Results of the Search for Sterile Neutrinos with IceCube

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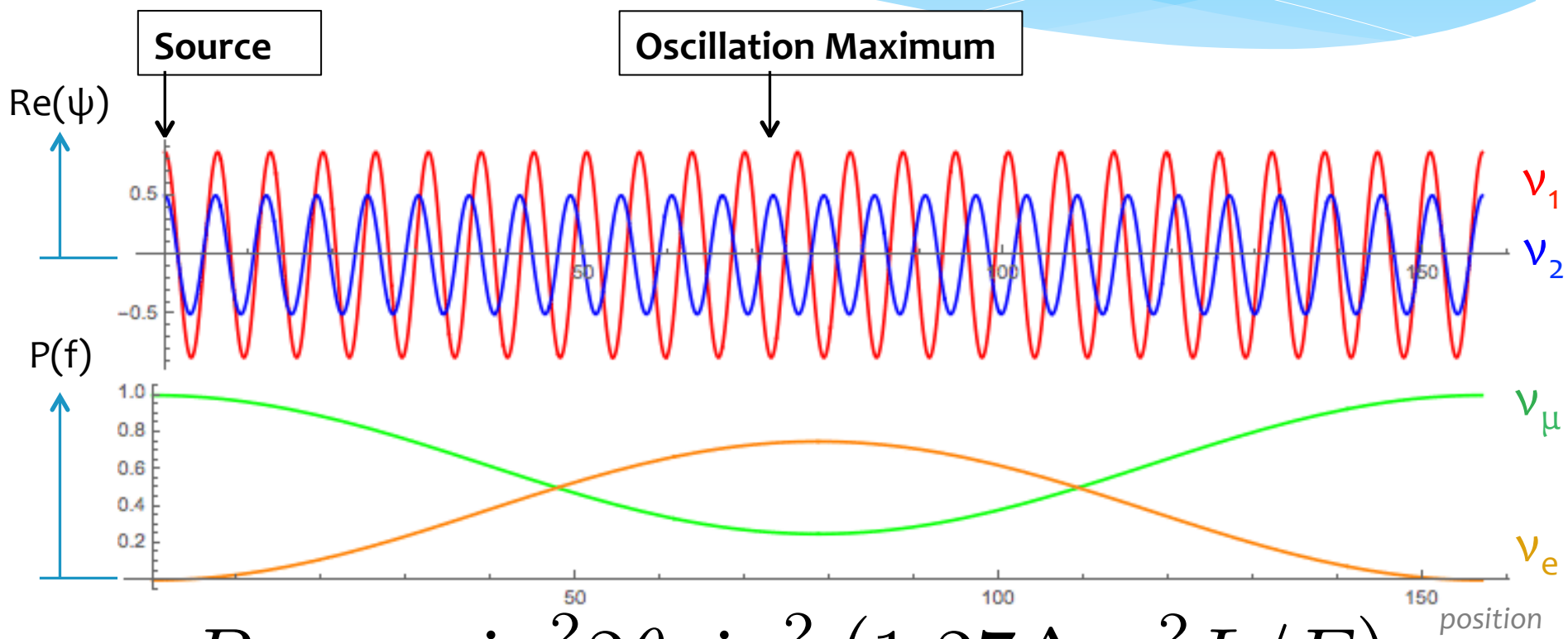
Todays Menu:

* **Sterile Neutrinos, Anomalies and MSW Resonances**
* The IceCube Experiment
* IceCube Sterile Neutrino Search

A Neutrino Oscillation:



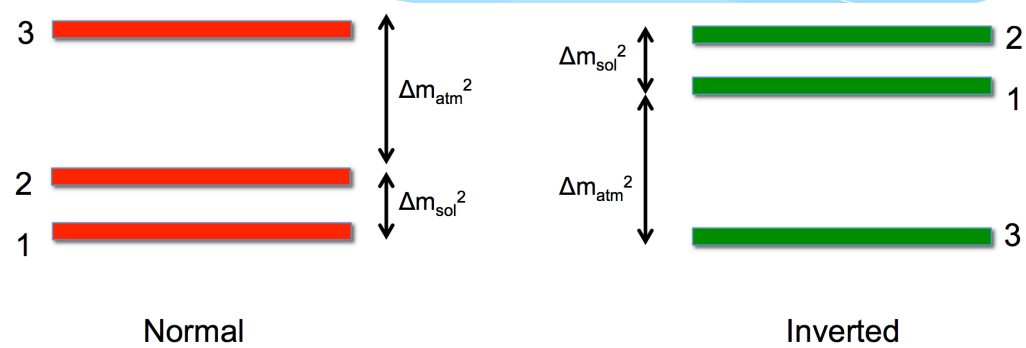
$$P_{osc} = \underbrace{\sin^2 2\theta}_{\textit{amplitude}} \sin^2 \underbrace{\left(1.27 \Delta m^2 L/E\right)}_{\textit{wavelength}}$$

Mass and Mixing : 3 neutrino model

* Experimentally, $\Delta m_{31}^2 >> \Delta m_{21}^2$

* Two characteristic oscillation wavelengths.

* Mass ordering unknown (though hints exist)



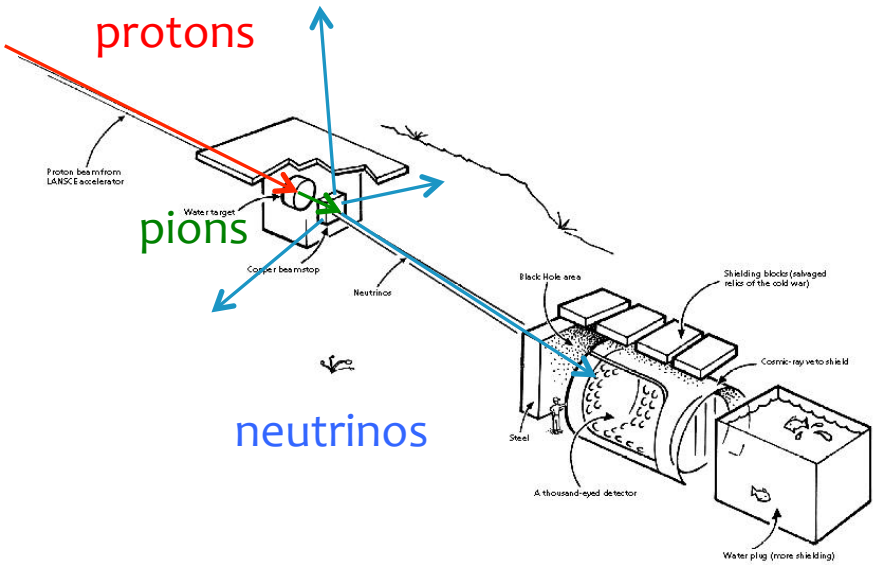
From PDG :

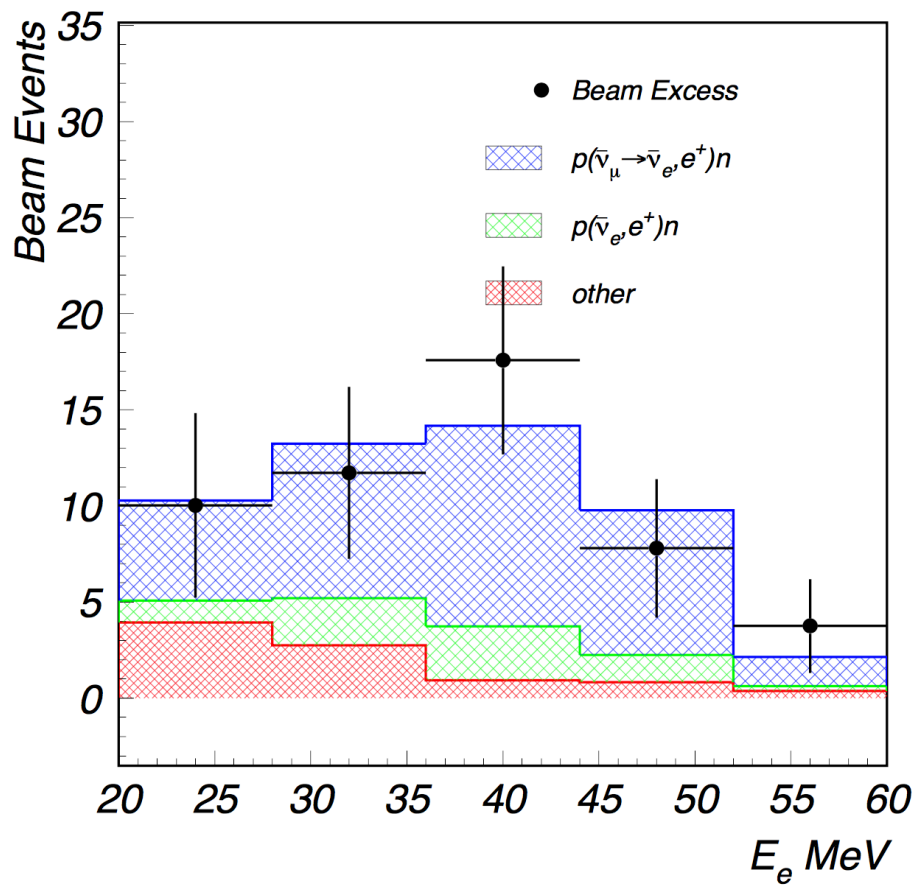
Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$

* Mixing between 3 states dictated by 3 mixing angles and (1 or 3) CP phases.

Oscillation Anomalies : LSND

$$\Delta m^2_{14} >> \Delta m^2_{13}, \Delta m^2_{23}$$



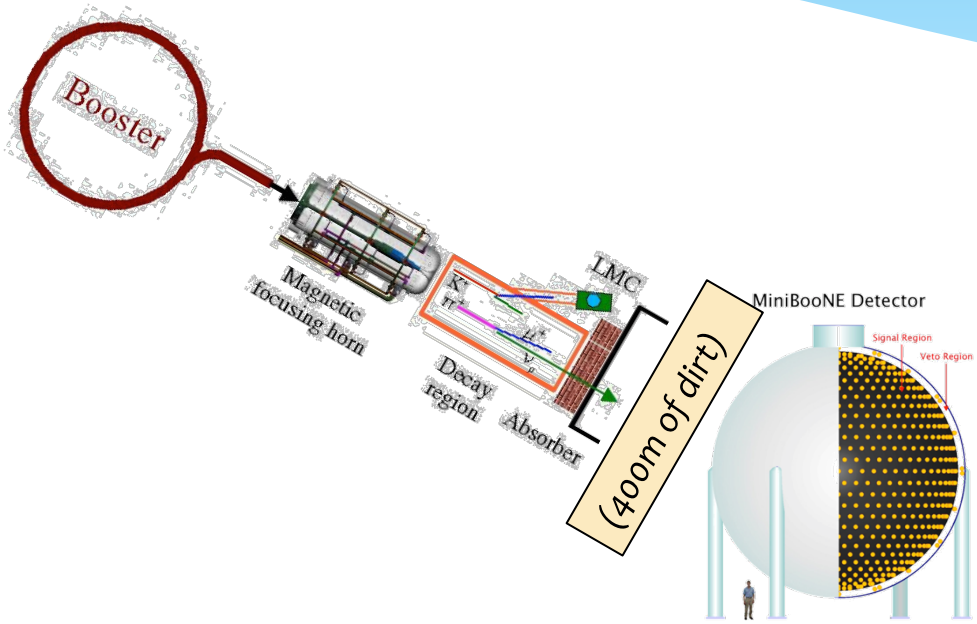


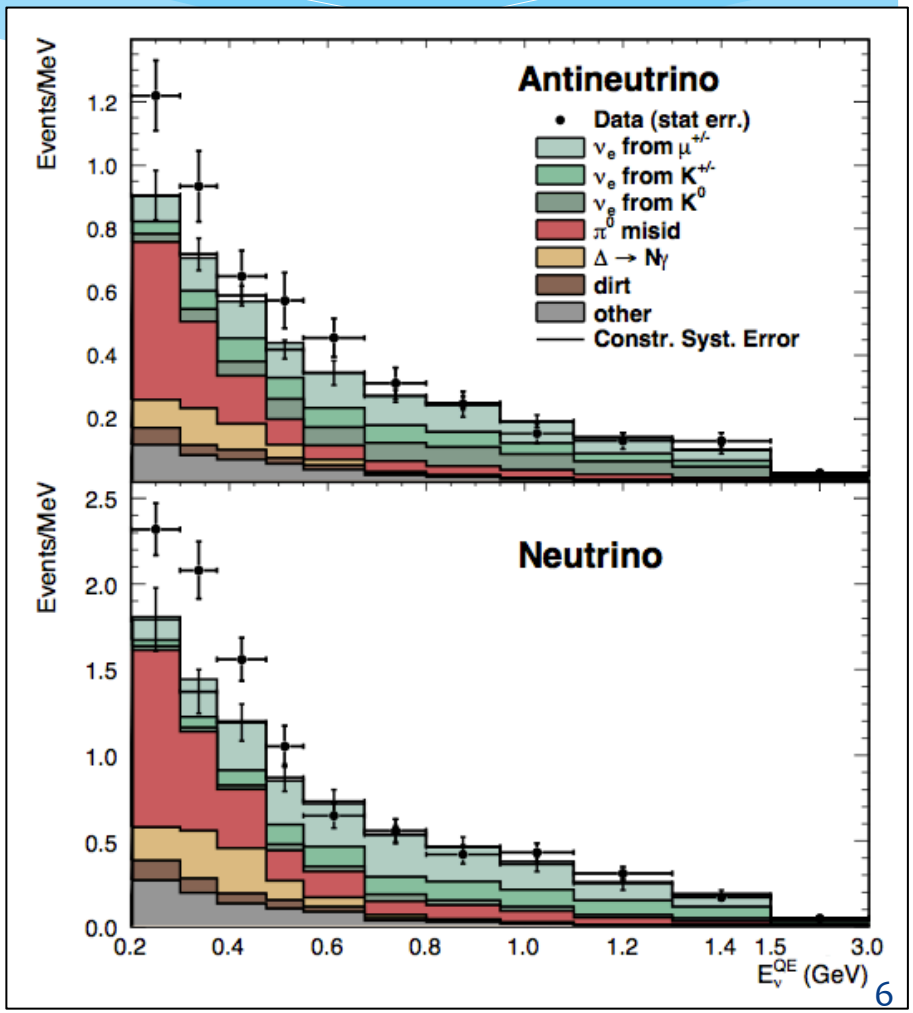
π+ stop in material, then decay:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Very small intrinsic $\bar{\nu}_e$ *background*

Oscillation Anomalies : MiniBooNE

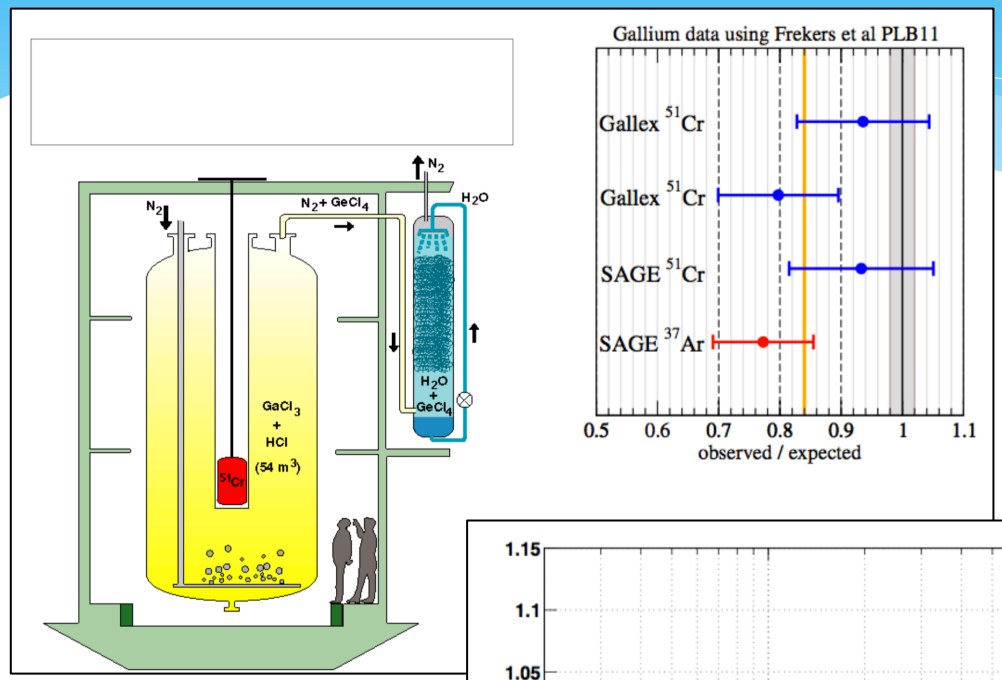




Focussed π+ or π- decay in flight to make mostly ν_μ or $\bar{\nu}_\mu$

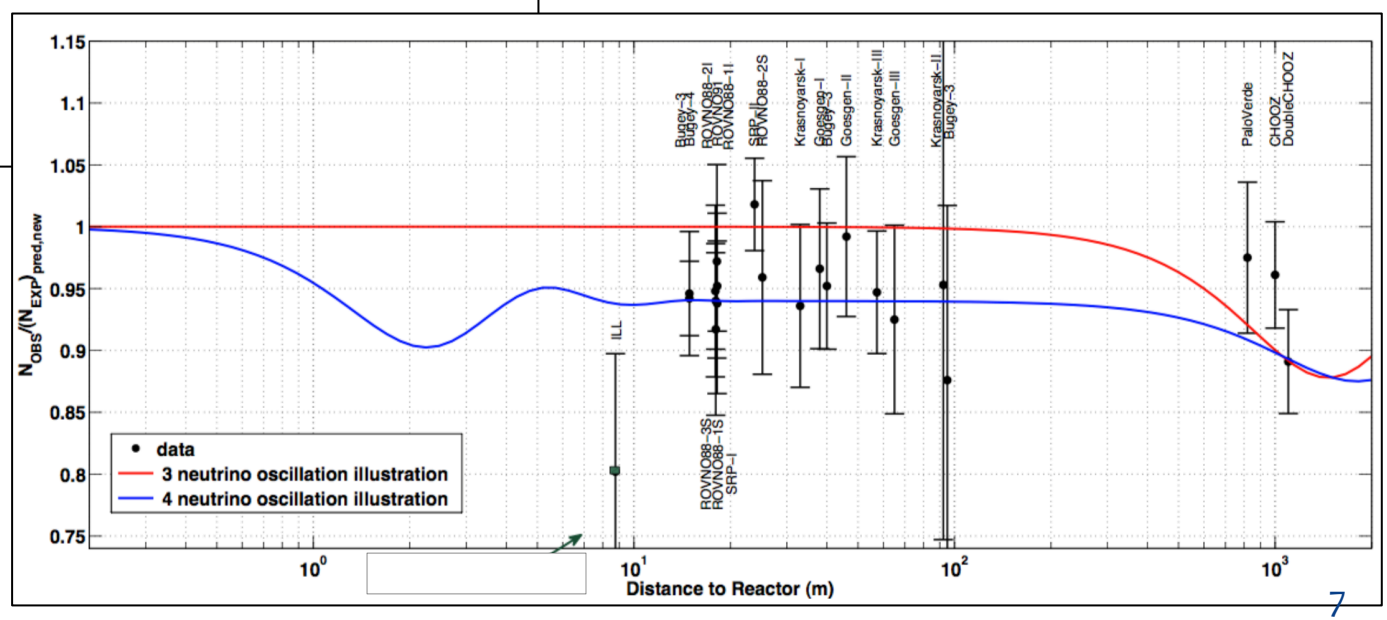
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

Other Anomalies at Short Baselines



← **Gallium Anomaly**
2.7σ deficit of ν_e from intense electron capture calibration sources

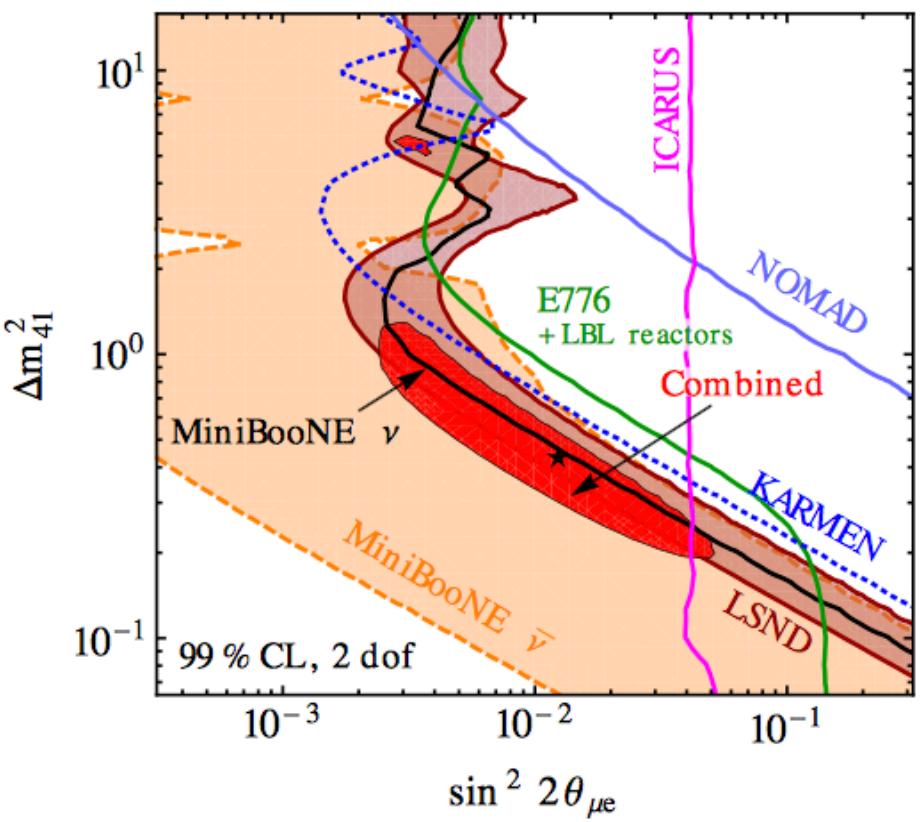
Reactor Anomaly →
3σ deficit of $\overline{\nu}_e$ from reactors after applying modern flux calculations to old data



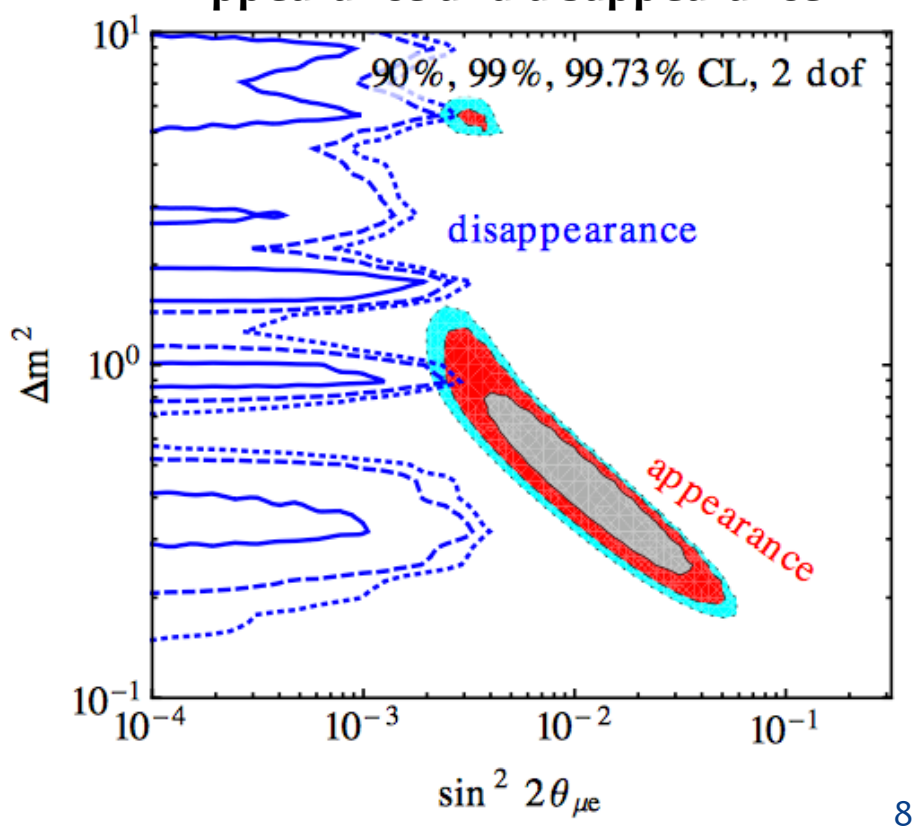
What does world data say?

Kopp et al:
JHEP 1305 (2013) 050

Appearance only



Appearance and disappearance

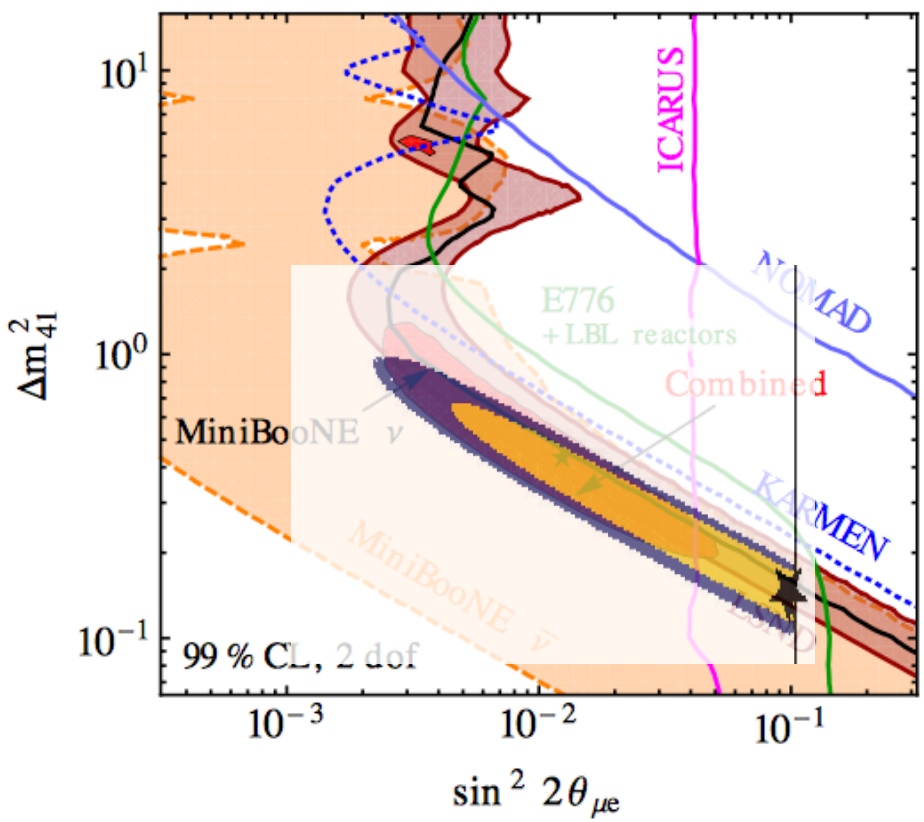


What does world data say?

Compare to Conrad et al

Adv.High Energy Phys. 2013 (2013) 163897

Appearance only



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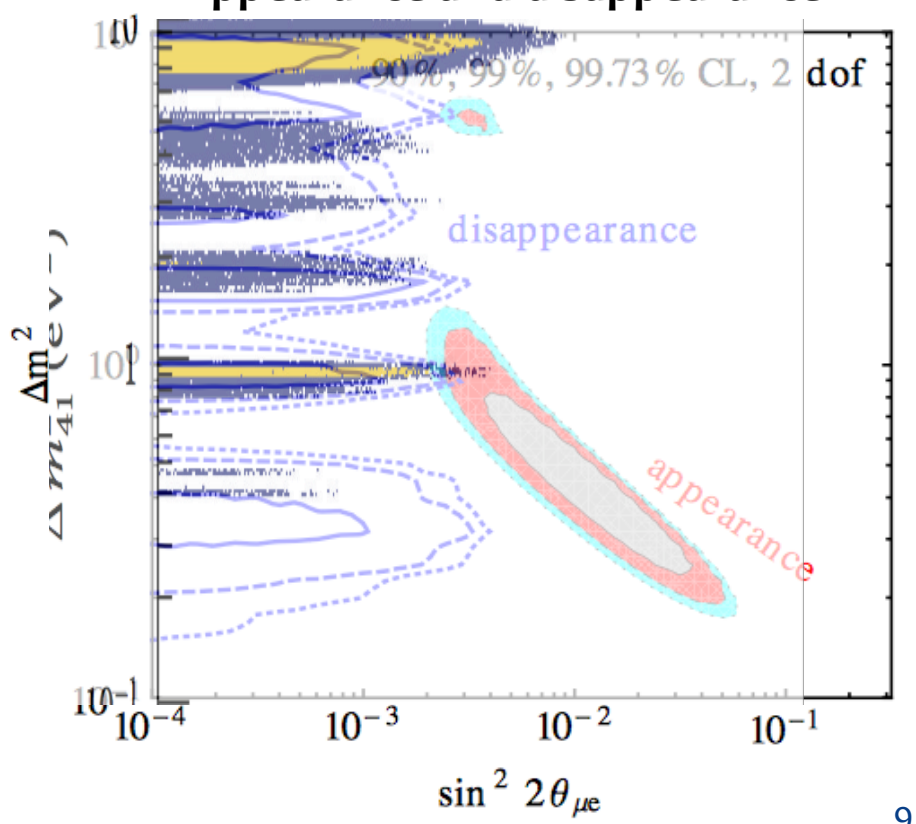
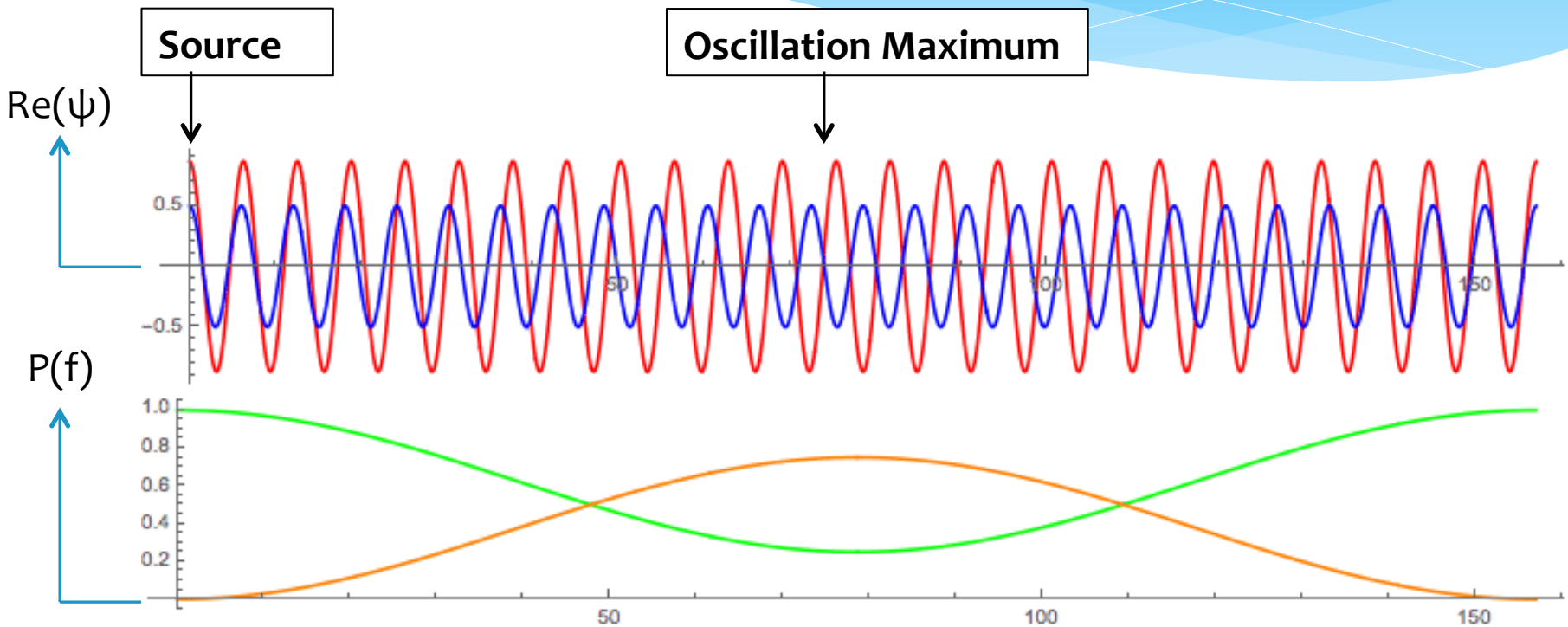


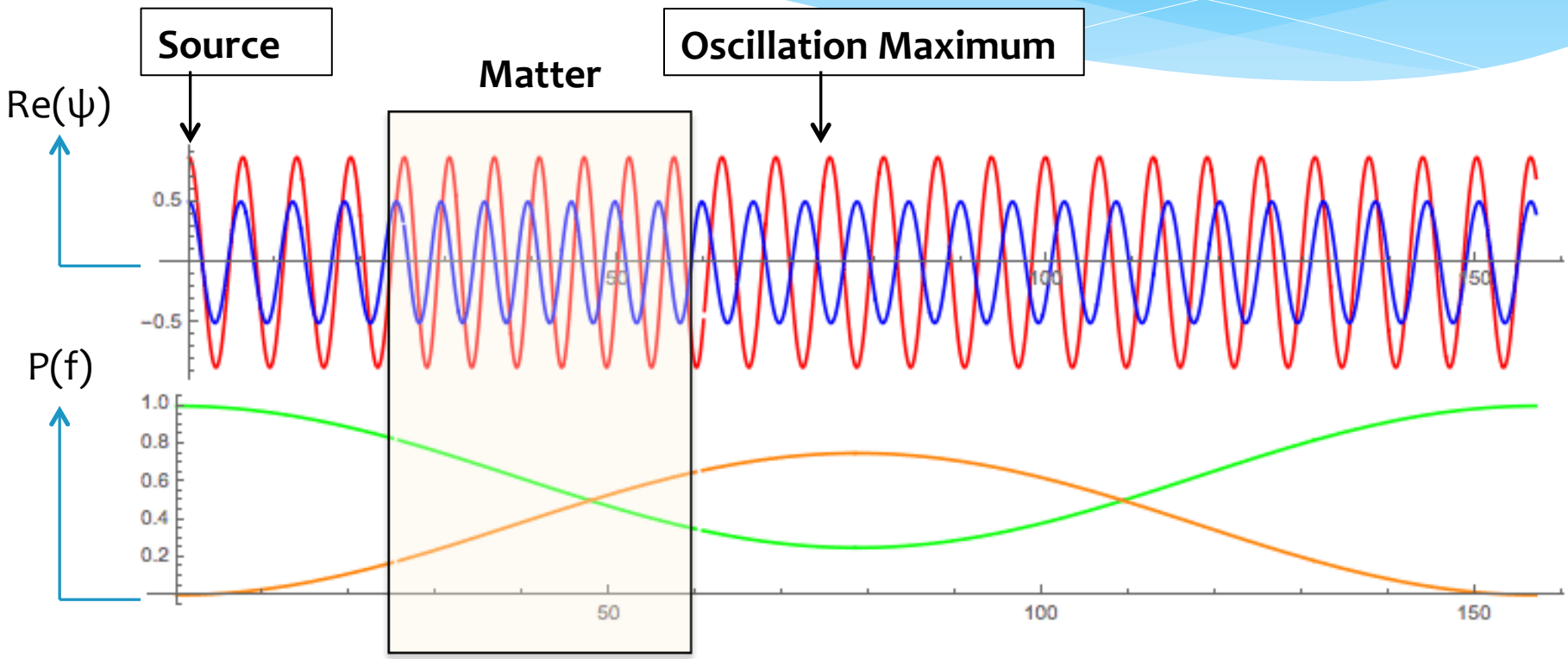
So far, matter did not matter…

$$P_{Osc} = A_{mixing} \sin^2\left(1.27\Delta m^2 L / E\right)$$



Neutrinos in matter with refraction

$$P_{Osc} = A_{mixing} \sin^2\left(1.27\Delta m^2 L / E\right)$$

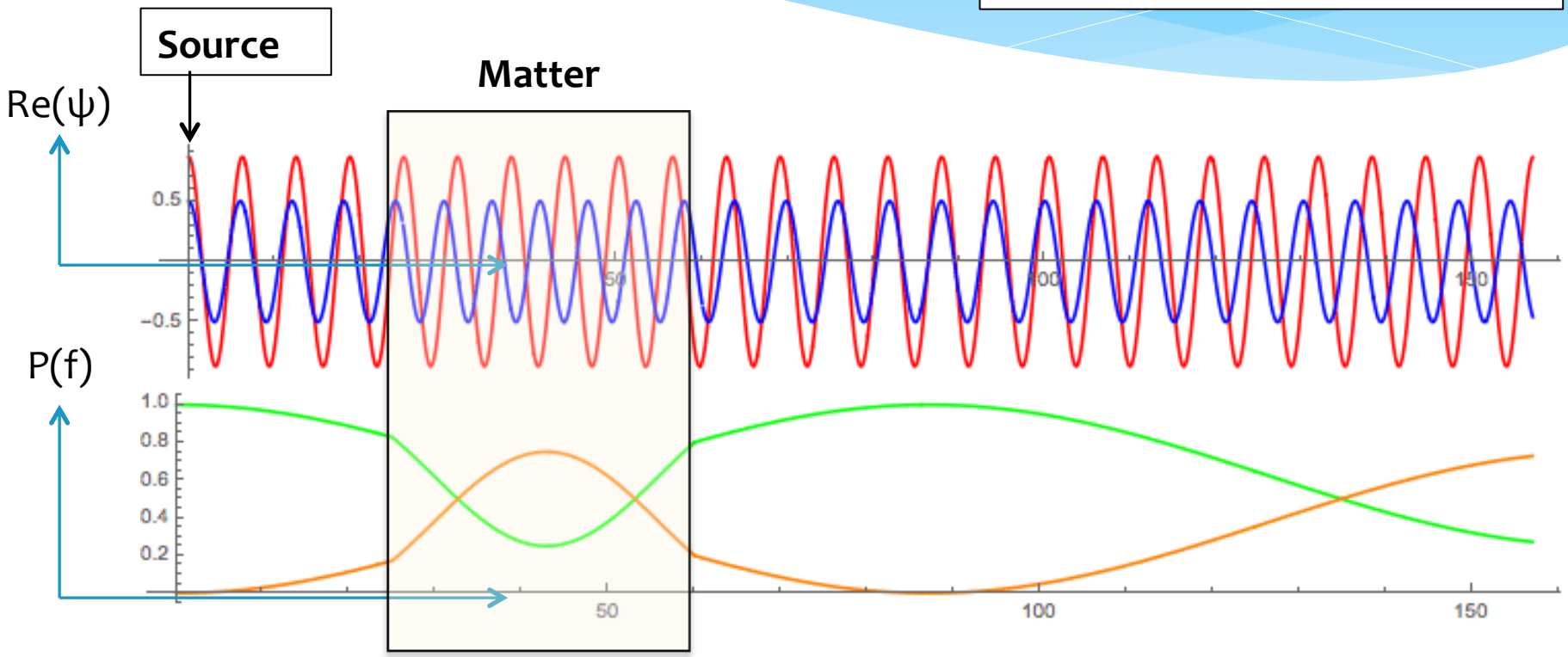


In this example, phases roll faster in matter → mass states are effectively **heavier**

Both states have same interaction strength → **Δm^2 unchanged**

From now on, matter matters!

$$P_{Osc} = A_{mixing} \sin^2\left(1.27\Delta m^2 L / E\right)$$



Couplings in matter change effective masses of the neutrinos. In the above cartoon (not physical!), one mass state has a matter coupling and the other does not.

