Upgoing ANITA events as evidence of a heavy dark matter component in the Earth's interior

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University of Pittsburgh

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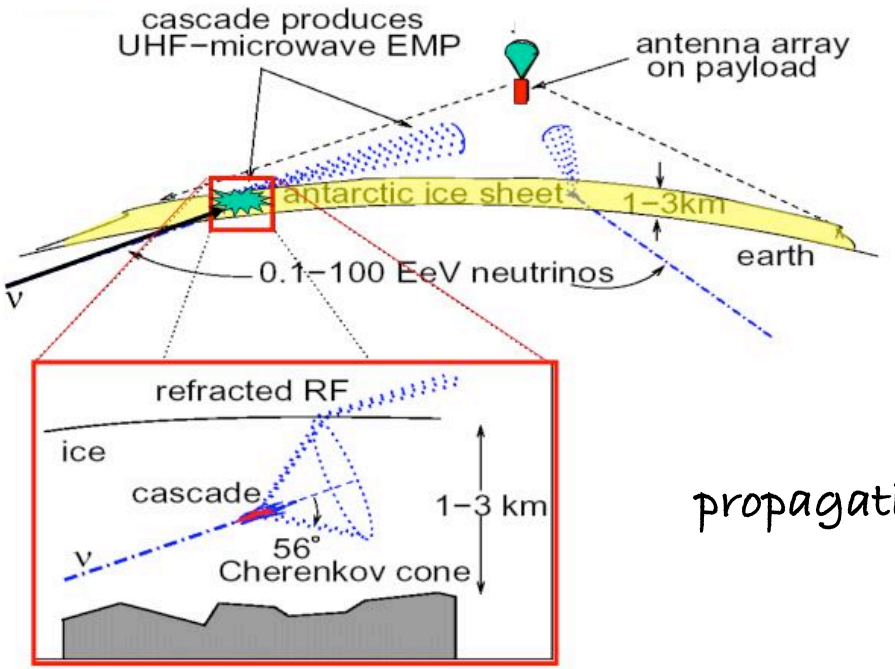


2 unusual upgoing showers

$E \sim (600 \pm 400)$ PeV

$E \sim (560 \pm 300)$ PeV

characteristics of ν_τ events

BUT ☛ arrival nadir angles

$\theta_n \sim 62.6^\circ$ and $\theta_n \sim 55^\circ$

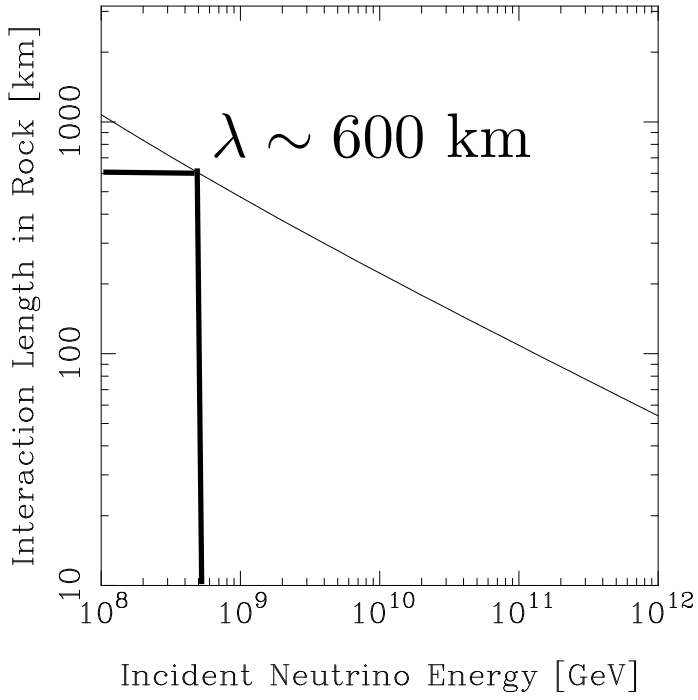
(angular uncertainty $\sim 1.5^\circ$)

