Tests of Lorentz and CPT violation with Neutrinos

Teppei Katori
Massachusetts Institute of Technology
ICHEP2012, Melbourne, Australia, July 10, 2012

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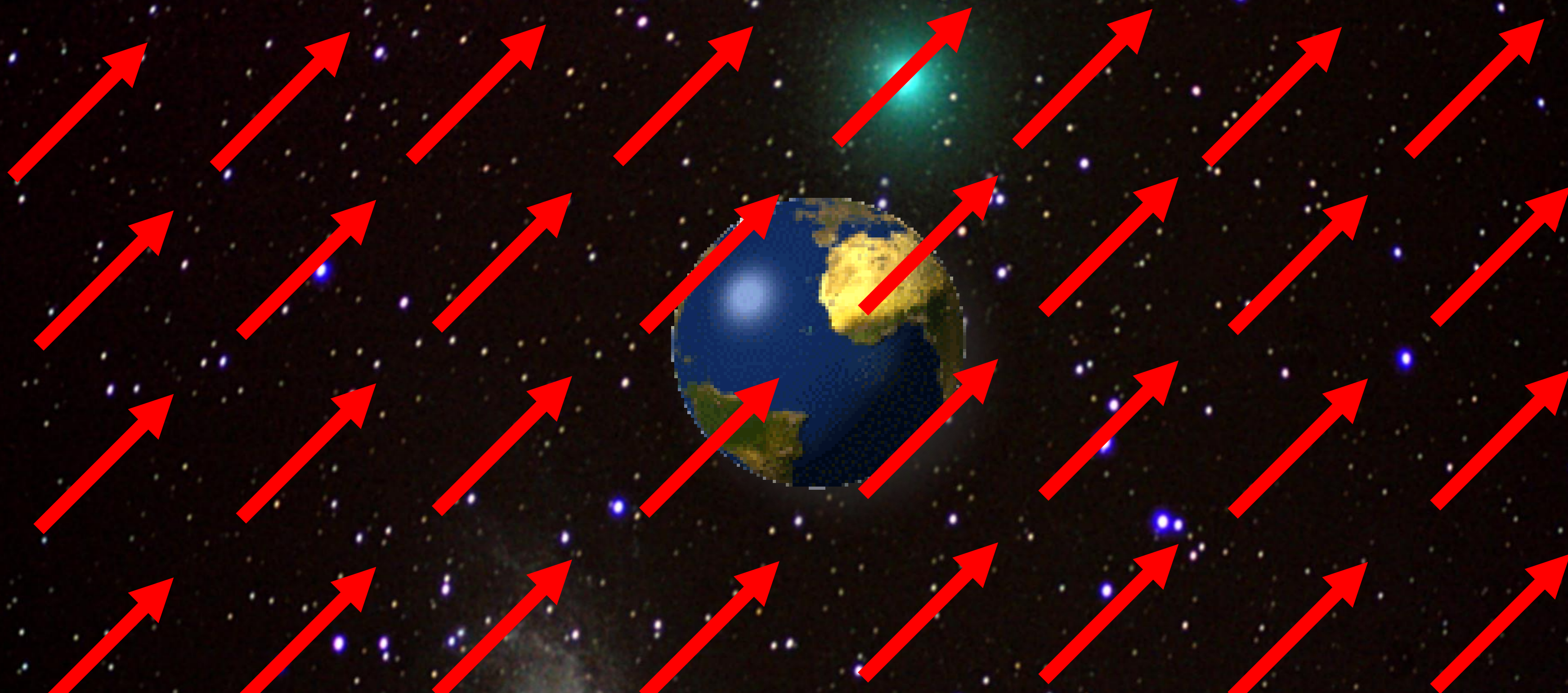

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Tests of Lorentz and CPT violation with Neutrinos

Outline

1. Spontaneous Lorentz symmetry breaking
2. What is Lorentz and CPT violation?
3. Test for Lorentz violation with neutrinos
4. Conclusion

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1. **Spontaneous Lorentz symmetry breaking**

2. **What is Lorentz and CPT violation?**

3. **Test for Lorentz violation with Neutrinos**

4. **Conclusion**

1. Spontaneous Lorentz symmetry breaking (SLSB)

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

After the recognition of the theoretical processes that create Lorentz violation, testing Lorentz invariance became 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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- etc

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Spontaneous Symmetry Breaking (SSB)!

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

1. Spontaneous Lorentz symmetry breaking (SLSB)

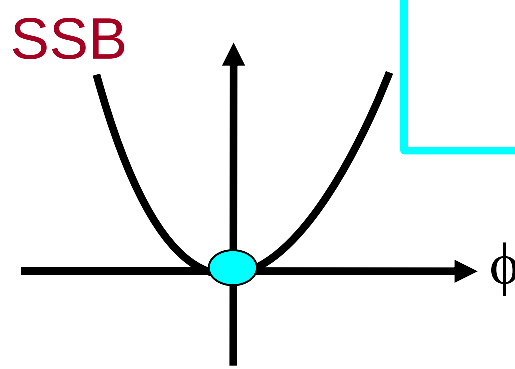
vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi$

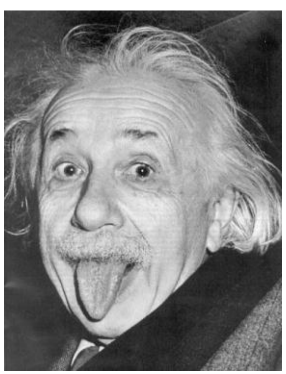
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

$$M(\phi) = m^2 < 0$$





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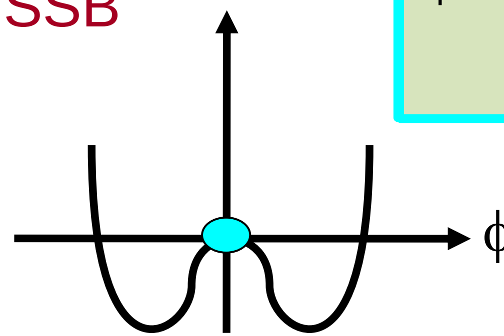
SSB



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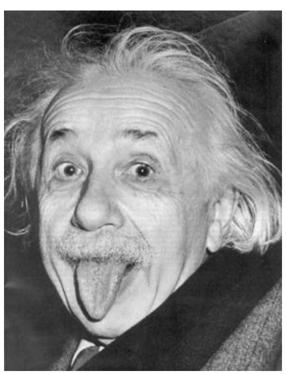

Particle acquires
mass term!

Kostelecký and Samuel
PRD39(1989)683

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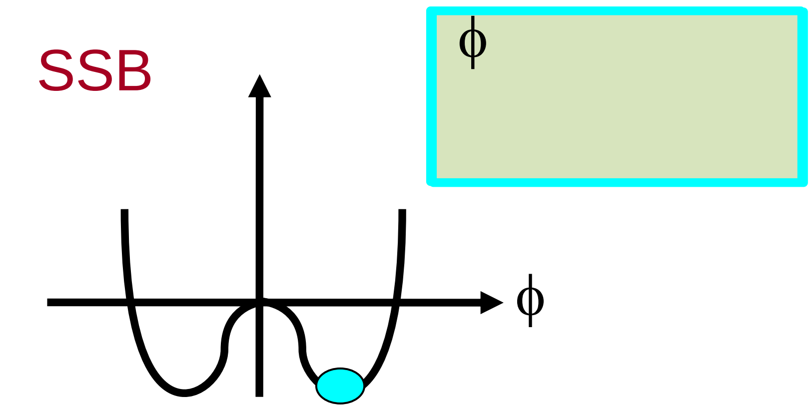
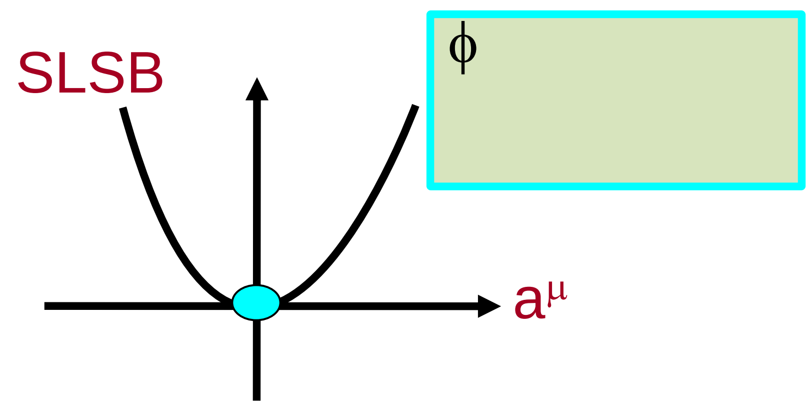
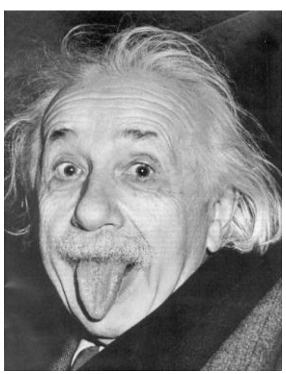


e.g.) SLSB in string field theory

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

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





Kostelecký and Samuel
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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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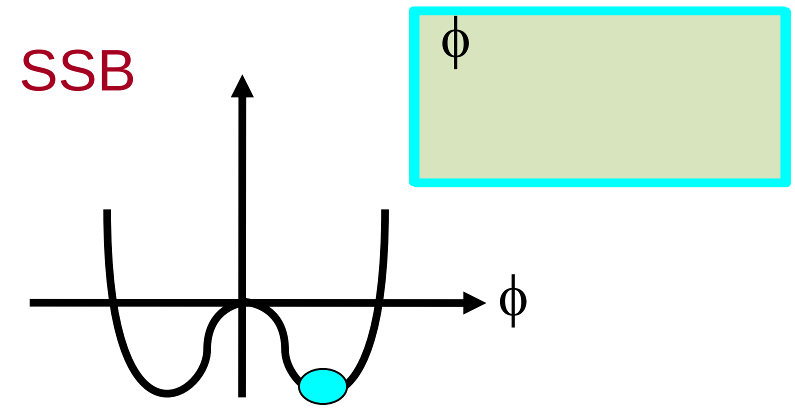

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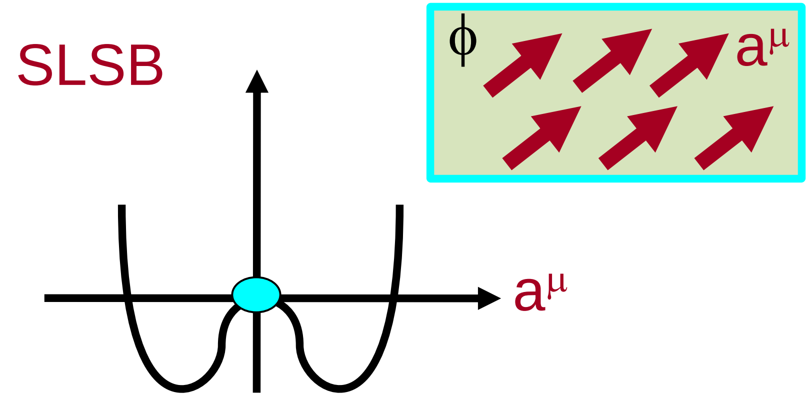
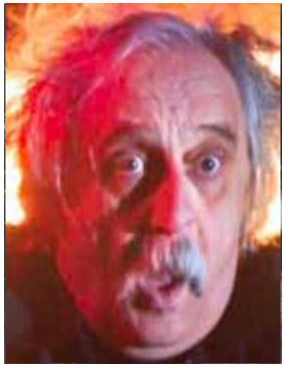




Lorentz symmetry is spontaneously broken!

