IceCube and Sterile Neutrinos (pheno)

Jordi Salvado Serra

CrossTalk Workshop: The Fate of Sterile Neutrinos

VUB Sterile neutrinos 2017

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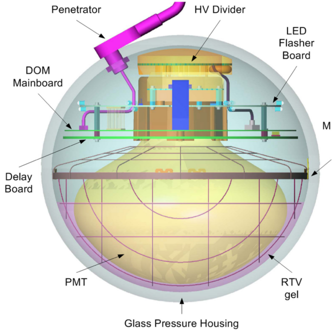
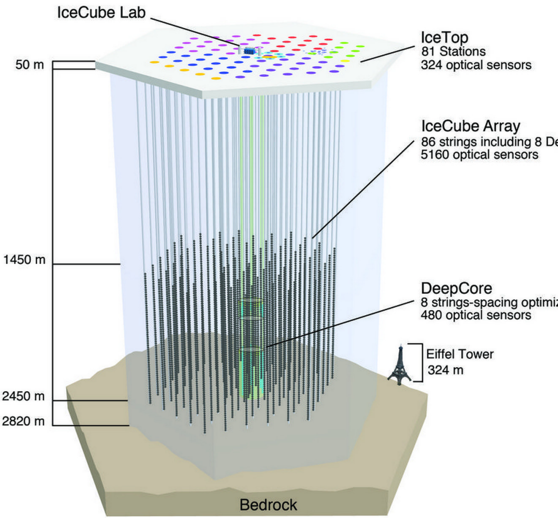
CSIC

The **IceCube** experiment.

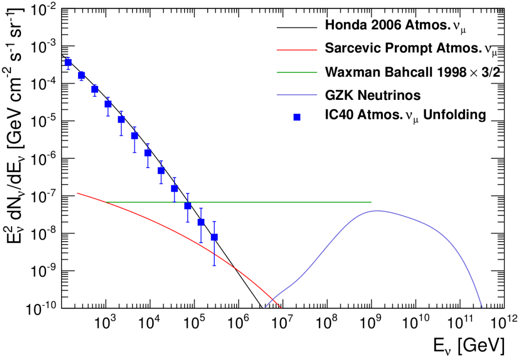
- 10^2 to 10^7 GeV
- $< 0.5^\circ$ μ angular resolution
- $< 15\%$ energy resolution



D.O.M.



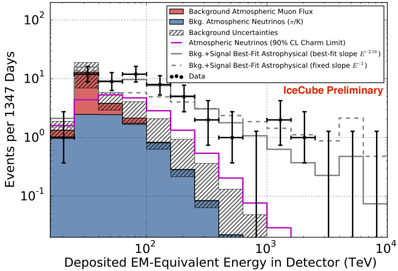
IceCube Goal

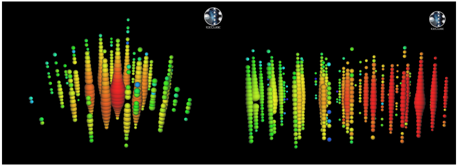


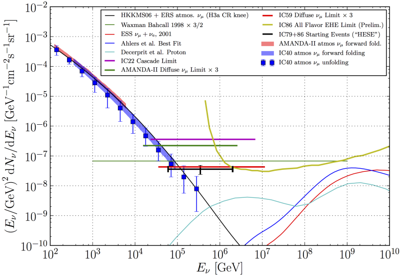
- Atmospheric Neutrinos
- Charm Atmospheric Neutrinos
- Astrophysical Neutrinos
- Cosmogenic Neutrinos

IceCube Goal

- More that 5σ evidence.
- Consistent with the other limits.
- Still a lot of questions.
- We have neutrinos from few 100GeV to few PeV
- Still a lot of questions







First Publication: Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

Science 342 (2013) 1242856

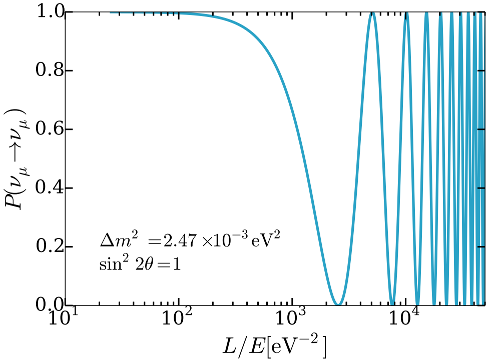
Neutrino Oscillations

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m$$

M, V and U are 3×3 matrices. In two generations the oscillation probability at a given distance L and energy E in vacuum

