Explaining the ANITA events by a $L_e - L_\tau$ gauge model

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Multi-messenger era

- Photon detectors in different electromagnetic spectrum: INTEGRAL, FERMI-LAT, HESS, SKA and etc
- Cosmic ray: AMS-02, AUGER, VOYAGER, etc
- Gravitational Wave (GW) detectors: LIGO, VIRGO, etc
- Neutrino Telescopes: ICECUBE, ANTARES, KM3NET, ANITA

Unprecedented opportunity

Explore cosmos as well as exotic properties of particles

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We crave for anomalies.

Unprecedented opportunity

Explore cosmos as well as exotic properties of particles

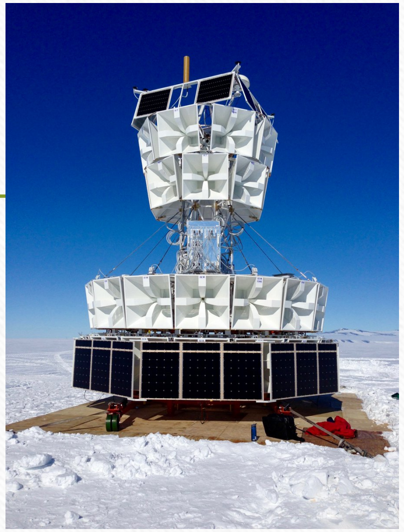
We crave for anomalies.

ANITA has provided us with anomalies.

ANITA

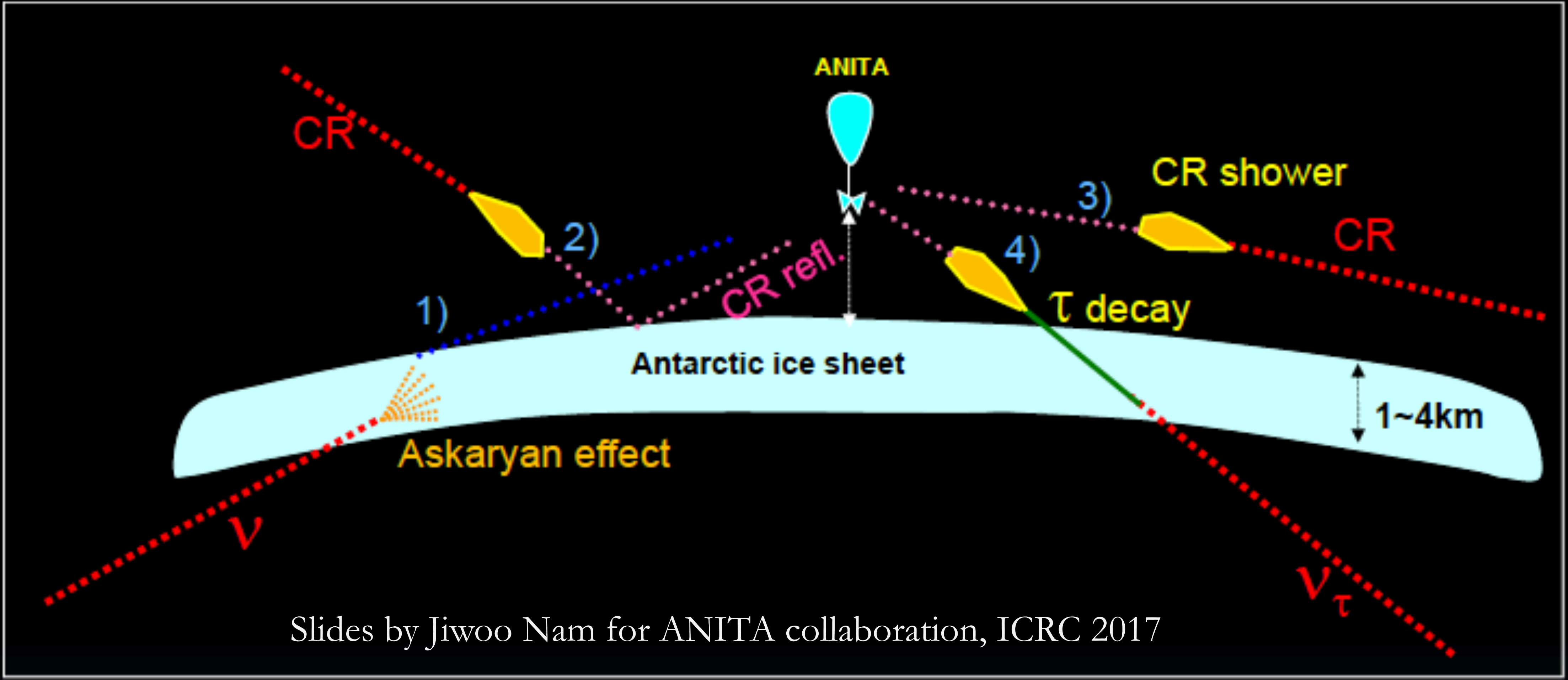
ANtarctic Impulse Transient Antenna (ANITA)

Flying over an altitude of 37 km



Radio detectors

ANITA's signatures



Slides by Jiwoo Nam for ANITA collaboration, ICRC 2017

Two anomalous events

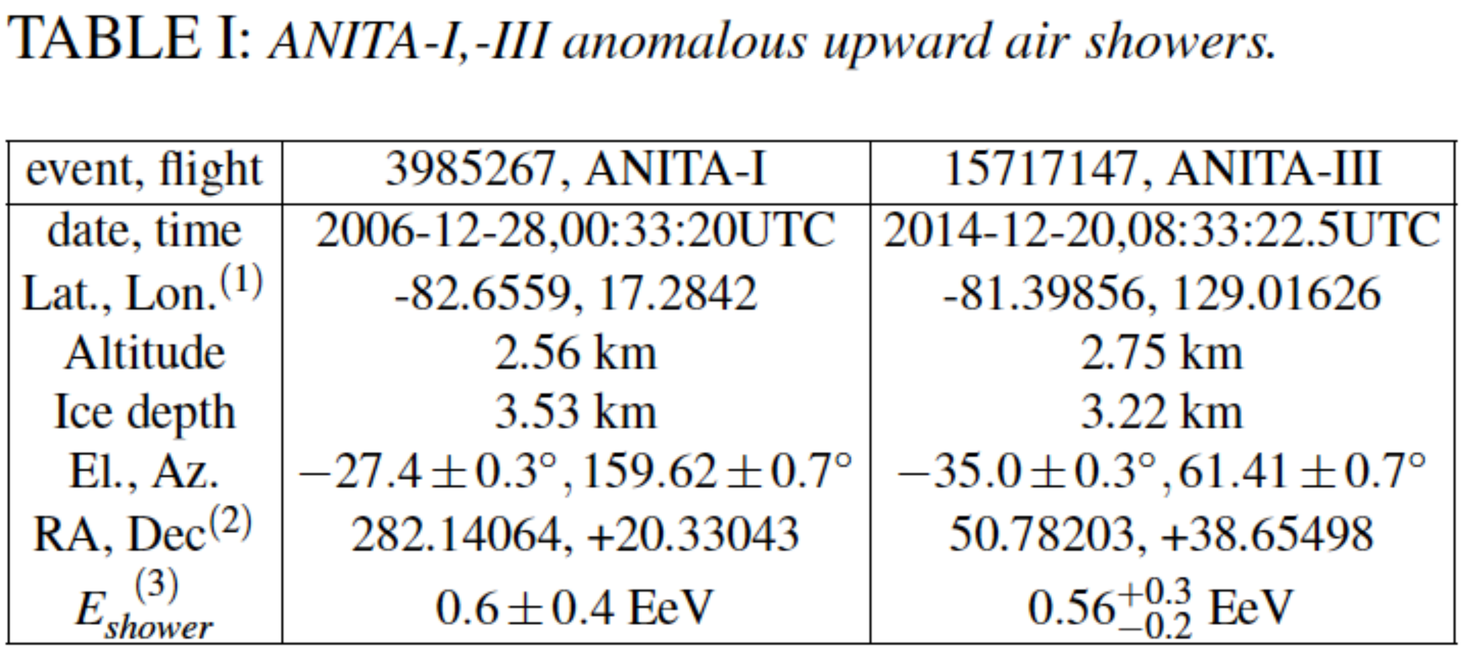


TABLE I: *ANITA-I,-III anomalous upward air showers.*

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.$^{(1)}$	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec$^{(2)}$	282.14064, +20.33043	50.78203, +38.65498
$E^{(3)}_{shower}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