1. Test of Lorentz violation

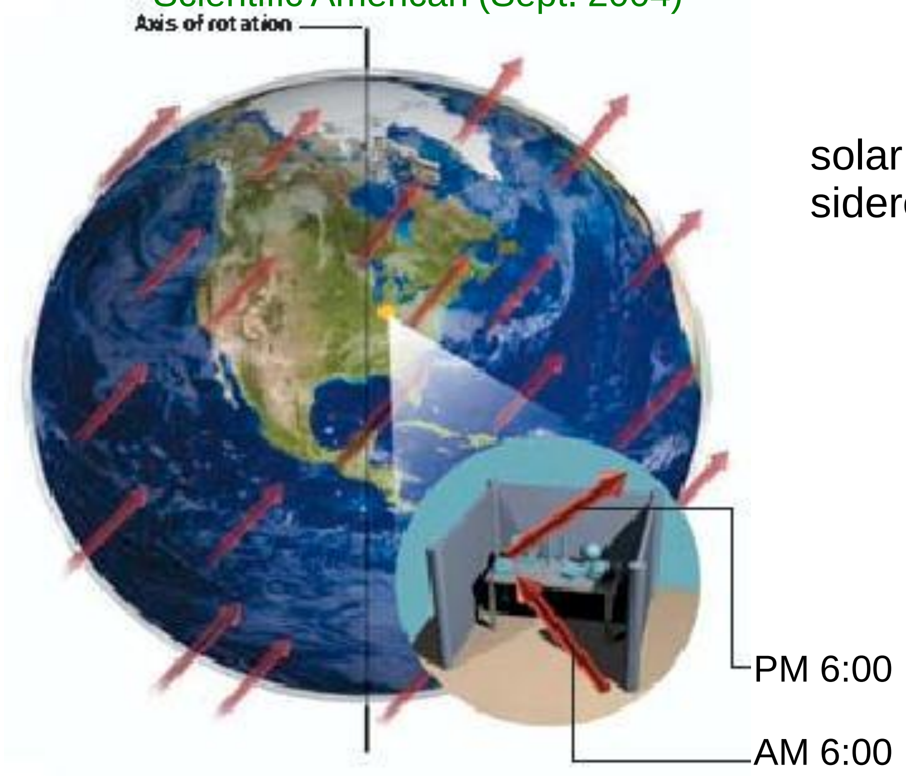
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos, etc); then the physical quantities may depend on the rotation of the earth (sidereal time dependence).

background fields of the universe

vacuum Lagrangian for fermion

$$L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi + \bar{\Psi}\gamma_\mu a^\mu\Psi + \bar{\Psi}\gamma_\mu c^{\mu}\partial_\nu\Psi \ldots$$

Scientific American (Sept. 2004)



solar time: 24h 00m 00.0s
sidereal time: 23h 56m 04.1s (Earth rotation period)

1. Spontaneous Lorentz symmetry breaking

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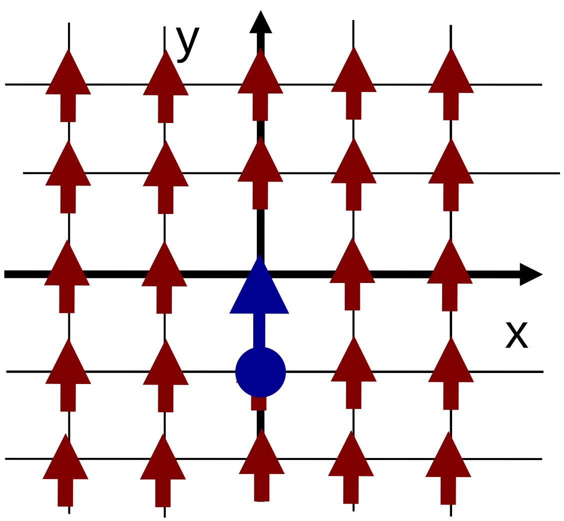
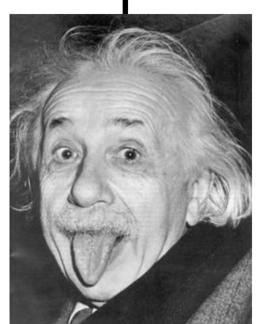
2. What is Lorentz violation?

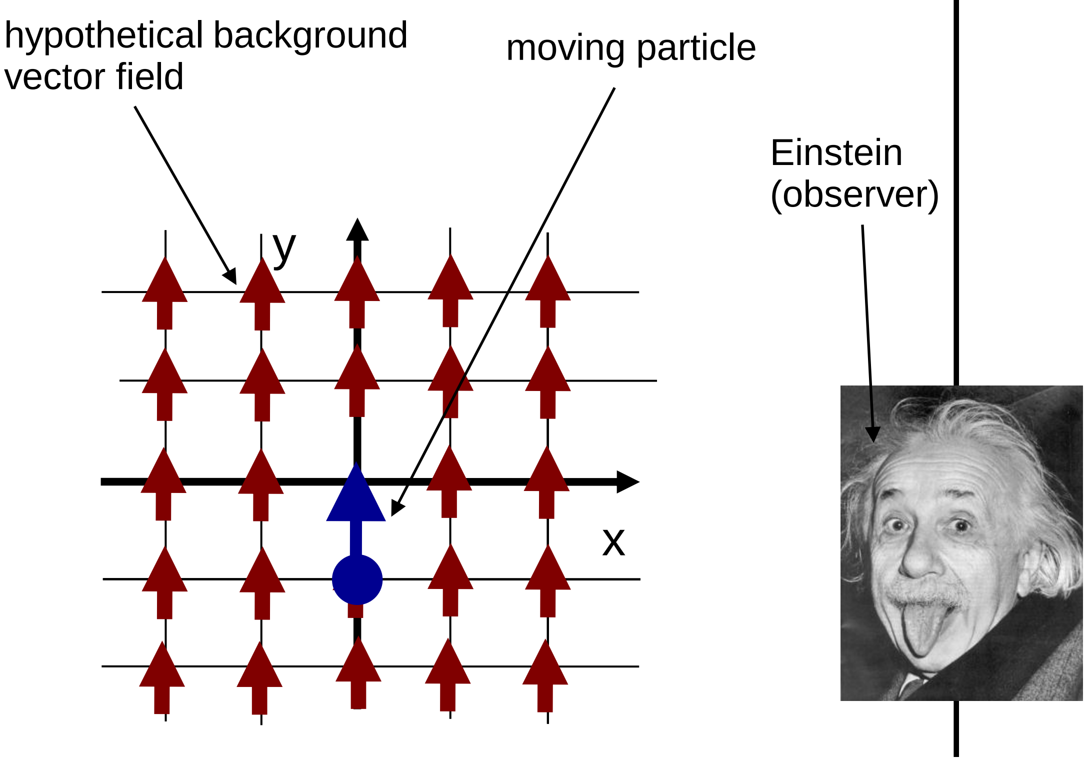
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)$$





2. What is Lorentz violation?

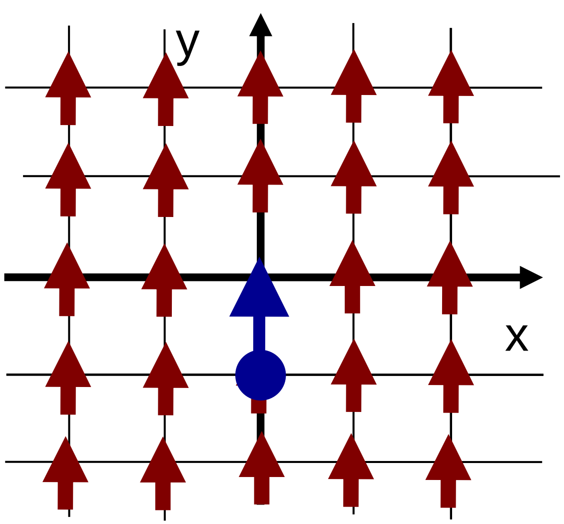
$$\overline{Y}(x) g_m a^m Y(x)$$

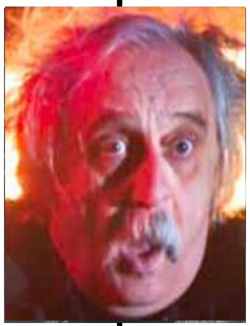


2. What is Lorentz violation?

Under the particle Lorentz transformation:

$$U\overline{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)U^{-1}$$





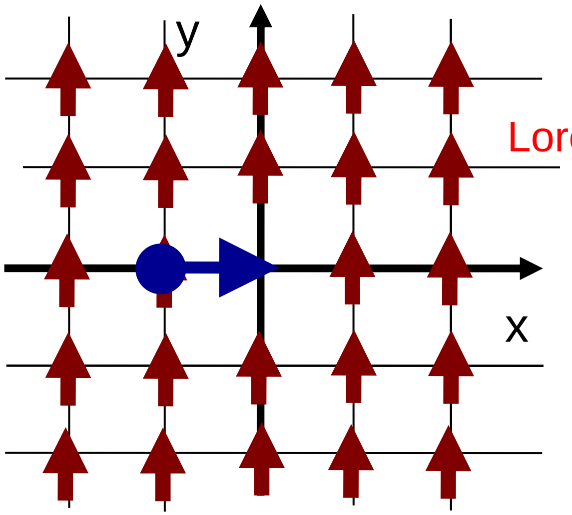
2. What is Lorentz violation?

