

On the flavor composition of the high-energy neutrino events in IceCube

based on

O. Mena, SPR and A.C. Vincent, arXiv:1404.0017, submitted to PRL

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XXX International Workshop on High Energy Physics
Protvino, June 26, 2014



WHY DO WE CARE ABOUT HIGH-ENERGY NEUTRINOS?

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Extreme energies allow studies of neutrino cross sections beyond the reach of terrestrial accelerators

THE ICECUBE TELESCOPE

At the South Pole

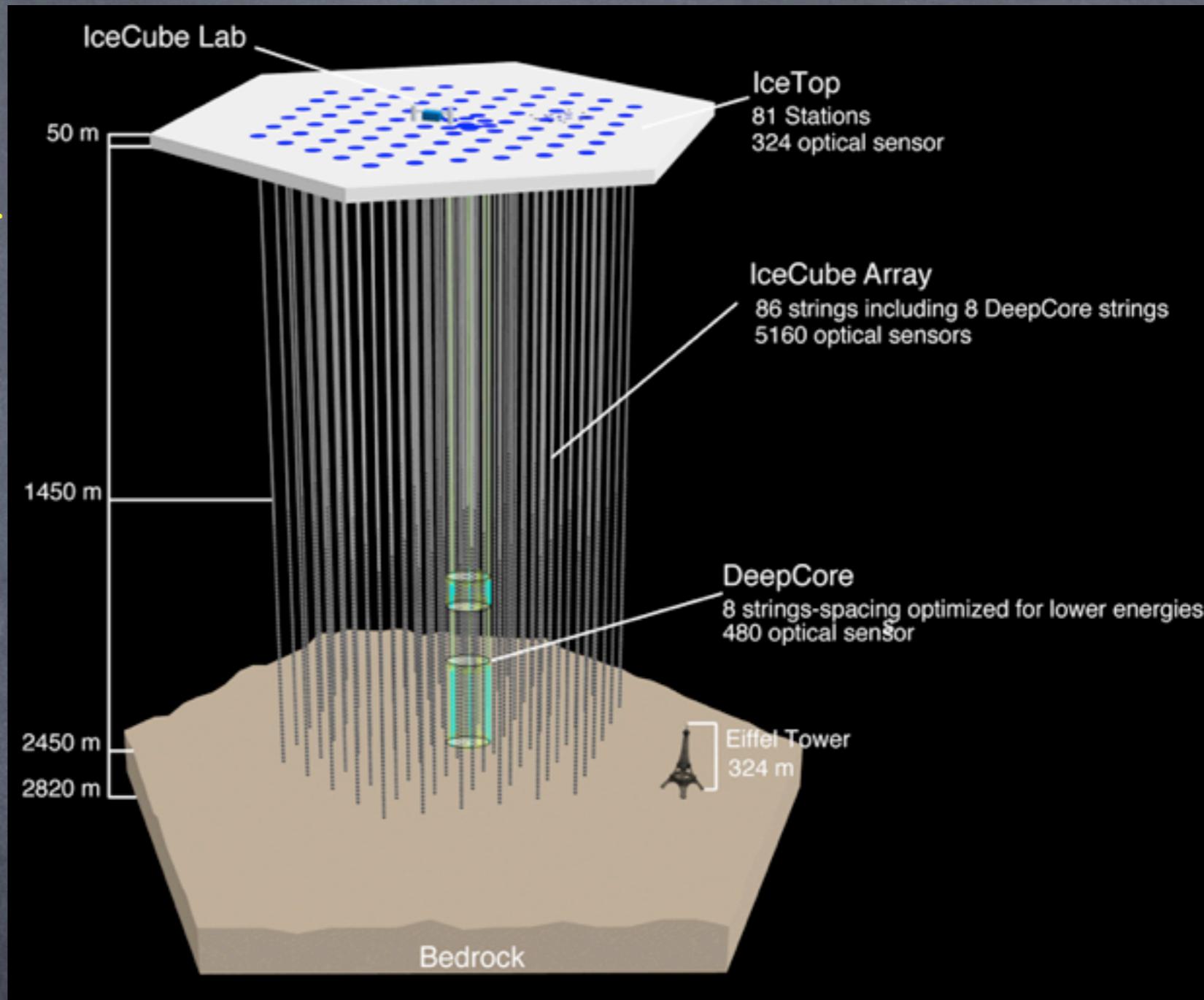
86 strings with 60 DOM/string
125 m apart on triangular grid

