Tests of new physics scenarios at neutrino telescopes

Bhavesh Chauhan

SRF, THEPH, PRL.

April 5th, 2019

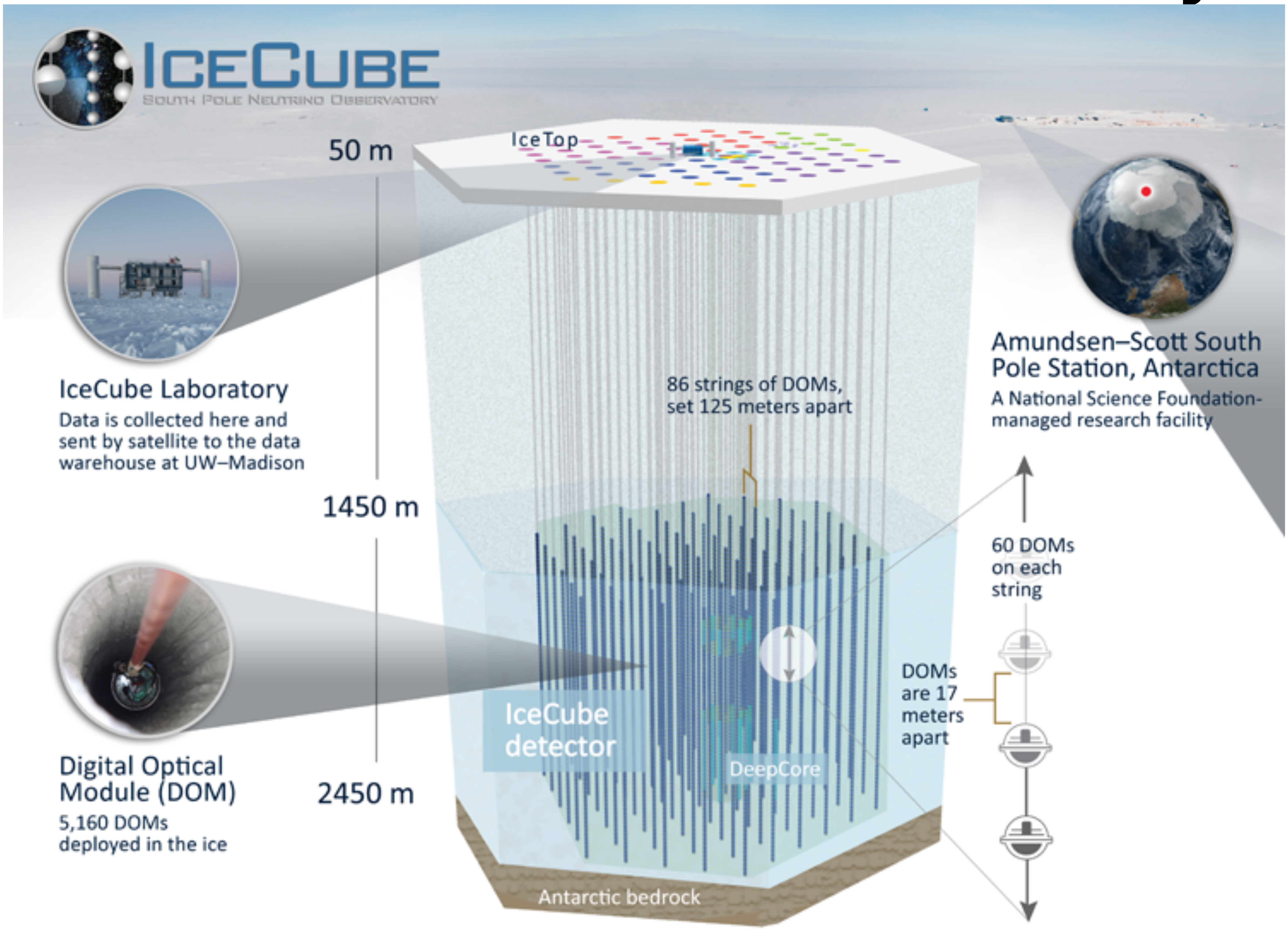
Based on
BC and Subhendra Mohanty "A leptoquark explanation for flavour and ANITA anomalies"
arXiv:1812.00919

Outline of the talk:

- Self interacting sterile neutrino at IceCube

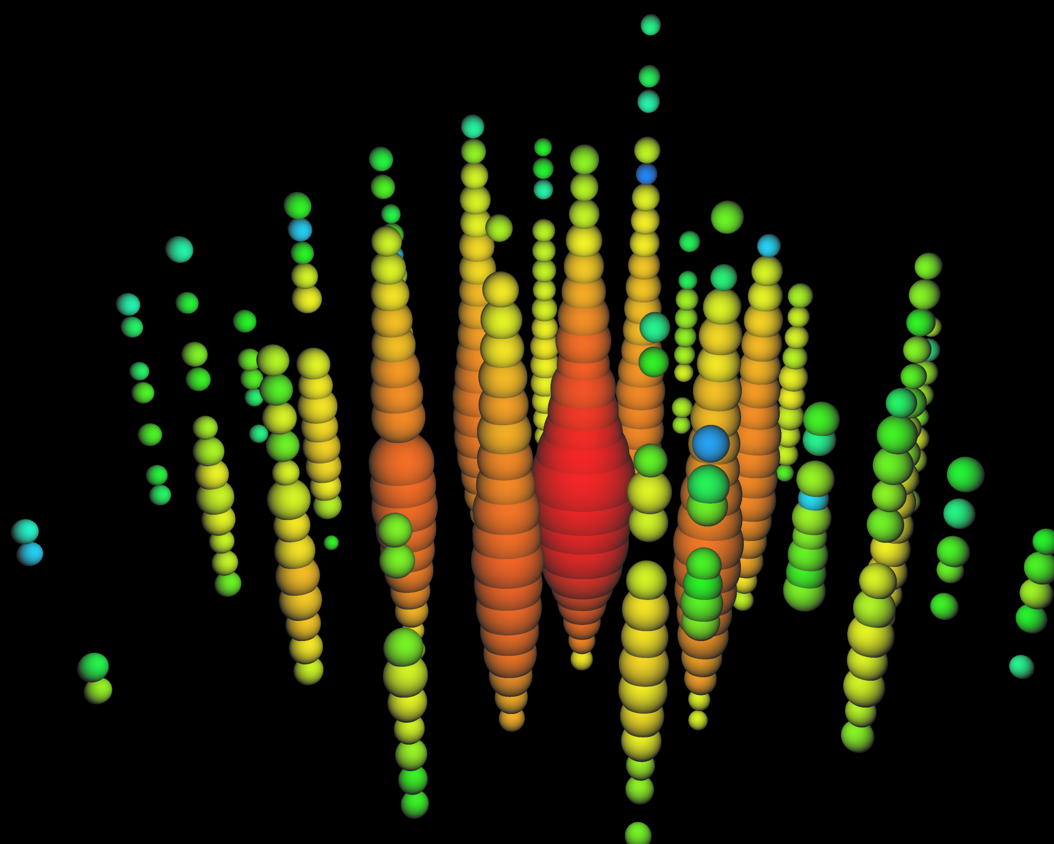
- Leptoquark resolution of flavour anomalies at ANITA

