Abstract

IceCube has measured high energy astrophysical neutrinos for the first time providing a powerful new probe of the universe, but many questions still remain. I will explore one strange quirk in the data. Despite generally large astrophysical uncertainties, I will show that this tension cannot be resolved with standard physics. The simplest consistent explanation is that some neutrinos are decaying. Finally, I will wrap up with predictions and a path forward.

Partial Neutrino Decay Addresses the Track – Cascade Tension at IceCube

Peter B. Denton

Pheno 2019

May 6, 2019

with I. Tamborra

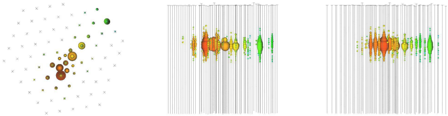
1805.05950

BROOKHAVEN NATIONAL LABORATORY

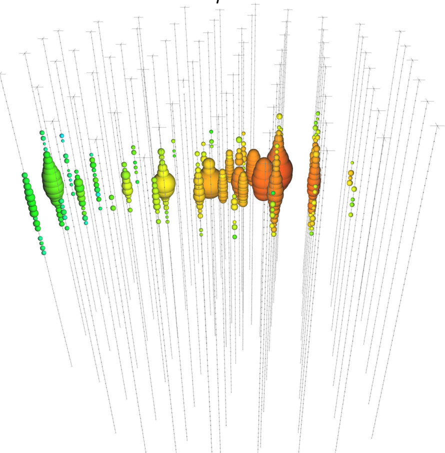
IceCube Measures:

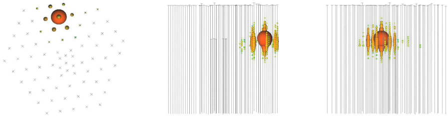
- Flavor(ish)
- Energy
- Direction

IceCube Measures: Tracks and Cascades ≈ Flavor

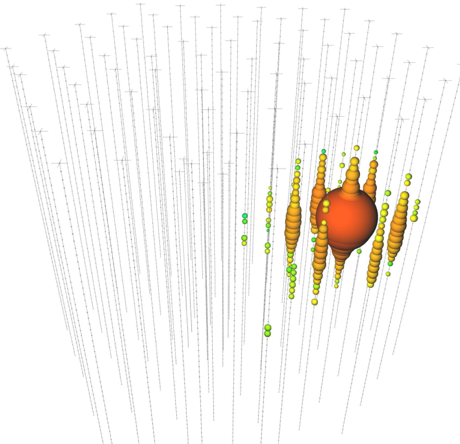


ν_μ CC



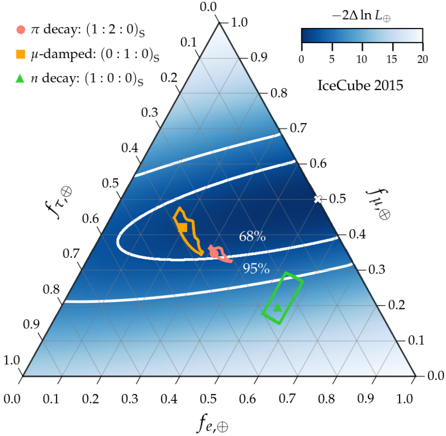


ν_e, ν_τ CC (and all NC)



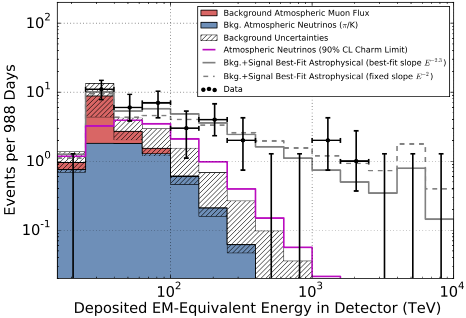
IceCube Measures: Flavor

Flavor alone disfavors neutron decay:



M. Bustamante, M. Ahlers 1901.10087

IceCube Measures: Energy



IC 1405.5303

IceCube has measured the spectrum:

- Cascade: $\Delta E_\nu/E_\nu \sim 10\%$
- Track: $\Delta E_\nu/E_\nu > 10\%$

Can constrain various source models:

