Tests of Lorentz and CPT violation with Neutrinos

Teppei Katori
Massachusetts Institute of Technology
SMU HEP seminar, Dallas, TX, Sep. 24, 2012

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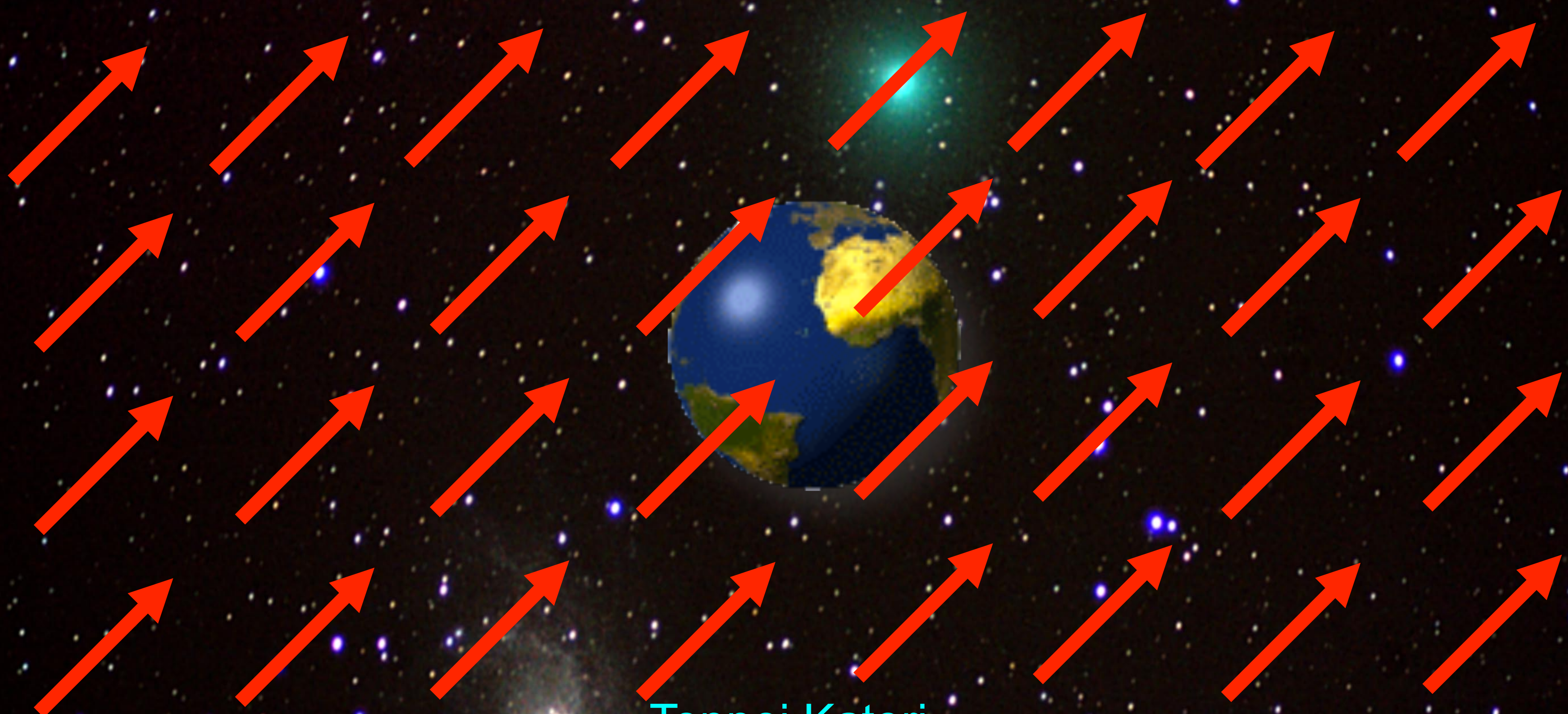

Teppei Katori
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Tests of Lorentz and CPT violation with Neutrinos

outline

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

Teppei Katori
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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

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1. Spontaneous symmetry breaking

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

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

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

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

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

Spontaneous Symmetry Breaking (SSB)!

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

1. Spontaneous Lorentz symmetry breaking (SLSB)

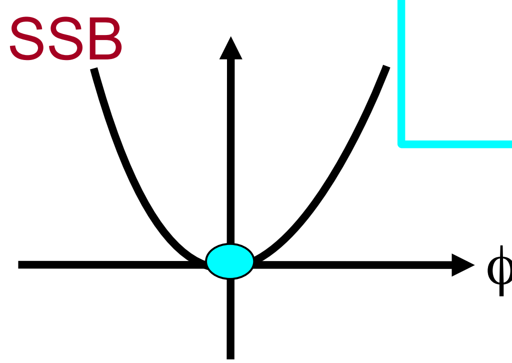
vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_{\mu}\partial^{\mu}\Psi$

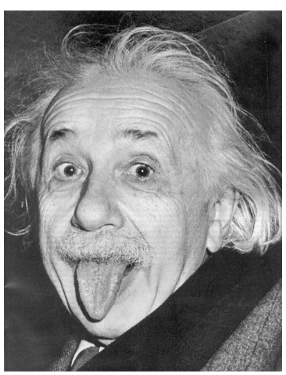
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

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





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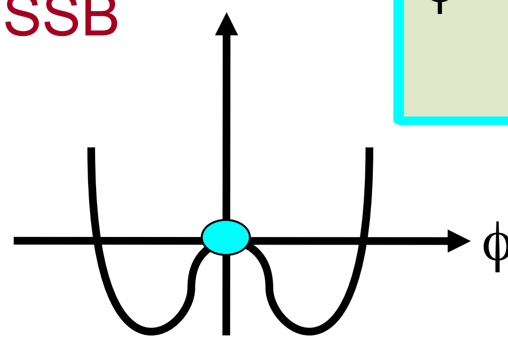
SSB



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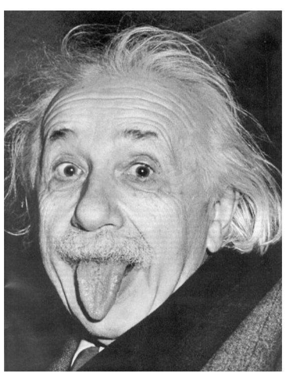

Particle acquires
mass term!

Kostelecký and Samuel
PRD39(1989)683

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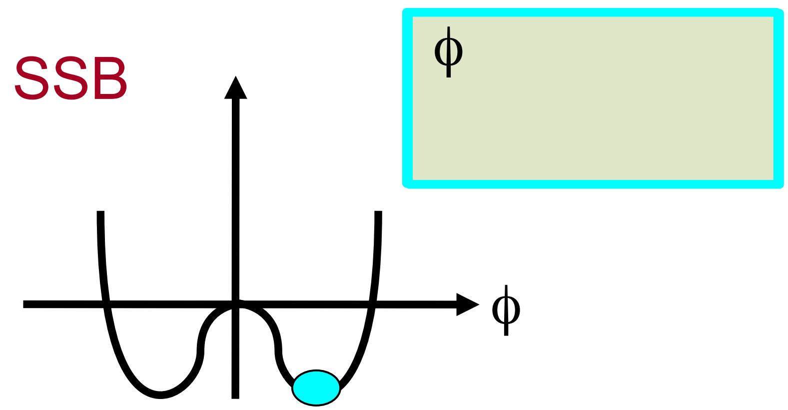
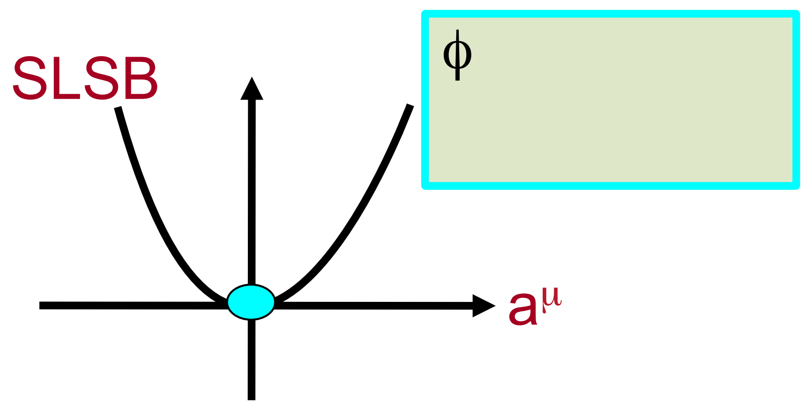
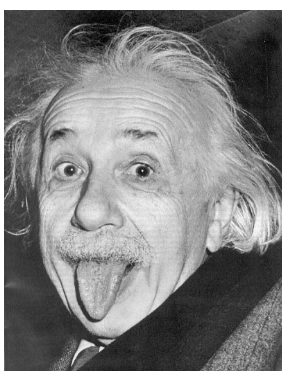


e.g.) SLSB in string field theory

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

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





Kostelecký and Samuel
PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking (SLSB)

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

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

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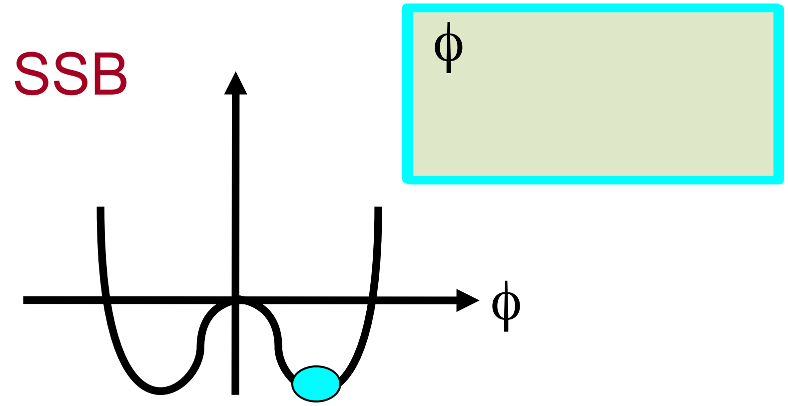

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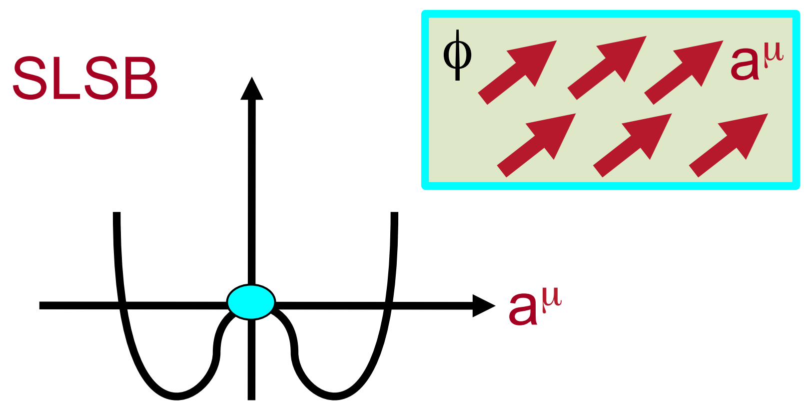
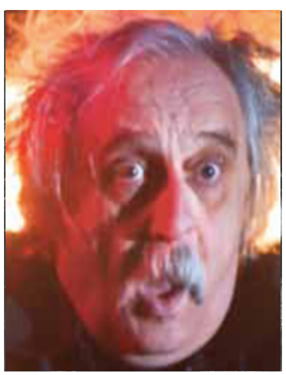




Lorentz symmetry is spontaneously broken!

1. Spontaneous Lorentz symmetry breaking

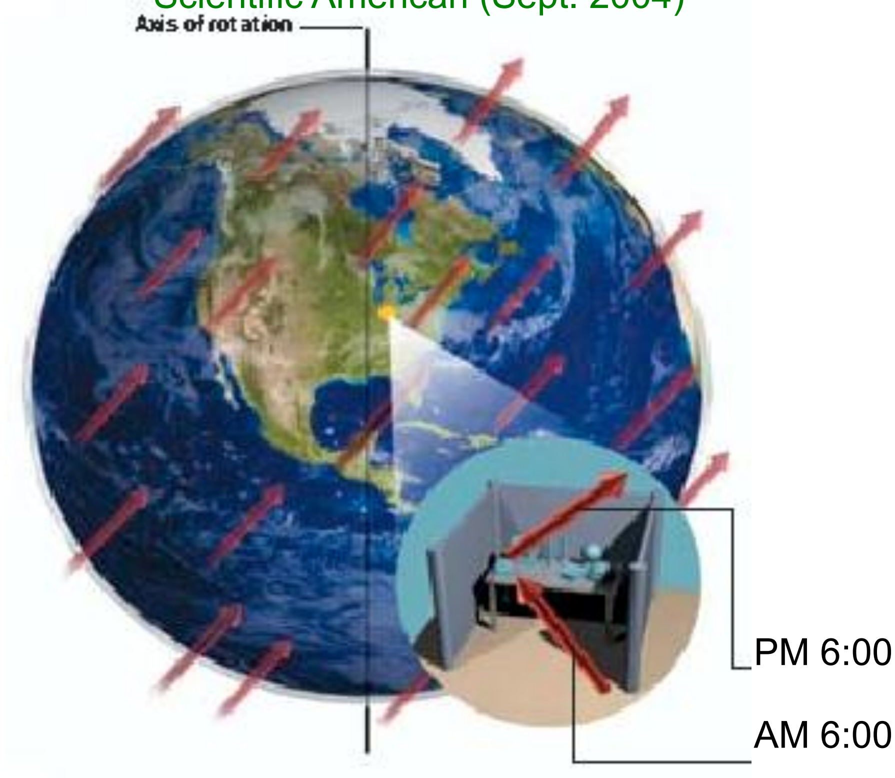
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos etc), then physical quantities may depend on the rotation of the earth.

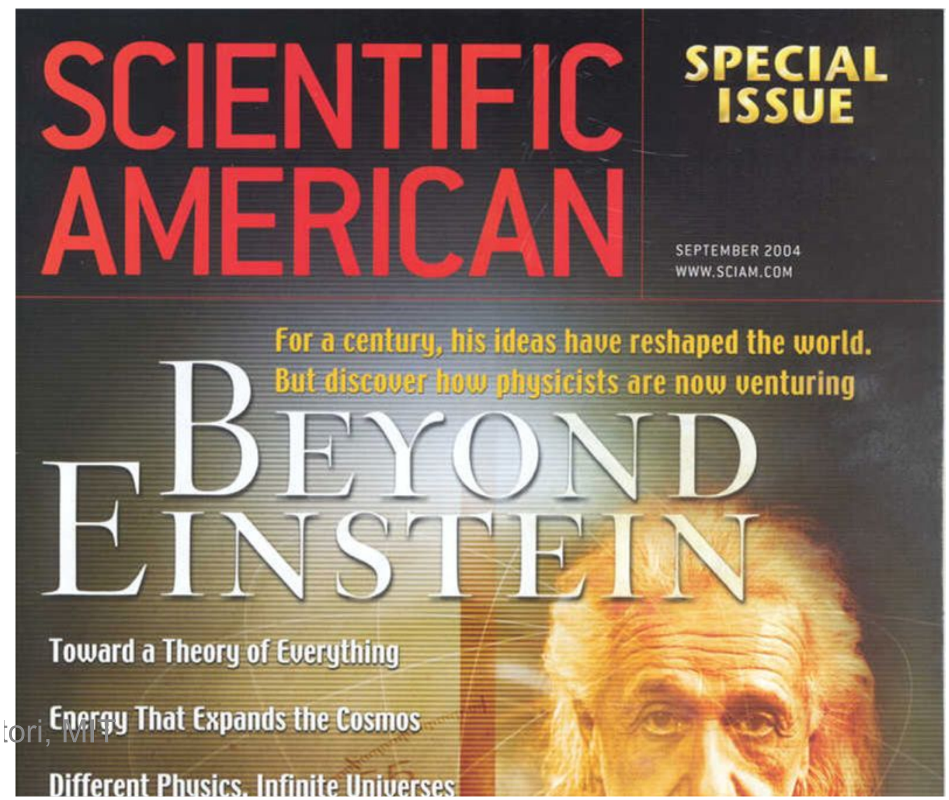
background field of the universe

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)




SCIENTIFIC AMERICAN

SPECIAL ISSUE

SEPTEMBER 2004
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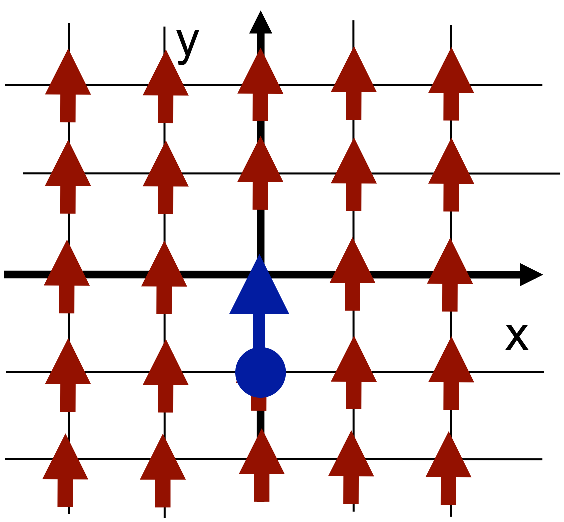
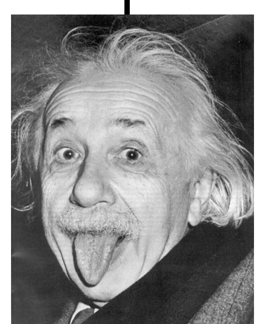
$$\overline{\Psi}(x)\gamma_{\mu}a^{\mu}\Psi(x)$$