Under the particle Lorentz transformation:

$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$

$$\neq \overline{\Psi}(\Lambda x)\gamma_\mu a^\mu \Psi(\Lambda x)$$

Lorentz violation is observable
when a particle is moving in the
fixed coordinate space



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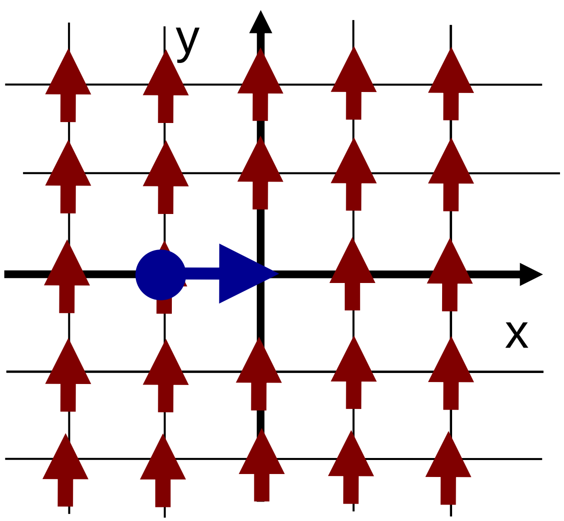

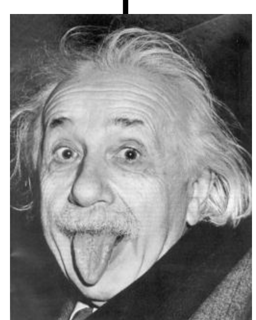

Under the observer Lorentz transformation:

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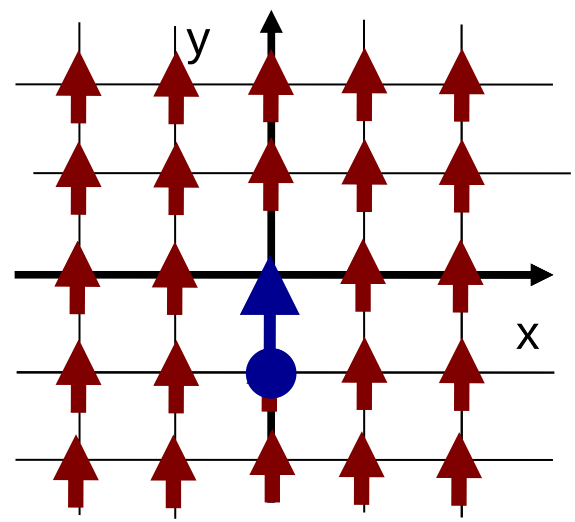

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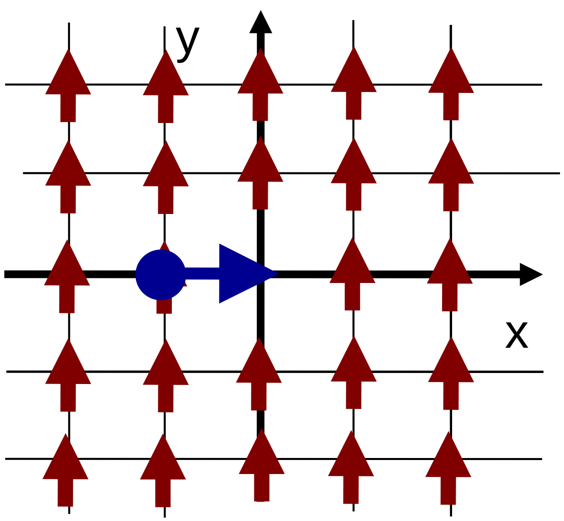
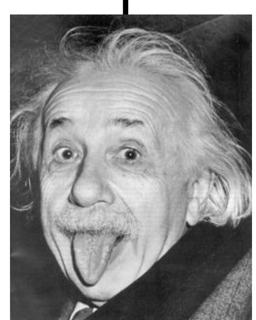
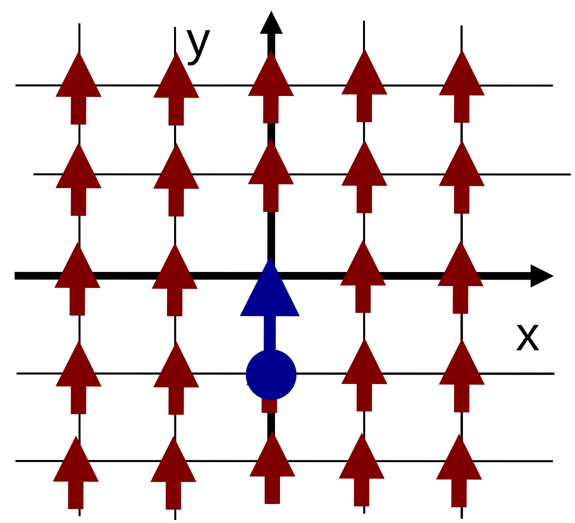




Under the observer Lorentz transformation:

$$\overline{Y}(x)g_{m}a^{m}Y(x)$$

$$x \rightarrow \Lambda^{-1}x$$



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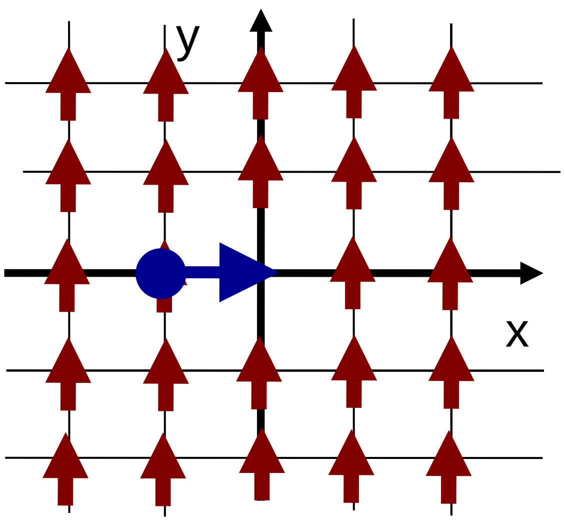
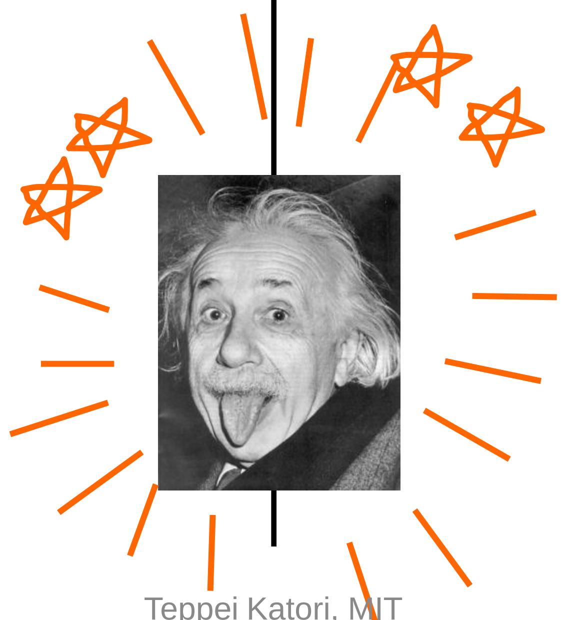


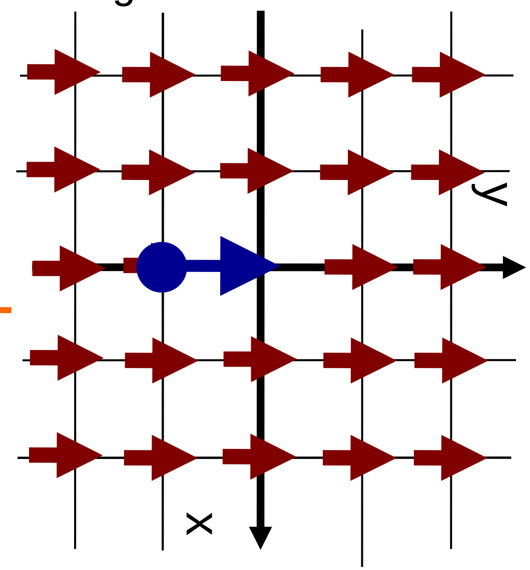
Under the observer Lorentz transformation:

$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \xrightarrow{\Lambda^{-1}} \overline{\Psi}(\Lambda^{-1}x)\gamma_\mu a^\mu \Psi(\Lambda^{-1}x)$$

Lorentz violation cannot be generated by observers motion (coordinate transformation is unbroken)

all observers agree for all observations





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3. Test for Lorentz violation with neutrinos

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3. Test of Lorentz violation with neutrino oscillation experiments

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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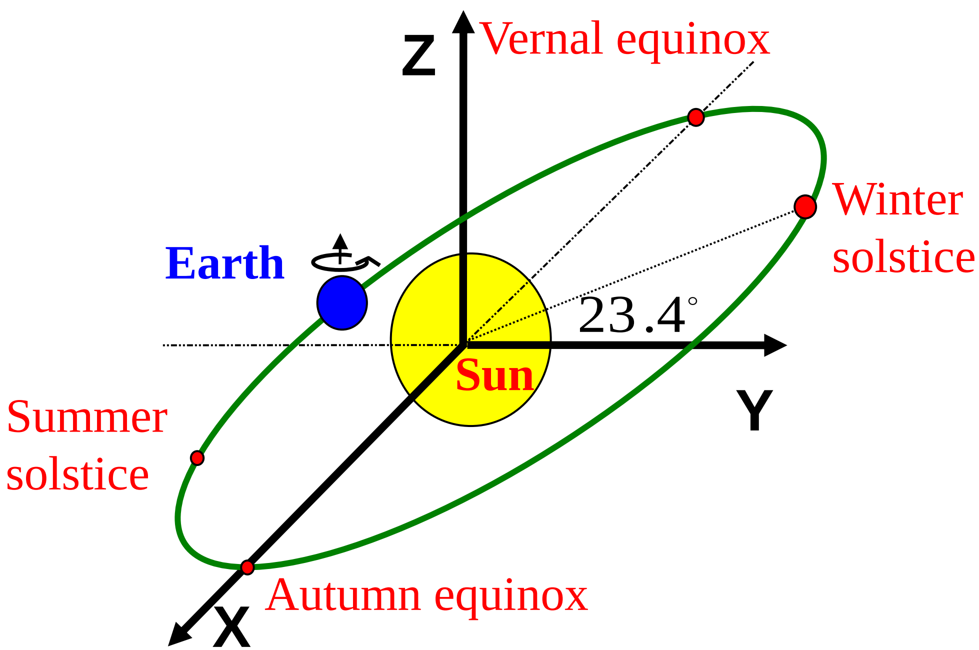
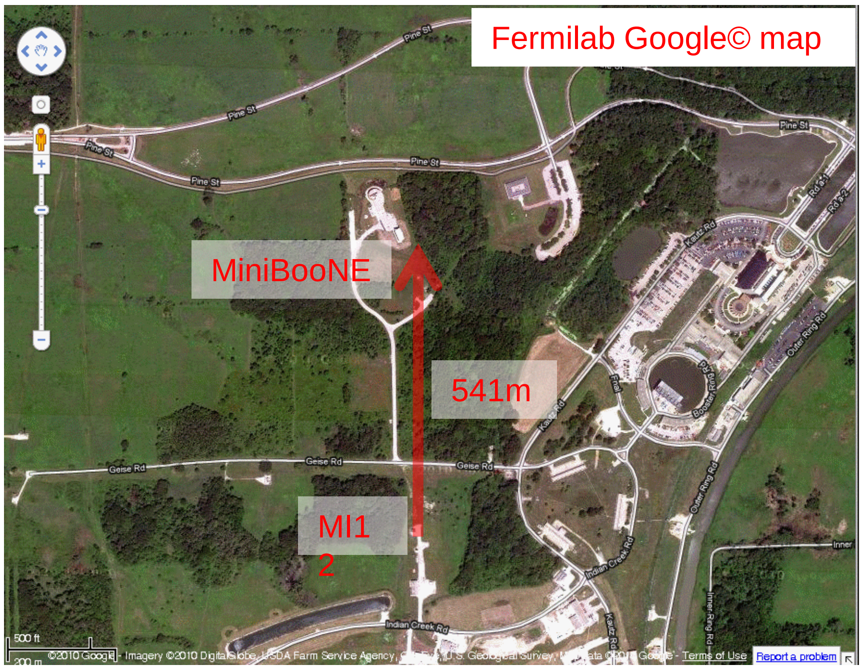
- Neutrino beamline is described in Sun-centred coordinates





