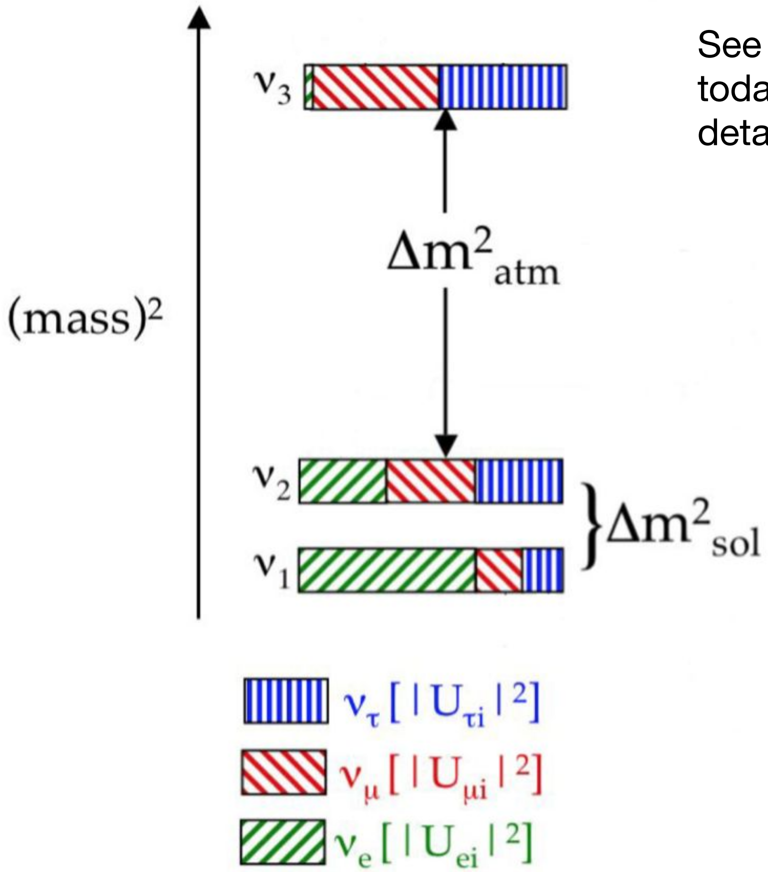
Status of searches for light-sterile neutrinos at TeV energies in IceCube

Carlos Argüelles

PPNT
Uppsala, Sweden, 2019

The standard neutrino oscillation picture



See talk by M. Maltoni today for much more details.

www.nu-fit.org

$$\begin{aligned} \Delta m^2_{\text{sol}} &= 7.5 \times 10^{-5}\,\text{eV}^2 \\ |\Delta m^2_{\text{atm}}| &= 2.4 \times 10^{-3}\,\text{eV}^2 \end{aligned}$$

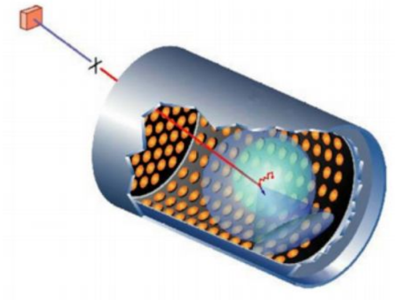
$$\nu_i = \sum_\beta U_{\beta i}\nu_\beta$$

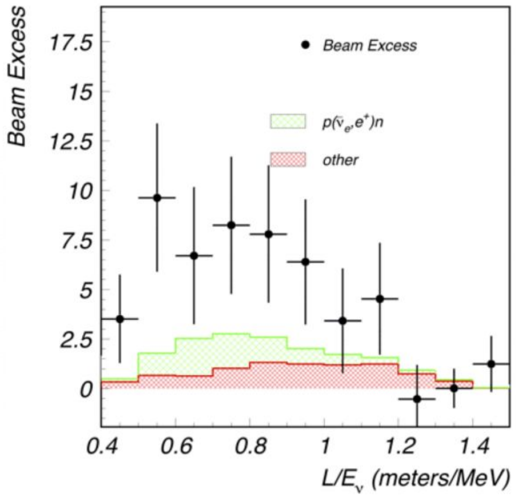
$$\begin{aligned} U &= \mathrm{U}(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP}) \\ |\mathrm{U}| &\simeq \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix} \end{aligned}$$

Except for the CP-phase, we have measured these quantities to the few-percent level

The pieces that do not fit our three-neutrino model

LSND
(3.8 sigma!)

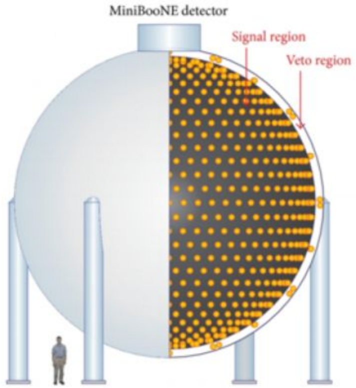


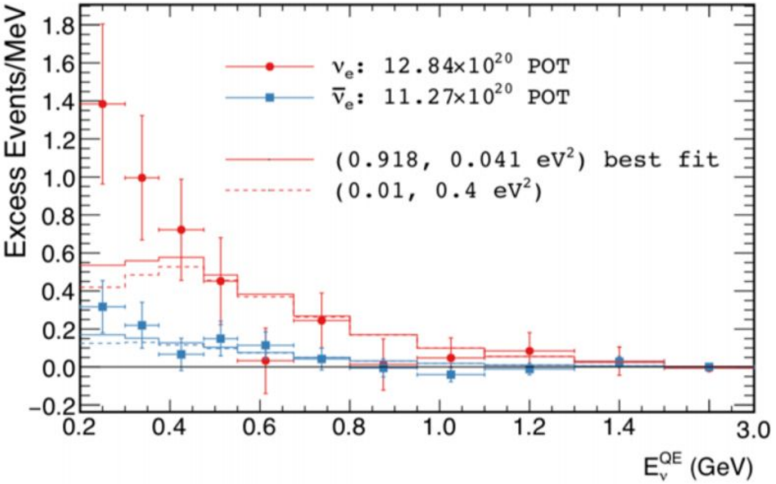


These experiments observe electron-neutrino appearance at L/E ~ 1 km/GeV!

This points to
$\Delta m^2 \sim 1 eV^2$

MiniBooNE
(4.8 sigma!)



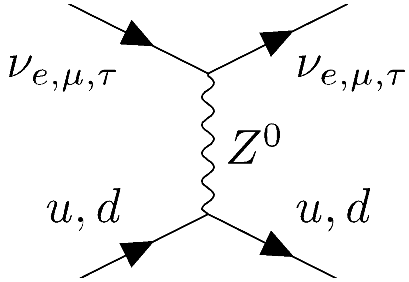


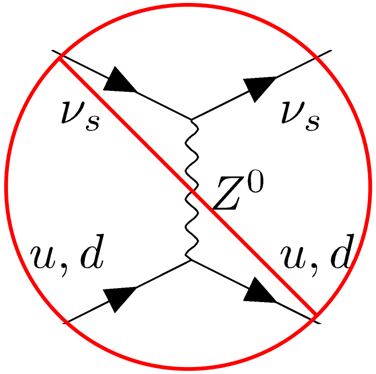
LSND Collaboration
Phys.Rev. D64 (2001) 112007

MiniBooNE Collaboratoin
Phys.Rev.Lett. 121 (2018) no.22, 221801

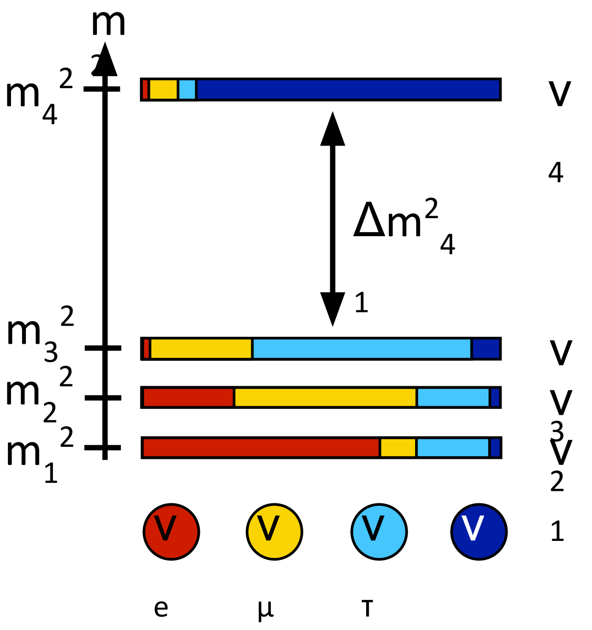
Introducing a sterile neutrino

- 3+1 -- a model with 3 active and one sterile flavor
- Can parameterize a 3+1 model with **Δm^2_{41}** and **θ_{24}**





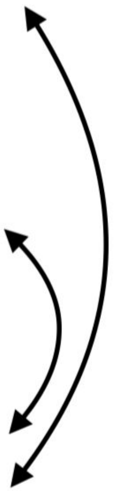
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



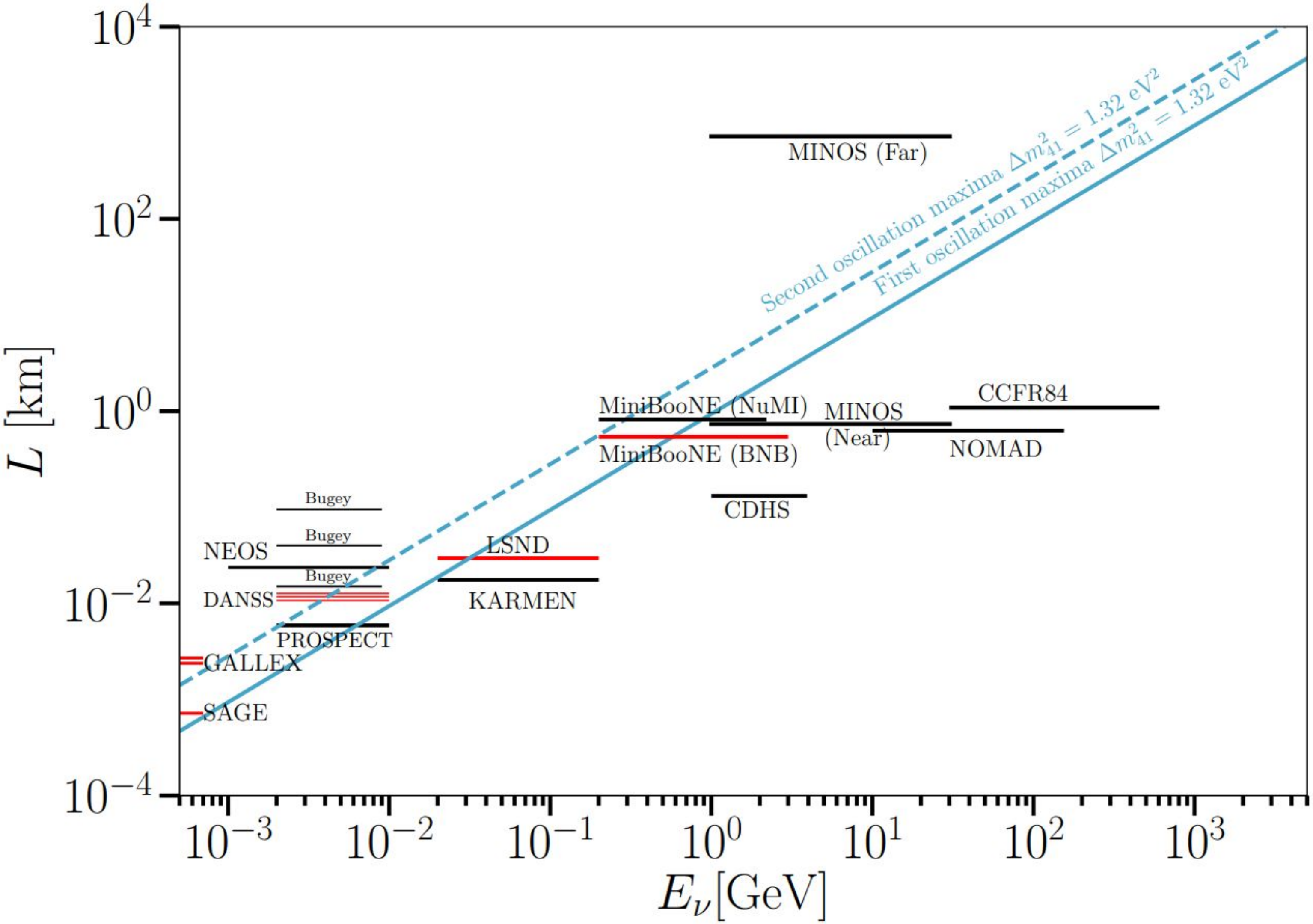
Assuming Normal Ordering

More pieces that do not fit our three-neutrino model

Oscillation Channel	Class	Experiments	Oscillation amplitude
Electron Disappearance **$P(\nu_e \to \nu_e)$**	Reactor Experiments	GALLEX ($\underline{\nu}$) SAGE ($\underline{\nu}$) {Global Reactors}	$4\vert U_{e4}\vert^2 (1-\vert U_{e4}\vert^2)$
Muon Disappearance **$P(\nu_\mu \to \nu_\mu)$**	Long Baseline Experiments	Not yet!	$4\vert U_{\mu4}\vert^2 (1-\vert U_{\mu4}\vert^2)$
Electron Appearance **$P(\nu_\mu \to \nu_e)$**	Short Baseline Experiments	LSND ($\underline{\nu}$) MiniBooNE ($\underline{\nu}$, ν)	$4\vert U_{\mu4} U_{e4}\vert^2$



