On the flavor composition of the IceCube neutrinos

based on O. Mena, SPR and A.C. Vincent,
PRL 113:091103, 2014 ; arXiv:1411.2998 (proc. ICHEP 2014) ;
arXiv:1502.02649 (accepted in PRD)

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Heidelberg, April 27, 2015

Max-Planck-Institut für Kernphysik
Particle & Astroparticle Physics

WHY DO WE CARE ABOUT HIGH-ENERGY NEUTRINOS?

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Neutrinos carry a quantum number that
cosmic rays and photons do not have: flavor

WHY DO WE CARE ABOUT FLAVOR?

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It carries information about the mechanism of production...

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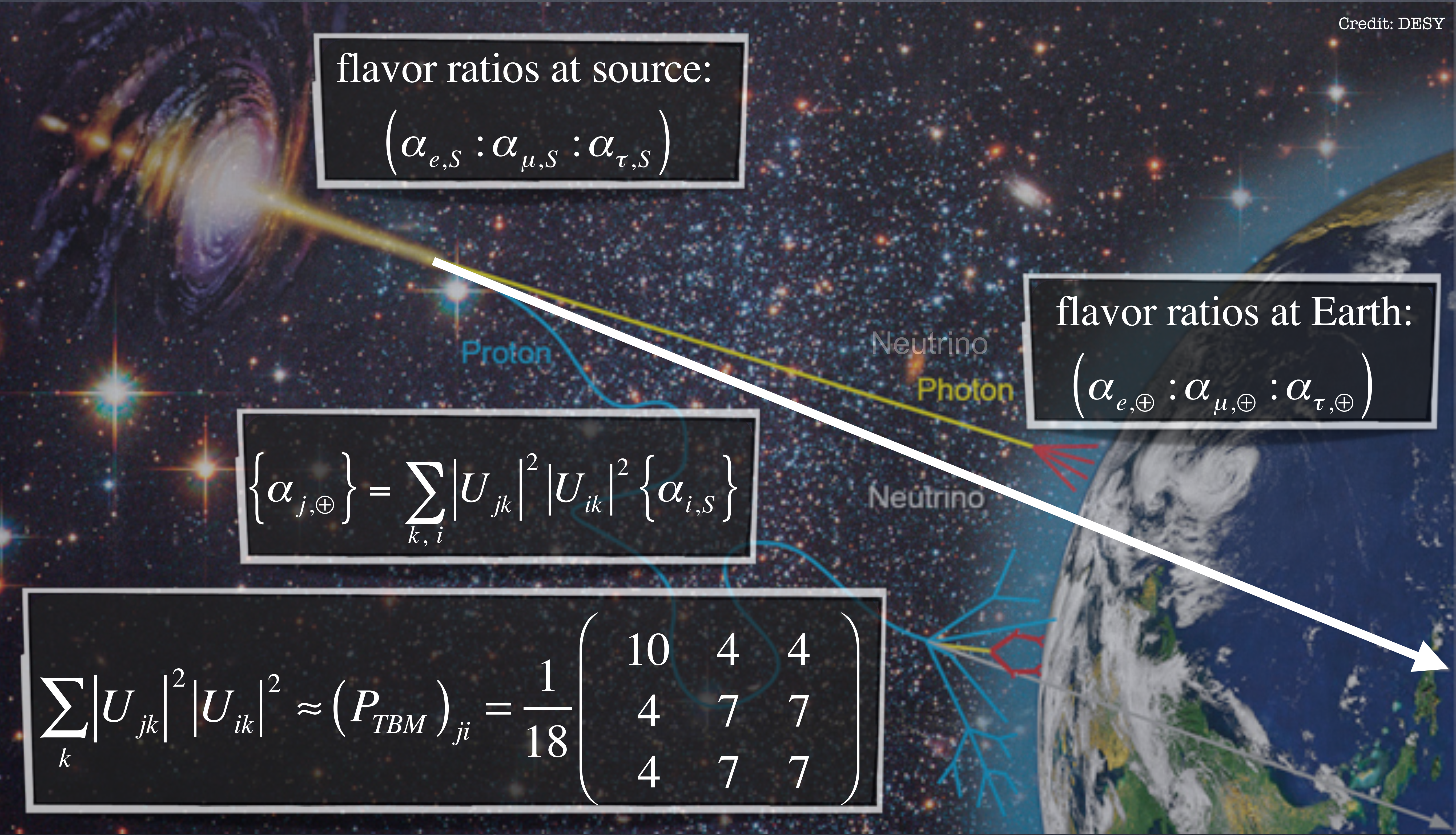
It carries information about the mechanism of production...

...but also about the way neutrinos propagate from the sources to the detector

Exotic physics could produce deviations from the standard expectations

STANDARD COSMIC PROPAGATION



Credit: DESY

flavor ratios at source:

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

flavor ratios at Earth:

$$\left(\alpha_{e,\oplus} : \alpha_{\mu,\oplus} : \alpha_{\tau,\oplus}\right)$$

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

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

FLAVOR RATIOS AT SOURCE AND EARTH

$$\begin{tikzcd} \pi^{\pm} \arrow[r] & \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \arrow[d] \\ & e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu}) \end{tikzcd}$$

Pion sources $\left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{S} = \left(1:2:0\right) \Rightarrow \left(\nu_{\mathrm{e}} : \nu_{\mu} : \nu_{\tau}\right)_{\oplus} = \left(1:1:1\right)$

FLAVOR RATIOS AT SOURCE AND EARTH

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

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$$\xcancel{\downarrow}$$
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Pion sources

$$\left(\nu_\mathrm{e} : \nu_\mu : \nu_\tau\right)_S = (1:2:0) \Rightarrow \left(\nu_\mathrm{e} : \nu_\mu : \nu_\tau\right)_\oplus = (1:1:1)$$

Muon damped sources

$$\left(\nu_\mathrm{e} : \nu_\mu : \nu_\tau\right)_S = (0:1:0) \Rightarrow \left(\nu_\mathrm{e} : \nu_\mu : \nu_\tau\right)_\oplus = (4:7:7)$$

FLAVOR RATIOS AT SOURCE AND EARTH

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

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

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

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

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

FLAVOR RATIOS AT SOURCE AND EARTH

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

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

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

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

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

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NEUTRINO DECAY

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 90:181301, 2003

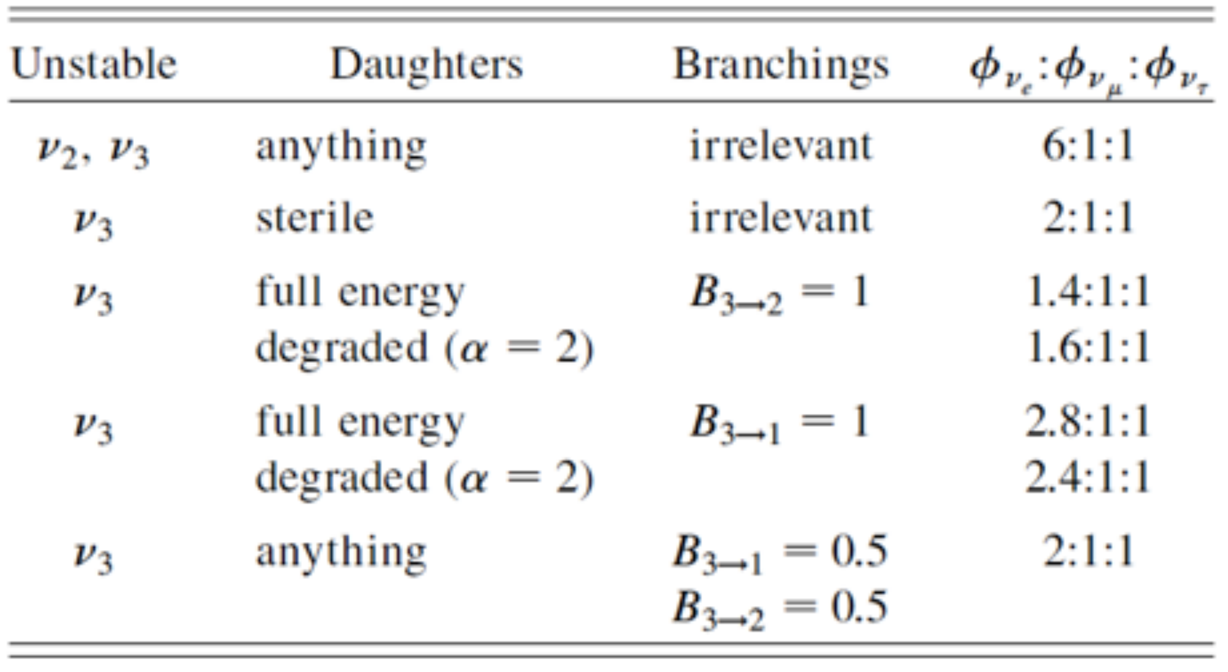
$$\nu_i \to \nu_j + X$$

Invisible daughters

$$\{\alpha_{j,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\} e^{-Lm_k/E\tau_k} \xrightarrow{L \gg E\tau_k/m_k} \sum_{k(stable),\, i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\}$$

Daughters with full energy

$$\{\alpha_{j,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\} e^{-Lm_k/E\tau_k} \xrightarrow{L \gg E\tau_k/m_k} \sum_{k(stable),\, i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\} + \sum_{k(stable),\, l,\, i} |U_{jk}|^2 |U_{il}|^2 Br_{l\to k} \{\alpha_{i,S}\}$$



Unstable	Daughters	Branchings	$\phi_{\nu_e}:\phi_{\nu_\mu}:\phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	6:1:1
ν_3	sterile	irrelevant	2:1:1
ν_3	full energy	$B_{3\to 2} = 1$	1.4:1:1
	degraded ($\alpha = 2$)		1.6:1:1
ν_3	full energy	$B_{3\to 1} = 1$	2.8:1:1
	degraded ($\alpha = 2$)		2.4:1:1
ν_3	anything	$B_{3\to 1} = 0.5$ $B_{3\to 2} = 0.5$	2:1:1

PSEUDO-DIRAC NEUTRINOS

R. M. Crocker, F. Melia and R. R. Volkas, Astrophys. J. Suppl. 130: 339, 2000; and 141:147, 2002

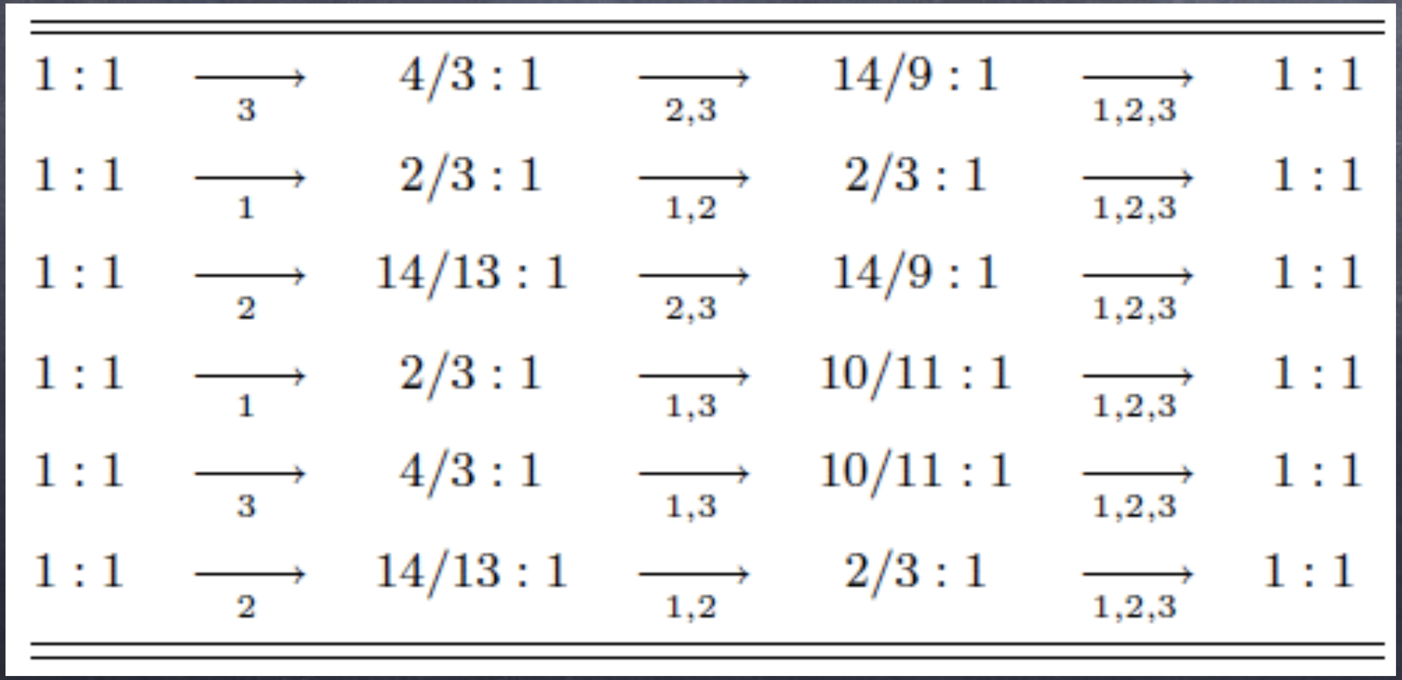
J. F. Beacom, N. F. Bell, D. Hooper, J. G. Learned, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 92:011101, 2004

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

Dirac neutrino: $m_L = m_R = 0$

Pseudo-Dirac neutrinos: $m_L, m_R \ll m_D$

$$\{\alpha_{j,\oplus}\} = \sum_{k,i} |U_{jk}|^2 |U_{ik}|^2 \{\alpha_{i,S}\} \left[1 - \sin^2\left(\frac{\delta m_k^2 L}{4E}\right)\right]$$



1 : 1	$\xrightarrow[3]{}$	4/3 : 1	$\xrightarrow[2,3]{}$	14/9 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[1]{}$	2/3 : 1	$\xrightarrow[1,2]{}$	2/3 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[2]{}$	14/13 : 1	$\xrightarrow[2,3]{}$	14/9 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[1]{}$	2/3 : 1	$\xrightarrow[1,3]{}$	10/11 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
1 : 1	$\xrightarrow[3]{}$	4/3 : 1	$\xrightarrow[1,3]{}$	10/11 : 1	$\xrightarrow[1,2,3]{}$	1 : 1
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J. F. Beacom, N. F. Bell, D. Hooper, J. G. Learned, S. Pakvasa and T. J. Weiler, Phys, Rev. Lett. 92:011101, 2004


123
SESAME STREET

THE ICECUBE TELESCOPE

At the South Pole

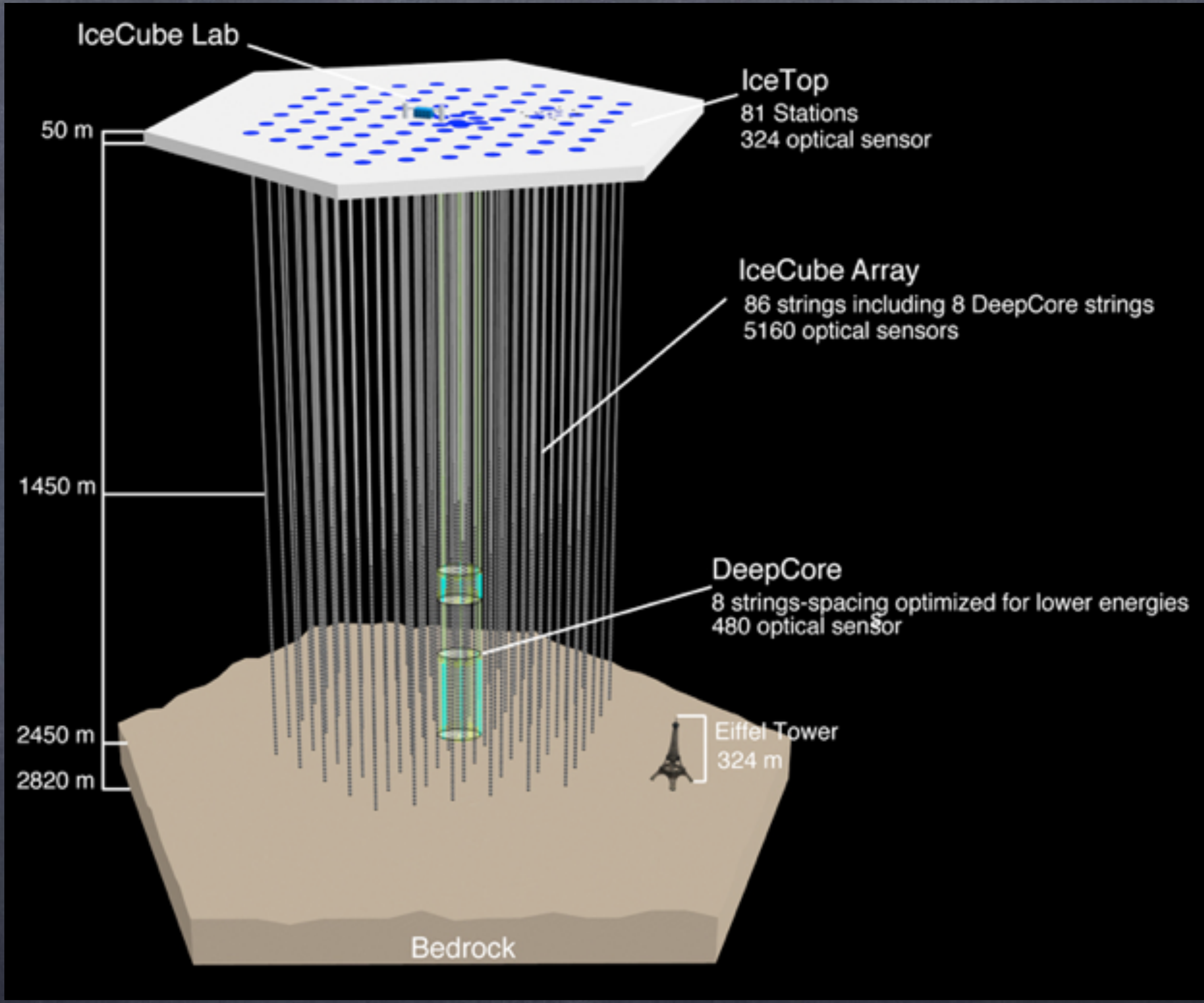
86 strings with 60 DOM/string
125 m apart on triangular grid

17 m vertical spacing between PMTs

8 DeepCore strings 75 m apart

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

completed in 2010



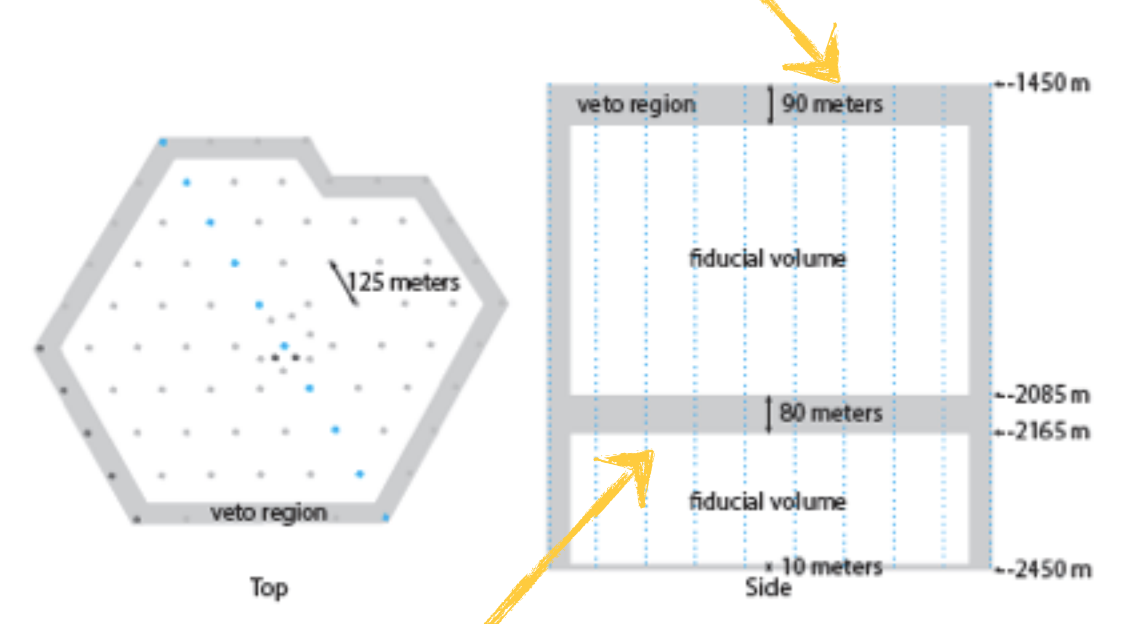
Secondary particles detected via Cherencov radiation

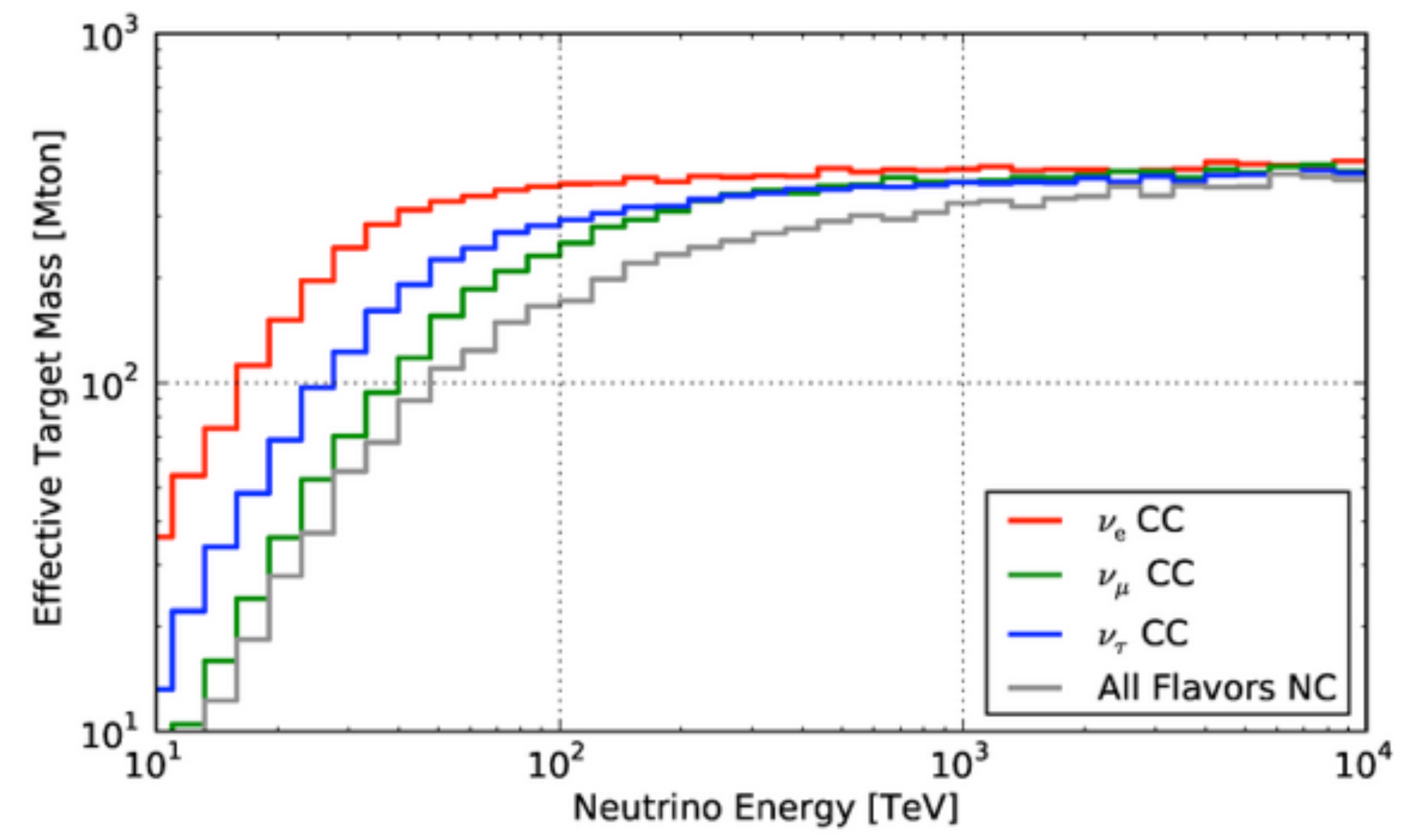
EFFECTIVE MASSES

*H*igh *E*nergy *S*tarting *E*vents

~400 Mton effective target mass

Rejection of atmospheric muons





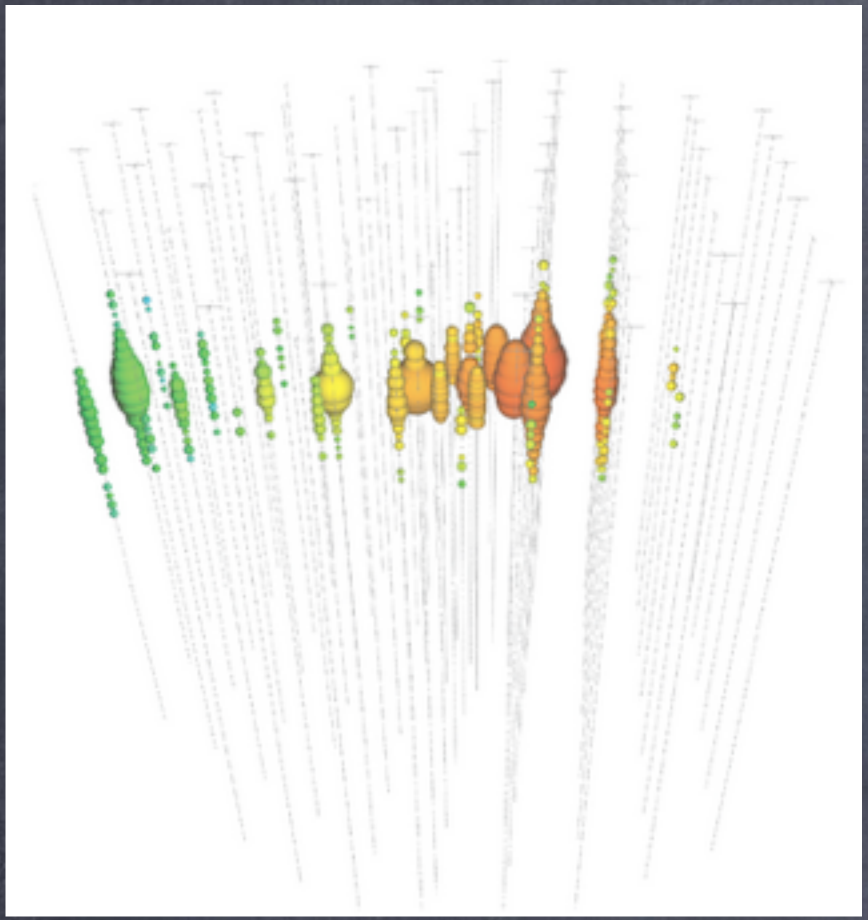
M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

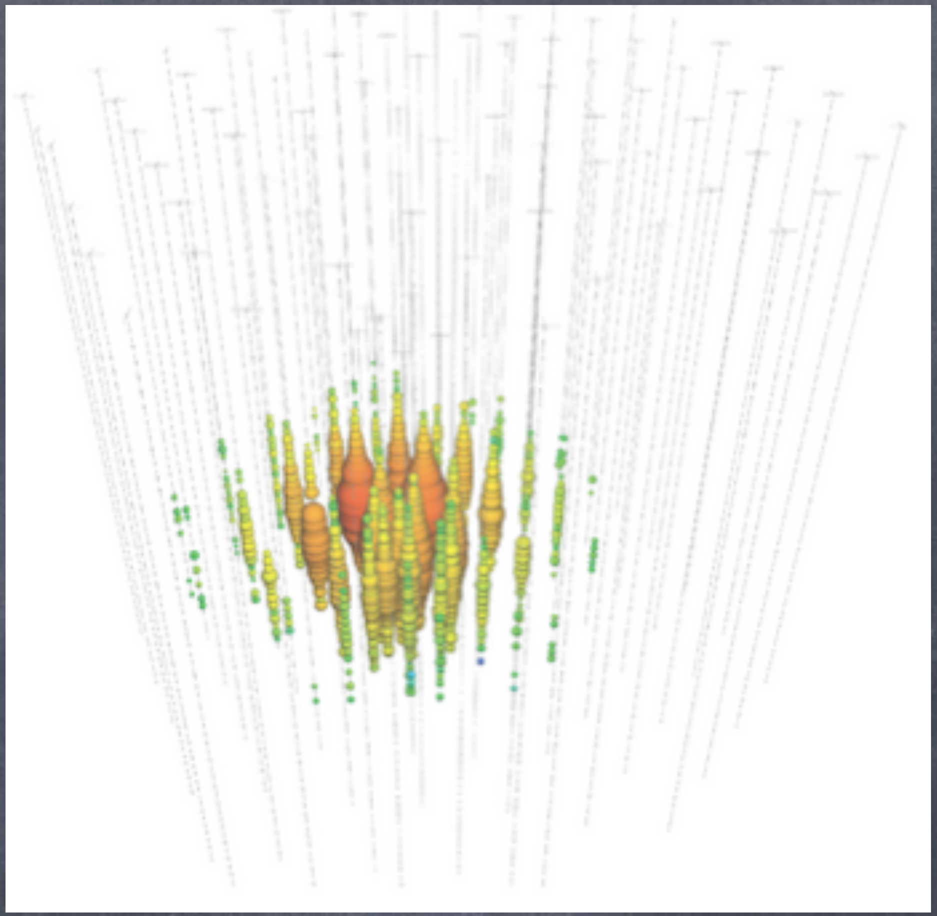
High dust concentration

TYPE OF EVENTS

Muon tracks

Showers





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

Good angular resolution

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

Poor angular resolution

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

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

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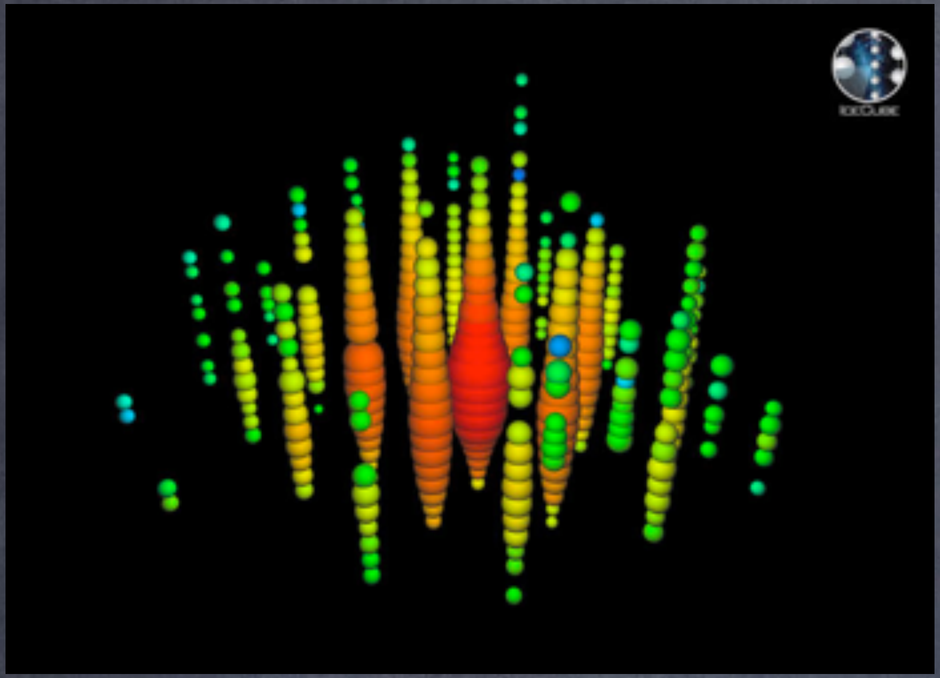
THE FIRST PEV NEUTRINOS

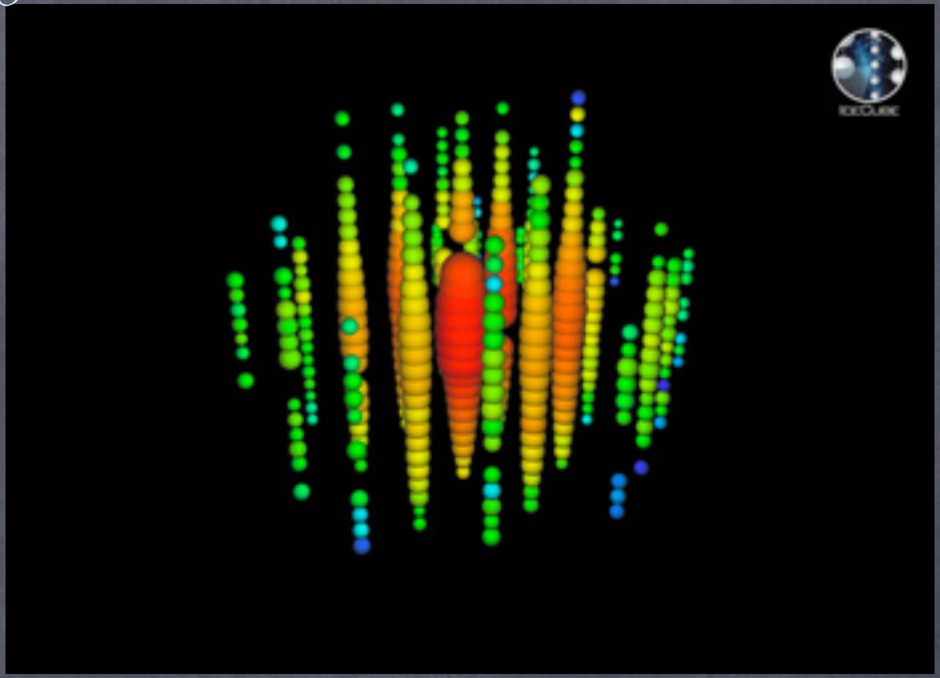
M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 111:021103, 2013



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...)

