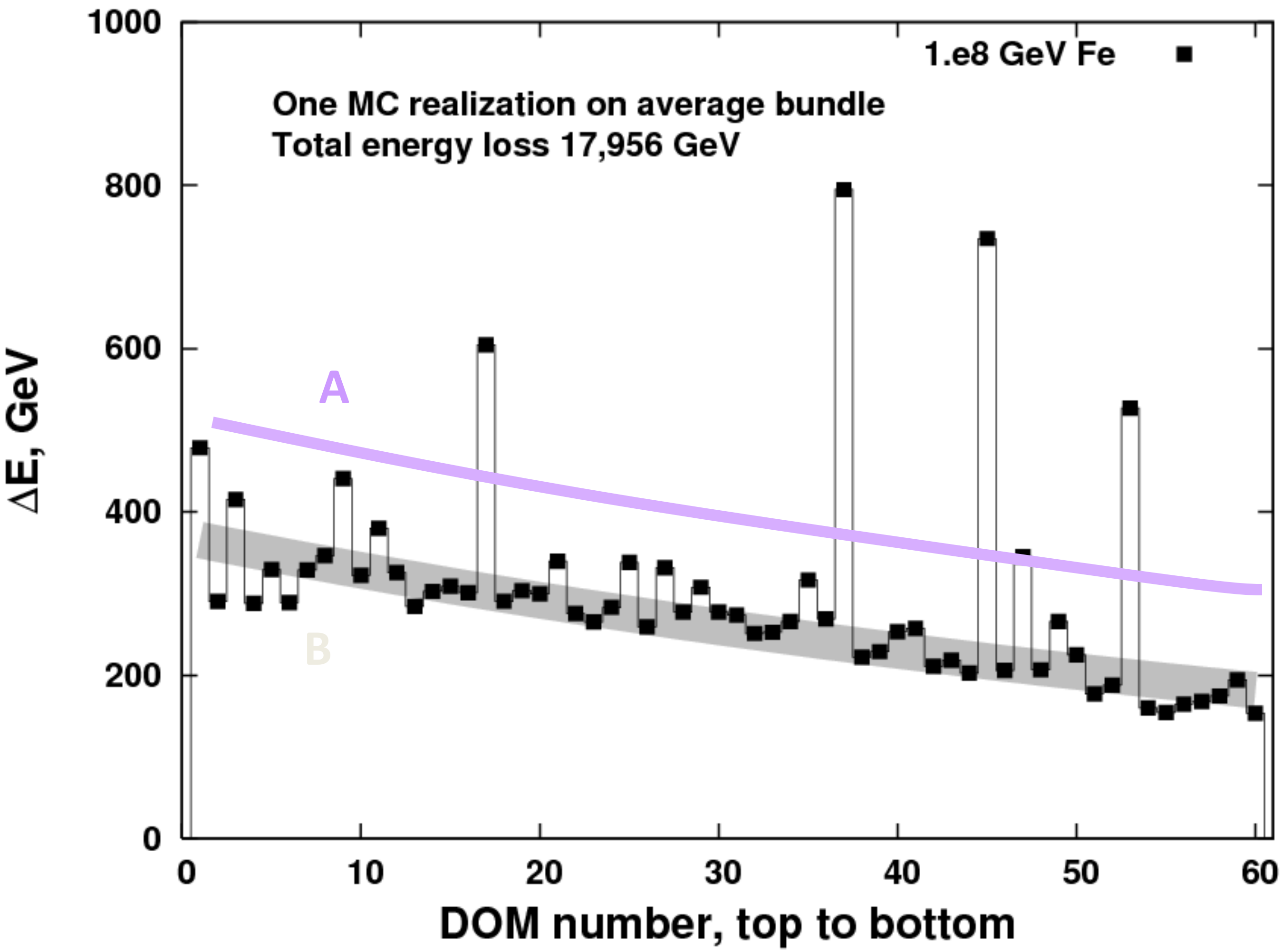
Comments on muons in IceCube

Mostly seasonal variation

Energy deposit per 17 m

Todor's plot:
--a single event



The basics

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

Same form for μ;
Different kinematics
→ μ, ν differences

ε_π = 115 GeV
ε_K = 850 GeV
ε_{charm} > 10 PeV

$$A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \qquad Z_{pK^+} = \frac{1}{\sigma}\int x^\gamma \frac{\mathrm{d}\sigma(x)}{\mathrm{d}x}\mathrm{d}x$$

$$x = \frac{E_{\mathrm{secondary}}}{E_{\mathrm{beam}}}$$

$$Z_{\pi\mu} = \frac{1 - r_\pi^{\gamma+1}}{(\gamma+1)(1-r_\pi)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{1-r_\pi^{\gamma+2}}{(\gamma+2)(1-r_\pi)}$$

$$Z_{\pi\nu} = \frac{(1-r_\pi)^\gamma}{(\gamma+1)} \text{ and } \frac{\epsilon_\pi}{\cos\theta E_\mu}\frac{(1-r_\pi)^{(\gamma+1)}}{(\gamma+2)}$$

r_π = 0.573 but
r_K = 0.0458

T dependence of critical energies

$$\frac{gX_v}{-\mathrm{d}X_v/\mathrm{d}h} = \frac{P}{\rho} = \frac{RT}{M},$$

$$X_v \approx X_0\, e^{-h/h_0}, \text{ where } h_0(X) = \frac{RT(X)}{Mg}$$

$$\epsilon_i = \frac{m_i c^2}{c\tau_i} h_0(X) = \epsilon_i(T_0)\frac{T(X)}{T_0}$$

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

$$T_{eff}(\theta) = \frac{\int dE_\mu \int dX\, A_{eff}(E_\mu, \theta) P(E_\mu, \theta, X) T(X)}{\int dE_\mu \int dX\, A_{eff}(E_\mu, \theta) P(E_\mu, \theta, X)}$$

Muon production spectrum

$$\mathcal{P}_{\pi\mu}(E_\mu, \theta, X) = \frac{Z_{N\pi}}{\lambda_N} \frac{e^{-X/\Lambda_N}}{1 - r_\pi} \frac{N_0(E\mu)}{\gamma + 1} (1 - r_\pi^{\gamma+1}) \times \frac{1}{1 + B_{\pi\mu}(X) \cos\theta \, E_\mu / \epsilon_\pi}, \quad \text{(A9)}$$