create tension with SM $\sigma_{\nu N}$

propagating chord distance through Earth

$$D = 2R_\oplus \cos\theta_n$$

E of event #2 is lowered by 30% if shower is initiated 4 km above ice



Dutta-Huang-Reno'05

2 unusual upgoing showers

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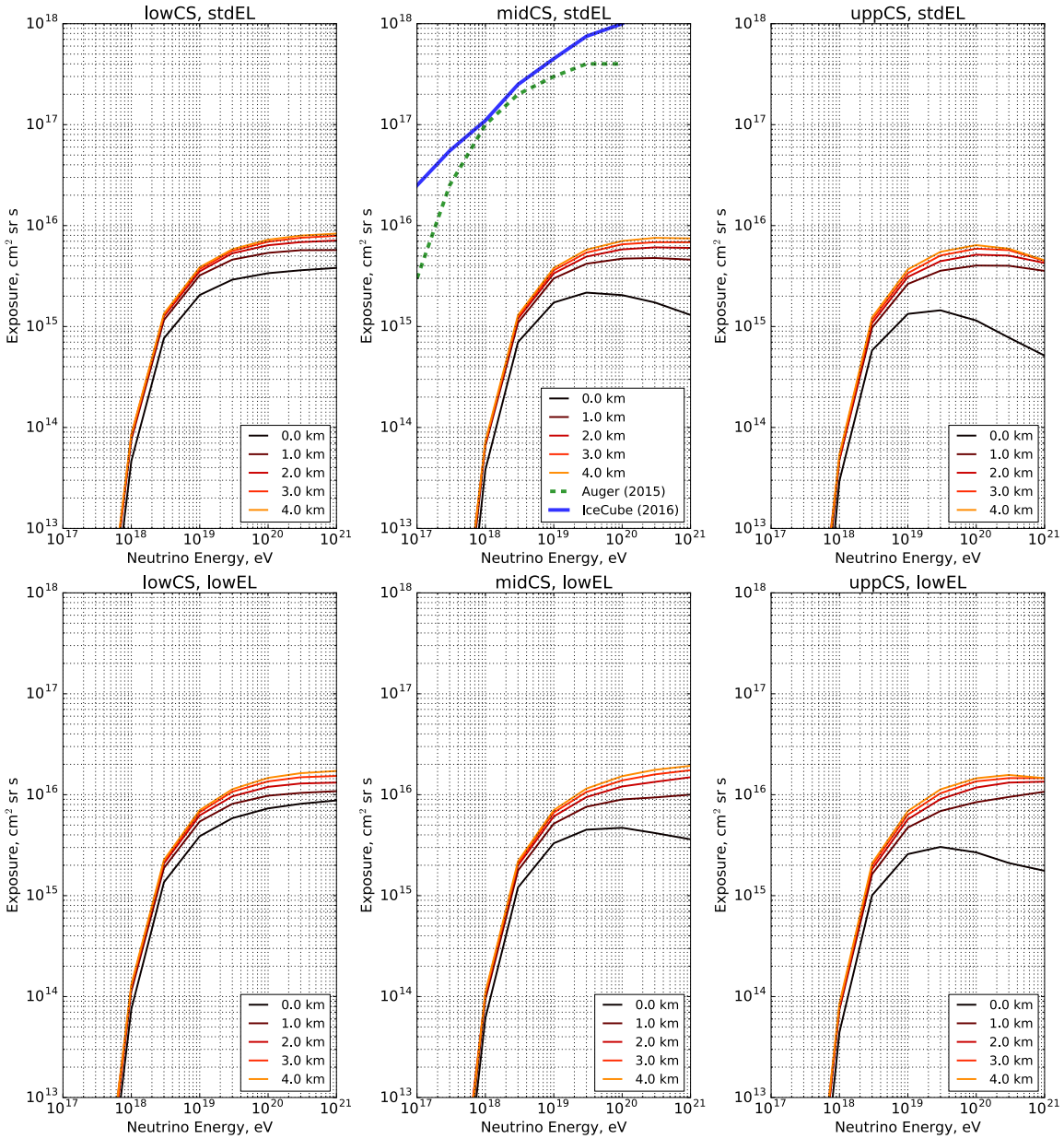
10 and 12 SM interaction lengths @ E ~ 500 PeV

