Tests of Lorentz and CPT violation with Neutrinos

Teppei Katori
Massachusetts Institute of Technology
ACP seminar, , Kavli IPMU, Feb. 6, 2013

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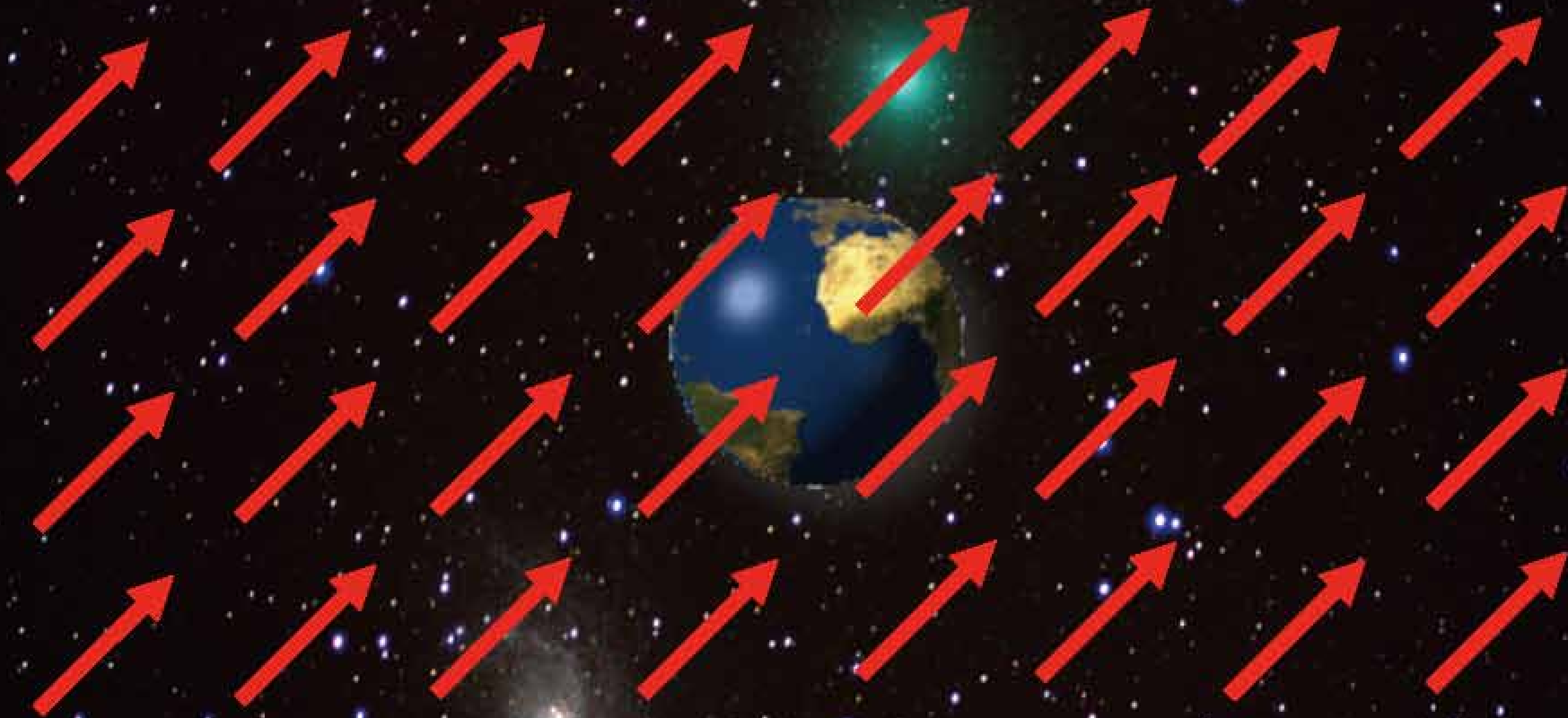

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Tests of Lorentz and CPT violation with Neutrinos

outline

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

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1. **Spontaneous Lorentz symmetry breaking**

2. What is Lorentz and CPT violation?

3. Lorentz violation with neutrino oscillation

4. MiniBooNE experiment

5. Test for Lorentz violation with MiniBooNE data

6. Test for Lorentz violation with Double Chooz data

7. Future of neutrino physics

8. Conclusion

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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Spontaneous Symmetry Breaking (SSB)!