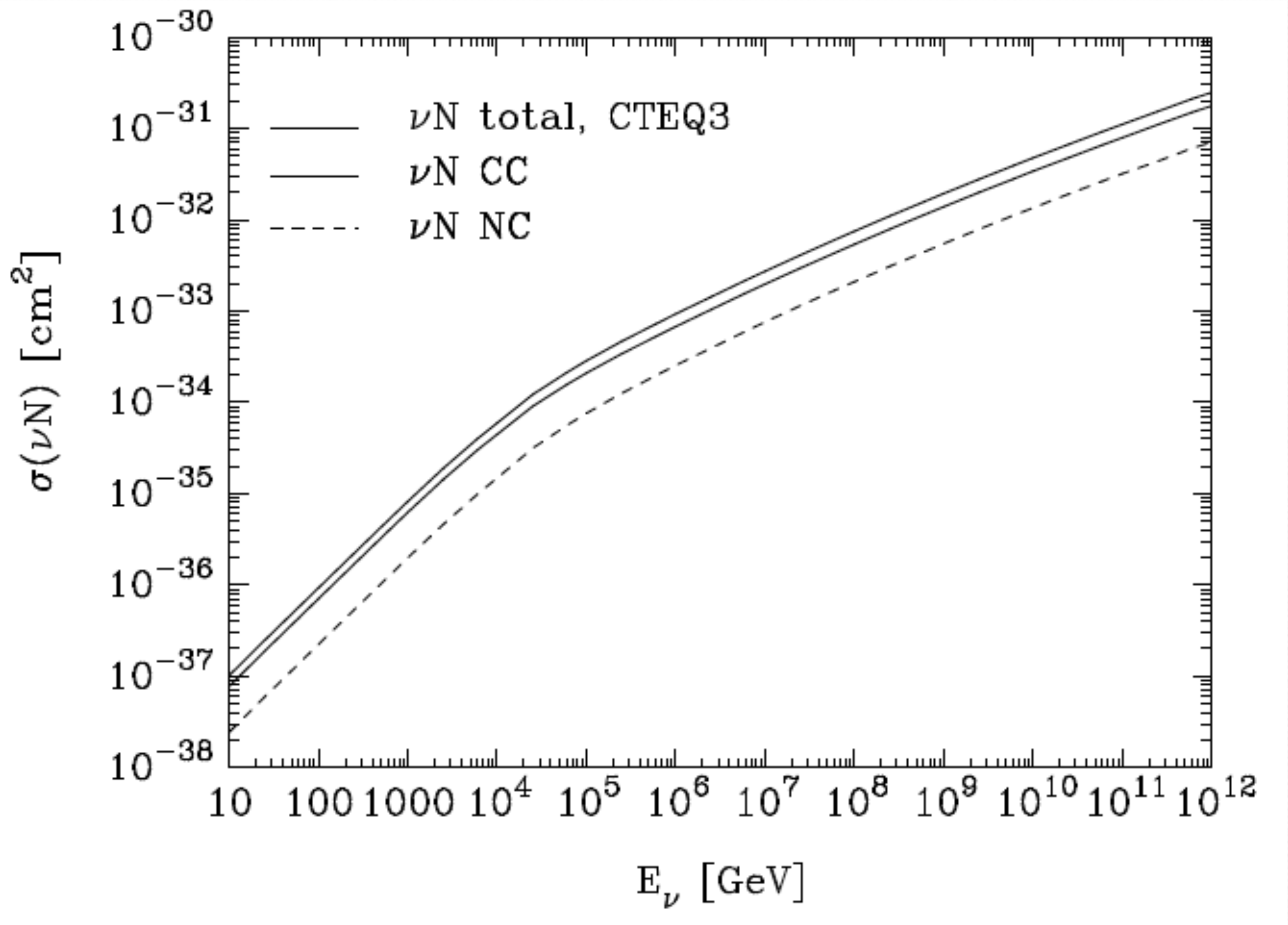
ANITA collaboration, PRL 117 (2017) 071101

Extensive Air Shower (EAS)

ANITA collaboration,
PRL 121 (2018), no 16, 161102

Event characteristics

- Zenith angles: $117.4^\circ \pm 0.3^\circ$ and $125^\circ \pm 0.3^\circ$
- Chord sizes: 5800 km and 7300 km
- Energies $0.6 \pm 0.4\ \mathrm{E}e\mathrm{V}$ and $0.56^{+0.4}_{-0.2}\ \mathrm{E}e\mathrm{V}$



Gandhi et al,
Astropart phys 5
(1996) 81-110

Mean free path for neutrino

- The mean free path in mantle for neutrinos of energy of EeV

500-800 km << chord size → Neutrinos will be absorbed.

The probability of neutrinos passing the Earth is $\sim 10^{-9}$.

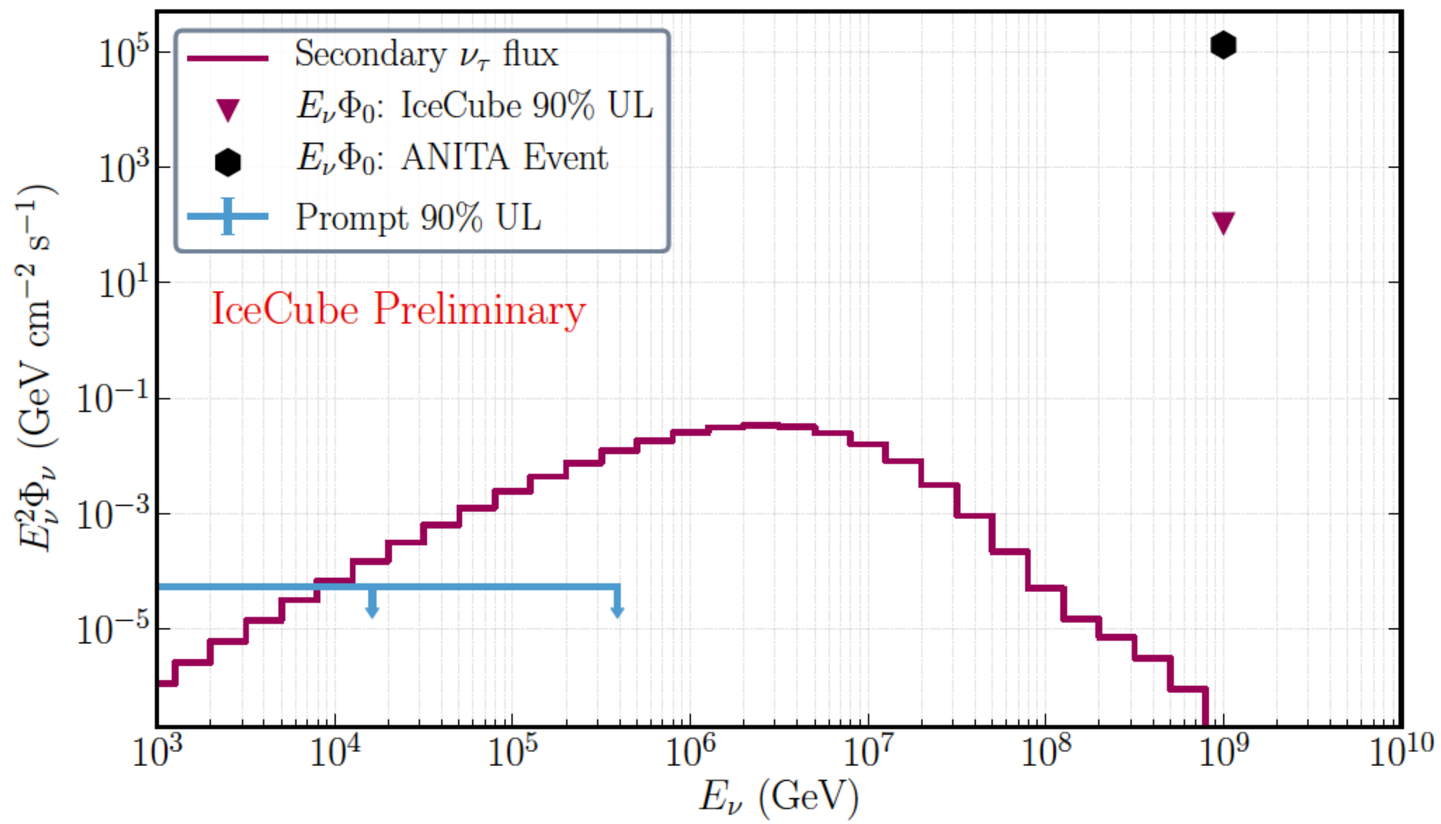
Neutrino recreation

$$\nu_\tau \to \tau \to \nu_\tau \to \ldots \to \nu_\tau$$

$$P \sim 10^{-7}$$

See however, Cumming et al, arXiv:1910.00992

Bounds from AUGER and ICECUBE



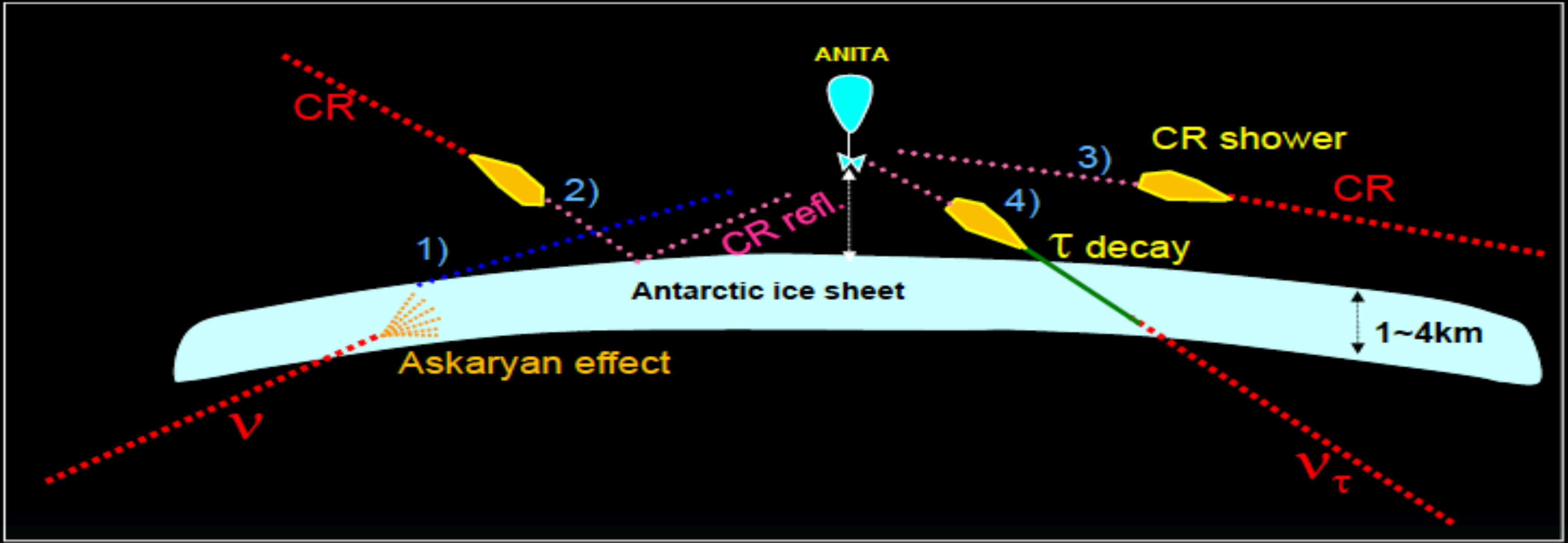
Transient source

ICECUBE collaboration,
arXiv: 1908.08060

See also, Safa, Pizzuto, Arguelles, Halzen, Hussain, Kheirandish, Vandenbroucke, *JCAP* 01 (2020) 012
arXiv: 1909.10487

