成均館大學校
SUNG KYUN KWAN UNIVERSITY

Superheavy DM and neutrino signals

s.park (skku)

"Basis of Universe with Revolutionary Ideas"
Toyama University, Feb 13, 2014

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

Plan

- My Place
- Physics

Sungkyunkwan University (SKKU)

1398

founded as the highest educational institution in Chosun dynasty

1443

Korean Alphabet (Hangul) invented
-Many scholars from SKKU participated

1996

"renew" by Samsung

-strong and well-known in nano-physics so far
-has vision for fundamental sciences (particle/astro/bio)

Two campuses

www.skku.edu

Humanities and Sciences Campus in Seoul

Natural Sciences Campus in Suwon (~15km south of Seoul)

SISAC 2012, 2013 & 2014

http://astrophysics.skku.edu/SISAC201X/

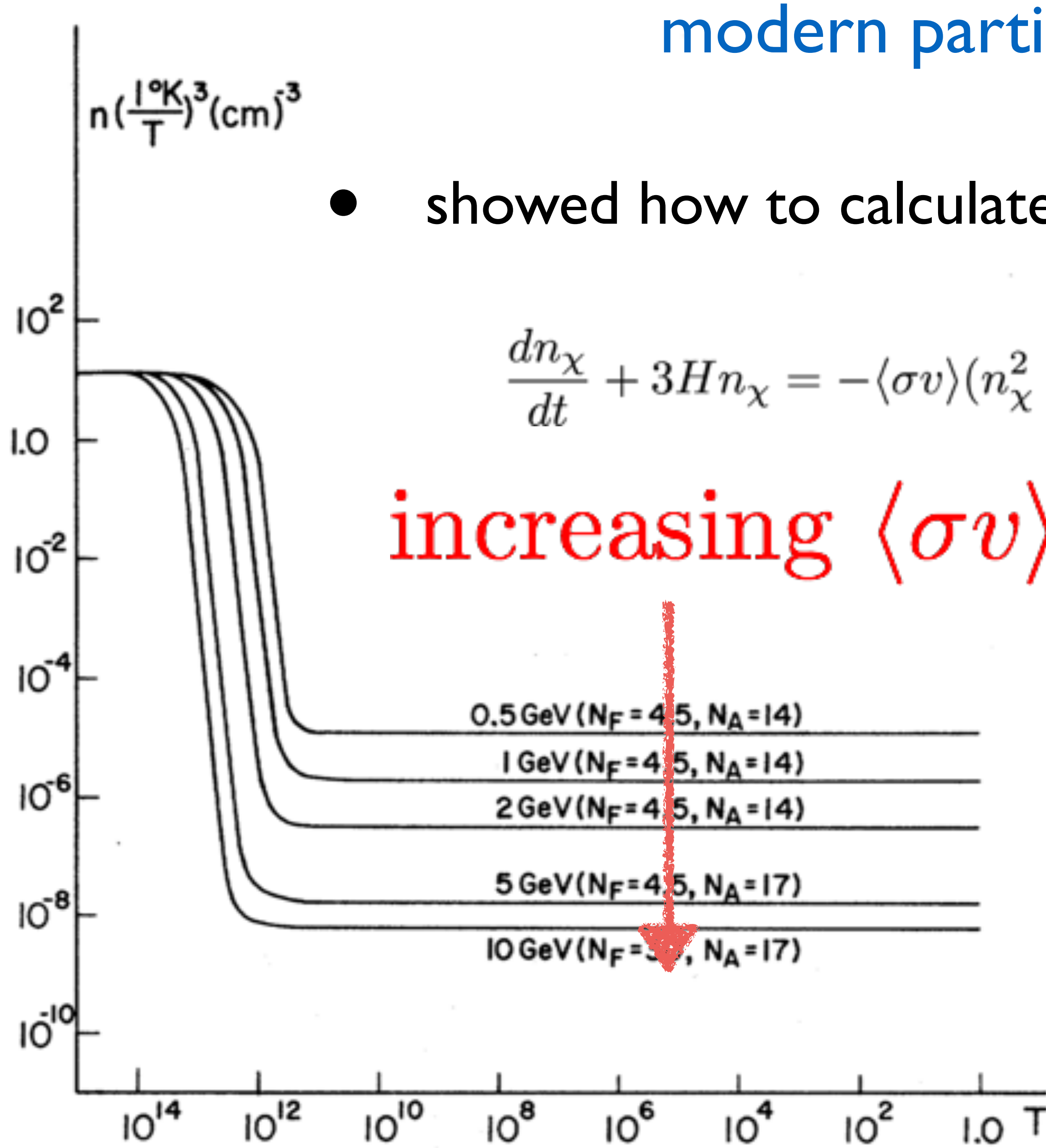
Physics Disclaimer

- I learned in grad school that DM is in GeV - TeV..
- ..if not K(SVZ) axion..
- ..no other place is worth considering
- In Korea, we almost too much emphasize the importance of Lee-Weinberg paper (1977) that I even feel guilty when I have to talk some other stuff…

Lee-Weinberg *PRL (1977)*

"The 1st paper, which open modern particle-cosmology"

- showed how to calculate the DM abundance in BB framework



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,eq}^2)$$

$$\Omega_\chi h^2 \simeq \frac{0.1\mathrm{Pb}\cdot c}{\langle\sigma v\rangle} \lesssim 0.11$$

increasing $\langle\sigma v\rangle$

$$\langle\sigma v\rangle \simeq 1\mathrm{pb}$$

"WIMP miracle"

Unitarity bound

j-th partial wave:

[Griest, Komionkowski, PRL 1990]

$$\sigma_j \leq \frac{4\pi(2j+1)}{m_\chi^2 v^2}\left(1 - \frac{v_r^2}{4}\right) \qquad v_r = 2\sqrt{1 - 4m_\chi^2/\bar{s}}$$

$$\langle \sigma v \rangle = \frac{1}{8 m_\chi^4 T K_2^2(x)} \int_{4m_\chi^2}^{\infty} d\bar{s}(\bar{s} - 4m_\chi^2)\sqrt{\bar{s}} K_1\left(\frac{\sqrt{\bar{s}}}{T}\right) \sigma_j$$

$$\Omega_\chi h^2 \simeq \frac{0.1\mathrm{Pb}\cdot c}{\langle \sigma v \rangle} \lesssim 0.11 \qquad \Rightarrow m_\chi \lesssim 120\ \mathrm{TeV}$$

Don't even think about it!

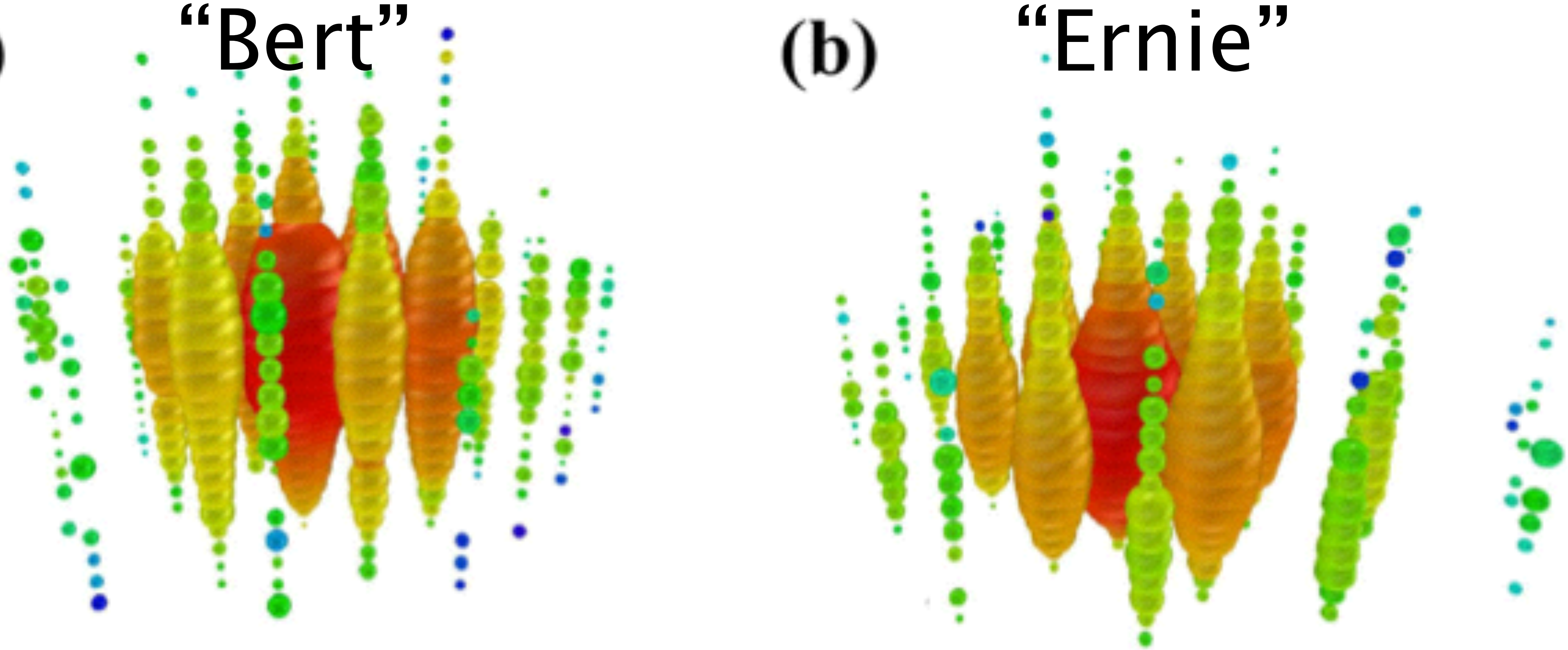
- We only had listened that no evidence found in *all attempts* to detect DM on earth.. (other than DAMA/LIBRA)
- ..in colliders as well as direct detection experiments below TeV all failed so far
- Cosmic ray observations, on the other hand, recently produce a lot of noise everywhere
- SPACE (PAMELA, FERMI-LAT, AMS2..) as well as under ice (IceCube)

Two PeV neutrinos observed by IceCube

in 615.9 days

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

(a) "Bert" (b) "Ernie"