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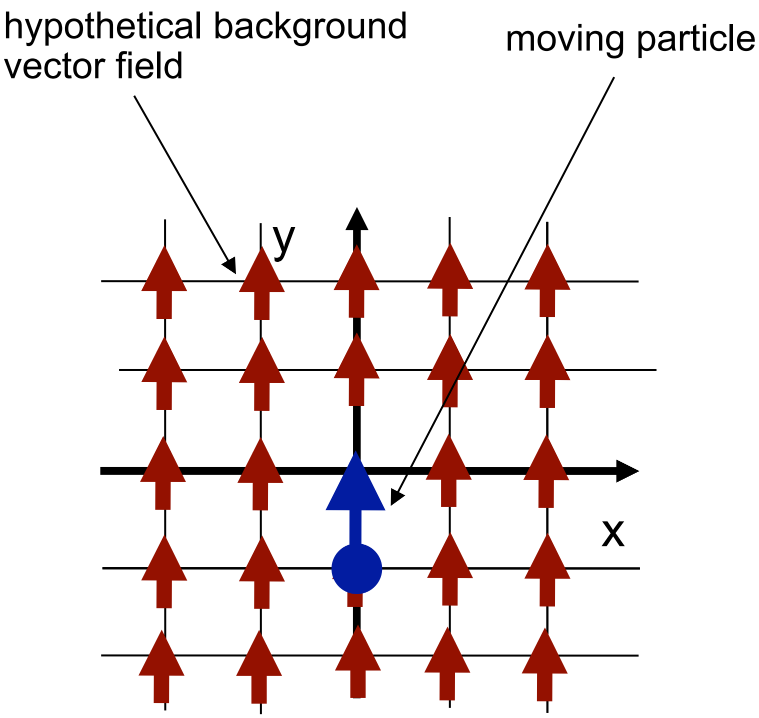
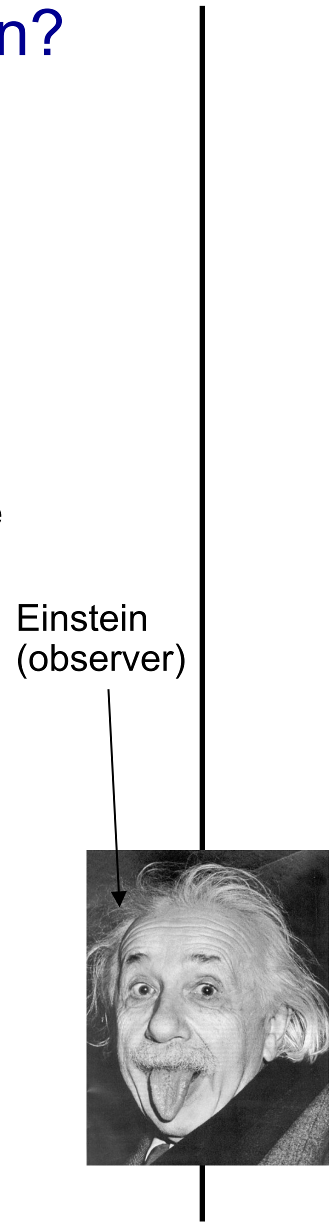
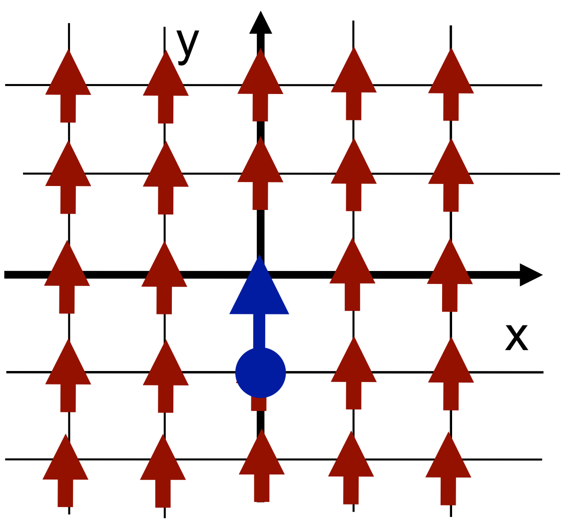


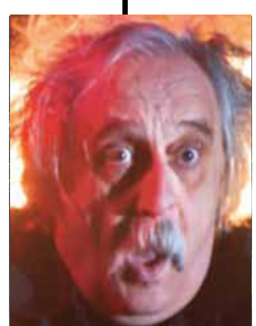


2. What is Lorentz violation?

Under the particle Lorentz transformation:

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





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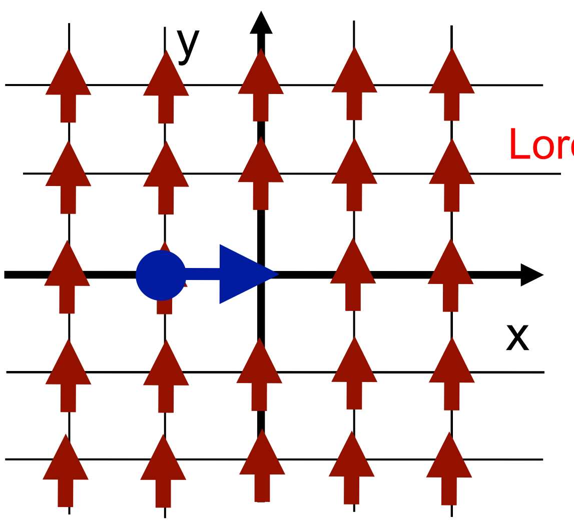
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$

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

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



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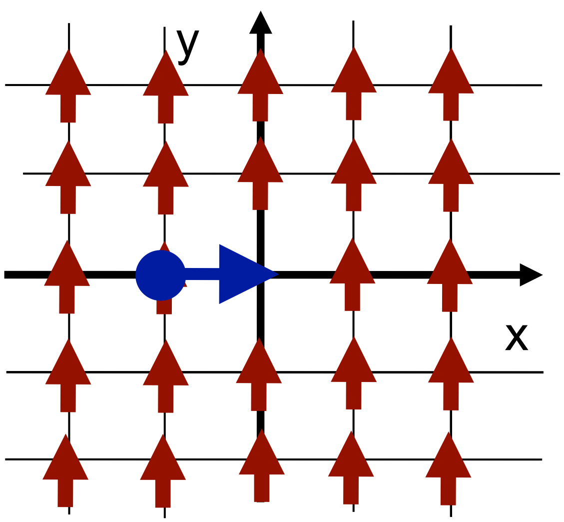

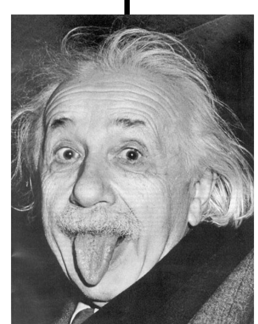

Under the observer Lorentz transformation:

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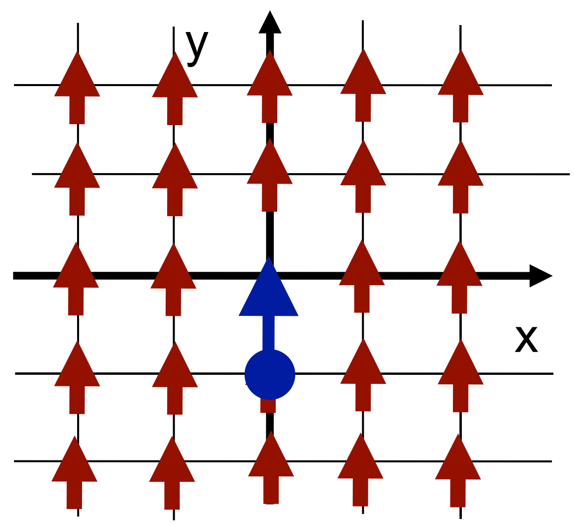

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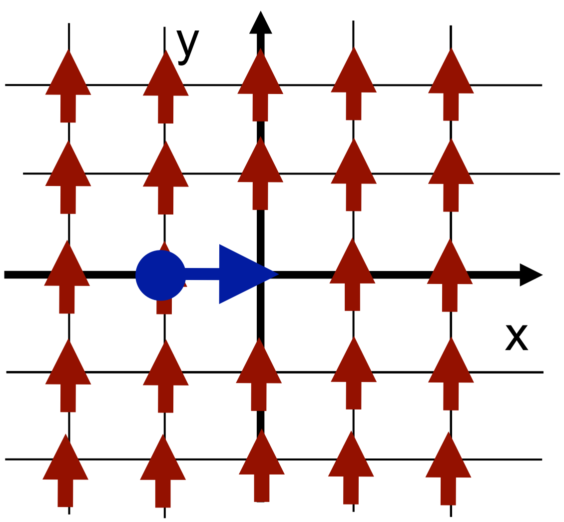

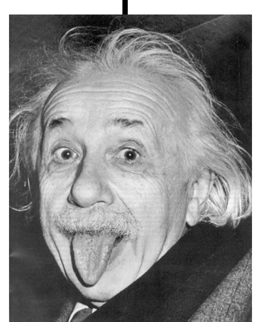

Under the observer Lorentz transformation:

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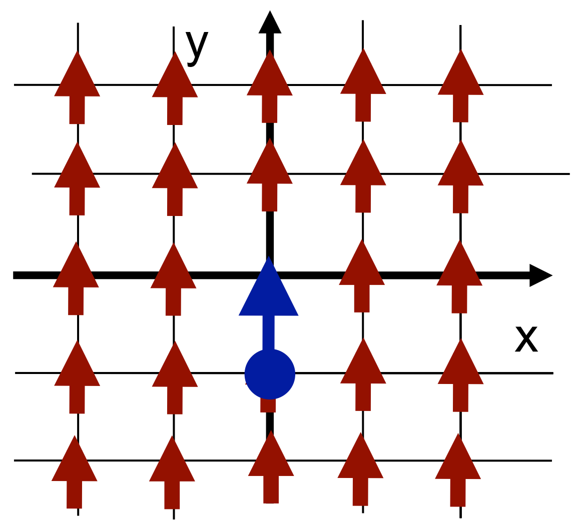
$$x \rightarrow \Lambda^{-1} x$$



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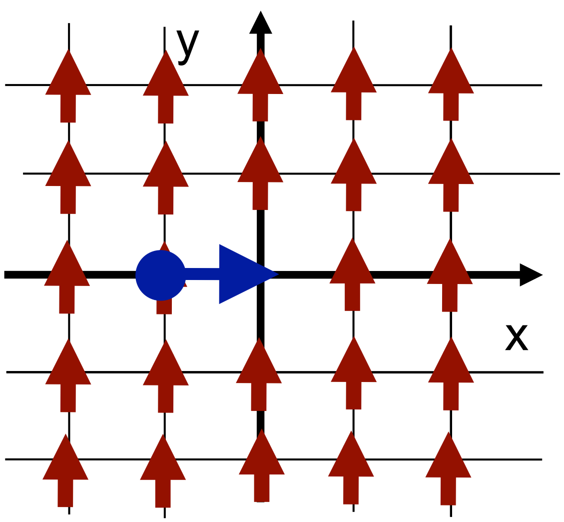
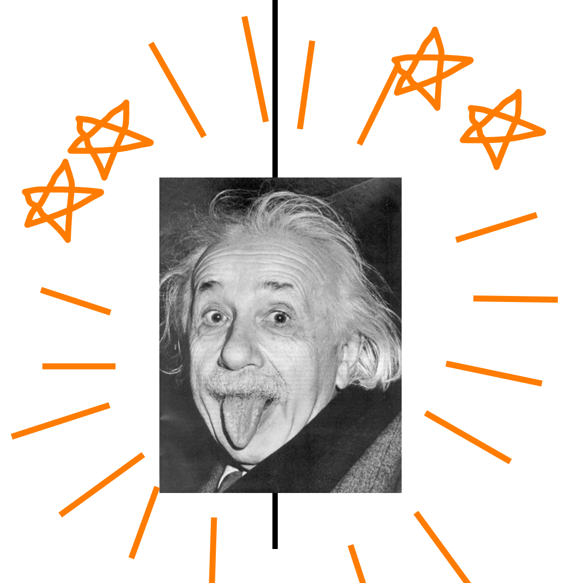


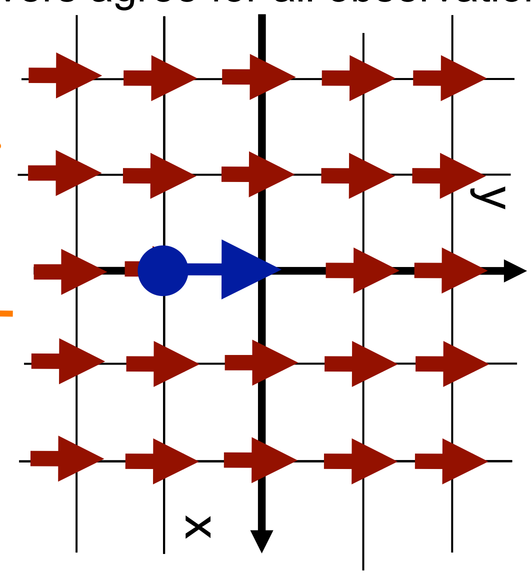
Under the observer Lorentz transformation:

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

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

all observers agree for all observations



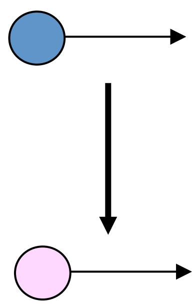


2. What is CPT violation?

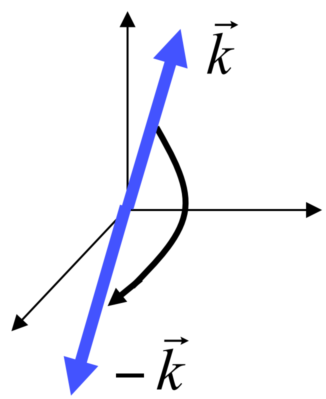
CPT symmetry is the invariance under the CPT transformation

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

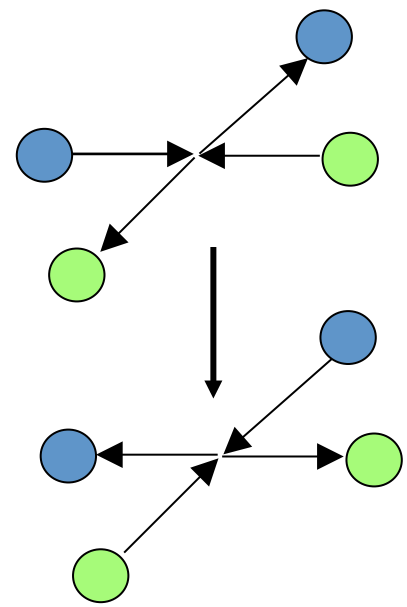
C: charge conjugation



P: parity transformation



T: time reversal



Jost, Helv.Phys.Acta.30(1957)409

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

CPT theorem
If the relativistic transformation law and the weak microcausality holds in a real neighbourhood of a Jost point, the CPT condition holds everywhere.

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↓

$$\text{CPT phase} = (-1)^n$$

number of Lorentz indices
→ always even number

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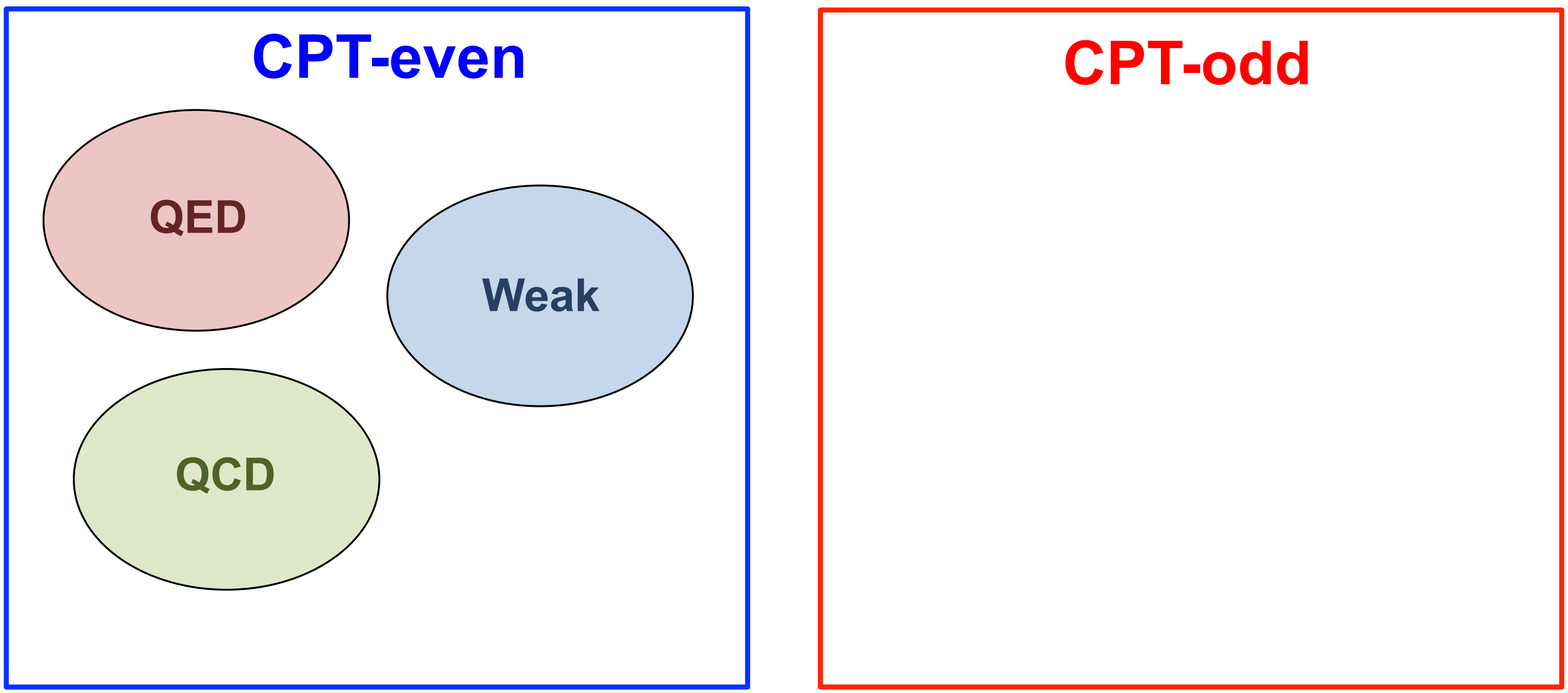

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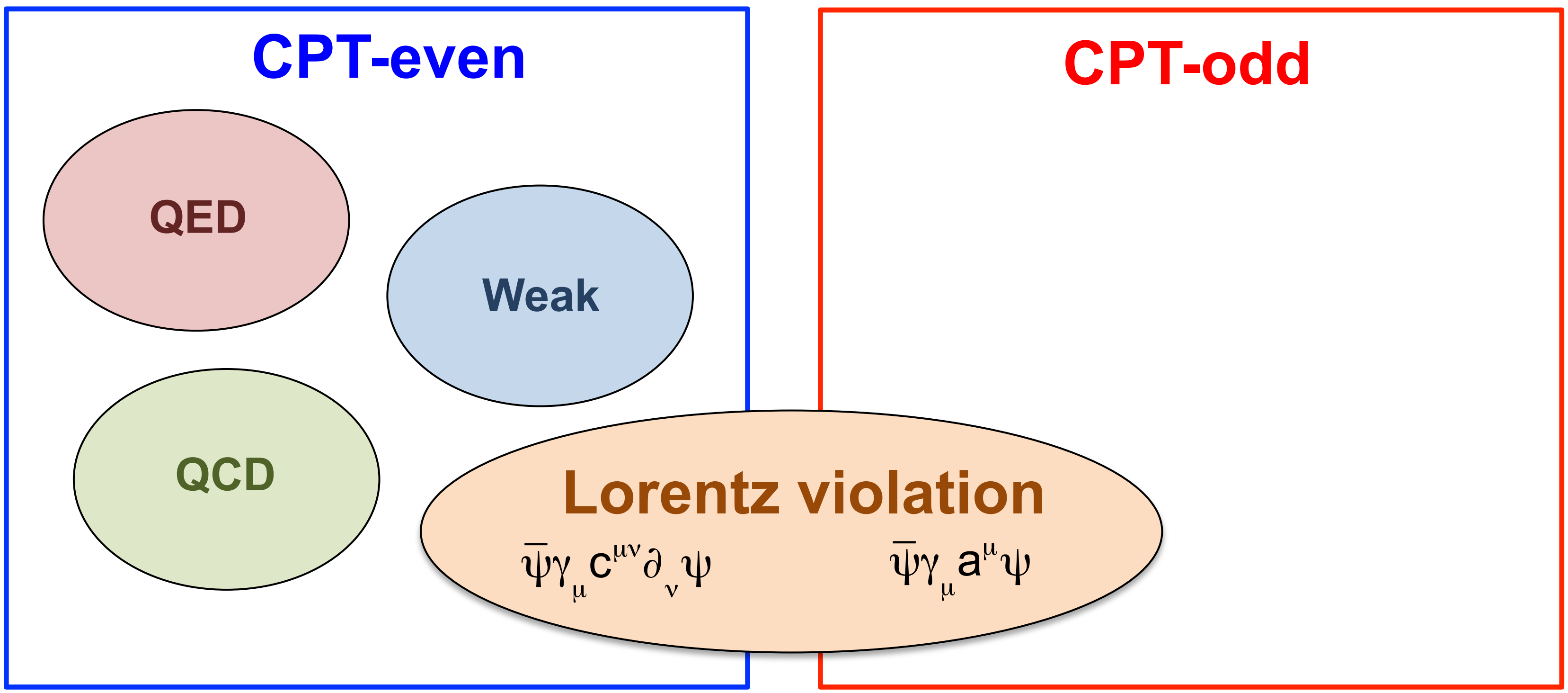


