Abstract

Neutrino decay modifies neutrino propagation in a unique way; not only is there flavor changing as there is in neutrino oscillations, there is also energy transport from initial to final neutrinos. The most sensitive direct probe of neutrino decay is currently IceCube which can measure the energy and flavor of neutrinos traveling over extragalactic distances. For the first time we calculate the flavor transition probability for the cases of visible and invisible neutrino decay, including the effects of the expansion of the universe, and consider the implications for IceCube. As an example, we demonstrate how neutrino decay addresses a tension in the IceCube data.

Astrophysical Neutrino Decay

Peter B. Denton

ICHEP

July 28, 2020

1805.05950 with Irene Tamborra
and
2005.07200 with Asli Abdullahi
github.com/PeterDenton/Astro-Nu-Decay
peterdenton.github.io/Data/Visible_Decay/index.html

BROOKHAVEN NATIONAL LABORATORY

Brookhaven NDI
Neutrino Discovery Initiative

Overview

1. The global neutrino decay picture
2. How to calculate visible neutrino decay for astrophysics
3. The impact of the different parameters
4. Hints of neutrino decay at IceCube

Neutrino Decay

Since neutrinos have different masses, they decay

- Loop suppressed
- Long lifetime: $\tau \gtrsim 10^{35}$ years

Test this!

Typical Lagrangian for $\nu_i \to \nu_j + \phi$ with $m_i > m_j$

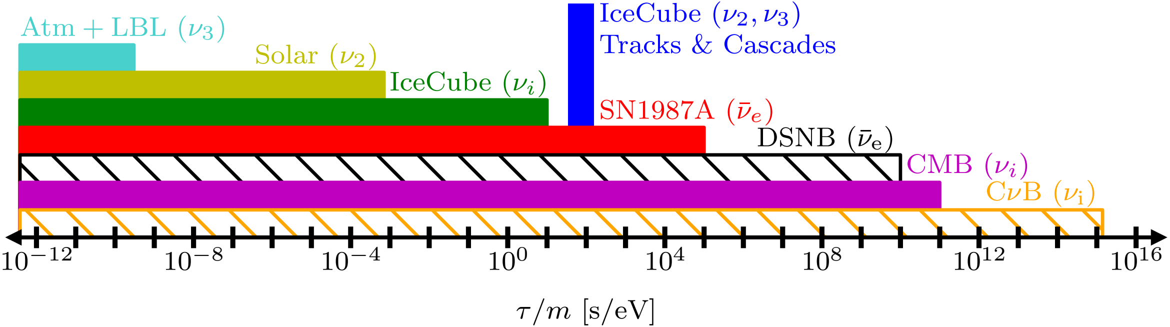
$$\mathcal{L} \supset \frac{g_{ij}}{2}\bar{\nu}_j \nu_i \phi + \frac{g'_{ij}}{2}\bar{\nu}_j i\gamma_5 \nu_i \phi$$

Neutrino Decay Phenomenology

Neutrino decay is phenomenologically classified into:

- **Invisible decay**:
  - The decay products are sterile or too low energy to be detected
  - Results in a *depletion* of the flux below the relevant energy
- **Visible decay**:
  - Decay products are detected
  - In addition to depletion, there is *regeneration*
  - Regeneration happens at a lower energy than depletion

Invisible ν Decay Constraints and Evidence



M. Gonzalez-Garcia and M. Maltoni 0802.3699

J. Berryman, A. de Gouvea, D. Hernandez 1411.0308

G. Pagliaroli, et al. 1506.02624

PBD, I. Tamborra 1805.05950

Kamiokande-II, PRL 58 1490 (1987)

S. Ando hep-ph/0307169

S. Hannestad, G. Raffelt hep-ph/0509278

A. Long, C. Lunardini, E. Sabancila 1405.7654

Why IceCube for Neutrino Decay

- DSNB and CνB are still some time off
- The next galactic supernova could come tomorrow, or in fifty years
- If ν_1 is stable SN1987A isn't too relevant (25 events + theory uncertainties)
  - Mass ordering looks to be normal at $\sim 3 - 3.5\ \sigma$

    Less now: K. Kelly, et al. 2007.08526
  - Texture in the mixing matrix
  - If $m_1 \gtrsim m_\phi$
- Early universe constraints mostly constrain the typical decay diagram

  G. Dvali and L. Funcke 1602.03191

  M. Escudero and M. Fairbairn 1907.05425
- IceCube measures **all three flavors** over > 1 decade in energy
- Astrophysical uncertainties seem like a problem, aren't really

How to Calculate Visible Neutrino Decay

Ingredients:

1. Oscillation averaged/decohered SM contribution
2. Depletion component
   - This takes us to invisible decay
3. Regeneration component at lower energies
   - This takes us to visible decay

Steps:

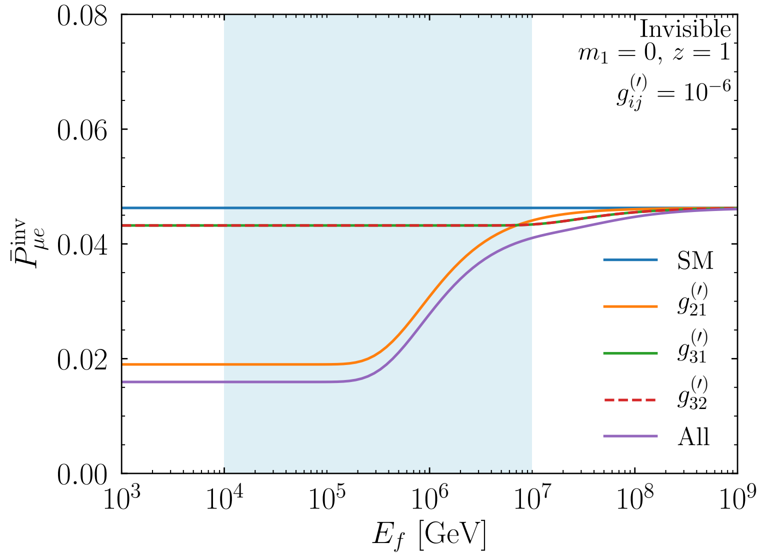
1. Integrate over decay location
2. Integrate over initial energy spectrum due to regeneration
3. Include multiple decays
4. Include cosmology
5. Mix thoroughly, let bake for an hour

