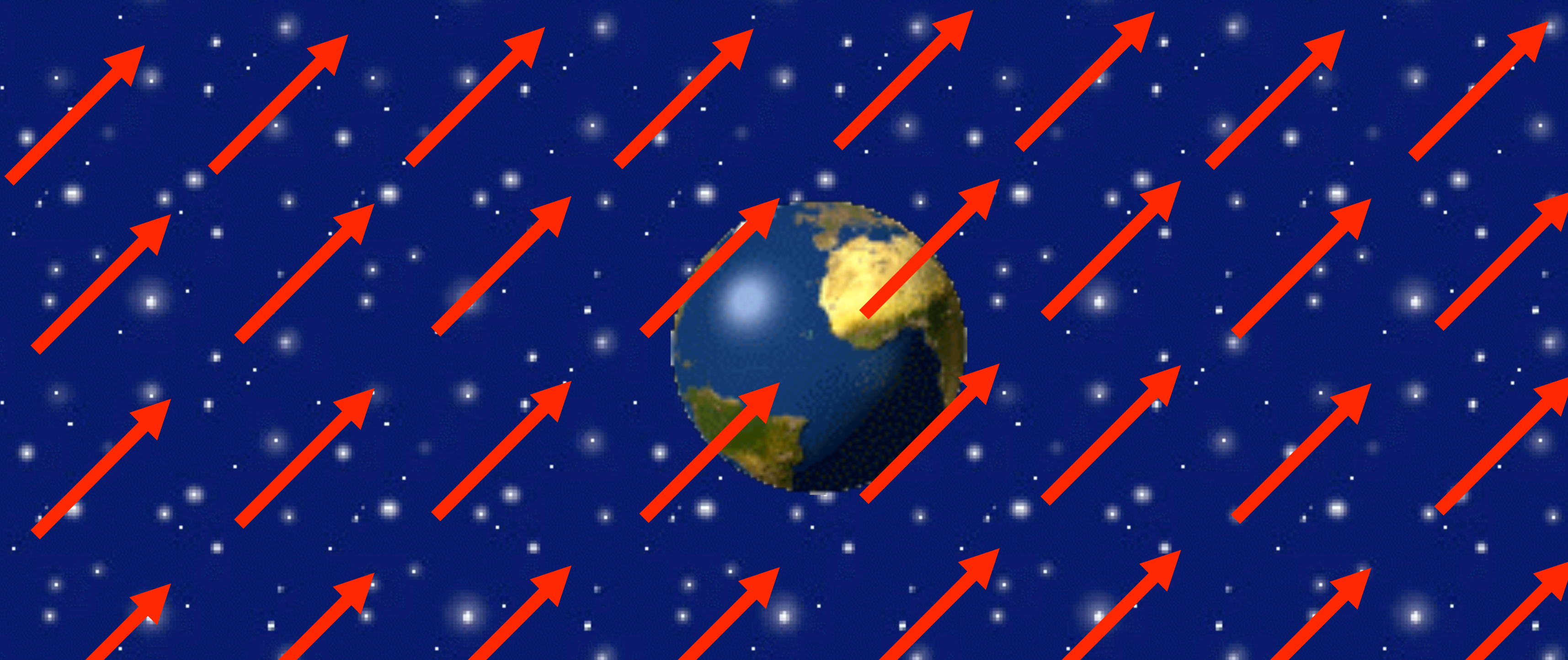
Test for Lorentz violation in the neutrino oscillation experiments

Teppei Katori
Massachusetts Institute of Technology
KEK seminar, June 05, 09

Test for Lorentz violation in the neutrino oscillation experiments



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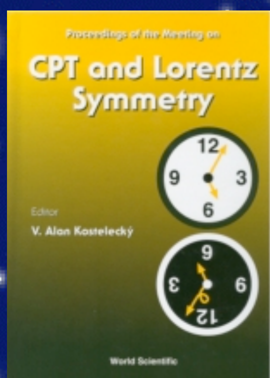
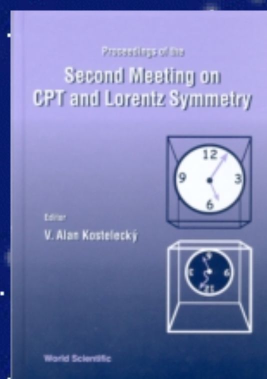
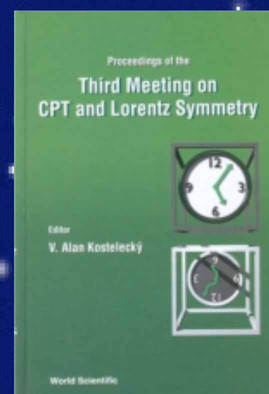
Test for Lorentz violation in the neutrino oscillation experiments

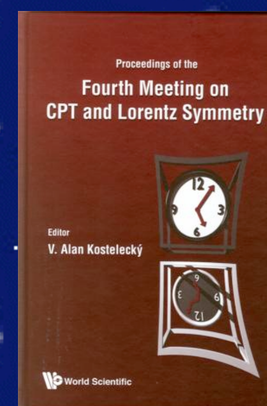
general information about Lorentz violation
http://www.physics.indiana.edu/~kostelec/faq.html
(go google, type "Lorentz violation")

proceedings of *Lorentz and CPT symmetry* (world scientific)









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Test for Lorentz violation in the neutrino oscillation experiments

outline

1. Spontaneous Lorentz symmetry breaking
2. What is Lorentz violation?
3. What is CPT violation?
4. Standard Model Extension (SME)
5. Modern tests of Lorentz and CPT violation
6. Lorentz violation with neutrino oscillation
7. Lorentz violation with LSND
8. Global neutrino oscillation model, "Tandem" model
9. Lorentz violation with MiniBooNE
10. Conclusion

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1. Spontaneous Lorentz symmetry breaking

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

After the discovery 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 physics, 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 taken from CPT04 at
Bloomington, IN

1. Spontaneous Lorentz symmetry breaking

e.g.) SSB of scalar field

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

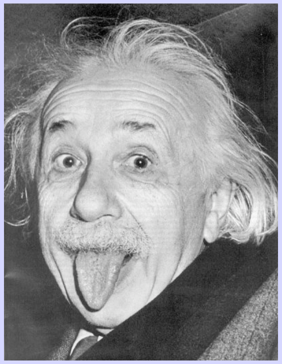
$$V(\varphi) = \frac{1}{2}\mu^2(\varphi^* \varphi) + \frac{1}{4}\lambda(\varphi^* \varphi)^2$$

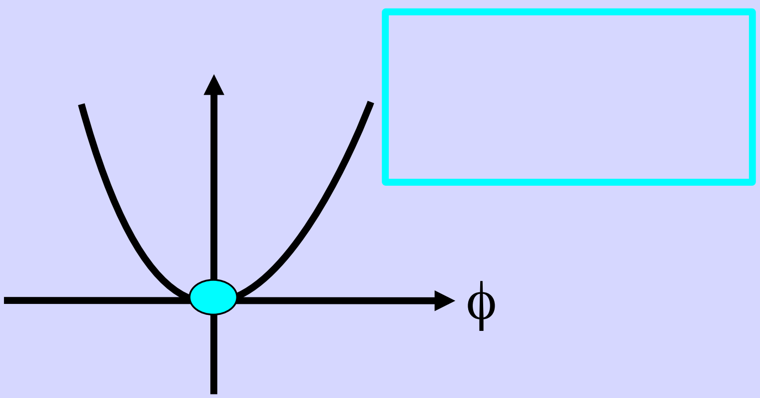
If fields have negative mass term

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

e.g.) vacuum Lagrangian for fermions

$$L = i\overline{\Psi}\gamma_\mu \partial^\mu \Psi$$





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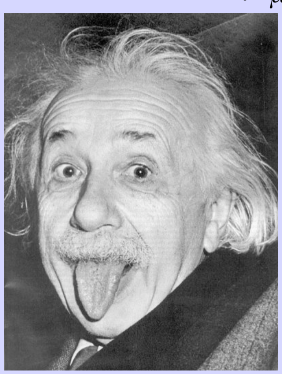
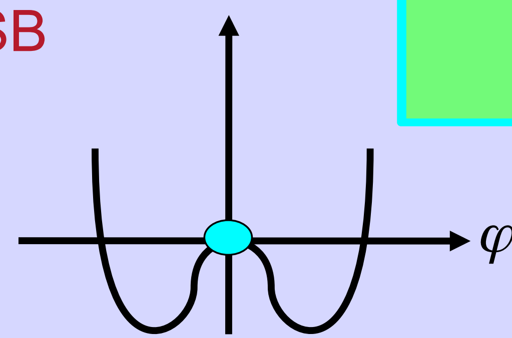
$$L = i\overline{\Psi}\gamma_\mu \partial^\mu \Psi - m\overline{\Psi}\Psi$$



Particle acquires
mass term!

SSB



1. Spontaneous Lorentz symmetry breaking

ex) Spontaneous Lorentz symmetry breaking in string field theory

there is a possibility that Lorentz vector field makes non zero vacuum expectation values.

If Lorentz vector fields have negative square mass term

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

ex) vacuum Lagrangian for fermion

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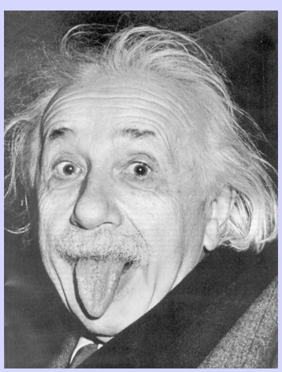

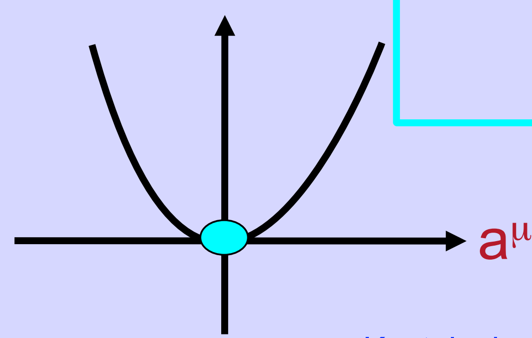

Kostelecky and Samuel
PRD39(1989)683

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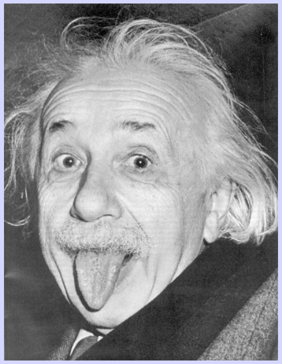

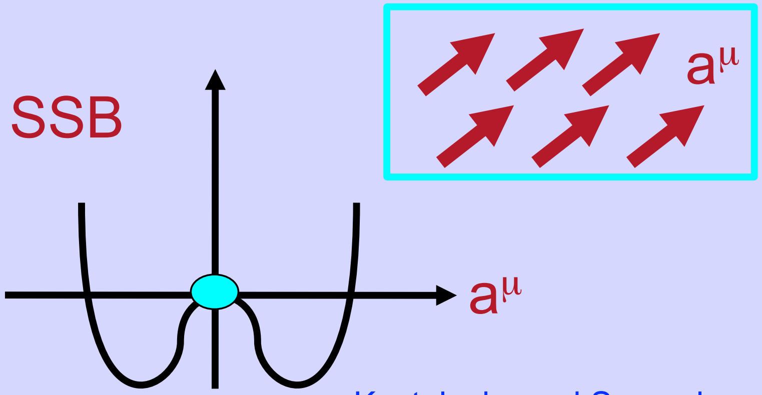

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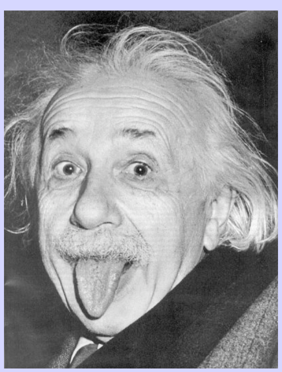
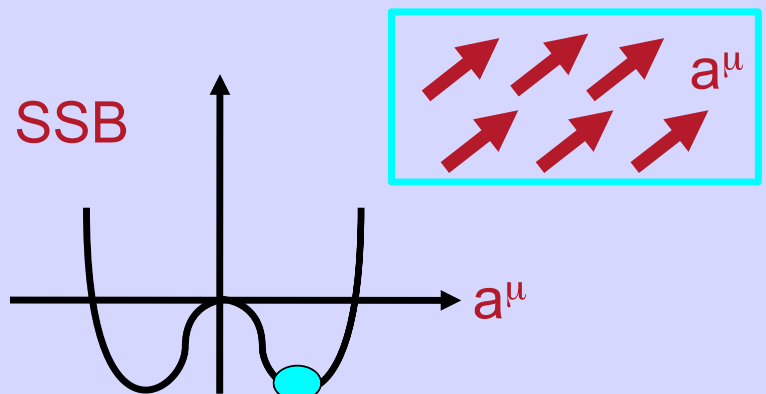


Lorentz symmetry is spontaneously broken!



Kostelecky and Samuel
PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking

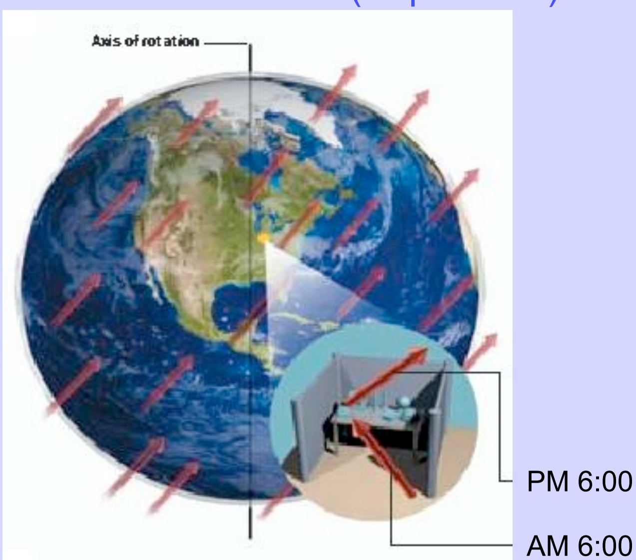
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos etc), then physical quantities may depend on the rotation of the earth.

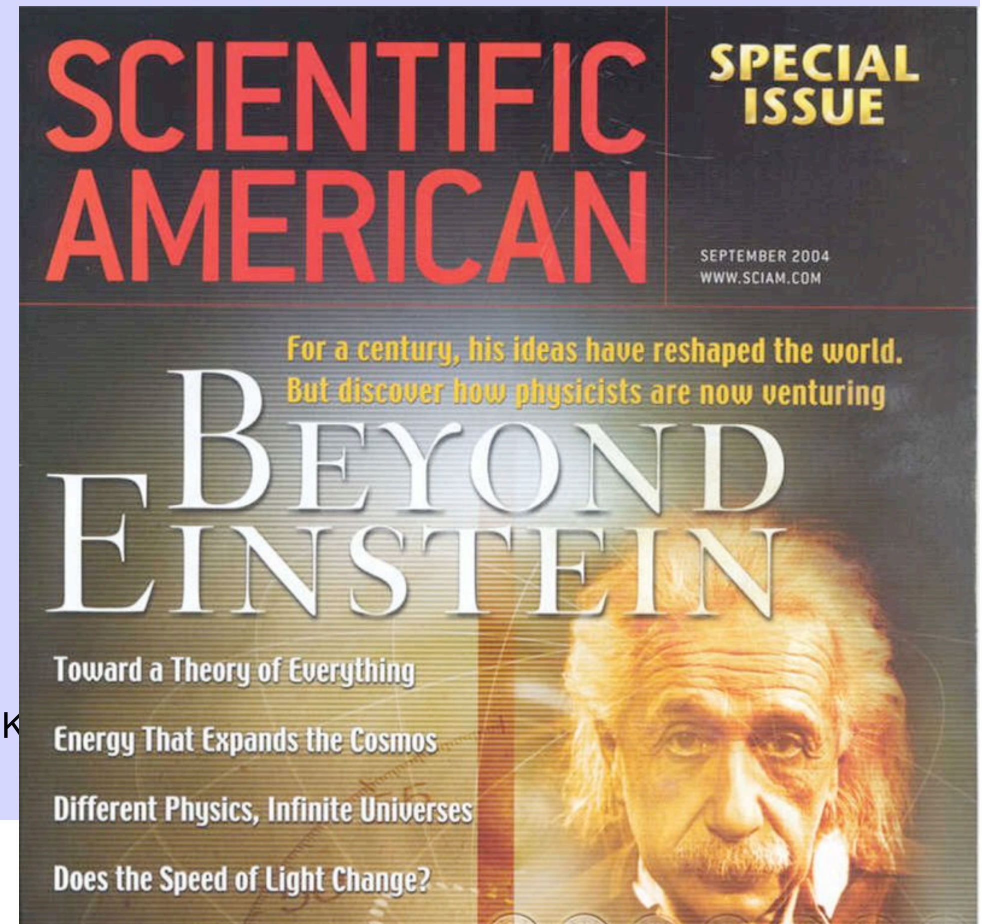
background field of the universe

vacuum Lagrangian for fermion

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

Scientific American (Sept. 2004)





1. Spontaneous Lorentz symmetry breaking

FAQ

Q. How can Lorentz violation happen?

A. Lorentz violation has been shown to occur in Planck scale physics, especially, by Spontaneous Symmetry Breaking.

Q. What is the expected scale of Lorentz violation?

A. Since it is Planck scale physics, either >10^{19}GeV or <10^{-19}GeV is the interesting region. >10^{19}GeV is not achievable (LHC is 10^{4}GeV), but <10^{-19}GeV is possible.

ex1) Zeeman frequency change of double gas maser ~100nHz ~ 10^{-32}GeV
ex2) measured atmospheric neutrino eigenvalue difference ~ $\Delta m^2/E$ ~ 10^{-23}GeV

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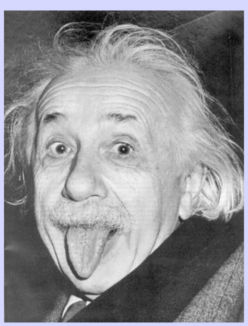
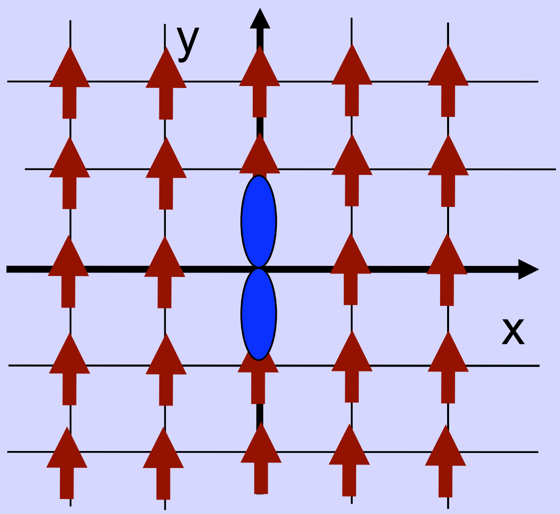
2. What is Lorentz violation?

Under the particle (active) Lorentz Transformation;

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





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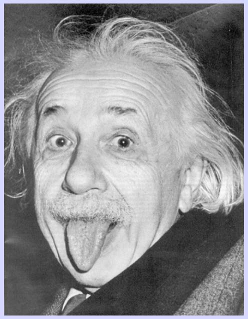
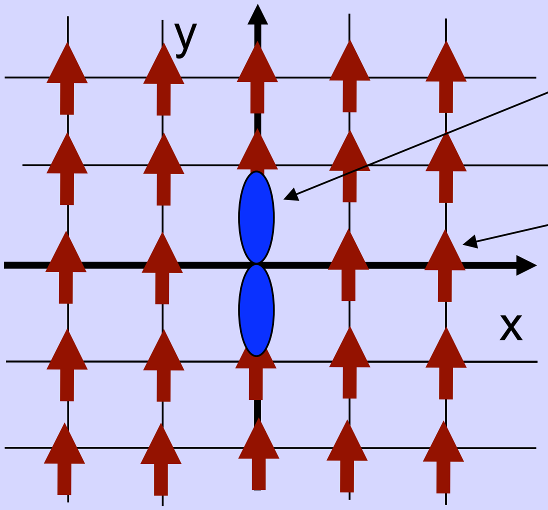
Under the particle (active) Lorentz Transformation;

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

Einstein
(observer)

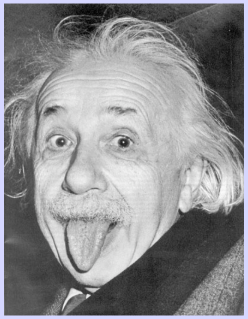


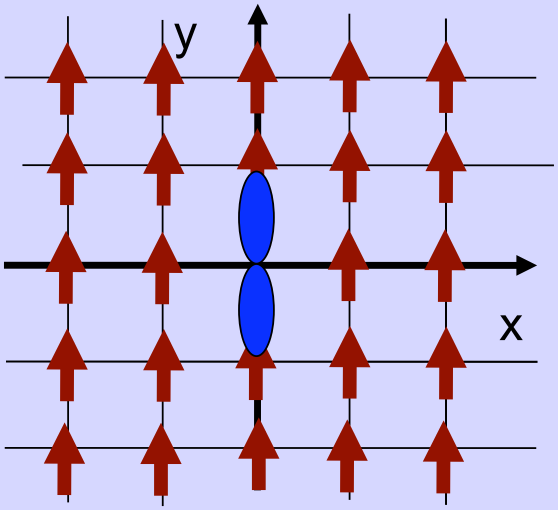


2. What is Lorentz violation?

Under the particle (active) Lorentz Transformation;

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





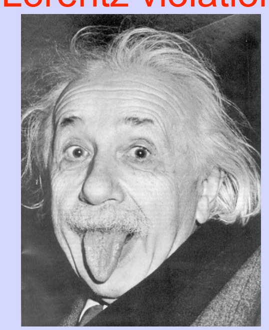
2. What is Lorentz violation?

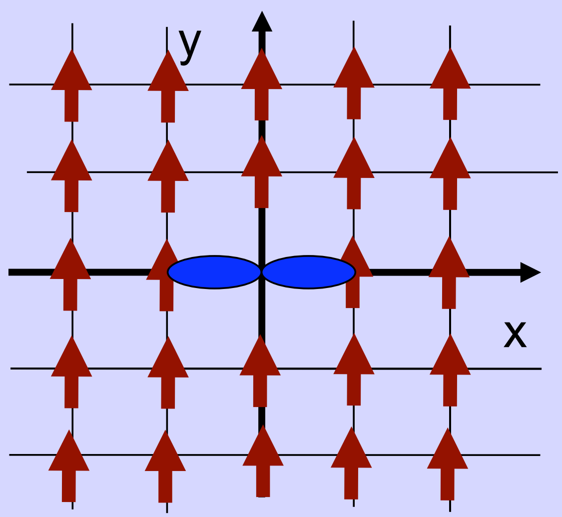
Under the particle (active) Lorentz Transformation;

$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$
$$= [U\overline{\Psi}(x)U^{-1}][U\gamma_\mu U^{-1}][Ua^\mu U^{-1}][U\Psi(x)U^{-1}]$$
$$= [\overline{\Psi}(\Lambda x)S^{-1}][(\Lambda)^\lambda_\mu \gamma_\lambda]\cdot a^\mu \cdot [S\Psi(\Lambda x)]$$
$$= \overline{\Psi}(\Lambda x)[(\Lambda)^\lambda_\mu \gamma_\lambda]\cdot a^\mu \cdot \Psi(\Lambda x)$$

by definition, "a" is insensitive to active transformation law

Lorentz violation!



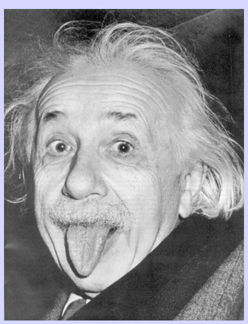


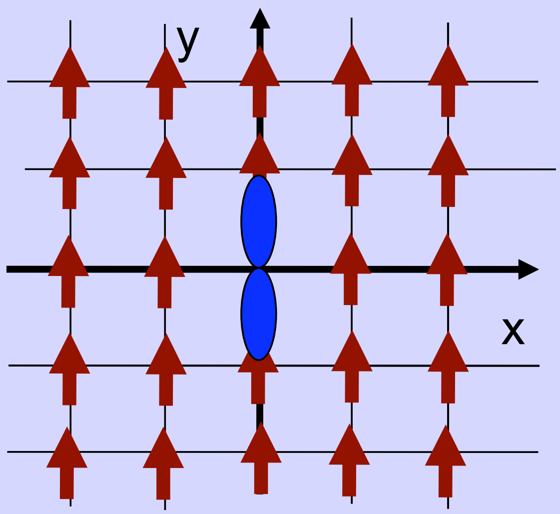
Lorentz violation is observable when particle is moving in the fixed coordinate space

2. What is Lorentz violation?

Under the observer (passive) Lorentz Transformation;

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



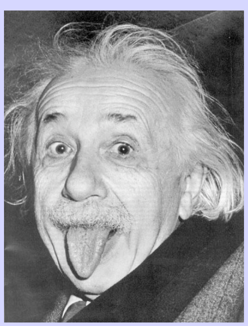


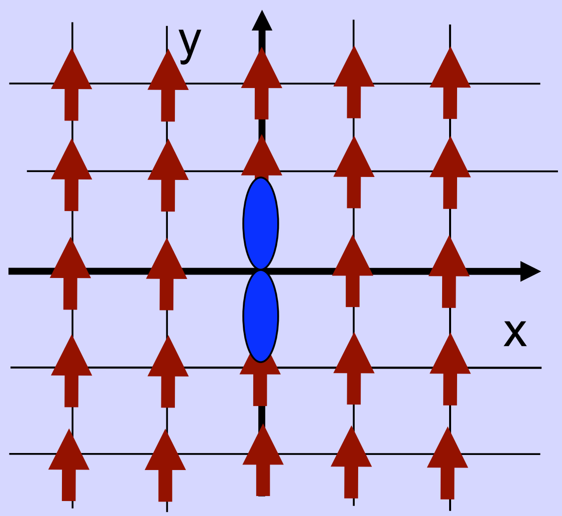
2. What is Lorentz violation?