MiniBooNE beamline

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

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

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

Kostelecký and Mewes
PRD70(2004)076002

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

solar time: 24h 00m 00.0s
sidereal time: 23h 56m 04.1s

sidereal frequency $\omega_\oplus = \dfrac{2\pi}{23h56m4.1s}$

sidereal time $T_\oplus$

Lorentz-violating neutrino oscillation probability for short-baseline experiments

$$P_{\nu_\mu \to \nu_e} = \left(\frac{L}{\hbar c}\right)^2 \left| (C)_{e\mu} + (A_s)_{e\mu} \sin \omega_\oplus T_\oplus + (A_c)_{e\mu} \cos \omega_\oplus T_\oplus + (B_s)_{e\mu} \sin 2\omega_\oplus T_\oplus + (B_c)_{e\mu} \cos 2\omega_\oplus T_\oplus \right|^2$$

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sidereal frequency $w_{\oplus} = \frac{2p}{23h56m4.1s}$

sidereal time $T_{\oplus}$

Lorentz-violating neutrino oscillation probability for short-baseline experiments

time independent amplitude

sidereal time dependent amplitude

$$P_{n_m \rightarrow n_e} = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{em} + (A_s)_{em} \sin w_{\oplus} T_{\oplus} + (A_c)_{em} \cos w_{\oplus} T_{\oplus} + (B_s)_{em} \sin 2 w_{\oplus} T_{\oplus} + (B_c)_{em} \cos 2 w_{\oplus} T_{\oplus}\right|^2$$

Sidereal variation analysis for short baseline neutrino oscillation is 5-parameter fitting problem

3. LSND experiment

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

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

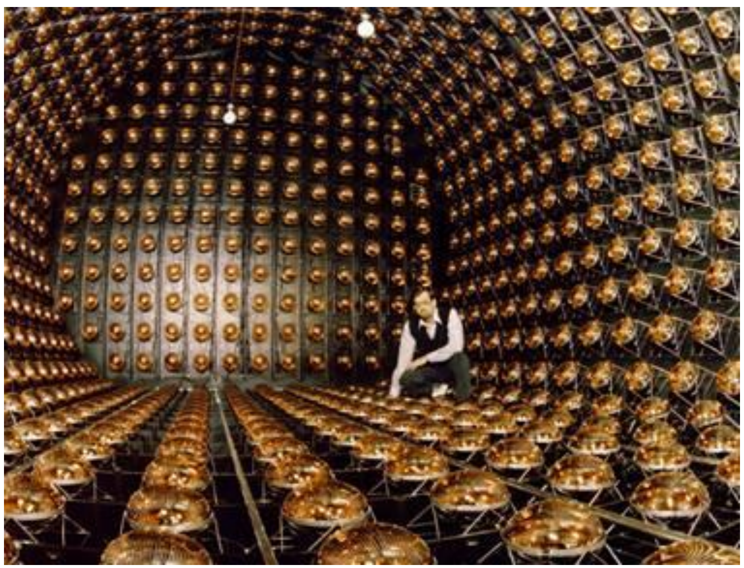
$$n + p \rightarrow d + \gamma$$

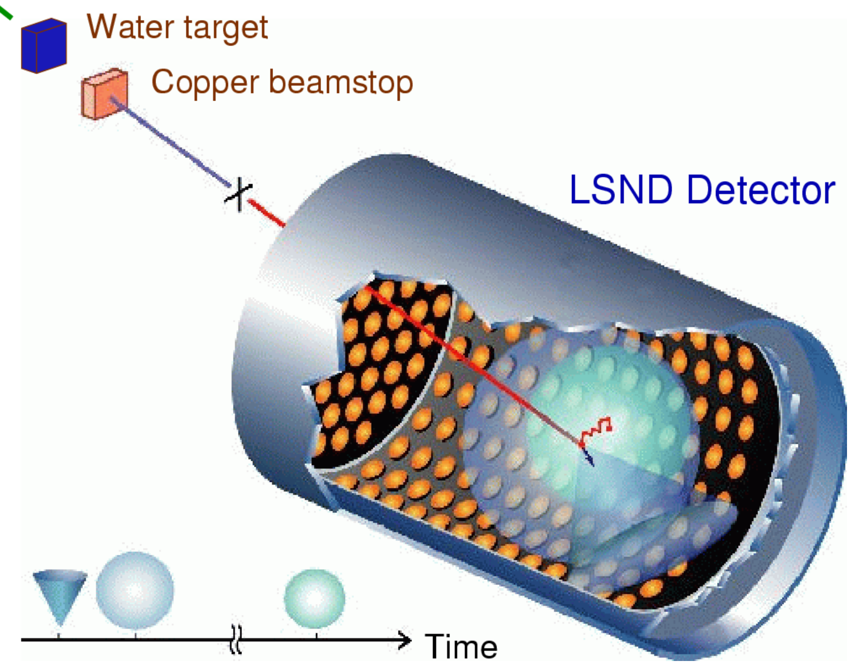
LSND saw the 3.8σ excess of electron antineutrinos from muon antineutrino beam; since this excess is not understood by neutrino Standard Model, it might be new physics

800 MeV proton beam from
LANSCE accelerator

L/E~30m/30MeV~1

LSND detector





LSND collaboration,
PRD72(2005)076004

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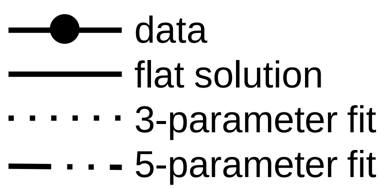
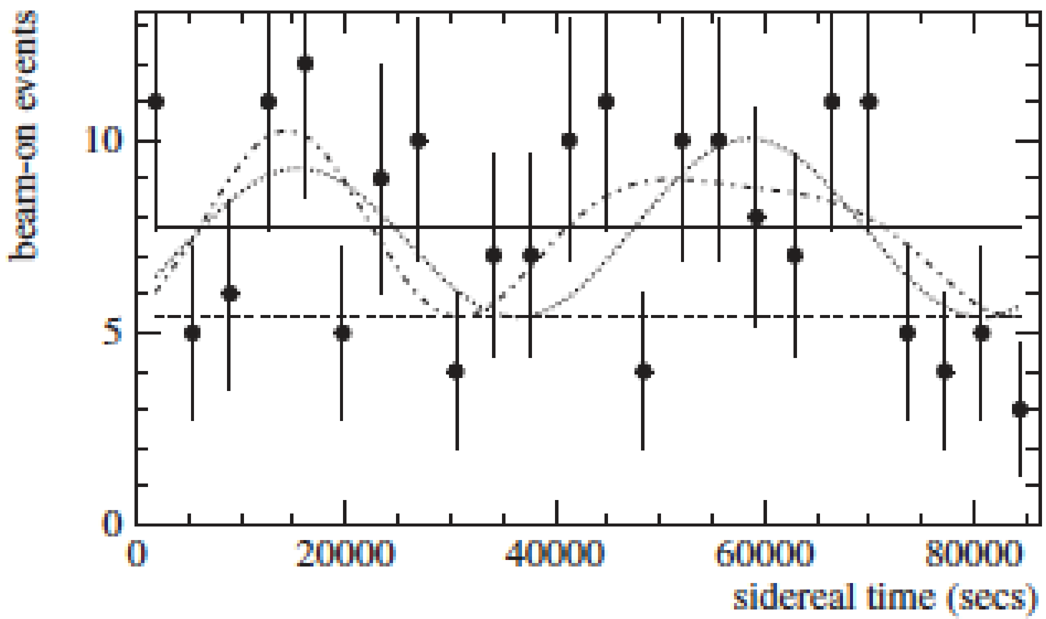
Data is consistent with flat solution, but sidereal time solution is not excluded.



LSND oscillation candidate sidereal time distribution



Small Lorentz violation could be the solution of LSND excess

TK, Kostelecký, Tayloe
PRD74(2006)105009

3. Tandem Model

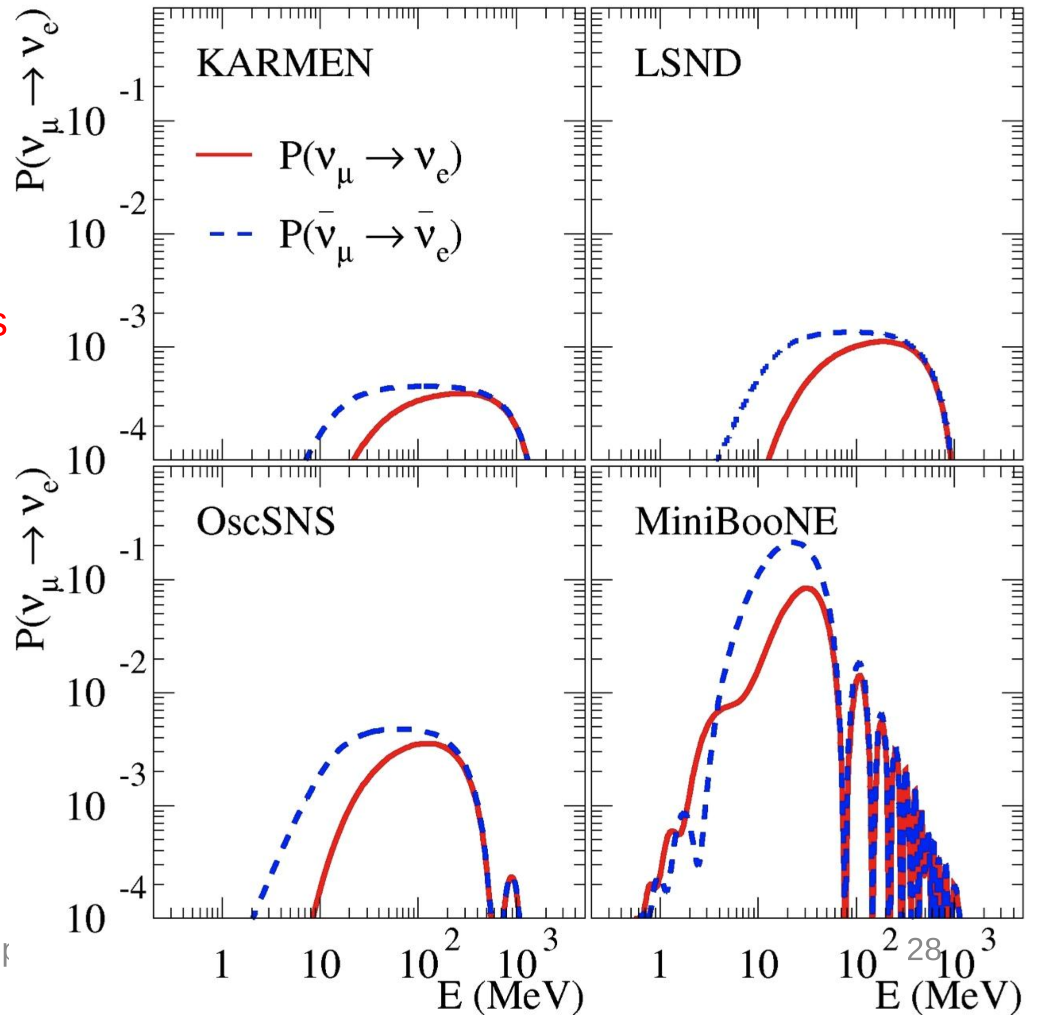
$$(h^{\nu}_{\text{eff}})_{ab} \approx E\delta_{ab} + \frac{(m^2)_{ab}}{2E} + (a_L)_{ab} - \frac{4}{3}(c_L)_{ab}E.$$