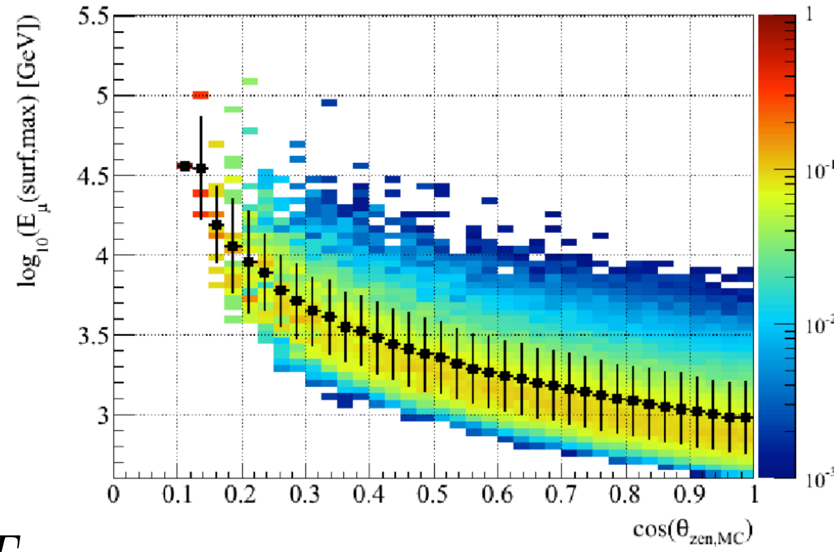
where

$$B_{\pi\mu}(X) = \frac{1 - r_\pi^{\gamma+1}}{1 - r_\pi^{\gamma+2}} \frac{\gamma + 2}{\gamma + 1} \frac{X \, e^{-X/\Lambda_N}}{\{e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\}} \frac{\Lambda_\pi - \Lambda_N}{\Lambda_\pi \Lambda_N}. \quad \text{(A10)}$$

The contribution from kaons has the same form with the replacements $r_\pi \to r_K$ and $\Lambda_\pi \to \Lambda_K$.

Expectations for TeV μ and ν

ε_{π} = 115 GeV
ε_{K} = 850 GeV
ε_{charm} > 10 PeV



$$\frac{\delta\phi_\mu}{\phi_\mu} = \frac{1}{\phi_\mu}\frac{\mathrm{d}\phi_\mu}{\mathrm{d}T}\delta T = \alpha_T(E_\mu\cos\theta)\,\frac{\delta T}{T_0}.$$

$$\epsilon_\pi = \frac{m_\pi c^2}{c\tau_\pi}\frac{RT}{Mg} = \epsilon_\pi(T_0)\frac{T}{T_0}.$$

$$\alpha_T \approx \frac{T_0}{\phi_{\mu,\nu}}\left\{\frac{\mathrm{d}\phi_\pi}{\mathrm{d}T} + \frac{\mathrm{d}\phi_K}{\mathrm{d}T} + \frac{\mathrm{d}\phi_{prmpt}}{\mathrm{d}T}\right\}$$

TeV leptons: expectations 2

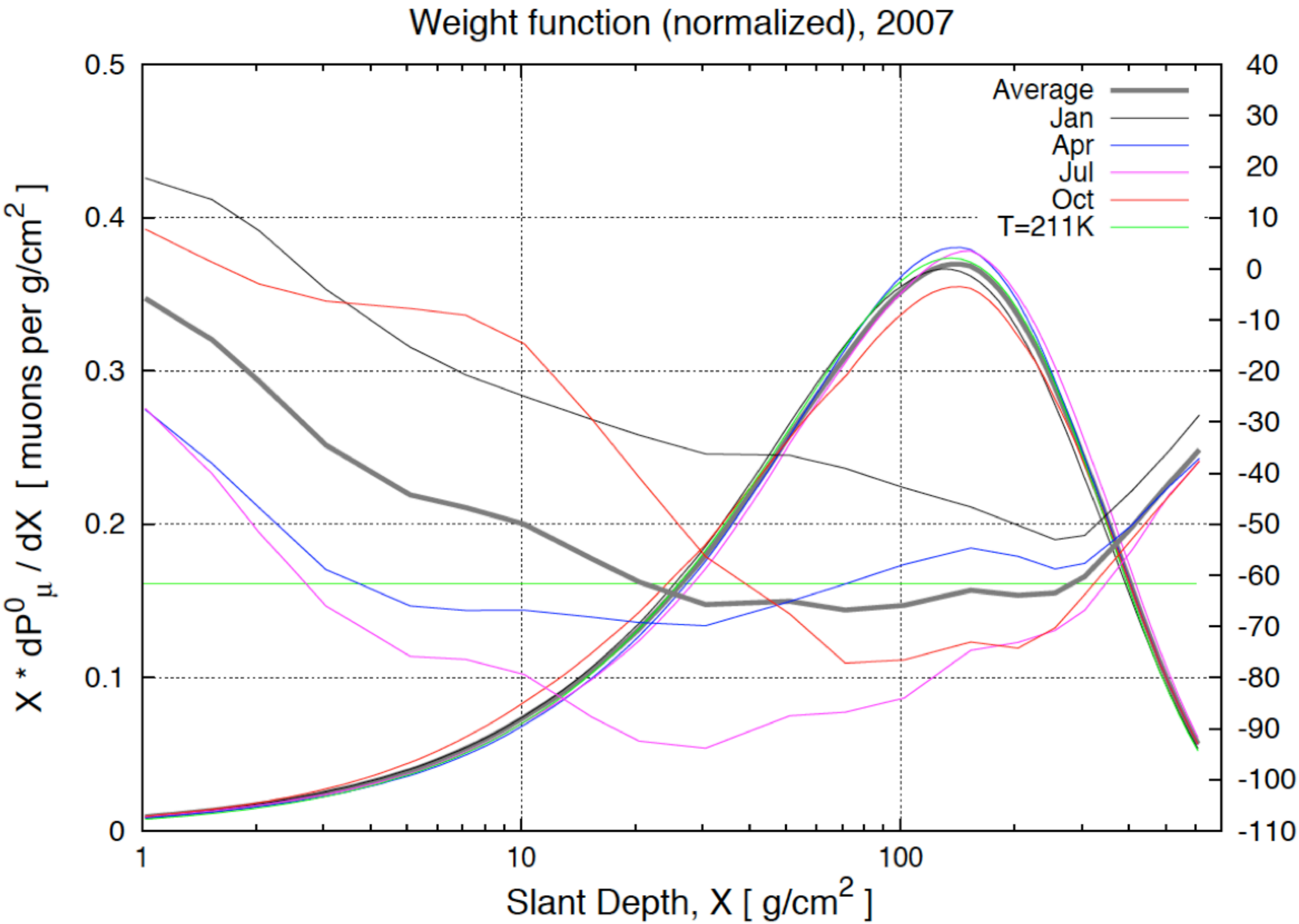
$$\alpha_T \approx \frac{T_0}{\phi_{\mu,\nu}} \left\{ \frac{\mathrm{d}\phi_\pi}{\mathrm{d}T} + \frac{\mathrm{d}\phi_K}{\mathrm{d}T} + \frac{\mathrm{d}\phi_{prmpt}}{\mathrm{d}T} \right\}$$

