成均館大學校
SUNG KYUN KWAN UNIVERSITY

# PeV scale DM

s.park (SKKU)

## KIAS phenomenology workshop
## Nov 11, 2013

work with K. Kohri (KEK), C. Rott (IceCube, SKKU)

Making Everything Easier!™

Novelty Edition

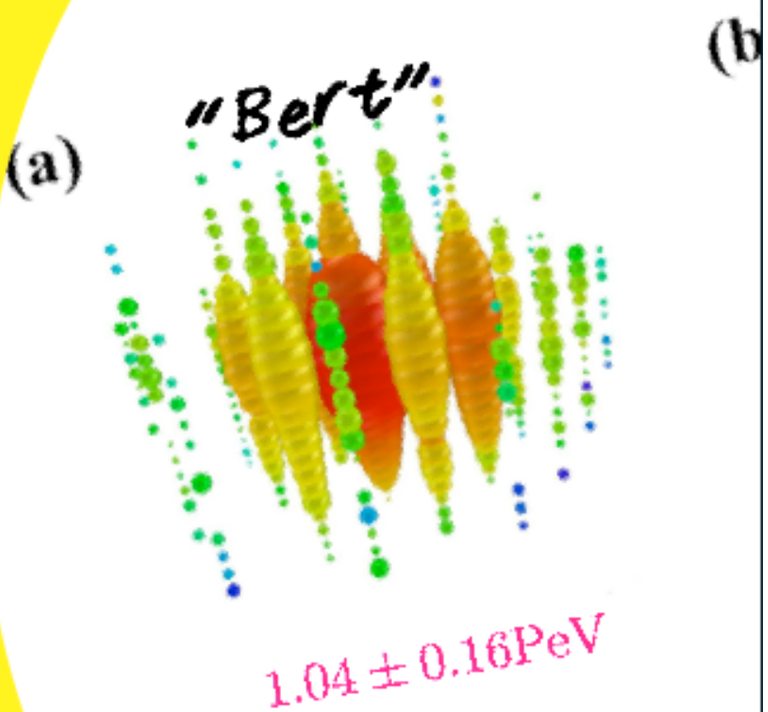
# PeV DM

FOR DUMMIES®

## Learn to:

- New observation by IceCube
- Annihilation vs Decay
- A simple model


Seongchan Park (SKKU)
K. Kohri (KEK)
C. Rott (IceCube, SKKU)

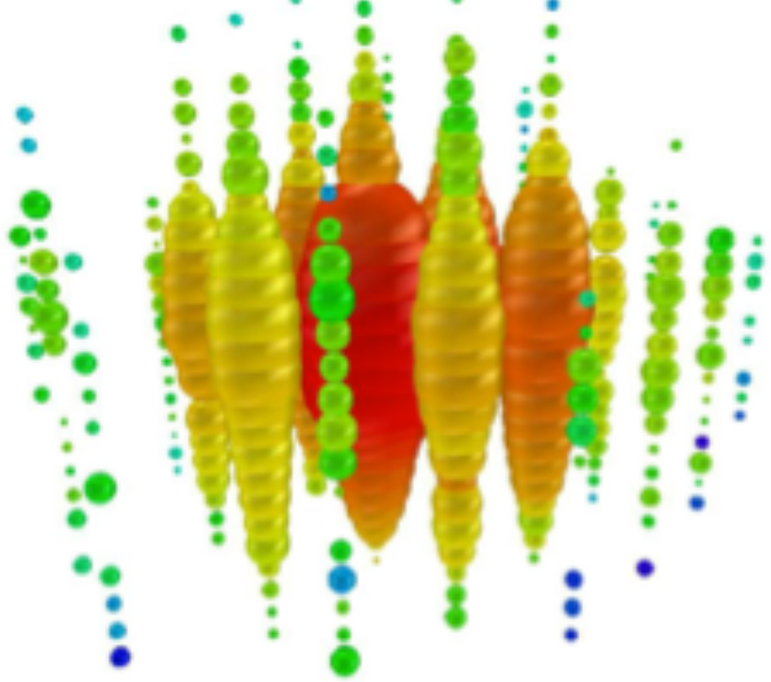



NEW!

# Two PeV neutrinos observed by IceCube in 615.9 days

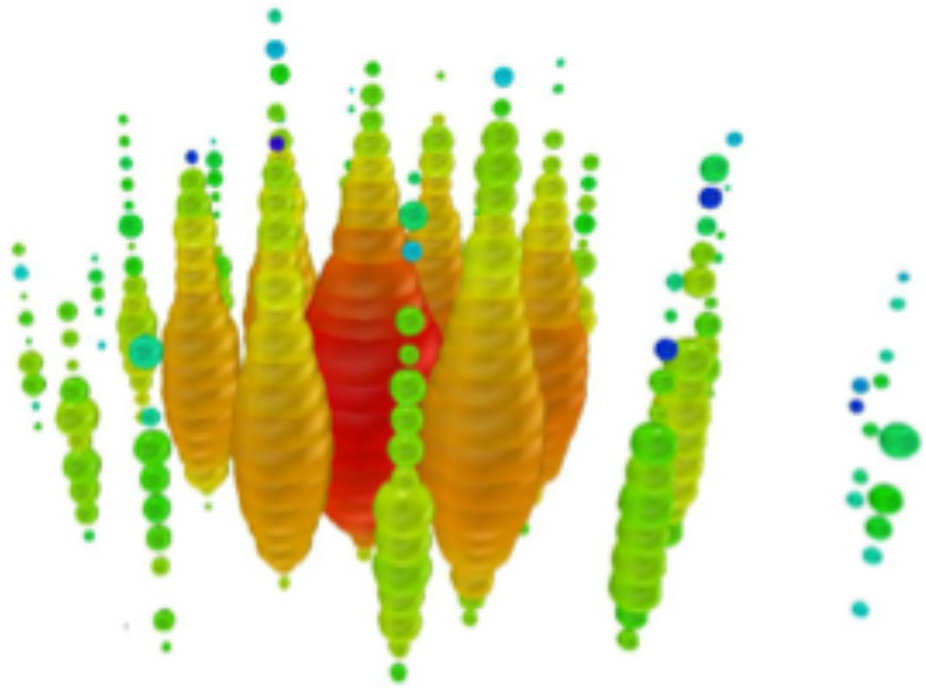
[Aartsen et. al. (IceCube) Phys.Rev.Lett. 111 (2013) 021103]