K. Murase 1511.01590

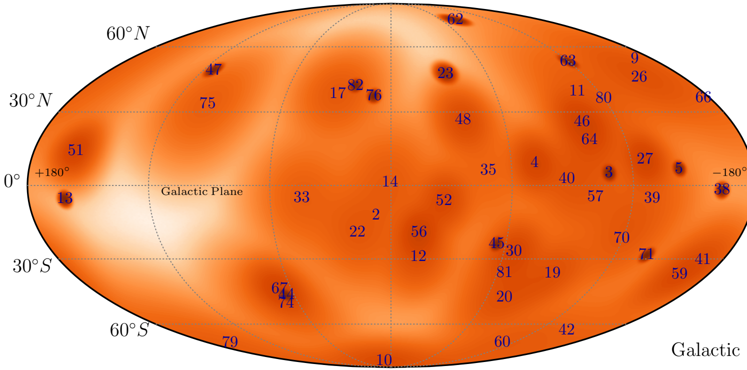
PBD, I. Tamborra 1711.00470

T. Sudoh, T. Totani, N. Kawanaka, 1801.09683

PBD, I. Tamborra 1802.10098

⋮

IceCube Measures: Direction



$< 9.5\%$ galactic fraction at 90% CL

PBD, D. Marfatia, T. Weiler 1703.09721

IC 1707.03416

IceCube Measures:

- Flavor(ish)
- Energy
- Direction

Both Flavor and Energy Information Together

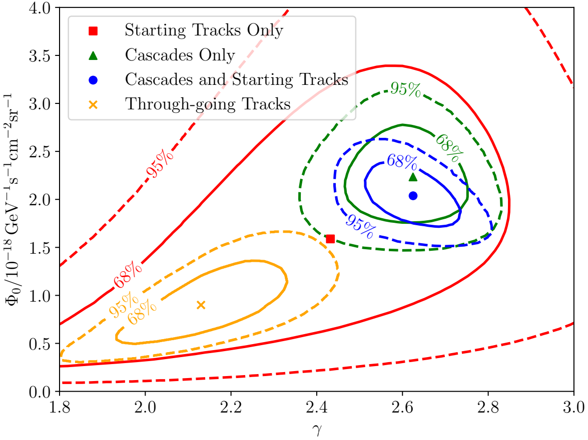
	π	μ	n
$r_{\rm th}$	0.21 ± 0.01	0.29 ± 0.04	0.11 ± 0.02
$r_{\rm obs}^{\rm HESE+TGM}$	2.0σ	2.6σ	compatible
$r_{\rm obs}^{\rm HESE\ only}$	compatible	compatible	1.7σ

A. Palladino 1902.08630

Preference for neutron decay over pion decay or damped muon!

Tension

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



$$\Delta\gamma = 0.54$$

"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

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

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Some of these *must* be incorrect.

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

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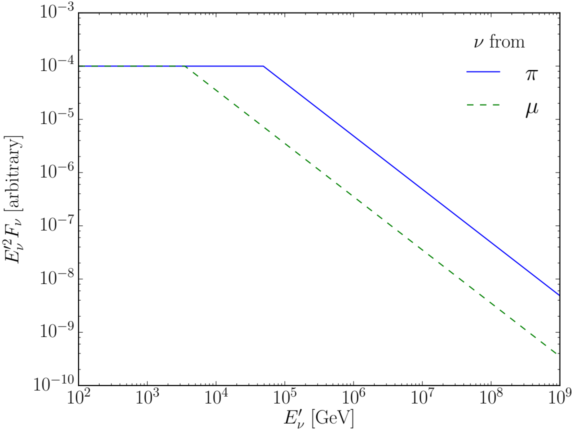
Need a phenomenon that non-trivially depends on
energy and **flavor** at the same time

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

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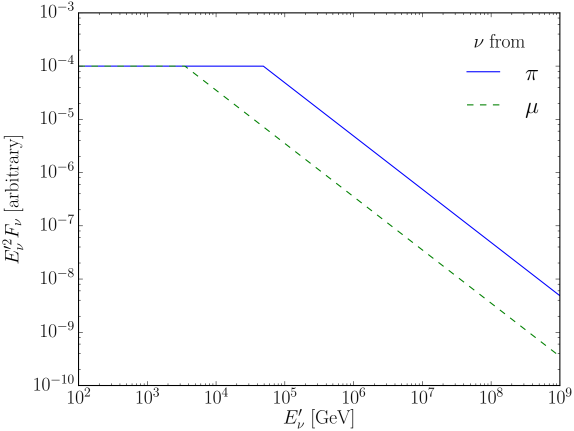

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- More ν_μ at high energy
- E_b determined by B field

- 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

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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)

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

  M. Bustamante, S. Agarwalla 1808.02042

- Pseudo-dirac neutrinos

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

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

- Electrophilic dark matter decay
- Neutrino decay

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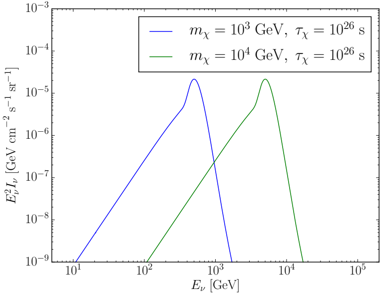

New Physics!