Asymptotic because ε_π << TeV

$\varepsilon_K \approx$ TeV, intermediate

0 because ε(prompt) >> TeV

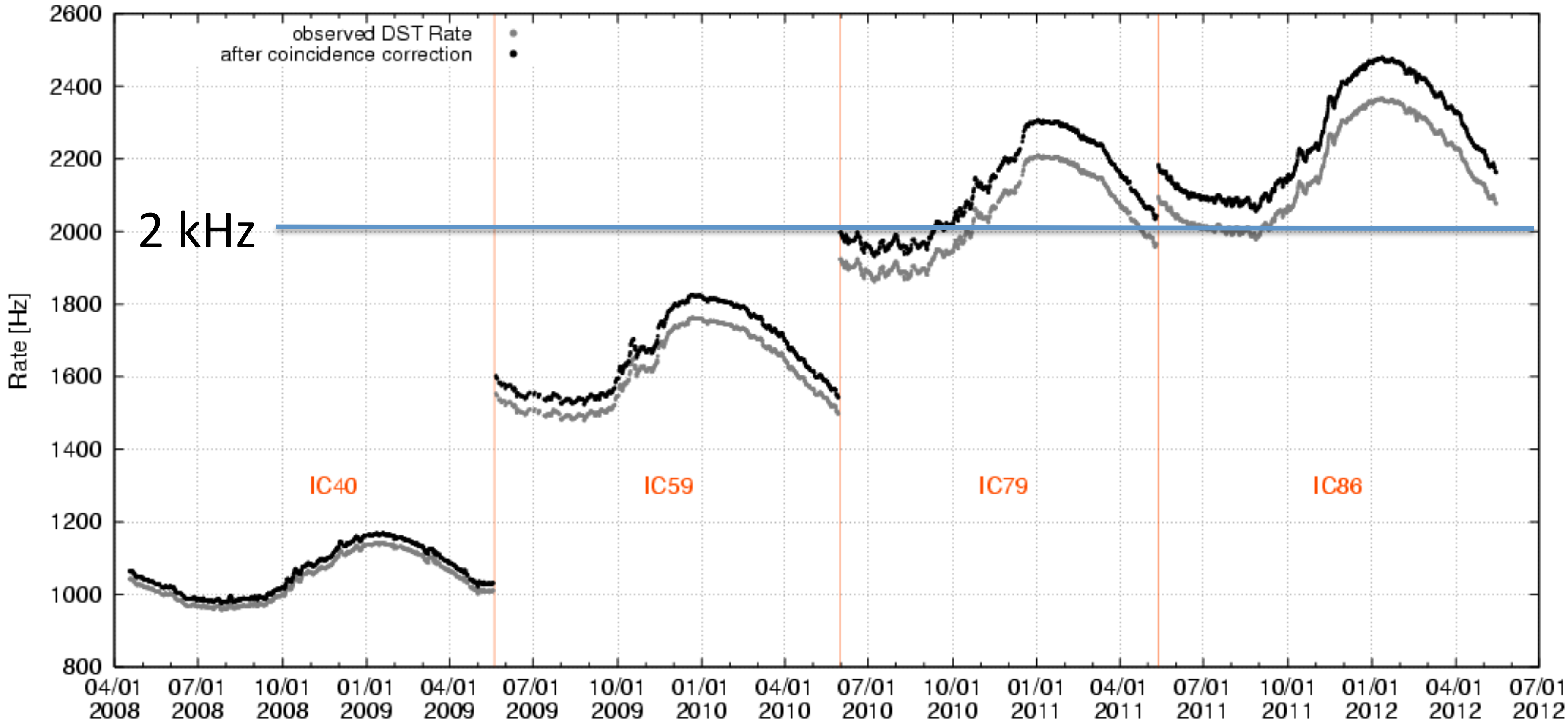
- If there were only pions then $\alpha_T \rightarrow 1$
- Prompt component does not vary with temperature
- Kaons contribute a larger fraction of ν than μ, so $\alpha_\nu < \alpha_\mu$
- Expect α_T to increase with energy (e.g. depth) until prompt leptons



Weight function (normalized), 2007
Average
Jan
Apr
Jul
Oct
T=211K
X * dP0μ / dX [muons per g/cm2]
Atmospheric Temperature [oC]
Slant Depth, X [g/cm2]
0.5
0.4
0.3
0.2
0.1
0
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
1
10
100

