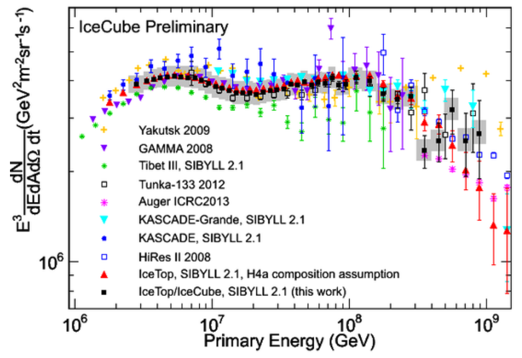
Recent Observations of Atmospheric Neutrinos with the IceCube Observatory

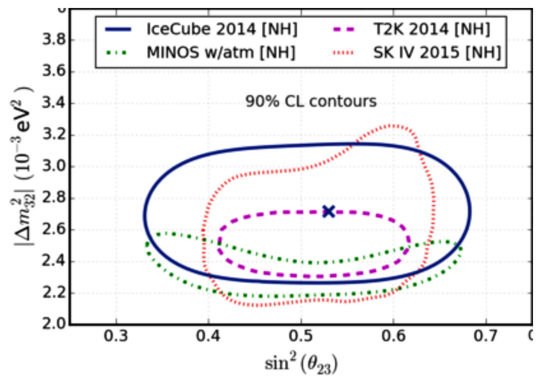
Paolo Desiati
WIPAC - UW-Madison
for the IceCube Collaboration

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference

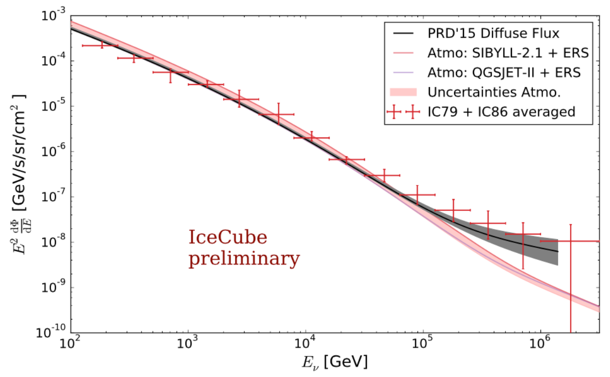
outline



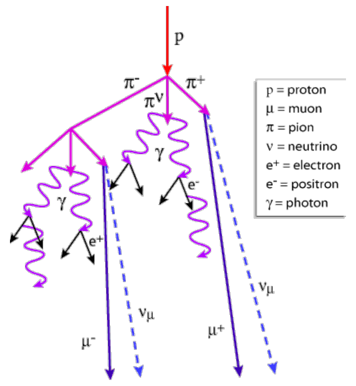
cosmic rays & atmospheric leptons



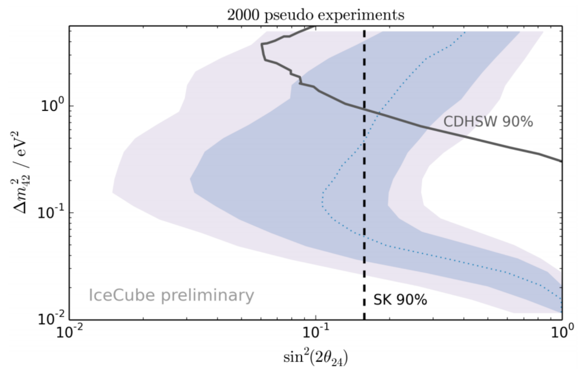
low energy neutrinos



high energy neutrinos & muons



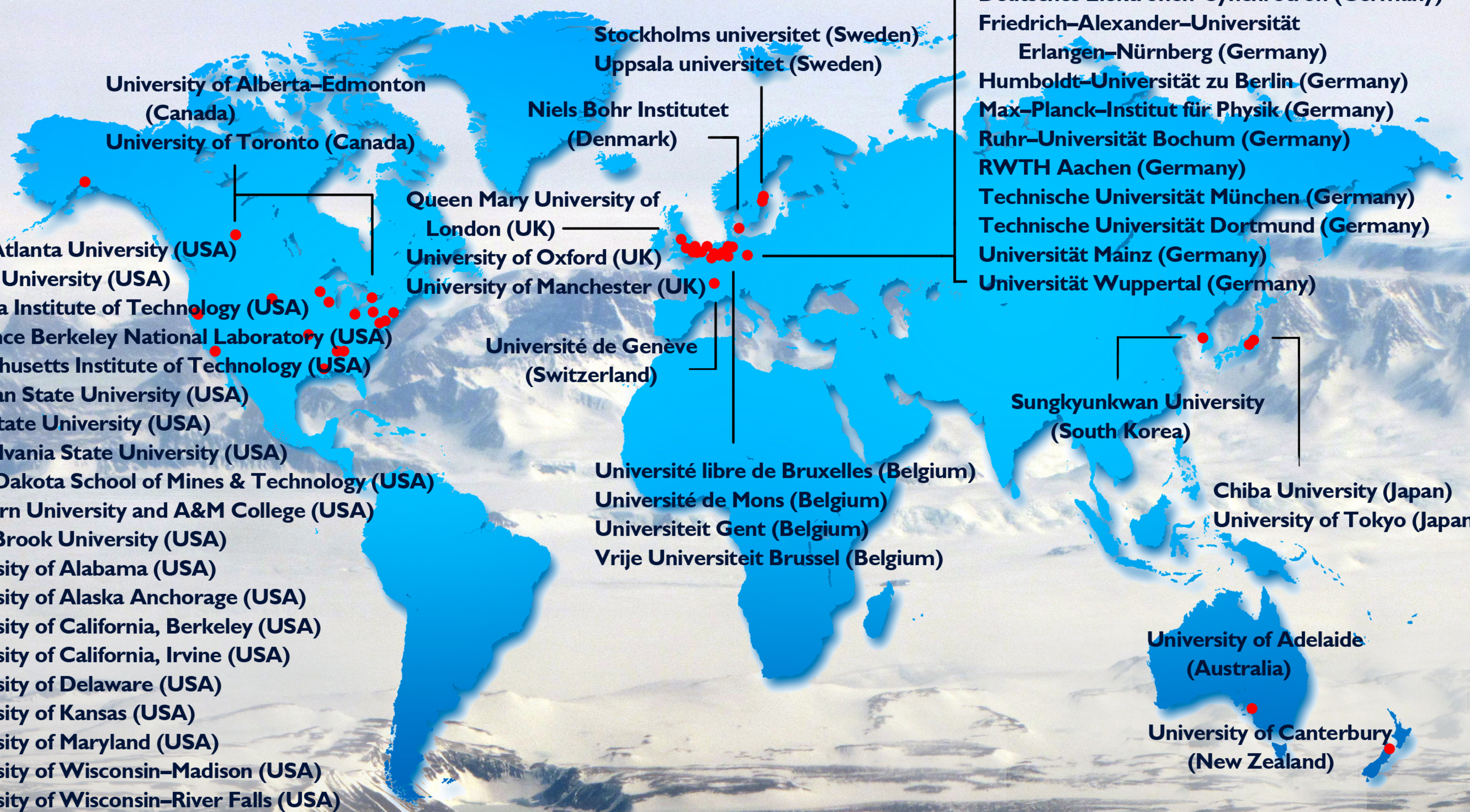
hadronic interaction models



non-standard physics

48 institutions
300+ members

The IceCube–PINGU Collaboration



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International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
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German Research Foundation (DFG)
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Swedish Polar Research Secretariat
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University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

ICRC 2015

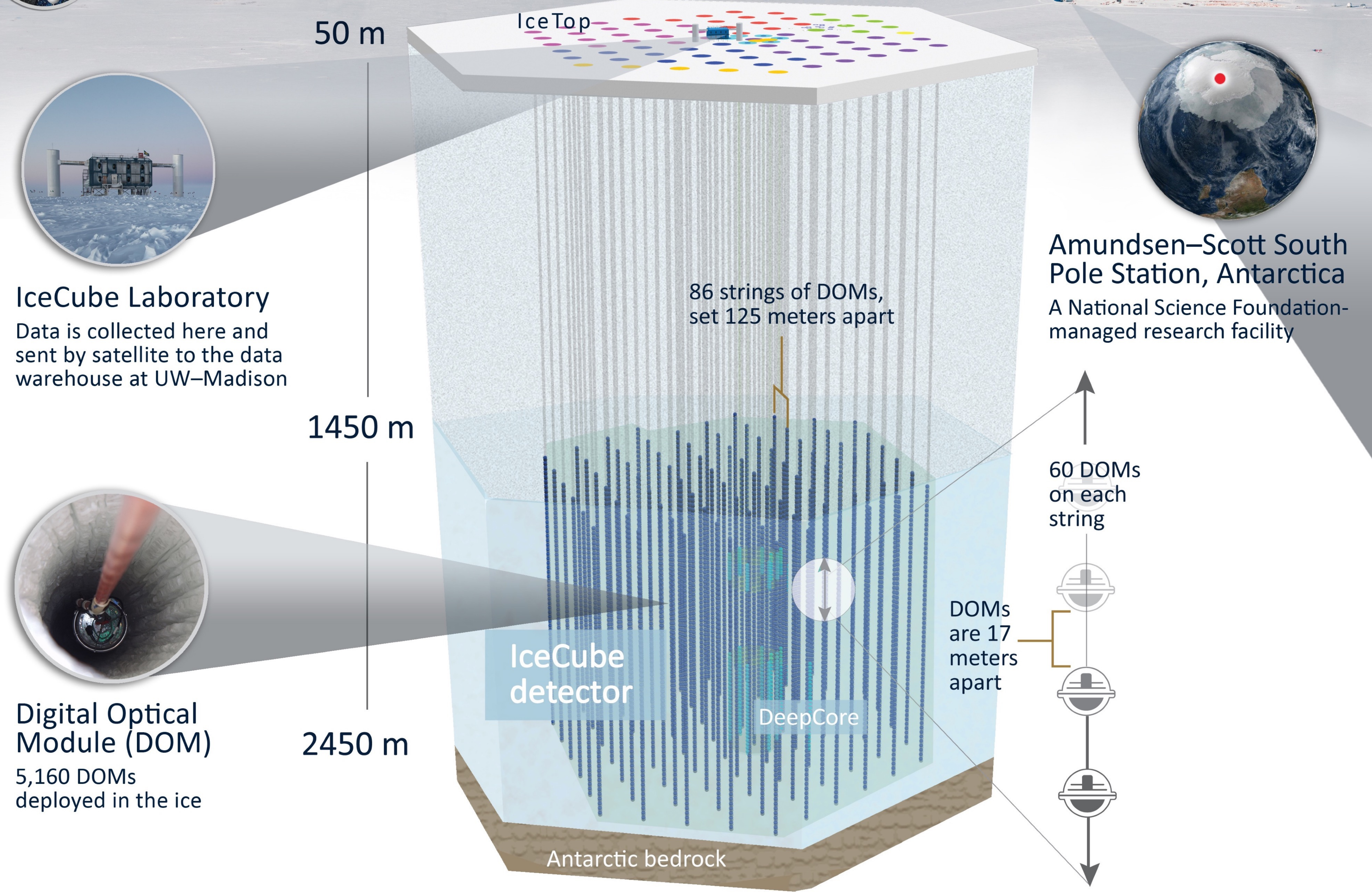
T. Karg

cosmic ray
surface
detector

ICRC 2015

ν
astrophysics
C. Kopper

in-ice
neutrino
telescope



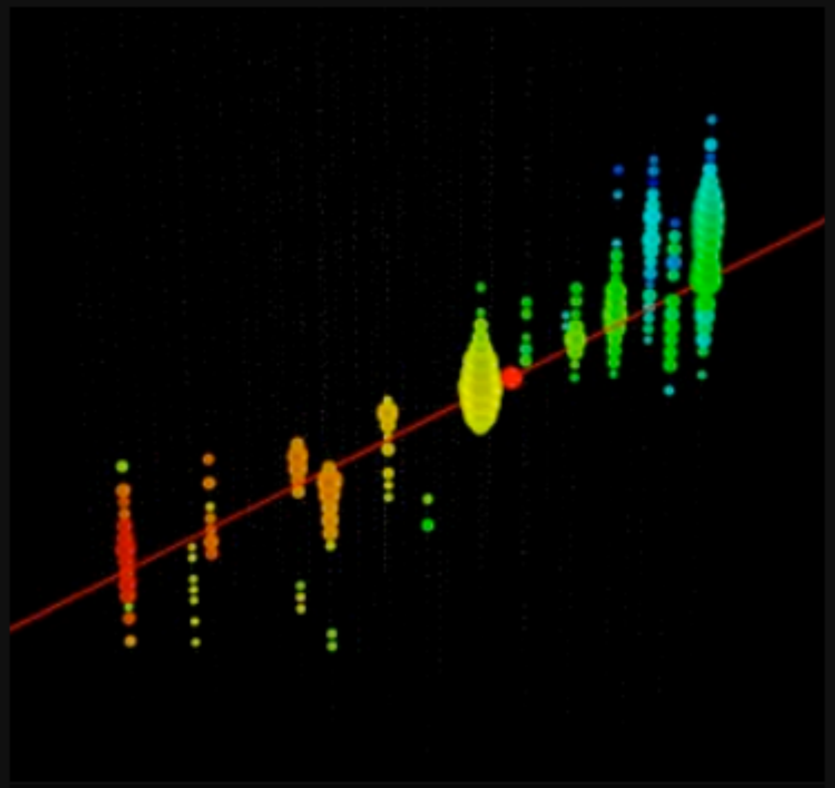
IceCube Observatory

detection technique

time

track

CC Muon Neutrino



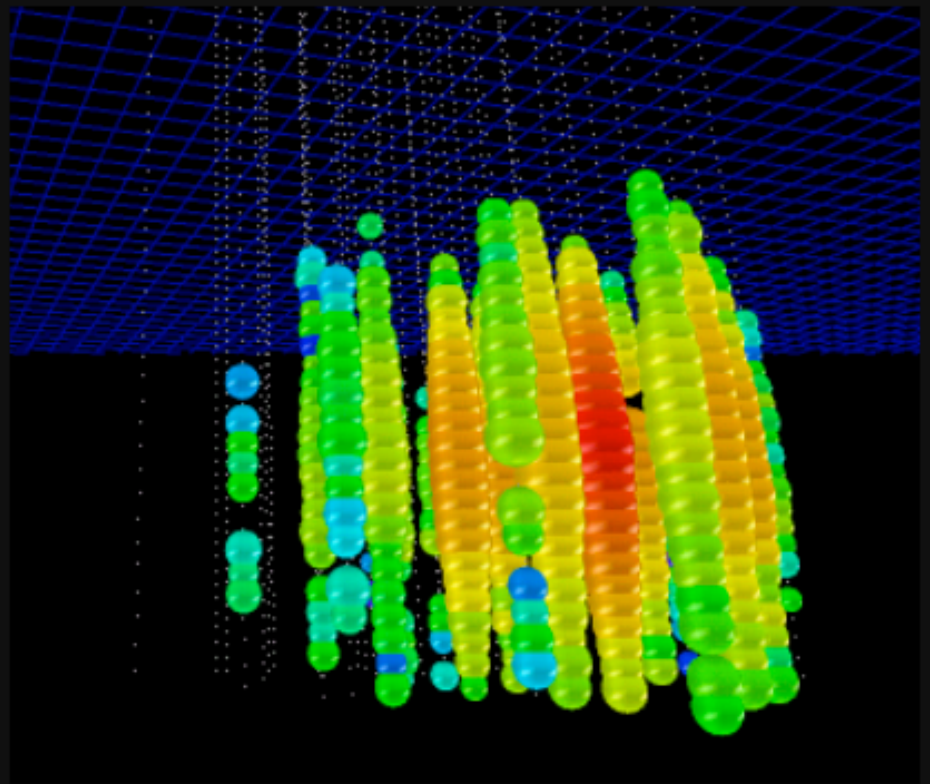
$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

cascade

Neutral Current /Electron Neutrino



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

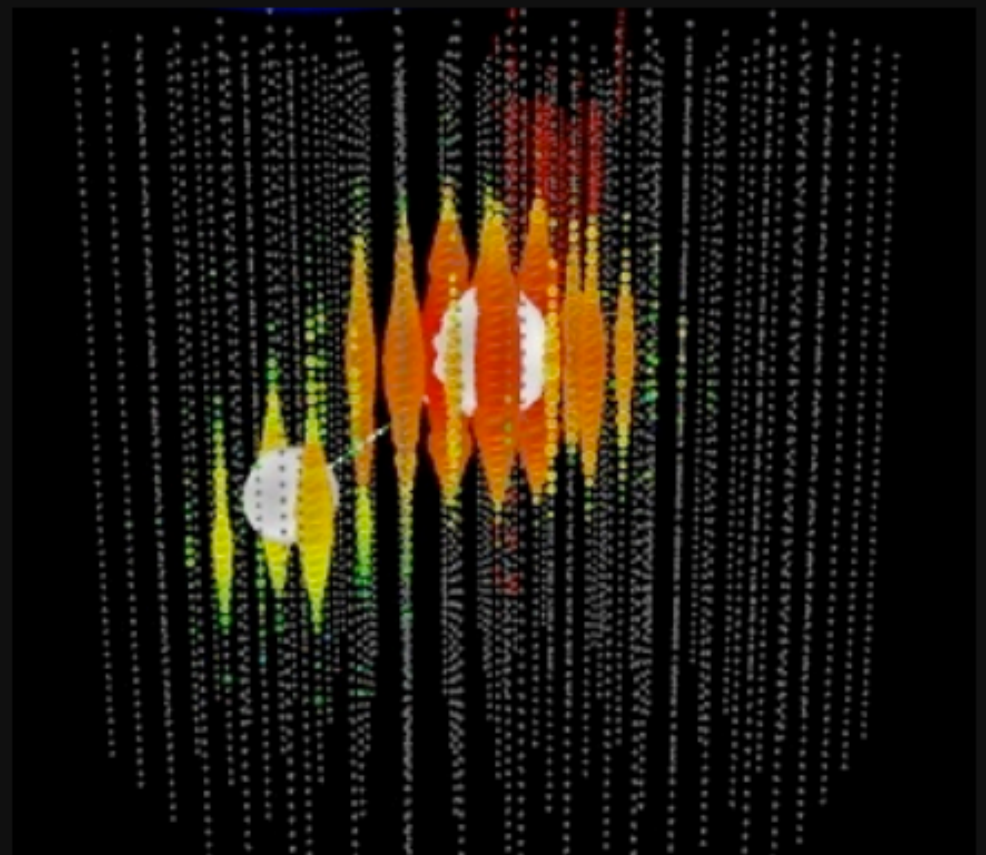
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

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

hybrid

CC Tau Neutrino



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

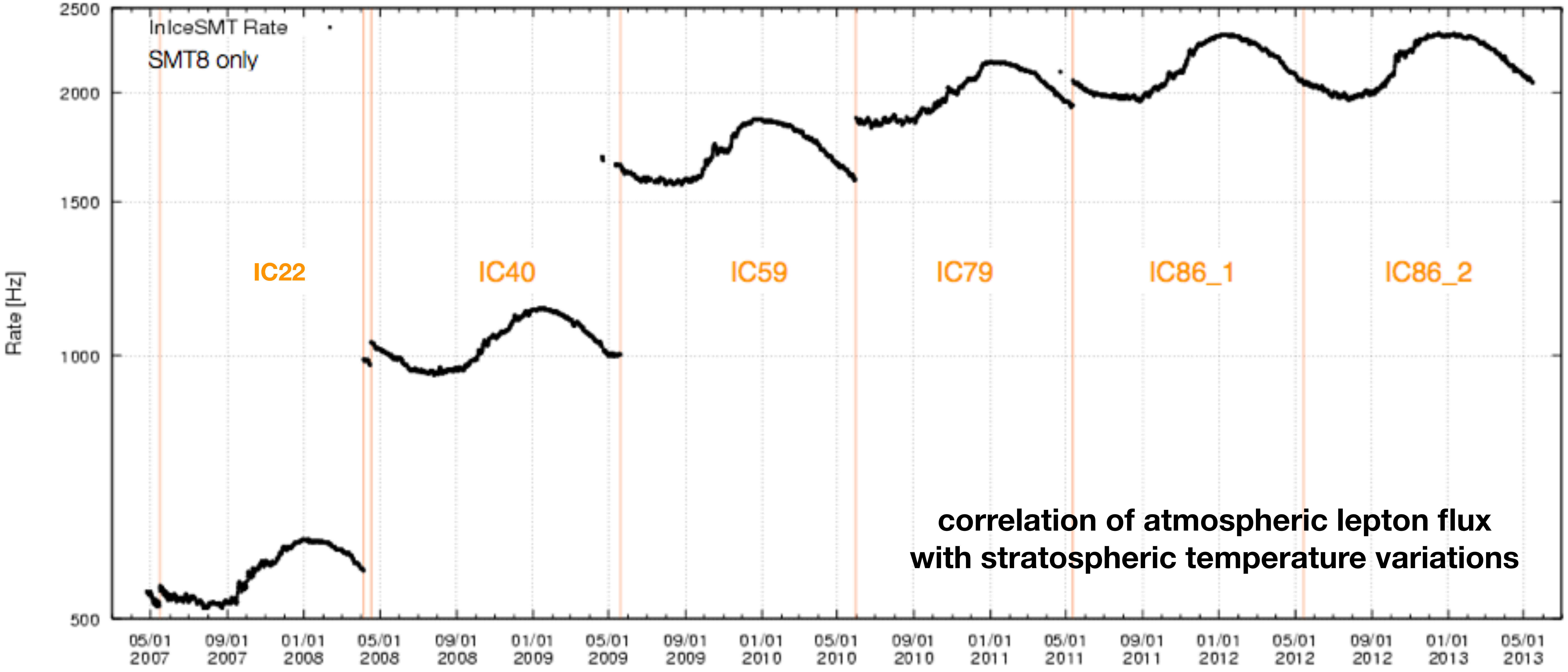
"double-bang" and other signatures
(simulation)

(not observed yet)

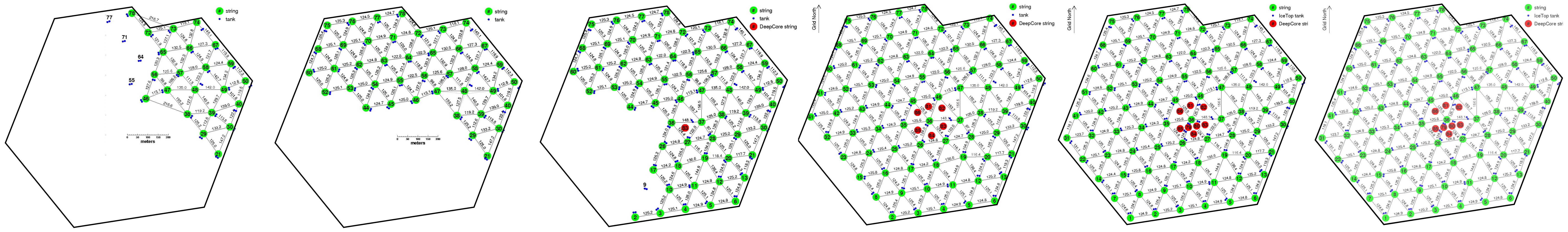
C. Kopper

IceCube Observatory

growing IceCube



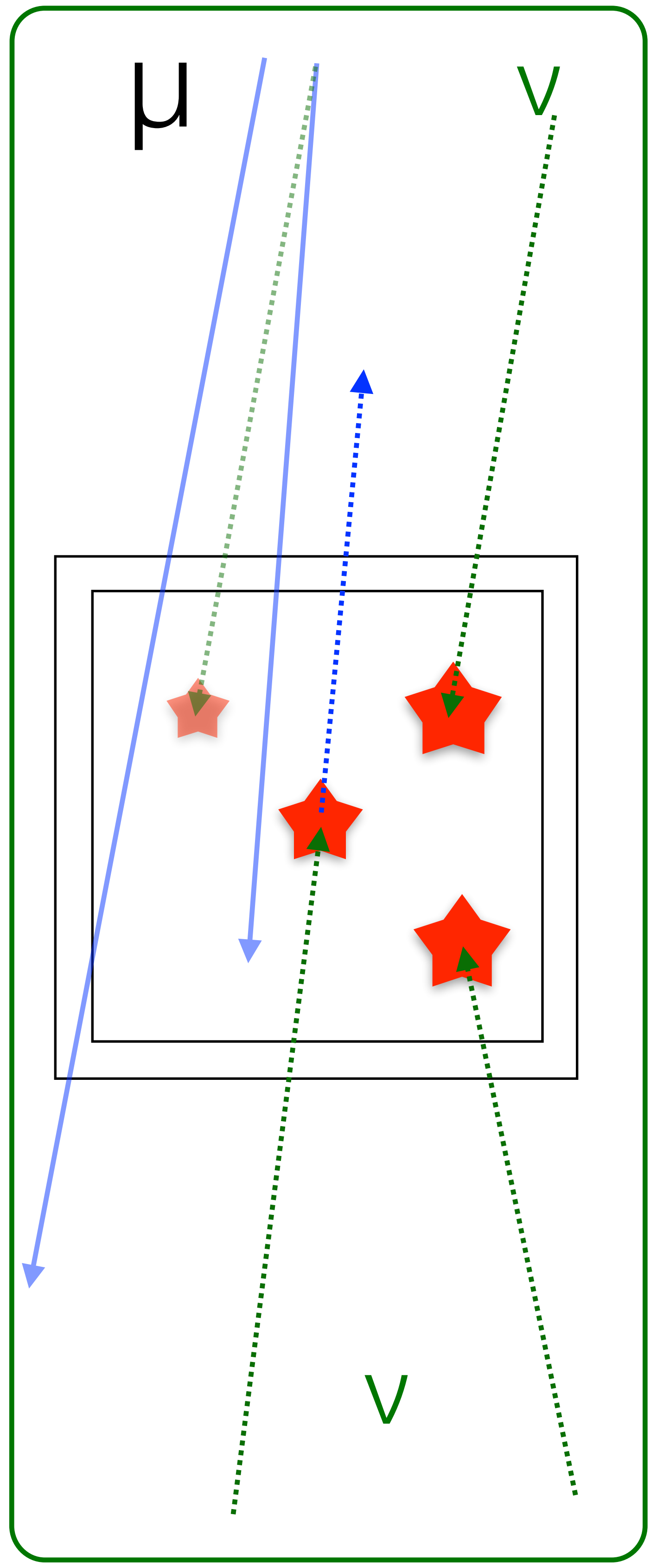
2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>



