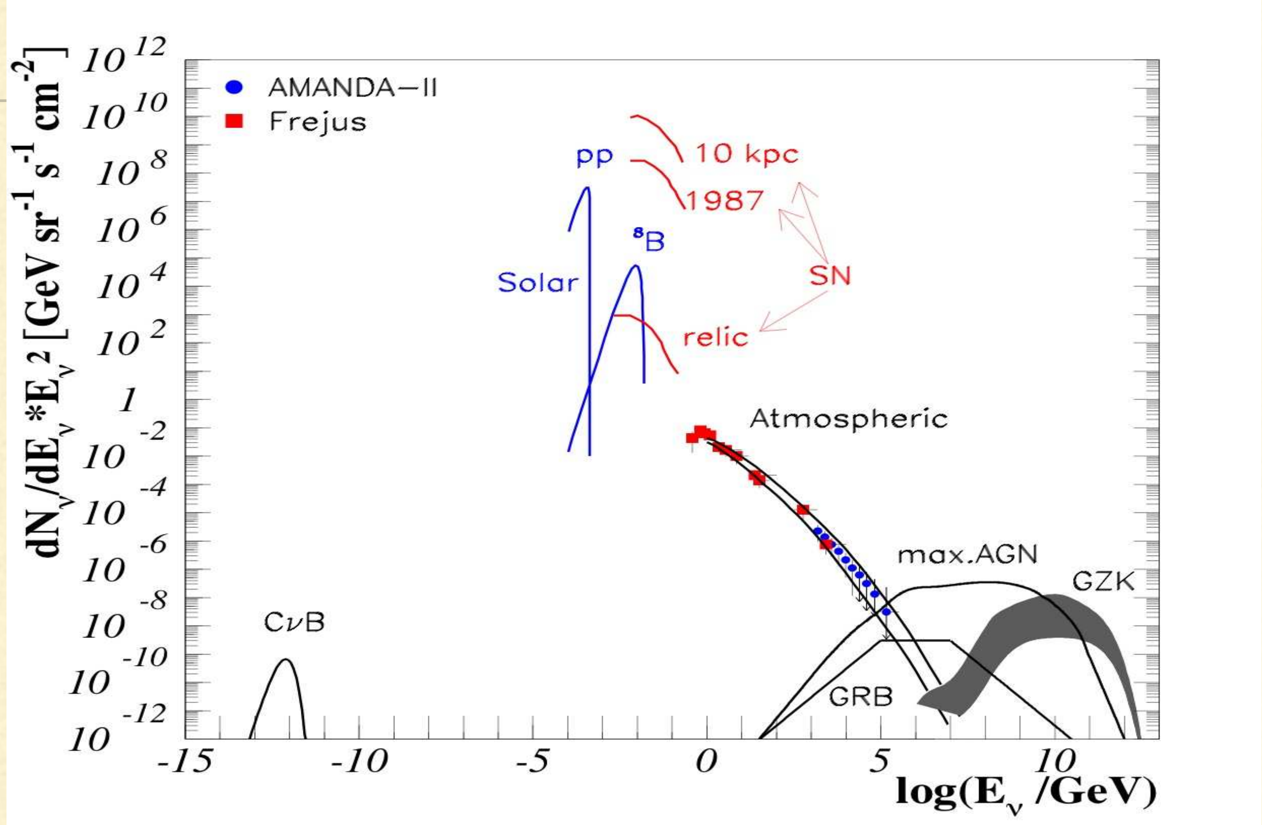
Recent Directions in Neutrino Theory and Phenomenology

Raj Gandhi

Harish Chandra Research Institute
Allahabad

Neutrino Physics is an extensive field, with experiments spanning a very wide range in energy and sources. similarly, theoretical and phenomenological areas of study span a wide range



Impossible to review comprehensively all active theoretical areas

Focus (for most part) on topics where there is recent theoretical interest and new ideas motivated by recent results of experiments.

Given the number of young people in the audience , also guided by the question: What are good questions to work on now?

Choose 4 topics of current theoretical/phenomenological activity, 2 in low energy neutrino physics and two in high energy neutrino physics .

Choose signals/ issues which cannot be easily explained away or dismissed.

- ► The MiniBooNE excess and related theoretical developments

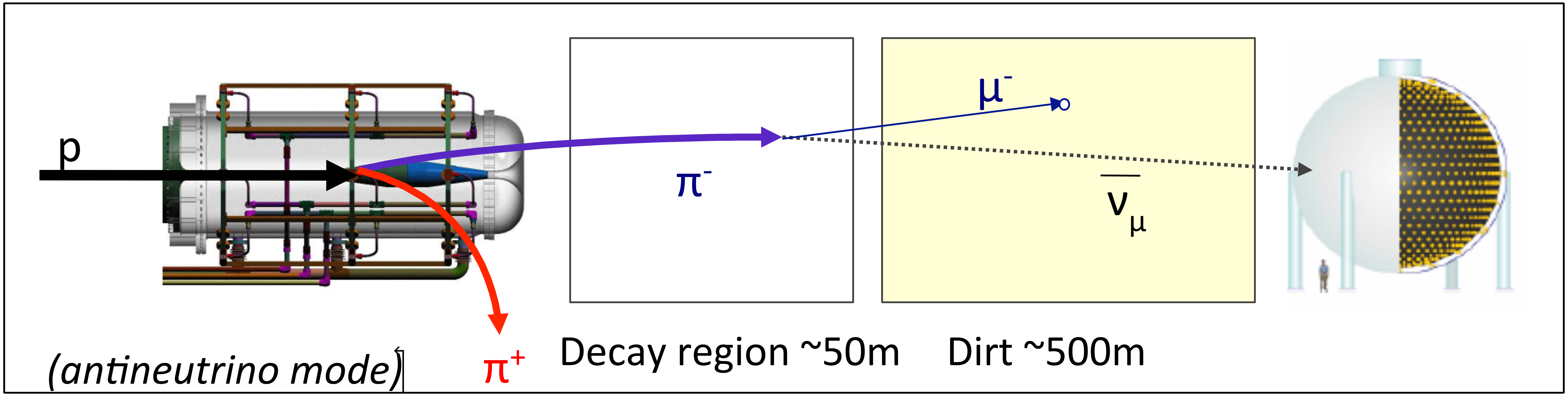
- ► The Dirac vs Majorana nature of neutrinos

- ► The IceCube events and Dark matter

- ► The ANITA observations of the highest energy events

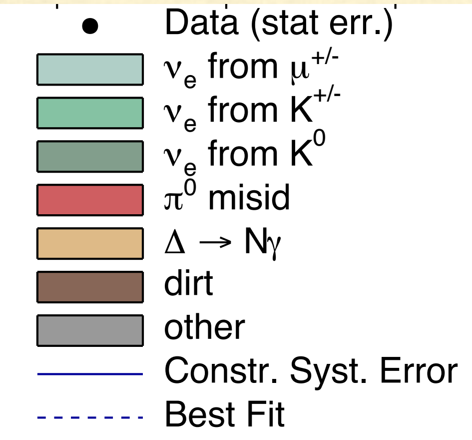
- The MiniBooNE excess and related theoretical developments

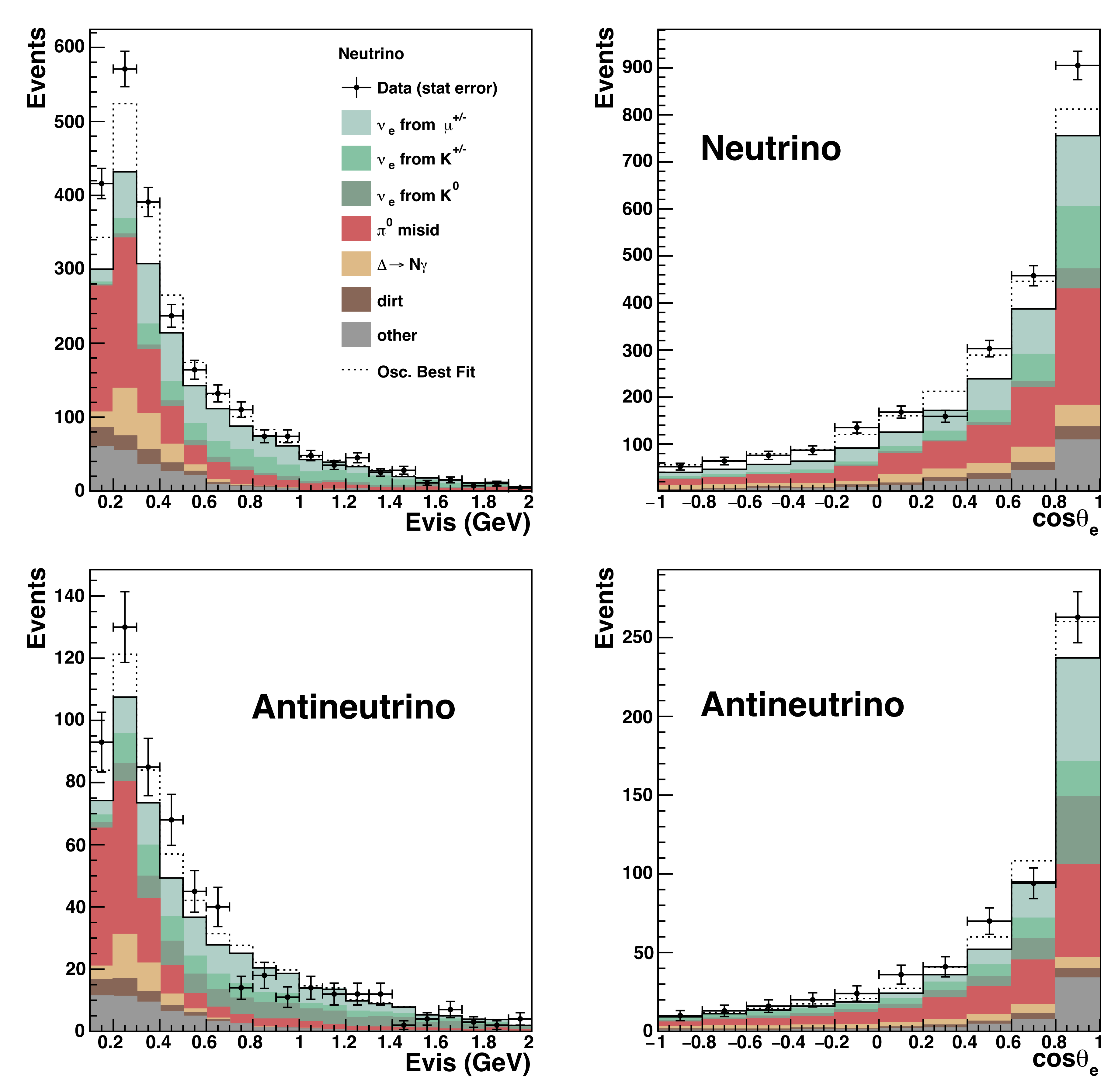
MiniBooNE Experiment



- Similar L/E as LSND for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ & $\nu_\mu \rightarrow \nu_e$ oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

The MiniBooNE excess……….





Excesses in neutrino and antineutrino mode qualitatively consistent

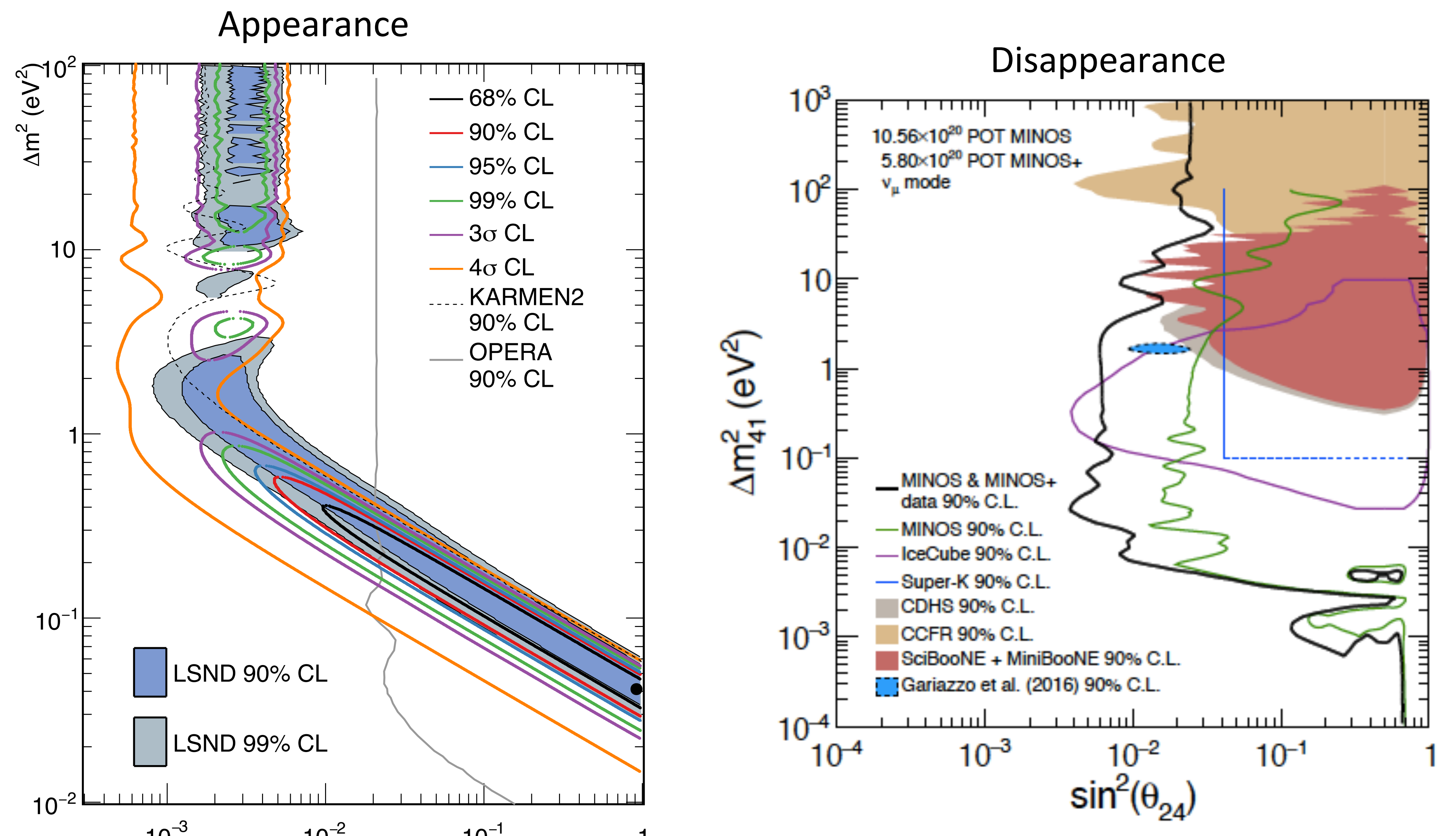
MiniBooNE confirms LSND excess at 4.7σ, and their combined significance is 6.0σ

MiniBooNE unable to tell if excess is electrons or photons.

