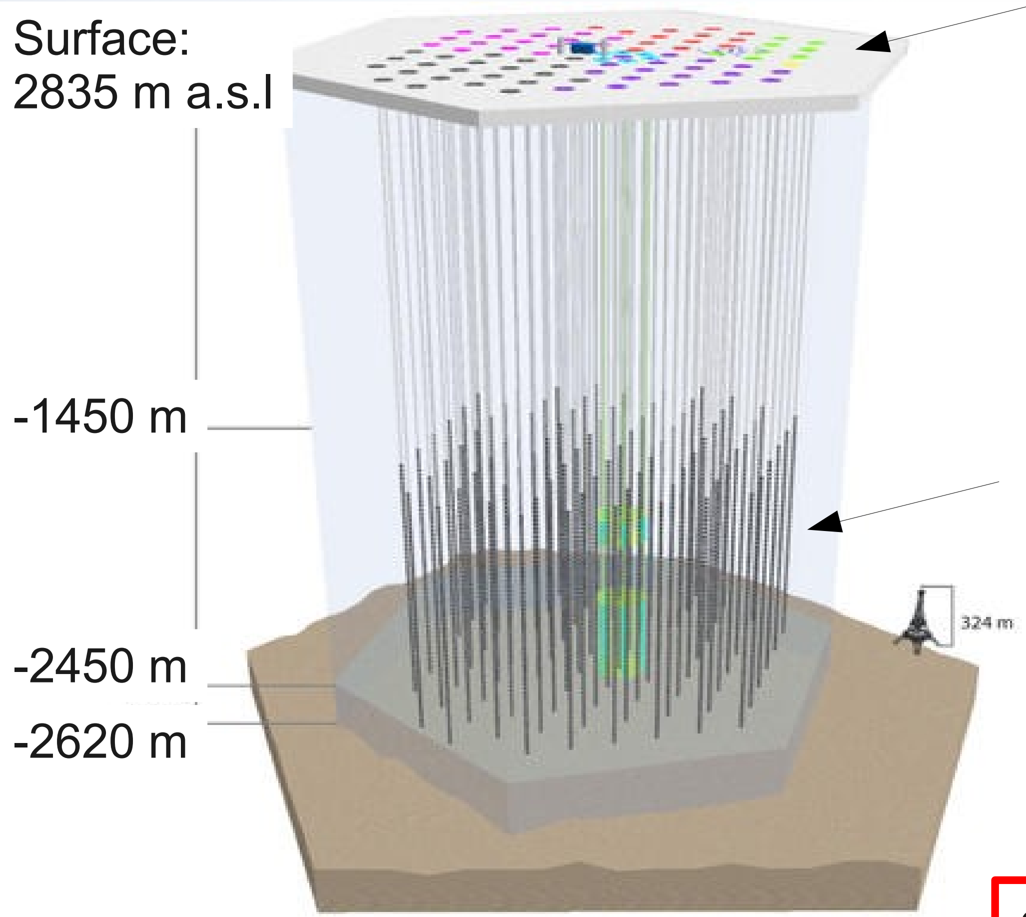
# Cosmic Rays in IceCube

Patrick Berghaus
University of Delaware

# IceCube Components

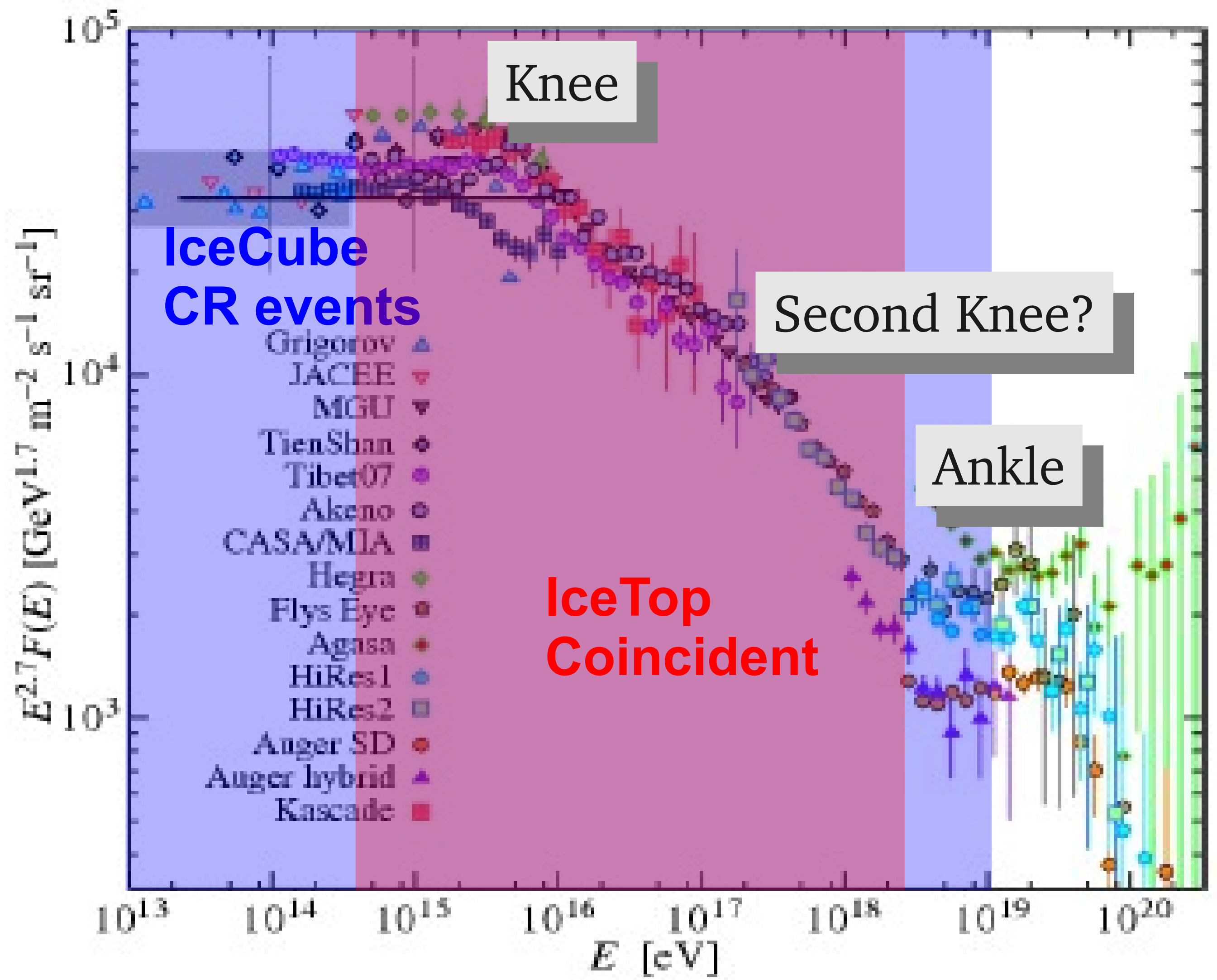



**IceTop** Surface Array:
1km² area
LE electromagnetic

**InIce** Volume Detector:
1km³ volume
HE muons

See also plenary talk by I. Taboada

# CR Energy range of IceCube/IceTop



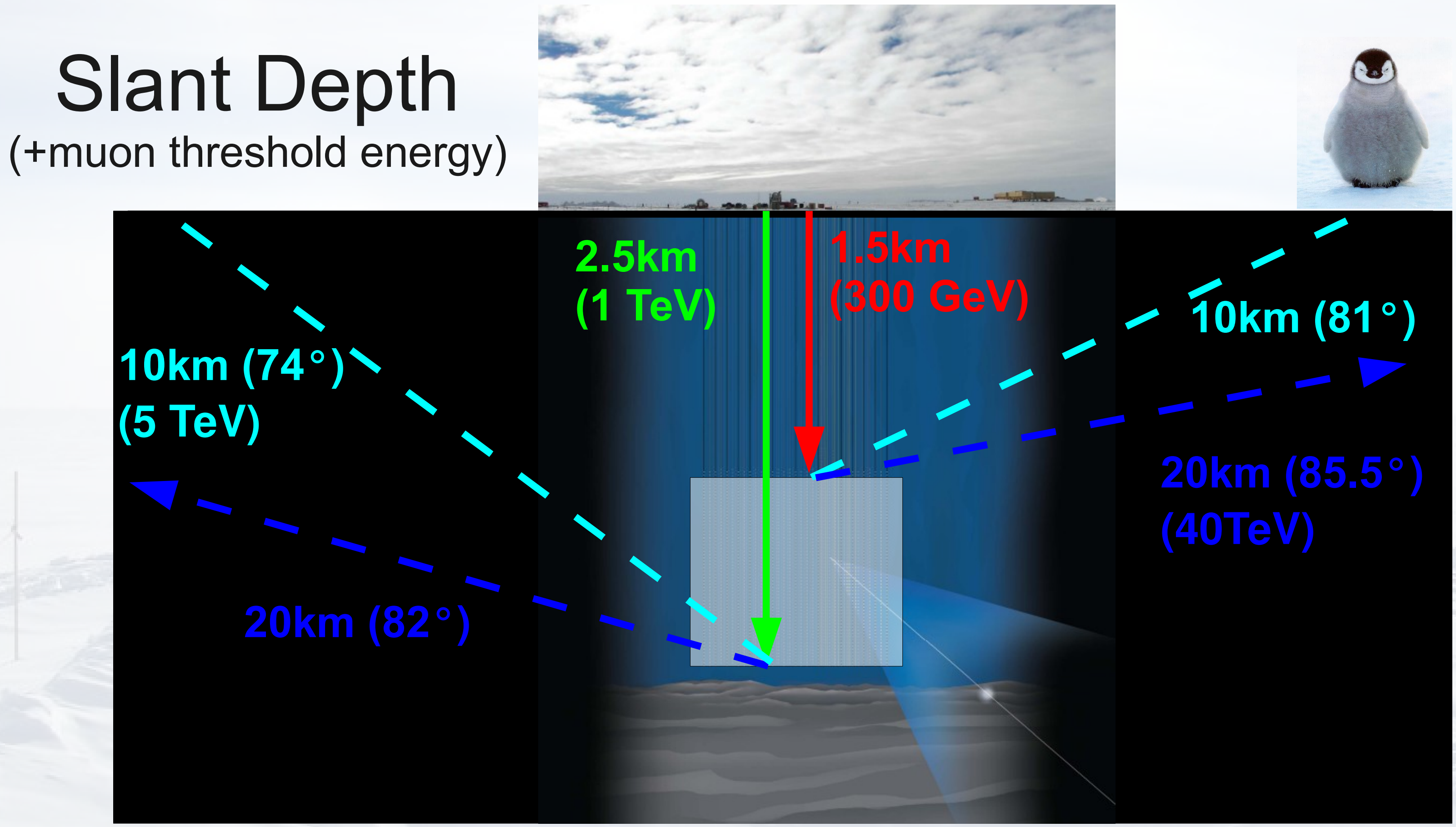

**Main Science Goals:**

Primary composition change around Knee

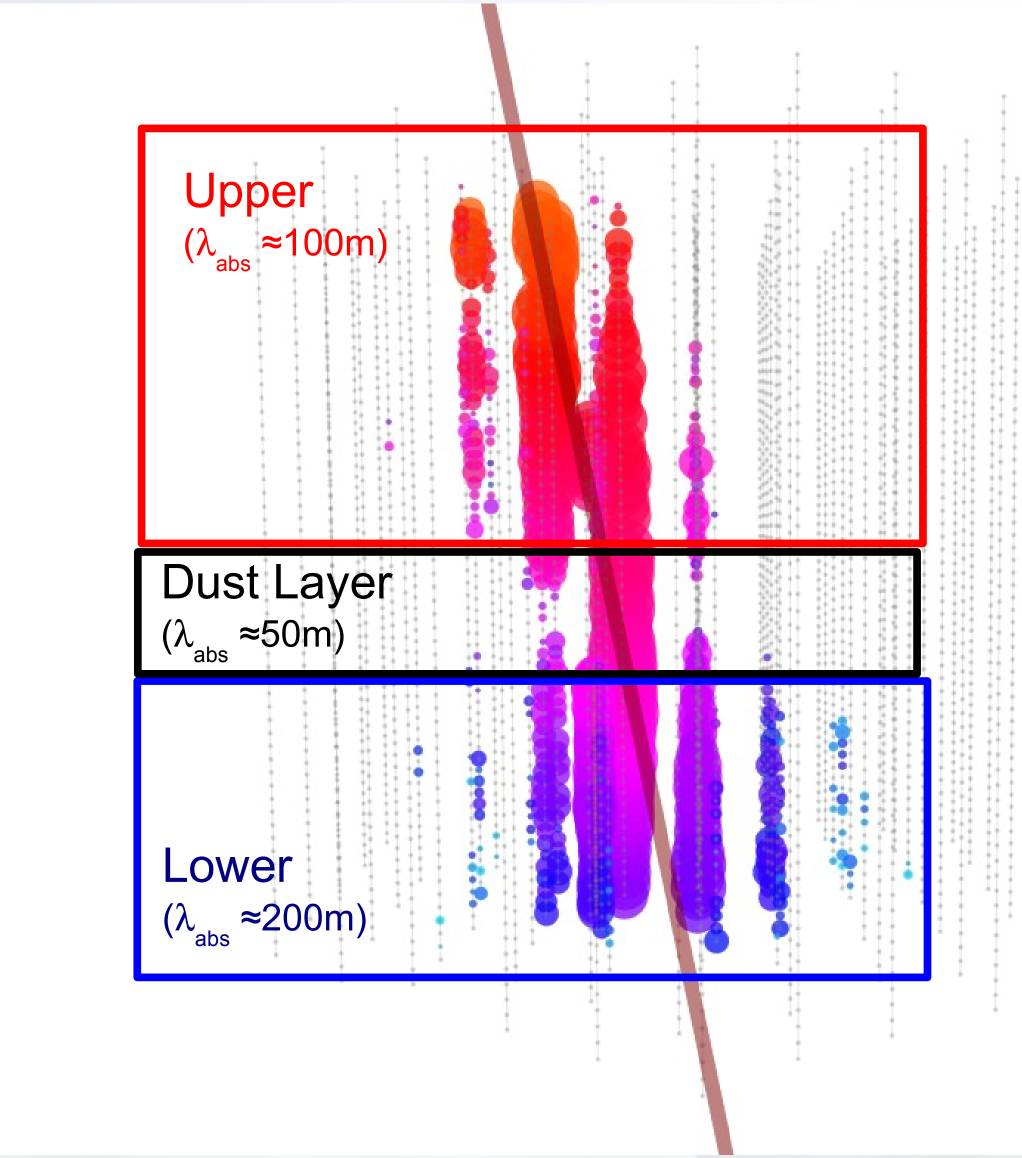
Transition to Extragalactic CR at “Second Knee”?

CR-induced lepton Flux up to PeV energies

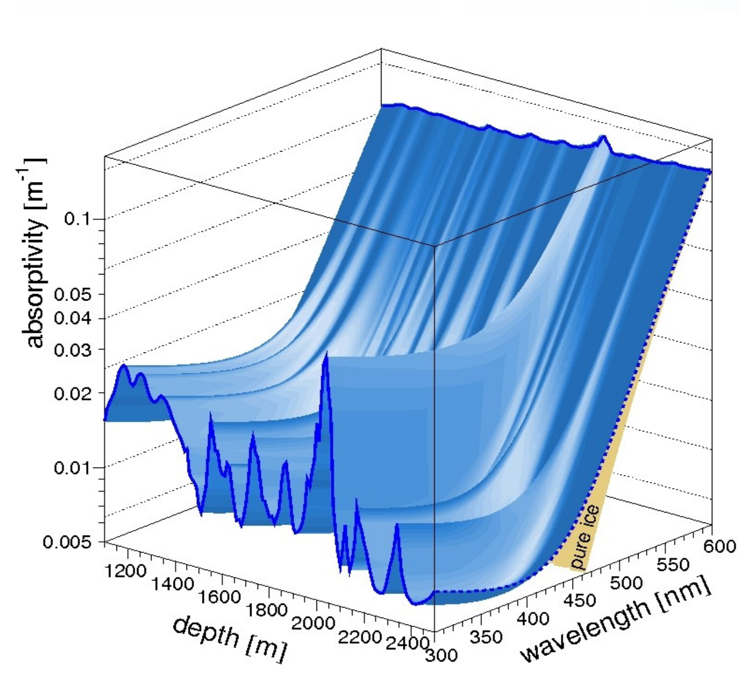
# InIce CR-Induced Muons



# High-Multiplicity Muon Bundle



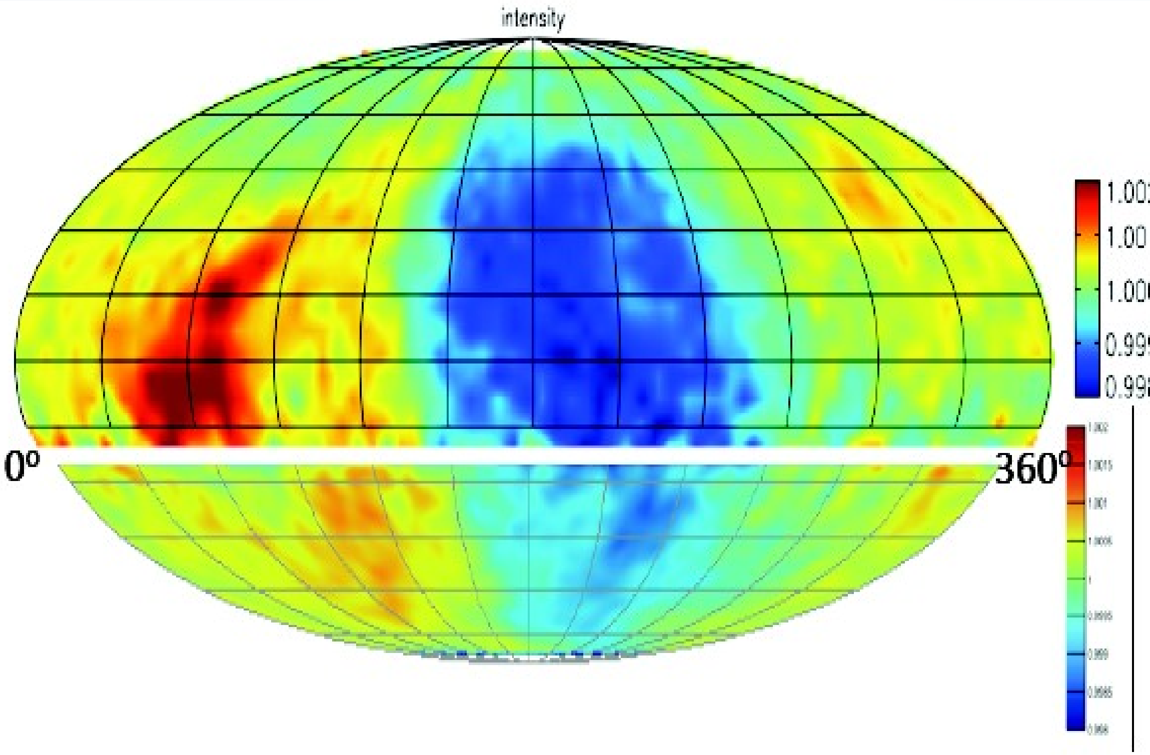




# CR Anisotropy

Tibet Array

5TeV




IceCube-59

20 TeV

(predominantly protons)