M. Lindner, T. Ohlsson, W. Winter astro-ph/0105309

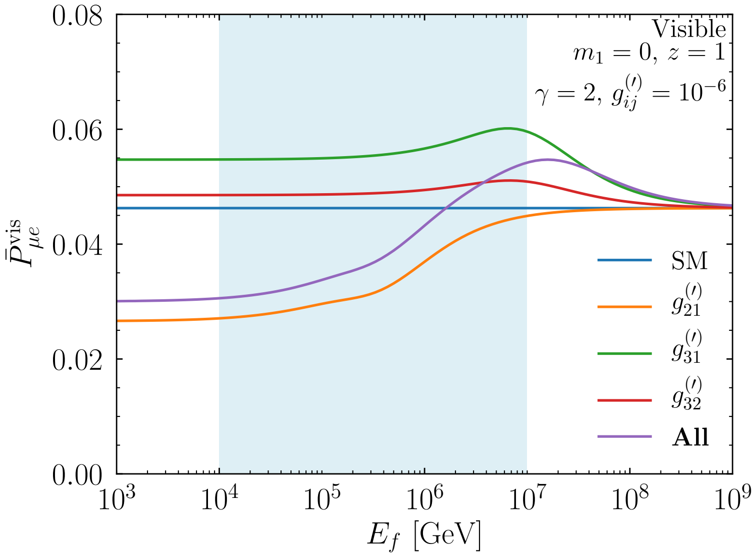
J. Beacom et al. hep-ph/0211305

P. Baerwald, M. Bustamante, W. Winter 1208.4600

Results: Invisible Decay



Results: Visible Decay



Summary of Parameters

More important

1. γ: harder spectra $\Rightarrow$ large regeneration component
2. m_1: higher mass scale $\gtrsim 0.1$ eV $\Rightarrow$ large regeneration component
3. g_{ij}: different features depending on the texture

Less important

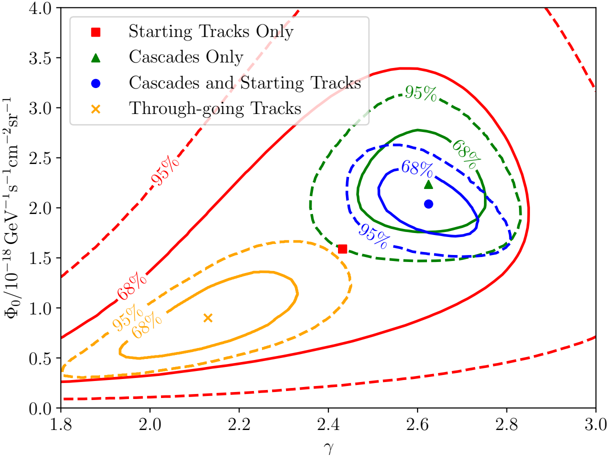
4. Redshift evolution $\Rightarrow$ small effect
5. Scalar/Pseudo-scalar $\Rightarrow$ small effect
6. $\nu \to \nu$, $\nu \to \bar{\nu}$ $\Rightarrow$ small effect

IceCube Measures:

- Energy
- Direction
- Flavor(ish)

Tension

$$\Phi(E) = \Phi_0 E^{-\gamma}$$



$$\boxed{\Delta\gamma = +0.54}$$

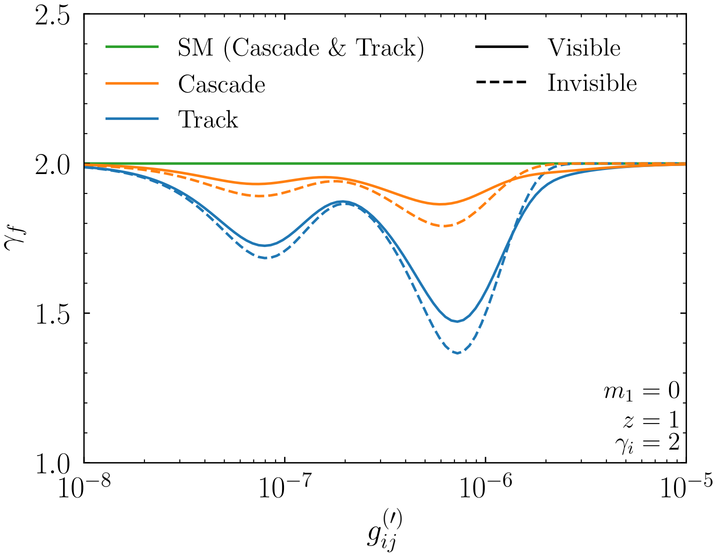
"The p-value for obtaining the combined fit result and the result reported here from an unbroken powerlaw flux is 3.3σ, and is therefore in significant **tension**."

IC 1607.08006

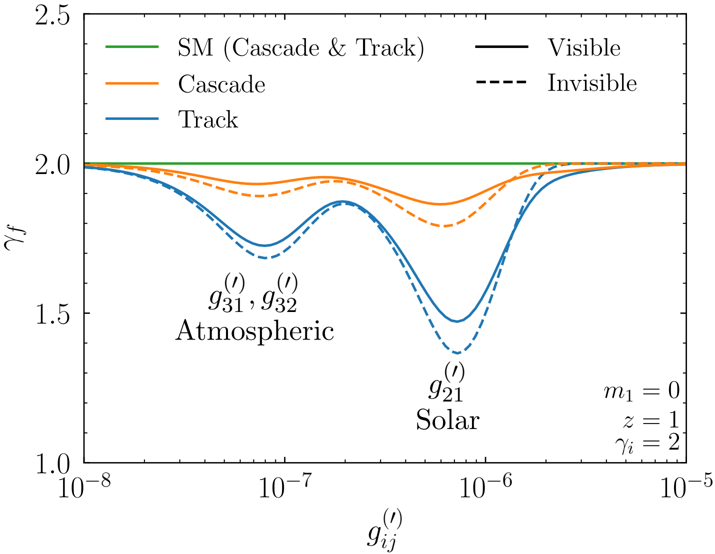
"This [cascade] fit [is] in **tension** with previous results based on through-going muons"

IC 1808.07629

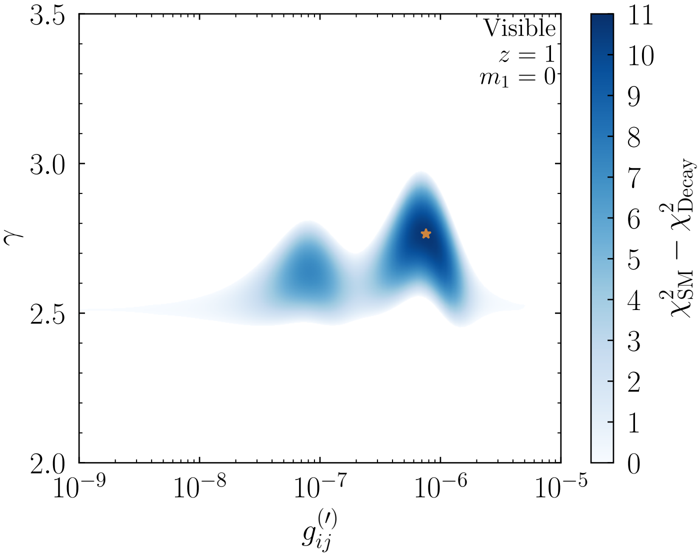
Spectral Indices at IceCube



Spectral Indices at IceCube



Preferred Region: Visible



Key Points

- Neutrino decay pheno can be probed in a broad range of experimental regions
- Visible neutrino decay contains depletion and regeneration terms
- Varying the initial spectrum, mass scale, and couplings leads to a range of spectra
- IceCube is uniquely sensitive to this
- IceCube's track/cascade spectrum can be well described by neutrino decay
- Neutrino decay within the NO predicts the same kind of tension that IceCube sees

Thanks!