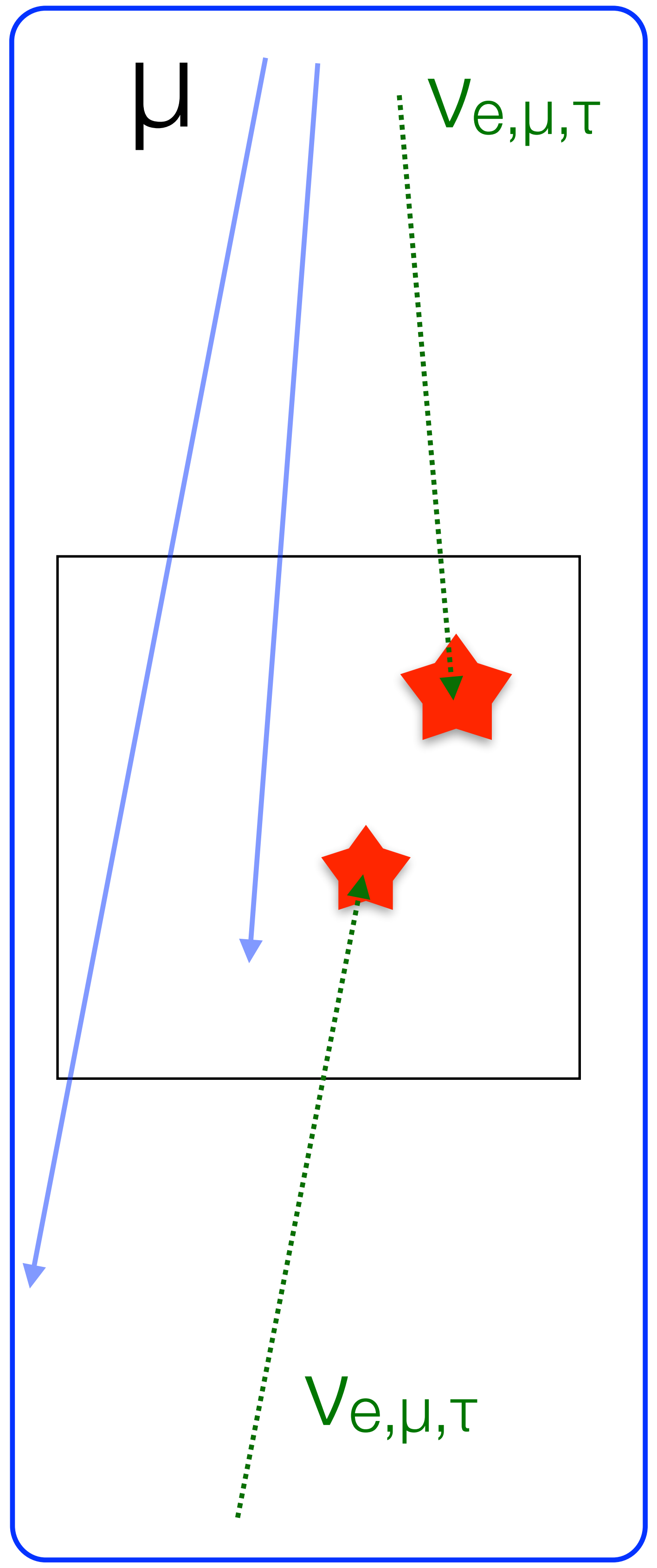
identifying neutrinos

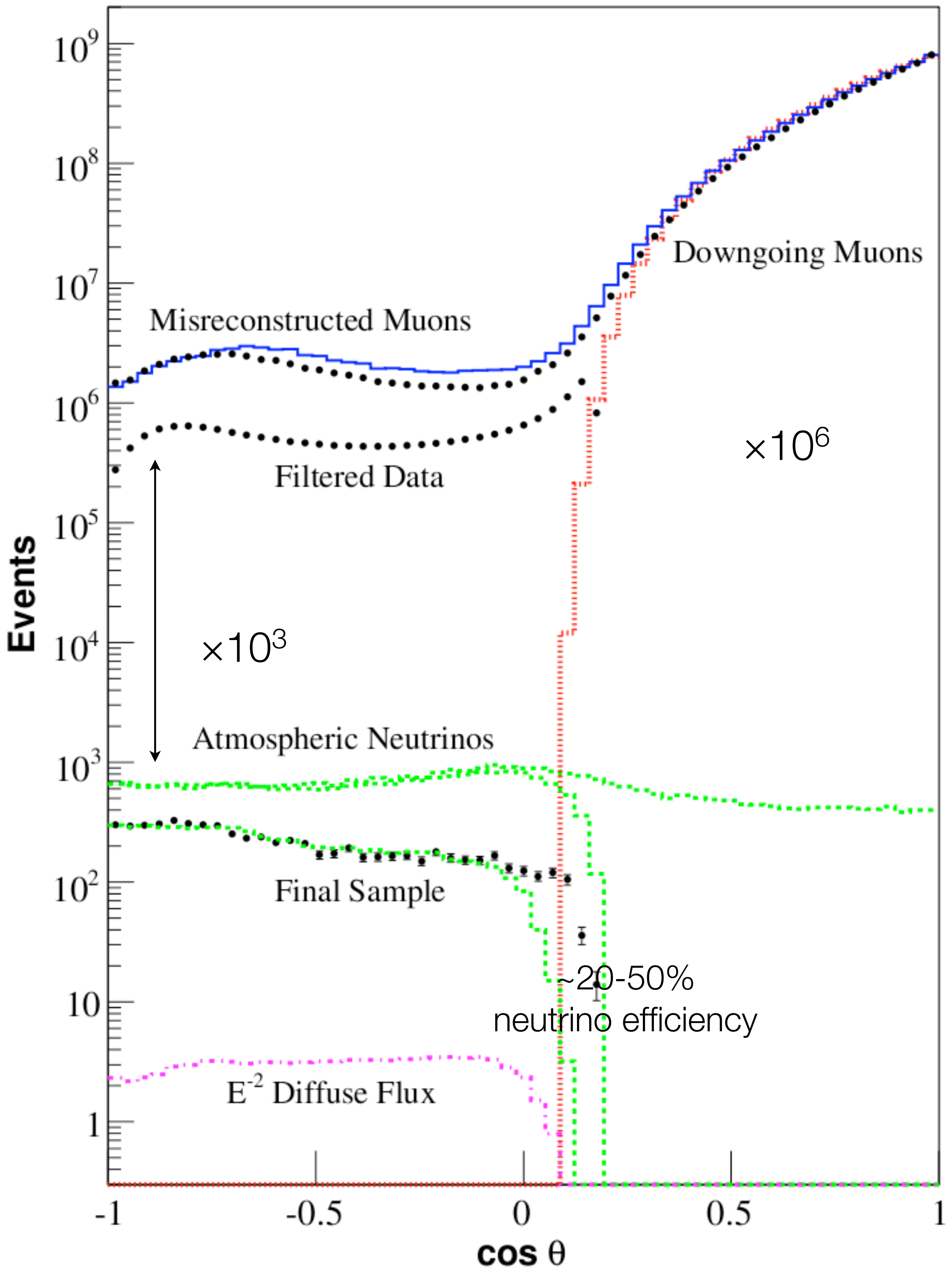
background rejection

starting
(veto)

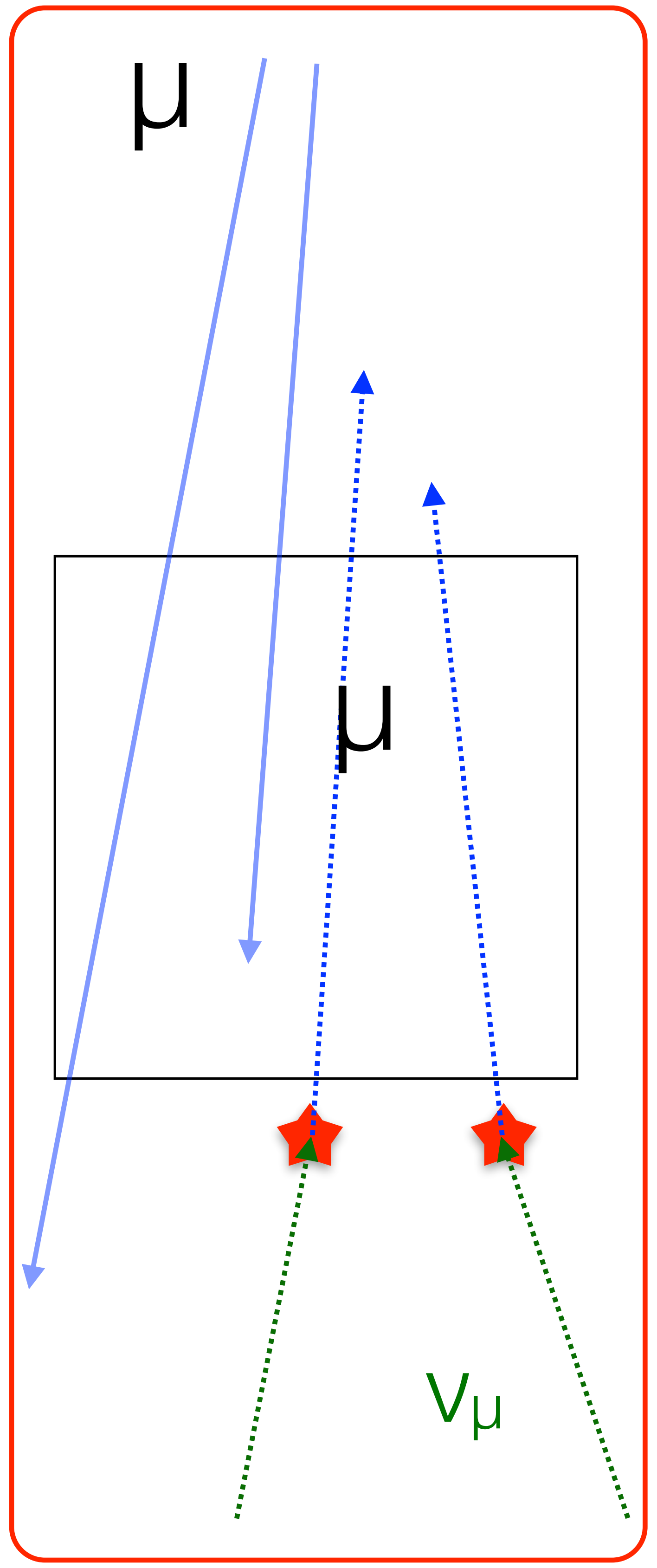


contained
(cascades)



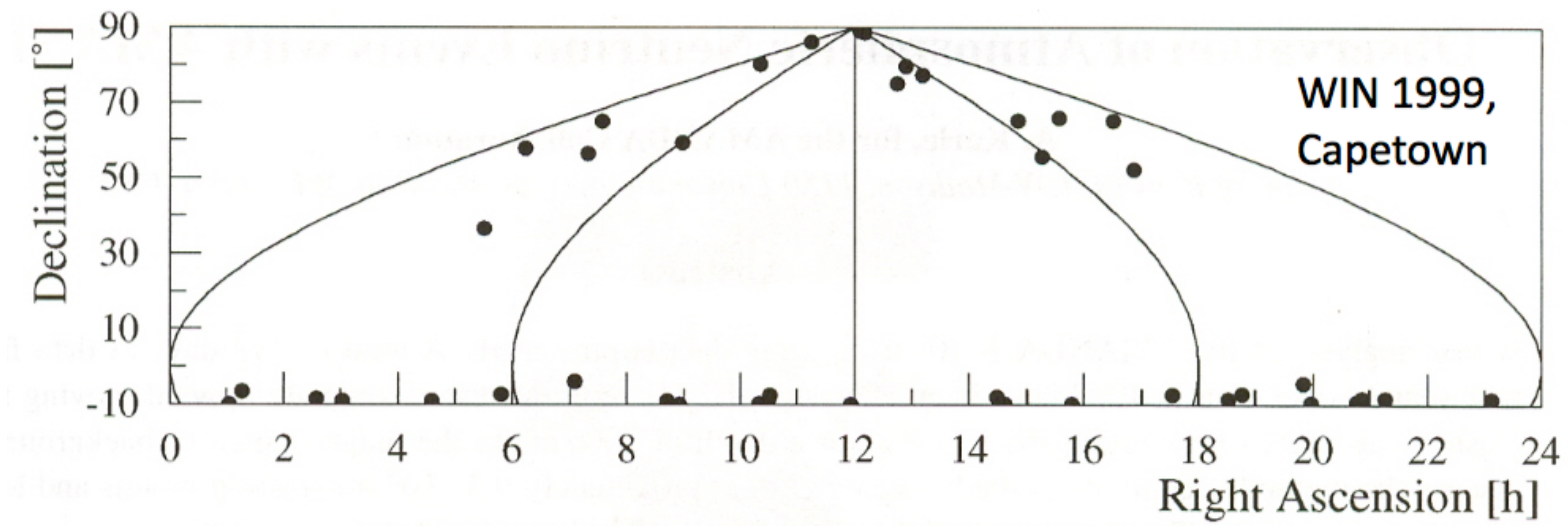


through-going
(tracks)



