



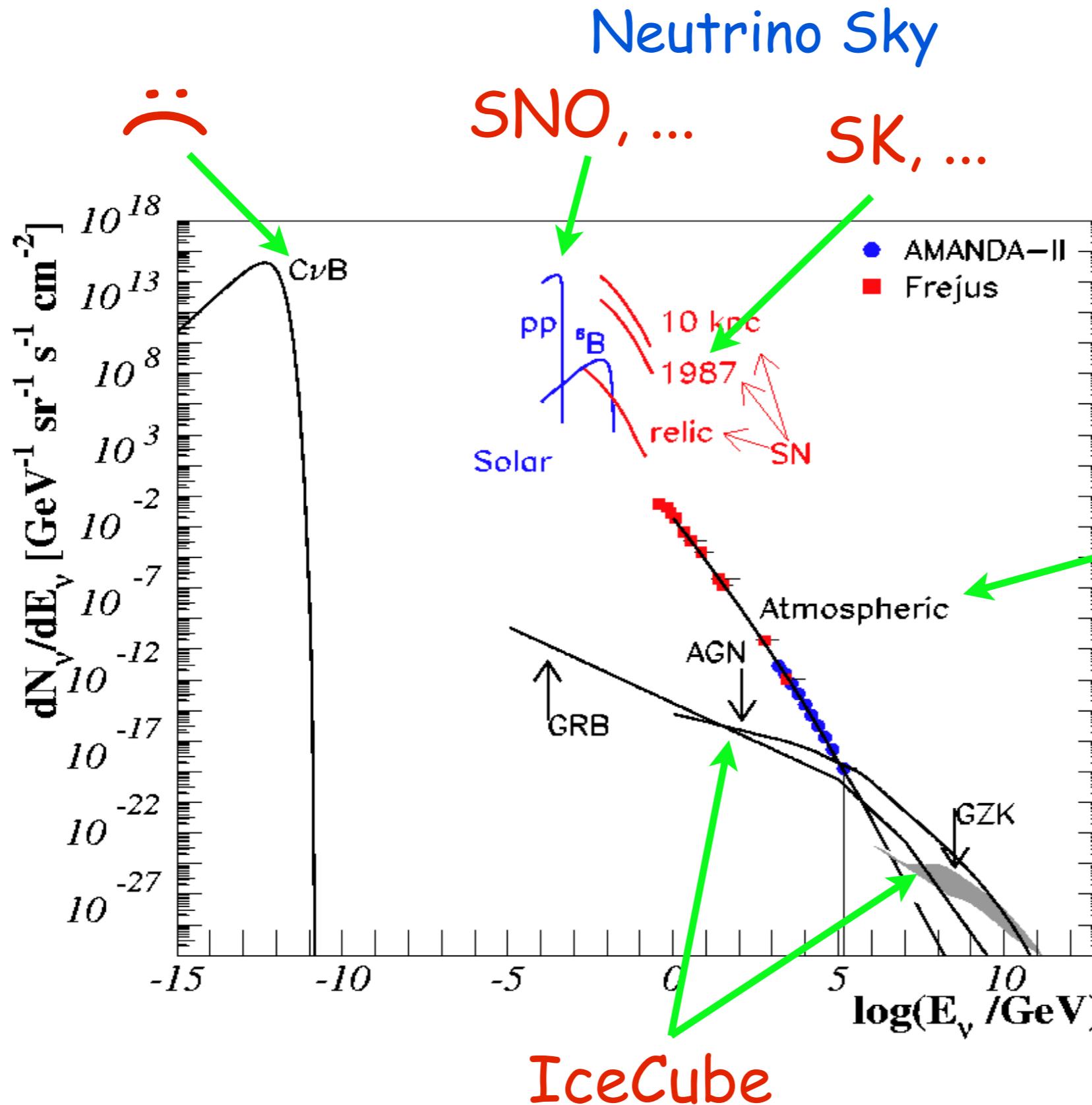
Sterile Neutrinos at Neutrino Telescopes

Arman Esmaili

27/June/2014

Seoul National University of Science and Technology
Institute of Convergence Fundamental Studies

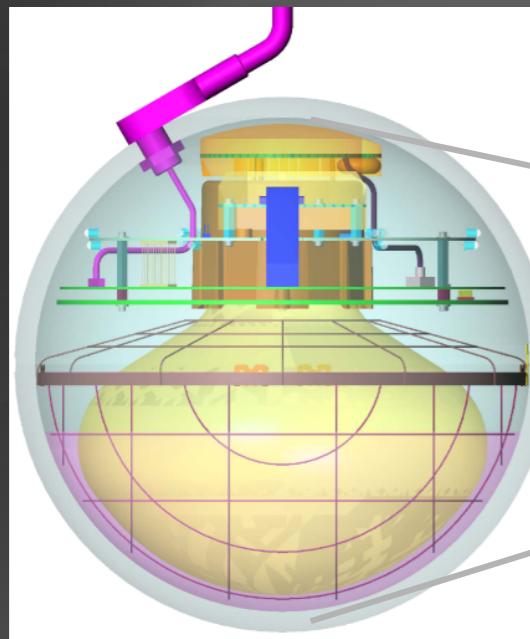




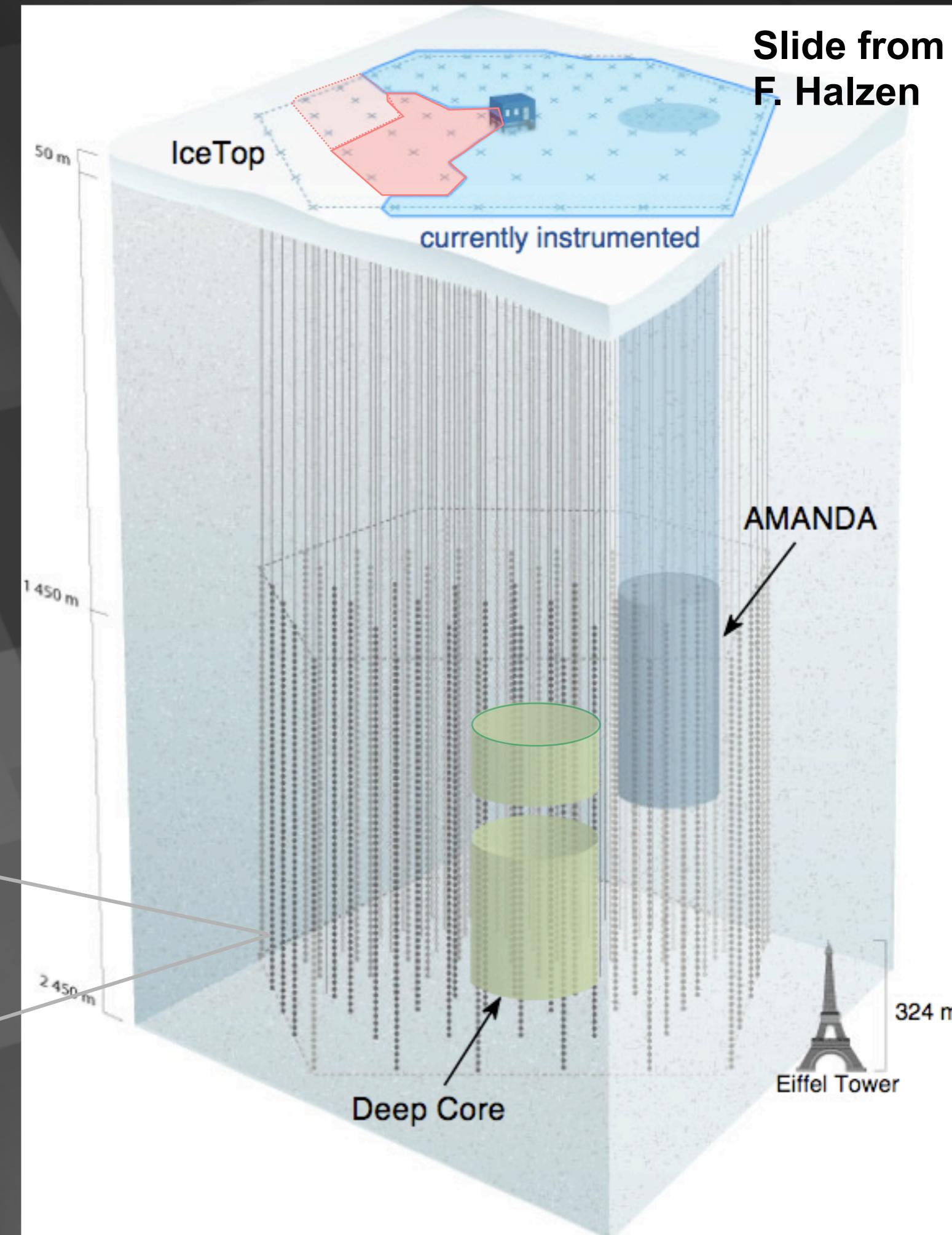
IceCube / Deep Core

Slide from
F. Halzen

- 5320 optical modules on 86 strings (+ IceTop)
- detects ~ 220 neutrinos and 1.7×10^8 muons per day
- threshold 10 GeV
- angular resolution < 1 degree

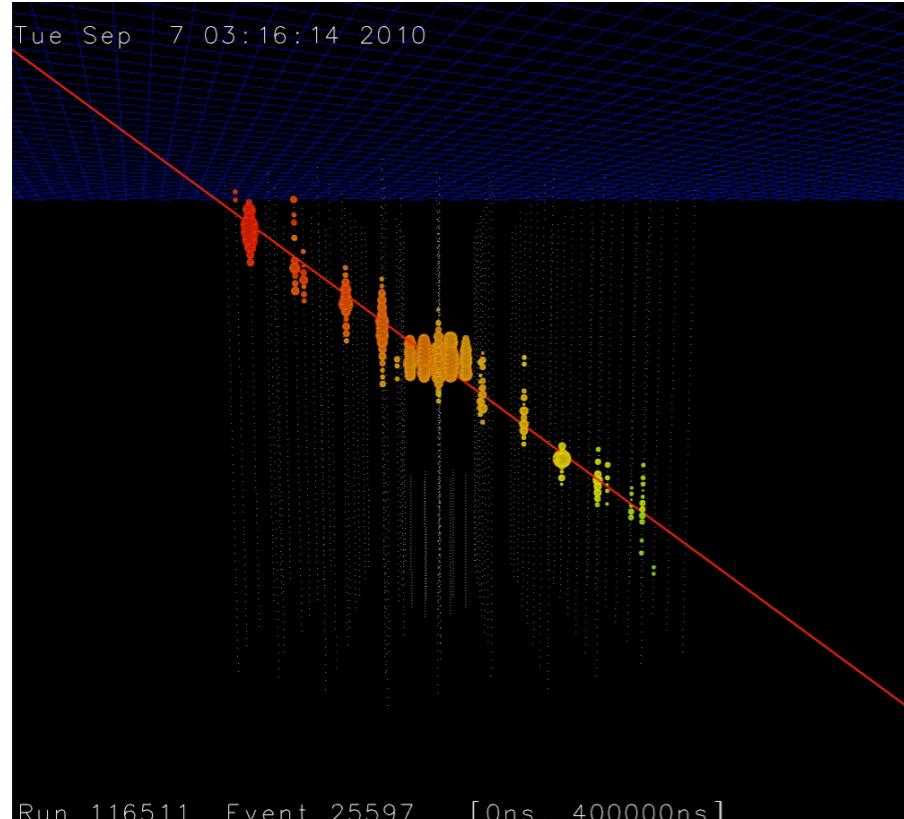
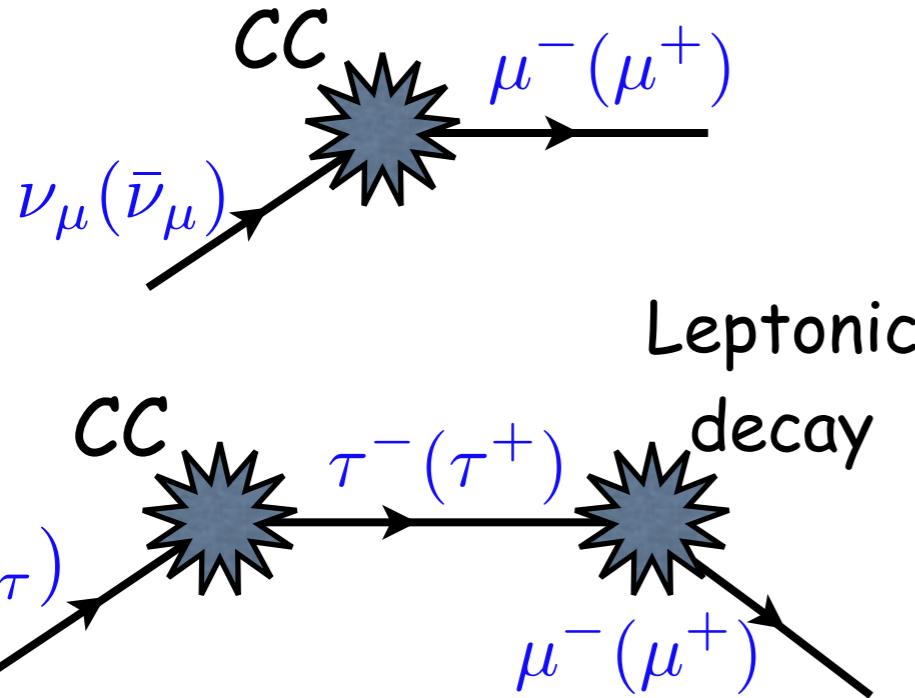


Digital Optical Module (DOM)

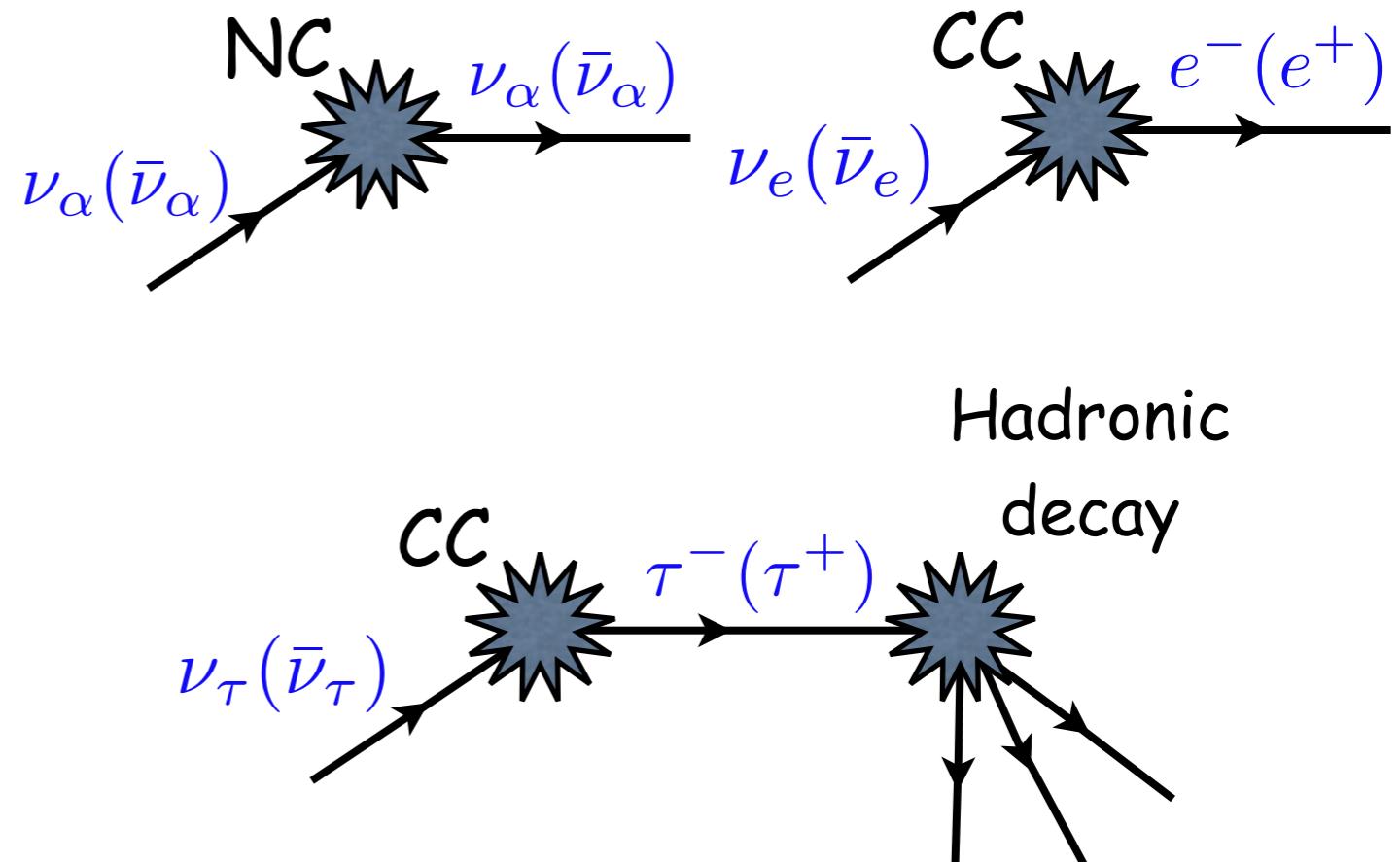


Flavoring at IceCube

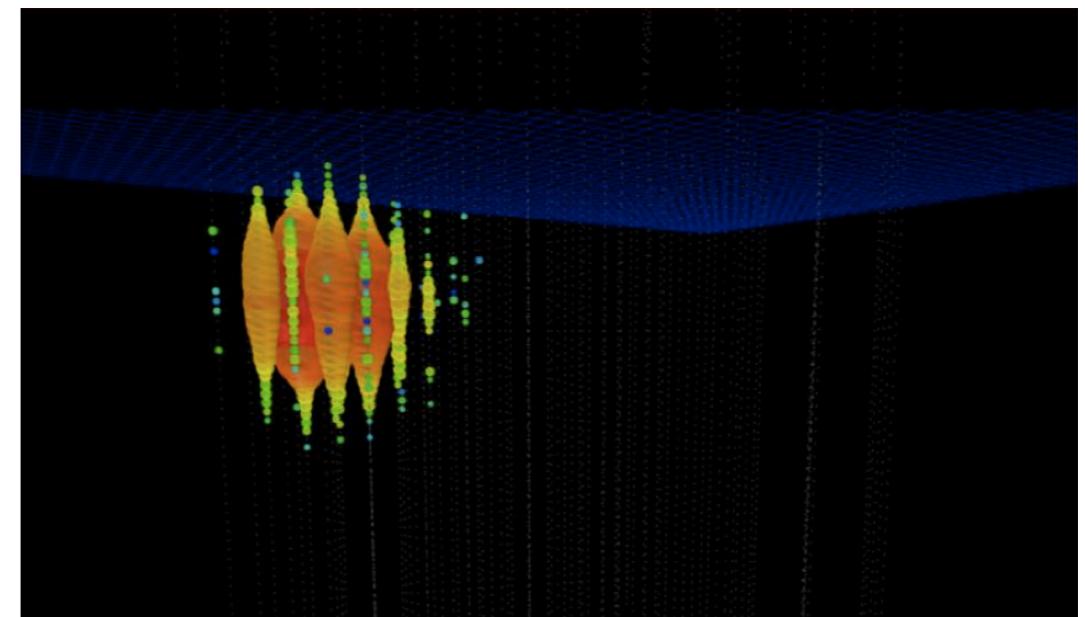
muon-track events



cascade events



figures from
IceCube
website



Measuring the atmospheric "background"

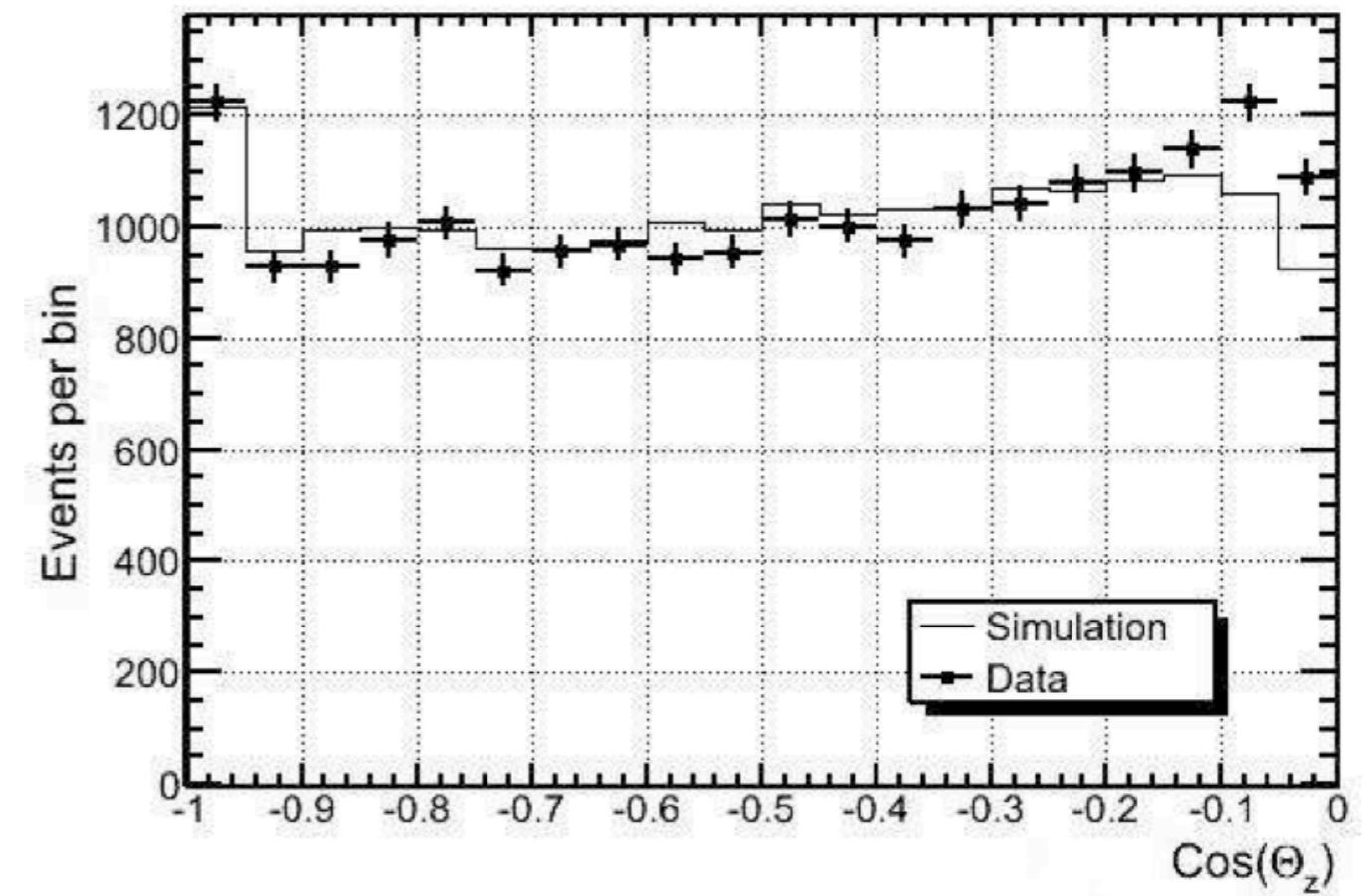
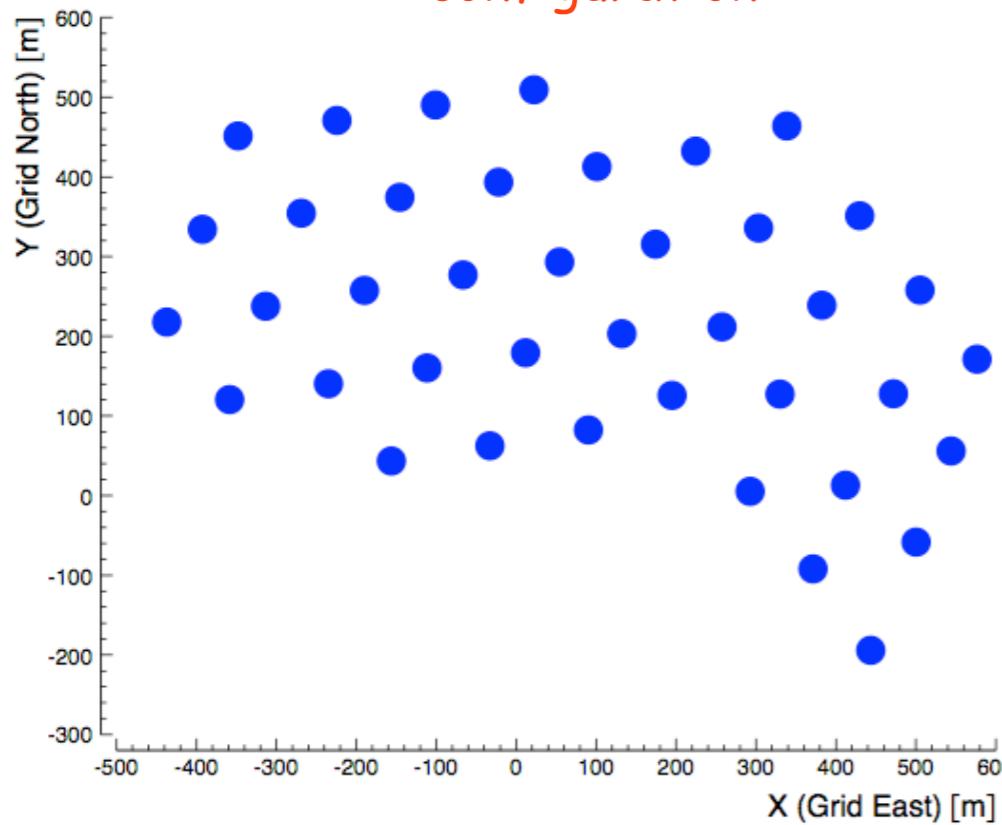
Phys. Rev. D83 (2011) 012001

muon-tracks

Measurement of the atmospheric neutrino energy spectrum from 100 GeV to 400 TeV with IceCube

R. Abbasi,²⁸ Y. Abdou,²² T. Abu-Zayyad,³³ J. Adams,¹⁶ J. A. Aguilar,²⁸ M. Ahlers,³² K. Andeen,²⁸ J. Auffenberg,³⁹ X. Bai,³¹ M. Baker,²⁸ S. W. Barwick,²⁴ R. Bay,⁷ J. L. Bazo Alba,⁴⁰ K. Beattie,⁸ J. J. Beatty,^{18, 19} S. Bechet,¹³ J. K. Becker,¹⁰ K.-H. Becker,³⁹ M. L. Benabderrahmane,⁴⁰ S. BenZvi,²⁸ J. Berdermann,⁴⁰ P. Berghaus,²⁸ D. Berley,¹⁷ E. Bernardini,⁴⁰ D. Bertrand,¹³ D. Z. Besson,²⁶ M. Bissok,¹ E. Blaufuss,¹⁷ J. Blumenthal,¹ D. J. Boersma,¹ C. Bohm,³⁴ D. Bose,¹⁴ S. Böser,¹¹ O. Botner,³⁷ J. Braun,²⁸ S. Buitink,⁸ M. Carson,²² D. Chirkin,²⁸ B. Christy,¹⁷ J. Clem,³¹ F. Clevermann,²⁰ S. Cohen,²⁵ C. Colnard,²³ D. F. Cowen,^{36, 35} M. V. D'Agostino,⁷ M. D. Dwyer,³⁴ J. G. Dunford,¹⁸ G. D. Glusman,¹⁴ T. D. Hall,²² S. S. H. Hansen,²⁵ O. D. Harris,¹⁴ F. D. Hartman,²² P. D. Heintzelman,²⁸

