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

based on

O. Mena, SPR and A.C. Vincent, arXiv:1404.0017v2

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IFIC, CSIC-U. Valencia, Valencia

News in Neutrino Physics

NORDITA

Stockholm, April 28, 2014


123
SESAME STREET

THE ICECUBE TELESCOPE

At the South Pole

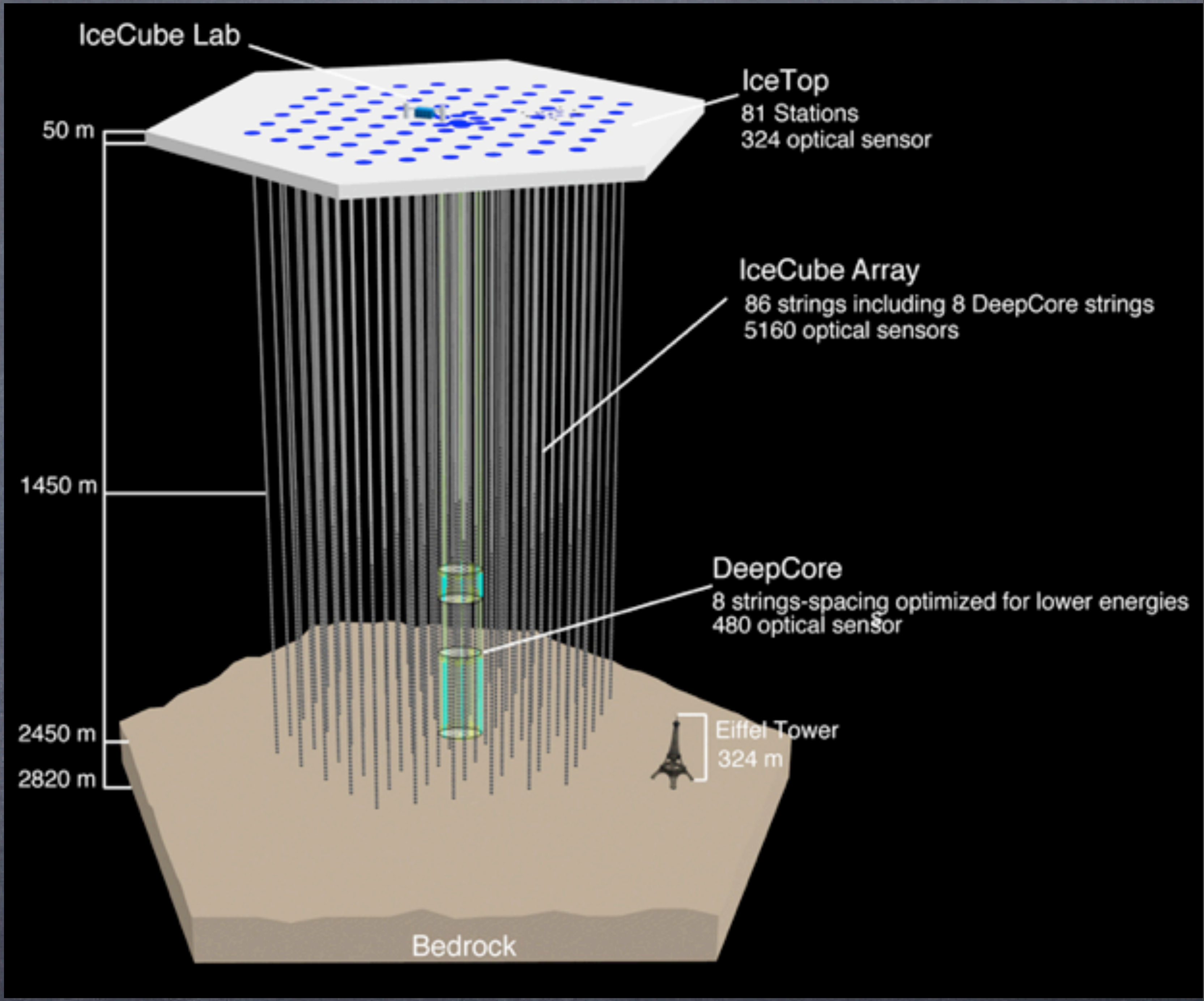
86 strings with 60 DOM/string
125 m apart on triangular grid

17 m vertical spacing between PMTs

8 DeepCore strings 75 m apart

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

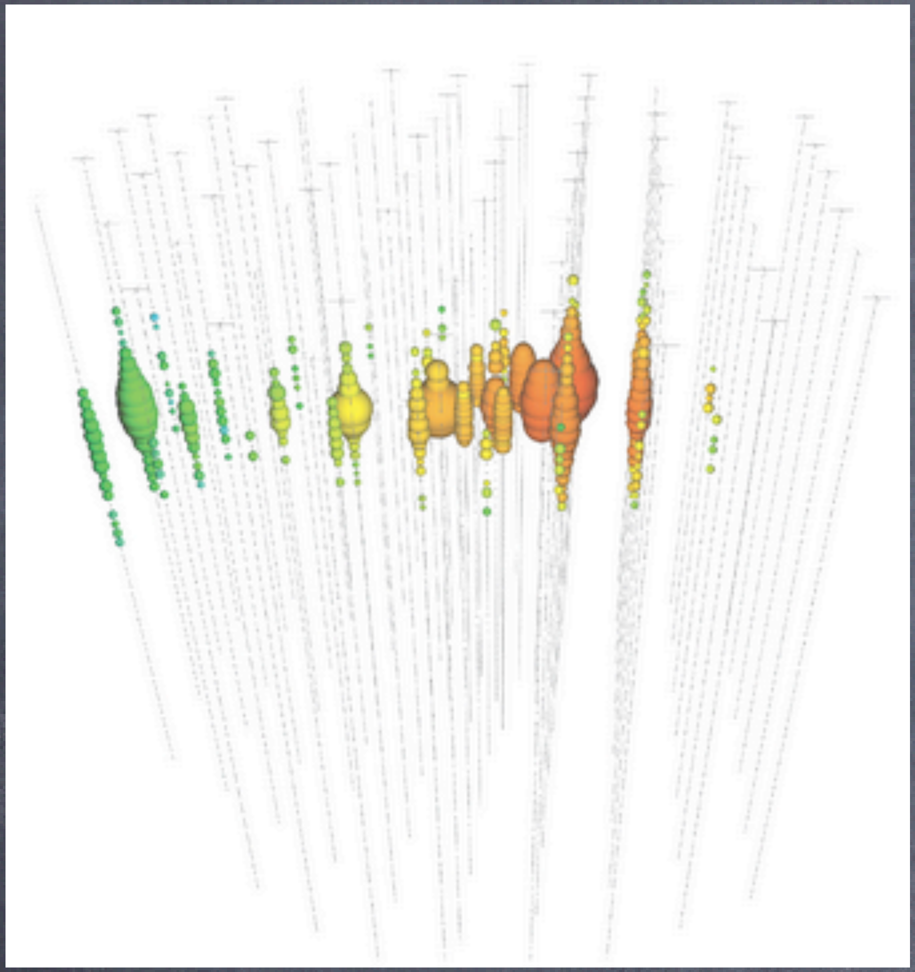
completed in 2010



Secondary particles detected via Cherencov radiation

TYPE OF EVENTS

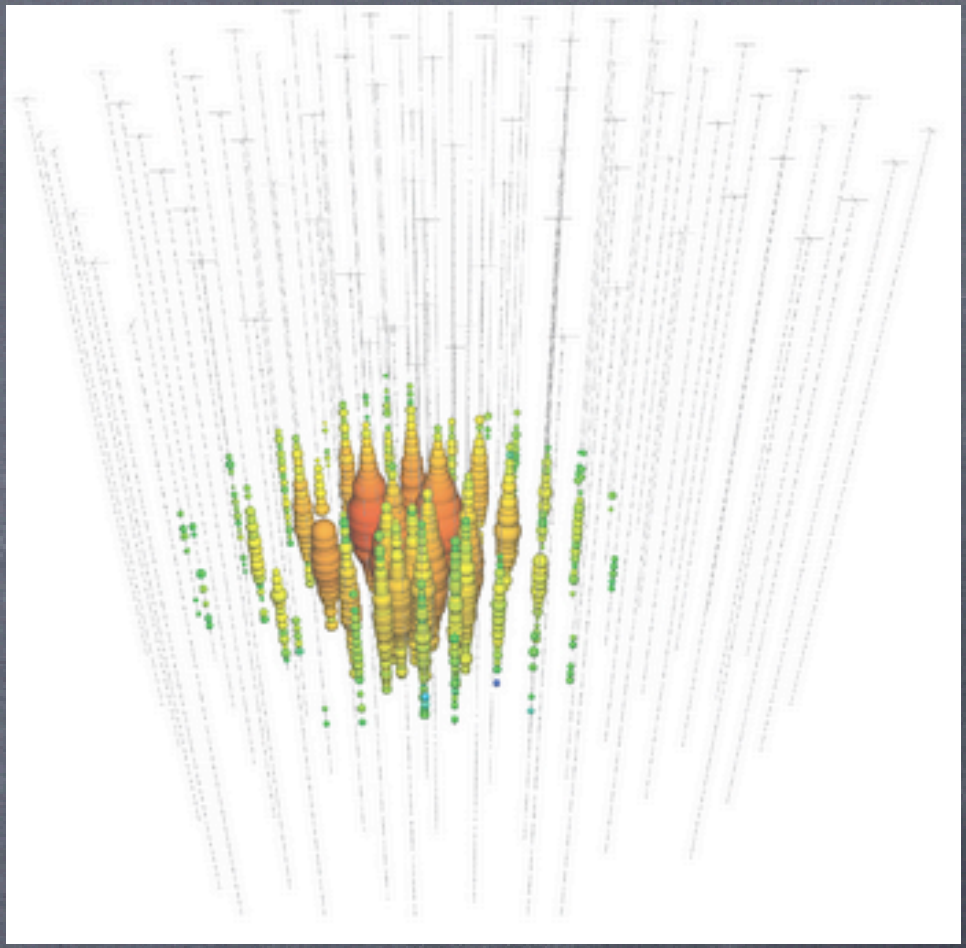
Muon tracks



$\text{CC } \nu_\mu + 18\% \text{ CC } \nu_\tau$

Good angular resolution

Showers



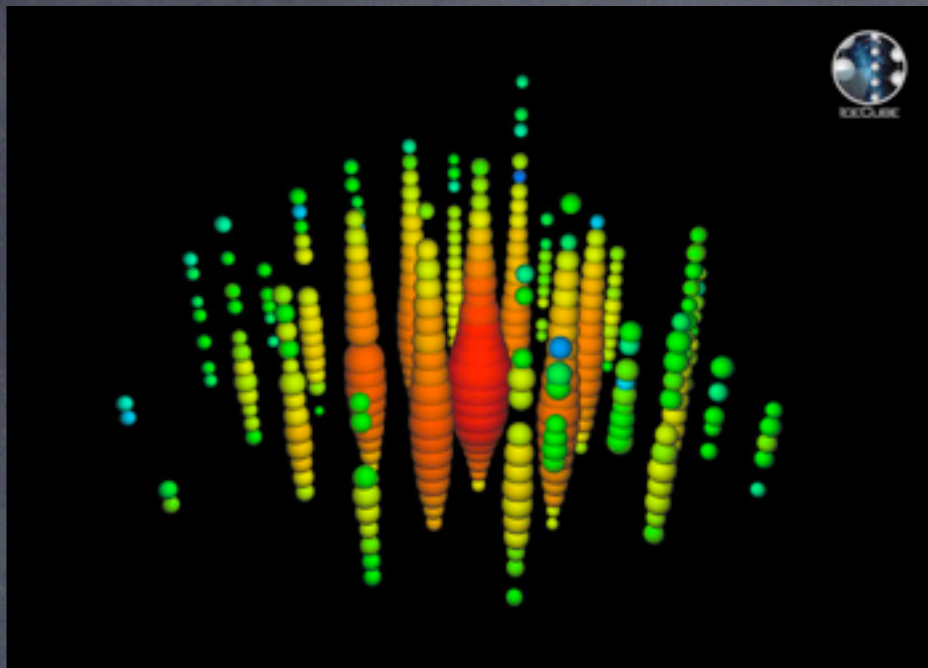
$\text{NC} + \text{CC } \nu_e + 82\% \text{ CC } \nu_\tau$

