Tests of Lorentz and CPT Violation with Neutrinos

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IUCSS lecture, Indiana University, Bloomington, IN, USA, June 14, 2015
1. Neutrino physics

2. Lorentz violating neutrino oscillation

3. MiniBooNE experiment

4. MINOS experiment

5. OPERA experiment

6. Double Chooz experiment

7. IceCube experiment

8. Conclusions
1. Neutrinos

Neutrinos in the standard model
The standard model describes 6 quarks and 6 leptons and 3 types of force carriers.

Neutrinos are special because,

1. they only interact with weak nuclear force.

\[
\begin{align*}
\nu_\mu & \quad \text{charged current (CC) interaction} \\
& \quad \text{"W-boson exchange"} \\
\mu & \quad \text{charged current (NC) interaction} \\
& \quad \text{"Z-boson exchange"} \\
\end{align*}
\]

2. interaction eigenstate is not Hamiltonian eigenstate (propagation eigenstate). Thus propagation of neutrinos changes their species, called neutrino oscillation.
1. Neutrino Standard Model (νSM)

Standard Model (SM) + 3 active massive neutrinos
- 6 new parameters to describe neutrino oscillations
- 3 mixing angles
- 2 neutrino mass square differences
- 1 Dirac CP phase

\[ P_{\alpha \rightarrow \beta}(L) = 1 - 4 \sum_{i > j} \text{Re}(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}) \sin^2 \left( \frac{\Delta m_{ij}^2}{4E} L \right) + 2 \sum_{i > j} \text{Im}(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}) \sin \left( \frac{\Delta m_{ij}^2}{2E} L \right) \]

Flavor state
\[ |\nu_\alpha\rangle = \sum U_{\alpha i}^* |\nu_i\rangle \]

Mass state

```
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \times \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix} \times \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
e^{i\alpha_1}/2 & 0 & 0 \\
0 & e^{i\alpha_2}/2 & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
```

Note: \( c_{ij} = \cos(\theta_{ij}) \), \( s_{ij} = \sin(\theta_{ij}) \)

“Atmospheric ν” (Super-K, K2K, MINOS) \( \sin^2 2\theta_{23} > 0.95 \) (90% C.L.)

“Reactor/Acc. ν” (Daya Bay, RENO, Double Chooz, T2K, NOνA) \( \sin^2 2\theta_{13} = 0.098 \pm 0.013 \)

“Solar ν” (SNO, Super-K, KamLAND) \( \sin^2 2\theta_{12} = 0.857 \pm 0.024 \)

Majorana phases: Not yet observed
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Current unknowns
- Dirac CP phase
- $\theta_{23}$ ($\theta_{23}=40^\circ$ and 50$^\circ$ are same for $\sin 2\theta_{23}$, but not for $\sin \theta_{23}$)
- order of mass (normal hierarchy $m_1<m_2<m_3$ or inverted hierarchy $m_3<m_1<m_2$)

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\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

Mass state

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Other νSM parameters
- Dirac or Majorana neutrinos
- Majorana phase (x2)
- Absolute neutrino mass scale

\[ P_{\alpha \rightarrow \beta} (L) = 1 - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}) \sin^2 \left( \frac{\Delta m_{ij}^2}{4E} L \right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}) \sin \left( \frac{\Delta m_{ij}^2}{2E} L \right) \]
1. Neutrino Standard Model ($\nu$SM)

Long baseline accelerator neutrino oscillation experiments
- K2K, MINOS, OPERA, T2K, NOvA, etc
- $\nu_\mu/\bar{\nu}_\mu$-bar disappearance from $\nu_\mu/\bar{\nu}_\mu$-bar beam
- $\nu_\tau/\bar{\nu}_\tau$-bar appearance from $\nu_\mu/\bar{\nu}_\mu$-bar beam
- $\nu_e/\bar{\nu}_e$-bar appearance from $\nu_\mu/\bar{\nu}_\mu$-bar beam ($\nu$SM)

Short baseline accelerator neutrino oscillation experiments
- LSND, MiniBooNE, etc
- $\nu_e/\bar{\nu}_e$-bar appearance from $\nu_\mu/\bar{\nu}_\mu$-bar beam (exotic)

Long baseline reactor neutrino oscillation experiments
- Double Chooz, RENO, Daya Bay, etc
- $\nu_e$-bar disappearance from $\nu_e$-bar reactor neutrinos
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8. Conclusions
2. Neutrino oscillations, natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment).

For double slit experiment, if path $\nu_1$ and path $\nu_2$ have different length, they have different phase rotations and it causes interference.
2. Neutrino oscillations, natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)

If 2 neutrino Hamiltonian eigenstates, $\nu_1$ and $\nu_2$, have different phase rotation, they cause quantum interference.
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If 2 neutrino Hamiltonian eigenstates, $\nu_1$ and $\nu_2$, have different phase rotation, they cause quantum interference.

If $\nu_1$ and $\nu_2$, have different mass, they have different velocity, so thus different phase rotation.
2. Neutrino oscillations, natural interferometers

Neutrino oscillation is an interference experiment (cf. double slit experiment)

If 2 neutrino Hamiltonian eigenstates, ν₁ and ν₂, have different phase rotation, they cause quantum interference.

If ν₁ and ν₂, have different mass, they have different velocity, so thus different phase rotation.

The detection may be different flavor (neutrino oscillations).
2. Lorentz violation with neutrino oscillation

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If 2 neutrino Hamiltonian eigenstates, $\nu_1$ and $\nu_2$, have different phase rotation, they cause quantum interference.

If $\nu_1$ and $\nu_2$, have different coupling with Lorentz violating field, neutrinos also oscillate. The sensitivity of neutrino oscillation is comparable to the target scale of Lorentz violation ($<10^{-19}$GeV).
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If neutrino oscillation is caused by Lorentz violation, interference pattern (oscillation probability) may have sidereal time dependence.
2. Test of Lorentz violating neutrino oscillations

Lorentz violation is realized as a coupling of particle fields and background fields, so the basic strategy to find Lorentz violation is:

1. choose the coordinate system
2. write down the Lagrangian, including Lorentz-violating terms under the formalism
3. write down the observables using this Lagrangian
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- Neutrino beamline is described in **Sun-centred coordinates**

![Diagram showing Earth and Sun with equinoxes and solstices, and MiniBooNE beamline location on map]
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Standard Model Extension (SME) is the standard formalism for the general search for Lorentz violation. SME is a minimum extension of QFT with Particle Lorentz violation.