Overhead view of IceCube 40 string configuration



Measuring the atmospheric "background"

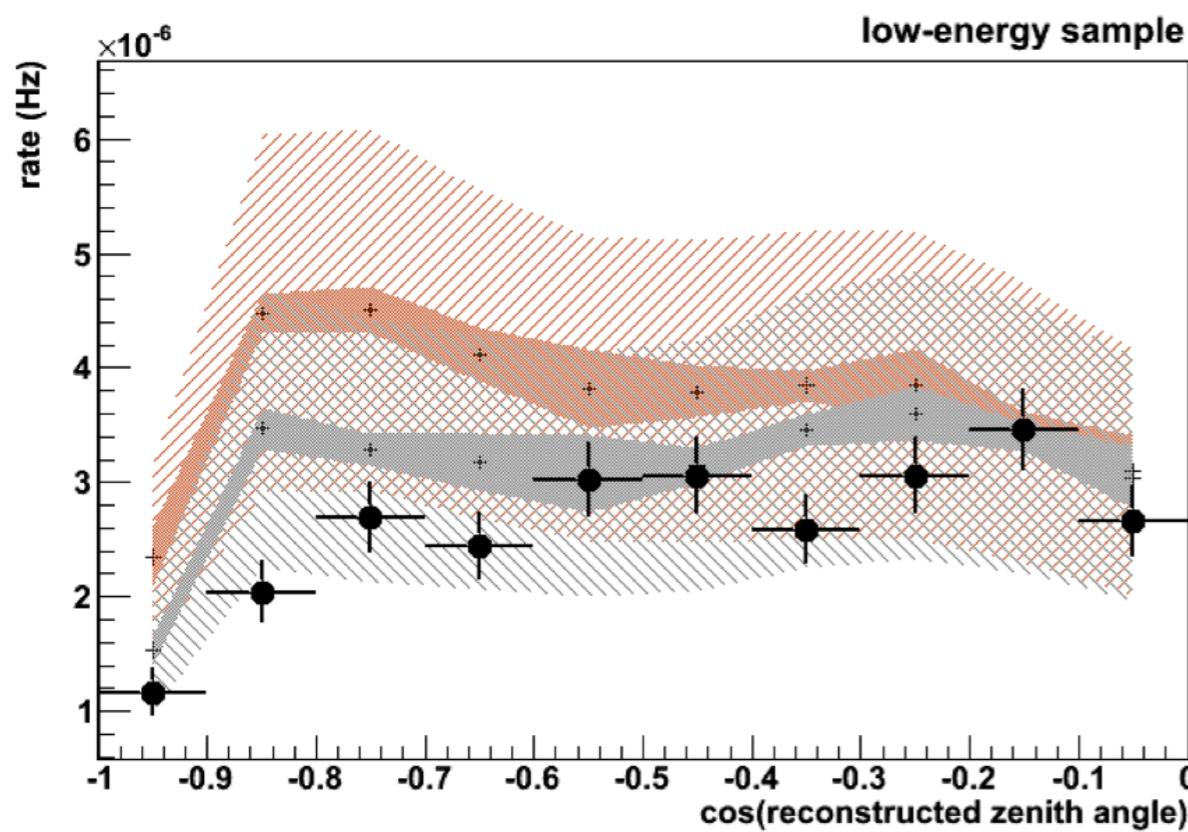
muon-tracks

Phys. Rev. Lett. 111 (2013)

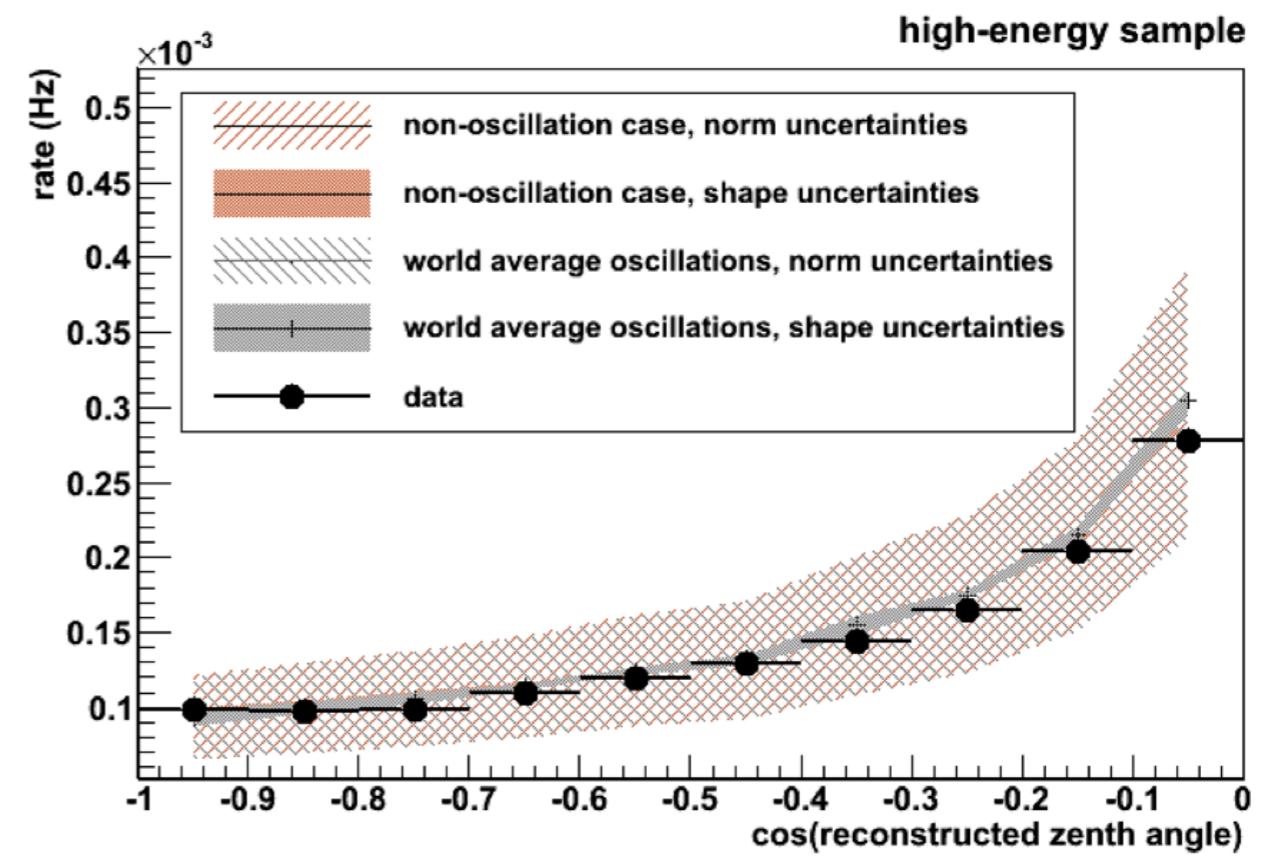
Measurement of Atmospheric Neutrino Oscillations with IceCube

M. G. Aartsen,² R. Abbasi,²⁷ Y. Abdou,²² M. Ackermann,⁴¹ J. Adams,¹⁵ J. A. Aguilar,²¹ M. Ahlers,²⁷ D. Altmann,⁹ J. Auffenberg,²⁷ X. Bai,^{31,*} M. Baker,²⁷ S. W. Barwick,²³ V. Baum,²⁸ R. Bay,⁷ J. J. Beatty,^{17,18} S. Bechet,¹² J. Becker Tjus,¹⁰ K.-H. Becker,⁴⁰ M. Bell,³⁸ M. L. Benabderrahmane,⁴¹ S. BenZvi,²⁷ J. Berdermann,⁴¹ P. Berghaus,⁴¹ D. Berley,¹⁶ E. Bernardini,⁴¹ A. Bernhard,³⁰ D. Bertrand,¹² D. Z. Besson,²⁵ G. Binder,^{8,7} D. Bindig,⁴⁰ M. Bissok,¹ E. Blaufuss,¹⁶ J. Blumenthal,¹ D. J. Boersma,³⁹ S. Bohaiichuk,²⁰ C. Bohm,³⁴ D. Bose,¹³

20 GeV - 100 GeV



100 GeV - 10 TeV



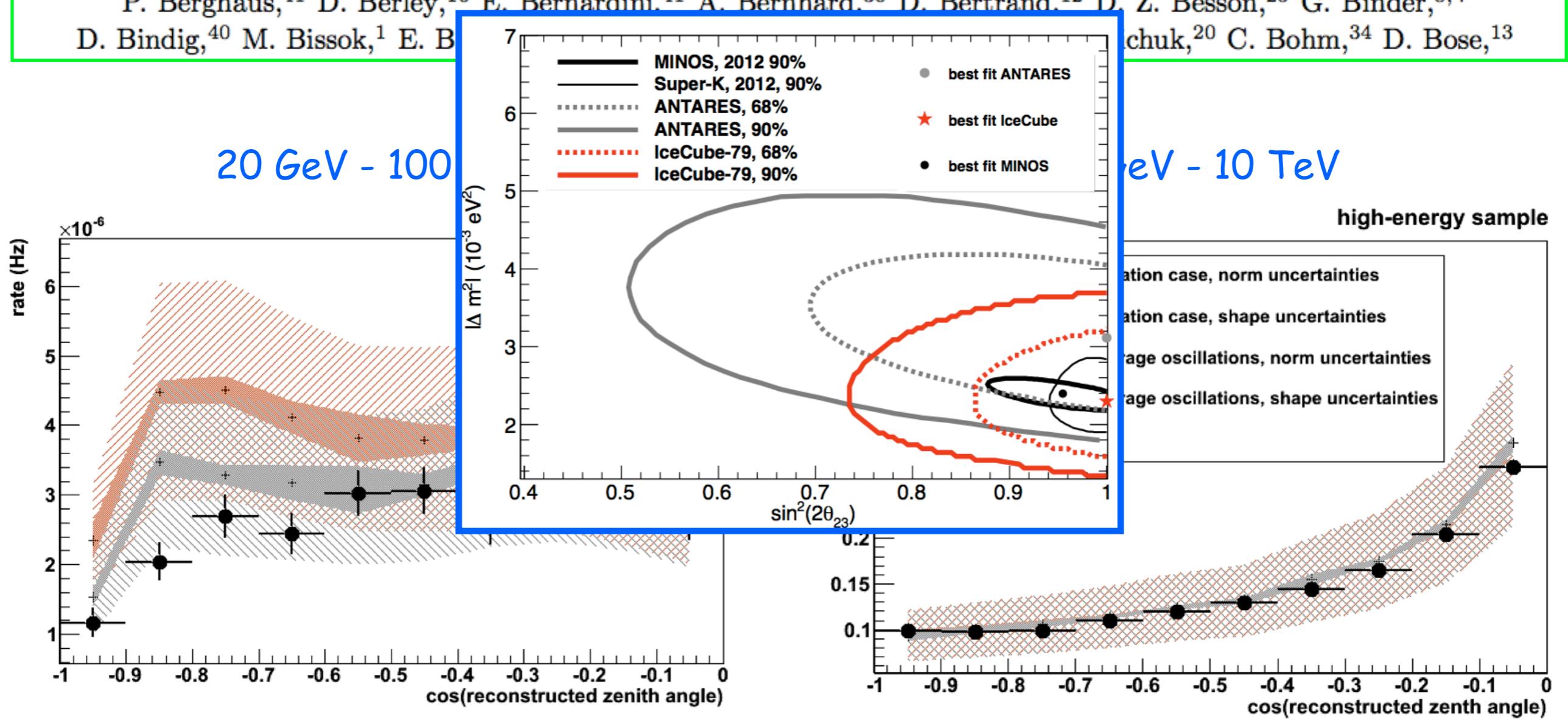
Measuring the atmospheric "background"

muon-tracks

Phys. Rev. Lett. 111 (2013)

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Measuring the atmospheric "background"

muon-tracks

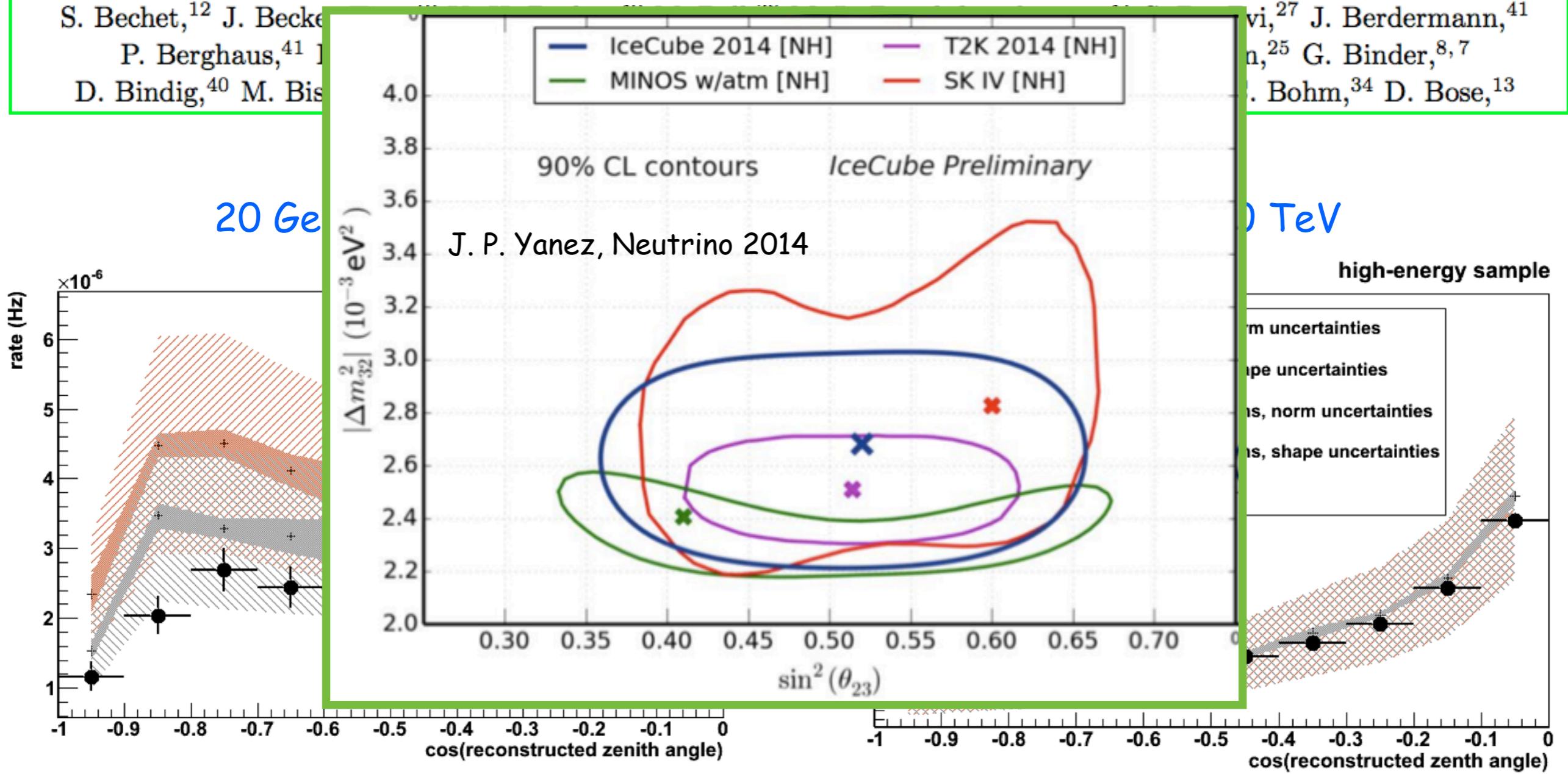
Phys. Rev. Lett. 111 (2013)

Measurement of Atmospheric Neutrino Oscillations with IceCube

M. G. Aartsen
D. Altmann,⁹ J. A.
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,²¹ M. Ahlers,²⁷
,⁷ J. J. Beatty,^{17,18}
vi,²⁷ J. Berdermann,⁴¹
n,²⁵ G. Binder,^{8,7}
. Bohm,³⁴ D. Bose,¹³

3 years of IC-86 , 7-56 GeV



Measuring the atmospheric "background"

cascades

Phys. Rev. Lett. 110 (2013)

PRL 110, 151105 (2013)

PHYSICAL REVIEW LETTERS

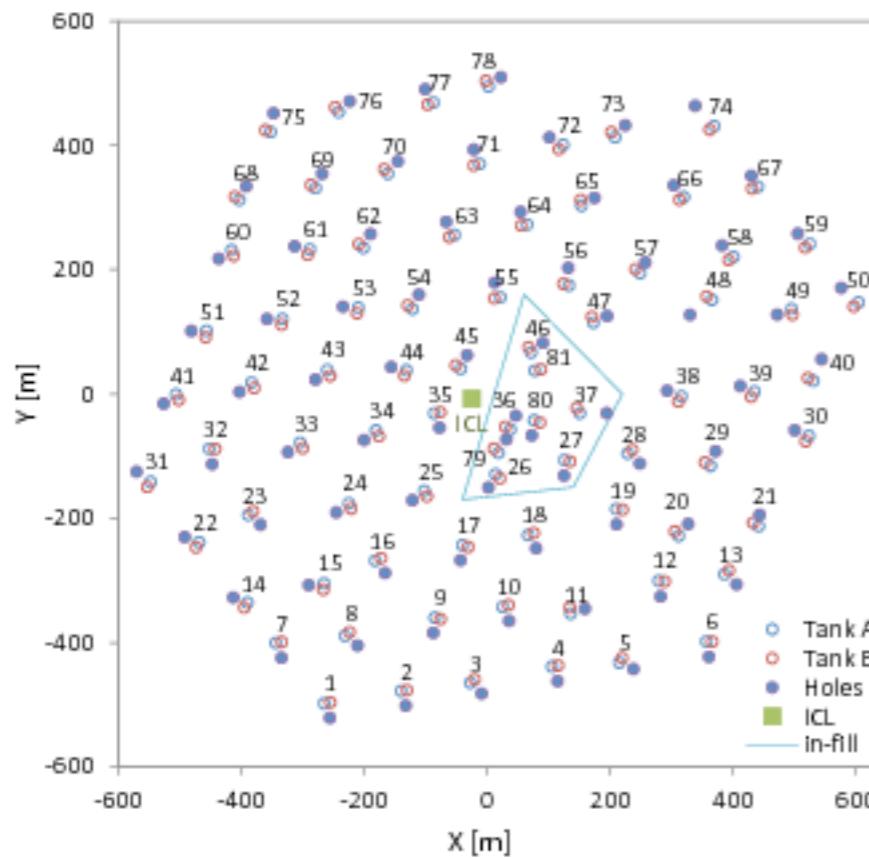
week ending
12 APRIL 2013



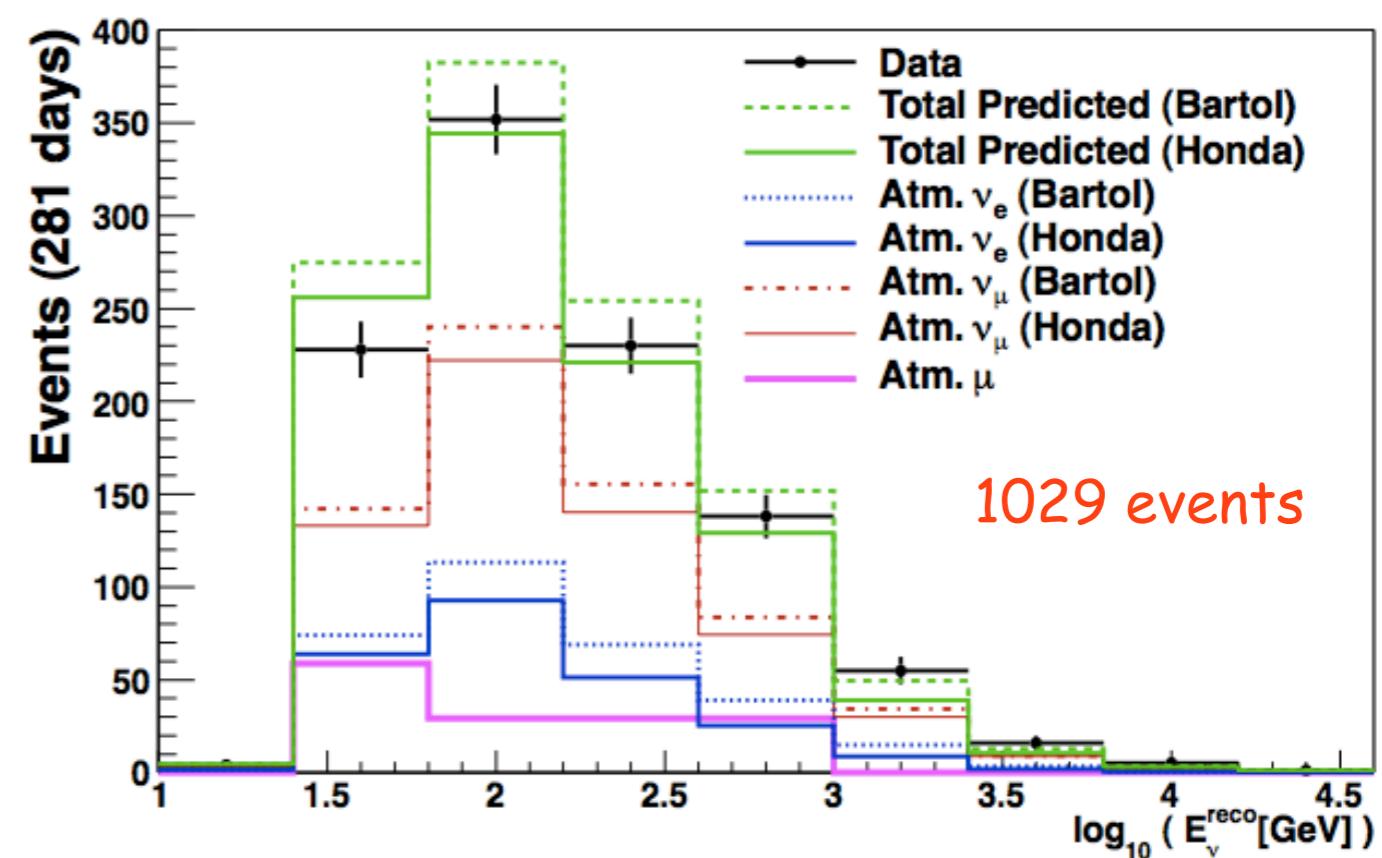
Measurement of the Atmospheric ν_e Flux in IceCube

M. G. Aartsen,² R. Abbasi,²⁷ Y. Abdou,²² M. Ackermann,⁴¹ J. Adams,¹⁵ J. A. Aguilar,²¹ M. Ahlers,²⁷ D. Altmann,⁹ J. Auffenberg,²⁷ X. Bai,^{31,*} M. Baker,²⁷ S. W. Barwick,²³ V. Baum,²⁸ R. Bay,⁷ K. Beattie,⁸ J. J. Beatty,^{17,18} S. Bechet,¹² J. Becker Tjus,¹⁰ K.-H. Becker,⁴⁰ M. Bell,³⁸ M. L. Benabderrahmane,⁴¹ S. BenZvi,²⁷ J. Berdermann,⁴¹ P. Berghaus,⁴¹ D. Berley,¹⁶ E. Bernardini,⁴¹ A. Bernhard,³⁰ D. Bertrand,¹² D. Z. Besson,²⁵ D. Bindig,⁴⁰ M. Bissok,¹ E. Blaufuss,¹⁶ J. Blumenthal,¹ D. J. Boersma,^{39,1} S. Bohaičuk,²⁰ C. Bohm,³⁴ D. Bose,¹³ S. Böser,¹¹ O. Botner,³⁹ L. Brayeur,¹³

IceCube-79 (including DeepCore)



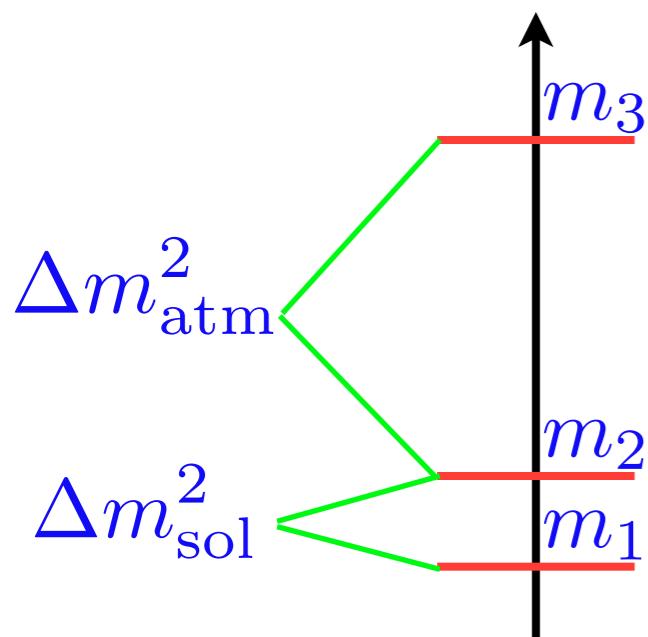
80 GeV - 6 TeV



Outline

- ✓ Constraining sterile neutrinos with the IC-40 data
- ✓ Prospect of IceCube sensitivity to sterile neutrinos
- ✓ Other "New Physics" searches
- ✓ Conclusions

