Recent Observations of Atmospheric Neutrinos with the IceCube Observatory

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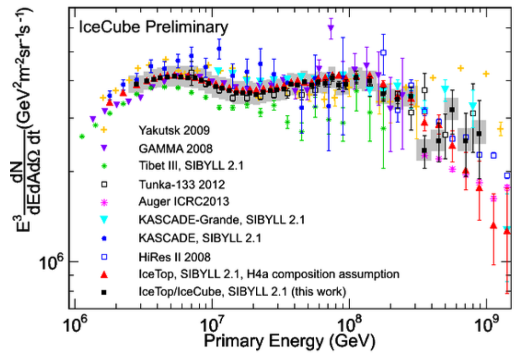
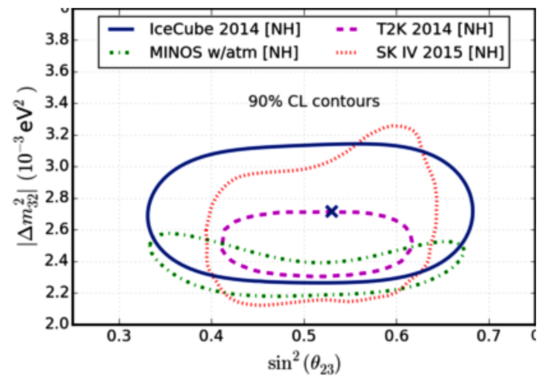
WIPAC - UW-Madison
for the IceCube Collaboration

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference

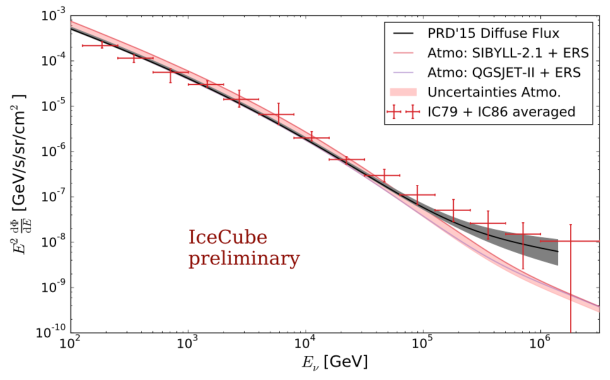
outline



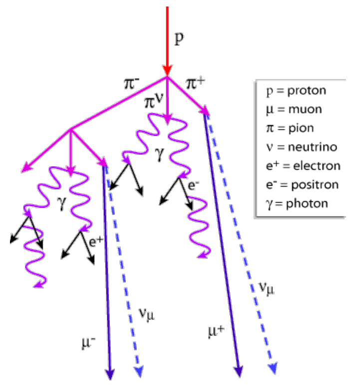
cosmic rays & atmospheric leptons



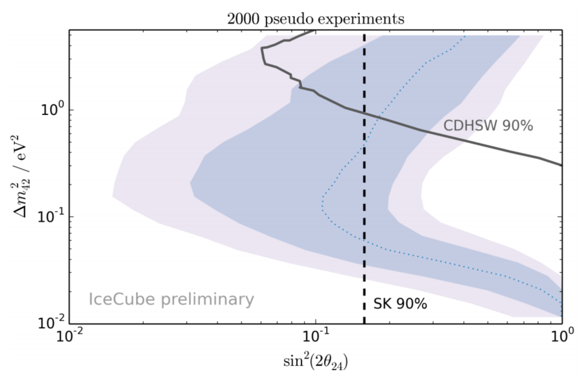
low energy neutrinos



high energy neutrinos & muons



hadronic interaction models



non-standard physics

48 institutions
300+ members

The IceCube–PINGU Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

ICRC 2015

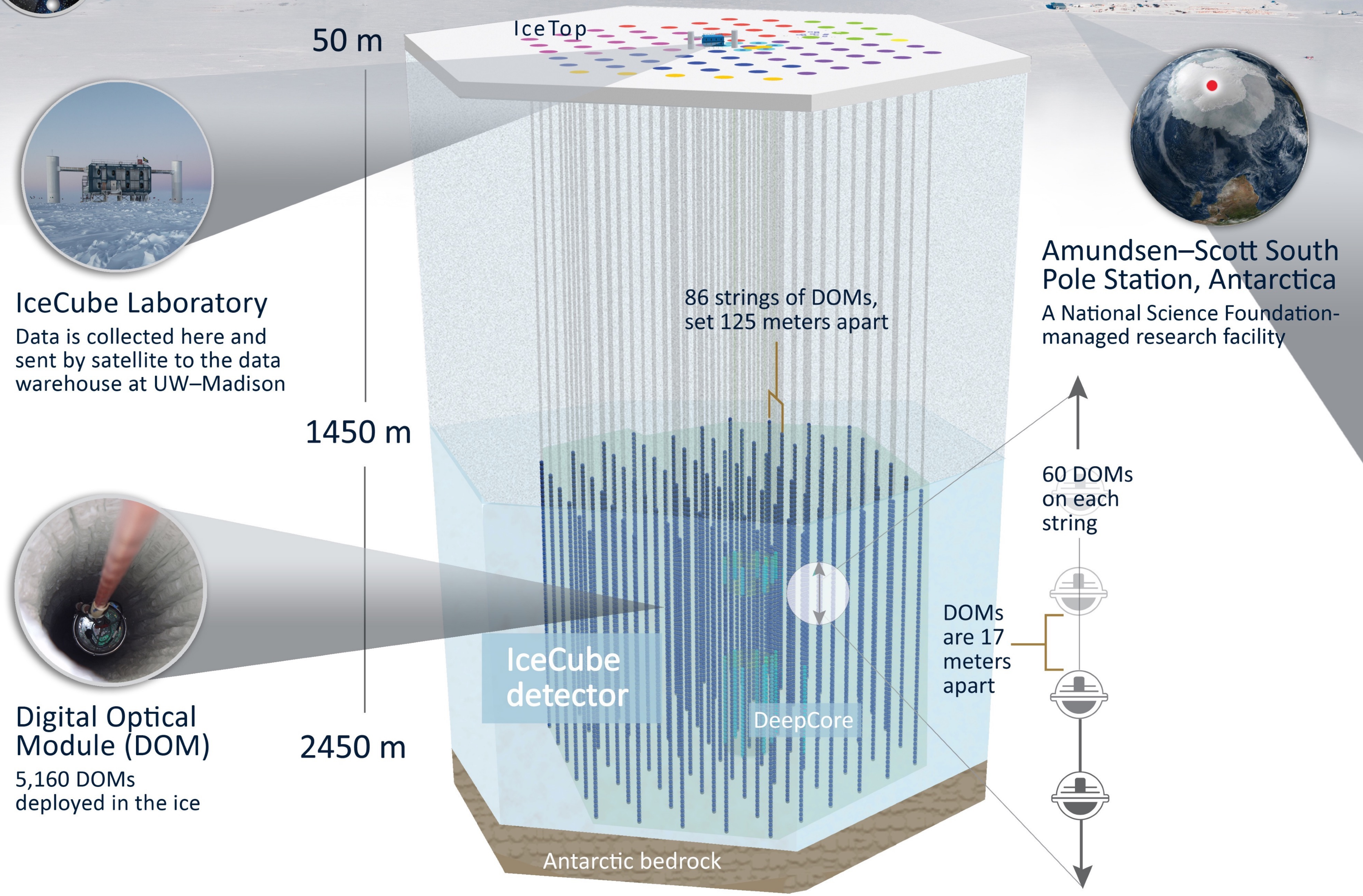
T. Karg

cosmic ray
surface
detector

ICRC 2015

ν
astrophysics
C. Kopper

in-ice
neutrino
telescope



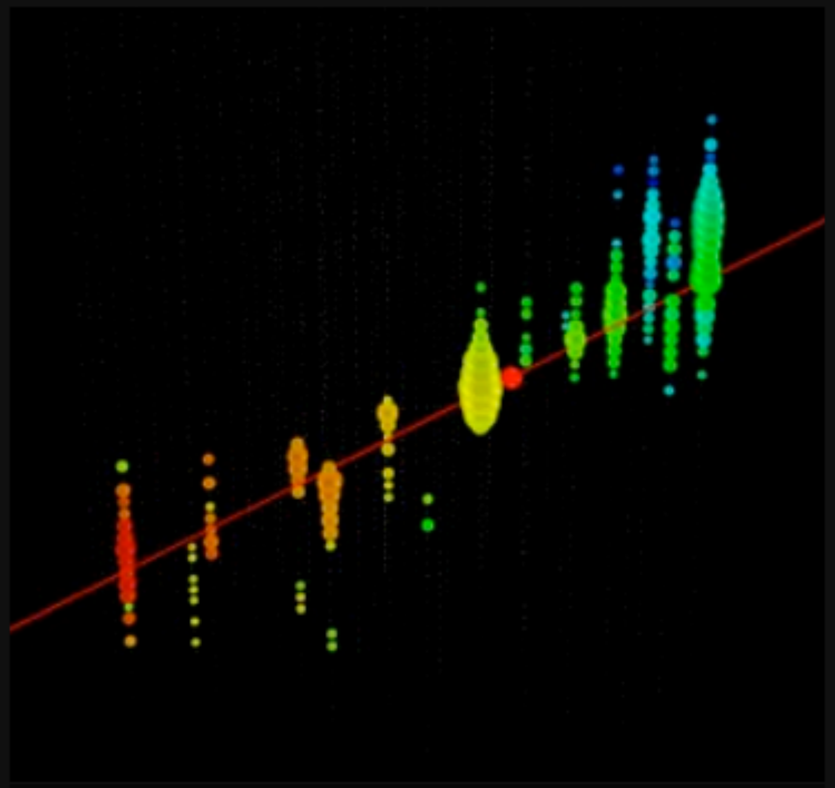
IceCube Observatory

detection technique

time

track	cascade	hybrid

CC Muon Neutrino

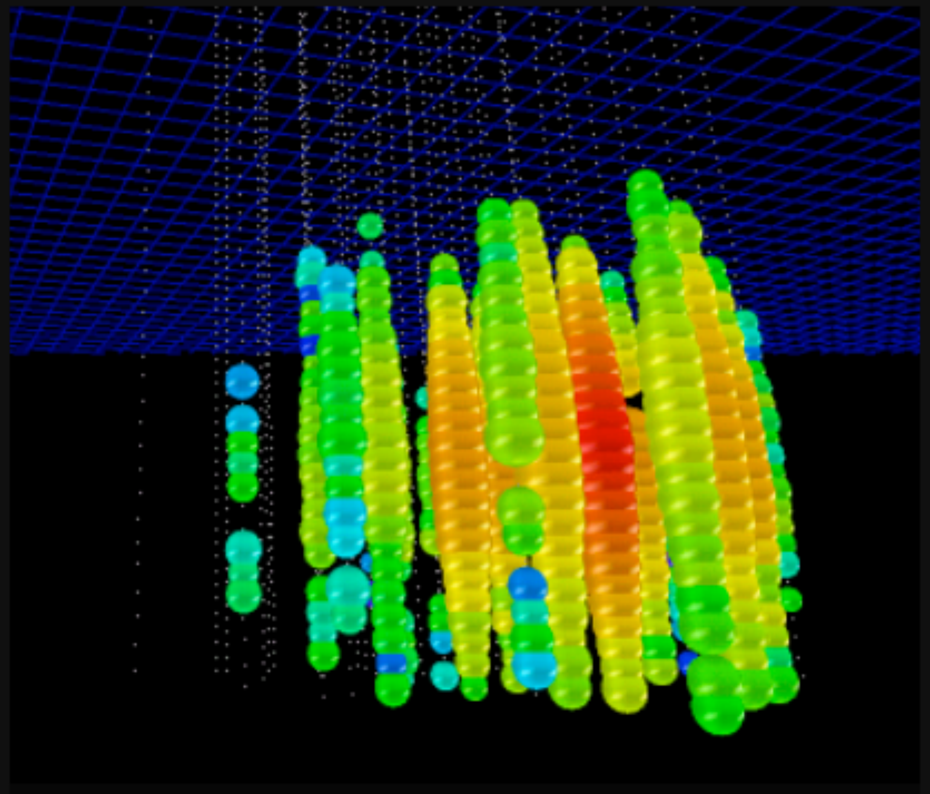


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

Neutral Current /Electron Neutrino



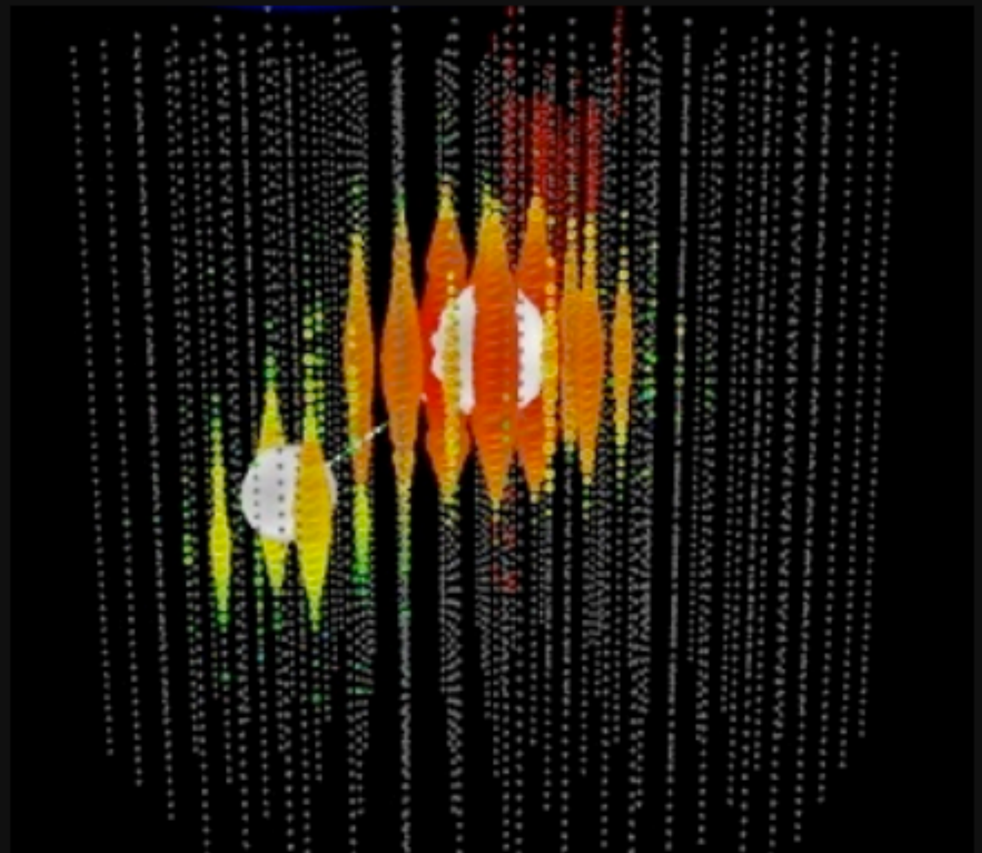
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrsim$ 100 TeV)

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

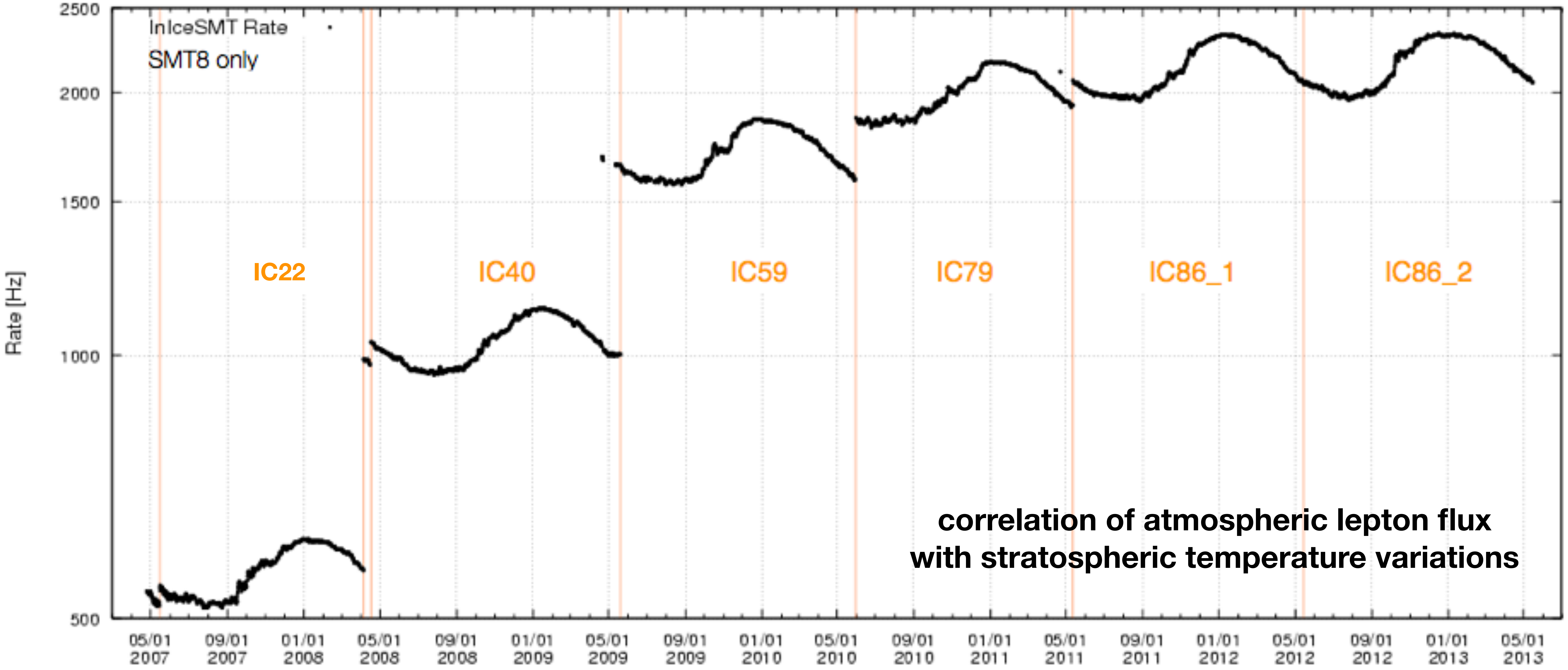
"double-bang" and other signatures
(simulation)

(not observed yet)

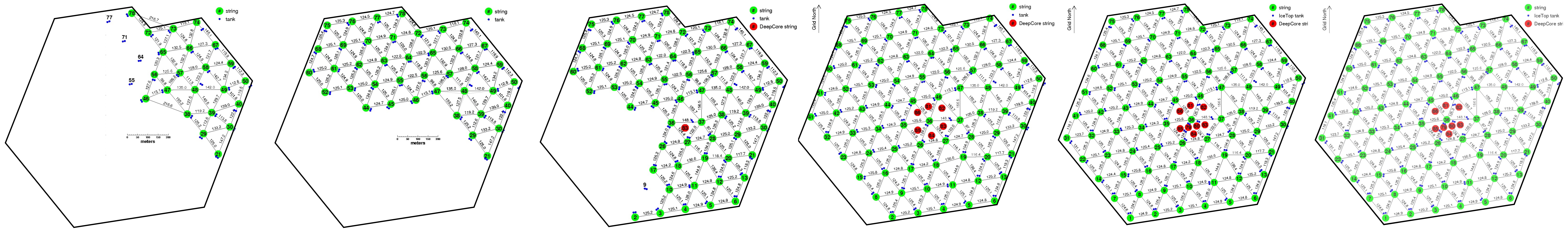
C. Kopper

IceCube Observatory

growing IceCube



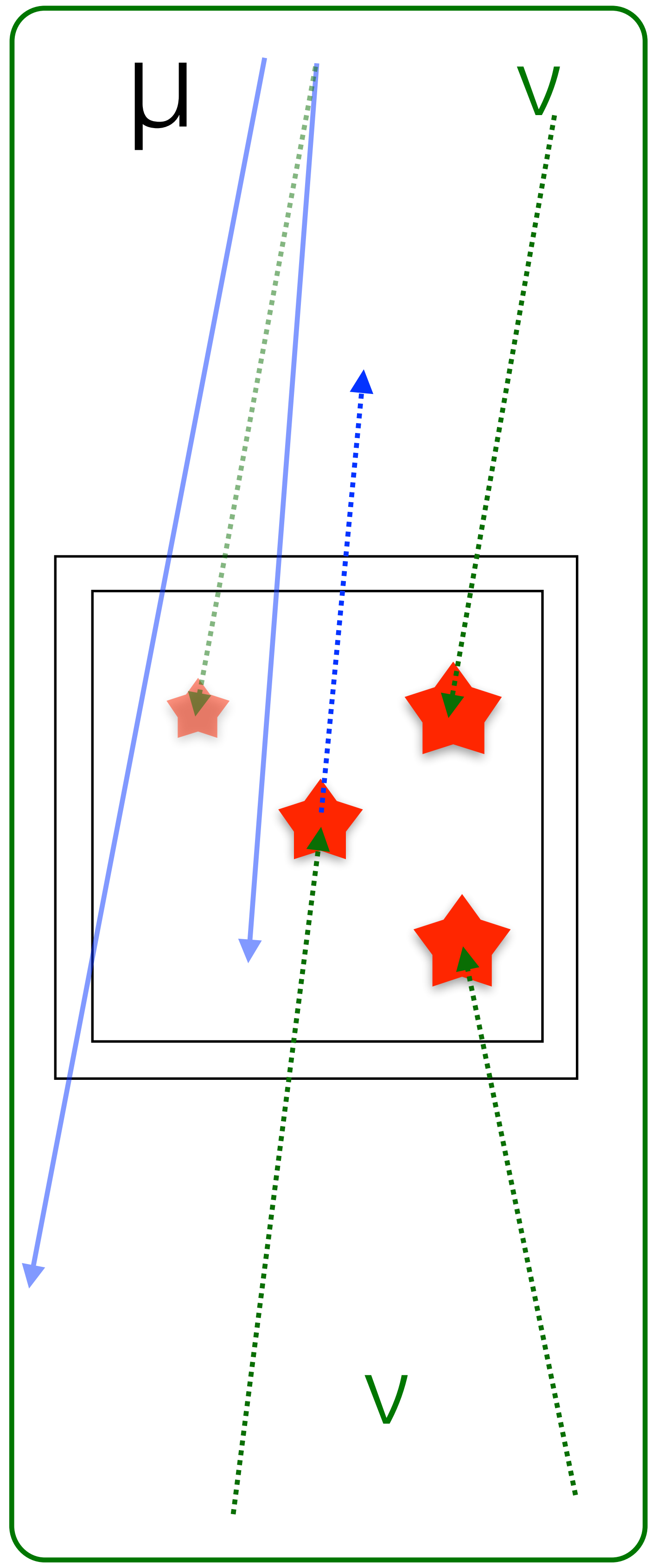
2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>



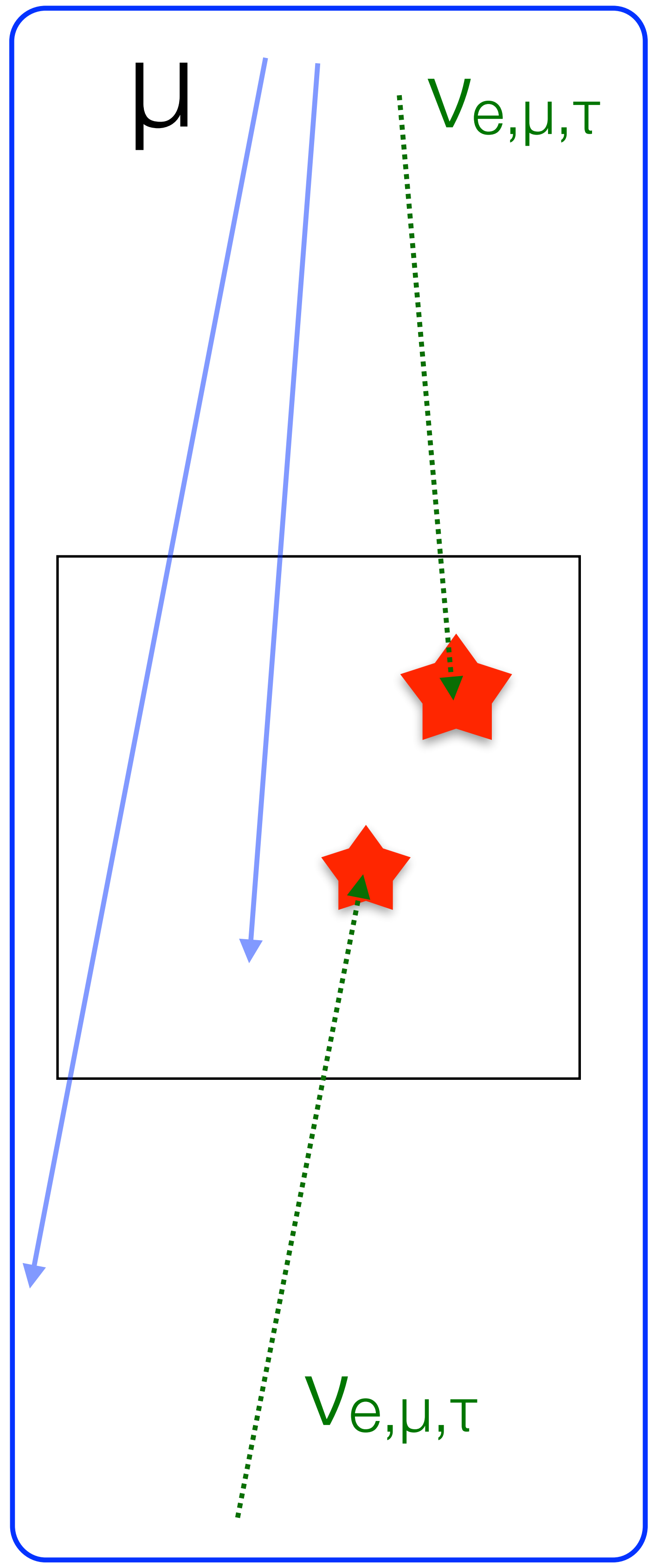
identifying neutrinos

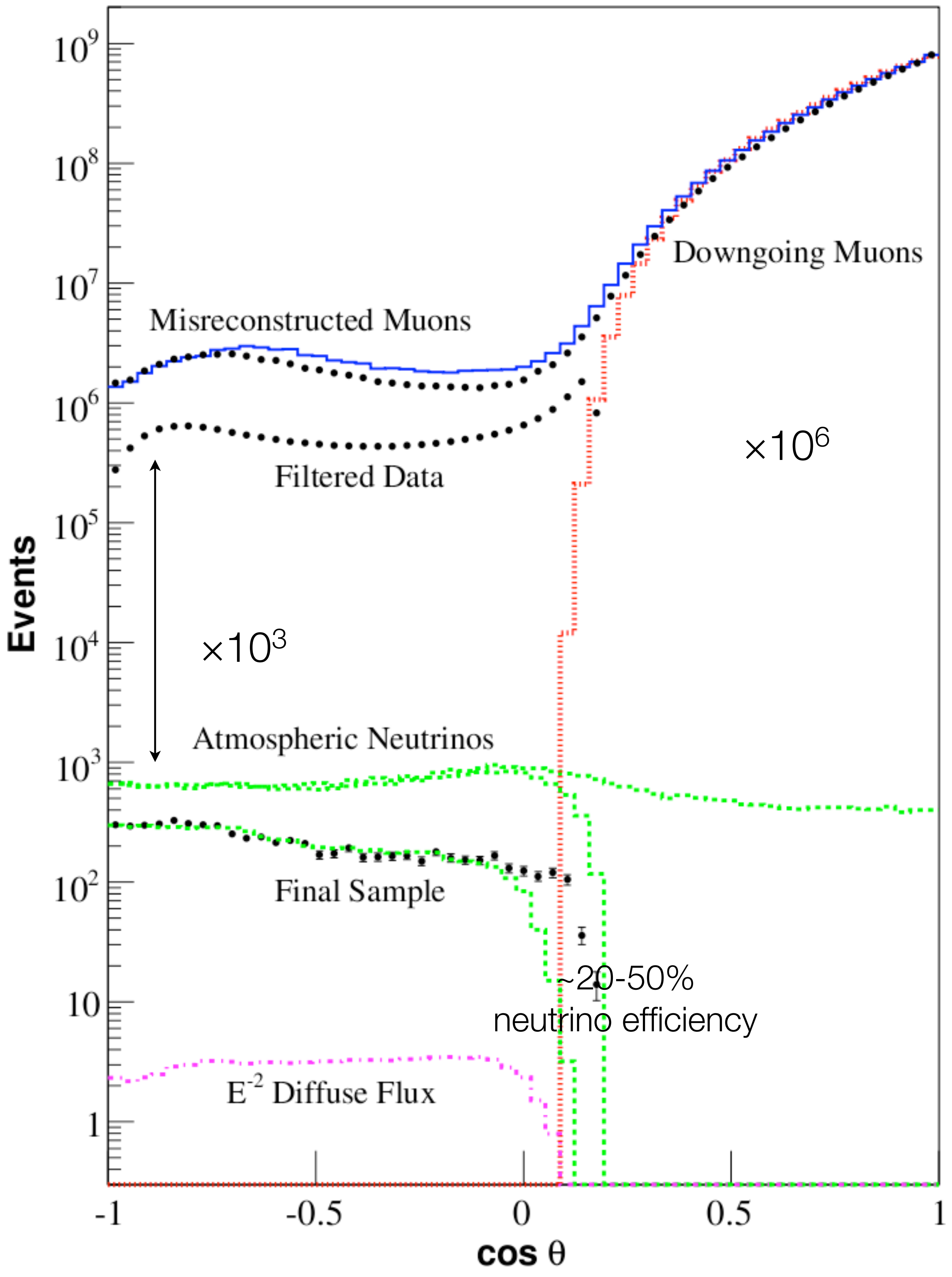
background rejection

starting
(veto)

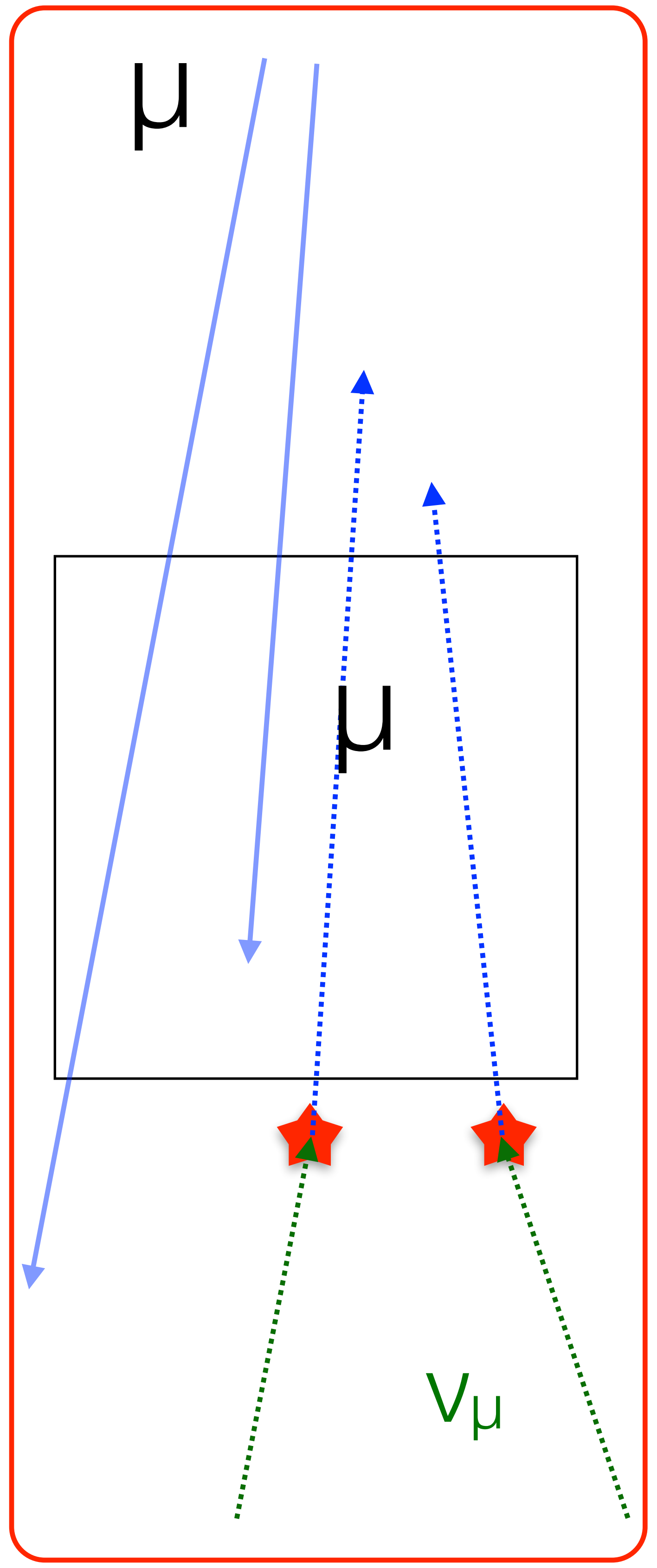


contained
(cascades)



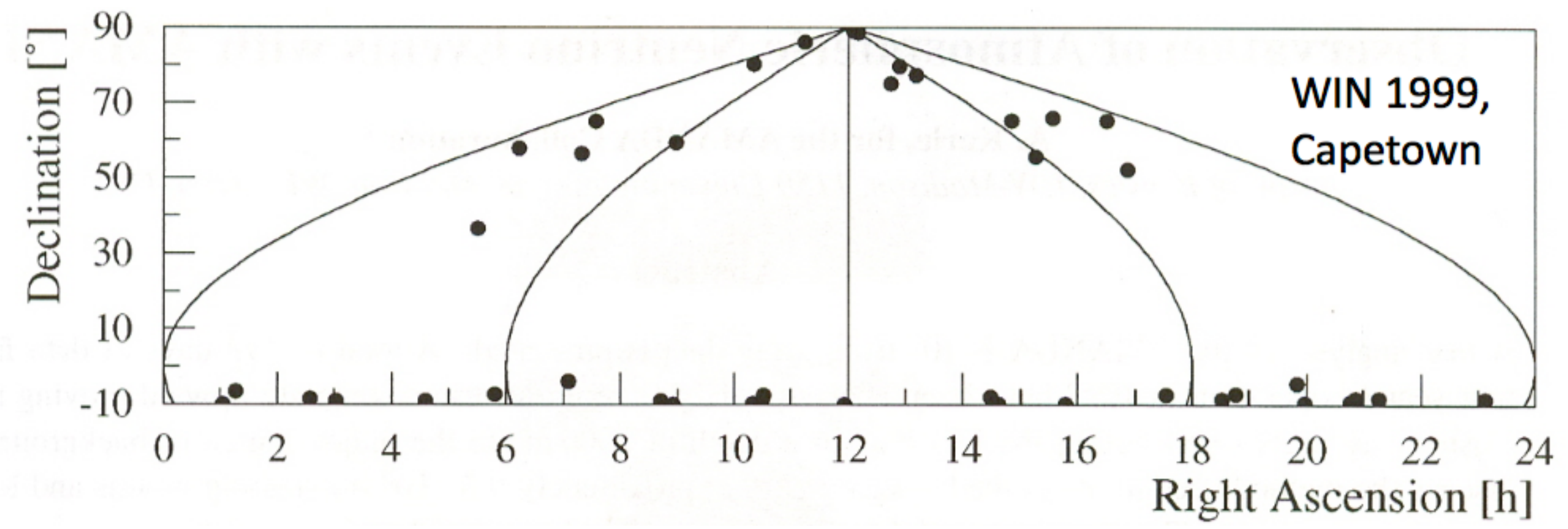


through-going
(tracks)



neutrino telescopes in Antarctica

AMANDA → IceCube



AMANDA

1999

10 strings

1.5×10^{-2} km^3

206 optical modules

17 up-ward ν_μ's

resolution ~ **4°**

E_ν ~ **1 TeV**

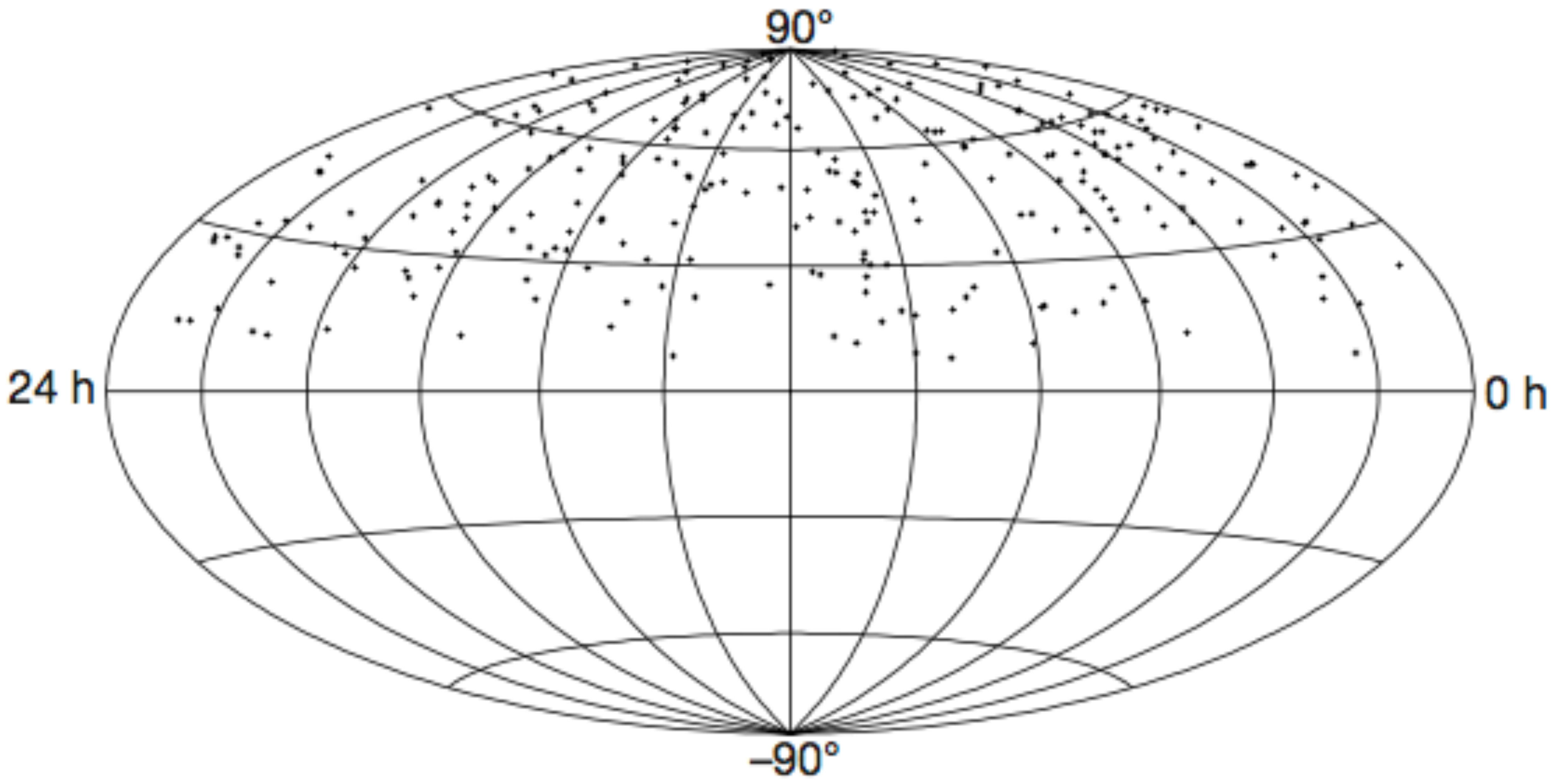
neutrino telescopes in Antarctica

AMANDA → IceCube

AMANDA

1999

2001



10 strings

1.5×10^{-2} km^3

206 optical modules

263 up-ward ν_μ's

resolution ~ **4°**

E_ν ~ **1 TeV**

neutrino telescopes in Antarctica

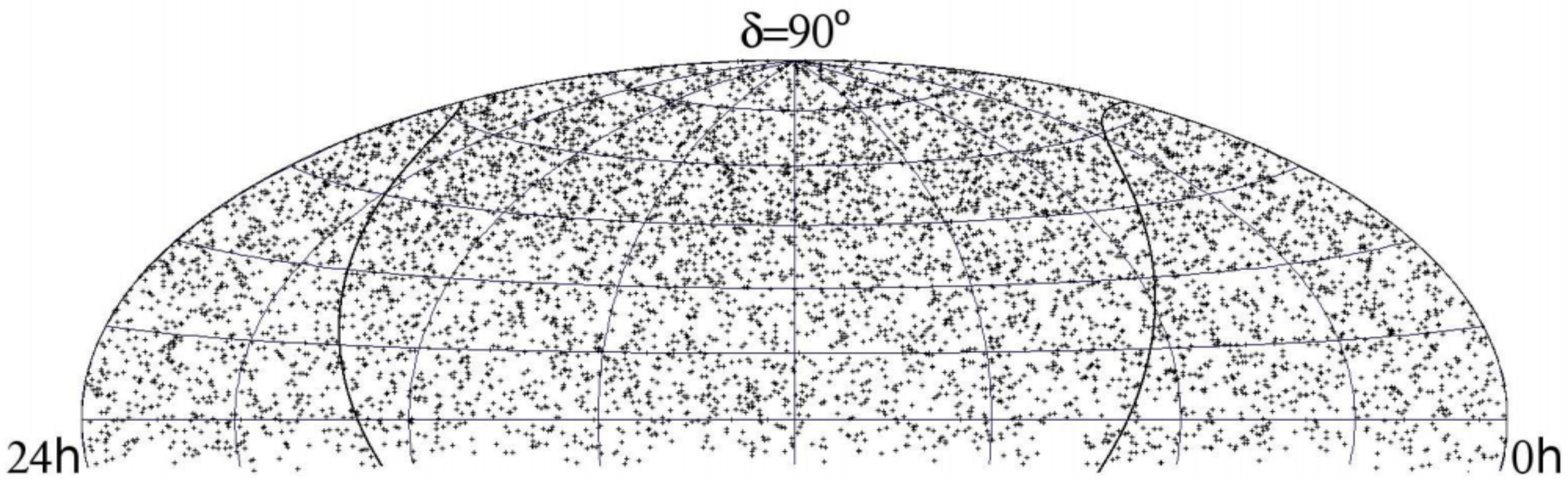
AMANDA → IceCube

AMANDA

1999

2001

2000-2006



19 strings

7×10^{-2} km^3

677 optical modules

6595 up-ward ν_μ's

resolution ~ **2°**

$\langle E_\nu \rangle$ ~ **1-5 TeV**

neutrino telescopes in Antarctica

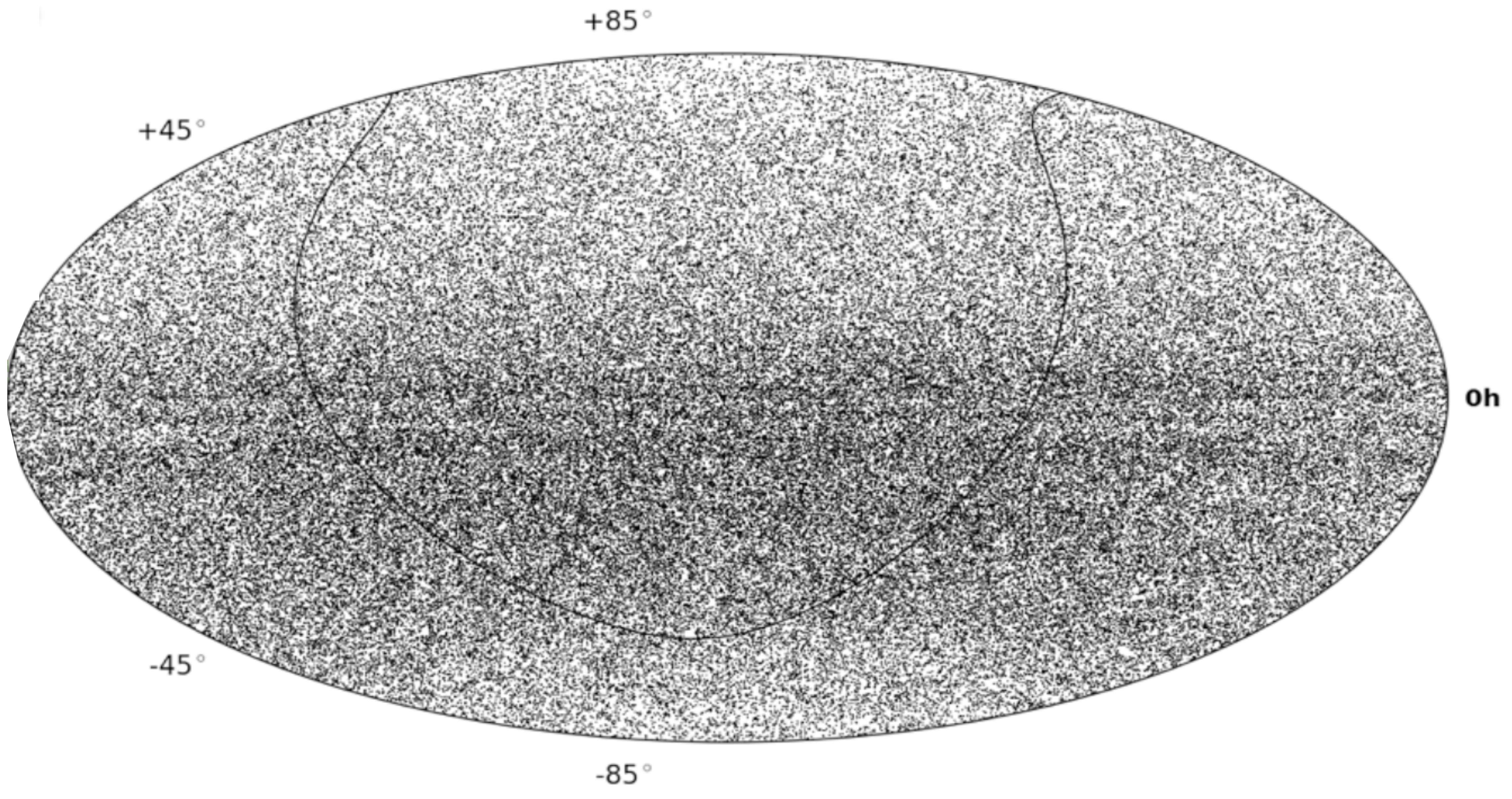
AMANDA → IceCube

AMANDA **1999**

2001

2000-2006

IceCube **2008-2009**



40-59 strings

~0.5 km^3

4800 optical modules

43339 up-ward ν_μ's

64230 down-ward μ

resolution ~ **0.7°**

$\langle E_\nu \rangle$ ~ **1-5 TeV**

neutrino telescopes in Antarctica

AMANDA → IceCube

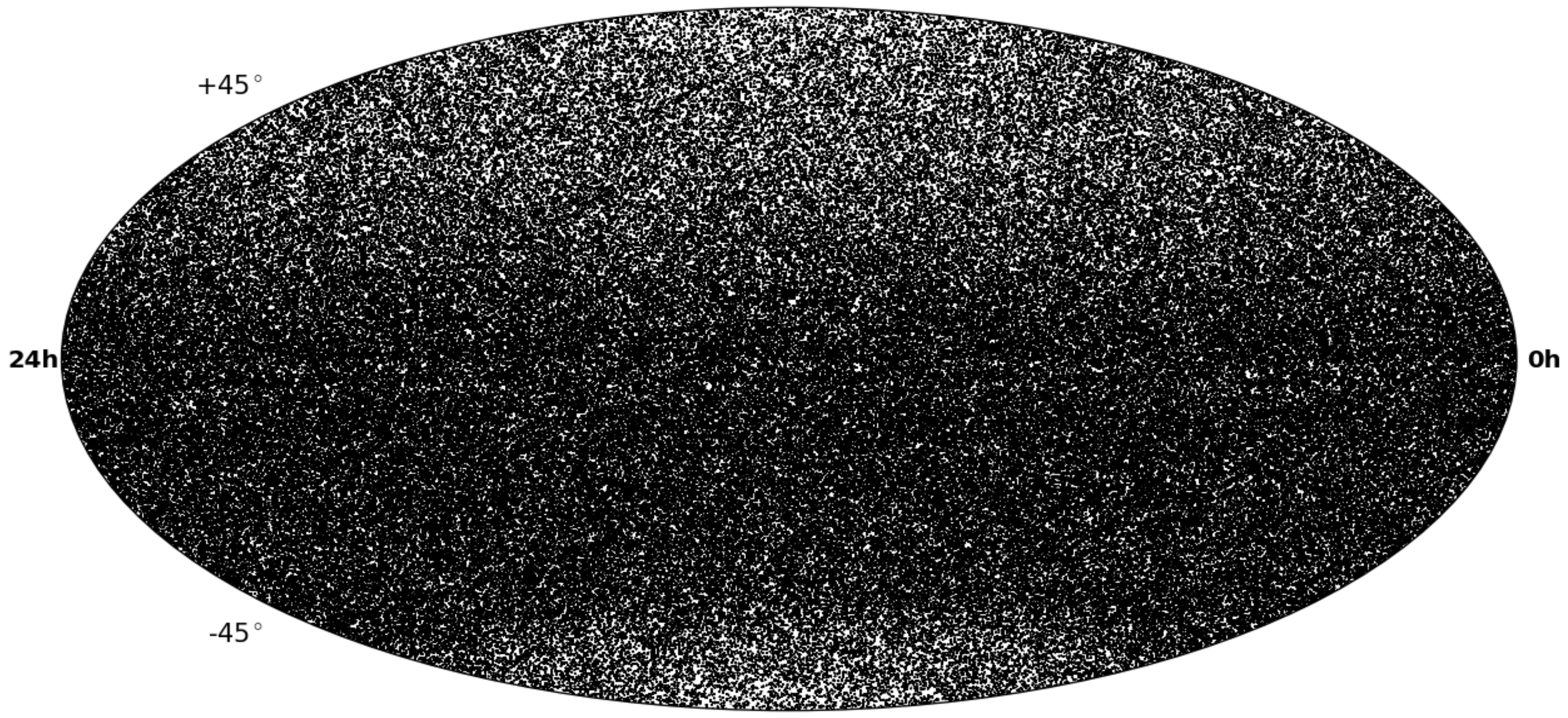
AMANDA **1999**

2001

2000-2006

IceCube **2008-2009**

2008-2010



40-59-79 strings

~1 km^3

4800 optical modules

108317 up-ward ν_μ's

146018 down-ward μ

resolution ~ **0.4°**

$\langle E_\nu \rangle$ ~ **1-5 TeV**

neutrino telescopes in Antarctica

AMANDA → IceCube

AMANDA 1999

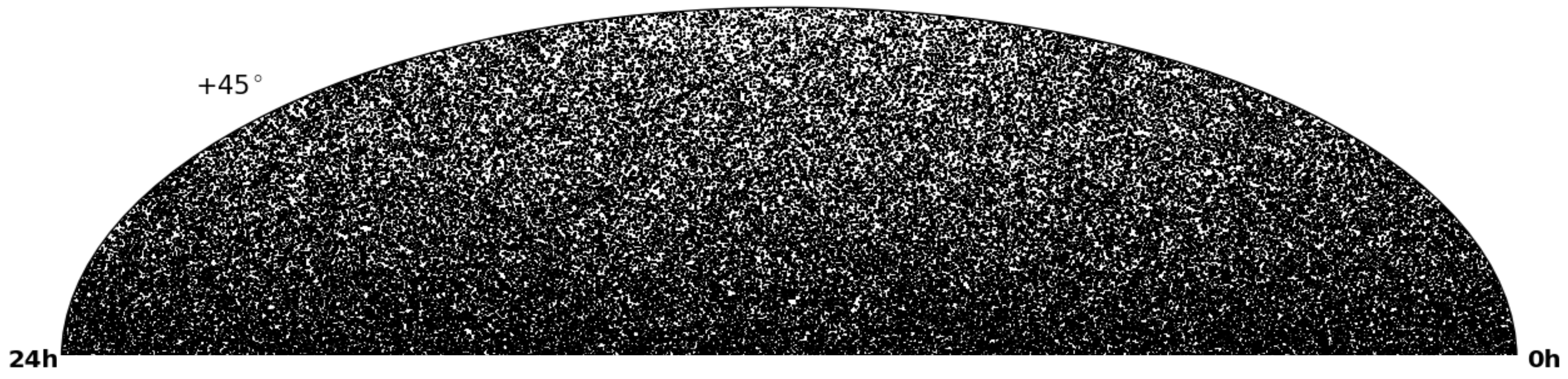
2001

2000-2006

IceCube 2008-2009

2008-2010

→ 2008-2014



40-59-79+86's strings

1 km^3

4800 optical modules

~**360000** up-ward ν_μ's

170 ν's / day

resolution ~ **0.4°**

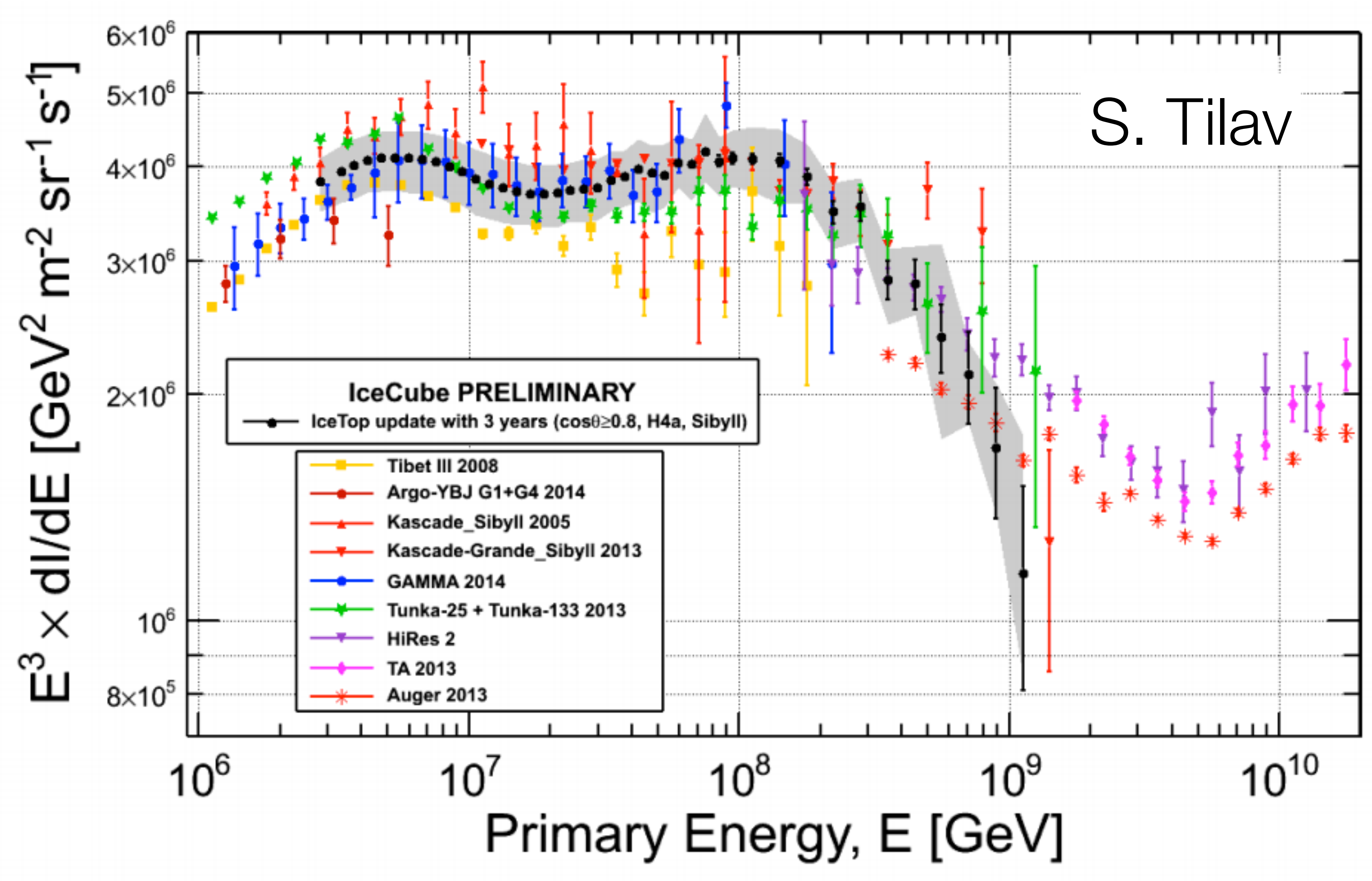
$\langle E_\nu \rangle$ ~ **1-5 TeV**

cosmic rays & atmospheric leptons

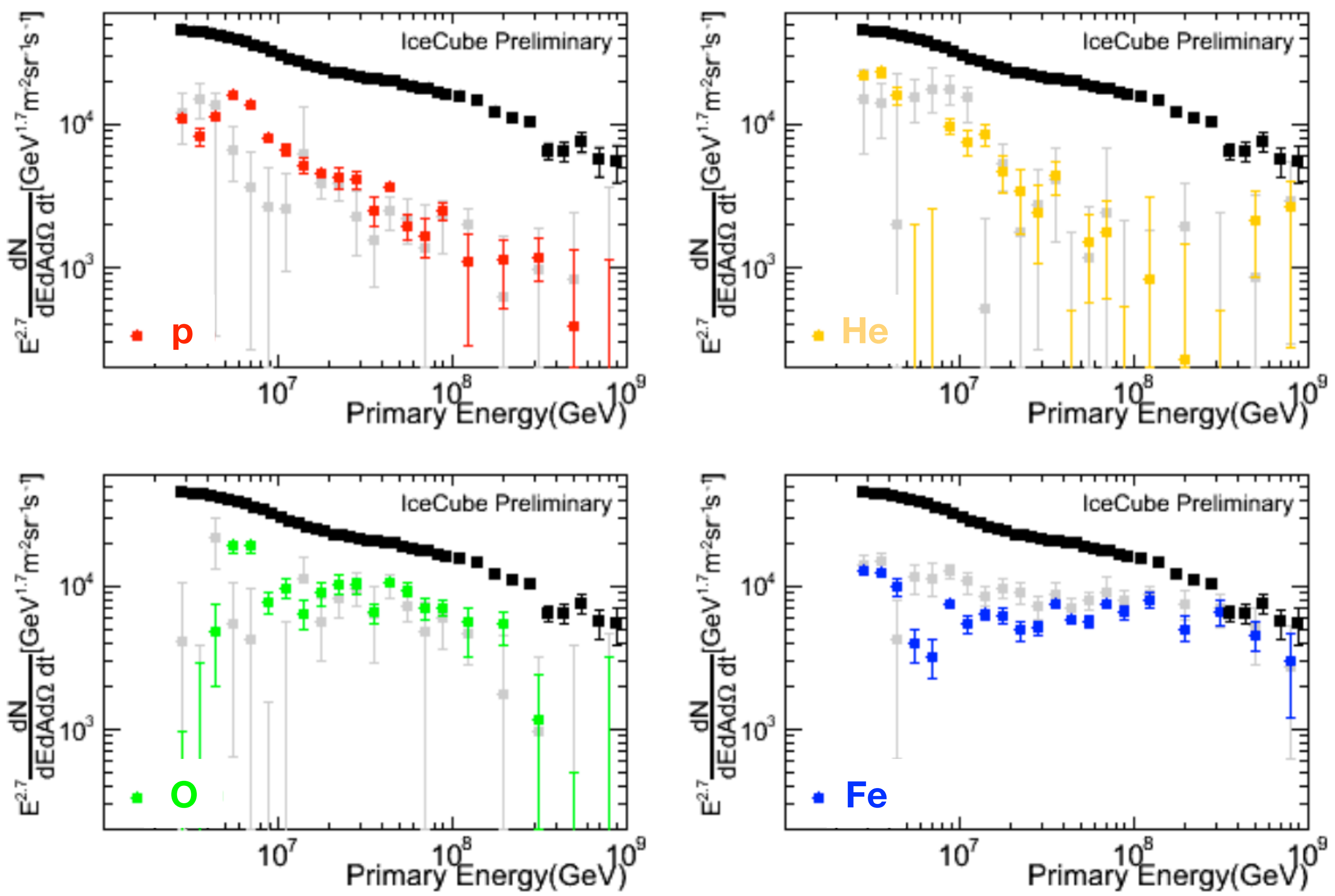
ICRC 2015
K. Rawlins
T. Feusels

IceTop

all-particle energy spectrum

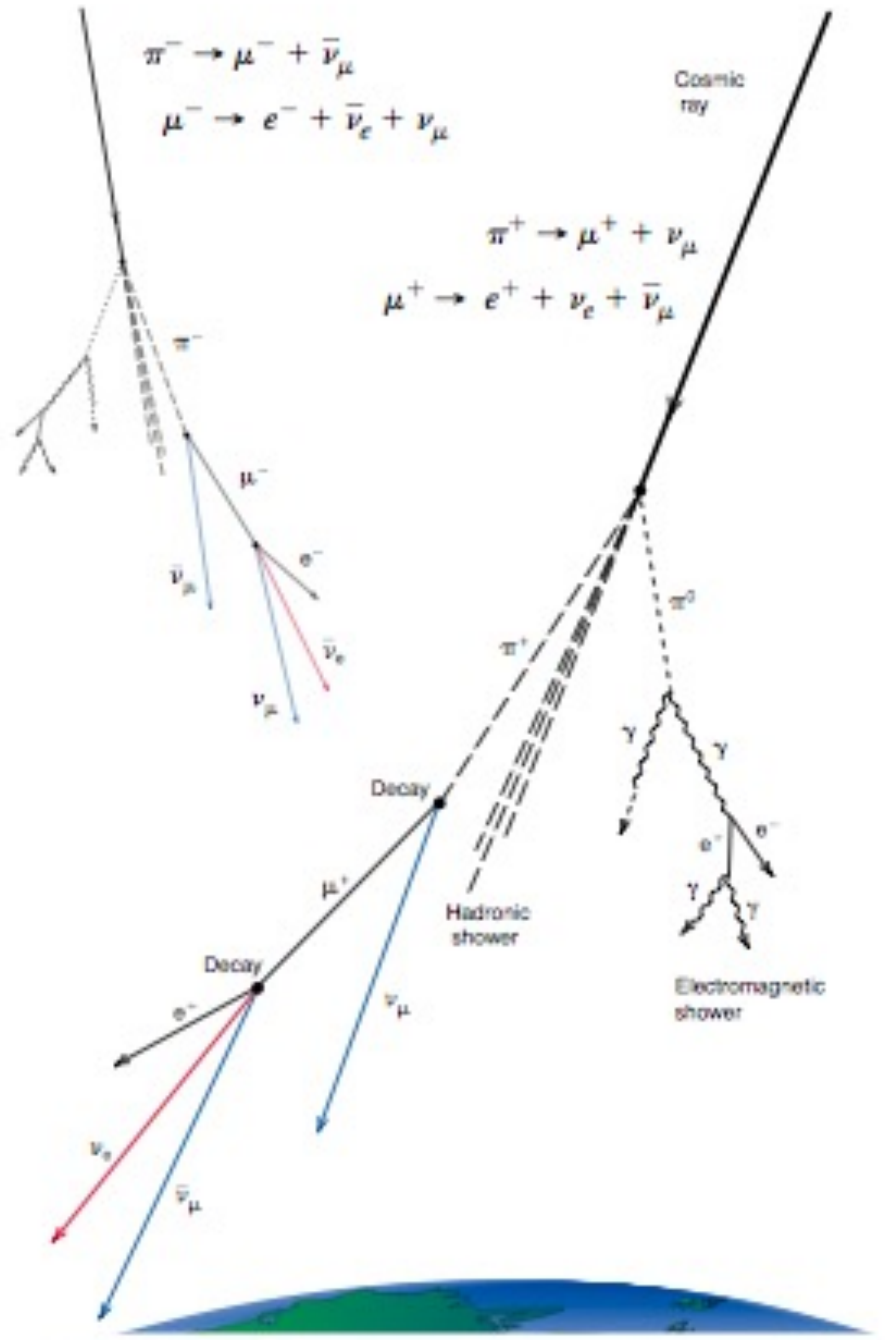


cosmic ray composition



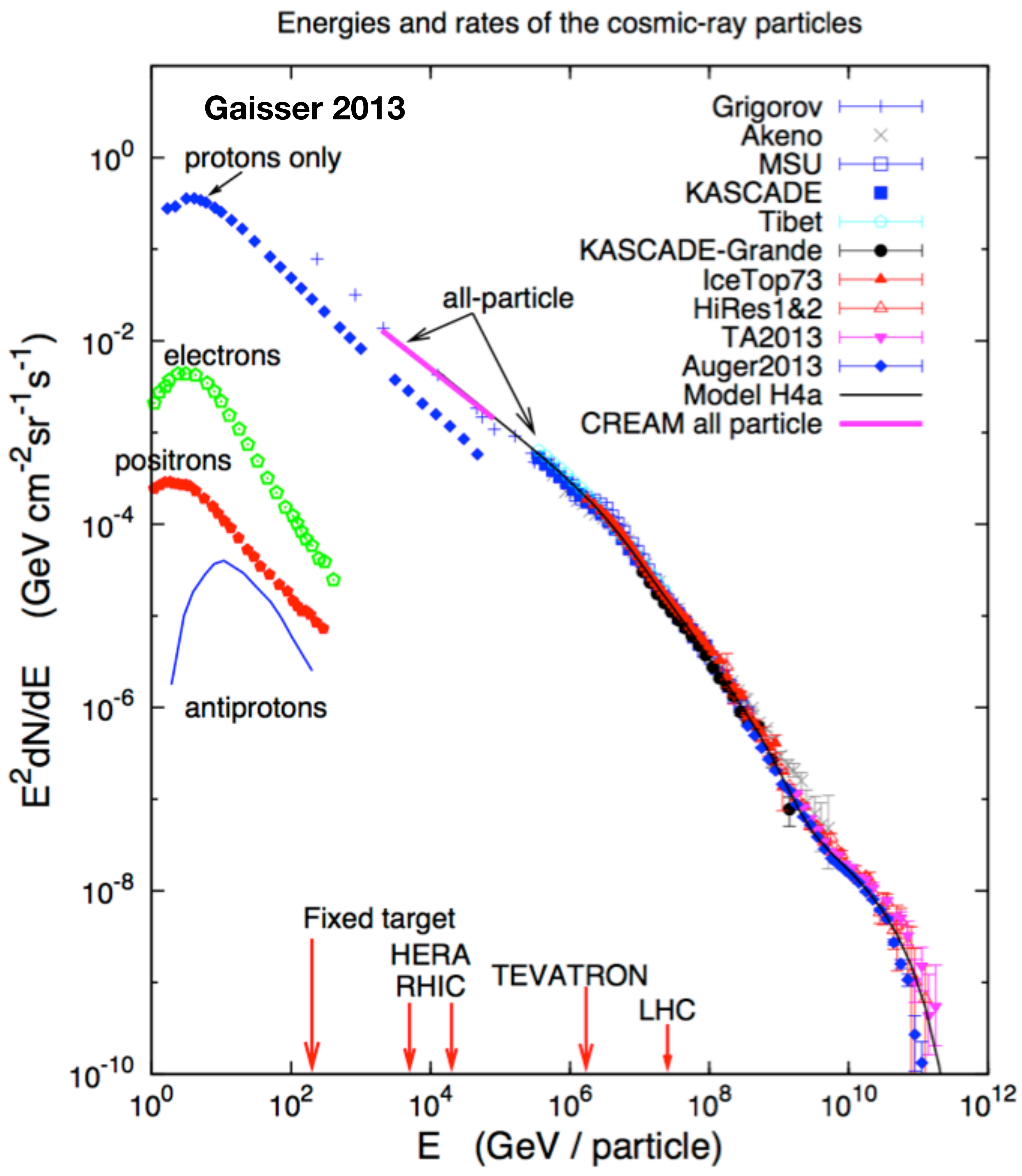
CR spectrum & composition determines **shape** of atmospheric ν and μ spectrum

cosmic rays & atmospheric leptons



$$
\begin{aligned}
N_{CR} + N_{air} \longrightarrow X \quad & + \pi + K \\
& + D + \Lambda \\
& + \ldots
\end{aligned}
$$

hadronic interactions determine **shape** of atmospheric ν and μ spectrum



cosmic rays & atmospheric leptons

		$(\nu_e : \nu_\mu : \nu_\tau)$
$\pi^\pm\ K^\pm \to\ \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$ (63.5% for K) $\hookrightarrow e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$		$(1:2:0)$
→ E_ν ~ 100/cosθ GeV	**conventional**	
$K^\pm \longrightarrow \pi^0 e\nu_e$ (5%) $K^0_L \longrightarrow \pi e\nu_e$ (40%)		$(1:20:0)$
→ E_ν ~ 100/cosθ TeV		
$K^0_S \longrightarrow \pi e\nu_e$ (Gaisser & Klein 2014) (0.07%)	**prompt**	
$D, \Lambda_c \longrightarrow \ell + \nu_\ell + \ldots$ (order %)		$(1:1:1/10)$
$\eta, \eta' \longrightarrow \mu^+\mu^-$		

cosmic rays & atmospheric leptons

$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu}\cos\theta\, E_\nu/\epsilon_{\mathrm{charm}}} \right\}$$