(a) "Bert"



$1.04 \pm 0.16\text{PeV}$

(b) "Ernie"

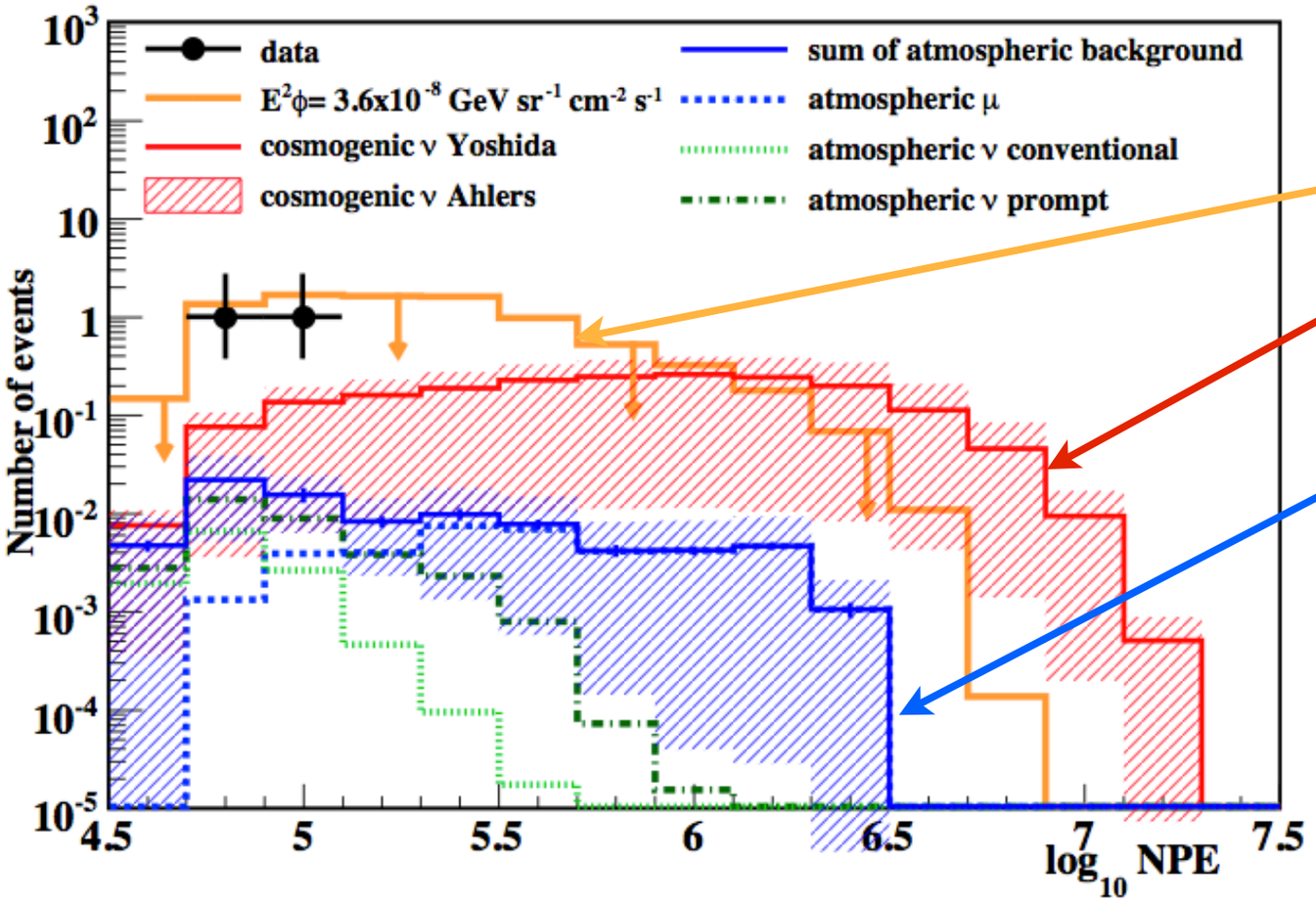


$1.14 \pm 0.17\text{PeV}$

~consistent with fully contained simulated particle showers induced by neutral-current $\nu_{e,\mu,\tau}$ or charged-current $\nu_e$ interactions within the IceCube detector.

# The observational result looks odd ..

**Expected: $0.082 \pm 0.0024^{+0.041}_{-0.057}$




~$E^{-2}$ ??