The anomalies lie along a line



A. Diaz et al.1906.00045 see also Boser et al. 1906.01739

Global-fit solution

$$\Delta m^2_{41} = 1.32 \text{ eV}^2$$

$$|U_{e4}| = 1.16$$

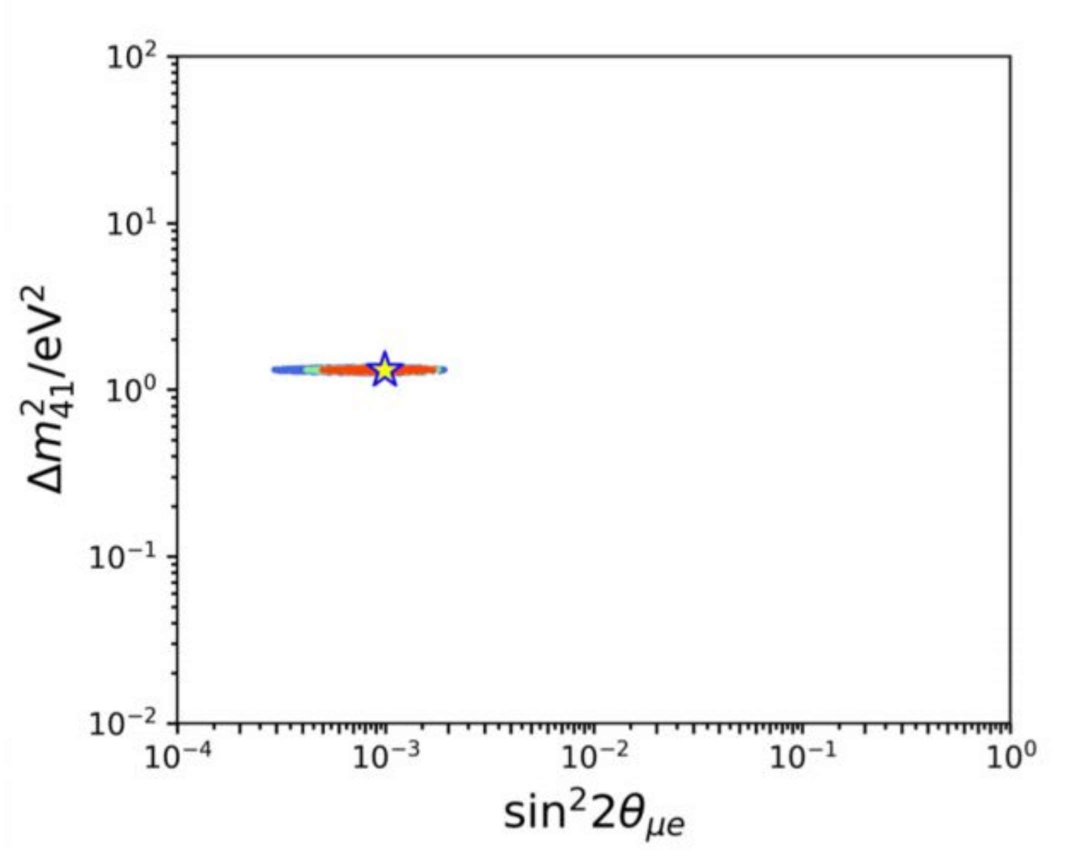
$$|U_{\mu 4}| = 1.35$$

$$\sin^2(2\theta_{\mu e}) = 1.05 \times 10^{-3}$$

$$\chi^2_{\text{BF}} = 458 \text{ (506 dof)}$$

$$\chi^2_{\text{Null}} = 493 \text{ (509 dof)}$$

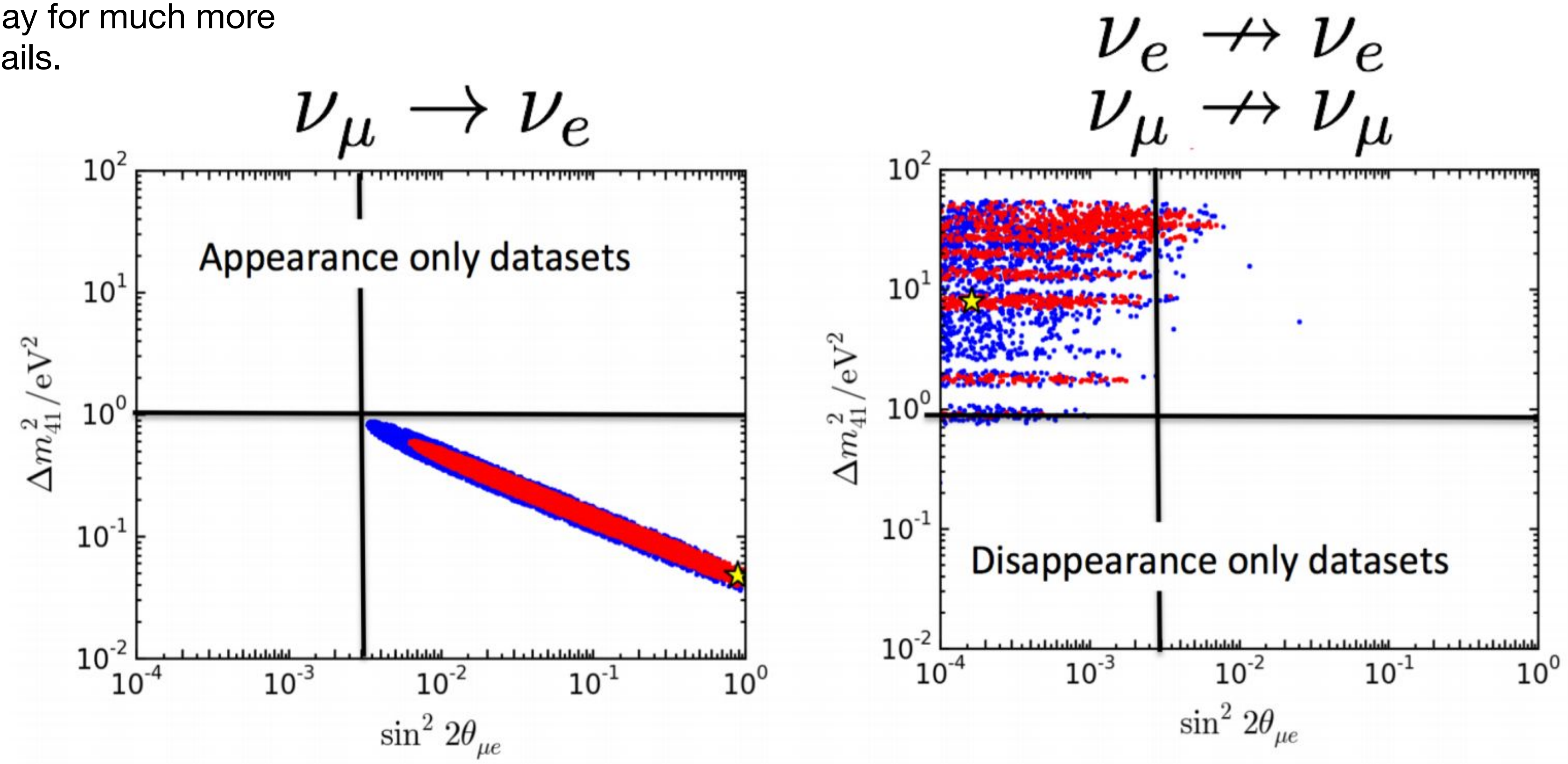
$$\Delta\chi^2_{\text{Null - BF}} = 35 \text{ (3)}$$



A Diaz et al. arXiv:1906.00045

Appearance and disappearance "preference regions" don't overlap!

See talk by M. Maltoni today for much more details.



$\nu_\mu \rightarrow \nu_e$

$\nu_e \not\rightarrow \nu_e$
$\nu_\mu \not\rightarrow \nu_\mu$

See A. Diaz et al. arXiv:1906.00045 similar conclusions from other groups see Gariazzo et al. 1703.00860 and Dentler et al JHEP 1808 (2018)

3+1 model inconsistency opens up several questions

Do we understand all SM background/process well enough?

Are all the anomalies related? Or only some of them? Are LSND and MiniBooNE observing the same physics?

Since null results are not scrutinized as carefully as anomalous ones. Are all null results reliable?

Is there a significant signal of electron-neutrino disappearance in reactors?

If the anomalies are confirmed as new physics, in what theories are they embedded?

How about more complicated scenarios: 3+2, 3+3, 3+1+NSI (Liao et al Phys.Rev. D99 (2019) no.1, 015016), 3+1+Decay (see talk by Marjon Moulai tomorrow!)

Can we test the LSND-anomaly in a completely new way?

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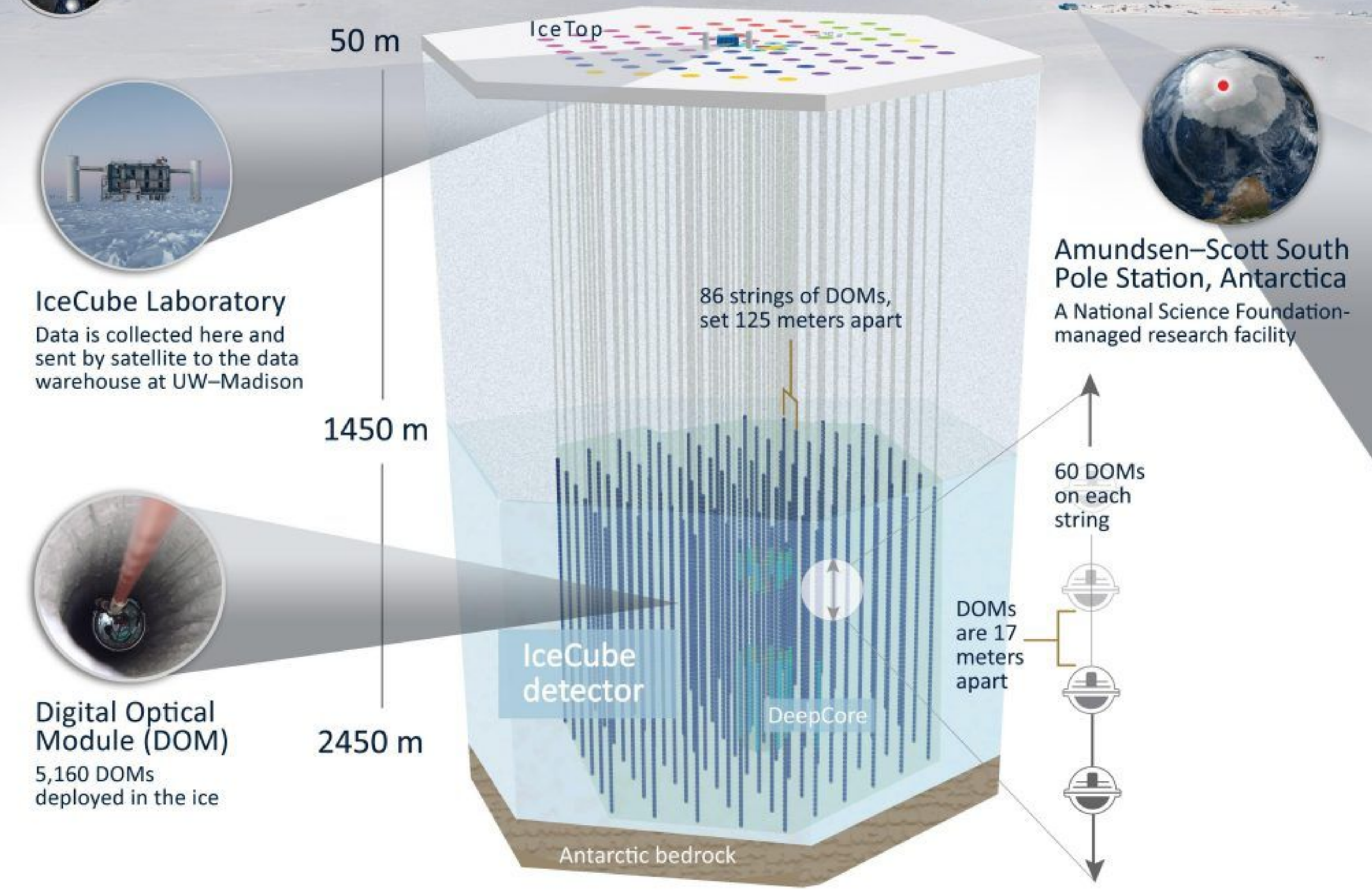
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



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

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

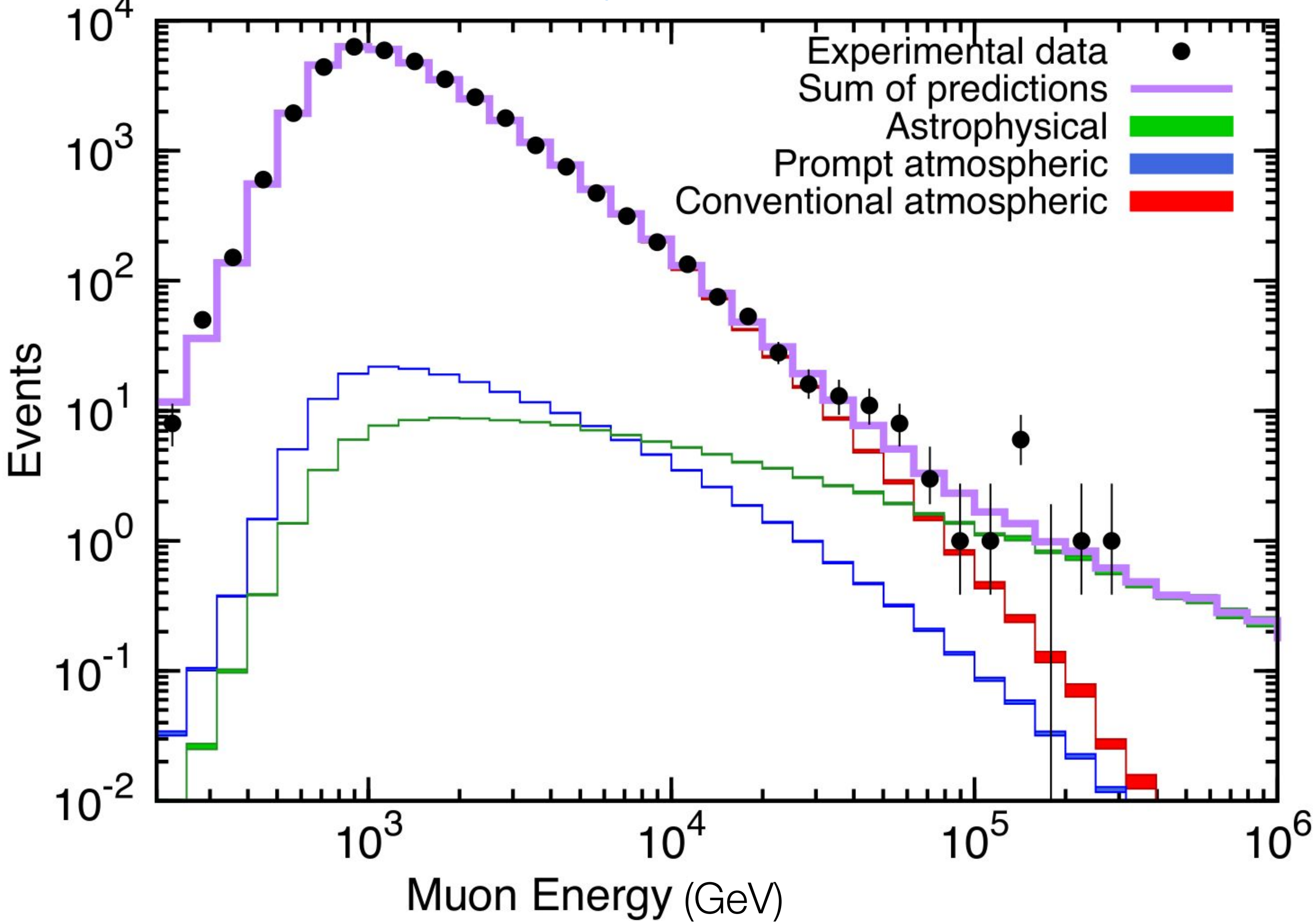
86 strings of DOMs, set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