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**

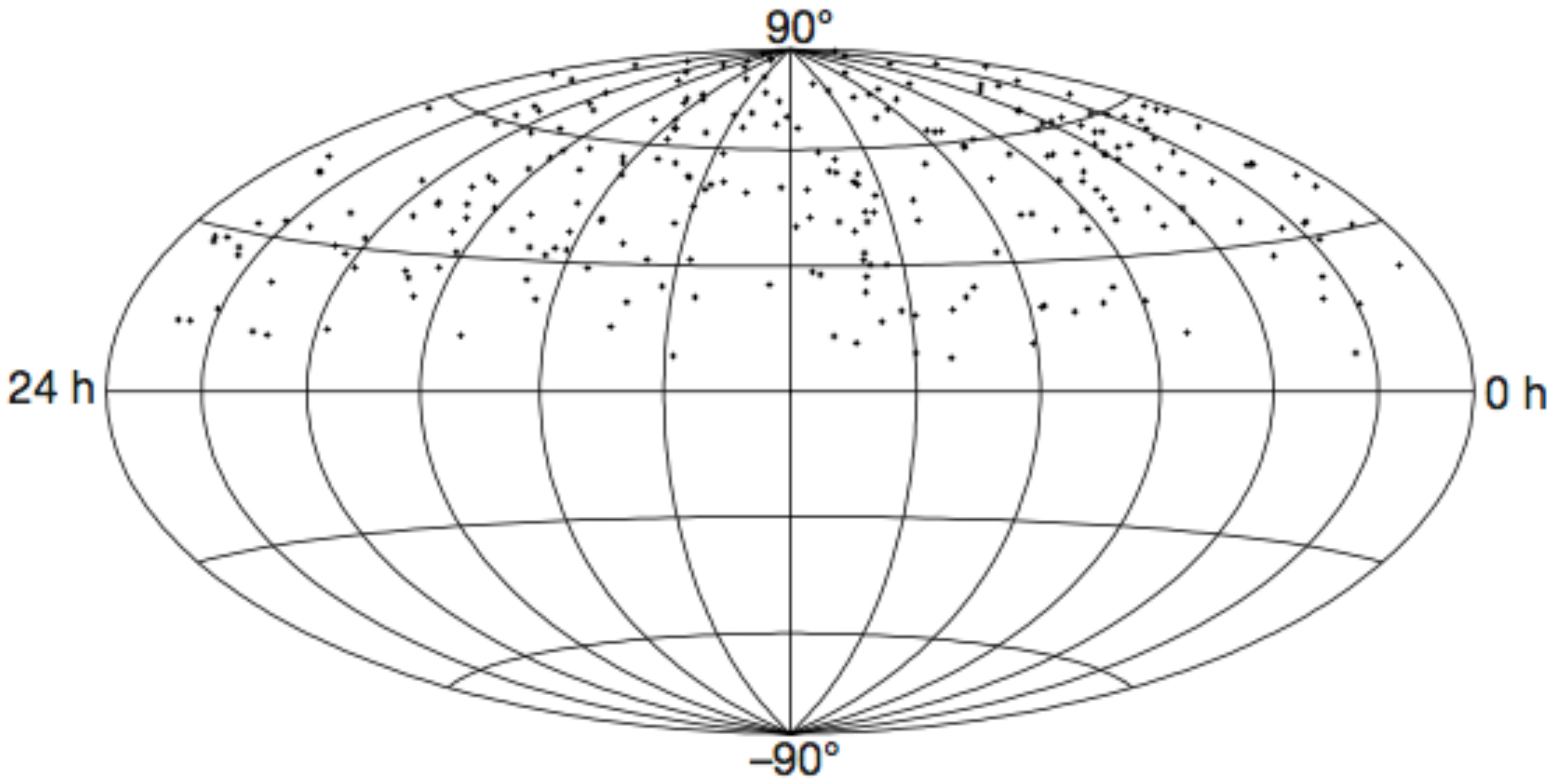
neutrino telescopes in Antarctica

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

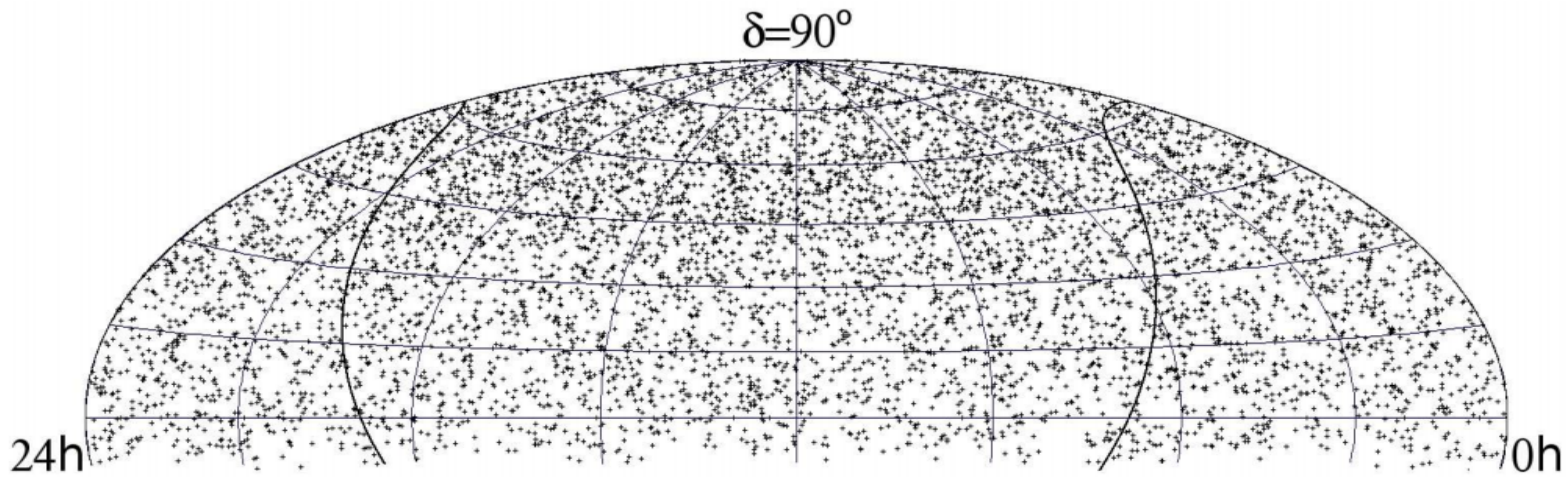
AMANDA → IceCube

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

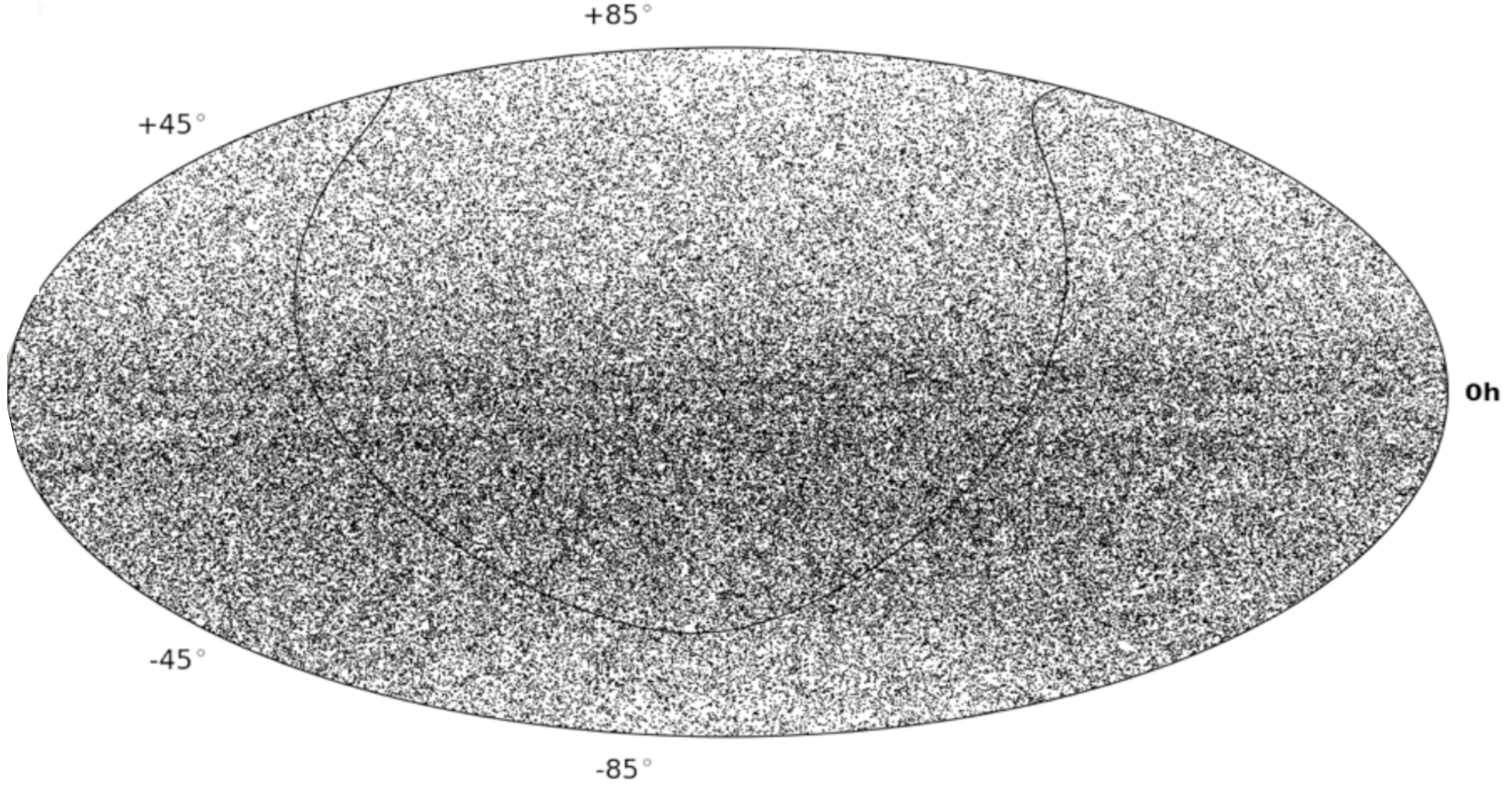
AMANDA → IceCube

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

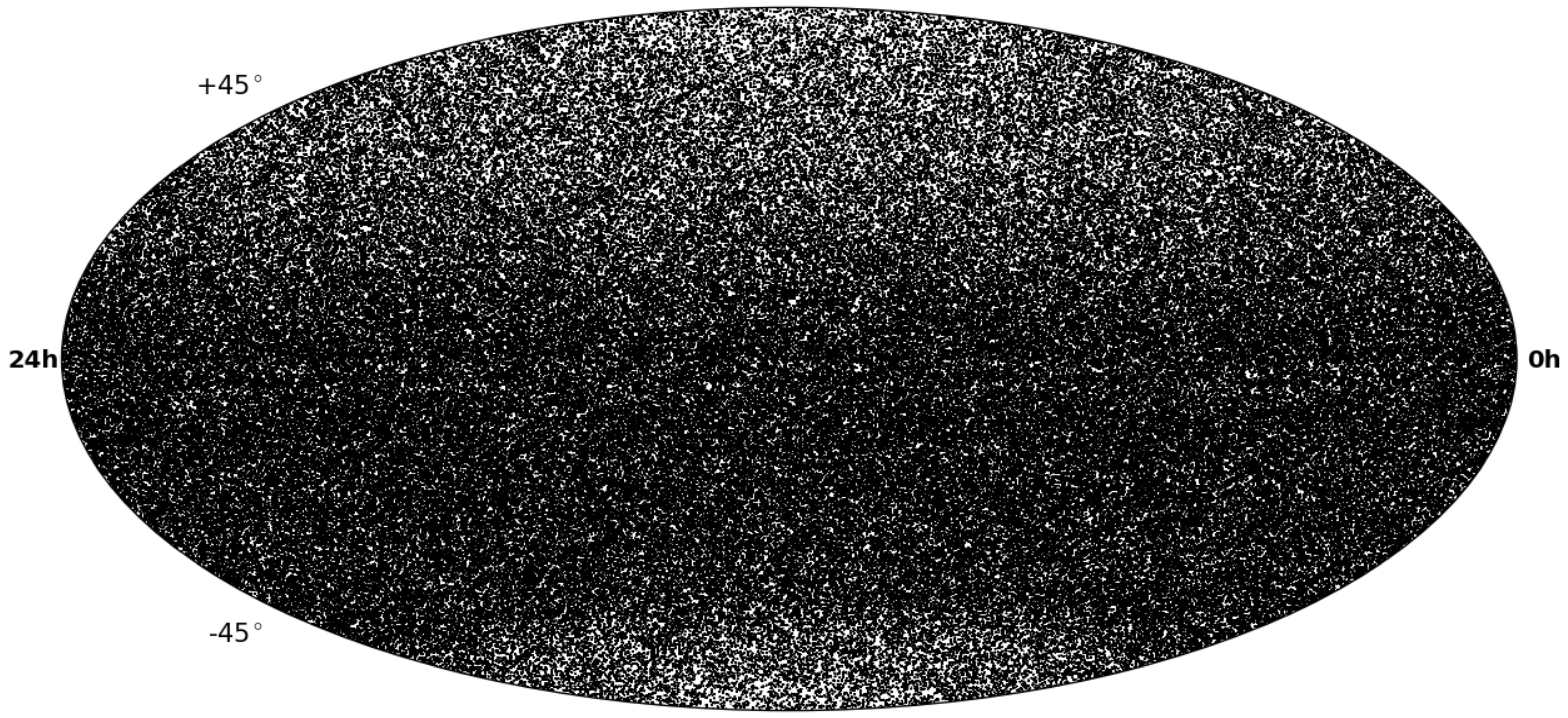
AMANDA **1999**

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

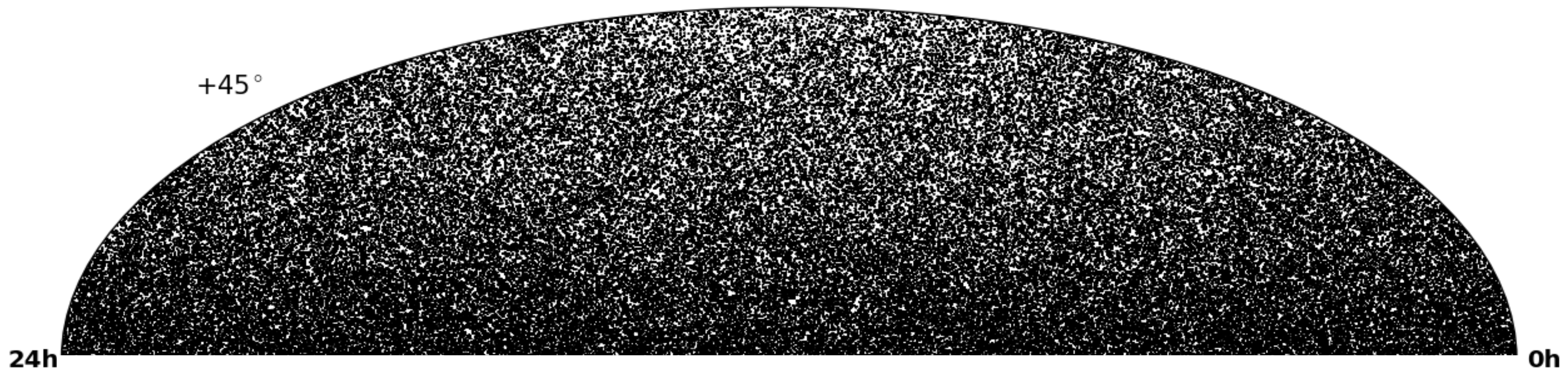
2001

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°**

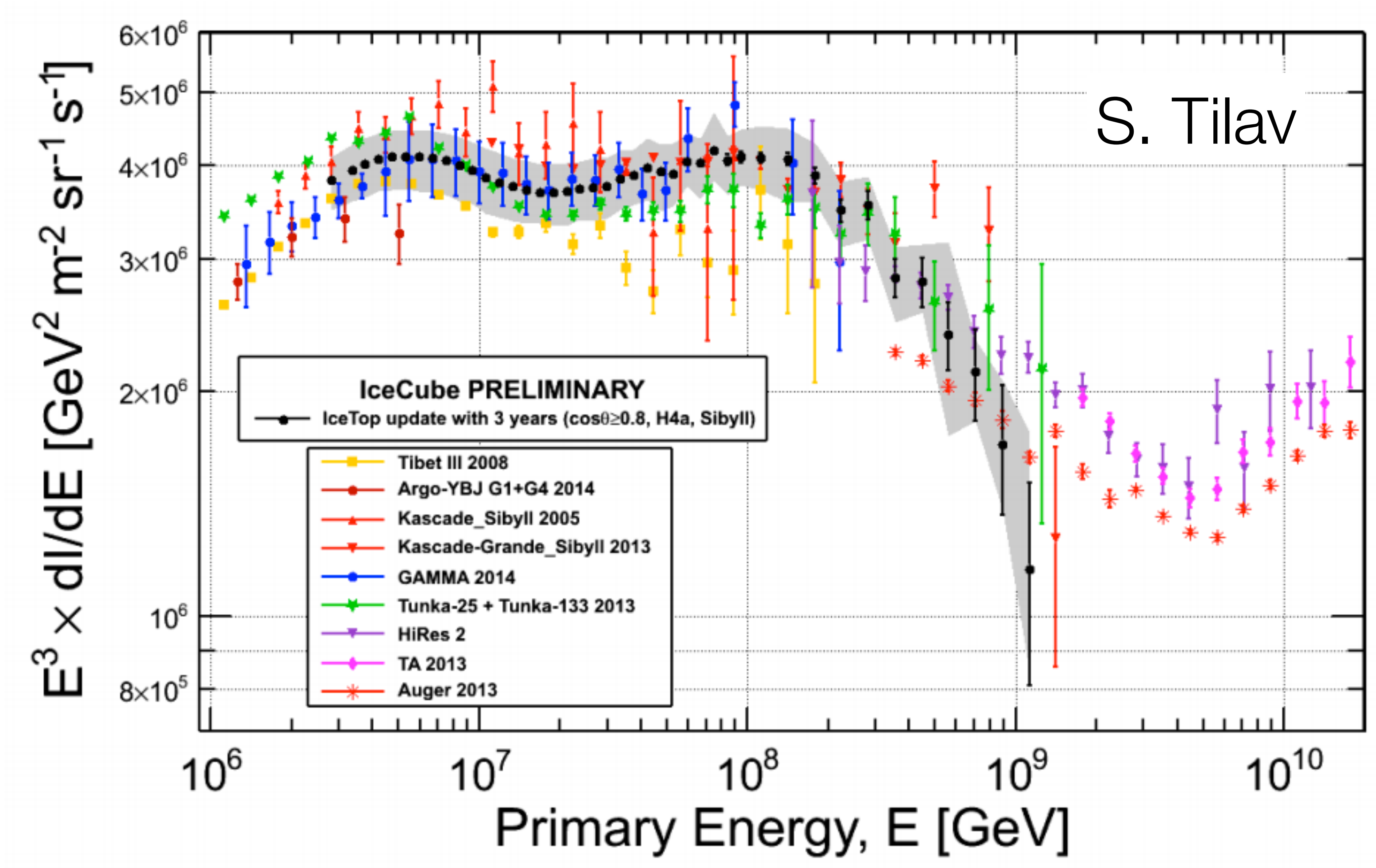
$\langle E_\nu \rangle$ ~ **1-5 TeV**

cosmic rays & atmospheric leptons

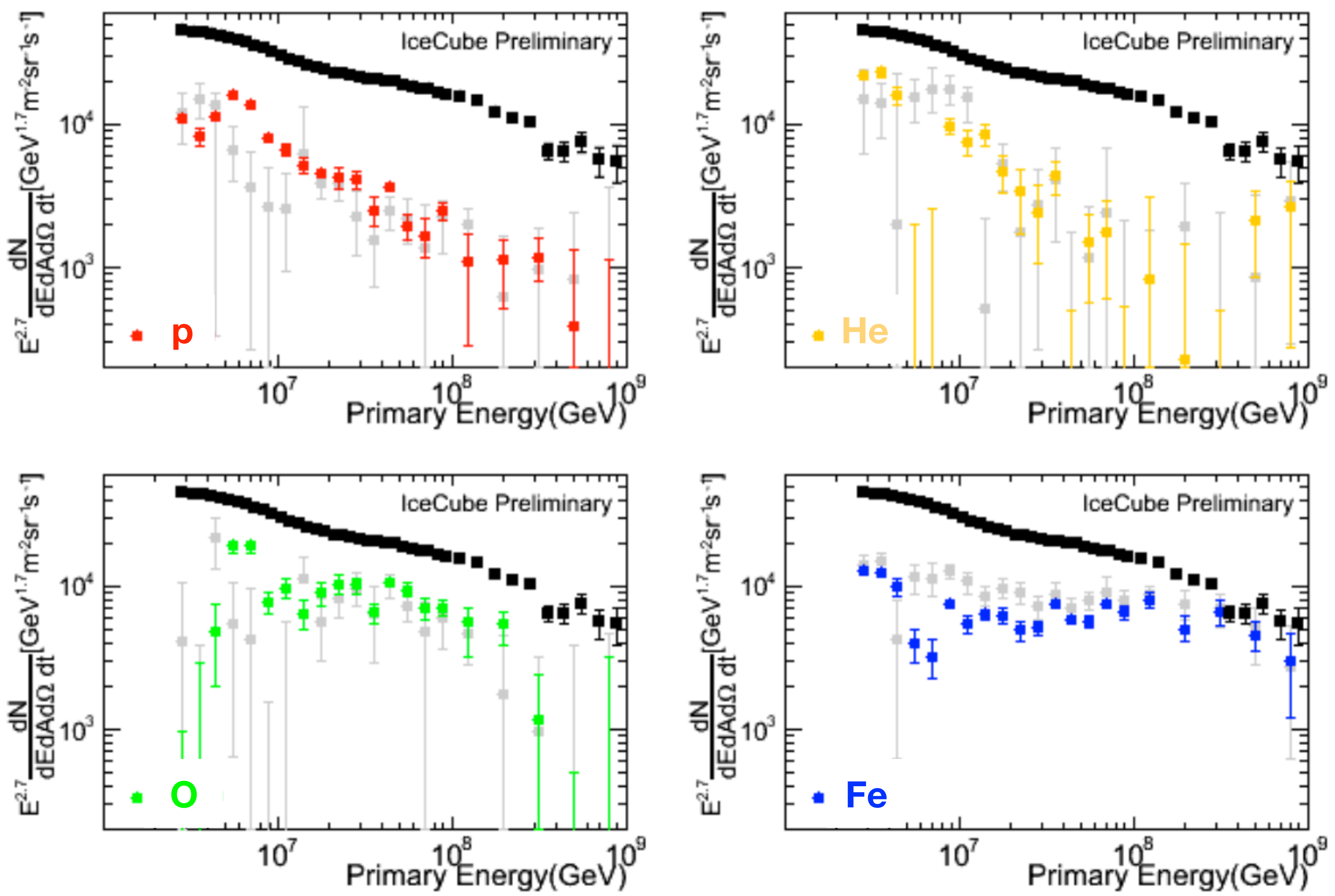
ICRC 2015
K. Rawlins
T. Feusels

IceTop

all-particle energy spectrum

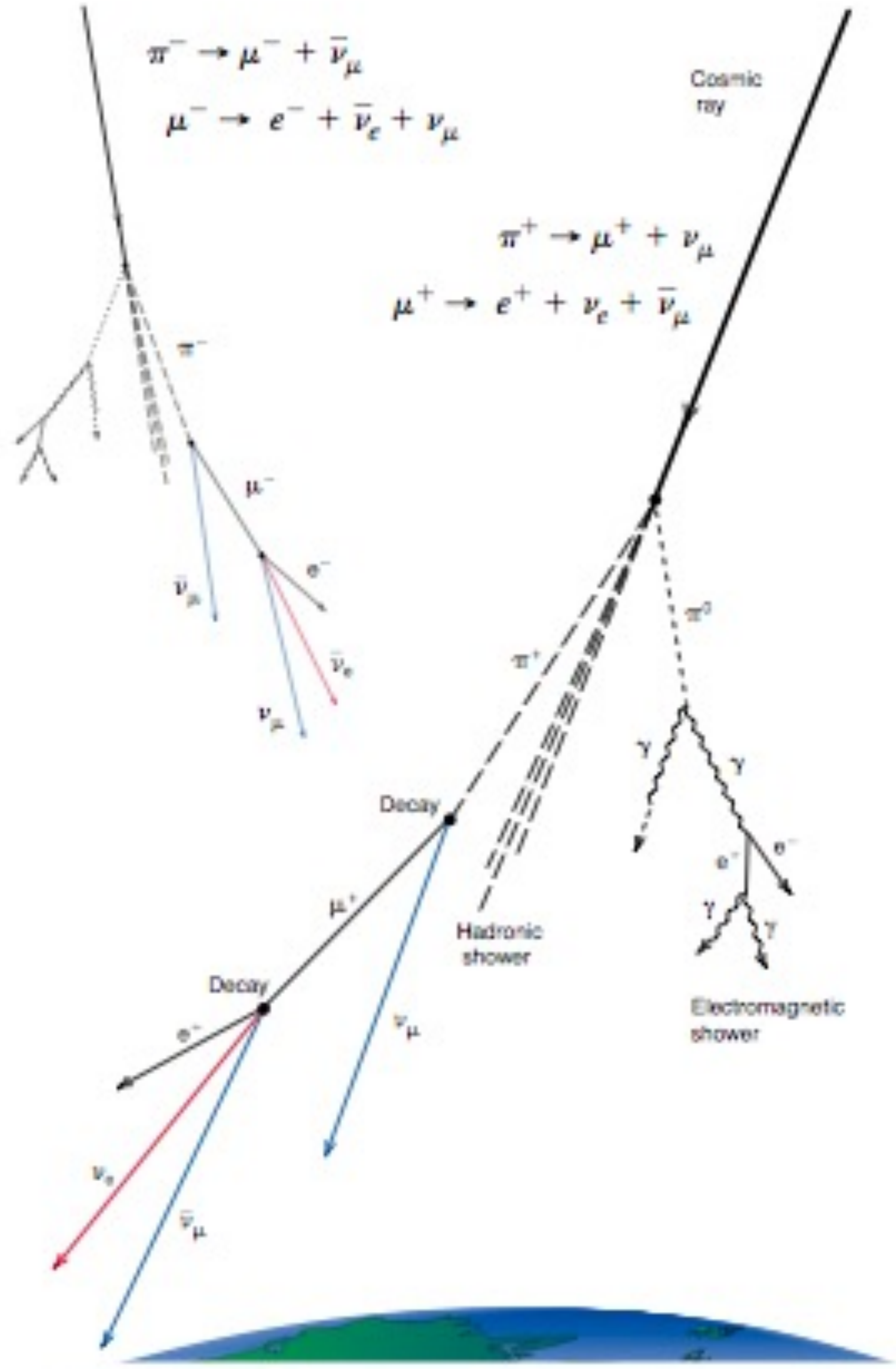


cosmic ray composition

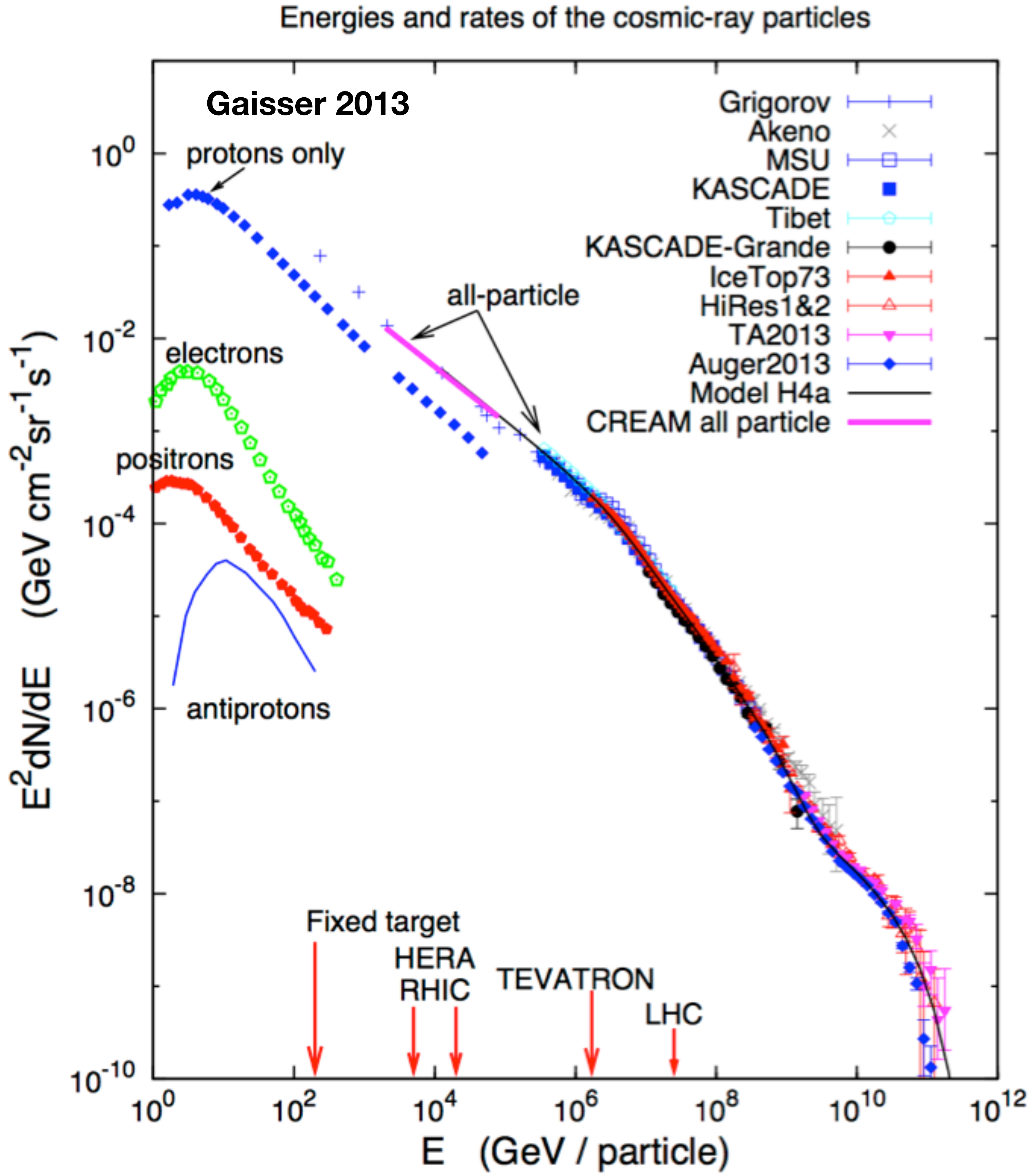


CR spectrum & composition determines **shape** of atmospheric ν and μ spectrum

cosmic rays & atmospheric leptons



$$N_{CR} + N_{air} \longrightarrow X + \pi + K + D + \Lambda + \ldots$$



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

cosmic rays & atmospheric leptons

		$(\nu_e : \nu_\mu : \nu_\tau)$
$\pi^\pm\ K^\pm \rightarrow\ \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$ (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 %)		$(1 : 1 : 1/10)$
$\eta, \eta' \rightarrow \mu^+\mu^-$		

cosmic rays & atmospheric leptons

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

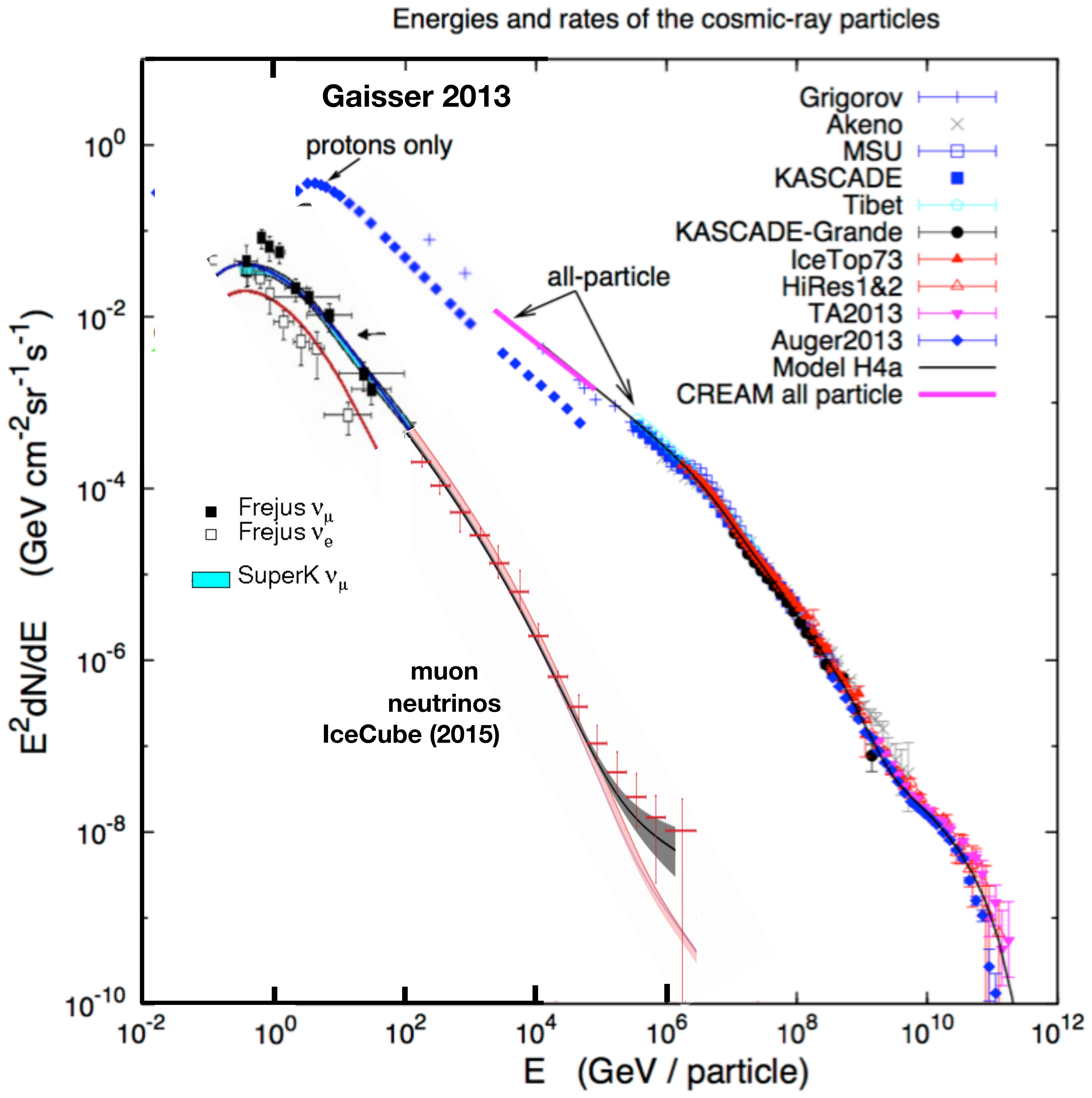
Gaisser 1990

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

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

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

$Particle\,(i)$	$\pi^\pm$	$K^\pm$	K_L^0	K_S^0	$charm$
$\epsilon_i\,(GeV)$	115	850	205	1.2×10^5	$\sim 3\times10^7$

