New Physics in Astrophysical Neutrino Flavor

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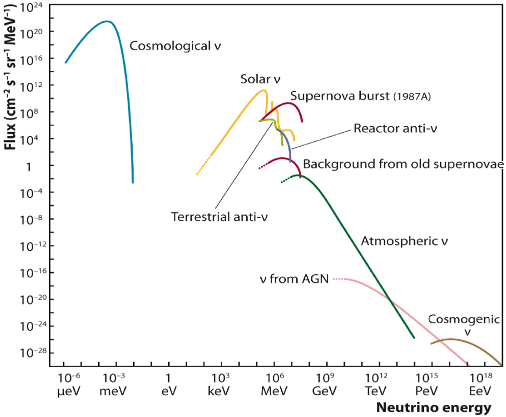
Talk based on: Phys.Rev.Lett. 115 (2015) 161303 [arXiv:1506.02043]

In collaboration with **Carlos Argüelles** and **Teppei Katori**

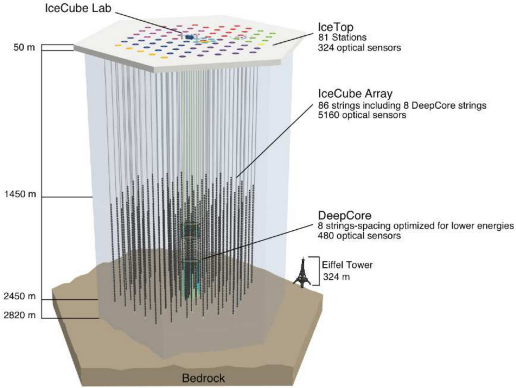
NuFact 2016

Introduction



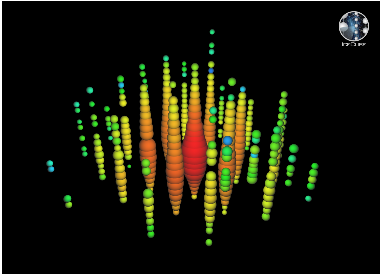
1. We measure neutrinos spread more than 21 orders of magnitude in energy.
2. The last years IceCube saw the first events in the high energy tail.

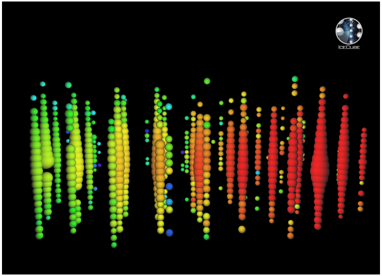
IceCube Results



- $1 \mathrm{km}^3$ volume
- 86 string
- 5160 PMTs

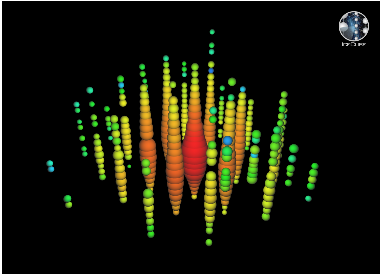
Introduction

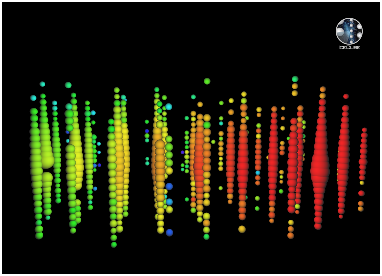




1. For the first time we measure Ultra High Energy Extraterrestrial neutrinos!
2. In 4 Yrs 54 events above 20TeV(Deposited)
3. The origin and nature of this neutrinos remains UNKNOWN!

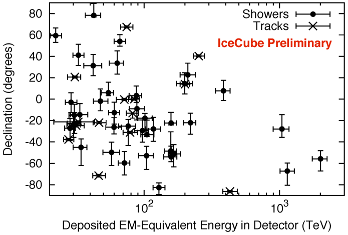
Detection Physics

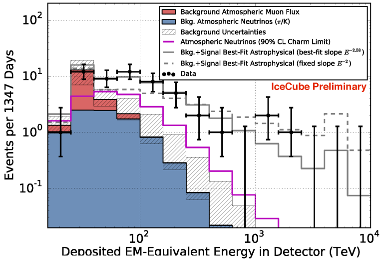


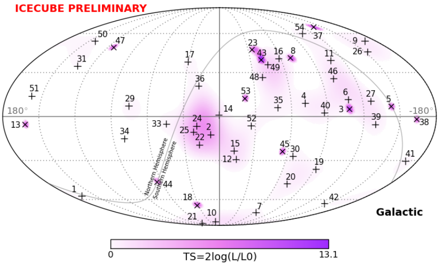


1. In the data we can distinguish two event topologies.
    - Tracks, produced by a ν_μ via CC interaction.
    - Cascade, produced by all the ν in NC or by ν_e and ν_τ CC.
2. The $\bar{\nu}_e$ may produce cascade events via the Glashow resonance $\approx 6PeV$