Backups

Decay Regimes

The decay width in *lab frame* is Γ_i

ν_i has lifetime $\tau_i = E/m_i\Gamma_i$

- **No decay (SM)**: $\Gamma_i L \ll 1$
- **Partial decay**: $\Gamma_i L \sim 1$
- **Full decay**: $\Gamma_i L \gg 1$

SM Contribution: How to Calculate

First we define a "probability"

$$P_{\alpha\beta}(E_f) \equiv \frac{\Phi^E_{\alpha\beta}(E_f)}{\Phi^S_\alpha(E_f)}$$

Not actually a probability as it can be more than 1, but is probability-like and is useful

Over large distances the mass states decohere and/or the wave packets separate

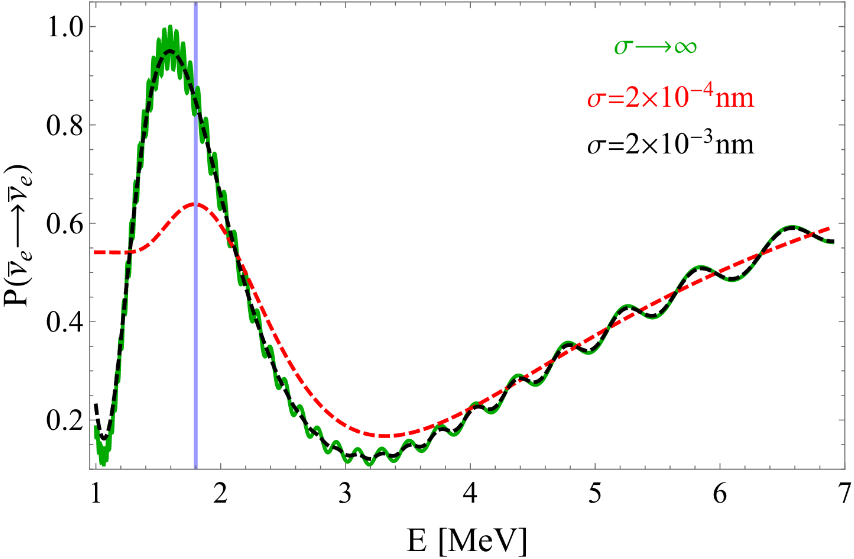
$$\frac{\Delta m^2 L}{E} \gg 1$$

This is easily satisfied for extragalactic sources

Wave packet separation results in an identical flux to oscillation averaging:

$$\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \to \frac{1}{2}$$

The effect of decoherence



SM Contribution: The Probability

Given the usual Hamiltonian,

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger_{\text{PMNS}}$$

The SM oscillation probability is:

$$P^{\text{SM}}_{\alpha\beta} = \left| U^*_{\alpha 1} U_{\beta 1} + U^*_{\alpha 2} U_{\beta 2} e^{-i\frac{\Delta m^2_{21} L}{2E}} + U^*_{\alpha 3} U_{\beta 3} e^{-i\frac{\Delta m^2_{31} L}{2E}} \right|^2$$

When averaged/decohered:

$$\bar{P}^{\text{SM}}_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

No interference terms.

Depletion Component: How to Calculate

$$H = U_{\text{PMNS}} \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} - \frac{i}{2}\Gamma_2 & \\ & & \frac{\Delta m^2_{31}}{2E} - \frac{i}{2}\Gamma_3 \end{pmatrix} U^\dagger_{\text{PMNS}}$$

Assume here and throughout that ν_1 is stable (no lighter sterile neutrino) and the normal ordering

Depletion Component: How to Calculate

$$H = U_{\rm PMNS} \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} - \frac{i}{2}\Gamma_2 & \\ & & \frac{\Delta m^2_{31}}{2E} - \frac{i}{2}\Gamma_3 \end{pmatrix} U^\dagger_{\rm PMNS}$$

Assume here and throughout that ν_1 is stable (no lighter sterile neutrino) and the normal ordering

The partial width including scalar and pseudo-scalar as well as $\nu \to \nu$ and $\nu \to \bar\nu$

$$\Gamma_{ij} = \frac{m_i m_j}{16\pi E_i}\left\{g^2_{ij}\left[f(x_{ij}) + k(x_{ij})\right] + g'^2_{ij}\left[h(x_{ij}) + k(x_{ij})\right]\right\}$$

$$f(x) = \frac{x}{2} + 2 + \frac{2}{x}\log x - \frac{2}{x^2} - \frac{1}{2x^3}$$

$$h(x) = \frac{x}{2} - 2 + \frac{2}{x}\log x + \frac{2}{x^2} - \frac{1}{2x^3}$$

$$k(x) = \frac{x}{2} - \frac{2}{x}\log x - \frac{1}{2x^3}$$

$\Gamma_i = \sum_j \Gamma_{ij}$
$\tau_i = m_i / E_i \Gamma_i$
$x_{ij} \equiv m_i / m_j$
See slide 37 on $\nu/\bar\nu$

Depletion Component: The Probability

$$\bar{P}^{\rm dep}_{\alpha\beta}(E,L) = -|U_{\alpha2}|^2|U_{\beta2}|^2(1-e^{-\Gamma_2L}) - |U_{\alpha3}|^2|U_{\beta3}|^2(1-e^{-\Gamma_3L})$$

The invisible probability is:

$$\bar{P}^{\rm inv}_{\alpha\beta} = \bar{P}^{\rm SM}_{\alpha\beta} + \bar{P}^{\rm dep}_{\alpha\beta}$$

$$\bar{P}^{\rm inv}_{\alpha\beta} = |U_{\alpha1}|^2|U_{\beta1}|^2 + |U_{\alpha2}|^2|U_{\beta2}|^2e^{-\Gamma_2L} + |U_{\alpha3}|^2|U_{\beta3}|^2e^{-\Gamma_3L}$$

Regeneration Component: How to Calculate

Steps:

1. Shift to mass basis
2. Integrate amplitude squared over decay position

   Assume everything is incoherent, see slide 31
3. Integrate over initial neutrino energy weighted by initial neutrino flux
4. Add double decays and cosmology

This is where the meat in the recipe is.

Regeneration Component: Amplitude

The $\nu_i \to \nu_j$ amplitude contains

1. the survival of ν_i over a distance L_1, $e^{-\frac{1}{2}\Gamma_i L_1}$,
2. the phase accumulation of ν_i from the source to L_1, $e^{-iE_i L_1}$,
3. the decay of ν_i and appearance of ν_j, $\sqrt{\Gamma_{ij} W_{ij}}$,
4. for unstable ν_j, survival until Earth, $e^{-\frac{1}{2}\Gamma_j (L-L_1)}$,
5. and the phase accumulation of ν_j until Earth, $e^{-iE_f (L-L_1)}$.

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4. for unstable ν_j, survival until Earth, $e^{-\frac{1}{2}\Gamma_j (L-L_1)}$,
5. and the phase accumulation of ν_j until Earth, $e^{-iE_f (L-L_1)}$.