SME Lagrangian in neutrino sector

\[
L = \frac{1}{2} i \bar{\psi}_A \Gamma^\nu_{AB} \partial_\nu \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.
\]

SME coefficients

\[
\Gamma^\nu_{AB} = \gamma^\nu \delta_{AB} + c^{\mu\nu}_{AB} \gamma_\mu + d^{\mu\nu}_{AB} \gamma_\mu \gamma_5 + e^\nu_{AB} + i f^\nu_{AB} \gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB} \sigma_{\lambda\mu} \cdots
\]

\[
M_{AB} = m_{AB} + i m_{5AB} \gamma_5 + a^\mu_{AB} \gamma_\mu + b^\mu_{AB} \gamma_5 \gamma_\mu + \frac{1}{2} H^{\mu\nu}_{AB} \sigma_{\mu\nu} \cdots
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CPT odd

CPT even

Not gauge invariant
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CPT odd

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Not gauge invariant

4X4 Lorentz indices

6X6 flavor indices

nonminimal SME
2. SME effective hamiltonian for neutrinos

\( (h_{\text{eff}})_{AB} = E \left( \begin{array}{cc} \delta_{ab} & 0 \\ 0 & \delta_{ab} \end{array} \right) + \frac{1}{2E} \left( \begin{array}{cc} (m^2)_{ab} & 0 \\ 0 & (m^2)_{ab}^* \end{array} \right) + \frac{1}{E} \left( \begin{array}{cc} [a_L]^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu & [g^{\mu\nu\sigma} p_\sigma - H^{\mu\nu}] C \right]_{ab} \\
\sqrt{2} (\epsilon_+)_\nu [g^{\mu\nu\sigma} p_\sigma + H^{\mu\nu}] C^* \left[ - (a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu \right]_{ab} \end{array} \right) \)
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SME effective Hamiltonian for neutrino-neutrino oscillation

usual Hamiltonian (3X3)

\[
(h_{\text{eff}})_{ab} = E \delta_{ab} + \frac{1}{2E} (m^2)_{ab} + \frac{1}{E} [(a_L)^{\mu} p_\mu - (c_L)^{\mu \nu} p_\mu p_\nu]_{ab}
\]

Lorentz violating terms (3X3)
2. Test of Lorentz violating neutrino oscillations

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Various physics are predicted under SME, but among them, the smoking gun of Lorentz violation is the \textit{sidereal time dependence} of the observables:

- Solar time: 24h 00m 00.0s
- Sidereal time: 23h 56m 04.1s

Lorentz-violating neutrino oscillation probability for short-baseline experiments:

\[
P_{\nu_{\mu} \rightarrow \nu_e} = \left( \frac{L}{\hbar c} \right)^2 \left| (C)_{e\mu} + (A_s)_{e\mu} \sin \omega_\oplus T_\oplus + (A_c)_{e\mu} \cos \omega_\oplus T_\oplus + (B_s)_{e\mu} \sin 2\omega_\oplus T_\oplus + (B_c)_{e\mu} \cos 2\omega_\oplus T_\oplus \right|^2
\]
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Sidereal variation analysis for short baseline neutrino oscillation is 5-parameter fitting problem
2. Test of Lorentz violating neutrino oscillations

Sidereal variation of neutrino oscillation probability for MiniBooNE (5 parameters)

\[ P_{\nu_e \rightarrow \nu_\mu} = \left( \frac{L}{hc} \right)^2 \left| (C)_{\nu_e \nu_\mu} + (A)_{\nu_e \nu_\mu} \sin w T + (A)_{\nu_e \nu_\mu} \cos w T + (B)_{\nu_e \nu_\mu} \sin 2w T + (B)_{\nu_e \nu_\mu} \cos 2w T \right|^2 \]

Expression of 5 observables (14 SME parameters)

\[
\begin{align*}
(C)_{\nu_e \nu_\mu} &= (a_L^{T})_{\nu_e \nu_\mu} - N^Z(a_L)^Z_{\nu_e \nu_\mu} + E \left[ -\frac{1}{2} (3 - N^Z N^Z) (c_L^{T})_{\nu_e \nu_\mu} + 2 N^Z (c_L)^Z_{\nu_e \nu_\mu} + \frac{1}{2} (1 - 3 N^Z N^Z) (c_L)^ZZ_{\nu_e \nu_\mu} \right] \\
(A)_{s^{\nu_e \nu_\mu}} &= N^Y (a_L^X)_{\nu_e \nu_\mu} - N^X (a_L)^Y_{\nu_e \nu_\mu} + E \left[ -2 N^Y (c_L)^TX_{\nu_e \nu_\mu} + 2 N^X (c_L)^TY_{\nu_e \nu_\mu} + 2 N^Y N^Z (c_L)^XZ_{\nu_e \nu_\mu} - 2 N^X N^Z (c_L)^YZ_{\nu_e \nu_\mu} \right] \\
(A)_{c^{\nu_e \nu_\mu}} &= -N^X (a_L^Y)_{\nu_e \nu_\mu} - N^Y (a_L)^X_{\nu_e \nu_\mu} + E \left[ 2 N^X (c_L)^TX_{\nu_e \nu_\mu} + 2 N^Y (c_L)^TY_{\nu_e \nu_\mu} - 2 N^X N^Z (c_L)^XZ_{\nu_e \nu_\mu} - 2 N^Y N^Z (c_L)^YZ_{\nu_e \nu_\mu} \right] \\
(B)_{s^{\nu_e \nu_\mu}} &= E \left[ N^X N^Y ((c_L)^X)_{\nu_e \nu_\mu} - (c_L)^YY_{\nu_e \nu_\mu} - (N^X N^X - N^Y N^Y) (c_L)^XY_{\nu_e \nu_\mu} \right] \\
(B)_{c^{\nu_e \nu_\mu}} &= E \left[ -\frac{1}{2} (N^X N^X - N^Y N^Y) ((c_L)^X)_{\nu_e \nu_\mu} - (c_L)^YY_{\nu_e \nu_\mu} - 2 N^X N^Y (c_L)^XY_{\nu_e \nu_\mu} \right] \\
\end{align*}
\]

\[
\begin{pmatrix} N^X \\
N^Y \\
N^Z \end{pmatrix} = \begin{pmatrix} \cos \chi \sin \theta \cos \phi - \sin \chi \cos \theta \\
\sin \theta \sin \phi \\
- \sin \chi \sin \theta \cos \phi - \cos \chi \cos \theta \end{pmatrix} \quad \text{coordinate dependent direction vector} \\
\text{(depends on the latitude of FNAL, location of BNB and MiniBooNE detector)}
\]
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2. Lorentz violating neutrino oscillation

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8. Conclusions
3. MiniBooNE experiment

MiniBooNE experiment is designed to test LSND neutrino oscillation anomaly.
Keep L/E same with LSND, while changing systematics, energy & event signature;
\[ P(\nu_\mu - \nu_e) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \]
MiniBooNE is looking for the single isolated electron like events, which is the signature of \( \nu_e \) events

\[ \nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + e^- \]
\[ \bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + e^+ \]

MiniBooNE has;
- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)
3. Neutrino beam

MiniBooNE extracts beam from the 8 GeV Booster

FNAL Booster

Booster

Target Hall

target and horn

decay region

primary beam
(protons)

secondary beam
(mesons)

tertiary beam
(neutrinos)

FNAL Booster

absorber
dirt
detector

$\nu_\mu \rightarrow \nu_e$ ???
3. Neutrino beam

8GeV protons are delivered to a 1.7 λ Be target within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6

FNAL Booster | target and horn | decay region | absorber | dirt | detector
---|---|---|---|---|---
primary beam (protons) | secondary beam (mesons) | tertiary beam (neutrinos)

νμ → νe ???

MiniBooNE collaboration,
PRD79(2009)072002
3. Neutrino beam

Modeling of meson production is based on the measurement done by HARP collaboration.

- Identical, but 5% \( \lambda \) Beryllium target
- 8.9 GeV/c proton beam momentum

3. Events in the Detector

The MiniBooNE Detector

- 541 meters downstream of target
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH\textsubscript{2})
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
- 240 veto phototubes
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3. Events in the Detector

Times of hit-clusters (subevents)
Beam spill (1.6µs) is clearly evident
   simple cuts eliminate cosmic backgrounds

Neutrino Candidate Cuts
<6 veto PMT hits
   Gets rid of muons

>200 tank PMT hits
   Gets rid of Michels

Only neutrinos are left!
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- **Muons**
  - Sharp, clear rings
  - Long, straight tracks

- **Electrons**
  - Scattered rings
  - Multiple scattering
  - Radiative processes

- **Neutral Pions**
  - Double rings
  - Decays to two photons
3. Events in the Detector

- Sharp, clear rings
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MiniBooNE collaboration, NIM.A599(2009)28
3. MiniBooNE $\nu_e$ appearance candidate data

Neutrino mode low energy excess

MiniBooNE didn't see the signal at the region where LSND data suggested under the assumption of standard 2 massive neutrino oscillation model, but MiniBooNE did see the excess where neutrino standard model doesn't predict the signal.