Relative Intensity

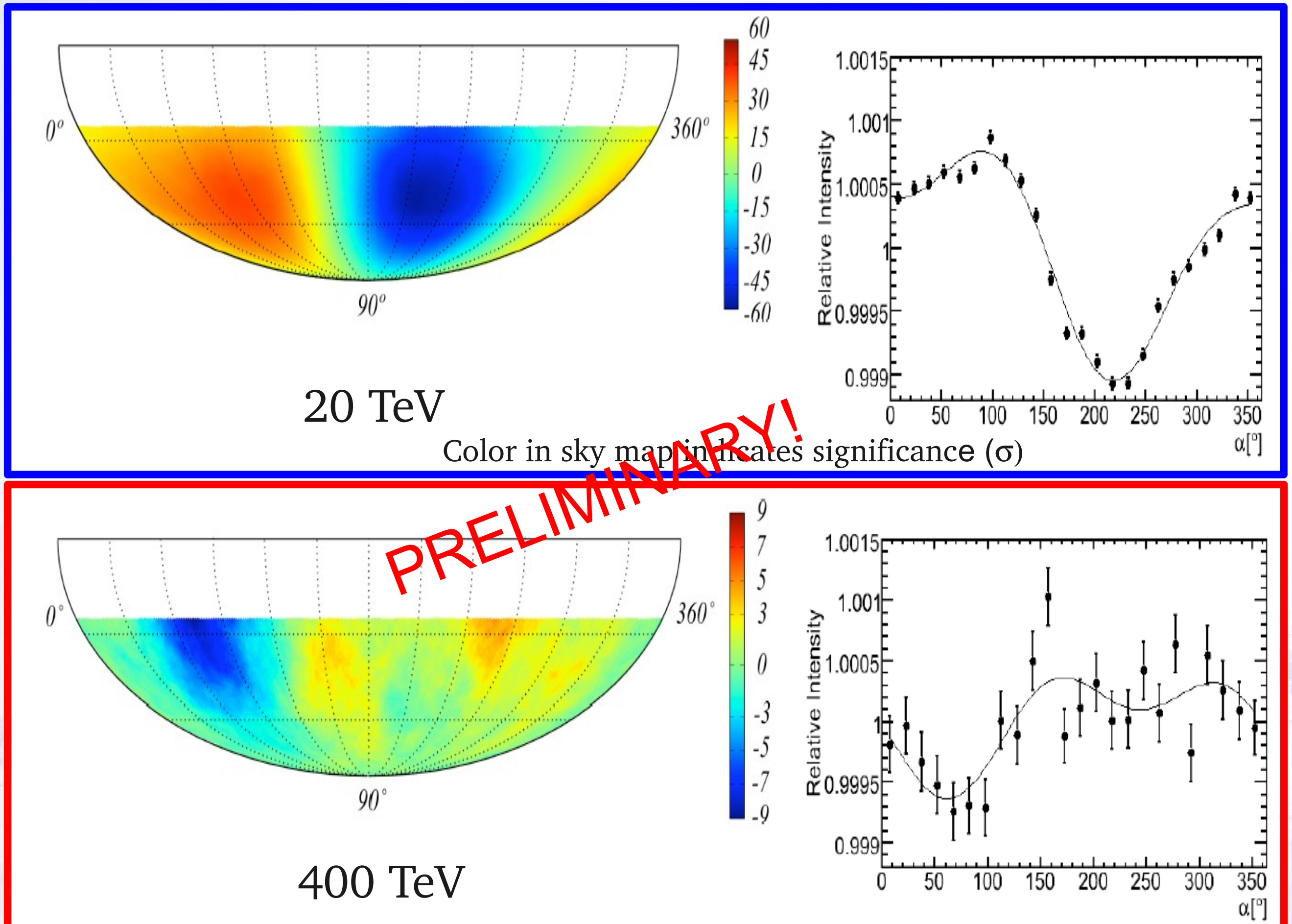
$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

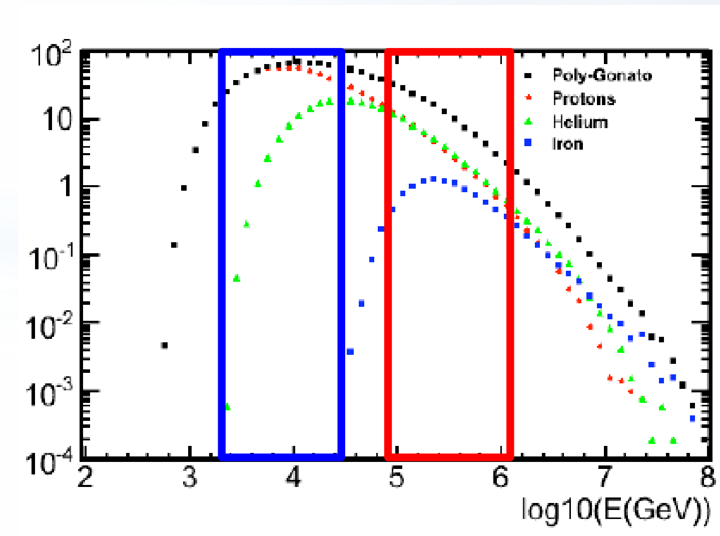
$\gamma = 2.7$ cosmic ray spectral index

$v = 220$ km/s speed

The anisotropy in IceCube data is *not a pure dipole* and does not have the right phase to be explained by the Compton-Getting effect. If the Compton-Getting effect is present in the data, it is overshadowed by a stronger effect.

# CR Anisotropy: Energy Dependence



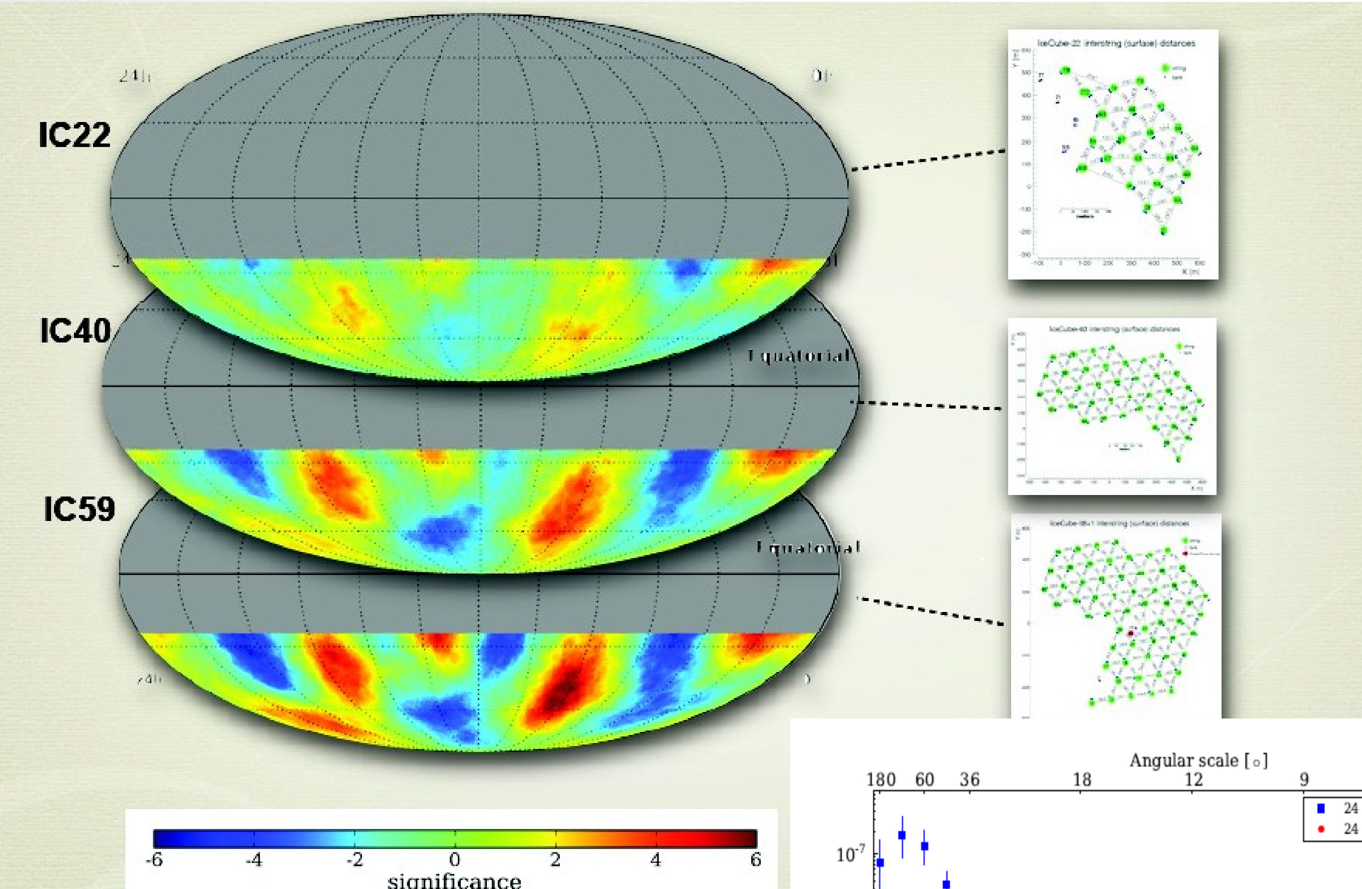




Primary composition dependence on nuclear mass due to muon energy threshold (400 GeV)

Cut on bundle energy

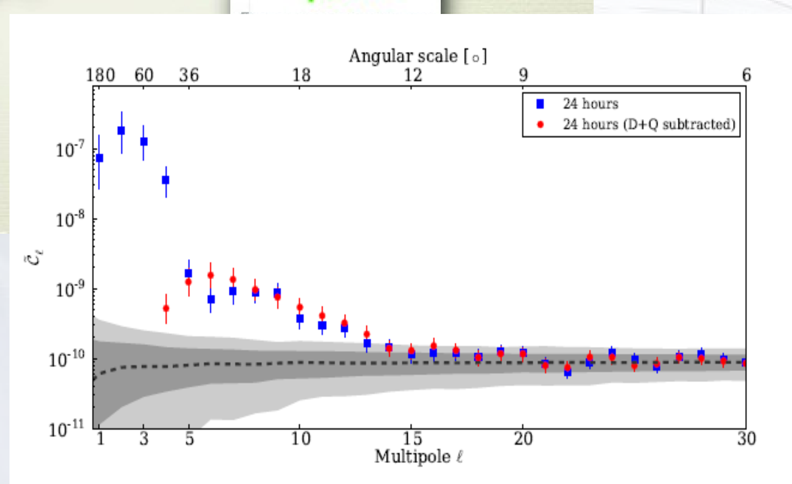
# First Detection of Anisotropy at 400 TeV

# CR Anisotropy: Small-Scale Structure



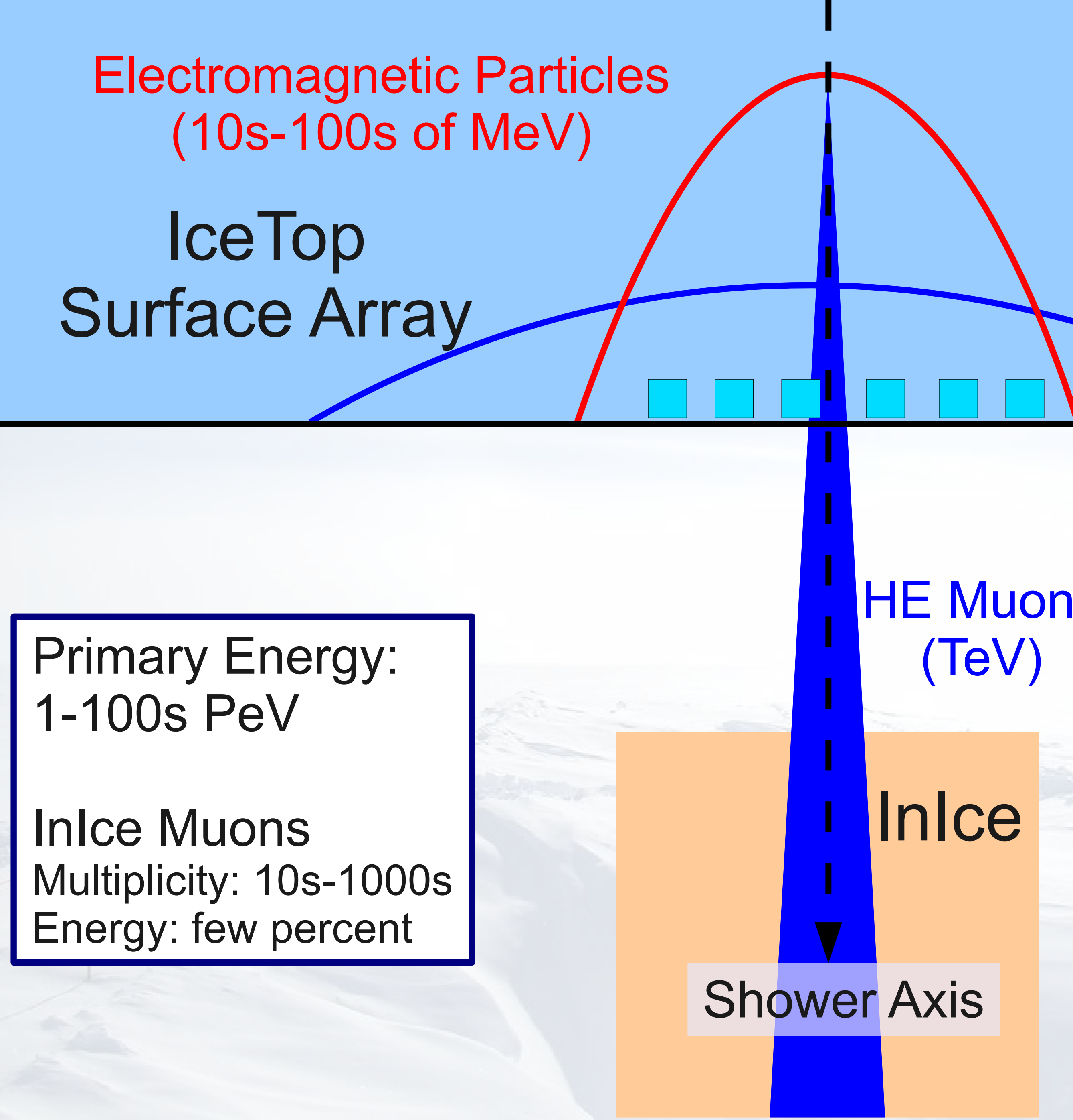

arxiv:1105.2326

- **5.6x10[10]** events
- time scrambling (4 hr)
- 10° smoothing
- median energy **20 TeV**



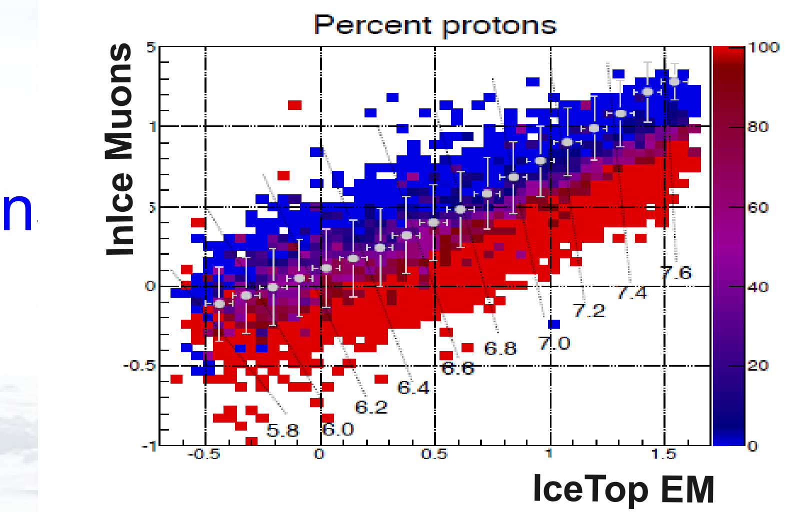

Evidence for structures with angular size ~30°

Currently no theoretical explanation (heliospheric?)