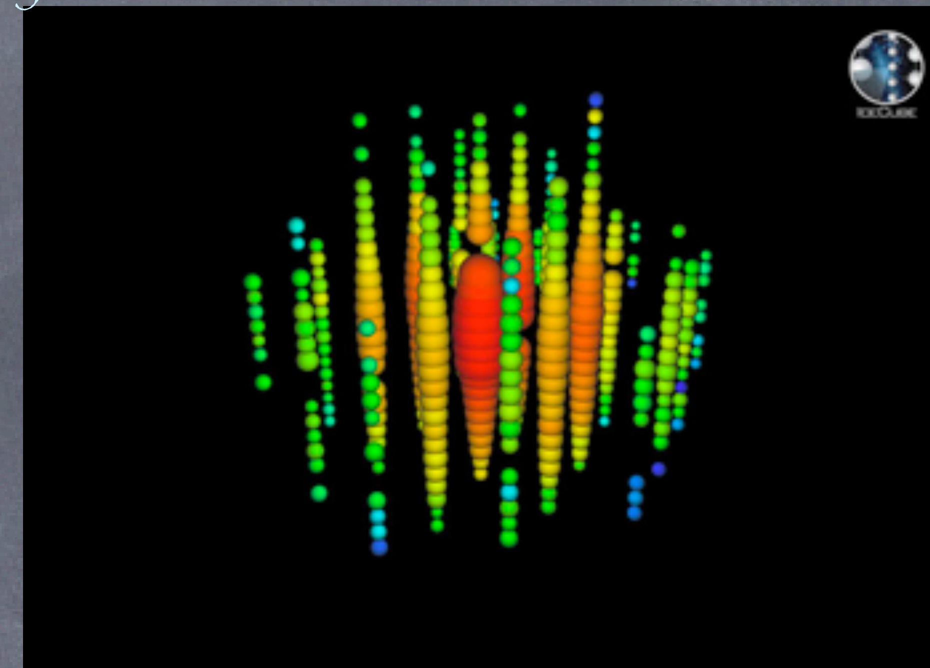
Poor angular resolution

Backgrounds: atmospheric muons and neutrinos

The First PeV Neutrinos

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





January 3, 2012: 1.14 PeV

Ernie

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

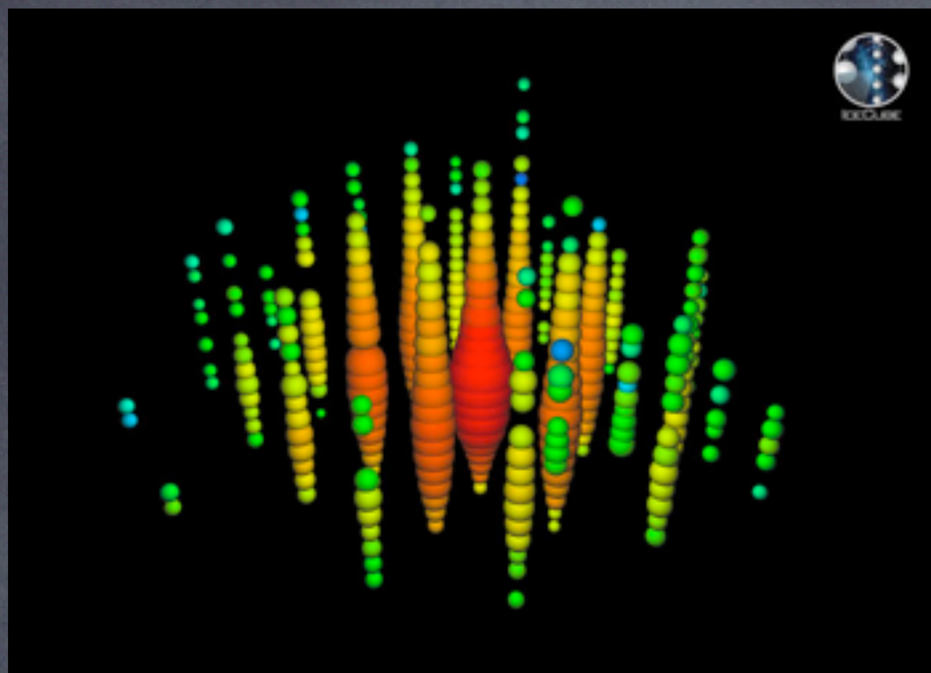
August 9, 2011: 1.04 PeV

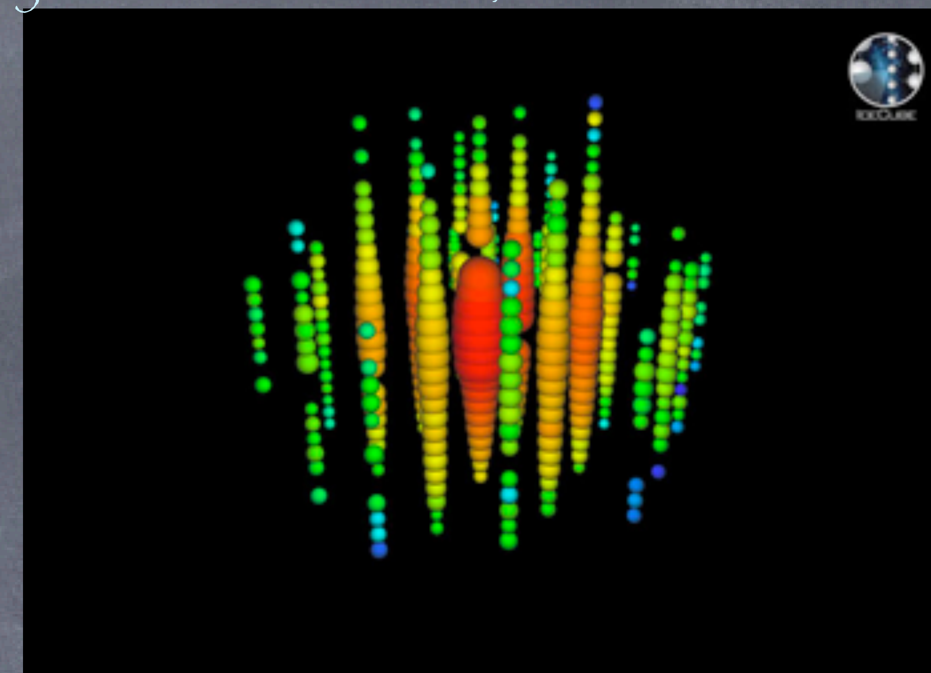
Bert

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

THE FIRST PEV NEUTRINOS

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





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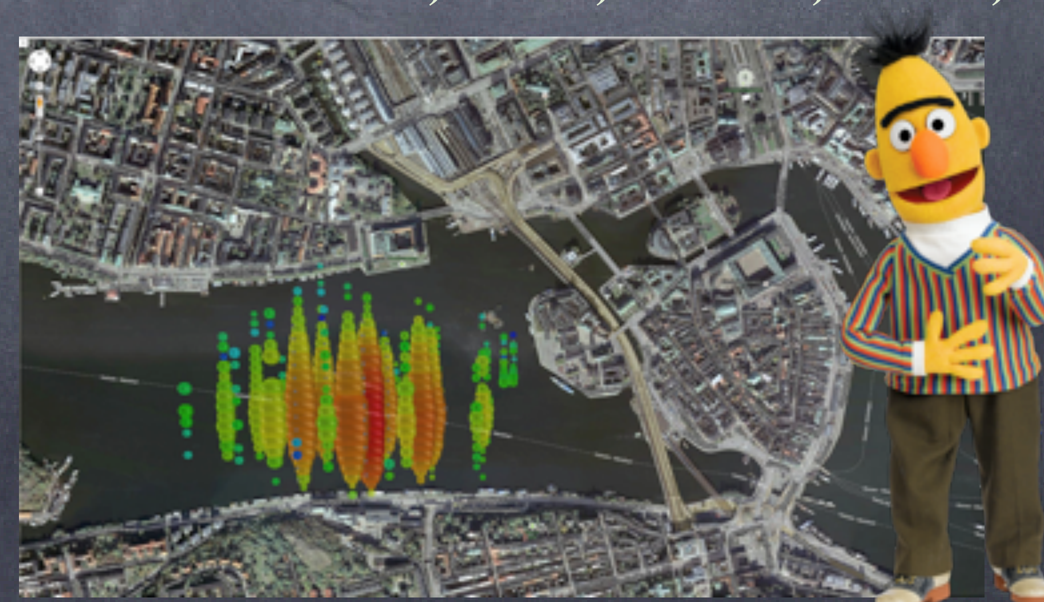
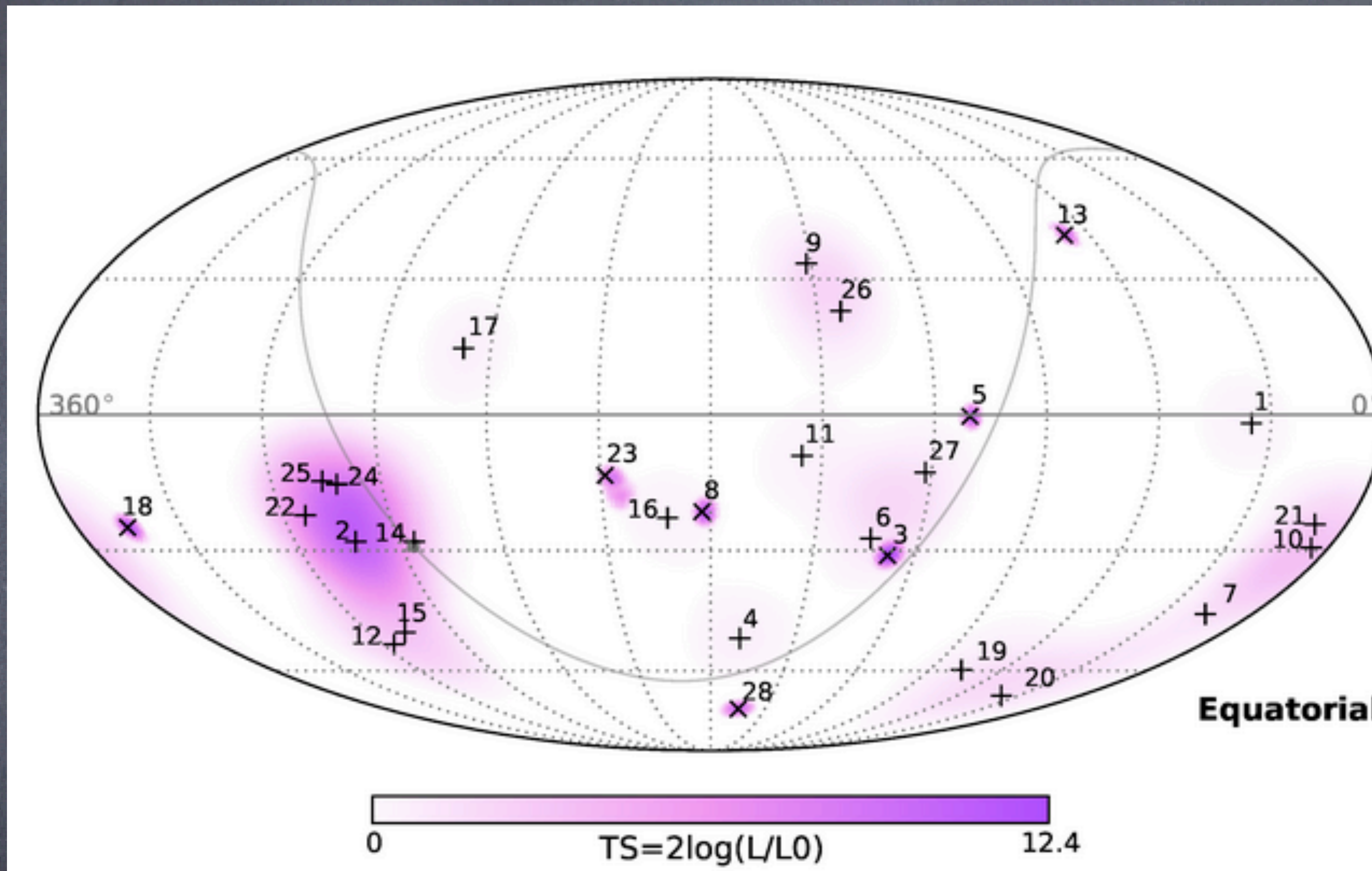


+26 events above 30 TeV

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



From May 2010 to May 2012:

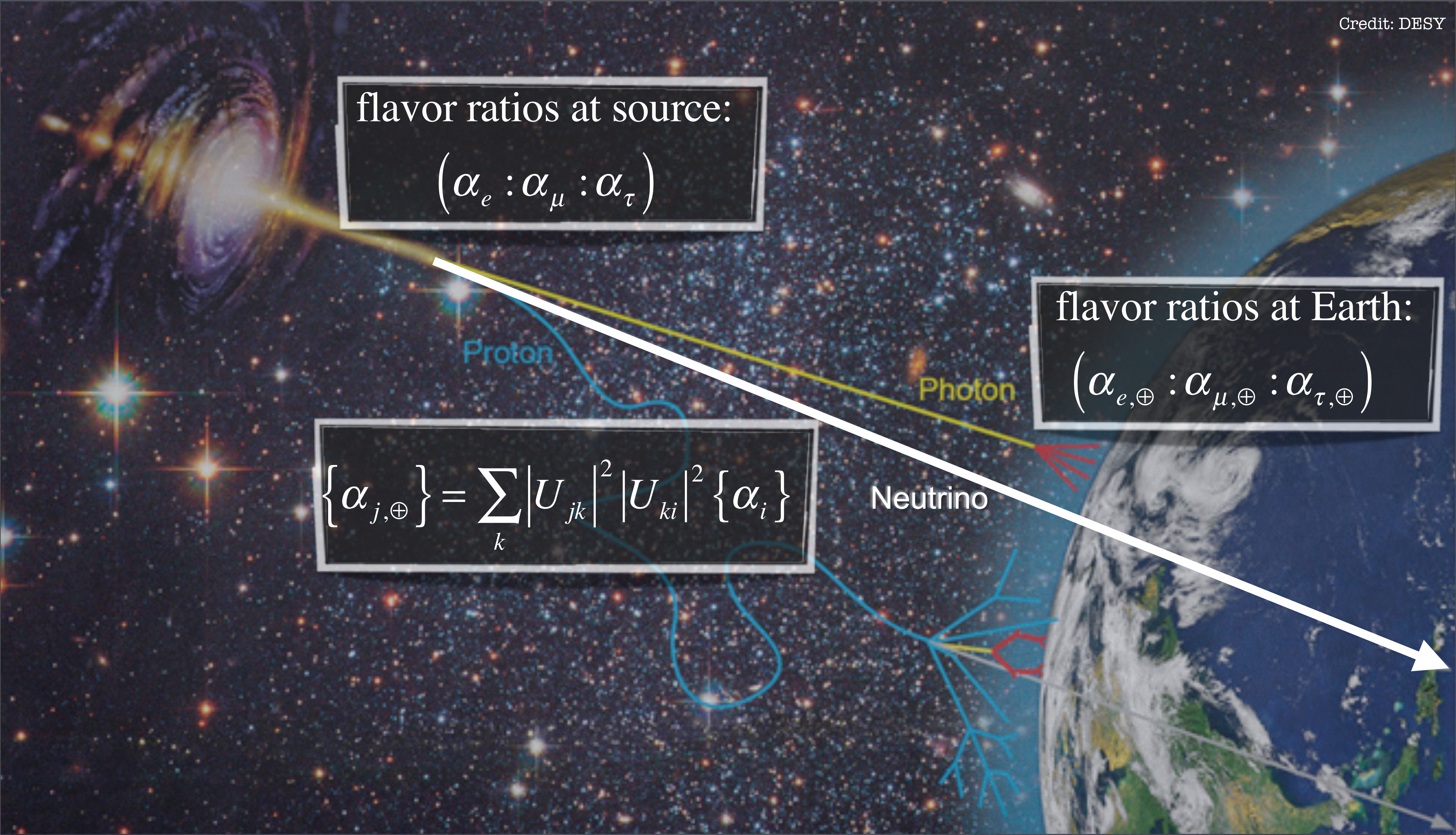
7 tracks + 21 showers

between 30 TeV and 2 PeV (deposited energy)