Oscillation length changes → **Effective Δm^2 is modified**

Effective mass and mixing:

* The previous slide showed one mass state coupled more strongly than other
  * → **Effective Δm^2 modified**

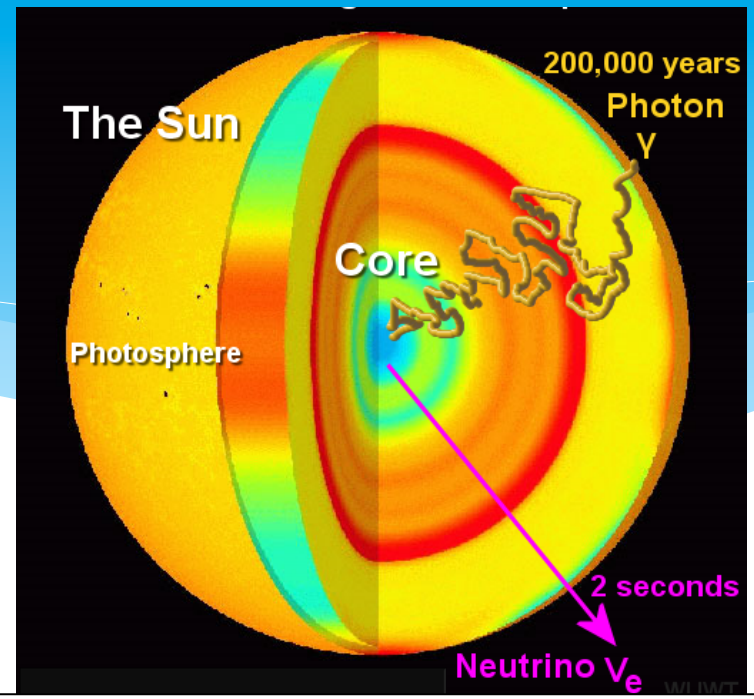
* Matter couplings are to flavor states, not directly to mass states
  * → **Effective mixing is also modified**

$$\Delta m_M^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

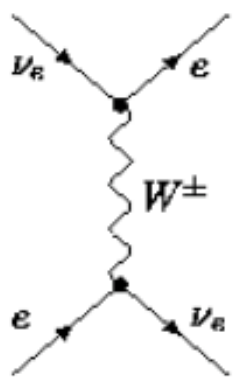
$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

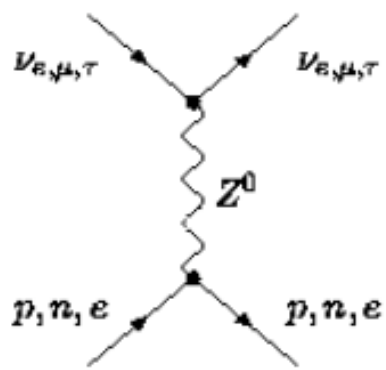
X="how different are the matter couplings between neutrino flavors"

MSW Effect in the Sun

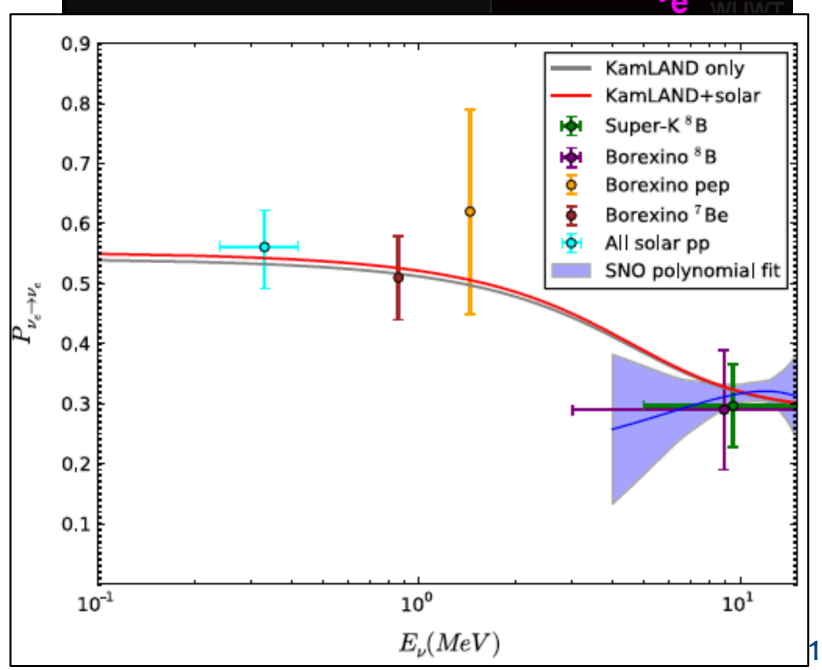


* neutrinos in the sun are all born as ν_e
* Their flavors change as they cross the sun due to oscillations
* Higher energy neutrinos feel stronger matter coupling, emerge with different flavor composition ("MSW effect")





Electron flavor ONLY **All flavors**



The MSW resonance

$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

Maximal flavor change when x = cos 2θ leads to **MSW resonance**

If x = cos 2θ, maximal mixing → largest possible amplitude of oscillation

Can happen even when original mixing angle is tiny.

Full disclosure : I am sweeping important details under the carpet...

The MSW resonance

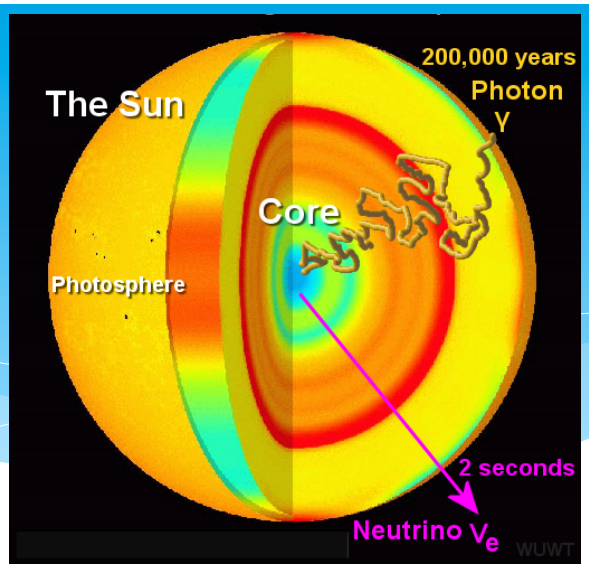
$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

Neutrino energy

Electron density

MSW resonance in the Sun



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Neutrino energy

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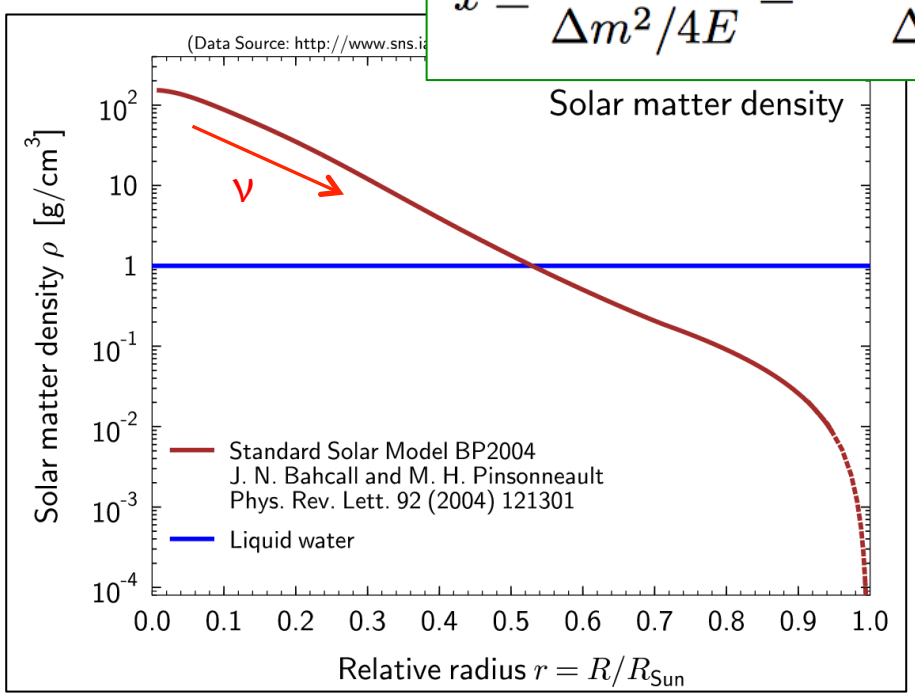


Neutrinos in the sun move from center to surface, exploring a range of x values

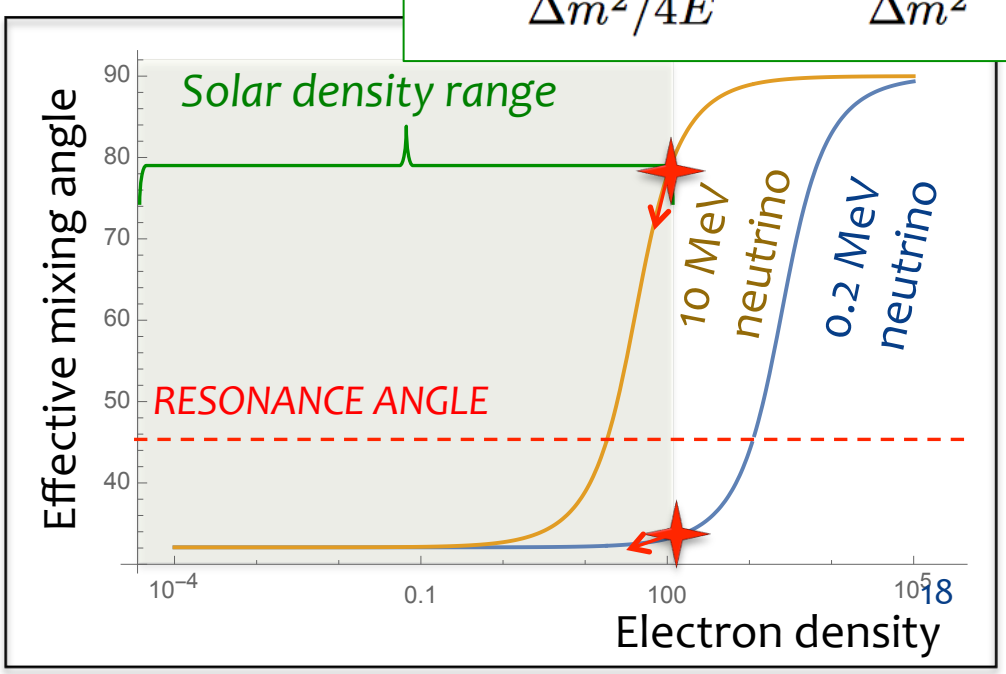
MSW resonance in the Sun

$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

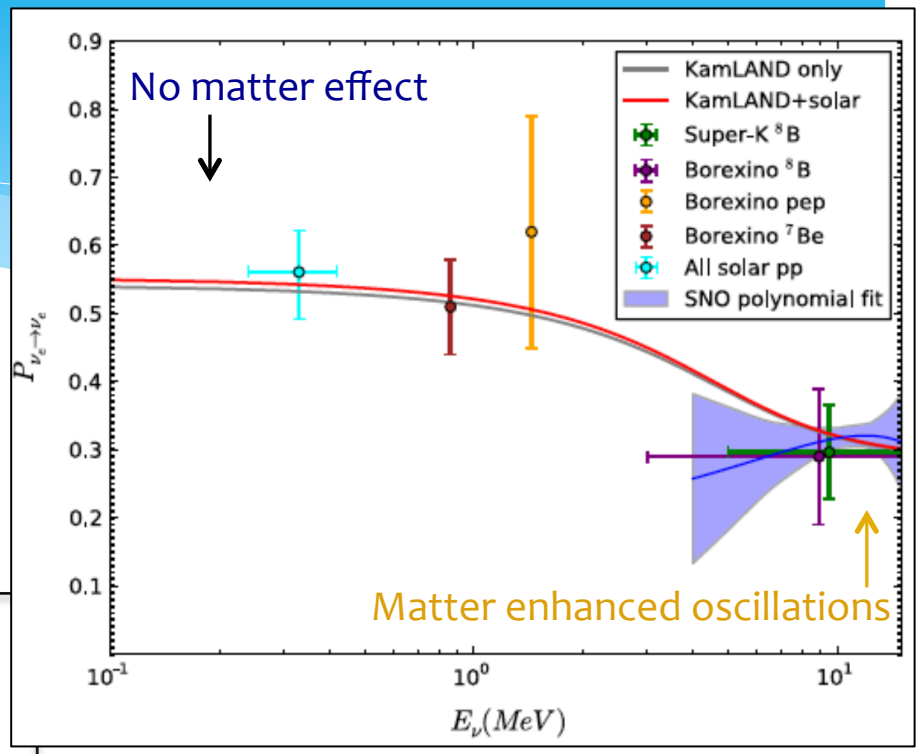
Neutrino energy

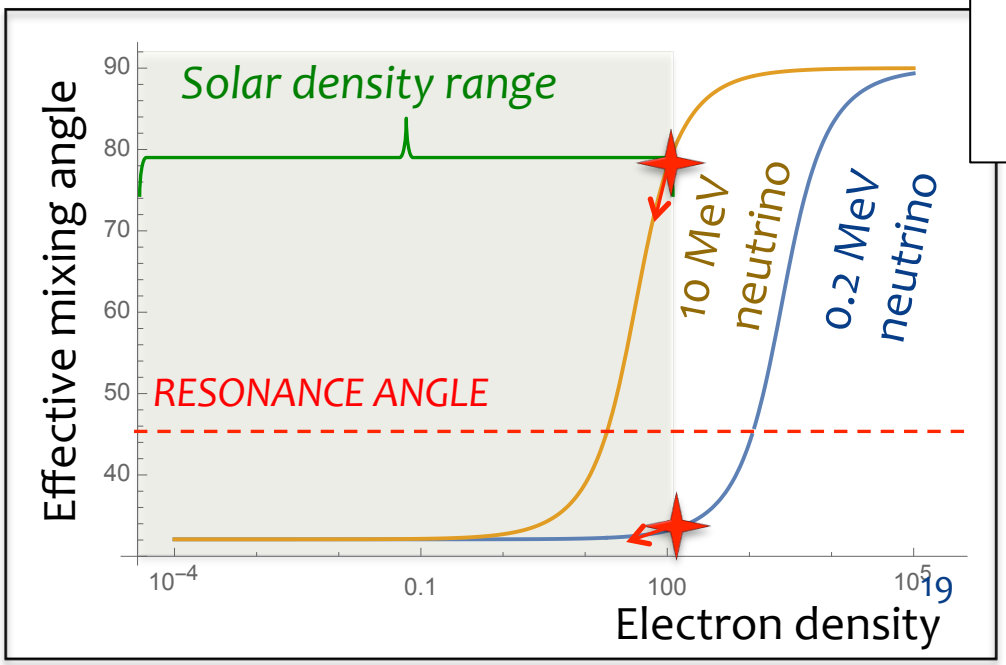
Electron density



When crossing the resonance angle (sufficiently slowly) we expect maximal flavor conversion

MSW resonance in the Sun

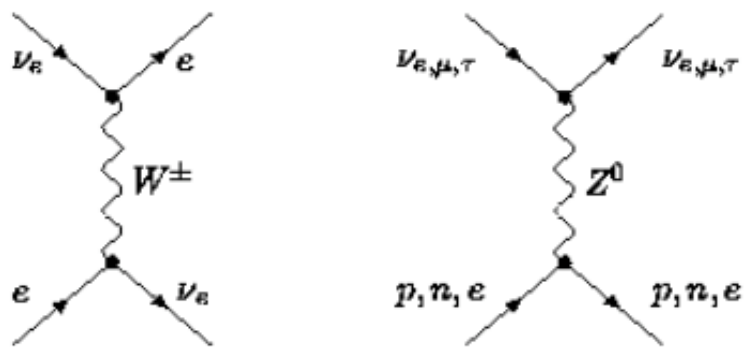




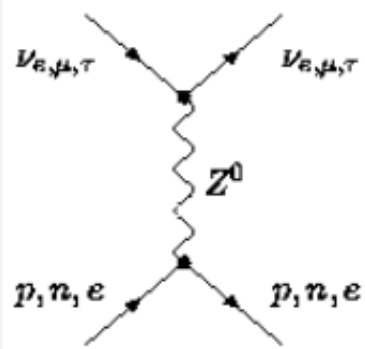
When crossing the resonance angle (sufficiently slowly) we expect maximal flavor conversion

Sterile Neutrinos in Matter

* Sterile neutrinos do not interact with matter AT ALL!
* Thus new MSW-type effects are to be expected.



Electron flavor



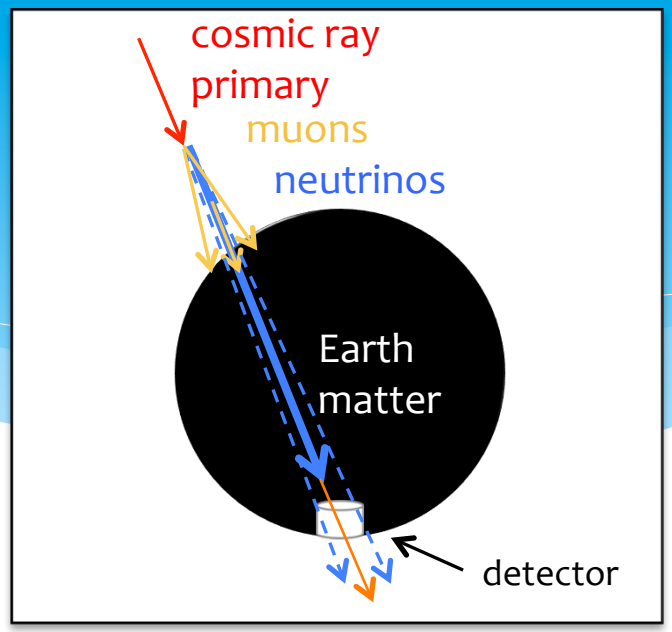
mu / tau flavor

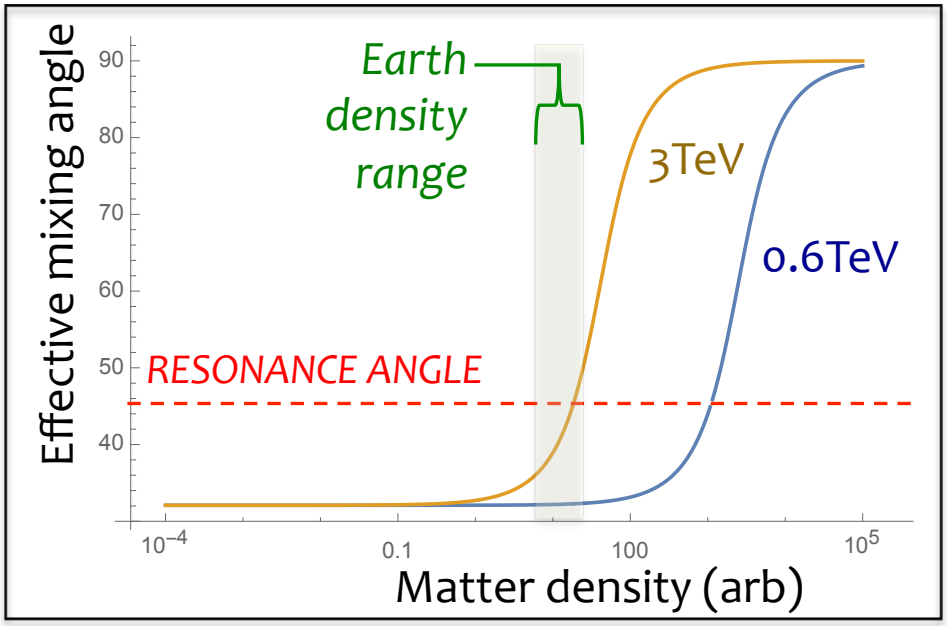
Sterile flavor

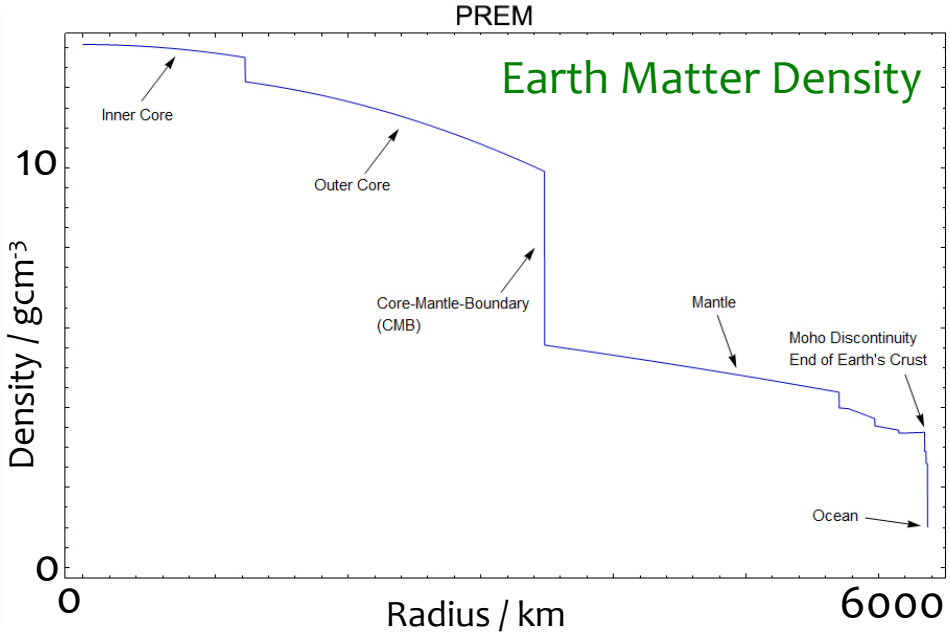
For full phenomenology : ***Esmali and Smirnov, JHEP 1312 (2013) 014***

MSW Resonant Sterile Neutrinos

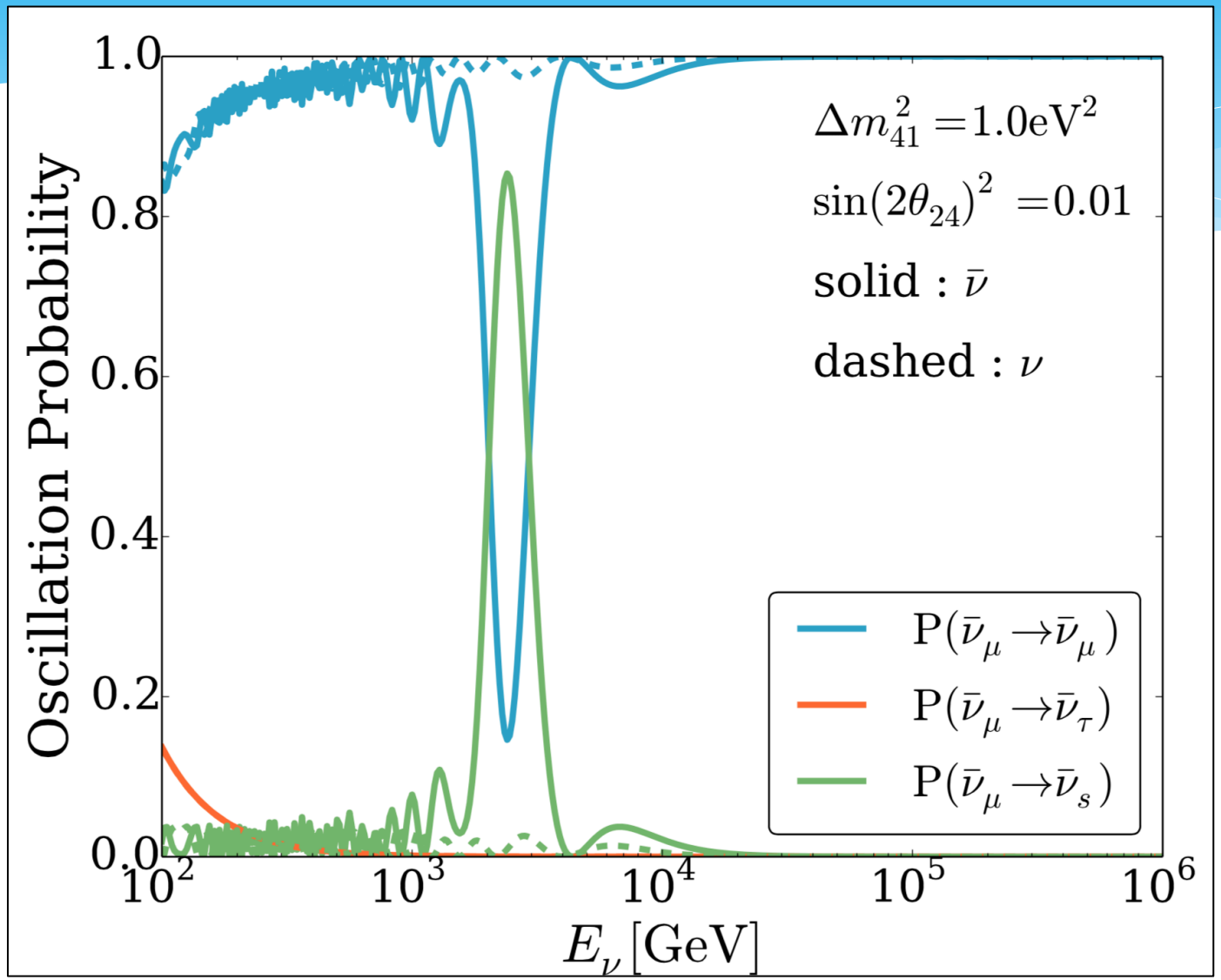
* Δm^2 too large for resonance in the Sun
* Much higher energy neutrinos and antineutrinos are produced in cosmic ray air showers
* They cross the Earth, with active species feeling the matter potential