Small Lorentz violation could be the solution of LSND excess. But can such solution be allowed by other experiments?
→ It is possible to construct a phenomenological neutrino oscillation model, based on Lorentz violation, using only 3 free parameters (tandem model).

Tandem model can reproduce:
- solar neutrino oscillation
- atmospheric neutrino oscillation
- reactor neutrino oscillation
- LSND neutrino oscillation

Tandem model also predicts small excess at the low energy region for MiniBooNE

LSND oscillation candidate sidereal time distribution



Recent development of Lorentz violating neutrino oscillation models, see for example,
Diaz and Kostelecký, PRD85(2012)016013

MiniBooNE collaboration,
ArXiv:1109.3480

3. MiniBooNE experiment

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

$$n_m \xrightarrow{oscillation} n_e + n \rightarrow e^- + p$$

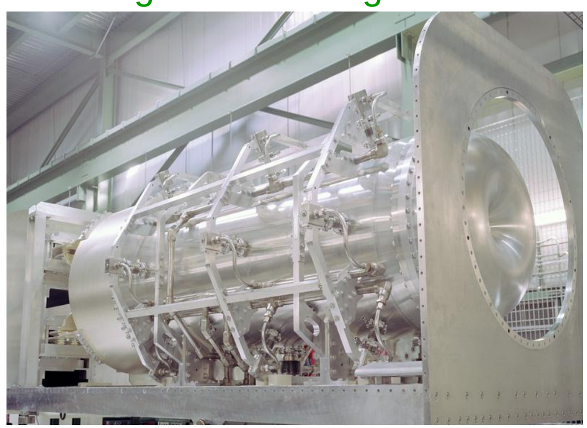
$$\bar{n}_m \xrightarrow{oscillation} \bar{n}_e + p \rightarrow e^+ + n$$

Neutrino mode analysis: MiniBooNE saw the 3.0σ excess at low energy region
Antineutrino mode analysis: MiniBooNE saw the 1.4σ excess at low and high energy region

(however MiniBooNE low energy excesses are much bigger than tandem model prediction)

FNAL Booster

Magnetic focusing horn



~520m →

MiniBooNE detector

primary beam (8 GeV protons) → secondary beam (2 GeV pions) → tertiary beam (700 MeV neutrinos)

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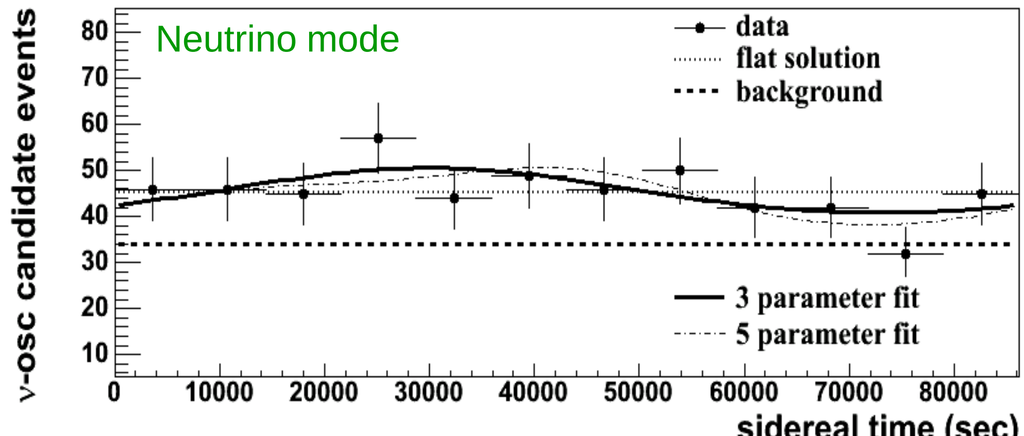
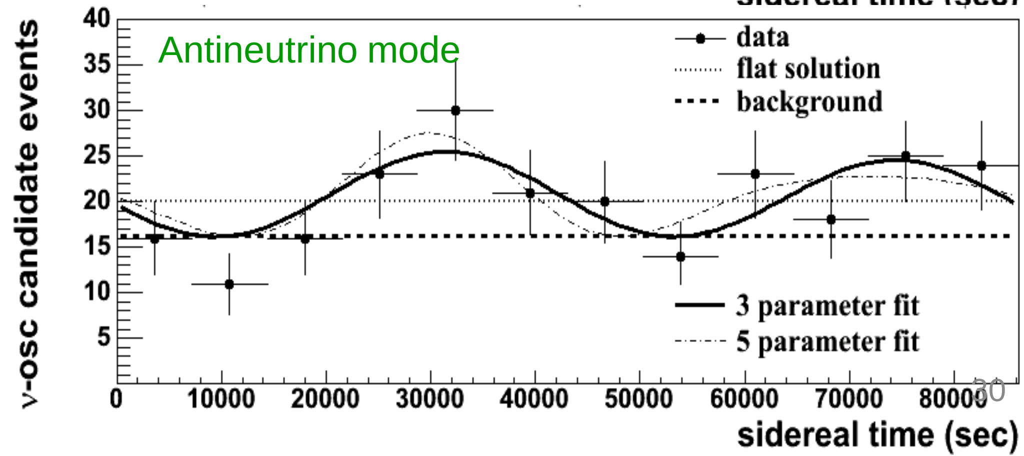
Electron neutrino candidate data prefer sidereal time independent solution (flat)



Electron antineutrino candidate data prefer sidereal time dependent solution, but statistical significance is marginal



We find no evidence of Lorentz violation

3. MiniBooNE experiment

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

$$n_m \xrightarrow{oscillation} n_e + n \rightarrow e^- + p$$

$$\bar{n}_m \xrightarrow{oscillation} \bar{n}_e + p \rightarrow e^+ + n$$

Neutrino mode analysis: MiniBooNE saw the 3.0σ excess at low energy region
Antineutrino mode analysis: MiniBooNE saw the 1.4σ excess at low and high energy region.

Since we find no evidence of Lorentz violation, 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

Coefficient	$e\mu$ (ν mode low energy region)	$e\mu$ ($\bar{\nu}$ mode combined region)
$\mathrm{Re}(a_L)^T$ or $\mathrm{Im}(a_L)^T$	4.2×10^{-20} GeV	2.6×10^{-20} GeV
$\mathrm{Re}(a_L)^X$ or $\mathrm{Im}(a_L)^X$	6.0×10^{-20} GeV	5.6×10^{-20} GeV
$\mathrm{Re}(a_L)^Y$ or $\mathrm{Im}(a_L)^Y$	5.0×10^{-20} GeV	5.9×10^{-20} GeV
$\mathrm{Re}(a_L)^Z$ or $\mathrm{Im}(a_L)^Z$	5.6×10^{-20} GeV	3.5×10^{-20} GeV
$\mathrm{Re}(c_L)^{XY}$ or $\mathrm{Im}(c_L)^{XY}$	—	—
$\mathrm{Re}(c_L)^{XZ}$ or $\mathrm{Im}(c_L)^{XZ}$	1.1×10^{-19}	6.2×10^{-20}
$\mathrm{Re}(c_L)^{YZ}$ or $\mathrm{Im}(c_L)^{YZ}$	9.2×10^{-20}	6.5×10^{-20}
$\mathrm{Re}(c_L)^{XX}$ or $\mathrm{Im}(c_L)^{XX}$	—	—
$\mathrm{Re}(c_L)^{YY}$ or $\mathrm{Im}(c_L)^{YY}$	—	—
$\mathrm{Re}(c_L)^{ZZ}$ or $\mathrm{Im}(c_L)^{ZZ}$	3.4×10^{-19}	1.3×10^{-19}
$\mathrm{Re}(c_L)^{TT}$ or $\mathrm{Im}(c_L)^{TT}$	9.6×10^{-20}	3.6×10^{-20}
$\mathrm{Re}(c_L)^{TX}$ or $\mathrm{Im}(c_L)^{TX}$	8.4×10^{-20}	4.6×10^{-20}
$\mathrm{Re}(c_L)^{TY}$ or $\mathrm{Im}(c_L)^{TY}$	6.9×10^{-20}	4.9×10^{-20}
$\mathrm{Re}(c_L)^{TZ}$ or $\mathrm{Im}(c_L)^{TZ}$	7.8×10^{-20}	2.9×10^{-20}