7 tracks : 21 showers

7 tracks : 21 showers

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



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

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

SHOWERS IN ICECUBE

Neutral Current events : all flavors

deposited energy = hadronic shower energy

$$N_{\nu_i}^{sh,NC} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M^{NC}(E_\nu) Att_{\nu_i}(E_\nu) \phi(E_\nu) \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{NC}(E_\nu, y)}{dy}$$

time of observation:
662 days

effective
detector mass

attenuation/regeneration
factor

neutrino flux
(taken as power-law)

$y_{min} = E_{min} / E_\nu$

$y_{max} = \min\{1, E_{max} / E_\nu\}$

$y = 1 - E'_\nu / E_\nu$

$E_\nu y$ = shower energy

DIS NC
differential cross section

SHOWERS IN ICECUBE

Charged Current events : ν_e

deposited energy = hadronic shower energy + electromagnetic shower energy = neutrino energy

$$N_{\nu_e}^{sh,CC} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_e}^{CC}(E_\nu) Att_{\nu_e}(E_\nu) \phi(E_\nu) \int_0^1 dy \frac{d\sigma_{\nu_e}^{CC}(E_\nu, y)}{dy} \times \theta(E_{\max} - E_\nu)$$

SHOWERS IN ICECUBE

Charged Current events : ν_τ

deposited energy = hadronic shower energy + hadronic shower (from tau decay) energy

$$N_{\nu_\tau}^{sh,CC-had} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\tau}^{CC}(E_\nu) Att_{\nu_\tau}(E_\nu) \phi(E_\nu) \int_0^1 dy \frac{d\sigma_{\nu_\tau}^{CC}(E_\nu, y)}{dy} \times$$

$$\int_0^1 \frac{dn(\tau \to had)}{dz} \times \theta\left(E_\nu (y + (1-y)(1-z)) - E_{\min}\right) \theta\left(E_{\max} - E_\nu (y + (1-y)(1-z))\right)$$

spectrum of the daughter neutrino in hadronic tau decays

deposited energy = hadronic shower energy + electromagnetic shower (from tau decay) energy

$$N_{\nu_\tau}^{sh,CC-em} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M_{\nu_\tau}^{CC}(E_\nu) Att_{\nu_\tau}(E_\nu) \phi(E_\nu) \int_0^1 dy \frac{d\sigma_{\nu_\tau}^{CC}(E_\nu, y)}{dy} \times$$

$$\int_0^1 \frac{dn(\tau \to e)}{dz} \times \theta\left(E_\nu (y + (1-y)z) - E_{\min}\right) \theta\left(E_{\max} - E_\nu (y + (1-y)z)\right)$$

spectrum of the electron in tau decays

CONTAINED TRACKS IN ICECUBE

Contained Charged Current events : ν_μ

deposited energy* = hadronic shower energy

$$N^{tr}_{\nu_\mu} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M^{CC}_{\nu_\mu}(E_\nu) Att_{\nu_\mu}(E_\nu) \phi(E_\nu) \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{CC}_{\nu_\mu}(E_\nu, y)}{dy}$$

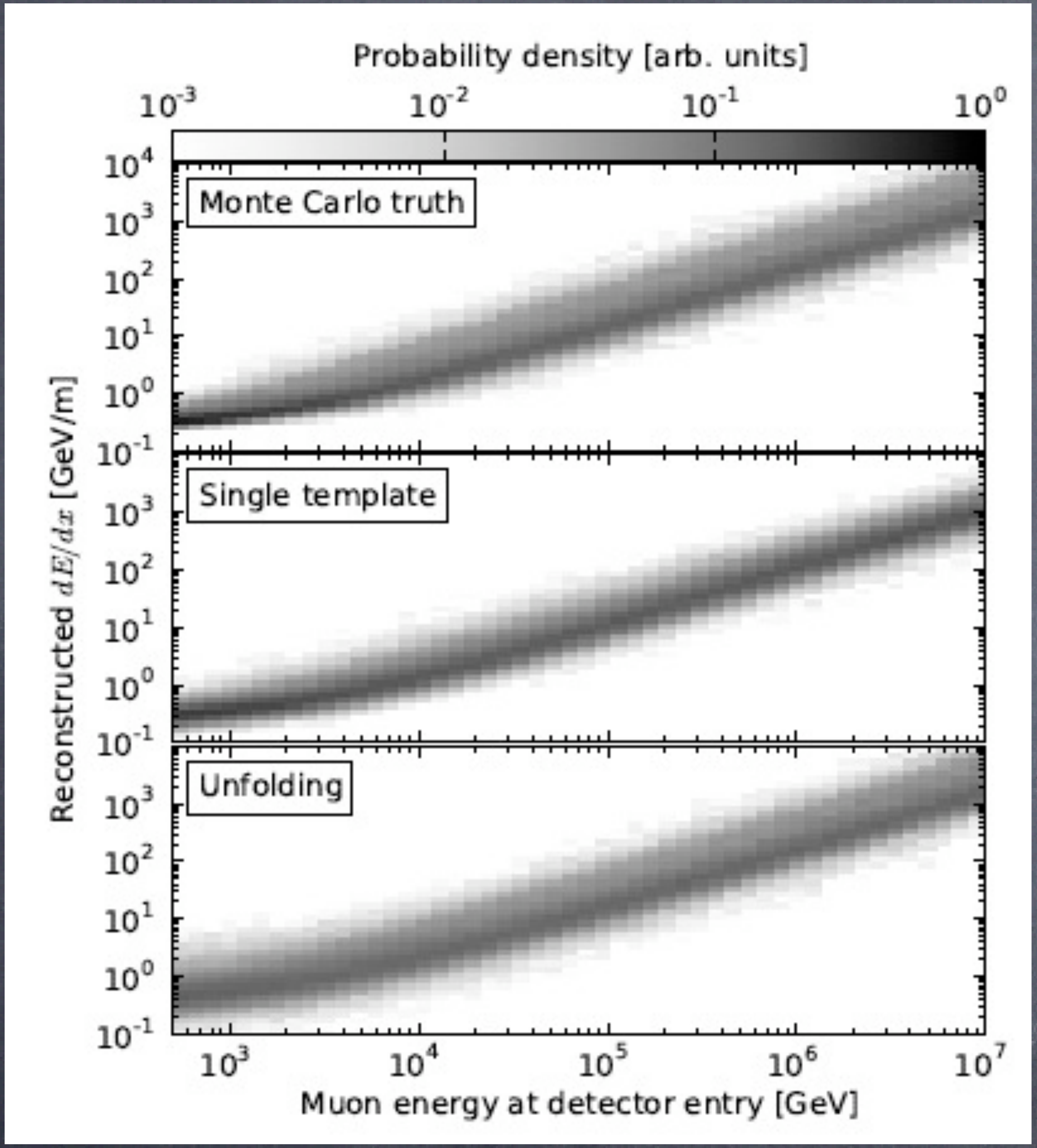
Contained Charged Current events : ν_τ

deposited energy* = hadronic shower energy

$$N^{tr}_{\nu_\tau} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M^{CC}_{\nu_\tau}(E_\nu) Att_{\nu_\tau}(E_\nu) \phi(E_\nu) \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{CC}_{\nu_\tau}(E_\nu, y)}{dy} \times Br(\tau \to \mu)$$

* the deposited energy by the muon in the detector is neglected

* the deposited energy by the muon in the detector is neglected: underestimation of the number tracks



the muon deposits little energy in the detector

$$\frac{E_f}{E_i} \simeq e^{-d/(10km)} \gtrsim 0.9$$

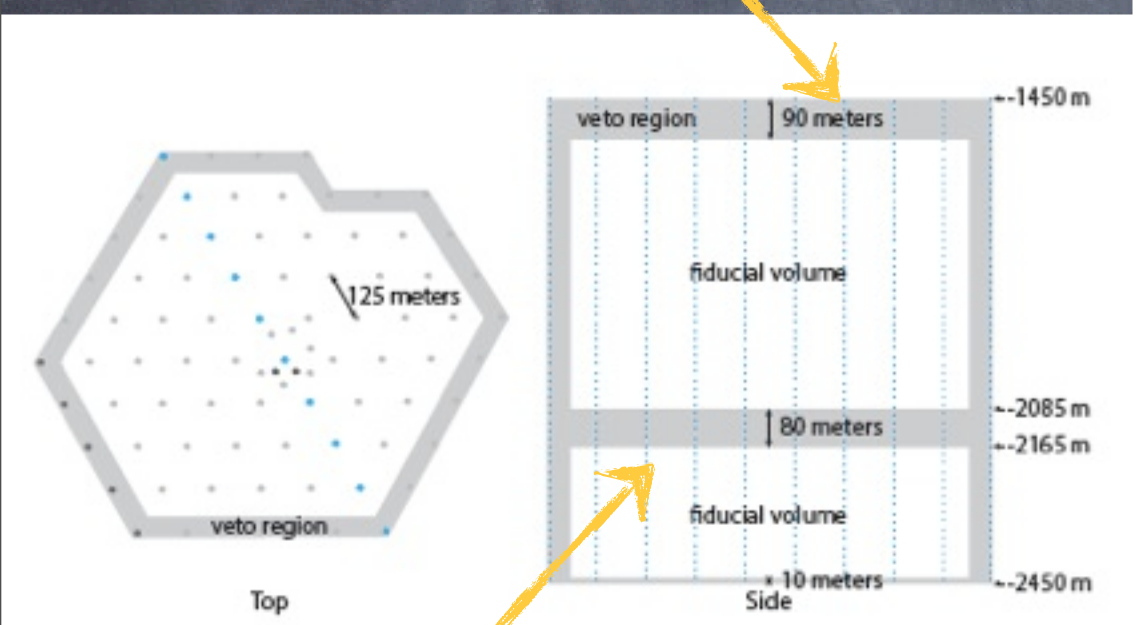
$$\Delta E \lesssim 0.1 \;\; E_i$$

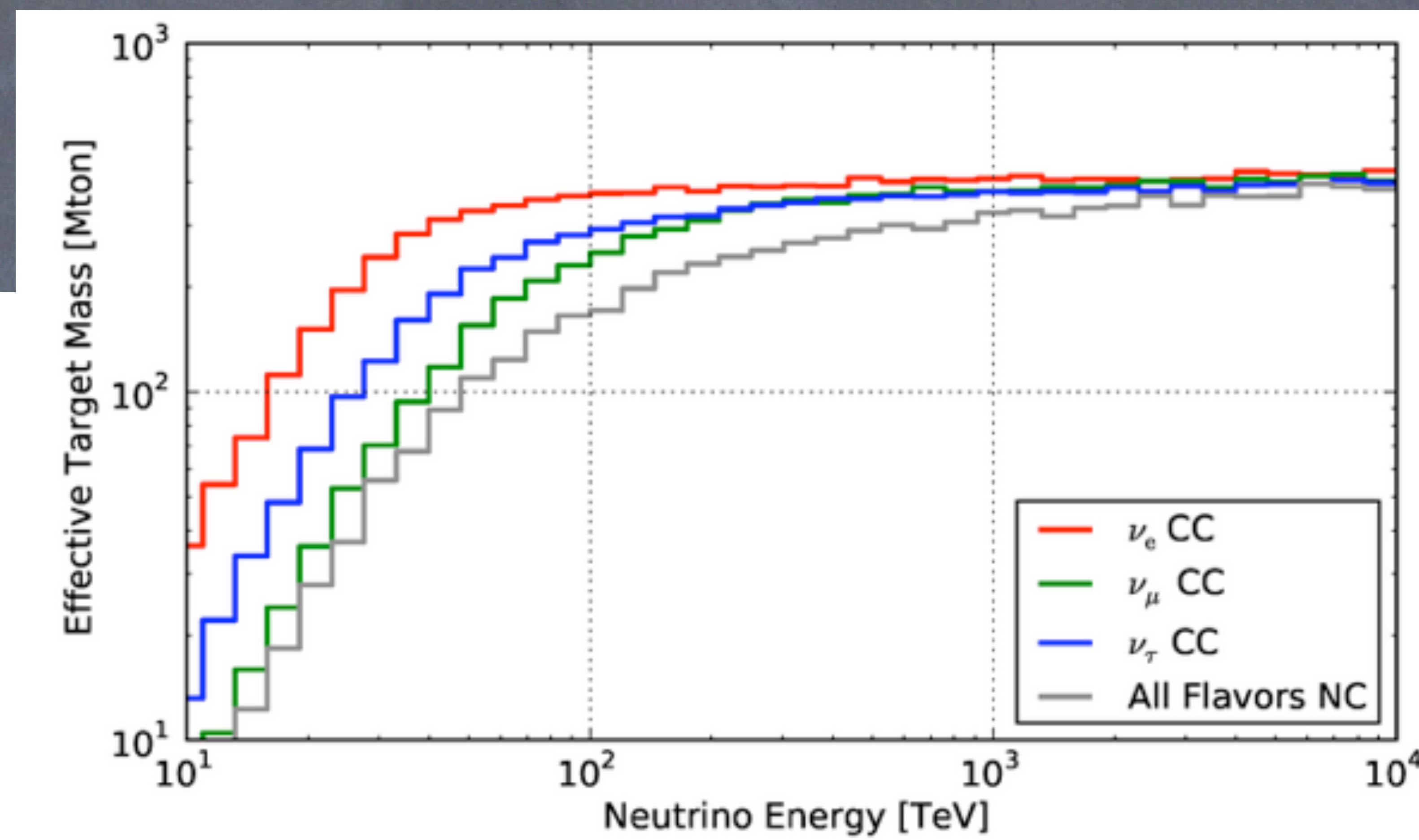
M. G. Aartsen et al. [IceCube Collaboration], JINST 9:P03009, 2014