IceCube Neutrino Observatory

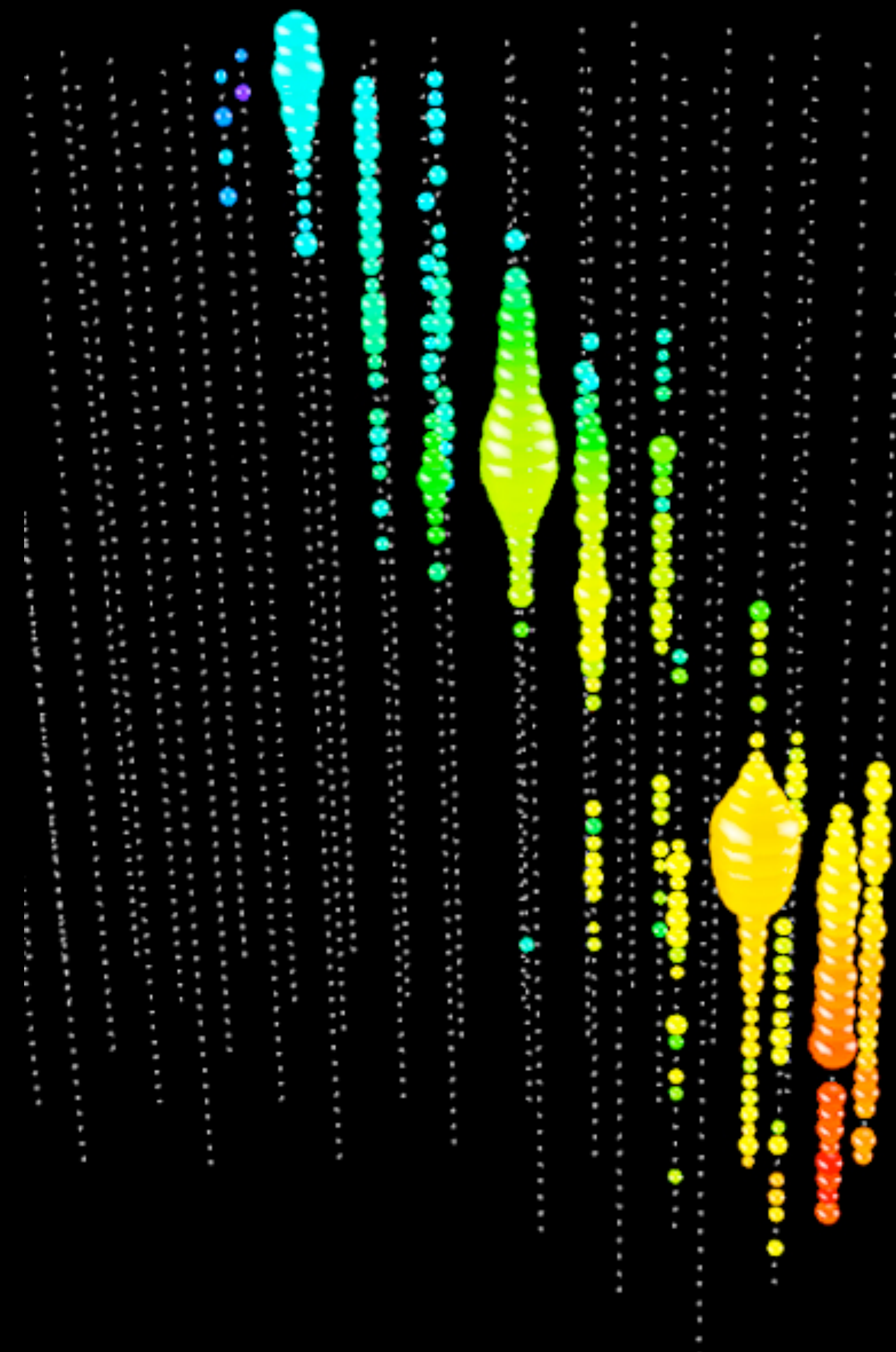


From: http://gallery.icecube.wisc.edu/

Shower

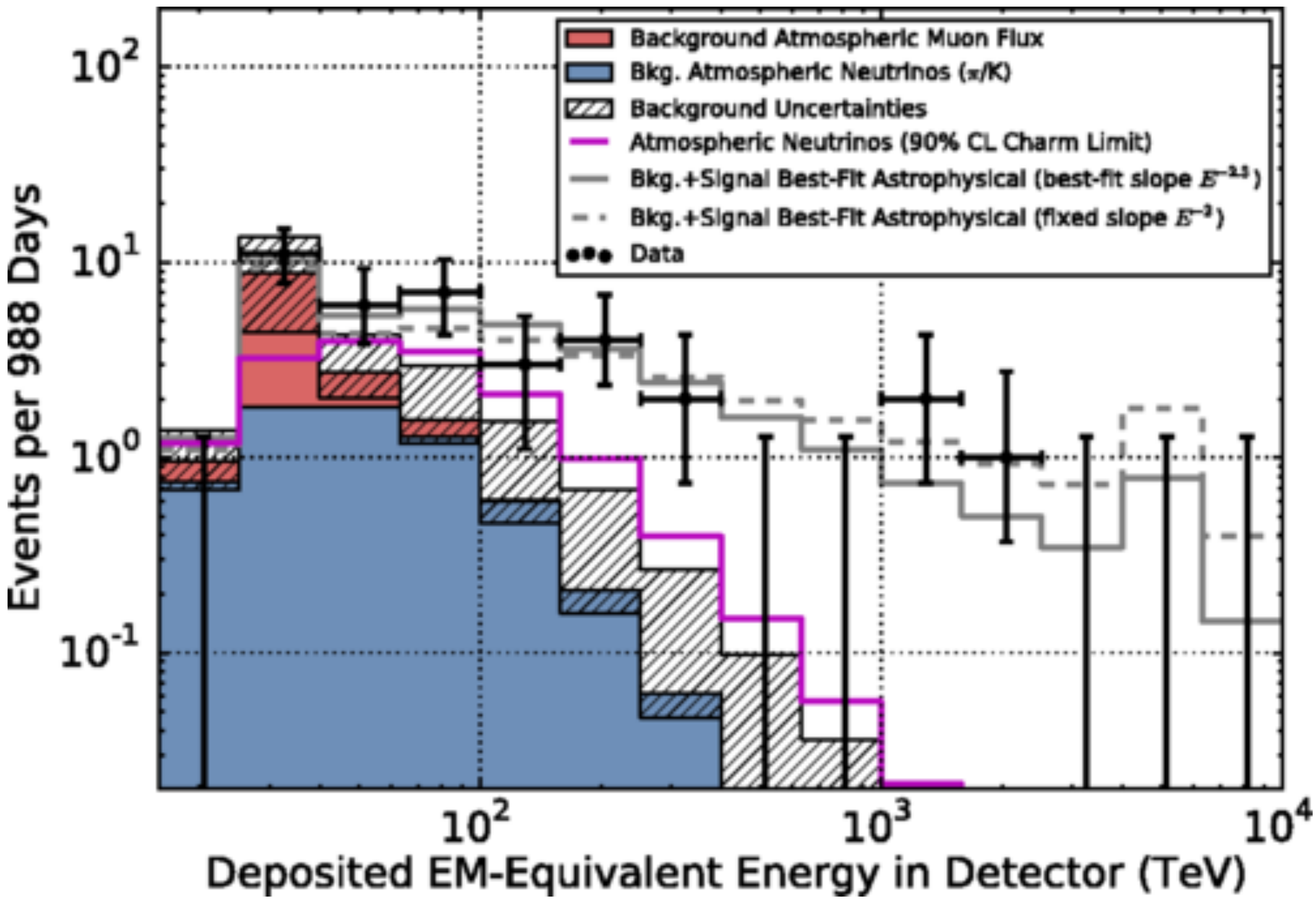


Track



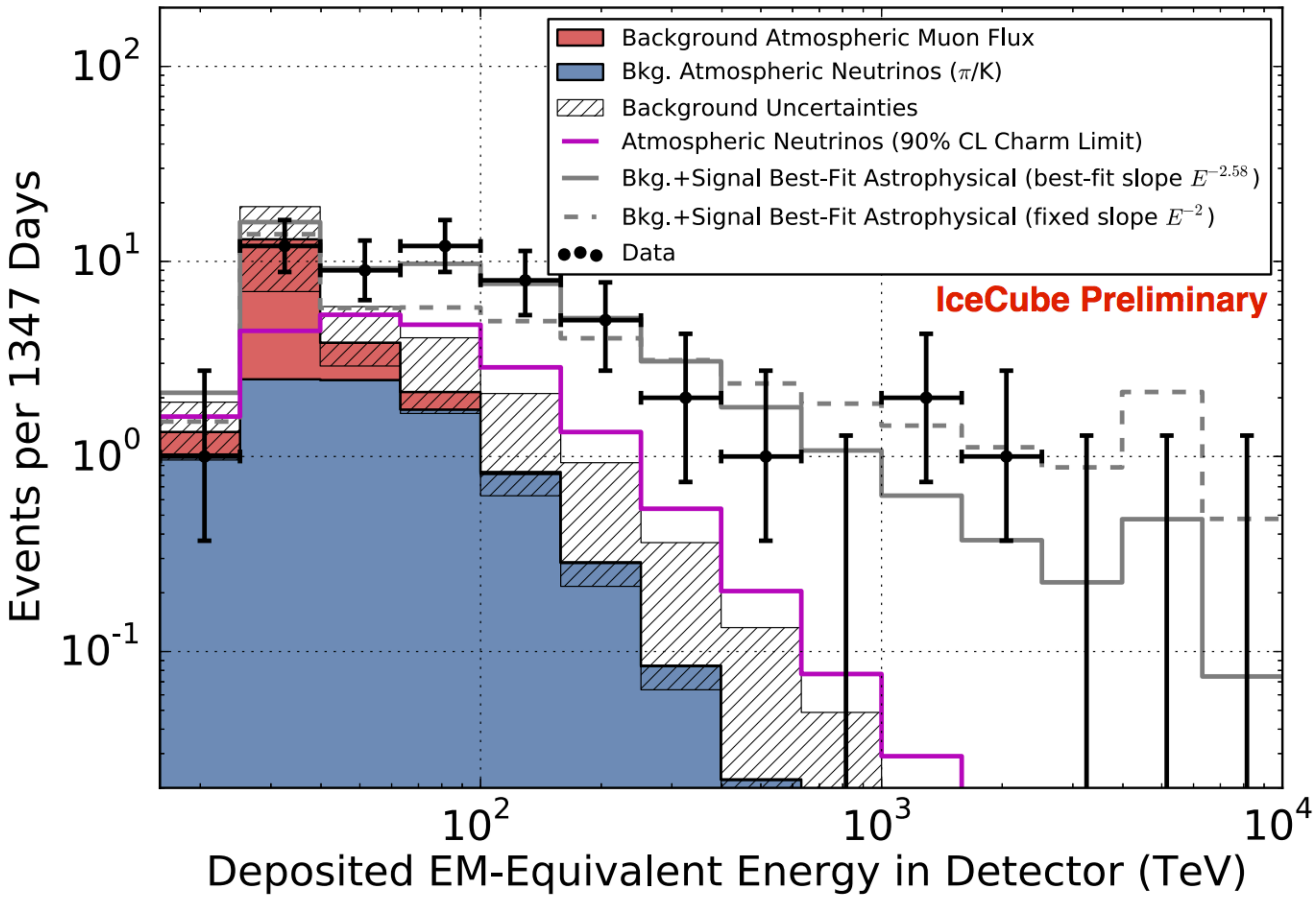
From: http://gallery.icecube.wisc.edu/

IceCube 3-year Data



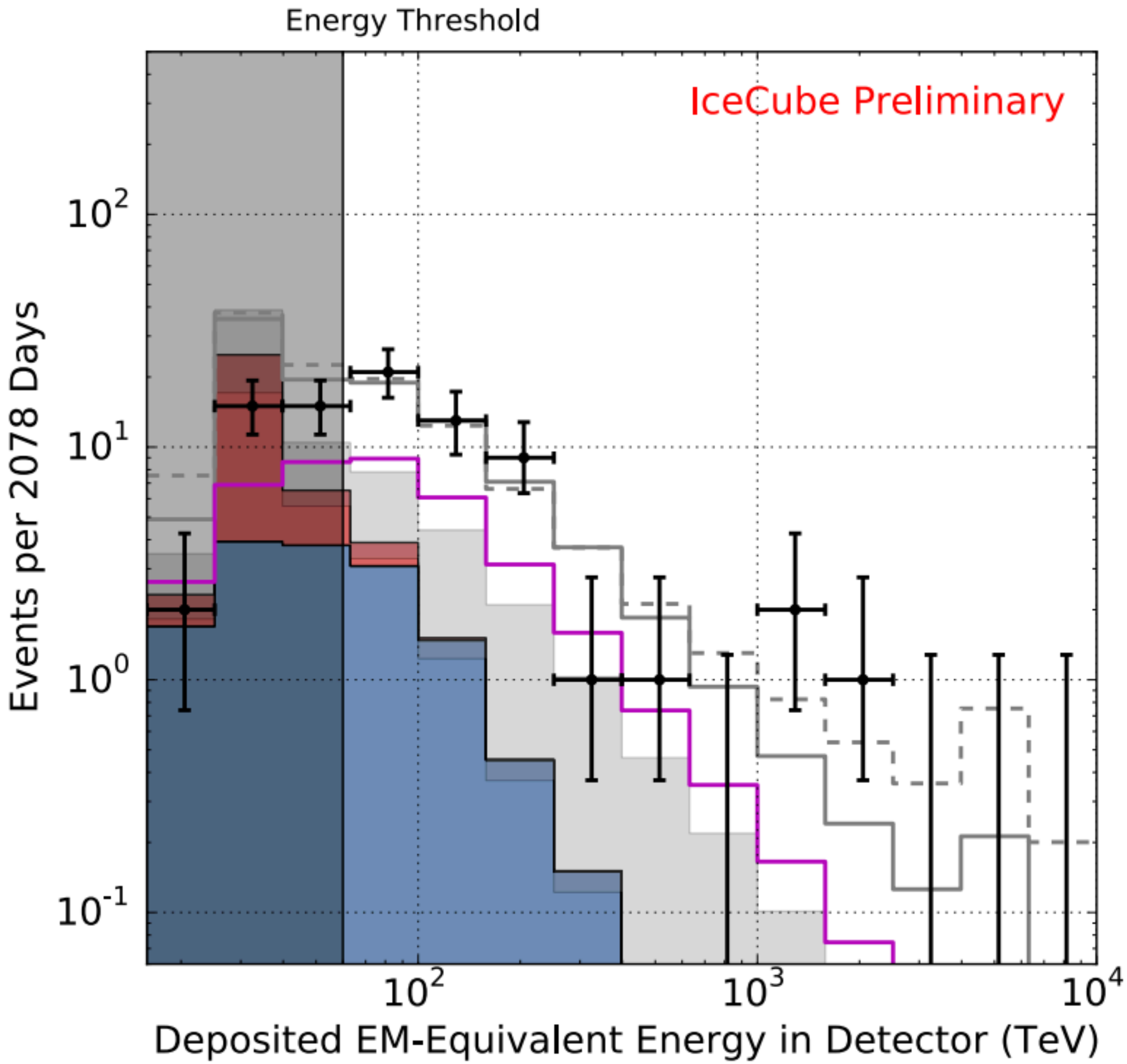
IceCube, Phys. Rev. Lett. **113**, 101101

