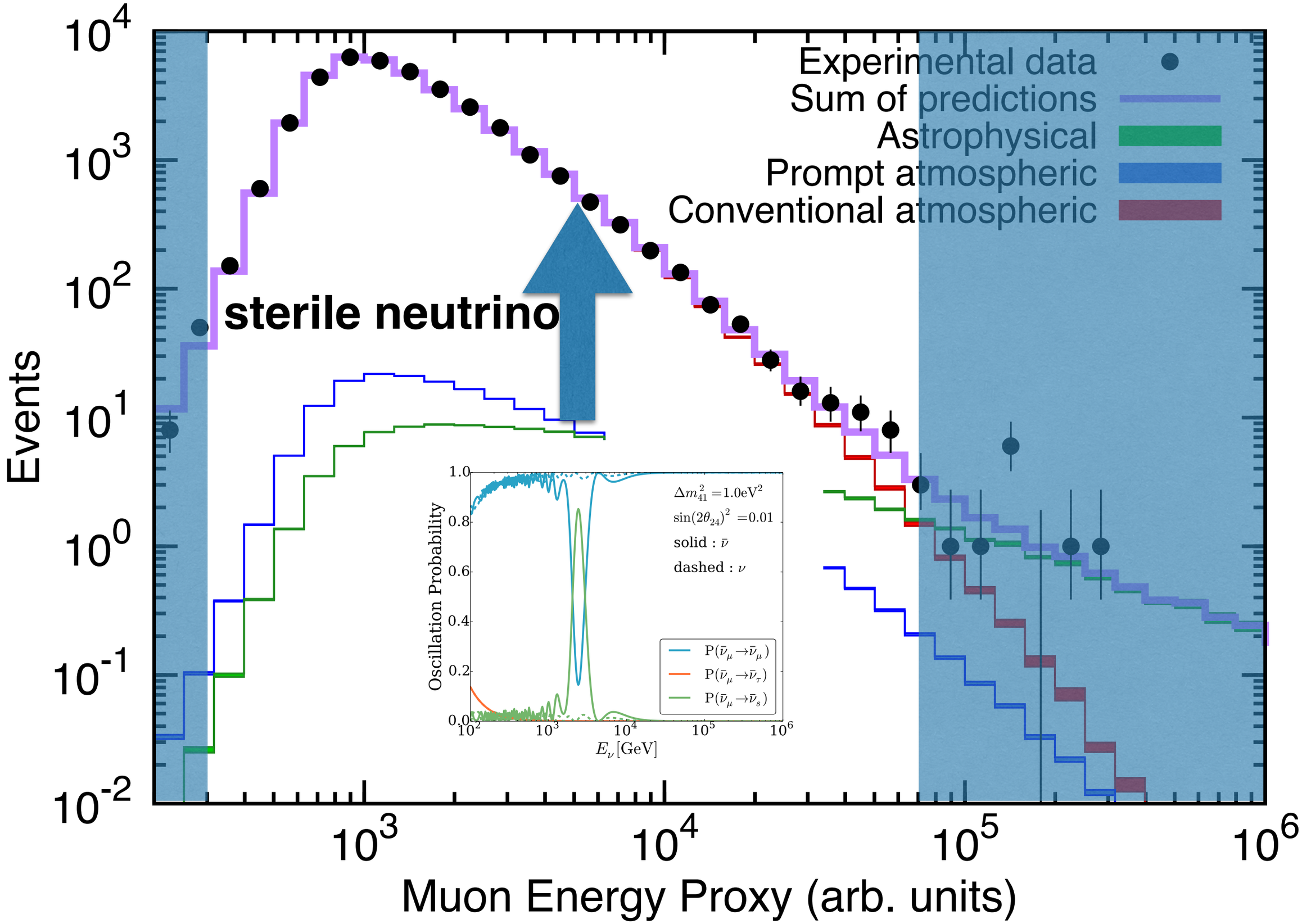


Phys. Rev. Lett. 115, 081102 (2015)

Today

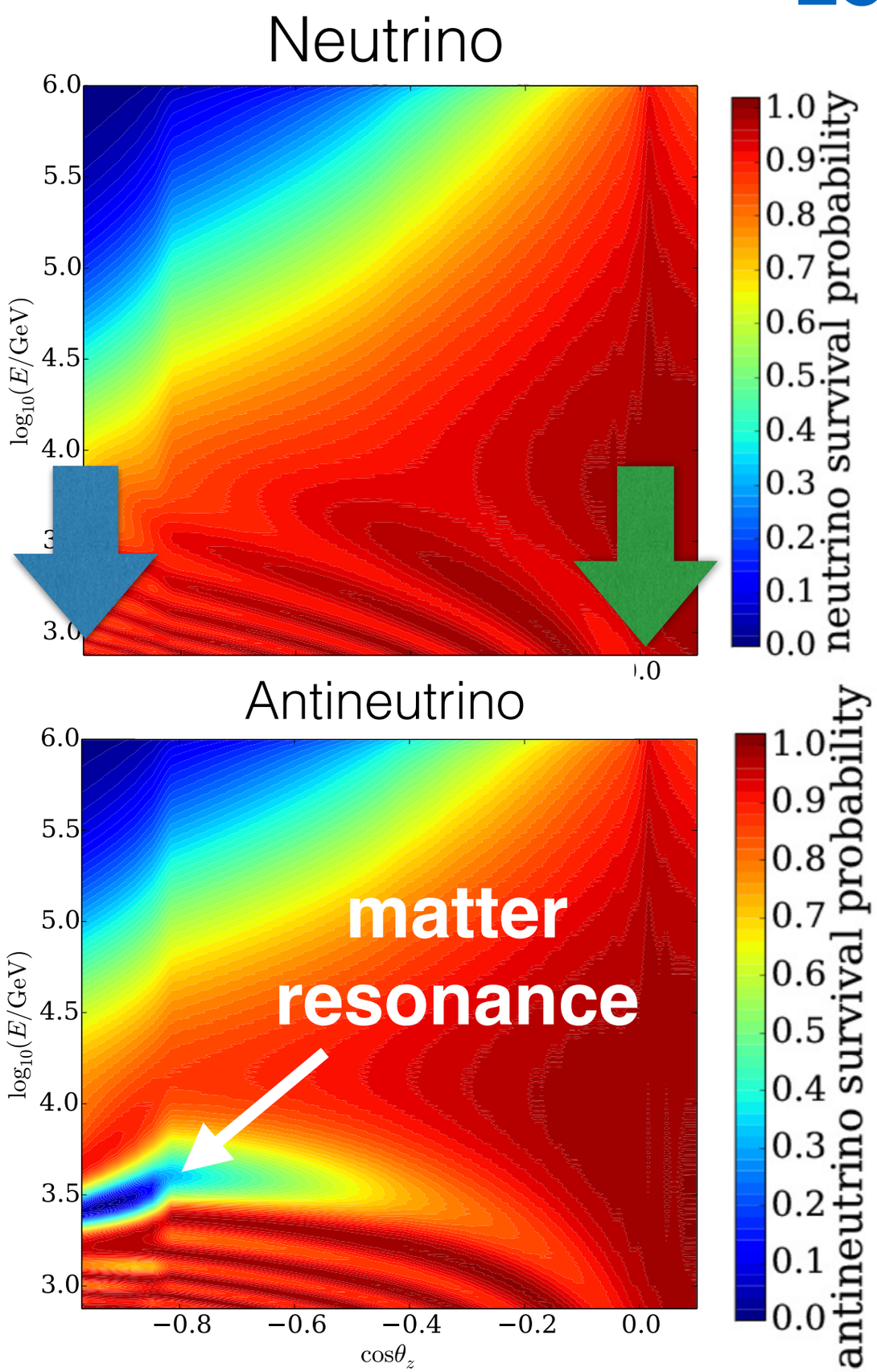
- ➡Neutrino oscillations and the MSW effect
- ➡IceCube
- ➡**The IceCube sterile neutrino search**

Through-going nu-mu energy distribution



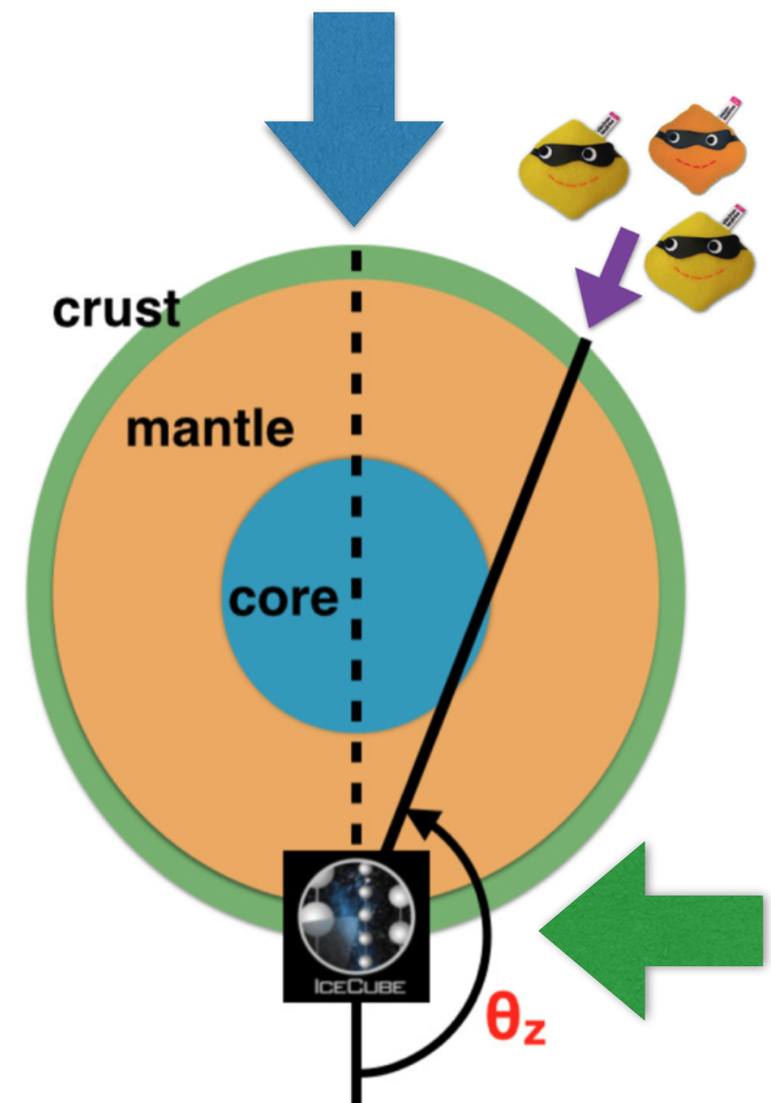
Phys. Rev. Lett. 115, 081102 (2015)