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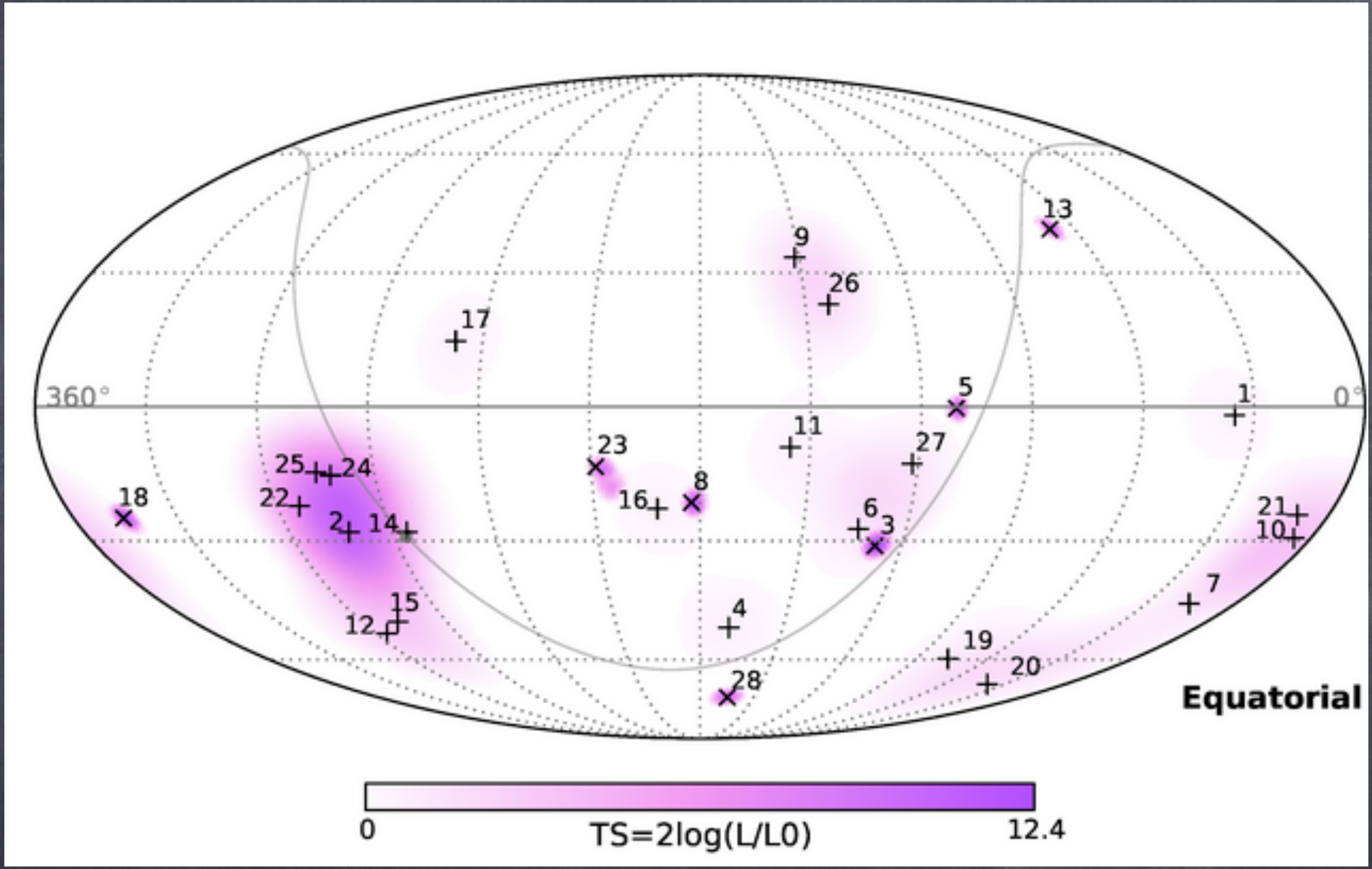
+26 EVENTS ABOVE 30 TEV

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)

+26 EVENTS ABOVE 30 TEV

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

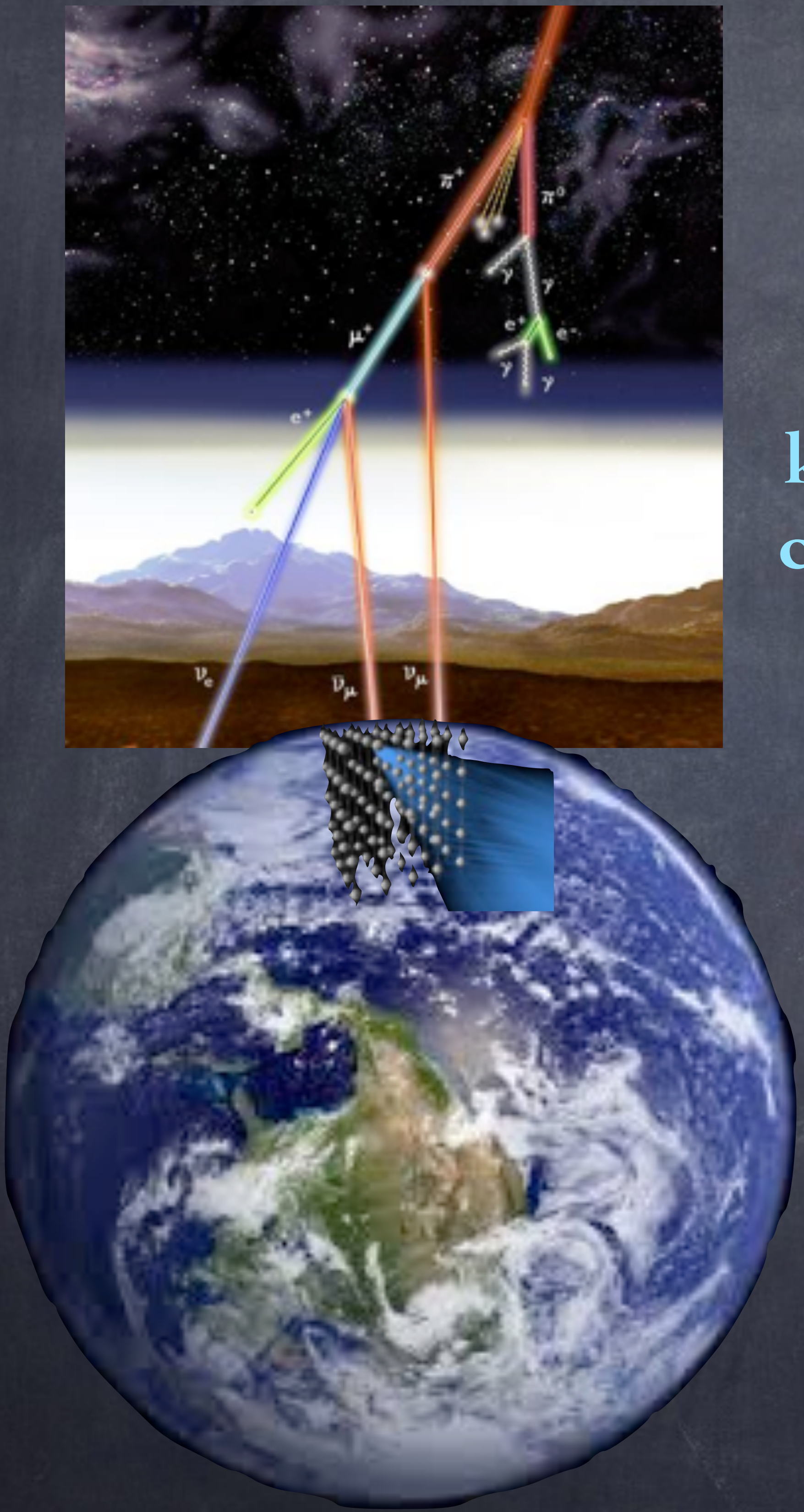
For making the first observations of high-energy cosmic neutrinos

From May 2010 to May 2012:

7 tracks + 21 showers

between 30 TeV and 2 PeV (deposited energy)

ATMOSPHERIC BACKGROUND



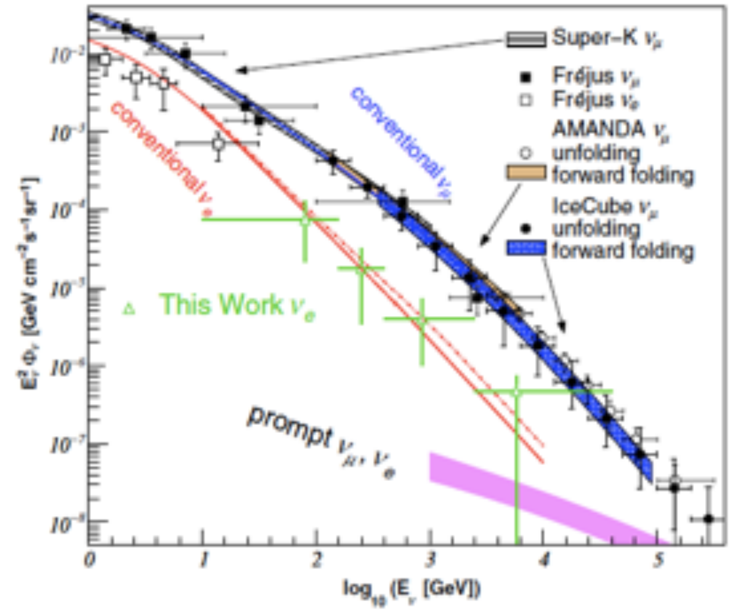
Conventional flux

$$p + X \rightarrow \pi^\pm / K^\pm + Y$$

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

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

At high energies pions/kaons do not decay: only charm mesons with short lifetimes (prompt flux)

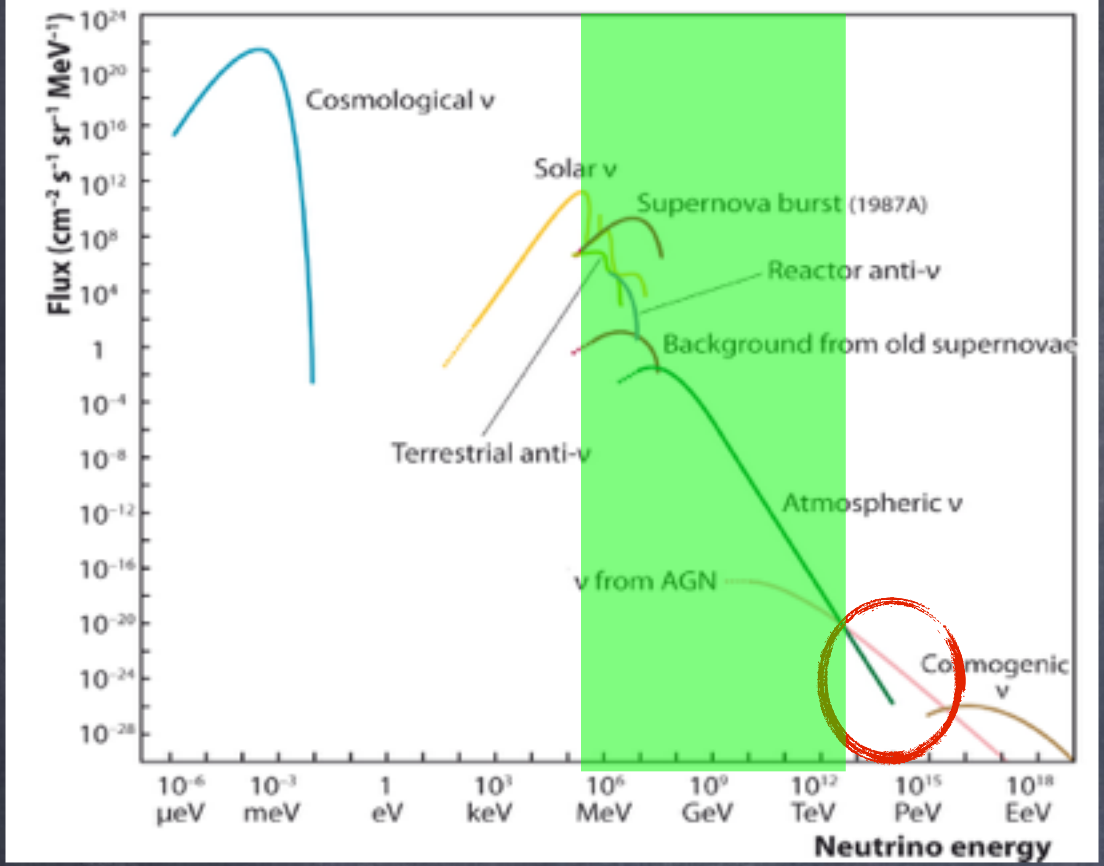


M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 110:151105, 2013

Neutrinos: ~50%-70% tracks

Muons: ~90%-100% tracks

7 tracks : 21 showers



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

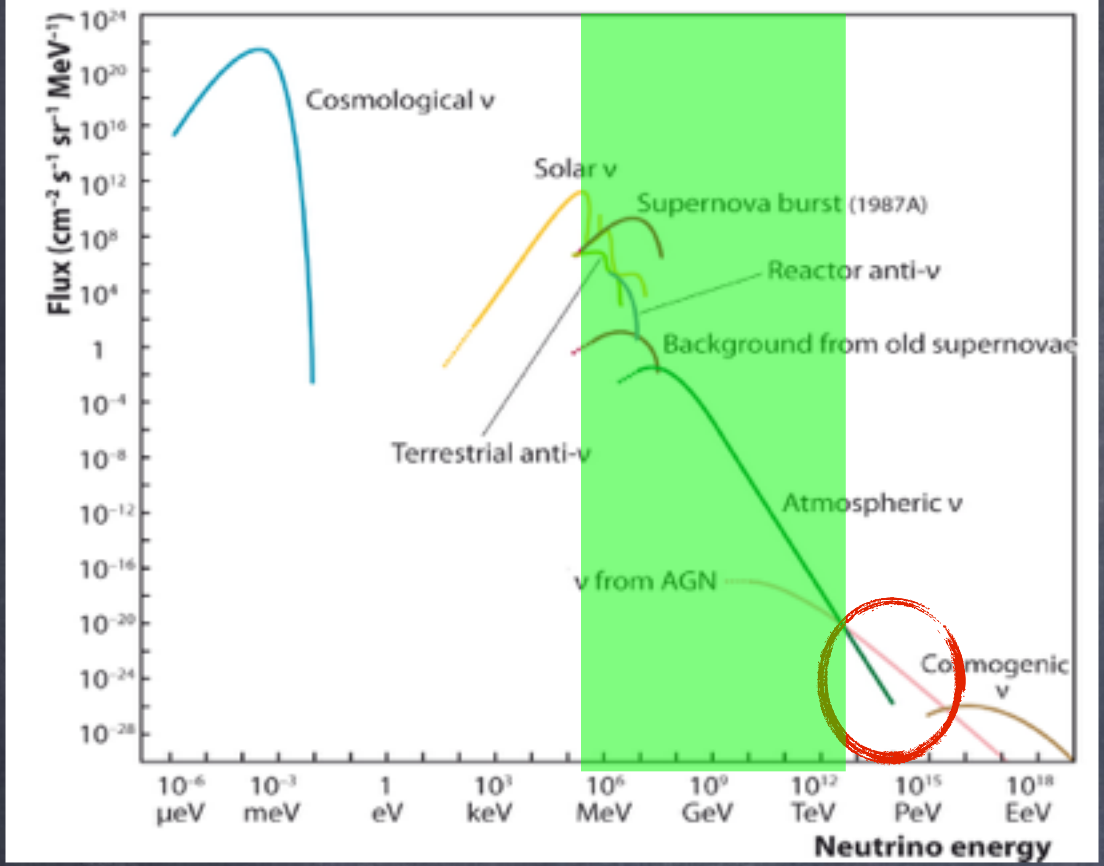
atmospheric neutrinos (<100 TeV)?

prompt neutrinos (~100 TeV)?

astrophysical neutrinos (> 100 TeV)?

cosmogenic neutrinos (>1 EeV)?

7 tracks : 21 showers



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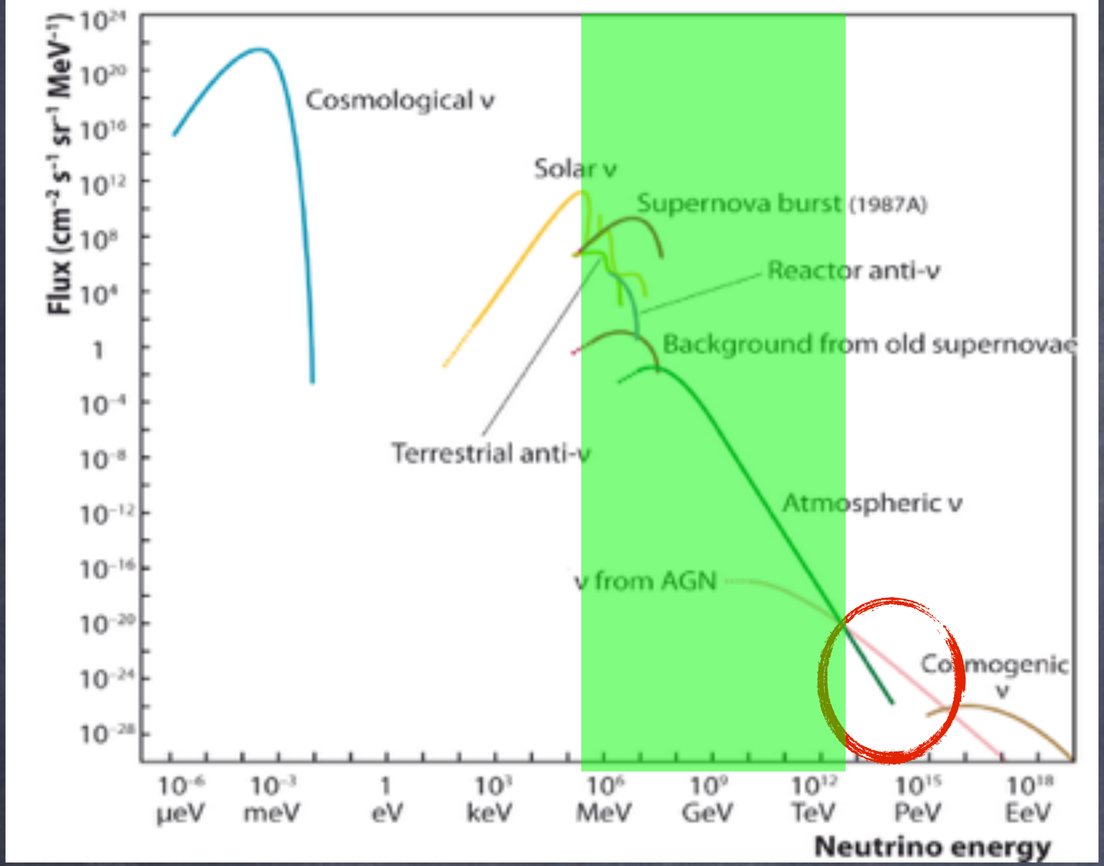

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What is the compatibility of that event ratio with different neutrino flavor ratios (assuming isotropy of the sources)?

Two-bin (topology) flavor analysis

$$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$$

PRL 113:091103, 2014 (arXiv:1404.0017)

Proceedings ICHEP14, arXiv:1411.2998

SHOWERS IN ICECUBE

Neutral Current events : all flavors

deposited energy = hadronic shower energy

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

time of observation:
662 days

effective
detector mass

attenuation/regeneration
factor in the Earth

neutrino flux
(taken as a 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

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

SHOWERS IN ICECUBE

Charged Current events : ν_τ

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

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

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

spectrum of the daughter neutrino in hadronic tau decays

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

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

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

spectrum of the electron in tau decays

CONTAINED TRACKS IN ICECUBE

Contained Charged Current events : ν_μ

deposited energy* = hadronic shower energy

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

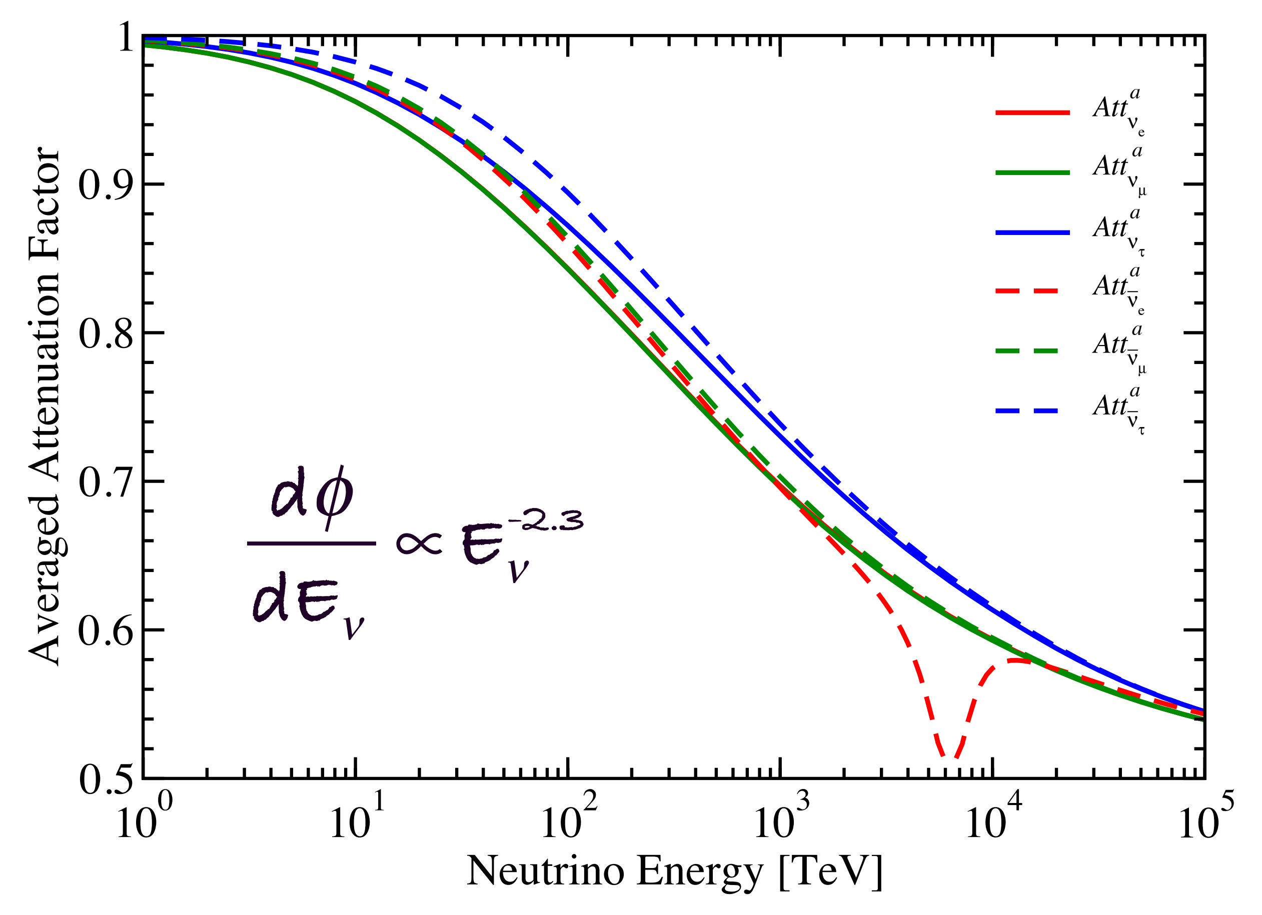
Contained Charged Current events : ν_τ

deposited energy* = hadronic shower energy

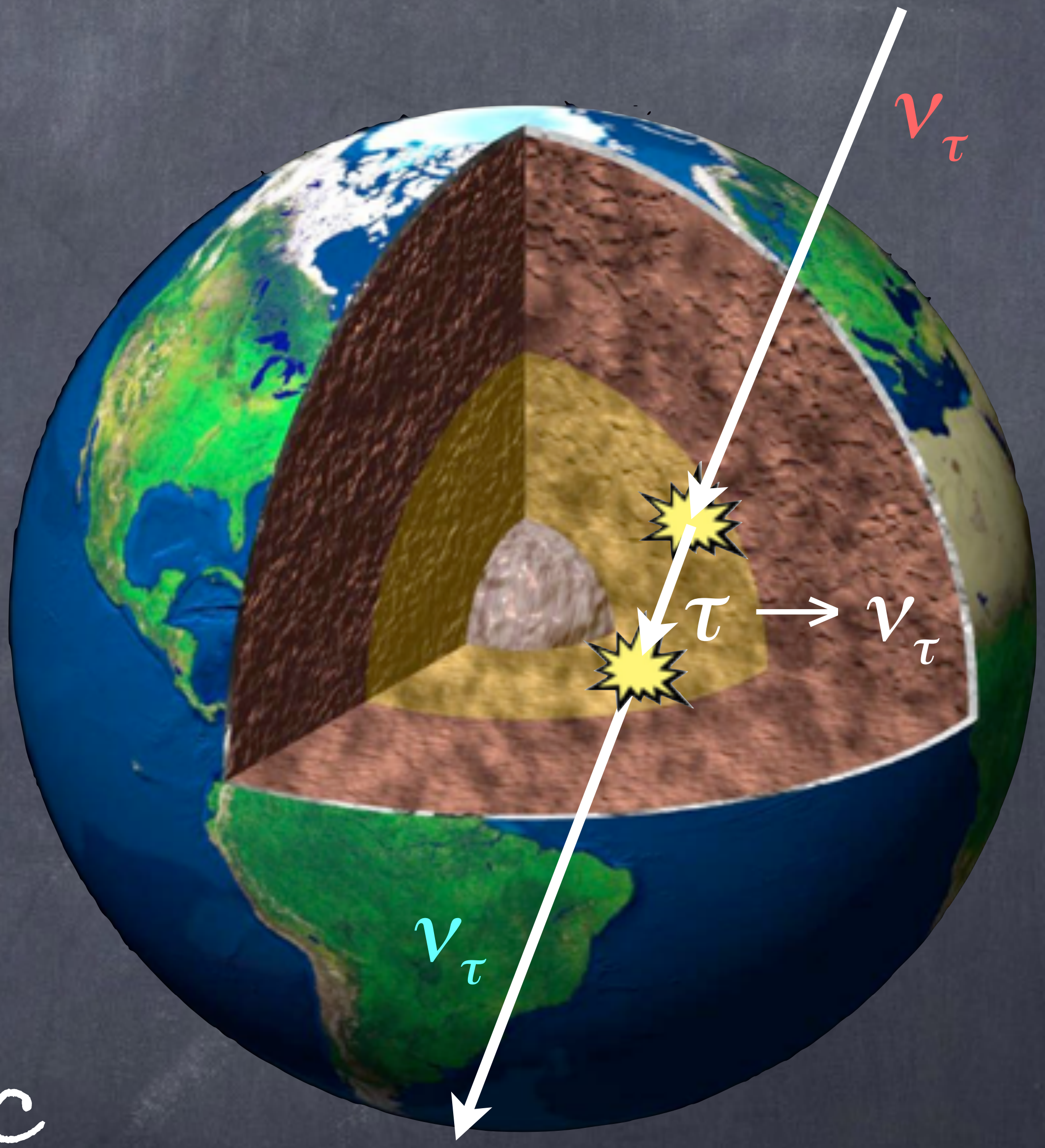
$$N^{tr}_{\nu_\tau} = T \cdot N_A \int_{E_{\min}}^{\infty} dE_\nu M^{CC}_{\nu_\tau}(E_\nu) Att_{\nu_\tau}(E_\nu) \frac{d\phi(E_\nu)}{E_\nu} \int_{y_{\min}}^{y_{\max}} dy \frac{d\sigma^{CC}_{\nu_\tau}(E_\nu, y)}{dy} \times Br(\tau \rightarrow \mu)$$