IceCube 4-year Data



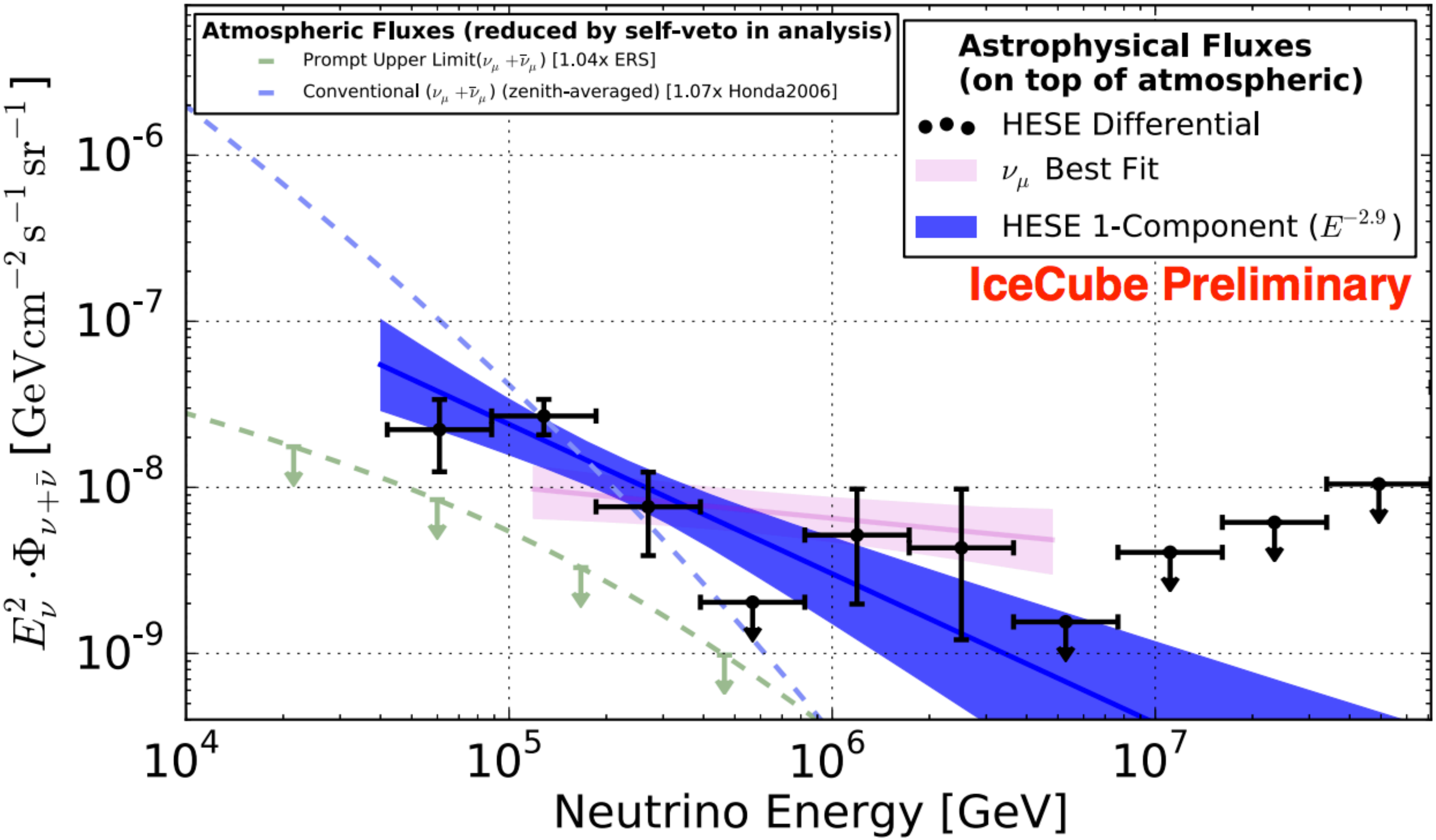
IceCube **arXiv:1510.05223**

IceCube 6-year Data

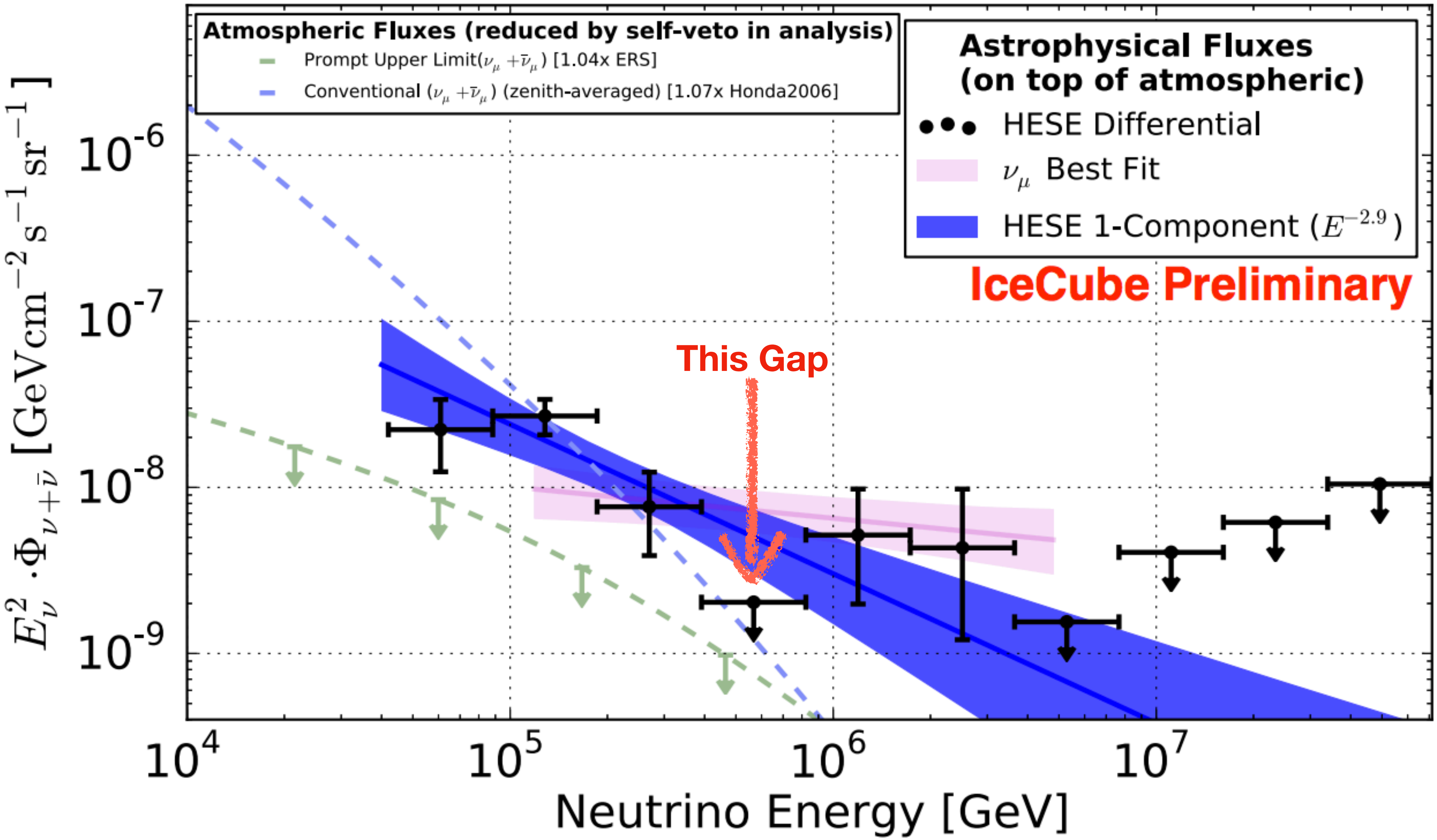


IceCube **arXiv:1710.01191**

IceCube 6-year Data



IceCube 6-year Data



Sterile Neutrino vs Cosmology

- A ev-scale sterile neutrino with large mixing angles (as required by MiniBooNE/LSND) will contribute to neutrino energy density during the Nucleosynthesis era (~ 1 MeV).

- Present day abundance of H, He, D, and other light elements severely constrain the "*effective relativistic degrees of freedom*" at T = 1 MeV.

- Planck (2018): $N_{eff} = 2.99^{+0.34}_{-0.33}$

- Consistent with Standard Model Prediction of 3.046

- The *simple* sterile neutrino is inconsistent with cosmology.

Cosmologically safe sterile neutrino

- If the sterile neutrino has very small mixing with active neutrino, then they decouple in the early universe and their contribution to N_{eff} is negligible.

- The other possibility is to introduce "*secret*" interactions of the sterile neutrino. (Chu, Dasgupta, Kopp **arXiv:1505.02795**)

$$-\mathscr{L}_s = g_X \bar{\nu}_s \gamma^\mu P_L \nu_s X_\mu$$

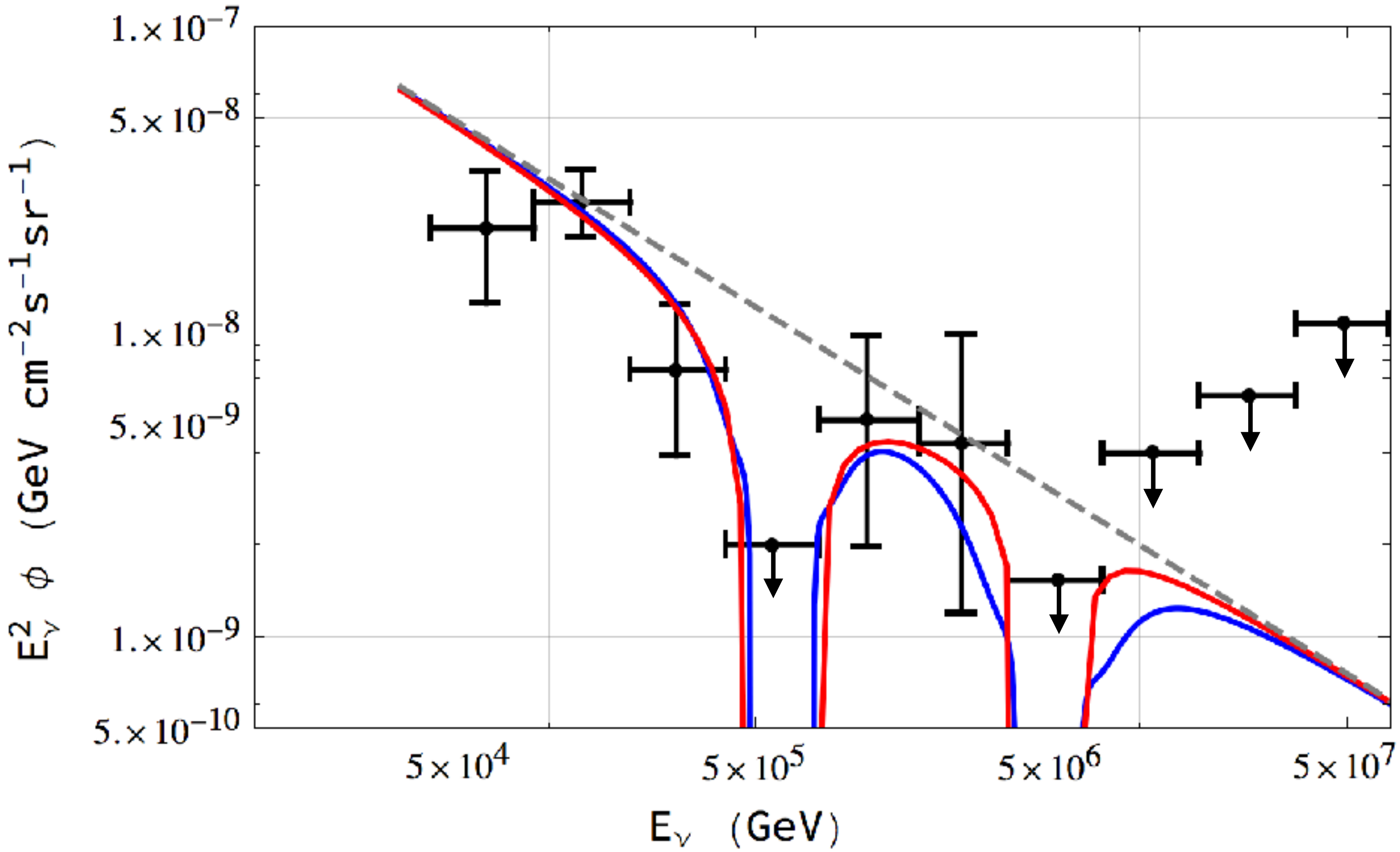
- The new interaction generates large temperature dependent potential for the sterile neutrinos. This leads to suppression of mixing angle in early universe.

- At low temperatures, the mixing angle is unsuppressed and is allowed to be large.

- For certain region of the parameter space (gx, Mx), we get a Cosmic Sterile Neutrino Background (CsB) in present universe

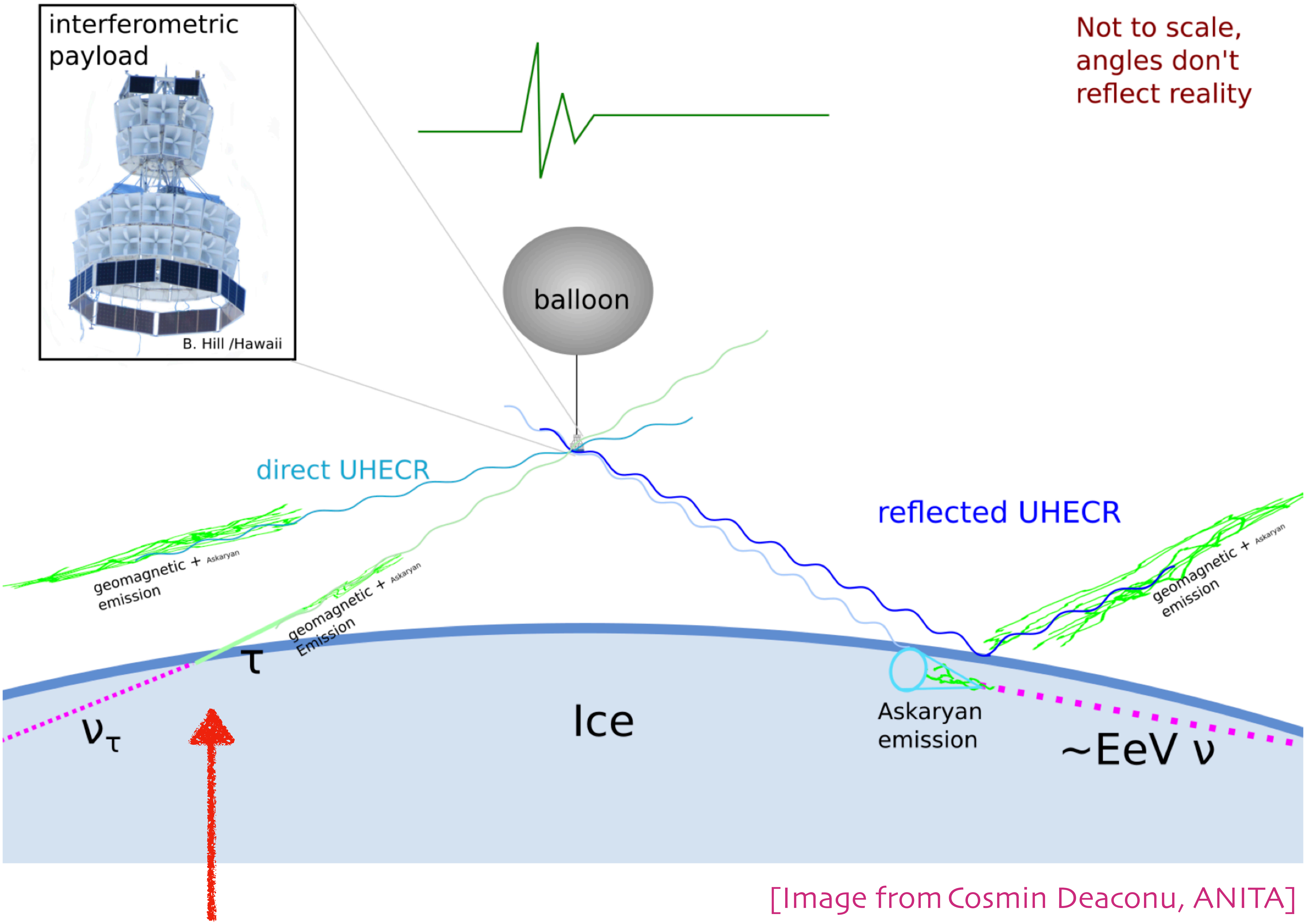
Absorption of UHE neutrino

- The astrophysical neutrinos can interact with the background sterile neutrinos.
- This results in an absorption line in the Ultra High Energy (UHE) neutrino spectrum.
- Such absorption lines can be seen by neutrino telescopes like IceCube.