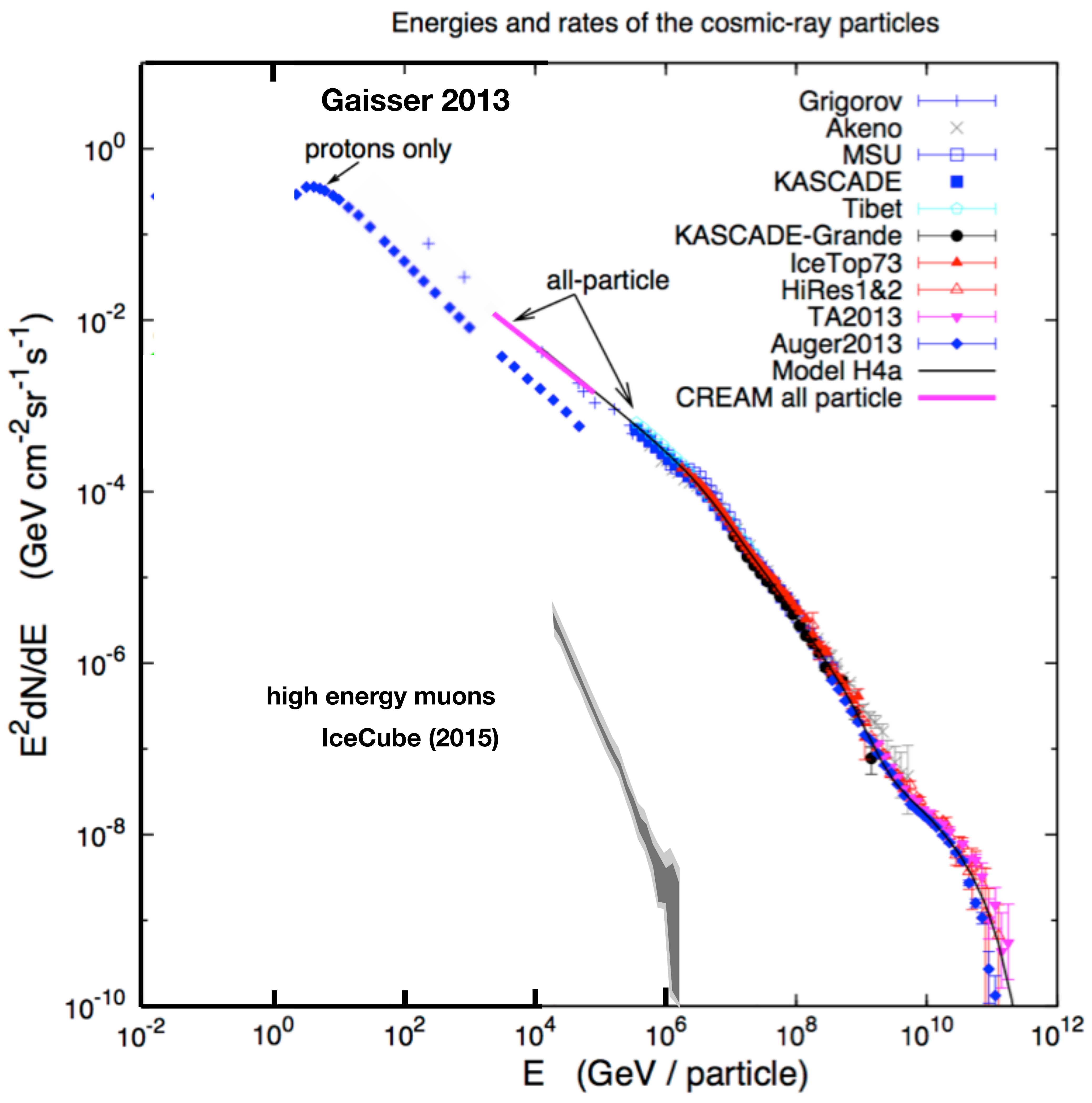


cosmic rays & atmospheric leptons

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

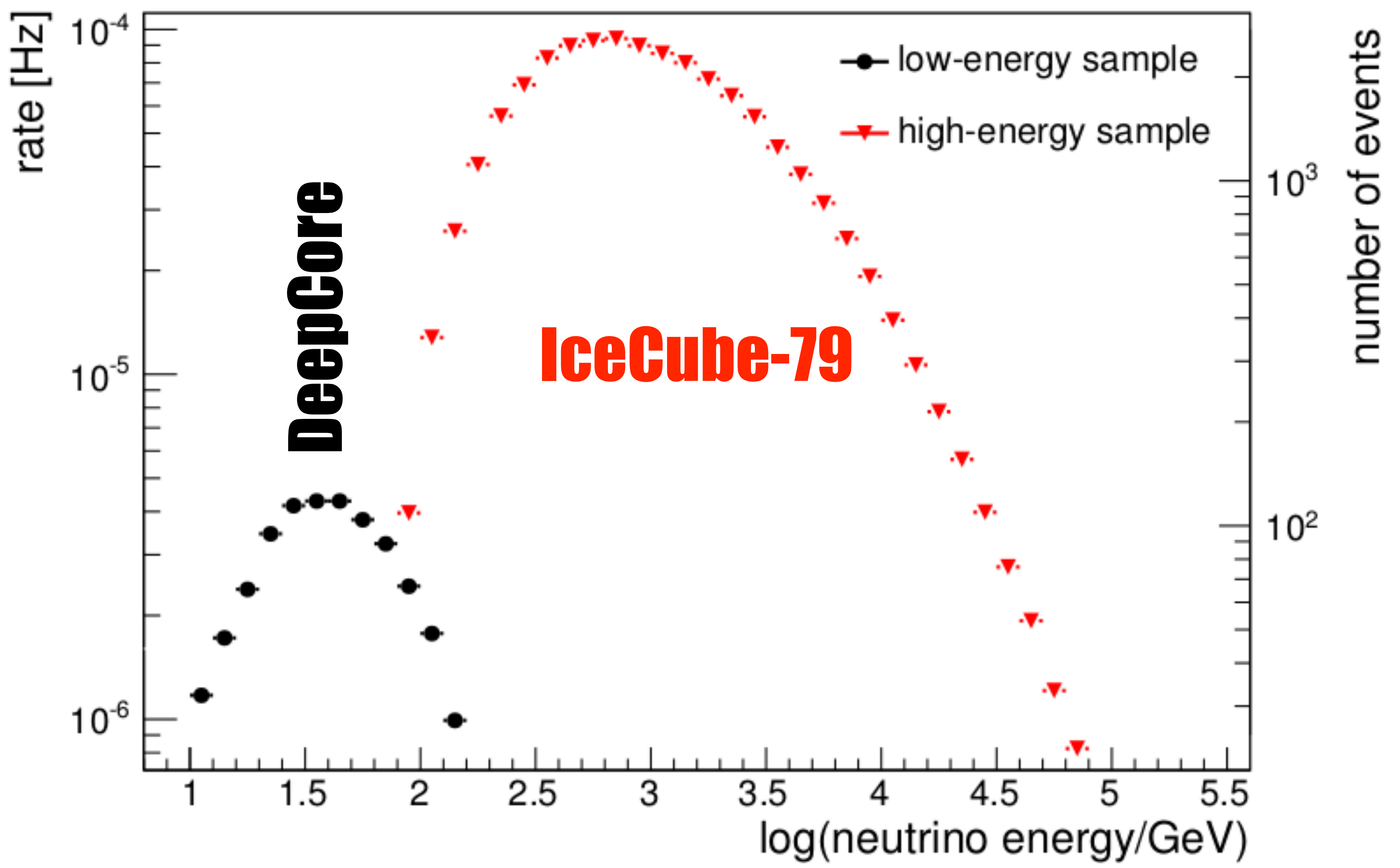
Gaisser 1990

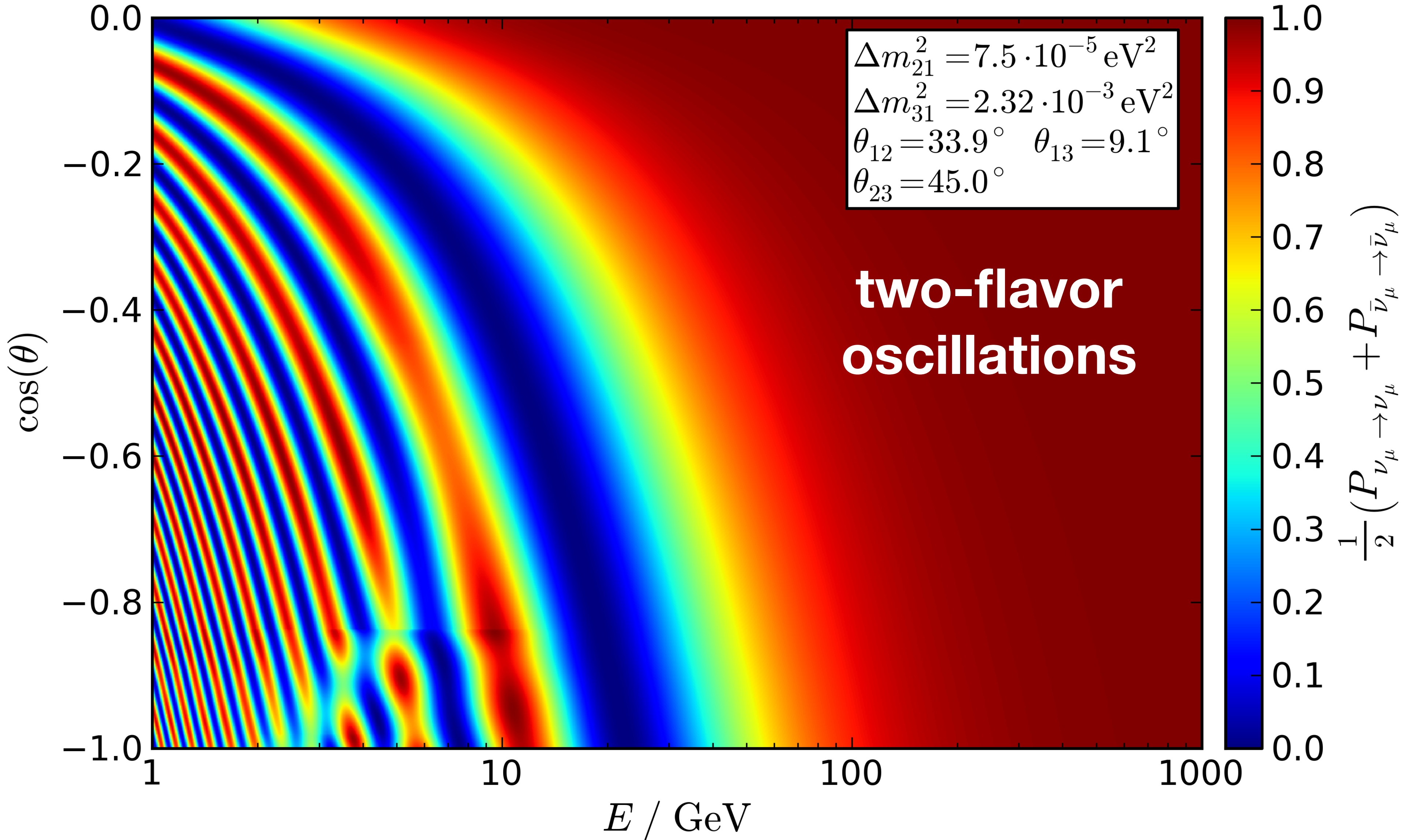
- **ν**’s and **μ**’s from same hadronic processes in cosmic ray atmospheric showers
- high level **cross-calibration** sensitive to hadronic interaction models



