Tests of Lorentz and CPT Violation with Neutrinos

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Teppei Katori
Queen Mary University of London
HEP seminar, Univ. Nottingham, Nottingham, UK, Nov. 25, 2016

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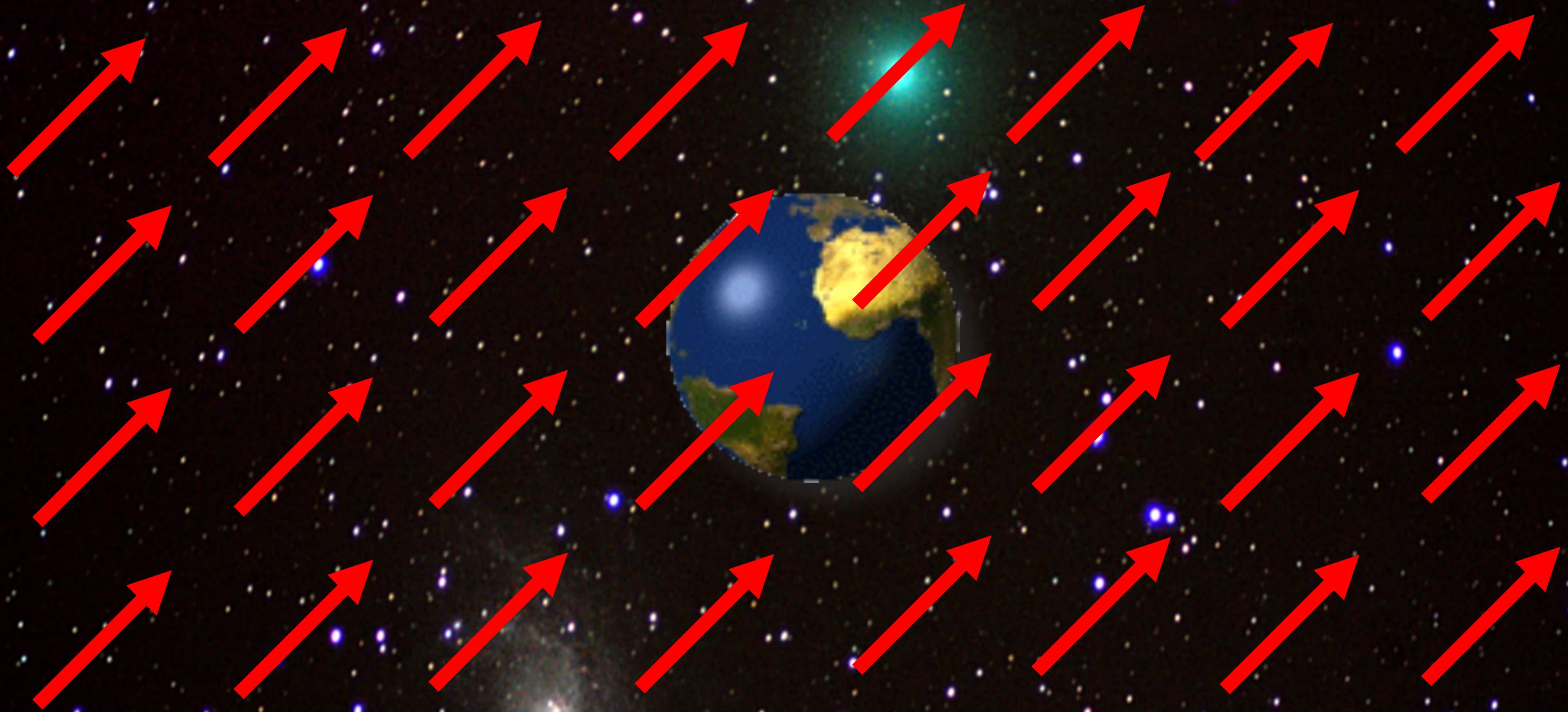

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Tests of Lorentz and CPT Violation with Neutrinos

outline

1. Spontaneous Lorentz symmetry breaking
2. Modern test of Lorentz violation
3. Sensitivity of Lorentz violation by neutrinos
4. New test of Lorentz violation with neutrinos
5. Conclusion

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1. **Spontaneous Lorentz symmetry breaking**
2. Modern test of Lorentz violation
3. Sensitivity of Lorentz violation by neutrinos
4. New test of Lorentz violation with neutrinos
5. Conclusion

1. Spontaneous Lorentz symmetry breaking (SLSB)

Every fundamental symmetry needs to be tested, including Lorentz symmetry.

After the recognition of theoretical processes that create Lorentz violation, testing Lorentz invariance becomes very exciting

Lorentz and CPT violation has been shown to occur in Planck scale theories, including:
- string theory
- noncommutative field theory
- quantum loop gravity
- extra dimensions
- etc

However, it is very difficult to build a self-consistent theory with Lorentz violation...

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Spontaneous Symmetry Breaking (SSB)!

Y. Nambu
(Nobel prize winner 2008),
picture from CPT04 at
Bloomington, IN

1. Spontaneous Lorentz symmetry breaking (SLSB)

vacuum Lagrangian for fermion $\mathrm{L} = i\overline{\Psi}\gamma_{\mu}\partial^{\mu}\Psi$

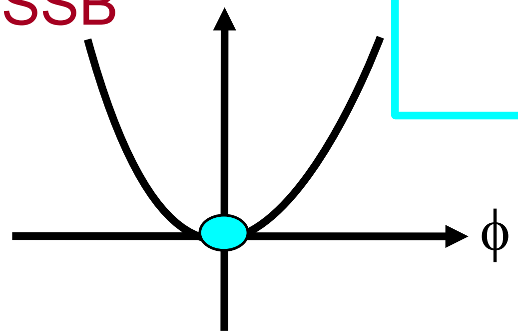
e.g.) SSB of scalar field in Standard Model (SM)

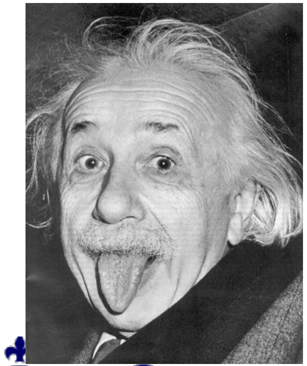
- If the scalar field has Mexican hat potential

$$L = \frac{1}{2}(\partial_{\mu}\varphi)^2 - \frac{1}{2}\mu^2(\varphi^*\varphi) - \frac{1}{4}\lambda(\varphi^*\varphi)^2$$

$$M(\varphi) = \mu^2 < 0$$

SSB





1. Spontaneous Lorentz symmetry breaking (SLSB)

vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_{\mu}\partial^{\mu}\Psi - m\bar{\Psi}\Psi$

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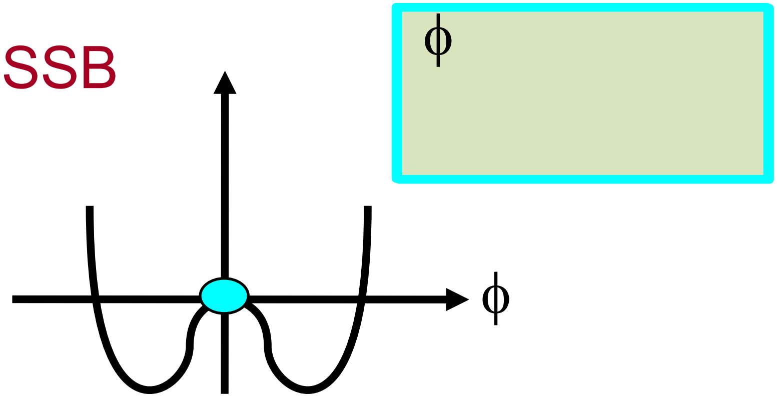

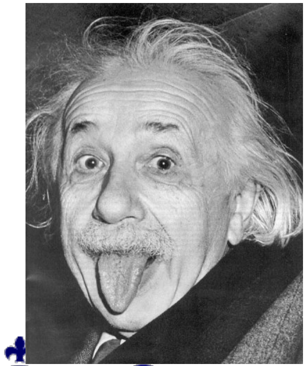

Particle acquires mass term!

Kostelecký and Samuel
PRD39(1989)683

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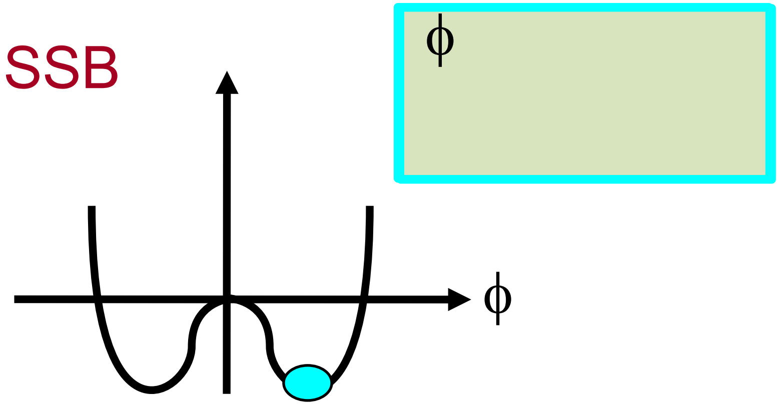
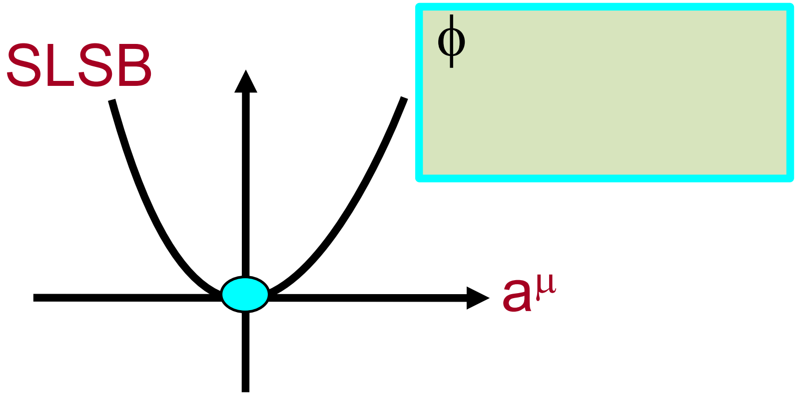
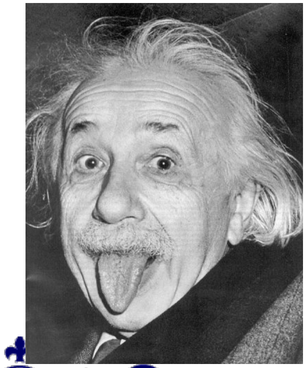
e.g.) SLSB in string field theory

- There are many Lorentz vector fields
- If any of vector field has Mexican hat potential

$$M(a^\mu) = \mu^2 < 0$$







Kostelecký and Samuel
PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking (SLSB)

vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi + \bar{\Psi}\gamma_\mu a^\mu\Psi$

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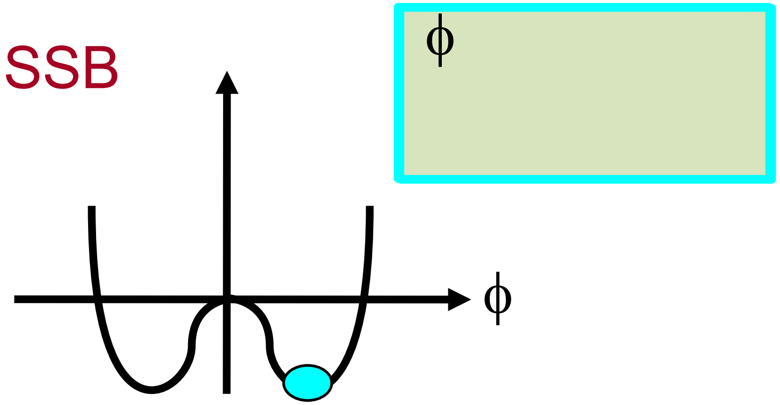

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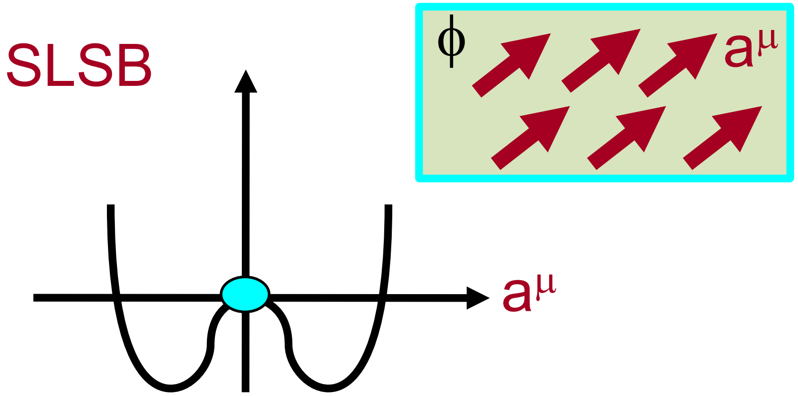

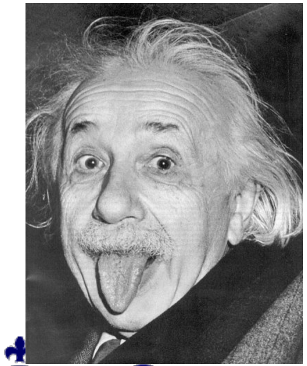

Lorentz symmetry
is spontaneously
broken!