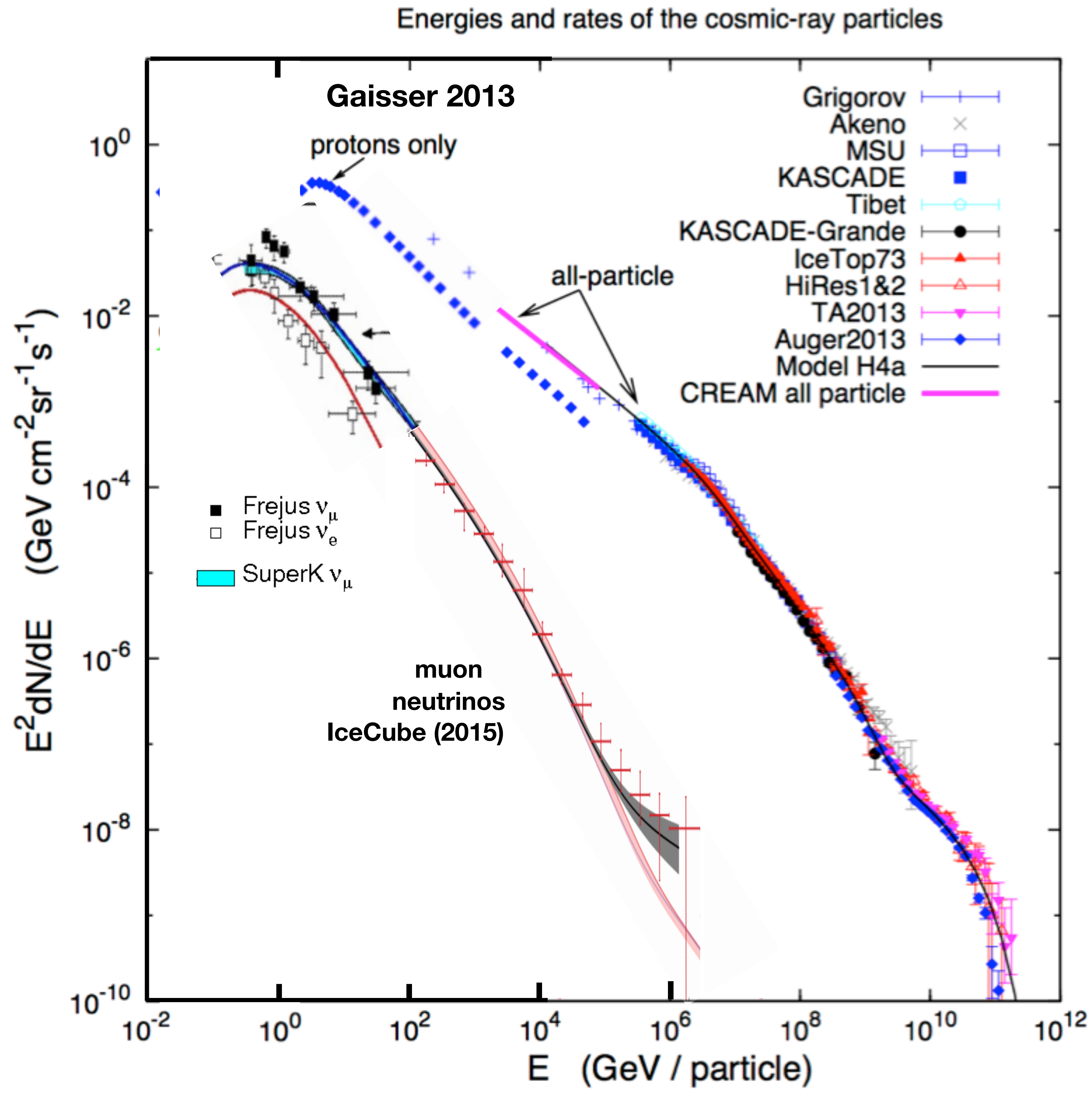
Gaisser 1990

$$A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \qquad (Z_{NN} = Z_{pp} + Z_{pn})$$

$$Z_{N\pi^\pm}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{\pi^\pm}(E',E)}{\mathrm{d}E}$$

$$\epsilon_i = \frac{kT}{Mg}\frac{m_i c^2}{c\tau_i} \qquad i = \pi, K, charm, \ldots$$

$Particle\,(i)$	$\pi^\pm$	$K^\pm$	K^0_L	K^0_S	$charm$
$\epsilon_i\,(GeV)$	115	850	205	1.2×10^5	$\sim 3 \times 10^7$

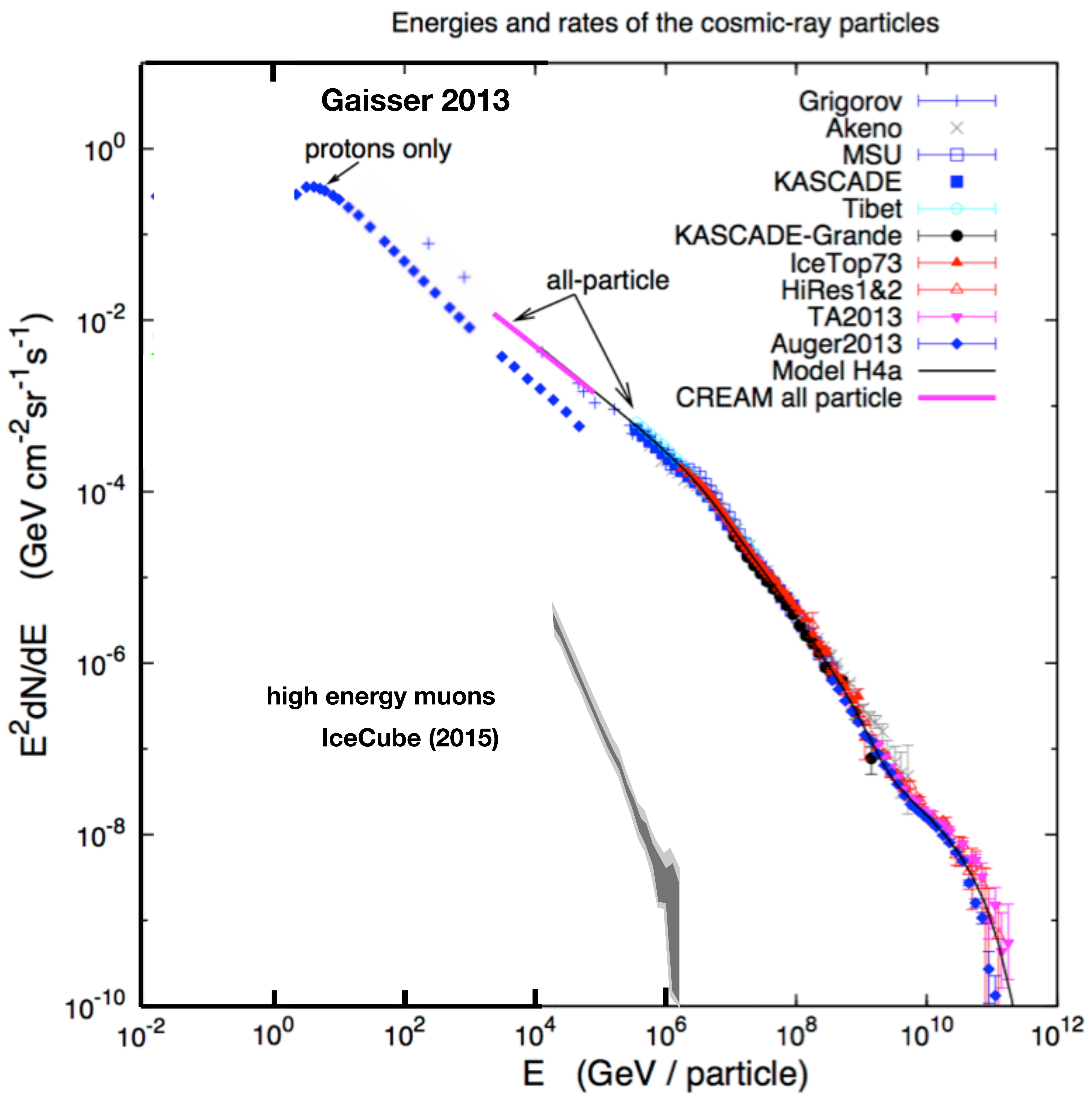


cosmic rays & atmospheric leptons

$$\phi_\nu(E_\mu) = \phi_N(E_\mu) \times \left\{ \frac{A_{\pi\mu}}{1 + B_{\pi\mu}\cos\theta\, E_\mu/\epsilon_\pi} + \frac{A_{K\mu}}{1 + B_{K\mu}\cos\theta\, E_\mu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\mu}}{1 + B_{\mathrm{charm}\,\mu}\cos\theta\, E_\mu/\epsilon_{\mathrm{charm}}} \right\}$$

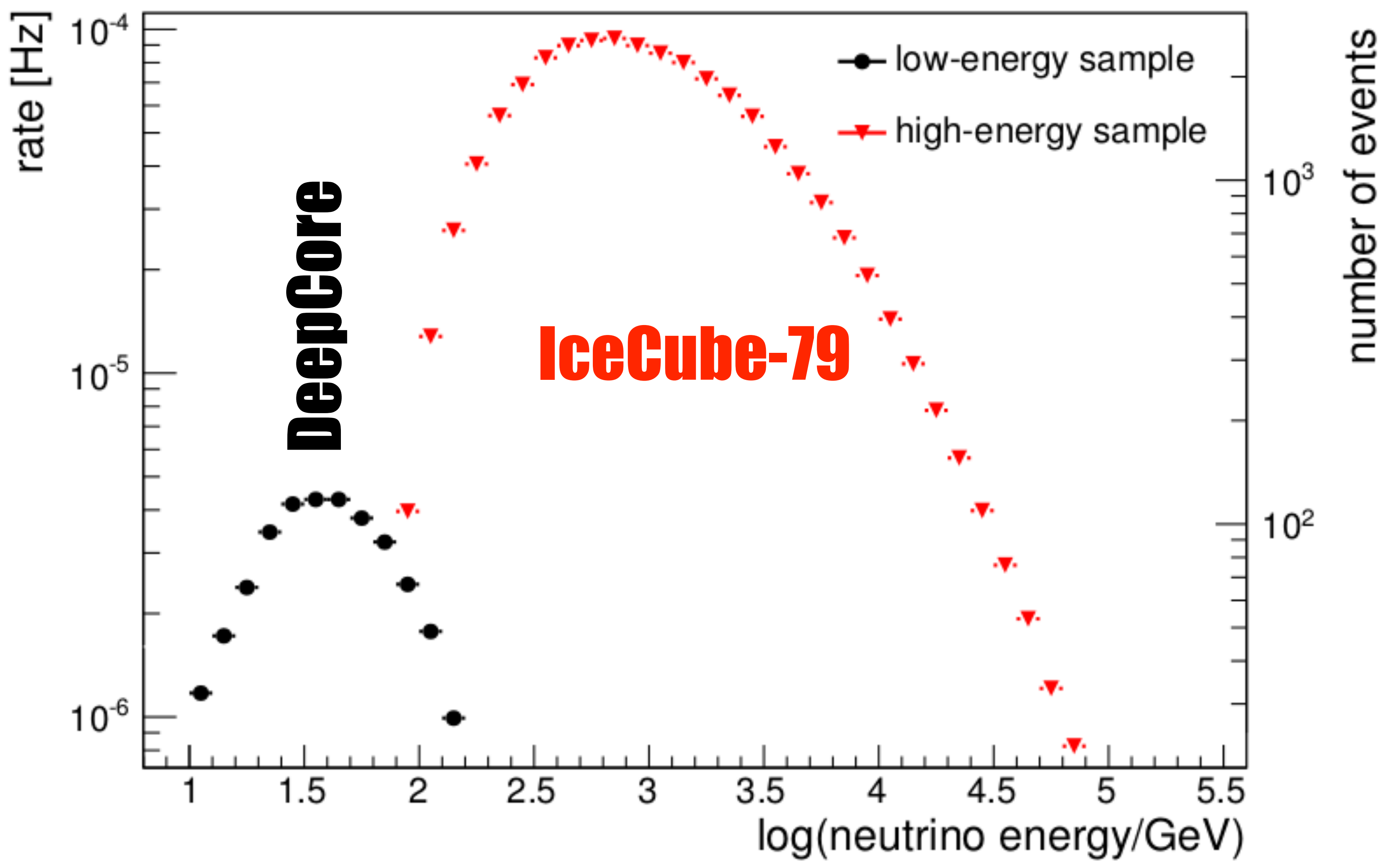
Gaisser 1990

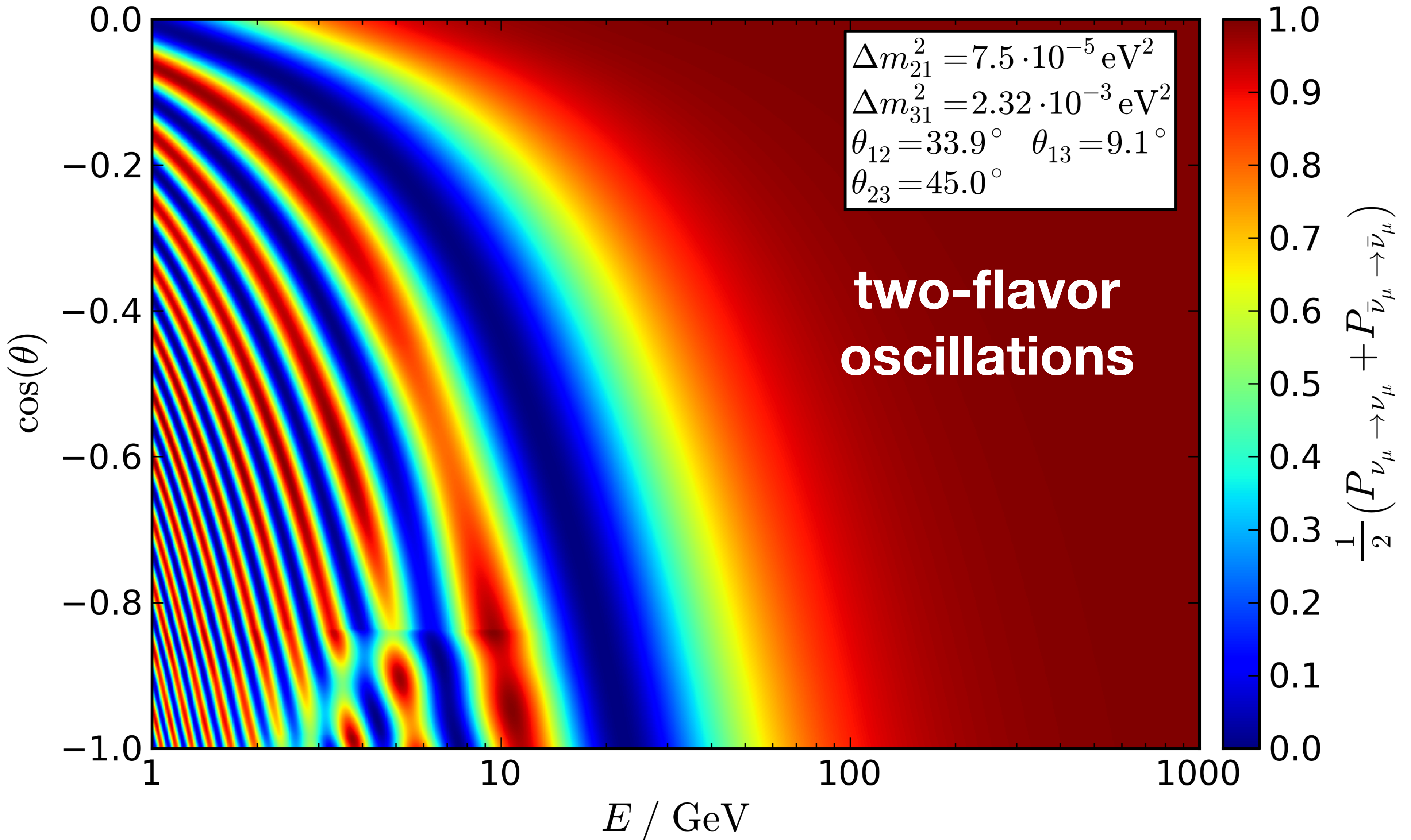
- **ν**'s and **μ**'s from same hadronic processes in cosmic ray atmospheric showers
- high level **cross-calibration** sensitive to hadronic interaction models



low energy neutrinos

10 GeV - 300 GeV



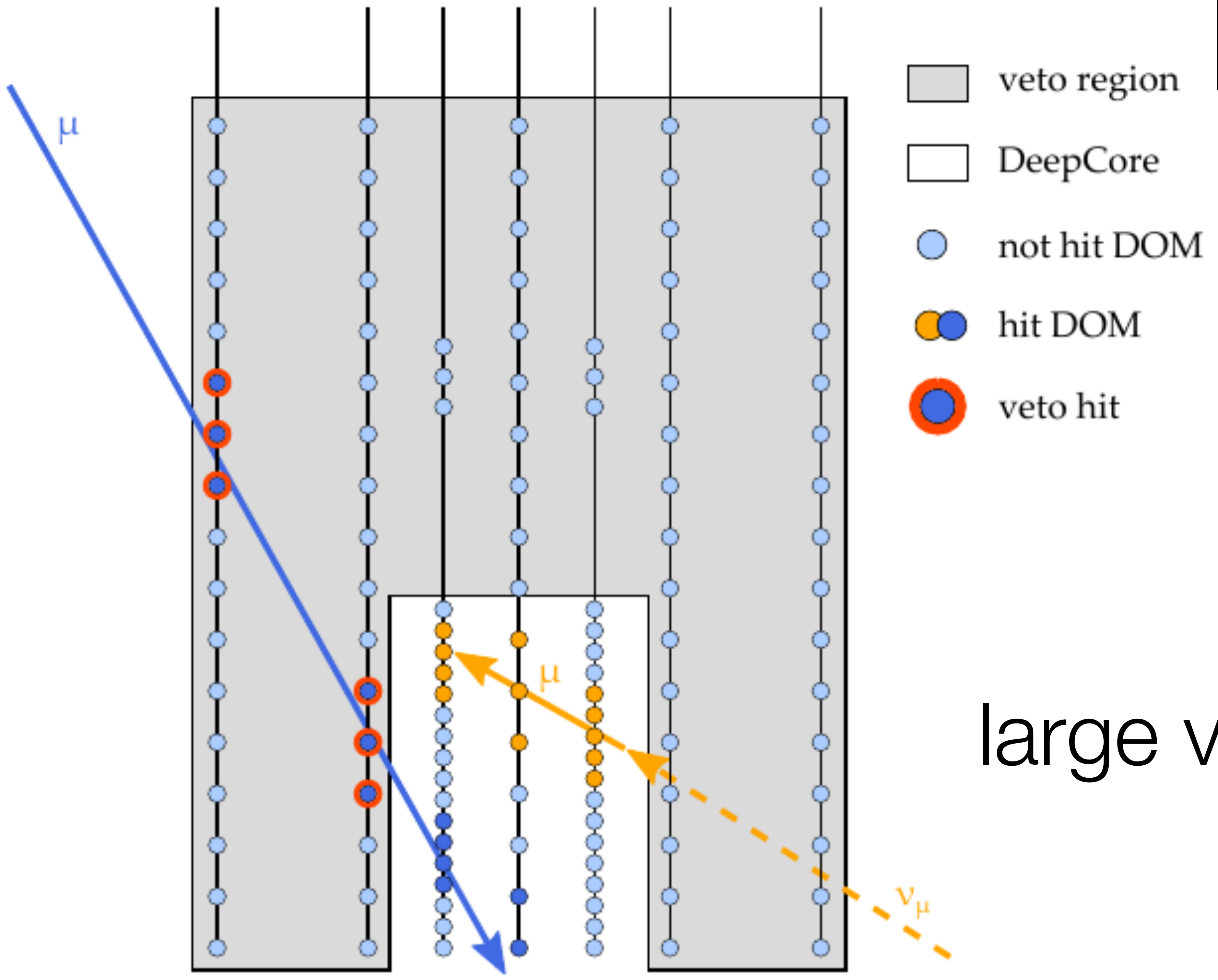


Phys. Rev. Lett. 111, 081801 2013

719 low energy events

39638 high energy events

in 318.9 days

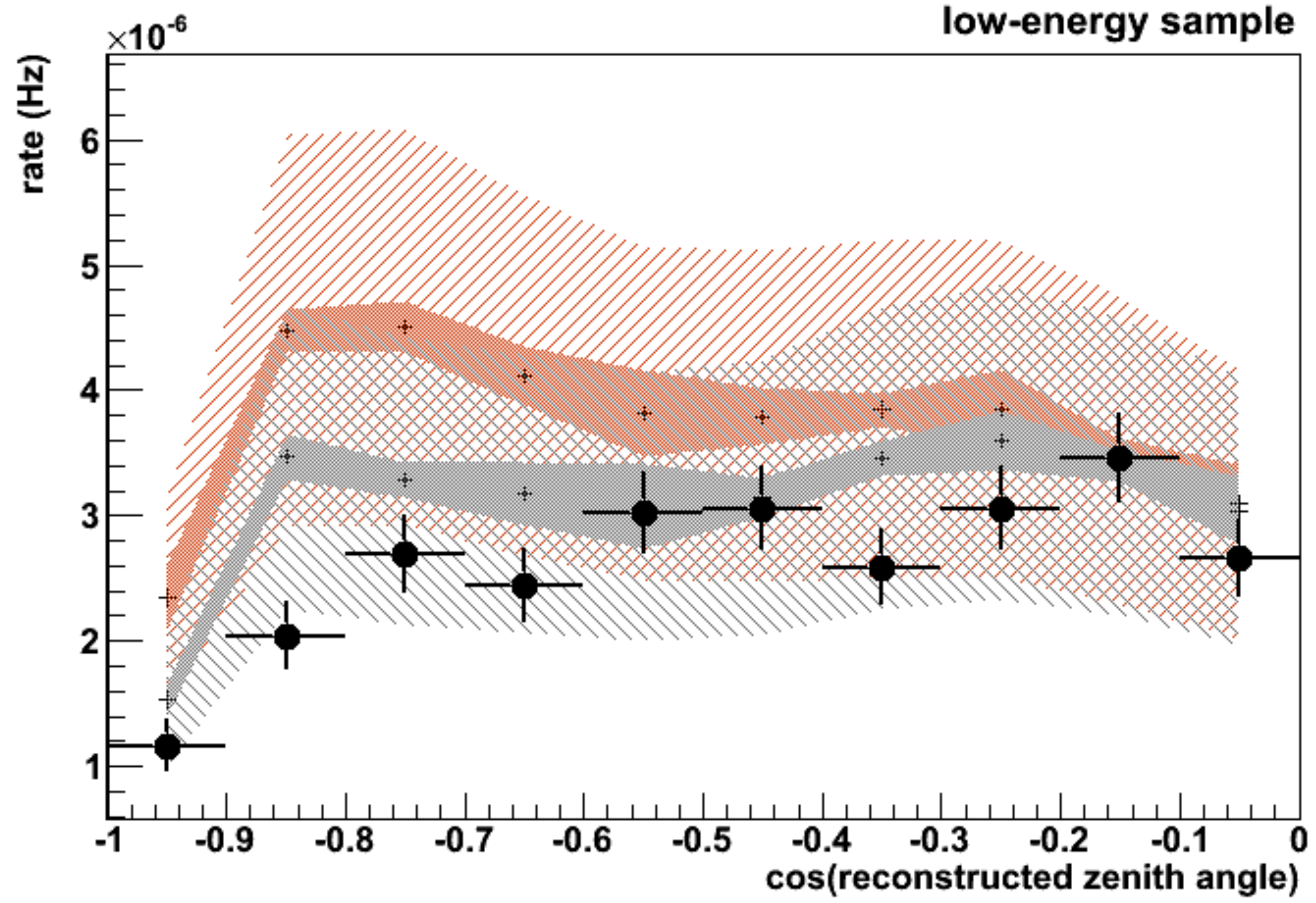


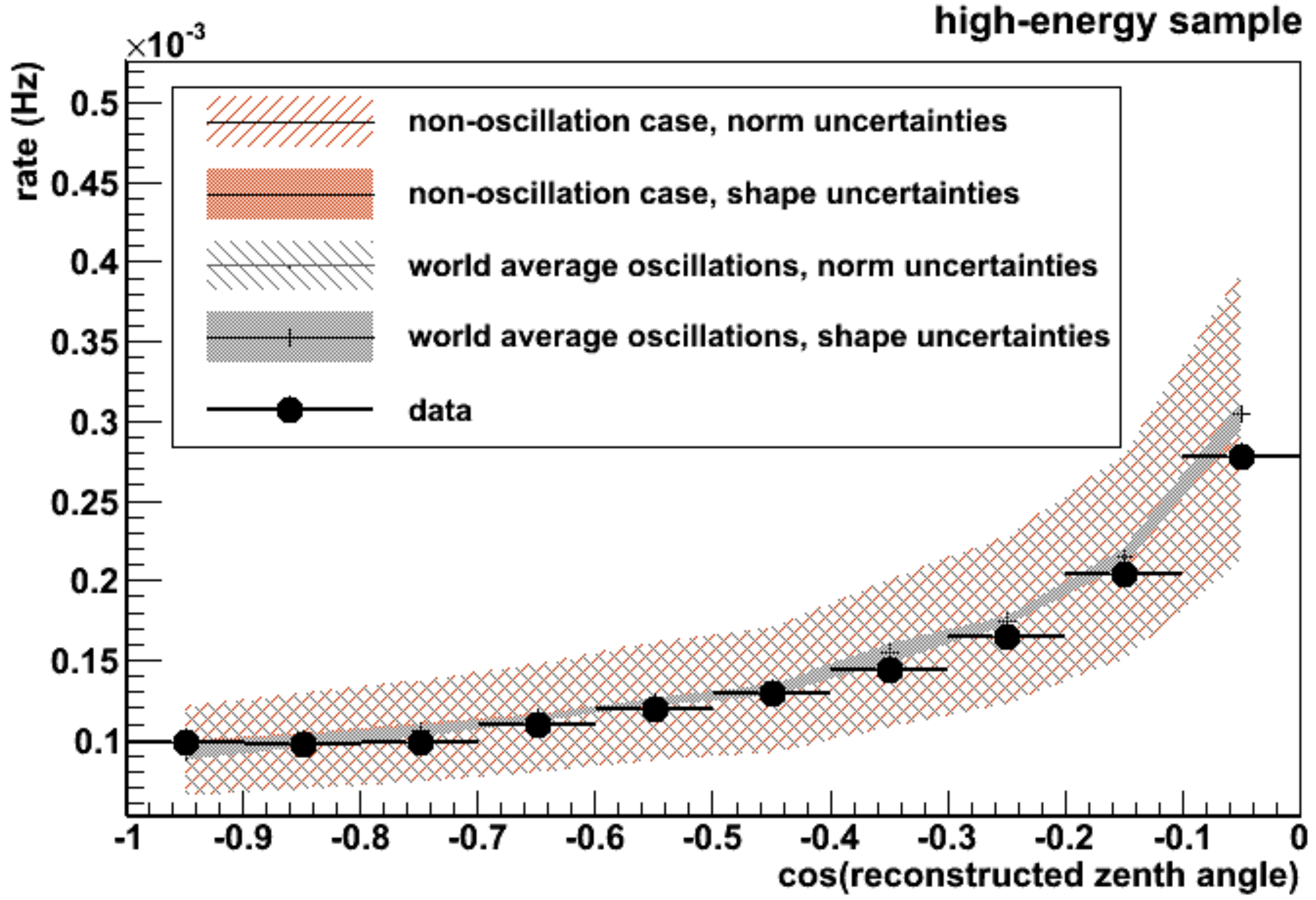
large volume → VETO

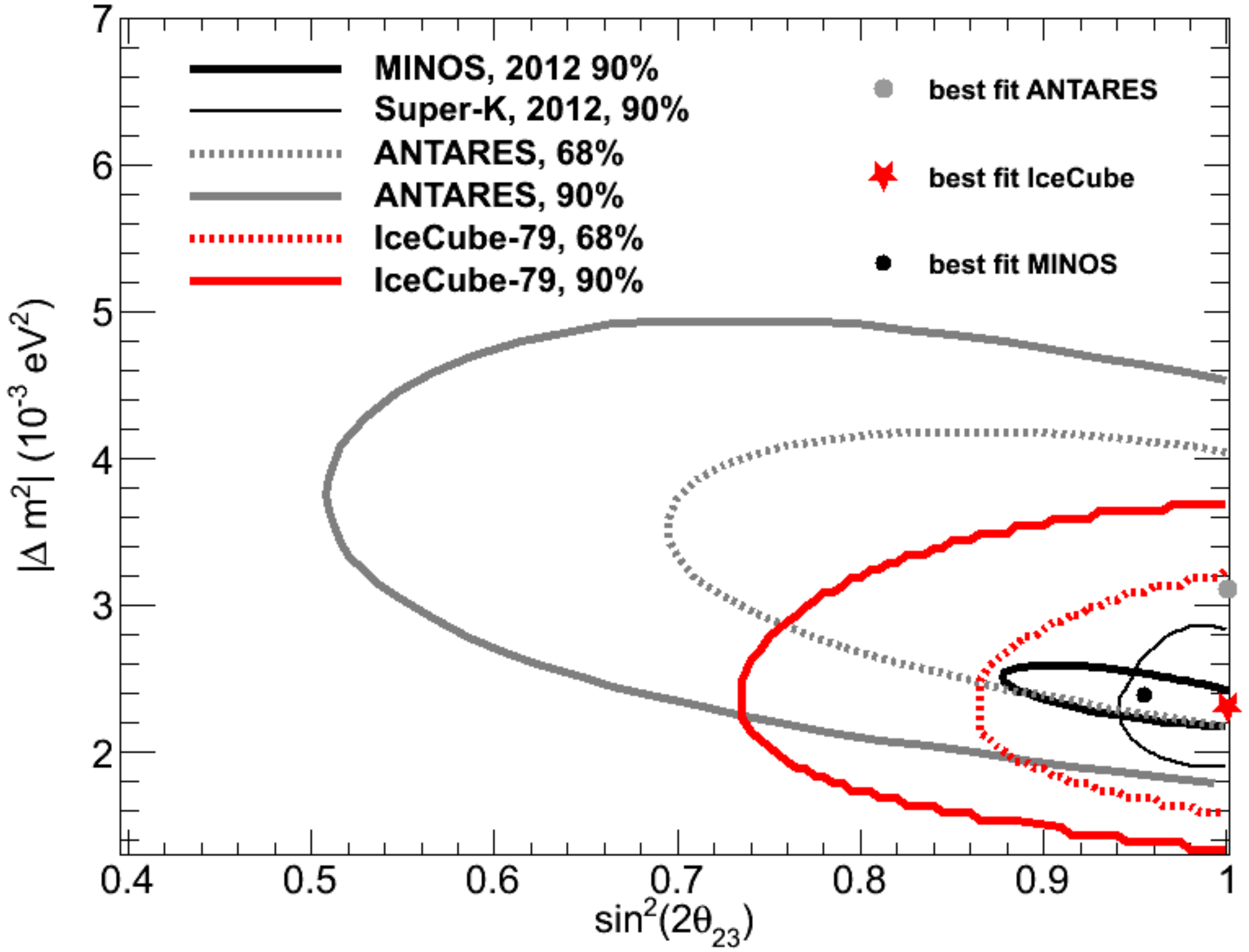
low energy neutrinos

10 GeV - 300 GeV

Phys. Rev. Lett. 111, 081801 **2013**







non-oscillation hypothesis rejected at 5.6σ (p-value ~ 10^{-8})

best fit

$$\Delta m^2_{23} = 2.3 \times 10^{-3}\, eV^2$$

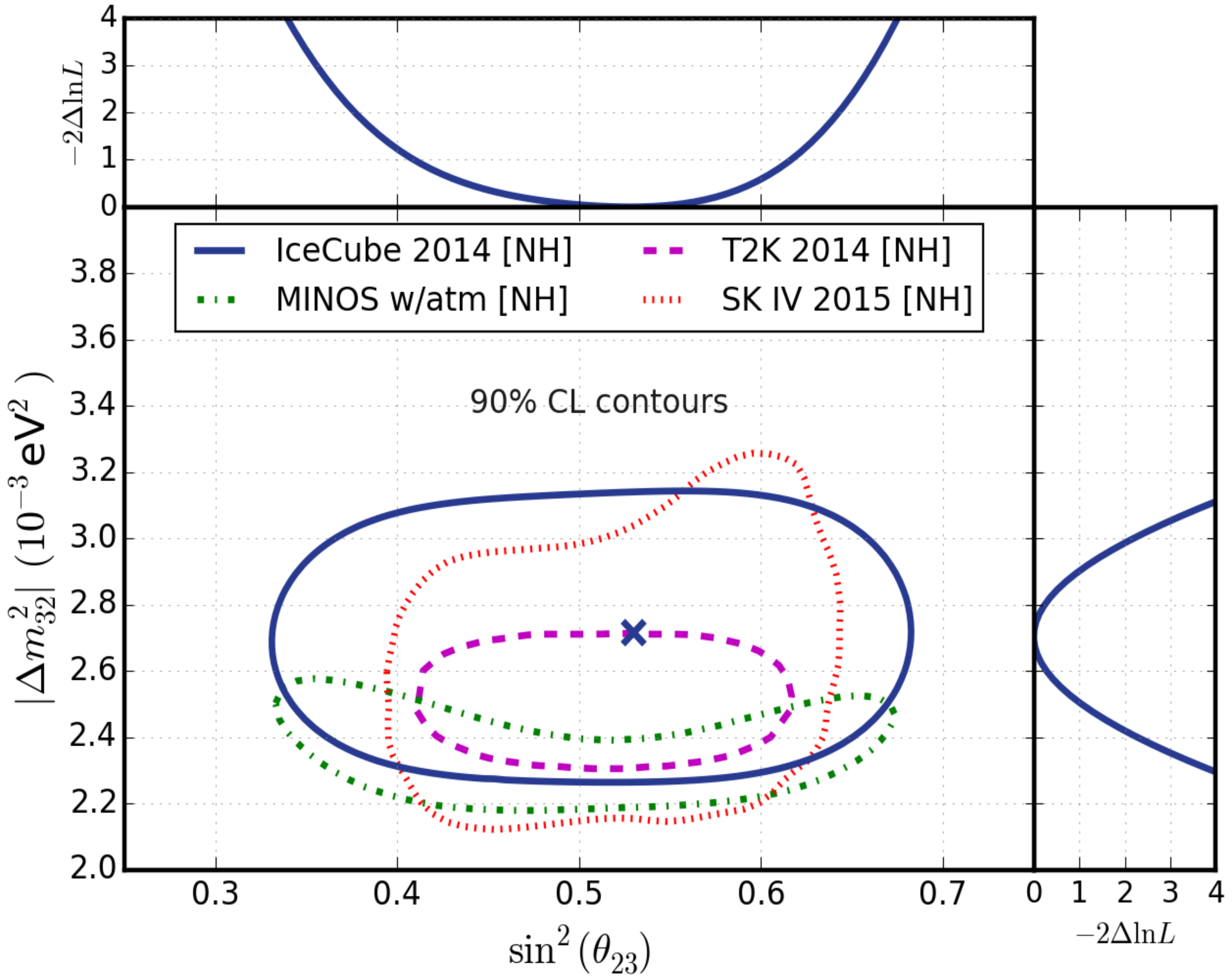
$$sin^2(2\theta_{23}) = 1$$

$$\chi^2 = 15.7/18$$

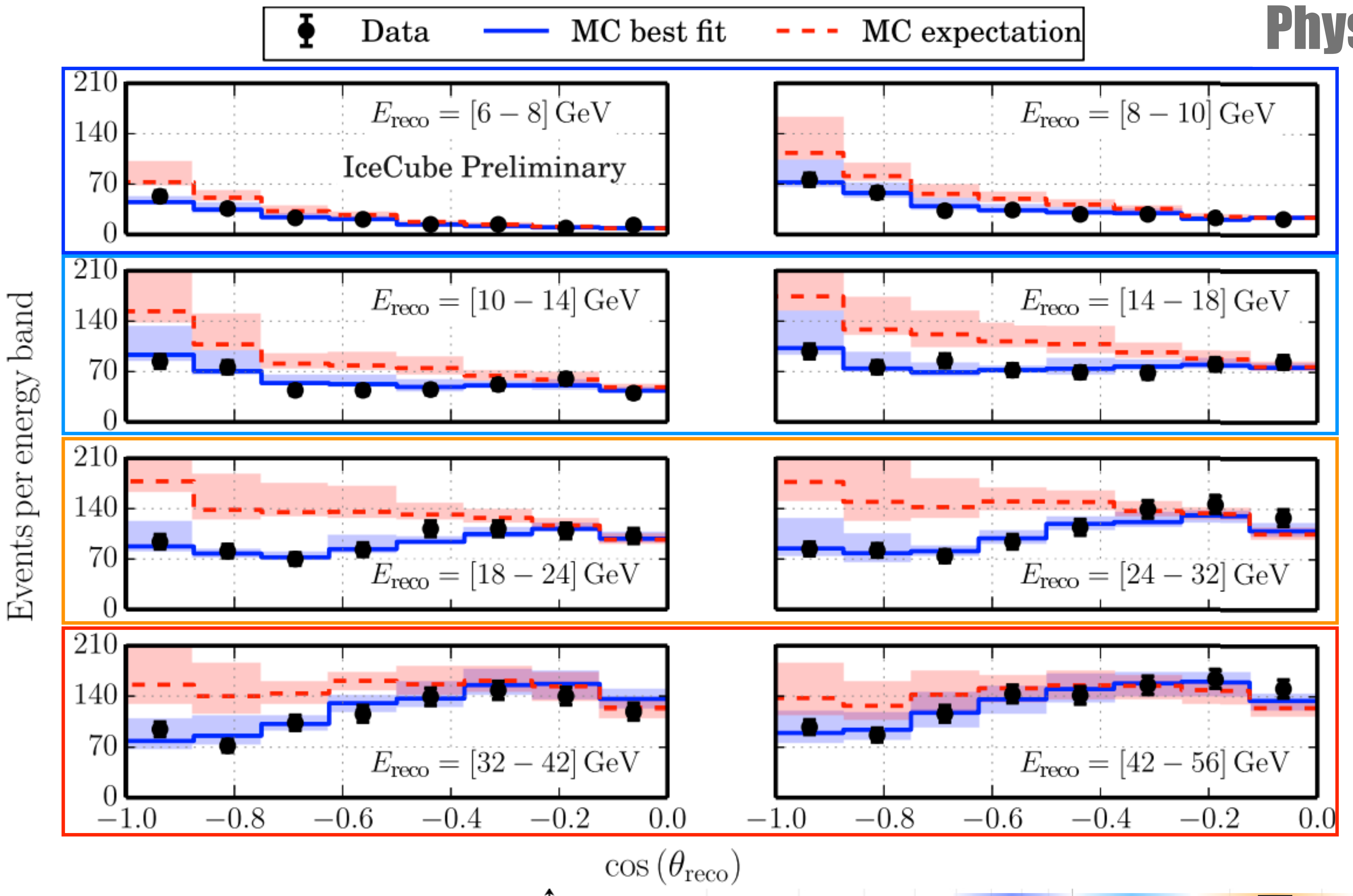
low energy neutrinos

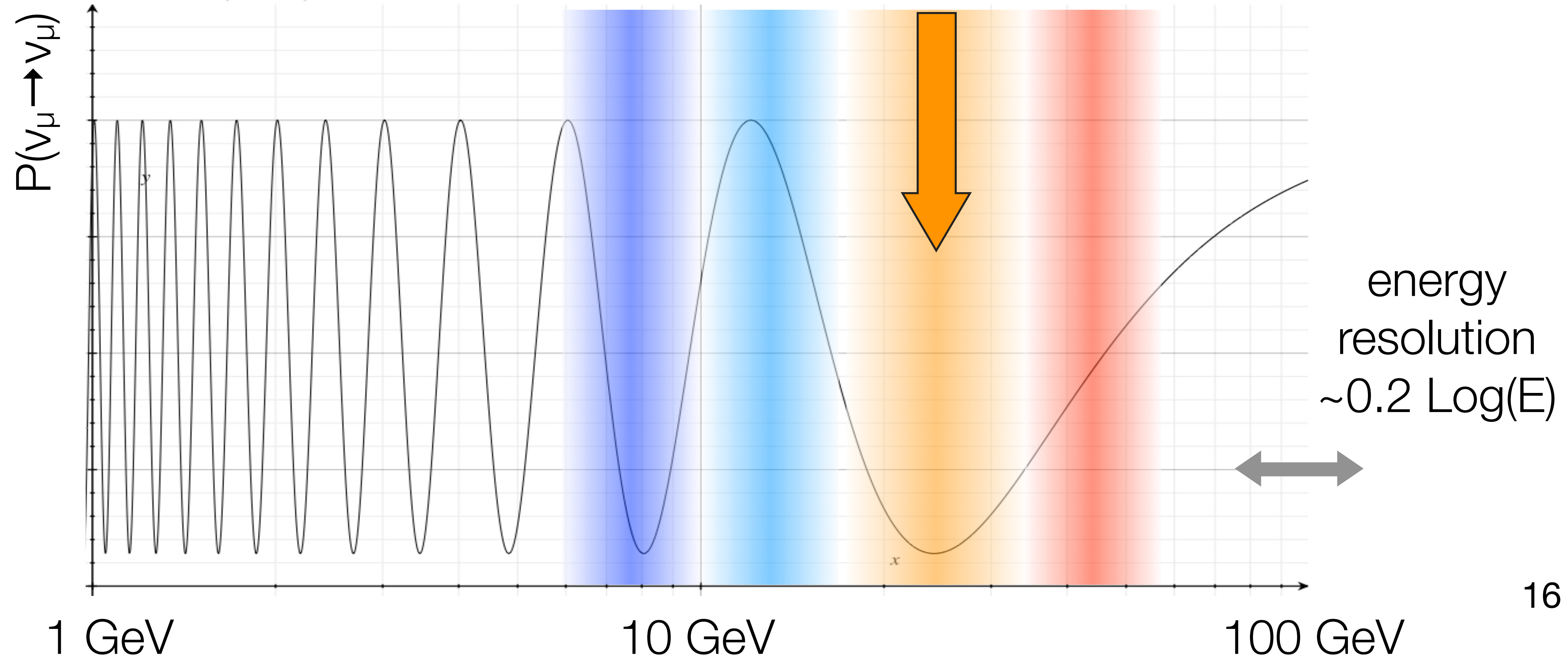
IceCube - 3 years

- energy resolution resolves the wide minimum **@ 25 GeV**
- **competitive** with low energy experiments



Phys. Rev. D 91, 072004 **2015**



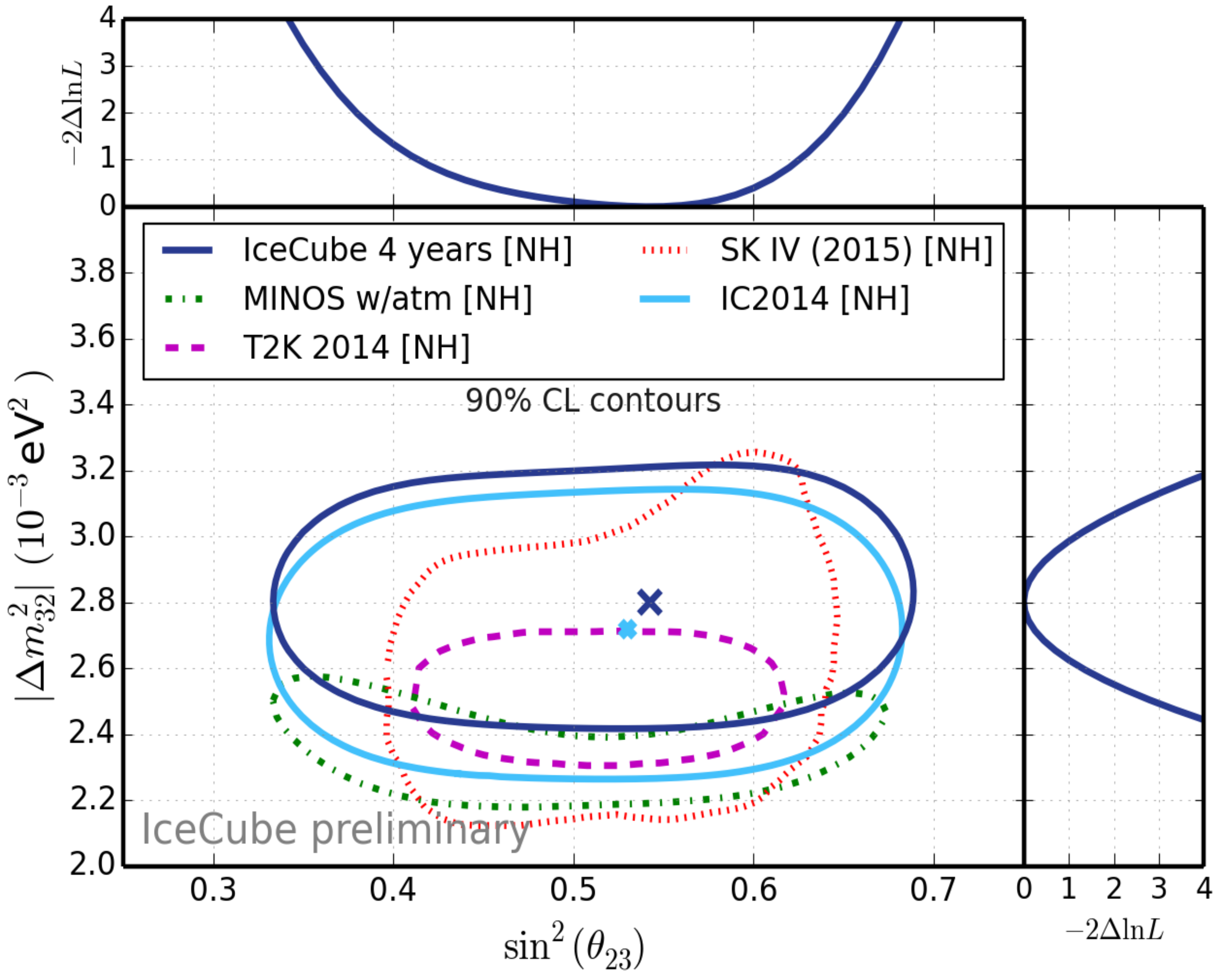


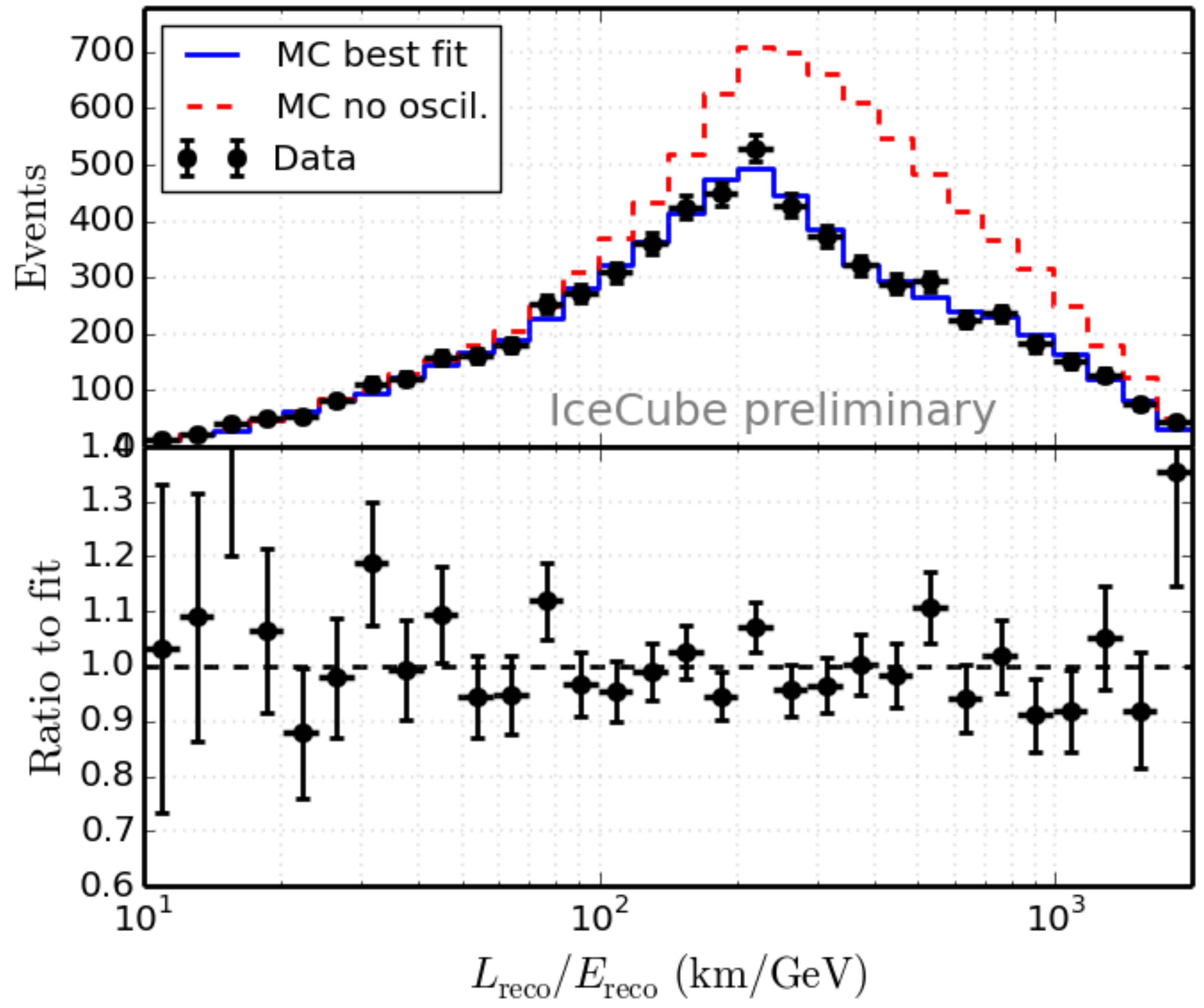
low energy neutrinos

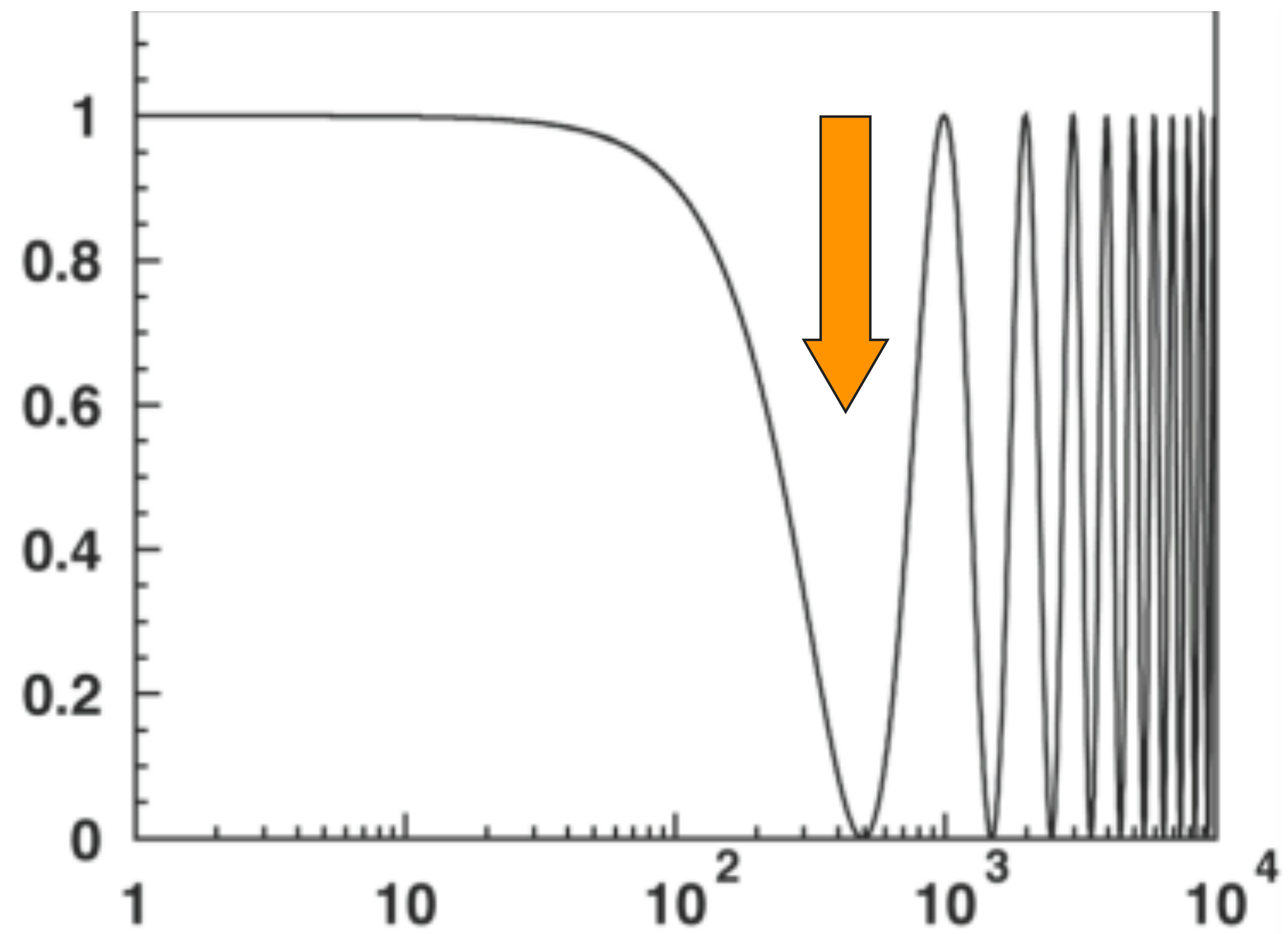
IceCube - 4 years

PRELIMINARY 2015

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\,\sin^2\left(1.27\,\frac{\Delta m^2_{23}\,L}{E_\nu}\right)$$







high energy neutrinos

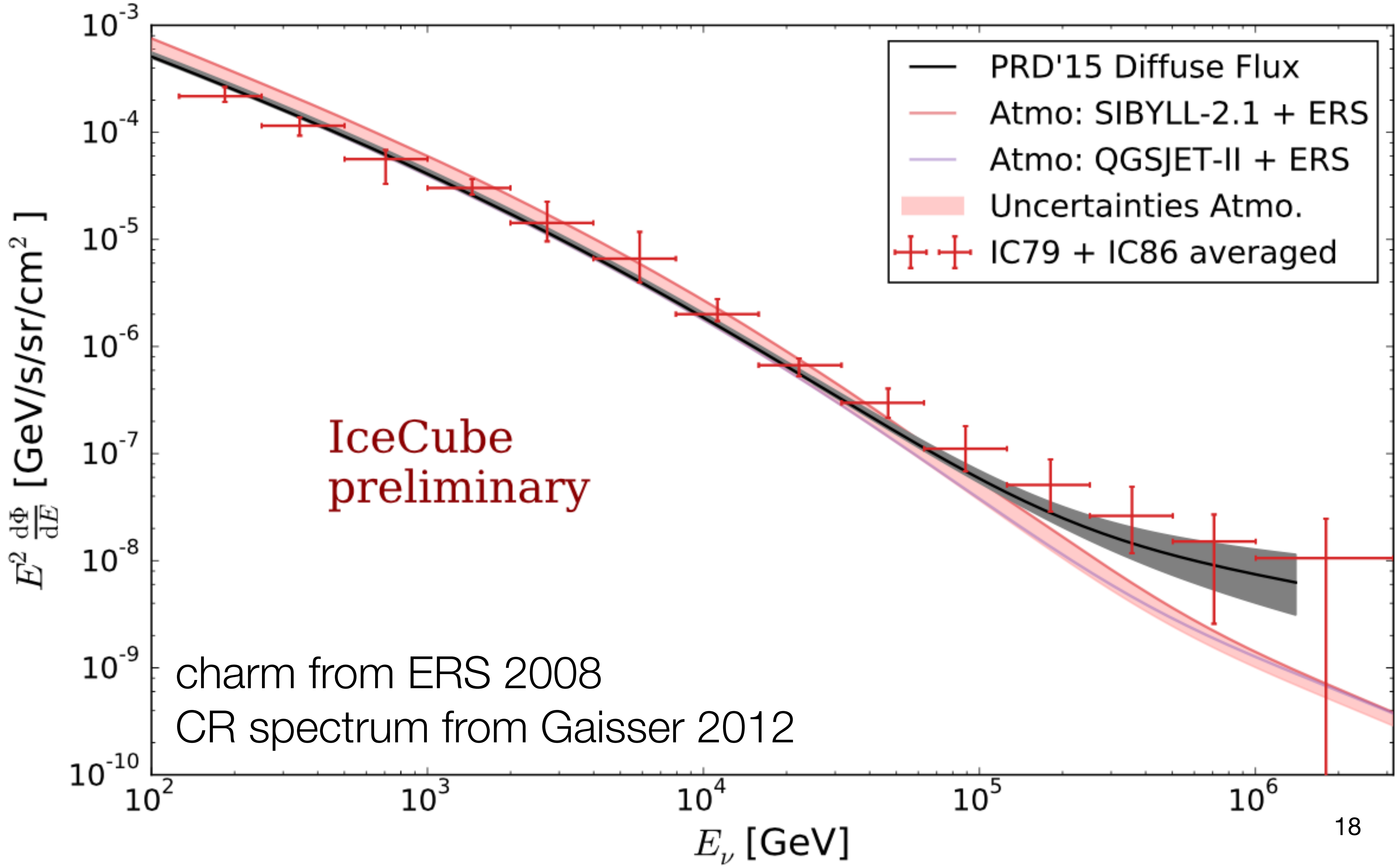
up-ward through-going $\nu_\mu + \bar{\nu}_\mu$

ICRC 2015
M. Börner
Poster 3

AMANDA	Phys. Rev. D79, 102005	2009
	Astropart. Phys. 34, 48	2010
IceCube-40	Phys. Rev. D83, 012001	2011
IceCube-59	Eur. Phys. J. C75, 116	2015

- **increasing** data volume
- refined **shape** of spectrum
- reach **PeV** energy range
- sensitivity to **heavy quark** production in the atmosphere (for $E_\nu \gtrsim 0.4$-1 PeV)
- where is transition to **astrophysical** contribution of neutrinos ?