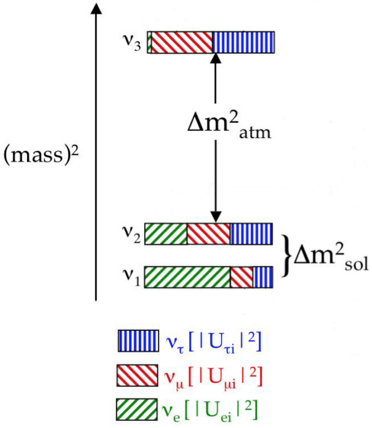
$$P_{\nu_\alpha \to \nu_\alpha}\left(\frac{L}{E}\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- $\sin^2 2\theta$: oscillation amplitude
- Δm^2: oscillation frequency
  - $L/E \ll 1/\Delta m^2 \to$ no oscillations
  - $L/E \sim 1/\Delta m^2 \to$ oscillations
  - $L/E \gg 1/\Delta m^2 \to$ fast oscillations ("averaged")



Neutrino Oscillations

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



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

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

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

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

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

[M.C. Gonzalez-Garcia et. al. JHEP 11 (2014) 052 www.nu-fit.org]

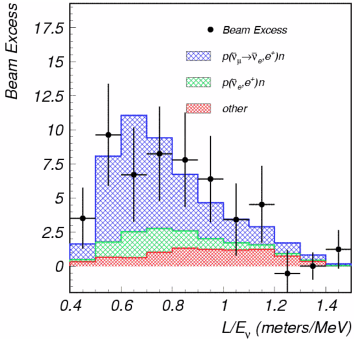
Beyond "standard" Neutrino Oscillations

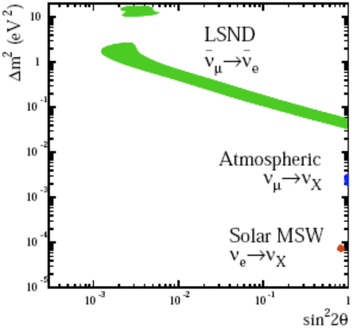
$$H = \frac{1}{2E} U M^2 U^\dagger + V_m + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

- A extension of the 3-ν model would imply:
  1. Extend the dimension 3+N or N+3: Motivated by the Short Base Line Neutrino Anomalies
  2. Extend with high powers of the energy: Not very motivated by anomalies but interesting to explore. NSI, LV,...

The LSND experiment (in 90's)

- The LSND experiment saw an excess of $\bar{\nu}_e$ over background.
- 3.8σ signal.





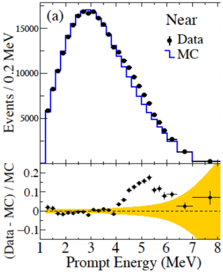
More motivation: short baseline anomalies

- **LSND** found $\bar{\nu}_\mu \to \bar{\nu}_e$ **oscillation** with $\Delta m^2 \sim 1eV^2$ and $\sin^2 2\theta \sim 0.003$

- MiniBoone $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
  - No significant excess at high energies (E > 475 MeV)
  - Unexplained events at low energies, interpretation as oscillations similar to LSND: $\Delta m^2 \sim 1eV^2$

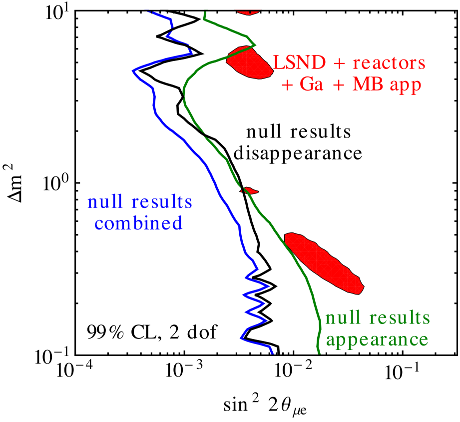
- Gallium Anomaly, SAGE and GALLEX event rates lower than expected, can be explained by ν_e disappearance with $\Delta m^2 \geq 1eV^2$

- New reactor flux calculation (Mueller et al., 1101.2663, P. Huber, 1106.0687) 3% higher, tension in short-baseline ($L \leq 100m$) experiments, can be explained by ν_e disappearance with oscillation with $\Delta m^2 \sim 1eV^2$. **BUT!!**→



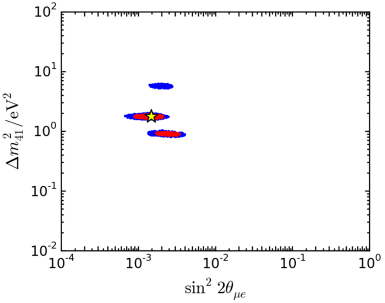
What does the World data say?