Primary Energy:
1-100s PeV

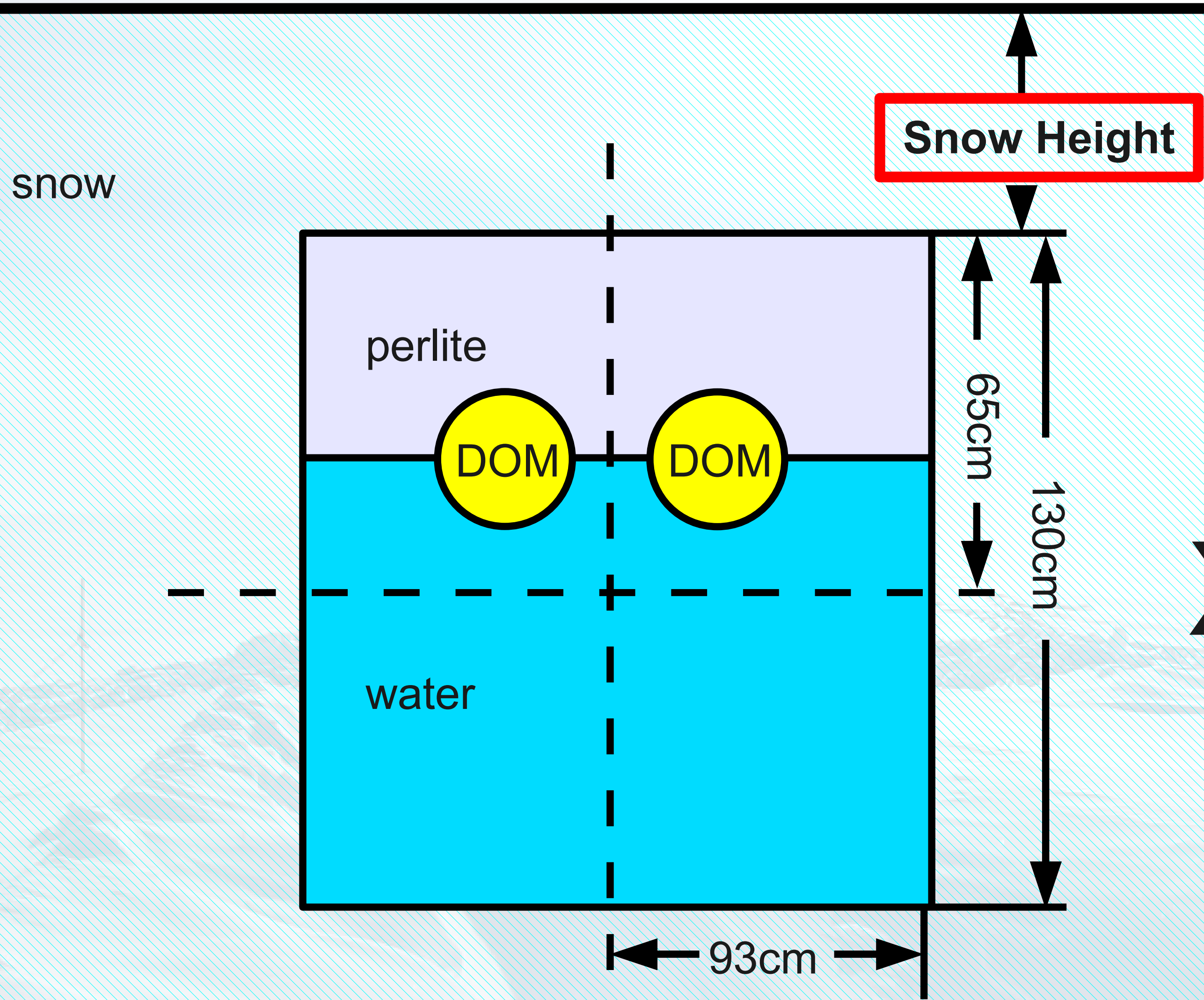
InIce Muons
Multiplicity: 10s-1000s
Energy: few percent

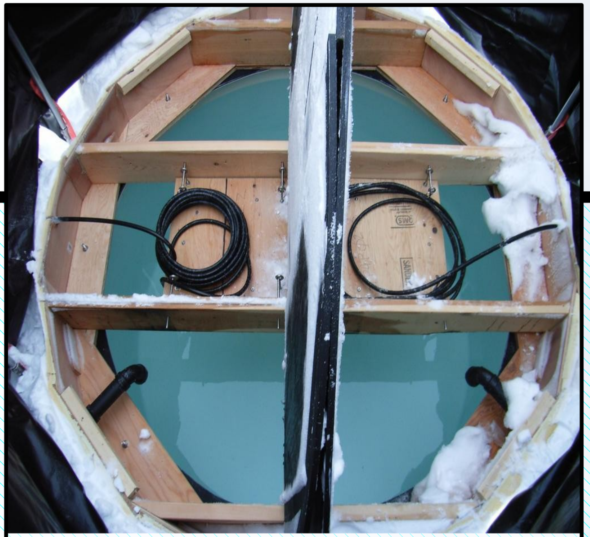



Ratio of EM particles to muons depends on primary type
Heavy: +mu -EM
Light: -mu +EM


Temporary Cover
2 Tanks
per Station
Freezing Unit
IceTop
Deployment

# IceTop Tank



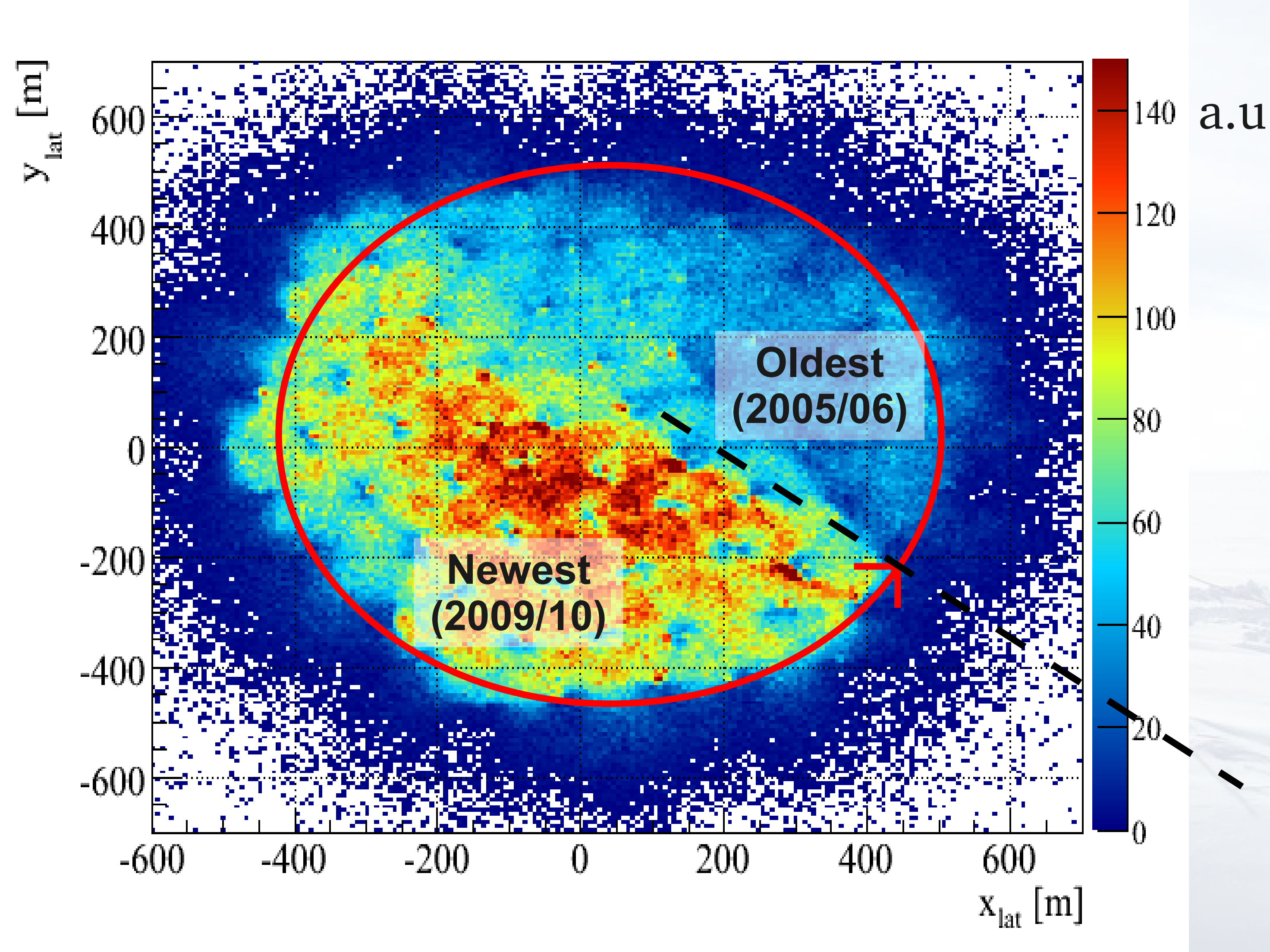



view from above, unfrozen

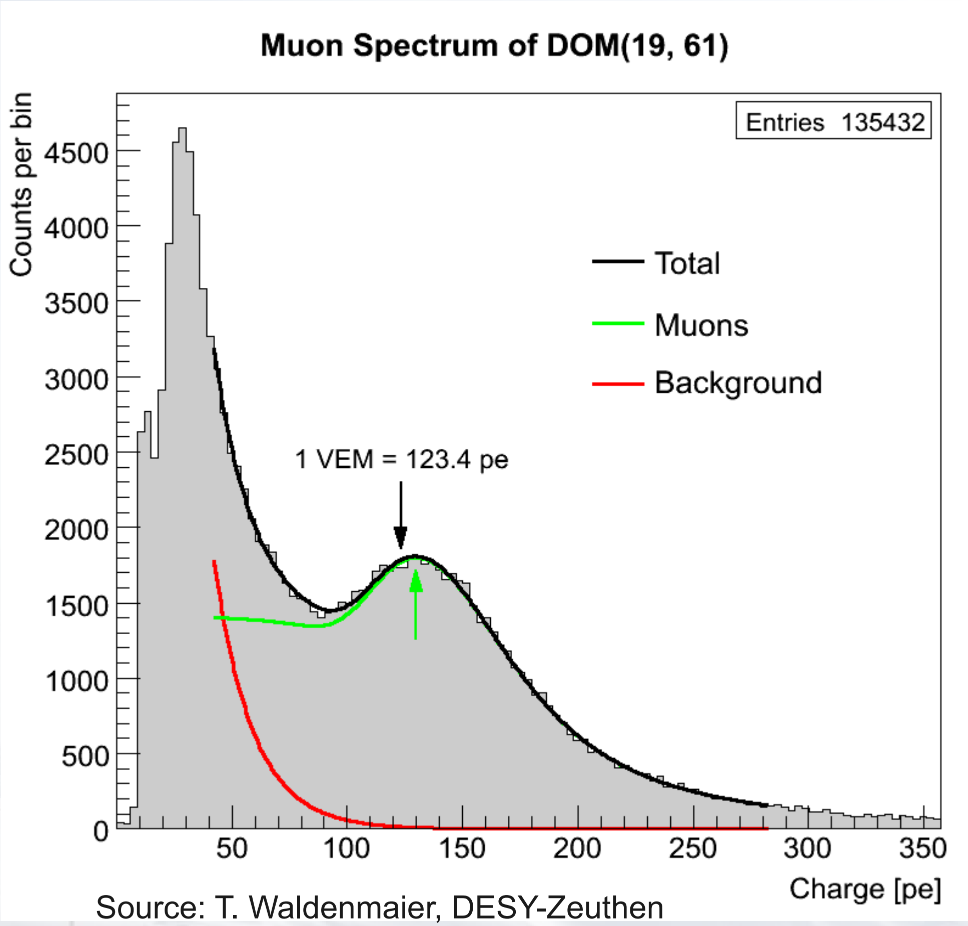
x2 x81

# Effect of Snow Coverage

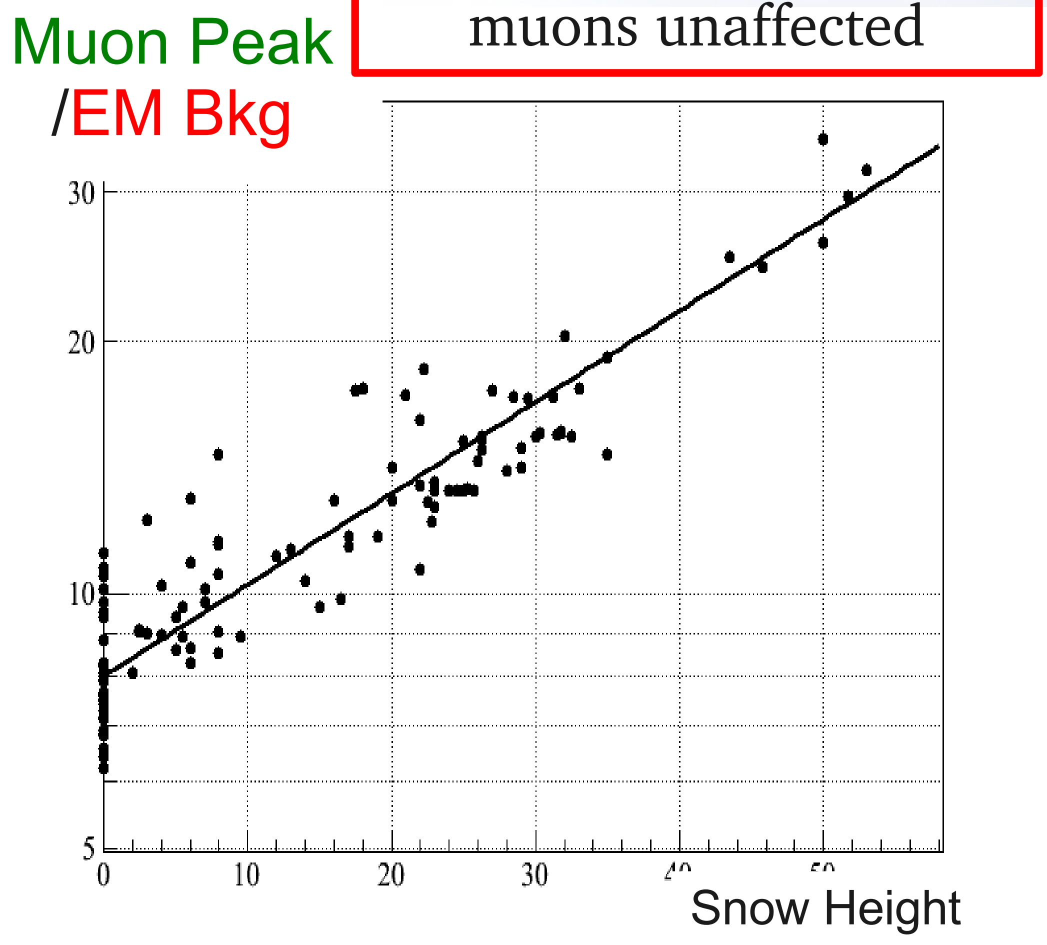
(Reconstructed Shower Core Position)



# Tank Calibration

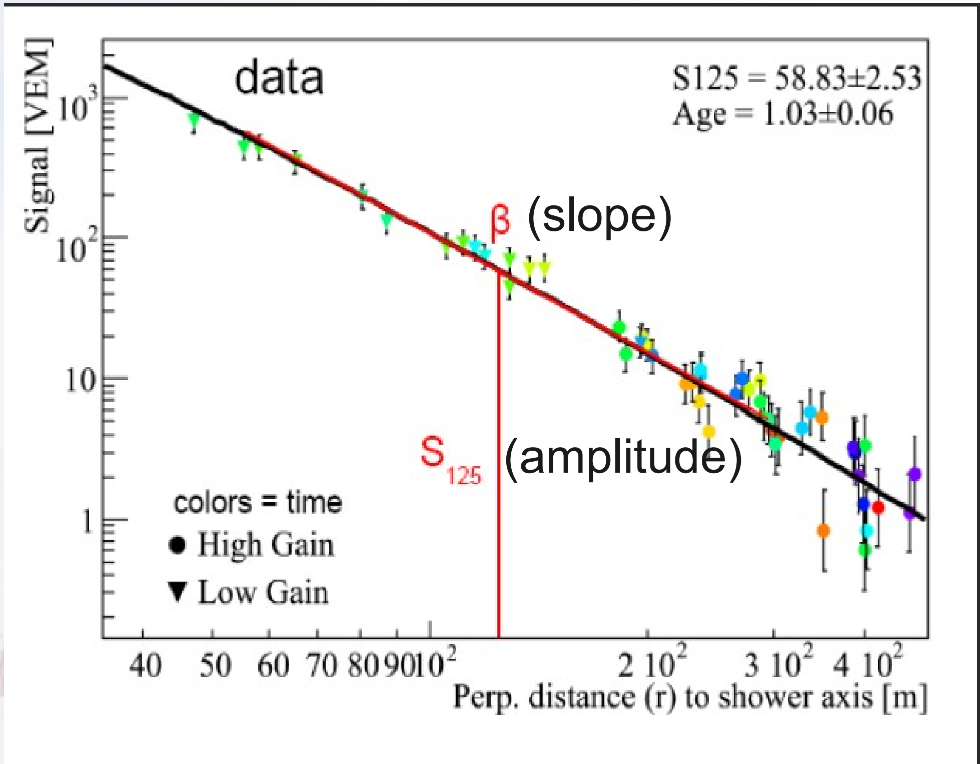



Snow reduces EM signal, muons unaffected




$$S_\mu / B_{EM} \simeq \exp\left(\frac{h_{snow}}{40.0''} + 2.08\right)$$

# IceTop Shower Reconstruction




Lateral shower profile at 125m

$$S(r) = S_{125}\left(\frac{r}{125m}\right)^{-\beta-\kappa\log_{10}\left(\frac{r}{125m}\right)}$$