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

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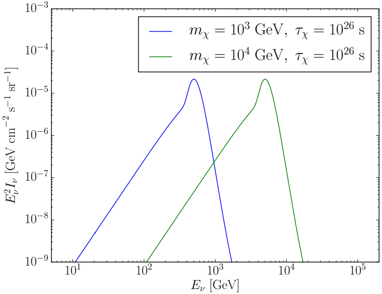
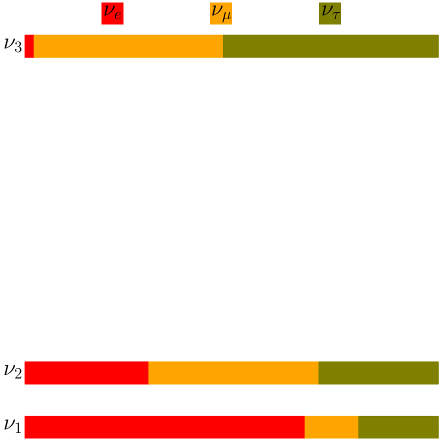
  L. Wolfenstein Nucl. Phys. B186, 147 (1981)

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

- Electrophilic dark matter decay strong but CMB
- Neutrino decay
  strong, 3.4 σ



Some Neutrinos Decay



Model recipe:

1. ν-decay depletes ν's at low energy
2. Want fewer ν_μ at low energy
3. Let ν_2 and ν_3 decay
4. Keep ν_1 stable

*NO preferred at $\sim 3\sigma$
P. F. de Salas, et al. 1708.01186

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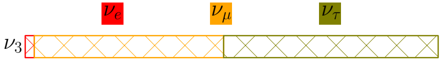
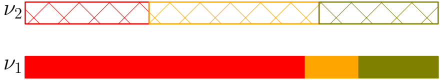


Mr. Stark,
I don't feel so good...



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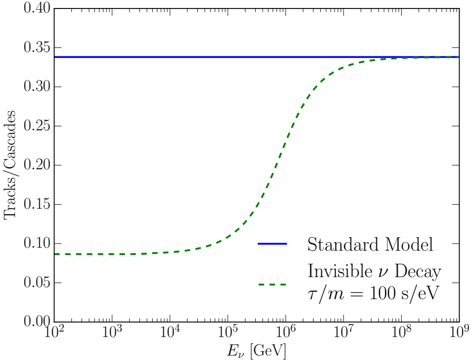
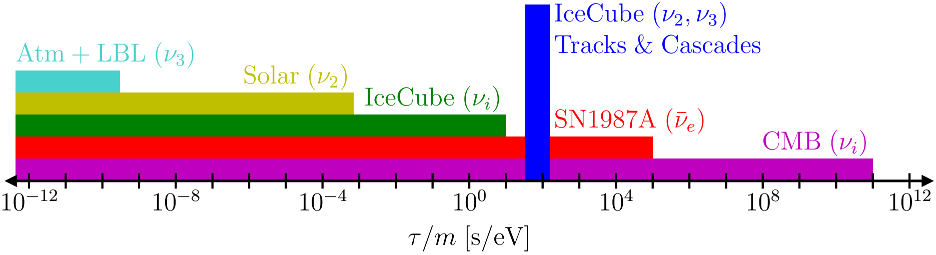
Track to Cascade Ratio (At Earth)



*the deviation from 1/2 as expected is due to SM corrections that are accounted for

Invisible ν Decay Constraints and Evidence



PBD, I. Tamborra 1805.05950

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

KamiokaNDE-II PRL 58 1490 (1987)

G. Pagliaroli, et al. 1506.02624

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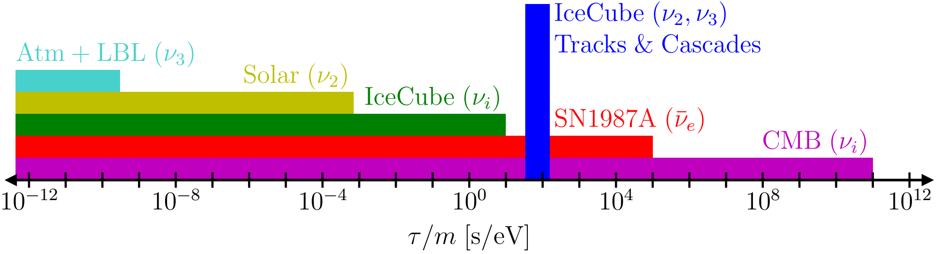