Under the observer (passive) Lorentz Transformation;

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

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





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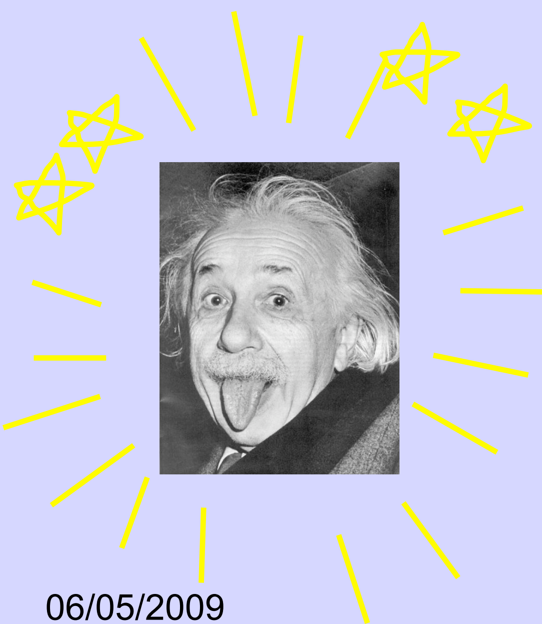
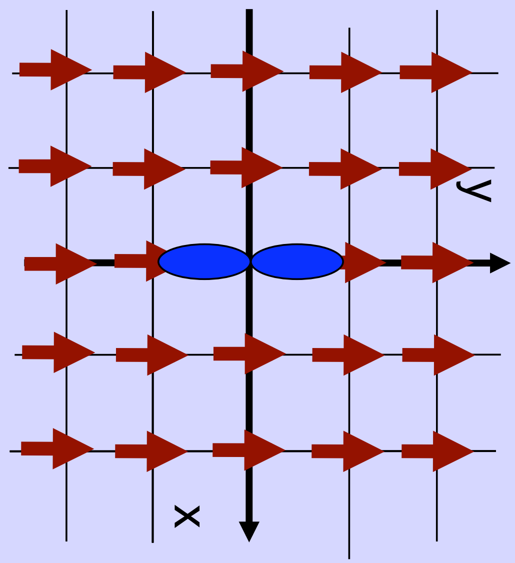
Under the observer (passive) Lorentz Transformation;

$$\overline{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x) \to [\overline{\Psi}(\Lambda^{-1}x)S^{-1}][(\Lambda^{-1})^{\lambda}_{\ \mu}\gamma_{\lambda}][\Lambda^{\mu}_{\ \sigma}a^{\sigma}][S\Psi(\Lambda^{-1}x)]$$

$$= \overline{\Psi}(\Lambda^{-1}x)\gamma_{\sigma}a^{\sigma}\Psi(\Lambda^{-1}x)$$





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

any observers agree for all observations

2. What is Lorentz violation?

FAQ

Q. What is Lorentz violation?

A. Lorentz violation is the violation of the particle Lorentz transformation, either Lorentz boost or rotation, and the observer Lorentz transformation is unbroken.

all observers agree with the particle Lorentz transformation violation phenomena through observer Lorentz transformation.

1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz violation?

3. What is CPT violation?

4. Standard Model Extension (SME)

5. Modern tests of Lorentz and CPT violation

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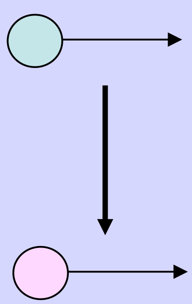
3. What is CPT violation?

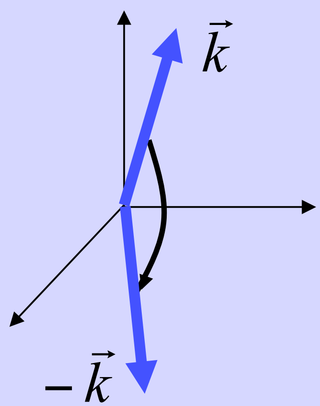
CPT symmetry is the invariance under the CPT transformation

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

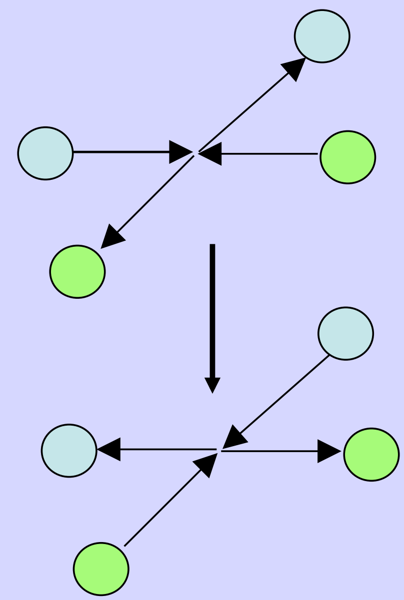
C: charge conjugation



P: parity transformation



T: time reversal



3. What is CPT violation?

CPT symmetry is the invariance under the CPT transformation

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

CPT violation happens when

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

3. What is CPT violation?

CPT violation doesn't mean CPT operator is broken.

ex) parity violation for weak current

$$J \sim \overline{\psi}(\gamma_\mu - \gamma_\mu \gamma_5)\psi \ldots$$

under the parity transformation

$$\gamma_\mu \xrightarrow{P} P\gamma_\mu P^{-1} = -\gamma_\mu \qquad \gamma_\mu \gamma_5 \xrightarrow{P} P\gamma_\mu \gamma_5 P^{-1} = \gamma_\mu \gamma_5$$

therefore, the current is not invariant under the parity transformation

$$J \xrightarrow{P} J \sim \overline{\psi}(\gamma_\mu + \gamma_\mu \gamma_5)\psi \ldots$$

It doesn't mean parity operator P is broken. It just means this combination cannot be invariant under the parity transformation, because each term change its sign differently.

3. What is CPT violation?

Similarly, we don't want to break CPT operator, but just make Lagrangian not CPT invariant.

ex) QED Lagrangian

$$L = i\overline{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\overline{\psi}\psi + ie\overline{\psi}\gamma_{\mu}A^{\mu}\psi \ldots$$

$$L \xrightarrow{CPT} L' = \Theta[i\overline{\psi}\gamma_{\mu}\partial^{\mu}\psi]\Theta^{-1} - \Theta[m\overline{\psi}\psi]\Theta^{-1} + \Theta[ie\overline{\psi}\gamma_{\mu}A^{\mu}\psi]\Theta^{-1} \ldots = L?$$

What is the transformation law of each term?

3. What is CPT violation?

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What is the transformation law of each term?

...is give by CPT theorem

CPT theorem guarantees all Lorentz invariant terms gives phase +1 (CPT-even), because there are always even number of active Lorentz indices.

$$(-1)^{2n} = +1 \qquad \Rightarrow \qquad L \xrightarrow{CPT} L' = L$$

3. What is CPT violation?

Similarly, we don't want to break CPT operator, but just make Lagrangian not CPT invariant.

ex) QED Lagrangian with Lorentz violating terms

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

$$L \xrightarrow{CPT} L' = \Theta[i\bar{\psi}\gamma_\mu \partial^\mu \psi]\Theta^{-1} - \Theta[m\bar{\psi}\psi]\Theta^{-1} + \Theta[ie\bar{\psi}\gamma_\mu A^\mu \psi]\Theta^{-1} \ldots \neq L$$

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$$(-1)^{2n} = +1 \qquad \Rightarrow \qquad L \xrightarrow{CPT} L' = L$$

when you have odd number of particle Lorentz violating indices, CPT violation happens

$$(-1)^{2n+1} = -1 \qquad \Rightarrow \qquad L \xrightarrow{CPT} L' \neq L$$

There are 2 types of Lorentz violation,

CPT-odd Lorentz violating term (odd number Lorentz indices, ex., a^μ , $g^{\lambda\mu\nu}$)

CPT-even Lorentz violating term (even number Lorentz indices, ex., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

3. What is CPT violation?

FAQ

Q. What is CPT theorem?

A. CPT theorem guarantees all terms in the Lagrangian are CPT-even.
Greenberg,hep-ph/0309309 "Why is CPT fundamental?"

Q. What is CPT violation?

A. CPT violation can happen when Lagrangian has CPT-odd term. The particle mass and the antiparticle mass don't need to be different.

Q. What is the relationship of Lorentz violation and CPT violation?

A. There are 2 types of Lorentz violation,

CPT-odd Lorentz violating term (odd number Lorentz indices)
CPT-even Lorentz violating term (even number Lorentz indices)

CPT-odd term violates CPT, but CPT-even term keeps CPT symmetry. Note CPT violation implies Lorentz violation in interactive quantum field theory.

Greenberg
PRL(2002)231602

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4. Standard Model Extension (SME)

How to detect Lorentz violation?

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

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

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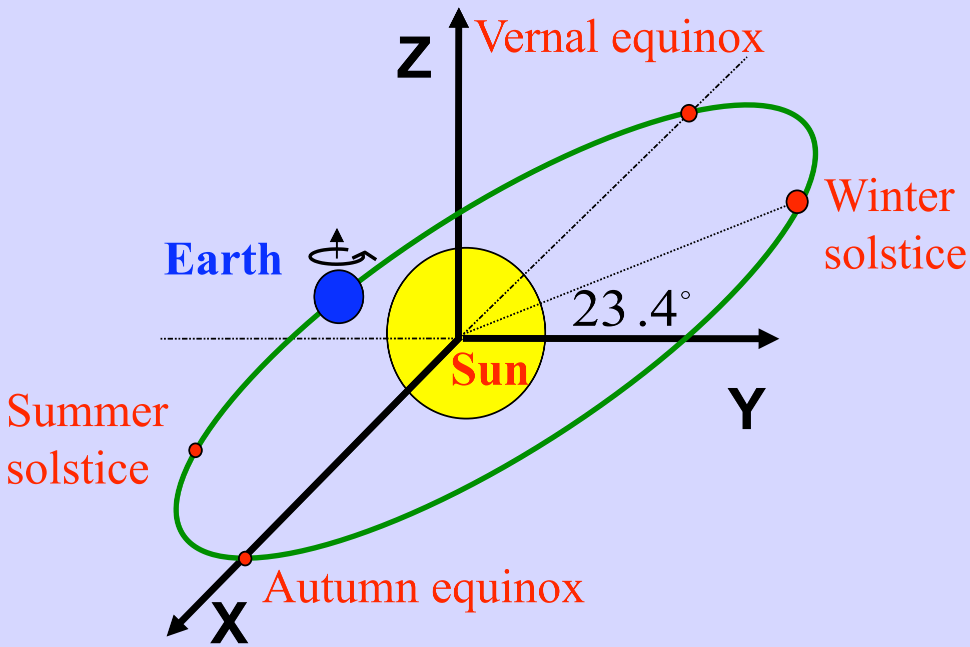
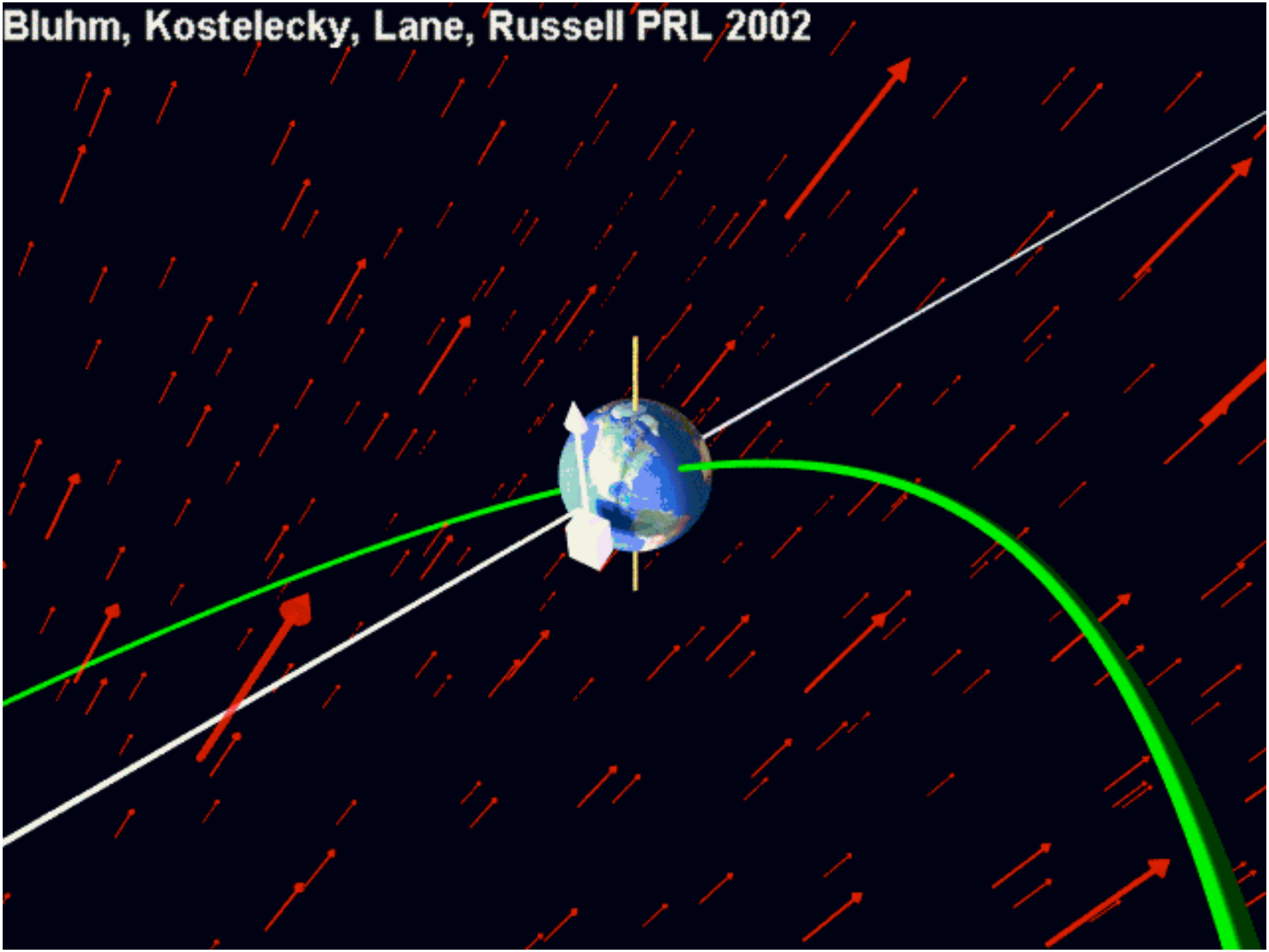
The standard choice of the coordinate is Sun centred coordinate system




Bluhm, Kostelecky, Lane, Russell PRL 2002

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(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

As a standard formalism for the general search of Lorentz violation, Standard Model Extension (SME) is widely used in the community. SME is self-consistent low-energy effective theory with Lorentz and CPT violation within conventional QM (minimum extension of QFT with Particle Lorentz violation)

Colladay and Kostelecky
PRD55(1997)6760;58(1998)116002

4. Standard Model Extension (SME)

ex) minimal SME formalism for neutrino

Modified Dirac Equation (MDE)

$$i(\Gamma^{\nu}_{AB}\partial_{\nu} - M_{AB})\nu_{B} = 0$$

SME parameters

$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_{\mu} + d^{\mu\nu}_{AB}\gamma_{\mu}\gamma_{5} + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_{5} + \frac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu}$$

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

Direction dependence
Hamiltonian with SME parameters has direction dependent physics, so, it is important to fix the coordinate system to describe the effect

$c^{\mu\nu}_{AB}$ ← 4X4 Lorentz indices ← 6X6 flavor indices

Lorentz and CPT violating term
$a^{\mu}, b^{\mu}, e^{\mu}, f^{\mu}, g^{\mu\nu\lambda}$

Lorentz violating term
$c^{\mu\nu}, d^{\mu\nu}, H^{\mu\nu}$

SU(3)XSU(2)XU(1) gauge invariance violating term
$g^{\mu\nu\lambda}, H^{\mu\nu}$

Kostelecky and Mewes
PRD69(2004)016005

4. Standard Model Extension (SME)

How to detect Lorentz violation?

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

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

The observables can be, energy spectrum, frequency of atomic transition, number of oscillated neutrinos, etc. Among the non standard phenomena predicted by Lorentz violation, the smoking gun is the sidereal time dependence of the observables.

ex) Sidereal variation of LSND signal

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

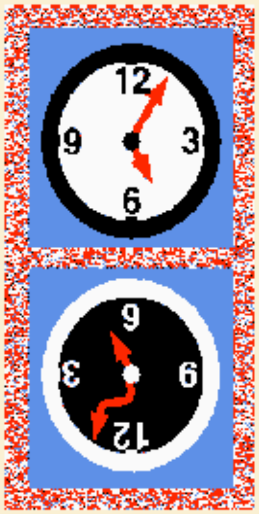
sidereal frequency $w_\oplus = \dfrac{2\pi}{23h56m4.1s}$

sidereal time $T_\oplus$

Kostelecky and Mewes
PRD70(2004)076002

5. Modern tests of Lorentz violation

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



Meeting home

Registration

Program

Proceedings

Travel

Accommodations

Very focused group of people starts to meet since 1998.

MEETING ON
CPT AND LORENTZ SYMMETRY

November 6 - 8, 1998

Physics Department
Indiana University, Bloomington

A meeting on CPT and Lorentz symmetry will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on November 6 - 8, 1998. The meeting will focus on recent developments involving tests of these fundamental symmetries, including both experimental and theoretical aspects.

Topics to be covered include:

- experimental bounds on CPT and Lorentz symmetry from
  - measurements on K, B, and D mesons
  - precision comparisons of particle and antiparticle properties (anomalous moments, charge-to-mass ratios, lifetimes, etc.)
  - spectroscopy of hydrogen and antihydrogen
  - clock-comparison tests
  - properties of light
  - other tests
- theoretical descriptions of and constraints on possible violations

5. Modern tests of Lorentz violation

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

Topics:

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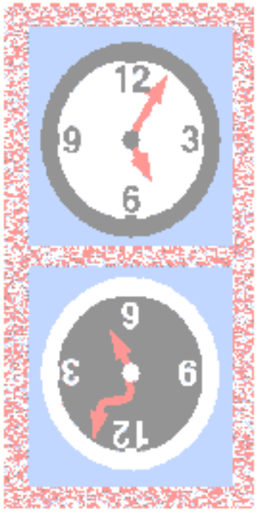

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  - other tests
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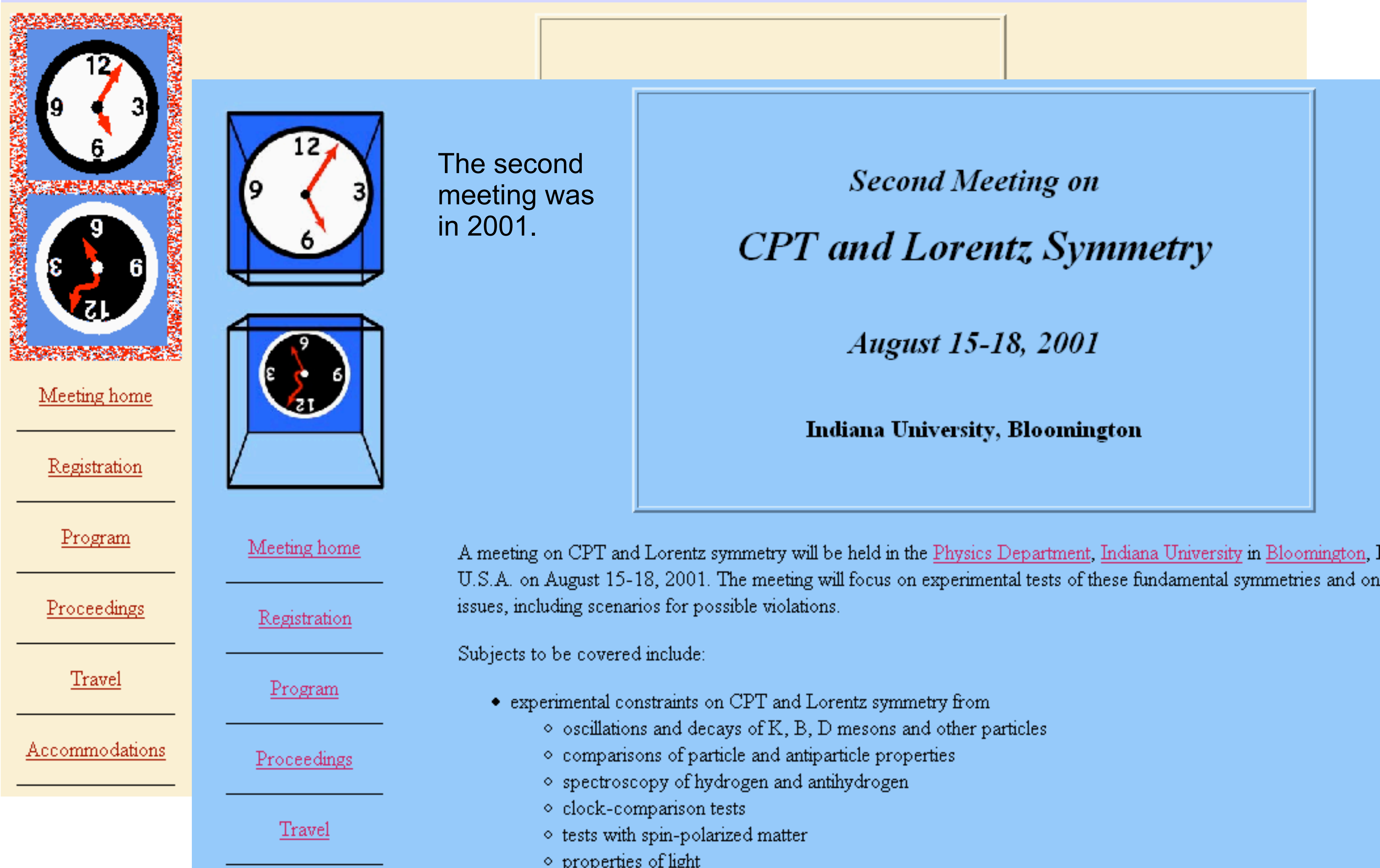
5. Modern tests of Lorentz violation

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



Meeting home

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Travel

Accommodations

The second meeting was in 2001.

Meeting home

Registration

Program

Proceedings

Travel

Second Meeting on

CPT and Lorentz Symmetry

August 15-18, 2001

Indiana University, Bloomington

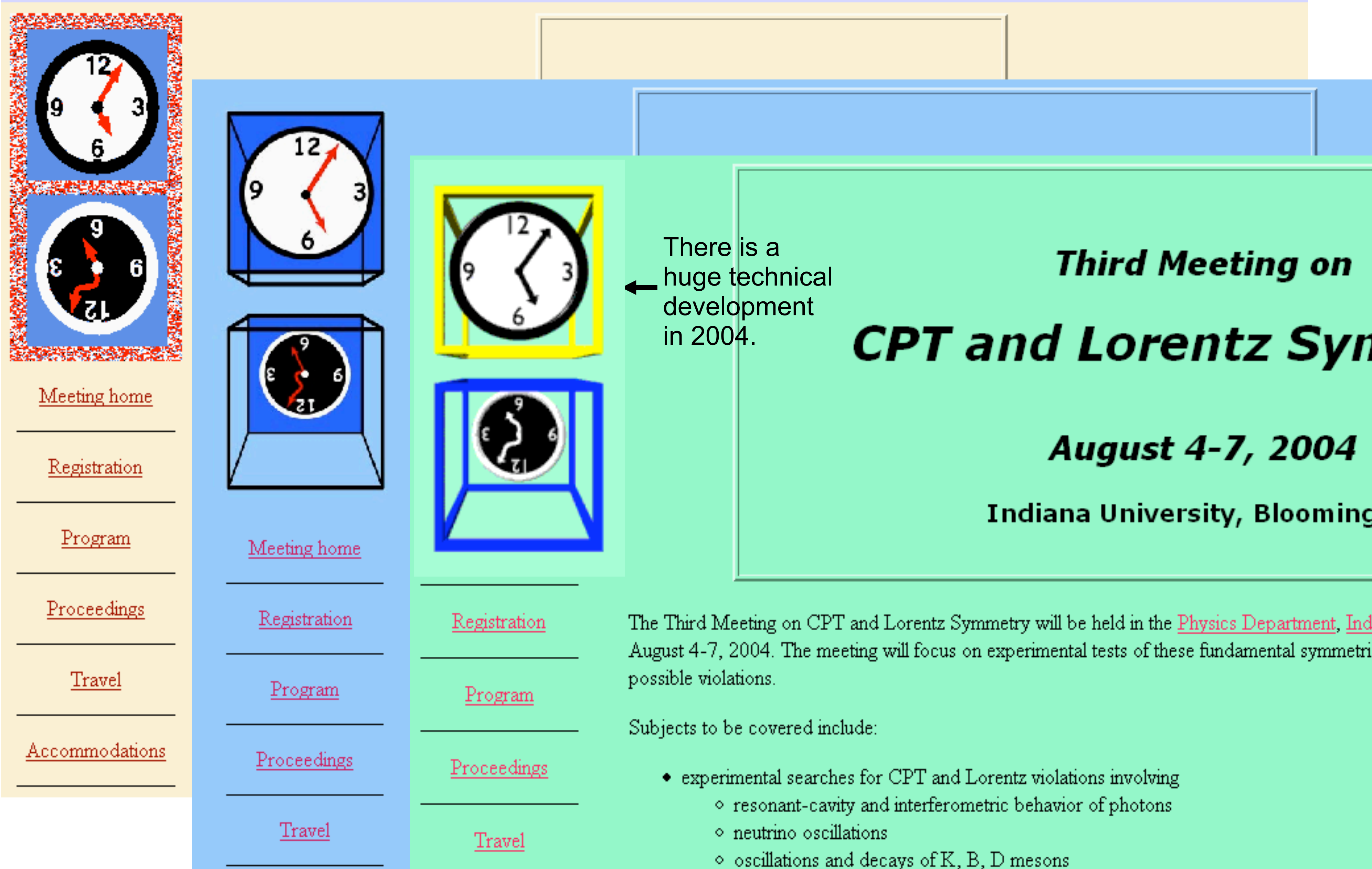
A meeting on CPT and Lorentz symmetry will be held in the Physics Department, Indiana University in Bloomington, I U.S.A. on August 15-18, 2001. The meeting will focus on experimental tests of these fundamental symmetries and on issues, including scenarios for possible violations.