ICRC 2015 review talk by C. Kopper

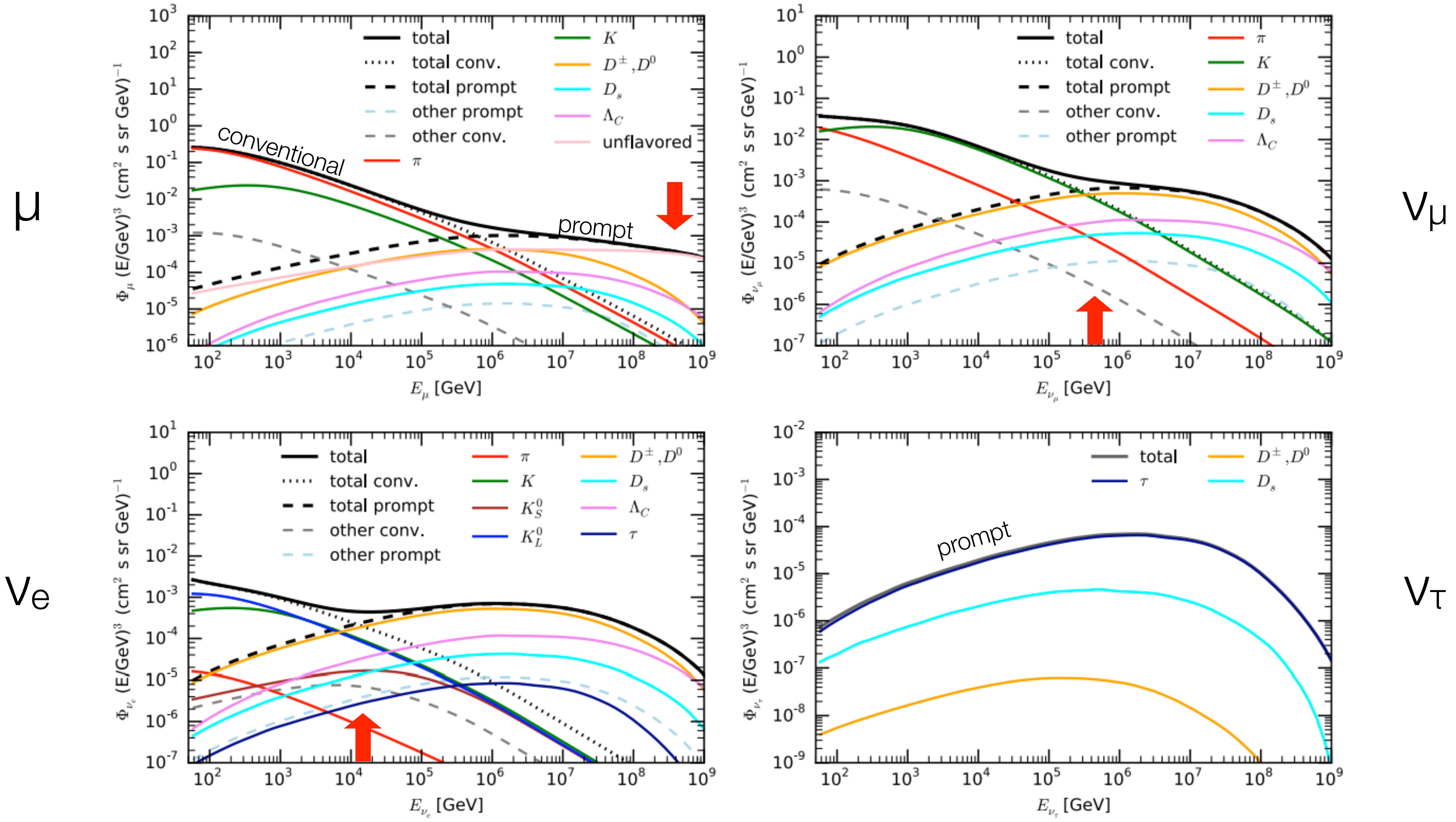


hadronic interaction models

heavy quarks in the atmosphere

MCEq cascade calculations (Fedynitch) - **Poster 2**

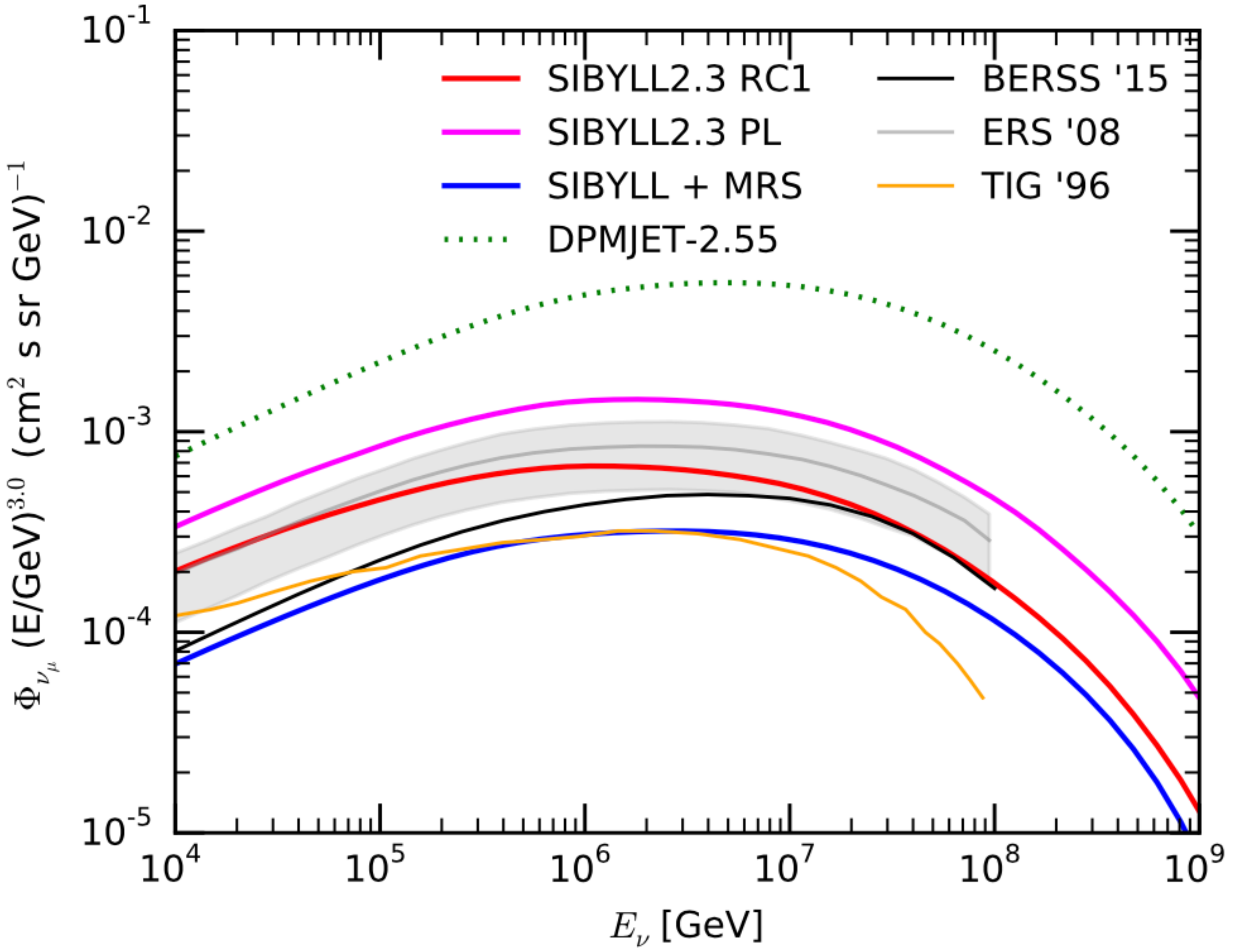
Sibyll 2.3 - Fedynitch+ ISVHECRI 2014



hadronic interaction models

heavy quarks in the atmosphere

Sybill 2.3 RC - Fedynitch+ IPA 2015



non-perturbative effects

intrinsic charm

inclusive charm cross-section

partonic saturation

hadronic models

Bhattacharya+ 2015

Garzelli, Moch & Sigl 2015

BERSS: A. Bhattacharya, R. Enberg, M.H. Reno, I. Sarcevic and A. Stasto, arXiv:1502.01076

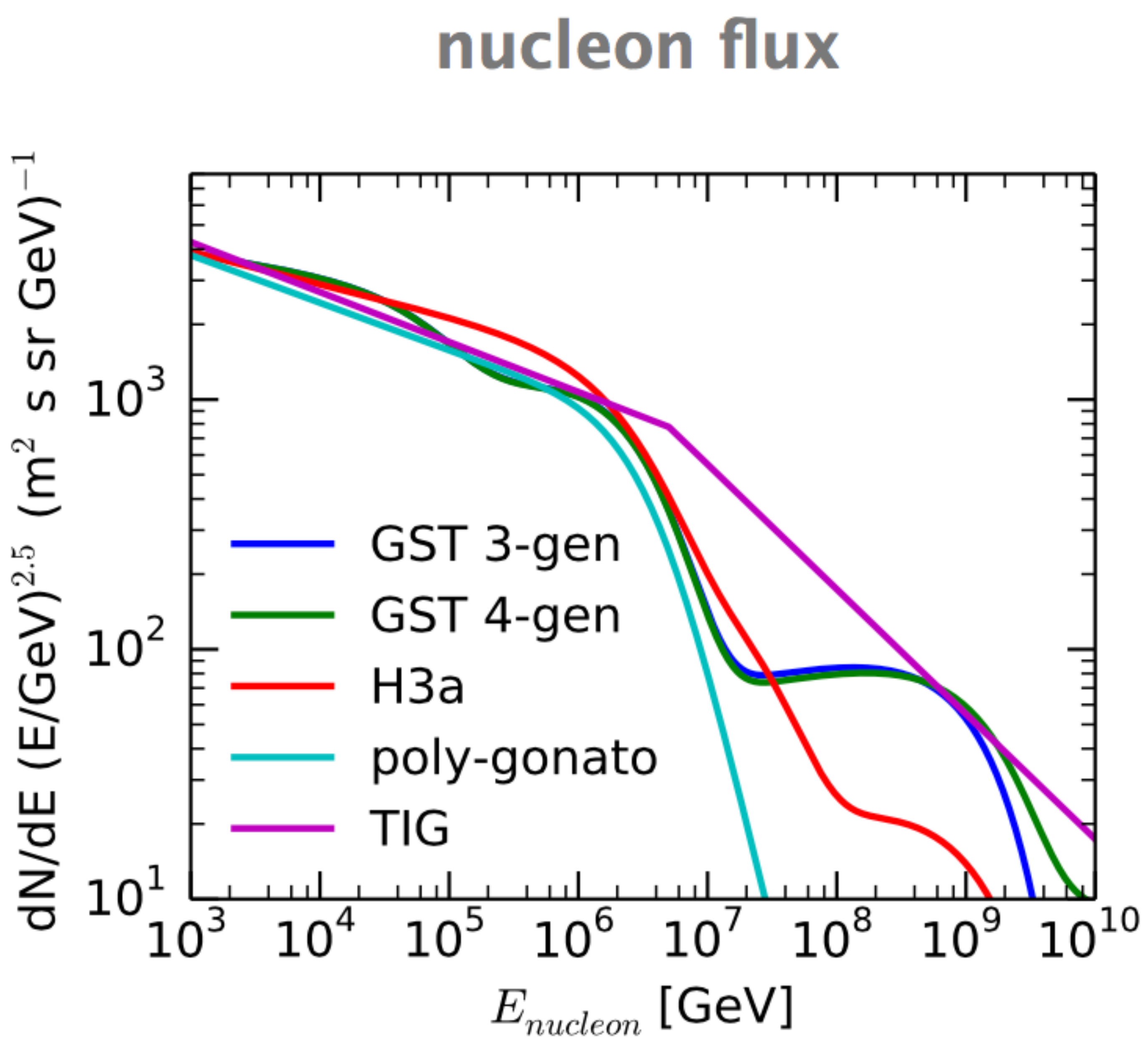
ERS: R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 43005 (2008).

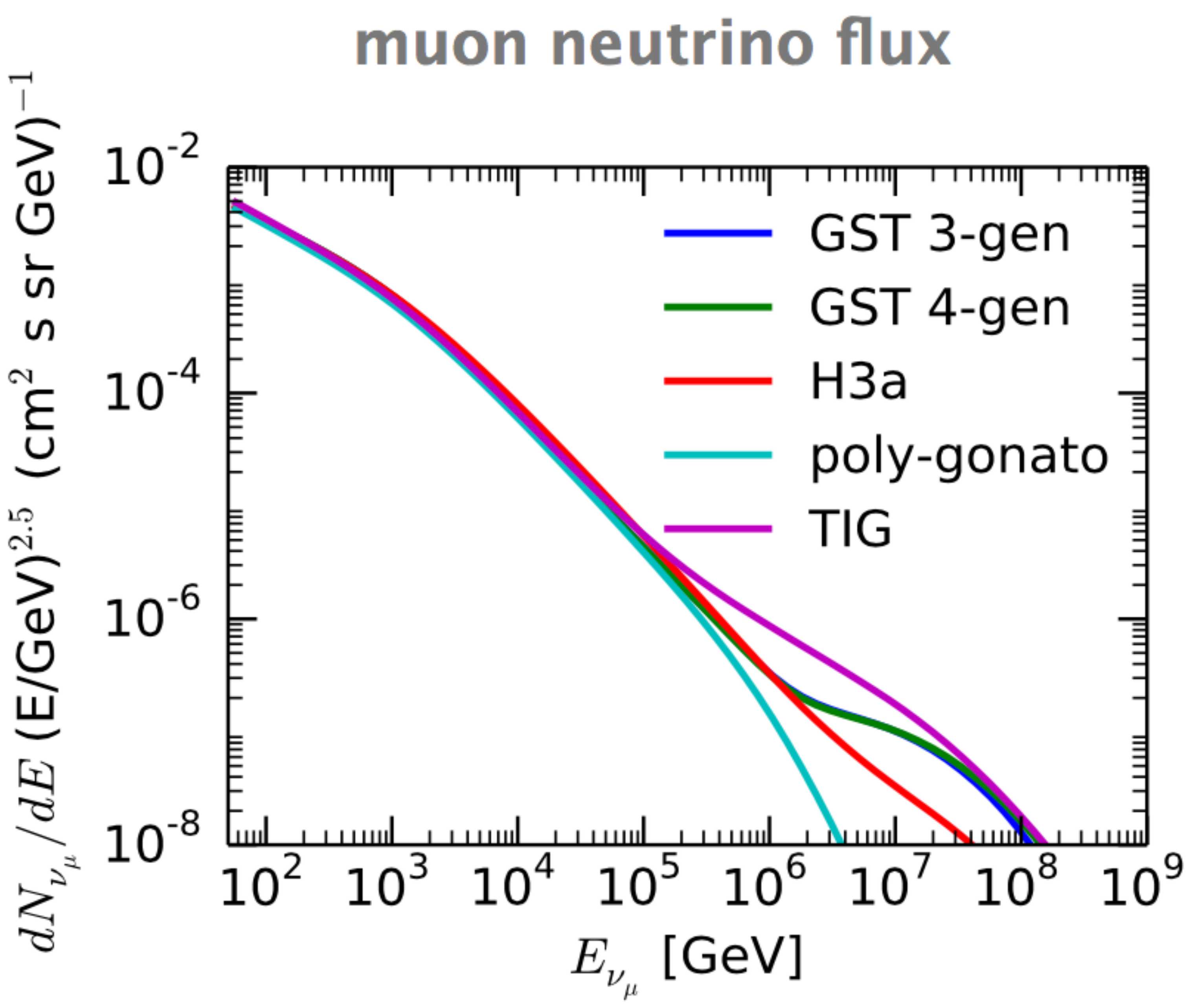
MRS: A. D. Martin, M. G. Ryskin, and A. M. Stasto, Acta Physica Polonica B ***34****, 3273 (2003).*

SIBYLL: arXiv:1503.00544 and arXiv:1502.06353

TIG: M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

Sybill 2.3 RC - Fedynitch+ IPA 2015





cosmic rays

GST - T. K. Gaisser, T. Stanev, and S. Tilav, arXiv: 1303.3565, (2013).

H3a - T. K. Gaisser, Astroparticle Physics 35, 801 (2012).

TIG - M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

poly-gonato - [1] J. R. Hörandel, Astroparticle Physics 19, 2 (2003)

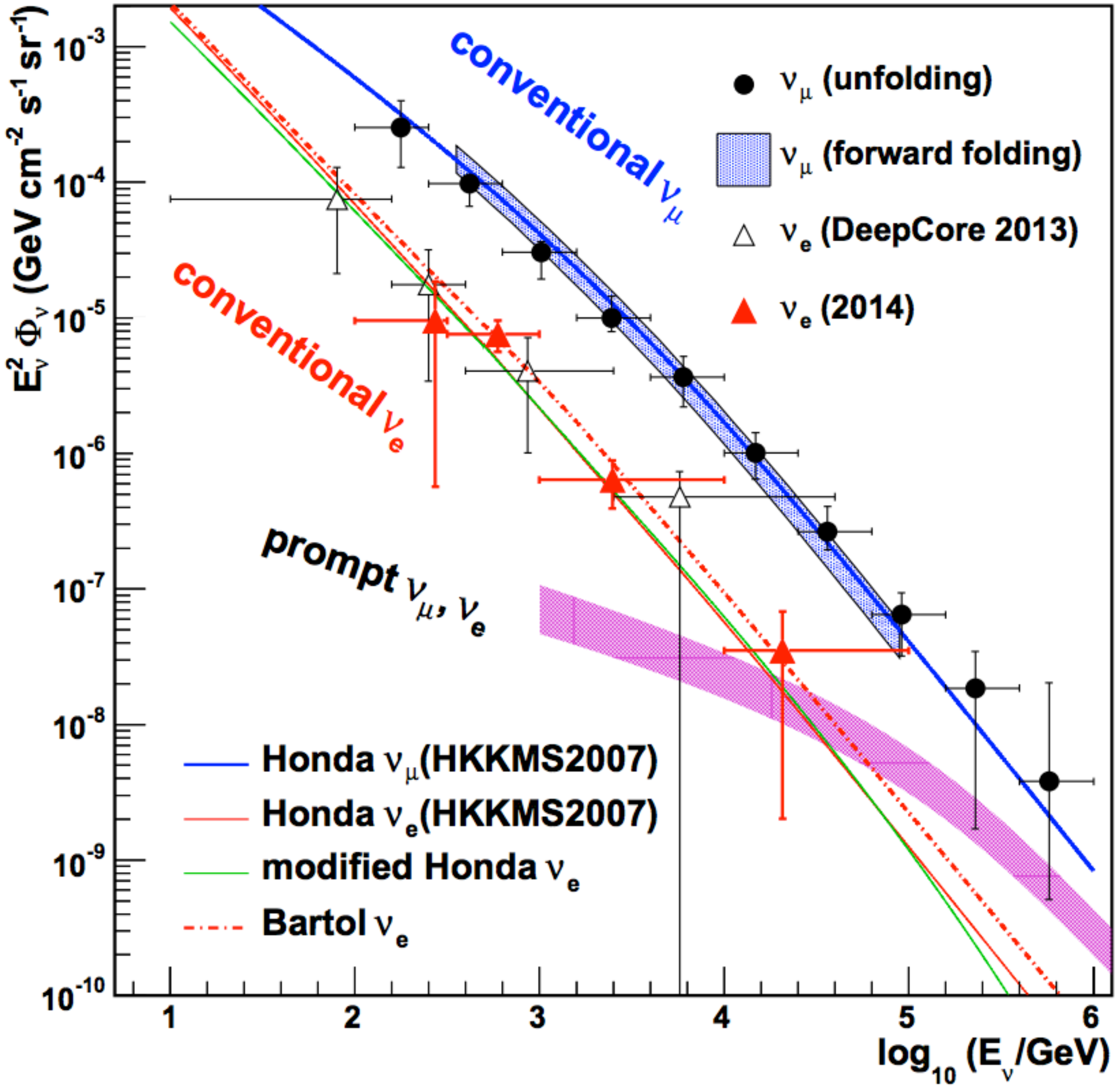
high energy neutrinos

contained $\nu_e+\bar{\nu}_e$

- using IceCube as muon **VETO**
- **lower energy** with DeepCore
- events **starting** inside DeepCore
- **particle ID**: cascade-like events vs. track-like / hybrid events
- **higher** sensitivity to **heavy quark** production in the atmosphere (for $E_\nu \gtrsim 10$ TeV)

IceCube-79 - DeepCore Phys. Rev. Lett. 110, 151105 **2013**

IceCube-86 Phys. Rev. D91 12, 122004 **2015**



high energy neutrinos

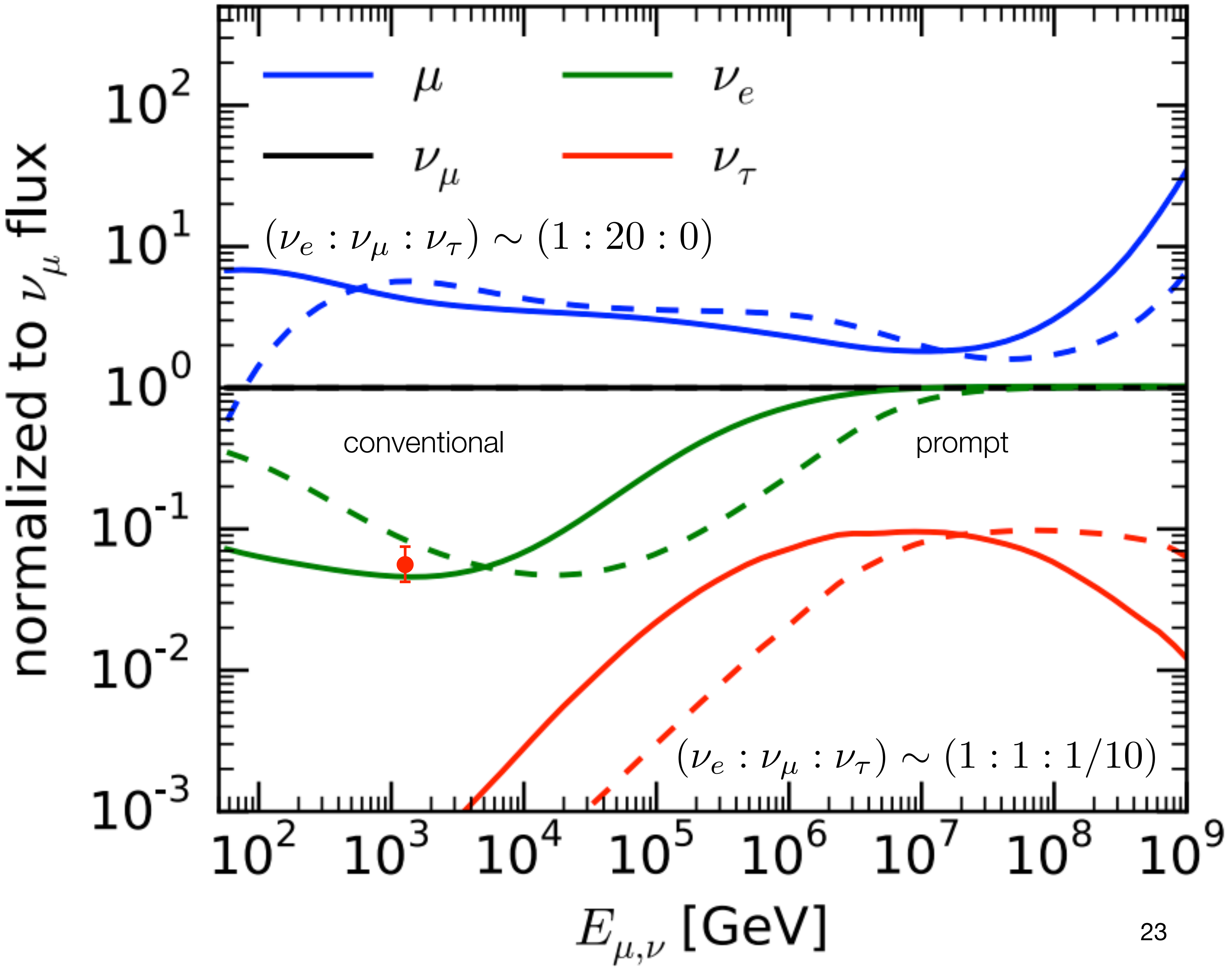
flavor composition

IceCube-86 **Phys. Rev. D91 12, 122004** **2015**

Fedynitch et al. arXiv:1503.00544
Sibyll 2.3RC1
H3a CR composition

$$\langle E_\nu \rangle \sim 1.7\,TeV$$

$$R\left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right) = 16.9^{+6.4}_{-4.0}$$

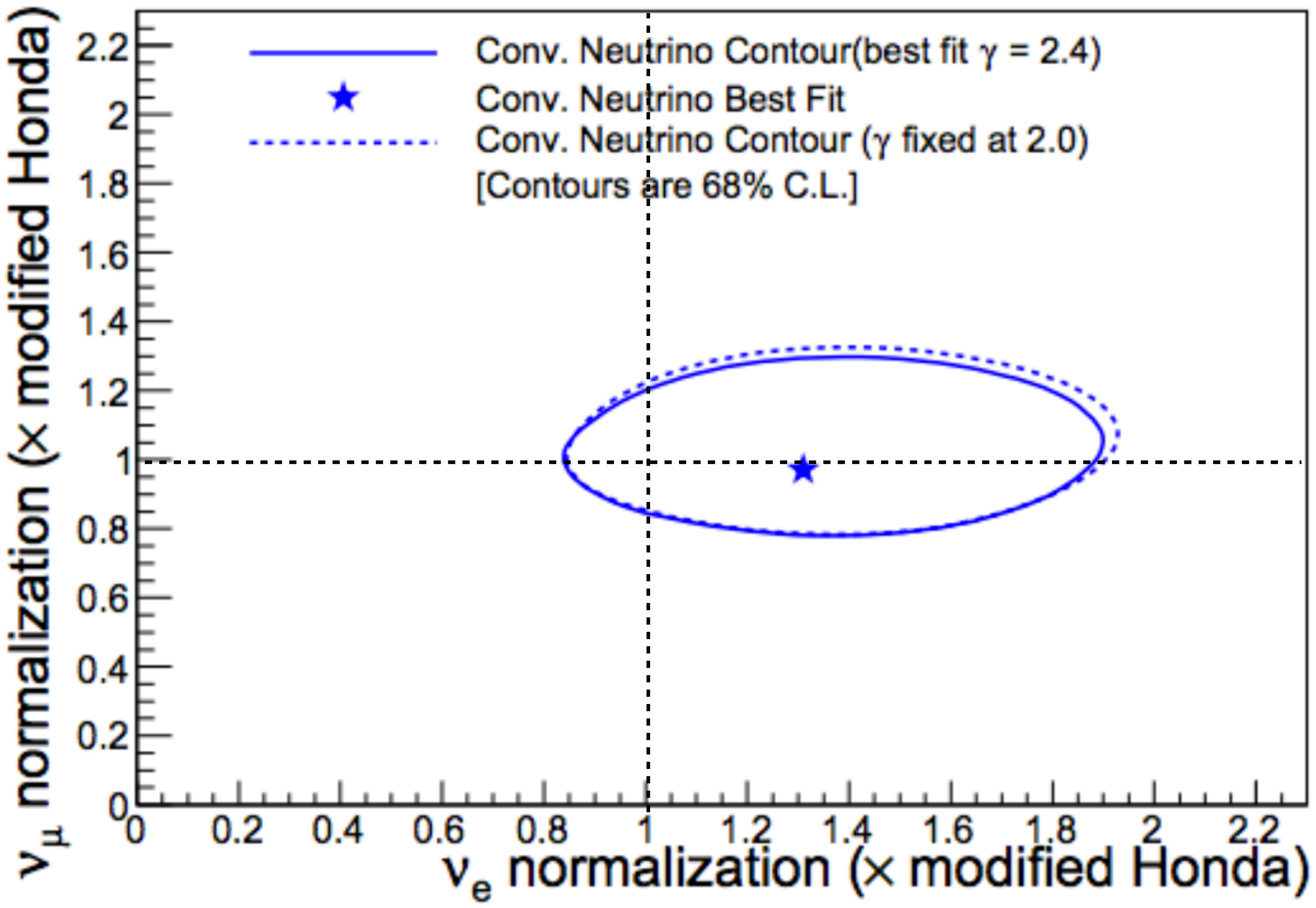


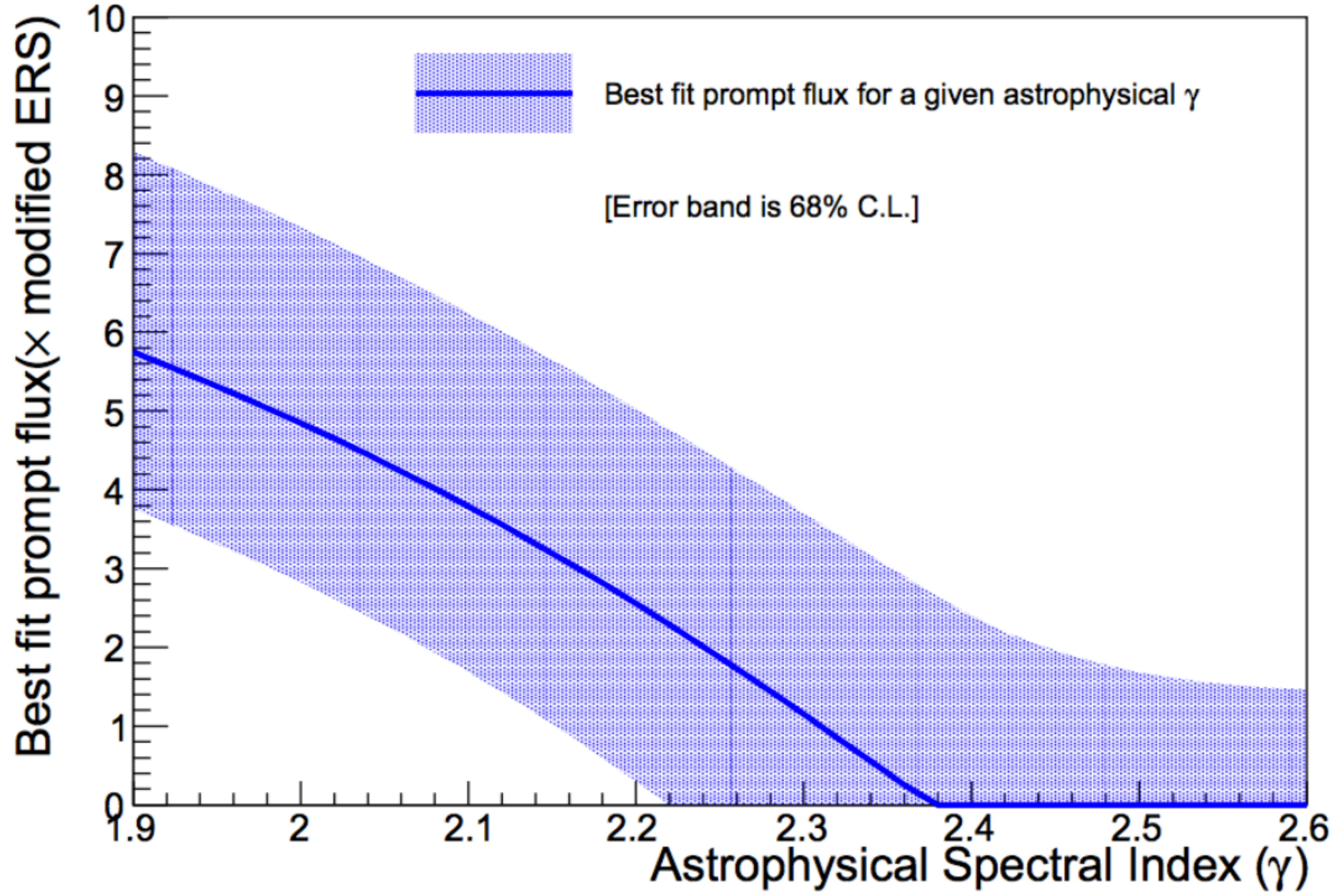
- flavor ratio depends on **uncertain** K/π
- **associated production** $p + N \rightarrow \Lambda + K^+$
- that affects $\bar{\nu}/\nu$ and μ^+/μ^-
- and affects **spectral shape** > 1 TeV

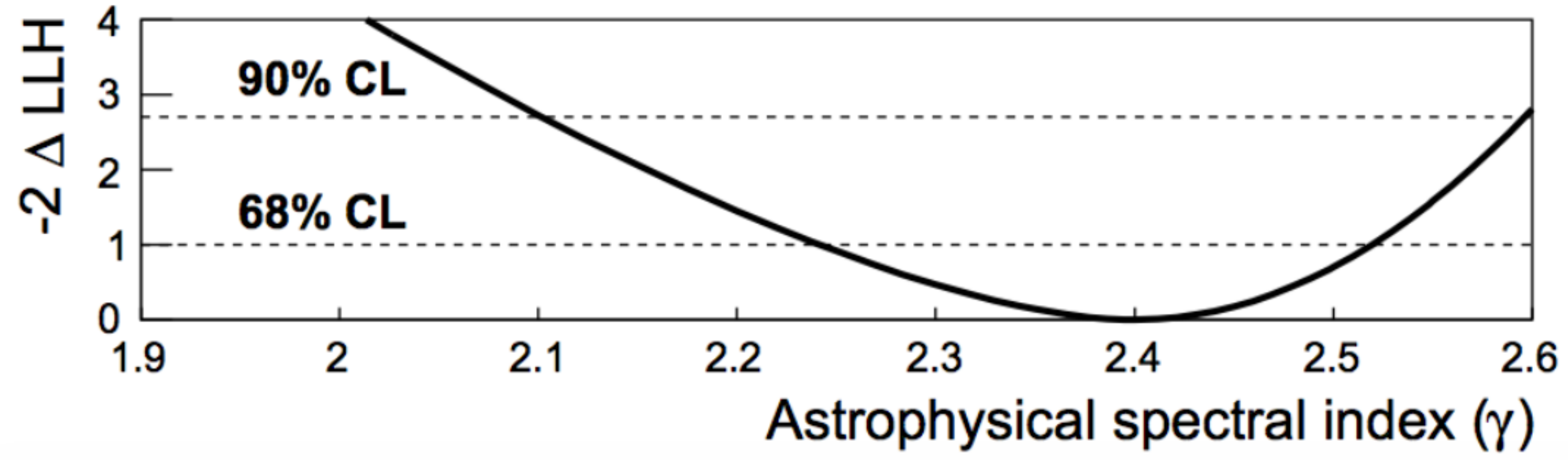
high energy neutrinos

charm and astrophysics

IceCube-86 **Phys. Rev. D91 12, 122004** **2015**







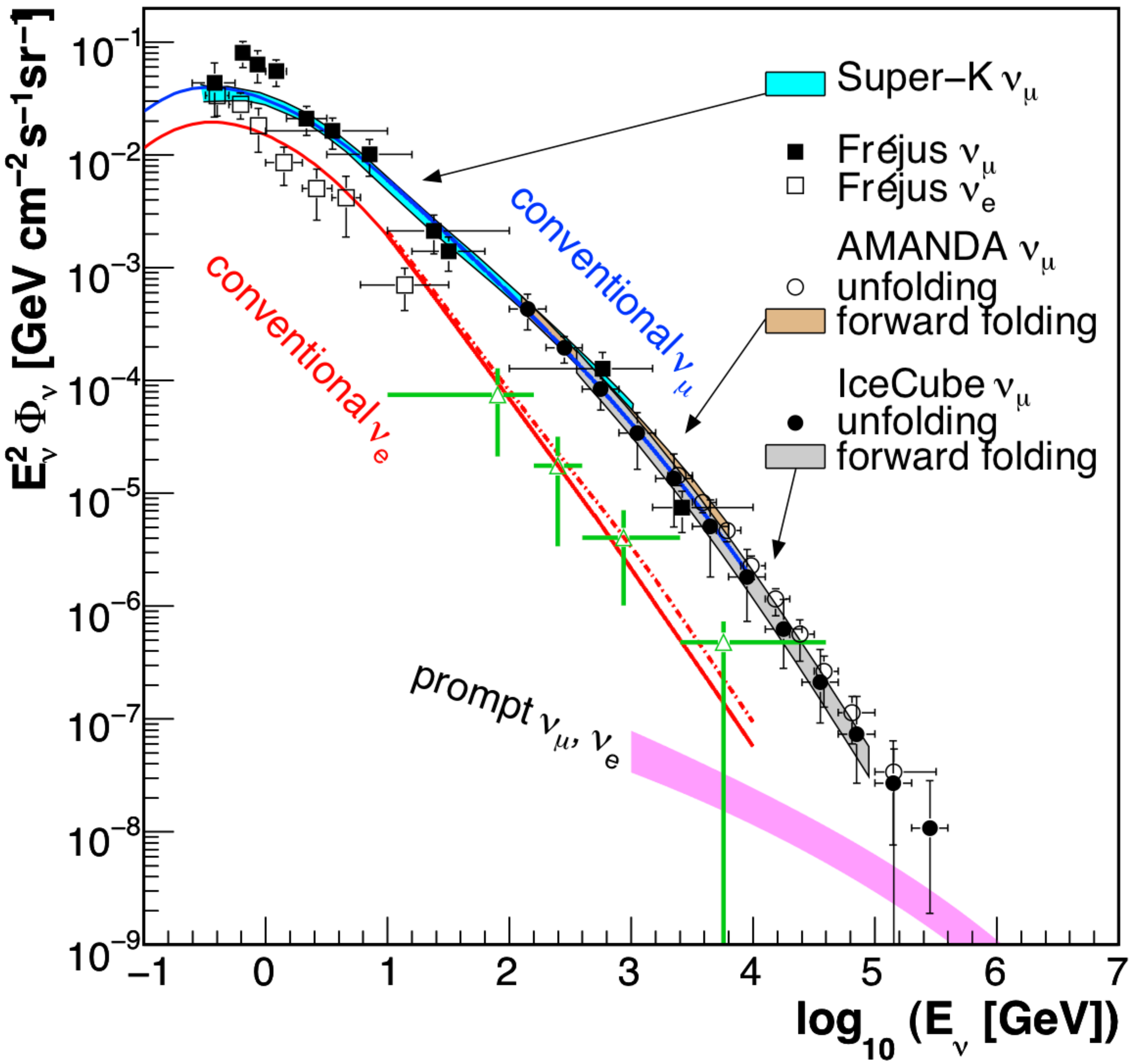
- determination of **conventional** flux independent of high energy contribution
- determination of **charm** flux **influenced** on astrophysical hypothesis (review talk by C. Kopper)

charm from ERS 2008
CR spectrum from Gaisser 2012

high energy neutrinos
constrains from low energy

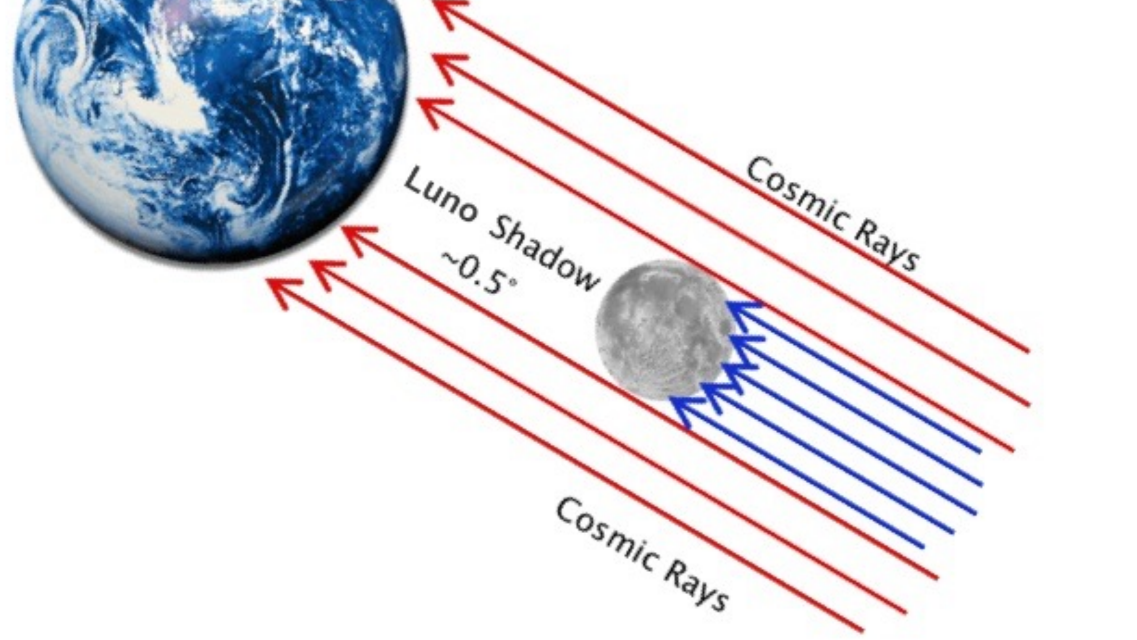
ICRC 2015
T. Kuwabara
Poster 2

- <100 TeV CR **directly measured**
- <100 GeV ν's from **pions**
- <10 GeV ν's **geomagnetic** effects
- ν **oscillations** constrained
- **low energy** ν's with SuperK
- **mid-high energy** ν's with IC / DC
- **6 orders of magnitude** in energy



high energy muons
pointing resolution and interplanetary magnetic fields

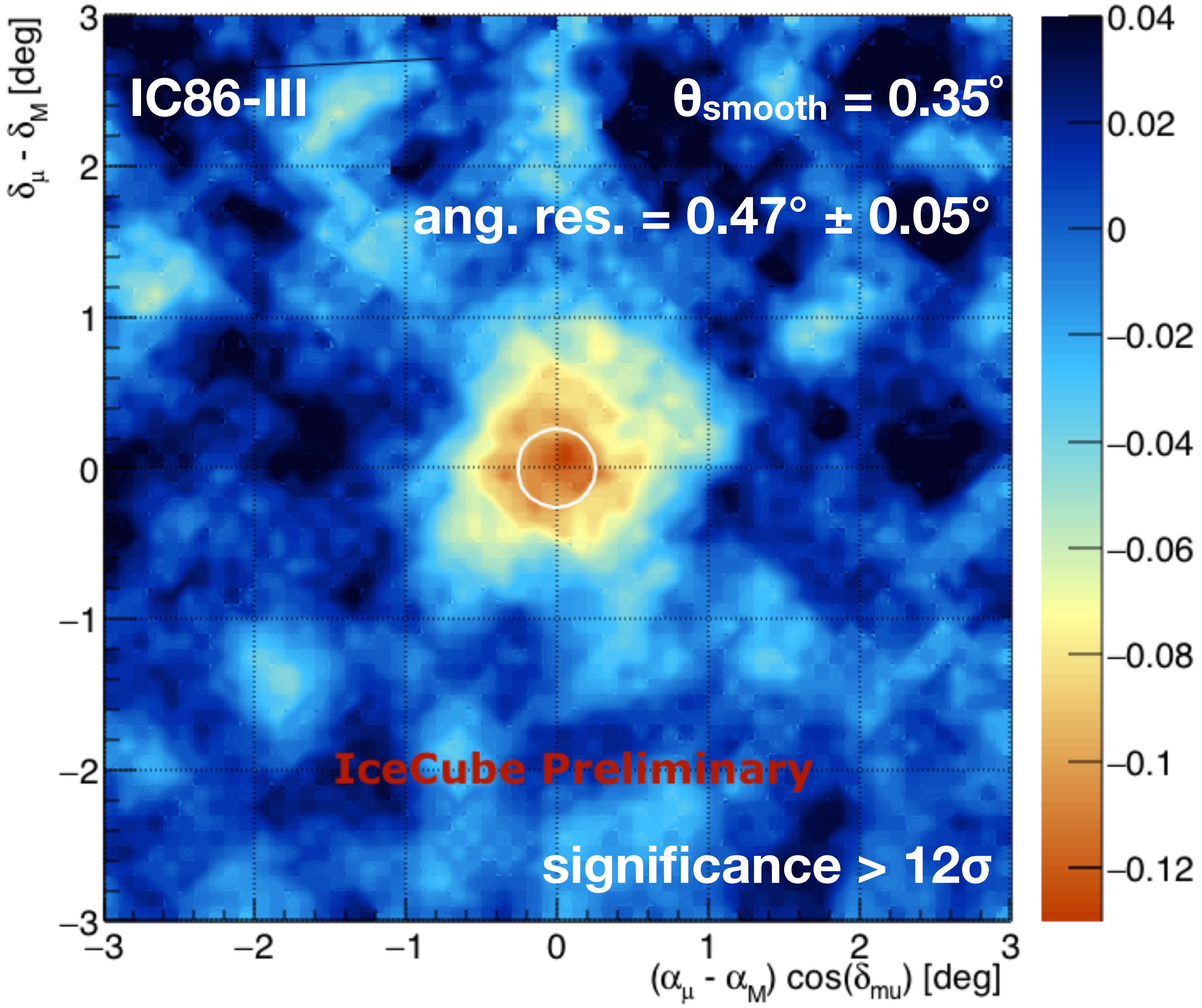
moon's shadow

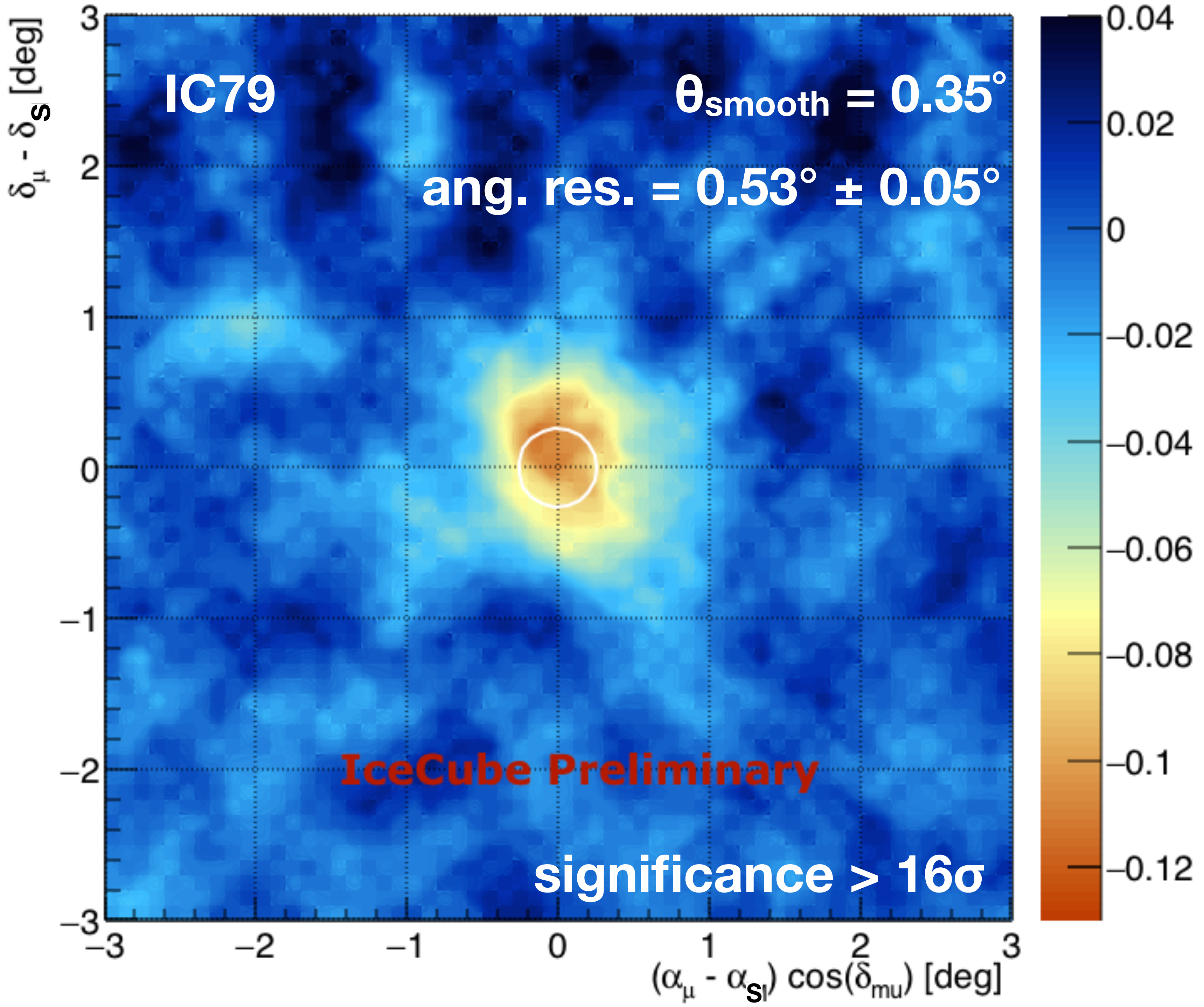


Phys. Rev. D 89, 102004 2014

IceCube-40+59

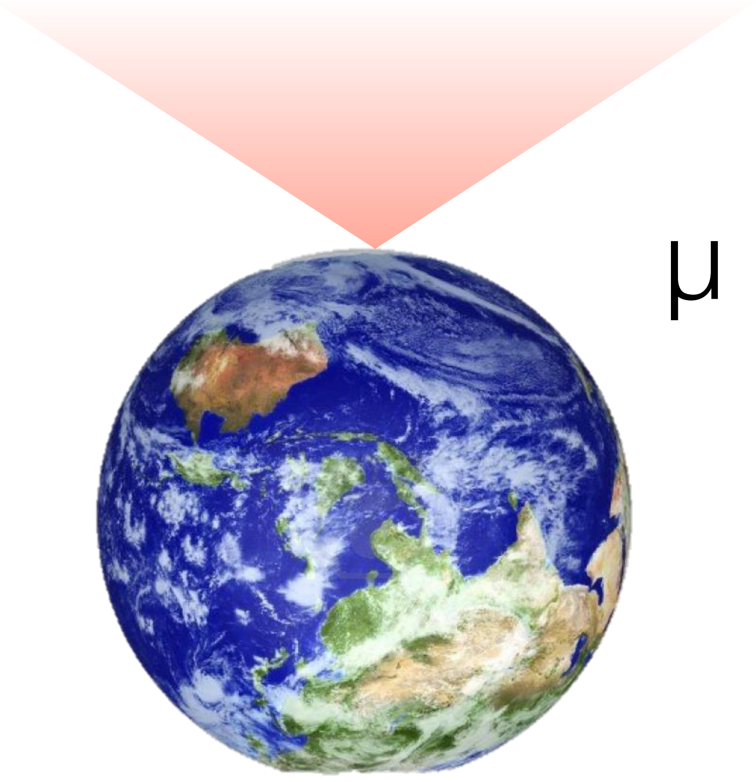
Cosmic Ray Anisotropy Workshop 2015
(Bad Honnef)