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

ATTENUATION/REGENERATION FACTORS



SPR, A. C. Vincent and O. Mena, arXiv:1502.02649



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

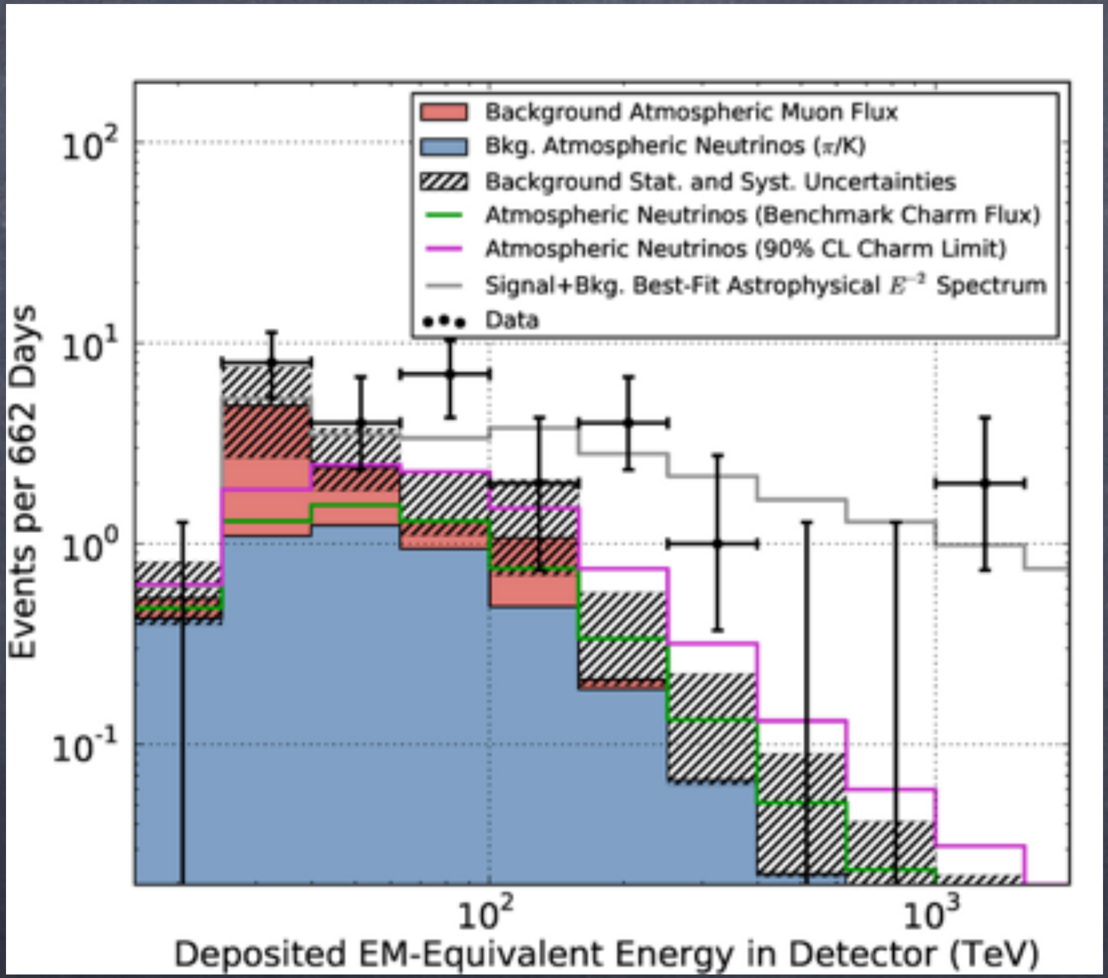
V. A. Naumov and L. Perrone, Astropart. Phys. 10:239, 1999

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

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

7 tracks : 21 showers

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



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

Good fit for an E^{-2} spectrum

Reject a purely atmospheric origin at 4.1σ

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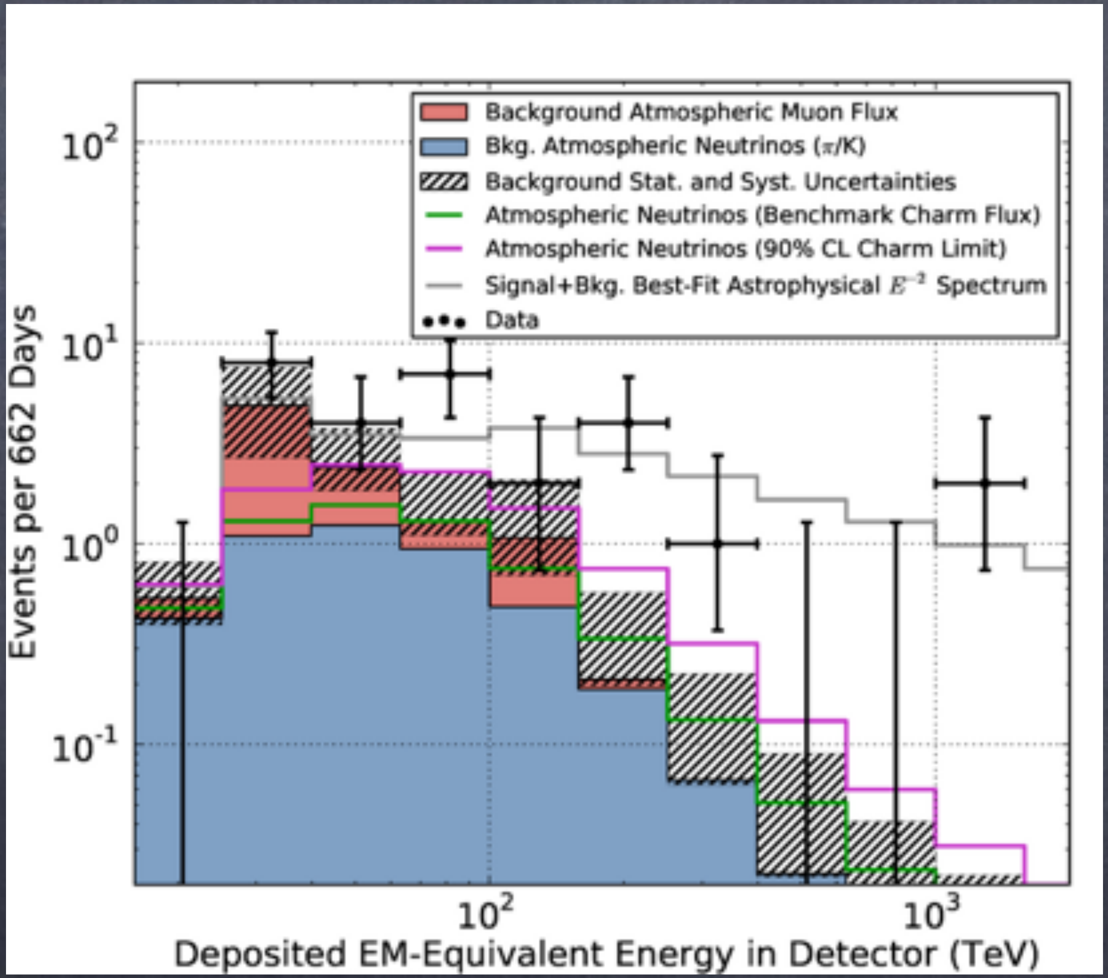


M. G. Aartsen et al. [IceCube Collaboration], Science 342: 1242856, 2013

Good fit for an E^{-2} spectrum

Reject a purely atmospheric origin at 4.1σ

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

STATISTICAL ANALYSIS

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

$b_\mu \equiv$ atmospheric muon background = **6** $(p_\mu^{tr}=0.90)$

$b_\nu \equiv$ atmospheric neutrino background = **4.6** $(p_\nu^{tr}=0.69)$

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 113:101101, 2014

$N_{tr} \equiv$ 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:

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

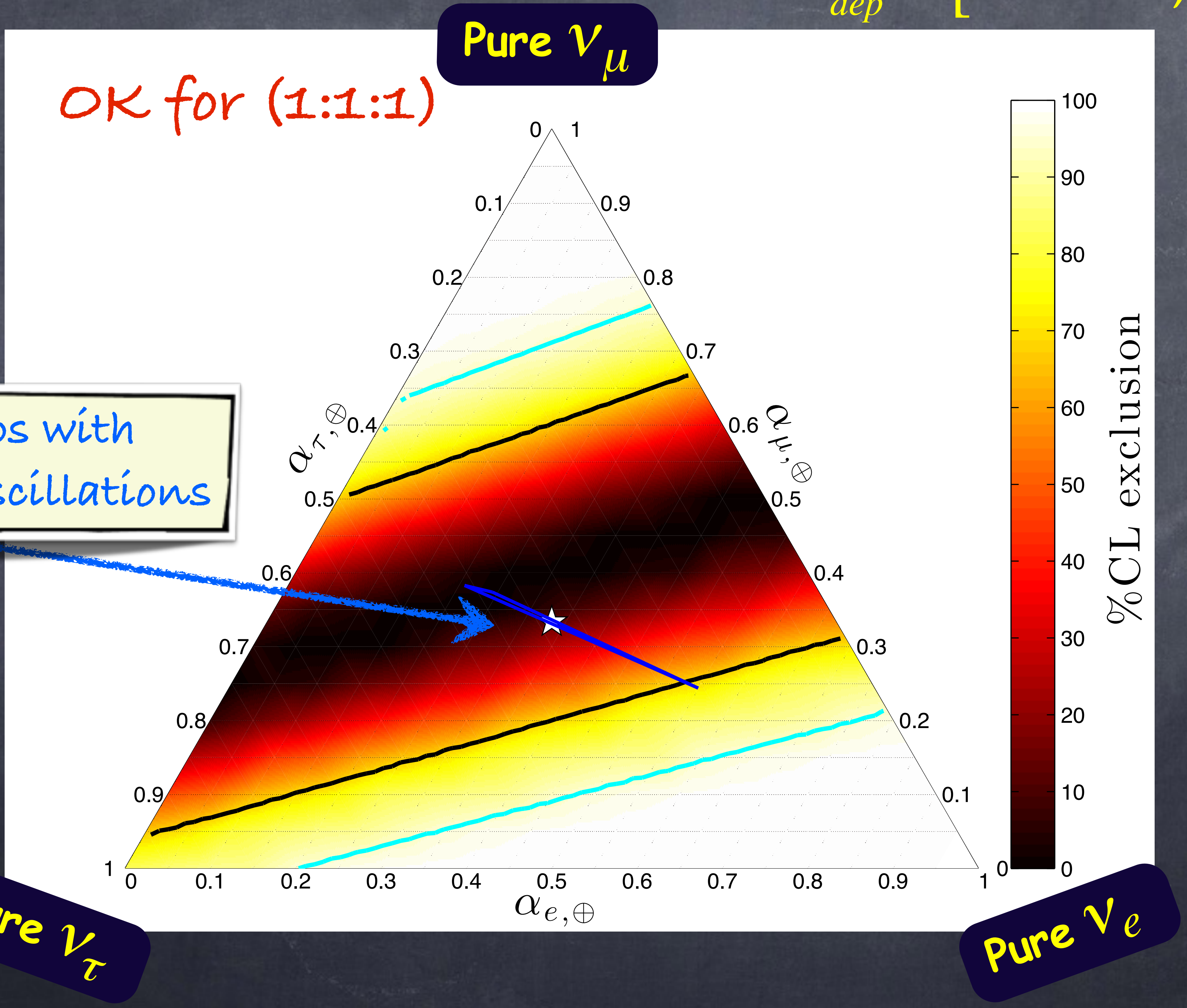
Exact definition of p-value:
no need to approximate it
with the χ^2 result

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

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

NO BACKGROUND?

$E_{dep} = [30 \text{ TeV}, 3 \text{ PeV}]$



OK for (1:1:1)

Flavor ratios with averaged oscillations

BUT THERE IS BACKGROUND....

observed → 7 tracks : 21 showers

background → 8.6 tracks : 2 showers

BUT THERE IS BACKGROUND....

observed → 7 tracks : 21 showers

background → 8.6 tracks : 2 showers

astrophysical =

observed - background

↓

astrophysical tracks=7-8.6=0

BUT THERE IS BACKGROUND....

observed → 7 tracks : 21 showers

background → 8.6 tracks : 2 showers

astrophysical =
observed - background

↓

astrophysical tracks=7-8.6=0

Only showers in the astrophysical signal!

2-YEAR RESULTS

$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$

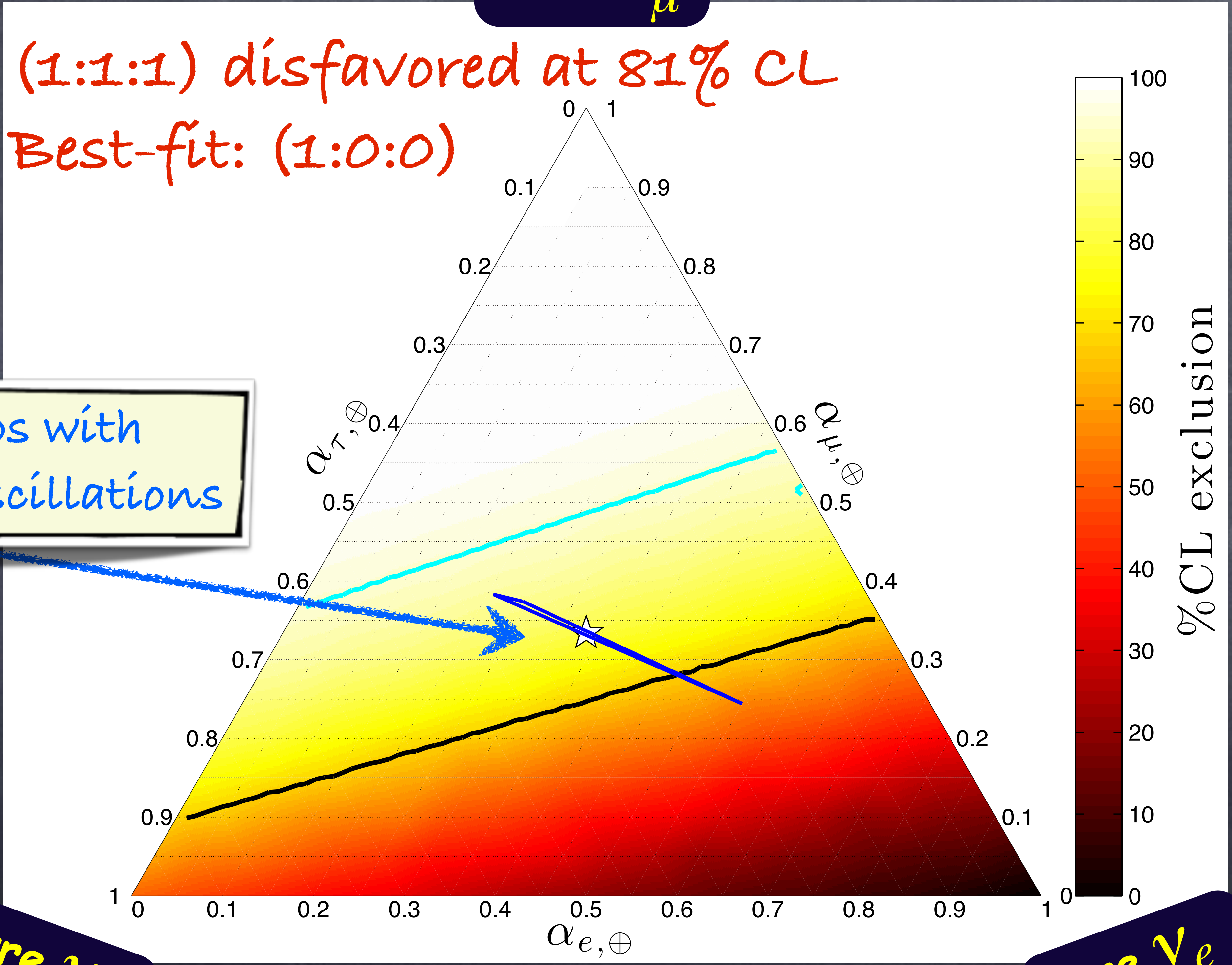
For E^{-2}

Pure ν_μ

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

Best-fit: (1:0:0)

Flavor ratios with averaged oscillations



Pure ν_τ

Pure ν_e

Adapted from:

O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014

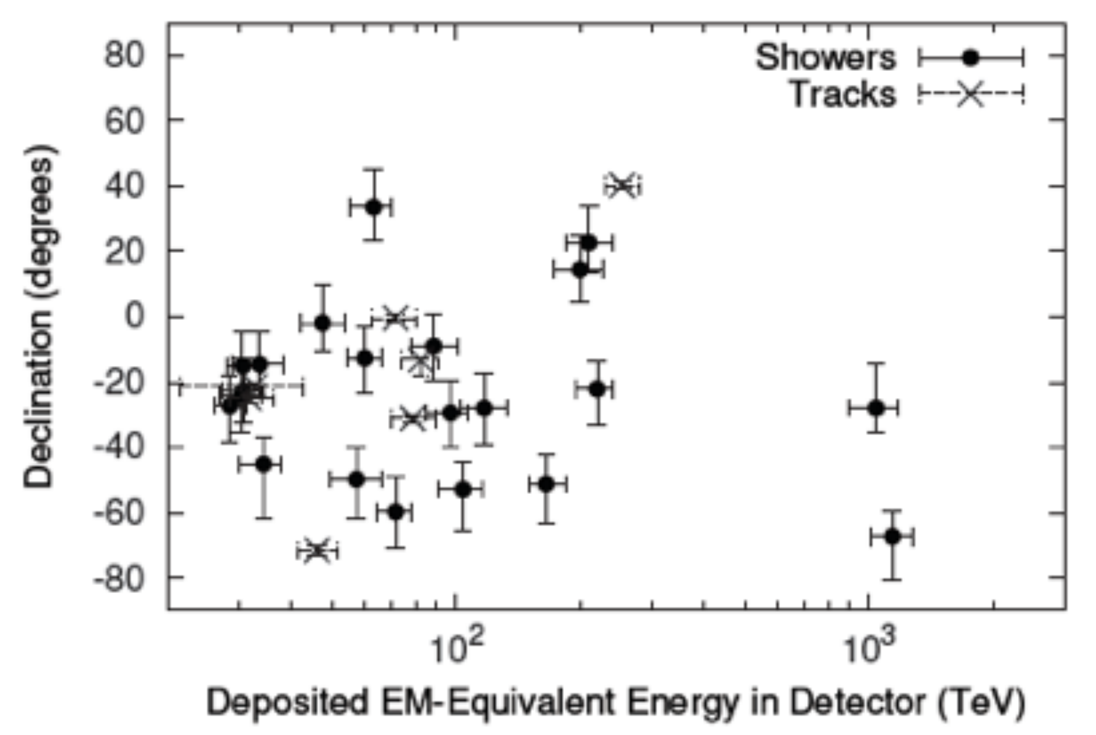
3-YEAR DATA

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 113:101101, 2014

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



3-YEAR DATA

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 113:101101, 2014

2-year data: May 2010 - May 2012

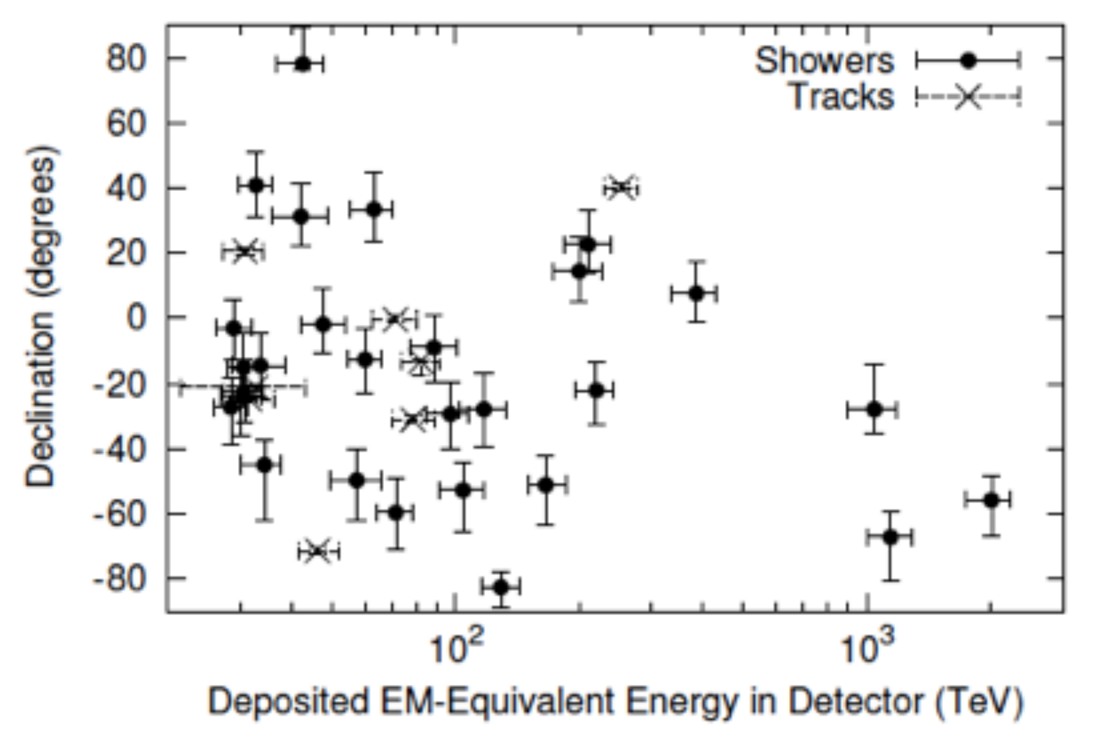
Observed: 7 tracks + 21 showers

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

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

3-YEAR DATA

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 113:101101, 2014

2-year data: May 2010 - May 2012

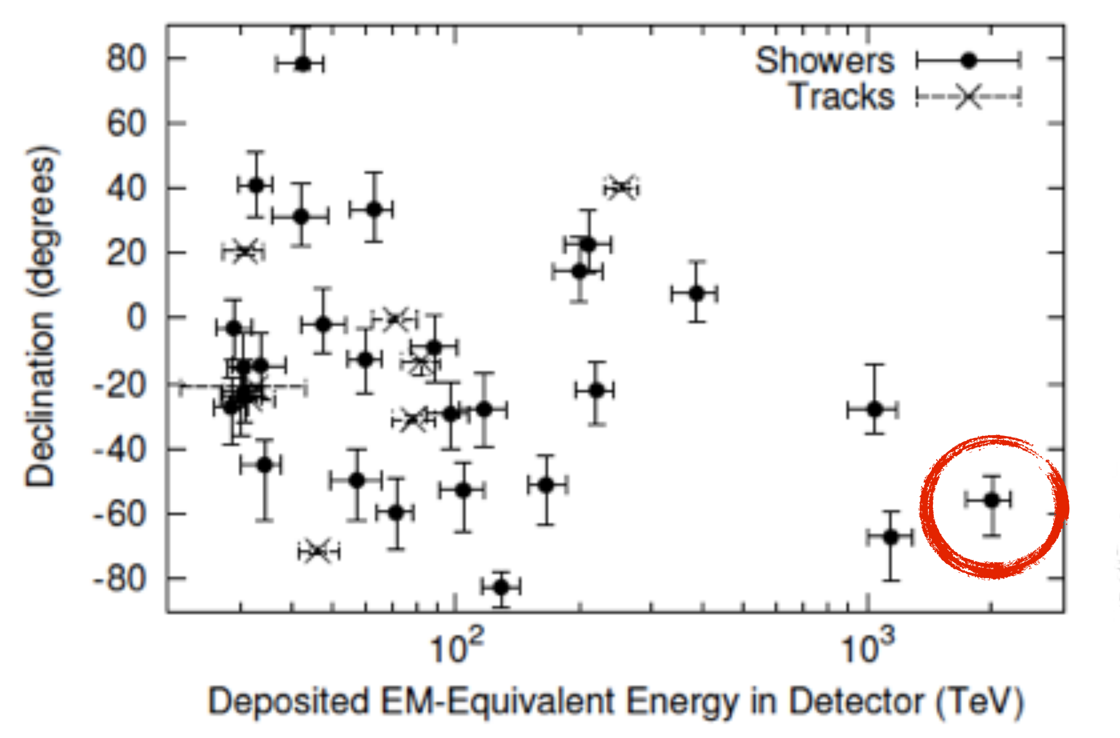
Observed: 7 tracks + 21 showers

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

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

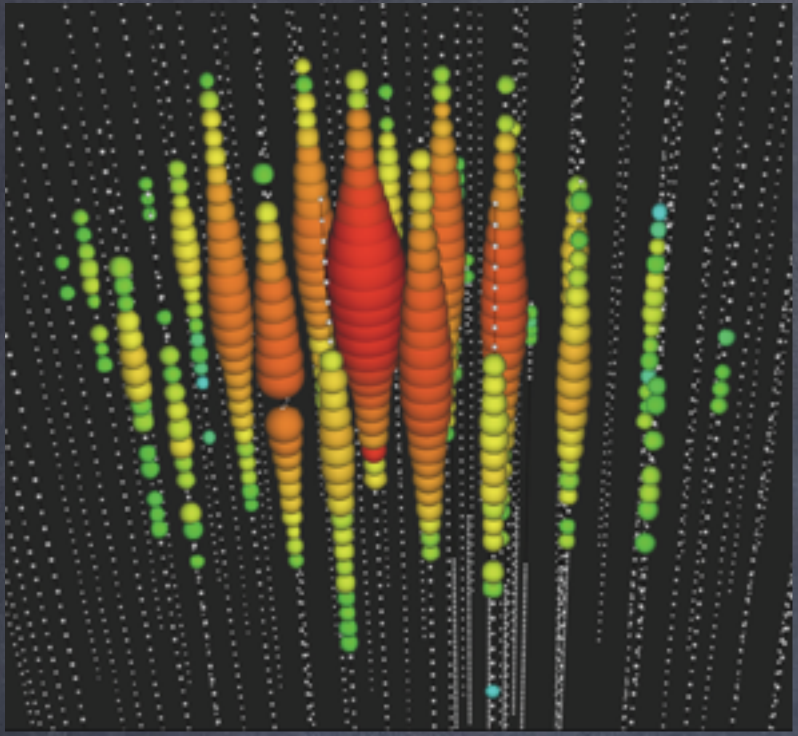


2 extra tracks

7 extra showers

another record breaker

THE 2 PEV NEUTRINO

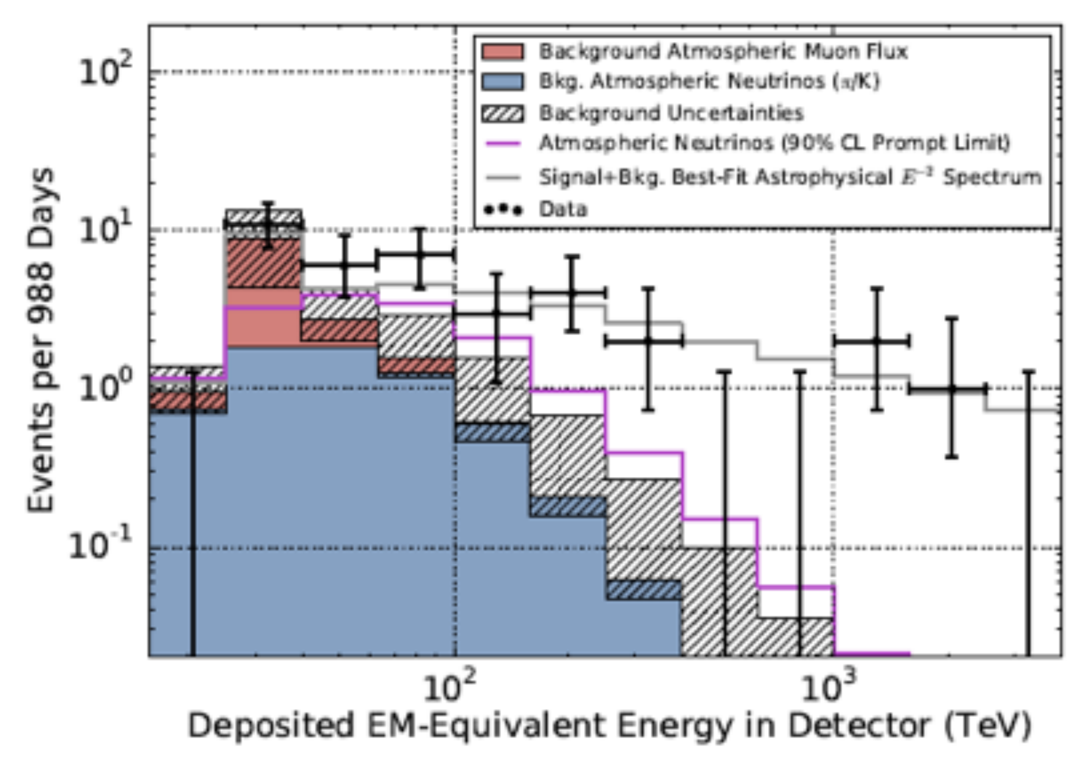


C. Kopper, talk at Moriond 2014

December 4, 2012: 2.004 PeV

Big Bird

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



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

Reject a purely atmospheric origin at 5.7σ

M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 113:101101, 2014

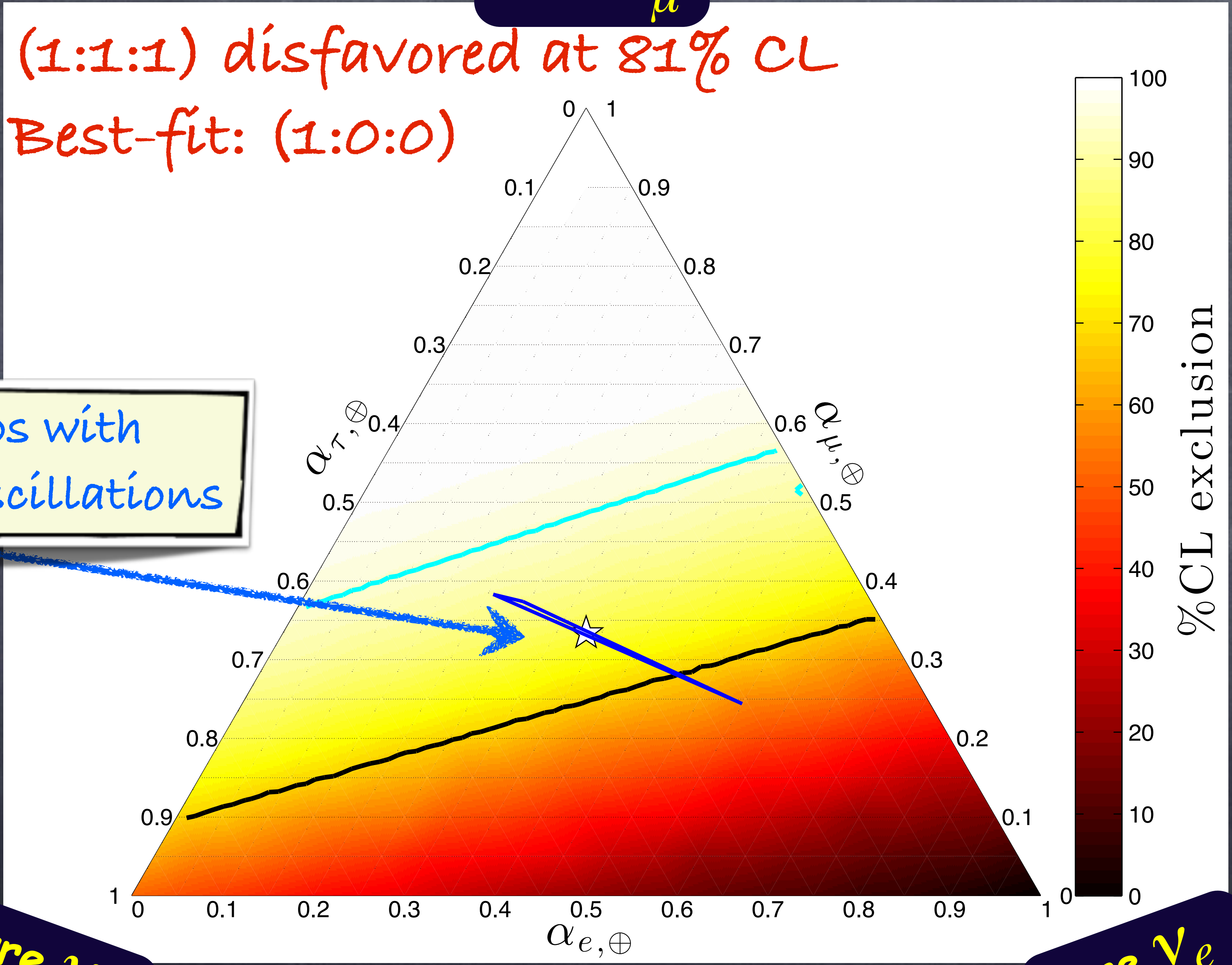
2-YEAR RESULTS

$E_{dep} = [30 \text{ TeV}, 3 \text{ PeV}]$

Pure ν_μ

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

Best-fit: (1:0:0)



