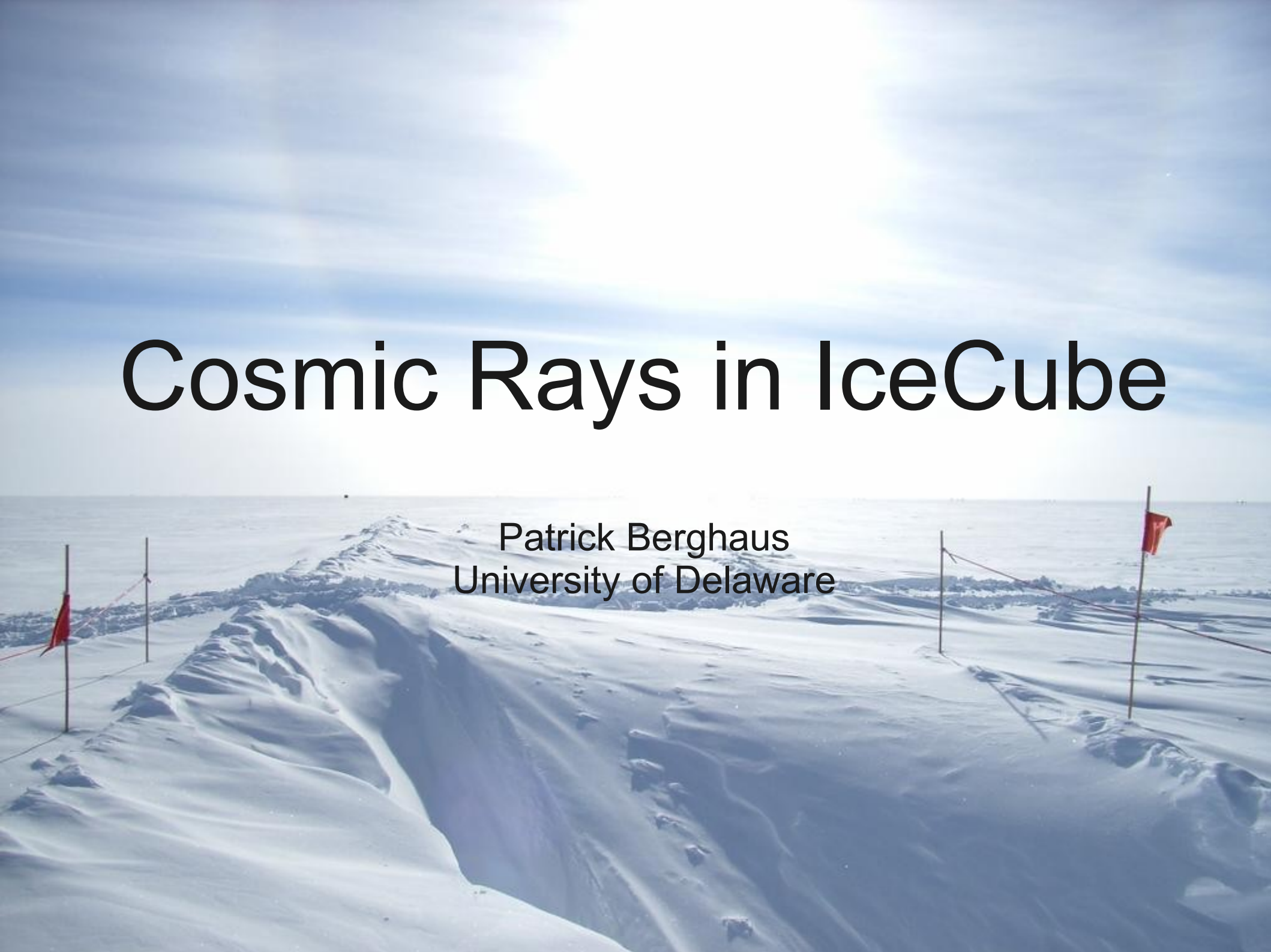
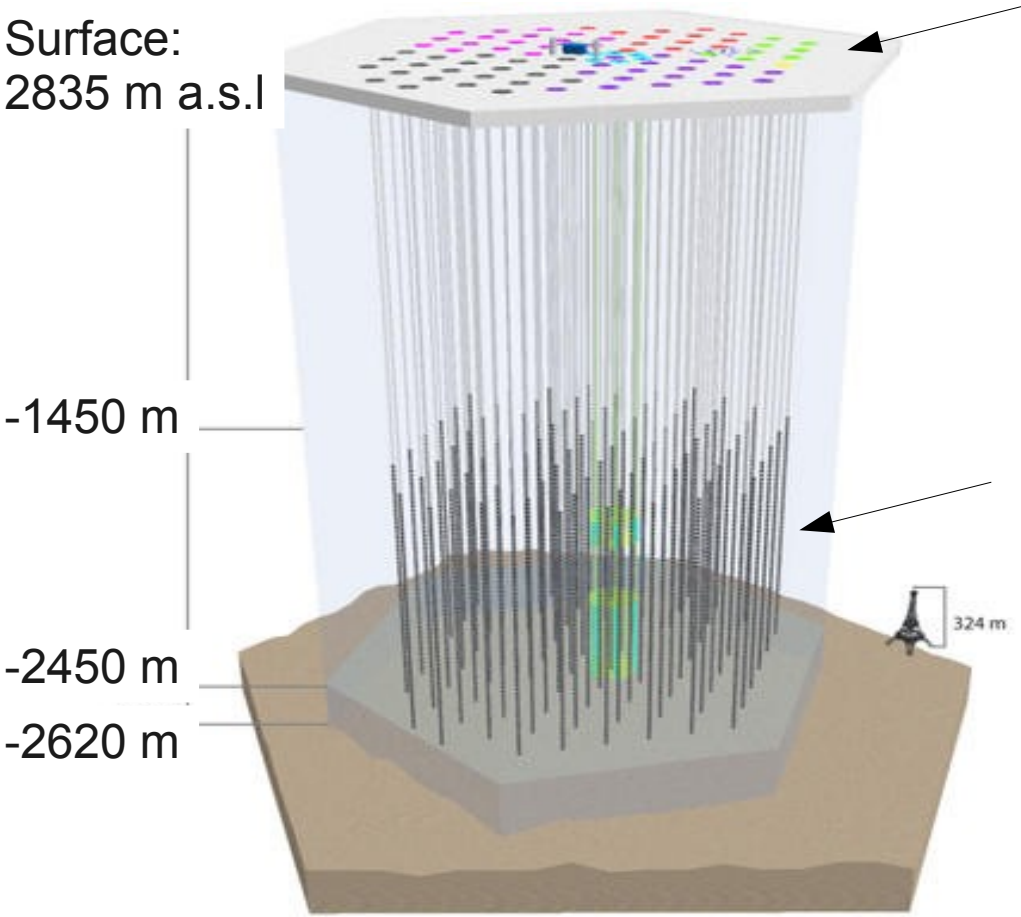