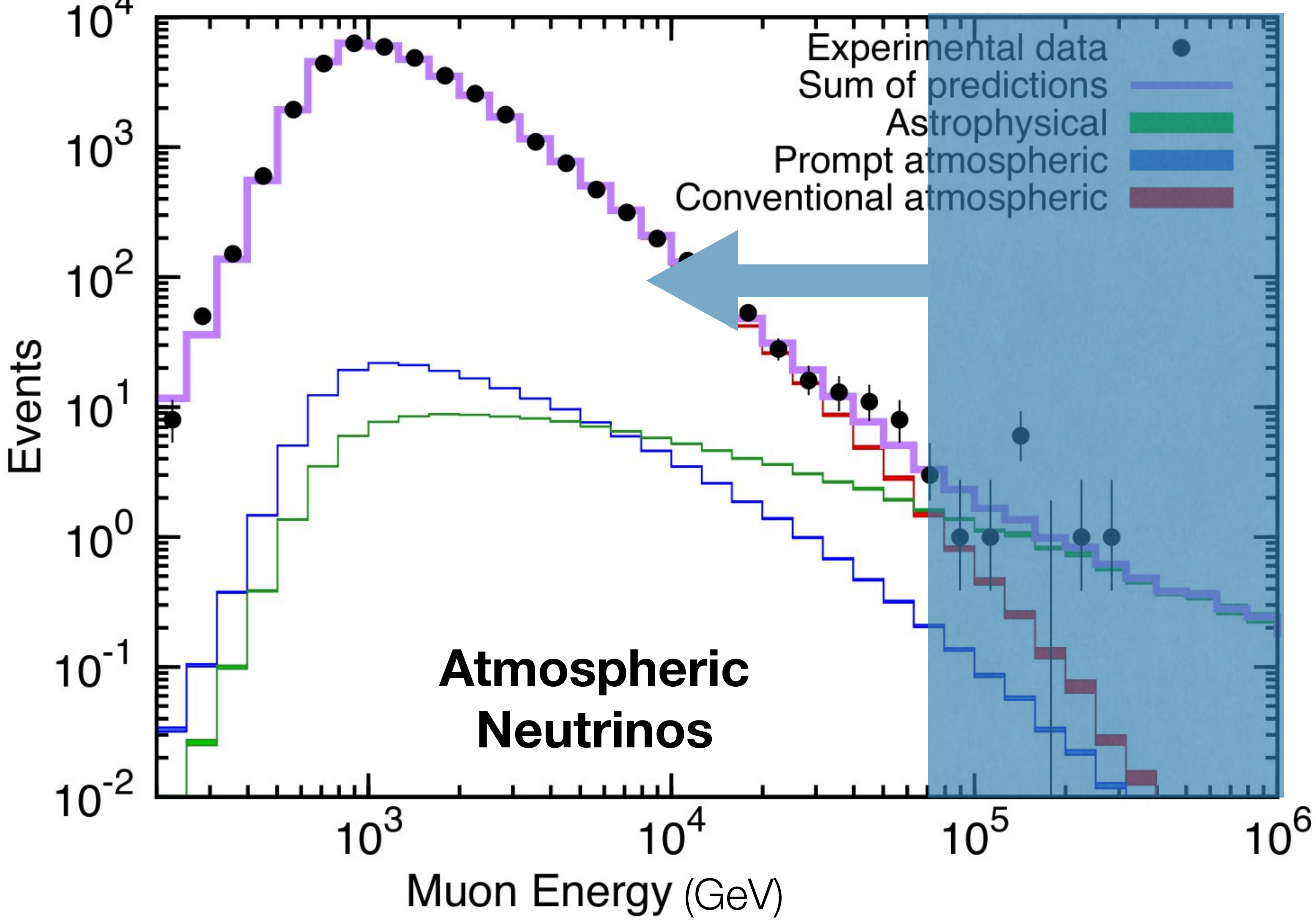
DOMs are 17 meters apart

Through-going ν_μ energy distribution



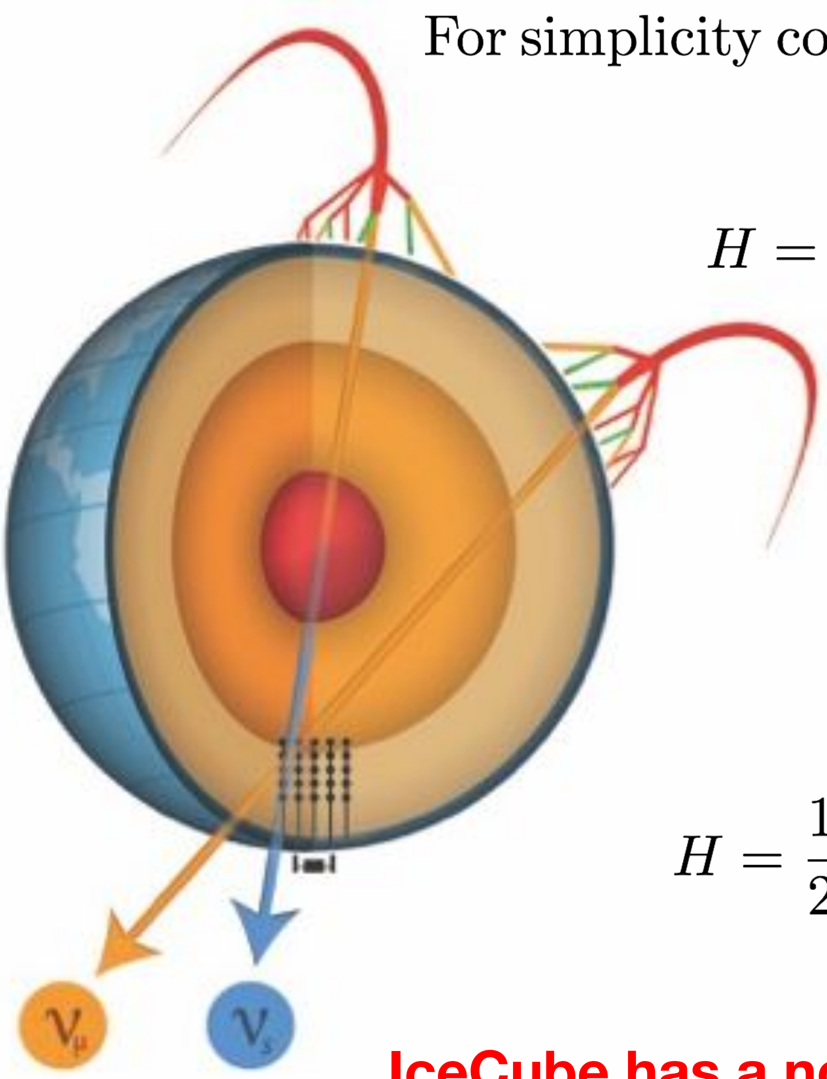
Phys. Rev. Lett. 115, 081102 (2015)

IceCube observes a lot of atmospheric neutrinos!



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

All anomalies are from (anti)neutrinos traversing vacuum



For simplicity consider a 2-neutrino transition : $\nu_\mu \to \nu_s$

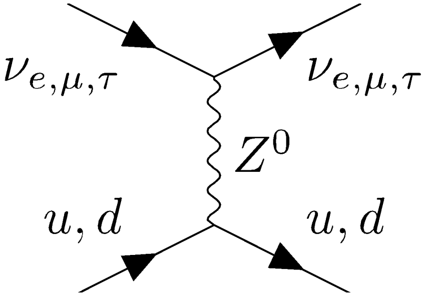
$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U$$

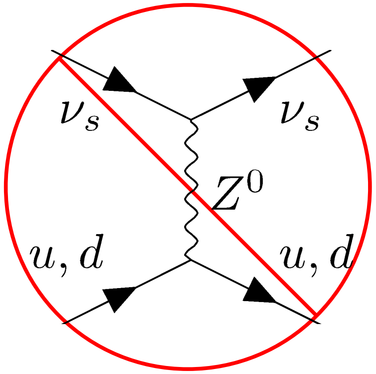
IceCube atmospheric neutrinos traverse large regions of matter.

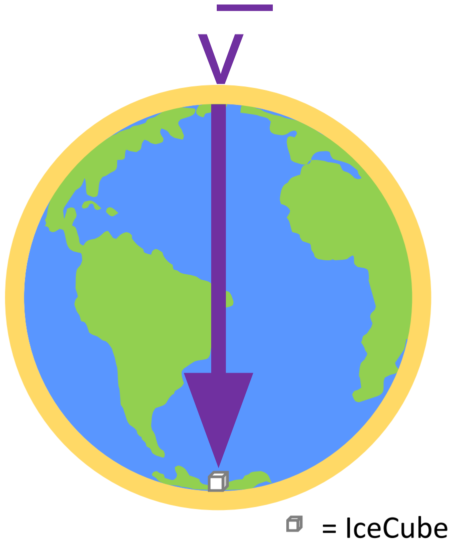
$$H = \frac{1}{2} U^\dagger \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{41} \end{pmatrix} U \mp \frac{G_F}{\sqrt{2}} \begin{pmatrix} N_{\text{nuc}} & 0 \\ 0 & 0 \end{pmatrix}$$

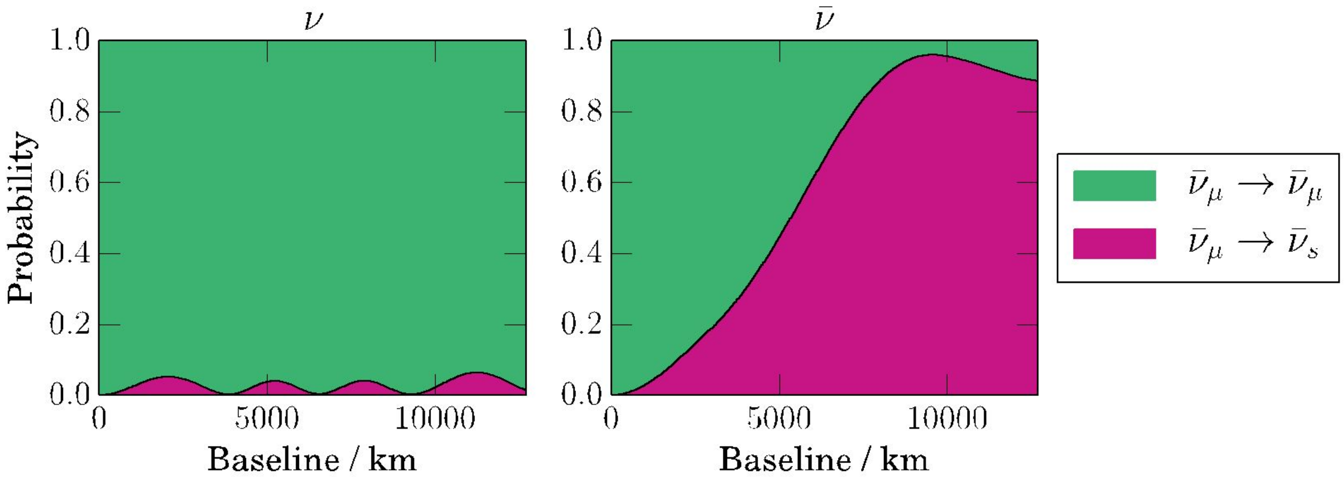
IceCube has a novel way of addressing muon-neutrino disapperance!

Effects of Matter Effects





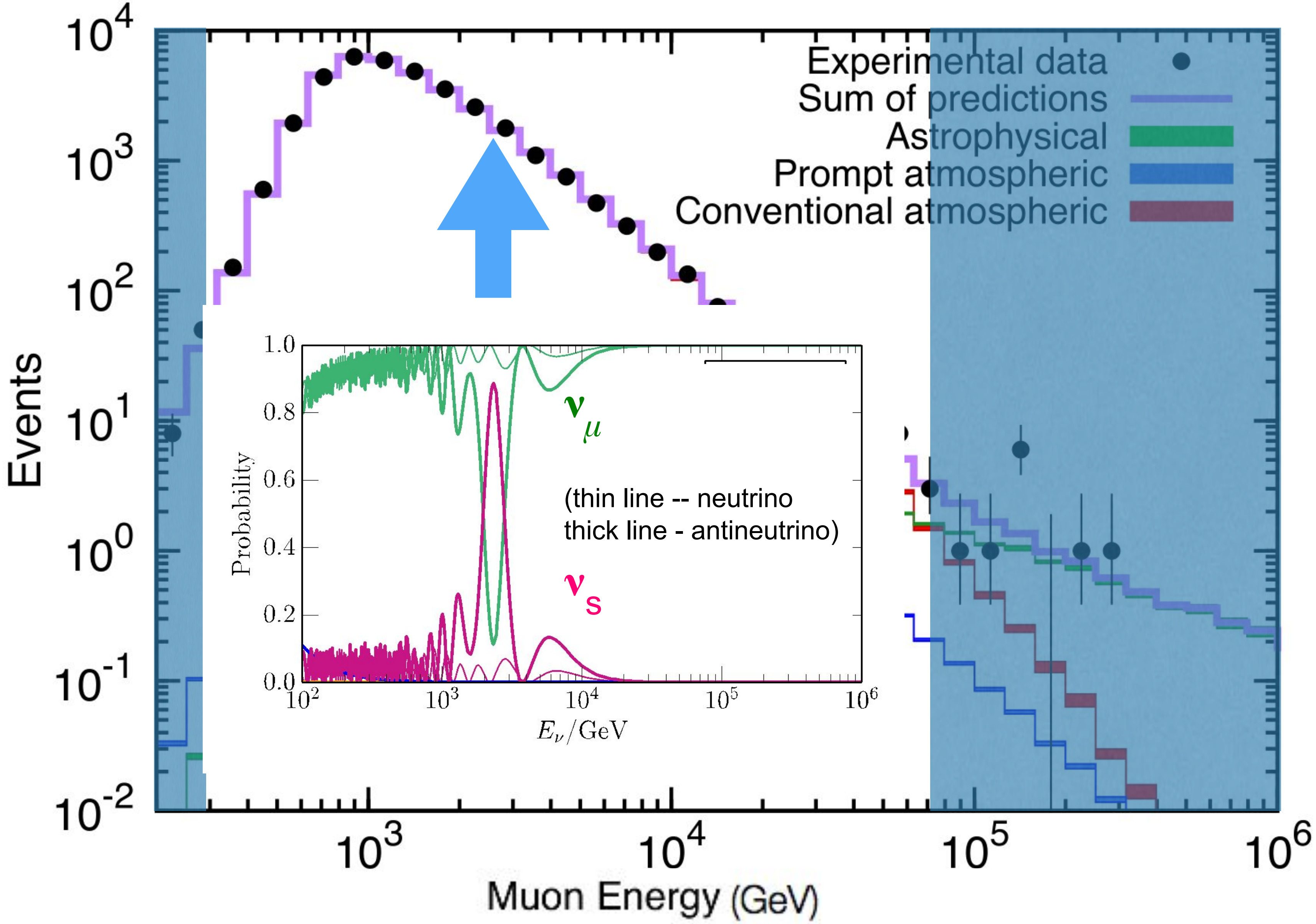




Plotted for:

- 2.3 TeV
- $\Delta m^2_{41} = 1\ \text{eV}^2$, $\sin^2 2\theta_{24} = 0.1$

Where is the resonance effect?



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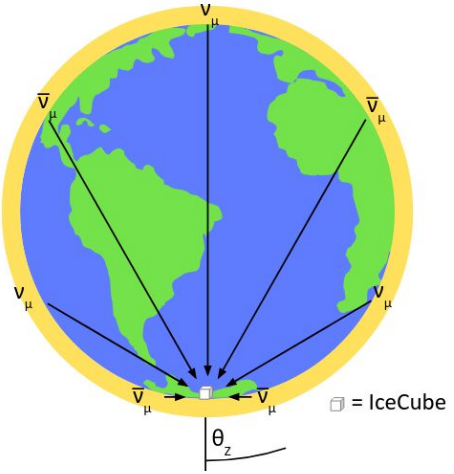
Position of resonance maps onto sterile parameter space

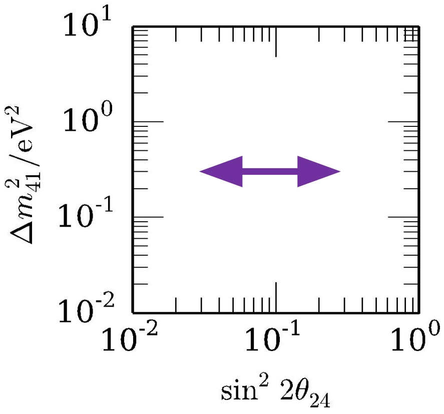


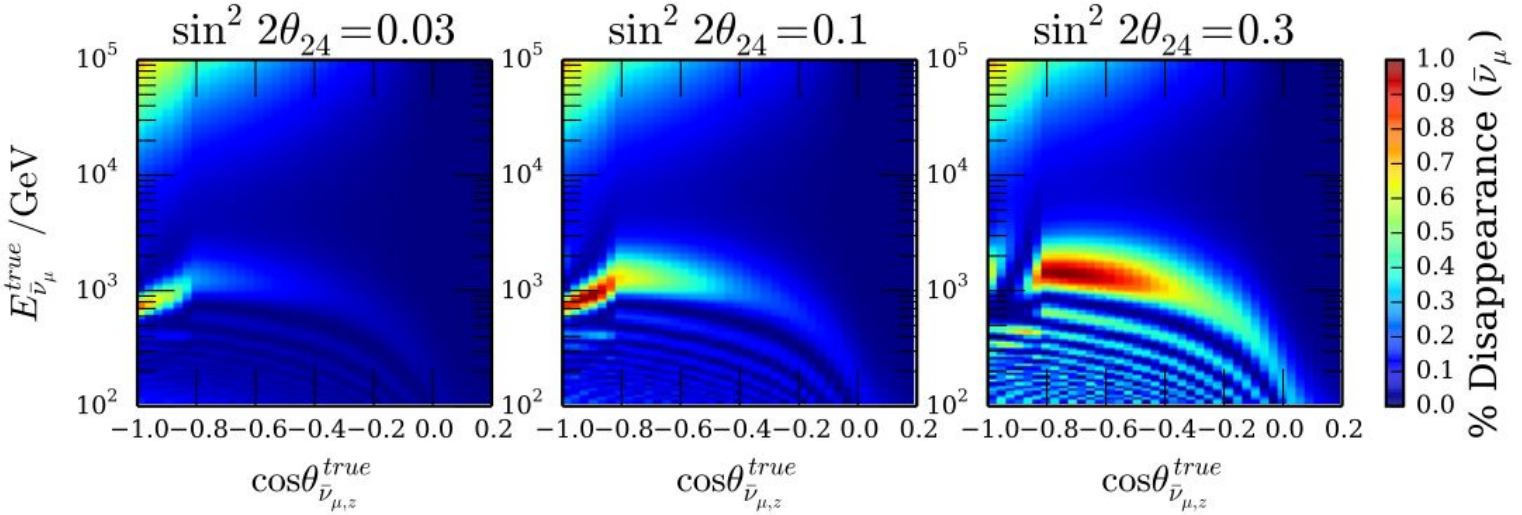
We measure two things:

- cos(theta) ⇨ length
- energy

We extract two parameters:

- squared mass difference
- mixing angle





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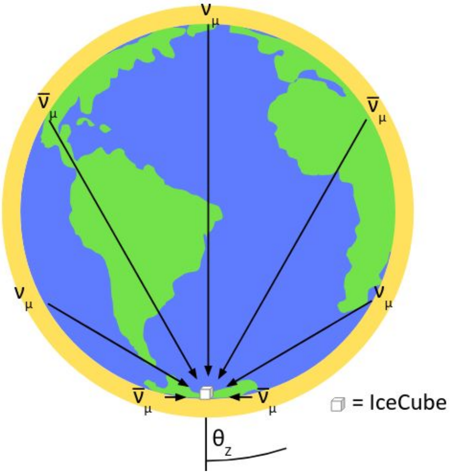