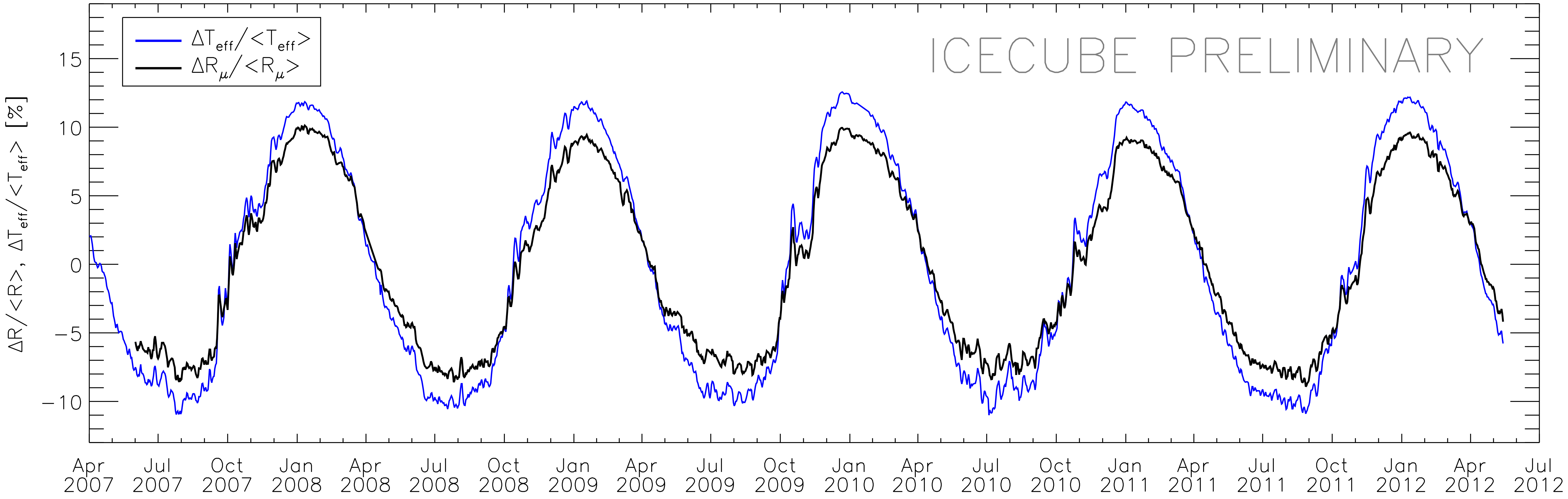




high energy leptons

correlation with stratospheric temperatures





μ multiplicity - **ICRC 2013**

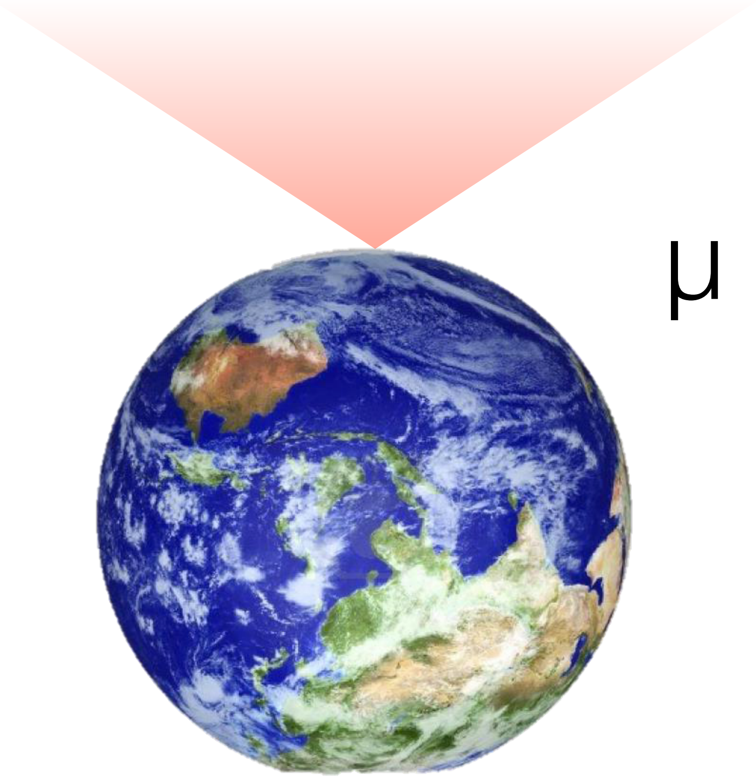
2e8 events / day

ICRC 2009
ICRC 2011

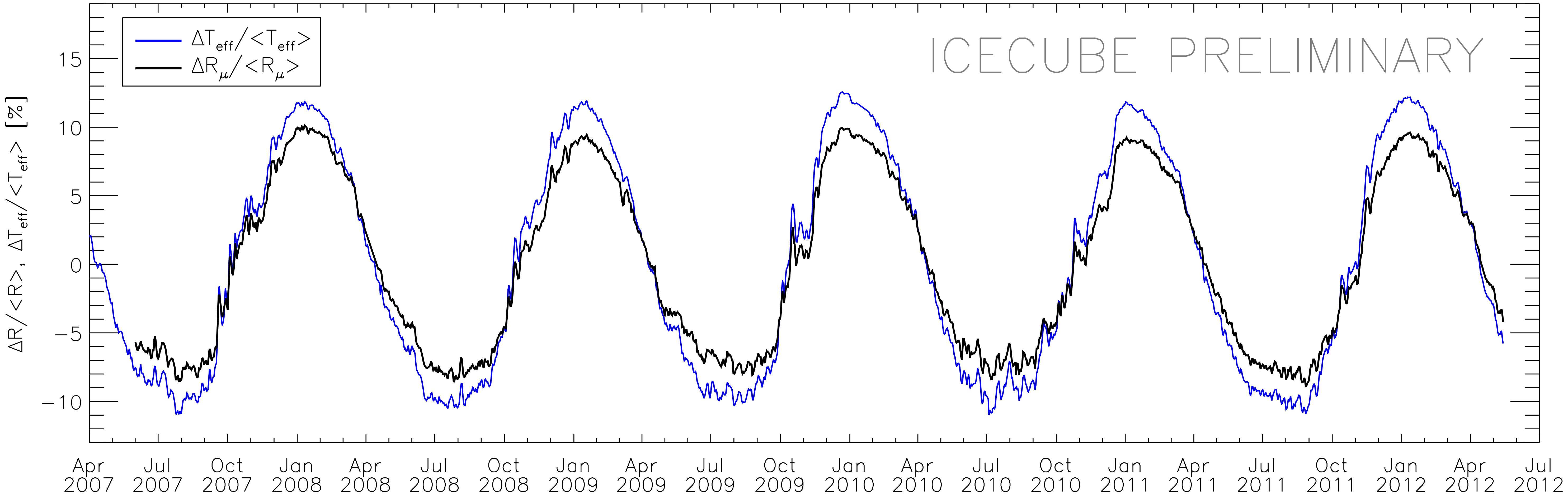
- **long** & **short** term correlations with high statistical precision: dynamical effects on air density
- temperature correlation coefficient indirect probe into **K/π**
- no temperature correlation if prompt (**charm**) contribution dominates (PD & Gaisser, 2010)

high energy leptons

correlation with stratospheric temperatures



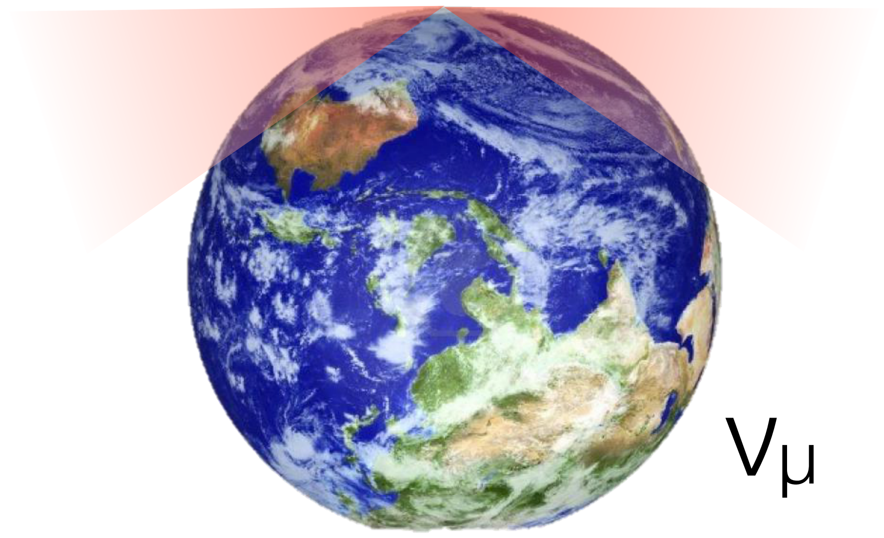
μ



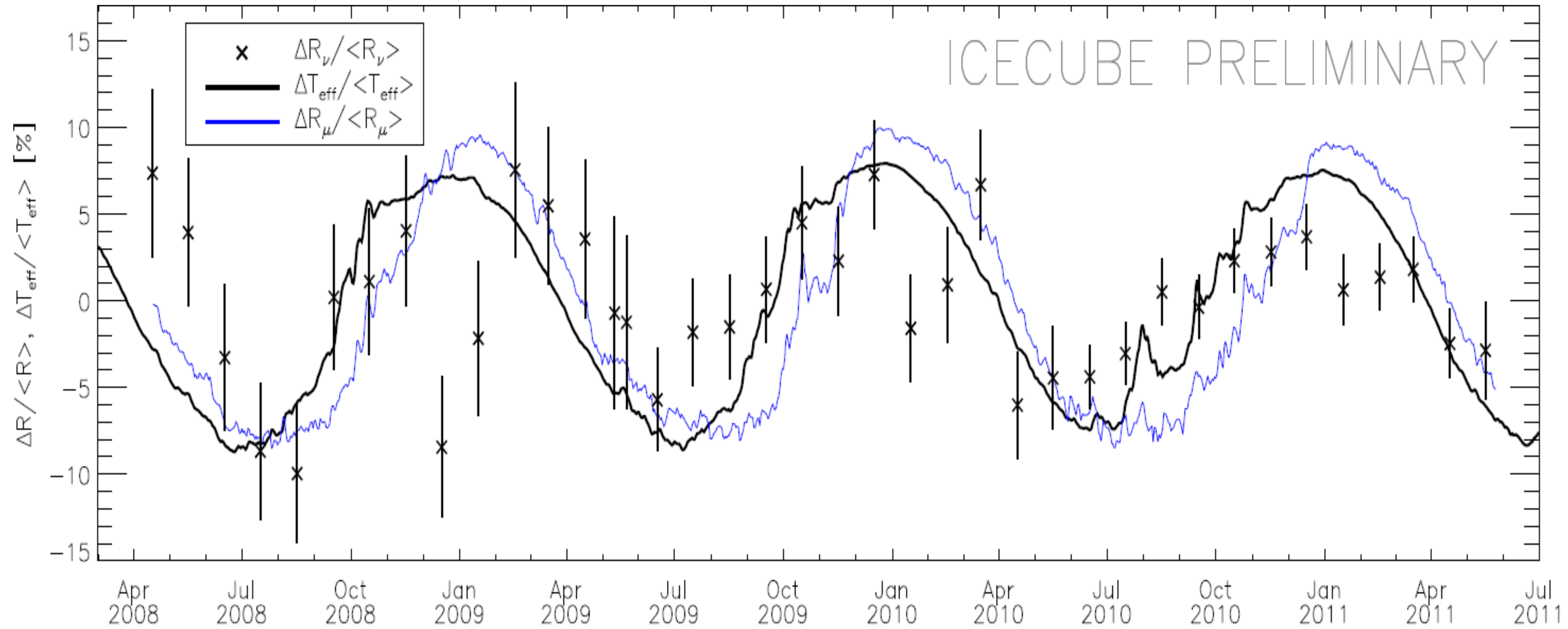
μ multiplicity - **ICRC 2013**

2e8 events / day

ICRC 2009
ICRC 2011



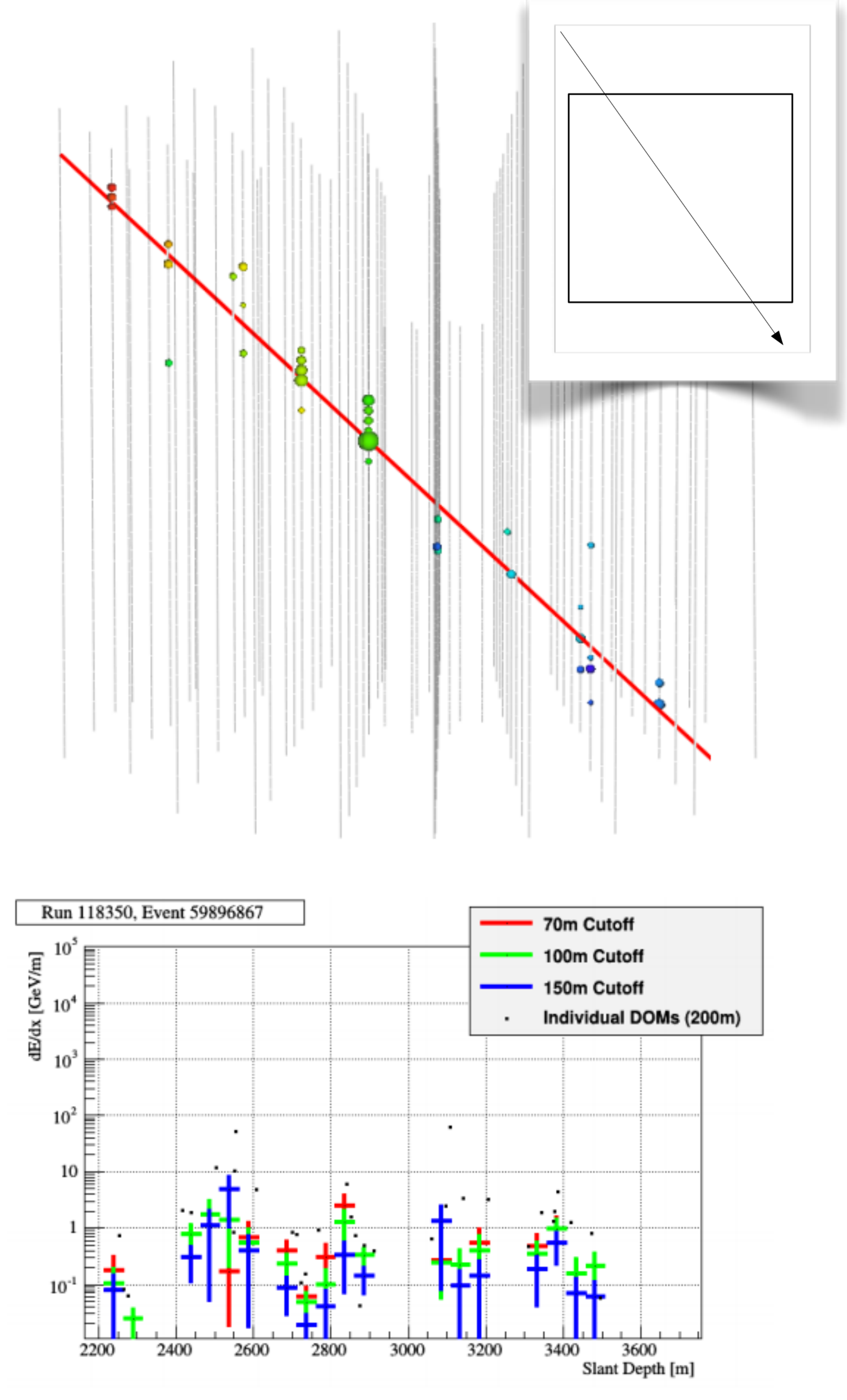
νμ



ICRC 2013

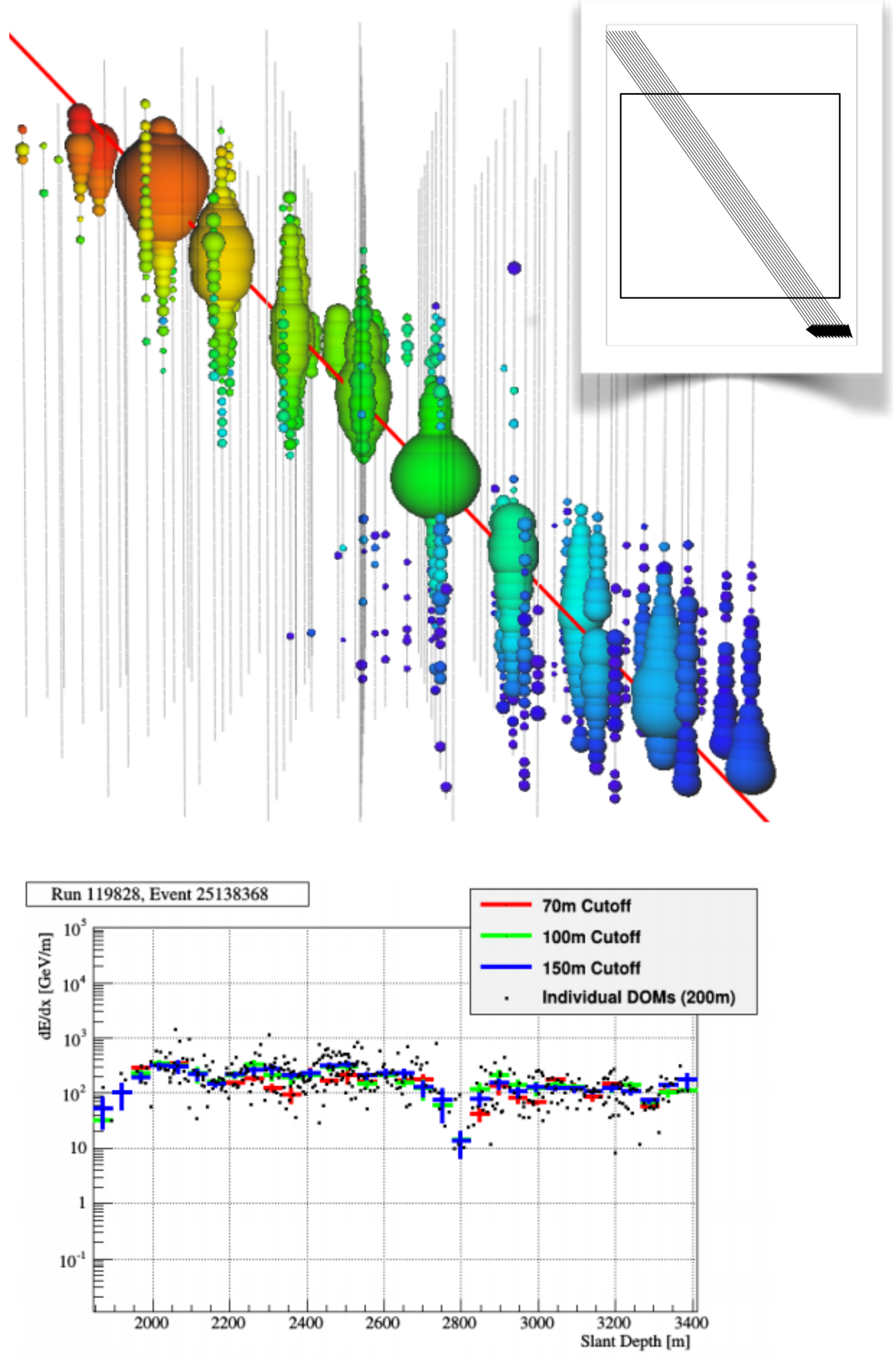
high energy muons

Low-Energy



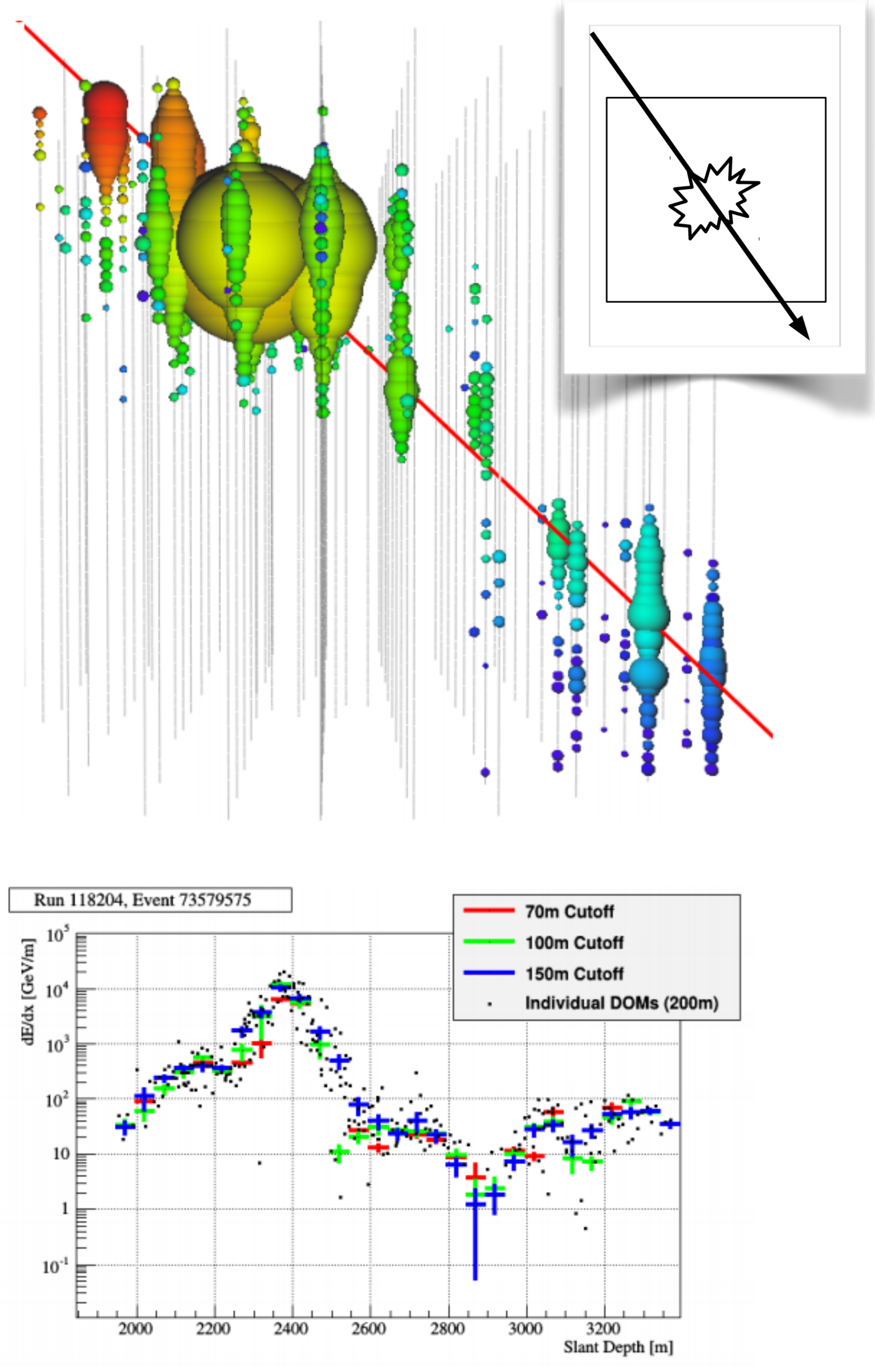
minimum ionizing

Bundles



minimum ionizing

HE Muons



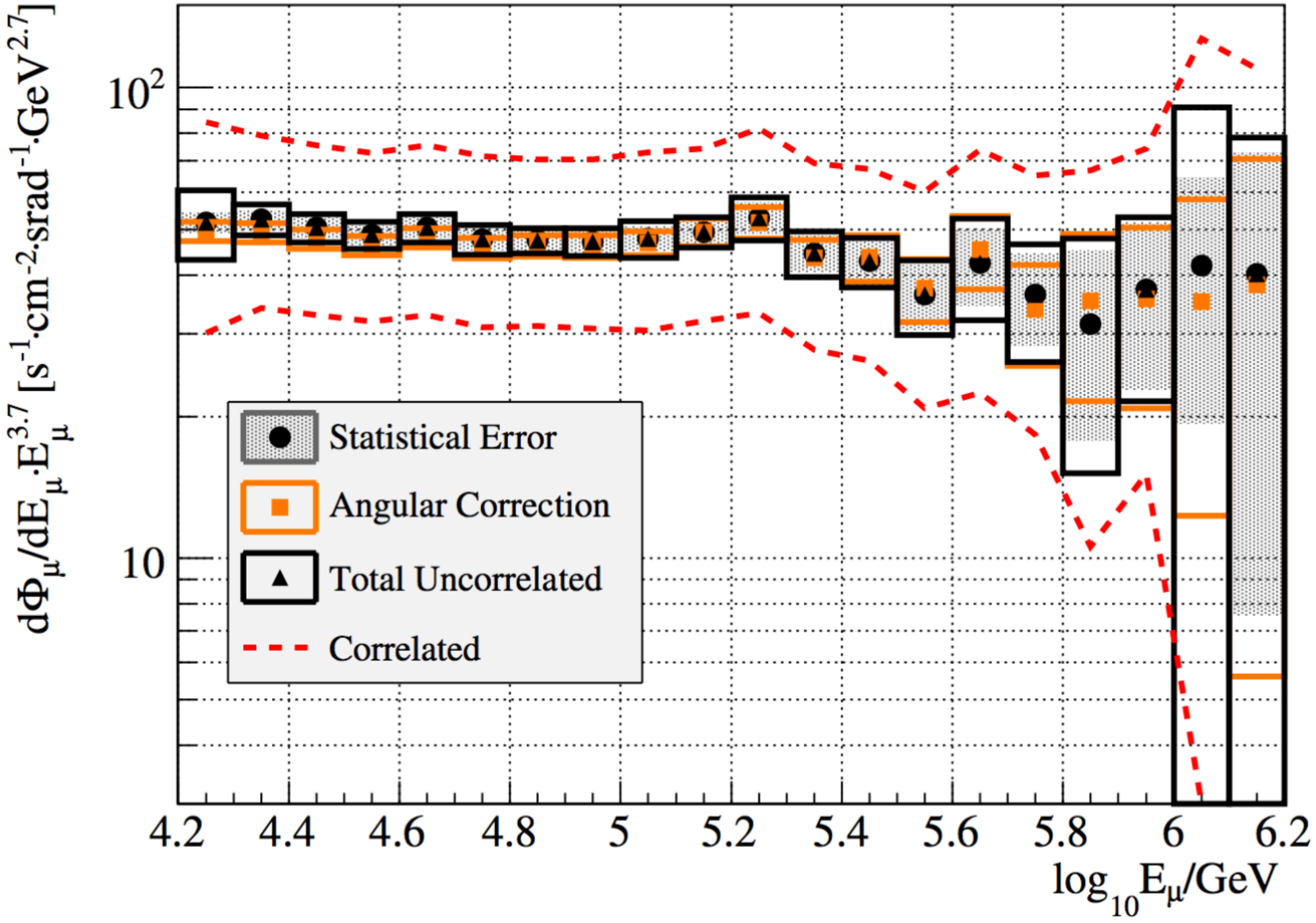
P. Berghaus

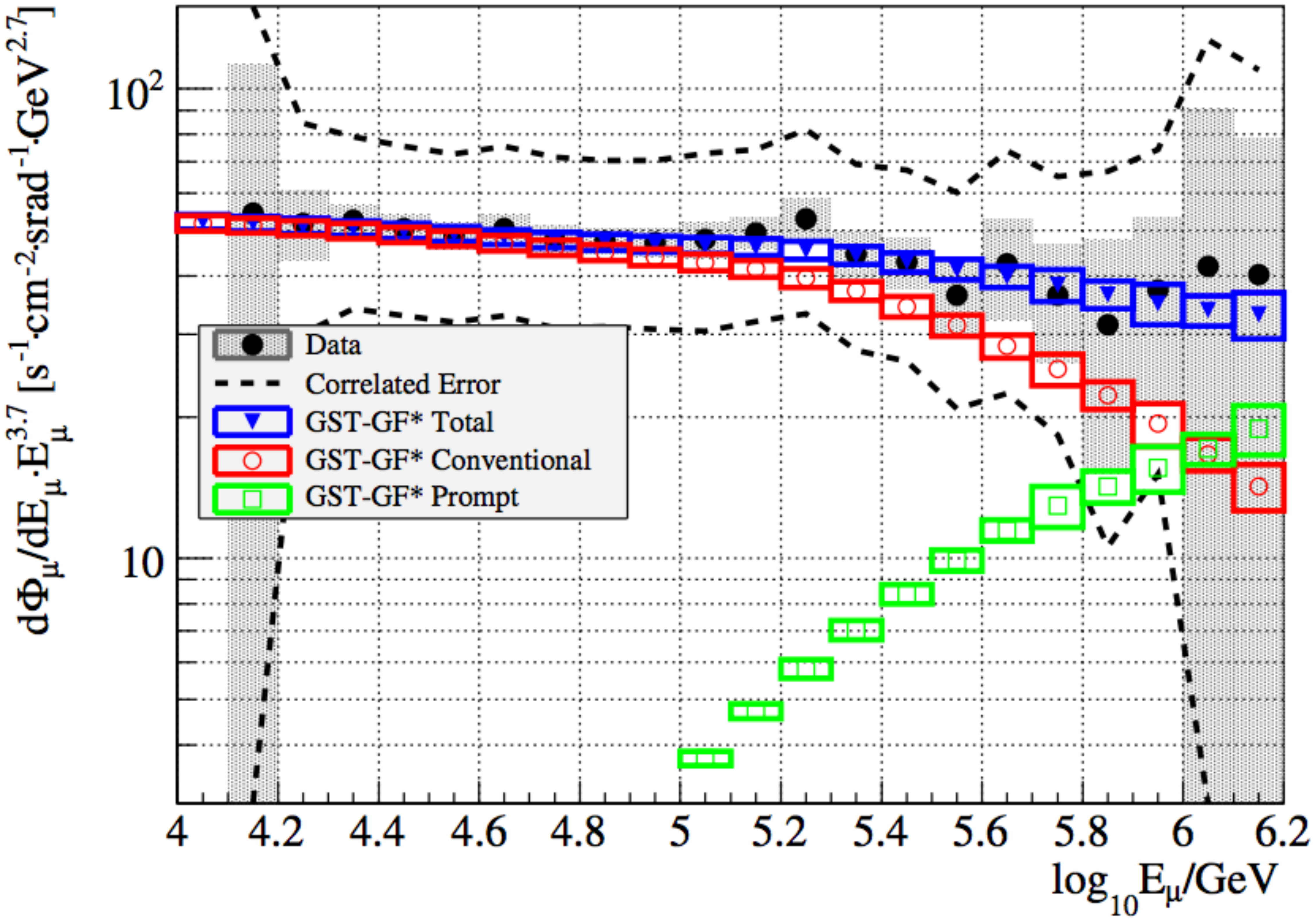
stochastic energy losses

high energy muons

ICRC 2015
T. Karg
Tue 4/8

arXiv:1506.07981 (ApP) **2015**

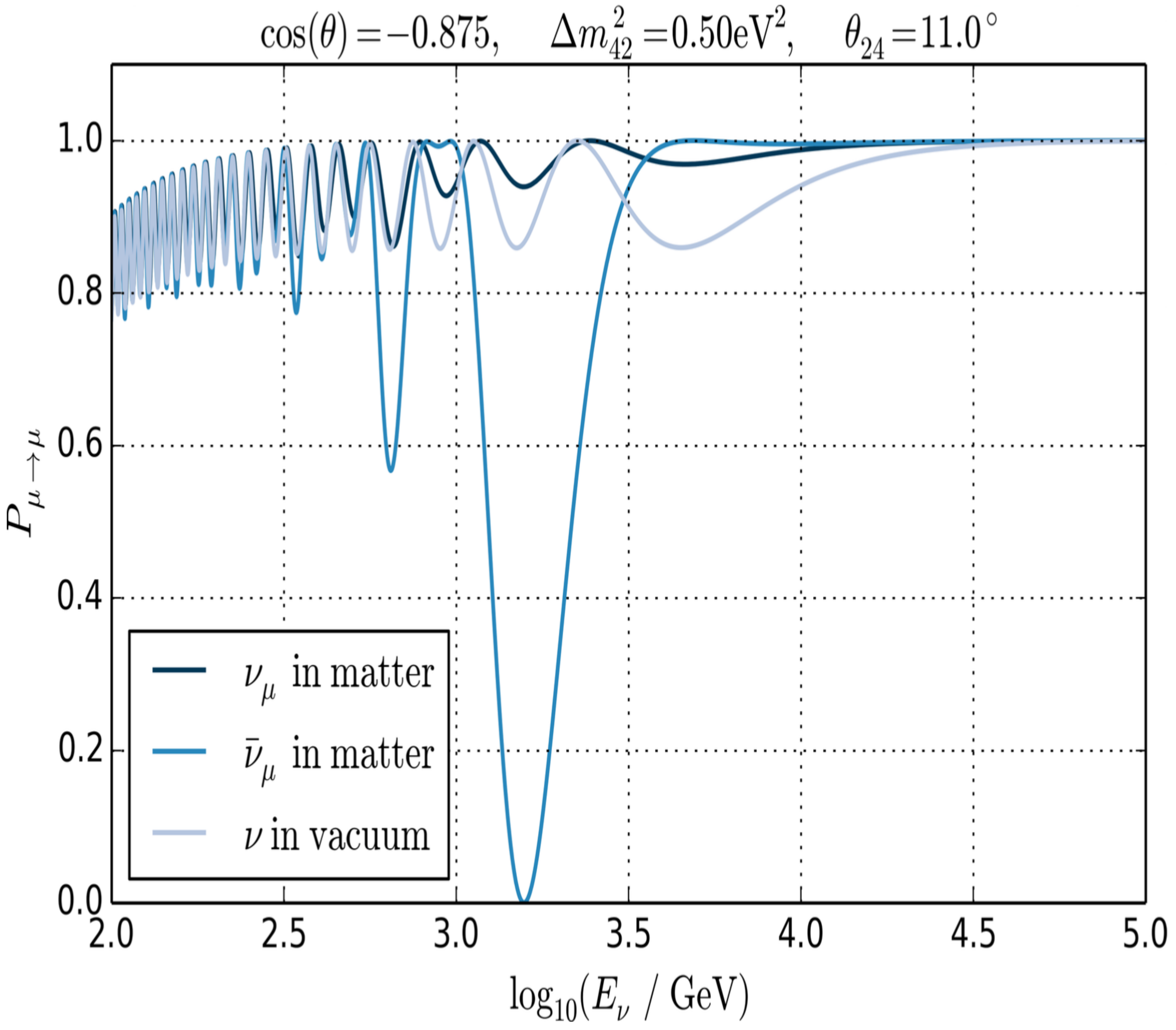




- high energy inclusive muon spectrum compatible with additional contribution at HE
- prompt component from **charm production** and **unflavored η mesons**

non-standard physics
ν_μ disappearance to sterile neutrino

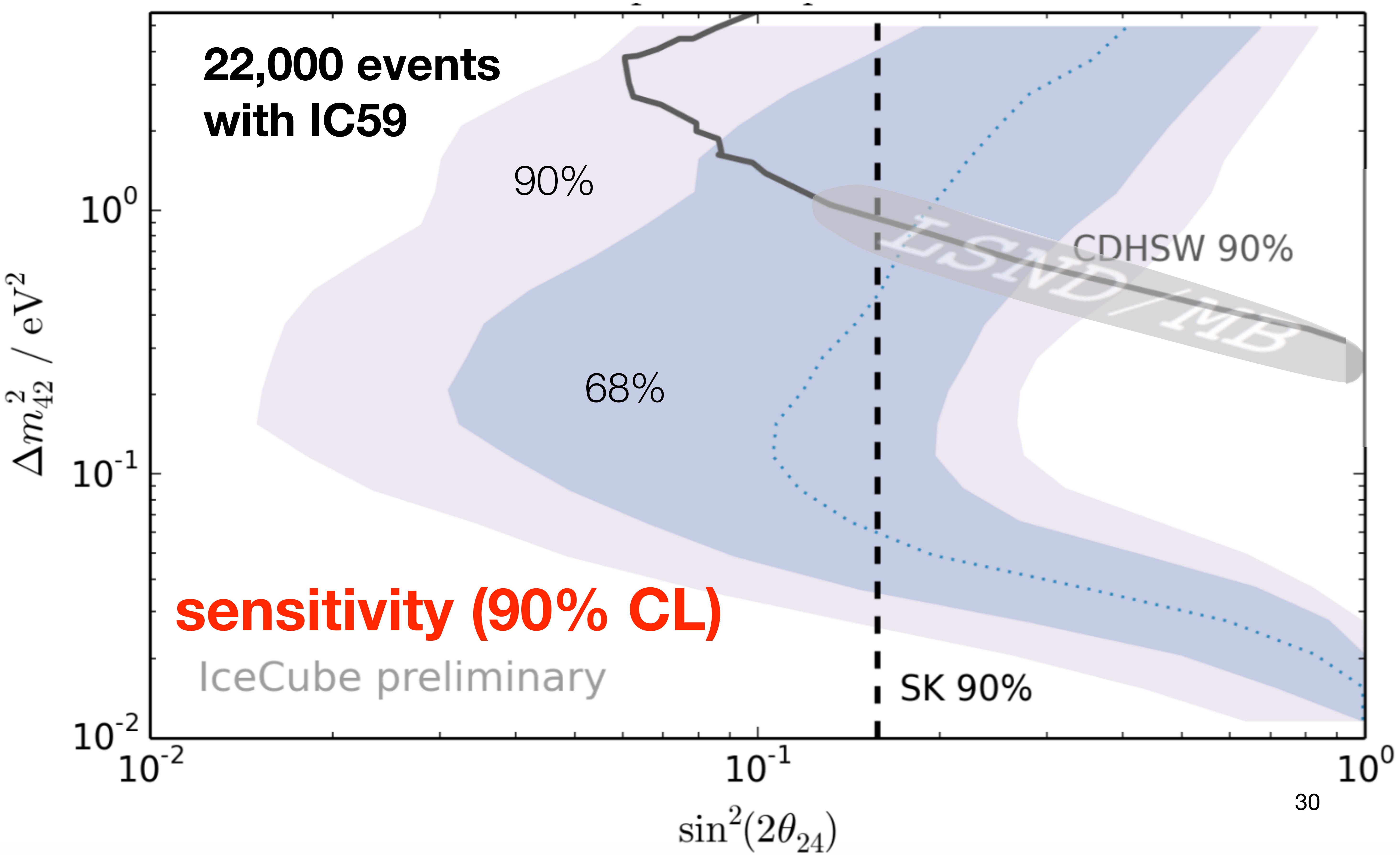
in normal hierarchy
large effect on anti-ν



search being extended to full IC86

- sterile neutrino with *large* mass splitting
- effects of matter oscillations @TeV - where most of IceCube ν's are

from 2000 pseudo-experiments



particle physics ($\nu + \mu$)

- ν oscillations
- high energy hadronic models
- forward physics
- heavy quarks
- ν mass hierarchy

atmospheric ν and μ

detector calibration

- angular pointing/resolution
- energy calibration

geo-sciences

- stratospheric temperatures
- upper atmosphere winds
- short & long time temp. variations
- Earth science

cosmic ray astrophysics (μ)

- cosmic ray anisotropy
- probe of local interstellar fields
- probe of local sources of CR

test of Standard Model

- non standard oscillations
- sterile ν's
- Lorentz invariance
- quantum gravity

ν astronomy

- transition to astrophysics of energy spectrum & flavor composition
- point and diffuse sources of cosmic rays

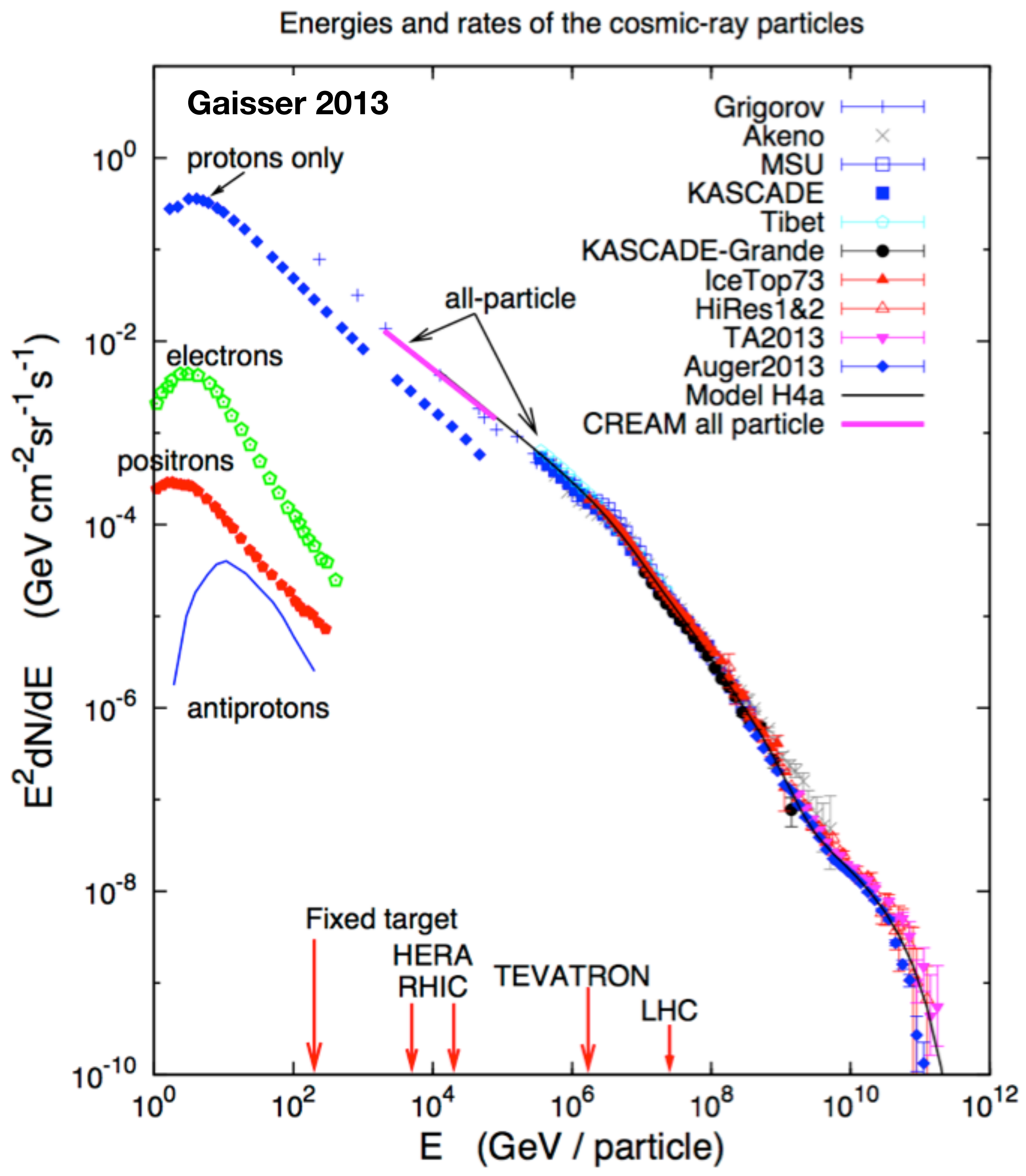
Pingu - K. Clark
Fri 31/7

Gen2 - E. Blaufuss
Fri 31/7

supporting material

cosmic rays & atmospheric leptons

- are **accelerated** in *unidentified* sources
- are composed of **atomic nuclei**
- **propagate** across magnetized plasmas
- hit Earth's **atmosphere**
- generate hadronic & e.m. **showers**



cosmic rays & atmospheric leptons

SLAC-PUB-11092

Calculation of atmospheric muons from cosmic gamma rays

J. Poirier[1], **S. Roesler**[2], **and A. Fassò**[3]

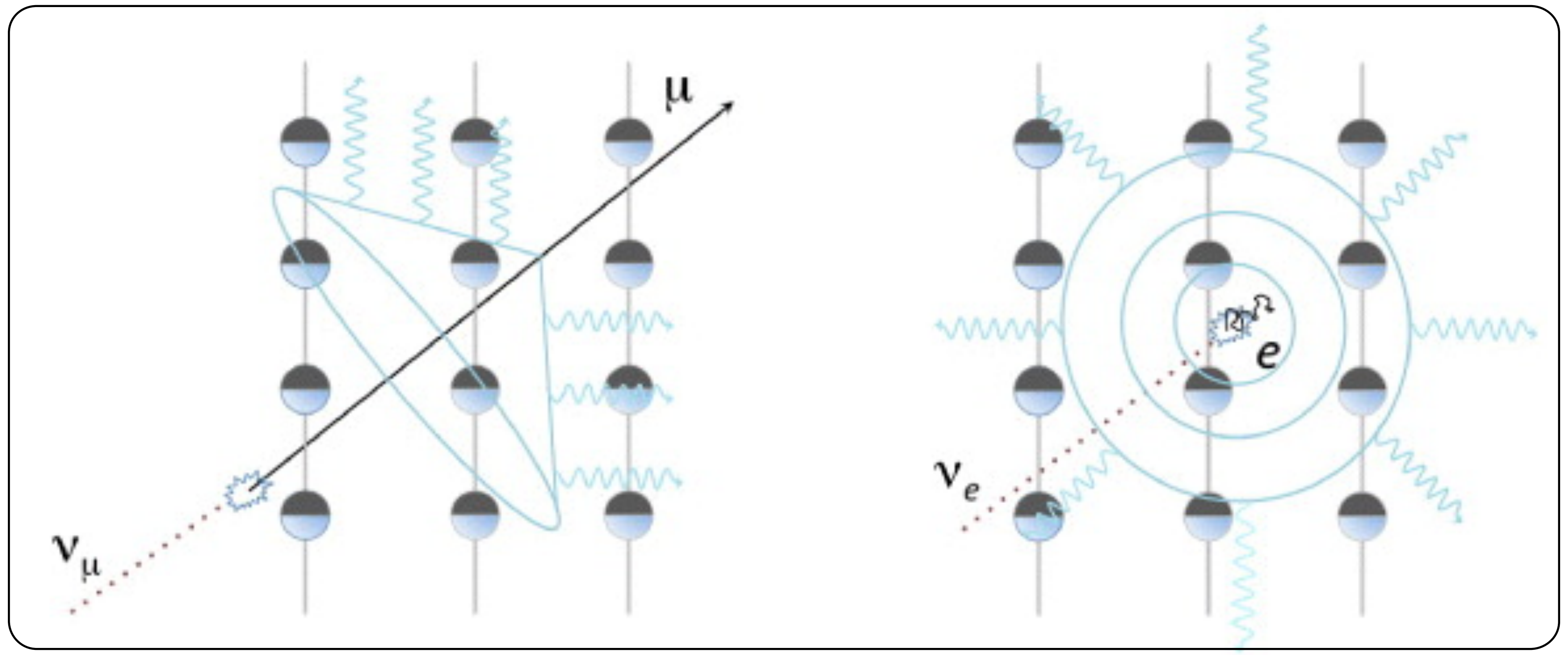
[1]Center for Astrophysics at Notre Dame, Physics Dept., University of Notre Dame, Notre Dame, Indiana 46556 USA
[2]Stanford Linear Accelerator Center, Stanford, California 94309 USA
[3]CERN-EP/AIP, CH-1211 Geneva 23, Switzerland

Table 2. Fractional contributions to the parents of the muons which reach sea level.

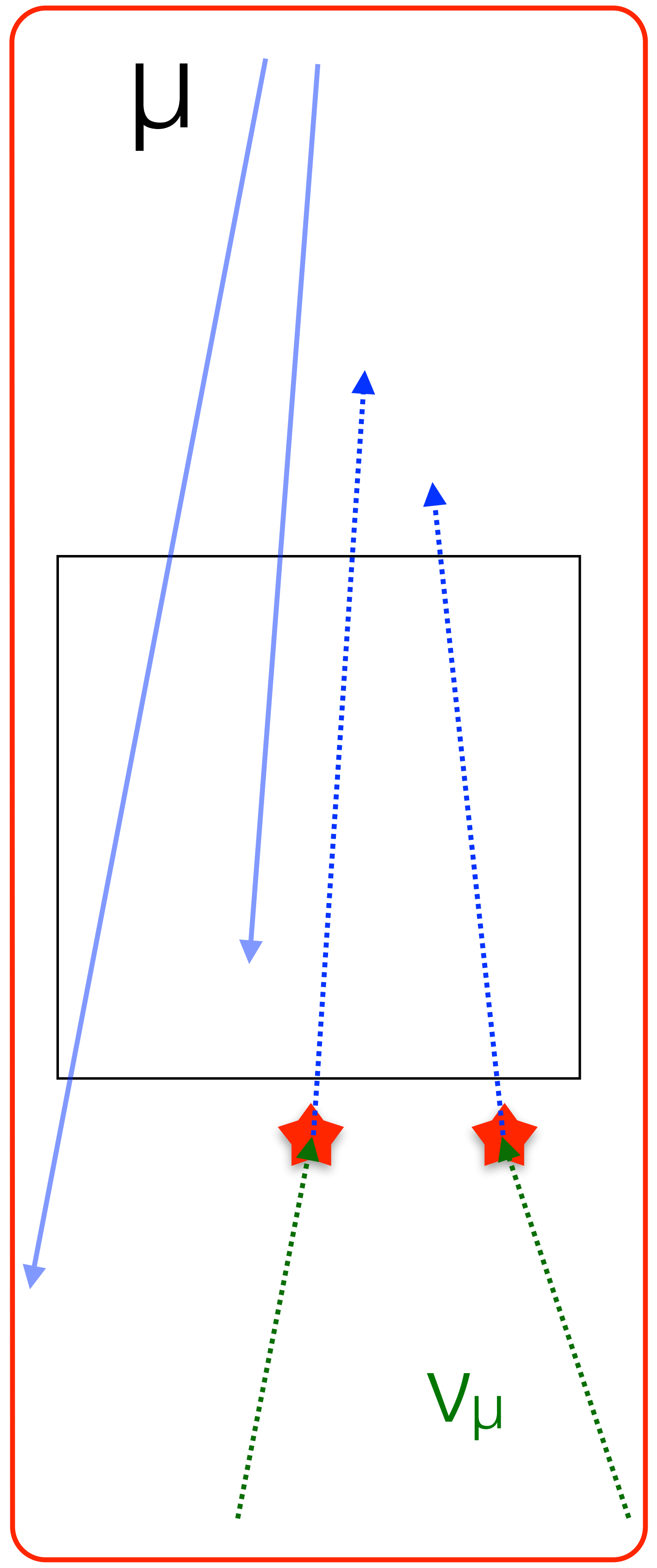
E_γ (GeV)	π^+	π^-	K^+	K^-	neutral kaons
1	0.106	0.894	0.0	0.0	0.0
3	0.495	0.485	0.020	0.0	1.7×10^{-4}
10	0.492	0.489	0.011	0.007	9.8×10^{-4}
30	0.482	0.482	0.019	0.014	3.1×10^{-3}
100	0.478	0.477	0.022	0.018	4.4×10^{-3}
300	0.477	0.476	0.023	0.019	4.7×10^{-3}
1000	0.475	0.476	0.024	0.019	5.2×10^{-3}
3000	0.476	0.475	0.025	0.020	5.1×10^{-3}
10000	0.474	0.477	0.024	0.020	5.2×10^{-3}

searching for neutrinos
background rejection

- all-flavor searches: ν_μ, ν_e & ν_τ

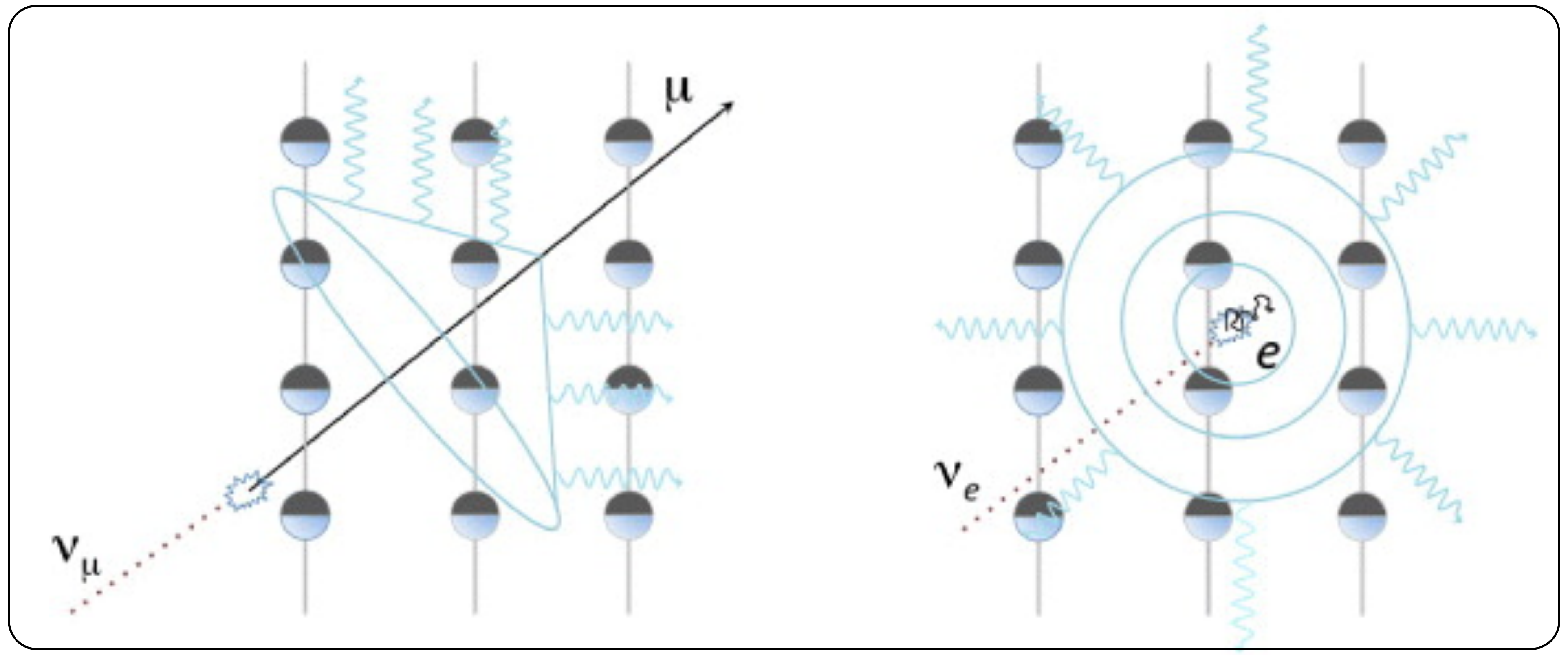


- **through-going up-ward μ's & HE down-ward μ's**



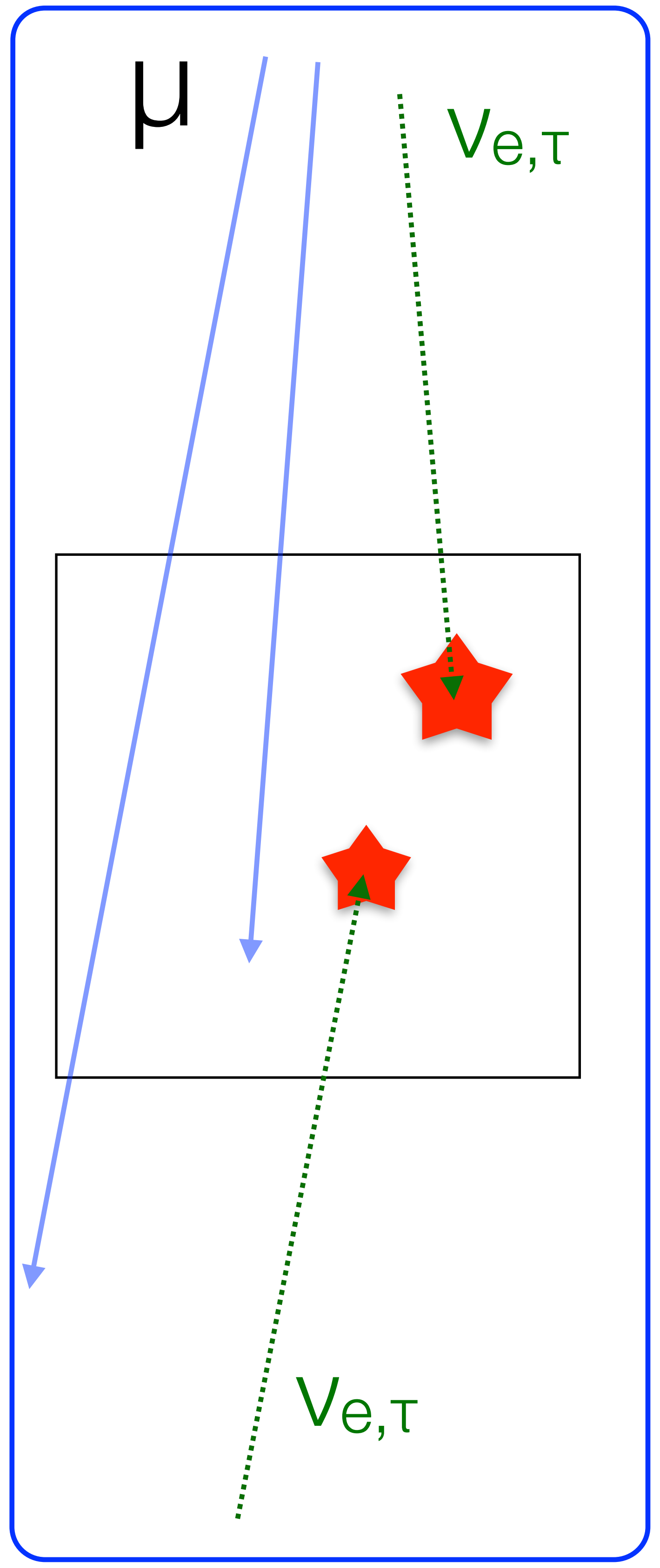
searching for neutrinos
background rejection