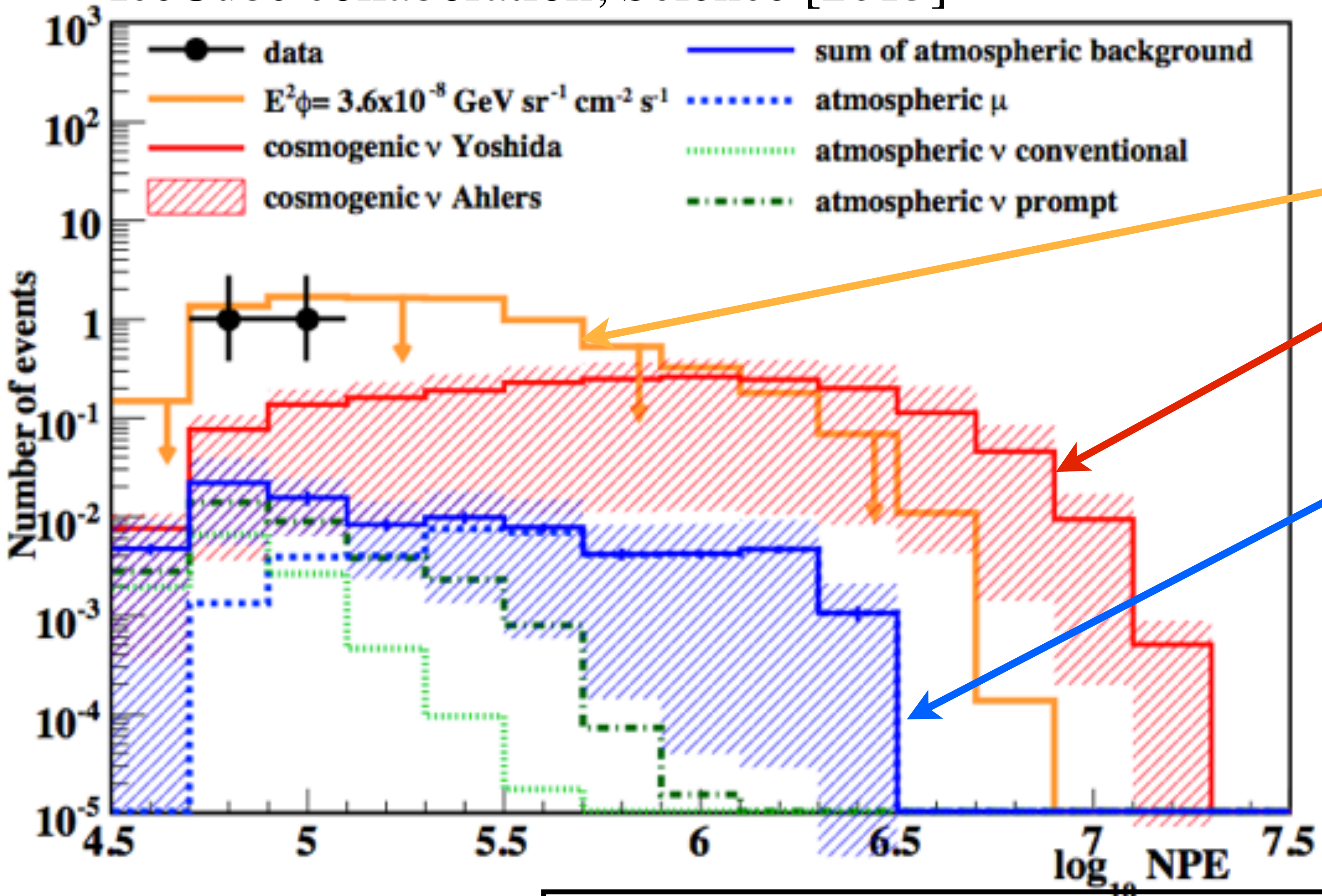
$1.04 \pm 0.16\text{PeV}$ $1.14 \pm 0.17\text{PeV}$

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

The observational result looks odd ..

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

IceCube collaboration, Science [2013]



~E^{-2} ??

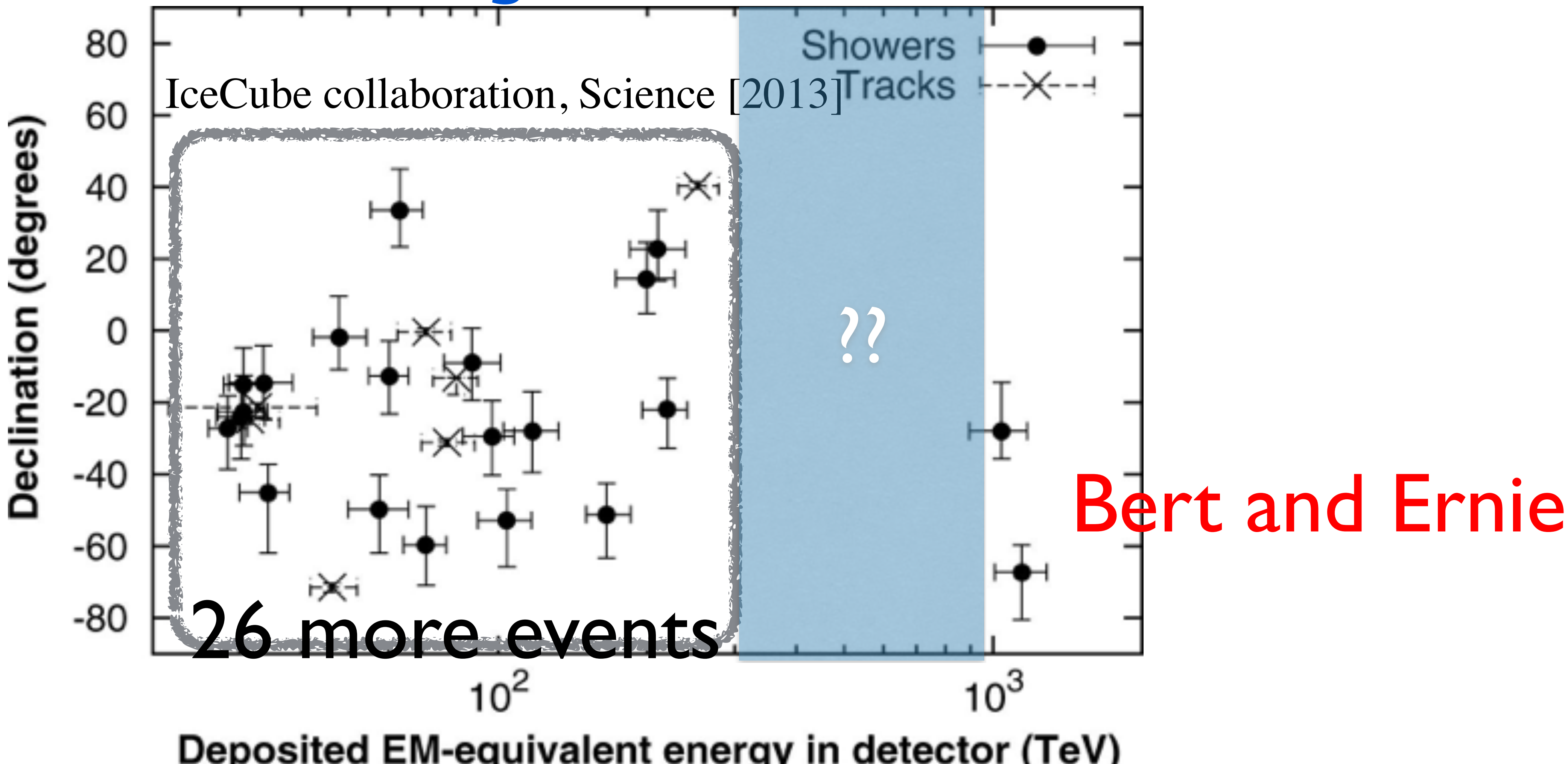
– Too low in energy for GZK

– Too high in energy for atmospheric nu.

<u>upshot:</u>

The source is unidentified even though E^{-2} is typical..

In addition,
26 more neutrinos observed in 1TeV–300TeV window,
(cf) background is 10.6+-4.5



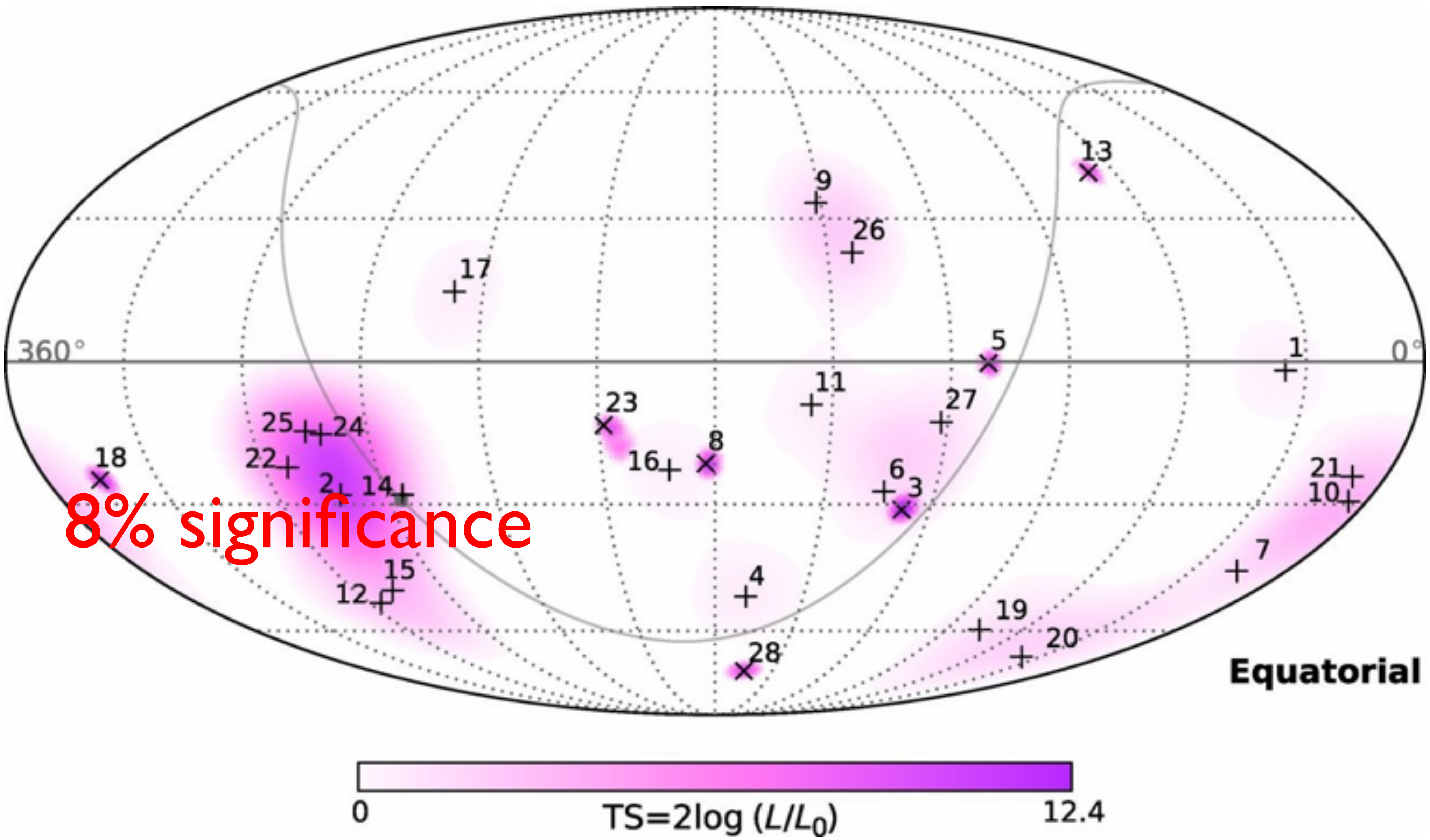
The gap in Edep between 300 TeV and 1 PeV does not appear to be significant: Gaps of this size or larger appear in 28% of realizations of the best-fit continuous power-law flux.