Flavor ratios with averaged oscillations

Pure ν_τ

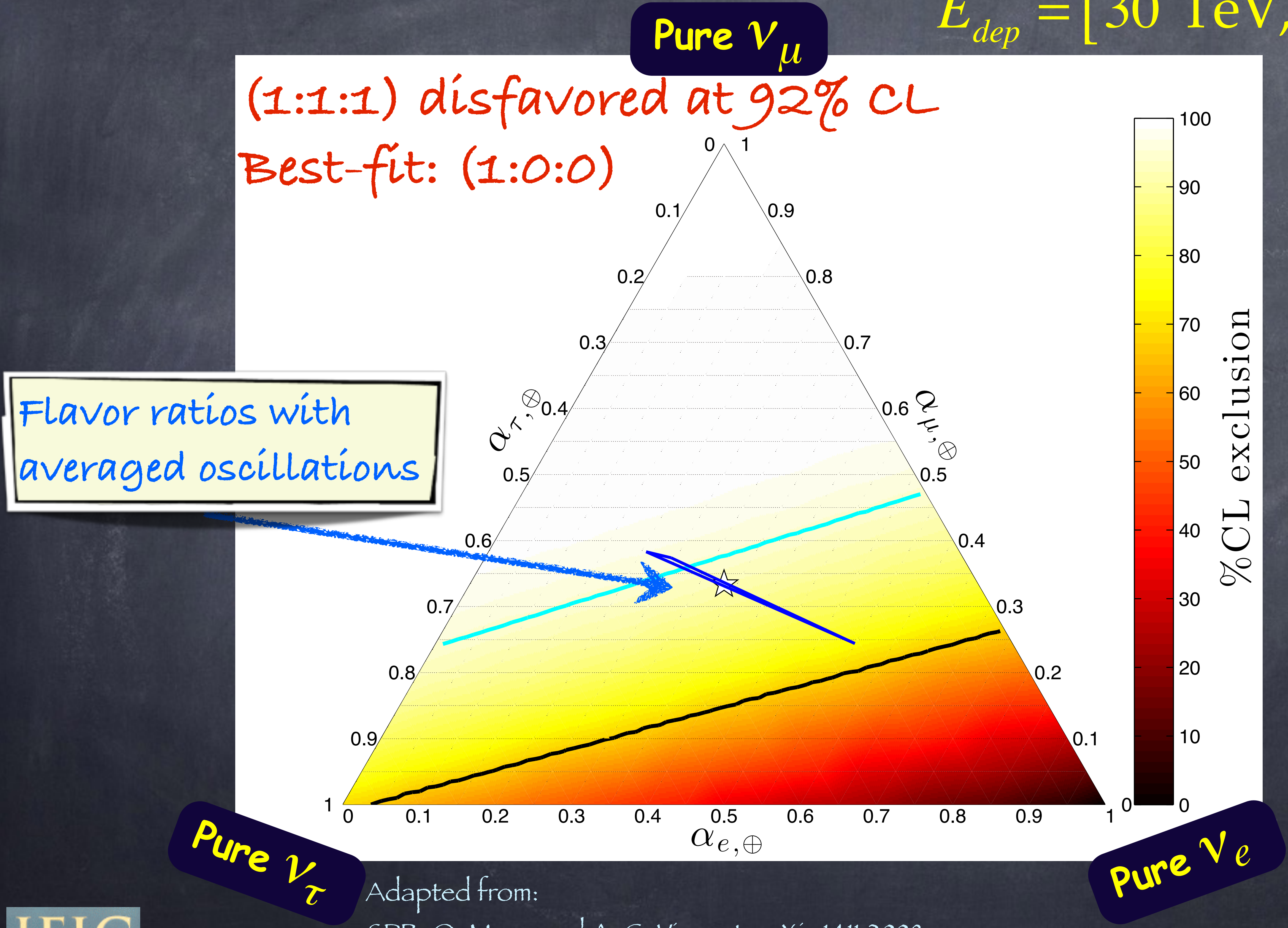
Pure ν_e

Adapted from:

O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014

3-YEAR RESULTS

$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$



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

Best-fit: (1:0:0)

Flavor ratios with averaged oscillations

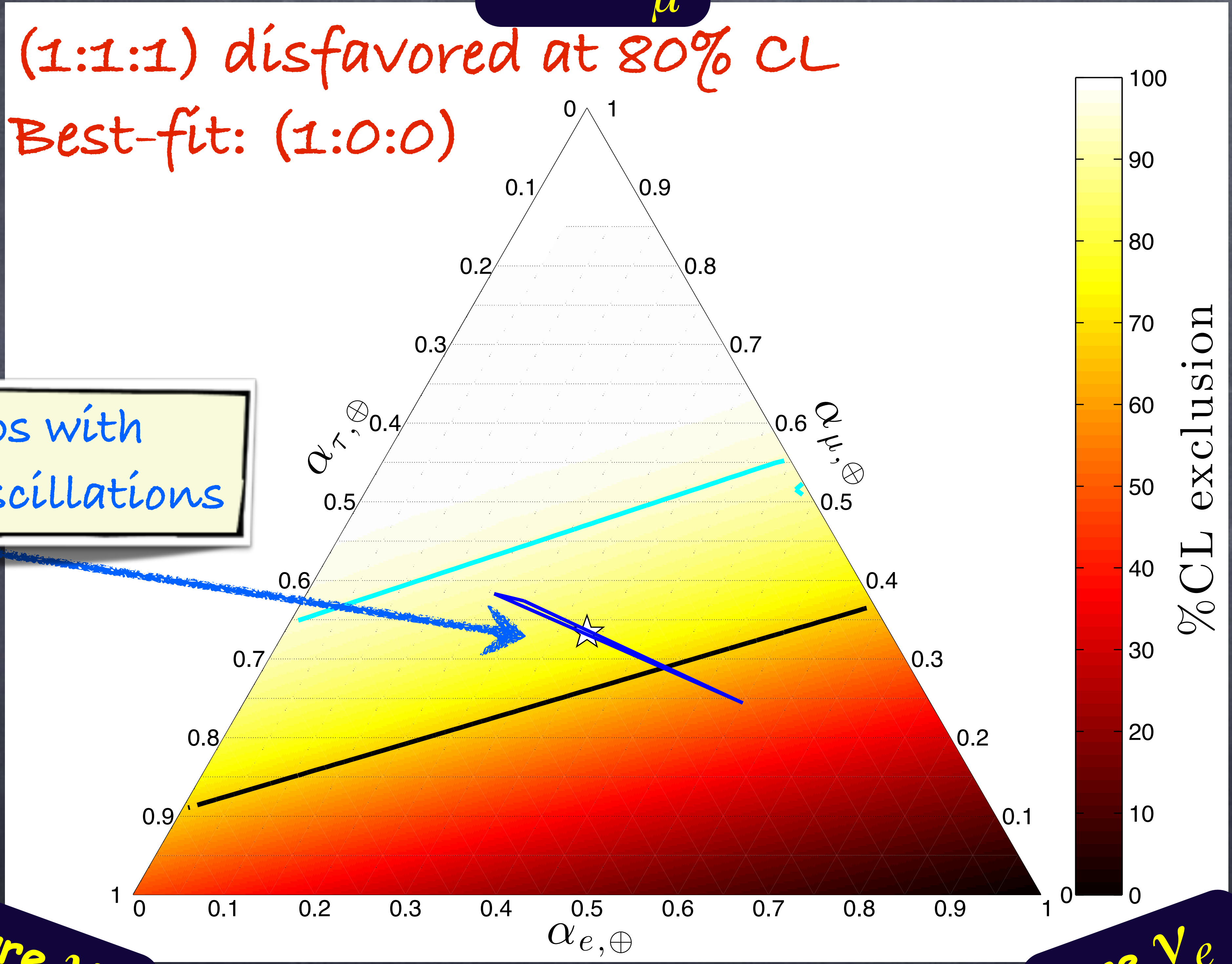
Adapted from:

SPR, O. Mena and A. C. Vincent, arXiv:1411.2998

3-YEAR RESULTS WITH ERRORS

$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$

Pure ν_μ



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

Best-fit: (1:0:0)

Flavor ratios with averaged oscillations

Pure ν_τ

Pure ν_e

- 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

- Although not statistically significant yet, the best-fit lies outside the "standard" triangle

→ Non-standard physics (neutrino decay, pseudo-Dirac neutrinos, CPT violation, shortcuts in extradimensions, non-standard cross sections)?

→ Has the atmospheric background been overestimated?

→ Have some tracks been misidentified as showers?

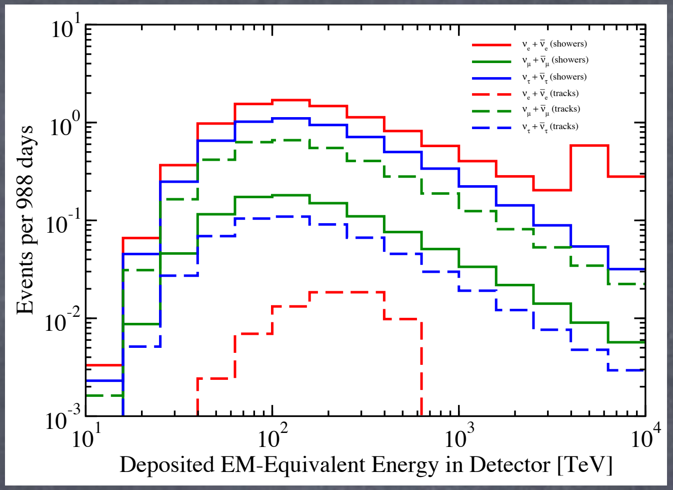
Spectral analysis

(unbinned extended maximum likelihood)

arXiv:1502.02649 (accepted in PRD)

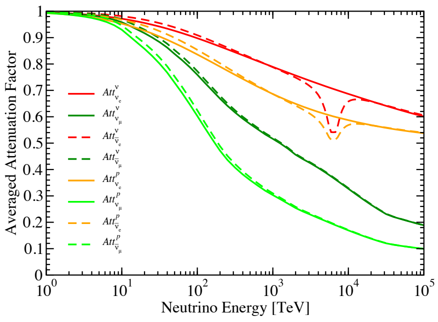
IMPROVED CALCULATION

- Full energy spectral information using EM-equivalent deposited energies (and energy resolution)

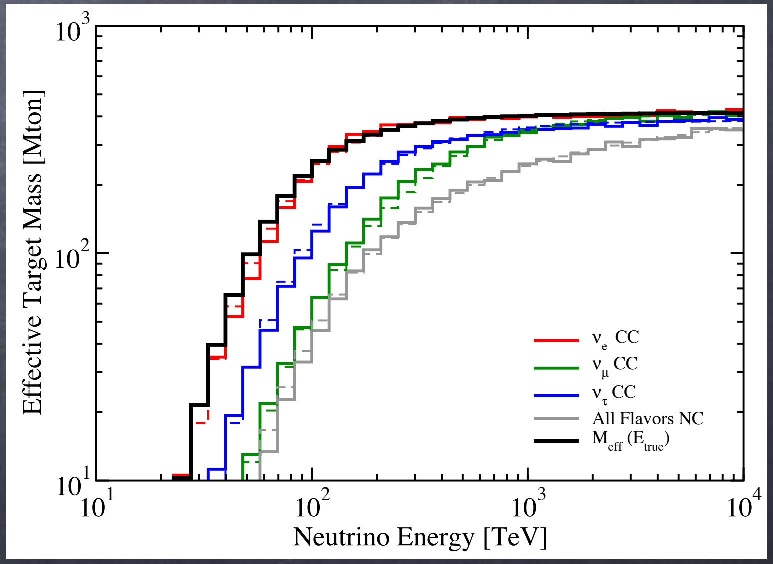


- All interactions with electrons

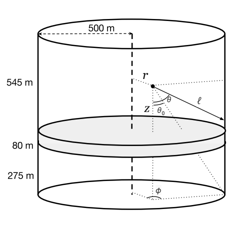
- Veto for the atmospheric neutrino background



- Effective mass as a function of the deposited energy (in contrast to the neutrino energy)

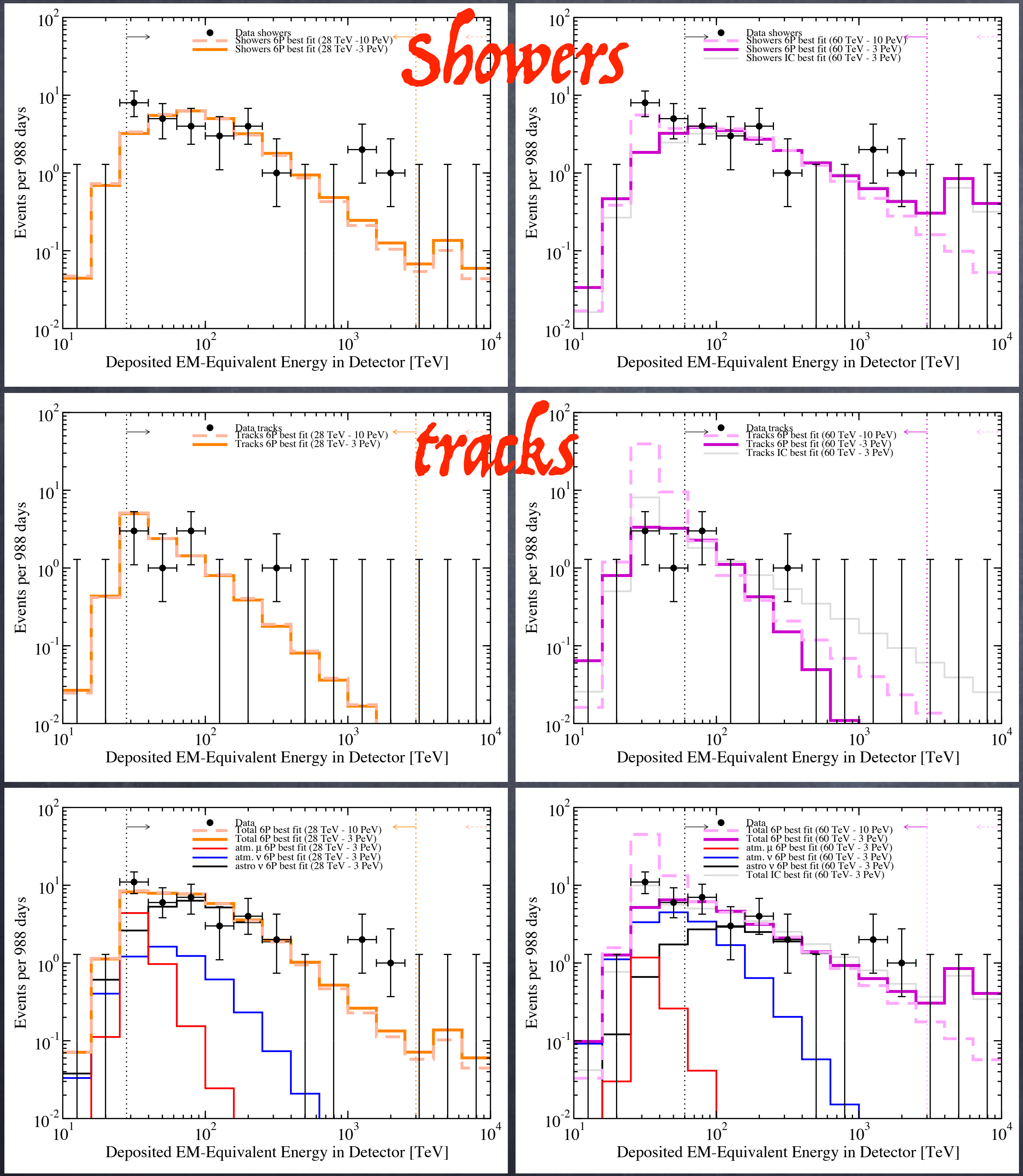


- Computation of the average energy deposition along a muon track taking into account the detector's geometry

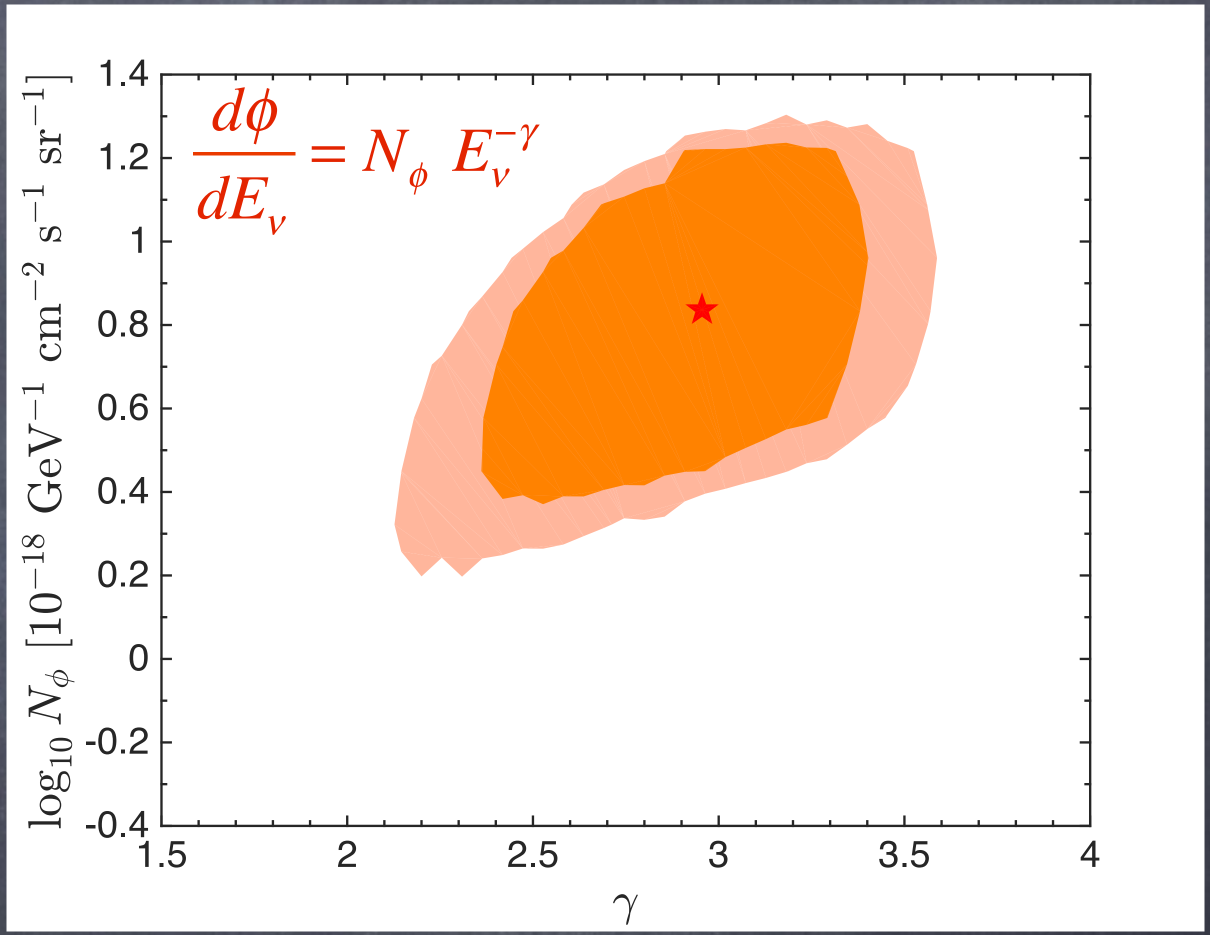


- Fitting the spectral index, the normalizations of backgrounds and signal, and the flavor ratios: *unbinned extended maximum likelihood analysis*

4 different (deposited) energy intervals:
28 TeV-3 PeV; 28 TeV-10 PeV; 60 TeV-3 PeV; and 60 TeV-10 PeV

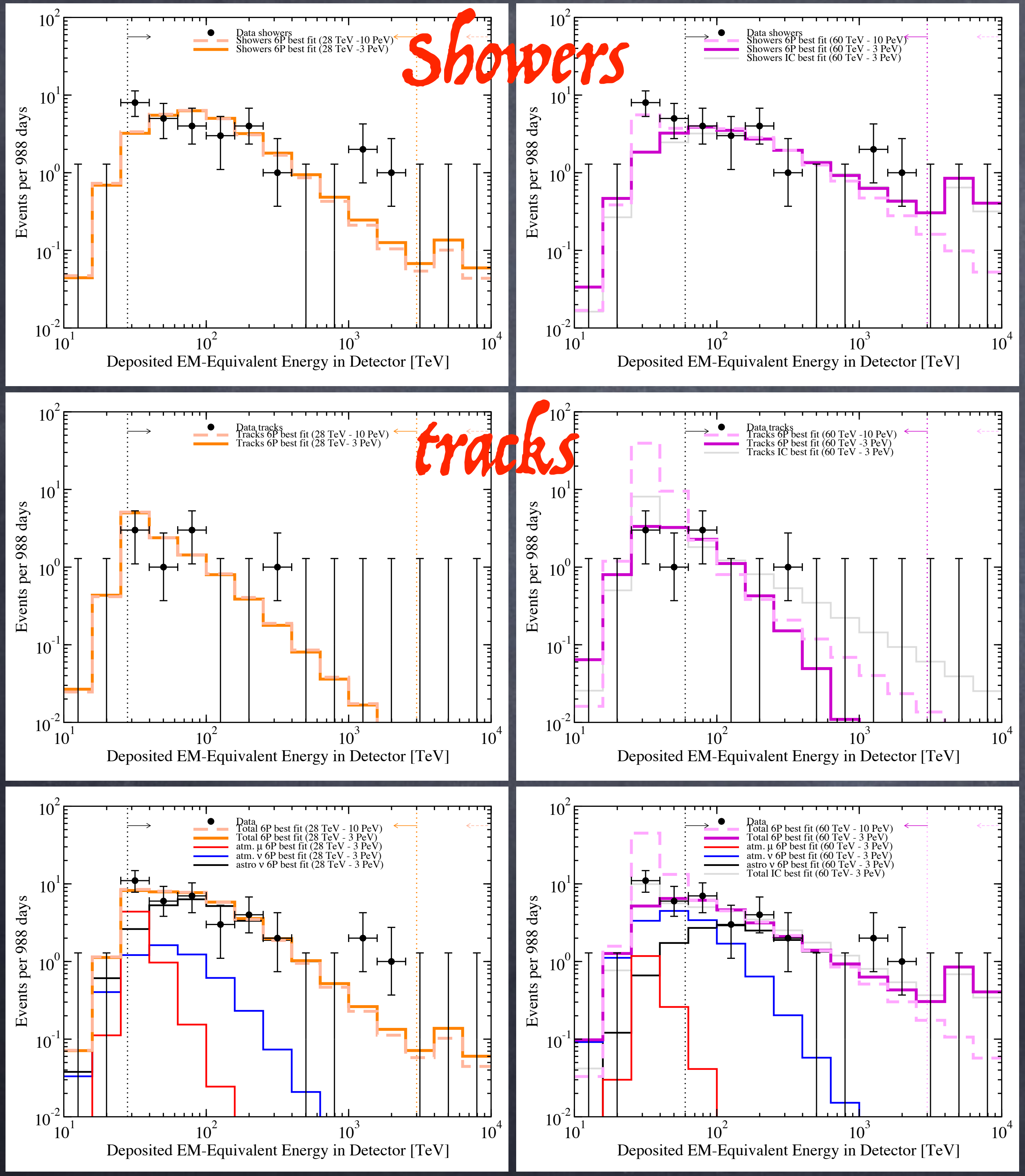


28 TeV - 3 PeV

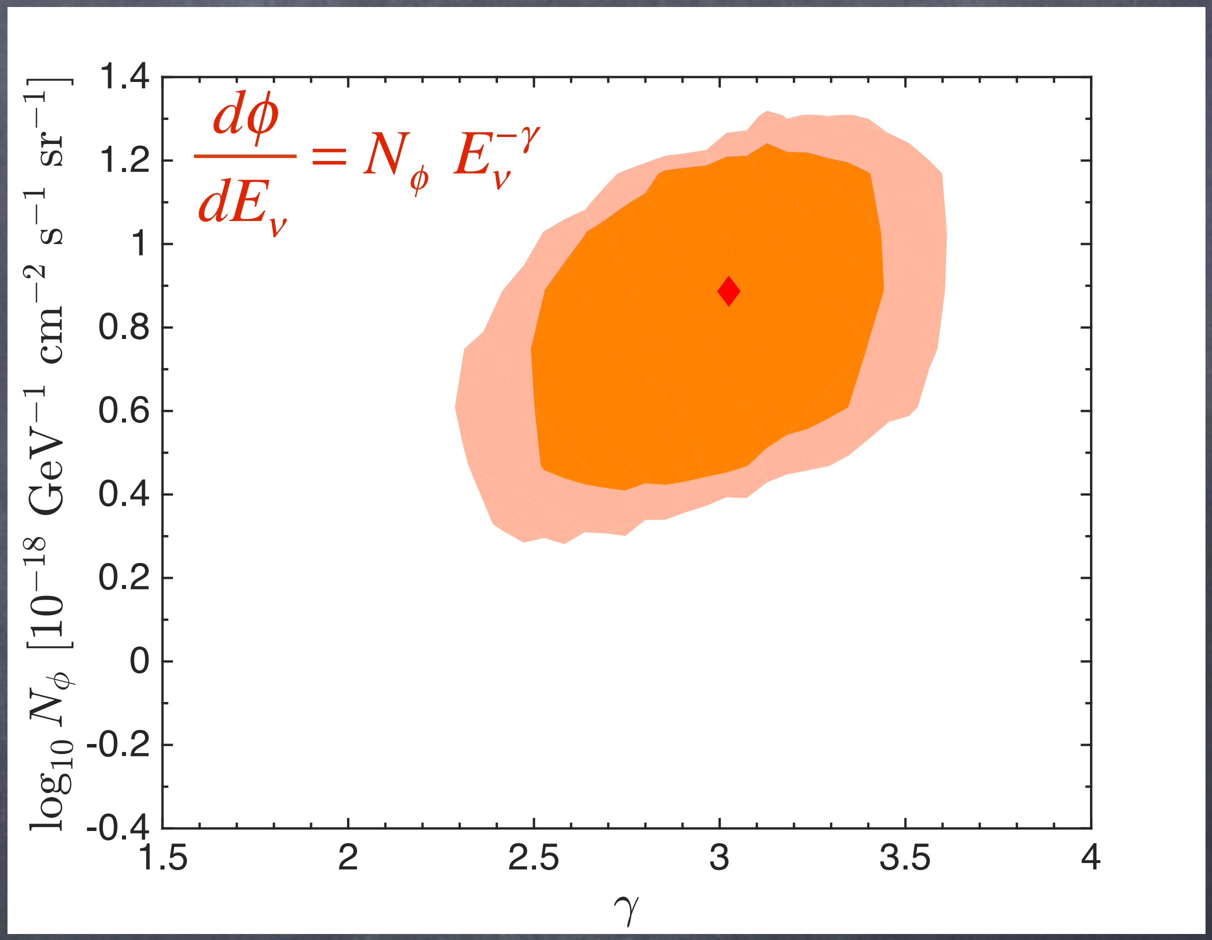


SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

4 different (deposited) energy intervals:
28 TeV-3 PeV; 28 TeV-10 PeV; 60 TeV-3 PeV; and 60 TeV-10 PeV