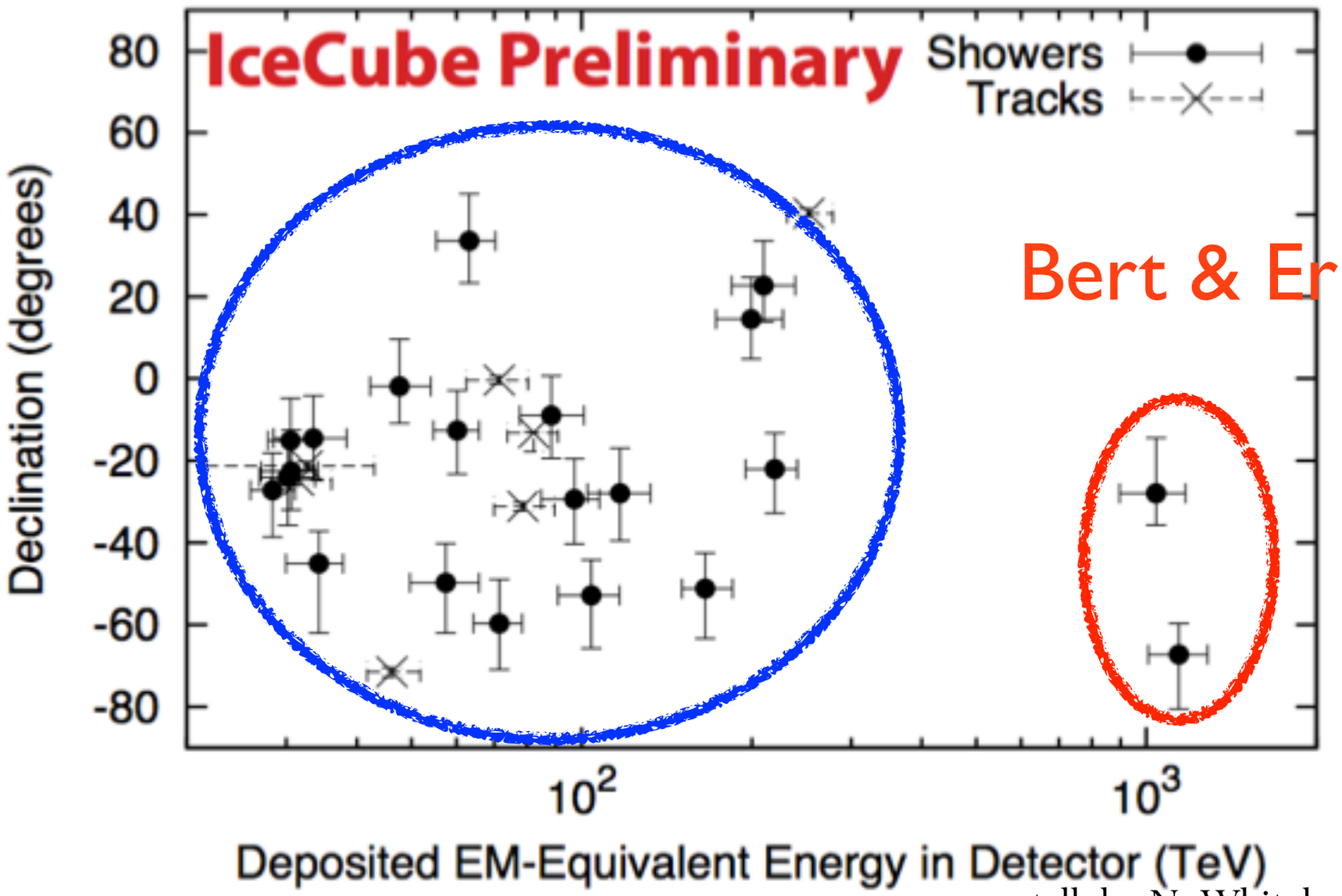
-Too low in energy for GZK

-Too high in energy for atmospheric nu.

upshot:

These events cannot be understood by known sources!

# In addition,
# 26 more neutrinos observed in 1Tev-250Tev window,
# (cf) background is 10.6+-4.5



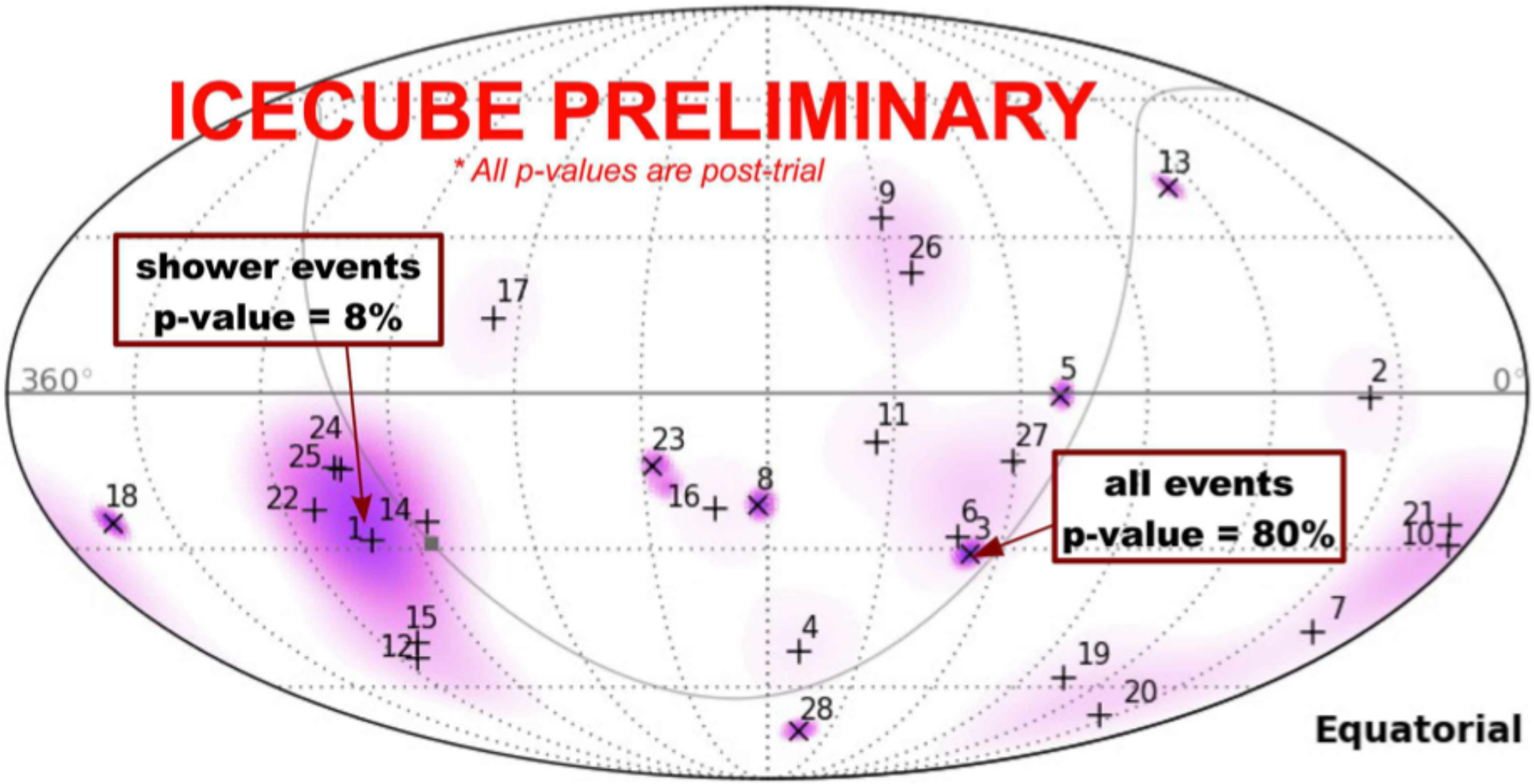

'northern sky (upgoing)'

