The Cosmic Ray Neutrino Deficit and IceCube

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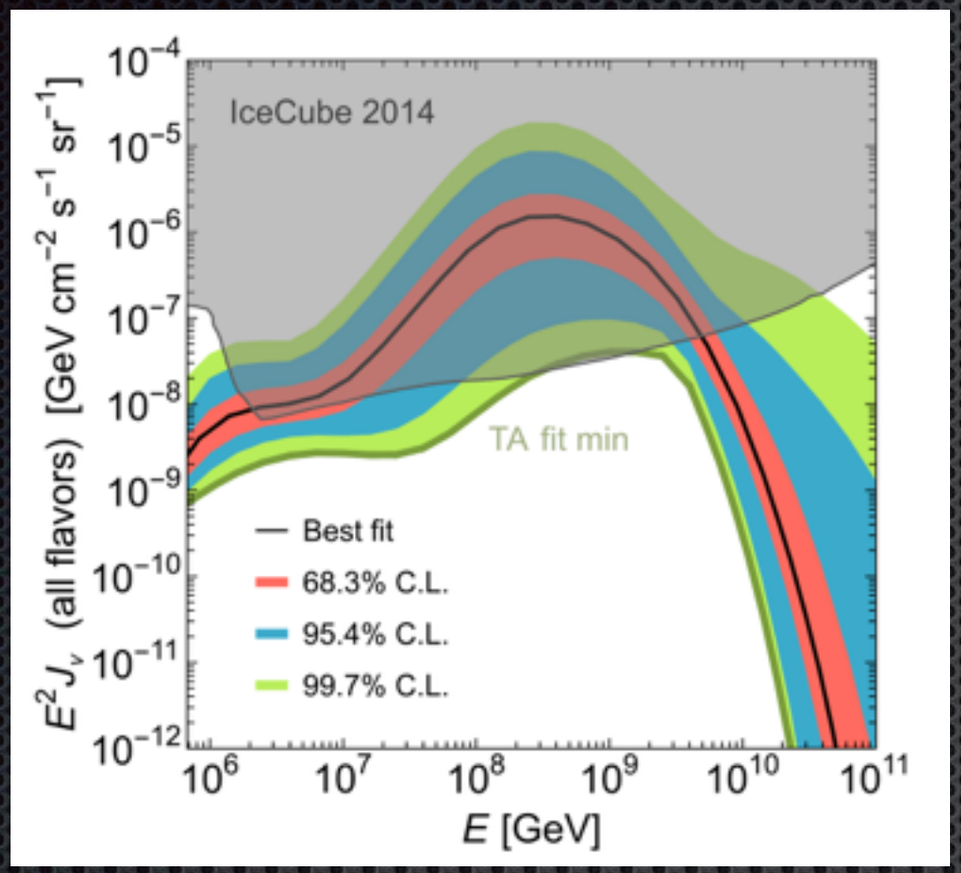
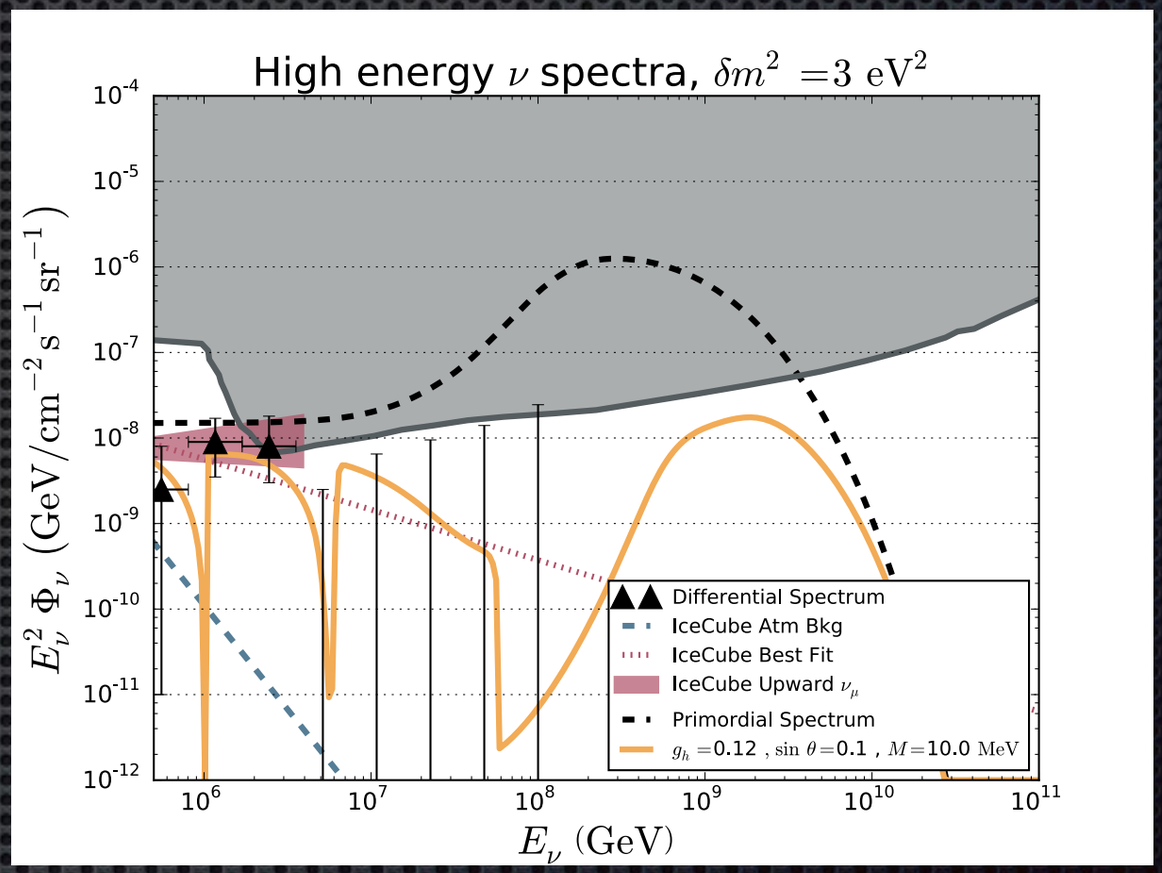
arXiv:1411.1071
arXiv:1605.06506

MACROS Workshop, Penn. State, June 2016

Alternate title: Why finding UHECR neutrinos may be more difficult and more rewarding than previously advertised.



Heinze, et al., arxiv:1512.05988



Alt. alt. title: So you thought this was complicated with just the source physics?

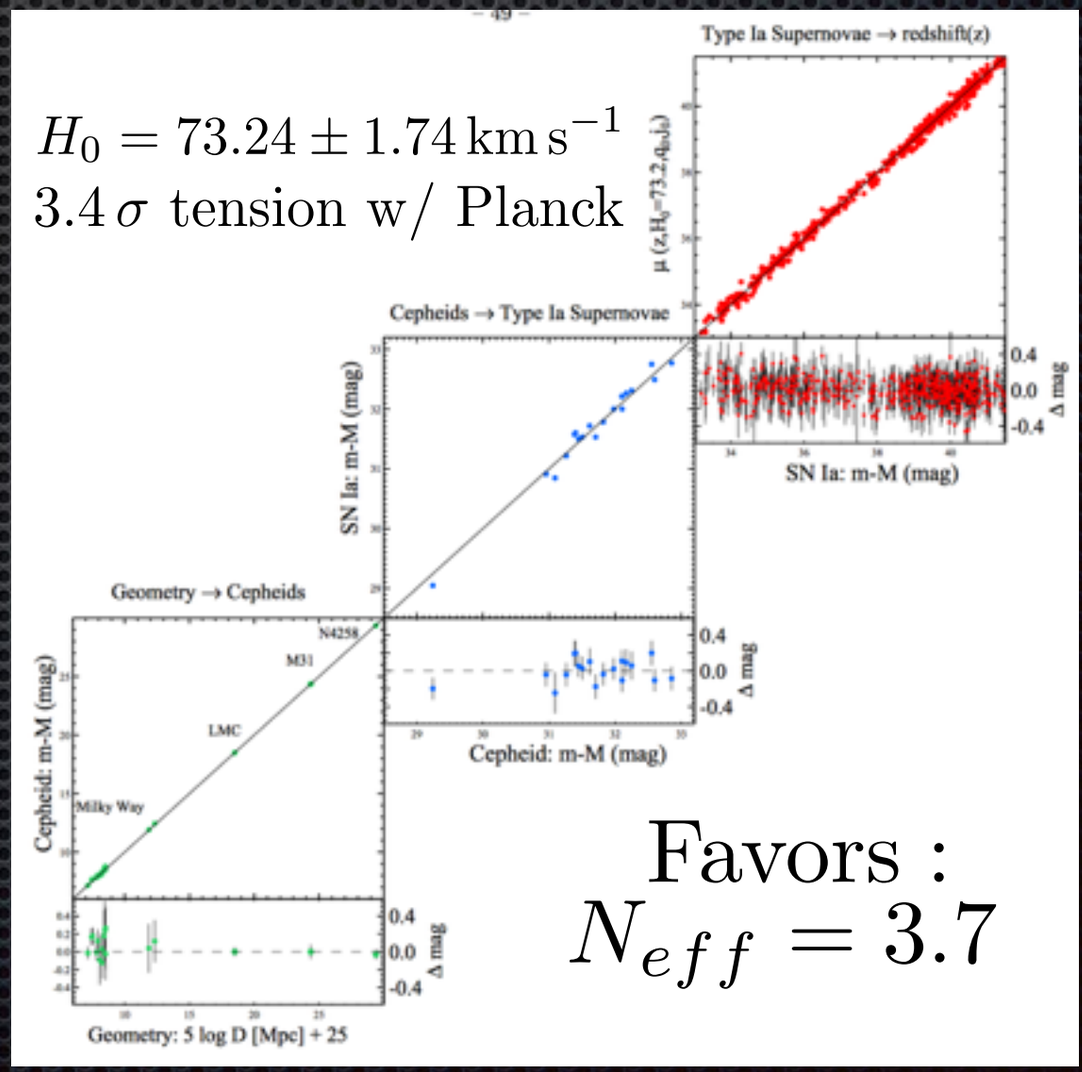
An incomplete list of mildly dubious spectral features in IceCube

- UHECR neutrino flux predictions are starting to cross the 2015 data set exclusion limits.
- HESE spectral index fit disagrees with up-going muon track spectral index fit
- Missing events from the Glashow resonance?
- Missing events from 500-1000 TeV ?