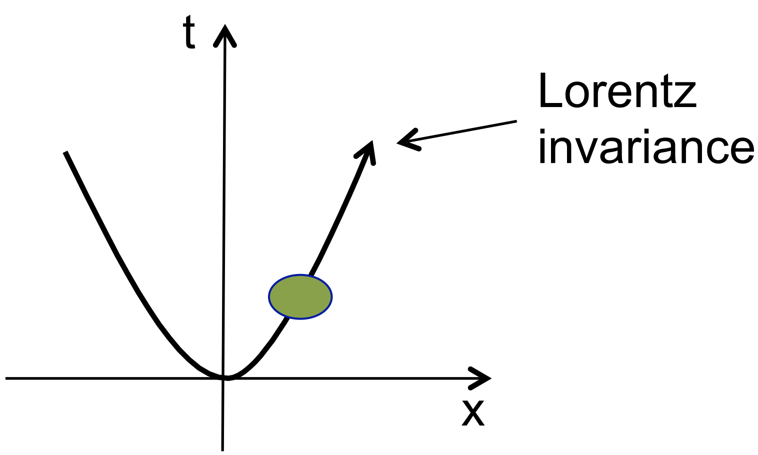
CPT-odd Lorentz violating coefficients (odd number Lorentz indices, e.g., a^μ , $g^{\lambda\mu\nu}$)
CPT-even Lorentz violating coefficients (even number Lorentz indices, e.g., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

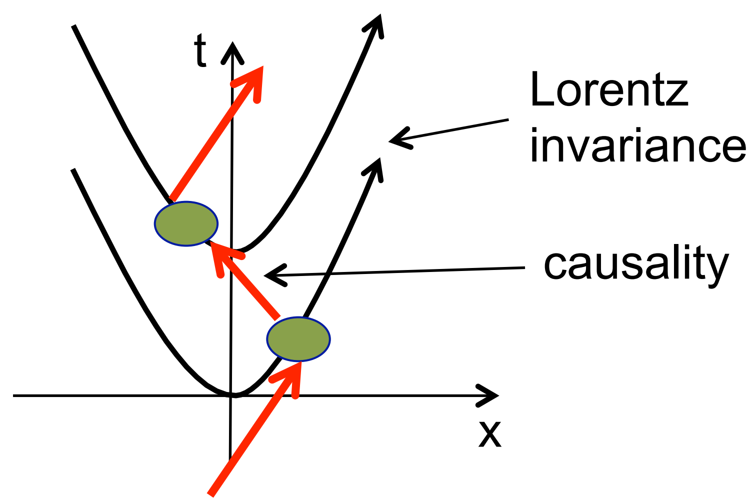
Greenberg, PRL(2002)231602

2. CPT violation implies Lorentz violation

Lorentz invariance → CPT → Lorentz invariance of quantum field theory

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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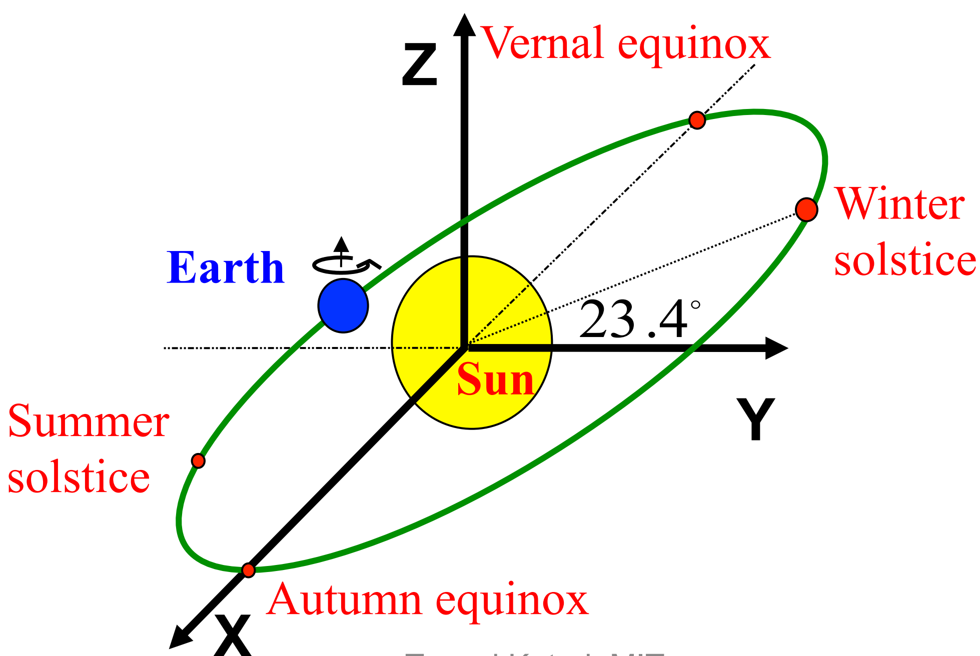
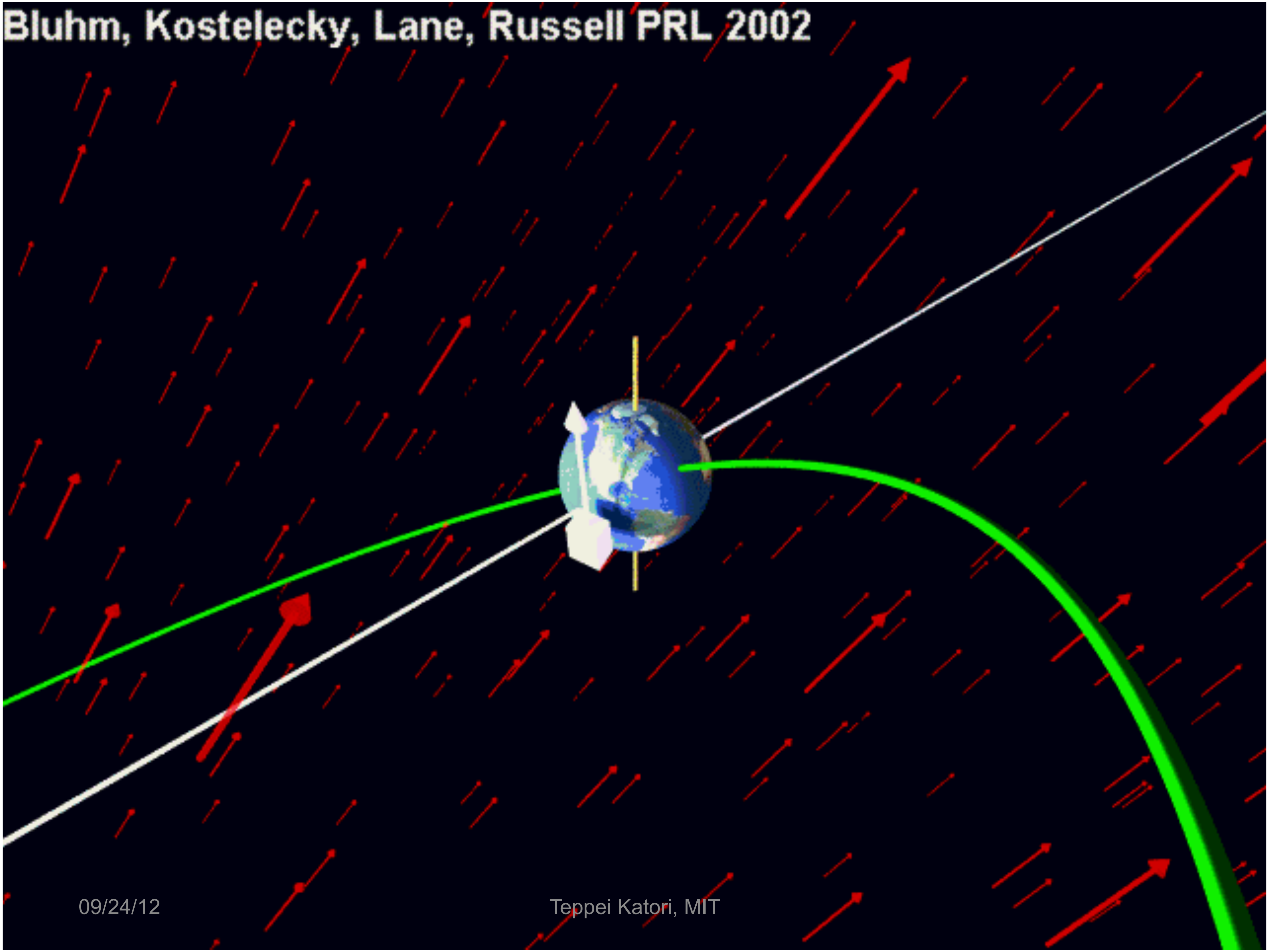
The standard choice of the coordinate is Sun-centred coordinates




Bluhm, Kostelecky, Lane, Russell PRL 2002

Colladay and Kostelecký
PRD55(1997)6760

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Standard Model Extension (SME) is a standard formalism for the general search of Lorentz violation. SME is a minimum extension of QFT with Particle Lorentz violation

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

Colladay and Kostelecký
PRD55(1997)6760

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Standard Model Extension (SME) is a standard formalism for the general search of Lorentz violation. SME is a minimum extension of QFT with Particle Lorentz violation

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

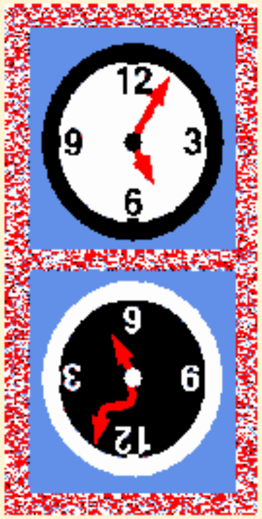
Solar time: 24h 00m 00.0s
sidereal time: 23h 56m 04.1s

Sidereal time dependent physics is often smeared out in solar time distribution
→ Maybe we have some evidence of Lorentz violation but we just didn't notice?!

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

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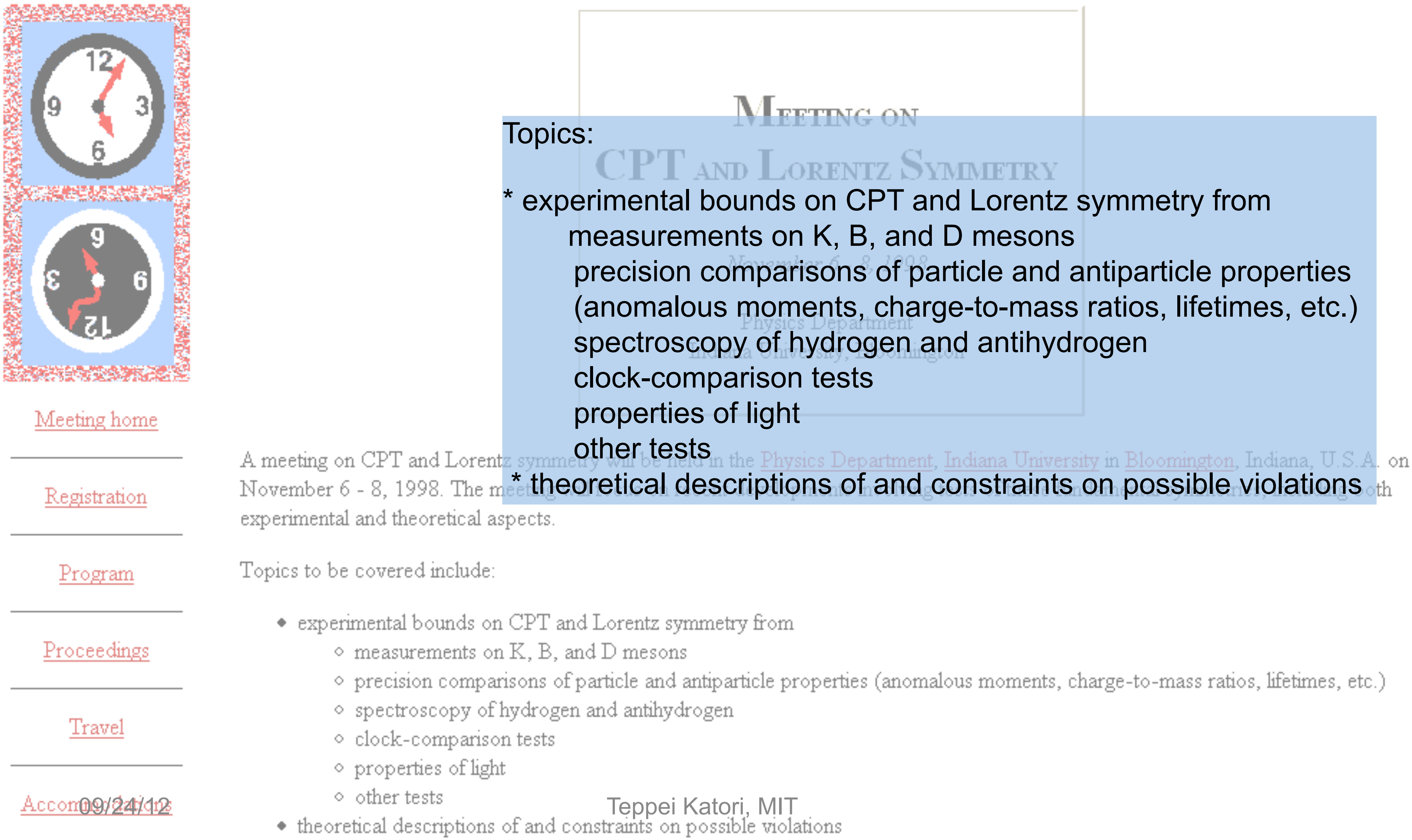
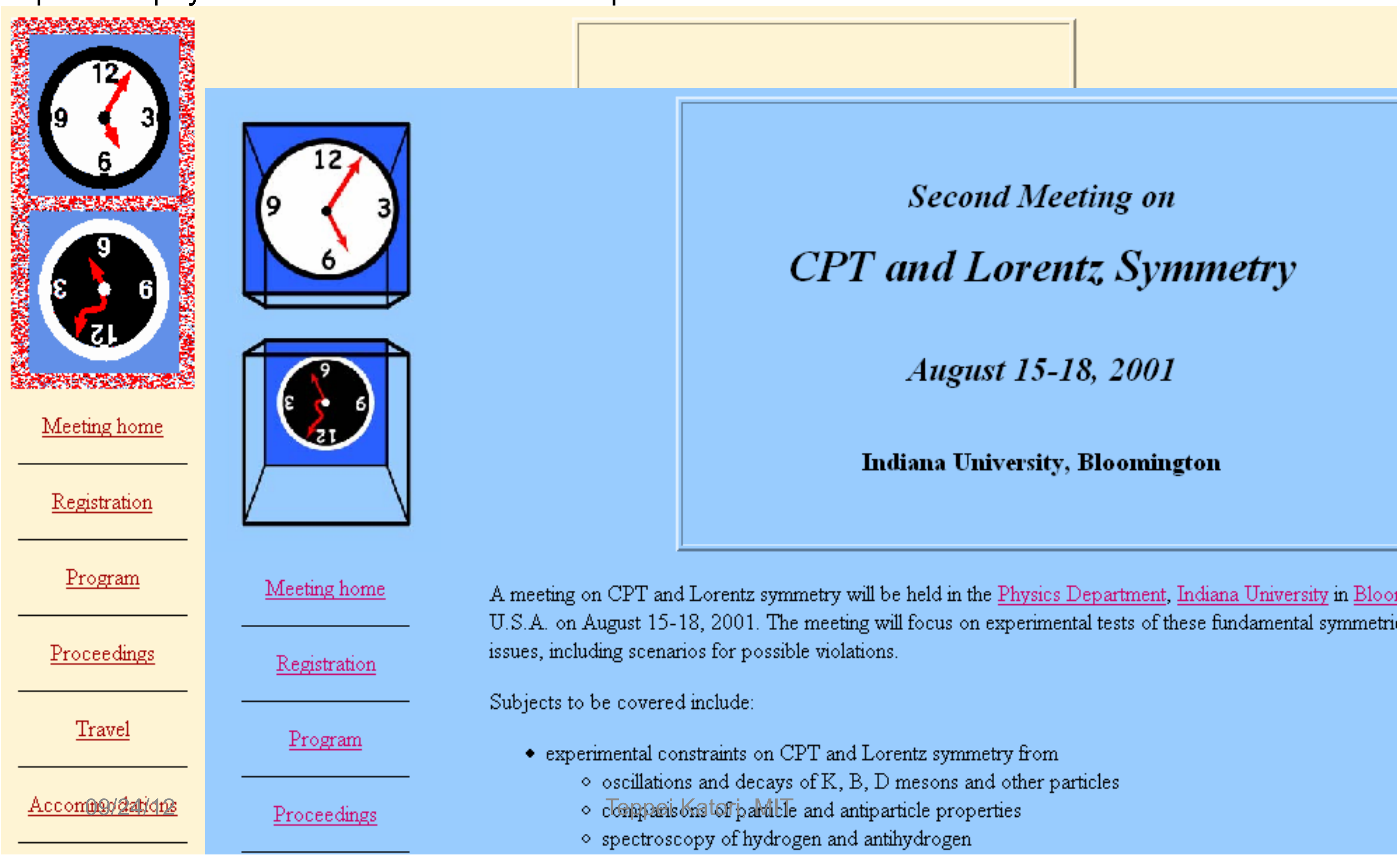
    - other tests
* theoretical descriptions of and constraints on possible violations



3. Modern tests of Lorentz violation

The second meeting was in 2001.