MiniBooNE low E $\nu_e$ excess

All backgrounds are measured in other data sample and their errors are constrained

475MeV
3. Lorentz violation with MiniBooNE neutrino data

Time distribution of MiniBooNE neutrino mode low energy region

MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

solar local time
24h00m00s (86400s)
sidereal time
23h56m04s (86164s)
3. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics
- Beam and detector day night effect is evaluated from high statistics $\nu_\mu$ CCQE sample
- $\nu_\mu$ CCQE events show ±6% day-night variation

![Graph showing $\nu_\mu$ CCQE events day-night distribution]

±6%
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- Beam and detector day night effect is evaluated from high statistics $\nu_\mu$ CCQE sample
- $\nu_\mu$ CCQE events show $\pm 6\%$ day-night variation
- Furthermore, neutrinos know when the weekend is!

$\nu_\mu$ CCQE events distribution, Monday to Friday

$\nu_\mu$ CCQE events distribution, Saturday and Sunday

Teppei Katori, Queen Mary University of London

15/06/14
3. Lorentz violation with MiniBooNE neutrino data

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- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)

$\nu_\mu$ CCQE events distribution, Monday to Friday

$\nu_\mu$ CCQE events distribution, Saturday and Sunday

POT distribution, Monday to Friday

POT distribution, Saturday and Sunday
3. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics
- Beam and detector day night effect is evaluated from high statistics $\nu_\mu$ CCQE sample
- $\nu_\mu$ CCQE events show $\pm 6\%$ day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)
- After correcting this, $\nu_\mu$ CCQE events exhibit flat
3. Lorentz violation with MiniBooNE neutrino data

Null hypothesis test

The flatness hypothesis is tested by unbinned Kolmogorov-Smirnov test (K-S test). K-S test has 3 advantages;
1. unbinned, so it has the maximum statistical power
2. no argument with bin choice
3. sensitive with systematic shift of the distribution (e.g., sinusoidal)

None of the tests shows any statistically significant results.
All data sets are compatible with flat hypothesis by K-S test

<table>
<thead>
<tr>
<th>Neutrino mode</th>
<th>low energy</th>
<th>high energy</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>solar</td>
<td>sidereal</td>
<td>solar</td>
</tr>
<tr>
<td>$&lt;E_\nu&gt;$</td>
<td>0.36 GeV</td>
<td>0.82 GeV</td>
<td>0.71 GeV</td>
</tr>
<tr>
<td>#evt</td>
<td>544</td>
<td>420</td>
<td>964</td>
</tr>
<tr>
<td>$P(KS)$</td>
<td>0.42</td>
<td>0.13</td>
<td>0.81</td>
</tr>
</tbody>
</table>
3. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum likelihood fit

- It has the maximum statistic power
- Assuming excess is Lorentz violation, extract Lorentz violation parameters (SME parameters) from unbinned likelihood fit.

likelihood function

\[
\Lambda = \frac{e^{-(\mu_s + \mu_b^v)}}{N!} \prod_{i=1}^{N} (\mu_s \mathcal{F}_s^i + \mu_b^v \mathcal{F}_b^i) \times \frac{1}{\sqrt{2\pi}\sigma_b^2} \exp \left( -\frac{(\mu_b^v - \mu_b)^2}{2\sigma_b^2} \right)
\]  

(22)

N total number of event

\(\mu_s\) predicted signal event number, function of fitting parameters

\(\mu_b\) predicted background event number

\(\mathcal{F}_s\) probability distribution of signal, function of sidereal time and fitting parameters

\(\mathcal{F}_b\) probability distribution of background, not function of sidereal time

\(\sigma_b\) the 1 – \(\sigma\) error of predicted the background

\(\mu_b^v\) floating background event number floating within 1 – \(\sigma\)
3. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum loglikelihood fit

- It has the maximum statistic power
- Assuming excess is Lorentz violation, extract Lorentz violation parameters (SME parameters) from unbinned likelihood fit.
- technically, we add loglikelihood of each event to calculate loglikelihood value of each grid point in a parameter space (grid search). The maximum loglikelihood point is the best fit point, and grid of loglikelihood define 1-σ and 2-σ contour (corrected by fake data)
- due to high correlation of parameters, 5 parameter fit cannot provide contours, so we focus on 3 parameter fit

loglikelihood function for an event

\[ \ell_i = -\frac{1}{N} (\mu_s + \mu_b^0) + \ln[\mu_s F_s^i + \mu_b^0 F_b^i] - \frac{1}{2N} \left( \frac{\mu_b^0 - \mu_b}{\sigma} \right)^2 \]

Sidereal variation of neutrino oscillation probability for MiniBooNE

\[ P_{\nu_e \rightarrow \nu_\mu} = \left( \frac{L}{hc} \right)^2 | (C)_{e\mu} + (A_s)_{e\mu} \sin w_0 T_0 + (A_c)_{e\mu} \cos w_0 T_0 |^2 \]

sidereal frequency \( w_0 = \frac{2\pi}{23h56m4.1s} \)

sidereal time \( T_0 \)
3. Lorentz violation with MiniBooNE neutrino data

Neutrino mode result, low energy region

Only C-parameter is nonzero, but this is sidereal independent parameter.

26.9% of fake data based on null hypothesis have bigger $\Delta \chi^2$ than data.

The neutrino mode low energy excess is consistent with no sidereal variation.
3. Lorentz violation with MiniBooNE anti-neutrino data

Anti-neutrino mode result, combined energy region

As and Ac-parameters are nonzero, which are sidereal dependent parameters.

3.0% of fake data based on null hypothesis have bigger \( \Delta \chi^2 \) than data.

The anti-neutrino mode combined energy region excess prefer sidereal time dependent solution, but not statistically significant level.
3. Fake data study

No signal in fake data, with background fluctuation

- 15 fake data out of 499 fake data have larger $\Delta \chi^2$ than data
  $\Rightarrow$ fit is significant over null hypothesis, $\sim 97\%$
3. Fake data study

Signal in fake data, with background fluctuation

The fake data distribute on the 1-sigma contour of data fit. 302 fake data is in a-1sigma (61%) 180 fake data out of 499 fake data have larger $\Delta \chi^2$ than data, this is 36%.

$\rightarrow$ constant likelihood surface underestimate 1-$\sigma$ region
3. Fake data study

Signal in fake data, with background fluctuation

The fake data distribute on the 1-sigma contour of data fit. 302 fake data is in a-1sigma (61%) 180 fake data out of 499 fake data have larger $\Delta \chi^2$ than data, this is 36%.

$\rightarrow$ likelihood surface underestimate 1-\(\sigma\) region

- new 1-sigma defined by MLL-2.1 contains 336/499 fake data (67%)
3. Lorentz violation with MiniBooNE neutrino data

MiniBooNE is a short-baseline neutrino oscillation experiment at Fermilab.

\[
\begin{align*}
\nu_\mu \stackrel{\text{oscillation}}{\rightarrow} \nu_e + n \rightarrow e^- + p \\
\bar{\nu}_\mu \stackrel{\text{oscillation}}{\rightarrow} \bar{\nu}_e + p \rightarrow e^+ + n
\end{align*}
\]

Since we find no evidence of Lorentz violation, we set limits on the combination SME coefficients.