MicroBooNE will help resolve this question.

SBN program will resolve whether excess due to sterile neutrino oscillations.

The MiniBooNE excess…………



arXiv:1710.06488v2

Possible explanation: 3+1 sterile neutrino

Problem: Best fit ruled out by other experiments.

Problem: Solution implies ν_μ disappearance in addition to ν_e appearance, but this is ruled out by IceCube and MINOS/MINOS+

MiniBooNE backgrounds have been well-checked and measured for the most part.

All of this may be pointing to a non-oscillation new physics explanation

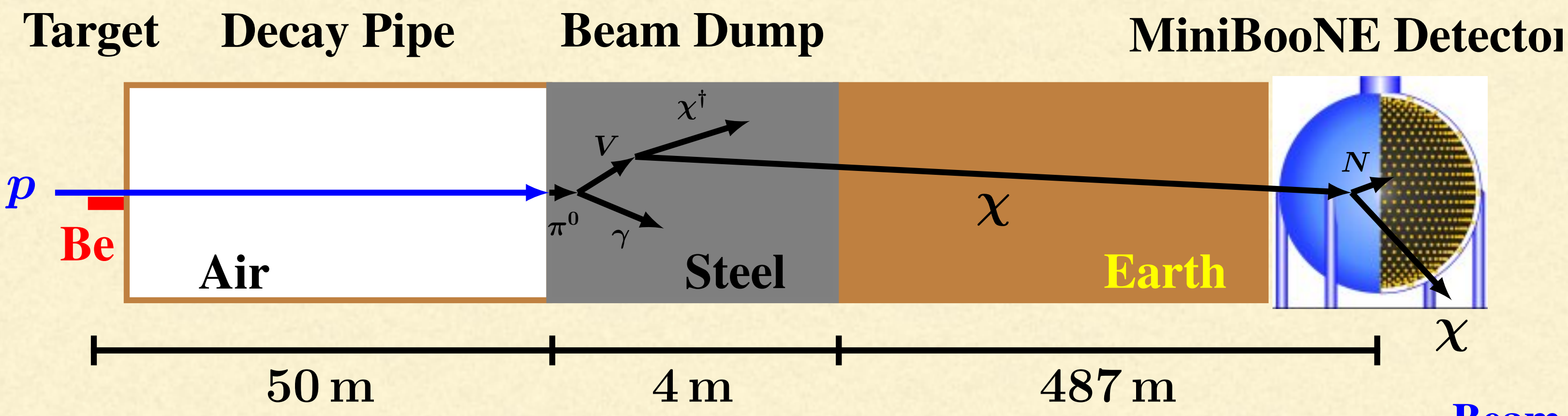
Problems not mitigated by going to 3+n sterile neutrinos

The MiniBooNE excess…………

Before considering an example of new physics, it is important to note that this is a very constrained situation, and any new physics explanation must satisfy many conditions.

As part of a dark matter search, MiniBooNE did an off target run, where beam hits the dump.

MB collab, arXiv: 1807.06137

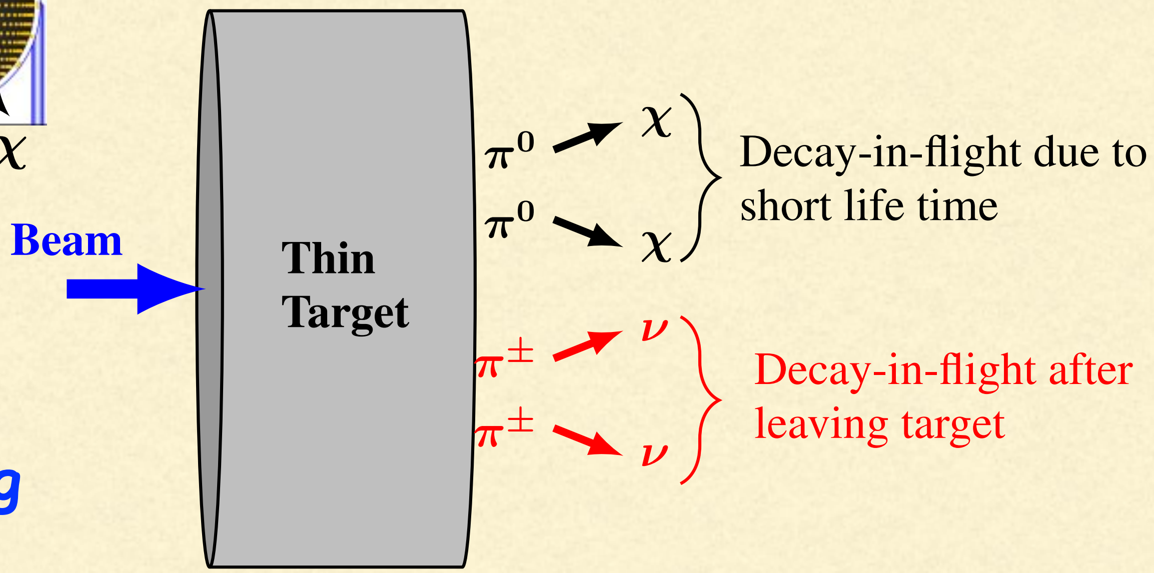


Importantly, the excess disappeared when this was done.

Thus, excess cannot be due to new particle (e.g , DM, χ) produced in dump/target and scattering off electrons, via a portal .

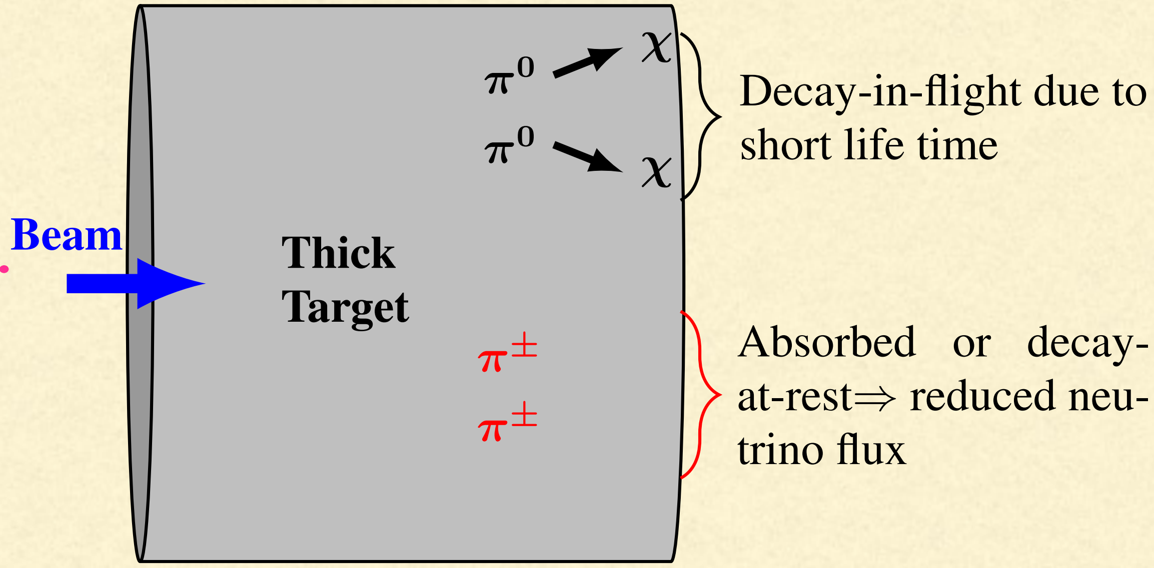
Excess cannot be due to photons, for instance, which are produced via decay of new particle, since background of entering photons measured. Also, π^0 to 2γ background well measured.

Thus, production of neutrinos, present in target case and absent/reduced in off target, must be playing a role in the "true" explanation



Decay-in-flight due to short life time

Decay-in-flight after leaving target



Decay-in-flight due to short life time

Absorbed or decay-at-rest⇒ reduced neutrino flux

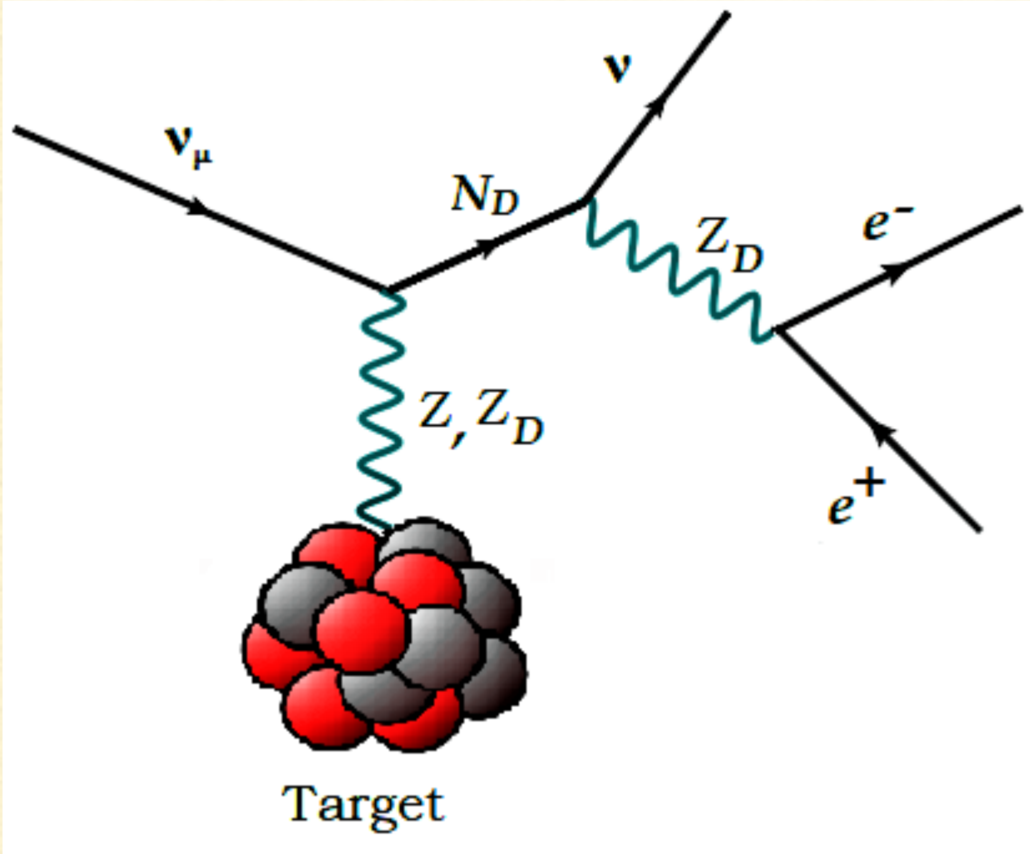
The MiniBooNE excess…………

In addition, any new physics explanation must reproduce both the energy and angular distribution seen in the data.