- all-flavor searches: ν_μ, ν_e & ν_τ



- through-going up-ward μ's & HE down-ward μ's

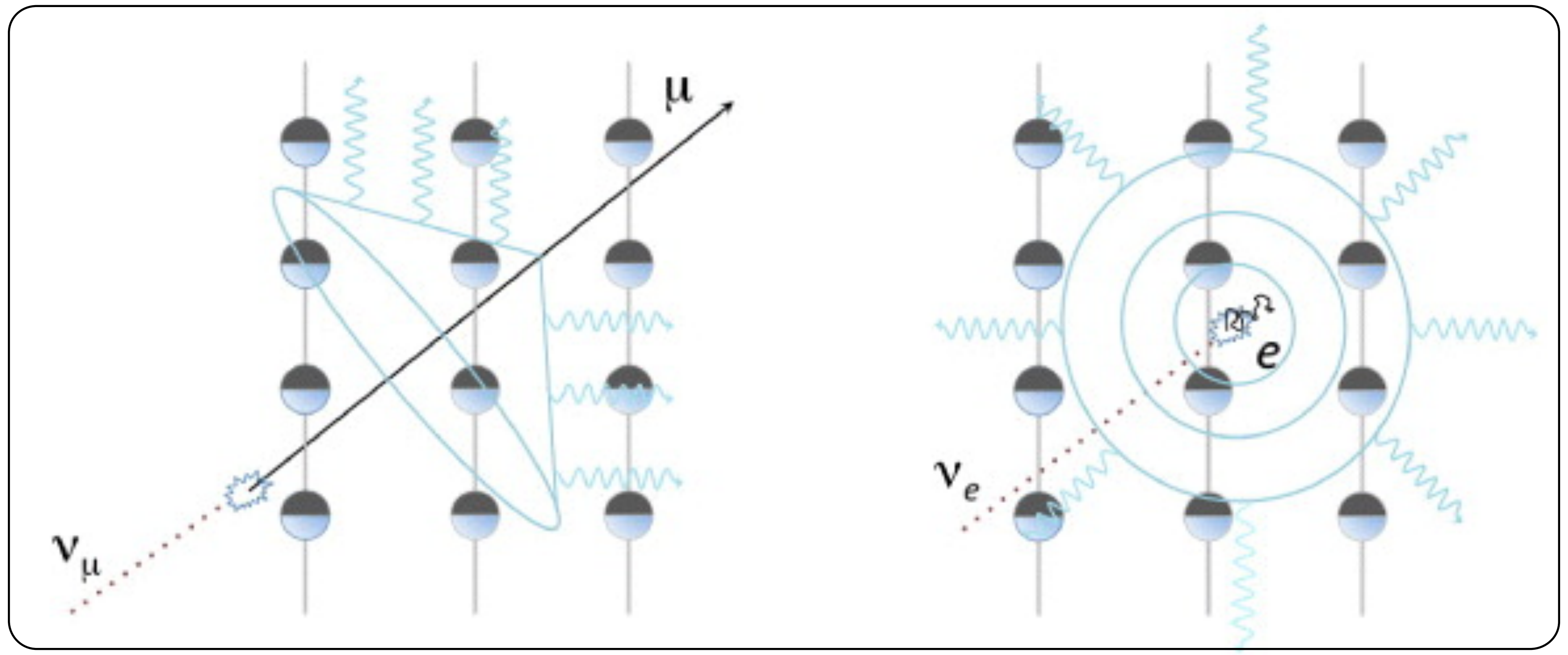
- **contained cascades**



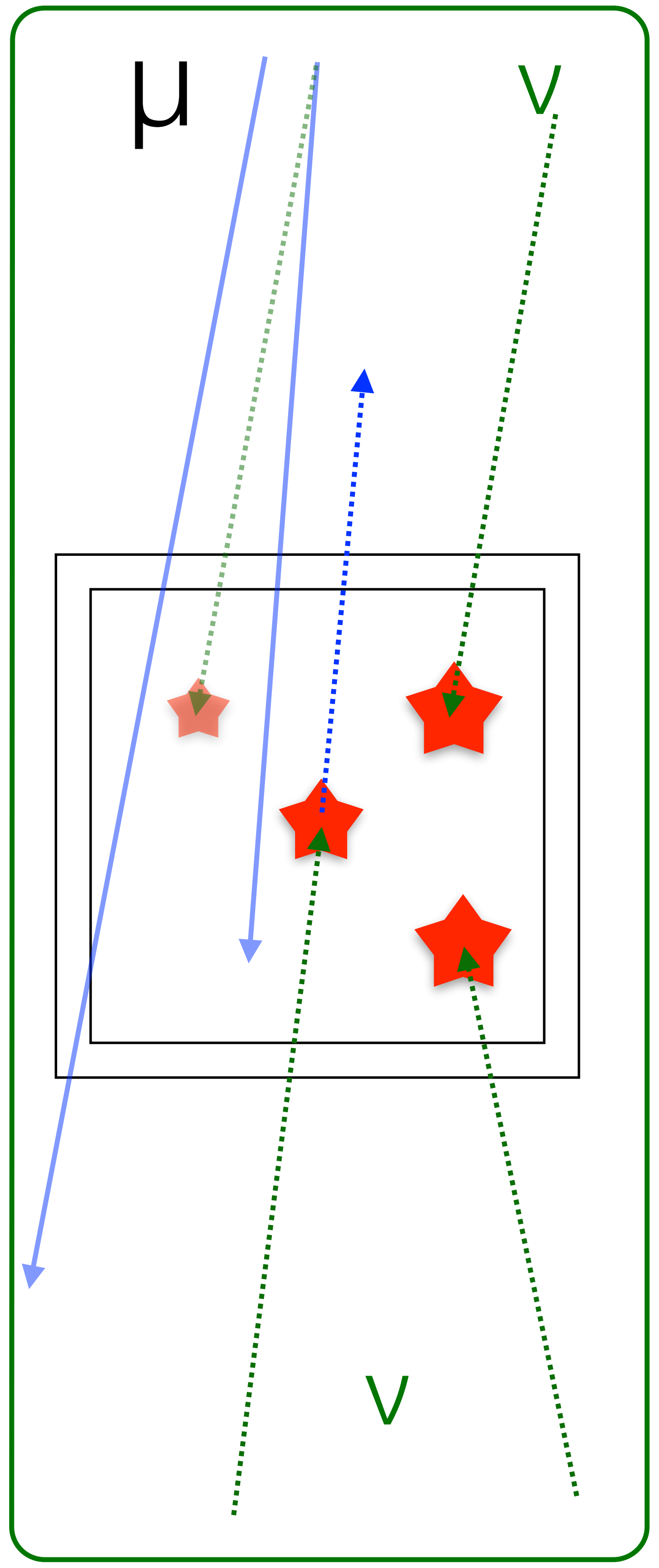
searching for neutrinos

background rejection

- all-flavor searches: ν_μ, ν_e & ν_τ

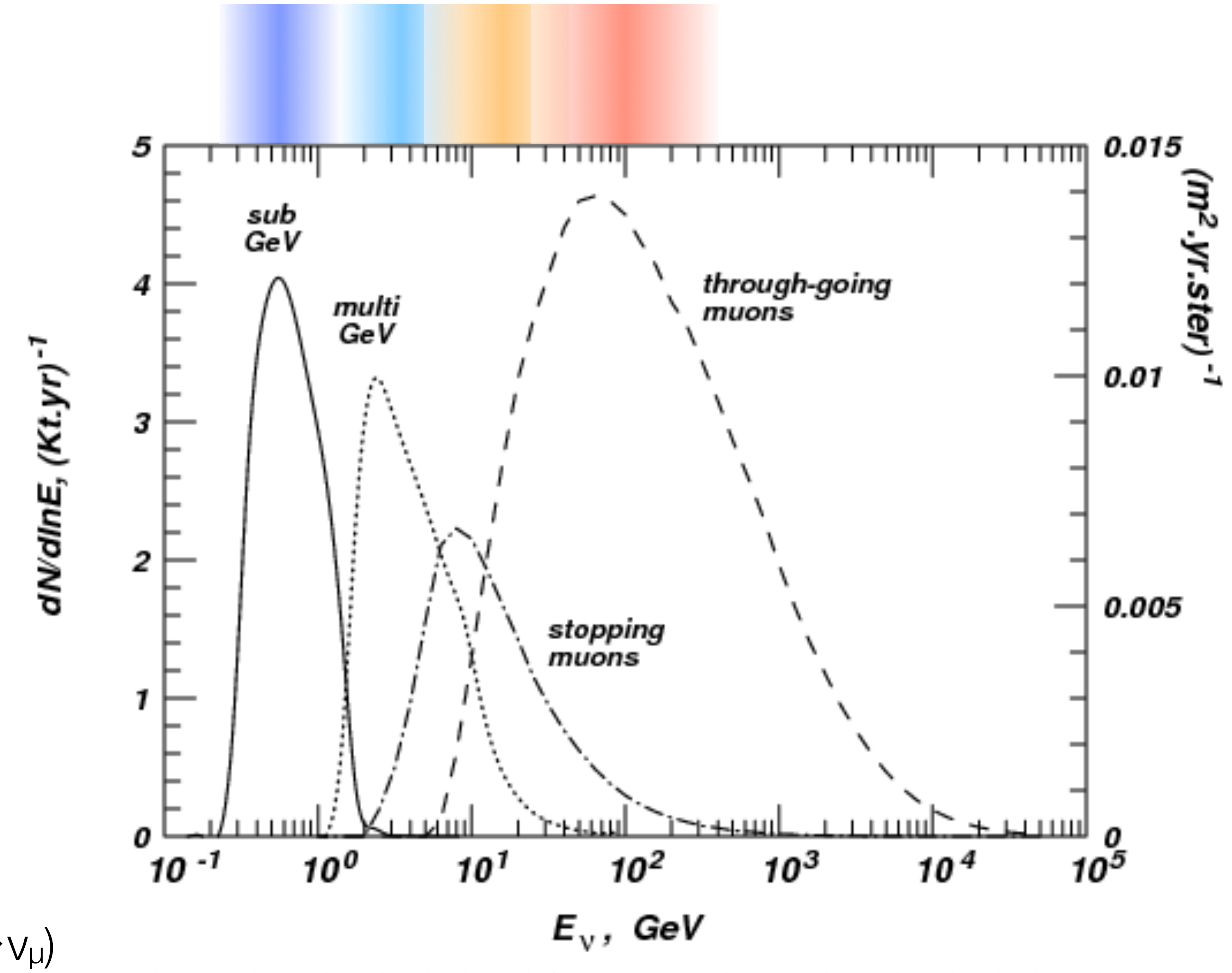


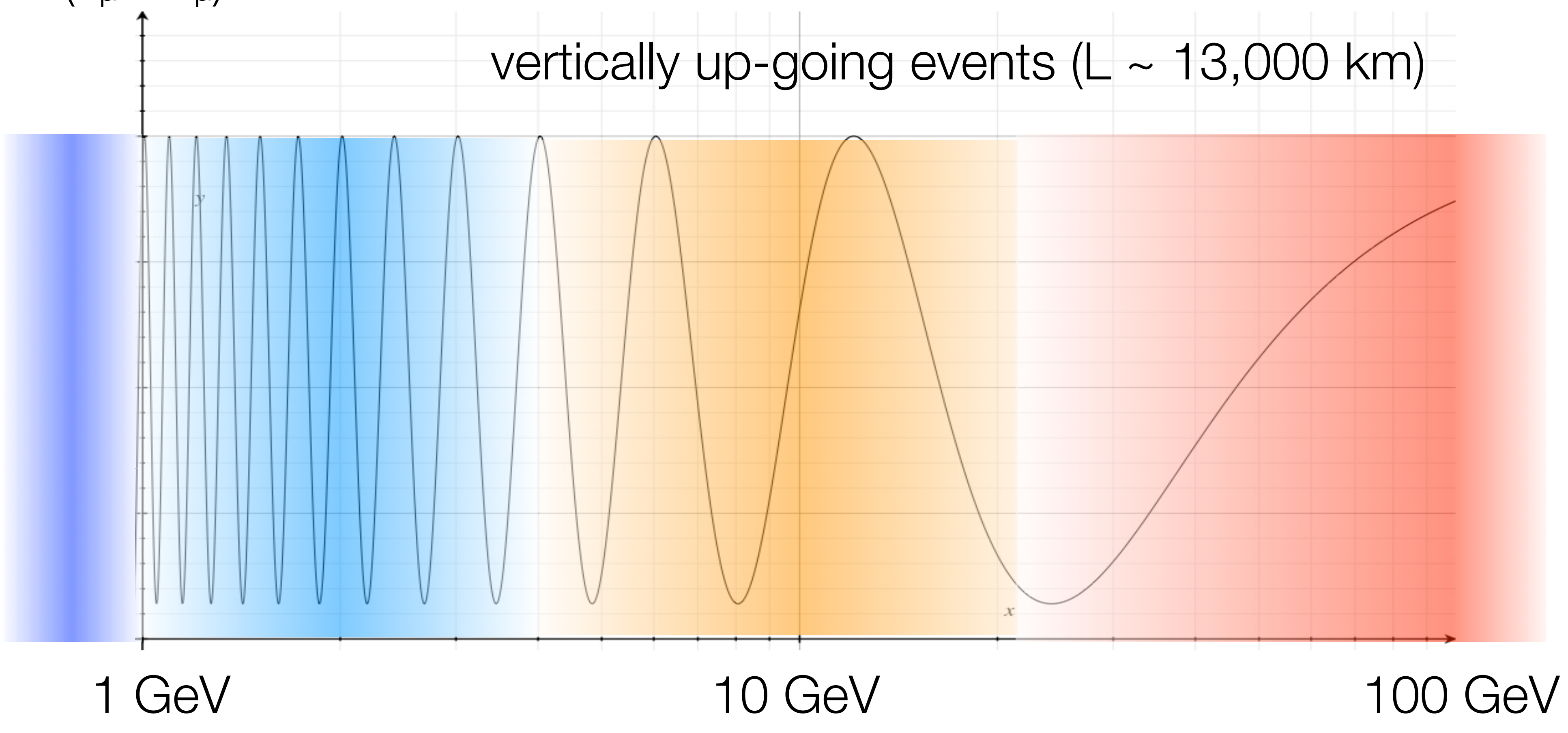
- through-going up-ward μ's & HE down-ward μ's
- contained cascades
- **HE starting events + self-veto & outer-veto**

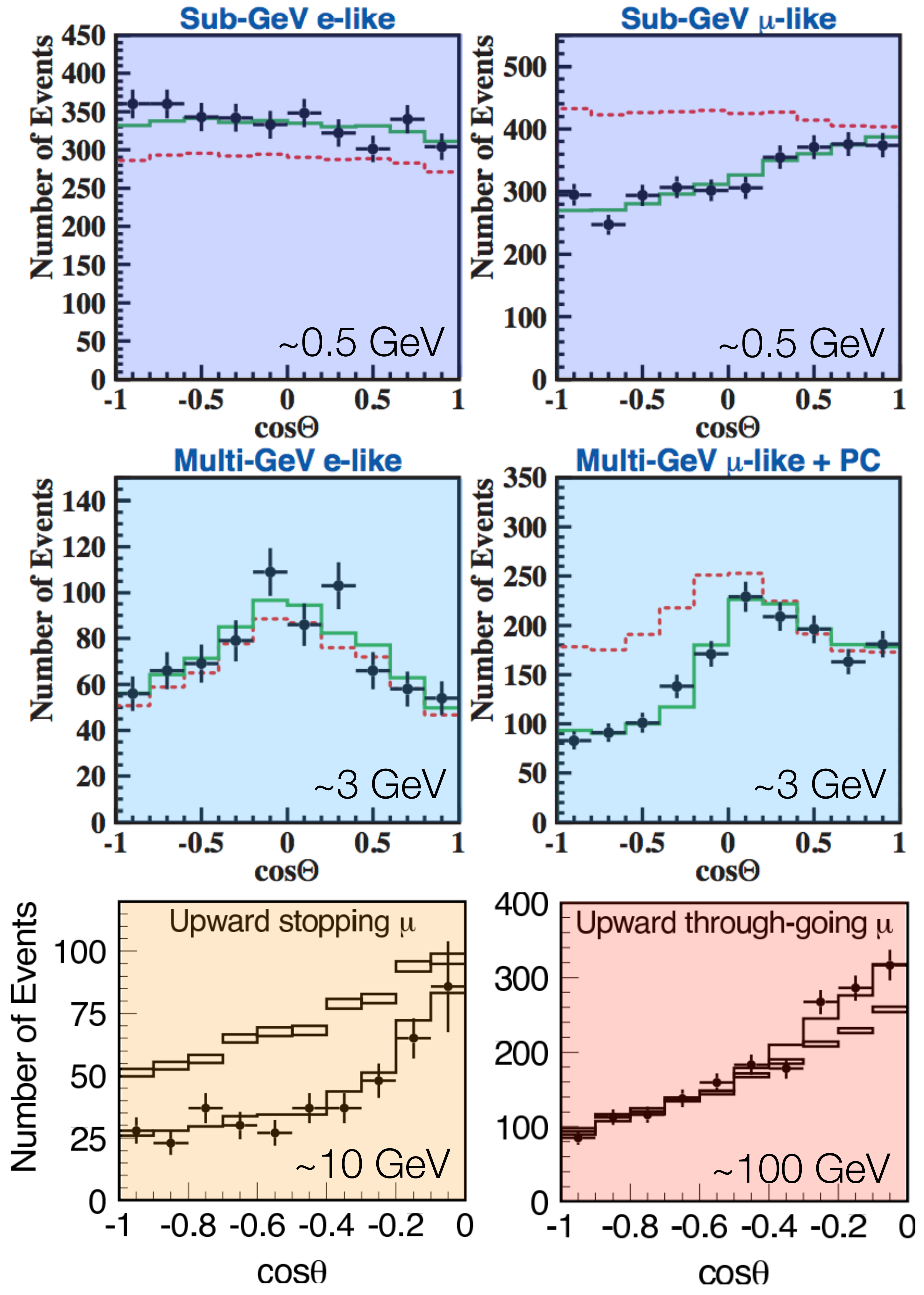


low energy neutrinos

Super-Kamiokande



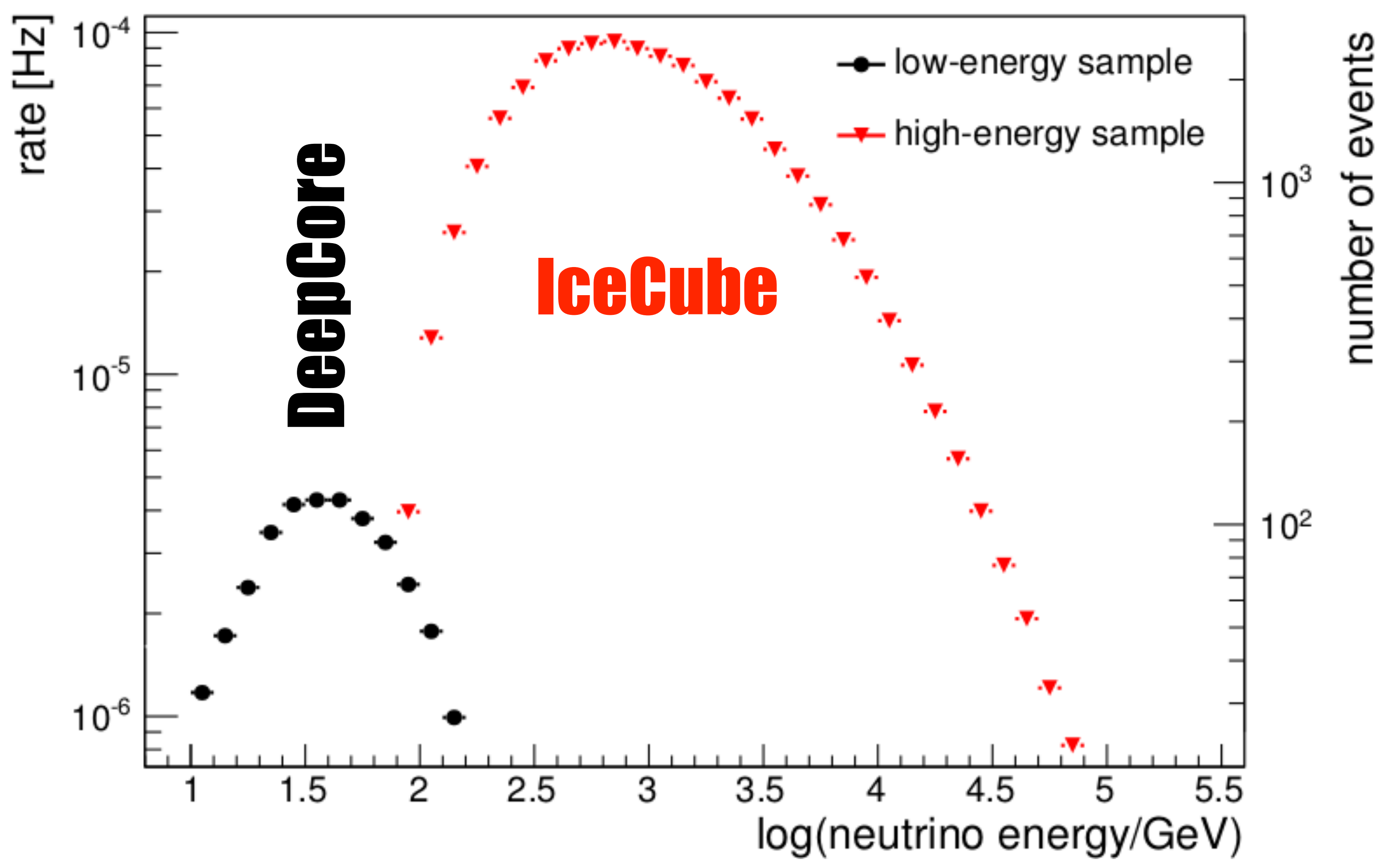


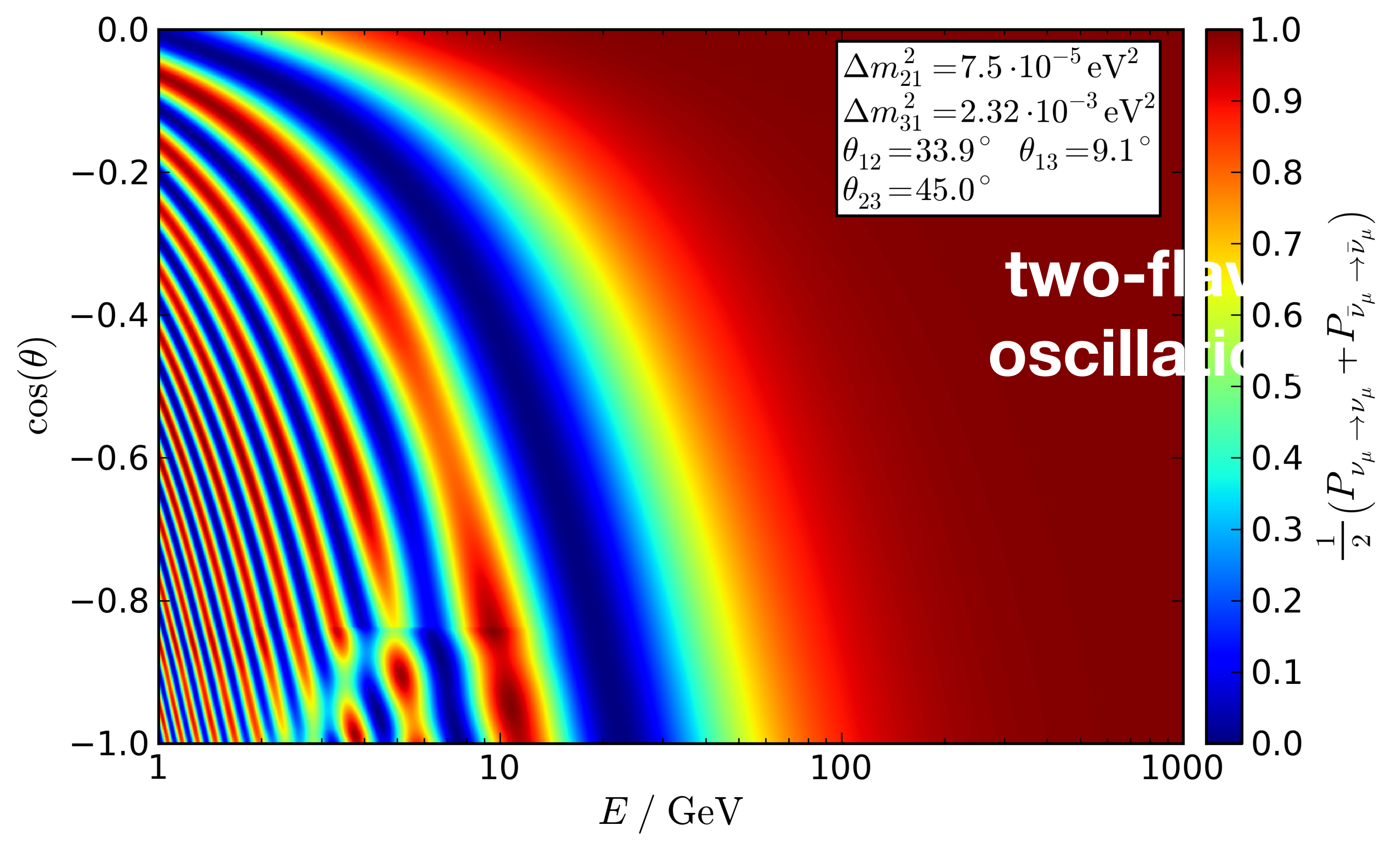


low energy neutrinos

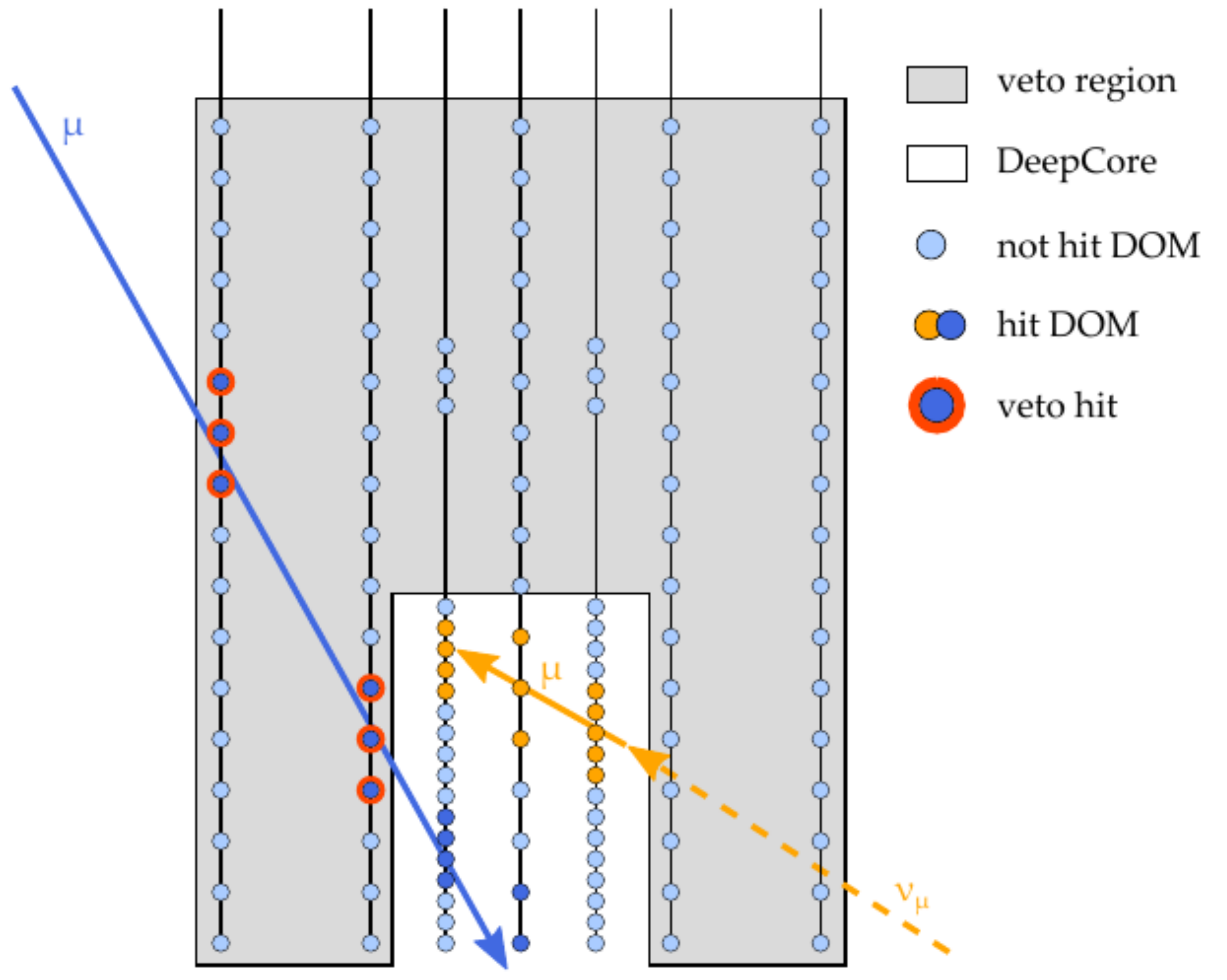
IceCube79 - DeepCore

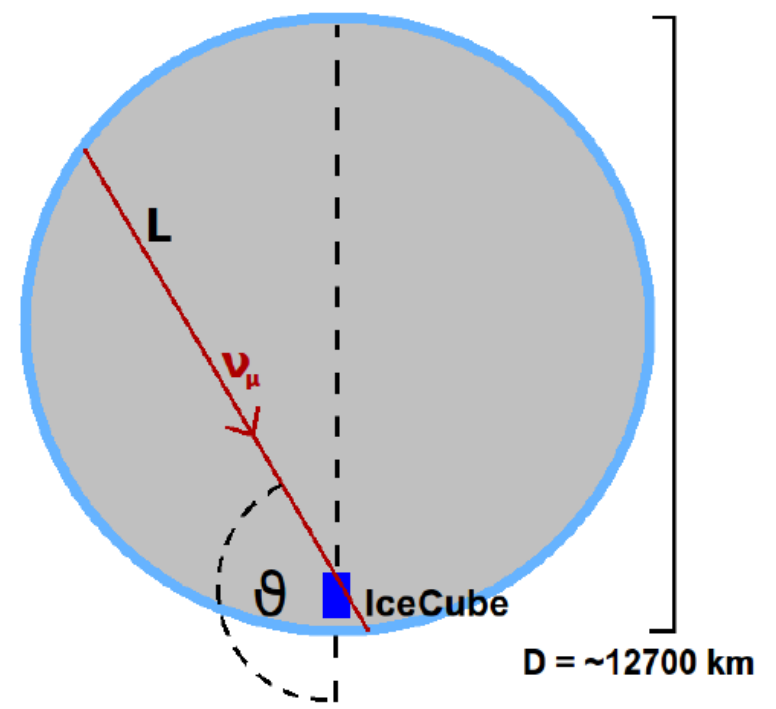
Phys. Rev. Lett. 111, 081801 **2013**





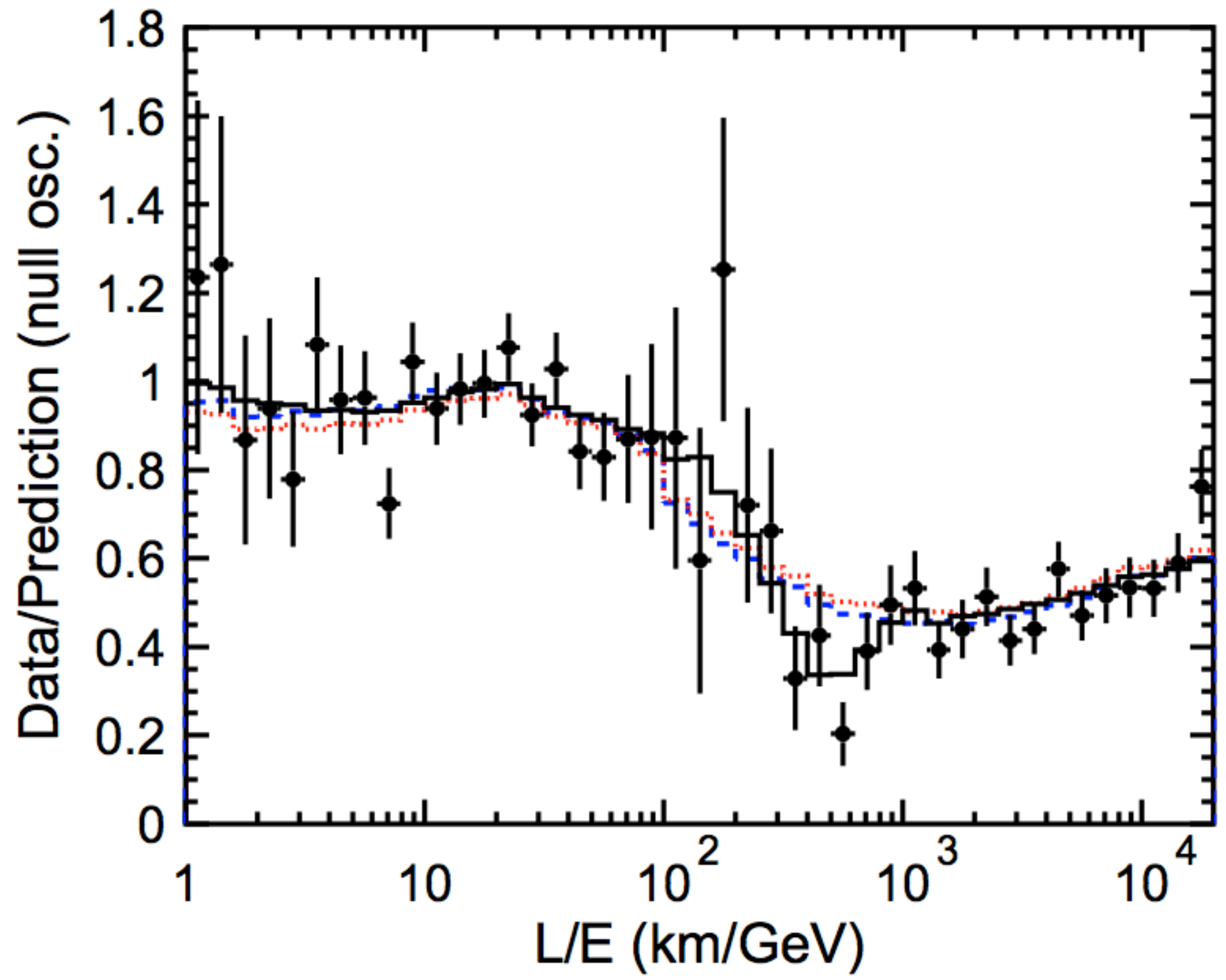
large volume → VETO

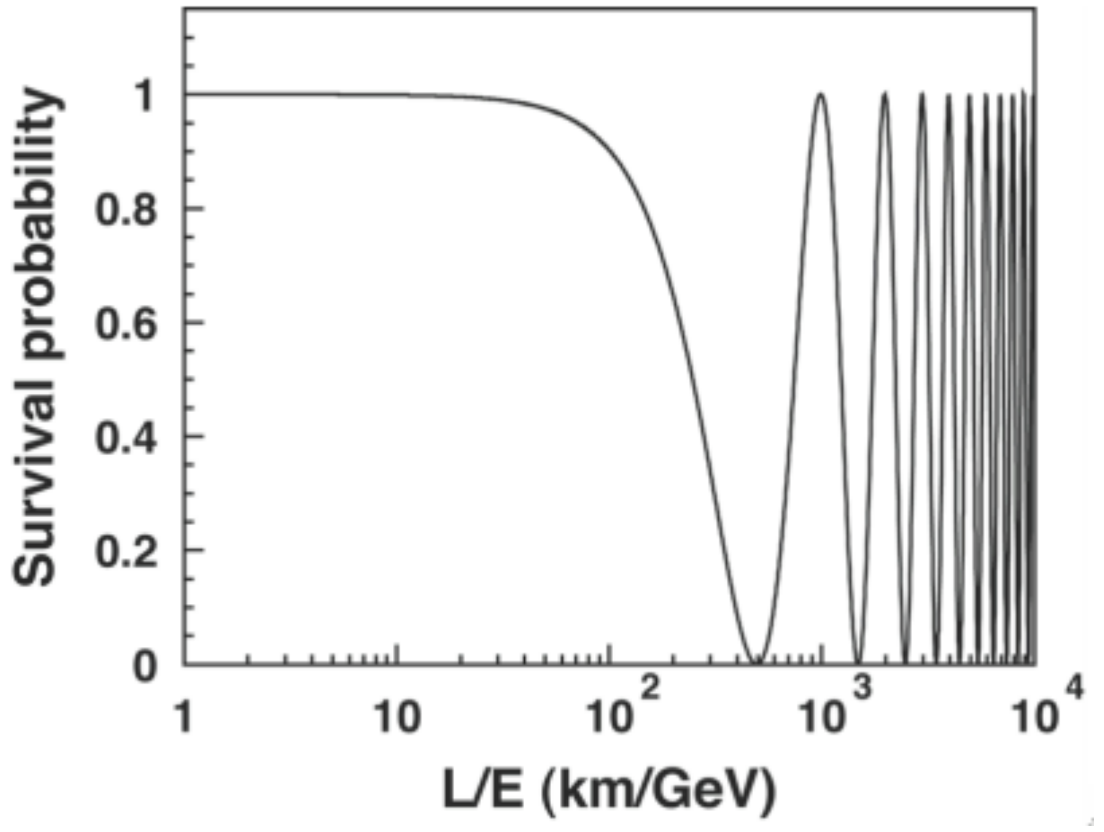




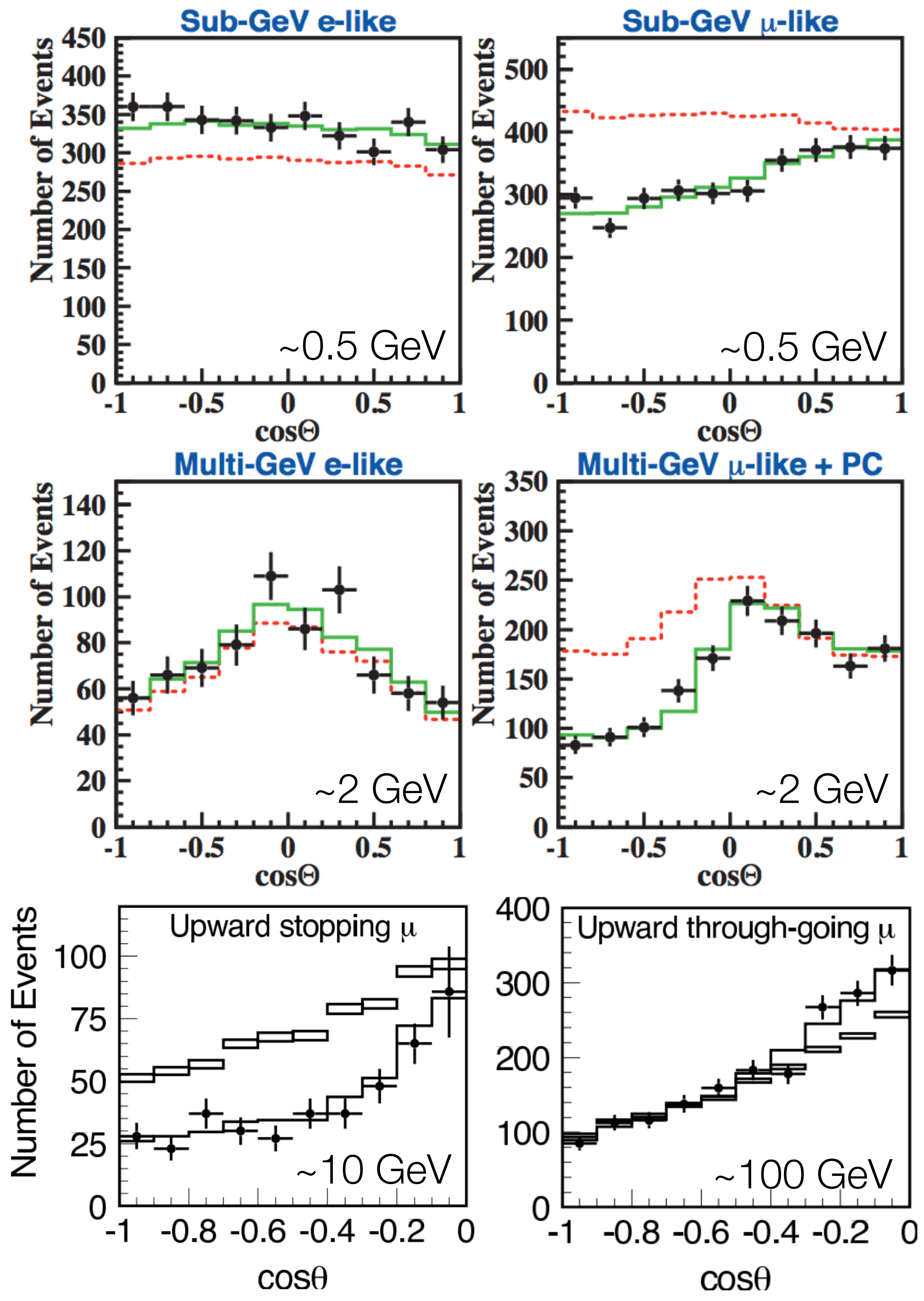
low energy neutrinos

Super-Kamiokande





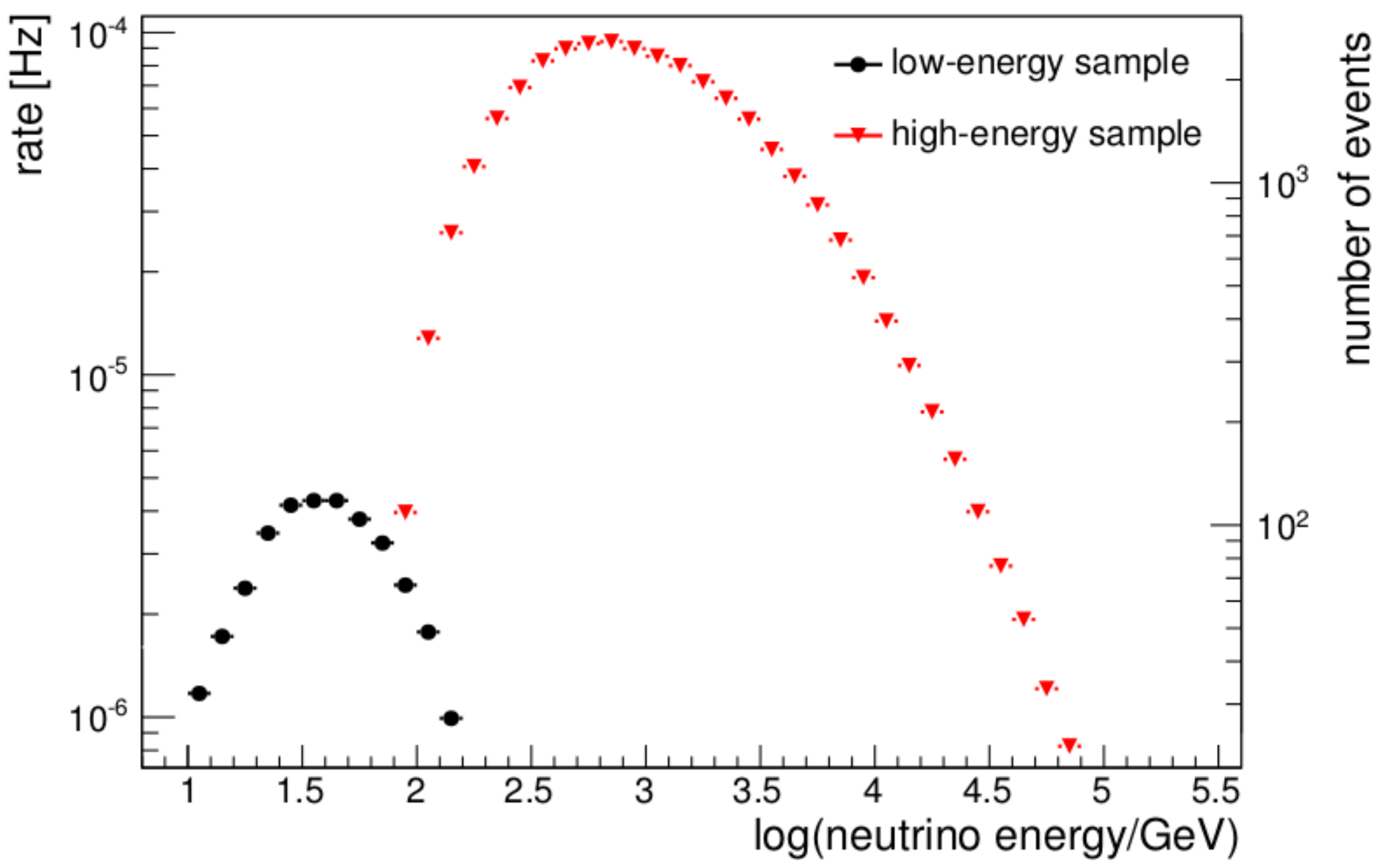
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\,\sin^2\left(1.27\,\frac{\Delta m^2_{23}\,L}{E_\nu}\right)$$

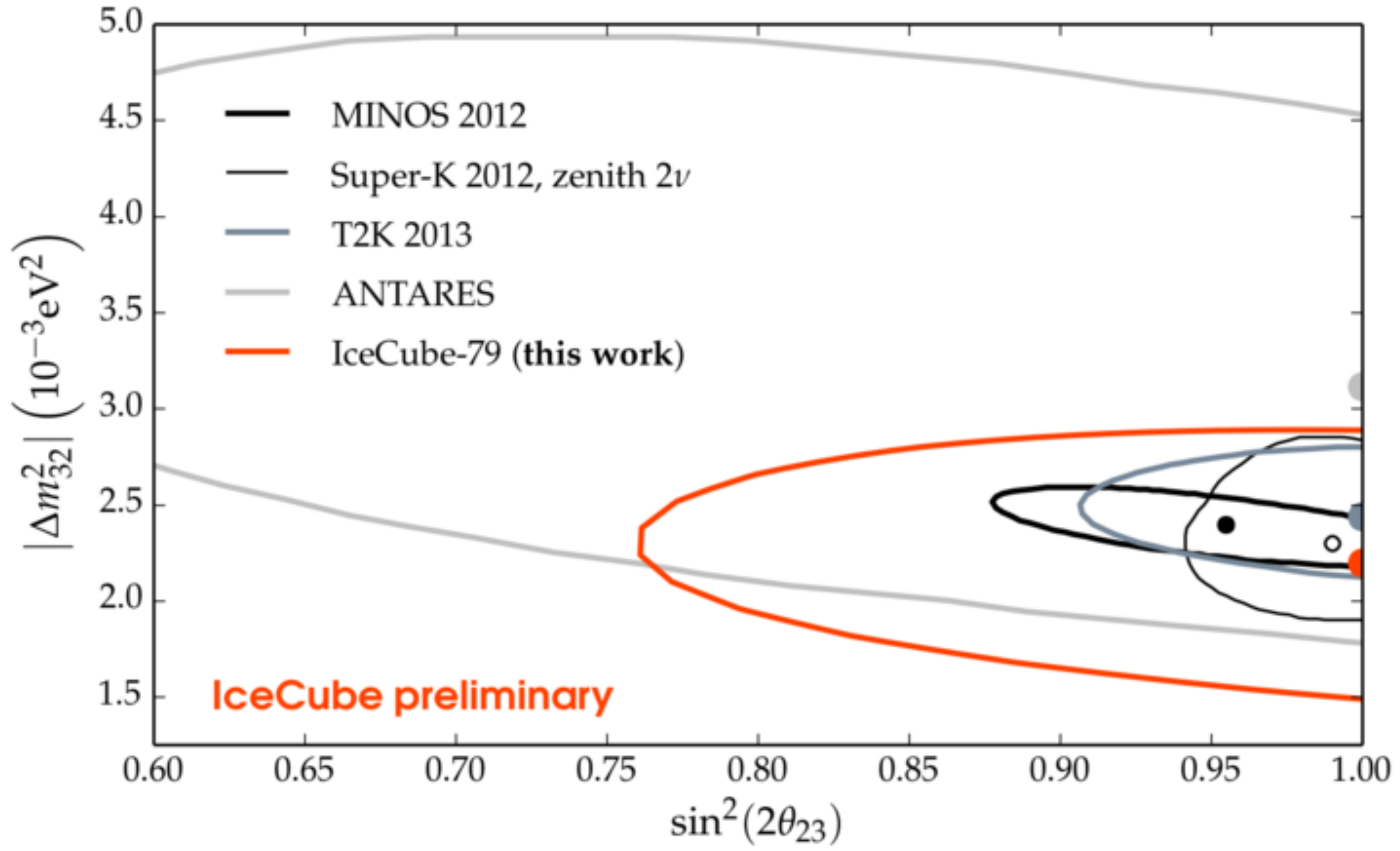


low energy neutrinos

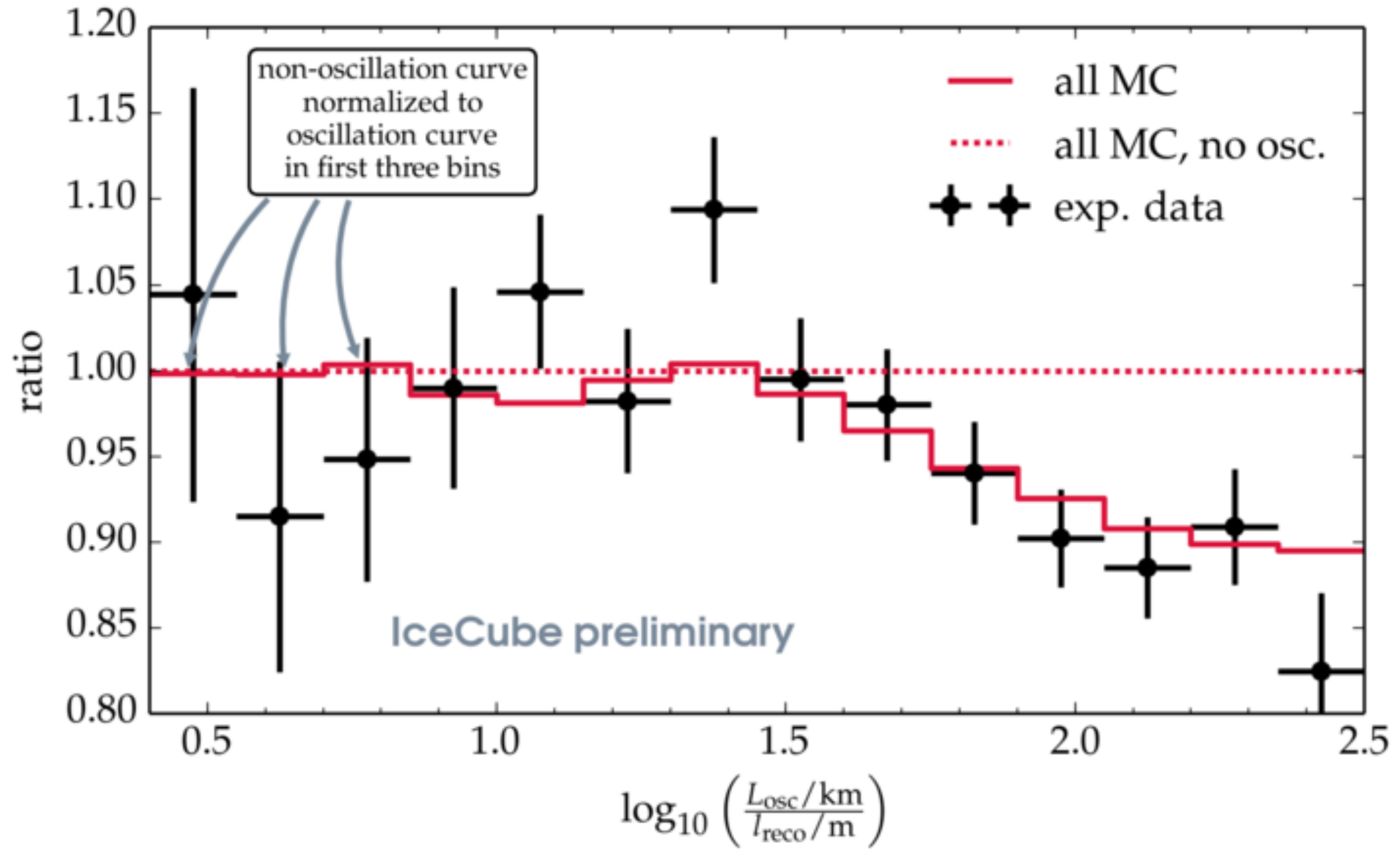
IceCube79 - DeepCore

2013





$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\ \sin^2\left(1.27\,\frac{\Delta m^2_{23}\,L}{E_\nu}\right)$$



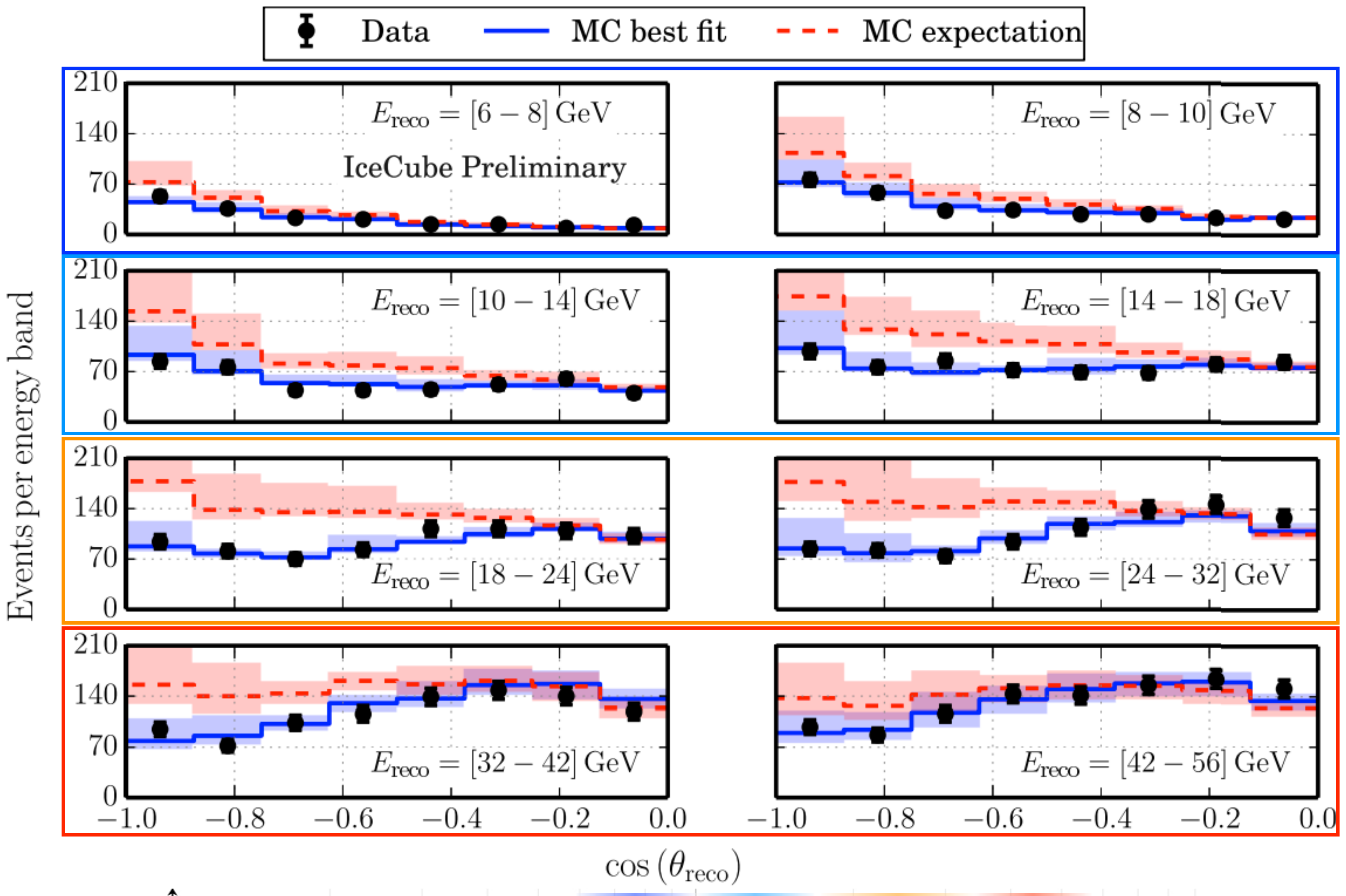
low energy neutrinos

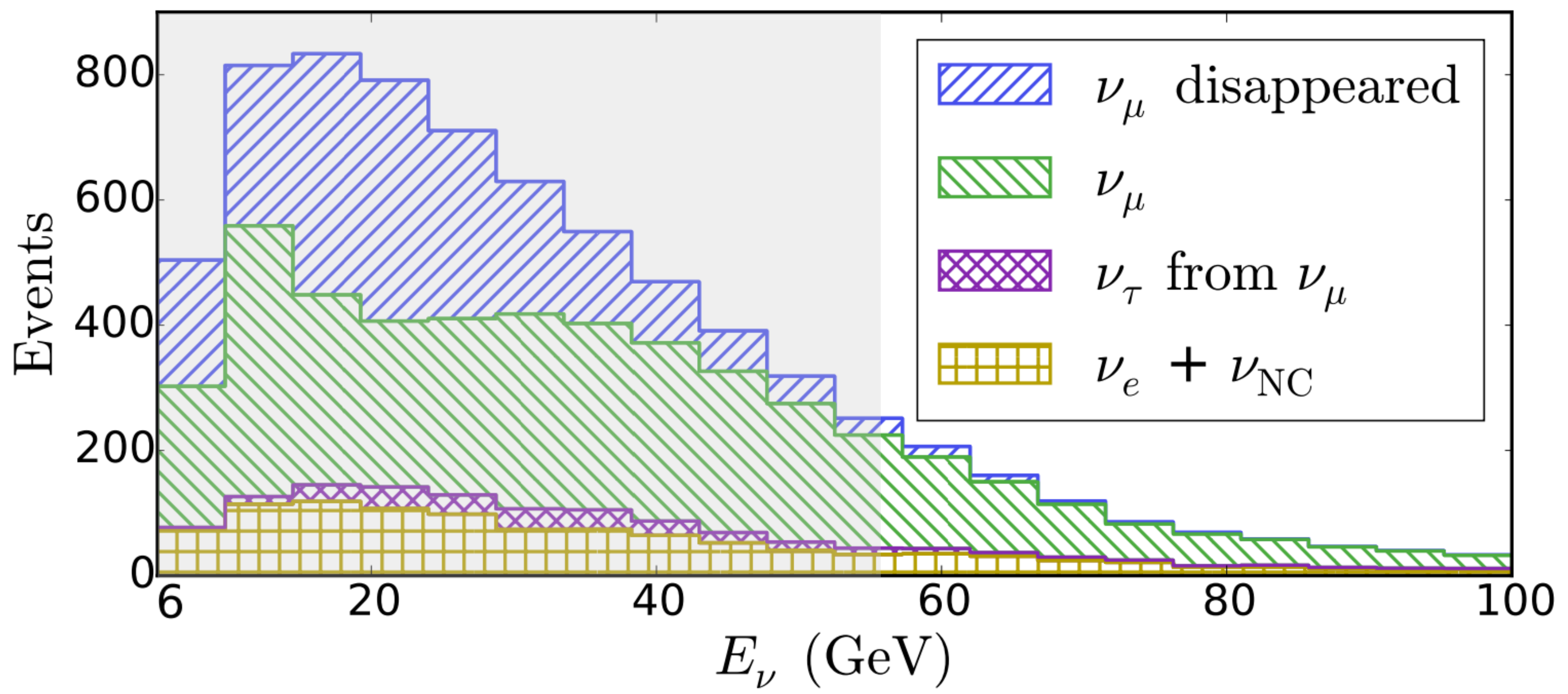
IceCube - 3 years

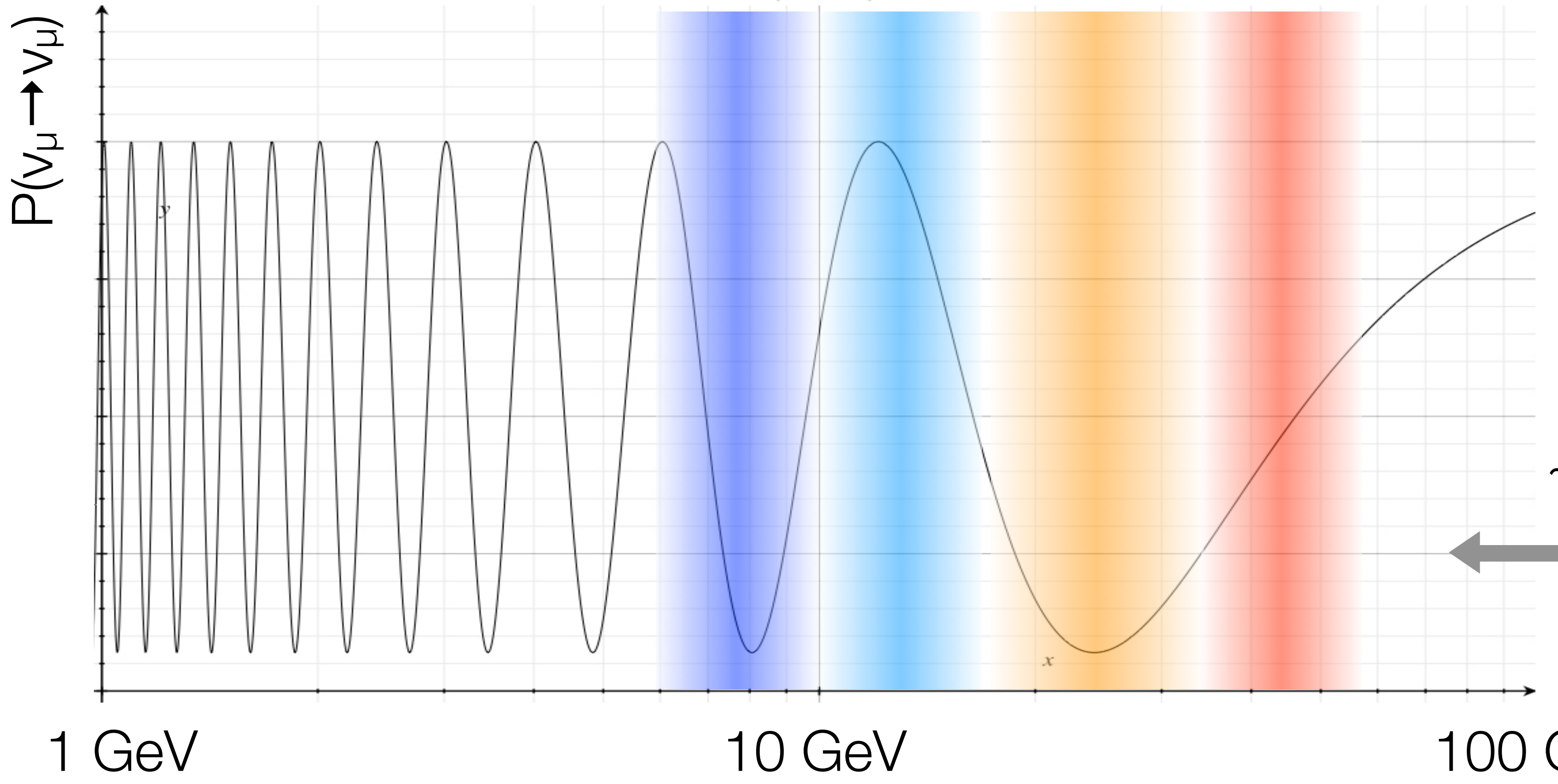
Phys. Rev. D 91, 072004 **2015**

5174 observed events
6830 expected events

in 953 days







energy resolution ~0.2 Log(E)

low energy neutrinos

IceCube - 3 years

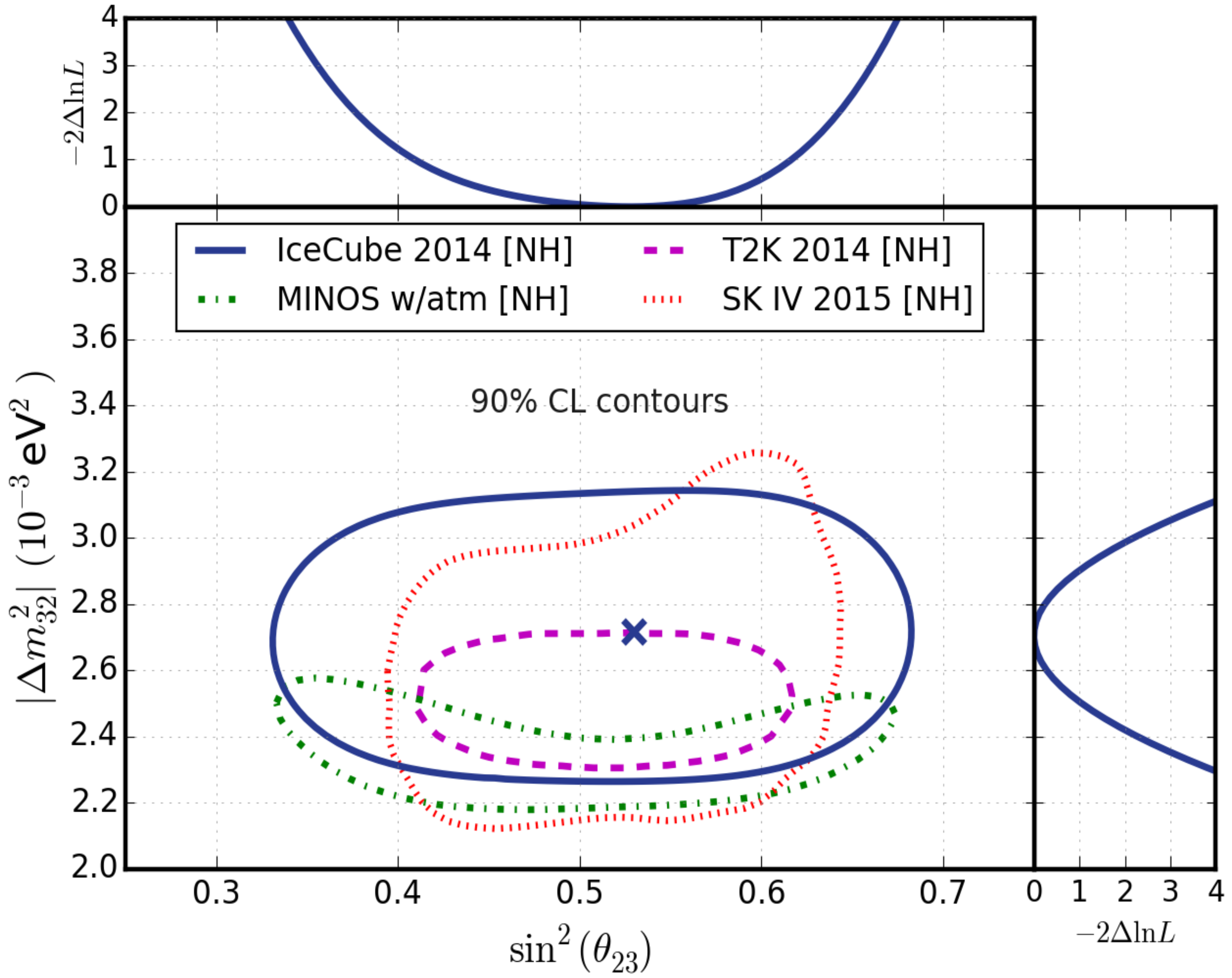
Phys. Rev. D 91, 072004 **2015**

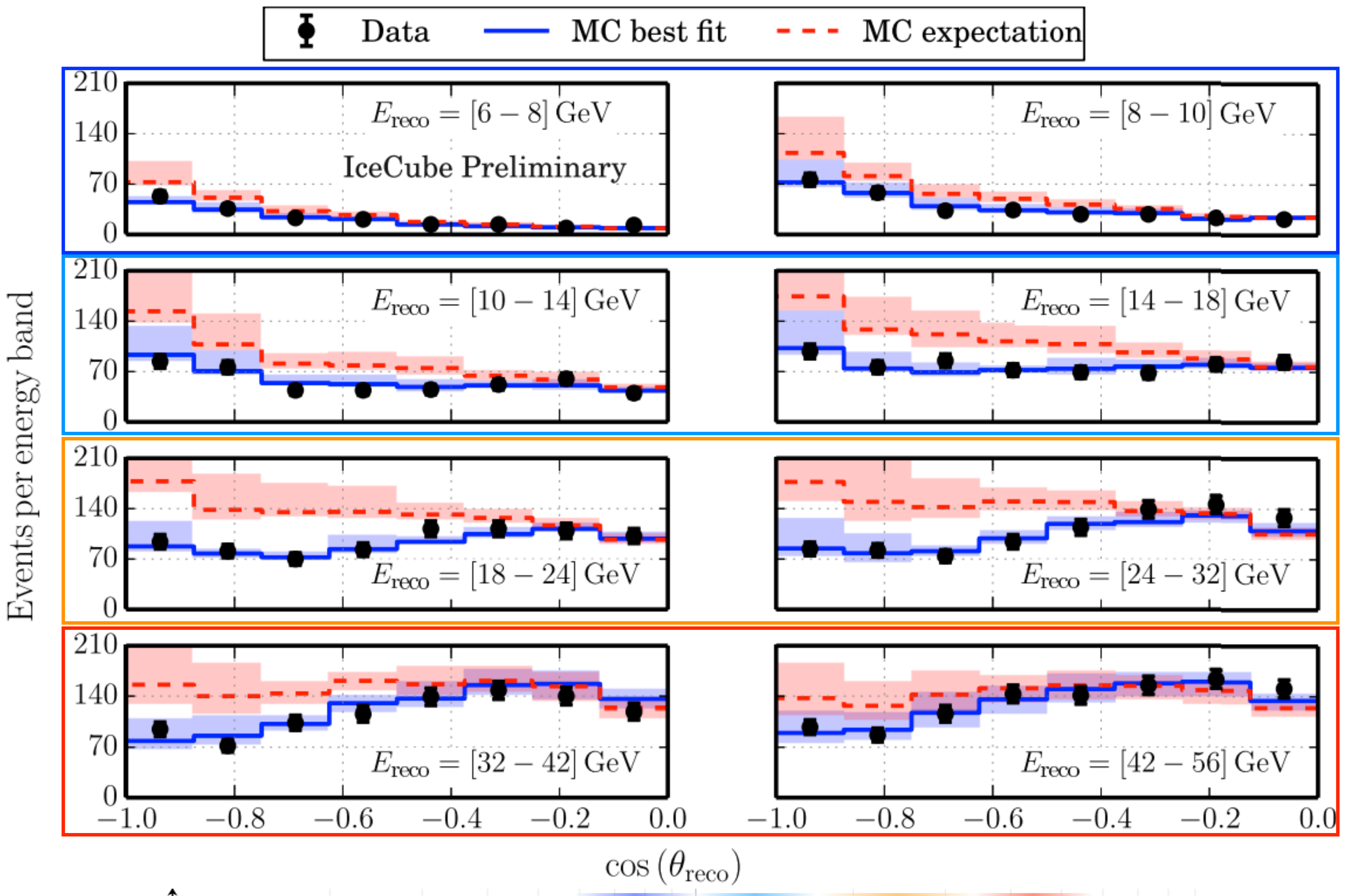
$$\Delta m^2_{23} = 2.72^{+0.19}_{-0.20} \times 10^{-3}\, eV^2$$
$$sin^2\,\theta_{23} = 0.53^{+0.09}_{-0.12}$$

