Test for Lorentz and CPT violation with MiniBooNE excesses

ArXiv:1109.3480

Teppei Katori
Massachusetts Institute of Technology
Wine and Cheese seminar, Fermilab, Batavia, Nov. 11, 2011

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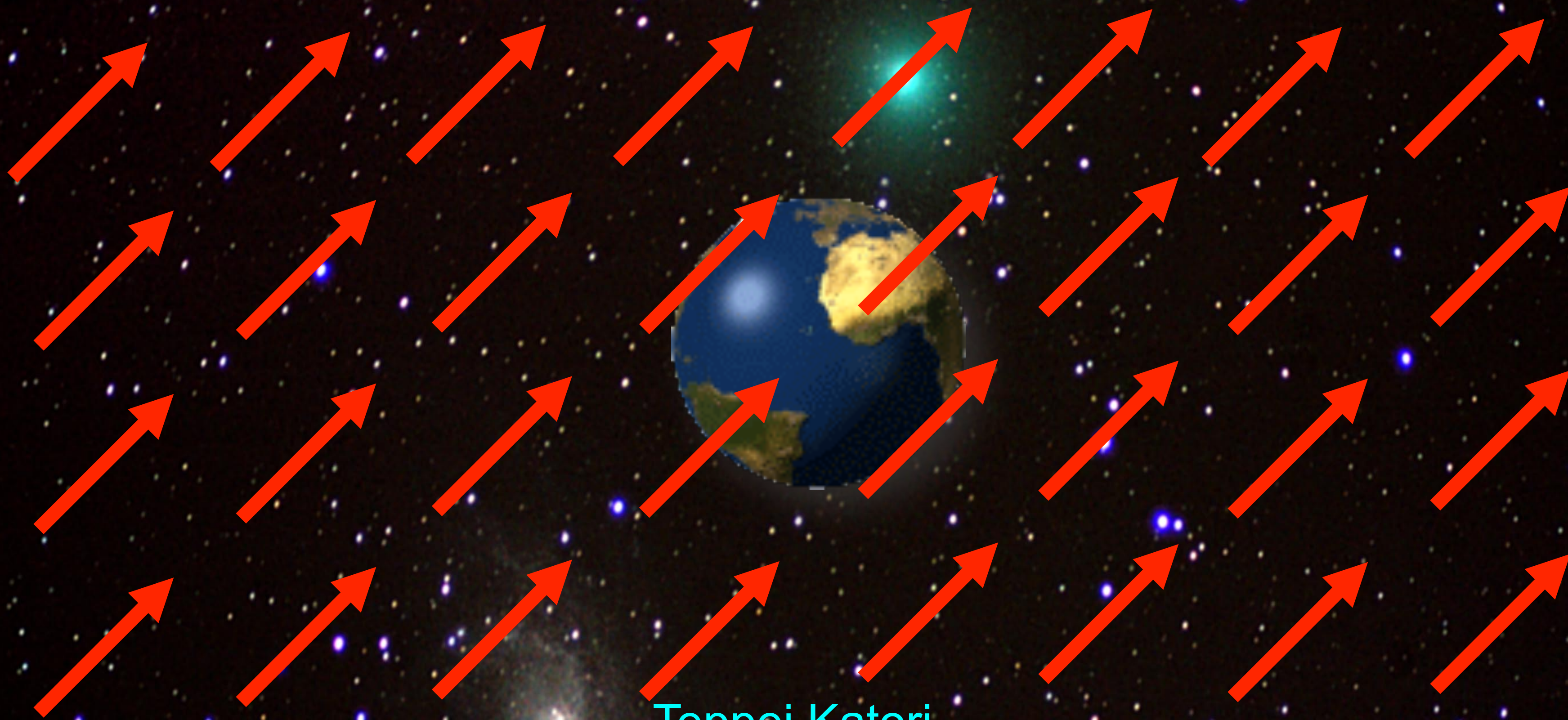

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outline

1. Spontaneous Lorentz symmetry breaking
2. What is Lorentz and CPT violation?
3. Modern test of Lorentz and CPT violation
4. Lorentz violation with neutrino oscillation
5. MiniBooNE experiment
6. Lorentz violation with MiniBooNE neutrino data
7. Lorentz violation with MiniBooNE anti-neutrino data
8. Conclusion

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3. Modern tests of Lorentz and CPT violation

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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

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

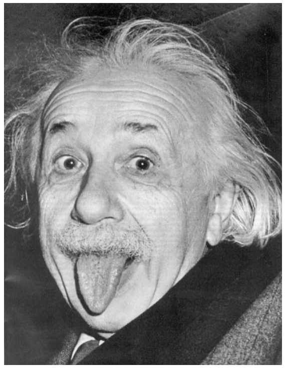
$$V(\varphi) = \frac{1}{2}\mu^2(\varphi^*\varphi) + \frac{1}{4}\lambda(\varphi^*\varphi)^2$$

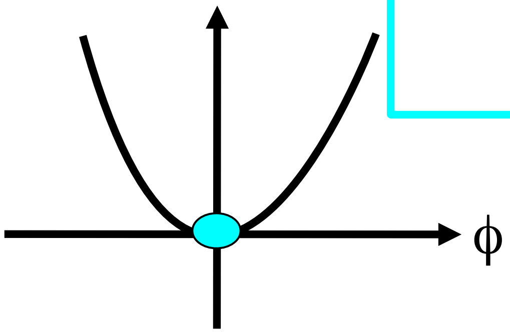
If fields have negative mass term

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

e.g.) vacuum Lagrangian for fermions

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





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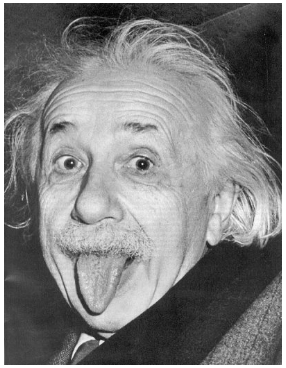
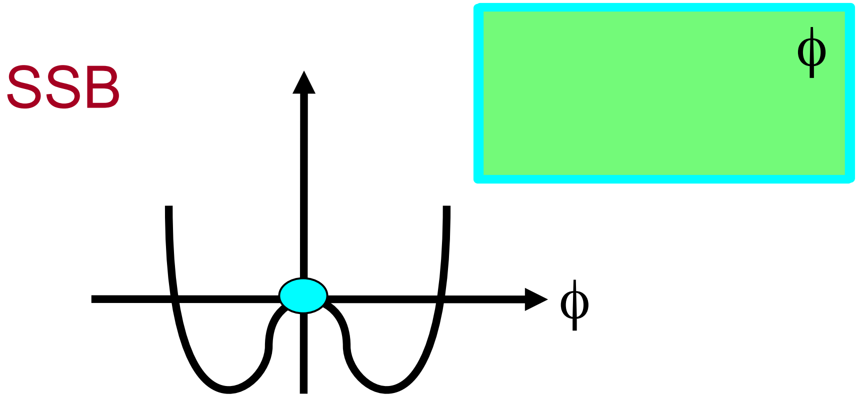


Particle acquires mass term!



Kostelecký and Samuel
PRD39(1989)683

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,

ex) scalar-vector-vector coupling

$$\phi a^{\mu} a_{\mu} \rightarrow <\phi> a^{\mu} a_{\mu}$$

If the scalar field creates negative v.e.v, then the vector field has negative square mass term

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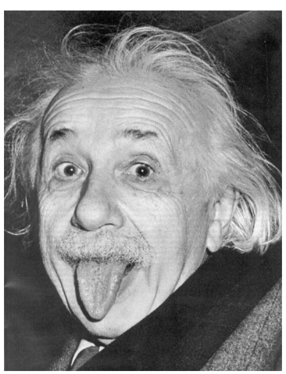

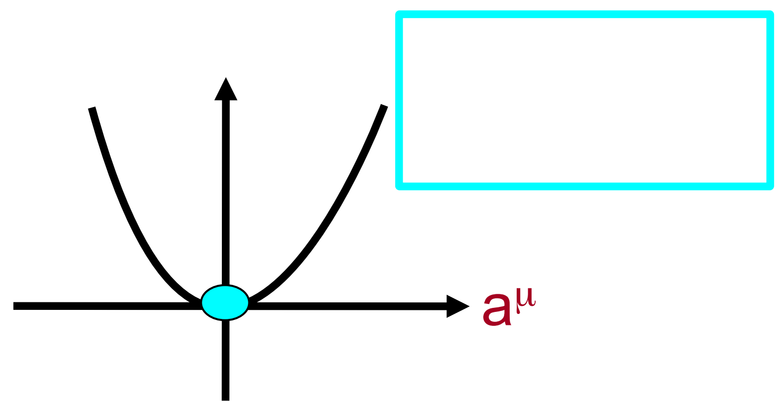

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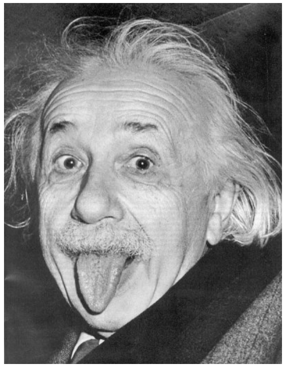

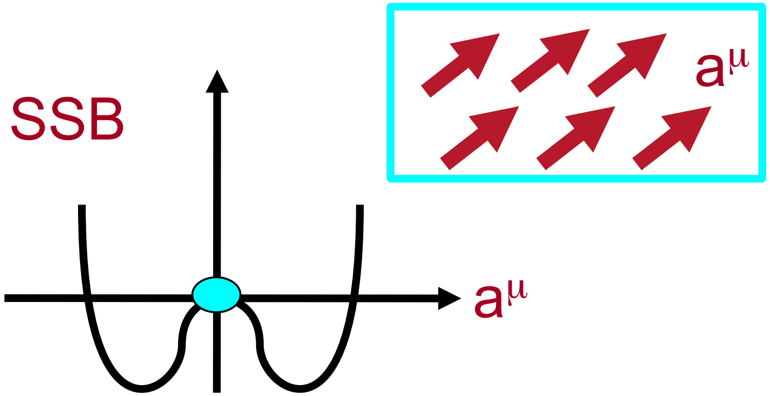

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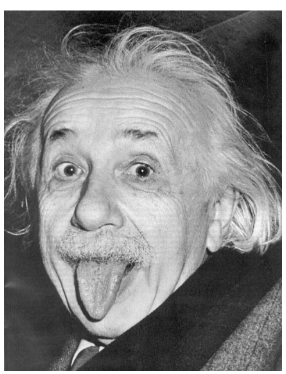
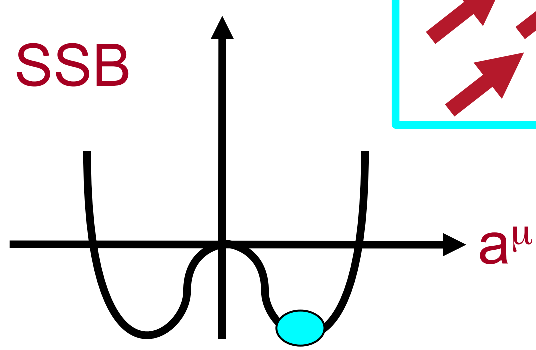
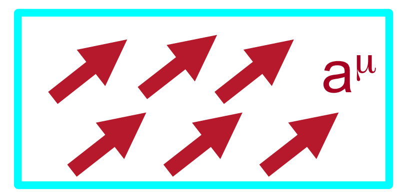


Lorentz symmetry is spontaneously broken!





1. Spontaneous Lorentz symmetry breaking

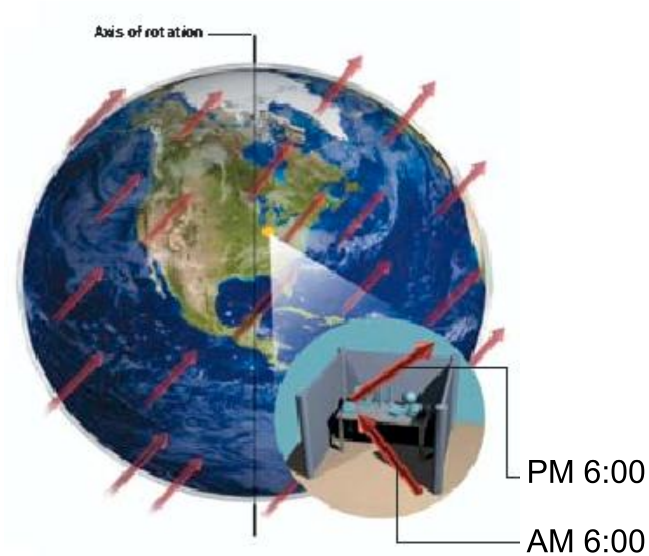
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos etc), then physical quantities may depend on the rotation of the earth.

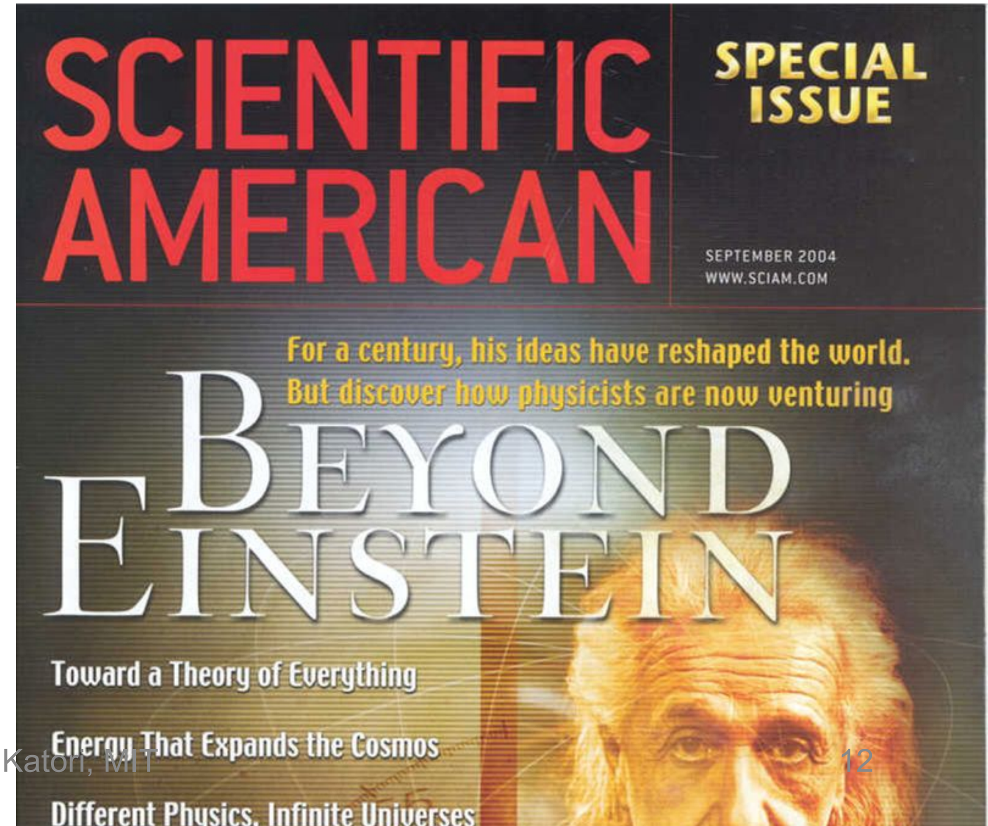
background field of the universe

vacuum Lagrangian for fermion

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

Scientific American (Sept. 2004)





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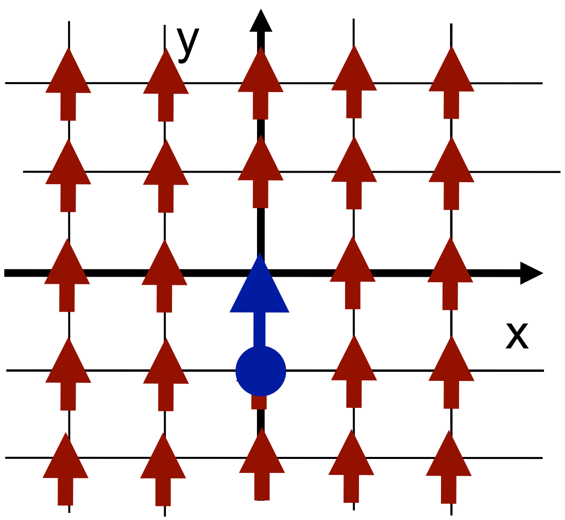
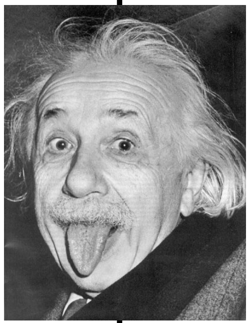
2. What is Lorentz violation?

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





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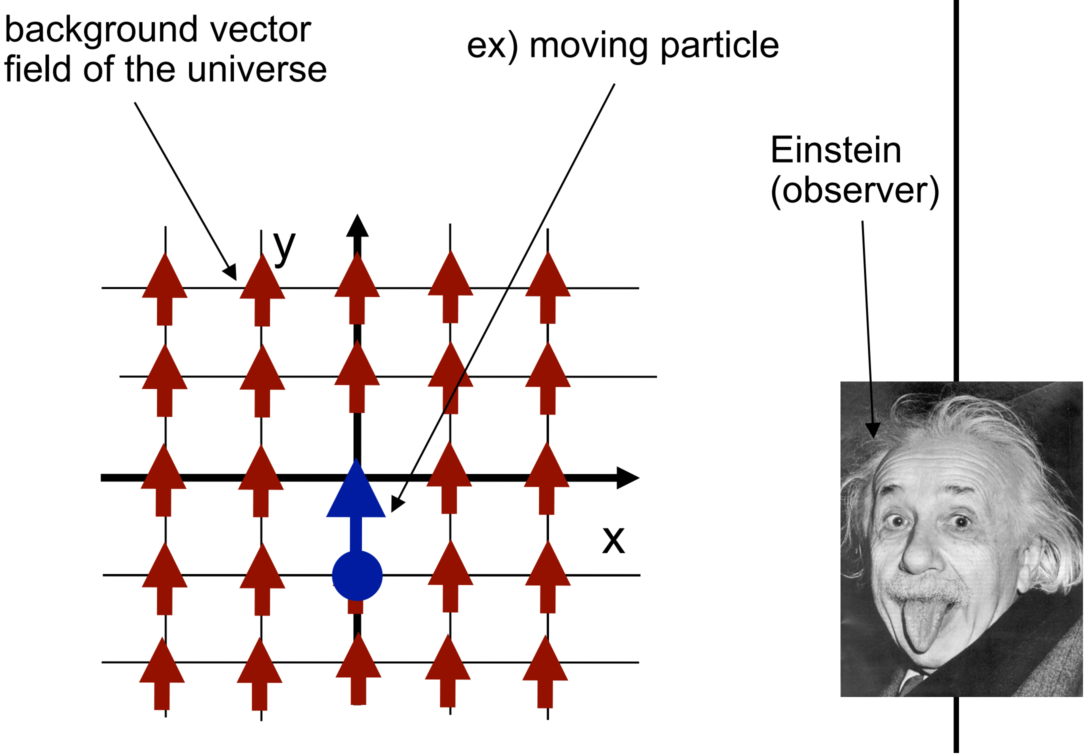
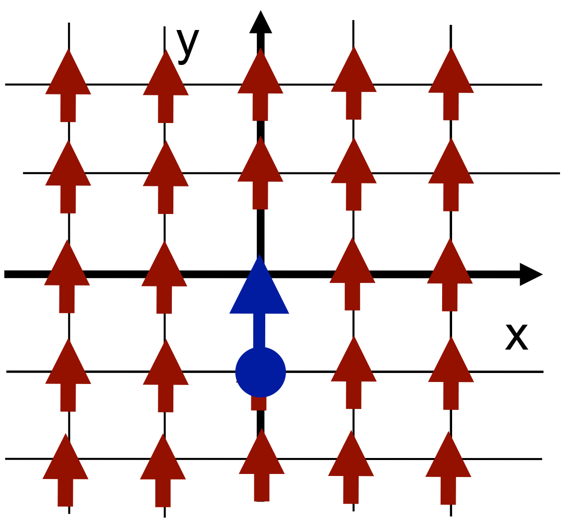
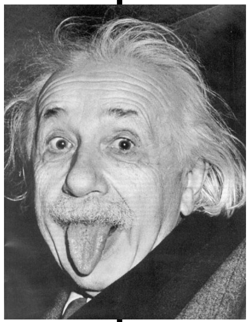


2. What is Lorentz violation?

Under the particle Lorentz Transformation;

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





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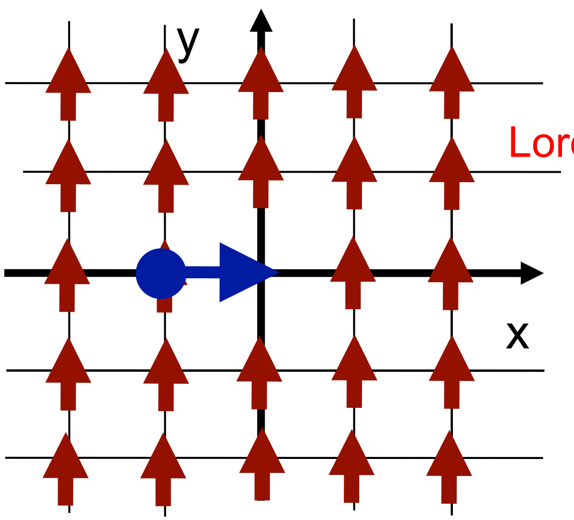
Under the particle Lorentz Transformation;

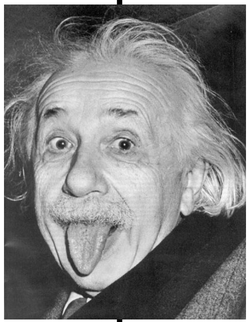
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$

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

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



Lorentz violation!



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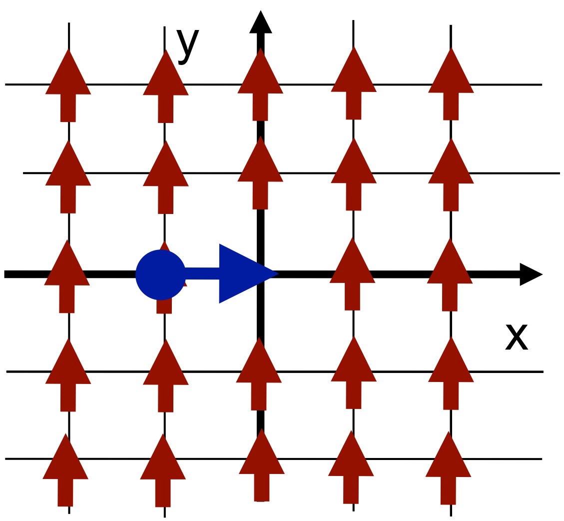
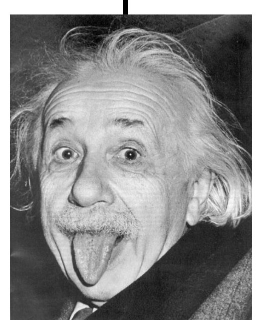
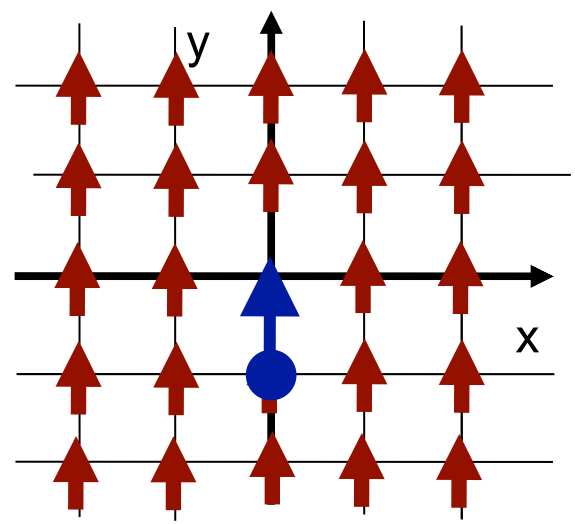




Under the observer Lorentz Transformation;

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



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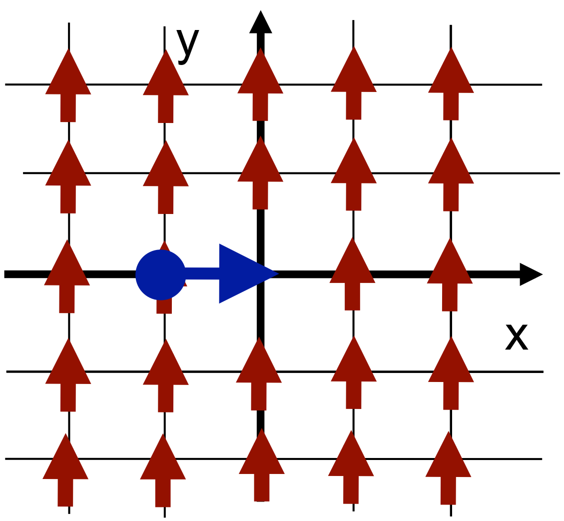

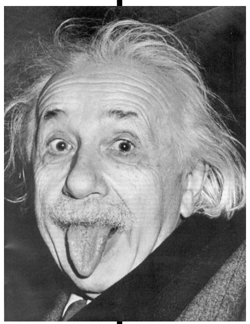

Under the observer Lorentz Transformation;

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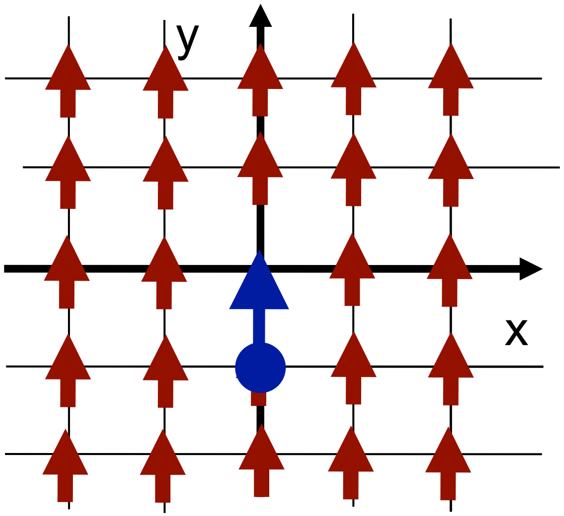
$$x \rightarrow \Lambda^{-1}x$$



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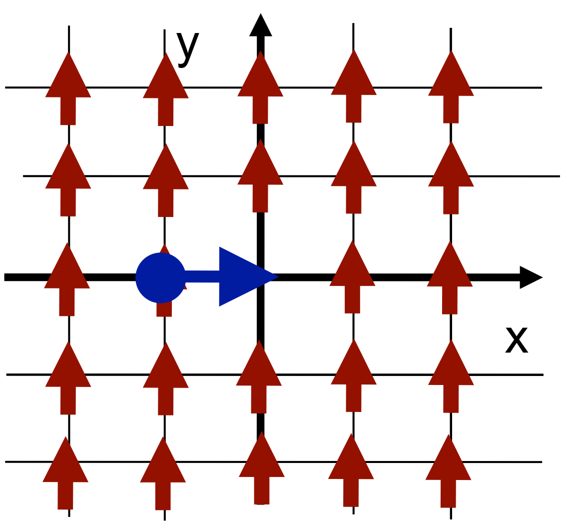
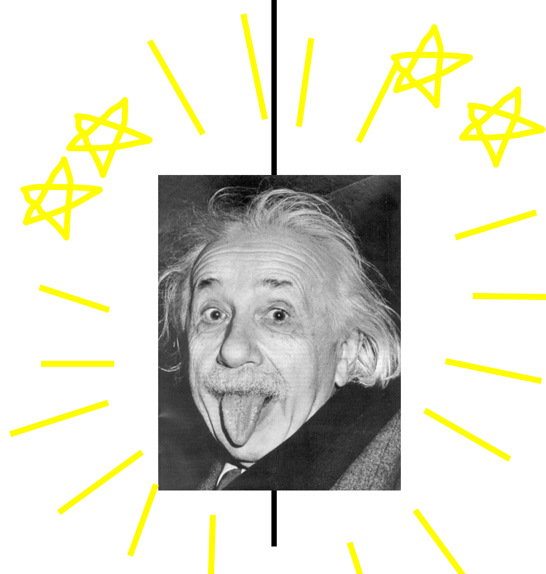


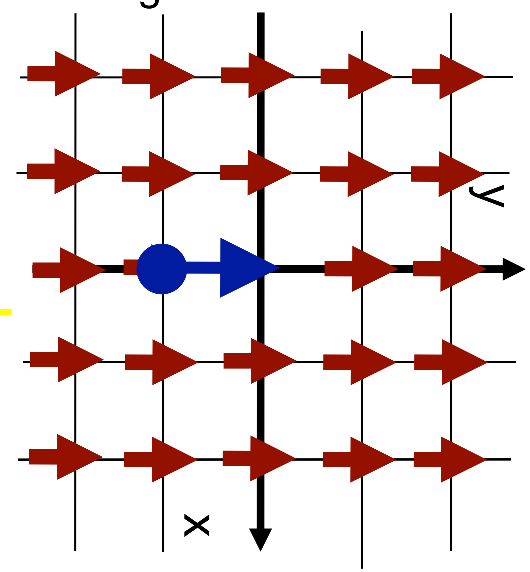
Under the observer Lorentz Transformation;

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

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

any observers agree for all observations





2. What is CPT violation?

Parity violation for weak current

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

under the parity transformation

$$\gamma_\mu \xrightarrow{P} P\gamma_\mu P^{-1} = -\gamma_\mu \quad \text{parity odd} \qquad \gamma_\mu\gamma_5 \xrightarrow{P} P\gamma_\mu\gamma_5 P^{-1} = \gamma_\mu\gamma_5 \quad \text{parity even}$$

therefore, the current is not invariant under the parity transformation

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

The combination cannot be invariant under the parity transformation, because each term change its sign differently.

In the case of CPT violation, the combination of CPT even and CPT odd term violate CPT symmetry, then particle mass and anti-particle mass need not to be different for CPT violation.

2. What is CPT violation?

What is the analogy of Parity violation?

QED Lagrangian

CPT even CPT even CPT even....

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

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

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

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

2. What is CPT violation?

Lorentz violation makes CPT-odd term in Lagrangian.

QED Lagrangian with Lorentz violating terms

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

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

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

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

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

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

Greenberg, PRL(2002)231602

2. CPT violation implies Lorentz violation

Lorentz invariance → CPT → Lorentz invariance of propagator

CPT violation implies Lorentz violation in interactive quantum field theory.