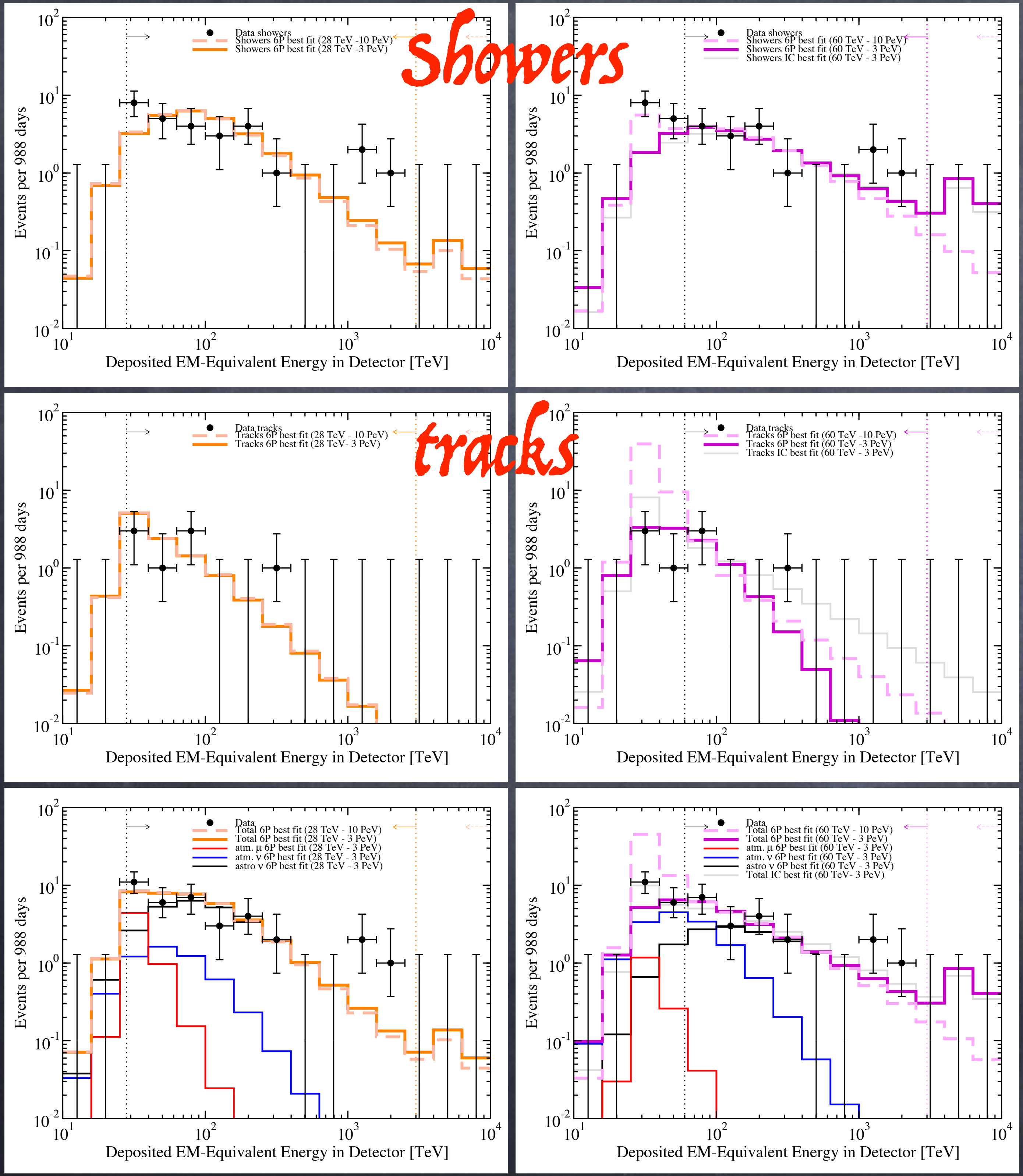


28 TeV - 10 PeV

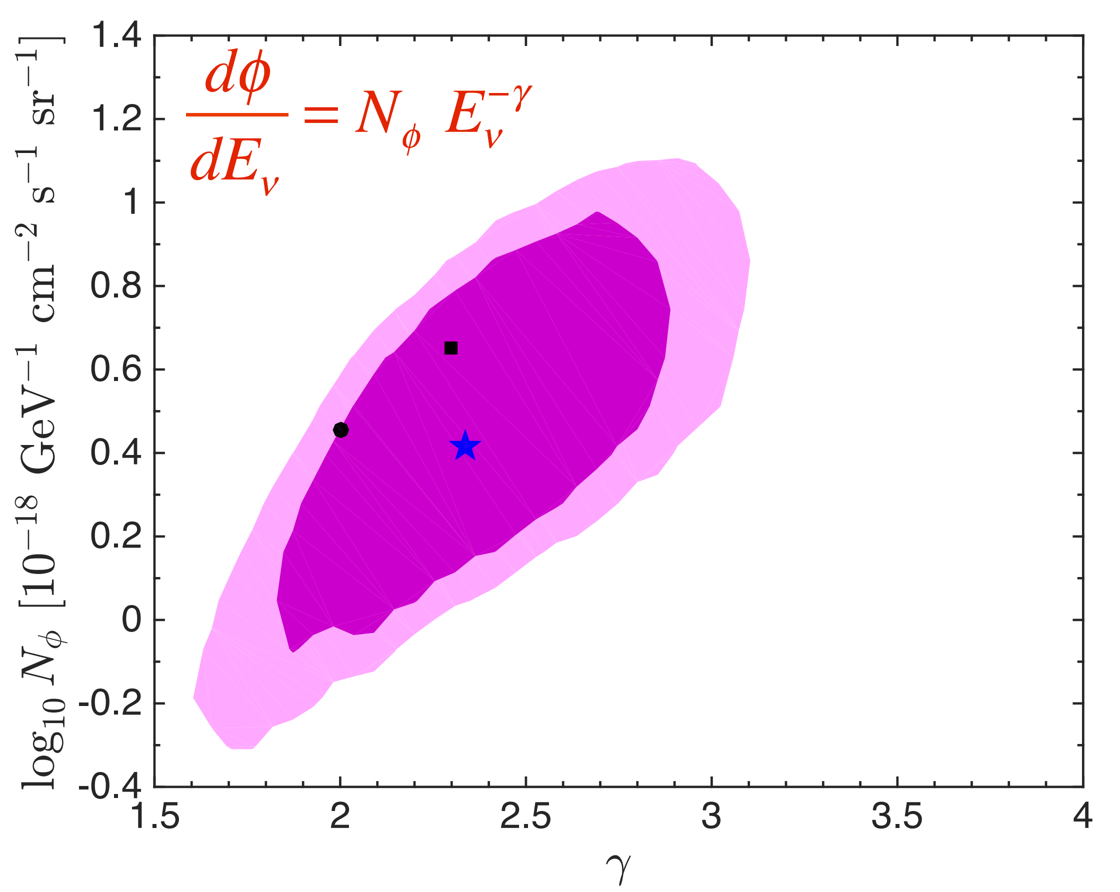


SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

4 different (deposited) energy intervals:
28 TeV-3 PeV; 28 TeV-10 PeV; 60 TeV-3 PeV; and 60 TeV-10 PeV

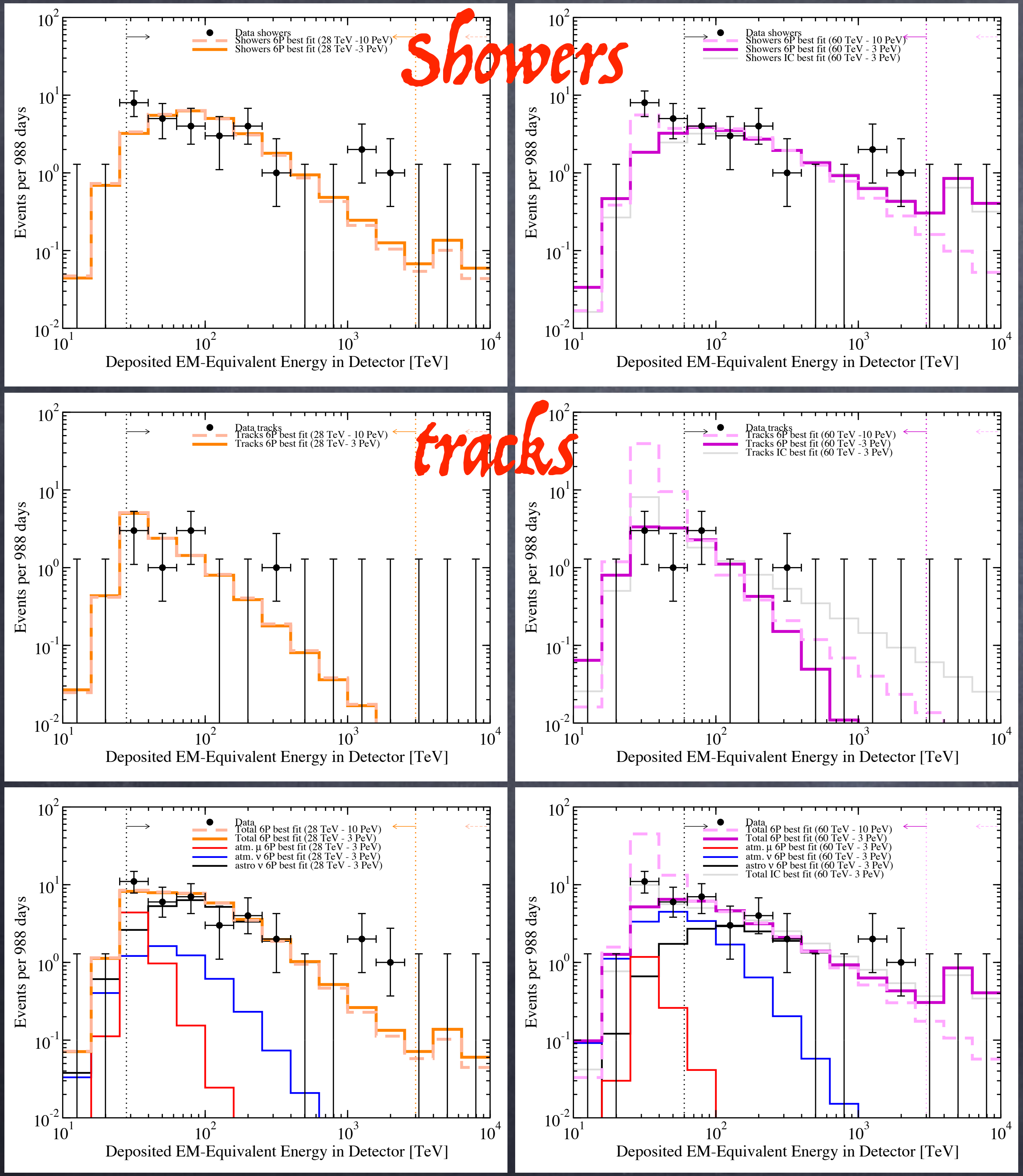


60 TeV - 3 PeV

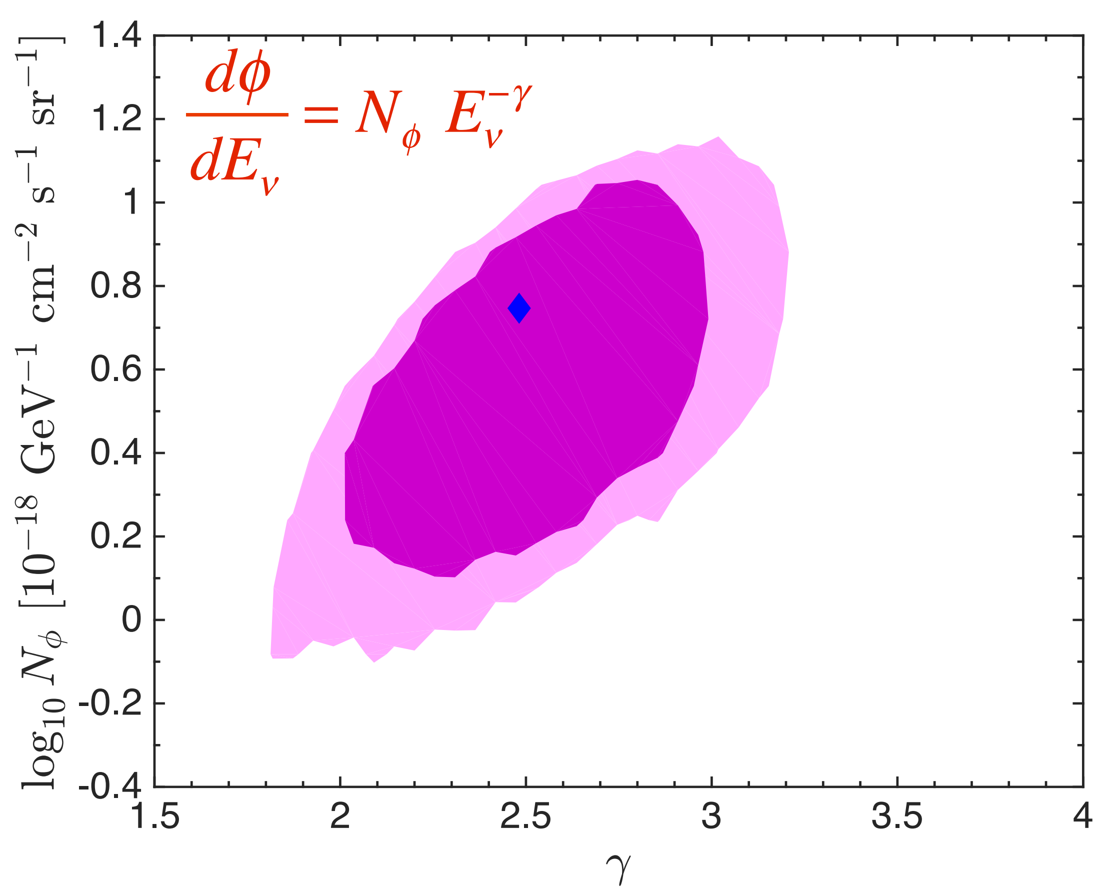


SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

4 different (deposited) energy intervals:
28 TeV-3 PeV; 28 TeV-10 PeV; 60 TeV-3 PeV; and 60 TeV-10 PeV

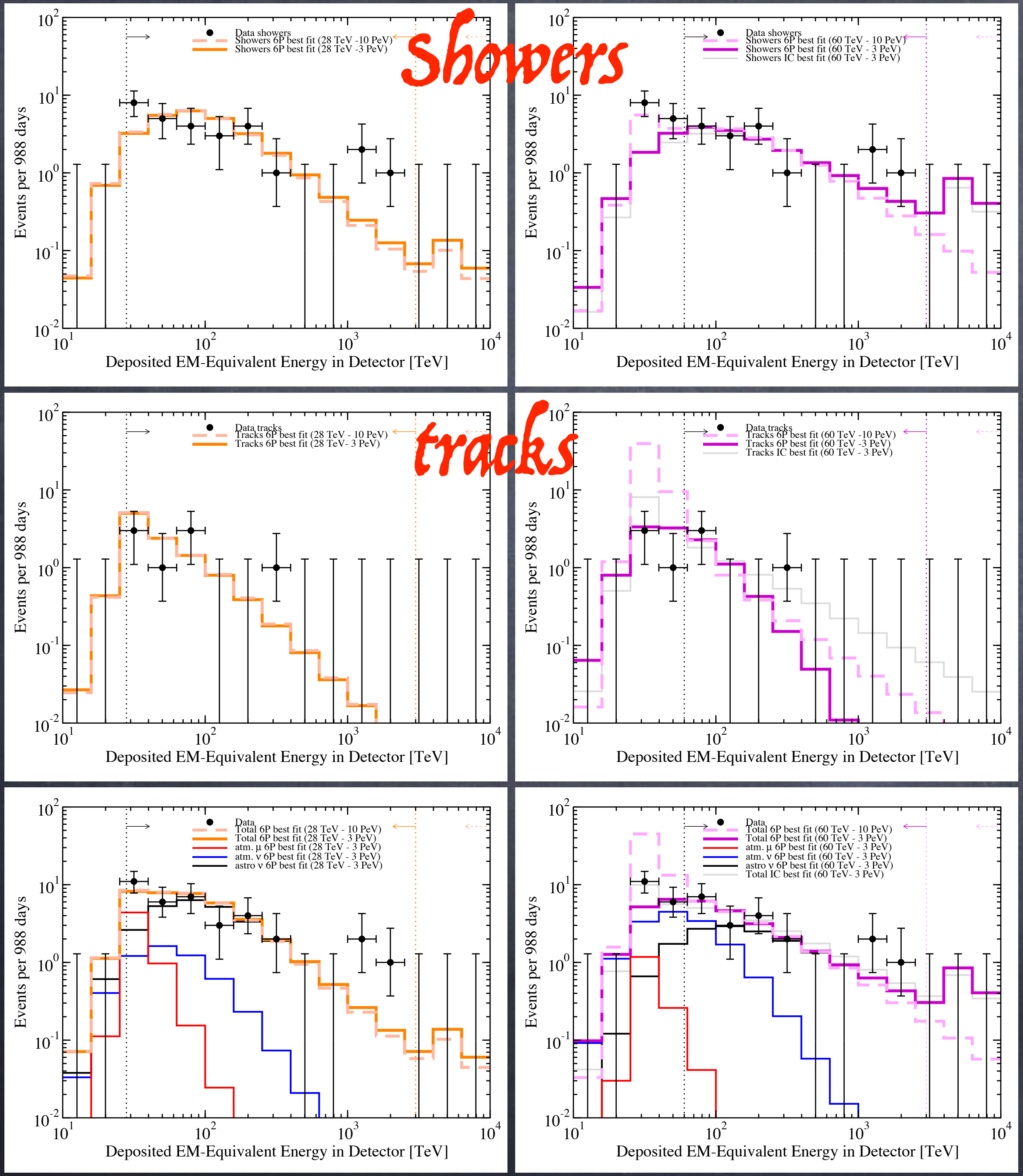


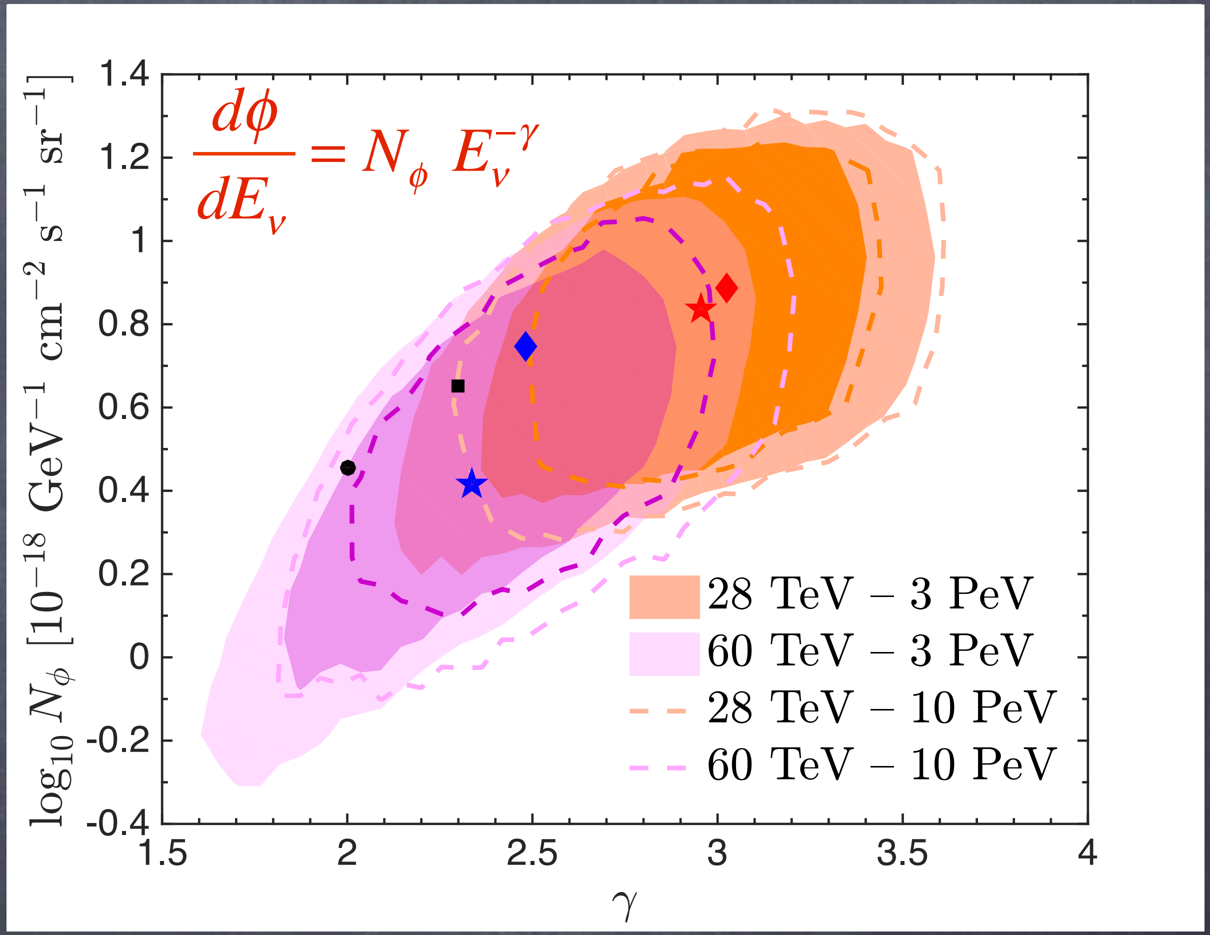
60 TeV - 10 PeV



SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

4 different (deposited) energy intervals:
28 TeV-3 PeV; 28 TeV-10 PeV; 60 TeV-3 PeV; and 60 TeV-10 PeV





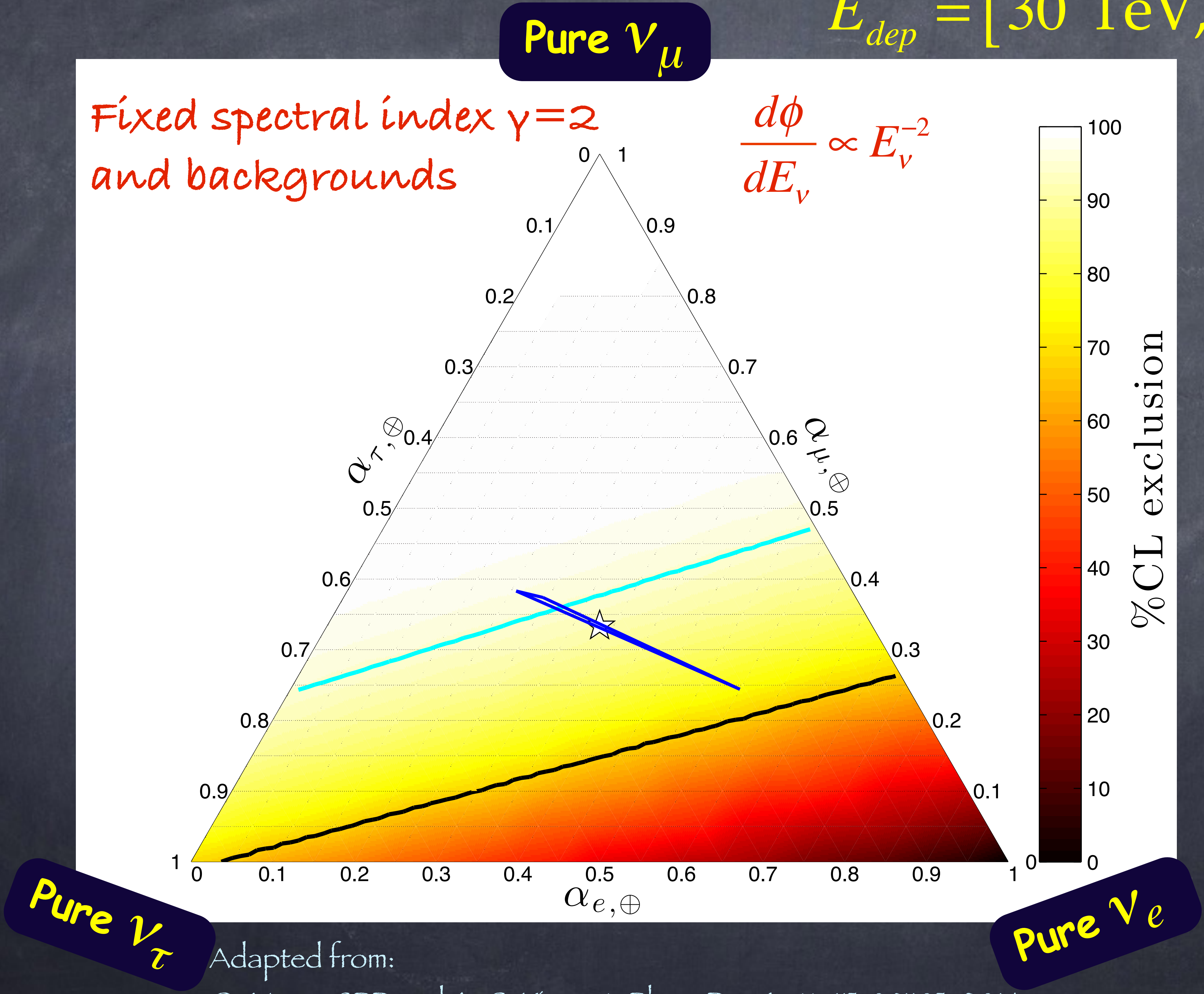
Cut at 60 TeV → harder spectrum

Cut at 10 PeV → softer spectrum

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

ONLY TOPOLOGY

$$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$$



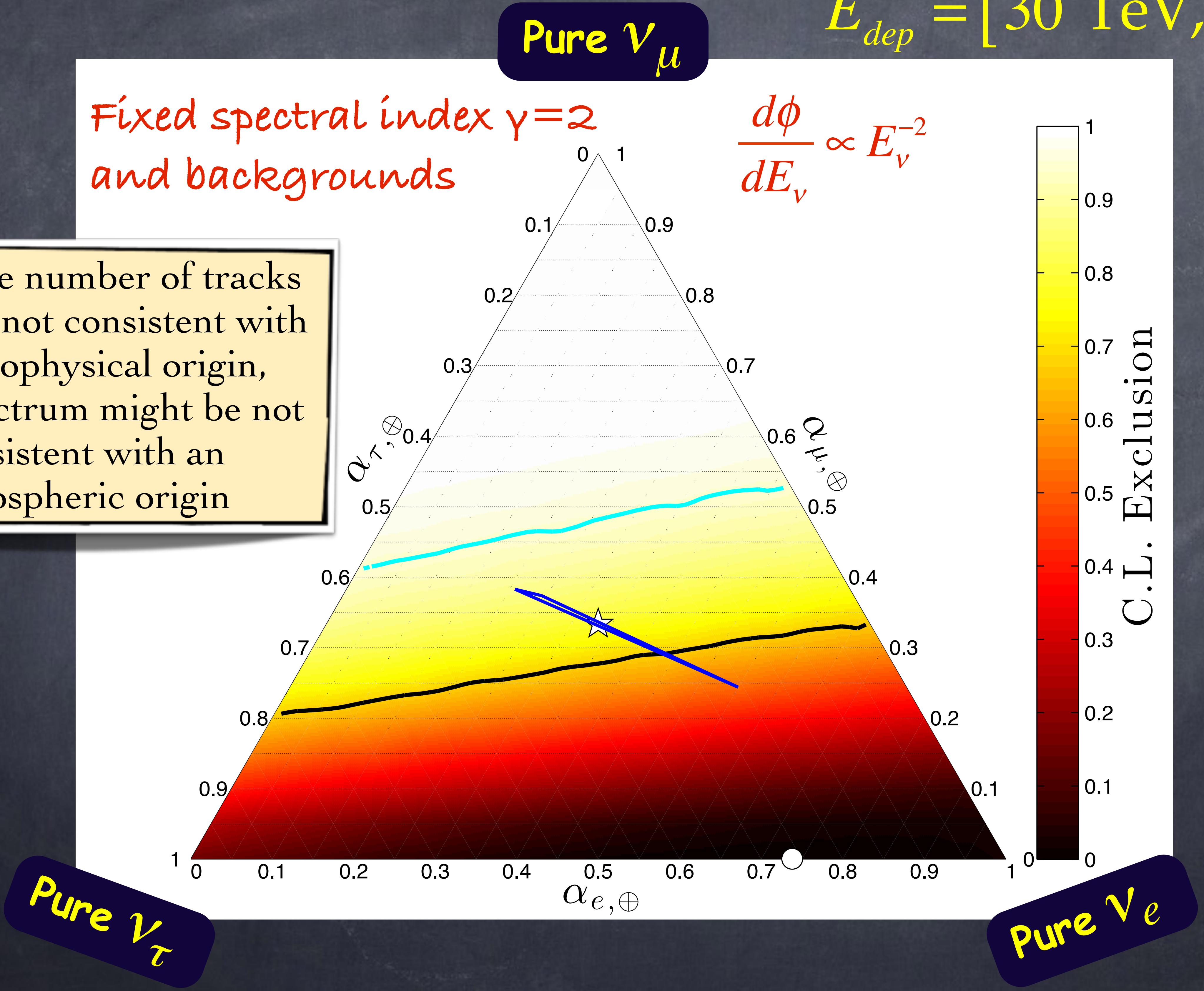
Adapted from:

O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014

INCLUDING SPECTRAL INFO

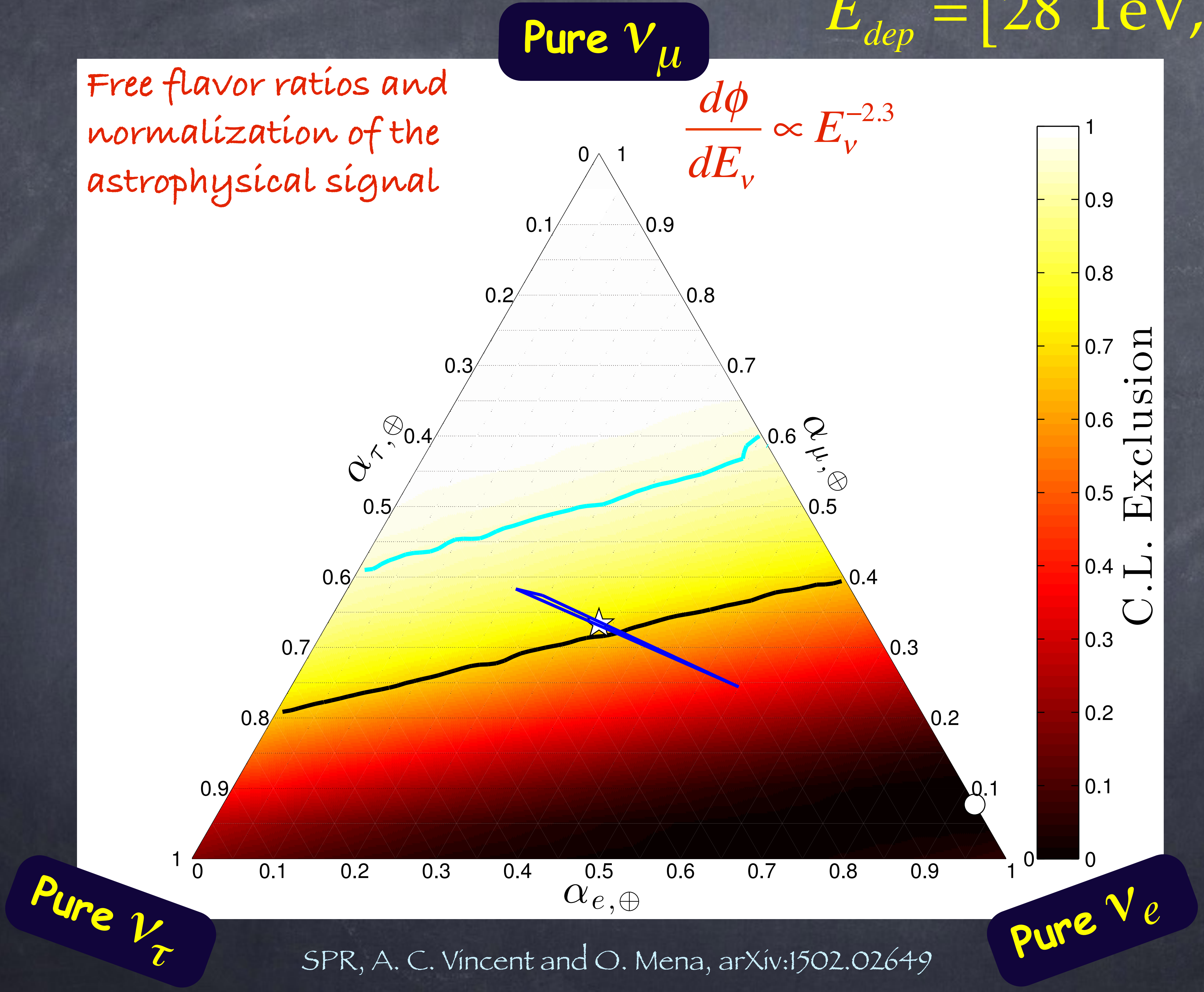
$E_{dep} = [30\ \text{TeV}, 3\ \text{PeV}]$

