Beyond the Standard Model effects on neutrino flavor
Experimental overview and prospects:
High energies: neutrinos above the TeV scale

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Snowmass white paper “Beyond the Standard Model effects on Neutrino Flavor”, ArXiv:2203.10811

Beyond the Standard Model effects on Neutrino Flavor

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3 Experimental overview and prospects

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3.3.1 High-energy atmospheric neutrinos

3.3.2 High-energy astrophysical neutrinos

3.3.3 Extremely-high-energy astrophysical neutrinos

4 Summary and outlook

5 Acknowledgements
“Neutrino flavour effect” covers many topics in particle physics!

We want to discover any of these!
- Lorentz and CPT violation
- Long-range interaction
- Dark matter-neutrino interaction
- Dark energy-neutrino interaction
- Neutrino self-interaction
- Non-standard interaction
- Neutrino decay
- Neutrino decoherence
- Sterile neutrinos
- Extra dimension, etc
Astrophysical neutrino flavour physics

Natural place to look for new physics

1. Longest propagation distance (> pc)
2. Direct highest energy particles (> 10 TeV)
3. Quantum mixing
Astrophysical neutrino flavour physics

Flavour information is sensitive to the leading order of new physics

\[ H = H_{SM} + H_{BSM} \]

\[ P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots \]

We need high statistics flavour data to look for new physics
Astrophysical neutrino flavour physics

Flavour information is sensitive to the leading order of new physics

\[ H = H_{SM} + H_{BSM} \]

\[ P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots \]

Standard neutrino Hamiltonian in vacuum

\[ H_{SM} \sim \frac{m^2}{2E} \]

In highest energy, SM term is suppressed, BSM term becomes relatively larger

\[ P = |H_{SM}|^2 + |H_{SM} \cdot H_{BSM}| + |H_{BSM}|^2 + \cdots \]

Higher-energy neutrinos have better sensitivity to new physics
Astrophysical neutrino flavour physics

The goal is to find

\[ P \neq P_{SM}(\Delta m^2 \pm \delta \Delta m^2, \theta \pm \delta \theta) \]

Sensitivity is improved by better oscillation parameter measurements
Astrophysical neutrino flavour physics

Astrophysical neutrino flavour simulation depends on astrophysical neutrino flavour assumption at the source

\[ f_{\beta,\oplus} = \sum_\beta P_{\alpha \rightarrow \beta}(H_{SM}, H_{BSM}) \times f_{\alpha, S} \]

New physics sensitivity depends on astrophysical neutrino production model
Astrophysical neutrino flavour physics (2022)

IceCube data allows almost all astrophysical neutrino flavour ratio
- New physics limits have astrophysical neutrino production model dependencies

\[ h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a_{\alpha\beta}^{(3)} - E c_{\alpha\beta}^{(4)} + E^2 a_{\alpha\beta}^{(5)} - E^3 c_{\alpha\beta}^{(6)} \ldots \]
Summary

Astrophysical neutrino flavour physics is a cross-frontier topic.
- Neutrino frontier, high-energy frontier, cosmic frontier
Very high discovery potential is supported by an interdisciplinary study
- Theory & experiment, particle physics & astrophysics
Astrophysical neutrino flavour physics is a cross-frontier topic.
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Summary

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- Theory & experiment, particle physics & astrophysics

Neutrino telescopes
High-Energy (IceCube, ANTARES, KM3NeT, P-ONE, Baikal-GVD, etc)
Ultra-high-energy (IceCube-Gen2, TAMBO, Trinity, RET-N, ARIANNA, RNO-G, GRAND, POEMMA, BEACON, PUEO, Trinity, EUSO-SPB2, Auger/GCOS, etc)

Oscillation experiments
Beam (T2K, NOvA, DUNE, Hyper-Kamiokande)
Atmospheric (Super-Kamiokande, DUNE, Hyper-Kamiokande, IceCube-Upgrade, KM3NeT, INO)
Reactor (JUNO), etc

Multi-messenger astronomy
Optics (Radio, infrared, VIS, UV, X-ray, γ-ray)
Comic rays (Auger, TA, GCOS, etc)
Gravitational wave (LIGO, VARGO, KAGRA, LIGO-India, Einstein Telescope, LISA, etc)

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Backup
Beyond the Standard Model effects on Neutrino Flavor

Fundamental physics with high-energy cosmic neutrinos today and in the future:
- Natural place to look for new physics
  1. Longest propagation distance (> pc)
  2. Direct highest energy particles (> 10 TeV)
  3. Quantum mixing

Almost all particle physics topics are covered!
Non-standard interactions

Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.

