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
IceCube Measures:

- Flavor(ish)
- Energy
- Direction
IceCube Measures: Tracks and Cascades ≈ Flavor

\[ \nu_\mu \text{ CC} \]

\[ \nu_e, \nu_\tau \text{ CC (and all NC)} \]
Flavor alone disfavors neutron decay:

M. Bustamante, M. Ahlers 1901.10087
IceCube Measures: Energy

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
### Preference for neutron decay over pion decay or damped muon!

<table>
<thead>
<tr>
<th></th>
<th>$\pi$</th>
<th>$\mu$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{th}$</td>
<td>$0.21 \pm 0.01$</td>
<td>$0.29 \pm 0.04$</td>
<td>$0.11 \pm 0.02$</td>
</tr>
<tr>
<td>$r_{obs}^{\text{HESE+TGM}}$</td>
<td>$2.0\sigma$</td>
<td>$2.6\sigma$</td>
<td>compatible</td>
</tr>
<tr>
<td>$r_{obs}^{\text{HESE only}}$</td>
<td>compatible</td>
<td>compatible</td>
<td>$1.7\sigma$</td>
</tr>
</tbody>
</table>
“The p-value for obtaining the combined fit result and the result reported here from an unbroken powerlaw flux is $3.3\sigma$, 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 $\pi$ 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 $\pi$ decay
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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

\[ \pi \rightarrow \nu_\mu + \mu \]

\[ \mu \rightarrow \nu_\mu + \nu_e + e \]

- E.g. synchrotron
- More \( \nu_\mu \) at high energy
- \( E_b \) determined by \( B \) field
Muon Cooling

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- E.g. synchrotron
- More \( \nu_\mu \) at high energy
- \( E_b \) determined by \( B \) field
- This doesn’t work at all!
- Oscillations kill this
  - \( \mu - \tau \) symmetry
- \( \text{max } \Delta \gamma \approx 0.2 \)
Other Options

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

- Produces extra $\nu_e$'s
- Produced with pions in $p\gamma$ interactions
- Also come from photodisociation of heavy ions
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- Produces extra $\nu_e$'s
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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** \((m \ll 1 \text{ eV})\)
  
  
  M. Bustamante, S. Agarwalla [1808.02042](http://arxiv.org/abs/1808.02042)

- **Pseudo-dirac neutrinos**
  
  
  S. Pakvasa, A. Joshipura, S. Mohanty [1209.5630](http://arxiv.org/abs/1209.5630)

- **Electrophilic dark matter decay**

- **Neutrino decay**
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New Physics!

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

- **NSI with ultra-light mediators** \((m \ll 1 \text{ eV})\) weak
  
  
  M. Bustamante, S. Agarwalla [1808.02042](https://arxiv.org/abs/1808.02042)

- **Pseudo-dirac neutrinos** weak
  
  
  S. Pakvasa, A. Joshipura, S. Mohanty [1209.5630](https://arxiv.org/abs/1209.5630)

- **Electrophilic dark matter decay** strong but CMB

- **Neutrino decay** strong, \(3.4 \sigma\)
Some Neutrinos Decay

Model recipe:
1. $\nu$-decay depletes $\nu$’s at low energy
2. Want fewer $\nu_\mu$ at low energy
3. Let $\nu_2$ and $\nu_3$ decay
4. Keep $\nu_1$ stable

*NO preferred at $\sim 3\sigma$

P. F. de Salas, et al. 1708.01186
Some Neutrinos Decay

Mr. Stark,
I don’t feel so good…

Model recipe:
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P. F. de Salas, et al. 1708.01186
Track to Cascade Ratio (At Earth)

*the deviation from 1/2 as expected is due to SM corrections that are accounted for*
Invisible $\nu$ Decay Constraints and Evidence

- Atm + LBL ($\nu_3$)
- Solar ($\nu_2$)
- IceCube ($\nu_i$)
- SN1987A ($\bar{\nu}_e$)
- CMB ($\nu_i$)