After removing phases which are irrelevant for averaging,

$$\bar{\mathcal{A}}_{ij}^{\text{reg}} = e^{-\frac{1}{2}\Gamma_i L_1} \sqrt{\Gamma_{ij} W_{ij}} e^{-\frac{1}{2}\Gamma_j (L-L_1)}$$

Note that $\Gamma_1 = 0$

For $\nu \to \nu$ and $\nu \to \bar{\nu}$:

$$\Gamma_{ij} W_{ij} = \frac{m_i m_j}{16\pi E_i^2} \left[g_{ij}^2 \left(\frac{1}{x_{ij}} + x_{ij} + 2 \right) + g_{ij}'^2 \left(\frac{1}{x_{ij}} + x_{ij} - 2 \right) \right]$$

Significantly simpler than expected or in either $\nu \to \nu$ or $\nu \to \bar{\nu}$ cases!

Regeneration Component: Integrals

$$\bar{P}_{ij}^{\rm reg}(E_f,L)=\frac{1}{\Phi_i^S(E_f)}\int_0^L dL_1\int_{E_f}^{x_{ij}^2E_f}dE_i|\bar{\mathcal{A}}_{ij}^{\rm reg}(E_i,E_f,L,L_1)|^2\Phi_i^S(E_i)$$

$$x_{ij}\equiv m_i/m_j$$

Regeneration Component: Integrals

$$\bar{P}_{ij}^{\rm reg}(E_f,L)=\frac{1}{\Phi_i^S(E_f)}\int_0^L dL_1\int_{E_f}^{x_{ij}^2E_f}dE_i|\bar{\mathcal{A}}_{ij}^{\rm reg}(E_i,E_f,L,L_1)|^2\Phi_i^S(E_i)$$

$$x_{ij}\equiv m_i/m_j$$

After the L_1 integral,

$$\bar{P}_{ij}^{\rm reg}(E_f,L)=\frac{1}{\Phi_i^S(E_f)}\int_{E_f}^{x_{ij}^2E_f}dE_i\frac{\Gamma_{ij}W_{ij}}{\Gamma_i-\Gamma_j}\left[1-e^{-(\Gamma_i-\Gamma_j)L}\right]\Phi_i^S(E_i)$$

Regeneration Component: Integrals

$$\bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{1}{\Phi_i^S(E_f)} \int_0^L dL_1 \int_{E_f}^{x_{ij}^2 E_f} dE_i |\bar{\mathcal{A}}_{ij}^{\text{reg}}(E_i, E_f, L, L_1)|^2 \Phi_i^S(E_i)$$

$$x_{ij} \equiv m_i/m_j$$

After the L_1 integral,

$$\bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{1}{\Phi_i^S(E_f)} \int_{E_f}^{x_{ij}^2 E_f} dE_i \frac{\Gamma_{ij} W_{ij}}{\Gamma_i - \Gamma_j} \left[1 - e^{-(\Gamma_i - \Gamma_j)L}\right] \Phi_i^S(E_i)$$

After the E_i integral,

$$\bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{z(x)}{\gamma y(x)} \left\{1 - \frac{1}{x^{2\gamma}} + \gamma T^{-\gamma} \left[\Gamma(\gamma, T) - \Gamma\left(\gamma, \frac{T}{x^2}\right)\right]\right\}$$

$$T \equiv \frac{m_i m_j L}{16\pi E_f} y(x)$$

$$y(x) = g_{ij}^2 \left[f(x) + k(x)\right] + g_{ij}'^2 \left[h(x) + k(x)\right]$$

$$z(x) = g_{ij}^2 \left(\tfrac{1}{x} + x + 2\right) + g_{ij}'^2 \left(\tfrac{1}{x} + x - 2\right)$$

Regeneration Component: Analytic Limits

- Verify that as $E_f \to \infty$, $\bar{P}_{ij}^{\rm reg} \to 0$ as expected

SM

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SM

- As $E_f \to 0$:

Full decay

$$\lim_{E_f \to 0} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{z(x)}{\gamma y(x)}\left(1 - \frac{1}{x^{2\gamma}}\right)$$

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  - As $m_1 \to \infty$

Degenerate masses

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{ij}^{\rm reg}(E_f, L) = 1$$

Regeneration Component: Analytic Limits

- Verify that as $E_f \to \infty$, $\bar{P}_{ij}^{\text{reg}} \to 0$ as expected

SM

- As $E_f \to 0$:

Full decay

$$\lim_{E_f \to 0} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{z(x)}{\gamma y(x)} \left(1 - \frac{1}{x^{2\gamma}}\right)$$

  - As $m_1 \to \infty$

Degenerate masses

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = 1$$

  - As $m_1 \to 0$

Depends on nature of interaction!

$$\lim_{\substack{E_f \to 0 \\ m_1 \to 0}} \bar{P}_{ij}^{\text{reg}}(E_f, L) = \frac{1}{\gamma}$$

Cosmology

Two main changes:

1. $L \to L(z_a, z_b)$

$$L(z_a, z_b) = L_H \int_{z_a}^{z_b} \frac{dz'}{(1+z')h(z')}$$

$$h(z) \equiv \sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

2. $E \to E(1+z)$
   - $\Gamma \to \Gamma/(1+z)$
   - $\Gamma W \to \Gamma W/(1+z)^2$
   - $\exp(-\Gamma L) \to \exp[-L_H \int_{z_a}^{z_b} \frac{dz'}{(1+z')^{\mathbf{2}} h(z')}]$

By definition, the "probability" now is:

$$\bar{P}_{ij}^{\mathrm{SM}} = \delta_{ij}(1+z)^{-\gamma}$$

Affects both depletion and regeneration!

Regeneration Component: Analytic Limits with Cosmology

- As $m_1 \to \infty$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}^{\rm reg}_{ij}(E_f, L) = (1+z)^{-2\gamma}$$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}^{\rm vis}_{\alpha\beta} = (1+z)^{-\gamma}\left[|U_{\alpha1}|^2|U_{\beta1}|^2 + |U_{\alpha2}|^2|U_{\beta2}|^2 + (1+z)^{-\gamma}|U_{\alpha3}|^2|U_{\beta1}|^2\right]$$

Regeneration Component: Analytic Limits with Cosmology

- As $m_1 \to \infty$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{ij}^{\rm reg}(E_f, L) = (1+z)^{-2\gamma}$$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to \infty}} \bar{P}_{\alpha\beta}^{\rm vis} = (1+z)^{-\gamma}\left[|U_{\alpha1}|^2|U_{\beta1}|^2 + |U_{\alpha2}|^2|U_{\beta2}|^2 + (1+z)^{-\gamma}|U_{\alpha3}|^2|U_{\beta1}|^2\right]$$