Growing tension between precision cosmology fits

- Planck 2015 : $N_{eff} = 3.04 \pm 0.33$
- Internal tension with Planck results seem to favor additional radiation energy density, which also resolves tension with Lensing, Clustering, and H_0 measurements.

Wyman, et al., Phys. Rev. Lett. **112** (2014)



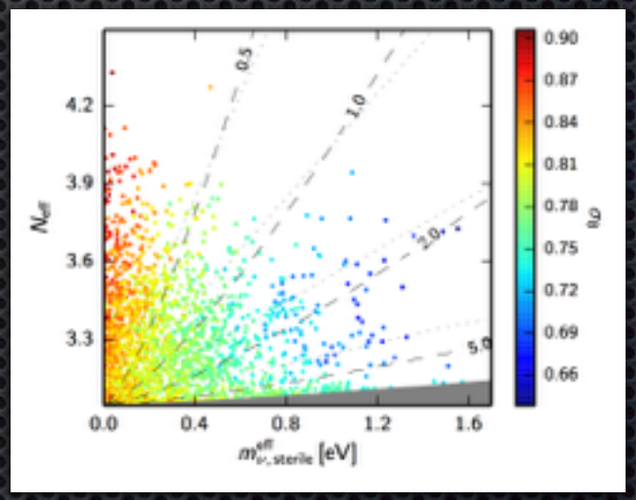
Reiss, et al., arxiv:1604.01424

LSND/MiniBooNE sterile ν

- The Planck 2015 data places strong constraints the relic abundance of new neutrinos.

$$\left.\begin{aligned} N_{\rm eff} &< 3.7 \\ m^{eff}_{\nu,\rm sterile} &< 0.52eV \end{aligned}\right\} 95\%\, CI$$

Planck Collaboration, arXiv:1502.01589v2



- Hamann, J. and Hasenkamp, J. , JCAP **10**, 044 (2013) : These limits rule out plain vanilla sterile neutrino models which have large mixing angles and ~eV masses.

$$\Delta N_{\rm eff} = 1$$

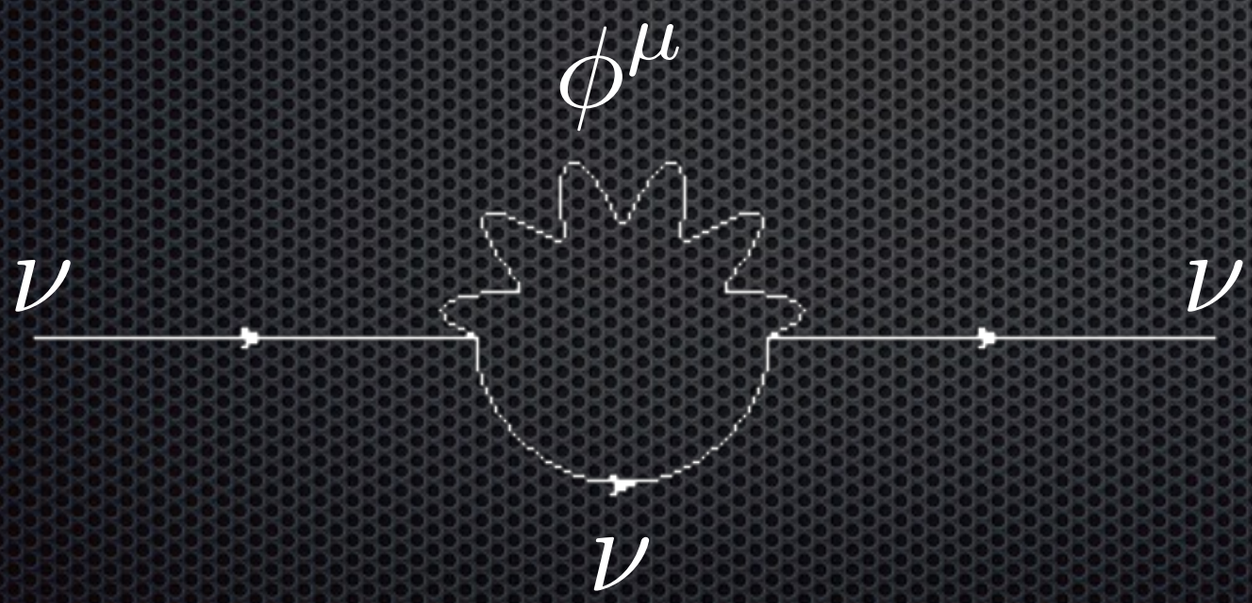
$$m^{eff}_{\nu,\rm sterile} = \Delta N_{\rm eff} \times m_{\nu,\rm sterile} \sim 1\,\rm eV$$

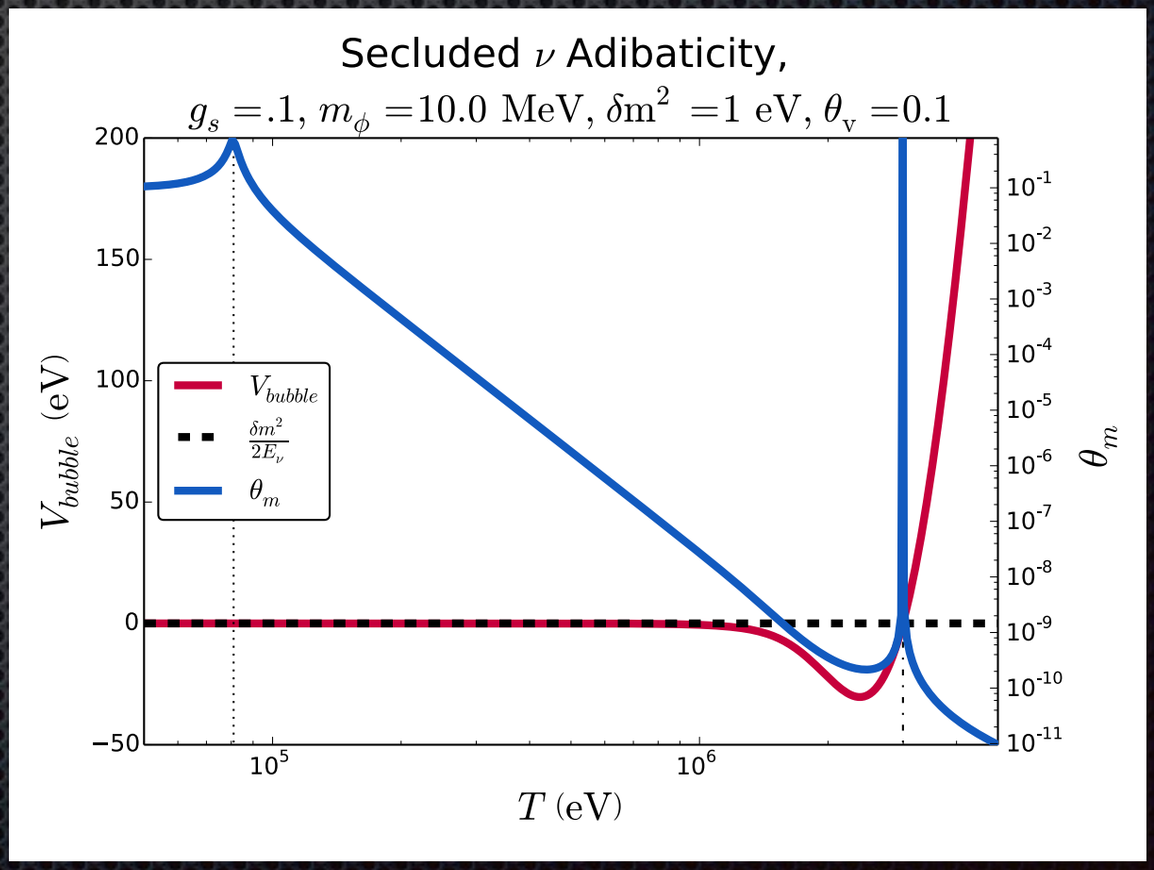
Sterile Interactions Suppress Mixing

B. Dasgupta and J. Kopp, PRL **112**, 031803 (2014)
S. Hannestad, R. S. Hansen, and T. Tram, PRL **112**, 031802 (2014)

$$\sin 2\theta_{\rm eff} = \frac{\frac{\delta m_V^2}{2E_\nu}\sin 2\theta_V}{\sqrt{\left(\frac{\delta m_V^2}{2E_\nu}\cos 2\theta_V + A\right)^2 + \left(\frac{\delta m_V^2}{2E_\nu}\sin 2\theta_V\right)^2}}$$