ANITA Collaboration'18



ANITA Collaboration ICRC 2017

cross-section

Connolly-Thorne-Waters'11

tau energy loss

standard

Abramowicz-Levy'97

saturated model

Armesto-Salgado-Wiedemann'05

ANITA (solid angle integrated) exposure $\times$ 60 $\lesssim$ Auger or IceCube exposure

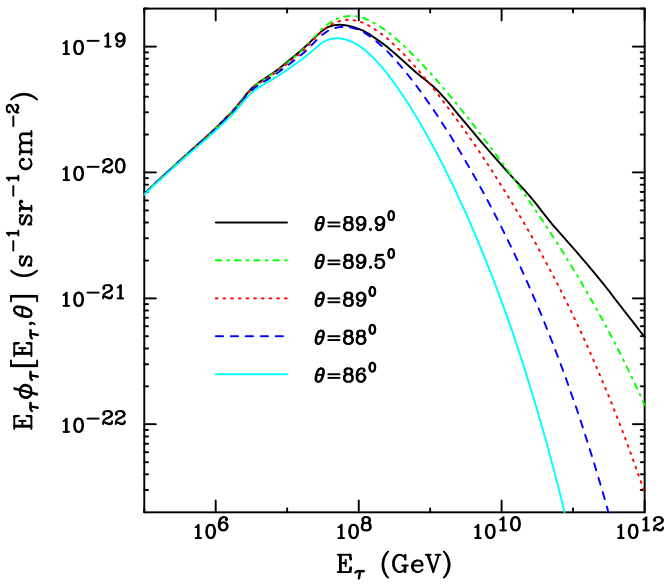
Large transient point-source flux of ν_τ's

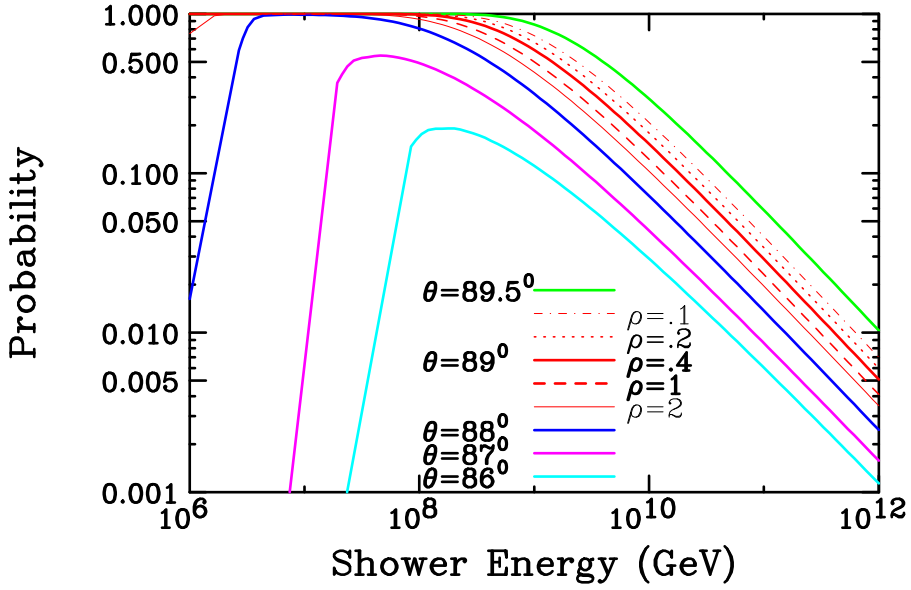
- Source candidate ☞ SN2014dz @ $\begin{cases} 1.19^\circ \text{ from event \#2} \\ z = 0.017 \end{cases}$
- SN2014dz discovery ☞ 5 hr before event detection
- *A posteriori* probability of chance association $\sim 3.4 \times 10^{-4}$ ☞ 2.7σ
- 1 km^2 IceCube's effective point-source area
  comparable to ANITA's 4 km^2 @ arrival nadir angle
- Auger has potentially much larger effective point-source area
  but only limited exposure around time of ANITA event
- Caveats
  - Peak isotropic neutrino luminosity of SN2014dz
    must far exceed bolometric luminosity ☞ $L = 4.4 \times 10^{42}\ \mathrm{erg\,s^{-1}}$
  - Beaming may come to the rescue ☞ but neeed short-time emission
- No SNe or any other significant association for event #1
- Sky position within $\sim 10^\circ$ from galactic plane
  extinction yields low SNe detection efficiency for this region of sky