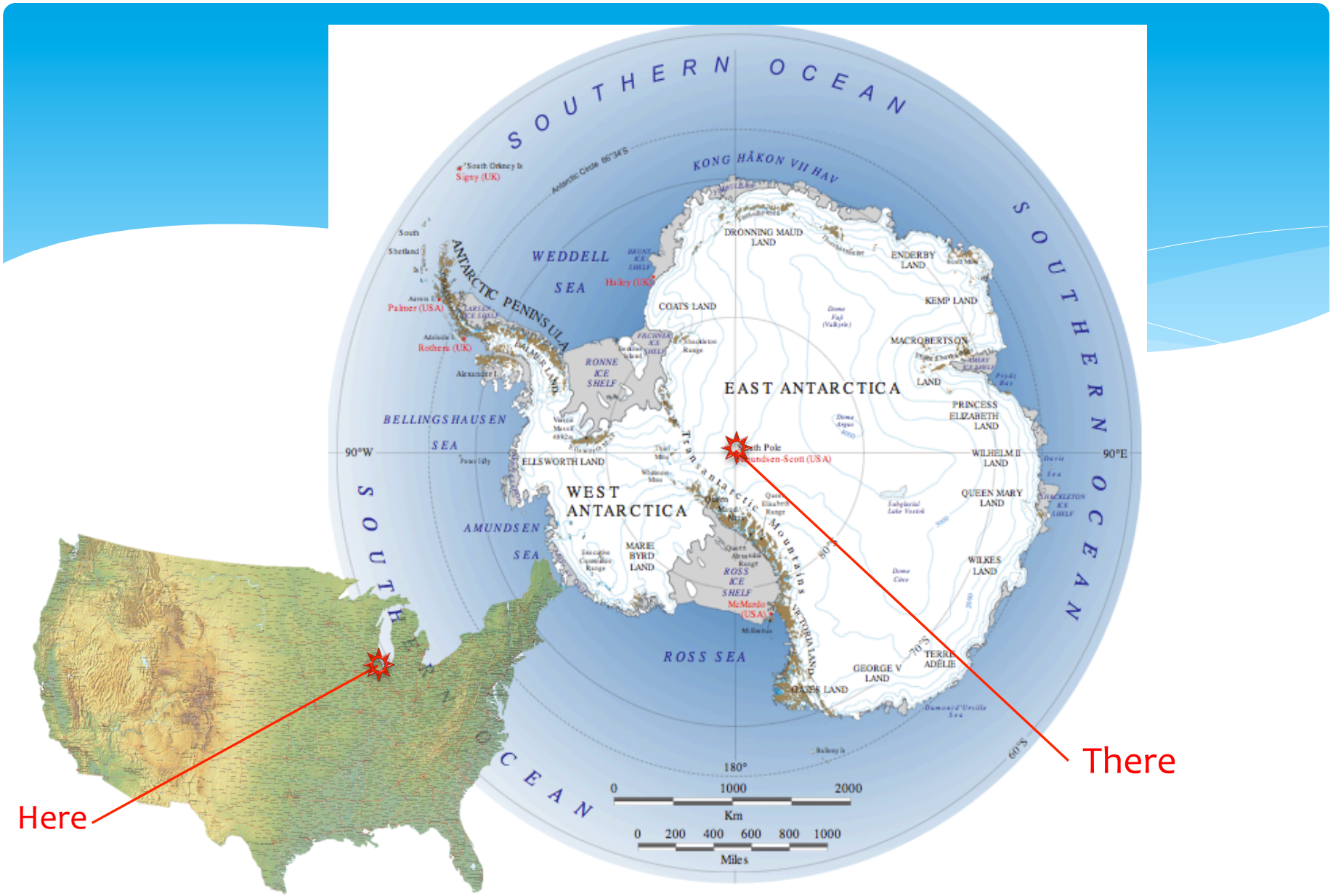


MSW Resonant Sterile Neutrinos

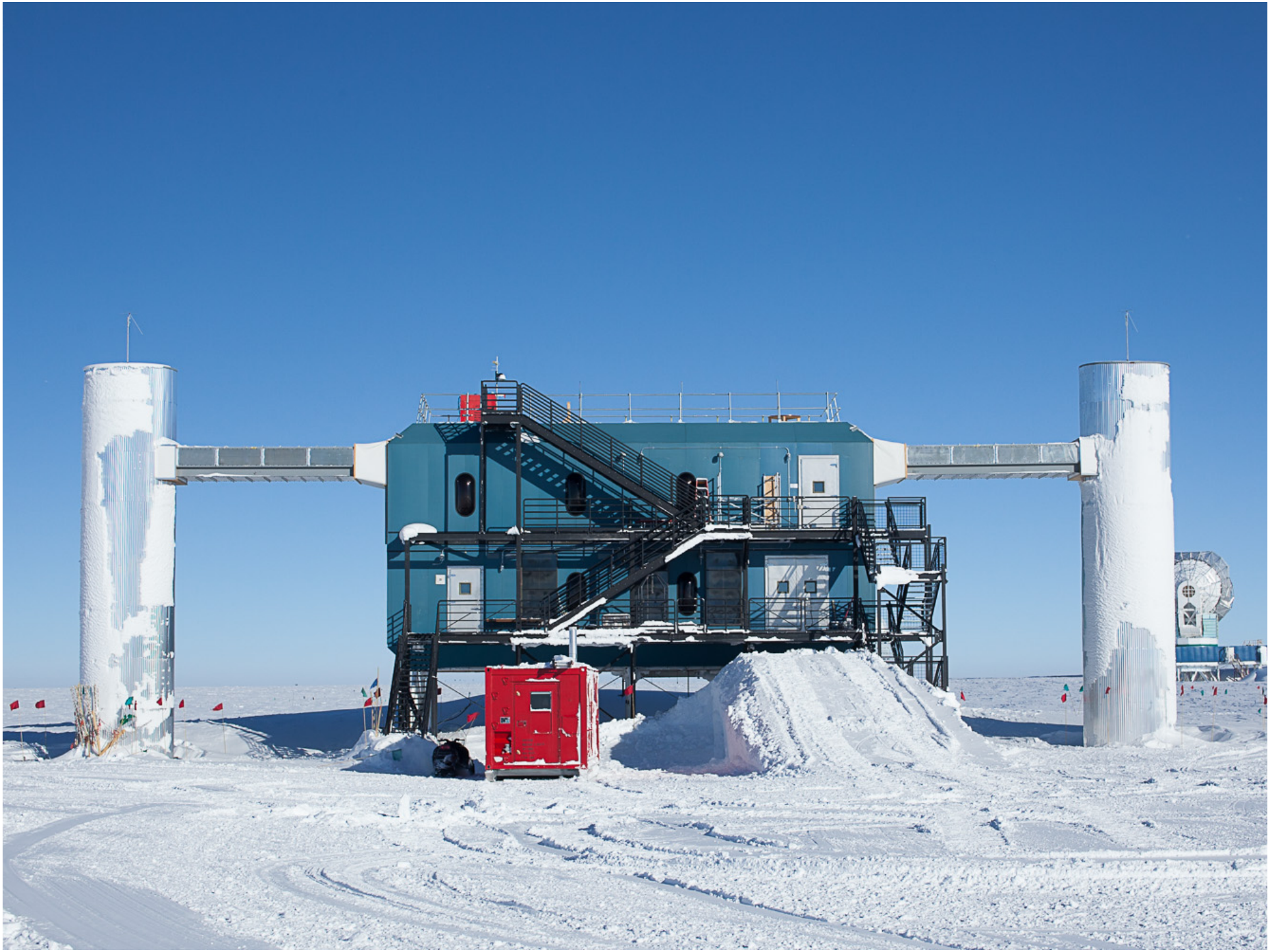


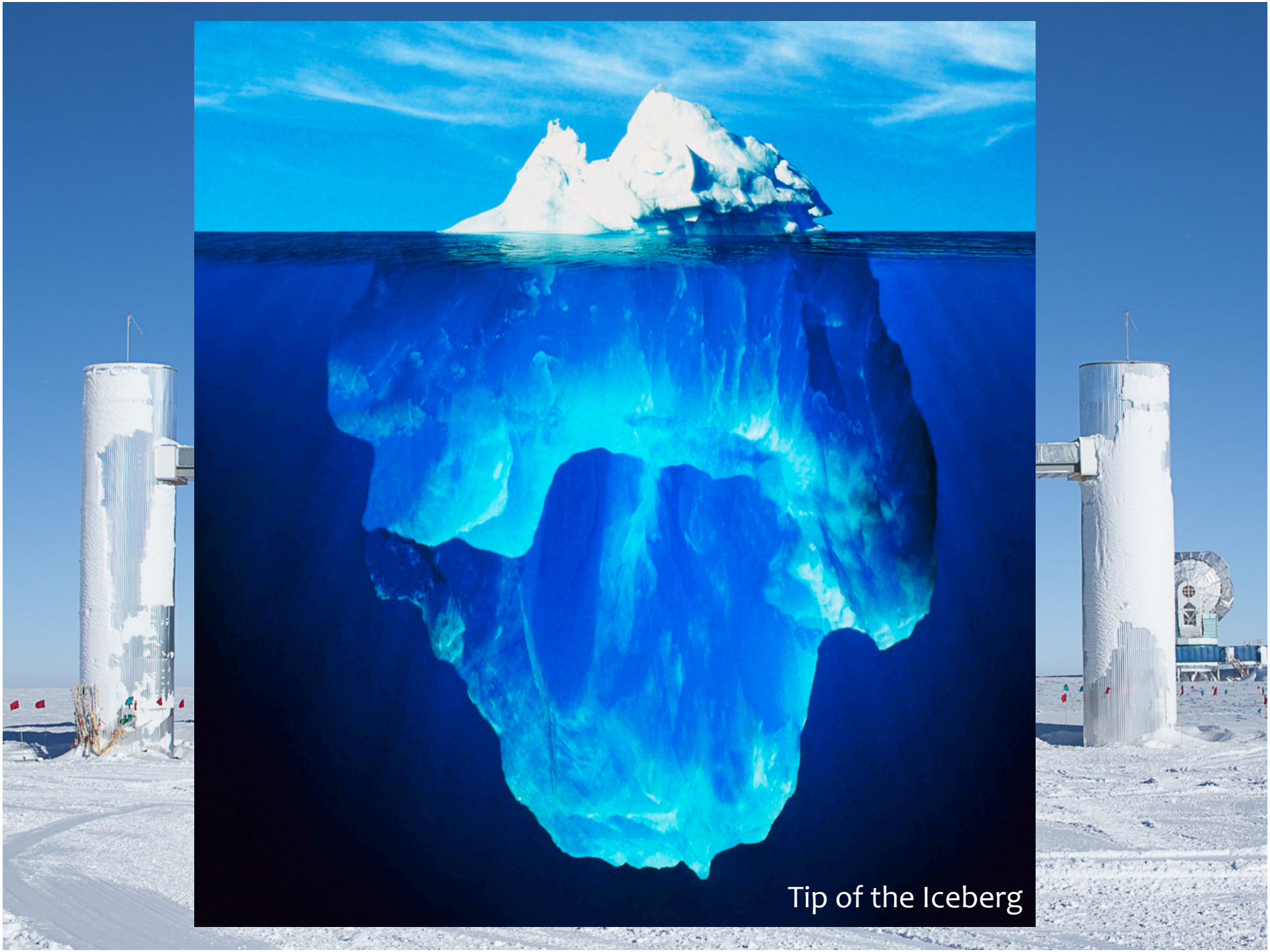
Todays Menu:

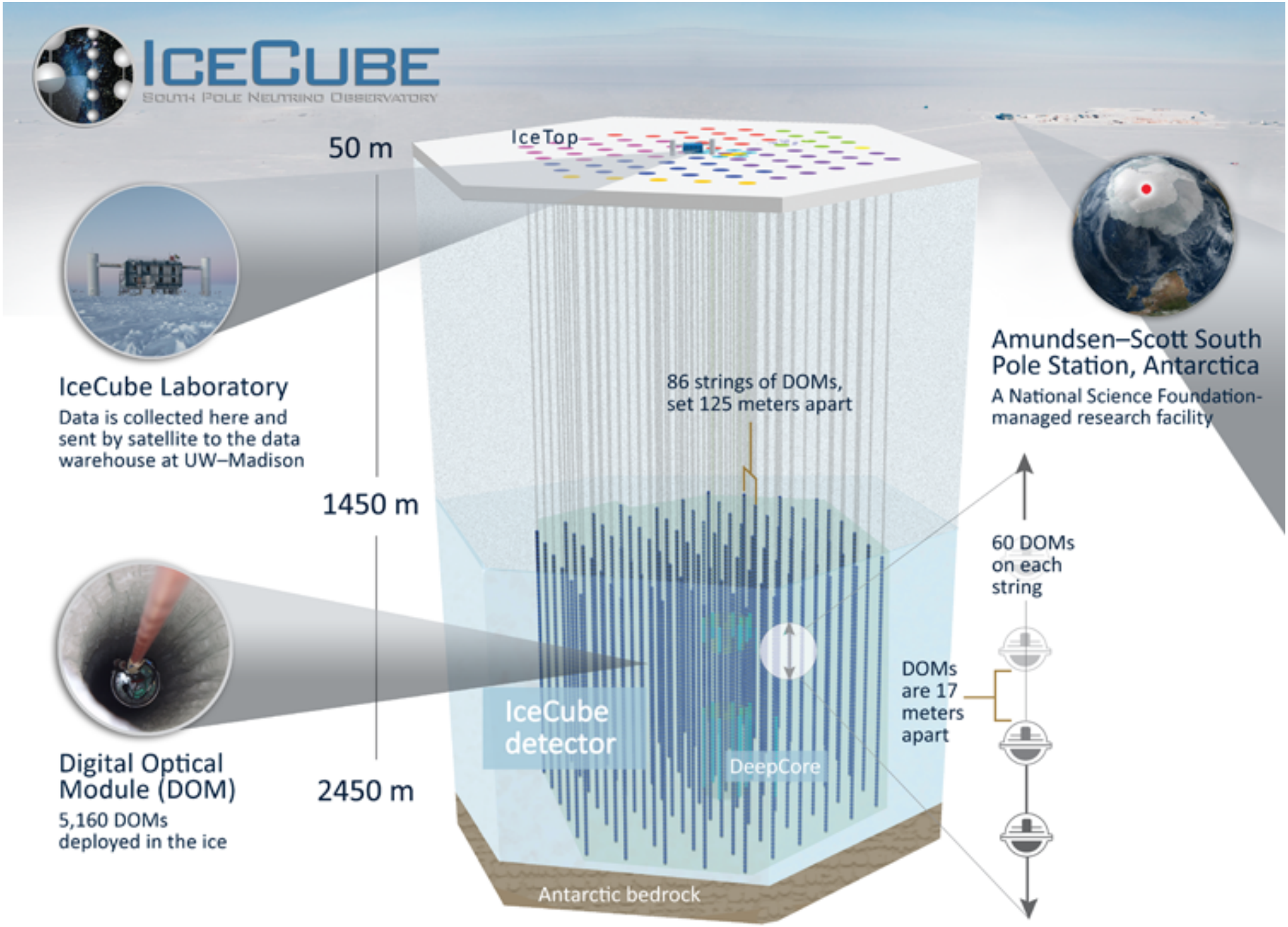
* Sterile Neutrinos and MSW Resonances
* **The IceCube Experiment**
* IceCube Sterile Neutrino Search


SOUTHERN OCEAN
KONG HÅKON VII HAV
WEDDELL SEA
ANTARCTIC PENINSULA
DRONNING MAUD LAND
ENDERBY LAND
KEMP LAND
COATS LAND
MACROBERTSON LAND
EAST ANTARCTICA
PRINCESS ELIZABETH LAND
WILHELM II LAND
QUEEN MARY LAND
WILKES LAND
TERRE ADÉLIE
GEORGE V LAND
BELLINGSHAUSEN SEA
ELLSWORTH LAND
WEST ANTARCTICA
AMUNDSEN SEA
MARIE BYRD LAND
ROSS ICE SHELF
ROSS SEA
RONNE ICE SHELF
Transantarctic Mountains
90°W
90°E
180°
0 1000 2000
Km
0 200 400 600 800 1000
Miles
Here
There

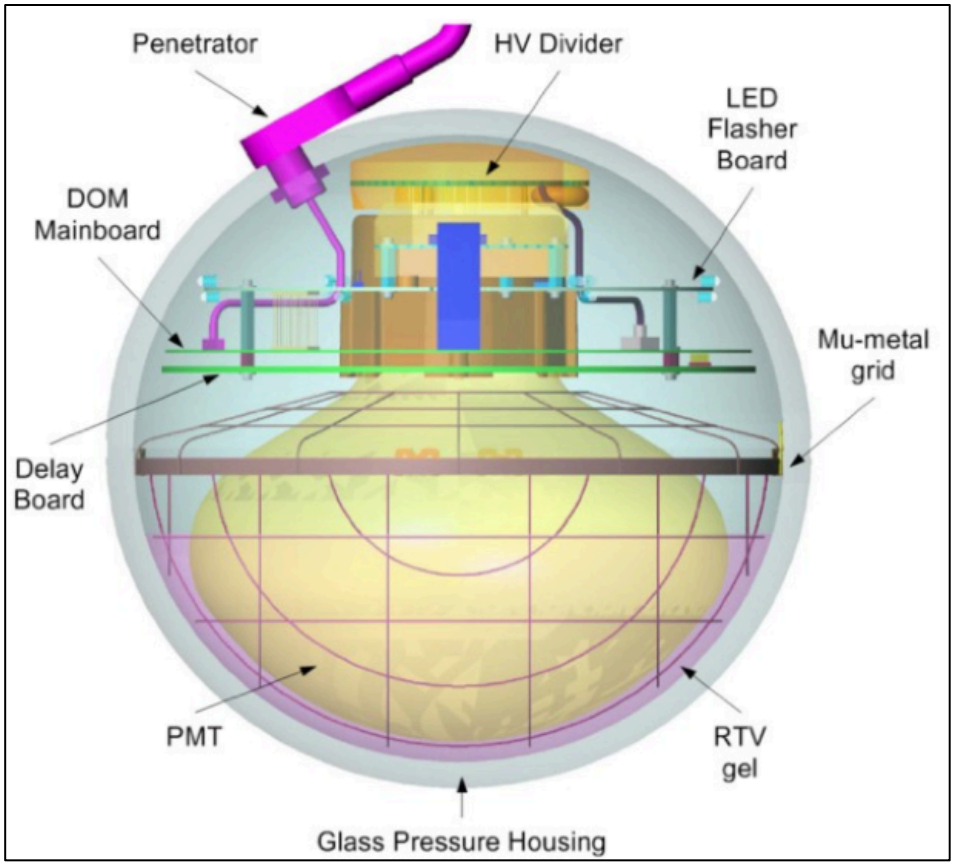
(To scale)

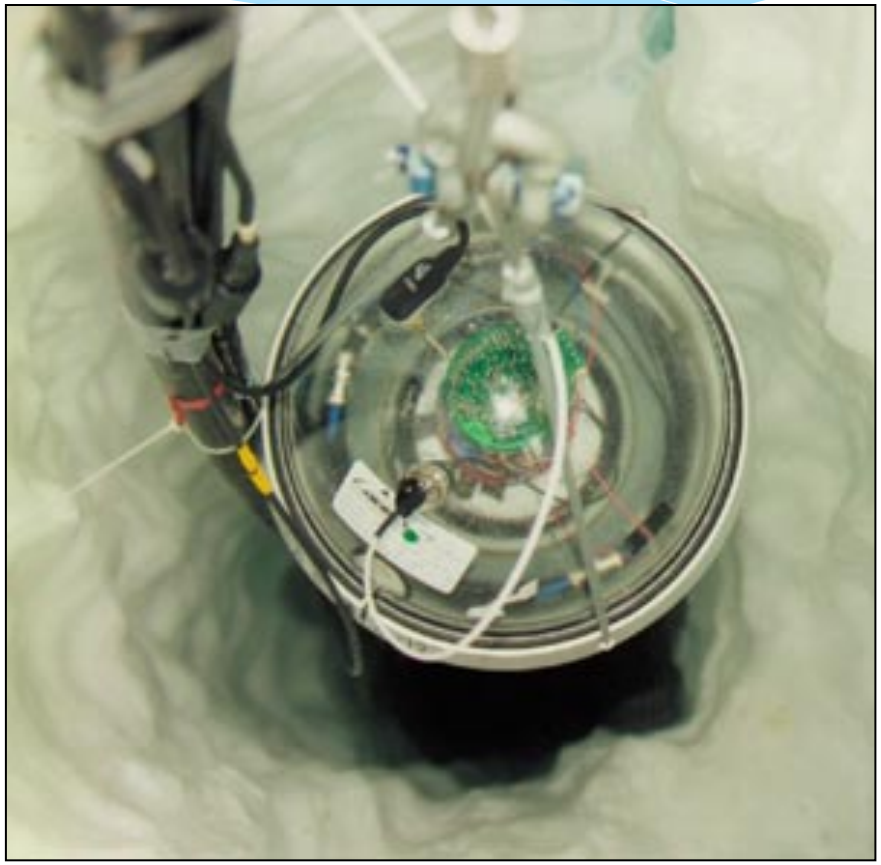



Tip of the Iceberg


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

Digital Optical Modules



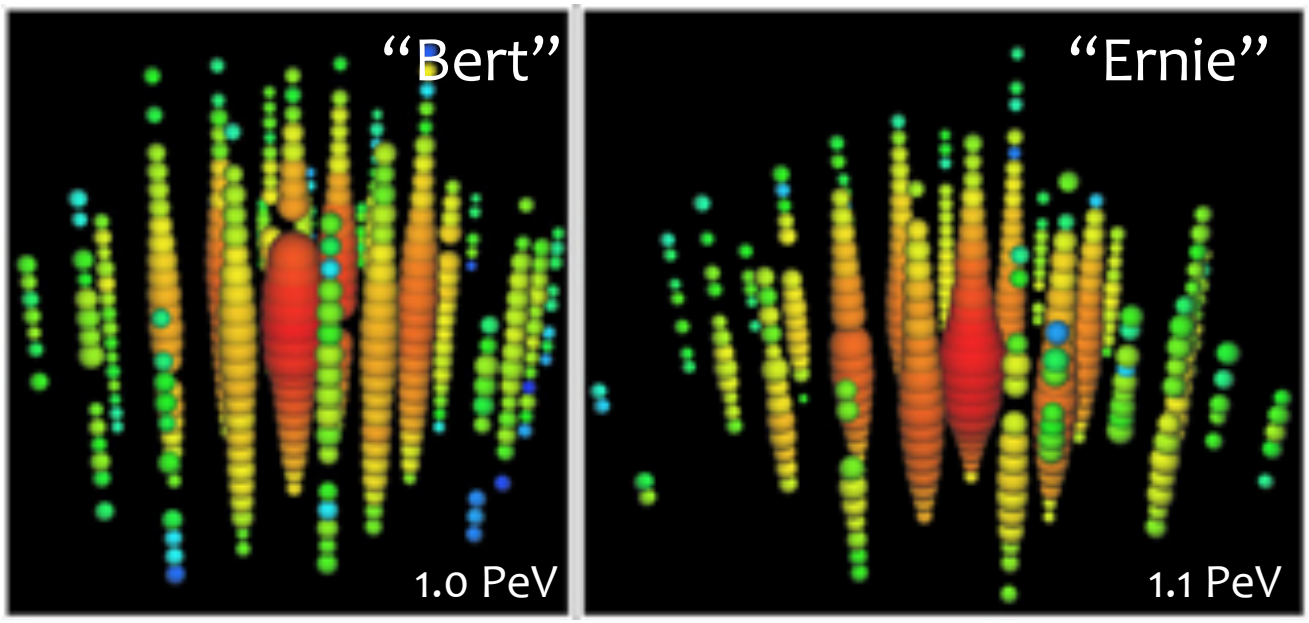


Astrophysical Neutrinos

IceCube observed the flux of ultra-high-energy astrophysical neutrinos in 2013

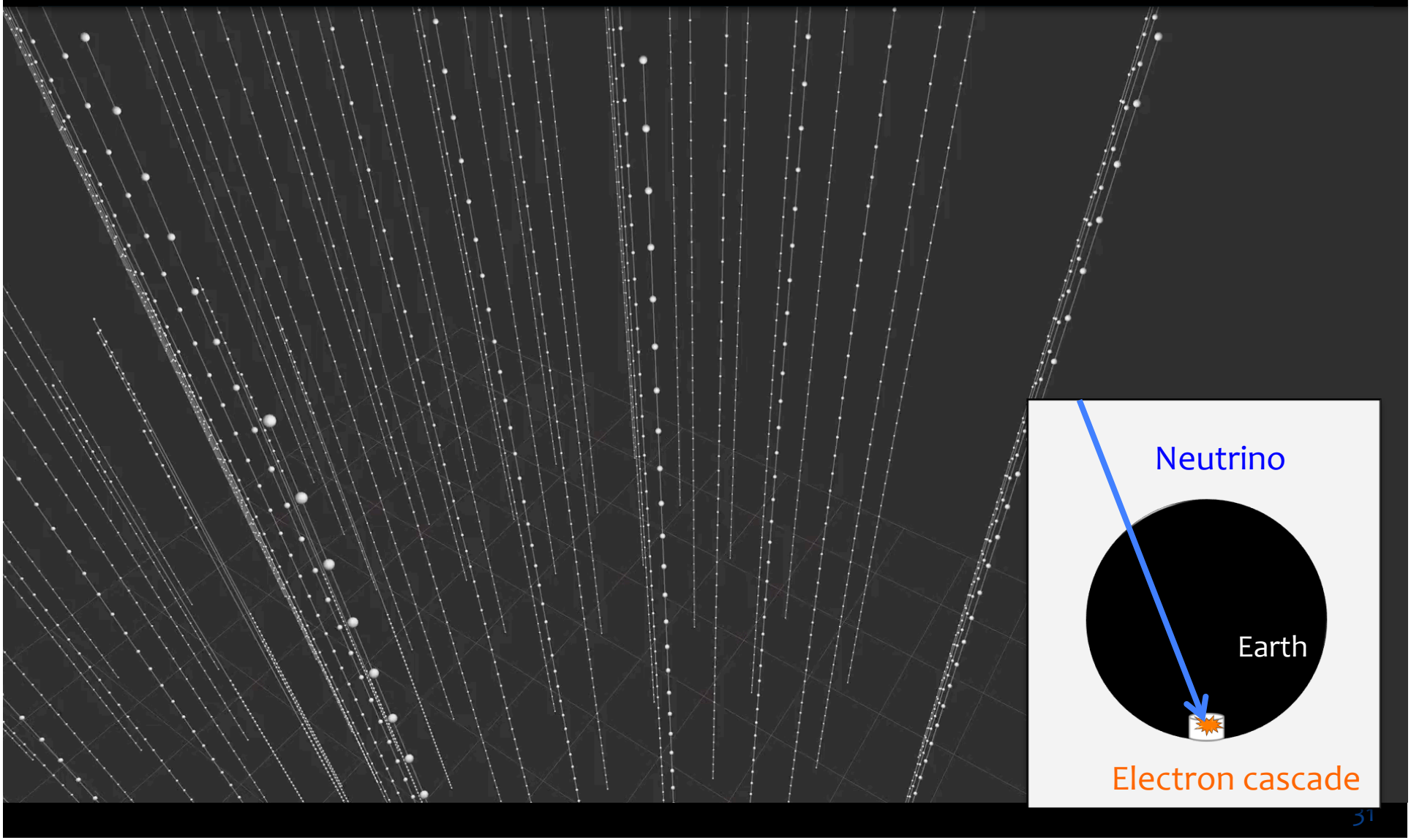
At present there are 54 astrophysical neutrino candidates

Phys.Rev.Lett. 113 (2014) 101101

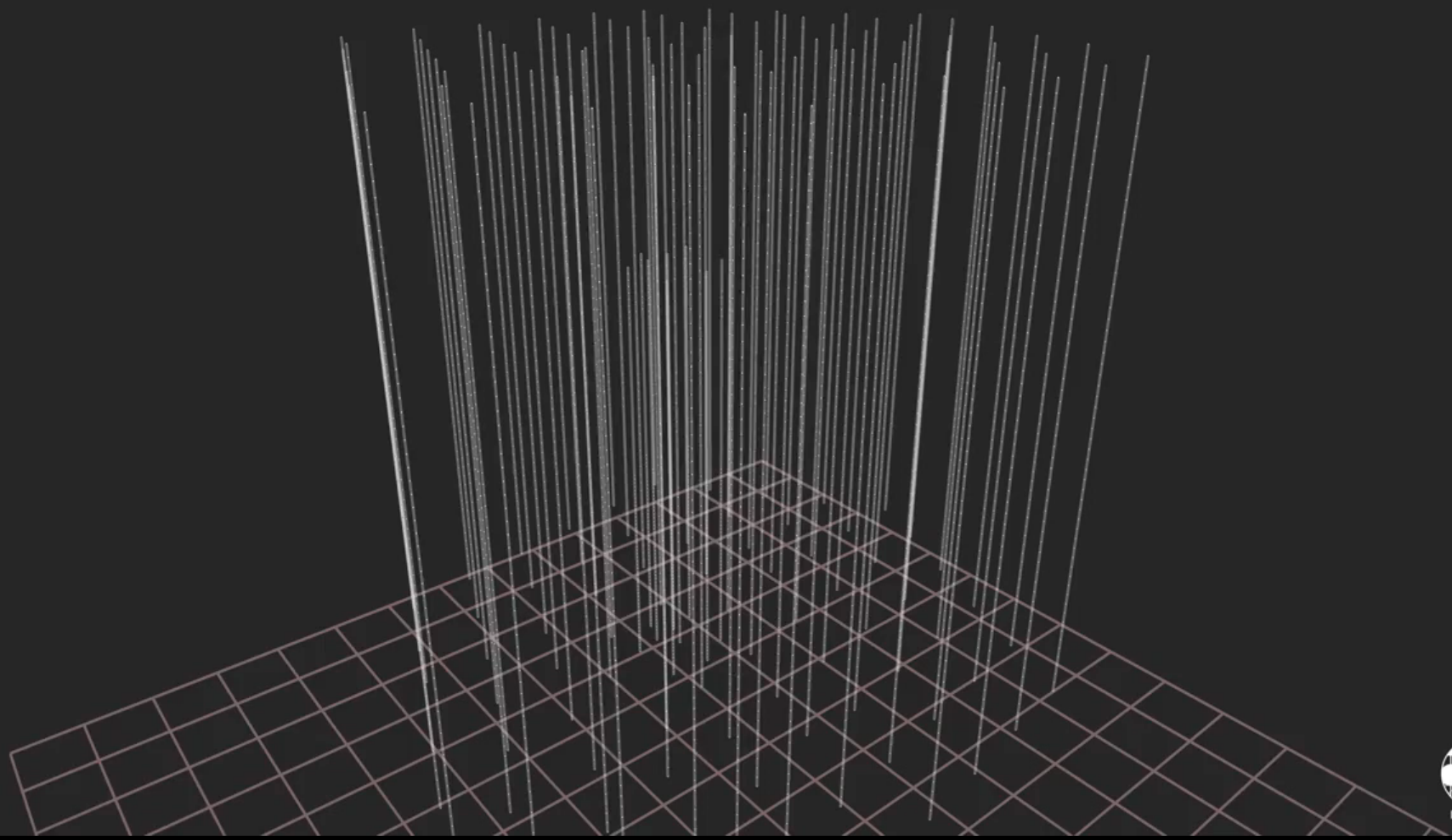


These are HESE (High Energy Starting Event) cascades

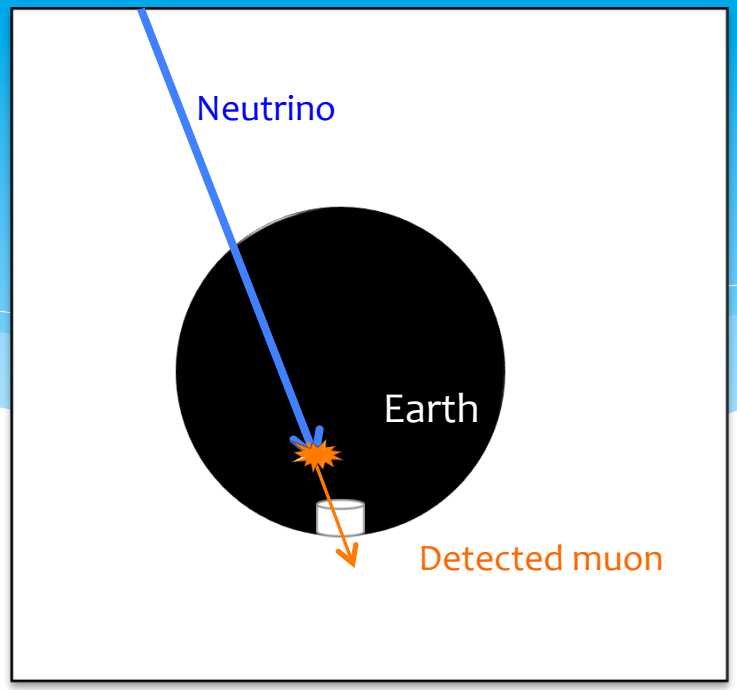
- Charged particles in IceCube emit Cerenkov light
- Ice is very transparent at Cerenkov wavelengths
- Dispersed dust particles cause Mie scattering which makes photons “diffuse”



- Photons are detected at DOMs with 125 m spacing
- On-board DAQ digitizes the pulse and sends digital data to ICL at surface
- Space and time information provide event geometry and direction

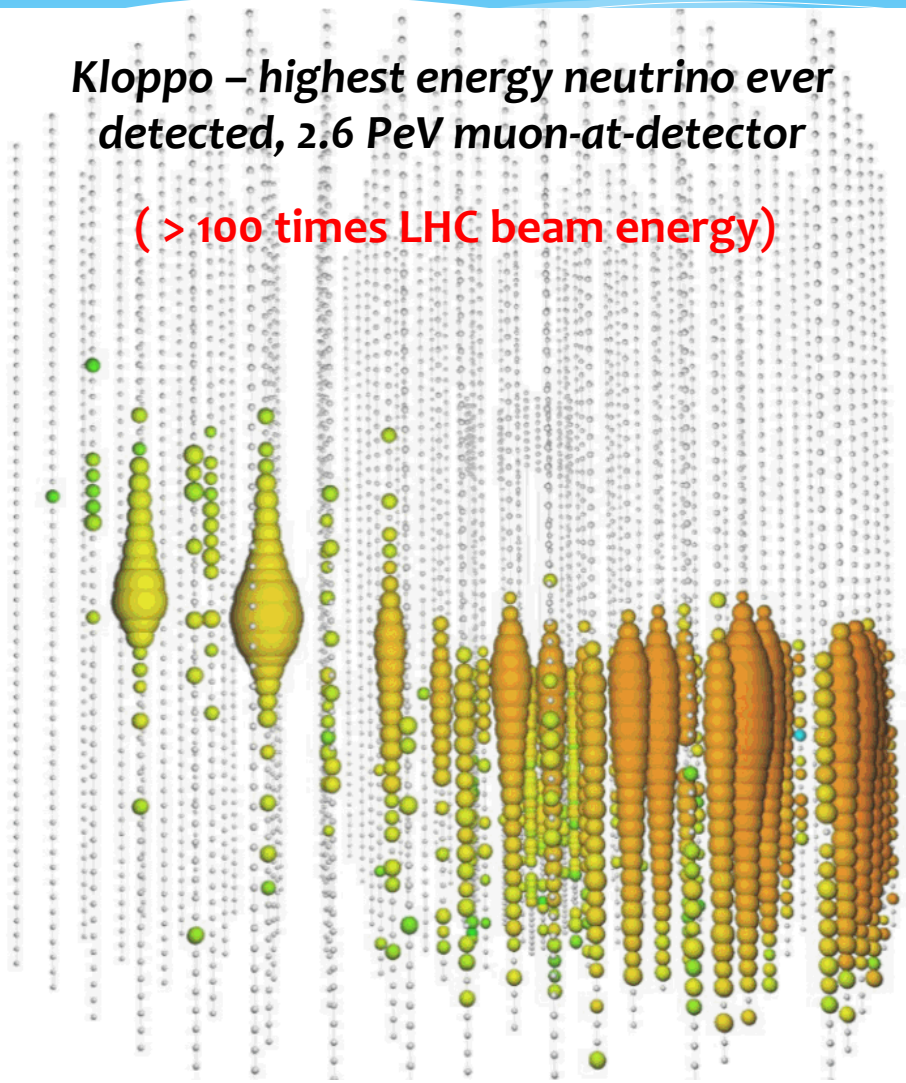


ν_μ detection in IceCube

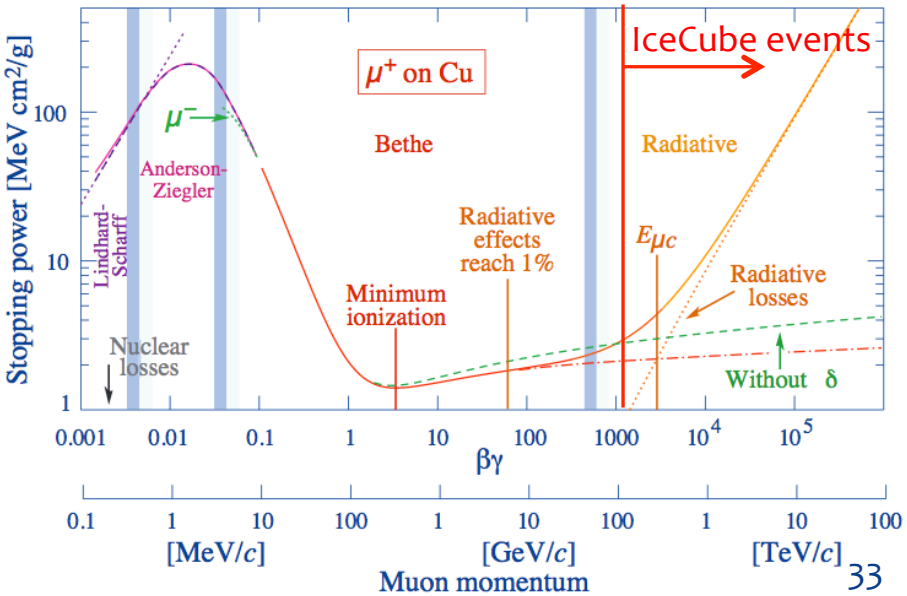


Kloppo – highest energy neutrino ever detected, 2.6 PeV muon-at-detector

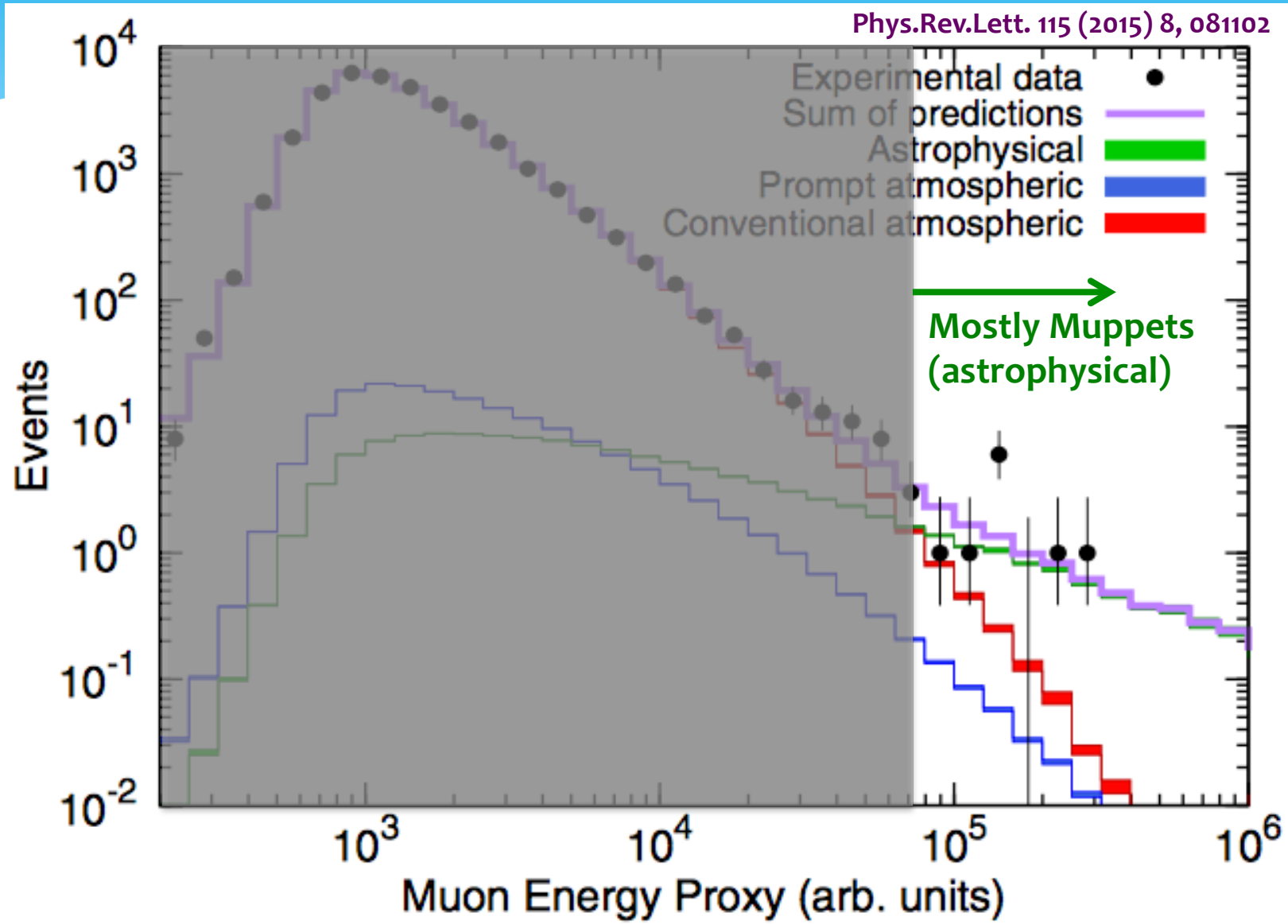
(> 100 times LHC beam energy)