Subjects to be covered include:

- experimental constraints on CPT and Lorentz symmetry from
  - oscillations and decays of K, B, D mesons and other particles
  - comparisons of particle and antiparticle properties
  - spectroscopy of hydrogen and antihydrogen
  - clock-comparison tests
  - tests with spin-polarized matter
  - properties of light

5. Modern tests of Lorentz violation

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



5. Modern tests of Lorentz violation

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

Meeting home

Registration

Program

Proceedings

Travel

Accommodations

The latest meeting was in summer 2007.

Fourth Meeting on

CPT and Lorentz Symmetry

August 8-11, 2007

Indiana University, Bloomington

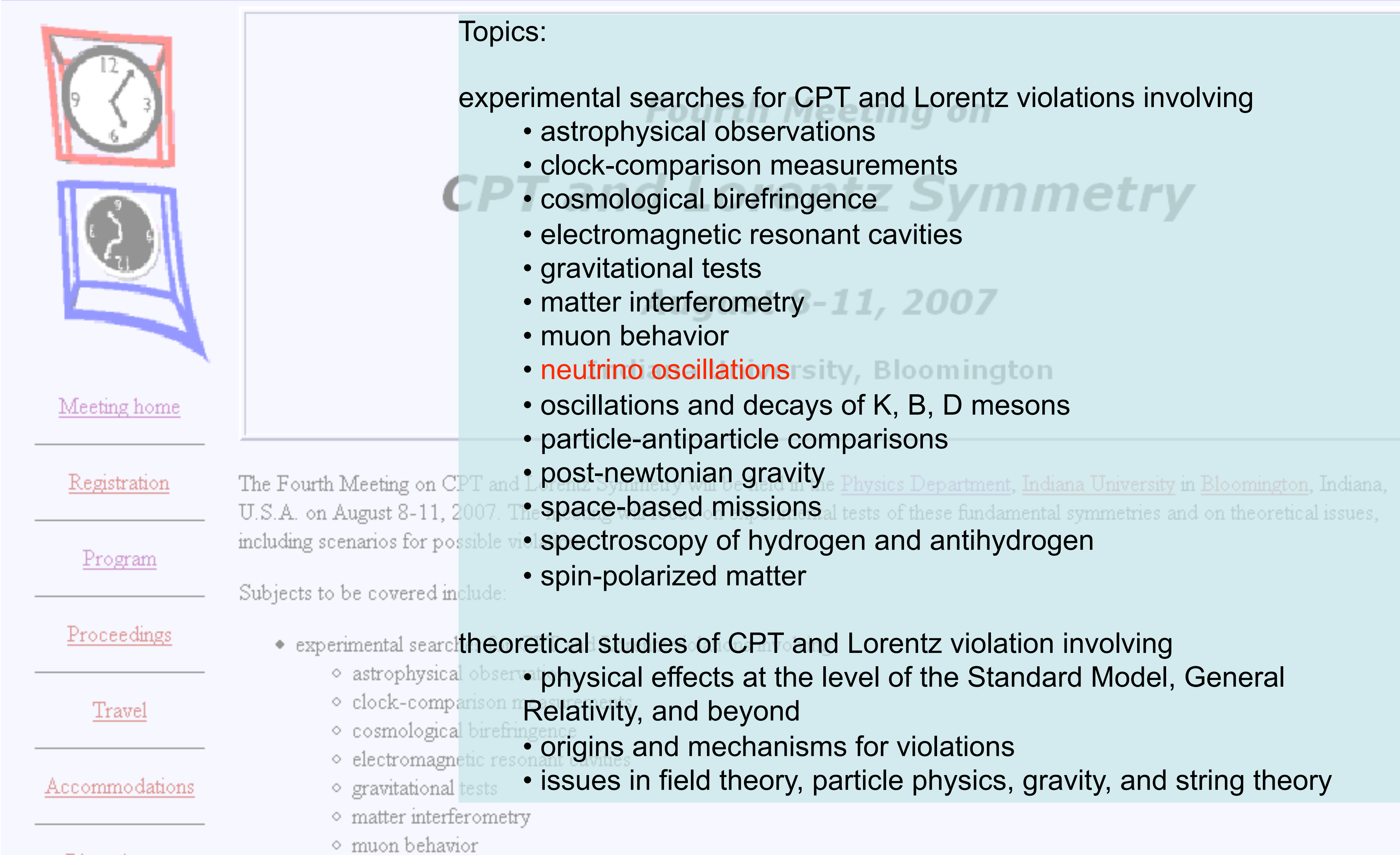
The Fourth Meeting on CPT and Lorentz Symmetry will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on August 8-11, 2007. The meeting will focus on experimental tests of these fundamental symmetries and on theoretical issues, including scenarios for possible violations.

Subjects to be covered include:

- experimental searches for CPT and Lorentz violations involving
  - astrophysical observations
  - clock-comparison measurements
  - cosmological birefringence
  - electromagnetic resonant cavities
  - gravitational tests
  - matter interferometry
  - muon behavior

5. Modern tests of Lorentz violation

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



Topics:

experimental searches for CPT and Lorentz violations involving

- astrophysical observations
- clock-comparison measurements
- cosmological birefringence
- electromagnetic resonant cavities
- gravitational tests
- matter interferometry
- muon behavior
- neutrino oscillations
- oscillations and decays of K, B, D mesons
- particle-antiparticle comparisons
- post-newtonian gravity
- 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
- issues in field theory, particle physics, gravity, and string theory

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

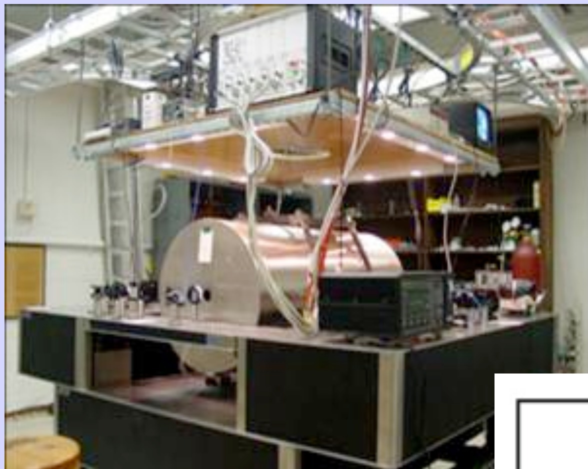
Astrophysics

Particle accelerator

Meson sector

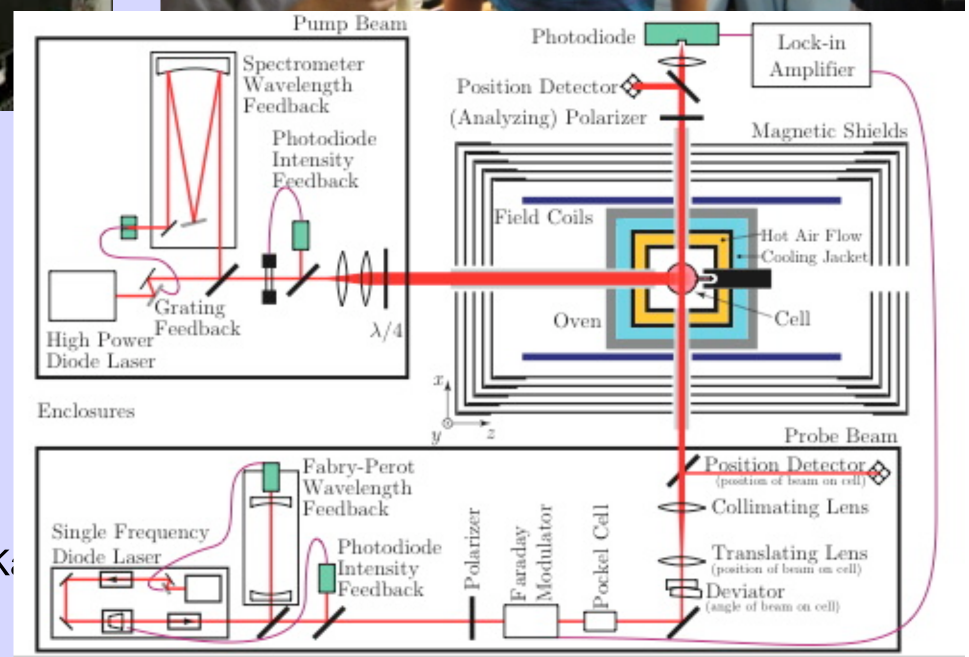
Neutrino sector

co-magnetometer



Mike Romalis (Princeton)

Ron Walsworth (Harvard-Smithsonian)



Double gas meser

b_n(rotation)<10^{-32}GeV

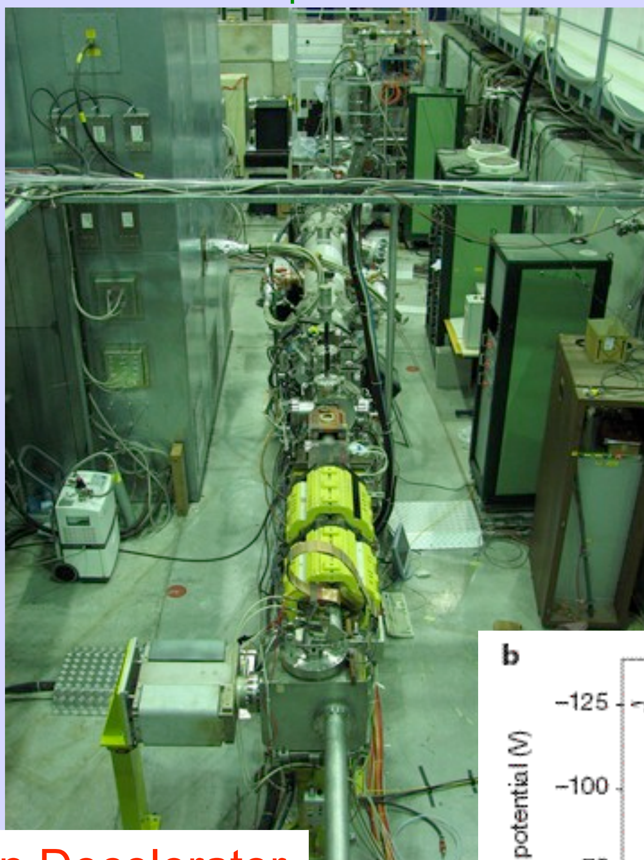
b_n(boost)<10^{-27}GeV

Walsworth et al.
PRL93(2004)230801

5. Modern tests of Lorentz violation

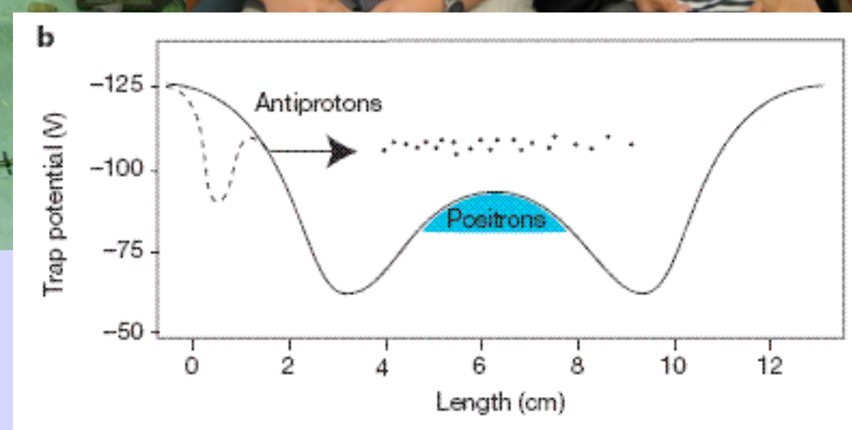
- Neutron/proton sector
- **Direct CPT test**
- Photon sector
- Electron sector
- Gravity sector
- Astrophysics
- Particle accelerator
- Meson sector
- Neutrino sector

ASACUSA experiment



Bertalan Juhasz (Stefan Meyer Institute)

Ryogo Hayano (Tokyo)



CERN Antiproton Decelerator

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

ATHENA collaboration
Nature419(2002)456

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

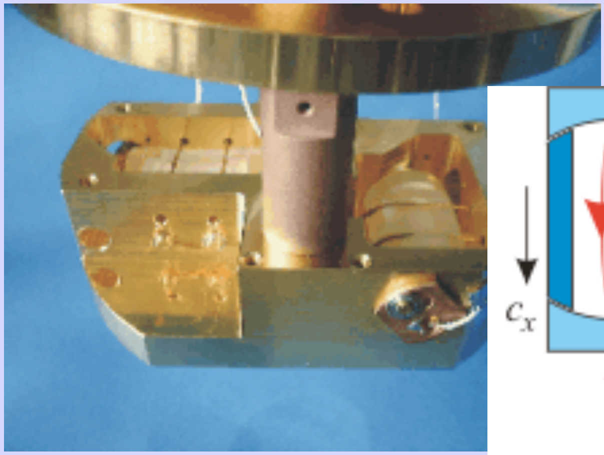
Astrophysics

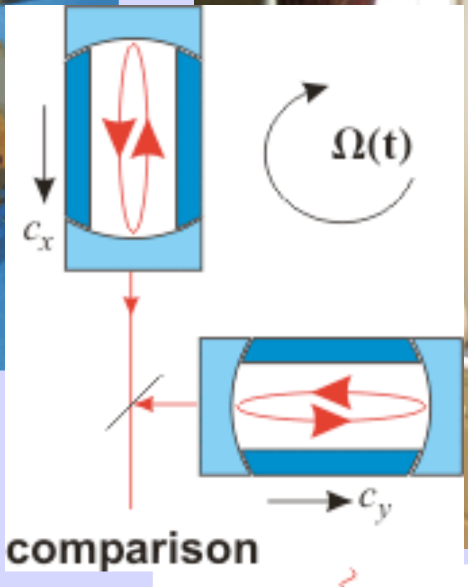
Particle accelerator

Meson sector

Neutrino sector

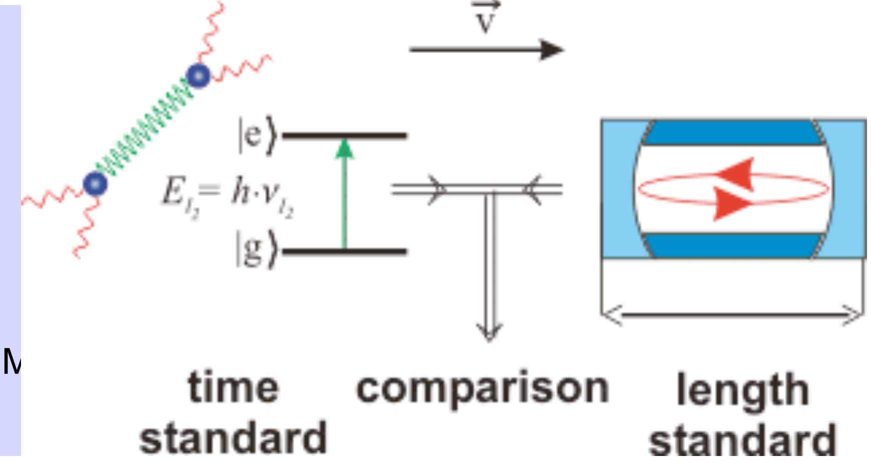
crystalline sapphire resonator





Achim Peters (Humboldt)

Mike Tobar (Western Australia)



Cryogenic optical resonator
$\Delta c/c < 10^{-16}$
($\Delta c/c < 10^{-9}$ for M-M expt.)

Peters et al.
PRL99(2007)050401

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

Particle accelerator

Meson sector

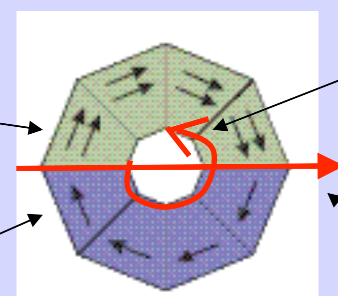
Neutrino sector

spin-pendulum

Blayne Heckel
(Washington)

Alnico
μ ~ e-spin

total μ = 0



SmCo
μ ~ e-spin + e-orbit

net spin $\neq$ 0

Spin pendulum
$b_e < 10^{-30}$ GeV

Heckel et al.
PRL97(2006)021603

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

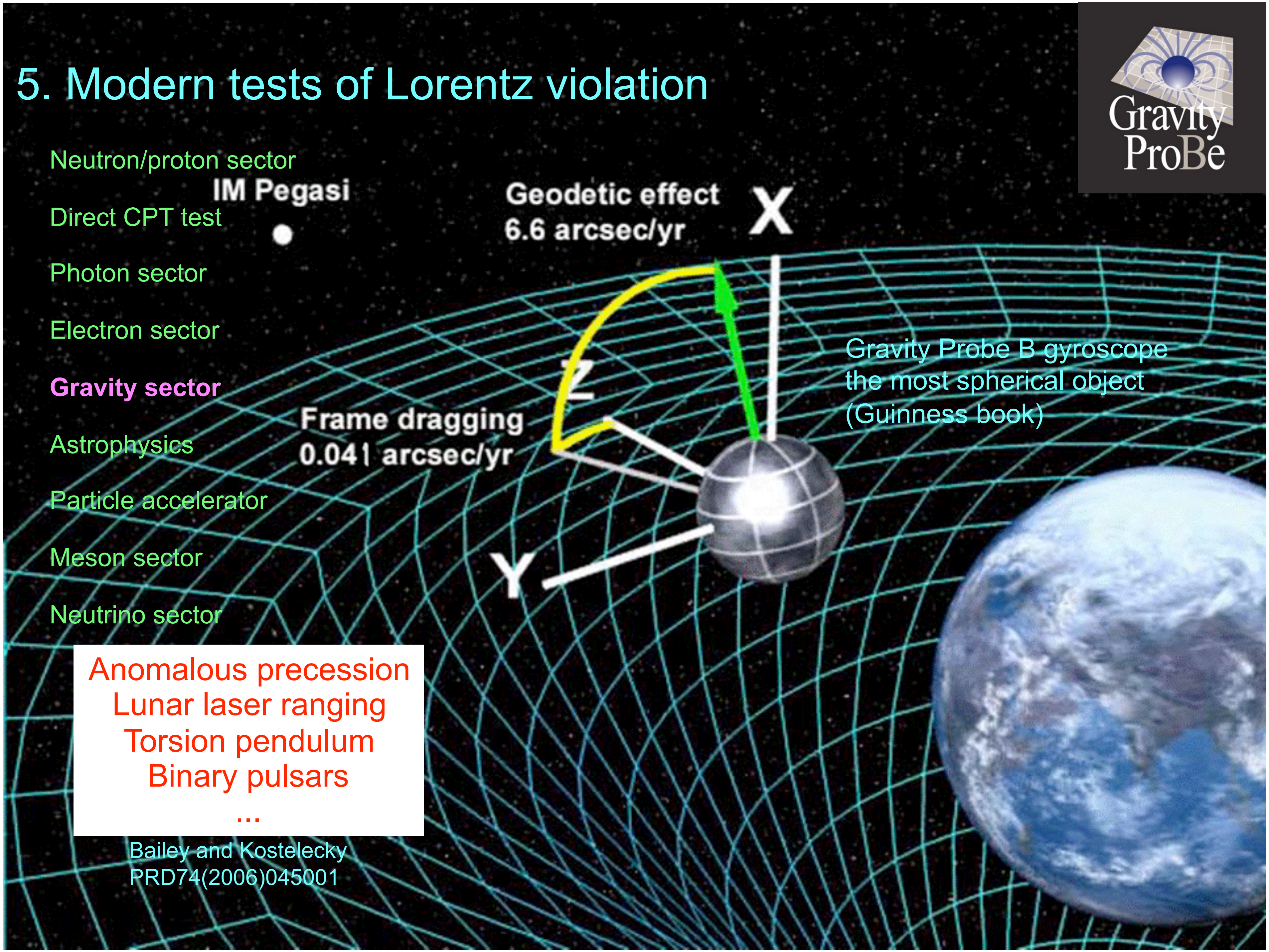
Gravity sector

Astrophysics

Particle accelerator

Meson sector

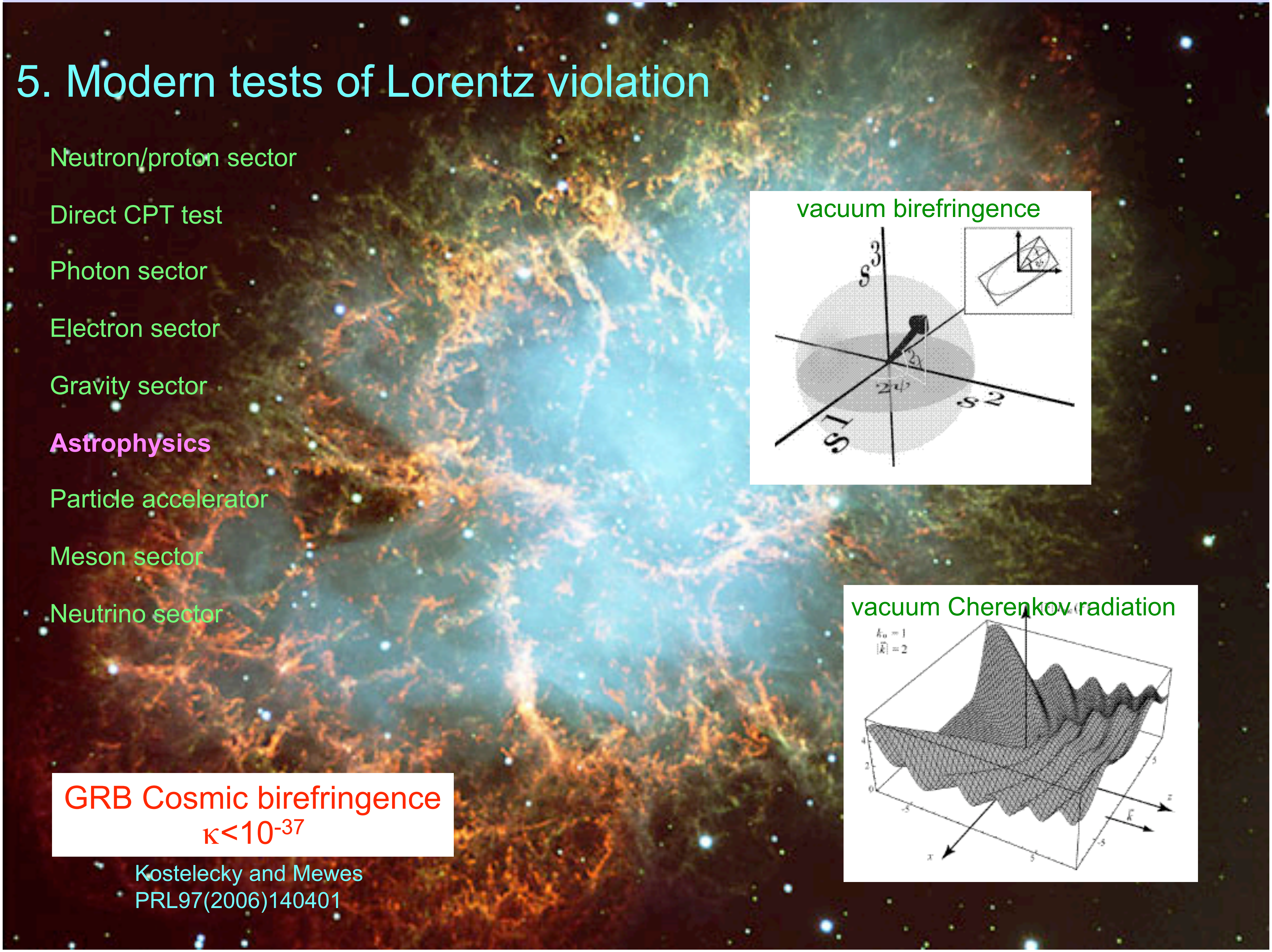
Neutrino sector



Gravity Probe B gyroscope
the most spherical object
(Guinness book)

Anomalous precession
Lunar laser ranging
Torsion pendulum
Binary pulsars
...