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3. 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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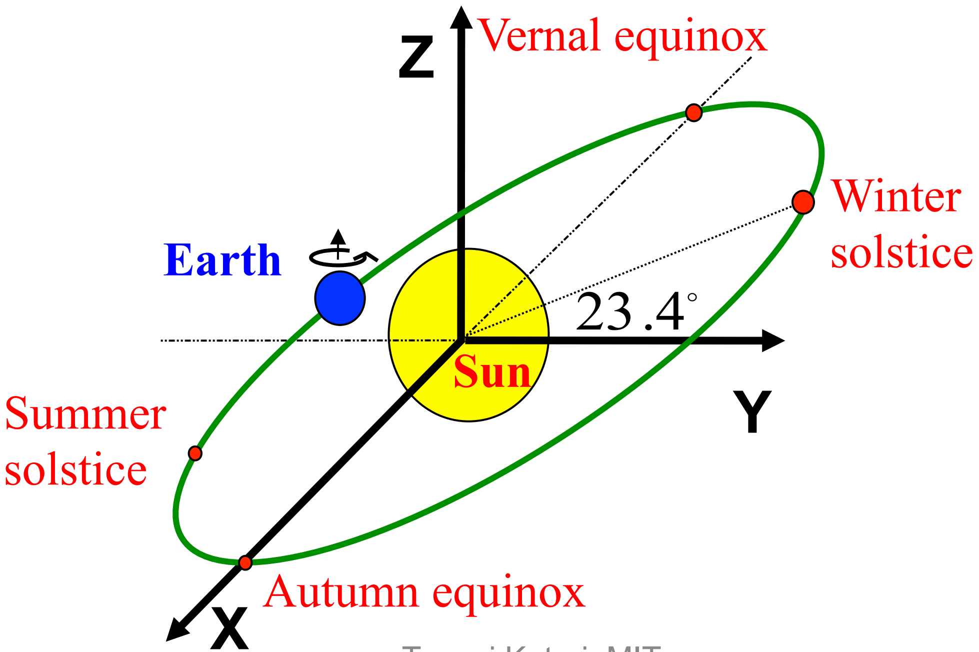
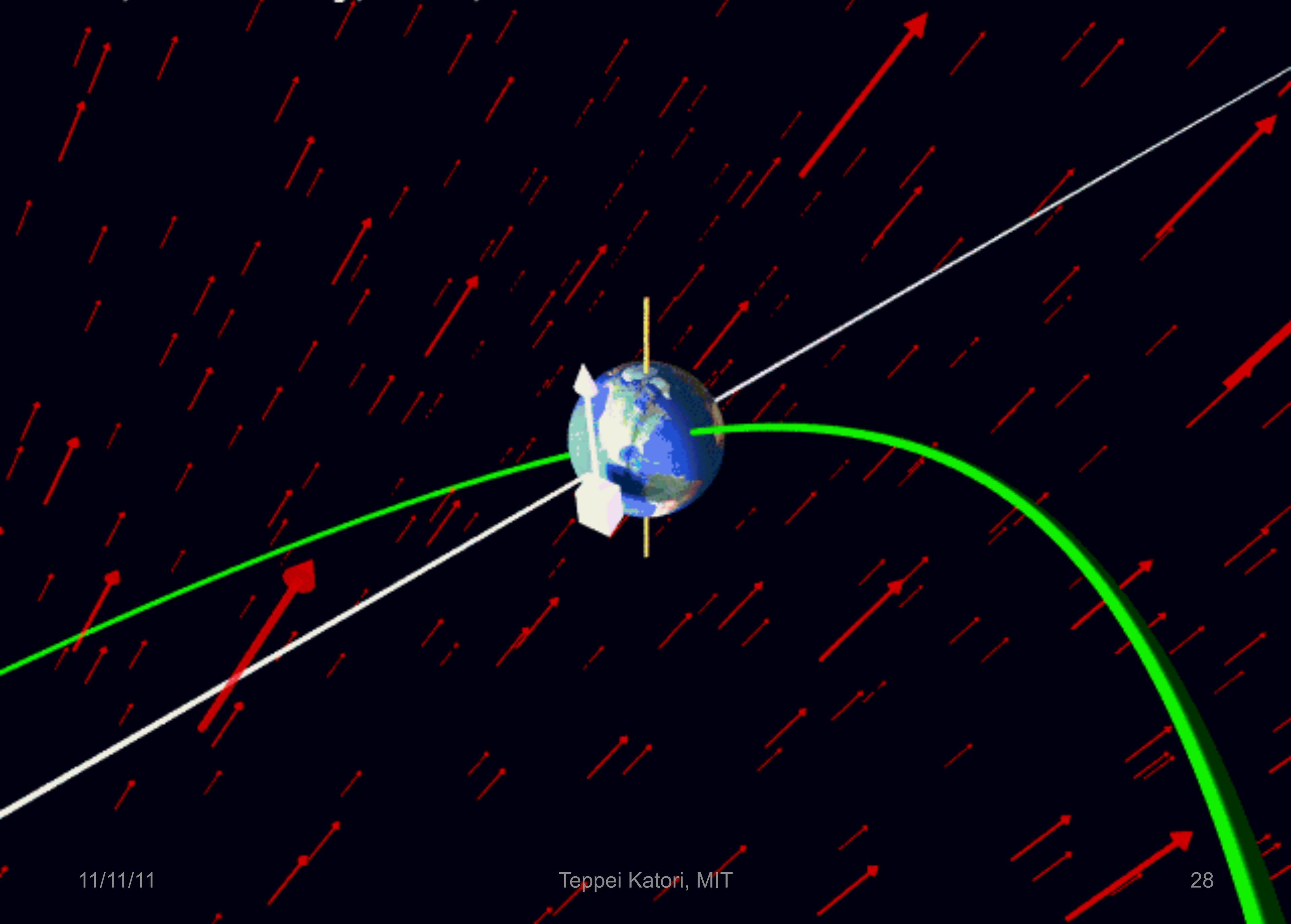
The standard choice of the coordinate is Sun-centred coordinates



Bluhm, Kostelecky, Lane, Russell PRL 2002



Colladay and Kostelecký
PRD55(1997)6760

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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)

$$L_{SME} = L_{SM} + \delta L$$
$$\delta L = \bar{\Psi}\gamma_{\mu} a^{\mu}\Psi + \bar{\Psi}\gamma_{\mu} c^{\mu\nu}\partial_{\nu}\Psi \ldots$$

Kostelecký and Mewes
PRD69(2004)076002

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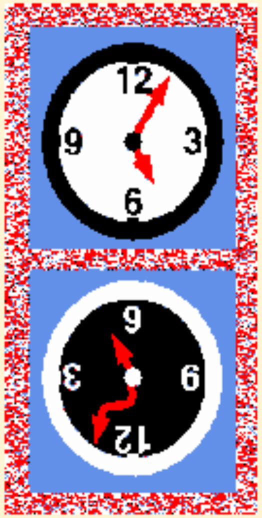
The observables can be, energy spectrum, frequency of atomic transition, neutrino oscillation probability, etc. Among the non standard phenomena predicted by Lorentz violation, the smoking gun is the sidereal time dependence of the observables.

3. Modern tests of Lorentz violation

Dedicated group of people formed a meeting since 1998.

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



Meeting home

Registration

Program

Proceedings

Travel

Accommodations

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

3. Modern tests of Lorentz violation

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

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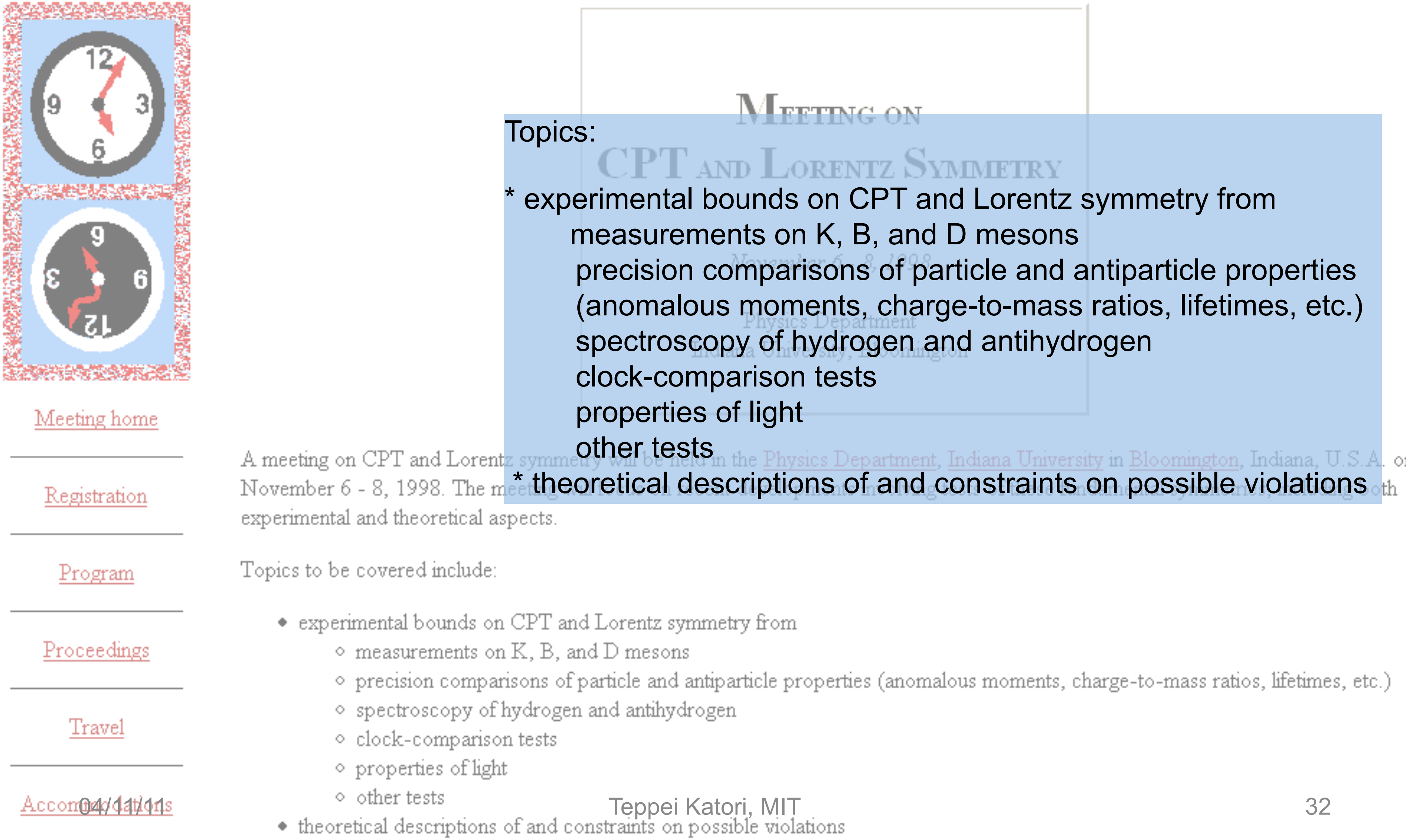
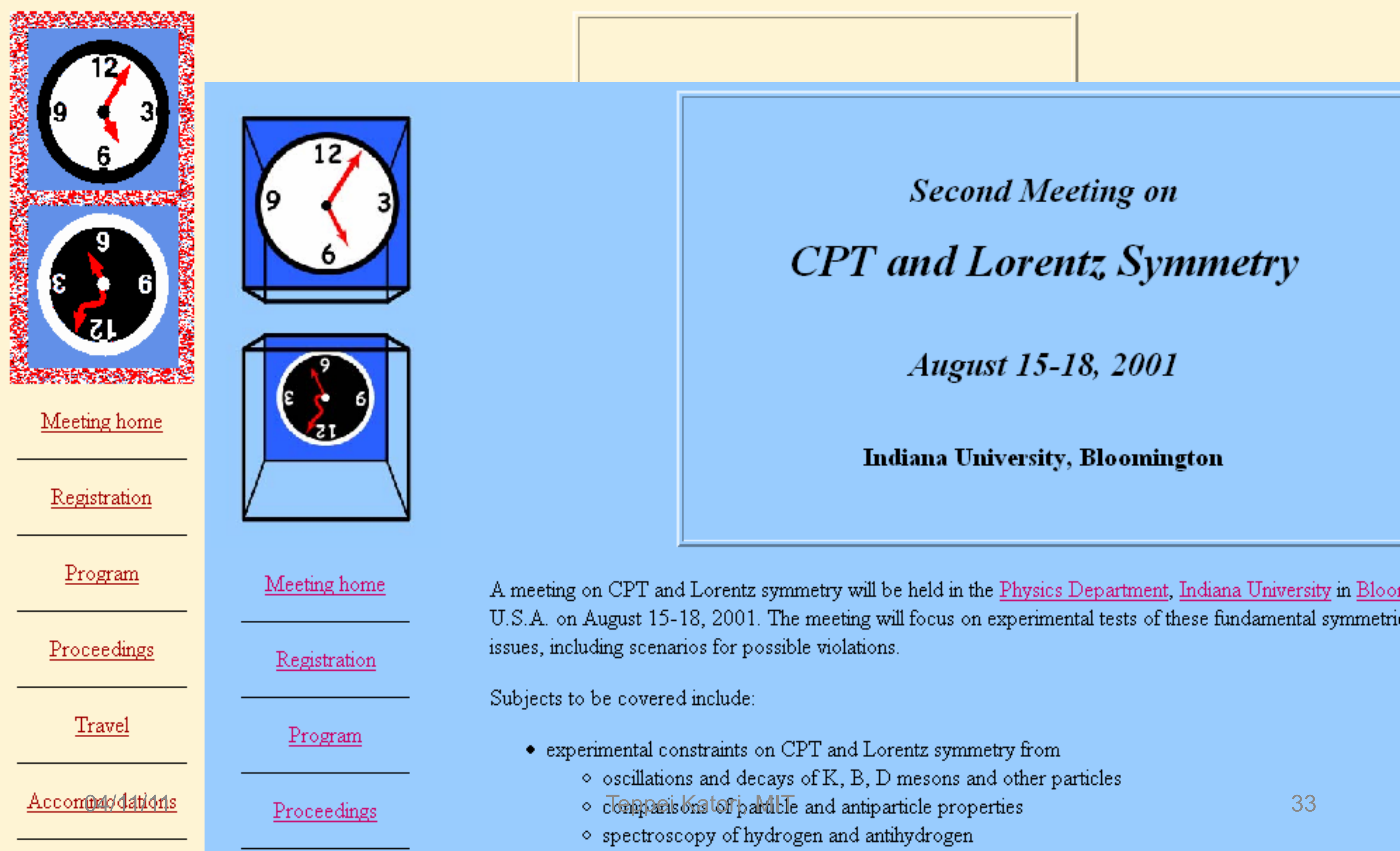


3. Modern tests of Lorentz violation

The second meeting was in 2001.

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



Meeting home
Registration
Program
Proceedings
Travel
Accommodations

Meeting home
Registration
Program
Proceedings

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 Bloo[...] U.S.A. on August 15-18, 2001. The meeting will focus on experimental tests of these fundamental symmetri[...] issues, including scenarios for possible violations.

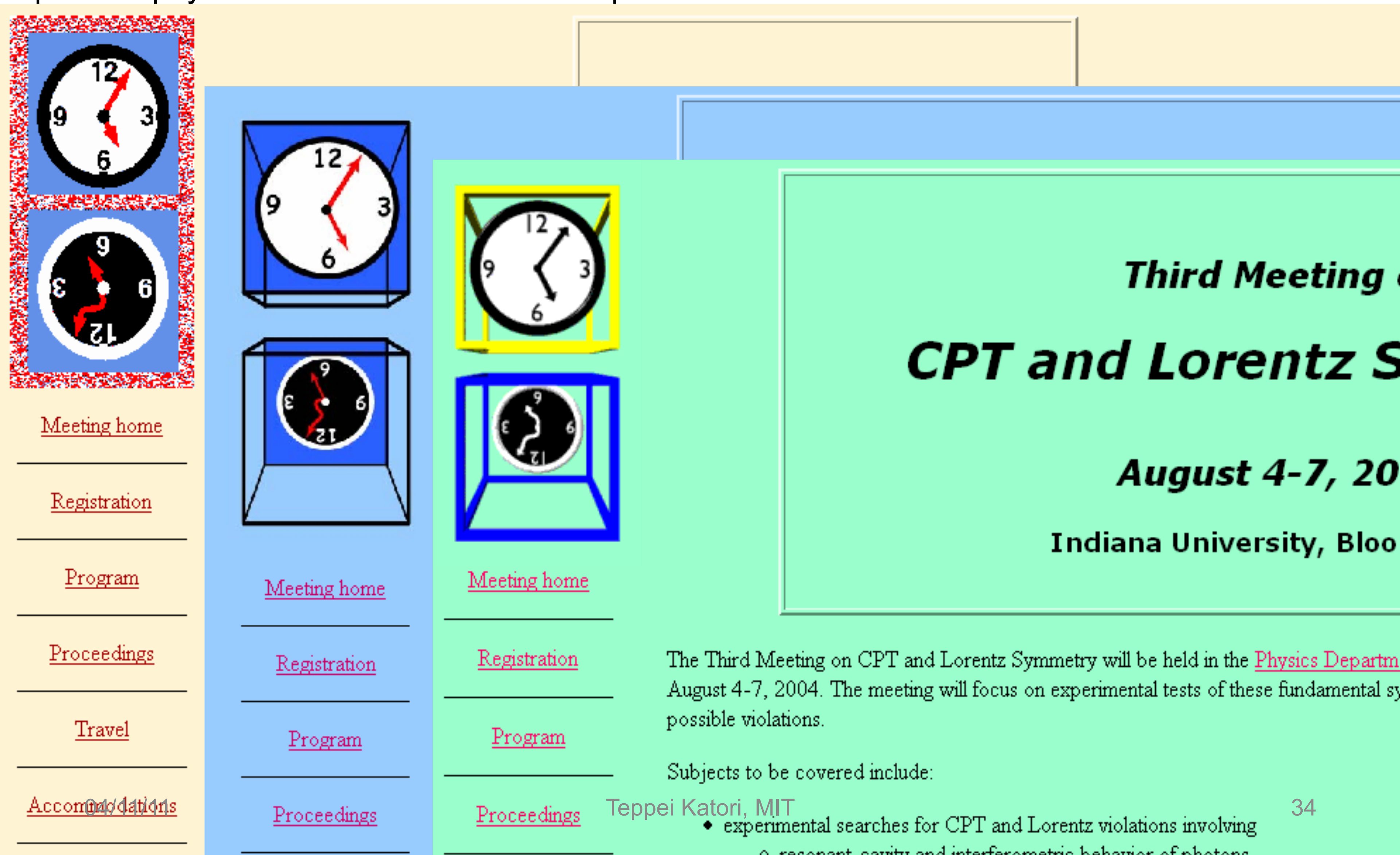
Subjects to be covered include:

- 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

3. Modern tests of Lorentz violation

The second meeting was in 2004.

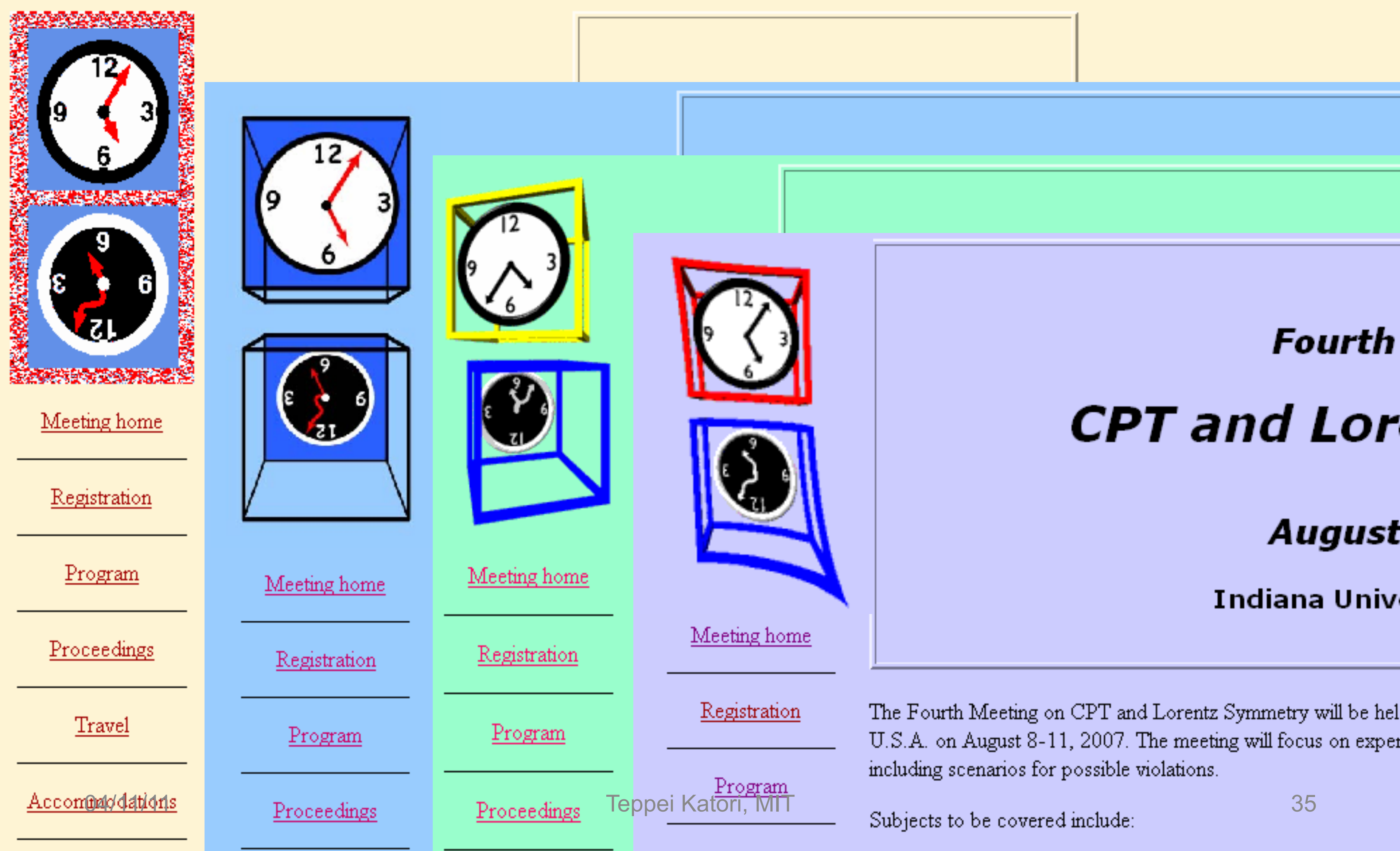
http://www.physics.indiana.edu/~kostelec/faq.html



3. Modern tests of Lorentz violation

The second meeting was in 2007.

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



3. Modern tests of Lorentz violation

The latest meeting was in summer 2010.

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

3. Modern tests of Lorentz violation

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

Topics:

* searches for CPT and Lorentz violations involving
  - birefringence and dispersion from cosmological sources
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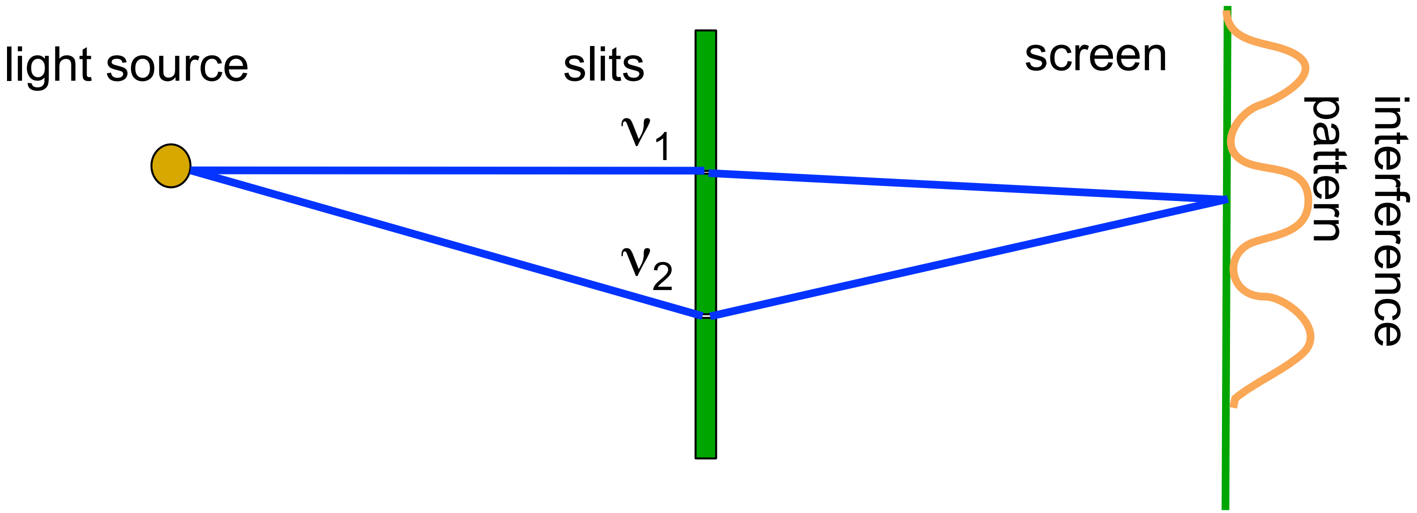
  - equivalence principle
  - gauge and Higgs particles
  - high-energy astrophysical observations
  - laboratory and gravimetric tests of gravity
  - matter interferometry
  - neutrino oscillations
  - oscillations and decays of K, B, D mesons
  - particle-antiparticle comparisons
  - post-newtonian gravity 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}
Steven Chu
PRL106(2011)151102
CERN Antiproton Decelerator
(M_p-M̄_p)/M_p<10^{-8}
Nature419(2002)456
Tevatron and LEP
-5.8x10^{-12}<κ_tr-4/3c_e^{00}<1.2x10^{-11}
GRB vacuum birefringence
κ_{e+}, κ_{o-}<10^{-37}
PRL97(2006)140401
Double gas maser
b_n(rotation)<10^{-33}GeV
b_n(boost)<10^{-27}GeV
g-2 Δω_a measurement
b^μ <10^{-23} GeV
KTeV/KLOE (strange)
Δa_K<10^{-22} GeV
proceedings of Lorentz and CPT symmetry I, II, III, IV, V (world scientific)
Proceedings of the Meeting on
CPT and Lorentz Symmetry
Second Meeting on CPT and Lorentz Symmetry
Third Meeting on CPT and Lorentz Symmetry
Fourth Meeting on CPT and Lorentz Symmetry
Fifth Meeting on CPT and Lorentz Symmetry
Editor
V. Alan Kostelecký
World Scientific
Δc/c<10^{-16}
LSND
PRD72(2005)076004
MINOS ND
PRL101(2008)151601
MINOS FD
PRL105(2010)151601
IceCube
PRD82(2010)112003
MiniBooNE
arXiv:1109.3480

4. Lorentz violation with neutrino oscillation

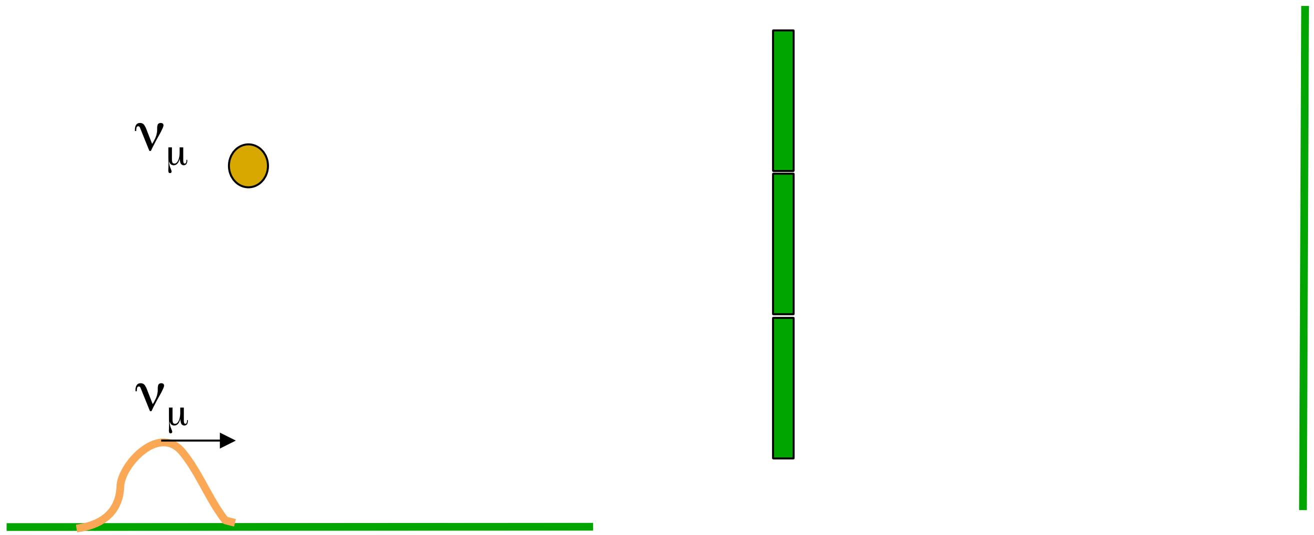
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

4. 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.

4. Lorentz violation with neutrino oscillation

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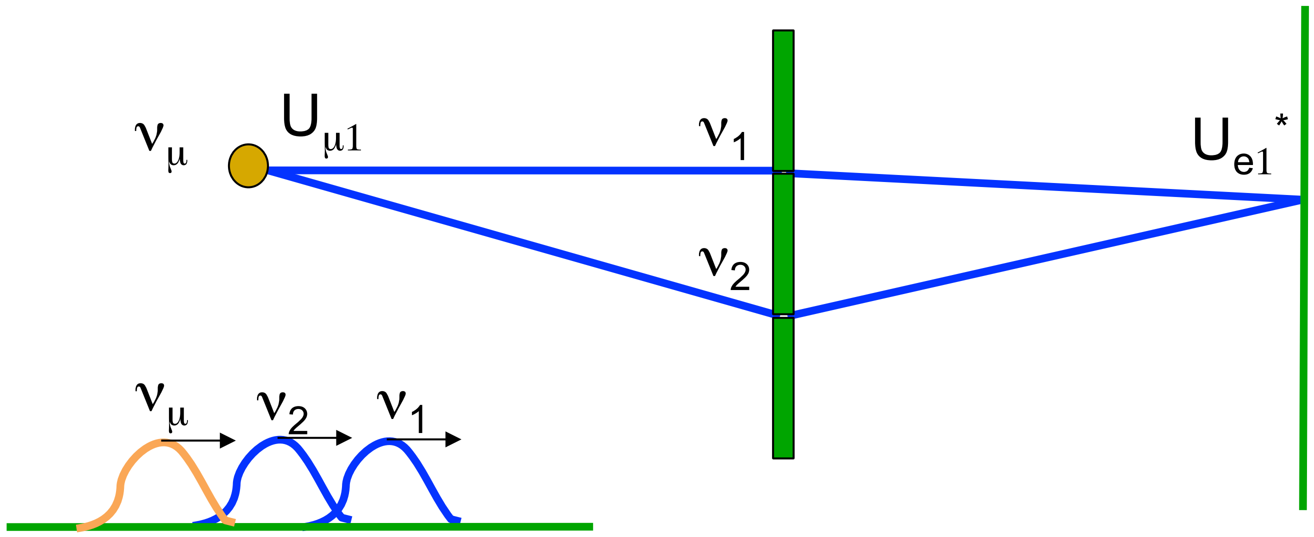

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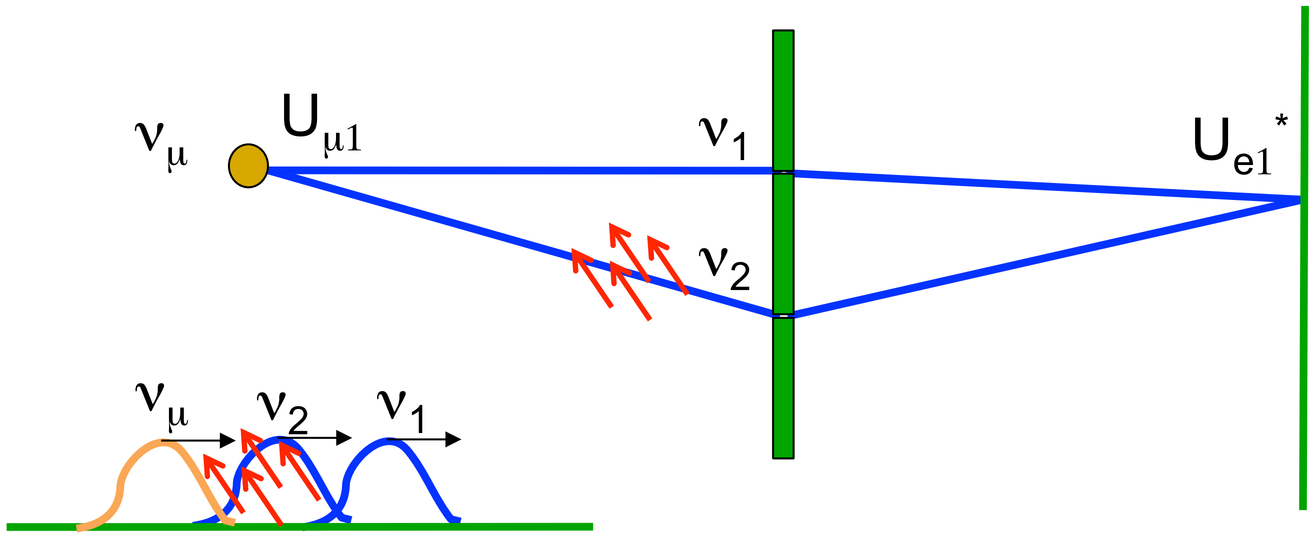

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

4. Lorentz violation with neutrino oscillation

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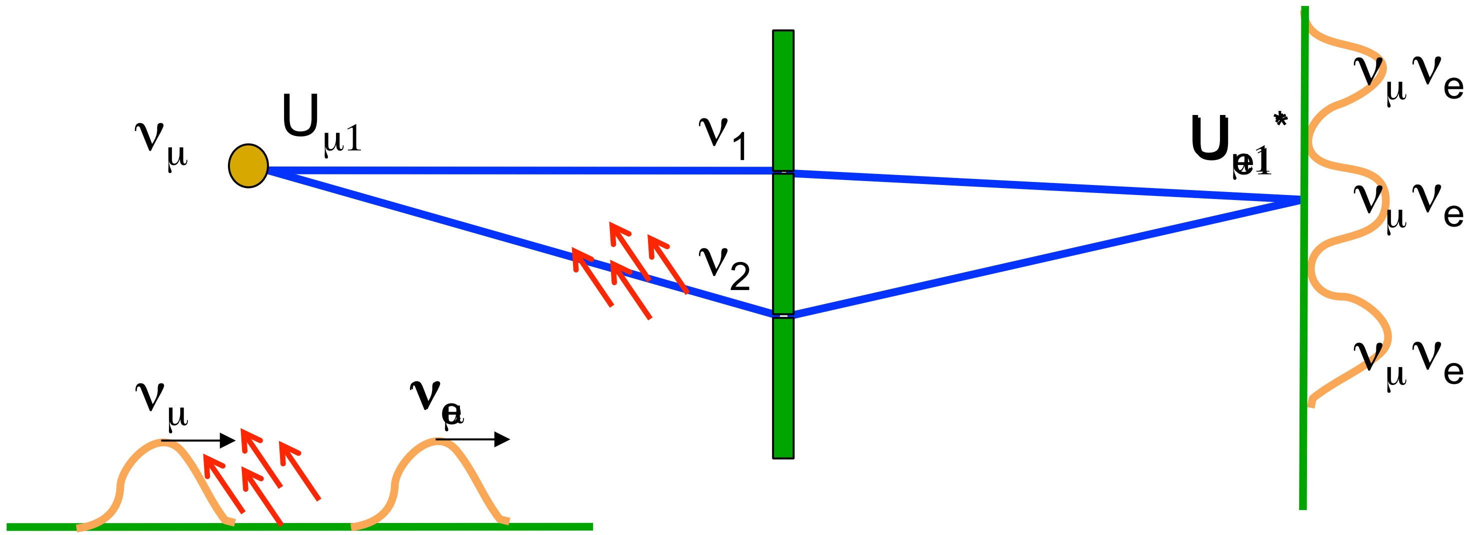


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different coupling with Lorentz violating field, 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).