Example of possible new physics explanation :

Bertuzzo et al arXiv: 1807.09877;

Ballett et al arXiv: 1808.02915;



Introduce a dark sector composed by a new vector boson, ZD, coupling directly solely to a dark neutrino, ν_D

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i + U_{\alpha 4}\, N_\mathcal{D}\,, \quad \alpha = e, \mu, \tau, \mathcal{D},$$

kinetic mixing mass mixing

$$\mathcal{L}_\mathcal{D} \supset \frac{m_{Z_\mathcal{D}}^2}{2} Z_{\mathcal{D}\mu} Z_\mathcal{D}^\mu + g_\mathcal{D} Z_\mathcal{D}^\mu \, \overline{\nu}_\mathcal{D} \gamma_\mu \nu_\mathcal{D} + e\epsilon\, Z_\mathcal{D}^\mu \, J_\mu^{\mathrm{em}} + \frac{g}{c_W} \epsilon' \, Z_\mathcal{D}^\mu \, J_\mu^{Z}\,,$$

$$m_{N_\mathcal{D}} > m_{Z_\mathcal{D}} \qquad m_{Z_\mathcal{D}} < 2\, m_\mu$$

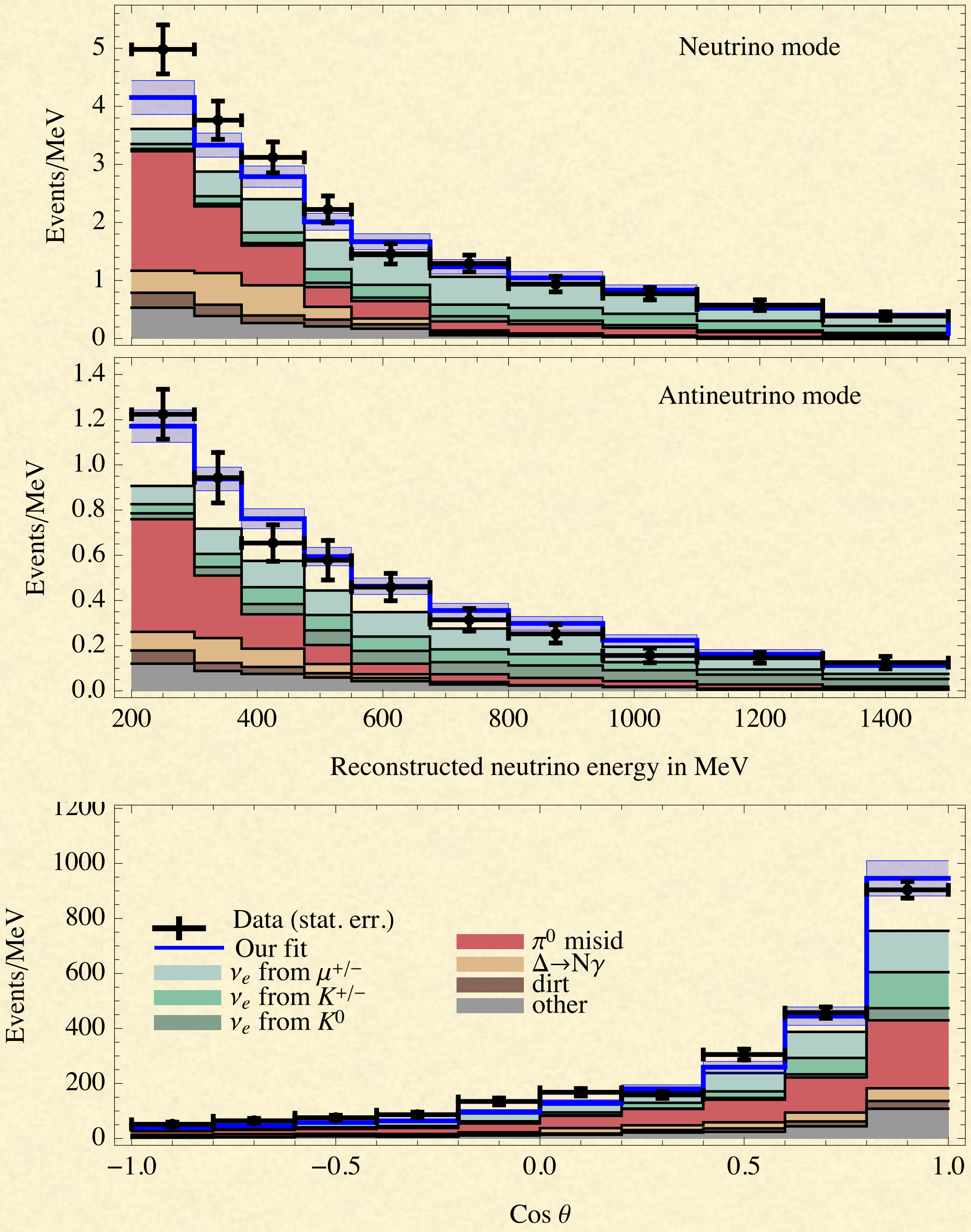
Kinetic mixing: from $B^{\mu\nu}X_{\mu\nu}$ term, which is gauge invariant

Kinematics is such that many of the e^+e^- pairs will be collimated, and Mini- BooNE would interpret ZD → e^+e^- decays as electron- like events

The MiniBooNE excess...........

Bertuzzo et al arXiv: 1807.09877;

Good agreement with observed energy and angular distribution :



Questions open for exploration:

Is this the right solution? How does it fit into the larger framework of BSM physics?

What are the ways in which it can be tested?

Would signals of this have been already seen in existing detectors? What will planned/ upcoming neutrino detectors see if this is true?

- The Dirac vs Majorana nature of neutrinos

The Dirac vs Majorana nature of neutrinos………..

This remains one of the most important unanswered questions in neutrino physics.

Majorana neutrinos offer, in principle, a window to physics at very high scales, and thus an opportunity to better understand what lies beyond the Standard Model (SM).

For Dirac neutrinos, if we add RH neutrinos to the SM, the Yukawa term

$$L_Y = -yH^0 \bar{\nu}_R \nu_L + h.c$$

$$\nu = \nu_L + \nu_R$$

leads, after electroweak symmetry breaking, to the mass term

$$L_D = -m_D \bar{\nu}_R \nu_L + h.c. , = -m_D \bar{\nu} \nu ,$$

only minimal extension of SM necessary

For Majorana neutrinos, however, 2 types of terms are possible, both connected in different ways to possible BSM/high scale physics

The Dirac vs Majorana nature of neutrinos…………

Dirac and Majorana mass terms

$$L_R = -m_R/2\ (\overline{\nu_R})^c\ \nu_R + \text{h.c.}\ ,$$

$$\nu = \nu_R + (\nu_R)^c.$$

breaks total lepton number

Since no other conserved quantum number carried by ν_R, m_R can be very large in principle.

Even if there are no RH neutrinos, physics at high scales (Λ) can induce a LH majorana mass term via the effective operator, via an interaction with the SM Higgs field,

$$(\overline{\nu_L})^c\ H^0 H^0\ \nu_L/\Lambda$$

Or, if there is a weak isospin (BSM) Higgs triplet, Δ, it can induce a similar term via

$\Delta^0(\overline{\nu_L})^c\ \nu_L$, where Δ^0 is the neutral member of the triplet which acquires a vev

In either case, the mass term has the form

$$L_L = -1/2 m_L\ (\overline{\nu_L})^c\ \nu_L + \text{h.c.}\ ,$$

LH Majorana mass term

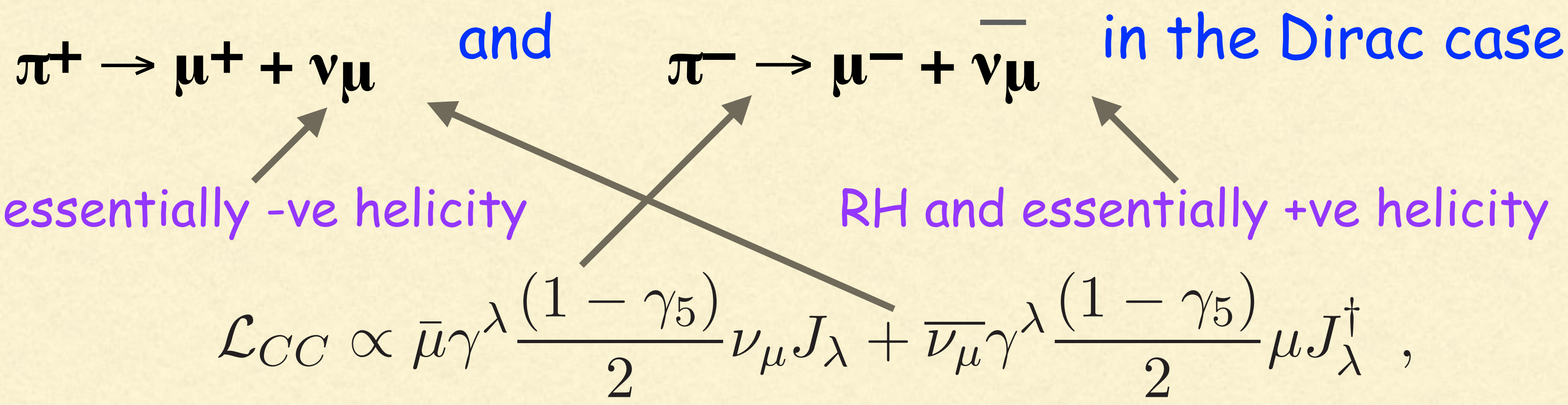
The Dirac vs Majorana nature of neutrinos..........Distinguishing between Dirac and Majorana neutrinos experimentally

This is very hard to do.......Why?

Chirality and helicity

For any fermonic field, $\boldsymbol{\Psi_L} \simeq \Psi_- + \mathbf{m/E}\ \Psi_+$ and $\boldsymbol{\Psi_R} \simeq \Psi_+ + \mathbf{m/E}\ \Psi_-$

Thus, for a relativistic fermion, chirality and helicity are almost identical.



Consider $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$ in the Dirac case,

LH and essentially -ve helicity

RH and essentially +ve helicity

$$\mathcal{L}_{CC} \propto \bar{\mu}\gamma^\lambda \frac{(1-\gamma_5)}{2}\nu_\mu J_\lambda + \overline{\nu_\mu}\gamma^\lambda \frac{(1-\gamma_5)}{2}\mu J^\dagger_\lambda \ ,$$

In the case when neutrinos are Dirac, only one term contributes to each of the two decays, since neutrinos and antineutrinos are distinct particles

The Dirac vs Majorana nature of neutrinos……….Distinguishing between Dirac and Majorana neutrinos experimentally

In the majorana case, neutrinos and antineutrinos are one and the same particle, hence both terms can contribute. However, contribution of the second term is severely helicity suppressed , by a factor m/E.

Thus, since in almost all circumstances, neutrinos are ultra-relativistic, whether neutrinos are majorana or Dirac makes no practical difference in an experiment.

However, if the neutrino is non-relativistic , from
$\boldsymbol{\Psi_L} \simeq \Psi_- + \mathbf{m/E}\ \Psi_+$ and $\boldsymbol{\Psi_R} \simeq \Psi_+ + \mathbf{m/E}\ \Psi_-$

$$\mathcal{L}_{CC} \propto \bar{e}\gamma^\lambda \frac{(1-\gamma_5)}{2}\nu_e J_\lambda + \overline{\nu_e}\gamma^\lambda \frac{(1-\gamma_5)}{2} e J_\lambda^\dagger \quad .$$

Now, in the Majorana case, the contribution from the “second” term is no longer small, since each chirality is a mix of both helicities.

In the decay of a heavy, sterile neutrino, this leads to different energy and angular distributions for the daughters in the Dirac and Majorana cases.

Kayser, 1805.07523; Balantekin and Kayser, 1805.00922

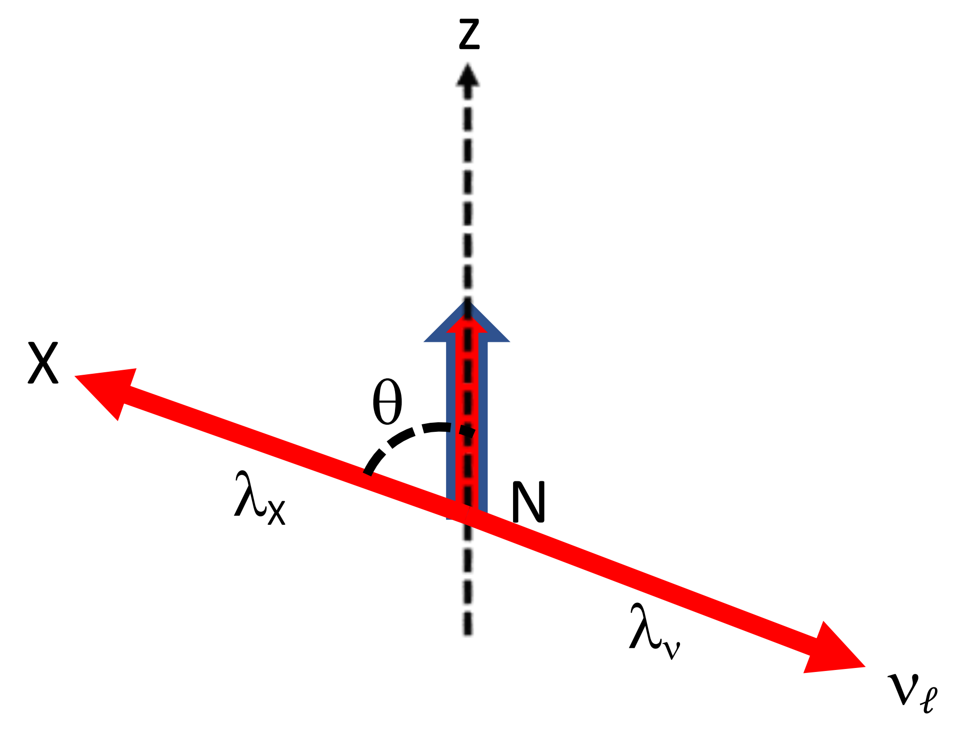
The Dirac vs Majorana nature of neutrinos…………

Distinguishing between Dirac and Majorana neutrinos experimentally. Consider, in the parent's rest frame, the decay N → ν_l + X of a heavy neutrino N that is fully polarized by its production mechanism, with its spin pointing along +z. X is a self-conjugate boson and ν_l is a SM neutrino

X and emerges at an angle θ with respect to the +z direction (with ν_l emerging oppositely), with helicities λ_X , and λ_ν , respectively. With $\lambda \equiv \lambda_X - \lambda_\nu$, rotational invariance dictates that the

$\Gamma \equiv$ Total decay rate

$\alpha = (\Gamma_{\lambda=+1/2} - \Gamma_{\lambda=-1/2})/\Gamma \in [-1, +1]$



Example: N → ν_l π^0.
ν_l is always -ve helicity,
so $\lambda = \lambda_X - \lambda_\nu = 1/2$; and
α=1. Thus this decay
will have angular
distribution
of the form (1+cosθ)

$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \frac{\Gamma_{\lambda=+1/2}}{2}(1+\cos\theta) + \frac{\Gamma_{\lambda=-1/2}}{2}(1-\cos\theta)$$

$$= \frac{\Gamma_0}{2}(1+\alpha\cos\theta)\ ;\ -1 \leq \alpha \leq +1 \ .$$

$$\Gamma_0 = \Gamma_{\lambda=+1/2} + \Gamma_{\lambda=-1/2} > 0 \ ,$$

Kayser, 1805.07523; Balantekin and Kayser, 1805.00922; Balantekin, de Gouvea and Kayser, 1808.10518

From CPT and rotational invariance, it can be shown that for Majorana neutrinos, α=0, whereas for Dirac neutrinos

$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \frac{\Gamma_0}{2}(1 + \alpha\cos\theta)$$

μ and d are the magnetic and electric transition dipole moments

X	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im m(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_N^2-2m_\rho^2}{m_N^2+2m_\rho^2}$	$\frac{m_N^2-2m_Z^2}{m_N^2+2m_Z^2}$	1

Thus, if mass of N is known, the angular distribution can in principle determine if SM neutrinos are Majorana or Dirac, because even if one neutrino that mixes with the others is Majorana, all of them are majorana.