Effective mass term





Mixing Portal Prescription

Cherry, Friedland, Shoemaker, arXiv:1411.1071

$$\mathcal{L} \supset LH\nu_R + \nu_s H'\nu_R + \Lambda\nu_R\nu_R$$

$$\mathcal{L} \supset \underbrace{\frac{(LH)(\nu_s H')}{\Lambda}}$$

Basic seesaw type operator

Similar to M. Pospelov, Phys. Rev. D **84**, 085008 (2011)

$\nu_s,\ \theta_s \qquad \langle \nu_s | \nu_{e,\mu,\tau} \rangle \equiv 0$

$\phi^\mu,\ m_\phi$

Goldstone Boson associated with ν_s acquires mass when H' symmetry is broken

$$\mathcal{L} \supset g_s \phi^\mu \bar{\nu}_s \gamma_\mu \nu_s$$

Does this solve the N_{eff} problem?

$$\Gamma_{rel} = \frac{V_x^2}{V_z^2 + V_x^2 + \Gamma_s^2/4}\Gamma_s$$

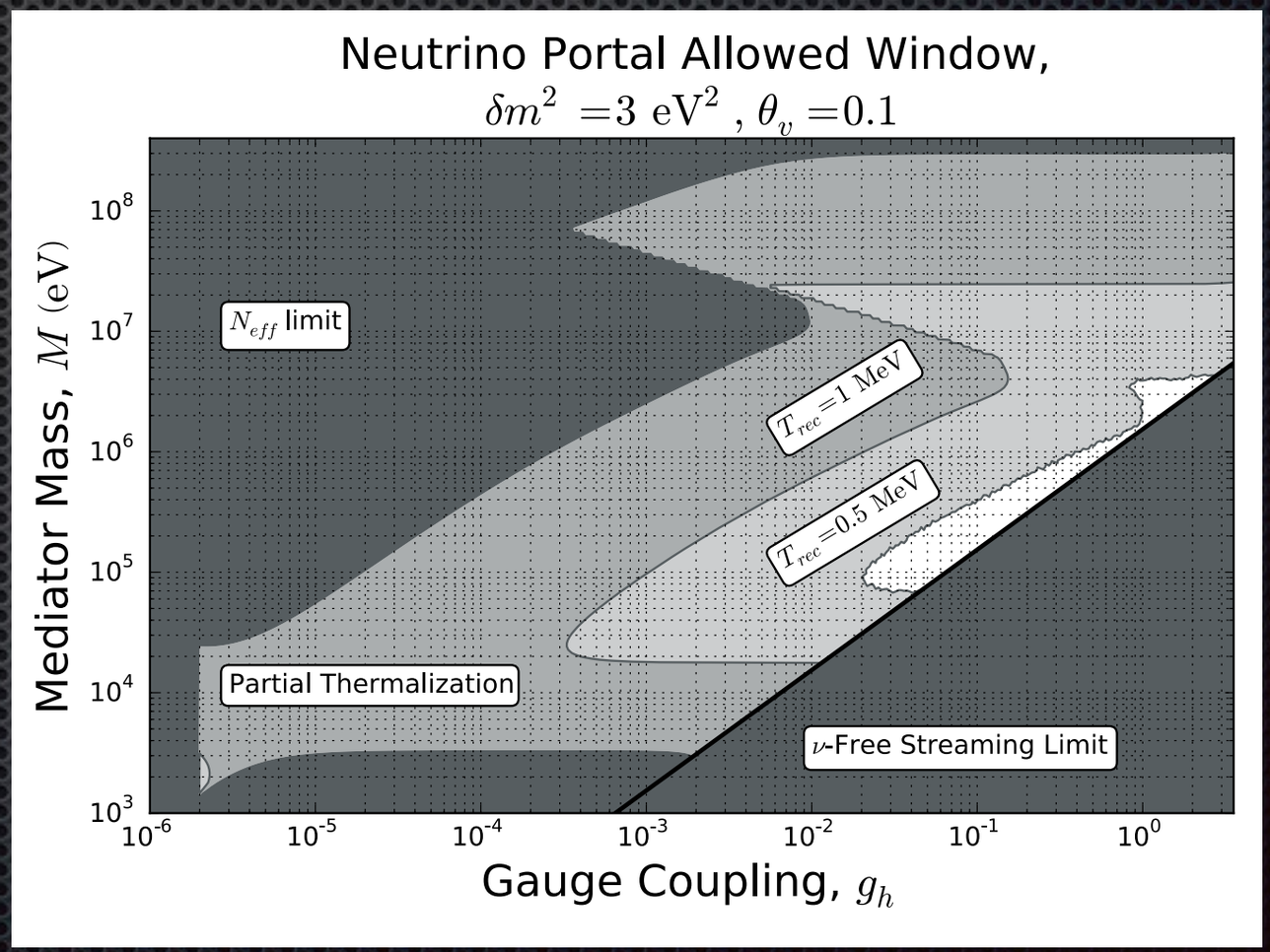
- Yes! Cherry, Friedland, Shoemaker, arXiv:1605.06506
- So long as

$$\Gamma_{rel} \ll H = \frac{1.66\sqrt{g_\star}T^2}{m_{pl}}$$

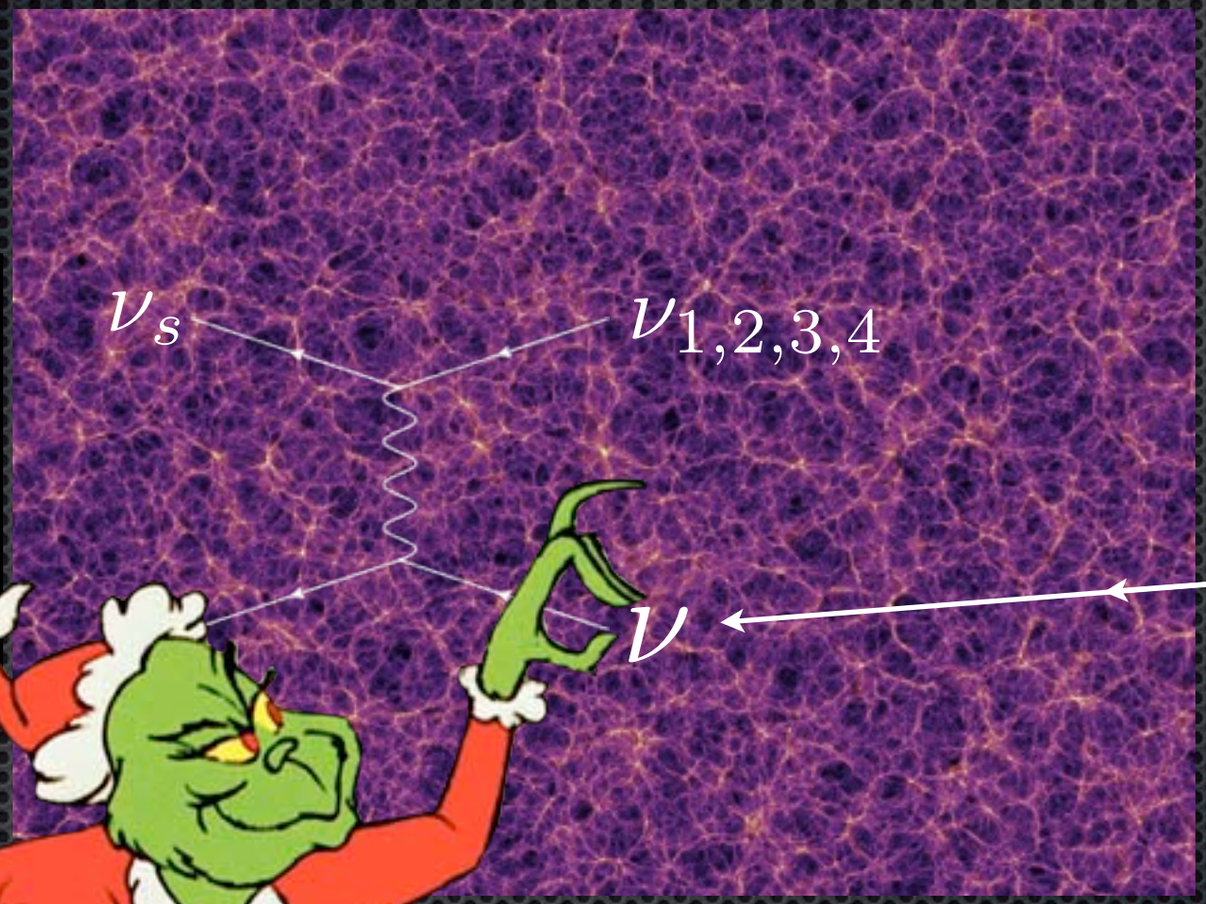
- Delay recoupling to a temperature below