- As $m_1 \to 0$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to 0}} \bar{P}_{ij}^{\rm reg}(E_f, L) = \frac{(1+z)^{-2\gamma}}{\gamma}$$

$$\lim_{\substack{E_f \to 0 \\ m_1 \to 0}} \bar{P}_{\alpha\beta}^{\rm vis} = (1+z)^{-\gamma}\left[|U_{\alpha1}|^2|U_{\beta1}|^2 + |U_{\alpha2}|^2|U_{\beta2}|^2 + \frac{(1+z)^{-\gamma}}{\gamma}|U_{\alpha3}|^2|U_{\beta1}|^2\right]$$

Regeneration Component: Multiple Decays

If g_{32} and g_{21} are nonzero, there is another way to get from $\nu_3 \to \nu_1$:

1. Decay from $\nu_3 \to \nu_2$ at z_1 from $E_i \to E_{\rm int}$
2. Decay from $\nu_2 \to \nu_1$ at z_2 from $E_{\rm int} \to E_f$

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2. Decay from $\nu_2 \to \nu_1$ at z_2 from $E_{\rm int} \to E_f$

$$\bar{P}_{31}^{\rm reg,2} = \frac{L_H^2}{\Phi_i^S(E_f)} \int_0^z dz_2 \int_{z_2}^z dz_1 \int_{E_f(1+z_2)}^{E_f x_{21}^2(1+z_2)} dE_{\rm int} \int_{E_{\rm int}(1+z_1)}^{E_{\rm int} x_{32}^2(1+z_1)} dE_i$$
$$\frac{\Gamma_{32}W_{32}\Gamma_{21}W_{21}e^{-\Gamma_3 L(z_1,z)-\Gamma_2 L(z_2,z_1)}}{(1+z_1)^2 h(z_1)(1+z_2)^2 h(z_2)} \Phi_i^S(E_i(1+z_1))$$

Where

$$\Gamma_3 \to \Gamma_3(E_i) \qquad \text{and} \qquad \Gamma_2 \to \Gamma_2(E_{\rm int})$$
$$\Gamma_{32}W_{32} \to \Gamma_{32}W_{32}(E_i, E_{\rm int}) \qquad \text{and} \qquad \Gamma_{21}W_{21} \to \Gamma_{21}W_{21}(E_{\rm int}, E_f)$$

Regeneration Component: Coherency

Now coherency is a problem:

1. If the decay happens before they decohere/separate the interference term should be included
2. If the decay happens after they decohere/separate it shouldn't be included

In principle there should be a $\exp[-(L/L_{\rm COH})^2]$ type term

A. de Gouvea, V. De Romeri, C. Ternes 2005.03022

We ignore this

1. For partial decay this effect is negligible, only matters for full decay
2. Production regions could be anywhere in the 10^9 - 10^{17} cm region

Backup slide 20 has a plot

Results: SM

Assuming an initial flavor ratio of $(1:2:0)$ (pion decay):

$$(1:2:0) \to (1:1:1)$$

This is a result of several coincidences

- The neutrino energies from pion decay are all roughly the same
- The mixing matrix is approximately tri-bimaximal
    - The deviations we know that exist from TBM don't affect this flavor ratio much

Expect the same flux of each flavor

See slide 53 for deviations from this

Results: Benchmark Values

- Include both scalar and pseudo-scalar interactions with equal couplings
- Include both $\nu \to \nu$ and $\nu \to \bar{\nu}$ channels
- Assume a power law spectrum $\Phi_\alpha^S(E_i) = \Phi_{\alpha,0}^S E^{-\gamma}$ with $\gamma = 2$
- Assume $m_1 = 0$ eV

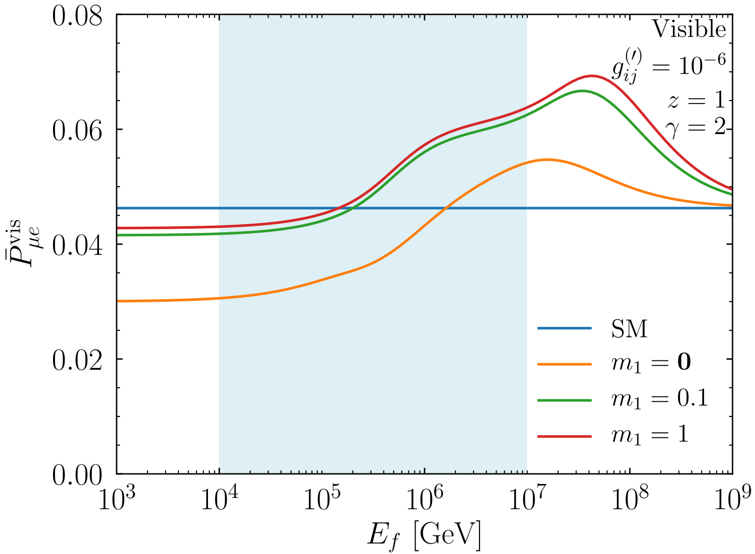
  Anything less than $\sim 10^{-3}$ eV is equivalent to zero
- Assume they are all coming form $z = 1$

  See backup slide 38
- Assume all six couplings are 10^{-6}

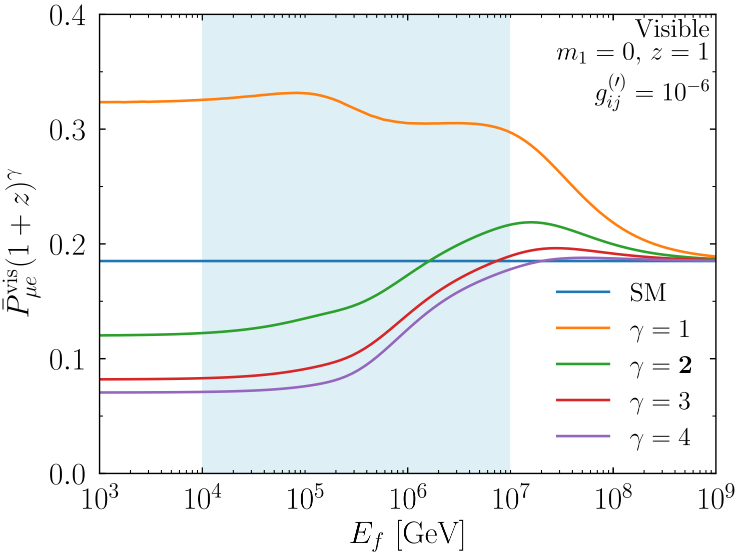
  Puts the partial decay feature in IceCube's view

Turn all the knobs!