This requires experiments to look for heavy sterile neutrinos, and possibly measure their decays.

The Dirac vs Majorana nature of neutrinos…………Detection and Challenges

There are several experiments planning to or looking for heavy sterile neutrinos, some of them are MicroBooNE, SHiP, DUNE, NA48/2, and NA62

What are some of the possible challenges in such a program to determine the Dirac or Majorana nature of neutrinos?

►Such a neutrino should exist! (Models?) (More work and investigation needed!)

►They must be produced in a sufficient number (e.g. say by meson decays) and be massive enough (few hundred MeV or more) to decay quickly in the detector and give a statistically significant number of events.

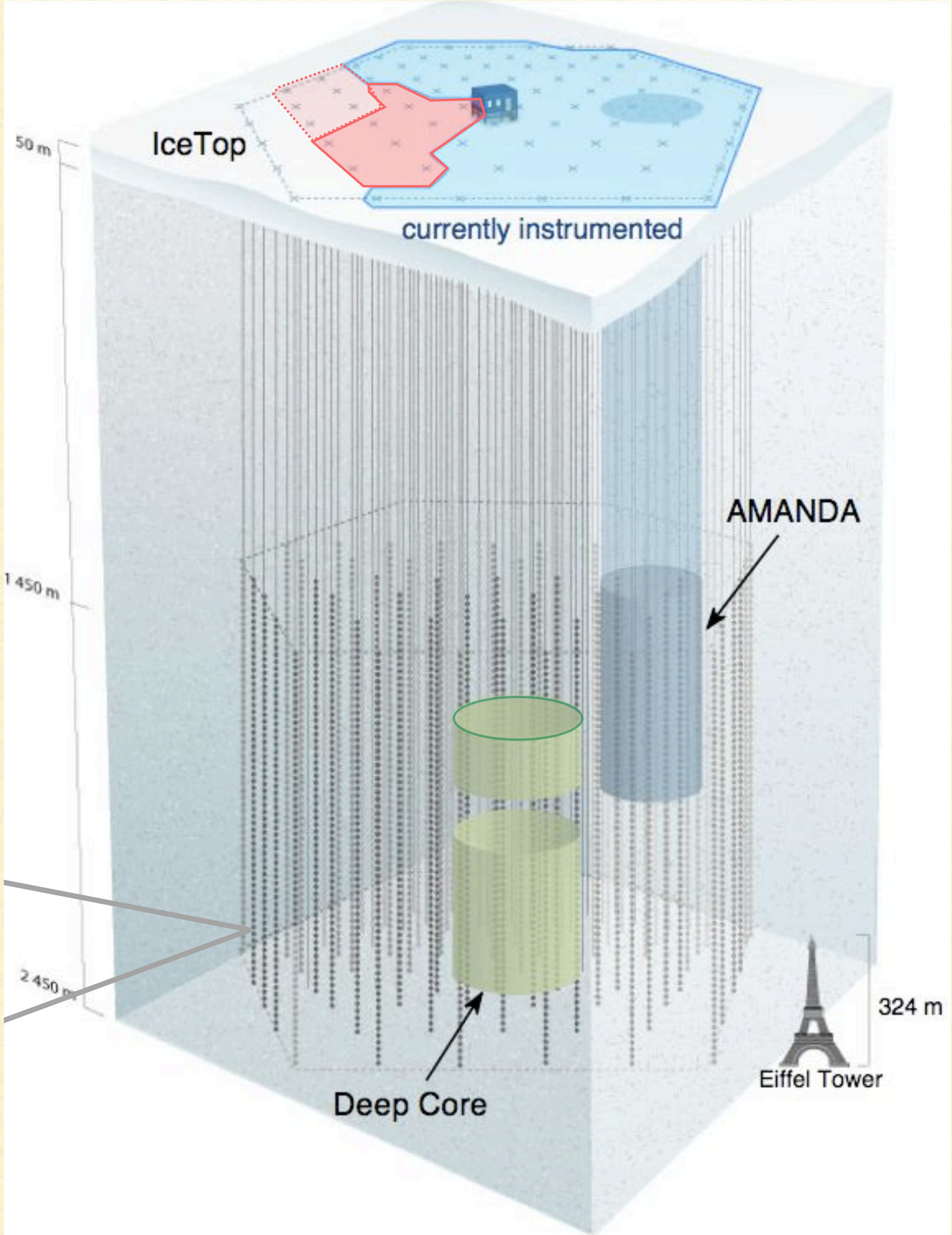
►The sample must be polarized. If produced in a weak decay, this is the case.

►If there is a charged lepton in decay final state, its charge identification needs to be made to get supplementary information on lepton number violation. This is often not possible in many neutrino experiments, e.g, Super-K, Hyper-K, NovA, DUNE, etc

►In order to do an angular distribution analysis in the rest frame, the momentum of N in the lab frame must be accurately reconstructed. This can be difficult if there is a neutrino in the final state, whose momentum cannot be directly measured.

- The IceCube events and Dark matter

The IceCube Detector



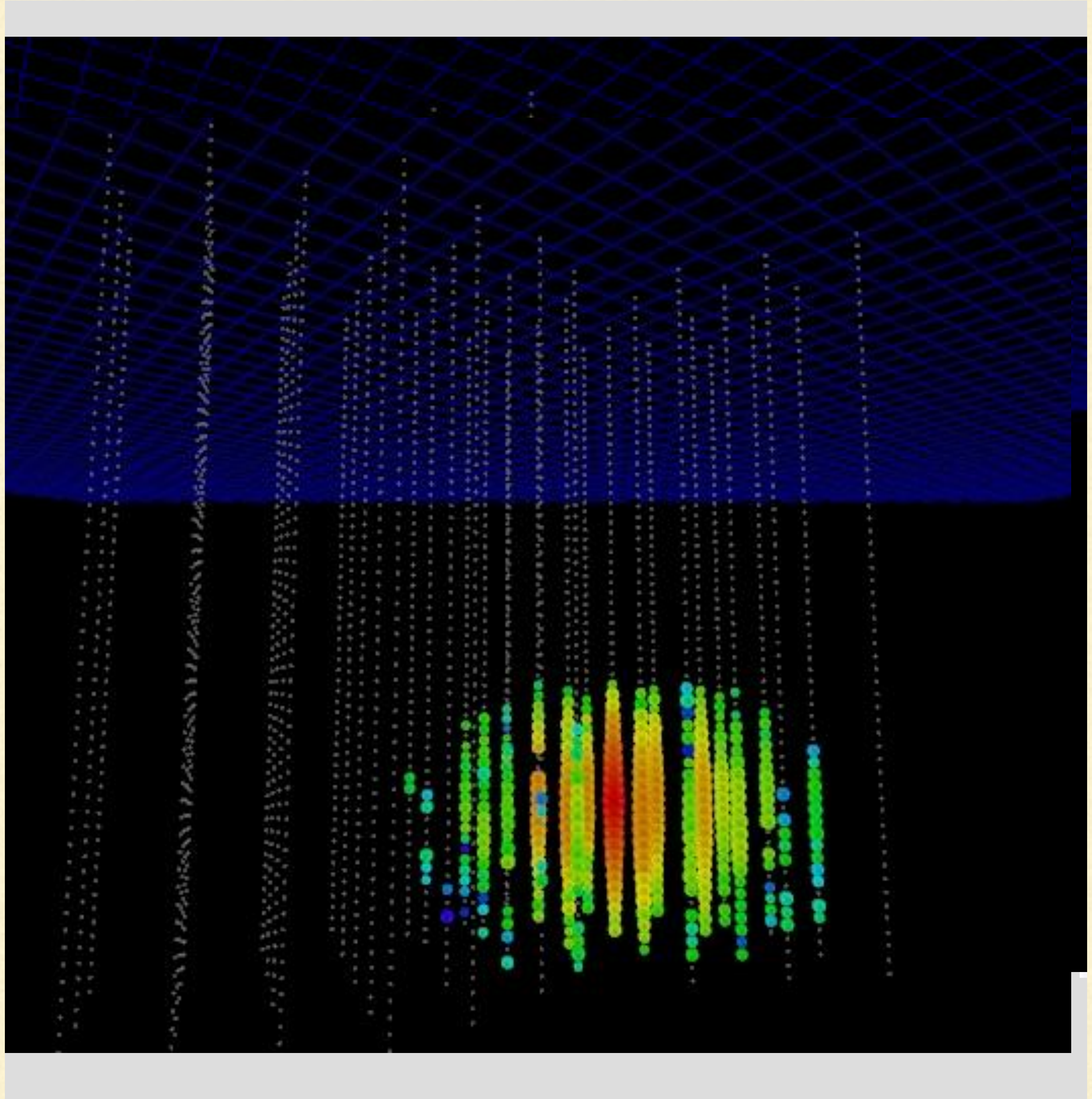
86 strings, 60 OM/string

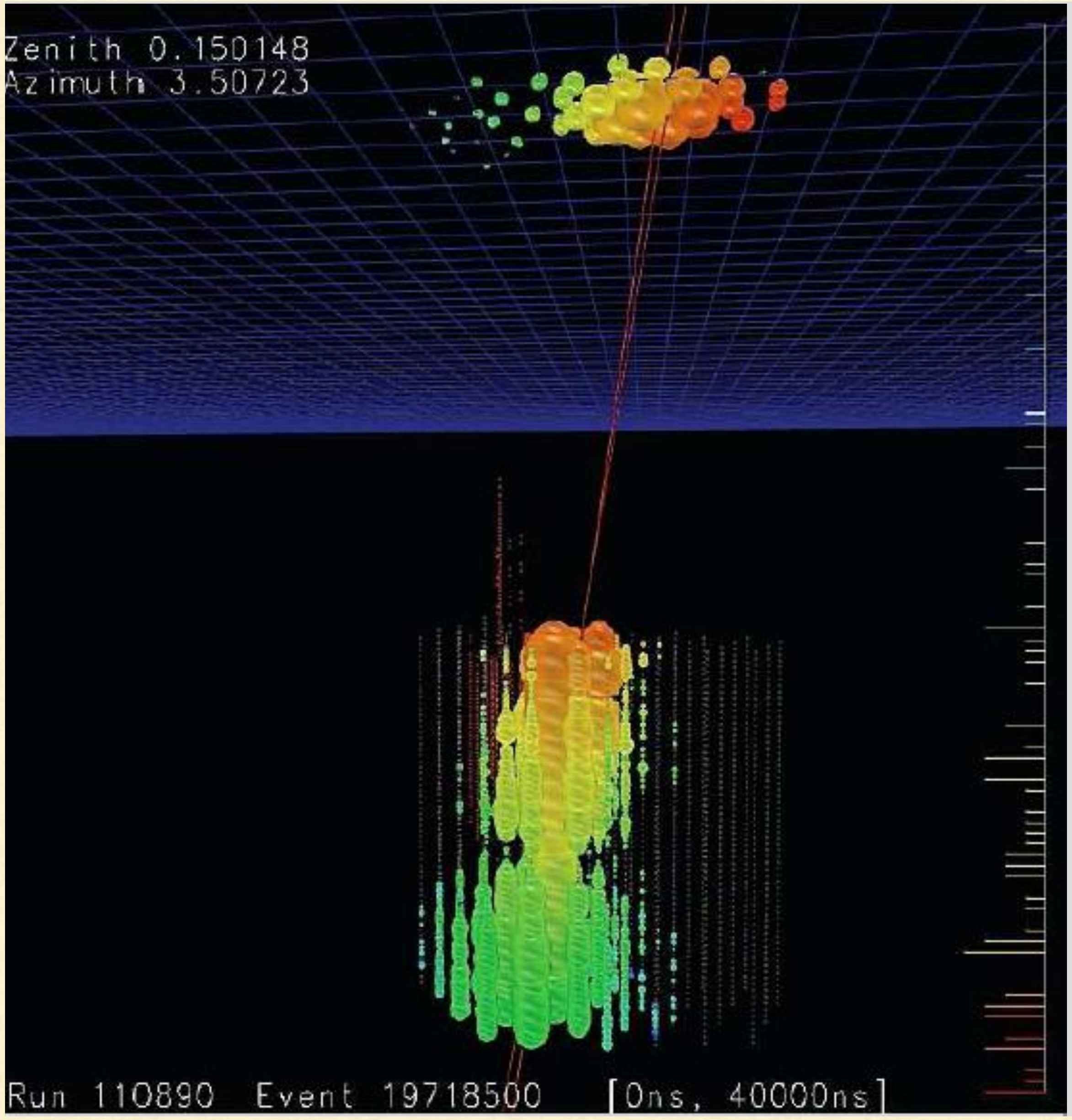
17 m distance between 2 OM on same string

125 m distance between 2 consecutive strings

1 km^3 instrumented volume

Signals in Icecube..... Showers/





Shower/Cascade

All NC, most CC ν_τ all CC ν_e

15 % resolution on the deposited energy

10° angular resolution (above 100 TeV)