They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the high-density material (~13g/cm³) on Earth.

\[ h_{eff} \sim \frac{1}{2E} M^2 + V_{CC}, \quad P_{\alpha\beta} = \left| \langle \nu_\alpha | U(h_{eff}, t) | \nu_\beta \rangle \right|^2 \]

\[ M^2 = \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^2 & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^2 & m_{\mu\tau}^2 & m_{\tau\tau}^2 \end{pmatrix}, \quad V_{CC} = \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \]

Non-standard interaction limits in IceCube is order ~10⁻²⁵ GeV

cf) The highest precision hydrogen 1S-2S transition (PRL107(2011)203001)
Fractional frequency uncertainty ~ 4x10⁻¹⁵ \( \rightarrow \) new physics sensitivity ~10⁻²³ GeV
Flavor new physics search with effective operators

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

\[ L = i \bar{\psi} \gamma^\mu \partial_\mu \psi - m \bar{\psi} \psi + \bar{\psi} \gamma^\mu a_\mu \psi + \bar{\psi} \gamma^\mu c_{\mu \nu} \partial^\nu \psi \cdots \]

Effective Hamiltonian can be written from here

\[ h_{\text{eff}} \sim \frac{1}{2E} U^\dagger M^2 U + \frac{a^{(3)}}{E} - \frac{E c^{(4)}}{a} + \frac{E^2 a^{(5)}}{E} - \frac{E^3 c^{(6)}}{E} \cdots \]

Astrophysical neutrino flavour sensitivity of dim-6 operator goes beyond the natural scale

\[ c^{(6)} \sim \frac{1}{M_{\text{Planck}}^2} \sim 10^{-38} GeV^{-2}, \]

first time in any known scientific system
Flavor new physics search with effective operators

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

\[
P_{\alpha \to \beta}(E, L) = 1 - 4 \sum_{i>j} Re(\mathcal{V}_{\alpha i}^* \mathcal{V}_{\beta i}^* \mathcal{V}_{\alpha j} \mathcal{V}_{\beta j}) \sin^2 \left( \frac{\lambda_i - \lambda_j}{2} L \right) + 2 \sum_{i>j} Im(\mathcal{V}_{\alpha i}^* \mathcal{V}_{\beta i}^* \mathcal{V}_{\alpha j} \mathcal{V}_{\beta j}) \sin \left( (\lambda_i - \lambda_j)L \right)
\]

However, astrophysical neutrinos propagate O(100Mpc) \(\rightarrow\) lost coherence

\[
P_{\alpha \to \beta}(E, \infty) \sim 1 - 2 \sum_{i>j} Re(\mathcal{V}_{\alpha i}^* \mathcal{V}_{\beta i}^* \mathcal{V}_{\alpha j} \mathcal{V}_{\beta j}) = \sum_{i} |V_{\alpha i}|^2 |V_{\beta i}|^2
\]

Astrophysical neutrino flux of flavour \(\alpha\) at production is \(\phi_{\alpha}^P(E) \sim \phi_{\alpha}^P \cdot E^{-\gamma}\). Since it’s low statistics, we consider energy-averaged flavour composition \(\beta\) on Earth

\[
\bar{\phi}_{\beta}^\oplus = \frac{1}{\Delta E} \int_{\Delta E} \sum_{\alpha} P_{\alpha \to \beta}(E, \infty) \phi_{\alpha}^P(E) dE
\]

We take the fraction of this for each flavour.

\[
f_{\beta}^\oplus = \frac{\bar{\phi}_{\beta}^\oplus}{\sum_{e,\mu,\tau} \bar{\phi}_{\gamma}^\oplus}
\]
High-energy astrophysical neutrino flavour

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

Quantum foam
Ellis, Mavromatos, Nanopoulos
PLB293(1992)37

new long-range force
Bustamante, Agarwalla
PRL122(2019)061103

Lorentz violating field
Kostelecký Mewes, PRD69(2004)016005

neutrino-dark energy coupling
etc...