Bailey and Kostelecky
PRD74(2006)045001



5. Modern tests of Lorentz violation
Neutron/proton sector
Direct CPT test
Photon sector
Electron sector
Gravity sector
Astrophysics
Particle accelerator
Meson sector
Neutrino sector
vacuum birefringence
vacuum Cherenkov radiation
GRB Cosmic birefringence
$\kappa < 10^{-37}$
Kostelecky and Mewes
PRL97(2006)140401

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

Particle accelerator

Meson sector

Neutrino sector

No vacuum Cerenkov radiation from the highest energy electrons at LEP constrains upper bound

The highest photon observed at D0 detector at Tevatron constrains lower bound

Fermilab

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

Hohensee et al.
arXiv:0904.2031

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

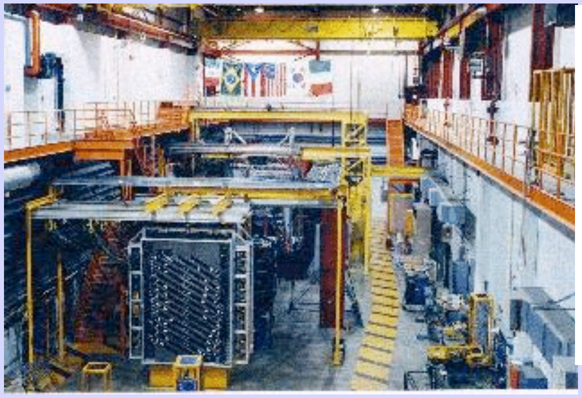
Astrophysics

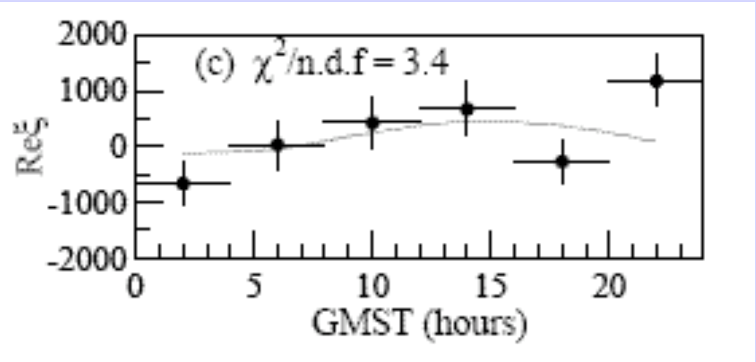
Particle accelerator

Meson sector

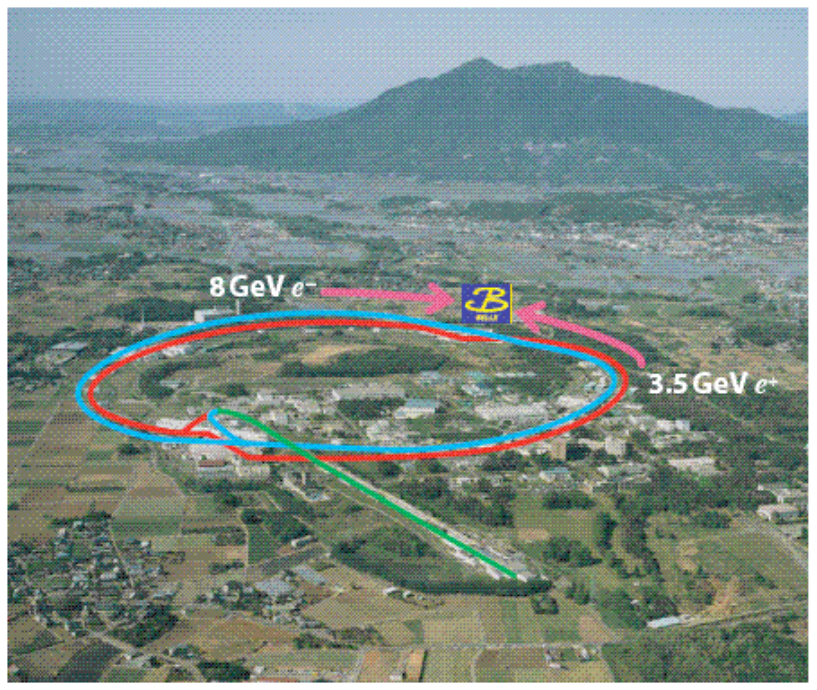
Neutrino sector

FOCUS and its data

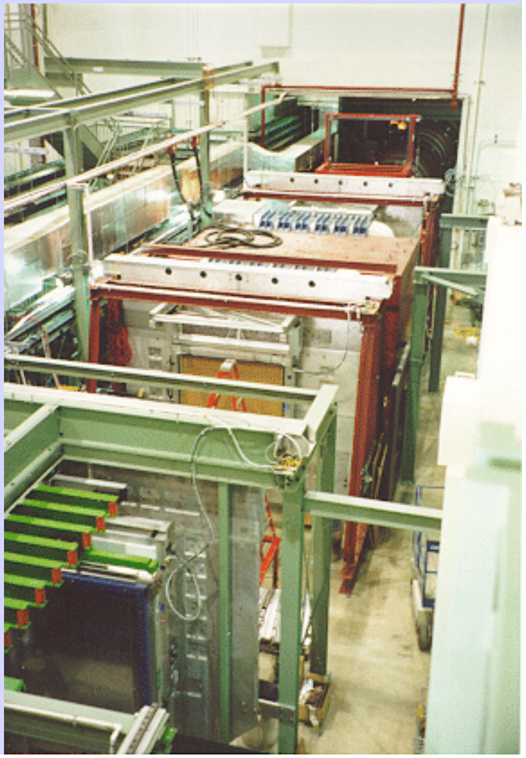




Belle



KTeV



KTeV (strange)
$\Delta a_K < 10^{-22}$ GeV
FOCUS (charm)
$\Delta a_D < 10^{-16}$ GeV
BaBar/Belle (bottom)
$\Delta m_B / m_B < 10^{-14}$

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

Particle accelerator

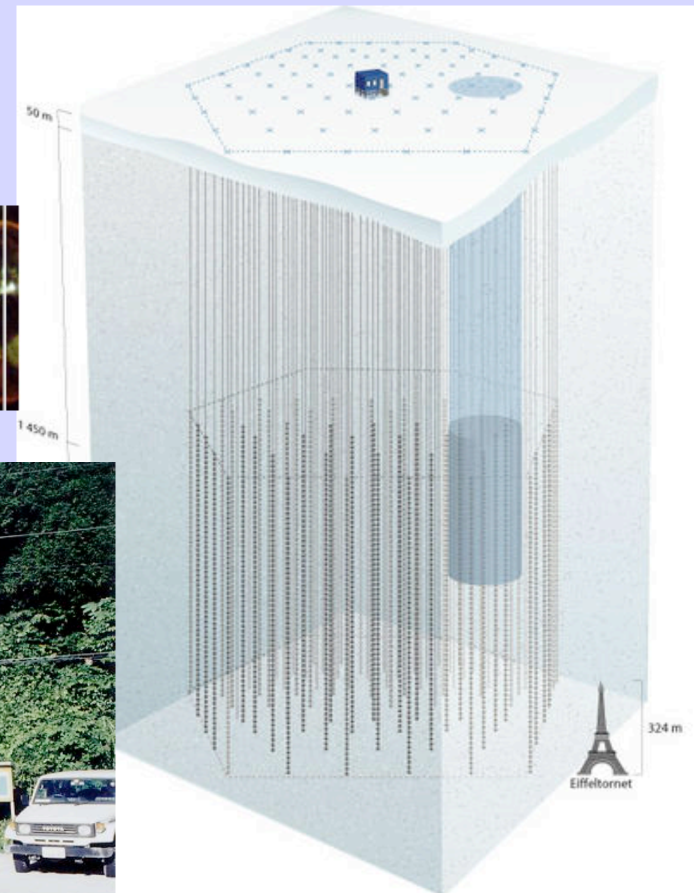
Meson sector

Neutrino sector

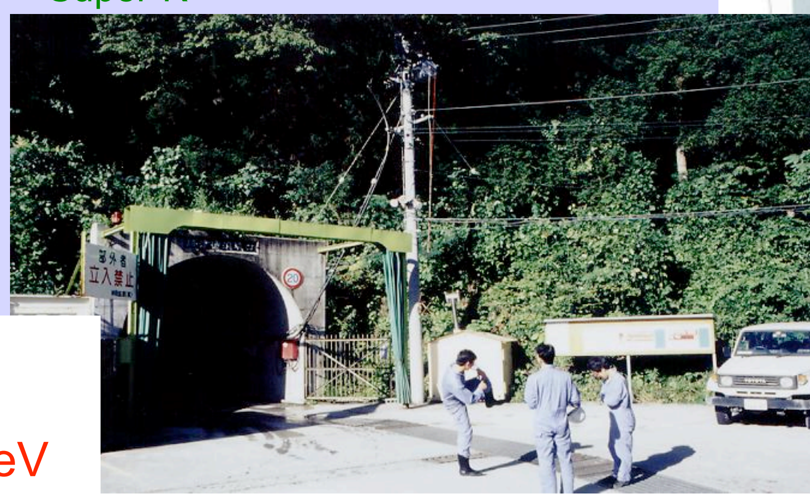
If, three neutrino massive model is correct, the deviation from standard Δm^2 can be understood as the upper limit of Lorenz violation

In this approach, longer baseline and higher energy neutrino experiments have more sensitivity

IceCube



Super-K



Kelly et al.,
PRD74(2008)046801

Super-K/IceCube
c(CPT-even)$<10^{-25}$
a(CPT-odd)$<10^{-23}$ GeV

5. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

Particle accelerator

Meson sector

Neutrino sector

However, Lorentz violation can mimic neutrino masses

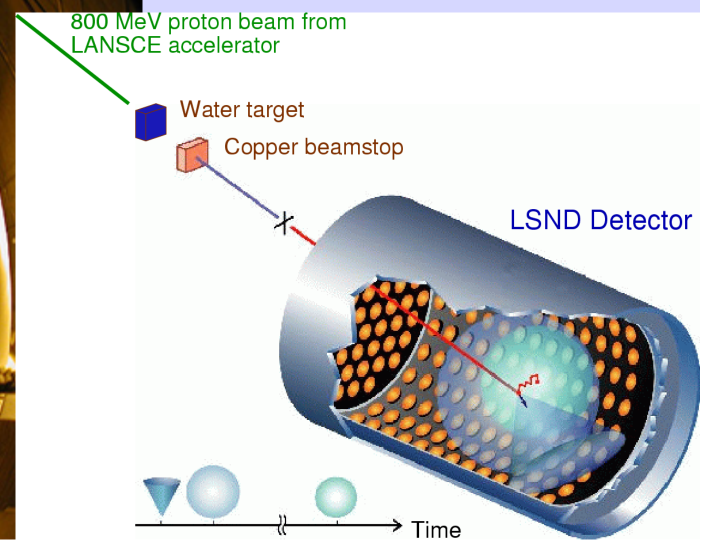
All signals which we are seeing, are perhaps Lorentz violation

In this approach, it is important to test Lorentz violation for neutrino signals from precise terrestrial experiments, such as SciBooNE, T2K, NOvA, Double Chooz etc

Later of my talk is based on this approach

MiniBooNE

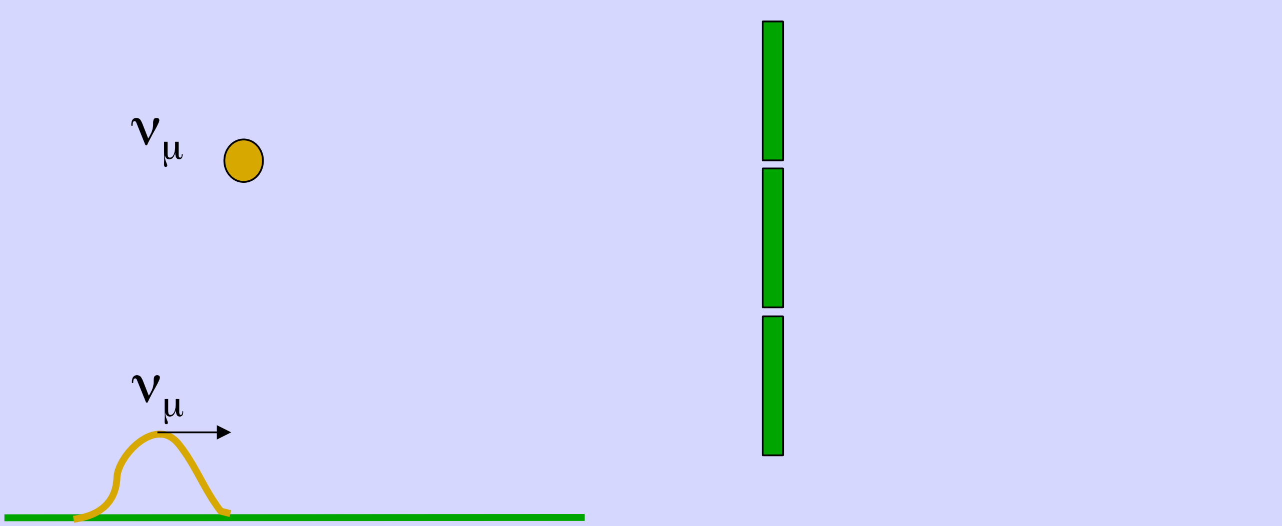
LSND



LSND
$a = 4.0 \pm 1.4 \times 10^{-19}$ GeV
MiniBooNE
??? (see next)

6. Lorentz violation with neutrino oscillation

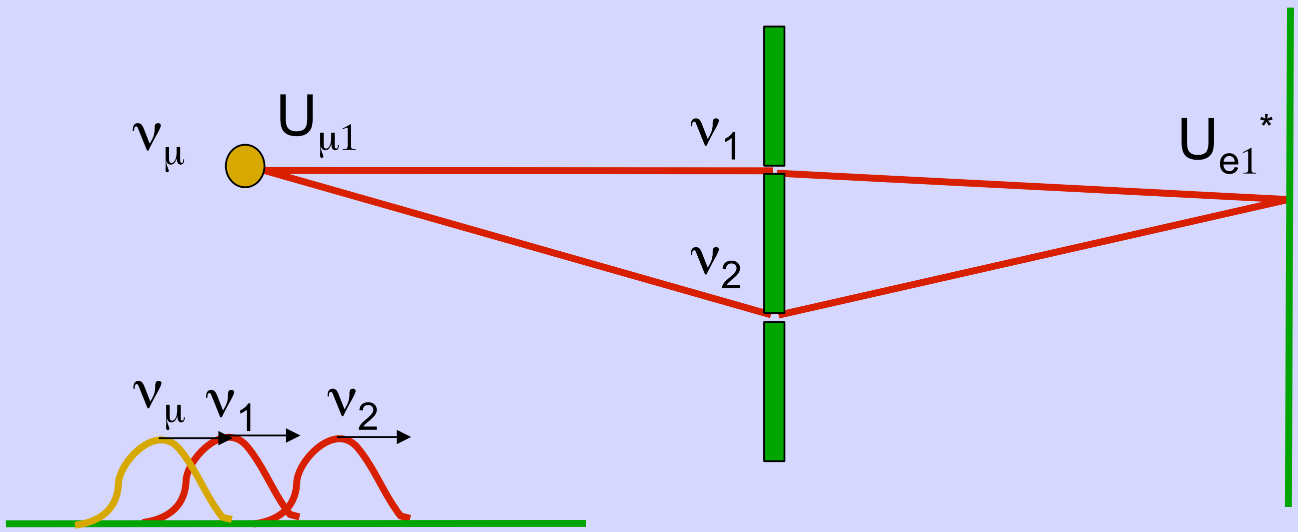
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

6. Lorentz violation with neutrino oscillation

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

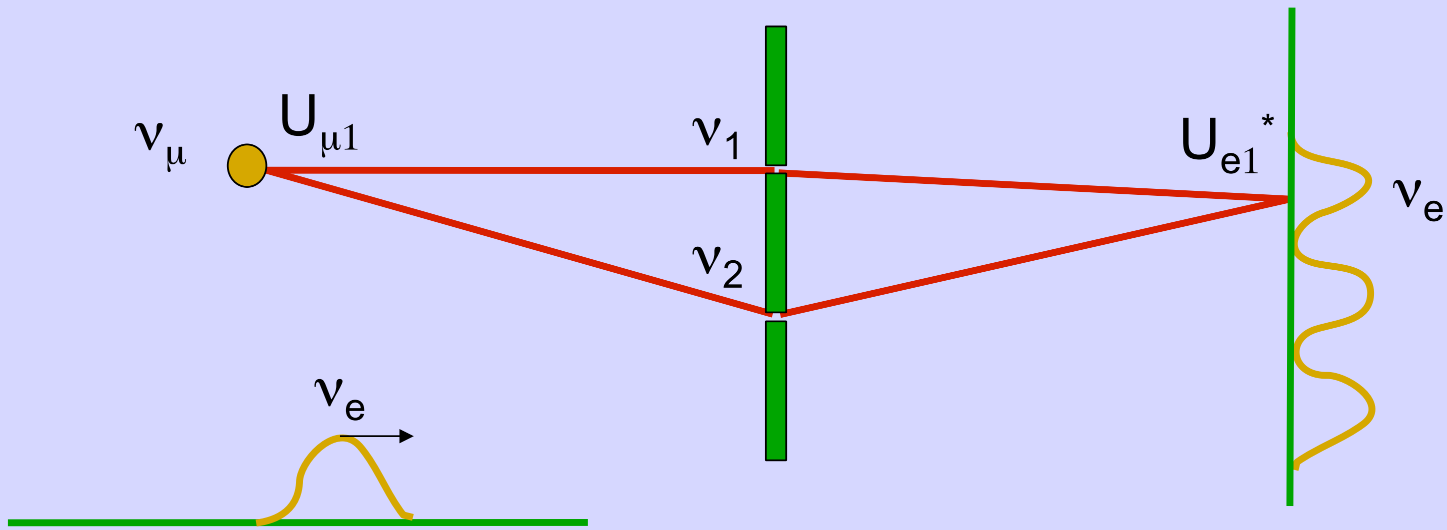


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different coupling with Lorentz violating field, interference fringe (oscillation pattern) depend on the sidereal motion.

6. 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.

If ν_1 and ν_2, have different coupling with Lorentz violating field, interference fringe (oscillation pattern) depend on the sidereal motion.

The measured scale of neutrino eigenvalue difference is comparable the target scale of Lorentz violation ($<10^{-19}$GeV).

6. Lorentz violation with neutrino oscillation

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1, ν_2, and ν_3 and Hamiltonian mixing matrix elements.

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1, ν_2, and ν_3.

$$|\nu_e(t)\rangle = \sum_{i=1}^{3} U_{ei} e^{-i\lambda_i t} |\nu_i\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is (assuming everything is real)

$$P_{\mu\to e}(t) = \left|\langle \nu_e(t) | \nu_\mu \rangle\right|^2 = -4\sum_{i>j}\left(U_{\mu i}U_{\mu j}U_{ei}U_{ej}\right)\sin^2\left(\frac{\Delta_{ij}}{2}L\right)$$

This formula is model independent

6. Lorentz violation with neutrino oscillation

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This formula is model independent

What is the signature of Lorentz violation in neutrino oscillation experiments?

6. Lorentz violation with neutrino oscillation

The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

Kostelecky and Mewes
PRD69(2004)016005

(1) Spectral anomalies
(2) L-E conflict
(3) Sidereal variation

6. Lorentz violation with neutrino oscillation

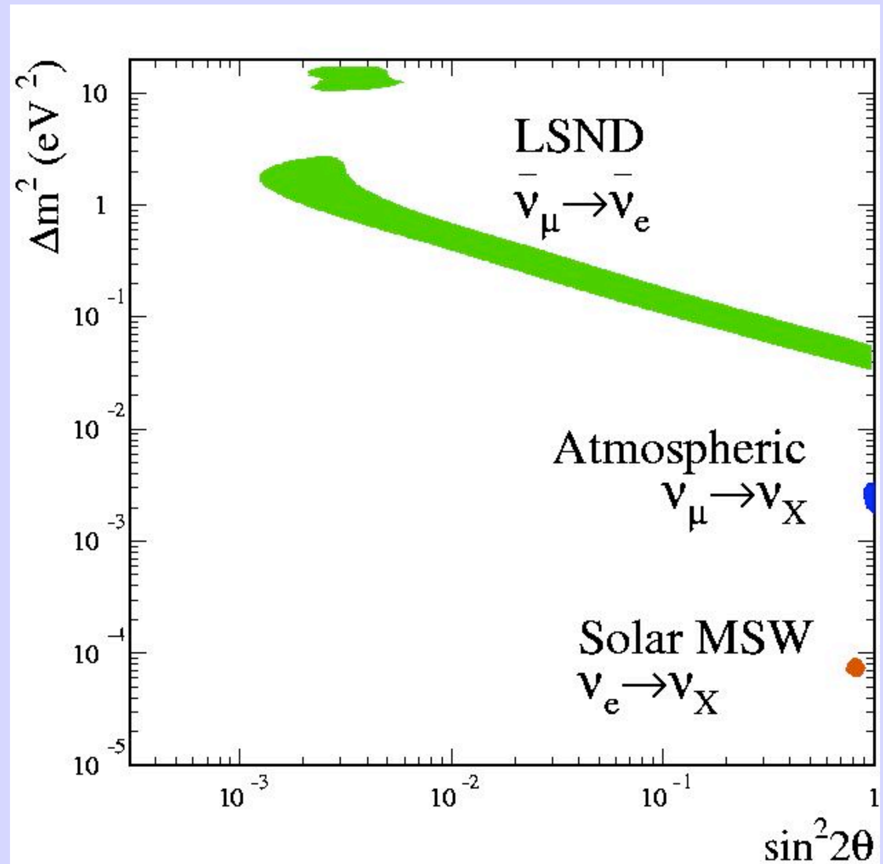
The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

Kostelecky and Mewes
PRD69(2004)016005

(1) Spectral anomalies
(2) L-E conflict
(3) Sidereal variation

Any signals cannot be mapped on Δm^2-$\sin^2 2\theta$ plane (MS-diagram) could be Lorentz violation, since under the Lorentz violation, MS diagram is no longer useful way to classify neutrino oscillations

LSND is the example of this class of signal.



6. Lorentz violation with neutrino oscillation

The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

Kostelecky and Mewes
PRD69(2004)016005

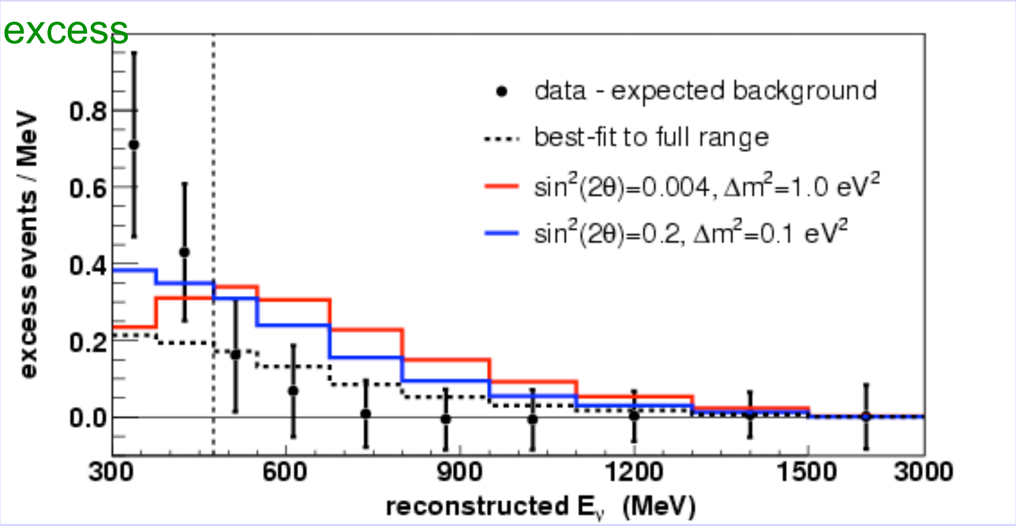
(1) Spectral anomalies
(2) L-E conflict
(3) Sidereal variation

Any signals do not have L/E oscillatory dependence could be Lorentz violation. Lorentz violating neutrino oscillation can have various type of energy dependences.

MiniBooNE has appearance signal in the low energy region, but any naive neutrino mass models (either sterile or active) cannot make the energy dependence right.

MiniBooNE signal falls into this class.

MiniBooNE low E ν_e excess



MiniBooNE collaboration
PRL98(2007)231801

usual term (3X3)

additional terms (3X3)

effective Hamiltonian
of neutrino oscillation

$$(h_{eff})_{ab} = \frac{1}{2E}(m^2)_{ab} + a_{ab} + c_{ab}E + \cdots$$

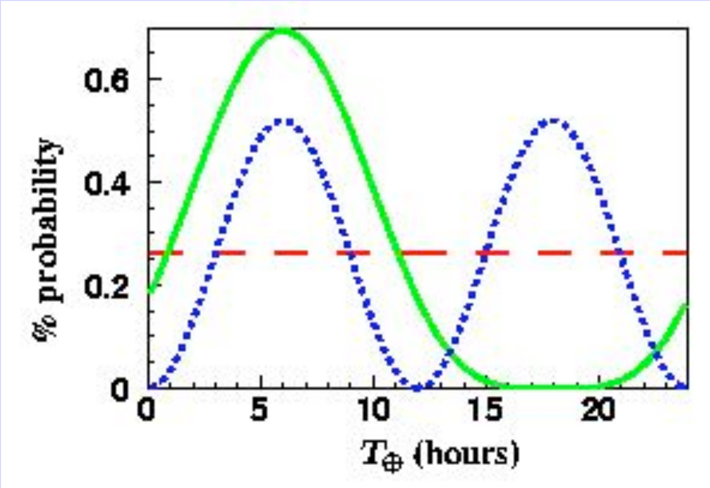
6. Lorentz violation with neutrino oscillation

The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

Kostelecky and Mewes
PRD69(2004)016005

(1) Spectral anomalies
(2) L-E conflict
(3) Periodic variation

example of sidereal variation for LSND signal



sidereal variation of the neutrino oscillation signal is the signal of Lorentz violation

This signal is the exclusive smoking gun of Lorentz violation.

6. Lorentz violation with neutrino oscillation

FAQ

Q.why neutrino oscillation is interesting for the test of Lorentz violation ?

A. Lorentz violation is not well-tested with neutrinos. Since neutrinos only feel weak force, they can avoid all constraints come from QED, and offers new possibilities to test Lorentz violation.

Q. Is neutrino oscillation sensitive enough to Lorentz violation?

A. The measured scale of neutrino eigenvalue difference is comparable size with high precision optical test, $\Delta m^2/E < 10^{-19}$GeV.

Very exciting LSND and MiniBooNE data give enough motivation to test Lorentz violation in neutrino physics, because Lorentz violation is the interesting candidate solution for the neutrino oscillation (see next).