ANITA's signatures

Slides by Jiwoo Nam for ANITA collaboration, ICRC 2017



Origin	RF production	Polarization	RF Direction	Polarity
1) Neutrinos	Askaryan	V-pol	Below Horizon	Normal
2) CR-reflected	Geo-synchrotron	H-pol	Below Horizon	Inverted
3) CR-direct	Geo-synchrotron	H-pol	Above Horizon	Normal
4) Tau Neutrino?	Geo-synchrotron	H-pol	Below Horizon	Normal

Explanation within standard model

- Shoemaker et al. The Antarctic Subsurface as a possible explanation, *Annals Glaciol.* 61 (2020) 81, 92-98 arXiv:1905.02846

- Sub-surface reflection → no phase inversion

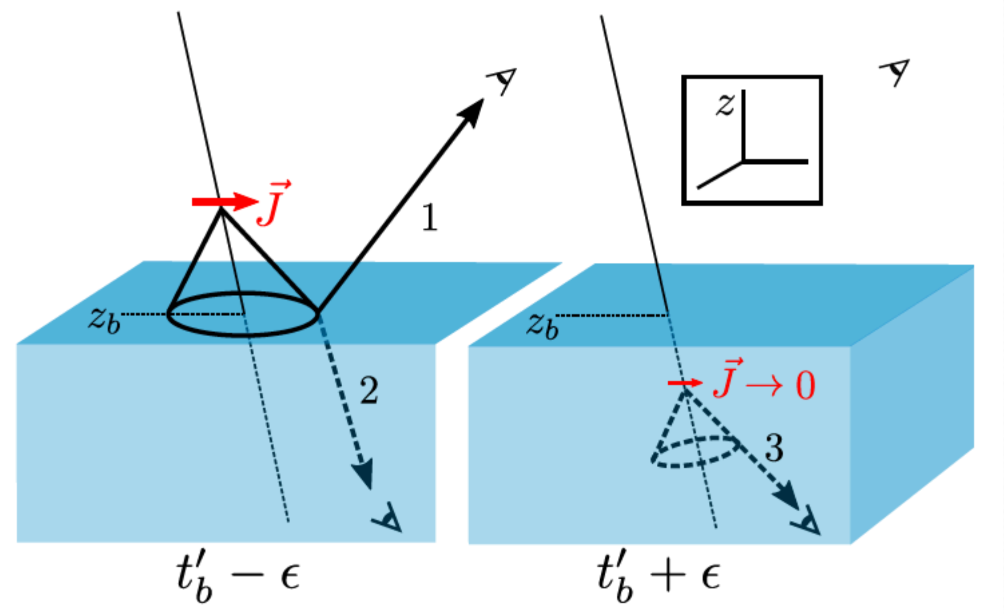
(subsurface layers and firn density inversions)

- Could be tested by radar surveying the Antarctic region

Another explanation within standard model

- Coherent transition radiation (CTR) Geomagnetically induced current

From downward going cosmic ray



K. D. de Vries and S. Prohira, PRL 123 (2019) 091102

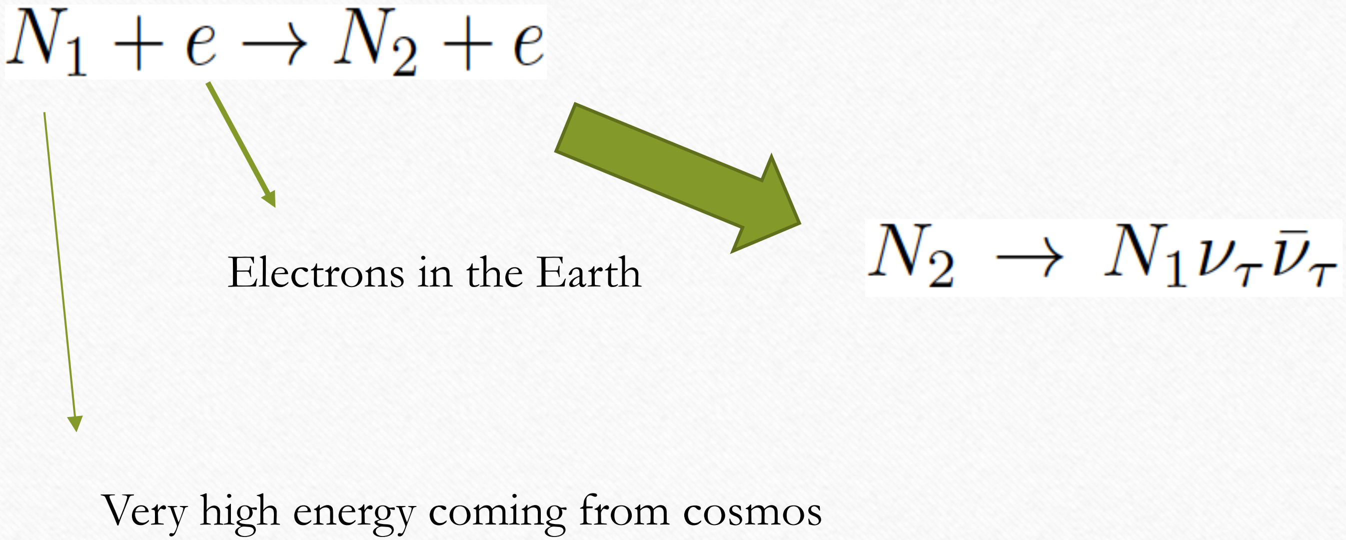
Beyond SM explanations

For a review, see Anchordoqui et al, "The pros and cons of beyond standard model interpretations of ANITA events, arXiv:1907.06308

Three classes of models

1) Messenger lives inside the Earth
2) Originate from the neutrino-nucleon collisions inside the Earth
3) Messenger comes from cosmological distances.

Our scenario



$$N_1 + e \to N_2 + e$$

Electrons in the Earth

Very high energy coming from cosmos

$$N_2 \;\to\; N_1 \nu_\tau \bar{\nu}_\tau$$

A. Esmaili and YF, *JCAP* 12 (2019) 017
B. arXiv:1909.07995

Probability of producing tau neutrino or tau

γ is the inverse of the mean free path of N_1 (as well as that of N_2): $\gamma(x) = n_e(x)\sigma$.

mean free path of ν_τ, $\tau_\nu = (\sigma_{SM}\ \rho/m_p)^{-1}$

Γ_{tot} The total decay rate of N_2 including the time dilation

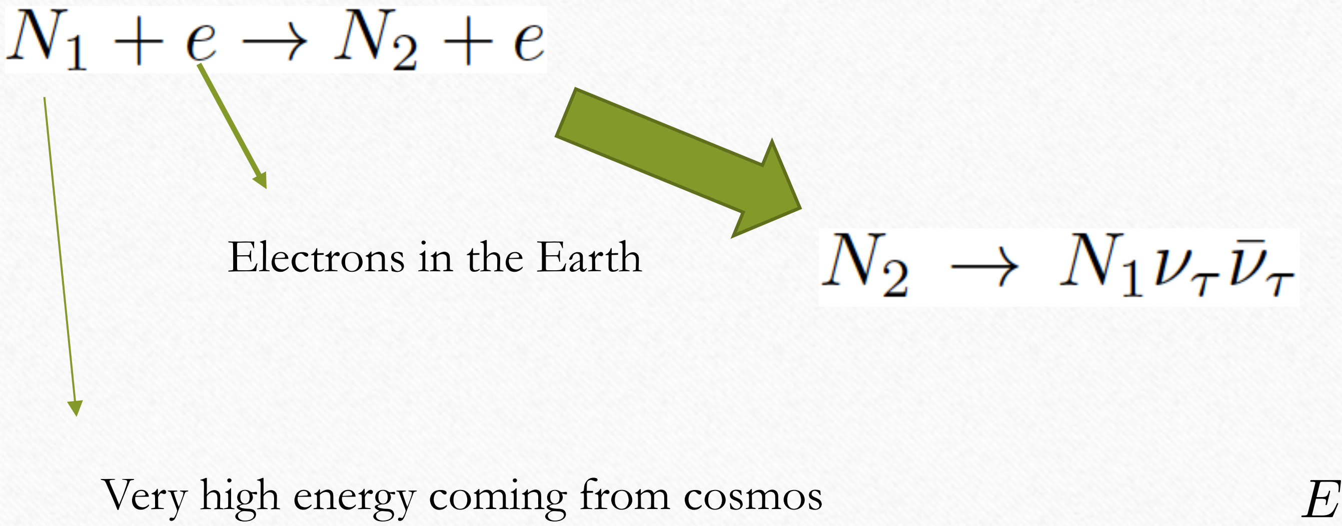
$$P = \mathrm{Min}[1, \Gamma_{tot}\tau_\nu]\underbrace{(2B)}_{\text{Branching ratio}} \int_0^L \underbrace{e^{-\int_0^x \gamma(y)dy}\, e^{-\int_x^L (\gamma(z)+\Gamma_{tot})dz}}_{\text{Survival probability of } N_1} \underbrace{\gamma dx}_{\text{Interaction probability}}$$

For constant density

$$P \simeq \mathrm{Min}[1, \Gamma_{tot}\tau_\nu] \frac{\gamma}{\Gamma_{tot}} \left[e^{-L\gamma} - e^{-L(\gamma+\Gamma_{tot})} \right]$$

P is maximal for $\Gamma_{tot} \sim 1/\tau_\nu \sim (500\ \mathrm{km})^{-1}$ and $\gamma \sim 1/L \sim (5000\ \mathrm{km})^{-1}$.