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



tension between experiments

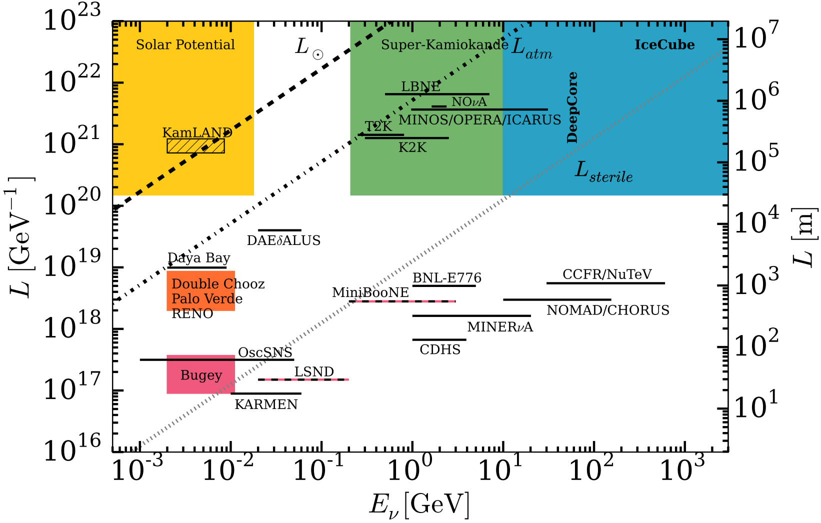
G. Collins et al., arXiv: 1602.00671



On updated fits solutions remain…

We need new measurements!

Experiments: $L_{\rm osc} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m^2_{\rm LSND} = 1 eV^2$



[modified from J.S. Diaz and V.A. Kostelecky, Phys.Lett. B700, 25 (2011)]

Matter effects: Mikheyev-Smirnov-Wolfenstein

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_M \sin^2 \left(\frac{\Delta {m_M}^2 L}{4 E_\nu} \right)$$

where θ_M and Δm_M^2 satisfy

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

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A}{\Delta m^2 \cos 2\theta}}$$

and $A = \pm 2\sqrt{2} E G_F N$, N number density. Resonant flavor transition can happen if

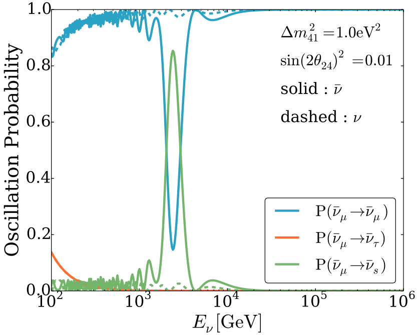
$$E_\nu^{res} = \mp \cos 2\theta \frac{\Delta m^2}{2N} \frac{1}{\sqrt{2} G_F}$$

this resonance can enhance the transition between active and sterile neutrinos.

MSW with the Sterile Neutrino at Earth

In the **Earth**, sterile neutrino with small mixing and $\Delta m^2 = O(1eV^2)$ the resonance happens when

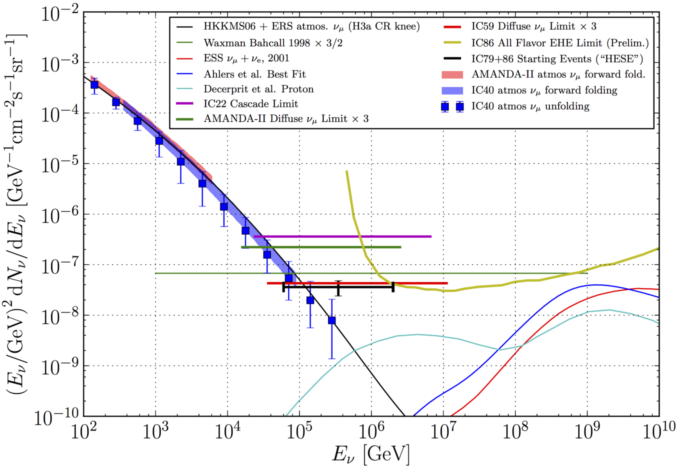
$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



M.V. Chizhov, S.T. Petcov. Phys.Rev. D63 (2001) 073003
H. Nunokawa et al. Phys.Lett. B562 (2003) 279-290
Barger et al.,Phys.Rev.D85:011302,(2012)
Arman Esmaili et al. JCAP 1211 (2012) 041