The ANITA Experiment

- ANITA is a balloon-borne experiment aimed to study the extremely high energy (EHE) cosmic rays.
- The instrument consists of an array of sensitive radio antennas.
- Altitude~ 35 km; Horizon ~ 700 km; Effective Area > 1 million km^2; Four flights.
- When ultra-high energy particles interact in the ice or the atmosphere, they produce a shower of secondary particles.
- These secondary particles produce coherent radio pulses either through **the Askaryan effect** or through the separation of charges in the Earth's magnetic field.



interferometric payload
B. Hill /Hawaii
Not to scale, angles don't reflect reality
balloon
direct UHECR
reflected UHECR
geomagnetic + Askaryan emission
geomagnetic + Askaryan Emission
geomagnetic + Askaryan emission
τ
ν_τ
Ice
Askaryan emission
~EeV ν
[Image from Cosmin Deaconu, ANITA]

ANITA Anomalous Events

Property	**AAE 061228**	**AAE 141220**
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. $282\overset{\circ}{.}14064$, Dec. $+20\overset{\circ}{.}33043$	R.A. $50\overset{\circ}{.}78203$, Dec. $+38\overset{\circ}{.}65498$
Energy $\varepsilon_{\rm cr}$	$0.6 \pm 0.4\,$EeV	$0.56^{+0.30}_{-0.20}\,$EeV
Zenith angle z'/z	$117\overset{\circ}{.}4$ / $116\overset{\circ}{.}8 \pm 0\overset{\circ}{.}3$	$125\overset{\circ}{.}0$ / $124\overset{\circ}{.}5 \pm 0\overset{\circ}{.}3$
Earth chord length ℓ	$5740 \pm 60\,$km	$7210 \pm 55\,$km
Mean interaction length for $\varepsilon_\nu = 1\,$EeV	290 km	265 km
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1\,$EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1\,$EeV, $\varepsilon_\tau > 0.1\,$EeV	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1\text{–}10\,{\rm PeV}) : n_\tau(10\text{–}100\,{\rm PeV}) : n_\tau(> 0.1\,{\rm EeV})$	34 : 35 : 1	270 : 120 : 1

[Fox et. al. arXiv:1809.09615]

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[Fox et. al. arXiv:1809.09615]

$$\mathcal{N} = A \cdot \delta T \cdot \delta\Omega \int_{E_{min}}^{E_{max}} dE_\nu \cdot \epsilon \cdot \frac{dN}{dE_\nu}$$

Using GZK flux:

$$\epsilon \geq 10^{-3}$$

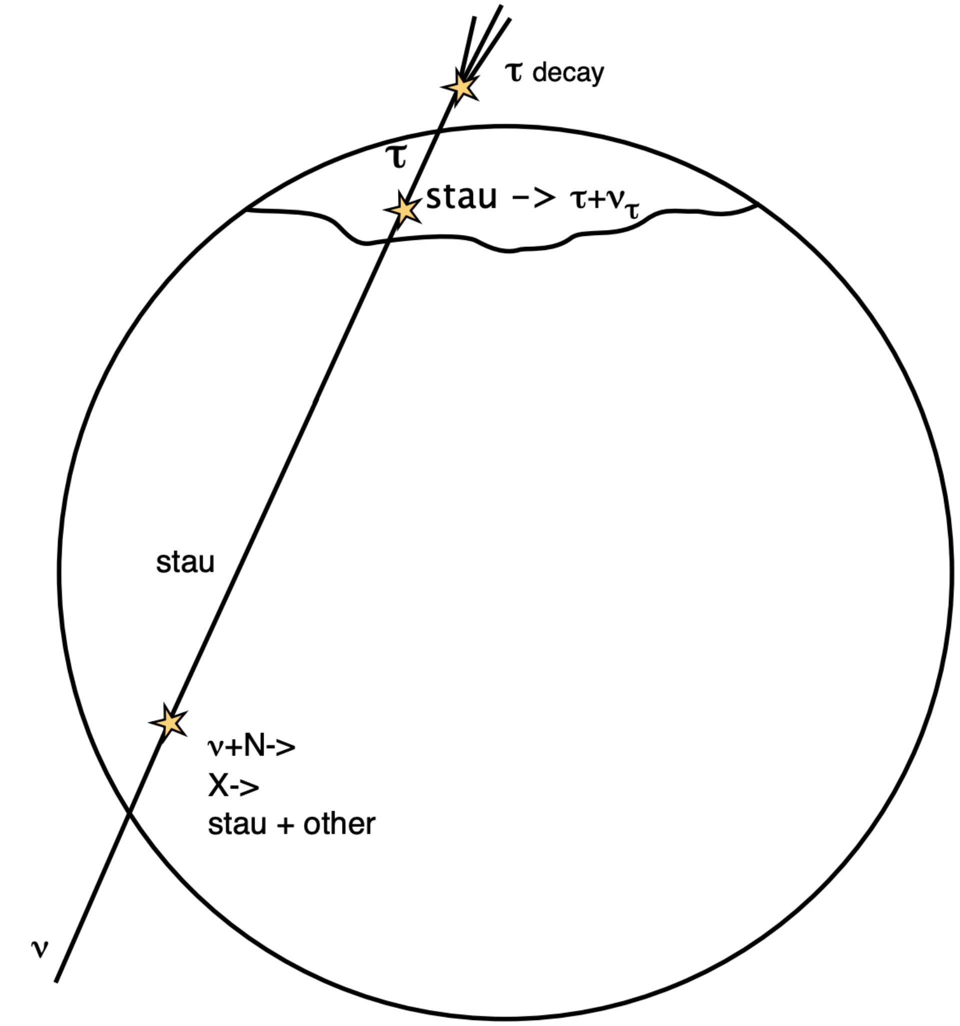
Using Anisotropic flux:

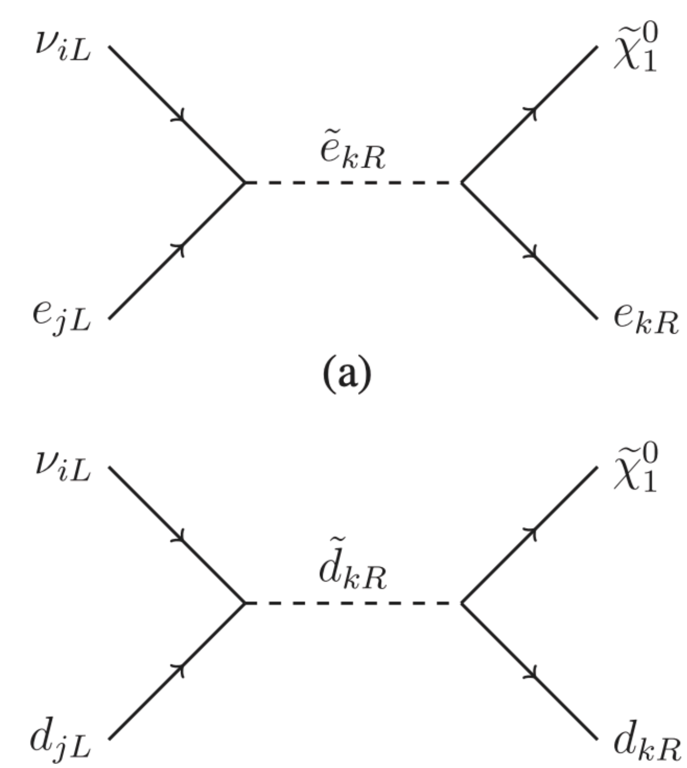
$$\epsilon \geq 10^{-5}$$

[Collins et. al. arXiv:1810.08479]

Explanations so far:

- Sterile Neutrinos
  [Cherry & Shoemaker arXiv:1802.01611; Huang arXiv:1804.05362]
- Supersymmetry
  [Fox et. al. arXiv:1809.09615; Collins et. al. arXiv:1810.08479]
- Dark Matter
  [Anchordoqui et. al. arXiv:1803.11554; Heurtier et. al. arXiv:1902.04584]
- Susy Sphalerons
  [Anchordoqui and Antoniadis arXiv:1812.01520]
- Leptoquarks
  [BC and Mohanty arXiv:1812.00919]





What are leptoquarks?

- Leptoquarks are bosons (scalar or vector) that simultaneously couple to a lepton and a quark.
- They appear naturally in many extensions of the Standard Model.
- SU(3)$_C$ Triplets;
  SU(2)$_L$ Singlet/Doublet/Triplet;
  Non-Zero Hypercharge.
- There are twelve types of leptoquarks.

$$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$
$$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$$
$$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$$
$$\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$$
$$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$
$$\bar{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, -2/3)$$
$$U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$$
$$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$$
$$\tilde{V}_2 = (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$$
$$\tilde{U}_1 = (\mathbf{3}, \mathbf{1}, 5/3)$$
$$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$$
$$\bar{U}_1 = (\mathbf{3}, \mathbf{1}, -1/3)$$

[Dorsner et. al. arXiv:1603.04993]

Leptoquarks in Flavor Anomalies:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\Bigg|_{l\in\{e,\mu\}}$$

$$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \frac{\mathcal{B}'(B \to K^{(*)}\mu\mu)}{\mathcal{B}'(B \to K^{(*)}ee)}$$

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

[Angelescu et. al. arXiv:1808.08179]

Leptoquarks in Flavor Anomalies:

$$R_{D^{(*)}} = \left.\frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\right|_{l\in\{e,\mu\}}$$

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S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

$$-\mathscr{L} \supset (V\cdot g_L)_{ij}\;\bar{u}_L^i\gamma^\mu U_{1,\mu}\nu_L^j + (g_L)_{ij}\;\bar{d}_L^i\gamma^\mu U_{1,\mu}e_L^j + (g_R)_{ij}\;\bar{d}_R^i\gamma^\mu U_{1,\mu}e_R^j$$

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{s\mu} & g_{s\tau} \\ 0 & g_{b\mu} & g_{b\tau} \end{pmatrix} \qquad g_R = 0$$

Benchmark:

$M_U = 1.5\ TeV$

$g_{s\mu} = -0.012, \quad g_{b\mu} = 0.2,$

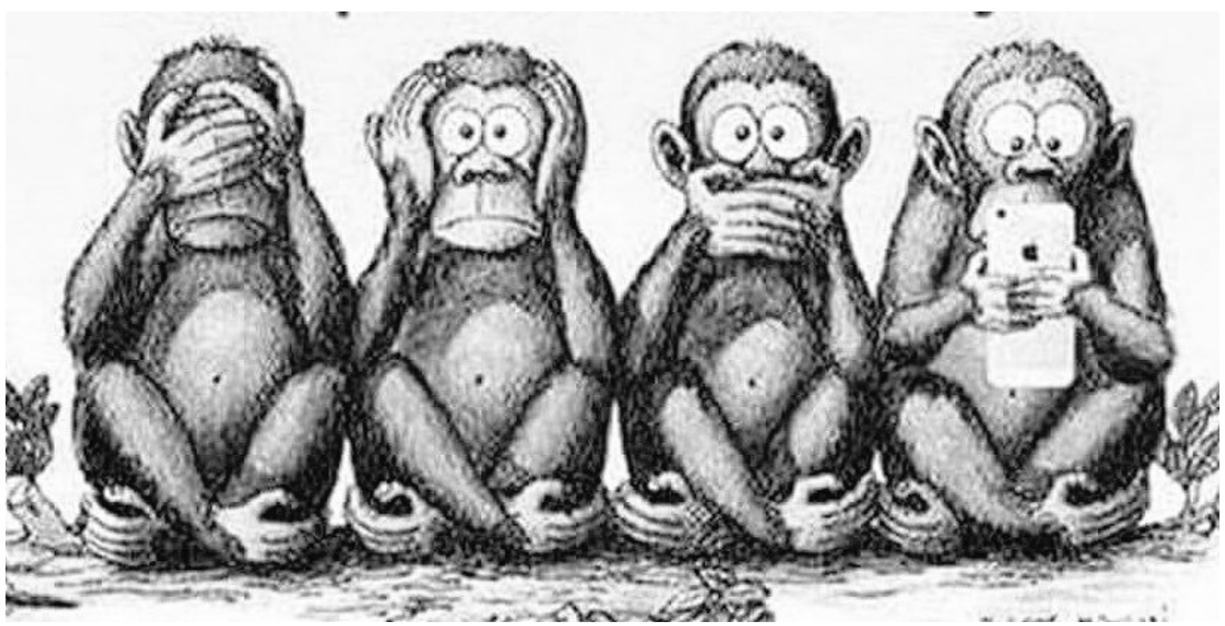
$g_{s\tau} = 0.5, \quad g_{b\tau} = 0.5$