4. 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)

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

Especially, if we want to see the oscillatory shape of neutrino oscillation,

$$\frac{\Delta_{ij}(E)}{2} L \approx 1 \longrightarrow L \propto [\Delta_{ij}(E)]^{-1}$$

In the case of massive neutrino oscillation model,

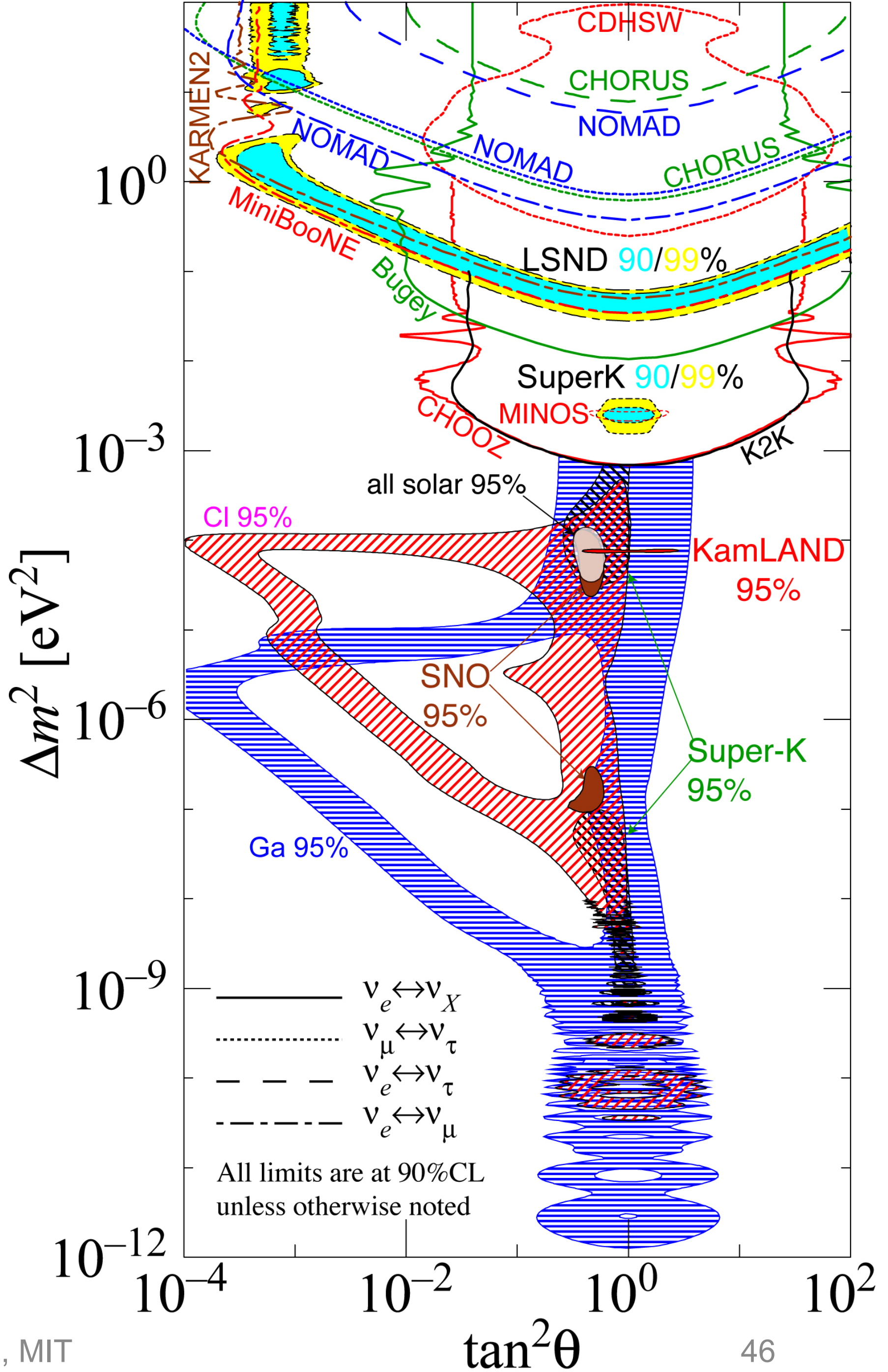
$$\frac{\Delta_{ij}(E)}{2} L \approx \frac{\Delta m^2}{4E} L \approx 1 \longrightarrow L \propto E$$

4. Neutrino standard Model (νSM)

This is the world data of neutrino oscillation, the positive oscillation signals are pinned down in very narrow region, and vast regions are rejected.

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

What is model independent diagram look like?

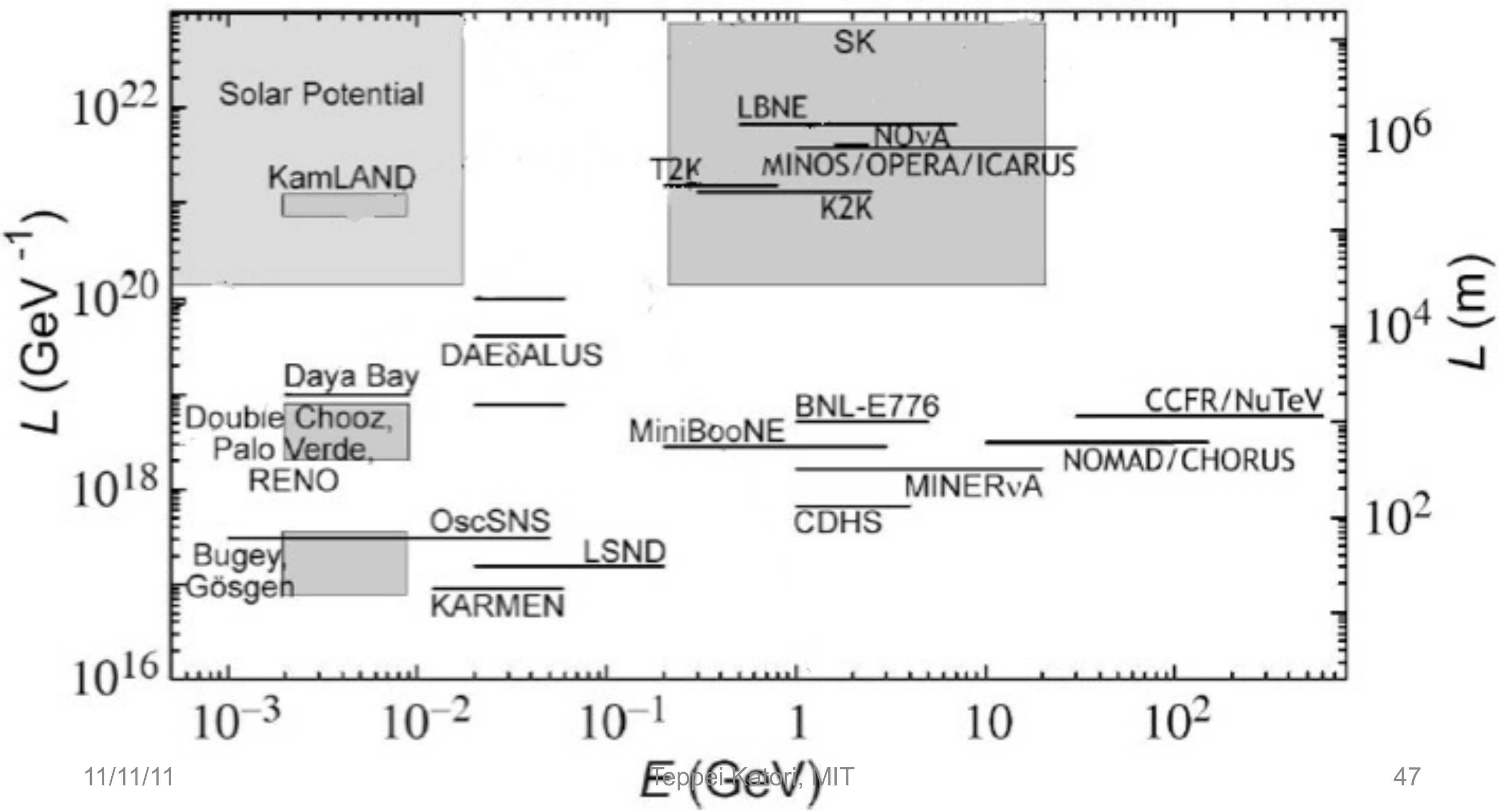


http://hitoshi.berkeley.edu/neutrino

Diaz and Kostelecký
PLB700(2011)25

4. Lorentz violation with neutrino oscillation

Model independent neutrino oscillation data is the function of neutrino energy and baseline.



Diaz and Kostelecký
PLB700(2011)25

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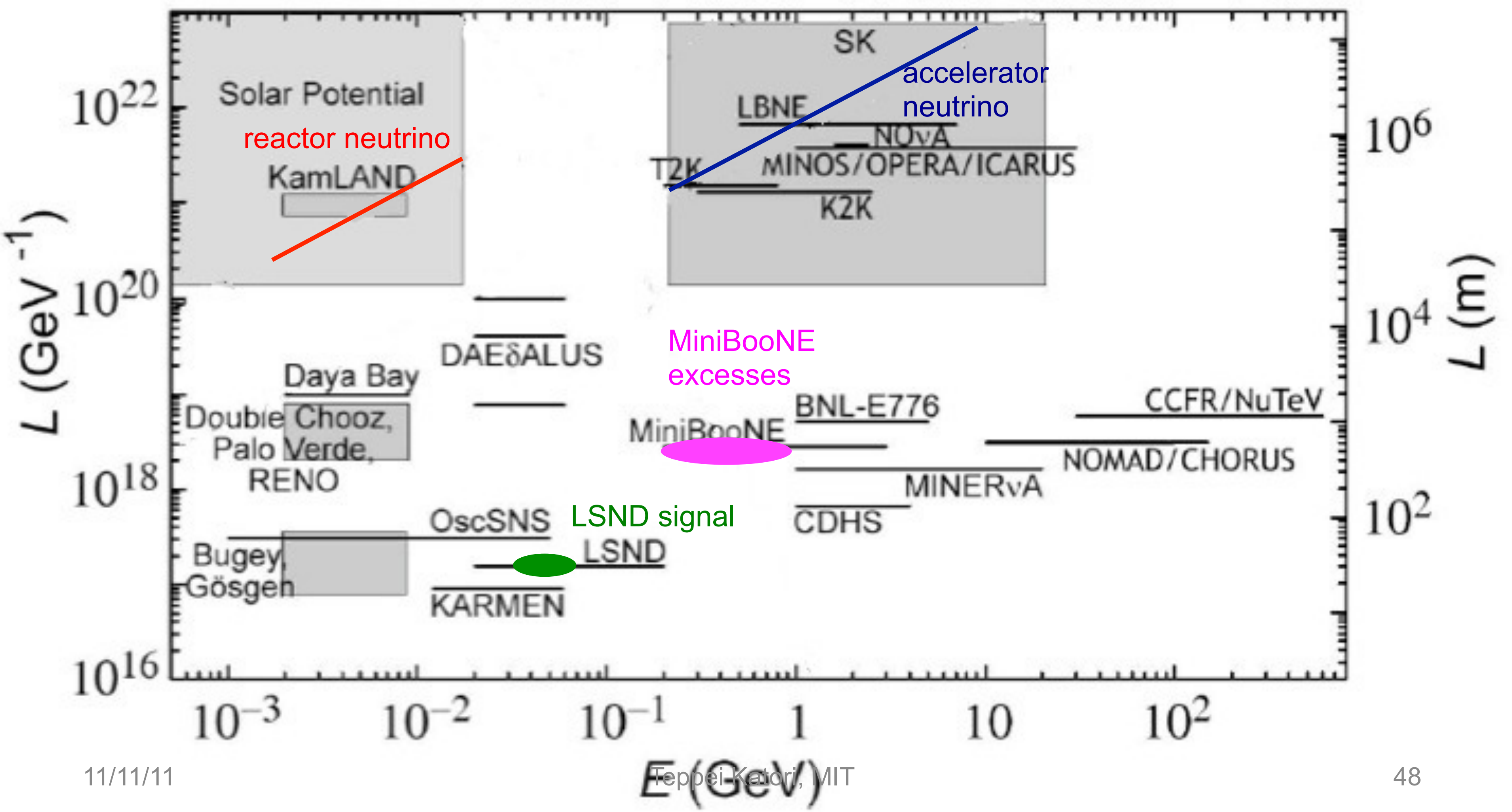

Diaz and Kostelecký
PLB700(2011)25

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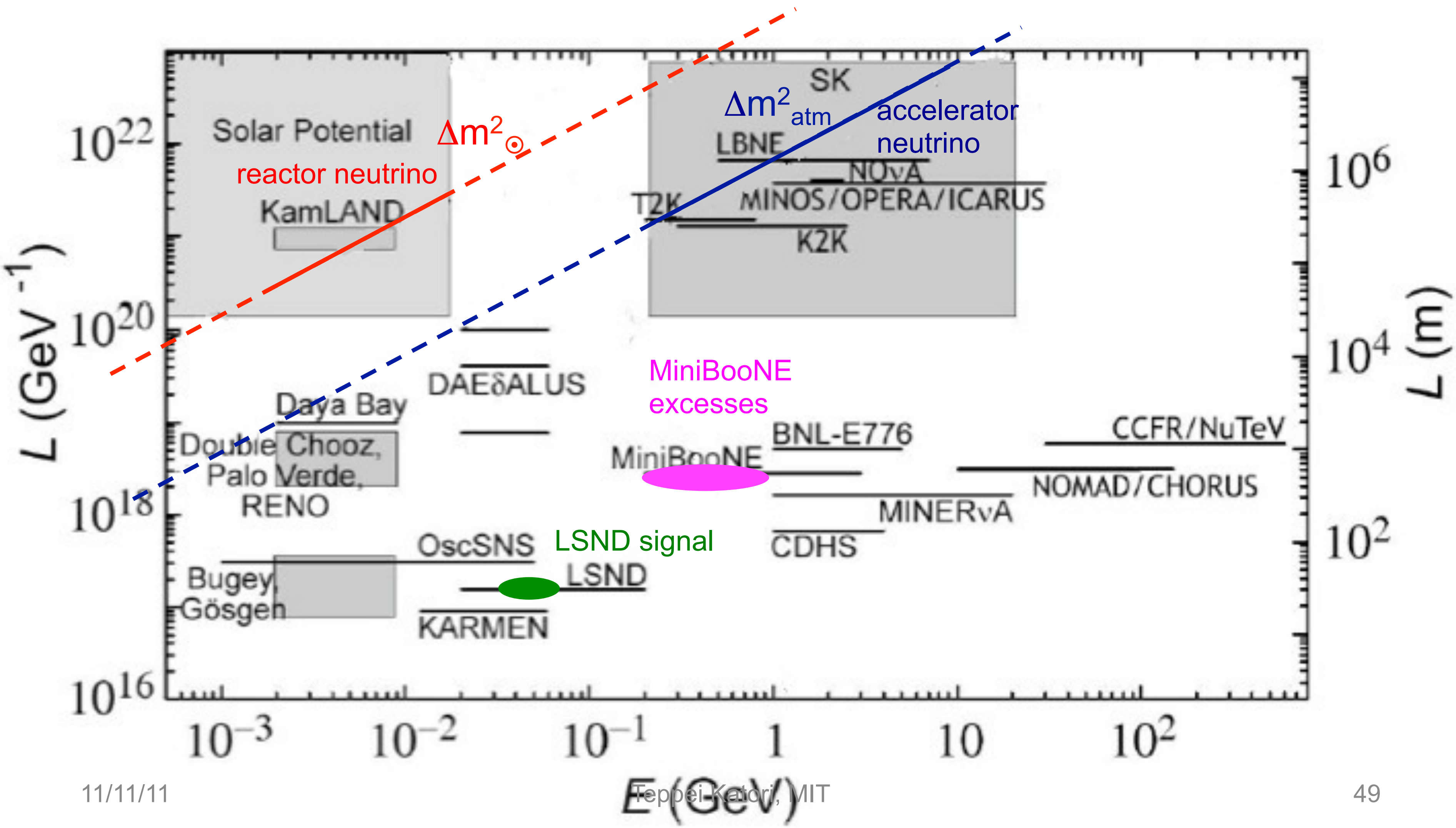

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PLB700(2011)25

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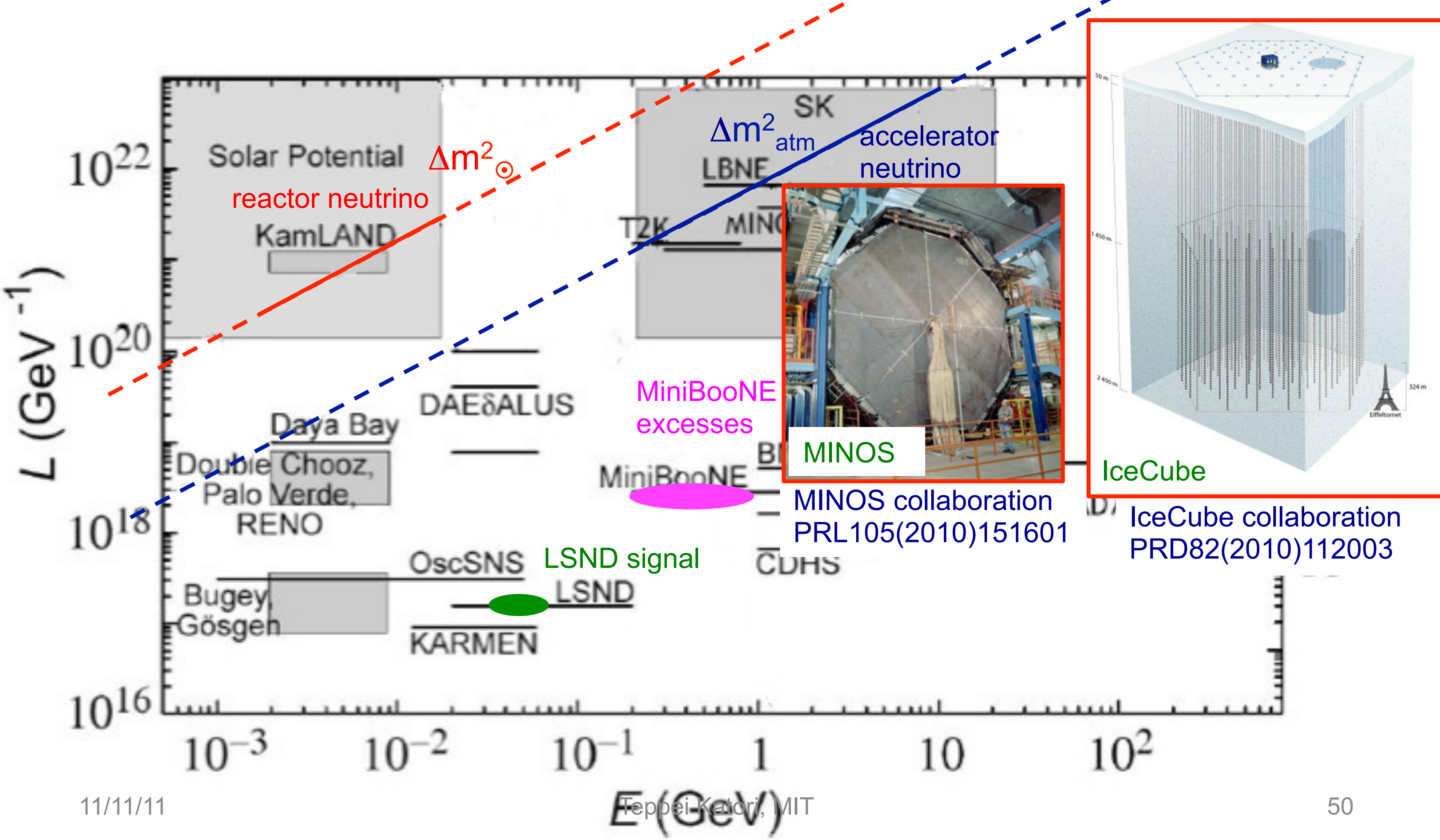

MINOS collaboration
PRL105(2010)151601

IceCube collaboration
PRD82(2010)112003

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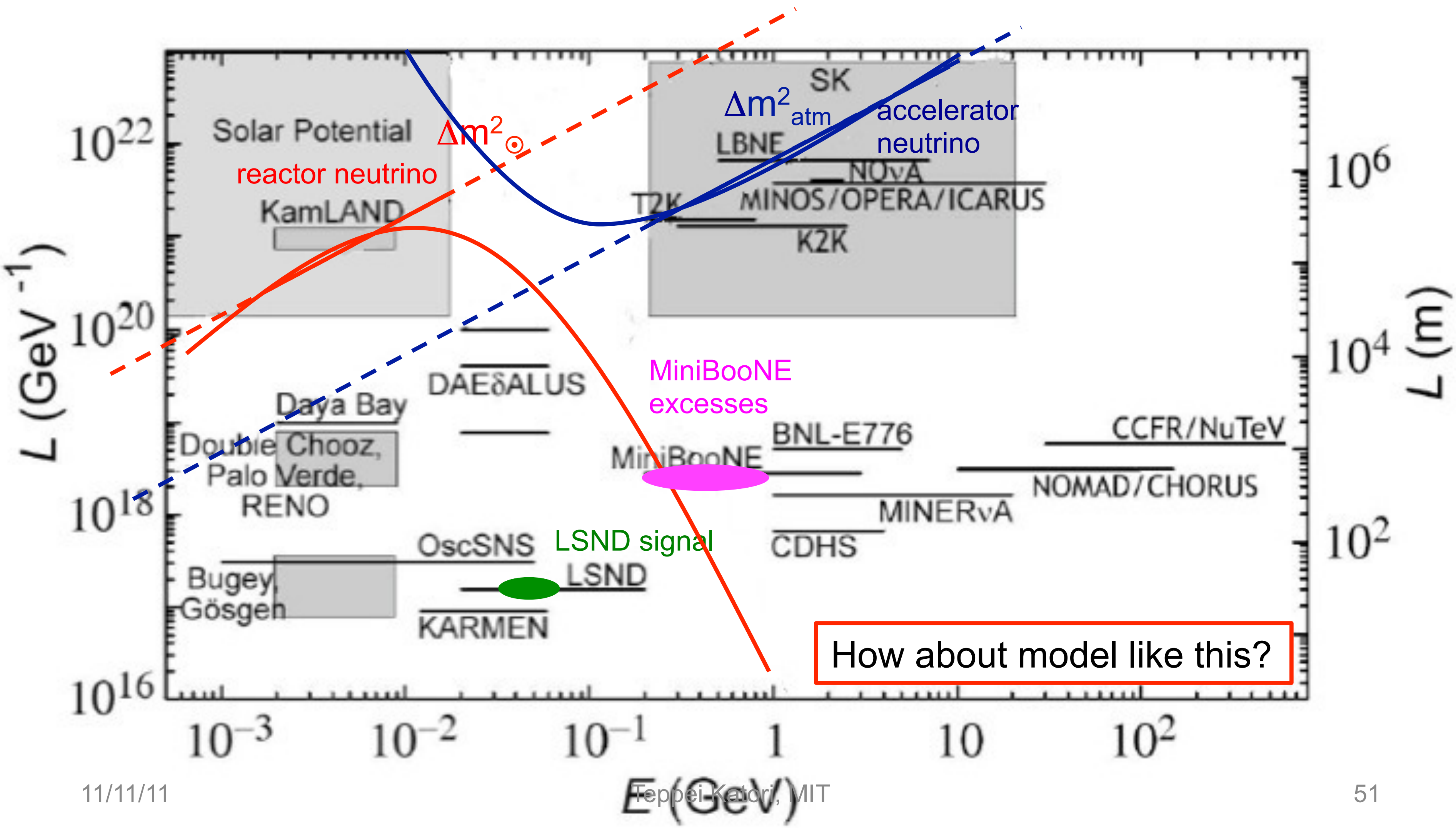
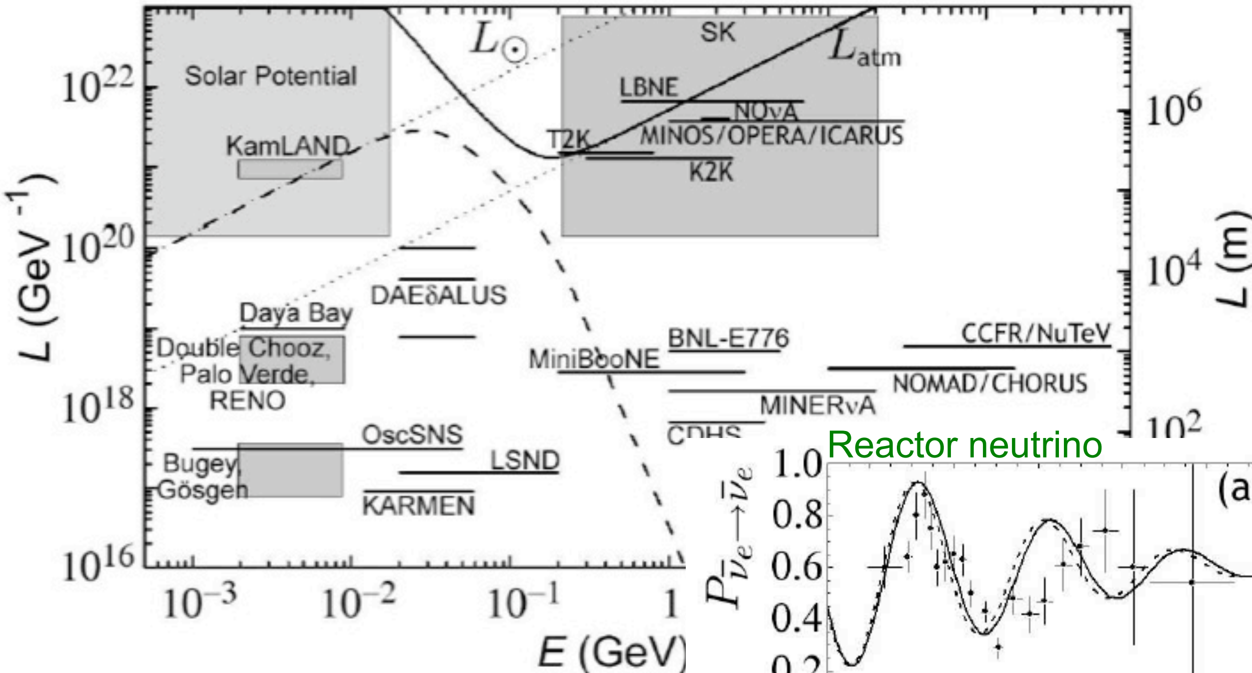
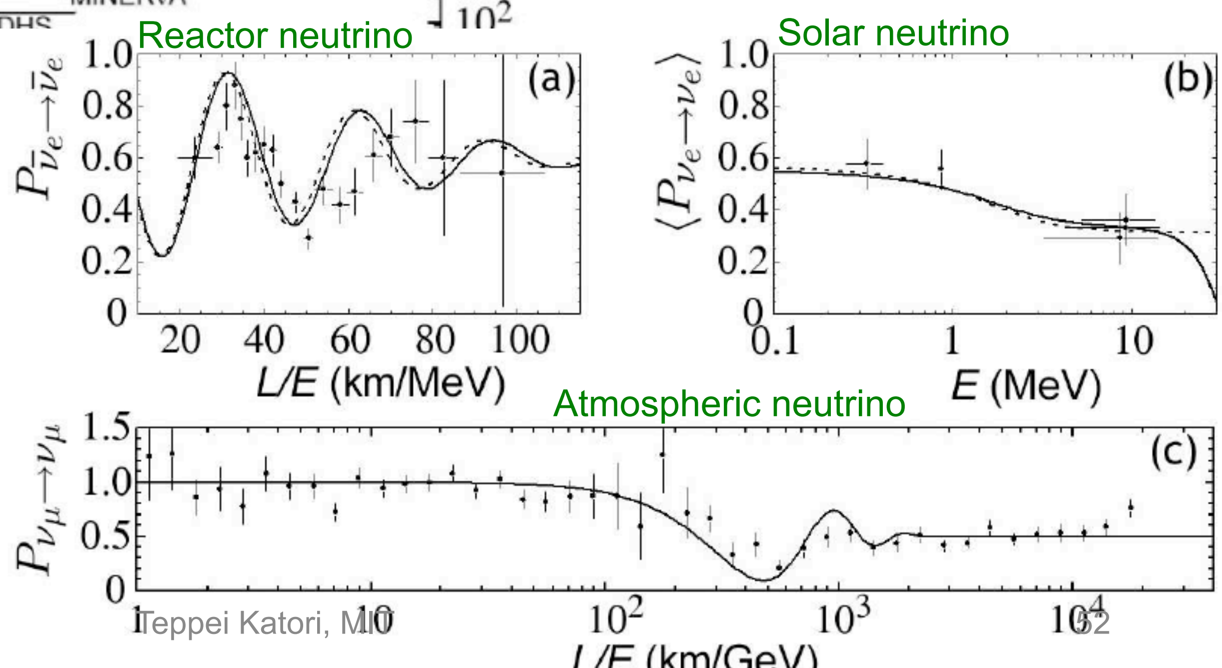


Diaz and Kostelecký
PLB700(2011)25

4. Puma model

Puma model has only 3 parameters, and perfectly describe all neutrino oscillation signal, including MiniBooNE low energy excess (neutrino mode only!)