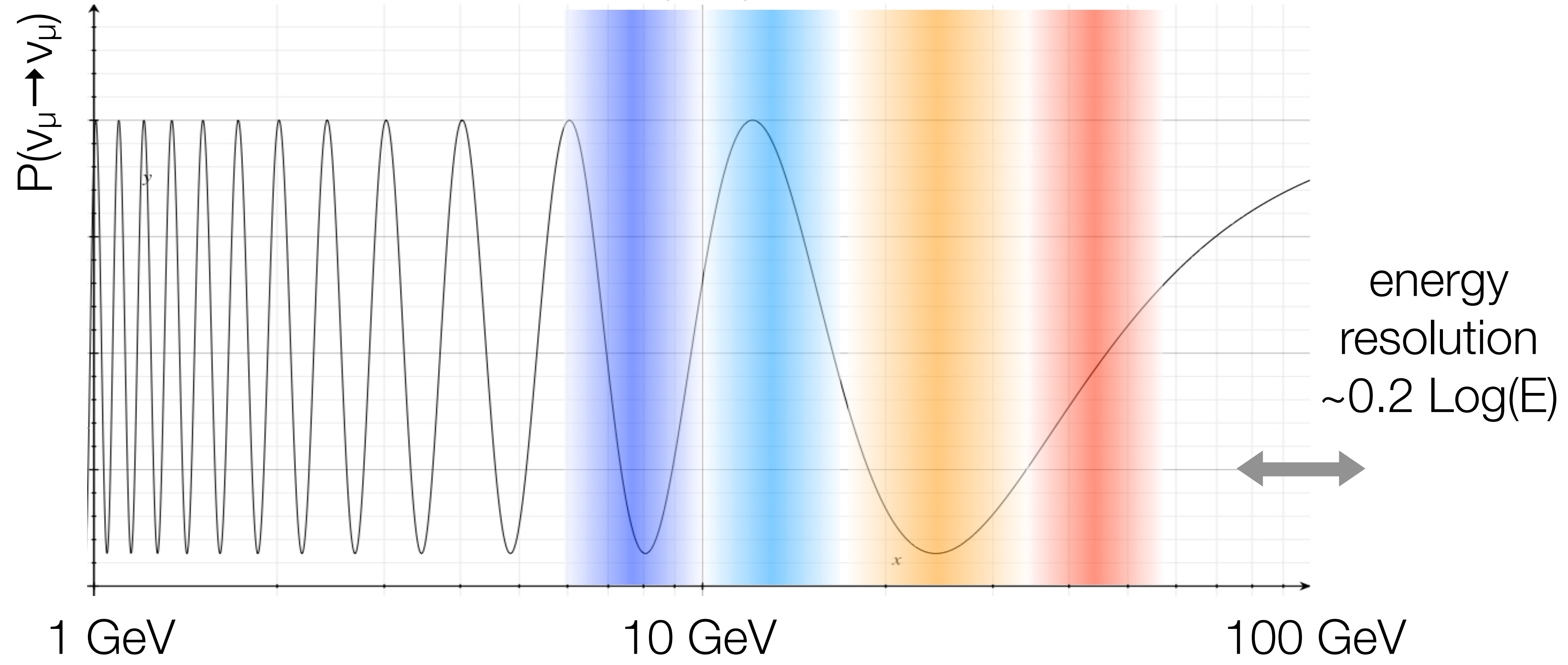
NH

$$\Delta m^2_{23} = -2.73^{+0.18}_{-0.21} \times 10^{-3}\, eV^2$$
$$sin^2\,\theta_{23} = 0.51^{+0.09}_{-0.11}$$

IH



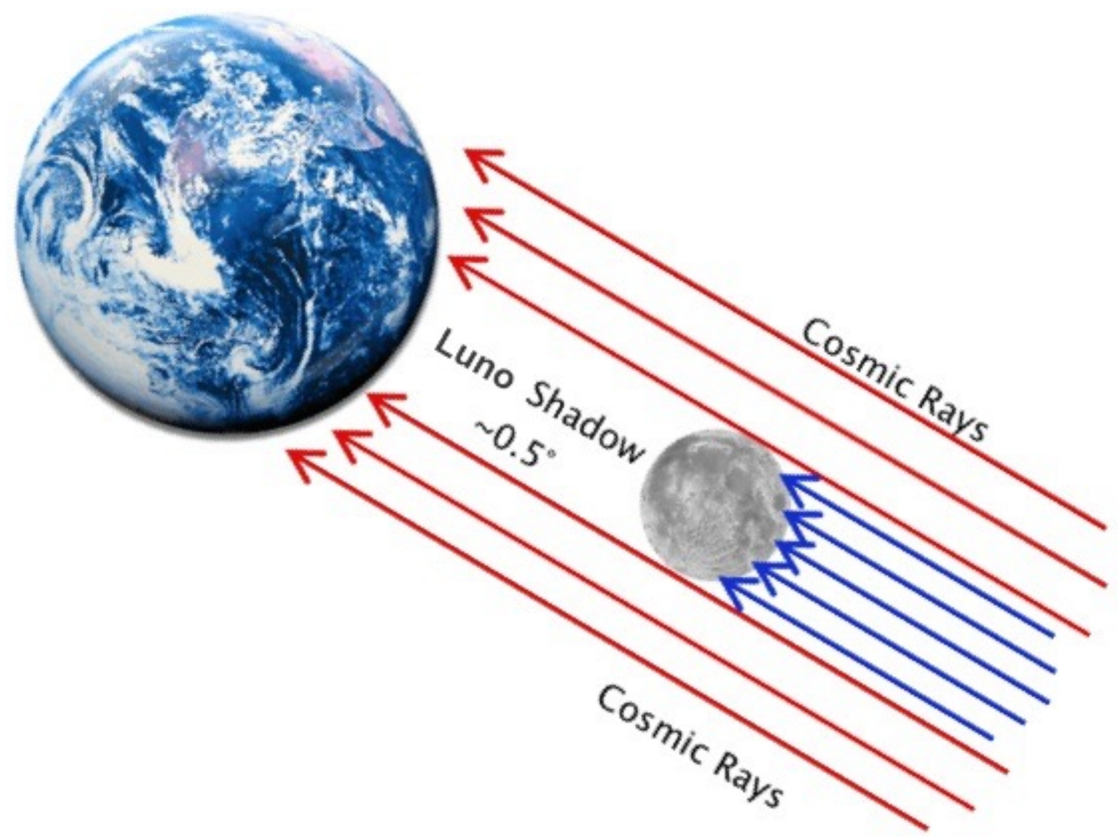


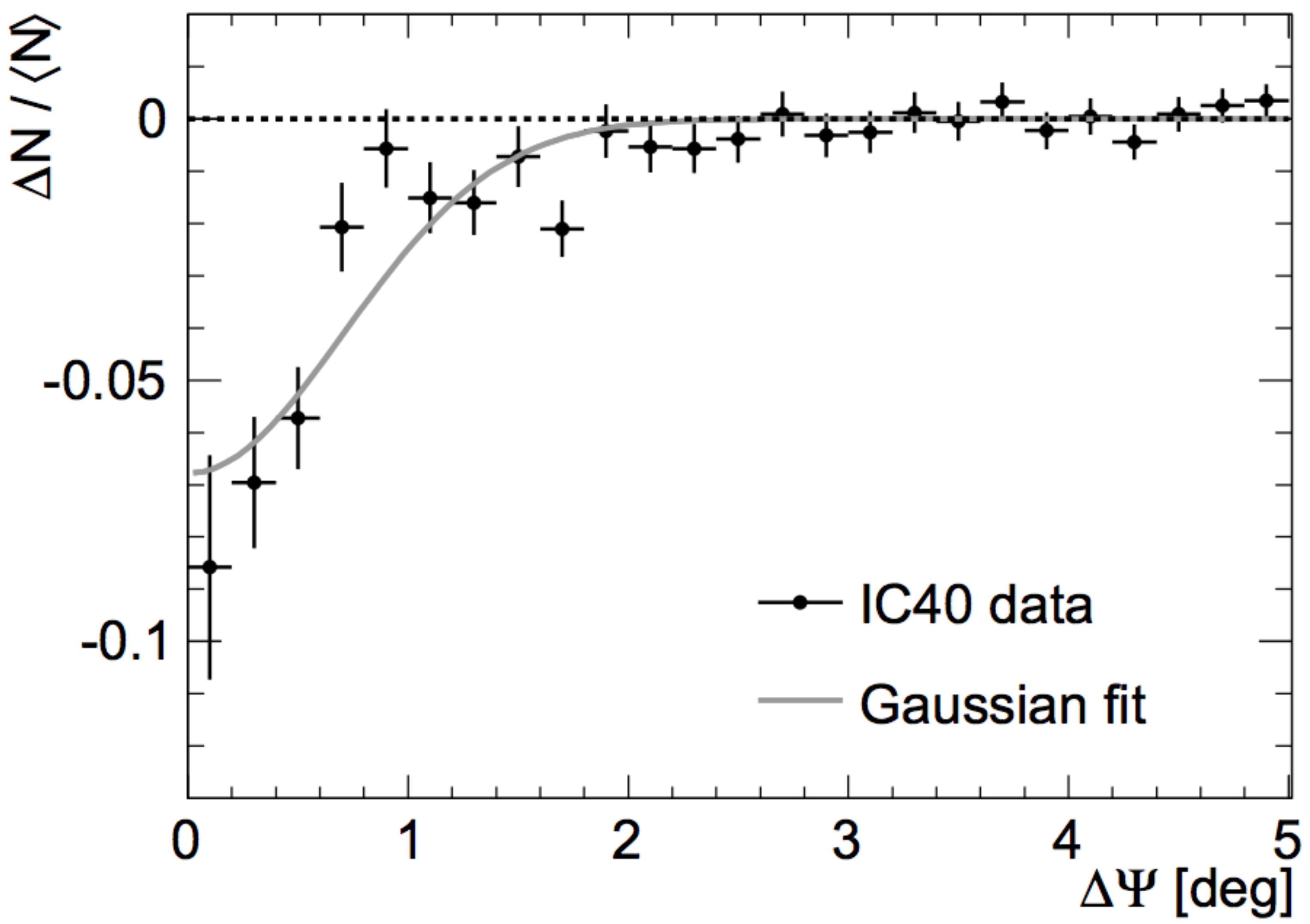


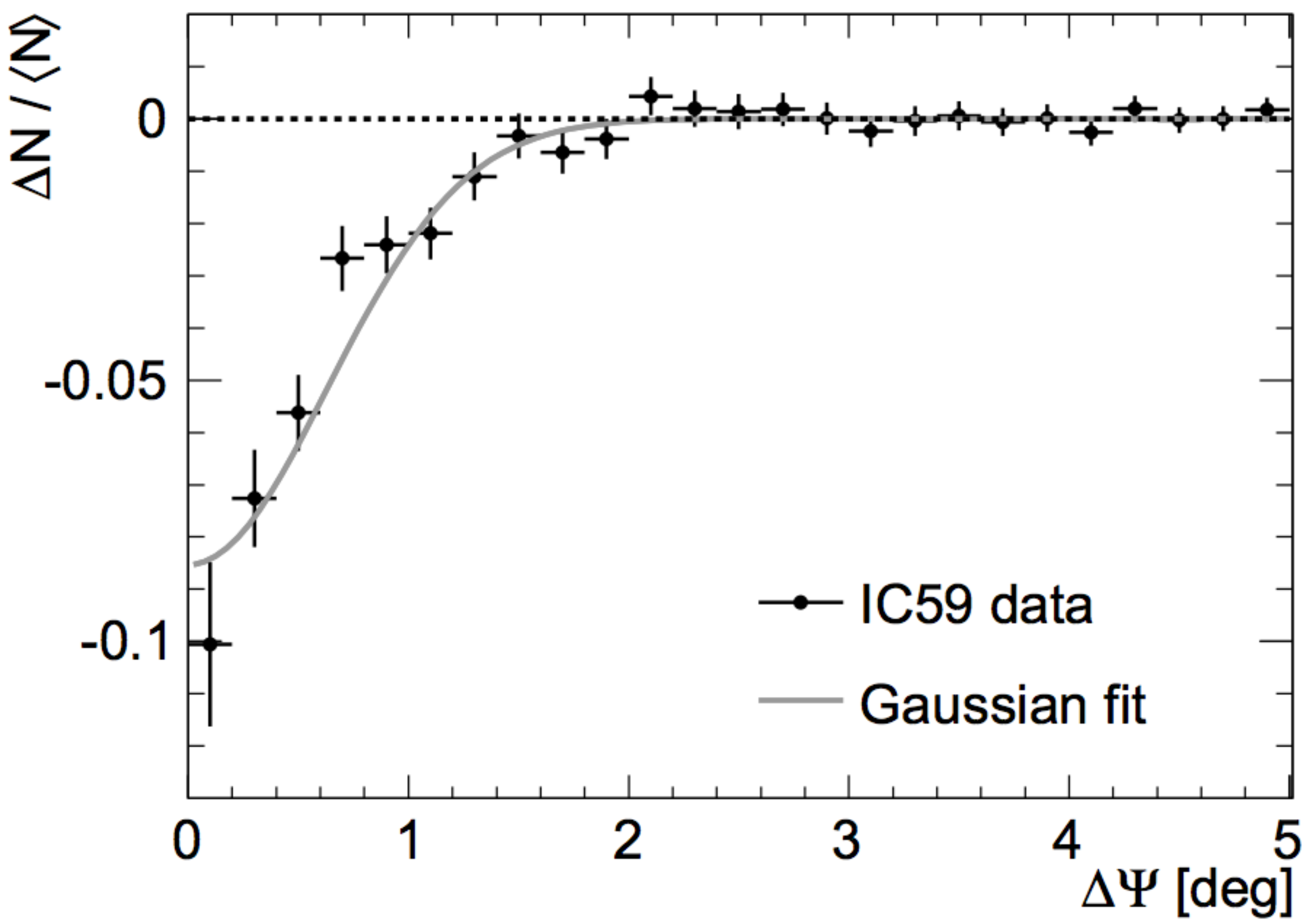
high energy muons

pointing calibration and . . .

IceCube-40+59 | **Phys. Rev. D 89, 102004** | **2014**



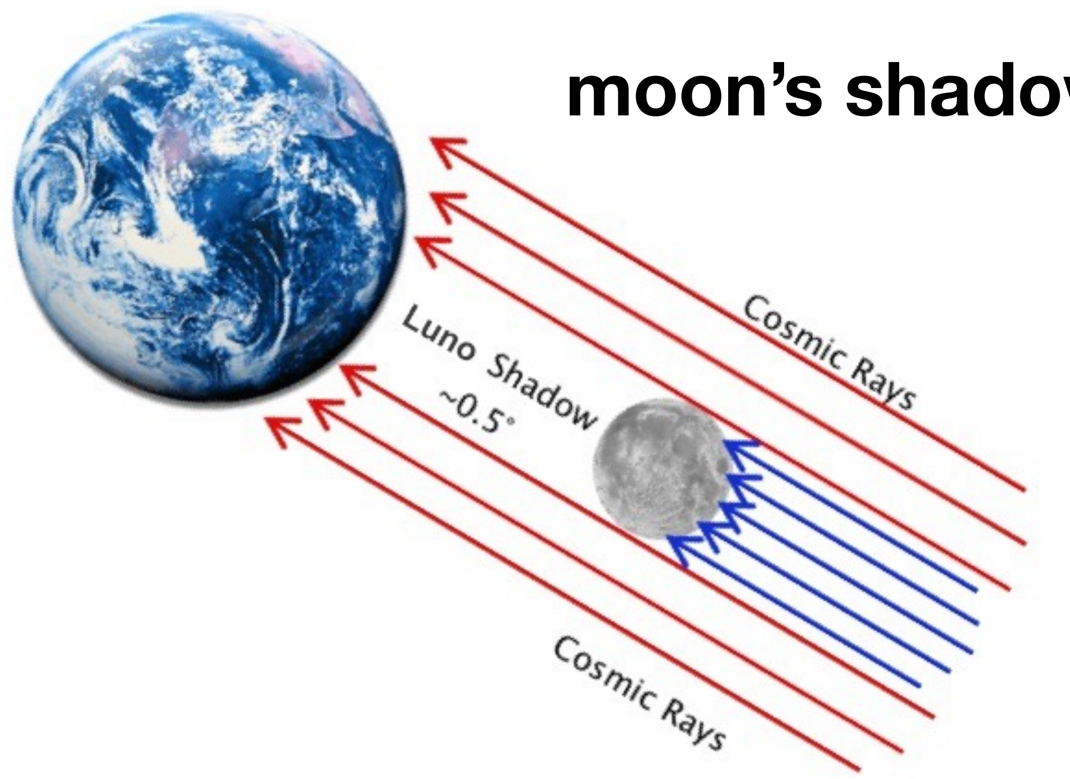


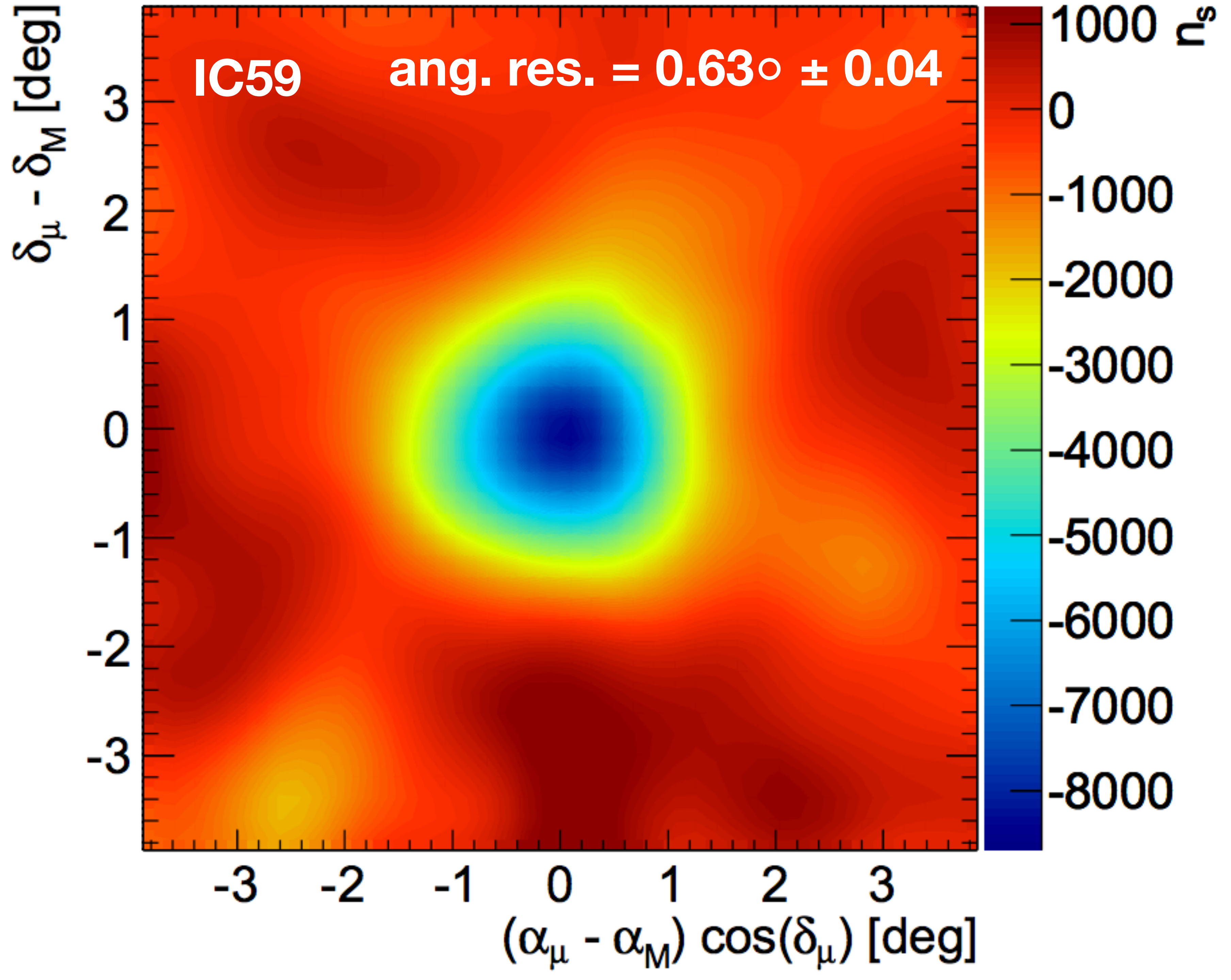


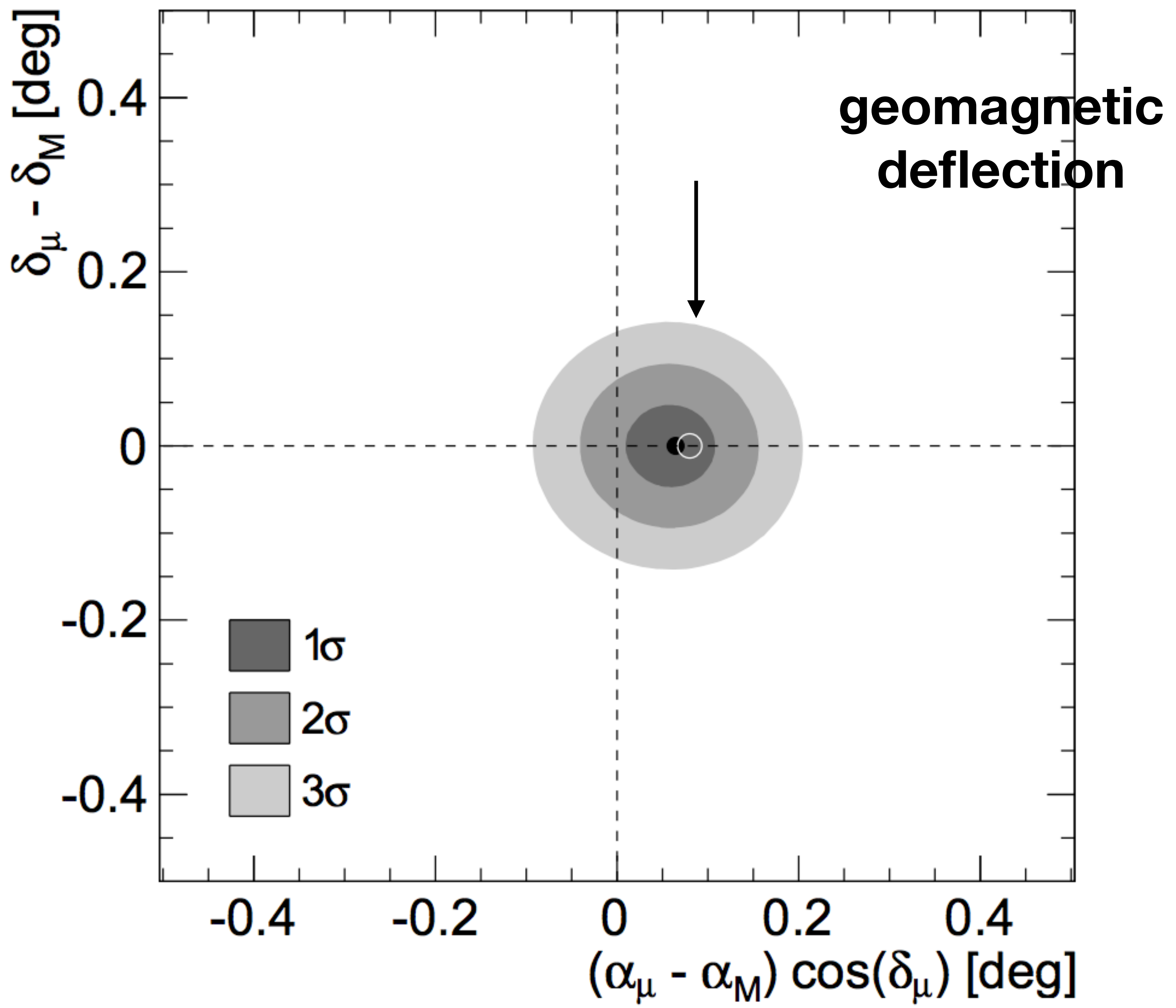
high energy muons
pointing resolution and angular resolution

IceCube-40+59 Phys. Rev. D 89, 102004 **2014**

moon's shadow



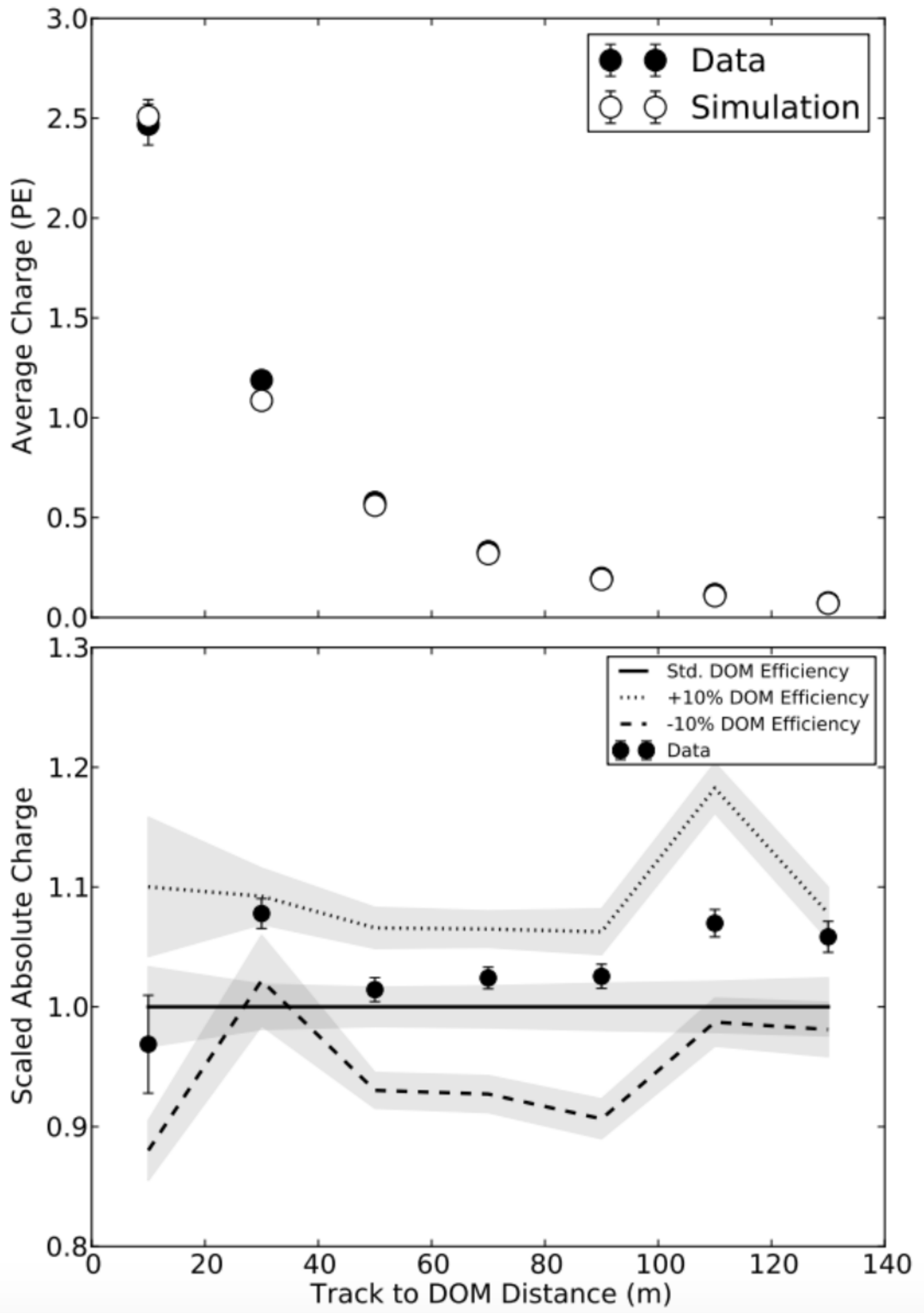




high energy muons

DOM calibration with muons

IceCube calibrations JINST 9, P03009 **2014**



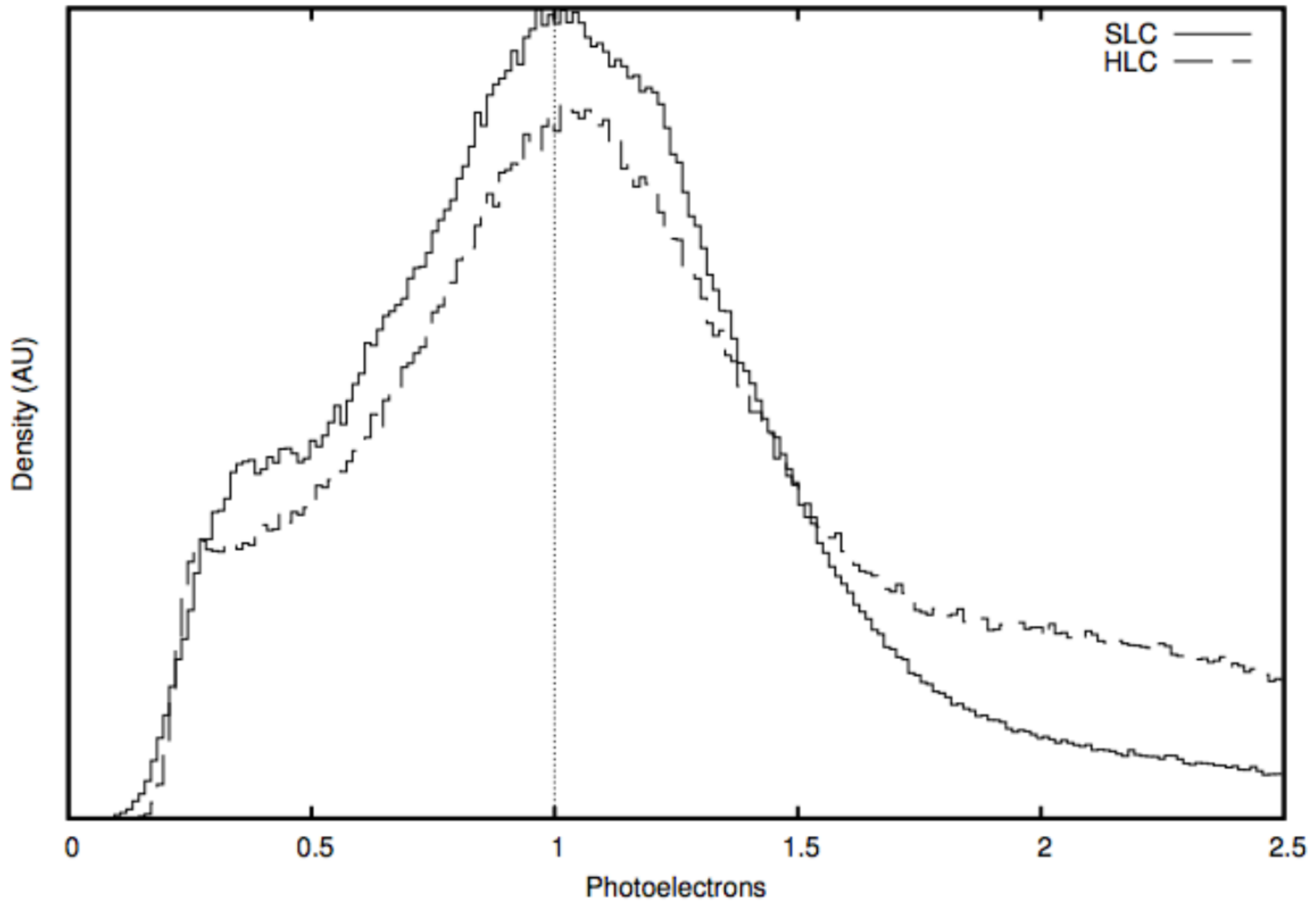
- minimum ionizing *quasi-horizontal* muons
- energy-independent losses in the ice
- single p.e. detected by DOM optical sensors
- **absolute charge measurement**
- DOM sensitivity measurement

high energy muons

DOM calibration with muons

IceCube calibrations JINST 9, P03009 2014

- charge distribution of PMTs
- **single p.e. peak** from minimum ionizing muons
- 0.2 p.e. trigger threshold
- **HLC** less likely to be from noise

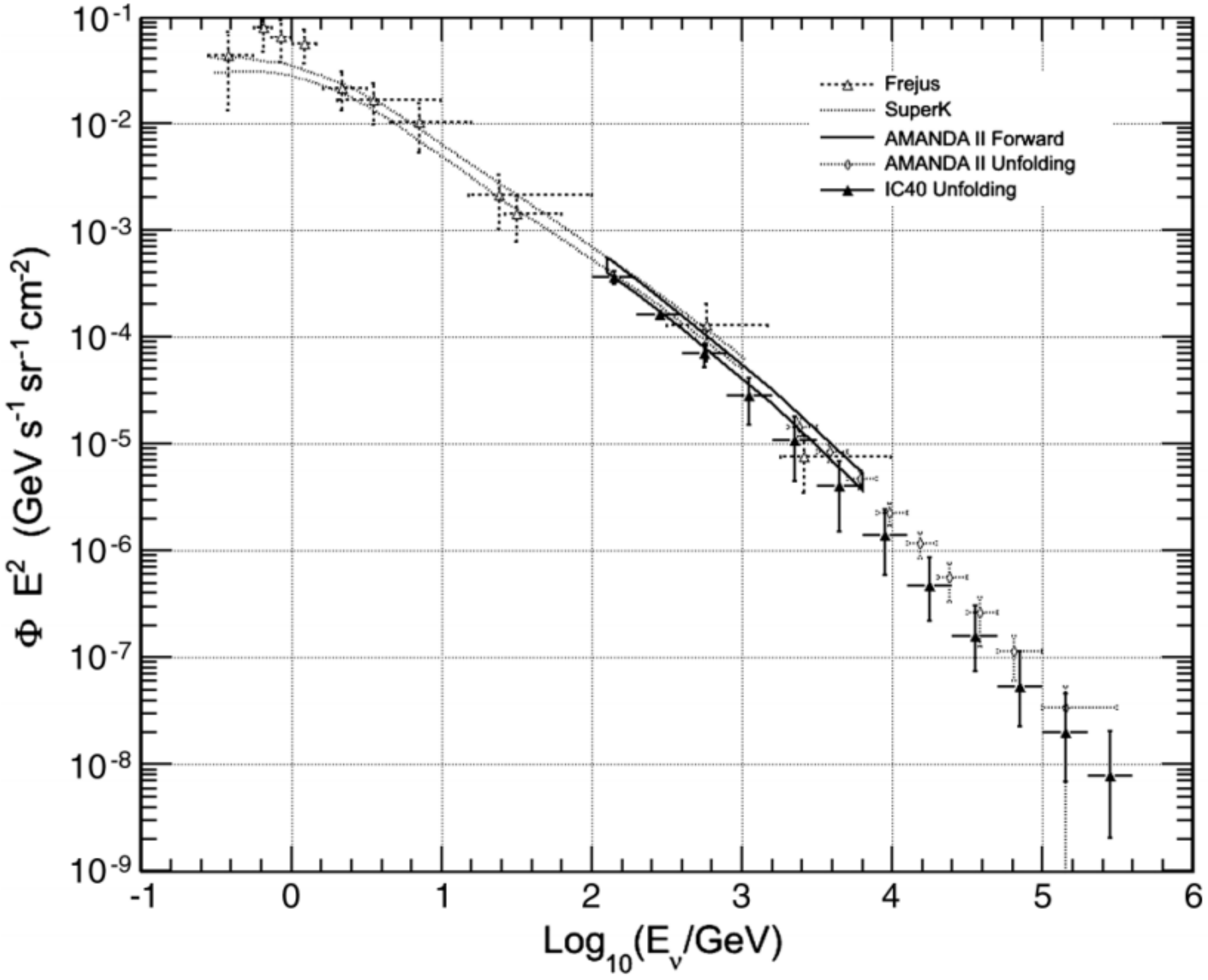


high energy neutrinos

up-ward through-going $\nu_\mu+\bar{\nu}_\mu$

AMANDA	Phys.Rev.D79:102005	2009
	Astropart.Phys.34:48-58	2010
IceCube-40	Phys.Rev.D83:012001	2011

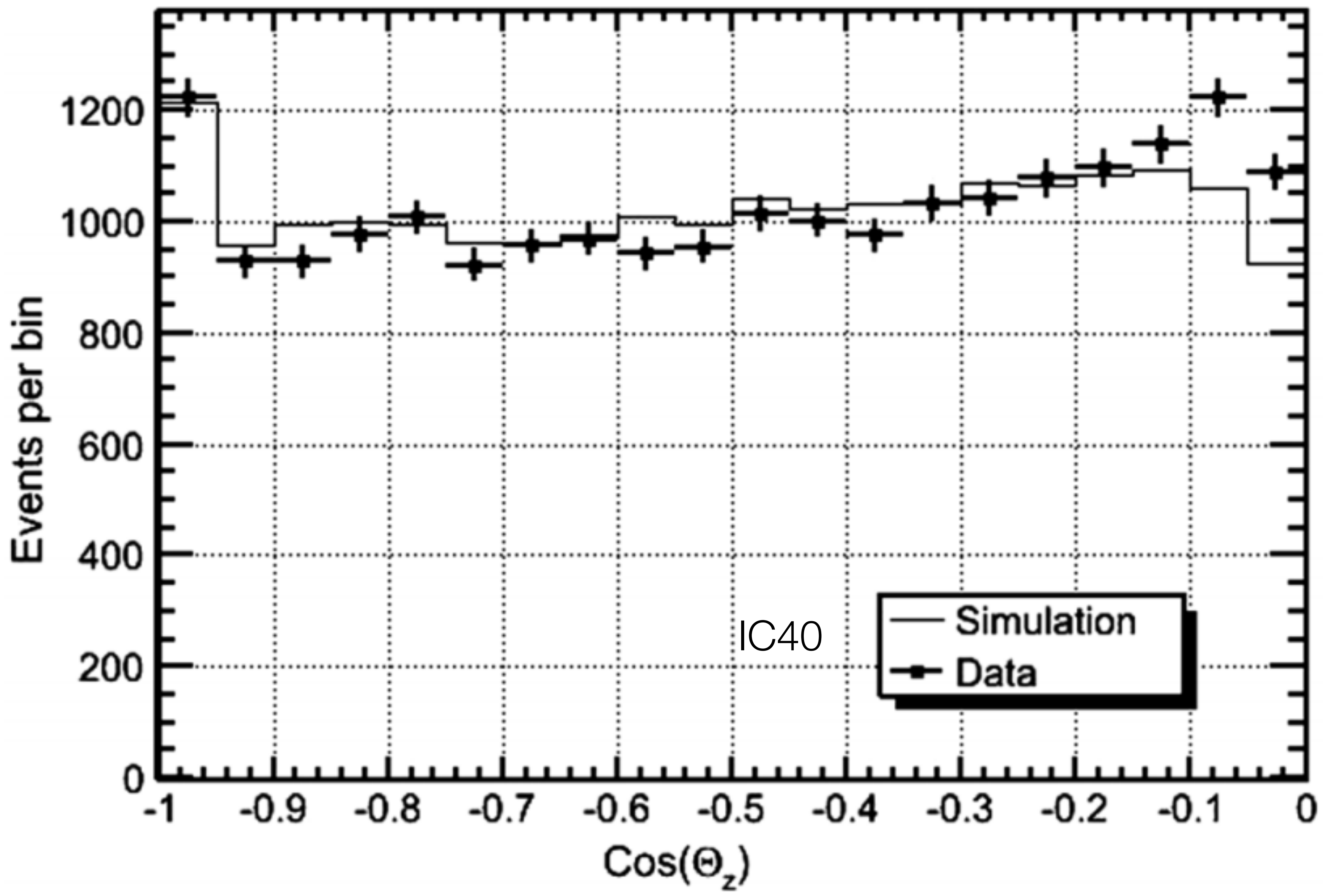
- high quality **through-going muons**
- energy spectrum smoothly merge with "*low energy*" determinations (Super-Kamiokande, Fréjus)
- first time high energy atmospheric neutrinos

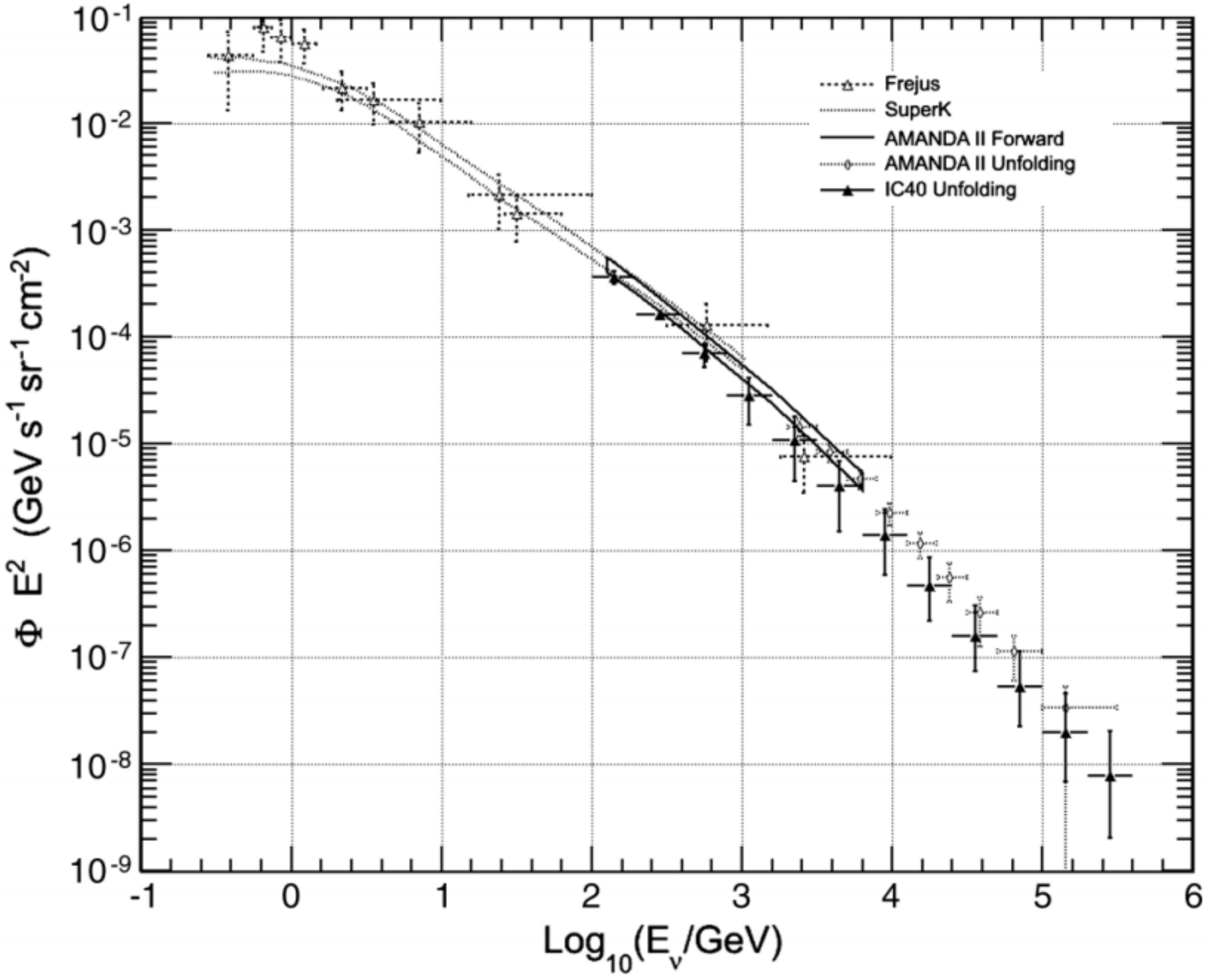


high energy neutrinos

up-ward through-going $\nu_\mu+\bar{\nu}_\mu$

AMANDA	Phys.Rev.D79:102005	2009
	Astropart.Phys.34:48-58	2010
IceCube-40	Phys.Rev.D83:012001	2011





high energy neutrinos

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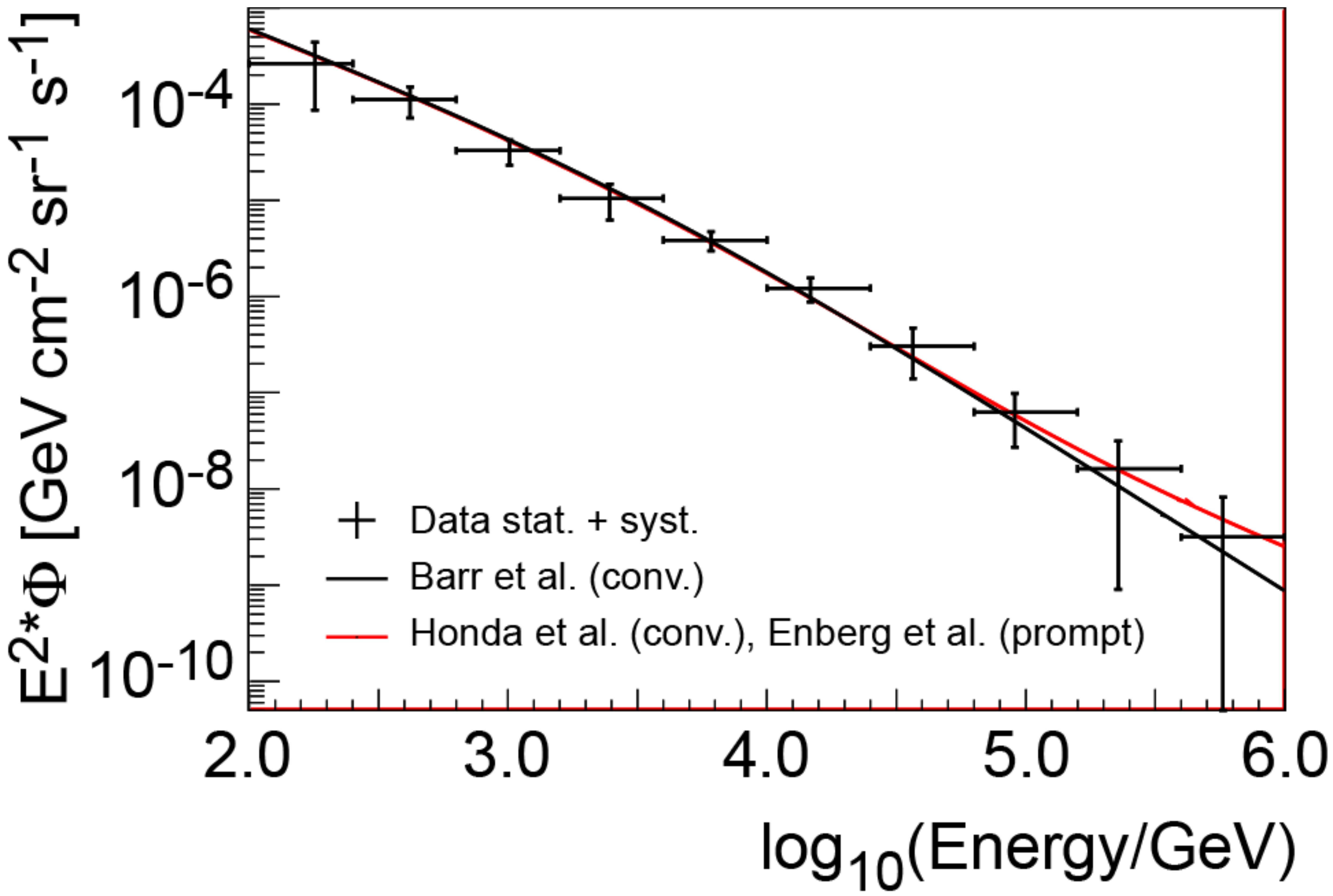
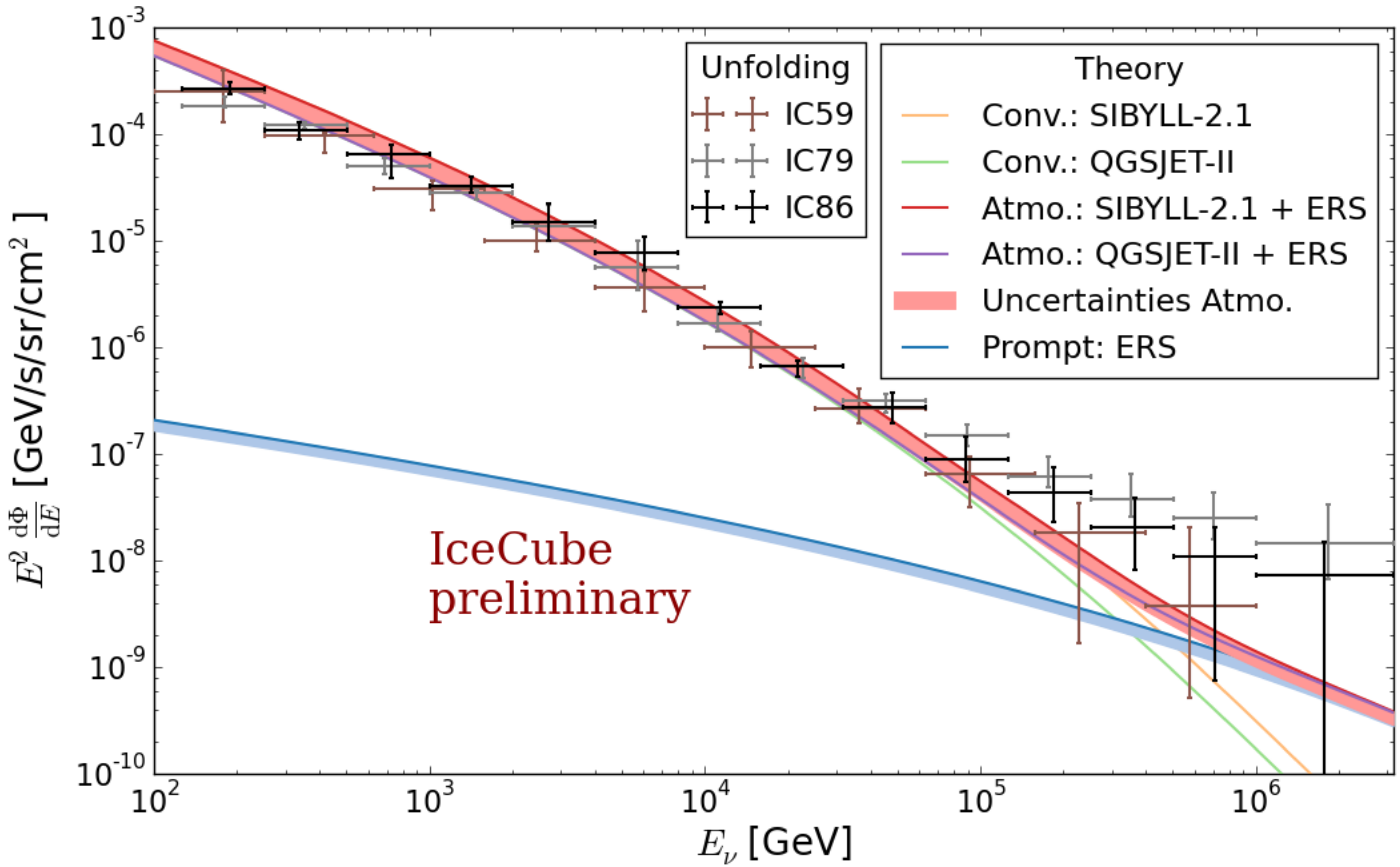
AMANDA	Phys.Rev.D79:102005	2009
	Astropart.Phys.34:48-58	2010
IceCube-40	Phys.Rev.D83:012001	2011
IceCube-59	Eur. Phys. J. C75, 116	2015