Bert & Ernie

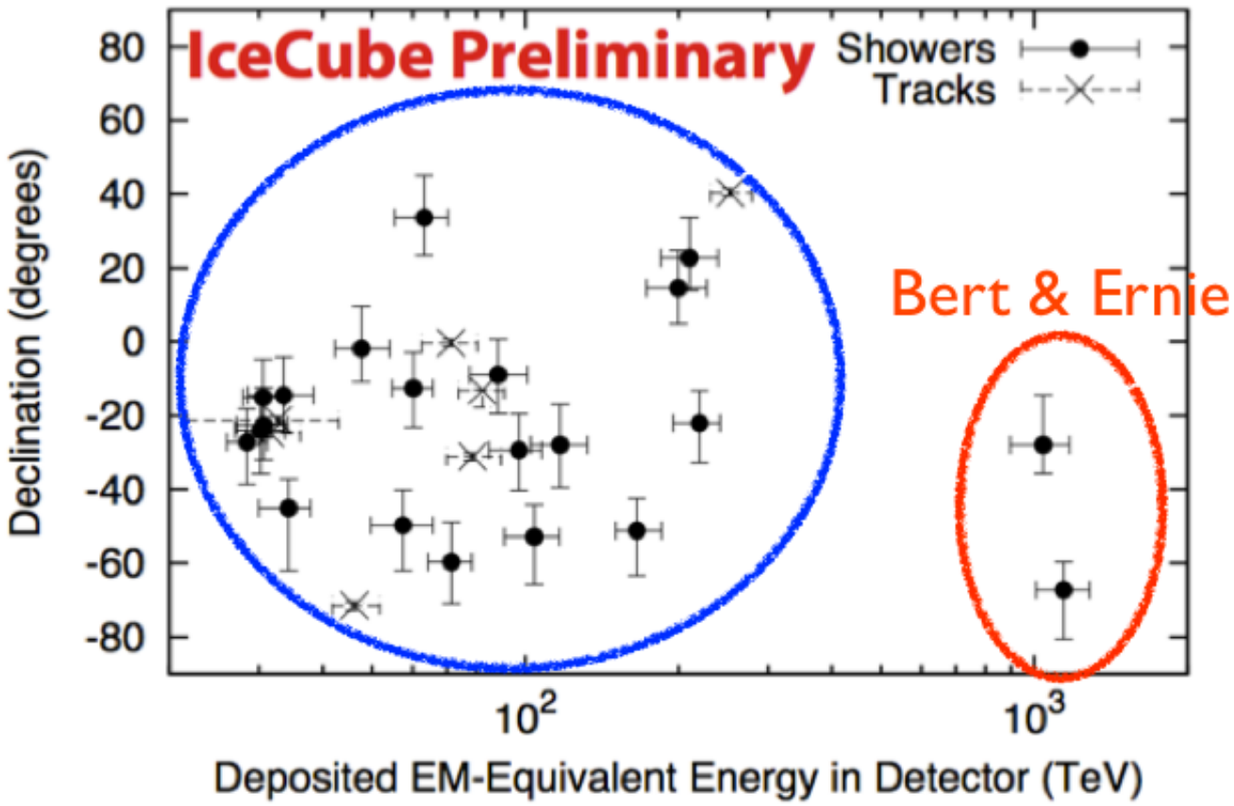
'southern sky(downgoing)'

-talk by N. Whitehorn at IPA2013

# Skymap: No Significant Clustering ~not from a local source



# Closer look at the DATA



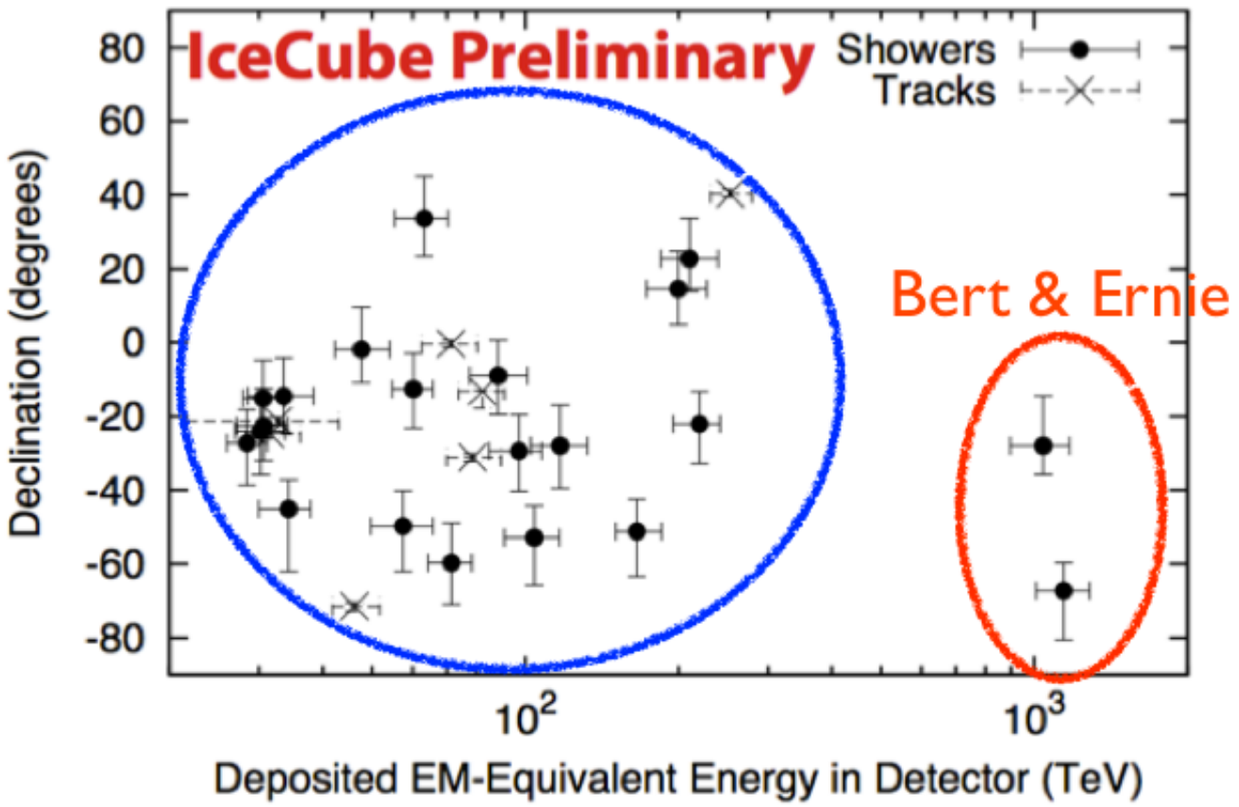

**Properties of observed neutrinos**

- "Continuous" in 1-250 TeV
- "Peak" at ~1 PeV
- Consistent with isotropic distribution
- 1:1:1 neutrino flavor