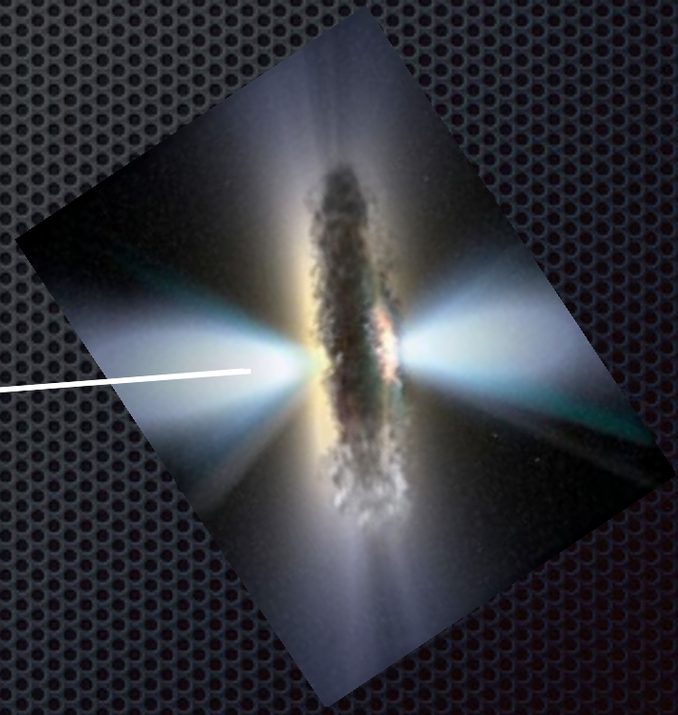
$$T = 3\,\mathrm{MeV}$$

$$\Longrightarrow \Delta N_{eff} \ll 1$$



Scattering = Measurement





$$\langle \nu_s | \nu_{e,\,\mu,\,\tau} \rangle \equiv 0$$

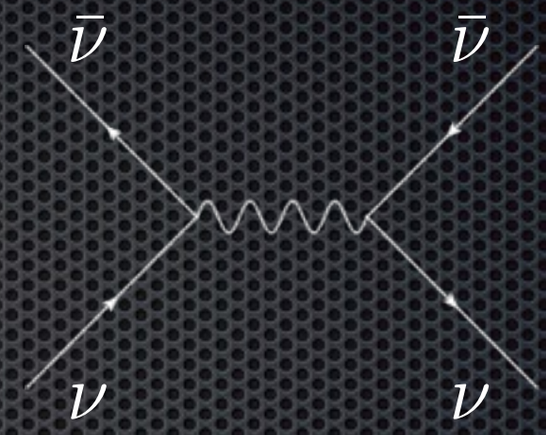
We can put our differences behind us. For Science.
You monster.

The Z-burst

- T. Weiler, PRL (1982): A very high energy neutrino might meet a $\mathrm{C}\nu\mathrm{B}$ neutrino and produce a Z boson on resonance.
- Simply requires the Cosmogenic neutrino to have an energy of $\sim 10^{23}\,\mathrm{eV}$.

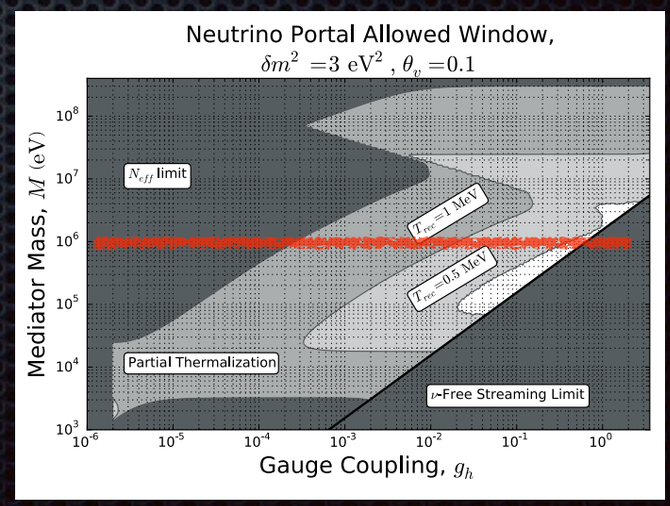
$$E_{CM} \sim \sqrt{(100\,\mathrm{meV})(10^{23}\,\mathrm{eV})} \sim 100\,\mathrm{GeV} \sim m_Z$$

Rather than a burst, IceCube misses neutrinos

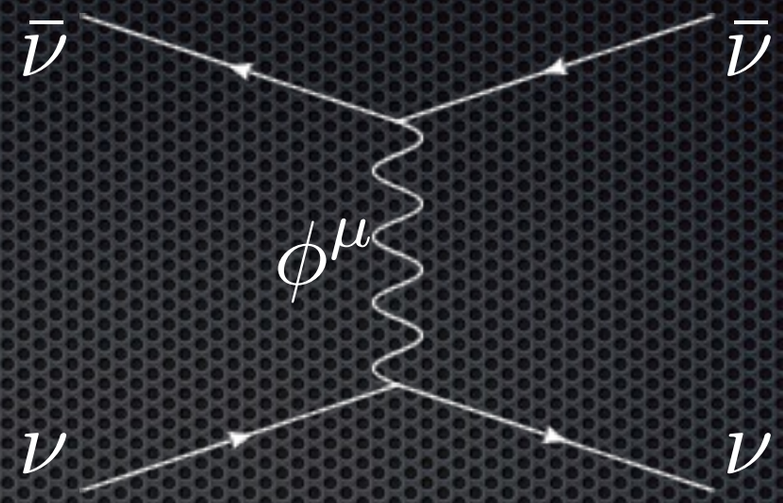


- The same basic physics as the Z-burst, but the end state “burst” is predominantly invisible secluded sector particles.
- IceCube has observed neutrinos in TeV-PeV range, which naturally makes its observations sensitive to particle resonances in the mass range:

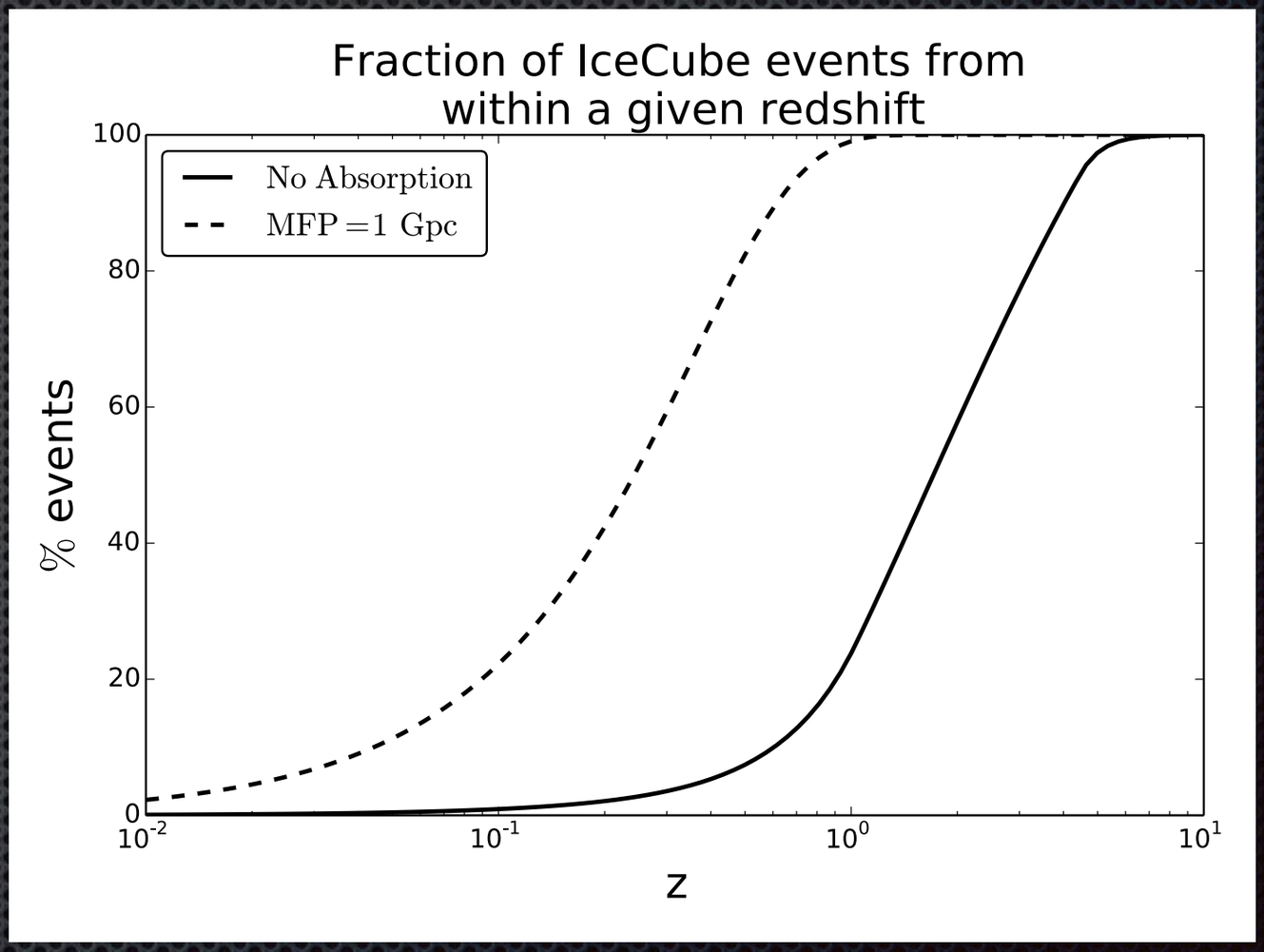
$$\sqrt{m_\nu \times 100\,\mathrm{TeV}} \sim E_{CM} \sim \mathcal{O}(\mathrm{MeV})$$