<table>
<thead>
<tr>
<th></th>
<th>(\nu)-mode BF</th>
<th>2(\sigma) limit</th>
<th>(\bar{\nu})-mode BF</th>
<th>2(\sigma) limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>((C)_{e\mu})</td>
<td>(3.1 \pm 0.6 \pm 0.9)</td>
<td>(&lt; 4.2)</td>
<td>(0.1 \pm 0.8 \pm 0.1)</td>
<td>(&lt; 2.6)</td>
</tr>
<tr>
<td>((A_s)_{e\mu})</td>
<td>(0.6 \pm 0.9 \pm 0.3)</td>
<td>(&lt; 3.3)</td>
<td>(2.4 \pm 1.3 \pm 0.5)</td>
<td>(&lt; 3.9)</td>
</tr>
<tr>
<td>((A_c)_{e\mu})</td>
<td>(0.4 \pm 0.9 \pm 0.4)</td>
<td>(&lt; 4.0)</td>
<td>(2.1 \pm 1.2 \pm 0.4)</td>
<td>(&lt; 3.7)</td>
</tr>
</tbody>
</table>

SME coefficients combination (unit \(10^{-20}\) GeV)

<table>
<thead>
<tr>
<th></th>
<th>((C)_{e\mu})</th>
<th>((A_s)_{e\mu})</th>
<th>((A_c)_{e\mu})</th>
</tr>
</thead>
<tbody>
<tr>
<td>((C)_{e\mu})</td>
<td>(\pm [(a_L)^T_{e\mu} + 0.75 (a_L)^Z_{e\mu}] - \langle E \rangle [1.22 (c_L)<em>{e\mu}^{TT} + 1.50 (c_L)</em>{e\mu}^{TZ} + 0.34 (c_L)_{e\mu}^{ZZ}] )</td>
<td>(\pm [0.66 (a_L)^Y_{e\mu}] - \langle E \rangle [1.33 (c_L)<em>{e\mu}^{TY} + 0.99 (c_L)</em>{e\mu}^{YZ}] )</td>
<td>(\pm [0.66 (a_L)^X_{e\mu}] - \langle E \rangle [1.33 (c_L)<em>{e\mu}^{TX} + 0.99 (c_L)</em>{e\mu}^{XZ}] )</td>
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1. Neutrino physics

2. Lorentz violating neutrino oscillation

3. MiniBooNE experiment

4. MINOS experiment

5. OPERA experiment

6. Double Chooz experiment

7. IceCube experiment

8. Conclusions
MINOS (Main Injector Neutrino Oscillation Search)
- NuMI neutrino beam line (3-15 GeV)
- 735km baseline, from Fermilab to Soudan mine
4. MINOS experiment

MINOS (Main Injector Neutrino Oscillation Search)
- NuMI neutrino beam line (3-15 GeV)
- 735km baseline, from Fermilab to Soudan mine
4. Massive Lorentz-violating model

MINOS observed the standard neutrino oscillation.

All possible Lorentz violating neutrino oscillations are secondary effect.

By assuming main source of neutrino oscillation is neutrino mass, we can study perturbation terms to find secondary effect to cause oscillations.

\[
P(\nu_\mu \rightarrow \nu_\tau) = P^0(\nu_\mu \rightarrow \nu_\tau) + P^1(\nu_\mu \rightarrow \nu_\tau) + \cdots
\]

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) = P^0(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) + P^1(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) + \cdots
\]

In this way, we can access to different types of Lorentz violation

\[
P^{(1)}_{\mu\tau} = 2L \left\{ (P^{(1)}_C)_{\mu\tau} + (P^{(1)}_A)_{\mu\tau} \sin \omega T + (P^{(1)}_A)_{\mu\tau} \cos \omega T + (P^{(1)}_B)_{\mu\tau} \sin 2\omega T + (P^{(1)}_B)_{\mu\tau} \cos 2\omega T \right\}
\]
4. FFT (Fast Fourier Transformation)

The sidereal variation data’s Fourier powers are analysed.

First, fake data set is made. Then FFT is performed to all of them.

Square sum of 2 powers, \( p_1 \) and \( p_2 \), are defined.

From distributions of \( p_1 \) and \( p_2 \), discovery threshold (3-\( \sigma \)) is set.

Then data \( p_1 \) and \( p_2 \) are checked, and neither are greater than discovery threshold, therefore sidereal variation is not discovered.

\[
p_1 = \sqrt{S_1^2 + C_1^2}, \quad p_2 = \sqrt{S_2^2 + C_2^2}
\]
4. FFT (Fast Fourier Transformation)

The sidereal variation data’s Fourier powers are analysed.

First, fake data set is made. Then FFT is performed to all of them.

Square sum of 2 powers, $p_1$ and $p_2$, are defined.

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Then data $p_1$ and $p_2$ are checked, and neither are greater than discovery threshold, therefore sidereal variation is not discovered.

Then, SME coefficient is increased in MC one by one, until either $p_1$ or $p_2$ hit $3-\sigma$ threshold

→ $3-\sigma$ limits of SME coefficients

<table>
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<tr>
<th>Coeff.</th>
<th>Limit</th>
<th>I</th>
<th>Coeff.</th>
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<th>I</th>
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</thead>
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<tr>
<td>$(a_L)_X^{\mu\tau}$</td>
<td>$5.9 \times 10^{-23}$</td>
<td>510</td>
<td>$(a_L)_Y^{\mu\tau}$</td>
<td>$6.1 \times 10^{-23}$</td>
<td>490</td>
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<tr>
<td>$(c_L)_T^{\mu\tau}$</td>
<td>$0.5 \times 10^{-23}$</td>
<td>20</td>
<td>$(c_L)_T^{\mu\tau}$</td>
<td>$0.5 \times 10^{-23}$</td>
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<tr>
<td>$(c_L)_X^{\mu\tau}$</td>
<td>$2.5 \times 10^{-23}$</td>
<td>220</td>
<td>$(c_L)_Y^{\mu\tau}$</td>
<td>$2.4 \times 10^{-23}$</td>
<td>230</td>
</tr>
<tr>
<td>$(c_L)_X^{\mu\tau}$</td>
<td>$1.2 \times 10^{-23}$</td>
<td>230</td>
<td>$(c_L)_Y^{\mu\tau}$</td>
<td>$0.7 \times 10^{-23}$</td>
<td>170</td>
</tr>
<tr>
<td>$(c_L)_X^{\mu\tau}$</td>
<td>$0.7 \times 10^{-23}$</td>
<td>190</td>
<td></td>
<td></td>
<td></td>
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</tbody>
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5. Superluminal neutrinos

What about..., OPERA result?
5. Superluminal neutrinos

OPERA (Oscillation Project with Emulsion-tRacking Apparatus)
- CNGS neutrino beam line (~17 GeV)
- 730km baseline, from CERN (Switzerland) to Gran Sasso (Italy)
5. Superluminal neutrinos

**OPERA (Oscillation Project with Emulsion-tRacking Apparatus)**
- CNGS neutrino beam line (~17 GeV)
- 730km baseline, from CERN (Switzerland) to Gran Sasso (Italy)

**Neutrino Time of Flight (TOF) measurement**
- GPS information for beam and detector
- Neutrinos arrive faster than expected time

\[ v(\text{neutrino}) = c + (2.37 \pm 0.32) \times 10^{-5} c \]
\[ = c + (16000 \pm 2000) \text{ mph} \]
5. Superluminal neutrinos

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- GPS information for beam and detector
- Neutrinos arrive faster than expected

Neutrinos still faster than light in latest version of experiment
Finding that contradicts Einstein’s theory of special relativity is repeated with fine-tuned procedures and equipment

Neutrinos may have traveled faster than the speed of light
By Elizabeth Flock
Scientists at CERN, the world’s largest physics lab, announced a startling finding yesterday that would be enough to make Albert Einstein roll over in his grave: Subatomic particles, called neutrinos, have been found to be traveling faster than the speed of light.