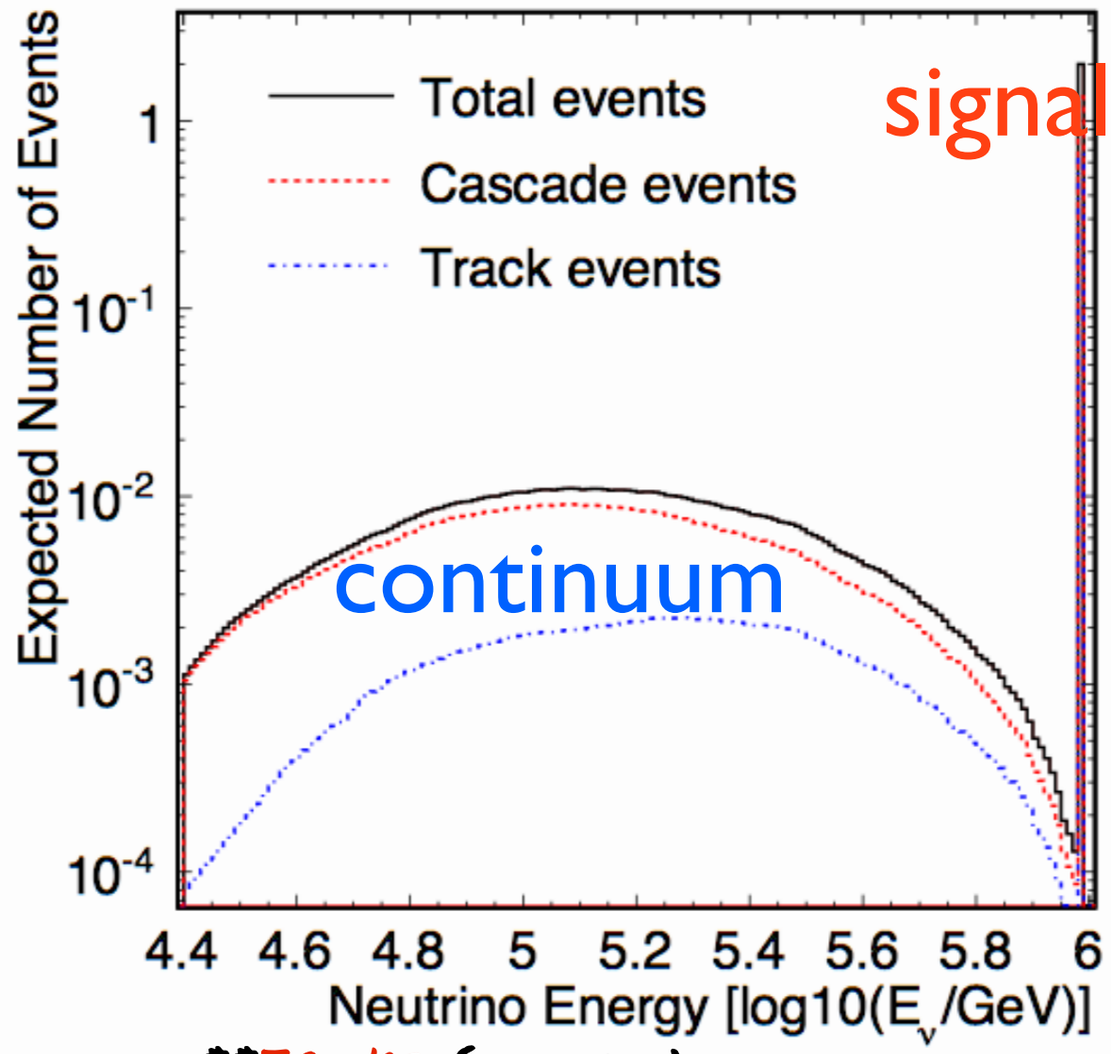
understandable since after a long enough propagation, neutrino flavor info. would disappear

$$P(\nu_e \leftrightarrow \nu_e) = 0.56\,,$$
$$P(\nu_e \leftrightarrow \nu_\mu) = P(\nu_e \leftrightarrow \nu_\tau) = 0.22\,,$$
$$P(\nu_\mu \leftrightarrow \nu_\mu) = P(\nu_\mu \leftrightarrow \nu_\tau) = P(\nu_\tau \leftrightarrow \nu_\tau) = 0.39\,.$$

# The "continuum+peak" may imply particle DM!




$\chi \to \nu_L + X(\nu + \cdots)$




**Tracks (nu_mu)

**Cascades (nu_e+nu_tau)

# Annihilation vs Decaying DM

[Feldman, Kusenko, Matsumoto, Yanagida (2013)]
[Kohri, SCP, Rott (2013)]

$$Rate = \sigma_{\rm eff}^{\nu N} \times \frac{d\mathcal{L}}{dt} \qquad R \simeq 2/615.9 days$$

$$\left(\frac{d\mathcal{L}}{dt}\right)_A = \langle\sigma v\rangle n_{DM}^2 L_{DM} \qquad \left(\frac{d\mathcal{L}}{dt}\right)_D = \Gamma_{\rm DM} n_{DM} L_{DM}$$

$$n_{DM} = \rho_{DM}/m_{DM} \simeq 0.4{\rm GeV/cm^3}/1.2{\rm PeV} \simeq 3.3 \times 10^{-6}/{\rm cm^3}$$

$$L_{DM} \sim 10{\rm kpc} \simeq 3.1 \times 10^{22}{\rm cm} \qquad v \sim 10^{-3} c$$

$$R \sim 1.53 \times 10^{15} \times \langle\sigma_A v\rangle/{\rm cm^3},$$

$$R \sim 4.5 \times 10^{21} \Gamma_{DM}$$

$$\langle\sigma v\rangle \sim 2.45 \times 10^{-23} {\rm cm^3/sec}, \qquad \sigma_A \leq 4\pi/(m_{\rm DM}^2 v^2)$$