GZK-like horizon



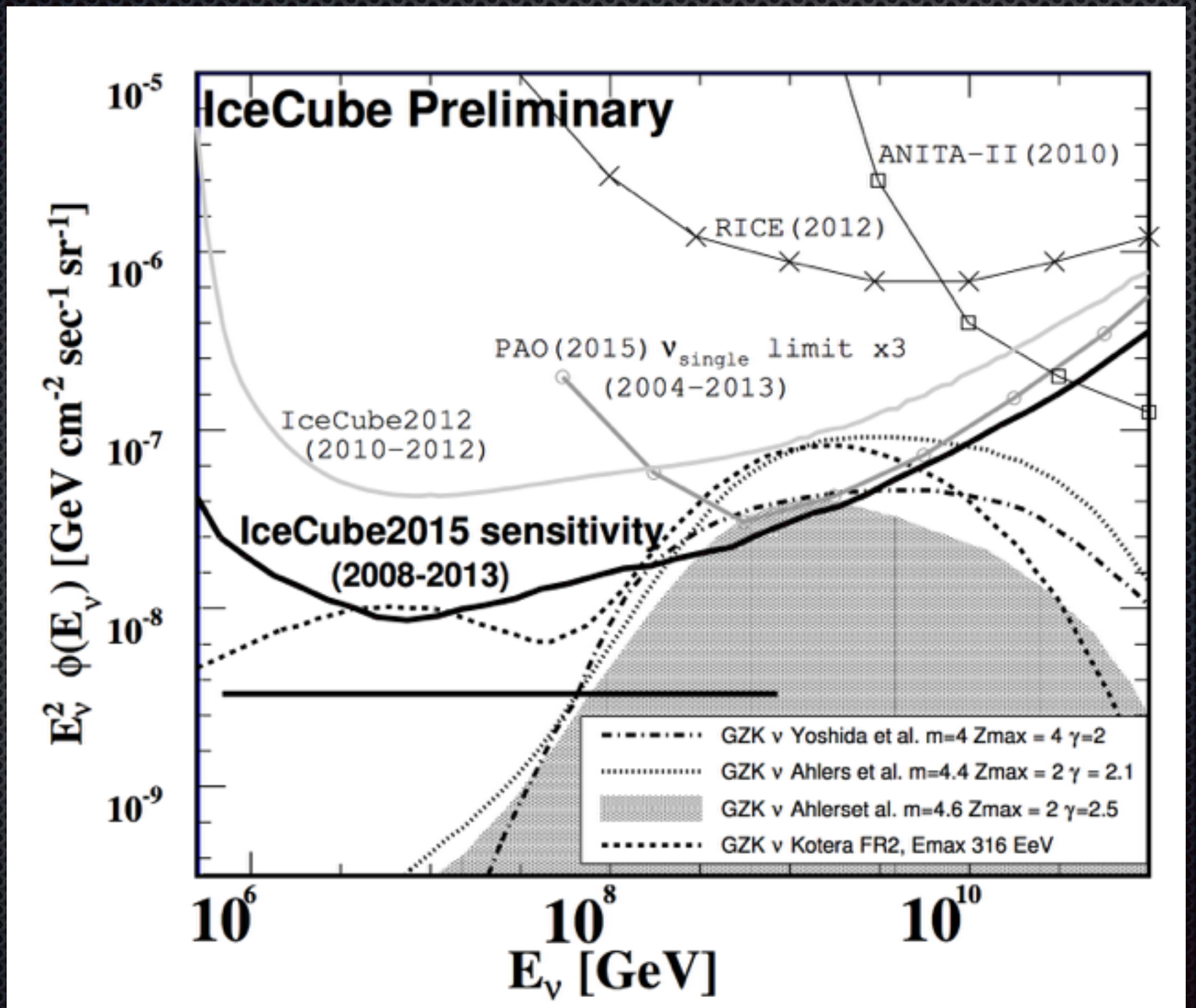
- Continuum limit scattering will also produce apparent absorption of SM neutrinos.
- This could be detected through correlation of low redshift sources with IC events.



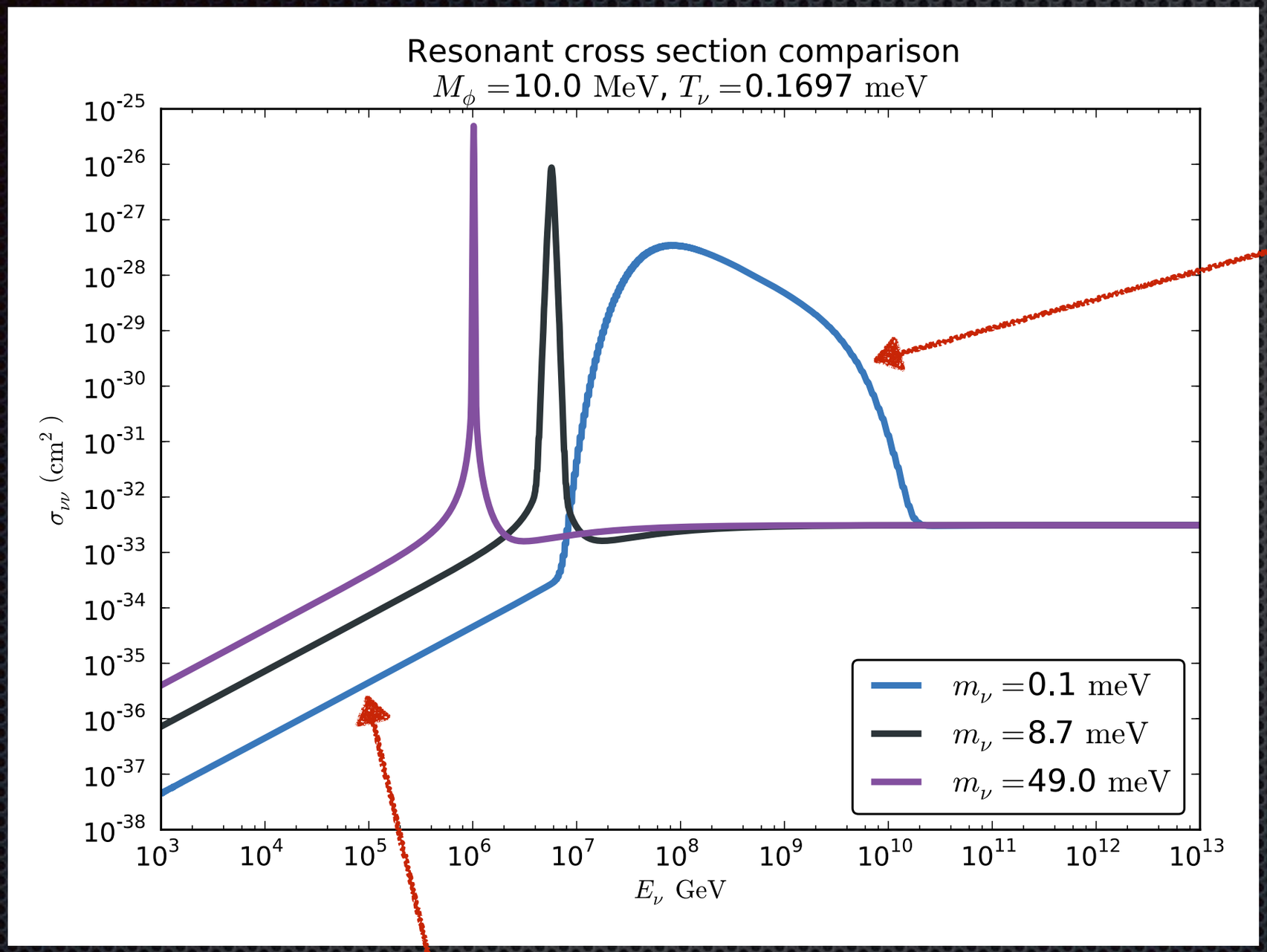
Cherry, Friedland, Shoemaker, arXiv:1411.1071