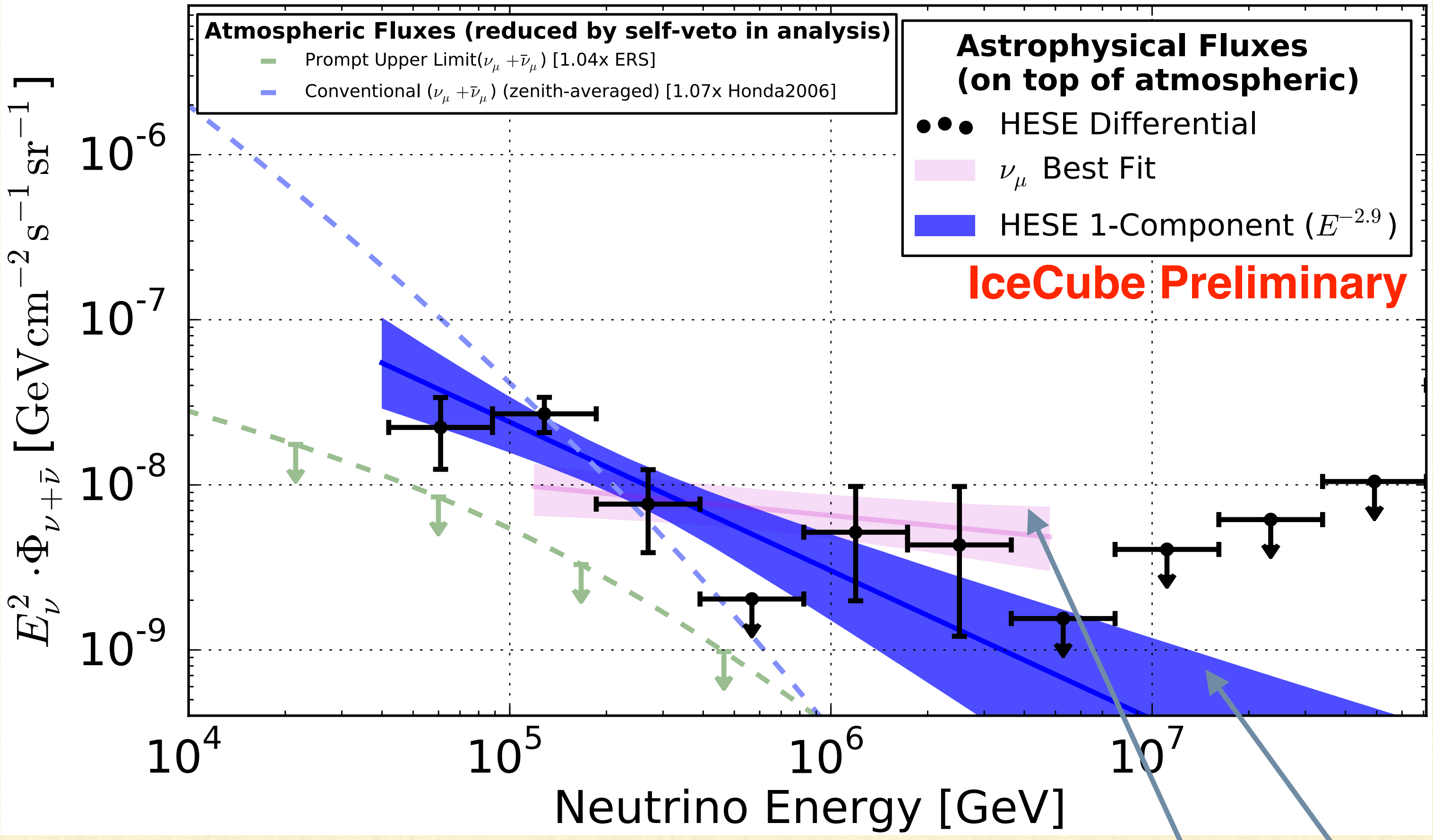
Track event (muons)

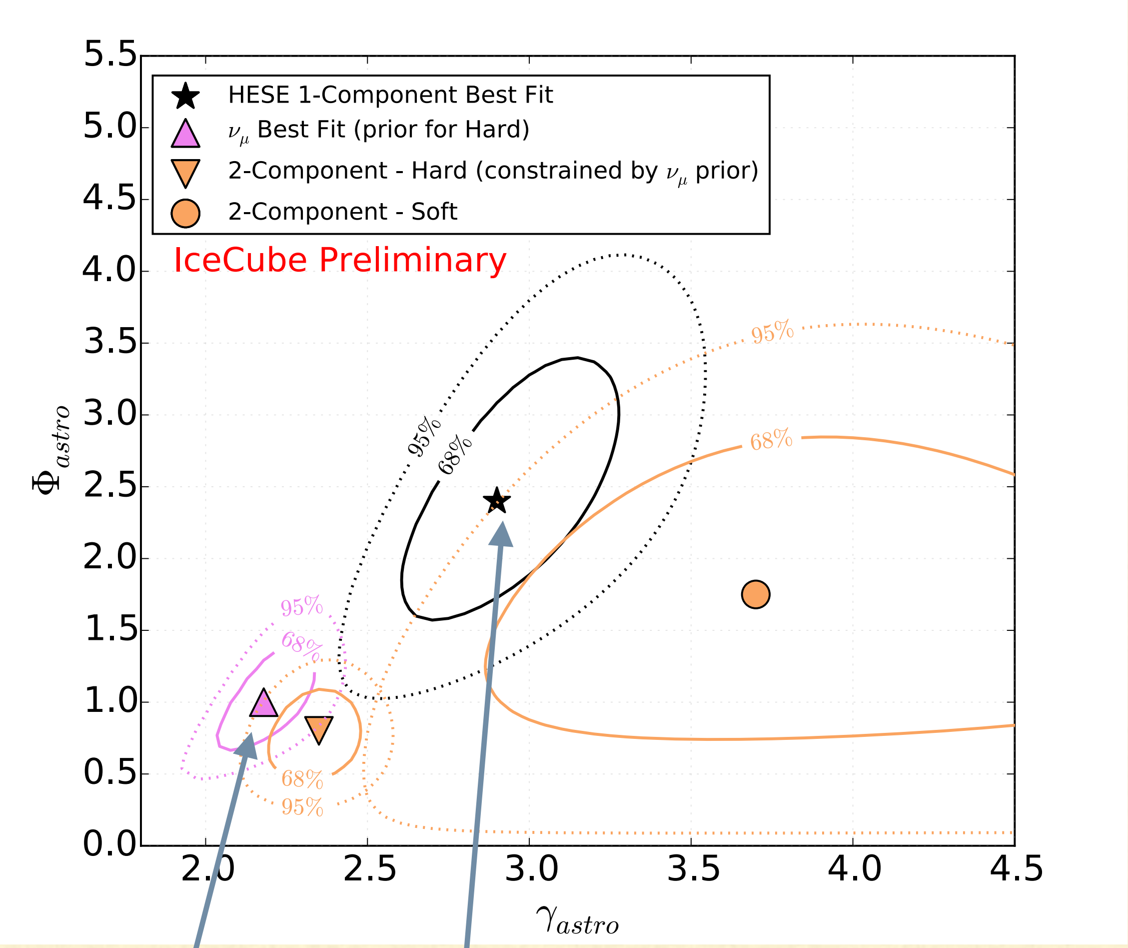
Charged current ν_μ

Factor ~2 energy resolution

<1° angular resolution

Questions/Issues: Power-law behavior of observed neutrino fluxes…..





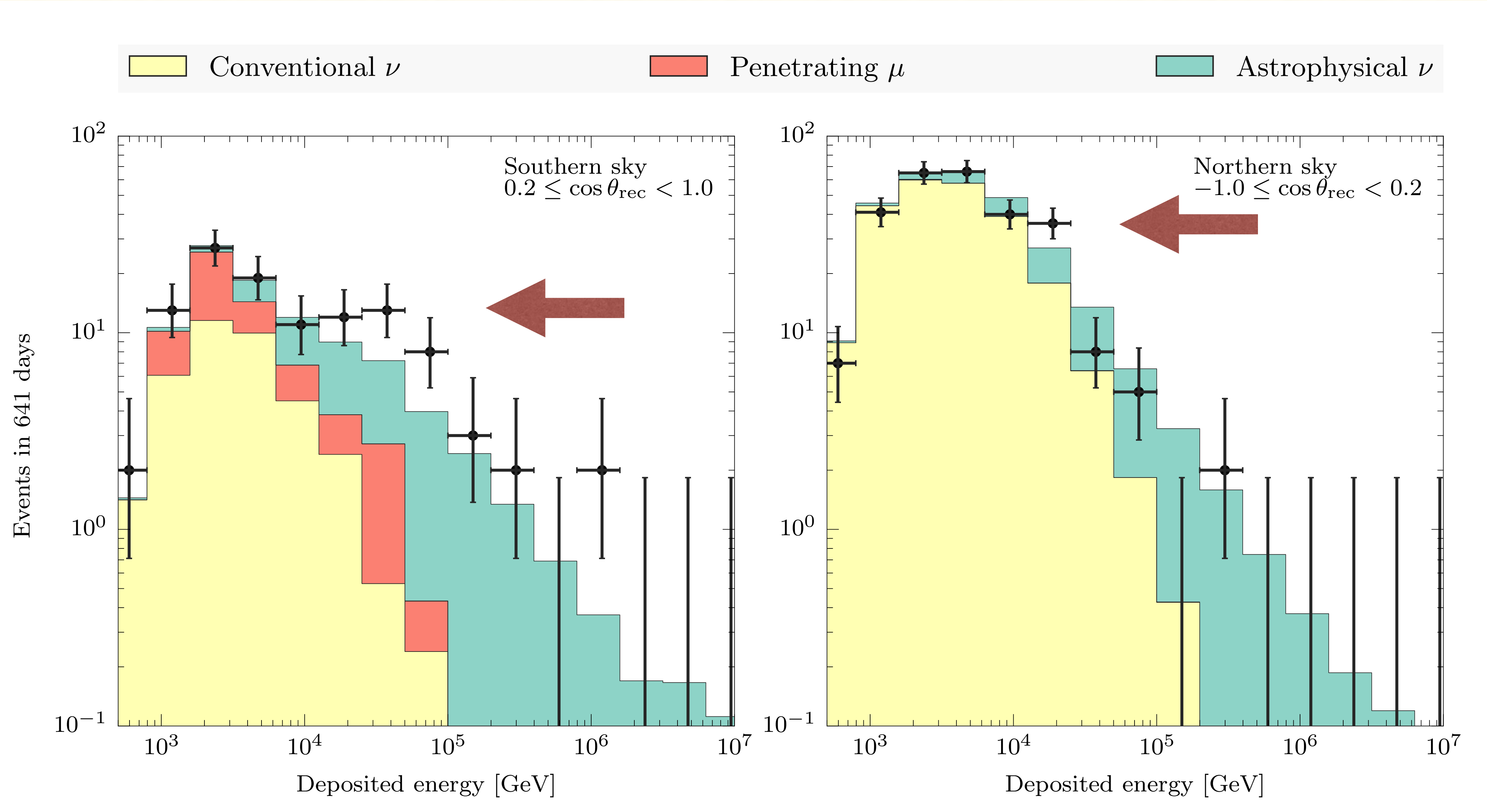
It is widely believed that UHE neutrinos are produced in charged pion decays produced in pp and or pγ interactions in the source. Such neutrinos are expected to follow a E^{-2} spectrum

However….

Power-law behavior (index) of 8 yr up-going muon data and HESE data significantly different.

Questions/Issues: Excess in 30-100 GeV region……

At lower energies, in the range of 50 – 200 TeV, there appears to be an excess, with a bump-like feature (compared to a simple power-law spectrum), which is prominently present in events from the southern hemisphere, but also visible in events from the northern hemisphere.The maximum local significance of this excess is about 2.3σ.

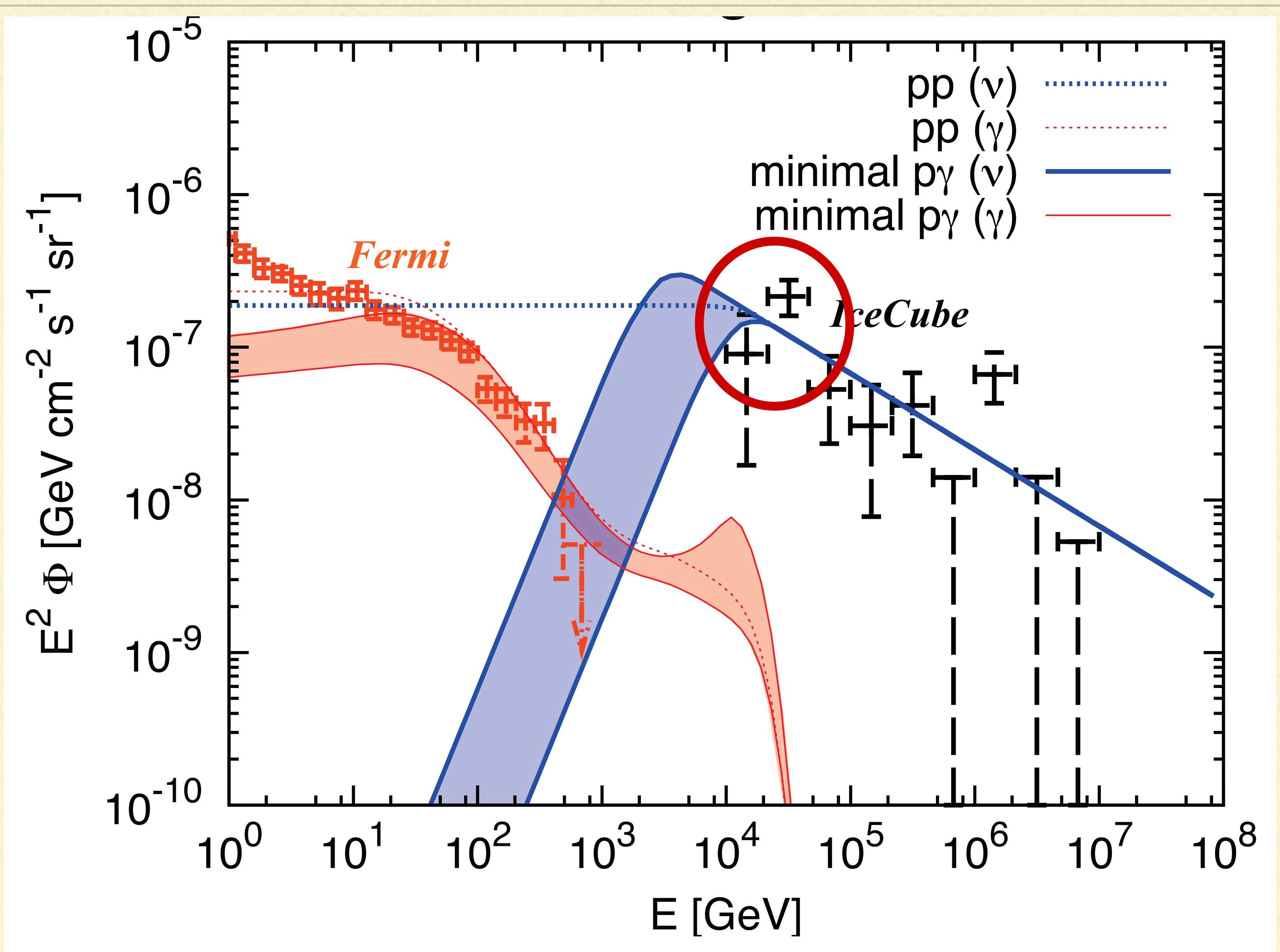


Fermi Gamma-ray data in tension with IC neutrino data in >30 TeV range………

For any source, the same processes that produce charged pions which decay to give you the UHE neutrino flux also produce neutral pions which decay to HE photons.