high energy neutrinos

up-ward through-going $\nu_\mu + \bar{\nu}_\mu$

IceCube-59 **Eur. Phys. J. C75, 116** **2015**

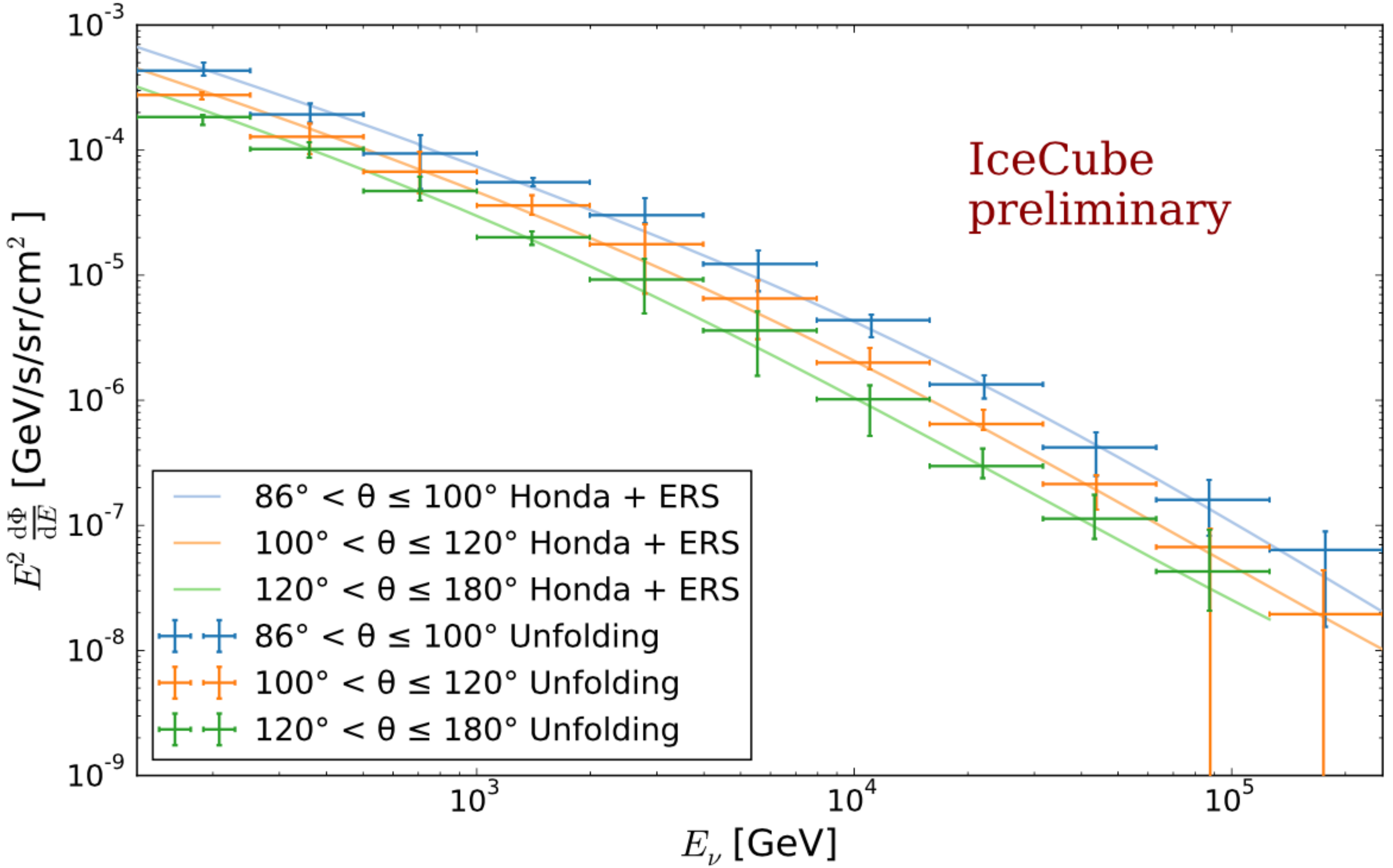


high energy neutrinos

up-ward through-going $\nu_\mu + \bar{\nu}_\mu$

ICRC 2015
M. Börner
Poster 3

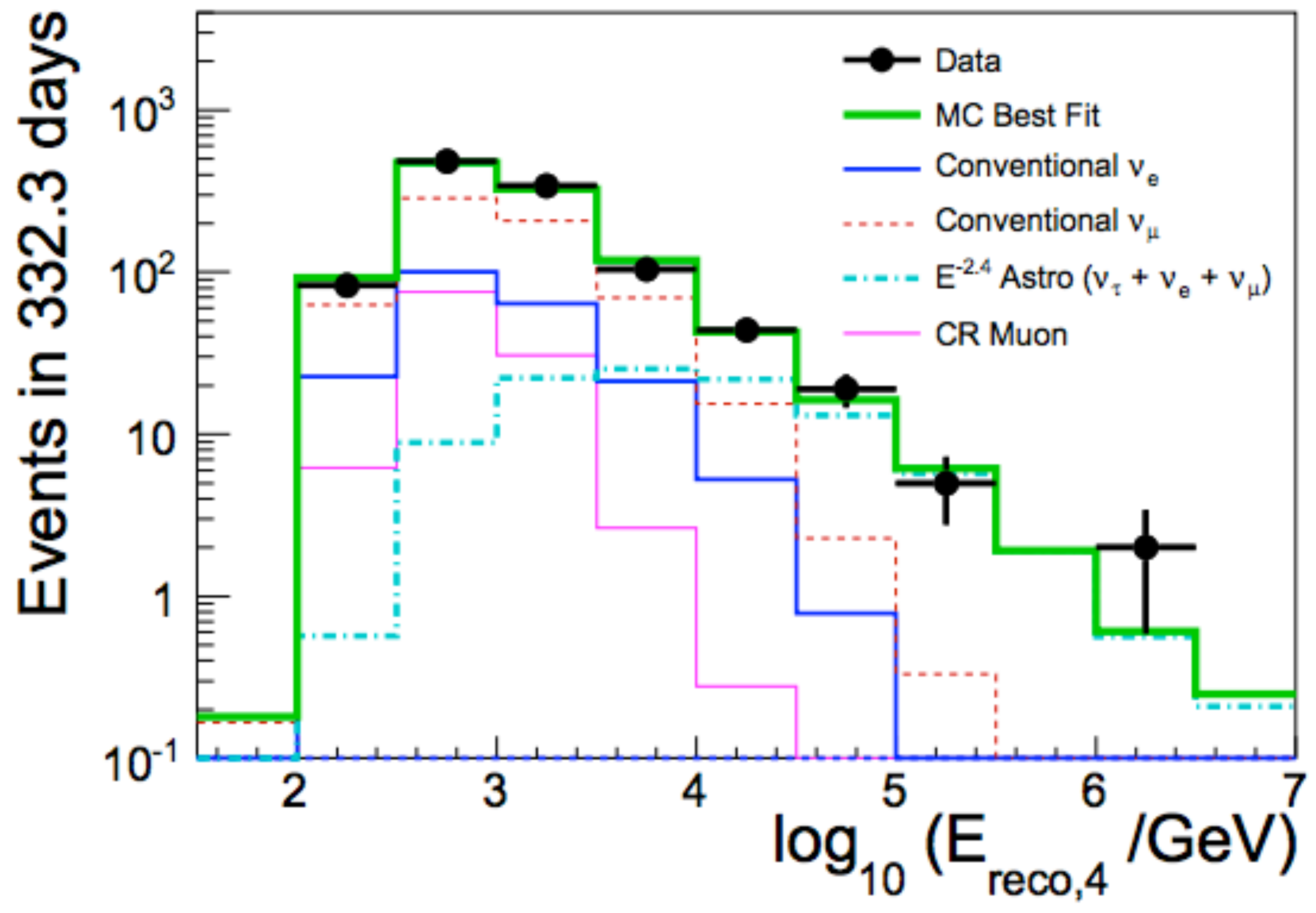
IceCube-59 Eur. Phys. J. C75, 116 2015

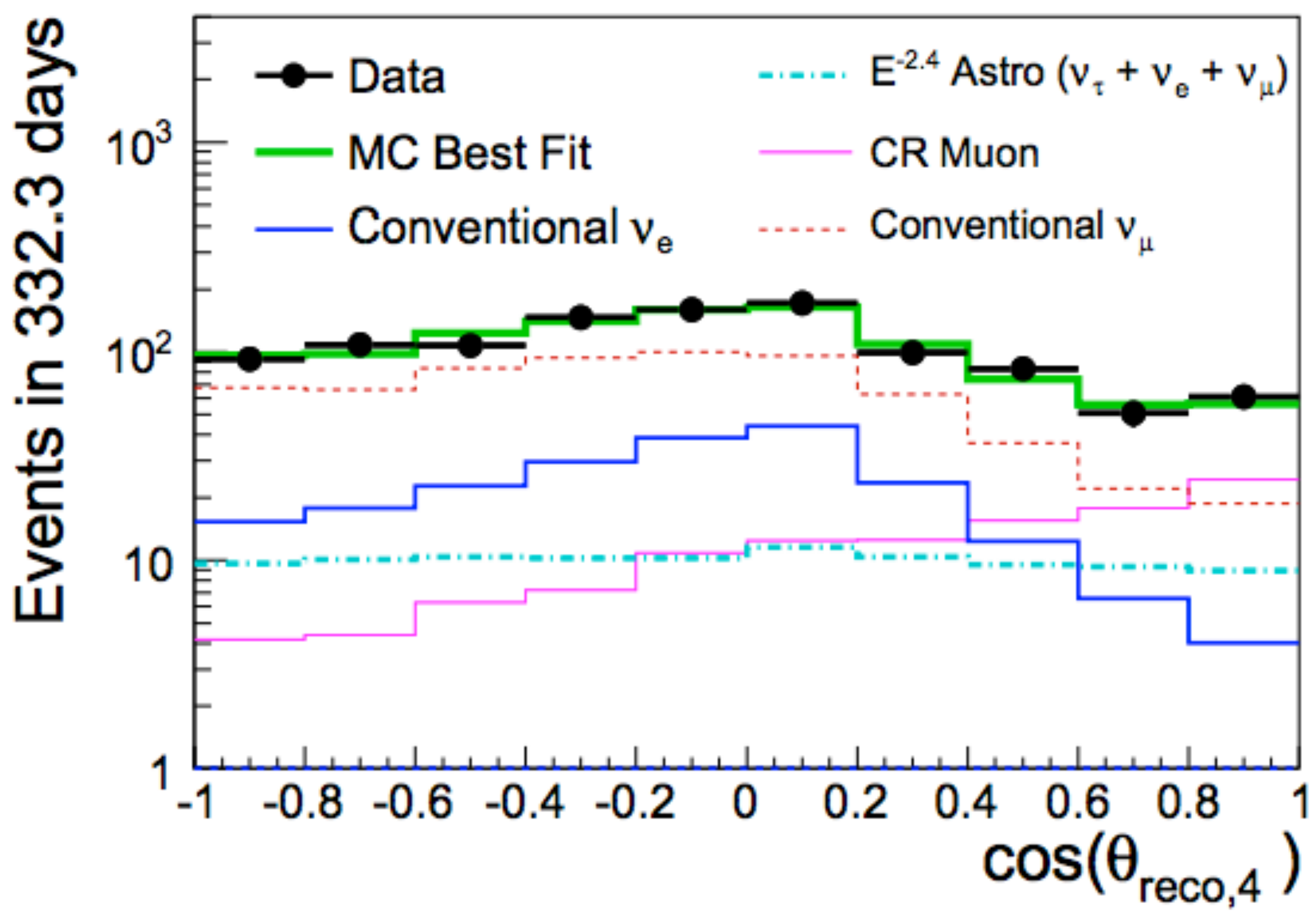


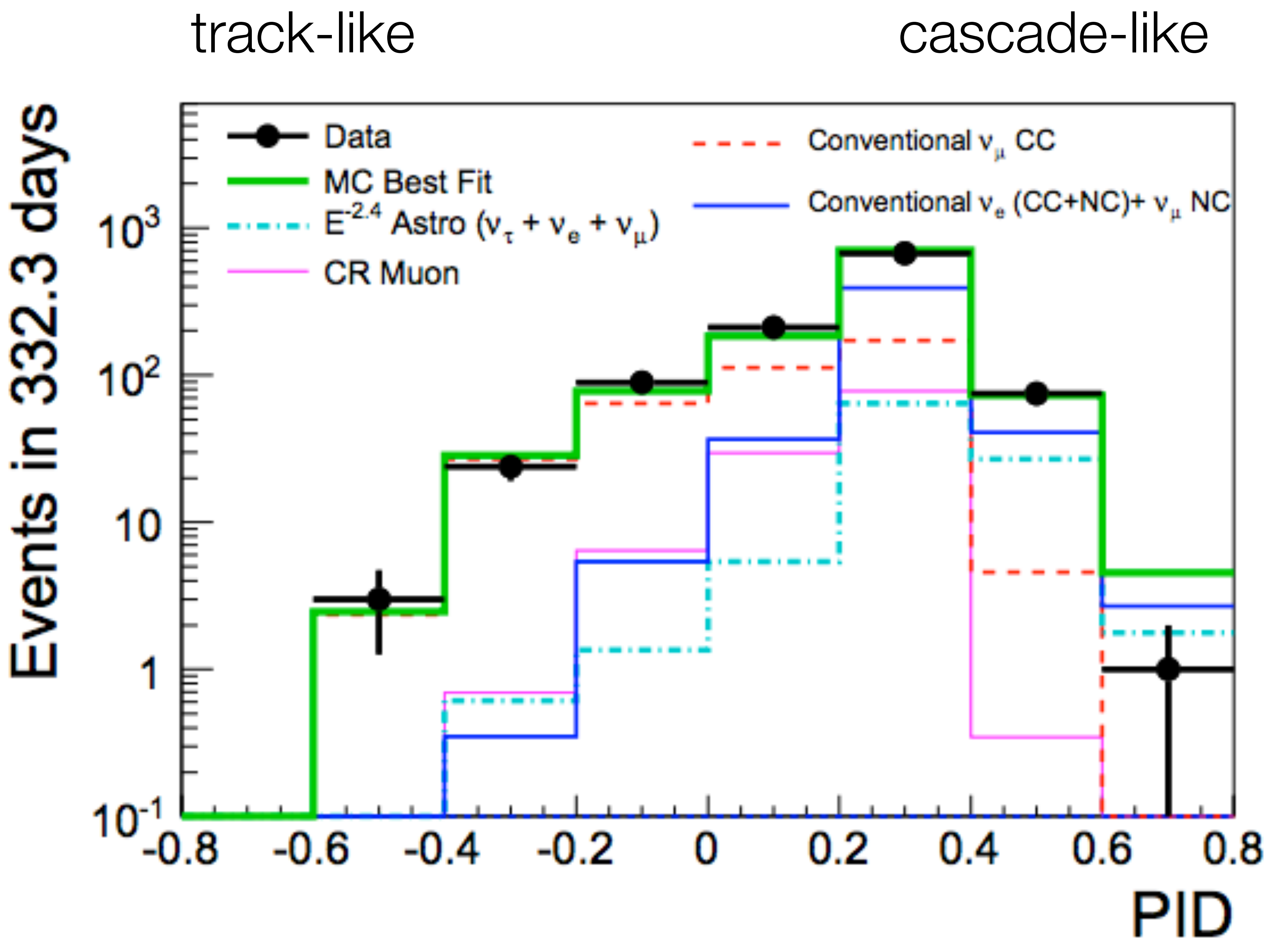
high energy neutrinos and muons

contained $\nu_e+\bar{\nu}_e$

IceCube-86 arXiv:1504.03753 (PRD) 2015



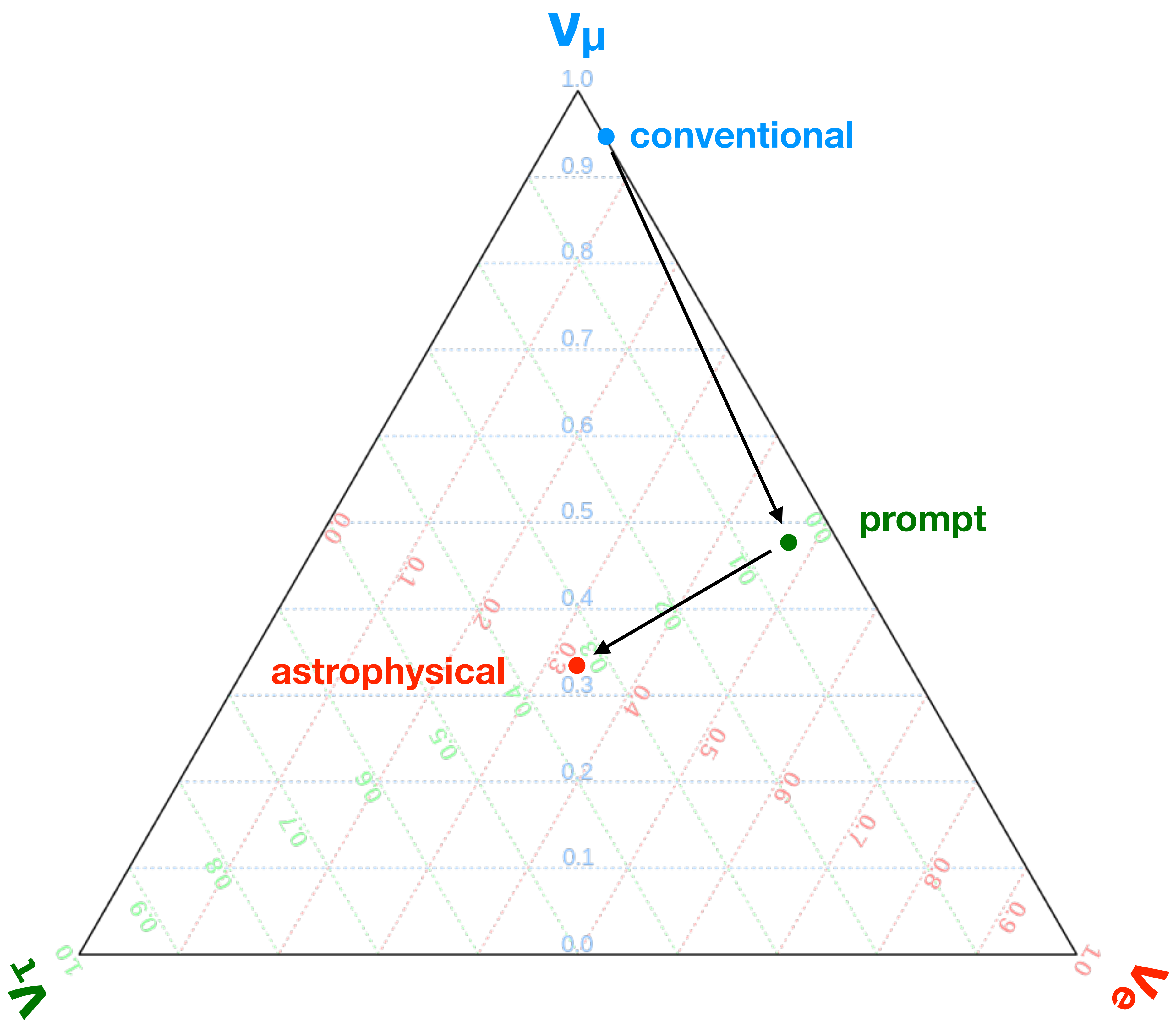




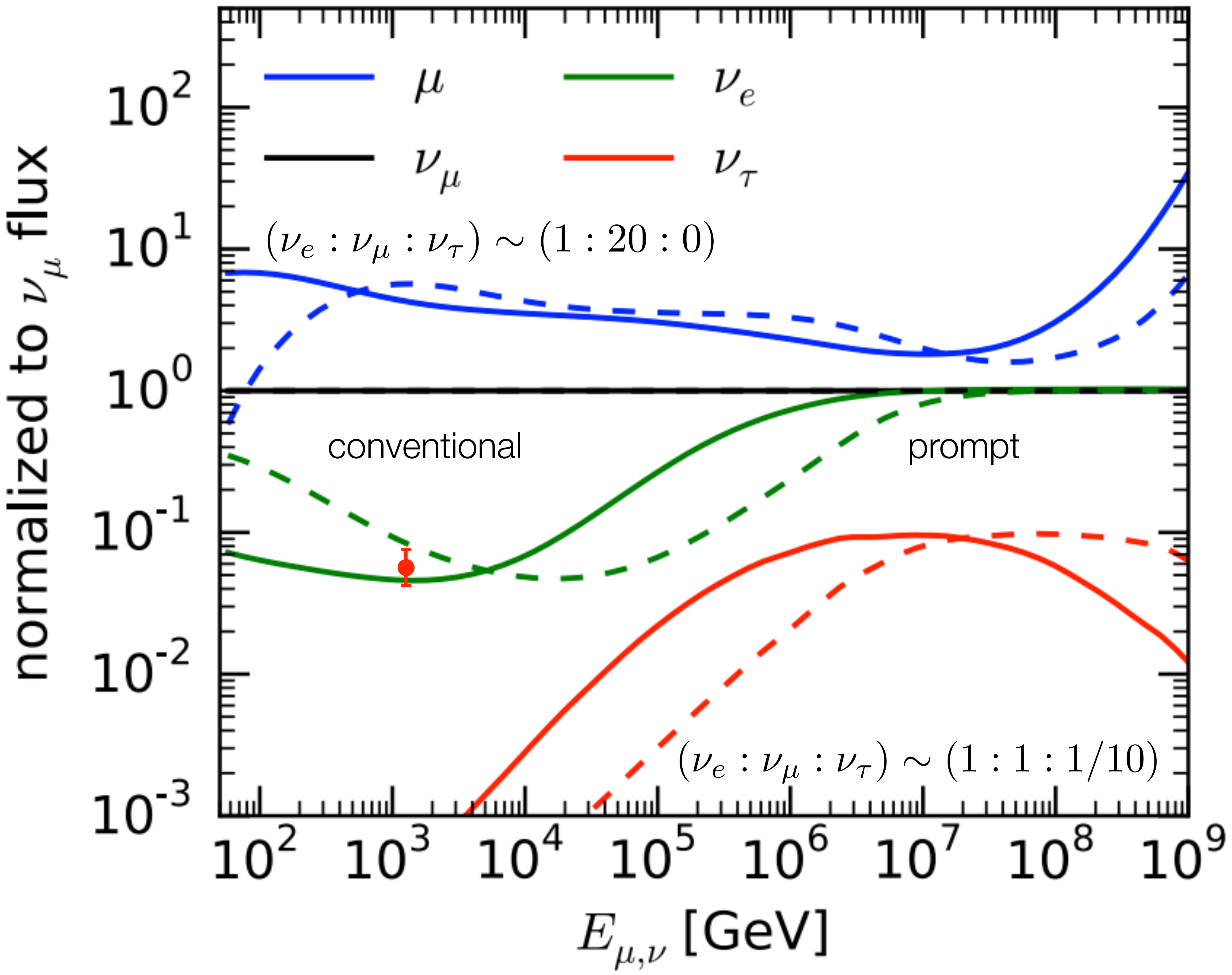
high energy neutrinos

flavor composition

IceCube-86 **Phys. Rev. D91 12, 122004** **2015**



Fedynitch et al. arXiv:1503.00544 - Sibyll 2.3RC1 - H3a CR composition



high energy leptons

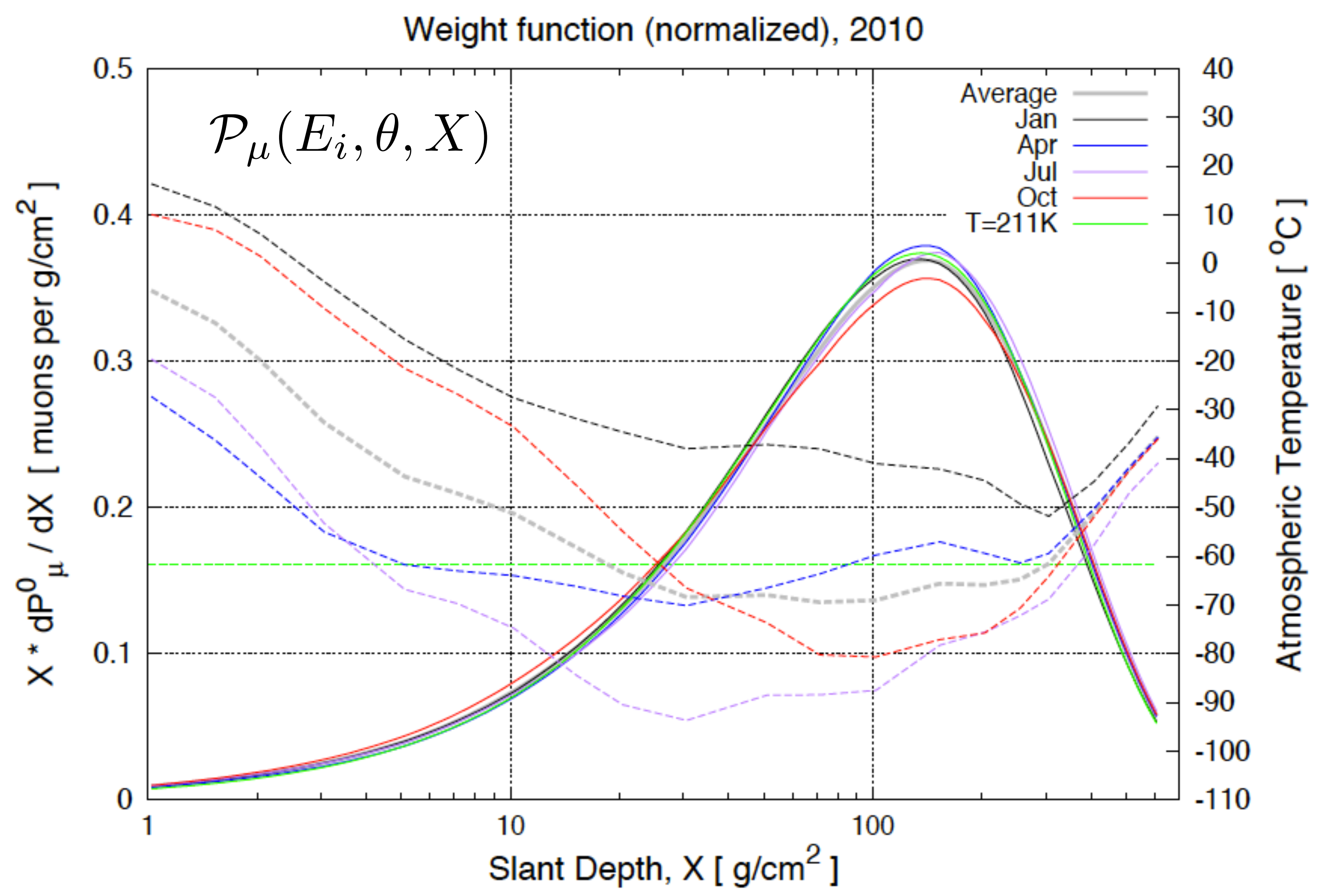
correlation with stratospheric temperatures

$$T_{eff}(E_i,\theta) = \frac{\int dE_i \int dX\, \epsilon(E_i,\theta)\, \mathcal{P}_\mu(E_i,\theta,X)\, T(\theta,X)}{\int dE_i \int dX\, \epsilon(E_i,\theta)\, \mathcal{P}_\mu(E_i,\theta,X)}$$

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_i\, \phi_i(E_i,\theta)\, \epsilon(E_i,\theta)}{\int dE_i\, \phi_i(E_i,\theta)\, \epsilon(E_i,\theta)}$$

$$\frac{\Delta I_i}{\langle I_i \rangle} = \alpha_T^{th} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

temperature data from NASA AIRS instrument on board the Aqua satellite



$$\frac{\Delta R_i}{\langle R_i \rangle} = \alpha_T^{exp} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

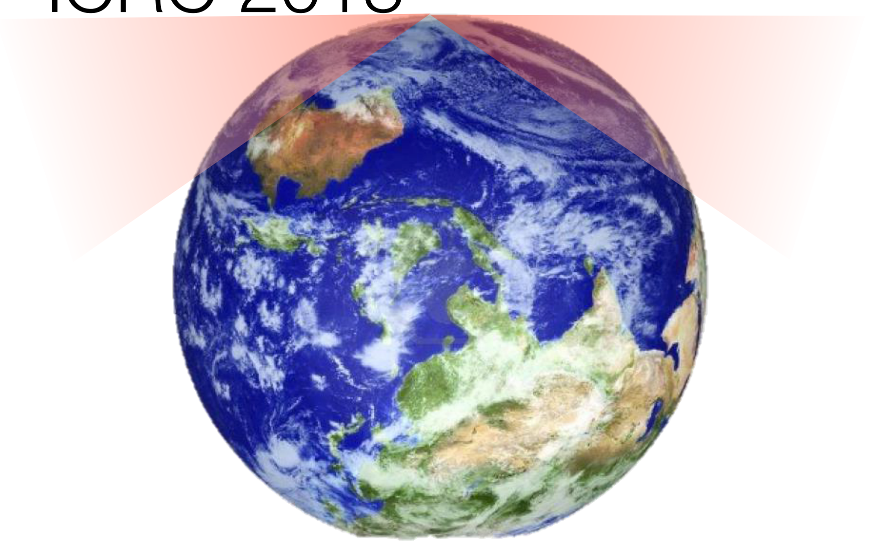
$$\alpha_T^{\mu,exp} = 0.860 \pm 0.002(stat.) \pm 0.010(syst.)$$

PD et al., **ICRC 2011**

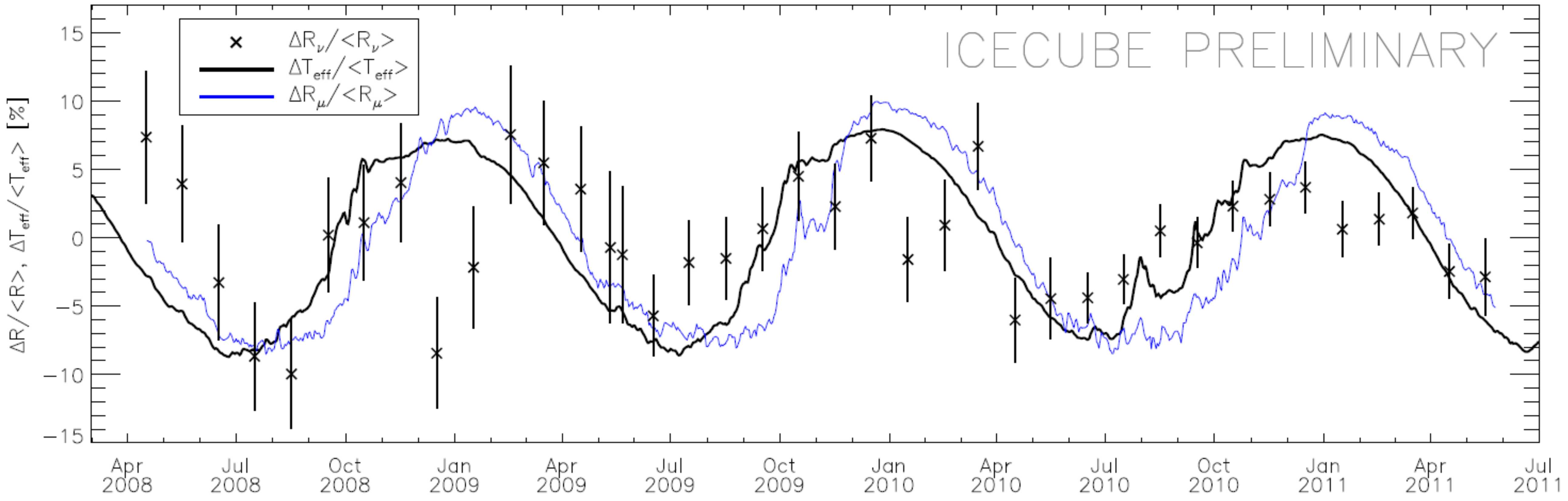
high energy leptons

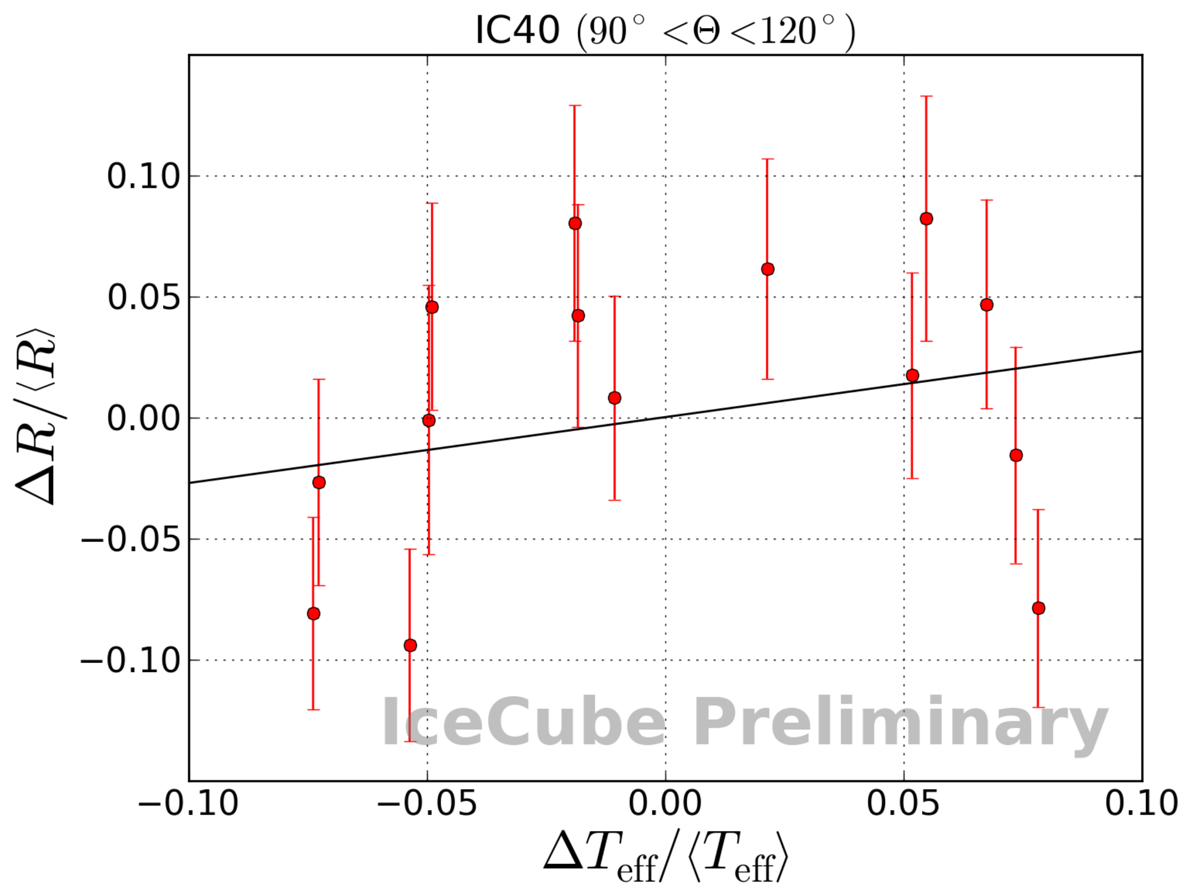
correlation with stratospheric temperatures

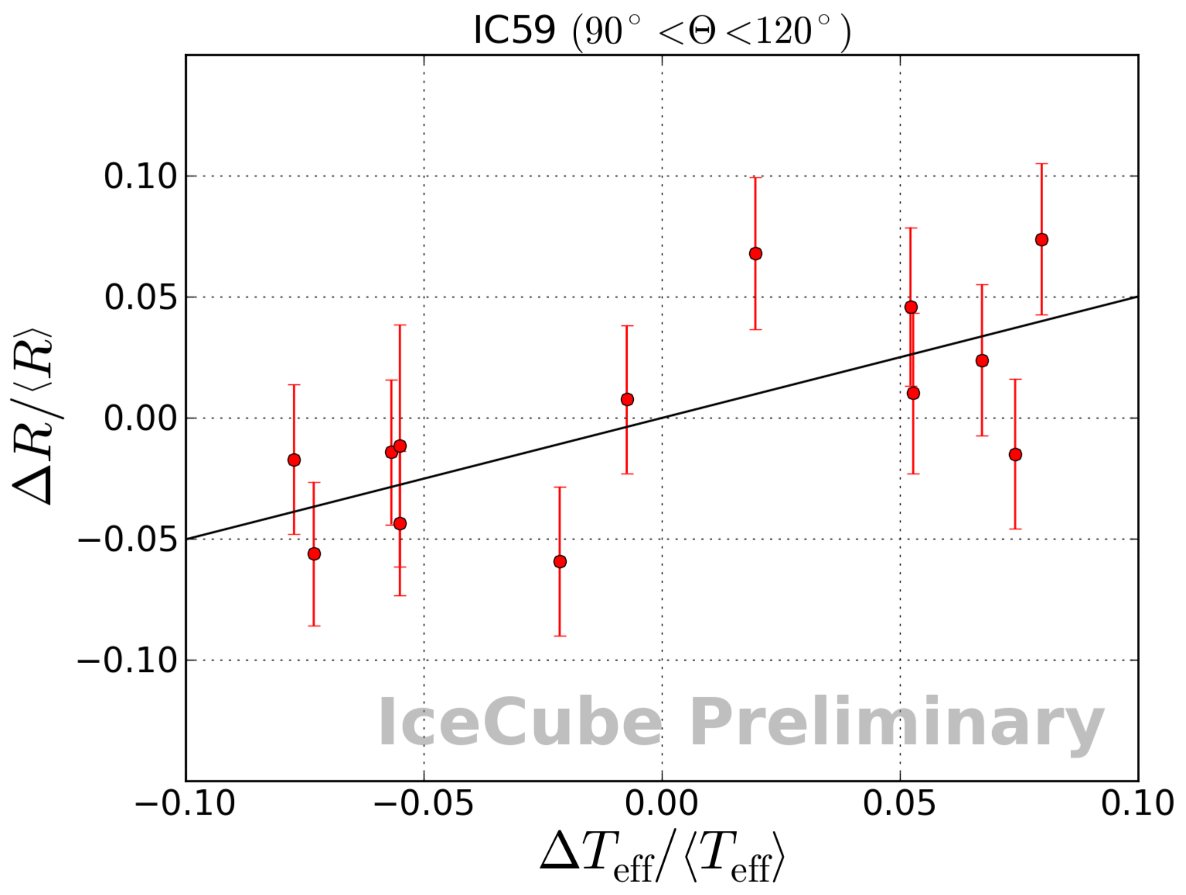
ICRC 2013

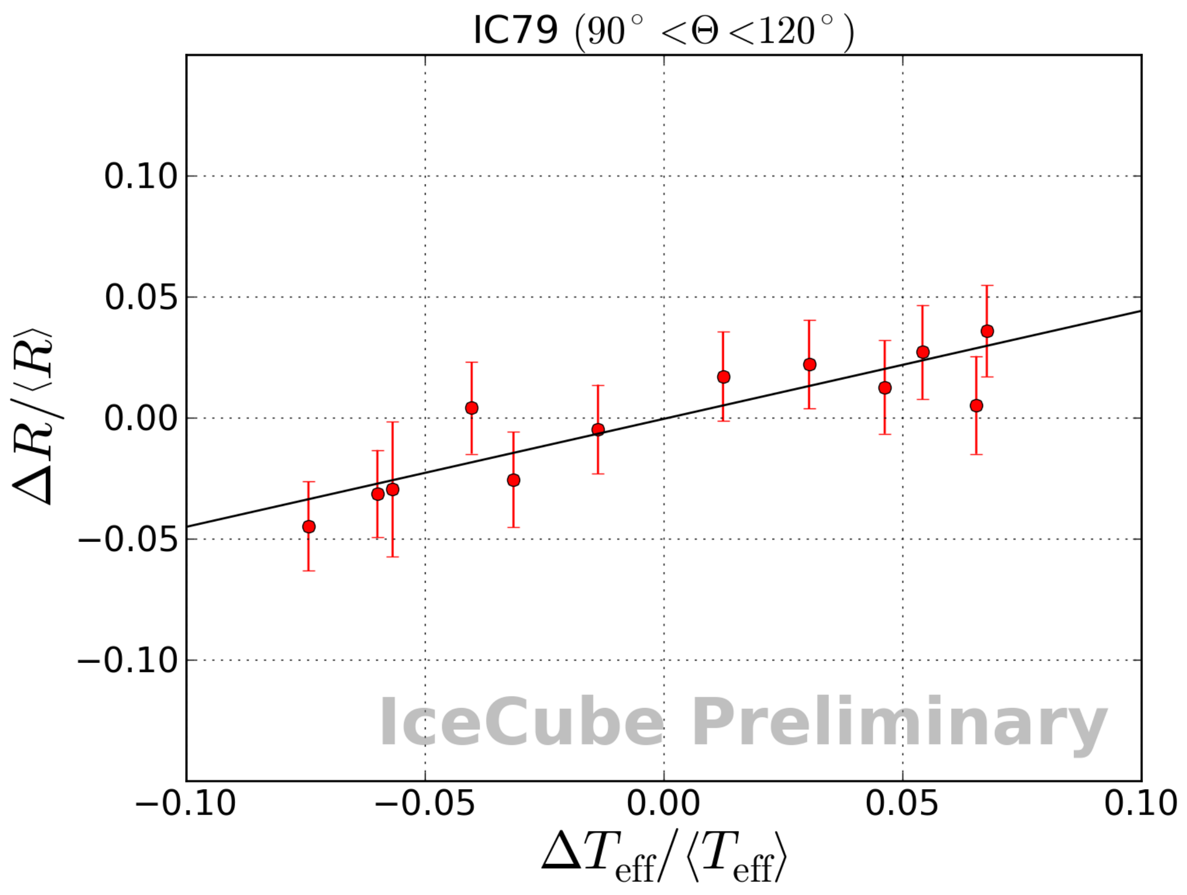


ν_μ









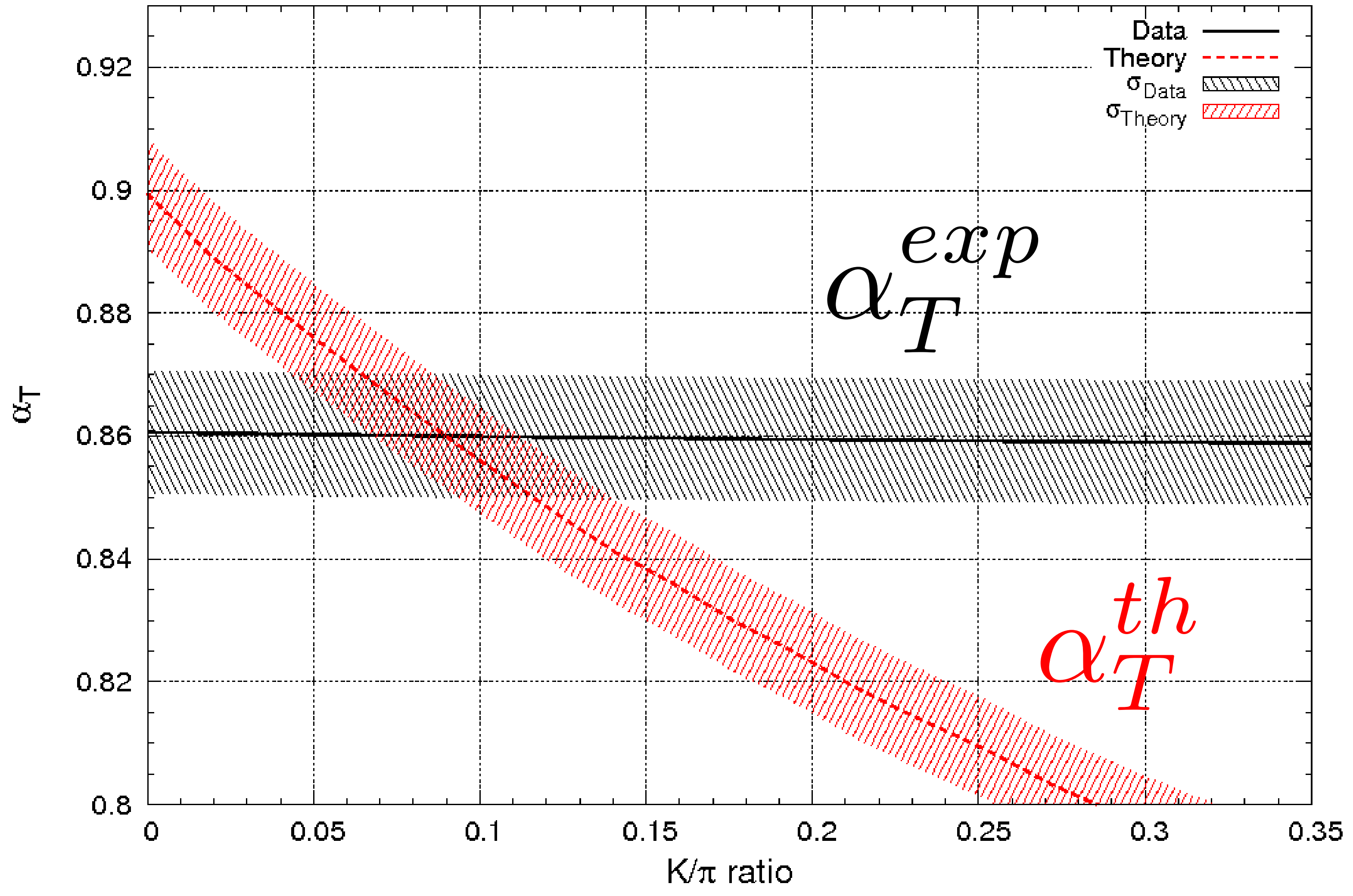
high energy leptons

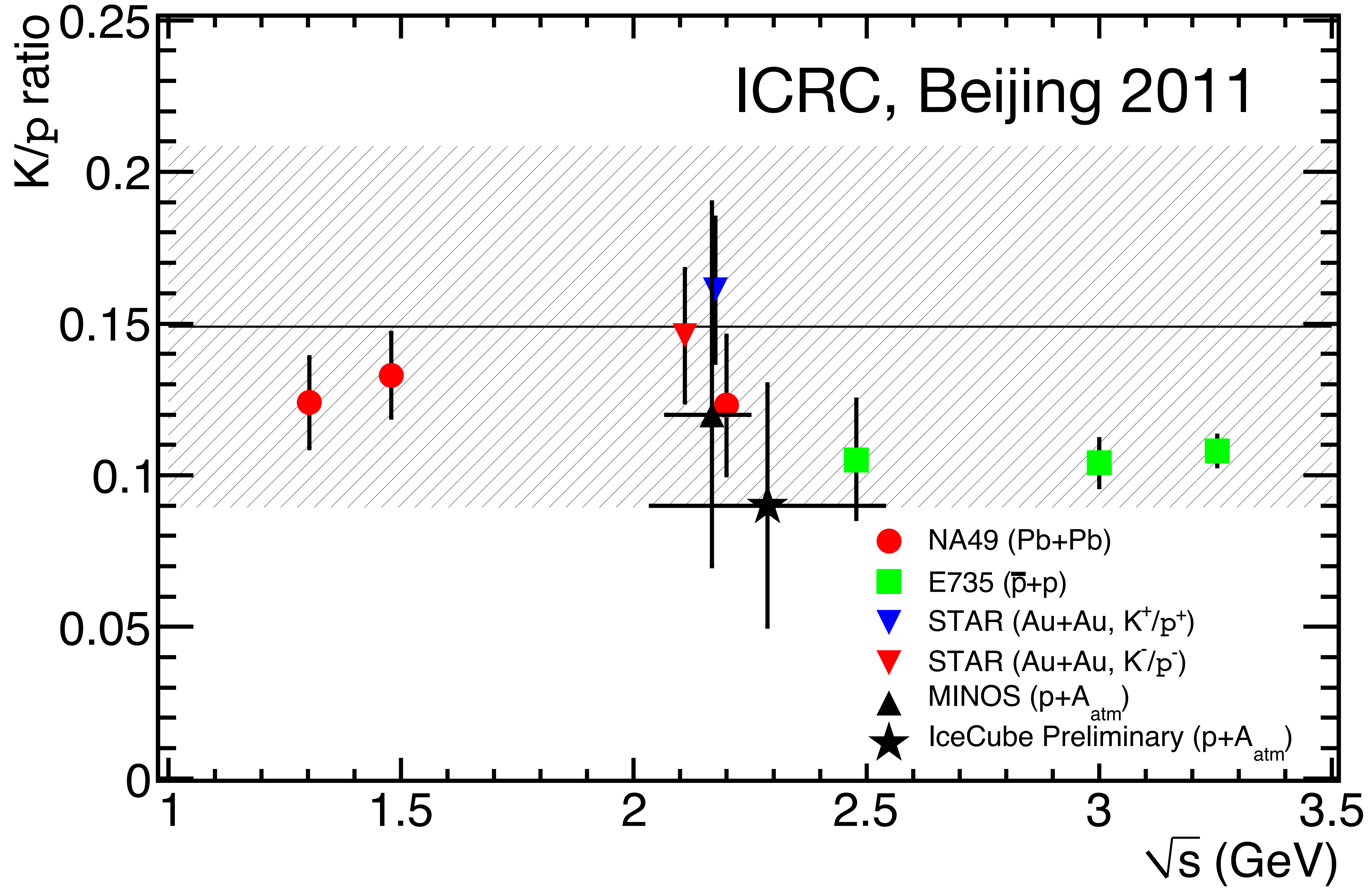
K/π ratio

$$\phi_\mu(E_\mu,\theta) = \phi_N(E_\mu) \times \left(\frac{1}{1 + B_{\pi\mu}\, cos\theta^\star\, E_\mu/\epsilon_\pi} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\, cos\theta^\star\, E_\mu/\epsilon_K} \right) \quad \gamma \approx 1.7$$

$$A_{K\,\mu}/A_{\pi\,\mu} = \left(\frac{BR_{K\,\mu}}{BR_{\pi\,\mu}}\right)\left(\frac{Z_{K\,\mu}}{Z_{\pi,\mu}}\right)\left(\frac{Z_{N\,K}}{Z_{N\,\pi}}\right)$$

kaon/pion ratio $R(K/\pi) = \frac{Z_{N\,K}}{Z_{N\,\pi}}$

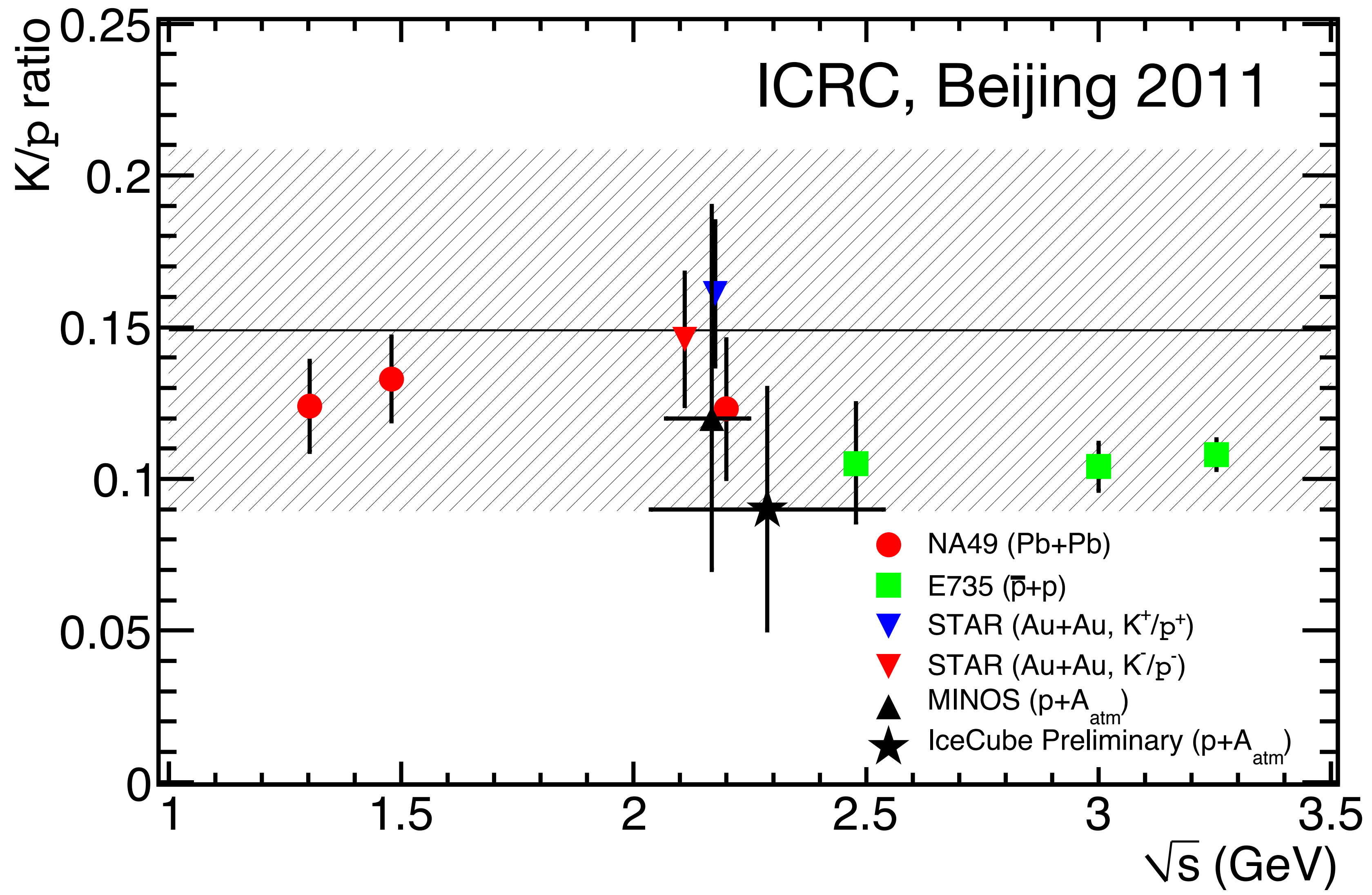




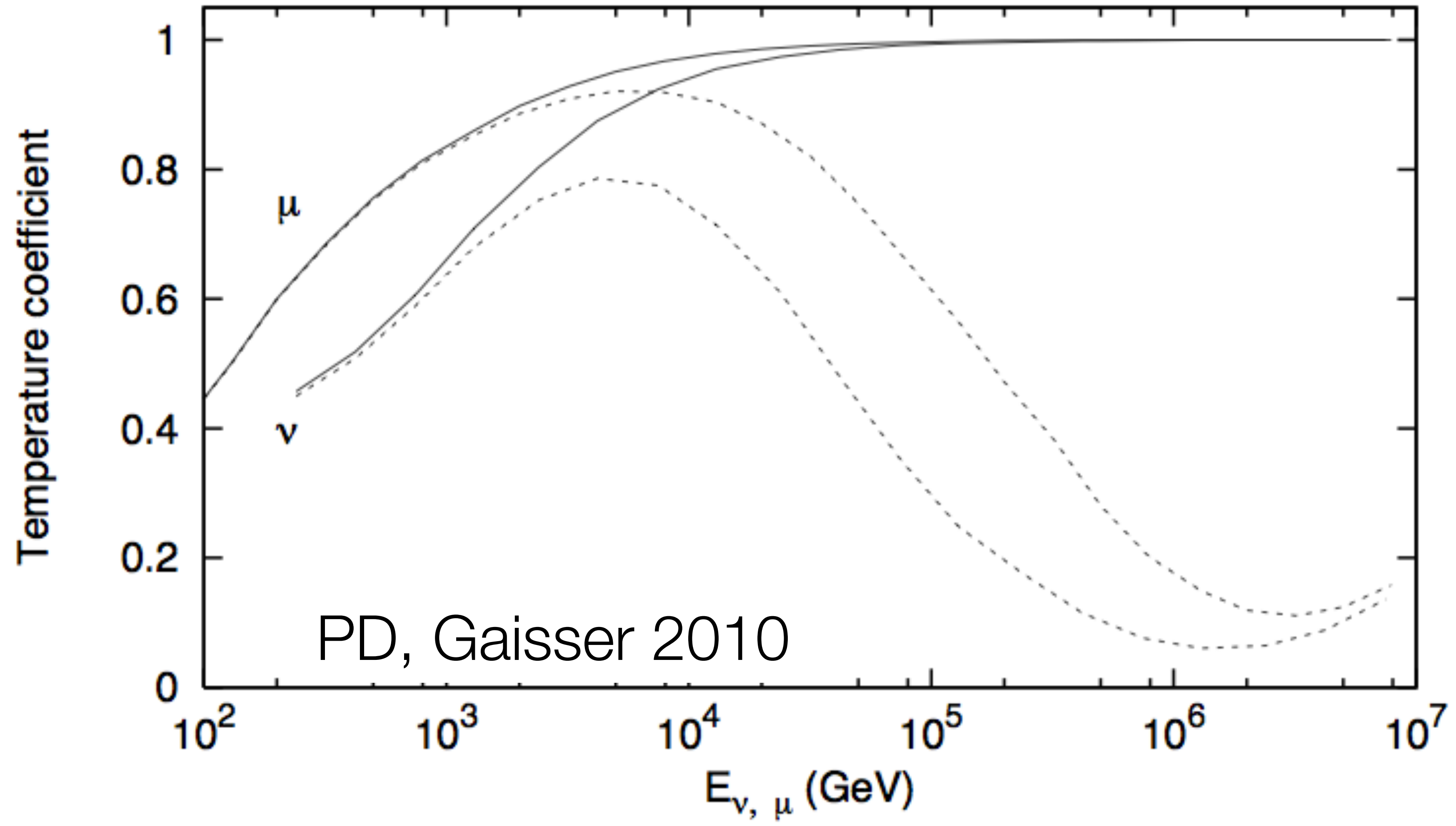
experimental systematics under strict control

high energy leptons
correlation with stratospheric temperatures

- indirect probe into **K/π ratio**



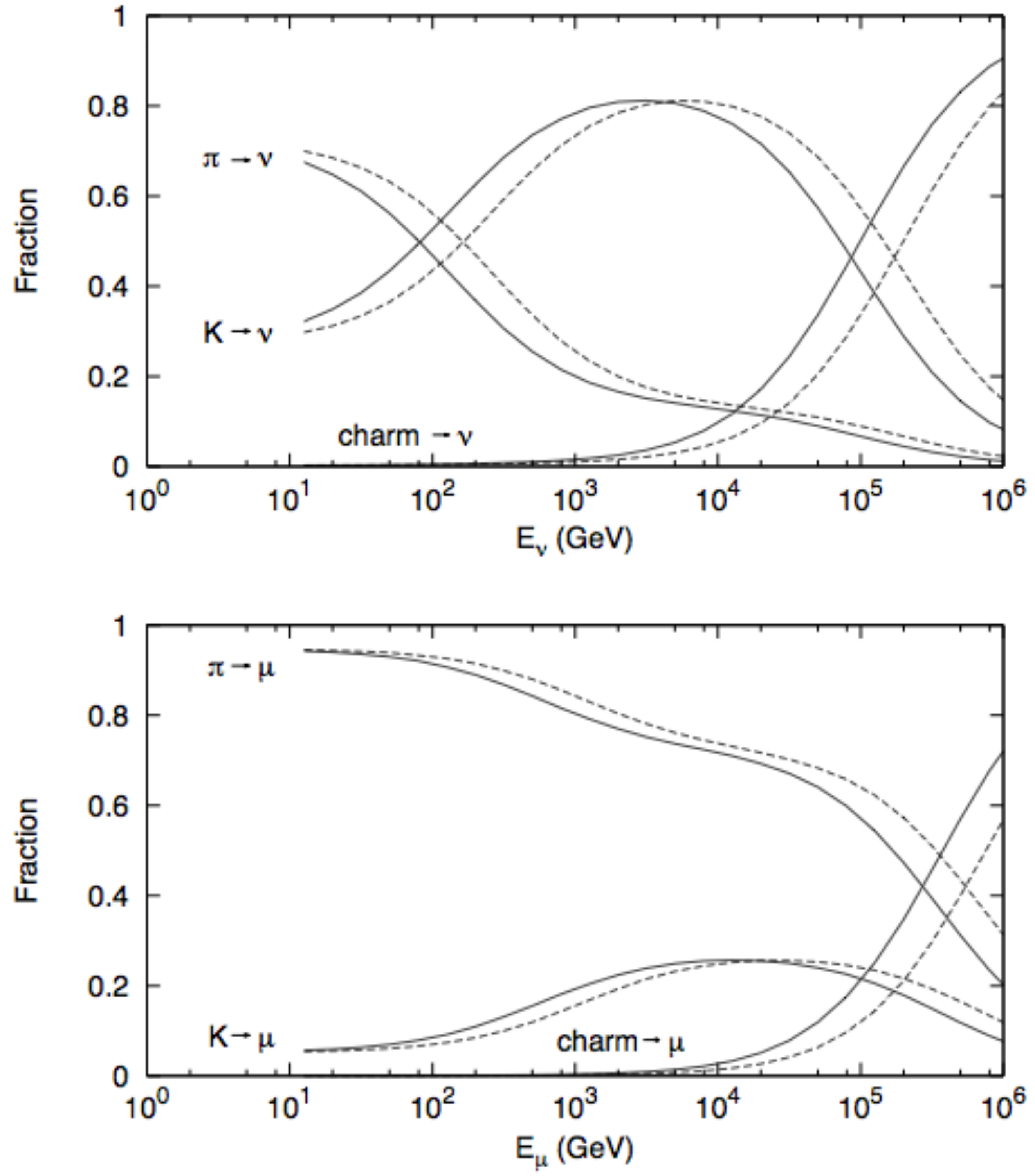
- prompt particles (**charm**) decay fast
- do not correlate with temperature



$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}{\int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}$$