Neutrino horizon and UHECR fits

IceCube collaboration, arxiv:1510.05223



More types of absorption

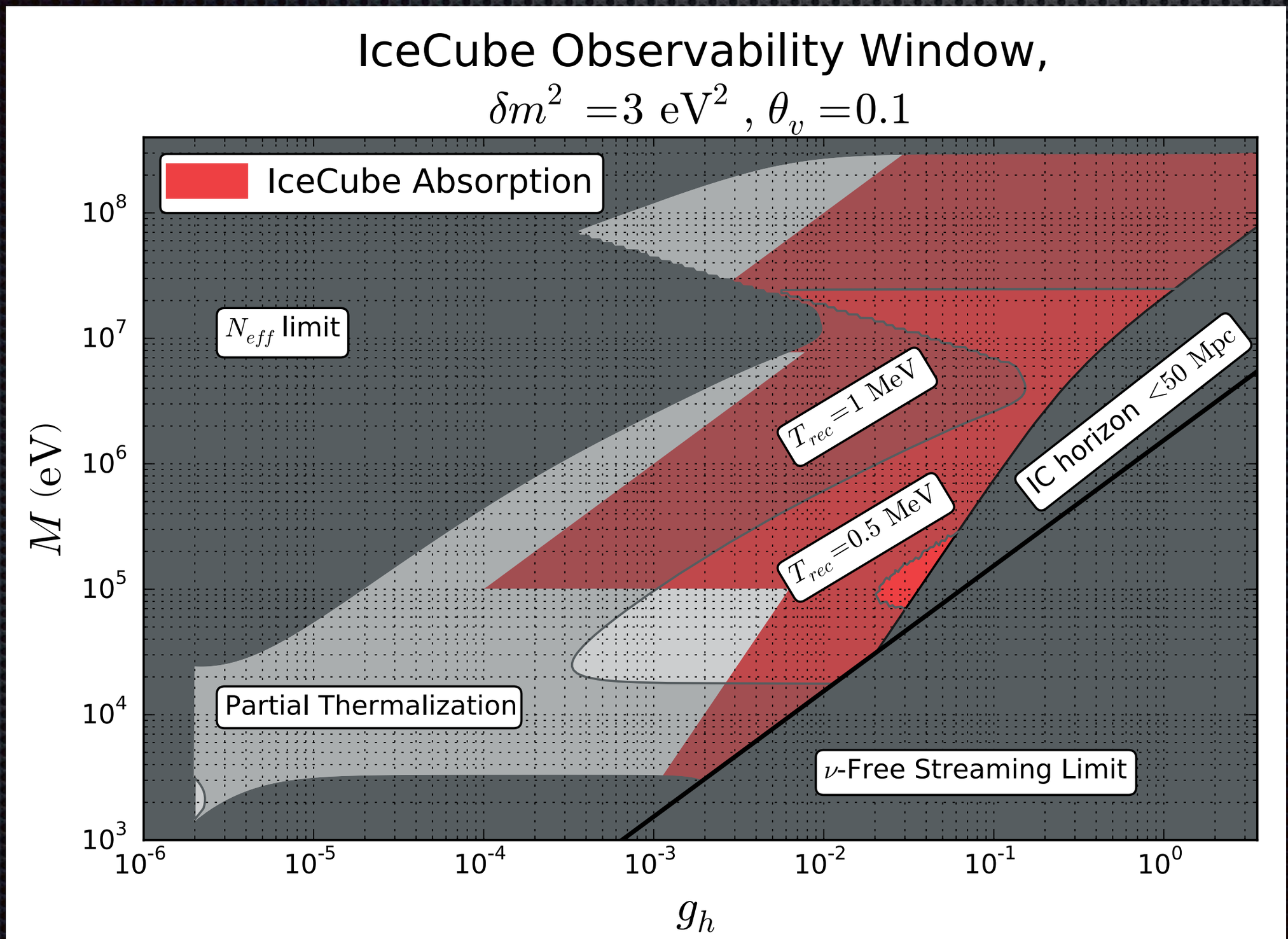


Thermal broadening creates wide absorption features

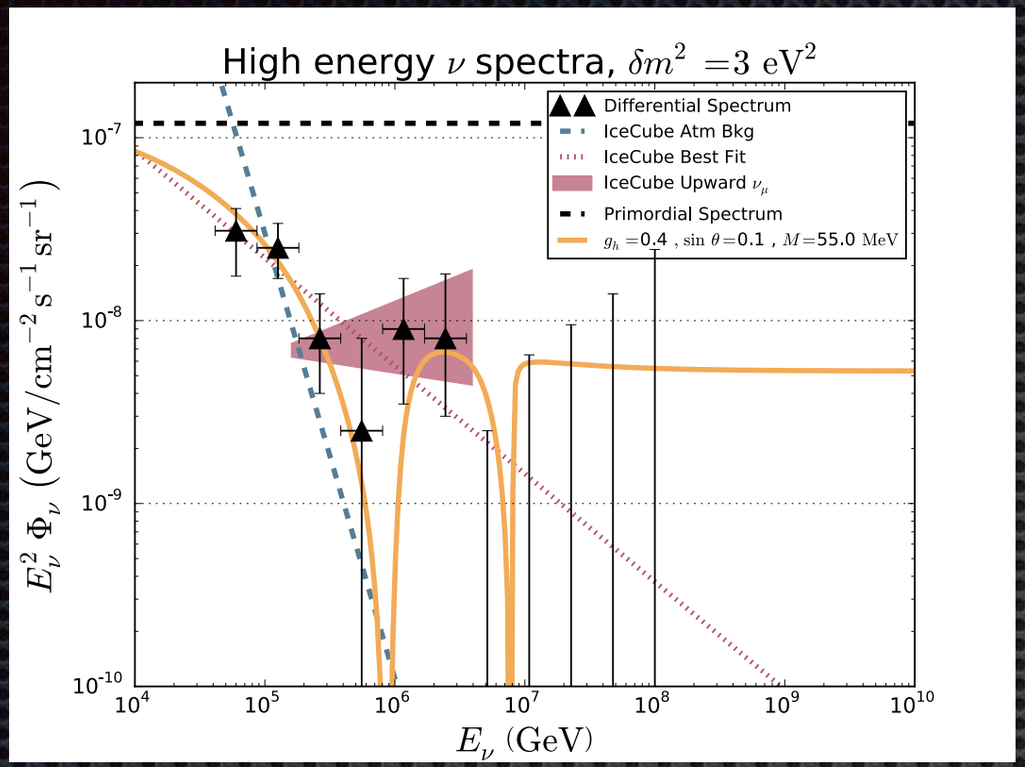
Contact interaction limit shifts the observed spectral index by -1

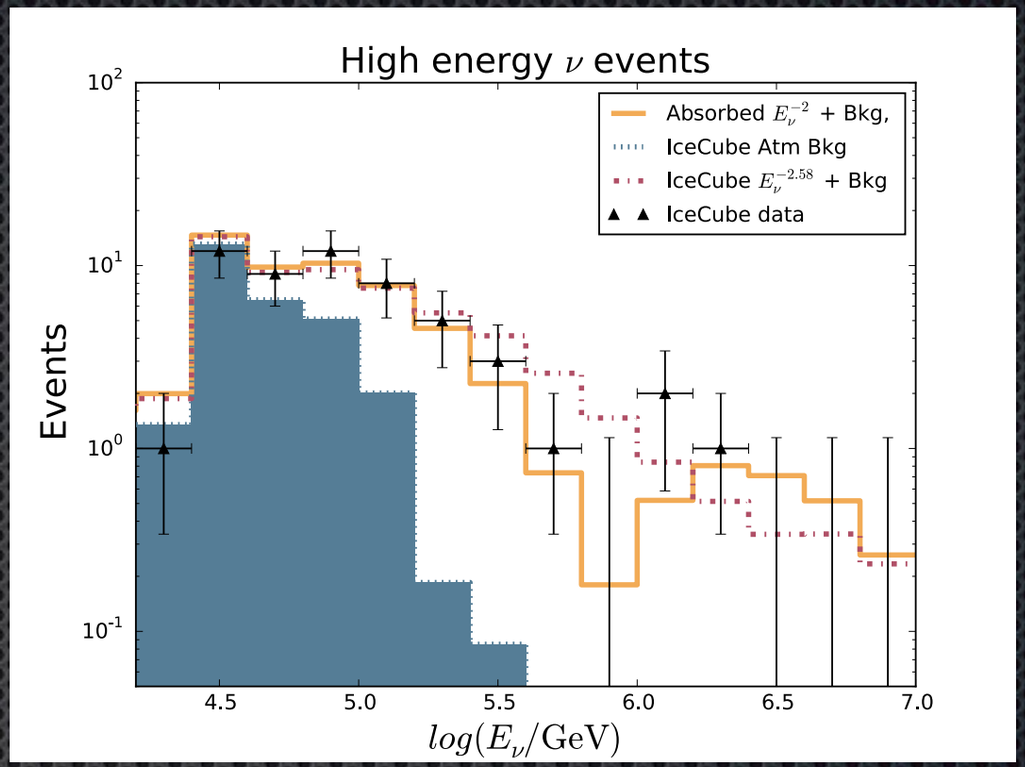
IceCube sensitivity?

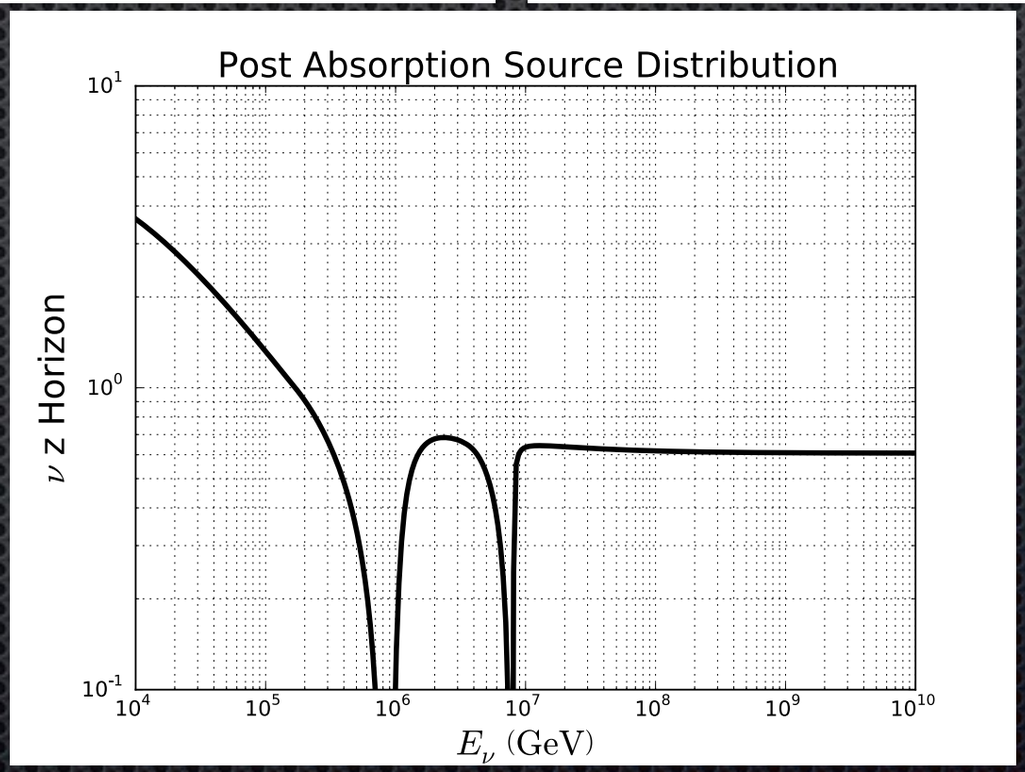
Cherry, Friedland, Shoemaker,
arXiv:1605.06506