$S_{125}$ : signal at $r$ = 125m

$\beta$ : slope at $r$ = 125m

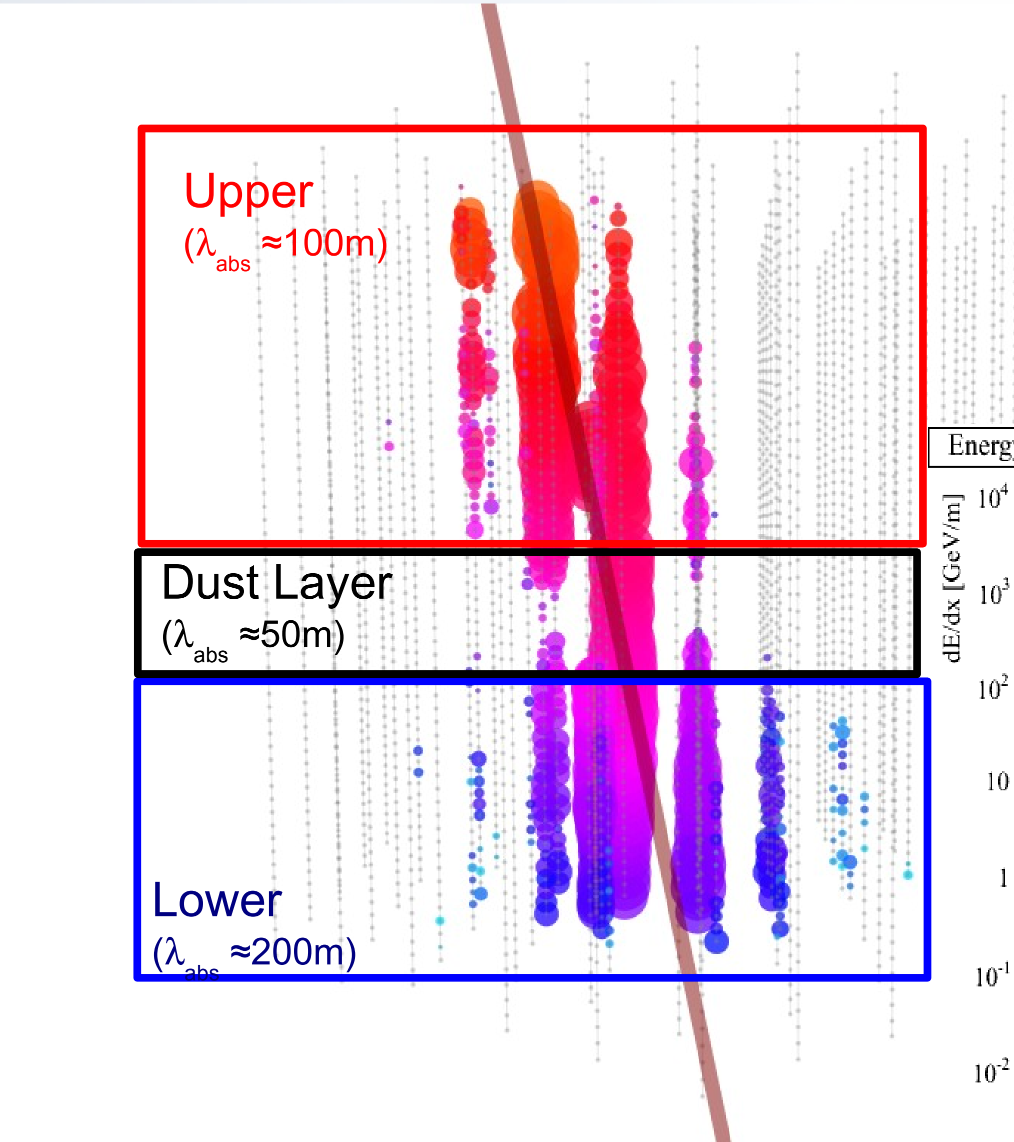
$\kappa$ = 0.303 fixed

arXiv: 0711.0353

$E_{prim} = f(S_{125}, \theta_{zen})$

"Double-Logarithmic Parabola": MC-derived empirical description

# High-Multiplicity Muon Bundle

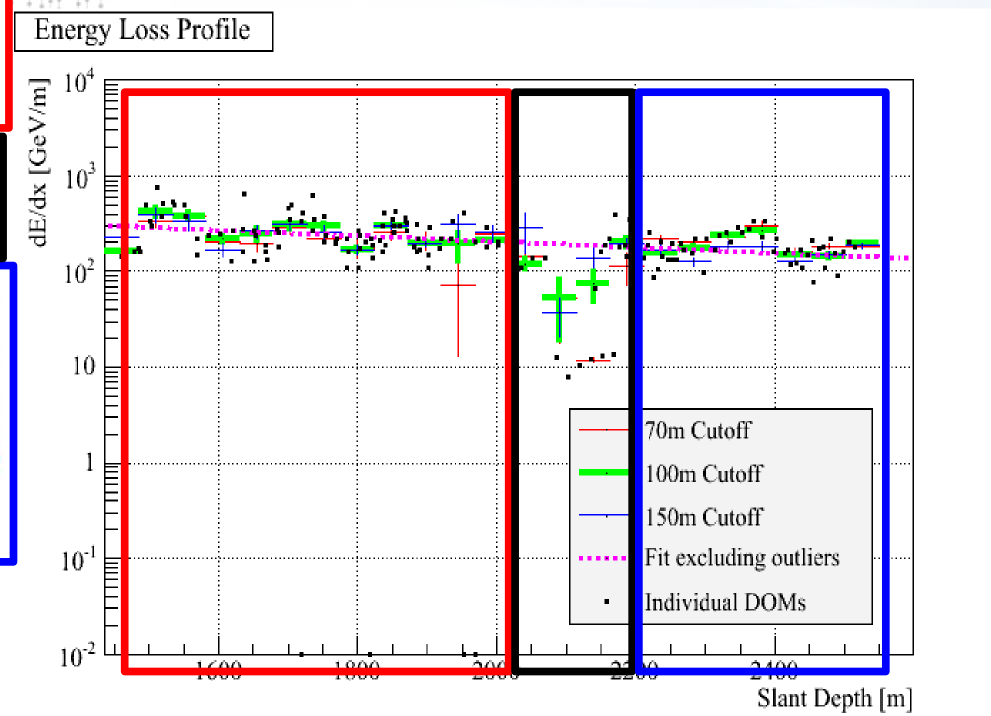



Differential Energy Loss Reconstruction:

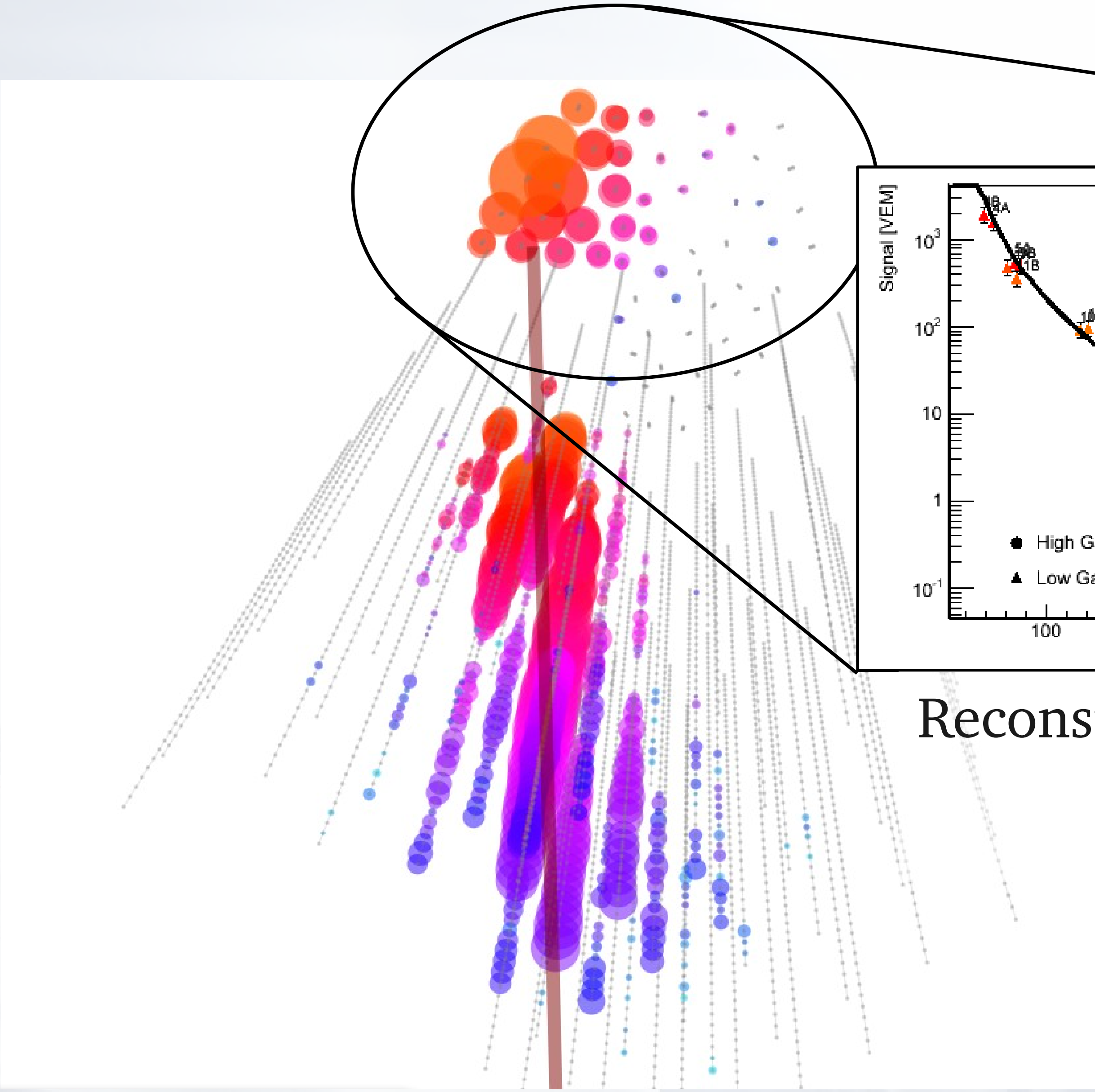
Smooth Distribution

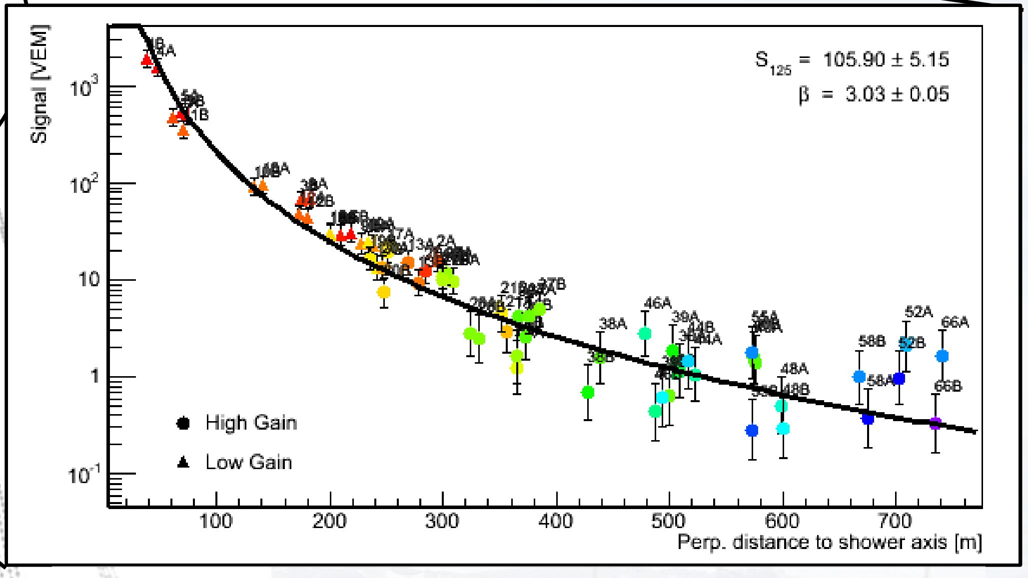
Gradual Slope (Range-Out)

300-600 Muons



# IceTop EM Content Measurement



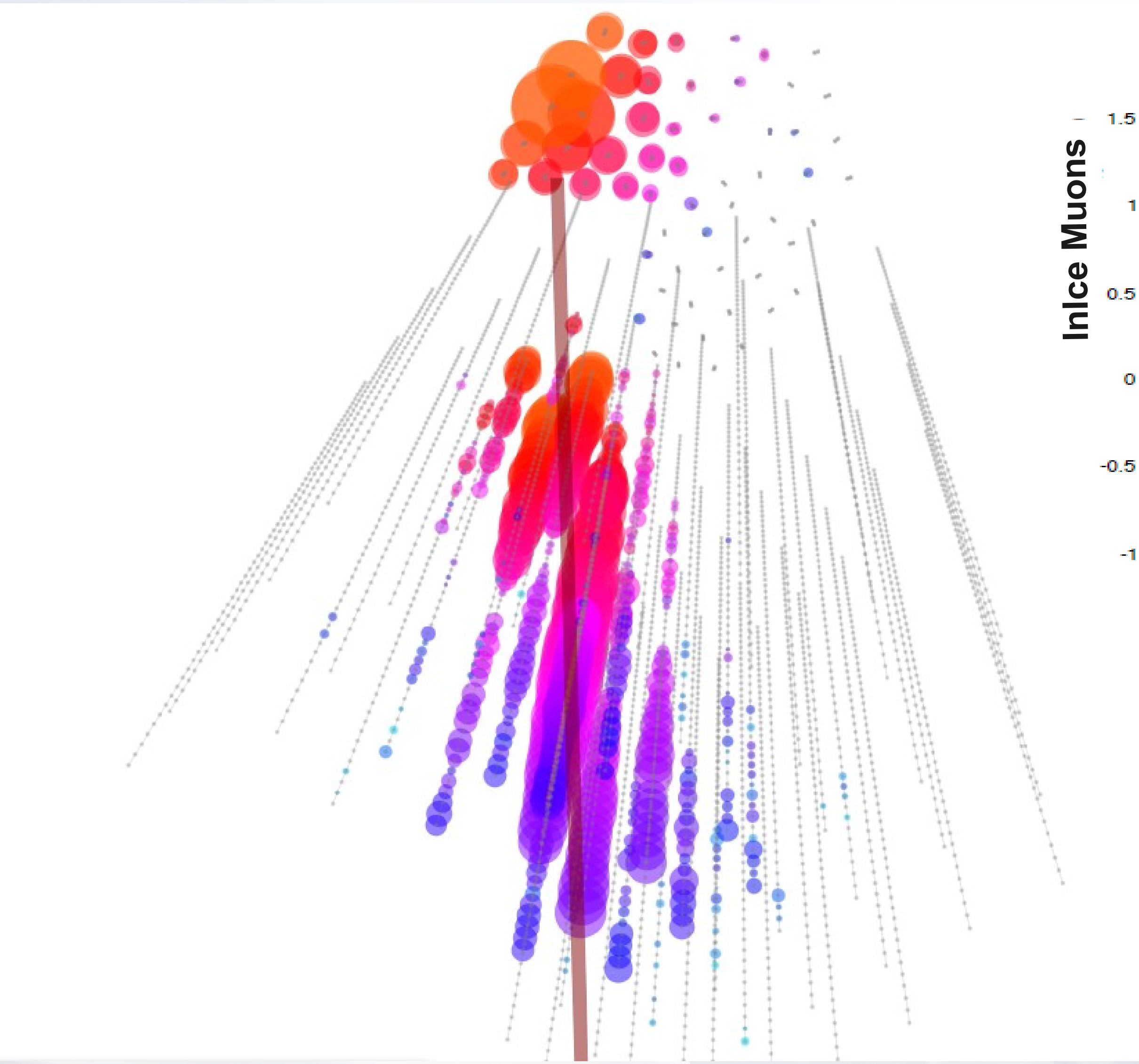


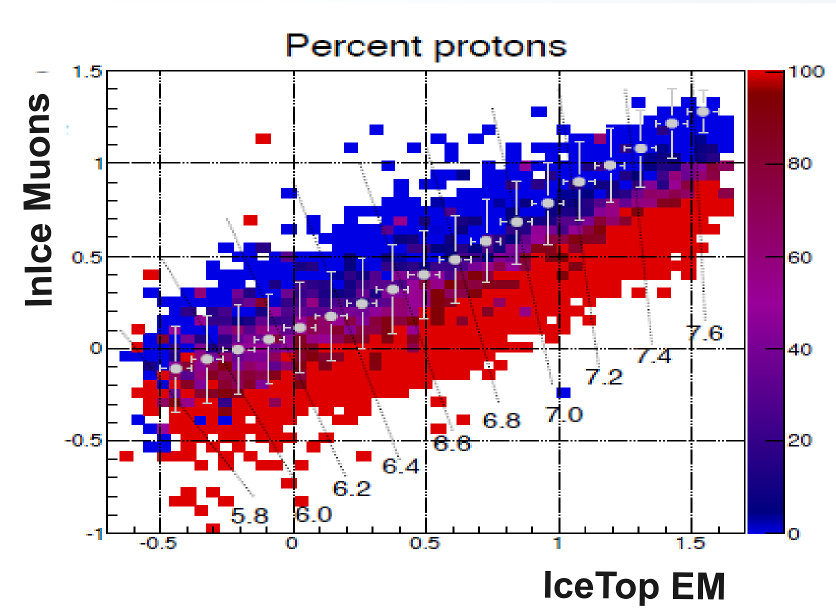

Reconstructed Primary Energy:

150 PeV

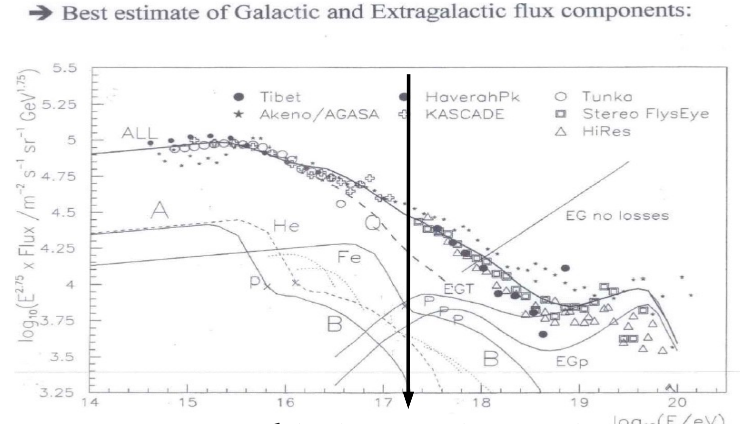
# IceTop EM Content Measurement

Off the Chart (so far)!