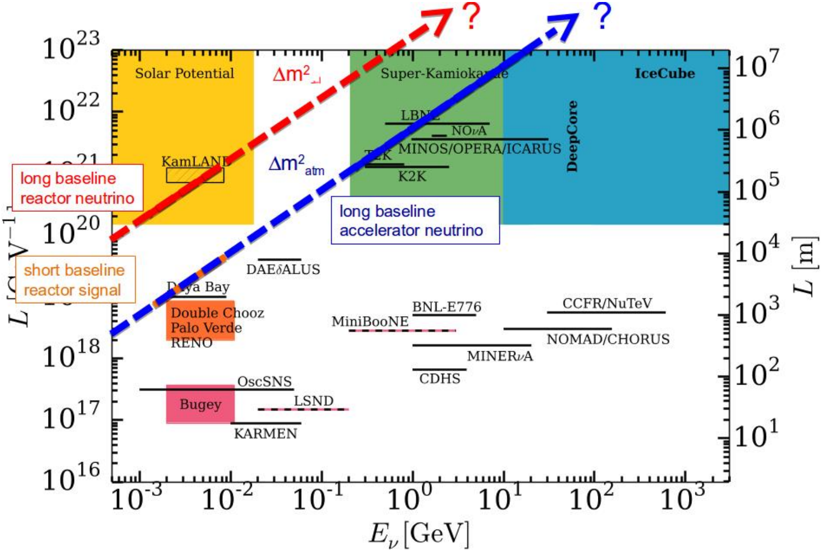
Data


Showers
Tracks
IceCube Preliminary
Declination (degrees)
Deposited EM-Equivalent Energy in Detector (TeV)

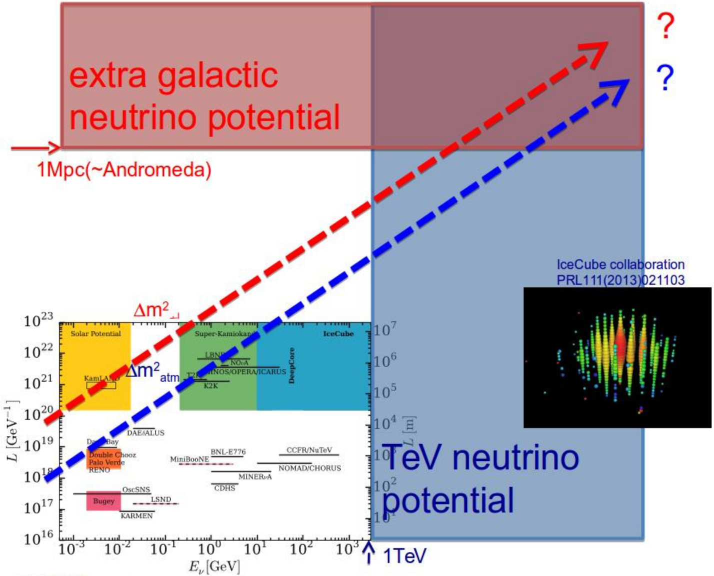

Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
Data
IceCube Preliminary
Events per 1347 Days
Deposited EM-Equivalent Energy in Detector (TeV)


ICECUBE PRELIMINARY
Northern Hemisphere
Southern Hemisphere
Galactic
TS=2log(L/L0)

Exploring new physics



Exploring new physics

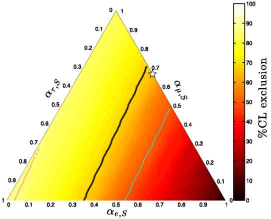


Flavor content of the Extraterrestrial Neutrinos

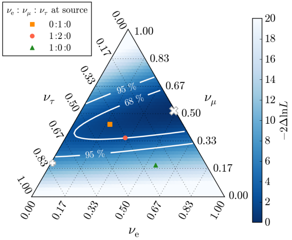
- Flavor content, is the ratio of the events that are electron, muon and tau neutrinos in the arrival flux.