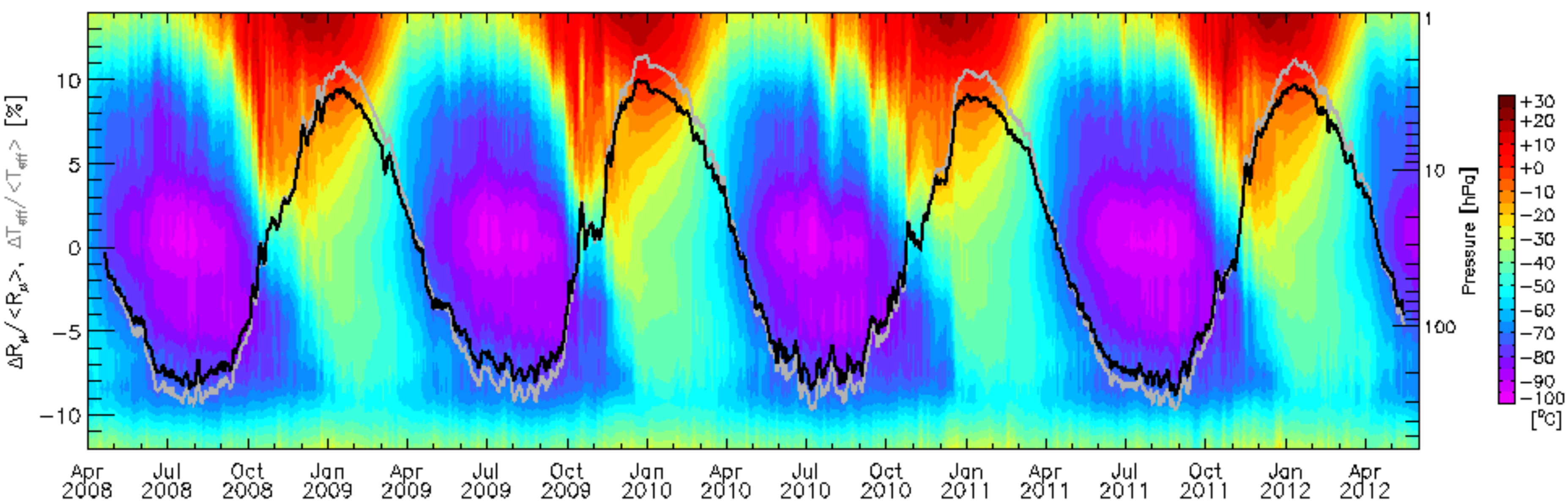
Atmospheric μ in IceCube

To reach 2 km depth, typical energy at production is TeV



Muon rates map stratosphere

- Variations of temperature cause atmosphere to expand and contract
- Muon production from meson decay increases and decreases
- Main effect comes from stratosphere
- Both seasonal effects and sudden changes can be studied
- Potential sensitivity to production of heavy hadrons (kaons, charm)



History and status

- Many people have worked on seasonal effects in IceCube
  - Paolo, Takao, Tom
  - Anne Schukraft, Denise Hellwig (Aachen)
  - Gary, Bruce Dawson, Kai (Adelaide)
  - Tom F., Sam (muon bundles)
- But we still need an IceCube paper

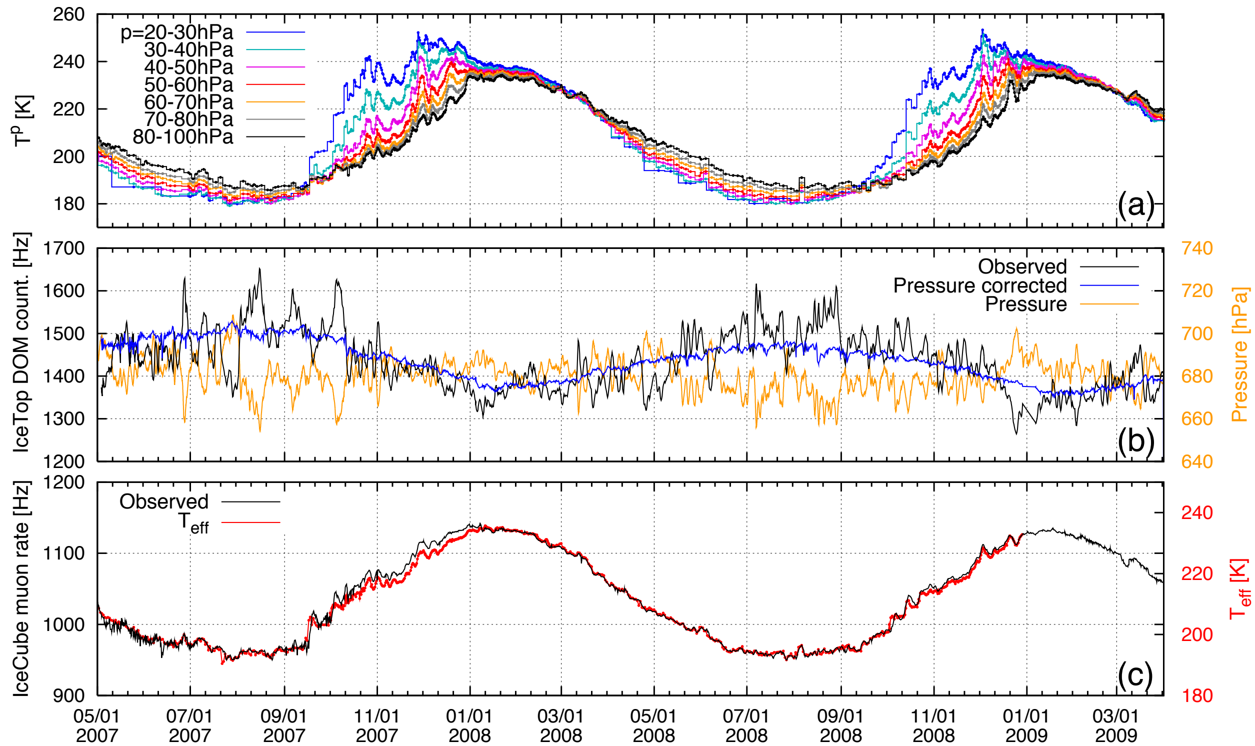
Tilav et al., ICRC 2009

arXiv:1001.0776v2

Temperature at various pressure levels

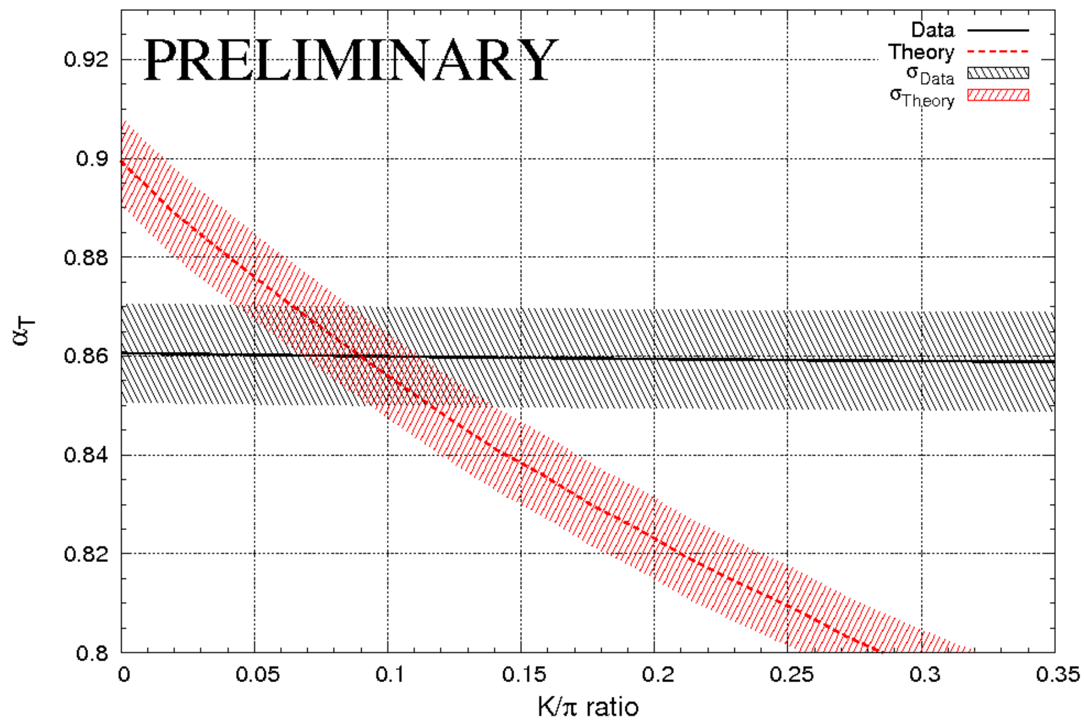
Variation of IceTop rates (pressure corrected)