low energy neutrinos

10 GeV - 300 GeV



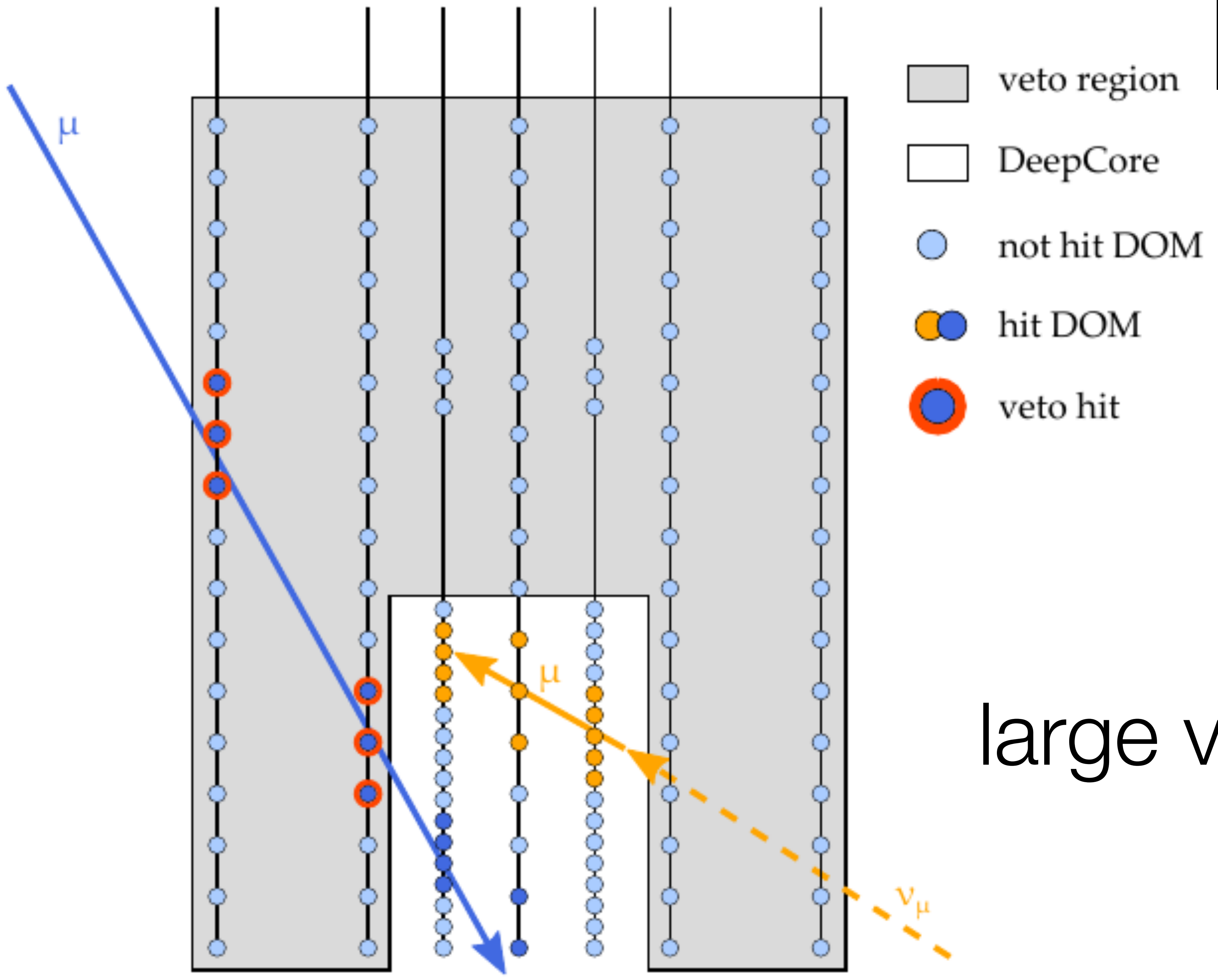


Phys. Rev. Lett. 111, 081801 **2013**

719 low energy events

39638 high energy events

in 318.9 days

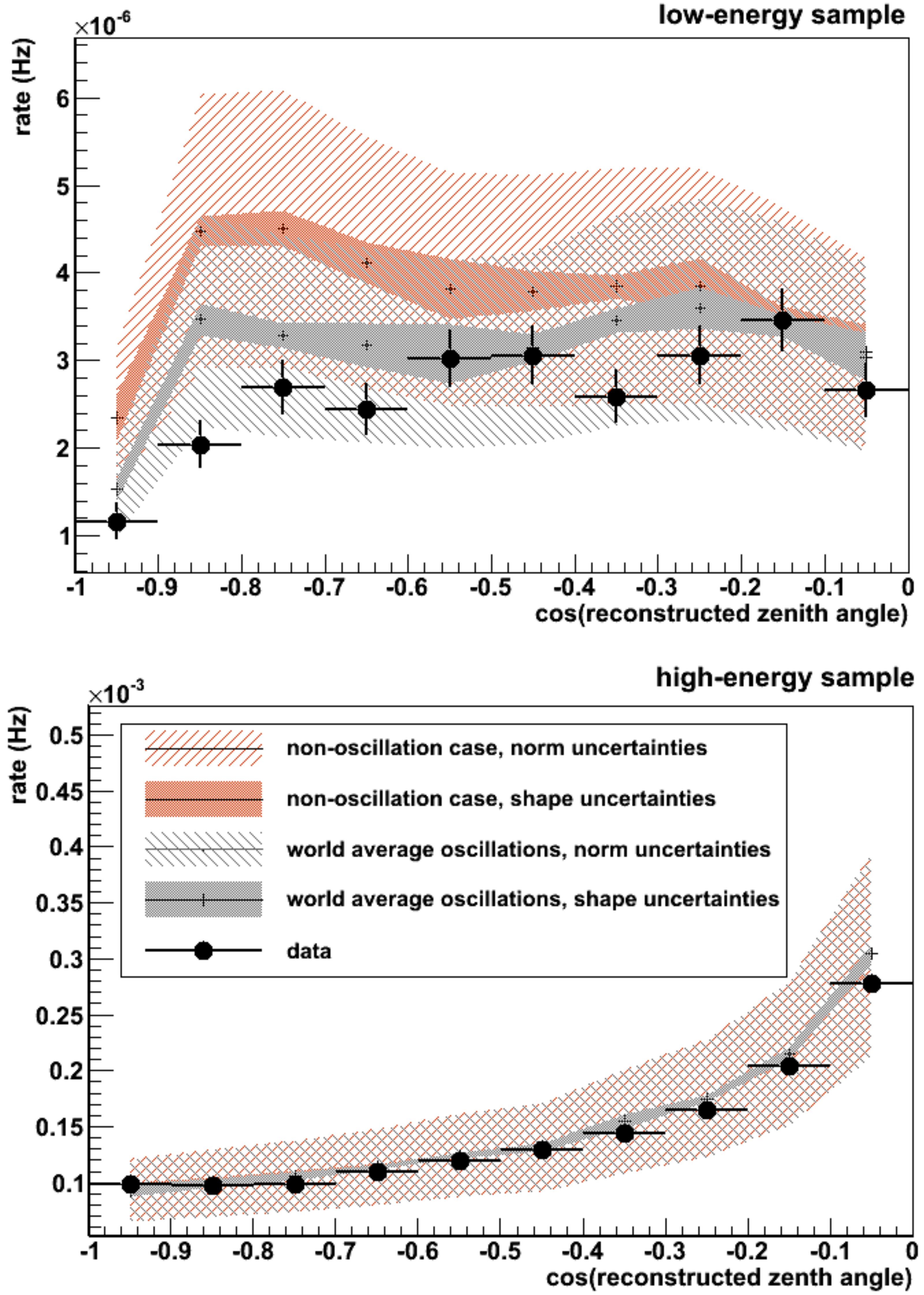


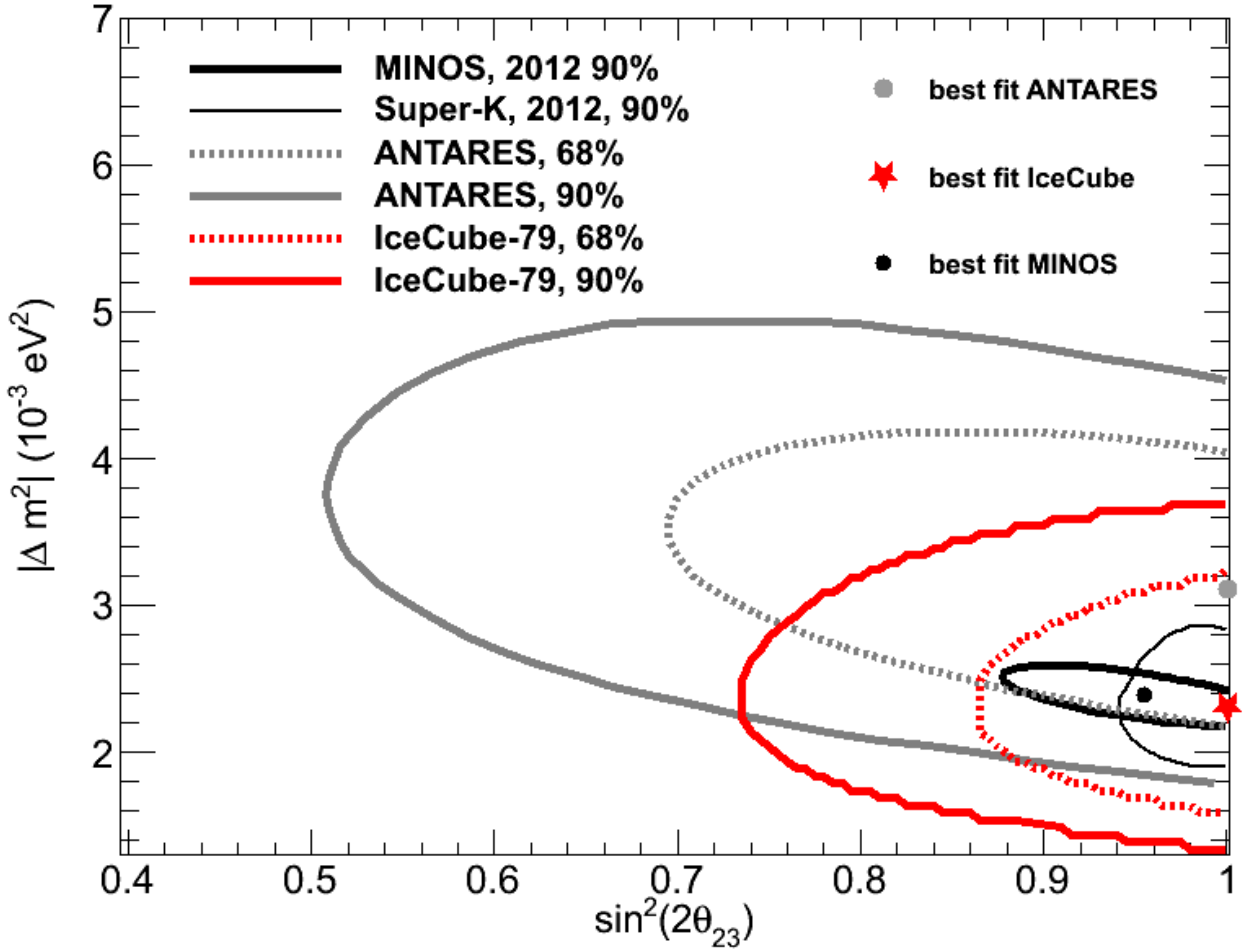
large volume → VETO

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

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

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

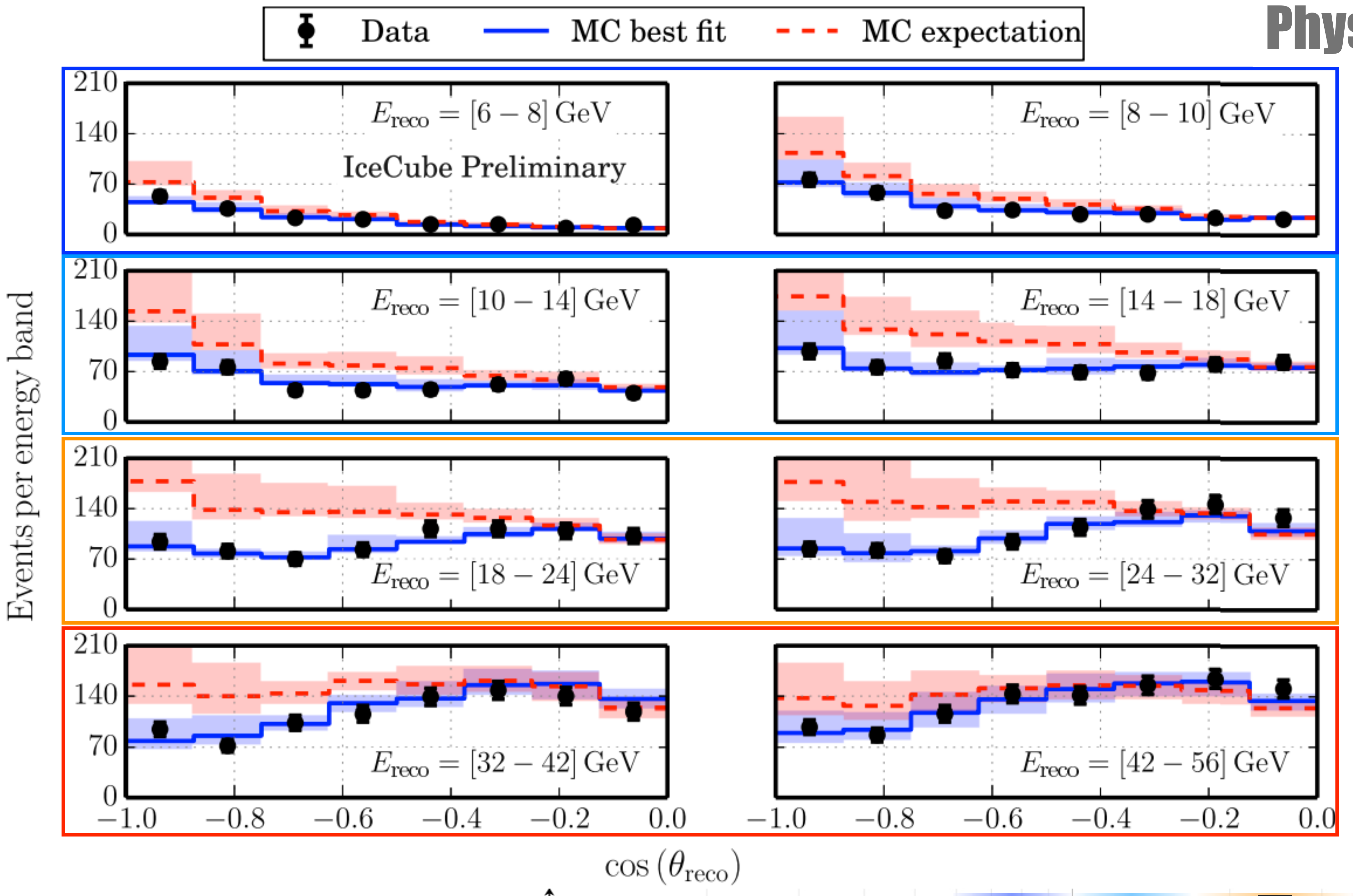
$$\chi^2 = 15.7/18$$

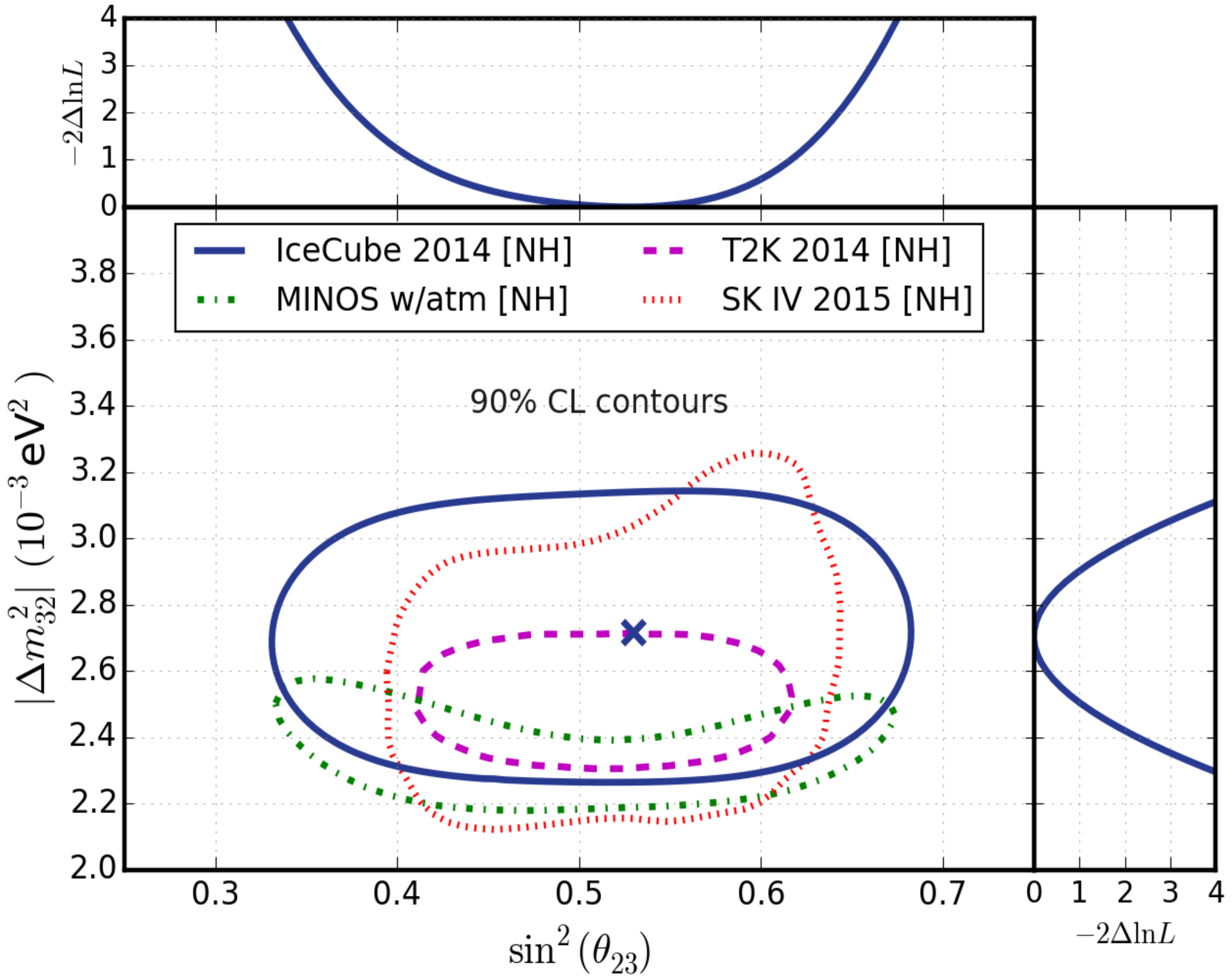
low energy neutrinos

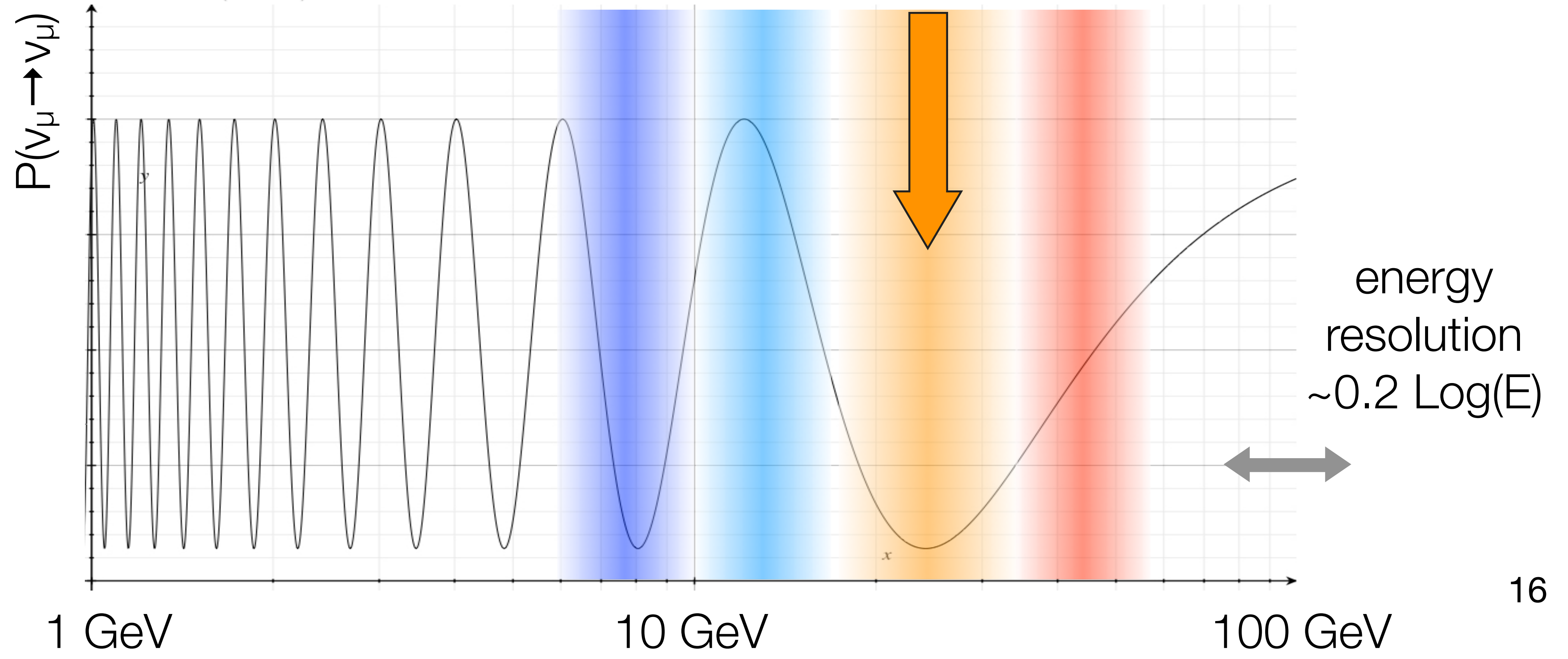
IceCube - 3 years

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

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





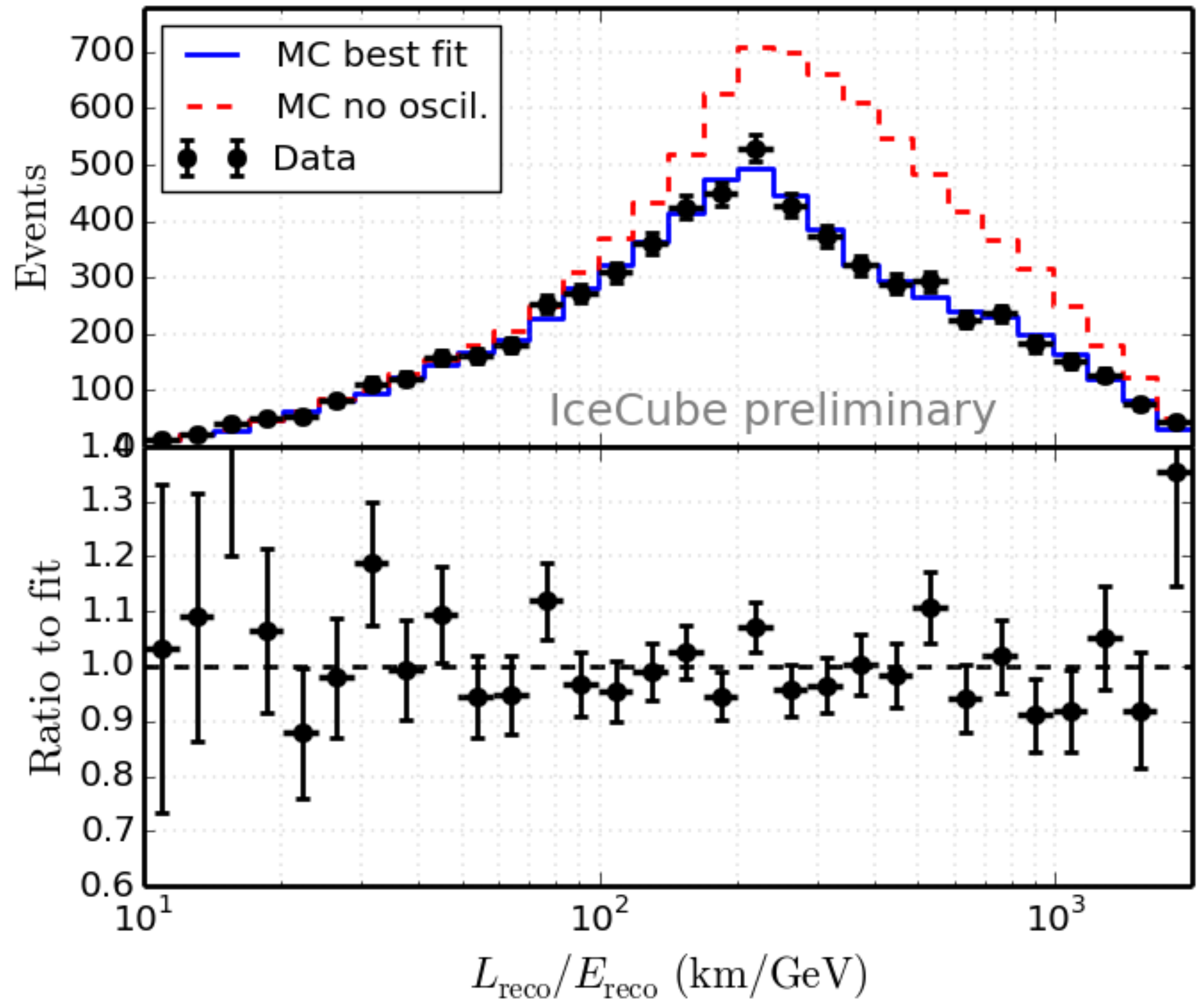


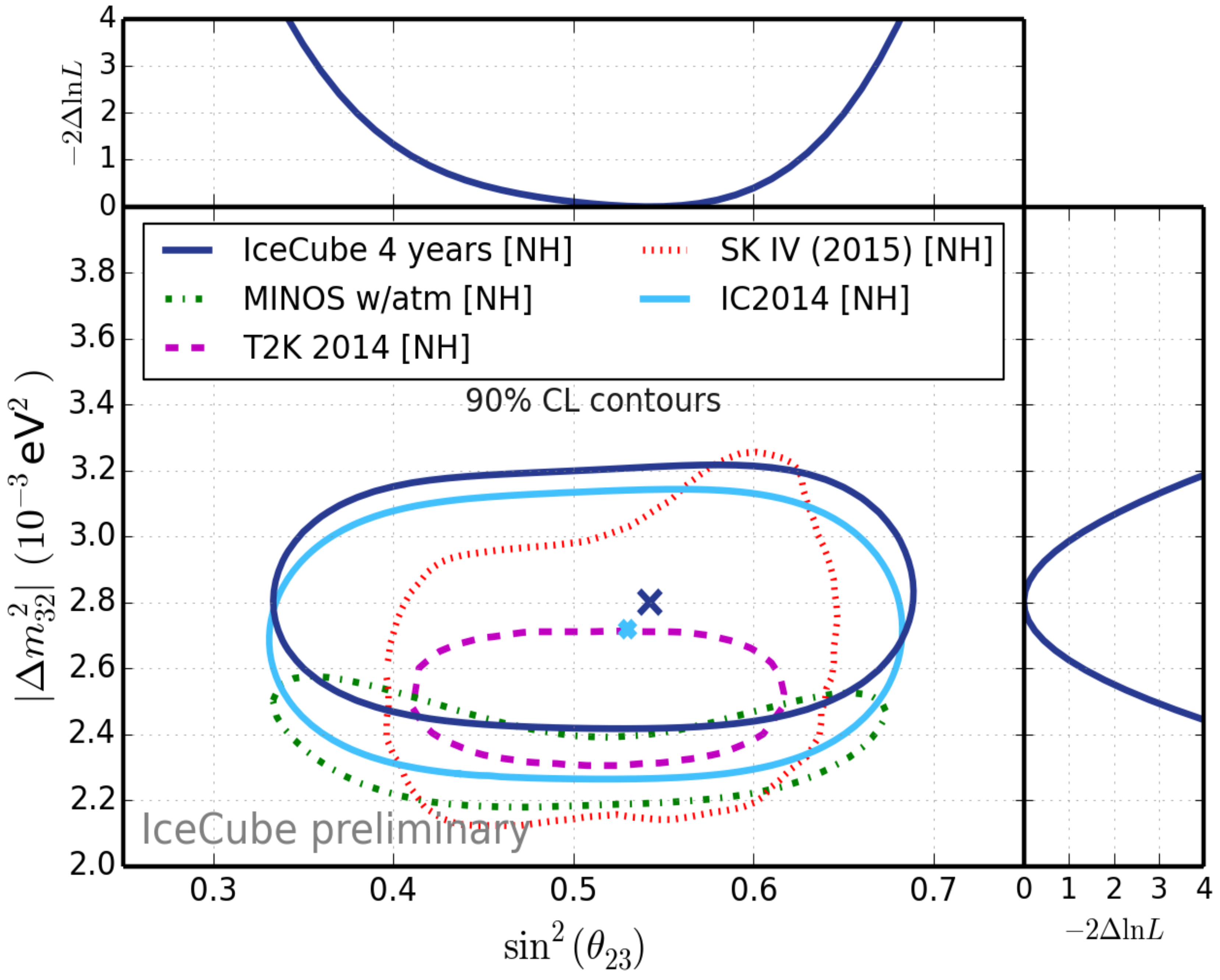
low energy neutrinos

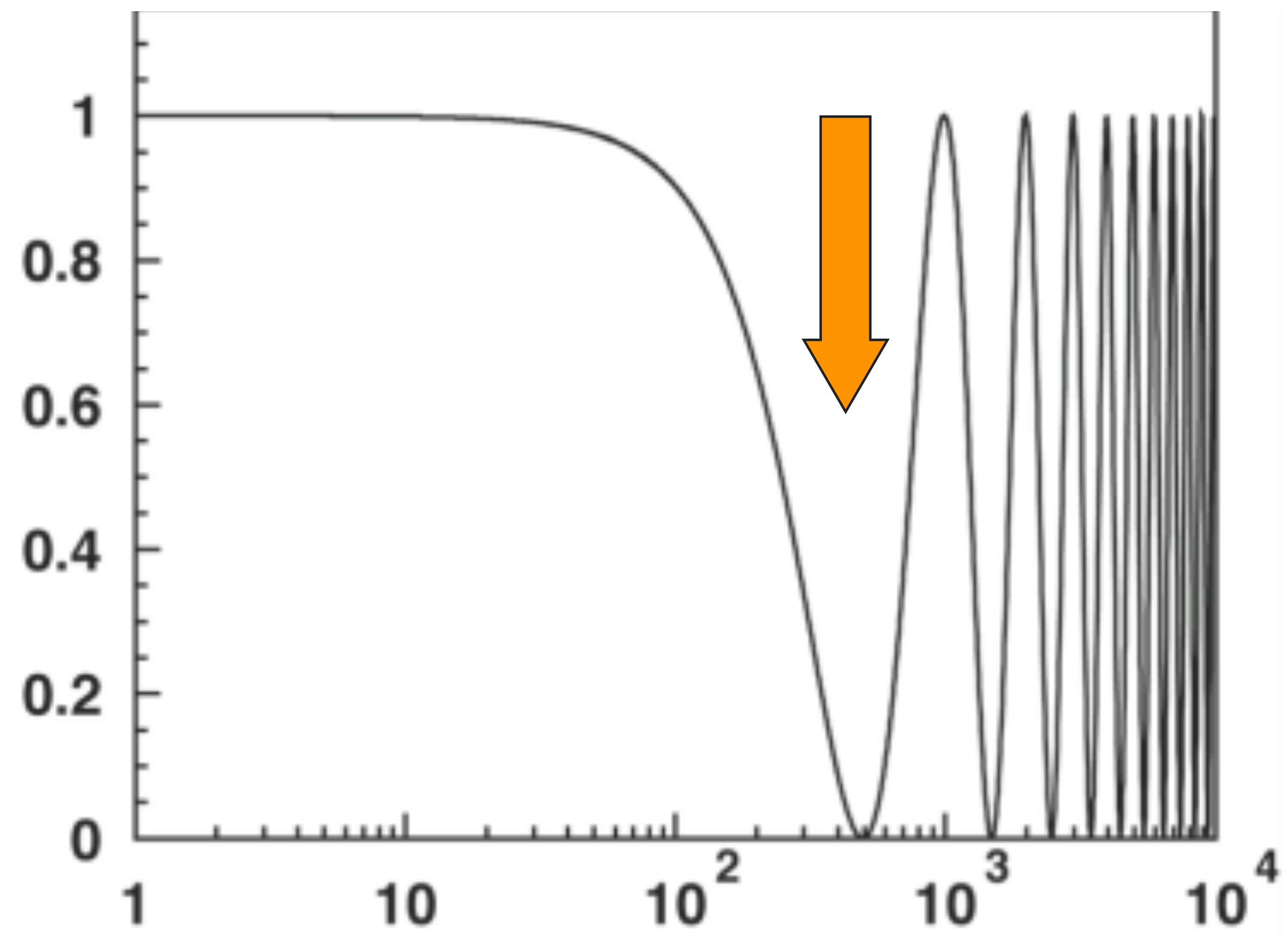
IceCube - 4 years

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

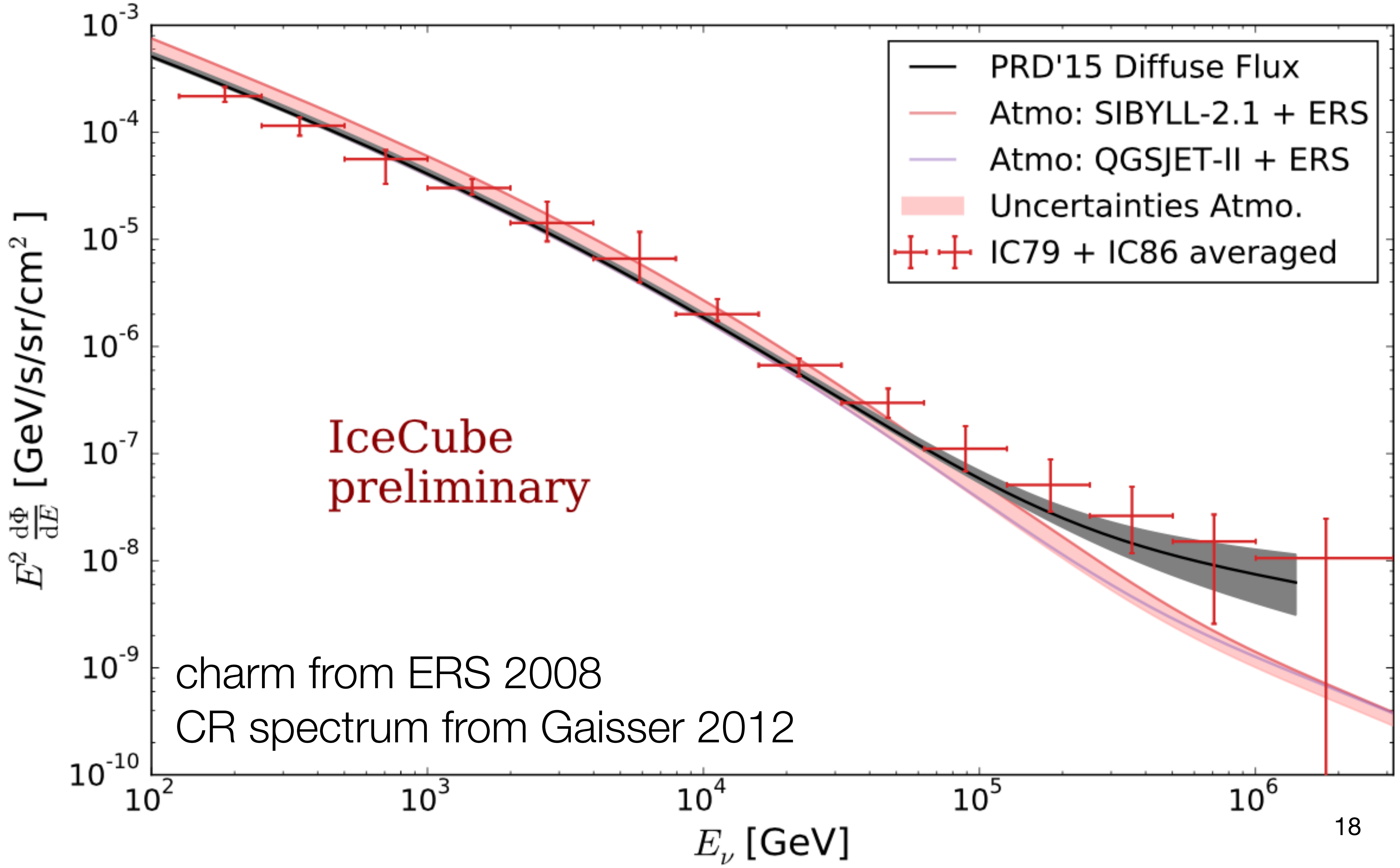
M. Börner

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

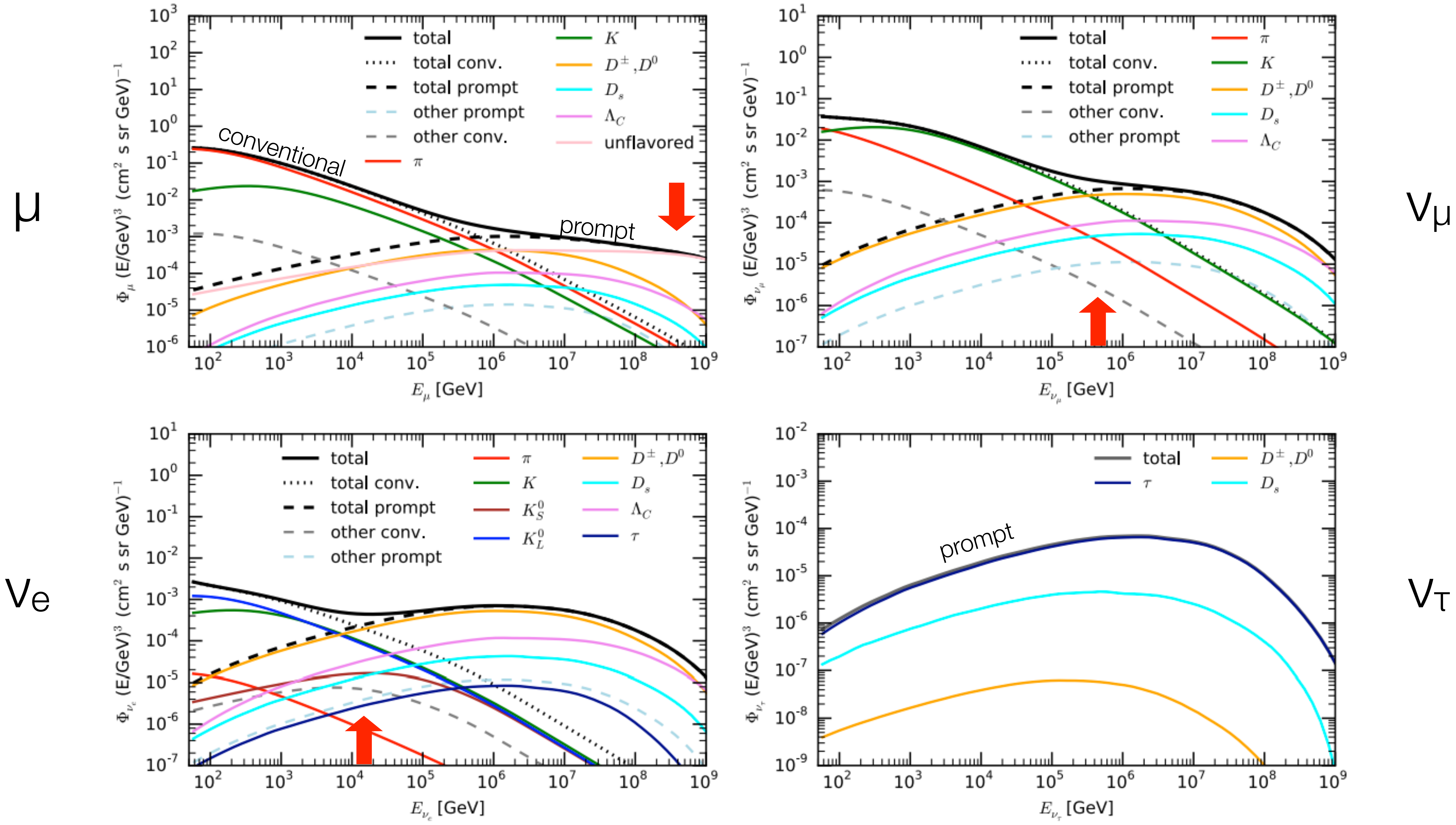


hadronic interaction models

heavy quarks in the atmosphere

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

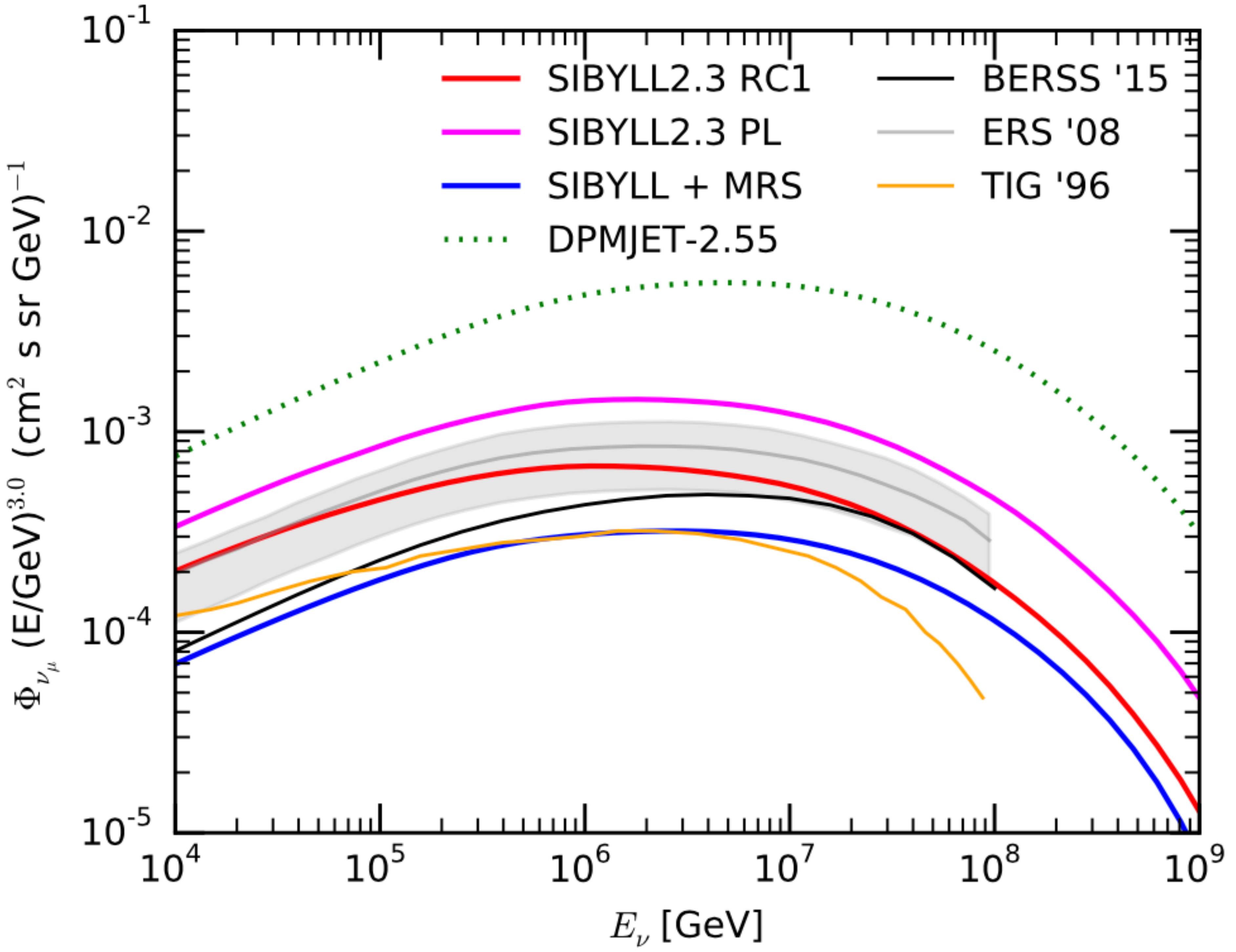