Cosmic Rays in IceCube

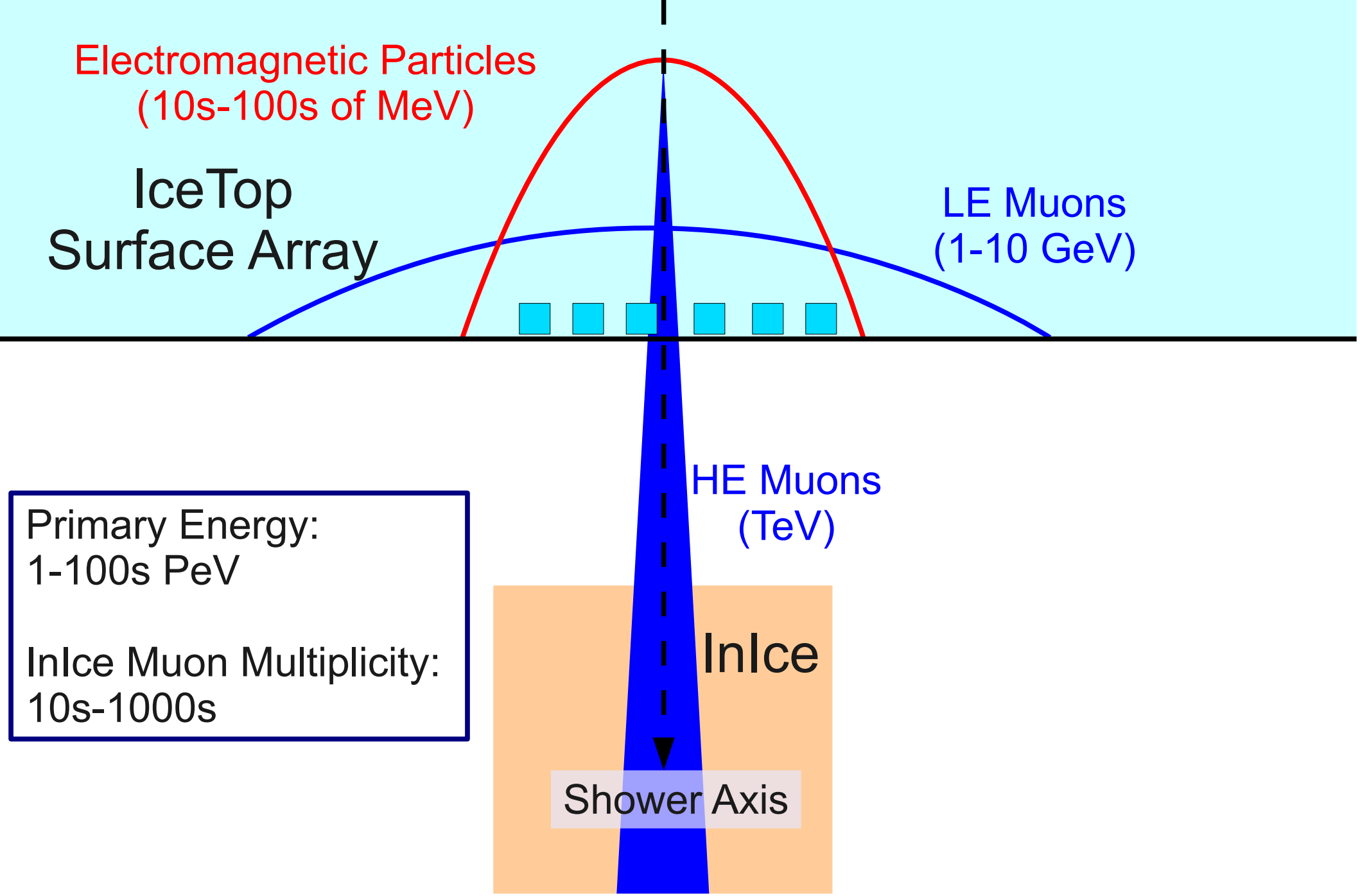
Patrick Berghaus
University of Delaware

IceCube Components



IceTop Surface Array:
$1km^2$ area
LE electromagnetic

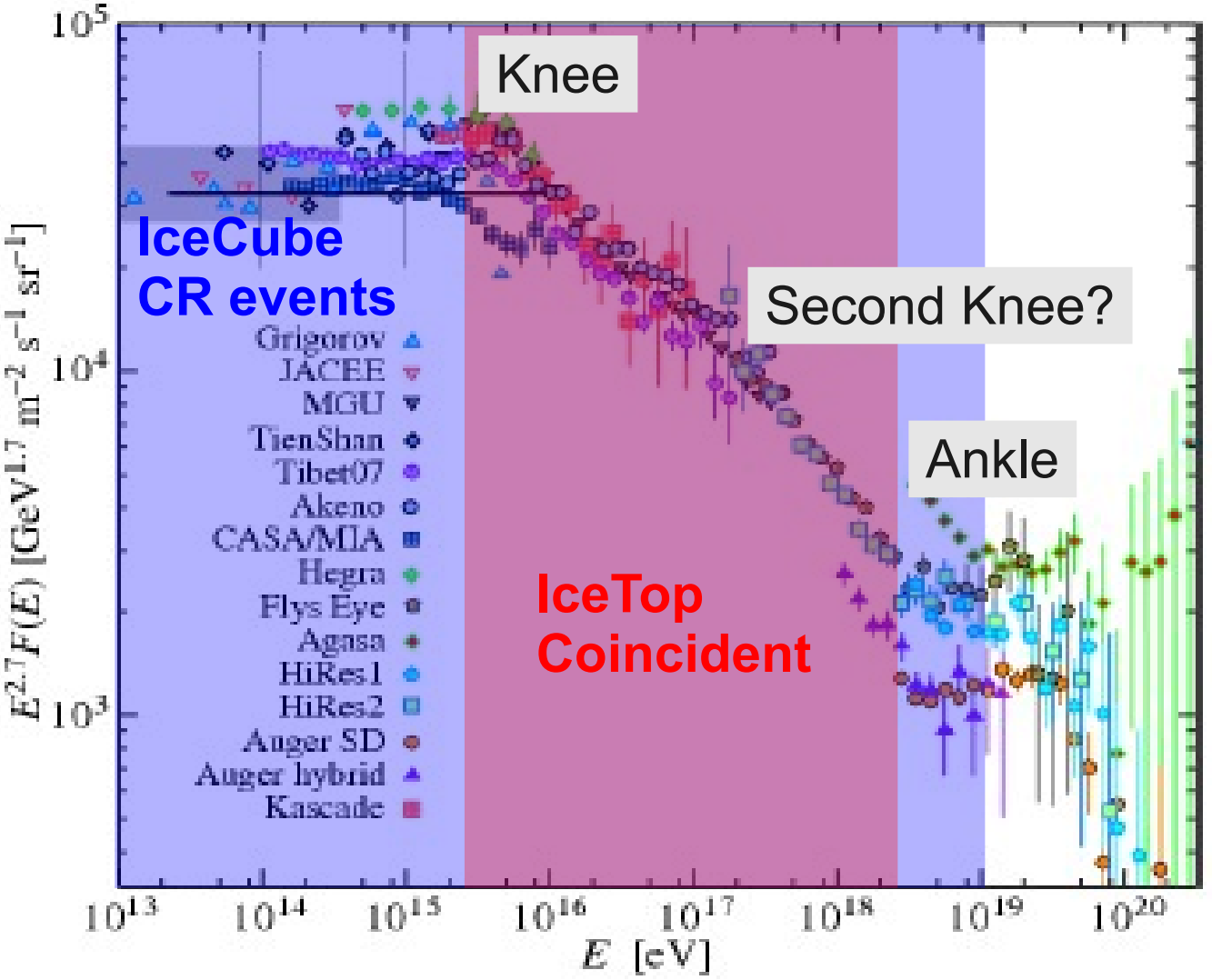
InIce Volume Detector:
$1km^3$ volume
HE muons



Primary Energy:
1-100s PeV

InIce Muon Multiplicity:
10s-1000s

CR Energy range of IceCube/IceTop



Main Science Goals:

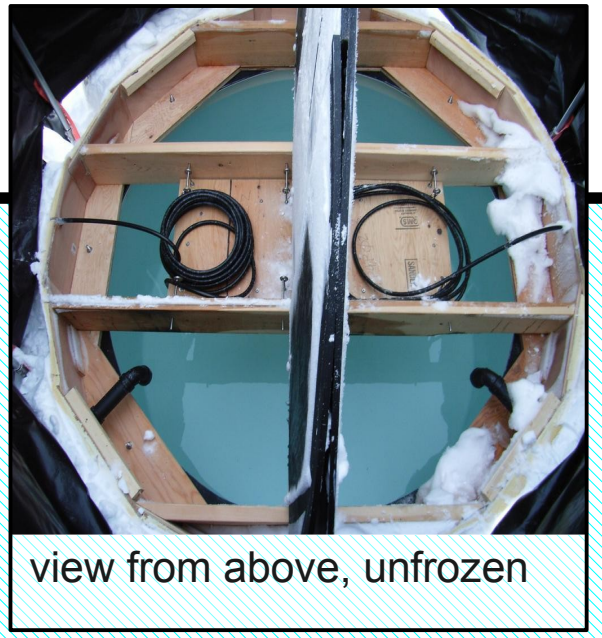
Primary composition change around Knee

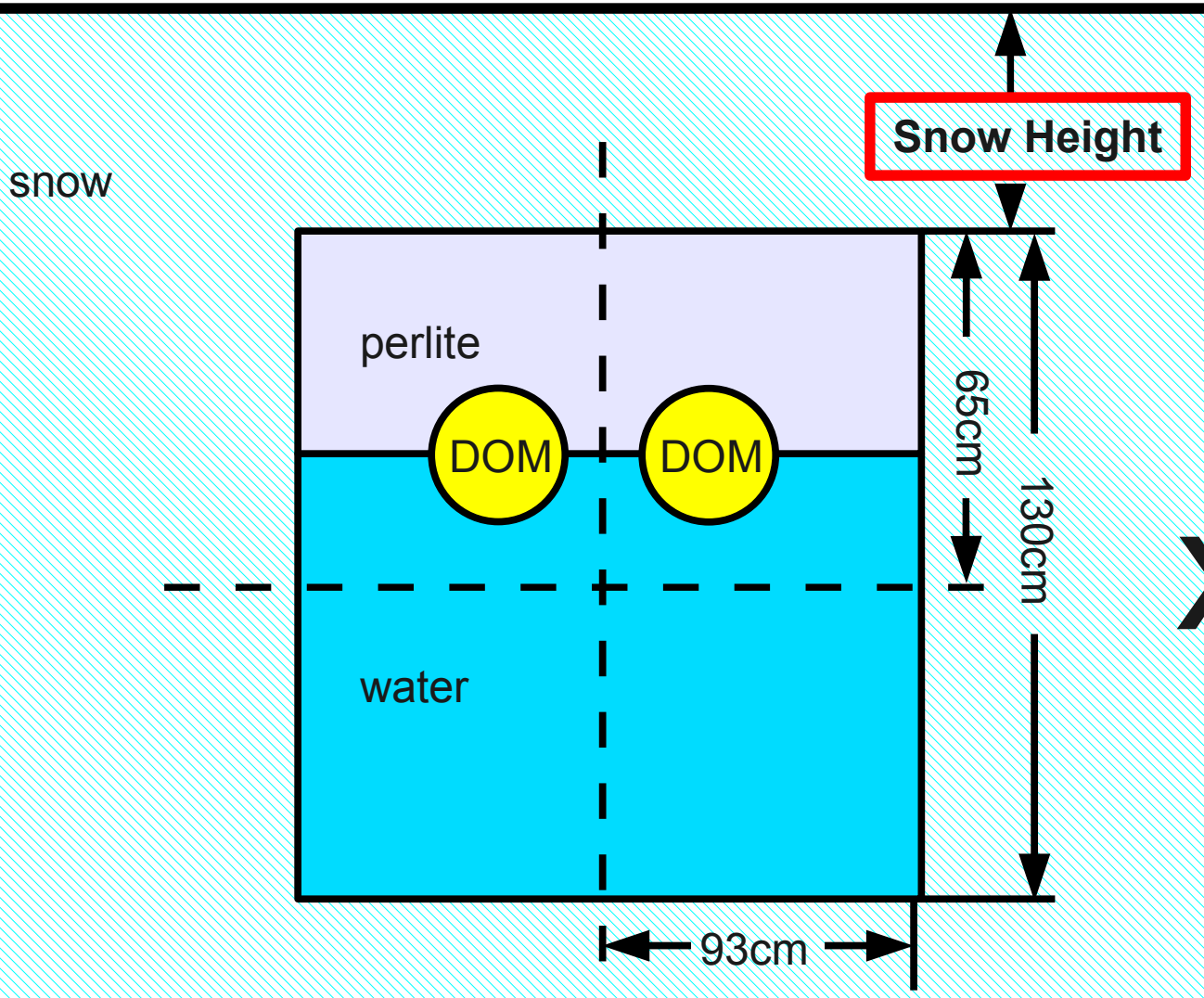
Transition to Extragalactic CR at “Second Knee”?

IceTop Deployment


IceTop Station

IceTop Tank

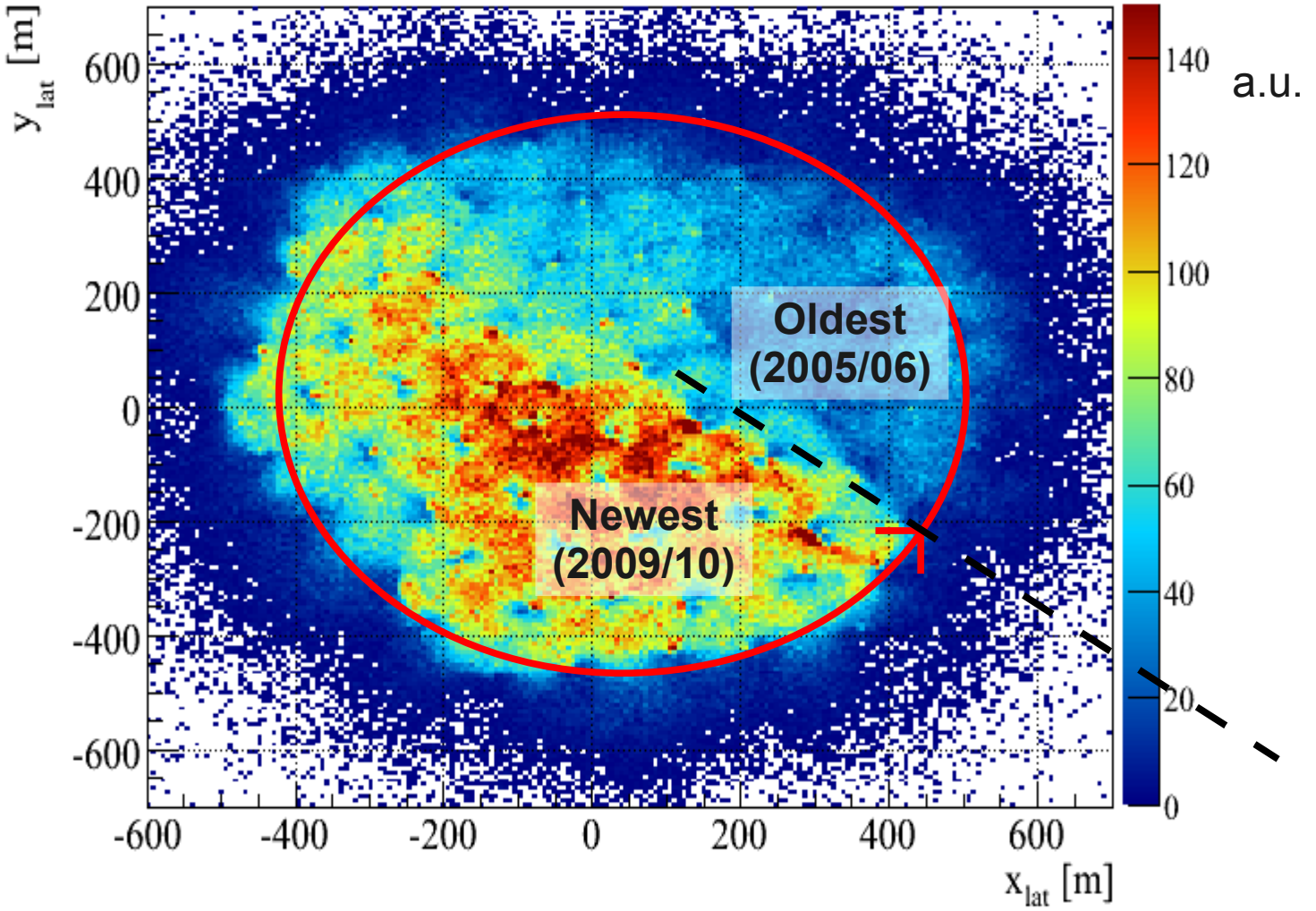

view from above, unfrozen



x2 x78

Effect of Snow Coverage

(Reconstructed Shower Core Position)