Energy of final neutrinos



$$N_1 + e \to N_2 + e$$

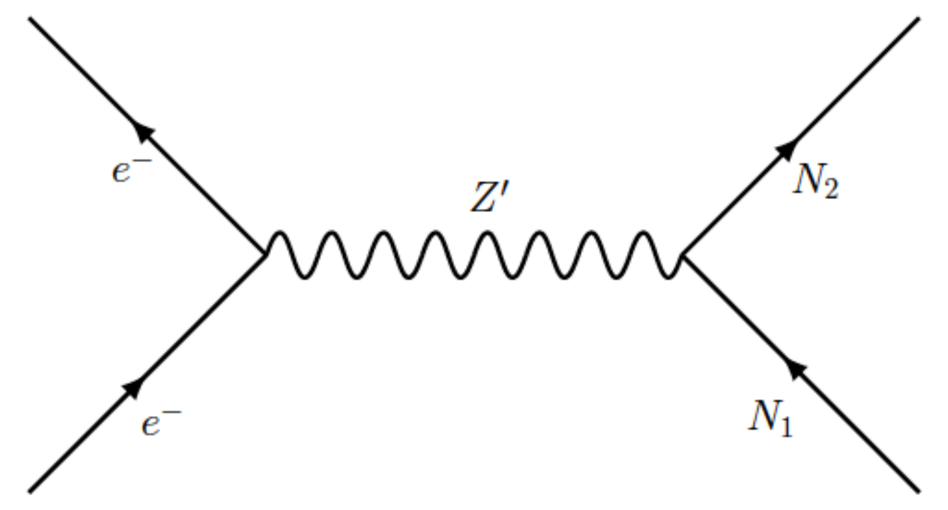
Electrons in the Earth

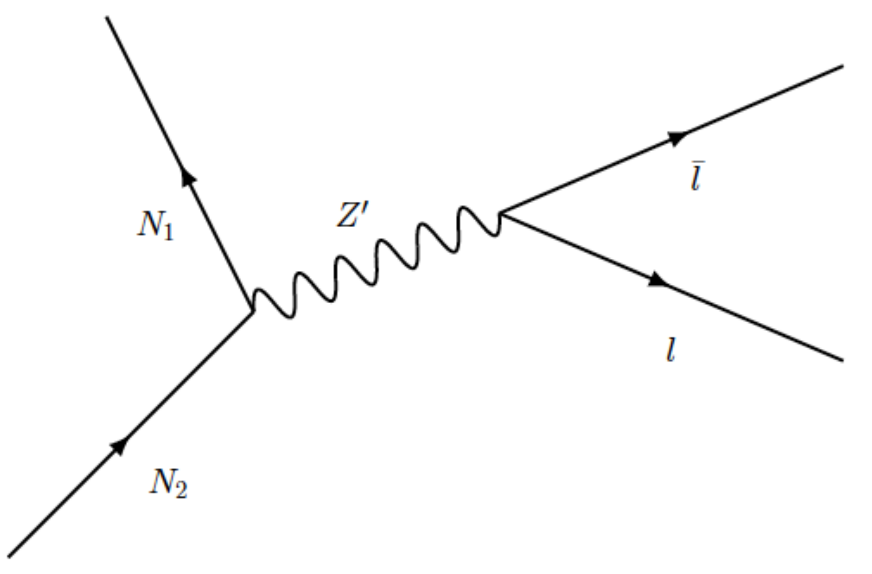
Very high energy coming from cosmos

$$N_2 \;\to\; N_1 \nu_\tau \bar{\nu}_\tau$$

$$E_\nu \sim \frac{M_2 - M_1}{M_1} \frac{E_{N_1}}{4}$$

Scattering and decay





New gauge interaction

$L_e - L_\tau$ with a gauge coupling of $g_{e-\tau}$

$$g_N Z'_\mu \bar{N}_2 \sigma^\mu N_1 + \text{H.c.}$$

$$\sigma(N_1 + e \to N_2 + e) = \frac{g_N^2 g_{e-\tau}^2}{8\pi} s \int_{-1}^{1} \frac{4 + (1 + \cos\theta)^2}{(s(1 - \cos\theta)/2 + m_{Z'}^2)^2} d\cos\theta$$

$s \gg m_{Z'}^2$ → $\sigma \simeq (2 g_N^2 g_{e-\tau}^2 / \pi m_{Z'}^2)$

LEP bounds

$e^-e^+ \to \gamma Z'$

$$\begin{aligned}
\frac{g_{e-\tau}}{m_{Z'}} &< 2.0 \times 10^{-4}\mathrm{GeV}^{-1} \quad \text{for} \quad 200 \text{ GeV} < m_{Z'} \\
\frac{g_{e-\tau}}{m_{Z'}} &< 6.9 \times 10^{-4}\mathrm{GeV}^{-1} \quad \text{for} \quad 100 \text{ GeV} < m_{Z'} < 200 \text{ GeV}.
\end{aligned}$$

Freitas and Westhoff, JHEP 1410 (2014) 116

Saturating LEP bounds

$$g_{e-\tau} = 6.9 \times 10^{-2} (m_{Z'}/100 \text{ GeV})$$

$$\Downarrow$$

$$\sigma(e + N_1 \to e + N_2) = \sigma(e + N_2 \to e + N_1) = 10^{-34} g_N^2 \text{ cm}^2$$

$$\boxed{\gamma^{-1} = (n_e \sigma)^{-1} = 8 \times 10^4 \text{ km}/g_N^2}$$

Decay rate of N_2

$$\boxed{\Gamma_{tot} = \frac{g_N^2 g_{e-\tau}^2}{10\pi^3} \frac{(M_2 - M_1)^5}{m_{Z'}^4} \left(\frac{M_2}{E_{N_2}}\right)}$$

For given g_N and $\frac{g_{e-\tau}}{m_{Z'}}$, Γ_{tot} can be fixed by tuning $(M_2 - M_1)$

The stability of N_1

Z_2 symmetry

$$N_1 \to -N_1 \quad N_2 \to -N_2 \quad SM \to SM$$

Lightest one is stable and travels long distances

N_1 in early universe

$$\langle\sigma(N_1\bar{N}_2 \to \text{lepton pairs})v\rangle \sim 3\frac{g_N^2 g_{e-\tau}^2 M_1^2}{\pi m_{Z'}^4} = 1.6 \times 10^{-35}\left(\frac{M_1/m_{Z'}}{0.1}\right)^2 \text{cm}^2 \gtrsim 1 \text{ pb}$$

A proper dark matter component

How to obtain

$$g_N Z'_\mu \bar{N}_2 \sigma^\mu N_1 + \text{H.c.}$$

Within

$$L_e - L_\tau$$

The $L_e - L_\tau$ model

- Two Weyl fermions with opposite U(1) charges

$$\psi_1 = (N_1 + N_2)/\sqrt{2} \text{ and } \psi_2 = (N_1 - N_2)/\sqrt{2}.$$

Anomaly cancelation

$$g_N(\bar{\psi}_1 \sigma^\mu \psi_1 - \bar{\psi}_2 \sigma^\mu \psi_2) Z'_\mu = g_N(\bar{N}_1 \sigma^\mu N_2 + \bar{N}_2 \sigma^\mu N_1) Z'_\mu$$

Mass terms

$$m(\psi_1^T c\psi_2 + \psi_2^T c\psi_1) = m(N_1^T cN_1 - N_2^T cN_2)$$

$$c = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\psi_1 \leftrightarrow \psi_2 \text{ and } \Phi \leftrightarrow \Phi^* \text{ (and } Z' \leftrightarrow -Z' \text{ and } e \leftrightarrow \tau)$$

$$Y\langle\Phi\rangle(N_1^T cN_1 + N_2^T cN_2)$$

$$M_1 = |m + Y\langle\Phi\rangle| \quad \text{and} \quad M_2 = |m - Y\langle\Phi\rangle|$$

Quasi-degeneracy

$$\boxed{M_1 = |m + Y\langle\Phi\rangle| \quad \text{and} \quad M_2 = |m - Y\langle\Phi\rangle|}$$

It is natural to have

$$m \ll |Y\langle\Phi\rangle|$$

Or

$$m \gg |Y\langle\Phi\rangle|$$

Typical values giving rise to large P

$$\frac{g_{e-\tau}}{m_{Z'}} \sim 7 \times 10^{-4}\text{GeV}^{-1}$$

$$g_N \sim 3$$

$$M_2 \simeq M_1 \sim 10\ \text{GeV}$$

$$M_2 - M_1 \sim \text{GeV}\frac{10\ \text{GeV}}{M_2}$$

$$\Rightarrow$$

$$\Gamma_{tot} \sim \tau_\nu^{-1} \sim (500\ \text{km})^{-1}$$

$$\sigma \sim L^{-1}$$

Prediction for the ILC

$$\boxed{e^- e^+ \to \gamma Z'}$$

$$\boxed{(P_{e^-} + P_{e^+} - P_\gamma)^2 = m_{Z'}^2}$$

$$\boxed{Z' \to N_1 \bar{N}_2, N_2 \bar{N}_1}$$

$$M_2 - M_1 > 2m_\tau$$

In 1/3 of cases: $N_2 \to N_1 \nu_e \bar{\nu}_e, N_1 \nu_\tau \bar{\nu}_\tau$

In 1/3 of cases: $N_2 \to N_1 e^- e^+$

In 1/3 of cases: $N_2 \to N_1 \tau \bar{\tau}$

Non-Standard Interactions

$$2\sqrt{2}\epsilon^e G_F(\bar{\nu}_e\gamma^\mu P_L\nu_e - \bar{\nu}_\tau\gamma^\mu P_L\nu_\tau)(\bar{e}\gamma_\mu e)$$