Double Chooz collaboration,
paper in preparation

3. Double Chooz experiment

So far, we have set limits on

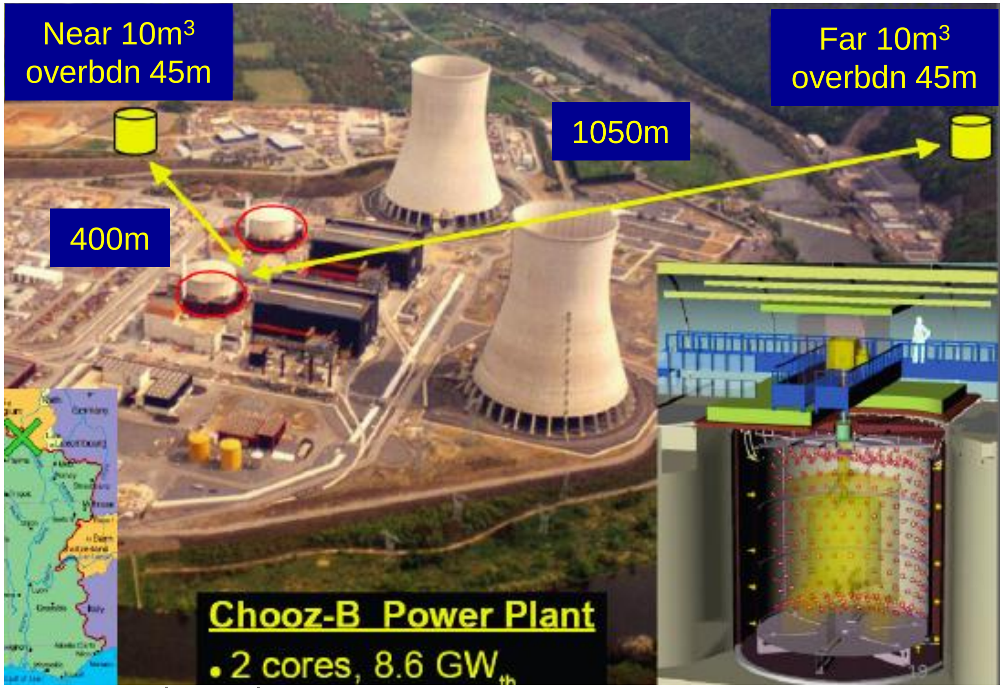
1. $\nu_e \leftrightarrow \nu_\mu$ channel: LSND, MiniBooNE, MINOS ($<10^{-20}$ GeV)
2. $\nu_\mu \leftrightarrow \nu_\tau$ channel: MINOS, IceCube ($<10^{-23}$ GeV)

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

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

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

Double Chooz observed the 3.1σ disappearance signal of electron antineutrinos from the reactor



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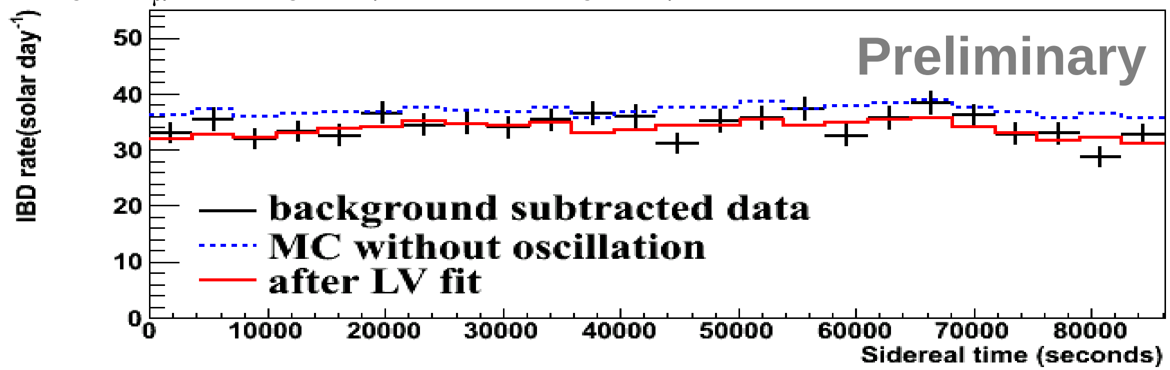
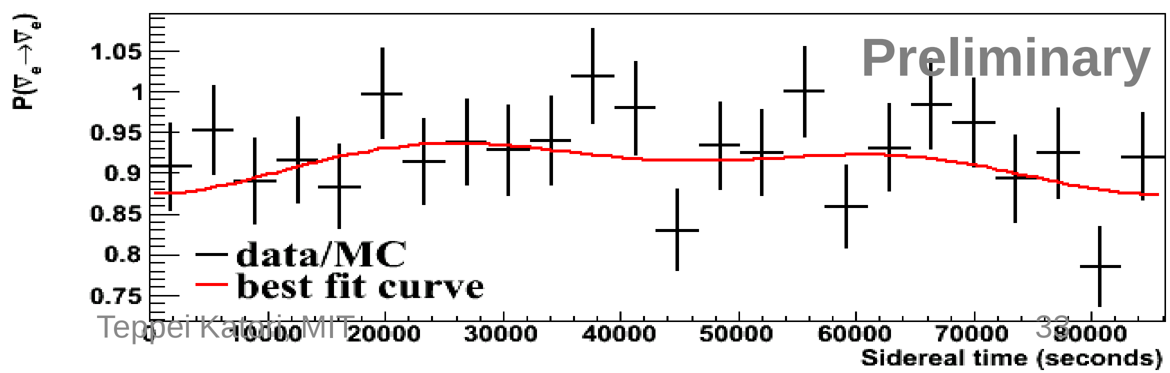
Double Chooz observed the 3.1σ disappearance signal of electron antineutrinos from the reactor

Preliminary result shows small disappearance signal prefers sidereal time independent solution (flat)

We will be able to set limits in the e-τ sector for the first time;
$\nu_e \leftrightarrow \nu_\tau$ ($<10^{-21}$ GeV)





Conclusion

Lorentz and CPT violation has been shown to occur in Planck-scale physics.

There is a world wide effort to test Lorentz violation with various state-of-the-art technologies.

LSND and MiniBooNE data suggest Lorentz violation is an interesting solution to neutrino oscillation.

MiniBooNE antineutrino mode data prefer sidereal time dependent solution, although statistical significance is not high. Limits from MiniBooNE exclude simple Lorentz violation motivated scenario for LSND.

MiniBooNE, LSND, MINOS, IceCube, and Double Chooz set stringent limits on Lorentz violation in neutrino sector in terrestrial level

Bluhm, Kostelecky, Lane, Russell PRL.88(2002)090801
Animation for proposed atomic clock experiment in space

Thank you for your attention!

Backup

3. MiniBooNE oscillation analysis results

MiniBooNE collaboration,
PRL102(2009)101802,
PRL105(2010)181801

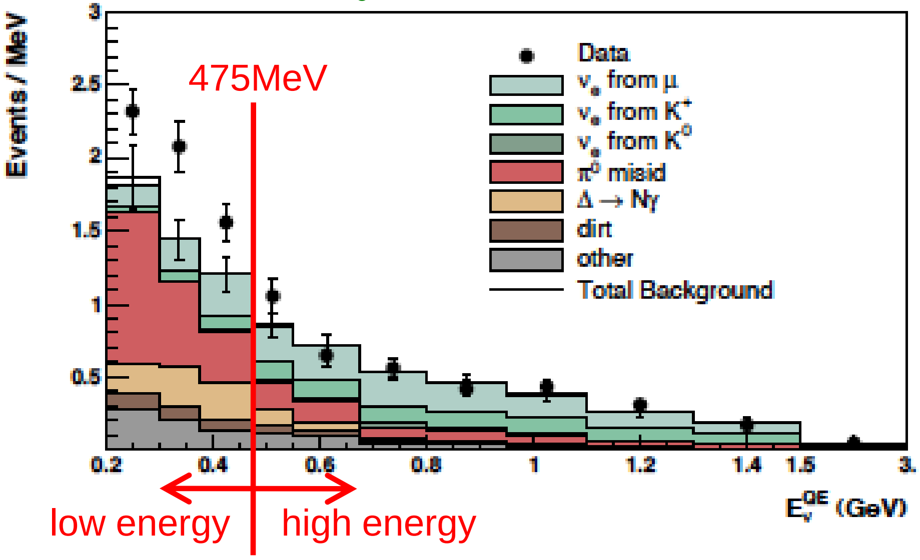
Neutrino mode low energy excess

MiniBooNE see the excess in low energy region.

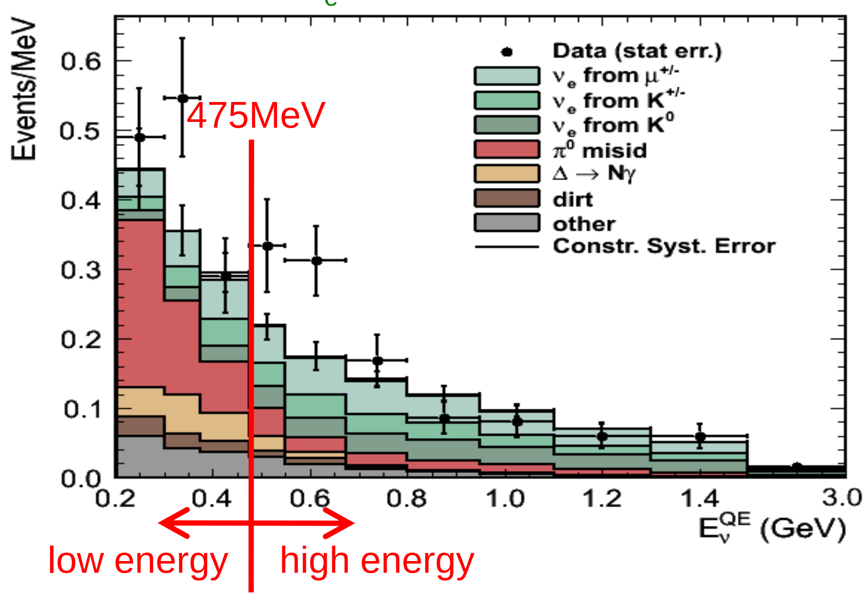
Antineutrino mode excess

MiniBooNE see the excess in combined region.

MiniBooNE low E ν_e excess



MiniBooNE anti-ν_e excess



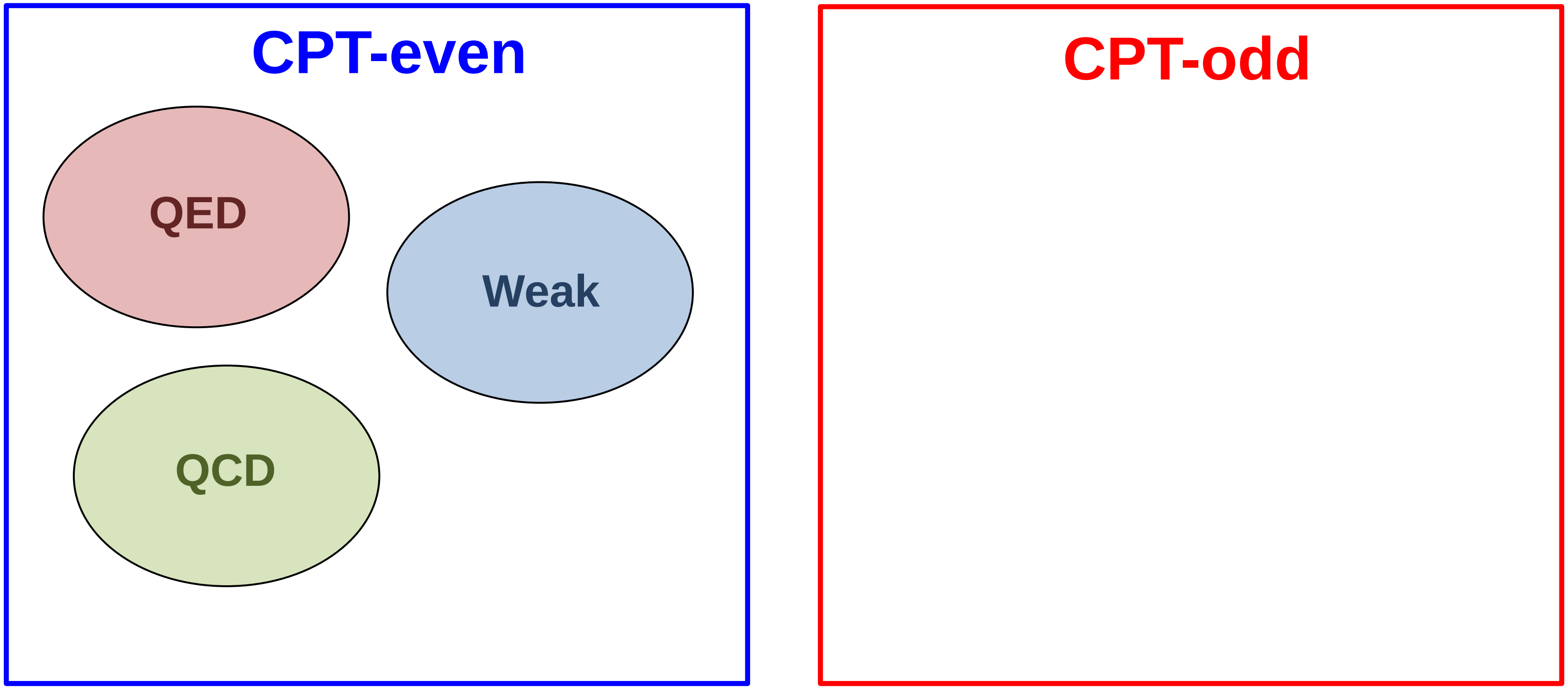
These excesses are not predicted by neutrino Standard Model (νSM).
Oscillation candidate events may have sidereal time dependence.