In-ice muons

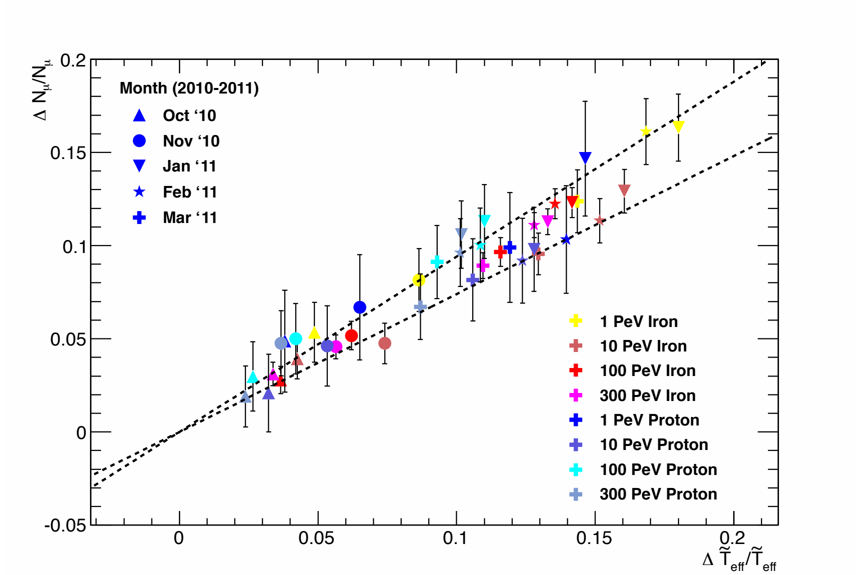


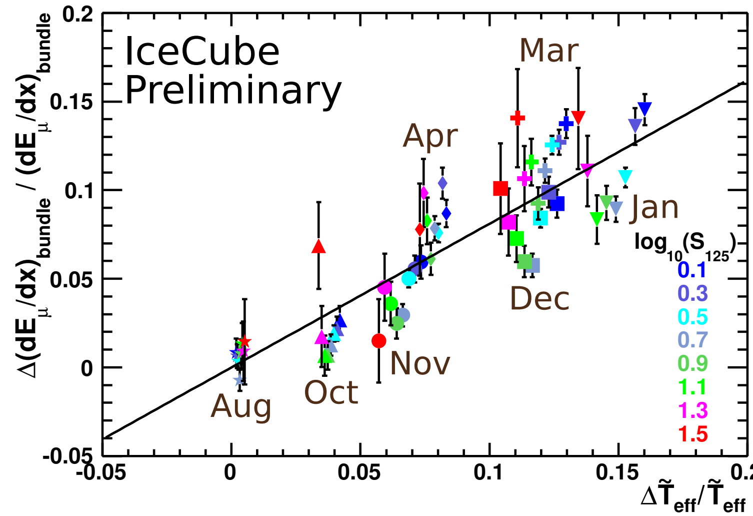
Note the fine time resolution in the muon data

Desiati et al. ICRC 2011



Feusels, de Ridder et al., ICRC 2013: Muon bundles

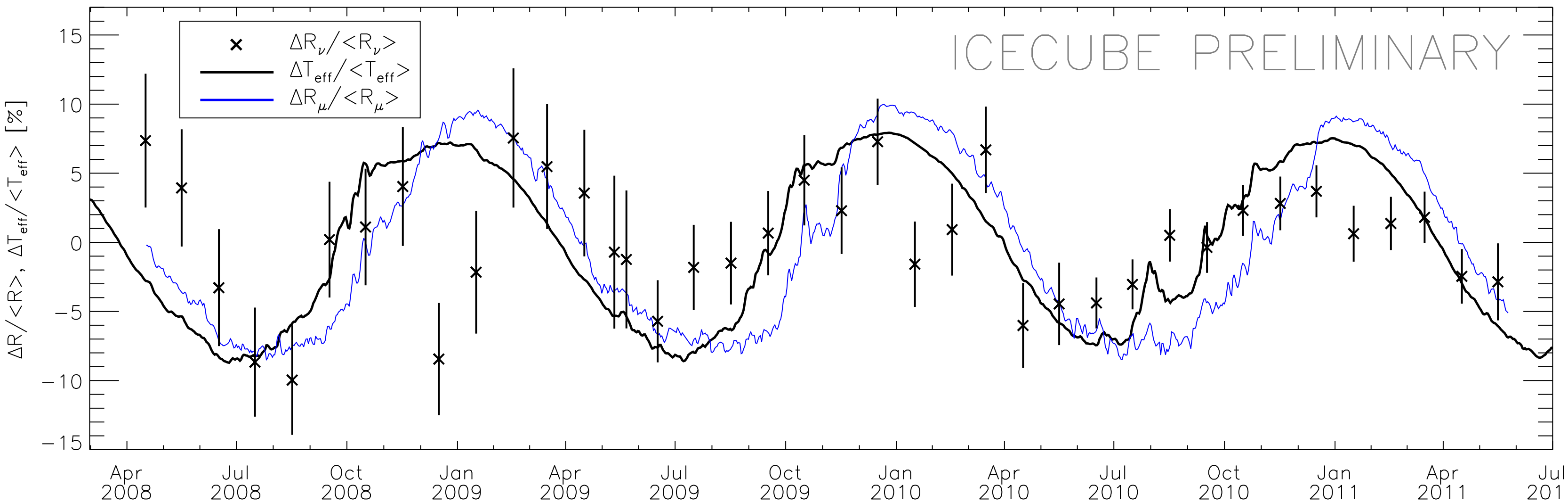




Correlation coefficient = 0.81 ± 0.28

Desiati et al. ICRC 2013

Seasonal variation of Neutrinos!