This leads to a natural co-relation

between the ν and the γ fluxes.



For both pp and pγ sources, the observed neutrino flux in IC in the 30-200 TeV region exhibits strong tension with Fermi gamma ray (IRGB) data in GeV region.

This implies either “dark” or opaque sources, or new physics.

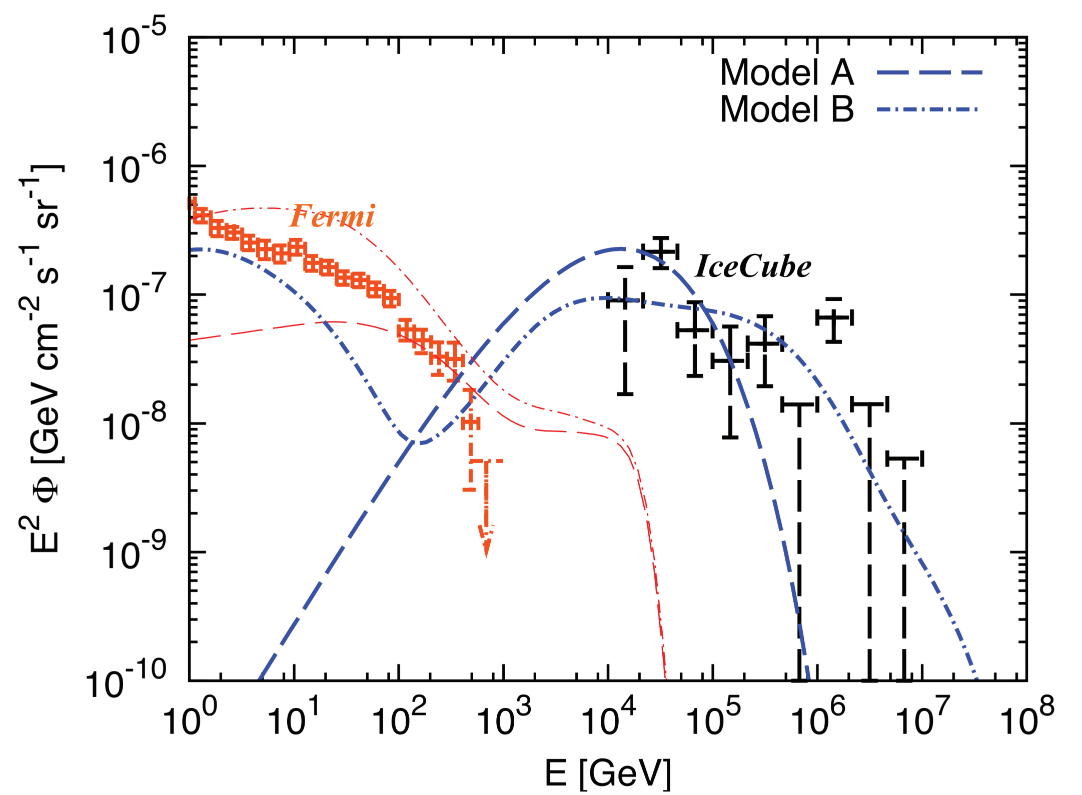
The “hidden source solution” to the IC signals………

γ rays above TeV energies initiate electromagnetic cascades in the extragalactic background light (EBL) and cosmic microwave background (CMB) as they propagate over cosmic distances. As a result, high-energy γ rays are regenerated at sub-TeV energies, and should have been seen by Fermi.

Thus , assume and study sources are such that two-photon annihilation, inverse-Compton scattering, and synchrotron radiation processes in them can prevent direct γ- ray escape —“dark/hidden sources”

Possible with $p\gamma$, but strong tension in case of pp sources persists.

Conclude that dark $p\gamma$ sources could alleviate this tension, examples of such sources are models of choked gamma-ray burst (GRB) jets and active galactic nuclei (AGN) cores which are opaque to GeV-TeV γ rays.



(Murase, Guetta , Ahlers 1509.00805)

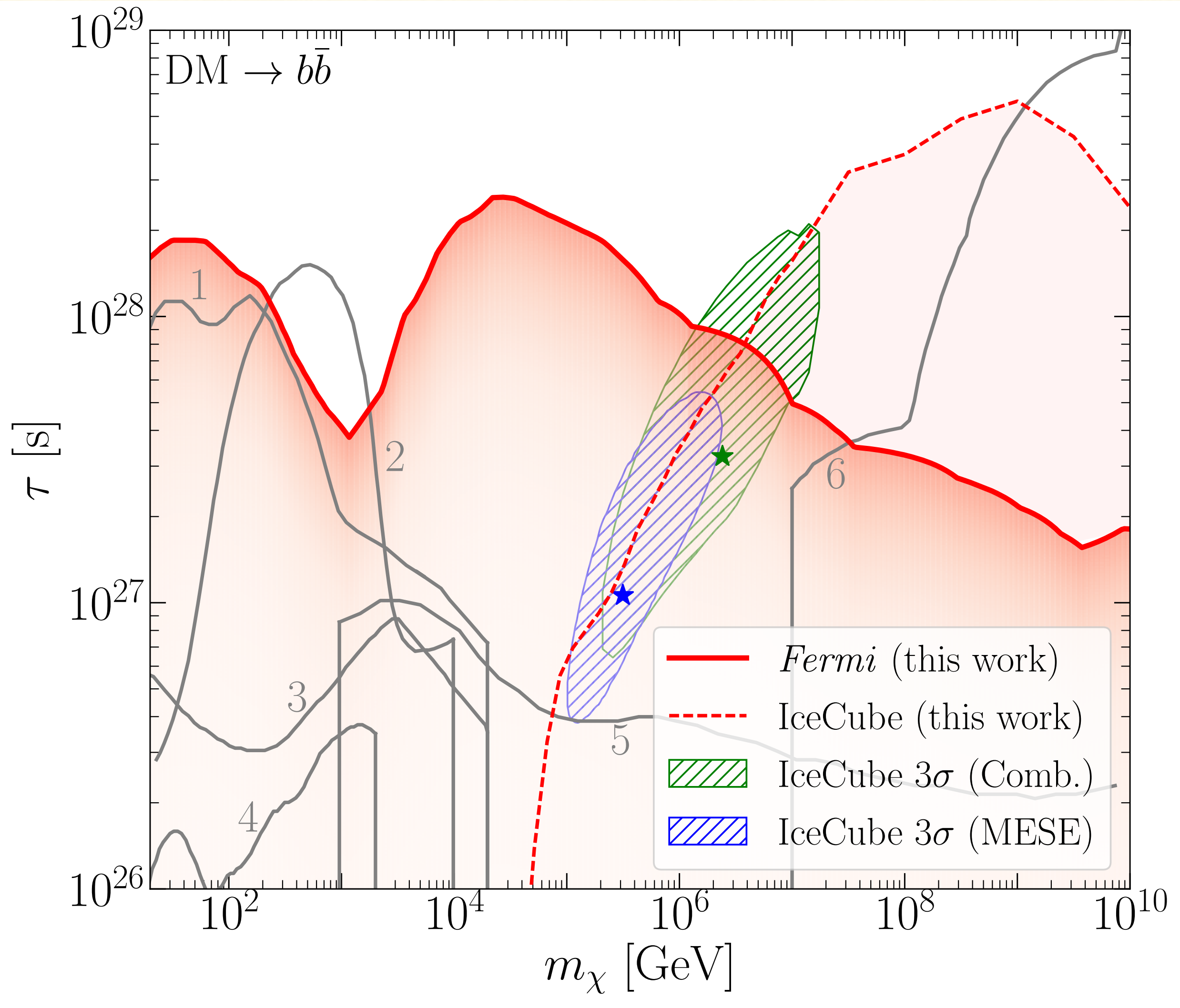
Power-law incompatibilities and DM………

The incompatibilities a) between expected E^-2 flux and observed spectrum b) between through going muons and HESE spectra, along with proximity of flux to WB bound have led to the speculation that IC sees more than one flux.

Secondly, the second component may not be astrophysical, but due to decay of DM to SM particles leading to neutrinos.

The γ-ray constraints from Fermi can also be used to constrain DM mass and lifetime in this scenario.

Cohen et al, 1612.05638



Explanation of MESE events (30-200 TeV) excess via DM——> SM particles very strongly constrained by Fermi-LAT.

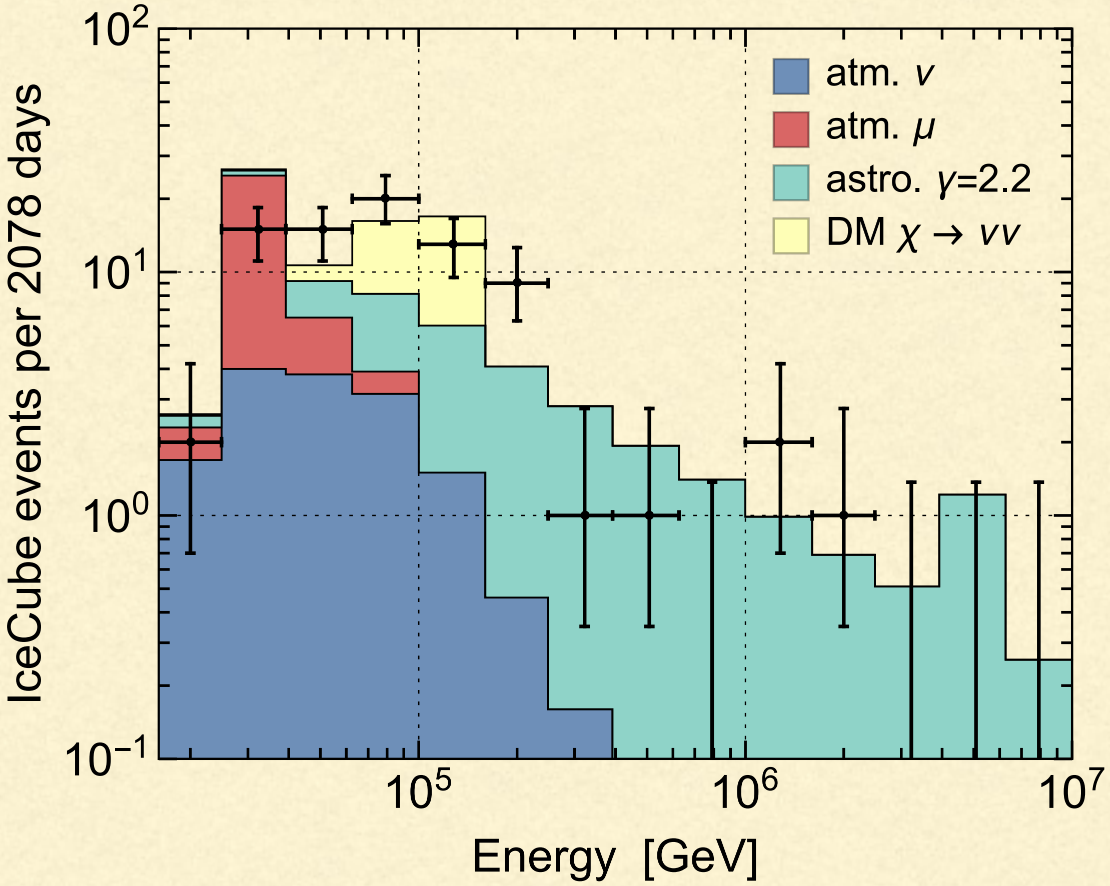
IceCube Anomalies and DM…………

This implies either "hidden" or opaque sources, or new physics.