17 m vertical spacing between
PMTs

8 DeepCore strings 75 m apart

81 IceTop stations: two tanks/
station, two DOMs/tank

completed in 2010

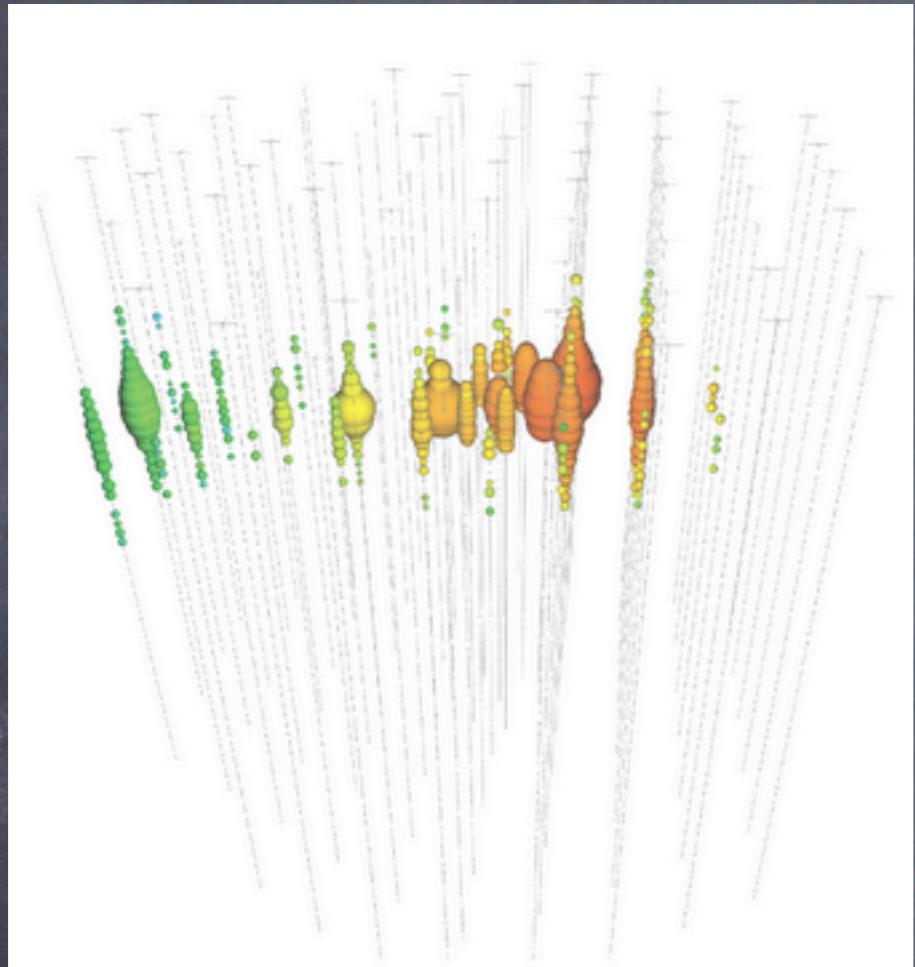


Secondary particles detected via Cherenkov radiation

TYPE OF EVENTS

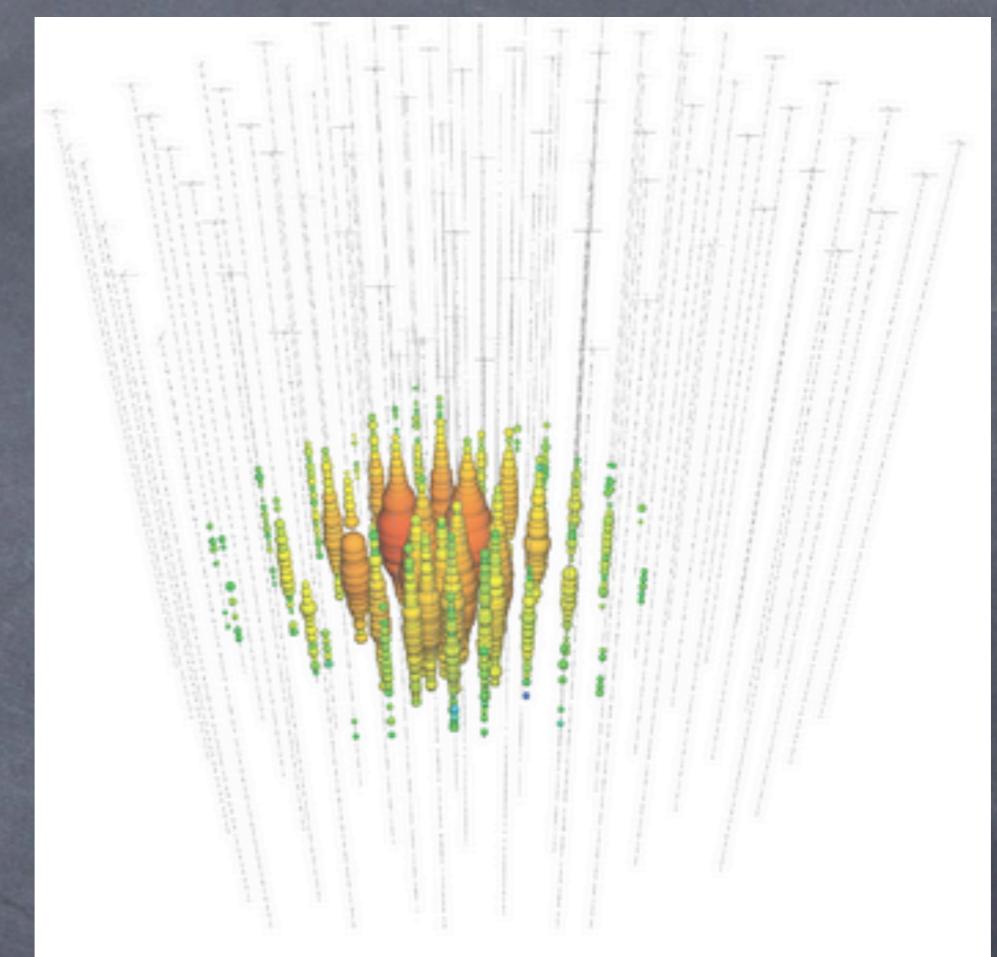
Muon tracks

Showers



CC $\nu_\mu + 18\%$ CC ν_τ

Good angular resolution



NC + CC $\nu_e + 82\%$ CC ν_τ

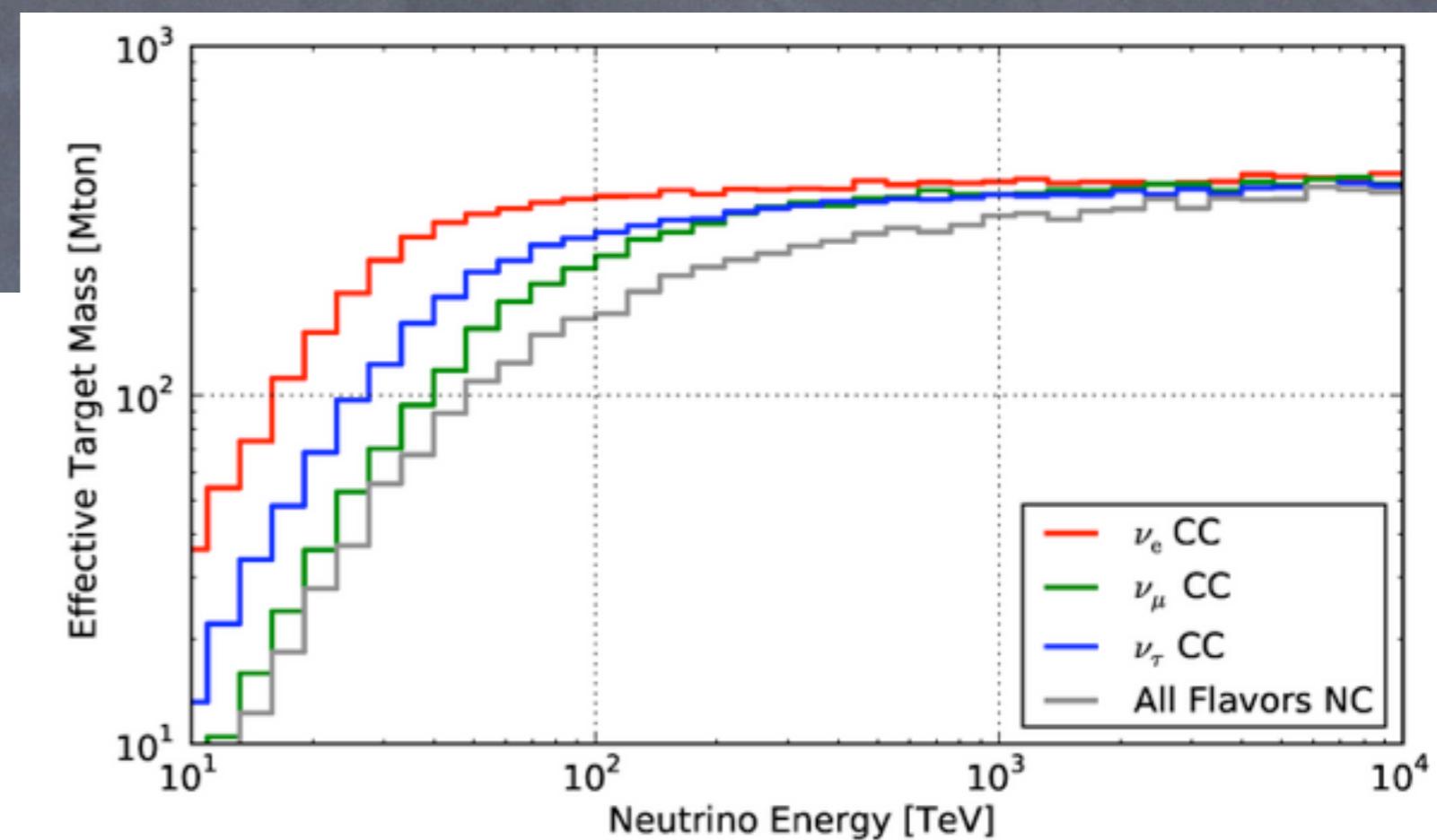
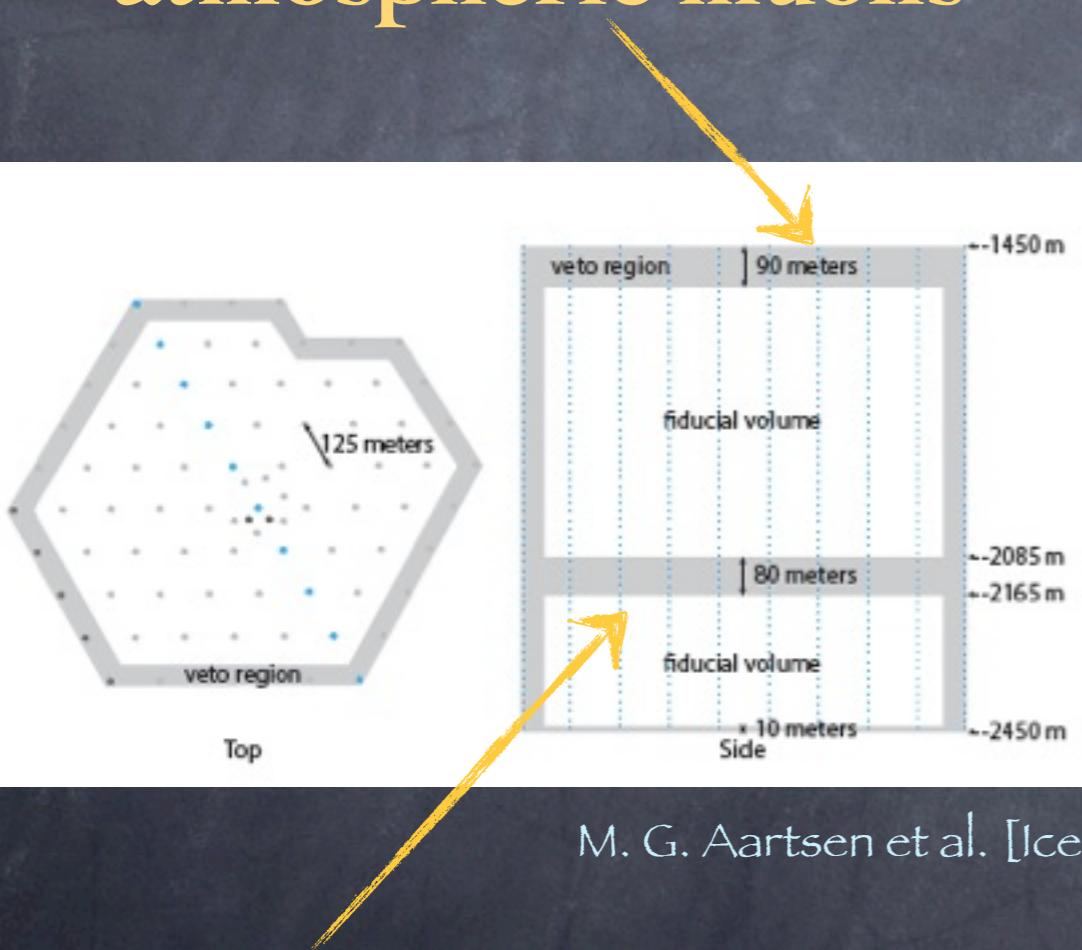
Poor angular resolution