DM decay in Earth's interior

- Moving explosions to Earth's interior ☞ solves short-time scale
- Rate of earth-skimmers dependends on $n^{(0)}_{\rm dm,\oplus}$
- 2 ANITA events $\left\{ \begin{array}{l} \text{have roughly same energy} \\ \text{were observed at similar angle above horizon} \end{array} \right.$
- Two events have similar energies
  because they result from two-body decay of quasi-stable relic
  itself gravitationally trapped inside Earth
- If DM particle is heavy ν_R ☞ for 2-body decays
  conservation of angular momentum forces $\nu_R \to \nu_L H$
- Non-observation of signal from GC or halo ☞ $\tau_{\nu_R} > 10^{29.5}$ s
  (IceCube Collaboration'18)
- Non-gravitational couplings chosen to produce long lifetime
  and needed abundance of ν_R inside Earth to yield 2 ANITA events
- To achieve sizable $n^{(0)}_{\rm dm,\oplus}$ ☞ self-interactions may be invoked

$$E_\nu^2 \Phi_\nu(E_\nu) = 6 \times 10^{-9}\ \mathrm{GeV\ s^{-1} cm^{-2}}$$

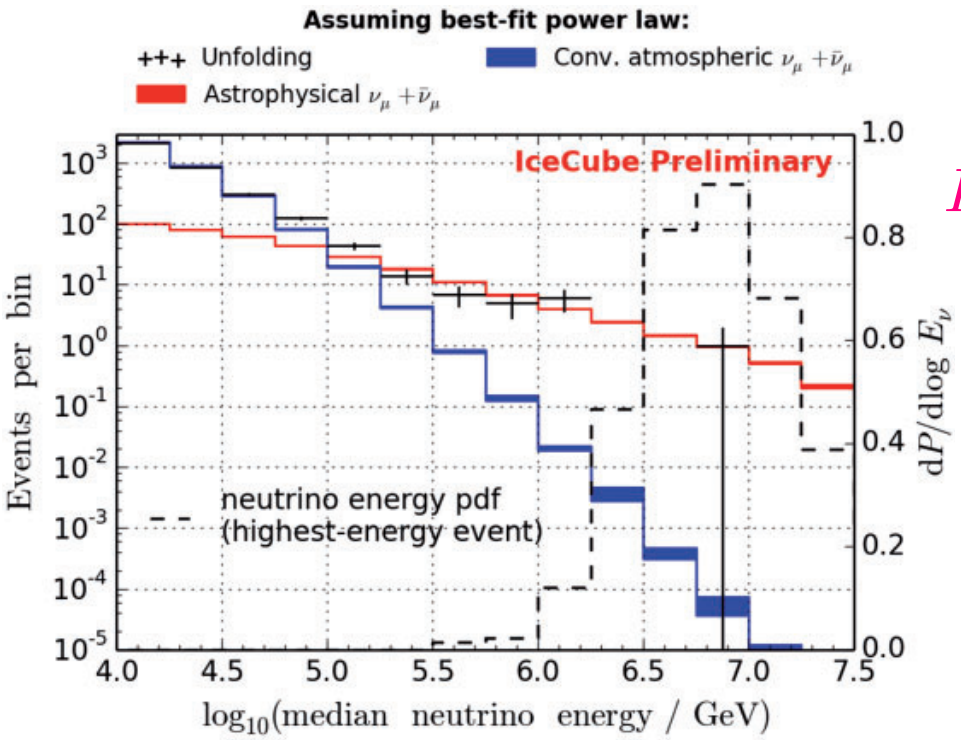




- Differential τ spectra produced by earth-skimming neutrinos.
- Integrated probability for τ to decay in atmosphere producing shower that reaches ground level with electron number density ϱ above threshold
- No sensitivity to showers coming few degrees below horizon
- Fluorescence detection subject to 10% duty cycle

Zas'05

$$\frac{\#\ \text{IceCube events}}{\#\ \text{ANITA events}} \sim \frac{1\ \text{km}^3 \times 2078\ \text{day}}{4\ \text{km}^2 \times \text{depth} \times 53\ \text{day}} \simeq \frac{10\ \text{km}}{\text{depth}}$$



E_{ν_μ} probability density function

$E_{\nu_\tau} > E_{\nu_\mu}$ by $\sim m_\tau/m_\mu$

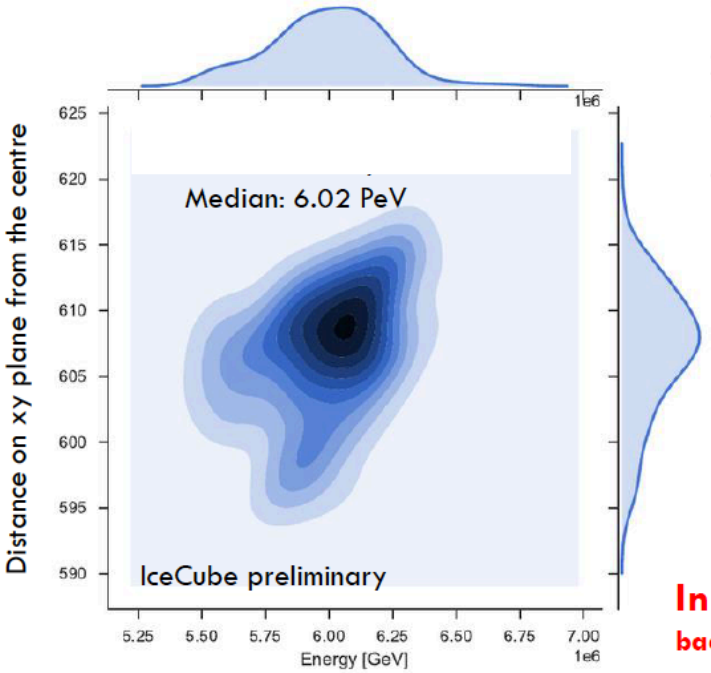
ν_τ with E ~ 200 PeV ?