EFFECTIVE MASSES

~400 Mton effective target mass

Rejection of atmospheric muons

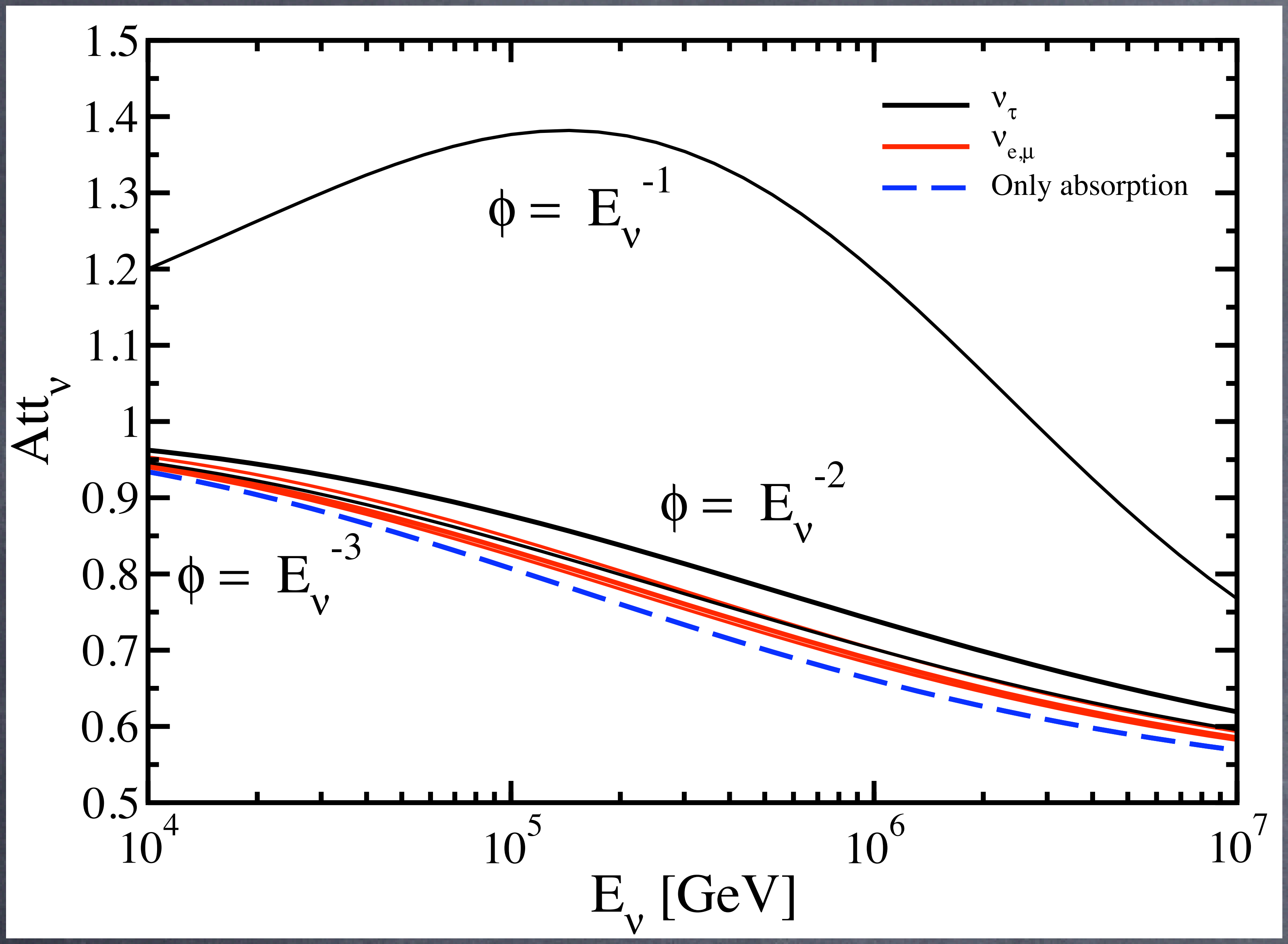


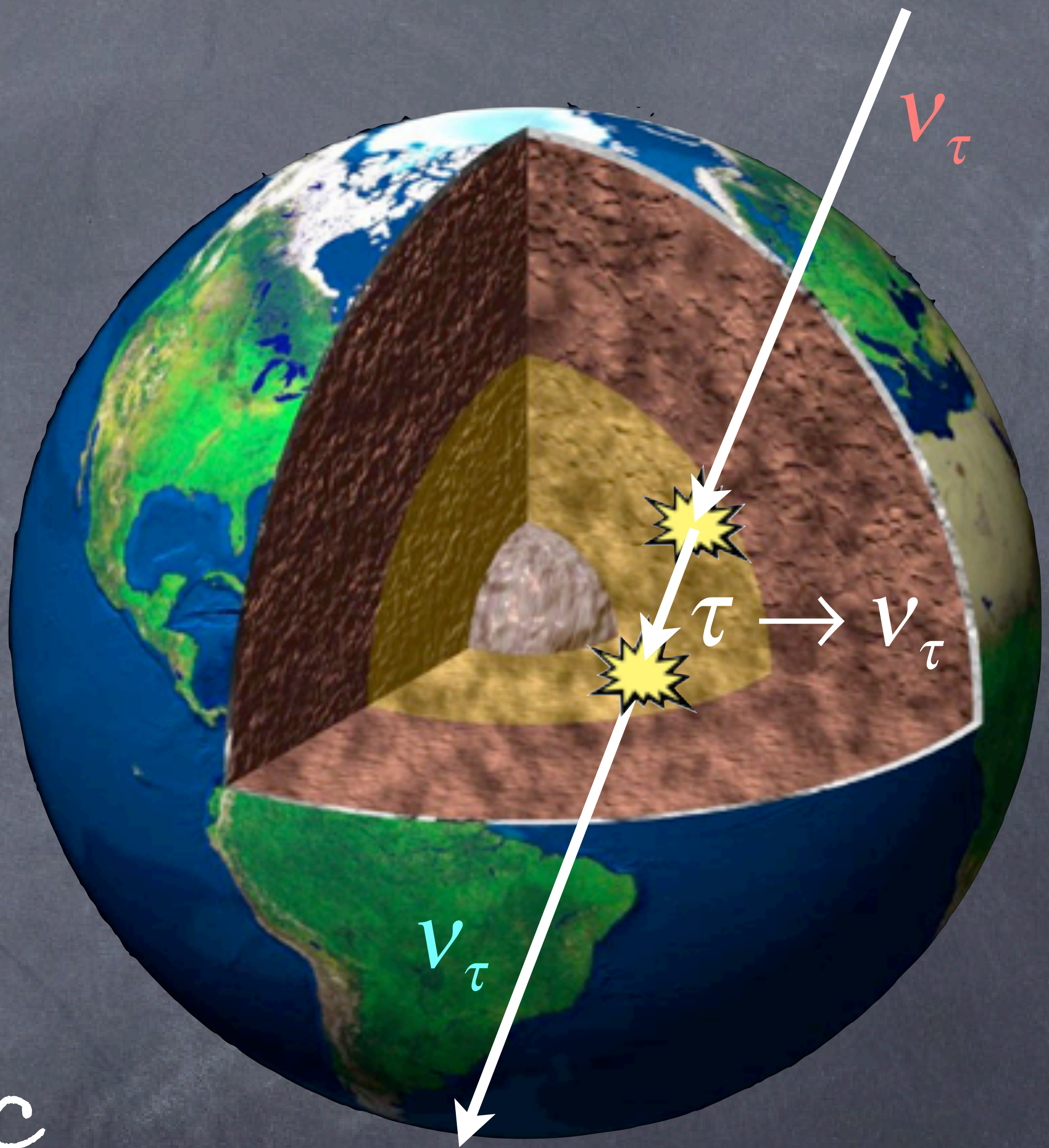


M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

High dust concentration

ATTENUATION/REGENERATION FACTORS





attenuation, redistribution due to NC and regeneration due to tau decays

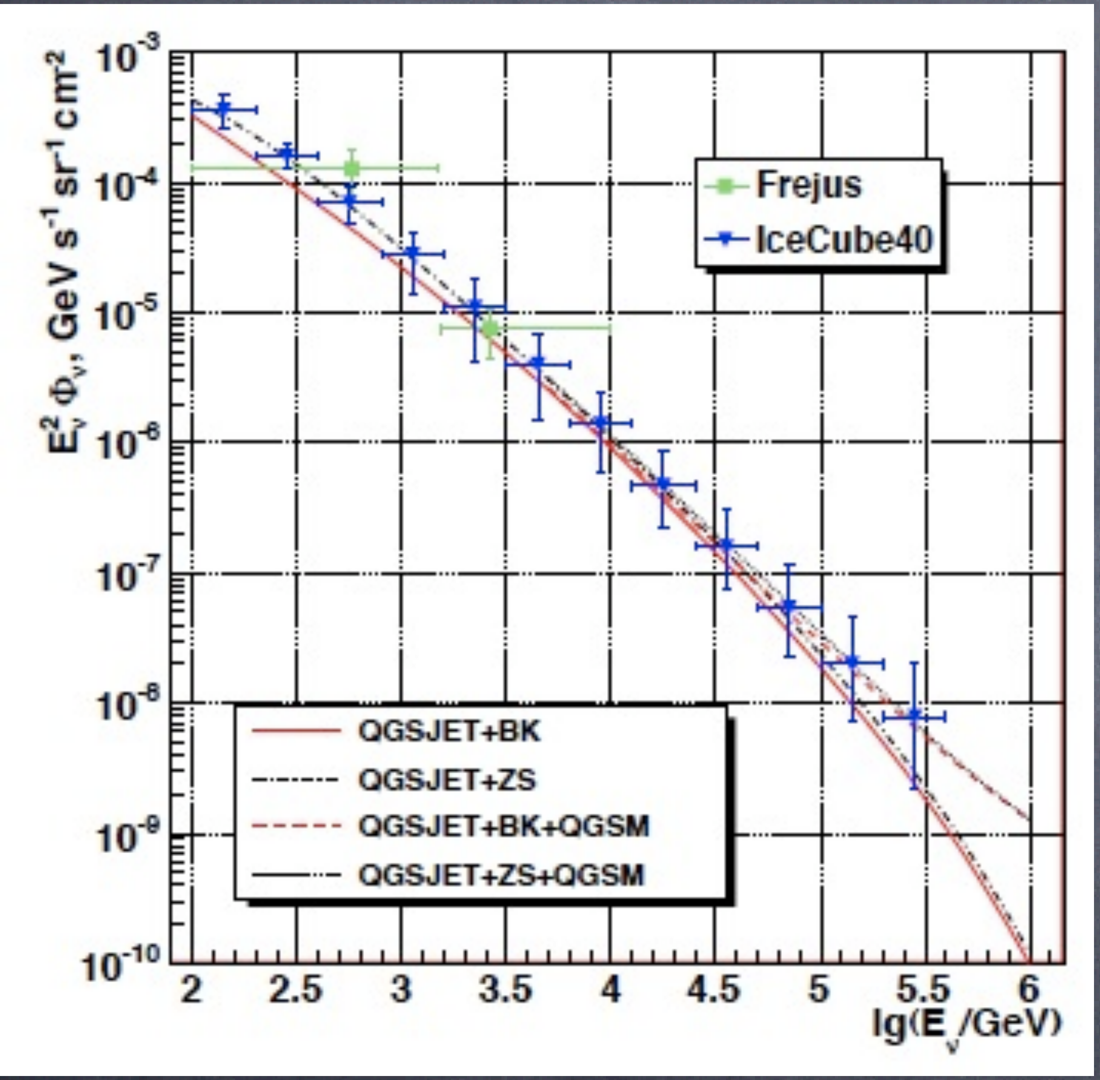
V. A. Naumov and L. Perrone, Astropart. Phys. 10:239, 1999

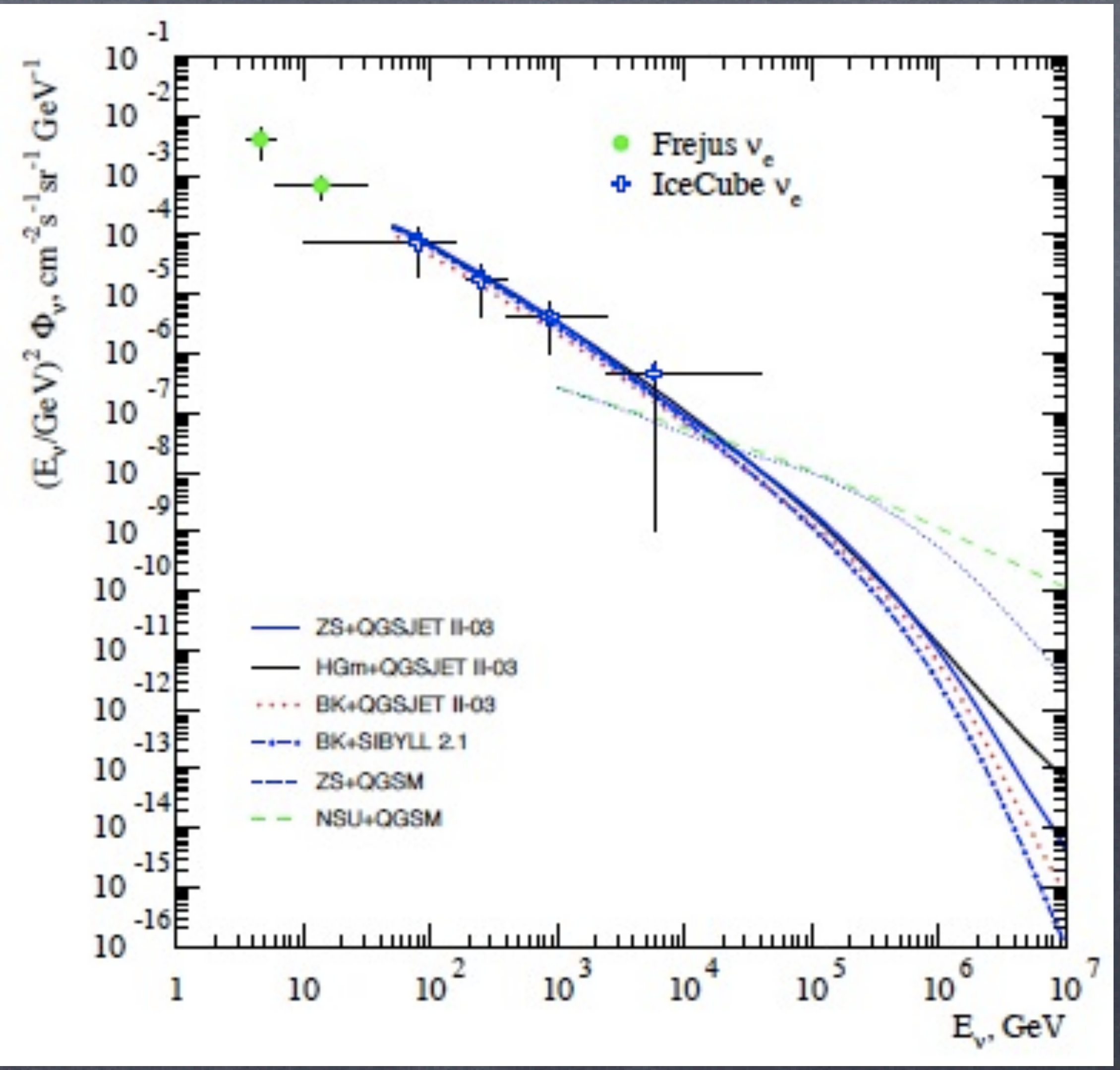
S. Iyer, M. H. Reno and I. Sarcevic, Phys. Rev. D61:053003, 2000