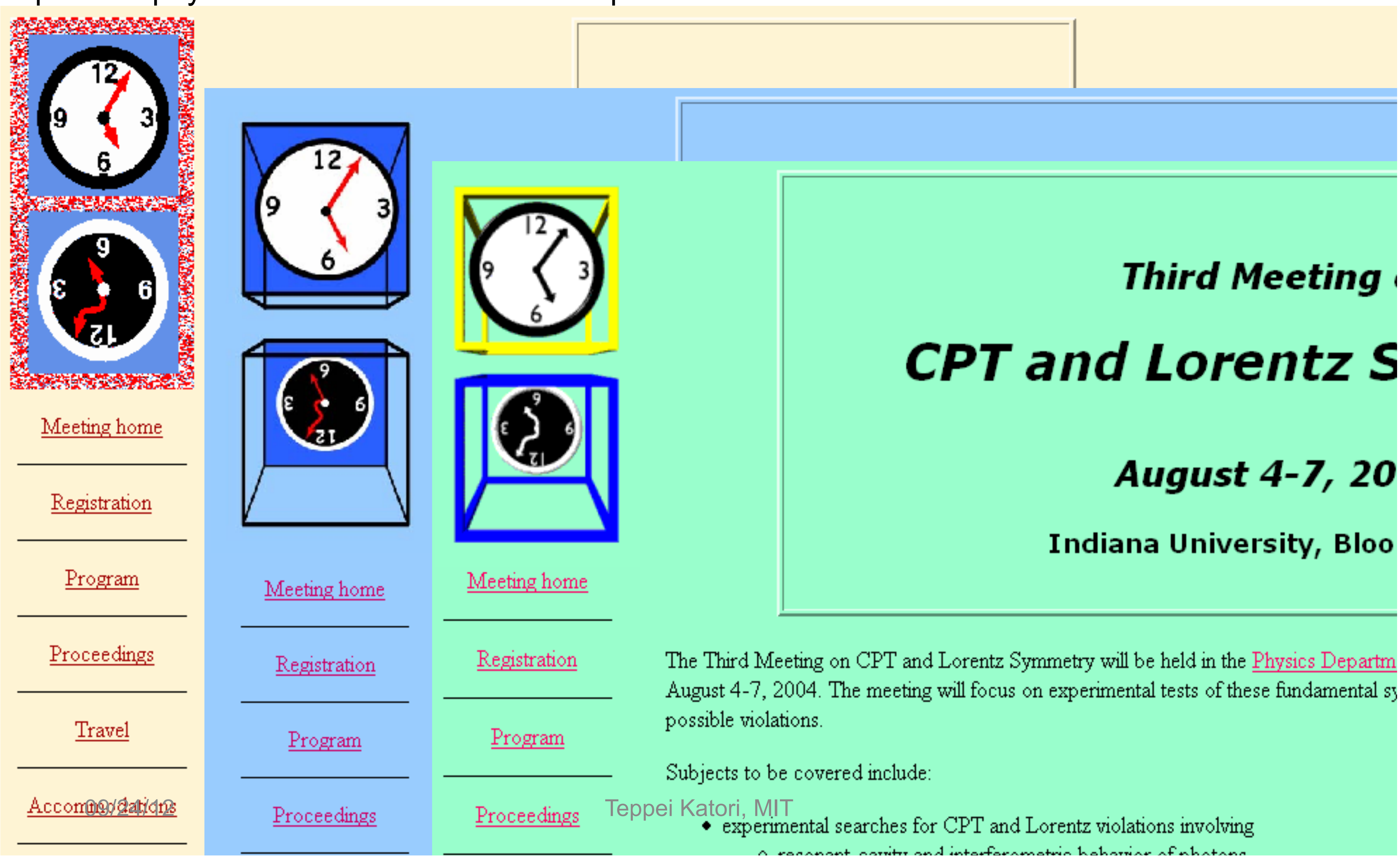
http://www.physics.indiana.edu/~kostelec/faq.html



3. Modern tests of Lorentz violation

The third meeting was in 2004.

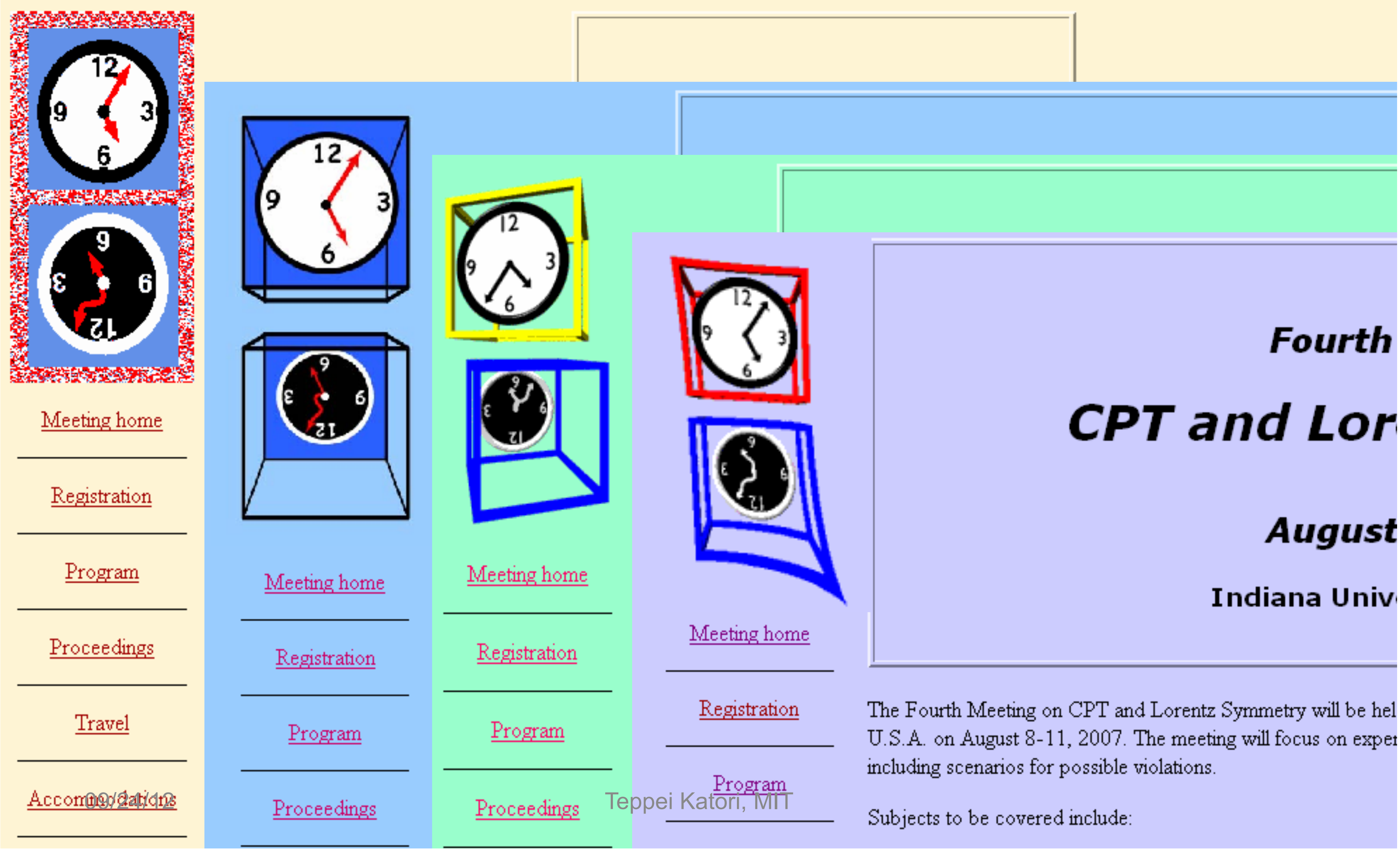
http://www.physics.indiana.edu/~kostelec/faq.html



3. Modern tests of Lorentz violation

The fourth meeting was in 2007.

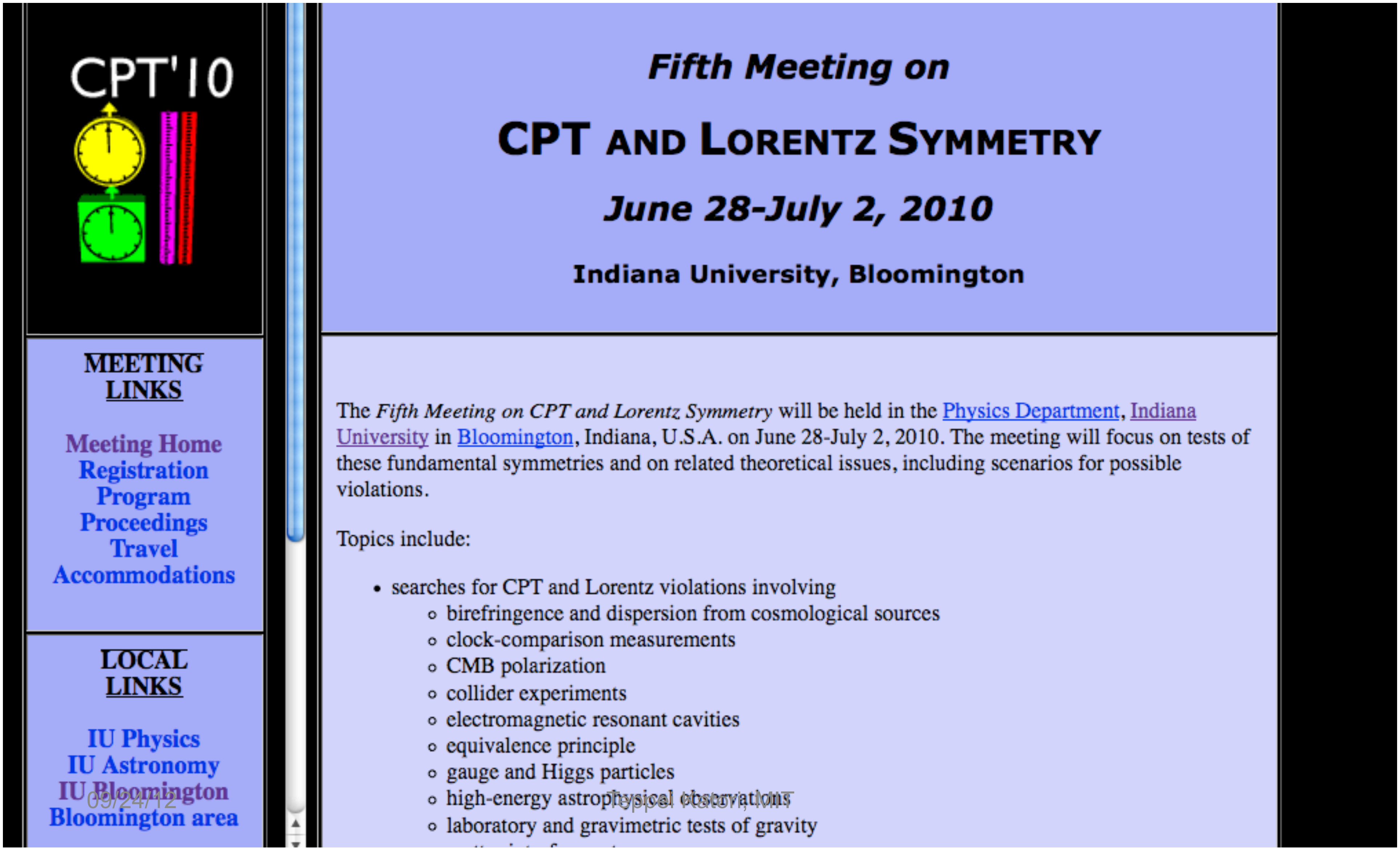
http://www.physics.indiana.edu/~kostelec/faq.html



3. Modern tests of Lorentz violation

The latest meeting was in summer 2010.
(next meeting will be June 2013)

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



CPT'10

MEETING LINKS

Meeting Home
Registration
Program
Proceedings
Travel
Accommodations

LOCAL LINKS

IU Physics
IU Astronomy
IU Bloomington
Bloomington area

Fifth Meeting on

CPT and Lorentz Symmetry

June 28-July 2, 2010

Indiana University, Bloomington

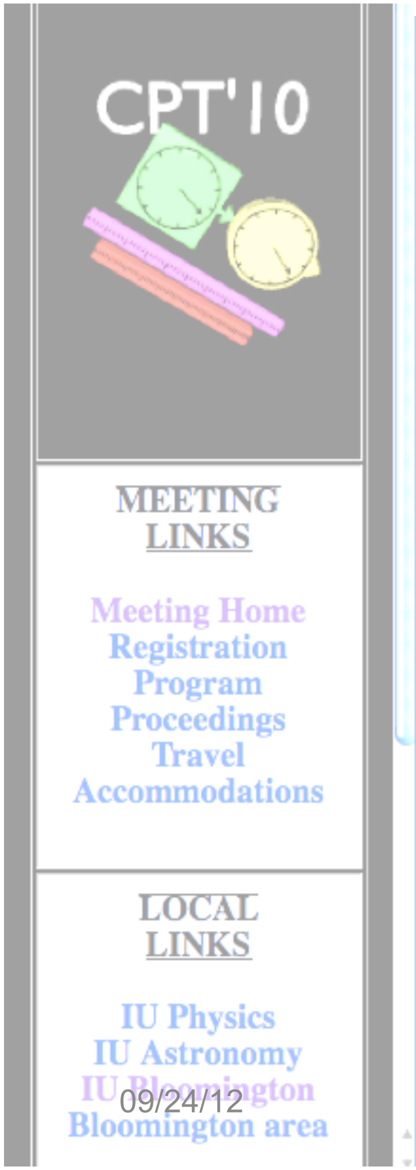
The *Fifth Meeting on CPT and Lorentz Symmetry* will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on June 28-July 2, 2010. The meeting will focus on tests of these fundamental symmetries and on related theoretical issues, including scenarios for possible violations.

Topics include:

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

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
  - 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
  - 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
(Mp-M̄p)/Mp<10-8
Nature419(2002)456
Tevatron and LEP
5.8x10-12<κtr-4/3ce00<1.2x10-11
2(2009)170402
GRB vacuum birefringence
κe+, κo-<10-37
PRL97(2006)140401
ources
Double gas maser
bn(rotation)<10-33GeV
ost)<10-27GeV
c optical resonator
Δc/c<10-16
KTeV/KLOE (strange)
ΔaK<10
FOCUS
ΔaD<10
BaBar/Bell
ΔmB/mB
proceedings of Lorentz and CPT symmetry I, II, III, IV, V (world scientific)
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
V. Alan Kostelecký
World Scientific
post-newtonian gravity
LSND
PRD72(2005)076004
MINOS ND
PRL101(2008)151601
MINOS FD
PRL105(2010)151601
IceCube
PRD82(2010)112003
MiniBooNE
arXiv:1109.3480
Teppei Katori, MIT

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

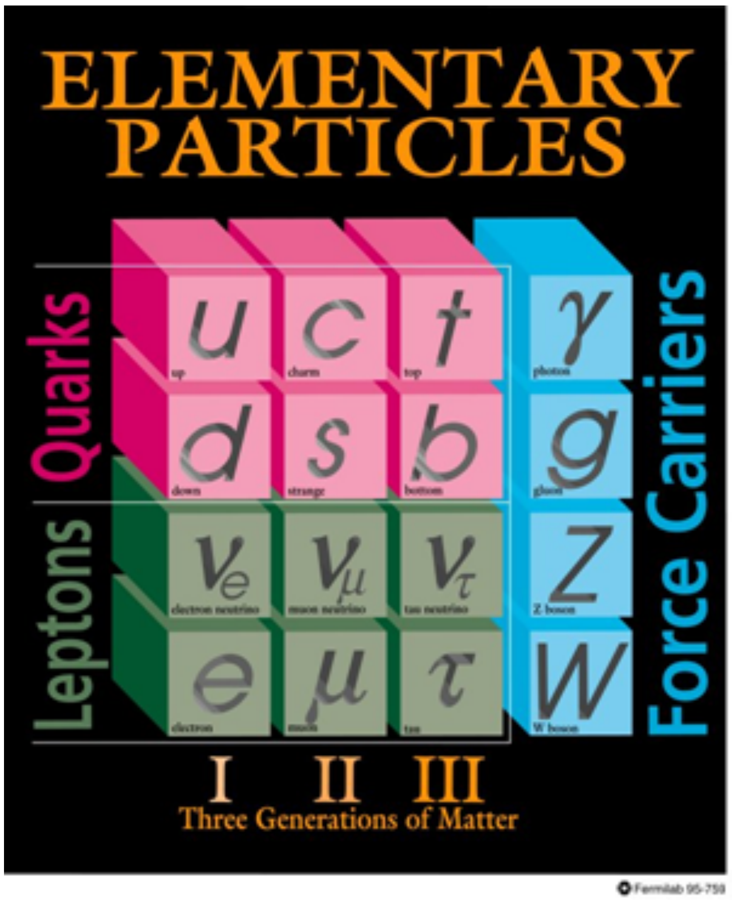
7. Future test of Lorentz violation with neutrinos

8. Conclusion

4. Neutrinos

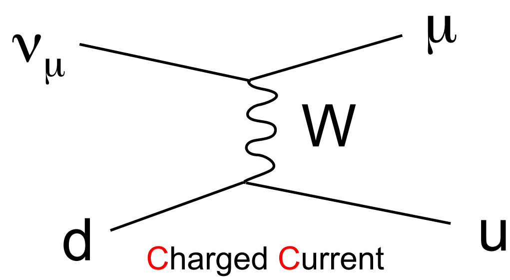
Neutrinos in the standard model

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

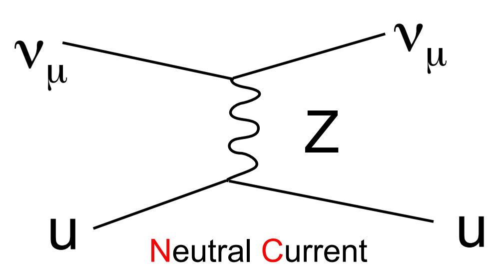


Neutrinos are special because,

1. they only interact with weak nuclear force.



Charged Current (CC) interaction "W-boson exchange"

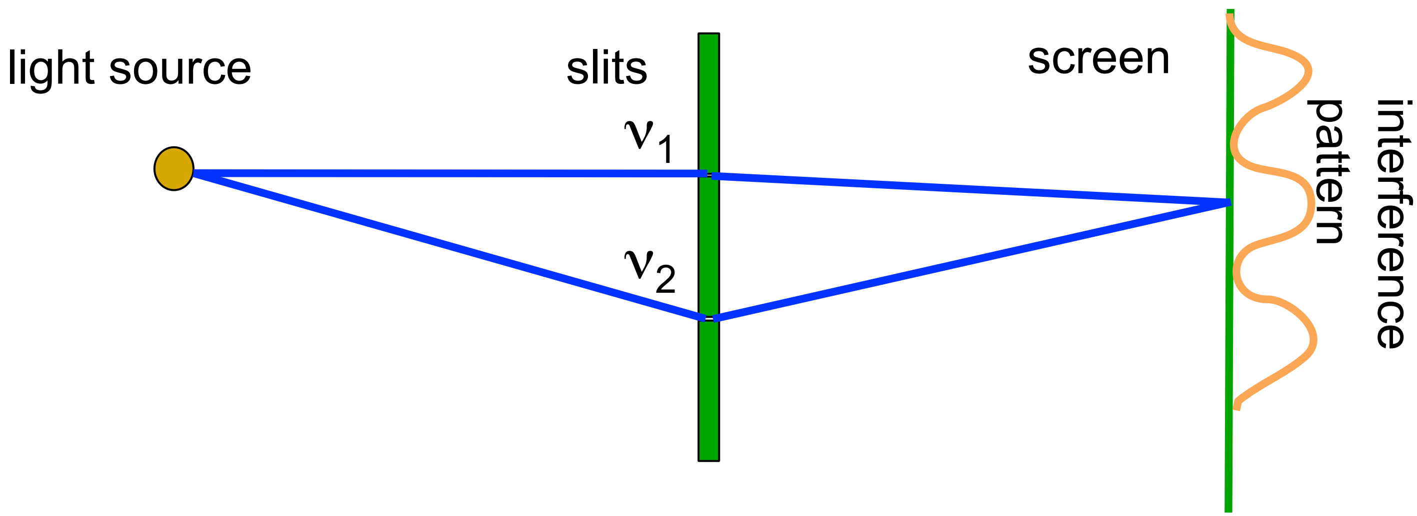


Neutral Current (NC) interaction "Z-boson exchange"