[Angelescu et. al. arXiv:1808.08179]

Caution: Pre Moriond-19

Singlet Extension:

$$-\mathscr{L} \supset (V \cdot g_L)_{ij}\ \bar{u}^i_L \gamma^\mu U_{1,\mu} \nu^j_L + (g_L)_{ij}\ \bar{d}^i_L \gamma^\mu U_{1,\mu} e^j_L + (g_R)_{ij}\ \bar{d}^i_R \gamma^\mu U_{1,\mu} e^j_R$$



ν_e ν_μ ν_τ χ

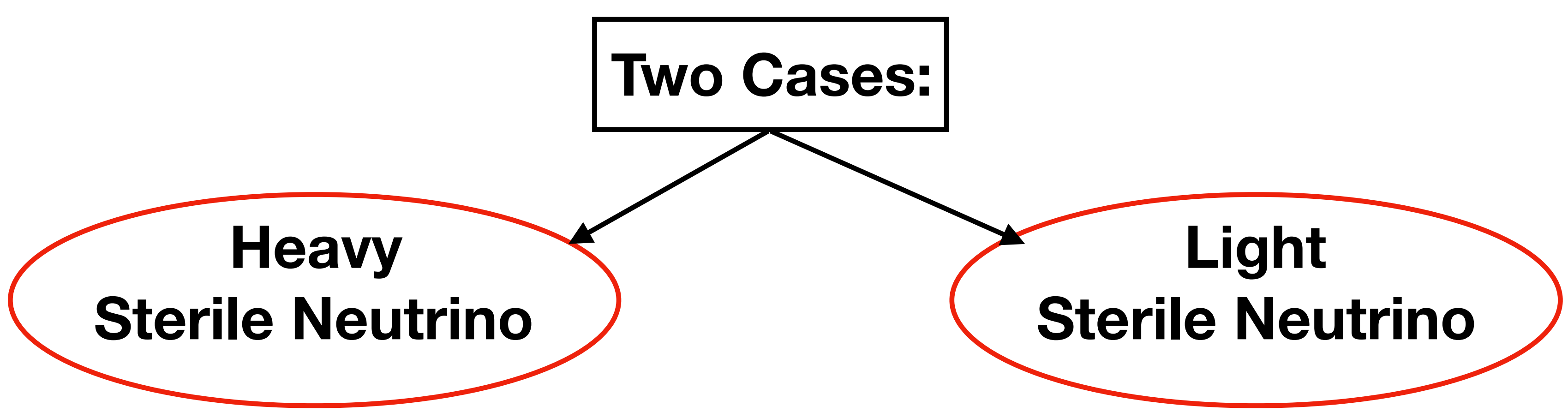
$$+(g_\chi)_i\ \bar{u}^i_R \gamma^\mu U_{1,\mu} \chi_R$$

$$g_\chi = (0\ \ g_x\ \ 0)$$

Singlet Extension:

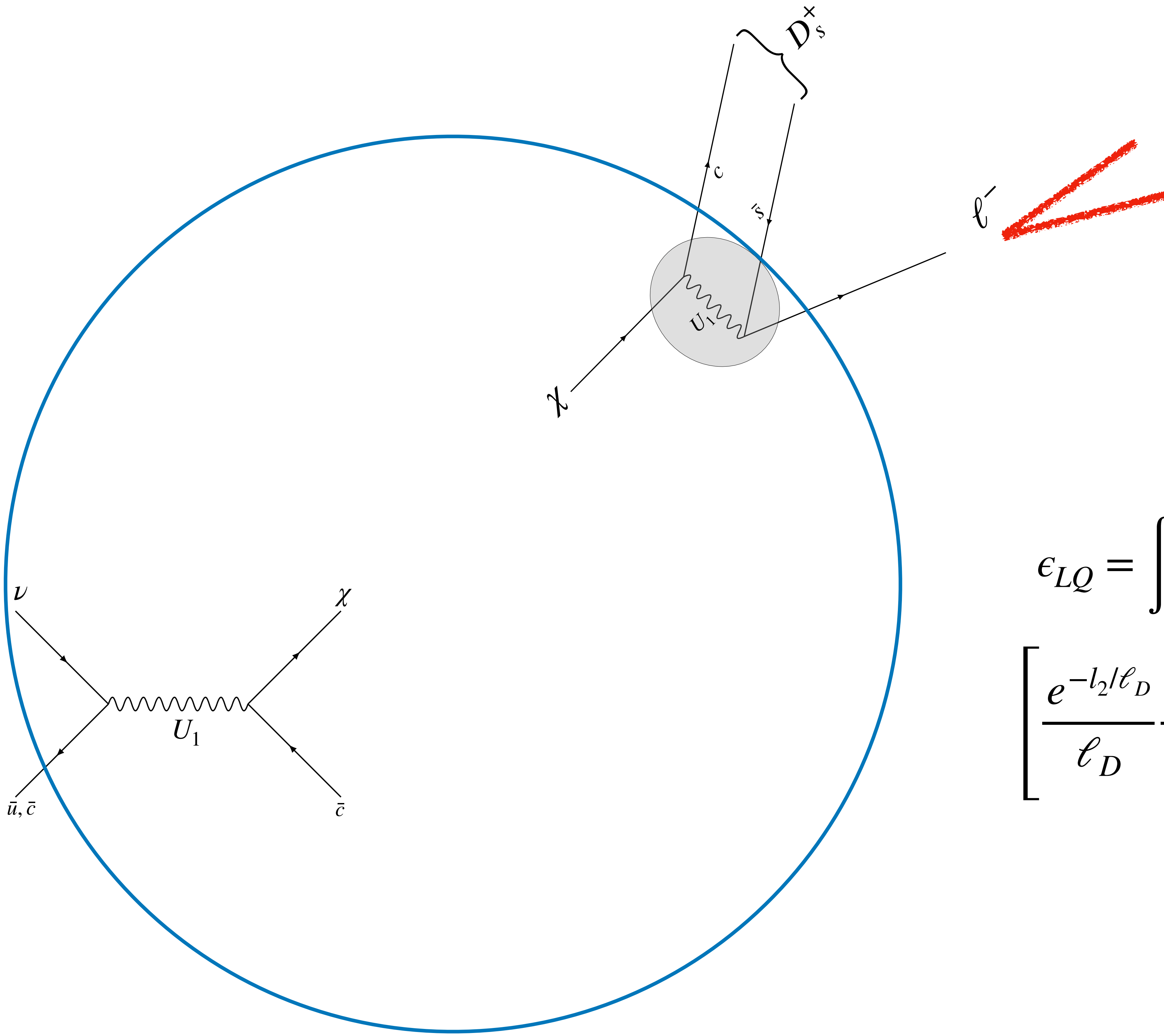
$$-\mathscr{L} \supset (V \cdot g_L)_{ij}\ \bar{u}_L^i \gamma^\mu U_{1,\mu} \nu_L^j + (g_L)_{ij}\ \bar{d}_L^i \gamma^\mu U_{1,\mu} e_L^j + (g_R)_{ij}\ \bar{d}_R^i \gamma^\mu U_{1,\mu} e_R^j$$

$$+(g_\chi)_i\ \bar{u}_R^i \gamma^\mu U_{1,\mu} \chi_R \qquad g_\chi = (0\ g_x\ 0)$$



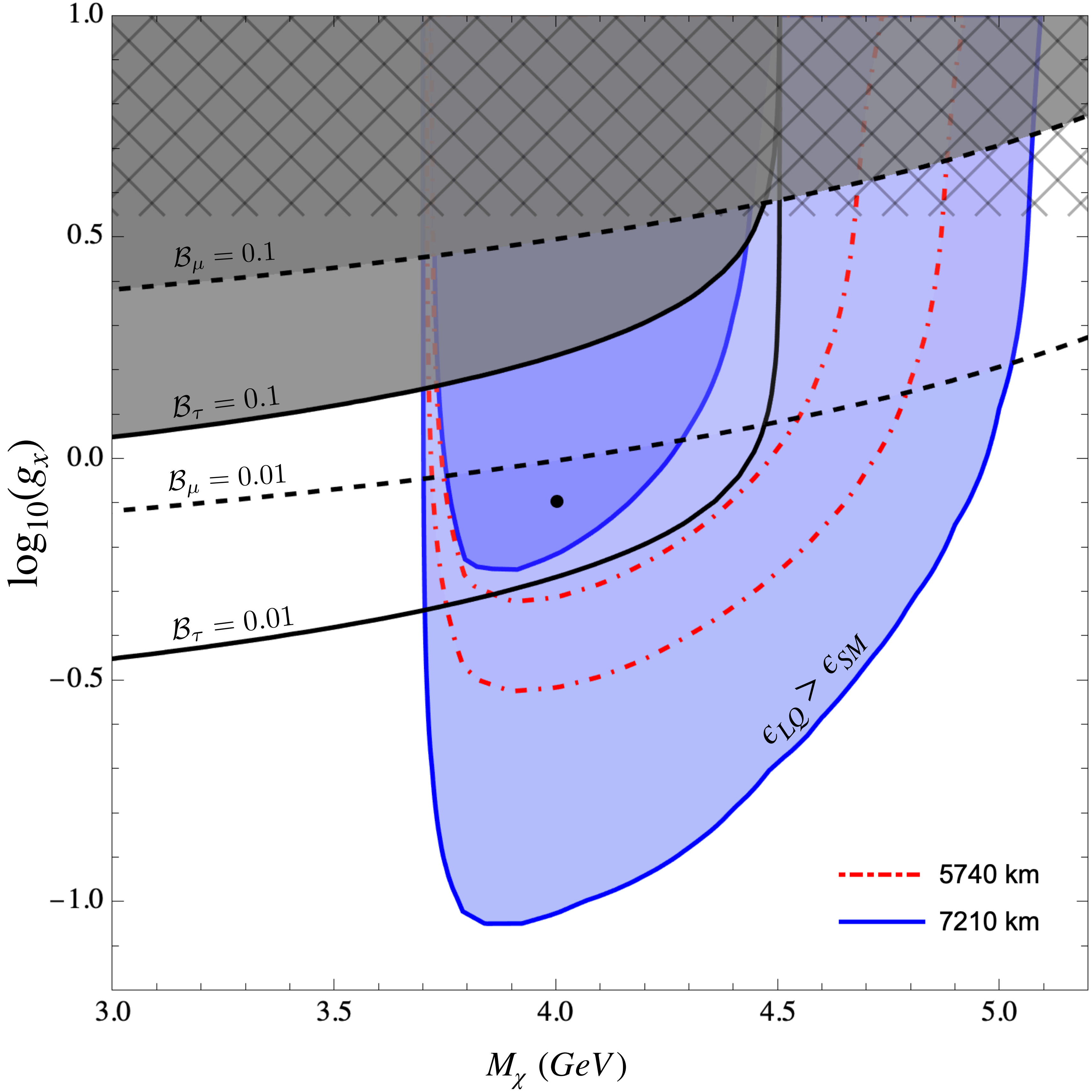
[Azatov et. al. arXiv:1807.10745]

Heavy Sterile Neutrino:



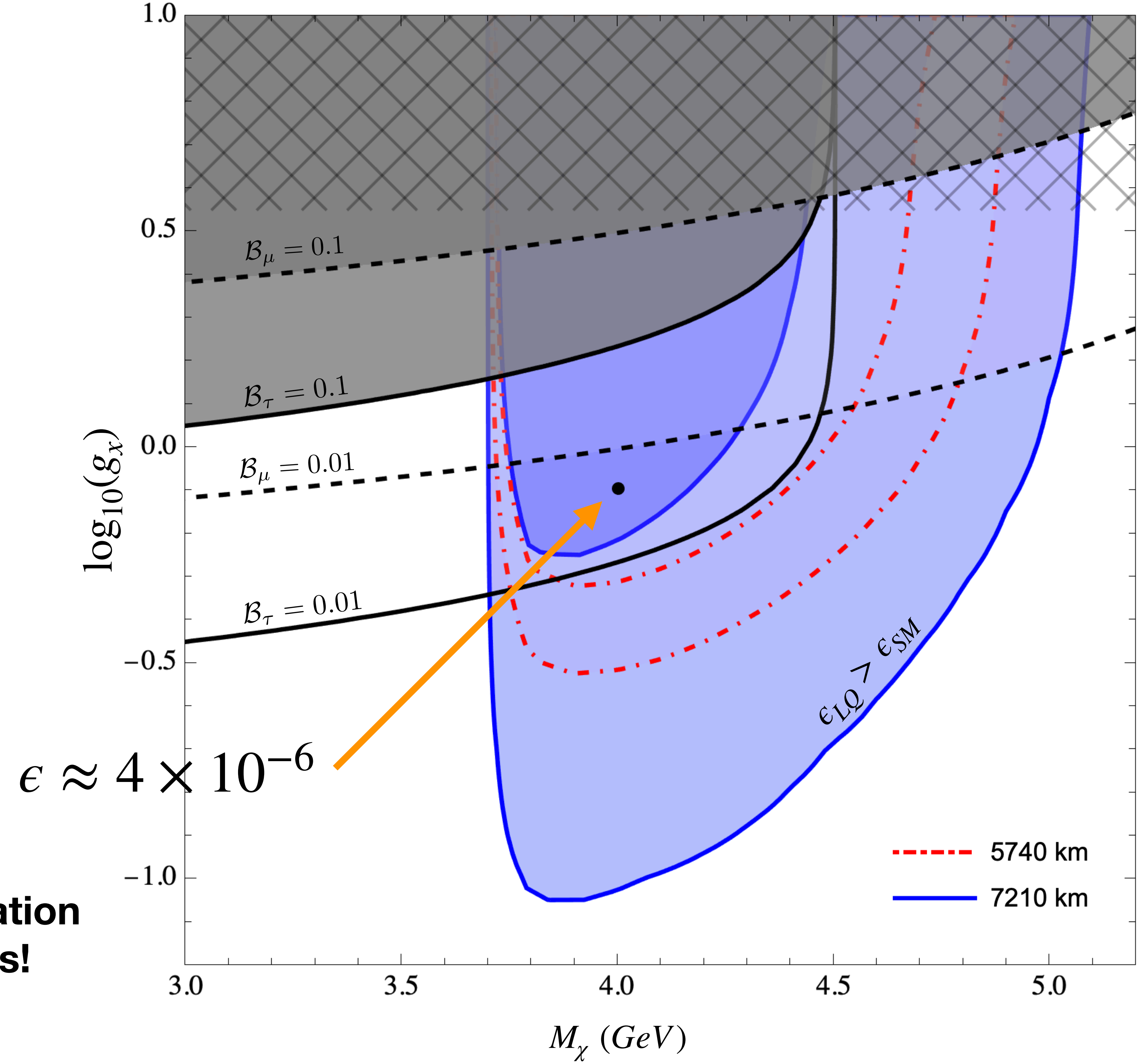
$$\epsilon_{LQ} = \int_0^{l_\oplus} dl_1 \int_{l_\oplus - l_1 - \delta}^{l_\oplus - l_1} dl_2 \times$$
$$\left[\frac{e^{-l_2/\ell_D}}{\ell_D} \frac{e^{-l_1/\ell_{LQ}}}{\ell_{LQ}} \left(1 - \int_0^{l_1} \frac{dl_3}{\ell_0} e^{-l_3/\ell_0} \right) \right]$$

Result:



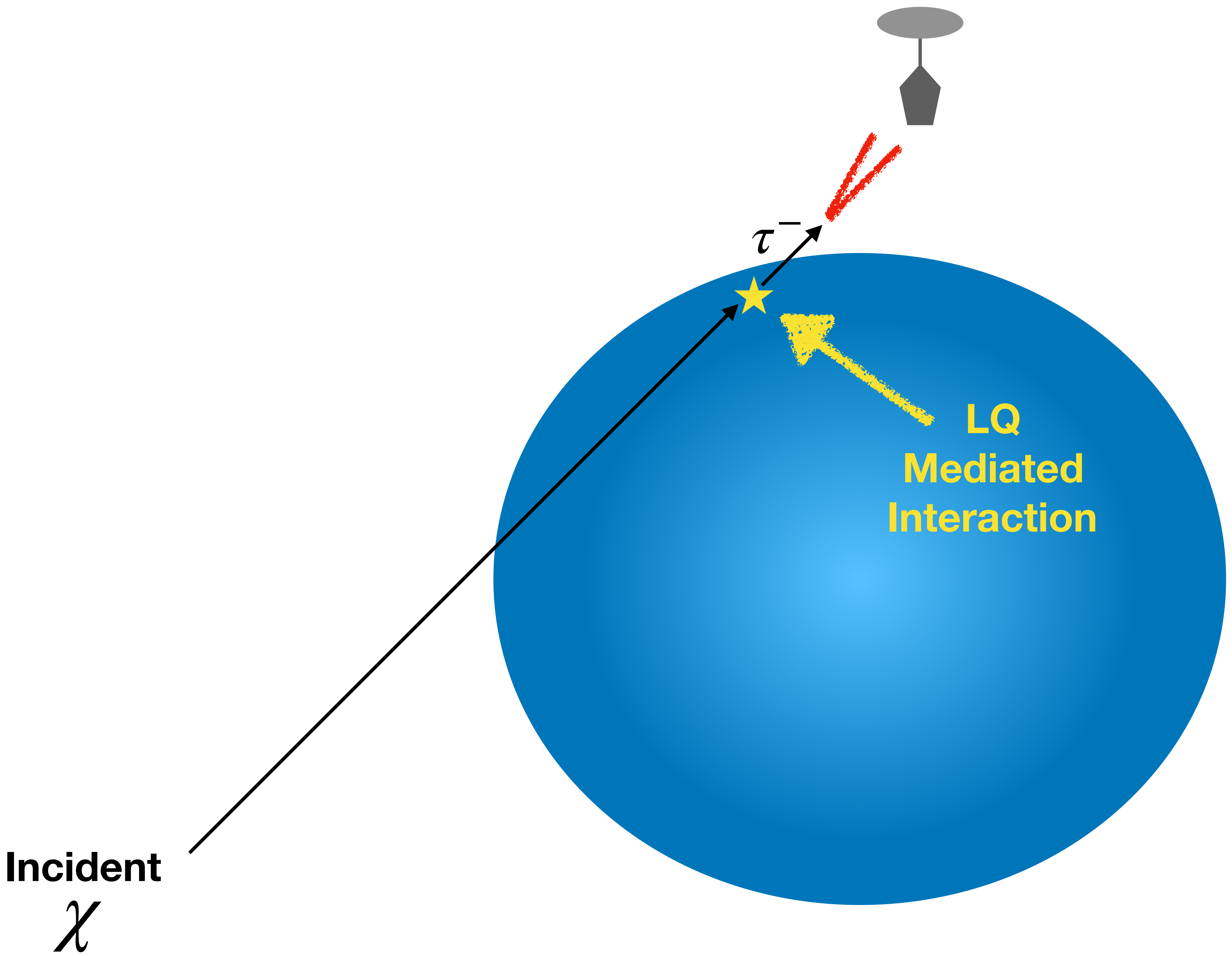
1.0
0.5
0.0
−0.5
−1.0
3.0
3.5
4.0
4.5
5.0
$\log_{10}(g_\chi)$
M_χ (GeV)
$\mathcal{B}_\mu = 0.1$
$\mathcal{B}_\tau = 0.1$
$\mathcal{B}_\mu = 0.01$
$\mathcal{B}_\tau = 0.01$
$\epsilon_{LQ} > \epsilon_{SM}$
5740 km
7210 km

Result:



w/o regeneration effects!

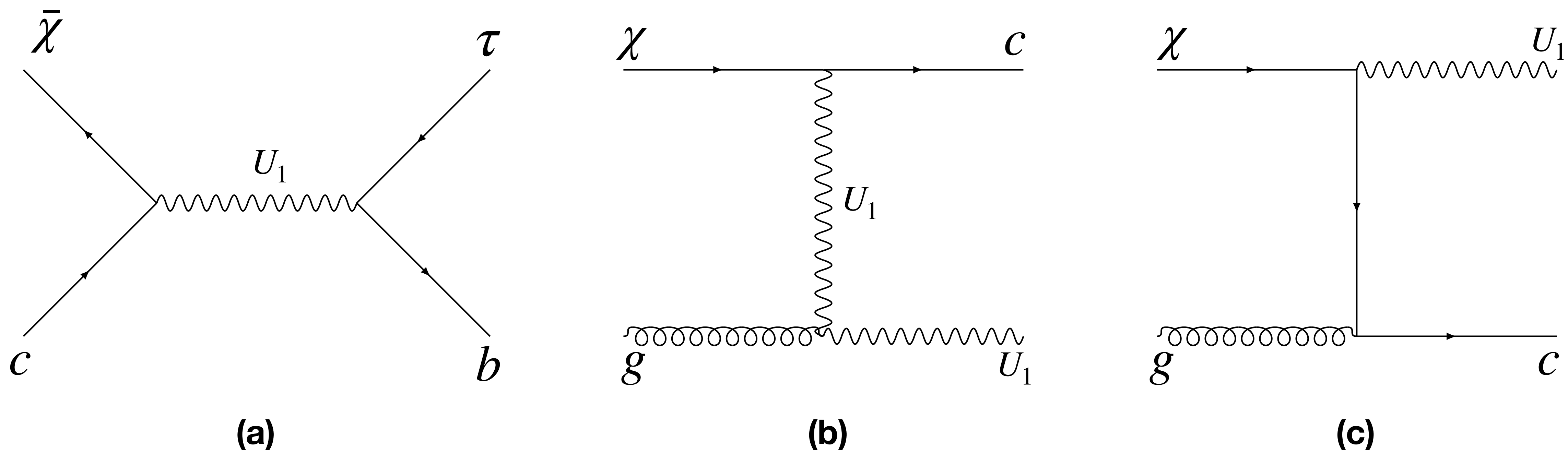
Light Sterile Neutrino:



Light Sterile Neutrino:

$$\mathscr{L}_{LQ} = -\frac{1}{2}U^{\dagger}_{\mu\nu}U^{\mu\nu} - ig_s\kappa U^{\dagger}_{\mu}T^aU_{\nu}G^{a\mu\nu} + M_U^2U^{\dagger}_{\mu}U^{\mu} + g_{b\tau}\bar{b}_R\gamma^{\mu}U_{1,\mu}\tau_R + g_x\bar{c}_R\gamma^{\mu}U_{1,\mu}\chi_R$$

[Azatov et. al. arXiv:1807.10745]