S. Rakshit and E. Reya, Phys. Rev. D74:103006, 2006

ATMOSPHERIC NEUTRINO BACKGROUND

We use them to compute the proportion of tracks and showers but the number of background events is fixed





T. S. Sinegovskaya, E. V. Ogorodnikova, S. I. Sinegovsky, arXiv:1306.5907

STATISTICAL ANALYSIS

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

$b_\mu \equiv$ atmospheric muon background = **6**

$b_\nu \equiv$ atmospheric neutrino background = **4.6** $(p_\nu^{tr} = 0.51)$

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

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

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

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

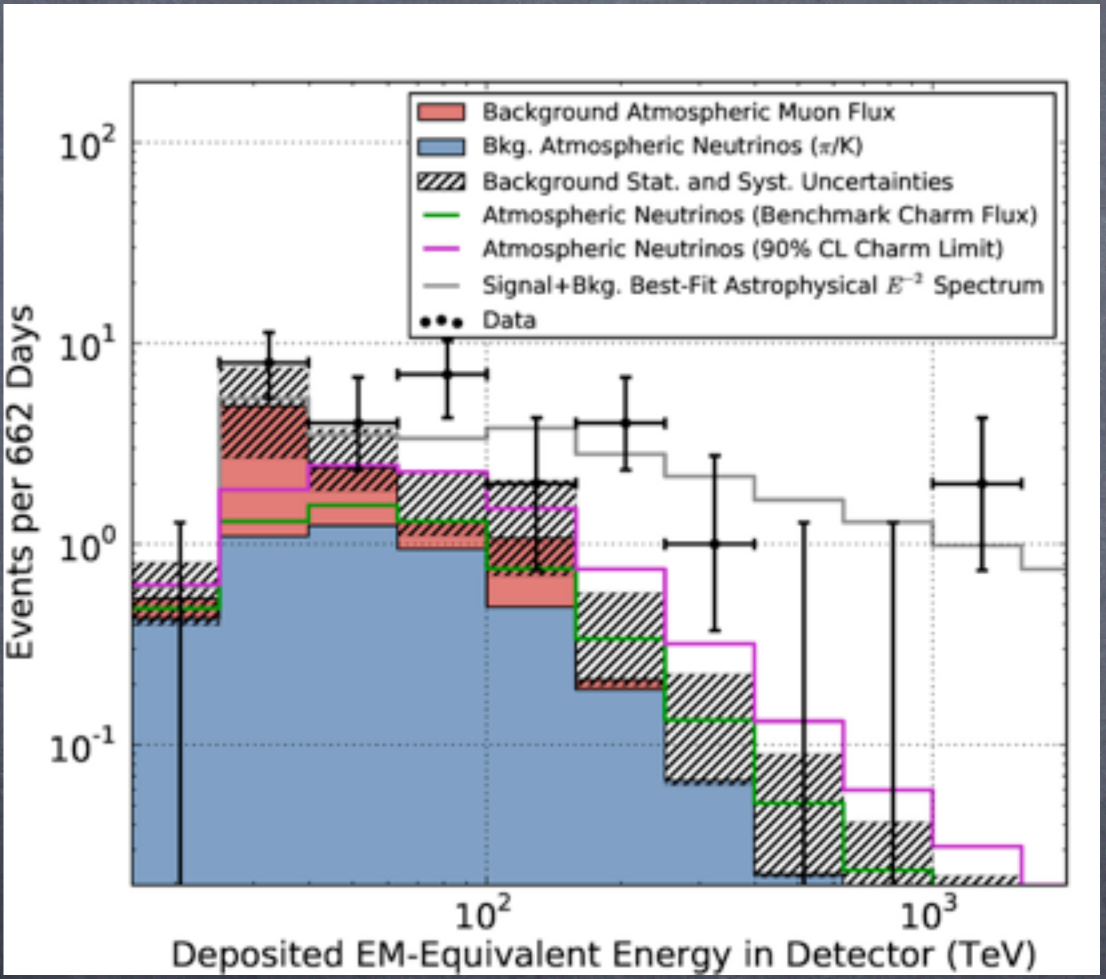
$$\lambda\left(N_{tr}, N_{sh} \middle| \{\alpha_{i,\oplus}\}\right) = -2\ln\left(\frac{\mathcal{L}_p\left(\{\alpha_{i,\oplus}\} \middle| N_{tr}, N_{sh}\right)}{\mathcal{L}_p\left(\{\alpha_{i,\oplus}\}_{\max} \middle| N_{tr}, N_{sh}\right)}\right)$$

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

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

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

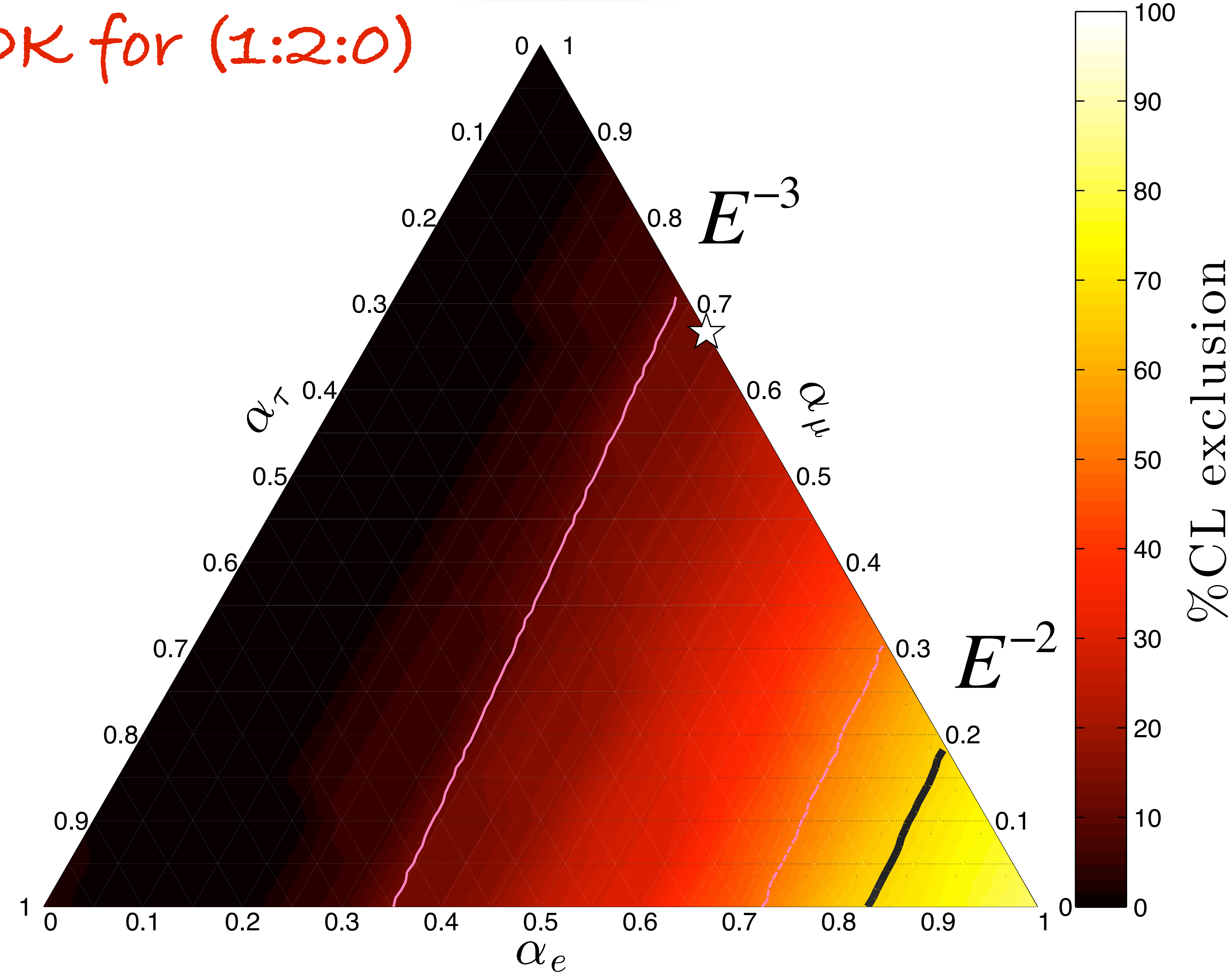
M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

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

NO BACKGROUND?

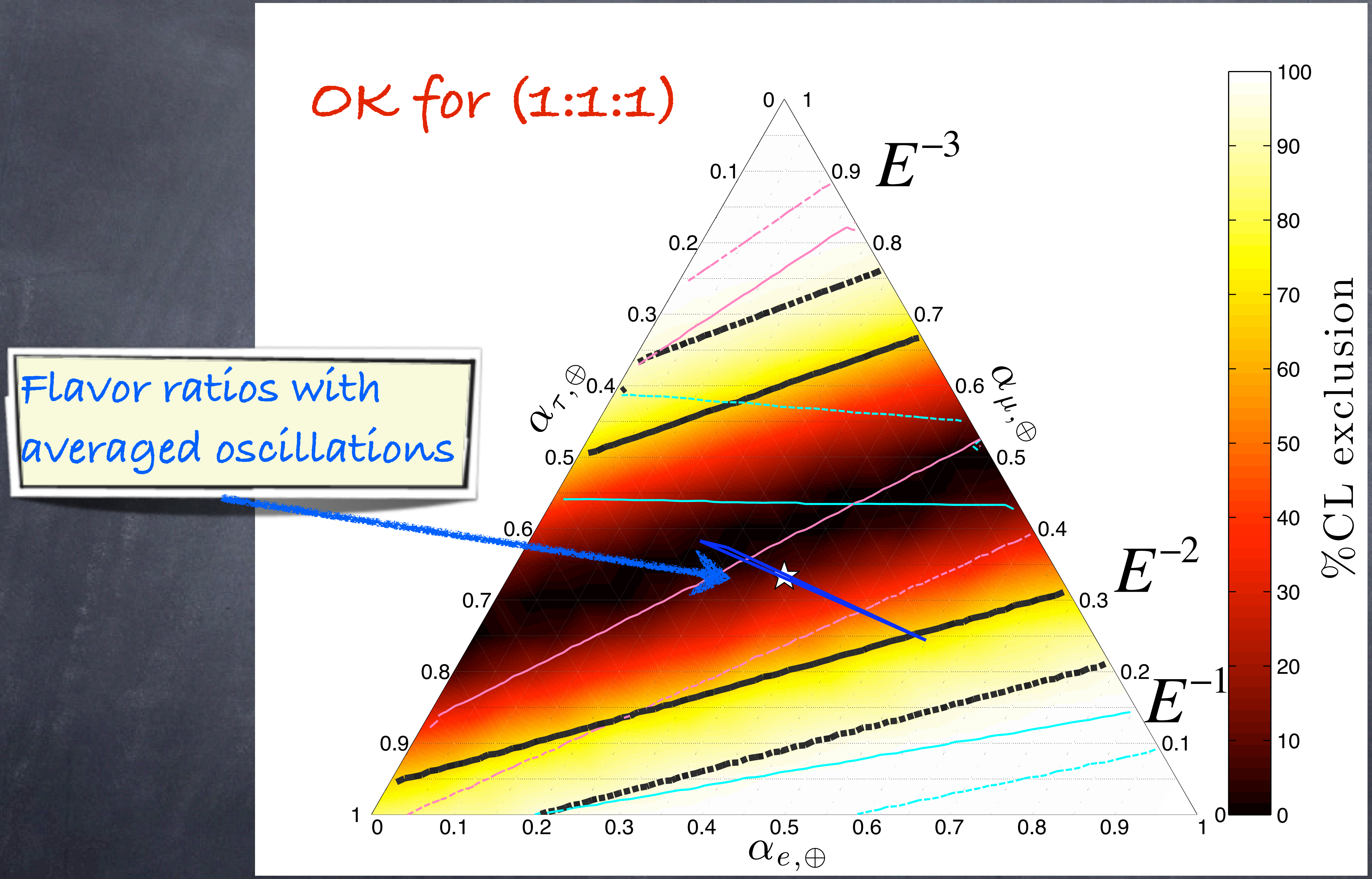
Flavor ratios with averaged oscillations

OK for (1:2:0)



Color code for E^{-2}

NO BACKGROUND?



Color code for E^{-2}

But there is background....

observed → 7 tracks : 21 showers

background → 8.3 tracks : 2.3 showers

But there is background....

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astrophysical =

observed - background

↓

astrophysical tracks = 7-8.3 = 0

BUT THERE IS BACKGROUND....

observed → 7 tracks : 21 showers

background → 8.3 tracks : 2.3 showers

astrophysical =
observed - background

↓

astrophysical tracks=7-8.3=0

Only showers in the astrophysical signal!