ν_2, ν_3 decay leads to 16% reduction in $\bar{\nu}_e$ flux: SN1987A doesn't apply

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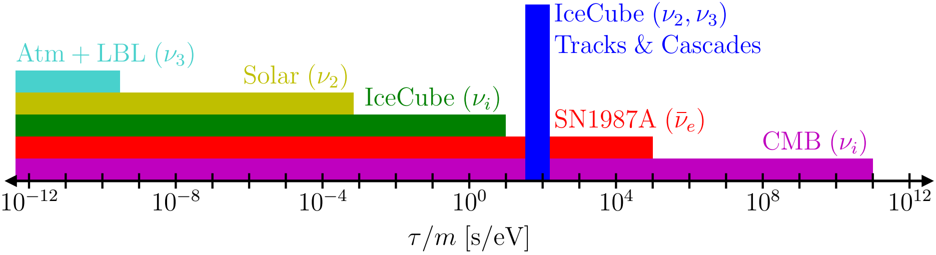

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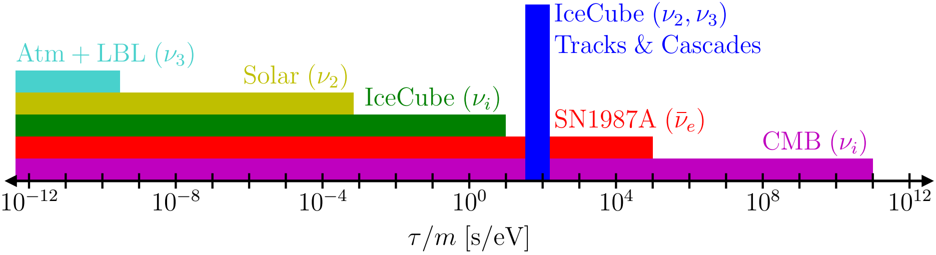

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SN1987A doesn't apply

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< 3 decaying is allowed...
and may be slightly preferred

PBD, I. Tamborra 1805.05950

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M. Gonzalez-Garcia and M. Maltoni 0802.3699

N. Bell, E. Pierpaoli, K. Sigurdson astro-ph/0511410

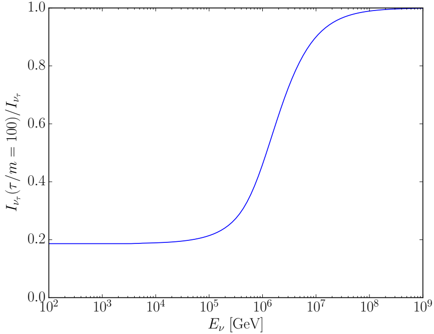
M. Archidiacono, et al. 1404.5915

Deficit(?) of ν_τ Events

- IceCube can *sometimes* identify ν_τ CC
- Should have seen 2-3 events, seen none*

IC 1710.01191

ν_τ suppression from decay:



Multiply with efficiency to find total sensitivity reduced by 59%

* ~ 1 new net event may exist, new sensitivities will be higher

The Message

- There seems to be some tension in IceCube's data
- Inconsistent with standard physics
  - Multiple sources don't help
  - Multi-zone type conspiracies could solve this
- DM is an option, not great
- Neutrino decay works, favored at 3.4 σ

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Looking forward:

- Play close attention to ν_τ searches
- Anisotropy + flavor (DM)
- More flavor + energy dependent fits: BPL

Thank you!

Backups

Decay Process

- Neutrinos couple to a light/massless scalar ϕ: **Majoron**
- Secondaries?

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- ν_L with much lower energies
- Unparticles, …

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Visible

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Invisible

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- ν_L with much lower energies
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To get *our* model:

- ν_1 decay is kinematically inaccessible
- Coupling to ν_1 is much smaller
- Lifetime estimated by typical $E \simeq 100$ TeV and $z \simeq 1$: $\tau_2/m_2 \simeq \tau_3/m_3 \sim 10^2$ s/eV

Neutrino Decay Affects Flavor

The oscillation averaged probability is

$$\bar{P}(\nu_\alpha \to \nu_\beta) = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 e^{-\Lambda_i}$$

$$\Lambda_i \equiv \frac{d_H f(z) m_i}{E_\nu \tau_i}$$

$$f(z) = \int_0^z \frac{dz'}{(1+z')^2\sqrt{(1+z')^3\Omega_m + \Omega_\Lambda}}$$

We take $\Lambda_2 = \Lambda_3$ for simplicity and $\Lambda_1 = 0$.

IceCube's Tracks and Cascades