$\tau/m$ [s/eV]

- $10^{-12}$
- $10^{-8}$
- $10^{-4}$
- $10^0$
- $10^4$
- $10^8$
- $10^{12}$

PBD, I. Tamborra 1805.05950
S. Hannestad, G. Raffelt hep-ph/0509278
KamiokaNDE-II PRL 58 1490 (1987)
G. Pagliaroli, et al. 1506.02624
J. Berryman, A. de Gouvea, D. Hernandez 1411.0308
M. Gonzalez-Garcia and M. Maltoni 0802.3699
ν₂, ν₃ decay leads to 16% reduction in νₑ flux: SN1987A doesn’t apply.
Invisible $\nu$ Decay Constraints and Evidence

$\nu_2$, $\nu_3$ decay leads to 16\% reduction in $\bar{\nu}_e$ flux:
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CMB constraints assume all flavors decay,
< 3 decaying is allowed...

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Invisible $\nu$ Decay Constraints and Evidence

$\nu_2, \nu_3$ decay leads to 16% reduction in $\bar{\nu}_e$ flux:
SN1987A doesn’t apply

CMB constraints assume all flavors decay,
< 3 decaying is allowed...
and may be slightly preferred

PBD, I. Tamborra 1805.05950
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KamiokaNDE-II PRL 58 1490 (1987)
G. Pagliaroli, et al. 1506.02624
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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

$\tau/m$ [s/eV]

$10^{-12}$ $10^{-8}$ $10^{-4}$ $10^{0}$ $10^{4}$ $10^{8}$ $10^{12}$
Deficit(?) of $\nu_\tau$ Events

- IceCube can *sometimes* identify $\nu_\tau$ CC
- Should have seen 2-3 events, seen none*

$\nu_\tau$ suppression from decay:

![Graph showing suppression from decay]

Multiply with efficiency to find total sensitivity reduced by 59%

* $\sim$ 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 $\sigma$
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It is possible to make strong particle physics statements in astrophysical environments
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Looking forward:

- Play close attention to $\nu_{\tau}$ searches
- Anisotropy + flavor (DM)
- More flavor + energy dependent fits: BPL
Thank you!
Backups
Decay Process

- Neutrinos couple to a light/massless scalar $\phi$: Majoron
- Secondaries?
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- Lighter states regenerated
- Energetics depend strongly on absolute mass scale
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**Invisible**
- Right handed neutrinos
- $\nu_L$ with much lower energies
- Unparticles, ...
Decay Process

- Neutrinos couple to a light/massless scalar $\phi$: **Majoron**
- Secondaries?

**Visible**
- Lighter states regenerated
- Energetics depend strongly on absolute mass scale

**Invisible**
- Right handed neutrinos
- $\nu_L$ with much lower energies
- Unparticles, ...

To get *our* model:
- $\nu_1$ decay is kinematically inaccessible
- Coupling to $\nu_1$ is much smaller
- Lifetime estimated by typical $E \simeq 100$ TeV and $z \simeq 1$:
  \[ \frac{\tau_2}{m_2} \simeq \frac{\tau_3}{m_3} \sim 10^2 \text{ s/eV} \]
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

\[ E^{2}_ν \nu_\nu \text{[GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ \log_{10}(\tau/m)/\text{s/ev} \]

\[ E_ν \text{[GeV]} \]

\[ 10^{-9} \quad 10^{-8} \quad 10^{-7} \]

\[ 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \]

\[ \gamma \]

\[ 2 \quad 3 \]

\[ 0 \quad 1 \quad 2 \quad 3 \]

\[ 10^{-1} \quad 1 \quad 2 \quad 3 \]

\[ 0 \quad 1 \quad 2 \quad 3 \]

\[ 10^{-9} \quad 10^{-8} \quad 10^{-7} \]

\[ 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \]

\[ \text{Cascade} \quad \text{Track} \]

\[ \text{Red} \quad \text{Blue} \]