Example of new physics: DM which decays only to neutrinos

Chianese et al arXiv: 1808.02486

Extend the Standard Model with a scalar $SU(2)_L$-triplet with hyper-charge Y = +1



$$\Delta = \sum_{i=1}^{3} \delta_i \tau_i = \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}$$

Role of Dark Matter is played by the neutral component of this triplet, χ, which couples to leptons via

$$\mathcal{L}_\nu = \frac{1}{2}\lambda_{ij} L_i^T C^{-1} i\tau_2 \Delta \, L_j + \text{h.c.} \, ,$$

$$L_i = \begin{pmatrix} \nu_{iL} \\ \ell^-_{iL} \end{pmatrix}$$

Impose new global U(1) and arrange its charges such that

it allows the χ to decay to only to neutrinos via

$$\frac{1}{\sqrt{2}}\lambda_{ij} \, \chi \, \nu_{iL}^T C^{-1} \nu_{jL} + \text{h.c.} \, ,$$

No coupling to quarks due to color conservation

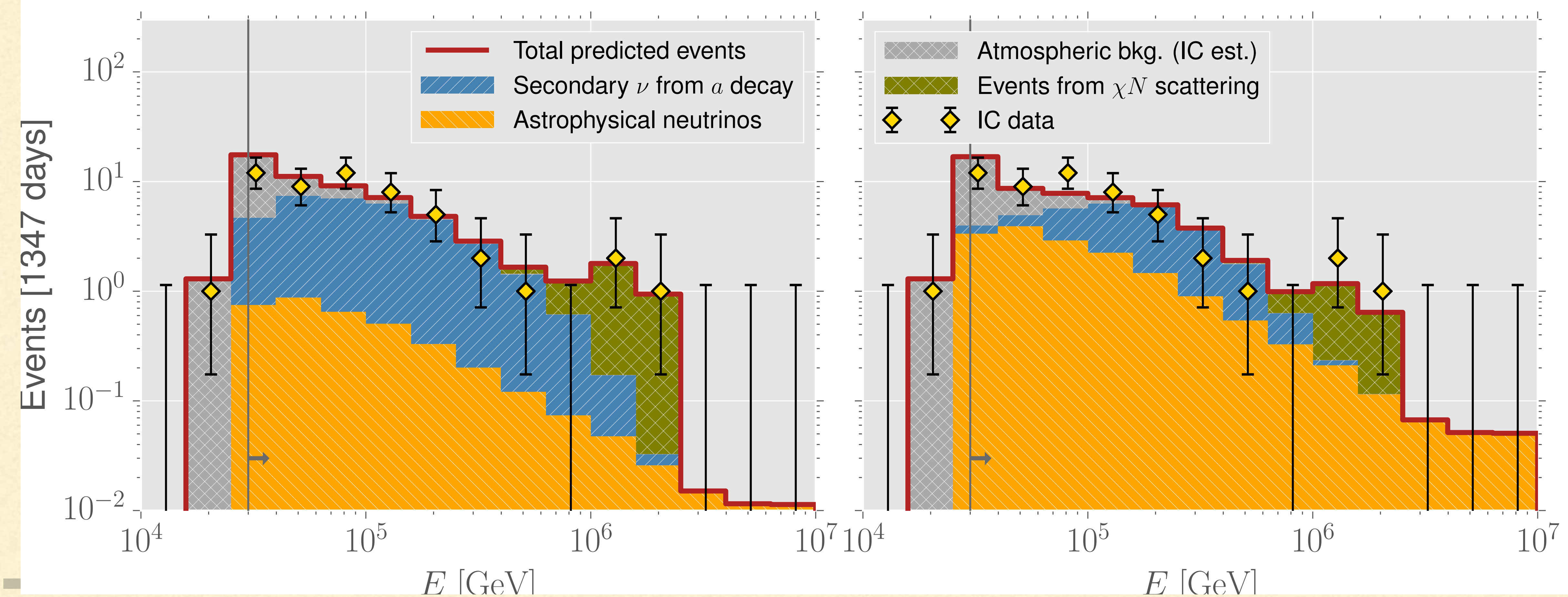
Another new physics possibility…. DM

Bhattacharya, RG, Gupta JCAP 1503 (2015), 027 (1407.3280)

Study the implications of the premise that any new, relativistic, highly energetic neutral particle that interacts with quarks and gluons would create cascade-like events in the IceCube (IC) detector.

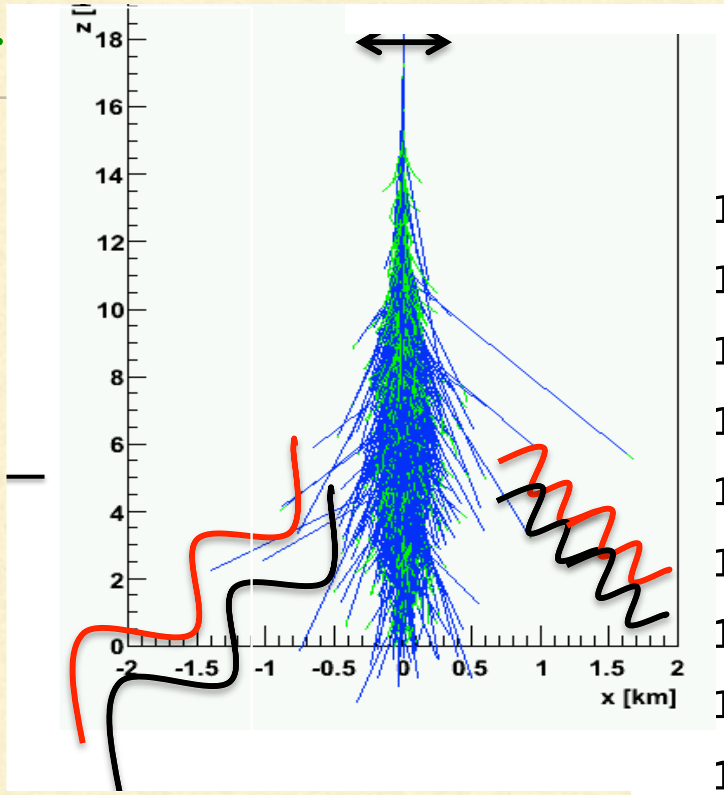
Bhattacharya, RG, Gupta, S. Mukhopadhyay JCAP 1705 (2017) no.05, 002 (1612.02834)

Premise: A flux of boosted light dark matter (LDM) particles (χ), which results from the late-time decay of a heavy dark matter (HDM) particle (φ). When χ is much lighter than φ, its scattering in IC resembles the NC DIS scattering of an energetic neutrino, giving rise to cascade-like events.

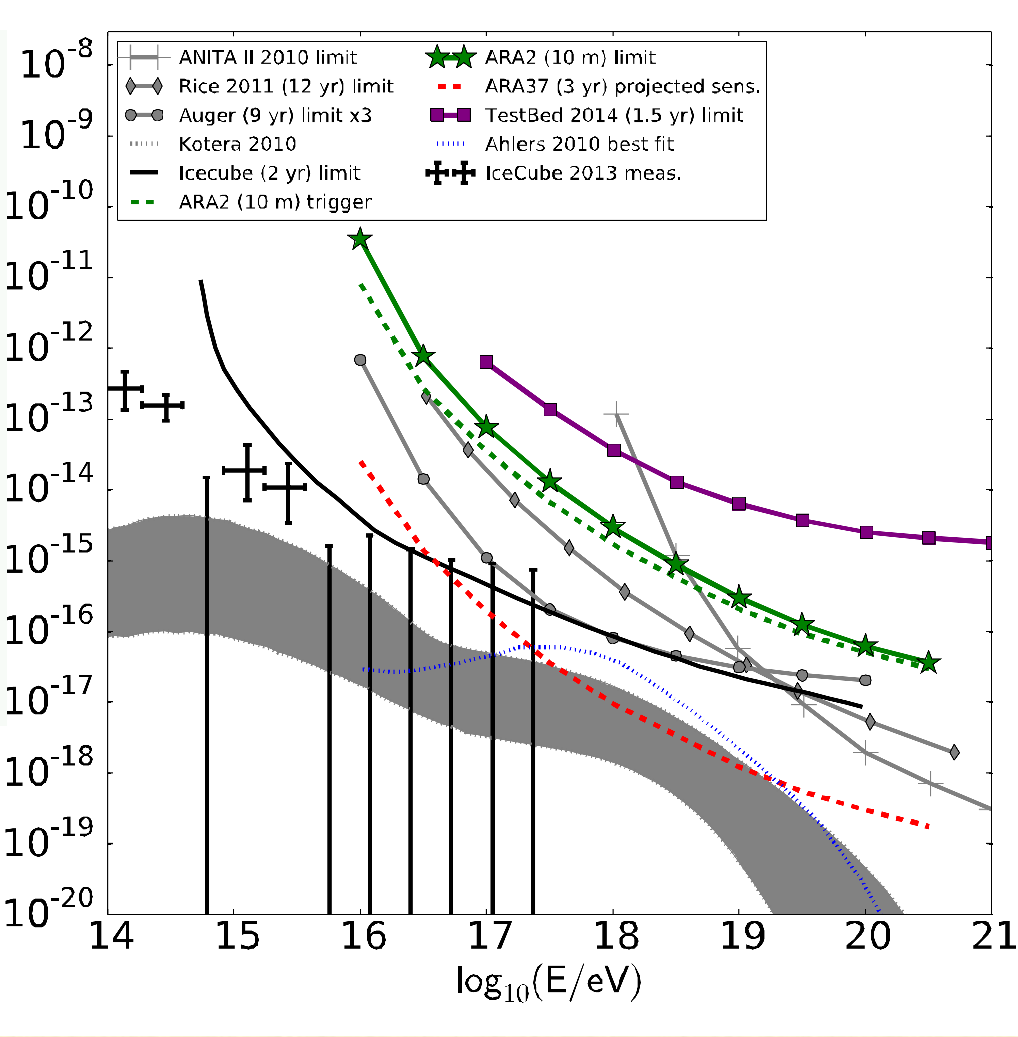


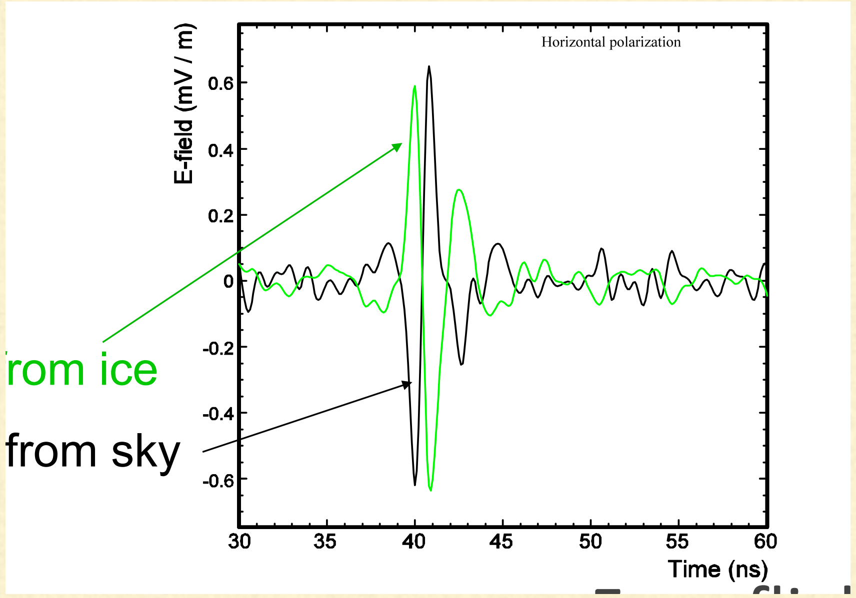
- The ANITA observations of the highest energy events

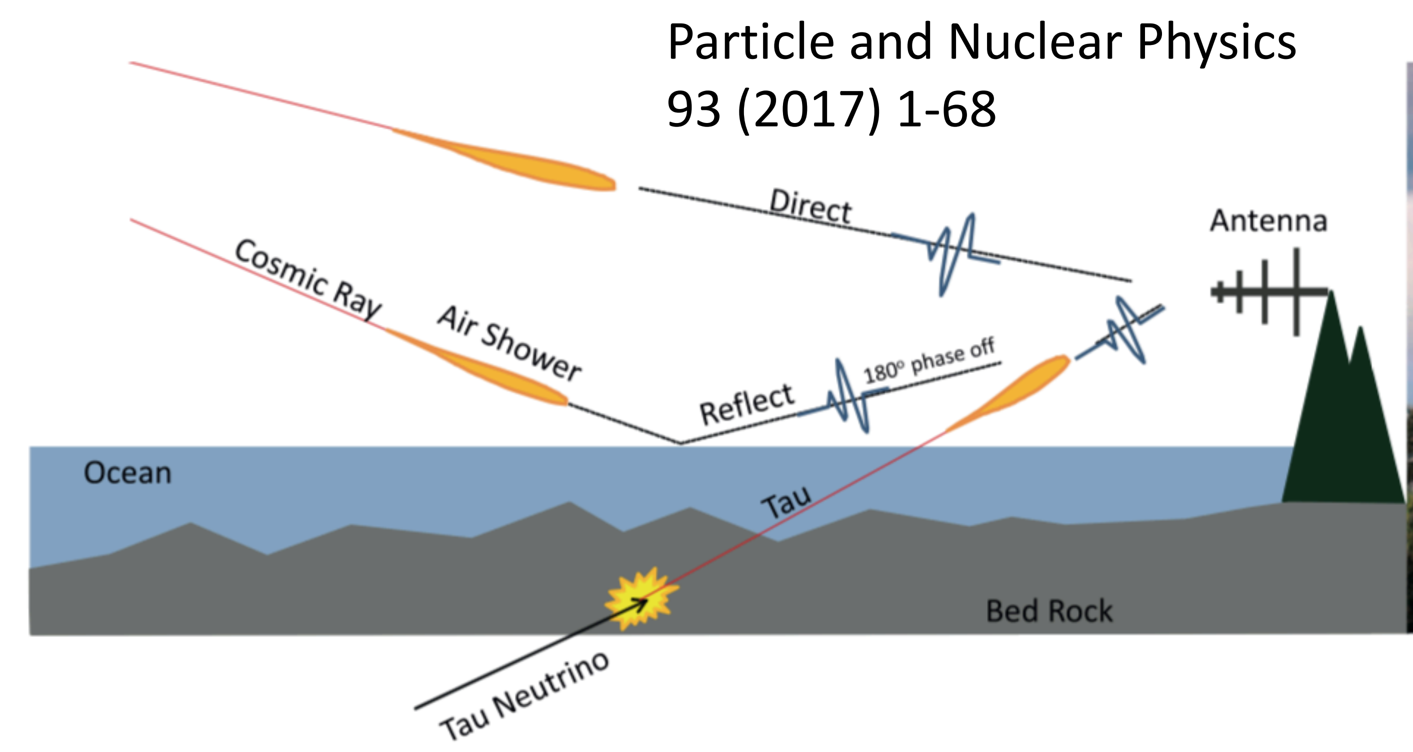
The ANITA Experiment



Radio pulses produced by UHE showers







Particle and Nuclear Physics 93 (2017) 1-68

TAROGE-1

The ANITA Anamolous Events…………

TABLE I. Properties of the 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 $\varepsilon_{\rm cr}$	$0.6 \pm 0.4\,{\rm EeV}$	$0.56^{+0.30}_{-0.20}\,{\rm EeV}$
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	$5740 \pm 60\,{\rm km}$	$7210 \pm 55\,{\rm km}$
Mean interaction length for $\varepsilon_\nu = 1\,{\rm EeV}$	290 km	265 km
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1\,{\rm EeV}$	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1\,{\rm EeV}$, $\varepsilon_\tau > 0.1\,{\rm EeV}$	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

τ must be produced close to and inside earth's surface. This implies many interactions for the primary ν_τ given zenith angle, and implies starting energies which are very high. Flux at these enemies is very low, and this flux violates bounds by Pierre Auger and IceCube.