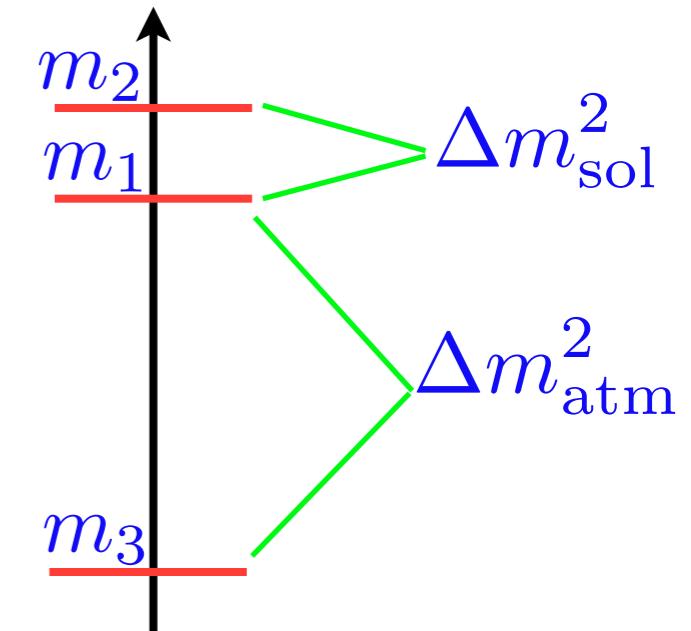
Standard picture of neutrino sector



Normal

$$\nu_\alpha = \sum_{i=1}^3 U_{\alpha i} \nu_i$$

$$\alpha = e, \mu, \tau$$



Inverted

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$U_{\text{PMNS}} = R^{23}(\theta_{23}) I_\delta R^{13}(\theta_{13}) I_{-\delta} R^{12}(\theta_{12})$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re} [U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{kj}^2 L}{4E} \right) + 2 \sum_{k>j} \text{Im} [U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*] \sin \left(\frac{\Delta m_{kj}^2 L}{2E} \right)$$

Standard picture of neutrino sector

NuFIT 1.1 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \rightarrow 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \rightarrow 36.01$	$34.03^{+0.81}_{-0.77}$	$31.78 \rightarrow 36.56$
$\sin^2 \theta_{23}$	$0.437^{+0.061}_{-0.031}$	$0.357 \rightarrow 0.654$	$0.436^{+0.047}_{-0.032}$	$0.356 \rightarrow 0.653$
$\theta_{23}/^\circ$	$41.4^{+3.5}_{-1.8}$	$36.7 \rightarrow 54.0$	$41.3^{+2.7}_{-1.8}$	$36.6 \rightarrow 53.9$
$\sin^2 \theta_{13}$	$0.0231^{+0.0023}_{-0.0022}$	$0.0161 \rightarrow 0.0299$	$0.0252^{+0.0022}_{-0.0023}$	$0.0181 \rightarrow 0.0320$
$\theta_{13}/^\circ$	$8.75^{+0.42}_{-0.44}$	$7.29 \rightarrow 9.96$	$9.13^{+0.40}_{-0.42}$	$7.73 \rightarrow 10.31$
$\delta_{\text{CP}}/^\circ$	341^{+58}_{-46}	$0 \rightarrow 360$	345^{+77}_{-46}	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \rightarrow 8.05$	$7.50^{+0.19}_{-0.17}$	$7.03 \rightarrow 8.08$
$\frac{\Delta m_{31}^2}{10^{-3} \text{ eV}^2}$ (N)	$+2.421^{+0.022}_{-0.023}$	$+2.248 \rightarrow +2.612$	$+2.429^{+0.029}_{-0.027}$	$+2.256 \rightarrow +2.635$
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$ (I)	$-2.410^{+0.062}_{-0.063}$	$-2.603 \rightarrow -2.226$	$-2.422^{+0.061}_{-0.063}$	$-2.618 \rightarrow -2.239$

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www.nu-fit.org

Standard picture of neutrino sector

NuFIT 1.1 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \rightarrow 0.355$
$\theta_{12}/^\circ$	$77^{+0.77}_{-0.77}$	$71 \rightarrow 81$	$77^{+0.81}_{-0.79}$	$71 \rightarrow 85$
$\sin^2 \theta_{23}$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \rightarrow 0.355$
$\theta_{23}/^\circ$	$9^{+0.77}_{-0.77}$	$5 \rightarrow 15$	$9^{+0.81}_{-0.79}$	$5 \rightarrow 16$
$\sin^2 \theta_{13}$	$0.006^{+0.006}_{-0.006}$	$0.001 \rightarrow 0.011$	$0.006^{+0.006}_{-0.006}$	$0.001 \rightarrow 0.011$
δ_{CP}	$-2.422^{+0.061}_{-0.063}$	$-2.603 \rightarrow -2.226$	$+2.429^{+0.029}_{-0.027}$	$+2.248 \rightarrow +2.612$
$\frac{\Delta}{10^{-3} \text{ eV}^2}$	$-2.410^{+0.059}_{-0.063}$	$-2.422^{+0.061}_{-0.063}$	$+2.256 \rightarrow +2.635$	$-2.618 \rightarrow -2.239$
Δm^2	$7.3^{+0.000}_{-0.000}$	$7.3 \rightarrow 7.3$	$7.3^{+0.000}_{-0.000}$	$7.3 \rightarrow 7.3$

3-neutrino framework gives a
consistent interpretation of data
but few anomalies remain (!)
which hint on the presence of
sterile neutrino(s)

Thomas Schwetz talk

10^{-3} eV^2

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www.nu-fit.org

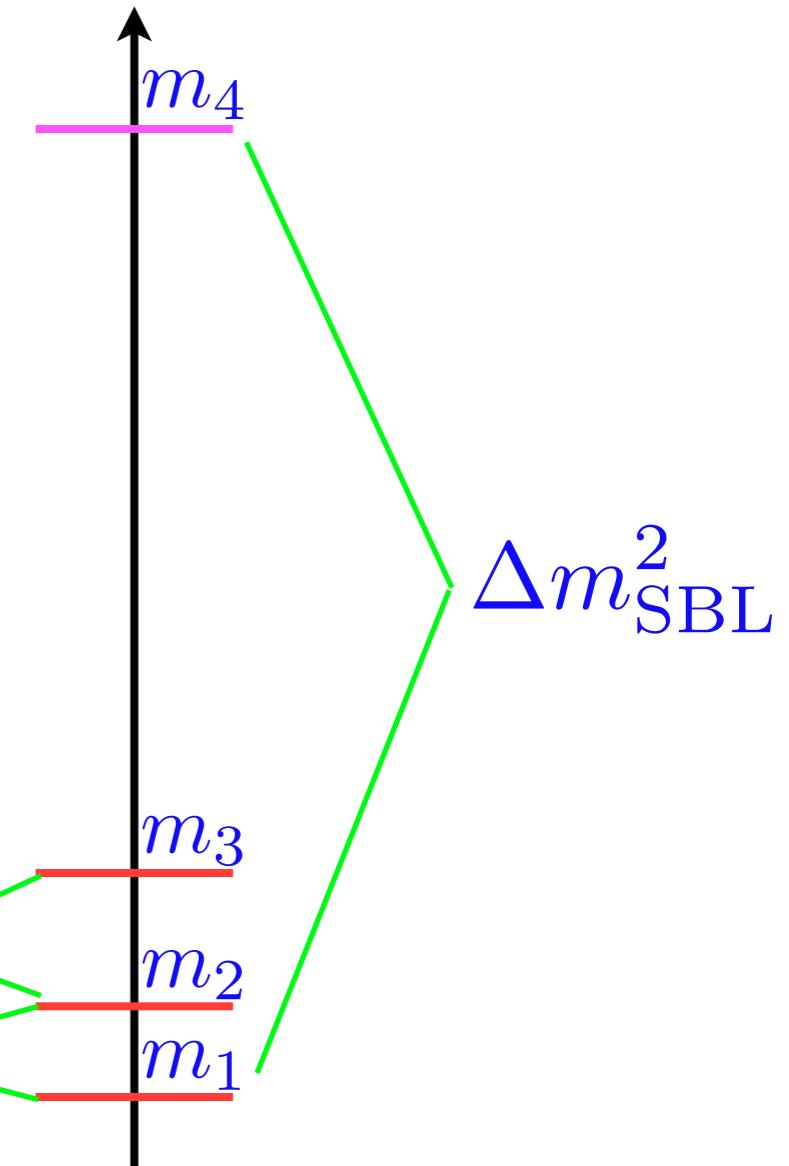
3+1 scheme

Sterile \longleftrightarrow No SM Interaction

$$\nu_\alpha = \sum_{i=1}^4 U_{\alpha i} \nu_i \quad \alpha = e, \mu, \tau, s$$

$$U_4 = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Existence of a sterile neutrino is **NOT** a small perturbation to SM



3+1 scheme

Fogli, Lisi and A. Marrone, Phys. Rev. D 63 (2001); O. L. G. Peres and A. Y. Smirnov, Nucl. Phys. B 599 (2001); Grimus and Schwetz, Eur. Phys. J. C 20 (2001); M. C. Gonzalez-Garcia, M. Maltoni and C. Pena-Garay, Phys. Rev. D 64 (2001); M. Maltoni, T. Schwetz and J. W. F. Valle, Phys. Lett. B 518 (2001); A. Strumia, Phys. Lett. B 539 (2002); G. Karagiorgi, Z. Djurcic, J. M. Conrad, M. H. Shaevitz and M. Sorel, Phys. Rev. D 80 (2009); A. Palazzo, Phys. Rev. D 83 (2011); C. Giunti and M. Laveder, Phys. Rev. D 84 (2011), ...

Existence of sterile neutrinos is **NOT** a small perturbation to SM

- ✓ Existence of sterile neutrinos have far-reaching consequences in neutrino physics, particle physics and DM detection.
- ✓ On neutrino model building side, the discrete symmetry considerations should be modified (TBM, BM, etc...) Barry, Rodejohann and Zhang, JHEP 2011
- ✓ From particle physics point of view, light sterile neutrino should be incorporated in SeeSaw, etc... Zhang, PLB 2012
Blennow and Fernandez-Martinez, PLB 2011
Mohapatra, Nasri and Yu, PRD 2005
- ✓ Existence of sterile neutrinos affect the indirect DM detection in neutrino telescopes A. E. and O. L. G. Peres, JCAP 2012 Arguelles and Kopp, JCAP 2012
- ✓ Existence of sterile neutrinos drastically affect SN neutrino flux (wrong mass hierarchy mimicking) A. E., O. Peres, P. D. Serpico, arXiv:1402.1453
Tamborra, Raffelt, Hudepohl and Janka, JCAP (2012)
Choubey, Harries and Ross, PRD (2007)

Existence of sterile neutrinos is NOT a small perturbation to SM

- ✓ Existence of sterile neutrinos have far-reaching consequences in neutrino physics, particle physics and DM detection. **Lamblin talk**

To name some:
STEREO, Neutrino-4, ICARUS-NESSIE, nUSTORM, Posseidon, DANSS, Prospect, SOLID, Nucifer, Hanaro, BEST, SOX, LENS, SCRAAM, OscSNS, MicroBooNE, IsoDAR, ...

- ✓ Existence of sterile neutrinos affect the muon-DM detection in neutrino telescopes

A. E. and O. L. G. Peres, JCAP 2012

Arguelles and Kopp, JCAP 2012

- ✓ Existence of sterile neutrinos drastically affect SN neutrino flux (wrong mass hierarchy mimicking)

A. E., O. Peres, P. D. Serpico, arXiv:1402.1453

Tamborra, Raffelt, Hudepohl and Janka, JCAP (2012)

Choubey, Harries and Ross, PRD (2007)

A note on parametrization

$$U_4 = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

3 new mixing angles
2 new CP-violating phases

$$U_4 = \underline{R^{34}(\theta_{34}) R_\delta^{24}(\theta_{24}) R_\delta^{14}(\theta_{14})} R^{23}(\theta_{23}) R_\delta^{13}(\theta_{13}) R^{12}(\theta_{12})$$

new mixing parameters

A note on parametrization

$$U_4 = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

3 new mixing angles
2 new CP-violating phases

$$U_4 = R^{34}(\theta_{34})R_\delta^{24}(\theta_{24})R_\delta^{14}(\theta_{14})R^{23}(\theta_{23})R_\delta^{13}(\theta_{13})R^{12}(\theta_{12})$$

new mixing parameters

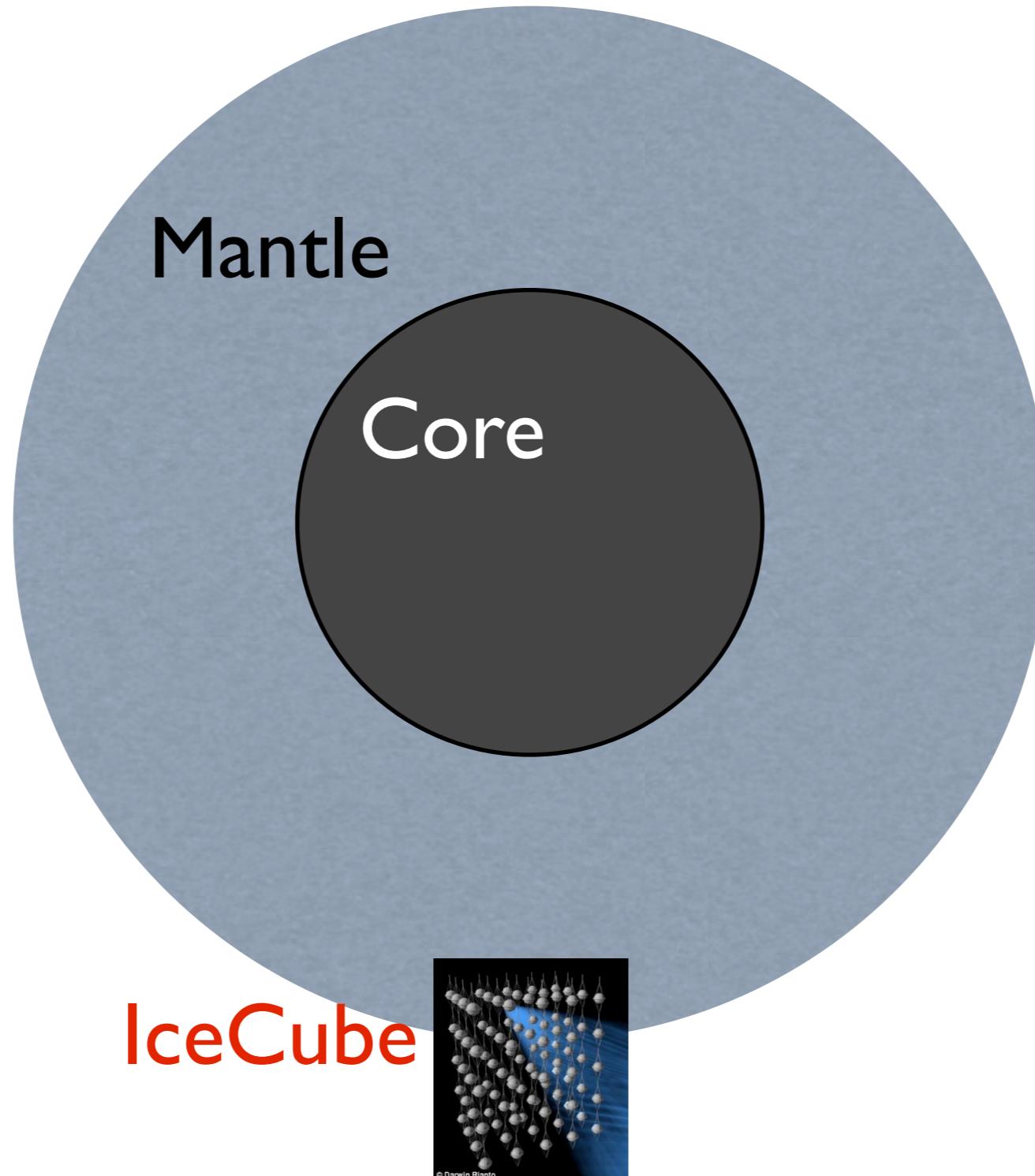
✓ Reactor anomaly $\rightarrow \theta_{14} \neq 0$

Why ? ✓ LSND/MiniBooNE anomaly $\rightarrow \theta_{14} \neq 0 \text{ & } \theta_{24} \neq 0$

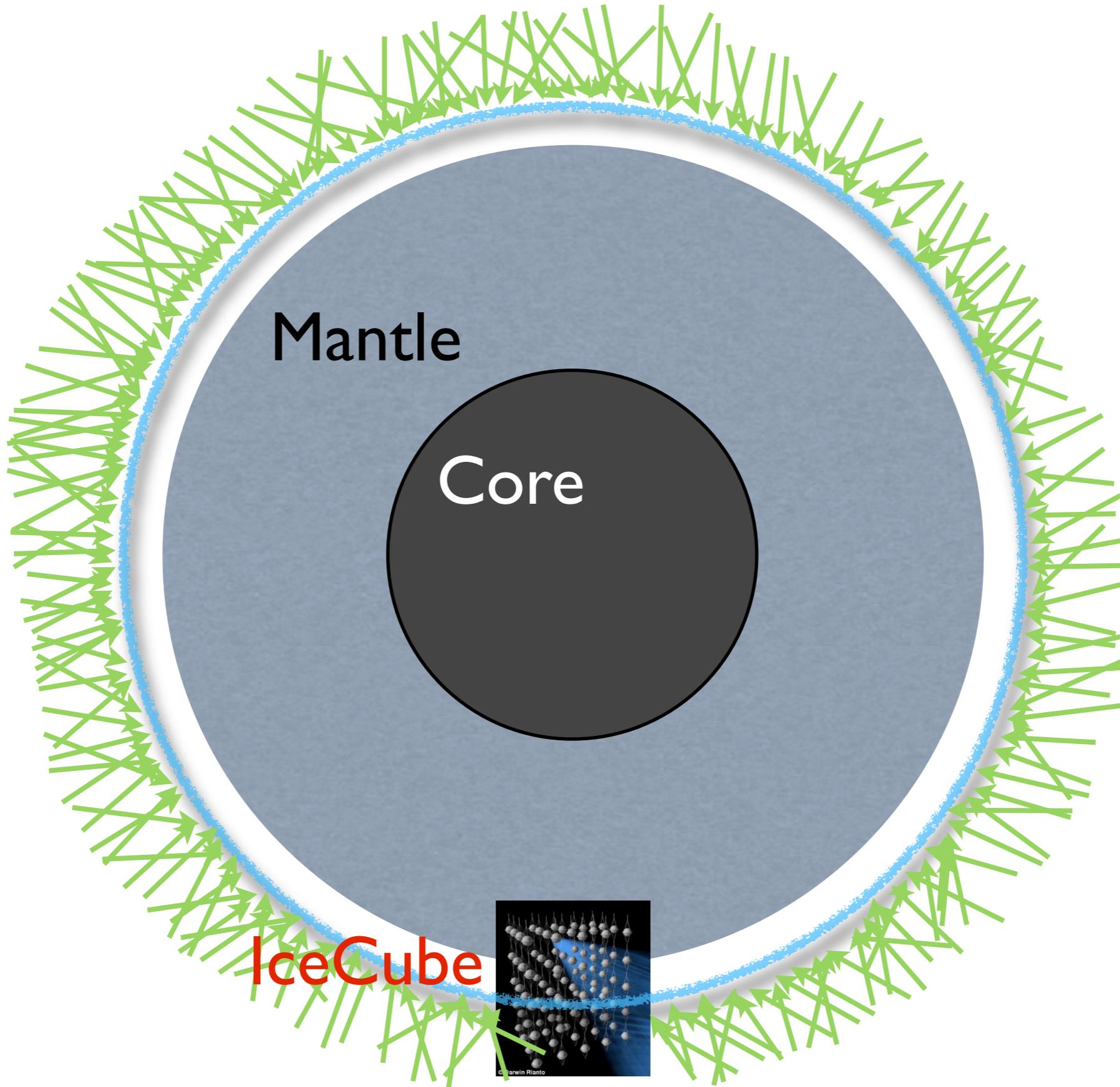
✓ $\nu_T - \nu_s$ mixing $\rightarrow \boxed{\theta_{34} \neq 0}$

weakly constrained
up to now

Impact of sterile neutrinos on atm ν flux



Impact of sterile neutrinos on atm ν flux



Impact of sterile neutrinos on atm ν flux

Liu, Mikheyev and Smirnov, Phys. Lett. (1998)

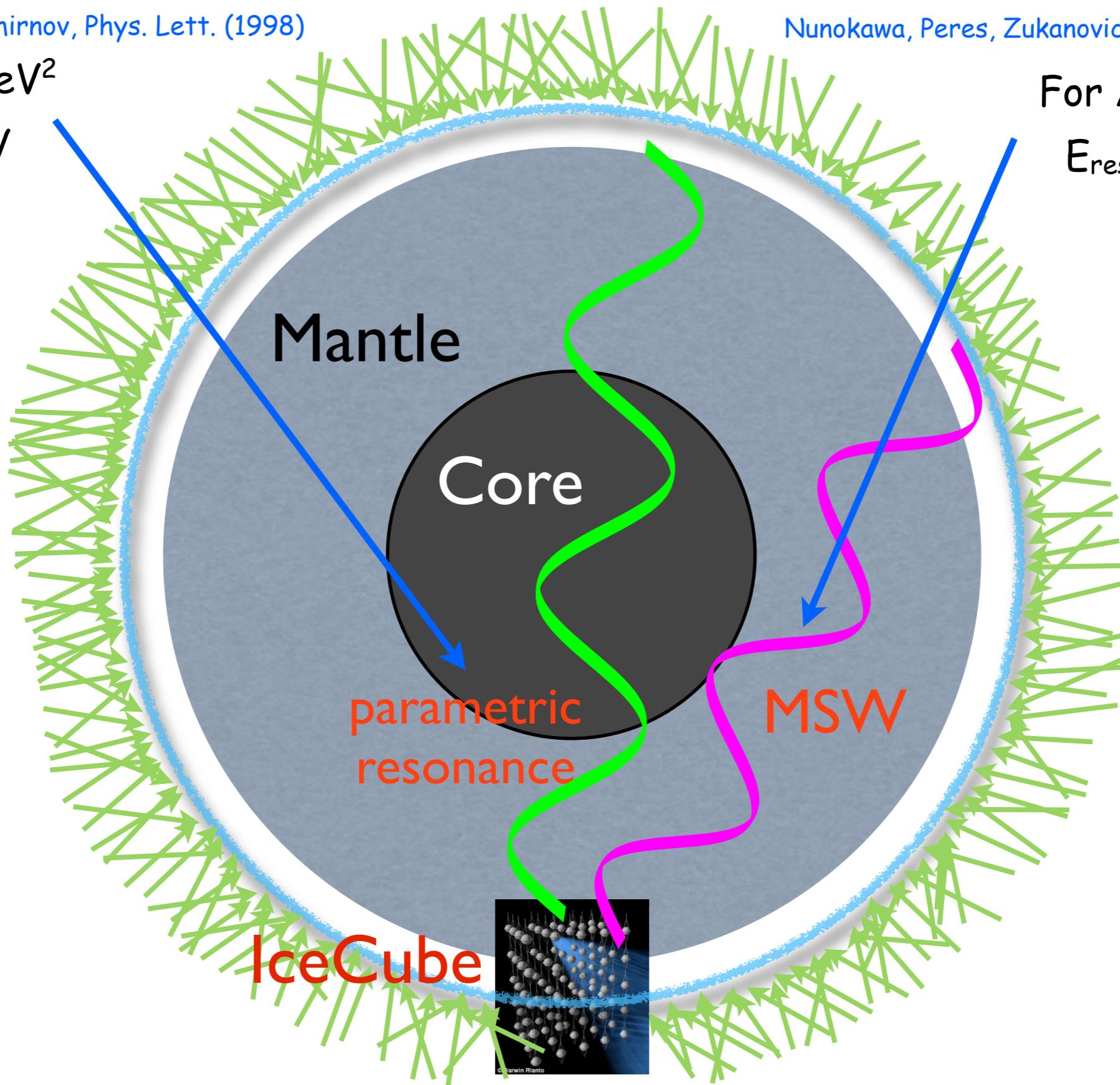
Nunokawa, Peres, Zukovich-Funchal, PLB (2003)

For $\Delta m^2 \sim 1 \text{ eV}^2$

$E_{\text{res}} \sim 2 \text{ TeV}$

For $\Delta m^2 \sim 1 \text{ eV}^2$

$E_{\text{res}} \sim 4 \text{ TeV}$



Impact of sterile neutrinos on atm ν flux

Liu, Mikheyev and Smirnov, Phys. Lett. (1998)

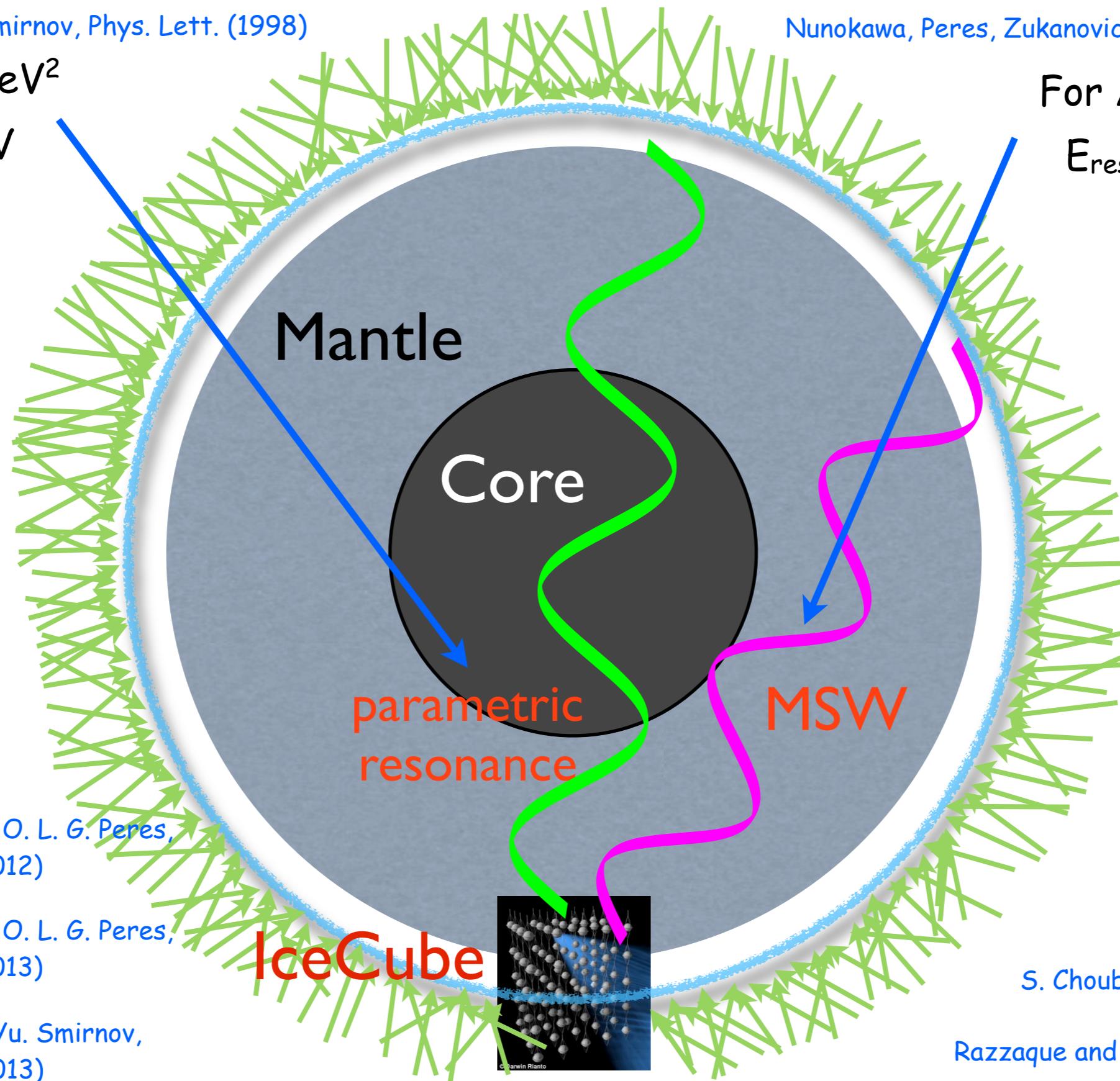
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For $\Delta m^2 \sim 1 \text{ eV}^2$