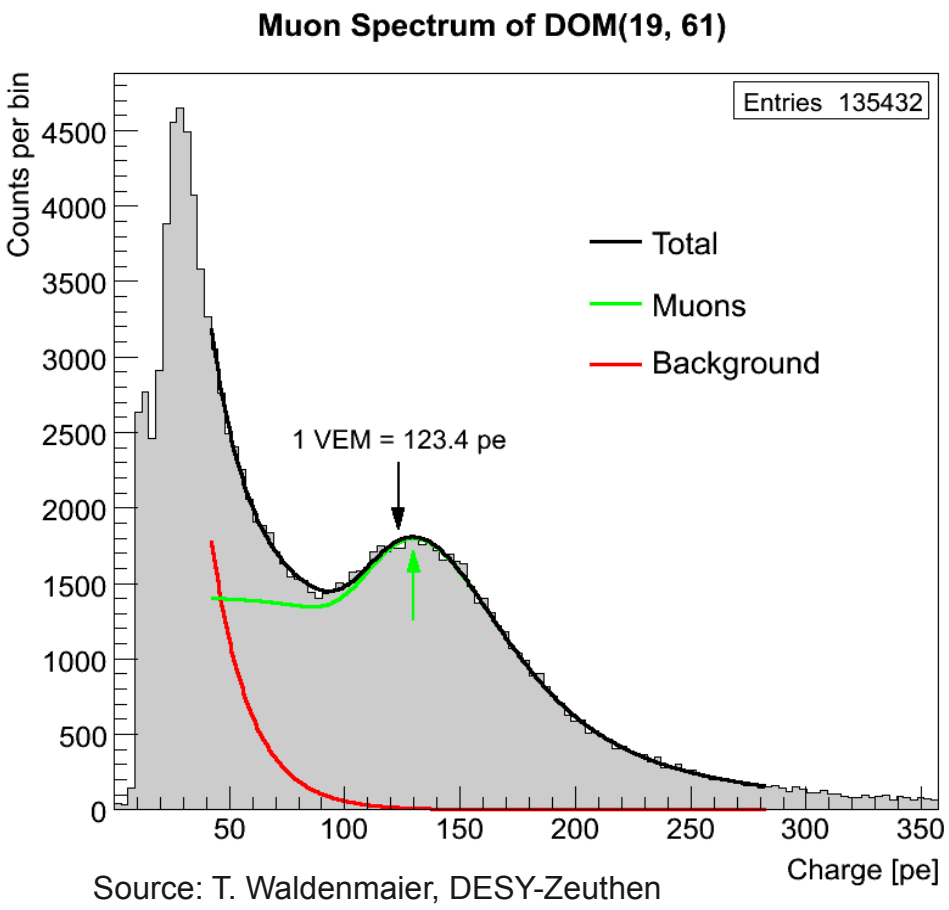
IceTop Calibration Procedure

Natural snow density: ~ 0.35 g/cm3

Snow density in trenches: ~ 0.4 g/cm3

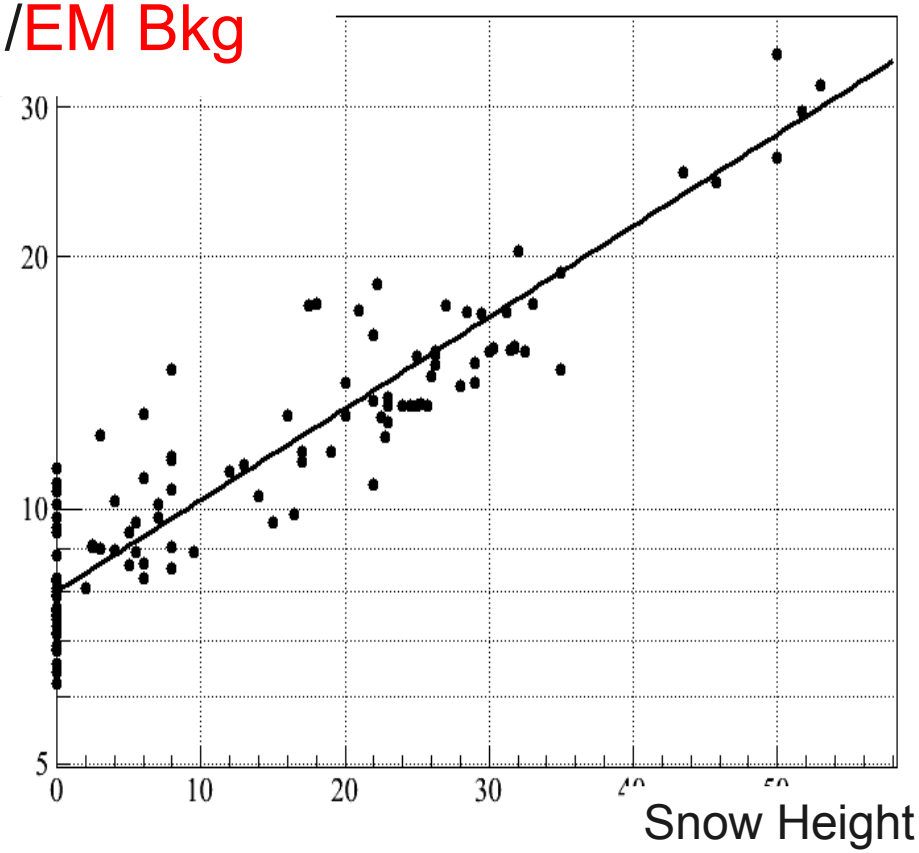
Tank Calibration

Snow reduces EM signal, muons unaffected



Source: T. Waldenmaier, DESY-Zeuthen

Muon Peak /EM Bkg

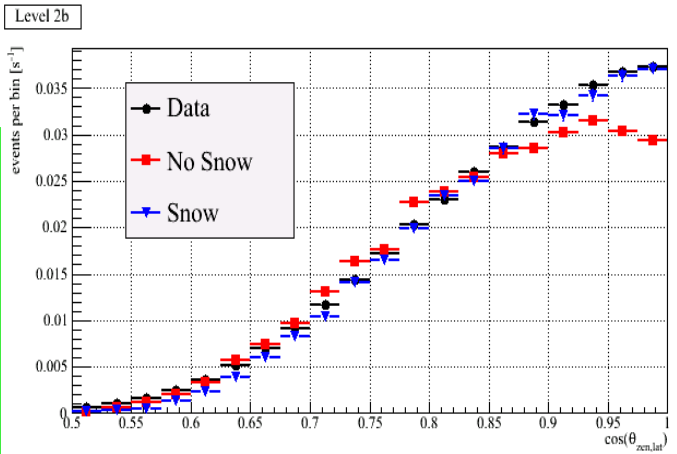


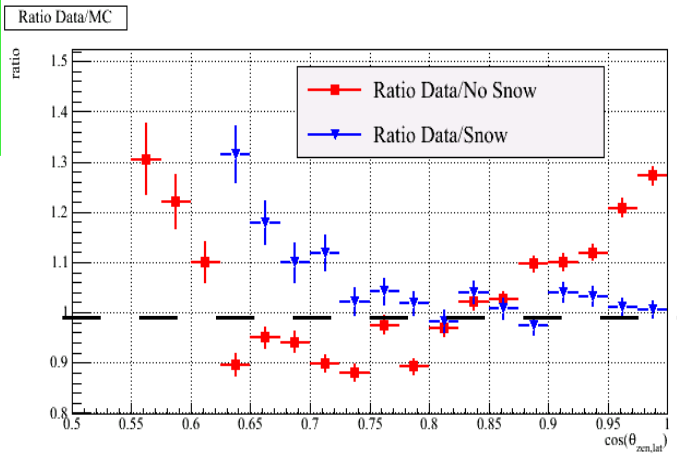
$$S_\mu / B_{EM} \simeq \exp\left(\frac{h_{snow}}{40.0''} + 2.08\right)$$

Snow Effects in Detector Simulation

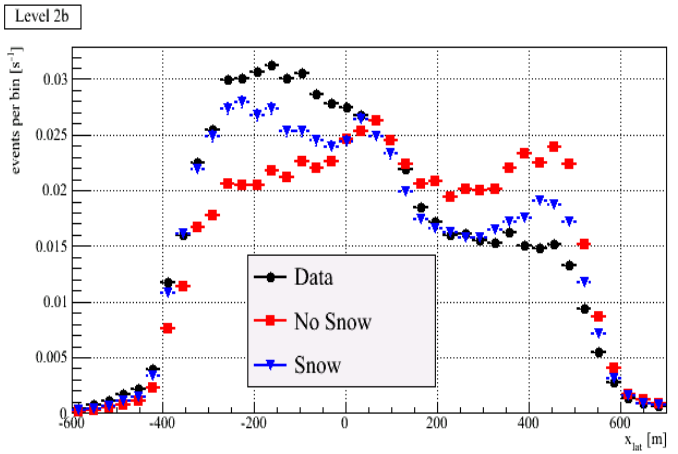
Here:
Parametrization of detector response in dependence of particle type and snow height