Speed of light broken again as scientists test neutrino result
The speed of light appears to have been broken again after scientists carried out a new set of experiments to test measurements that could require the laws of physics to be rewritten.
5. Superluminal neutrinos

OPERA

\[ v(\text{neutrino}) = c + (2.37 \pm 0.32) \times 10^{-5} c \]
\[ = c + (16 \pm 2) \times 10^3 \text{mph} \]

It is fascinating result, but...

- time of flight is kinematic test (less sensitive than neutrino oscillations)
- no indication of Lorentz violation from any neutrino oscillation experiments
- superluminal neutrino is unstable (vacuum Cherenkov radiation) \text{ArXiv:1109.6562}
- pion phase space is limited to create such neutrinos \text{ArXiv:1109.6630}
- SN1987A neutrinos provide severe limit to superluminal neutrinos \text{PRL58(1987)1490}
- etc...

It is very difficult to interpret superluminal neutrinos at OPERA by Lorentz violation
5. Superluminal neutrinos

Two Technical Problems Leave Neutrinos’ Speed in Question
By KENNETH CHANG
Published: February 23, 2012

Faster-than-light neutrinos could be down to bad wiring
By Jason Palmer
Science and technology reporter, BBC News

What might have been the biggest physics story of the past century may instead be down to a faulty connection.

In September 2011, the Opera experiment reported it had seen particles called neutrinos evidently travelling faster than the speed of light.

The team has now found two problems that may have affected their test in opposing ways: one in the timing near and one in an optical fibre.

The neutrinos are fired deep under the Italian

It is fascinating result, but...
- time of flight is kinematic test (less sensitive than neutrino oscillations)
- no indication of Lorentz violation from any neutrino oscillation experiments
- superluminal neutrino is unstable (vacuum Cherenkov radiation)
- pion phase space is limited to create such neutrinos
- SN1987A neutrinos provide severe limit to superluminal neutrinos
- etc...

It is very difficult to interpret superluminal neutrinos at OPERA by Lorentz violation

The Washington Post
Posted at 01:23 PM ET, 02/23/2012
Faster-than-light neutrinos aren’t?
By Alexandra Petri

You can return to your homes. There is nothing more to see.

It turns out those faster-than-light neutrinos at Europe’s CERN lab

The guardian

Faster-than-light neutrinos: was a faulty connection to blame?
A dodgy optical fibre connection may have skewed results that appeared to show neutrinos travelling faster than light

Alok Jha, science correspondent
guardian.co.uk, Thursday 23 February 2012 11:06 EST

Faster-than-light neutrinos would breach Einstein’s theory of special relativity.
5. Neutrino TOF experiments

Although OPERA was not right, neutrino ToF is an interesting test of Lorentz violation
- You cannot send a signal to kill your grandma by superluminal neutrinos (Ralf Lehnert)

Neutrino TOF is the kinetic test, and limits are weaker than oscillation experiments, however you can test SME coefficients only which oscillations are not sensitive (Matt Mewes)

nonminimal SME oscillation-free model neutrino energy

\[ E^\text{of}_\nu = |p| + \frac{|m_1|^2}{2|p|} + \sum_{d,j,m} |p|^{d-3} Y_{jm}(\hat{p})[(a^{(d)}_{\text{of}})_{jm} - (c^{(d)}_{\text{of}})_{jm}] \]

Neutrino group velocity

\[ \nu^\text{of} = 1 - \frac{|m_1|^2}{2p^2} + \sum_{d,j,m} (d - 3)|p|^{d-4} e^{im_0 T_0} \mathcal{N}_{jm}[(a^{(d)}_{\text{of}})_{jm} - (c^{(d)}_{\text{of}})_{jm}] \]
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6. Double Chooz experiment
6. Double Chooz experiment

How We Detect Anti-Nu?

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

(Energy Thres. 1.8 MeV)

**Inverse Beta Decay (IBD)**

\[ e^+ + e^- \rightarrow 2\gamma \]

Energy \( \approx E_\nu - 0.8 \text{ MeV} \)

- Immediately after IBD
- **Prompt signal**

**e^+e^- Annihilation**

\[ n + \text{Gd} \rightarrow \sum \gamma_i \]

Energy \( \approx 8 \text{ MeV} \)

- After neutron thermalization
- **Delayed signal**

**Neutron Capture on Gadolinium**

Buffer Tank

Gamma Catcher

Target
6. Double Chooz experiment

Reactor electron antineutrino disappearance
- Double Chooz, DayaBay and RENO experiments observed disappearance signals

Double Chooz reactor neutrino candidate

The Big Bang Theory (CBS)
6. Double Chooz experiment

Reactor electron antineutrino disappearance
- Double Chooz, DayaBay and RENO experiments observed disappearance signals

Double Chooz reactor neutrino candidate

Leonard: What do you think about the latest Double Chooz result?
Sheldon: I think this is Lorentz violation..., check the sidereal variation

The Big Bang Theory (CBS)
6. Inverse beta decay (IBD) rate

IBD rate is affected by day-night effect of reactor cycle. However, this feature is precisely simulated.
6. Inverse beta decay (IBD) rate

IBD rate is affected by day-night effect of reactor cycle. However, this feature is precisely simulated.

Although we simulate this effect, majorities are smeared out in sidereal distribution.
6. Double Chooz experiment

So far, we have set limits on

1. $\nu_e \leftrightarrow \nu_\mu$ channel: MiniBooNE, MINOS (<10\(^{-20}\) GeV)
2. $\nu_\mu \leftrightarrow \nu_\tau$ channel: MINOS, IceCube (<10\(^{-23}\) GeV)

The last untested channel is $\nu_e \leftrightarrow \nu_\tau$

It is possible to limit $\nu_e \leftrightarrow \nu_\tau$ channel from reactor $\nu_e$ disappearance experiment

$$P(\nu_e \leftrightarrow \nu_e) = 1 - P(\nu_e \leftrightarrow \nu_\mu) - P(\nu_e \leftrightarrow \nu_\tau) \sim 1 - P(\nu_e \leftrightarrow \nu_\tau)$$

Small disappearance signal prefers sidereal time independent solution (flat)

We set limits in the e-$\tau$ sector for the first time; $\nu_e \leftrightarrow \nu_\tau$ (<10\(^{-20}\) GeV)
6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels

...and no one found Lorentz violation...