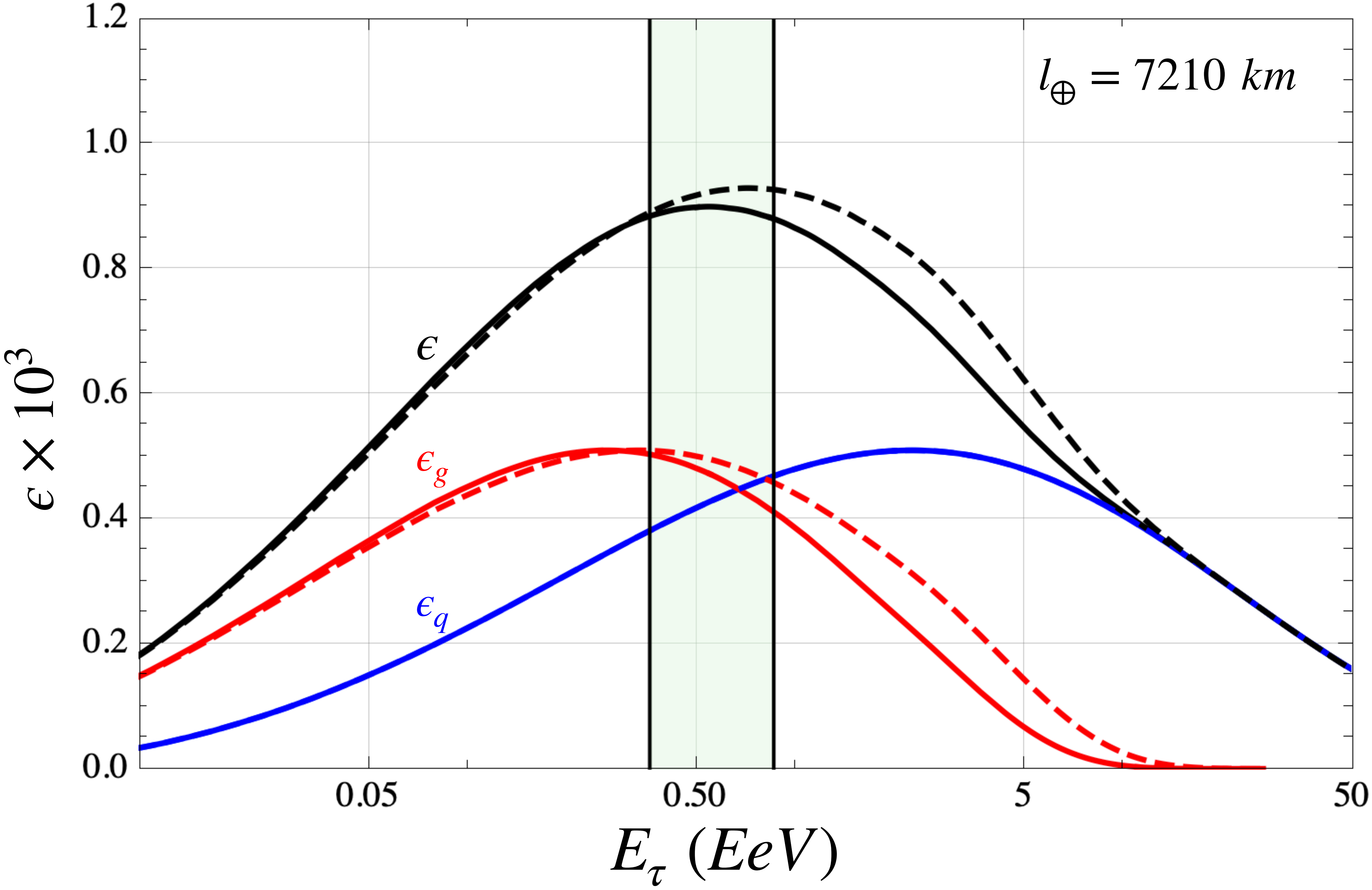


$$\epsilon_{q/g} = \int_{l_\oplus-\delta}^{l_\oplus} dl_1 \frac{e^{-l_1/\ell_{q/g}}}{\ell_{q/g}} \approx \frac{\delta}{\ell_{q/g}}\exp\left(-\frac{l_\oplus}{\ell_{q/g}}\right)$$

For M_U = 1.5 TeV, all parameters are fixed.

$$\epsilon = \epsilon_q + \epsilon_g$$

Discussion:



1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.05
0.50
5
50
$l_\oplus = 7210\ km$
ϵ
ϵ_g
ϵ_q
$\epsilon \times 10^3$
$E_\tau\ (EeV)$

Discussion:

1. Parametrise the flux as

$$\Phi = \phi_0 \times 10^{-20} \left(\frac{E_\chi}{EeV} \right)^{-\gamma} \quad (\textbf{GeV cm}^2 \textbf{ s sr})^{-1}$$

2. Number of Events is given by :

$$\mathcal{N} \approx \left(\frac{1800}{EeV} \right) \times \phi_0 \times \left[\int_{2E_\tau^{min}}^{2E_\tau^{max}} dE_\chi \cdot \epsilon_q(E_\chi) \cdot \left(\frac{E_\chi}{EeV} \right)^{-\gamma} + \int_{4E_\tau^{min}}^{4E_\tau^{max}} dE_\chi \cdot \epsilon_g(E_\chi) \cdot \left(\frac{E_\chi}{EeV} \right)^{-\gamma} \right]$$

3. We need $\phi_0 \sim 0.2 - 1.3$ which is below the limits from other experiments

4. What are the possible sources of this sterile neutrino flux?

Conclusion

- The ANITA neutrino telescope offers unique possibility to test neutrino-nucleon interactions at multi-TeV scale.
- The two EeV scale Earth emergent showers cannot be explained with only SM interactions.
- We have shown two *well motivated* scenario with significant enhancement in survival probability.
- In the second model, the distribution of emergent tau energy peaks in the 0.1-1 EeV range as observed by ANITA.
- New testing ground for your favourite model.


Thank you.

List of Publications

Published

- **Bhavesh Chauhan**, and Subhendra Mohanty, *"Constraints on Leptophilic light dark matter from internal heat flux of Earth"*, In: Phys.Rev.D94 (2016), DOI: 10.1103/PhysRevD.94.035024, arXiv: 1603.06350 [hep-ph]
- **Bhavesh Chauhan**, Bharti Kindra, and Ashish Narang, *"Discrepancies in simultaneous explanation of flavor anomalies and IceCube PeV events using leptoquarks"*, In: Phys.Rev.D97 (2018), DOI: 10.1103/PhysRevD.97.095007, arXiv: 1706.04598 [hep-ph]
- **Bhavesh Chauhan**, *"Sub-MeV Self Interacting Dark Matter"*, In: Phys.Rev.D97 (2018), DOI: 10.1103/PhysRevD.97.123017, arXiv: 1711.02970 [hep-ph]
- **Bhavesh Chauhan**, and Subhendra Mohanty, *"Signature of light sterile neutrinos at IceCube"*, In: Phys.Rev.D98 (2018), DOI: 10.1103/PhysRevD.98.083021, arXiv: 1808.04774 [hep-ph]

Proceedings

- **Bhavesh Chauhan**, and Subhendra Mohanty, *"Constraints on Leptophilic light dark matter from internal heat flux of Earth"*, In: Springer Proc.Phys. 203 (2018), DOI: 10.1007/978-3-319-73171-1-117

Pre-Print

- **Bhavesh Chauhan**, and Bharti Kindra, *"Invoking Chiral Vector Leptoquark to explain LFU violation in B decays"*, In: arXiv: 1709.09989 [hep-ph]
- **Bhavesh Chauhan**, and Subhendra Mohanty, *"A leptoquark resolution to flavor and ANITA anomalies"*, In: arXiv: 1812.00919 [hep-ph]

Back-up slides

The MiniBooNE Experiment

- MiniBooNE (Mini Booster Neutrino Experiment) is an experiment at Fermilab designed to test neutrino oscillations.

- 8 GeV protons are incident on Beryllium target inside a magnetic focussing horn.

	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Neutrino Mode	93.5	5.9	0.5	0.1
Anti-Neutrino mode	15.7	83.7	0.2	0.4

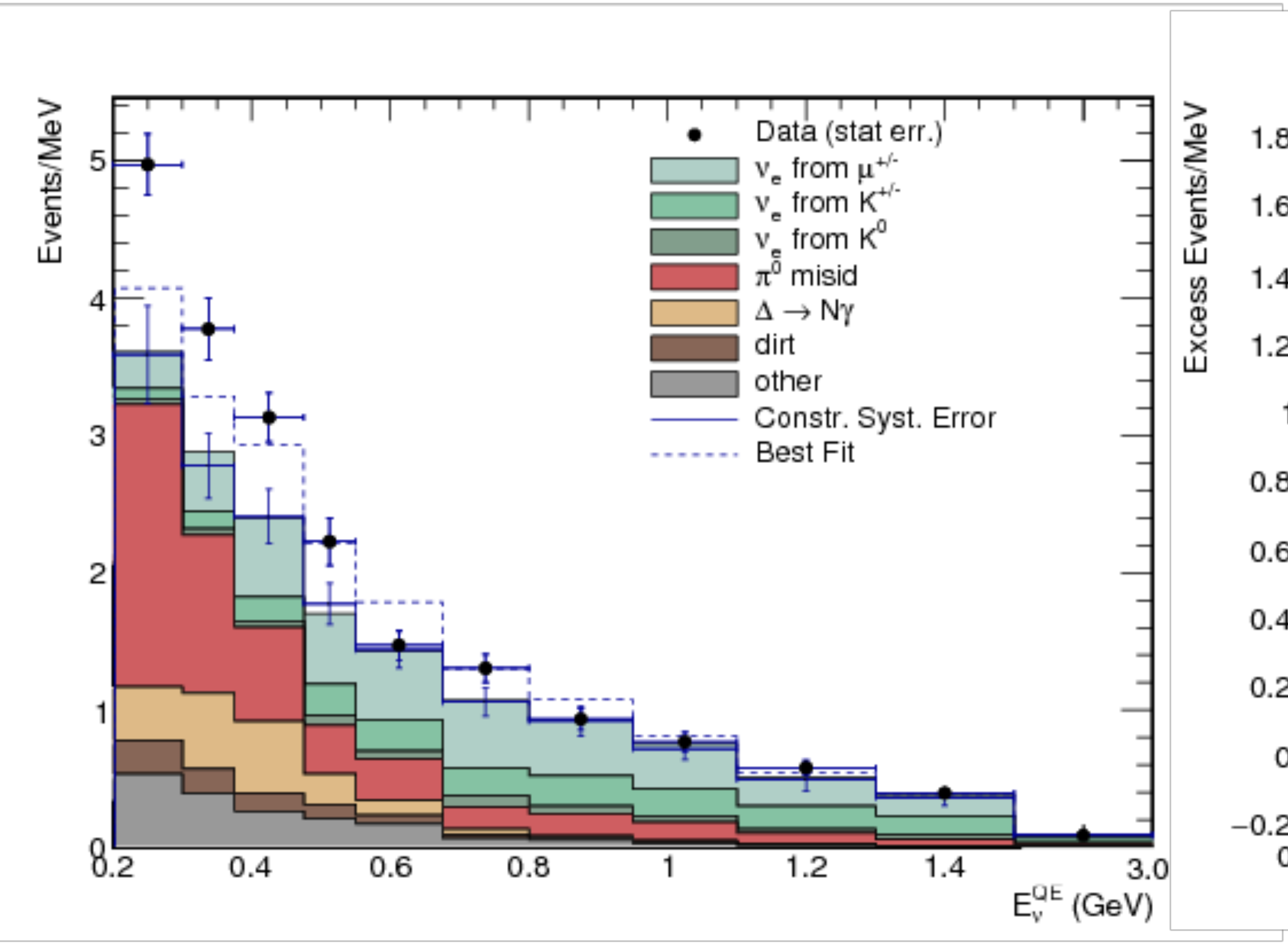
- The detector: 40 ft. (diameter) sphere filled with 818 tons of pure mineral oil (CH2).

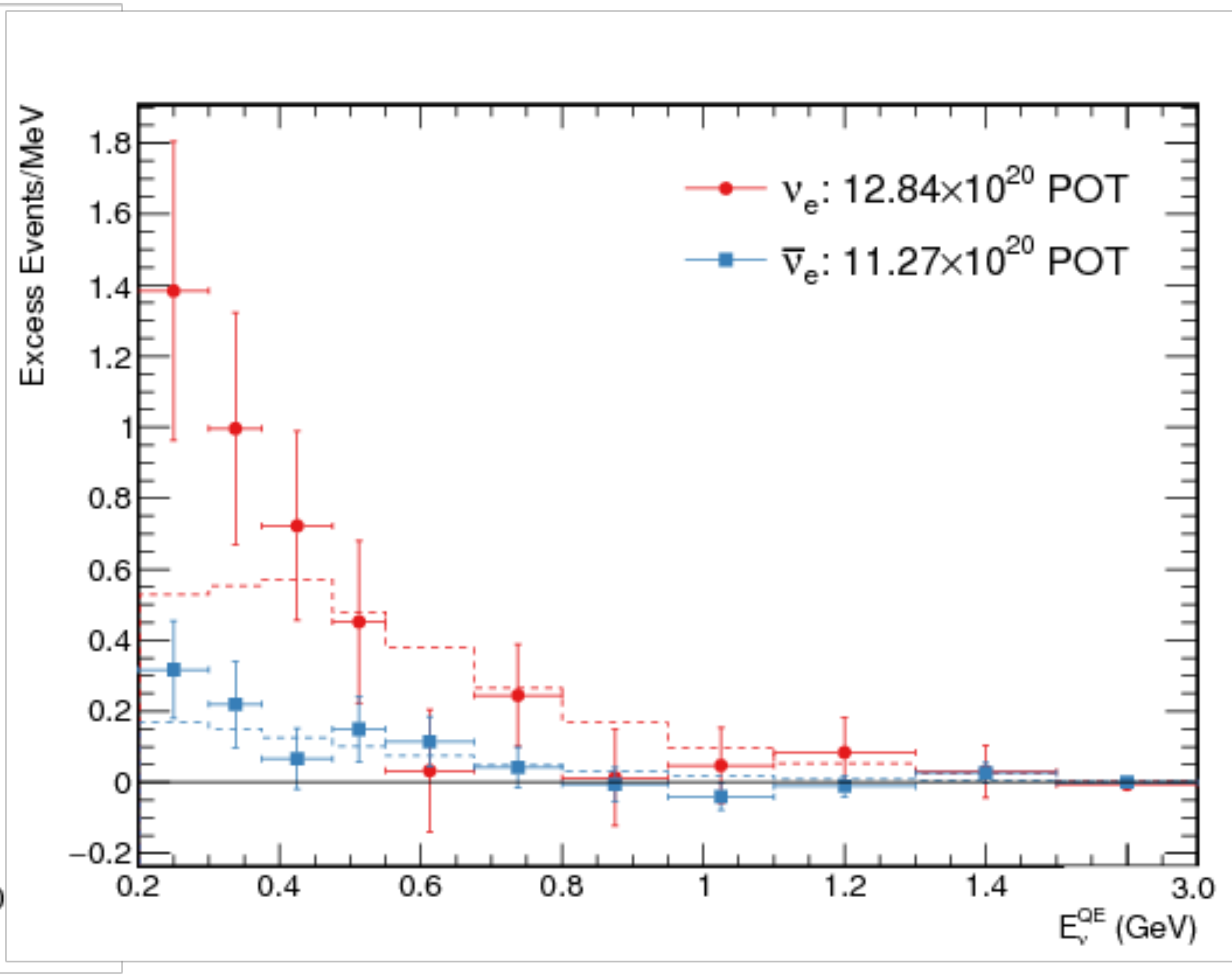
- Located 541 m from the Be target

- The neutrinos undergo Charged Current Quasi Elastic (CCQE) scattering and outgoing particles emit Cherenkov radiation that is detected by 1500+ PMTs.