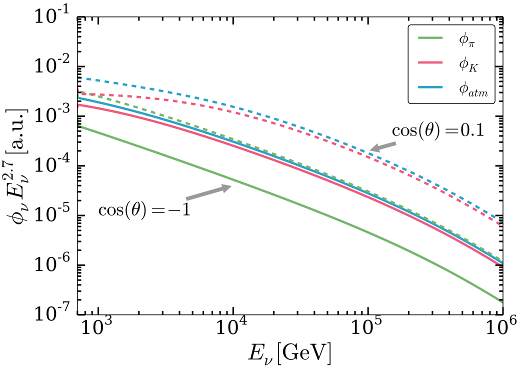
MSW with the Sterile Neutrino at Earth

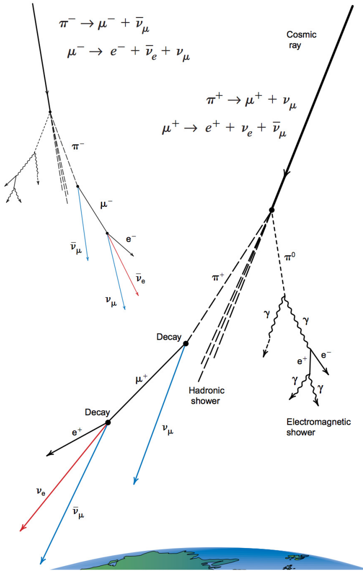
- TeV is in the center of the atmospheric data.
- Other experiments are not sensitive at this energies.



The **initial** atmospheric neutrino flux

The conventional atmospheric neutrino (muon) flux originates from the decay of $\pi^{\pm}$ and $K^{\pm}$ in the atmosphere.



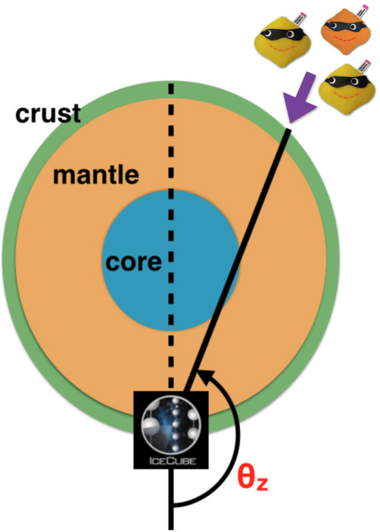


[Honda et al., Phys.Rev.D75:043006 (2007)]

[Louis et al., Los Alamos Science Number 25 (1997)]

Neutrinos through the Earth

The muon neutrinos come from different zenith angles (θ_z) transversing different Earth layers



core :

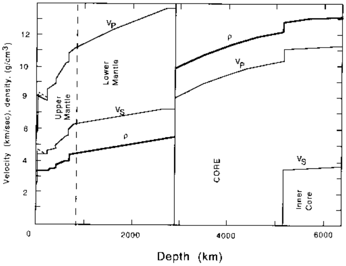
$\cos\theta_z \sim [-1, -0.8]$

mantle :

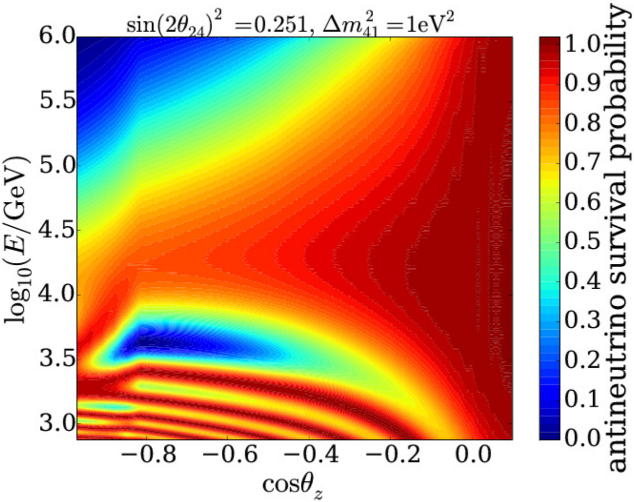
$\cos\theta_z \sim [-0.8, -0.1]$

crust :

$\cos\theta_z > -0.1$



3+1 Oscillogram



[Carlos Argüelles, J.S., C. Weaver. *SQuIDS*, CPC 2015.06.022.]