Oscillation probability as a function of energy and zenith



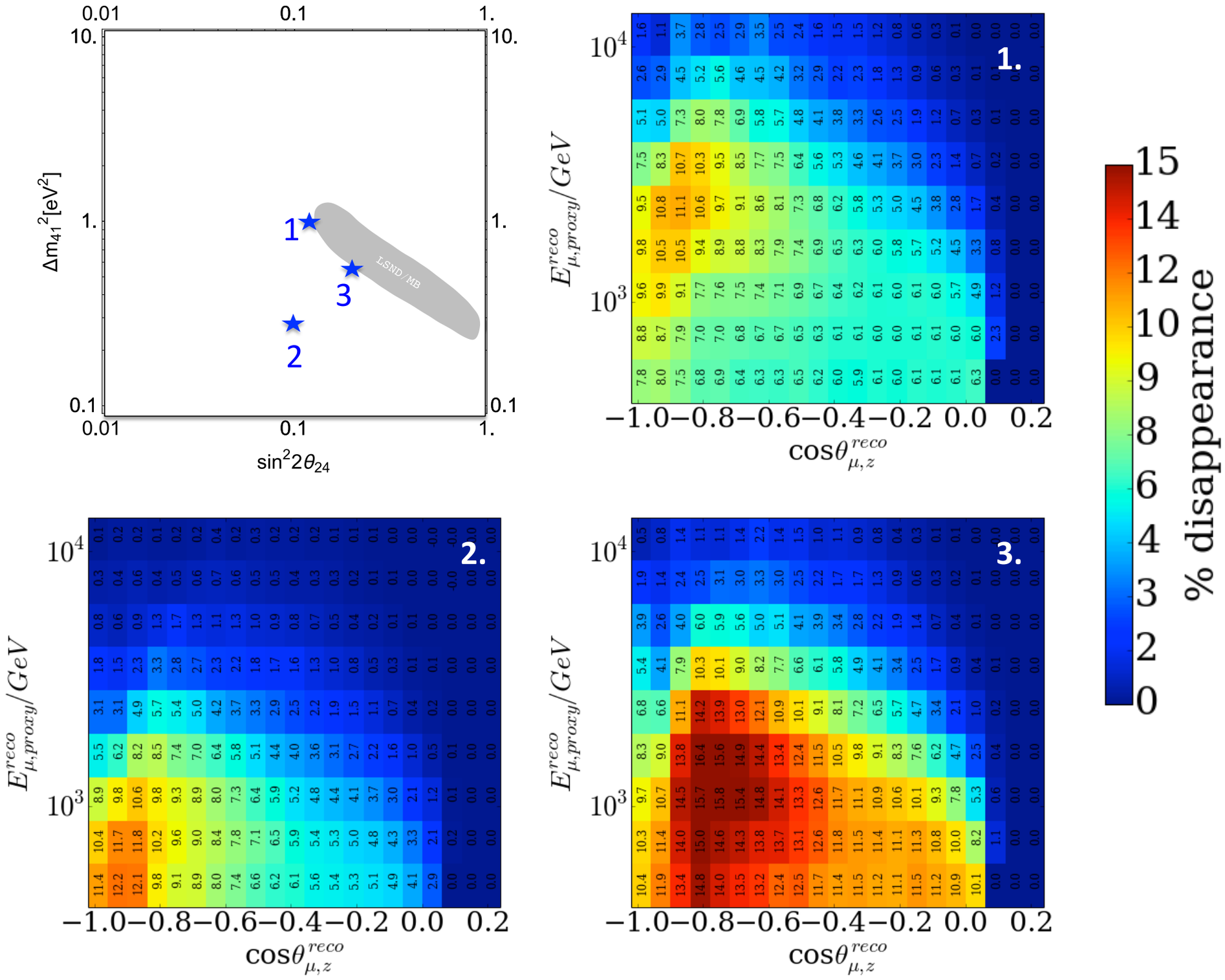
$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$

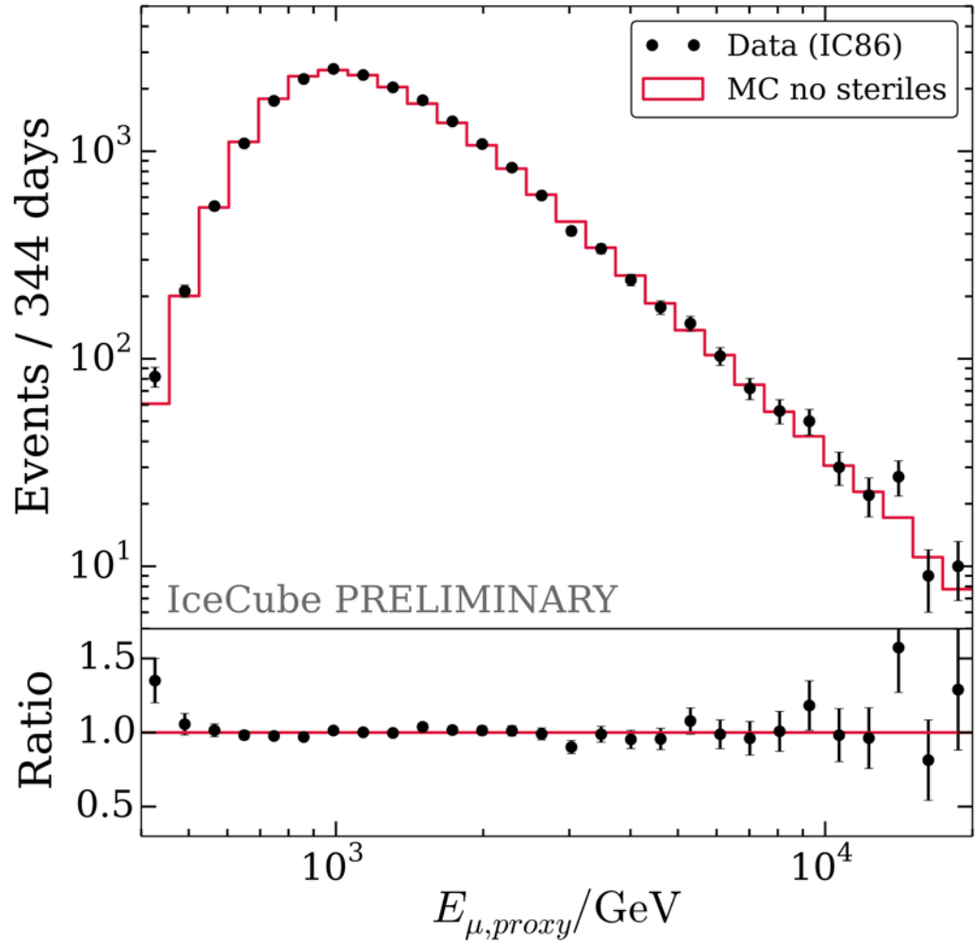
$$\left.\begin{aligned} \sin^2(2\theta) &= 0.1 \\ \Delta m^2 &= 1\mathrm{eV}^2 \end{aligned}\right\} \text{LSND/MB like}$$

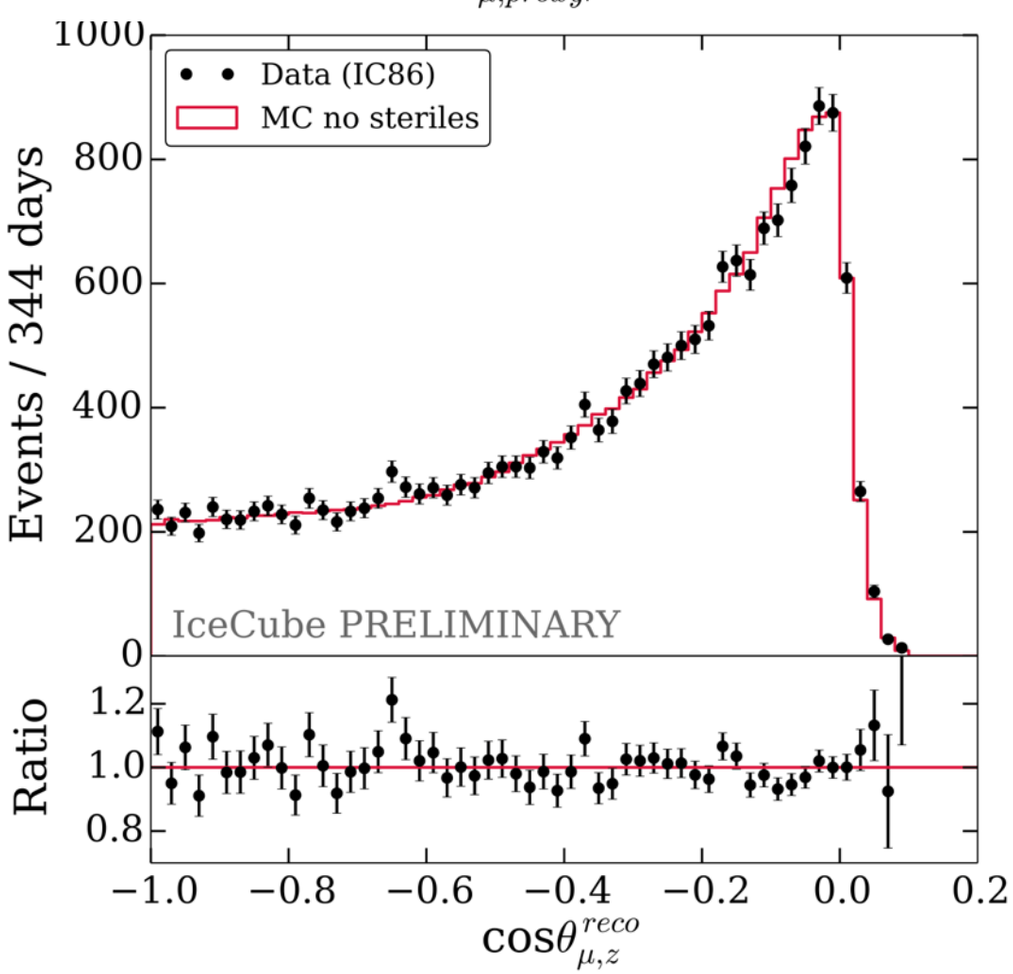


The Signal!