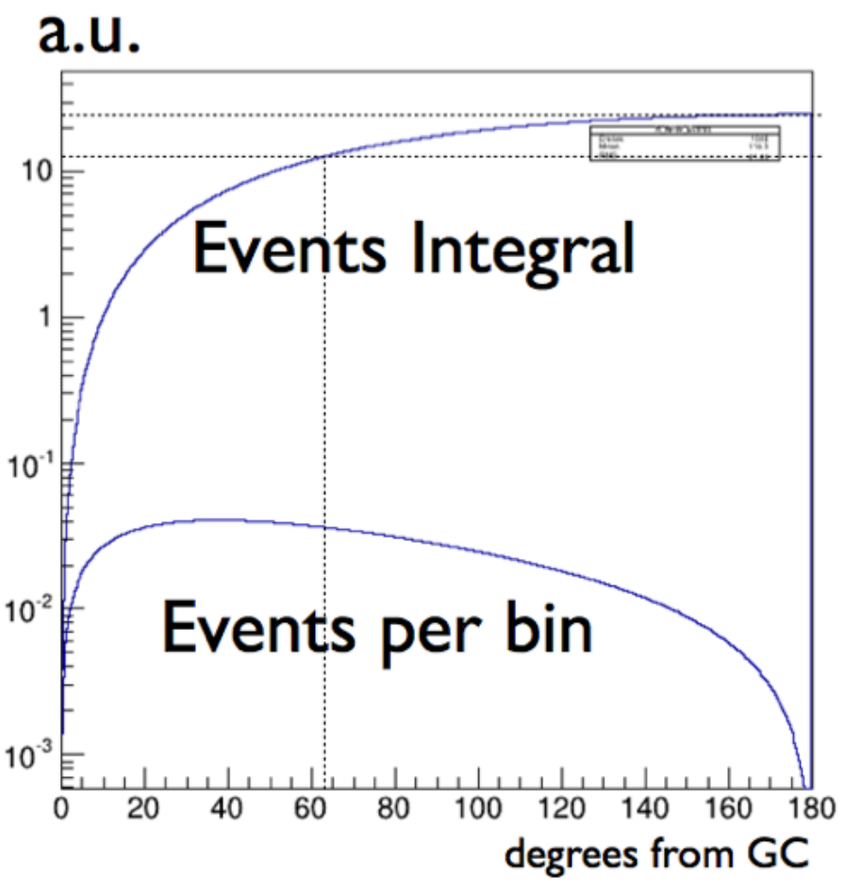
$$\Gamma_{DM} \sim 8.35 \times 10^{-30}/{\rm sec} \qquad \tau_{DM} \sim 1.2 \times 10^{29} {\rm sec}$$

# Directional information

[Kohri, SCP, Rott (2013)]

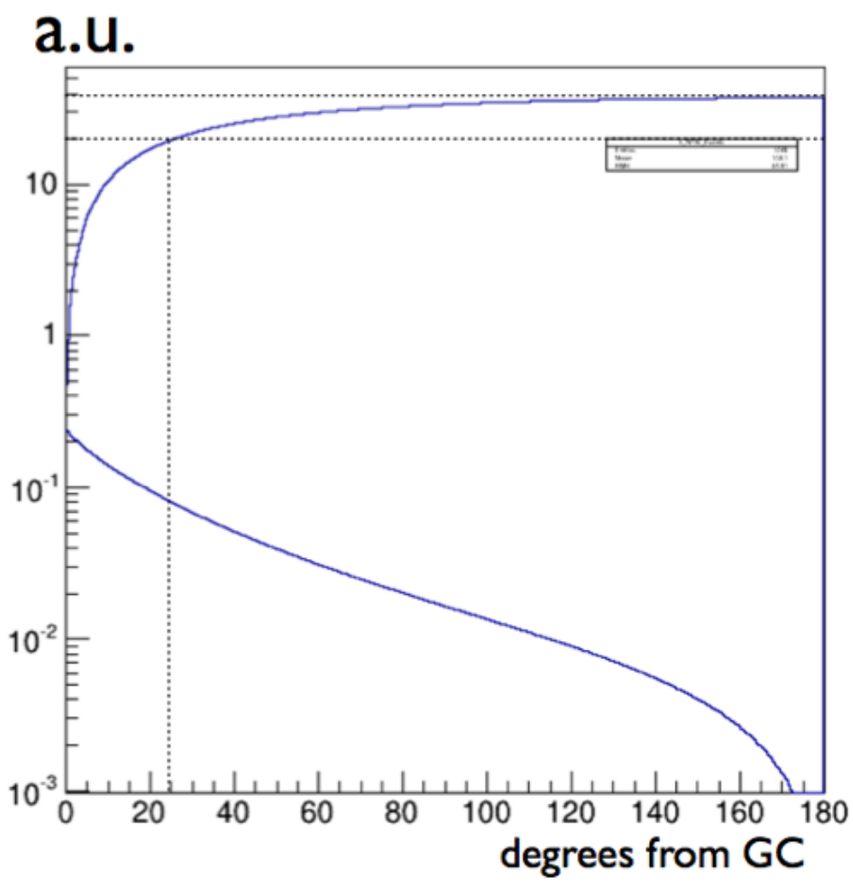
NFW Profile

**Decay**




50% of events within 65°

**Annihilation**




50% of events within 25°

# Ann vs Decay

[Kohri, SCP, Rott (2013)]

**Annihilating** $\chi\chi \to \nu_L + X(\to \nu + \cdots)$

-less than one event/100 years with PeV DMs

-centered (50% within 25°)