configuration	α_T^{exp}	χ^2/ndf	α_T^{th}
IC40	0.27±0.21	22.85/12	$0.557^{+0.008}_{-0.007}$
IC59	0.50±0.15	12.30/11	$0.518^{+0.008}_{-0.007}$
IC79	0.45±0.11	4.48/10	$0.489^{+0.007}_{-0.005}$

Atmospheric neutrinos

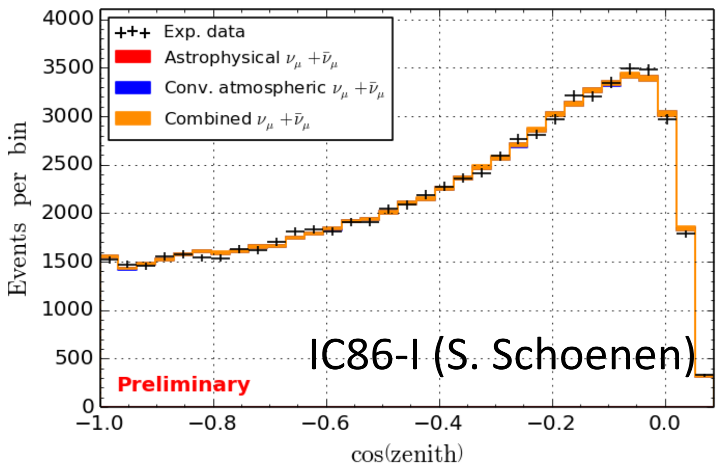
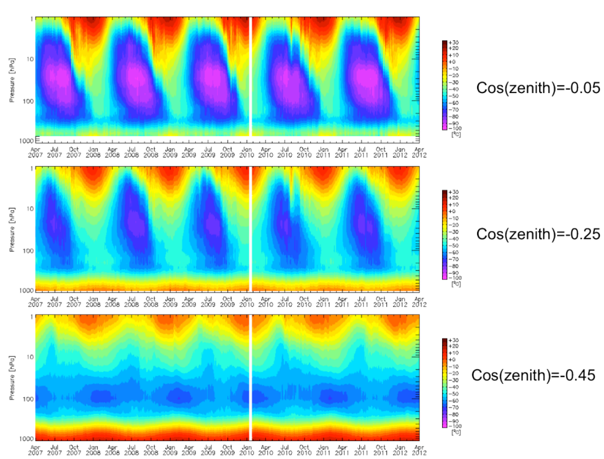
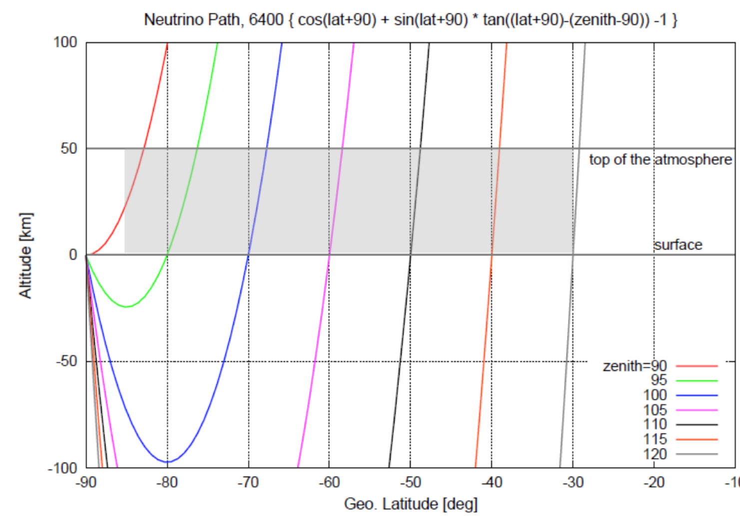


Table 1: Zenith angle, latitude of production and solid angle for three atmospheric zones as seen from the South Pole.

	local zenith angle	latitude at production	Solid angle
Zone 1	90°–120°	−90°– −30°	π
Zone 2	120°–150°	−30°– +30°	0.73π
Zone 3	150°–180°	+30°– +90°	0.27π





Trajectories for Zone 1 from Takao

Atmospheric neutrinos 2

$$T_{\rm eff}(\theta) = \frac{\int dE_\nu \int dX \, (T(X,\theta)\mathcal{P}_\nu(E_\nu, X, \theta^*)A_{\rm eff}(E_\nu,\theta)}{\int dE_\nu \int dX \, \mathcal{P}_\nu(E_\nu, X, \theta^*)A_{\rm eff}(E_\nu,\theta)}$$