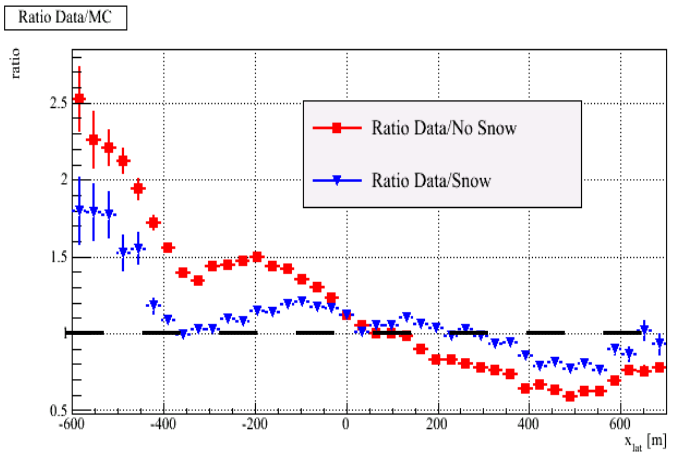
Soon:
Full GEANT-4 simulation





Zenith Angle



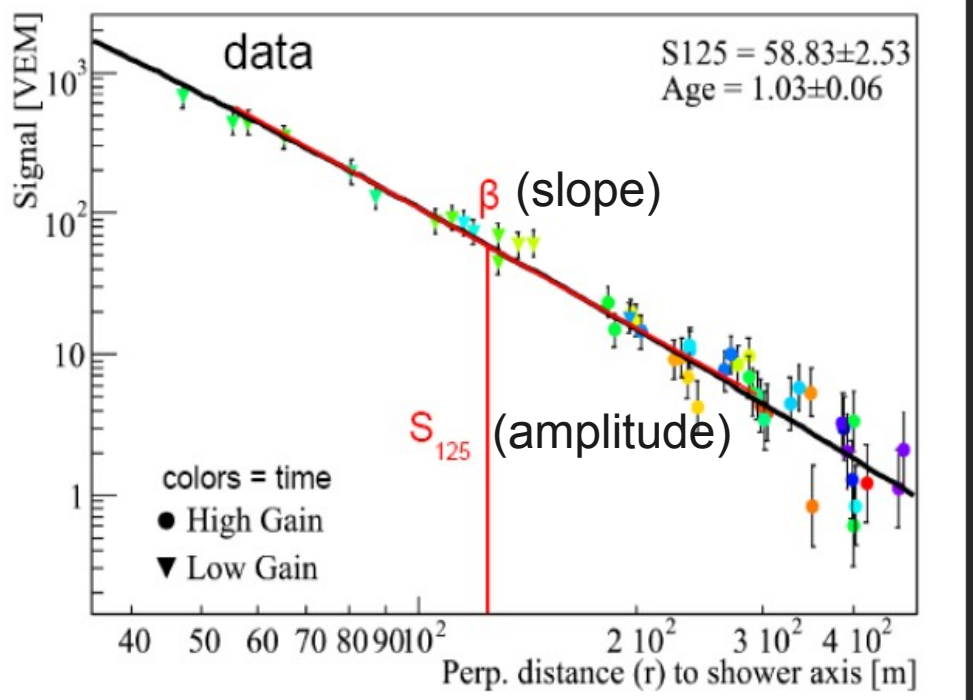


Shower Core Position

Red:
Default Response Parametrization

Blue:
Snow Attenuation and individual Snow Height for each tank

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

β: slope at r = 125m

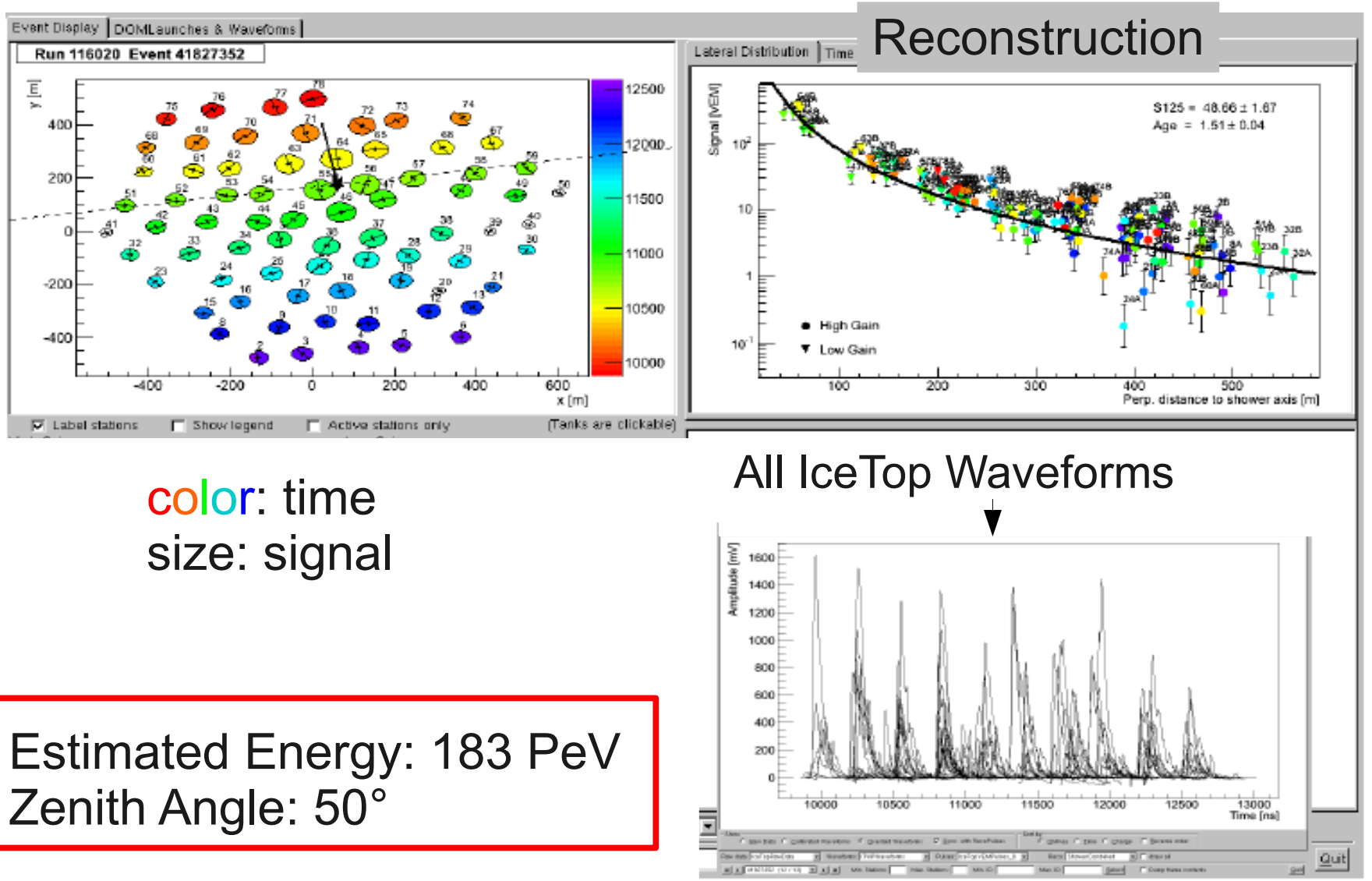
κ = 0.303 fixed

arXiv: 0711.0353

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

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

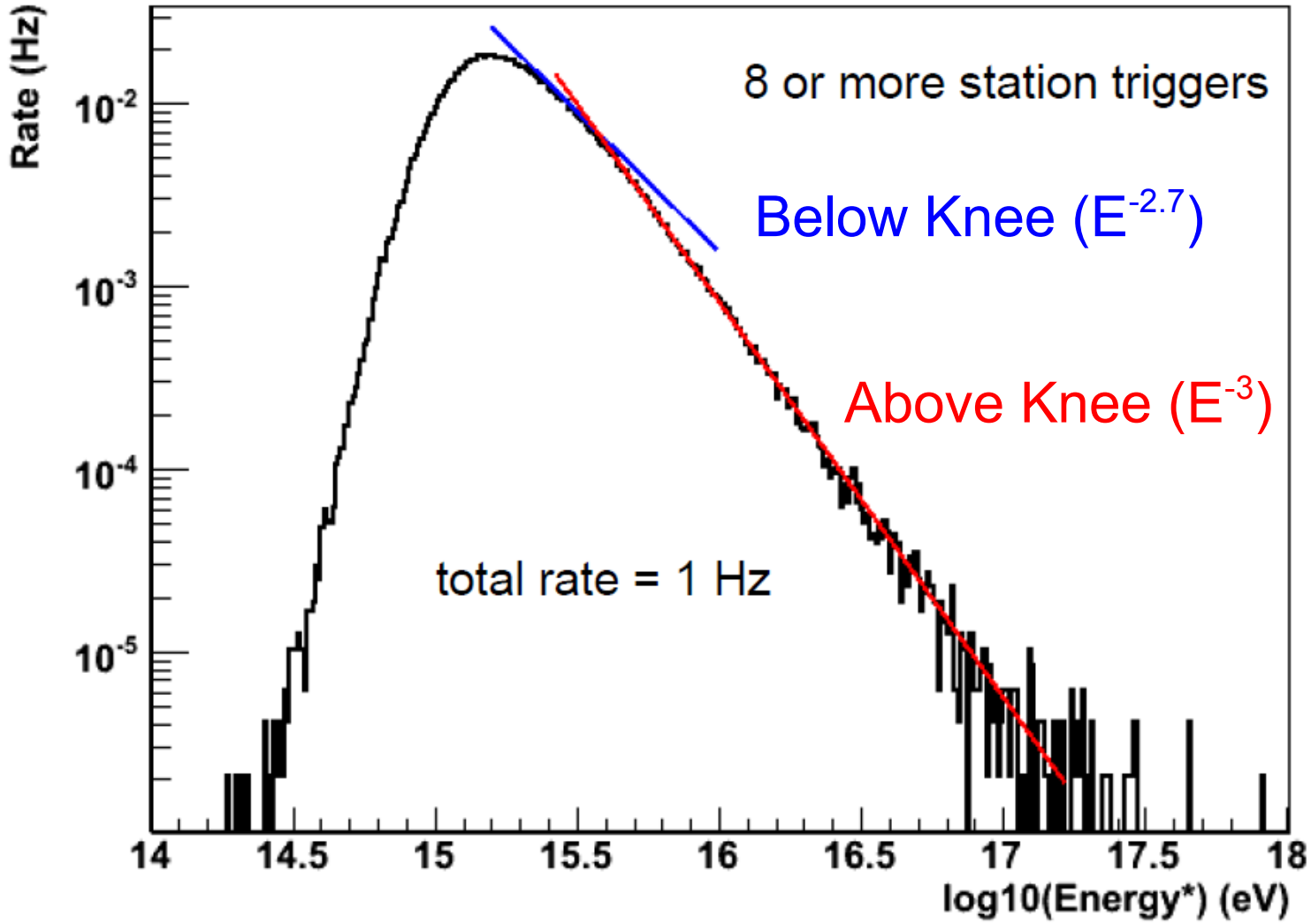
IceTop Event



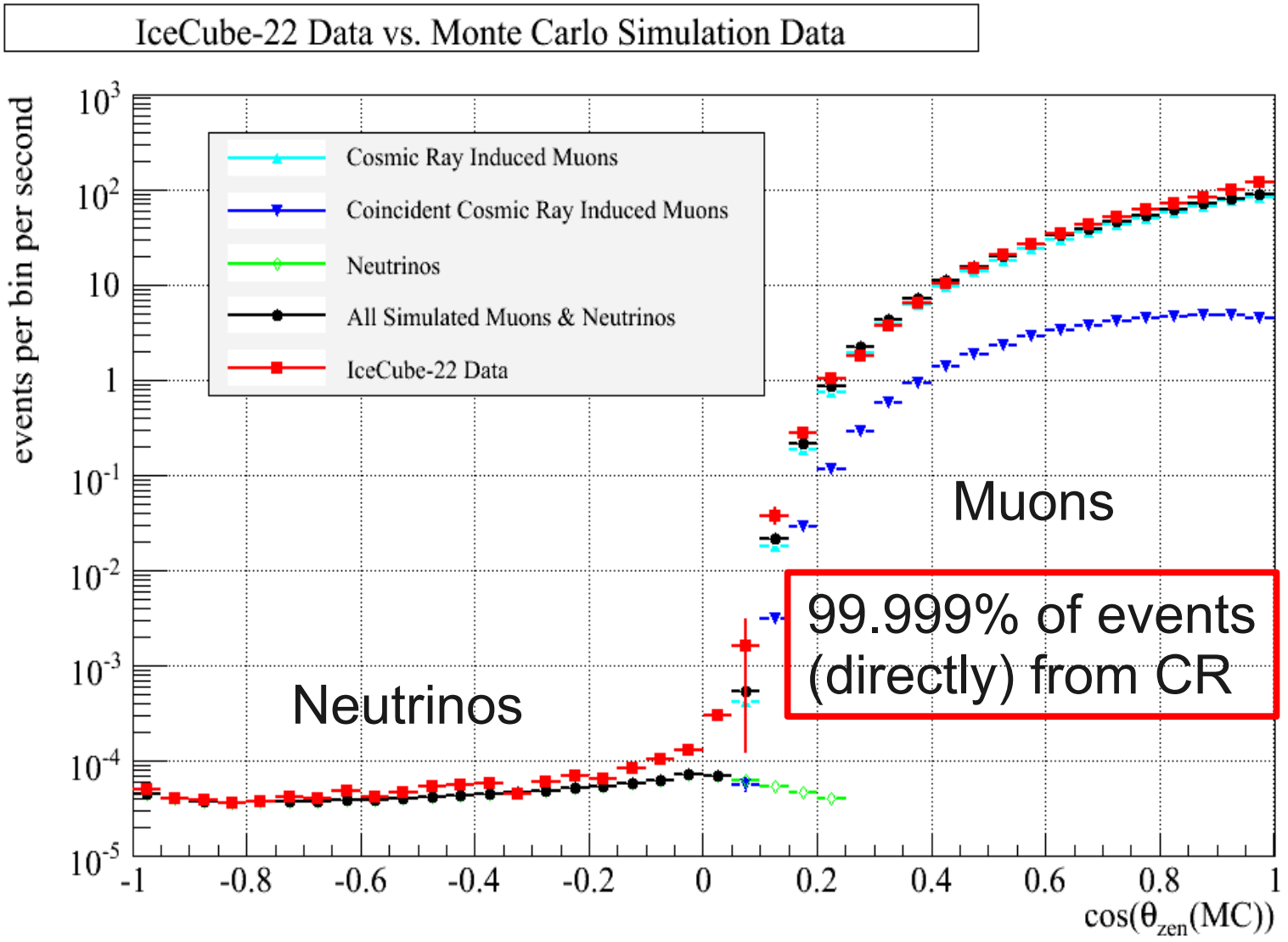
color: time
size: signal

Estimated Energy: 183 PeV
Zenith Angle: 50°

Raw IceTop-only CR Spectrum



InIce Muon Flux (IC22, 2008)