2. What is CPT violation?

CPT symmetry is the invariance under CPT transformation

$$L \xrightarrow{CPT} \Theta L \Theta^{-1} = L' = L, \qquad \Theta = CPT$$

CPT is the perfect symmetry of the Standard Model, due to CPT theorem



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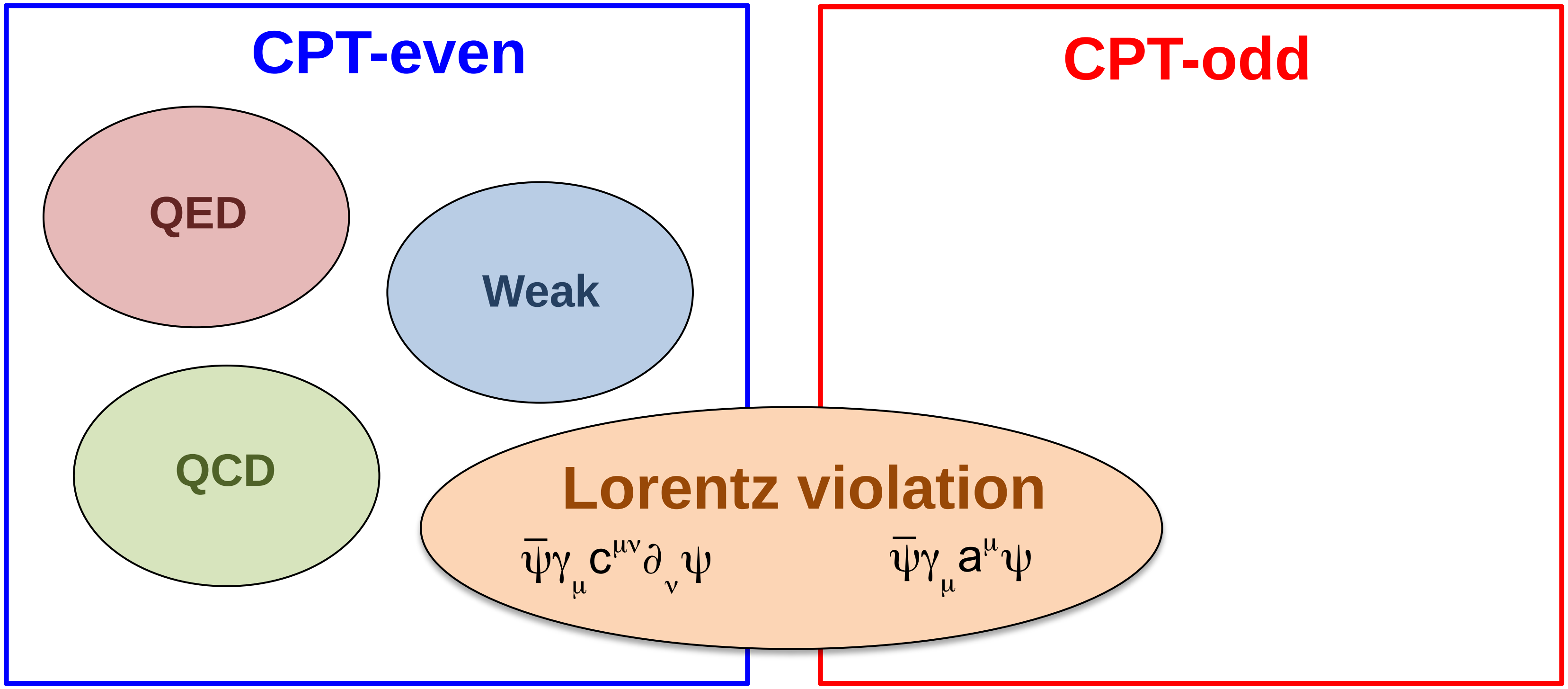

CPT-odd Lorentz violating coefficients (odd number Lorentz indices, ex., a^{μ} , $g^{\lambda\mu\nu}$)
CPT-even Lorentz violating coefficients (even number Lorentz indices, ex., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

2. Modern tests of Lorentz violation

The last meeting of Lorentz and CPT violation was in summer 2010.
Next meeting will be in summer 2013

http://www.physics.indiana.edu/~kostelec/faq.html

CPT'10

MEETING LINKS

Meeting Home
Registration
Program
Proceedings
Travel
Accommodations

LOCAL LINKS

IU Physics
IU Astronomy
IU Bloomington
Bloomington area

Fifth Meeting on

CPT AND LORENTZ SYMMETRY

June 28-July 2, 2010

Indiana University, Bloomington

The *Fifth Meeting on CPT and Lorentz Symmetry* will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on June 28-July 2, 2010. The meeting will focus on tests of these fundamental symmetries and on related theoretical issues, including scenarios for possible violations.

Topics include:

- searches for CPT and Lorentz violations involving
  - birefringence and dispersion from cosmological sources
  - clock-comparison measurements
  - CMB polarization
  - collider experiments
  - electromagnetic resonant cavities
  - equivalence principle
  - gauge and Higgs particles
  - high-energy astrophysical observations
  - laboratory and gravimetric tests of gravity

2. Modern tests of Lorentz violation

http://www.physics.indiana.edu/~kostelec/faq.html

Topics:

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  - equivalence principle
  - gauge and Higgs particles
  - high-energy astrophysical observations
  - laboratory and gravimetric tests of gravity
  - matter interferometry
  - neutrino oscillations
  - oscillations and decays of K, B, D mesons
  - particle-antiparticle comparisons
  - post-newtonian gravity in the solar system and beyond
  - second- and third-generation particles
  - space-based missions
  - spectroscopy of hydrogen and antihydrogen
  - spin-polarized matter
* theoretical studies of CPT and Lorentz violation involving
  - physical effects at the level of the Standard Model, General Relativity, and beyond
  - origins and mechanisms for violations
  - classical and quantum issues in field theory, particle physics, gravity, and strings

Atomic Interferometer
$(a,c)^{n,p,e} < 10^{-6}$

PRL106(2011)1

2 ... of Lorentz v...

ht... a.edu/~kostelec/fa...

...pics:

Tevatron and LEP
$-5.8\times10^{-12} < \kappa_{tr} - 4/3 c_e^{00} < 1.2\times10^{-11}$

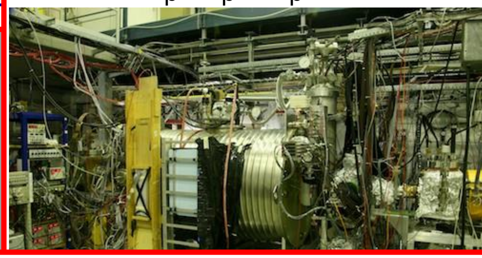
PRL102(2009)170402

GRB vacuum birefringence
$\kappa_{e+}, \kappa_{o-} < 10^{-37}$

PRL97(2006)140401

...ources

CERN Antiproton Decelerator
$(M_p - \overline{M}_p)/M_p < 10^{-8}$



...ts
...esonant cavities
...ple
...particles

Double gas maser
$b_n(\text{rotation}) < 10^{-33}$GeV
$b_n(\text{boost}) < 10^{-27}$GeV

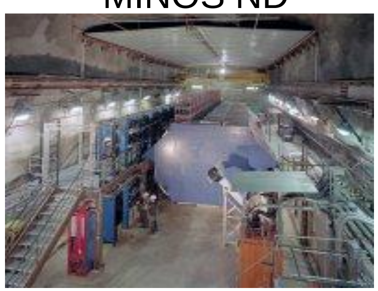
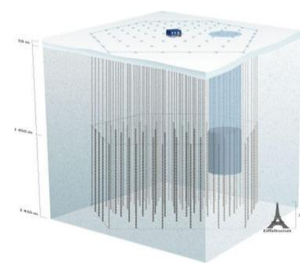
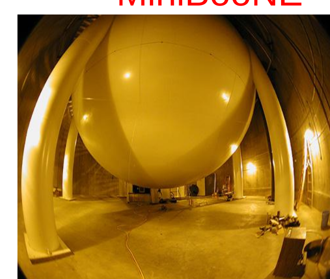
Test of Lorentz invariance with neutrinos is very interesting, because neutrinos are the least known standard model particles!

- ...matter interferometry
- ★ neutrino oscillations
- oscillations and decays o...
- ★ particle-antiparticle comp...
- post-newtonian gravity in...