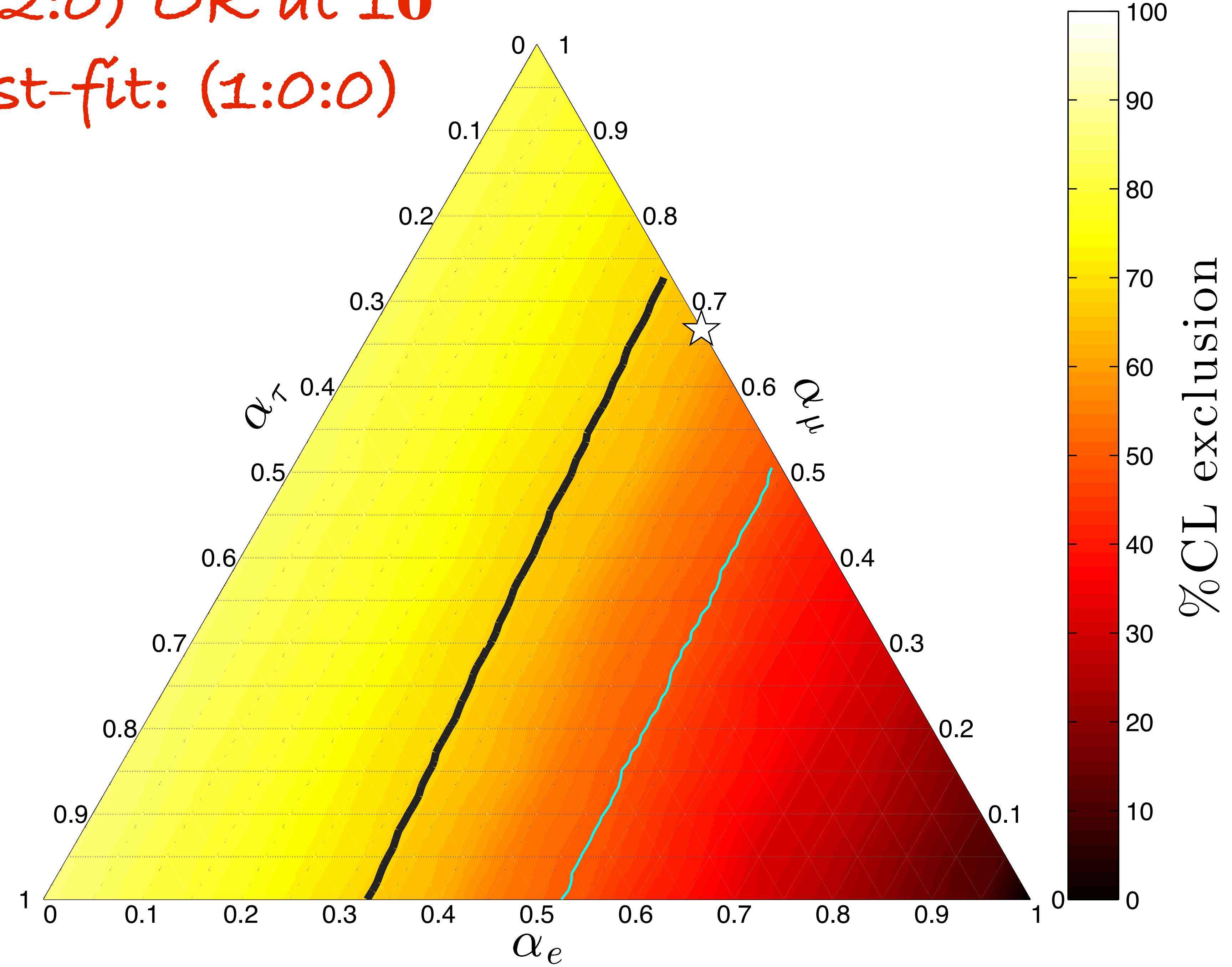
2-YEAR RESULTS

Flavor ratios with averaged oscillations

For E^{-2}

(1:2:0) OK at 1σ

Best-fit: (1:0:0)



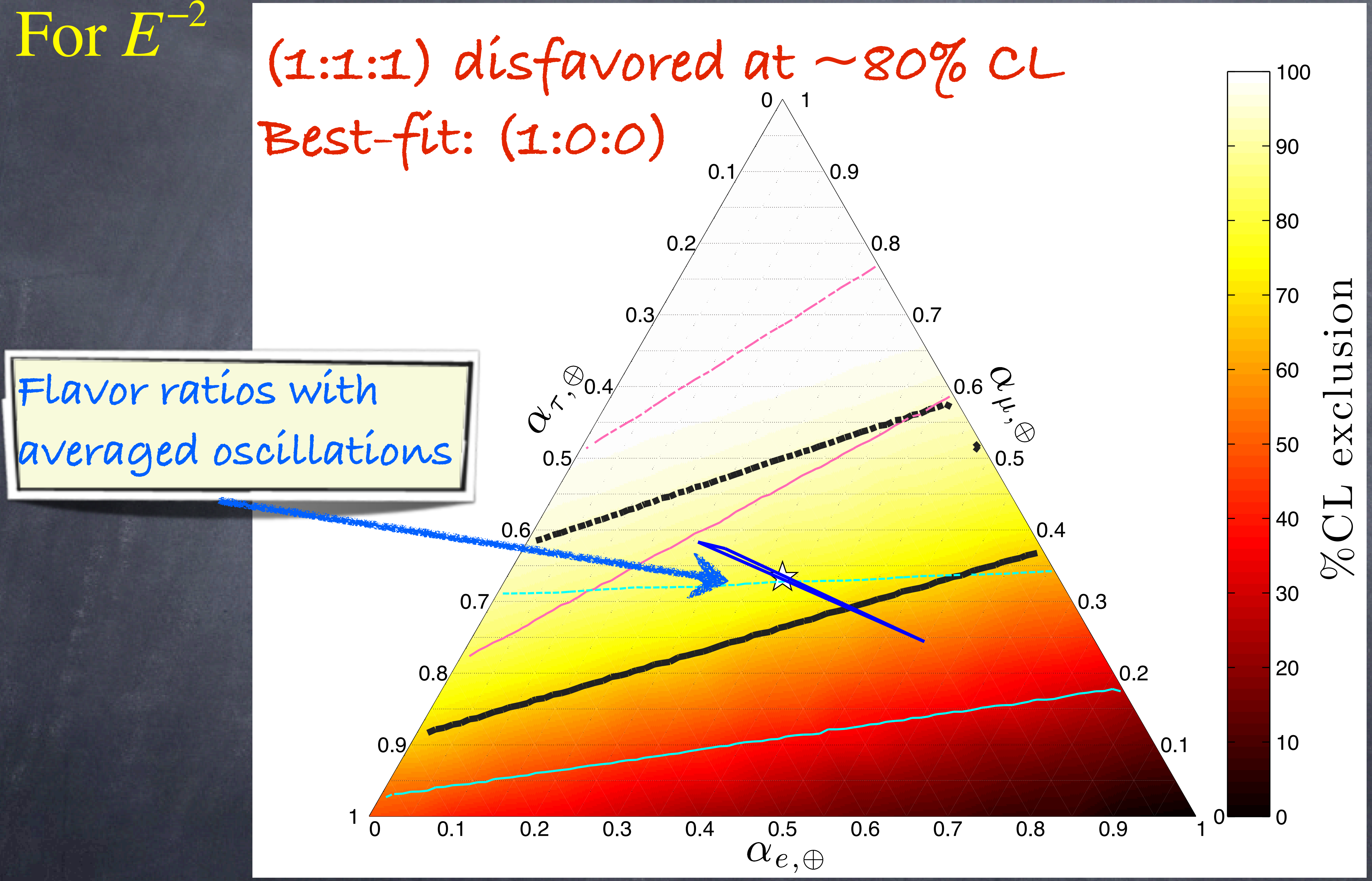
O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

2-YEAR RESULTS

For E^{-2}

(1:1:1) disfavored at ~80% CL

Best-fit: (1:0:0)



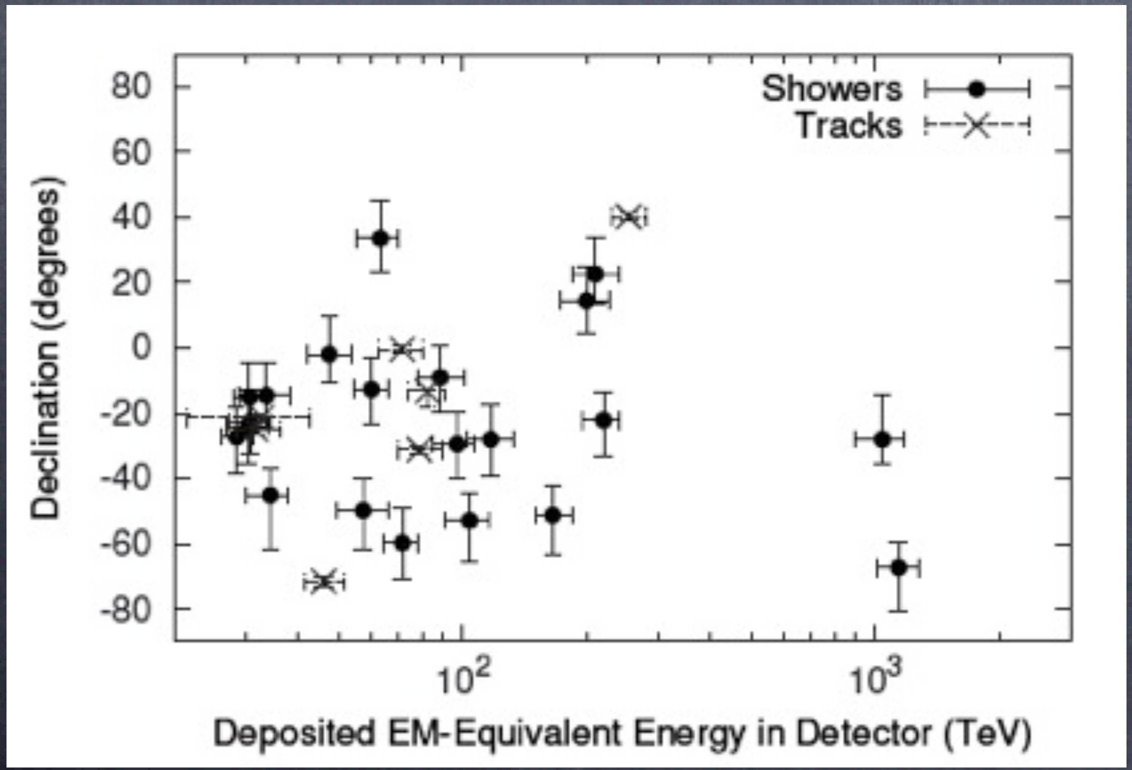
O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

PRELIMINARY 3-YEAR DATA

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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2-year data: May 2010 - May 2012

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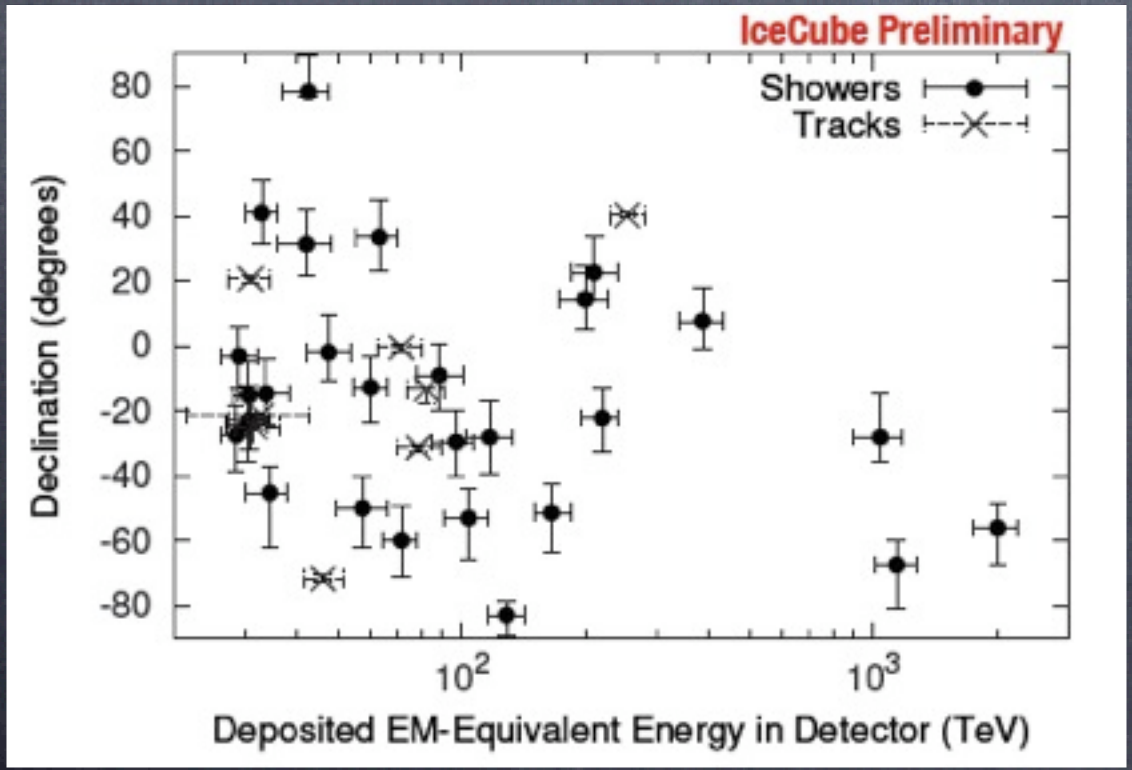
Estimated background : $4.6^{+3.7}_{-1.2}$ atm. ν + 6 ± 3.4 atm. μ