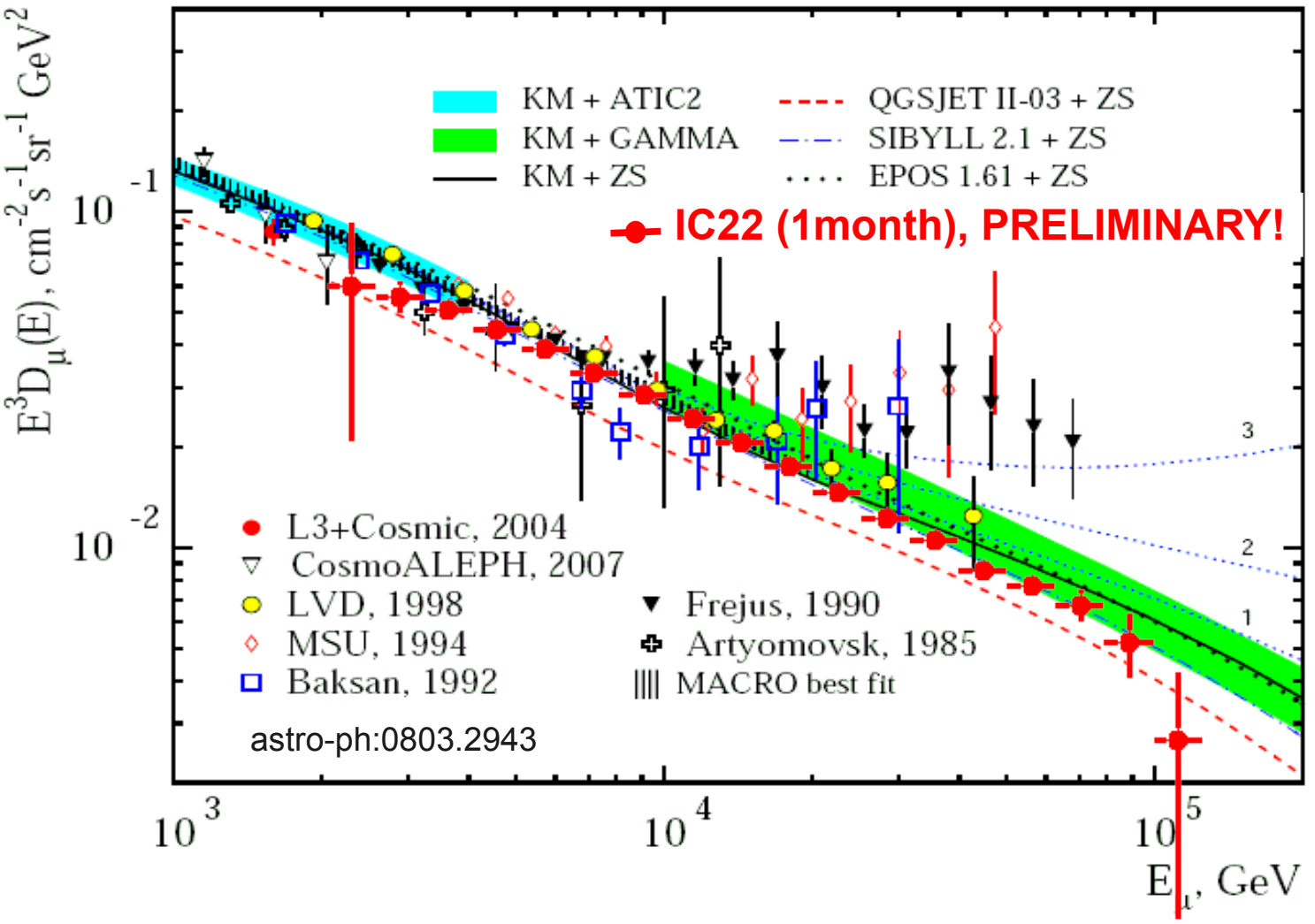


arXiv:0902.0021

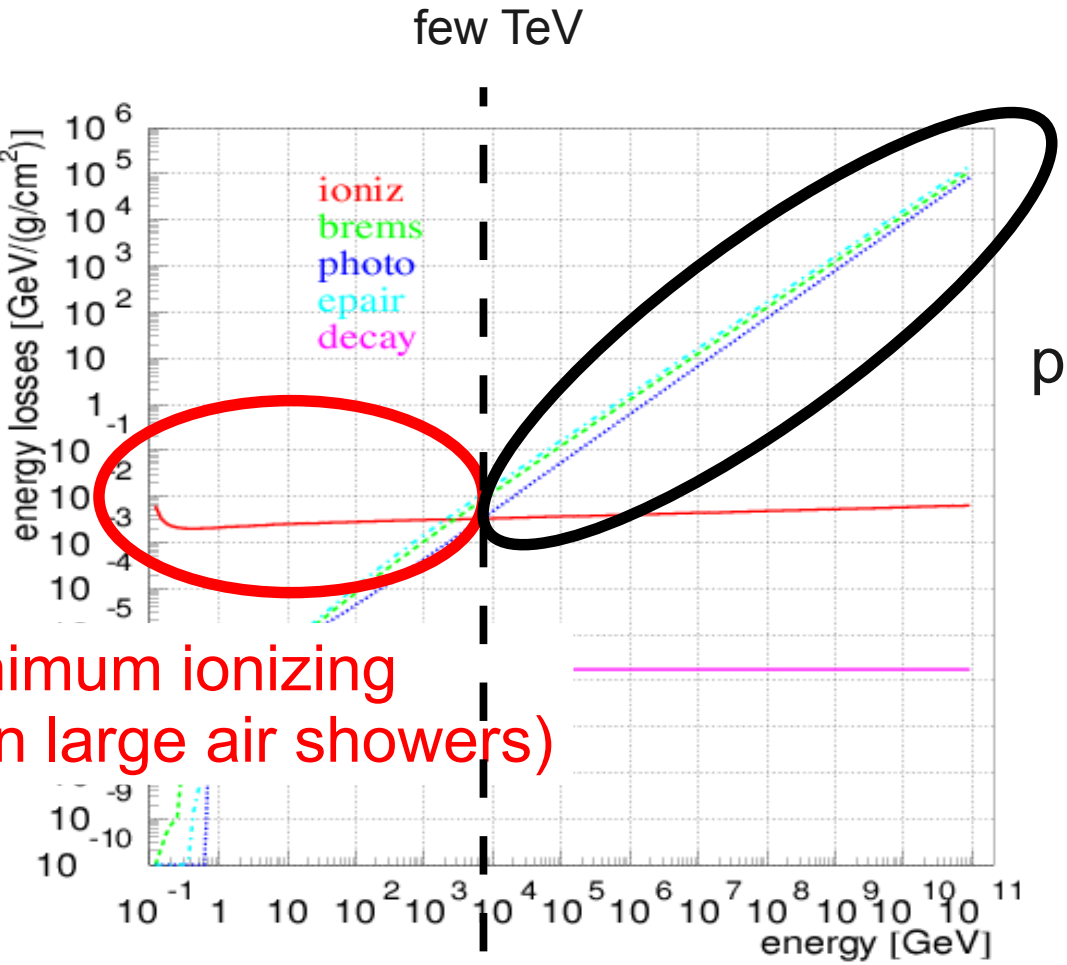
Muon Spectrum

Derived from muon tracks **near the horizon**

Higher angles: High-multiplicity muon bundles dominate over single HE muons

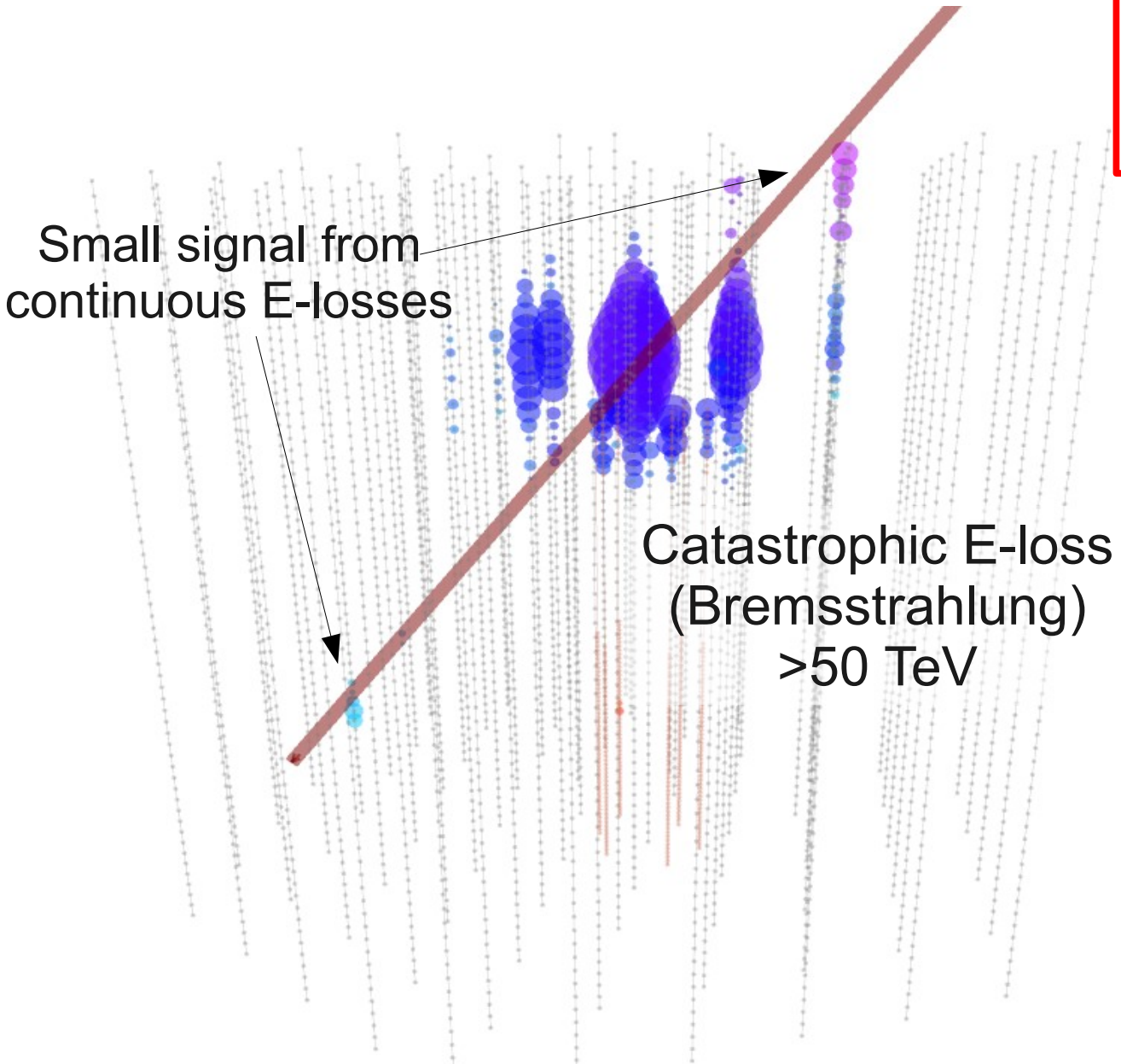


Muon Energy Losses in Matter (Ice)