1. Spontaneous Lorentz symmetry breaking

2. **Modern test of Lorentz violation**

3. Sensitivity of Lorentz violation by neutrinos

4. New test of Lorentz violation with neutrinos

5. Conclusion

2. Modern test of Lorentz violation

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
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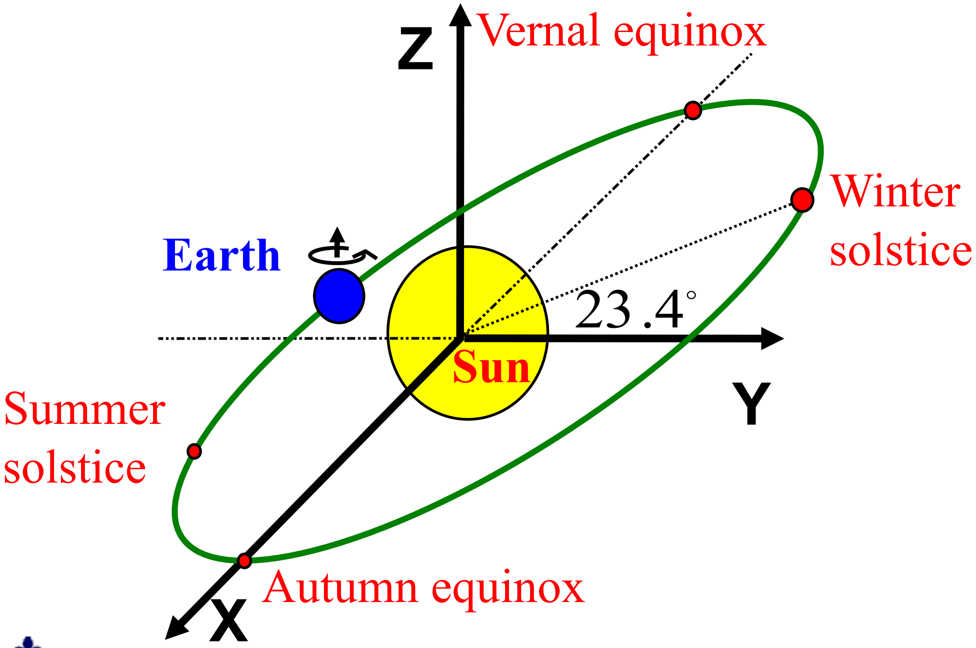
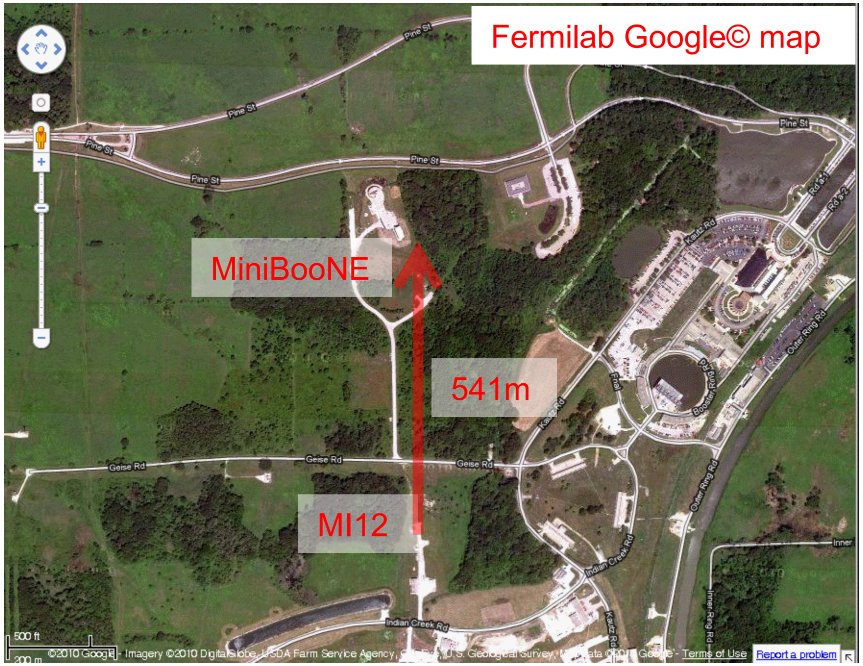
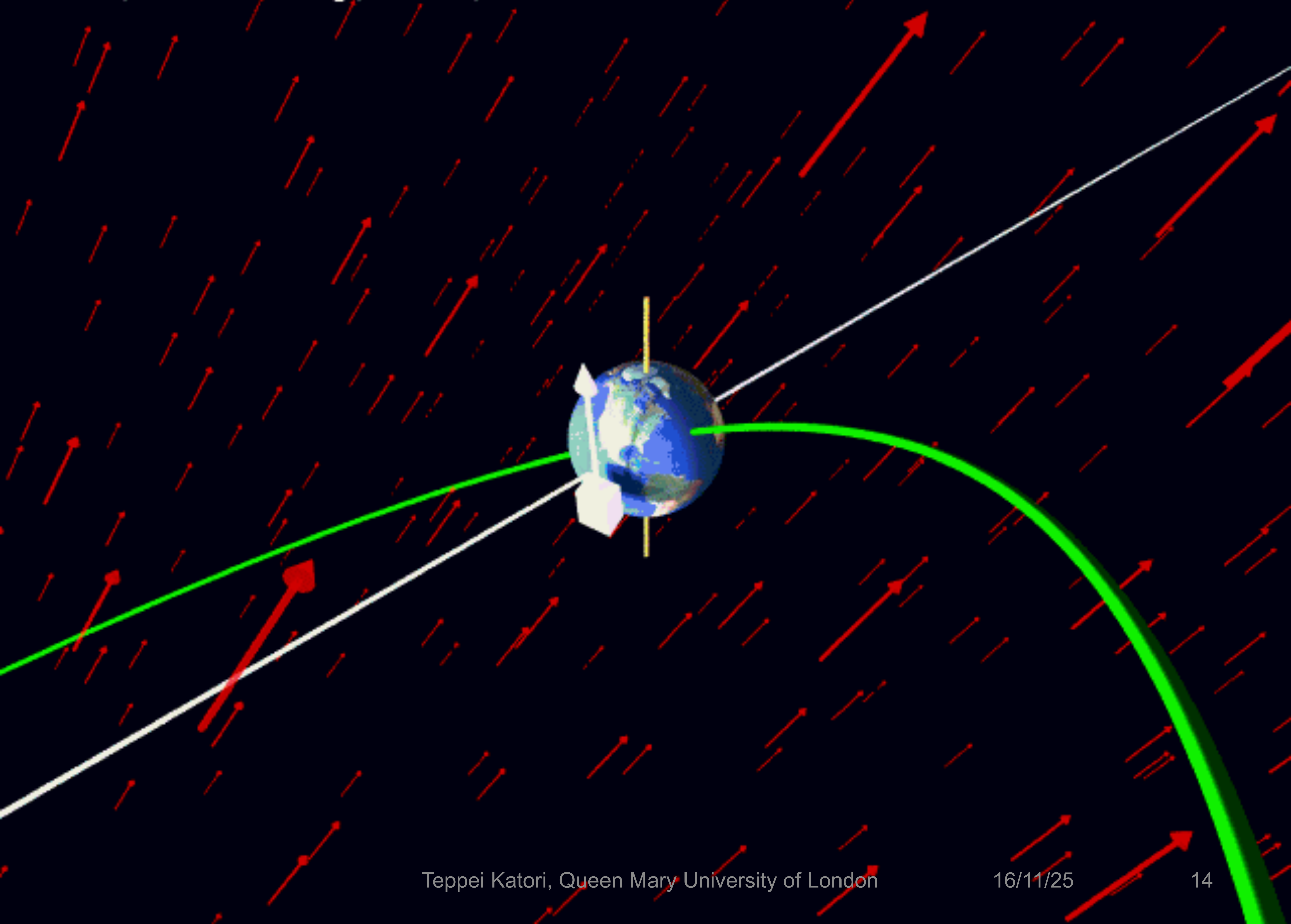
- Neutrino beamline is described in Sun-centred coordinates





MiniBooNE beamline

Bluhm, Kostelecky, Lane, Russell PRL 2002



Kostelecký and Mewes
PRD69(2004)016005

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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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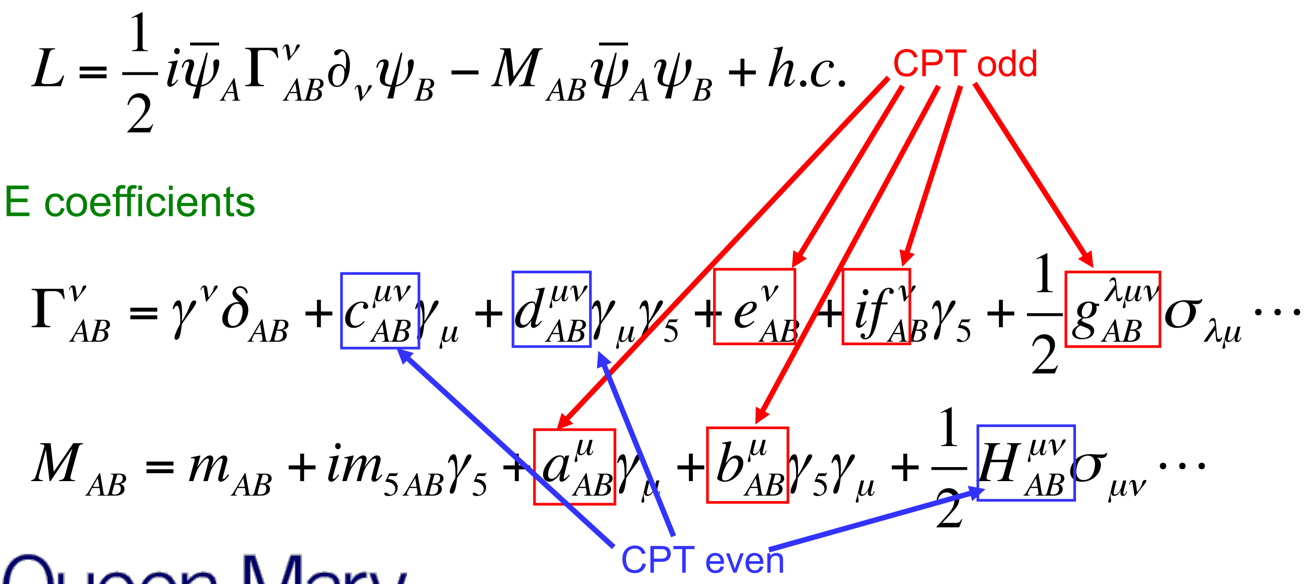

$$L = \frac{1}{2} i\bar{\psi}_A \Gamma^{\nu}_{AB} \partial_{\nu} \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.$$