While the number of tracks might be not consistent with an astrophysical origin, their spectrum might be not consistent with an atmospheric origin



FIXED SPECTRUM AND BACKGROUND

$E_{dep} = [28\ \mathrm{TeV}, 3\ \mathrm{PeV}]$



Free flavor ratios and normalization of the astrophysical signal

$$\frac{d\phi}{dE_\nu} \propto E_\nu^{-2.3}$$

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

FREE SPECTRUM AND BACKGROUND

$E_{dep} = [28\ \text{TeV}, 3\ \text{PeV}]$

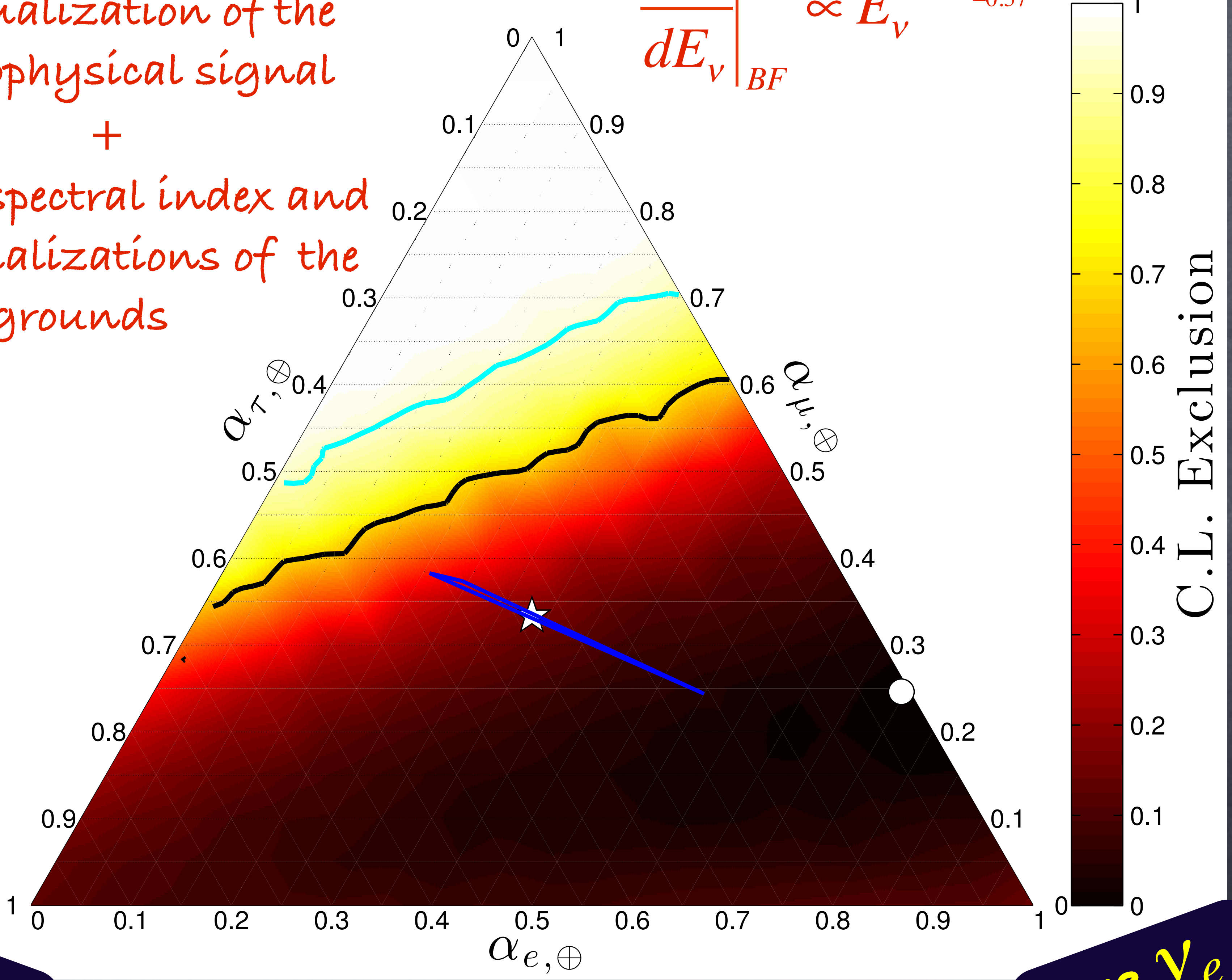
Free flavor ratios and normalization of the astrophysical signal

+

Free spectral index and normalizations of the backgrounds

$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.96^{+0.34}_{-0.37}}$$

Pure ν_μ



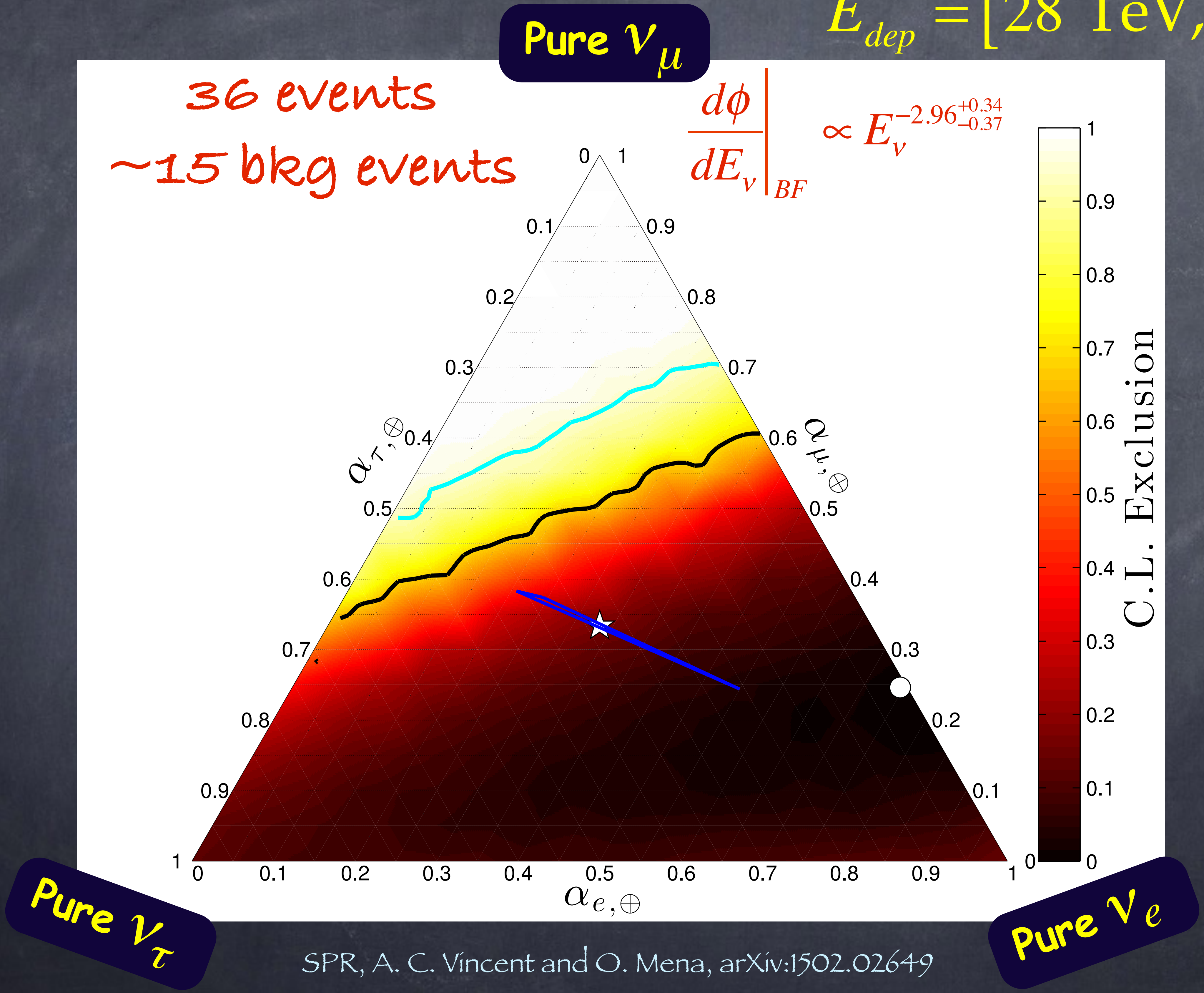
Pure ν_τ

Pure ν_e

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

CUT E<28 TEV

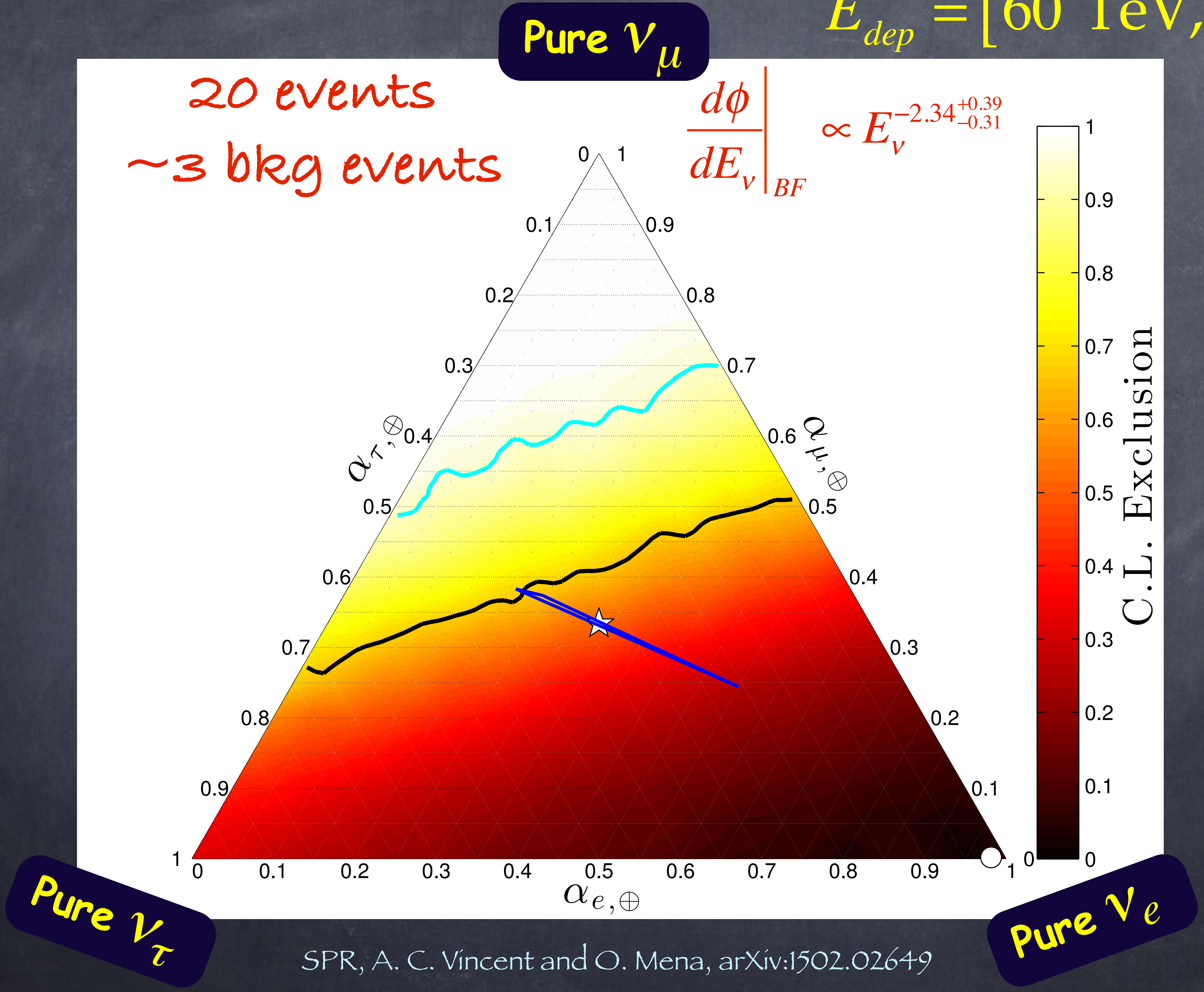
$E_{dep} = [28\ \text{TeV}, 3\ \text{PeV}]$



SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

CUT E<60 TEV

$E_{dep} = [60\text{ TeV}, 3\text{ PeV}]$



20 events

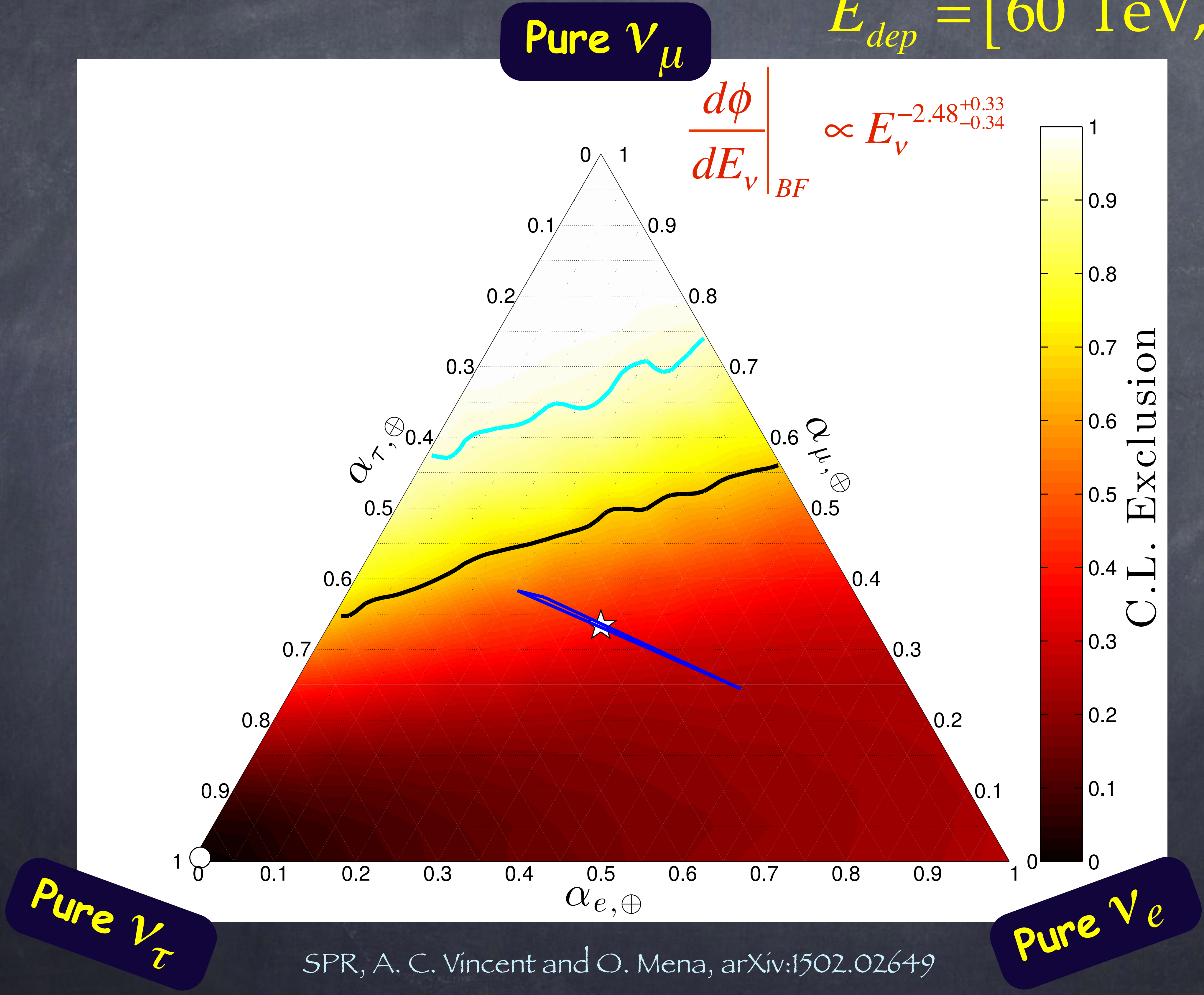
~3 bkg events

$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.34^{+0.39}_{-0.31}}$$

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

INCLUDING HIGHER ENERGIES

$$E_{dep} = [60\ \text{TeV}, 10\ \text{PeV}]$$

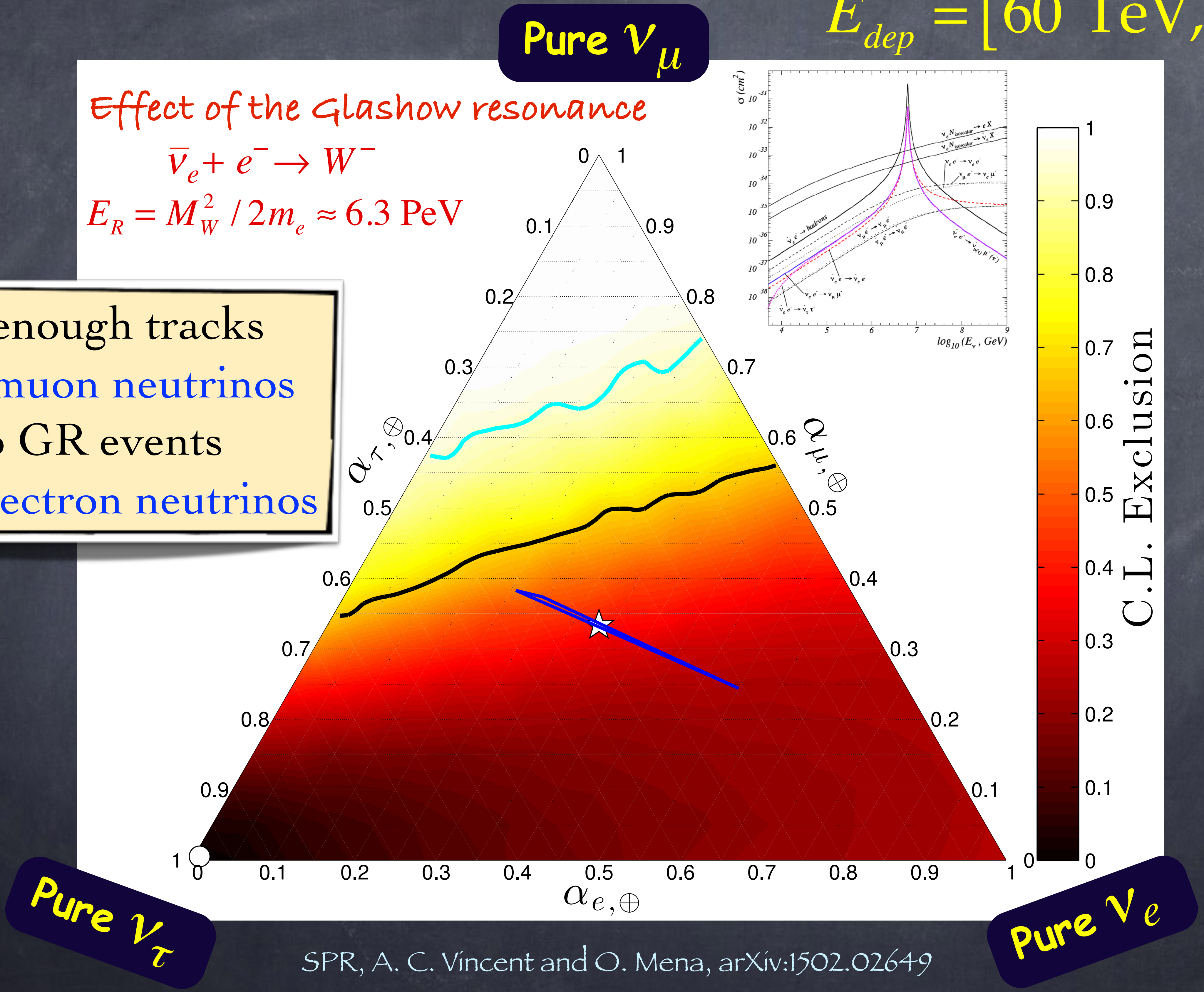


$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.48^{+0.33}_{-0.34}}$$

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

INCLUDING HIGHER ENERGIES

$E_{dep} = [60 \text{ TeV}, 10 \text{ PeV}]$



Effect of the Glashow resonance

$\bar{\nu}_e + e^- \to W^-$

$E_R = M_W^2 / 2m_e \approx 6.3 \text{ PeV}$

Not enough tracks

→ no muon neutrinos

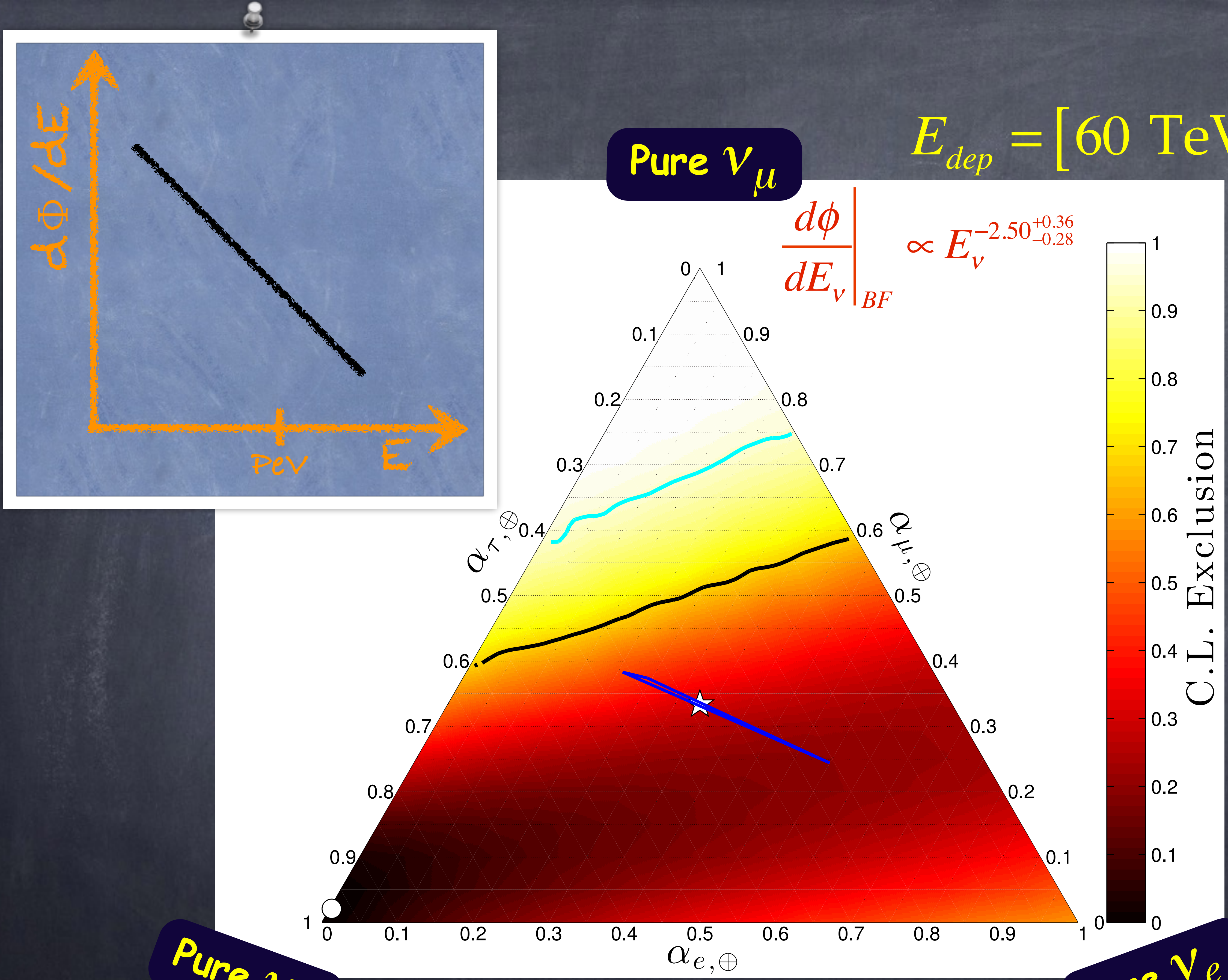
No GR events

→ no electron neutrinos

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

$$E_{dep} = [60\ \text{TeV}, 10\ \text{PeV}]$$

Pure ν_μ



$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.50^{+0.36}_{-0.28}}$$

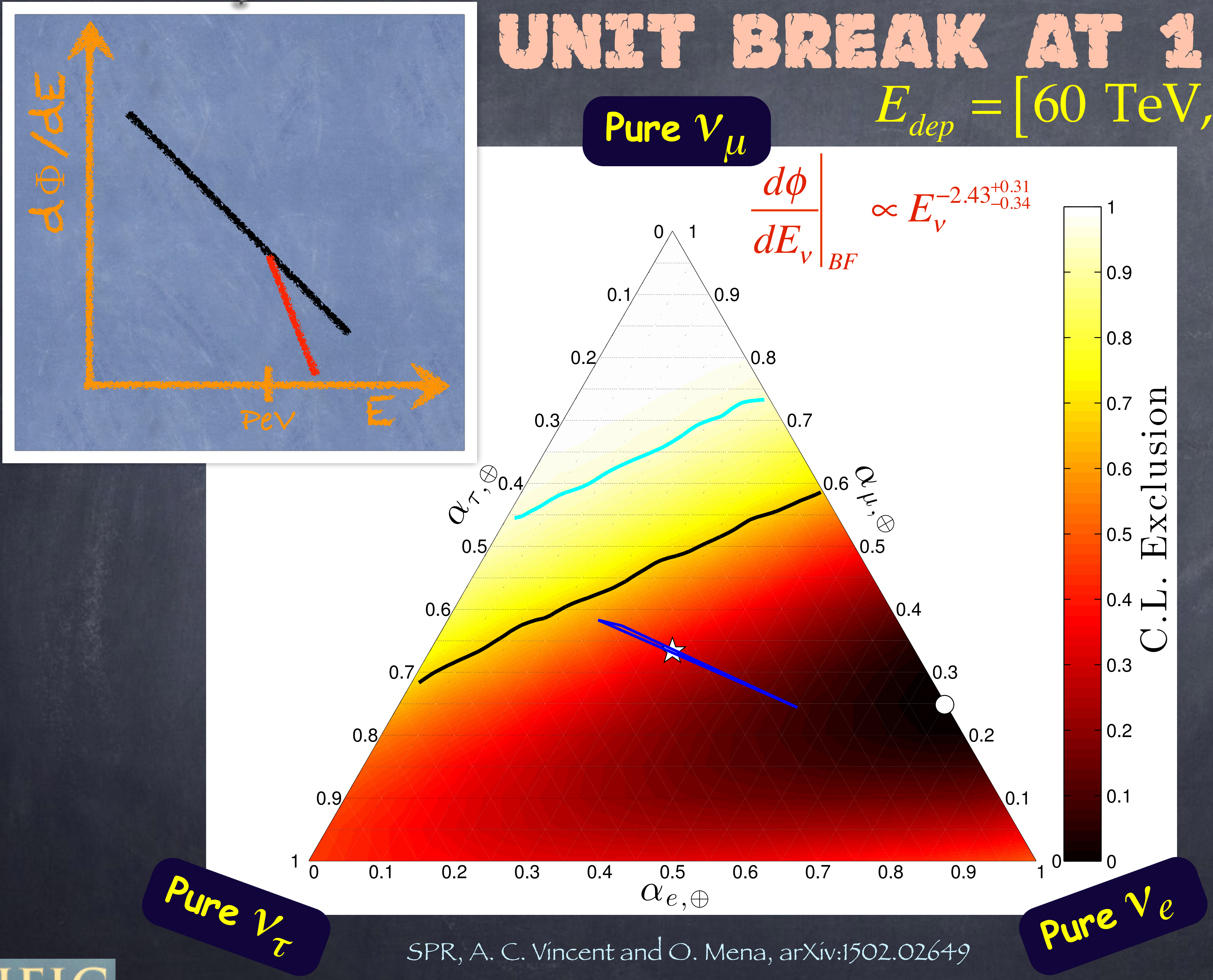
Pure ν_τ

Pure ν_e

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649

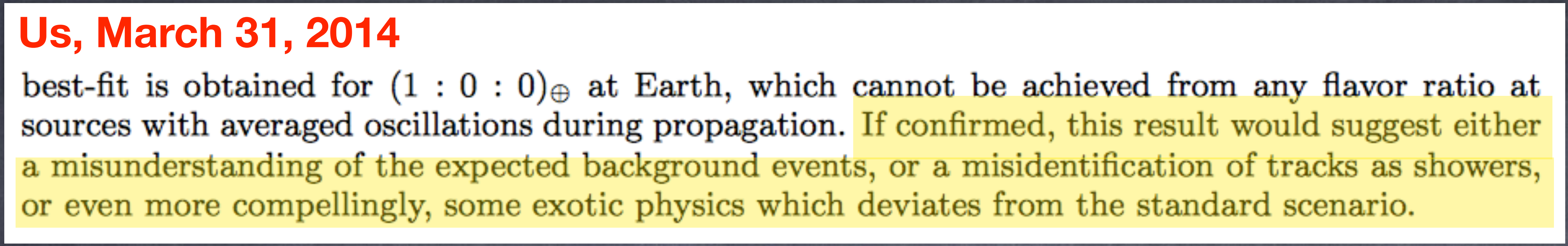
UNIT BREAK AT 1 PEV

$E_{dep} = [60 \text{ TeV}, 10 \text{ PeV}]$



$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.43^{+0.31}_{-0.34}}$$

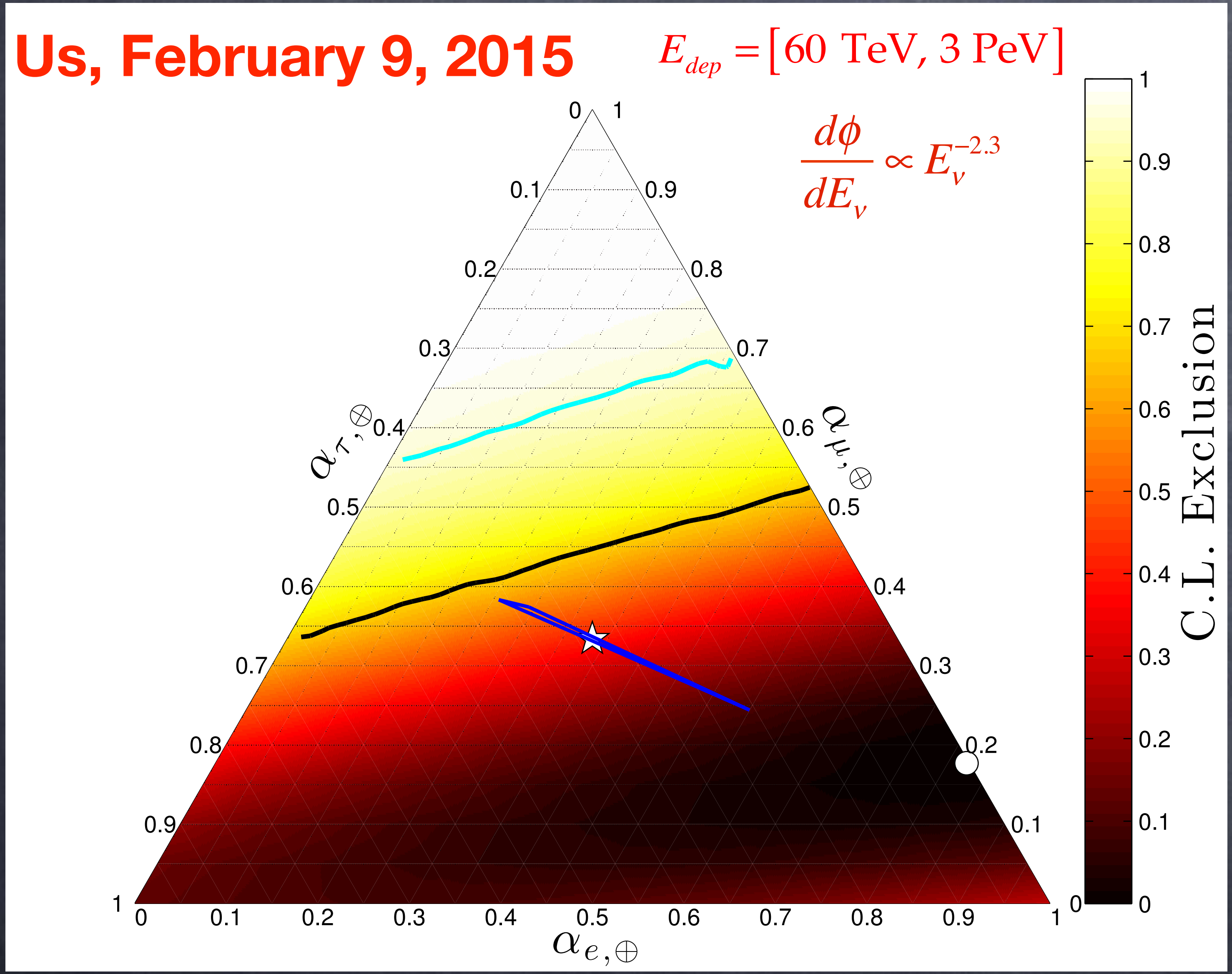
SPR, A. C. Vincent and O. Mena, arXiv:1502.02649



Us, March 31, 2014

best-fit is obtained for $(1:0:0)_\oplus$ at Earth, which cannot be achieved from any flavor ratio at sources with averaged oscillations during propagation. If confirmed, this result would suggest either a misunderstanding of the expected background events, or a misidentification of tracks as showers, or even more compellingly, some exotic physics which deviates from the standard scenario.