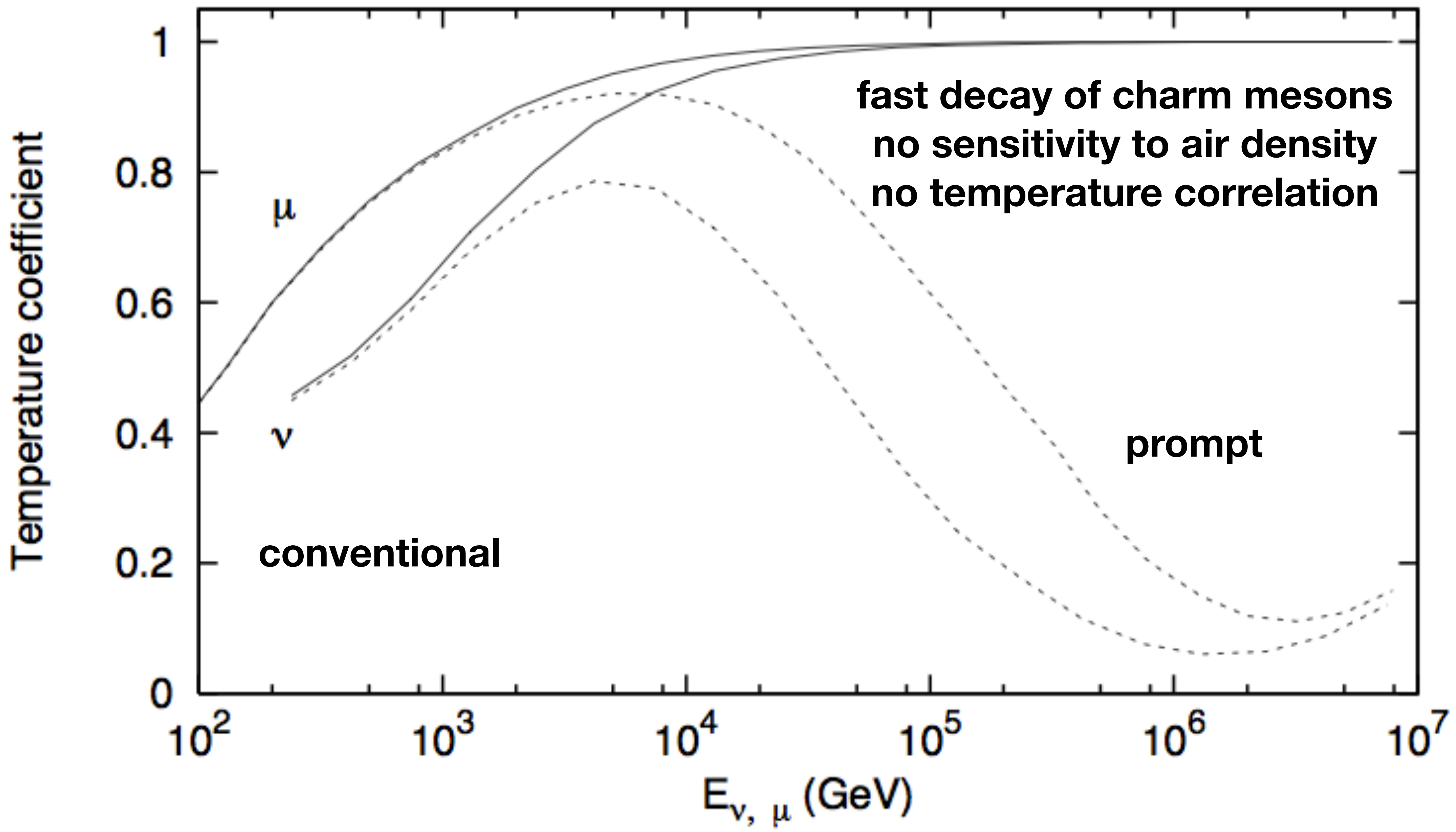
high energy leptons

charm production



PD, Gaisser 2010

charm contribution from RQPM model (Bugaev et al. 1998)



high energy μ's and ν's from charm decay not sensitive to temperature variations

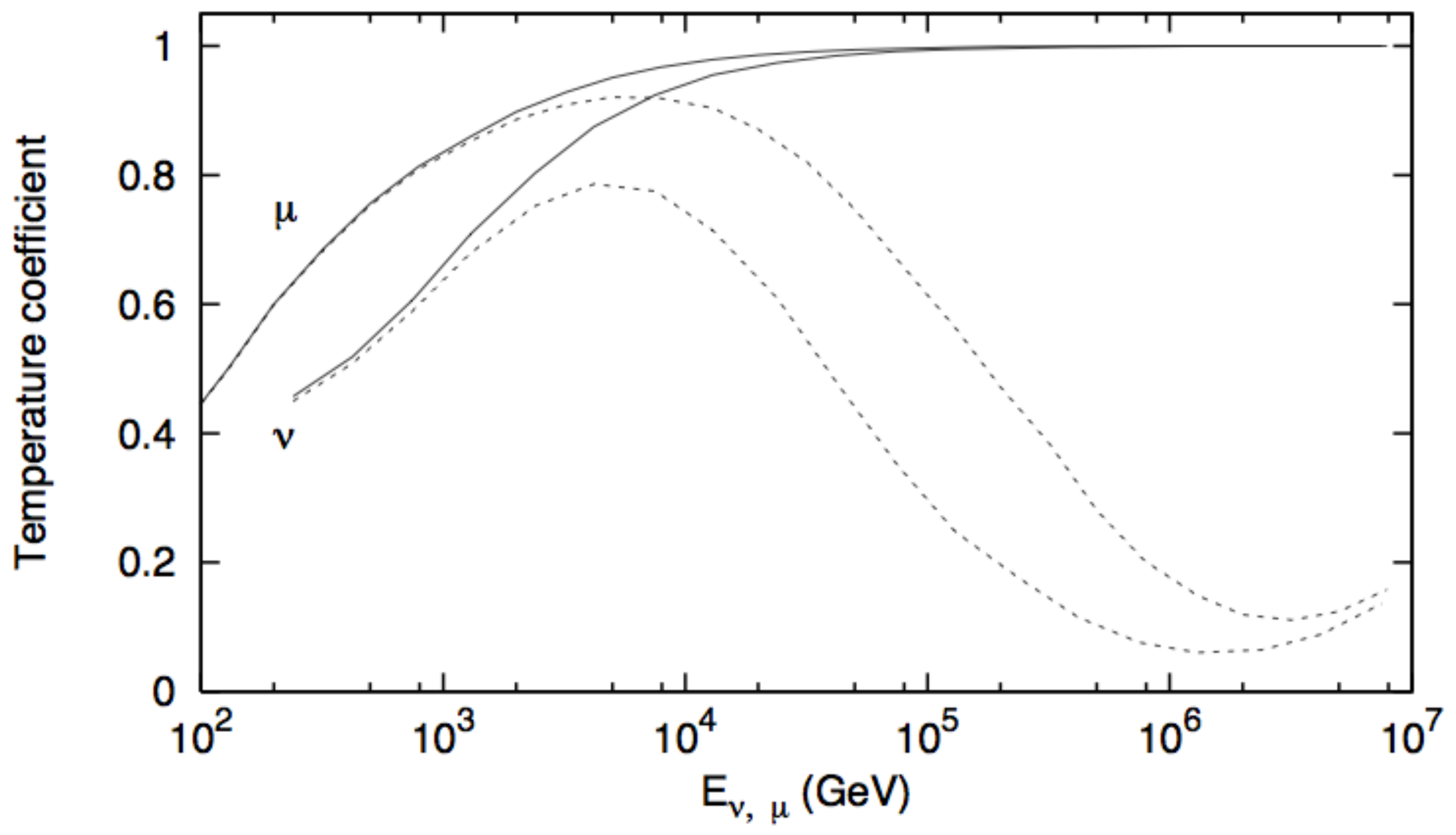
astrophysical neutrinos as well

complications from muon multiplicity

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}{\int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}$$

high energy leptons

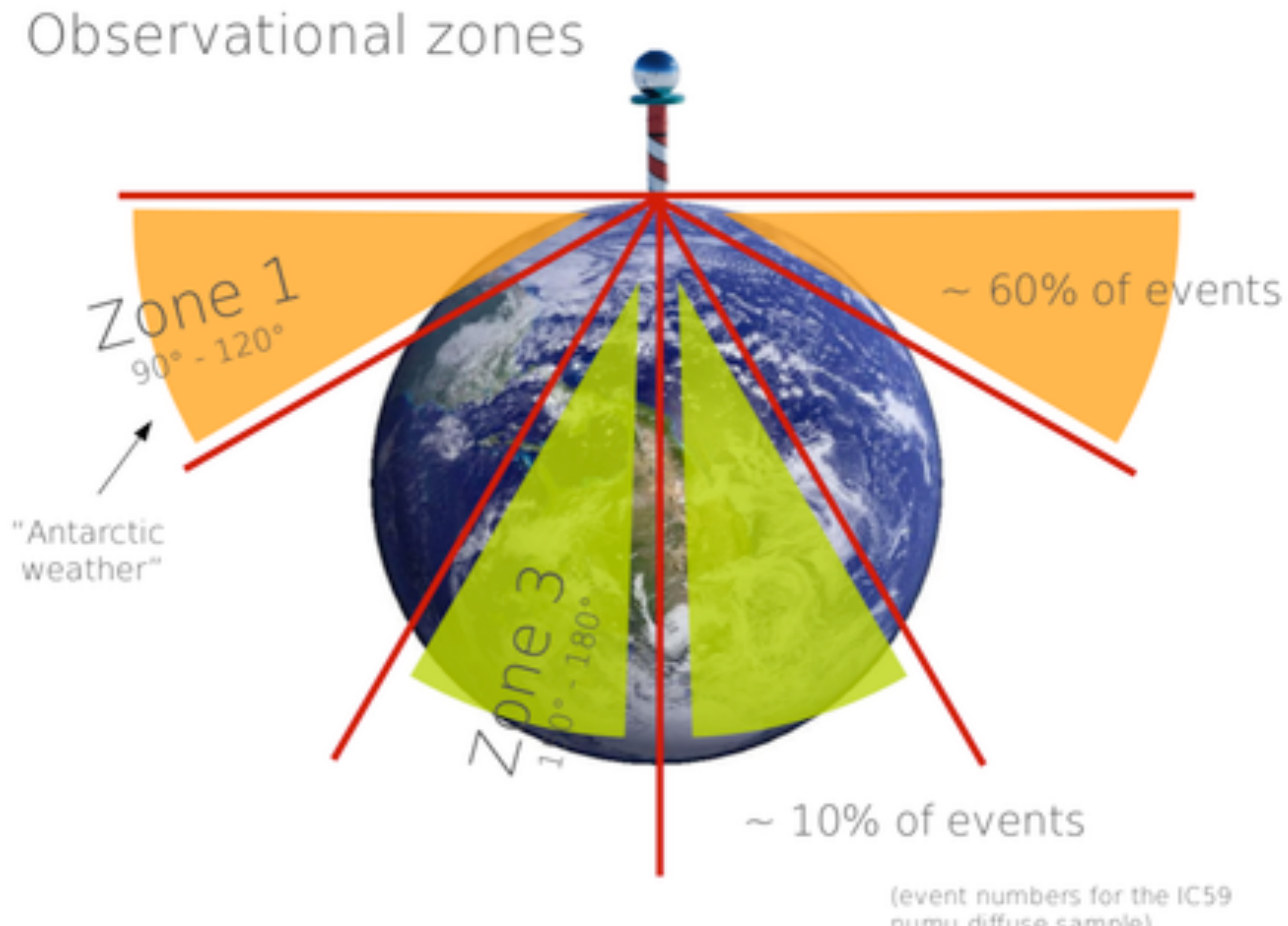
charm production



PD, Gaisser 2010

$E_{\mu,\min}$	no charm		RQPM charm		ERS charm		int. charm	
	α	Rate	α	Rate	α	Rate	α	Rate
0.5	0.83	2050	0.82	2070	0.82	2050	0.82	2060
10	0.98	1.26	0.89	1.40	0.97	1.26	0.94	1.34
100	1.0	0.0025	0.53	0.0049	0.91	0.0028	0.71	0.0036

TABLE I: Correlation coefficients for muons with ($\theta \leq 30°$) for three levels of charm (energy in TeV; rate in Hz/km^2).

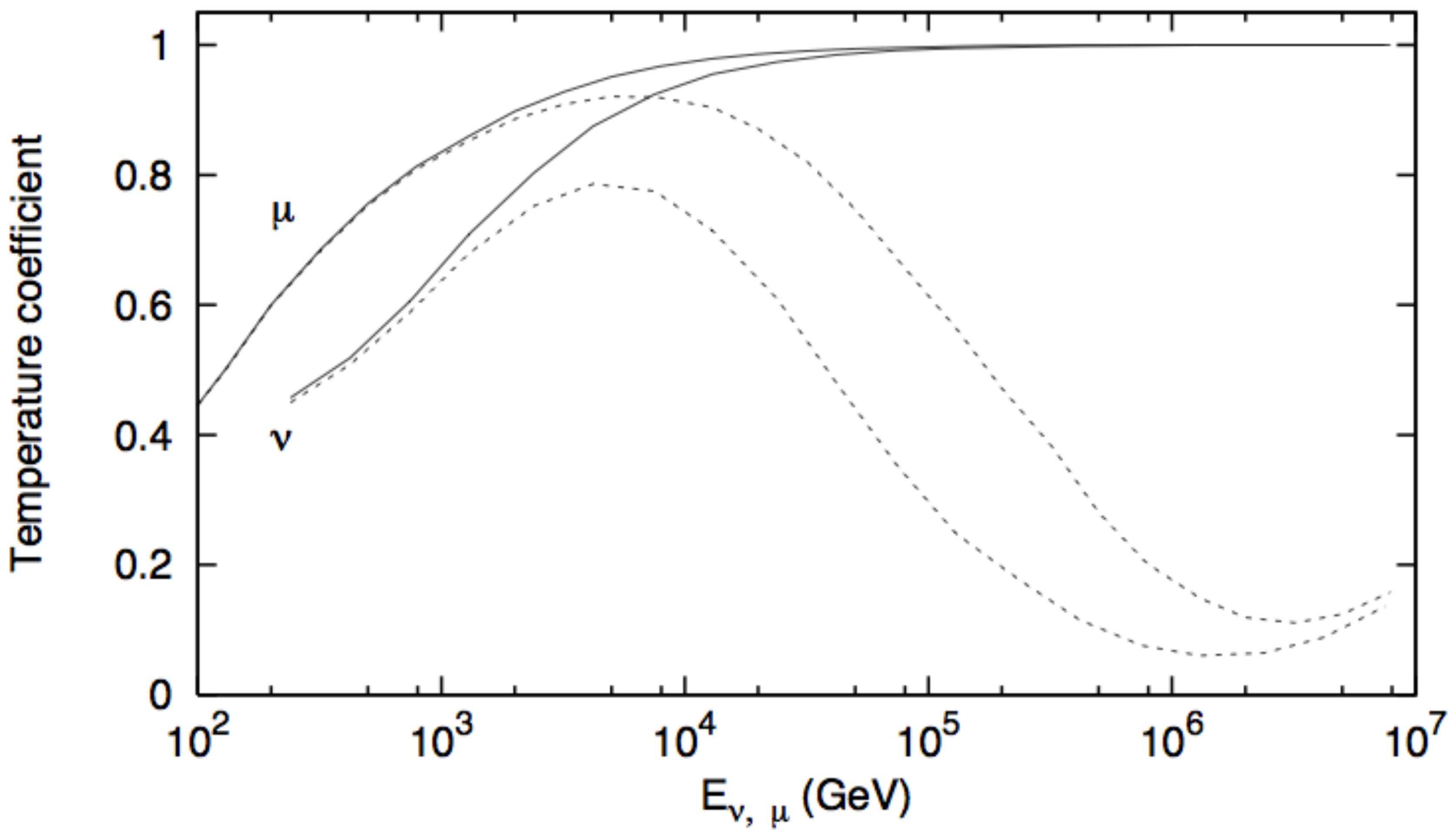


IC40×2

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	16000	0.52	17000
3	0.70	5900	0.62	6300
30	0.94	350	0.72	450

high energy leptons

charm production



PD, Gaisser 2010

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TABLE I: Correlation coefficients for muons with ($\theta \lesssim 30^\circ$) for three levels of charm (energy in TeV; rate in Hz/km^2).

muon multiplicity modifies temperature correlation (ICRC 2013)

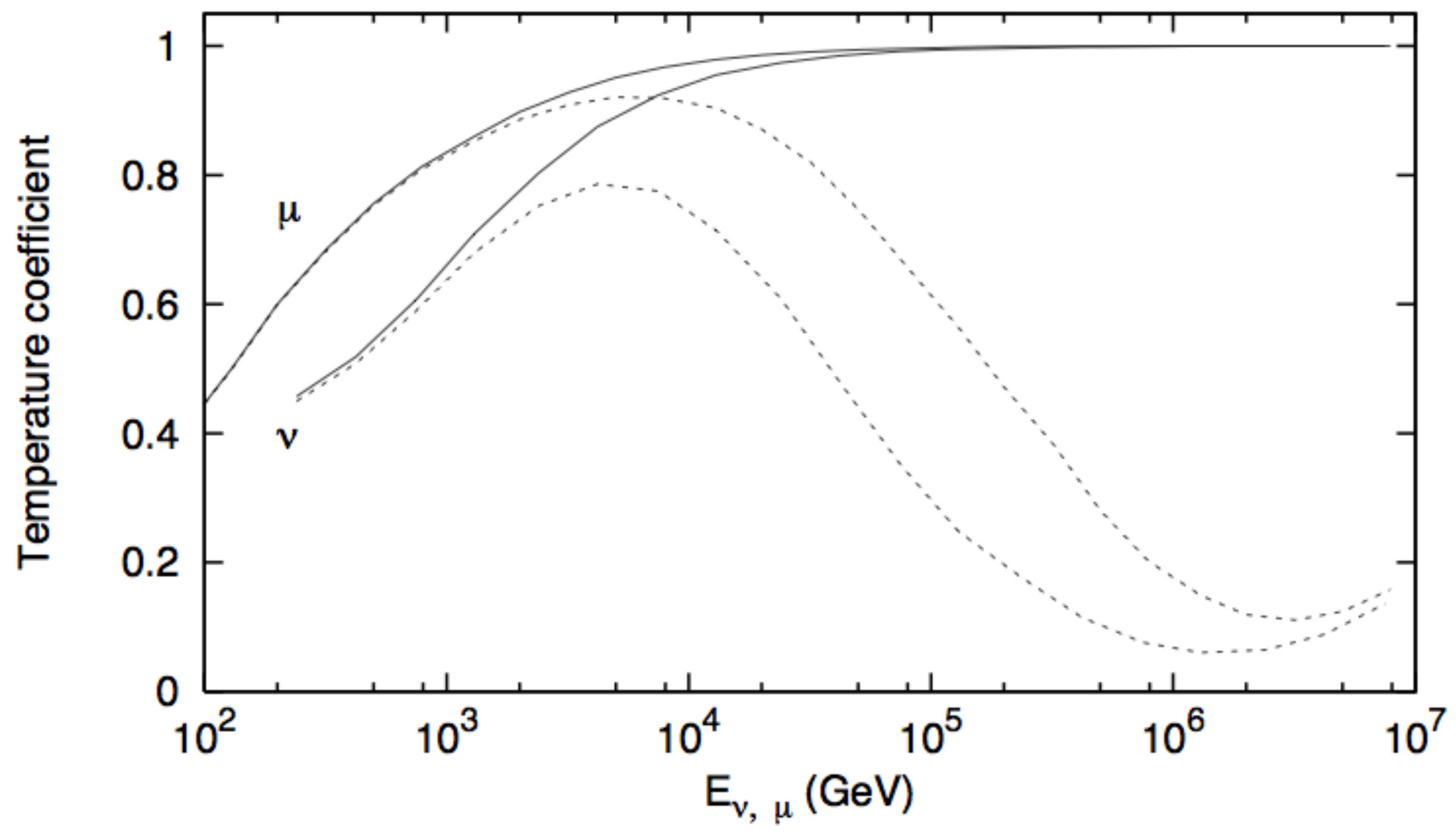
need to evaluate the energy of individual muons in the bundle

→ ***single muons***

- 2×10^8 μ/day → 220-430 μ/day
- α_T^{th} decreases 10-30% for E_μ > 100 TeV
- **10 years of HE muon data**

high energy leptons

charm production



PD, Gaisser 2010

astrophysical neutrinos do not correlate with atmospheric temperature

neutrinos produced in larger portion of Earth's atmosphere

small event statistics

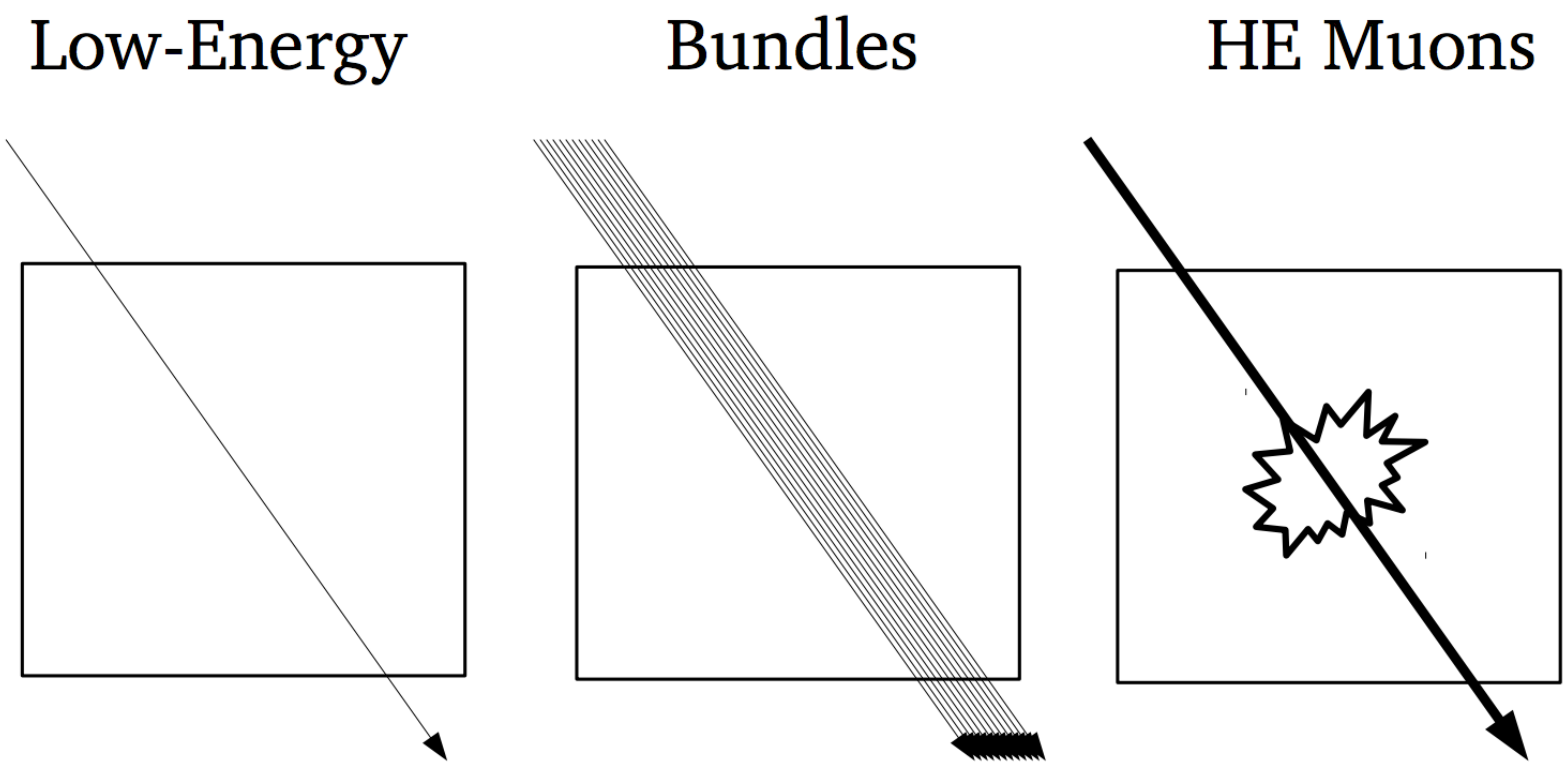
- 100 ν/day → 2-3 ν/day
- α_T^{th} decreases 20% for E_ν > 30 TeV
- long time to accumulate enough statistics

IC40×2 → **IC86** ~ 4.8×IC40

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	38400	0.52	40800
3	0.70	14160	0.62	15120
30	0.94	840	0.72	1080

high energy muons

T. Karg



Low-Energy	Bundles	HE Muons
1,000/second	1/second	0.1/second
Minimum Ionizing	Minimum Ionizing	Stochastic
Single Muons	20-10,000 Muons	1 HE Muon, 10-100 others
10-100 TeV CR	1 PeV-1 EeV CR	100 TeV-10 PeV CR

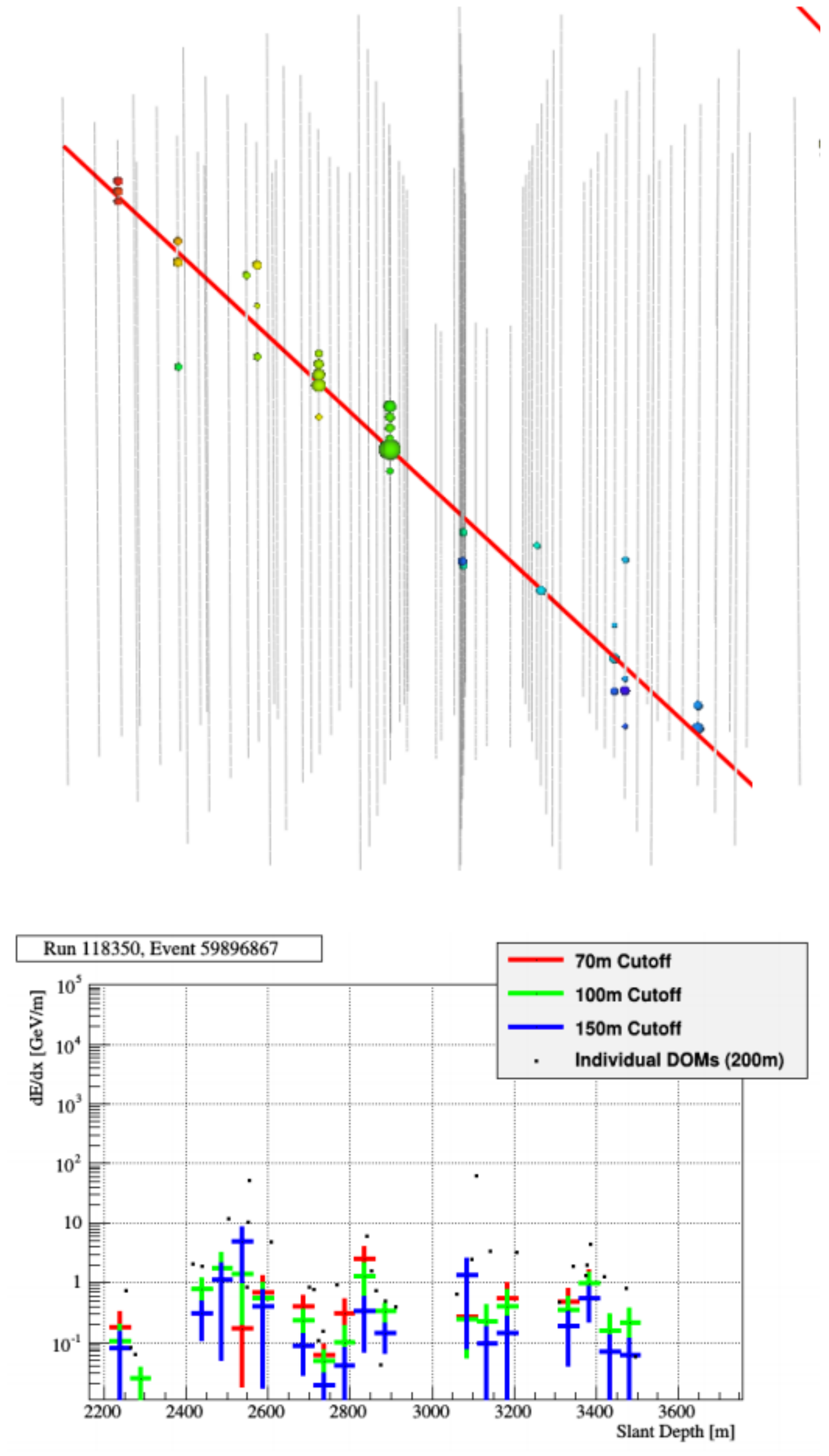
P. Berghaus

high energy muons

ICRC 2015

T. Karg

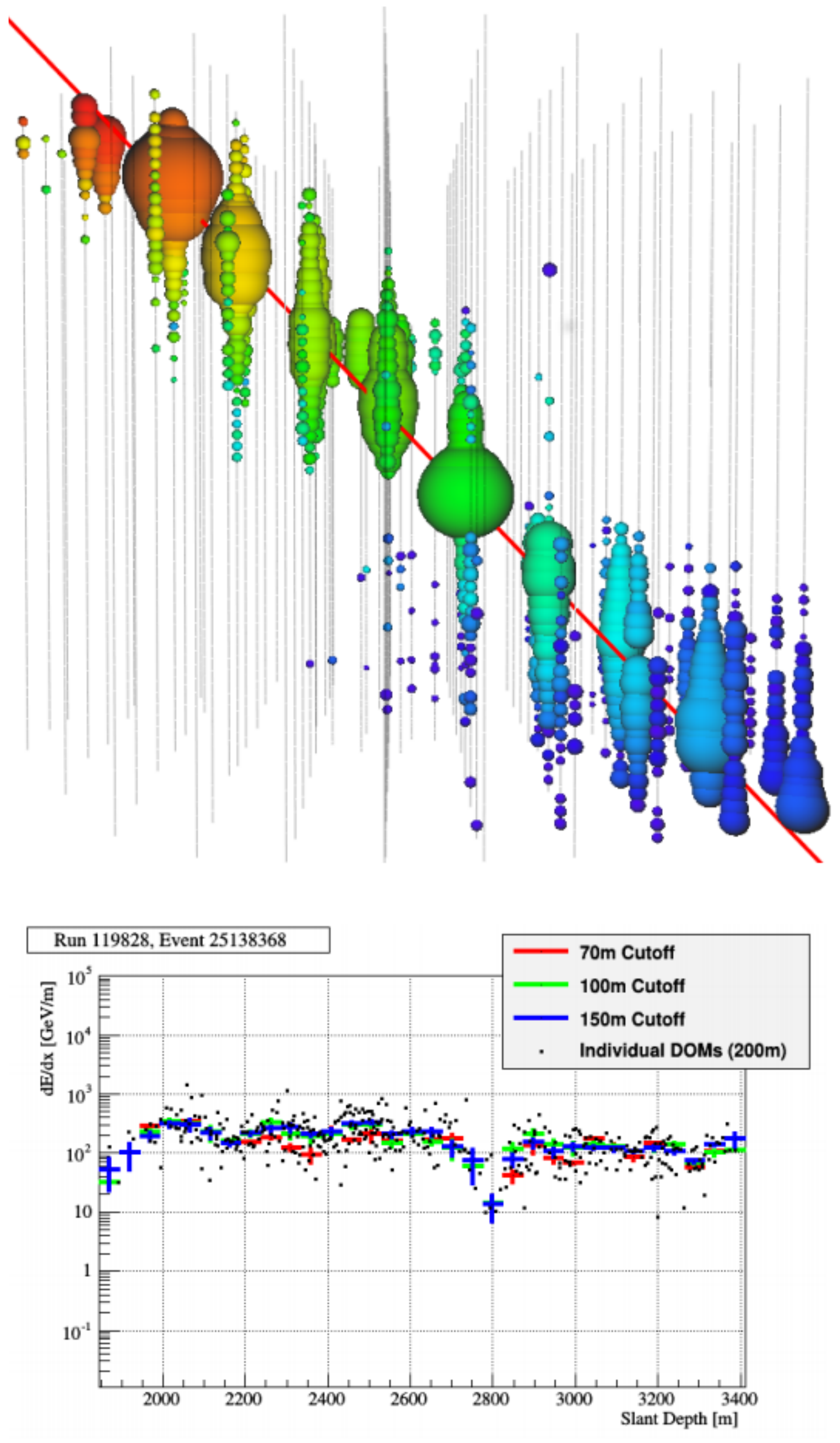
Low-Energy



a muon, maybe two

minimum ionizing

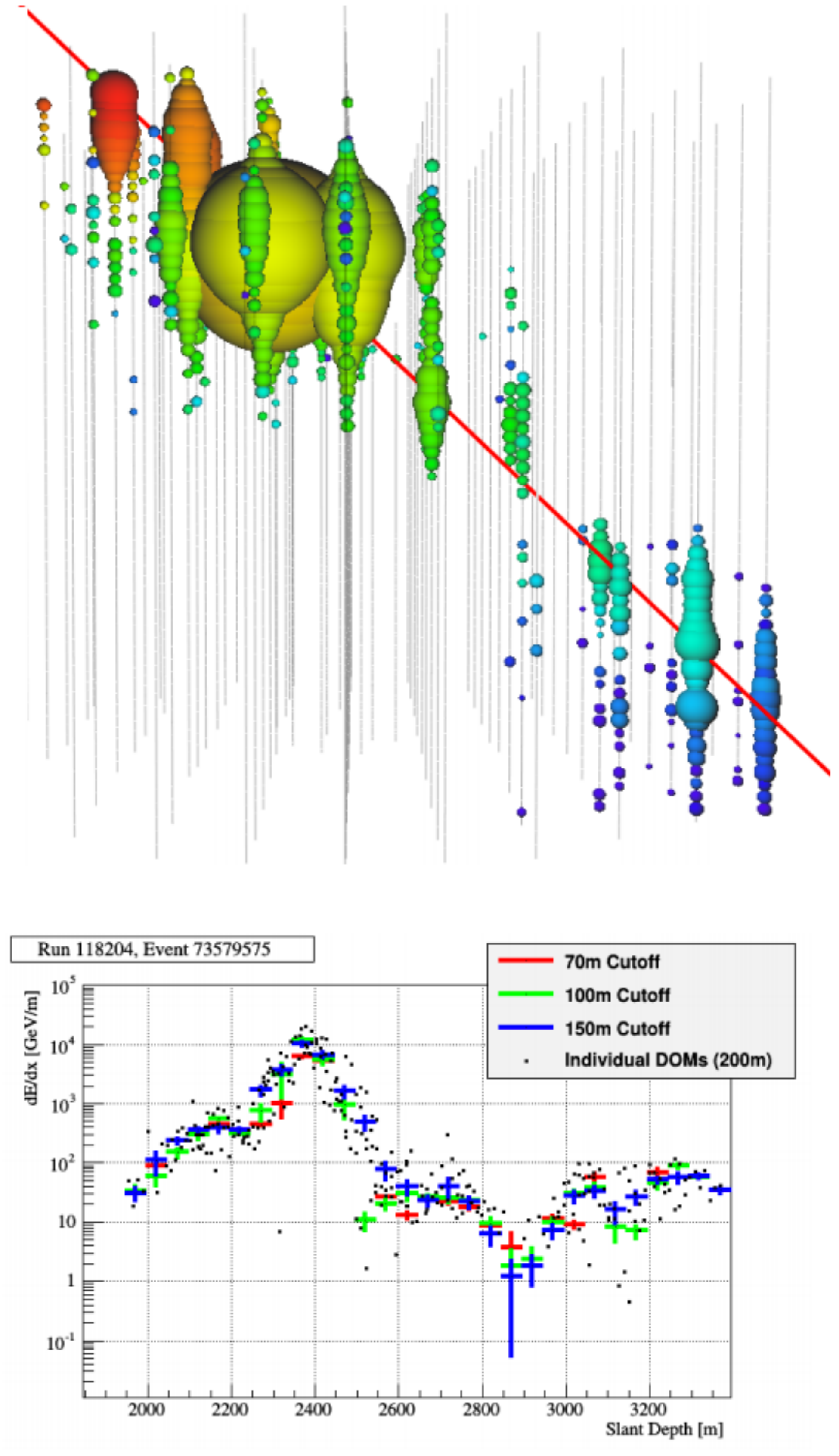
Bundles



200-310 muons

minimum ionizing

HE Muons



640-1,650 TeV

stochastic energy losses

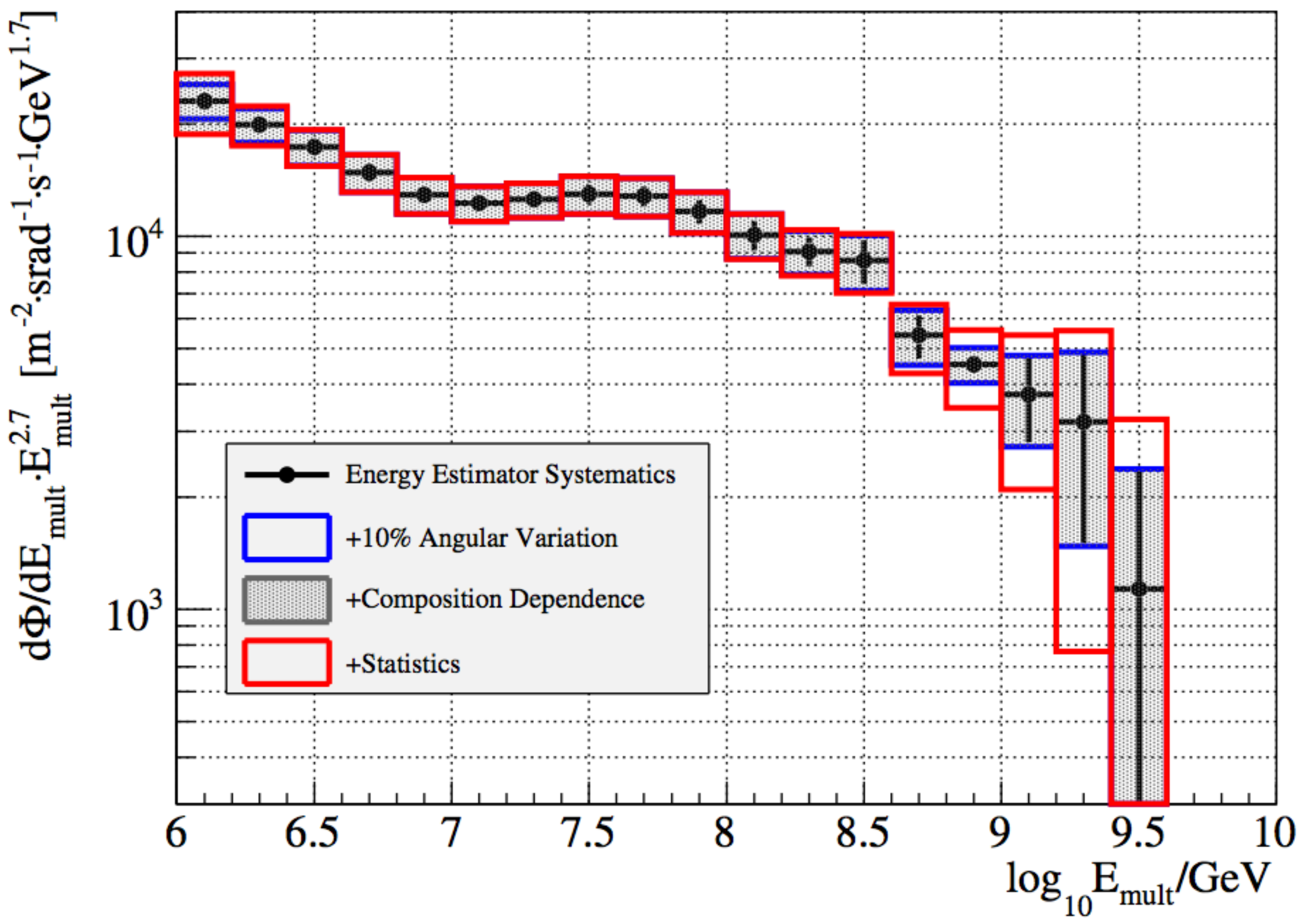
P. Berghaus

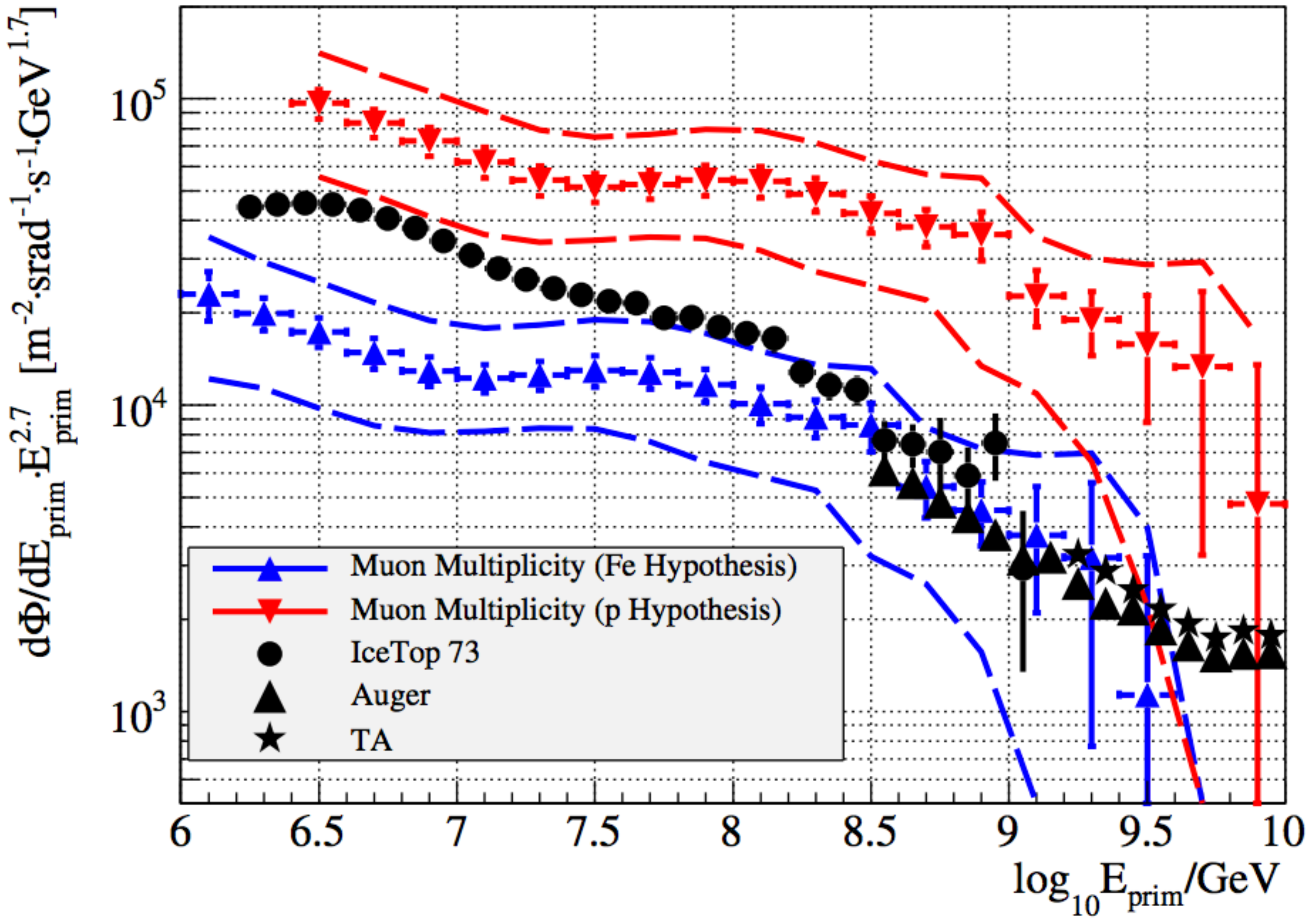
high energy muons

ICRC 2015

T. Karg

multiple muons IceCube arXiv:1506.07981 (ApP) **2015**



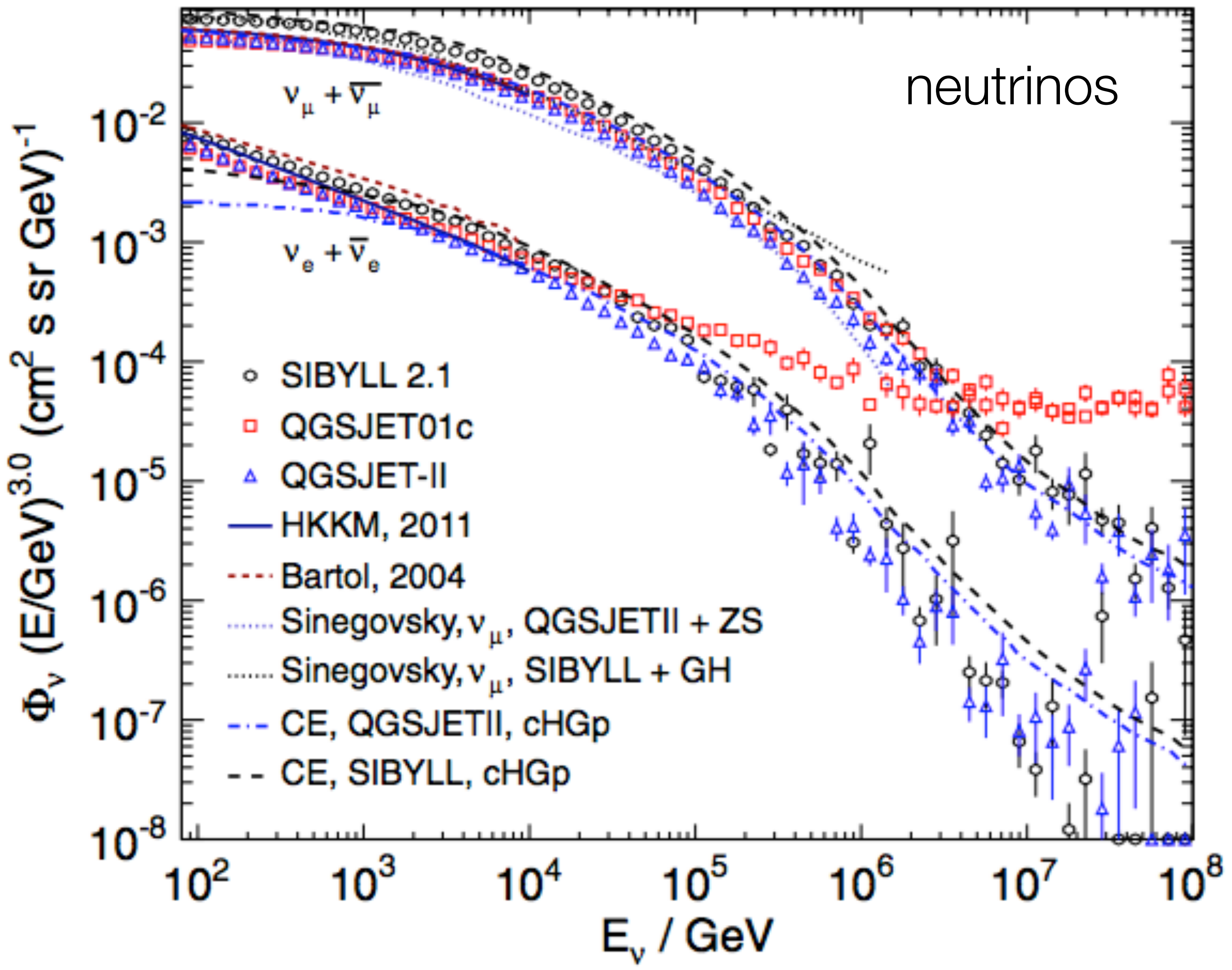


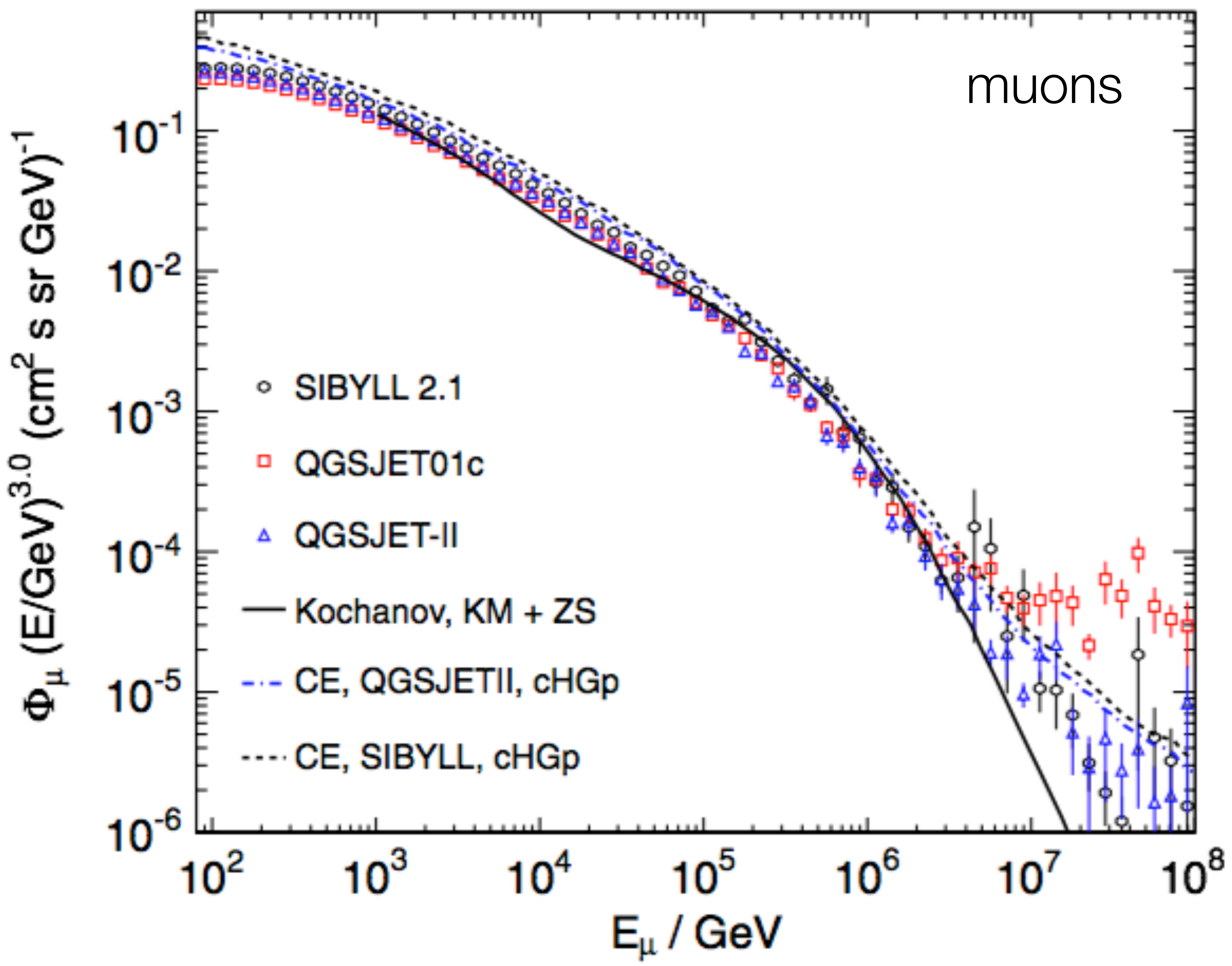
$$\sum E_\mu \propto N_\mu \propto E_{prim}^{\alpha} \cdot A^{1-\alpha}$$

$$E_{mult} \equiv E_{prim} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$

hadronic interaction models

Fedynitch, Becker-Tjus, PD 2010

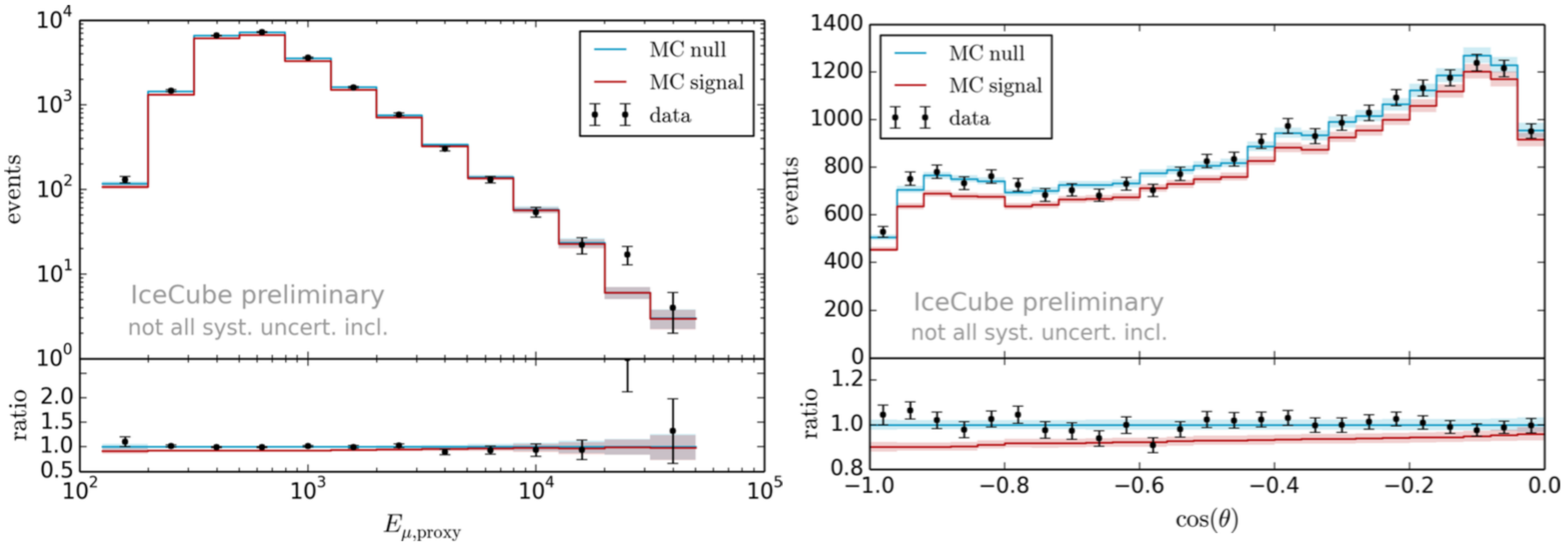




non-standard physics

ν_μ disappearance to sterile neutrino

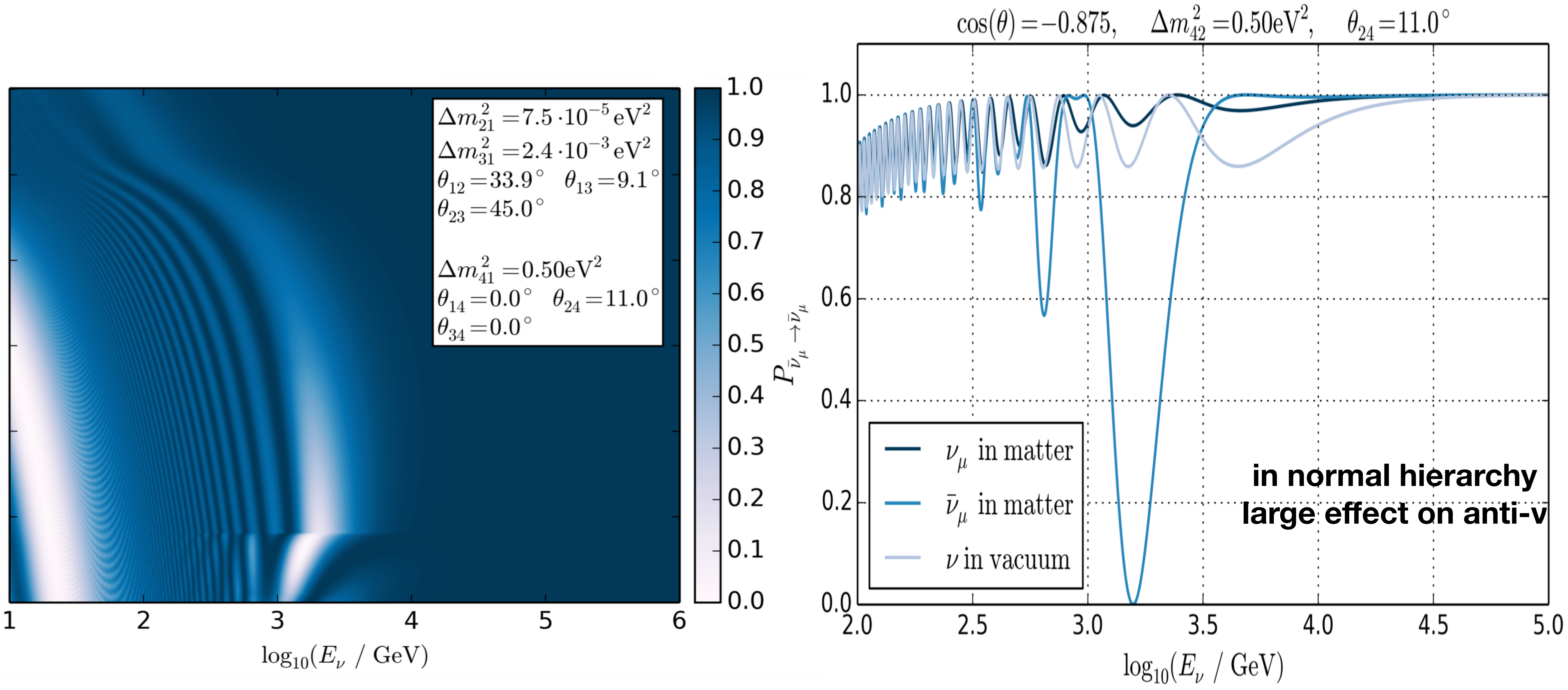
IceCube-59 **ICRC 2015**



non-standard physics

ν_μ disappearance to sterile neutrino

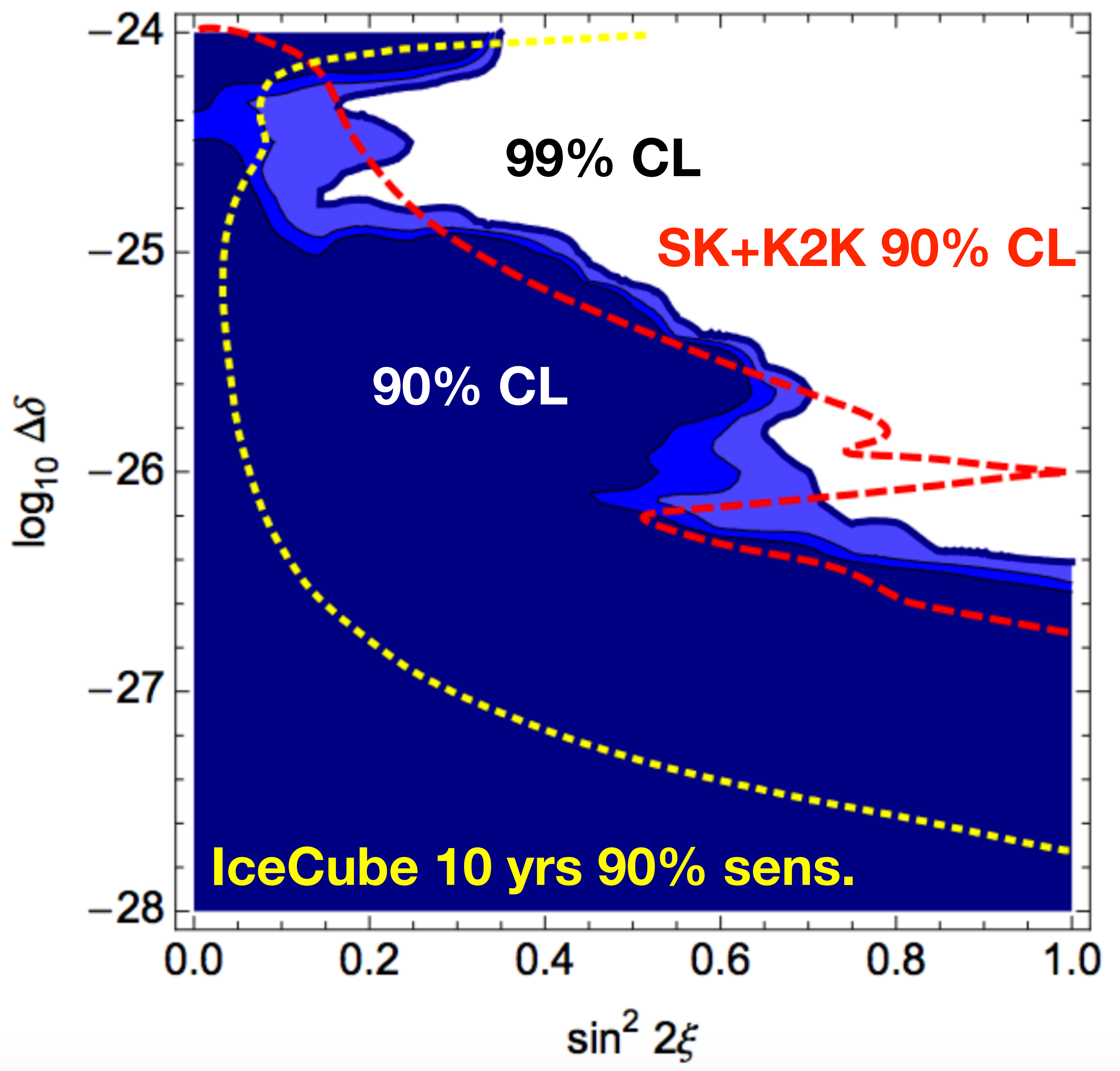
ICRC 2015
M. Wallraff
Wed 5/8



non-standard physics

non-standard oscillations

AMANDA Phys. Rev. D79, 102005 2013



standard oscillations

violation of Lorentz invariance