CPT odd

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$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + \boxed{c^{\mu\nu}_{AB}}\gamma_{\mu} + \boxed{d^{\mu\nu}_{AB}}\gamma_{\mu}\gamma_5 + \boxed{e^{\nu}_{AB}} + \boxed{if^{\nu}_{AB}}\gamma_5 + \frac{1}{2}\boxed{g^{\lambda\mu\nu}_{AB}}\sigma_{\lambda\mu} \cdots$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_5 + \boxed{a^{\mu}_{AB}}\gamma_{\mu} + \boxed{b^{\mu}_{AB}}\gamma_5\gamma_{\mu} + \frac{1}{2}\boxed{H^{\mu\nu}_{AB}}\sigma_{\mu\nu} \cdots$$

CPT even

Kostelecký and Mewes
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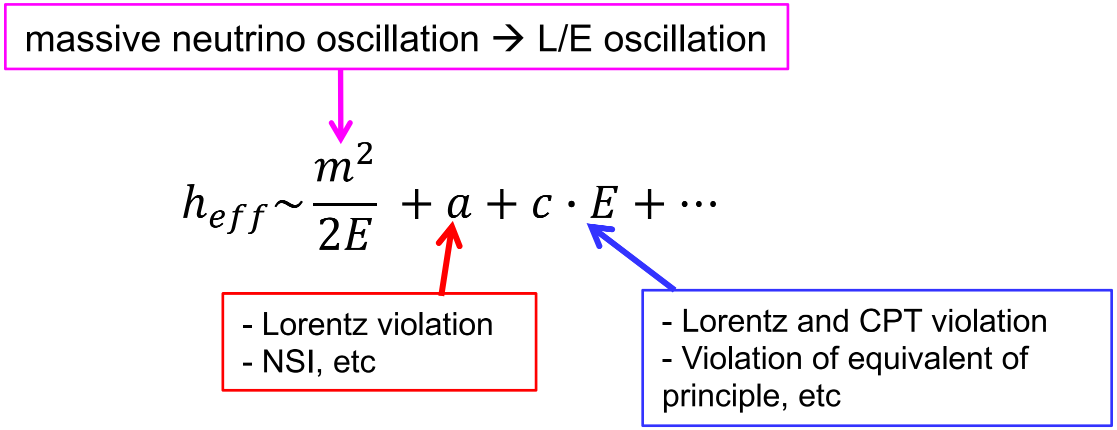
SME effective Hamiltonian in neutrino sector

Since we know neutrino oscillation follows L/E, new physics are second order effect (=smaller than neutrino mass)

→ at high energy, neutrino mass term is suppressed and there is higher chance to see new physics



massive neutrino oscillation → L/E oscillation

$$h_{eff} \sim \frac{m^2}{2E} + a + c \cdot E + \cdots$$

- Lorentz violation
- NSI, etc

- Lorentz and CPT violation
- Violation of equivalent of principle, etc

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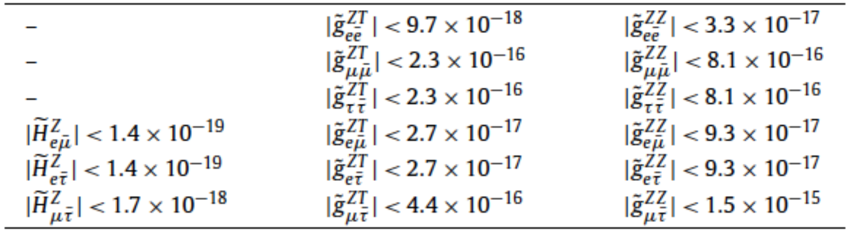
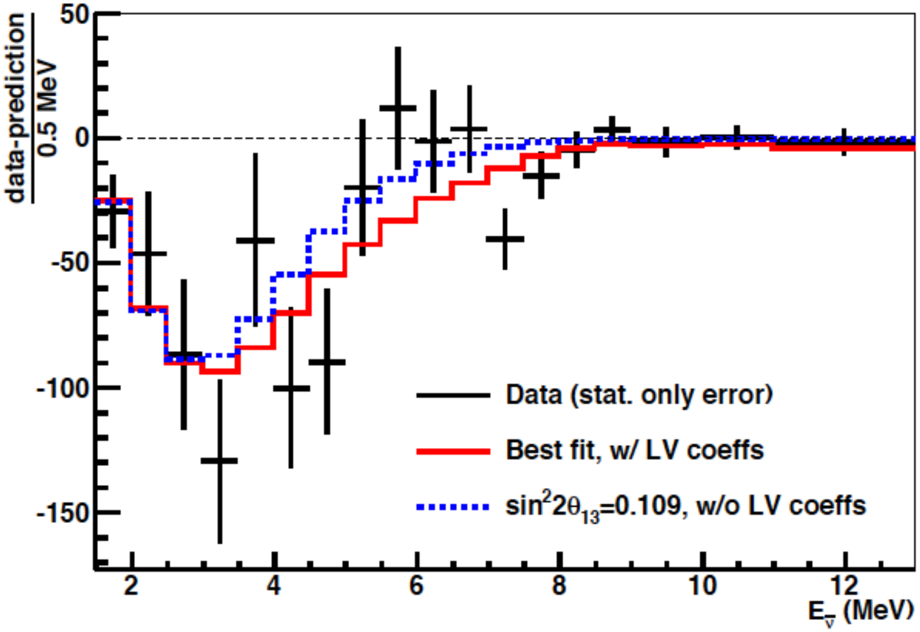
Various physics are predicted under SME
- spectrum anomaly
- sidereal variation
- neutrino-antineutrino oscillation

etc.

ex) Double Chooz antineutrino energy spectrum
Neutrino oscillation formula including LV is tested with data energy spectrum to constrain parameter space



–	$\lvert\tilde{g}^{ZT}_{e\bar{e}}\rvert < 9.7 \times 10^{-18}$	$\lvert\tilde{g}^{ZZ}_{e\bar{e}}\rvert < 3.3 \times 10^{-17}$
–	$\lvert\tilde{g}^{ZT}_{\mu\bar{\mu}}\rvert < 2.3 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\mu\bar{\mu}}\rvert < 8.1 \times 10^{-16}$
–	$\lvert\tilde{g}^{ZT}_{\tau\bar{\tau}}\rvert < 2.3 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\tau\bar{\tau}}\rvert < 8.1 \times 10^{-16}$
$\lvert\widetilde{H}^{Z}_{e\bar{\mu}}\rvert < 1.4 \times 10^{-19}$	$\lvert\tilde{g}^{ZT}_{e\bar{\mu}}\rvert < 2.7 \times 10^{-17}$	$\lvert\tilde{g}^{ZZ}_{e\bar{\mu}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{e\bar{\tau}}\rvert < 1.4 \times 10^{-19}$	$\lvert\tilde{g}^{ZT}_{e\bar{\tau}}\rvert < 2.7 \times 10^{-17}$	$\lvert\tilde{g}^{ZZ}_{e\bar{\tau}}\rvert < 9.3 \times 10^{-17}$
$\lvert\widetilde{H}^{Z}_{\mu\bar{\tau}}\rvert < 1.7 \times 10^{-18}$	$\lvert\tilde{g}^{ZT}_{\mu\bar{\tau}}\rvert < 4.4 \times 10^{-16}$	$\lvert\tilde{g}^{ZZ}_{\mu\bar{\tau}}\rvert < 1.5 \times 10^{-15}$



Double Chooz, PRD86(2012)112009
TK and Spitz, arXiv:1307.5805

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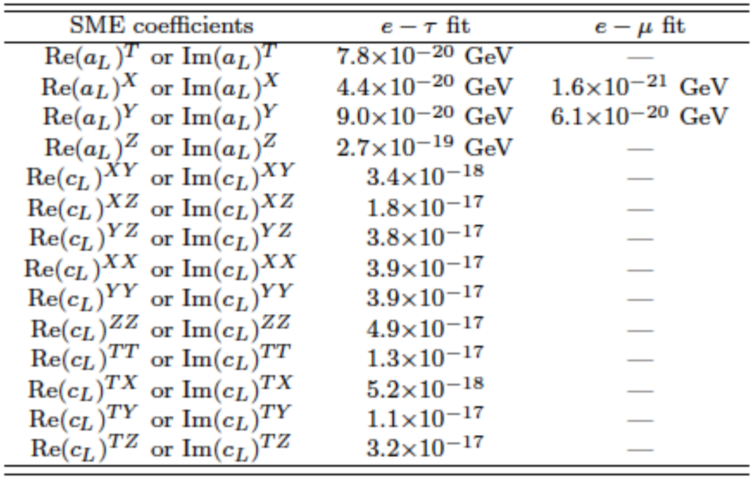
Various physics are predicted under SME
- spectrum anomaly
- sidereal variation
- neutrino-antineutrino oscillation

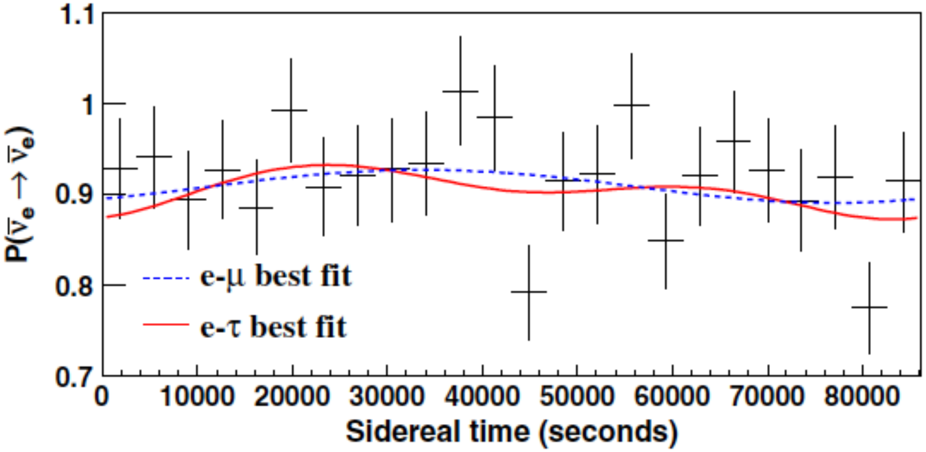
etc.

ex) ex) Double Chooz antineutrino time distribution

Sidereal time dependence is also tested



SME coefficients	$e-\tau$ fit	$e-\mu$ fit
$\mathrm{Re}(a_L)^T$ or $\mathrm{Im}(a_L)^T$	7.8×10^{-20} GeV	—
$\mathrm{Re}(a_L)^X$ or $\mathrm{Im}(a_L)^X$	4.4×10^{-20} GeV	1.6×10^{-21} GeV
$\mathrm{Re}(a_L)^Y$ or $\mathrm{Im}(a_L)^Y$	9.0×10^{-20} GeV	6.1×10^{-20} GeV
$\mathrm{Re}(a_L)^Z$ or $\mathrm{Im}(a_L)^Z$	2.7×10^{-19} GeV	—
$\mathrm{Re}(c_L)^{XY}$ or $\mathrm{Im}(c_L)^{XY}$	3.4×10^{-18}	—
$\mathrm{Re}(c_L)^{XZ}$ or $\mathrm{Im}(c_L)^{XZ}$	1.8×10^{-17}	—
$\mathrm{Re}(c_L)^{YZ}$ or $\mathrm{Im}(c_L)^{YZ}$	3.8×10^{-17}	—
$\mathrm{Re}(c_L)^{XX}$ or $\mathrm{Im}(c_L)^{XX}$	3.9×10^{-17}	—
$\mathrm{Re}(c_L)^{YY}$ or $\mathrm{Im}(c_L)^{YY}$	3.9×10^{-17}	—
$\mathrm{Re}(c_L)^{ZZ}$ or $\mathrm{Im}(c_L)^{ZZ}$	4.9×10^{-17}	—
$\mathrm{Re}(c_L)^{TT}$ or $\mathrm{Im}(c_L)^{TT}$	1.3×10^{-17}	—
$\mathrm{Re}(c_L)^{TX}$ or $\mathrm{Im}(c_L)^{TX}$	5.2×10^{-18}	—
$\mathrm{Re}(c_L)^{TY}$ or $\mathrm{Im}(c_L)^{TY}$	1.1×10^{-17}	—
$\mathrm{Re}(c_L)^{TZ}$ or $\mathrm{Im}(c_L)^{TZ}$	3.2×10^{-17}	—