Diaz and Kostelecký
PLB700(2011)25

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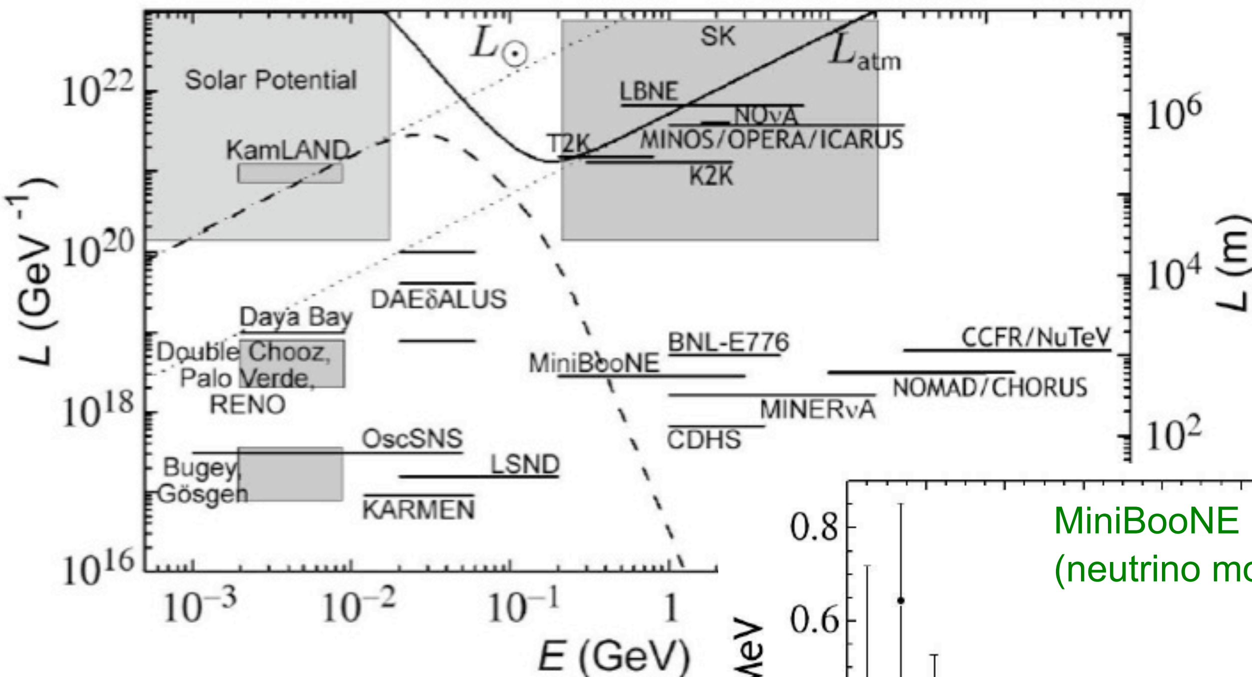

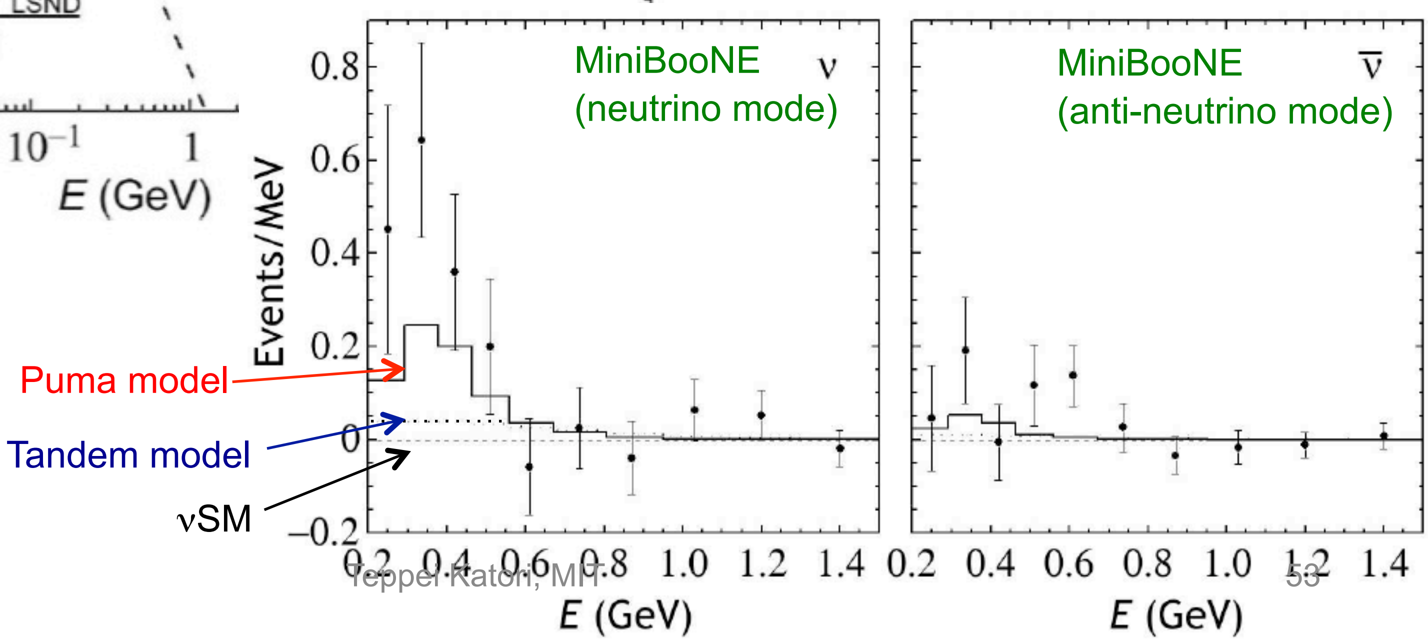

Diaz and Kostelecký
PLB700(2011)25

4. Lorentz violation with neutrino oscillation

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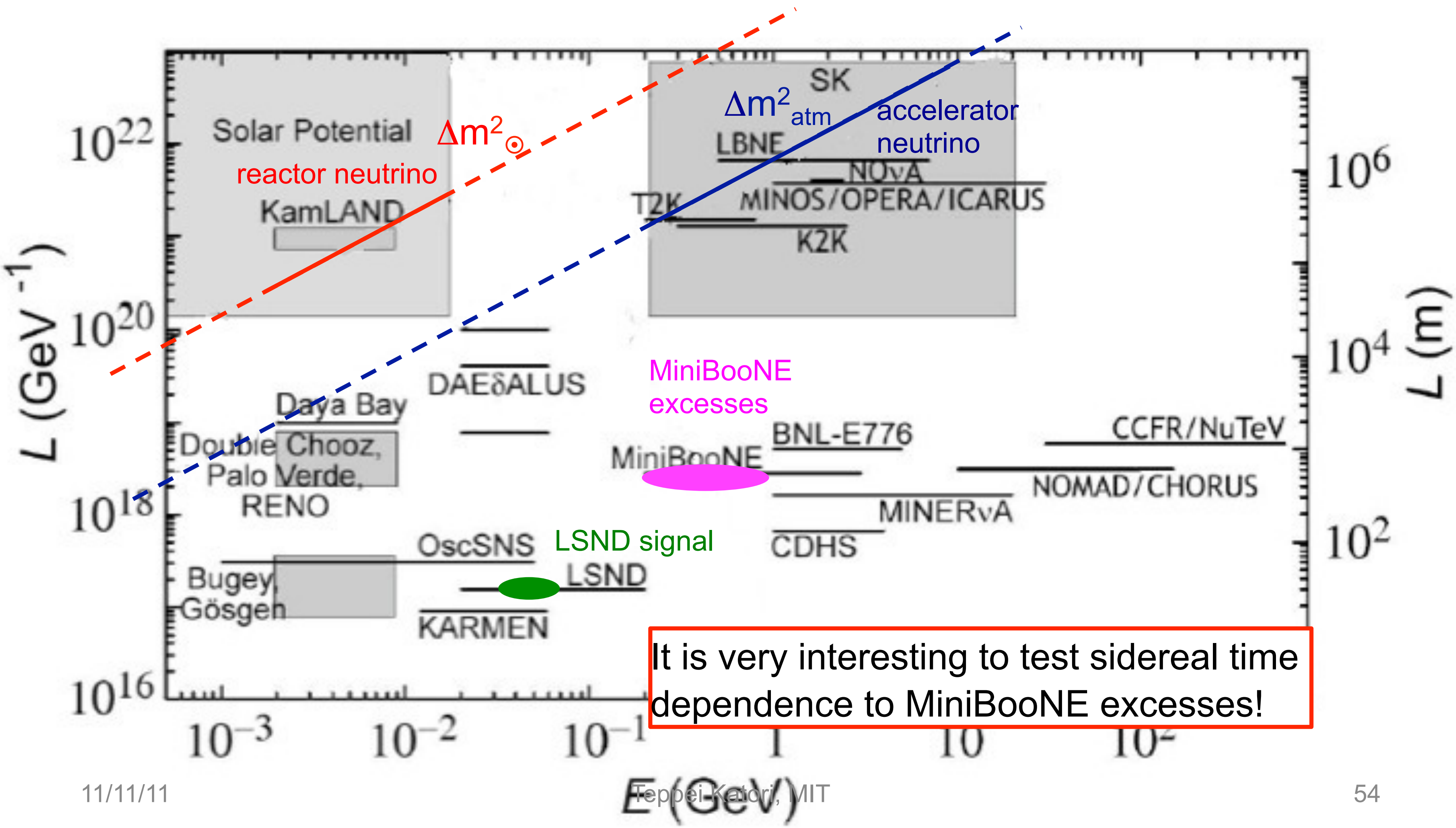


It is very interesting to test sidereal time dependence to MiniBooNE excesses!

1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Modern tests of Lorentz and CPT violation

4. Lorentz violation with neutrino oscillation

5. MiniBooNE experiment

6. Lorentz violation with MiniBooNE neutrino data

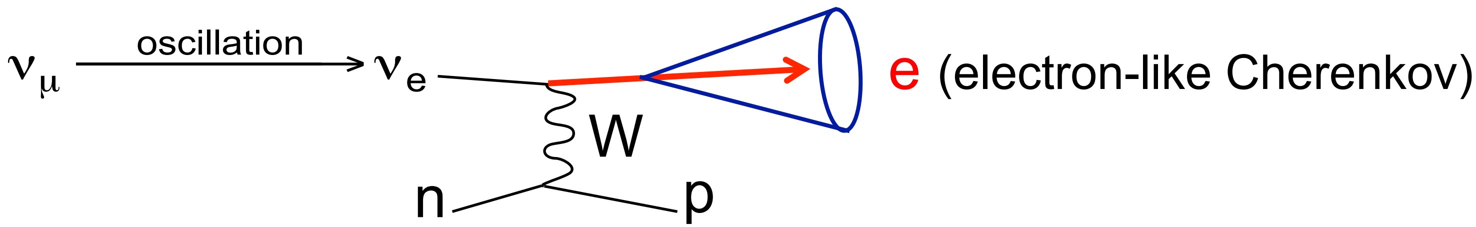
7. Lorentz violation with MiniBooNE anti-neutrino data

8. Conclusion

MiniBooNE collaboration,
PRD79(2009)072002

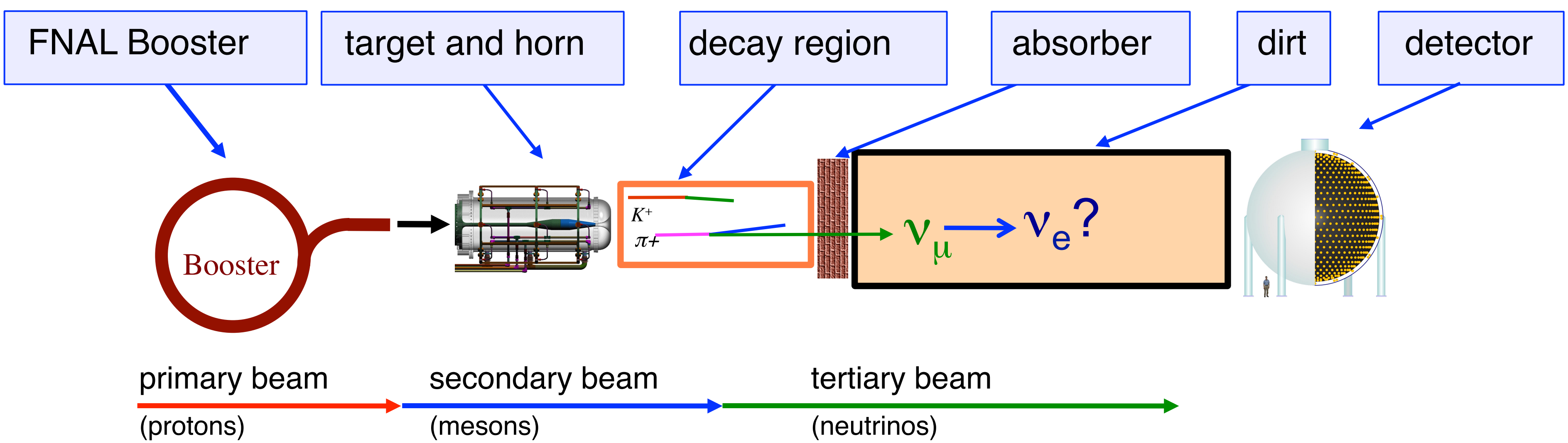
5. MiniBooNE experiment

MiniBooNE neutrino oscillation experiment at Fermilab is looking for ν_μ to ν_e oscillation



Signature of ν_e event is the single isolated electron like events

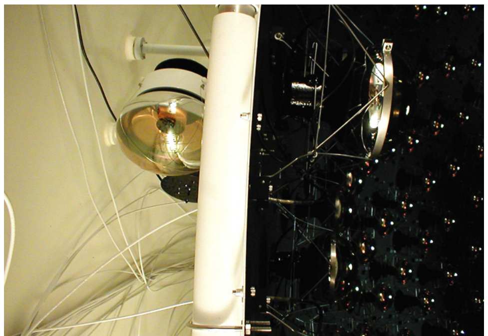
Booster Neutrino Beamline (BNB) creates ~800(600)MeV neutrino(anti-neutrino) by pion decay-in-flight from 8GeV Booster protons on Be-target in the magnetic focusing horn.

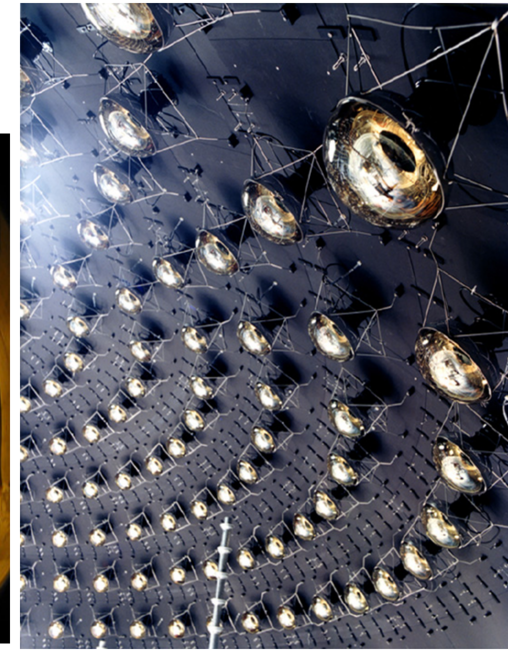


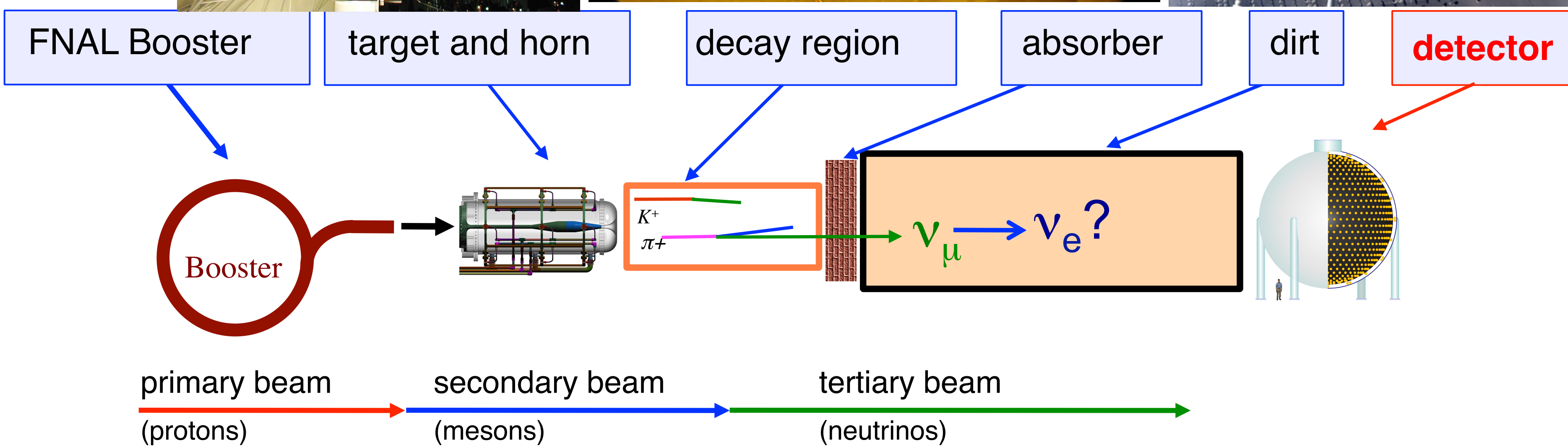
MiniBooNE collaboration, NIM.A599(2009)28

5. MiniBooNE experiment

MiniBooNE detector is the spherical Cherenkov detector
- ν-baseline is ~520m
- filled with 800t mineral oil
- 1280 of 8” PMT in inner detector
- 240 veto PMT in outer region



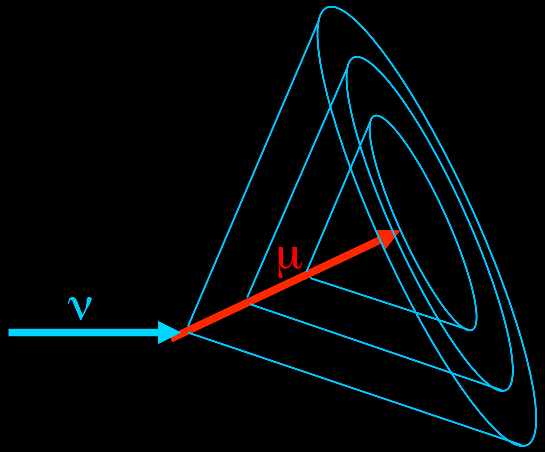


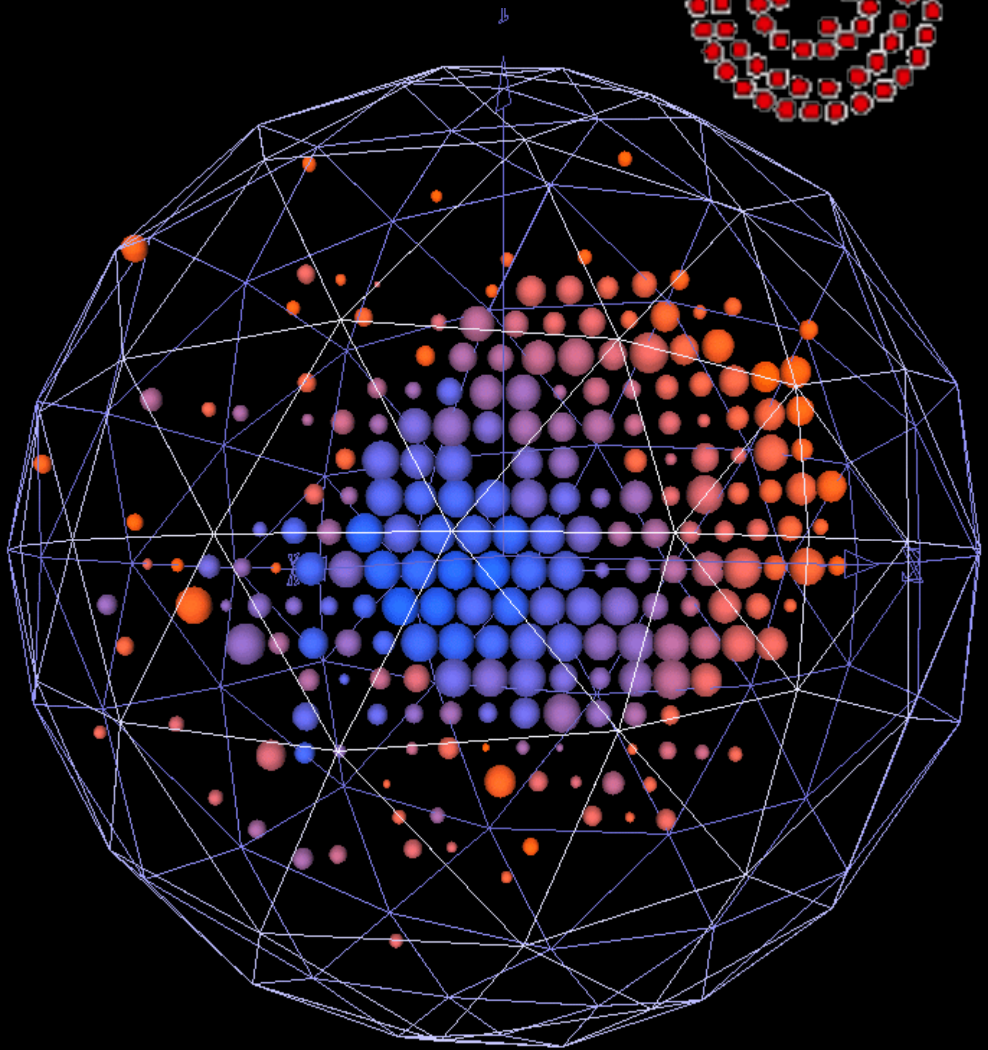


MiniBooNE collaboration,
NIM.A599(2009)28

5. MiniBooNE experiment

- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes





MiniBooNE collaboration,
NIM.A599(2009)28

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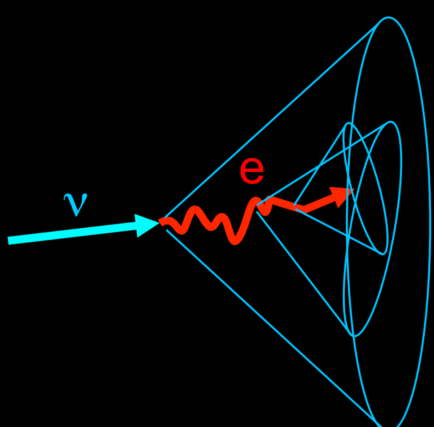

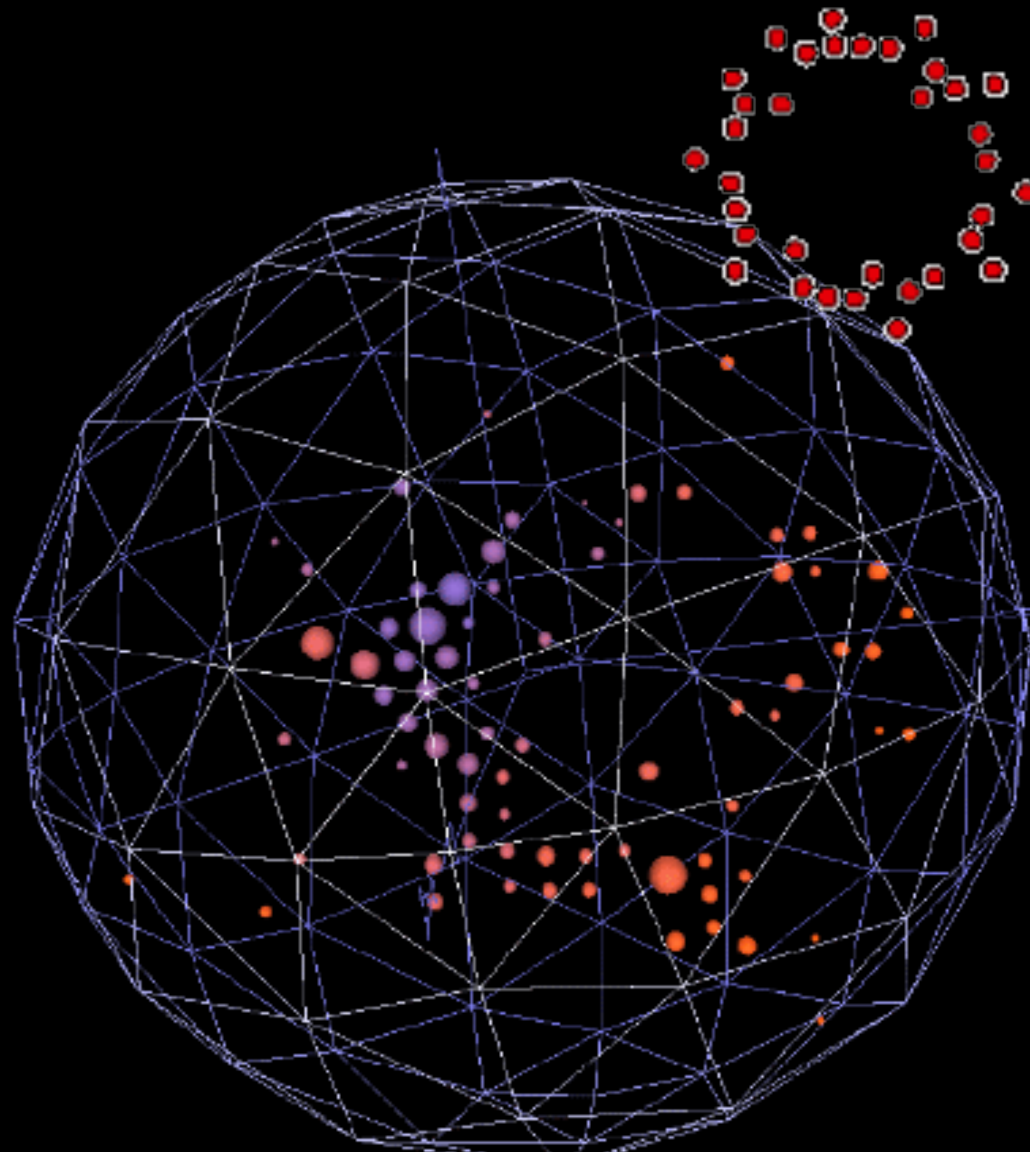

1. Spontaneous Lorentz symmetry breaking

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6. Lorentz violation with MiniBooNE neutrino data

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8. Conclusion

MiniBooNE collaboration,
PRL102(2009)101802

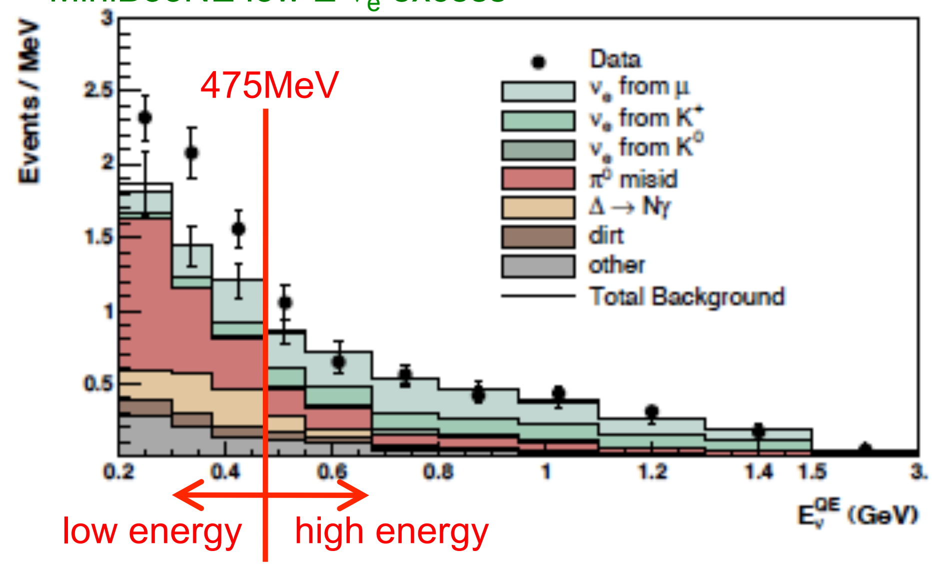
6. MiniBooNE ν_e appearance candidate data

Neutrino mode low energy excess

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

The energy dependence of MiniBooNE is reproducible by Lorentz violation motivated model, such as Puma model.
−>
The low energy excess may have sidereal time dependence.