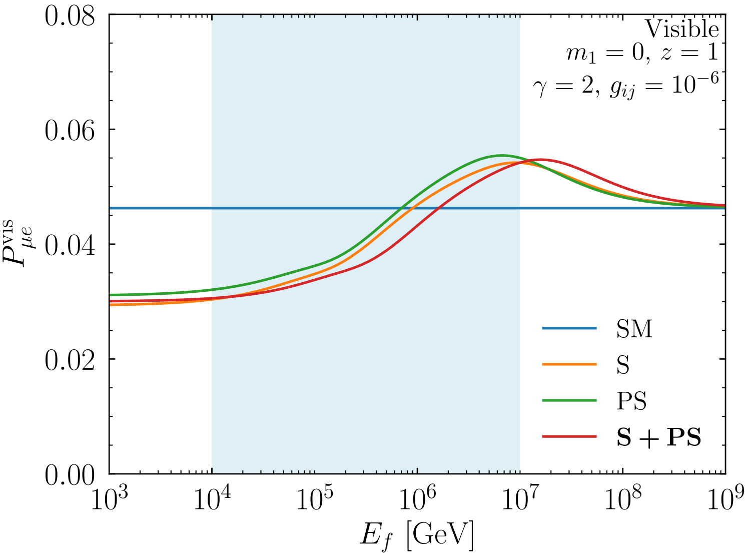
Results: Visible Decay: Neutrino mass scale



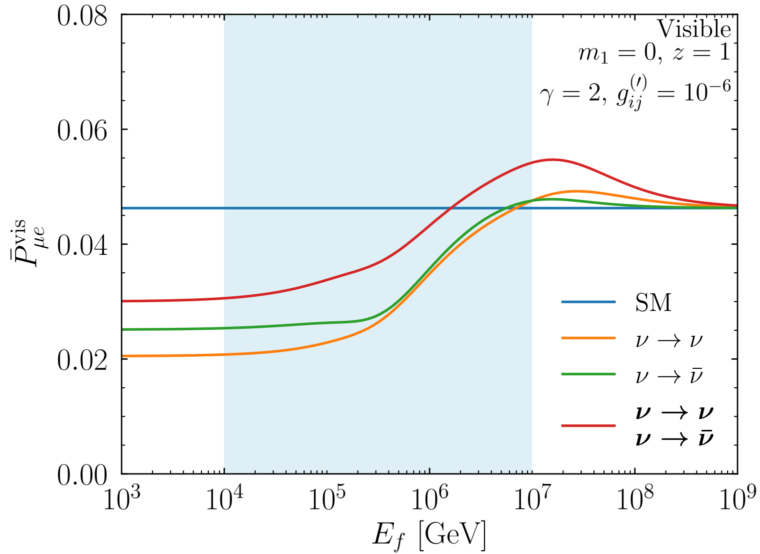
Results: Visible Decay: Spectral Index



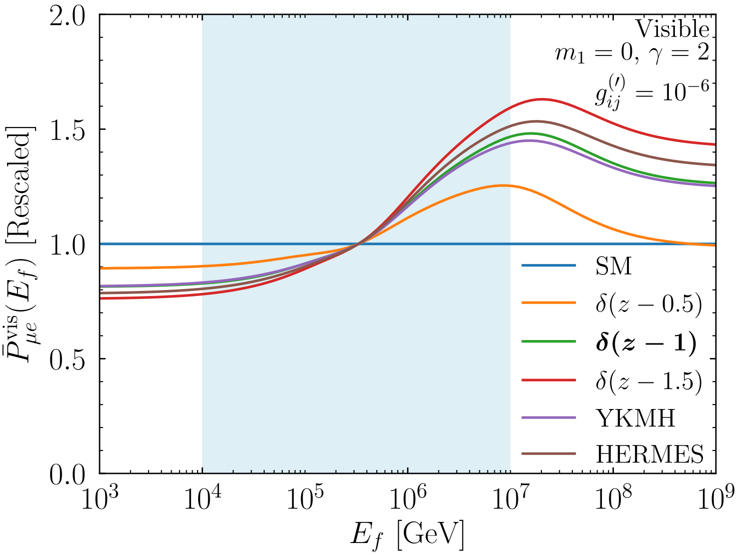
Results: Visible Decay: Scalar vs. Pseudo-scalar



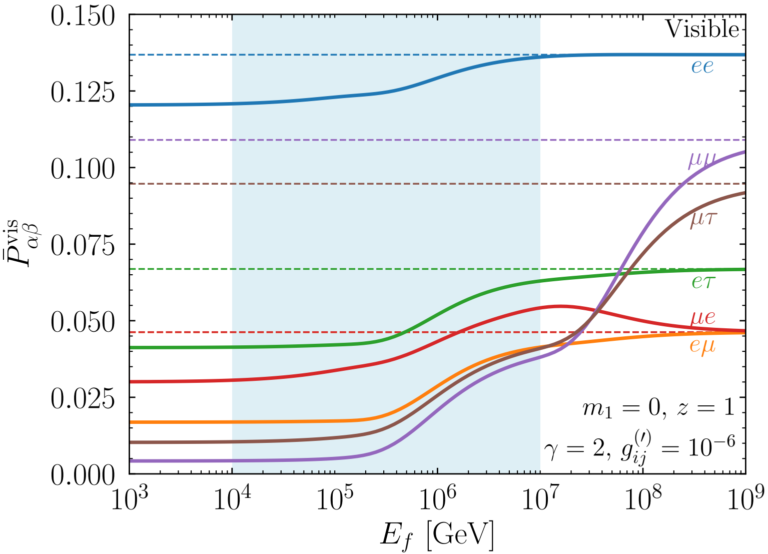
Results: Visible Decay: Neutrinos vs. Anti-neutrinos



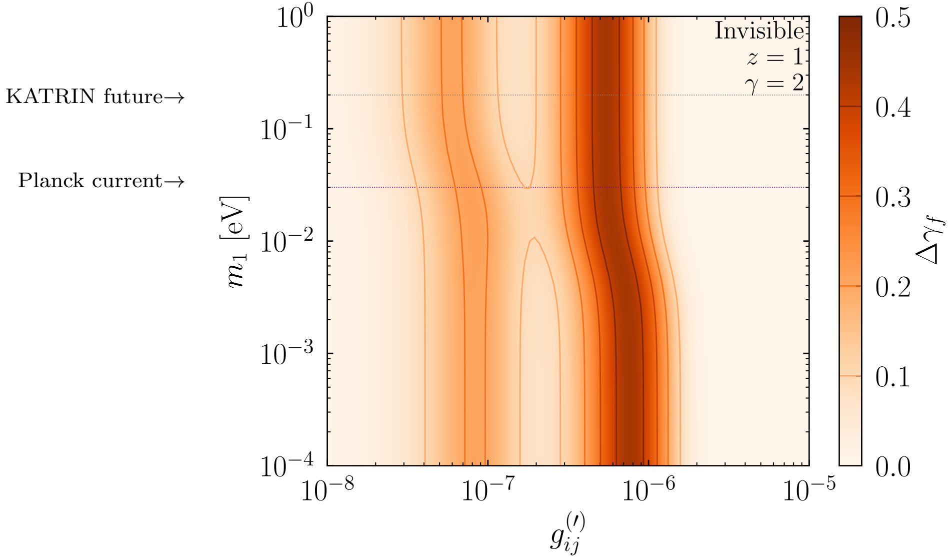
Visible Decay for Different Redshift Evolution Functions