Klop, Ando
PRD97(2018)063006

not to scale
HESE 7.5-yr flavor ratio (2018)


IceCube

1st flavor ratio result
(0.0:0.2:0.8)

2nd flavor ratio result
(0.5:0.5:0.0)

3rd flavor ratio result
(0.0:0.2:0.8)
HESE 7.5-yr flavor ratio (2018)

We are mainly testing scenarios where we assume astrophysical neutrino productions are dominated by $\nu_e$ or $\nu_\mu$.
# Neutrino interferometry – Atmospheric neutrinos

<table>
<thead>
<tr>
<th>dim.</th>
<th>CMB polarization</th>
<th>He-Xe comagnetometer</th>
<th>torsion pendulum</th>
<th>muon g-2</th>
<th>neutrino oscillation</th>
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<th>neutrino</th>
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<td>[10]</td>
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<td></td>
<td>torsion</td>
<td>tabletop</td>
<td>electron</td>
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<td>muon g-2</td>
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<td>$\sim 10^{-24}$ GeV</td>
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<td>neutrino oscillation</td>
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<td>neutrino</td>
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<td>$</td>
<td>\text{Re}(\tilde{c}^{(3)}_{\mu T})</td>
<td>,</td>
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<td>4</td>
<td>GRB vacuum</td>
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<td>$\sim 10^{-38}$ GeV</td>
<td>[7]</td>
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<td>birefringence</td>
<td>LIGO</td>
<td>photon</td>
<td></td>
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<td>[8]</td>
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<td></td>
<td>Sapphire cavity</td>
<td>tabletop</td>
<td>photon</td>
<td></td>
<td>$\sim 10^{-18}$</td>
<td>[5]</td>
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<td>Ne-Rb-K</td>
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<td></td>
<td>$\sim 10^{-29}$</td>
<td>[11]</td>
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<td>trapped Ca$^+$</td>
<td>tabletop</td>
<td>electron</td>
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<td>$\sim 10^{-19}$</td>
<td>[14]</td>
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<tr>
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<td>ion</td>
<td></td>
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<td>\text{Re}(\tilde{c}^{(4)}_{\mu T})</td>
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<tr>
<td>5</td>
<td>GRB vacuum</td>
<td>astrophysical</td>
<td>photon</td>
<td></td>
<td>$\sim 10^{-34}$ GeV</td>
<td>[7]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>birefringence</td>
<td>ultra-high-energy</td>
<td>astrophysical</td>
<td>proton</td>
<td>$\sim 10^{-22}$ to $10^{-18}$ GeV$^{-1}$</td>
<td>[7]</td>
<td>[9]</td>
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<tr>
<td></td>
<td></td>
<td>cosmic ray</td>
<td>astrophysical</td>
<td>proton</td>
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<td></td>
<td>gravitational</td>
<td>astrophysical</td>
<td>gravity</td>
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<td>neutrino</td>
<td>oscillation</td>
<td>atmospheric</td>
<td>neutrino</td>
<td>$</td>
<td>\text{Re}(\tilde{c}^{(5)}_{\mu T})</td>
<td>,</td>
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<tr>
<td>6</td>
<td>GRB vacuum</td>
<td>astrophysical</td>
<td>photon</td>
<td></td>
<td>$\sim 10^{-31}$ GeV</td>
<td>[7]</td>
<td>[9]</td>
</tr>
<tr>
<td></td>
<td>birefringence</td>
<td>ultra-high-energy</td>
<td>astrophysical</td>
<td>proton</td>
<td>$\sim 10^{-42}$ to $10^{-35}$ GeV$^{-2}$</td>
<td>[7]</td>
<td>[9]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cosmic ray</td>
<td>astrophysical</td>
<td>proton</td>
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<td></td>
<td></td>
<td>gravitational</td>
<td>astrophysical</td>
<td>gravity</td>
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<td>neutrino</td>
<td>oscillation</td>
<td>atmospheric</td>
<td>neutrino</td>
<td>$\sim 10^{-31}$ GeV</td>
<td>[7]</td>
<td>[9]</td>
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<td>7</td>
<td>GRB vacuum</td>
<td>astrophysical</td>
<td>photon</td>
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<td>$\sim 10^{-28}$ GeV</td>
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<td>8</td>
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<td>Cherenkov</td>
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<td></td>
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<td>oscillation</td>
<td>atmospheric</td>
<td>neutrino</td>
<td>$\sim 10^{-46}$ GeV</td>
<td>[15]</td>
<td></td>
</tr>
</tbody>
</table>