https://github.com/jsalvado/SQuIDS

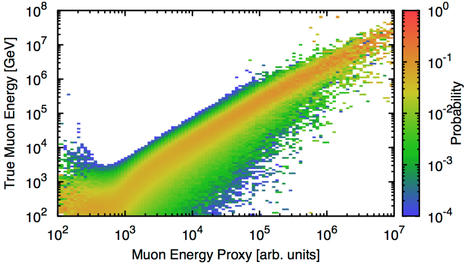
https://github.com/arguelles/nuSQuIDS

SQuIDS
Simple Quantum Integro Differential Solver

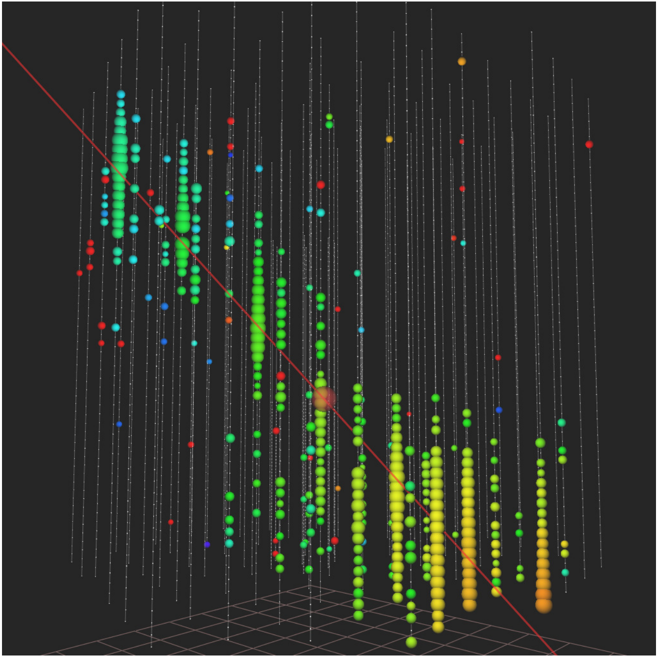
IceCube data set

We perform search using one year of **up-going** IceCube-86 high energy ν_μ data (Energy Range : 400 GeV to 20 TeV).

- Based on IC-86 diffuse astrophysical search cut-based event selection. [see arXiv:1507.04005, PRL 115, 081102 (2015)]
- Number of events $\sim$ 20000.
- Spans a zenith range from -1 to 0.2 in $\cos\theta_z$.
- 99% ν_μ purity.
- Blind Analysis

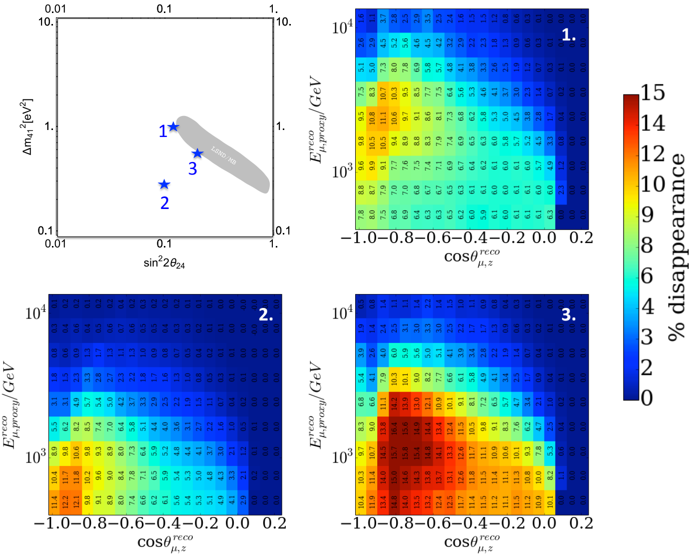


Muon event in IceCube



The Signal!

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

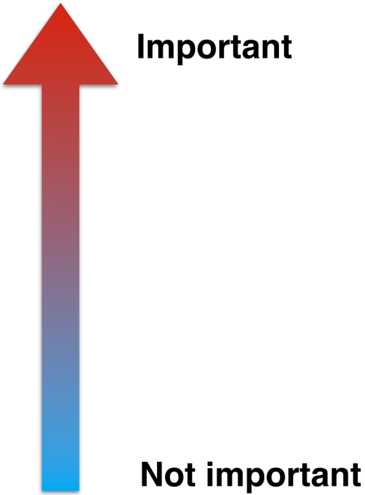


Systematics!

Systematics are very important; *some more than others*. This 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



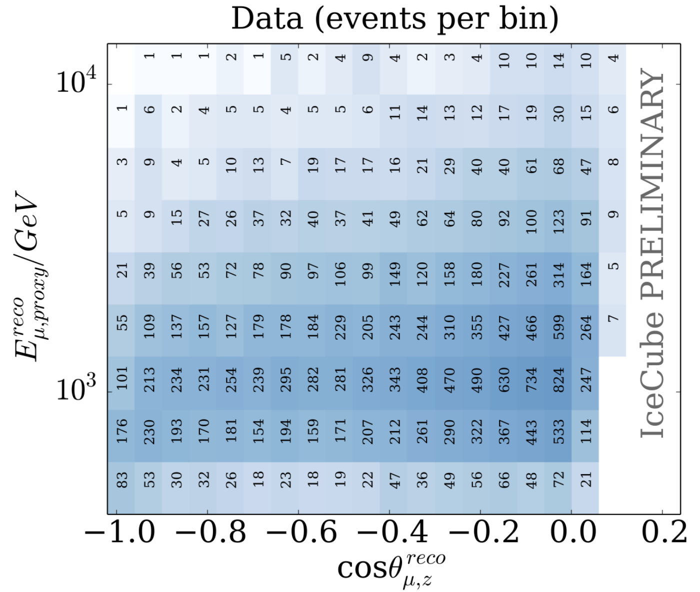
Flux Systematics!