$E_{\text{res}} \sim 4 \text{ TeV}$



A. E., F. Halzen and O. L. G. Peres,
JCAP (2012)

A. E., F. Halzen and O. L. G. Peres,
JCAP (2013)

A. E. and Alexei Yu. Smirnov,
JHEP (2013)

S. Choubey, JHEP (2007)

Razzaque and Smirnov, JHEP (2011)

Impact of sterile neutrinos on atm ν flux

For $\Delta m^2 > 0$

$$\theta_{14} \neq 0 \longrightarrow \nu_e \rightarrow \nu_s$$

$$\theta_{24} \neq 0 \longrightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_s$$

$$\theta_{34} \neq 0 \longrightarrow \bar{\nu}_\tau \rightarrow \bar{\nu}_s$$

$$\theta_{14} \neq 0 \text{ and } \theta_{24} \neq 0 \longrightarrow \nu_e \rightarrow \nu_s \text{ and } \bar{\nu}_\mu \rightarrow \bar{\nu}_s$$

$$\theta_{14} \neq 0 \text{ and } \theta_{34} \neq 0 \longrightarrow \nu_e \rightarrow \nu_s \text{ and } \bar{\nu}_\tau \rightarrow \bar{\nu}_s$$

$$\theta_{24} \neq 0 \text{ and } \theta_{34} \neq 0 \longrightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_s \text{ and } \bar{\nu}_\tau \rightarrow \bar{\nu}_s$$

and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$

Impact of sterile neutrinos on atm ν flux

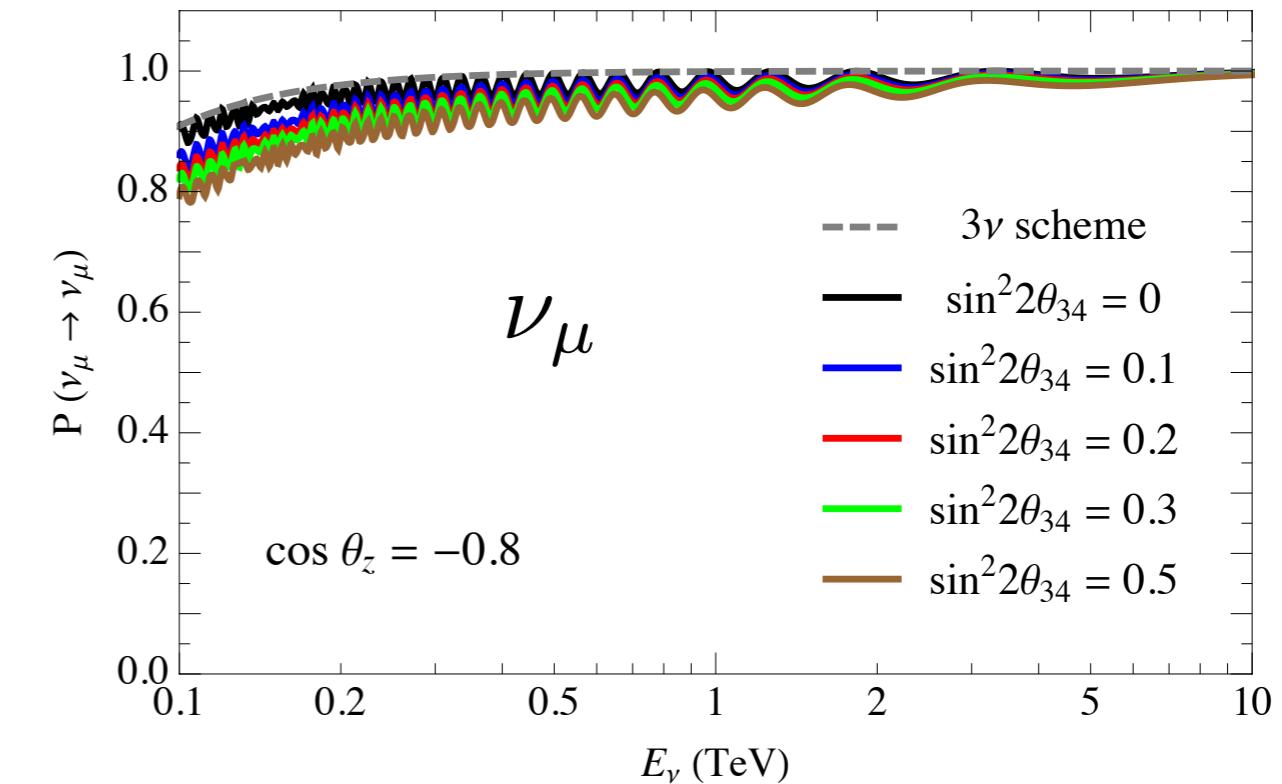
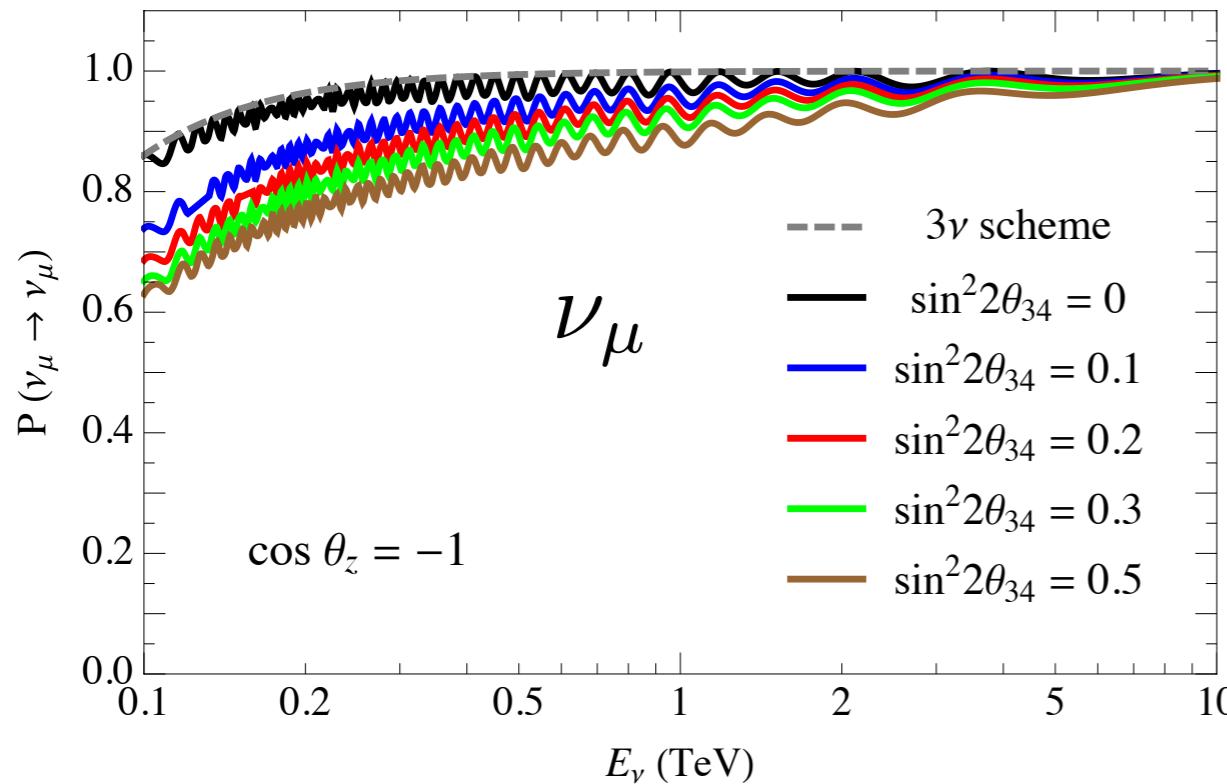
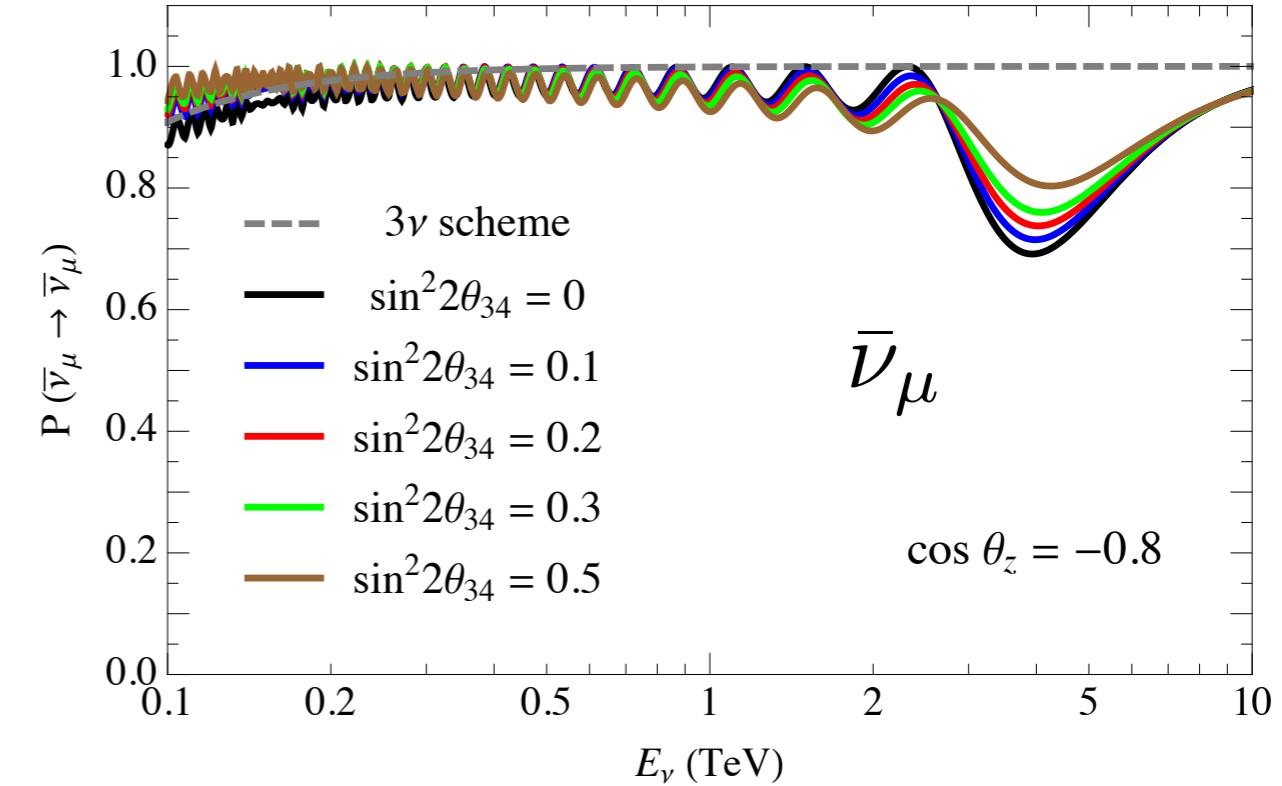
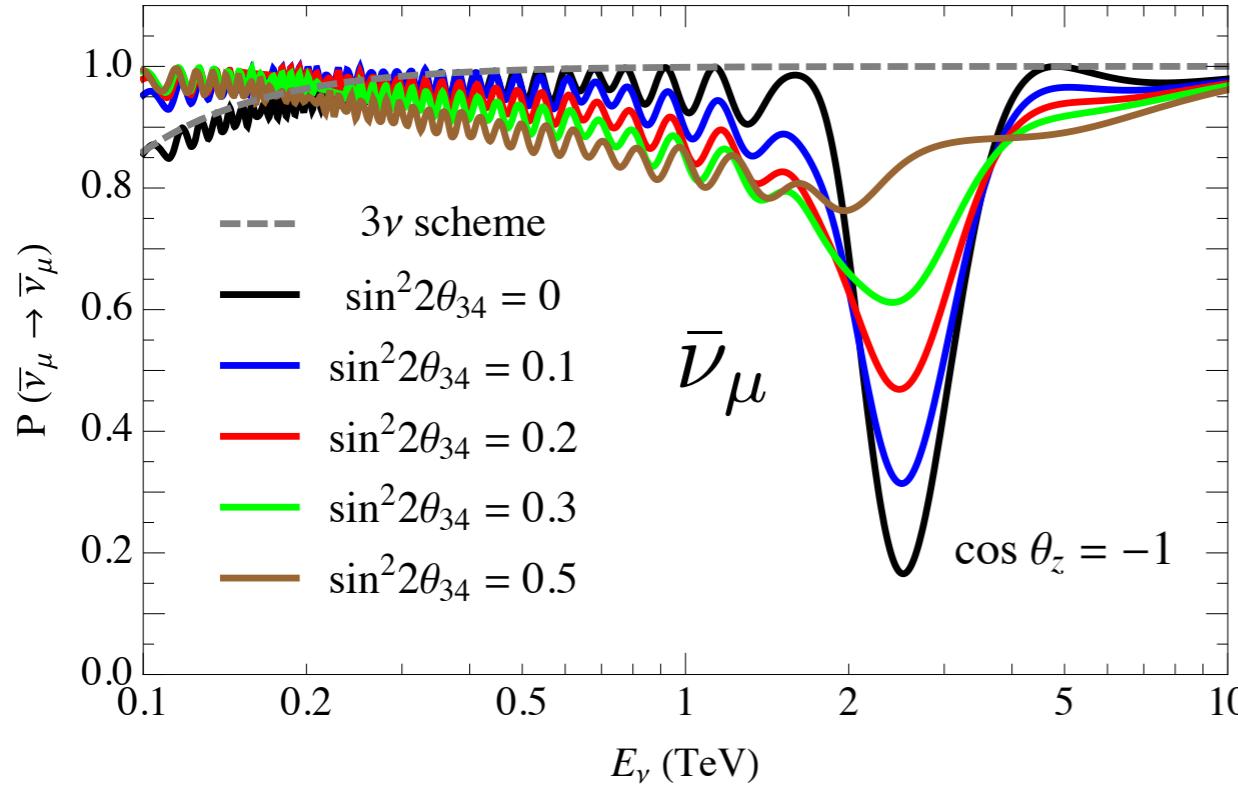
A. E. and Alexei Yu. Smirnov,
JHEP 1312, 014 (2013)

core crossing

$$\Delta m_{41}^2 = 1 \text{ eV}^2$$

$$\sin^2 2\theta_{24} = 0.04$$

mantle crossing



Impact of sterile neutrinos on atm $\bar{\nu}$ flux

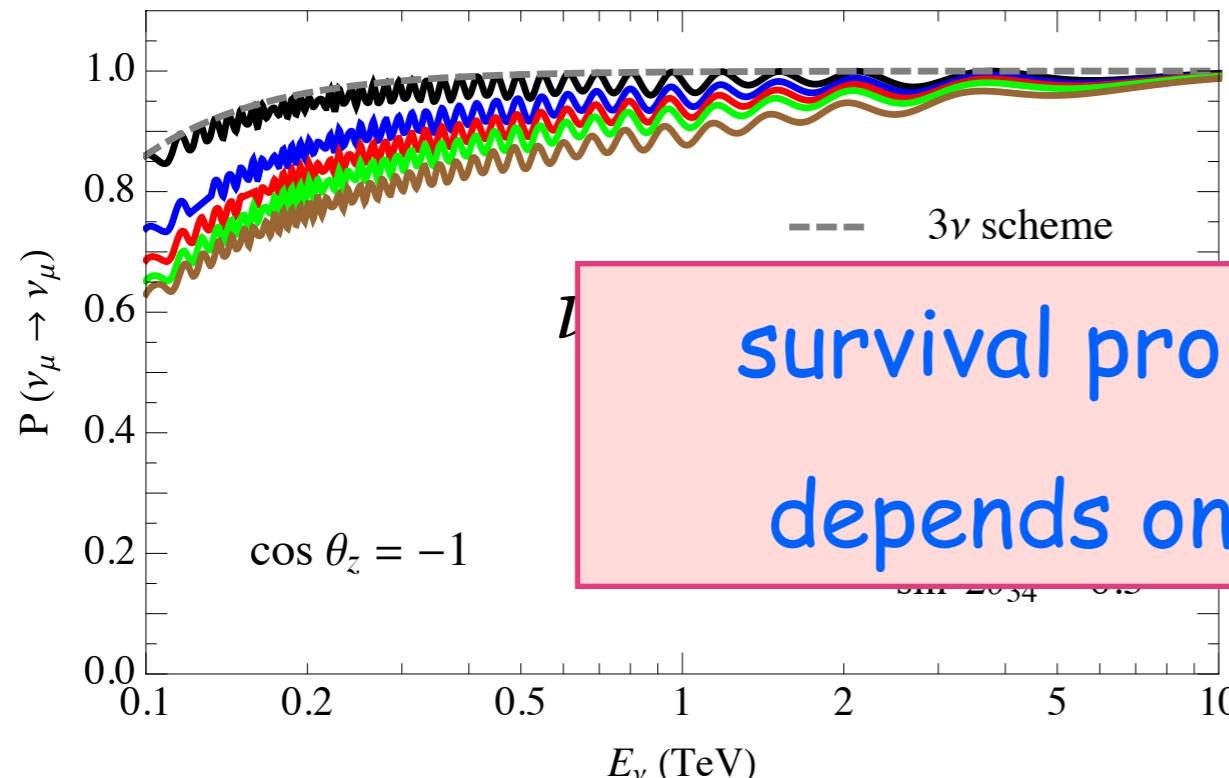
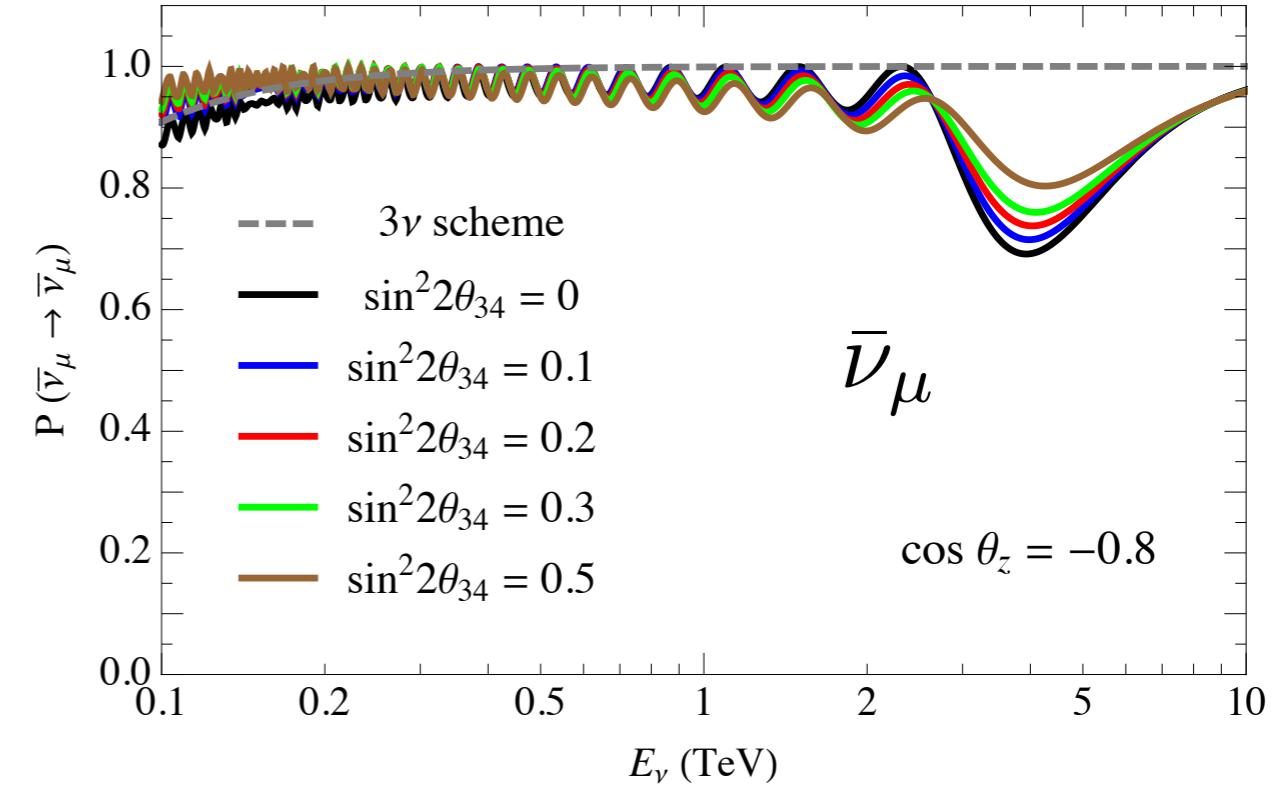
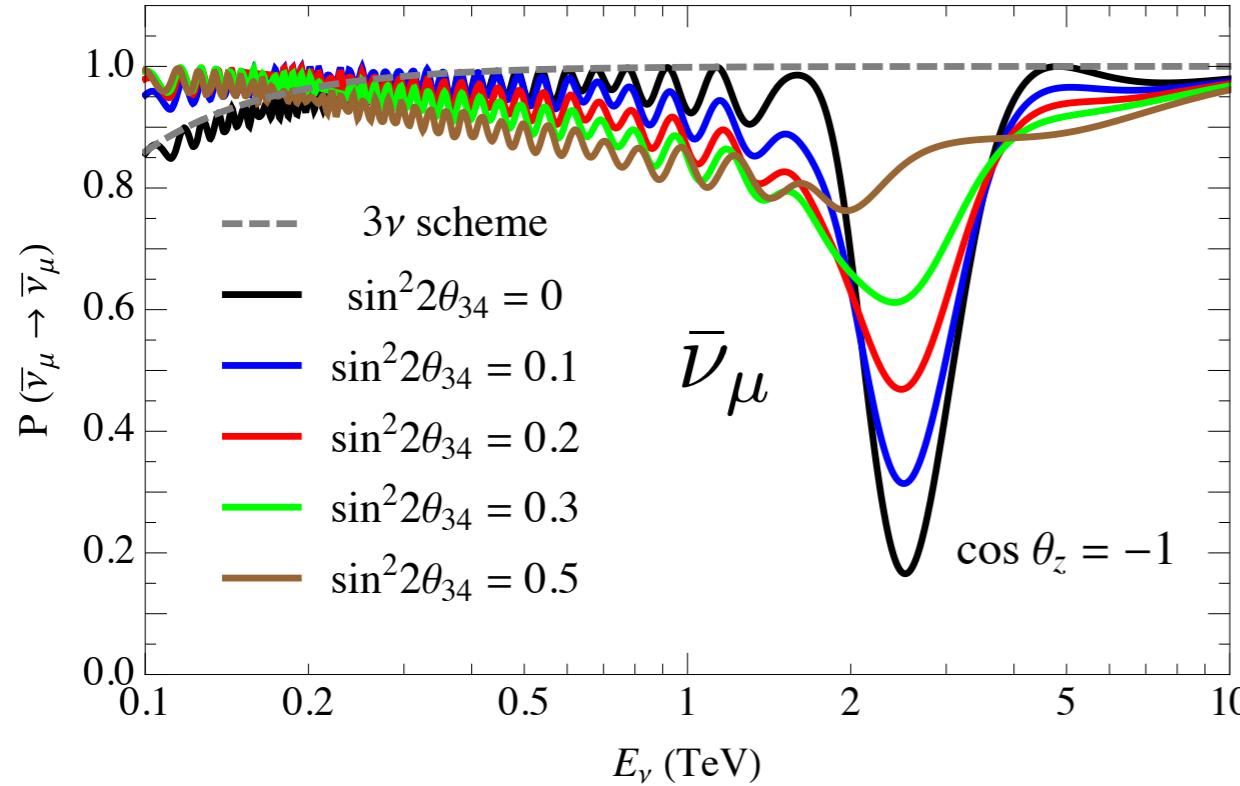
A. E. and Alexei Yu. Smirnov,
JHEP 1312, 014 (2013)