1. Spontaneous Lorentz symmetry breaking
2. What is Lorentz violation?
3. What is CPT violation?
4. Standard Model Extension (SME)
5. Modern tests of Lorentz and CPT violation
6. Lorentz violation with neutrino oscillation
7. **Lorentz violation with LSND**
8. Global neutrino oscillation model, "Tandem" model
9. Lorentz violation with MiniBooNE
10. Conclusion

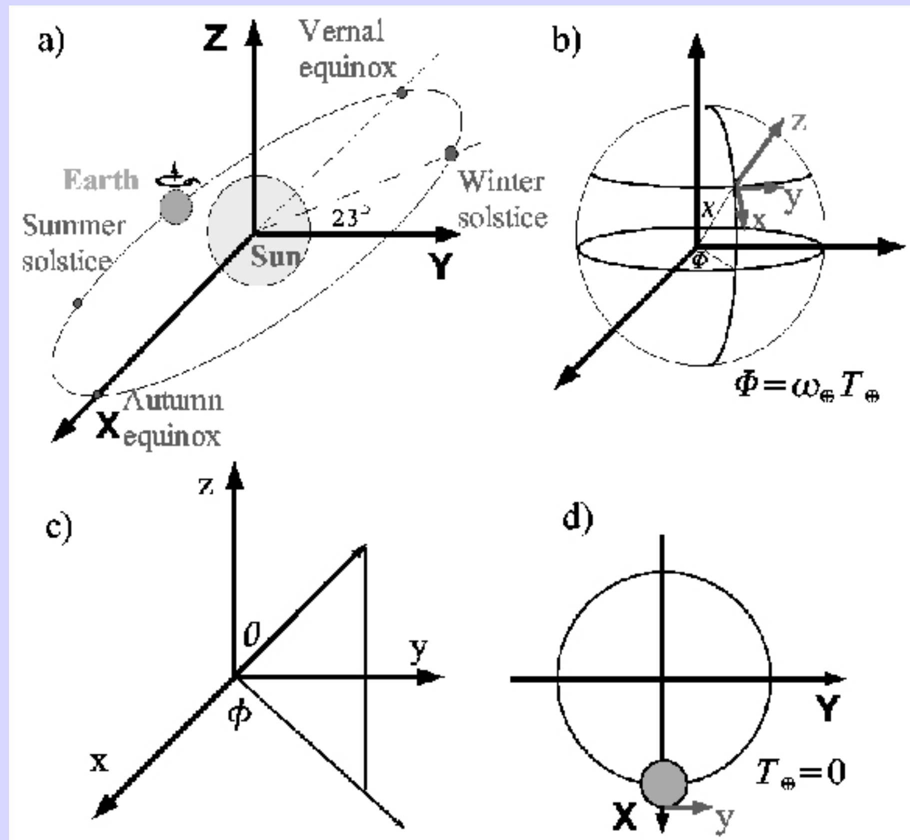
7. Lorentz violation with LSND

Test for Lorentz violation in LSND data;

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

LSND experiment neutrino beam direction

a) Sun centred system
2) Earth centred system
c) LANL local coordinate system
d) definition of the sidereal time



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Modified Dirac Equation (MDE)

$$i(\Gamma^{\nu}_{AB}\partial_{\nu} - M_{AB})\nu_{B} = 0$$

SME parameters

$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_{\mu} + d^{\mu\nu}_{AB}\gamma_{\mu}\gamma_{5} + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_{5} + \frac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu}$$

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

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$$i(\Gamma^{\nu}_{AB}\partial_{\nu} - M_{AB})\nu_{B} = 0$$

SME parameters

CPT odd

$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + \boxed{c^{\mu\nu}_{AB}}\gamma_{\mu} + \boxed{d^{\mu\nu}_{AB}}\gamma_{\mu}\gamma_{5} + \boxed{e^{\nu}_{AB}} + i\boxed{f^{\nu}_{AB}}\gamma_{5} + \frac{1}{2}\boxed{g^{\lambda\mu\nu}_{AB}}\sigma_{\lambda\mu}$$

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CPT even

7. Lorentz violation with LSND

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Sidereal variation of neutrino oscillation probability for LSND

$$P_{\bar{\nu}_e \to \bar{\nu}_\mu} \sim \frac{|(h_{eff})_{\bar{e}\bar{\mu}}|^2 L^2}{(\hbar c)^2}$$

$$= \left(\frac{L}{\hbar c}\right)^2 |(C)_{\bar{e}\bar{\mu}} + (A_s)_{\bar{e}\bar{\mu}} \sin w_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\mu}} \cos w_\oplus T_\oplus$$

$$+ (B_s)_{\bar{e}\bar{\mu}} \sin 2w_\oplus T_\oplus + (B_c)_{\bar{e}\bar{\mu}} \cos 2w_\oplus T_\oplus |^2$$

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

sidereal time $T_\oplus$

Sidereal variation analysis for LSND is 5 parameter fitting problem

Kostelecky and Mewes
PRD70(2004)076002

7. Lorentz violation with LSND

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

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

Expression of 5 observables (14 SME parameters)

$$(C)_{\bar{e}\bar{\mu}} = (a_L)^T_{\bar{e}\bar{\mu}} - N^Z (a_L)^Z_{\bar{e}\bar{\mu}} + E\left[-\frac{1}{2}(3 - N^Z N^Z)(c_L)^{TT}_{\bar{e}\bar{\mu}} + 2N^Z (c_L)^{TZ}_{\bar{e}\bar{\mu}} + \frac{1}{2}(1 - 3N^Z N^Z)(c_L)^{ZZ}_{\bar{e}\bar{\mu}}\right]$$

$$(A_s)_{\bar{e}\bar{\mu}} = N^Y (a_L)^X_{\bar{e}\bar{\mu}} - N^X (a_L)^Y_{\bar{e}\bar{\mu}} + E\left[-2N^Y (c_L)^{TX}_{\bar{e}\bar{\mu}} + 2N^X (c_L)^{TY}_{\bar{e}\bar{\mu}} + 2N^Y N^Z (c_L)^{XZ}_{\bar{e}\bar{\mu}} - 2N^X N^Z (c_L)^{YZ}_{\bar{e}\bar{\mu}}\right]$$

$$(A_c)_{\bar{e}\bar{\mu}} = -N^X (a_L)^X_{\bar{e}\bar{\mu}} - N^Y (a_L)^Y_{\bar{e}\bar{\mu}} + E\left[2N^X (c_L)^{TX}_{\bar{e}\bar{\mu}} + 2N^Y (c_L)^{TY}_{\bar{e}\bar{\mu}} - 2N^X N^Z (c_L)^{XZ}_{\bar{e}\bar{\mu}} - 2N^Y N^Z (c_L)^{YZ}_{\bar{e}\bar{\mu}}\right]$$

$$(B_s)_{\bar{e}\bar{\mu}} = E\left[N^X N^Y \left((c_L)^{XX}_{\bar{e}\bar{\mu}} - (c_L)^{YY}_{\bar{e}\bar{\mu}}\right) - (N^X N^X - N^Y N^Y)(c_L)^{XY}_{\bar{e}\bar{\mu}}\right]$$

$$(B_c)_{\bar{e}\bar{\mu}} = E\left[-\frac{1}{2}(N^X N^X - N^Y N^Y)\left((c_L)^{XX}_{\bar{e}\bar{\mu}} - (c_L)^{YY}_{\bar{e}\bar{\mu}}\right) - 2N^X N^Y (c_L)^{XY}_{\bar{e}\bar{\mu}}\right]$$

$$\begin{pmatrix} N^X \\ N^Y \\ N^Z \end{pmatrix} = \begin{pmatrix} \cos\chi \sin\theta \cos\phi - \sin\chi \cos\theta \\ \sin\theta \sin\phi \\ -\sin\chi \sin\theta \cos\phi - \cos\chi \cos\theta \end{pmatrix}$$

coordinate dependent direction vector (depends on the latitude of LANL, location of LANSCE and LSND detector)

7. Lorentz violation with LSND

Sidereal variation data of LSND signal

Fitting is done assuming only CPT-odd field in LSND (unit 10^{-19}GeV)

$$(C)_{\bar{e}\bar{\mu}} = -0.2 \pm 1.0 \pm 0.3$$

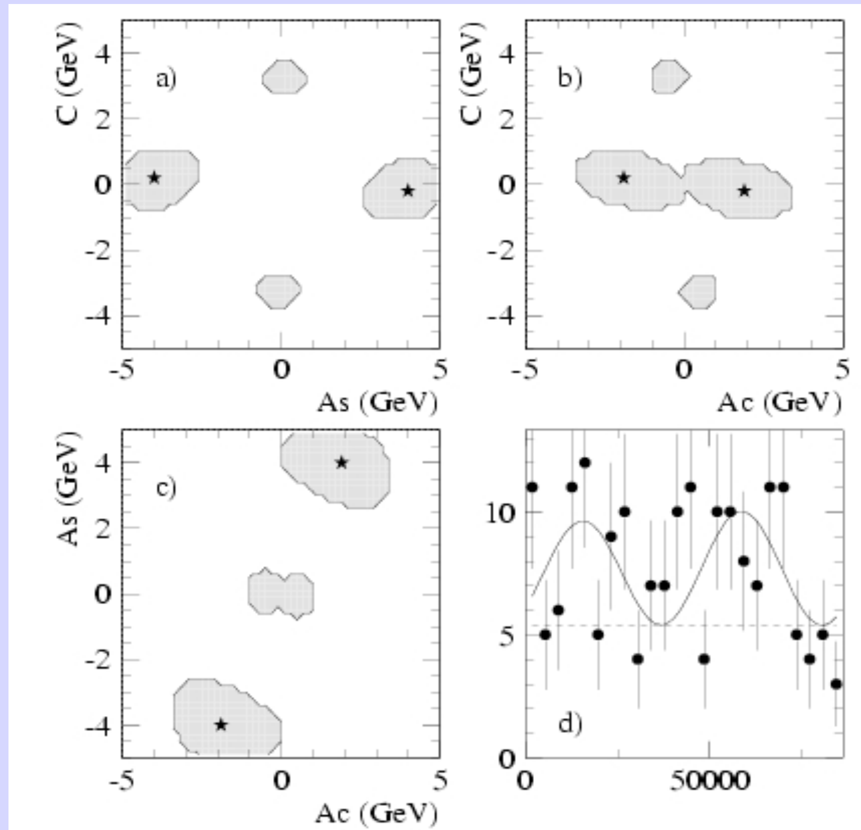
$$(A_s)_{\bar{e}\bar{\mu}} = 4.0 \pm 1.3 \pm 0.4$$

$$(A_c)_{\bar{e}\bar{\mu}} = 1.9 \pm 1.8 \pm 0.4$$

Within 1-sigma, there are 2 Solutions;

(1) large A_s-term solution
(2) large C-term solution

(1) indicates large a-term (CPT-odd) in the Hamiltonian, and (2) is sidereal time flat solution.



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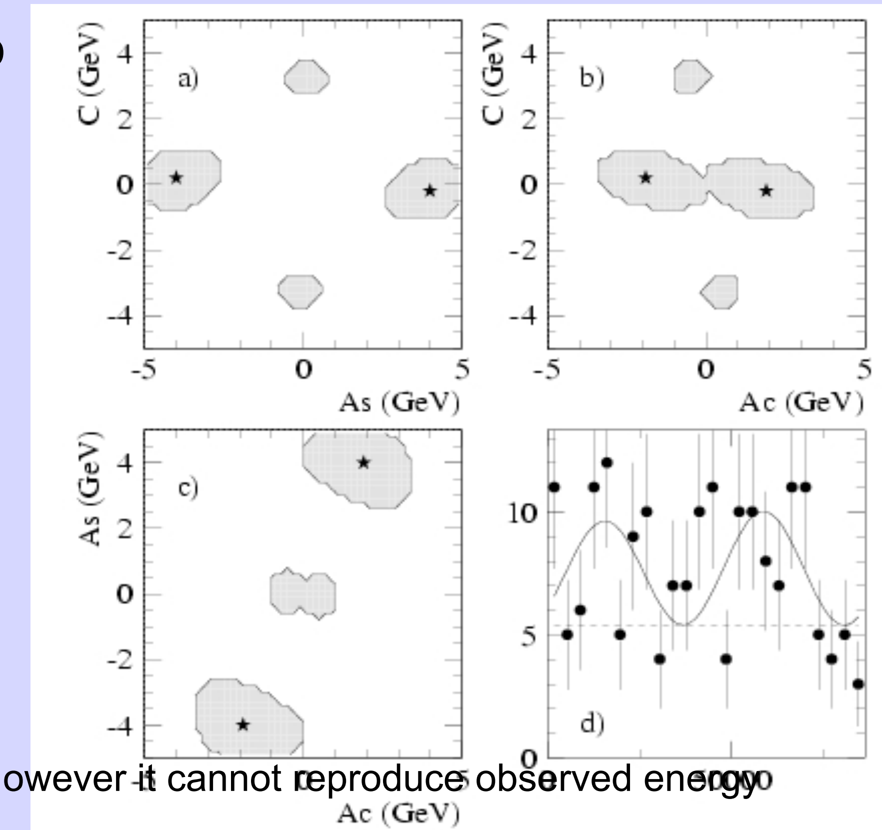

Within 1-sigma, there are 2 Solutions;

(1) large A_s-term solution
(2) large C-term solution

(1) indicates large a-term (CPT-odd) in the Hamiltonian, and (2) is sidereal time flat solution.

If the Lorentz violation is true process for LSND, large a-term (~ 10^{-19}GeV) exist in the Hamiltonian. However it cannot reproduce observed energy dependence of other experiments.

Can we make a model of neutrino oscillation satisfying world data, with Lorentz violation?

8. Tandem model

What kind of model do we want?

(1) acceptable description for atmospheric, solar, KamLAND, and LSND signal
(2) less than 5 parameters (standard 3 massive neutrino model has 4 parameters)
(3) allow to have neutrino mass term, but m<0.1eV to satisfy seesaw compatibility
(4) CPT-odd Lorentz violating term is order $\sim 10^{-19}$GeV to explain LSND
(5) CPT-even Lorentz violating term is order $<10^{-17}$ to be consistent with Planck scale suppression

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(5) CPT-even Lorentz violating term is order <10^{-17} to be consistent with Planck scale suppression

Tandem model satisfies all criteria;

(1) reasonably well describe all data, including LSND
(2) it uses only 3 parameters
(3) neutrino mass term is ~0.1eV
(4) CPT-odd Lorentz violating term is ~10^{-19}GeV
(5) CPT-even term is ~10^{-17}

$$m = 0.10 eV$$

$$a = -2.4 \times 10^{-19} GeV$$

$$c = 3.4 \times 10^{-17}$$

8. Tandem model

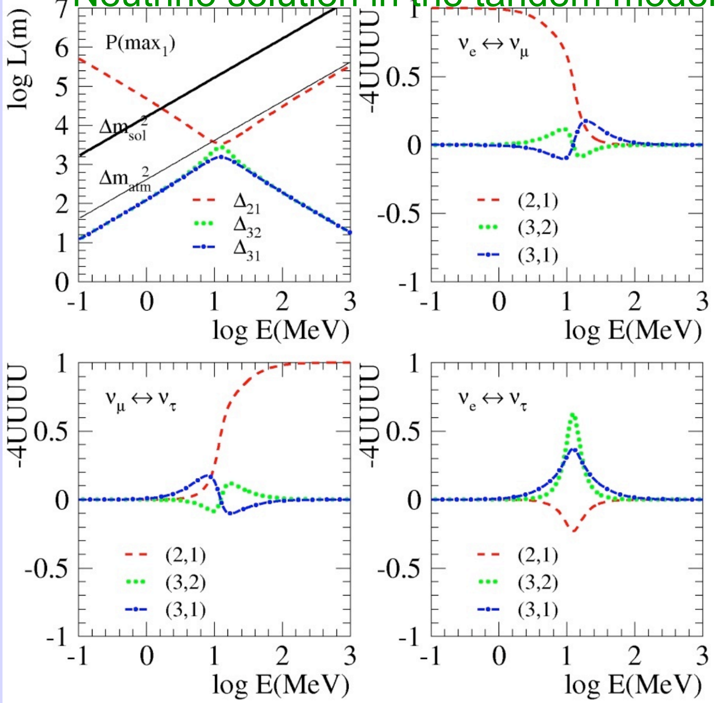
TK, Kostelecky, Tayloe
PRD74(2006)105009

Tandem model

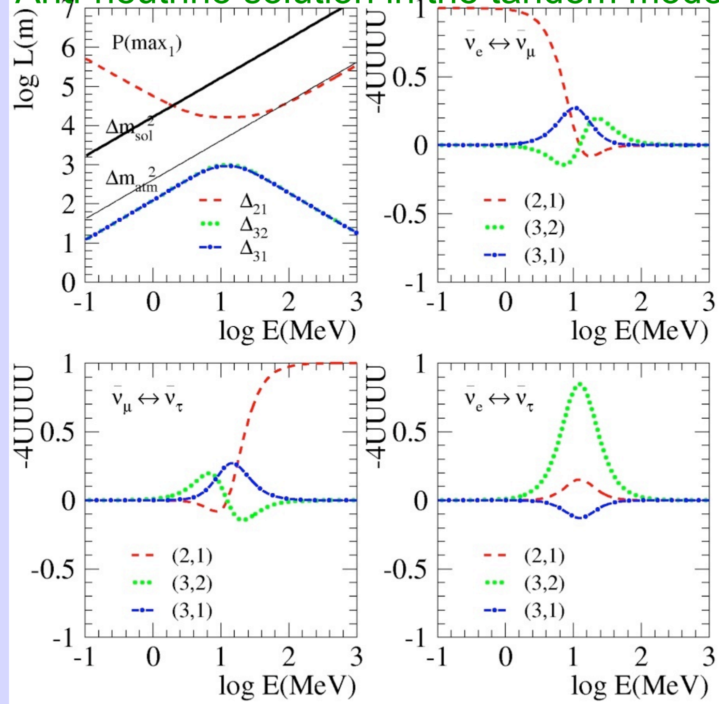
Tandem model has only 3 parameters, yet describes all neutrino oscillation data including LSND.

$$P_{\alpha\to\beta}(t) = \left|\langle \nu_\beta(t) | \nu_\alpha \rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j}\left(U_{\alpha i}U_{\alpha j}U_{\beta i}U_{\beta j}\right)\sin^2\left(\frac{\Delta_{ij}}{2}L\right)$$

Neutrino solution in the tandem model



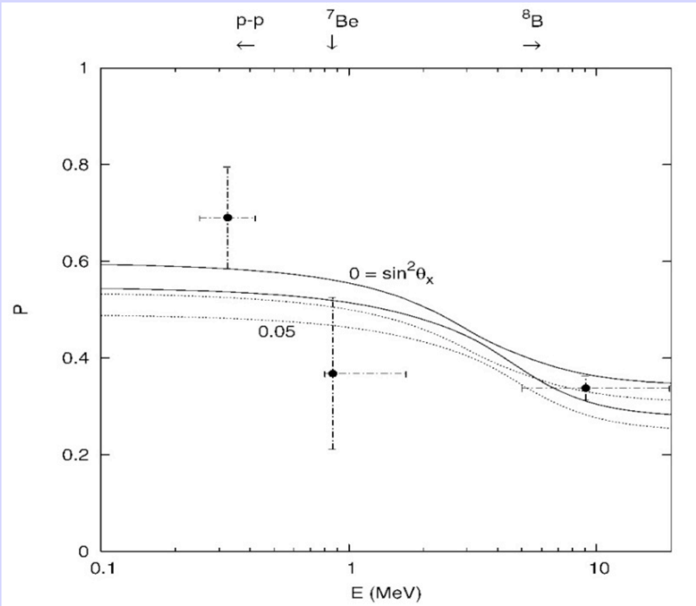
Anti-neutrino solution in the tandem model



8. Tandem model - Solar neutrinos

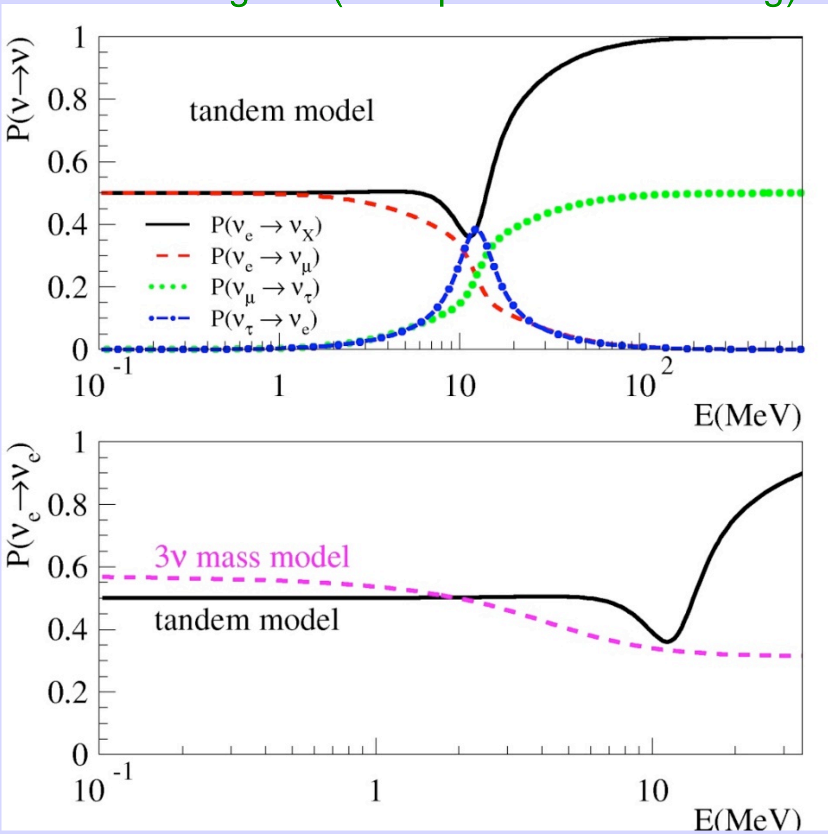
Solar neutrino suppression is created by the energy dependences of mixing angles. So even the long baseline limit has an energy dependence for neutrino oscillations.

Data



Barger,Marfatia,Whisnant, PLB617(2005)78

Theoretical signals (no experimental smearing)

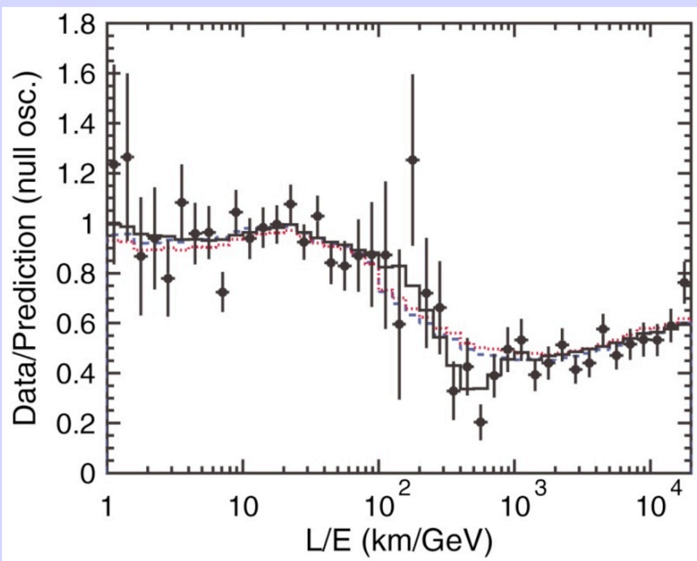


8. Tandem model - Atmospheric neutrinos

The tandem model has an L/E dependence for atmospheric neutrino oscillations. Although a model has a CPT-odd term, there is no difference for neutrino and anti-neutrino oscillations in the high energy region (consistent with MINOS).

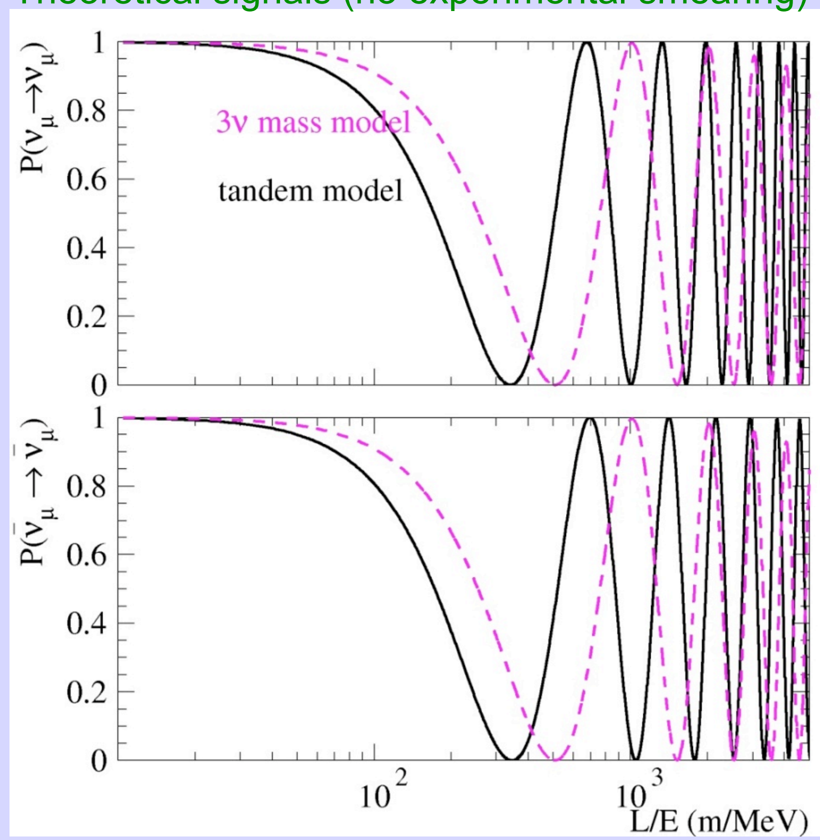
MINOS collaboration,
PRD73(2005)072002

Data



Super-K collaboration,
PRL94(2005)101801

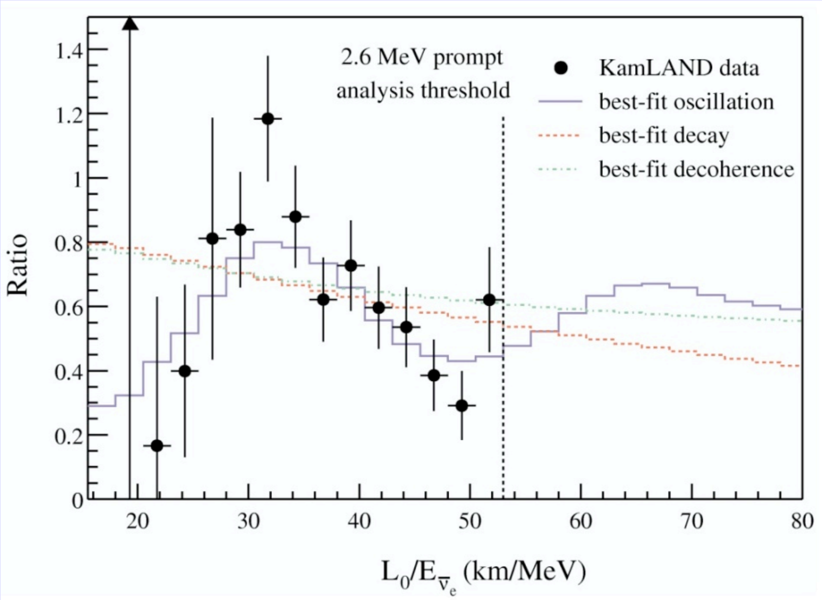
Theoretical signals (no experimental smearing)



8. Tandem model - KamLAND signal

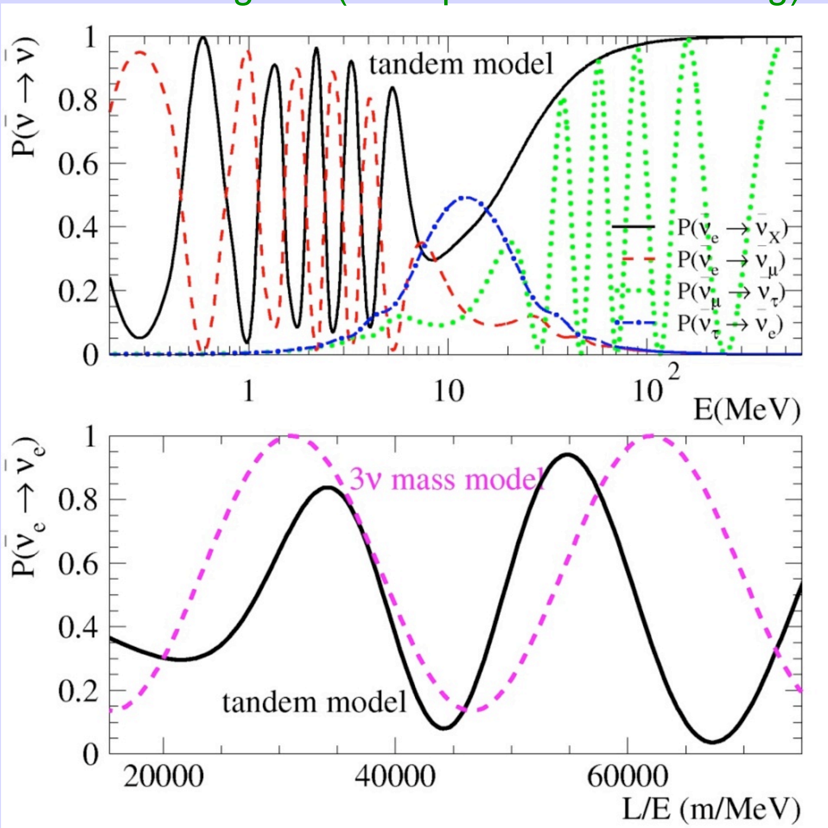
The KamLAND oscillation shape is made by the combination of all channels.
All ν_e oscillation amplitudes go to zero at the high energy limit (>100MeV), so the tandem model predicts the null signal for the NOvA and T2K ν_e appearance channel.