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

1. Spontaneous Lorentz symmetry breaking (SLSB)

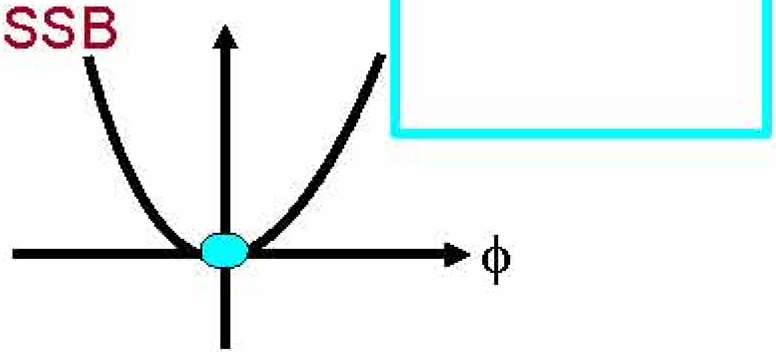
vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_{\mu}\partial^{\mu}\Psi$

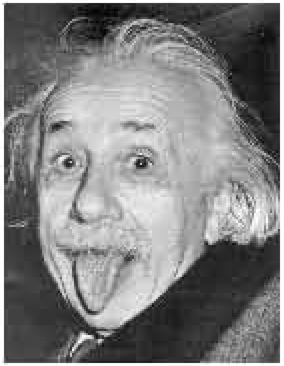
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

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





1. Spontaneous Lorentz symmetry breaking (SLSB)

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

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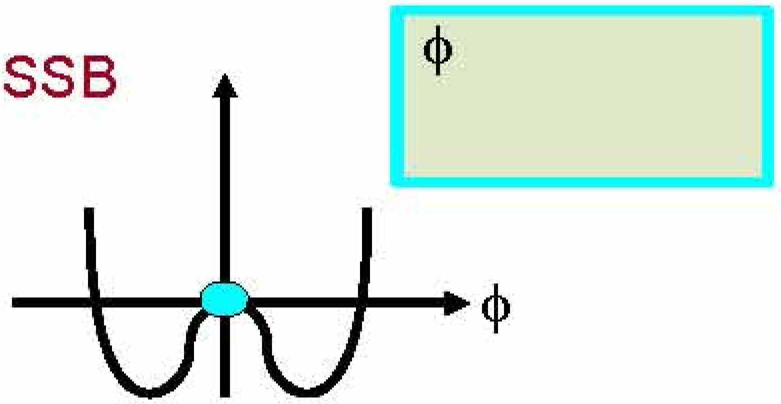

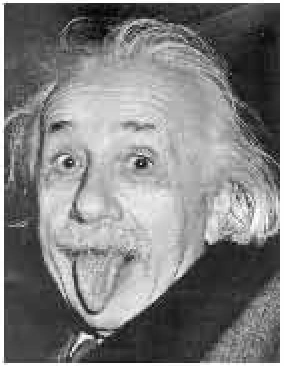

Particle acquires
mass term!

Kostelecký and Samuel
PRD39(1989)683

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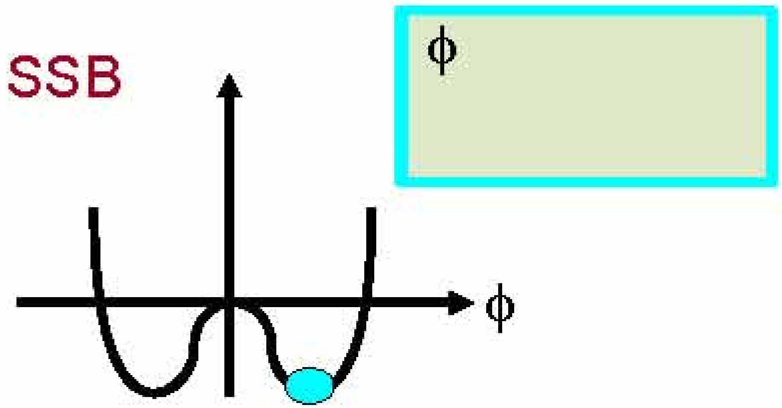
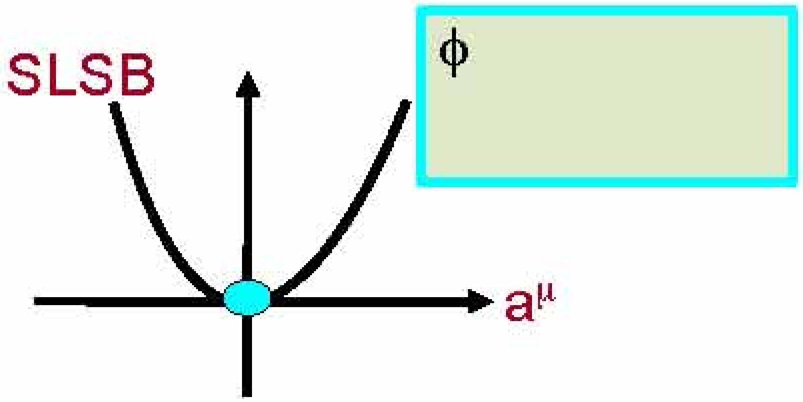
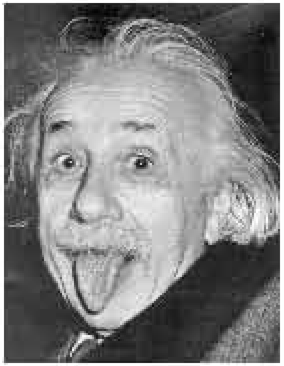


e.g.) SLSB in string field theory

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

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





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1. Spontaneous Lorentz symmetry breaking (SLSB)