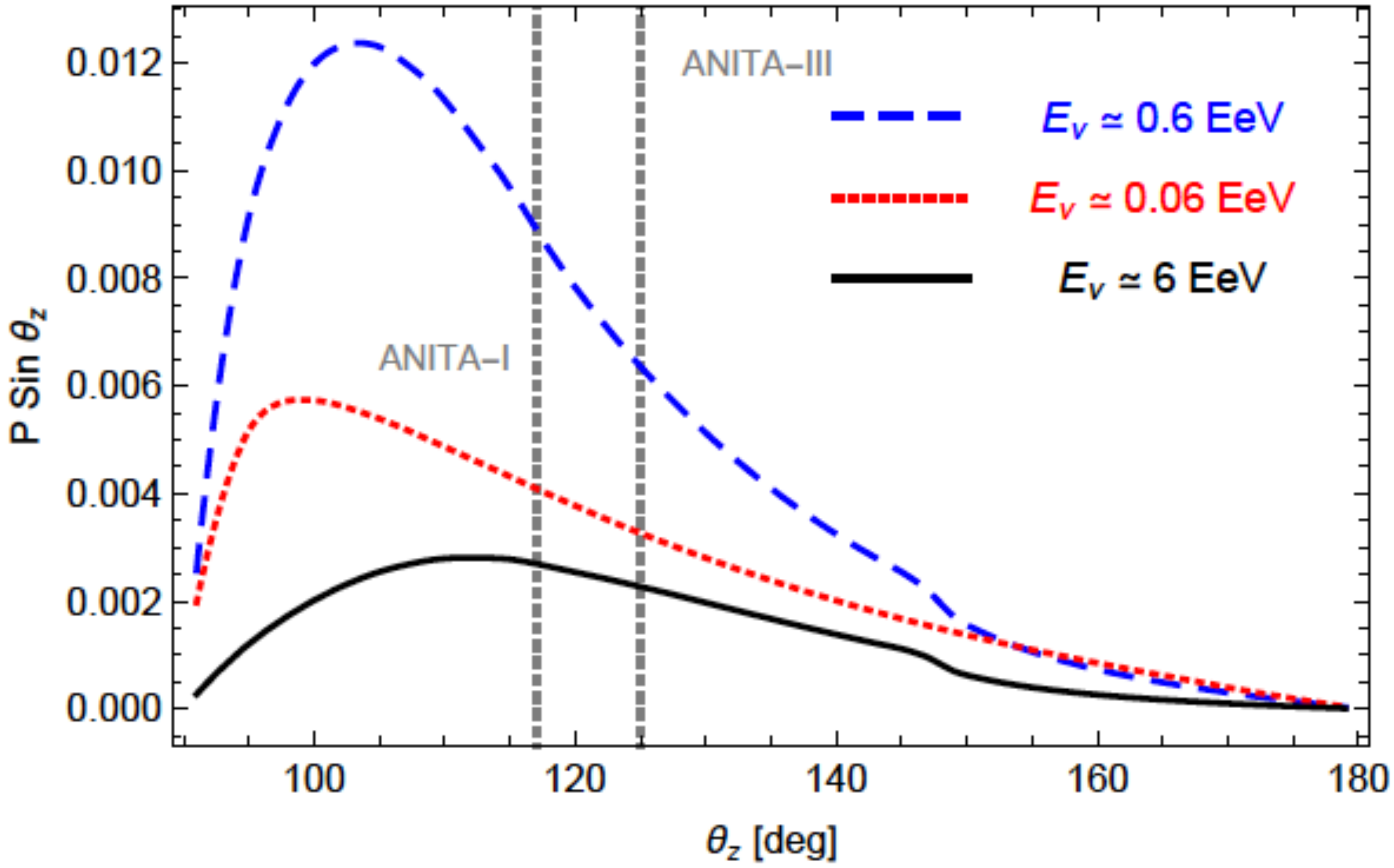
$$\epsilon^e \simeq 0.01$$

5 times improvement is required.

Agarwalla, Borexino collaboration, 1905.03512; Choubey and Ohlsson, 1410.0410

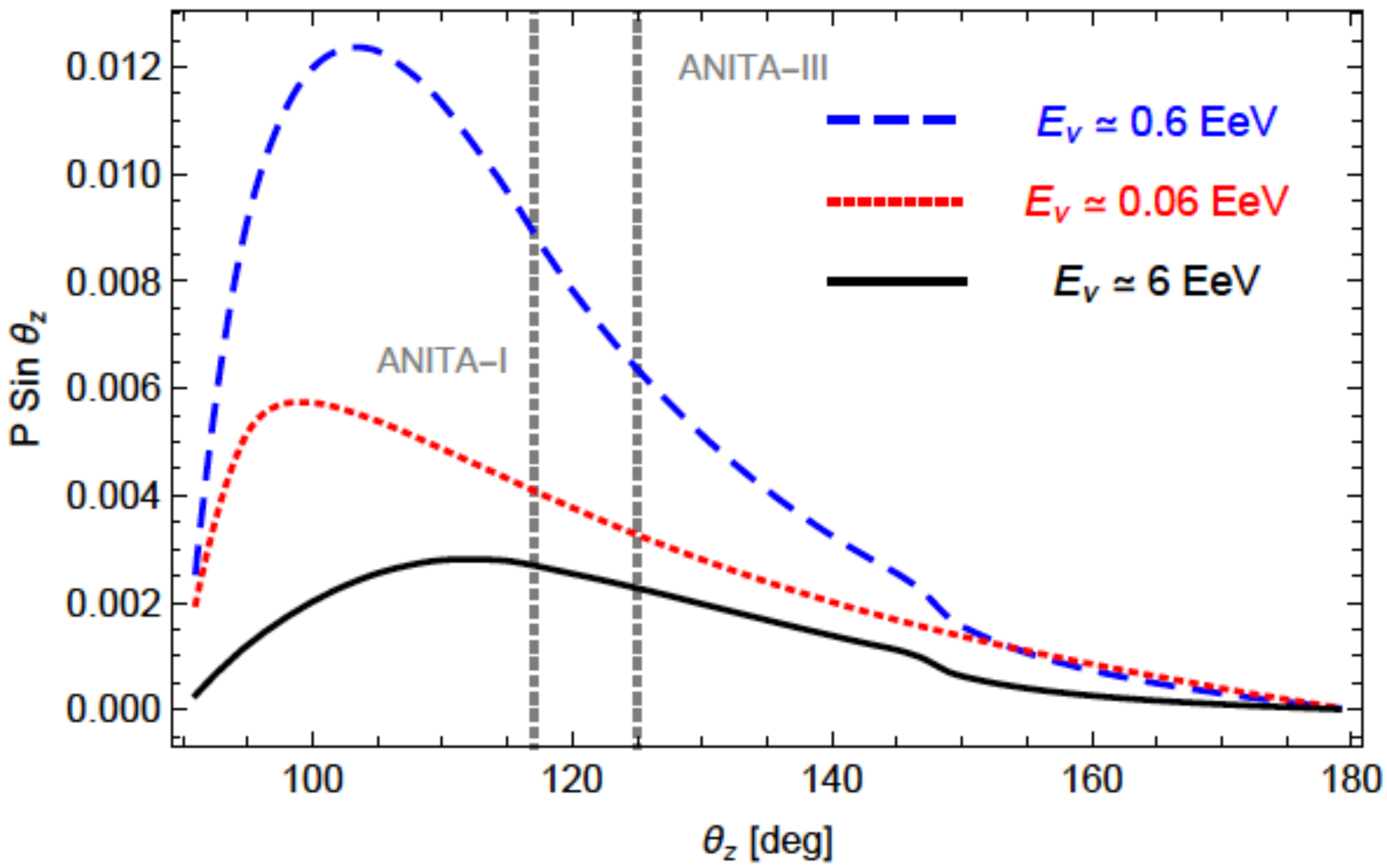
$$E_\nu \sim E_{N_1}(M_2 - M_1)/(4M_1)$$