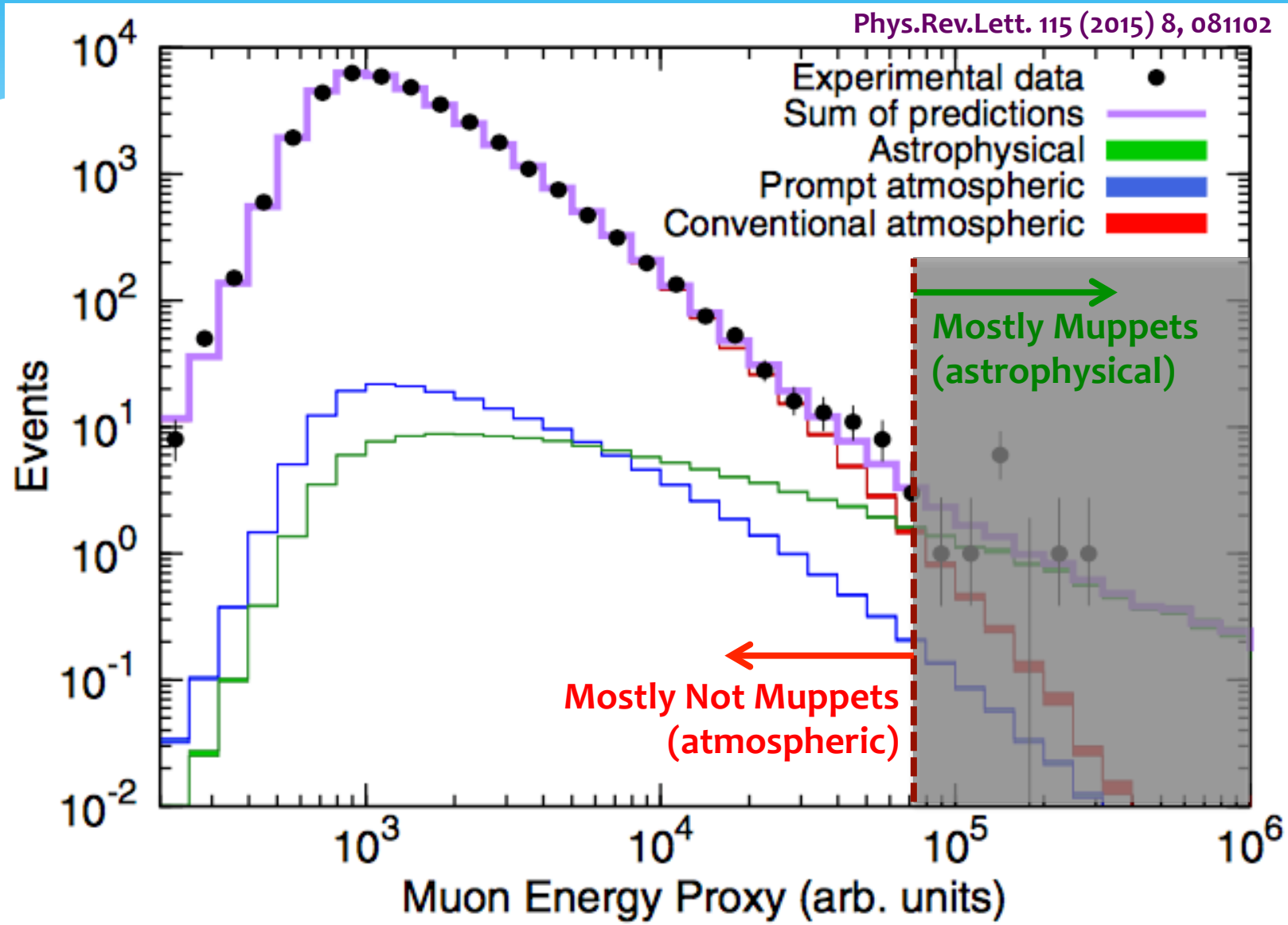
(Muon enegry losses are stochastic in this energy regime)



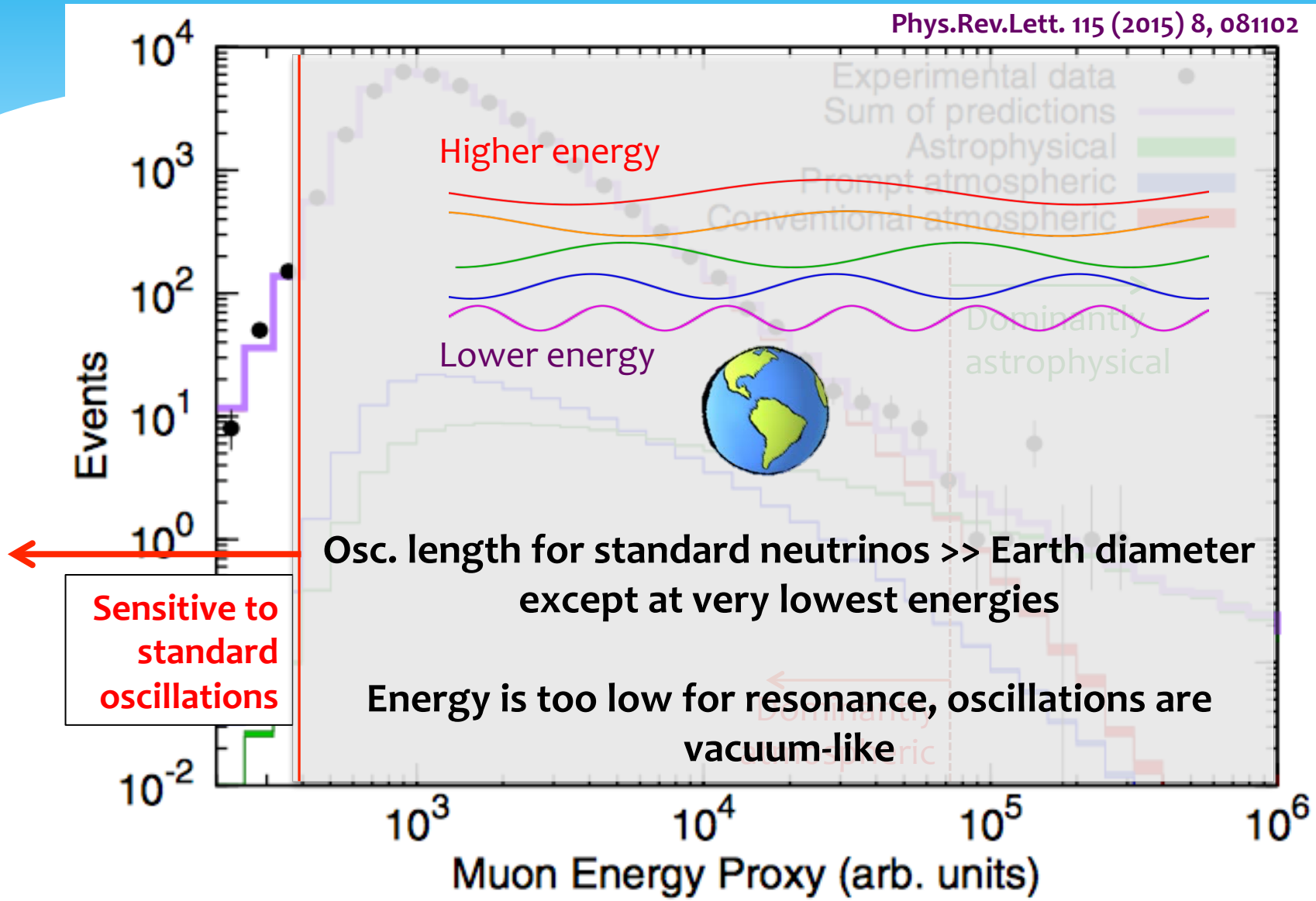
The Muppet Muons



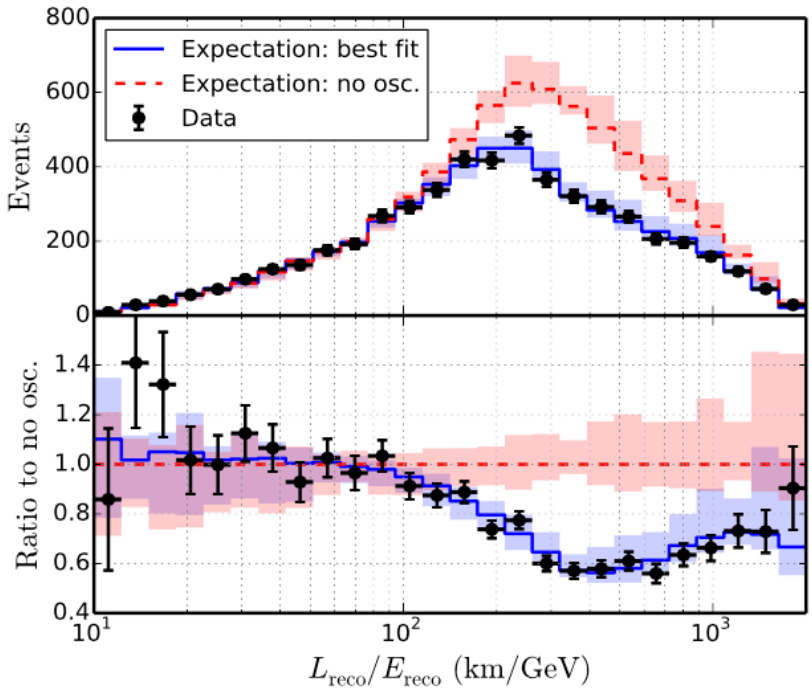
The Non-Muppet Muons

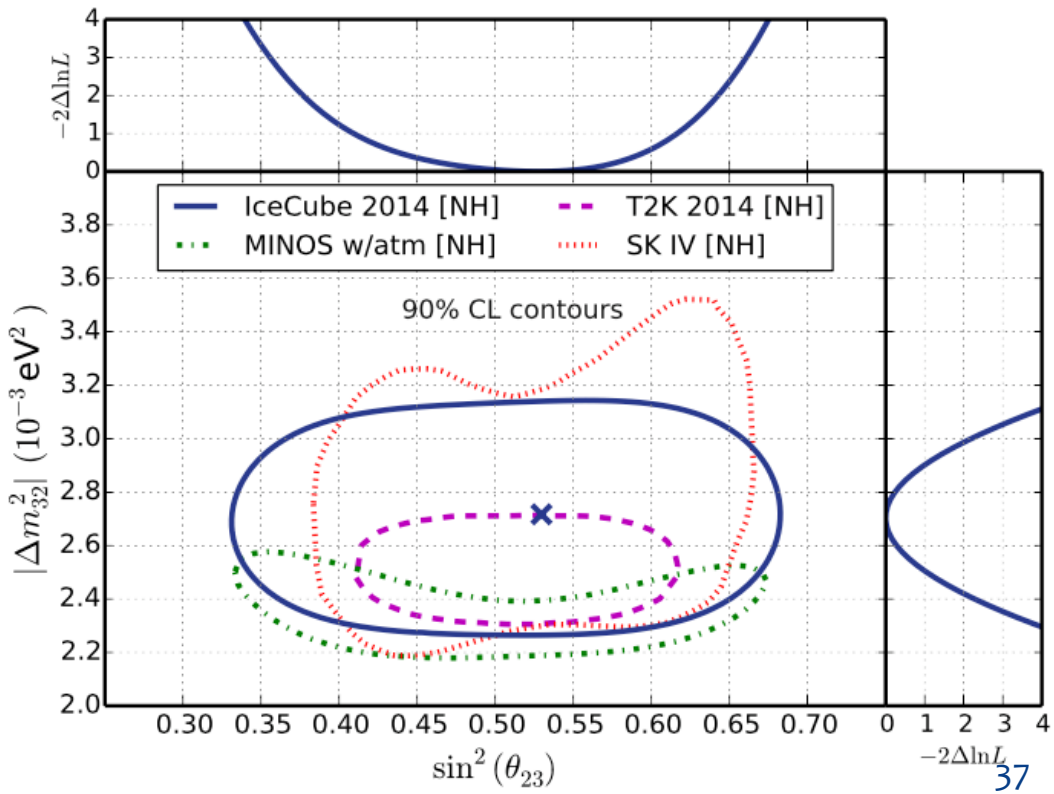


Where are the standard oscillations?



IceCube Standard Oscillation Result





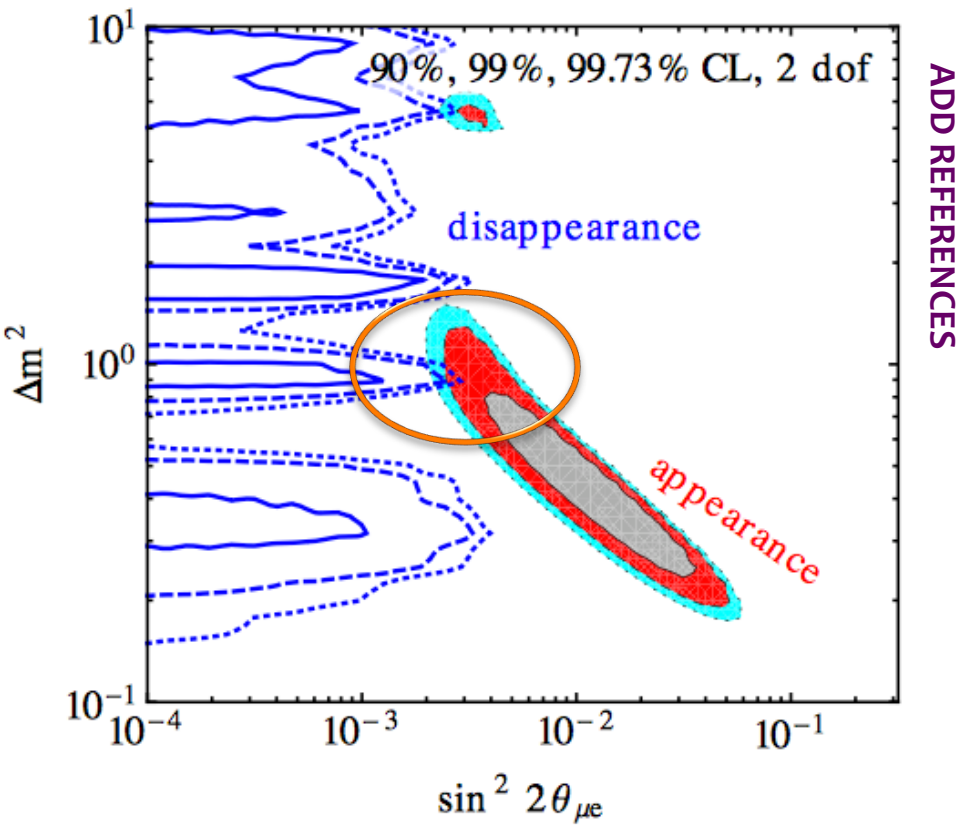
Phys.Rev.Lett. 111 (2013) 8, 081801

Todays Menu:

* Sterile Neutrinos and MSW Resonances
* The IceCube Experiment
* **IceCube Sterile Neutrino Search**

Where might there be sterile neutrino oscillations?

Island allowed by both appearance and disappearance expts is around Δm^2 = 1eV2



ADD REFERENCES

MSW resonance occurs at:

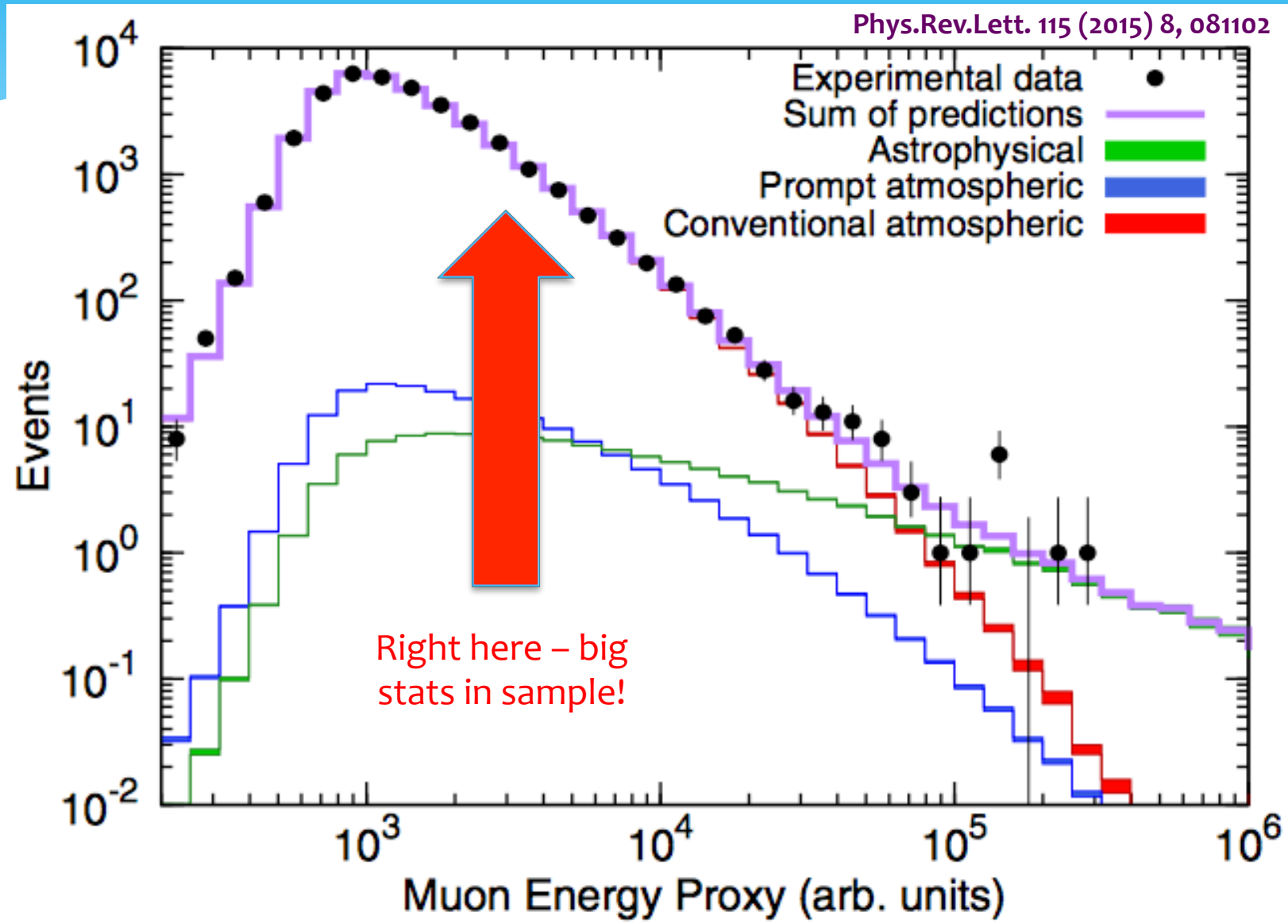
$$E_{res} = \frac{\Delta m^2 cos2\theta}{\sqrt{2} G_F N_e}$$

For Δm^2=1 eV^2 and Earth matter density:

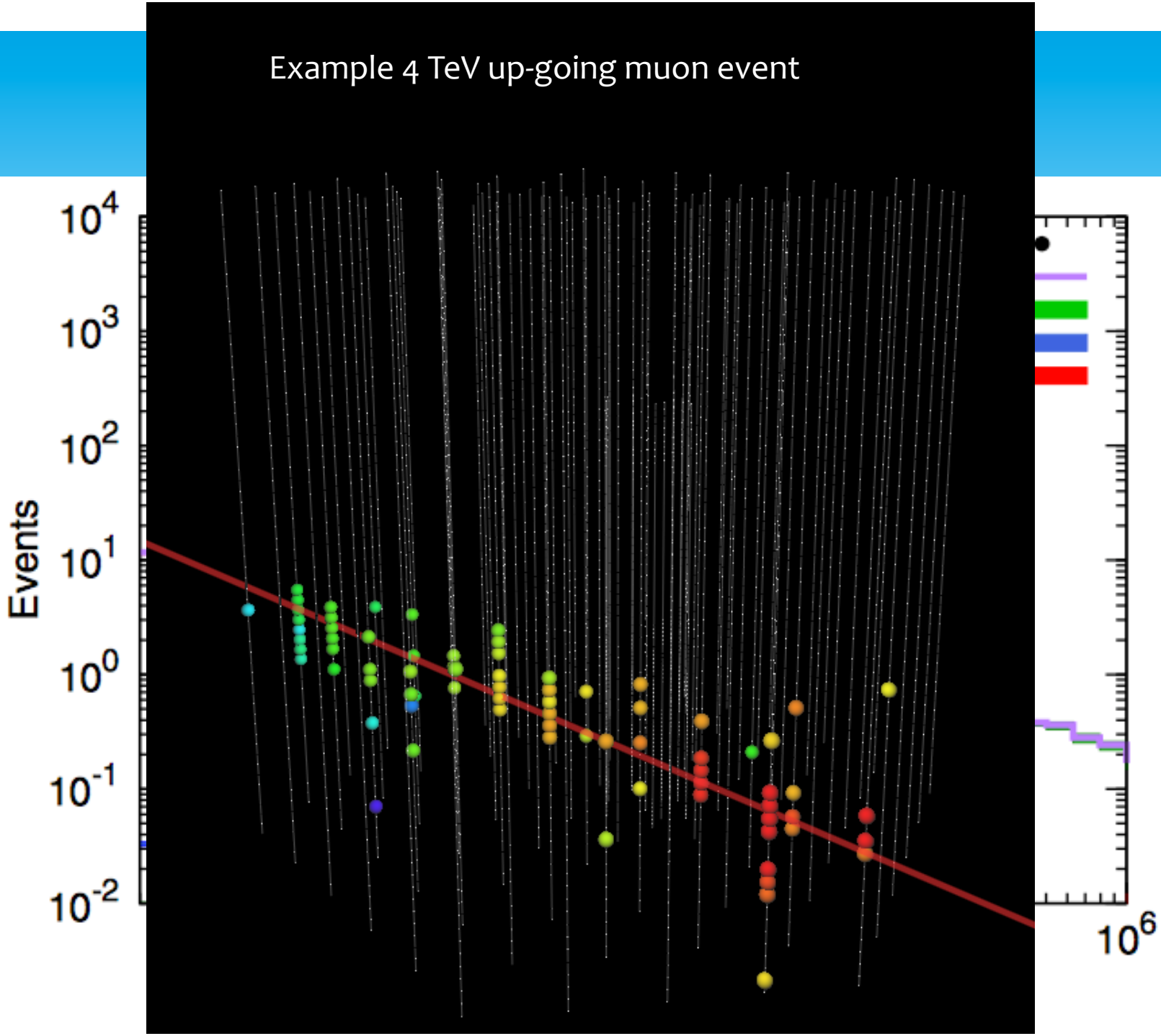
E_{crit} = 3 TeV

Resonance energy:

Sensitive to standard oscillations



Example 4 TeV up-going muon event

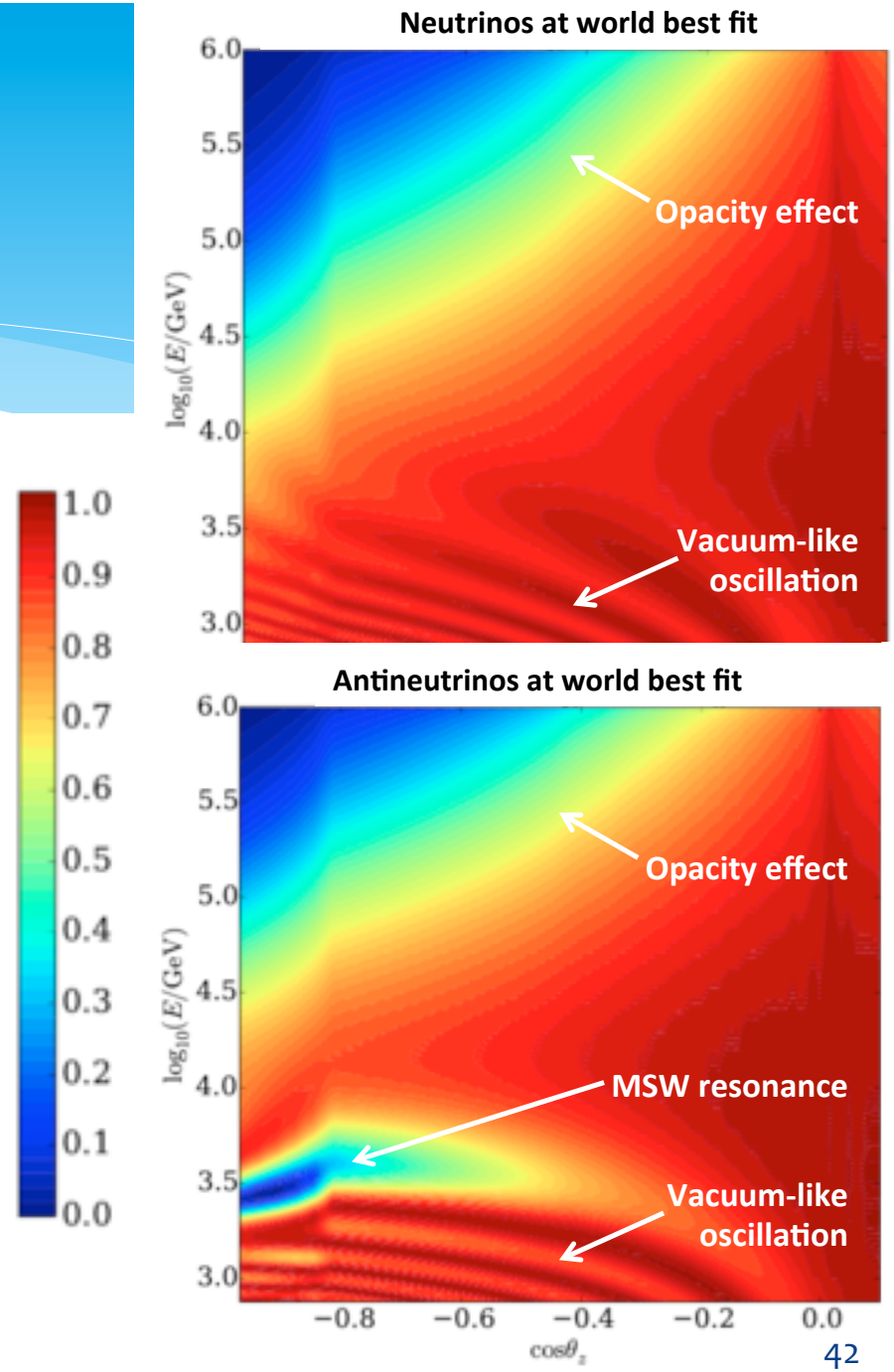


Predicting the MSW oscillation

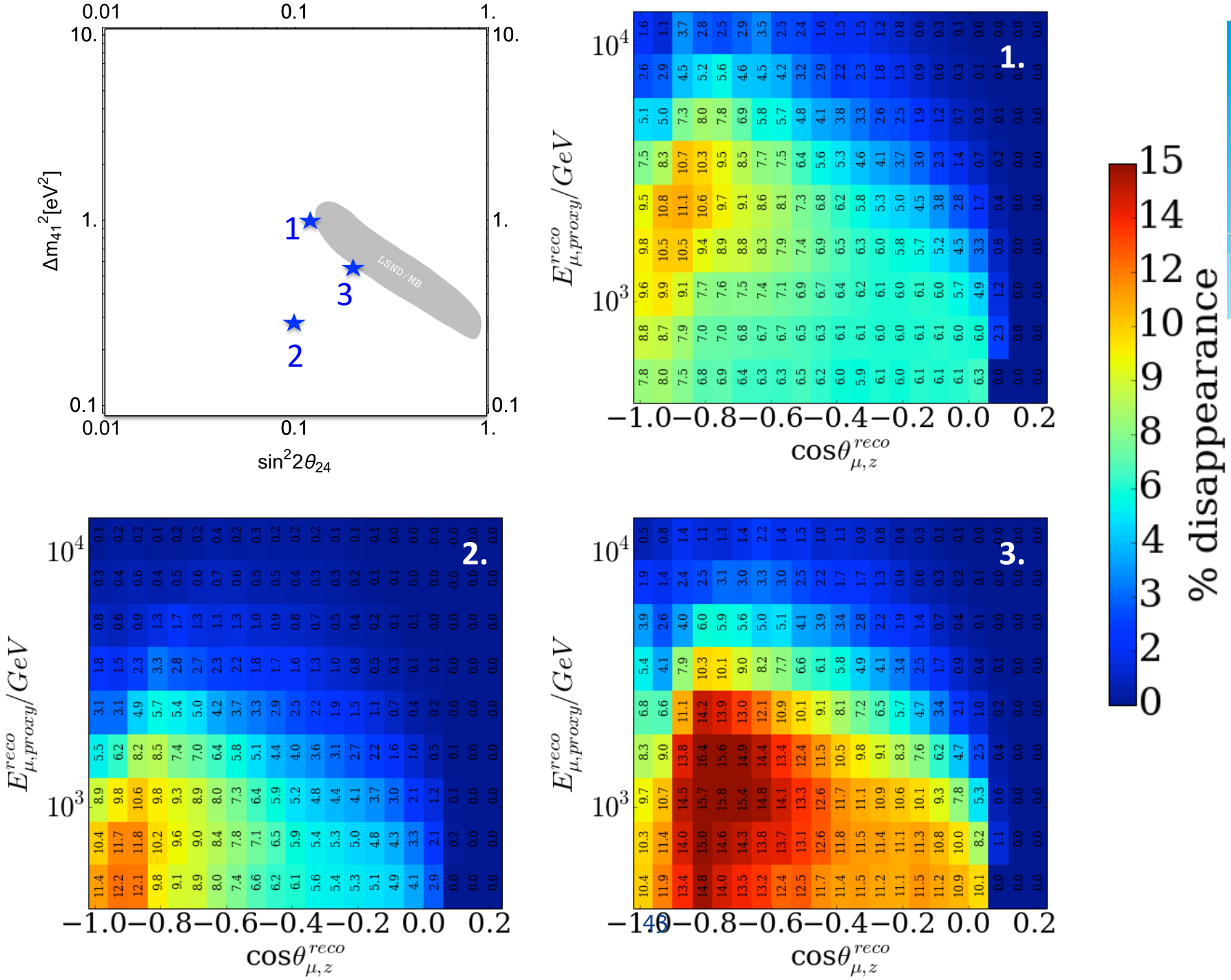
At these energies, have refractive (MSW) phenomena, and also significant incoherent scatter cross section.