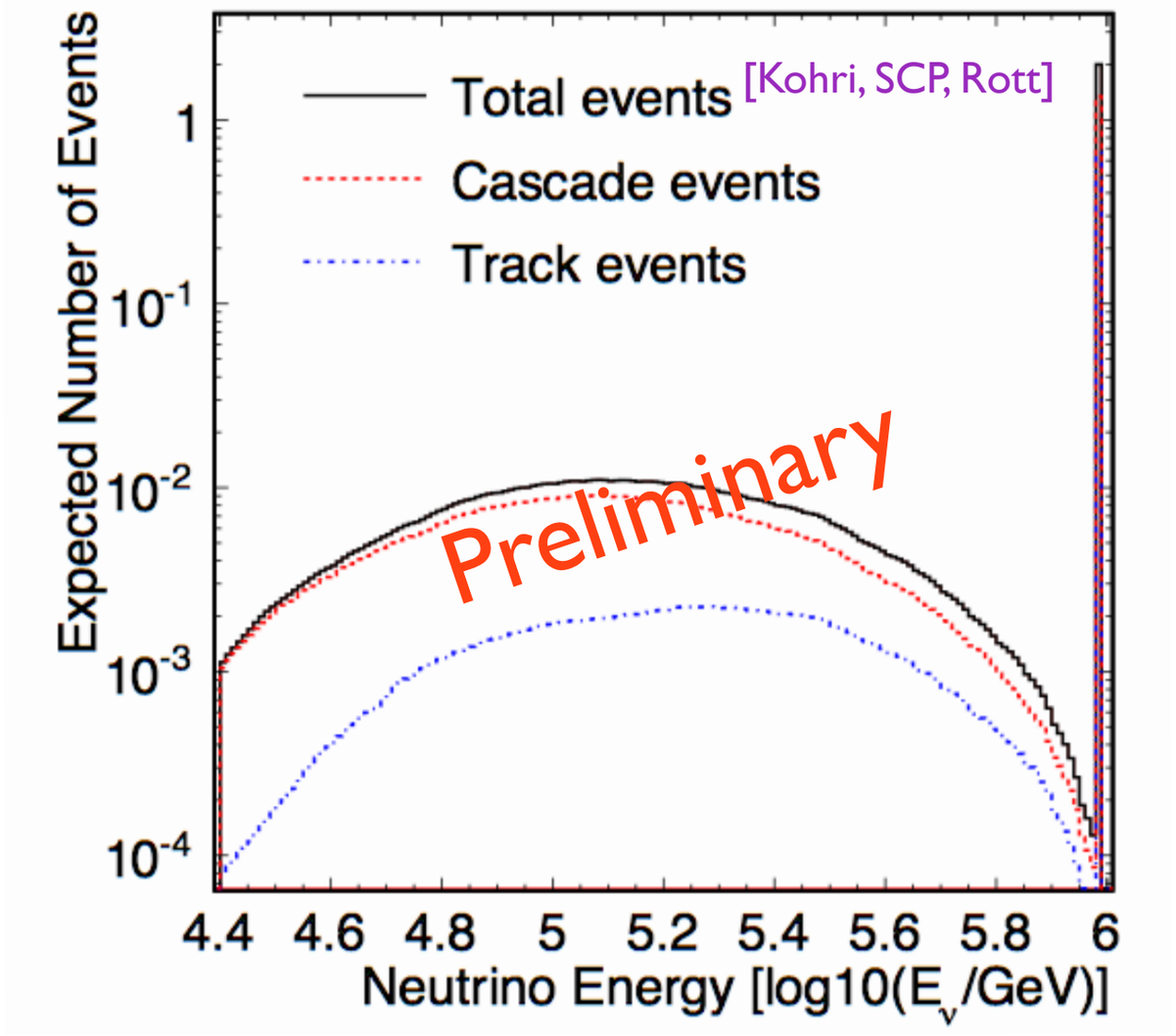
**Decaying** (preferred)

$\tau_\chi \sim 10^{28-29}\mathrm{sec}$ would fit the "peak"

-broadly distributed (50% within 65°)