MiniBooNE low E ν_e excess



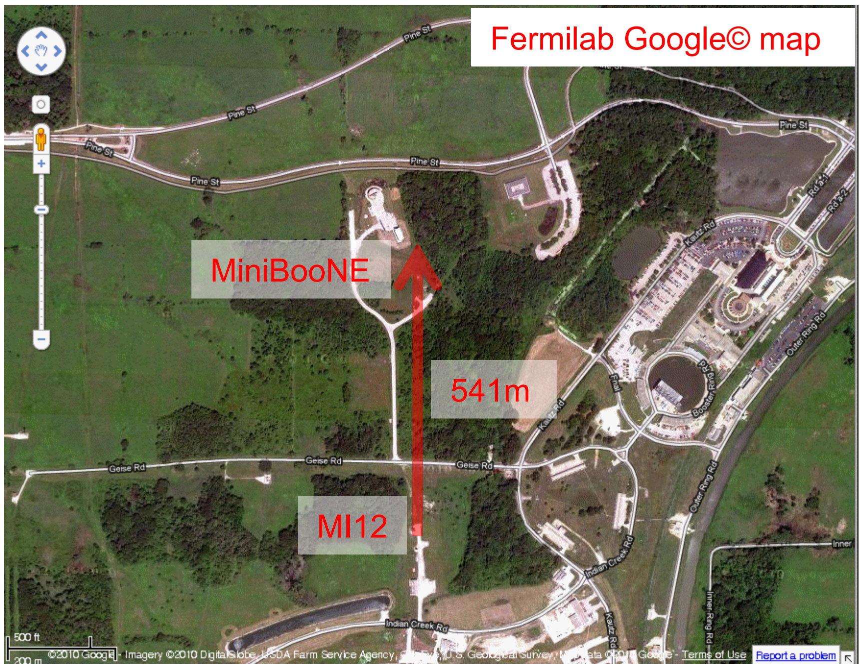
All backgrounds are measured in other data sample and their errors are constrained

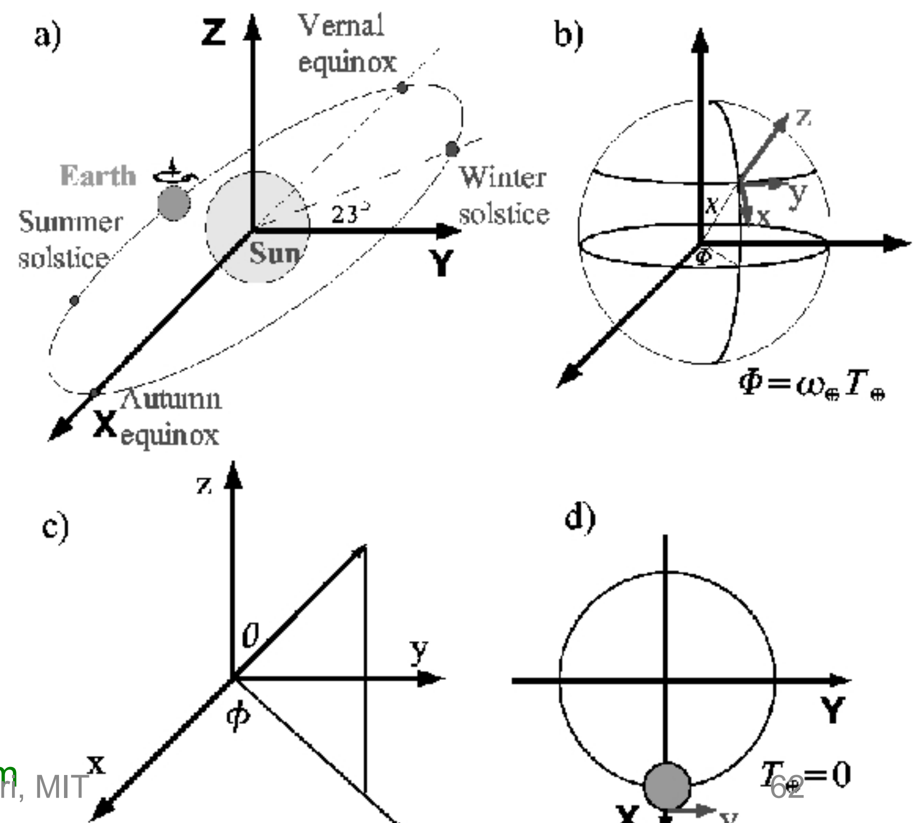
6. Lorentz violation with MiniBooNE

Test for Lorentz violation in MiniBooNE 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

- Booster neutrino beamline is described in Sun-centered coordinates





a) Sun centred system
b) Earth centred system
c) FNAL local coordinate system
d) definition of the sidereal time

Kostelecký and Mewes
PRD69(2004)016005

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- Booster neutrino beamline is described in Sun-centered coordinates
- Standard Model Extension (SME)

Modified Dirac Equation (MDE) of neutrinos

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

SME parameters

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

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

Kostelecký and Mewes
PRD69(2004)016005

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CPT odd

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CPT even

Kostelecký and Mewes
PRD70(2004)076002

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

- Booster neutrino beamline is described in Sun-centered coordinates
- Standard Model Extension (SME)
- Sidereal time dependent oscillation probability

Lorentz violating oscillation probability for MiniBooNE

$$P_{\nu_\mu \rightarrow \nu_e} \sim \frac{|(h_{eff})_{e\mu}|^2 L^2}{(\hbar c)^2}$$

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

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

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

sidereal time $T_\oplus$

Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

Kostelecký and Mewes
PRD70(2004)076002

6. Lorentz violation with MiniBooNE

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

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

Expression of 5 observables (14 SME parameters)

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

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

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

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

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

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

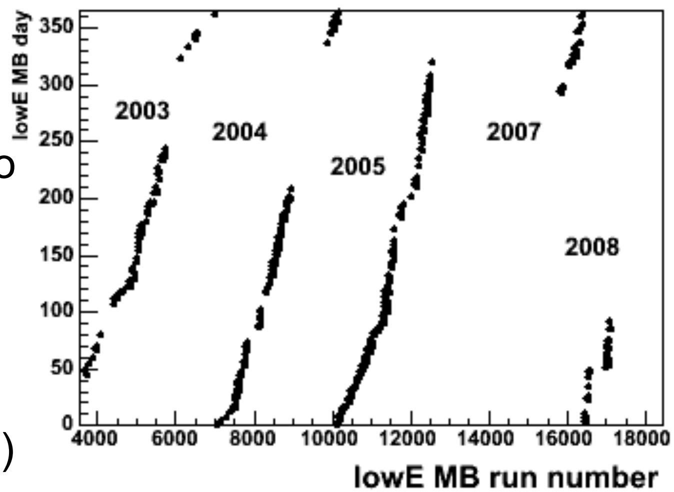
coordinate dependent direction vector
(depends on the latitude of FNAL, location of BNB and MiniBooNE detector)

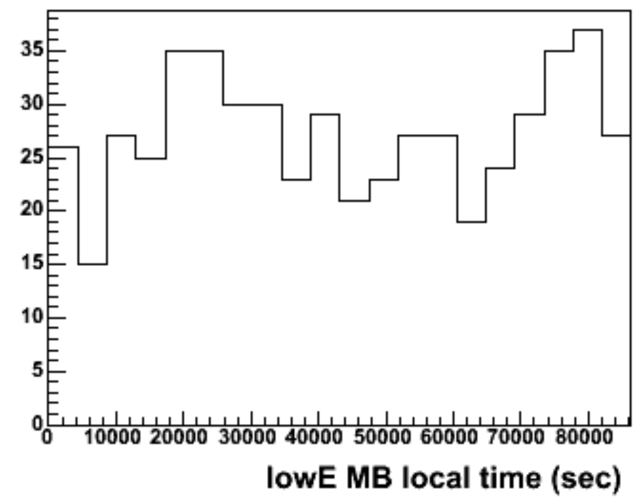
6. Lorentz violation with MiniBooNE neutrino data

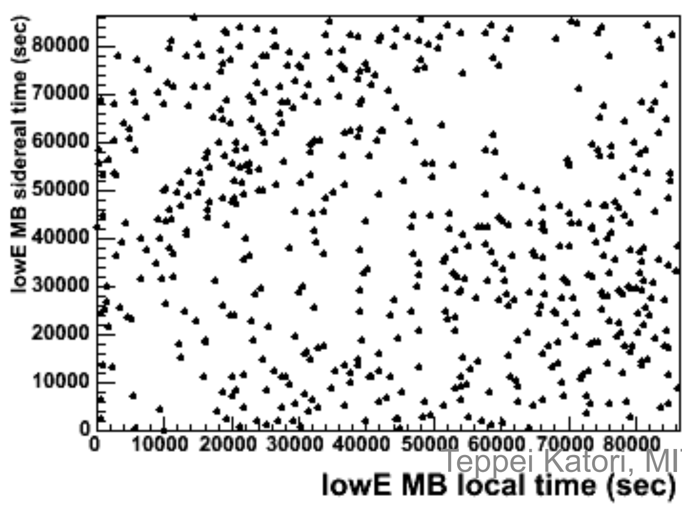
Time distribution of MiniBooNE neutrino mode low energy region

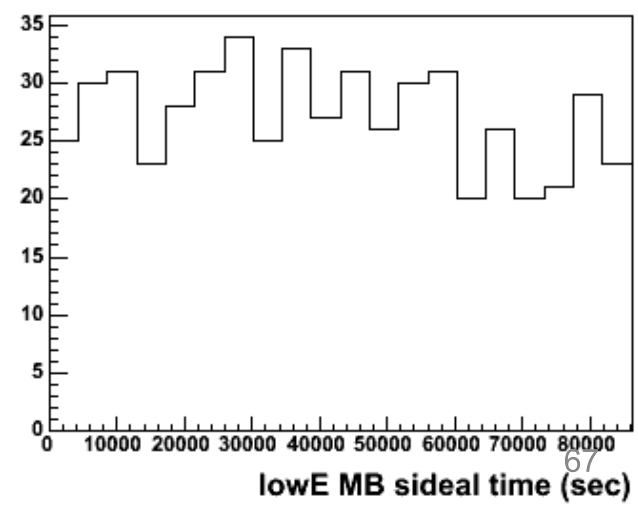
MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

solar local time
24h00m00s (86400s)
sidereal time
23h56m04s (86164s)





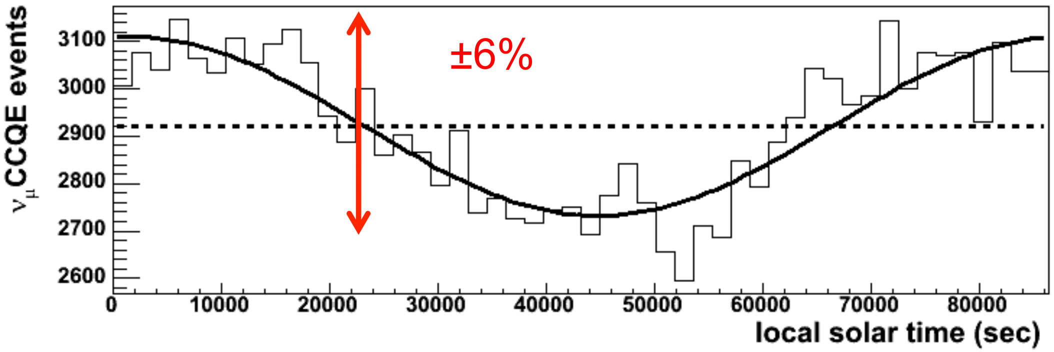




6. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation

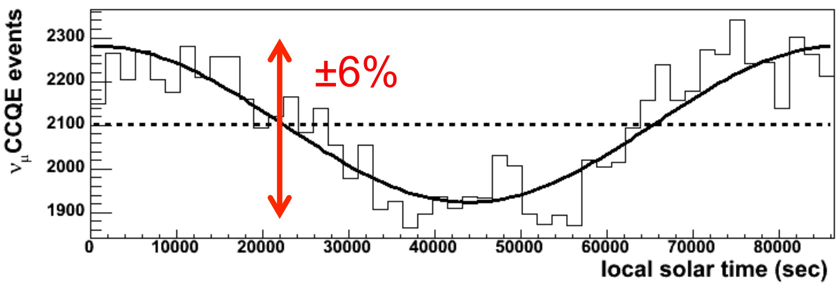
ν_μCCQE events day-night distribution



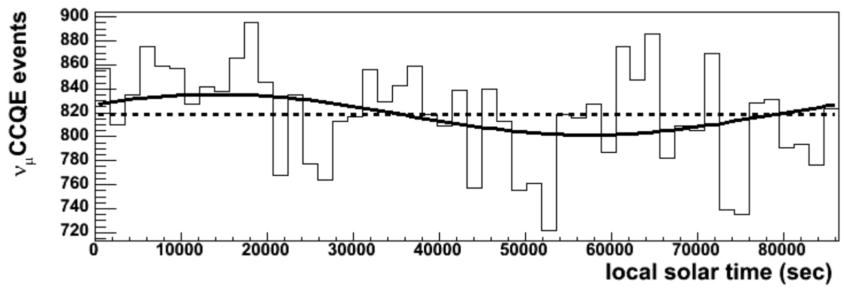
6. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!

ν_μCCQE events distribution, Monday to Friday



ν_μCCQE events distribution, Saturday and Sunday

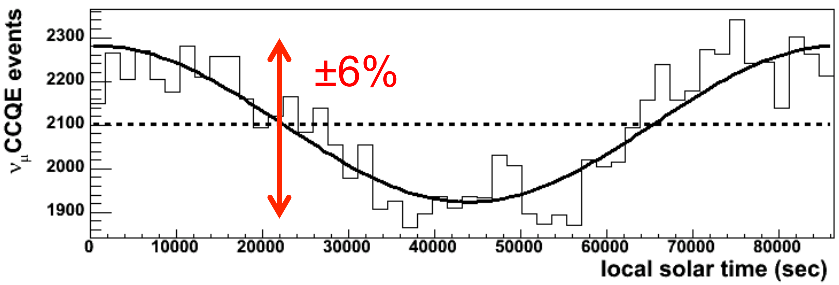


6. Lorentz violation with MiniBooNE neutrino data

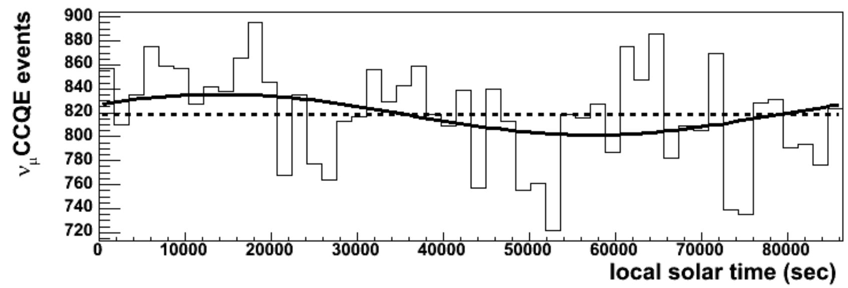
Time dependent systematics

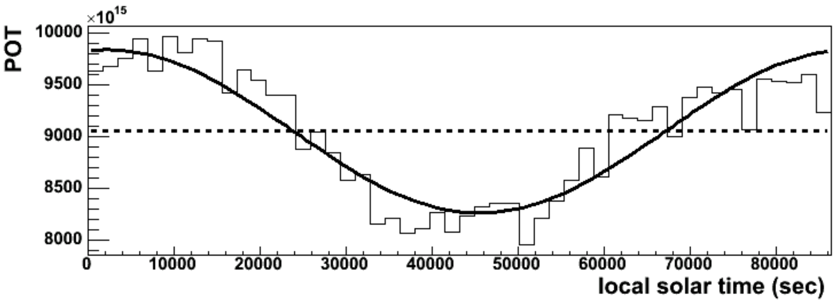
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)

ν_μCCQE events distribution, Monday to Friday

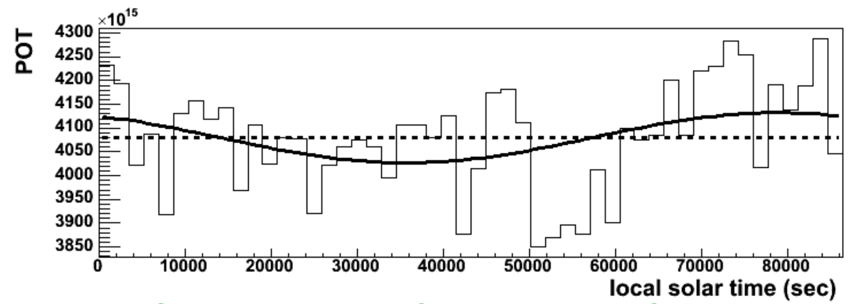


ν_μCCQE events distribution, Saturday and Sunday





POT distribution, Monday to Friday

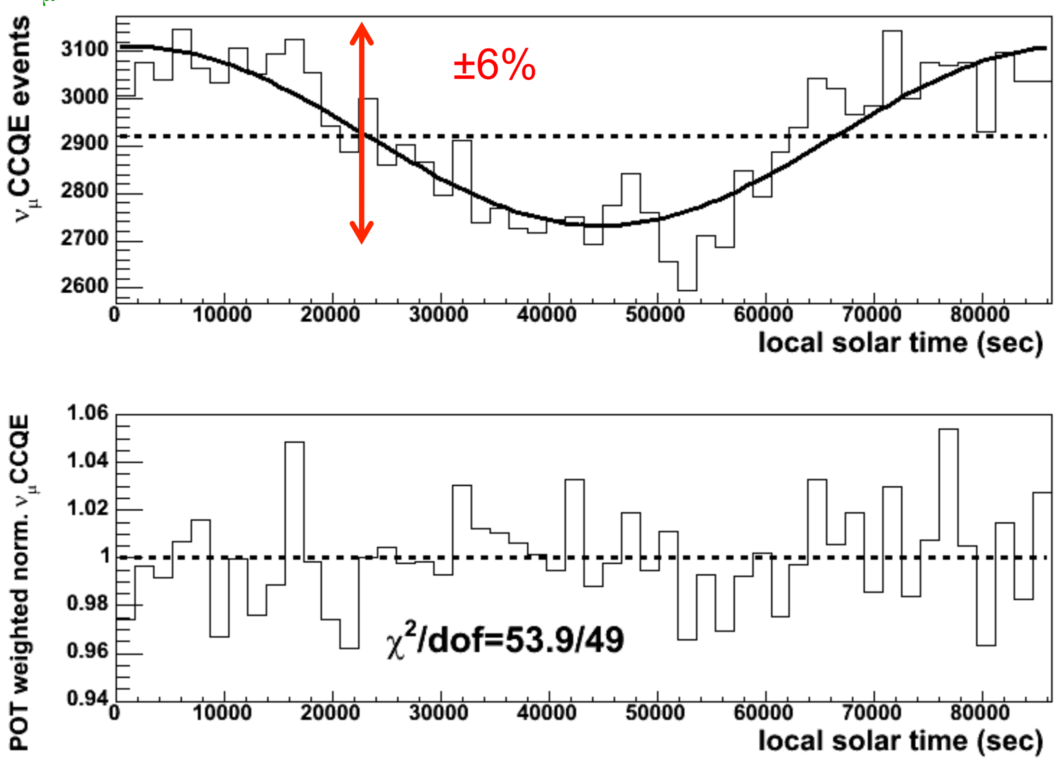


POT distribution, Saturday and Sunday

6. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)
- After correcting this, ν_μCCQE events exhibit flat

ν_μCCQE events day-night distribution



6. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics

- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)
- After correcting this, ν_μCCQE events exhibit flat.

An event weight is made to correct this from oscillation candidate sample

- however correct distributions only show negligible changes in χ^2
  - statistical fluctuation of oscillation candidate is bigger than 6% variation
  - day-night effect is washed out in sidereal distribution due to continuous data taking
- event weight for unbinned analysis is tricky

Therefore, we don't use an event weight to correct this in further analysis.

6. Lorentz violation with MiniBooNE neutrino data

Null hypothesis test

The flatness hypothesis is tested by unbinned Kolmogorov-Smirnov test (K-S test).
K-S test has 3 advantages;

1. unbinned, so it has the maximum statistical power
2. no argument with bin choice
3. sensitive with systematic shift of the distribution (e.g., sinusoidal)

Non of tests shows any statistically significant results.
All data sets are compatible with flat hypothesis by K-S test

	low energy		high energy		combined	
	solar	sidereal	solar	sidereal	solar	sidereal
Neutrino mode						
$< E_\nu >$	0.36 GeV		0.82 GeV		0.71 GeV	
#evt	544		420		964	
P(KS)	0.42	0.13	0.81	0.64	0.64	0.14

6. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum likelihood fit

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

likelihood function

$$\Lambda = \frac{e^{-(\mu_s+\mu_b^v)}}{N!}\prod_{i=1}^{N}(\mu_s\mathcal{F}_s^i+\mu_b^v\mathcal{F}_b^i)\times\frac{1}{\sqrt{2\pi\sigma_b{}^2}}\exp\left(-\frac{(\mu_b^v-\mu_b)^2}{2\sigma_b{}^2}\right) \qquad (22)$$

N total number of event

μ_s predicted signal event number, function of fitting parameters

μ_b predicted background event number

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

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

σ_b the $1-\sigma$ error of predicted the background

μ_b^v floating background event number floating within $1-\sigma$

6. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum loglikelihood fit

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

loglikelihood function for an event

$$\ell_i = -\frac{1}{N}(\mu_s + \mu_b^v) + ln[\mu_s \mathcal{F}_s^i + \mu_b^v \mathcal{F}_b^i] - \frac{1}{2N}\left(\frac{\mu_b^v - \mu_b}{\sigma}\right)^2$$

Sidereal variation of neutrino oscillation probability for MiniBooNE

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

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

sidereal time $T_\oplus$

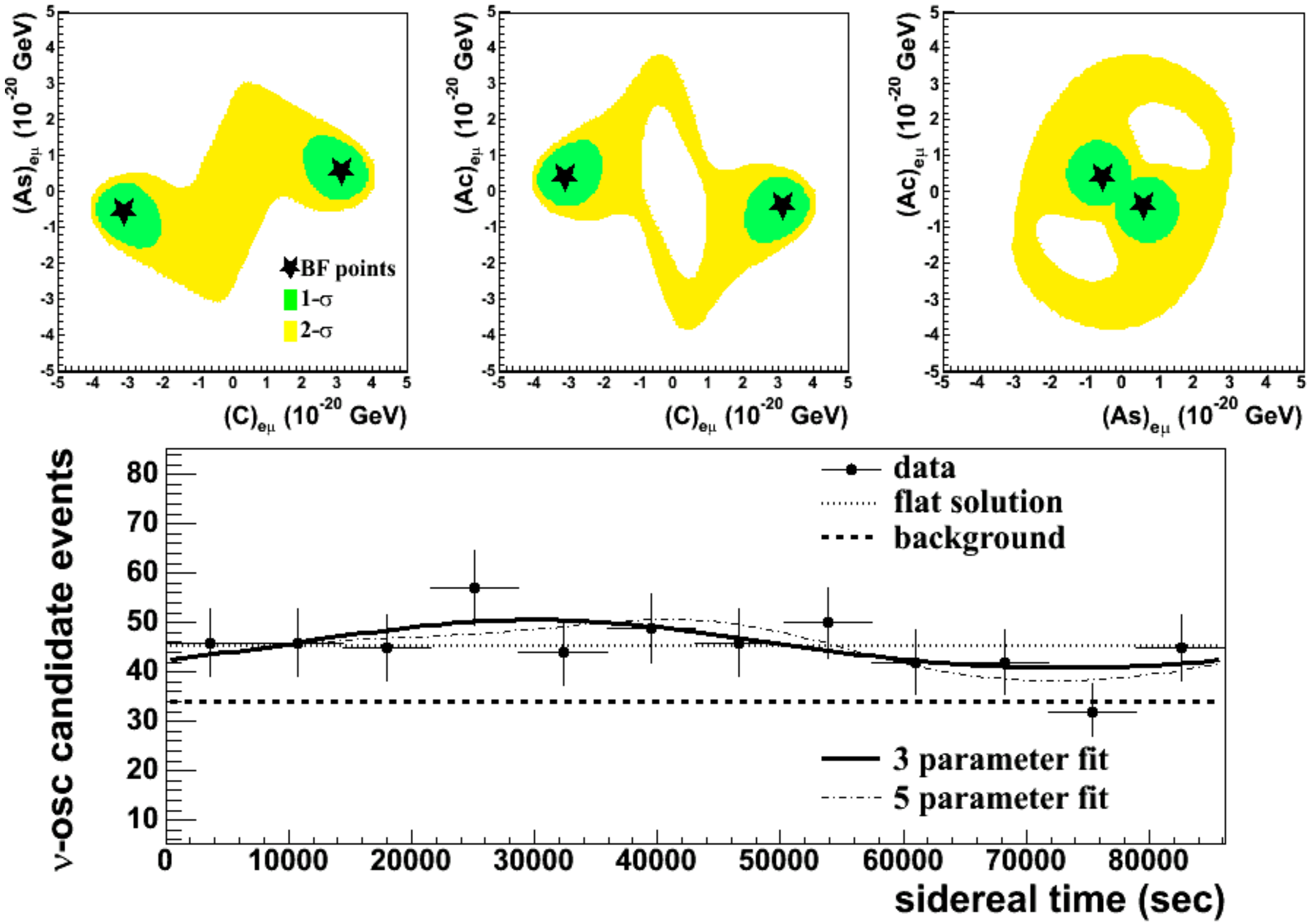
6. Lorentz violation with MiniBooNE neutrino data

Neutrino mode result, low energy region

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

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

The neutrino mode low energy excess is consistent with no sidereal variation.



1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Modern tests of Lorentz and CPT violation

4. Lorentz violation with neutrino oscillation

5. MiniBooNE experiment

6. Lorentz violation with MiniBooNE neutrino data

7. Lorentz violation with MiniBooNE anti-neutrino data

8. Conclusion

MiniBooNE collaboration,
PRL105(2010)181801

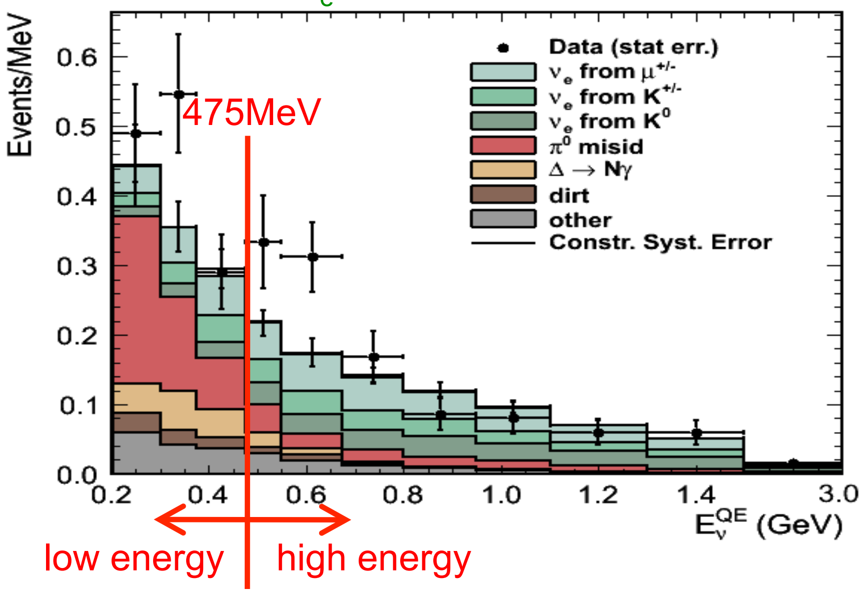
7. MiniBooNE anti-ν_e appearance candidate data

Antineutrino mode excess

MiniBooNE did see the signal at the region where LSND data suggested under the assumption of standard two massive neutrino oscillation model

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

MiniBooNE anti-ν_e excess



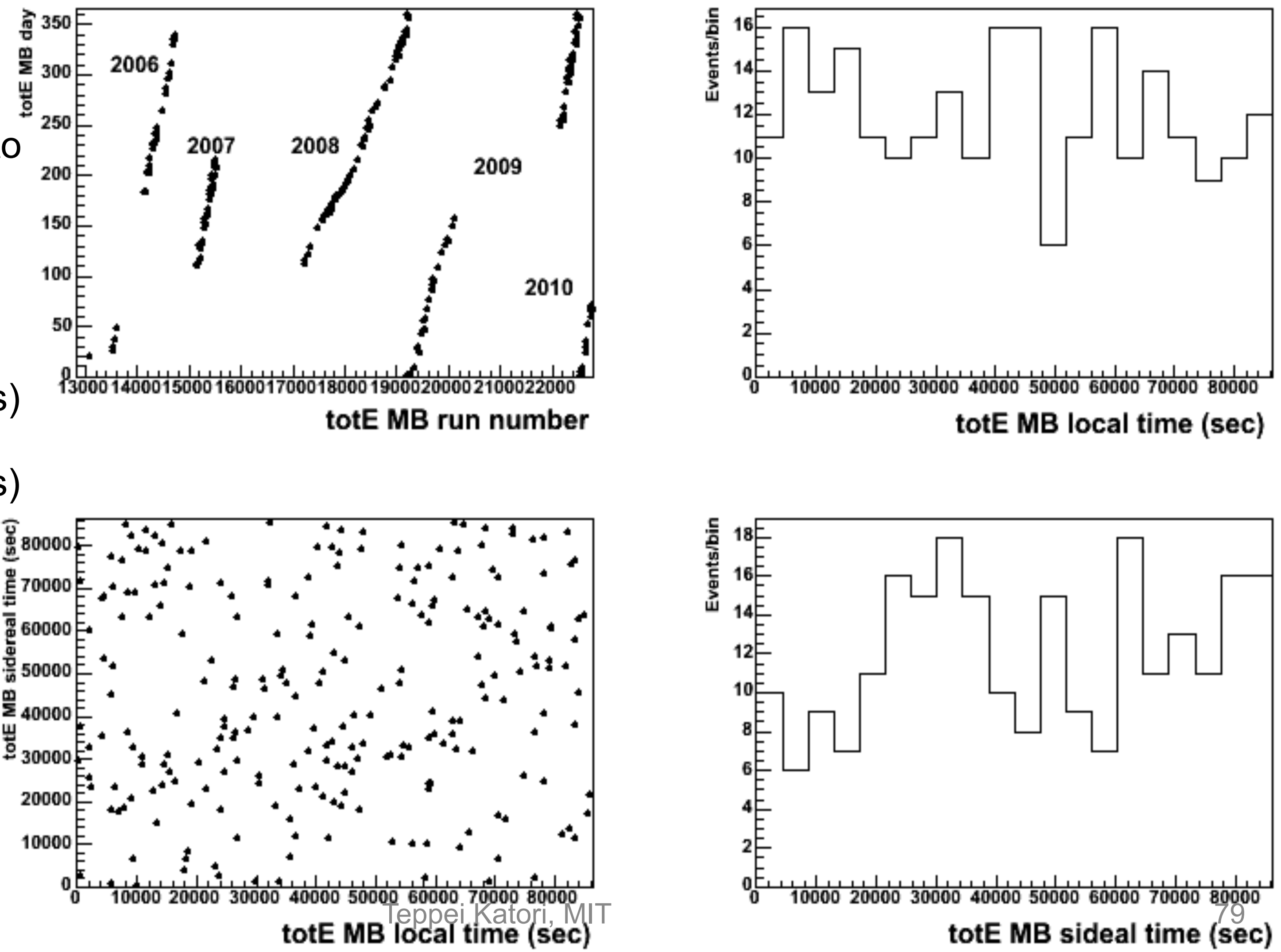
All backgrounds are measured in other data sample and their errors are constrained

7. Lorentz violation with MiniBooNE anti-neutrino data

Time distribution of MiniBooNE antineutrino mode oscillation region

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

solar local time 24h00m00s (86400s)
sidereal time 23h56m04s (86164s)



7. Lorentz violation with MiniBooNE anti-neutrino data

Null hypothesis test

The flatness hypothesis is tested by unbinned Kolmogorov-Smirnov test (K-S test).
K-S test has 3 advantages;

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#evt	544		420		964	
P(KS)	0.42	0.13	0.81	0.64	0.64	0.14
Anti-neutrino mode						
$< E_{\bar{\nu}} >$	0.34 GeV		0.78 GeV		0.60 GeV	
#evt	119		122		241	
P(KS)	0.62	0.15	0.79	0.39	0.69	0.08

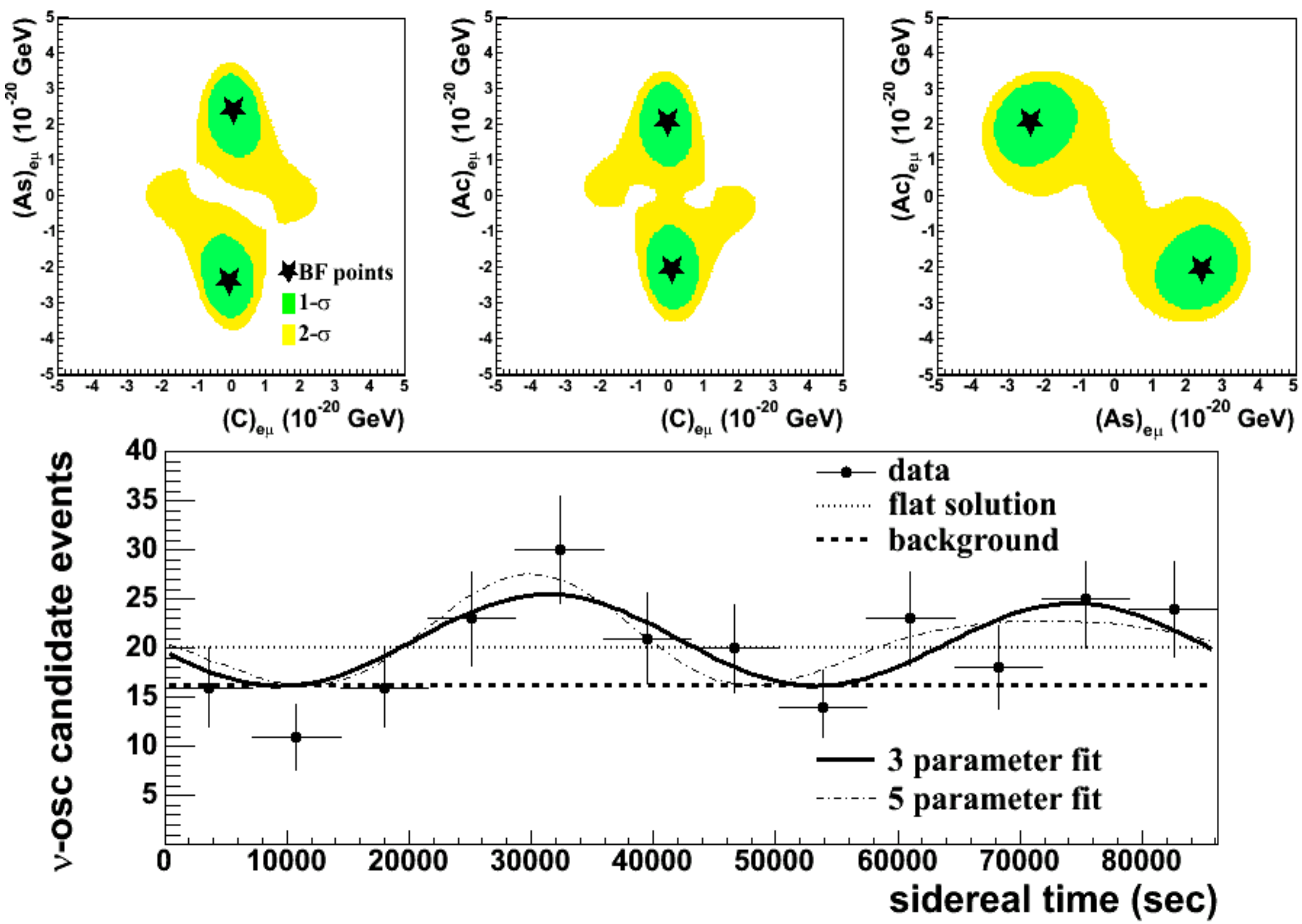
7. Lorentz violation with MiniBooNE anti-neutrino data

Anti-neutrino mode result, combined energy region

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

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

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



1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Modern tests of Lorentz and CPT violation

4. Lorentz violation with neutrino oscillation

5. MiniBooNE experiment

6. Lorentz violation with MiniBooNE neutrino data

7. Lorentz violation with MiniBooNE anti-neutrino data

8. Conclusion

8. Summary of results

Neutrino result summary
- Neutrino mode data is consistent with null hypothesis by K-S test.
- The low energy excess data fit prefer sidereal time independent solution.
- 26.9% of fake data based on null hypothesis have bigger $\Delta\chi^2$ than data.