<table>
<thead>
<tr>
<th>d = 3</th>
<th>Coefficient</th>
<th>$e\mu$</th>
<th>$e\tau$</th>
<th>$\mu\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re(a_L)^T$</td>
<td>$10^{-20}$ GeV</td>
<td>$10^{-19}$ GeV</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$Re(a_L)^X$</td>
<td>$10^{-20}$ GeV</td>
<td>$10^{-19}$ GeV</td>
<td>$10^{-23}$ GeV</td>
<td></td>
</tr>
<tr>
<td>$Re(a_L)^Y$</td>
<td>$10^{-21}$ GeV</td>
<td>$10^{-19}$ GeV</td>
<td>$10^{-23}$ GeV</td>
<td></td>
</tr>
<tr>
<td>$Re(a_L)^Z$</td>
<td>$10^{-19}$ GeV</td>
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</table>

<table>
<thead>
<tr>
<th>d = 4</th>
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<tbody>
<tr>
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<td>$Re(c_L)^{XZ}$</td>
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<tr>
<td>$Re(c_L)^{YZ}$</td>
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<td>$10^{-19}$</td>
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<tr>
<td>$Re(c_L)^{TT}$</td>
<td>$10^{-19}$</td>
<td>$10^{-17}$</td>
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<tr>
<td>$Re(c_L)^{TX}$</td>
<td>$10^{-22}$</td>
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</tbody>
</table>
6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels

…and no one found Lorentz violation...

Leonard: No neutrino experiments find Lorentz violation
Sheldon: Check neutrino-antineutrino oscillation…, Lorentz violation is there
Double Chooz oscillation spectrum is dominated by neutrino-mass like oscillation.

By assuming main source of neutrino oscillation is neutrino mass, we can study perturbation terms to find secondary effect to cause oscillations.

Following channels are all tightly constrained;

\[
\nu_e \leftrightarrow \nu_\mu, \nu_\mu \leftrightarrow \nu_\tau, \nu_\tau \rightarrow \nu_e, \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau, \bar{\nu}_\tau \leftrightarrow \bar{\nu}_e
\]

So the only interesting channels are \textit{neutrino-antineutrino oscillation}, which is possible only 2nd order perturbation

\[
P^2(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - P^2(\bar{\nu}_e \rightarrow \nu_e) - P^2(\bar{\nu}_e \rightarrow \nu_\mu) - P^2(\bar{\nu}_e \rightarrow \nu_\tau)
\]

Effective Hamiltonian of neutrino-antineutrino oscillation

\[
(h_{\text{eff}})_{ab} = \frac{-i}{E} \sqrt{2} p_\mu (\epsilon_+)\nu [(g^{\mu\nu\sigma} p_\sigma - H^{\mu\nu}) C]_{ab}
\]
6. Double Chooz spectrum fit

anti-$\nu_e \rightarrow \nu_e$ oscillation fit with Double Chooz data

These fits provide first limits on neutrino-antineutrino time independent Lorentz violating coefficients
6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels.

Neutrino-antineutrino oscillations are tested, but no Lorentz violation is discovered...

<table>
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<td>$10^{-19}$ GeV</td>
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<td>–</td>
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</tbody>
</table>

<table>
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<tr>
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<th>$e\tau$</th>
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<tbody>
<tr>
<td>Re $(c_L)^{XY}$</td>
<td>$10^{-21}$</td>
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<td>$10^{-23}$</td>
<td></td>
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<tr>
<td>Re $(c_L)^{XZ}$</td>
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<td>$10^{-23}$</td>
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</tr>
<tr>
<td>Re $(c_L)^{YZ}$</td>
<td>$10^{-21}$</td>
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</tr>
<tr>
<td>Re $(c_L)^{XX}$</td>
<td>$10^{-21}$</td>
<td>$10^{-16}$</td>
<td>$10^{-23}$</td>
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</tr>
<tr>
<td>Re $(c_L)^{YY}$</td>
<td>$10^{-21}$</td>
<td>$10^{-16}$</td>
<td>$10^{-23}$</td>
<td></td>
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<tr>
<td>Re $(c_L)^{ZZ}$</td>
<td>$10^{-19}$</td>
<td>$10^{-16}$</td>
<td>–</td>
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<tr>
<td>Re $(c_L)^{TT}$</td>
<td>$10^{-19}$</td>
<td>$10^{-17}$</td>
<td>–</td>
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<tr>
<td>Re $(c_L)^{TX}$</td>
<td>$10^{-22}$</td>
<td>$10^{-17}$</td>
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<tr>
<td>Re $(c_L)^{TY}$</td>
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<tr>
<td>Re $(c_L)^{TZ}$</td>
<td>$10^{-20}$</td>
<td>$10^{-16}$</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>
6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels

Neurino-antineutrino oscillations are tested, but no Lorentz violation is discovered…

Leonard: There is no Lorentz violation in neutrino experiment data
Sheldon: Check the spectrum distortion of atmospheric neutrinos…, Lorentz violation is there
6. Anomalous energy spectrum

Sidereal variation is one of many predicted phenomena of Lorentz violating neutrino oscillations.

Lorentz violation predicts unexpected energy dependence of neutrino oscillations from standard neutrino mass oscillations.

Effective Hamiltonian for neutrino oscillation

\[ h_{\text{eff}} = \frac{m^2}{2E} + a + cE + \cdots \]

This is very useful to differentiate 2 effects:
- massive neutrino oscillation
- sidereal time independent Lorentz violating neutrino oscillation

Atmospheric neutrinos propagate the longest distance on Earth → one of the most stringent test of Lorentz violating neutrino oscillation
6. Super-Kamiokande

Super-Kamiokande obtained the possible tightest limits on Lorentz violation on several parameters.
6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels

Neurino-antineutrino oscillations are tested, but no Lorentz violation is discovered…

Super-Kamiokande got the possible best Lorentz violation limits on Earth…

<table>
<thead>
<tr>
<th>$d = 3$</th>
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<tr>
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<td>$10^{-19}$ GeV</td>
<td>$10^{-23}$ GeV</td>
<td></td>
</tr>
<tr>
<td>$\text{Re} (a_L)^Z$</td>
<td>$10^{-19}$ GeV</td>
<td>$10^{-19}$ GeV</td>
<td>–</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
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<th>$d = 4$</th>
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<th>$e\tau$</th>
<th>$\mu\tau$</th>
</tr>
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<tbody>
<tr>
<td>$\text{Re} (c_L)^{XY}$</td>
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<td>$10^{-23}$</td>
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<tr>
<td>$\text{Re} (c_L)^{TX}$</td>
<td>$10^{-22}$</td>
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<td></td>
</tr>
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6. Double Chooz experiment

By this work, sidereal variation is tested with all neutrino channels

Neurino-antineutrino oscillations are tested, but no Lorentz violation is discovered…

Super-L: No neutrino experiments find sidereal variation on Earth…

Sheldon: Look at the astrophysical neutrinos, Lorentz violation is there

The Big Bang Theory (CBS)
1. Neutrino physics

2. Lorentz violating neutrino oscillation

3. MiniBooNE experiment

4. MINOS experiment

5. OPERA experiment

6. Double Chooz experiment

7. IceCube experiment

8. Conclusions
7. Neutrino standard Model (vSM)

This is the world data of neutrino oscillation

It looks majority of region is either accepted (positive signals) or excluded

But this is model dependent diagram, because it assumes neutrino mass as phase, and mass mixing matrix elements as amplitude of neutrino oscillations

What is model independent diagram look like?
7. Lorentz violation with neutrino oscillation
7. Lorentz violation with neutrino oscillation

- Long baseline reactor neutrino
- Long baseline accelerator neutrino
- Short baseline reactor signal

Diagram showing various experiments such as KamLAND, Super-Kamiokande, IceCube, Daya Bay, Double Chooz, Palo Verde, etc., with distance vs. energy axes.