Flavor content of the Extraterrestrial Neutrinos

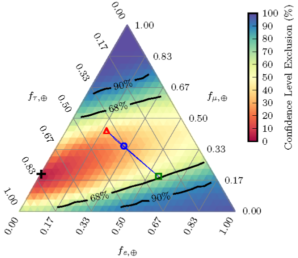
(Olga Mena, et al.) Phys.Rev.Lett. 113 (2014) 091103



(IceCube Collaboration) Phys. Rev. Lett. 114, 171102



(IceCube Collaboration)



- Measuring the flavor content is hard!
- It may depend in details about the energy spectrum. (Olga et al. arXiv:1502.02649)

Flavor content of the Extraterrestrial Neutrinos

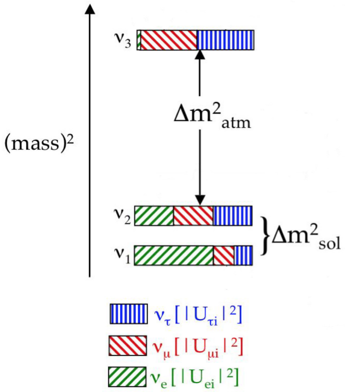
Details of the analysis that may effect the flavor ratio, and I'm not going to talk about

- Miss identification(Track-Cascade)
- Energy spectral index
- Cut-off in energy(especially before the Glashow resonance $\approx O(6PeV)$)
- ν anti $\bar{\nu}$ ratio
- We need a lot more statistics

IceCube extension needed, In the following we assume we have a measure, not necessarily very strong

Neutrino oscillations

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



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

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

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

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

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

Flavor content after propagating for long

- The propagation distance is much longer than the oscillation length.

$$\bar{P}_{\nu_\alpha \to \nu_\beta}(E) = \sum_i |U_{\alpha i}(E)|^2 \, |U_{\beta i}(E)|^2 \ \ ,$$

- U is the unitary matrix that relates the propagation and flavor eigenstates.

New Physics in ν Oscillations

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

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

O_n and Λ_n set the scale of the new physics.

New Physics in ν Oscillations

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

This is very generic, some examples are:

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	$O_1/\Lambda_1 < 10^{-27}$

Theory:

V. De Sabbata and M. Gasperini, Nuovo Cim. A65, 479 (1981)

V. A. Kostelecky and M. Mewes, Phys.Rev. D69, 016005 (2004), hep-ph/0309025

S. Glashow, A. Halprin, P. Krastev, C. N. Leung, and J. T. Pantaleone, Phys.Rev. D56, 2433 (1997), hepph/9703454

J. S. Diaz, A. Kostelecky, and M. Mewes, Phys.Rev. D89, 043005 (2014), 1308.6344

Best bounds:

K. Abe et al. (Super-Kamiokande), Phys.Rev. D91, 052003 (2015), 1410.4267

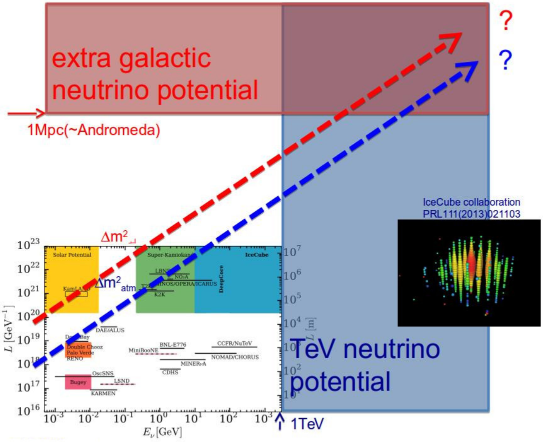
R. Abbasi et al. (IceCube), Phys.Rev. D82, 112003 (2010), 1010.4096

Is a Big Community

Made by Teppei

Exploring new physics

$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger = V^\dagger(E) \Delta V(E) \qquad (3)$$



Showing the effect in the Flavor Ratio

Showing the effect is not trivial:

1. Not only the strength of the new physics is not known but also the flavor structure (new Mixing Matrices $\tilde{U}$)
2. PMNS mixings have errors

Prescription

1. We use what we call anarchic sampling. The idea is use a flat prior in the Haar measure of $SU(3)$ for the mixing matrices to show the posterior probabilities in the flavor triangle(think Bayesian).[1]

$$d\tilde{U}_n = d\tilde{s}^2_{12} \wedge d\tilde{c}^4_{13} \wedge d\tilde{s}^2_{23} \wedge d\tilde{\delta} \ , \tag{4}$$

[1] This measure is the one used to show the possible anarchic origin of the standard mixing matrix. (L. J. Hall, H. Murayama, and N. Weiner, Phys.Rev.Lett. 84, 2572 (2000), hep-ph/9911341)