O. Mena, SPR and A. C. Vincent,
Phys. Rev. Lett. 113:091103, 2014

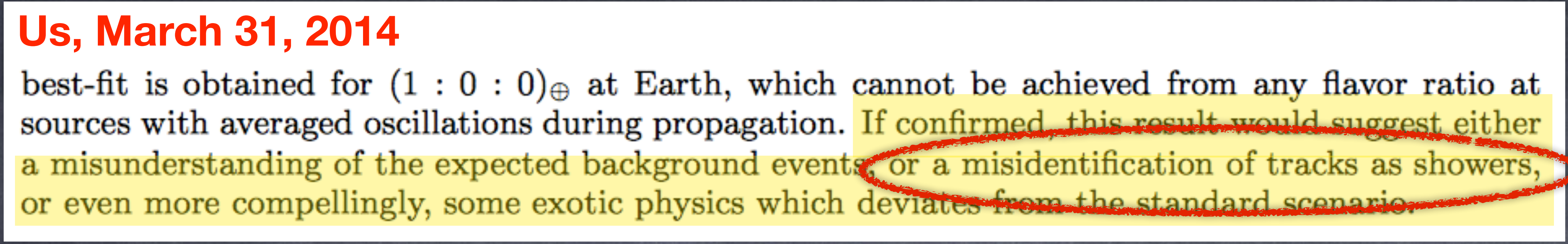


Us, February 9, 2015

$E_{dep} = [60\ \text{TeV}, 3\ \text{PeV}]$

$$\frac{d\phi}{dE_\nu} \propto E_\nu^{-2.3}$$

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v1



Us, March 31, 2014

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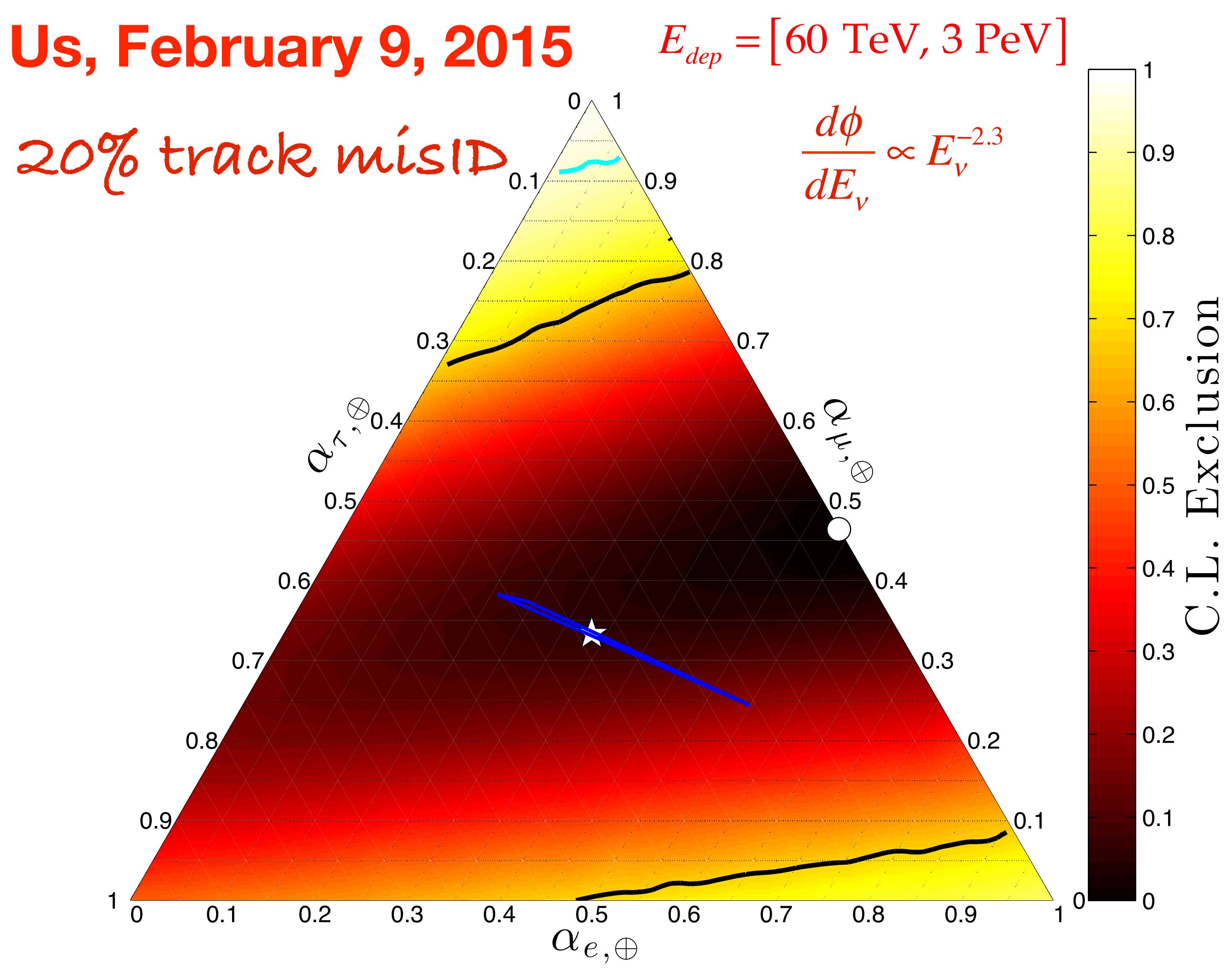
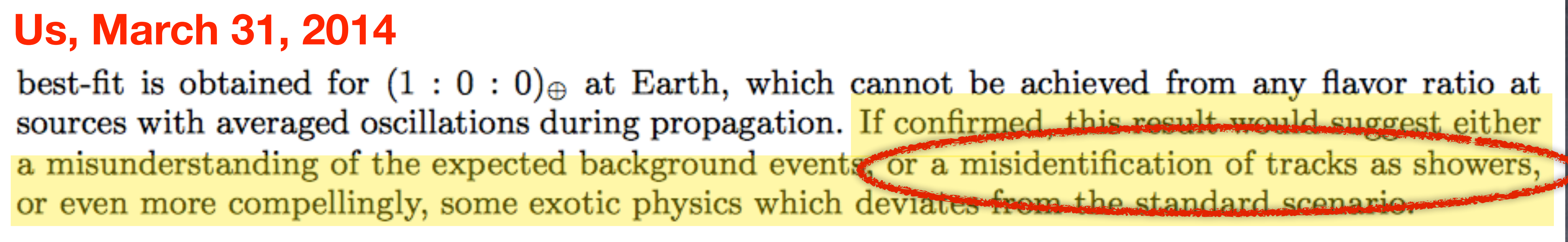
O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014

Us, February 9, 2015



SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v1



Us, March 31, 2014

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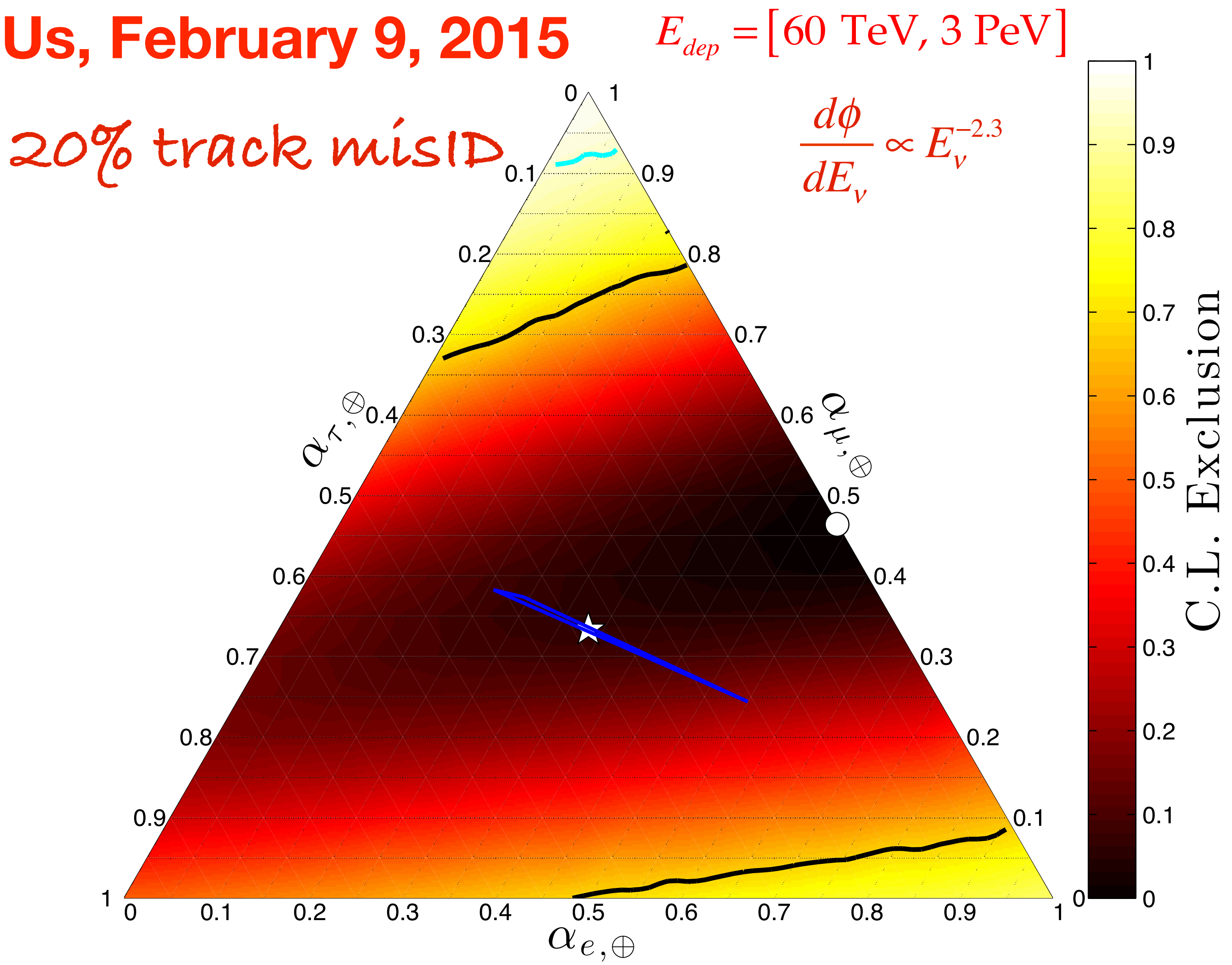
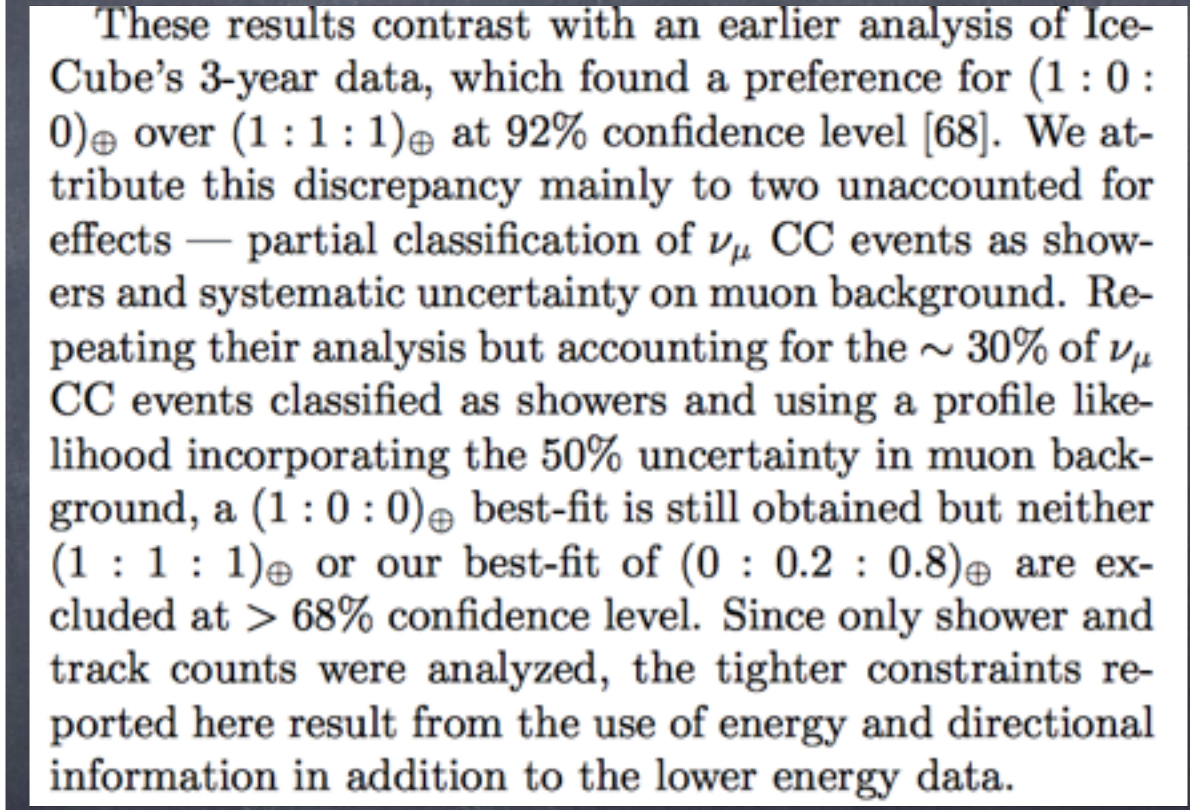
O. Mena, SPR and A. C. Vincent, Phys. Rev. Lett. 113:091103, 2014

Us, February 9, 2015



SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v1

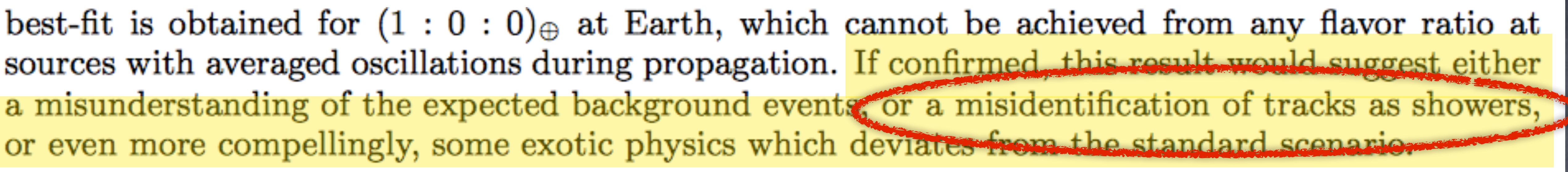
IceCube, February 11, 2015



These results contrast with an earlier analysis of IceCube's 3-year data, which found a preference for $(1:0:0)_\oplus$ over $(1:1:1)_\oplus$ at 92% confidence level [68]. We attribute this discrepancy mainly to two unaccounted for effects — partial classification of ν_μ CC events as showers and systematic uncertainty on muon background. Repeating their analysis but accounting for the $\sim 30\%$ of ν_μ CC events classified as showers and using a profile likelihood incorporating the 50% uncertainty in muon background, a $(1:0:0)_\oplus$ best-fit is still obtained but neither $(1:1:1)_\oplus$ or our best-fit of $(0:0.2:0.8)_\oplus$ are excluded at $> 68\%$ confidence level. Since only shower and track counts were analyzed, the tighter constraints reported here result from the use of energy and directional information in addition to the lower energy data.

M. G. Aartsen et al. [Icecube Collaboration], arXiv:1502.03376

Us, March 31, 2014



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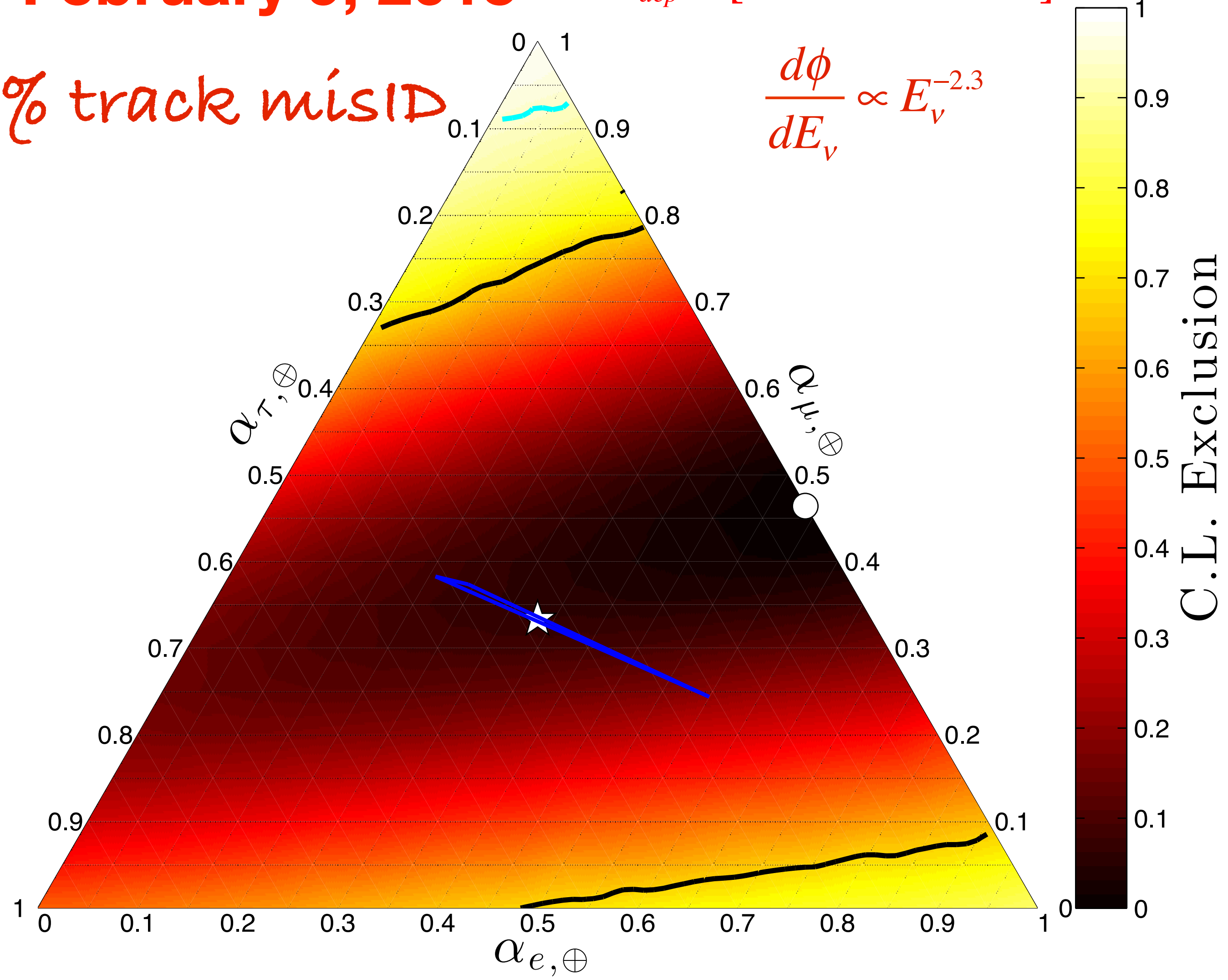
O. Mena, SPR and A. C. Vincent,
Phys. Rev. Lett. 113:091103, 2014

Us, February 9, 2015

$E_{dep} = [60 \text{ TeV}, 3 \text{ PeV}]$

20% track misID

$\frac{d\phi}{dE_\nu} \propto E_\nu^{-2.3}$



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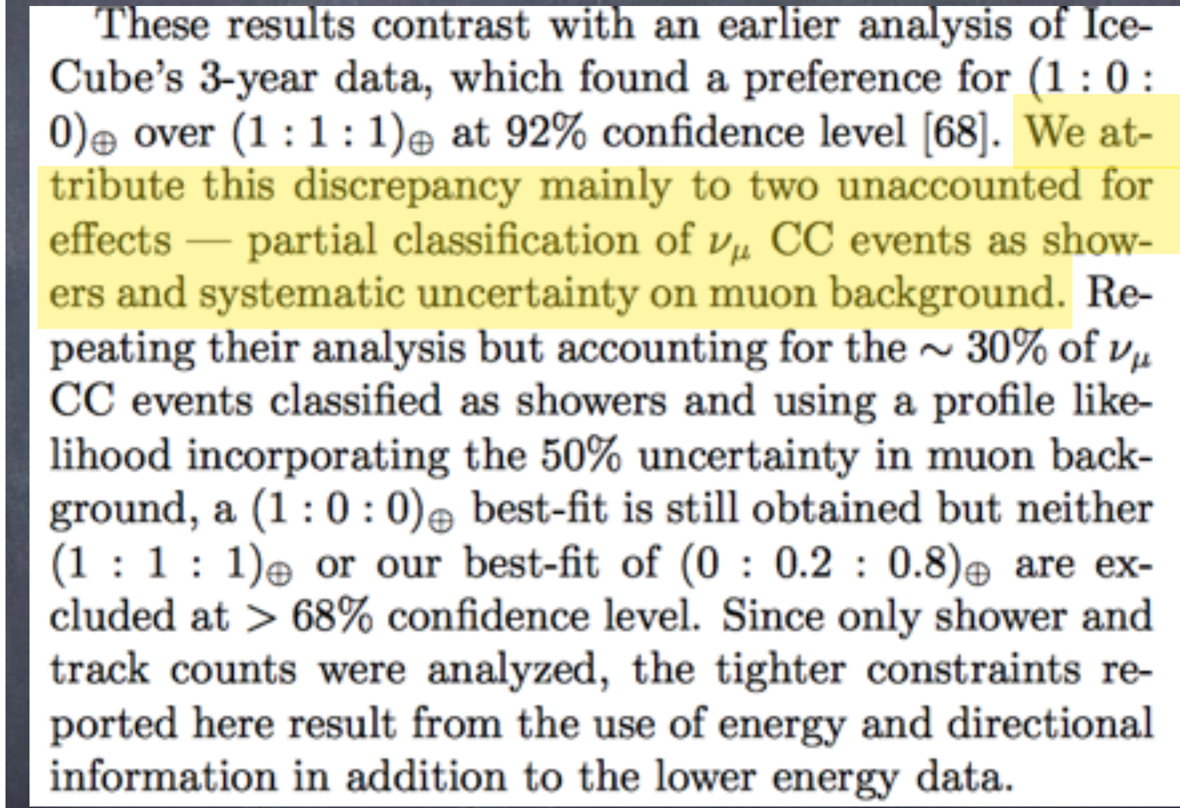
IceCube, February 11, 2015



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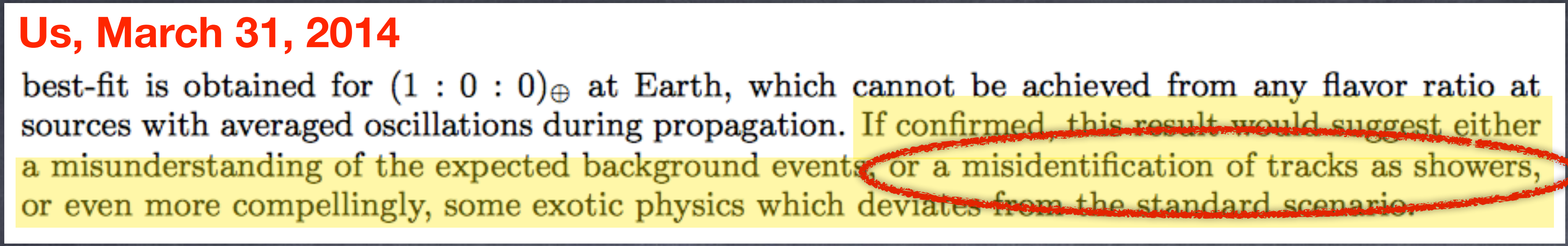

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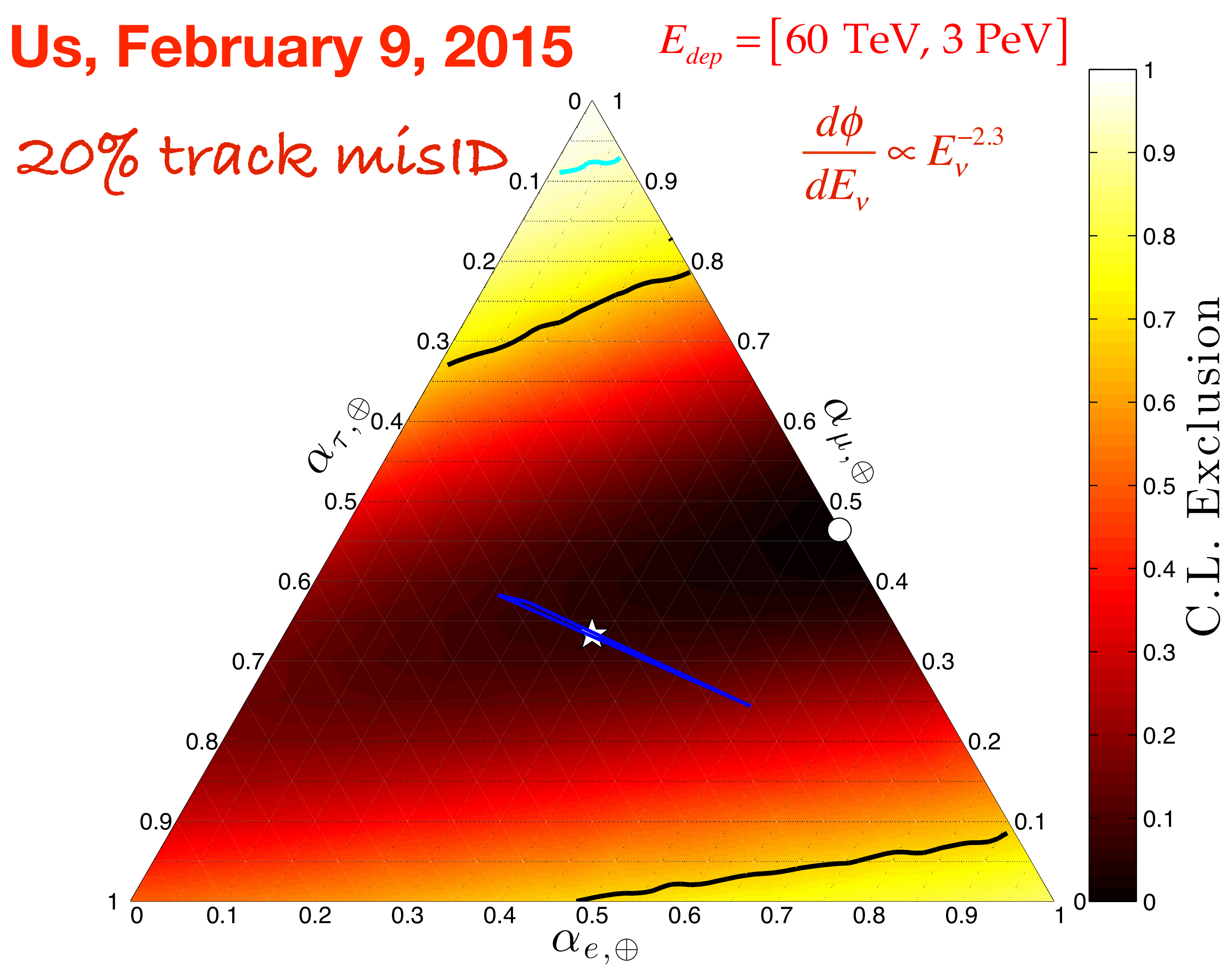
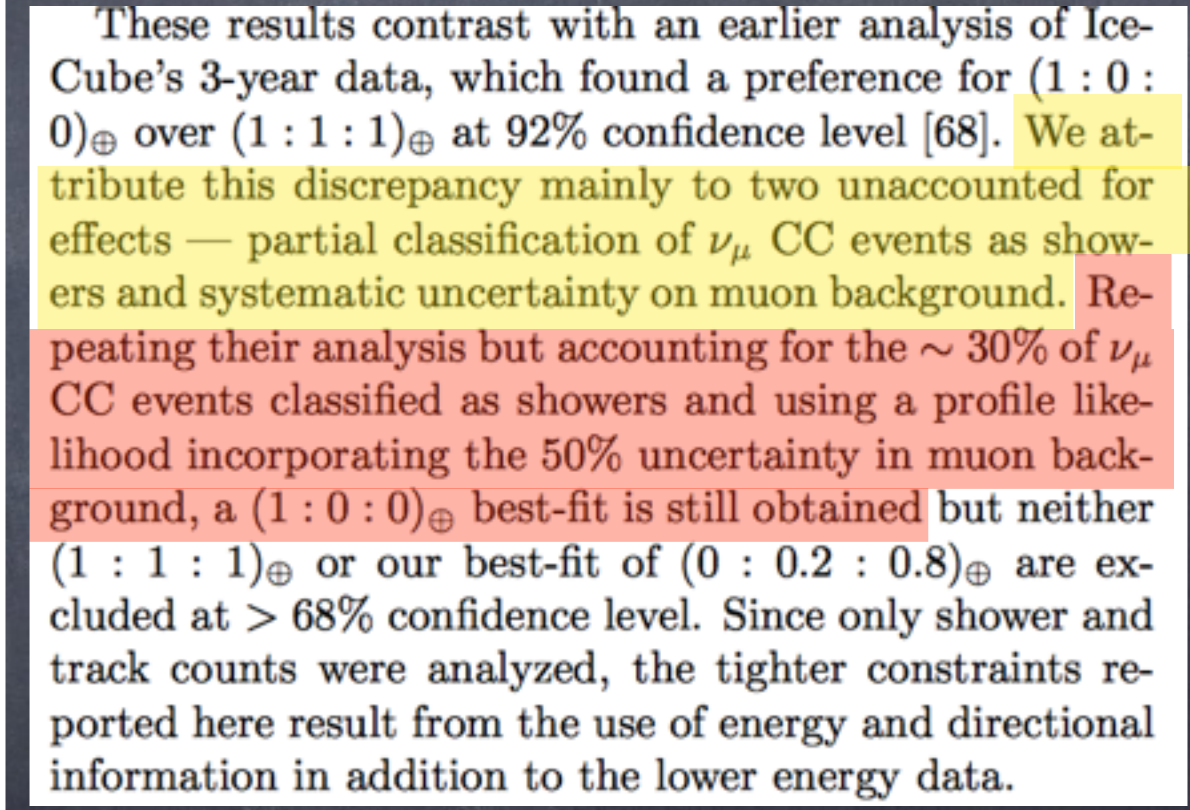