No strong indication of clustering found

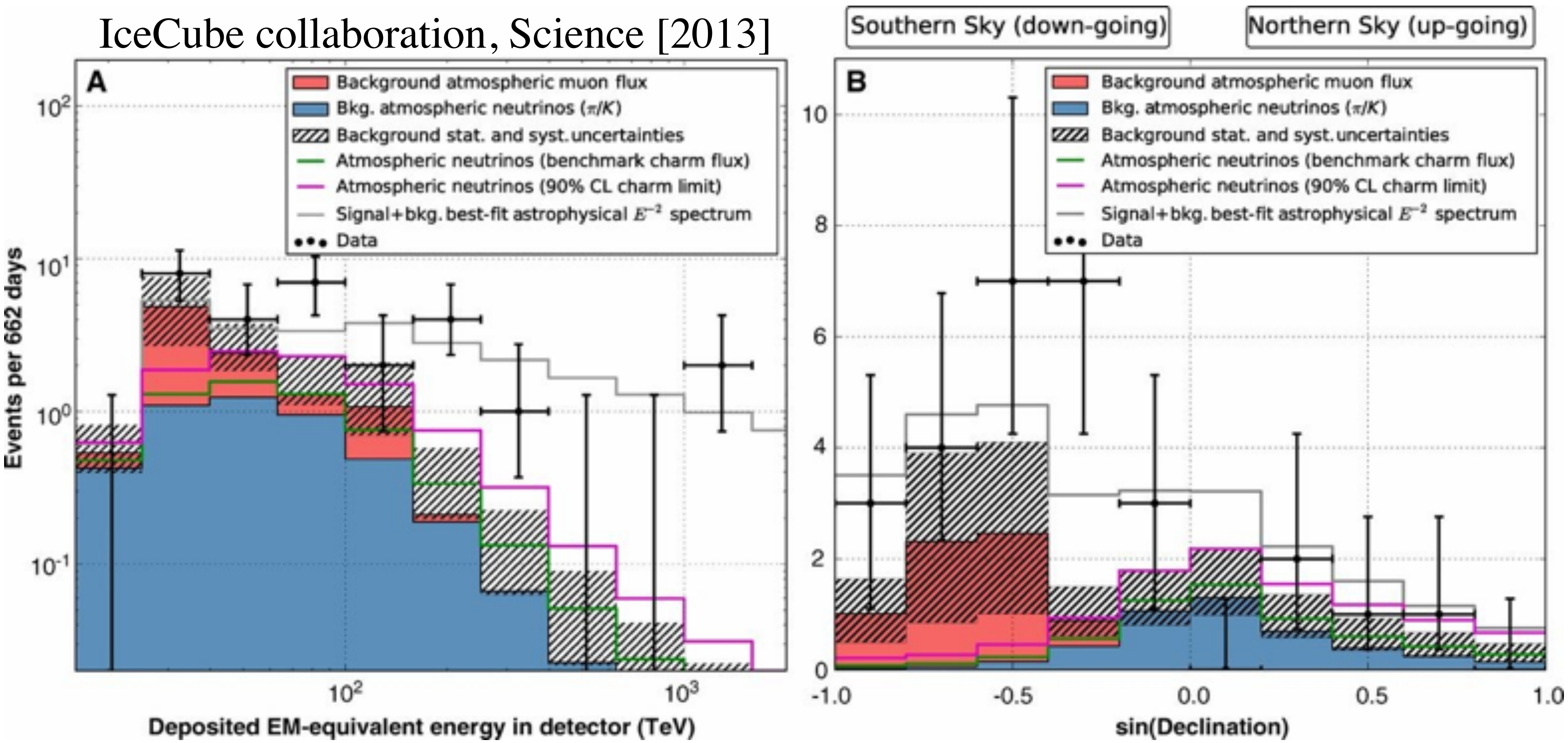
Essentially isotropic (slightly more south..)

+ showers

X muon-trck



IceCube collaboration, Science [2013]



Properties of observed neutrinos

"Continuous" in 1-250 TeV

– "Peak" at ~1 PeV

- Consistent with isotropic distribution

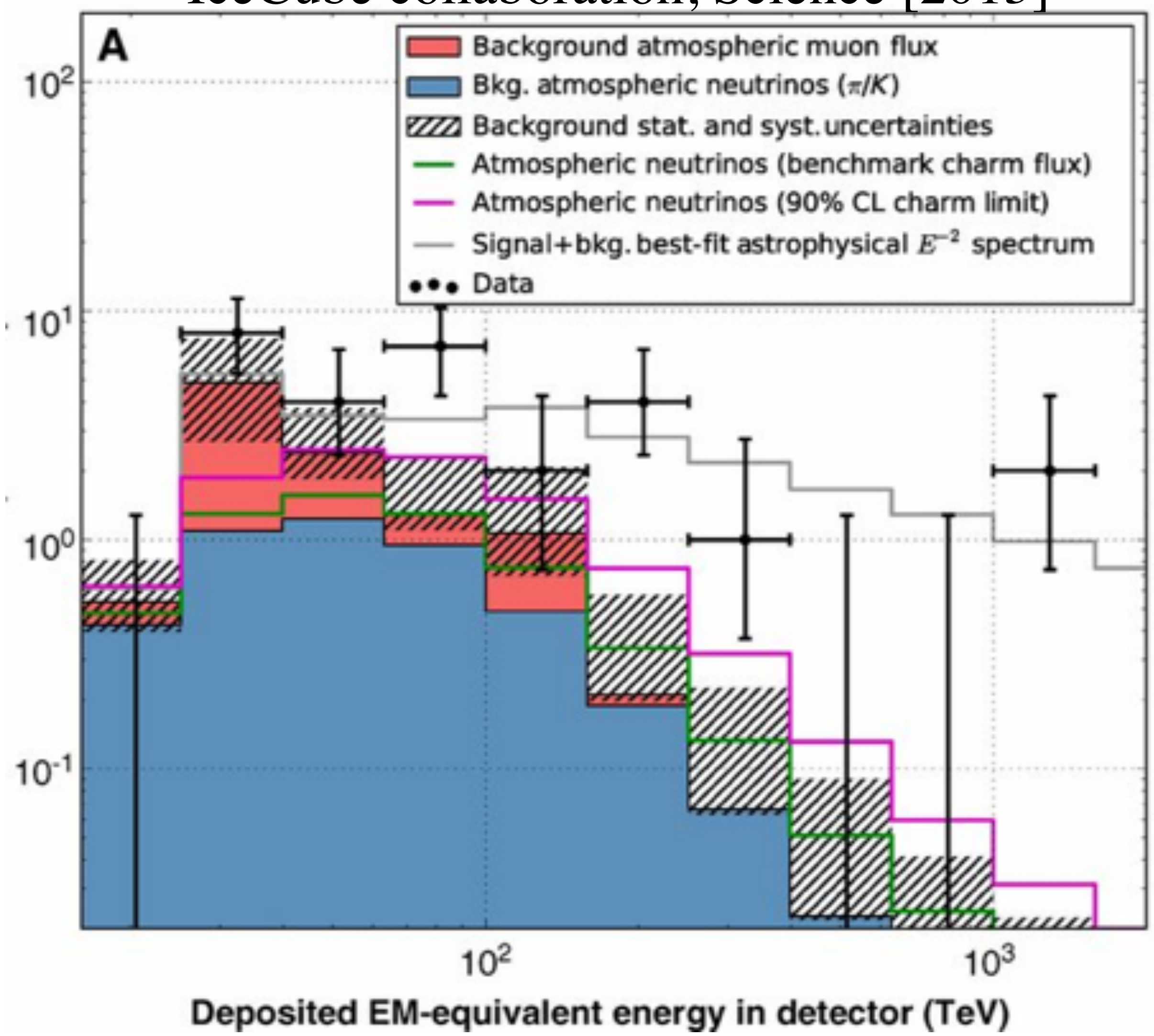
-1:1:1 neutrino flavour

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

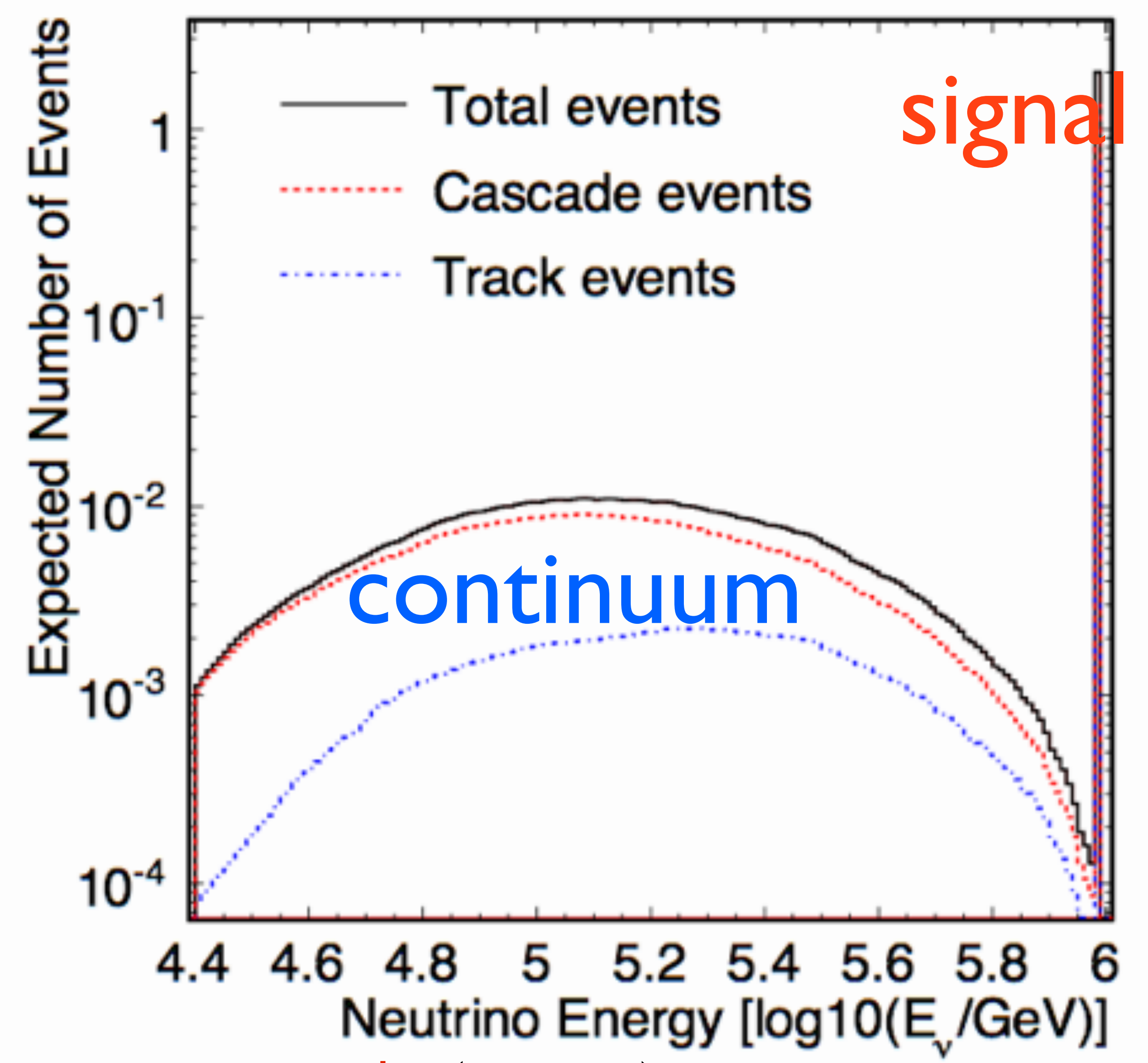
understandable since after a long enough propagation, neutrino flavour info. would disappear

The "peak (+gap)" may imply particle DM~PeV!