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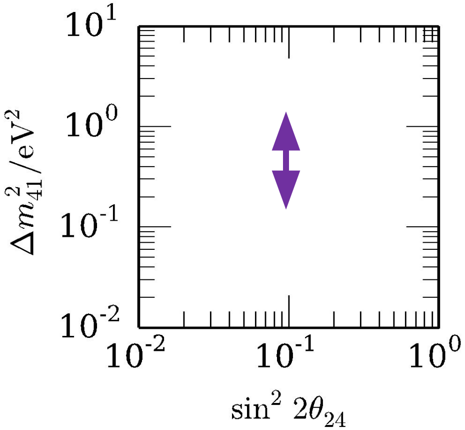
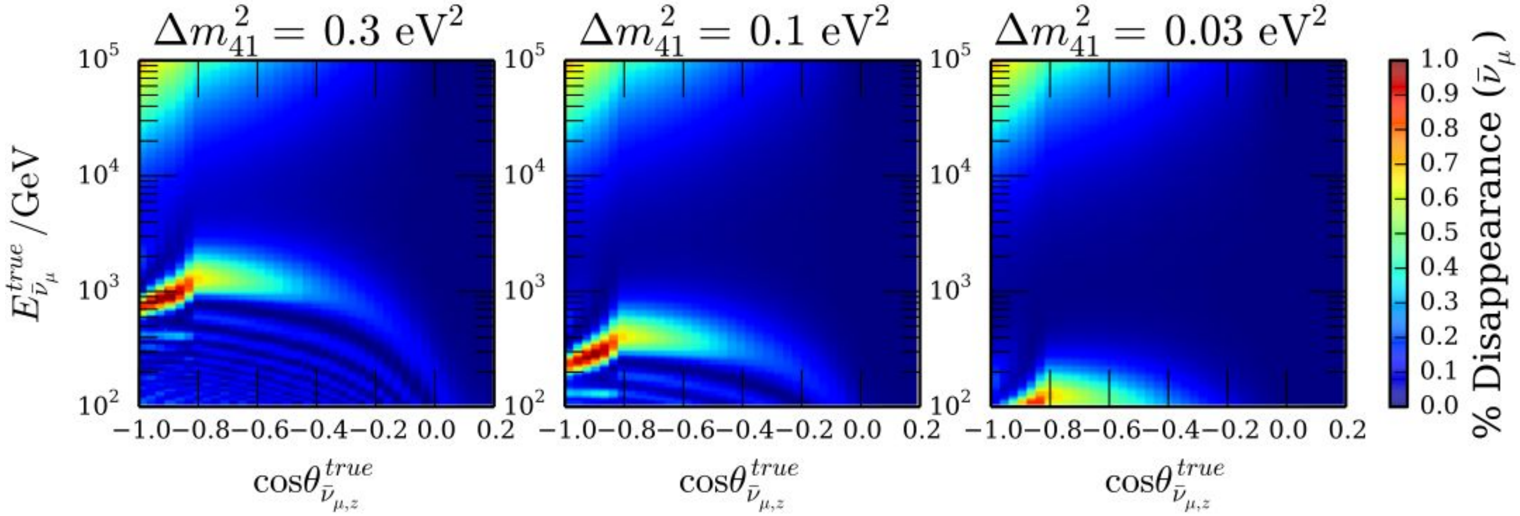
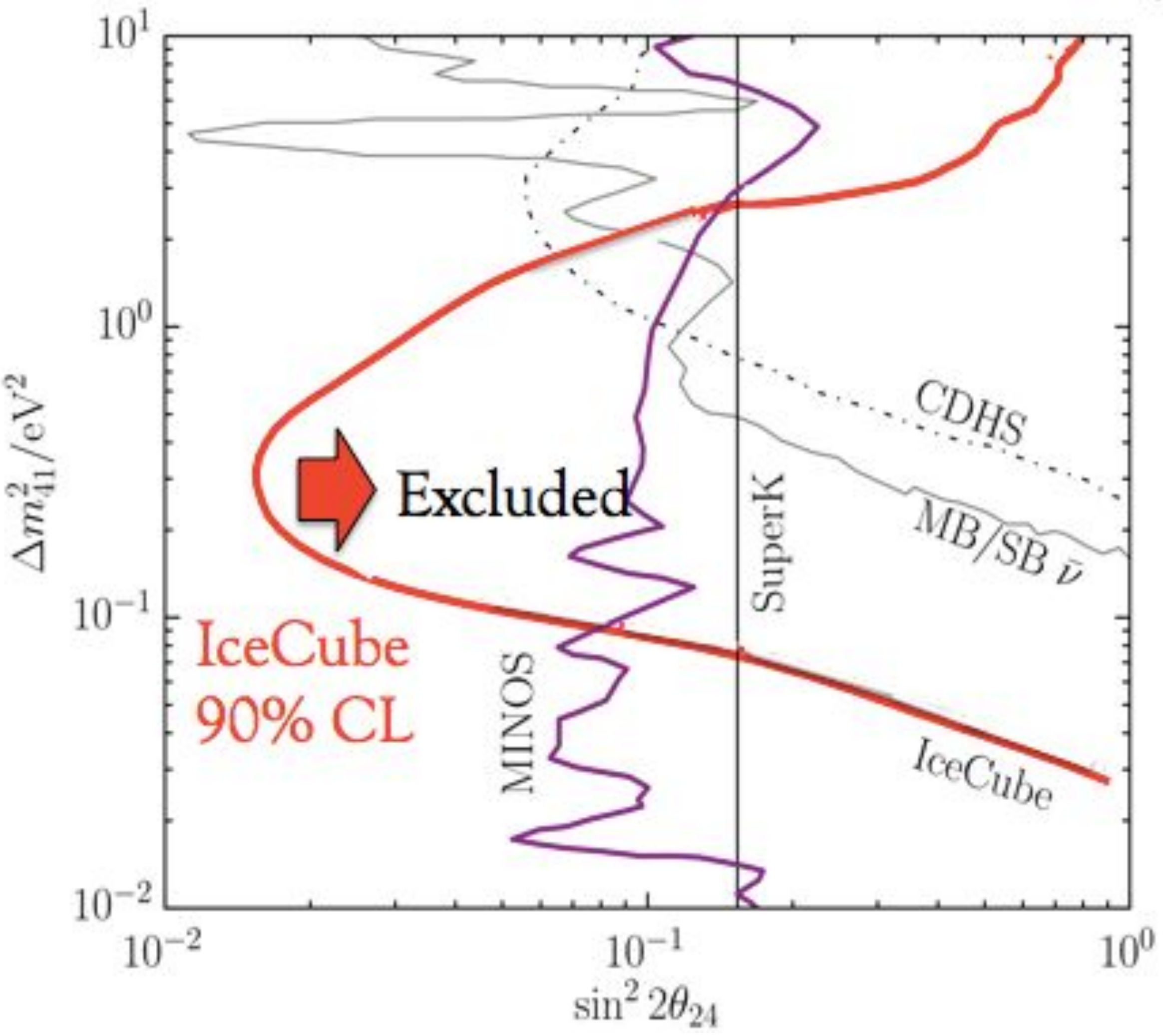
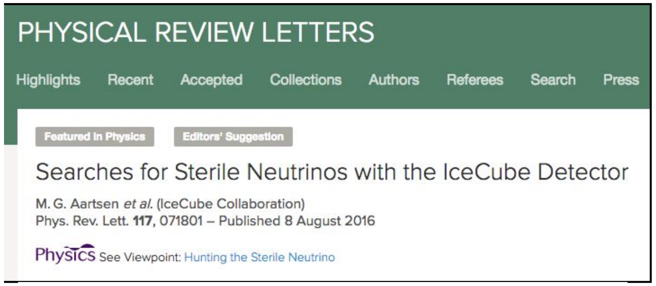




We searched for it with one year of data!



We analyzed one year of IceCube data ~ 20 000 events.
No evidence for a “dip” on the event distribution.

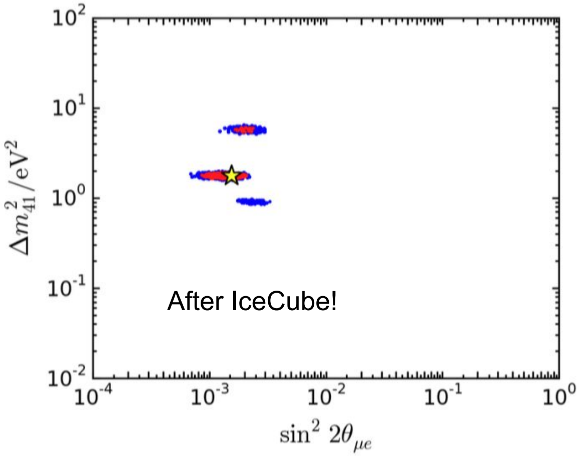


PHYSICAL REVIEW LETTERS

Searches for Sterile Neutrinos with the IceCube Detector

M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. Lett. **117**, 071801 – Published 8 August 2016

Physics See Viewpoint: Hunting the Sterile Neutrino

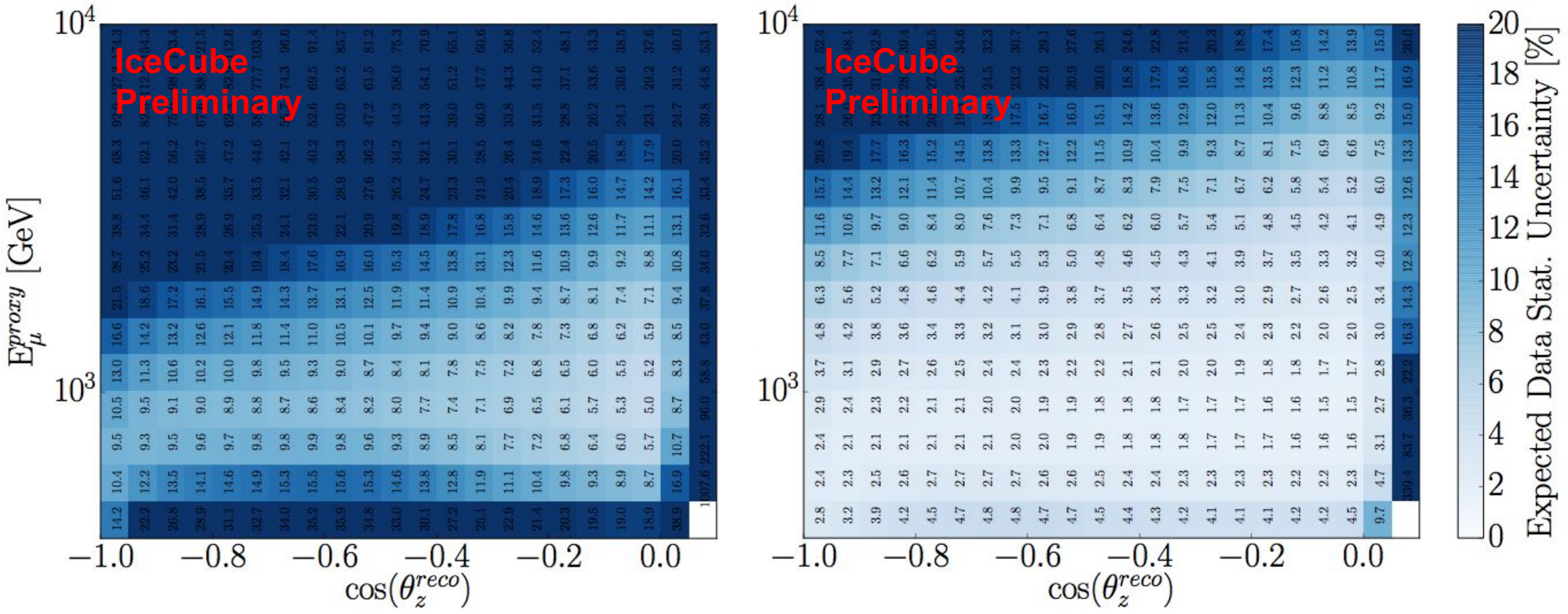


G.Collin, CA, J. Conrad, M. Shaevitz
Phys. Rev. Lett. 117, 221801
See also **Dentler et al JHEP 1808** (2018)

8-year search in IceCube

Matter-Enhanced Oscillations With Steriles (MEOWS)

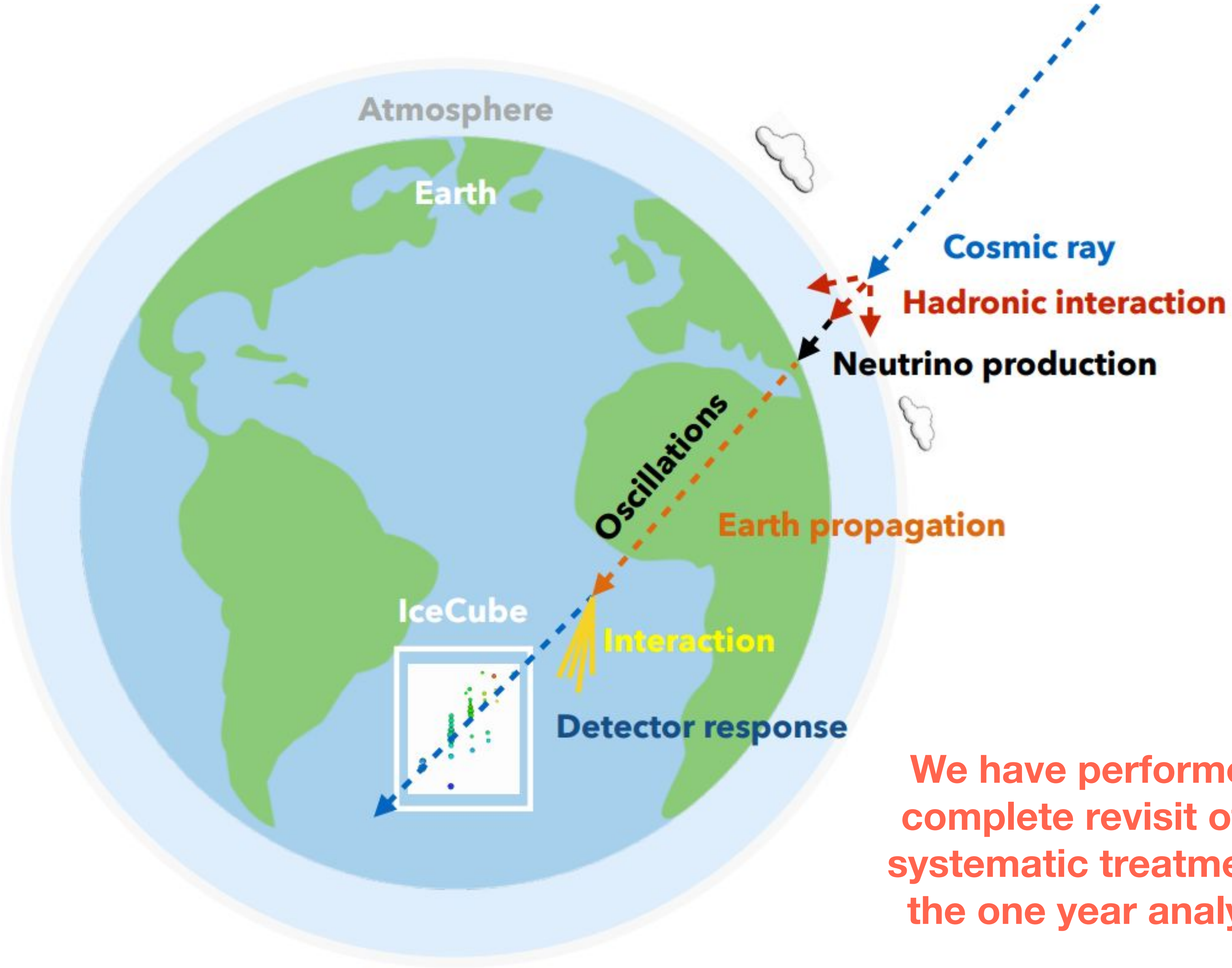
- ❖ Optimized event selection
- ❖ Improved systematics treatment



1 year / 20,000 events

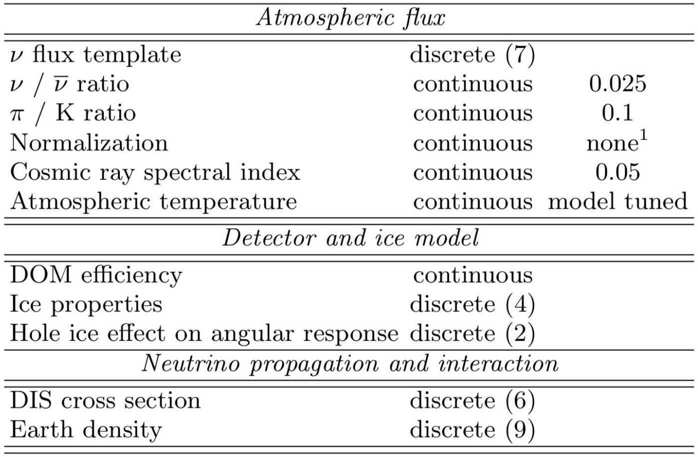
8 year / 300,000 events

Need to work on systematic treatment as statistical error bars shrink

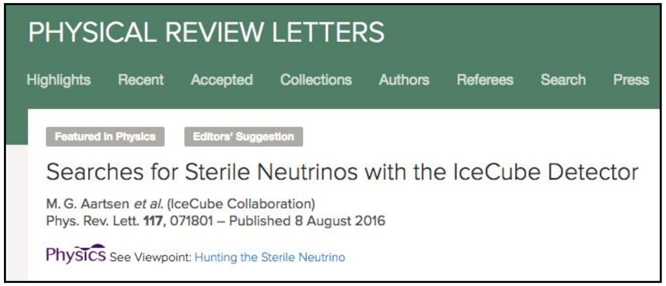


We have performed a complete revisit of the systematic treatment of the one year analysis!