1. Spontaneous Lorentz symmetry breaking

2. Modern test of Lorentz violation

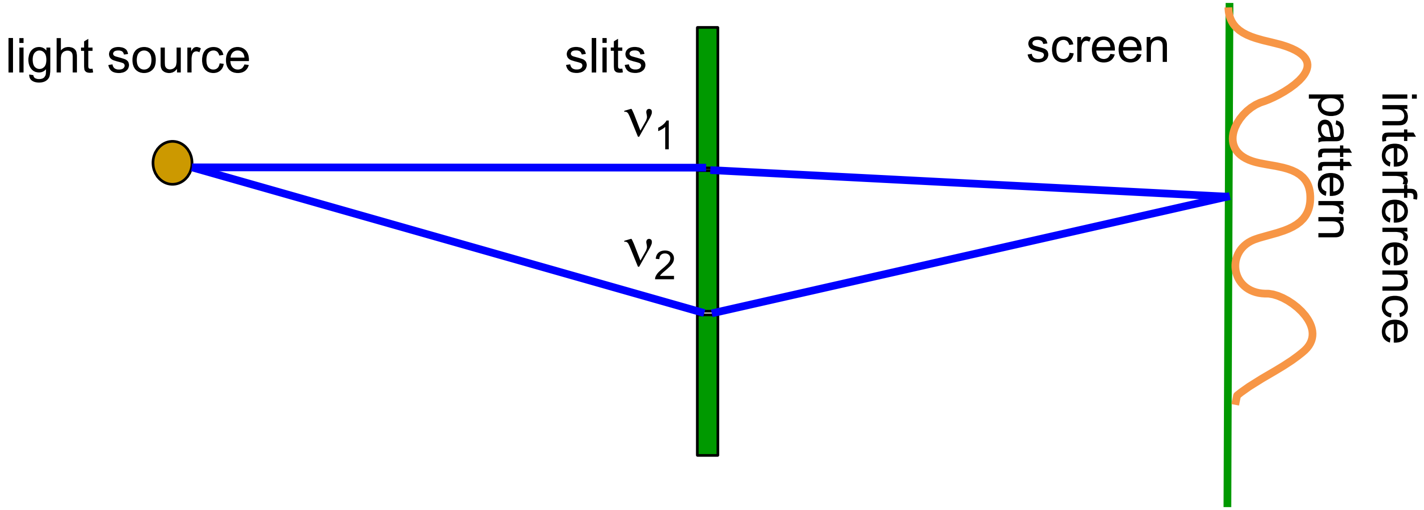
3. **Sensitivity of Lorentz violation by neutrinos**

4. New test of Lorentz violation with neutrinos

5. Conclusion

3. Neutrino oscillations, natural interferometers

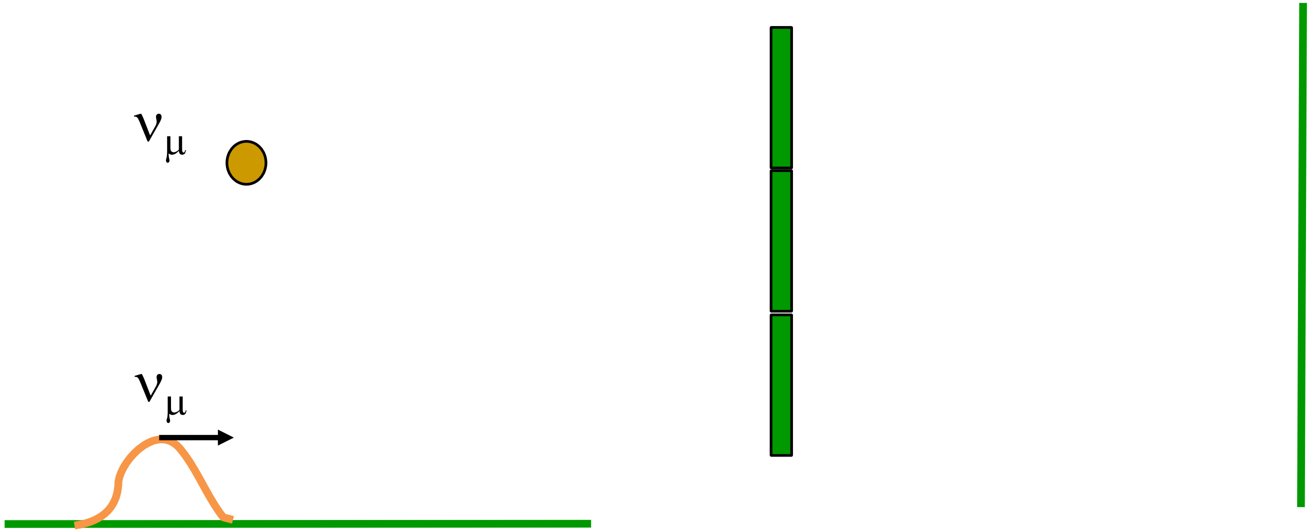
Neutrino oscillation is an interference experiment (cf. double slit experiment)



For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

3. Neutrino oscillations, natural interferometers

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



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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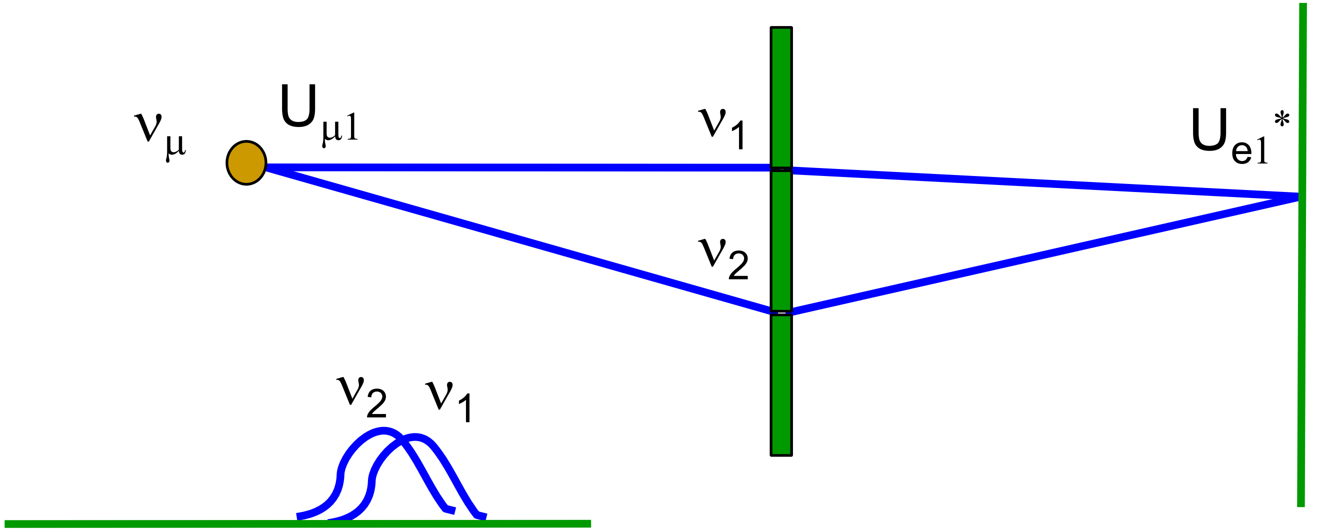

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

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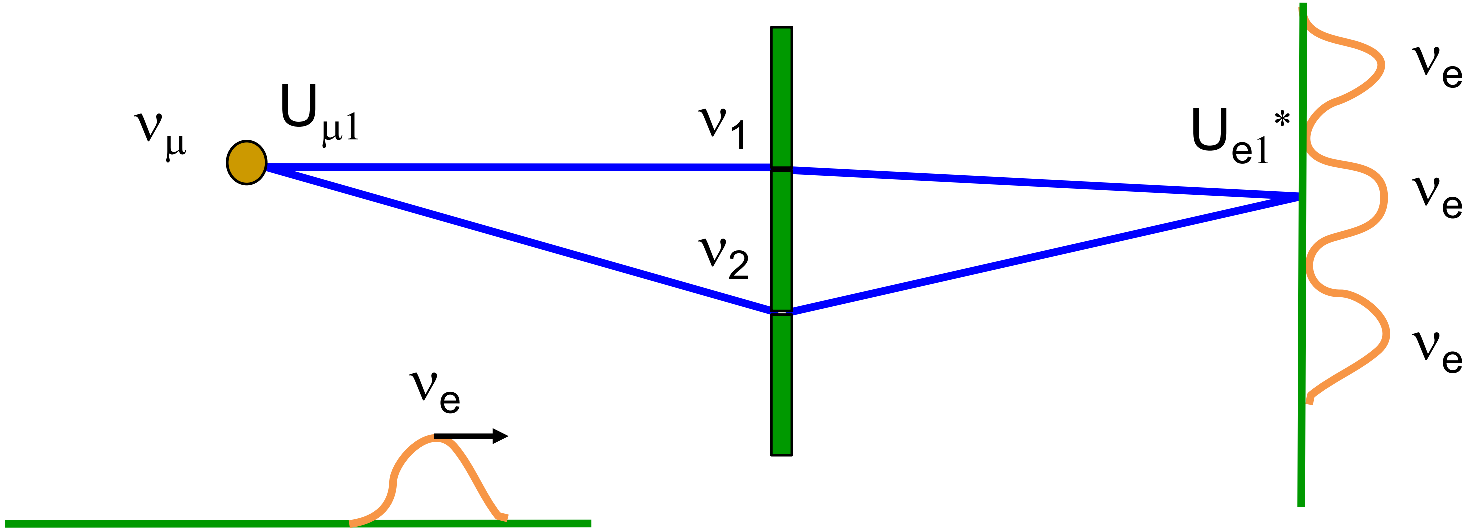

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If ν_1 and ν_2, have different mass, they have different velocity, so thus different phase rotation.

The detection may be different flavor (neutrino oscillations).