Sibyll 2.3 - Fedynitch+ ISVHECRI 2014



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).*

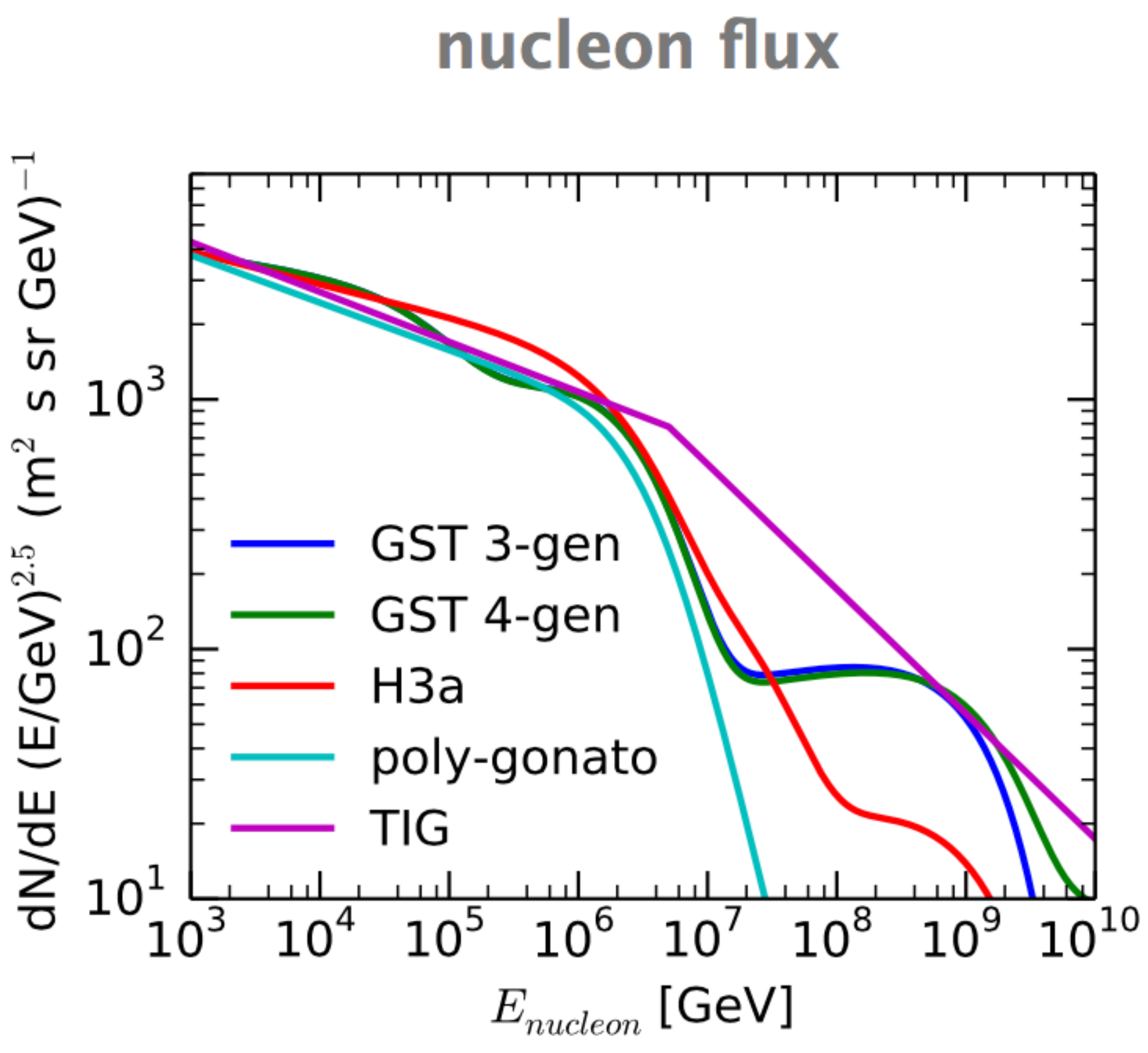
SIBYLL: arXiv:1503.00544 and arXiv:1502.06353

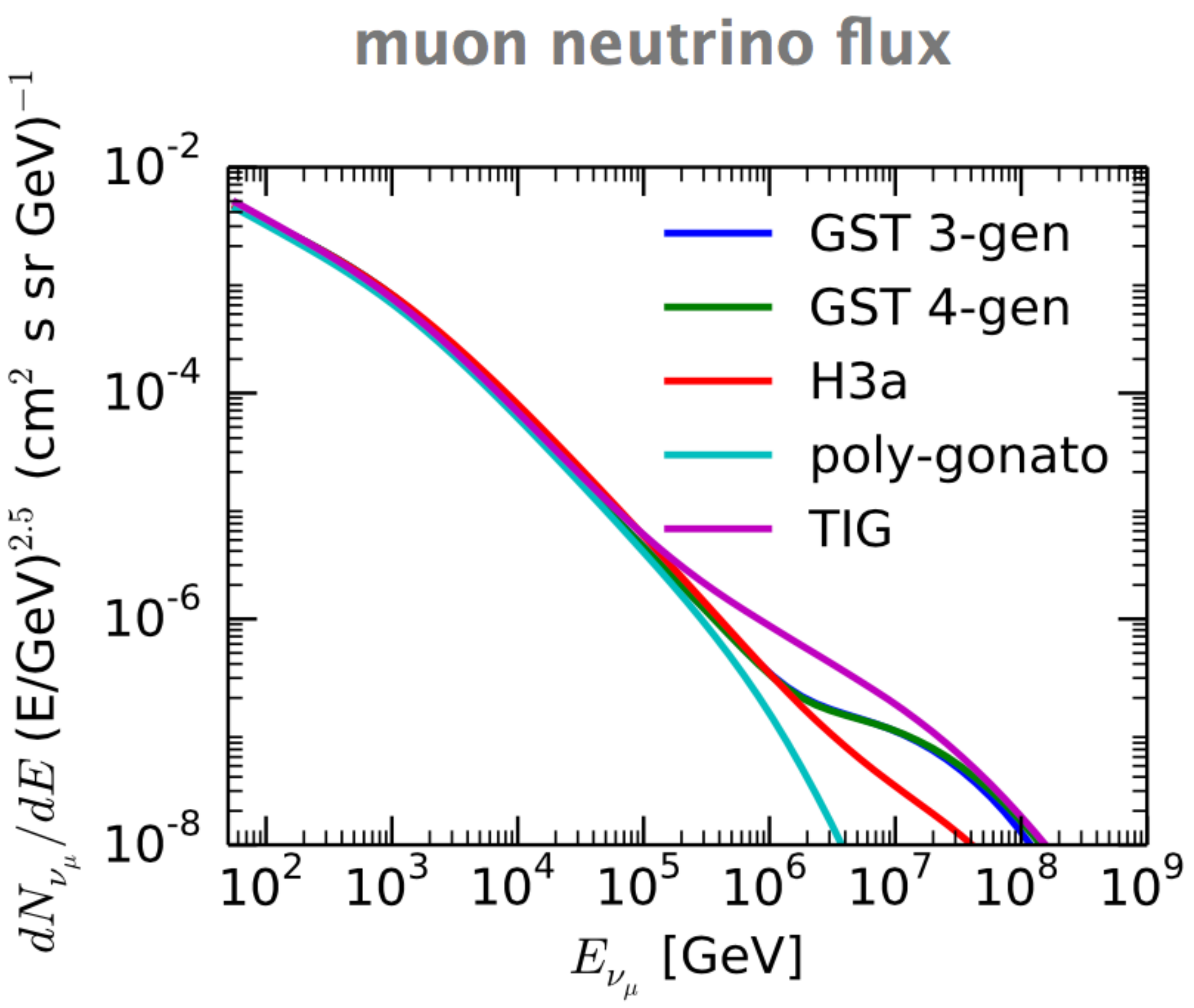
TIG: M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

hadronic interaction models

heavy quarks in the atmosphere

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)

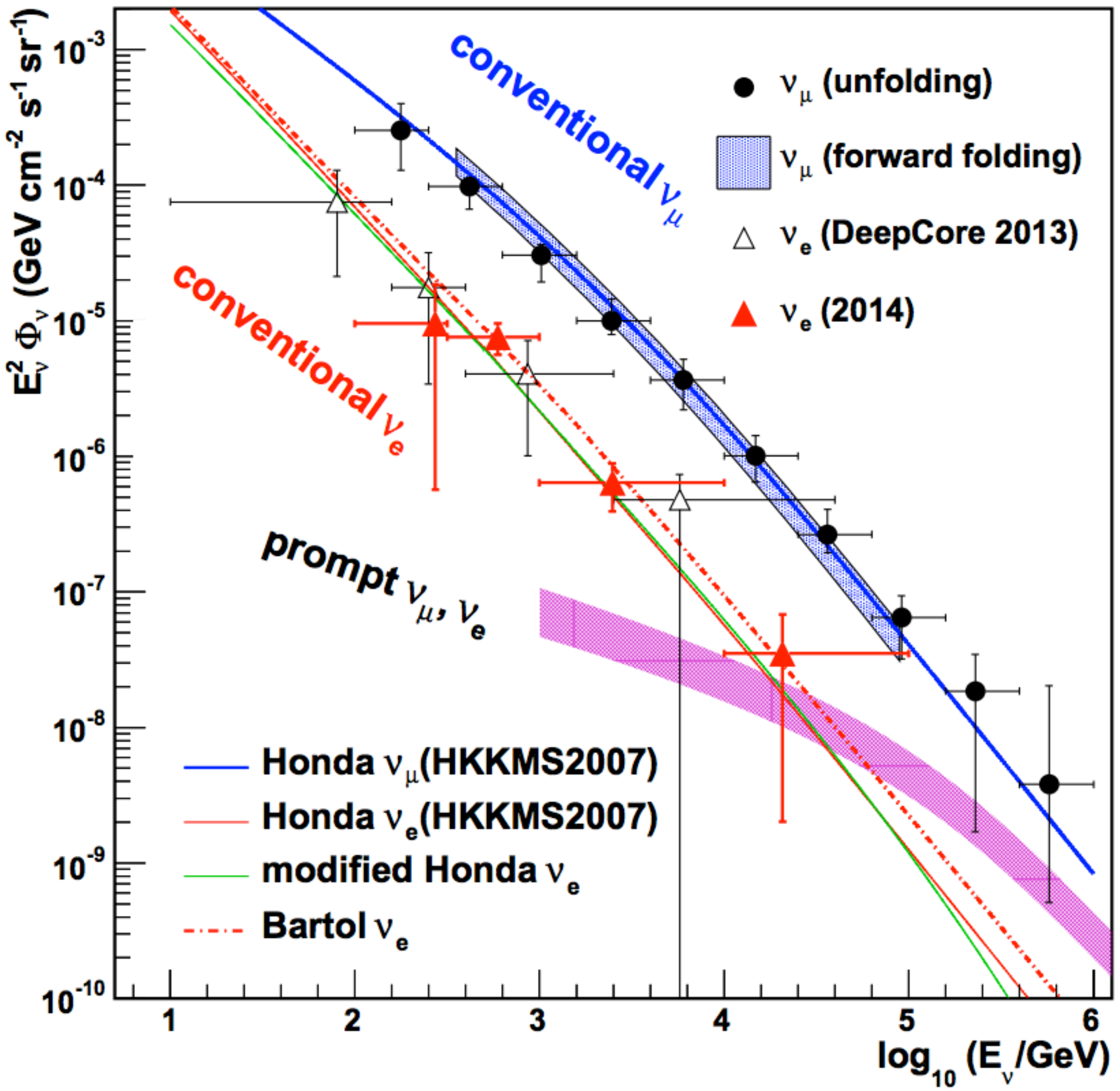
high energy neutrinos

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

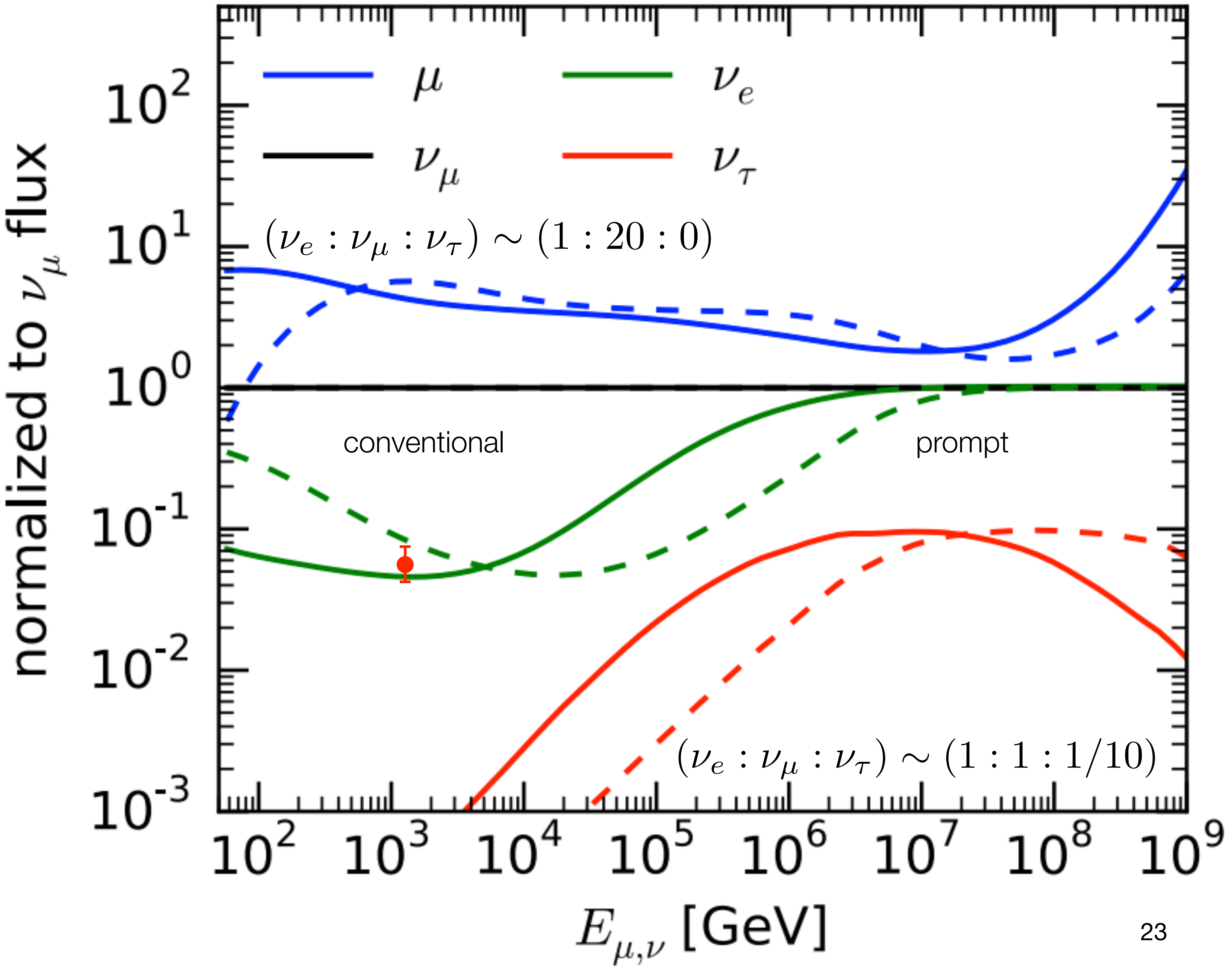
IceCube-86 **Phys. Rev. D91 12, 122004** **2015**

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

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

- 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

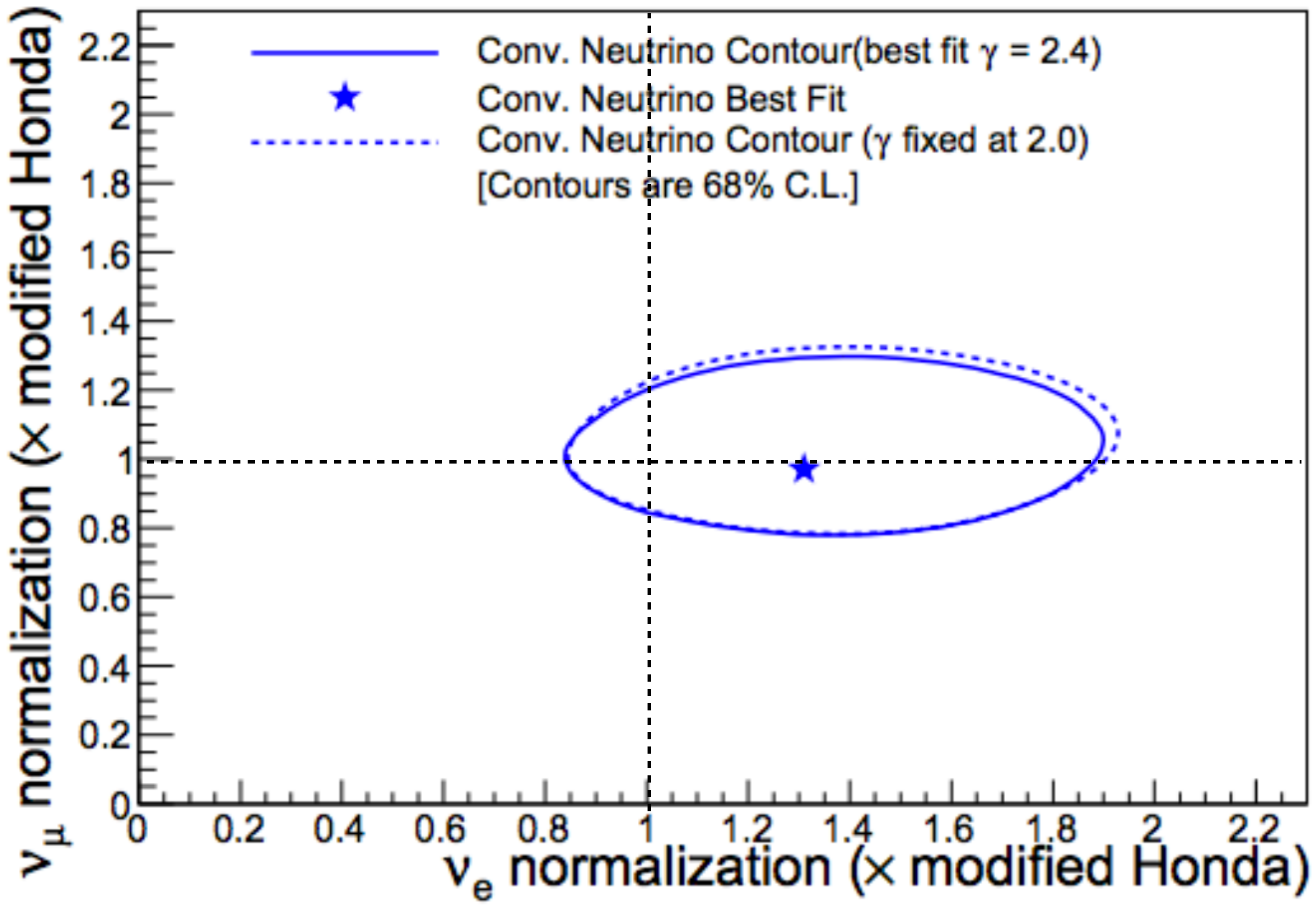
Fedynitch et al. arXiv:1503.00544
Sibyll 2.3RC1
H3a CR composition

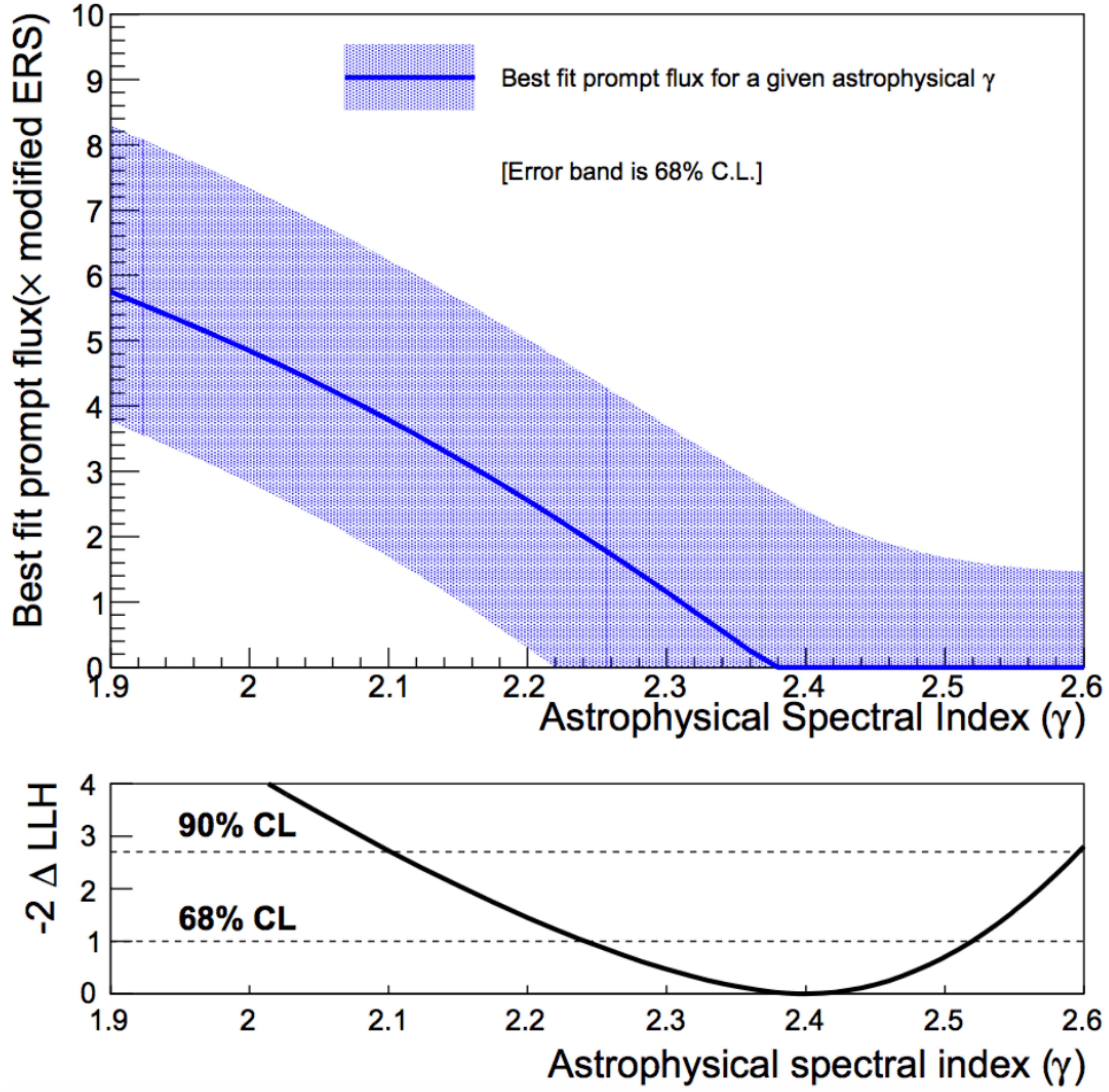


high energy neutrinos

charm and astrophysics

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





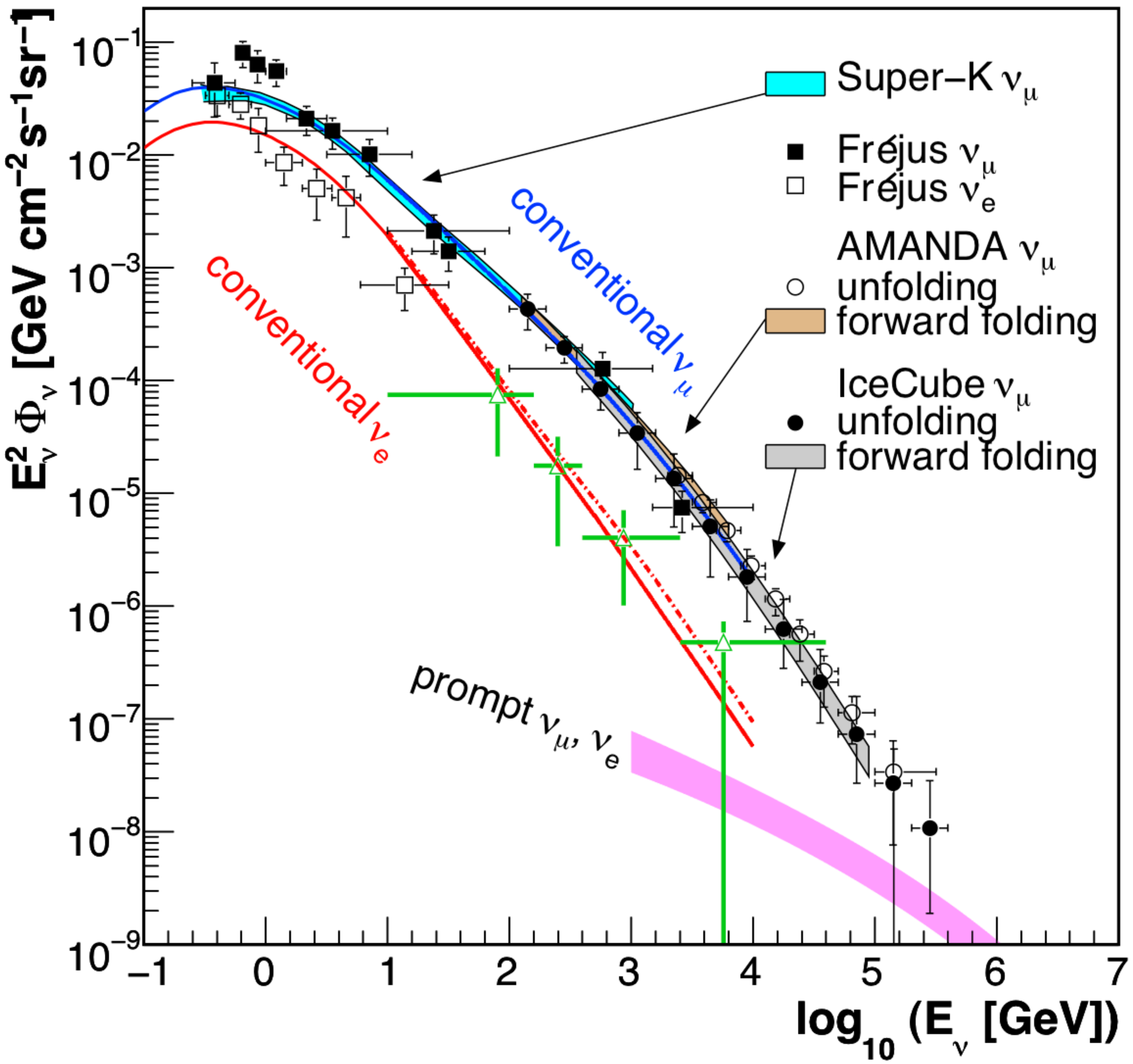
- determination of **conventional** flux independent of high energy contribution
- determination of **charm** flux **influenced** on astrophysical hypothesis (review talk by C. Kopper)