Backgrounds: atmospheric muons and neutrinos

EFFECTIVE MASSES

~400 Mton effective target mass

Rejection of
atmospheric muons

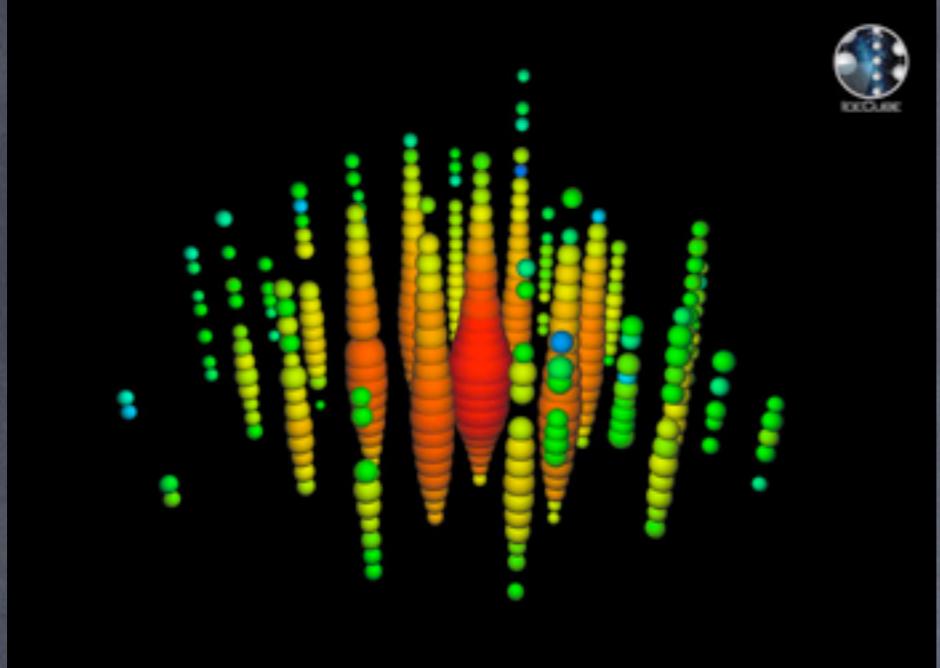


M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

High dust concentration

THE FIRST PEW NEUTRINOS

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 111:021103, 2013

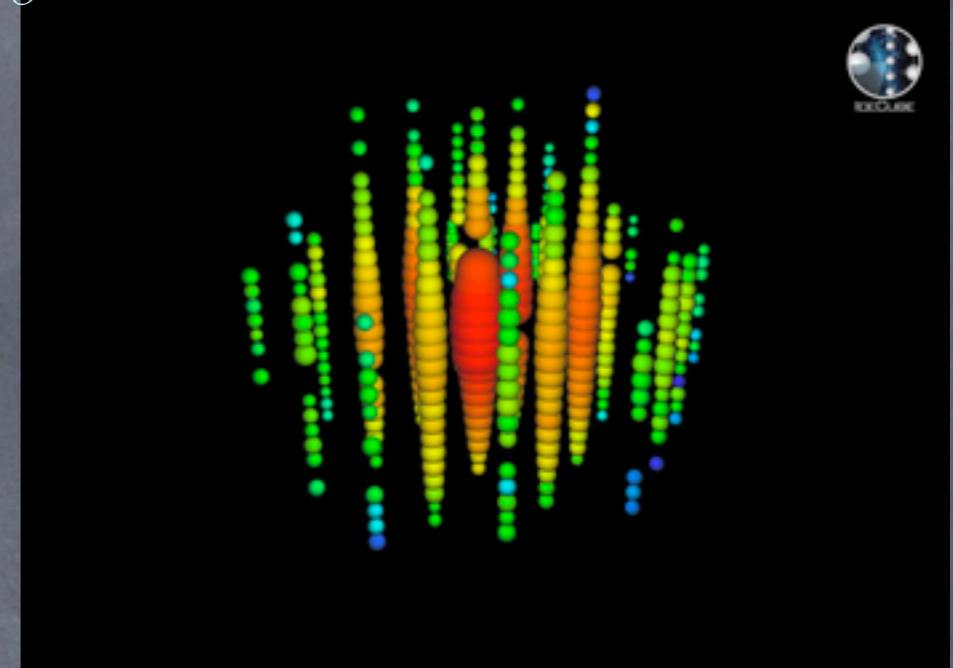


January 3, 2012: 1.14 PeV
Ernie/Еник

(or Epi, Egas, Ernesto, Ènio, Ernest, Enrique,
Erling, Edi, Emil, Arik, Shadi, Anis...)



Sergio Palomares-Ruiz



August 9, 2011: 1.04 PeV
Bert/Влас

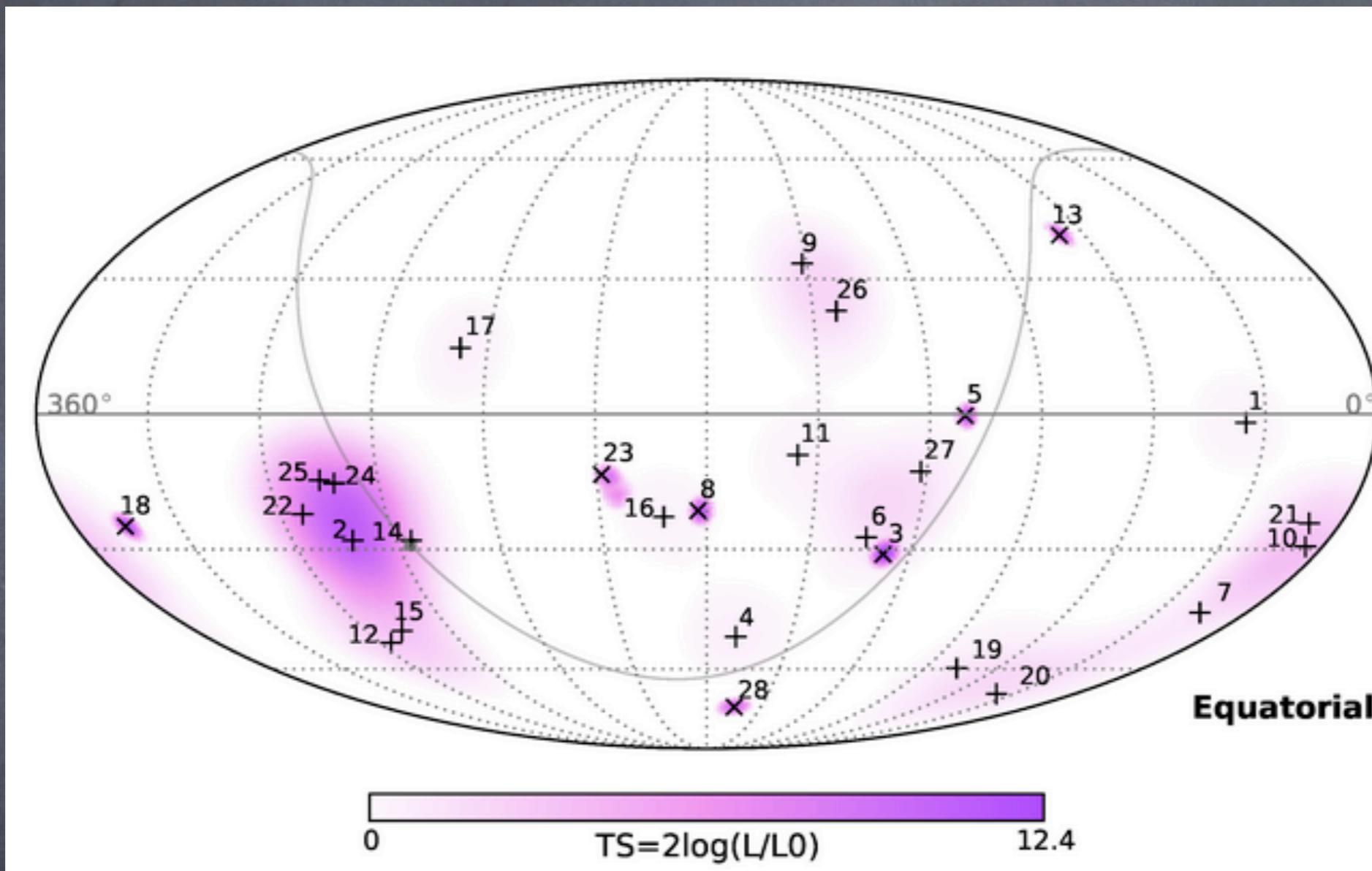
(or Blas, Becas, Berto, Beto, Bart, Bernt,
Büdü, Hubert, Bentz, Hadi, Badr...)



On the flavor composition of the high-energy neutrino events in IceCube, June 26, 2014

+26 EVENTS ABOVE 30 TEV

M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013



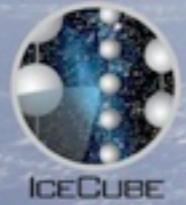
From May 2010 to May 2012:

**7 tracks + 21 showers
between 30 TeV and 2 PeV (deposited energy)**

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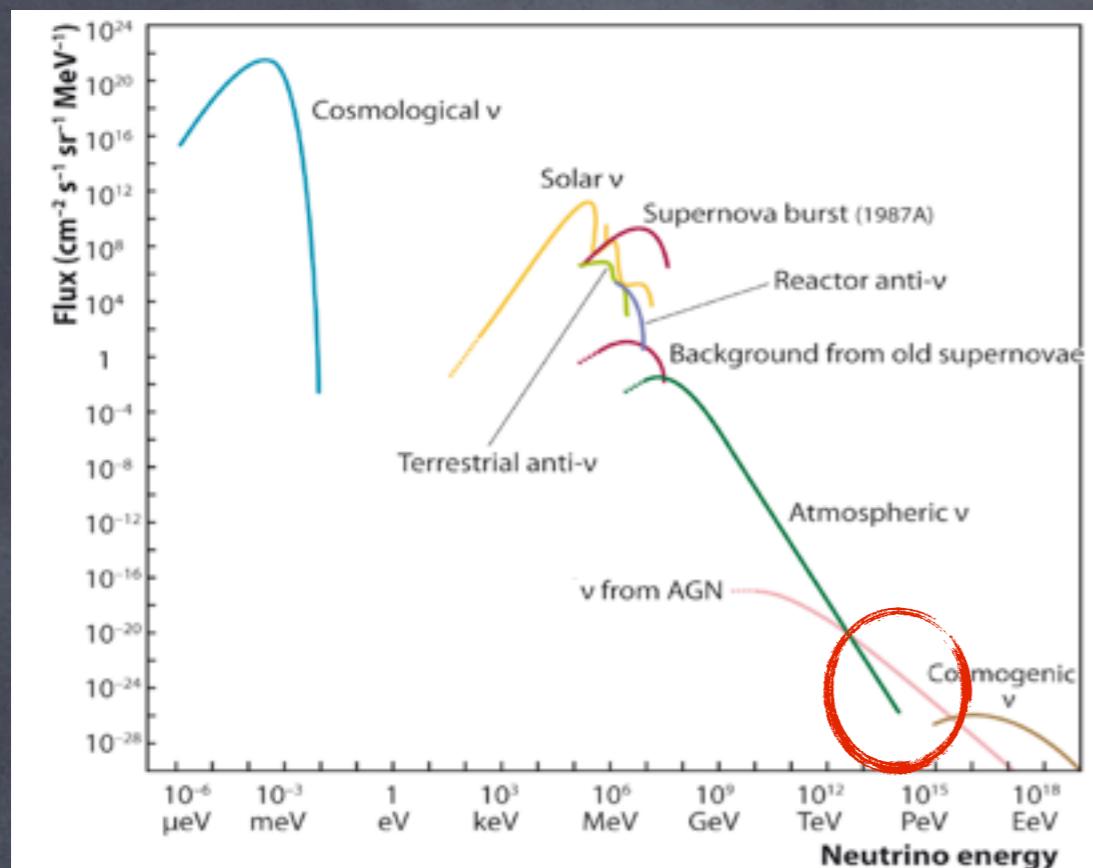
For making the first observations of high-energy cosmic neutrinos



From May 2010 to May 2012:

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between 30 TeV and 2 PeV (deposited energy)

7 tracks : 21 showers



atmospheric neutrinos (<100 TeV)?