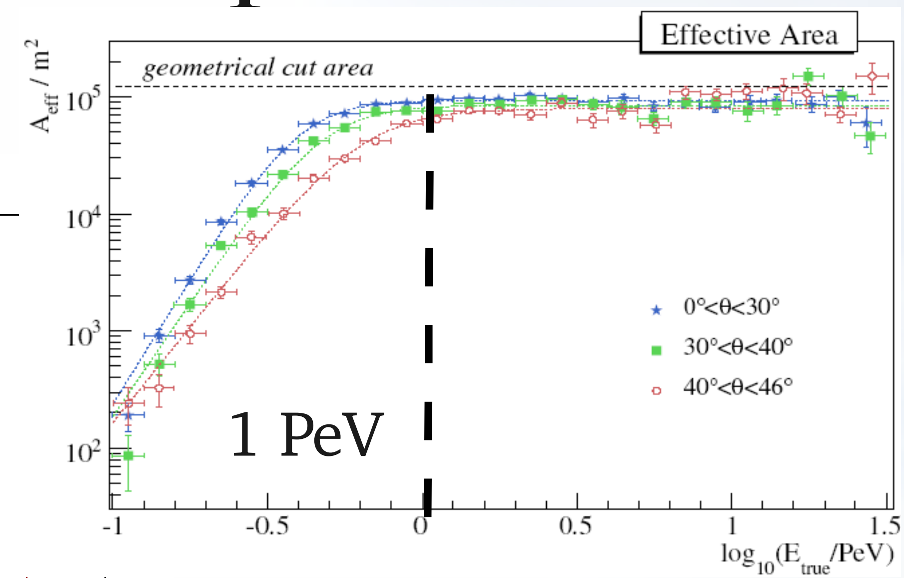


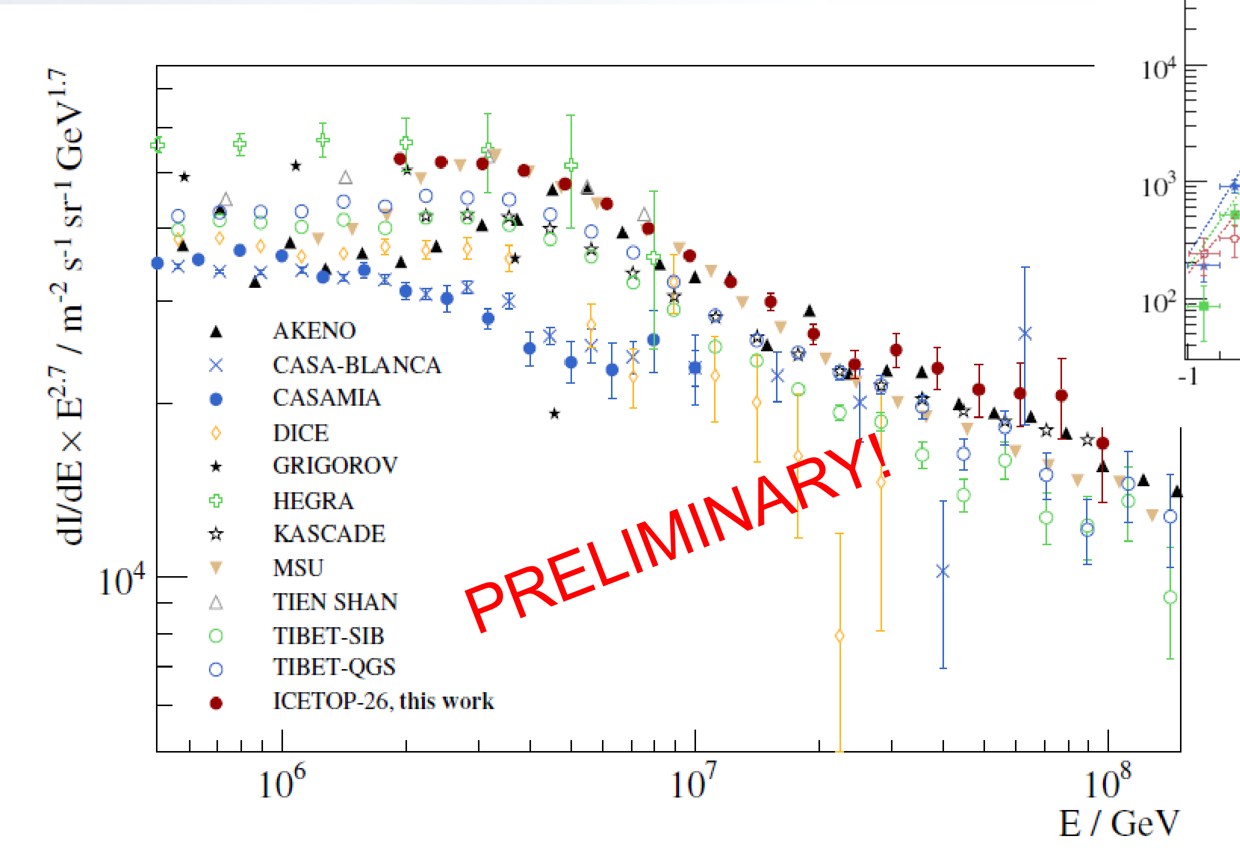

➔ Best estimate of Galactic and Extragalactic flux components:




Located in interesting region!

# 26-Station IceTop Result

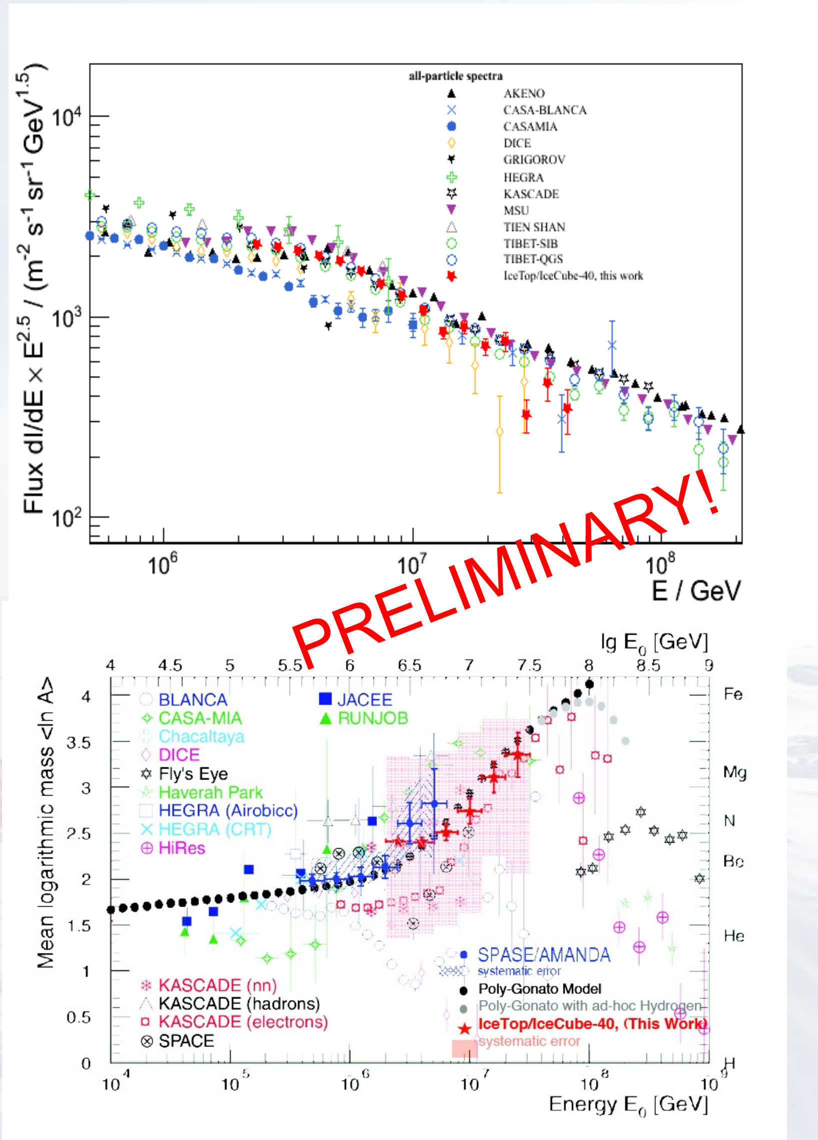



**Overall CR Flux**

agrees with previous results

# IC40 IT/II Result

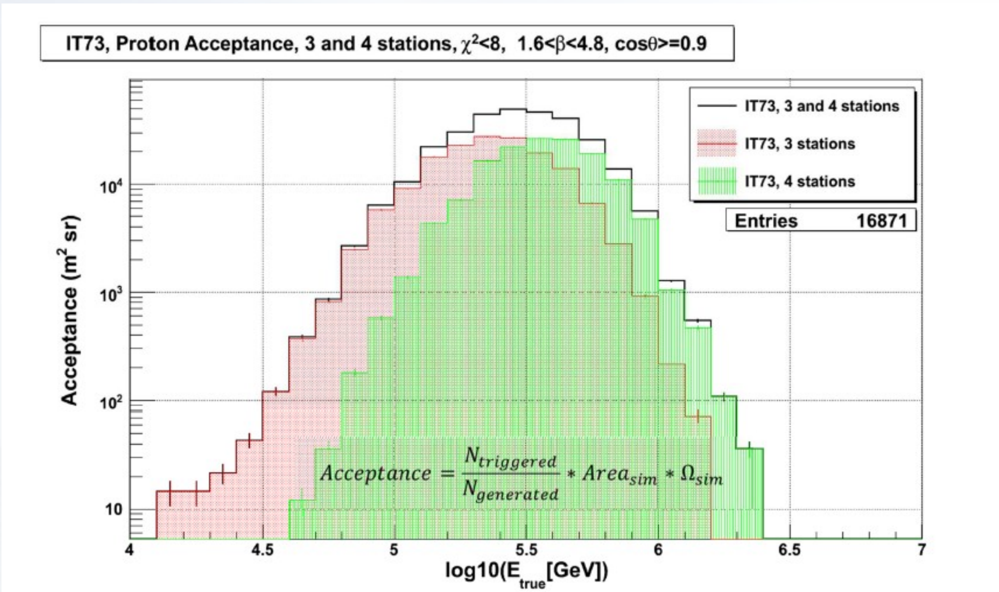


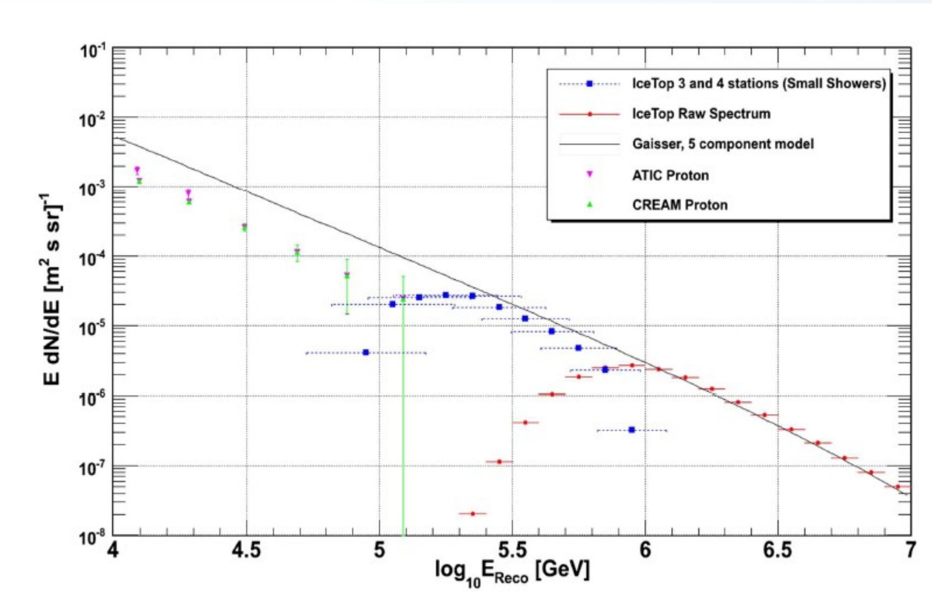

**Overall CR Flux**
agrees with previous results

Physics is limited by InIce

**Mean (log) CR Mass**
agrees with previous results

# LE IceTop Shower Analysis




Use of 3- and 4-Station events to bridge gap between ground and satellite-based experiments (100 TeV – 1 PeV)

# "Poly-gonato" Model

Knee caused by sharp cutoff in individual components

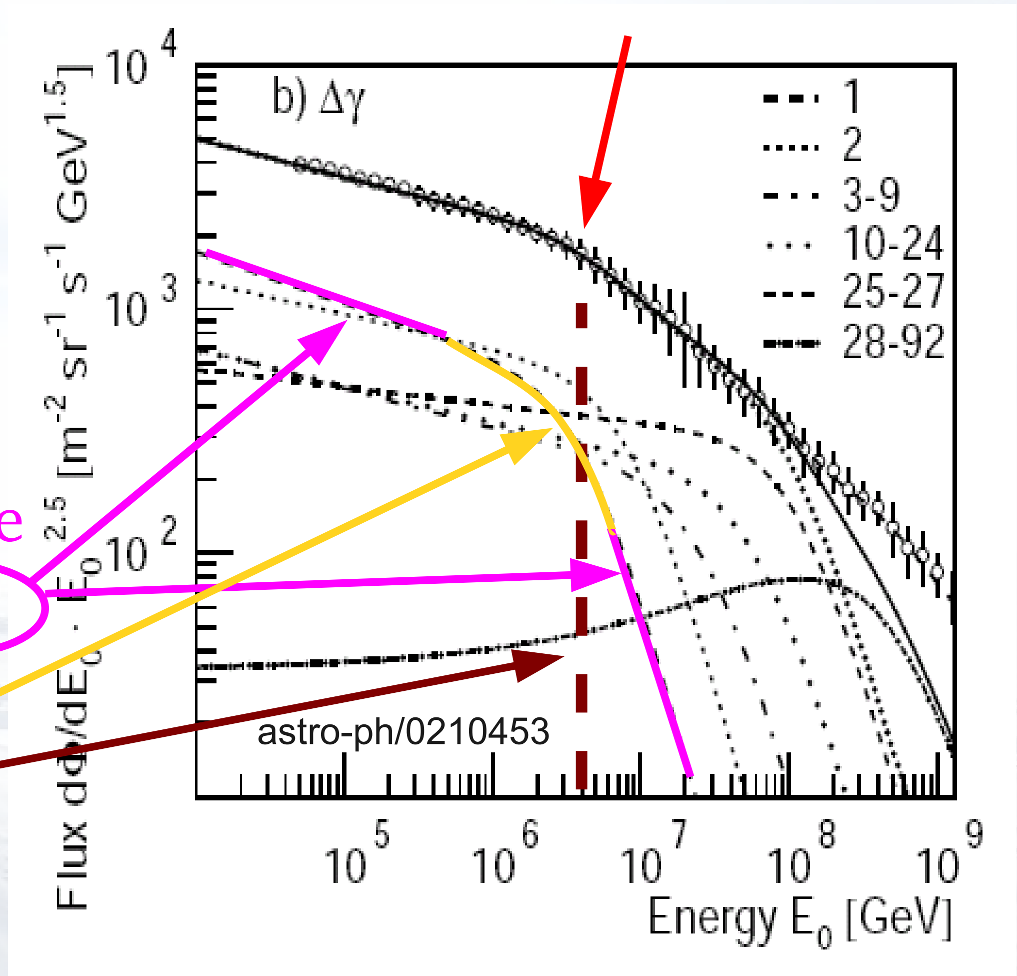
Smoothness of Transition

Slope Change

$$\frac{d\Phi_z}{dE_0} = \Phi_Z^0 \left[ 1 + \left( \frac{E_0}{E_{trans}} \right)^{\epsilon_c} \right]^{\frac{-\Delta\gamma}{\epsilon_c}}$$