Have to include both effects to predict survival probability - and they are non-trivially coupled

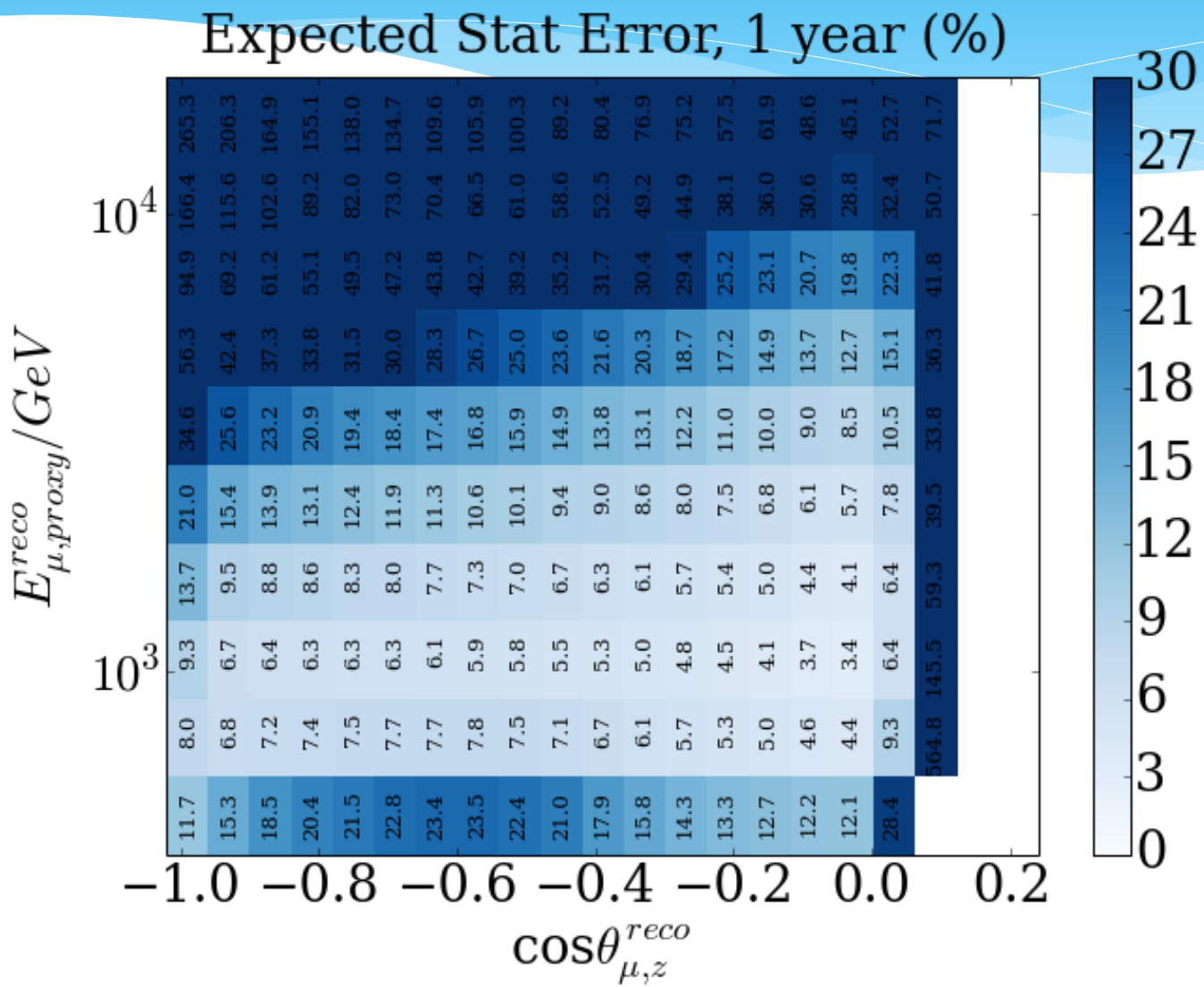
→ **numerically solve flavor evolution master equation through Earth density profile for truth-level oscillation solution.**



nuSQuIDs:
https://github.com/arguelles/nuSQuIDS


0.01
0.1
1.
10.
$\Delta m_{41}^2 [eV^2]$
$\sin^2 2\theta_{24}$
1
2
3
LSND / MB
1.
2.
3.
$E^{reco}_{\mu,proxy}/GeV$
$\cos\theta^{reco}_{\mu,z}$
% disappearance
0
2
3
4
6
8
9
10
12
14
15

Expected Stat Uncertainty per Bin



Continuous parameter	Central value	Gaussian prior width
normalization	1	no prior[1]
DOM Efficiency	0.99	no prior
cosmic ray spectral shift	0	0.05
π/K ratio	1	0.1
$\nu/\bar{\nu}$ ratio	1	0.025
atmospheric density shift	0	tuned per-model

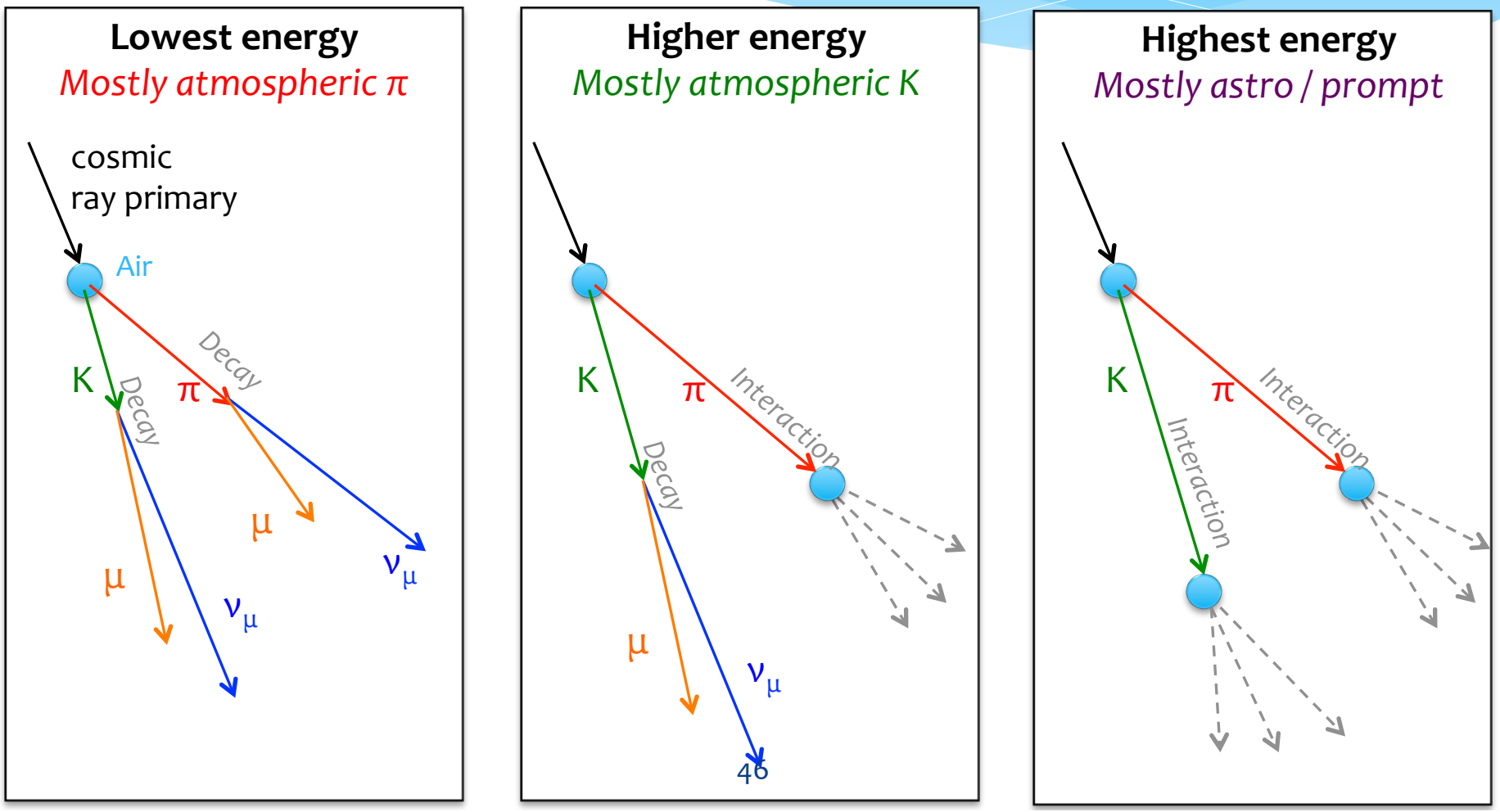
Table 4.1: Continuous nuisance parameters used in the fit

Sources of systematic uncertainty

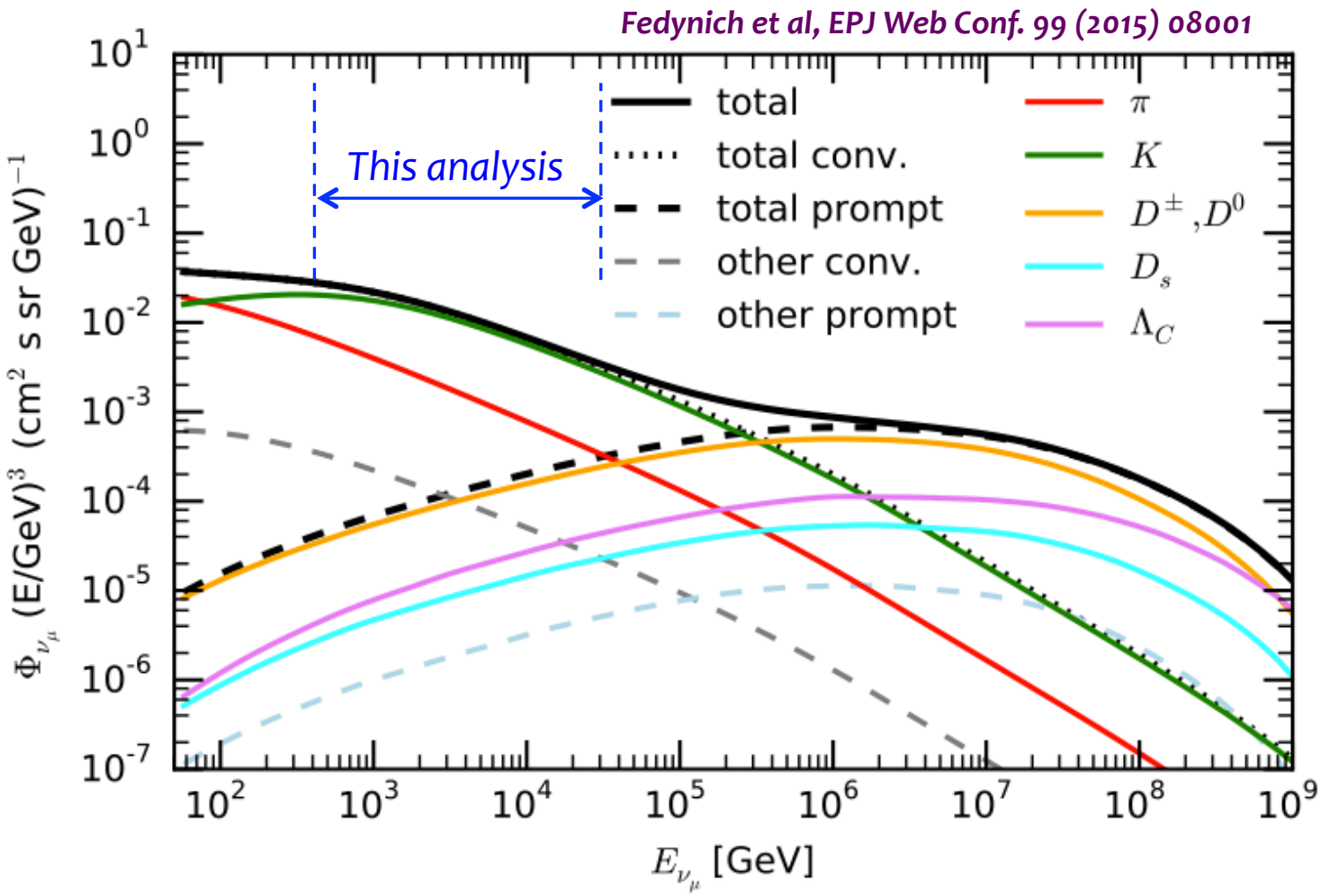
Discrete variant	Variant numbers
Central model *SPICEMie, PREM, HERAPDF*	0
Ice absorption +10%	1
Ice scattering +10%	2
SPICELea	3
No hole ice effect	4
Flux variants	5-10
Cross section variants	11-15
Earth model variants	16-24

Table 4.2: Discrete simulation sets compared for maximum likelihood

Production of Atmospheric Neutrinos



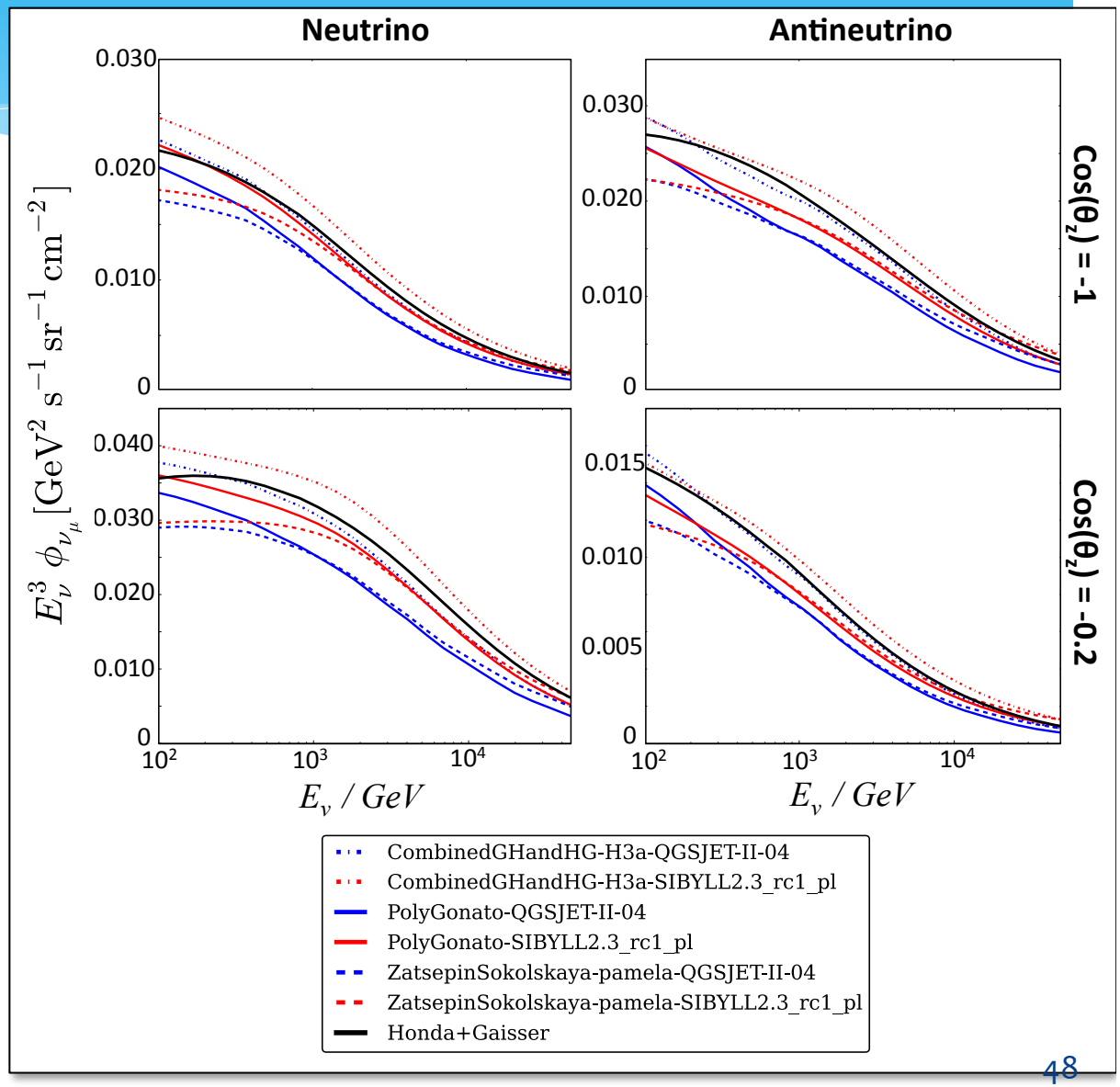
Atmospheric Flux Predictions



In our analyses, pi/K production ratio, spectral slope, nu/nubar ratio are all nuisance parameters with priors derived from published models

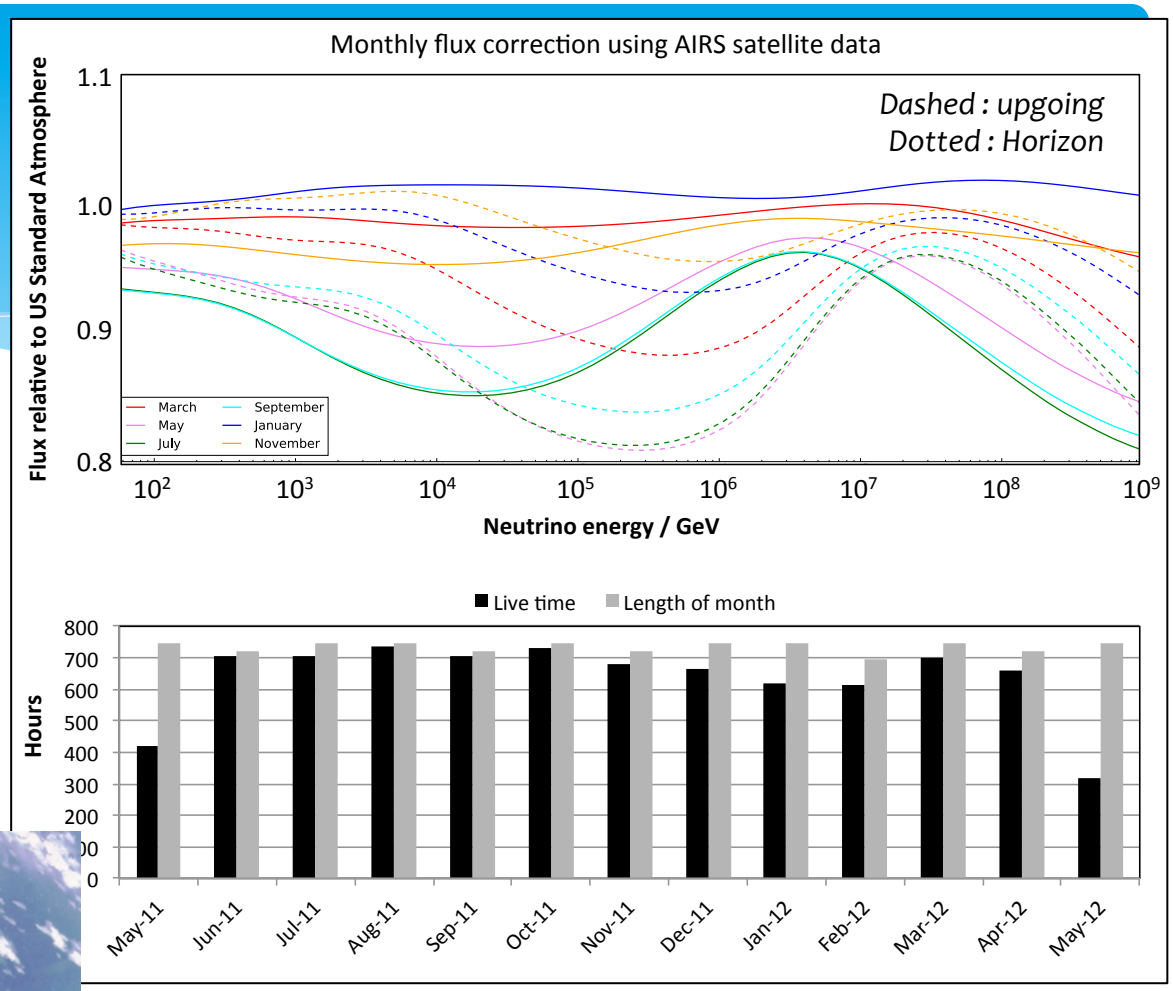
Uncertainties in Flux

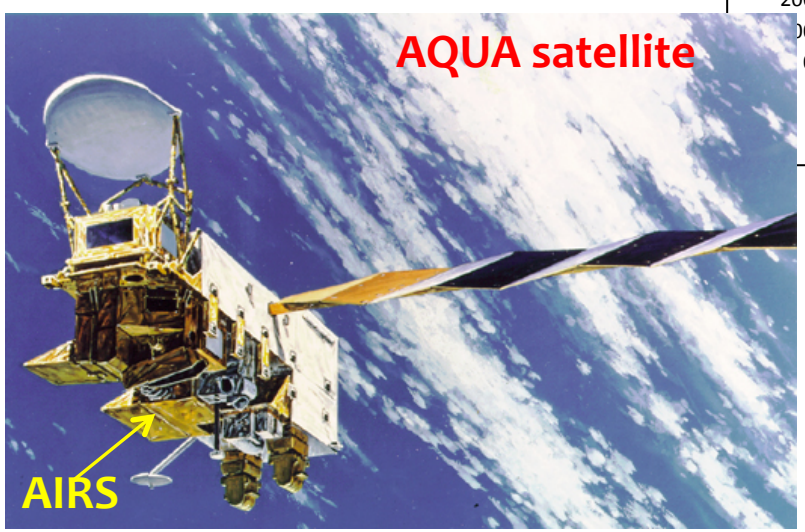
- **Discrete flux models :**
  - Honda / HKKM (tuned on atmospheric muon flux), plus six cascade calculations from MCEq, sampling 3 primary spectra and 2 hadronic models.
- **Primary models:**
  - ZatsepinSokolskaya, Polygonato, Gasser-Honda + Hillas knee correction
- **Hadronic models:**
  - SIBYLL 2.3
  - QGSJET II-04



Atmospheric density

* Atmospheric density over sample live-time from the Atmospheric Infra-Red Sounder (AIRS) instrument on the NASA AQUA satellite.



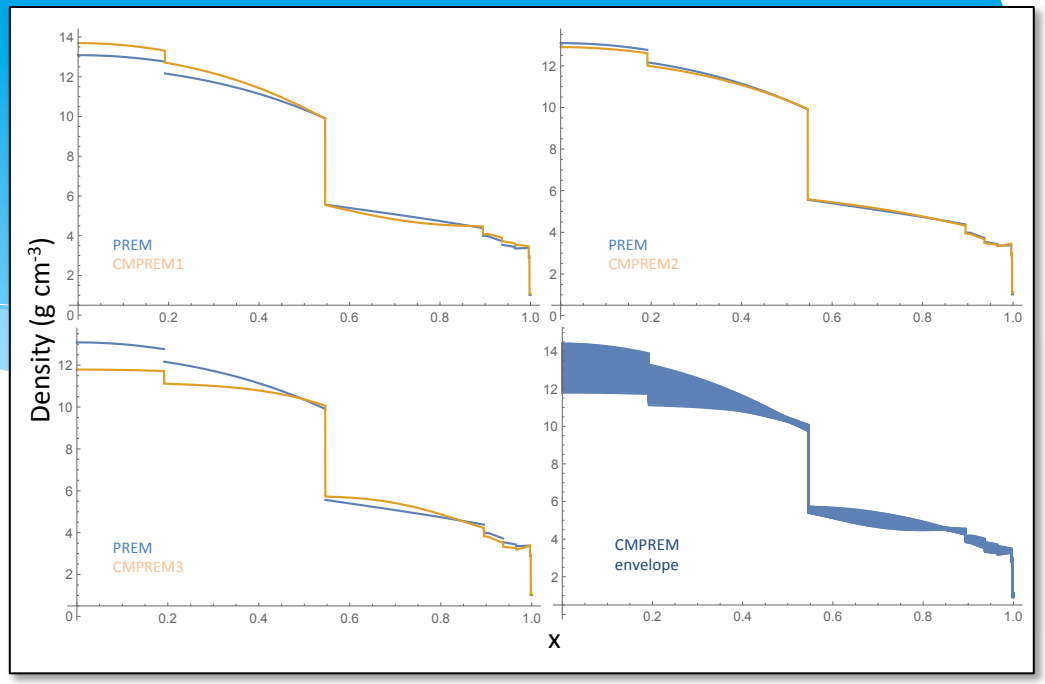


Propagated through air shower evolution calculation with stat. and syst. uncertainties.

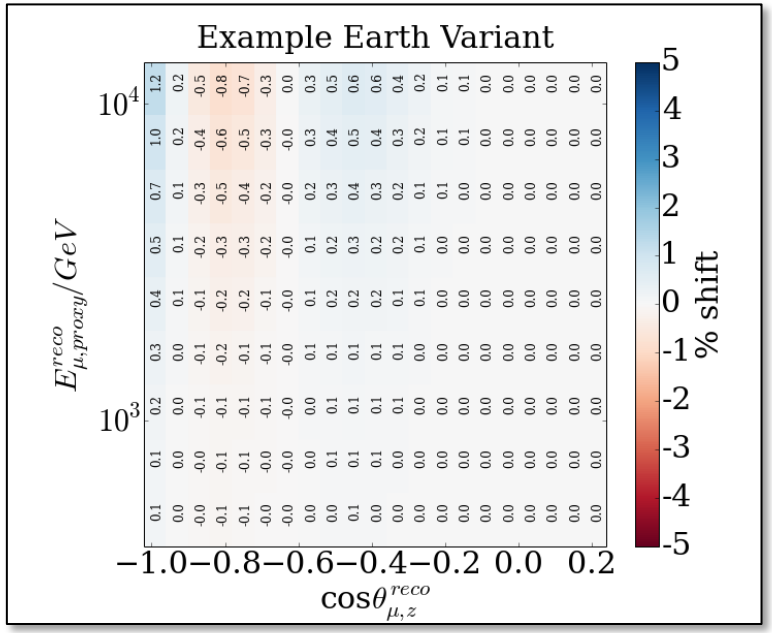
Earth density profile

* Default Earth model is the Preliminary Reference Earth Model (PREM)
* Constructed by fitting seismic wave data under geodetic constraints
* We polynomially perturb the PREM preserving those constraints to make distorted density models
* We minimize over 10 variants

Example PREM perturbations

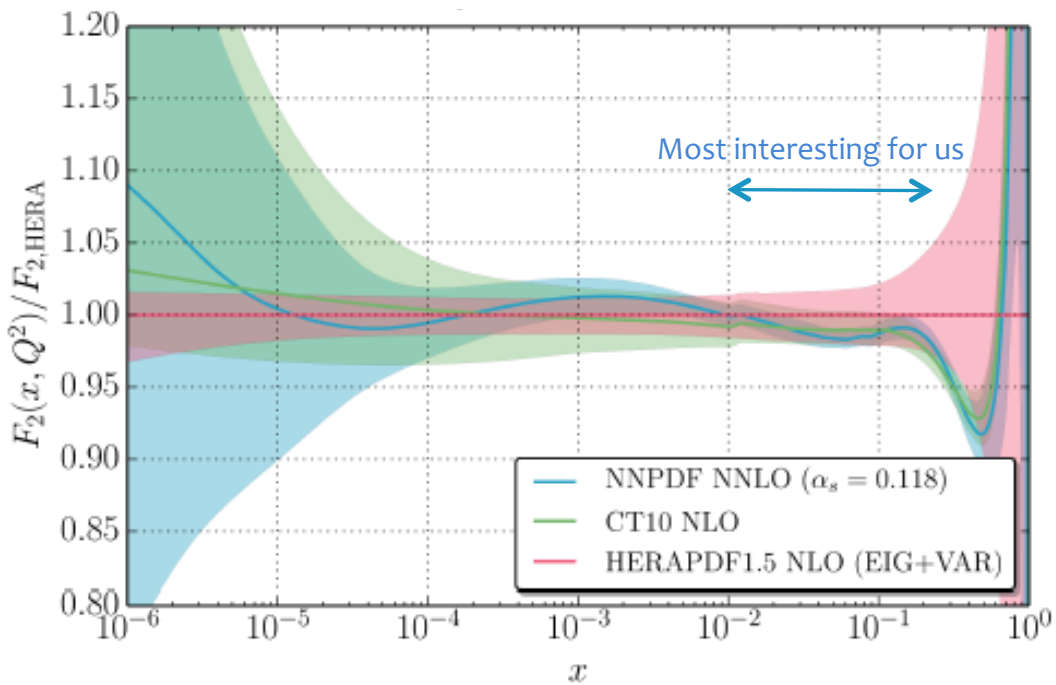


Effect in analysis space



Neutrino Cross Sectios

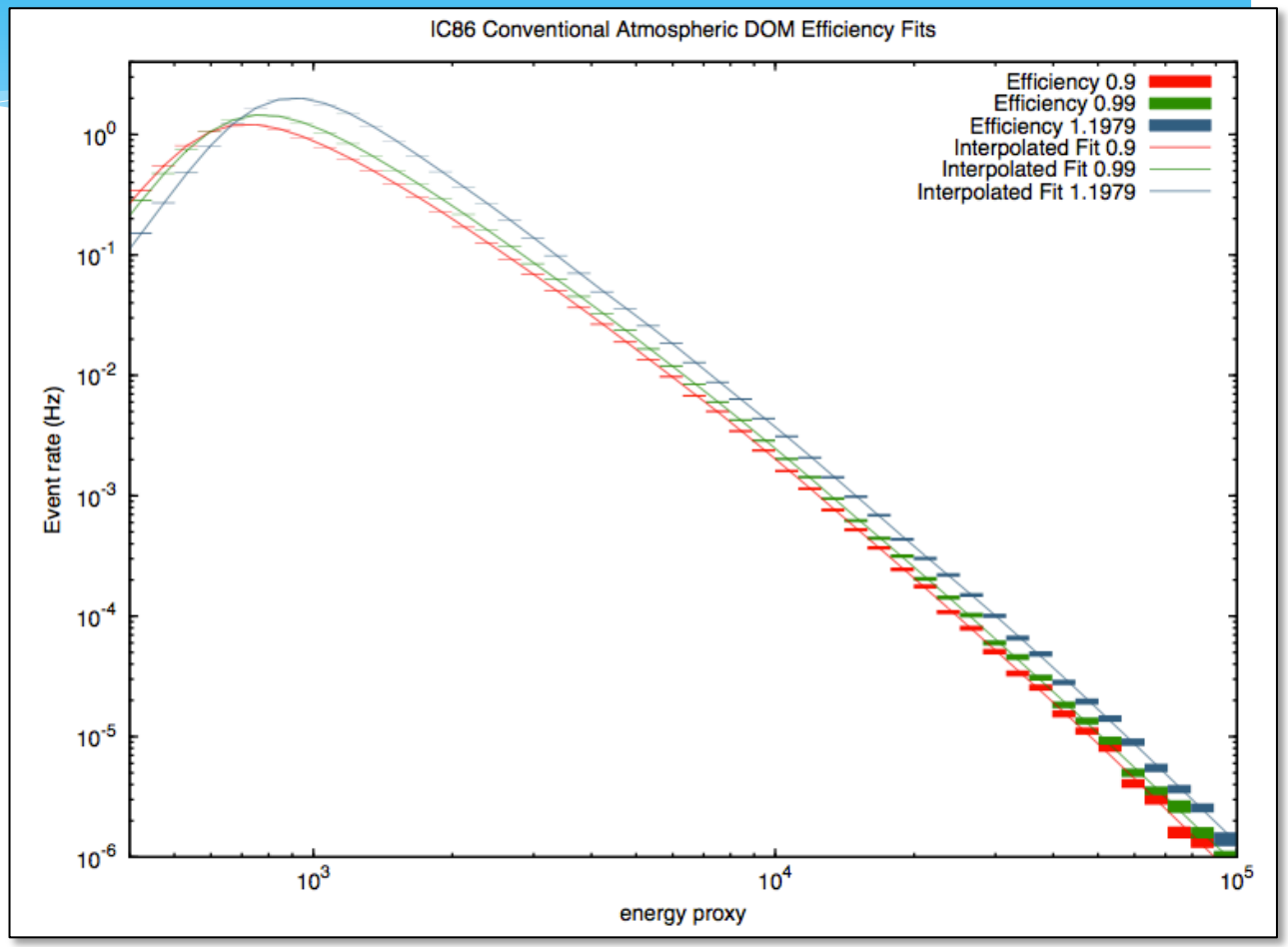
* In this energy range, scattering is all Deep Inelastic
* Uncertainty enters from parton distribution functions
* We use six PDFs HERAPDF and CT10 at NNLO, each at central and ±1σ
* Final shape effect is very small. Normalization effect is a few %.



Example structure function comparison

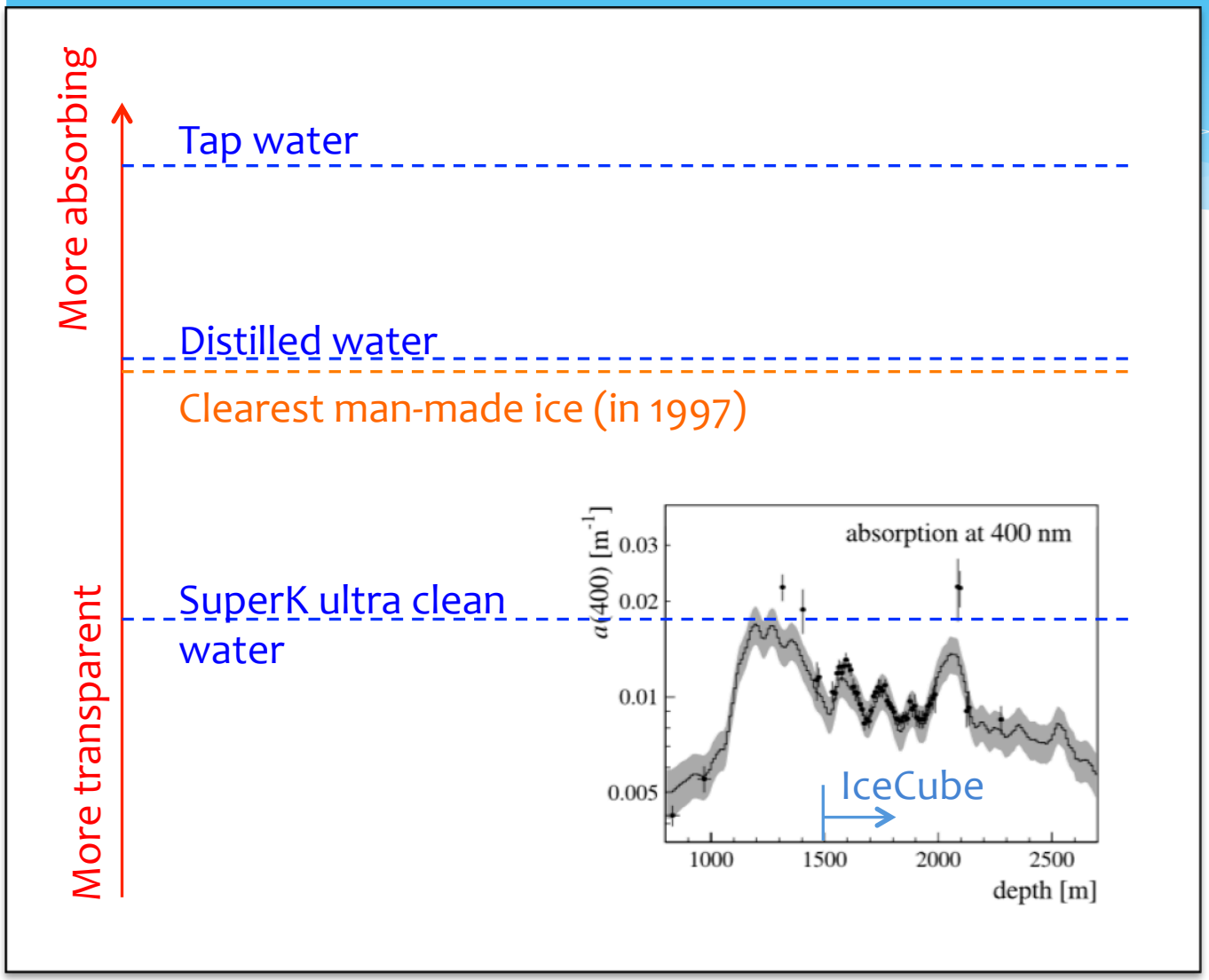
Optical module uncertainty

* Efficiency of DOM is imprecisely known.
* Lab measurements need correction due to local ice conditions and cable shadow.
* We continuously vary optical efficiency using a reweighting technique



In practice, tightly constrained by position of energy peak → we fit within 0.1% of dedicated in-ice calibration measurements

How Transparent is the Ice?