Results: Visible Decay: Flavors



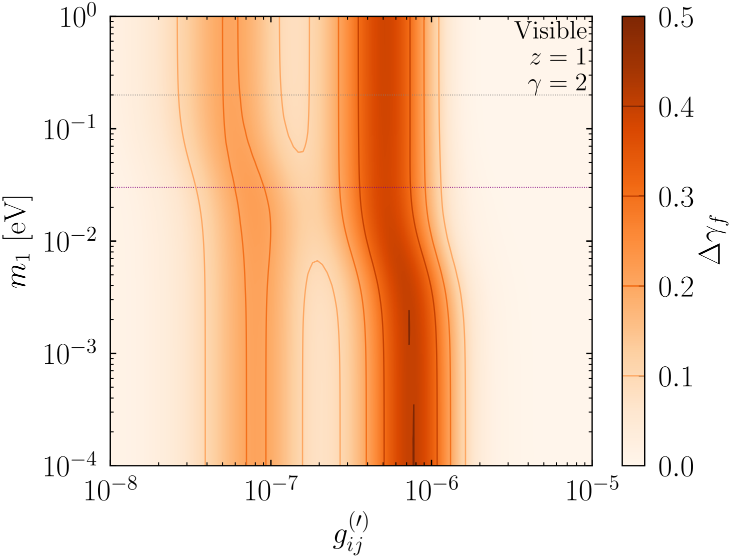
IceCube Track and Cascade Spectral Index Difference: Invisible Decay



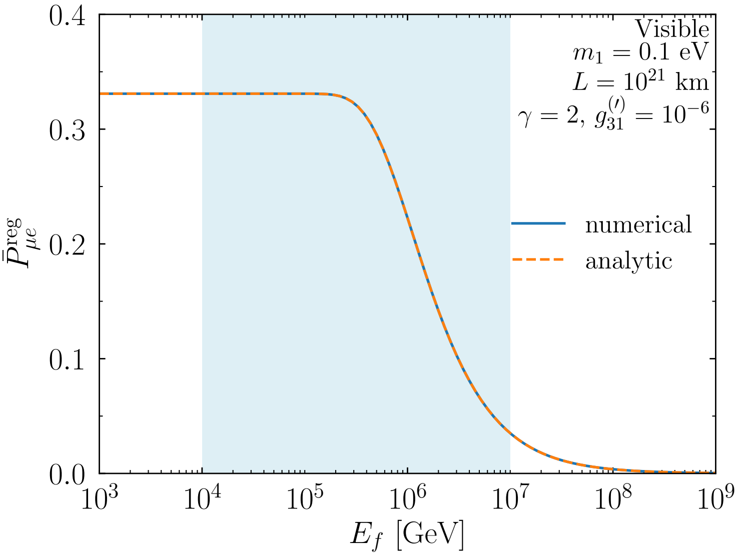
IceCube Track and Cascade Spectral Index Difference: Visible Decay

KATRIN future→

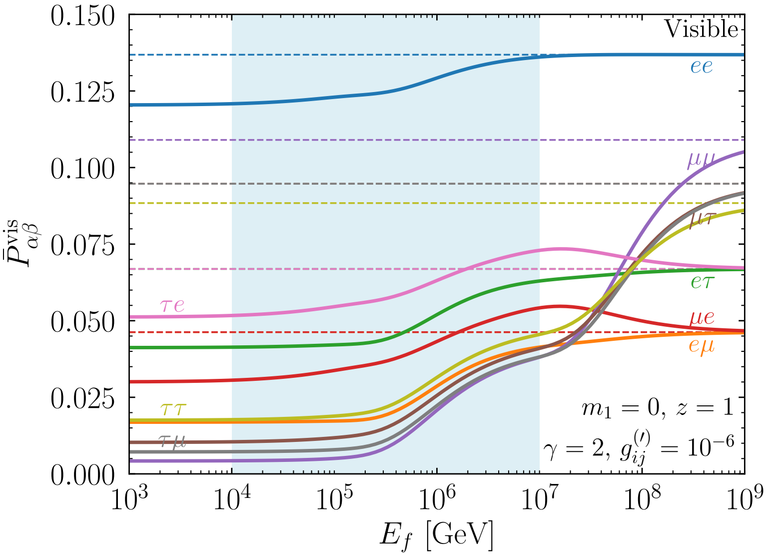
Planck current→



Analytic Validation

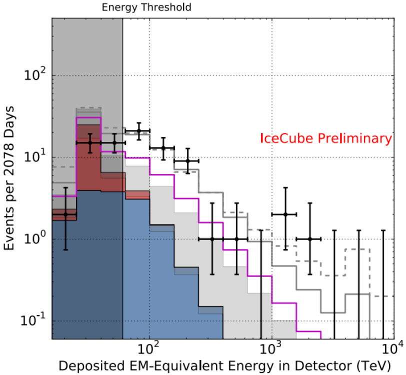


Results: Visible Decay: Flavors with ν_τ

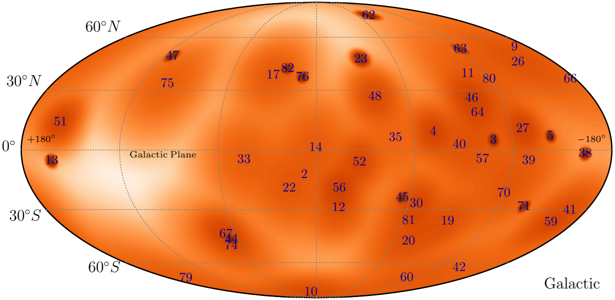


IceCube is Great for This!

IceCube has measured the extragalactic high energy (100 TeV - 1 PeV) flux!



IC ICRC 2017



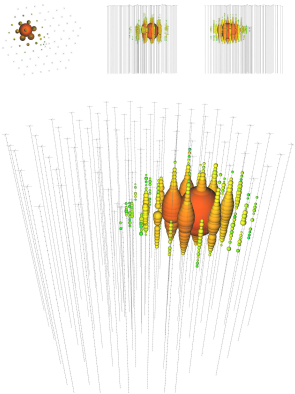
Galactic component is negligible

PBD, D. Marfatia, T. Weiler 1703.09721

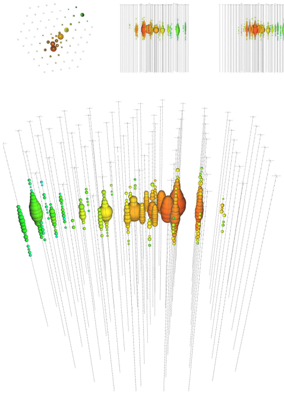
IceCube Can Detect Flavor (sort of)

High enough energy to be well about ν_τ threshold

Y. Jeong, M. Reno 1007.1966



Cascade topology
ν_e CC, ν_τ CC*, NC



Track topology
ν_μ CC, ν_τ CC $\to \tau \to \mu + 2\nu$

Conventional Wisdom

- High energy neutrinos are produced from full π decay
- Flavor ratio at source of 1:2:0 converts to 1:1:1* at Earth
- All neutrinos have the same energy†

*the fact that this ratio is 1:1:1 is coincidental not fundamental

†also a coincidence; kinematic corrections are small

Conventional Wisdom

- High energy neutrinos are produced from full π decay
- Flavor ratio at source of 1:2:0 converts to 1:1:1* at Earth
- All neutrinos have the same energy†

Some of these *must* be incorrect.