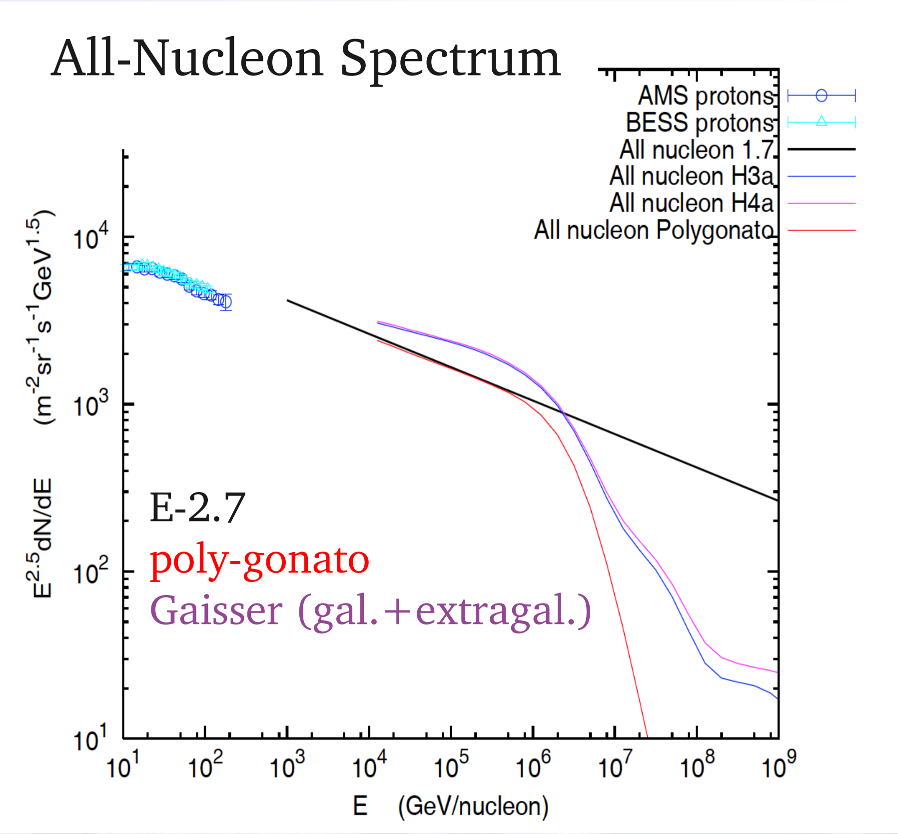
Transition Energy

CR-Knee



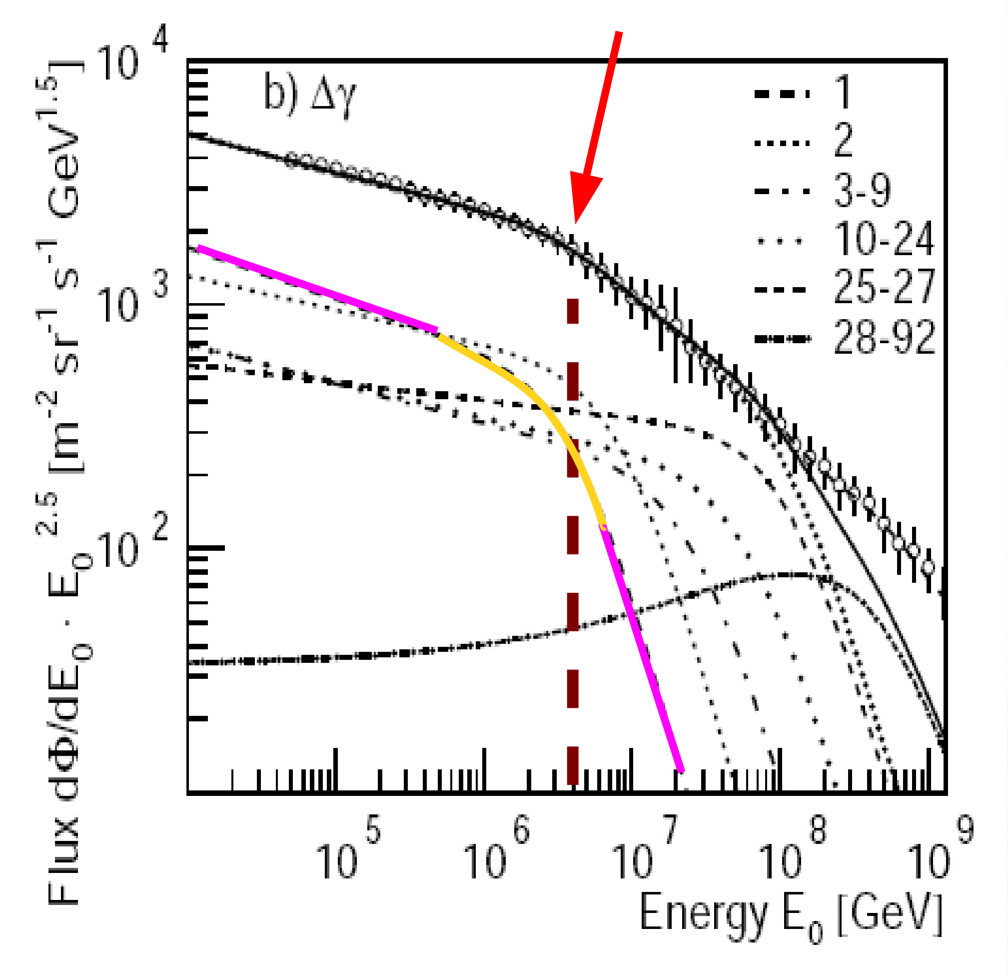

Primary composition becomes heavier

# "Poly-gonato" Model




Cutoff of Energy **per nucleon** in poly-gonato models

CR-Knee




Primary composition becomes heavier

# Influence of Cutoff on Muon Spectrum (Conventional)

## "Poly-Gonato" Benchmark Models

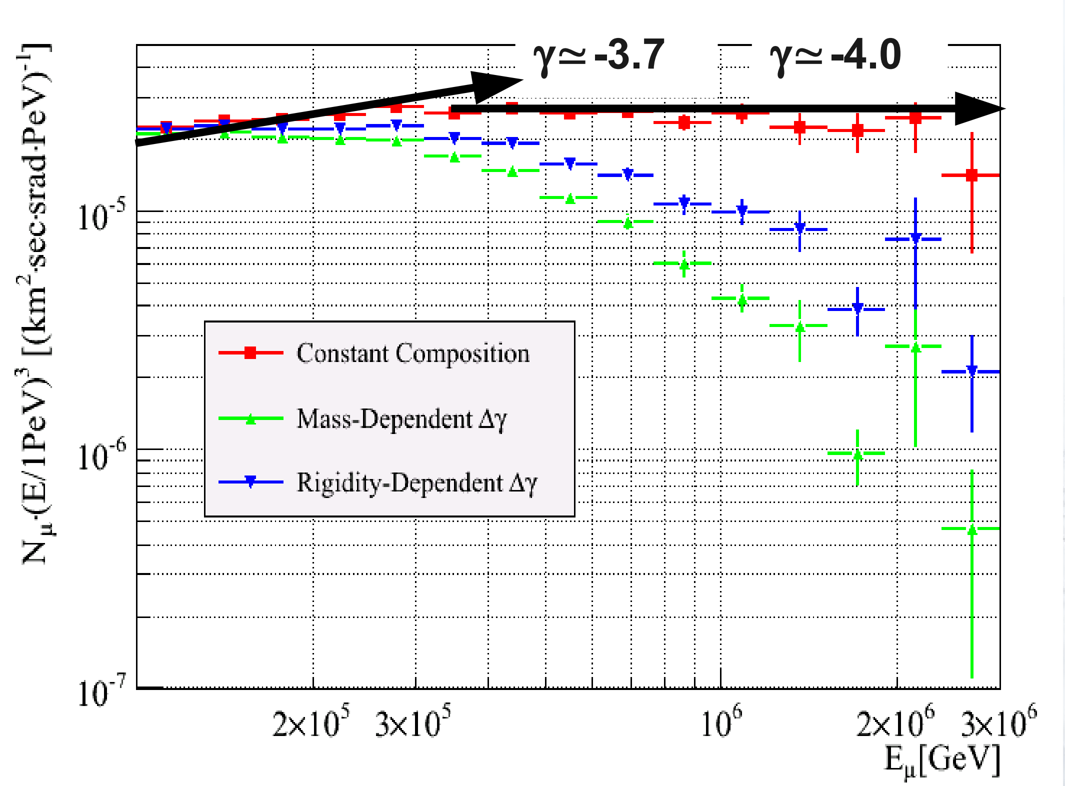
| cut-off: | rigidity dependent | mass dependent | constant | |
|---|---|---|---|---|
| $\hat{E}_Z =$ | $\hat{E}_p \cdot Z$ | $\hat{E}_p \cdot A$ | $\hat{E}_p$ | |
| $\hat{E}_p$ [PeV] = | $4.51 \pm 0.52$ | $3.66 \pm 0.41$ | $3.50 \pm 0.38$ | common $\gamma_c$ |
| $\gamma_c =$ | $-4.68 \pm 0.23$ | $-7.82 \pm 1.09$ | $-3.06 \pm 0.02$ | |
| $\epsilon_c =$ | $1.87 \pm 0.18$ | $2.30 \pm 0.23$ | $1.94 \pm 0.51$ | |
| $\chi^2$/d.o.f = | 0.116 | 0.290 | 0.086 | |
| $\hat{E}_p$ [PeV] = | $4.49 \pm 0.51$ | $3.81 \pm 0.43$ | $3.68 \pm 0.39$ | common $\Delta\gamma$ |
| $\Delta\gamma =$ | $2.10 \pm 0.24$ | $5.70 \pm 1.23$ | $0.44 \pm 0.02$ | |
| $\epsilon_c =$ | $1.90 \pm 0.19$ | $2.32 \pm 0.22$ | $1.84 \pm 0.45$ | |
| $\chi^2$/d.o.f. = | 0.113 | 0.292 | 0.088 | |

Rigidity | Mass | Constant Composition

-Dependent Cutoff

astro-ph/0210453

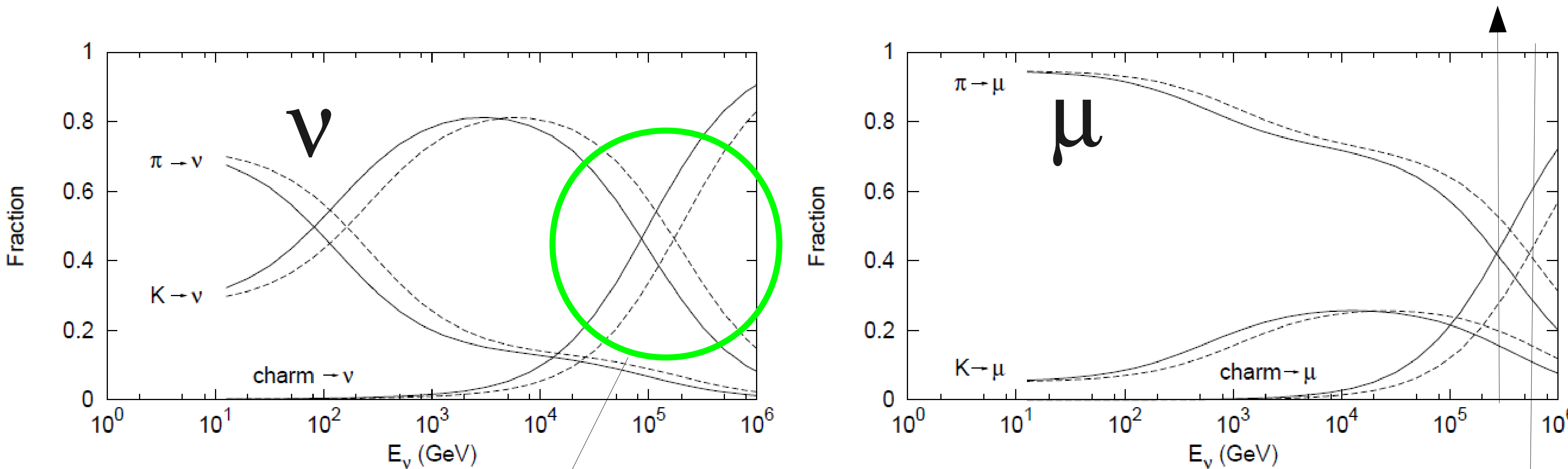
## Single Muon Spectrum



# Prompt Leptons from Charm Decay

Light mesons: Flux α $1/\cos\theta_{zen}$
Prompt: constant angular Flux

For **vertical** muons, prompt component becomes dominant at ≈**200 TeV**

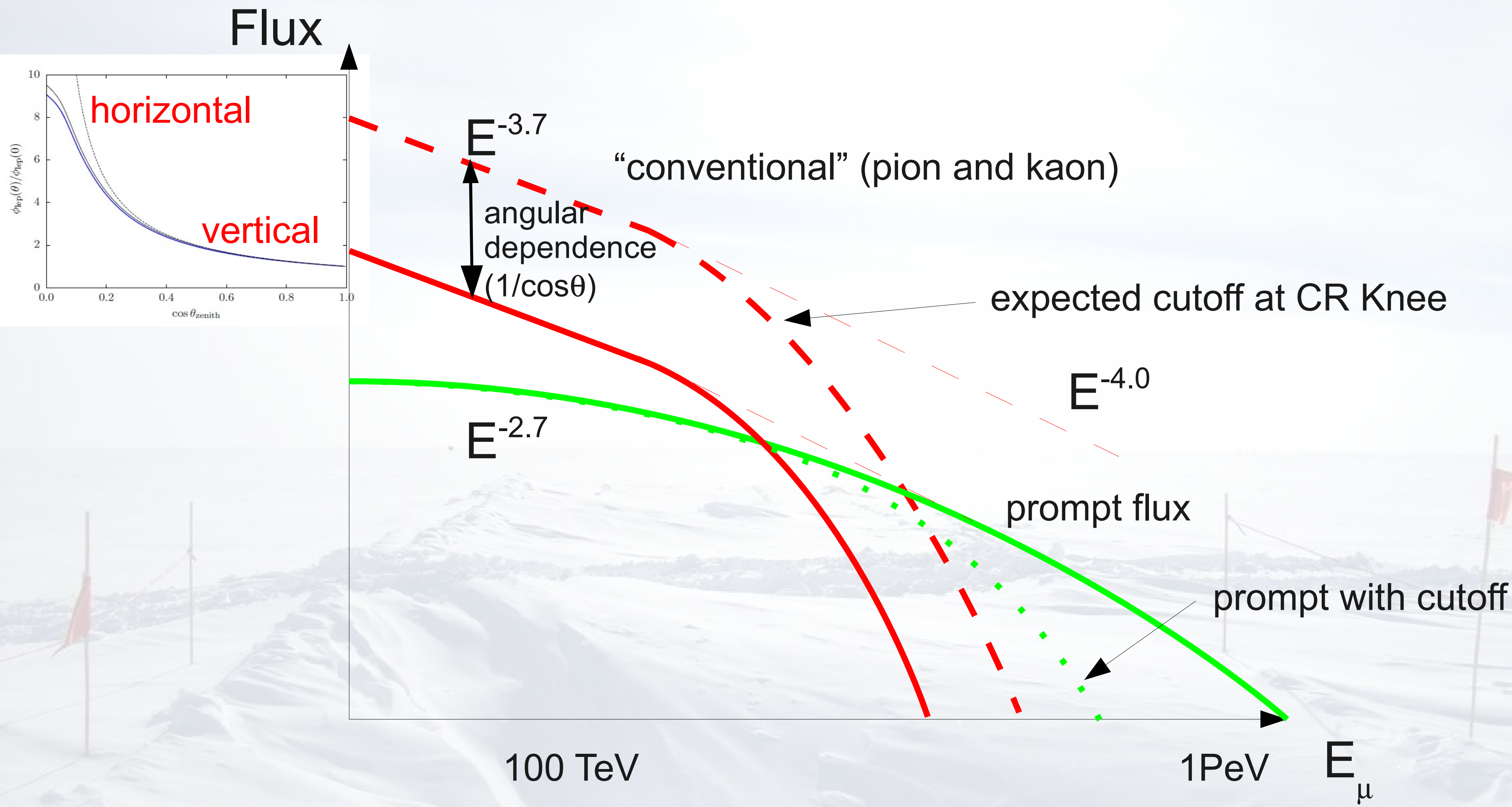



Source: T. Gaisser

Charm represents major systematic uncertainty for neutrinos above 100 TeV

At **60°**, light meson decay dominates up to ≈**500TeV**

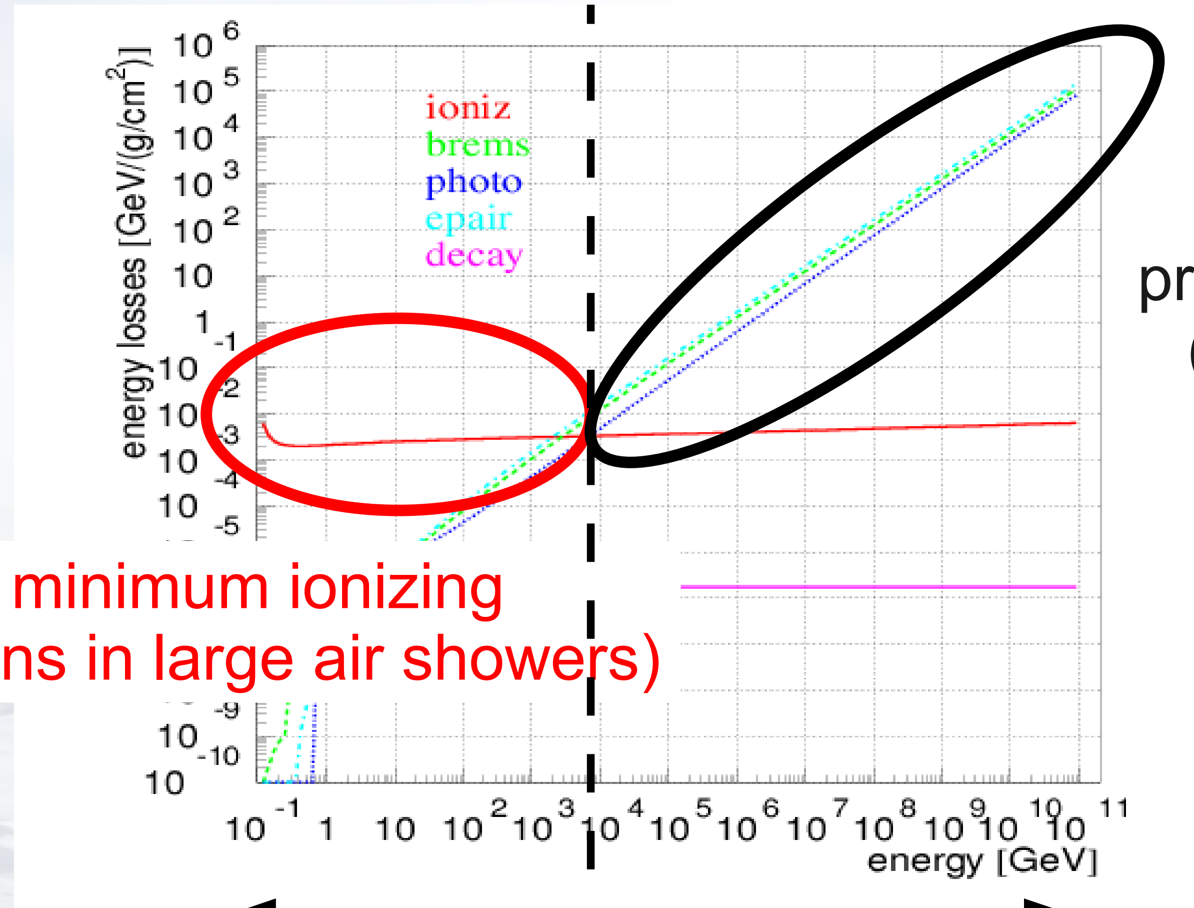
# Muon Spectrum (Qualitative)




prompt/non-prompt ratio is angular-dependent

# Muon Energy Losses in Matter (Ice)

few TeV




proportional losses
(high-E muons)