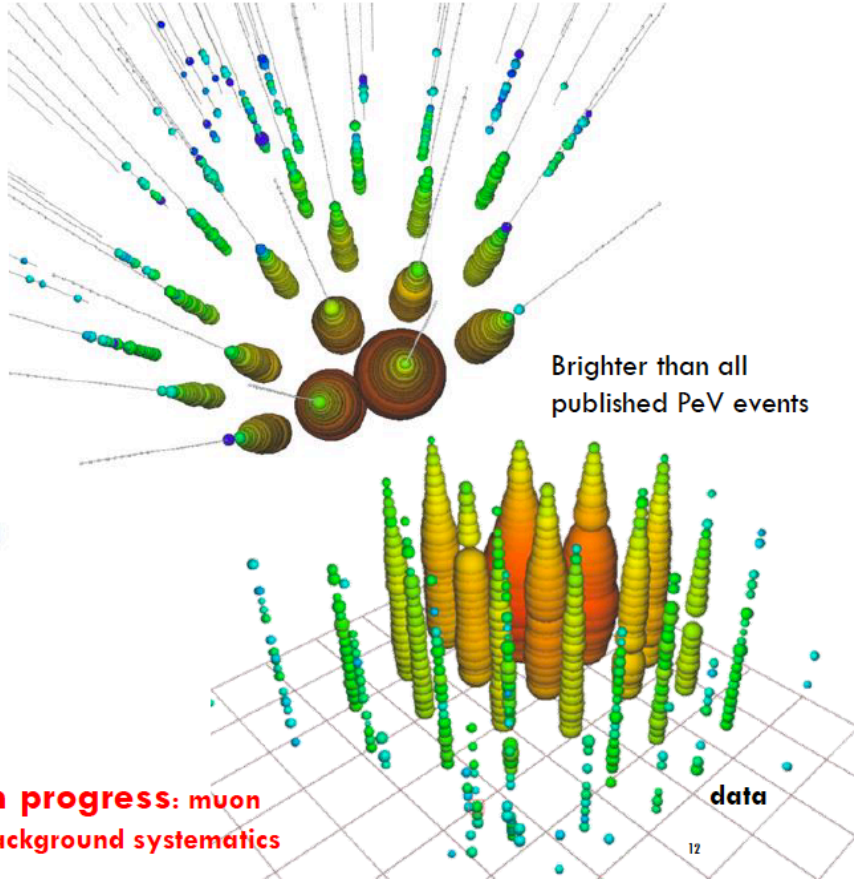
Kistler-Laha'16

- If typical depth of shower initiation for ANITA is taken to be 4 km then IceCube should have seen 5 events
- 95% CL interval for observing 1 event with no expected background [0.05, 5.14]
- IceCube data mau not be in tension with ANITA's 2 events

There may be others...

HIGHEST-ENERGY NEUTRINO CANDIDATE





In progress: muon background systematics

➢ Event rate integrated over entire Earth at particular time

$$\text{Rate} \equiv \frac{dN}{dt} = 4\pi \int_0^{R_\oplus} r^2\, dr\, \frac{n(r,t)}{\tau_{\nu_{R,1}}}$$

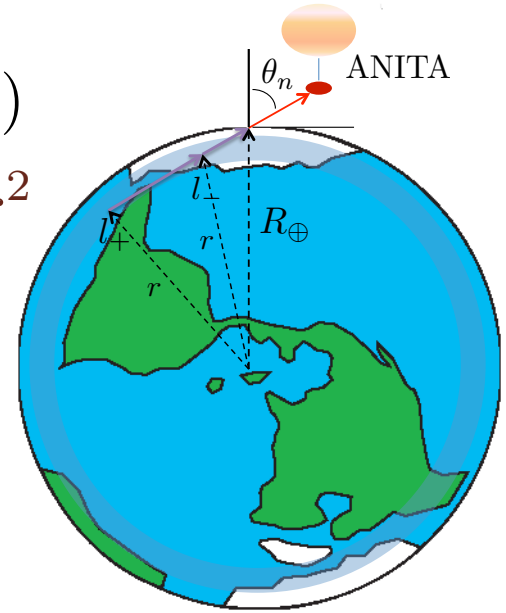
➢ Observable rate today (t=t0) as function of nadir angle

$$A_{\text{eff}} \frac{d\,\text{Rate}}{d\,|\cos\theta_n|} = 4\pi^2 A_0 \int_{R_\oplus \sin\theta_n}^{R_\oplus} r^2 dr\, \frac{n(r,t_0)}{\tau_{\nu_{R,1}}} \left(e^{-(l_+/\lambda)} + e^{-(l_-/\lambda)}\right) \mathcal{E}(\theta_n)$$

$$A_{\text{eff}} = A_0\, \mathcal{E}(\theta_n) \qquad n(r,t_0) \equiv n^{(0)}_{\text{dm},\oplus}(r)$$