Massive SM neutrinos

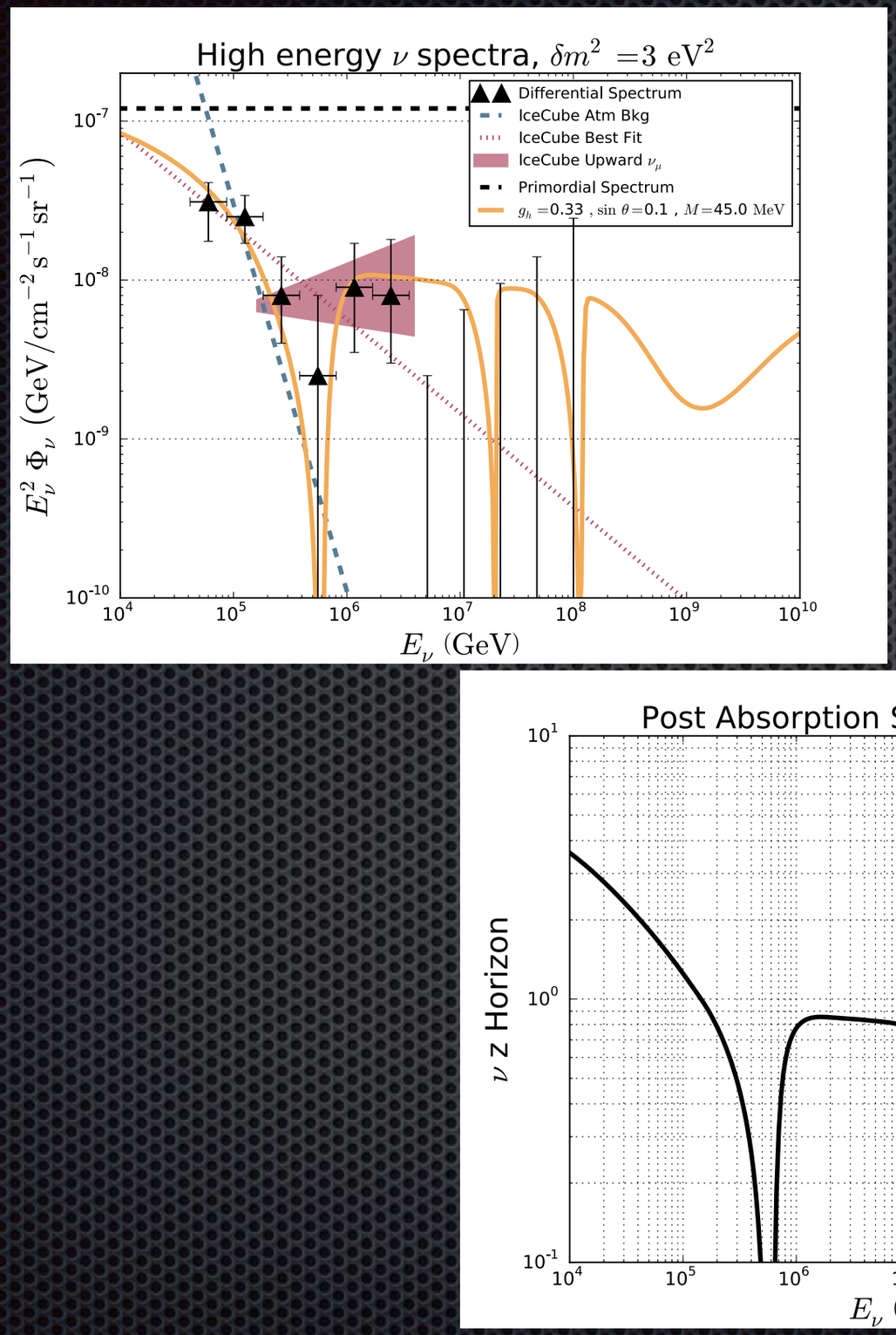


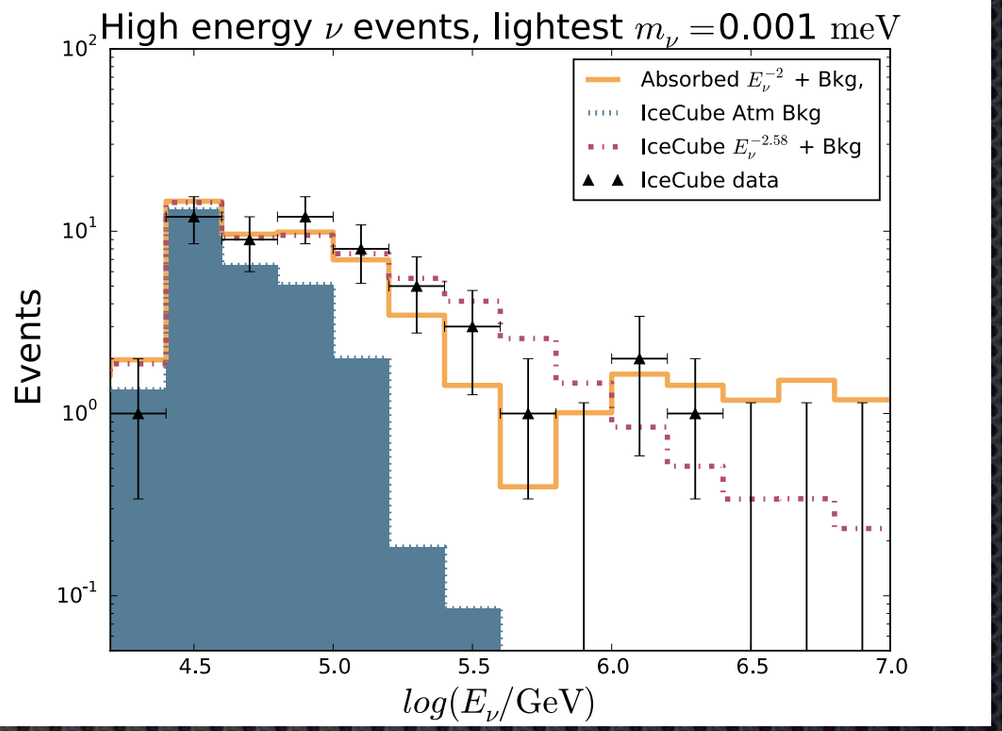


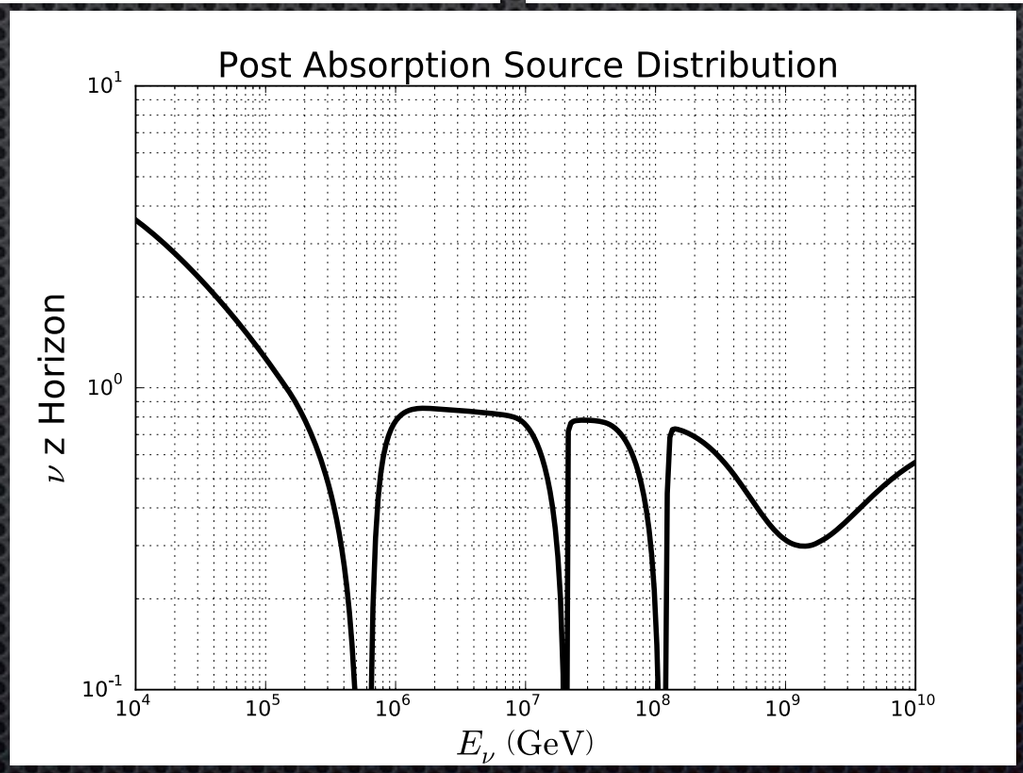


Cherry, Friedland, Shoemaker, in preparation (2016)