charm from ERS 2008
CR spectrum from Gaisser 2012

high energy neutrinos
constrains from low energy

ICRC 2015
T. Kuwabara
Poster 2

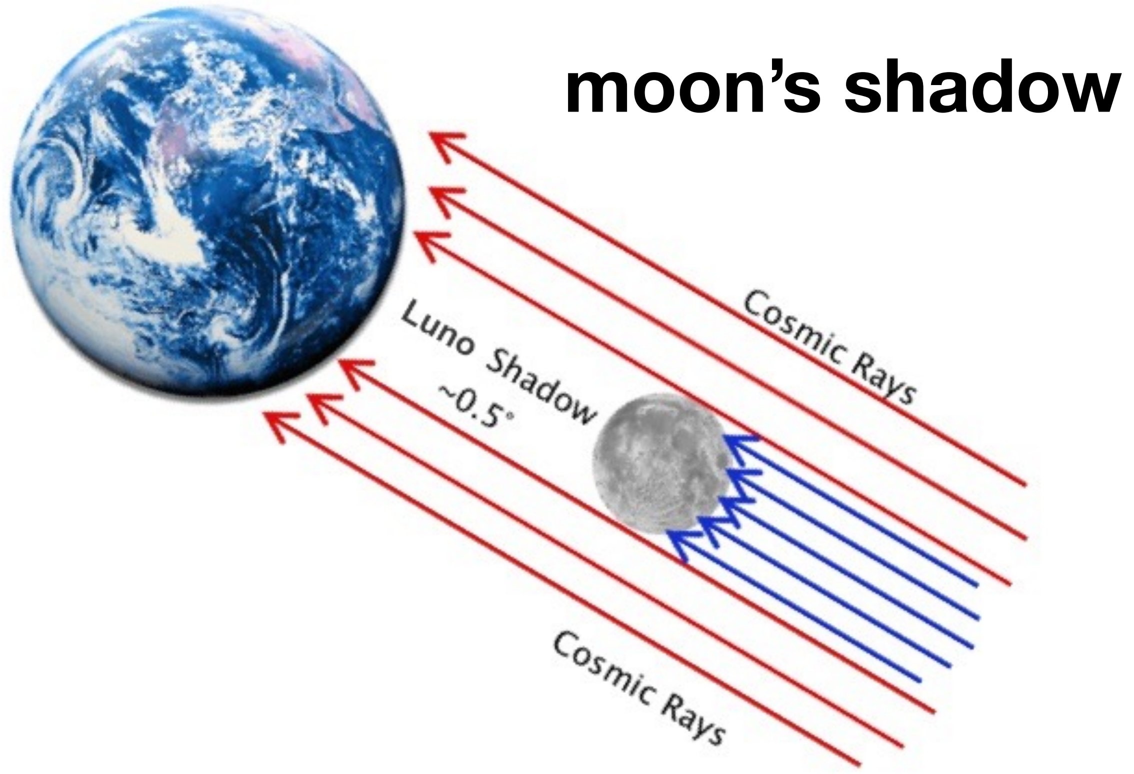
- <100 TeV CR **directly measured**
- <100 GeV ν's from **pions**
- <10 GeV ν's **geomagnetic** effects
- ν **oscillations** constrained
- **low energy** ν's with SuperK
- **mid-high energy** ν's with IC / DC
- **6 orders of magnitude** in energy



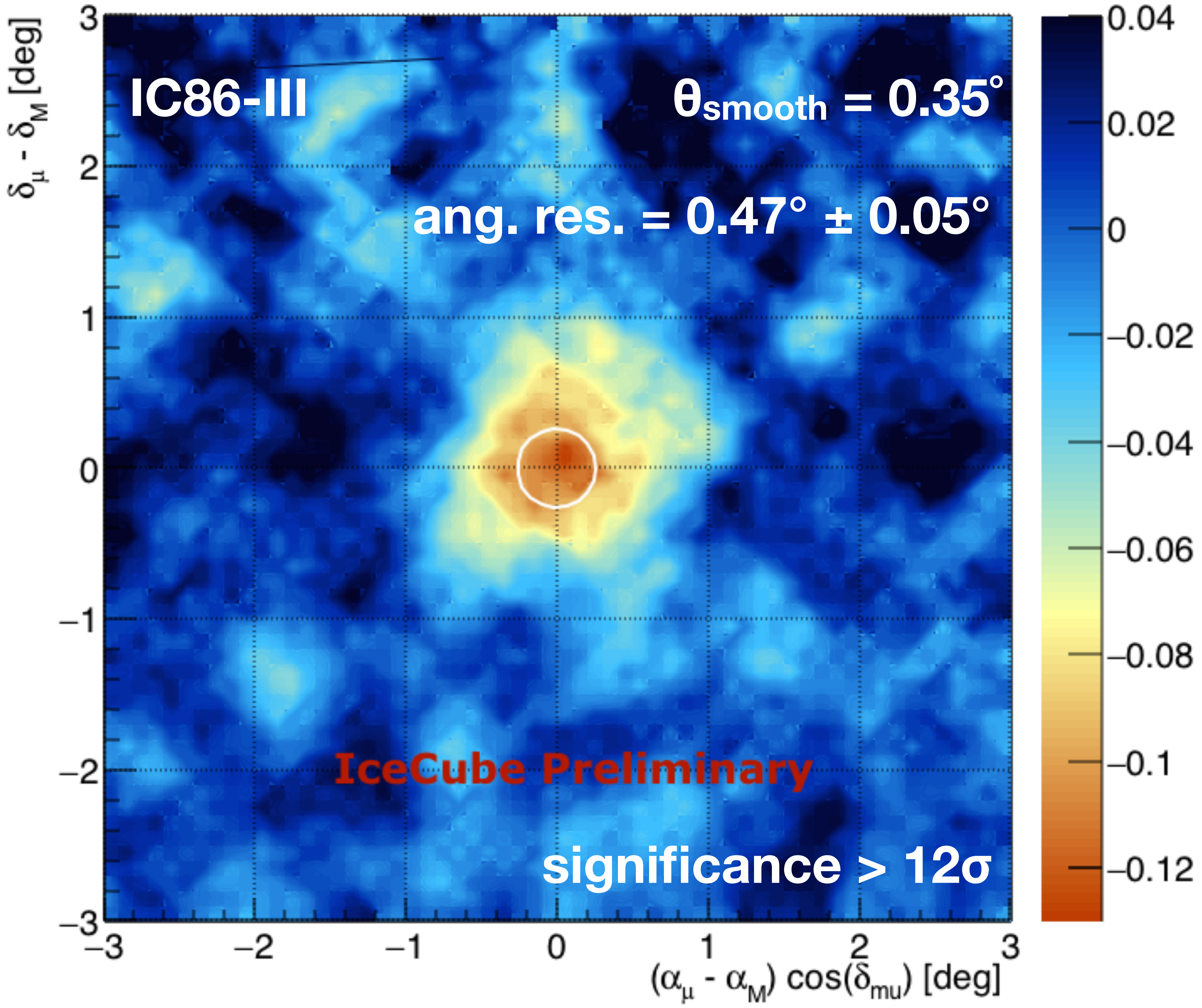
high energy muons
pointing resolution and interplanetary magnetic fields

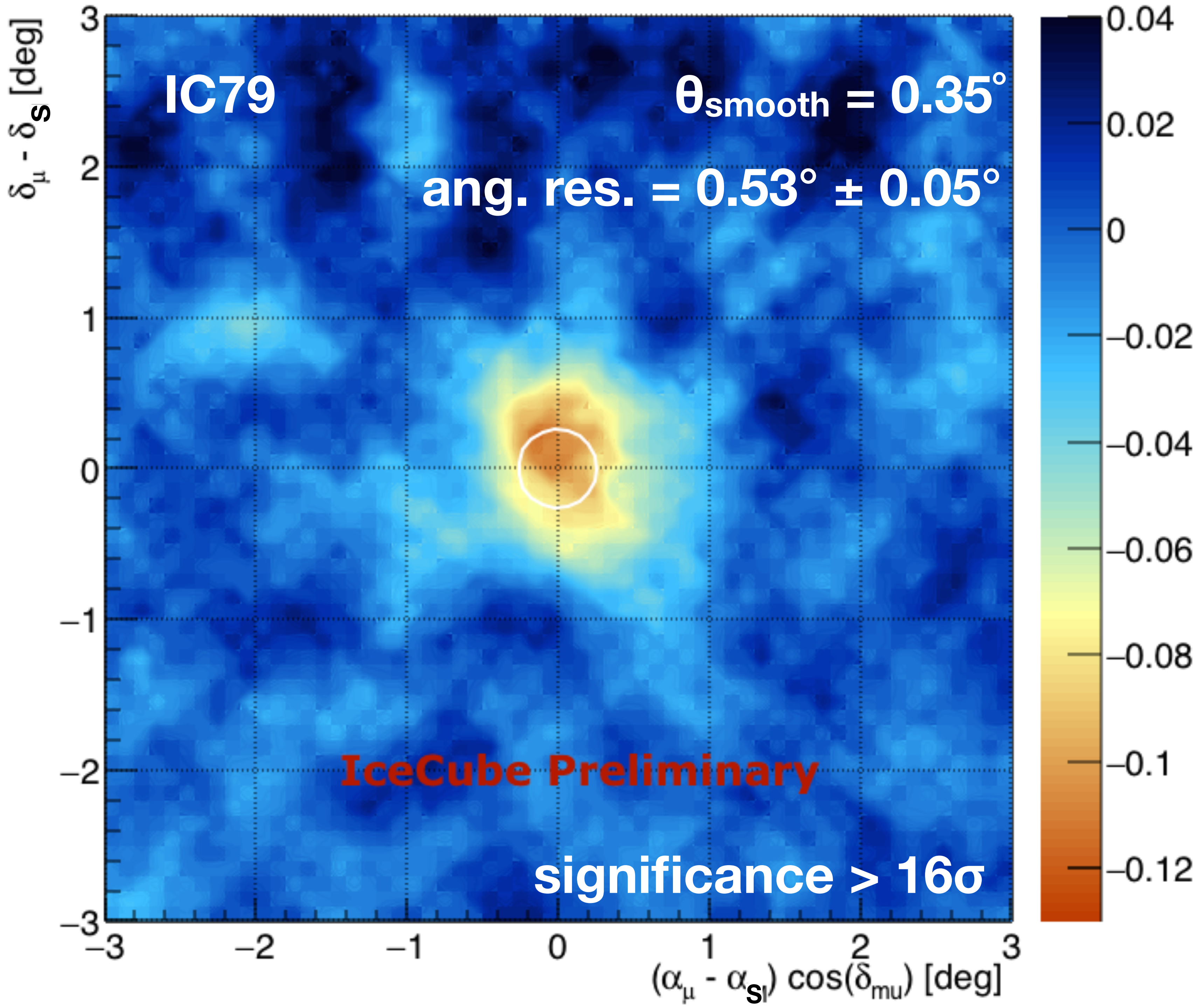
Phys. Rev. D 89, 102004 **2014**

IceCube-40+59



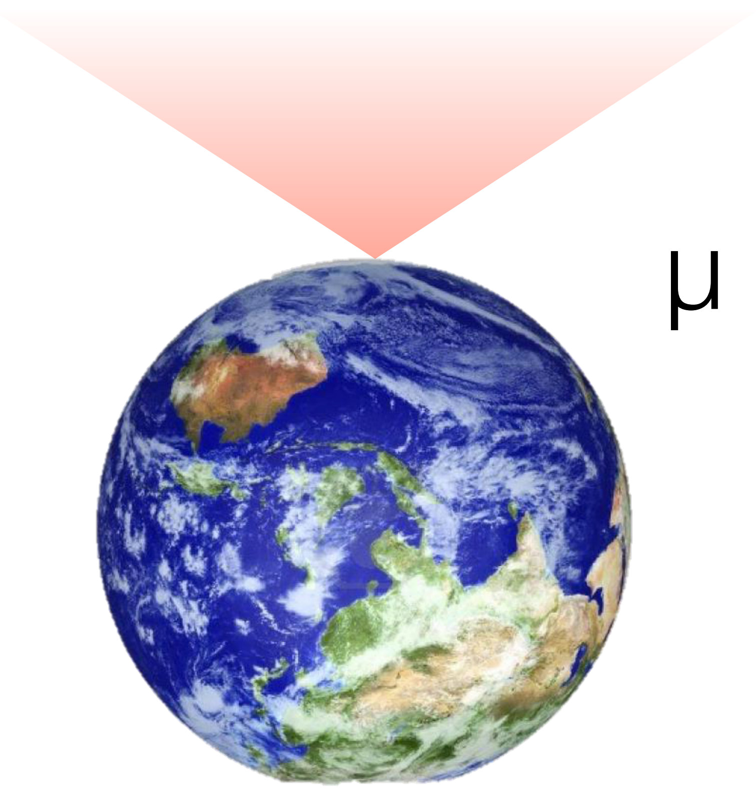
Cosmic Ray Anisotropy Workshop 2015 (Bad Honnef)



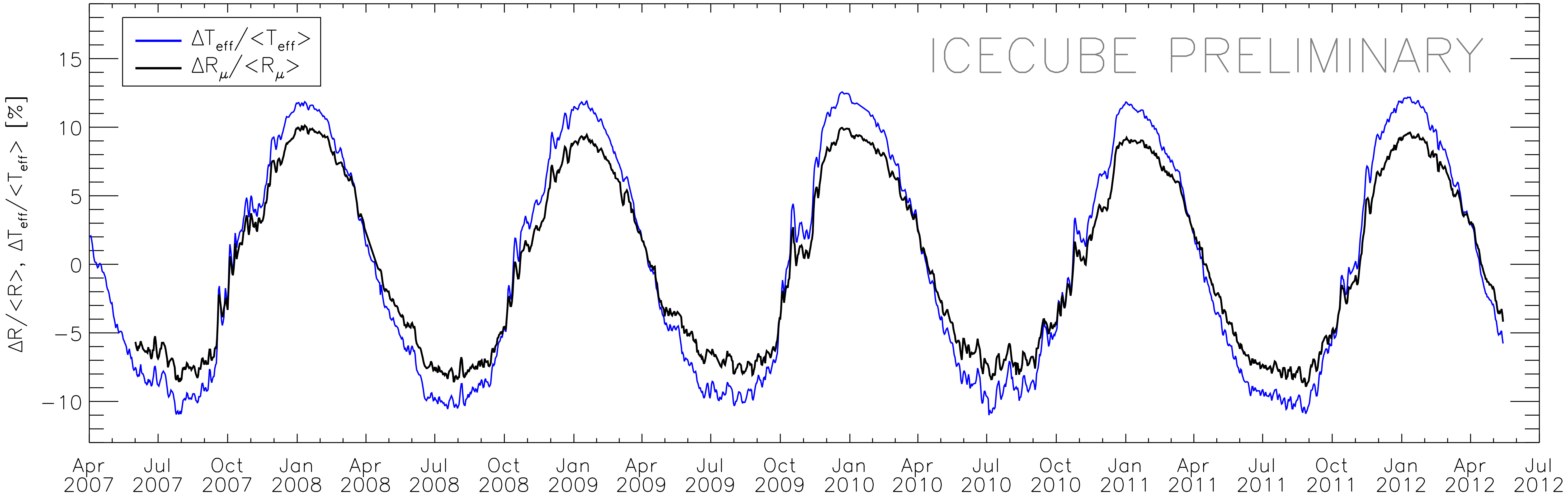


high energy leptons

correlation with stratospheric temperatures



μ



μ multiplicity - **ICRC 2013**

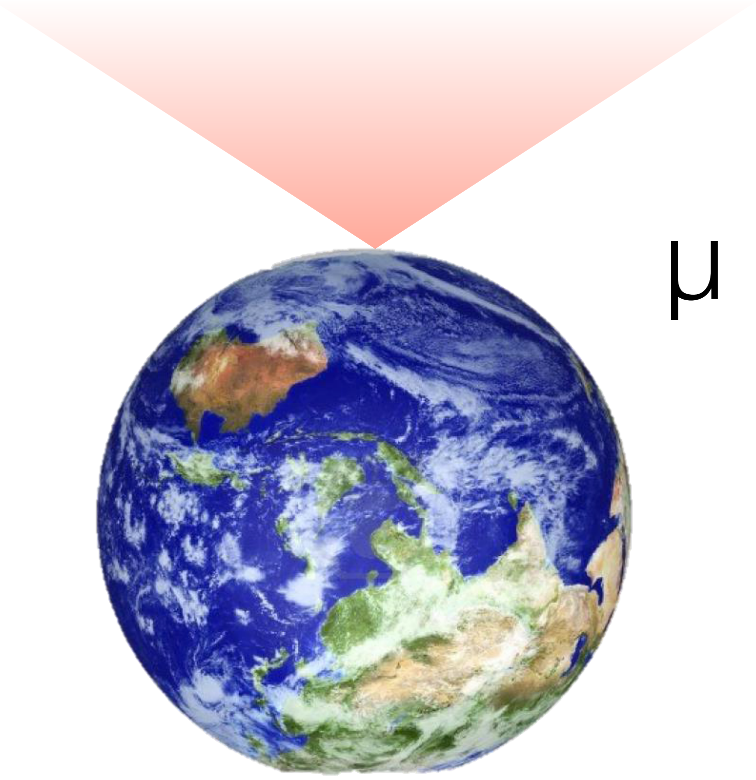
2e8 events / day

ICRC 2009
ICRC 2011

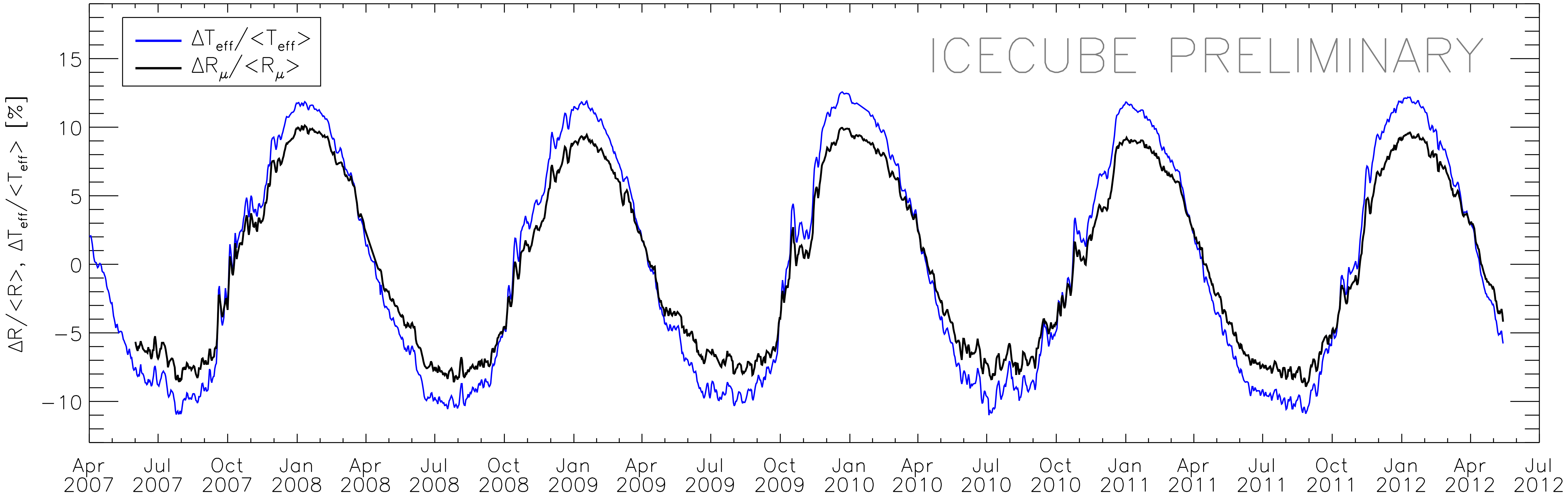
- **long** & **short** term correlations with high statistical precision: dynamical effects on air density
- temperature correlation coefficient indirect probe into **K/π**
- no temperature correlation if prompt (**charm**) contribution dominates (PD & Gaisser, 2010)