➢ $l_\pm$ ☛ roots of $R_\oplus^2 + l^2 - 2R_\oplus l \cos\theta_n = r^2$

$$l_\pm = R_\oplus \left(\cos\theta_n \pm \sqrt{\left(\frac{r}{R_\oplus}\right)^2 - \sin^2\theta_n}\right)$$



- Exponential suppression factor can be rewritten as

$$e^{-(l_+/\lambda)} + e^{-(l_-/\lambda)} = \quad 2\exp\left(-\frac{R_\oplus\,\cos\theta_n}{\lambda}\right)\cosh\left(\frac{\sqrt{r^2 - R_\oplus^2\sin^2\theta_n}}{\lambda}\right)$$

- Competition between falling (with increasing θ_n) $e^{-R_\oplus\cos\theta_n/\lambda}$ term and rising $\mathcal{E}(\theta_n)$ term ➡ determines most probable angle of observation

- Unusual ANITA events occur at 27.4° and 35° above horizon
  so we set peak of distribution at ~ 30° above horizon

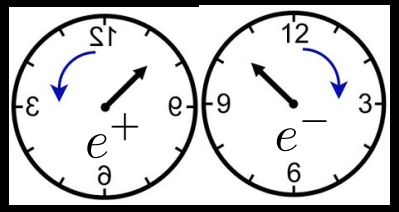
- Taking viewpoint that event distribution is maximized at $\theta_n = 60^\circ$
  by combination of ANITA's efficiency and DM distribution in Earth

$$\left.\frac{d^2\,\mathrm{Rate}}{d\,|\cos\theta_n|^2}\right|_{\cos\theta_n=\frac{1}{2}} = 0$$

- Atypical dark matter density distribution inside Earth

State of universe does not spontaneously violate CPT

universe/anti-universe pair production ☛



Boyle-Finn-Turok'18

Matter fields ☛ SM + right-handed neutrinos (with 1 stable heavy neutrino)

To compare with observation

Comoving abundance of DM neutrinos ☛ with entropy density as fiducial

$$Y_{\rm dm} = \frac{n_{\rm dm}}{s} = \frac{16}{9}\pi G^3 I \left(\frac{15}{g_*}\right)^{1/4} M_{\nu_{\rm dm}}^{3/2}$$

$g_* = 106.75$ ☛ # of effective degrees of freedom (excluding ν_R)

$$I \equiv \frac{1}{2\pi^2}\int_0^\infty dx\, x^2 \left[1-\sqrt{1-e^{-x^2}}\right] \approx 0.01276$$ ☛ dimensionless constant

Predicted present-day dark matter energy density

$$\rho_{\rm dm}^{(0)} = M_{\nu_{\rm dm}} n_{\rm dm}^{(0)} = M_{\nu_{\rm dm}} Y_{\rm dm} s^{(0)}$$

$s^{(0)} \approx 2.3\times 10^{-38}\ {\rm GeV}^3$ $\qquad$ $\rho_{\rm dm}^{(0)} \approx 9.7\times 10^{-48}\ {\rm GeV}^4$

$$M_{\nu_{\rm dm}} = 4.8\times 10^8\ {\rm GeV} = 480\ {\rm PeV}$$

Take Home Message

- Upgoing ultra-high energy shower events observed by ANITA may arise from decay in Earth's interior of quasi-stable dark matter
- E.g. ☛ heavy right-handed neutrino from CPT symmetric Universe
- Since both events emerge at same angle from Antarctic ice-cap model requires atypical dark matter density distribution inside Earth
- Challenging theoretical modeling is underway
- Data from 4th ANITA flight is currently being analyzed and may lead to further enlightenment
- EUSO-SPB2 (to be flown in 2022) will provide important test