Comparison between one to eight year treatment



Atmospheric flux		
ν flux template	discrete (7)	
ν / $\bar{\nu}$ ratio	continuous	0.025
π / K ratio	continuous	0.1
Normalization	continuous	none[1]
Cosmic ray spectral index	continuous	0.05
Atmospheric temperature	continuous	model tuned
Detector and ice model		
DOM efficiency	continuous	
Ice properties	discrete (4)	
Hole ice effect on angular response	discrete (2)	
Neutrino propagation and interaction		
DIS cross section	discrete (6)	
Earth density	discrete (9)	



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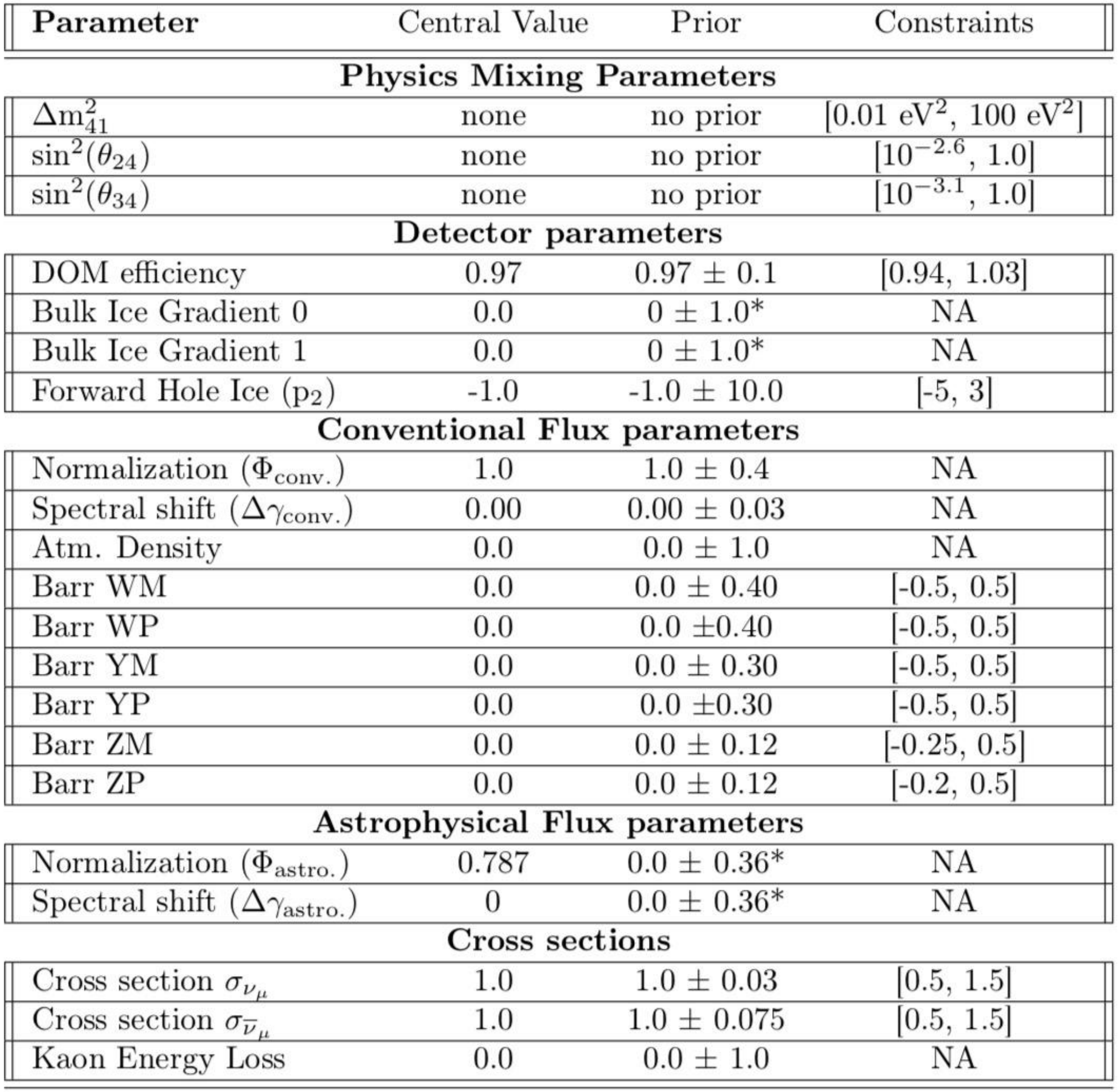
IceCube Preliminary



Parameter	Central Value	Prior	Constraints
Physics Mixing Parameters			
Δm^2_{41}	none	no prior	$[0.01\ \mathrm{eV}^2, 100\ \mathrm{eV}^2]$
$\sin^2(\theta_{24})$	none	no prior	$[10^{-2.6}, 1.0]$
$\sin^2(\theta_{34})$	none	no prior	$[10^{-3.1}, 1.0]$
Detector parameters			
DOM efficiency	0.97	0.97 ± 0.1	[0.94, 1.03]
Bulk Ice Gradient 0	0.0	0 ± 1.0*	NA
Bulk Ice Gradient 1	0.0	0 ± 1.0*	NA
Forward Hole Ice (p_2)	-1.0	-1.0 ± 10.0	[-5, 3]
Conventional Flux parameters			
Normalization ($\Phi_{\mathrm{conv.}}$)	1.0	1.0 ± 0.4	NA
Spectral shift ($\Delta\gamma_{\mathrm{conv.}}$)	0.00	0.00 ± 0.03	NA
Atm. Density	0.0	0.0 ± 1.0	NA
Barr WM	0.0	0.0 ± 0.40	[-0.5, 0.5]
Barr WP	0.0	0.0 ±0.40	[-0.5, 0.5]
Barr YM	0.0	0.0 ± 0.30	[-0.5, 0.5]
Barr YP	0.0	0.0 ±0.30	[-0.5, 0.5]
Barr ZM	0.0	0.0 ± 0.12	[-0.25, 0.5]
Barr ZP	0.0	0.0 ± 0.12	[-0.2, 0.5]
Astrophysical Flux parameters			
Normalization ($\Phi_{\mathrm{astro.}}$)	0.787	0.0 ± 0.36*	NA
Spectral shift ($\Delta\gamma_{\mathrm{astro.}}$)	0	0.0 ± 0.36*	NA
Cross sections			
Cross section σ_{ν_μ}	1.0	1.0 ± 0.03	[0.5, 1.5]
Cross section $\sigma_{\bar{\nu}_\mu}$	1.0	1.0 ± 0.075	[0.5, 1.5]
Kaon Energy Loss	0.0	0.0 ± 1.0	NA

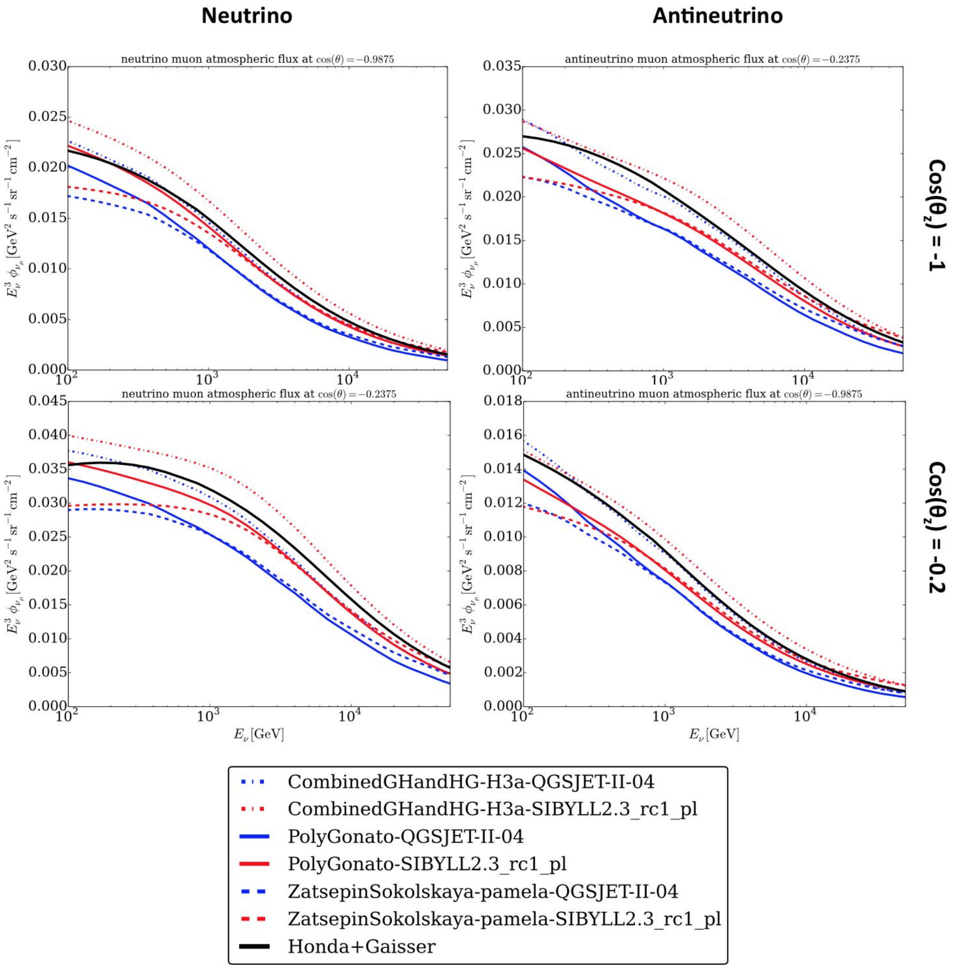
Improved treatment of atmospheric flux uncertainties

Before:

Atmospheric flux		
ν flux template	discrete (7)	
ν / $\overline{\nu}$ ratio	continuous	0.025
π / K ratio	continuous	0.1
Normalization	continuous	none[1]
Cosmic ray spectral index	continuous	0.05
Atmospheric temperature	continuous	model tuned

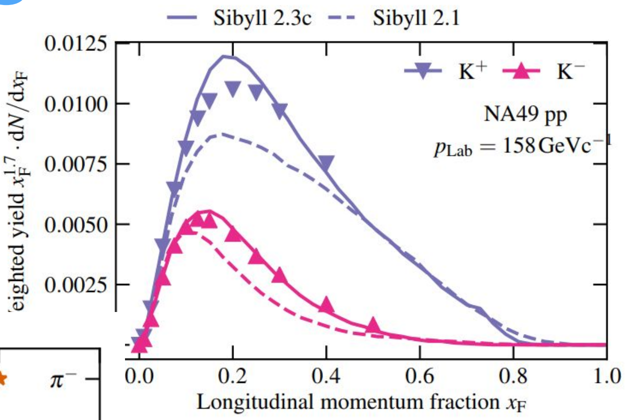
- We computed or obtained from the literature calculations of the neutrino flux of neutrinos from pions and kaons.
- We rescaled the neutrino fluxes from pion and kaons.
- We tested all the models and pick the best one at a given sterile parameter point.

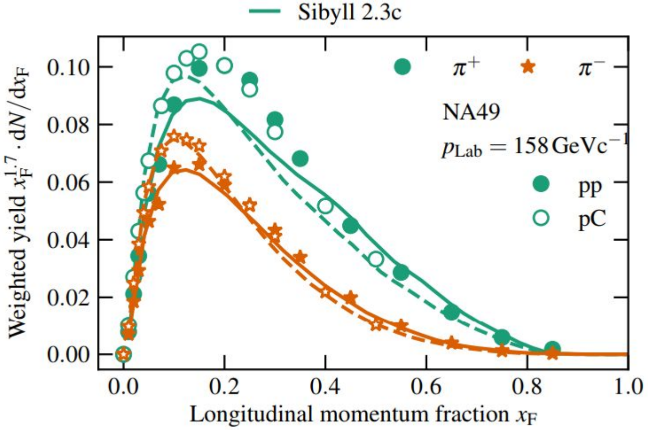
$$\phi_{\rm atm}(\cos\theta) = N_0\mathcal{F}(\delta)\left(\phi_\pi + R_{\pi/K}\phi_K\right)\left(\frac{E_\nu}{E_0}\right)^{-\Delta\gamma}$$



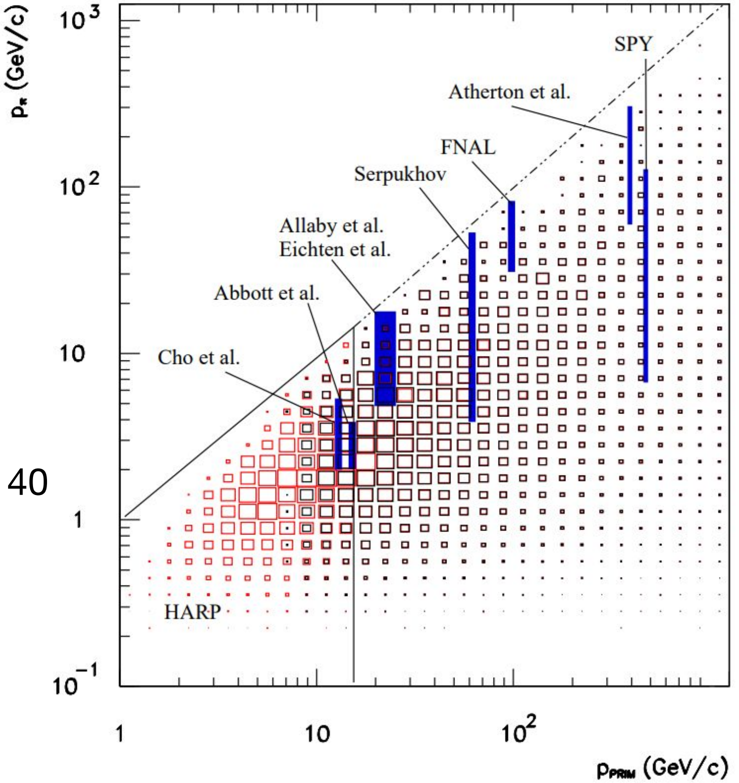
Improved treatment of atmospheric flux uncertainties

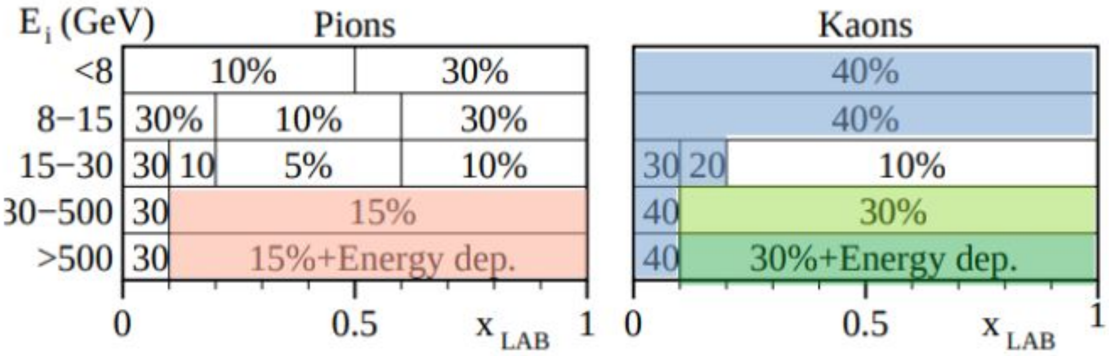
Now:





Fedynitch et al. arXiv:1806.04140
Fedynitch PANE2018.