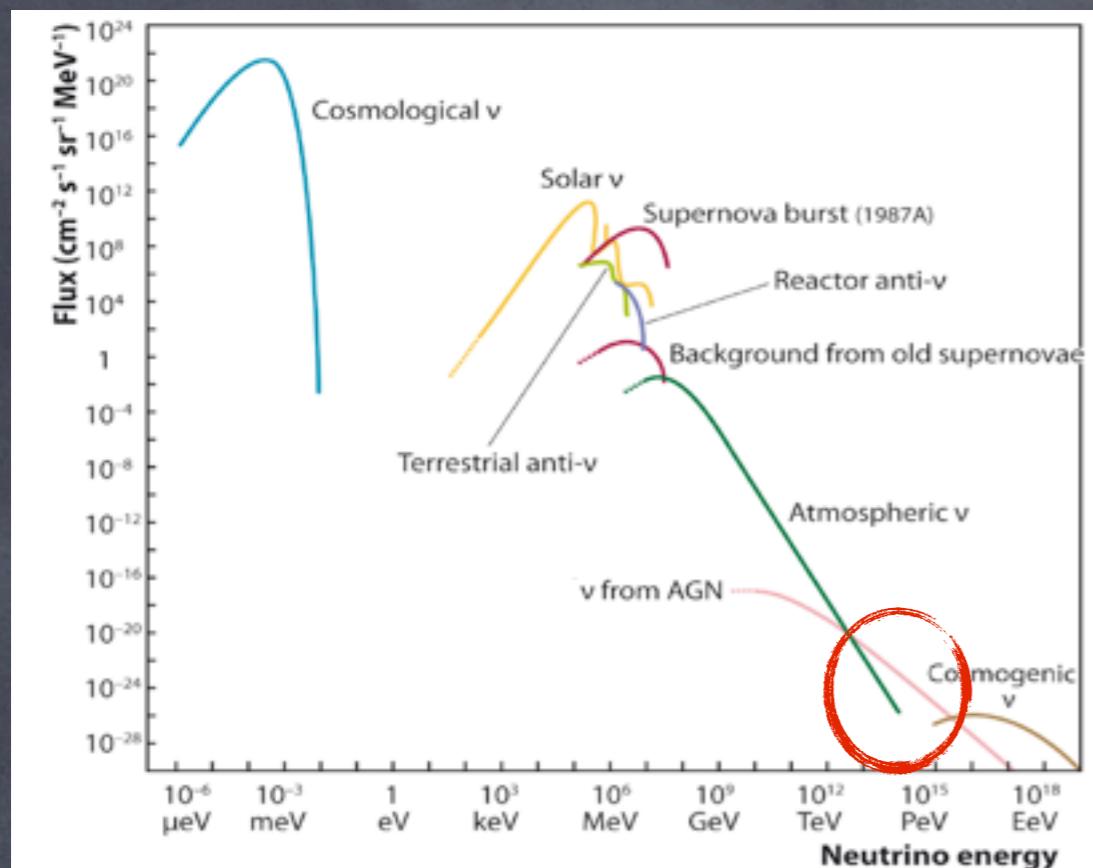
prompt neutrinos (~100 TeV)?

astrophysical neutrinos (> 100 TeV)?

cosmogenic neutrinos (>1 EeV)?

U. F. Katz and C. Spiering, Prog. Part. Nucl. Phys. 67:651, 2012

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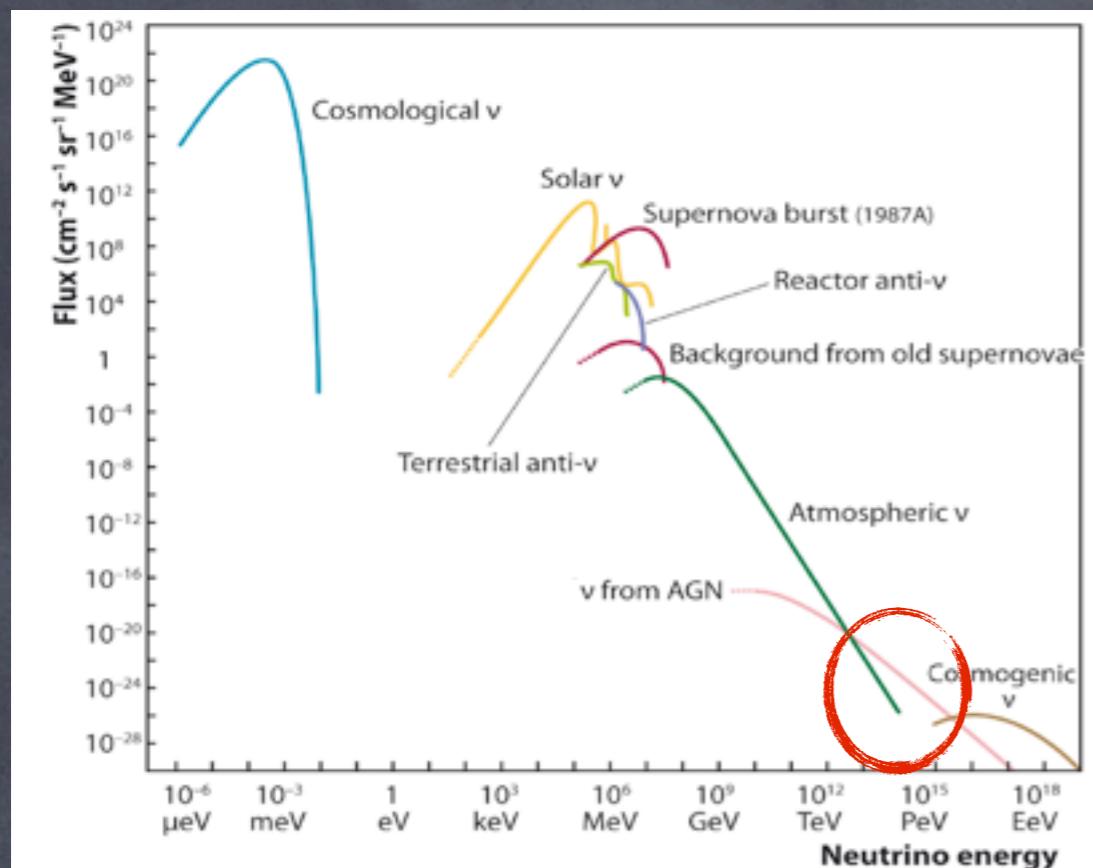
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What is the compatibility of that event ratio
with different neutrino flavor ratios
(assuming isotropy of the sources)?

flavor ratios at source:

$$(\alpha_{e,S} : \alpha_{\mu,S} : \alpha_{\tau,S})$$

$$\{\alpha_{j,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ki}|^2 \{\alpha_{i,S}\}$$

$$\sum_k |U_{jk}|^2 |U_{ki}|^2 \approx (P_{TBM})_{ji} = \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$

$$N_a = \alpha_{e,\oplus} (N_{\nu_e}^{sh,CC} + N_{\nu_e}^{sh,NC}) + \alpha_{\mu,\oplus} (N_{\nu_\mu}^{tr} + N_{\nu_\mu}^{sh,NC}) + \alpha_{\tau,\oplus} (N_{\nu_\tau}^{tr} + N_{\nu_\tau}^{sh,CC} + N_{\nu_\tau}^{sh,NC})$$

$$p_a^{tr} (\{\alpha_{i,\oplus}\}) \equiv \text{fraction of astrophysical signal tracks} = \frac{\alpha_{\mu,\oplus} N_{\nu_\mu}^{tr} + \alpha_{\tau,\oplus} N_{\nu_\tau}^{tr}}{N_a}$$

On the flavor composition of the high-energy neutrino events in IceCube, June 26, 2014

FLAVOR RATIOS AT SOURCE AND EARTH

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$



$$e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu)$$

Pion sources $\left(\nu_e : \nu_\mu : \nu_\tau \right)_S = (1 : 2 : 0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau \right)_\oplus = (1 : 1 : 1)$

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Muon damped
sources $\left(\nu_e : \nu_\mu : \nu_\tau \right)_S = (0 : 1 : 0) \Rightarrow \left(\nu_e : \nu_\mu : \nu_\tau \right)_\oplus = (4 : 7 : 7)$

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Muon sources $(\nu_e : \nu_\mu : \nu_\tau)_S = (1 : 1 : 0) \Rightarrow (\nu_e : \nu_\mu : \nu_\tau)_\oplus = (14 : 11 : 11)$

Neutron sources $(\nu_e : \nu_\mu : \nu_\tau)_S = (1 : 0 : 0) \Rightarrow (\nu_e : \nu_\mu : \nu_\tau)_\oplus = (5 : 2 : 2)$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

STATISTICAL ANALYSES

$$\mathcal{L}\left(\{\alpha_{i,\oplus}\}, N_a | N_{tr}, N_{sh}\right) = e^{-\left(p_a^{tr}N_a + p_\mu^{tr}b_\mu + p_v^{tr}b_v\right)} \frac{\left(P_a^{tr}N_a + P_\mu^{tr}b_\mu + P_v^{tr}b_v\right)^{N_{tr}}}{N_{tr}!} \times e^{-\left(p_a^{sh}N_a + p_\mu^{sh}b_\mu + p_v^{sh}b_v\right)} \frac{\left(P_a^{sh}N_a + P_\mu^{sh}b_\mu + P_v^{sh}b_v\right)^{N_{sh}}}{N_{sh}!}$$

$$\left. \begin{array}{l} b_\mu \equiv \text{atmospheric muon background} = 6 \quad (p_\mu^{tr} = 0.90) \\ b_v \equiv \text{atmospheric neutrino background} = 4.6 \quad (p_v^{tr} = 0.69) \end{array} \right\} \quad \begin{array}{l} \text{M. G. Aartsen et al. [IceCube Collaboration],} \\ \text{arXiv:1405.5303} \end{array}$$

$$N_{tr} \equiv \text{number of observed tracks} = 7$$

$$N_{sh} \equiv \text{number of observed showers} = 21$$

We maximize \mathcal{L} with respect to N_a and define the test statistic:

$$\lambda(N_{tr}, N_{sh} | \{\alpha_{i,\oplus}\}) = -2 \ln \left(\frac{\mathcal{L}_p(\{\alpha_{i,\oplus}\} | N_{tr}, N_{sh})}{\mathcal{L}_p(\{\alpha_{i,\oplus}\}_{\max} | N_{tr}, N_{sh})} \right)$$