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

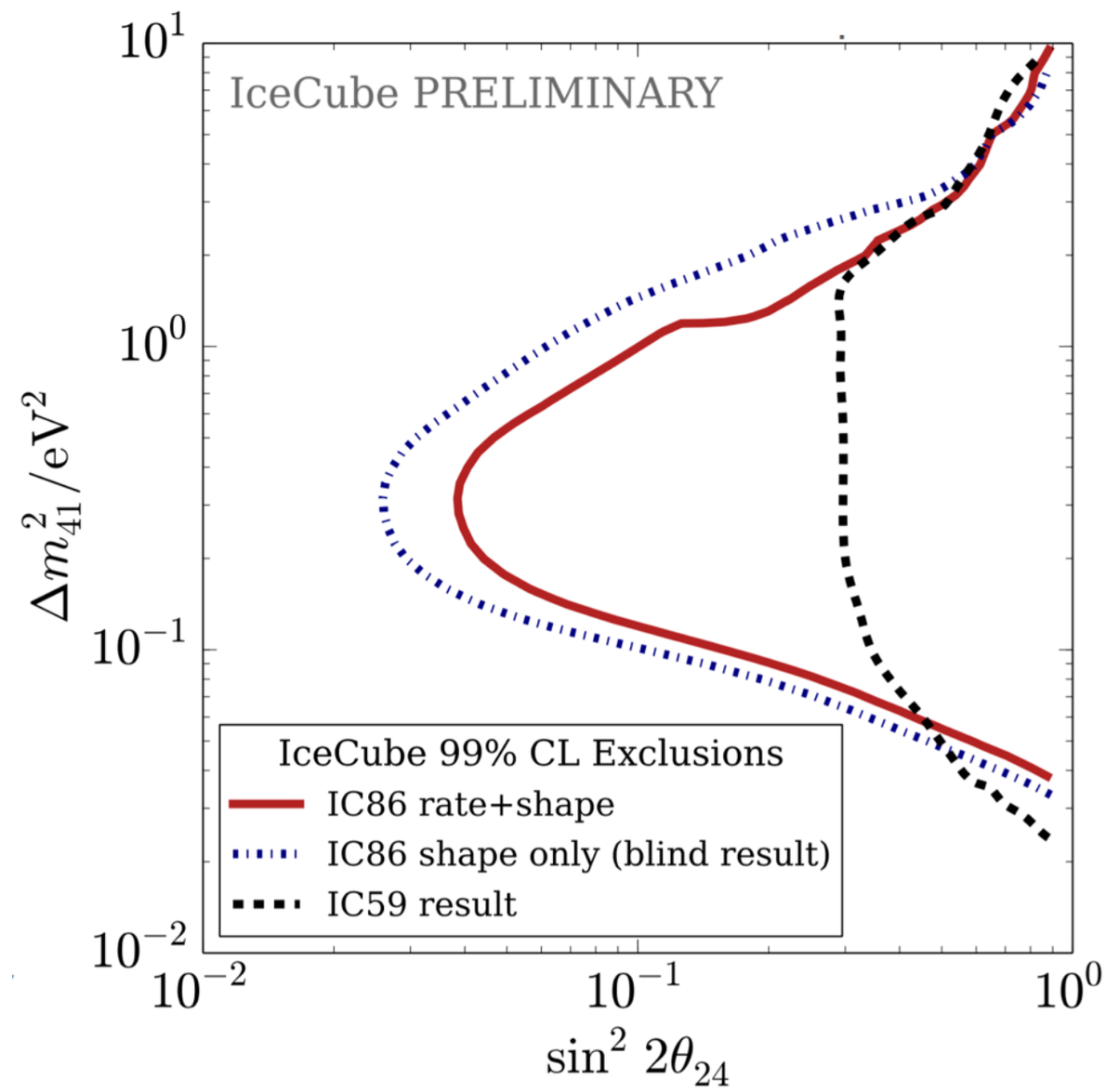




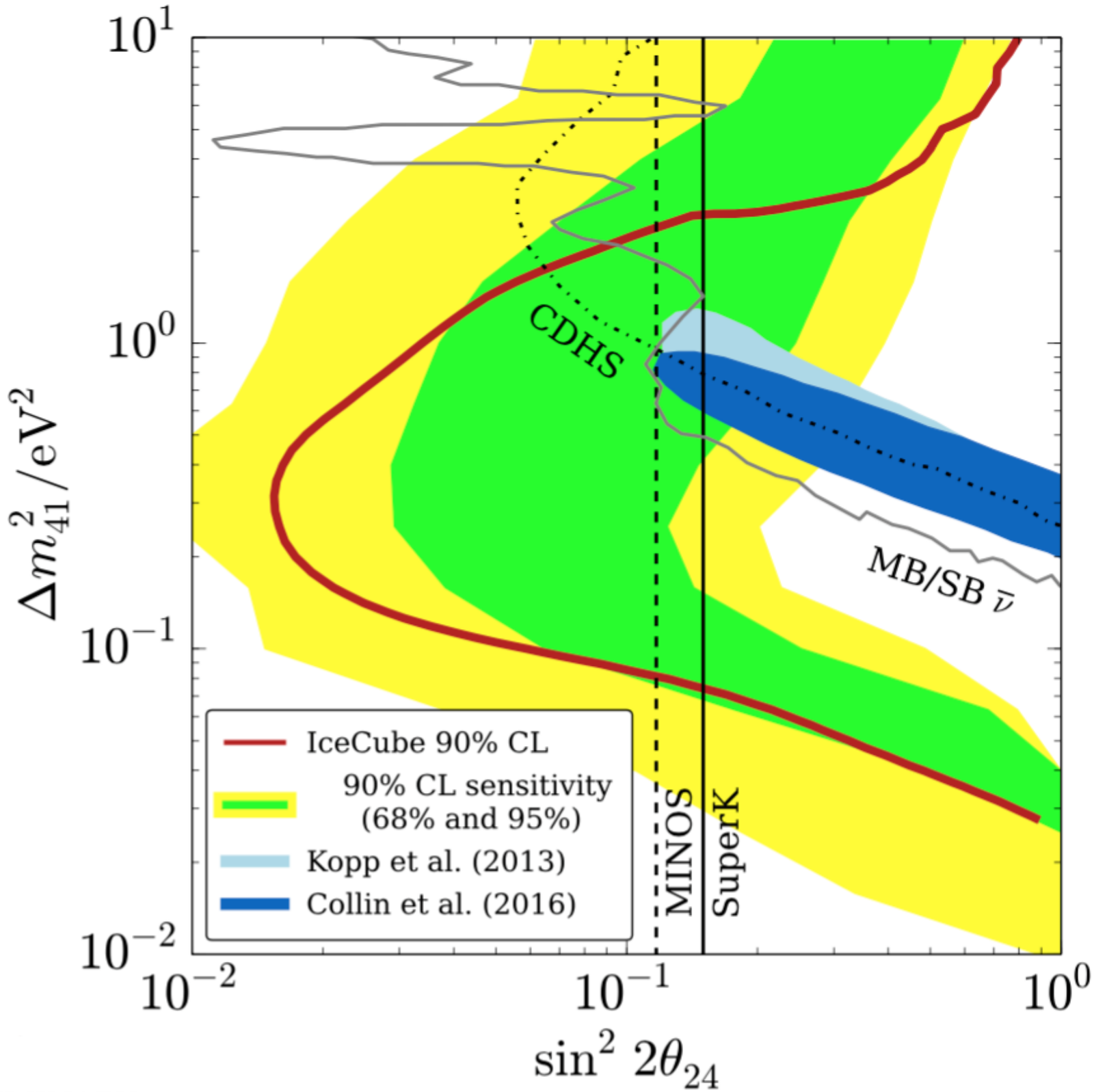


- We unblinded one year of data which had ~ 20 000 neutrino events.
- **Distributions compatible with the no sterile hypothesis.**

New Limit:

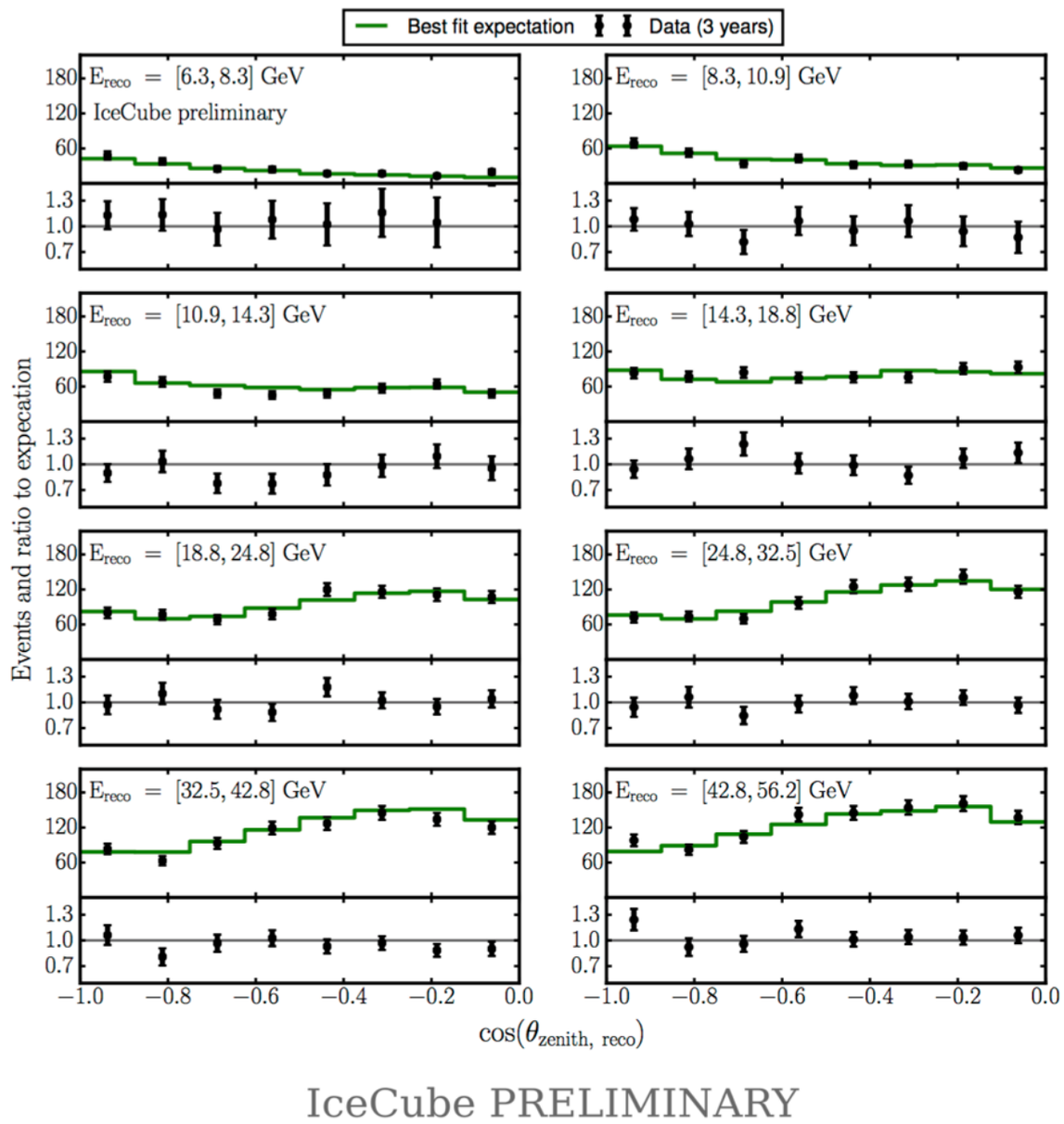


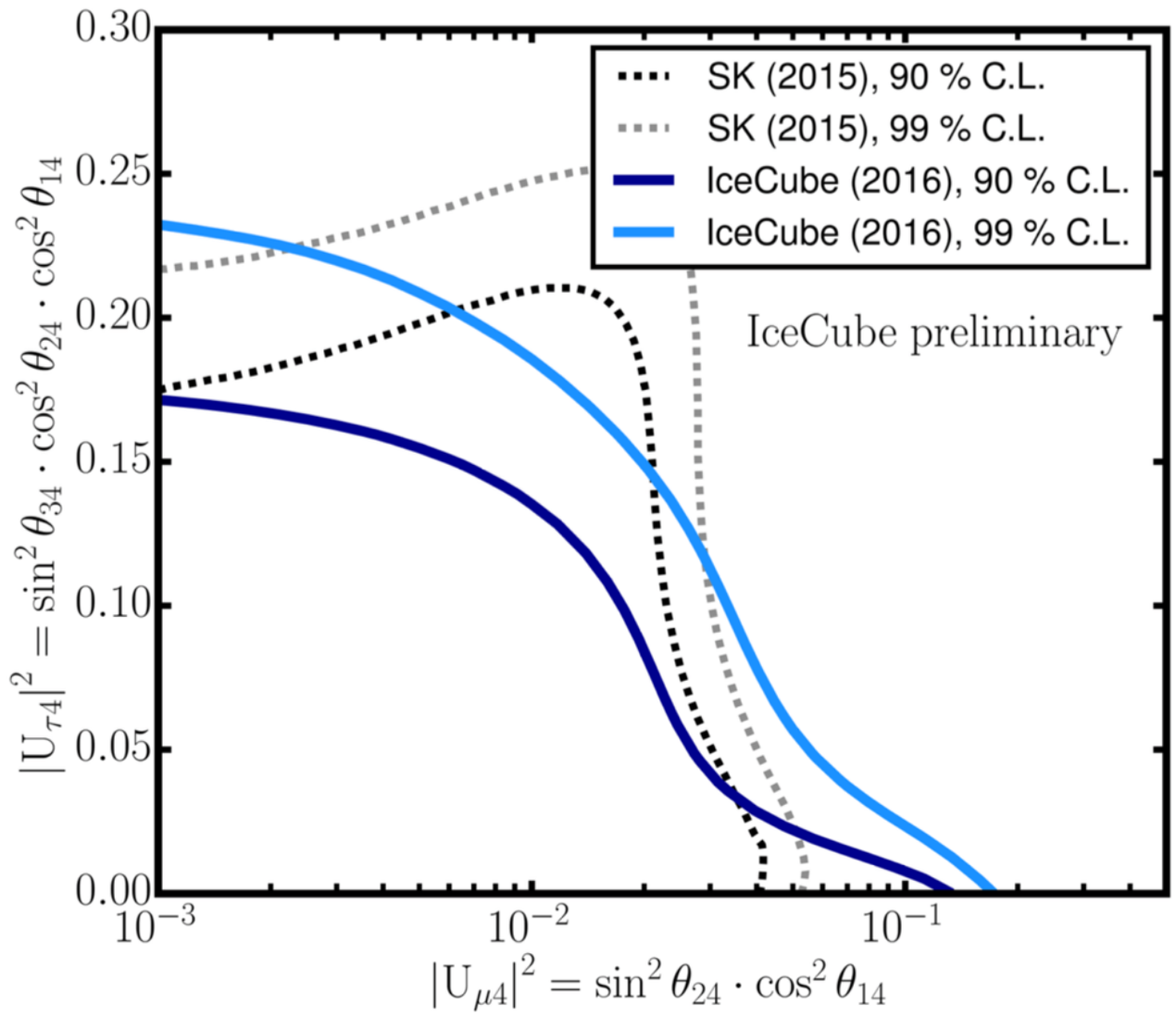
Main result!



IceCube PRELIMINARY

Also, IceCube + DeepCore analysis

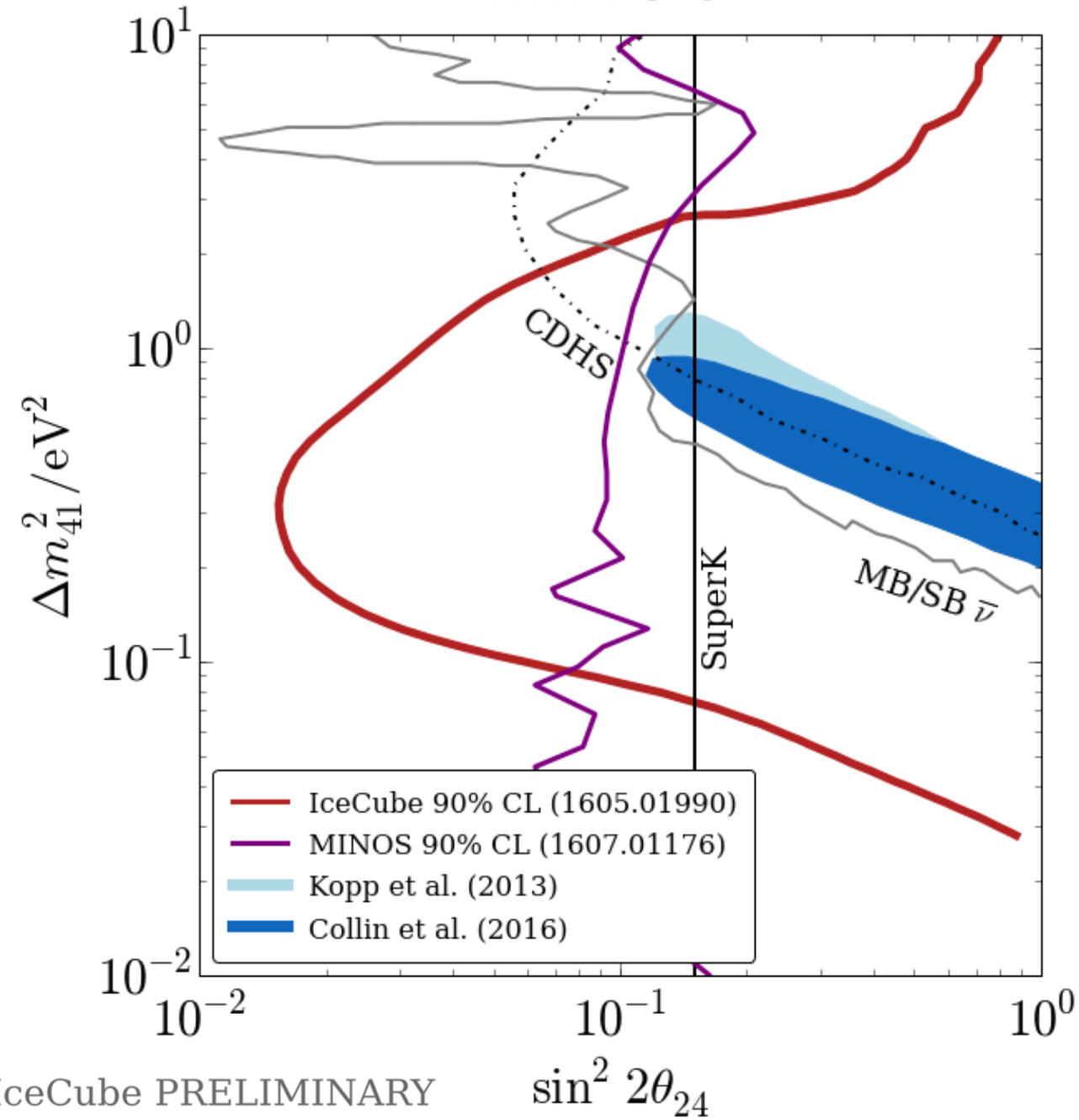




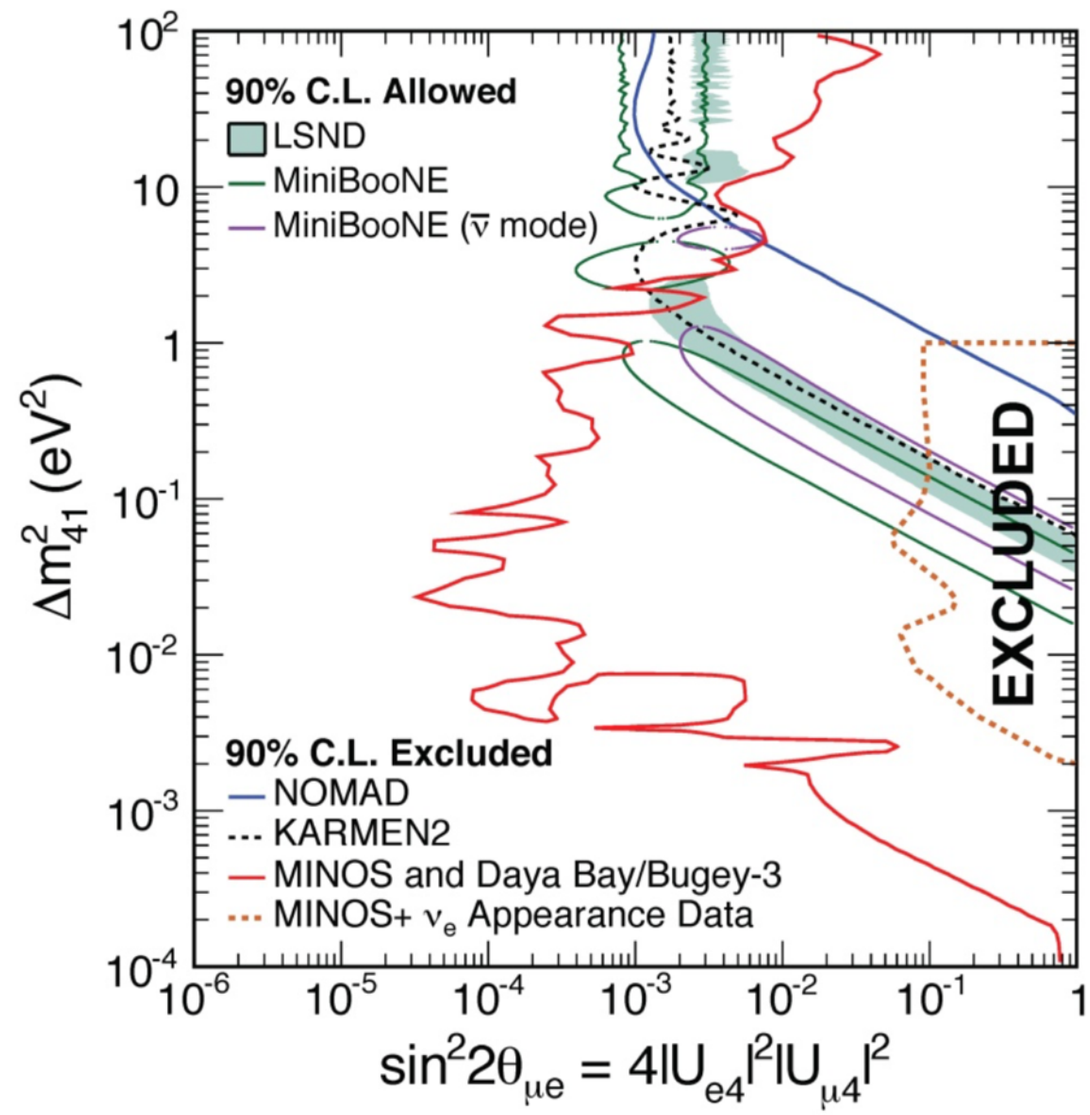
Using events below a 100 GeV we can also obtain constraints on sterile neutrinos by deviations from standard oscillations.