Reference: Kostelecký and Mewes, PRD69(2004)016005
7. Lorentz violation with neutrino oscillation

Kostelecký and Mewes
PRD69(2004)016005

$\Delta m^2_{\odot}$

$\Delta m^2_{\text{atm}}$

long baseline reactor neutrino

long baseline accelerator neutrino

short baseline reactor signal
7. Lorentz violation with neutrino oscillation

Kostelecký and Mewes
PRD69(2004)016005
7. Lorentz violation with neutrino oscillation

extra galactic neutrino potential

1Mpc (~Andromeda)
7. Lorentz violation with neutrino oscillation
extra galactic neutrino potential

1Mpc(~Andromeda)

IceCube collaboration
PRL111(2013)021103
7. IceCube detector

- IceTop
  - 81 Stations
  - 324 optical sensors

- IceCube Array
  - 86 strings including 8 DeepCore strings
  - 5160 optical sensors

- Amanda II Array
  - (precursor to IceCube)

- DeepCore
  - 8 strings-spacing optimized for lower energy
  - 480 optical sensors

- Eiffel Tower
  - 324 m

- Super-Kamiokande
  - \( \uparrow 40 \) m
7. IceCube detector

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

IceTop
81 Stations
324 optical sensors

Ski-way

South Pole Station

IceCube Lab Building

IceCube Outline
7. IceCube detector

Detector completed on 2010
- 86 strings, 125m separation
- 7 South Pole summer seasons
- Max 20 strings/season
- 1 hole ~ £1M (~mostly fuel)
7. Neutrino astronomy

Direct message from the furthest celestial objects
- Neutrinos are neutral
- Neutrinos only interact with weak force

IceCube detector

Charged particles
Gamma rays
Neutrinos

distant source
7. Astrophysical Neutrinos

First observation (2013)
- 35 TeV to 2 PeV ultra-high energy neutrinos
- Sources → unknown

Direction of astrophysical neutrinos in galactic coordinate

Measured high energy neutrino spectrum

Event display of the highest energy neutrino
7. Lorentz violation with extra-terrestrial neutrinos

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Vacuum Cherenkov radiation can limit new physics of neutrino up to $10^{-20}$.
7. Lorentz violation with extra-terrestrial neutrinos

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Vacuum Cherenkov radiation can limit new physics of neutrino up to $10^{-20}$.

However, the neutrino mixing properties of UHE neutrinos can push this limit further ($\sim10^{-34}$).
7. Neutrino flavour with new physics

Any new physics can end up in the effective Hamiltonian

\[ h_{\text{eff}} = \frac{1}{2E} U^\dagger M^2 U + \sum_n \left( \frac{E}{\Lambda_n} \right)^n \tilde{U}_n^\dagger O_n \tilde{U}_n = V^\dagger \Delta V \]

neutrino oscillation formula

\[ P_{\alpha \rightarrow \beta}(L) = 1 - 4 \sum_{i > j} \text{Re}(V_{\alpha i}^* V_{\beta i} V_{\alpha j} V_{\beta j}) \sin^2 \left( \frac{\Delta_{ij} L}{2} \right) + 2 \sum_{i > j} \text{Im}(V_{\alpha i}^* V_{\beta i} V_{\alpha j} V_{\beta j}) \sin(\Delta_{ij} L) \]

neutrino mixing formula

\[ P_{\alpha \rightarrow \beta}(L \rightarrow \infty) \sim 1 - 2 \sum_{i > j} \text{Re}(V_{\alpha i}^* V_{\beta i} V_{\alpha j} V_{\beta j}) = \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2 \]

Information of small contamination of new physics appears on neutrino flavours

At high energy, neutrino mass term is suppressed

\[ \rightarrow \text{Neutrino mixing effect is dominated by new physics term, such as Lorentz violation} \]
7. Standard flavour triangle diagram

There are 3 UHE neutrino production models
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1

Initial flavour ratio is modified on the Earth due to neutrino mixing

Aruguelles, TK, Salvado
arXiv:1506.02043
IceCube collaboration
PRL114(2015)171102
7. Standard flavour triangle diagram

There are 3 UHE neutrino production models
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Initial flavour ratio is modified on the Earth due to neutrino mixing
7. Neutrino flavour ratio with new physics

Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

An example Hamiltonian with new physics term
($\sim 10^{-26}$ GeV CPT odd Lorentz violation)

$$h_{\text{eff}} = \frac{1}{2E} \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^2 & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^2 & m_{\mu\tau}^2 & m_{\tau\tau}^2 \end{pmatrix} + E \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c_{\mu\tau} \\ 0 & c_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$
7. Neutrino flavour ratio with new physics

Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

Flavor triangle diagram is a convenient way to show these models.
7. Flavour triangle histogram

Exotic models can make variety of
flavour ratios, but not every flavour
ratio is possible.

Dimension-3 new physics

35 TeV scale
(a~10^{-26} GeV)

2 PeV scale
(a~10^{-28} GeV)
7. Flavour triangle histogram

Exotic models can make variety of flavour ratios, but not every flavour ratio is possible.

\[ h_{\text{eff}} = \frac{1}{2E} \left( \begin{array}{ccc} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^2 & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^2 & m_{\mu\tau}^2 & m_{\tau\tau}^2 \end{array} \right) + E \cdot \left( \begin{array}{ccc} c_{ee} & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & c_{\mu\mu} & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & c_{\tau\tau} \end{array} \right) \]

Dimension-4 new physics

35 TeV scale  
(c~10^{-30})

2 PeV scale  
(c~10^{-34})

Neutrino mixing is the most powerful tool to explore any new physics within neutrino physics.
7. IceCube-Gen2

Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

Ice is more transparent than we thought → string separation can be larger to cover larger volume
7. IceCube-Gen2

Bigger IceCube and denser DeepCore can push their physics.

Gen2
Larger string separations to cover larger area.

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement.

IceCube-Gen2 collaboration meeting (May 1, 2015)
Conclusion

Neutrinos are mysterious and interesting particles to study.

Anomalies from LSND, MiniBooNE, and OPERA suggest Lorentz violation may be a solution, but careful analysis found no Lorentz violation.

Standard neutrino oscillation data from MINOS, Double Chooz, Super-Kamiokande are checked, but there are no Lorentz violation.

There are still many possible tests haven’t done yet (TOF, kinematics, etc).

Extra-terrestrial neutrinos from IceCube are probably the most sensitive tool to test Lorentz violation in the neutrino sector.

Thank you for your attention!
backup
3. Neutrino beam

Neutrino flux from simulation by GEANT4

MiniBooNE is the $\nu_e$ (anti $\nu_e$) appearance oscillation experiment, so we need to know the distribution of beam origin $\nu_e$ and anti $\nu_e$ (intrinsic $\nu_e$)

<table>
<thead>
<tr>
<th></th>
<th>neutrino mode</th>
<th>antineutrino mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>intrinsic $\nu_e$ contamination</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>intrinsic $\nu_e$ from $\mu$ decay</td>
<td>49%</td>
<td>55%</td>
</tr>
<tr>
<td>intrinsic $\nu_e$ from $K$ decay</td>
<td>47%</td>
<td>41%</td>
</tr>
<tr>
<td>others</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>wrong sign fraction</td>
<td>6%</td>
<td>16%</td>
</tr>
</tbody>
</table>
5. MiniBooNE experiment

MiniBooNE is a short-baseline neutrino oscillation experiment at Fermilab.

\[ \nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow e^- + p \]

\[ \bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow e^+ + n \]

Neutrino mode analysis: MiniBooNE saw the 3.0\(\sigma\) excess at low energy region.
Antineutrino mode analysis: MiniBooNE saw the 1.4\(\sigma\) excess at low and high energy region.