IceCube collaboration, Science [2013]



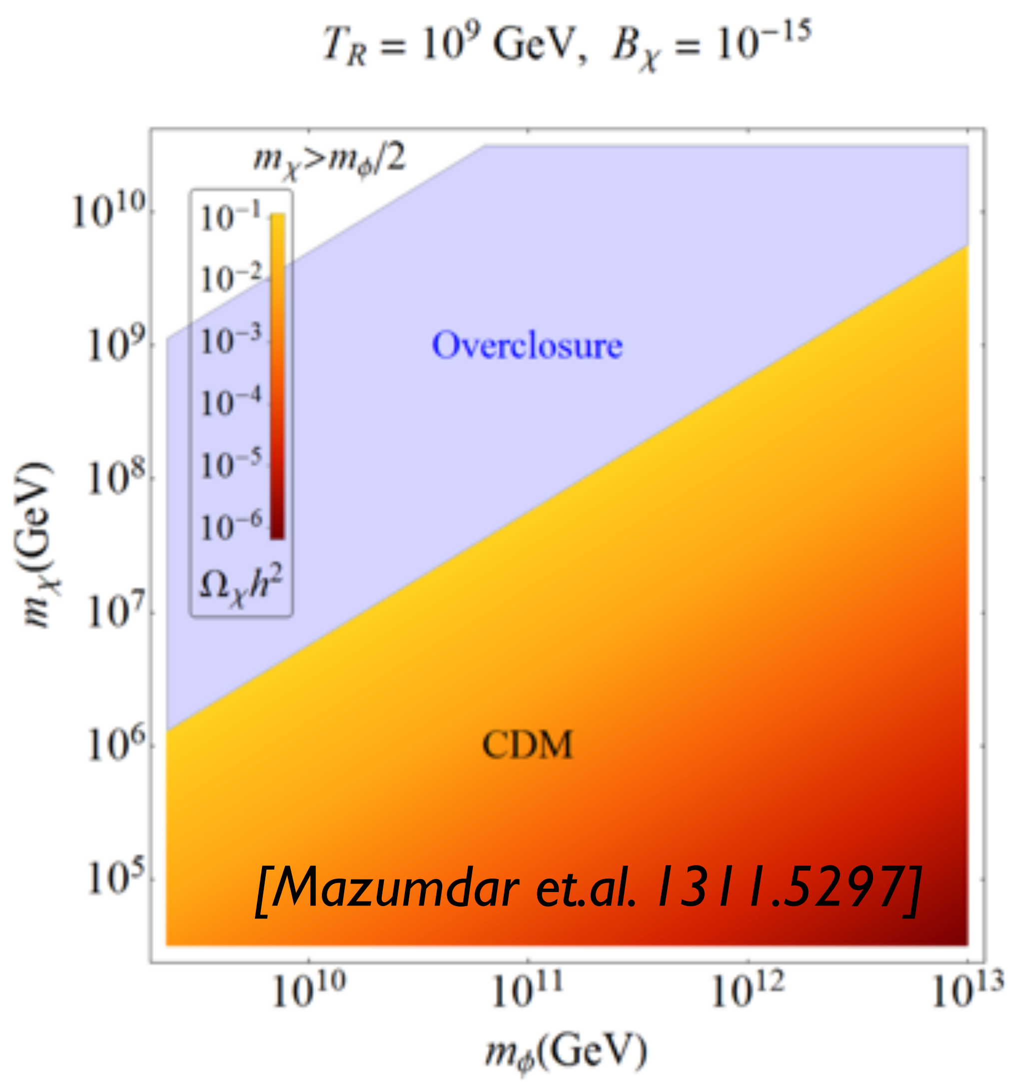
$$\chi \to \nu_L + X(\nu + \cdots)$$



**Tracks (nu_mu)
**Cascades (nu_e+nu_tau)

“WIMPZILLA”

[Chung, Kolb, Riotto PRL1998]



DM born out of equilibrium

$$m_\chi \geq 200\mathrm{TeV}$$

non-thermal production e.g. by inflaton decay would be a source for superheavy DM

“dark radiation”

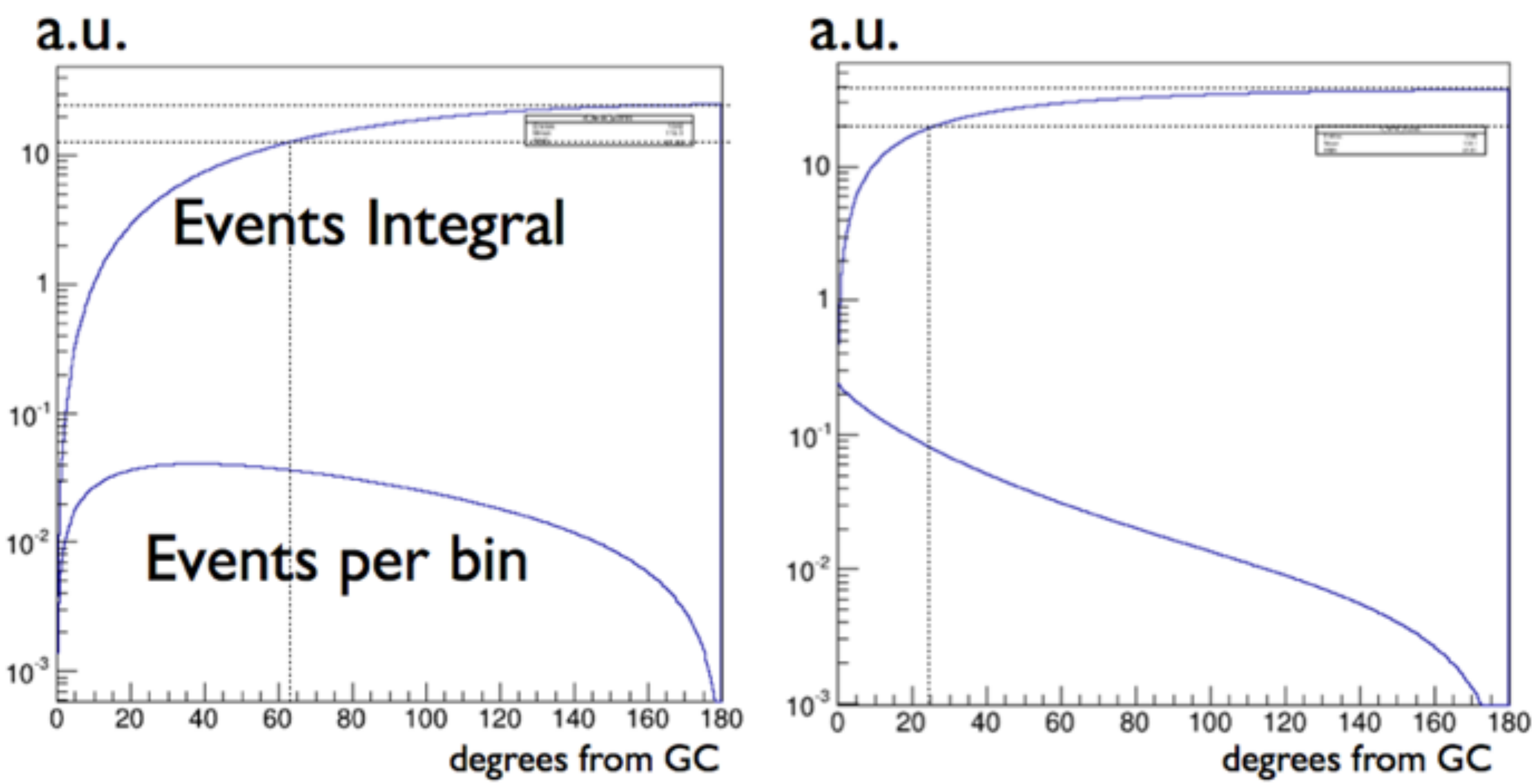
[J.Park and SCP, Phys.Lett. B728 (2014)]

Directional information

[Kohri, SCP, Rott]

NFW Profile

Decay **Annihilation**



50% of events within 65°

50% of events within 25°

Preferred

Ann vs Decay

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

- -inconsistent with unitarity bound (<120 TeV)
- -expected events are too small
- -centered (50% within 25°)

Decaying (preferred)

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

- -broadly distributed (50% within 65°)

A benchmark Model for PeV events

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

<u>seesaw mechanism + small mixing in n & DM</u>

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

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

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

whole sky cross check

$$\frac{d\phi_\nu}{dE} = \frac{1}{\tau} J_d(\psi) \frac{R_{sc}\rho_{sc}}{4\pi m_\chi} \frac{dN_\nu}{dE}.$$

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega}\int_{\cos\psi}^{1} \mathcal{J}(\psi')\, 2\pi\, d(\cos\psi')$$

$$\Delta\Omega = 2\pi(1-\cos\psi)$$

$J_{\Delta\Omega}$= 2.0

integrate all sky

$\chi \to \nu h$

T_{life}=662days = $5.72*10^7$s

N=1

N_{90}=2.3

$$N = \frac{1}{\tau}\frac{R_{sc}\rho_{sc}}{4\pi m_\chi} J_{\Delta\Omega} 4\pi A_{eff}(E = m_\chi/2) T_{life} N_\nu$$