New physics? Source must be inside earth.

SM cross sections imply that it is very unlikely that these are tau neutrinos.

Example of new physics: Model with heavy Rh neutrino in CPT symmetric universe, mass 480 PeV, which is also DM, decays inside earth to to Higgs and SM neutrino. need non-central distribution—-assume collision of earth with "dark disk"

Anchordoqui et al, 1803.11554

Summary

▶The MiniBooNE excess, when combined with previous LSND results, is an intriguing puzzle

▶Could be due to mundane physics (un-understood background)

▶ ▶But results have been carefully scrutinized over the long term and many important backgrounds measured may also imply that they are signals of new physics. If so, whatever new physics explains one or both is likely to be non-trivial and important.

▶The question whether neutrinos are Dirac or Majorana in nature remains unanswered. Recent progress offers possibly an additional handle on this if there exists a heavy sterile neutrino, by studying the energy and angular distributions in its decay.

▶While several experiments are looking for such a neutrino, determining angular and energy distributions in a decay to an active neutrino and a boson is very challenging.

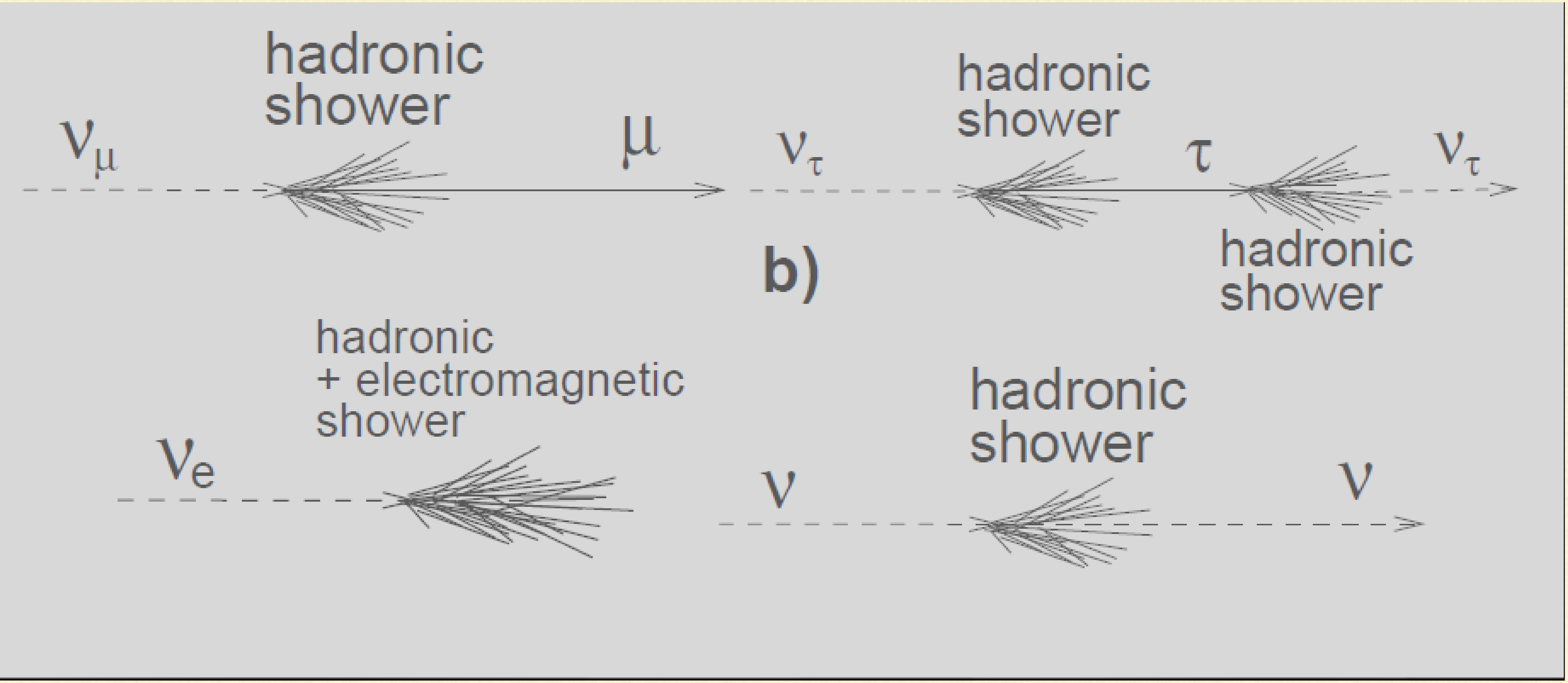
▶IceCube events show a power-law discrepancy between up going muon and contained HESE/MESE events, and a tension with Fermi-LAT gamma-ray data in GeV region. Hidden sources? or DM? DM decay to SM particles also in tension with Fermi-LAT. DM to DM decay?

▶ANITA, a ballon experiment, has recorded 2 events which are ~600 PeV with non-inversion in polarization of the detected radio signal. While ν_τ can in principle be responsible, angle of approach makes this highly unlikely. If new physics, need fresh ideas.

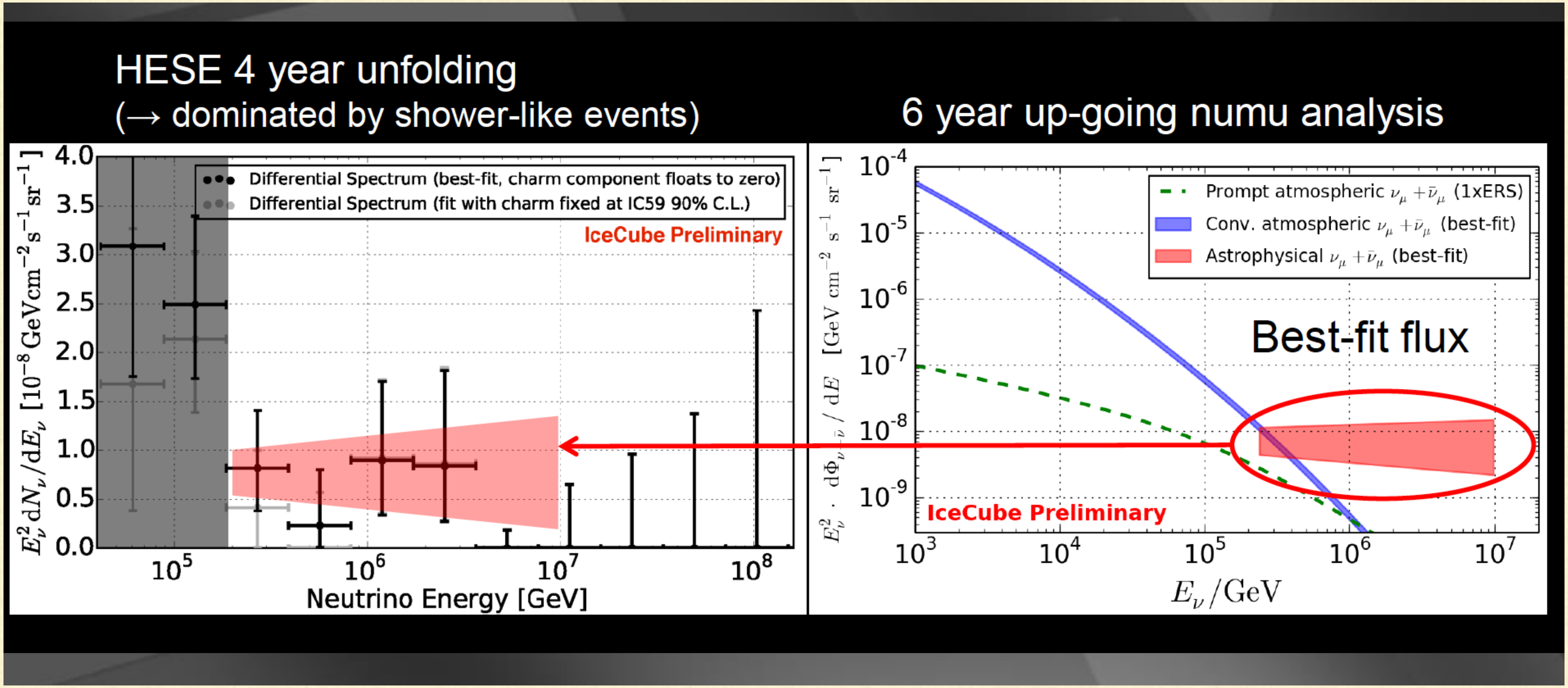
Thank You for your attention

Backup Slides

Neutrino Signals in IceCube.....



Questions/Issues: Power-law behavior of observed neutrino fluxes…..



HESE 4 year unfolding
(→ dominated by shower-like events)

6 year up-going numu analysis

Power-laws of the HESE and thoroughgoing muon fluxes seem consistent with each other only above 100 TeV, and with Fermi shock acceleration.

Difficult, in this way of looking at the data, to understand the 30-100 TeV data (MESE), or use single power-law for all data.

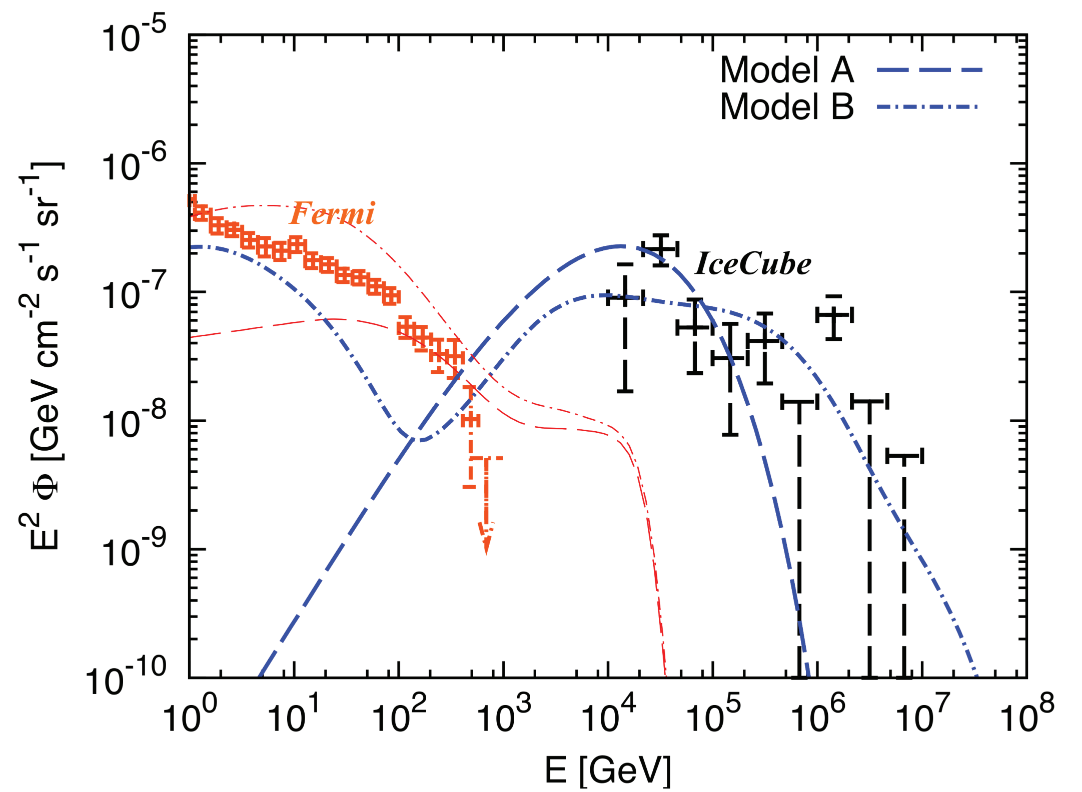
The "hidden source solution" to the IC signals………

γ rays above TeV energies initiate electromagnetic cascades in the extra-galactic background light (EBL) and cosmic microwave background (CMB) as they propagate over cosmic distances. As a result, high-energy γ rays are regenerated at sub-TeV energies, and should have been seen by Fermi.

Thus , assume and study sources are such that two-photon annihilation, inverse-Compton scattering, and synchrotron radiation processes in them can prevent direct γ- ray escape —"dark/hidden sources"

Possible with $p\gamma$, but strong tension in case of pp sources persists.

Conclude that dark $p\gamma$ sources could alleviate this tension, examples of such sources are models of choked gamma-ray burst (GRB) jets and active galactic nuclei (AGN) cores which are opaque to GeV-TeV γ rays.



(Murase, Guetta , Ahlers 1509.00805)