*TABLE I: Comparison of attainable best limits of SME coefficients in various fields.*

IceCube atmospheric neutrino limit, $c^{(6)} \leq 10^{-36} GeV^{-2}$

This is close to the target signal region, $c^{(6)} \sim 10^{-38} GeV^{-2}$
Strong limits on many parameters but they depend on the source flavour assumptions.

Substantial limits for $\tau \tau$ parameters are obtained through quantum Zeno effect.

<table>
<thead>
<tr>
<th>dim</th>
<th>coefficient</th>
<th>limit (BF &gt; 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$\text{Re}(\bar{a}_{\tau \tau}^{(3)})$</td>
<td>$2 \times 10^{-26}$ GeV</td>
</tr>
<tr>
<td>4</td>
<td>$\text{Re}(c_{\tau \tau}^{(4)})$</td>
<td>$2 \times 10^{-31}$</td>
</tr>
<tr>
<td>5</td>
<td>$\text{Re}(\bar{a}_{\tau \tau}^{(5)})$</td>
<td>$2 \times 10^{-37}$ GeV$^{-1}$</td>
</tr>
<tr>
<td>6</td>
<td>$\text{Re}(c_{\tau \tau}^{(6)})$</td>
<td>$3 \times 10^{-42}$ GeV$^{-2}$</td>
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<tr>
<td>7</td>
<td>$\text{Re}(\bar{a}_{\tau \tau}^{(7)})$</td>
<td>$3 \times 10^{-47}$ GeV$^{-3}$</td>
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<tr>
<td>8</td>
<td>$\text{Re}(c_{\tau \tau}^{(8)})$</td>
<td>$2 \times 10^{-52}$ GeV$^{-4}$</td>
</tr>
</tbody>
</table>
Astrophysical neutrino production mechanism is not known → production flavour ratio is not known

Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)


$\alpha_e^{\oplus}$ $\alpha_\tau$ $\alpha_\mu$

- (1:2:0) $\pi$-decay
- (1:0:0) $\beta$-decay
- (0:1:0) $\mu$-cooling
- (0:0:1) exotic $\nu_\tau$
Neutrino flavor ratio $(\nu_e : \nu_\mu : \nu_\tau)$

Astrophysical neutrino production mechanism is not known $\rightarrow$ production flavour ratio is not known.

Flavour ratio on Earth is different due to mixing by neutrino masses.
Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

Astrophysical neutrino production mechanism is not known $\rightarrow$ production flavour ratio is not known

Flavour ratio on Earth is different due to mixing by neutrino masses

All possible flavour ratio is confined in a small space
Neutrino flavor ratio \((\nu_e : \nu_\mu : \nu_\tau)\)

Astrophysical neutrino production mechanism is not known \(\Rightarrow\) production flavour ratio is not known

Flavour ratio on Earth is different due to mixing by neutrino masses

All possible flavour ratio is confined in a small space

e.g.) New physics just below the limit can produce any flavour ratio