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

4. Neutrino oscillations, natural interferometers

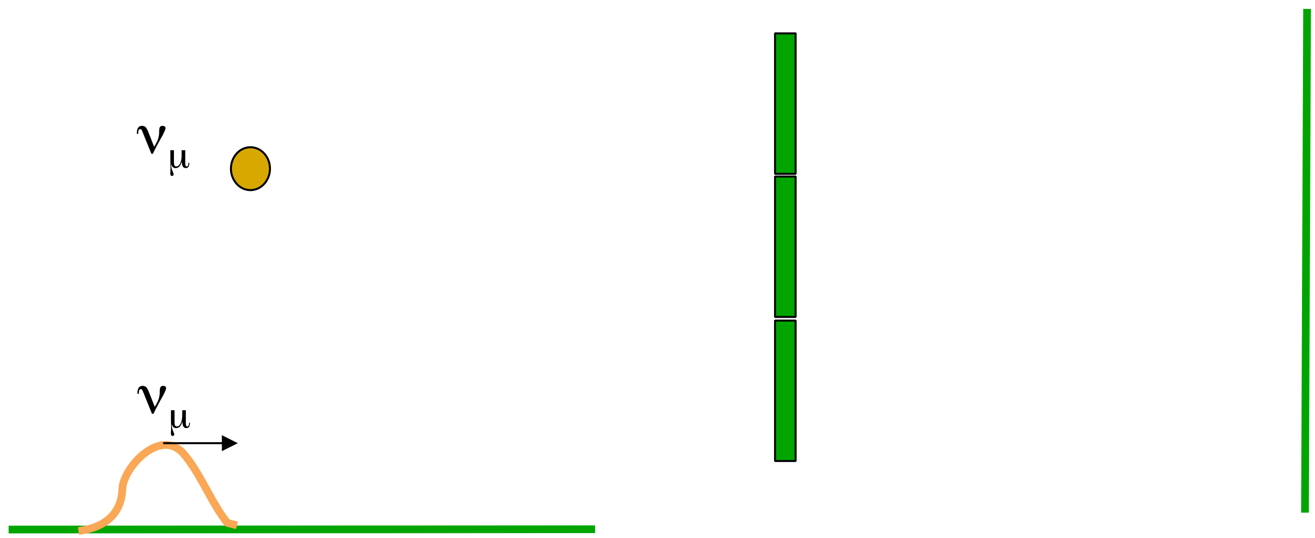
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

4. Neutrino oscillations, natural interferometers

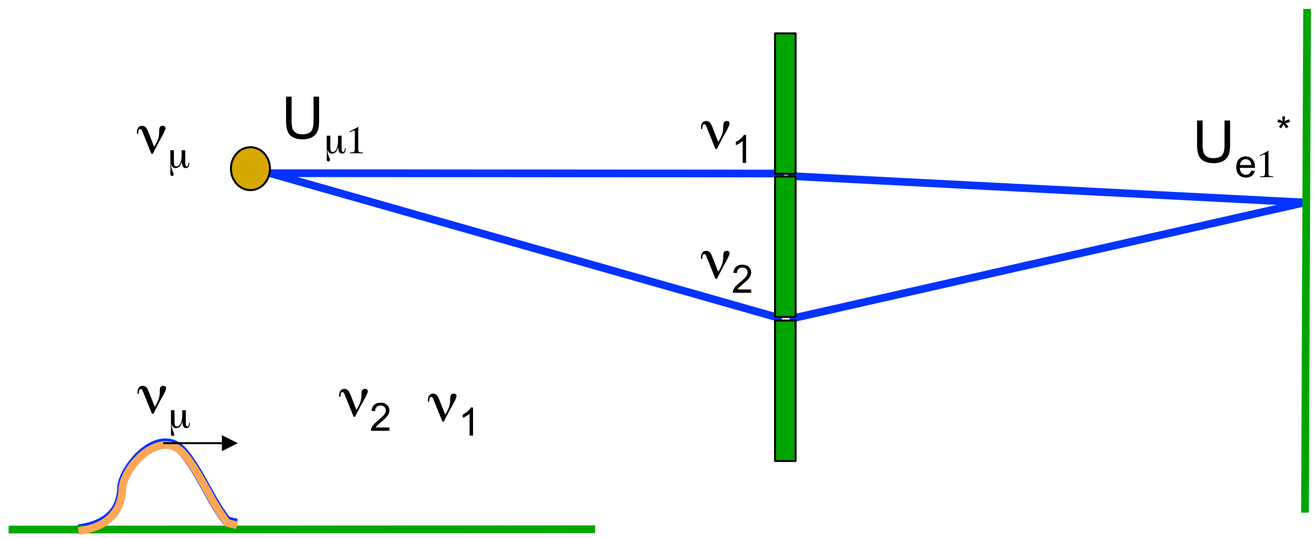
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

4. Neutrino oscillations, natural interferometers

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



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

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

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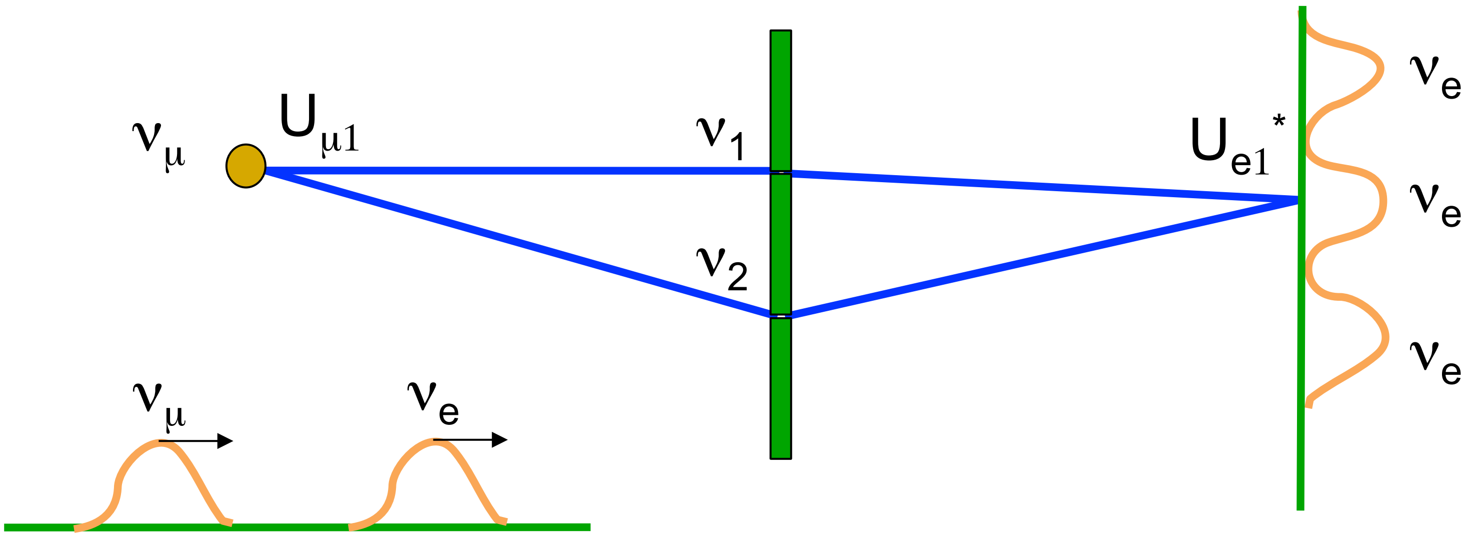


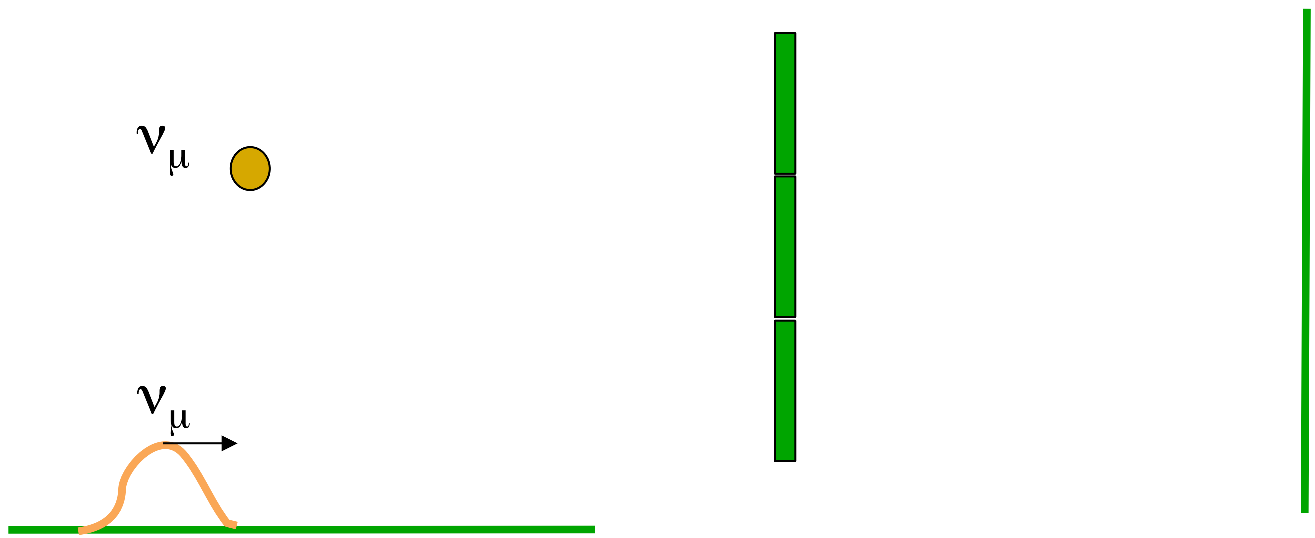
If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

The detection may be different flavor (neutrino oscillations).

4. Lorentz violation with neutrino oscillation

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



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4. Lorentz violation with neutrino oscillation

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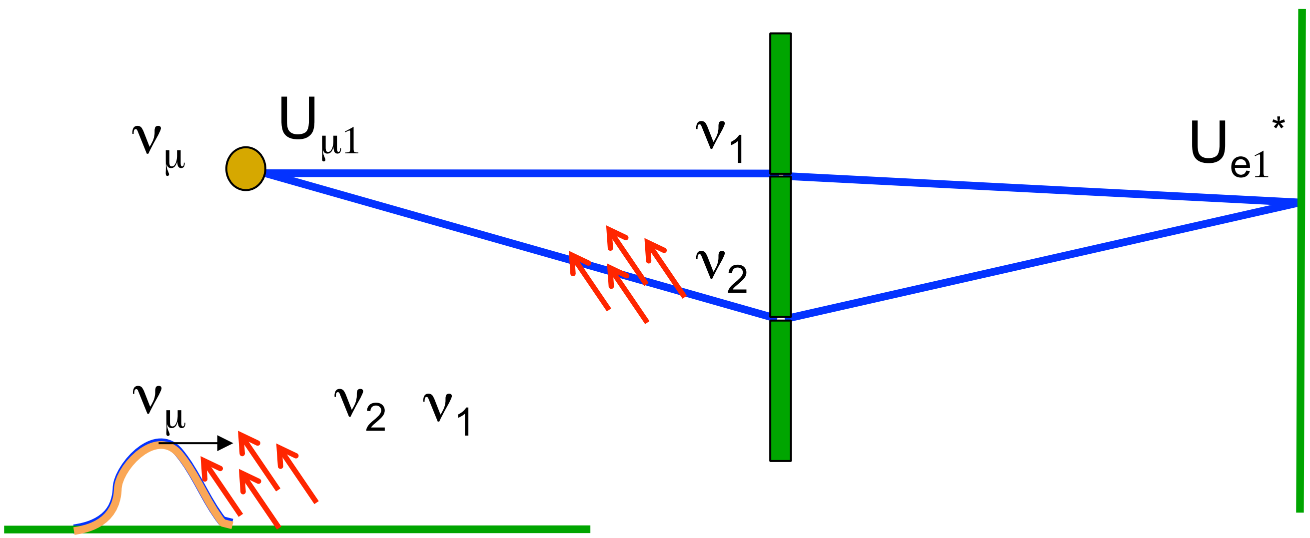
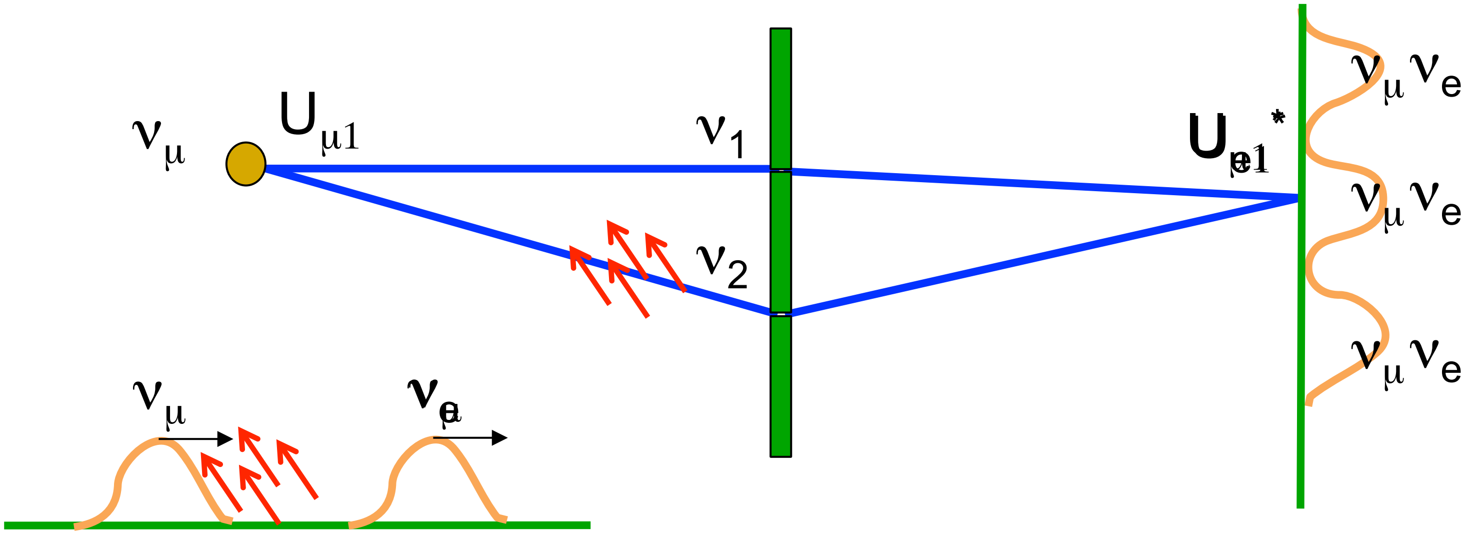


If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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

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.

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).

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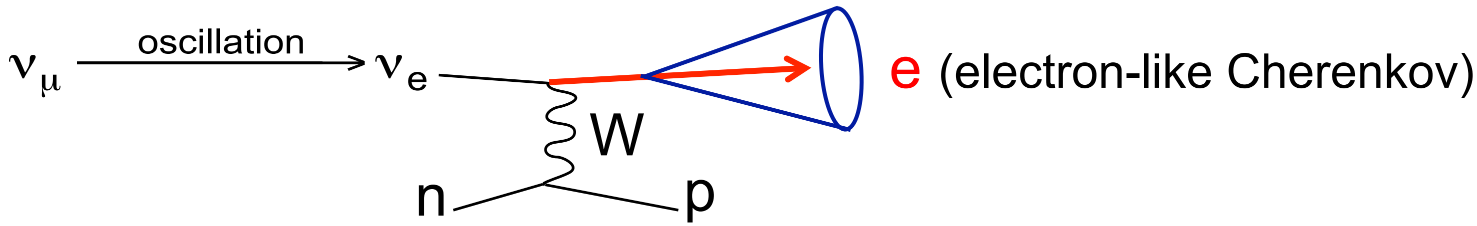
MiniBooNE collaboration,
PRD79(2009)072002

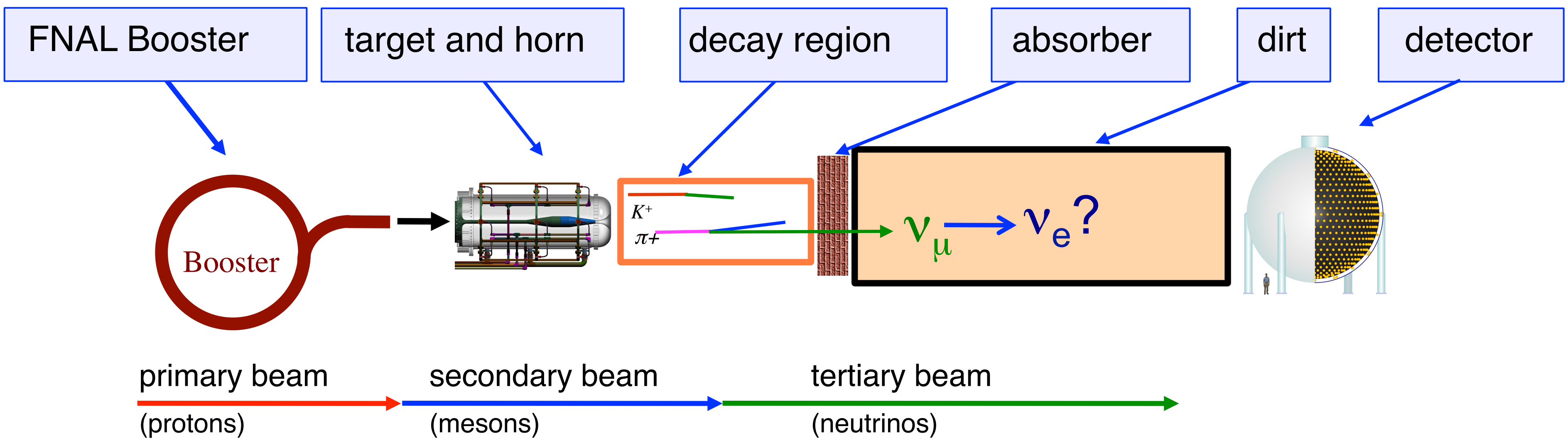
5. MiniBooNE experiment

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

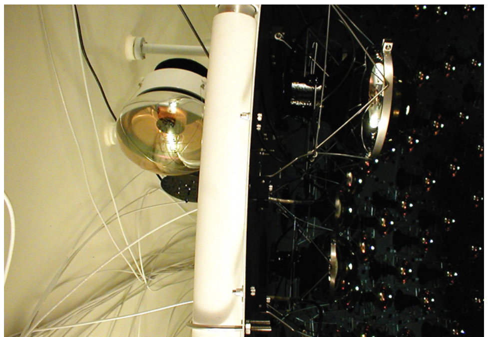
Booster Neutrino Beamline (BNB) creates ~800(600)MeV neutrino(anti-neutrino) by pion decay-in-flight from 8GeV Booster protons on Be-target in the magnetic focusing horn.