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

C. Kopper, talk at Moriond 2014

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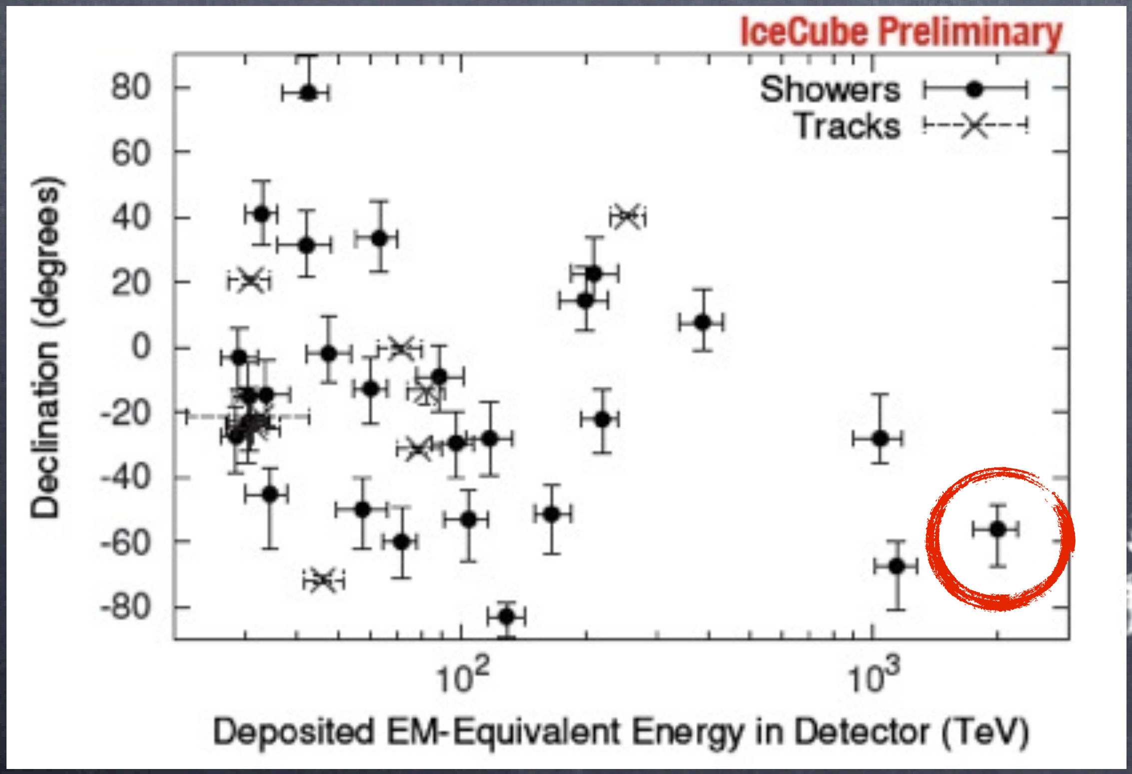


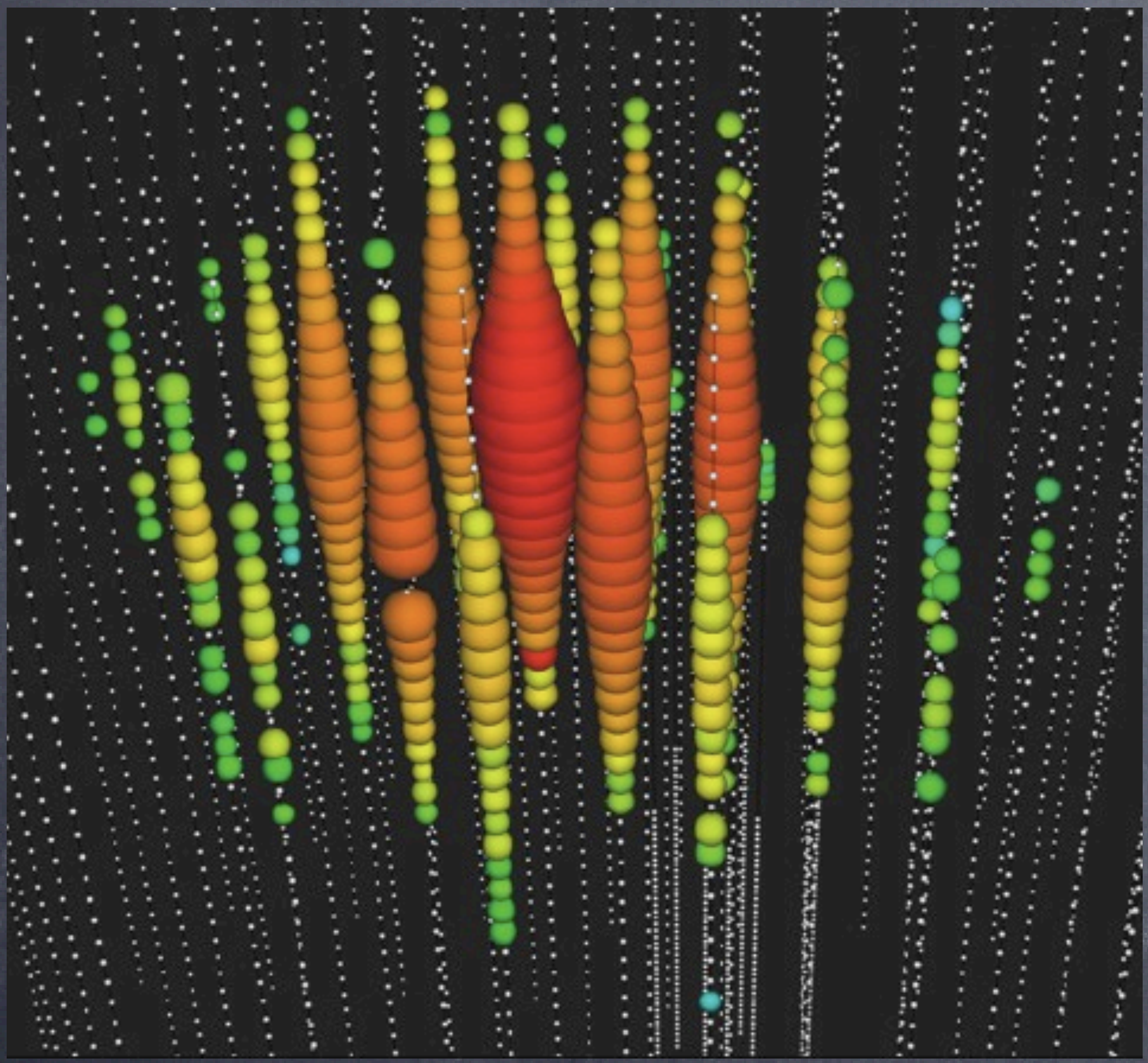
2 extra tracks

7 extra showers

another record breaker

C. Kopper, talk at Moriond 2014

THE 2 PEV NEUTRINO

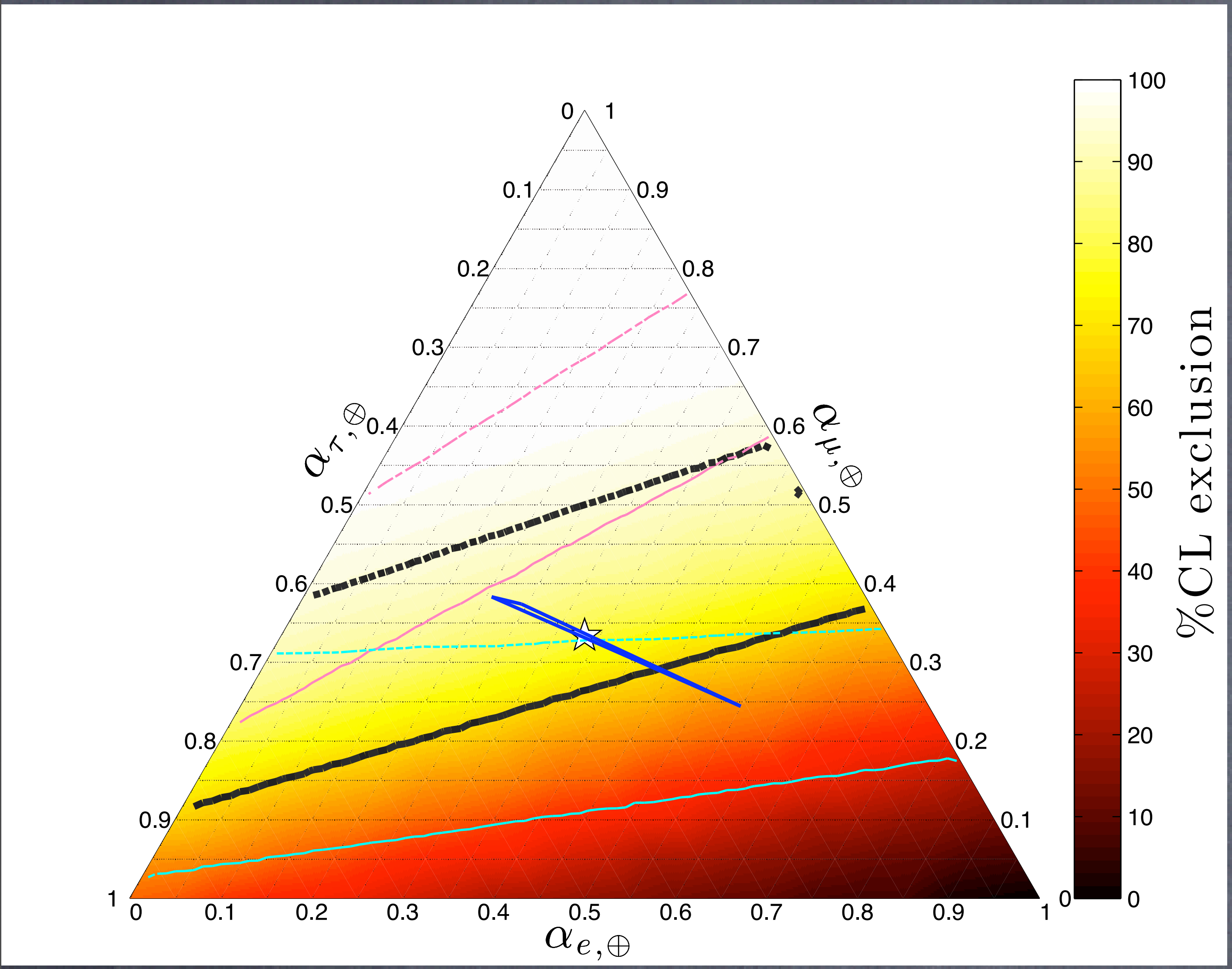


C. Kopper, talk at Moriond 2014

Big Bird

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

2-YEAR RESULTS

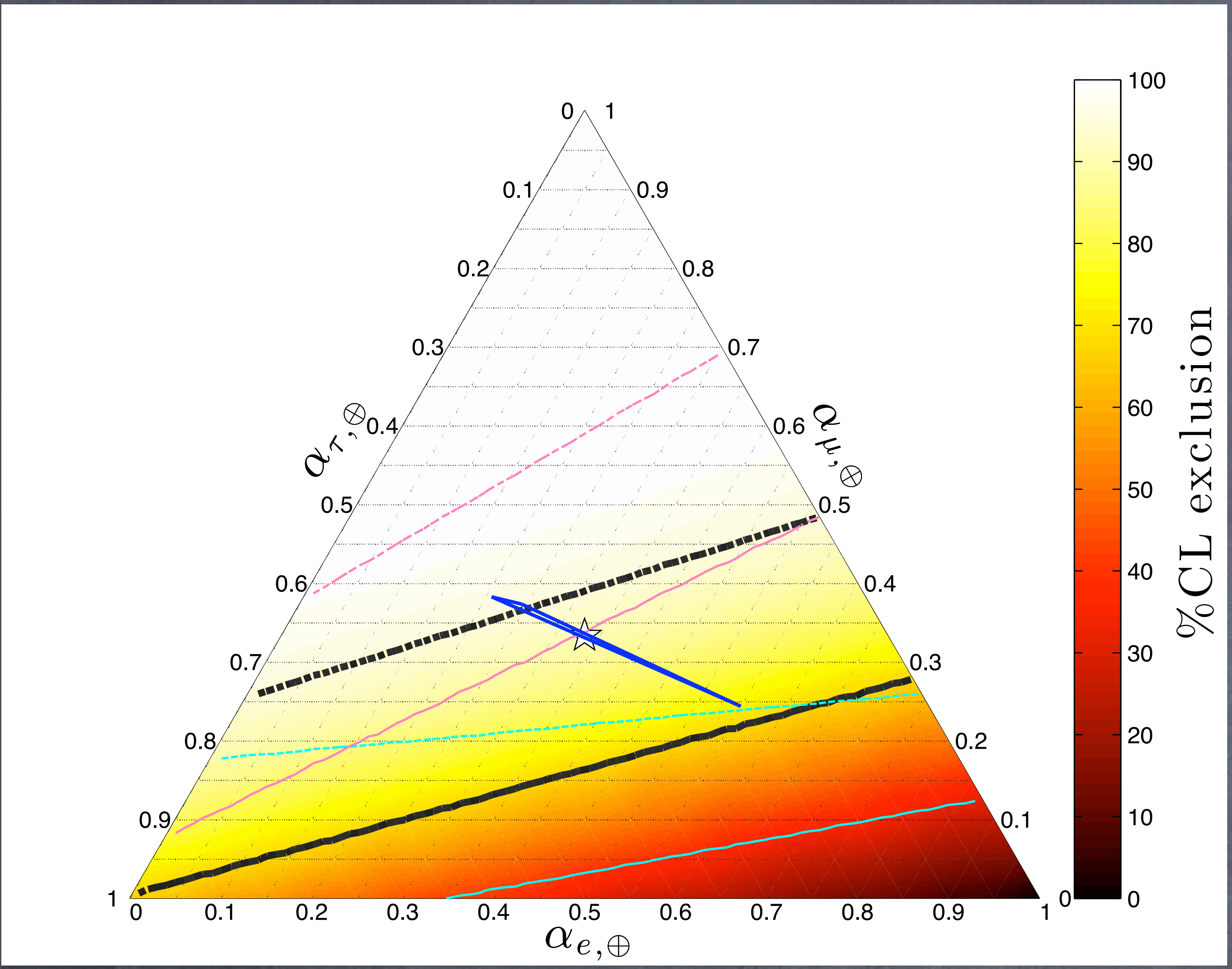


(1:1:1) disfavored at 79% CL

Best-fit: (1:0:0)