A_{eff} = 14m^2=$1.4*10^5$cm^2

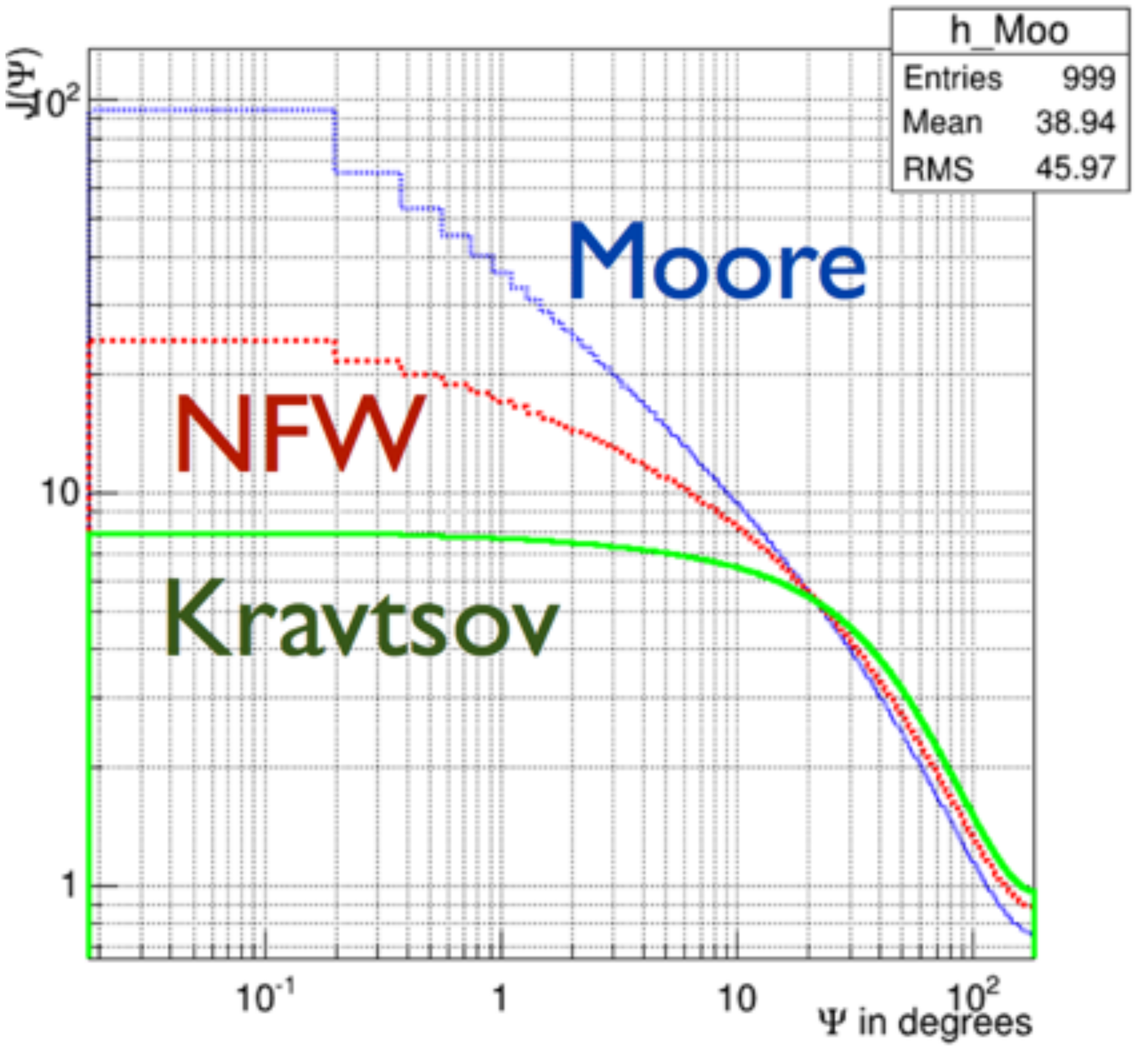
do not consider flavors as Aeff @ 1PeV is equal for all flavors

isotropic emission

ρ_{sc}=0.3GeV/cm^3

R_{sc}=8.5kpc=8.5*3.1e21cm=**$2.6*10^{22}$cm**

J-factor decay



my_headers/halo/test_JPsi_class.C

$J_{\Delta\Omega}$(NFW)= 2.0

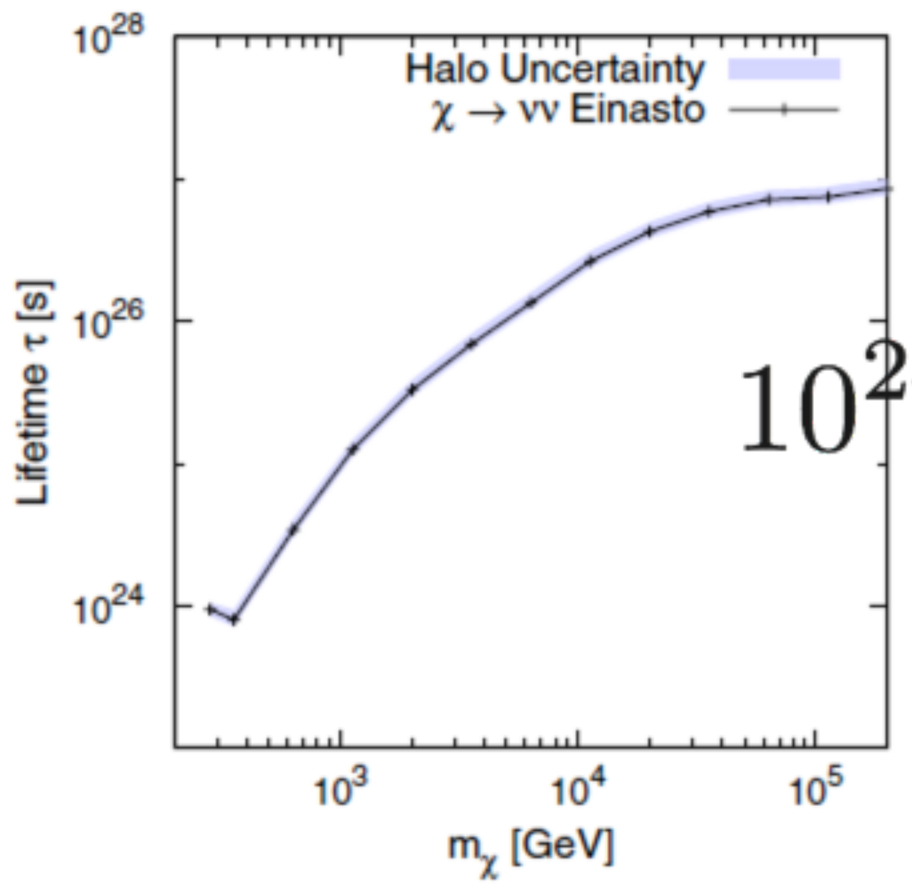
J-factor for S.Palomarez-Ruiz paper
(Phys.Lett. B665 (2008) 50-53)
J_{180}= 2.0 (for NFW)
http://arxiv.org/pdf/0712.1937.pdf

As we will see below, and following a similar approach as in Ref. [9], we are interested in signals corresponding to different components of the halo: the full-sky signal and the signal from a 30° half-angle cone around the galactic center. Whereas for the former, the value of the average of the line of sight integration of the DM density, J_{180}, for the three considered profiles, can vary at the very most from 1.3 to 8.1, for the latter, the value of J_{30} might be anything from 3.9 to 24. These limiting cases are obtained from the range of values for ρ_{sc}[15] which satisfy present constraints from the allowed range for the local rotational velocity [16], the amount of flatness of the rotational curve of the Milky Way and the maximal amount of its non-halo components [17]. For the usually quoted value of ρ_{sc}, for each of the profiles, $(\rho_{sc}, \mathcal{J}_{180}, \mathcal{J}_{30}) = (0.27\ \mathrm{GeV/cm^3},\ 1.9,\ 6.5)$[11], (0.30 GeV/cm^3, 2.0, 6.1) [12] and (0.37 GeV/cm^3, 2.2, 5.5) [13]. Thus, uncertainties in the halo profile have fairly small effects on our final results. Here we consider the simulation by Navarro, Frenk and White (NFW) [12] as our canonical profile. From the limiting cases just discussed, this implies that in the worst scenarios we could be overestimating (underestimating) the neutrino flux by a factor of about 1.5 (3.9).

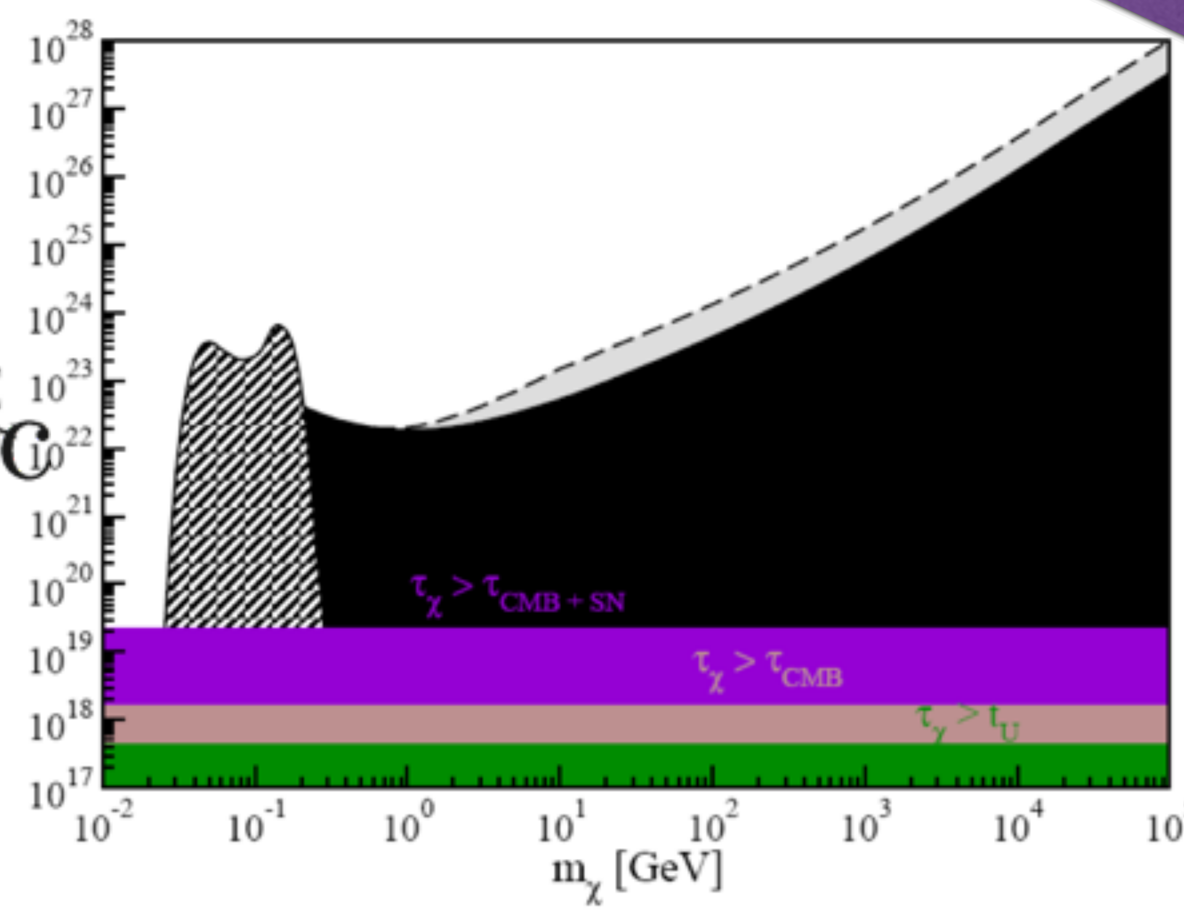
Old
IceCube

Relevant Plots

PHYSICAL REVIEW D 84, 022004 (2011)