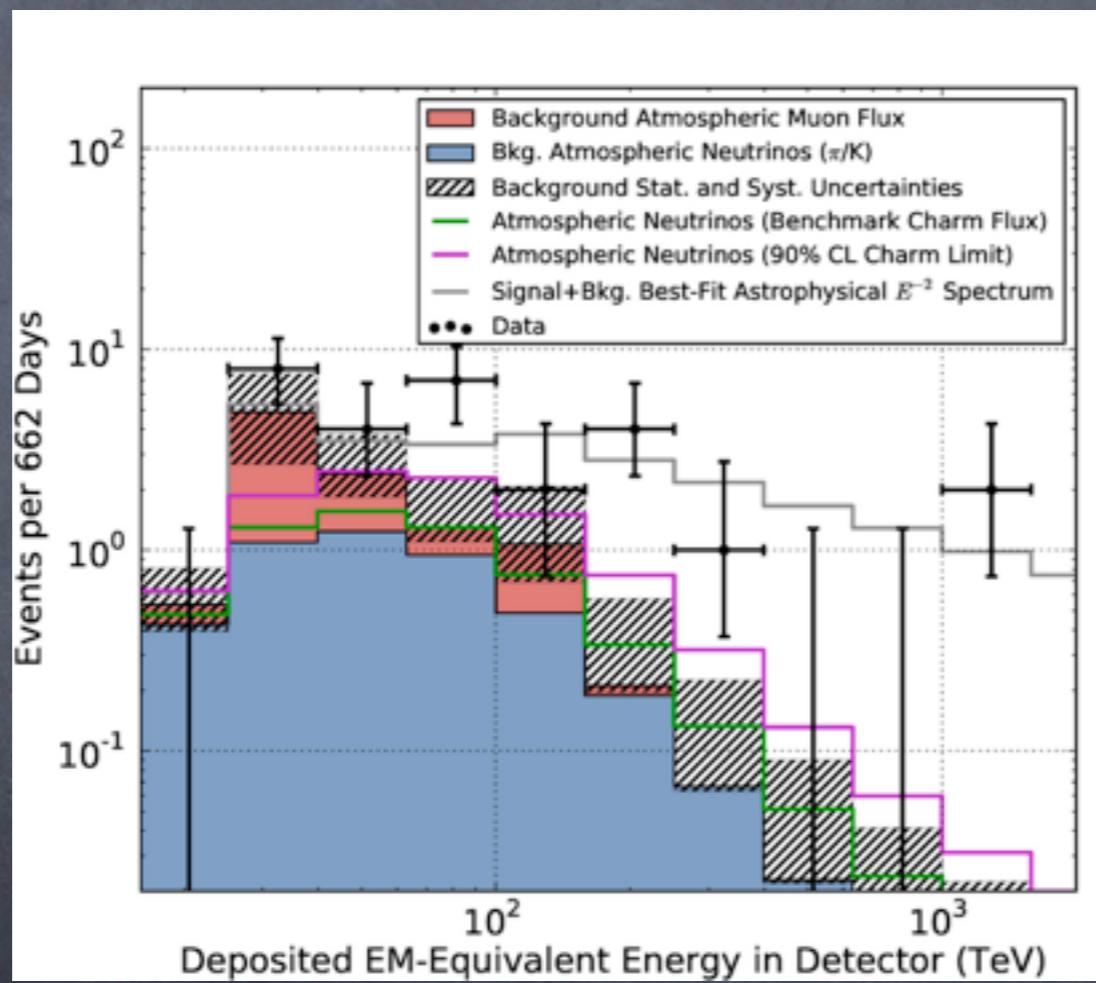
Exact definition of p-value:
no need to approximate it
with the χ^2 result

$$p(\{\alpha_{i,\oplus}\}) = \sum_{N_{tr}, N_{sh}} P(N_{tr}, N_{sh} | \{\alpha_{i,\oplus}\}) \quad ; \quad P(N_{tr}, N_{sh} | \{\alpha_{i,\oplus}\}) \equiv \mathcal{L}_p(\{\alpha_{i,\oplus}\} | N_{tr}, N_{sh})$$

$$\forall \lambda(N_{tr}, N_{sh} | \{\alpha_{i,\oplus}\}) > \lambda(N_{tr} = 7, N_{sh} = 21 | \{\alpha_{i,\oplus}\})$$

7 tracks : 21 showers

What is the compatibility of that event ratio with different neutrino flavor ratios (assuming isotropy of the sources)?



Good fit for a E^{-2} spectrum

Reject a purely atmospheric origin at 4.1σ

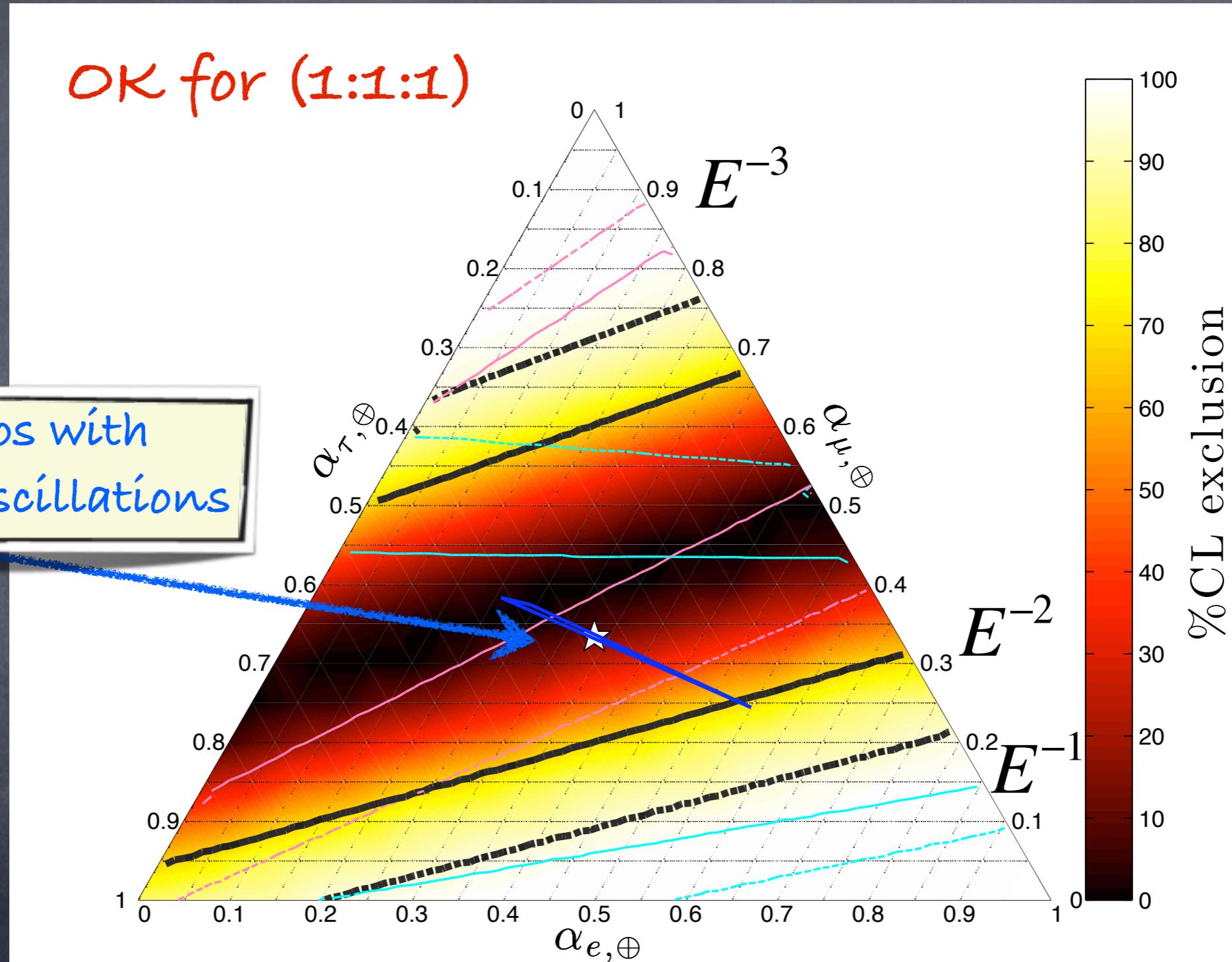
M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

For (1 : 1 : 1) and E^{-2} : $\sim 20\%$ tracks and $\sim 80\%$ showers

NO BACKGROUND?

OK for (1:1:1)

Flavor ratios with
averaged oscillations



Color code for E^{-2}

BUT THERE IS BACKGROUND...

observed \rightarrow 7 tracks : 21 showers

background \rightarrow 8.6 tracks : 2 showers

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astrophysical =

observed - background



astrophysical tracks = $7 - 8.6 = 0$

BUT THERE IS BACKGROUND...

observed \rightarrow 7 tracks : 21 showers

background \rightarrow 8.6 tracks : 2 showers

astrophysical =

observed - background



astrophysical tracks = $7 - 8.6 = 0$

Only showers in the astrophysical signal!