O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

3-YEAR RESULTS



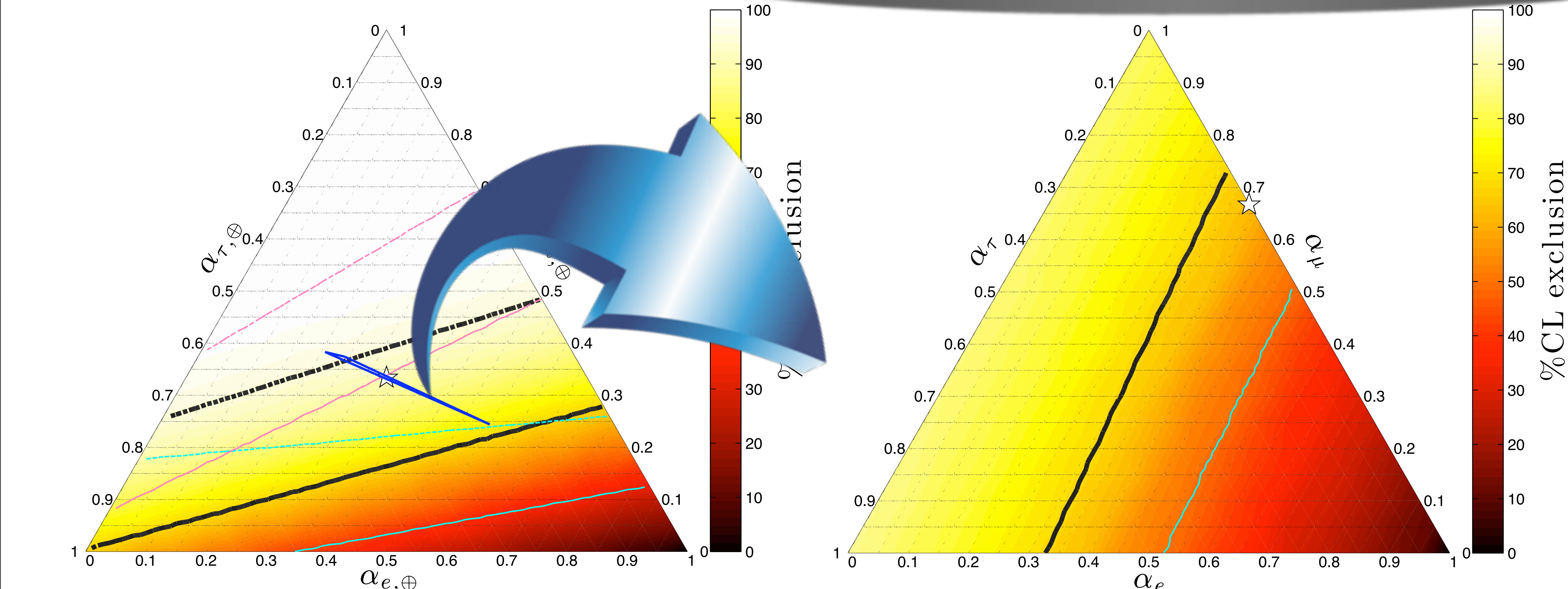
(1:1:1) disfavored at 91% CL

Best-fit: (1:0:0)

O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

3-YEAR RESULTS

Flavor ratios with averaged oscillations



(1:1:1) disfavored at 91% CL

Best-fit: (1:0:0)

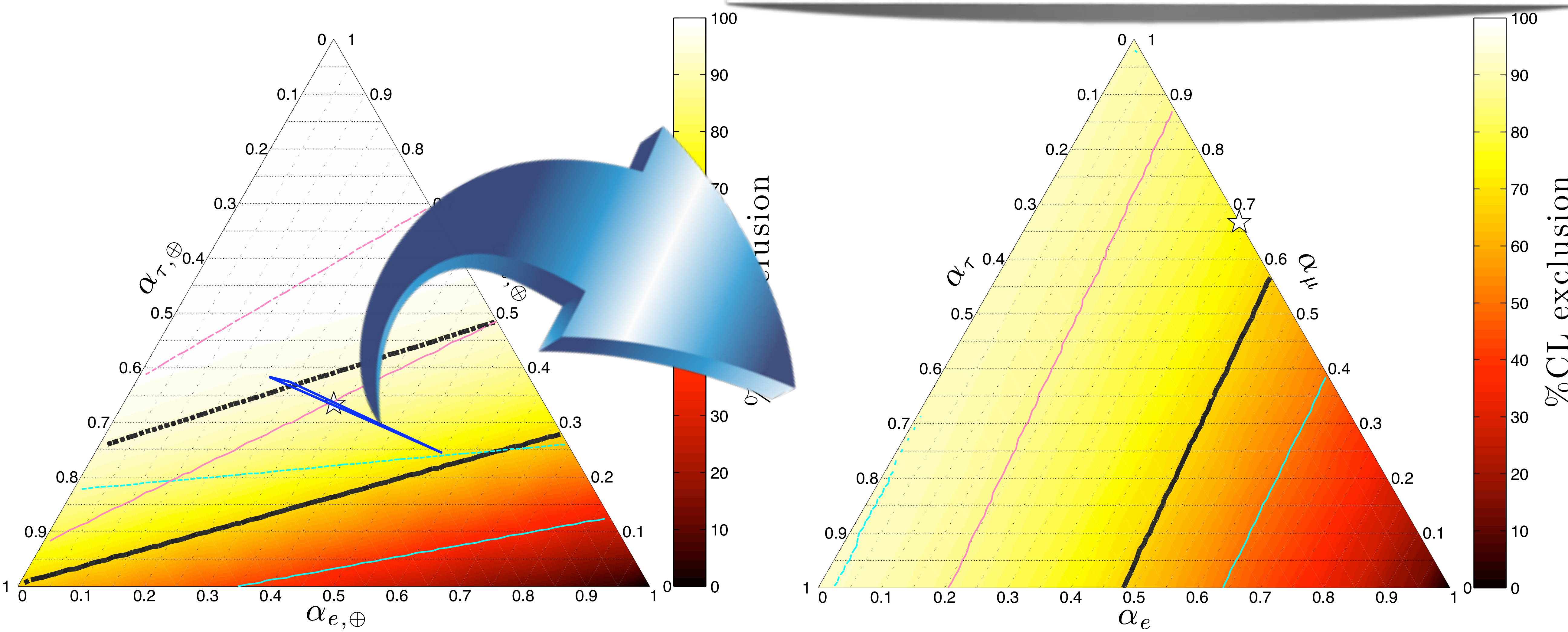
(1:2:0) disfavored at 64% CL

Best-fit: (1:0:0)

O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

3-YEAR RESULTS

Flavor ratios with averaged oscillations



(1:1:1) disfavored at 91% CL

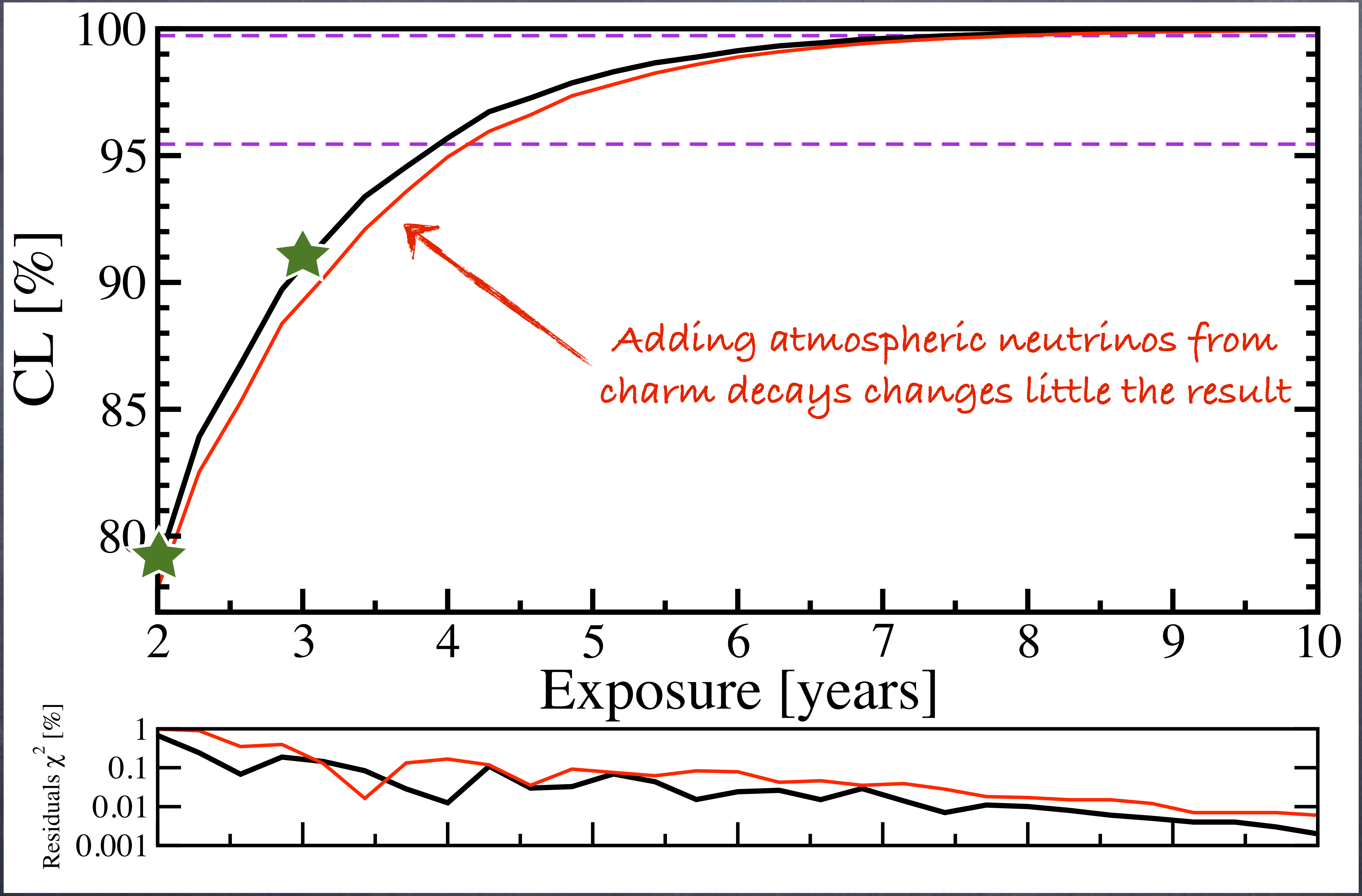
Best-fit: (1:0:0)

(1:2:0) disfavored at 76% CL

Best-fit: (1:0:0)

O. Mena, SPR and A. C. Vincent, arXiv:1404.0017v2

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?

WAITING FOR THE FIRST PEV TRACK EVENT

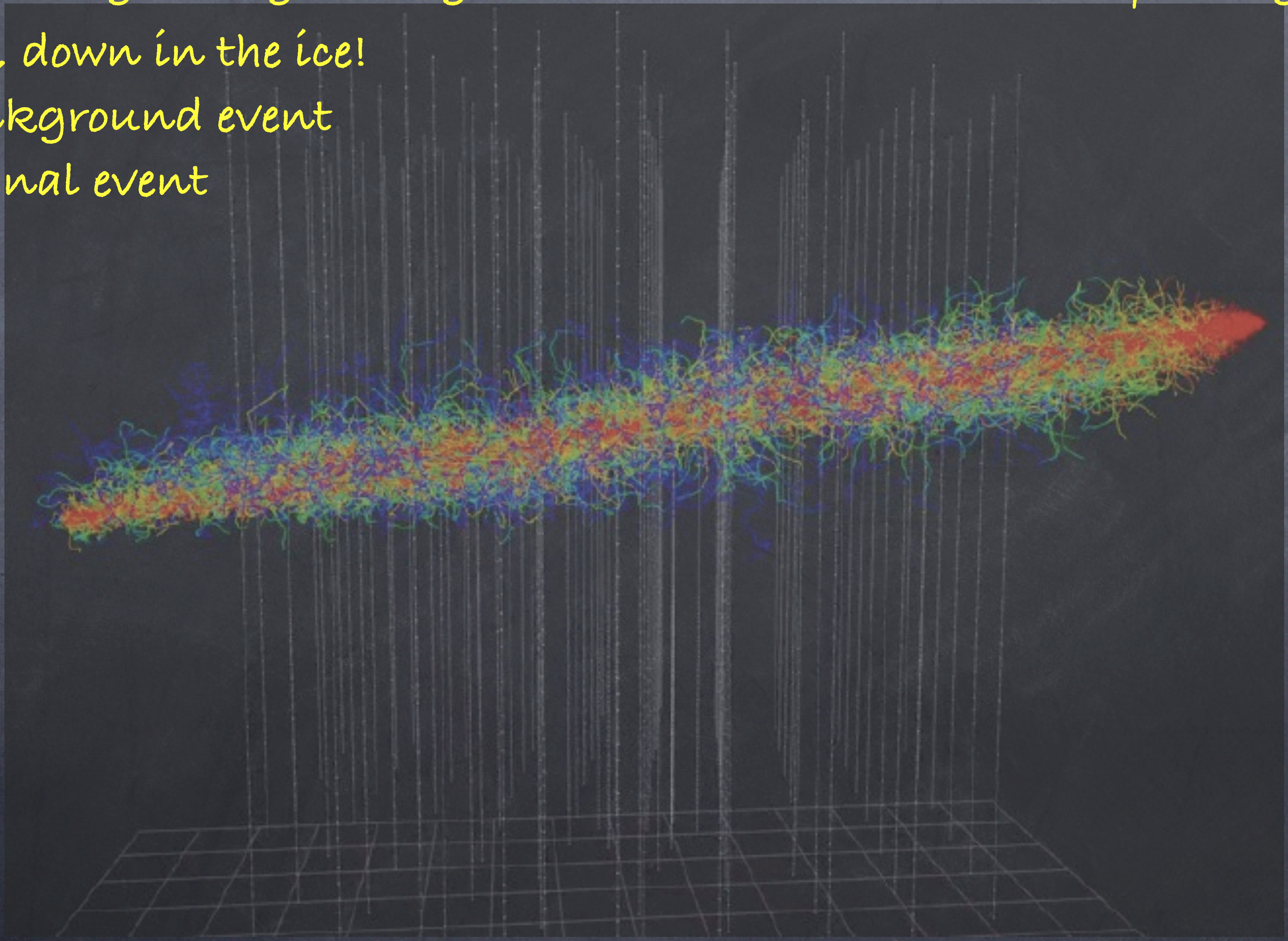
...faster than lightning, stronger than steel, smarter than a speeding bullet.

Oh, look, down in the ice!

It's a background event

It's a signal event

It's...



WAITING FOR THE FIRST PEV TRACK EVENT

...faster than lightning, stronger than steel, smarter than a speeding bullet.

Oh, look, down in the ice!

It's a background event

It's a signal event

It's...

Grover

(or Coco, Gualter, Archibaldo, Grobi, Arquibaldo, Gunnar, Açıkgöz, Florek, Antar, Kruvi, Kajkoal, Bohouš...)