Intrinsic background errors are constraint from MiniBooNE data.
Data driven corrections are applied to MisID backgrounds.
5. MiniBooNE experiment

MiniBooNE is a short-baseline neutrino oscillation experiment at Fermilab.

\[ \nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow e^- + p \]

\[ \bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow e^+ + n \]

Neutrino mode analysis: MiniBooNE saw the 3.0\(\sigma\) excess at low energy region

Antineutrino mode analysis: MiniBooNE saw the 1.4\(\sigma\) excess at low and high energy region

These excesses are not predicted by neutrino Standard Model (\(\nu\)SM), therefore it might be sterile neutrino or other new physics, such as Lorentz violation

\[ \nu_e \rightarrow \nu_e \]

Oscillation candidate events may have sidereal time dependence!
Antineutrino mode excess
MiniBooNE did see the signal at the region where LSND data suggested under the assumption of standard two massive neutrino oscillation model.

If the excess were Lorentz violation, the excess may have sidereal time dependence.

All backgrounds are measured in other data sample and their errors are constrained.
3. Lorentz violation with MiniBooNE anti-neutrino data

Time distribution of MiniBooNE antineutrino mode oscillation region

MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

- Solar local time: 24h00m00s (86400s)
- Sidereal time: 23h56m04s (86164s)
3. Lorentz violation with MiniBooNE anti-neutrino data

Null hypothesis test

The flatness hypothesis is tested by unbinned Kolmogorov-Smirnov test (K-S test). K-S test has 3 advantages;
1. unbinned, so it has the maximum statistical power
2. no argument with bin choice
3. sensitive with systematic shift of the distribution (e.g., sinusoidal)

Non of tests shows any statistically significant results.
All data sets are compatible with flat hypothesis.

<table>
<thead>
<tr>
<th></th>
<th>low energy</th>
<th>high energy</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>solar</td>
<td>sidereal</td>
<td>solar</td>
</tr>
</tbody>
</table>

|                |            |             |          |          |
|----------------|------------|-------------|----------|
| Neutrino mode  |            |             |          |          |
| $< E_{\nu} >$  | 0.36 GeV   | 0.82 GeV    | 0.71 GeV |
| #evt           | 544        | 420         | 964      |
| $P($KS$)$      | 0.42       | 0.13        | 0.81     | 0.64     | 0.64 | 0.14 |

| Anti-neutrino mode |            |             |          |          |
| $< E_{\bar{\nu}} >$ | 0.34 GeV  | 0.78 GeV    | 0.60 GeV |
| #evt              | 119        | 122         | 241      |
| $P($KS$)$         | 0.02       | 0.15        | 0.79     | 0.39     | 0.69 | 0.08 |
3. Fake data study

2. Signal in fake data, no background fluctuation

The fake data distribute on the 1-sigma contour of data fit. 322 fake data are in 1-sigma volume (65%). 173 fake data out of 499 fake data have larger $\Delta \chi^2$ than data, this is 35%.
3. Summary of results

LSND experiment
LSND is a short-baseline neutrino oscillation experiment at Los Alamos.

\[
\bar{\nu}_\mu \overset{\text{oscillation}}{\rightarrow} \bar{\nu}_e + p \rightarrow e^+ + n
\]

\[
n + p \rightarrow d + \gamma
\]

LSND saw the 3.8\(\sigma\) excess of electron antineutrinos from muon antineutrino beam; since this excess is not understood by neutrino Standard Model, it might be new physics.

Data is consistent with flat solution, but sidereal time solution is not excluded.

\(\sim10^{-19}\) GeV CPT-odd or \(\sim10^{-17}\) CPT-even Lorentz violation could be the solution of LSND excess.
3. Summary of results

Since we find no evidence of Lorentz violation from MiniBooNE analysis, we set limits on the SME coefficients.

These limits exclude SME values to explain LSND data, therefore there is no simple Lorentz violation motivated scenario to accommodate LSND and MiniBooNE results simultaneously.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$e \mu$ ($\nu$ mode low energy region)</th>
<th>$e \mu$ ($\bar{\nu}$ mode combined region)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Re}(a_L)^T$ or $\text{Im}(a_L)^T$</td>
<td>$4.2 \times 10^{-20}$ GeV</td>
<td>$2.6 \times 10^{-20}$ GeV</td>
</tr>
<tr>
<td>$\text{Re}(a_L)^X$ or $\text{Im}(a_L)^X$</td>
<td>$6.0 \times 10^{-20}$ GeV</td>
<td>$5.6 \times 10^{-20}$ GeV</td>
</tr>
<tr>
<td>$\text{Re}(a_L)^Y$ or $\text{Im}(a_L)^Y$</td>
<td>$5.0 \times 10^{-20}$ GeV</td>
<td>$5.9 \times 10^{-20}$ GeV</td>
</tr>
<tr>
<td>$\text{Re}(a_L)^Z$ or $\text{Im}(a_L)^Z$</td>
<td>$5.6 \times 10^{-20}$ GeV</td>
<td>$3.5 \times 10^{-20}$ GeV</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{XY}$ or $\text{Im}(c_L)^{XY}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{XZ}$ or $\text{Im}(c_L)^{XZ}$</td>
<td>$1.1 \times 10^{-19}$</td>
<td>$6.2 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{YZ}$ or $\text{Im}(c_L)^{YZ}$</td>
<td>$9.2 \times 10^{-20}$</td>
<td>$6.5 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{XX}$ or $\text{Im}(c_L)^{XX}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{YY}$ or $\text{Im}(c_L)^{YY}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{ZZ}$ or $\text{Im}(c_L)^{ZZ}$</td>
<td>$3.4 \times 10^{-19}$</td>
<td>$1.3 \times 10^{-19}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{TT}$ or $\text{Im}(c_L)^{TT}$</td>
<td>$9.6 \times 10^{-20}$</td>
<td>$3.6 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{TX}$ or $\text{Im}(c_L)^{TX}$</td>
<td>$8.4 \times 10^{-20}$</td>
<td>$4.6 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{TY}$ or $\text{Im}(c_L)^{TY}$</td>
<td>$6.9 \times 10^{-20}$</td>
<td>$4.9 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\text{Re}(c_L)^{TZ}$ or $\text{Im}(c_L)^{TZ}$</td>
<td>$7.8 \times 10^{-20}$</td>
<td>$2.9 \times 10^{-20}$</td>
</tr>
</tbody>
</table>
8. Superluminal neutrinos

\[ v(\text{neutrino}) = c + (2.37\pm0.32) \times 10^{-5}c \]
\[ = c + (16\pm2) \times 10^{3}\text{mph} \]

It is fascinating result, but...

- time of flight is kinematic test (less sensitive than neutrino oscillations)
- no indication of Lorentz violation from any neutrino oscillation experiments
- superluminal neutrino is unstable (vacuum Cherenkov radiation) \textbf{ArXiv:1109.6562}
- pion phase space is limited to create such neutrinos \textbf{ArXiv:1109.6630}
- SN1987A neutrinos provide severe limit to superluminal neutrinos \textbf{PRL58(1987)1490}
- etc...

It is very difficult to interpret superluminal neutrinos at OPERA by Lorentz violation within field theory approach.
7. Flavour triangle histogram

However, we don’t observe flavour ratio with function of energy 
→ neutrino flux model (\(\sim E^{-2} \)) is convoluted

Also, there are many possible models 
→ flavour triangle histogram

We follow the anarchic sampling scheme to choose the new physics model, and the model density is shown as a histogram on the triangle diagram.

\[
d\tilde{U} = ds_{12}^2 \land dc_{13}^4 \land ds_{23}^2 \land d\delta
\]

Large Lorentz violation \(\rightarrow\) observed flavour ratio can be many option
Small Lorentz violation \(\rightarrow\) only tiny deviation from the standard value is possible