3. Neutrino oscillations

2 neutrino oscillation

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1 and ν_2, and their mixing matrix elements.

$$\left|\nu_\mu\right\rangle = U_{\mu 1}\left|\nu_1\right\rangle + U_{\mu 2}\left|\nu_2\right\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1 and ν_2 .

$$\left|\nu_\mu(t)\right\rangle = U_{\mu 1}e^{-i\lambda_1 t}\left|\nu_1\right\rangle + U_{\mu 2}e^{-i\lambda_2 t}\left|\nu_2\right\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is,

$$P_{\mu\to e}(t) = \left|\left\langle\nu_e\middle|\nu_\mu(t)\right\rangle\right|^2 = -4U_{e1}U_{e2}U_{\mu 1}U_{\mu 2}sin^2\left(\frac{\lambda_1-\lambda_2}{2}t\right)$$

3. Neutrino oscillations

In the vacuum, 2 neutrino effective Hamiltonian has only the mass term,

$$h_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_1^2}{2E} \end{pmatrix} \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} = \frac{1}{2E} U^\dagger M^2 U$$

Therefore, 2 massive neutrino oscillation model is ($\Delta m^2 = |m_1^2 - m_2^2|$)

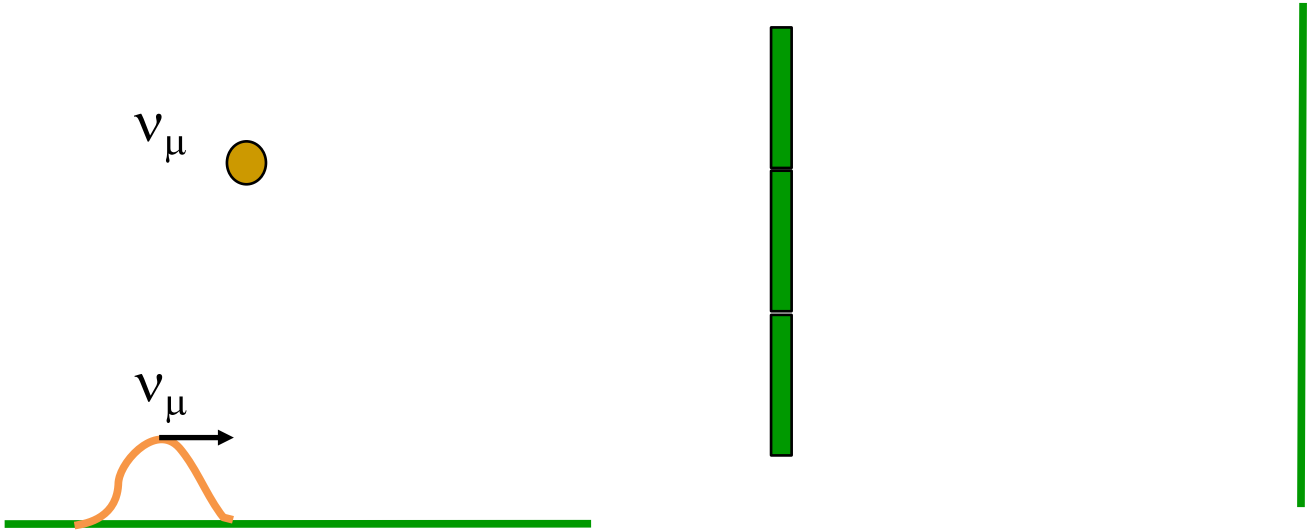
$$P_{\mu\rightarrow e}(L/E) = sin^2 2\theta sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

After adjusting the unit, 2 neutrino oscillation formula

$$\boxed{P_{\mu\rightarrow e}(L/E) = sin^2 2\theta sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)}$$

3. Lorentz violation with neutrino oscillation

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



If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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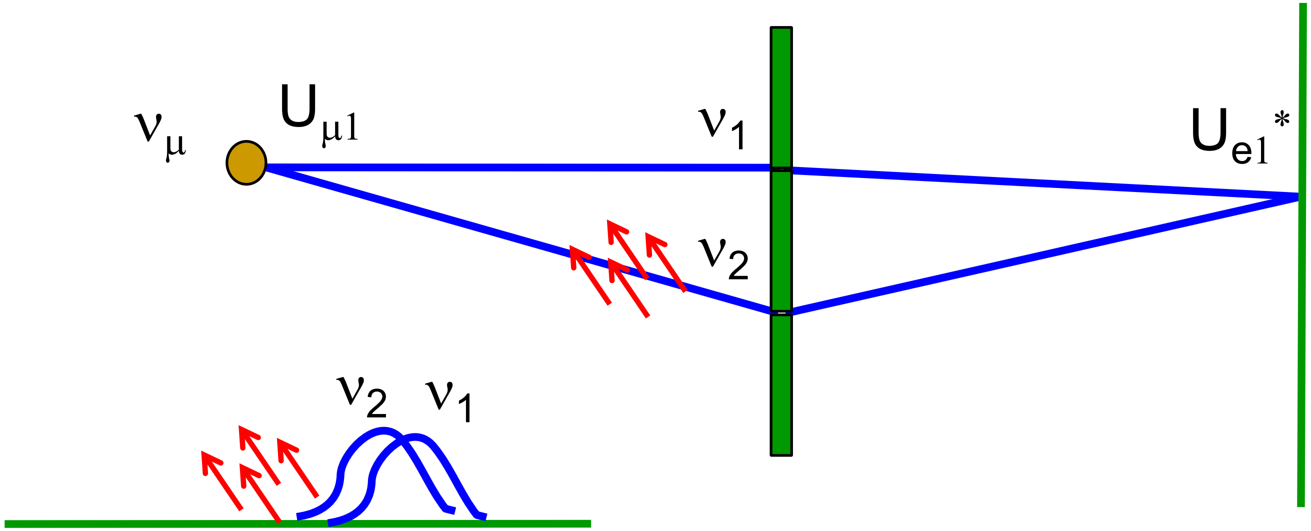

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different coupling with Lorentz violating field, neutrinos also oscillate.

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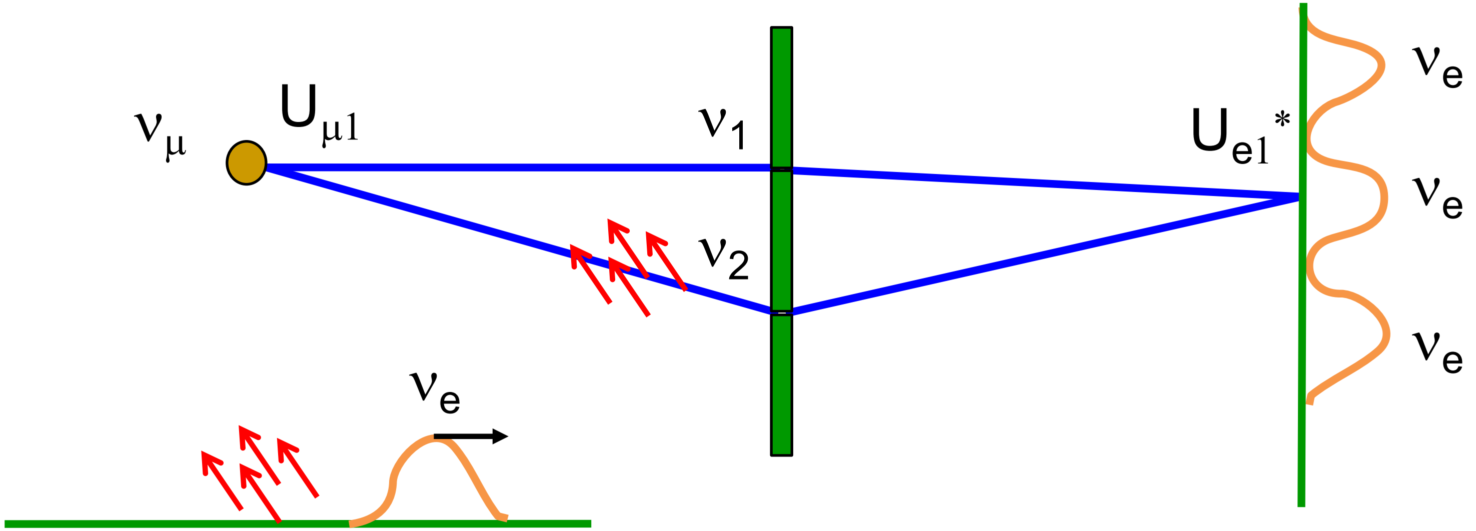

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Arugüelles, TK, Salvado, PRL115(2015)161303

3. Neutrino oscillations with New physics operator

Effective Hamiltonian is the combination of mass term and new physics term

$$h_{eff}=\frac{1}{2E}U^{\dagger}MU+a+c\cdot E+\cdots=V^{\dagger}(E)\Delta V(E)$$

Then, the oscillation formula will be ($\Delta\lambda$ is the difference of λ_1 and λ_2, 2 eigenvalues of h_{eff})

$$P_{\mu\to e}(t)=\left|\langle\nu_e|\nu_\mu(t)\rangle\right|^2=-4V_{e1}(E)V_{e2}(E)V_{\mu1}(E)V_{\mu2}(E)sin^2\left(\frac{\Delta\lambda(E)}{2}t\right)$$

Oscillation is visible when $\Delta\lambda(E)L\sim\pi$

ex) massive neutrino oscillation

$$\Delta\lambda(E)=\frac{\Delta m^2}{2E}\to L=\frac{2E\pi}{\Delta m^2}\propto E$$

Oscillation condition for massive neutrino oscillation is L proportion to E.

3. Neutrino oscillations with New physics operator

ex) massive neutrino oscillation

$$\Delta\lambda(E) = \frac{\Delta m^2}{2E} \rightarrow L = \frac{2E\pi}{\Delta m^2} \propto E$$

Oscillation condition for massive neutrino oscillation is L proportion to E.

Lorentz violating neutrino oscillation

$$\Delta\lambda(E) = a \rightarrow L = \frac{\pi}{a} \propto const$$

Oscillation condition is L ~ const

→ longer baseline experiments are more sensitive on smaller *a*

Lorentz and CPT violating neutrino oscillation

$$\Delta\lambda(E) = c \cdot E \rightarrow L = \frac{\pi}{cE} \propto \frac{1}{E}$$

Oscillation condition is L ~ E^{-1}

→ longer baseline and higher energy experiments are more sensitive on smaller c

IceCube,PRD82(2010)112003, SuperKamiokande,PRD91(2015)052003

3. Neutrino oscillations with New physics operator

ex) DUNE (2 GeV, 1300km baseline)

- The sensitivity of a is $\pi/L \sim 5 \bullet 10^{-22}$ GeV
- The sensitivity of c is $\pi/L/E \sim 5 \bullet 10^{-22}$

ex) IceCube/SuperK atmospheric neutrinos (<10 TeV, 12700km baseline)

- The sensitivity of a is $\pi/L \sim 10^{-23}$ GeV
- The sensitivity of c is $\pi/L/E \sim 10^{-27}$

Naturalness argument tells atmospheric neutrinos have the highest new physics sensitivity

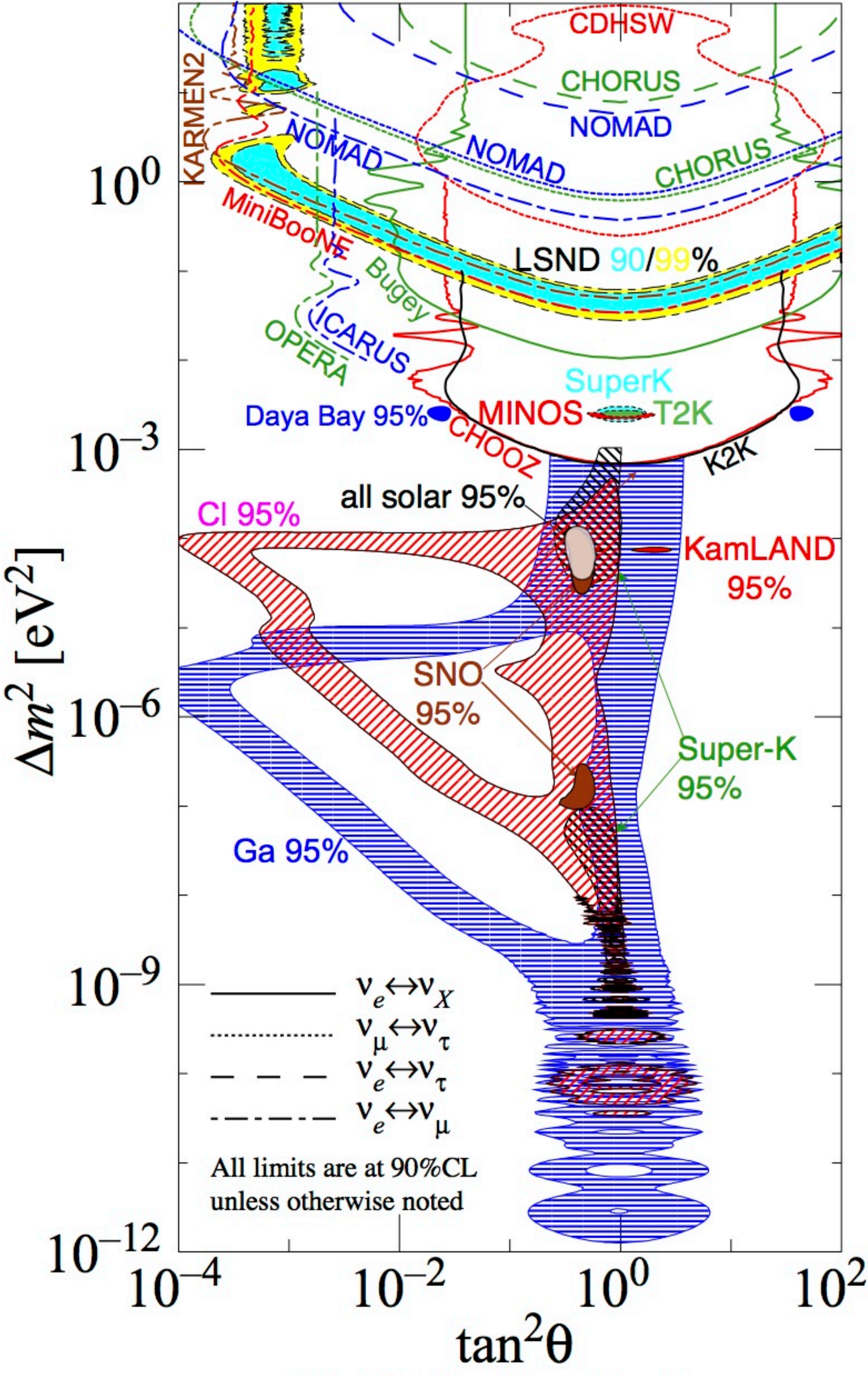
3. Neutrino standard Model (νSM)