Light SM neutrinos

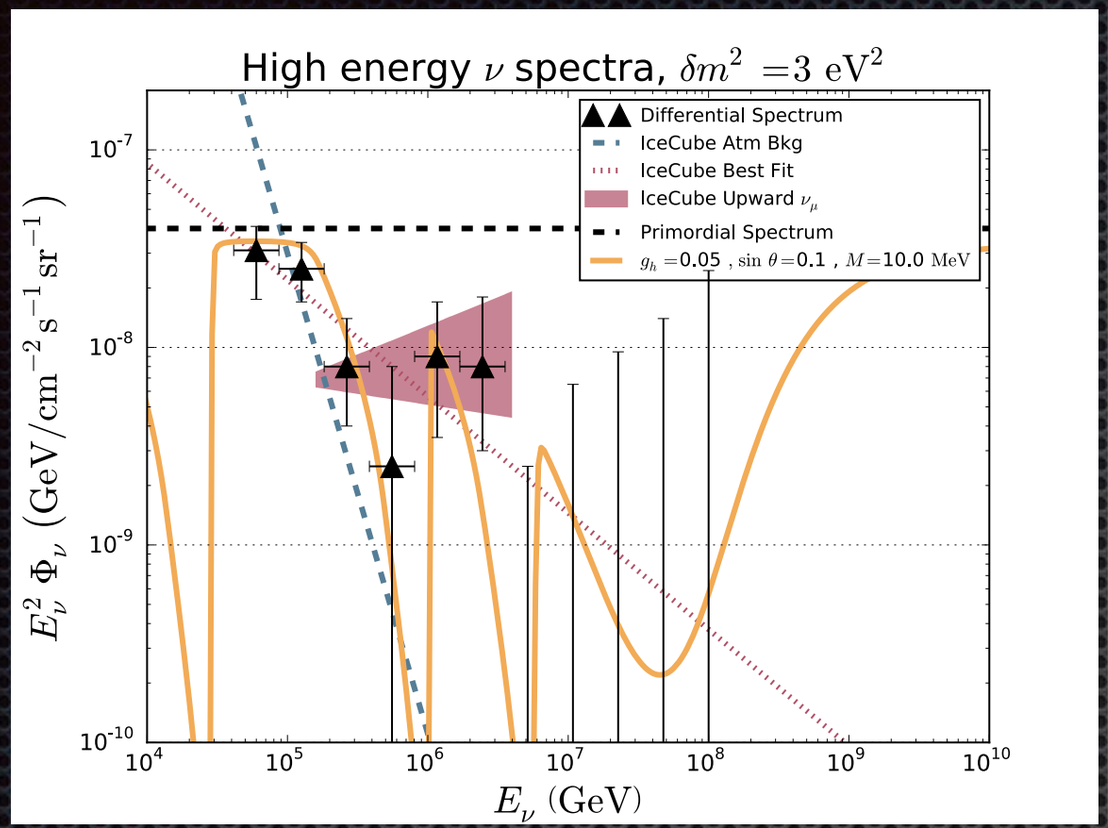


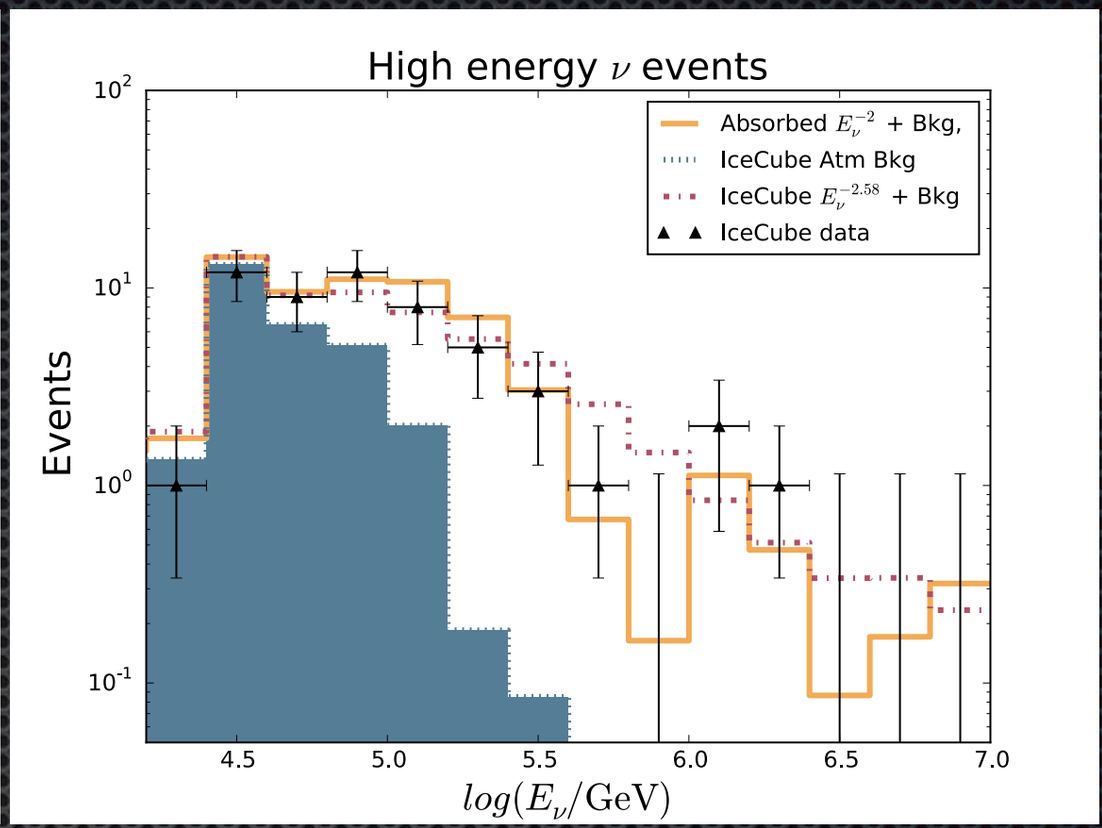


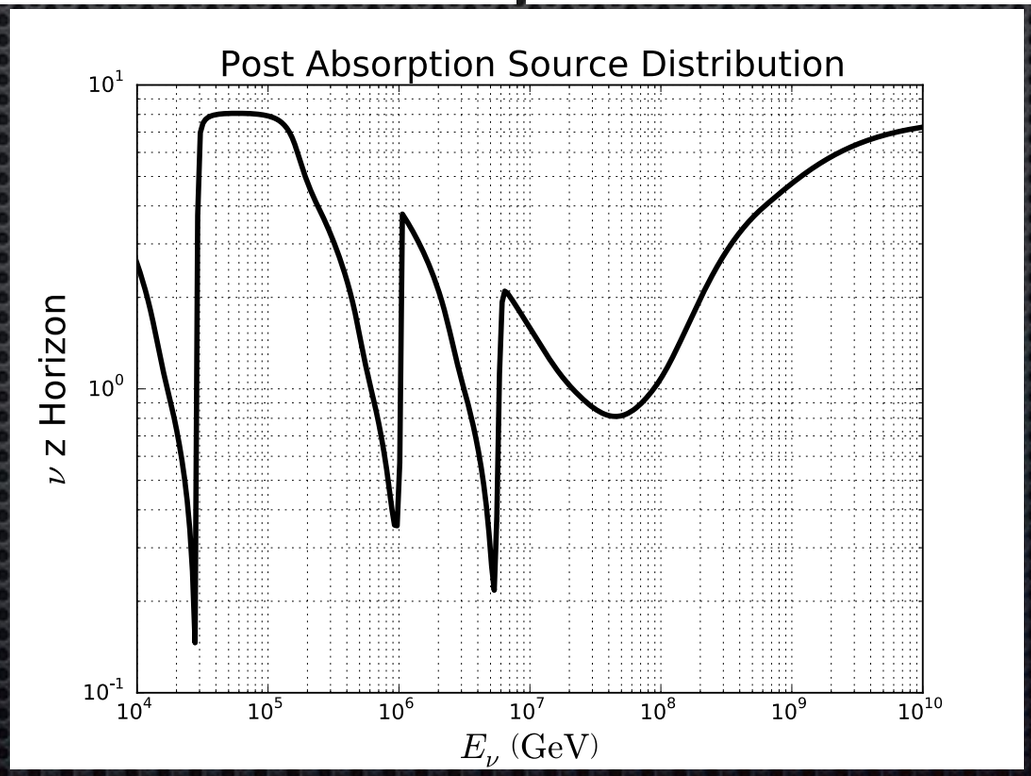


Cherry, Friedland, Shoemaker, in preparation (2016)

No t-channel absorption







Cherry, Friedland, Shoemaker, in preparation (2016)

Conclusions:

- Hidden neutrino interactions provide a novel modification of the UHECR and HESE neutrino signal in IceCube.
- The hidden interaction also reconciles LSND or reactor sterile neutrino anomalies with Precision Cosmology data.
- IceCube is taking data right now, and quirks/source correlations in the observed spectra could be evidence of BSM physics.

Thank you very much!