Cryogenic optical resonator
$\Delta c/c < 10^{-16}$

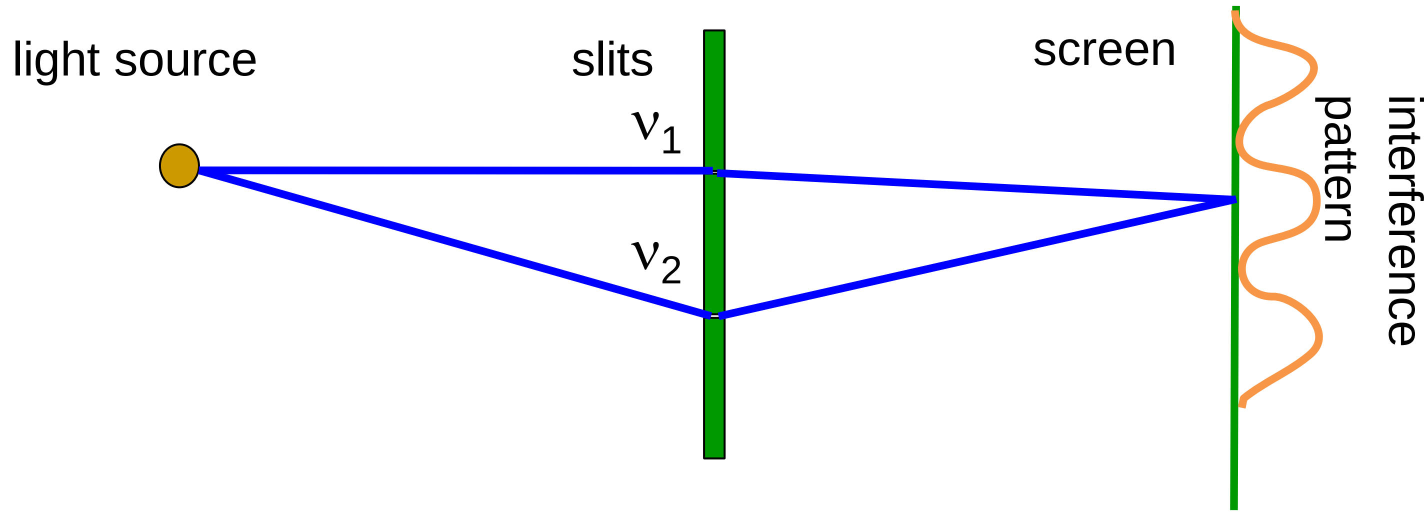
MEETING LINKS

Meeting Home
Registration
Program
Proceedings

LSND	MINOS ND	MINOS FD	IceCube	MiniBooNE
				
PRD72(2005)076004	PRL101(2008)151601	PRL105(2010)151601	PRD82(2010)112003	arXiv:1109.3480

2. Neutrino oscillations, natural interferometers

Neutrino oscillation is an interference experiment (e.g. double slit experiment)

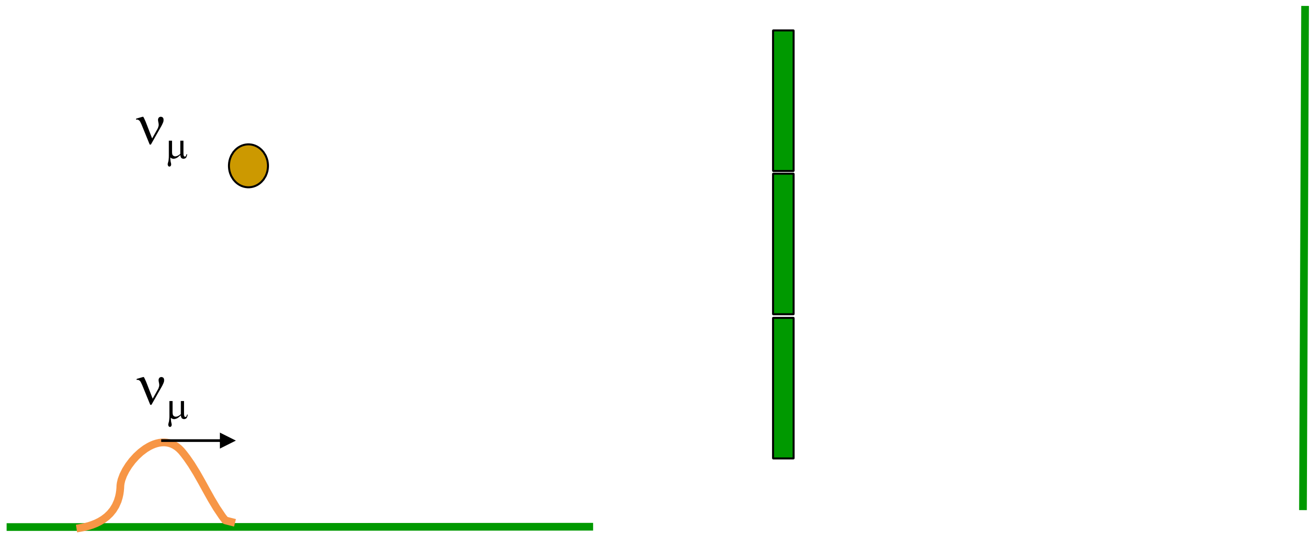


For double slit experiment, if path ν_1 and path ν_2 have different lengths, they have different phase rotations and it causes interference.

In terms of neutrinos, if Hamiltonian eigenstates ν_1 and ν_2 are different, that can be the source of neutrino oscillations.

2. Lorentz violation with neutrino oscillation

Neutrino oscillation is an interference experiment (e.g. double slit experiment)



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

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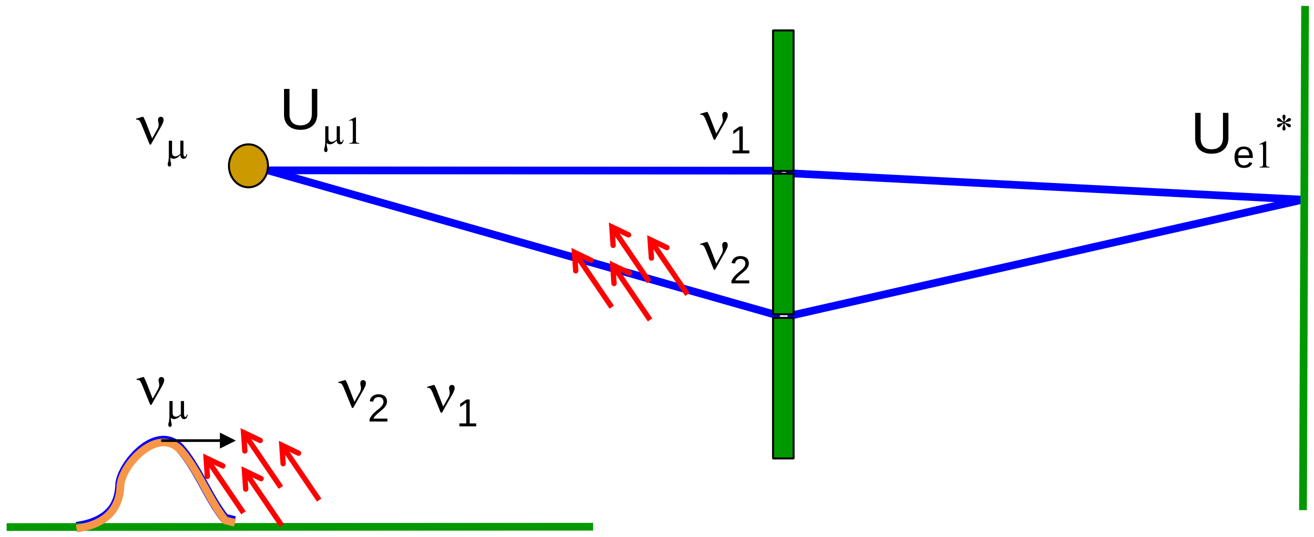

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotations, they cause quantum interference.

If ν_1 and ν_2 have different couplings with Lorentz-violating field, that can be the source of neutrino oscillations.

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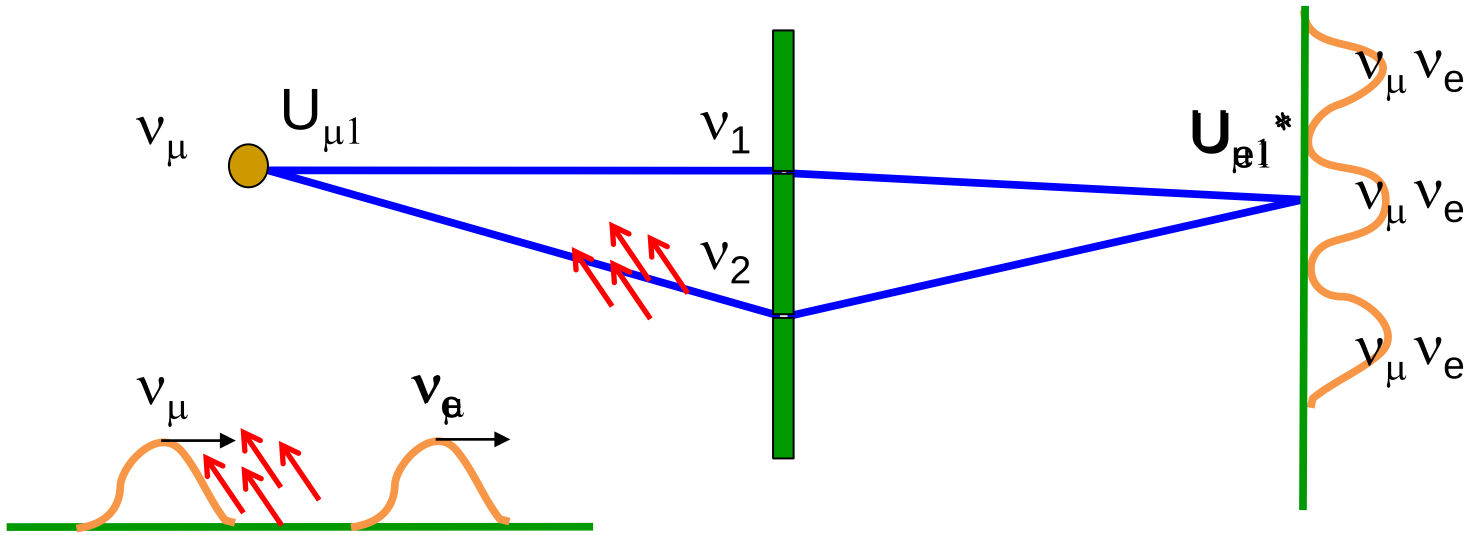

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If ν_1 and ν_2 have different couplings with Lorentz-violating field, that can be the source of neutrino oscillations.

Interference fringe (oscillation pattern) depends on the sidereal motion. The measured scale of neutrino eigenvalue difference is comparable the target scale of Lorentz violation ($<10^{-19}$GeV).

3. Test of Lorentz violation with neutrino oscillation experiments

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

(1) fix the coordinate system
(2) write down the Lagrangian, including Lorentz-violating terms under the formalism
(3) write down the observables using this Lagrangian

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

Modified Dirac Equation (MDE) of neutrinos

$$i(G^{n}_{AB}\P_{n} - M_{AB})n_{B} = 0$$

SME coefficients

CPT odd

$$G^{n}_{AB} = g^{n}d_{AB} + c^{mn}_{AB}g_{m} + d^{mn}_{AB}g_{m}g_{5} + e^{n}_{AB} + if^{n}_{AB}g_{5} + \frac{1}{2}g^{lmn}_{AB}s_{lm}$$

$$M_{AB} = m_{AB} + im_{5AB}g_{5} + a^{m}_{AB}g_{m} + b^{m}_{AB}g_{5}g_{m} + \frac{1}{2}H^{mn}_{AB}s_{mn}$$

CPT even