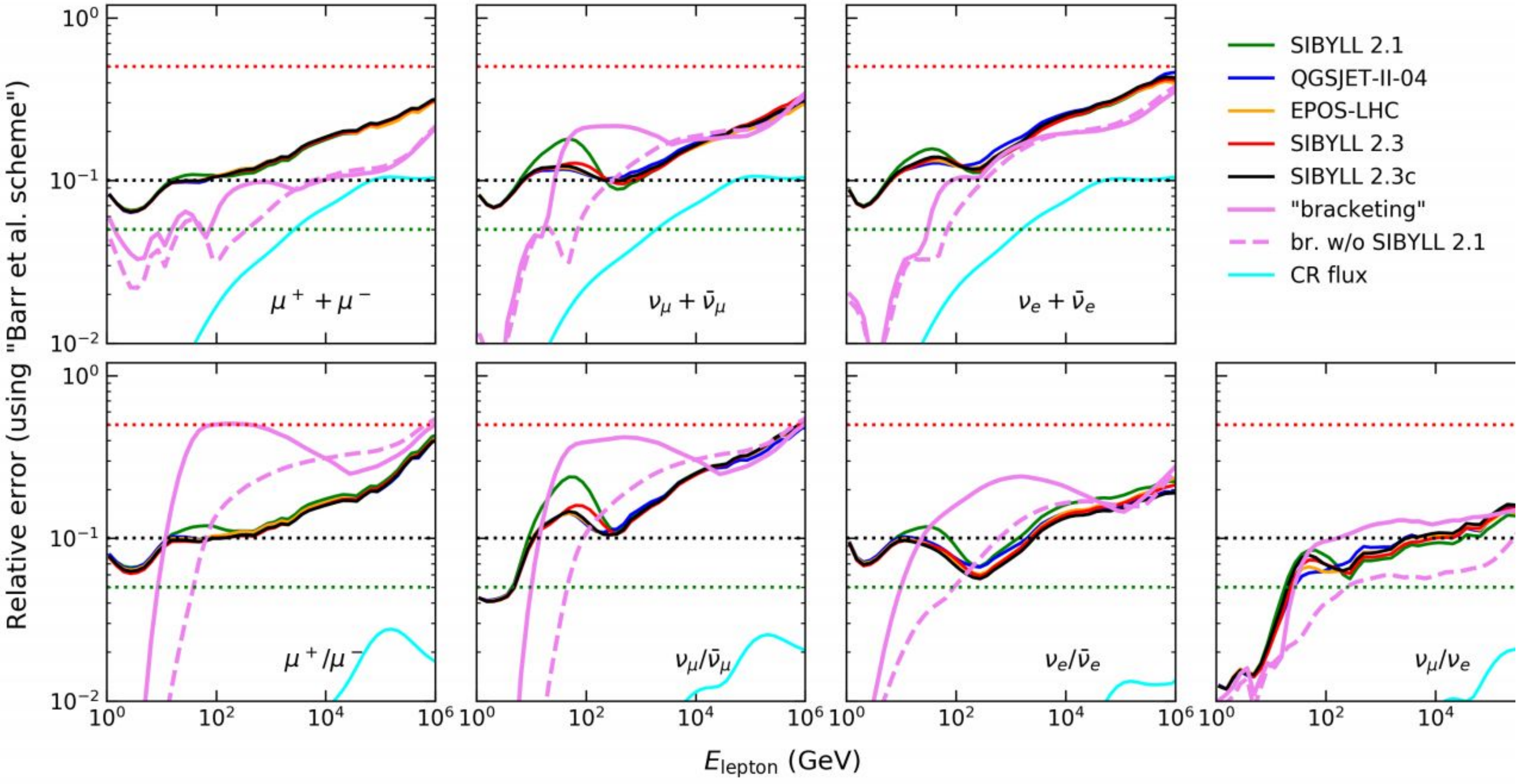


E_i (GeV)	Pions				Kaons		
<8	10%	30%			40%		
8–15	30%	10%	30%		40%		
15–30	30	10	5%	10%	30	20	10%
30–500	30	15%			40	30%	
>500	30	15%+Energy dep.			40	30%+Energy dep.	

H^+, H^-, W^+, W^-
Y^+, Y^-, Z^+, Z^-

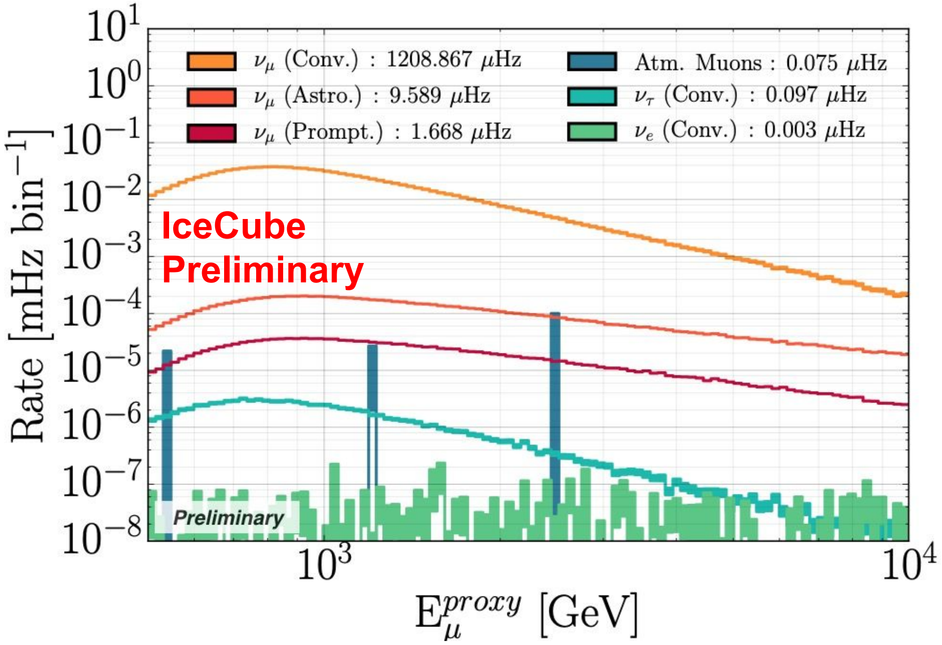
G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev, Phys. Rev. D 74 (Nov, 2006) 094009

Improved treatment of atmospheric flux uncertainties



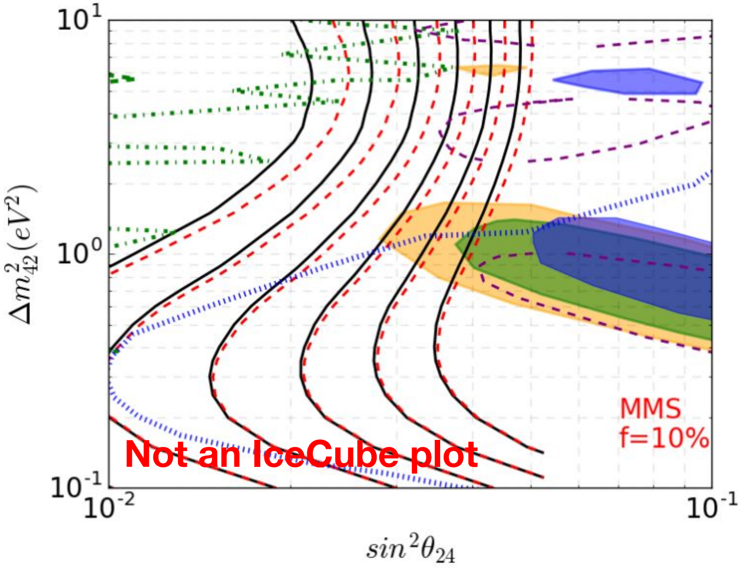
Fedynitch et al. arXiv:1806.04140
Fedynitch PANE2018.

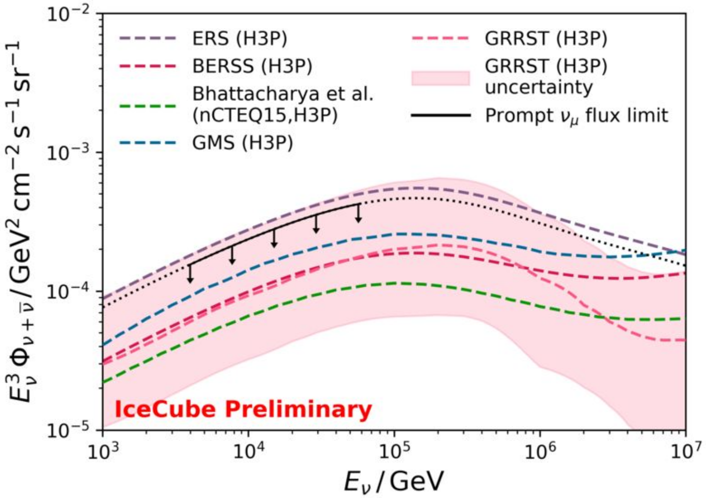
Taking into account high-energy non-conventional components



A. Bhattacharya et al. arXiv:1607.00193

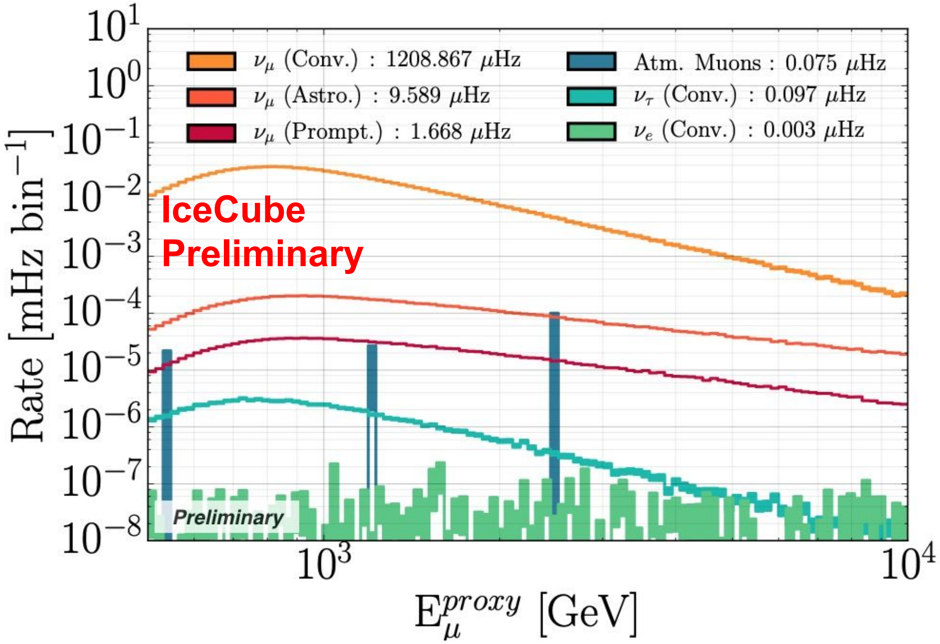
L. Miranda et al. arXiv:1812.00831



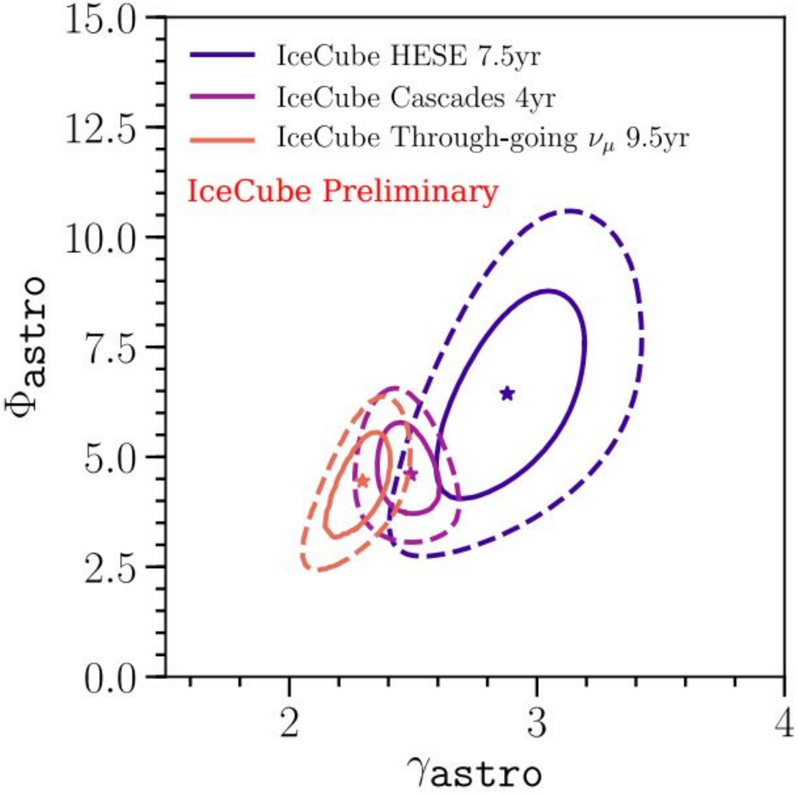


- Contributions from neutrinos from charmed meson decays are expected to be very small.
- Studied its impact in the one-year analysis and found to be negligable.
- Miranda et al have revisited its impact and found it small and confined to the high-mass region.

Taking into account high-energy non-conventional components



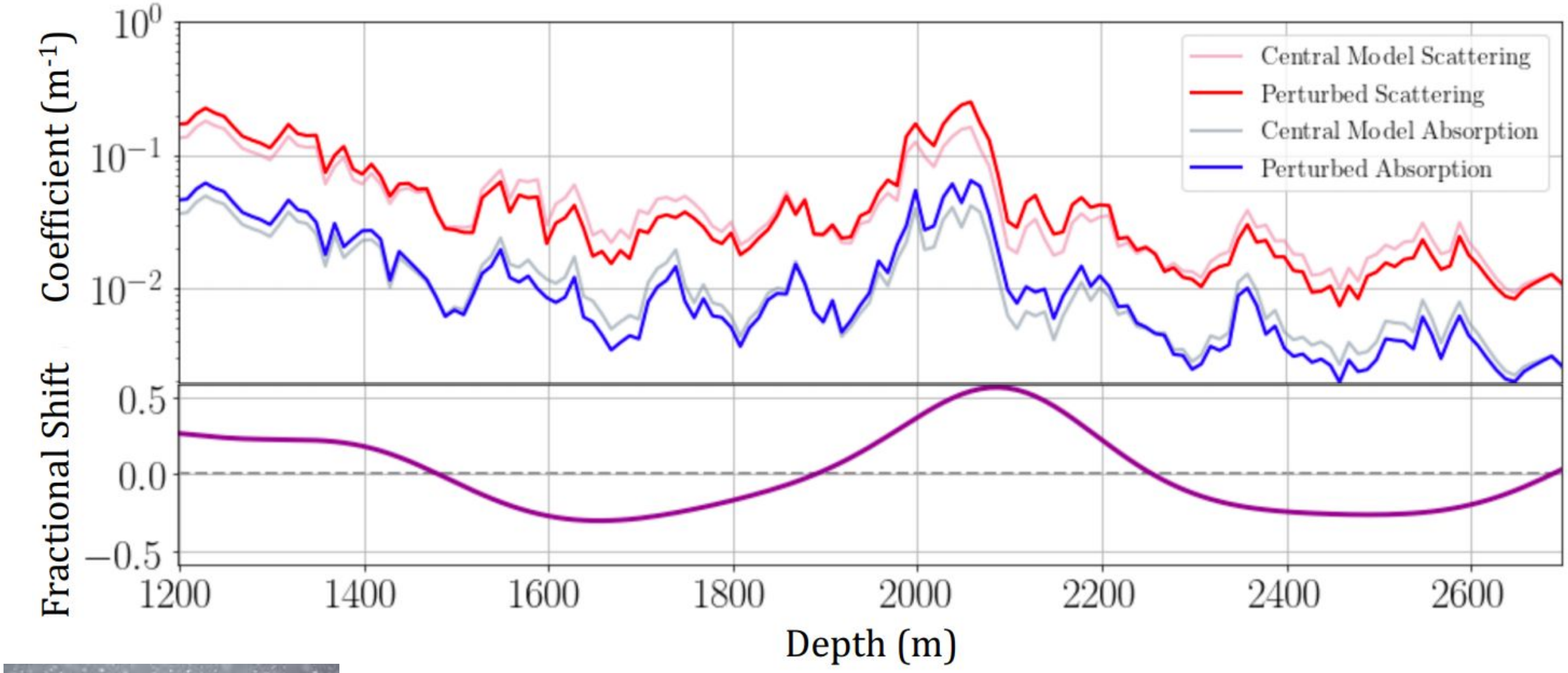
A. Schneider for the IceCube Collaboration
arXiv:1907.11266



- High-energy astrophysical neutrinos observed by IceCube are known to be much larger than the prompt flux.
- We include an astrophysical neutrino flux as an isotropic single power-law in energy.