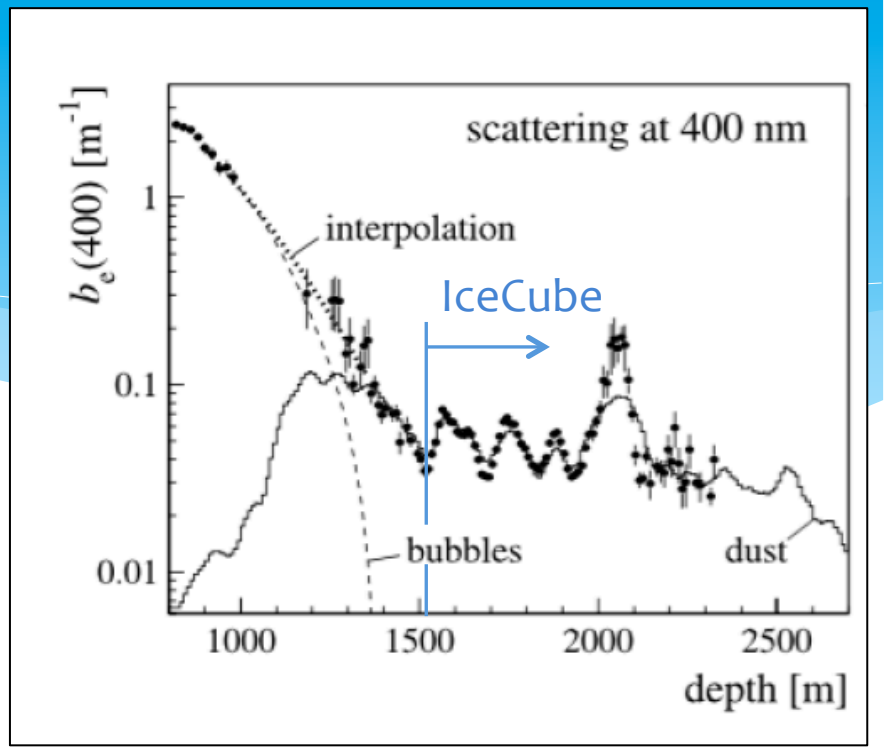


VERY TRANSPARENT!

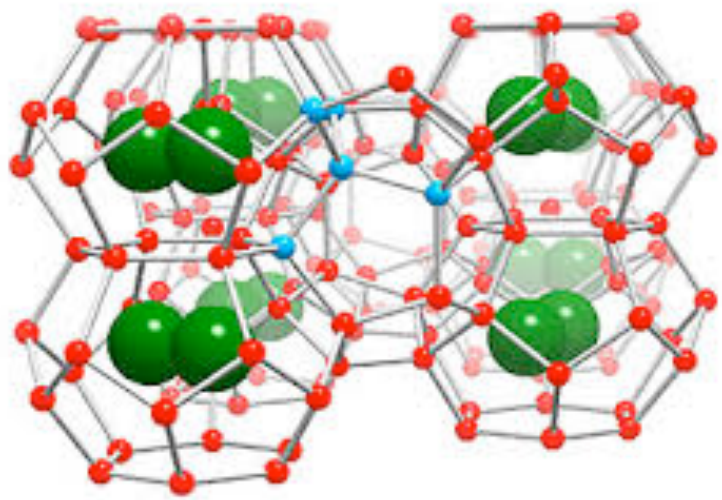
But the detector is big: 1km across!

Absorption on dust is a significant effect and a source of uncertainty

Bubble Scattering

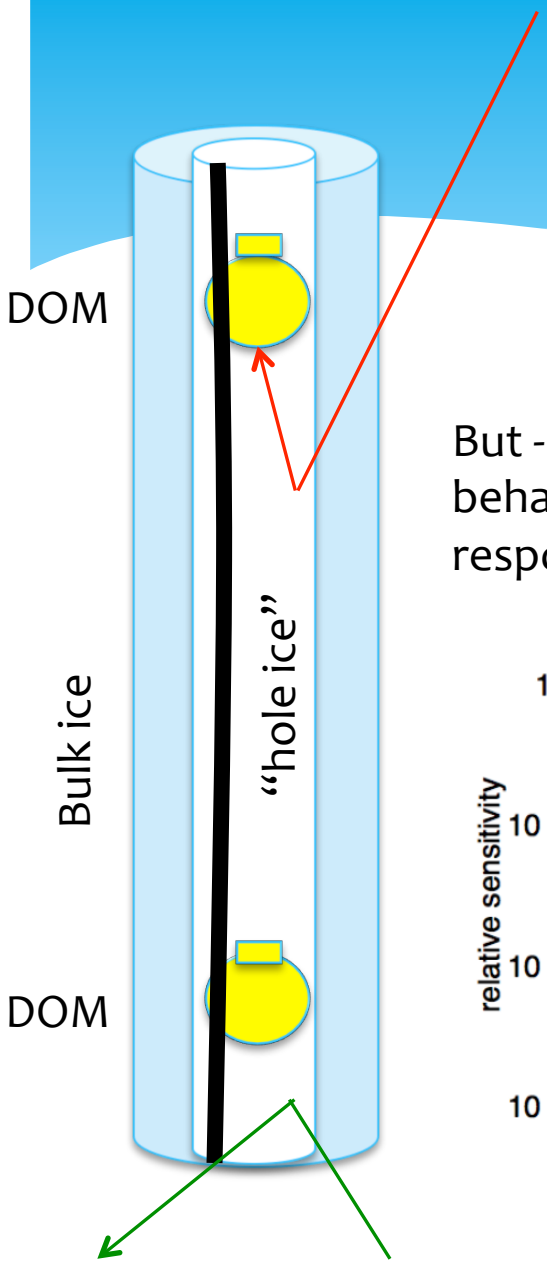


* South pole ice is compacted snow: initially has many bubbles
* At high pressures, bubbles dissolve into ice crystal creating clathrate hydrate phase.
* No bubbles in IceCube bulk ice
* Clathrate has refractive index within 0.4% of ice → negligible scattering.

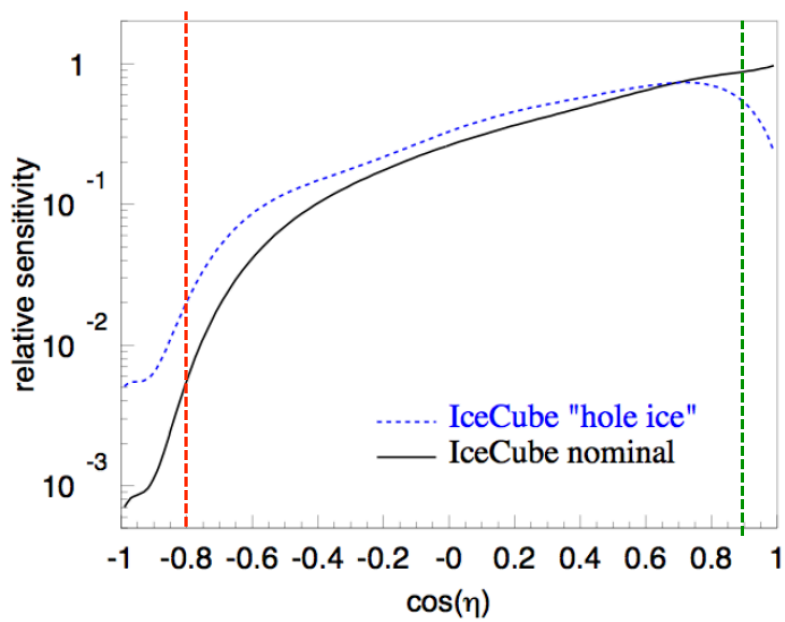


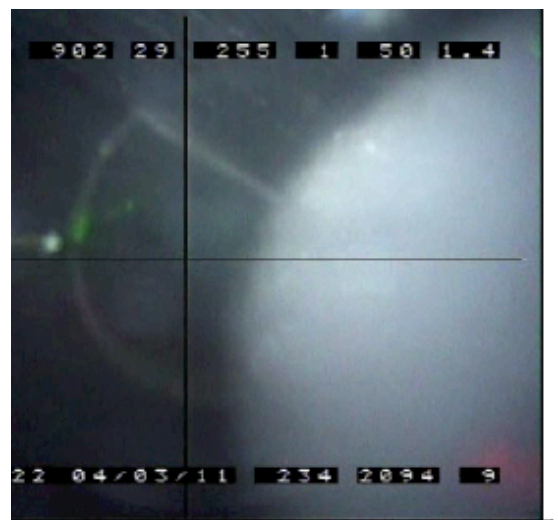
Clathrate Hydrate

"Hole ice" effect



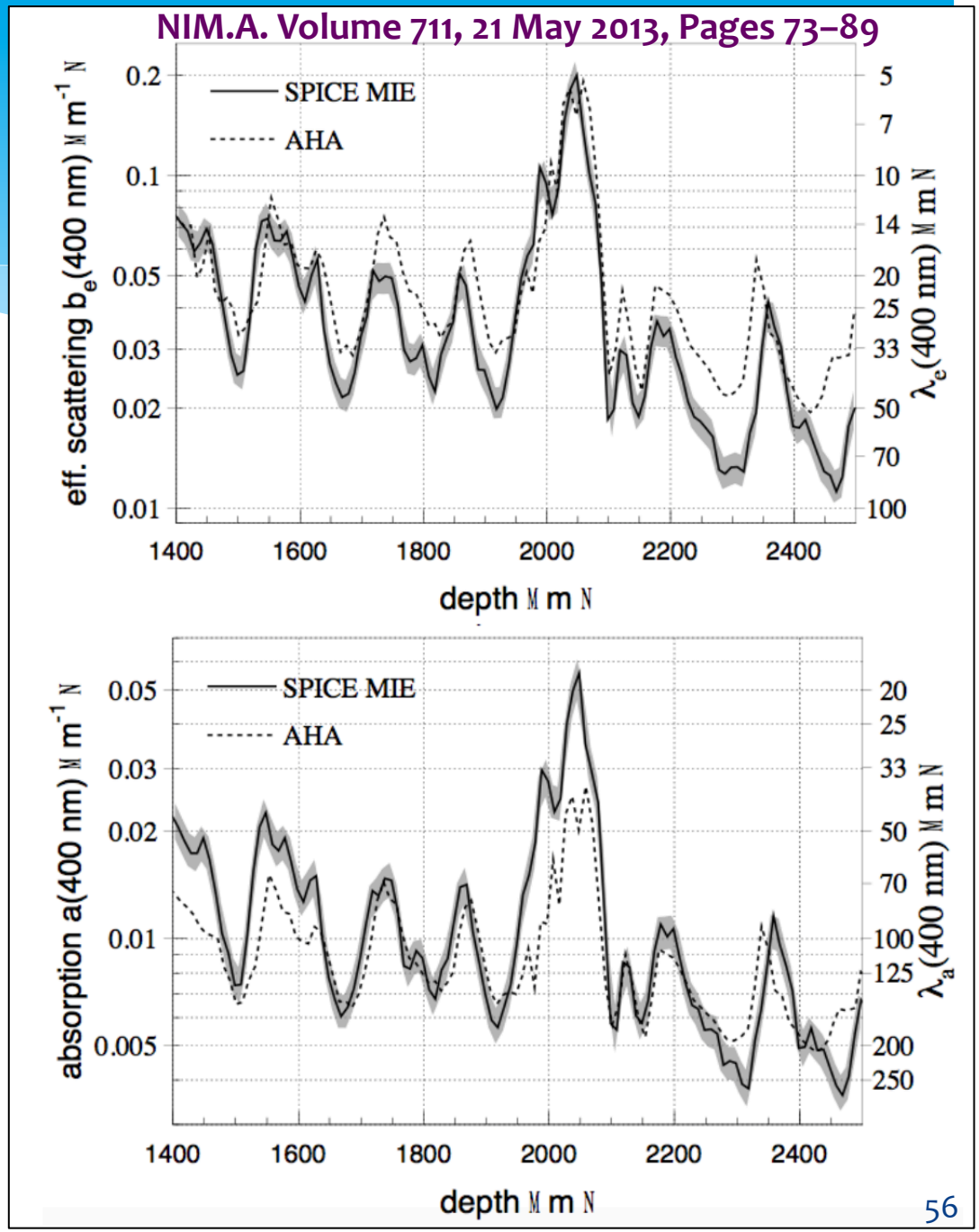
But - refrozen ice in hole does have bubbles, extra scattering behavior occurs in vicinity of DOMs → effective change to angular response function.





Dust

* Absorption and scattering in bulk ice are both dominated by dust
* Ice optical model built by fit to calibration data from flashers on each DOM
* Due to glacial flow, dust layers display :
  * Tilt / buckling
  * Anisotropy
* Both measured and incorporated into model.



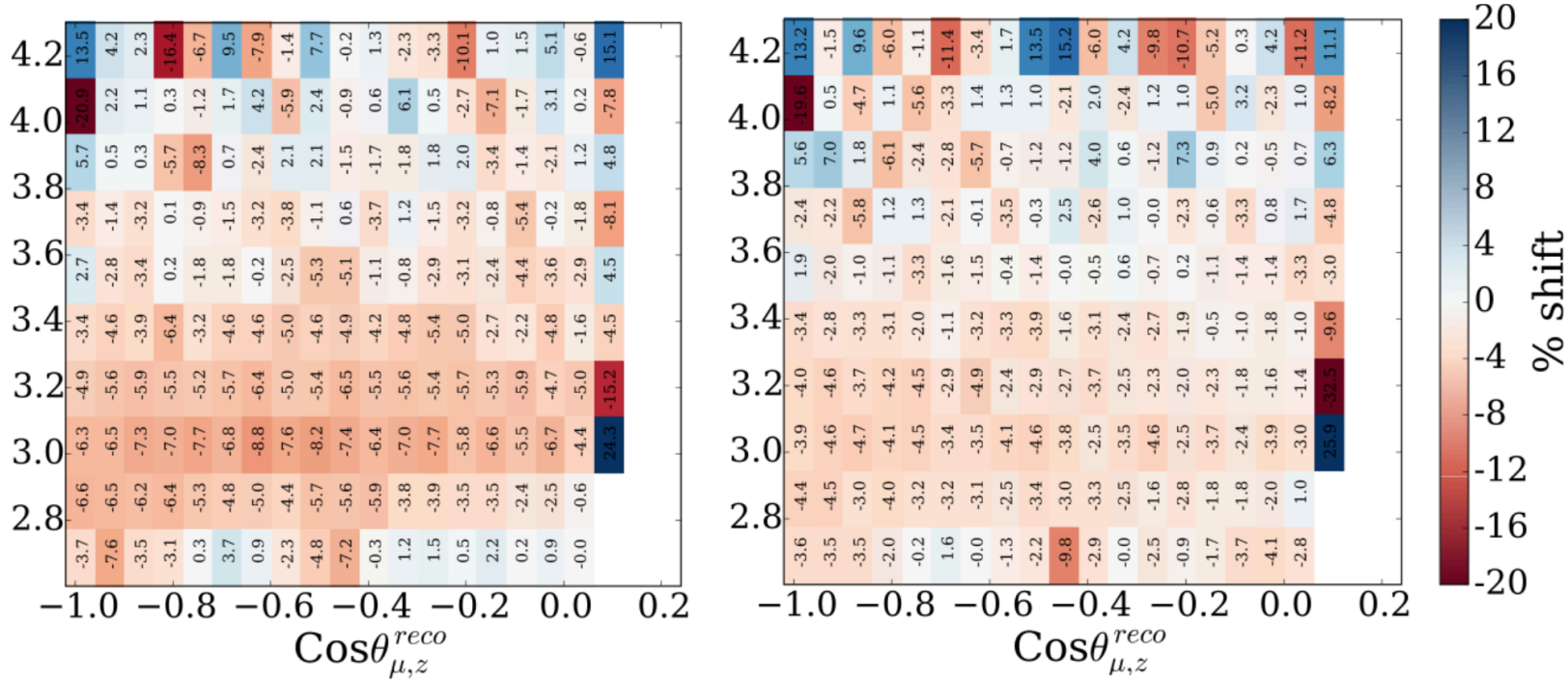
Ice systematics

We implement systematic uncertainties on **absorption** and **scattering** coefficients, **anisotropy** strength and **hole-ice.** These are small compared to flux and DOM efficiency uncertainties, and compared to expected stat error.

Examples-

Left : 90% CL **absorption** shift

Right: 90% CL **scattering** shift



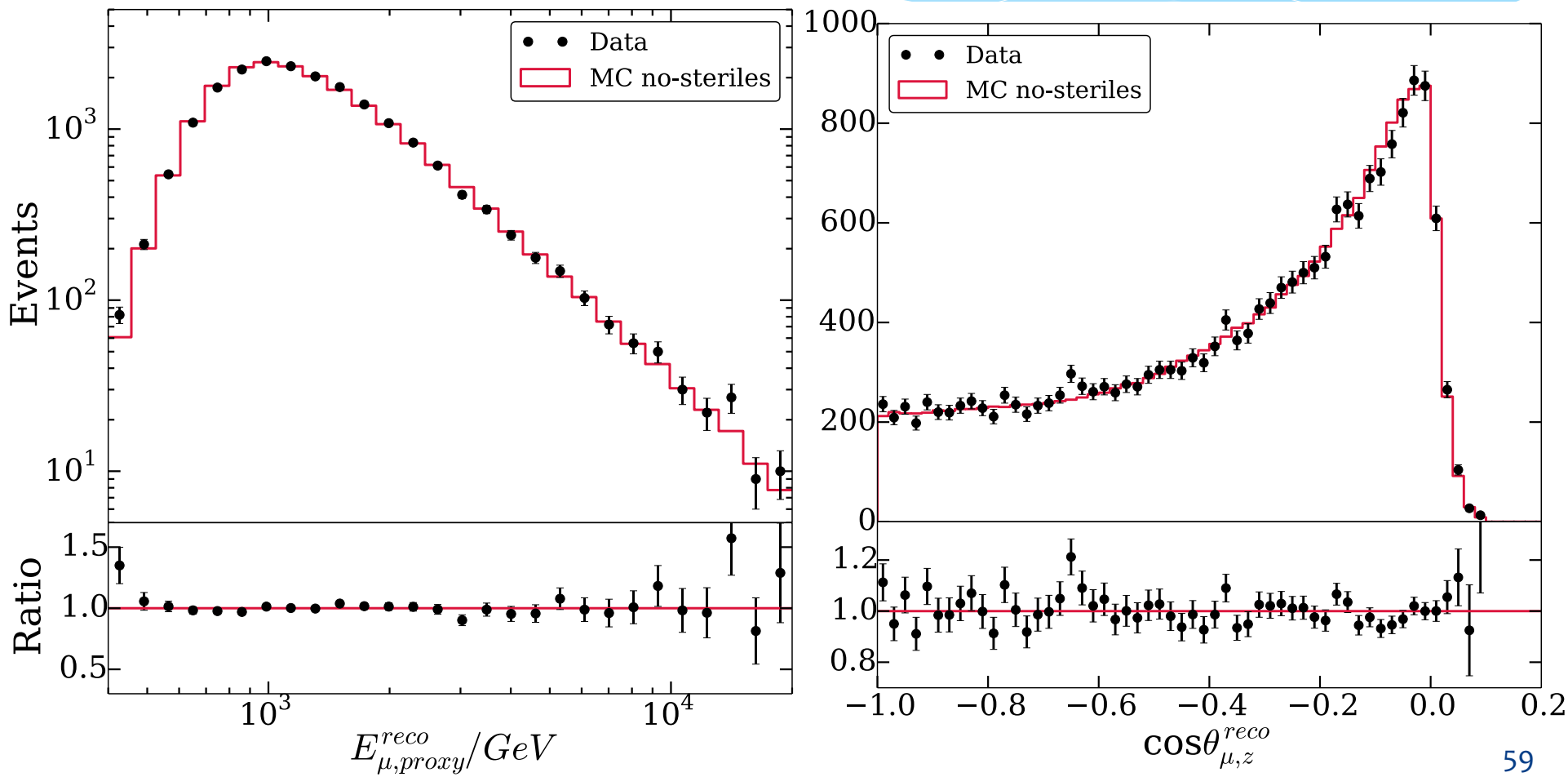
Now for the results…

Very important to recognize my two co-analyzers:

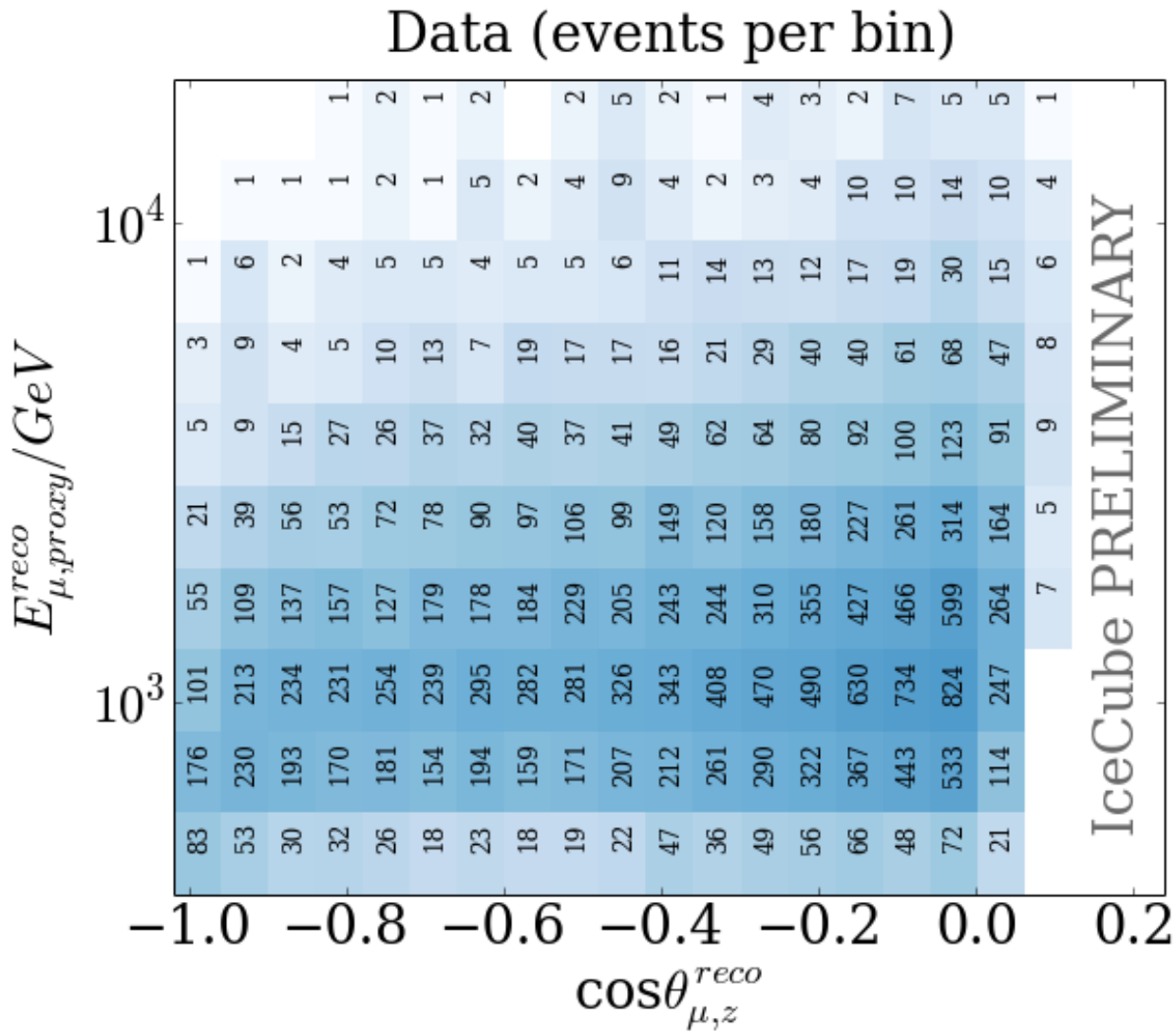
CARLOS ARGUELLES DELGADO (UW Madison / MIT)
and
JORDI SALVADO SERRA (UW Madison/ IFIC Valencia)

A first look at the data:

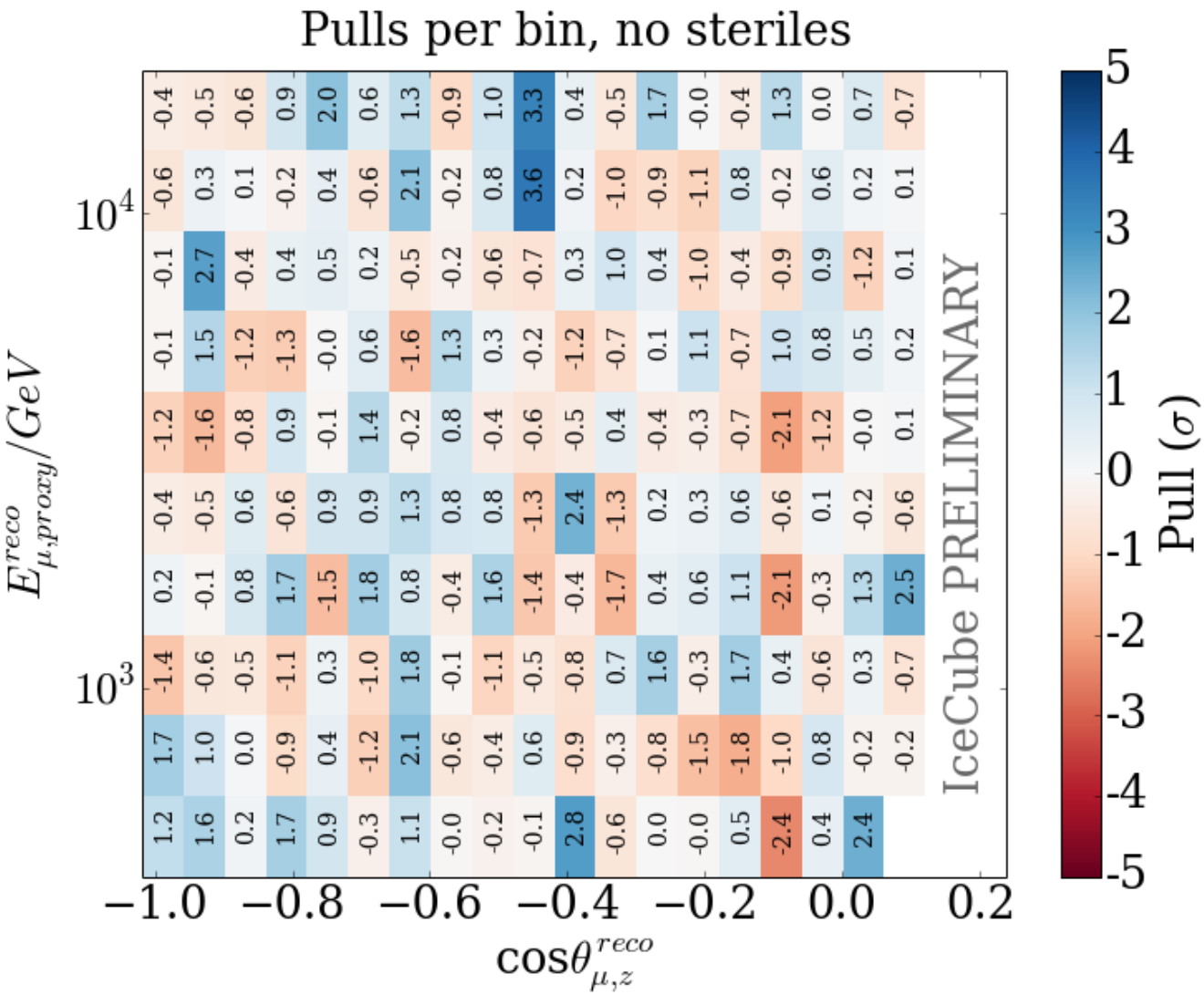
Comparison of data to no-steriles hypothesis, after accounting for systematics



Data in the binned analysis space:



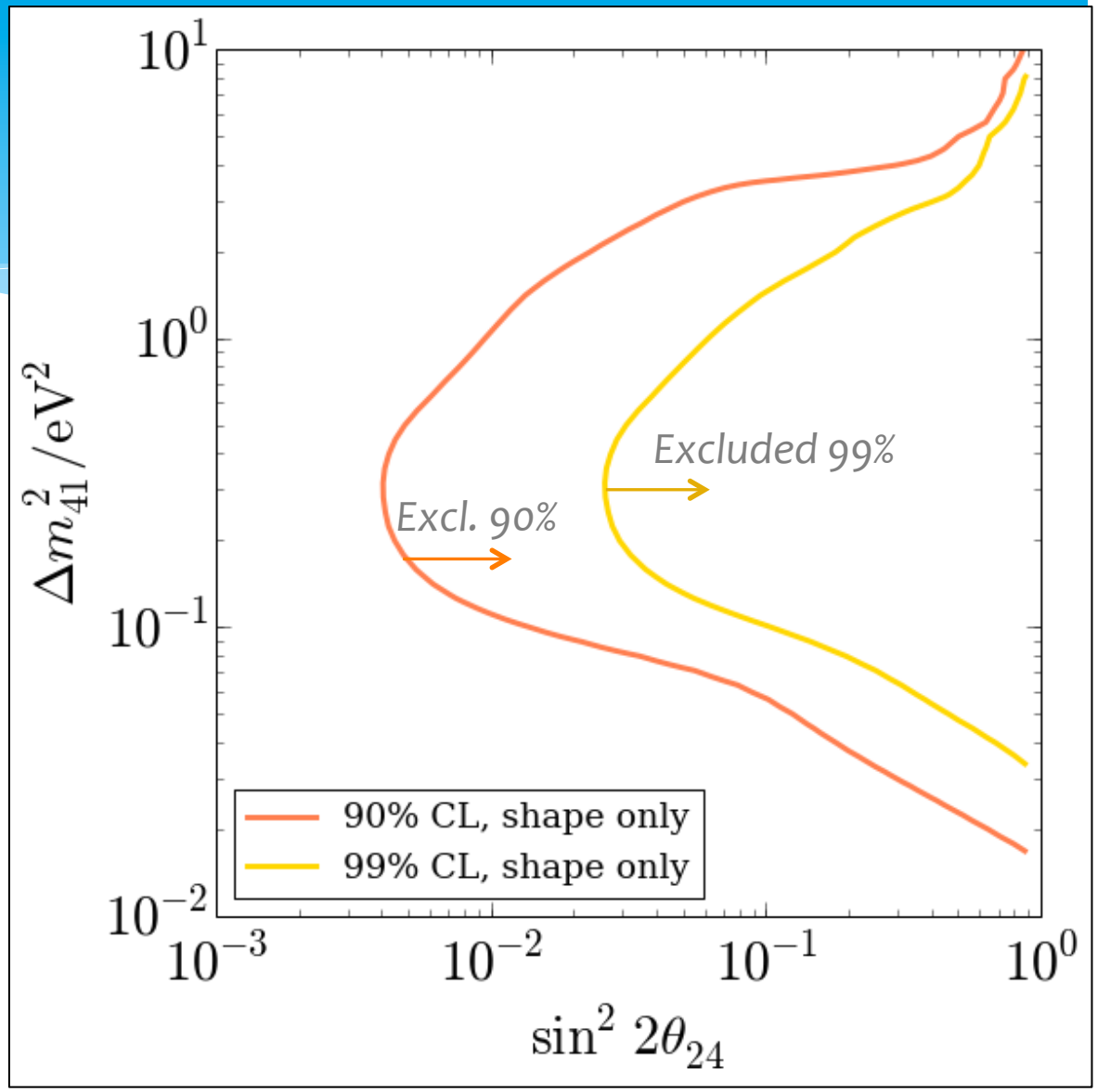
Pulls in the analysis space:



Blind analysis result:

No significant evidence for sterile neutrinos

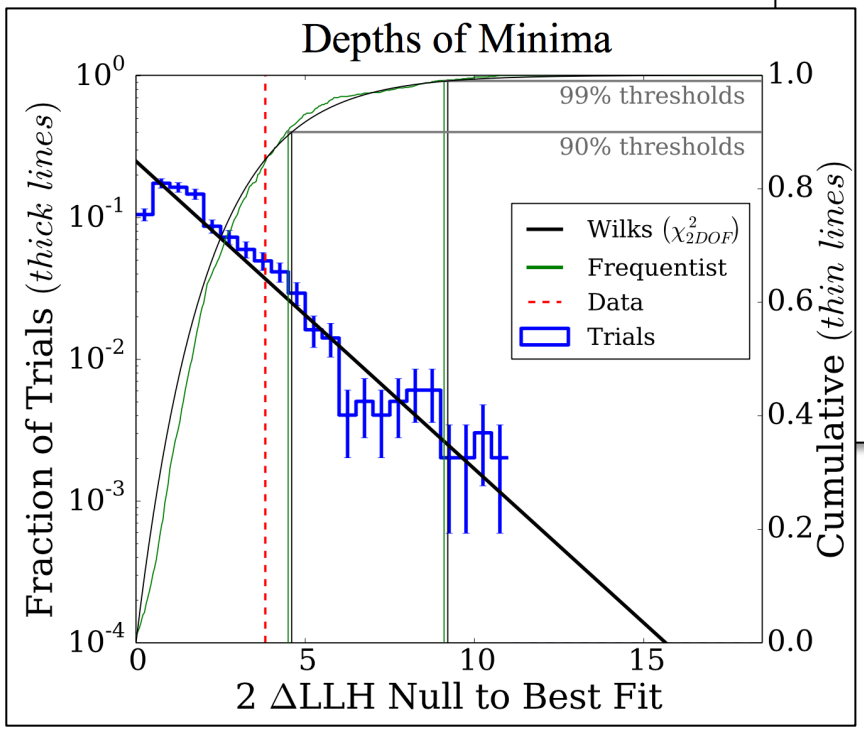
Exclusion of large parameter space at 99% confidence level