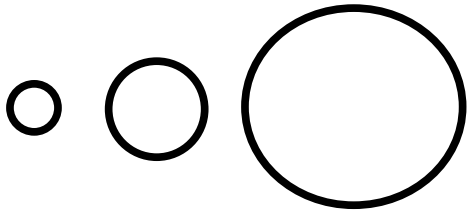


hep-ph/0407075

High-Energy Muon



Identify stochastic losses to distinguish HE muons from high-multiplicity muon bundles



Size: PMT Signal

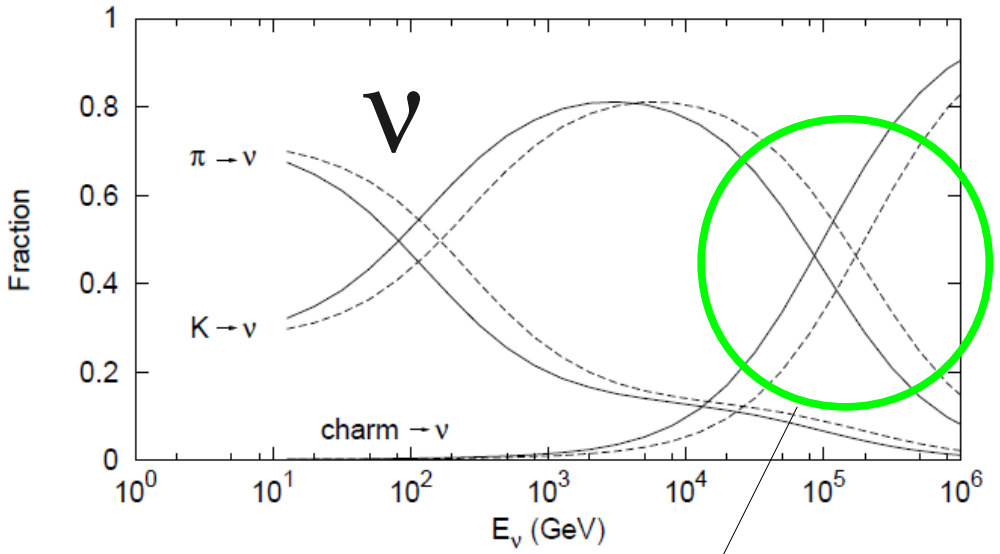
Color: Time

Prompt Leptons from Charm Decay

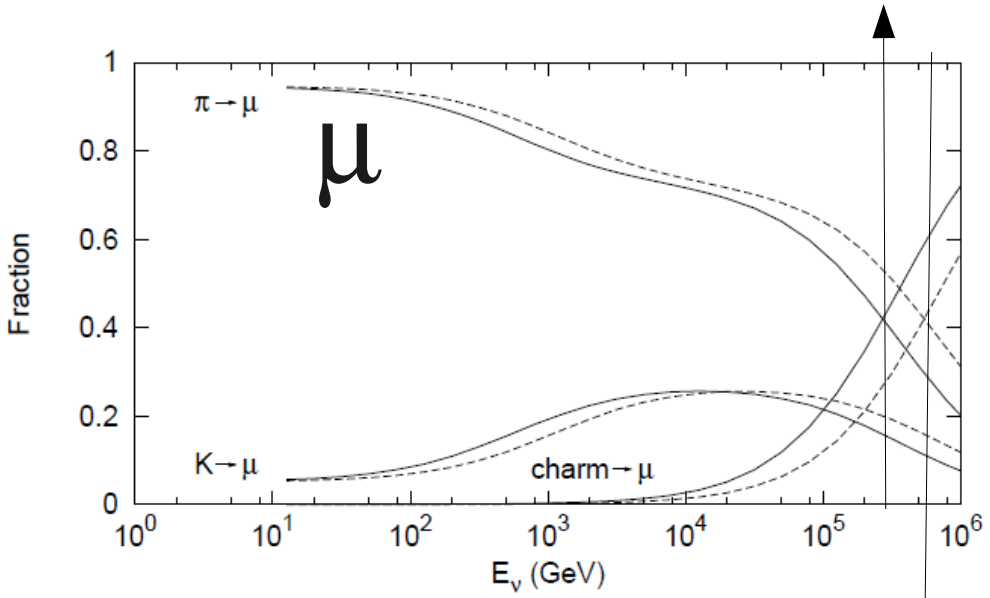
Light mesons: Flux α $1/\cos\theta_{zen}$

Prompt: constant angular Flux

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

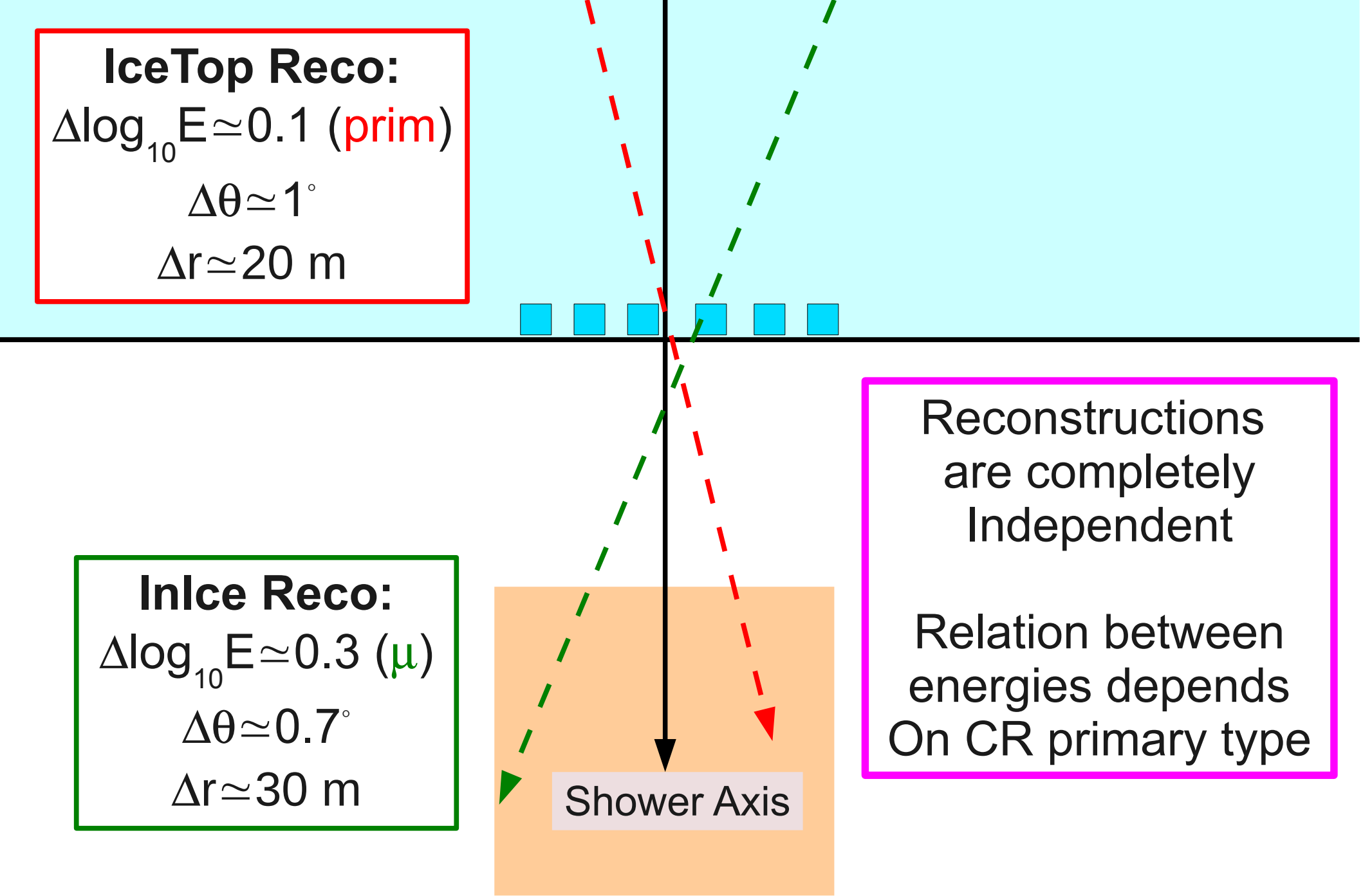


Source: T. Gaisser

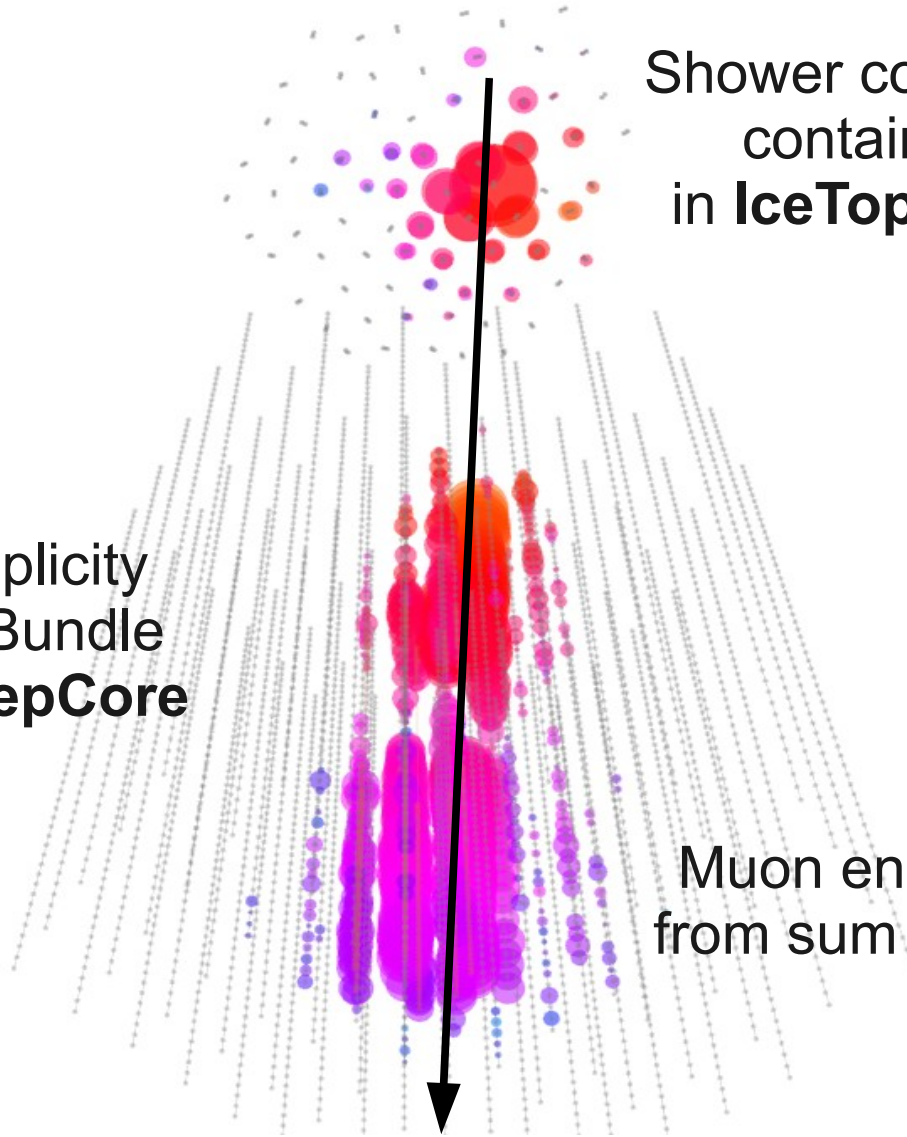


Charm represents major systematic uncertainty for neutrinos above 100 TeV

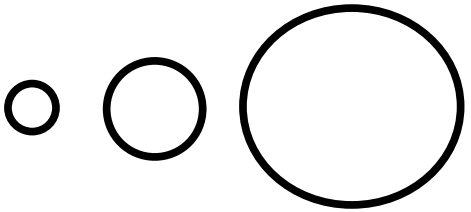
At **60°**, light meson decay dominates up to ≈**500TeV**