$$E_{N_1} = (3.2, 32, 320)\ \mathrm{EeV}$$



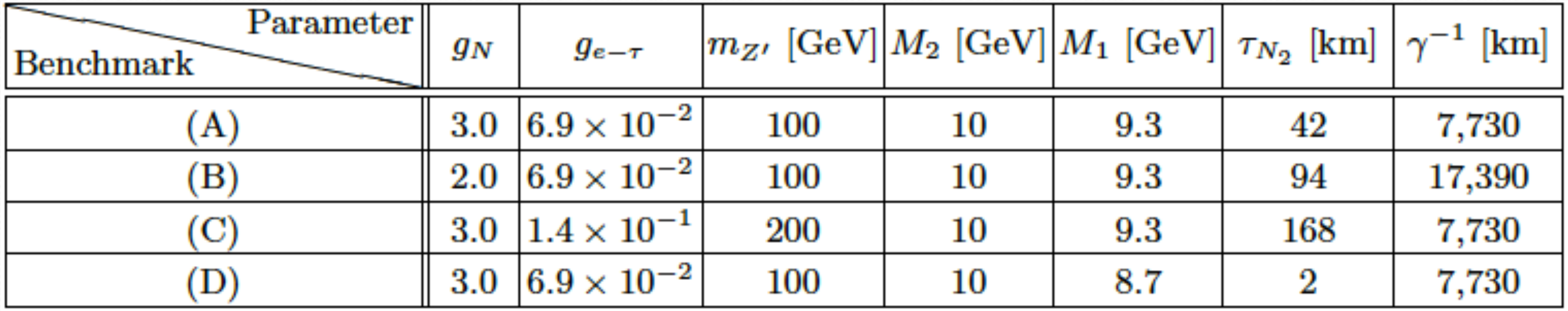
$$c\tau_{N_2} = 42\ \mathrm{km}$$

$$\gamma^{-1} = 7730\ \mathrm{km}$$

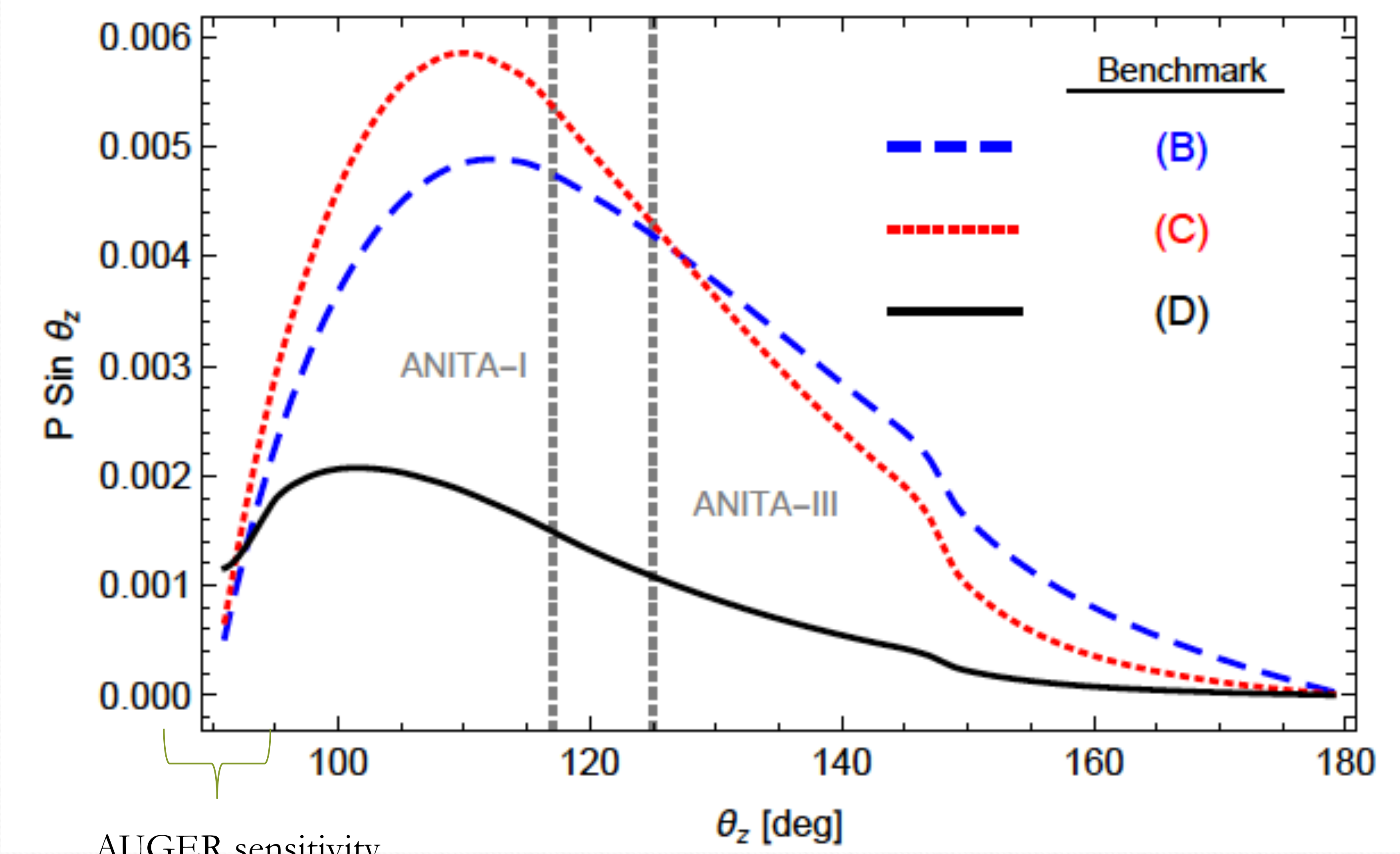


$$\boxed{\theta_z \simeq (100^\circ - 110^\circ).}$$

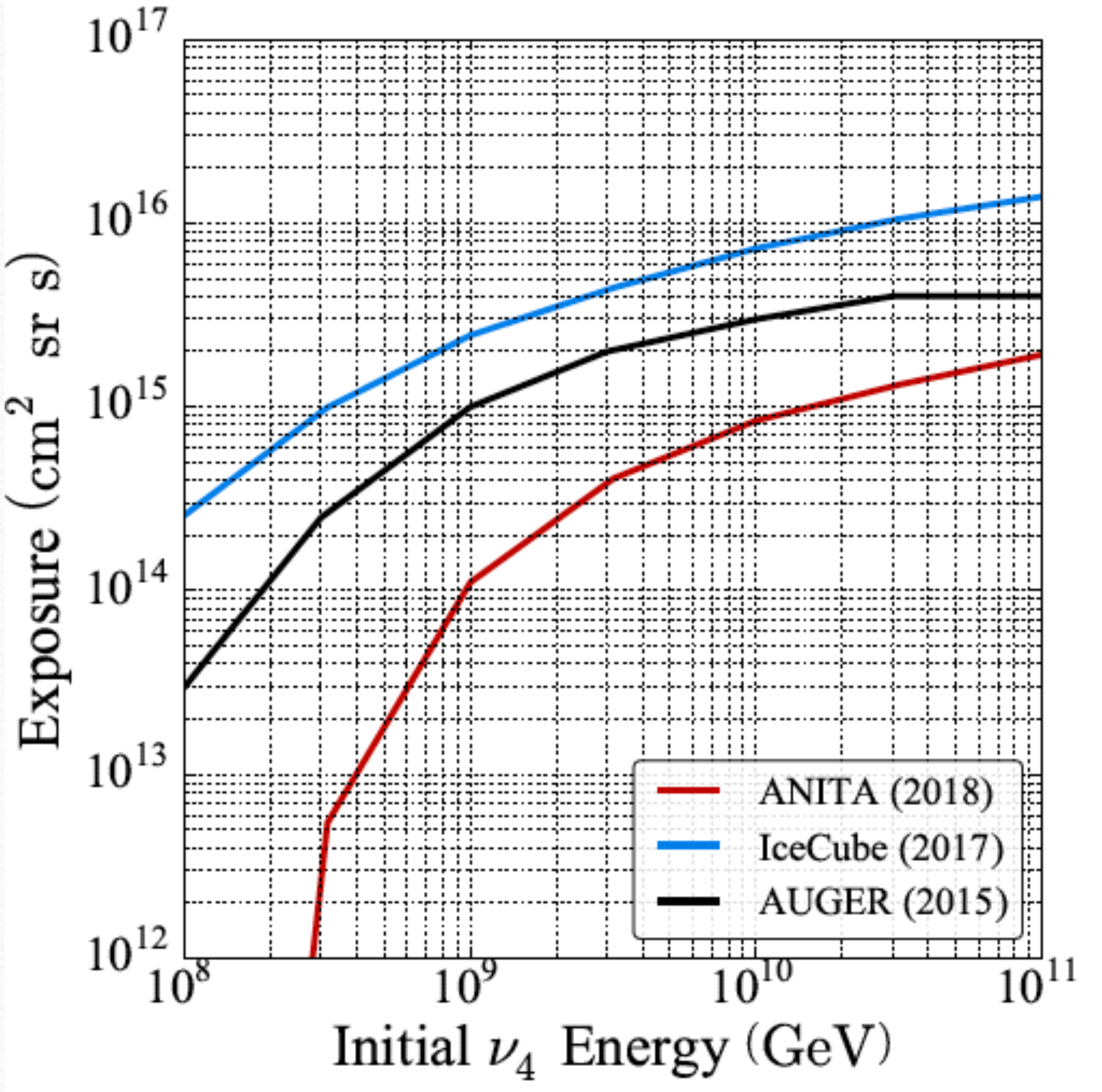
$$P \simeq 0.012$$



Parameter Benchmark	g_N	$g_{e-\tau}$	$m_{Z'}$ [GeV]	M_2 [GeV]	M_1 [GeV]	τ_{N_2} [km]	γ^{-1} [km]
(A)	3.0	6.9×10^{-2}	100	10	9.3	42	7,730
(B)	2.0	6.9×10^{-2}	100	10	9.3	94	17,390
(C)	3.0	1.4×10^{-1}	200	10	9.3	168	7,730
(D)	3.0	6.9×10^{-2}	100	10	8.7	2	7,730