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ [\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

Much more complete treatment of the ice uncertainties

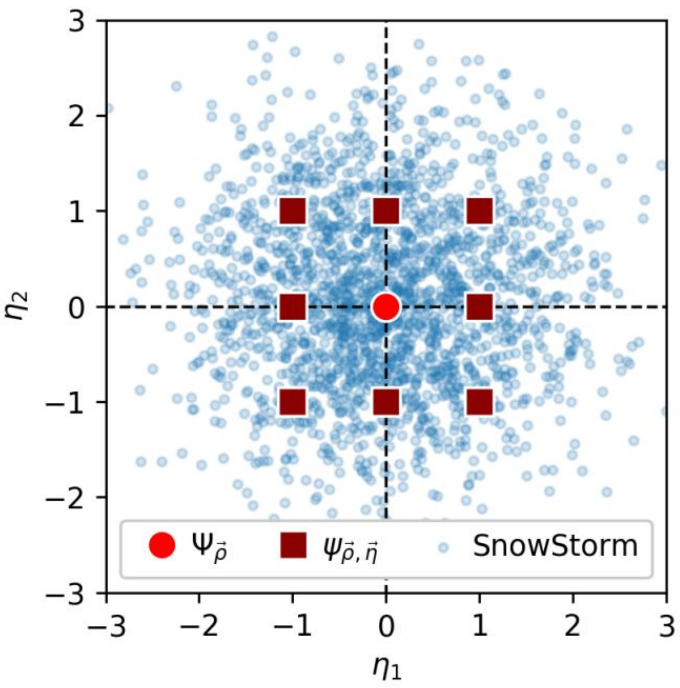


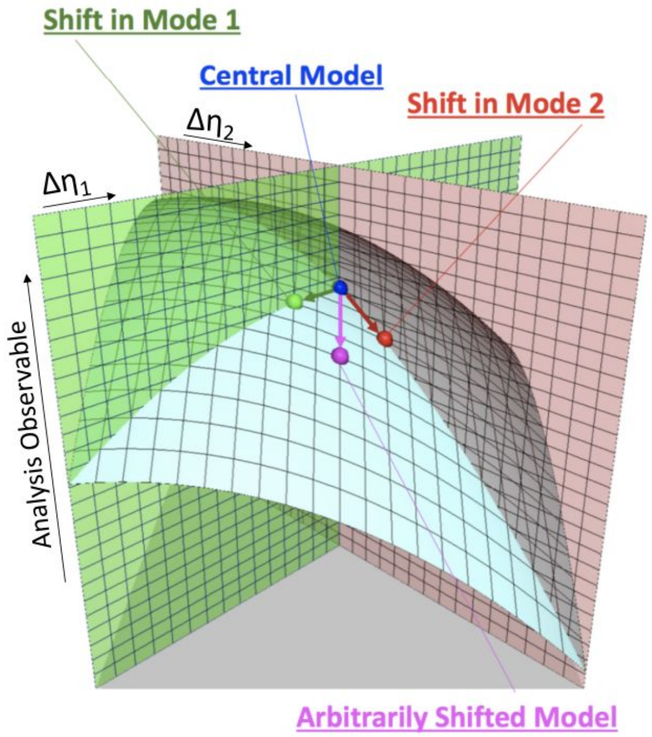
arXiv.org > hep-ex > arXiv:1909.01530

High Energy Physics - Experiment

Efficient propagation of systematic uncertainties from calibration to analysis with the SnowStorm method in IceCube

Much more complete treatment of the ice uncertainties





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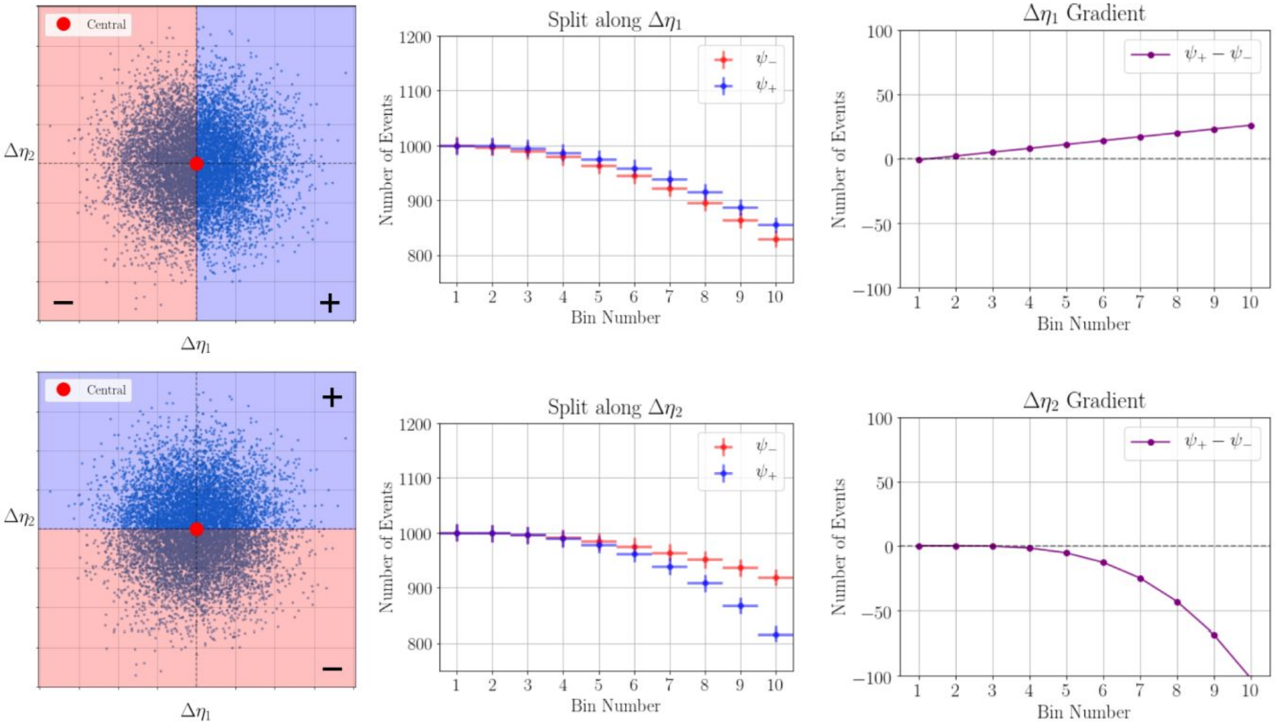


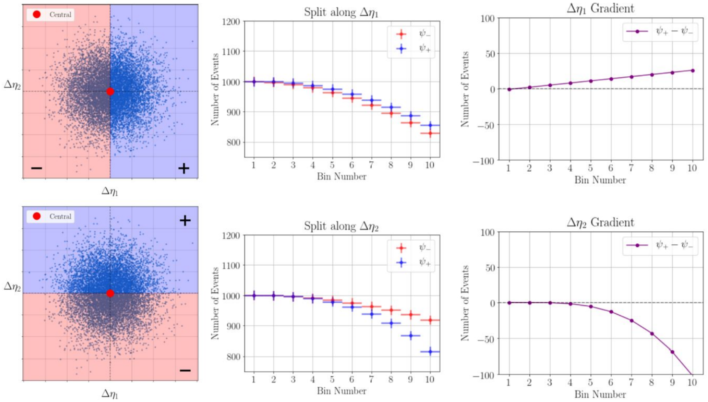

arXiv.org > hep-ex > arXiv:1909.01530

High Energy Physics - Experiment

Efficient propagation of systematic uncertainties from calibration to analysis with the SnowStorm method in IceCube

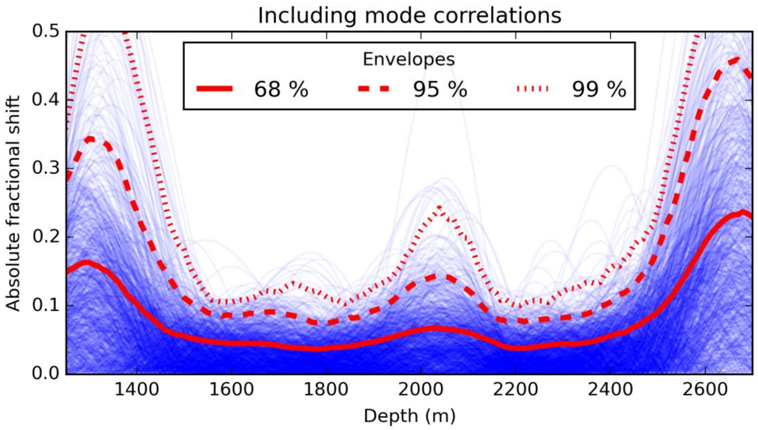
Much more complete treatment of the ice uncertainties

Prediction of the effect of changing the ice using the SnowStorm



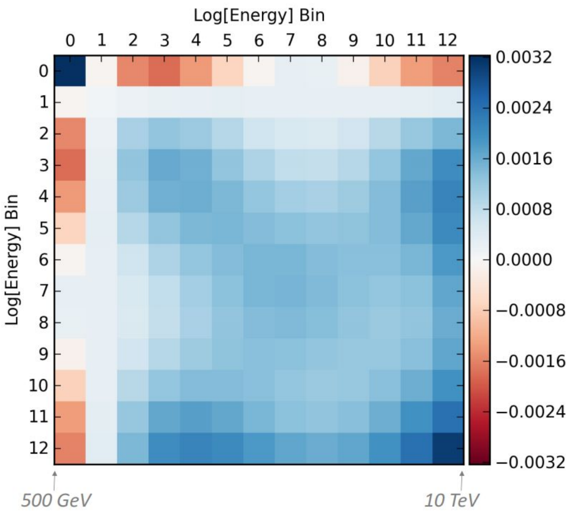
+

Uncertainties in the ice properties from flasher data

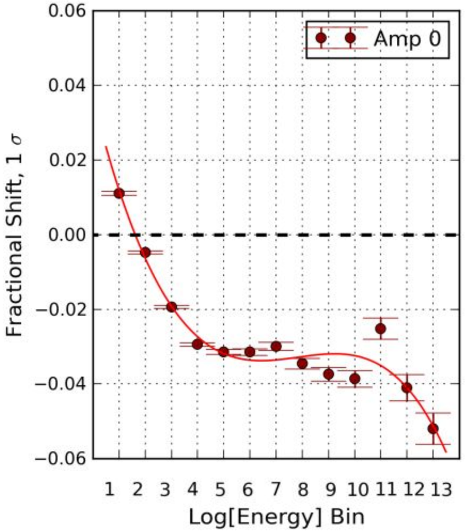


Analysis implementations can be done in two ways:

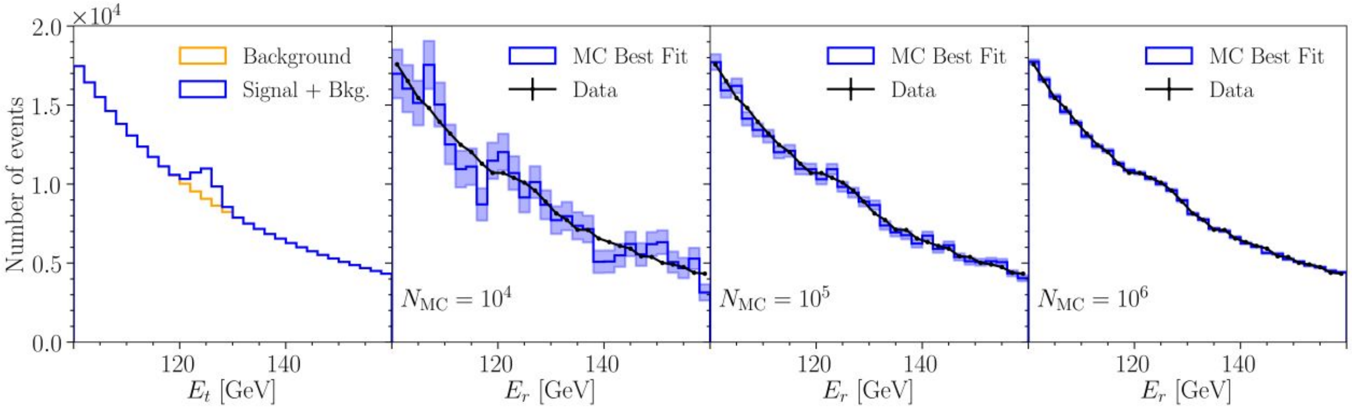
- We can compute the covariance matrix of the ice effects.
- <u>Or we can use directly the effect of the most important ice variants.</u>



or

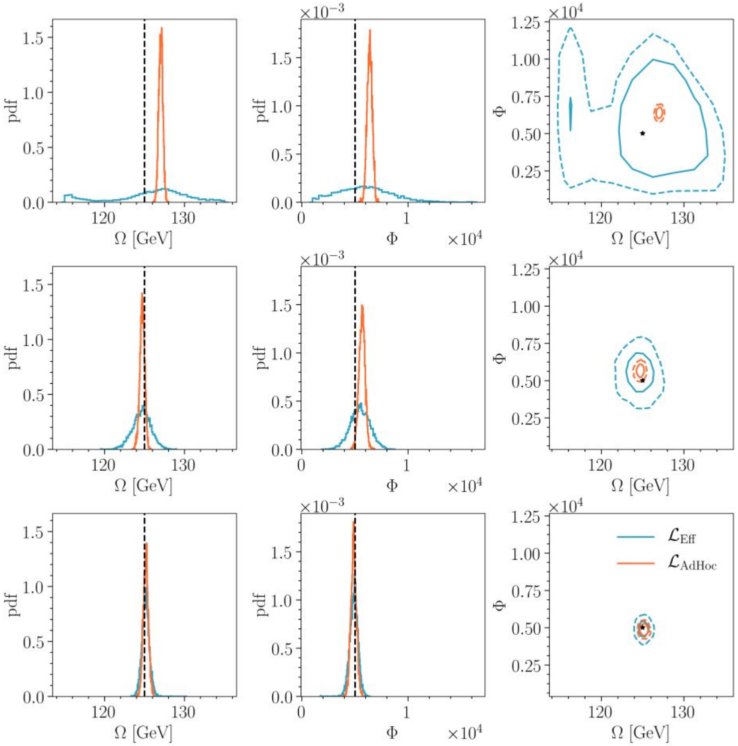


Improved statistical treatment to account for Monte Carlo statistical uncertainties



Various ideas in the literature:

- **Barlow et al. (1993),**
- **Bohm et al. (2012),**
- **Chirkin (2013),**
- **Glüsenkamp (2017).**



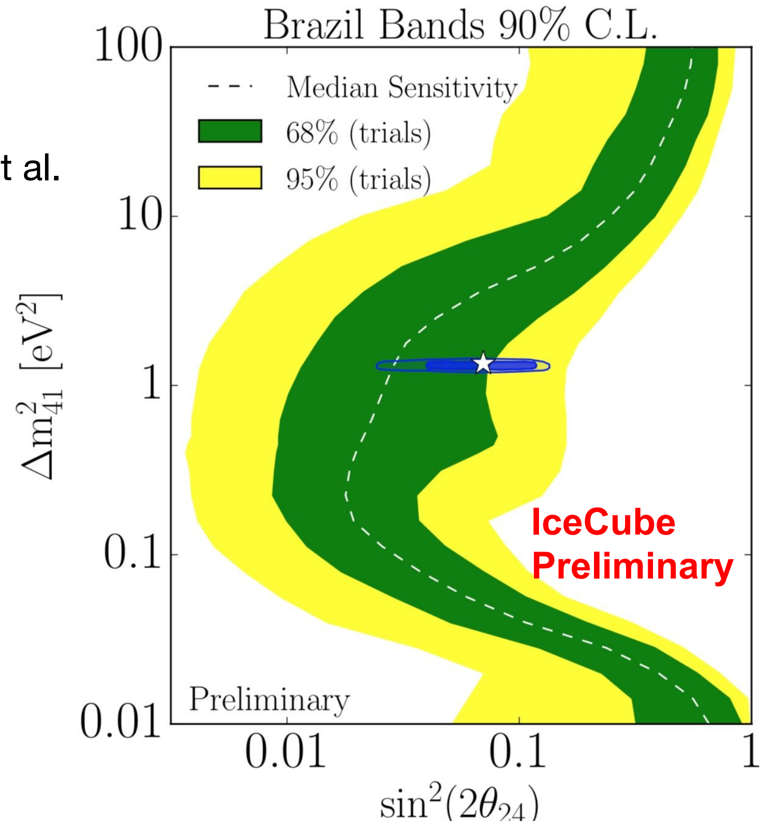
$$\mathcal{L}_{\mathrm{General}}(\vec{\theta}|k) = \int_0^\infty \frac{\lambda^k e^{-\lambda}}{k!} \mathcal{P}\left(\lambda|\vec{w}(\vec{\theta})\right)\, d\lambda$$

Parameters	$\mu \equiv \sum_{i=1}^m w_i,\ \sigma^2 \equiv \sum_{i=1}^m w_i^2$
$\mathcal{L}_{\mathrm{AdHoc}}$	$\frac{\mu^k e^{-\mu}}{k!}$
χ^2_{mod}	$\frac{(k-\mu)^2}{\mu+\sigma^2}$
$\mathcal{L}_{\mathrm{BB}}^{s=1}$	$\max_{\bar{m}} \left\{ \frac{1}{k!m!} \left(\frac{\mu\bar{m}}{m}\right)^k \bar{m}^m e^{-\frac{\mu\bar{m}}{m}-\bar{m}} \right\}$
$\mathcal{L}_{\mathrm{Mean}}$	$\left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}} \Gamma\left(k+\frac{\mu^2}{\sigma^2}\right) \left[k!\left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}} \Gamma\left(\frac{\mu^2}{\sigma^2}\right)\right]^{-1}$
$\mathcal{L}_{\mathrm{Eff}}$	$\left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1} \Gamma\left(k+\frac{\mu^2}{\sigma^2}+1\right) \left[k!\left(1+\frac{\mu}{\sigma^2}\right)^{k+\frac{\mu^2}{\sigma^2}+1} \Gamma\left(\frac{\mu^2}{\sigma^2}+1\right)\right]^{-1}$

CA, A. Schneider, T. Yuan, arXiv:1901.04645

Our sensitivities!