IceTop Reco:
$\Delta \log_{10} E \simeq 0.1$ (prim)
$\Delta\theta \simeq 1^\circ$
$\Delta r \simeq 20$ m
InIce Reco:
$\Delta \log_{10} E \simeq 0.3$ (μ)
$\Delta\theta \simeq 0.7^\circ$
$\Delta r \simeq 30$ m
Shower Axis
Reconstructions are completely Independent
Relation between energies depends On CR primary type

IceTop/InIce Coincident Event



Shower core fully contained in **IceTop** array



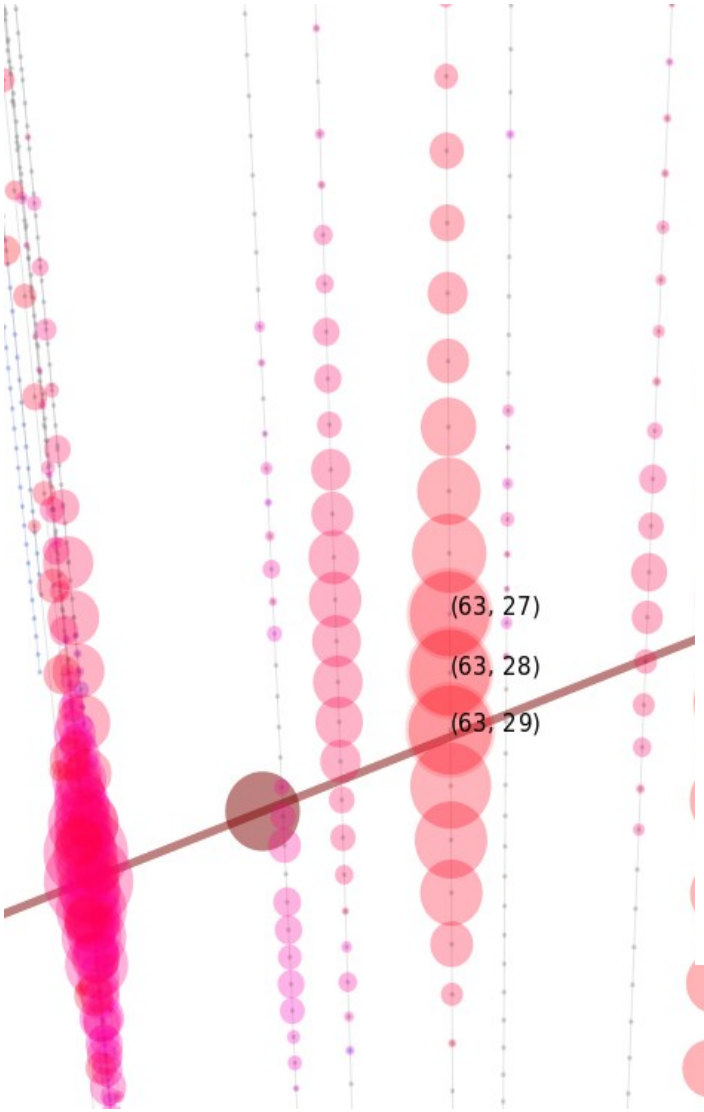
Size: PMT Signal

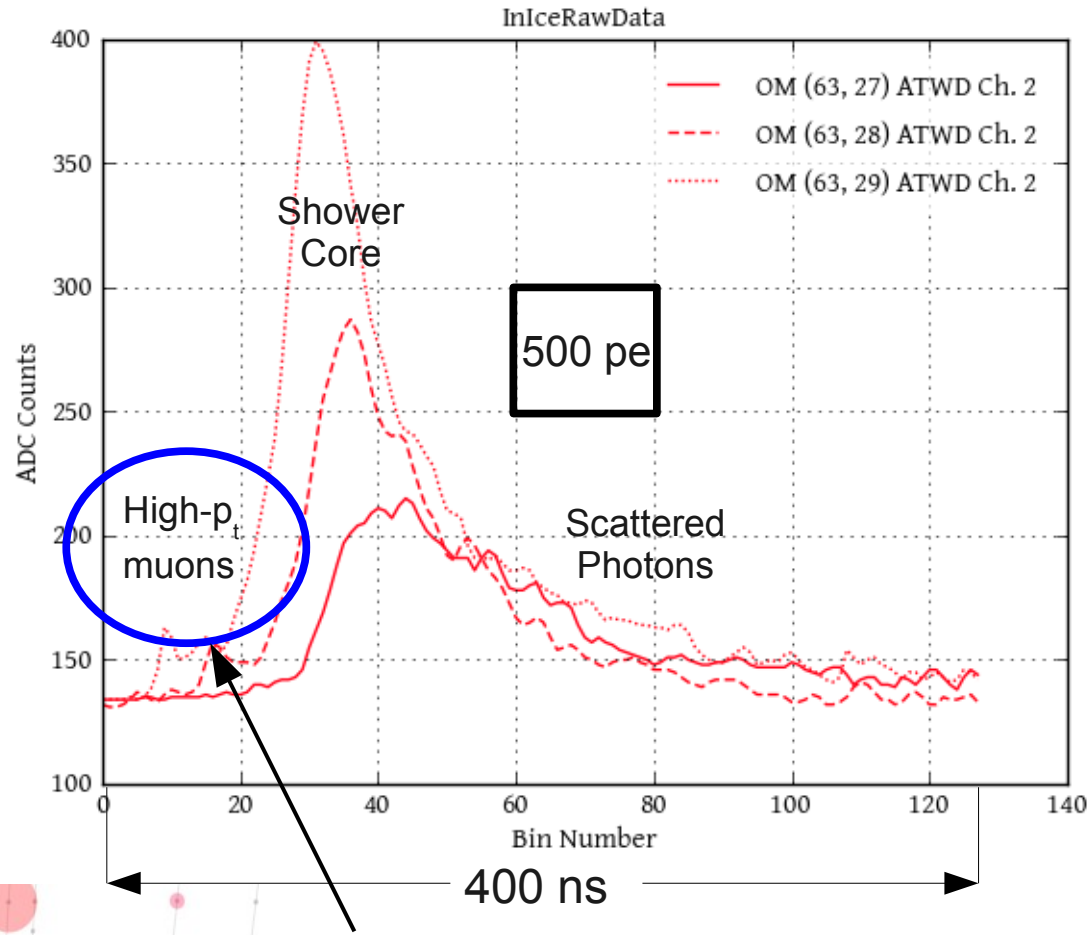
Color: Time

High-Multiplicity HE Muon Bundle In **InIce/DeepCore**

Muon energy estimated from sum of DOM signals

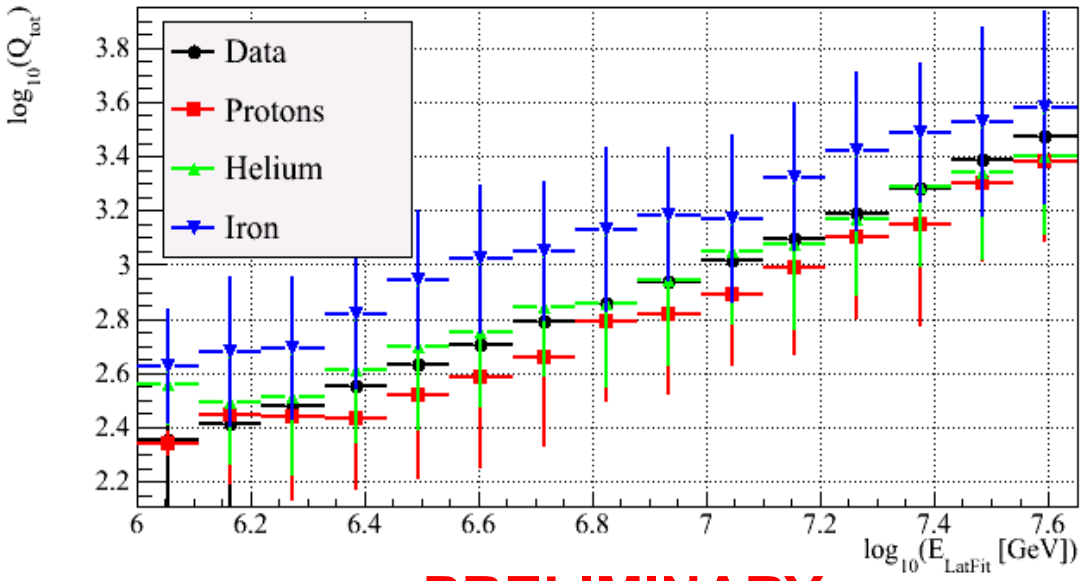
DOM Waveforms



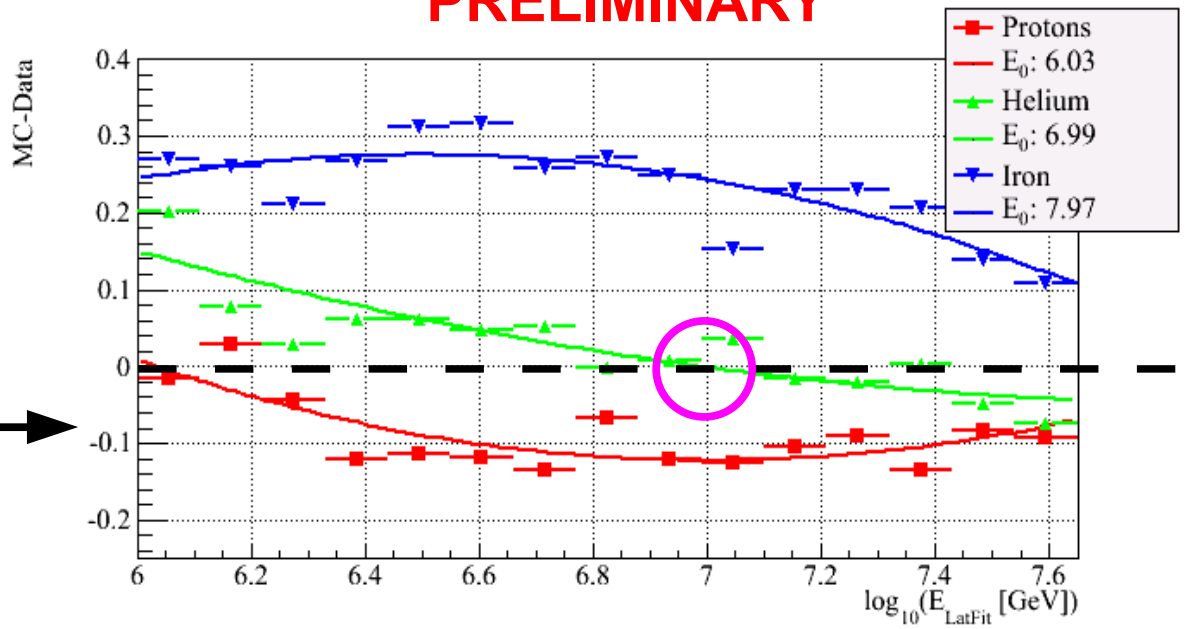


DOM readout triggered by outlying muons:
Characteristic for large CR bundles