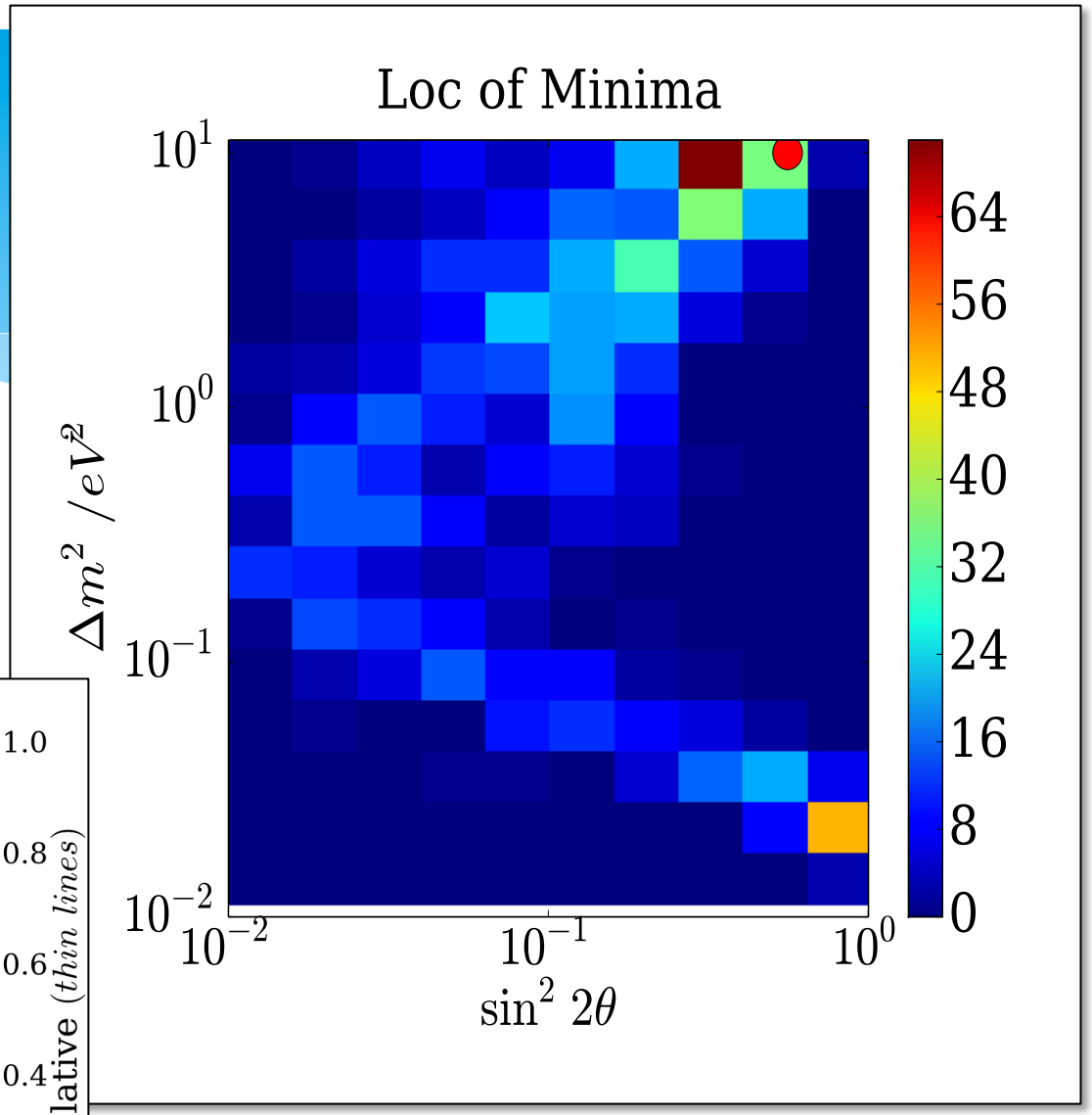


Checking the best-fit

The best fit point is a consistent realization of the no-steriles hypothesis ➔

Its frequentist p-value is 14% ➓

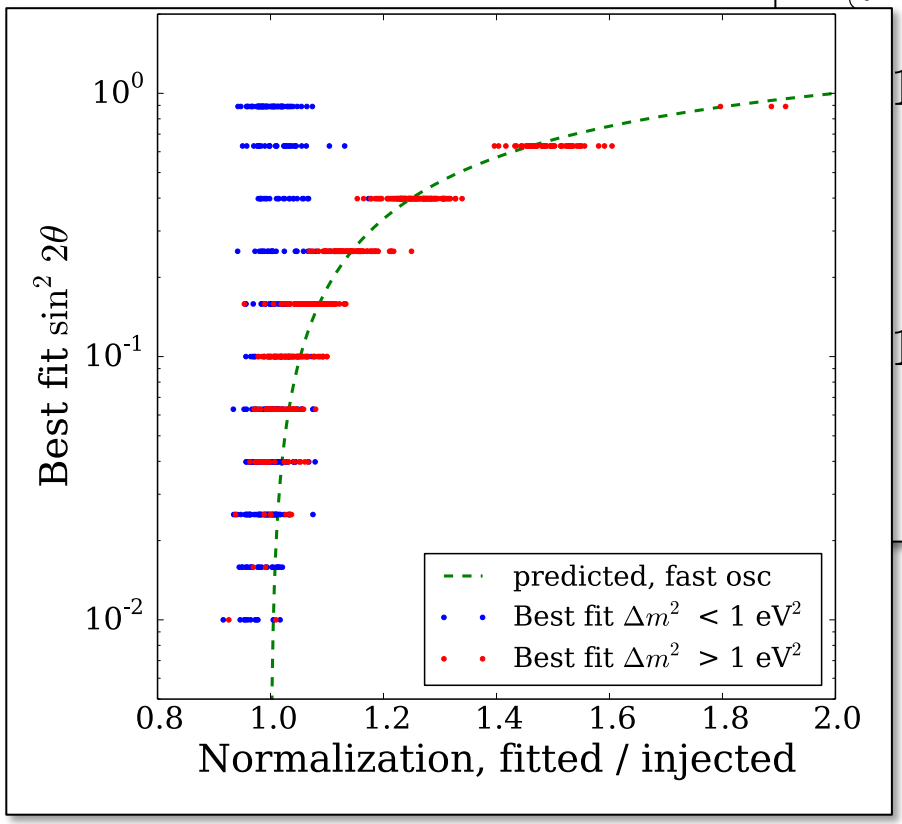


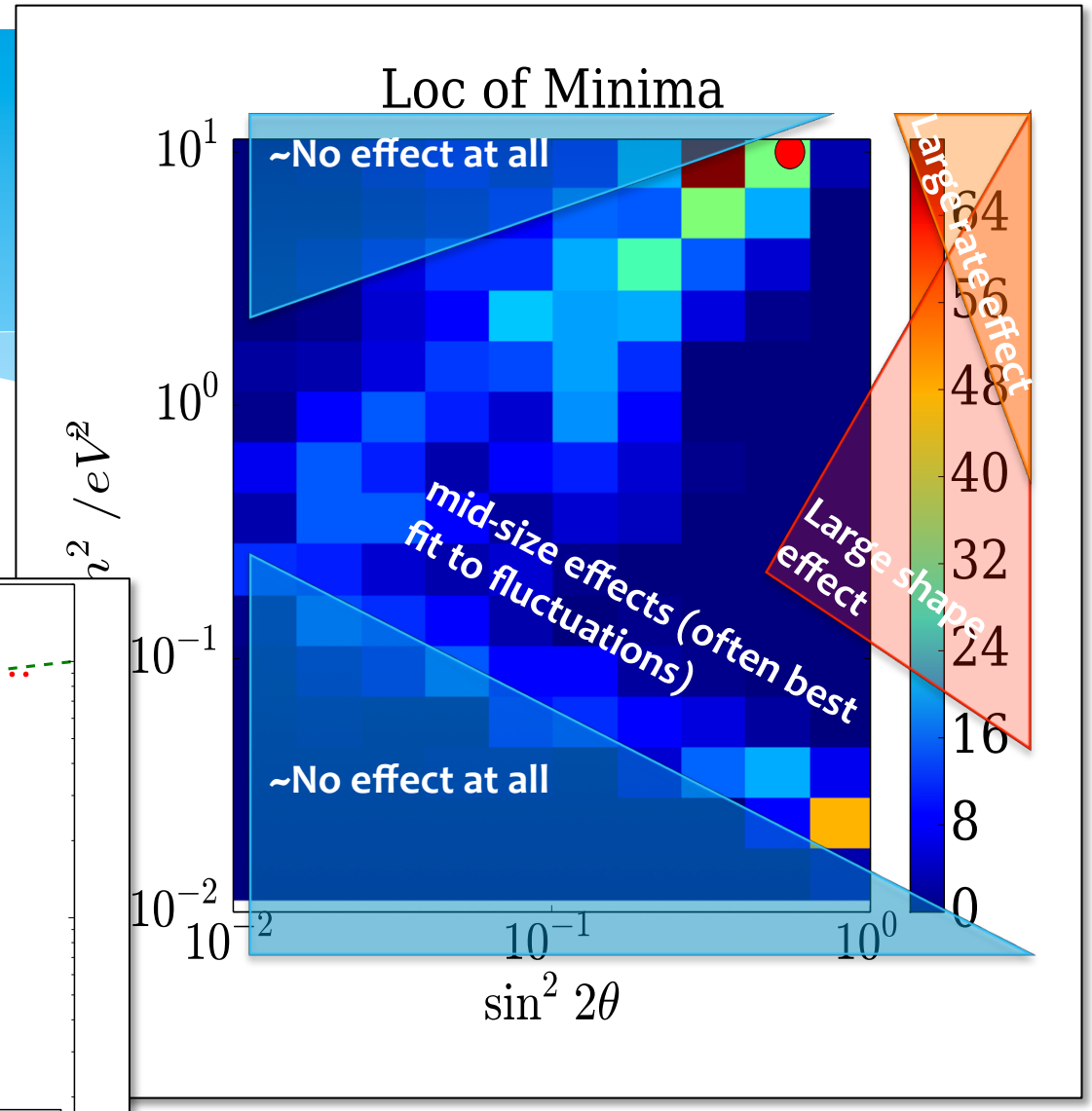


(this part of hypothesis space is a very fast vacuum-like oscillation, nearly indistinguishable from no-effect)

A Subtlety of Shape-Only Analysis

High-mixing null-like solutions lead to significant normalization pull.

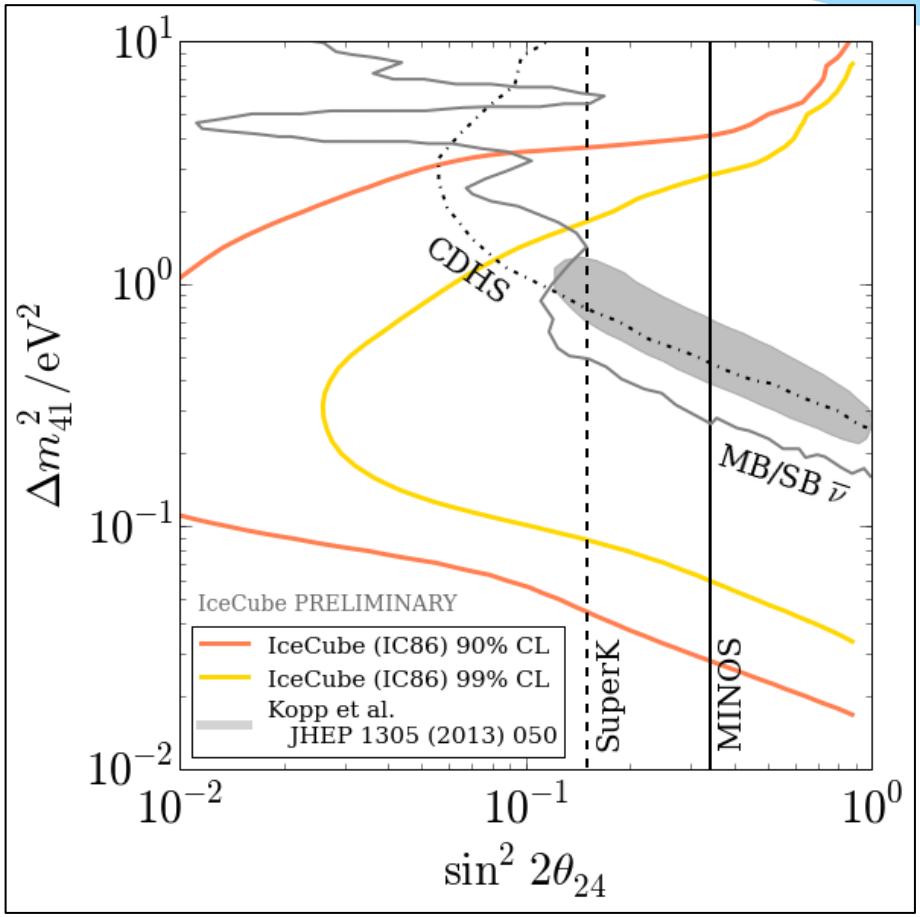




By incorporating other available information (knowledge of flux normalization), exclusion power of result could be reduced.

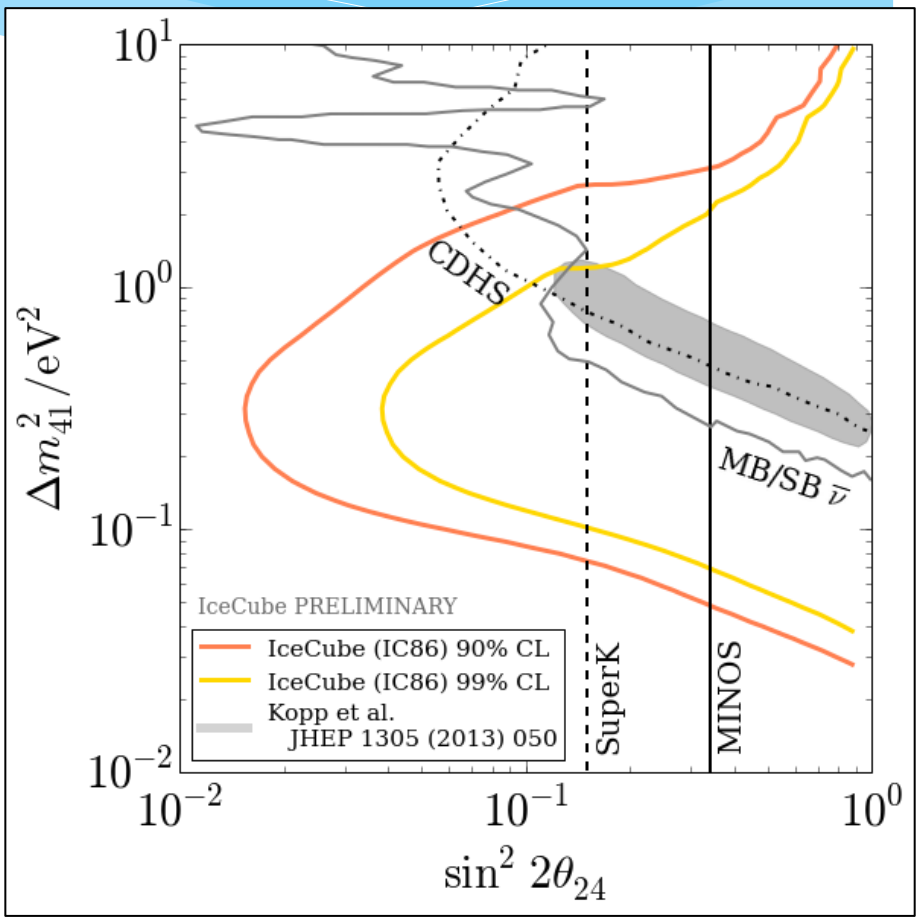
Comparison to world data:

Shape-only



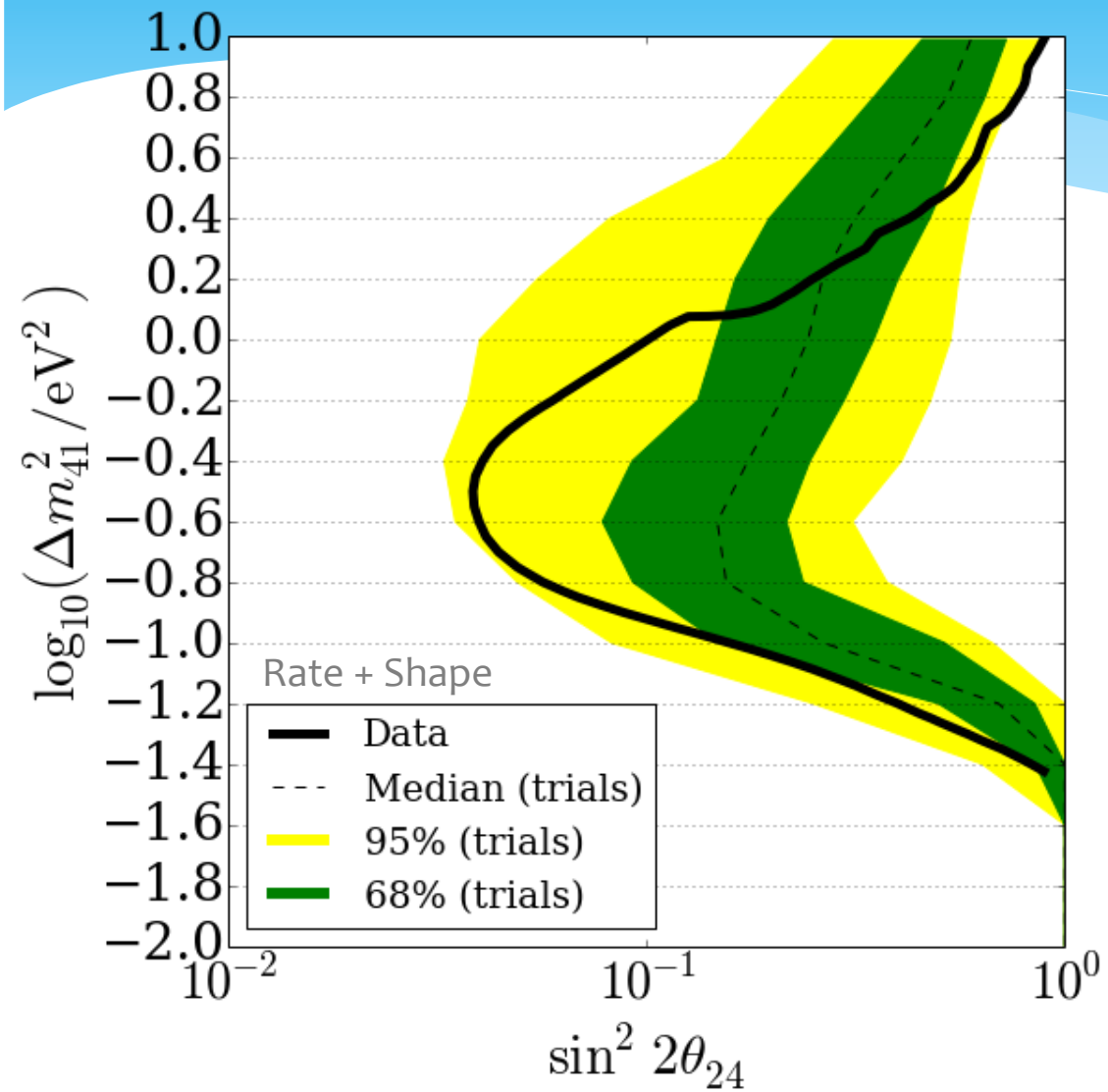
(blind result – stronger exclusion)

Rate + Shape



(added information - weakened exclusion)

Comparison to sensitivity

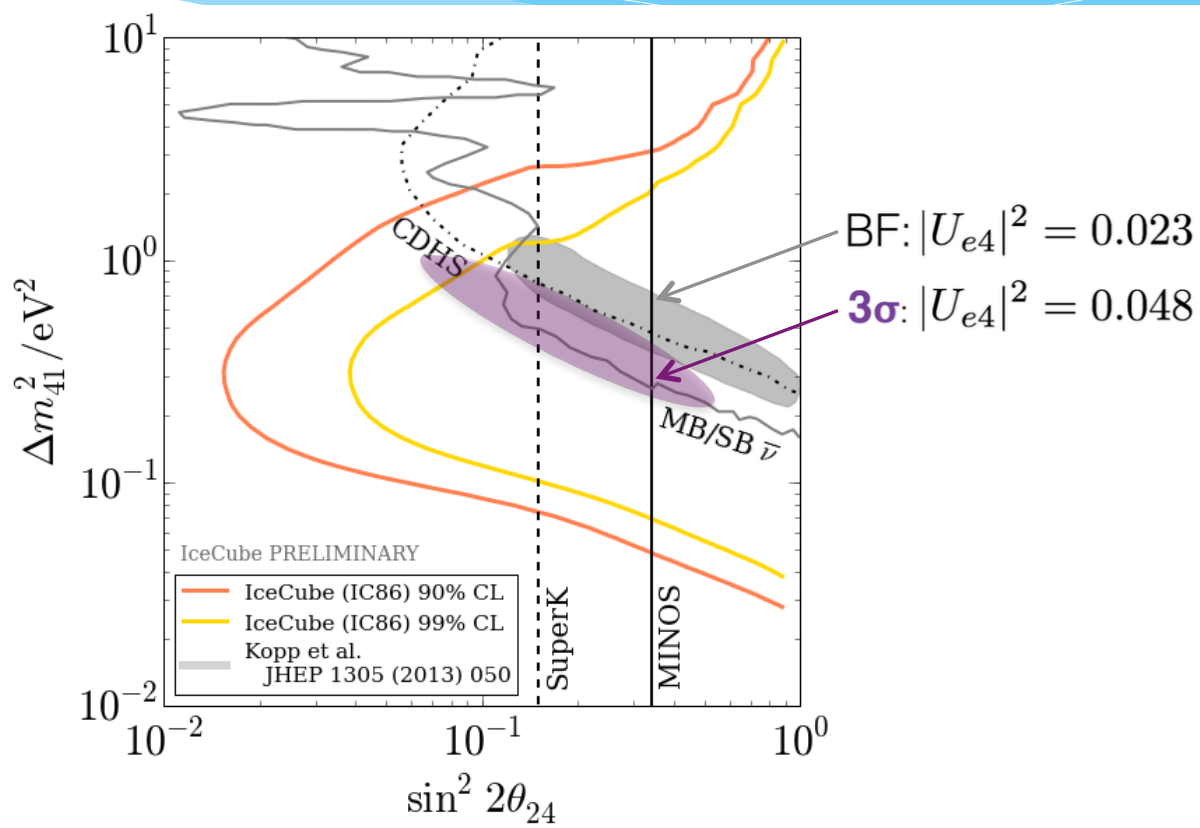


Realization is fairly typical:

- stronger than sensitivity in some areas, weaker in others
- Always within 95% band from pseudo-data

Mixing angle uncertainty in MB/ LSND region

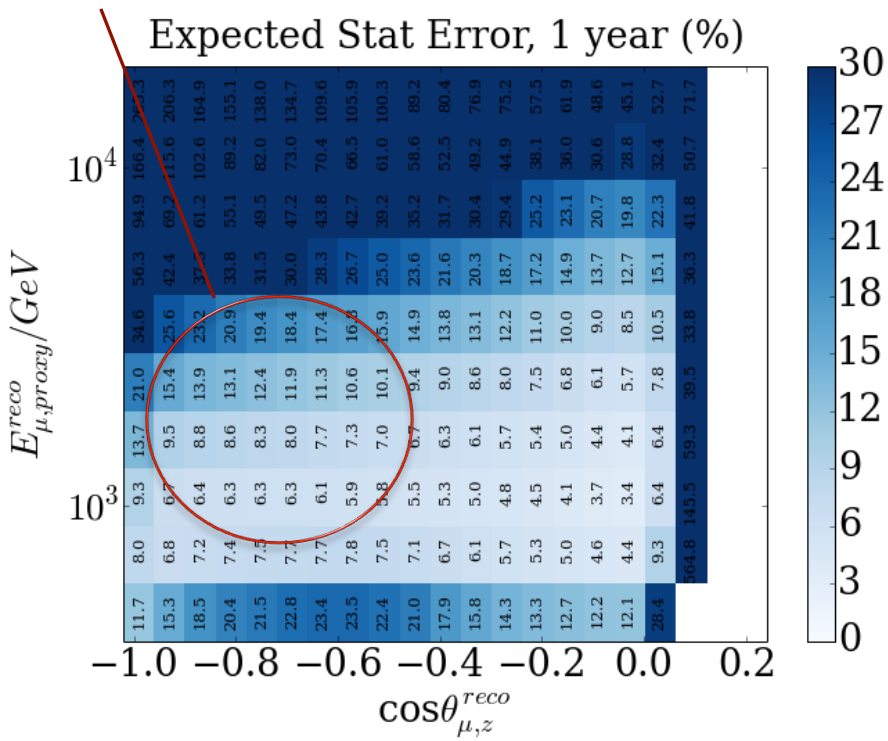
Based on other mixing angles, how far can MB / LSND slide?

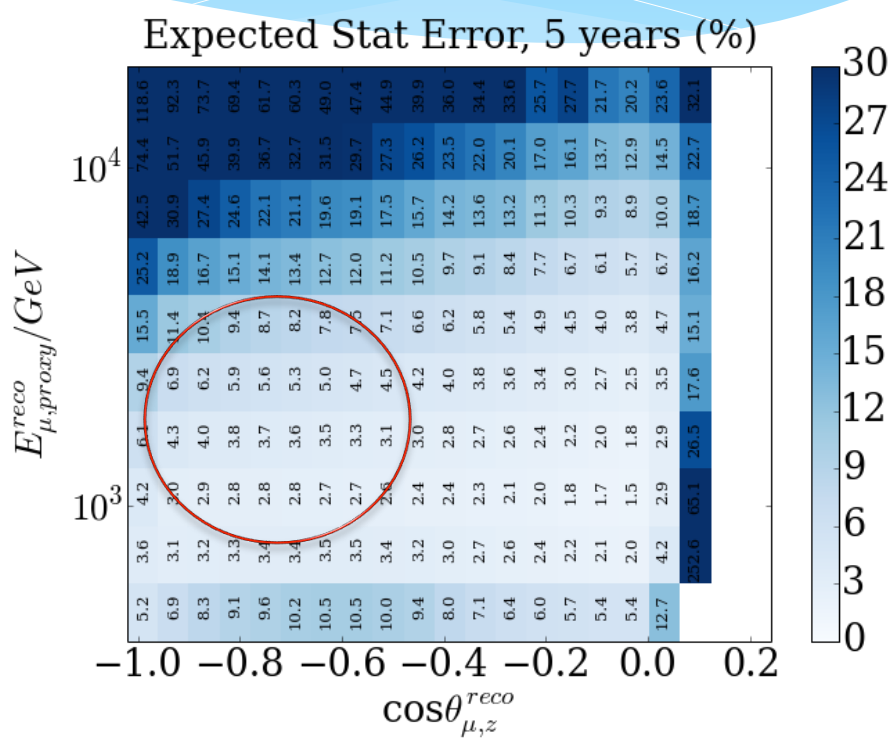


- $\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1-|U_{e4}|^2)$: reactor experiments.
- $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)$: MINOS, SK. (**this analysis**)
- $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu4}|^2|U_{e4}|^2$: LSND, MB, KARMEN, NOMAD.

The Future

Most interesting region for eV scale sterile neutrinos





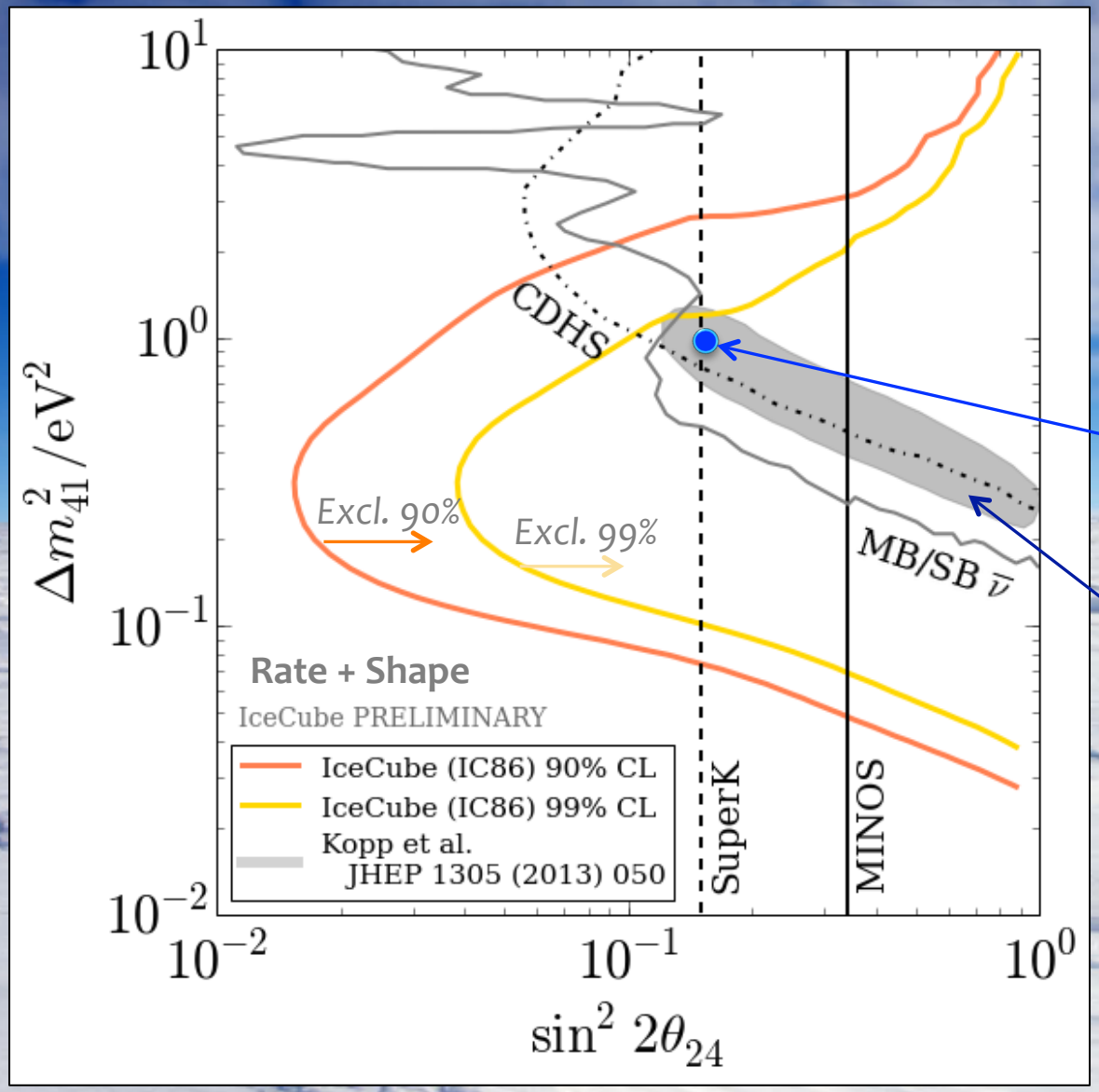
This analysis: 1 year of data, requiring control of systematics at ~6-7% per bin

Data already in hand: 4 more years, requiring control of systematics at ~2-3% per bin

We are only just getting started!

Conclusions

* Sterile neutrinos are a compelling explanation of several anomalies in short-baseline experiments
* Introduction of a ~1eV^2 sterile neutrino would lead to dramatic MSW-resonant signatures in the atmospheric neutrino flux
* A search for these features was made using the IceCube neutrino telescope
* No evidence for sterile neutrinos was found
* New limits have been set on the 3+1 model, ruling out appearance region at >99% CL (IceCube only)