Other new results from *Neutrino2016*

MINOS



MINOS+Daya Bay

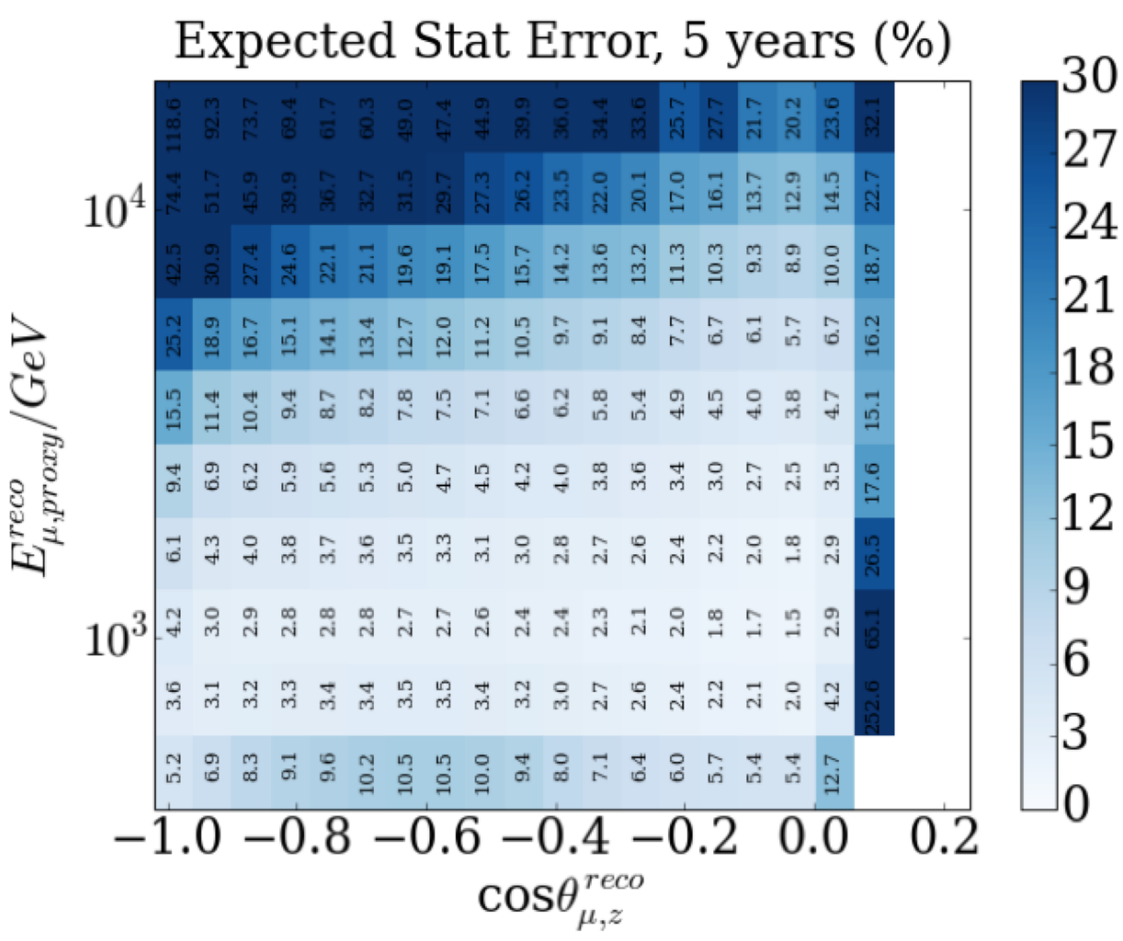


arXiv:1607.01176,1607.01177

Future steps: Two ways forward

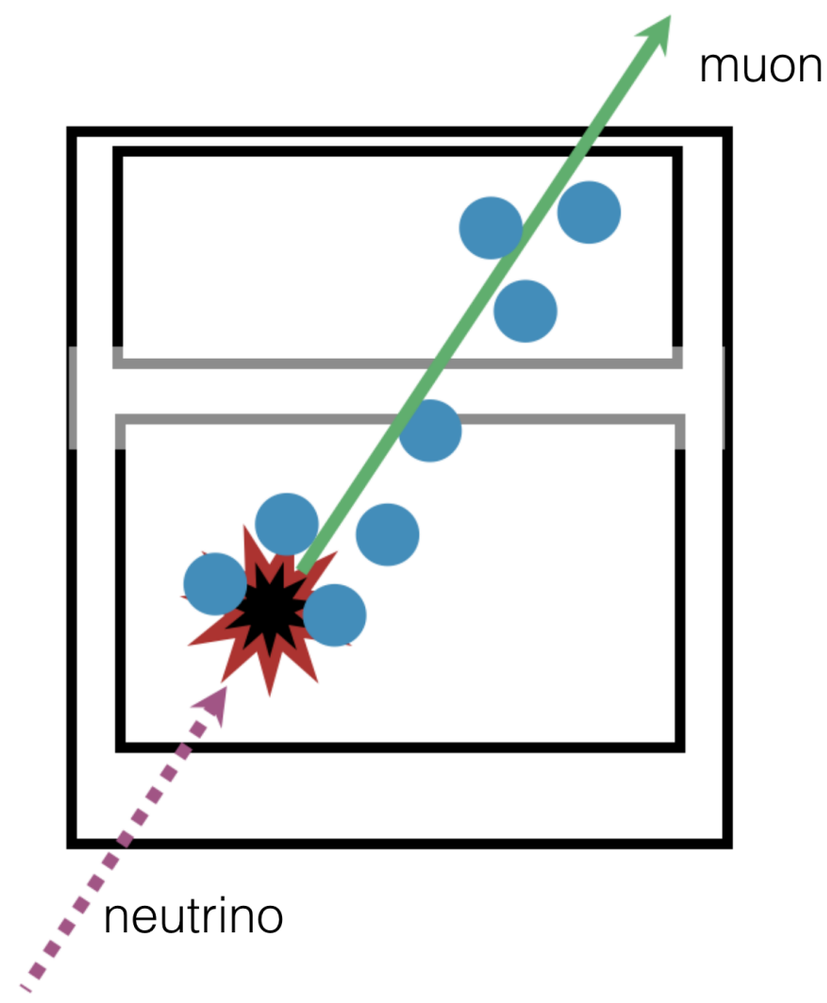
<u>More statistics</u>

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



<u>Better events</u>

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



Take home message

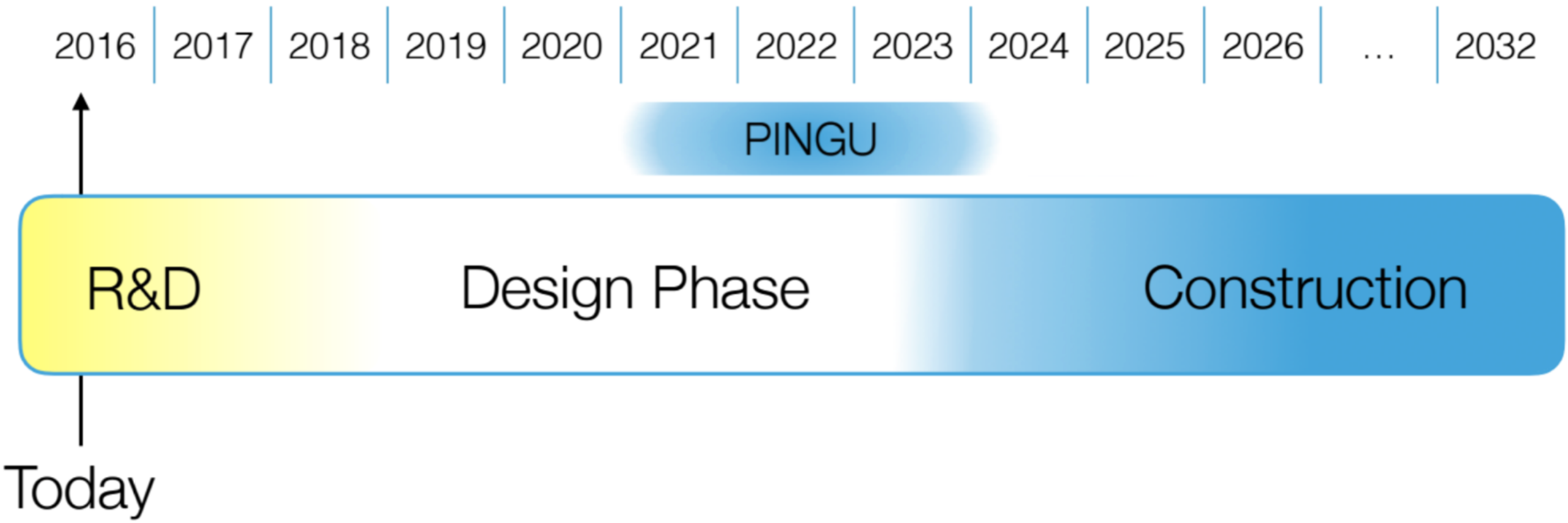
- ✤We have performed a search for eV-sterile neutrinos using one year of IceCube data. **No significant signal of sterile neutrinos was found.**
- ✤**IceCube result is competitive with other limits and the World best at ~ 0.1-1.0 eV^2.**
- ✤ IceCube has several more years of data ready to analyze: We are just getting started!