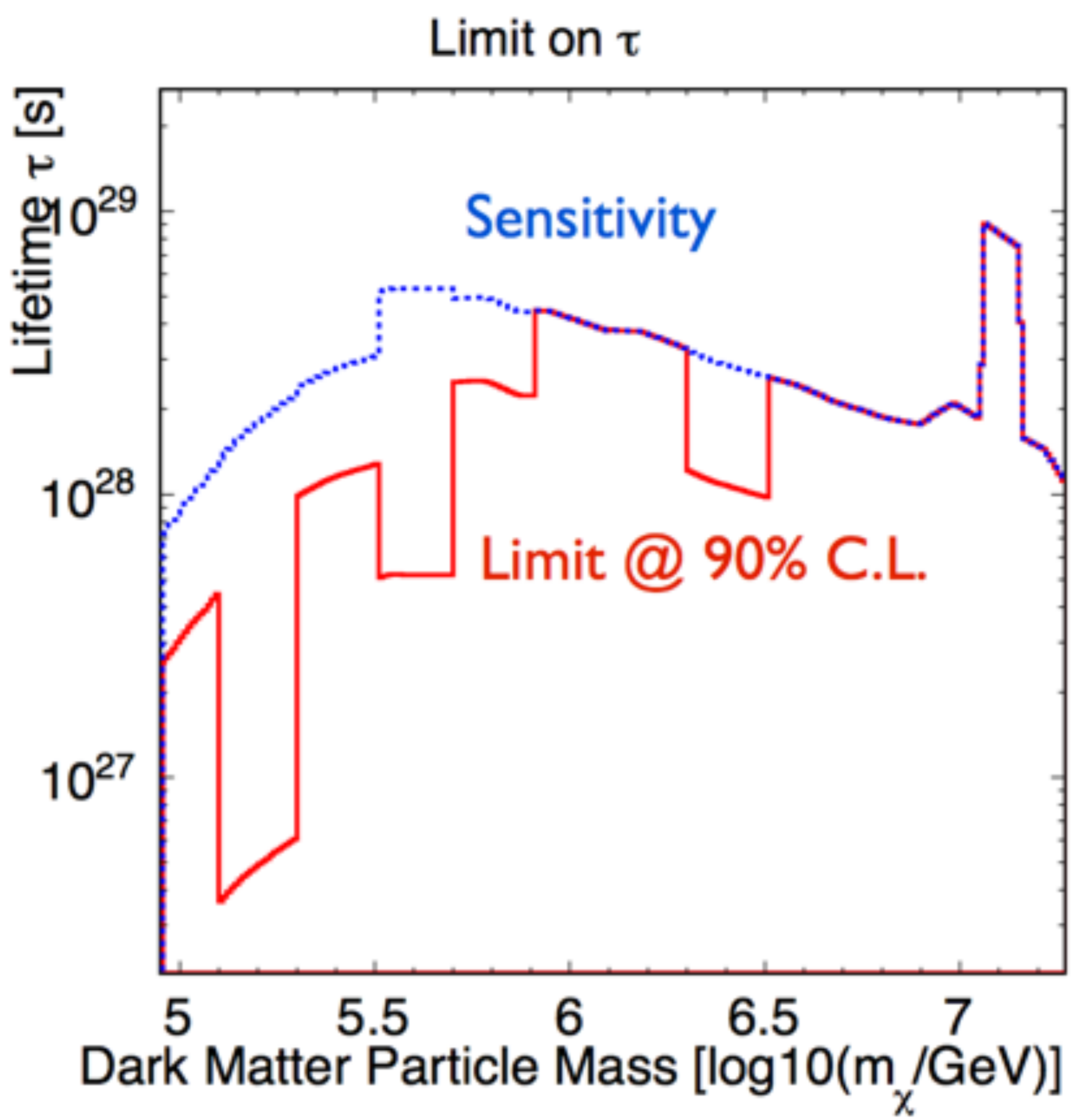
10^{24-27} sec

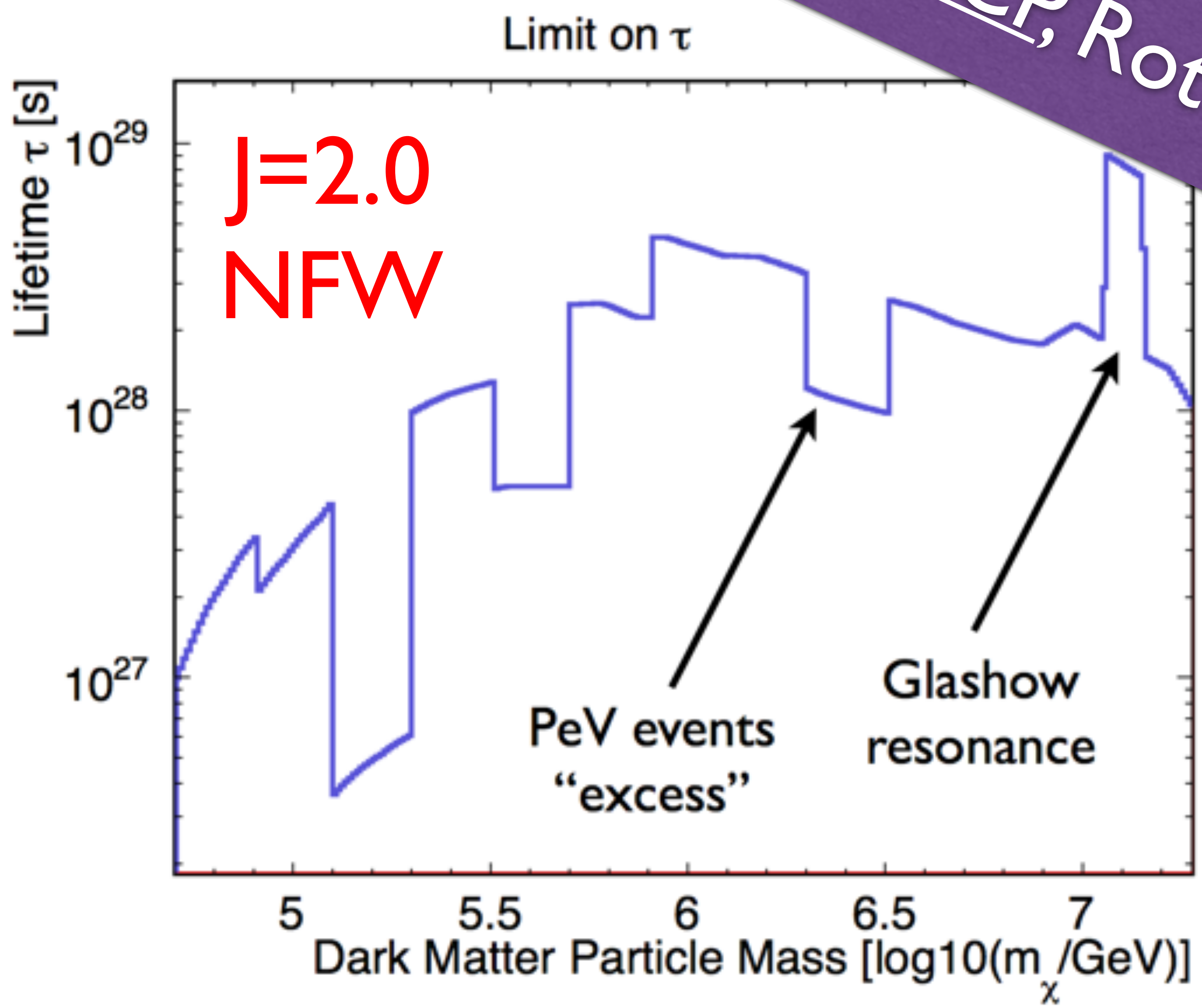


This is low energy plot.
we want to cover higher energy!

limit plot

NEW!
Kohri, SCP, Rott

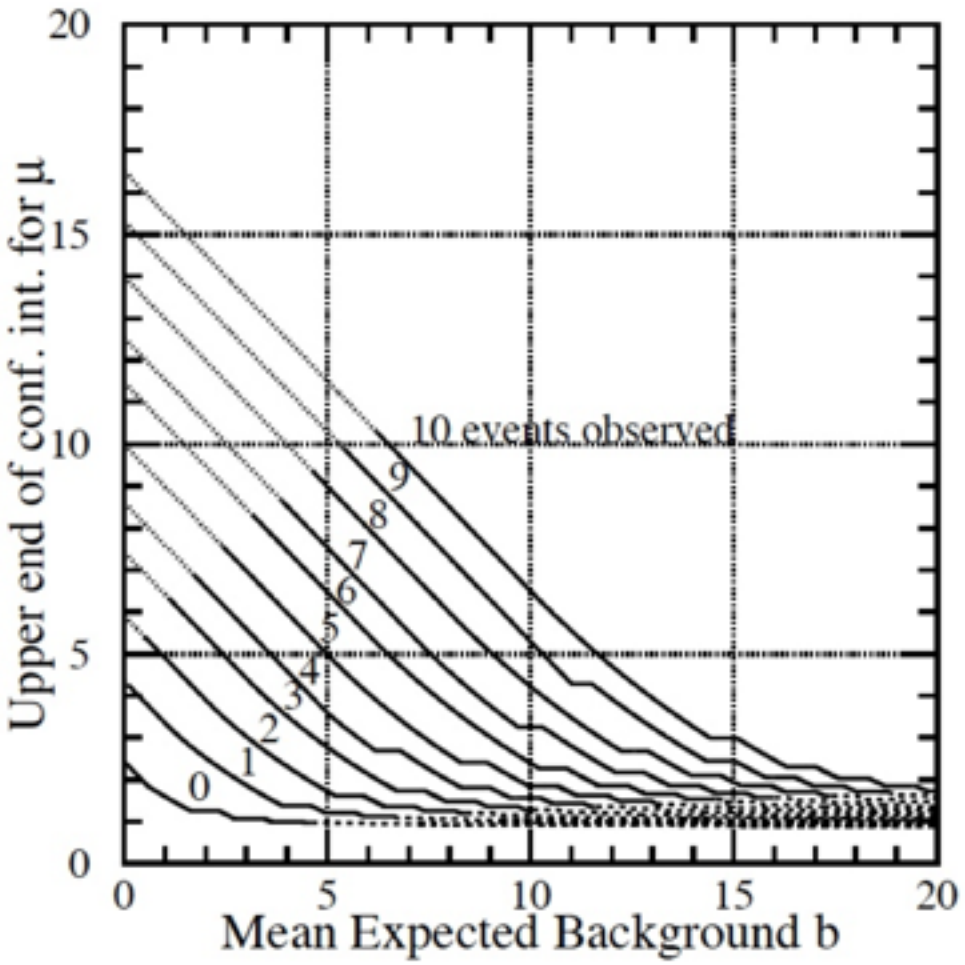




Sensitivity: Assume observed events = number of expected background

- -neglect extra galactic contribution (minor)
- -NFW taken (other profile changes ~%)
- -Feldman Cousin Method used