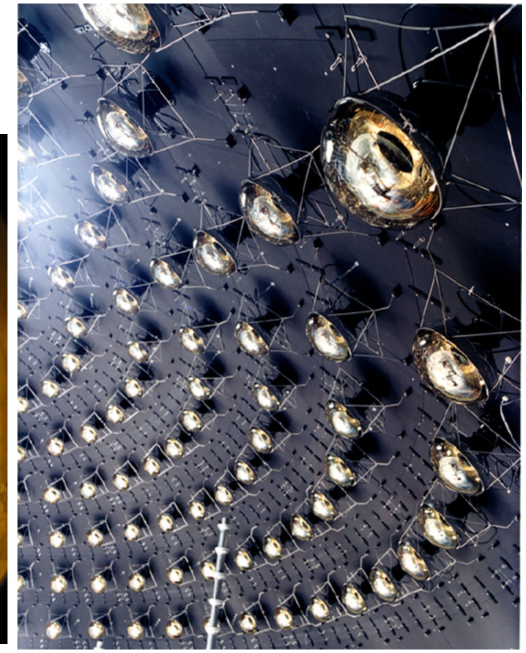


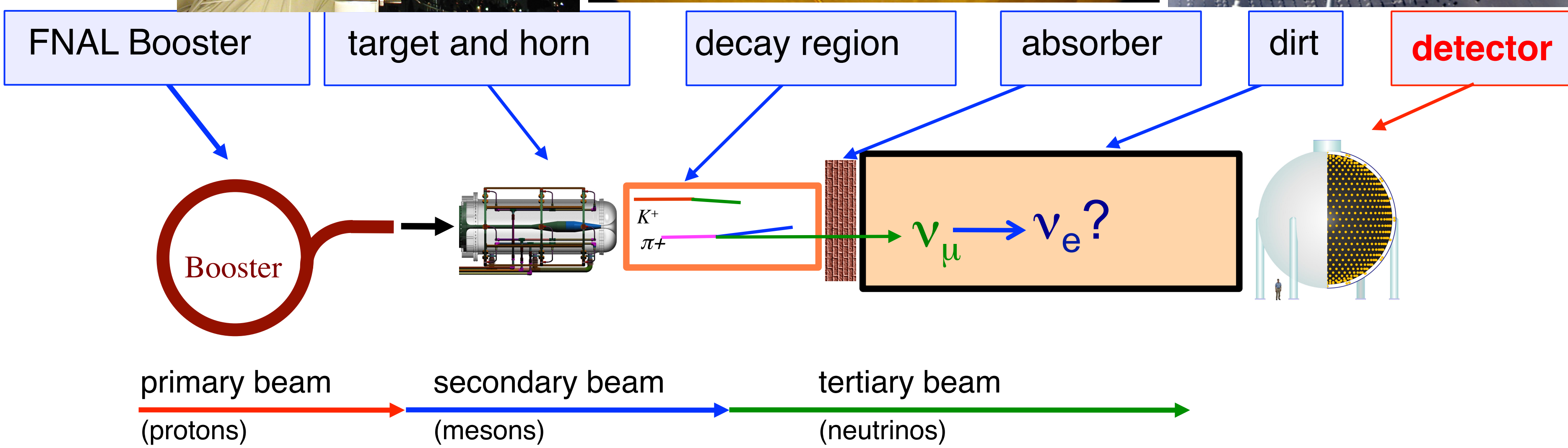
MiniBooNE collaboration,
NIM.A599(2009)28

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



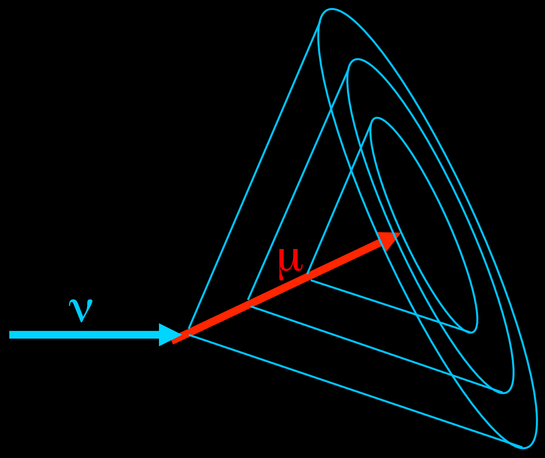


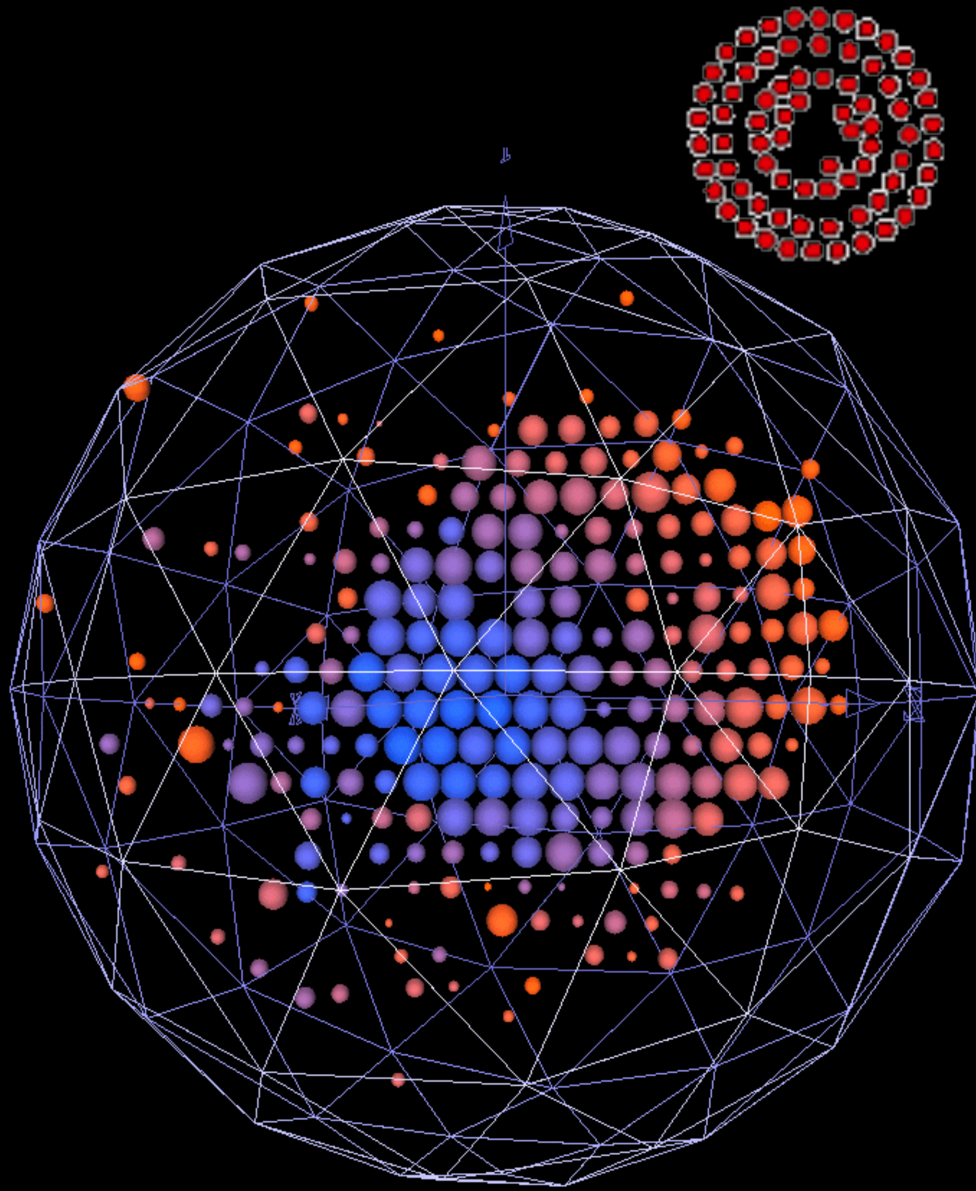


MiniBooNE collaboration,
NIM.A599(2009)28

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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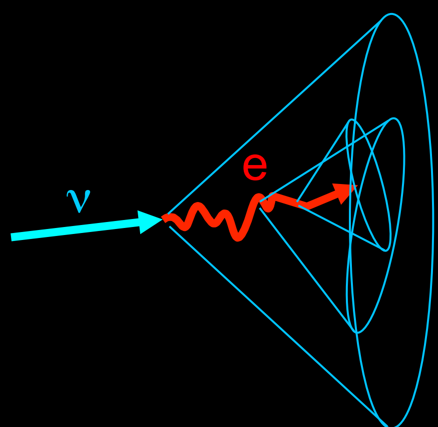
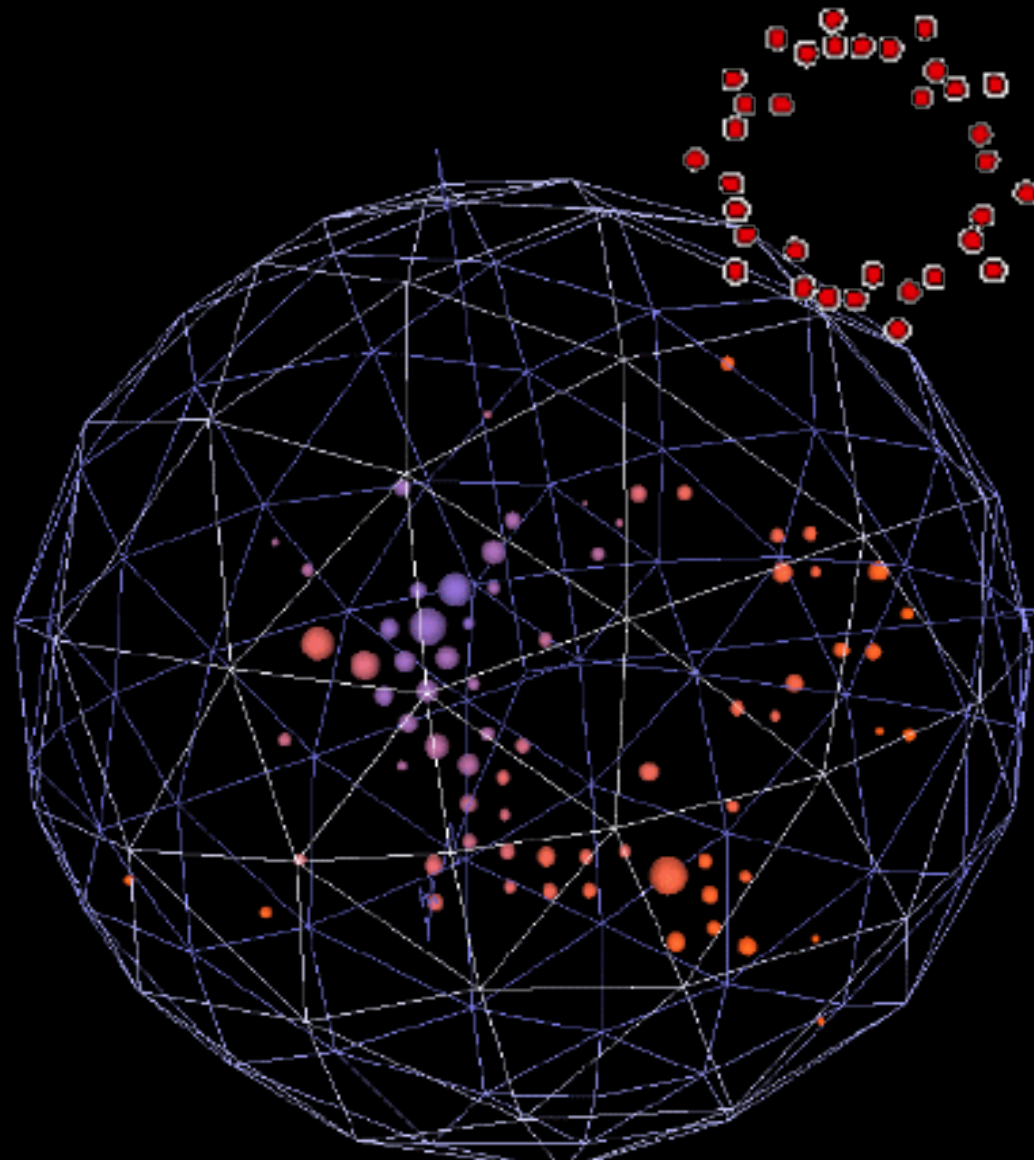




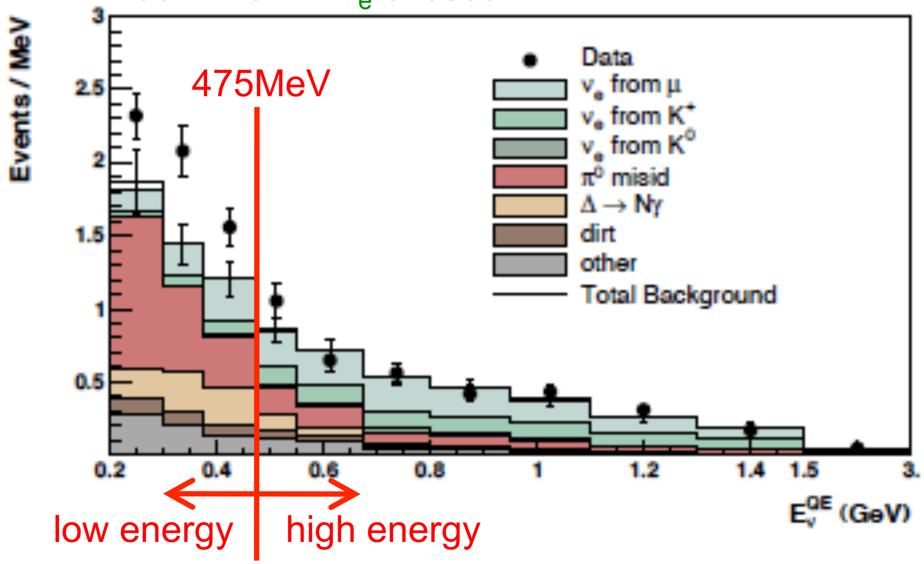
5. MiniBooNE oscillation analysis result

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

Neutrino mode low energy excess

MiniBooNE see the excess at low energy region.

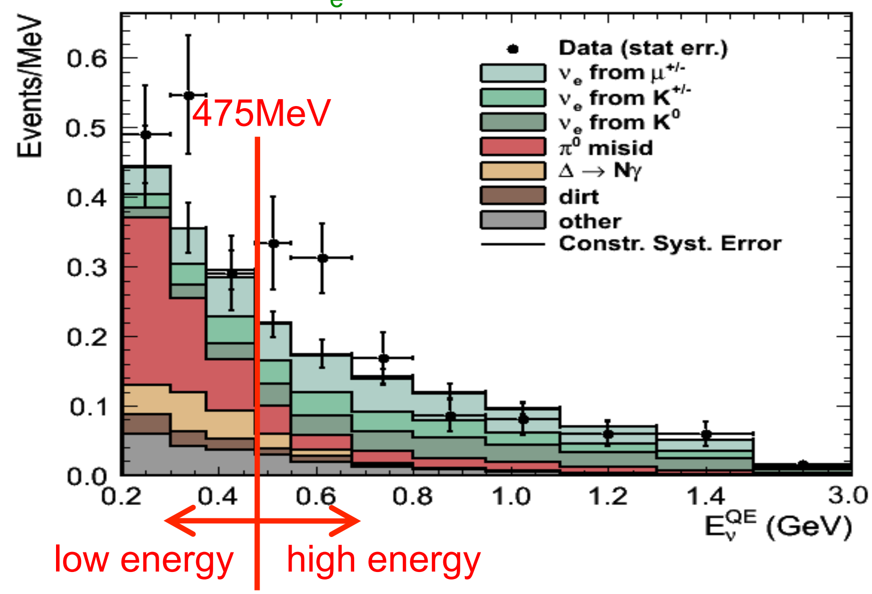
MiniBooNE low E ν_e excess



Antineutrino mode excess

MiniBooNE see the excess at combined region.

MiniBooNE anti-ν_e excess



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

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

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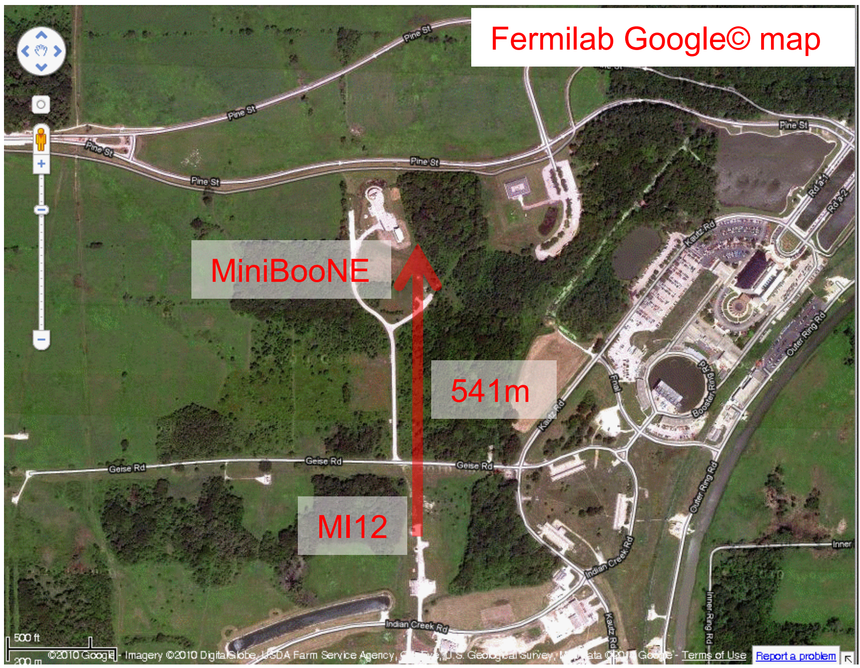
6. Lorentz violation with MiniBooNE

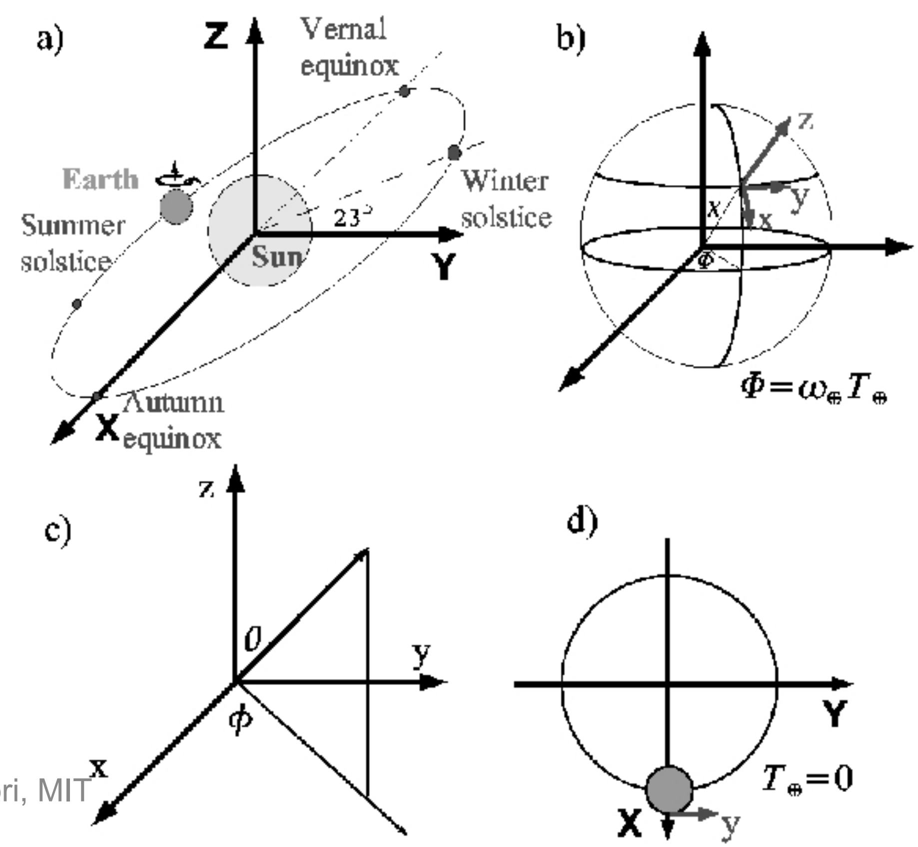
Test for Lorentz violation in MiniBooNE data;

(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-centred coordinates

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





Kostelecký and Mewes
PRD69(2004)016005

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-centred 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

6. Lorentz violation with MiniBooNE

Test for Lorentz violation in MiniBooNE data;