- The analysis is optimized to measure electron neutrino and anti-neutrino CCQE.

The MiniBooNE Anomaly

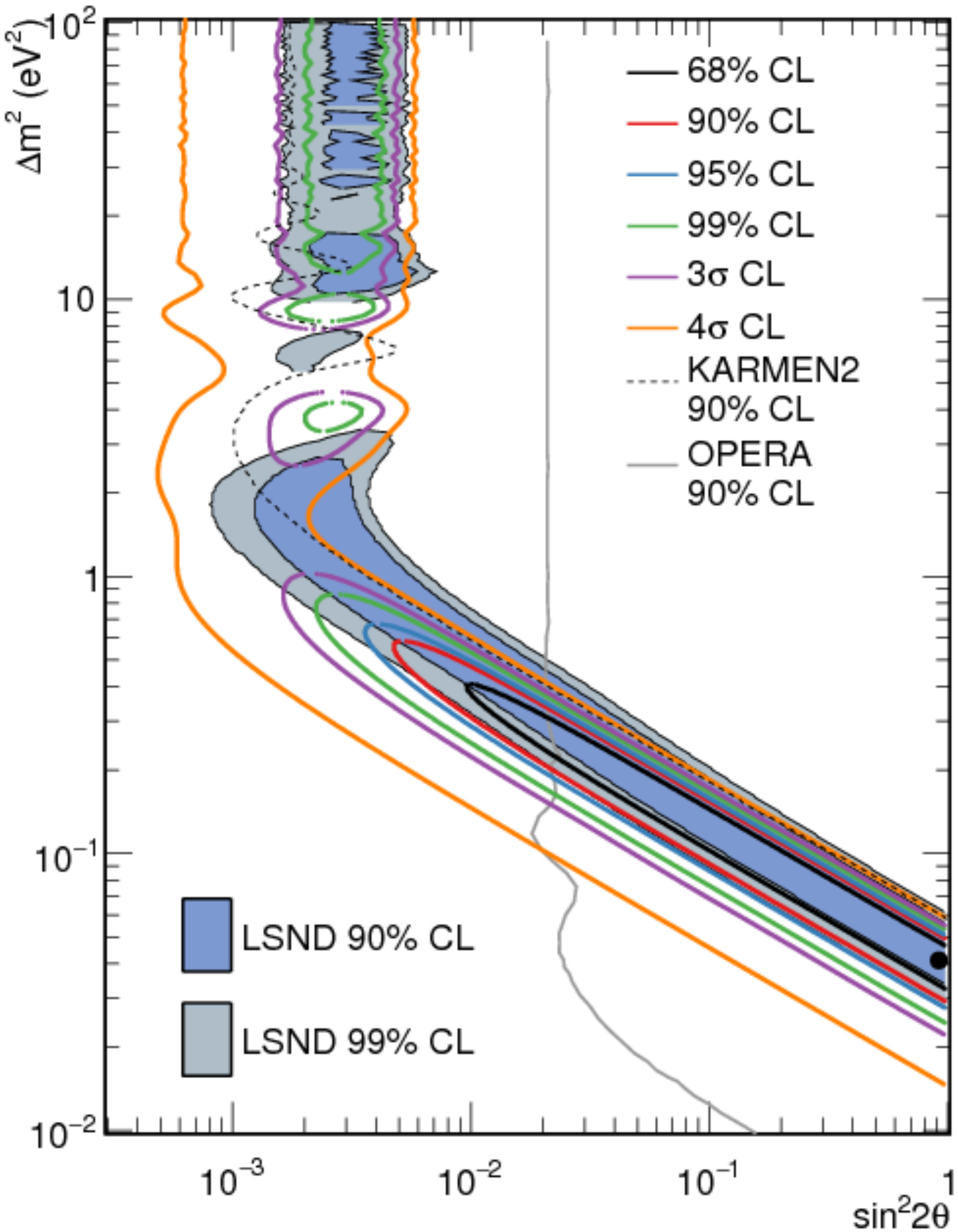




$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{\mu e})\sin^2(1.27\Delta m^2 L/E)$$

(two flavour approximation)

The MiniBooNE Resolution



Best-Fit Point:

$$\Delta m^2 = 0.041\ eV^2$$

$$\sin^2(\theta_{\mu e}) = 0.958$$

Very Different Mass Scale as compared to

$$\Delta m^2 = 7.4 \times 10^{-5}\ eV^2 \quad (solar)$$

$$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2 \quad (atm)$$

"Light Sterile Neutrino at eV scale"

Neutrino Absorption by CvB

- The Boltzmann Equation (Hooper et. al. 1507.03015)

$$-(1+z)H(z)\frac{d\phi_i}{dz} = J_i(E_0, z) - \phi \sum_j \langle n_j(z)\sigma_{ij}(E_0, z)\rangle + P_i\mathscr{R}$$

$$\ldots \quad \mathscr{R} = \int_{E_0}^{\infty} dE' \sum_{j,k} \phi_k \left\langle n_j \frac{d\sigma_{kj}}{dE_0} \right\rangle$$

- If neutrino reappearance is ignored, you get a simple analytical solution:

$$\phi_i = \phi_i^s \exp\left(-\int_0^{z_s} dz \frac{1}{(1+z)H(z)} \langle n(z)\sigma(E_0, z)\rangle \right)$$

Neutrino Absorption by CvB

- For Non Relativistic Neutrinos ($m \gg T_0 = 1.7 \times 10^{-4} eV$)

$$\langle n(z)\sigma(E_0, z)\rangle = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{e^{|\mathbf{p}|/T_0(1+z)} + 1} \sigma(E_0, z, p) \longrightarrow n(z)\sigma(E_0, z)$$

- The dominant contribution to the cross section comes from the s-channel resonance.

$$s = 2m_T E_0 (1+z) = M_{Z'}^2$$

- Due to the integral over z, there will be a dip in the spectrum for

$$\frac{E_{res}}{1+z_s} < E_0 < E_{res}$$

- For the typical scenario (0.2 eV sterile neutrino and 15 MeV Z')

$$E_{res} = \frac{M_{Z'}^2}{2m_T} = \frac{(15\ MeV)^2}{2(0.1\ eV)} \sim 1\ PeV$$

IceCube!

Back Up Equations

$$-\mathscr{L}_s = \sum_{i,j} g_X U^*_{si} U_{sj} \bar{\nu}_i \gamma^\mu P_L \nu_j X_\mu$$

$$V_{eff} = \begin{cases} -\frac{28\pi^3 \alpha_X E T_s^4}{45 M_X^4} & E, T_s \ll M \\ +\frac{\pi \alpha_X T_s^2}{2E} & E, T_s \gg M \end{cases}$$

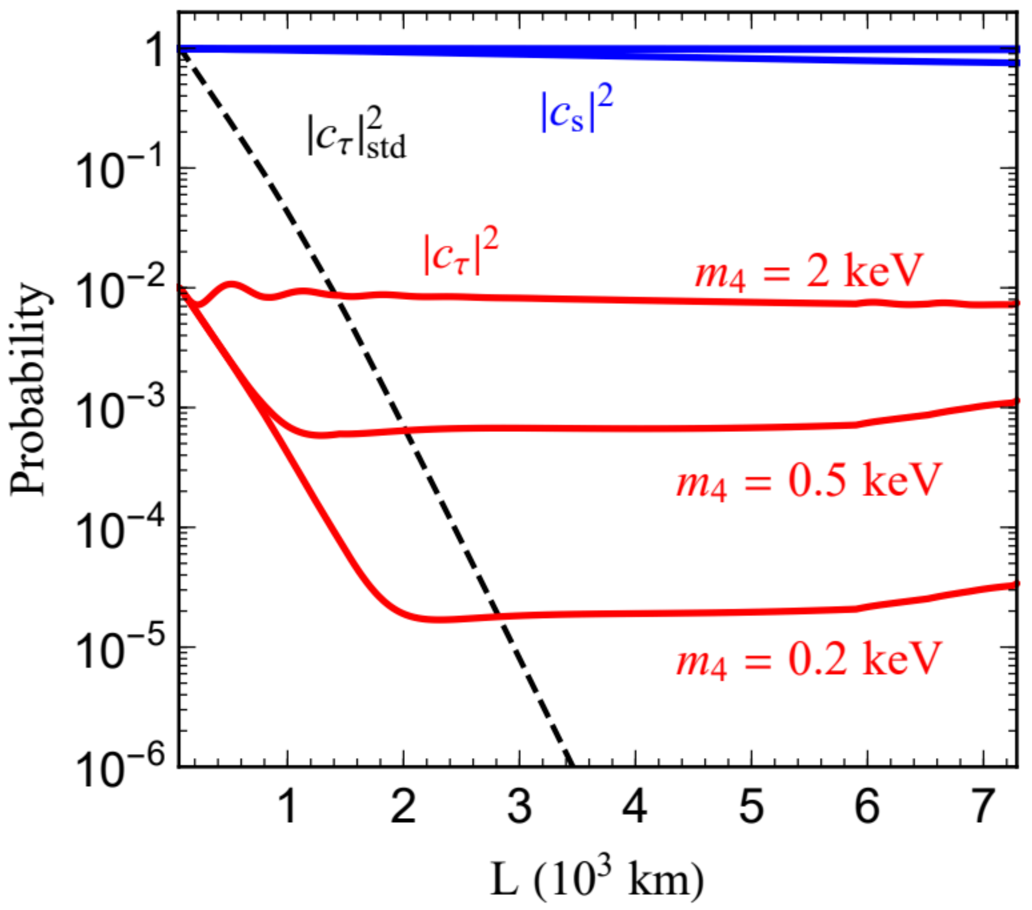
$$\sigma_{ij} = \sigma\left(\bar{\nu}_i \nu_j \to \bar{\nu}\nu\right) = \frac{1}{6\pi} |\, g_{ij}|^2 g_X^2 \frac{s}{(s - m_X^2)^2 + m_X^2 \Gamma_X^2}$$

$$\phi_\alpha = \sum_{j=1}^{4} |\, U_{\alpha j}|^2 \phi_j R_j = (\phi_0 E_\nu^{-\gamma}) \sum_{j=1}^{4} |\, U_{\alpha j}|^2 R_j \equiv (\phi_0 E_\nu^{-\gamma}) R_\alpha \,.$$

$$\phi = \phi_e + \phi_\mu + \phi_\tau = (\phi_0 E_\nu^{-\gamma}) \left(\sum_{f=e,\mu,\tau} \sum_{j=1}^{4} |\, U_{fj}|^2 R_j \right) \equiv \phi_0 E_\nu^{-\gamma} \langle R(\mathscr{P}, E_\nu) \rangle$$

Explanations so far:

- Sterile Neutrinos
  [Cherry & Shoemaker arXiv:1802.01611; Huang arXiv:1804.05362]
- Supersymmetry
  [Fox et. al. arXiv:1809.09615; Collins et. al. arXiv:1810.08479]
- Dark Matter
  [Anchordoqui et. al. arXiv:1803.11554; Heurtier et. al. arXiv:1902.04584]
- Susy Sphalerons
  [Anchordoqui and Antoniadis arXiv:1812.01520]
- Leptoquarks
  [BC and Mohanty arXiv:1812.00919]



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