IceTop/InIce Energy Correlation



PRELIMINARY



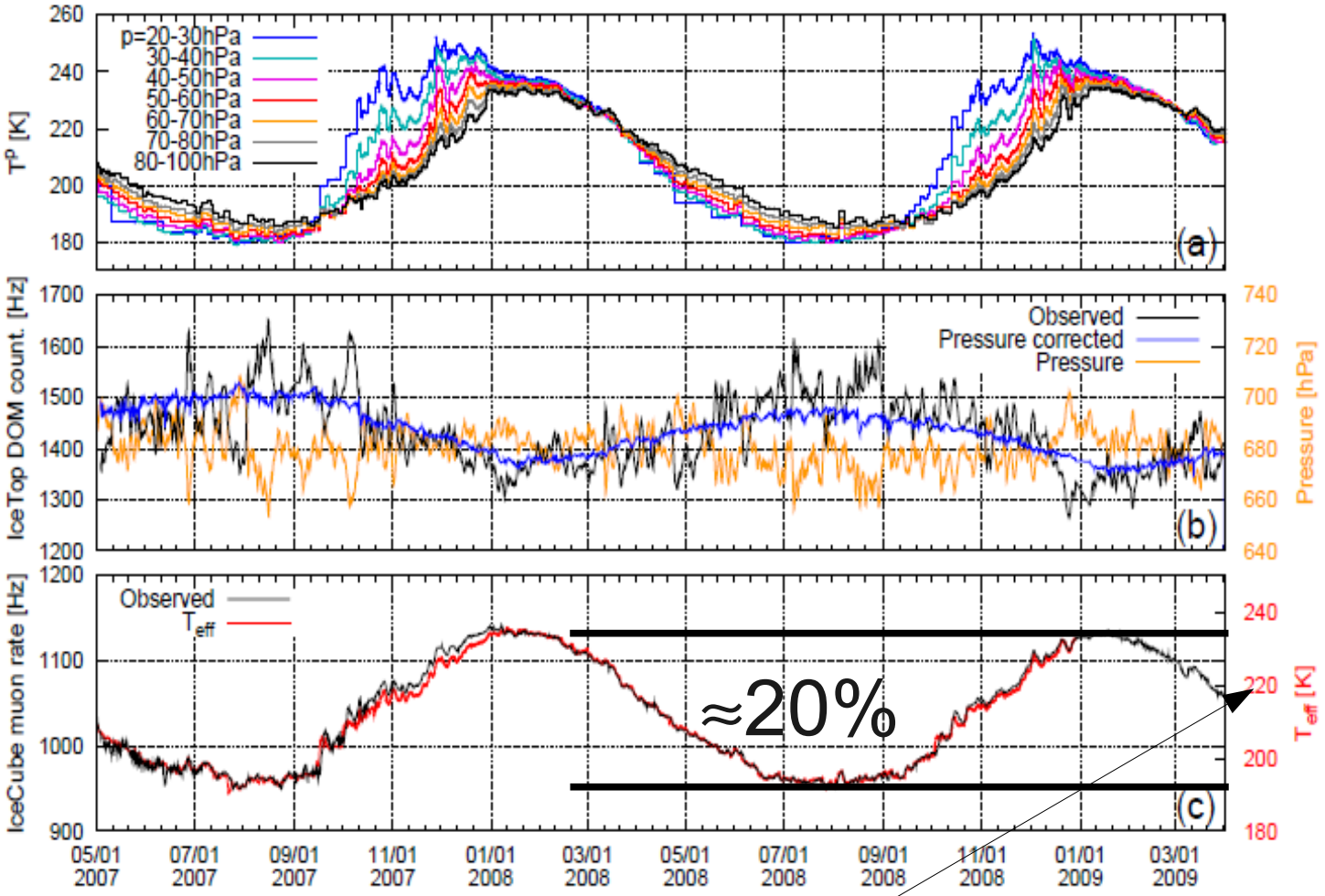
InIce
(HE muons)

IceTop (EM)

<log A> = He
at
$E_{prim} \approx 10$PeV

$\langle Q_{MC}(A) \rangle = \langle Q_{data} \rangle$

Seasonal Variations



Atmospheric Temperature

IceTop (**barometric**)

InIce (**temperature**)

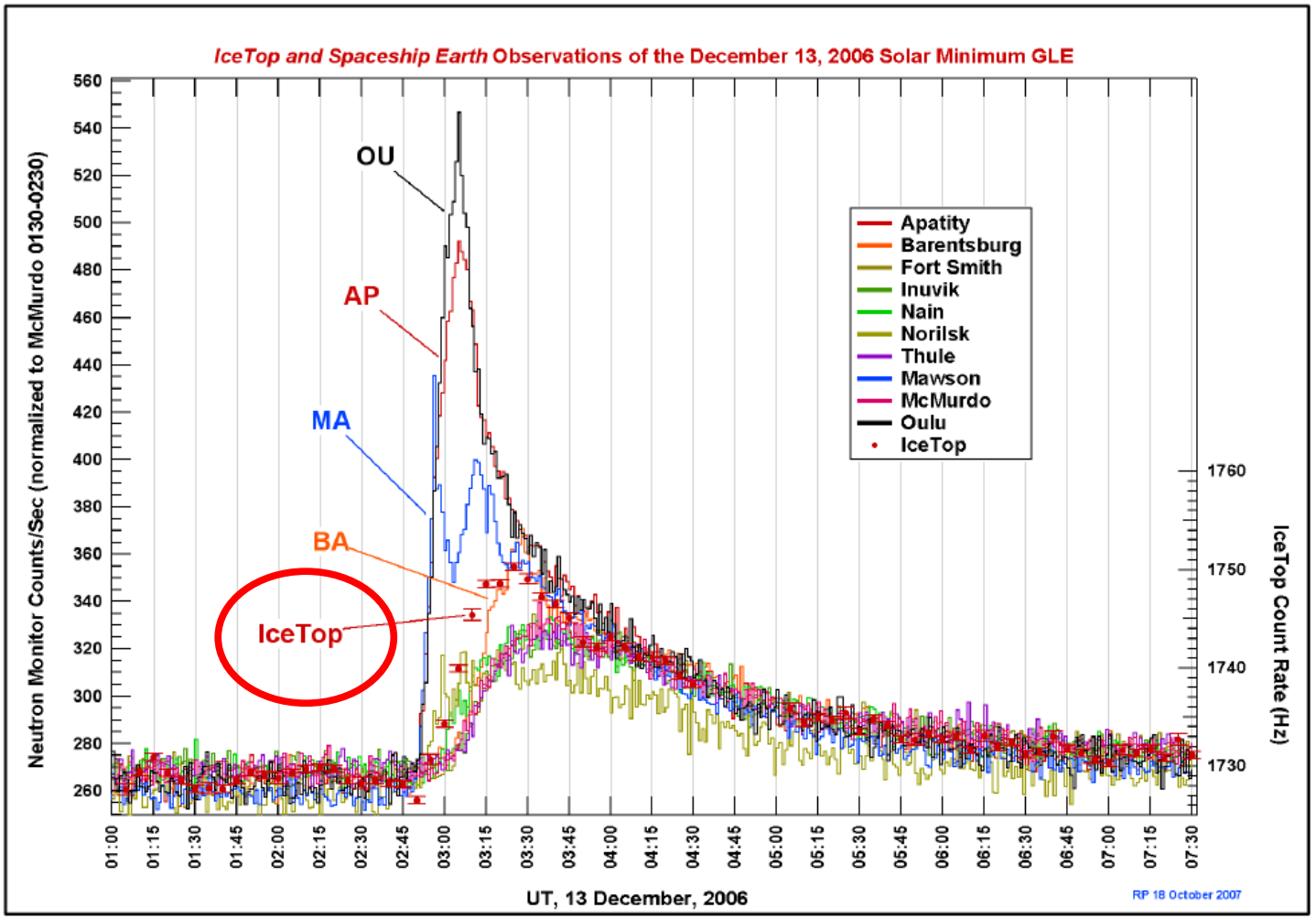
T_{eff}: Temperature weighted by muon production probability

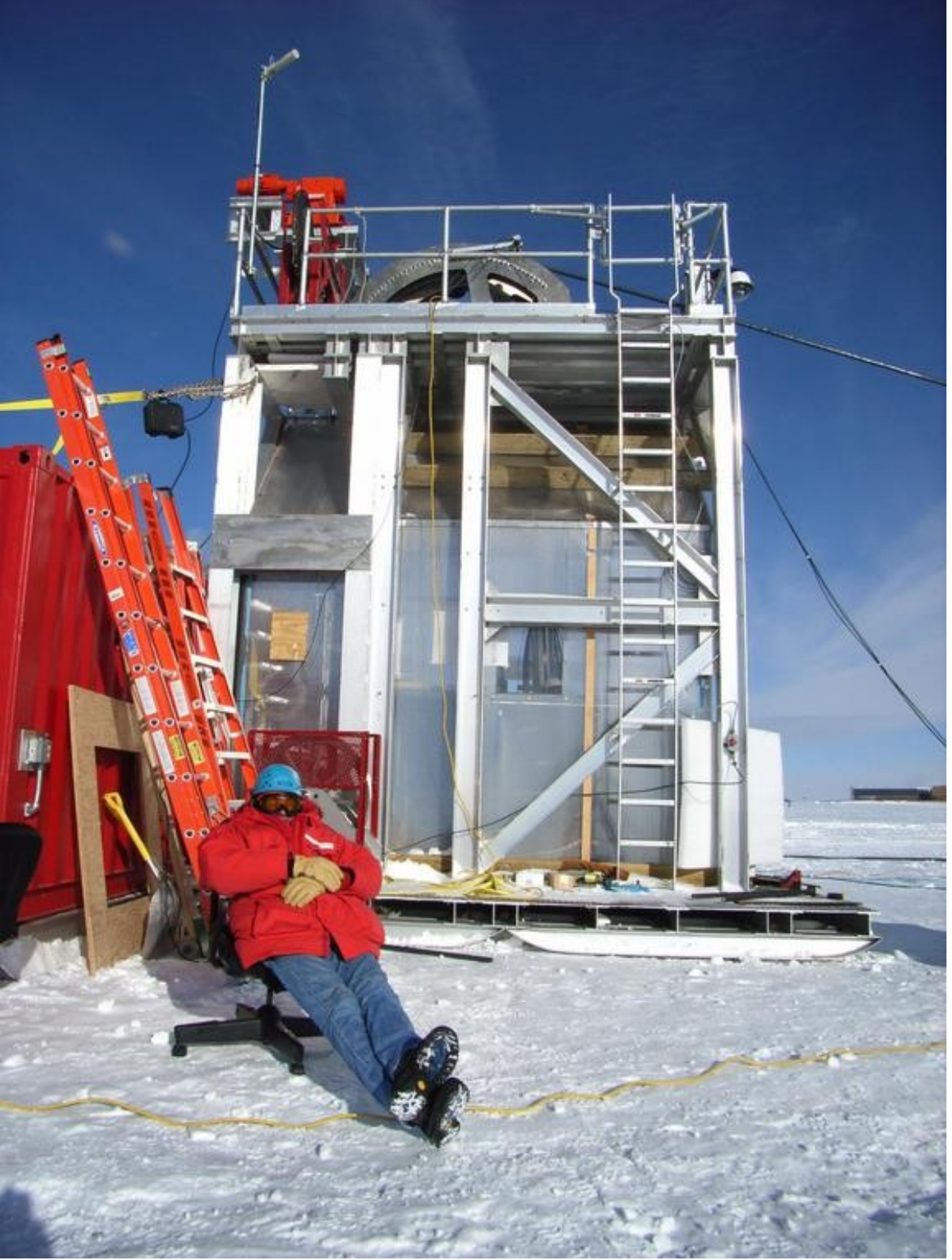
$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X)\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}{\int_0^\infty \frac{dX}{X}\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}$$

S. Tilav et al., arXiv:1001.0776

First Extraterrestrial IceCube Signal

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





Thank you for your attention!