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

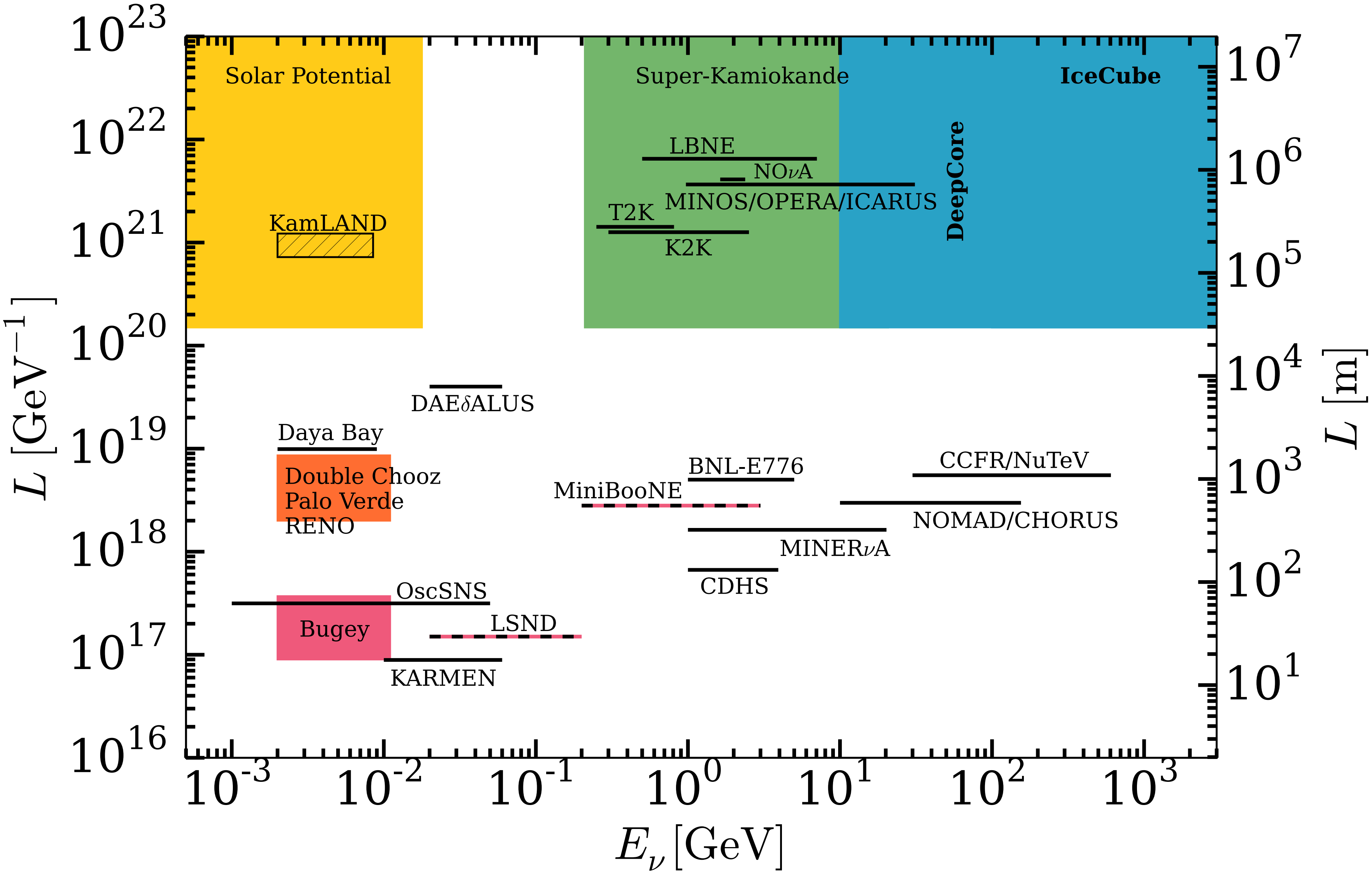
What is model independent diagram look like?



http://hitoshi.berkeley.edu/neutrino

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation



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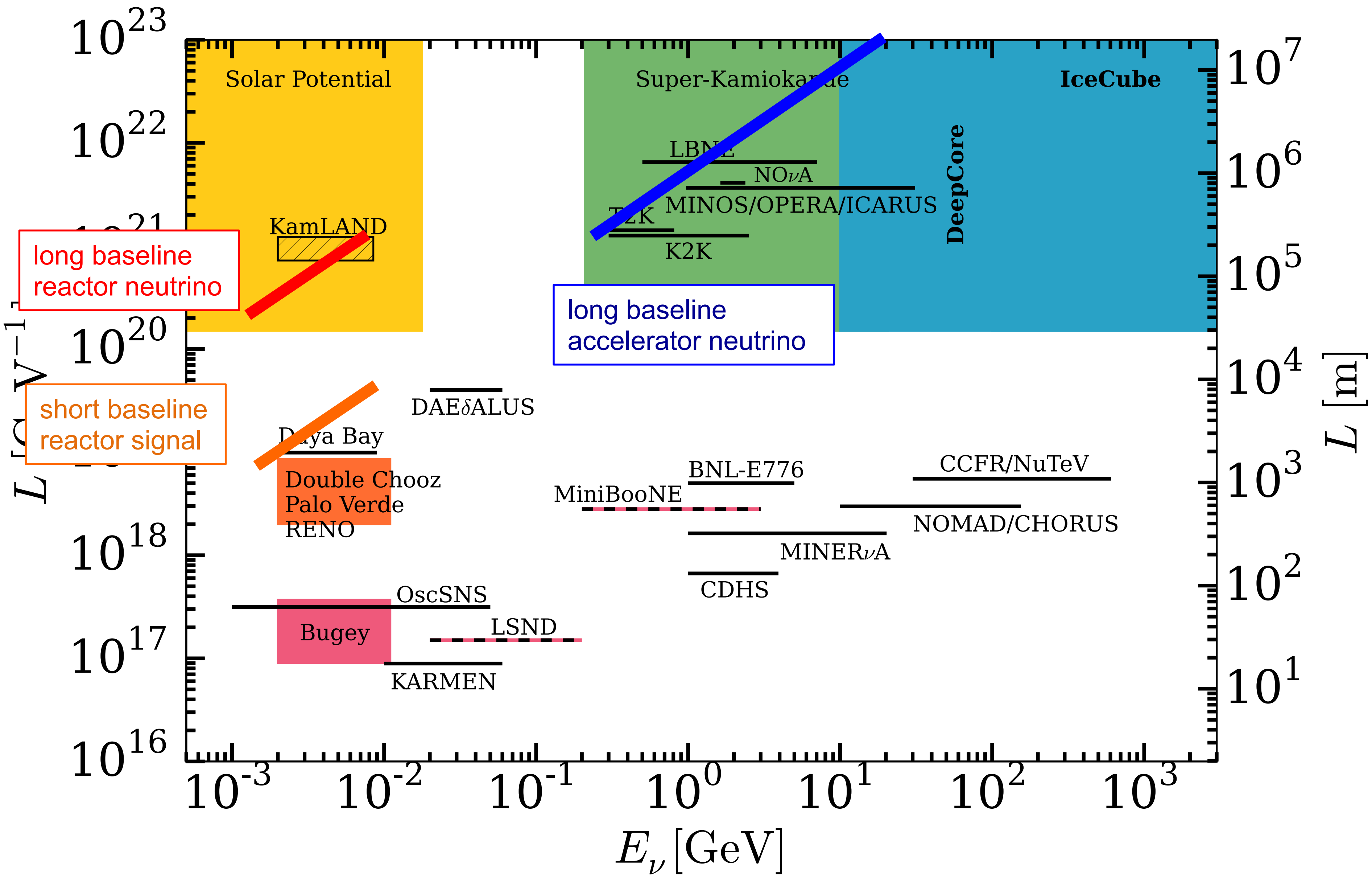
3. Lorentz violation with neutrino oscillation