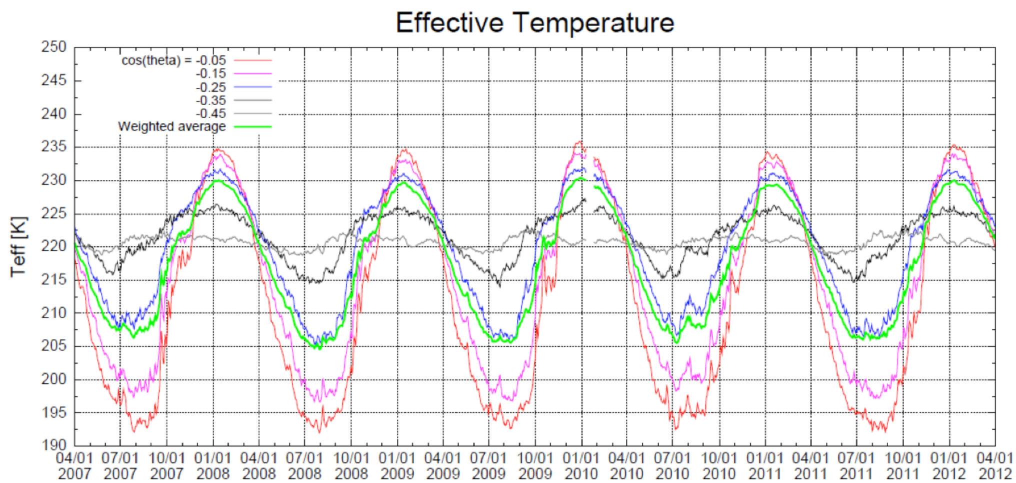
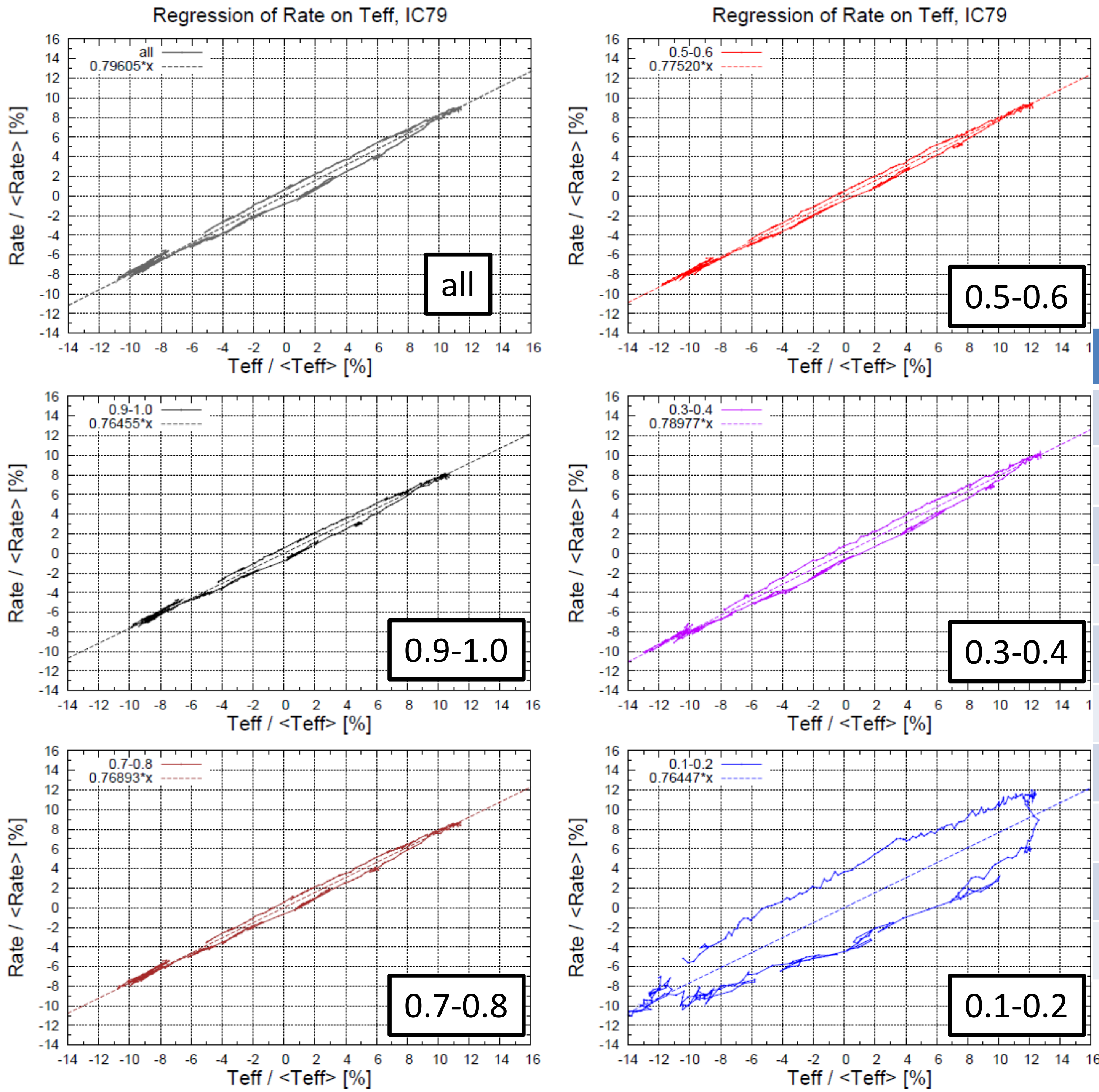


Figure 5: Effective temperature calculated along 5 directions along with the weighted average for $-0.5 < \cos(\theta) < 0$.

Use local zenith angle

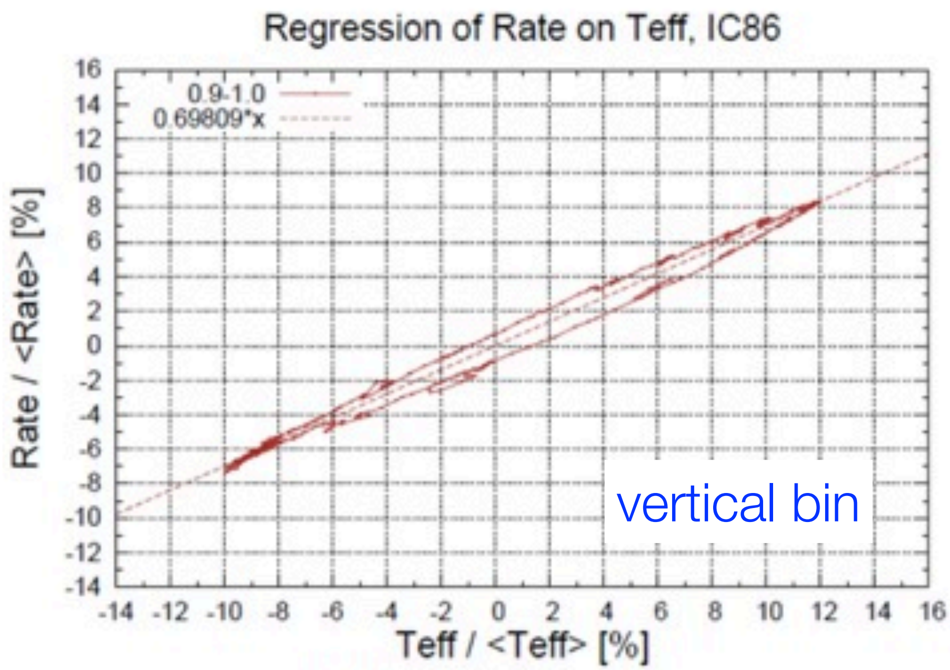
Takao: 20120907



cos(th)	α_T
all	0.796
0.9-1.0	0.765
0.8-0.9	0.767
0.7-0.8	0.769
0.6-0.7	0.772
0.5-0.6	0.775
0.4-0.5	0.782
0.3-0.4	0.790
0.2-0.3	0.800
0.1-0.2	0.764

Hysteresis ?