We parametrize the atmospheric flux with the following systematics parameters

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

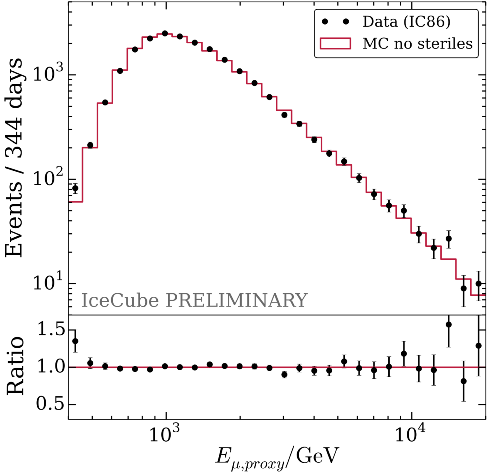
- Flux normalization (N_0): no prior.
- Atmospheric flux slope ($\Delta\gamma$): gaussian prior (0.,0.05).
- Pion/Kaon ratio ($R_{\pi/K}$): gaussian prior (1.0,0.1).
- atmospheric density uncertainty (δ): gaussian prior (0,0.05).
- $\nu/\bar{\nu}$ ratio: gaussian prior (1.,0.05).

1 year IC-86 data



How the fit looks

- We fitted the null hypothesis (no steriles) using the central sets (no variants) on the full 2D sample space.
- Blindness is preserved by only looking at projections.
- We recover a good fit and sensible nuisance parameters.



Parameter	Value	Prior
Normalization	1.02	No Prior
$\Delta\gamma$	0.05	G(0.,0.05)
DOMeff	0.985	No Prior
π/K	1.10	G(1.,0.1)
$\nu/\bar{\nu}$	1.0	G(1.,0.05)
δ	0.001	G(0.,0.05)

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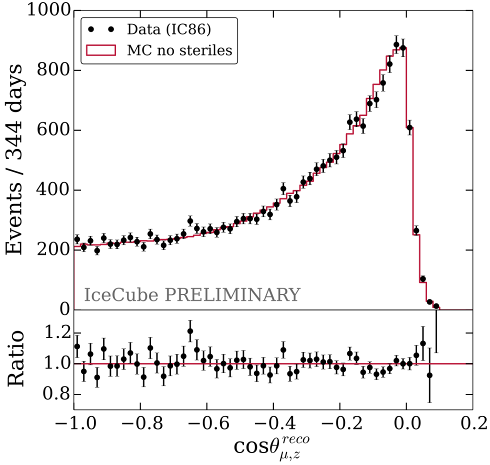

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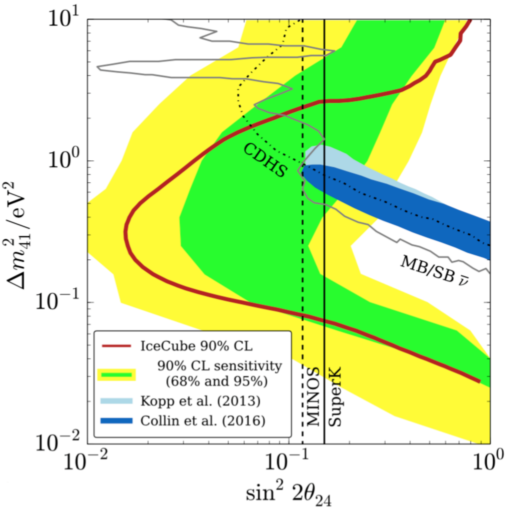
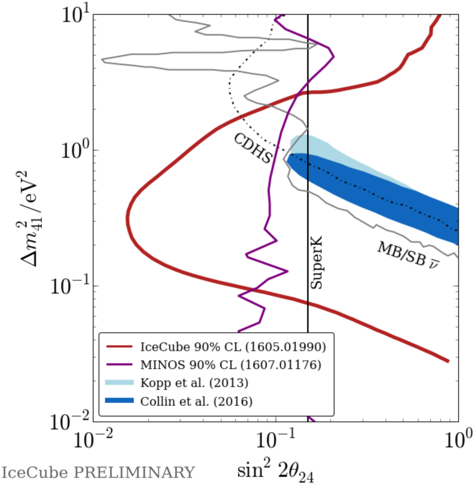
Main result!