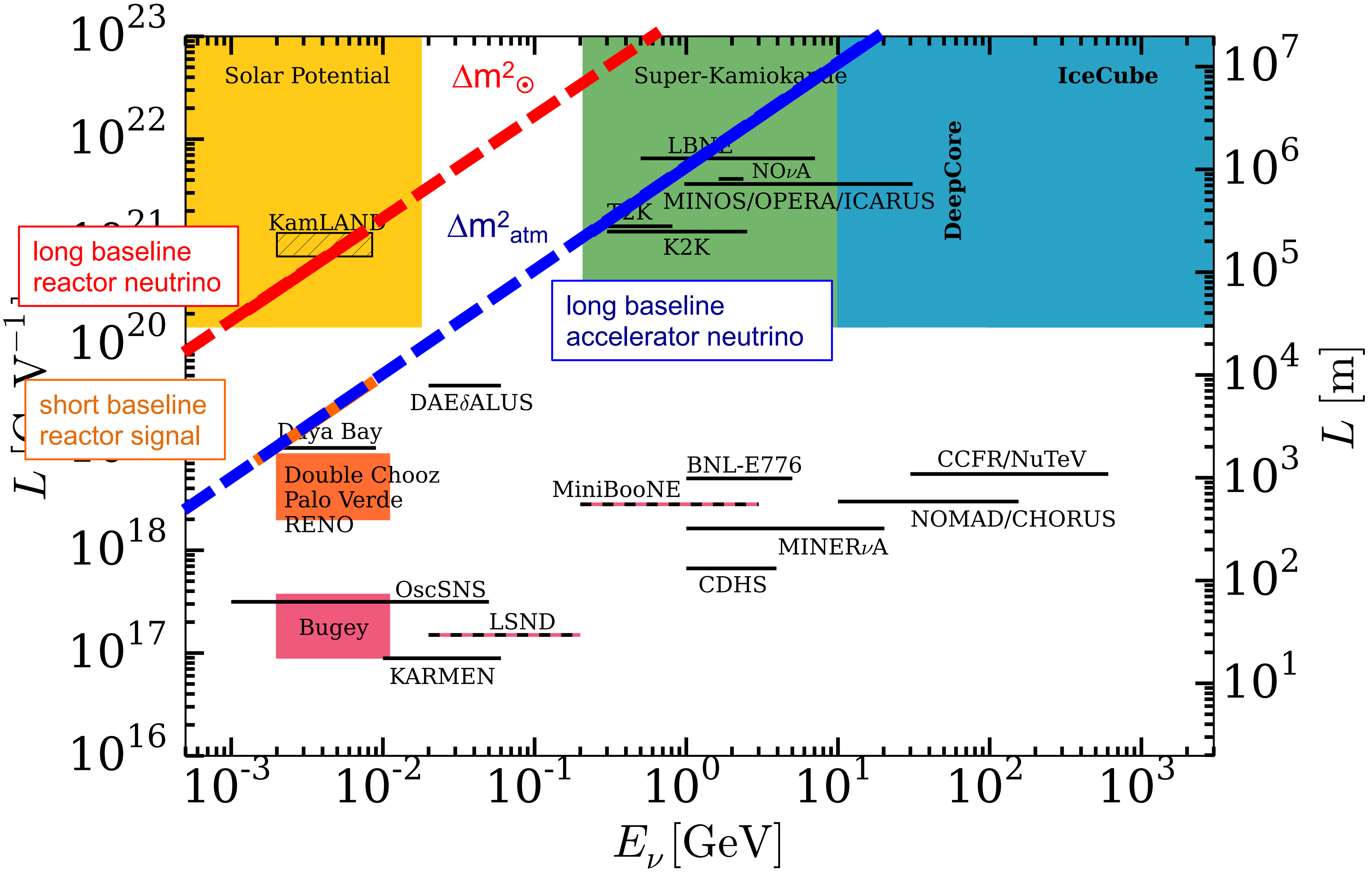
long baseline
reactor neutrino

short baseline
reactor signal

long baseline
accelerator neutrino

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation



long baseline
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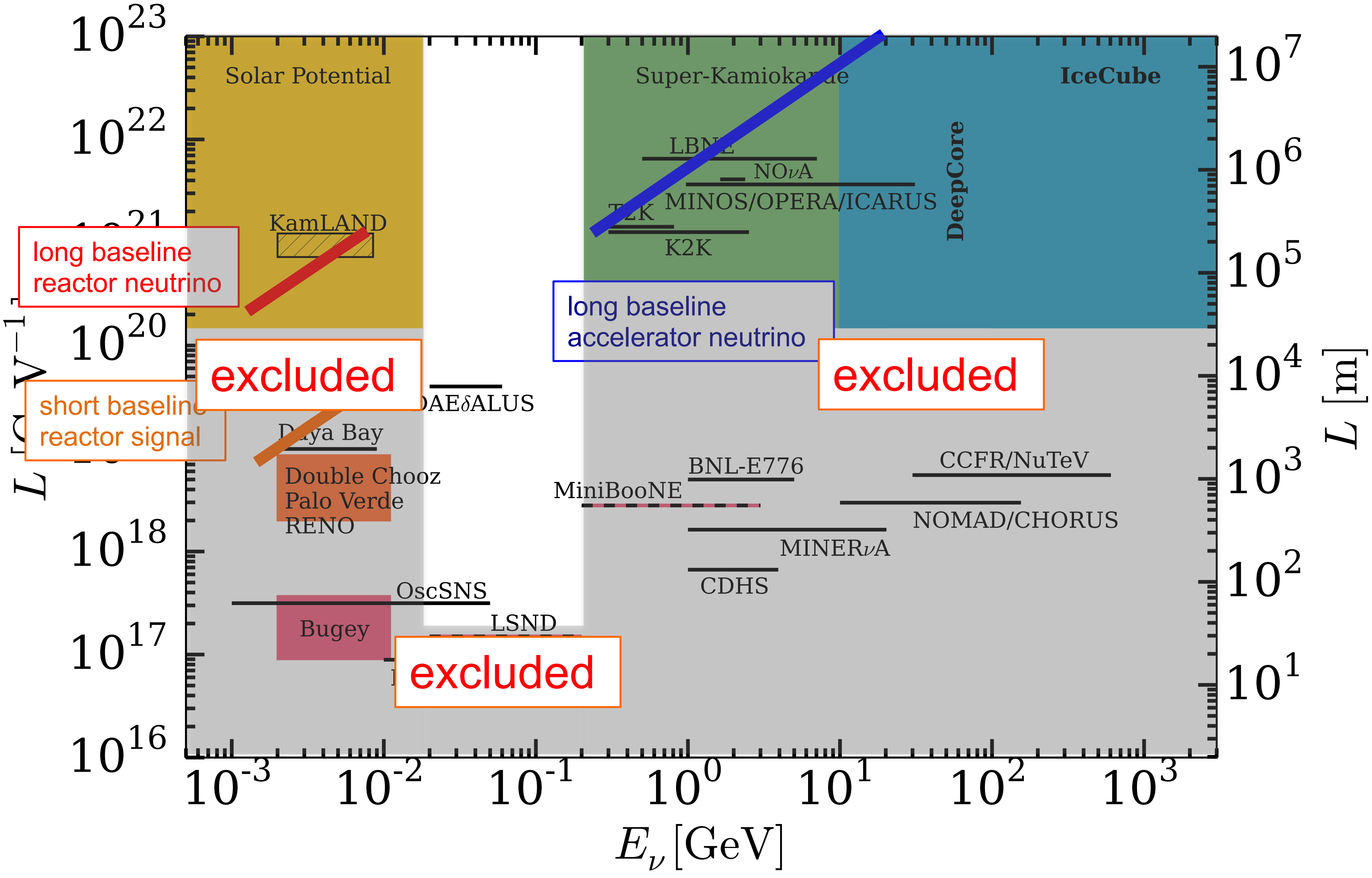
short baseline
reactor signal

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation

Parameter space of DUNE (and any other accelerator-based experiments) can explore is already rejected by atmospheric neutrino experiments



long baseline reactor neutrino

long baseline accelerator neutrino

short baseline reactor signal

excluded

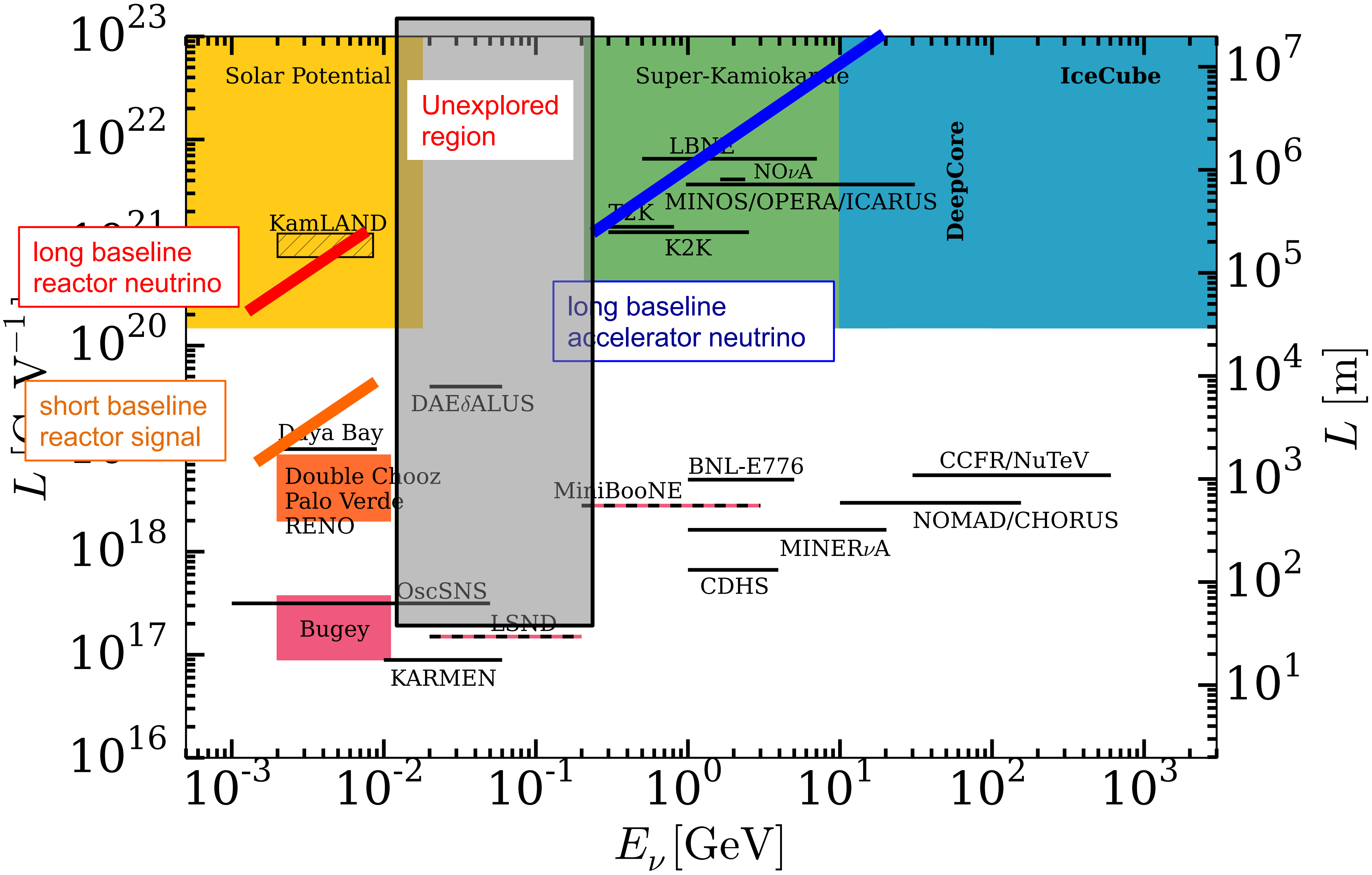
excluded

excluded

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation

Low energy (10-100 MeV) long-baseline experiments can explore new parameter space.



Unexplored region

long baseline reactor neutrino

short baseline reactor signal

long baseline accelerator neutrino

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation

Low energy (10-100 MeV) long baseline experiments

- there is no constraint for new physics (DAEδALUS?)

Coordinate element (X, Y, Z, XY, XZ, YZ)

- Although atmospheric neutrinos provide the strongest limits, they are all time averaged, or time-independent limit. For coordinate elements, MINOS provides the strongest limit for μ-τ channels

e-τ channels

Long baseline experiment limits are based on ν_μ disappearance (e-μ, μ-τ) or ν_e appearance. There are not many constraint on e-τ channels (KamLAND?)

In summary, Super-K/IceCube atmospheric neutrino tests exclude most of phase space of the new physics, there are still many undone tests

1. Spontaneous Lorentz symmetry breaking
2. Modern test of Lorentz violation
3. Sensitivity of Lorentz violation by neutrinos
4. **New test of Lorentz violation with neutrinos**
5. Conclusion

Kostelecký and Mewes, PRD85(2012)096005
EXO200, PRD93(2016)072001

4. New test of Lorentz violation with neutrinos

Recently, Kostecký and Mewes extended the formalism to test neutrino kinematics. One of purposes of this new formalism is to check OPERA results in more rigorous way.

Although OPERA anomaly is gone, none of tests proposed in this paper are performed.

Oscillation free model

- Although neutrino oscillations are more sensitive to new physics, kinematic tests are sensitive to features of new physics you cannot measure directly from oscillations.