Perhaps this assumption is the problem: $$\frac{gX_v}{-\mathrm{d}X_v/\mathrm{d}h} = \frac{P}{\rho} = \frac{RT}{M};$$



Gary Binder:
No reference to T

$$\epsilon_i^{\mathrm{eff}}(\theta) = \frac{m_i c}{\tau_i \ln(\Lambda_i/\Lambda_N)} \int \frac{dX}{\rho(X)} \left(e^{-X/\Lambda_i} - e^{-X/\Lambda_N}\right)$$

CERN-PH-TH/2012-096

The Gran Sasso muon puzzle

Enrique Fernandez-Martinez and Rakhi Mahbubani
Theory Division, CERN, 1211 Geneva 23, Switzerland.

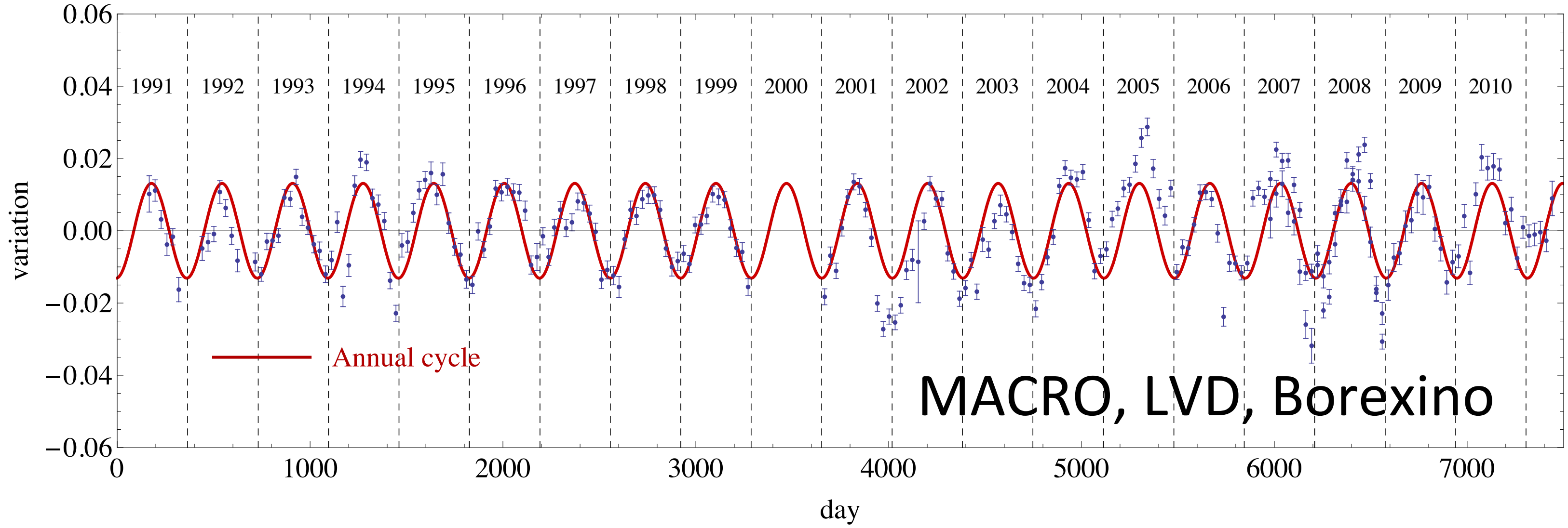
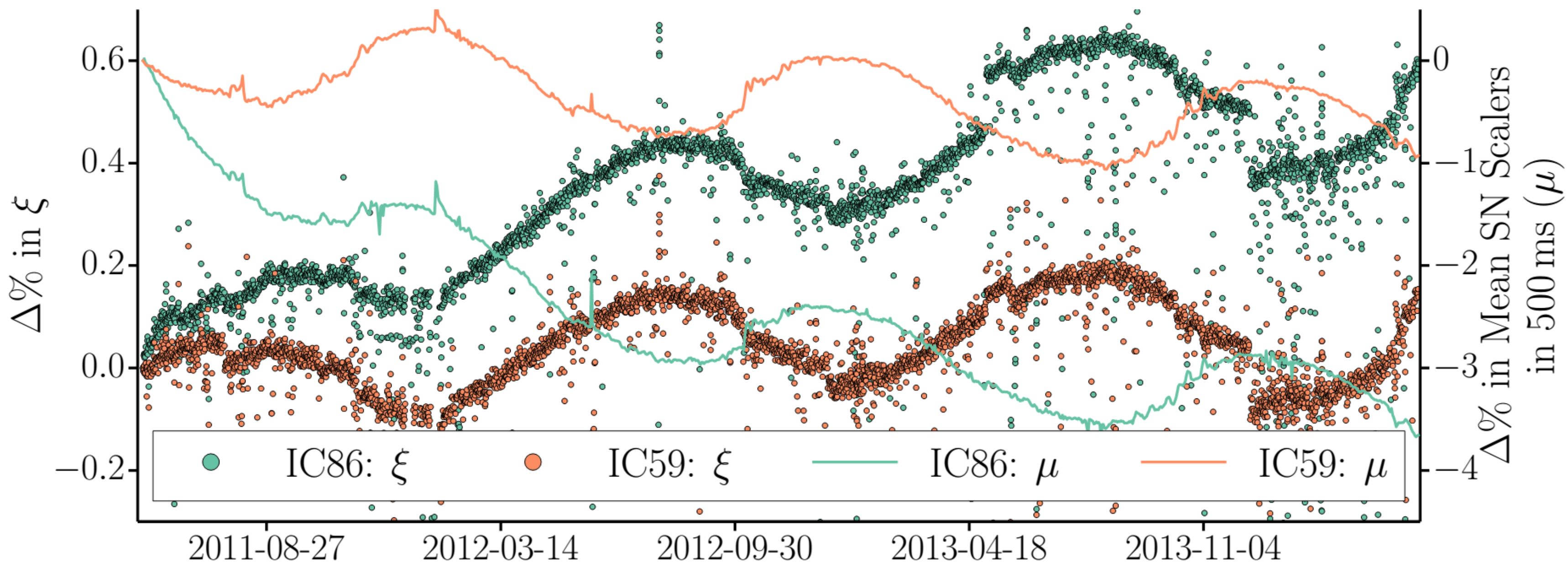


FIG. 1: Combined cosmic muon data from MACRO, LVD and Borexino after subtraction of the mean measured flux for each individual experiment. The best fit is to a cosine of period 365.9±0.2 days and phase 177.4±2.2 days, such that the first maximum occurs on June 26th 1991.

- **Not** the same phase as DAMA
- They also see a 11 year variation

The story of increasing SN alarm rate

Thesis Benedikt Riedel



Decreasing rates in DeepCore also one reason for bad MC description of IC86-I (ML)

most important thesis topics: development of GEANT based Monte Carlo for SNe