Anti-neutrino result summary
- Anti-neutrino mode data is consistent with null hypothesis by K-S test.
- The fit for combined region excess data prefers sidereal time dependent solution.
- 3.0% of fake data based on null hypothesis have bigger $\Delta\chi^2$ than data.

SME coefficients

	ν−mode BF	2σ limit	$\bar{\nu}$−mode BF	2σ limit	SME coefficients combination (unit 10^{-20} GeV)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$3.1 \pm 0.6 \pm 0.9$	< 4.2	$0.1 \pm 0.8 \pm 0.1$	< 2.6	$\pm[(a_L)^T_{e\mu} + 0.75(a_L)^Z_{e\mu}] - <E> [1.22(c_L)^{TT}_{e\mu} + 1.50(c_L)^{TZ}_{e\mu} + 0.34(c_L)^{ZZ}_{e\mu}]$
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$0.6 \pm 0.9 \pm 0.3$	< 3.3	$2.4 \pm 1.3 \pm 0.5$	< 3.9	$\pm[0.66(a_L)^Y_{e\mu}] - <E> [1.33(c_L)^{TY}_{e\mu} + 0.99(c_L)^{YZ}_{e\mu}]$
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$0.4 \pm 0.9 \pm 0.4$	< 4.0	$2.1 \pm 1.2 \pm 0.4$	< 3.7	$\pm[0.66(a_L)^X_{e\mu}] - <E> [1.33(c_L)^{TX}_{e\mu} + 0.99(c_L)^{XZ}_{e\mu}]$

8. Summary of results

SME coefficients sensitivity

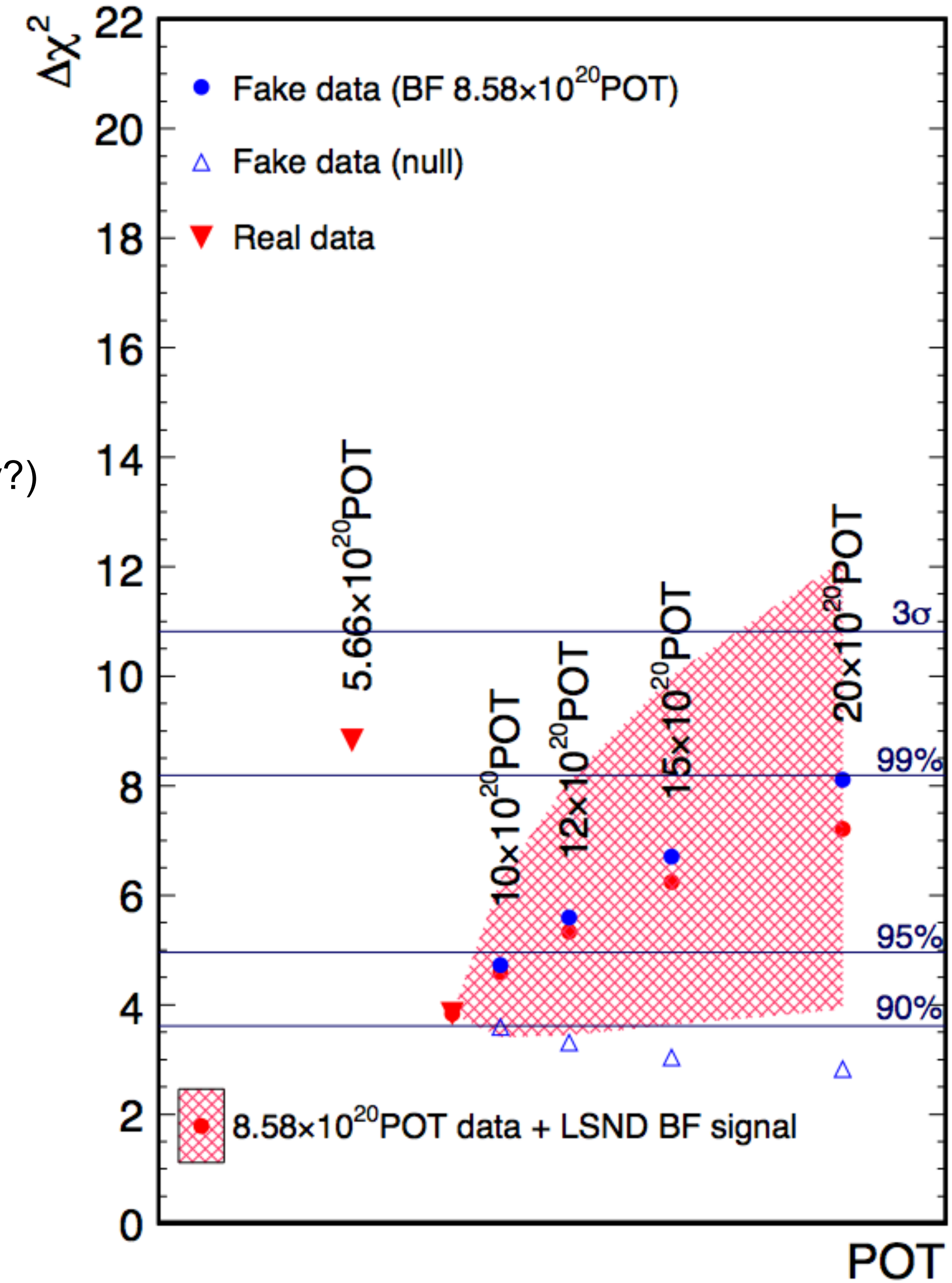
- The sensitivities are obtained by setting on one coefficient nonzero
- These result conflict with LSND (LSND signal needs ~10^{-19} GeV Lorentz violation), and simple Lorentz violation models leave tension between MiniBooNE and LSND
- First time constrained time independent SME coefficients for e-μ sector.

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

8. MiniBooNE future plan

This analysis is statistically limited.

We continue to take data until March (May?) 2012, then we will double the statistics.

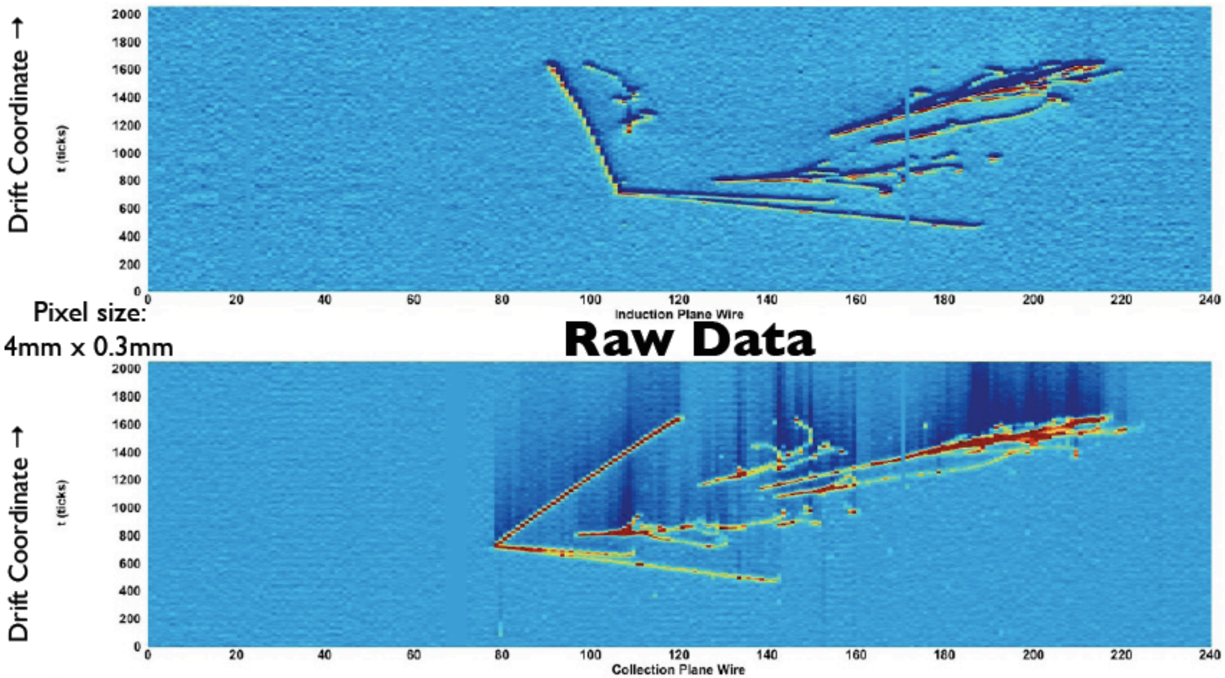


8. MicroBooNE

Liquid Argon Time Projection Chamber (LArTPC) neutrino experiment at Fermilab

- 150 ton volume of cryostat
- R&D detector for future large LArTPC
- 3D tracker (modern bubble chamber)
- data taking will start from 2014 (passed CD2)
- dE/dx can separate single electron from gamma ray

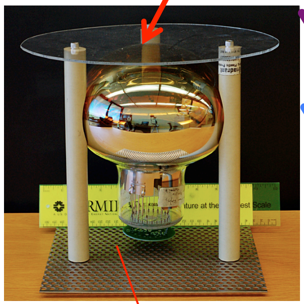
2 π^os decayed to 4 gammas, then converted to 4 e^+-e^- pairs (ArgoNeuT experiment)



TPB coated acrylic plate

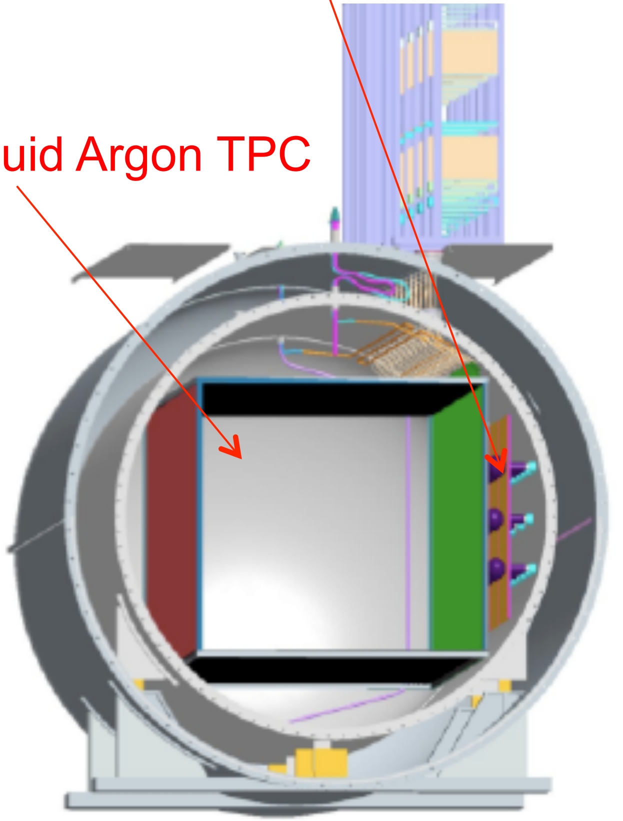
128nm

450nm



PMT system

liquid Argon TPC



MiniBooNE 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

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

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.

Comment - Modified dispersion relation

$$E^2 = m^2 + p^2 + f_i^{(1)} p^i + f_{ij}^{(2)} p^i p^j + \ldots$$

The models usually assume isotropy (rotation invariance)

$$E^2 = m^2 + p^2 + f^{(1)} |p| + f^{(2)} |p|^2 + \ldots$$

One can make such model in CMB frame.

However since we are not in CMB frame, physics in laboratory frame needs to be related by observer Lorentz transformation from CMB frame, so lab frame is always anisotropy.

2. Comment: Is there preferred frame?

As we see, all observers are related with observer’s Lorentz transformation, so there is no special “preferred” frame (all observer’s are consistent)

But there is a frame where universe looks isotropic even with a Lorentz violating vector field. You may call that is the “preferred frame”, and people often speculate the frame where CMB looks isotropic is such a frame (called “CMB frame”).

However, we are not on CMB frame (e.g., dipole term of WMAP is nonzero), so we can expect anisotropy by lab experiments even CMB frame is the preferred frame.

Greenberg
PRL(2002)231602

2. 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. In fact, any effective CPT violation cause Lorentz violation for Feynman propagator, hence interactive quantum field theory. That is why, this is called Lorentz and CPT violation.

3. Standard Model Extension (SME)

FAQ

Q. How to detect Lorentz violation?

A.
(1) choose the coordinate system to compare the experimental result
->
Sun centered celestial equatorial coordinate system
(2) write down Lagrangian including Lorentz violating terms under the formalism
->
SME
(3) write down the observables using this Lagrangian

Q. Do you take account the galactic motion?

A. No, the galactic motion is the fastest, but it takes ~1000 years to rotate 1 degree.
We are interested in the test of Lorentz symmetry, so translation motion is not important.
Rotation of the earth is important to test rotation symmetry, and revolution of the earth is important to test Lorentz boost.

5. 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).

4. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

Particle accelerator

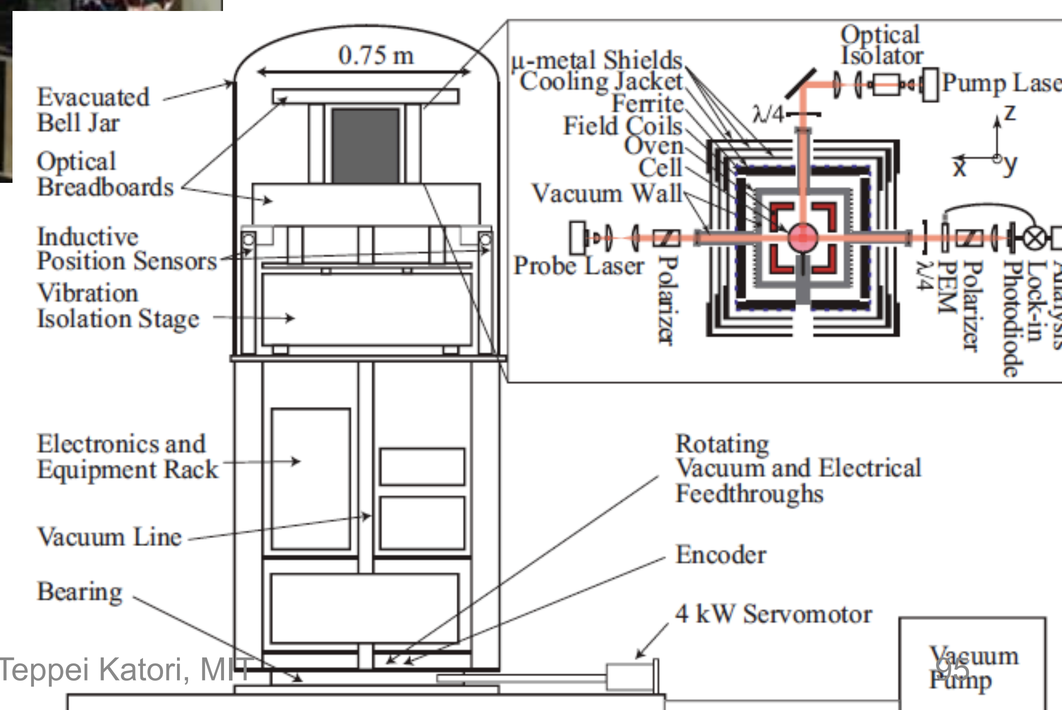
Meson sector

Neutrino sector

co-magnetometer

Mike Romalis (Princeton)

Ron Walsworth (Harvard-Smithsonian)



Double gas maser

b_n(rotation)<10^{-33}GeV

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

Walsworth et al. PRL93(2004)230801

Romalis et al. PRL105(2010)151604

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Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

Astrophysics

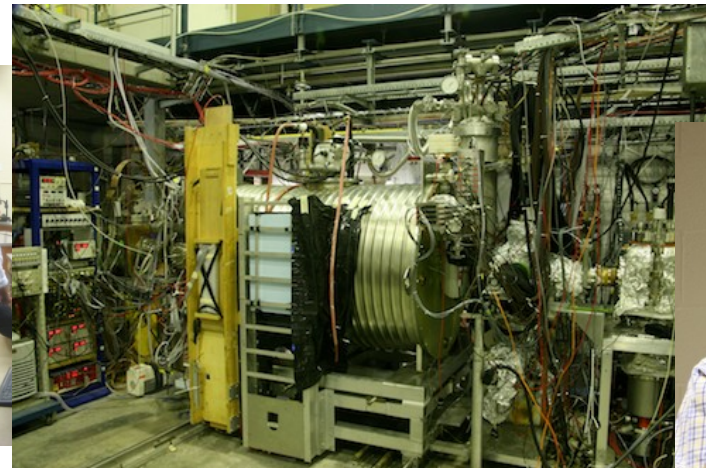
Particle accelerator

Meson sector

Neutrino sector

Max Fujiwara (TRIUMF)

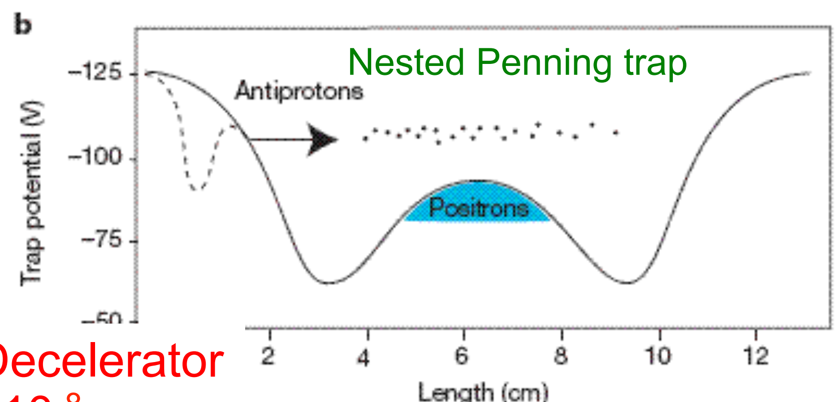
ALPHA experiment



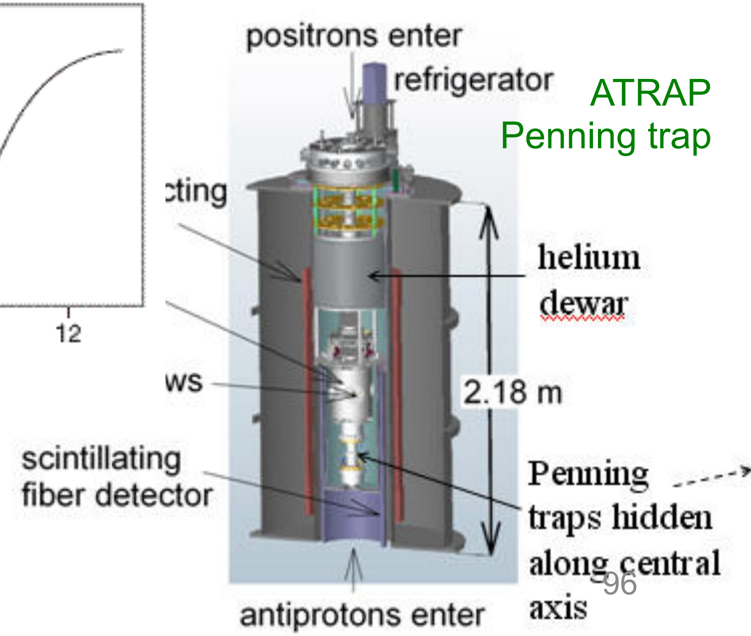
Gerry Gabrielse (Harvard)

Alan Kostelecký (Indiana)

Nested Penning trap



ATRAP Penning trap



CERN Antiproton Decelerator

$(M_p - M_{\bar{p}})/M_p < 10^{-8}$

ATHENA collaboration
Nature419(2002)456

4. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

Photon sector

Electron sector

Gravity sector

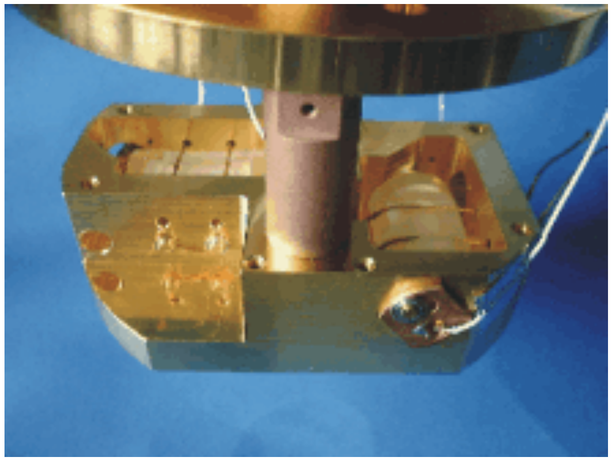
Astrophysics

Particle accelerator

Meson sector

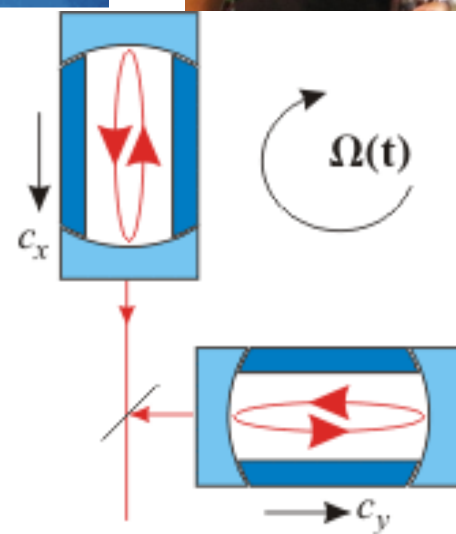
Neutrino sector

cryogenic sapphire resonator



Achim Peters (Humboldt)

Mike Tobar (Western Australia)



comparison

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

Peters et al.
PRL99(2007)050401

4. Modern tests of Lorentz violation

Neutron/proton sector

Direct CPT test

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Electron sector

Gravity sector

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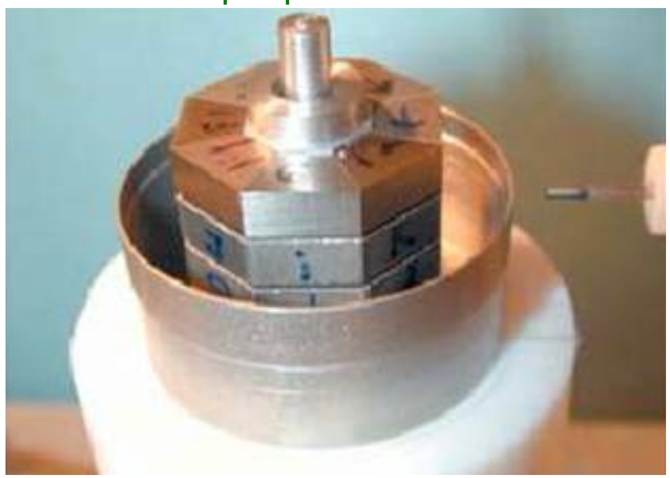
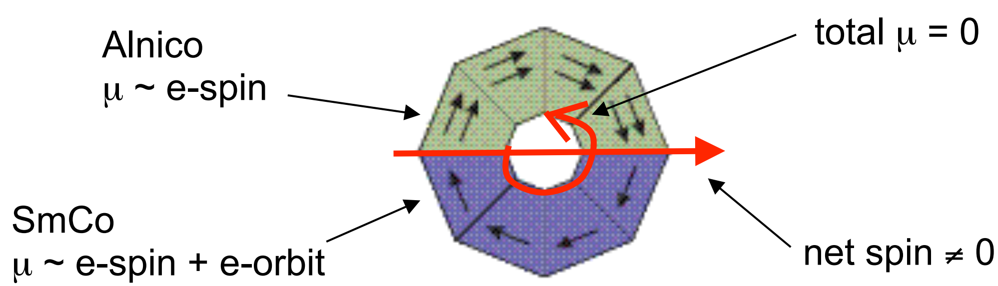
spin-pendulum



Blayne Heckel (Washington)

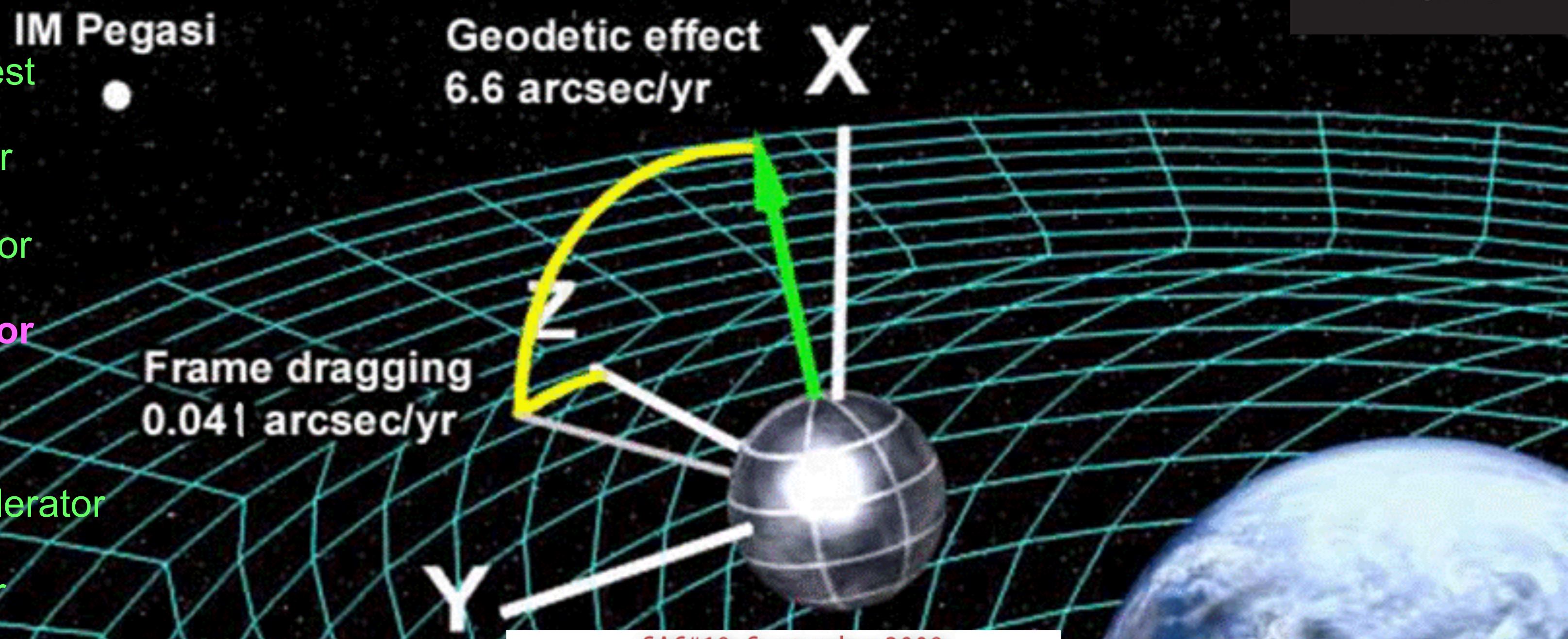
Spin pendulum
$b_e < 10^{-30}$ GeV

Heckel et al.
PRL97(2006)021603

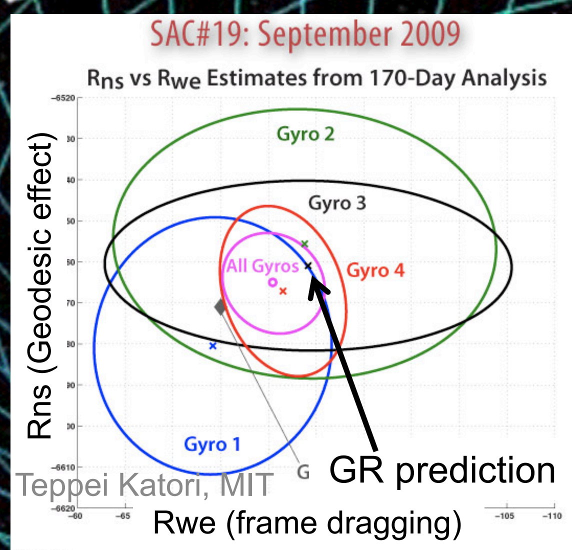


4. Modern tests of Lorentz violation

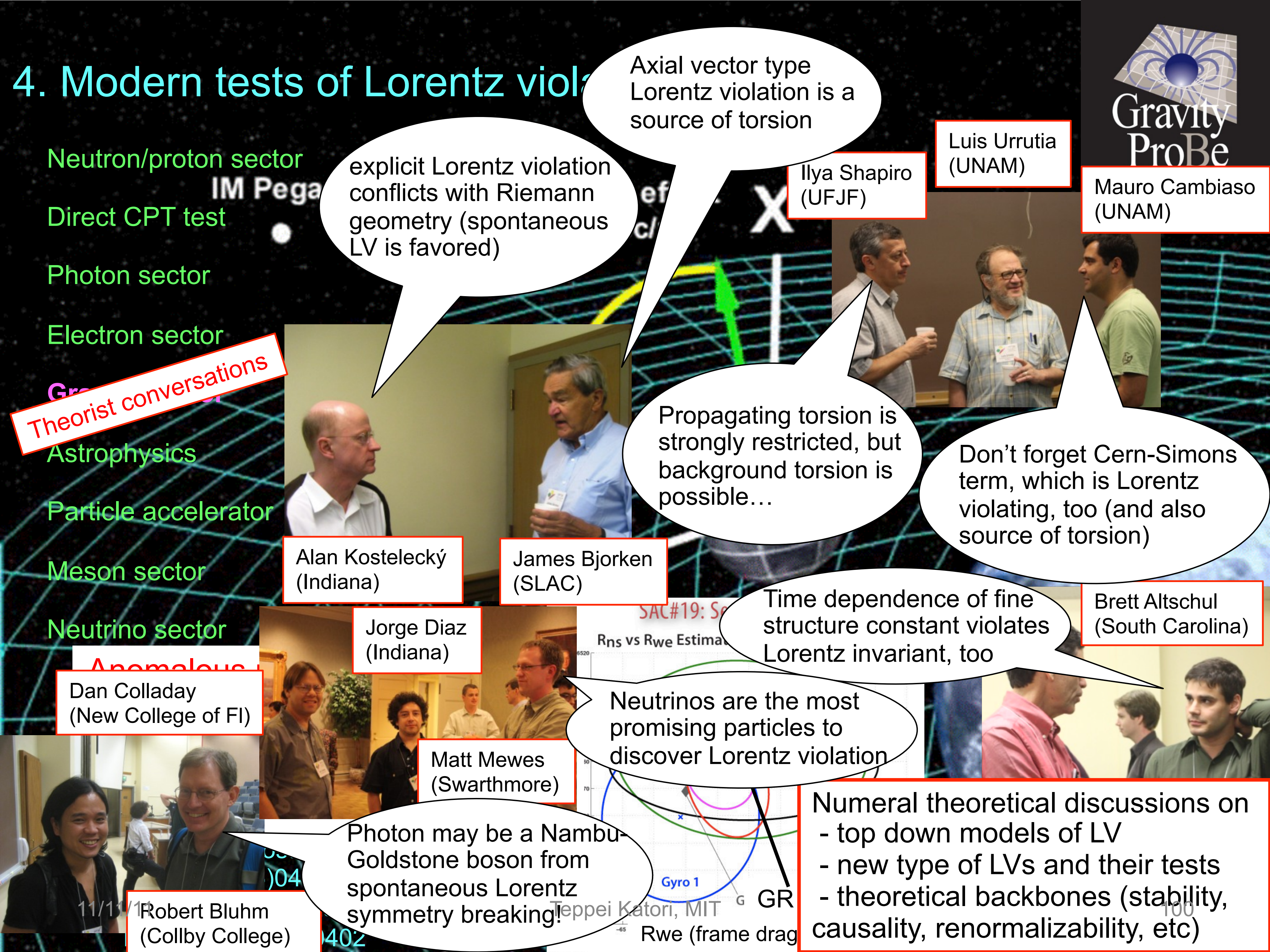
- Neutron/proton sector
- Direct CPT test
- Photon sector
- Electron sector
- **Gravity sector**
- Astrophysics
- Particle accelerator
- Meson sector
- Neutrino sector