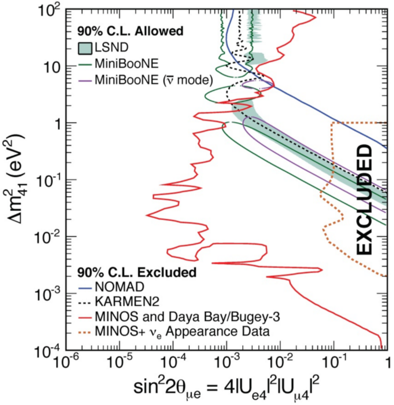
Phys.Rev.Lett. 117 (2016) no.7, 071801 [arXiv:1605.01990]

Other new results from *Neutrino2016*

MINOS



MINOS+Daya Bay



arXiv:1607.01176,1607.01177

Conclusions about the IceCube Sterile search

- The IceCube result excludes the main LSDN region at 99% CL.
- The tension is growing for the 3+1 O(eV) sterile neutrinos, but still the upper part survives.
- IceCube has more years of data to be analyzed and other experiments are in progress.

Questions About the Conclusions

- Is the anomaly "new physics"?
- The new IceCube result seams to point to NO.
  What do we need?
  - Is there a O(eV) (3+1) sterile? we need to be quantitative about the tension:today we know is 0.4×10^{-4} Global analysis talk by **Joachim**.

  Can we accommodate all(or only IceCube with other positive)?

  - May be is not O(eV) (3+1):
    - ✗ More light Steriles: The neutrino matter effects behind the IceCube power are well established and any oscillation physics with O(eV) masses would be potentially detectable.
    - ✓ Some other new physics hides the IceCube signal.
      Using NSI Phys.Rev.Lett. 117 (2016) no.7, 071802 *Jiajun Liao, et al.*
    - ✓Decay of heavy steriles O(KeV), IceCube bound not relevant since there is not matter effect enhancement.
      JHEP 0509 (2005) 048 Sergio Palomares, et al.
      Phys.Rev. D93 (2016) no.7, 073004 Yang Bai, et al.
- We still need more experiments!

Don't forget the second new physics extension (*n*-powers of E)

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

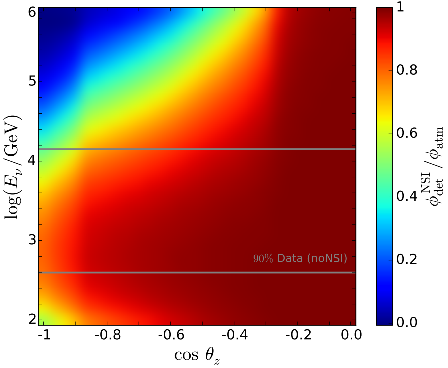
- $O_n = \mathrm{diag}(O_{n,1}, O_{n,2}, O_{n,3})$
- $V_m = \mathrm{diag}(V_e, 0, 0)$
- $\Delta = \mathrm{diag}(\Delta_1, \Delta_2, \Delta_3)$

O_n and Λ_n set the scale of the new physics.

Non-Standard Interactions (NSI) $n = 0$ *with ordinary matter*

$$H = \frac{1}{2E_\nu} U M^2 U^\dagger + V_m + \sum_f V_f \, \varepsilon^{fV}$$

- $V_m = \mathrm{diag}(V_e, 0, 0)$
- $\varepsilon_{\alpha\beta} \propto \sum \frac{n_f}{n_d}$
- IceCube is more sensitive to the $\mu\tau$ sector.
- The effect is proportional to the density crossing the earth
- The plot shows the ratio between the final and initial flux

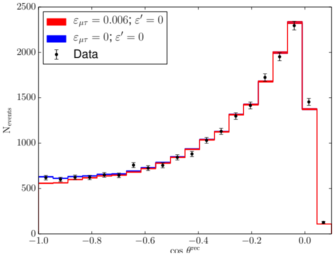


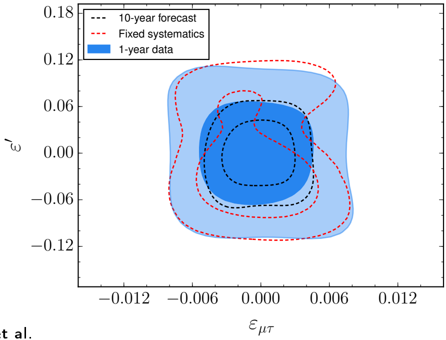
arXiv:1609.03450 JS., et al.