*the fact that this ratio is 1:1:1 is coincidental not fundamental

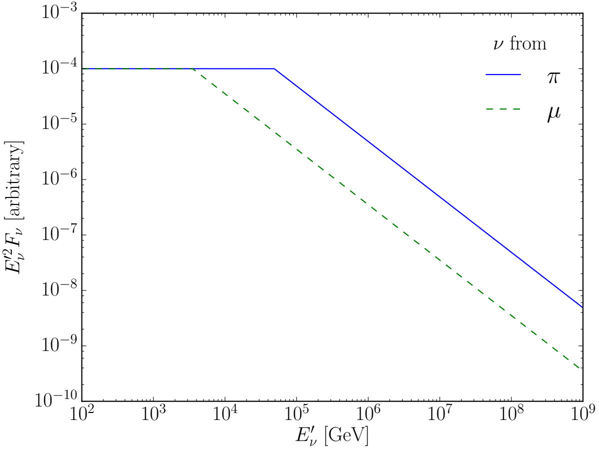
†also a coincidence; kinematic corrections are small

Need a phenomenon that non-trivially depends on
energy and **flavor** at the same time

Muon Cooling

$$\pi \to \nu_\mu + \mu$$

$$\mu \to \nu_\mu + \nu_e + e$$

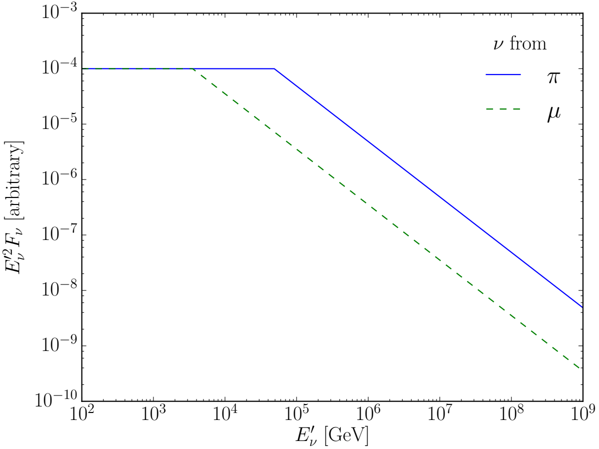


- E.g. synchrotron
- More ν_μ at high energy
- E_b determined by B field

Muon Cooling

$$\pi \to \nu_\mu + \mu$$

$$\mu \to \nu_\mu + \nu_e + e$$



- E.g. synchrotron
- More ν_μ at high energy
- E_b determined by B field

- This doesn't work at all!
- Oscillations kill this
  - $\mu - \tau$ symmetry
- $\max \Delta\gamma \simeq 0.2$

Other Options

Neutron decay: $n \to p + e + \bar{\nu}_e$

- Produces extra ν_e's
- Produced with pions in $p\gamma$ interactions
- Also come from photodisociation of heavy ions

A. Palladino 1902.08630

L. Anchordoqui 1411.6457

Other Options

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A. Palladino 1902.08630

L. Anchordoqui 1411.6457

But

- Neutrino energies are $\sim$ 2-3 orders of magnitude less for $p\gamma$
- Neutrino flux from heavy ions is also suppressed

D. Biehl, et al. 1705.08909

X. Rodrigues, et al. 1711.02091

New Physics!

We need a stronger effect, so we look to new physics.

- NSI with ultra-light mediators ($m \ll 1$ eV) weak

  A. Joshipura, S. Mohanty hep-ph/0310210

  M. Bustamante, S. Agarwalla 1808.02042

- Pseudo-dirac neutrinos weak

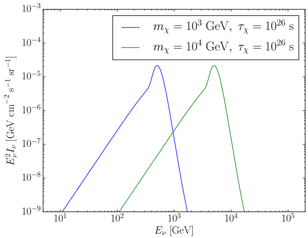
  L. Wolfenstein Nucl. Phys. B186, 147 (1981)

  S. Pakvasa, A. Joshipura, S. Mohanty 1209.5630

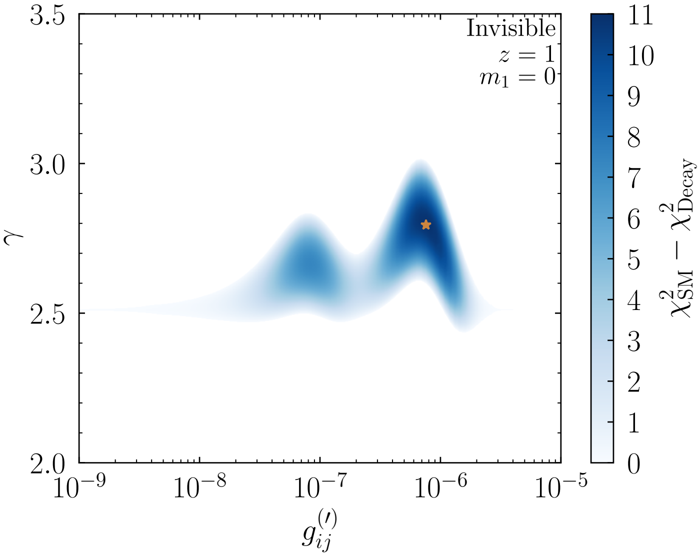
- Electrophilic dark matter decay strong but CMB

- Neutrino decay

  strong, $\sim 3.3\ \sigma$



Preferred Region: Invisible



Some Track to Cascade with Decay Observations

- Decay usually hardens the spectrum
  - Only $\bar{P}_{\mu e}^{\text{vis}} > \bar{P}_{\mu e}^{\text{SM}}$ for $m_1 \sim 0$ and $\gamma \sim 2$
  - While $\bar{P}_{\tau\beta}^{\text{vis}} > \bar{P}_{\tau\beta}^{\text{SM}}$, no ν_τ's are produced at the sources

See backup slide 43

- The effect is larger for tracks than cascades

$\max \Delta\gamma$	$g_{21}^{(\prime)}$	$g_{31}^{(\prime)}$	$g_{32}^{(\prime)}$	All
Invisible	0.006	0.200	0.200	0.438
Visible	0.042	0.227	0.172	0.400

$\min \Delta\gamma = -0.01$

$\Delta\gamma \equiv \gamma_c - \gamma_t$

- This is the same direction of the IceCube data!
- The other sign (cascades harder than tracks) requires the inverted ordering

Uncertainties

or "How to muck it all up with astrophysics"

What doesn't work:

- Multiple classes of sources with different spectra
- pp vs. $p\gamma$ sources
- Different redshift evolution $\Rightarrow$ shift the g_{ij}
- Neutron decay sources
- Varying the oscillation parameters
- IceCube track or cascade normalization

What could work: (other than neutrino decay)

- Muon damped $\Rightarrow \Delta\gamma \sim 0.2$
- Track and cascade spectra are fit over slightly different energy ranges $\Rightarrow$ broken power law can help
- Energy misreconstruction (tracks could be susceptible to this)
- Dark matter?