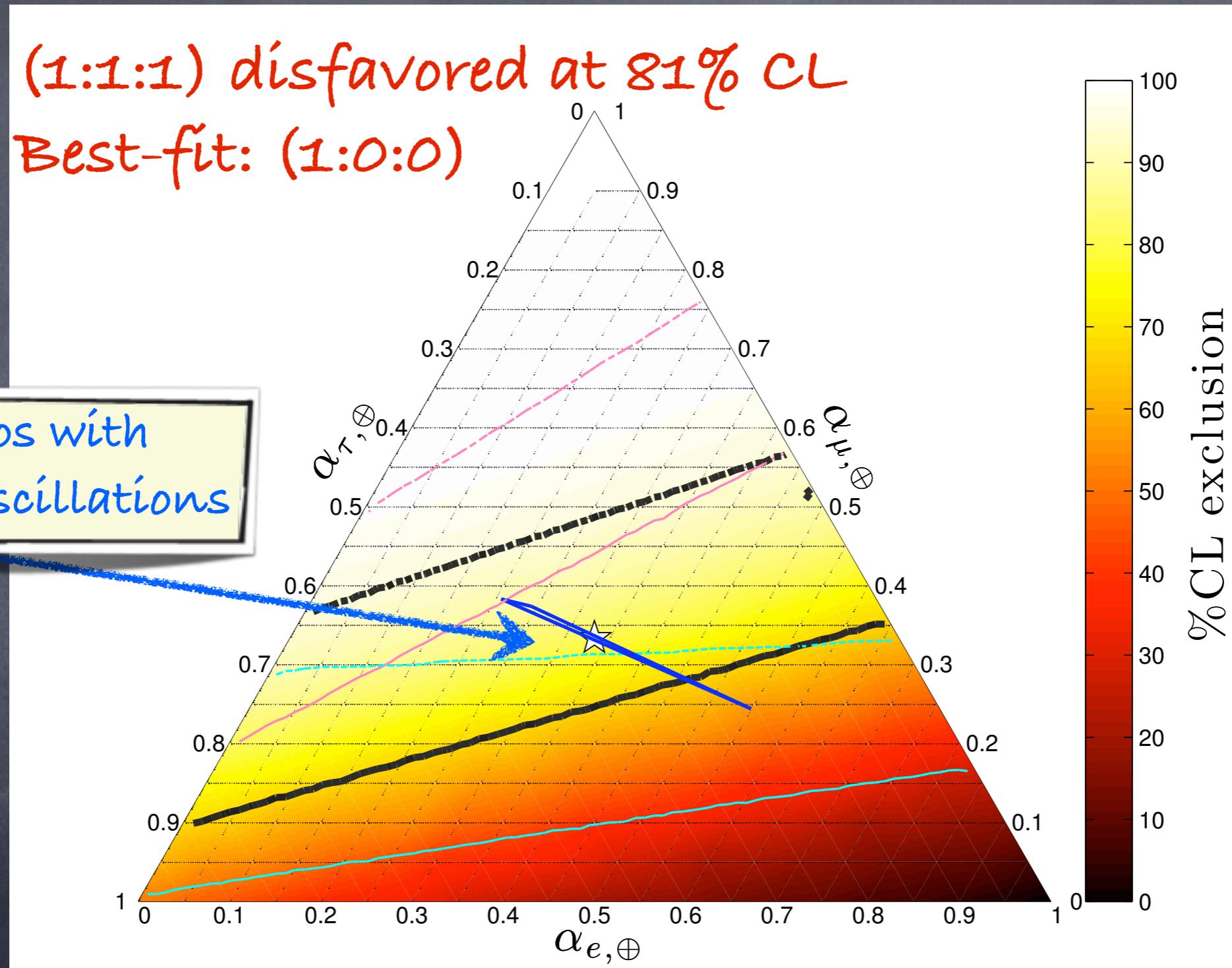
2-YEAR RESULTS

For E^{-2}

(1:1:1) disfavored at 81% CL

Best-fit: (1:0:0)

Flavor ratios with
averaged oscillations



O. Mena, SPR and A. C. Vincent, arXiv:1404.0017

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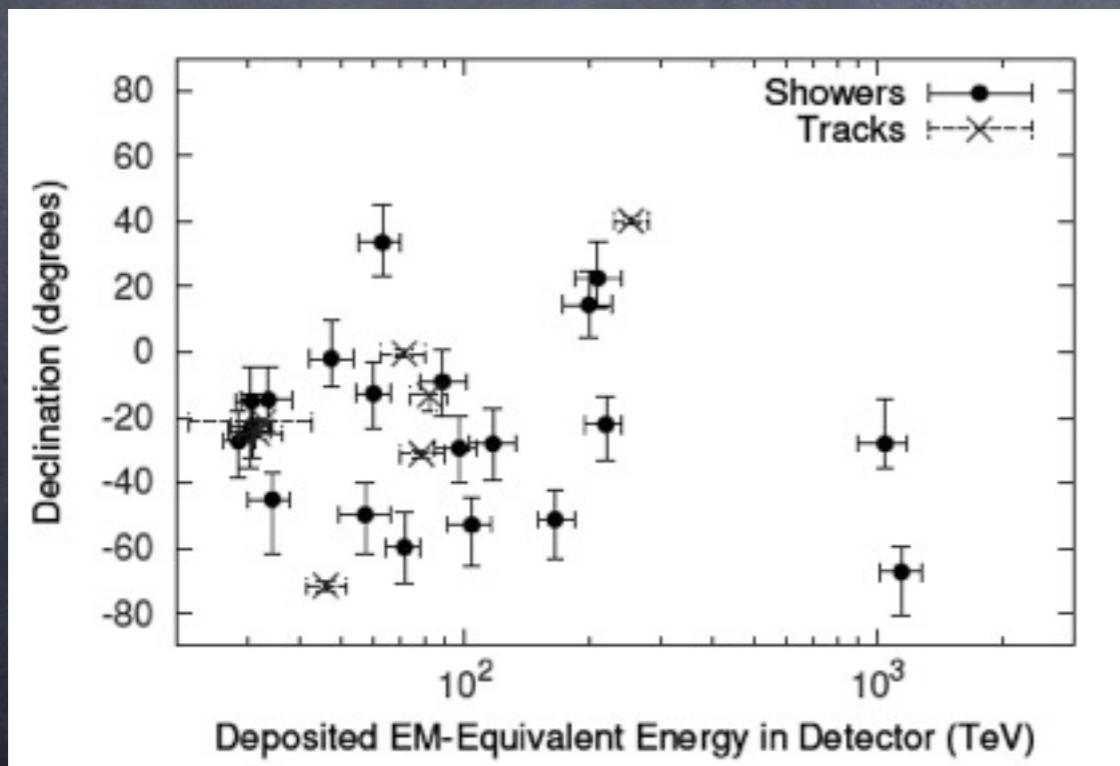
3-YEAR DATA

M. G. Aartsen et al. [IceCube Collaboration], arXiv:1405.5303

2-year data: May 2010 - May 2012

Observed: 7 tracks + 21 showers

Estimated background : $4.6^{+3.7}_{-1.2}$ atm. ν + 6 ± 3.4 atm. μ



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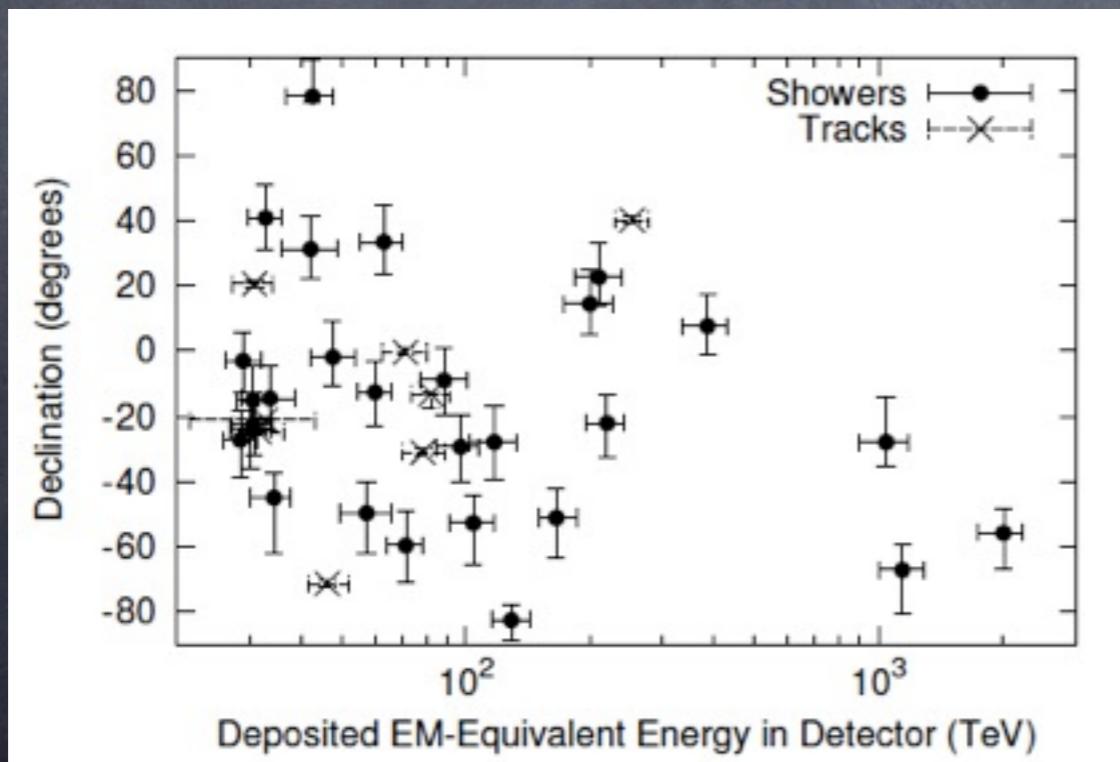
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3-year data: May 2010 - May 2013