THANKS!

See arXiv:1605.01990 for more details

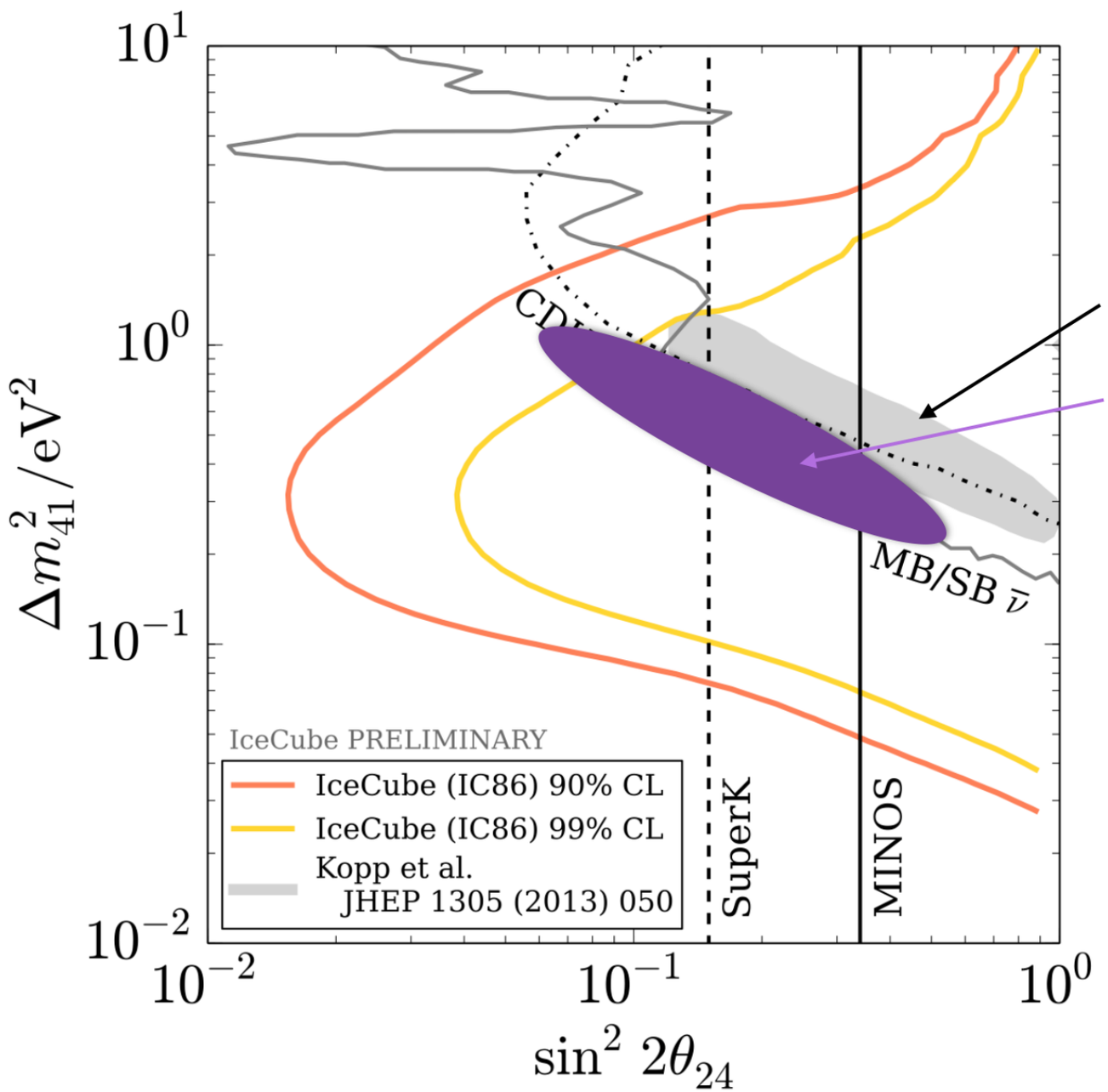
BONUS SLIDES

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.

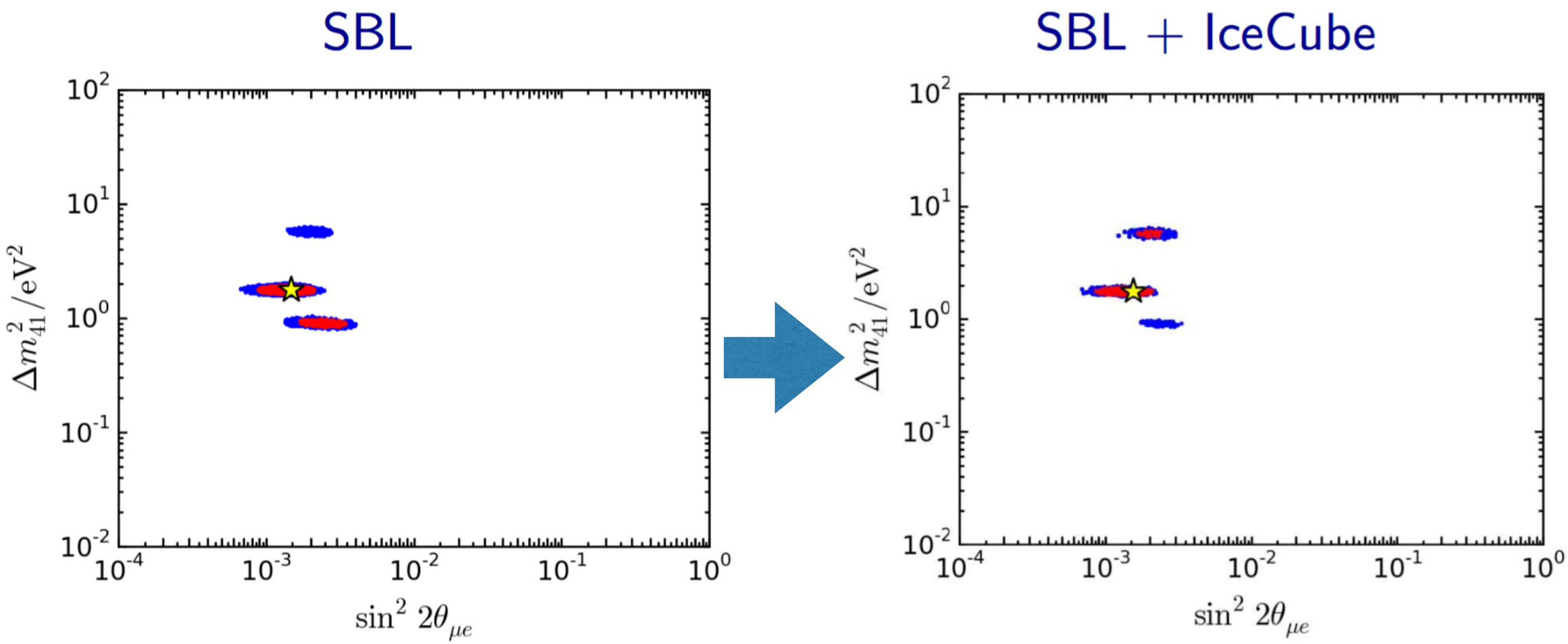


BF: $|U_{e4}|^2 = 0.023$

3σ: $|U_{e4}|^2 = 0.048$

(Kopp et al. arXiv:1303.3011)

A new global fit with IceCube



Red: 90% CL Blue: 99% CL

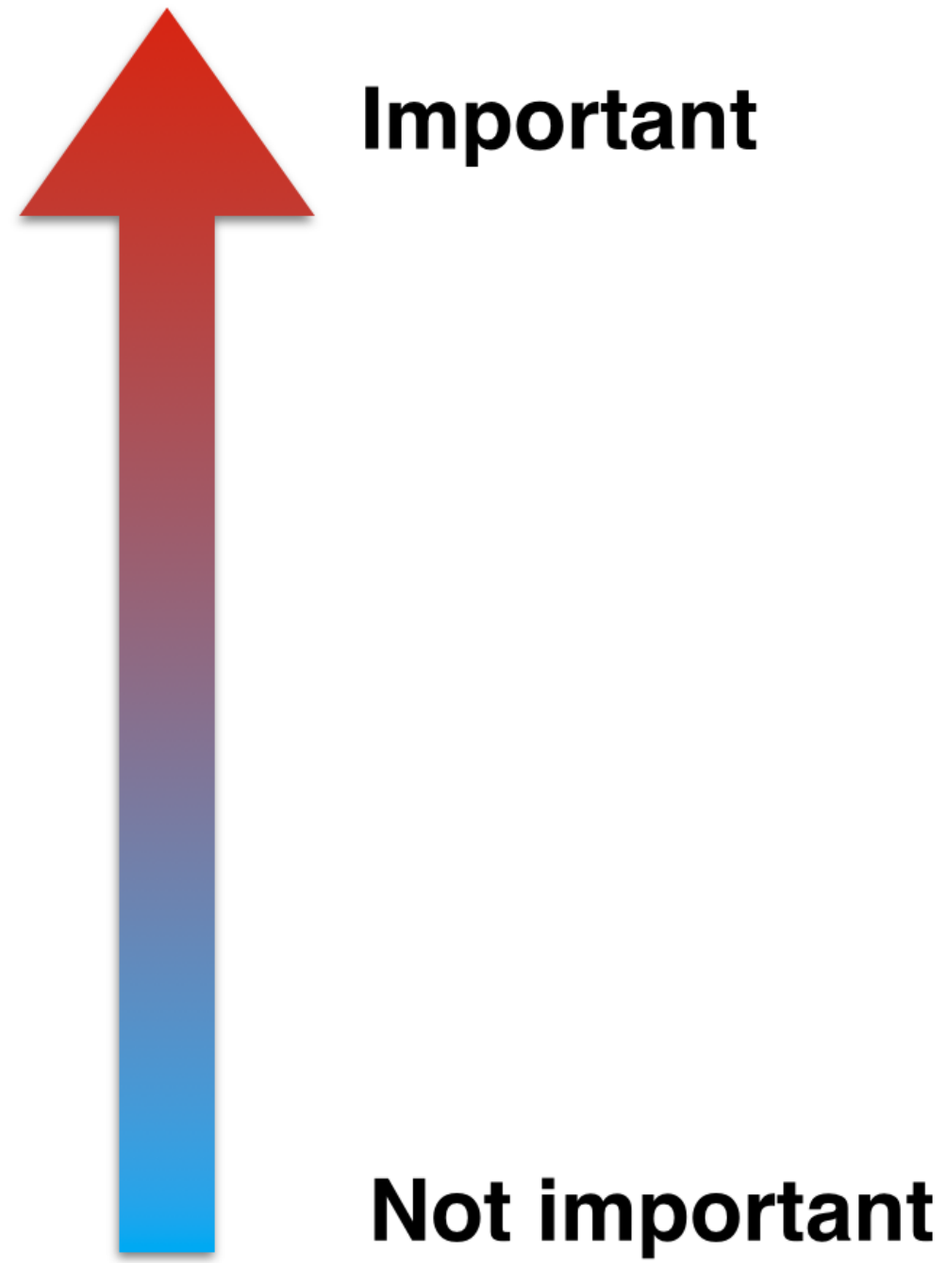
3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	χ^2_{min}	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

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

Systematics!