core crossing

$$\Delta m_{41}^2 = 1 \text{ eV}^2$$

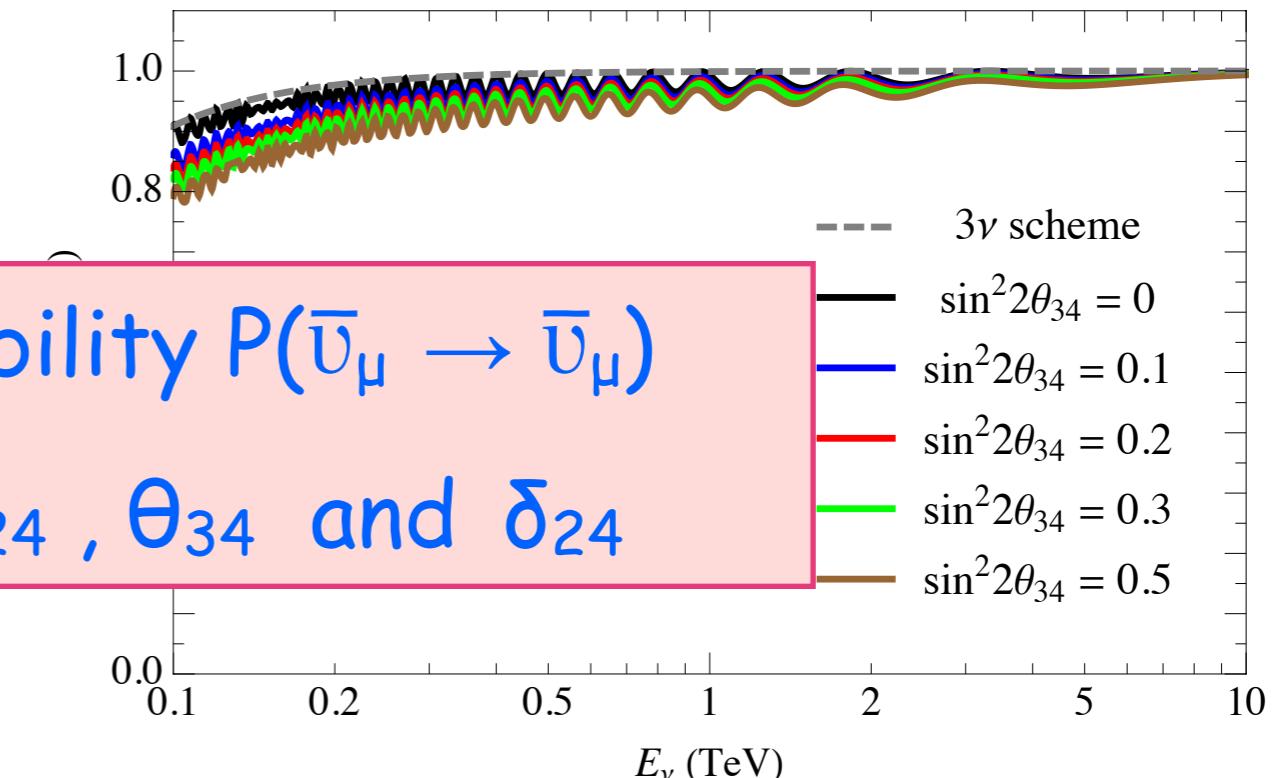
$$\sin^2 2\theta_{24} = 0.04$$

mantle crossing



survival probability $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

depends on Θ_{24} , Θ_{34} and δ_{24}



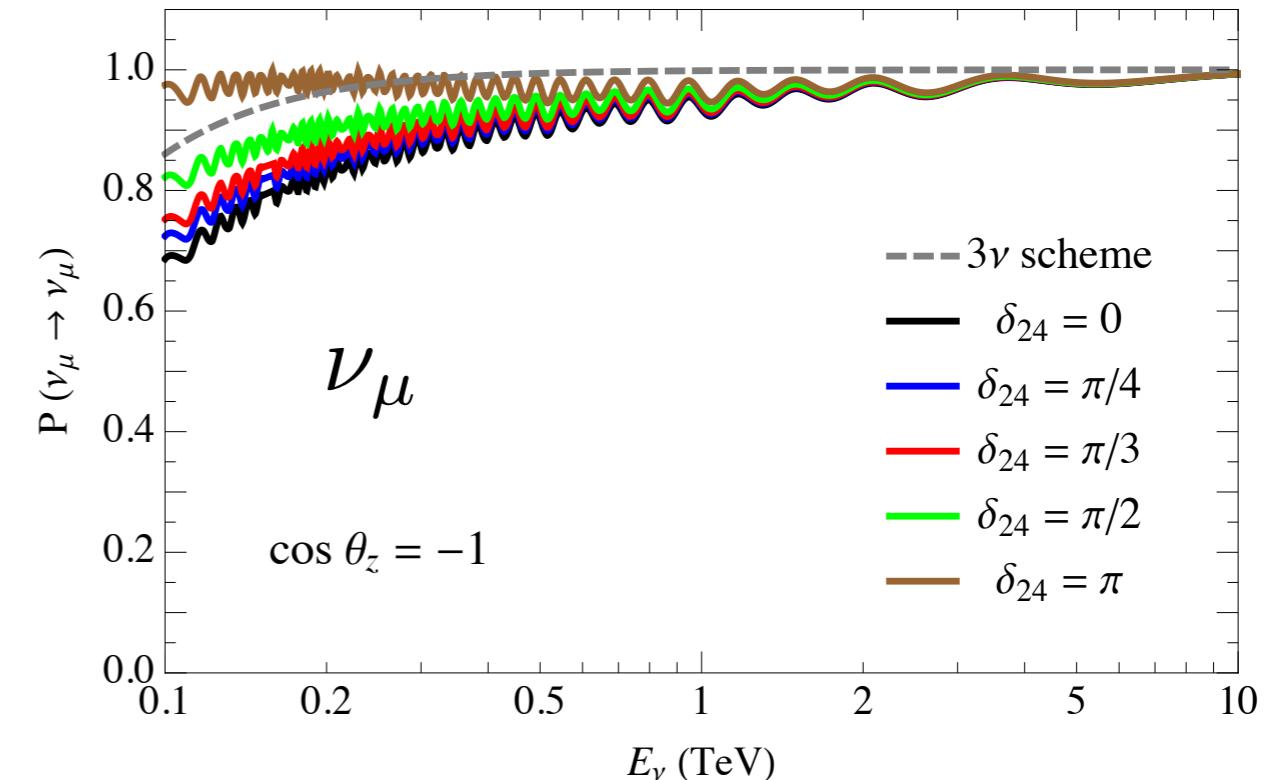
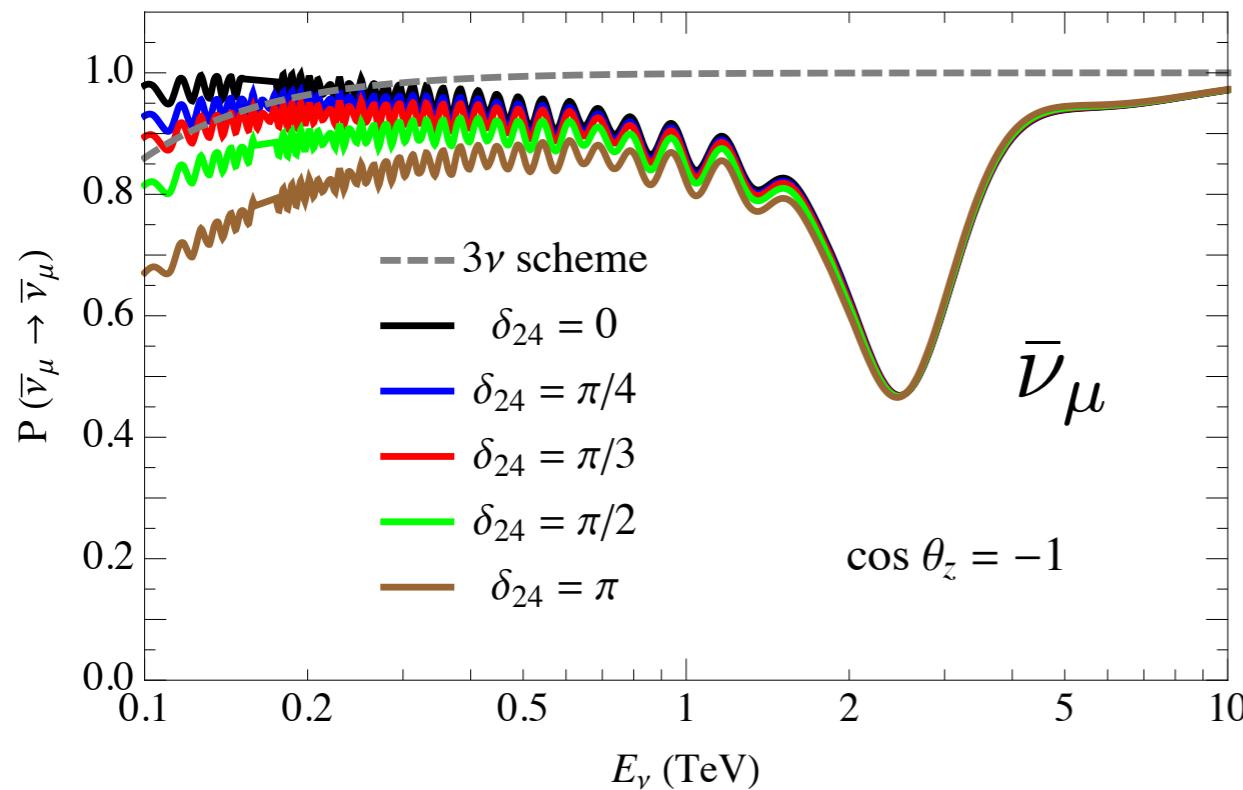
Impact of sterile neutrinos on atm ν flux

A. E. and Alexei Yu. Smirnov,
JHEP 1312, 014 (2013)

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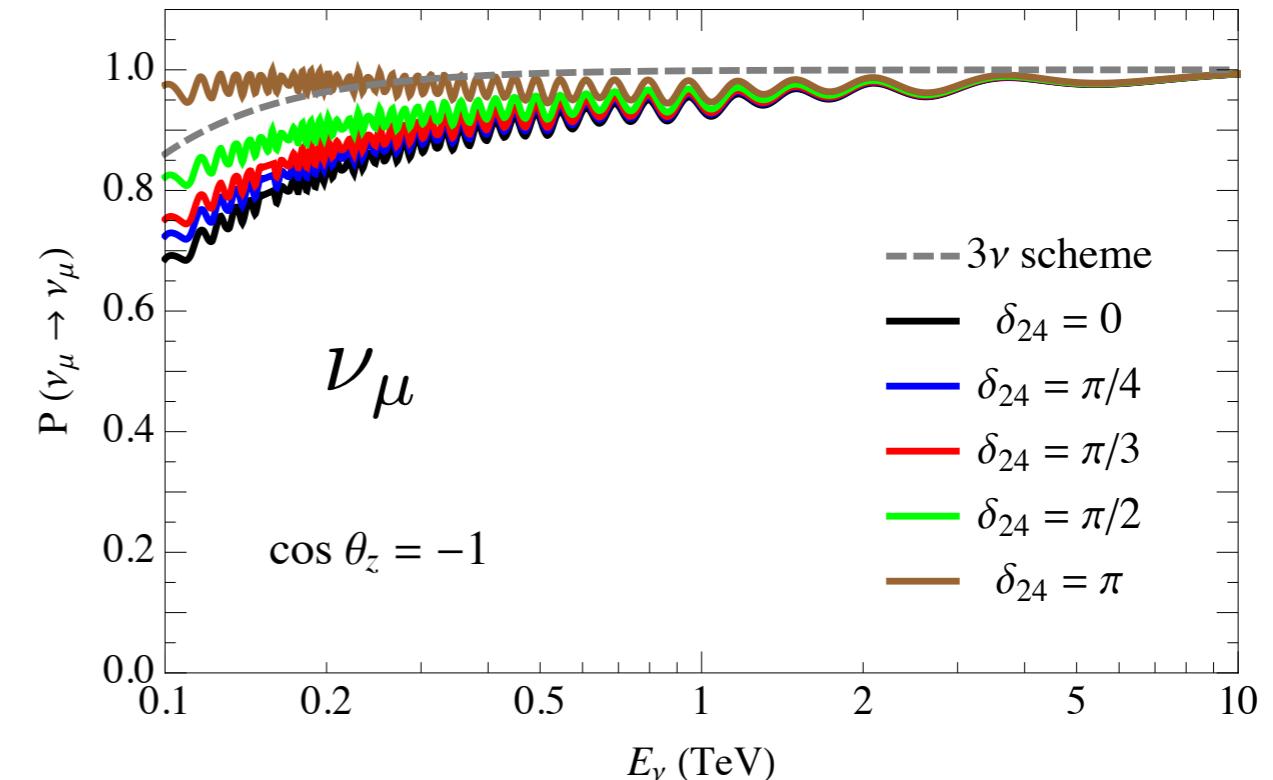
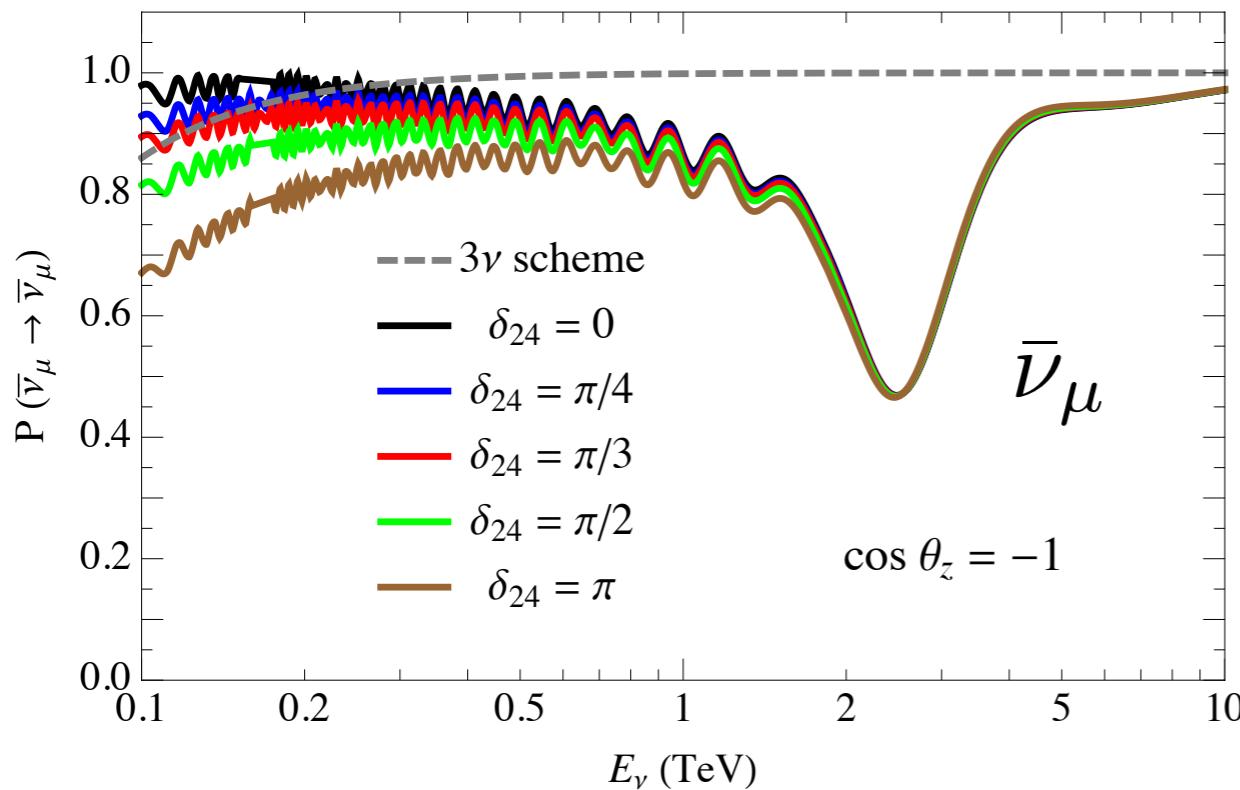
Impact of sterile neutrinos on atm ν flux

A. E. and Alexei Yu. Smirnov,
JHEP 1312, 014 (2013)

$$\Delta m_{41}^2 = 1 \text{ eV}^2$$

$$\sin^2 2\theta_{24} = 0.04$$

$$\sin^2 2\theta_{34} = 0.2$$



The weakest limit on sterile
neutrinos is for $\Theta_{34} = \delta_{24} = 0$

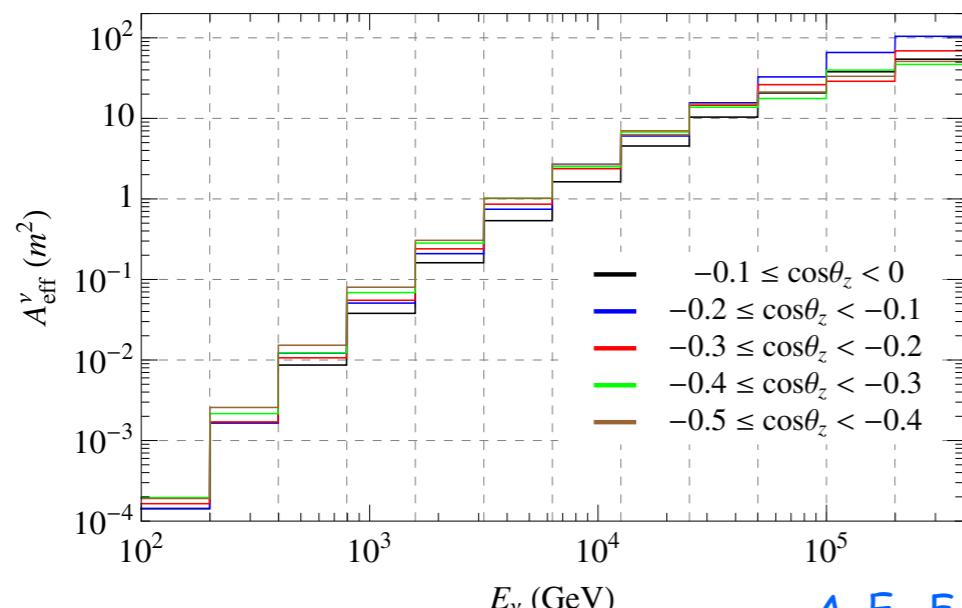
details in A. E. and Alexei Yu. Smirnov, JHEP 1312 (2013)

Constraining sterile neutrino with IC-40 data

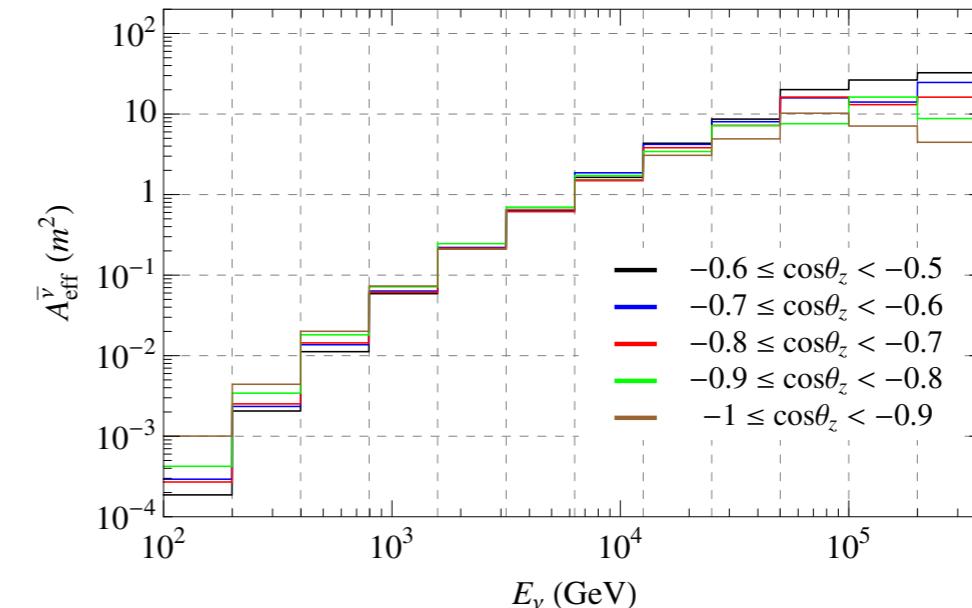
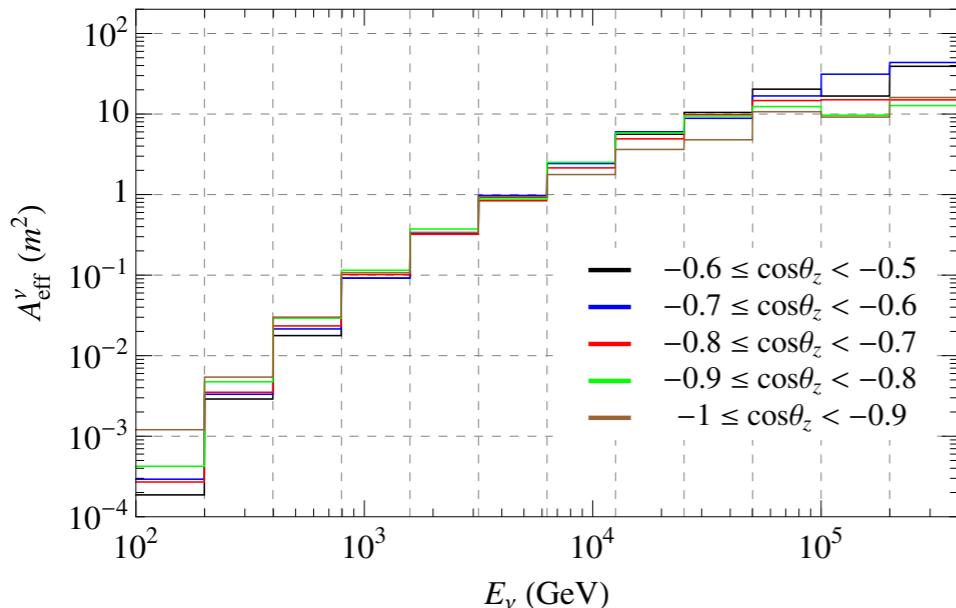
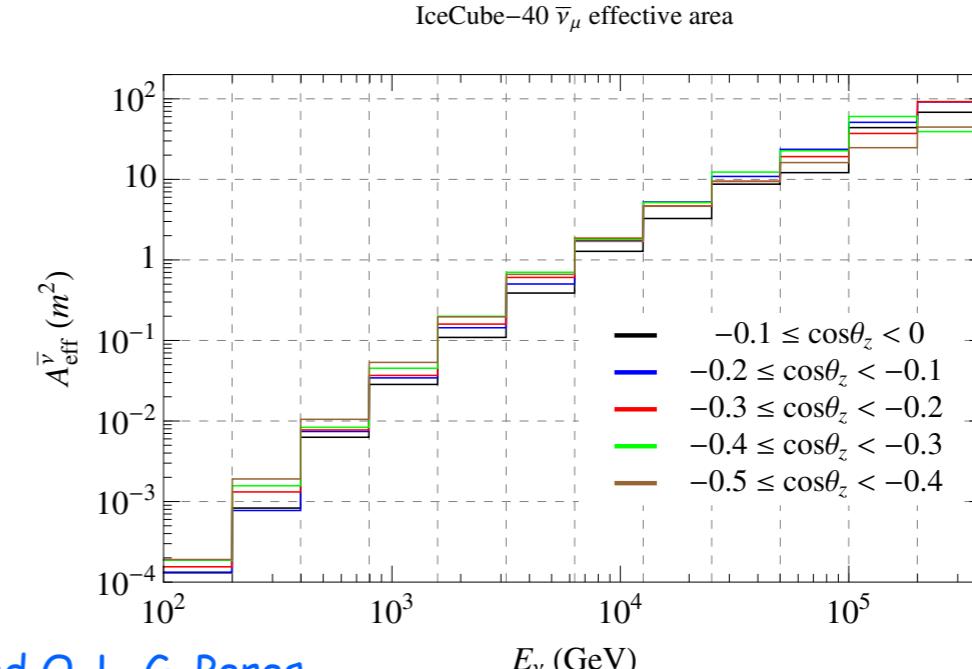
$$N = T(2\pi) \left[\int A_{\text{eff}}^{\nu}(E_{\nu}, \cos \theta_z) \Phi_{\nu}(E_{\nu}, \cos \theta_z) dE_{\nu} d\cos \theta_z + (\nu \rightarrow \bar{\nu}) \right]$$

IceCube-40 ν_{μ} effective area

atm flux (Honda+Volkova)

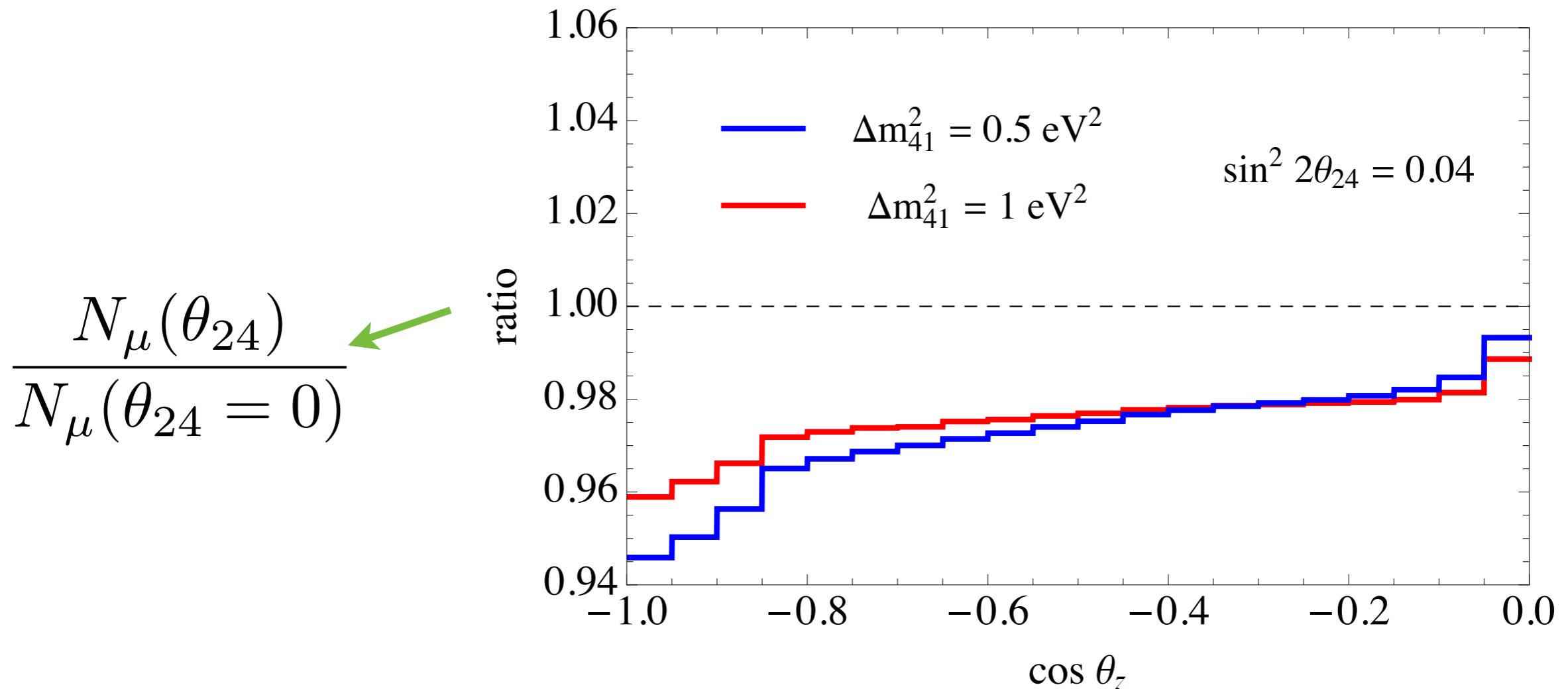


A. E., F. Halzen and O. L. G. Peres,
JCAP 1211 (2012) 041



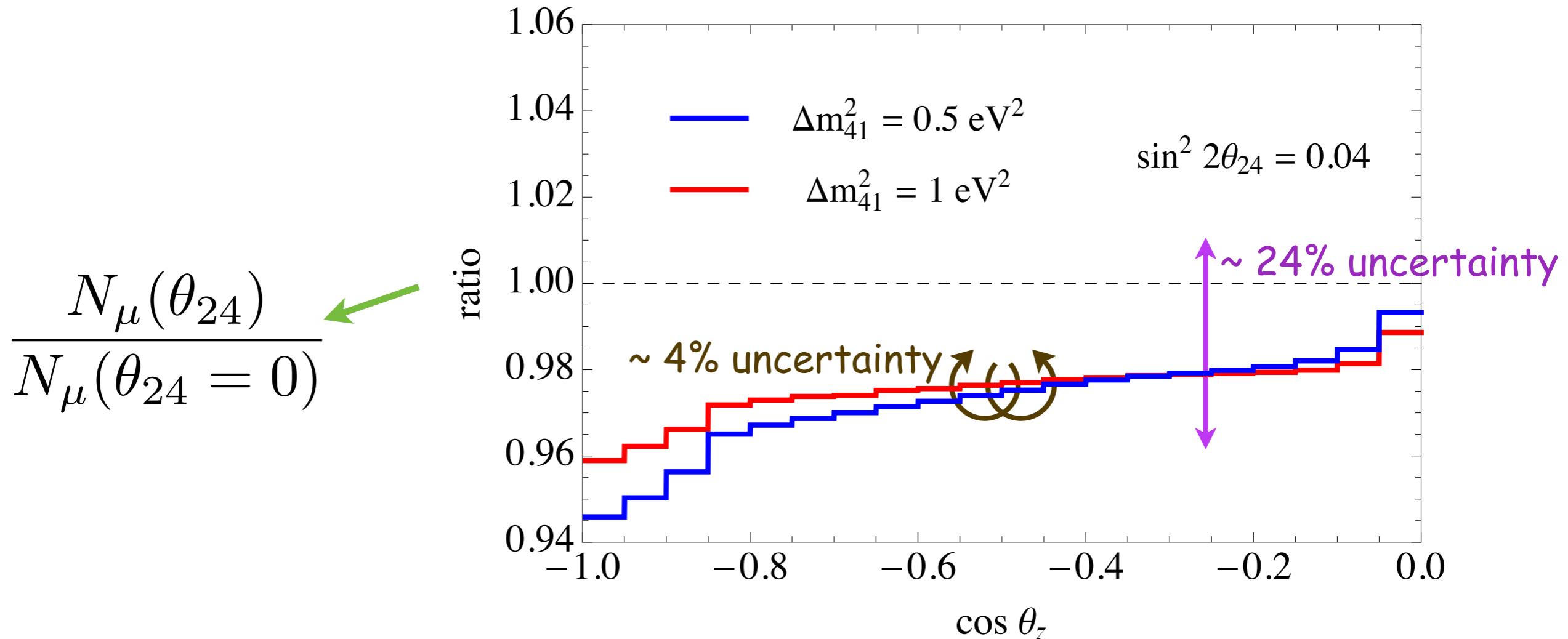
IceCube sensitivity to sterile neutrinos (muon-track events)