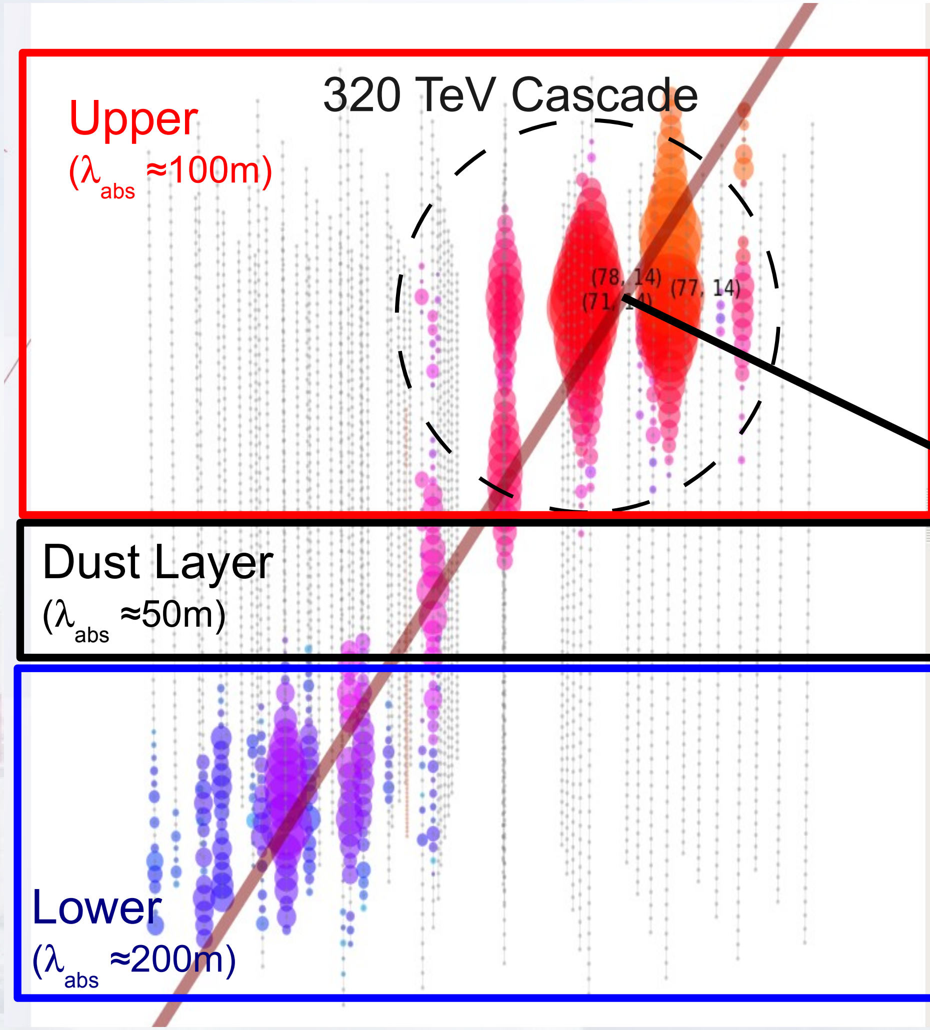
minimum ionizing
(muons in large air showers)

hep-ph/0407075

continuous

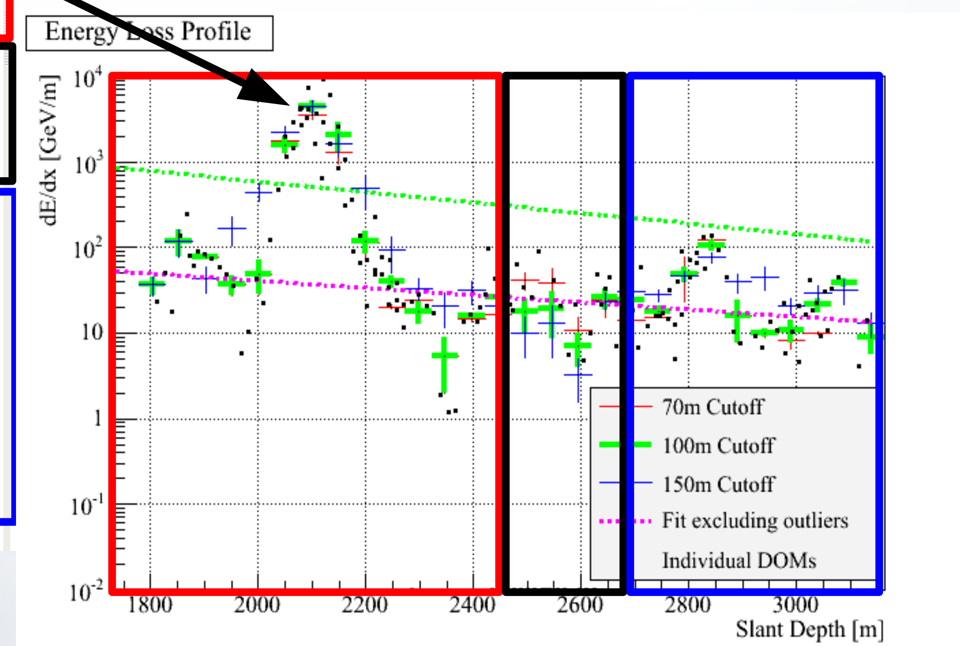
stochastic

# HE Muon




Energy deposition dominated by one HE muon

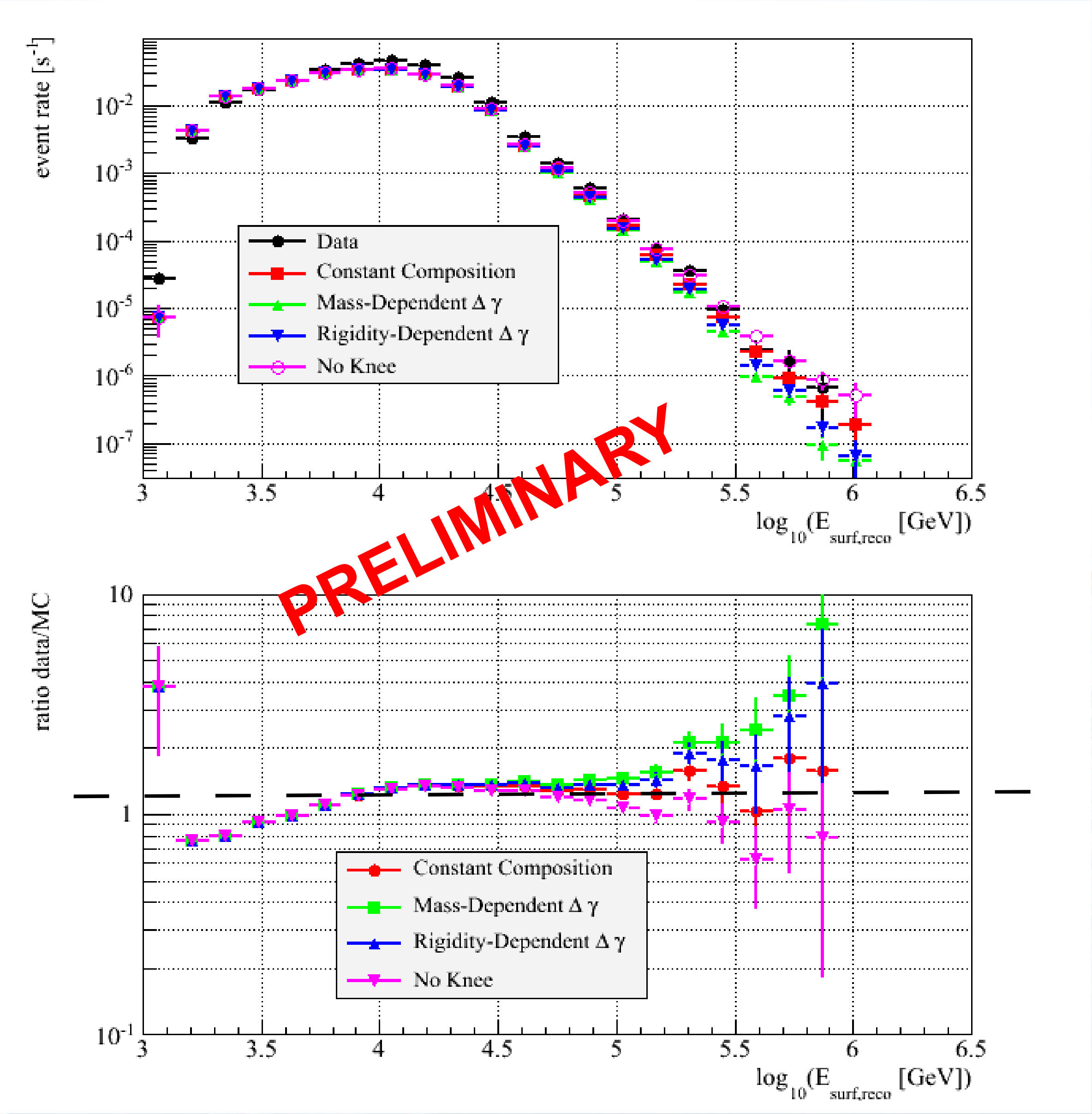
Here: 860TeV surface energy (estimated) - most energetic lepton ever observed



# All-Sky HE Muon Flux

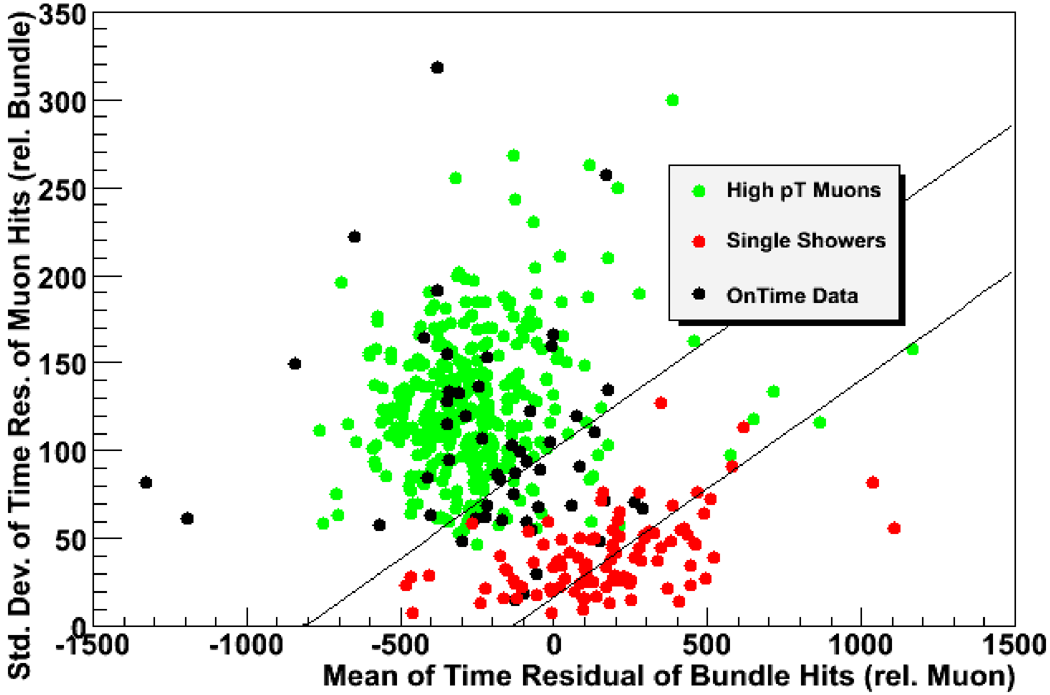
Based on 10% of IceCube-59 Data

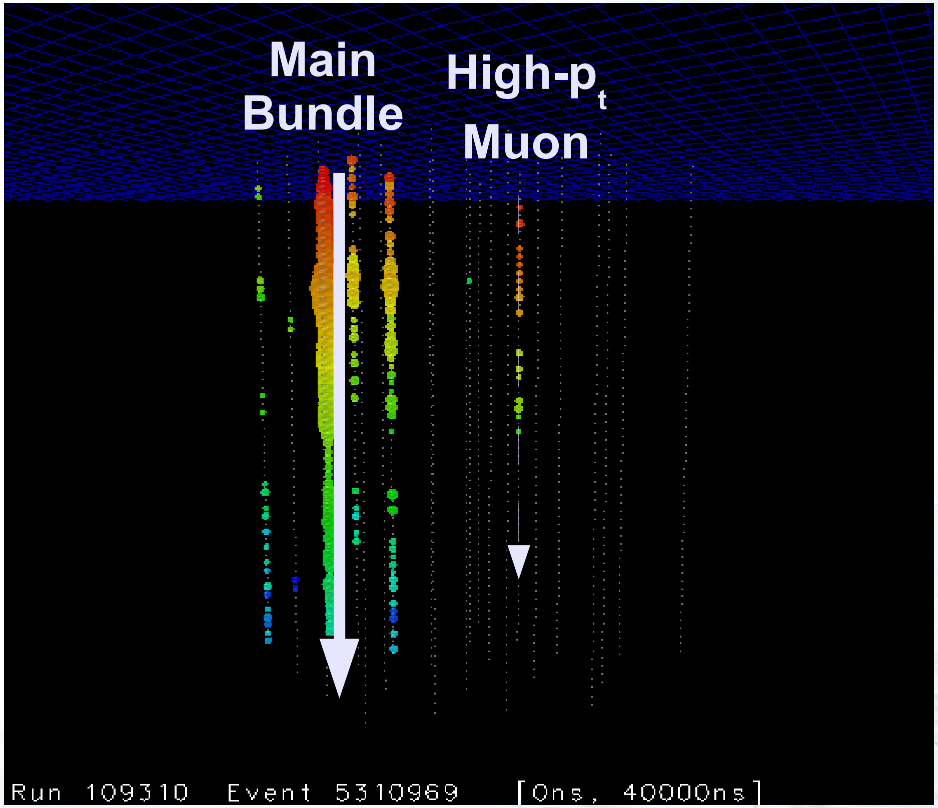
No indication for spectral cutoff so far



# High-$p_t$ Muons

L. Gerhard and S. Klein, ICRC 2011

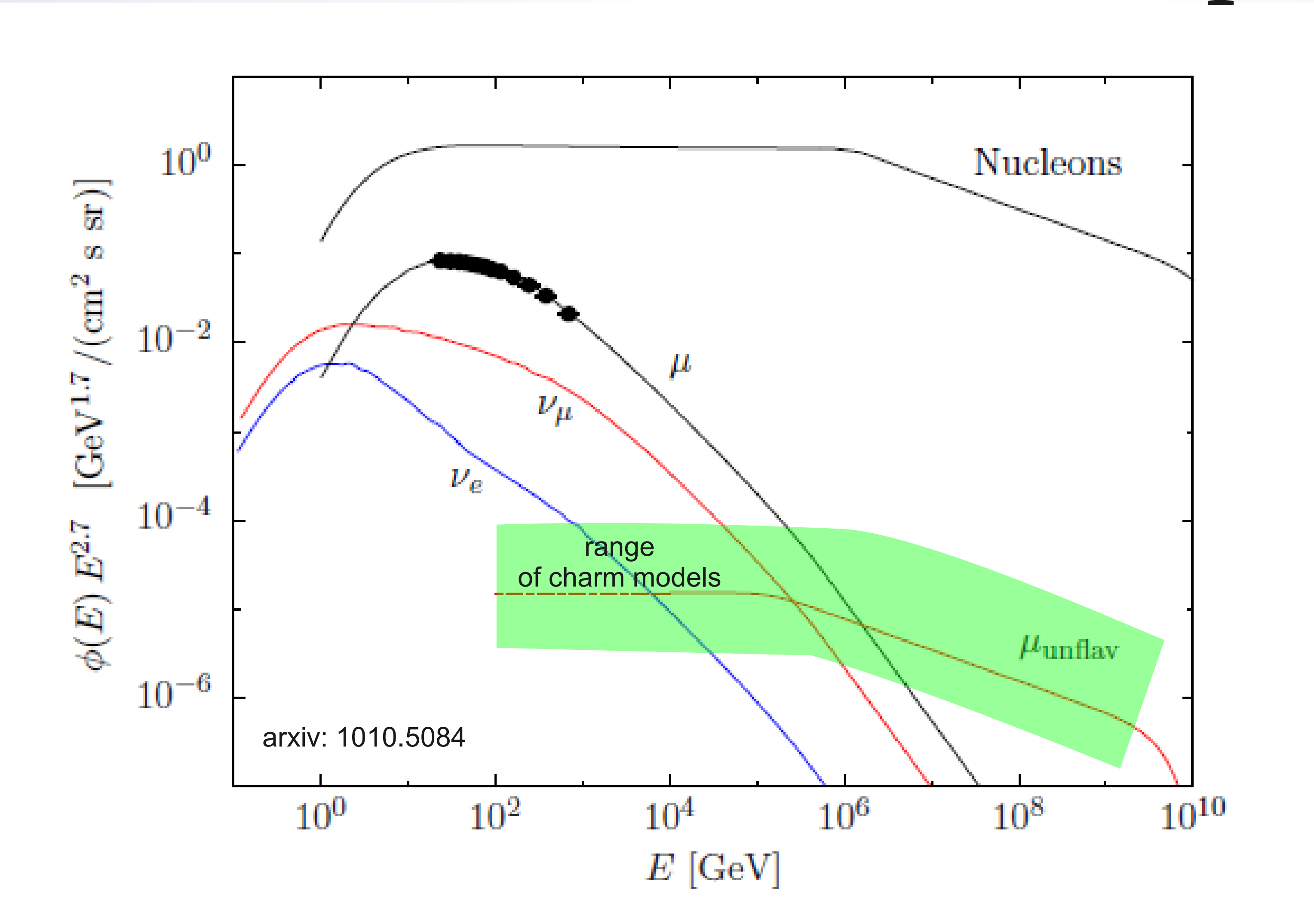



Sensitive to composition and heavy meson production

Theoretical interpretation challenging

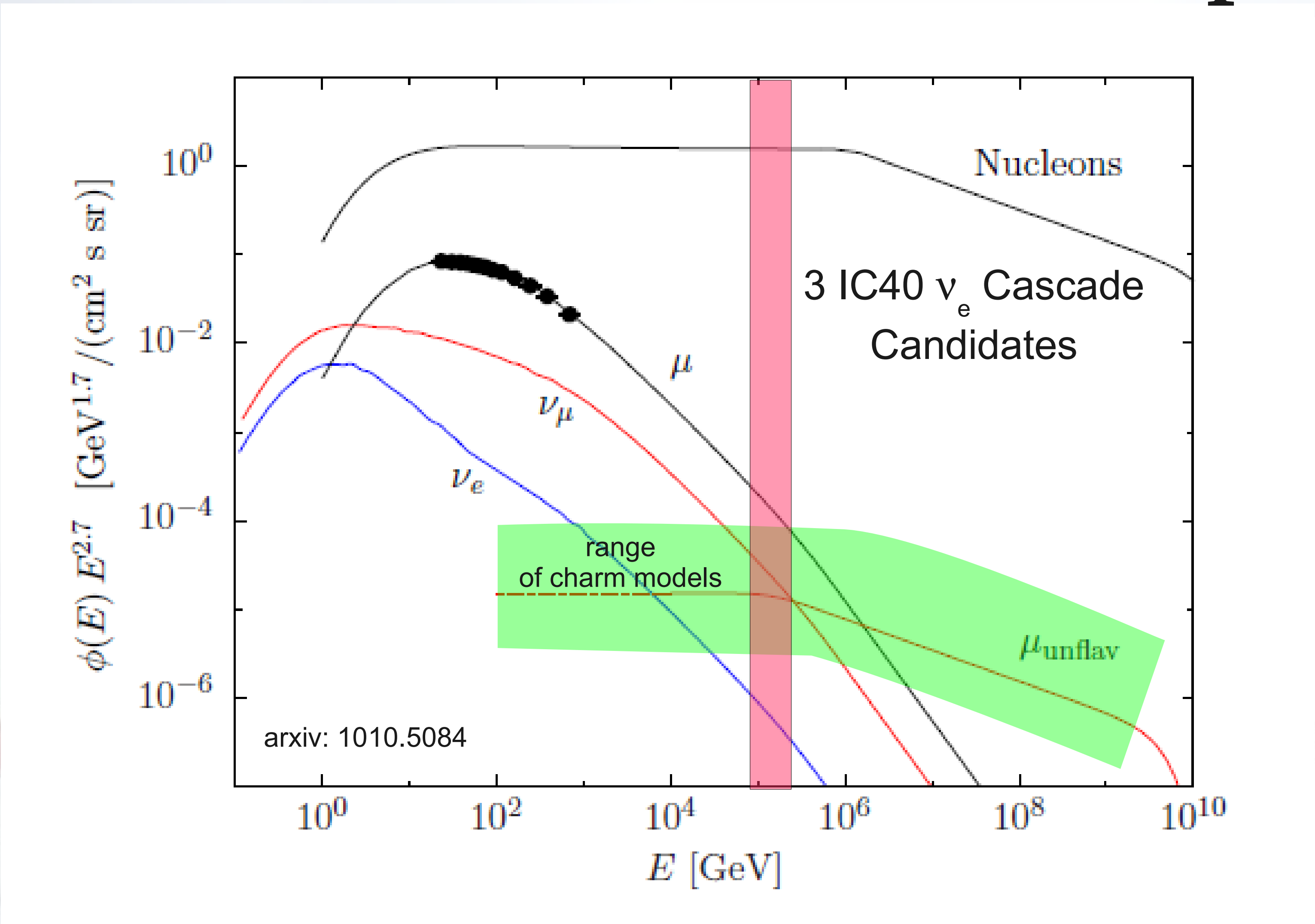
# Neutrinos and Prompt

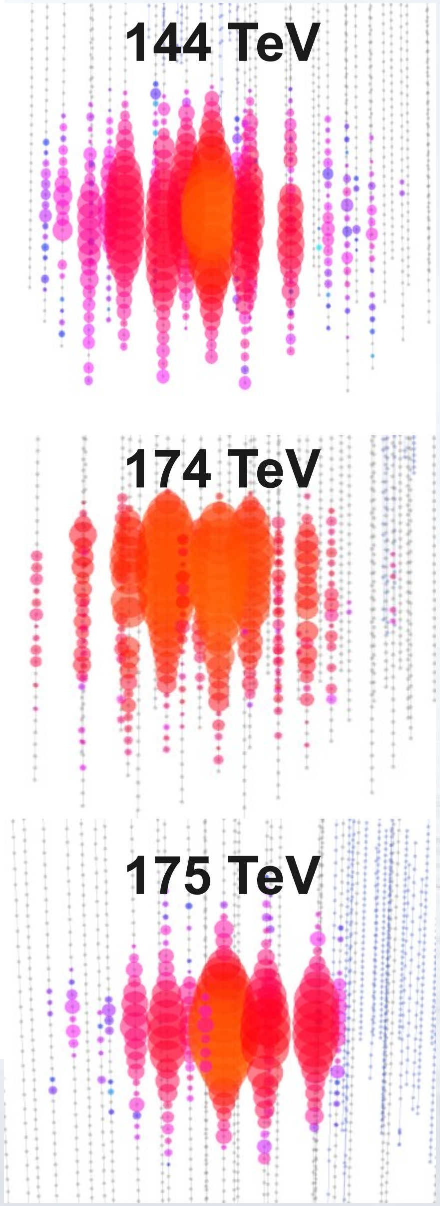



Prompt Flux is (approx.) equal for all light leptons ($m_{\text{lepton}} << m_{\text{charm}}$)