Feldman Cousin



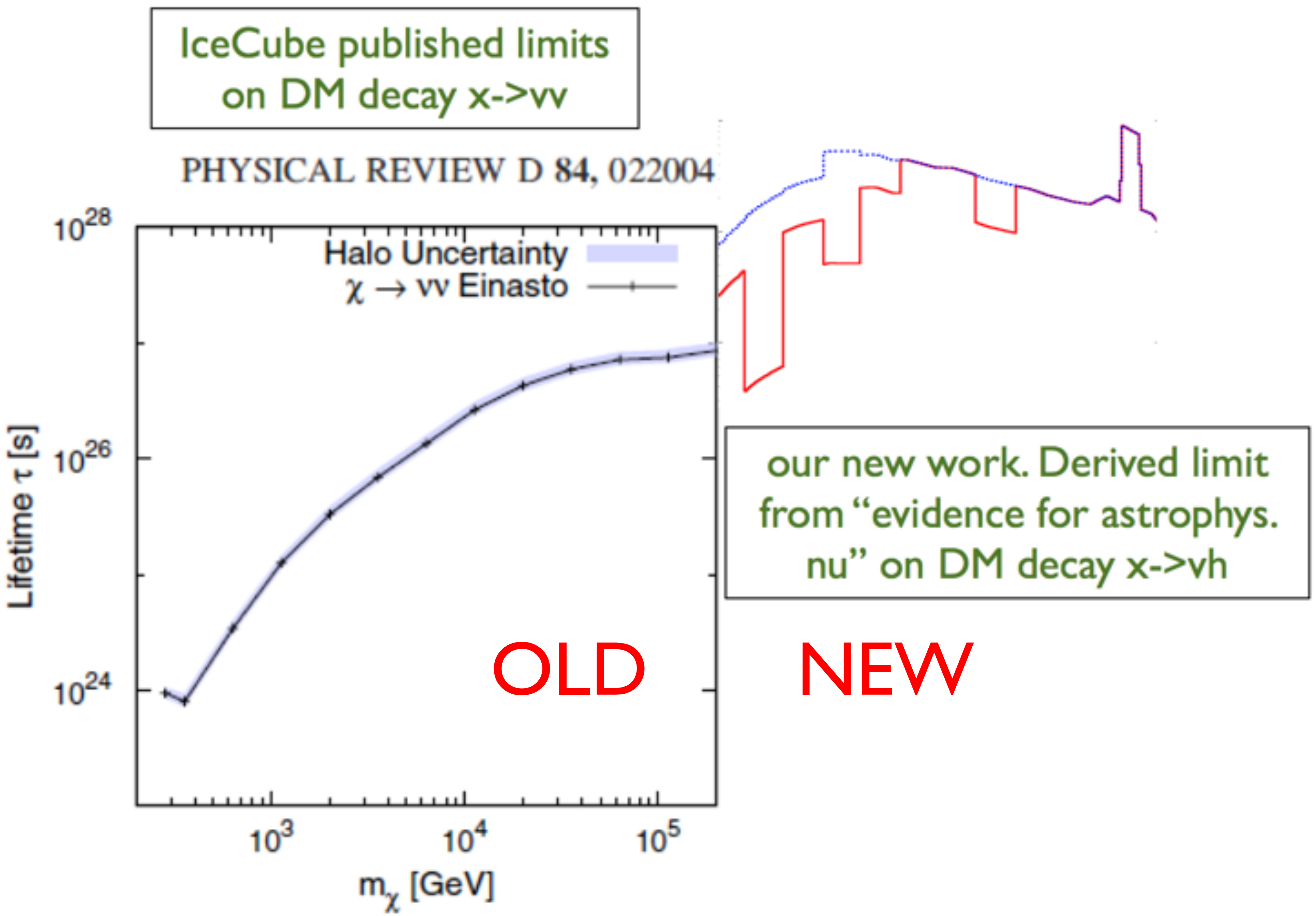
bgrd,obseved => bound

-Poisson distribution

-Upper end of conf. level

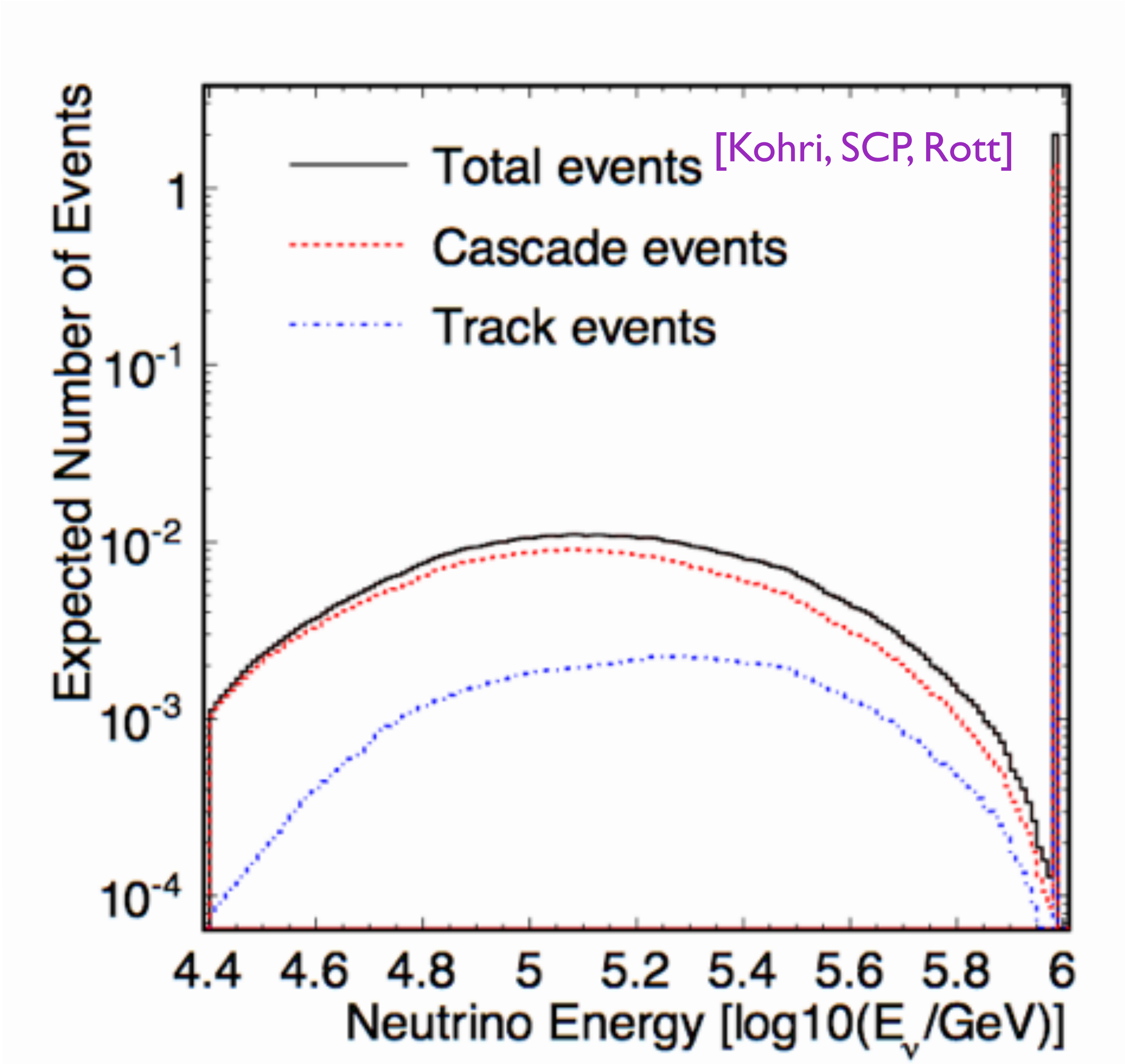
FIG. 8. Upper end μ_2 of our 90% C.L. confidence intervals $[\mu_1, \mu_2]$, for unknown Poisson signal mean μ in the presence of expected Poisson background with known mean b. The curves for the cases n_0 from 0 through 10 are plotted. Dotted portions on the upper left indicate regions where μ_1 is non-zero (and shown in the following figure). Dashed portions in the lower right indicate regions where the probability of obtaining the number of events observed or fewer is less than 1%, even if $\mu = 0$.

limit plot


IceCube published limits
on DM decay x->vv
PHYSICAL REVIEW D 84, 022004
Halo Uncertainty
χ → νν Einasto
Lifetime τ [s]
10^28
10^26
10^24
10^3
10^4
10^5
m_χ [GeV]
OLD
NEW
our new work. Derived limit
from “evidence for astrophys.
nu” on DM decay x->vh

Fit "peak"