Blue region is the best-fit from Diaz et al. arXiv:1906.00045



Standard PNMS matrix

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

$\rightarrow |U_{e4}|^2 = 0$ ← Assumption (pure ν_μ event selection)

$\rightarrow |U_{\mu 4}|^2 = \sin^2\theta_{24}$ ← Primary parameter of interest

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

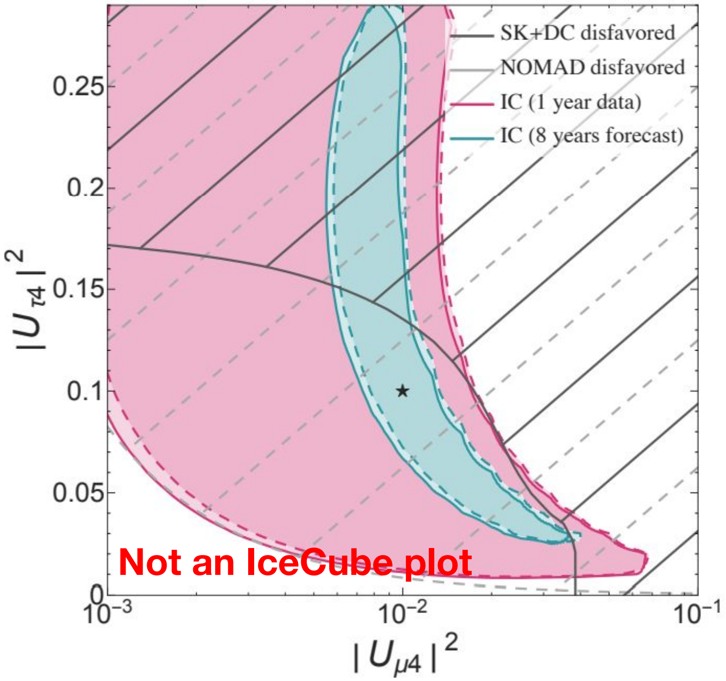
Not necessary since we assume the vPNMS matrix to be unitary.

Other interesting parameter space

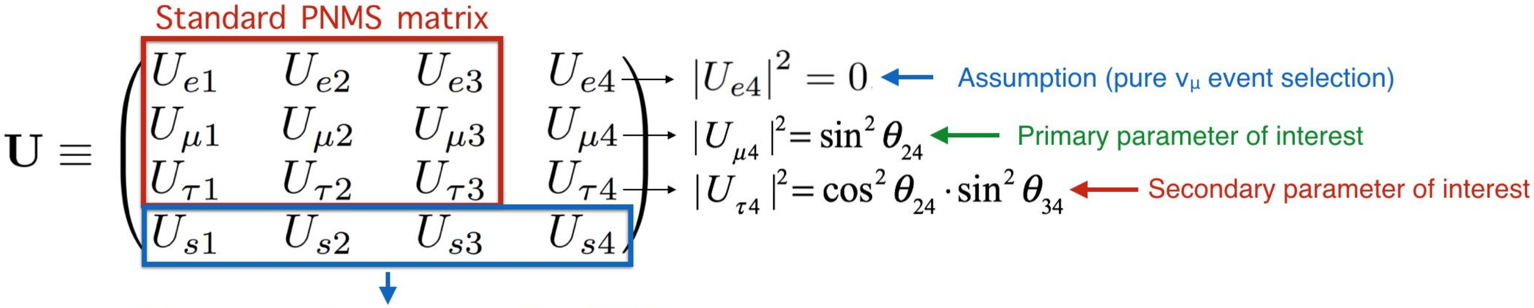
- Blennow et al. performed a fit of the one-year IceCube data and found small preference against the null hypothesis when considering a heavy sterile and non-zero U_{tau4}.
- This motivates studying high-mass-square difference parameter space. In this case signal is only zenith dependent.

$$P_{\mu\mu} \simeq 1 - V_{\rm NC}^2 |U_{\tau 4}|^2 |U_{\mu 4}|^2 L^2$$

Blennow et al.
arXiv:1803.02362



Not an IceCube plot



Standard PNMS matrix

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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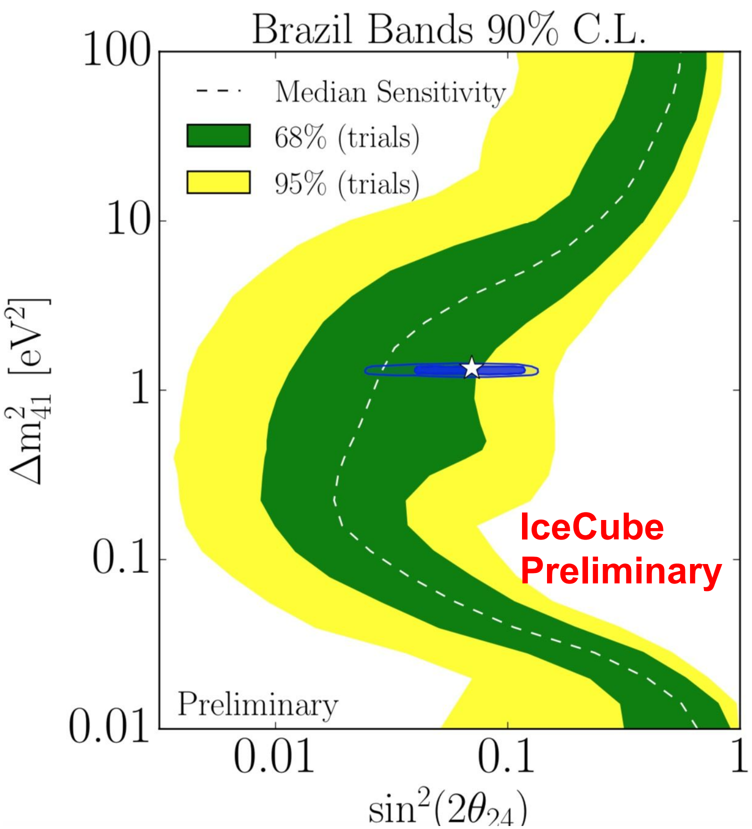
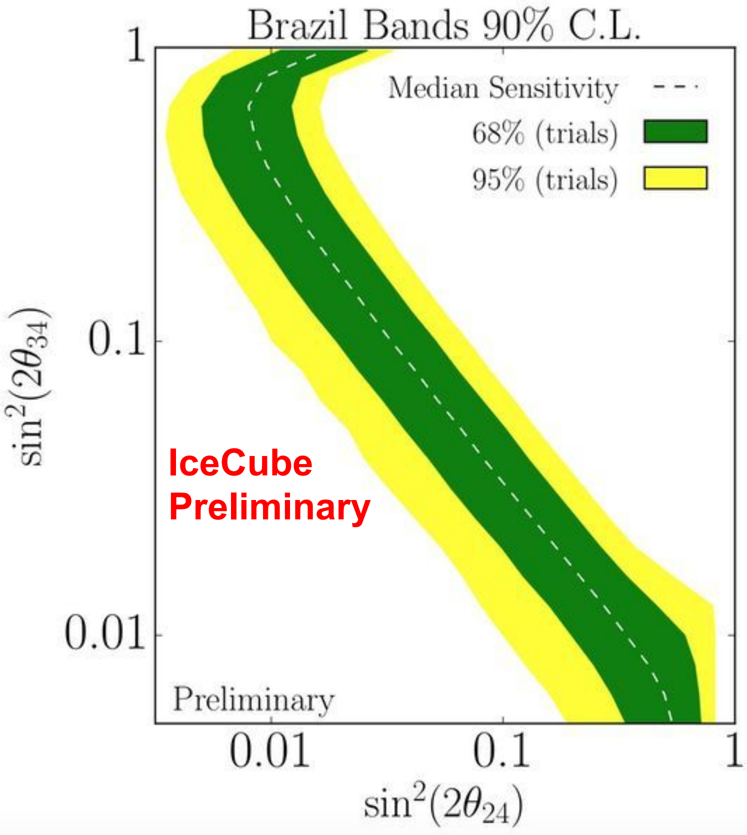
$|U_{\tau4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$ ← Secondary parameter of interest

Not necessary since we assume the vPNMS matrix to be unitary.

Money plots!





Standard PNMS matrix

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

$|U_{e4}|^2 = 0$ ← Assumption (pure ν_μ event selection)

$|U_{\mu 4}|^2 = \sin^2\theta_{24}$ ← Primary parameter of interest

$|U_{\tau 4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}$ ← Secondary parameter of interest

Not necessary since we assume the vPNMS matrix to be unitary.

Summary and outlook

- The LSND and MiniBooNE anomalies remain to have a consistent explanation with in light of the global data.
- IceCube brings new capabilities to search for sterile neutrinos via matter effects.
- We have updated our 1-year MEOWS analysis to 8 years. Statistics increased by a factor of 15!
- Improved systematic treatment has been developed.
- We hope to deliver exciting news soon!

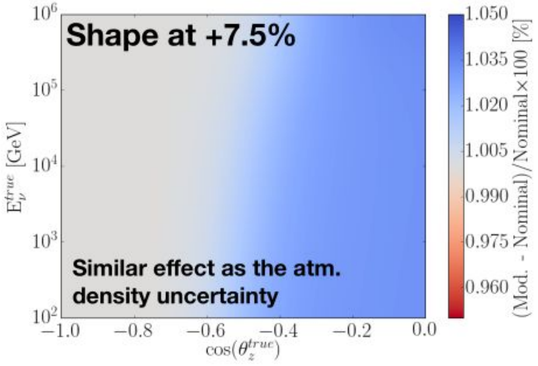
Thank you!
Gracias!

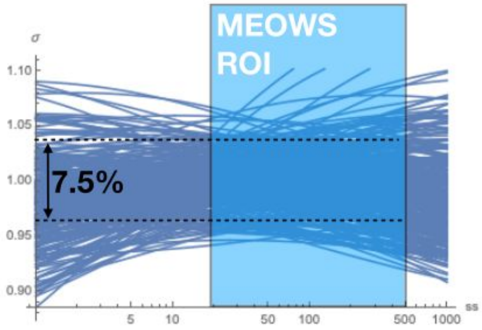
Meson interaction energy losses

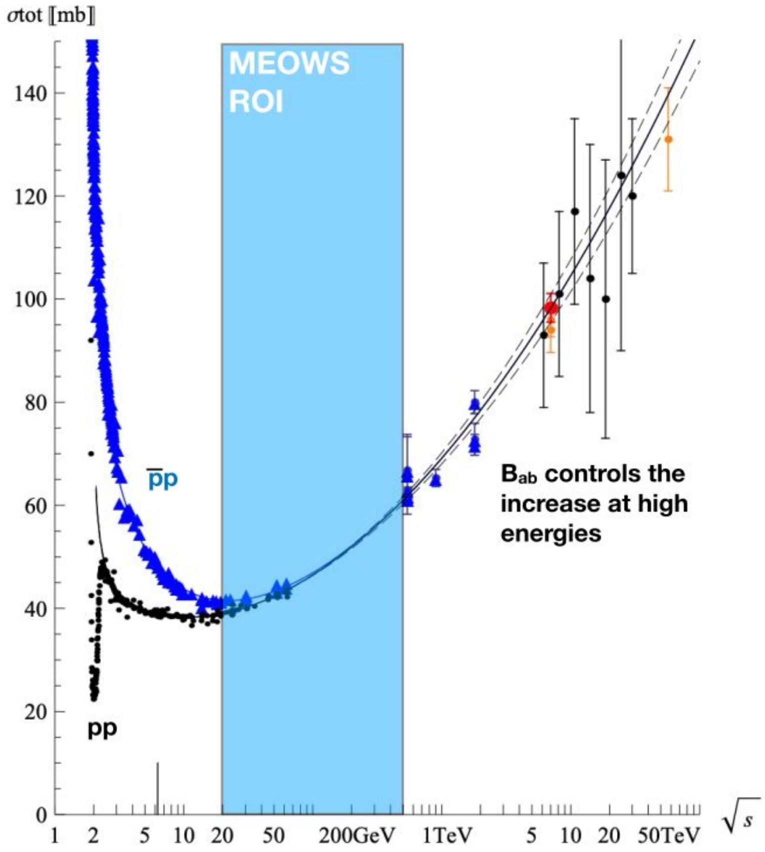
https://arxiv.org/pdf/1110.1479.pdf

$$\sigma^{\bar{a}b}_{\text{tot}}(s) \simeq \sigma^{ab}_{\text{tot}}(s) \quad \simeq \quad B_{ab}\log^2\frac{s}{s^{ab}_0} + Z_{ab}$$

ab	B(mb)	$\sqrt{s^{ab}_0}$(GeV)	Z_{ab}(mb)
Kp	0.293(26)	5.18(76)	17.76(43)







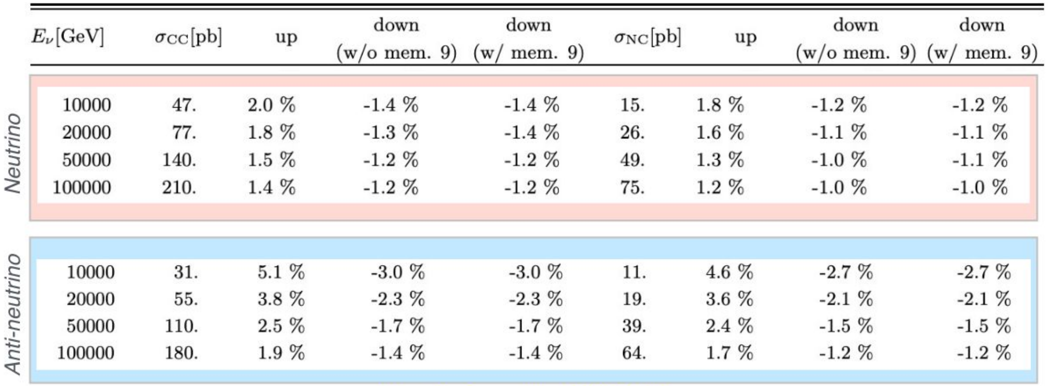
B_{ab} controls the increase at high energies

To estimate the cross section from Kaon-Air we use a scaling of sigma ~ A^⅔ and perform error propagation. Resulting error of ~ 5%.

Uncertainties in Earth absorption due to neutrino cross sections

For our prior, we are using +/-7.5% for the antineutrino cross section, and +/-3.0% for the neutrino cross section.

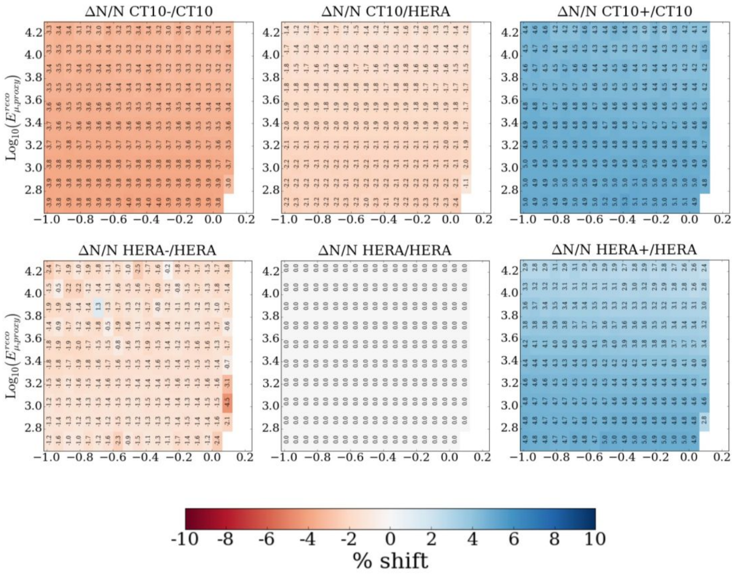
The systematic is implemented via a spline. The splined region goes from -50% to 150% in both v ad anti-v. We have 30 spline support points.



	E_ν[GeV]	σ_{CC}[pb]	up	down (w/o mem. 9)	down (w/ mem. 9)	σ_{NC}[pb]	up	down (w/o mem. 9)	down (w/ mem. 9)
Neutrino	10000	47.	2.0 %	-1.4 %	-1.4 %	15.	1.8 %	-1.2 %	-1.2 %
	20000	77.	1.8 %	-1.3 %	-1.4 %	26.	1.6 %	-1.1 %	-1.1 %
	50000	140.	1.5 %	-1.2 %	-1.2 %	49.	1.3 %	-1.0 %	-1.1 %
	100000	210.	1.4 %	-1.2 %	-1.2 %	75.	1.2 %	-1.0 %	-1.0 %
Anti-neutrino	10000	31.	5.1 %	-3.0 %	-3.0 %	11.	4.6 %	-2.7 %	-2.7 %
	20000	55.	3.8 %	-2.3 %	-2.3 %	19.	3.6 %	-2.1 %	-2.1 %
	50000	110.	2.5 %	-1.7 %	-1.7 %	39.	2.4 %	-1.5 %	-1.5 %
	100000	180.	1.9 %	-1.4 %	-1.4 %	64.	1.7 %	-1.2 %	-1.2 %

https://arxiv.org/abs/1106.3723

Effect on interaction



Effect on absorption