Data



KamLAND collaboration, PRL94(2005)081801

Theoretical signals (no experimental smearing)



8. Tandem model - LSND signal

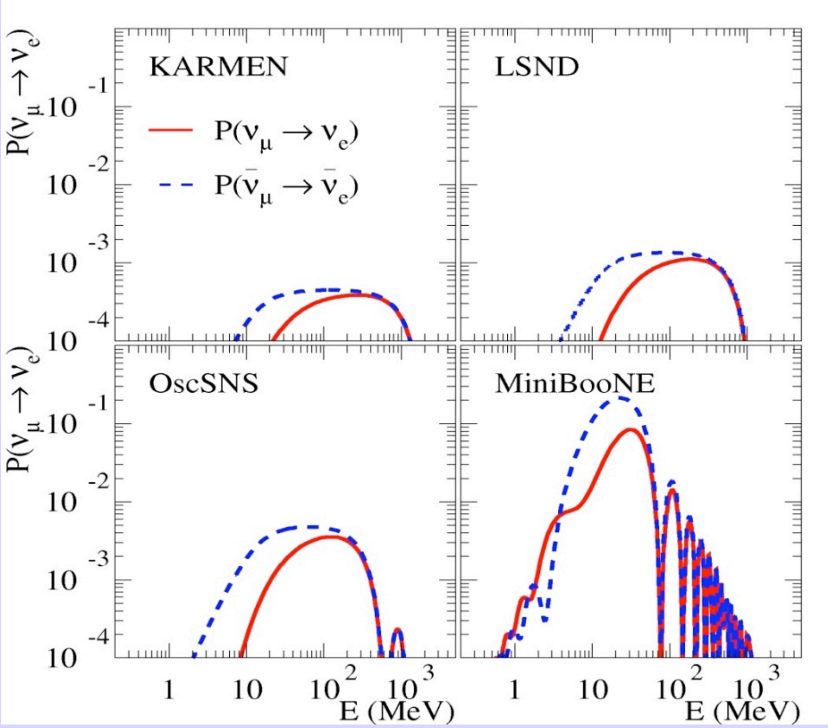
The LSND signal is created by small, yet nonzero amplitudes around the 10-100 MeV region.

The tandem model predicts:

(1) a factor 3 smaller appearance signal for KARMEN than LSND
(2) a small (~0.1%), but non zero appearance signal for LSND
(3) higher oscillation probabilities for antineutrinos at low energy region
(4) A signal at MiniBooNE low energy region

We were awaiting the MiniBooNE result (2006)!

Theoretical signals (no experimental smearing)



9. Lorentz violation with MiniBooNE

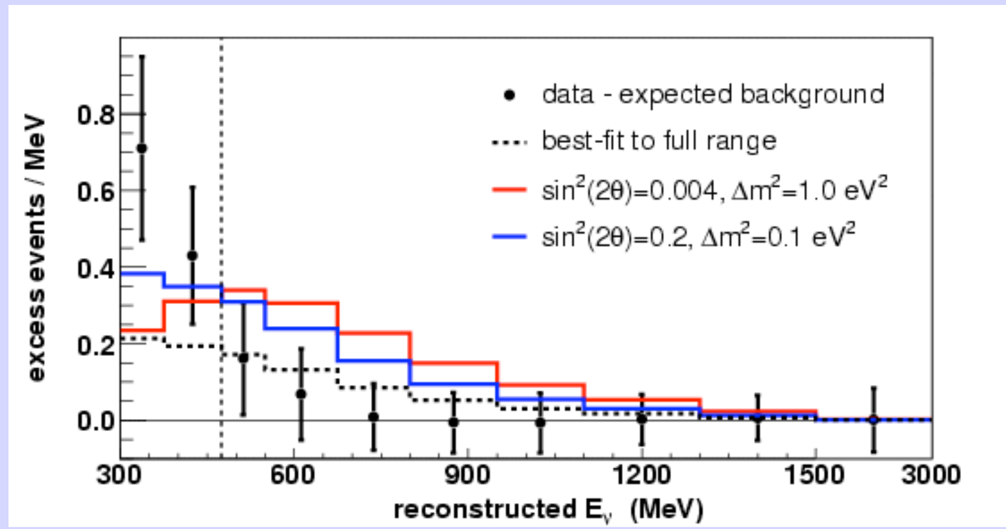
MiniBooNE didn't see the signal at the region where LSND data suggested under the assumption of standard 2 massive neutrino oscillation model, but did see the excess where standard model doesn't predict the signal. (spectral anomaly and L-E conflict)

If the low energy excess were Lorentz violation;

(1) The low energy excess may has sidereal time dependence.

(2) energy dependence of MiniBooNE is reproducible by tandem model

MiniBooNE low E ν_e excess



MiniBooNE collaboration
PRL98(2007)231801

9. Lorentz violation with MiniBooNE

Sidereal variation data of MiniBooNE signal

We applied statistics hypothesis test to MiniBooNE low E excess data.

MiniBooNE collaboration
CPT07 talk

(1) Pearson's χ^2 test

$$\chi^2 / d.o.f. = 79.5 / 74$$

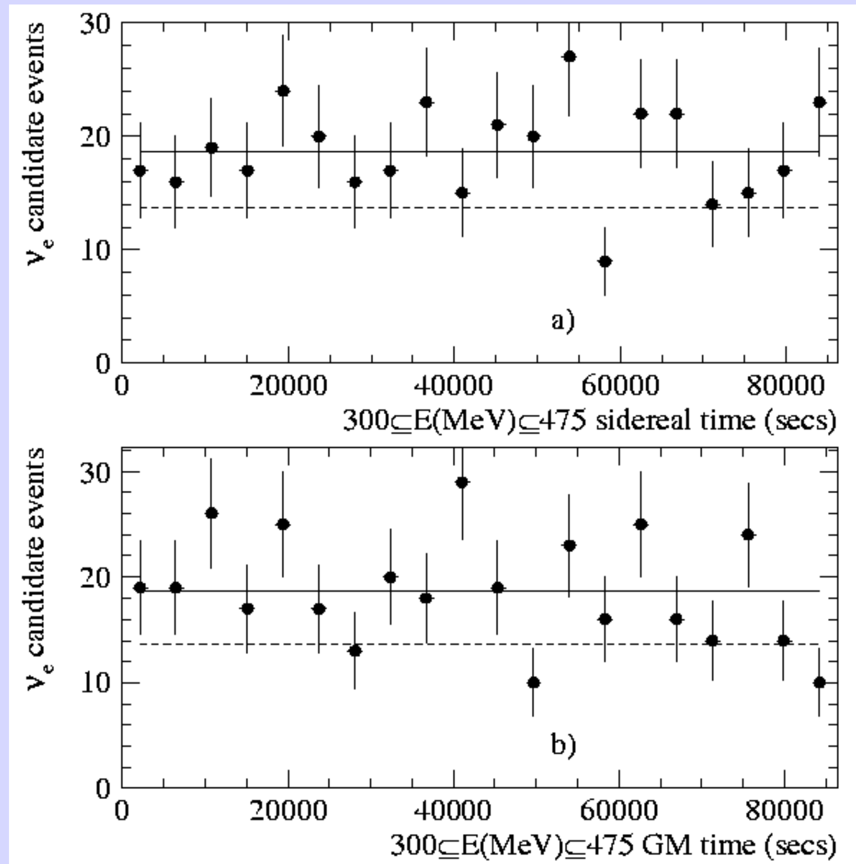
$$P(\chi^2) = 0.28$$

(2) Unbinned Kolmogorov-Smirnov test

$$D_{374} = 0.027$$

$$P(KS) = 1.00$$

Therefore, data is consistent with flat



9. Lorentz violation with MiniBooNE

Tandem model fit for MiniBooNE signal

Find the parameter set to give thee best fit for world neutrino oscillation data including MiniBooNE (ongoing)

I use the parameter set in the paper PRD74(2006)105009

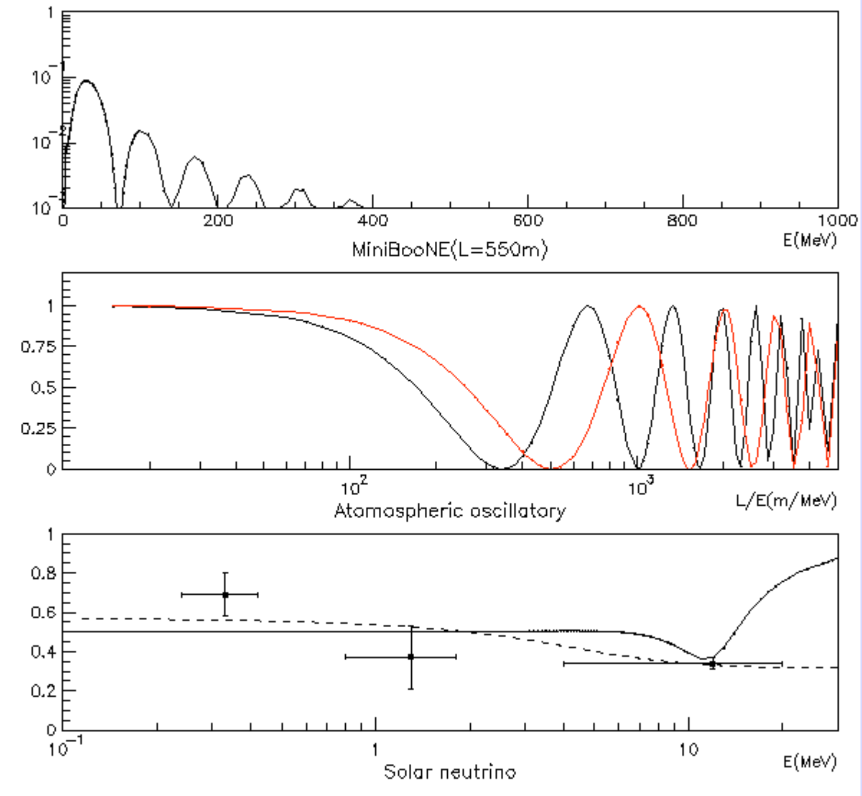
$$m = 0.10eV$$

$$a = -2.4\times10^{-19}GeV$$

$$c = 3.4\times10^{-17}$$

This parameter set is found from the world oscillation data except MiniBooNE

Tandem model prediction for oscillation probability



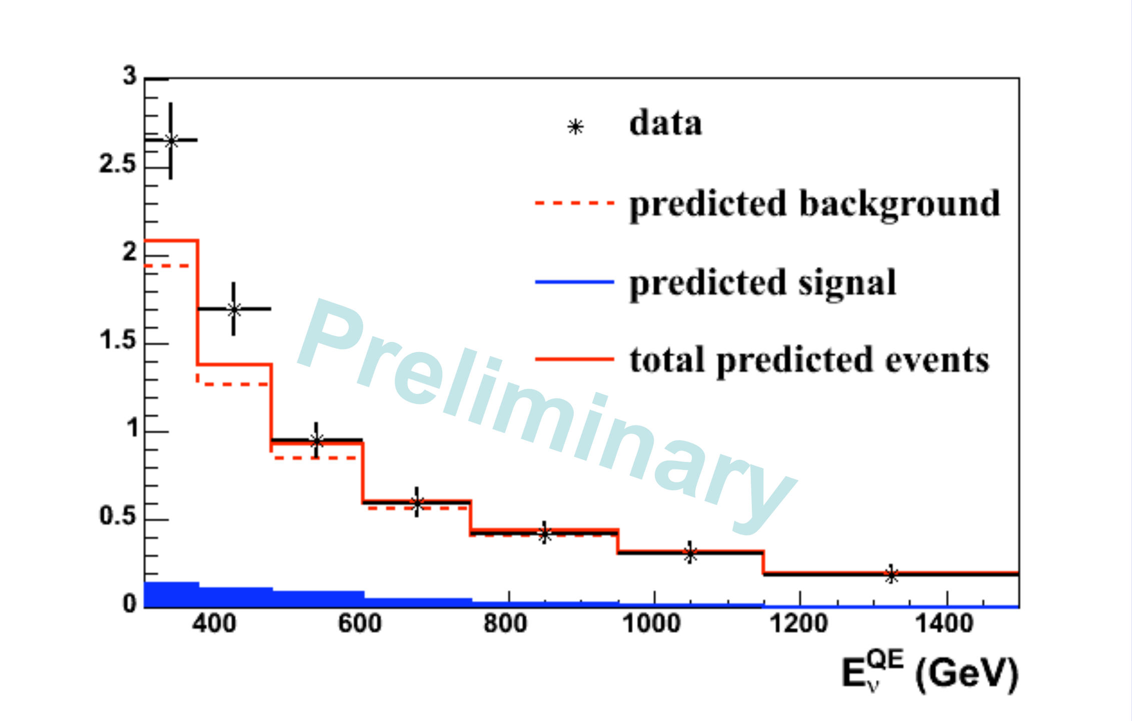
9. Lorentz violation with MiniBooNE

Tandem model fit for MiniBooNE signal

I used MiniBooNE public data;
http://www-boone.fnal.gov/for_physicists/april07datarelease/index.html

The rise of tandem model at low energy is not fast enough to explain MiniBooNE data.

A slight modification of the model helps a lot for the fitting with MiniBooNE and the world data (ongoing)



10. Conclusions

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

There are world wide effort for the test of Lorentz violation using various type of state-of-art technologies.

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

The tandem model reasonably describes the existing all 4 classes of neutrino oscillation data (solar, atmospheric, KamLAND, and LSND). The fit with MiniBooNE data is ongoing.

Relatively large ν_e appearance signal is predicted for OscSNS, and the null ν_e appearance signal is predicted for NOvA and T2K.

BooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle Aeronautical University
Fermi National Accelerator Laboratory
Indiana University
University of Florida

Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

Thank you for your attention!

Backup

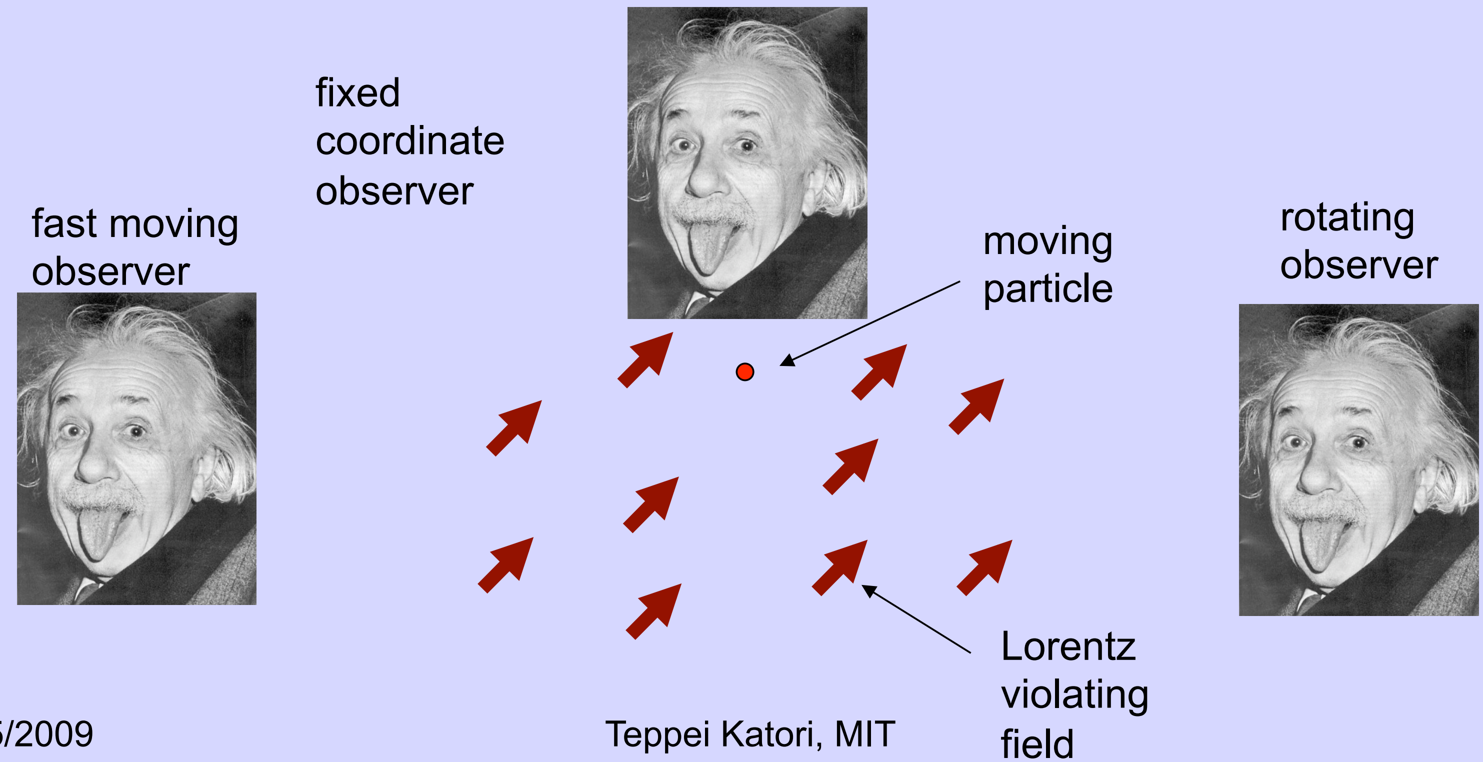
2. What is Lorentz violation?

FAQ

Q. What is Lorenz violation?

A. Lorentz violation is the violation of the particle Lorentz transformation, either Lorentz boost or rotation, and the observer Lorentz transformation is unbroken.

all observers agree with the particle Lorentz transformation violation phenomena through observer Lorentz transformation.



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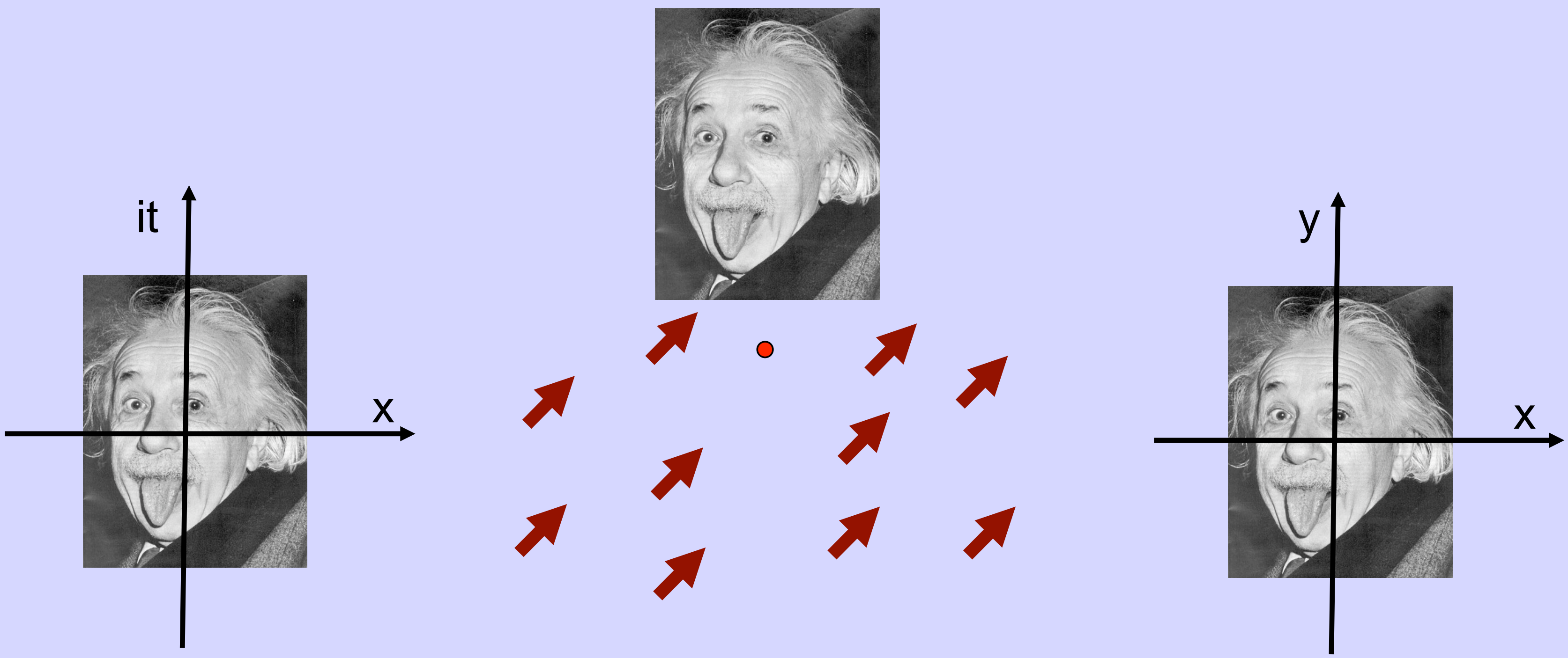

3. What is CPT violation?

CPT symmetry is the invariance under the CPT transformation

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

C: charge conjugation
particle-antiparticle transformation

$$\phi(x,t) \xrightarrow{C} C\phi(x,t)C^{-1} = \eta_C \phi^*(x,t)$$

P: parity transformation
reflection of spatial coordinate

$$\phi(x,t) \xrightarrow{P} P\phi(x,t)P^{-1} = \eta_P \phi(-x,t)$$

T: time reversal
reverse process in time

$$\phi(x,t) \xrightarrow{T} T\phi(x,t)T^{-1} = \eta_T \phi(x,-t)$$

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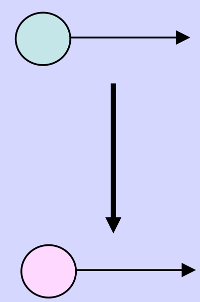

$$\phi(x,t) \xrightarrow{P} P\phi(x,t)P^{-1} = \eta_P \phi(-x,t)$$

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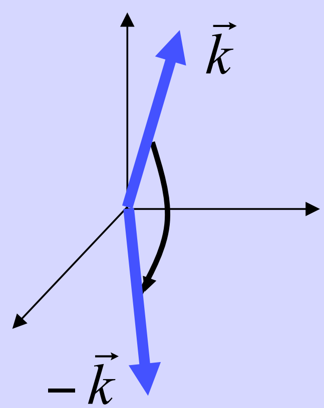

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reverse process in time

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reverse process in time

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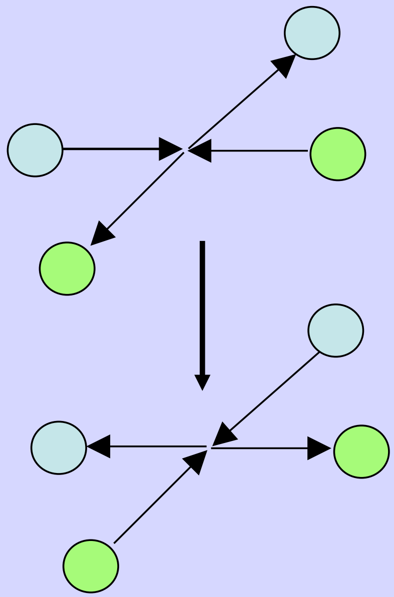

3. What is CPT violation?

There are 2 CPT theorems;

(1) Lagrangian CPT theorem (Bell '54, Luder and Pauli '55)
The series of operation of 3 operators, C, P, and T (order is not important) is the perfect symmetry for any Lagrangian in quantum field theory.