Observed: 9 tracks + 28 showers

Estimated background : $6.6^{+5.9}_{-1.6}$ atm. ν + 8.4 ± 4.2 atm. μ



2 extra tracks
7 extra showers

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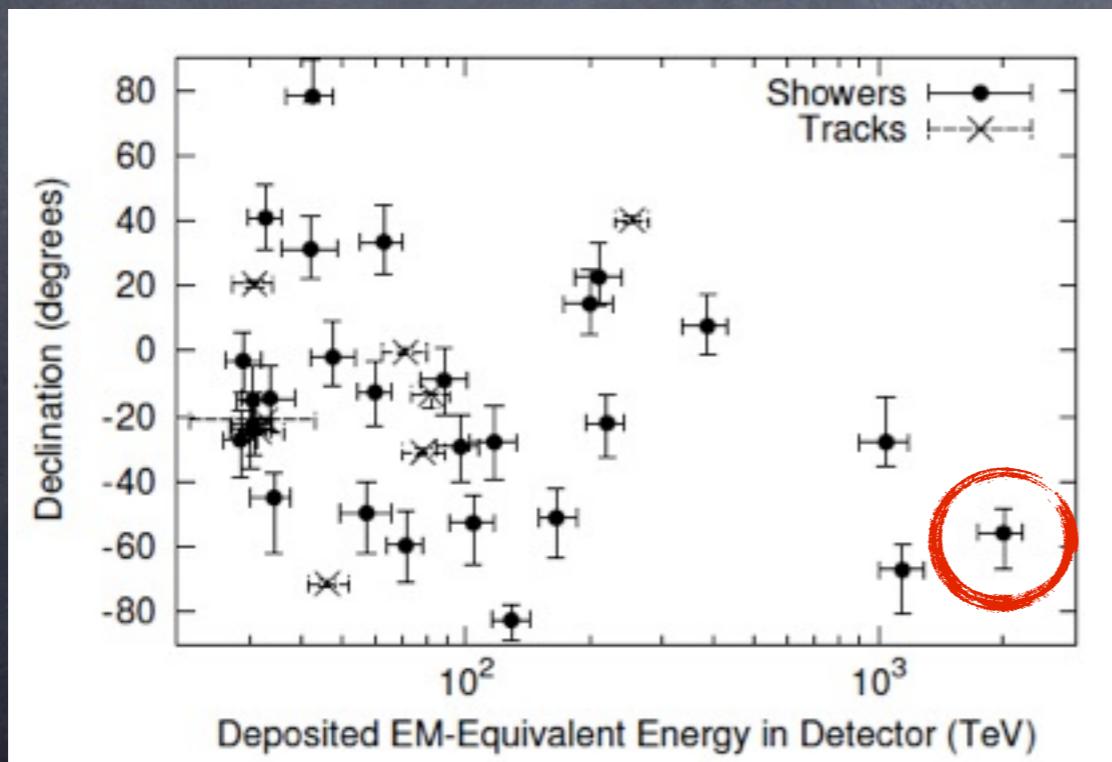
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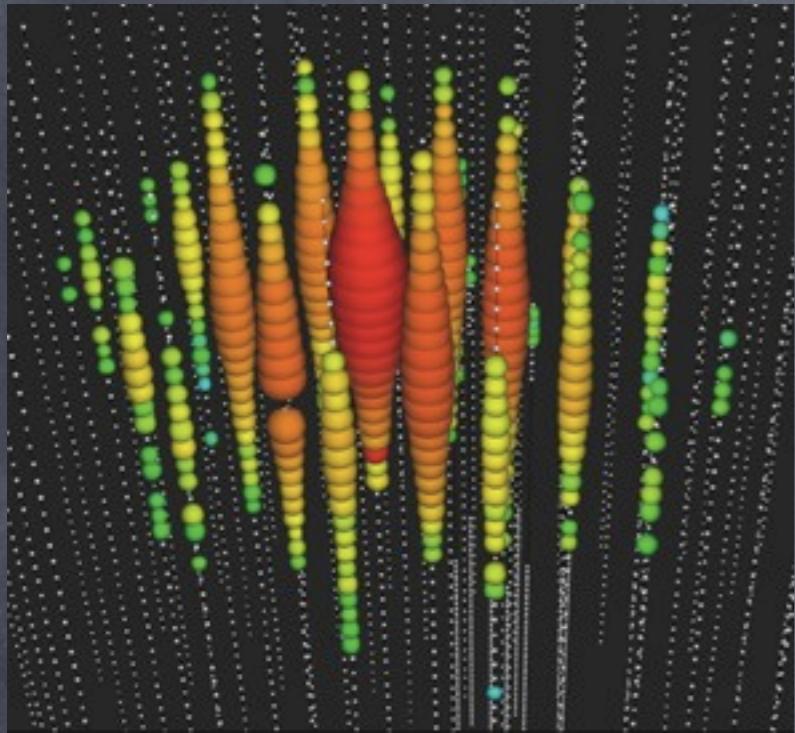
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2 extra tracks
7 extra showers

another record breaker

THE 2 PEW NEUTRINO



C. Kopper, talk at Moriond 2014



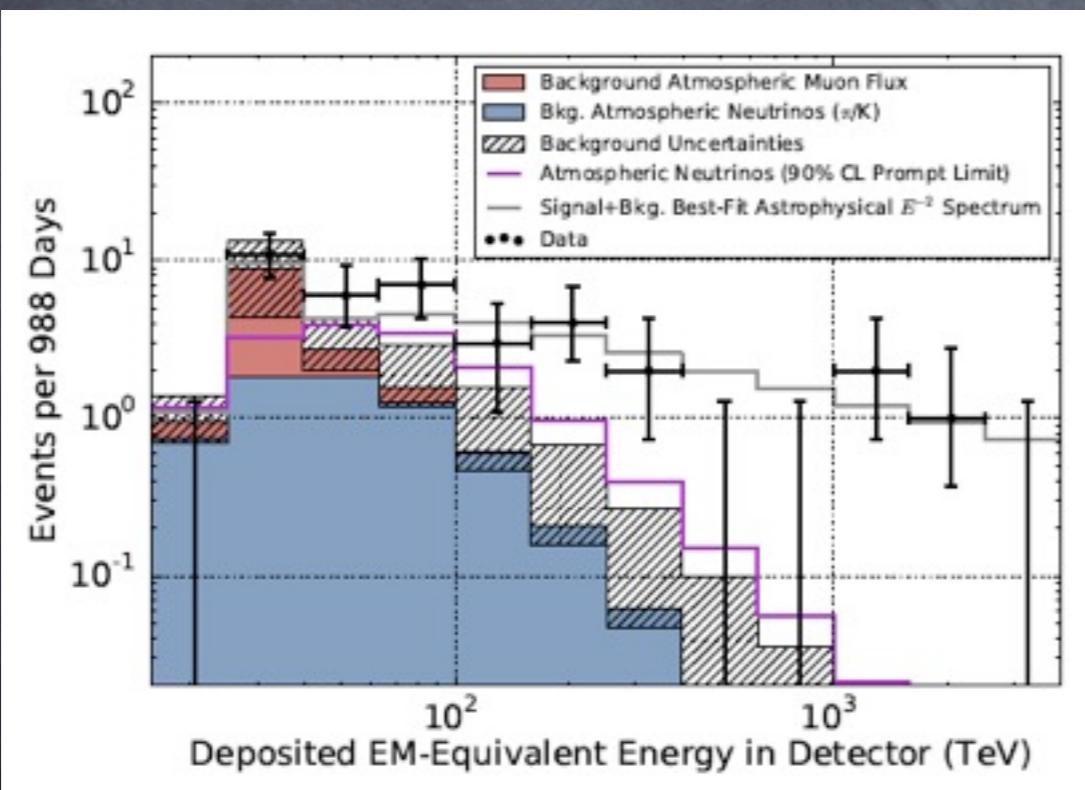
or its Russian cousin

Зелибоба



Big Bird

(or Caponata, Paco Pico, Poupas Amarelo, Montoya, Bibo, Garibaldo, Neef Jan, Minik Kuş, Pino, Da Niao, Velika Ptica, Store Pip, Wielki Ptak, Kippi ben Kippod...)