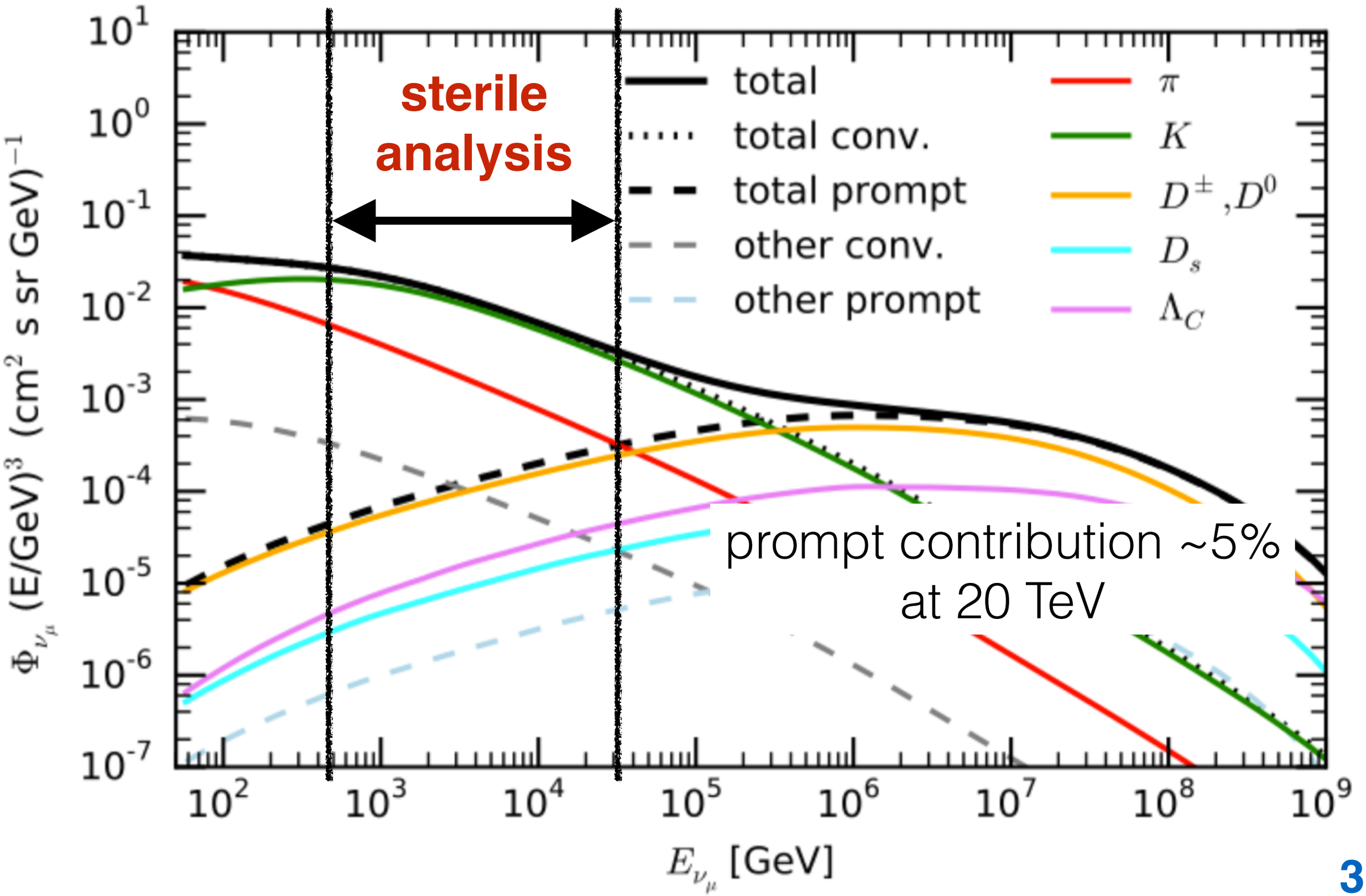
Systematics are super important; *some are more than others*.
These are the systematics we considered:

- *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



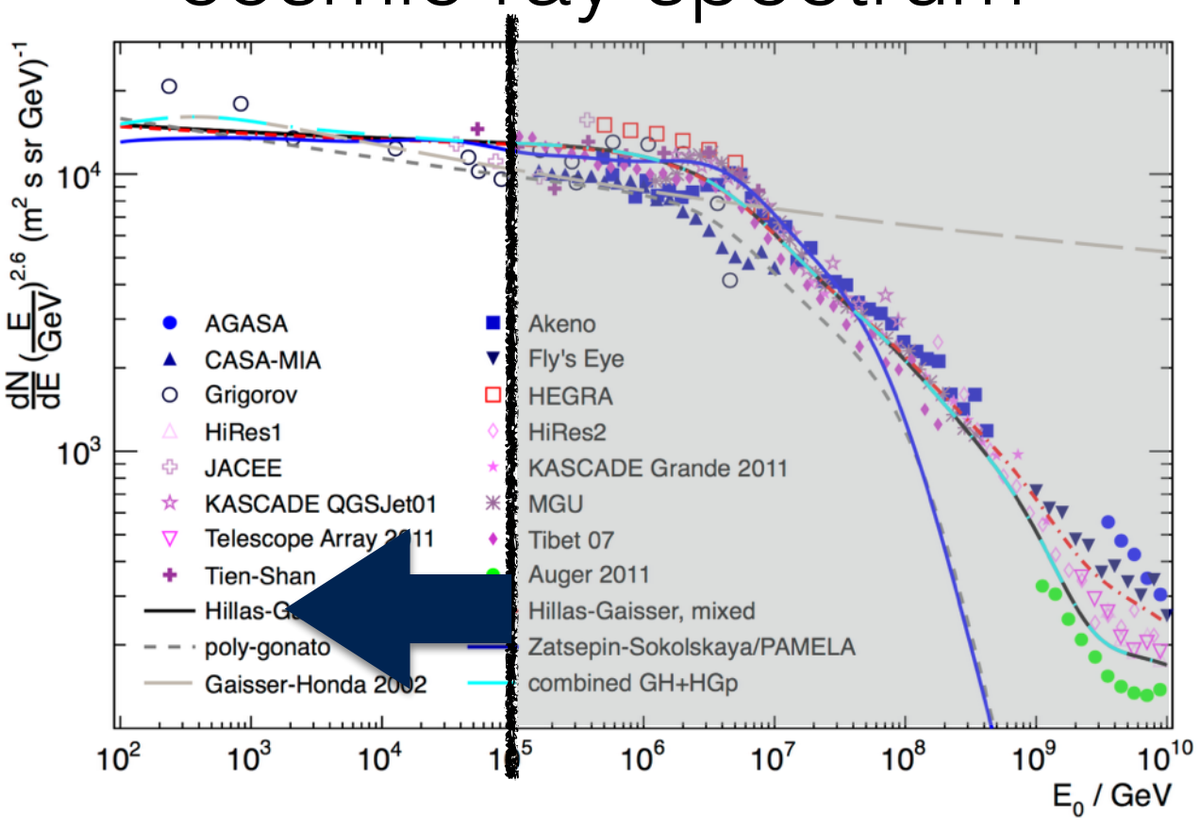
continuous systematics
discrete systematic

Atmospheric flux decomposed



Atmospheric neutrino flux uncertainties

cosmic ray spectrum

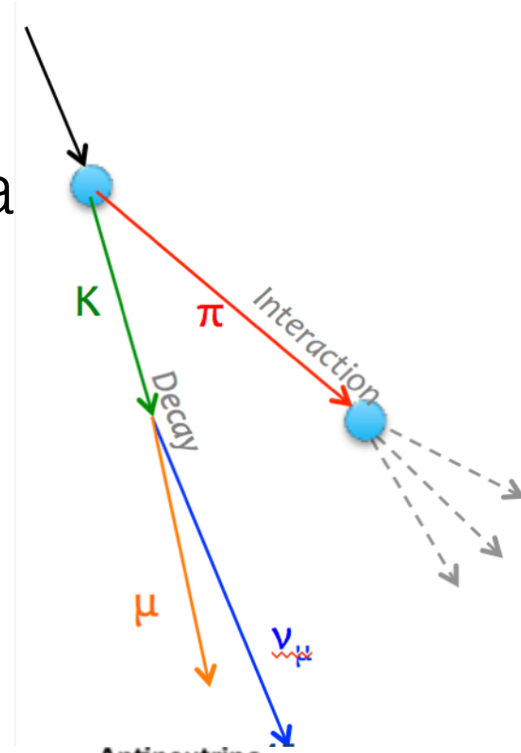


Cosmic ray models:

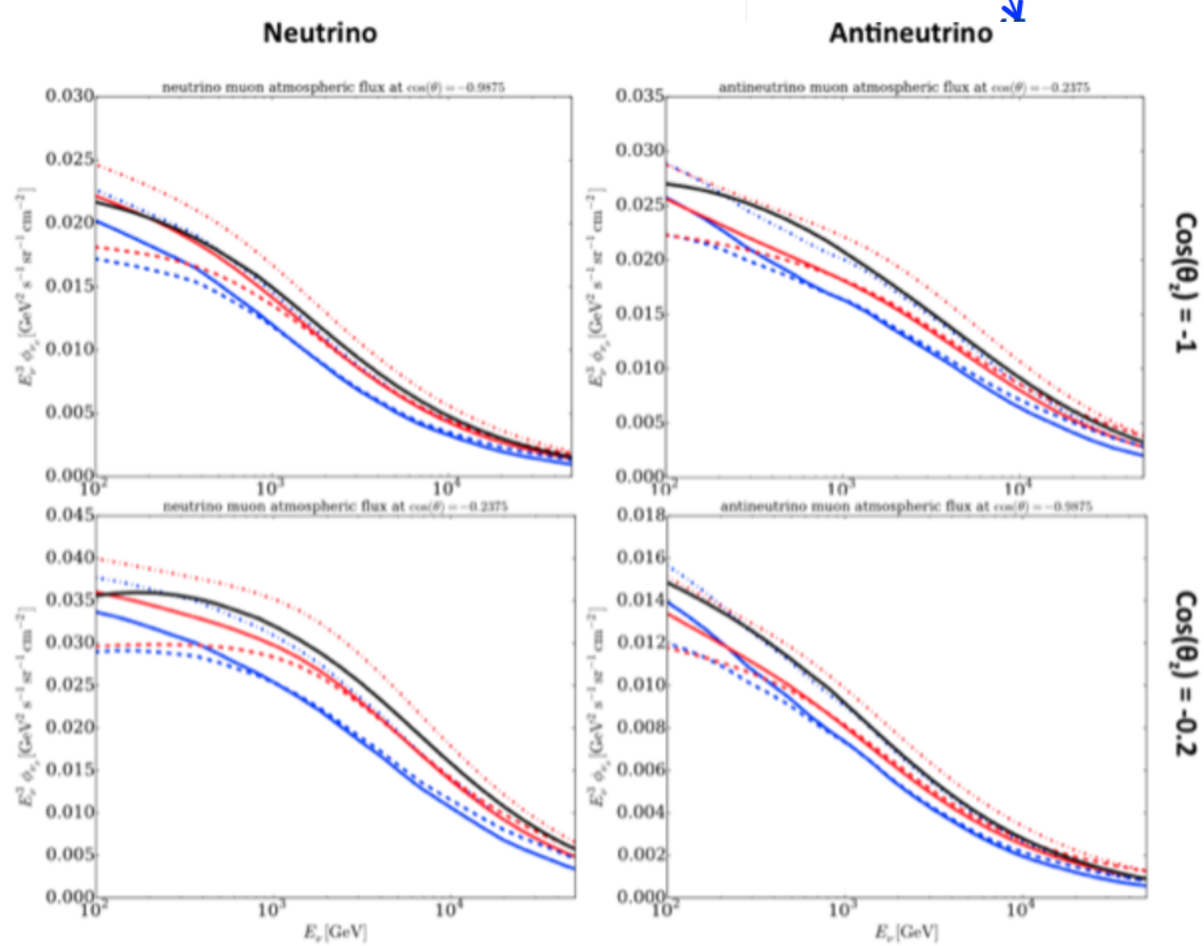
- Zatsepin-Sokolskaya
- Polygonato
- Gaisser+Honda

Hadronic models:

- Sibyll 2.3
- QGSJET II



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



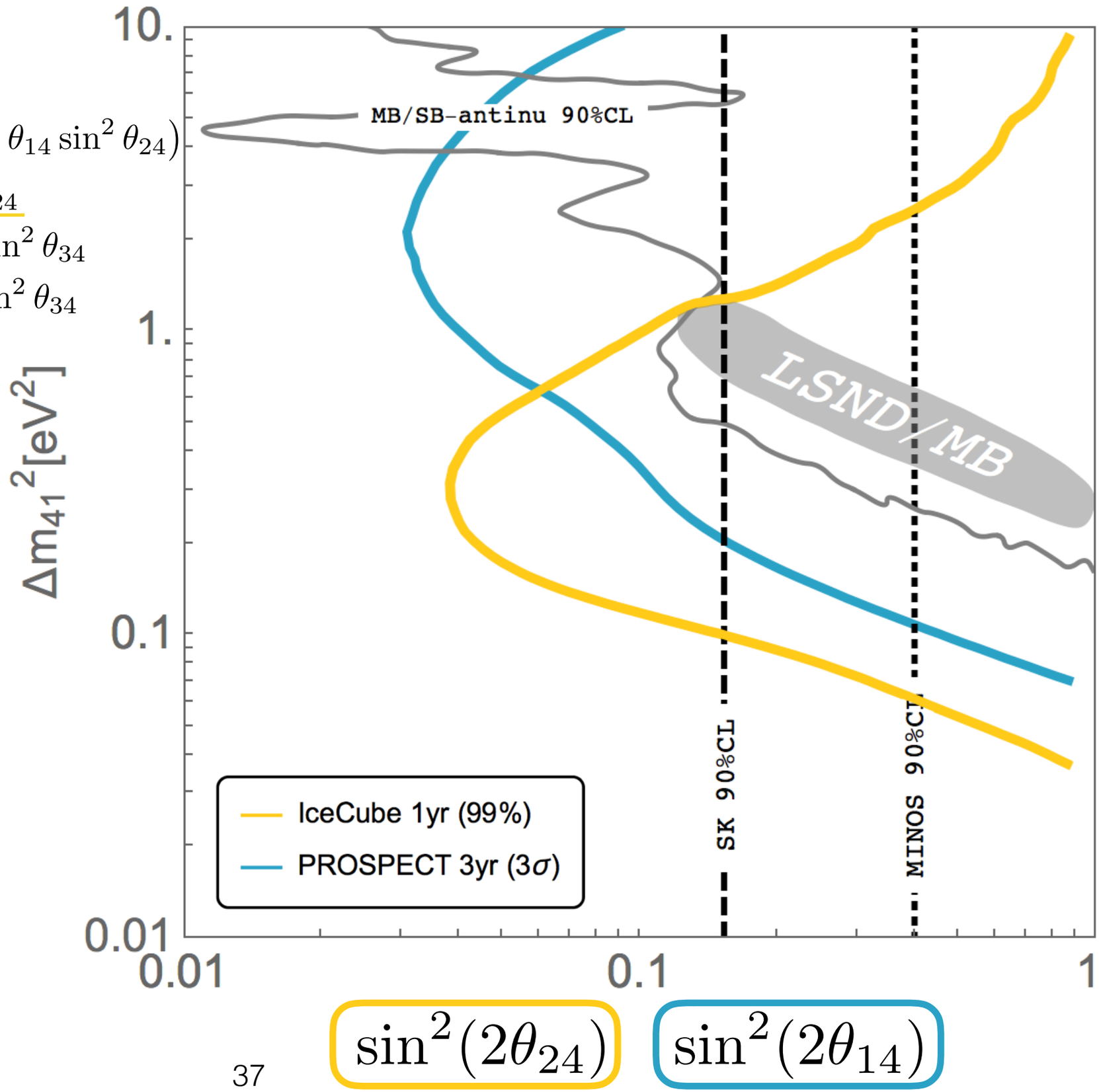
[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]

Very naïve IceCube + PROSPECT complementarity

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

(IceCube also sensitive to theta-34)

Warning:
angles are different!



More experiments complementarity…

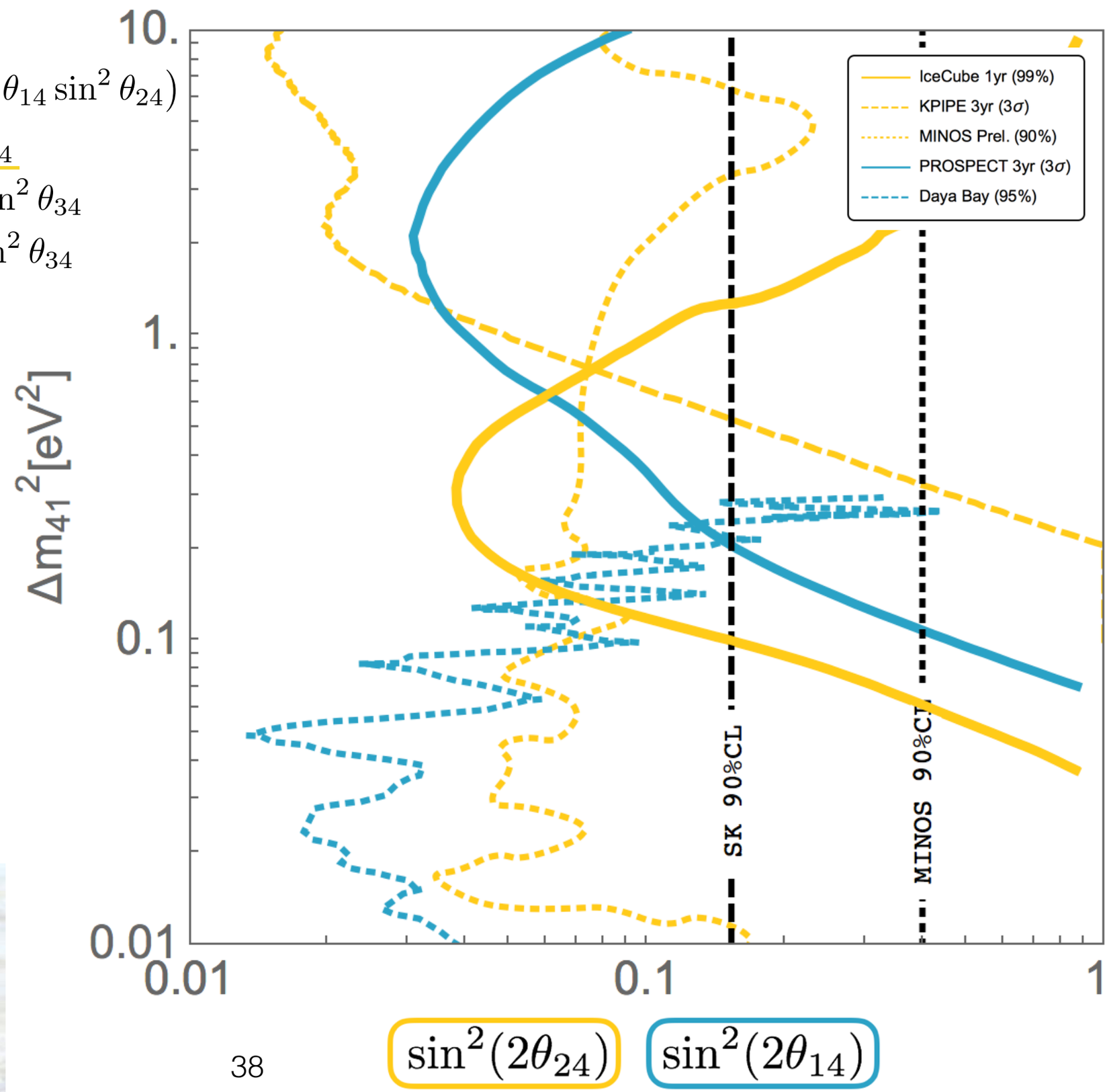
$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$$
$$\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}\left(1-\cos^2\theta_{14}\sin^2\theta_{24}\right)$$
$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$$
$$\sin^2 2\theta_{e\tau} = \sin^2 2\theta_{14}\cos^2 2\theta_{24}\sin^2\theta_{34}$$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

KPIPE

arXiv:1506.05811

PROSPECT

arXiv:1512.02202



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