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

SME parameters

CPT odd

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

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

CPT even

Kostelecký and Mewes
PRD70(2004)076002

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-centred coordinates
- Standard Model Extension (SME)
- Sidereal time dependent oscillation probability

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

sidereal time $T_{\oplus}$

Lorentz violating oscillation probability for MiniBooNE

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

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

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

Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

6. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum likelihood fit

- It has the maximum statistic power
- Best fit parameters are extracted

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

sidereal time $T_\oplus$

5 parameter fit

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

- Due to high correlation of parameters, we focus on 3 parameter fit for error evaluation
- Contours are evaluated from fake data study

3 parameter fit

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

MiniBooNE collaboration,
ArXiv:1109.3480

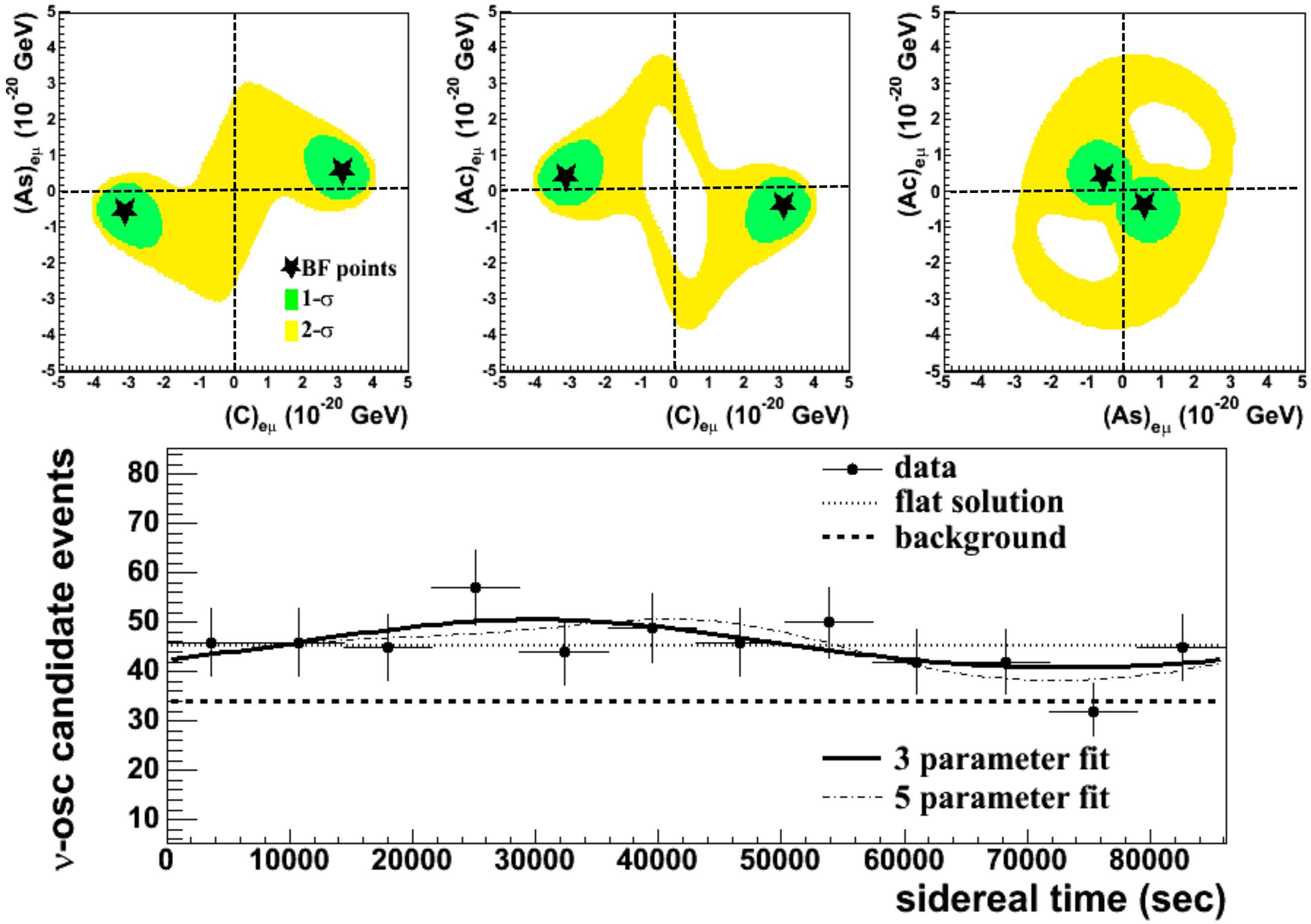
6. Lorentz violation with MiniBooNE neutrino data

Neutrino mode result, low energy region

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

26.9% C.L. with flat hypothesis by fake data $\Delta\chi^2$ study

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



MiniBooNE collaboration,
ArXiv:1109.3480

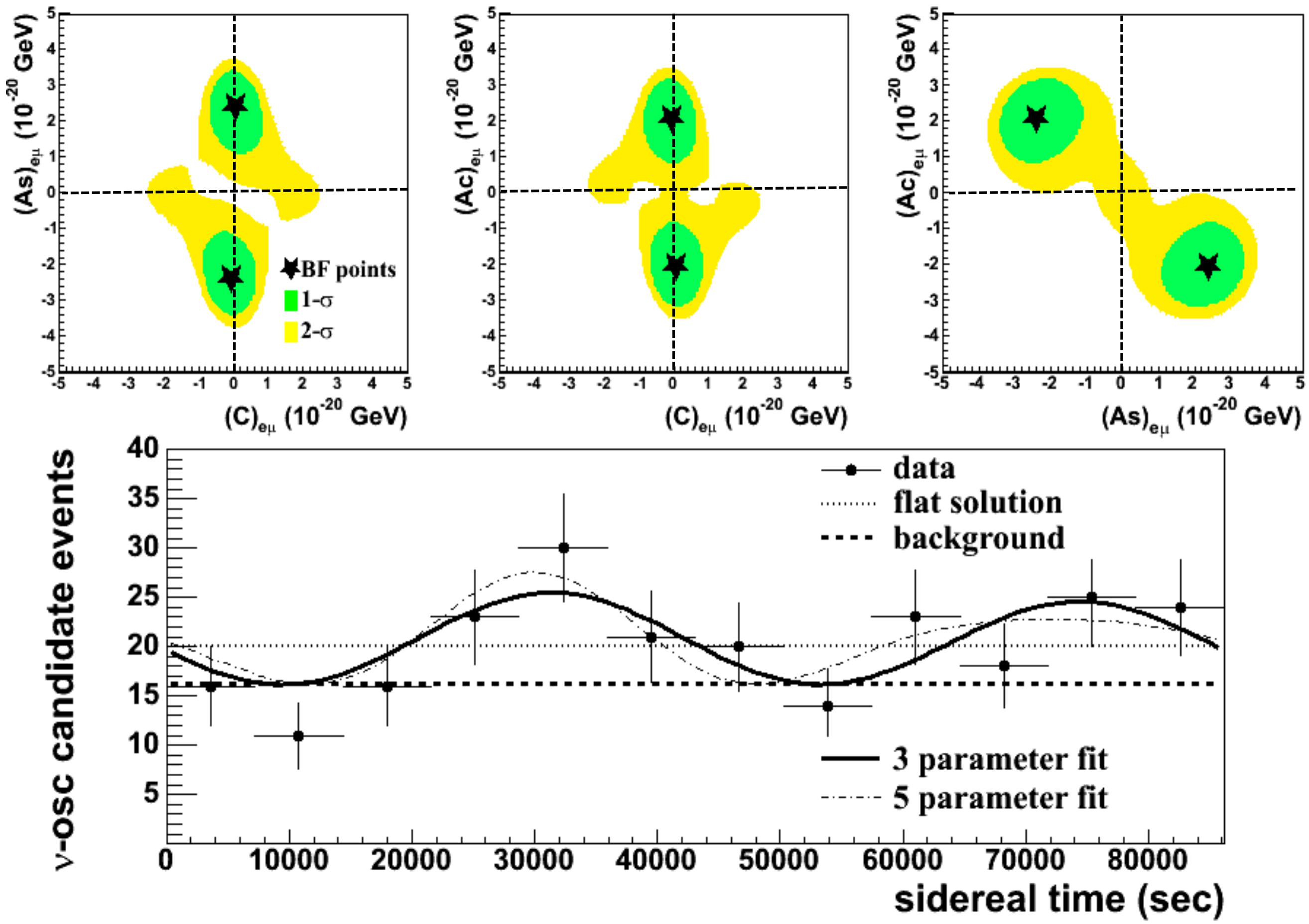
6. Lorentz violation with MiniBooNE anti-neutrino data

Anti-neutrino mode result, combined energy region

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

3.0% C.L. with flat hypothesis by fake data $\Delta\chi^2$ study

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



6. Summary of results

Neutrino result summary
- The low energy excess data fit prefer sidereal time independent solution.
- 26.9% C.L. with flat hypothesis

Anti-neutrino result summary
- The fit for combined region excess data prefers sidereal time dependent solution.
- 3.0% C.L. flat hypothesis

SME coefficients
- The combinations of SME coefficients are extracted
- 2σ limits are set
- First time constrained time independent SME coefficients for e-μ sector

	$\nu-$mode BF	2σ limit	$\bar{\nu}-$mode BF	2σ limit	SME coefficients combination (unit 10^{-20} GeV)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$3.1\pm0.6\pm0.9$	<4.2	$0.1\pm0.8\pm0.1$	<2.6	$\pm[(a_L)^T_{e\mu}+0.75(a_L)^Z_{e\mu}]-<E>[1.22(c_L)^{TT}_{e\mu}+1.50(c_L)^{TZ}_{e\mu}+0.34(c_L)^{ZZ}_{e\mu}]$
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$0.6\pm0.9\pm0.3$	<3.3	$2.4\pm1.3\pm0.5$	<3.9	$\pm[0.66(a_L)^Y_{e\mu}]-<E>[1.33(c_L)^{TY}_{e\mu}+0.99(c_L)^{YZ}_{e\mu}]$
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$0.4\pm0.9\pm0.4$	<4.0	$2.1\pm1.2\pm0.4$	<3.7	$\pm[0.66(a_L)^X_{e\mu}]-<E>[1.33(c_L)^{TX}_{e\mu}+0.99(c_L)^{XZ}_{e\mu}]$

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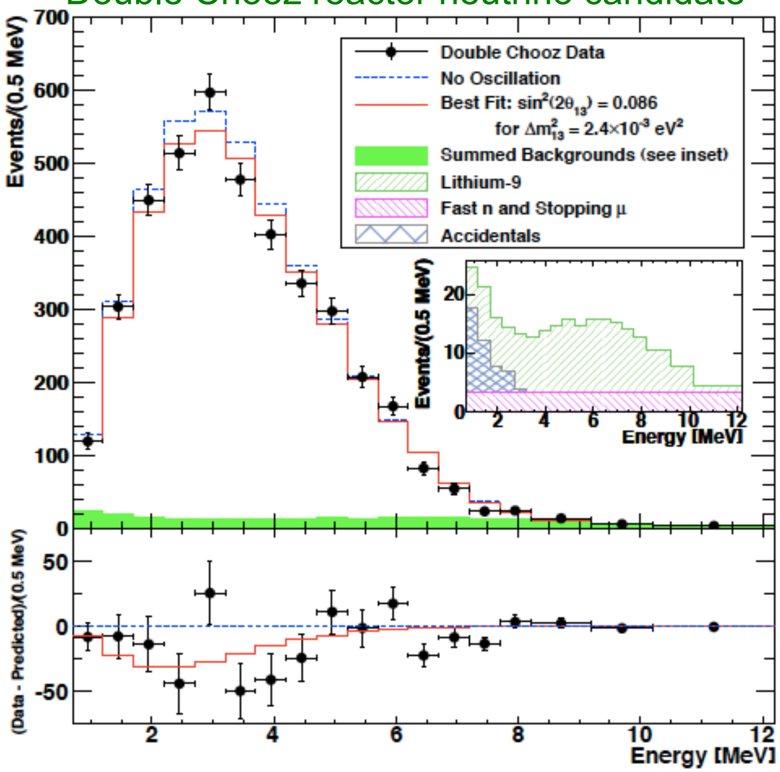
7. Double Chooz experiment

Reactor electron antineutrino disappearance experiment

- The first result shows small anti-ν_e disappearance!

Double Chooz reactor neutrino candidate

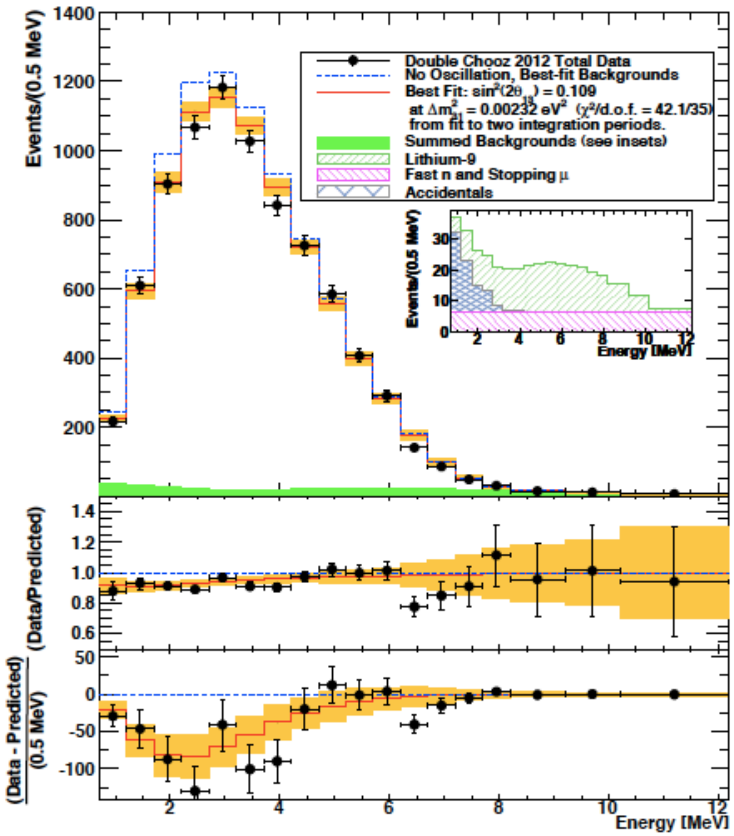


7. Double Chooz experiment

Double Chooz collaboration
PRL108(2012)131801
arXiv:1207.6632
DayaBay collaboration
PRL108(2012)171803
RENO collaboration
PRL108(2012)191802

Reactor electron antineutrino disappearance experiment
- The first result shows small anti-ν_e disappearance!
- The second result reaches 3.1σ signal
- DayaBay and RENO experiments saw disappearance signals, too

Double Chooz reactor neutrino candidate



Teppei Katori, MIT

7. Double Chooz experiment

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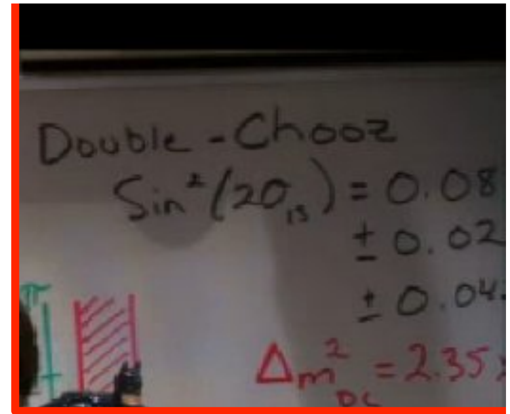
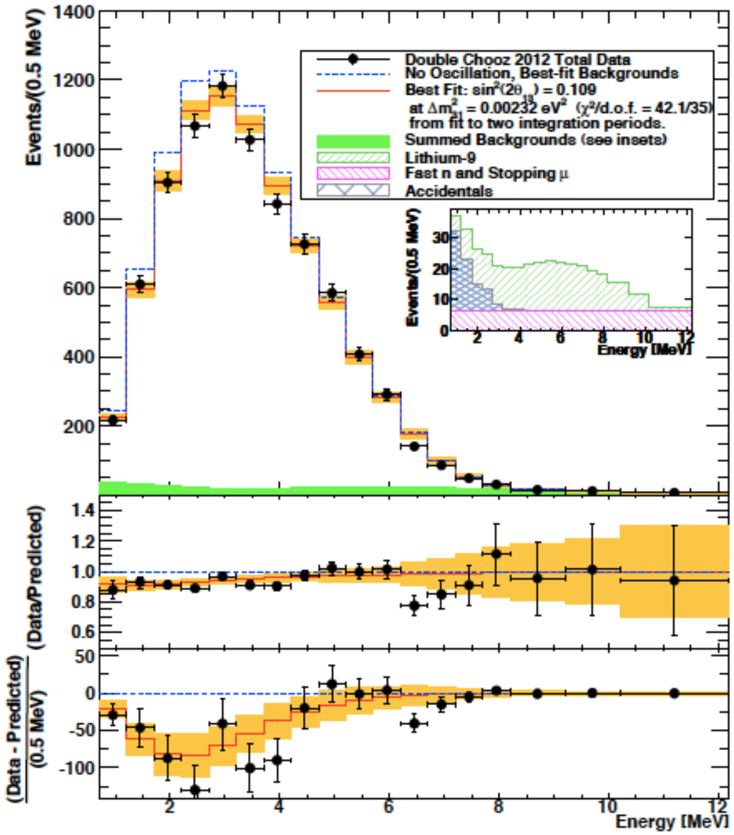
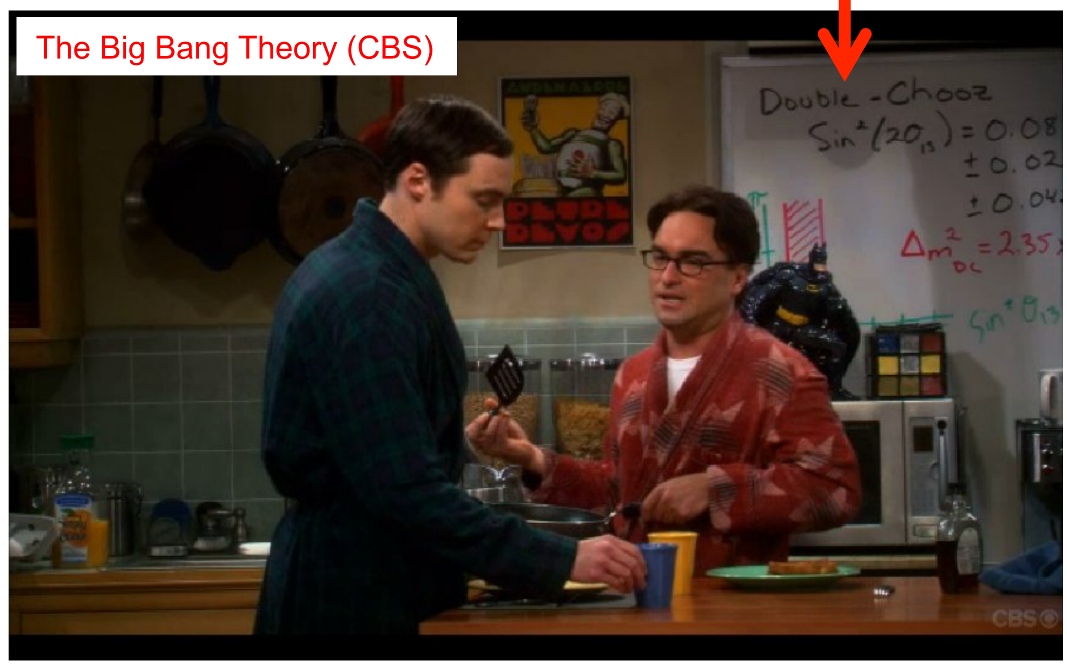