This is popular in many literatures, but it doesn't answer why CPT is essential more than C or P or T

(2) Axiomatic CPT theorem (Jost '57)
CPT is the perfect symmetry as a consequences of axioms of quantum field theory (Wightman's axioms)

This is highly mathematical, and hard to understand (at least the speaker doesn't understand), however it shows why CPT is essential, and even need not to define C nor P nor T.

3. What is CPT violation?

Axiomatic CPT theorem

In Hilbert space, with assuming to have correct relativistic transformation law, if weak local commutativity condition

$$(\Psi_0, \varphi_\mu(x_1)\cdots\phi_\nu(x_n)\Psi_0) = i^F(\Psi_0, \phi_\nu(x_n)\cdots\varphi_\mu(x_1)\Psi_0)$$

holds at real neighborhood of the Jost point, it gives CPT condition

$$(\Psi_0, \varphi_\mu(x_1)\cdots\phi_\nu(x_n)\Psi_0) = i^F(-1)^J(\Psi_0, \phi_\nu(-x_n)\cdots\varphi_\mu(-x_1)\Psi_0)$$

everywhere (and vice versa)

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everywhere (and vice versa)

very mathematical statement, but several observations;

(1) Lorentz transformation is important for CPT theorem
(2) Micro causality and spin statistics is important for CPT theorem
(3) $i^F(-1)^J$ is the phase of CPT transformation for any terms in the Langrangian

F=number of fermion field
J = number of spin 1/2 field pair (note, 1 Lorentz vector is counted as 1 spin 1/2 field pair)

3. What is CPT violation?

In a nutshell, under the several conditions, the phase of CPT transformation for each term is,

$$i^F (-1)^J$$

here;
F=number of spin 1/2 field
J = number of spin 1/2 filed pair (Lorentz vector is counted as 1 pair) dotted or undotted spinors

And, this combination is always +1 in Quantum Field Theory

note
There are 2 types of spinors, dotted and undotted spinors.
They have different transformation law, and dirac spinor contains 1 dotted and 1 undotted spinor.
ex) Dirac spinor and Majorana spinor

$$\varphi_D = \begin{pmatrix} \chi_\alpha \\ \overline{\psi}^{\dot{\alpha}} \end{pmatrix} \qquad \varphi_M = \begin{pmatrix} \chi_\alpha \\ \overline{\chi}^{\dot{\alpha}} \end{pmatrix}$$

If you have 2 spinors in VEV, dotted and undotted make pair.
Also, each Lorentz vector is created from one dotted and one undotted spinor.

3. What is CPT violation?

ex) QED Lagrangian

$$L = i\overline{\psi}\gamma_\mu\partial^\mu\psi - m\overline{\psi}\psi + ie\overline{\psi}\gamma_\mu A^\mu\psi \ldots$$

$$i\overline{\psi}\gamma_\mu\partial^\mu\psi \xrightarrow{CPT} \Theta[i\overline{\psi}\gamma_\mu\partial^\mu\psi]\Theta^{-1} = (-1)^{\boxed{2}} \times i\overline{\psi}\gamma_\mu\partial^\mu\psi = (+1)\times i\overline{\psi}\gamma_\mu\partial^\mu\psi$$

$$m\overline{\psi}\psi \xrightarrow{CPT} \Theta[m\overline{\psi}\psi]\Theta^{-1} = (-1)^{\boxed{0}} \times m\overline{\psi}\psi = (+1)\times m\overline{\psi}\psi$$

$$ie\overline{\psi}\gamma_\mu A^\mu\psi \xrightarrow{CPT} \Theta[ie\overline{\psi}\gamma_\mu A^\mu\psi]\Theta^{-1} = (-1)^{\boxed{2}} \times ie\overline{\psi}\gamma_\mu A^\mu\psi = (+1)\times ie\overline{\psi}\gamma_\mu A^\mu\psi$$

number of active Lorentz indices

$$L \xrightarrow{CPT} L' = L$$

CPT theorem guarantees all terms have +1 phase, hence CPT is the perfect symmetry of quantum field theory.

3. What is CPT violation?

ex) QED Lagrangian

$$L = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi + ie\bar{\psi}\gamma_{\mu}A^{\mu}\psi \ldots$$

$$i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi \xrightarrow{CPT} \Theta[i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi]\Theta^{-1} = [i^2(-1)^3]\times i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi = (+1)\times i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi$$

$$m\bar{\psi}\psi \xrightarrow{CPT} \Theta[m\bar{\psi}\psi]\Theta^{-1} = [i^2(-1)^1]\times m\bar{\psi}\psi = (+1)\times m\bar{\psi}\psi$$

$$ie\bar{\psi}\gamma_{\mu}A^{\mu}\psi \xrightarrow{CPT} \Theta[ie\bar{\psi}\gamma_{\mu}A^{\mu}\psi]\Theta^{-1} = [i^2(-1)^3]\times ie\bar{\psi}\gamma_{\mu}A^{\mu}\psi = (+1)\times ie\bar{\psi}\gamma_{\mu}A^{\mu}\psi$$

$$L \xrightarrow{CPT} L' \neq L$$

CPT theorem guarantees all terms have +1 phase, hence CPT is the perfect symmetry of quantum field theory.

3. What is CPT violation?

ex) QED Lagrangian with Lorentz violating terms

$$L = i\overline{\psi}\gamma_\mu \partial^\mu \psi - m\overline{\psi}\psi + ie\overline{\psi}\gamma_\mu A^\mu \psi + \boxed{\overline{\psi}\gamma_\mu a^\mu \psi} + \boxed{\overline{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu \psi} \ldots$$

$$i\overline{\psi}\gamma_\mu \partial^\mu \psi \xrightarrow{CPT} \Theta[i\overline{\psi}\gamma_\mu \partial^\mu \psi]\Theta^{-1} = [i^2(-1)^3] \times i\overline{\psi}\gamma_\mu \partial^\mu \psi = (+1) \times i\overline{\psi}\gamma_\mu \partial^\mu \psi$$

$$m\overline{\psi}\psi \xrightarrow{CPT} \Theta[m\overline{\psi}\psi]\Theta^{-1} = [i^2(-1)^1] \times m\overline{\psi}\psi = (+1) \times m\overline{\psi}\psi$$

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$$\overline{\psi}\gamma_\mu a^\mu \psi \xrightarrow{CPT} \Theta[\overline{\psi}\gamma_\mu a^\mu \psi]\Theta^{-1} = [i^2(-1)^{\boxed{2}}] \times \overline{\psi}\gamma_\mu a^\mu \psi = (-1) \times \overline{\psi}\gamma_\mu a^\mu \psi$$

$$\overline{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu \psi \xrightarrow{CPT} \Theta[\overline{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu \psi]\Theta^{-1} = [i^2(-1)^{\boxed{3}}] \times \overline{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu \psi = (+1) \times \overline{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu \psi$$

$$L \xrightarrow{CPT} L' \neq L$$

backgrounds are insensitive with active transformation law

CPT is not a perfect symmetry any more, due to Lorentz violating term a^μ (CPT-odd), however Lorentz violating term $c^{\mu\nu}$ (CPT-even) keeps CPT symmetry.

4. Standard Model Extension (SME)

How to detect Lorentz violation?

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

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

The standard choice of the coordinate is Sun centred coordinate system

FAQ. Why Sun centred coordinate, not galaxy centre coordinate?

Although galactic rotation is faster than earth revolution, it takes order 1000 years to change 1 degree. Since we are testing rotation violation and not translation violation, constant velocity motion is not important.

ex) various speeds
- galactic rotation ~ 220km/s
- earth revolution ~ 30km/s
- earth rotation ~ 0.5km/s

6. Lorentz violation with neutrino oscillation

There are 6 classes of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation (Kostelecky and Mewes '04)

(1) Spectral anomalies
(2) L-E conflict
(3) Periodic variation
(4) Compass asymmetries
(5) neutrino-antineutrino mixing
(6) classic CPT test

Even if sidereal time dependence is erased out, effect of preferred direction may remain and it could affect neutrino oscillation signal (time independent rotation symmetry violation)

need submarine cartoon from Matt Mewes

6. Lorentz violation with neutrino oscillation

There are 6 classes of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation (Kostelecky and Mewes '04)

(1) Spectral anomalies
(2) L-E conflict
(3) Periodic variation
(4) Compass asymmetries
(5) neutrino-antineutrino mixing
(6) classic CPT test

neutrino-antineutrino oscillation is forbidden by helicity conservation. But some Lorentz violating fields violate conservation of angular momentum

formalism also contain neutrino-antineutrino oscillation

$$\nu \Leftrightarrow \overline{\nu}\,?$$

6. Lorentz violation with neutrino oscillation

There are 6 classes of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation (Kostelecky and Mewes '04)

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(2) L-E conflict
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(4) Compass asymmetries
(5) neutrino-antineutrino mixing
(6) classic CPT test

CPT violation itself is the signal of Lorentz violation, so any difference between neutrino and anti-neutrino mode could be Lorentz violation

ex) Lorentz violating Hamiltonian for neutrino

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

ex) Lorentz violating Hamiltonian for anti-neutrino

$$(h_{eff})_{ab} = |\vec{p}|\delta_{ab} + \frac{1}{2|\vec{p}|}(m^2)^*_{ab} + \frac{1}{|\vec{p}|}[-(a^*_L)^\mu p_\mu - (c^*_L)^{\mu\nu} p_\mu p_\nu]_{ab}$$

7. Lorentz violation with LSND

Test for Lorentz violation in LSND data;

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

Effective Hamiltonian for neutrino oscillation

usual Hamiltonian (3X3)

additional terms (3X3)

$$(h_{eff})_{\bar{a}\bar{b}} = |\vec{p}|\delta_{\bar{a}\bar{b}} + \frac{1}{2|\vec{p}|}(m^2)_{\bar{a}\bar{b}} + \frac{1}{|\vec{p}|}[-(a_L)^{\mu} p_{\mu} - (c_L)^{\mu\nu} p_{\mu} p_{\nu}]_{\bar{a}\bar{b}}$$

7. Lorentz violation with LSND

Sidereal variation data of LSND signal

TK and LSND collaboration PRD72(2005)076004

Before trying any fitting, we applied statistics hypothesis test;

(1) Pearson's χ^2 test

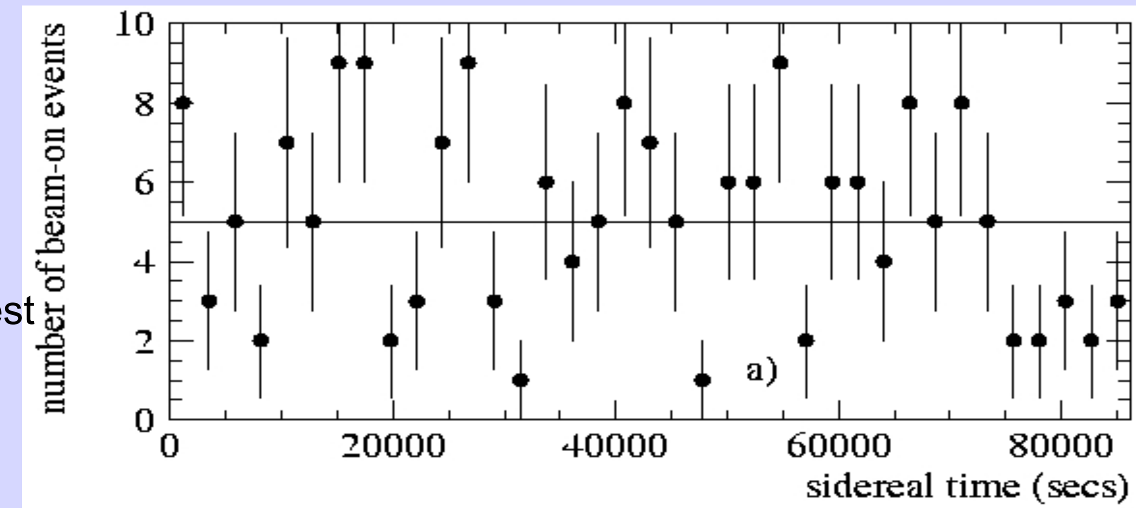
$$\chi^2 / d.o.f. = 44.8/36$$

$$P(\chi^2) = 0.15$$

(2) Unbinned Kolmogorov-Smirnov test

$$D_{186} = 0.076$$

$$P(KS) = 0.23$$



Therefore, data is consistent with flat

however, it doesn't reject sidereal variation scenario, so we performed the fit using unbinned log likelihood

$$\ln L = \ln\left[\frac{e^{-\mu}}{N!}\prod_{i=1}^{N}(\mu_s F_s + \mu_b F_b) \times \prod_{i=stat,sys}\frac{1}{\sqrt{2\pi\sigma_i^2}}\exp\left(-\frac{(\mu_i - \bar{\mu}_i)^2}{2\sigma_i^2}\right)\right]$$

8. Bicycle model

Bicycle model

Kostelecky and Mewes
PRD69(2004)016005

The observed energy dependence of neutrino oscillation from Super-K, K2K, MINOS, and KamLAND strongly suggest "L/E".

Lorentz violating terms are only either "L" (CPT-odd) or "LE" (CPT even).

However, the diagonarization of Hamiltonian can create "L/E" from "L" and "LE" (Lorentz violating Seesaw mechanism)

$$(h_{eff})_{ab} \rightarrow \begin{pmatrix} cE & a & a \\ a & 0 & 0 \\ a & 0 & 0 \end{pmatrix}$$

$$\Delta_{21} = \sqrt{(c'E)^2 + (a'\cos\Theta)^2} + c'E$$

$$\Delta_{31} = \sqrt{(c'E)^2 + (a'\cos\Theta)^2}$$

$$\Delta_{32} = \sqrt{(c'E)^2 + (a'\cos\Theta)^2} - c'E \xrightarrow{highE} \frac{(a'\cos\Theta)^2}{2c'E}$$

effective Δm^2

Therefore, at high energy limit (~100MeV);

$$P_{\nu\mu\rightarrow\nu\tau} \sim \sin^2\left(\Delta_{32}\frac{L}{2}\right) \sim \sin^2\left(\boxed{\frac{a'^2\cos^2\Theta}{4c'}}\frac{L}{E}\right)$$

8. Bicycle model

Barger,Marfatia,Whisnant
arXiv/0706.1085

Further analysis about bicycle model shows even general case, (bicycle model with direction dependence) is difficult to explain all feature of existing global neutrino oscillation data.
Also, bicycle model doesn't have a signal for LSND.

We want to create a new model, the requirements are;

(1) acceptable description for atmospheric, solar, KamLAND, and LSND signal
(2) less than 5 parameters (standard 3 massive neutrino model has 4 parameters)
(3) allow to have neutrino mass term, but $m<0.1$eV to satisfy seesaw compatibility
(4) CPT-odd Lorentz violating term is order $\sim 10^{-19}$GeV to explain LSND
(5) CPT-even Lorentz violating term is order $<10^{-17}$ to be consistent with Planck scale suppression

8. Tandem model

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(4) CPT-odd Lorentz violating term is order ~10^{-19}GeV to explain LSND
(5) CPT-even Lorentz violating term is order <10^{-17} to be consistent with Planck scale suppression

Tandem model satisfies all criteria;

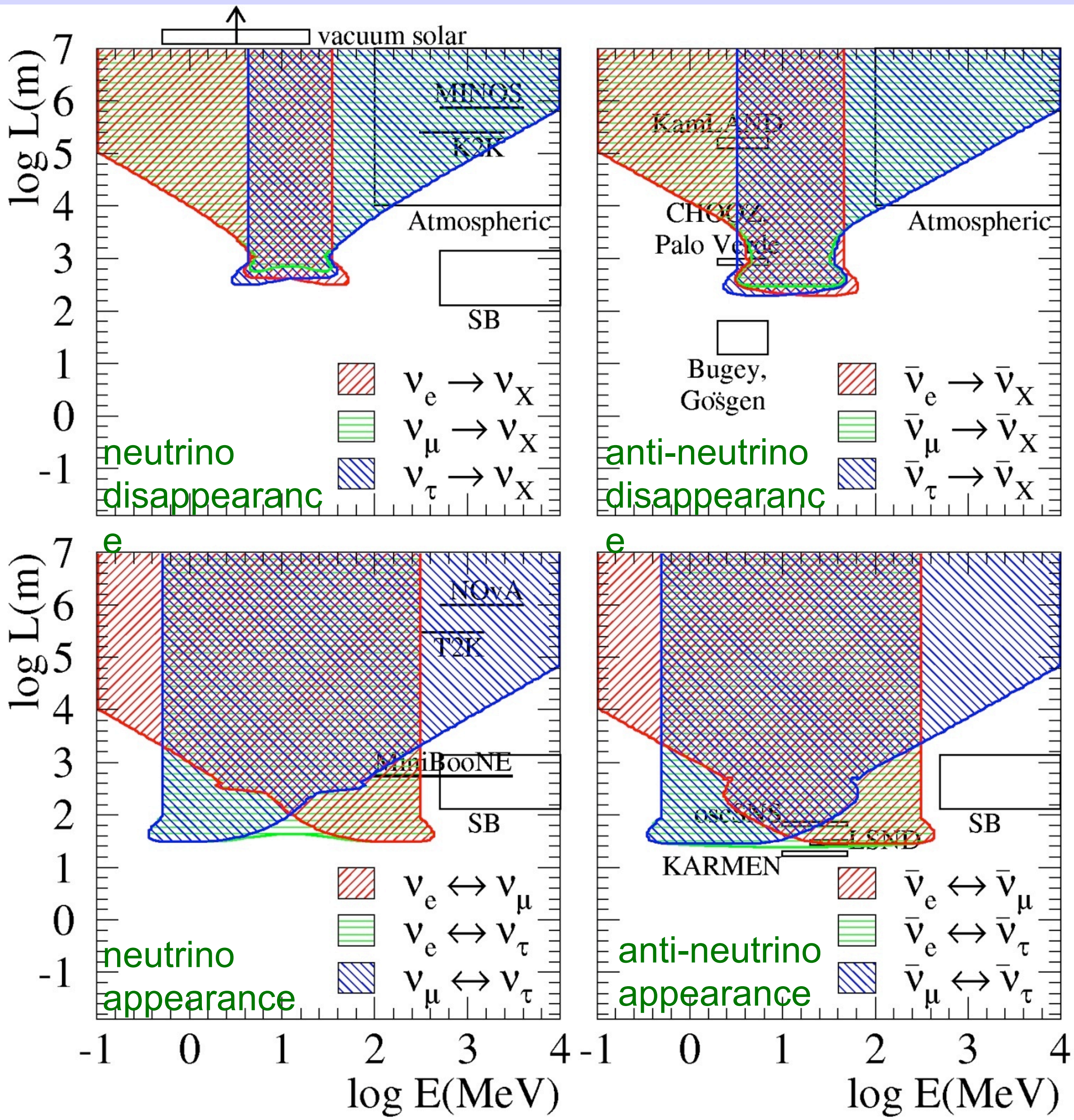
(1) reasonably well describe all data, including LSND
(2) it uses only 3 parameters
(3) neutrino mass term is ~0.1eV
(4) CPT-odd Lorentz violating term is ~10^{-19}GeV
(5) CPT-even term is ~10^{-17}

$$m = 0.10 eV$$

$$a = -2.4\times10^{-19}\, GeV$$

$$c = 3.4\times10^{-17}$$

8. Tandem model Global signal predictions



disappearance signals
P>10%

appearance signals
P>0.1%

8. General formalism

Hamiltonian can be diagonalized by eigenvalues and mixing matrix of Hamiltonian

$$\begin{pmatrix} h_{ee}(E) & h_{e\mu}(E) & h_{\tau e}(E) \\ h_{e\mu}(E) & h_{\mu\mu}(E) & h_{\mu\tau}(E) \\ h_{\tau e}(E) & h_{\mu\tau}(E) & h_{\tau\tau}(E) \end{pmatrix} = U^T(E) \begin{pmatrix} \lambda_1(E) & 0 & 0 \\ 0 & \lambda_2(E) & 0 \\ 0 & 0 & \lambda_3(E) \end{pmatrix} U(E)$$

Where,

$$U(E) = \begin{pmatrix} U_{ee}(E) & U_{e\mu}(E) & U_{e\tau}(E) \\ U_{\mu e}(E) & U_{\mu\mu}(E) & U_{\mu\tau}(E) \\ U_{\tau e}(E) & U_{\tau\mu}(E) & U_{\tau\tau}(E) \end{pmatrix}$$

$$\lambda_2(E) - \lambda_1(E) \equiv \Delta_{21}(E)$$
$$\lambda_3(E) - \lambda_1(E) \equiv \Delta_{31}(E)$$
$$\lambda_3(E) - \lambda_2(E) \equiv \Delta_{32}(E)$$

8. Tandem model

We used 2 independent methods to diagonalize our Hamiltonian.

(1) Analytical solution of cubic equation (Ferro-Cardano solution)

$$\lambda_1 = -2\sqrt{Q}\cos\left(\frac{\theta}{3}\right) - \frac{1}{3}A$$

$$\lambda_2 = -2\sqrt{Q}\cos\left(\frac{\theta + 2\pi}{3}\right) - \frac{1}{3}A$$

$$\lambda_3 = -2\sqrt{Q}\cos\left(\frac{\theta - 2\pi}{3}\right) - \frac{1}{3}A$$

$$A = -cE - m^2/2E$$

$$b = cm^2/2 - 3a^2$$

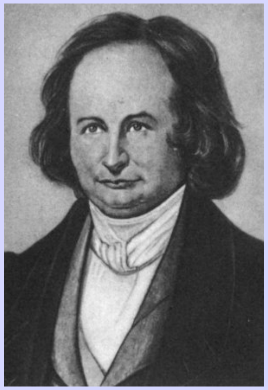
$$c = a^2\left(cE \mp 2a + m^2/2E\right)$$

$$Q = \left(A^2 - 3b\right)/9$$

$$R = \left(2A^3 - 9ab + 27c\right)/54$$

$$\theta = \arccos\left(R/\sqrt{Q^3}\right)$$

8. Tandem model



(2) Numerical matrix diagonalization (Jacobi method)

$$\begin{pmatrix} h_{ee} & h_{e\mu} & h_{\tau e} \\ h_{e\mu} & h_{\mu\mu} & h_{\mu\tau} \\ h_{\tau e} & h_{\mu\tau} & h_{\tau\tau} \end{pmatrix} = O_1^T \begin{pmatrix} h'_{ee} & 0 & h'_{\tau e} \\ 0 & h'_{\mu\mu} & h'_{\mu\tau} \\ h'_{\tau e} & h'_{\mu\tau} & h'_{\tau\tau} \end{pmatrix} O_1 = O_1^T O_2^T \begin{pmatrix} h''_{ee} & \delta & 0 \\ \delta & h''_{\mu\mu} & h''_{\mu\tau} \\ 0 & h'_{\mu\tau} & h''_{\tau\tau} \end{pmatrix} O_2 O_1 \cdots$$

$$= \underbrace{\cdots O^T O^T O^T}_{U^T} \begin{pmatrix} \sim\lambda_1 & \sim 0 & \sim 0 \\ \sim 0 & \sim\lambda_2 & \sim 0 \\ \sim 0 & \sim 0 & \sim\lambda_3 \end{pmatrix} \underbrace{OOO\cdots}_{U}$$

These 2 methods are independent algorithms, and important check for the diagonalization of the Hamiltonian.

8. Tandem model

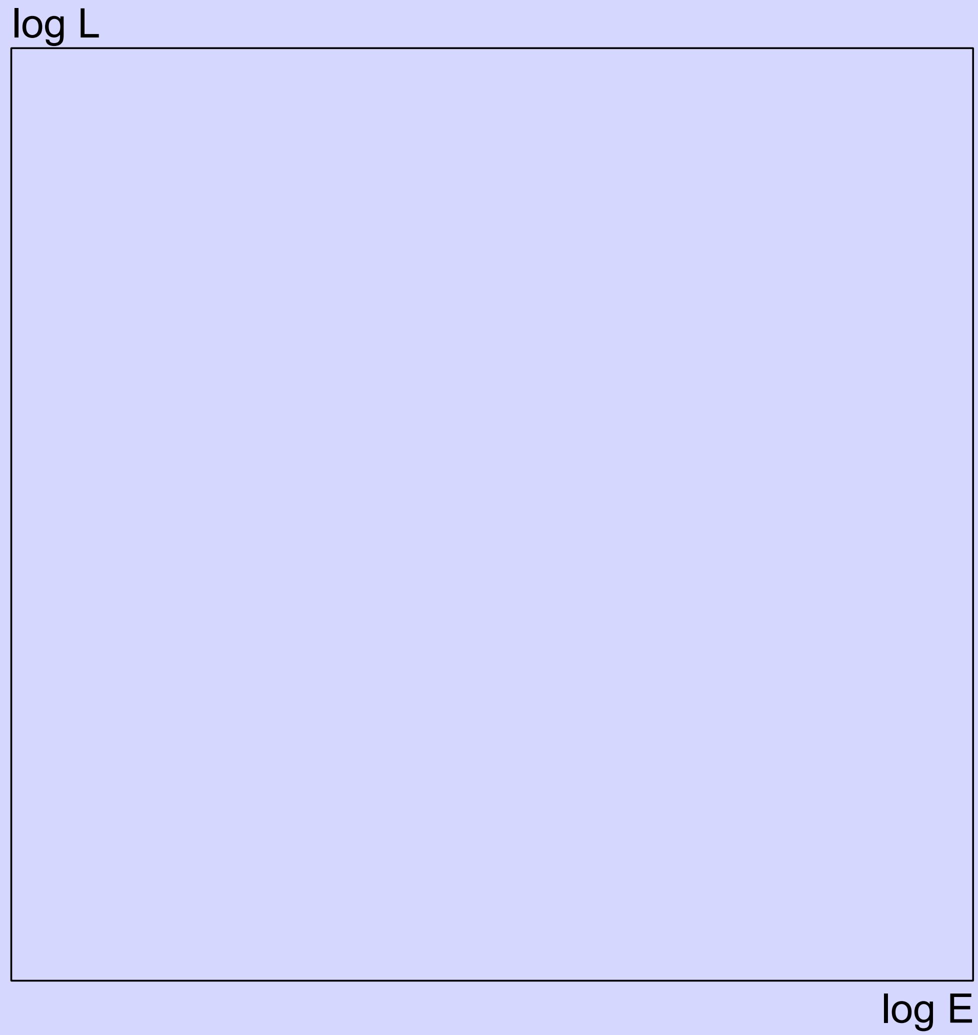
We use L-E plane for the phase space of neutrino oscillation (not Δm^2-$\sin^2\theta$ plane).