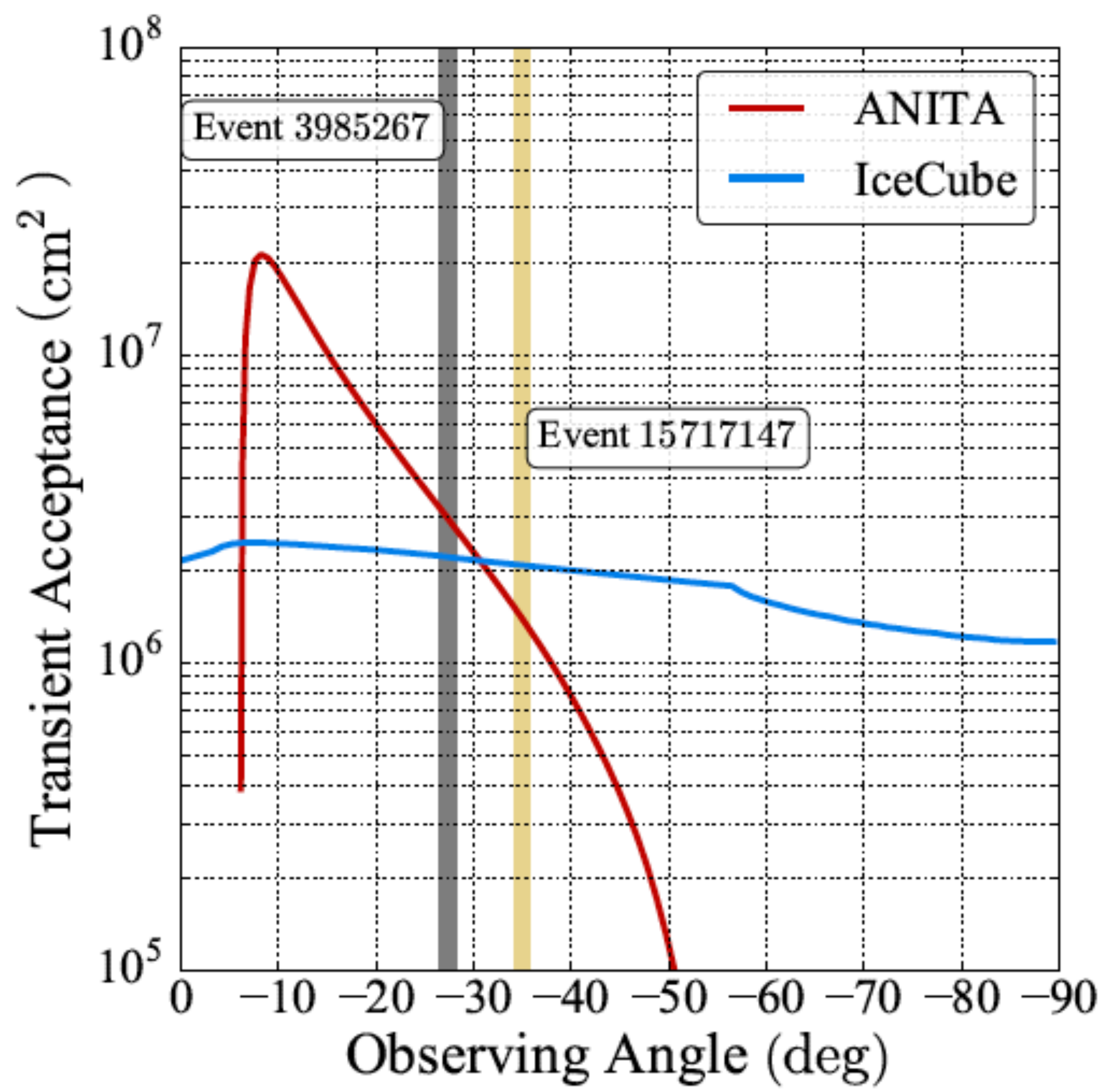
AUGER sensitivity



Cherry and Shoemaker, PRD99 (2019) 63016

ICECUBE data taking ~ 8 years

ANITA data taking~ 1 month



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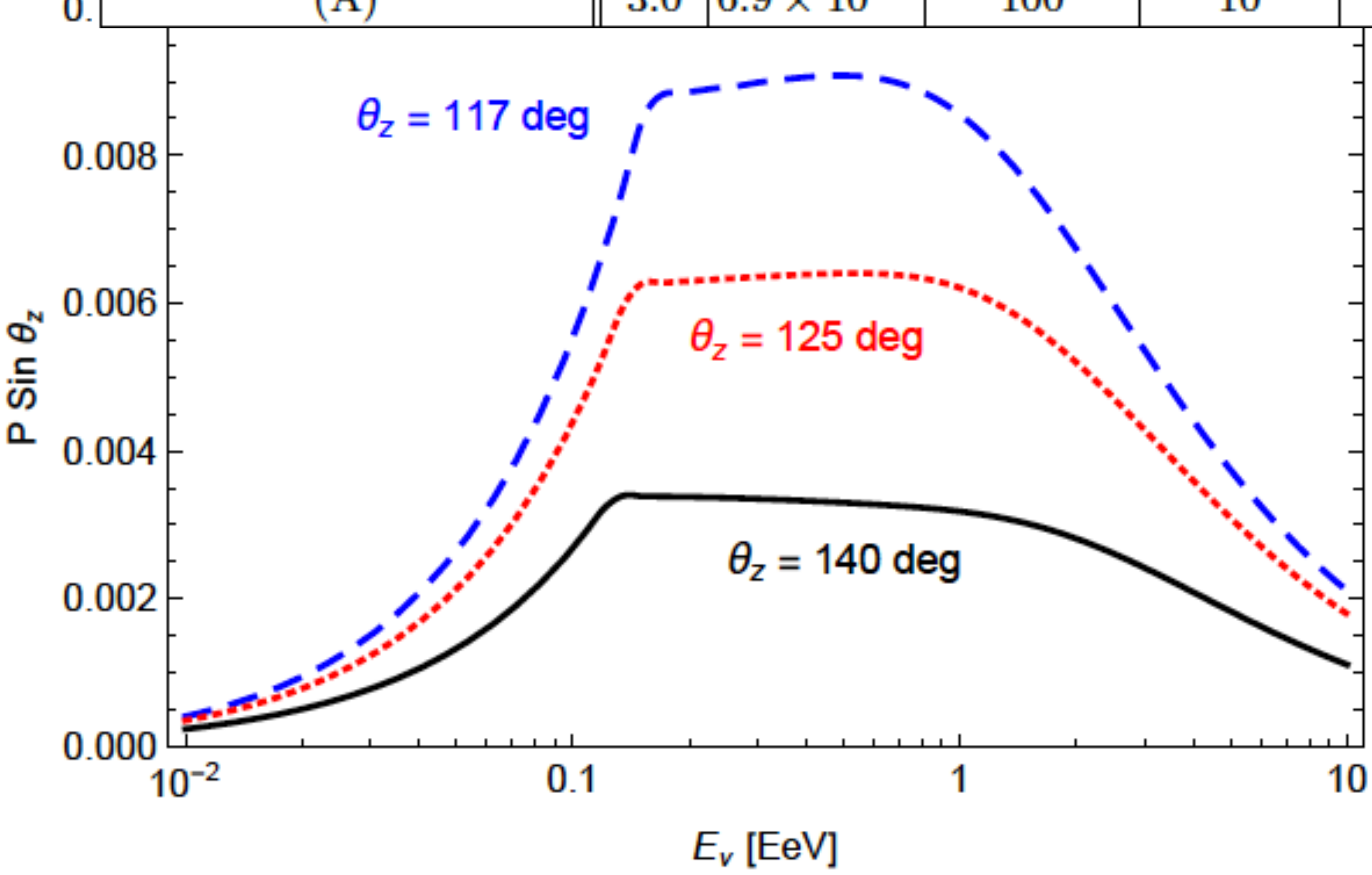


$$E_\nu \simeq E_{N_1}(M_2 - M_1)/(4M_1).$$

Summary and conclusions

- 2 anomalous ANITA events
- Our scenario: $N_1 + e \to N_2 + e$

  $N_2 \to N_1 \nu_\tau \bar{\nu}_\tau$
- Our model: $L_e - L_\tau$ with Z' to be discovered by ILC
- Bonus: A candidate for dark matter

Backup

Exposure and Flux

- ANITA exposure: $2.7\ \mathrm{km}^2\ \mathrm{yr\ sr}$

- Incident N_1 flux $\simeq 40\ \mathrm{km}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}$

$$40 \times 2.7 \times 0.012 \sim 1$$

Some possible signature at LHC

$$\boxed{\lambda_{H\Phi}|H|^2|\Phi|^2}$$

$$H \rightarrow \Phi\bar{\Phi} \rightarrow N_1\bar{N}_1N_2\bar{N}_2 \rightarrow 2N_12\bar{N}_1l\bar{l}l'\bar{l}'$$

$$\lambda_{H\Phi} \ll m_\tau/\langle H\rangle$$

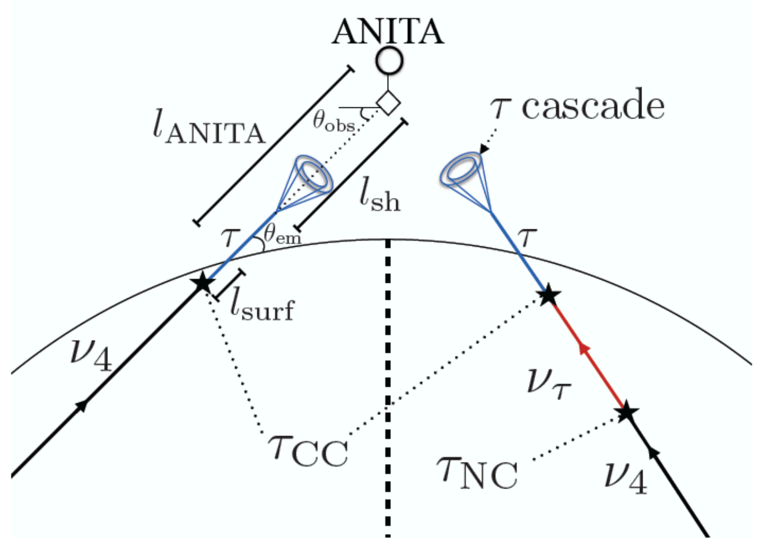
Some nice ideas

- I. Esteban et al, Reflection of radio pulse produced by axion-photon conversion in ionosphere, arXiv:1905.10372;
- Cherry and Shoemaker, A sterile neutrino origin

for the upward directed cosmic ray shower detected by

ANITA, PRD99 (2019) 063016

$$m_4 \leq 2\,\mathrm{MeV} \times \left(.01/\sin^2 2\theta_{\tau 4}\right)^{1/6}$$



Other possibilities to gauge

$B - 3L_\tau$

some other anomaly free combination of B, L_τ, L_μ and L_e

Maybe light Z’