✓ We analyzed the zenith distribution of muon-track events



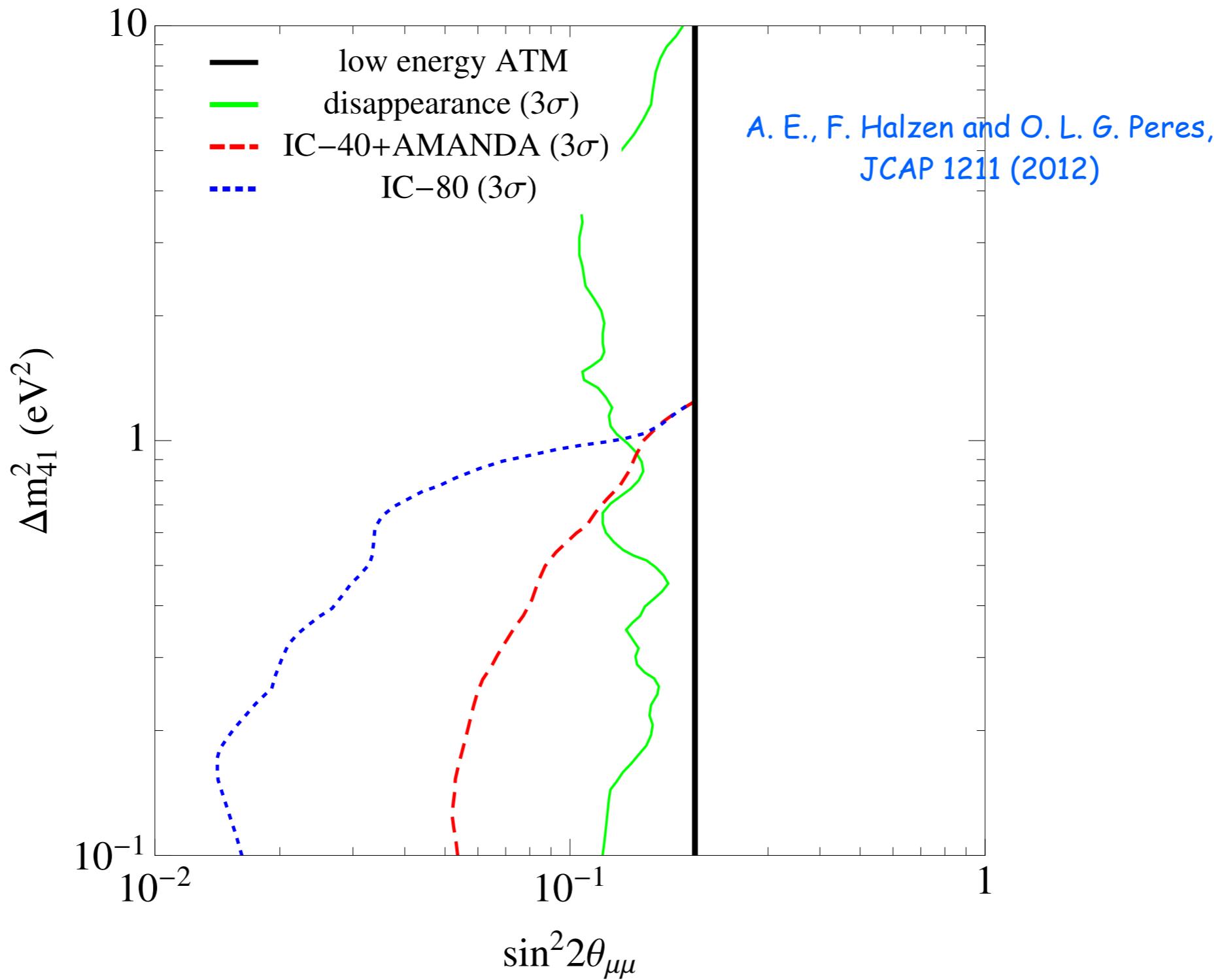
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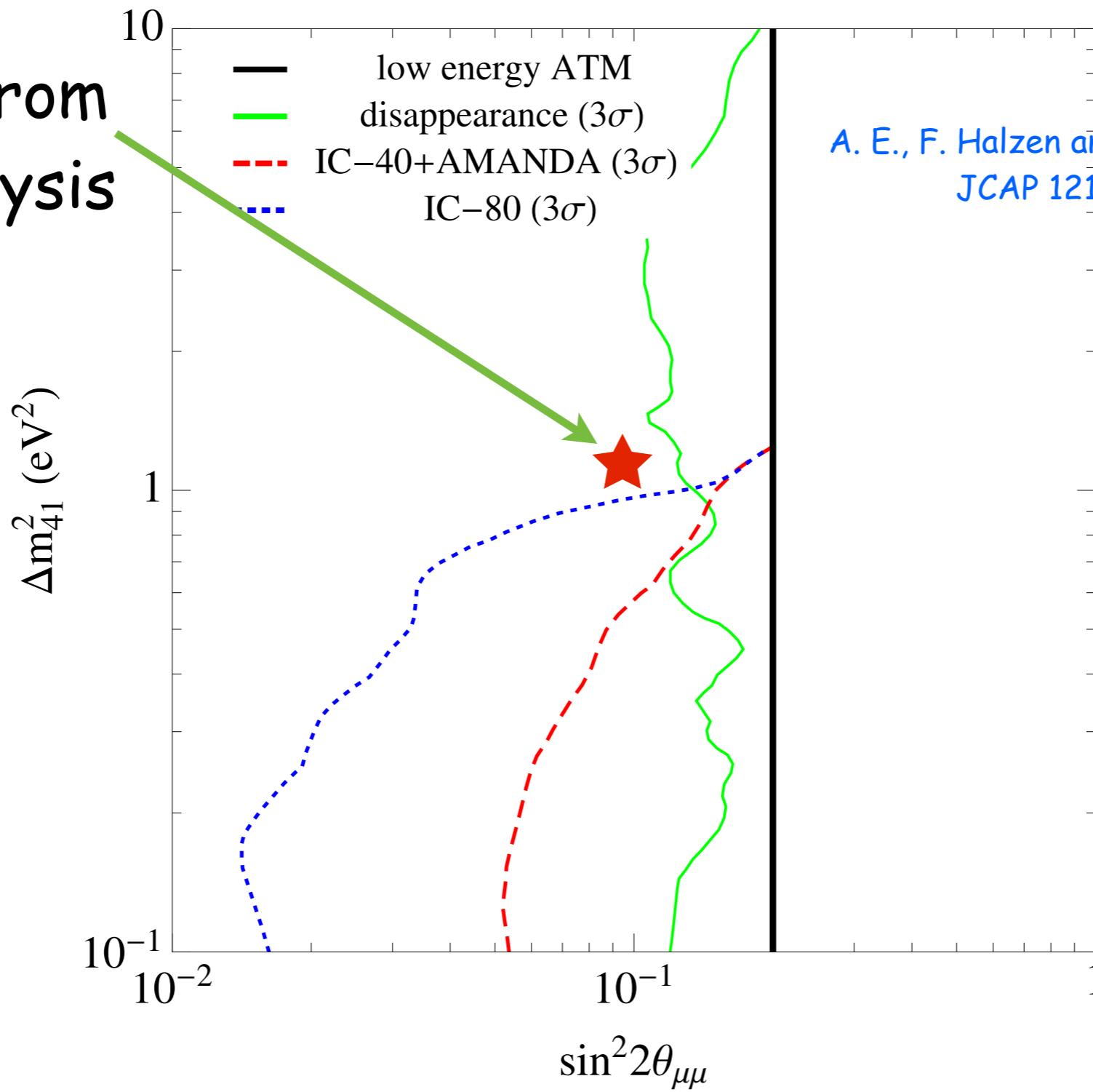
$$\chi^2(\Delta m_{41}^2, \theta_{24}; \alpha, \beta) = \sum_i \frac{\{N_i(\theta_{24} = 0) - \alpha[1 + \beta(0.5 + (\cos \theta_z)_i)]N_i(\theta_{24})\}^2}{\sigma_{i,\text{stat}}^2 + \sigma_{i,\text{sys}}^2} + \frac{(1 - \alpha)^2}{\sigma_\alpha^2} + \frac{\beta^2}{\sigma_\beta^2}$$

IceCube-40 + AMANDA limit



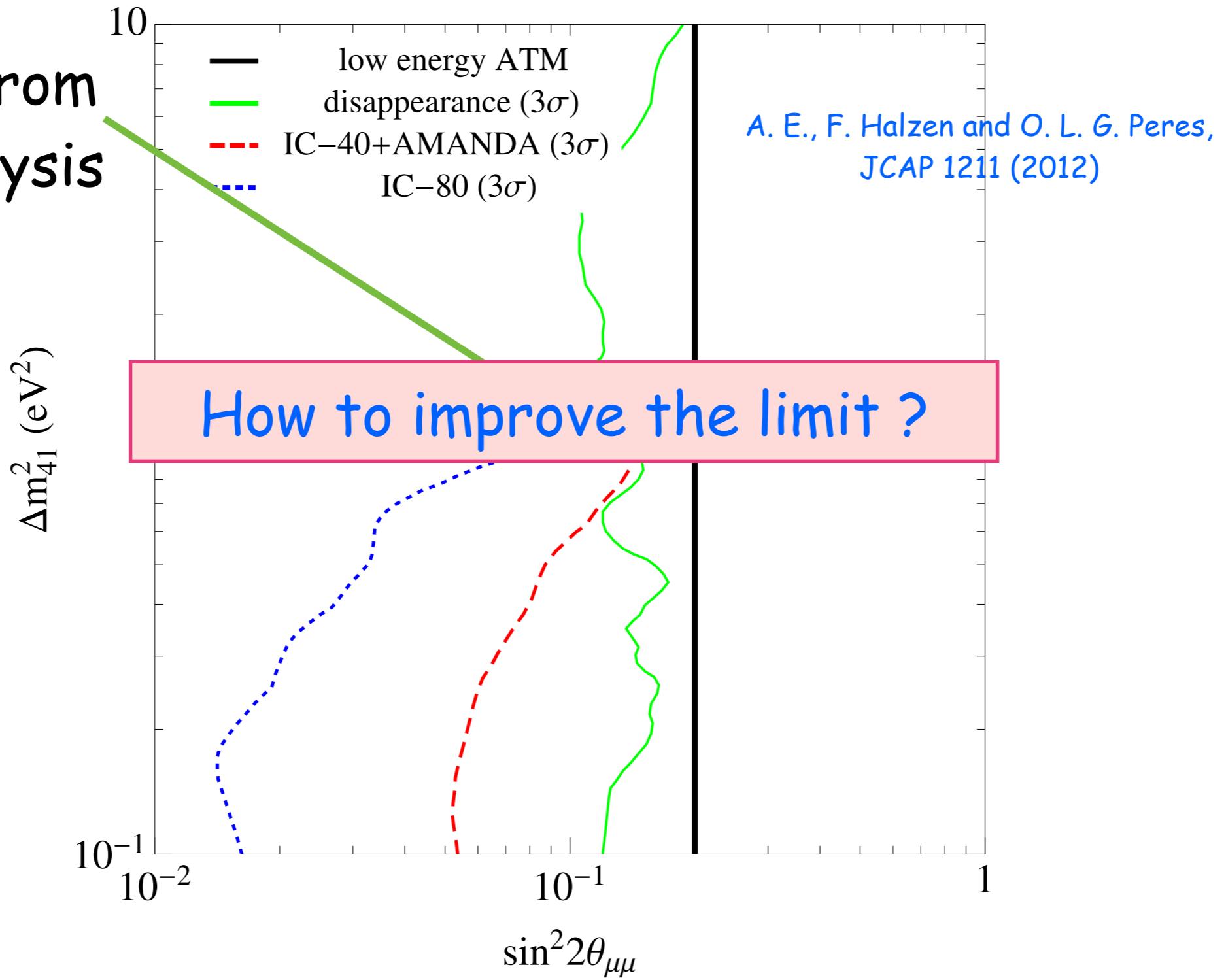
IceCube-40 + AMANDA limit

best-fit from
global analysis



IceCube-40 + AMANDA limit

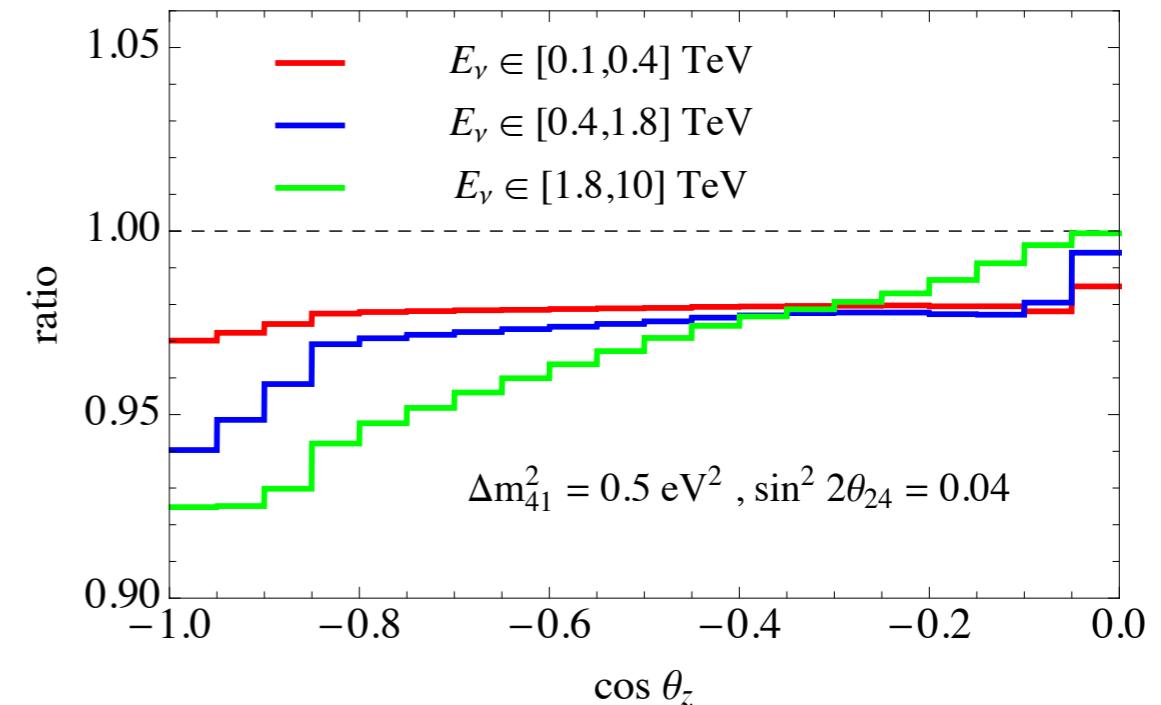
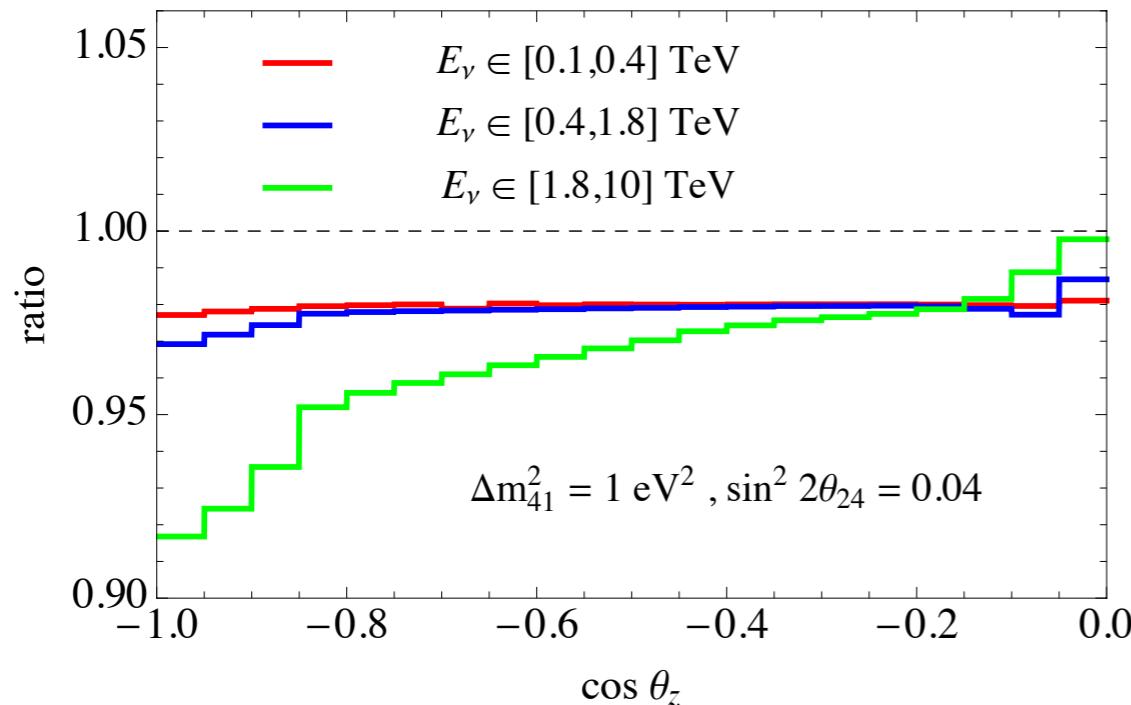
best-fit from
global analysis



IceCube sensitivity to sterile neutrinos

✓ The key point is the energy binning

A. E. and Alexei Yu. Smirnov,
JHEP 1312 (2013)



However,

✓ Energy resolution

events should be smeared in energy bins

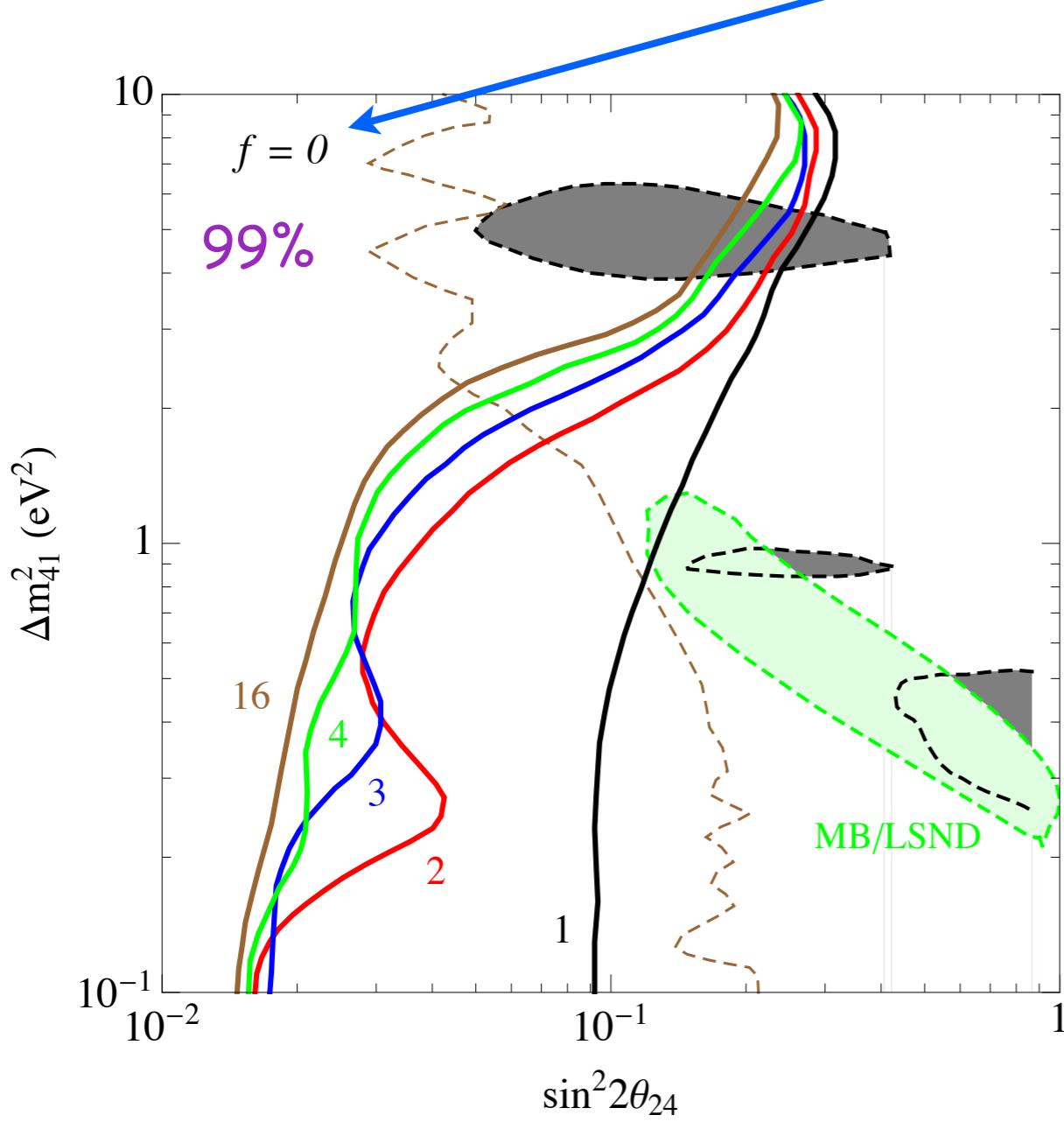
width of smearing can reach $\sim 0.3 \times \log(E/\text{GeV})$

as a conservative assumption we assume $\sigma_E = E$

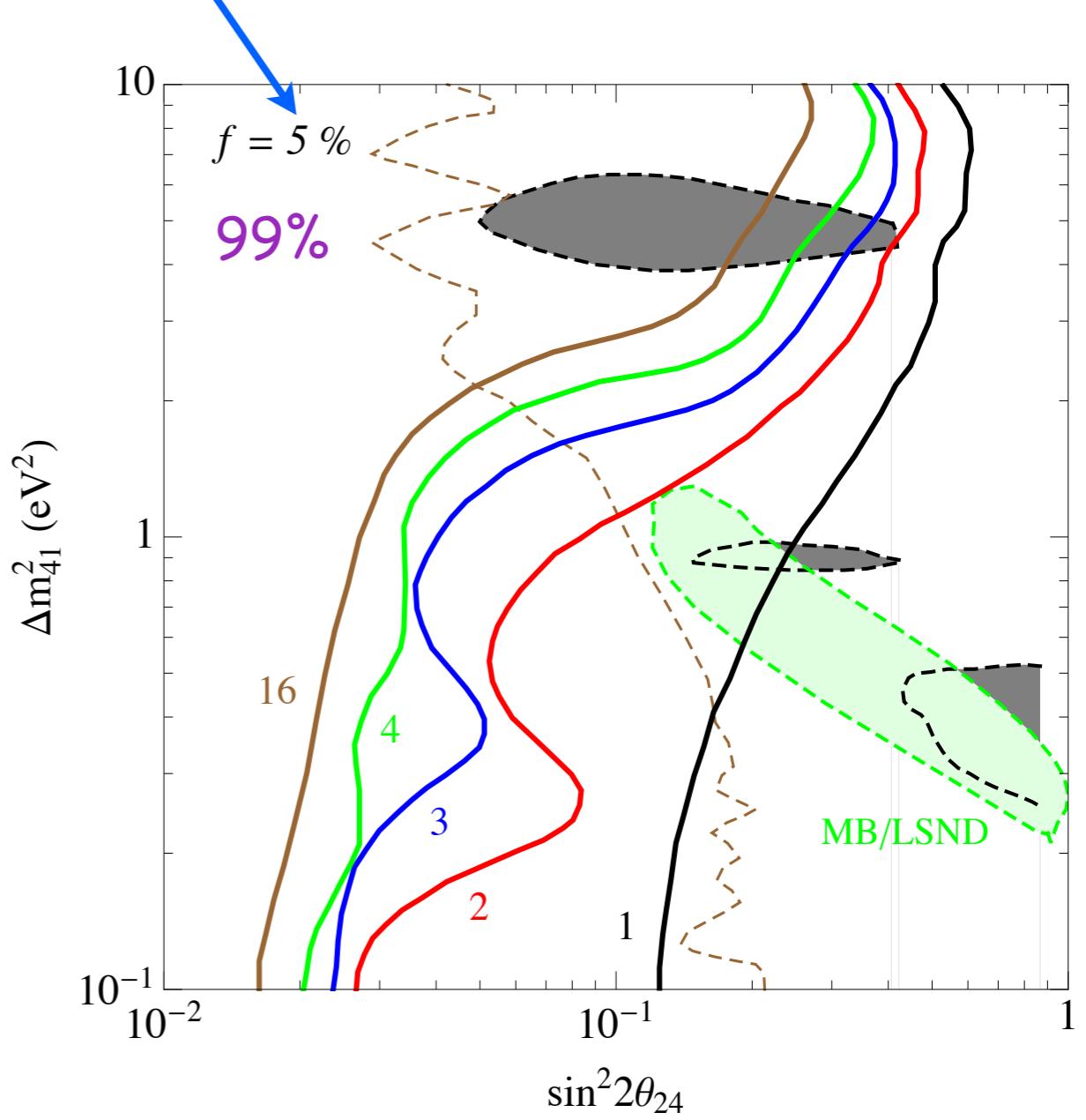
IceCube sensitivity to sterile neutrinos