Anomalous precession
Lunar laser ranging
Torsion pendulum
Free fall experiment
…



Bailey and Kostelecký PRD74(2006)045001
Kostelecký and Tasson PRL102(2009)010402


4. Modern tests of Lorentz viola
Neutron/proton sector
Direct CPT test
Photon sector
Electron sector
Theorist conversations
Astrophysics
Particle accelerator
Meson sector
Neutrino sector
explicit Lorentz violation conflicts with Riemann geometry (spontaneous LV is favored)
Axial vector type Lorentz violation is a source of torsion
Ilya Shapiro (UFJF)
Luis Urrutia (UNAM)
Mauro Cambiaso (UNAM)
Gravity Probe
Propagating torsion is strongly restricted, but background torsion is possible…
Don't forget Cern-Simons term, which is Lorentz violating, too (and also source of torsion)
Alan Kostelecký (Indiana)
James Bjorken (SLAC)
Time dependence of fine structure constant violates Lorentz invariant, too
Brett Altschul (South Carolina)
Jorge Diaz (Indiana)
Dan Colladay (New College of Fl)
Matt Mewes (Swarthmore)
Neutrinos are the most promising particles to discover Lorentz violation
Photon may be a Nambu-Goldstone boson from spontaneous Lorentz symmetry breaking!
Robert Bluhm (Collby College)
Numeral theoretical discussions on
- top down models of LV
- new type of LVs and their tests
- theoretical backbones (stability, causality, renormalizability, etc)
Gyro 1
GR
Rwe (frame drag

FERMI GBM/LAT collaboration
arXiv:1008.2913

4. Modern tests of Lorentz violation

- Neutron/proton sector
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- **Astrophysics**
- Particle accelerator
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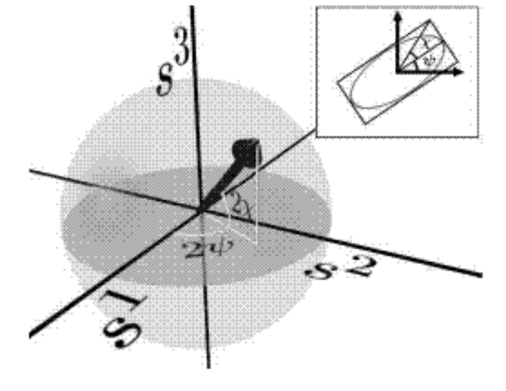
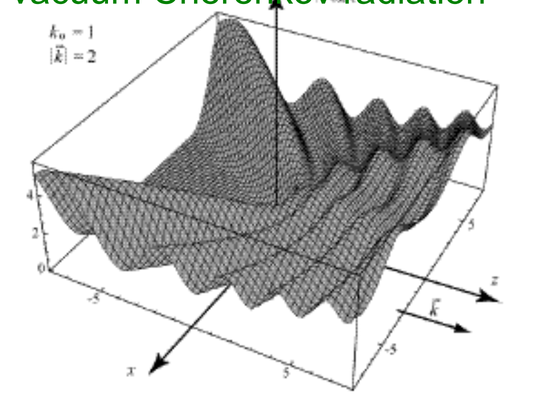
vacuum birefringence



vacuum Cherenkov radiation



GRB Lorentz violating dispersion
$c^{(6)}<10^{-22}$ GeV^{-2}, $c^{(8)}<10^{-25}$ GeV^{-4}
GRB vacuum birefringence
$\kappa<10^{-37}$

Kostelecký and Mewes
PRL97(2006)140401

4. Modern tests of Lorentz violation

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Particle accelerator

Meson sector

Neutrino sector

No vacuum Cherenkov 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.
PRL102(2009)170402

FOCUS collaboration, PLB556(2003)7
BaBar collaboration, PRL100(2008)131802

4. Modern tests of Lorentz violation

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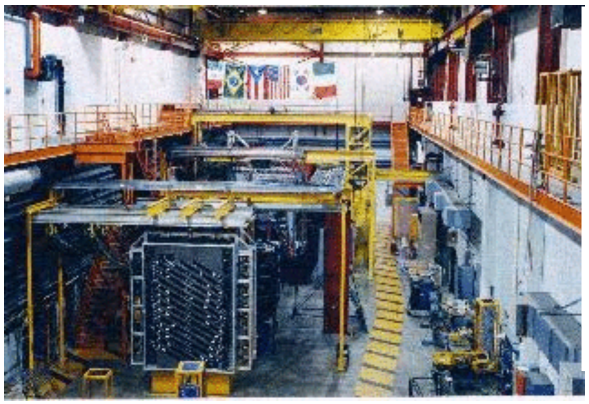
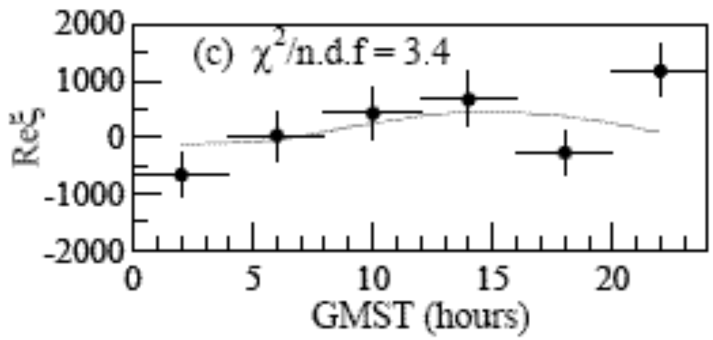
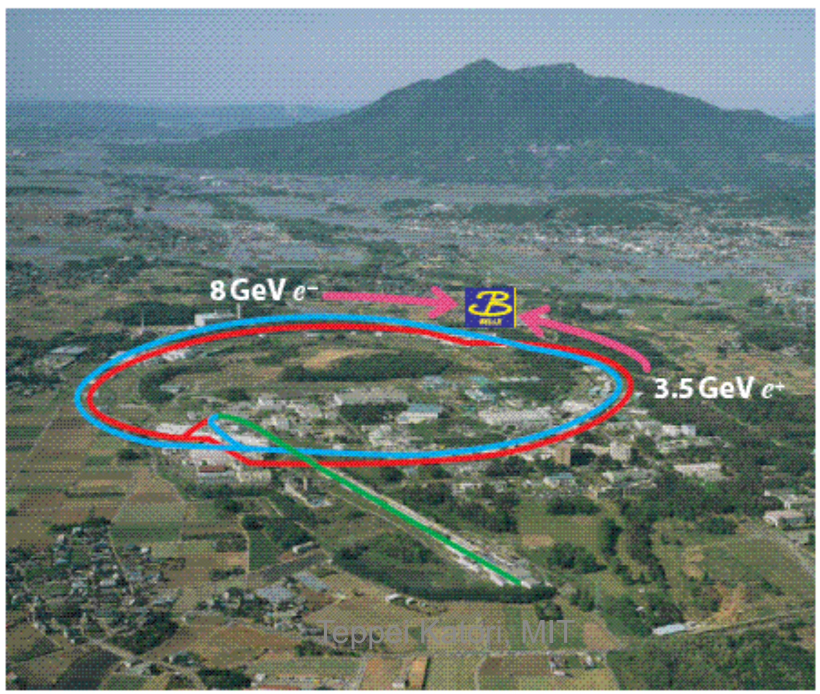
FOCUS and its data

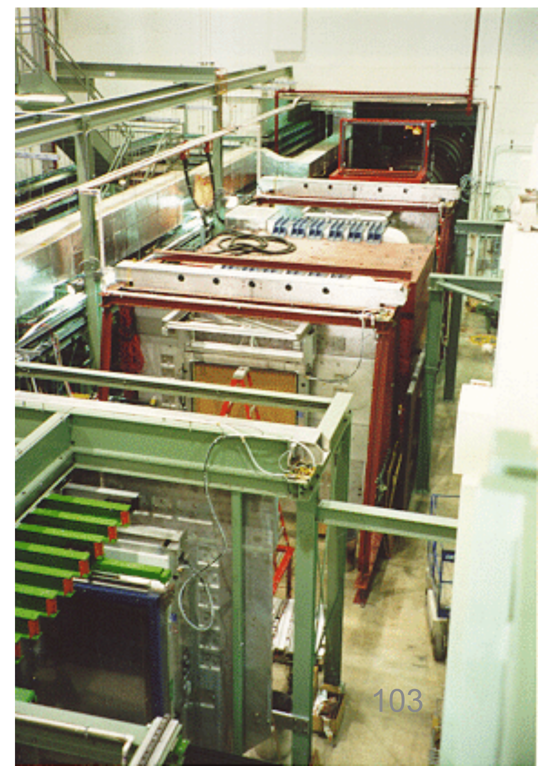




Belle



KTeV



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

4. Modern tests of Lorentz violation

Diaz et al., PRD80(2009)076007

Neutron/proton sector

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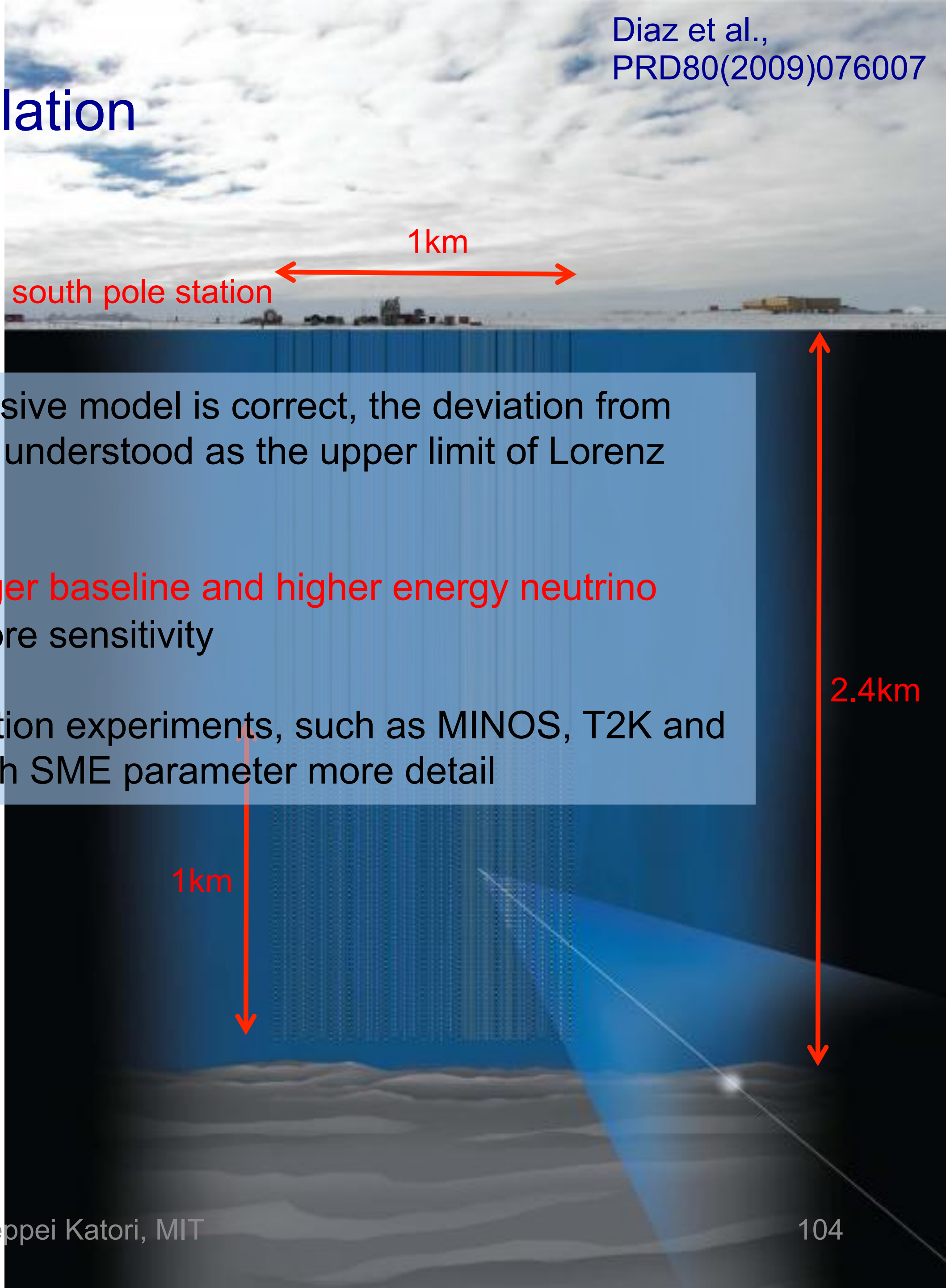
Neutrino sector

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

Long baseline oscillation experiments, such as MINOS, T2K and NOvA, can study each SME parameter more detail



IceCube experiment at south pole

IceCube collaboration PRD82(2010)112003

IceCube $c(\text{CPT-even})<10^{-27}$ $a(\text{CPT-odd})<10^{-23}$ GeV

Diaz et al.,
PRD80(2009)076007

4. Modern tests of Lorentz violation

- Neutron/proton sector
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- **Neutrino sector**

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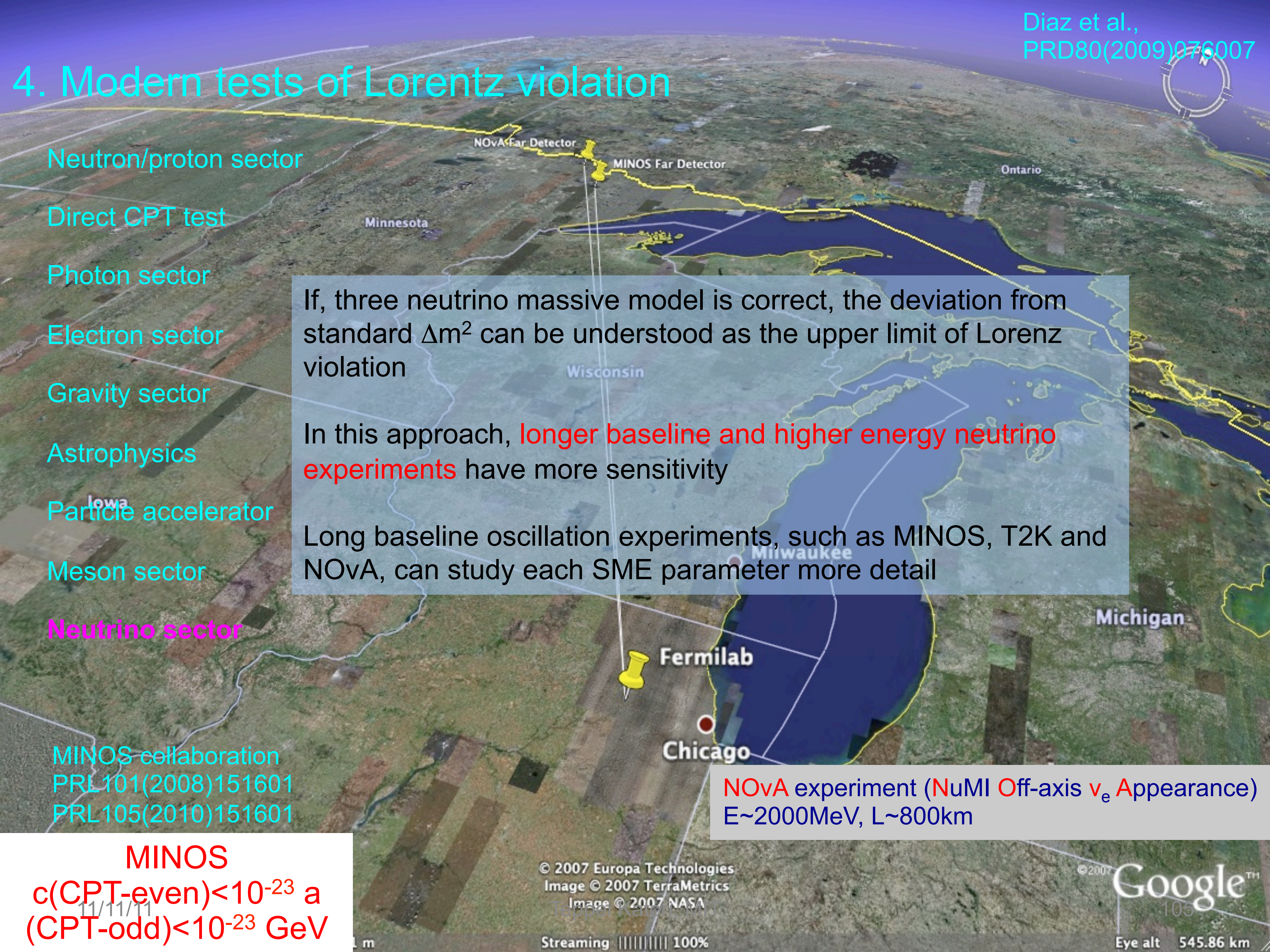

NOvA experiment (NuMI Off-axis ν_e Appearance)
E~2000MeV, L~800km

MINOS collaboration
PRL101(2008)151601
PRL105(2010)151601

MINOS
c(CPT-even)<10^{-23} a (CPT-odd)<10^{-23} GeV

LSND collaboration
PRD72(2005)076004

4. Modern tests of Lorentz violation

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Meson sector

Neutrino sector

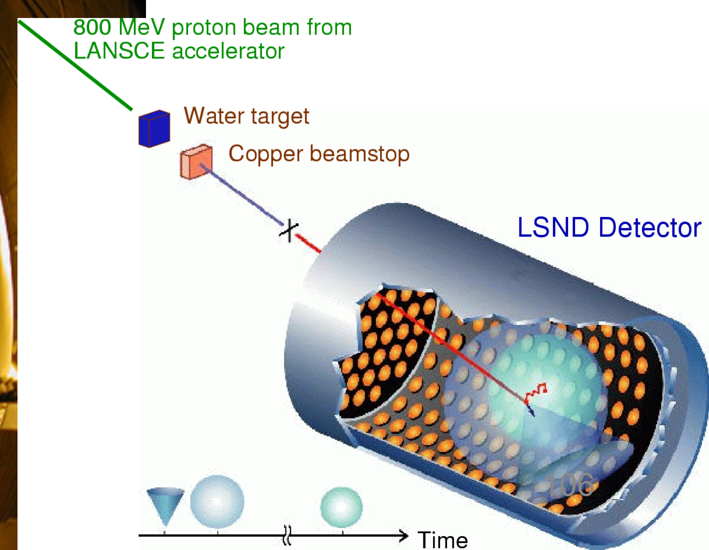
However, Lorentz violation could mimic neutrino masses.

We might be seeing Lorentz violation as an anomalous neutrino oscillation signal.

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

MiniBooNE

LSND



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

Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

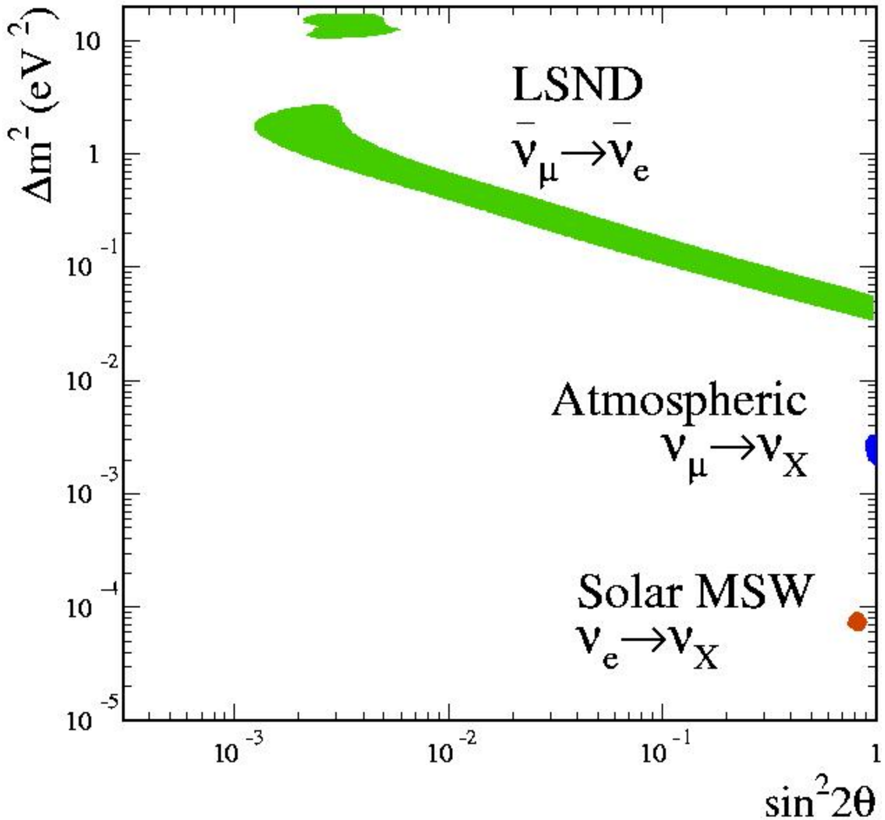
The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

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

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.

MS diagram of neutrino oscillation signal



Kostelecký and Mewes
PRD69(2004)016005

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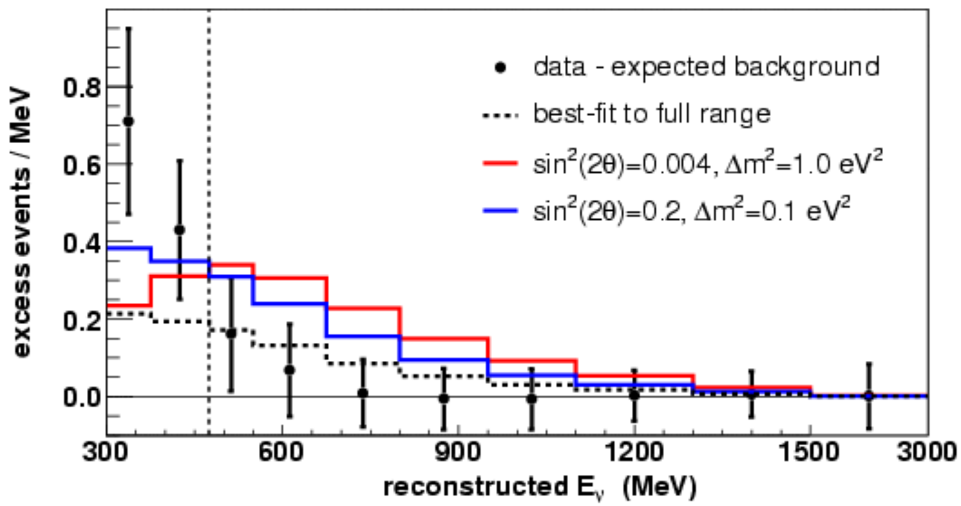
Any signals do not have L/E oscillatory dependence could be Lorentz violation. Lorentz violating neutrino oscillation can have various type of energy dependences.

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

effective Hamiltonian of neutrino oscillation

usual term (3X3) additional terms (3X3)

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

Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

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

(1) Spectral anomalies
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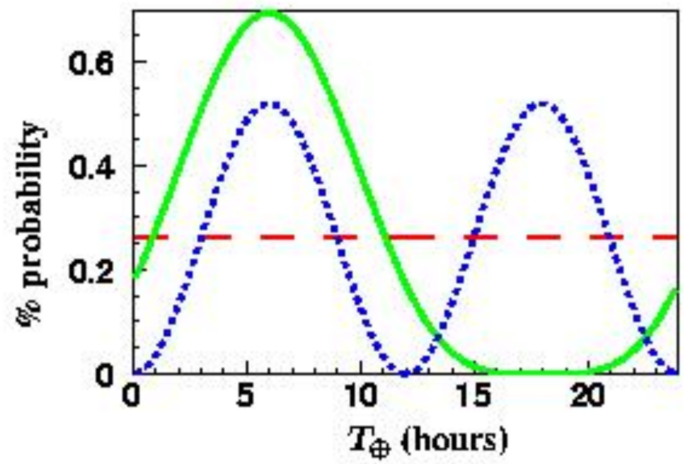
sidereal variation of the neutrino oscillation signal is the signal of Lorentz violation

This signal is the exclusive smoking gun of Lorentz violation.

example of sidereal variation for LSND signal



Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

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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)

Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

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

(1) Spectral anomalies
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$$\nu \leftrightarrow \bar{\nu} \,?$$

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

formalism also contain neutrino-antineutrino oscillation

Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

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

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

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

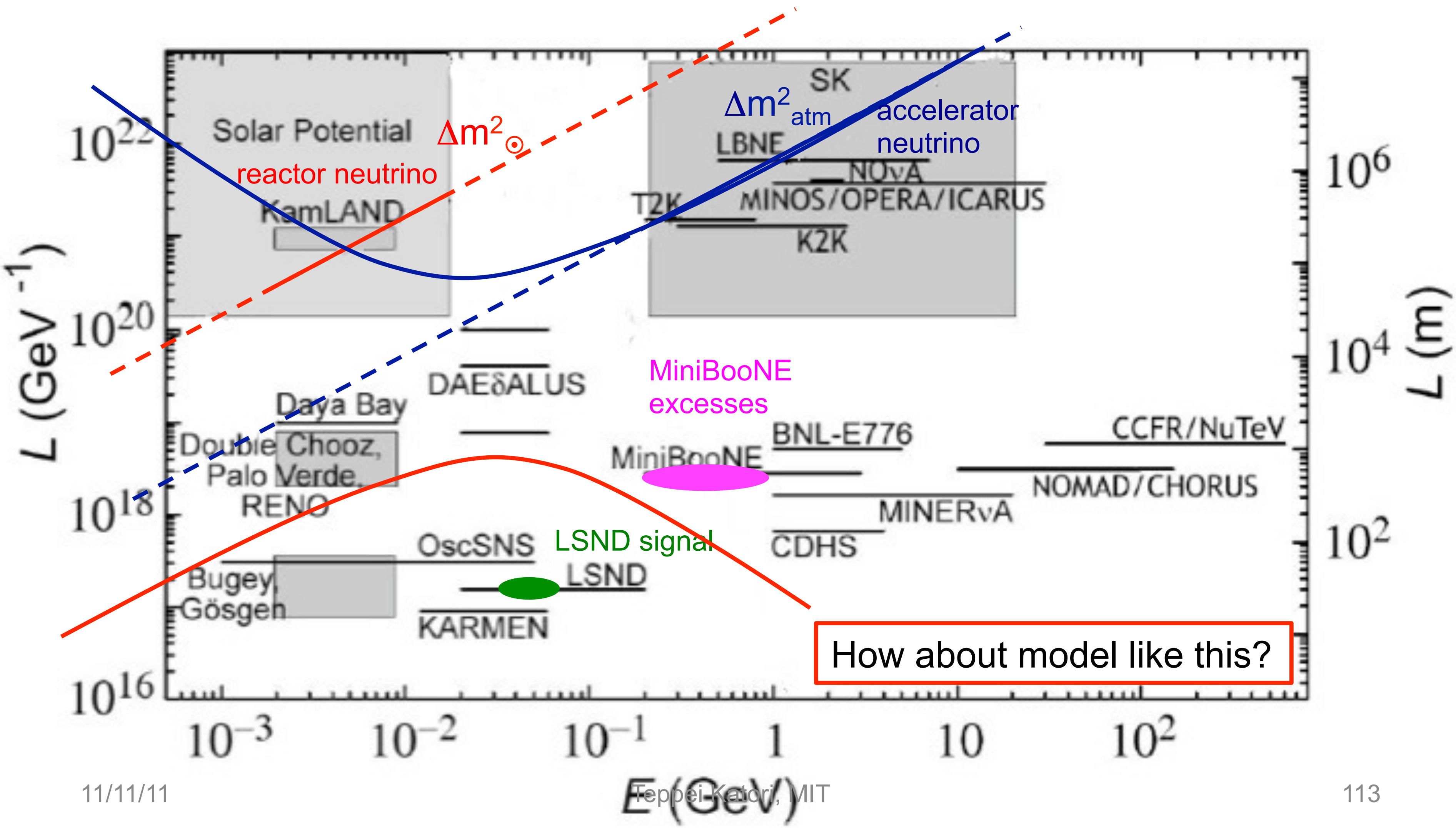
ex) Lorentz violating Hamiltonian for anti-neutrino

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

Diaz and Kostelecký
PLB700(2011)25

5. Lorentz violation with neutrino oscillation

Model independent neutrino oscillation data is the function of neutrino energy and baseline.