The benchmark model: $\chi \to \nu_L + H$



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

-peak by ν_L

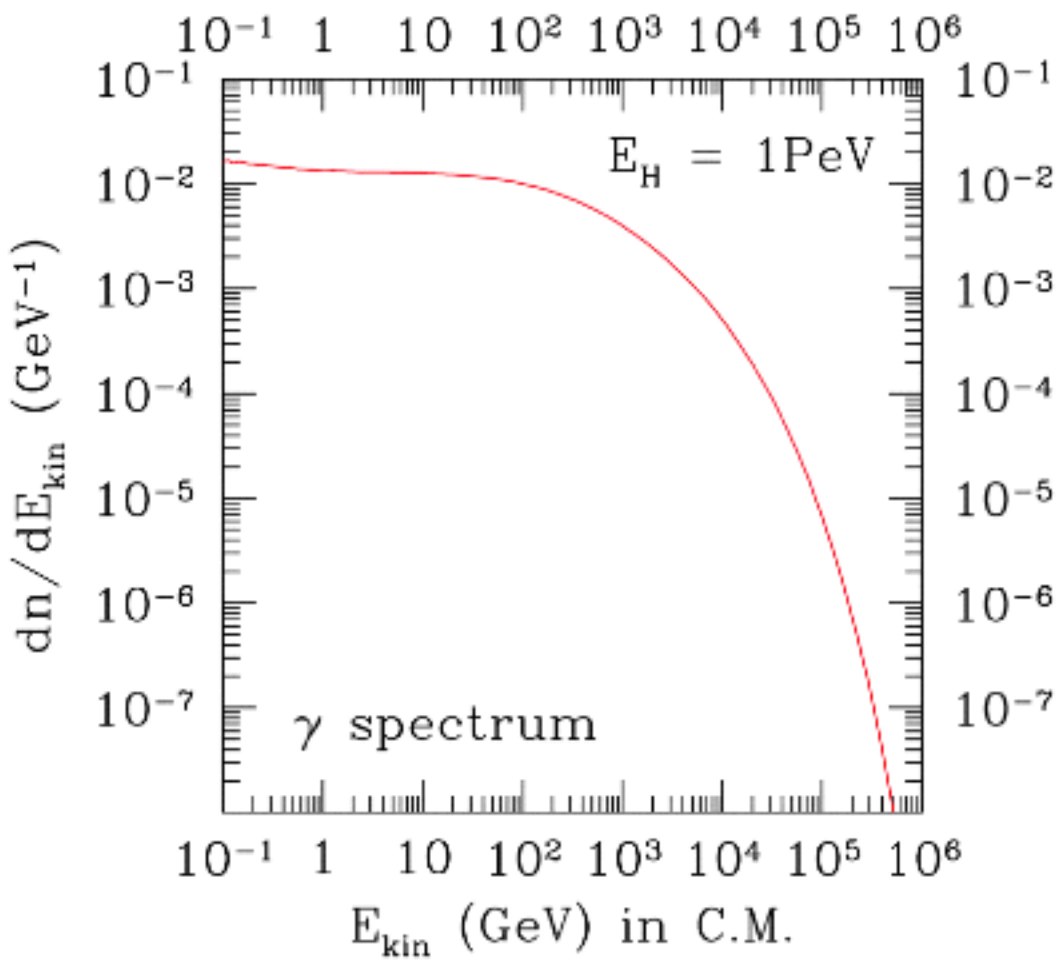
-continuum by nu from Higgs decay

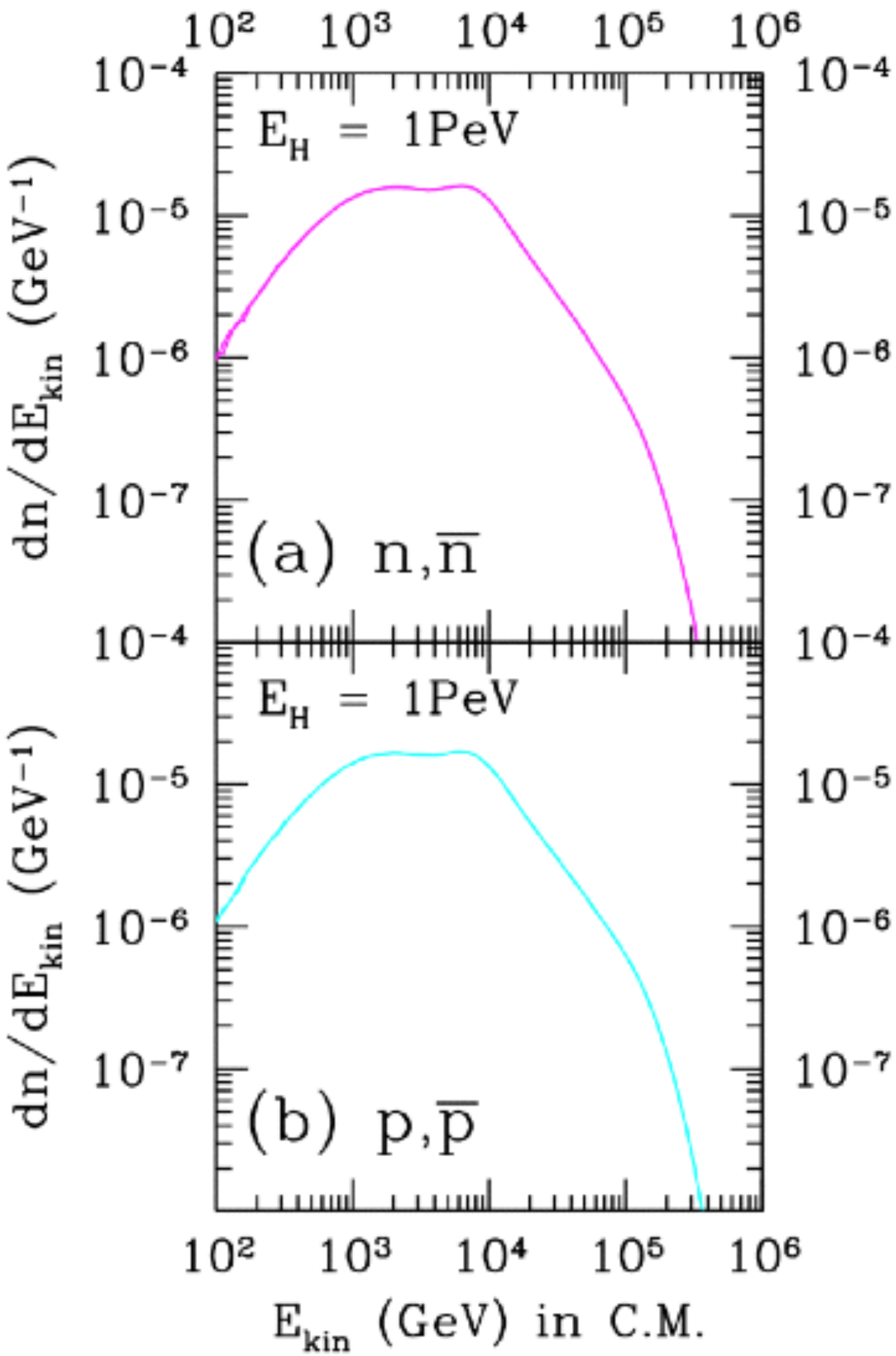
$$M_n \sim M_{\rm GUT}$$
$$M_\chi \sim {\rm PeV}$$
$$\sigma \sim \frac{m_\nu}{y}$$

**Tracks (muon neutrinos)

**Cascades (sum of electron and tau neutrino events)

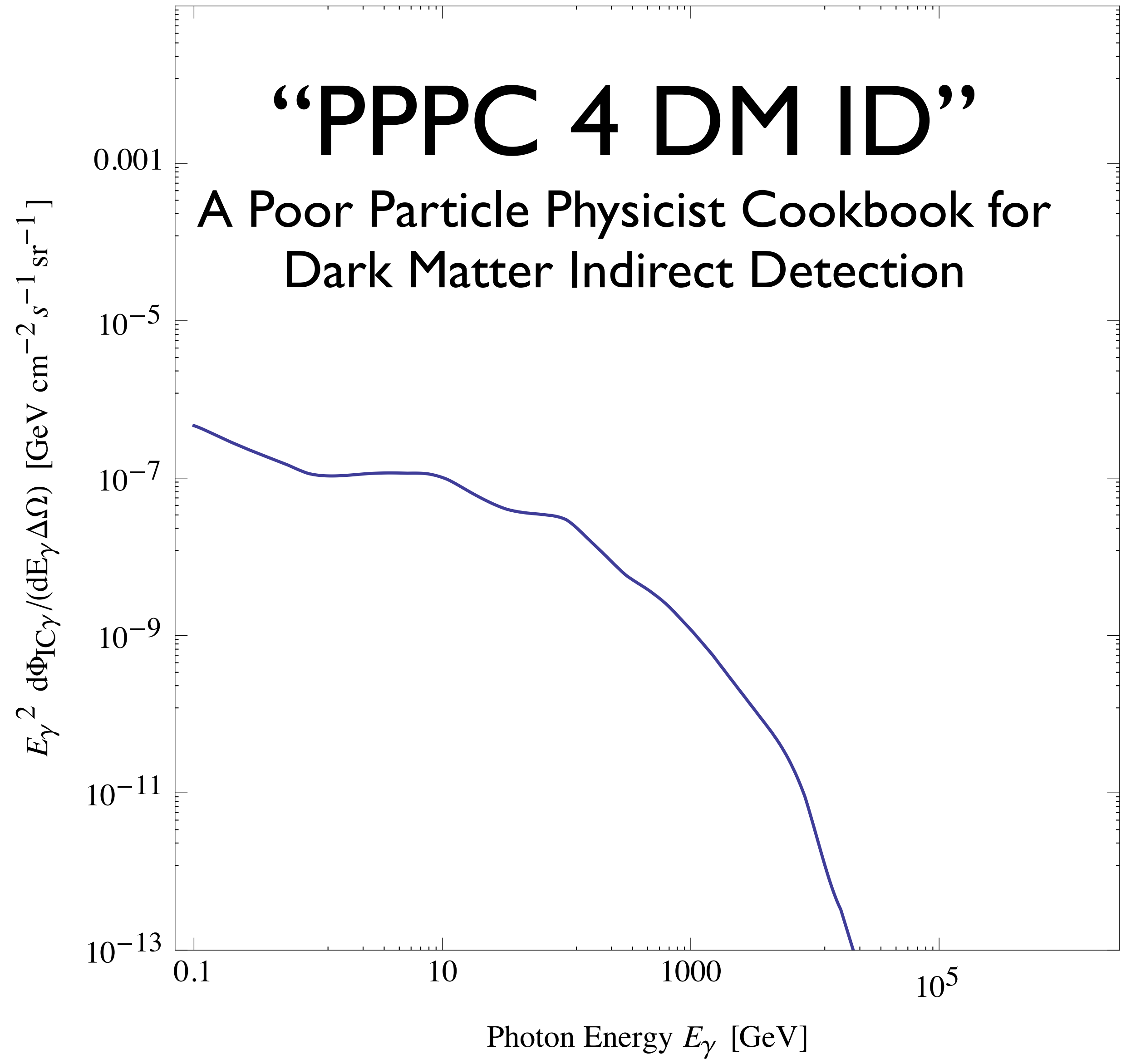
contributions to CR





*bottom line:
it looks safe in <TeV regime

gamma by ICS



*bottom line:
it looks safe in <TeV regime

Summary

- DM can be heavy (>200 TeV) if non-thermally produced
- IceCube, with its big size, has a great advantage to test DM by observing HE neutrinos …if there's one in >100TeV, IceCube is the place we should look at.
- We set the bound on lifetime-mass based on IceCube result for PeV-neutrinos using a benchmark model (see-saw+mixing)
- "peak" around PeV may be a hint of DM … will be clarified in the future