3 x IceCube-79 data (available now)

A. E., A. Yu. Smirnov,
JHEP 1312 (2013)



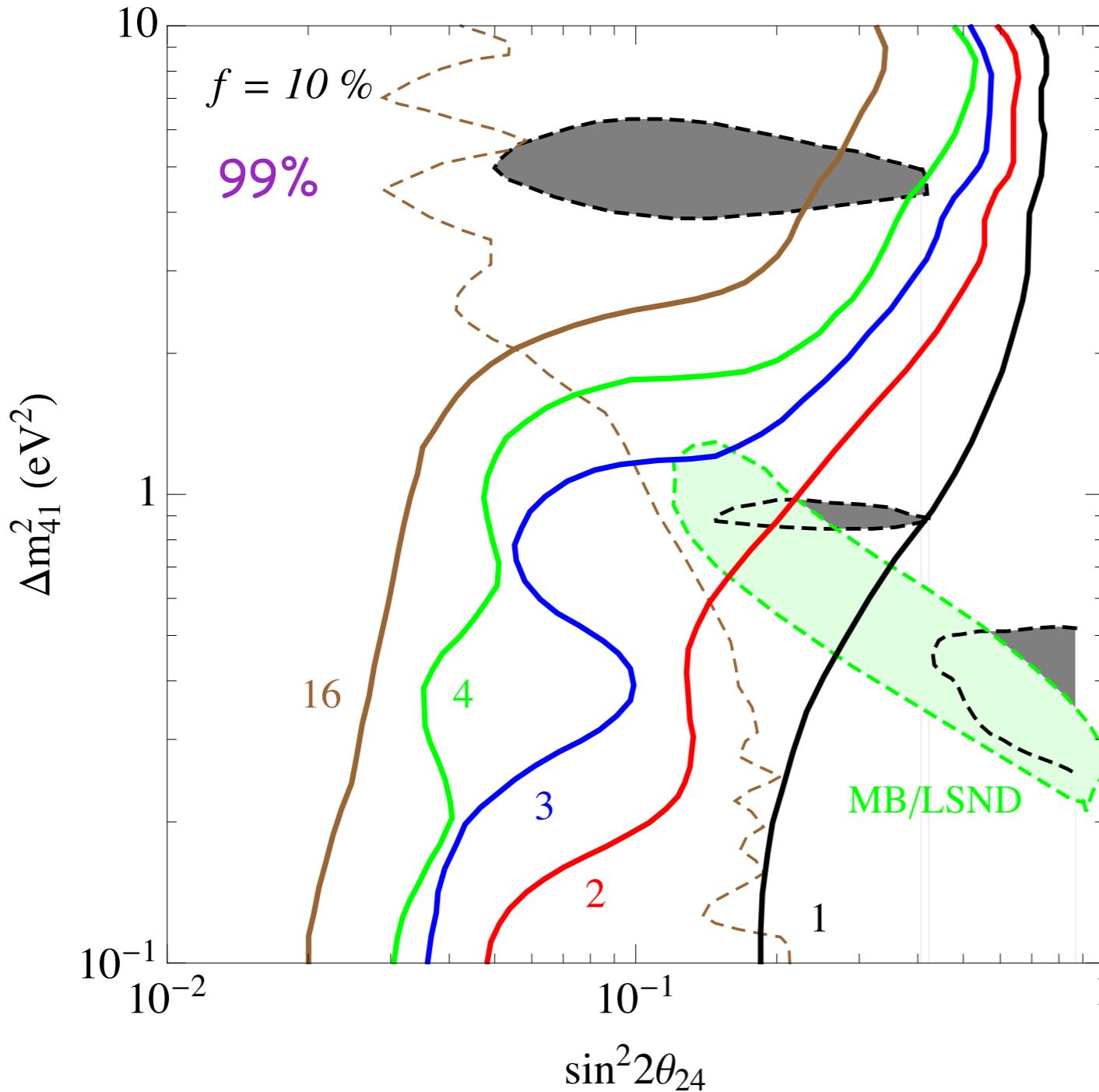
uncorrelated sys. error



IceCube sensitivity to sterile neutrinos

3 x IceCube-79 data (available now)

A. E., A. Yu. Smirnov,
JHEP 1312 (2013)



With the already collected data
the bound $|U_{\mu 4}|^2 < 0.01$ (99% C.L.)
can be established

Mixing required by
LSND/MiniBooNE can be
excluded at (4-6) σ

Cascade events

- ✓ Cascade events originate from NC interaction of all flavors and CC interaction of electron/tau neutrinos

advantages

better energy resolution

sensitivity all the new mixing angles: θ_{14} , θ_{24} and θ_{34}

sensitivity to θ_{34} due to an effective enhancement of $\bar{v}_\mu \rightarrow \bar{v}_\tau$

disadvantages

lower statistics with respect to muon-track events

zenith resolution is moderate

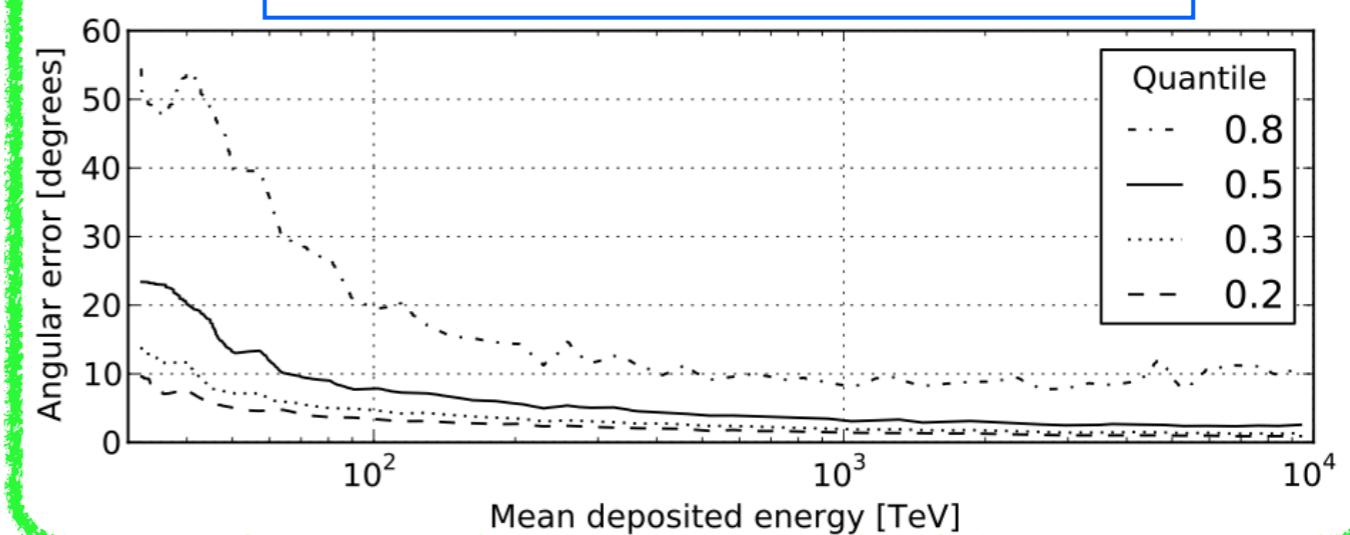


Figure from Whitehorn's talk

Cascade events

✓ number of cascade events

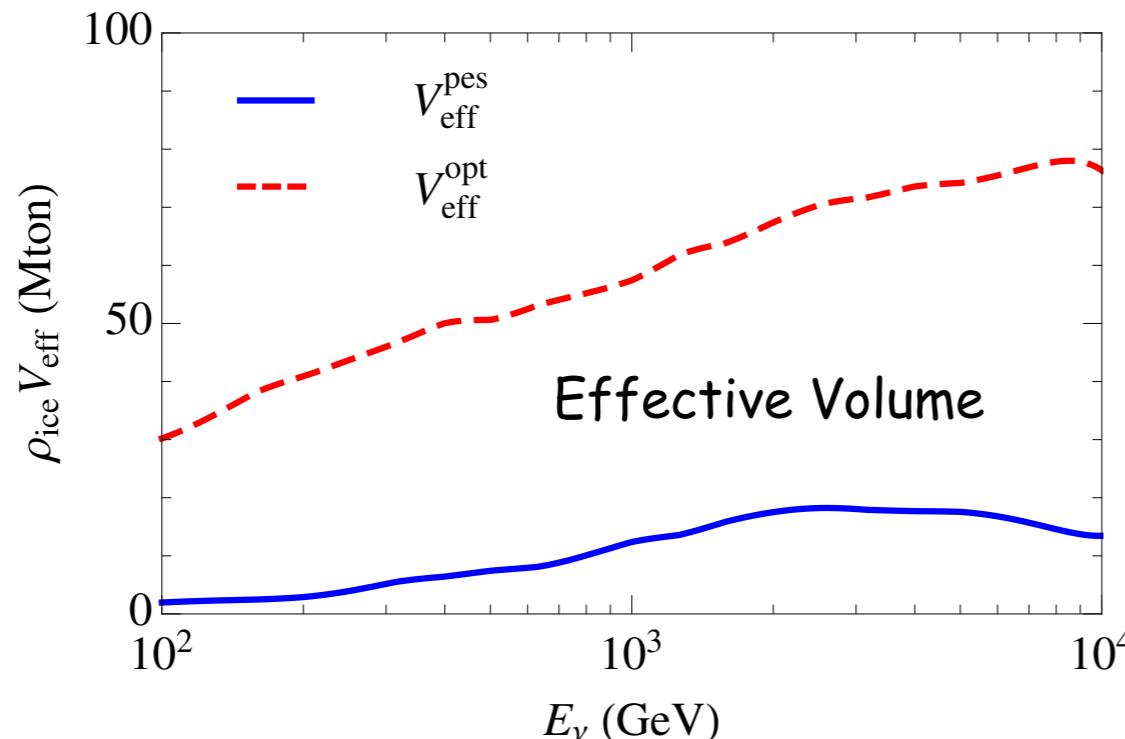
$$N_{\text{cas}} = N_{\text{cas}}^{\text{NC}} + N_{\text{cas}}^{\text{CC},e} + N_{\text{cas}}^{\text{CC},\tau}$$

↓

$$N_{\text{cas}}^{\text{NC}} = N_{\text{cas}}^{\text{NC},\nu_e \text{ atm}} + N_{\text{cas}}^{\text{NC},\nu_\mu \text{ atm}}$$

$$N_{\text{cas}}^{\text{NC},\nu_e(\nu_\mu) \text{ atm}} = T \Delta \Omega \rho_{\text{ice}} N_A \sum_{\alpha=e,\mu,\tau} \int \sigma^{\text{NC}}(E_\nu) \Phi_{\nu_e(\nu_\mu)}^{\text{atm}}(E_\nu, \cos \theta_z) P(\nu_e(\nu_\mu) \rightarrow \nu_\alpha) V_{\text{eff}}^{\text{DC}}(E_\nu, \cos \theta_z) dE_\nu d \cos \theta_z$$

$$N_{\text{cas}}^{\text{CC},e(\tau)} = T \Delta \Omega \rho_{\text{ice}} N_A \sum_{\alpha=e,\mu} \int \sigma^{\text{CC}}(E_\nu) \Phi_{\nu_\alpha}^{\text{atm}}(E_\nu, \cos \theta_z) P(\nu_\alpha \rightarrow \nu_e(\nu_\tau)) V_{\text{eff}}^{\text{DC}}(E_\nu, \cos \theta_z) dE_\nu d \cos \theta_z + (\nu \rightarrow \bar{\nu})$$



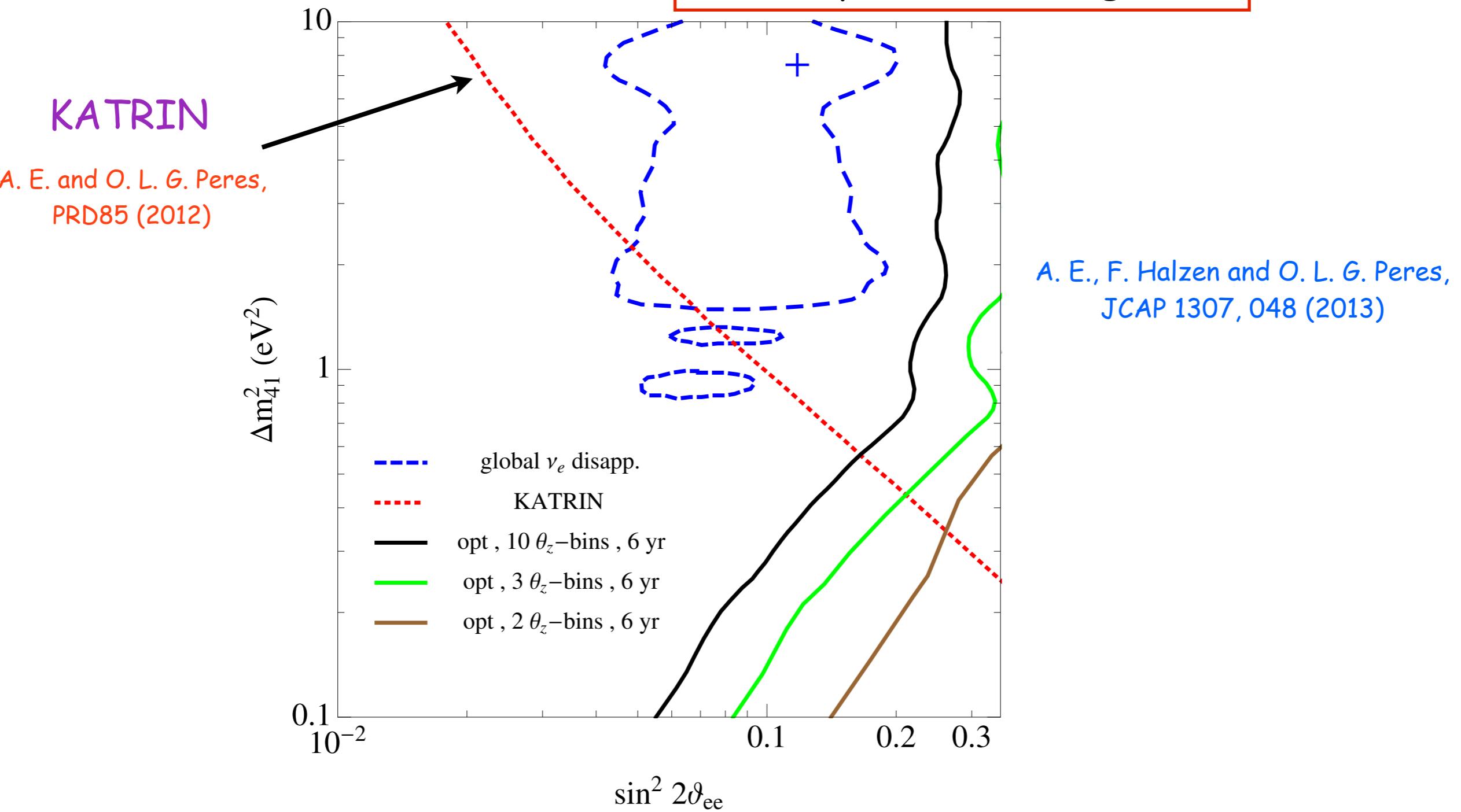
optimistic: DeepCore, arXiv:1109.6096

pessimistic: C. H. Ha, arXiv:1201.0801

Sensitivity to 3+1 parameters from cascades

✓ sensitivity to θ_{14}

promising result for low Δm^2
not competitive for high Δm^2

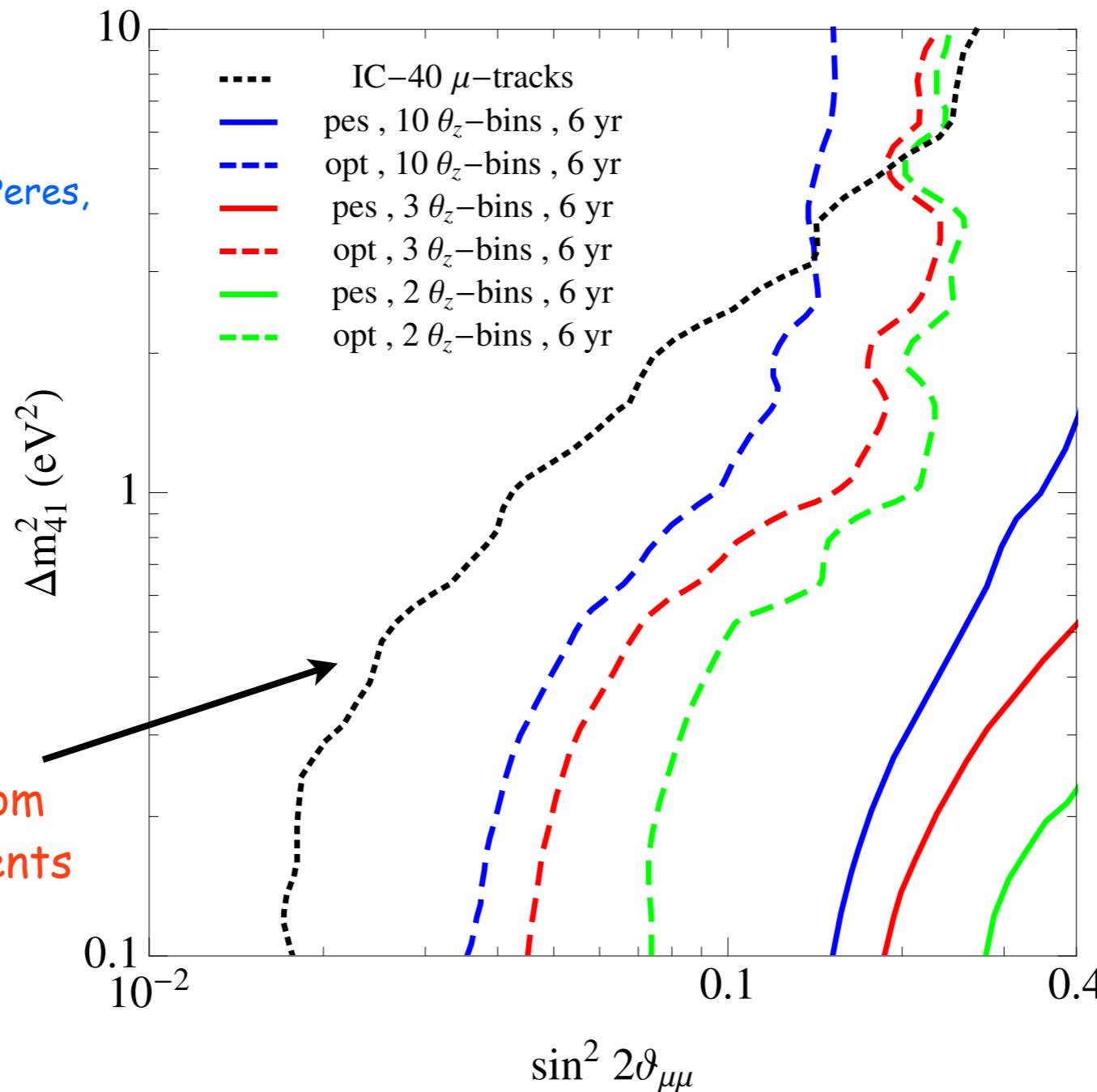


Sensitivity to 3+1 parameters from cascades

✓ sensitivity to θ_{24}

A. E., F. Halzen and O. L. G. Peres,
JCAP 1307 (2013)

not comparable to muon-track limit



sensitivity from
muon-track events

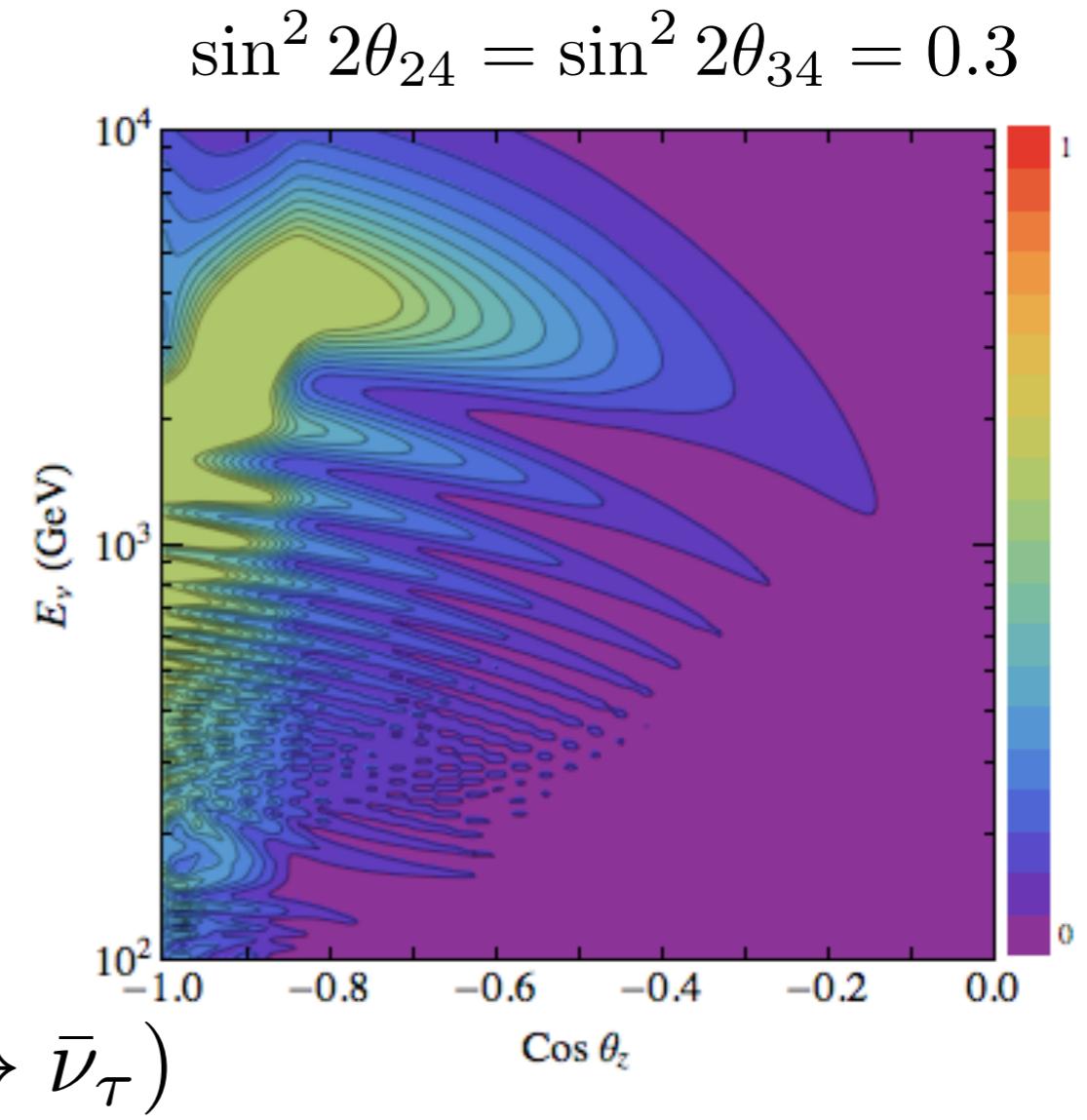
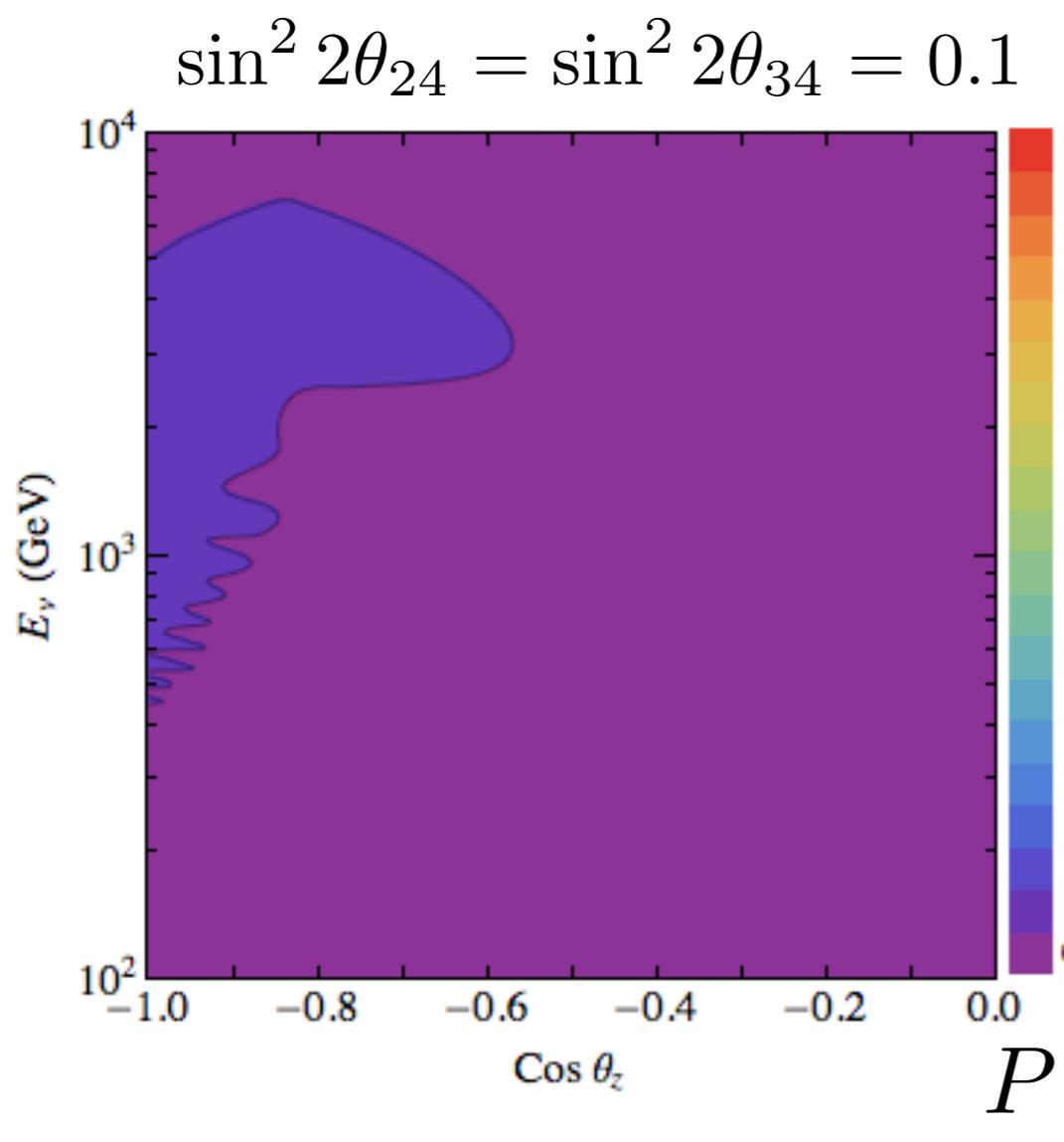
Sensitivity to θ_{34}