Us, February 9, 2015

SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v1

IceCube, February 11, 2015



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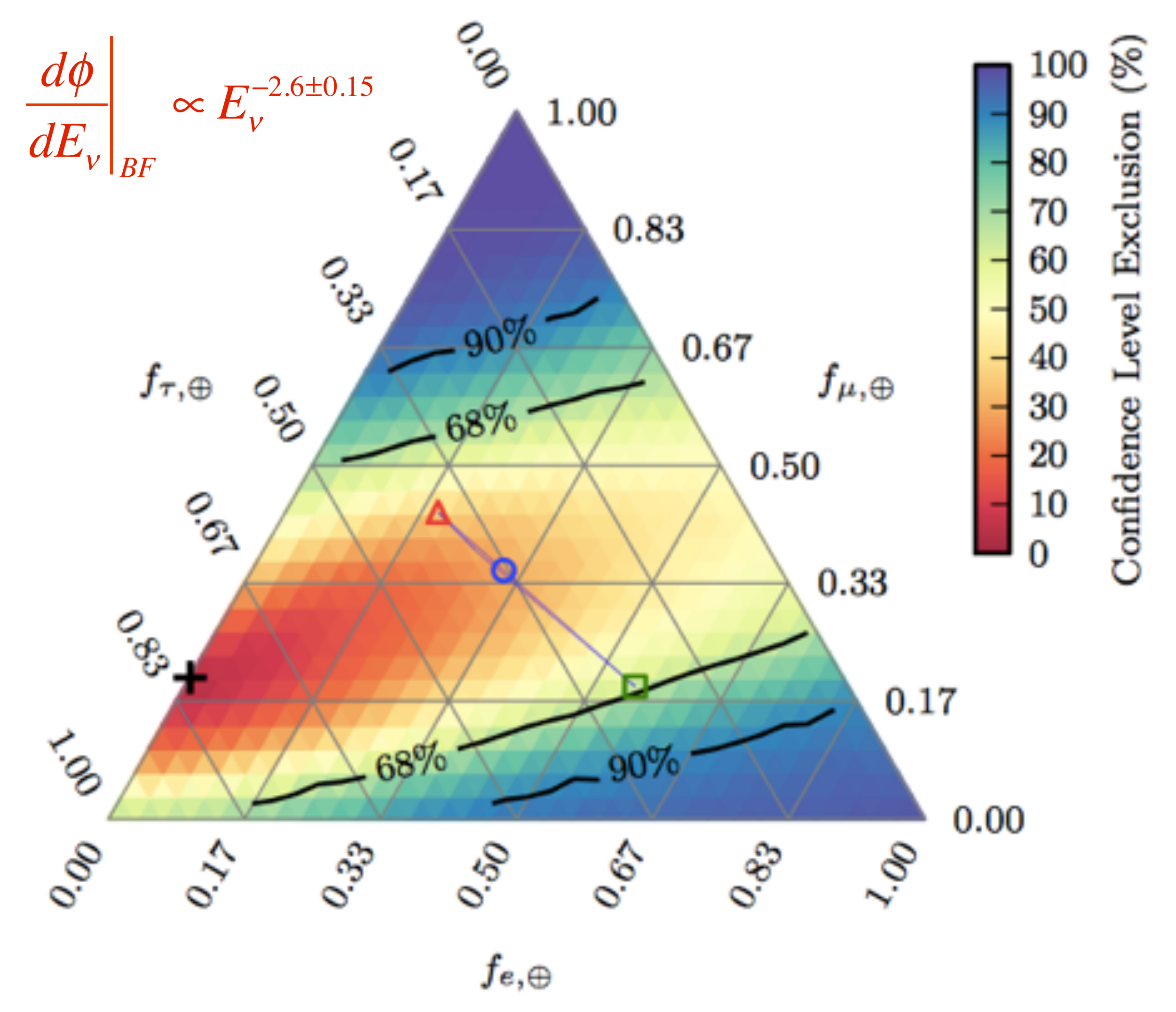
M. G. Aartsen et al. [Icecube Collaboration],
arXiv:1502.03376

30% track misID and deposited energies up to 10 PeV

IceCube analysis

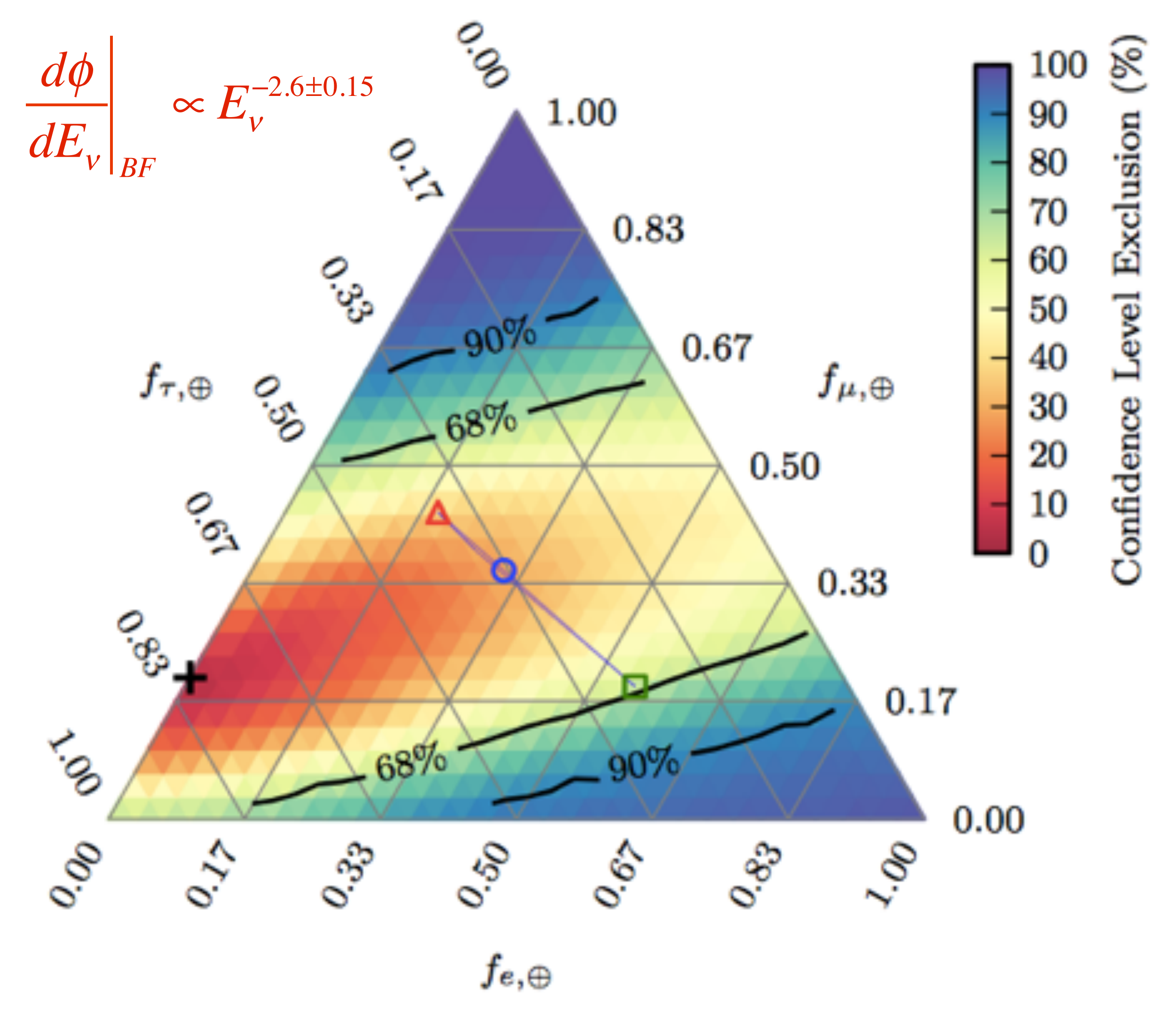


M. G. Aartsen et al. [Icecube Collaboration], arXiv:1502.03376

30% track misID and deposited energies up to 10 PeV

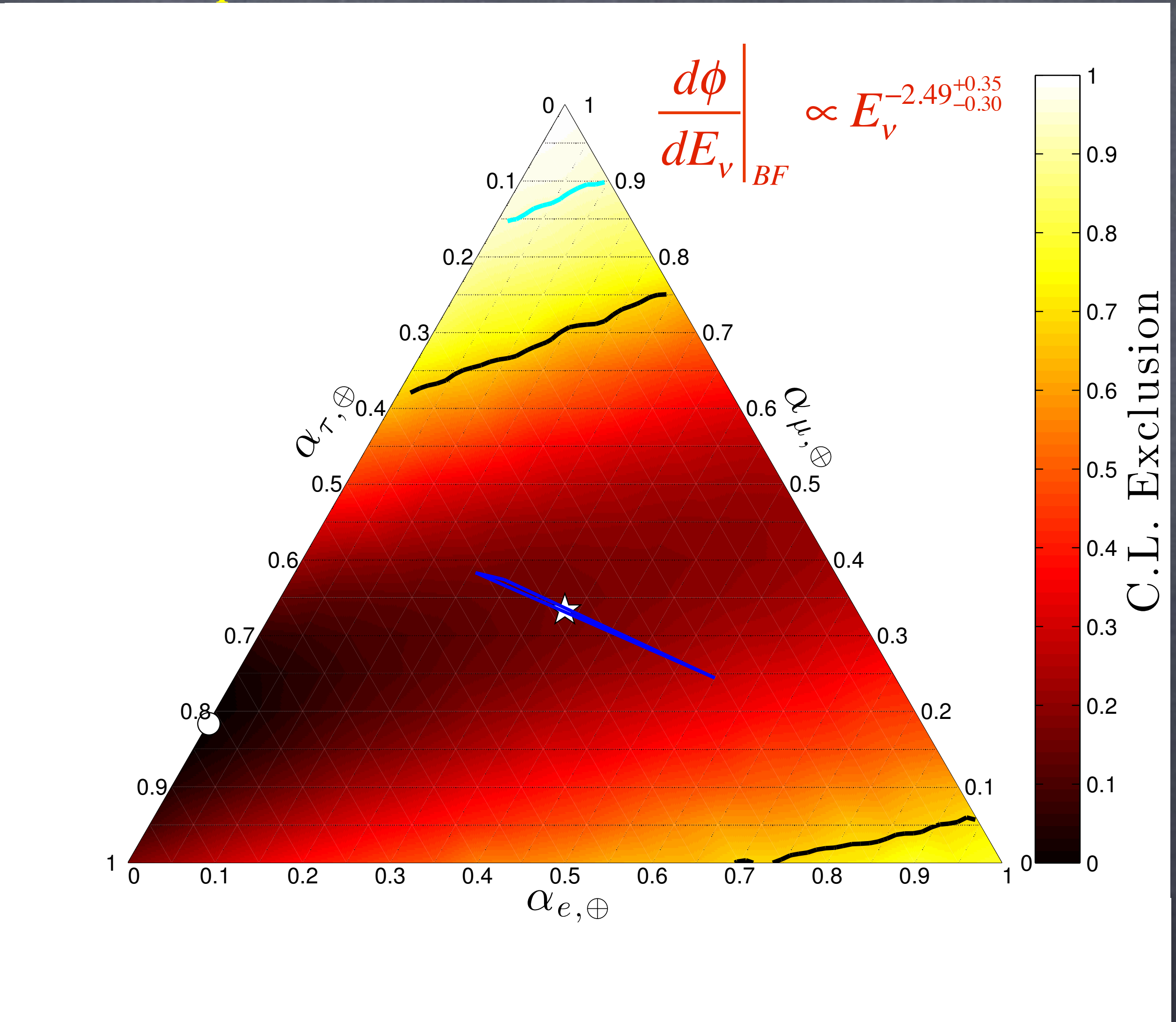
IceCube analysis

$$E_{dep} = [60\text{ TeV}, 10\text{ PeV}]$$



$$\left.\frac{d\phi}{dE_\nu}\right|_{BF} \propto E_\nu^{-2.6\pm0.15}$$

M. G. Aartsen et al. [Icecube Collaboration], arXiv:1502.03376



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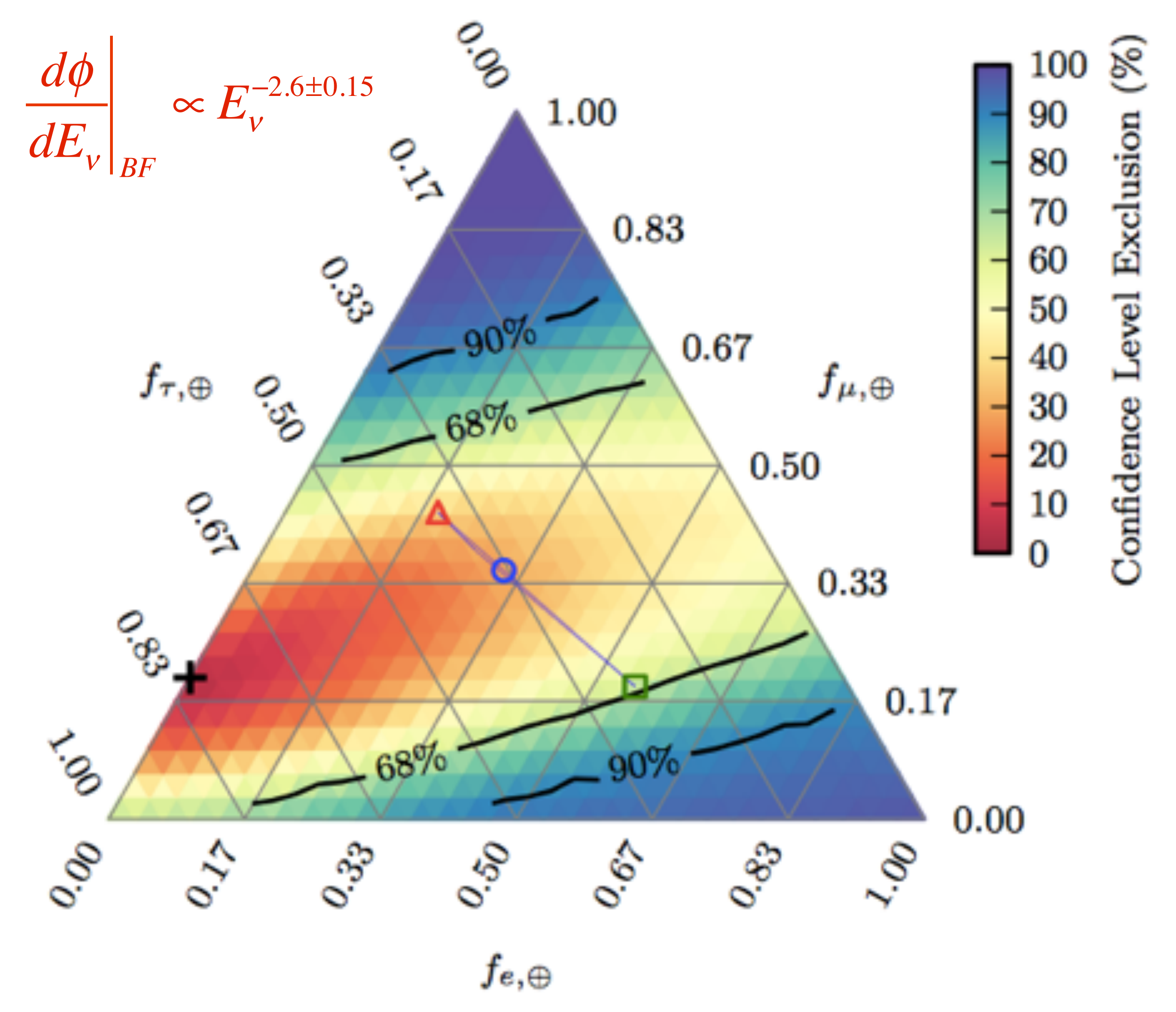
SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v2

30% track misID and deposited energies up to 10 PeV

IceCube analysis

$$E_{dep} = [60\ \text{TeV}, 10\ \text{PeV}]$$



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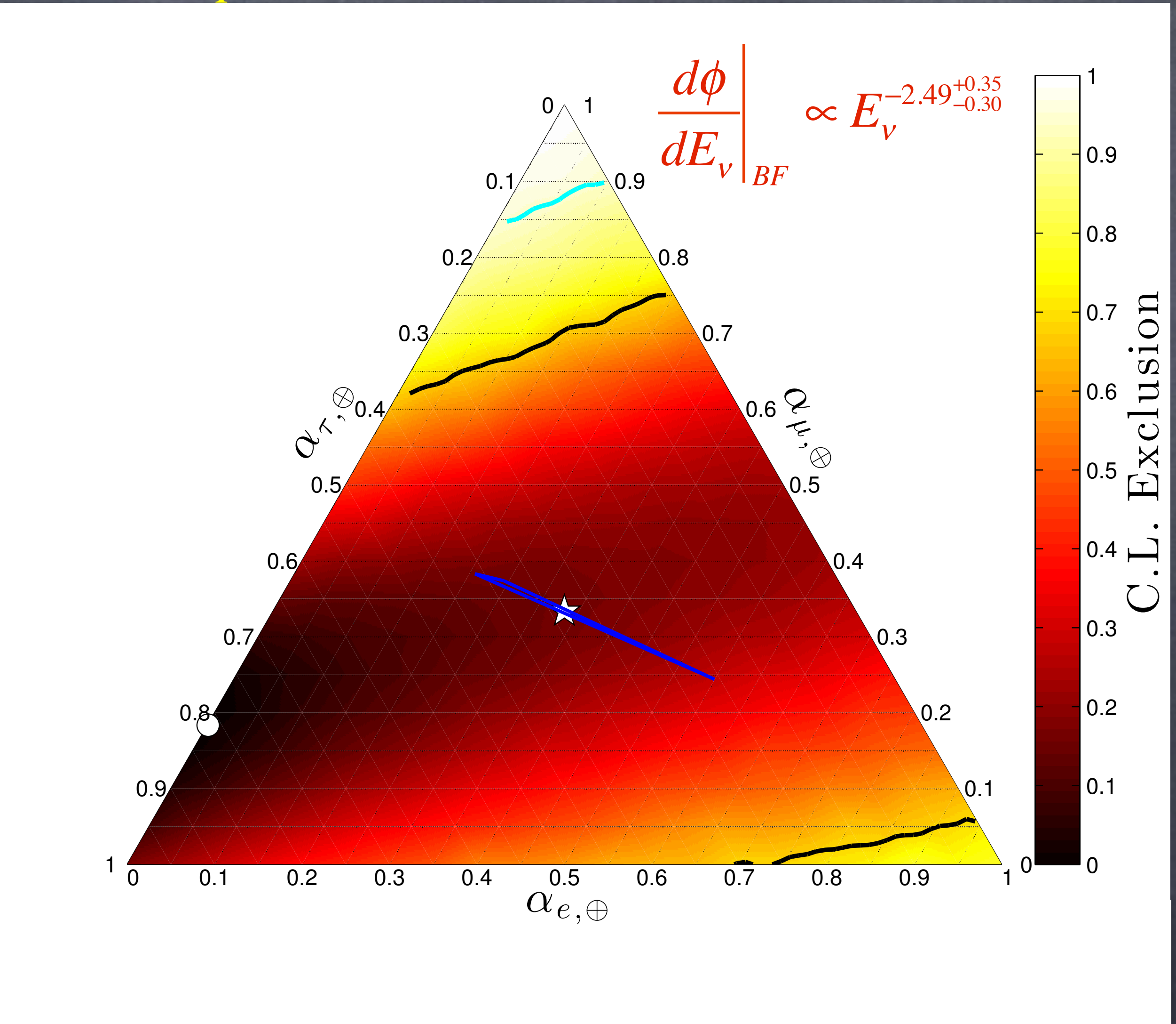
M. G. Aartsen et al.[Icecube Collaboration], arXiv:1502.03376



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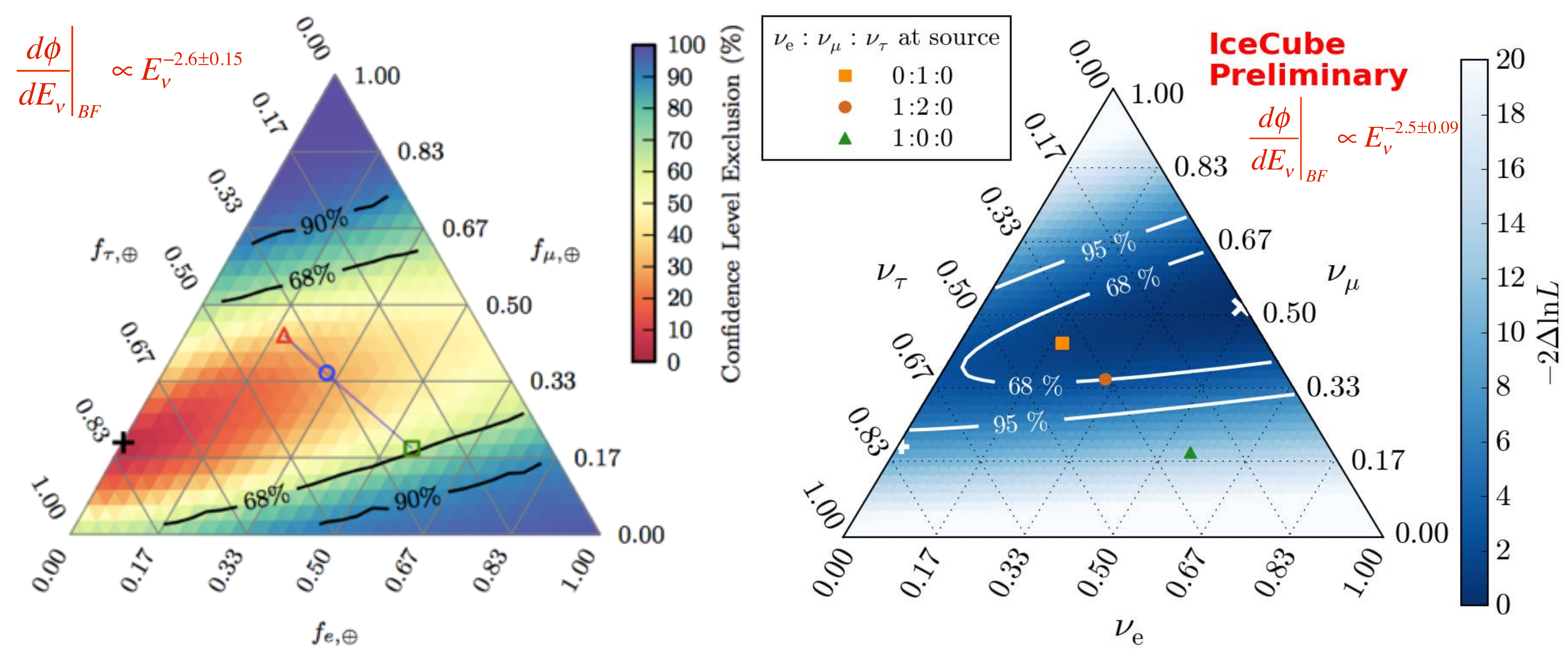
SPR, A. C. Vincent and O. Mena, arXiv:1502.02649v2

Differences between the IceCube analysis and our 2014 result are mainly due to extending the deposited energy range to cover the Glashow resonance (+ track misID)

30% track misID and deposited energies up to 10 PeV

IceCube analysis **New IceCube analysis!**



M. G. Aartsen et al. [Icecube Collaboration], arXiv:1502.03376

J. P. Yáñez, talk at Moriond 2015

Differences between the IceCube analysis and our 2014 result are mainly due to extending the deposited energy range to cover the Glashow resonance (+ track misID)

CONCLUSIONS

- Great discovery by IceCube: the era of neutrino astronomy

- Two potential issues:

→ Deficit of muon tracks... important track misID?

→ Deficit of electron antineutrinos E>PeV... spectral break?

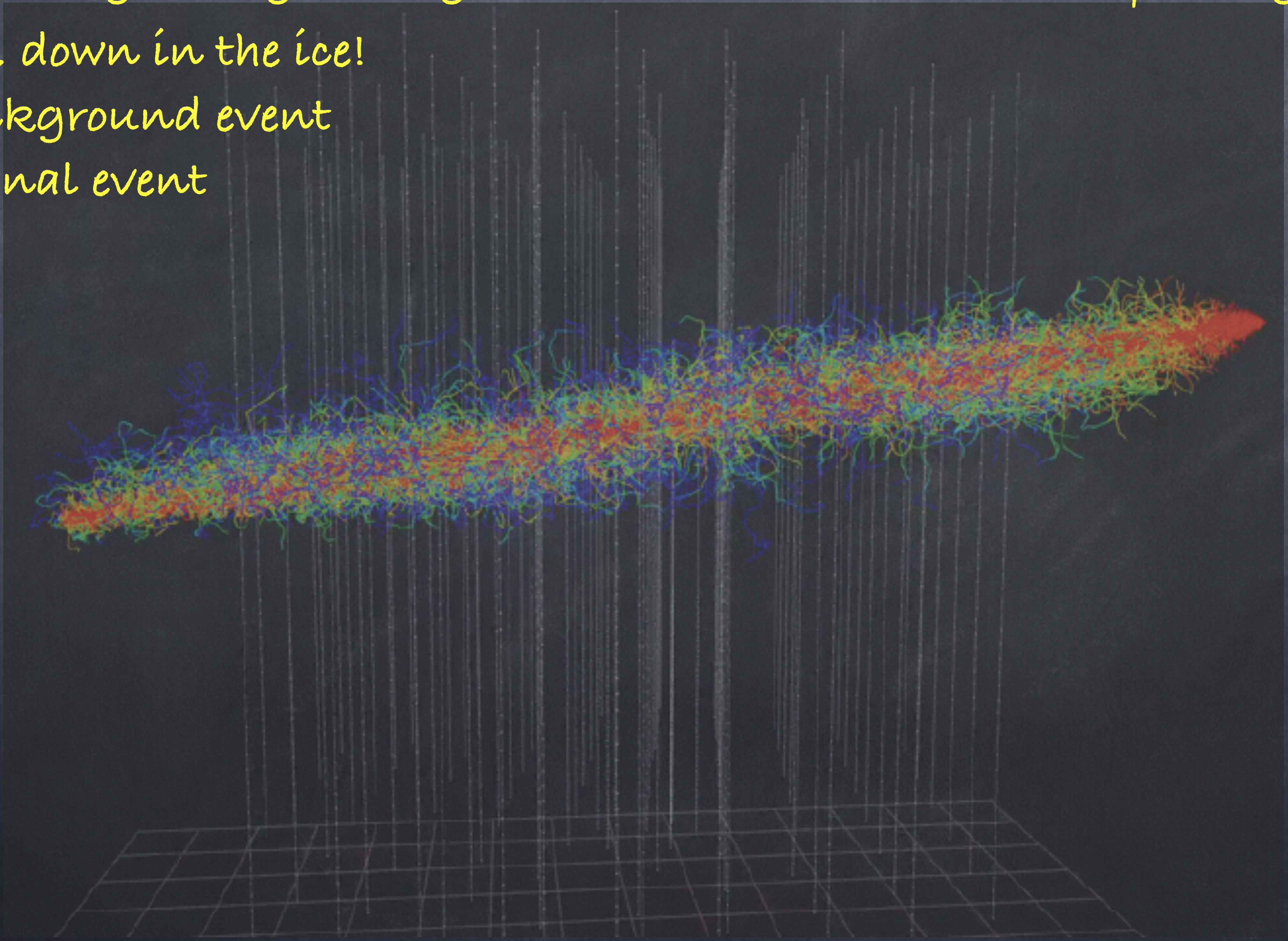
- Results depend on the energy range considered (not statistically conclusive yet)... structure in the spectrum? lack of statistics?

- A lot to be done... 17 more events coming up this year...

- We need more data: KM3NeT, Gen2 IceCube

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…)