Non-Standard Interactions (NSI) $n = 0$ *with ordinary matter*

With the Atmospheric neutrinos (sterile DATA)

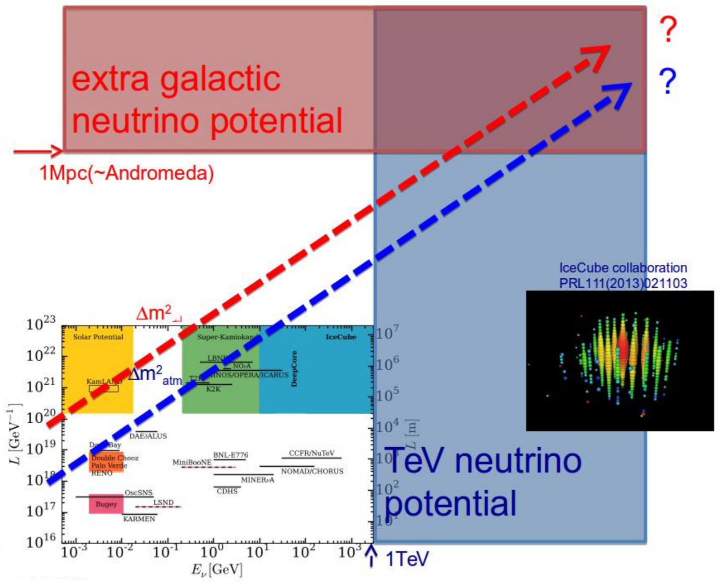
- Effect on the zenith distribution.
- The IceCube atmospheric data gives the strongest bound in the $\varepsilon_{\mu\tau}$ sector.





arXiv:1609.03450 JS., et al.

Wouldn't be great to use astrophysical ν !??



New Physics with Astrophysical Neutrinos

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

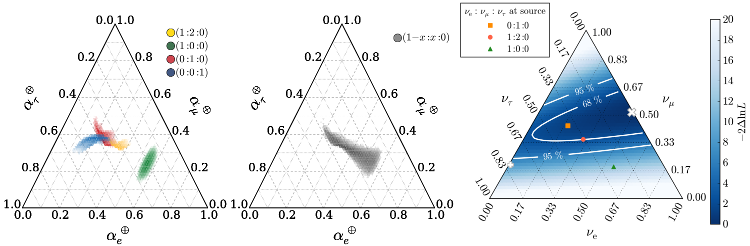
- High energy(PeV) and long propagation distance(Mpc) enhance the effect
- But we don't know the spectrum at the source

n	New Physics	Current Bound From SK and IC-atm
0	CPT-odd Lorentz Violation Coupling space time torsion Non Standard Neutrino Interactions	$O_0 < 10^{-23}$GeV
1	CPT-even Lorentz Violation Violation of the equivalence principle	$O_1/\Lambda_1 < 10^{-27}$

New Physics with Astrophysical Neutrinos

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger$$

- High energy(PeV) and long propagation distance(Mpc) enhance the effect
- But we don't know the spectrum at the source
- **The flavor content may be the answer**

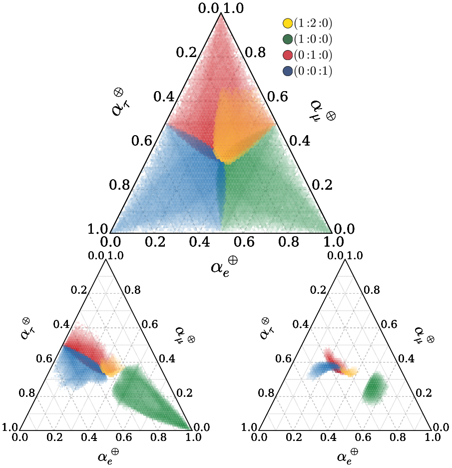


Phys.Rev.Lett. 115 (2015) 161303

(IC Col.) Phys. Rev. Lett. 114, 171102

(Olga Mena et al. Phys.Rev.Lett. 113 (2014) 091103

Astophysical neutrinos effect



- Top Value at the Current Bound
  Already maximal effect!
- Bottom-Left $O(10^{-3})$ times the Current Bound
  Potentially measurable
- Bottom-Right $O(10^{-5})$ times the Current Bound
- Source information is preserved.

Conclusions

- IceCube put the strongest constrain in the relevant light sterile neutrino parameter space. (There is more data and other experiments!)
- The resonance between oscillation frequency and the matter potential is behind the strength of IceCube: May be is not an oscillation! (Ex: decay,....)
- More IceCube data **together with** other experiment **may solve this**
- From the sterile technology: High energy atmospheric neutrinos may constrain other BSM physics (NSI, Lorentz Violation, ...).
- The flavor triangle matters!:The flavor content may explore new physics even not knowing the source. About three orders of magnitude! improvement.
- Astrophysics flavor information is relatively preserved.
- Great near future: Several years of data are already there to be analyzed, IceCube extensions and other experiments are planed.

¡Thanks!