$\theta_{24} \neq 0$ and $\theta_{34} \neq 0$: leads to an effective enhancement of
 $\text{anti-}\bar{\nu}_\mu \rightarrow \text{anti-}\bar{\nu}_\tau$ oscillation

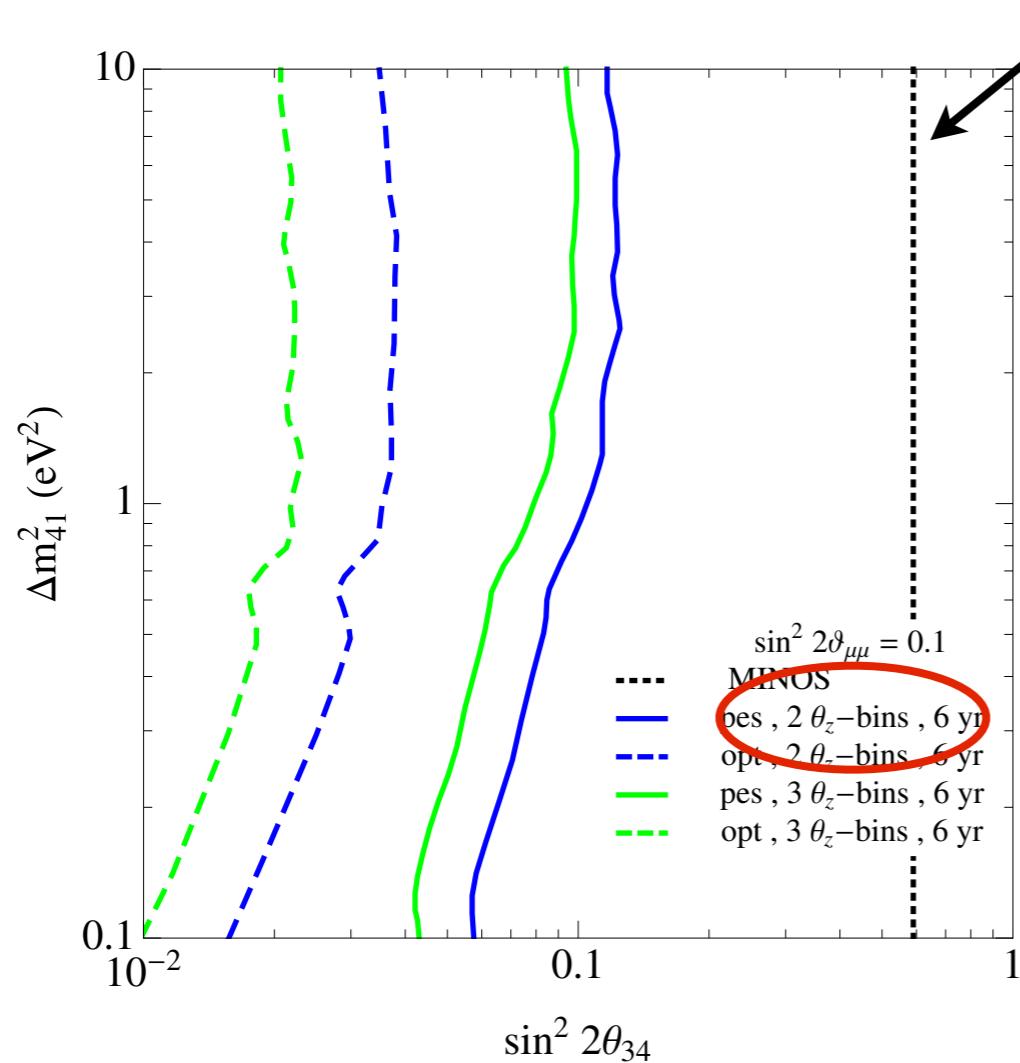
A. E., F. Halzen and O. L. G. Peres,
JCAP 1307 (2013)

$$\Delta m_{41}^2 = 1 \text{ eV}^2$$



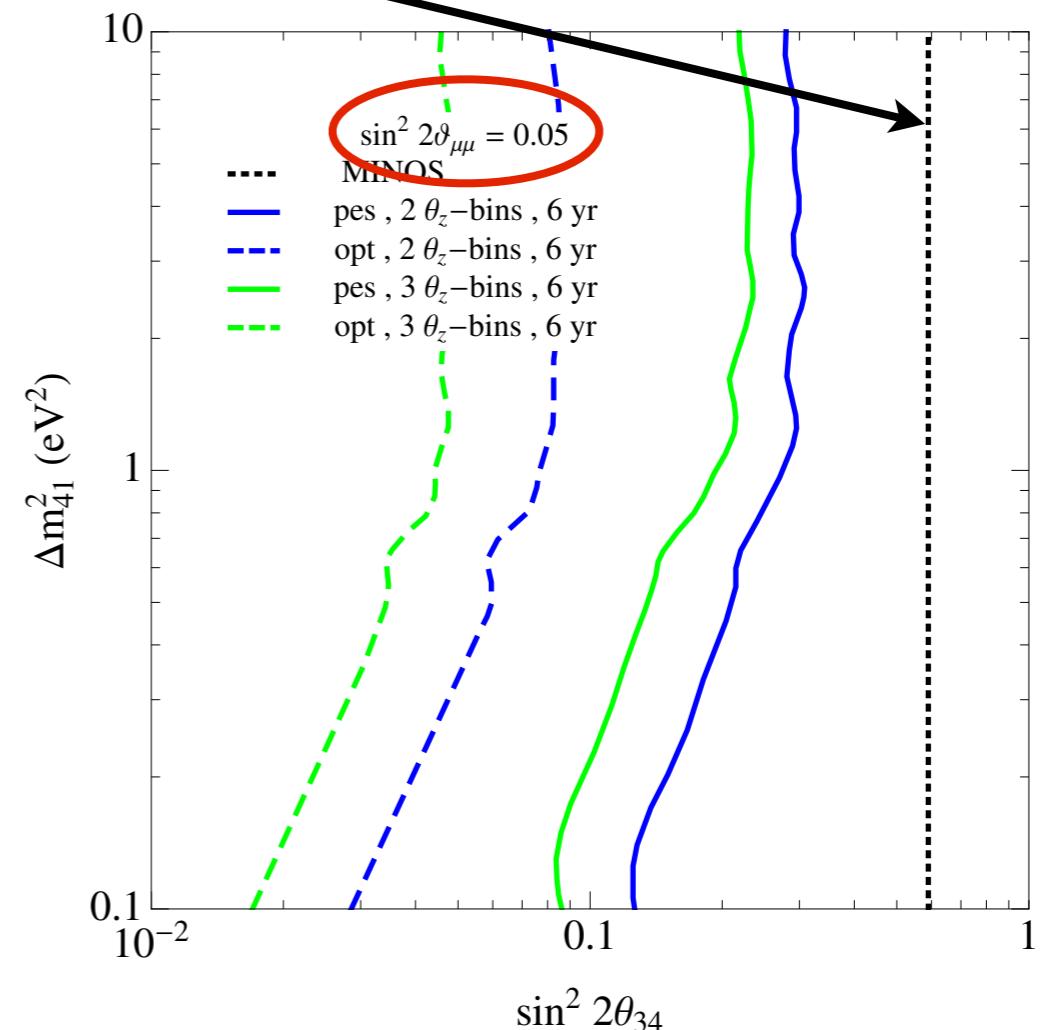
Sensitivity to 3+1 parameters from cascades

✓ sensitivity to θ_{34}



current upper
limit

A. E., F. Halzen and O. L. G. Peres,
JCAP 1307 (2013)

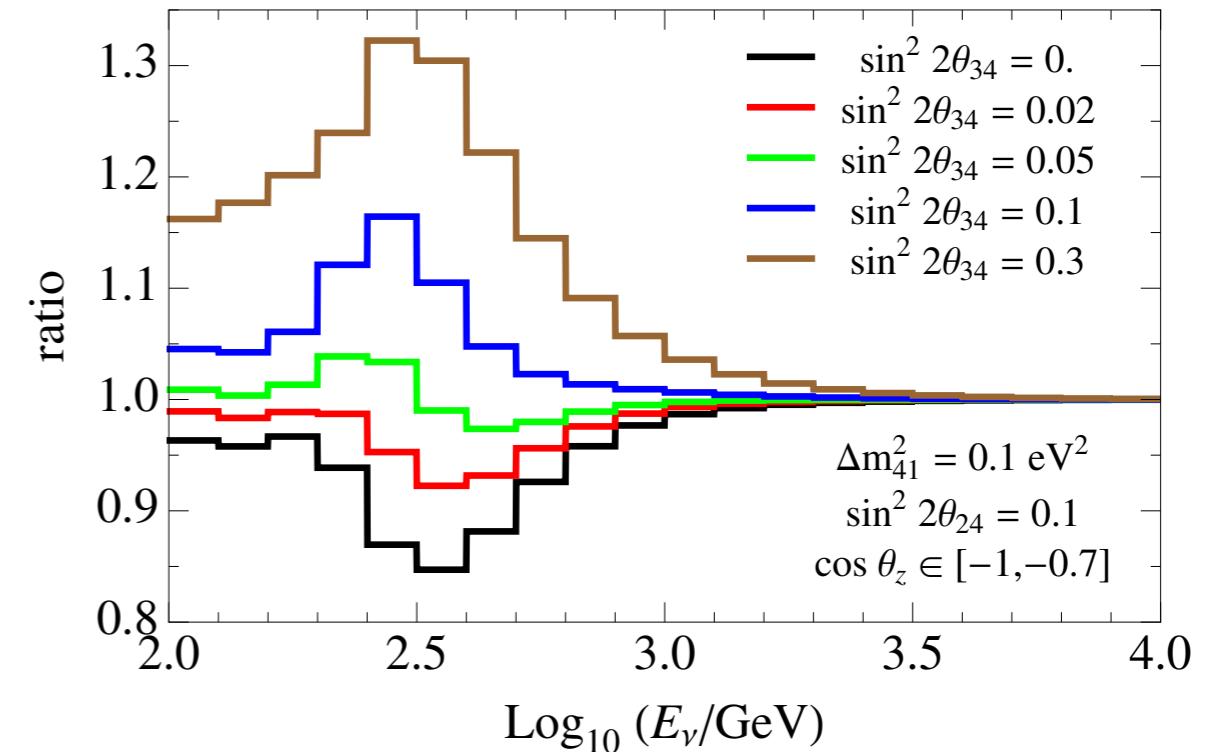
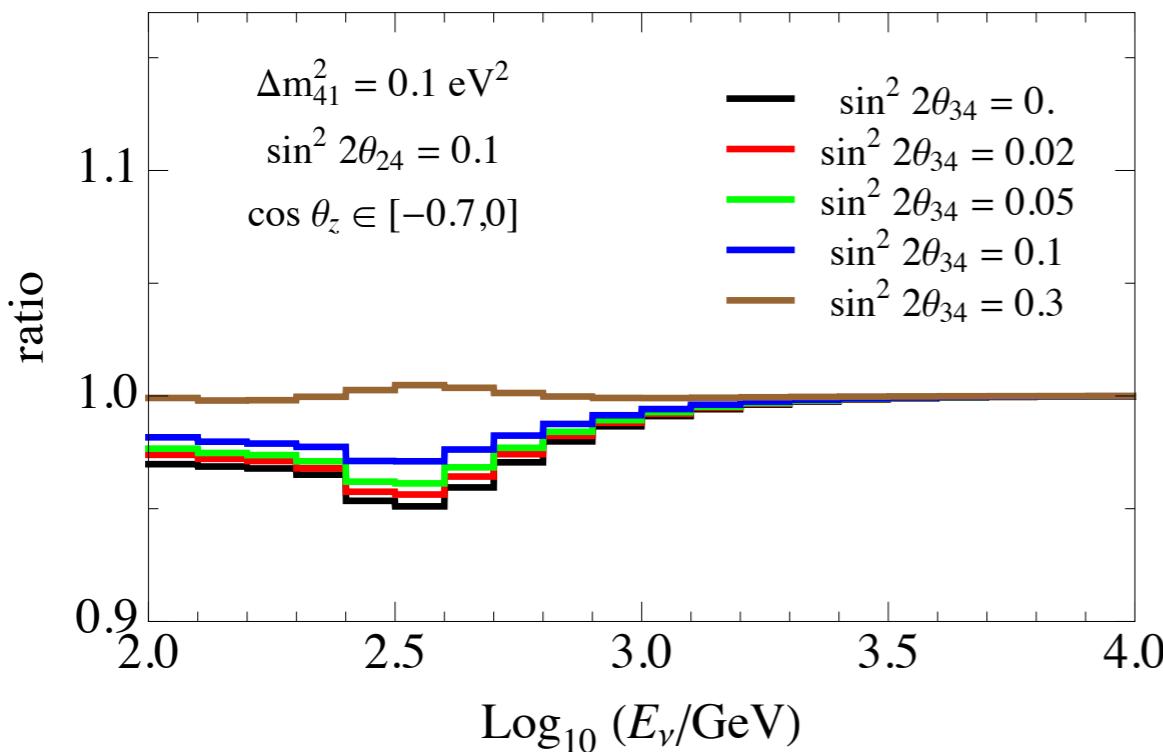


✓ limits depend on θ_{24} value

✓ at least a factor of few stronger than the present limit

Sensitivity to θ_{34}

✓ a clear signature of θ_{34}



- ✓ for a set of θ_{24} and θ_{34} , the distribution mimics the 3-nu distribution
- ✓ by increasing the value of θ_{34} , number of cascade events **increases** with respect to 3-nu case
- ✓ the increase in the number of cascade events comes from the effective $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ oscillation

other "New Physics" searches

✓ constraining Non-standard Neutrino Interactions

A. E. and A. Yu. Smirnov,
JHEP 1306 (2013)

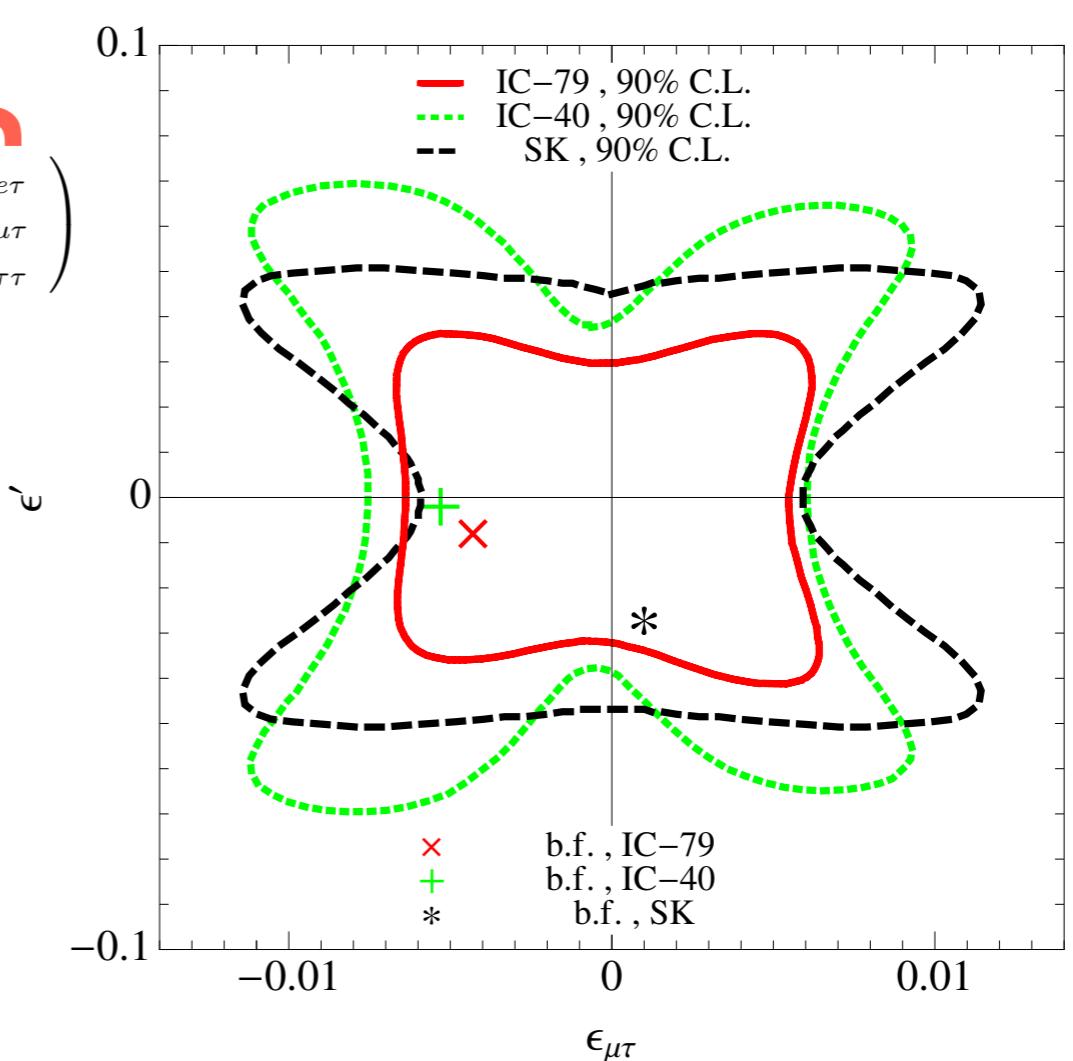
$$\mathcal{H} = \frac{1}{2E_\nu} U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U + \begin{pmatrix} V_{CC} & & \\ & 0 & \\ & & 0 \end{pmatrix} + rV_{CC} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$$-6.1 \times 10^{-3} < \epsilon_{\mu\tau} < 5.6 \times 10^{-3}$$

at 90% C.L.

$$-3.6 \times 10^{-2} < \epsilon' < 3.1 \times 10^{-2}$$

one order of magnitude
stronger than the current limit



other "New Physics" searches

✓ constraining Non-standard Neutrino Interactions

A. E. and A. Yu. Smirnov,
JHEP 1306 (2013)

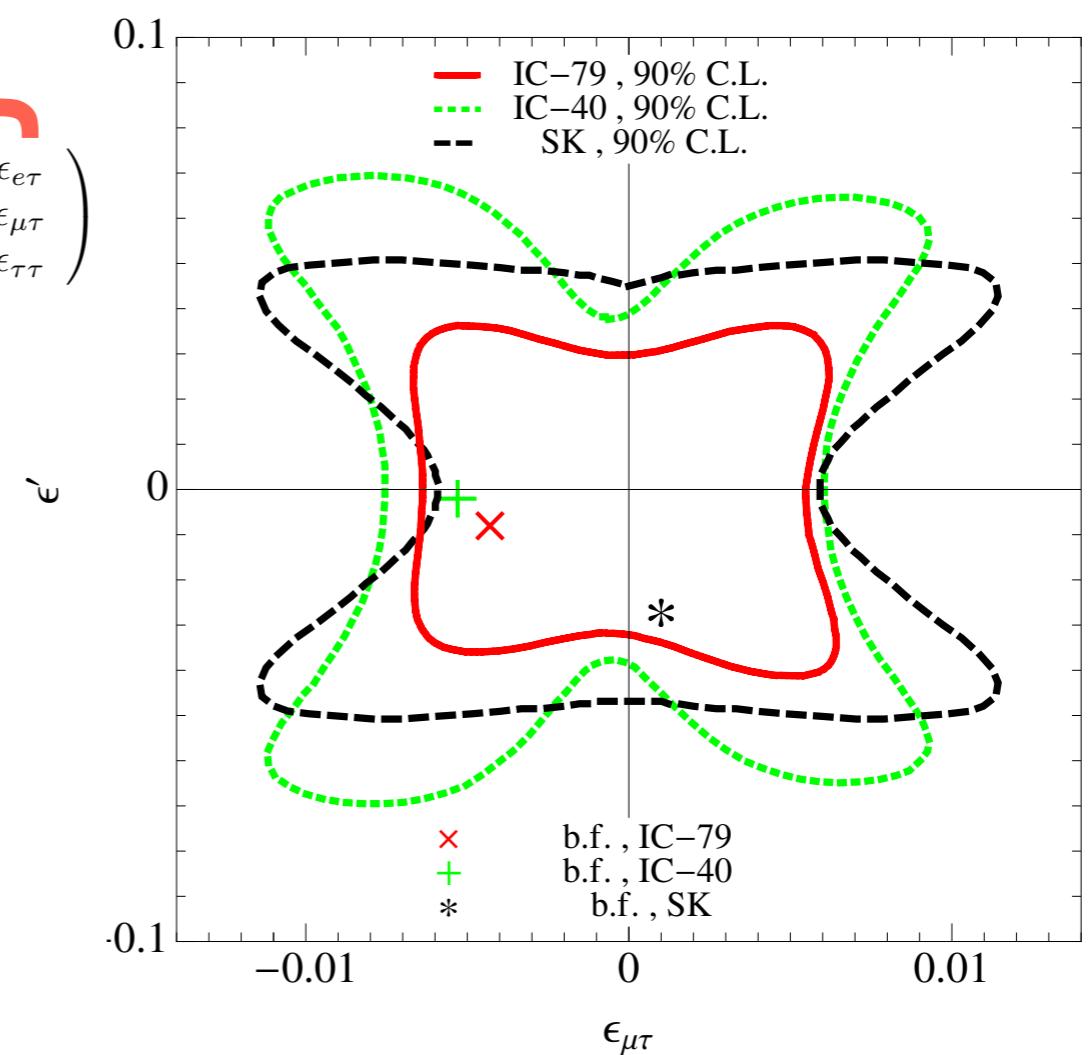
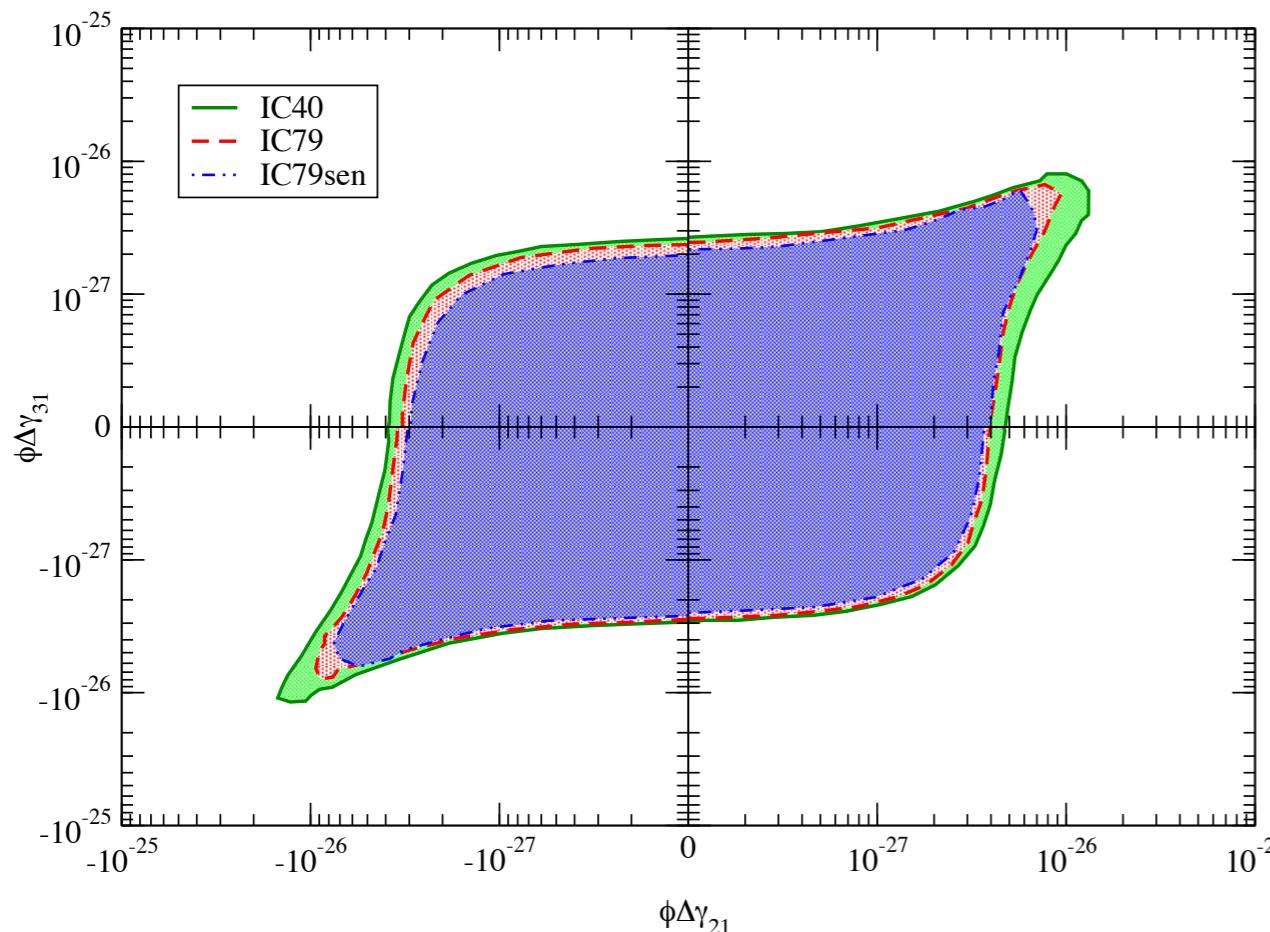
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$$-6.1 \times 10^{-3} < \epsilon_{\mu\tau} < 5.6 \times 10^{-3}$$

at 90% C.L.

$$-3.6 \times 10^{-2} < \epsilon' < 3.1 \times 10^{-2}$$

one order of magnitude
stronger than the current limit



constraining Violation of Equivalence Principle

~ four orders of magnitude
stronger than the current limit

A. E., D. Gratieri, M. Guzzo, P. de Holanda, O. Peres
and G. Valdivieso, PRD (2014)

conclusions

- ✓ The background in the searches of astrophysical neutrinos is not useless! Neutrino telescopes are perfect atmospheric neutrino detectors (mass hierarchy, CP-violation)
- ✓ Several new physics scenarios can be probed by neutrino telescopes, such as sterile neutrinos, NSI, VEP, LED, ...
- ✓ Existence of sterile neutrinos hinted by reactor, Gallium, LSND and MiniBooNE anomalies lead to distortions in the zenith and energy distributions of high energy atmospheric neutrinos. IceCube can resolve the sterile neutrino anomalies decisively $(4\text{-}6)\sigma$ and for free!
- ✓ Also, IceCube is sensitive to parts of the parameter space of 3+1 model which is untouchable by the other experiments. With the cascade events it is possible to constrain Θ_{34} uniquely.

Thank you !