Non-prompt flux varies due to different parent particles

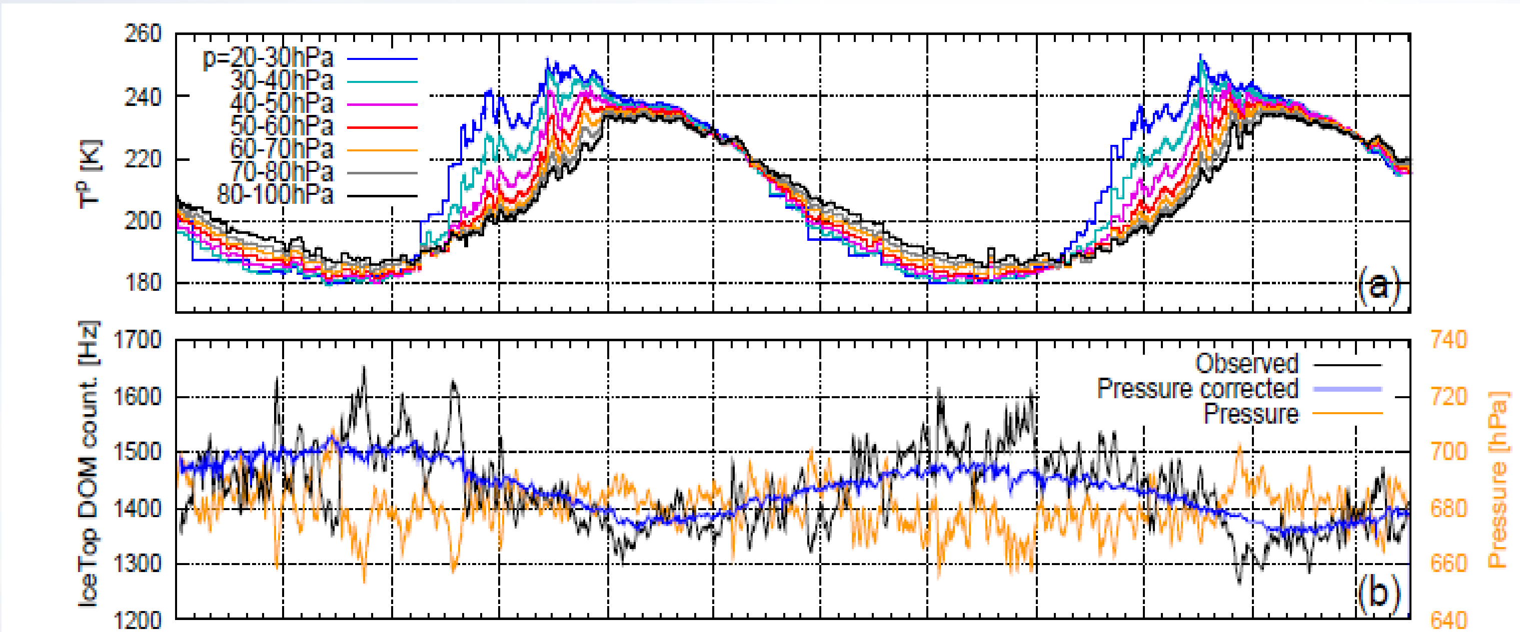
# Neutrinos and Prompt




Three strong $\nu_e$ candidate events above 100 TeV in IC40 (+1 in IC22)

# Seasonal Variations: IceTop




Atmospheric Temperature

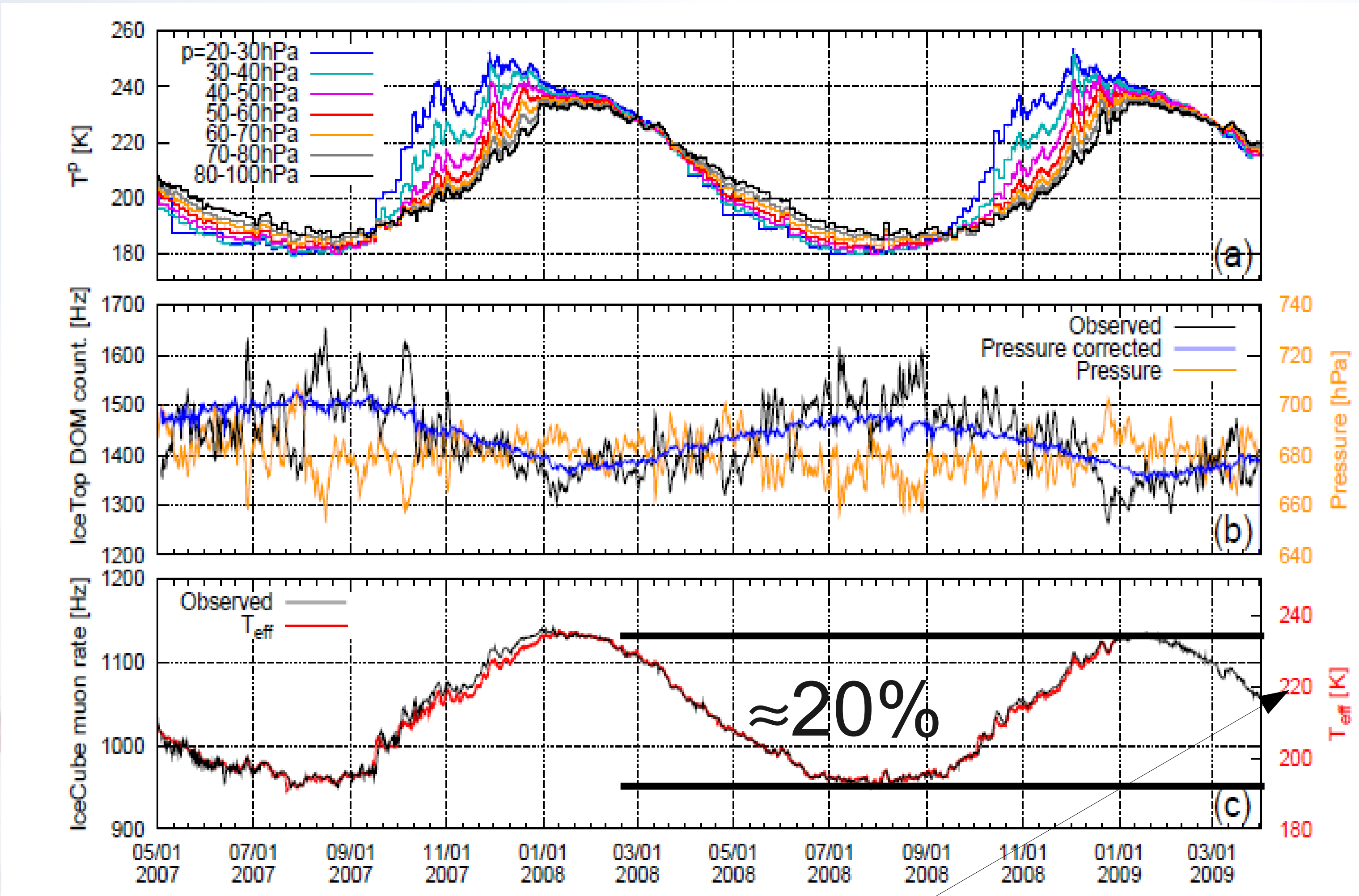
IceTop (**barometric anti-correlation, temperature anti-correlation**)

First Order: Barometric Anti-Correlation (matter above detector)

Second Order: Temperature Anti-Correlation (Muon vs. EM shower content)

S. Tilav et al., arXiv:1001.0776

# Seasonal Variations: InIce




Atmospheric Temperature

IceTop (**barometric anti-correlation, temperature anti-correlation**)

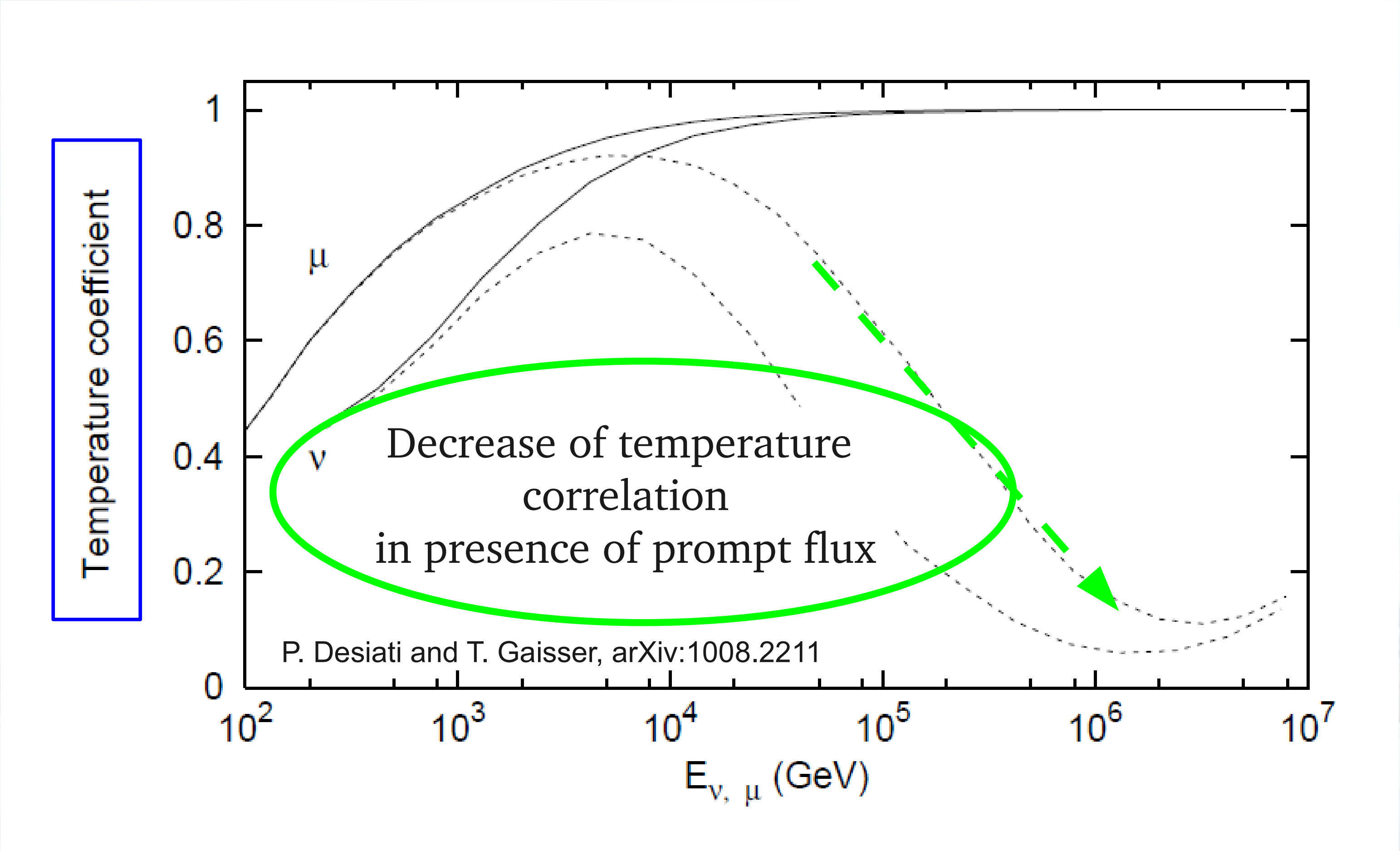
InIce (**temperature correlation**)

$T_{eff}$: Temperature weighted by muon production probability

$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X)\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}{\int_0^\infty \frac{dX}{X}\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}$$

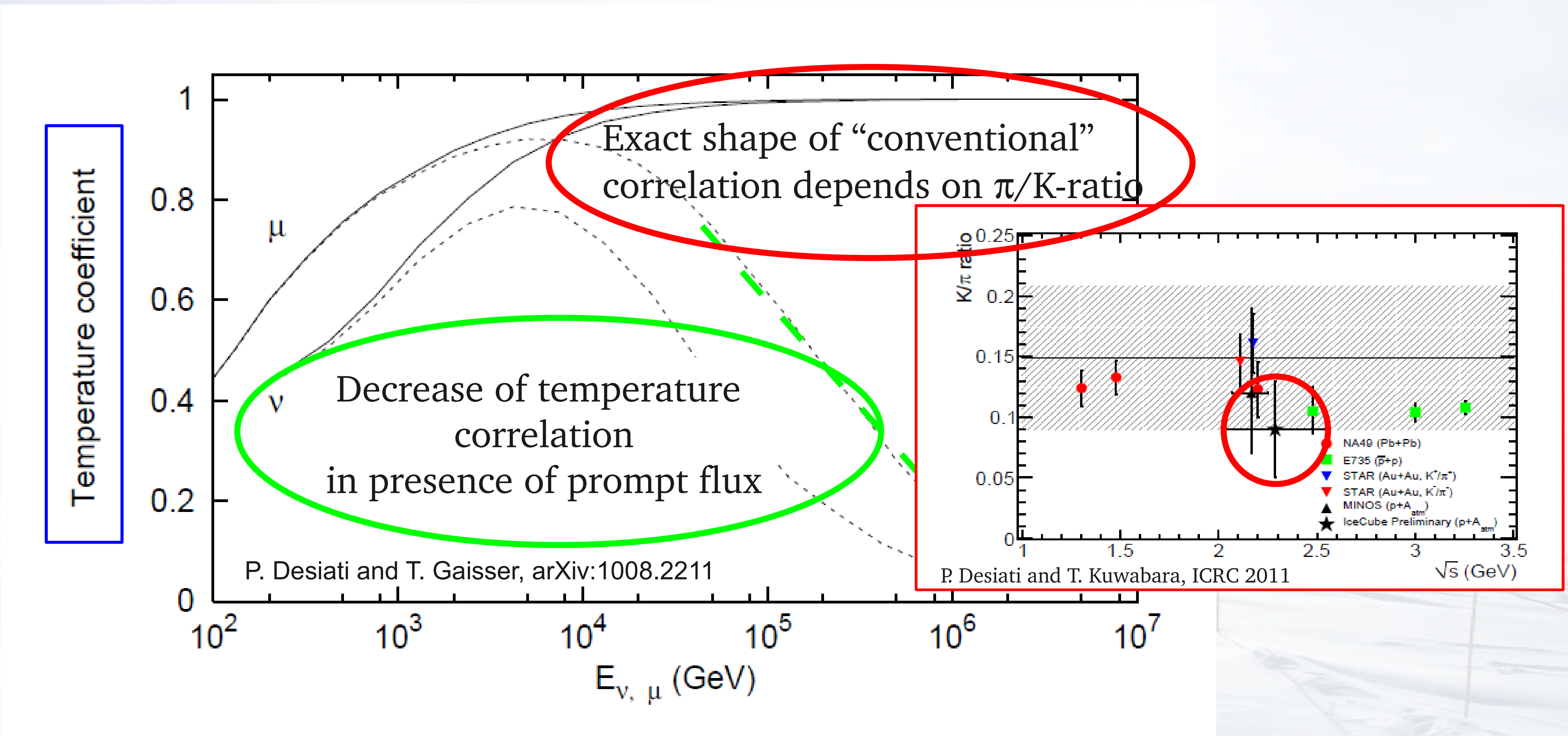
S. Tilav et al., arXiv:1001.0776

# InIce Temperature Correlation




$$\alpha(E,\theta) = T \frac{1}{\phi(E,\theta)} \frac{\mathrm{d}\phi(E,\theta)}{dT}$$

# InIce Temperature Correlation




$$\alpha(E,\theta) \ = \ T \, \frac{1}{\phi(E,\theta)} \frac{\mathrm{d}\phi(E,\theta)}{dT}$$

# Physics

Pion/Kaon Ratio

Prompt Leptons

CR Composition

Knee Location

# Measurement

Neutrino Cascades

Angular Muon Distribution

HE Muons

Up-going Neutrino Spectrum

Air Shower EM content (IT)

Seasonal Variations

Total Energy Deposition

High-$p_t$ Muons

Overdetermined problem allows detailed investigation of systematics by requiring consistency between individual measurements.

# Only Extraterrestrial IceCube Signal

13 Dec. 2006:
**Solar Flare** seen in IceTop Count Rate