high energy leptons

correlation with stratospheric temperatures



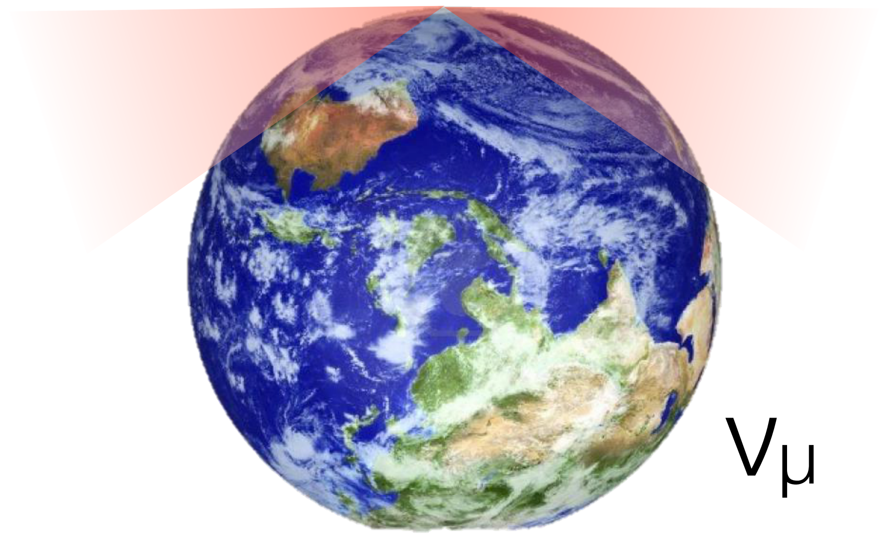
μ



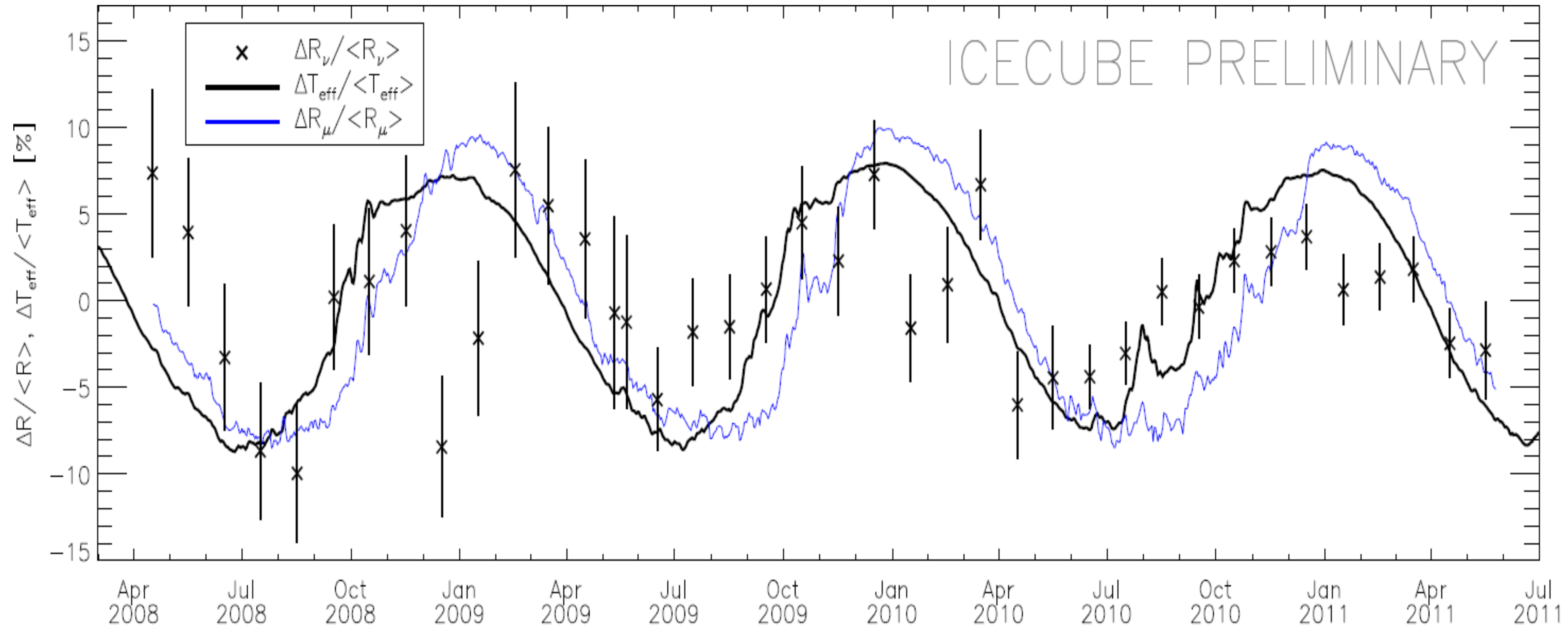
μ multiplicity - **ICRC 2013**

2e8 events / day

ICRC 2009
ICRC 2011



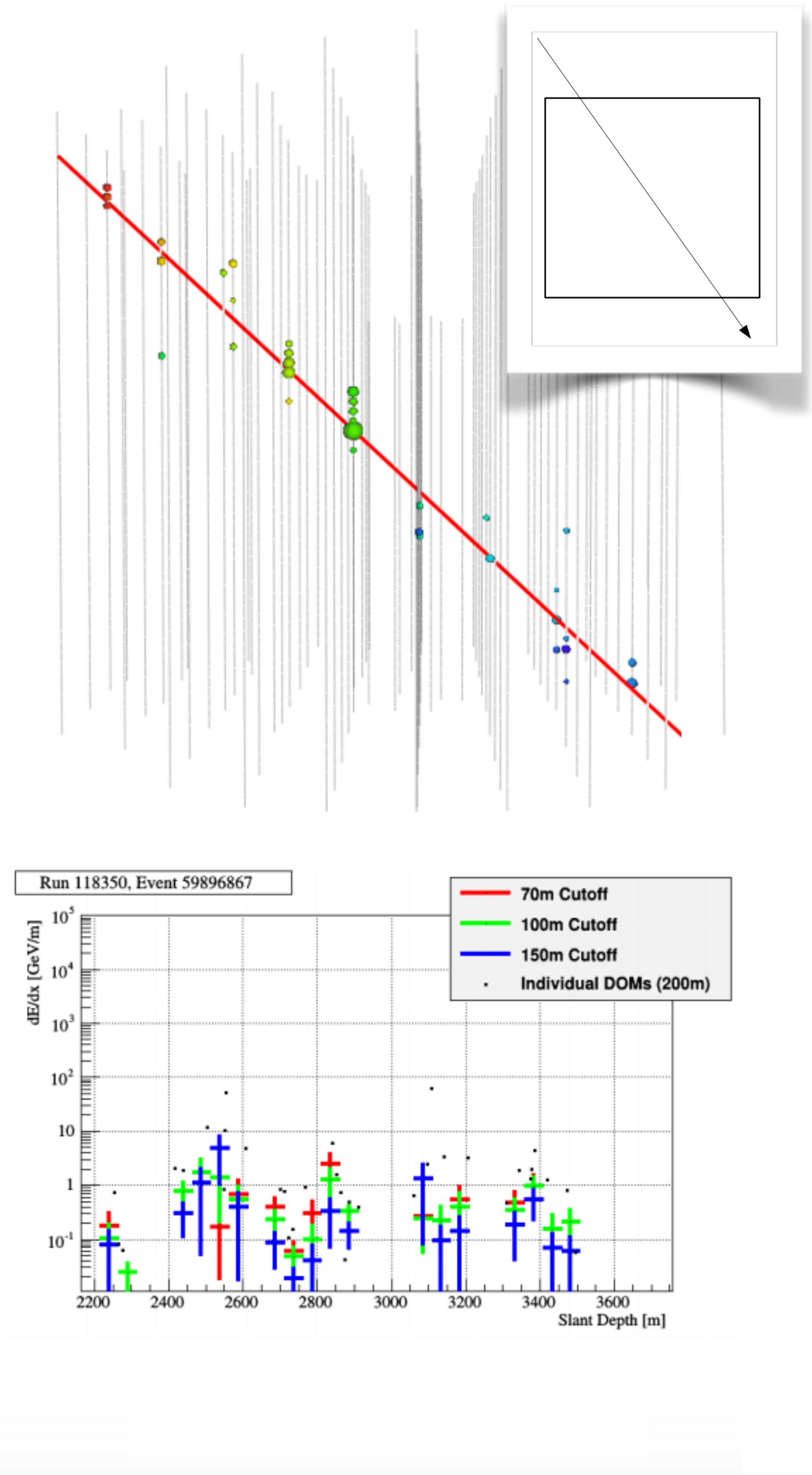
ν_μ



ICRC 2013

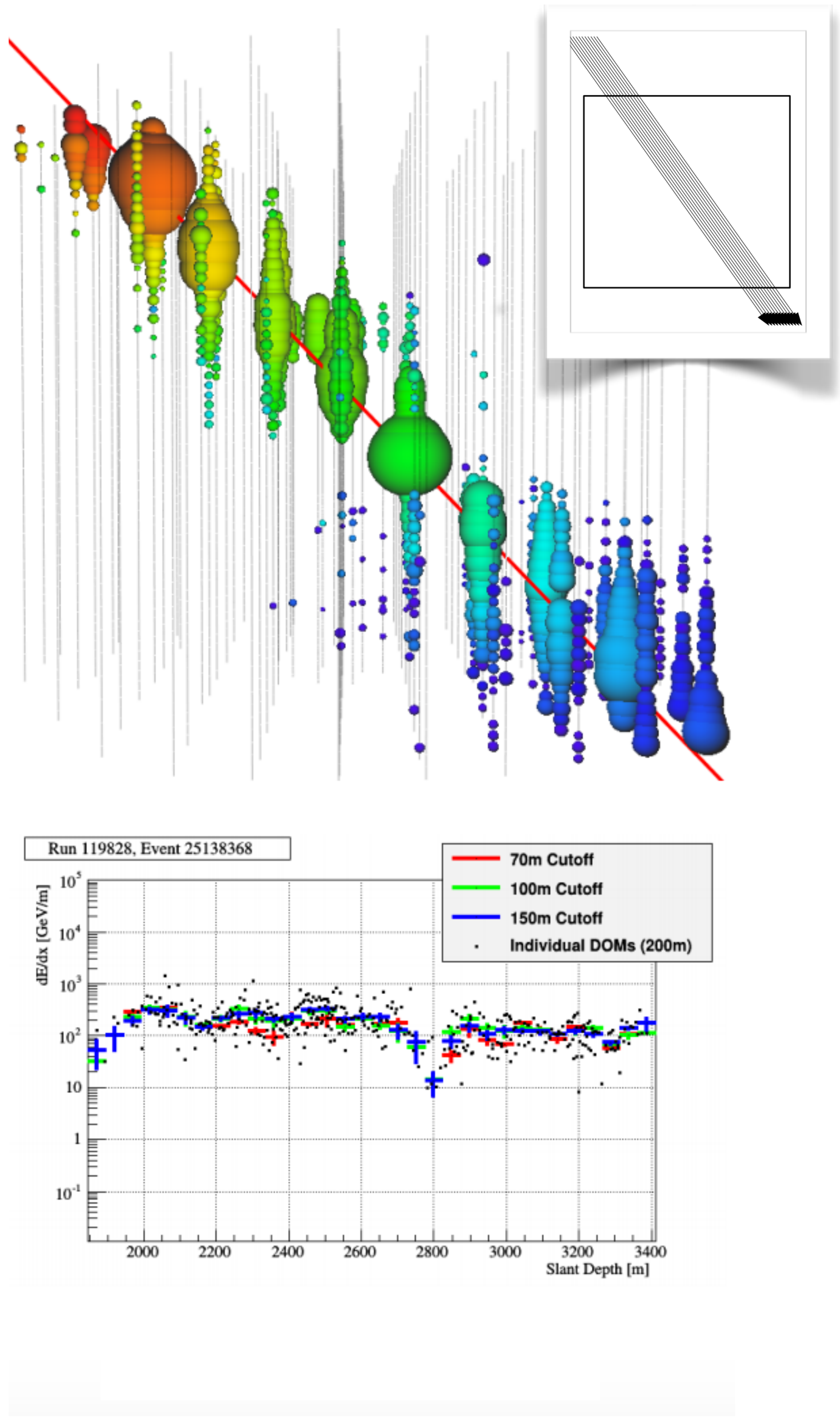
high energy muons

Low-Energy



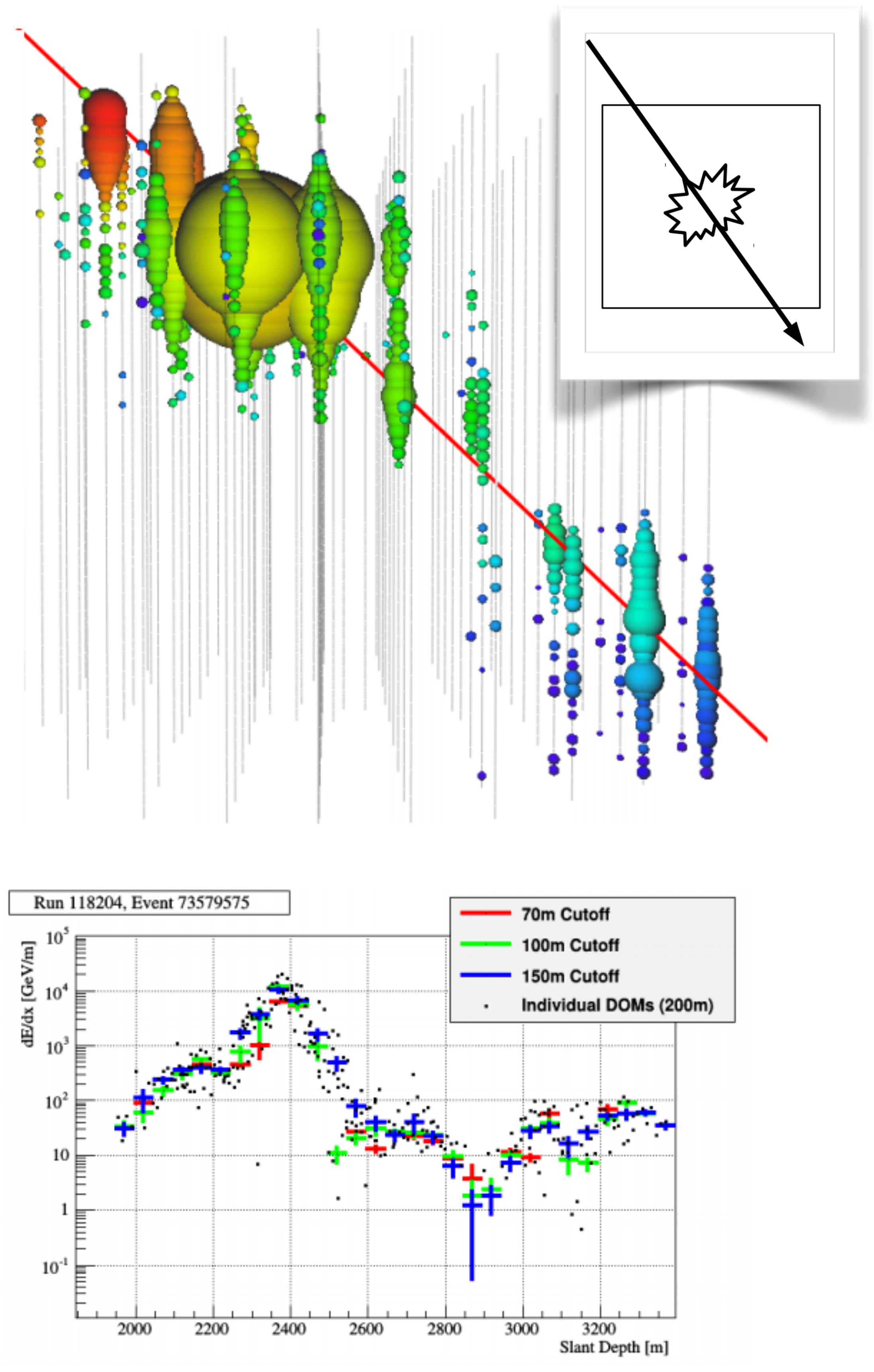
minimum ionizing

Bundles



minimum ionizing

HE Muons



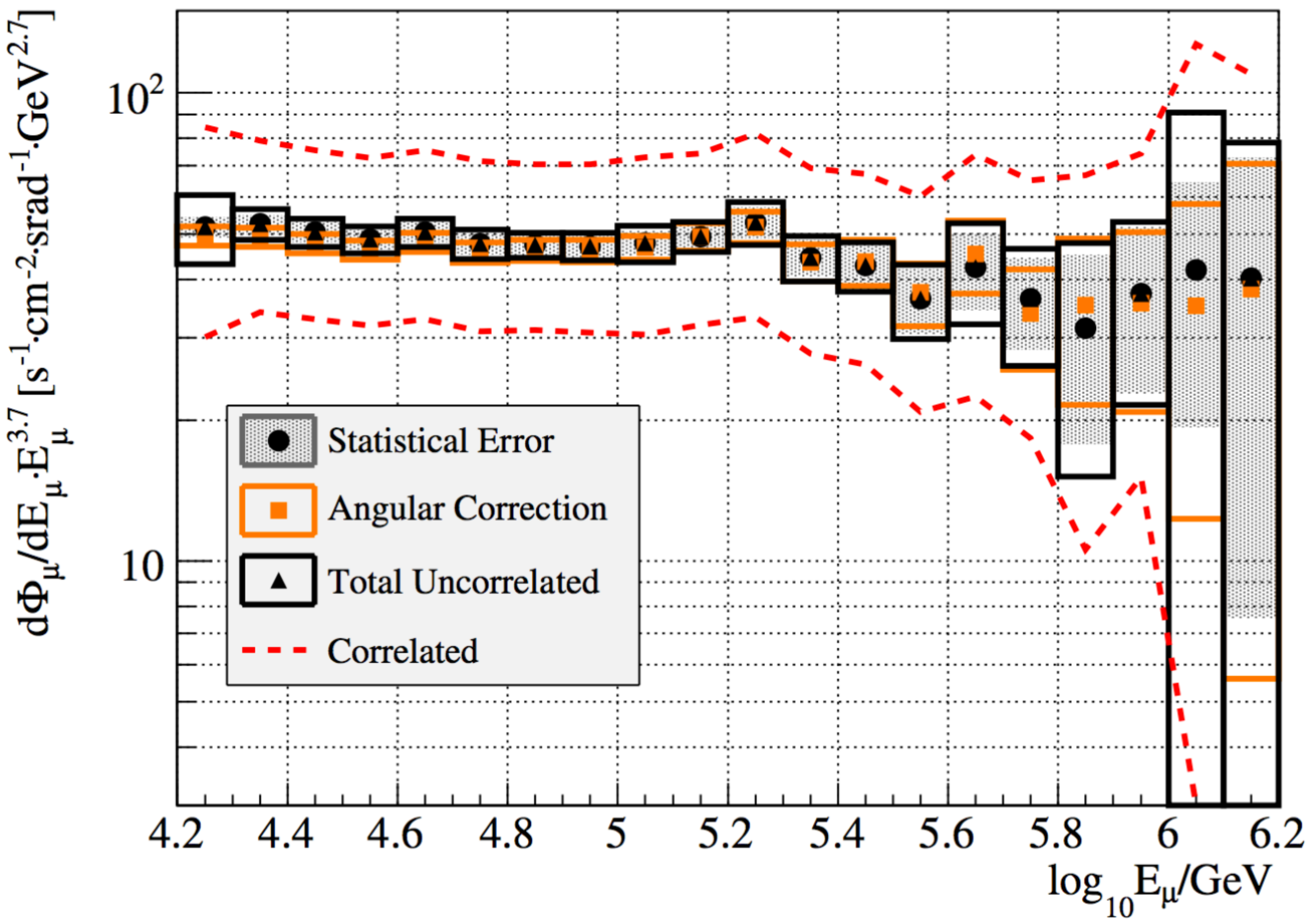
P. Berghaus

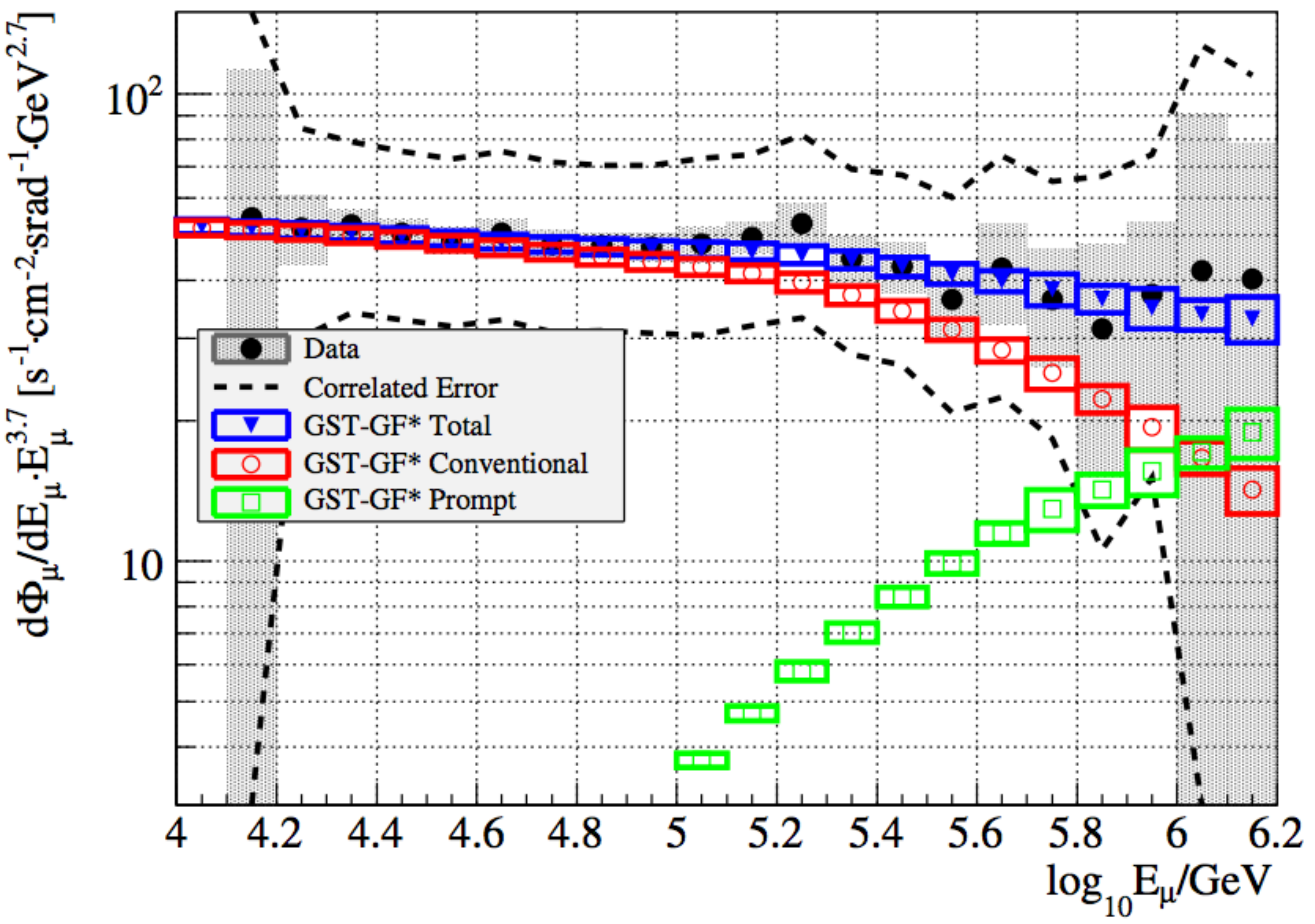
stochastic energy losses

high energy muons

ICRC 2015
T. Karg
Tue 4/8

arXiv:1506.07981 (ApP) **2015**

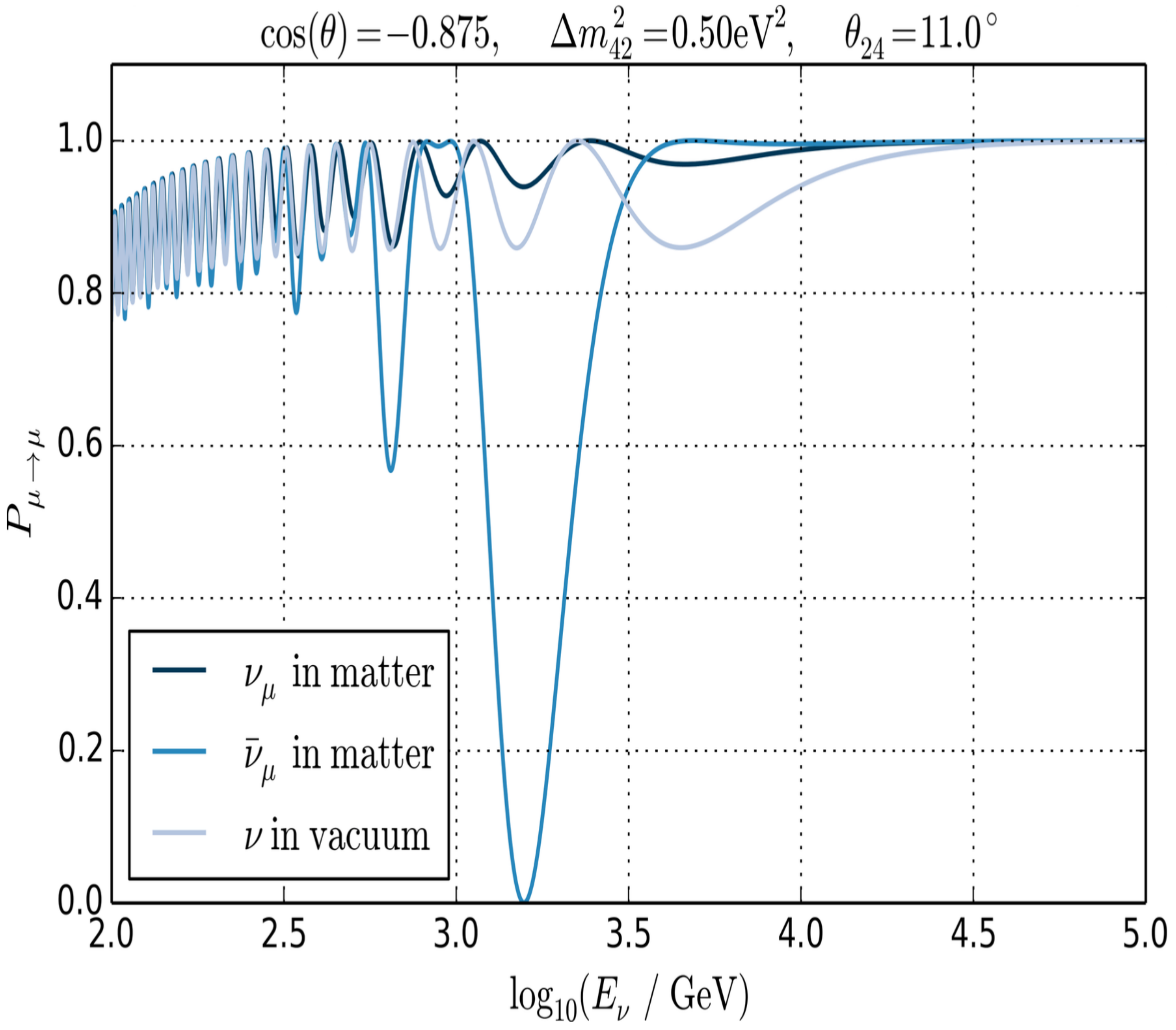




- high energy inclusive muon spectrum compatible with additional contribution at HE
- prompt component from **charm production** and **unflavored η mesons**

non-standard physics
ν_μ disappearance to sterile neutrino

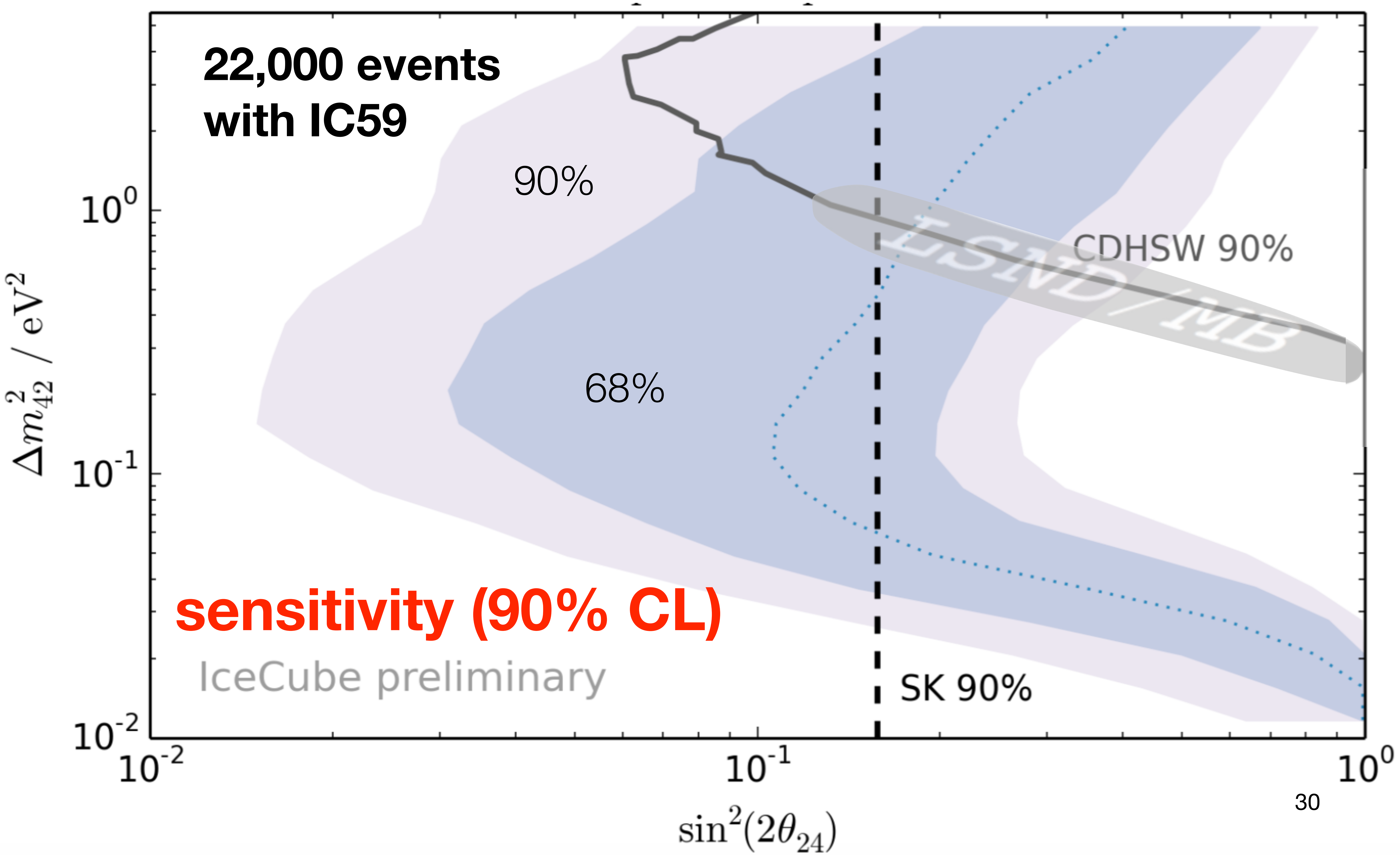
in normal hierarchy
large effect on anti-ν



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 (ν + μ)

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

atmospheric ν and μ

detector calibration

- angular pointing/resolution
- energy calibration

test of Standard Model

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

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

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