Displaced vertex

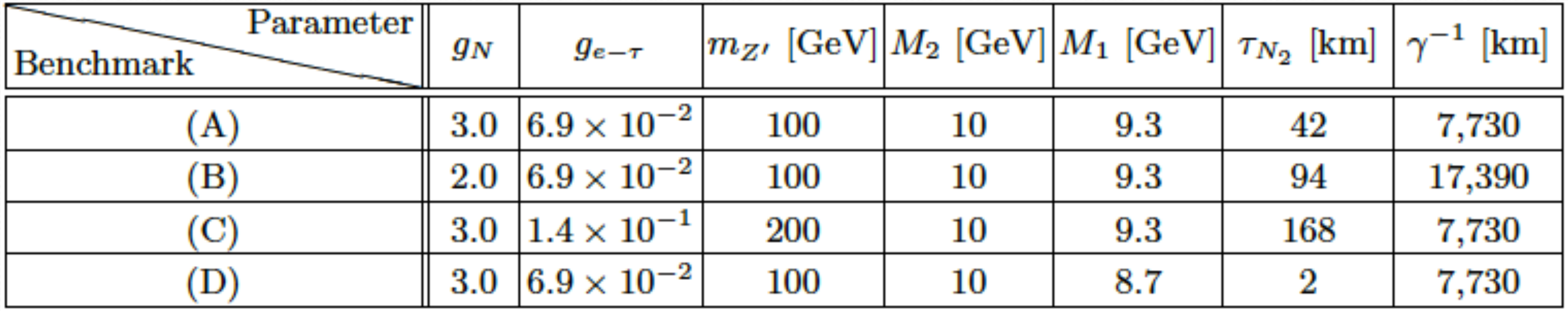
$\boxed{e^-e^+ \to \gamma Z'}$ $\boxed{Z' \to N_1\bar{N}_2, N_2\bar{N}_1}$ $N_2 \to N_1 e^- e^+$

The displacement is given by $(M_2 - M_1)^5 g_N^2$

$$E_{e^-} \sim E_{e^+} \sim \frac{s + m_{Z'}^2}{8\sqrt{s}}(1 - \frac{M_1}{M_2})$$

$\sqrt{s} = 500 \text{ GeV and } 1 - M_1/M_2 \sim 0.1$ ➡

$$E_{e^-} \sim E_{e^+} \sim 6 \text{ GeV}$$



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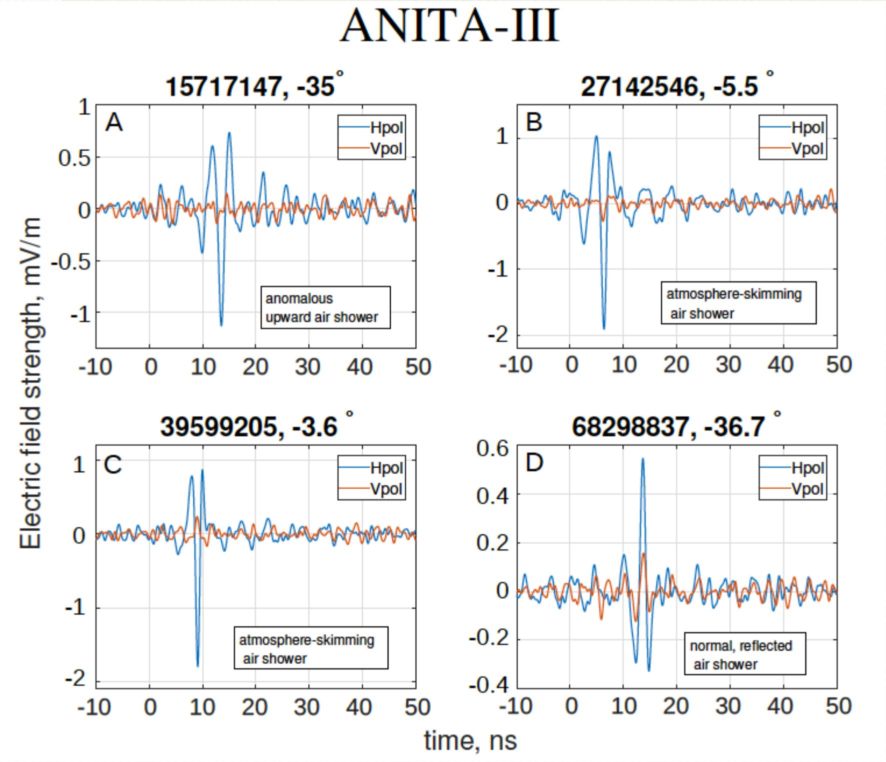
Waveform and polarity



PUEO collaboration, 2010.02892

Possible mechanism for N_1 production

- Very heavy dark matter

$$\Phi(\psi_1^T c\psi_2 + \psi_2^T c\psi_1) = \Phi(N_1^T cN_1 - N_2^T cN_2)$$

Similar fluxes for N_1 and N_2 .

$$N_2 \to N_1\nu_e\bar{\nu}_e, N_1\nu_\tau\bar{\nu}_\tau, N_1\tau\bar{\tau}$$

Transient source

$$\sigma(\nu_e + \text{nucleus} \to e + Z' + X) \sim \frac{g^2_{e-\tau}}{16\pi^2}\sigma(\nu_e + \text{nucleus} \to e + X)$$

$$Z' \to N_1\bar{N}_2, N_2\bar{N}_1$$

Downward or Upward

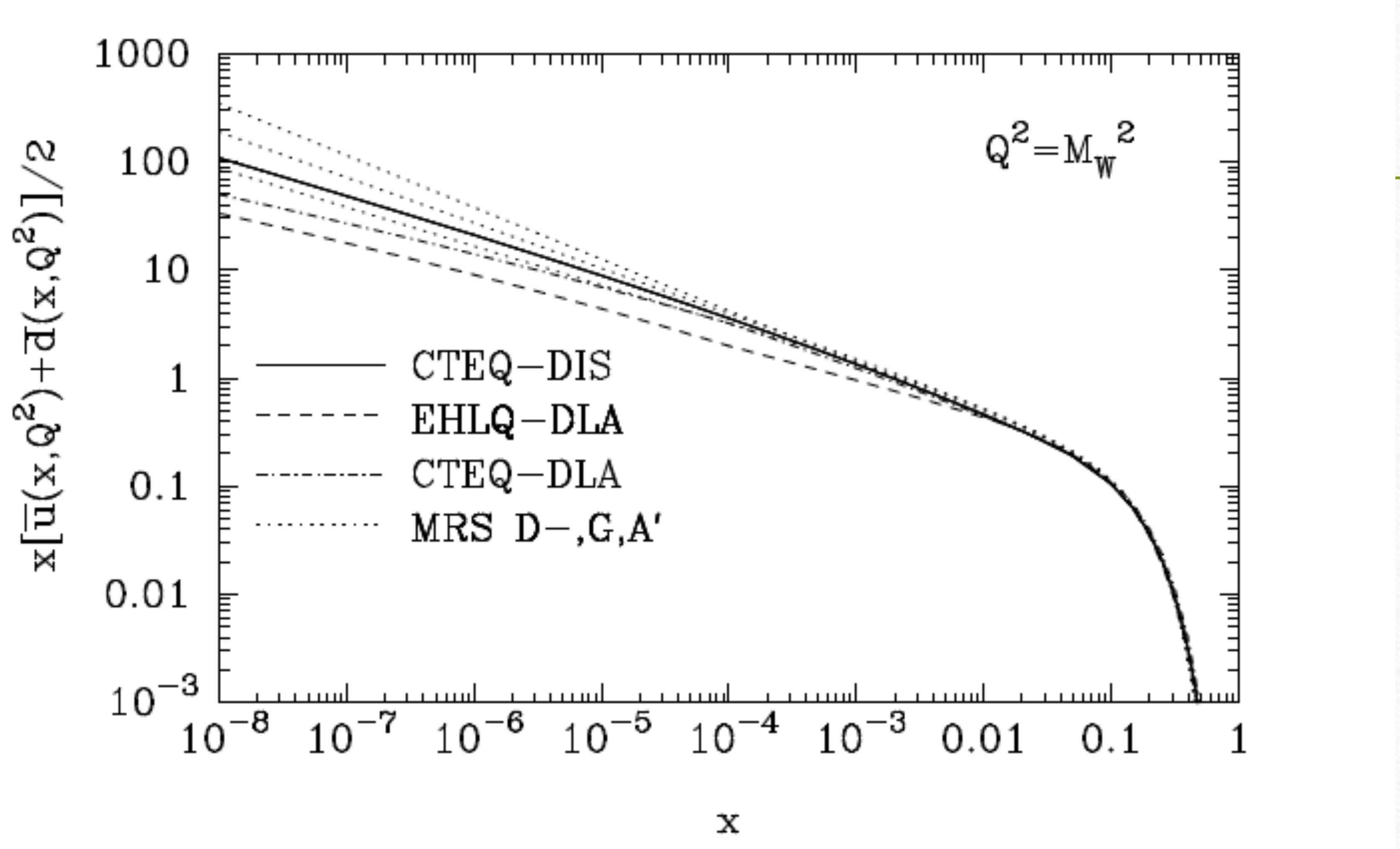
Optical Cherenkov instrument

EUSO-SPB2 (balloon-based) next run

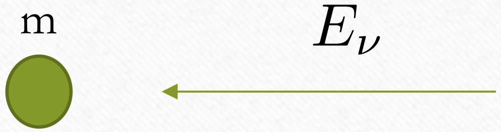
PUEO (balloon-based) , 2010.02892

POEMMA (satelite based) proposed

Cumming et al., arXiv:1910.00992



Gandhi et al, Astropart phys 5 (1996) 81-110



$$s = m^2 + m_\nu^2 + 2mE_\nu$$

$$E_\nu = 0.6\ EeV$$

$$m = m_e \quad \sqrt{s} \sim TeV \gg m_Z$$

For partons

$$\sqrt{s} \sim \sqrt{2xm_pE_\nu}$$

$$\sigma \propto \frac{1}{s}$$

????