Possible tests

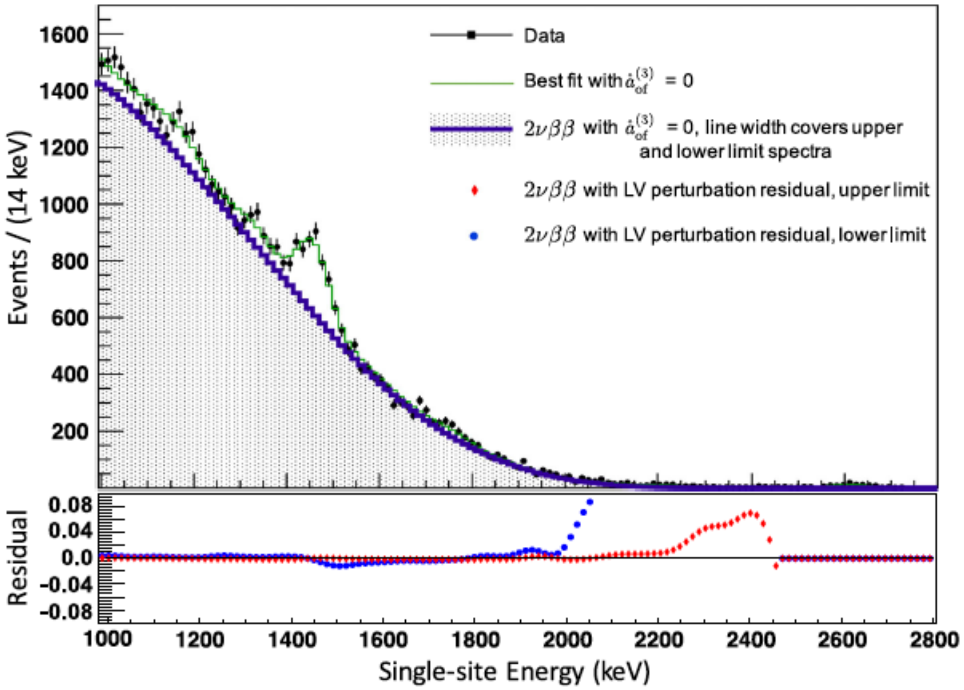
- anomalous beta decay spectrum
- vacuum weak Cherenkov radiation
- superluminal neutrinos
- time-dependent TOF

etc.

Direction-dependent effective neutrino energy

$$E_\nu^{\rm of} = |\boldsymbol{p}| + \frac{|m_l|^2}{2|\boldsymbol{p}|} + \sum_{djm} |\boldsymbol{p}|^{d-3} Y_{jm}(\hat{\boldsymbol{p}})[(a_{\rm of}^{(d)})_{jm} - (c_{\rm of}^{(d)})_{jm}].$$

ex) EXO200 double beta decay spectrum



Conclusion

- Lorentz and CPT violation has been shown to occur in Planck-scale theories.
- There is a world wide effort to test Lorentz violation with various state-of-the-art technologies.
- MiniBooNE, MINOS, IceCube, Double Chooz, and Super-Kamiokande set stringent limits on Lorentz violation in neutrino sector in terrestrial level.
- Although majority of phase space of Lorentz violation is excluded by atmospheric neutrino experiments, there are still many tests haven't performed with neutrino data.

Thank you for your attention!

backup

Arugüelles, TK, Salvado, PRL115(2015)161303

3. Neutrino oscillations with New physics operator

Arbitrary new physics are described in terms of effective operators

$$\sum_n \left(\frac{E}{\Lambda_n}\right)^n \widetilde{U}_n O_n \widetilde{U}_n^\dagger = \widetilde{U}_0 O_0 \widetilde{U}_0^\dagger + \left(\frac{E}{\Lambda_1}\right)^1 \widetilde{U}_1 O_1 \widetilde{U}_1^\dagger + \cdots = a + c \cdot E + \cdots$$

- Lorentz and CPT violation
- cosmic torsion
- Non-Standard interaction

etc

- Lorentz violation
- Violation of equivalent principle

etc

Effective Hamiltonian is the combination of mass term and new physics term

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

Then, the oscillation formula will be ($\Delta\lambda$ is the difference of λ_1 and λ_2, 2 eigenvalues of h_{eff})

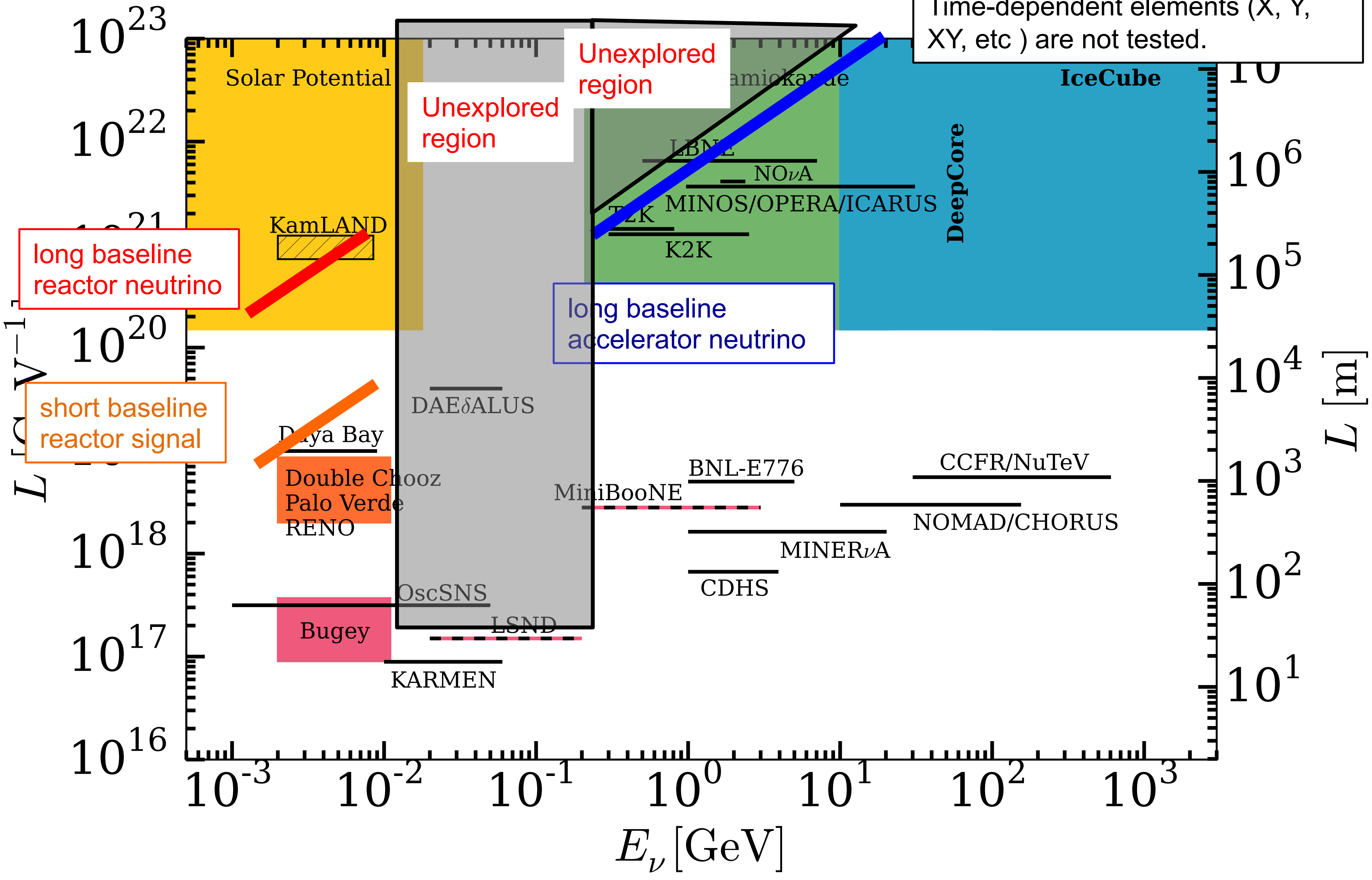
$$P_{\mu\to e}(t) = \left|\langle \nu_e | \nu_\mu(t) \rangle\right|^2 = -4 V_{e1}(E) V_{e2}(E) V_{\mu 1}(E) V_{\mu 2}(E) sin^2\left(\frac{\Delta\lambda(E)}{2} t\right)$$

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation

Low energy (10-100 MeV) long-baseline experiments can explore new parameter space.

Time-dependent elements (X, Y, XY, etc) are not tested.



Unexplored region

Unexplored region

long baseline reactor neutrino

short baseline reactor signal

long baseline accelerator neutrino

Kostelecký and Mewes, PRD69(2004)016005
Arugüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation

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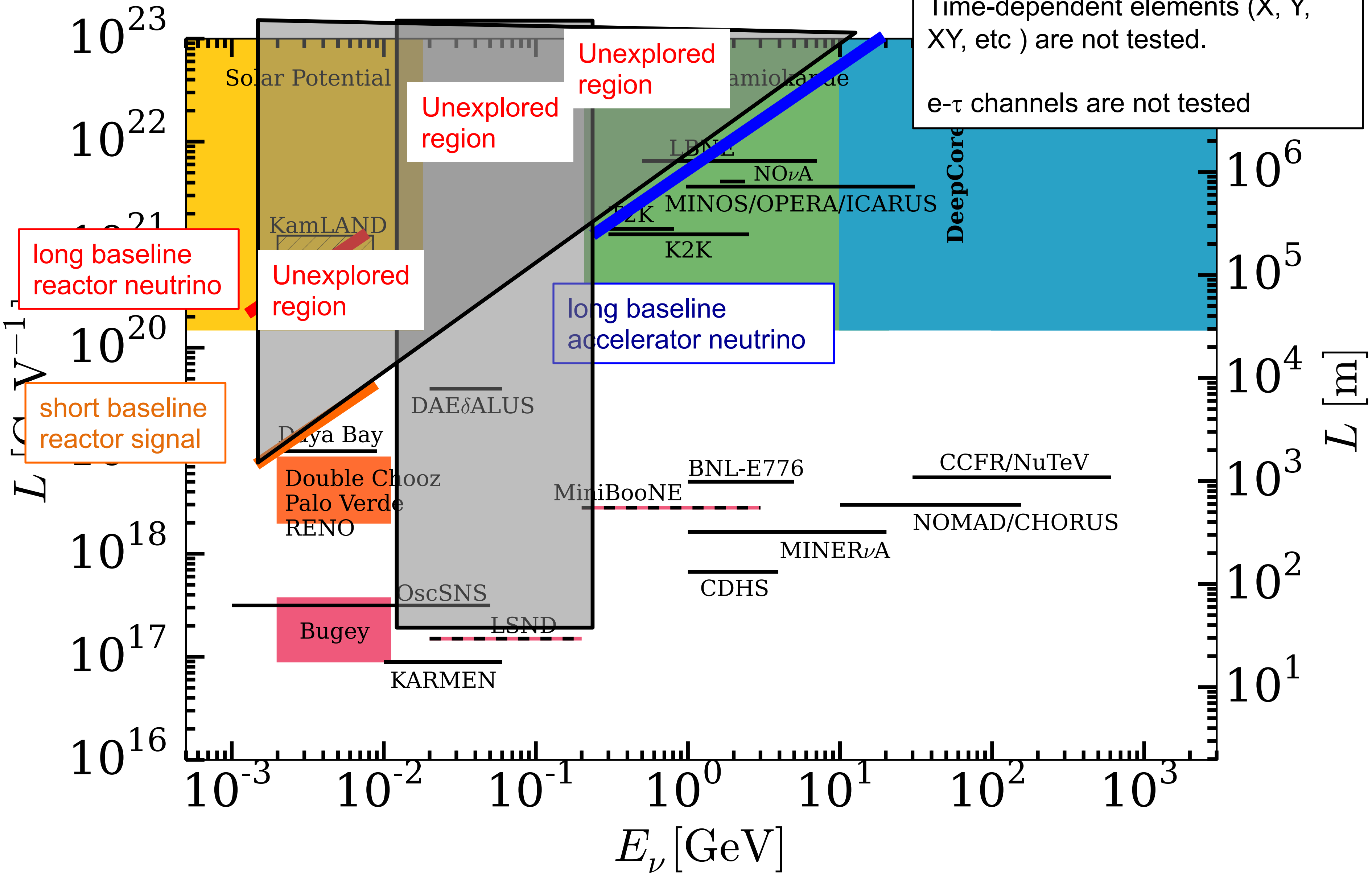
e-τ channels are not tested



Unexplored region

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