Double Chooz reactor neutrino candidate



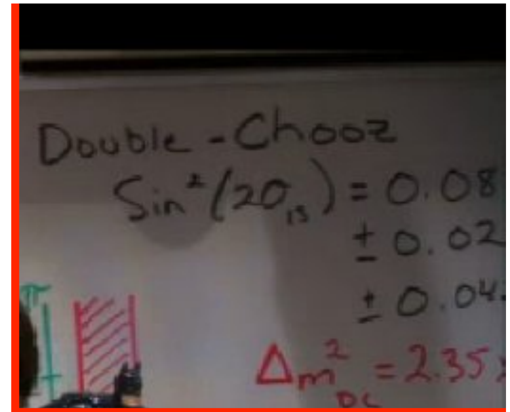


Teppei Katori, MIT

7. Double Chooz experiment

Reactor electron antineutrino disappearance experiment

- The first result shows small anti-ν_e disappearance!
- The second result reaches 3.1σ signal
- DayaBay and RENO experiments saw disappearance signals, too
- This small disappearance may have sidereal time dependence



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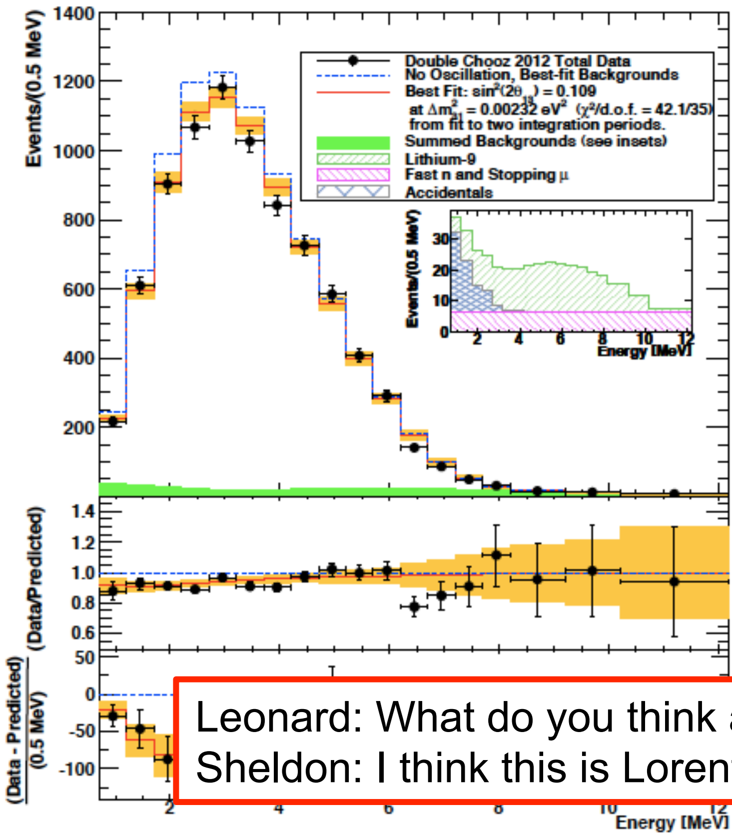
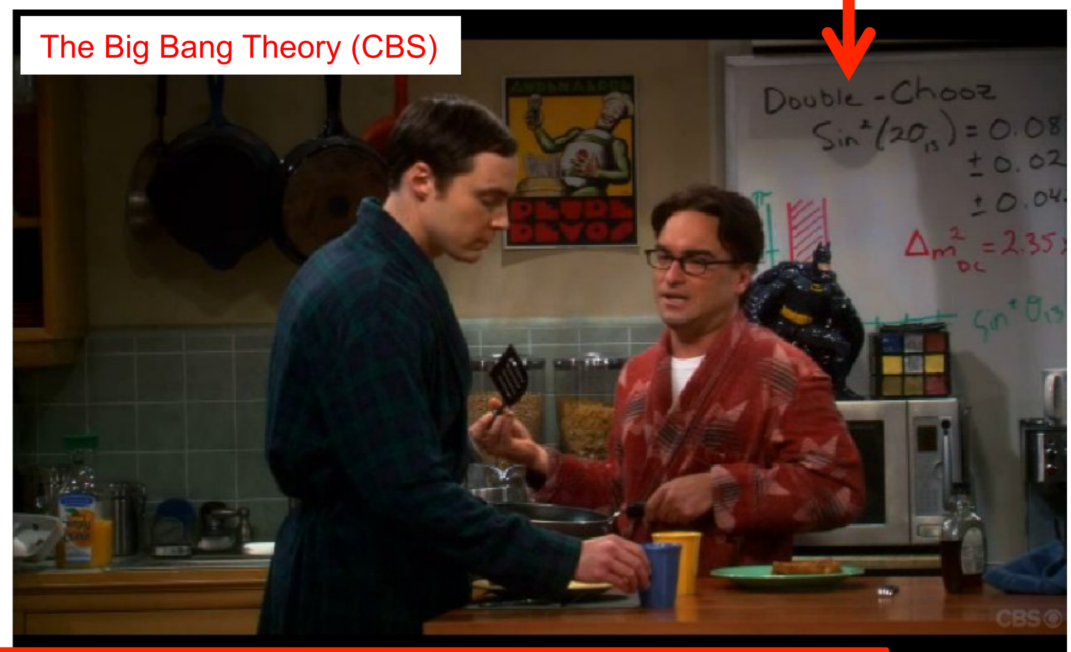
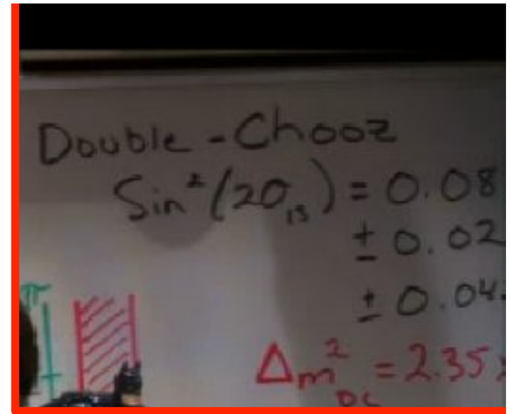


The Big Bang Theory (CBS)



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

7. Double Chooz experiment



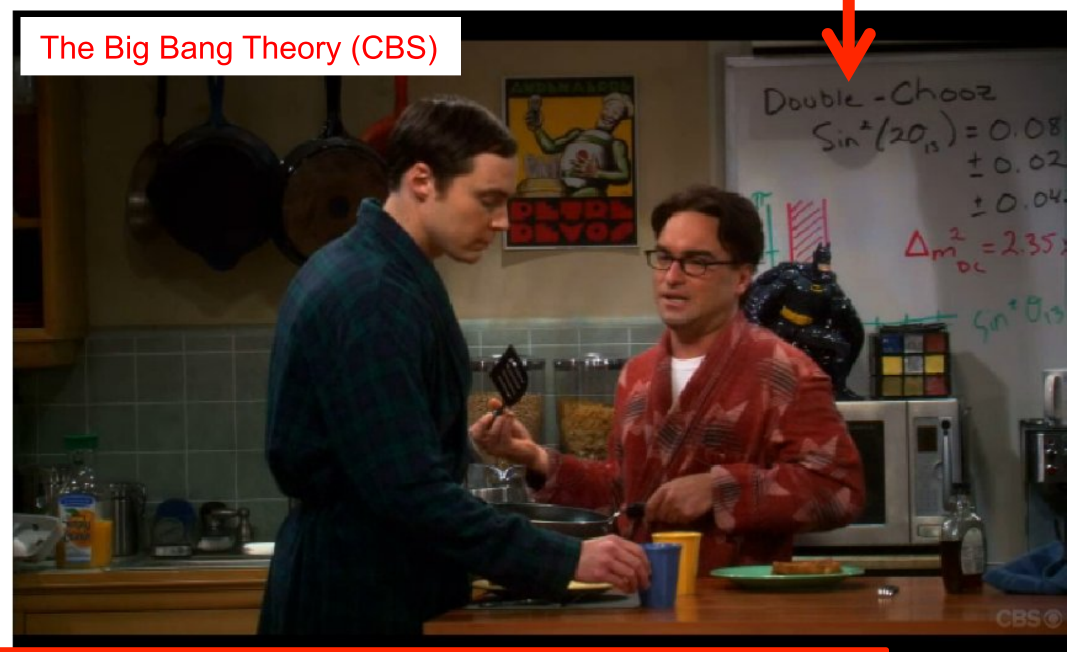
So far, we have set limits on

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

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

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

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



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Double Chooz collaboration,
paper in preparation

7. Double Chooz experiment

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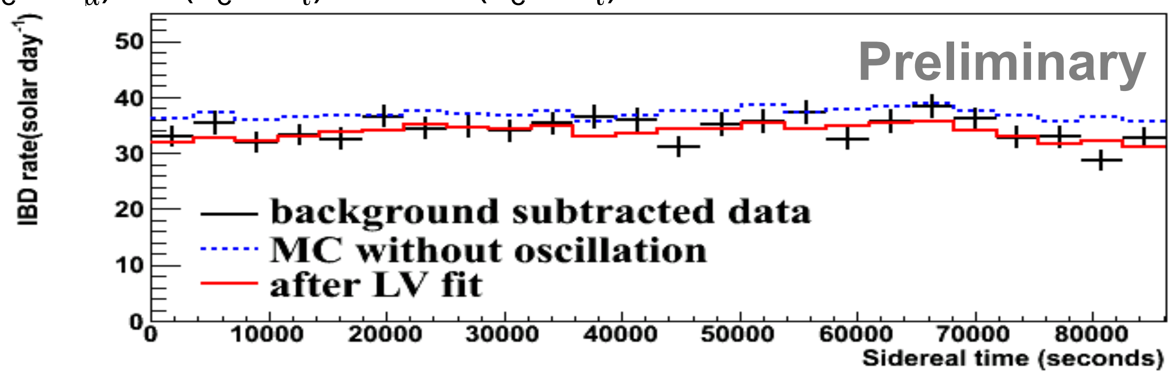
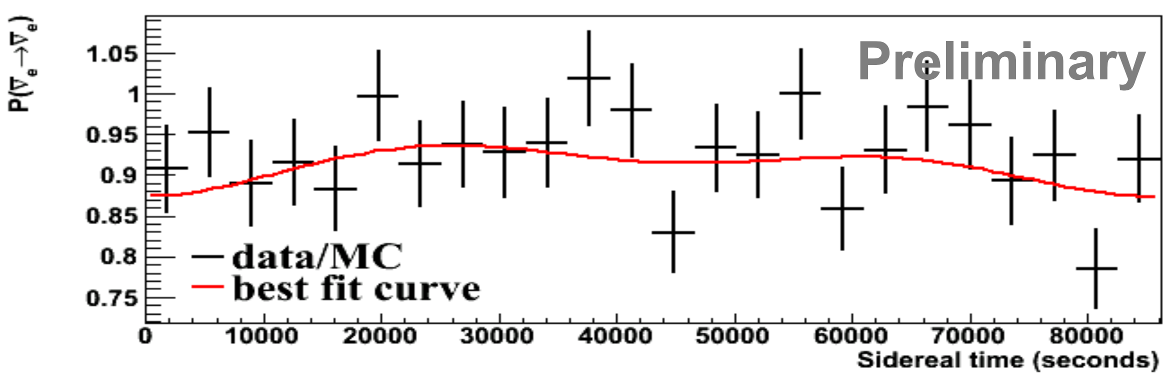
Double Chooz observed the 3.1σ disappearance signal of electron antineutrinos from the reactor

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

We will be able to set limits in the e-τ sector for the first time; $\nu_e \leftrightarrow \nu_\tau$ ($<10^{-20}$ GeV)





Futurama (Comedy Central)

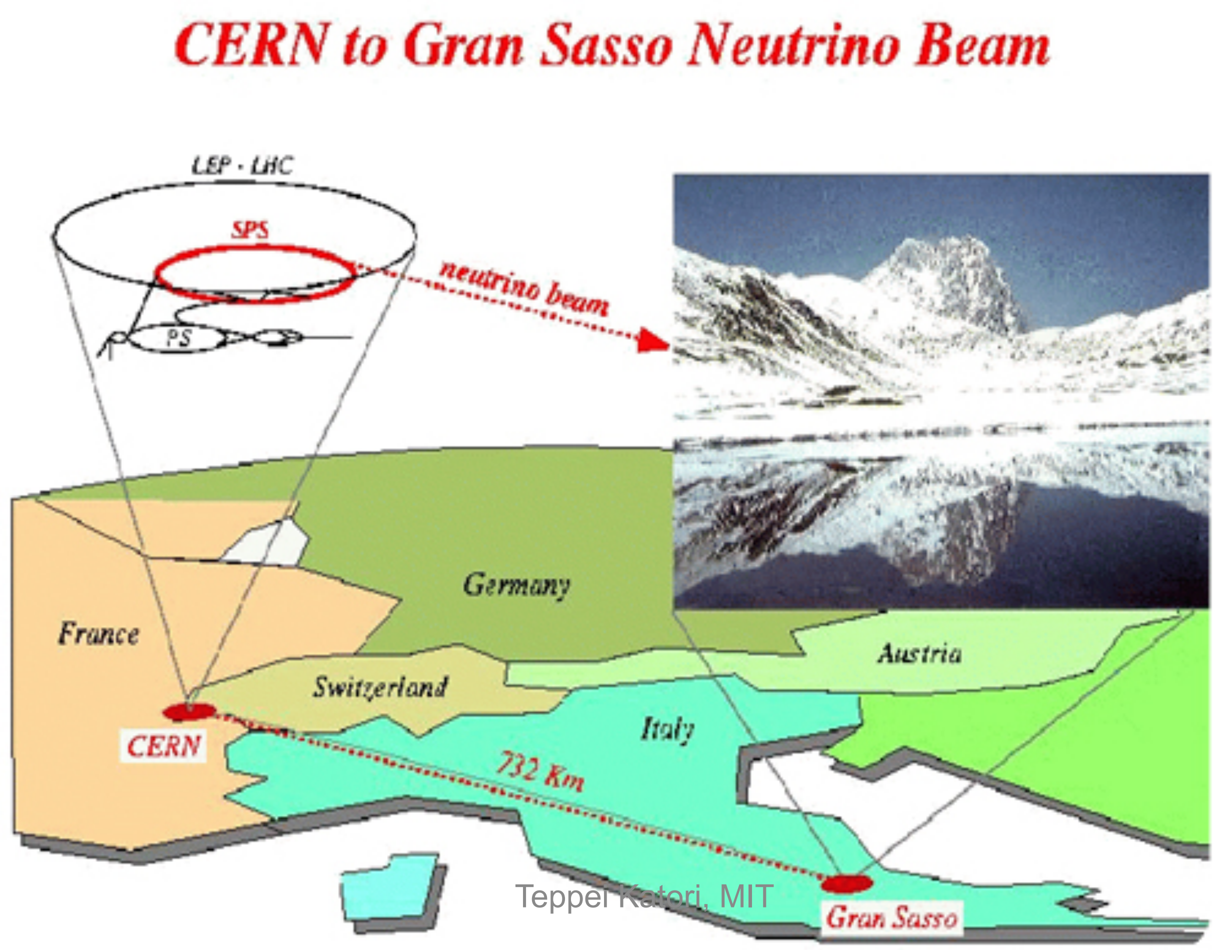
7. Superluminal neutrinos

OPERA collaboration,
ArXiv:1109.4897

7. Superluminal neutrinos

OPERA

v(neutrino) = c + (2.37±0.32) × 10^{-5} c
= c + (16±2) × 10^{3} mph



7. Superluminal neutrinos

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OPERA

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$$= c + (16 \pm 2) \times 10^{3}\ \text{mph}$$

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Neutrinos still faster than light in latest version of experiment

Finding that contradicts Einstein's theory of special relativity is repeated with fine-tuned procedures and equipment

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The Washington Post

Posted at 08:25 AM ET, 09/23/2011

Neutrinos may have traveled faster than the speed of light

By Elizabeth Flock

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

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Scientists Report Second Sighting of Faster-Than-Light Neutrinos

By DENNIS OVERBYE
Published: November 18, 2011

Few scientists are betting against Einstein yet, but the phantom neutrinos of Opera are still eluding explanation.

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Tiny Neutrinos May Have Broken

Two months after scientists reported that they had clocked subatomic particles known as neutrinos going

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Speed of light broken again as scientists test neutrino result

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

OPERA collaboration,
ArXiv:1109.4897

7. Superluminal neutrinos

OPERA

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

It is fascinating result, but...

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

It is very difficult to interpret superluminal neutrinos at OPERA by Lorentz violation with field theory approach.

7. Superluminal neutrinos

OPERA collaboration, ArXiv:1109.4897

The New York Times — Science

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ENVIRONMENT SPACE & COSMOS

Two Technical Problems Leave Neutrinos' Speed in Question

By KENNETH CHANG
Published: February 23, 2012

The Washington Post — Make us your start page

POSTOPINIONS

Posted at 01:23 PM ET, 02/23/2012

Faster-than-light neutrinos aren't?

By Alexandra Petri

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

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

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Faster-than-light neutrinos could be down to bad wiring

By Jason Palmer
Science and technology reporter, BBC News

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

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

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

The neutrinos are fired deep under the Italian

theguardian

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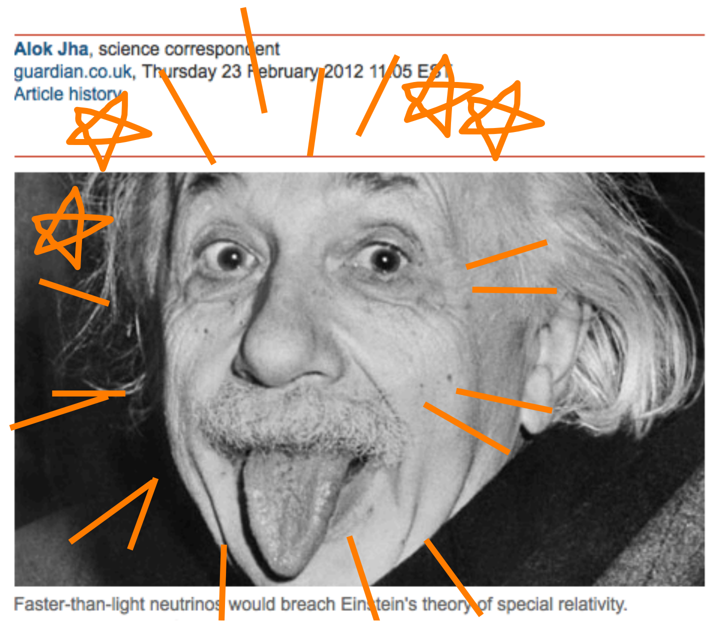
Faster-than-light neutrinos: was a faulty connection to blame?

A dodgy optical fibre connection may have skewed results that appeared to show neutrinos travelling faster than light

Alok Jha, science correspondent
guardian.co.uk, Thursday 23 February 2012 11.05 EST
Article history



Faster-than-light neutrinos would breach Einstein's theory of special relativity.

It is hard to topple the giant...

Conclusion

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.

MiniBooNE neutrino mode data prefer sidereal time independent solution. On the other hand, anti-neutrino mode data prefer sidereal time dependent solution, although statistical significance is not high enough.

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

Thank you for your attention!