# A simple case

## We consider a simple decay $\chi \to \nu_L + H$ and found it can fit the observation pretty well!




**Tracks (muon neutrinos)
**Cascades (sum of electron and tau neutrino events)

-peak by $\nu_L$
-continuum by nu from Higgs decay

$$m_\chi = 2\mathrm{PeV}$$
$$\tau_\chi = 9.7 \times 10^{28}\mathrm{sec}$$

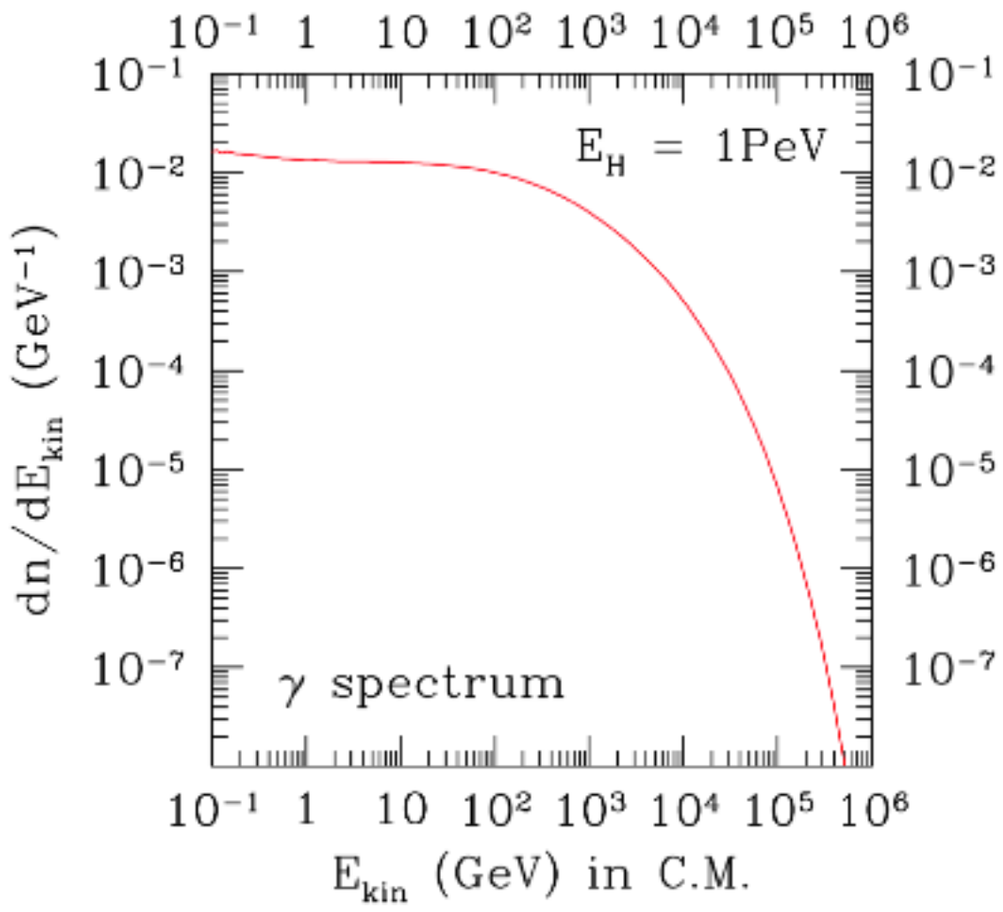
gives

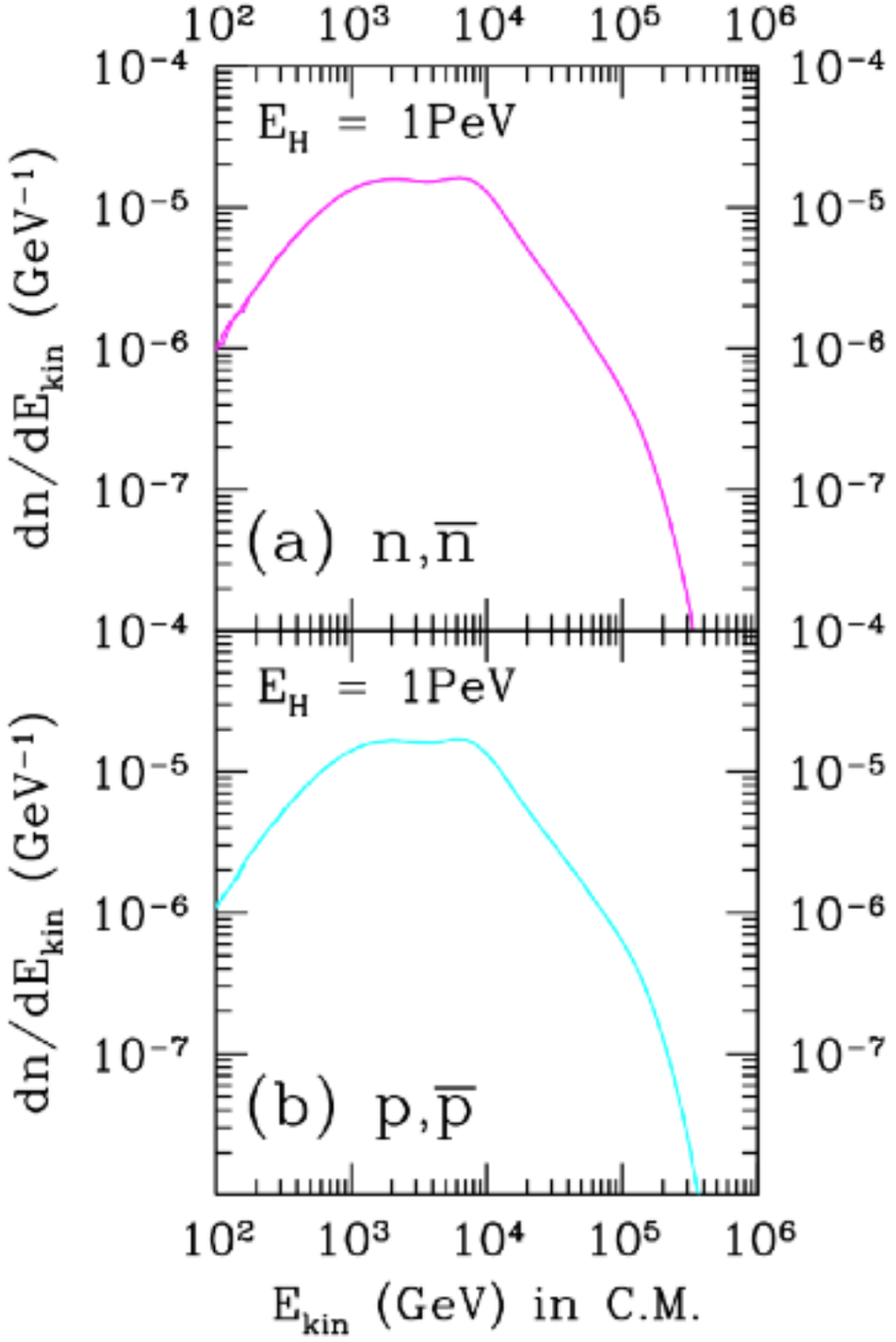
$$N_\nu(\mathrm{PeV}) = 2.04$$

with continuum

[Kohri, SCP, Rott (2013)]

# contributions to CR




*bottom line:
it looks safe in <TeV regime

# Model building

$$\mathcal{L} = y\bar{\nu}Hn + \overline{(n^c, \chi)} \begin{pmatrix} M_n & \sigma \\ \sigma & M_\chi \end{pmatrix} \begin{pmatrix} n \\ \chi \end{pmatrix}$$

we can arrange
<u>seesaw mechanism + small mixing in n & DM</u>
such that DM can decay to neutrino + Higgs
with a suppressed rate

$$\Gamma_{\chi \to \nu_L + H} = \frac{(y\epsilon)^2}{8\pi} M_-$$

$$\epsilon \approx -\frac{\sigma}{M_n - M_\chi} \ll 1$$

$$M_- \approx \frac{1}{2}(M_n + M_\chi) - \sqrt{\delta^2 + \sigma^2}, \delta = \frac{1}{2}(M_n - M_\chi)$$

# Conclusion

- IceCube observed 2 (background 0.082) with 1 PeV and 26 (background 10.6) neutrino events in 1Tev-250Tev
- Too low in energy for GZK neutrinos, too high in energy for atmospheric neutrinos.
- Can be explained by DM decay.
- A simple model based on seesaw + small mixing is suggested.