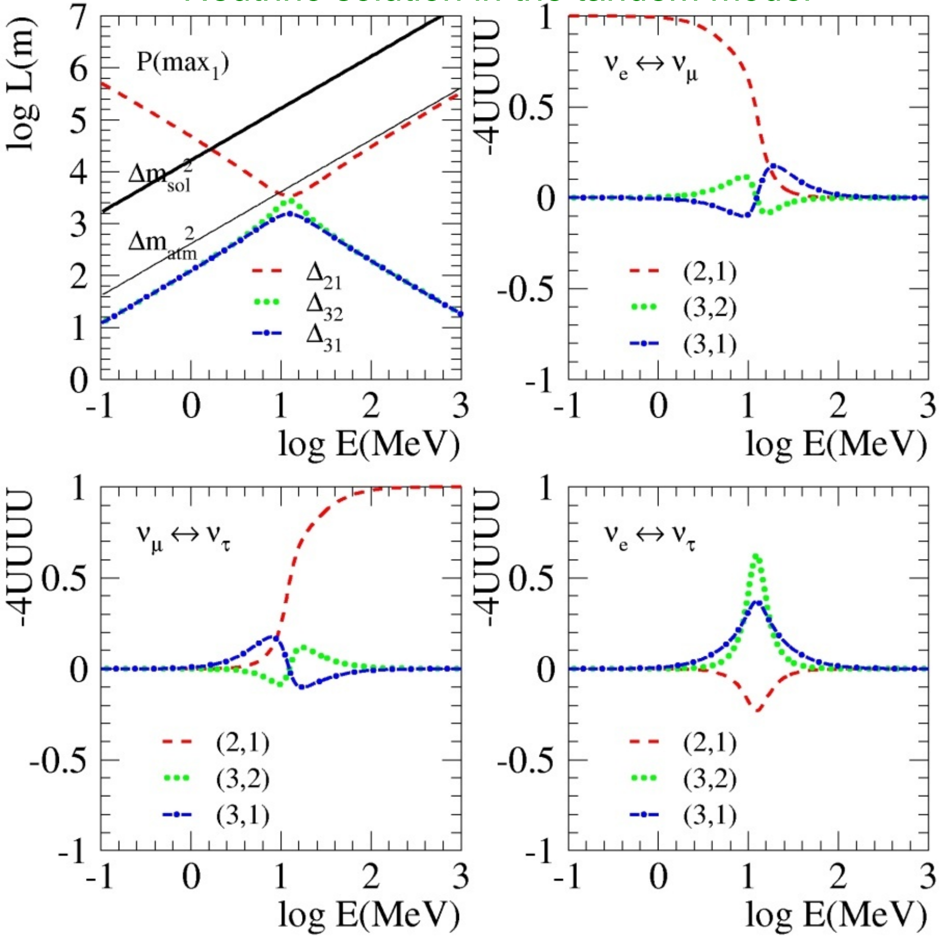
TK, Kostelecký, Tayloe
PRD74(2006)105009

5. Tandem model

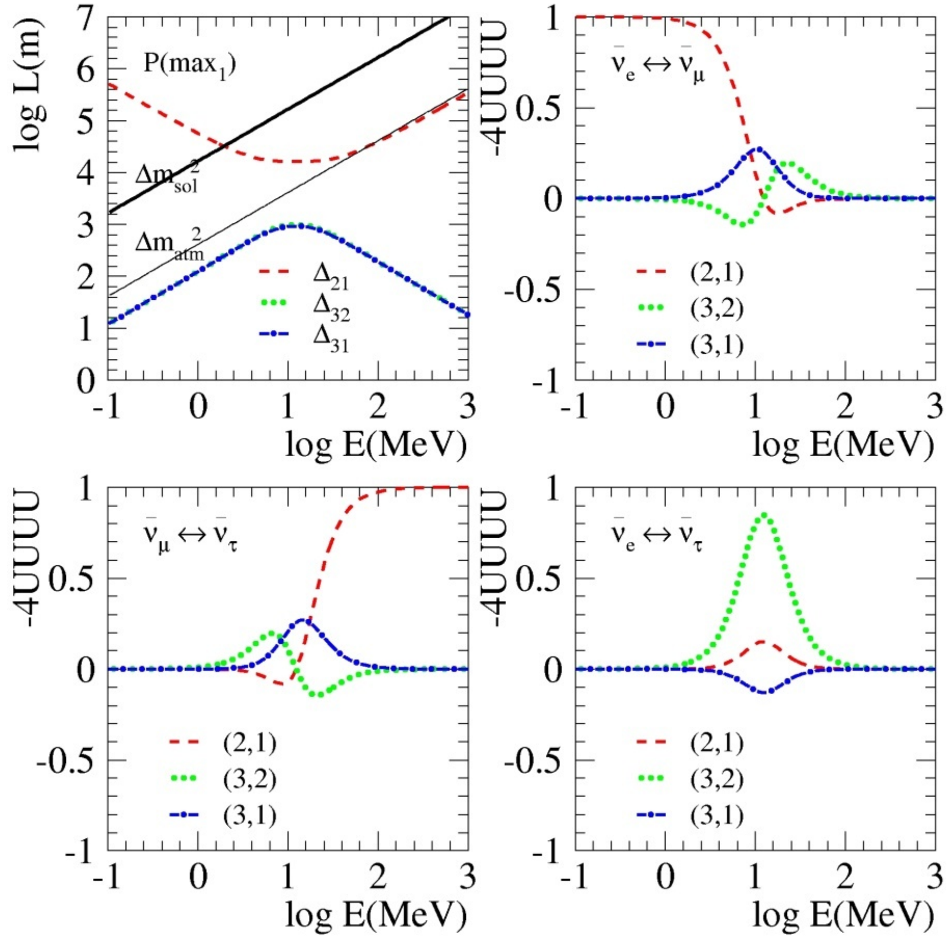
Tandem model

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

Neutrino solution in the tandem model



Anti-neutrino solution in the tandem model



TK, Kostelecký, Tayloe
PRD74(2006)105009

5. Tandem model

Tandem model

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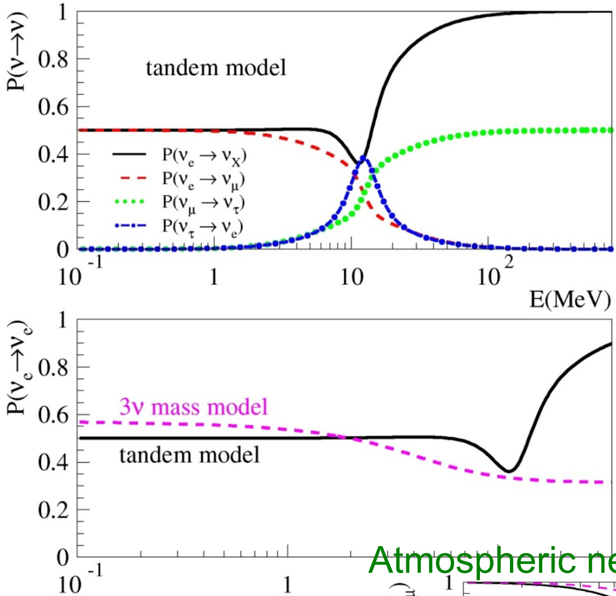
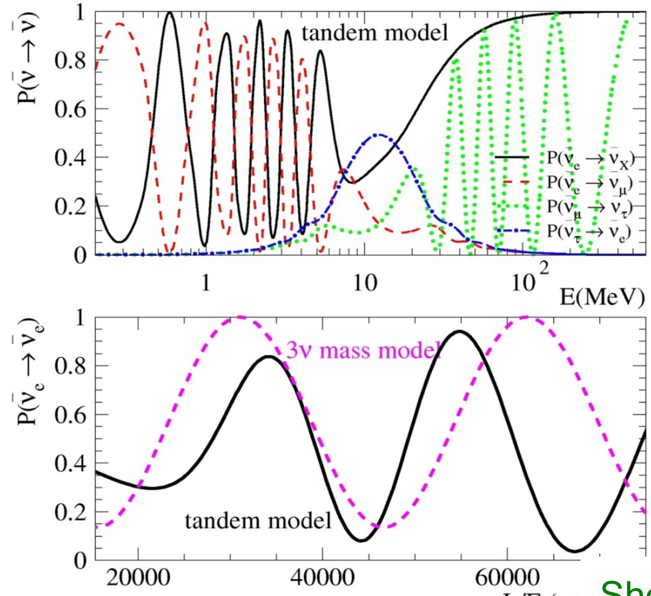
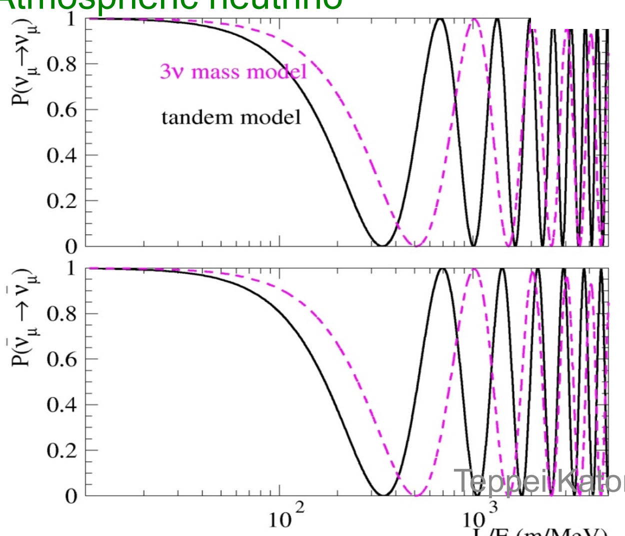
Solar neutrino



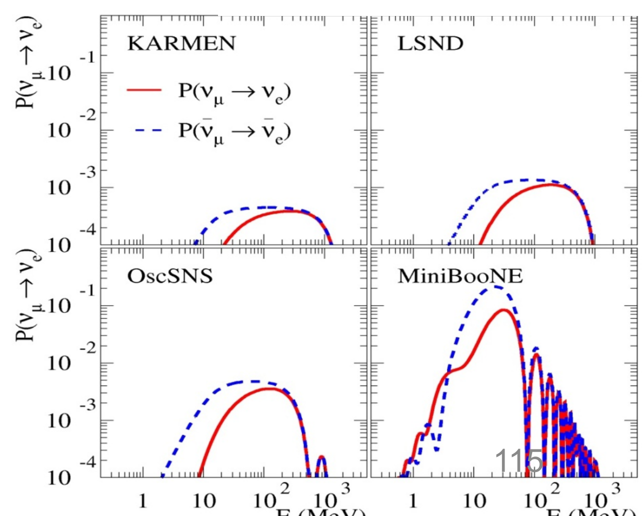
Reactor neutrino



Atmospheric neutrino



Short baseline neutrinos



5. Oscillation analysis background summary

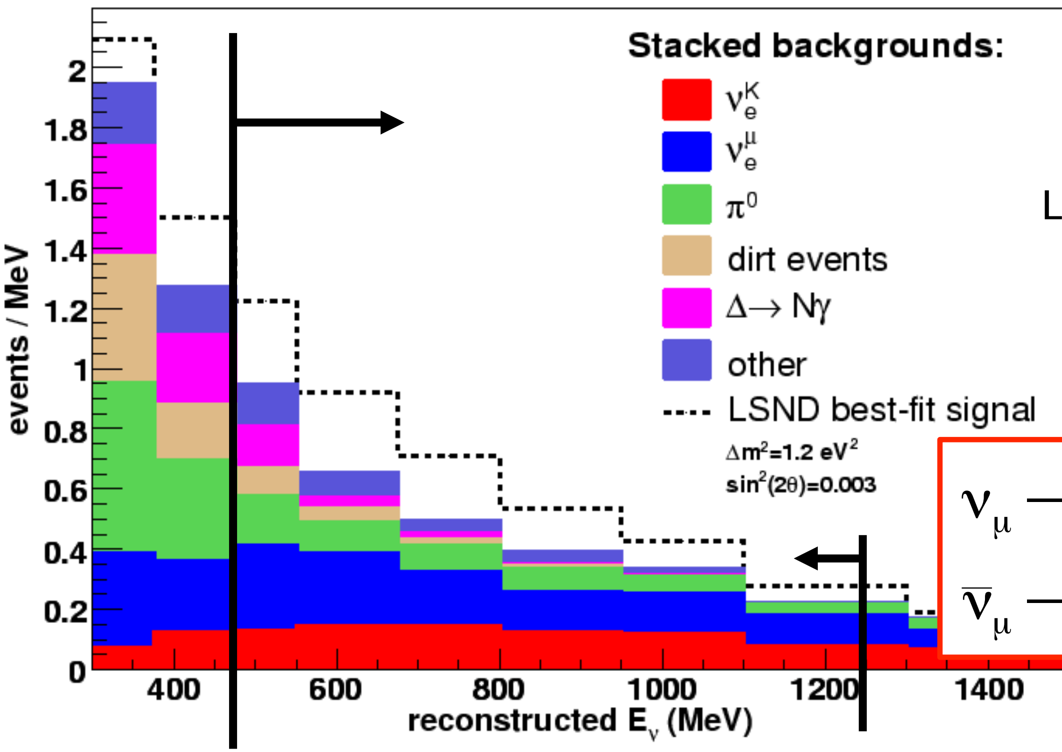
475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV



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

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

5. Oscillation analysis background summary

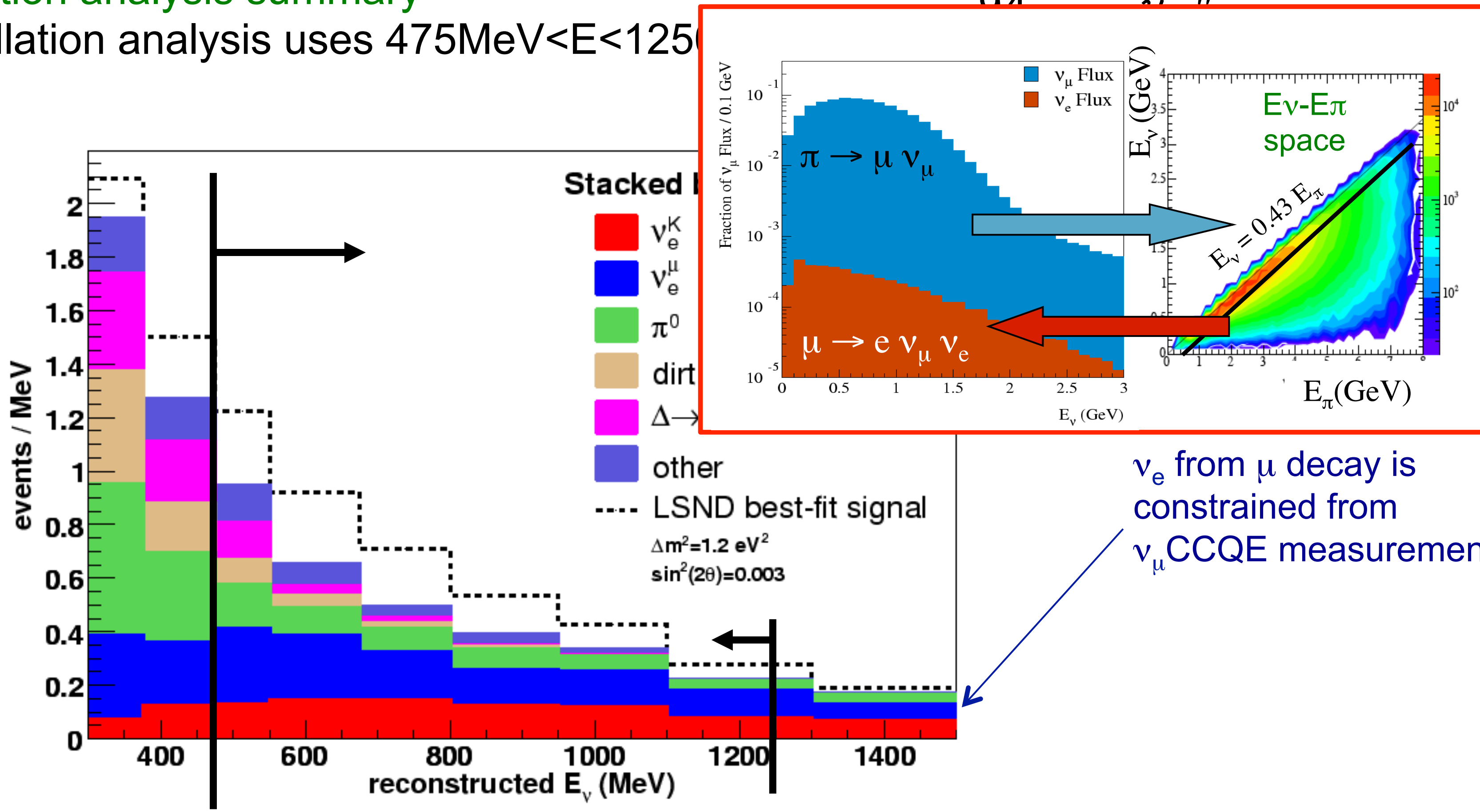
475 MeV – 1250 MeV

ν_e^K

94

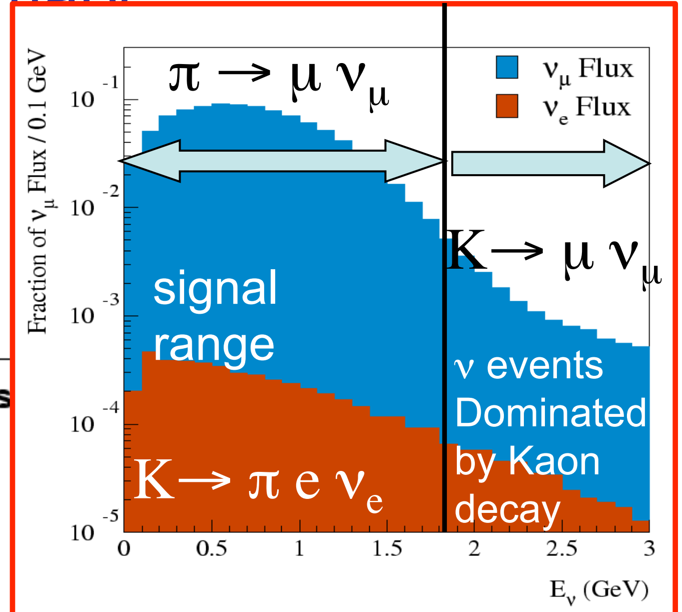
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<125



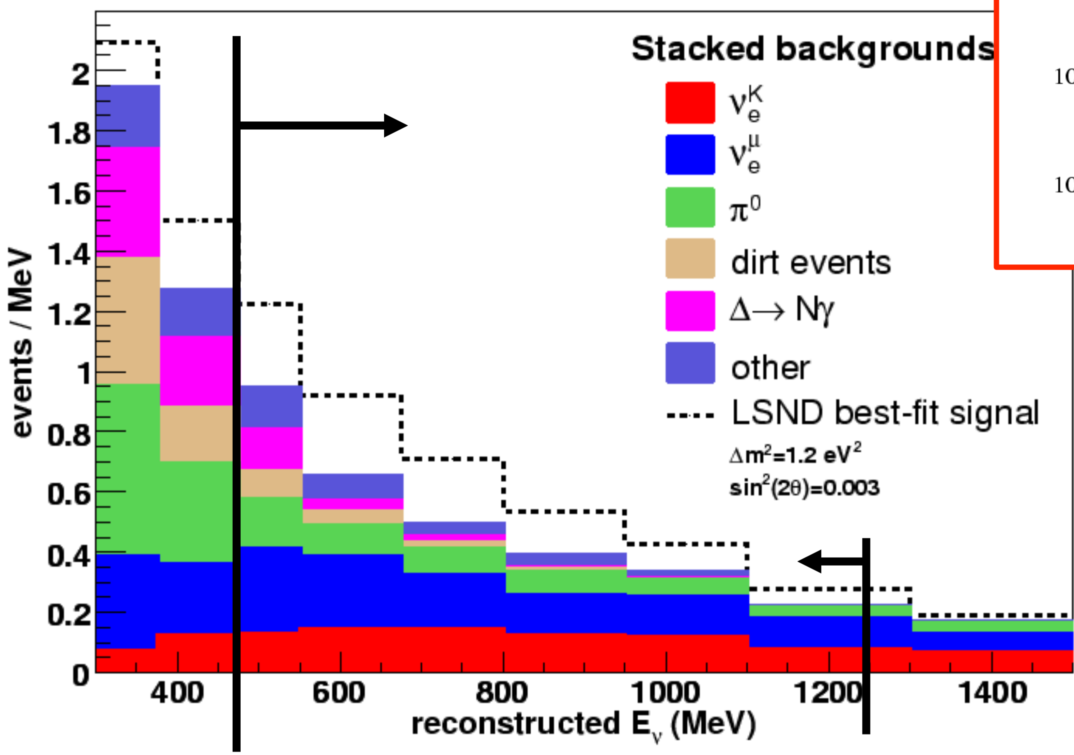
ν_e from μ decay is constrained from ν_μCCQE measurement

5. Oscillation analysis background summary



Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV



ν_e from μ decay is constrained from ν_μCCQE measurement

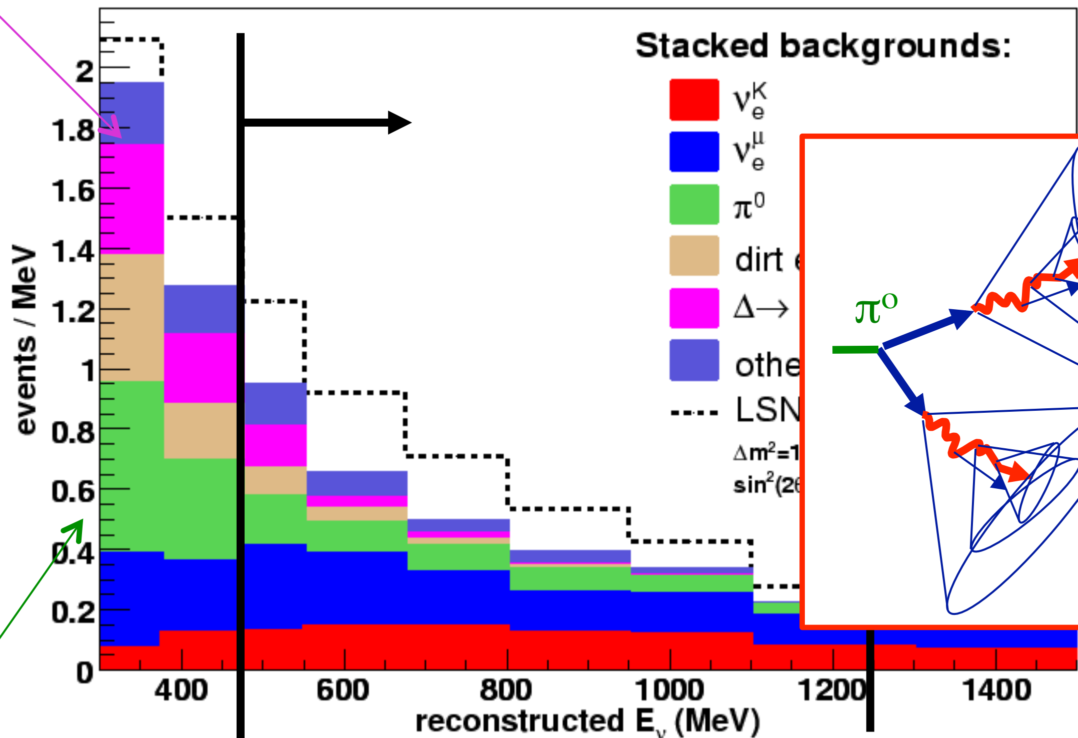
ν_e from K decay is constrained from high energy ν_e event measurement

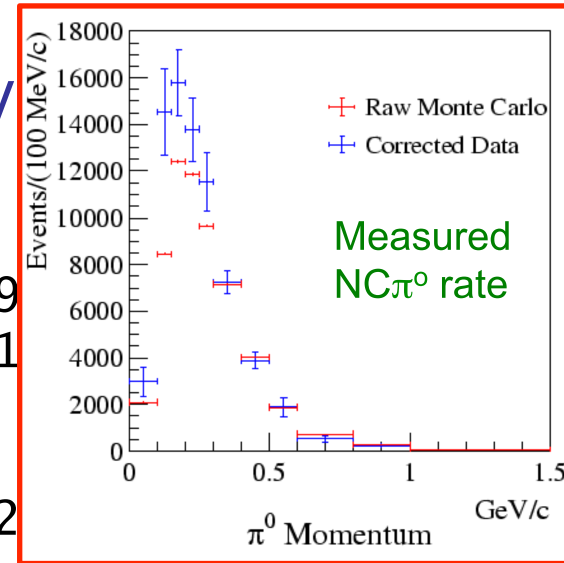
5. Oscillation analysis background summary

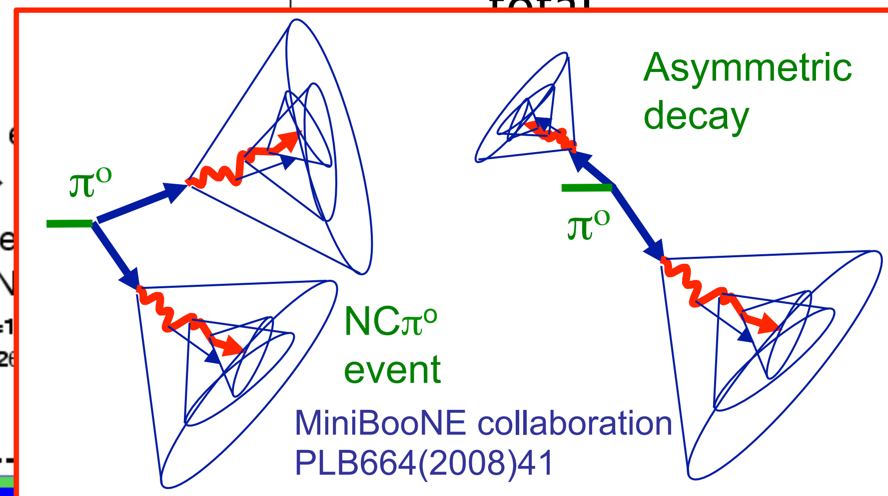
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured CCπ° rate







ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π° decay is constrained from measured CCπ° rate (π°→γ)

5. Oscillation analysis background summary

475 MeV – 1250 MeV

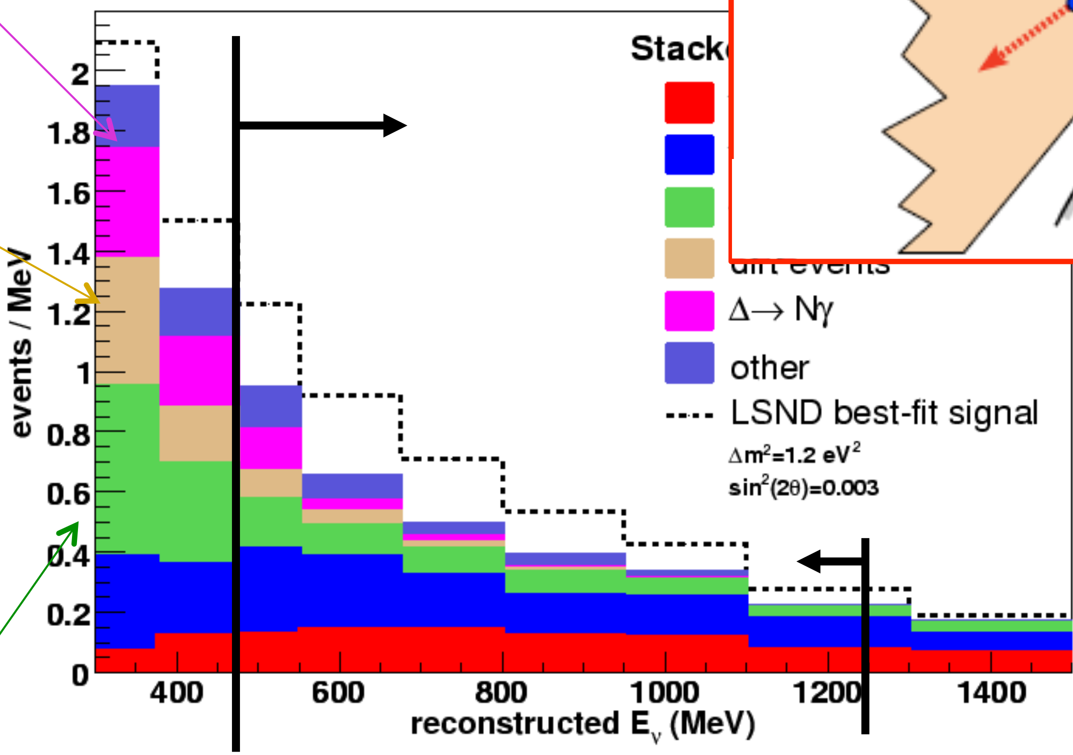
ν_e^K

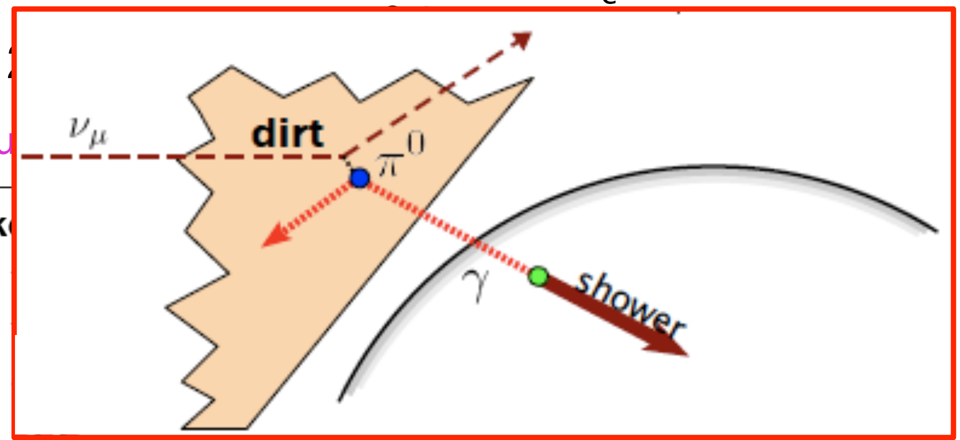
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1

Δ resonance rate is constrained from measu

dirt rate is measured from dirt data sample





ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

475 MeV – 1250 MeV	
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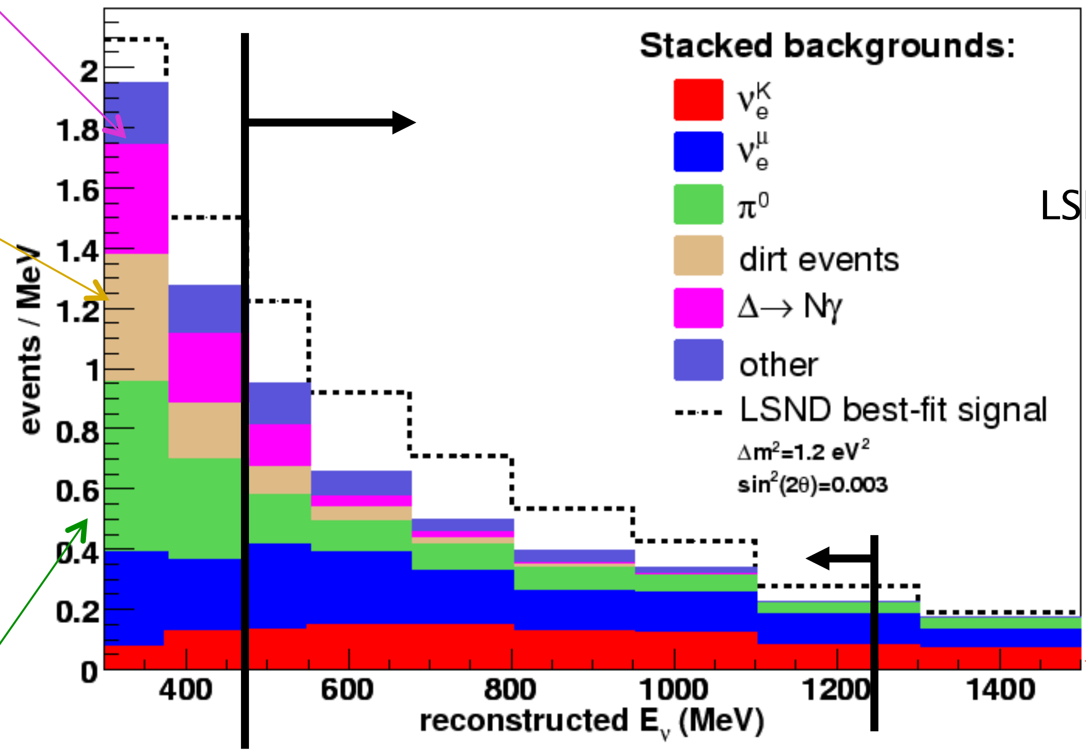
Δ resonance rate is constrained from measured CCπ^o rate

dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \to \gamma$)

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

7. Lorentz violation with MiniBooNE neutrino data

Neutrino mode result, high energy region

All parameters are consistent with zero (=no excess).