Still good fit for a E^{-2} spectrum

Reject a purely atmospheric origin at 5.7 σ

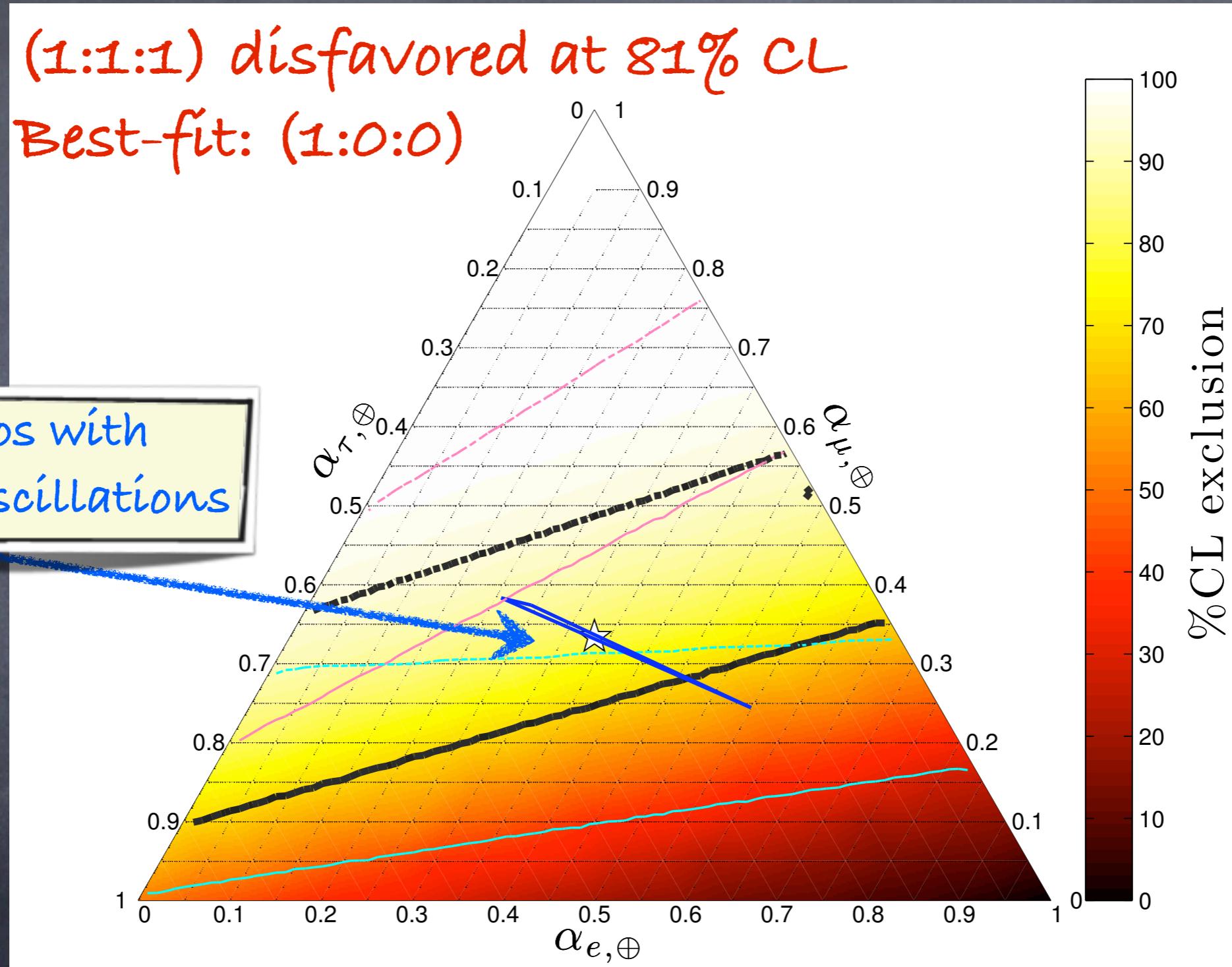
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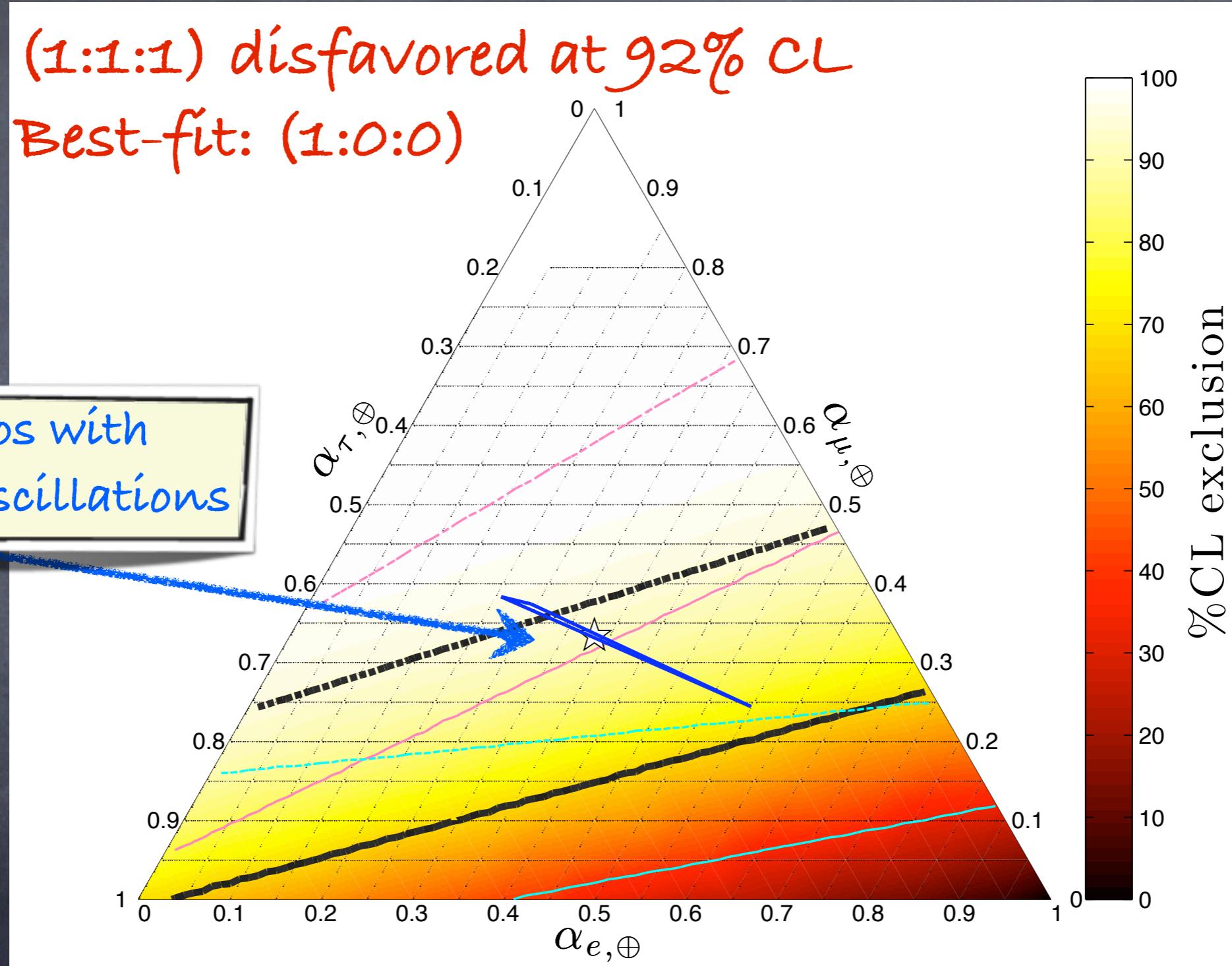
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3-YEAR RESULTS

(1:1:1) disfavored at 92% CL

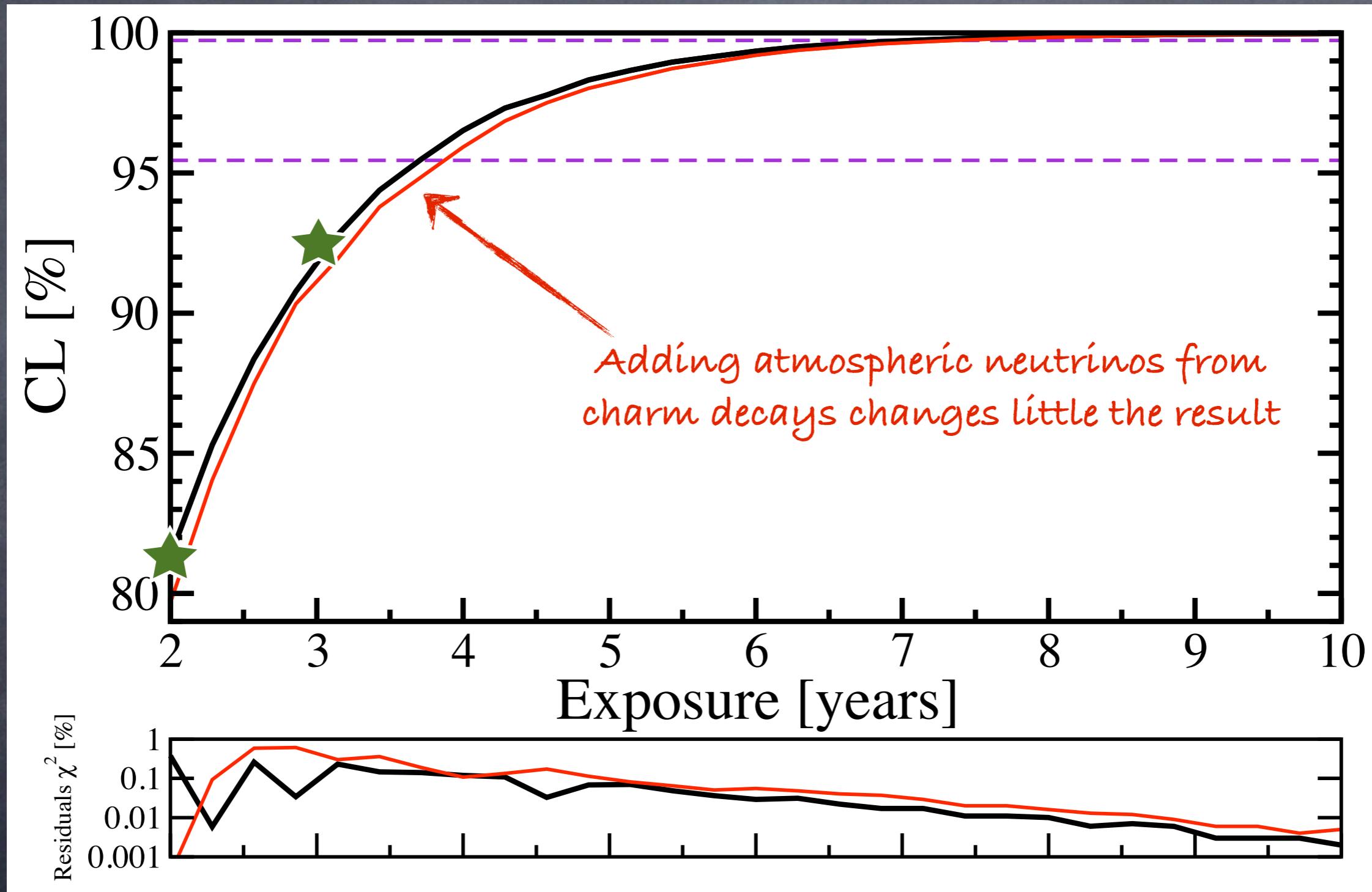
Best-fit: (1:0:0)

Flavor ratios with
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O. Mena, SPR and A. C. Vincent, arXiv:1404.0017

TIME EXTRAPOLATION FOR (1:1:1)



CONCLUSIONS

- No flavor combination at sources assuming averaged oscillations provides the best-fit:

the 3-year data follow the same trend of the 2-year data

- Best-fit is (1:0:0) at Earth

→ Non-standard physics (neutrino decay, CPT violation, pseudo-Dirac neutrinos)?

→ Has the atmospheric background been overestimated?

→ Have some tracks been misidentified as showers?

Otherwise, where are the missing tracks?