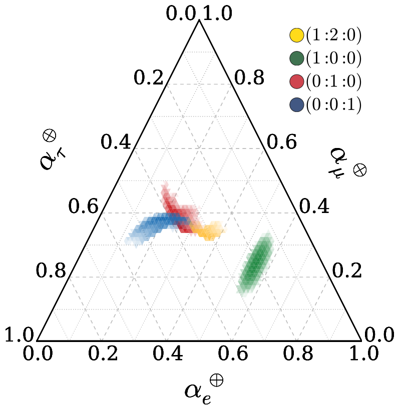
Showing the effect in the Flavor Ratio

Initial Fluxes:

- Pion Decay and Muon Energy Lost $(1:0:0)$
- Neutron Decay $(0:1:0)$
- Charged Pion Decay $(1:2:0)$
- Production of ν_τ $(0:0:1)$, non know mechanism

Result for the standard oscillation parameters

Result for different initial flavor content, and for a linear combinations. Only standard ν physics, www.nu-fit.org

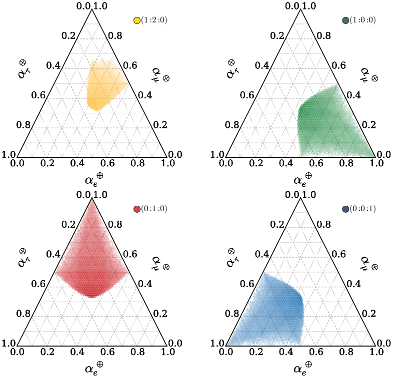


- Even not knowing the initial flux, the final ratios are in a relatively small region!

New Physics Dominated Effect

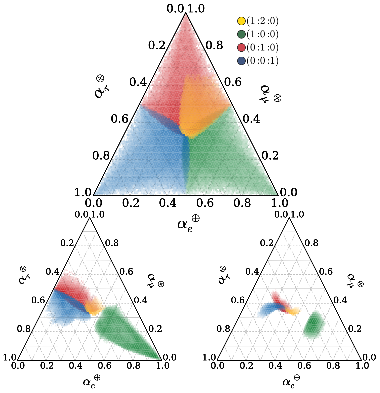
Result for different initial flavor content in the case dominated by new physics

$$H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger = V^\dagger(E) \Delta V(E) \qquad (5)$$



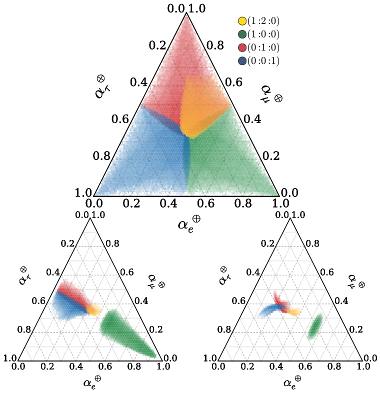
- Even in the New Physics dominated case not all the flavor ratio space is reachable for each initial flux.
- Therefore, even having new physics the measure of the flavor content is giving important information about the flavor ratio a the source.

Intermediate Case for $n = 0$



1. Top $O_0 = 10^{-23}$ Current Bound
   Already maximal effect!
2. Bottom-Left
   $O_0 = 3.6 \times 10^{-26}$
   Potentially measurable
3. Bottom-Right
   $O_0 = 6.3 \times 10^{-28}$
   I don't think so

Intermediate Case for $n = 1$

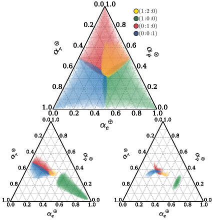


The power is not so important, same conclusions

1. Top $O_1/\Lambda_1 = 10^{-27}$ Current Bound
2. Bottom-Left $O_1/\Lambda_1 = 1.0 \times 10^{-30}$
3. Bottom-Right $O_1/\Lambda_1 = 3.2 \times 10^{-34}$

Conclusions

1. The flavor content of the astrophysical neutrinos may give very important information about a wide range of new physics scenarios.
2. Some information about the production flavor content is always preserved.
3. The current bounds on this operators produce the maximum effect in the flavor content observable i.e. any trustable measure of the flavor content will put the strongest bounds on the new physics operators.
4. 2 and 3 imply that a precise measurement of the flavor content will answer in a orthogonal way questions about production and propagation. The following positive scenarios are possible and discernible:



- Pion Decay and Muon Energy Lost + new physics (upper corner)
- Neutron Decay + new physics (lower right corner)
- Charged Pion Decay + new physics (middle right)
- Production of ν_τ + new physics. (lower left corner), it may imply new physics also in the production.