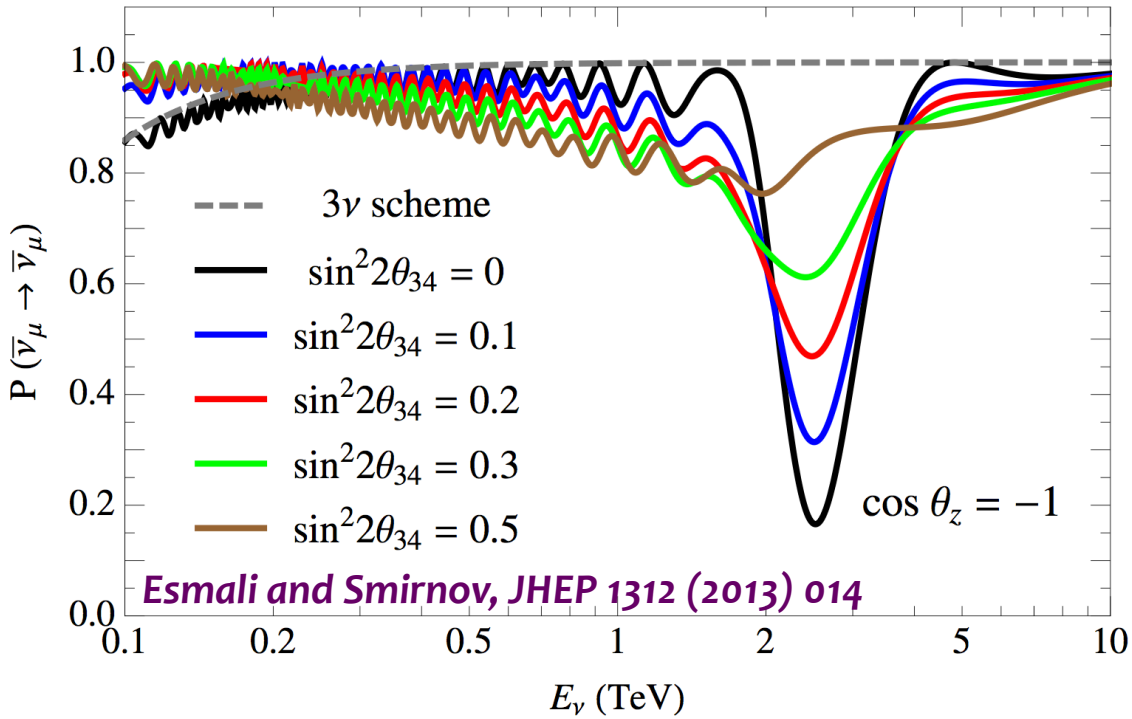


Previous world best fit 3+1

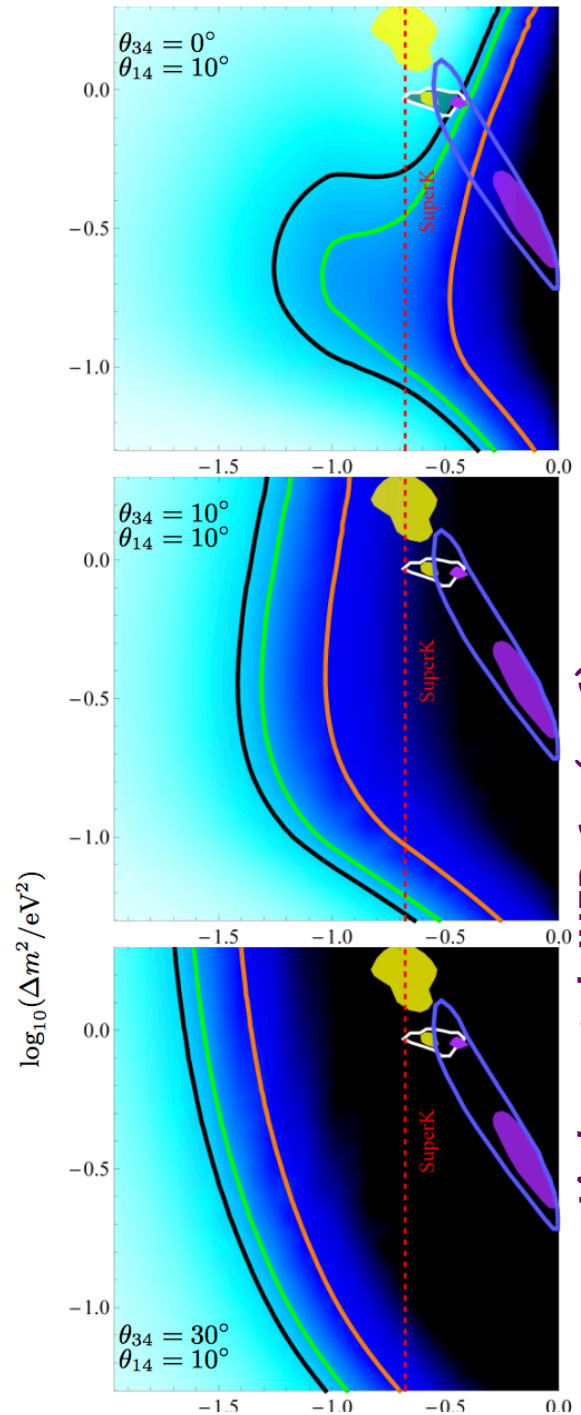
SBN anomalies allowed region

Thank you for your Attention

Conservatism of angle assumptions

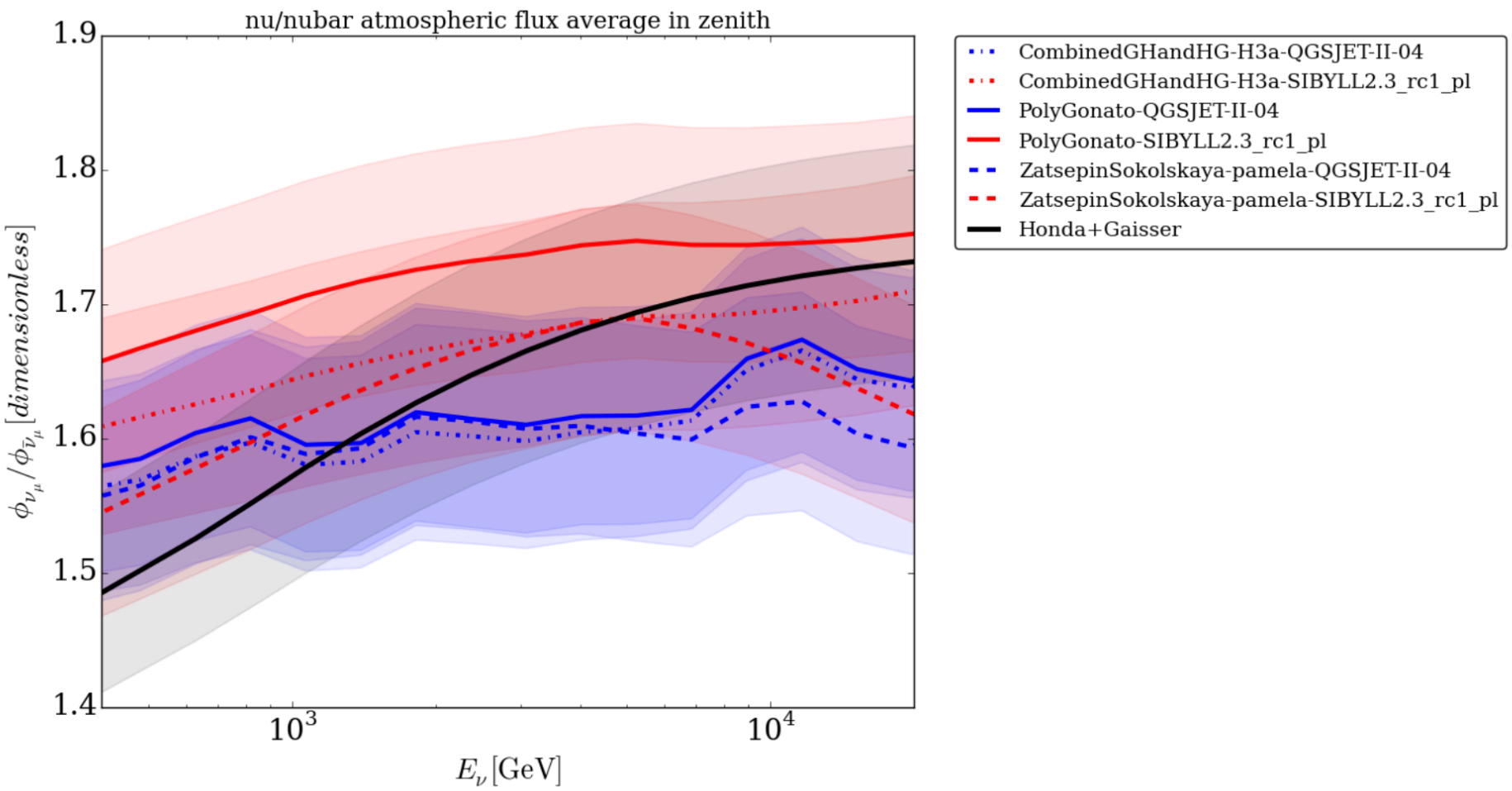


Esmali and Smirnov, JHEP 1312 (2013) 014

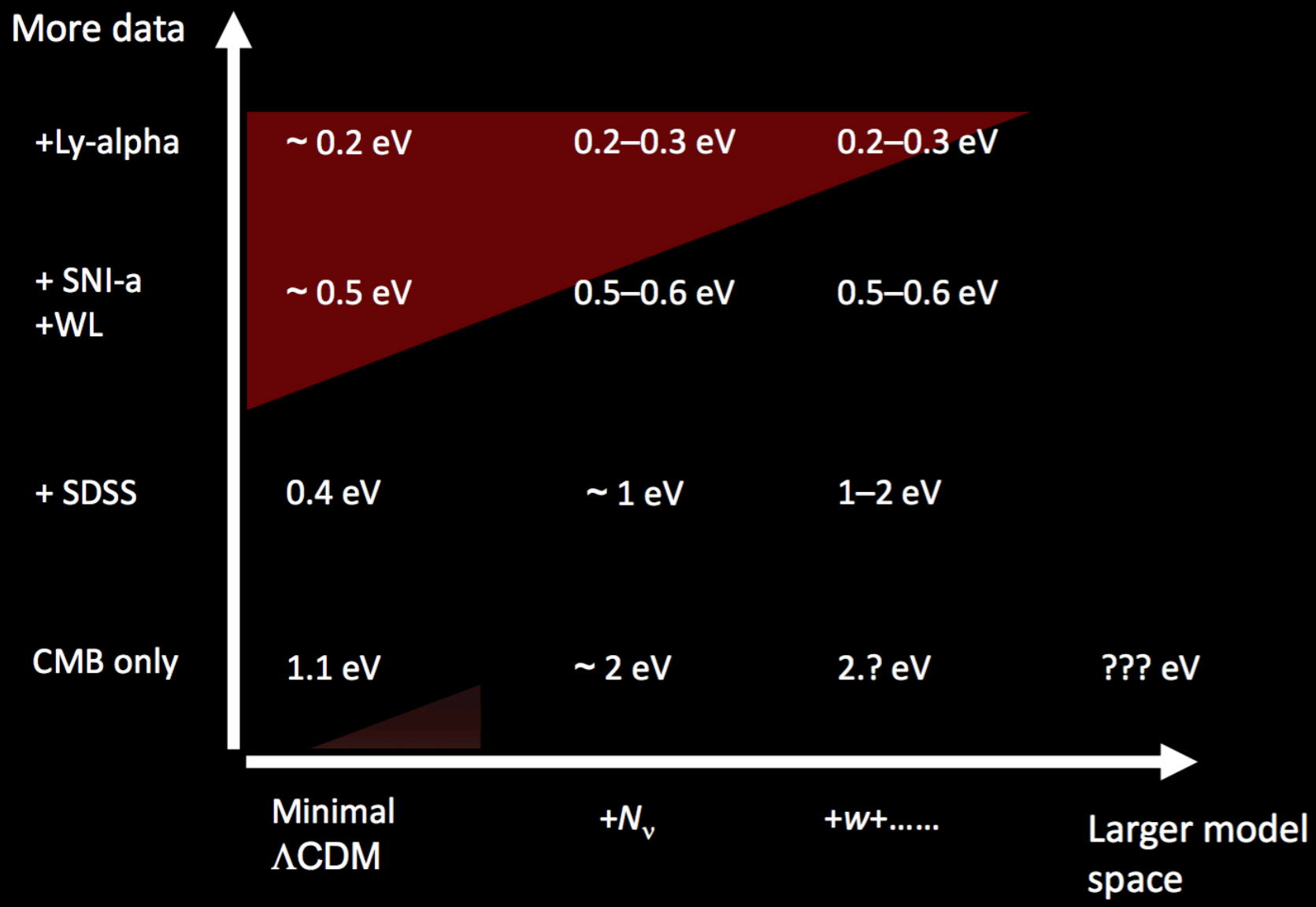


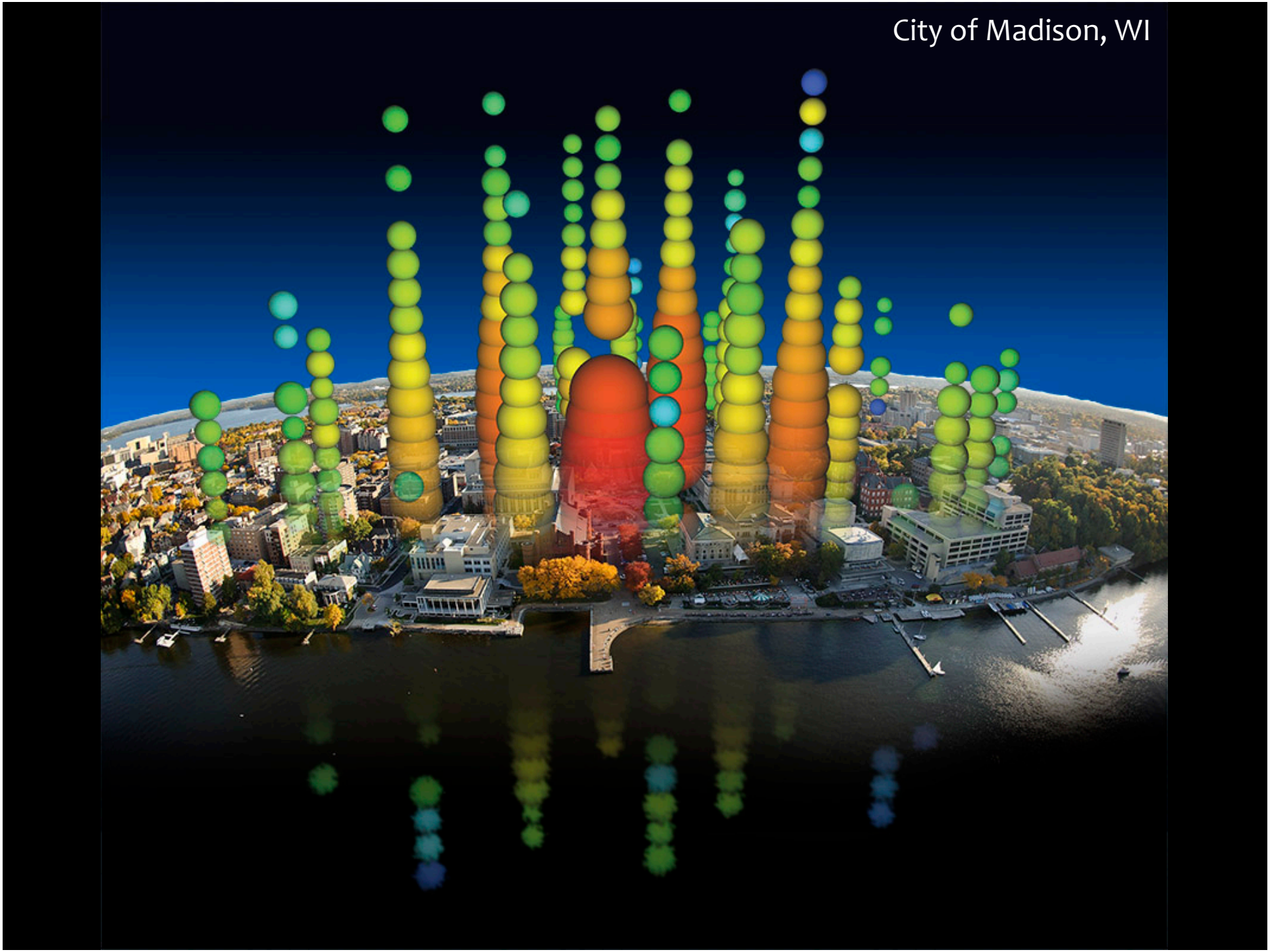
Lindner et al, JHEP 1601 (2016) 124

Constraint from Minos data, Th34 < 25 deg at 90%CL
Phys.Rev.Lett. 107 (2011) 011802


nu/nubar atmospheric flux average in zenith
1.9
1.8
1.7
1.6
1.5
1.4
10^3
10^4
E_ν [GeV]
$\phi_{\nu_\mu}/\phi_{\bar{\nu}_\mu}$ [dimensionless]
CombinedGHandHG-H3a-QGSJET-II-04
CombinedGHandHG-H3a-SIBYLL2.3_rc1_pl
PolyGonato-QGSJET-II-04
PolyGonato-SIBYLL2.3_rc1_pl
ZatsepinSokolskaya-pamela-QGSJET-II-04
ZatsepinSokolskaya-pamela-SIBYLL2.3_rc1_pl
Honda+Gaisser

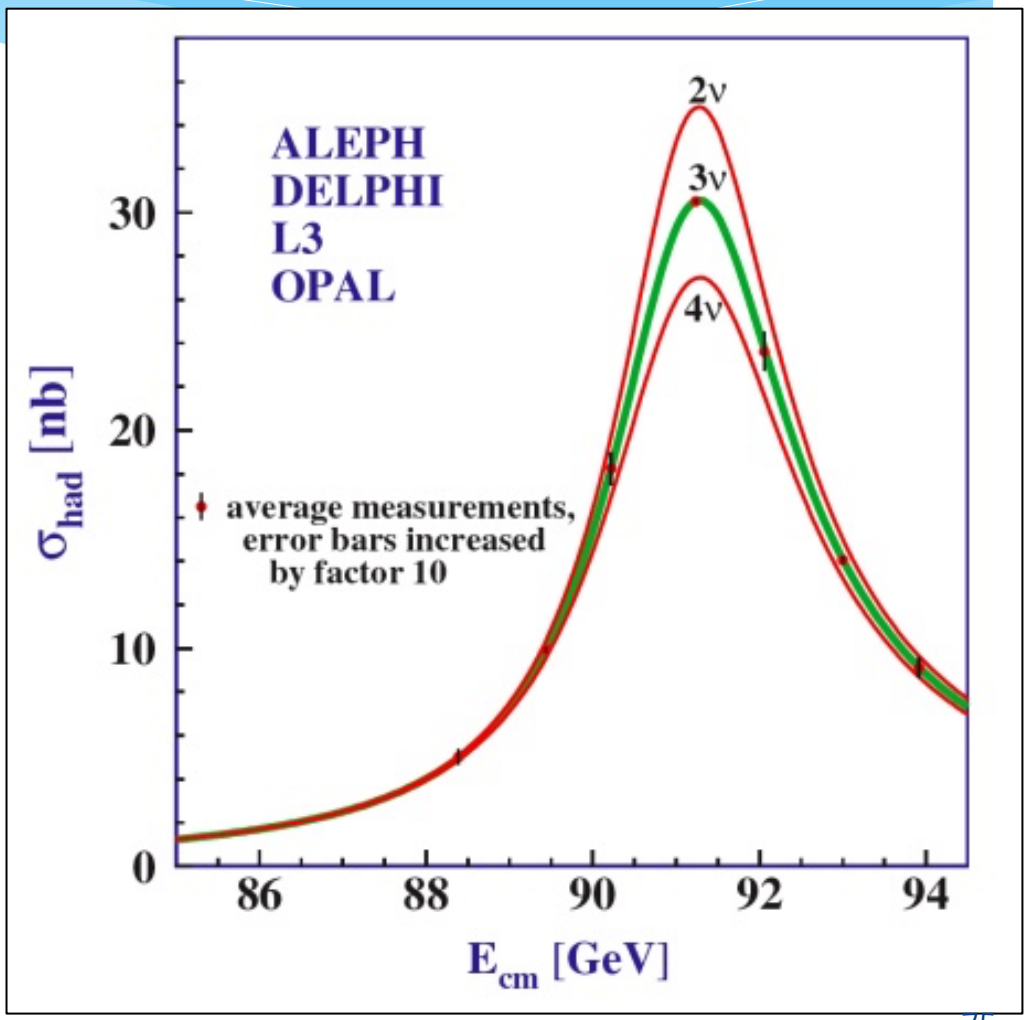
Neutrino Mass from Cosmology (Hannestad)




City of Madison, WI

An additional neutrino?

* Anomalous oscillations were at wavelengths shorter than expected given known Δm^2.
* Another neutrino state with larger mass (~1eV^2)?
* Constraints from LEP show that if such a particle exists, the corresponding extra flavor state must not be weakly interacting.
* → **A sterile neutrino?**

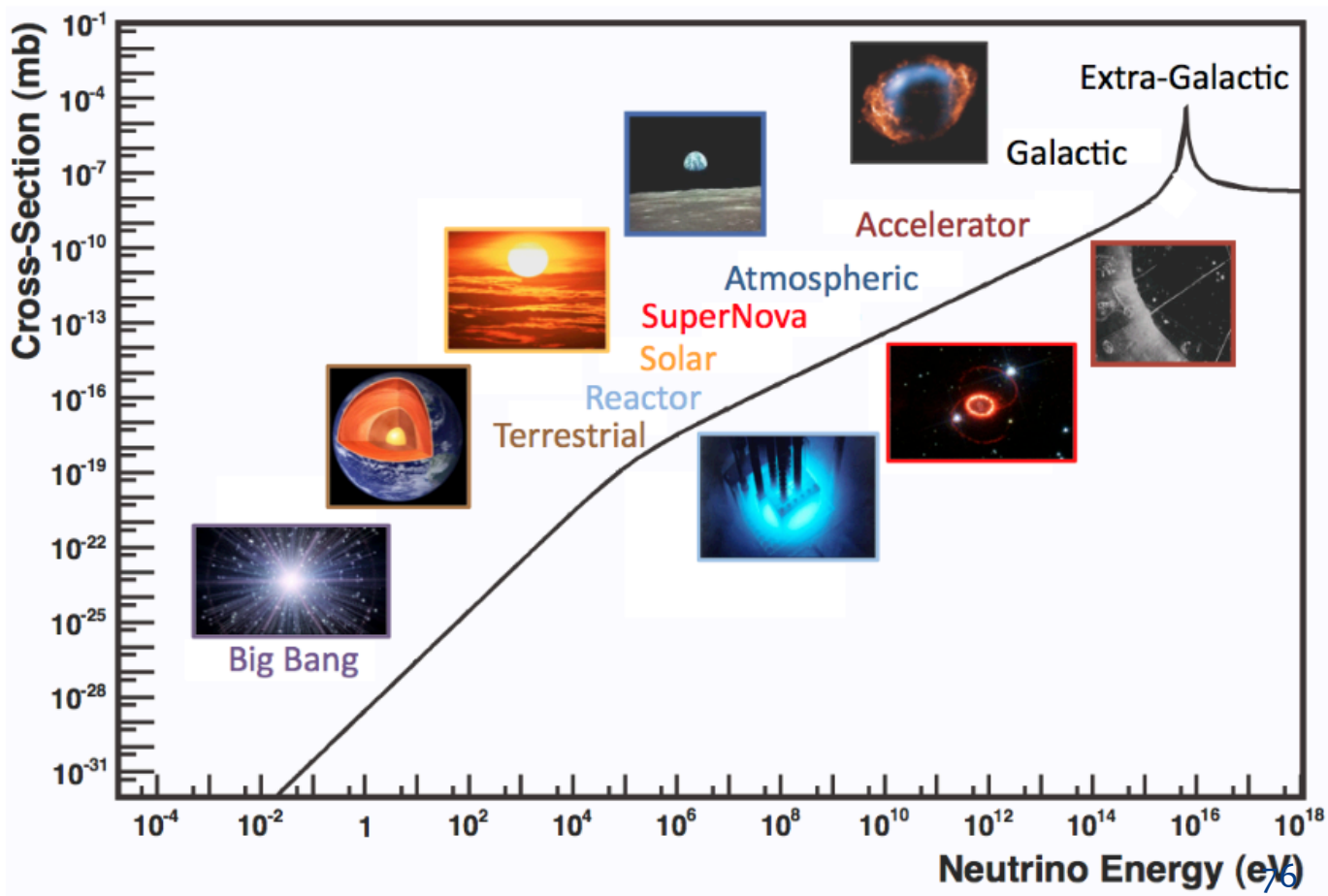


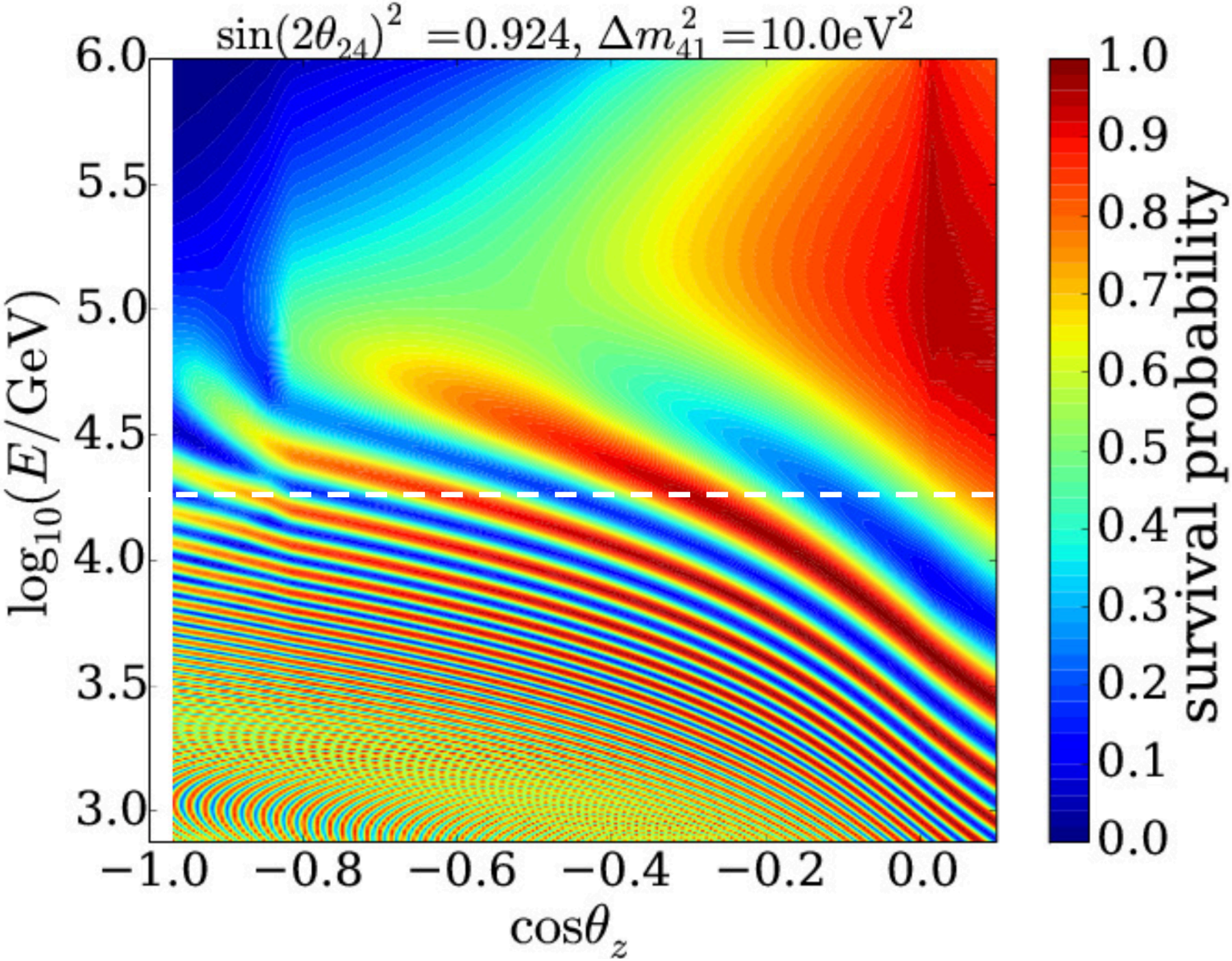
Neutrino Cross Sections

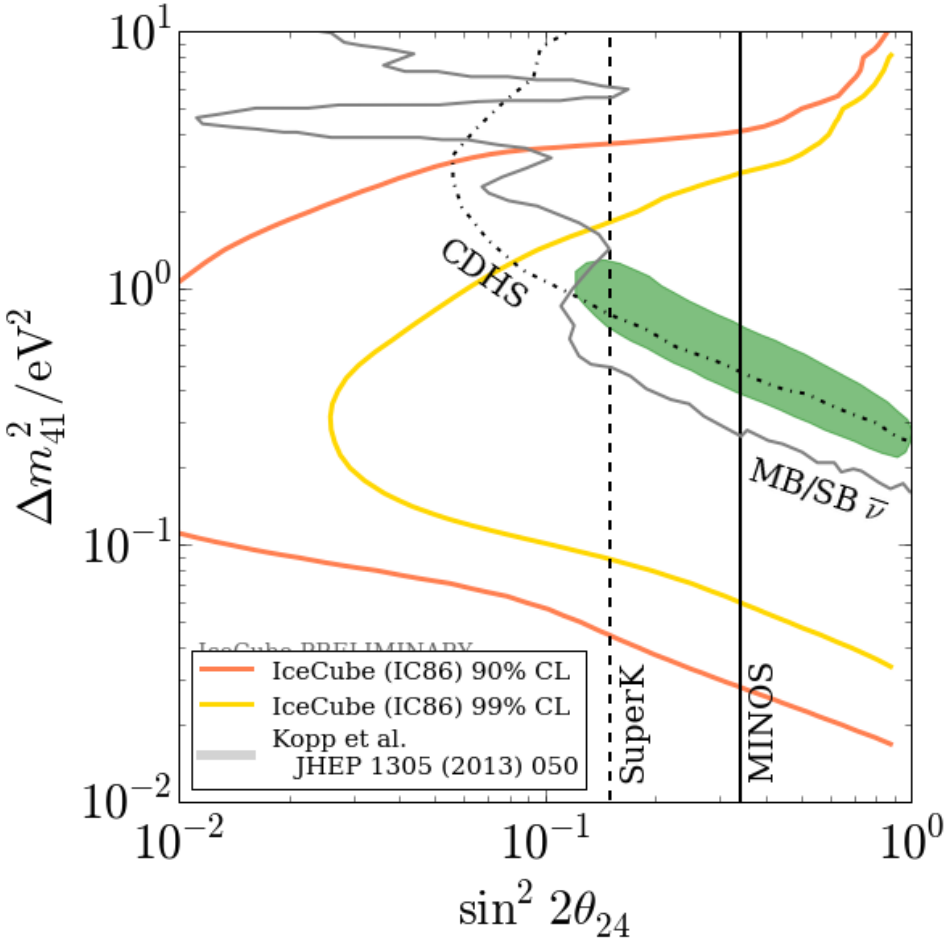
* Neutrinos interact very weakly, so g is very small
* Our experiments are typically more sensitive to refractive index than effects of incoherent scattering

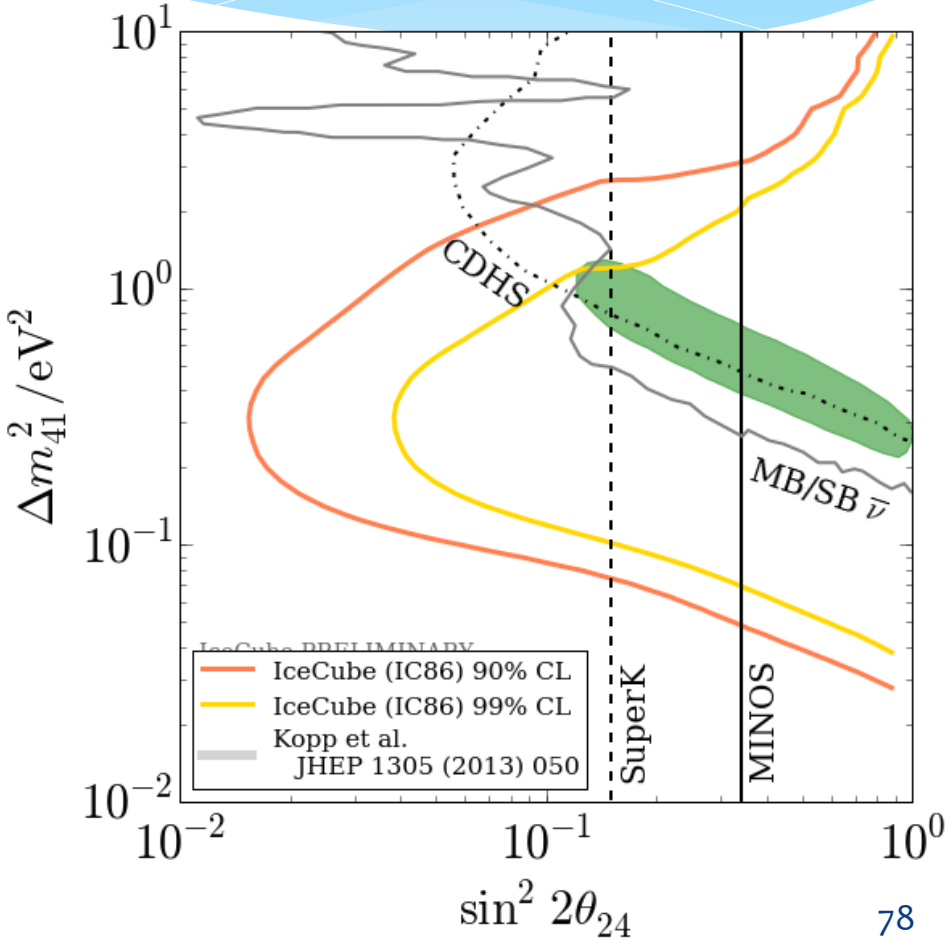
$$(n-1) \propto g$$

$$\sigma \propto g^2$$

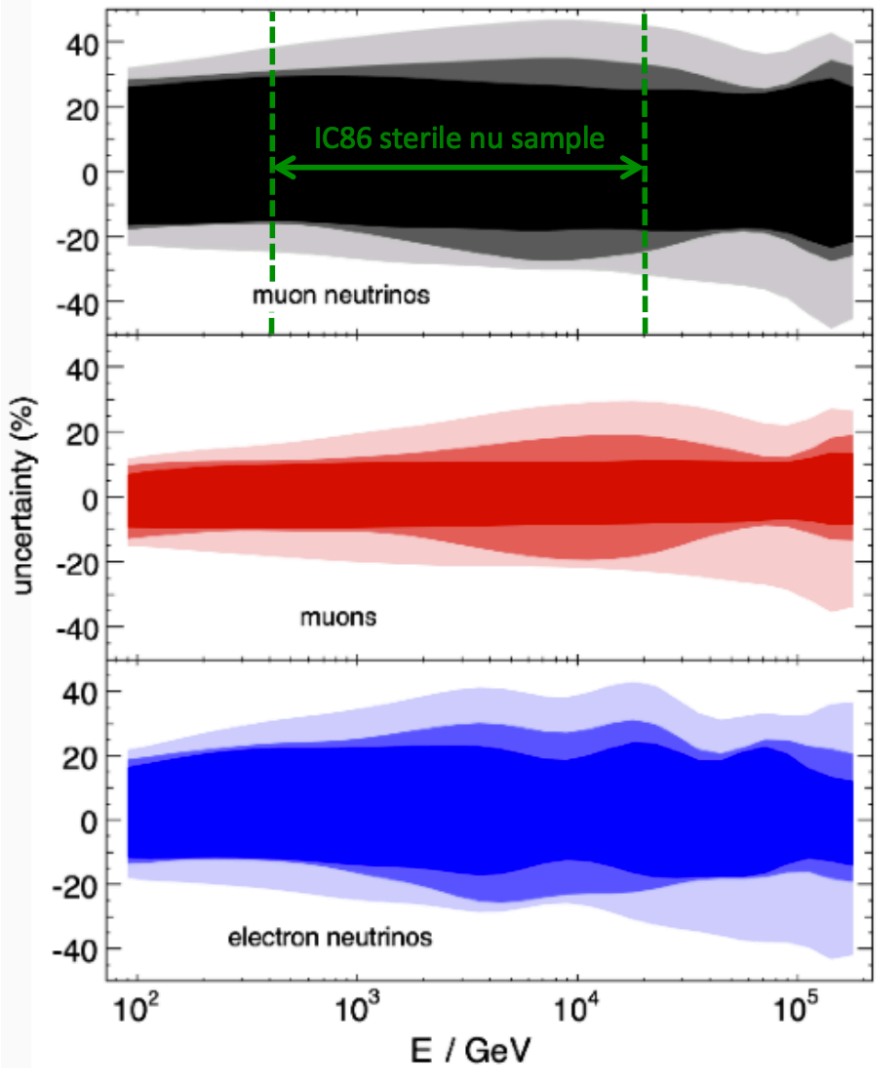



$\sin(2\theta_{24})^2 = 0.924$, $\Delta m^2_{41} = 10.0\mathrm{eV}^2$
6.0
5.5
5.0
4.5
4.0
3.5
3.0
$\log_{10}(E/\mathrm{GeV})$
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
$\cos\theta_z$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
survival probability

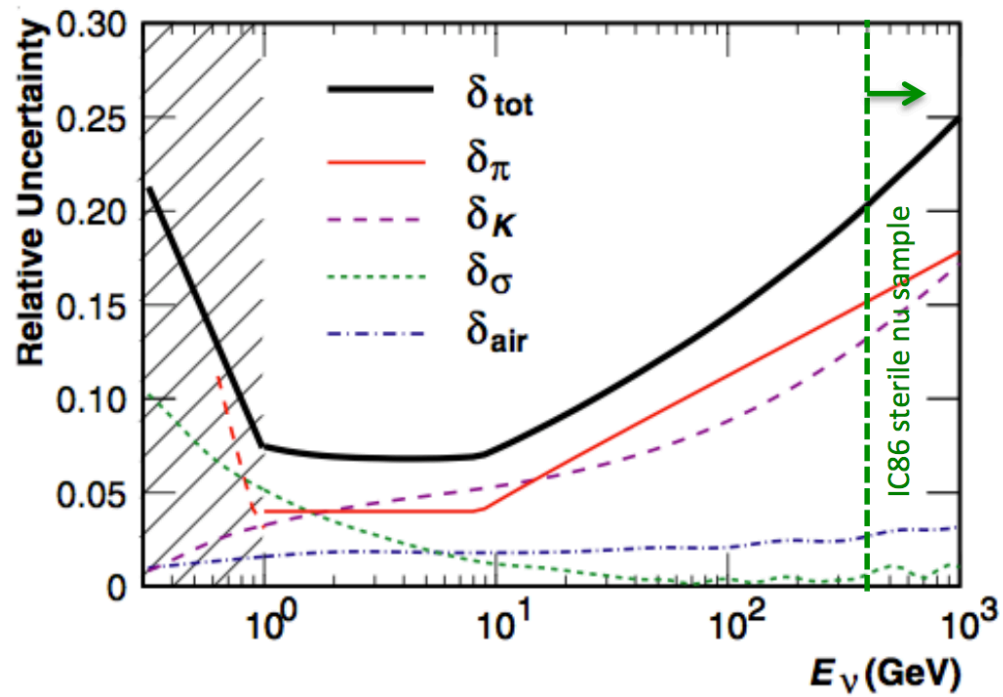

10^1
10^0
10^{-1}
10^{-2}
Δm^2_{41} /eV^2
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{24}$
CDHS
MB/SB $\bar{\nu}$
SuperK
MINOS
IceCube (IC86) 90% CL
IceCube (IC86) 99% CL
Kopp et al.
JHEP 1305 (2013) 050


10^1
10^0
10^{-1}
10^{-2}
Δm^2_{41} /eV^2
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta_{24}$
CDHS
MB/SB $\bar{\nu}$
SuperK
MINOS
IceCube (IC86) 90% CL
IceCube (IC86) 99% CL
Kopp et al.
JHEP 1305 (2013) 050

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



Phys. Rev. D86, p. 114 024, 2012.
Fedynitch et al



Phys. Rev. D75, p. 043006, 2007
Honda et al