Oscillatory shape (spectrum distortion) is only visible near the first oscillation maximum. The condition,

$$\sin^2\left(\frac{\Delta_{JK}(E)}{2}L\right) \approx \sin^2\left(\frac{\pi}{2}\right)$$

$$\rightarrow L = \frac{\pi}{\Delta_{JK}(E)}$$

gives the line shape solution of the first oscillation maximum.



8. Tandem model

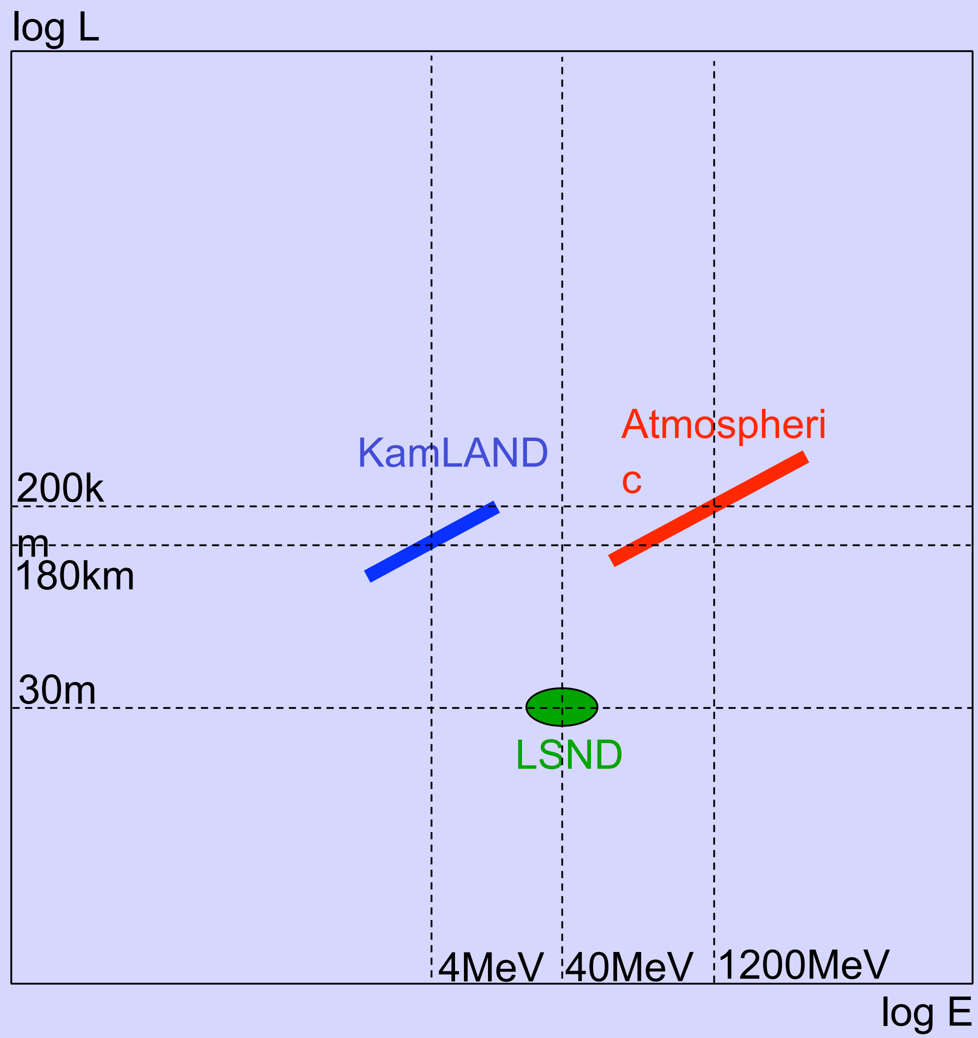
Current experimental data (ignoring solar neutrino suppression).

For standard 3 neutrino massive model;

$$\frac{\Delta_{JK}(E)}{2} L = \frac{\Delta m_{JK}^2}{4E} L \propto \frac{L}{E}$$

$$\rightarrow L = \frac{2\pi}{\Delta m_{JK}^2} E$$

L/E dependence for KamLAND and atmospheric is described as a straight line in L-E plane.



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Current data (ignoring solar neutrino suppression) are shown.

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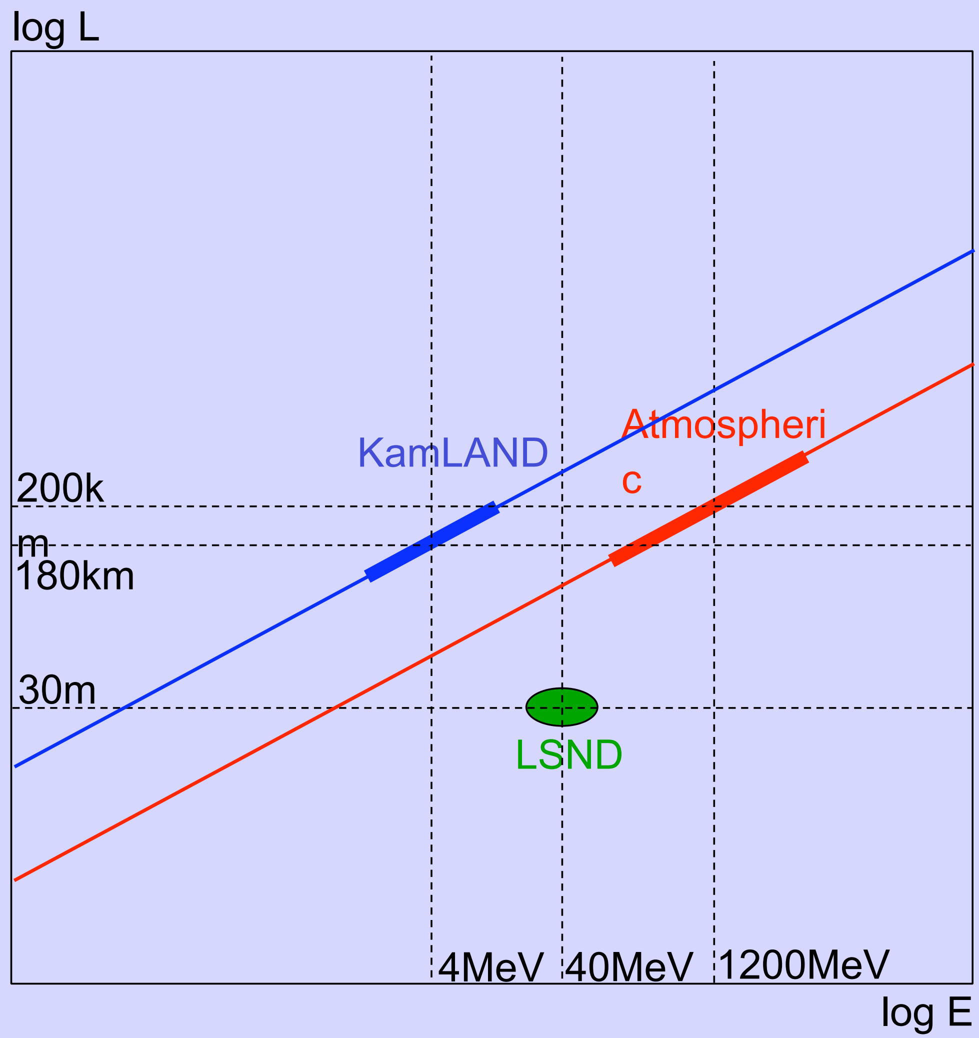

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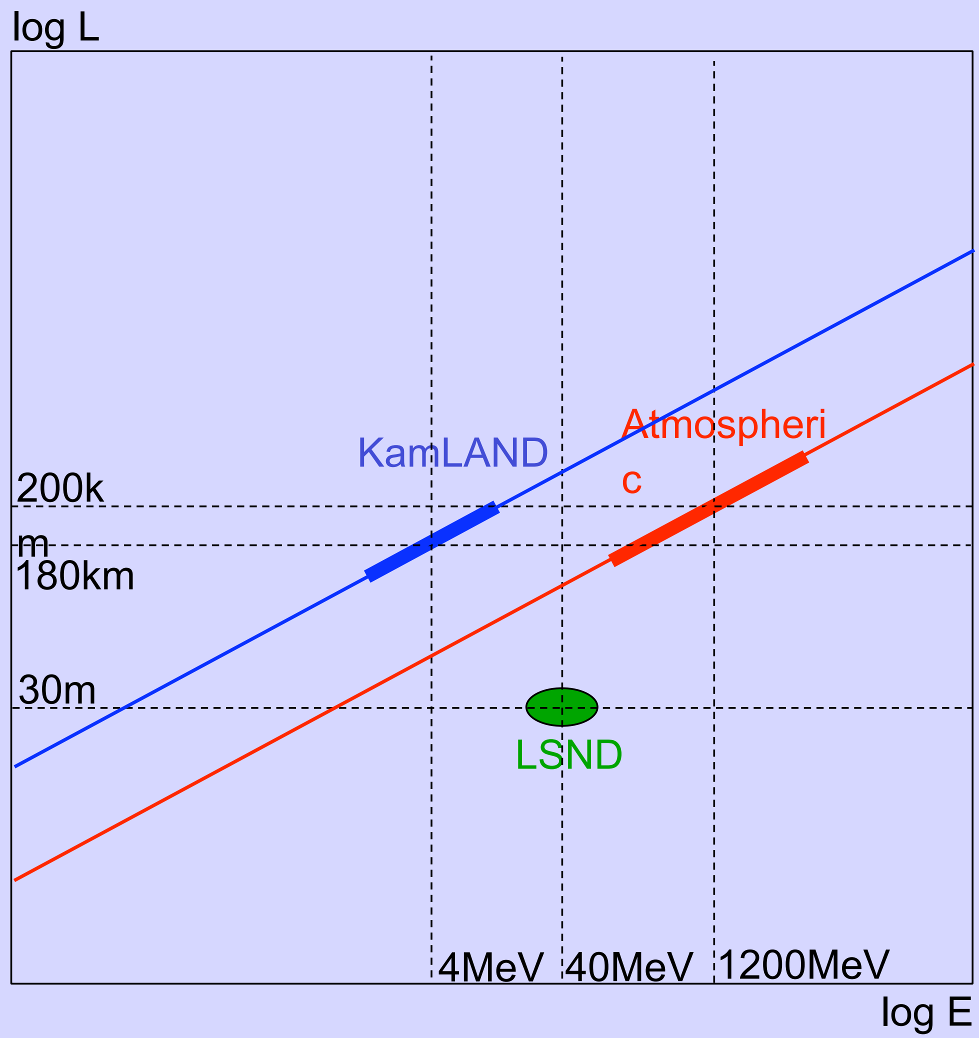
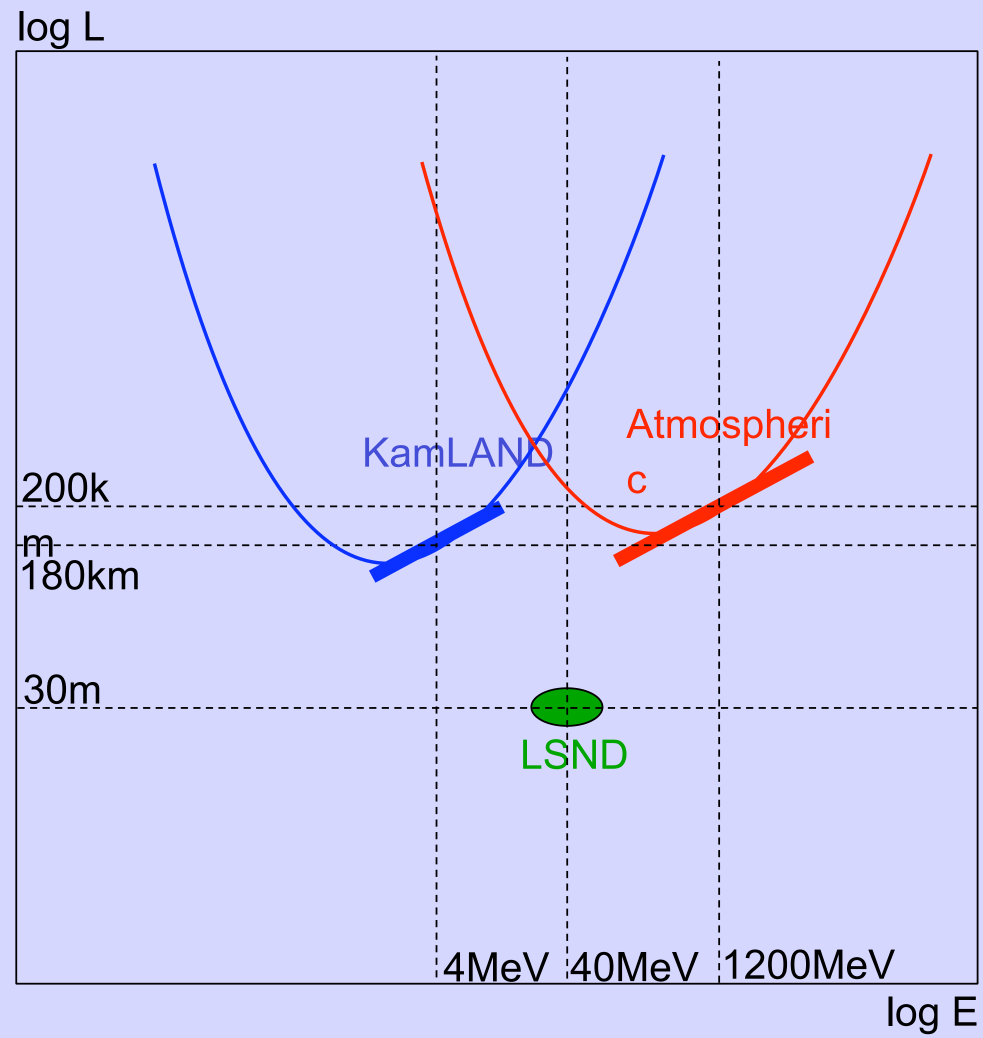
L/E dependence for KamLAND and atmospheric is described as a straight line in L-E plane.

We extrapolated 2 straight lines from 2 short segments, this is the current situation of neutrino oscillation physics



8. Tandem model

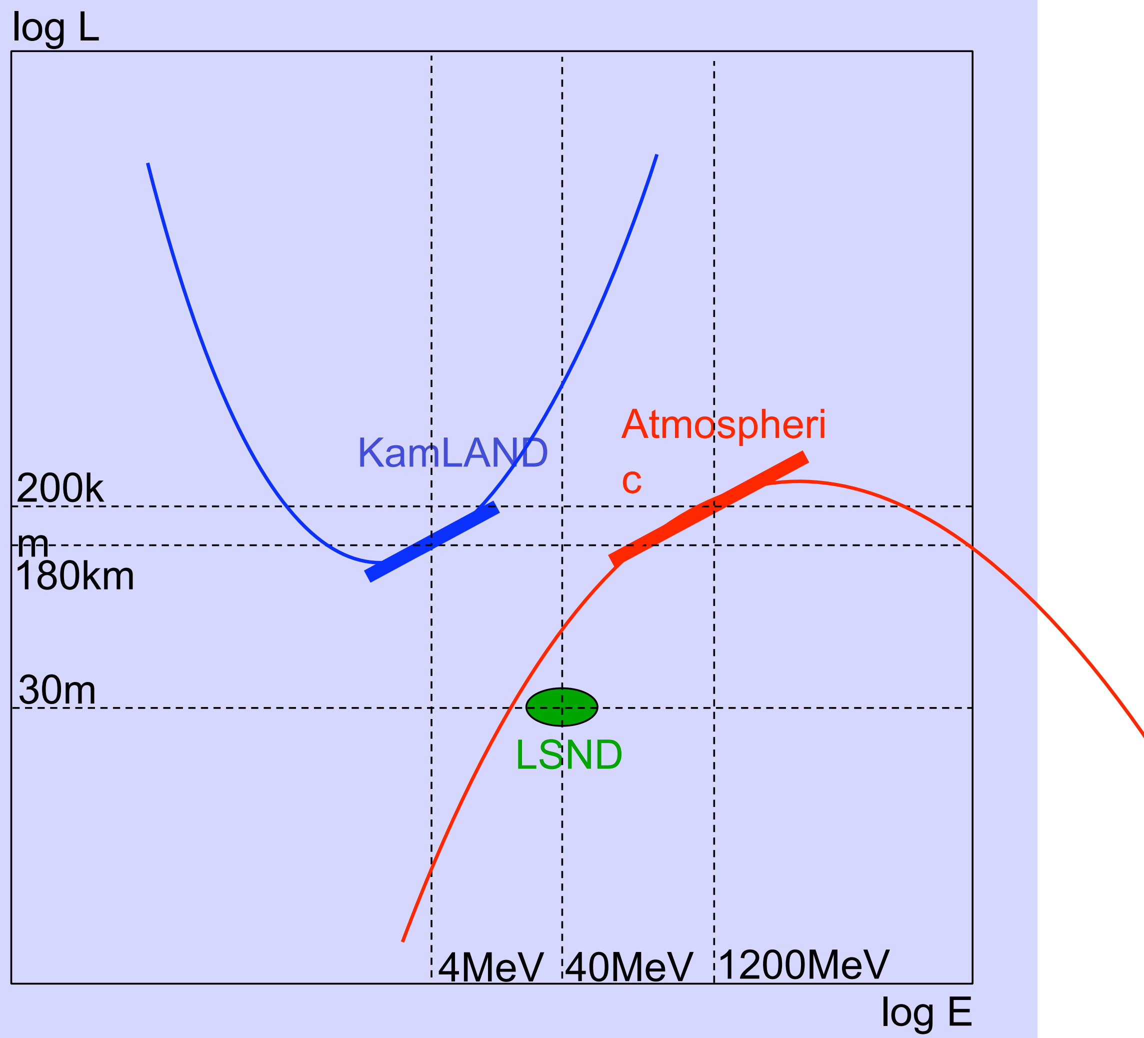
Why this is not the solution?



8. Tandem model

Why this is not the solution?

How about this?

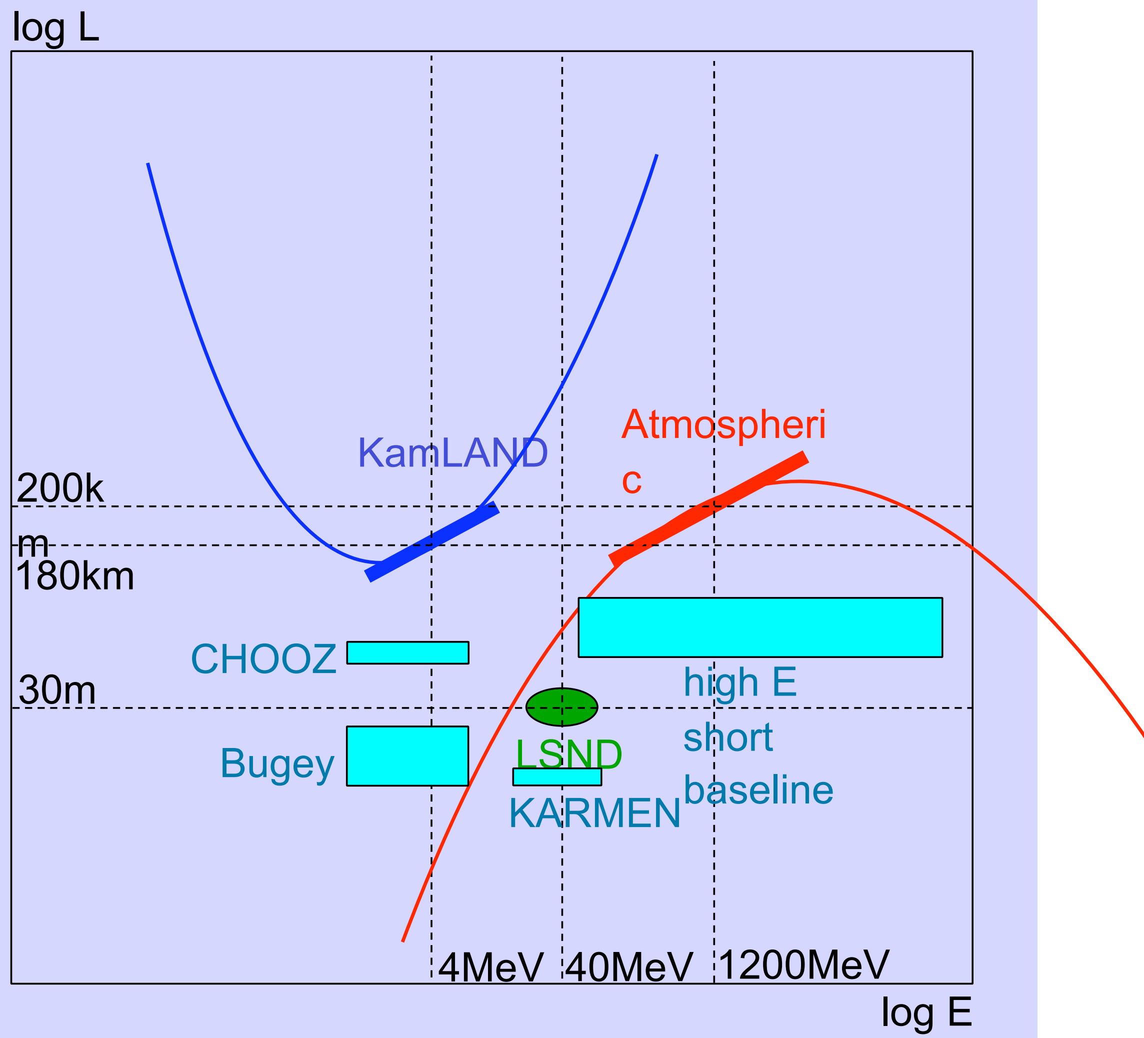


8. Tandem model

Why this is not the solution?

How about this?

No, we cannot, because such solution also gives signals to Bugey and CHOOZ.



8. Tandem model

Why this is not the solution?

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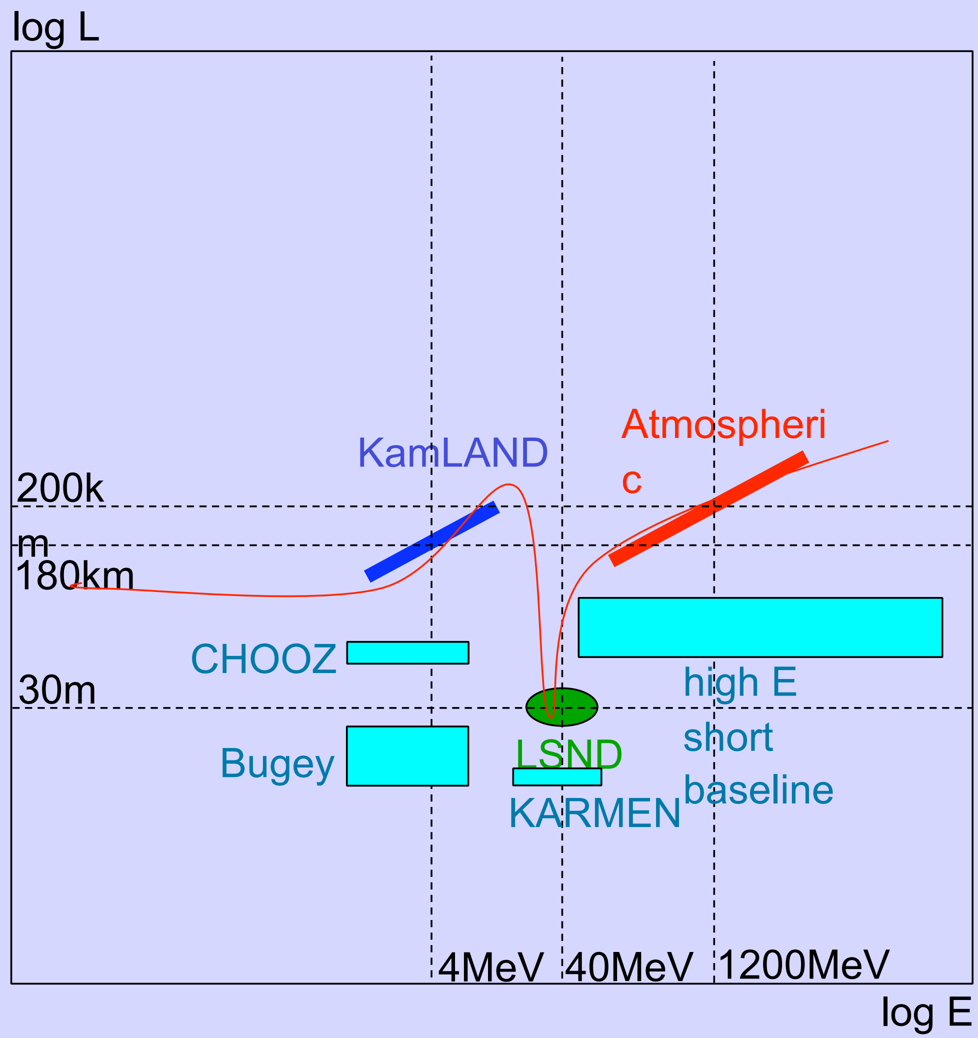
This solution satisfies all constraints from all data, but it needs many parameters

What is the minimum solution to satisfy all constraint?



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What is the minimum solution to satisfy all constraint?

Tandem model
(in fact, mixing angles also function of the energy)