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

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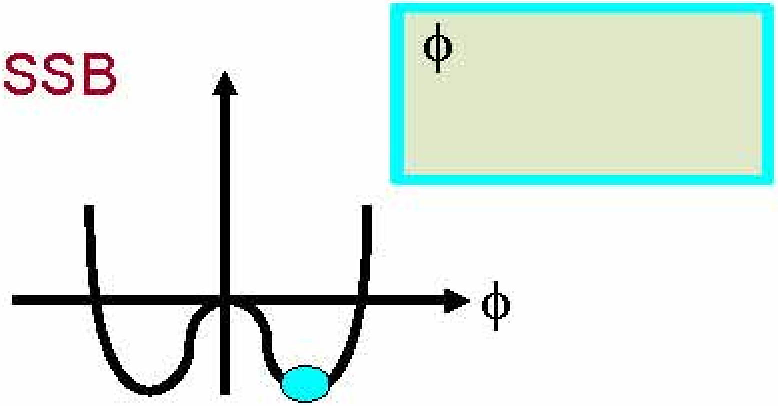

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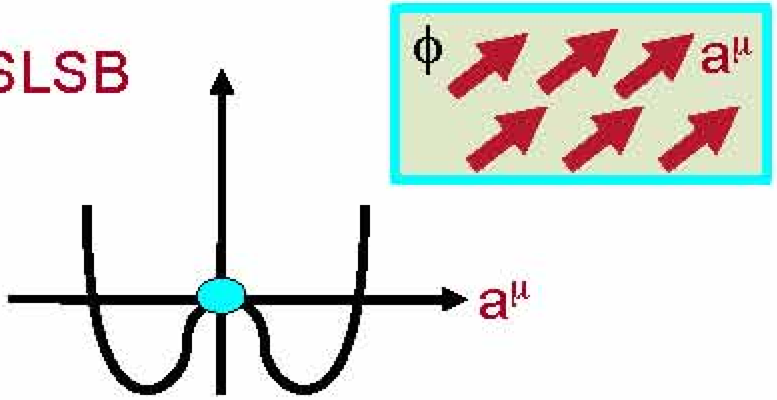
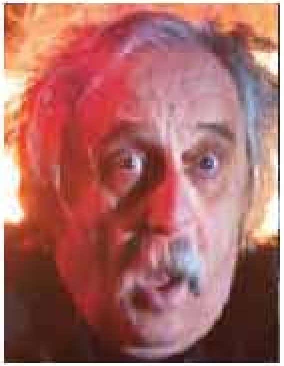




Lorentz symmetry
is spontaneously
broken!

1. Spontaneous Lorentz symmetry breaking

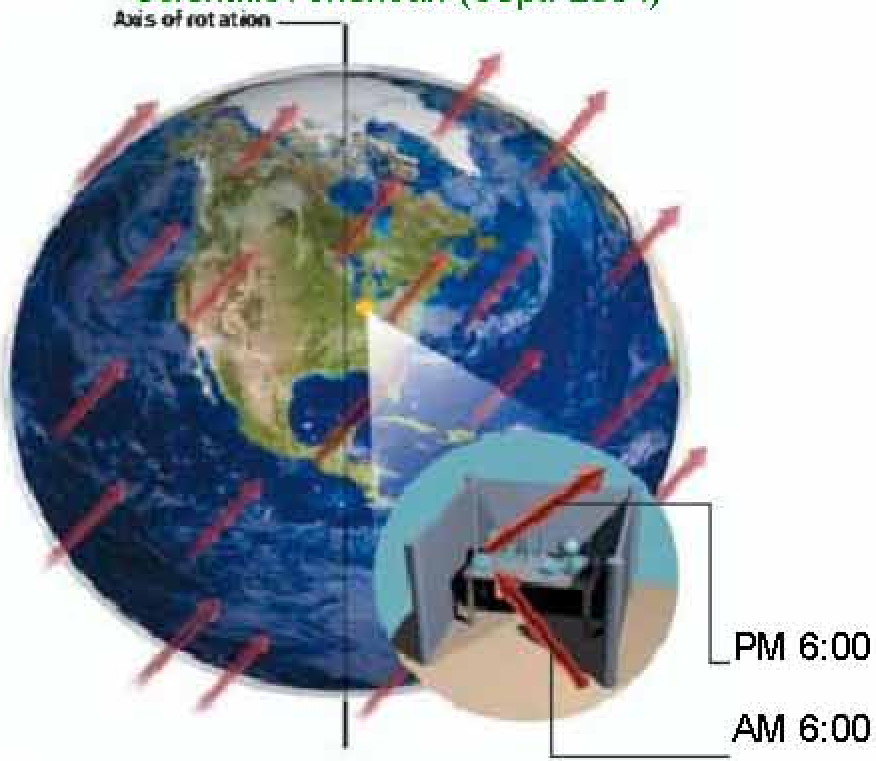
Test of Lorentz violation: Find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos etc). Do these quantities depend on rotation of the earth?

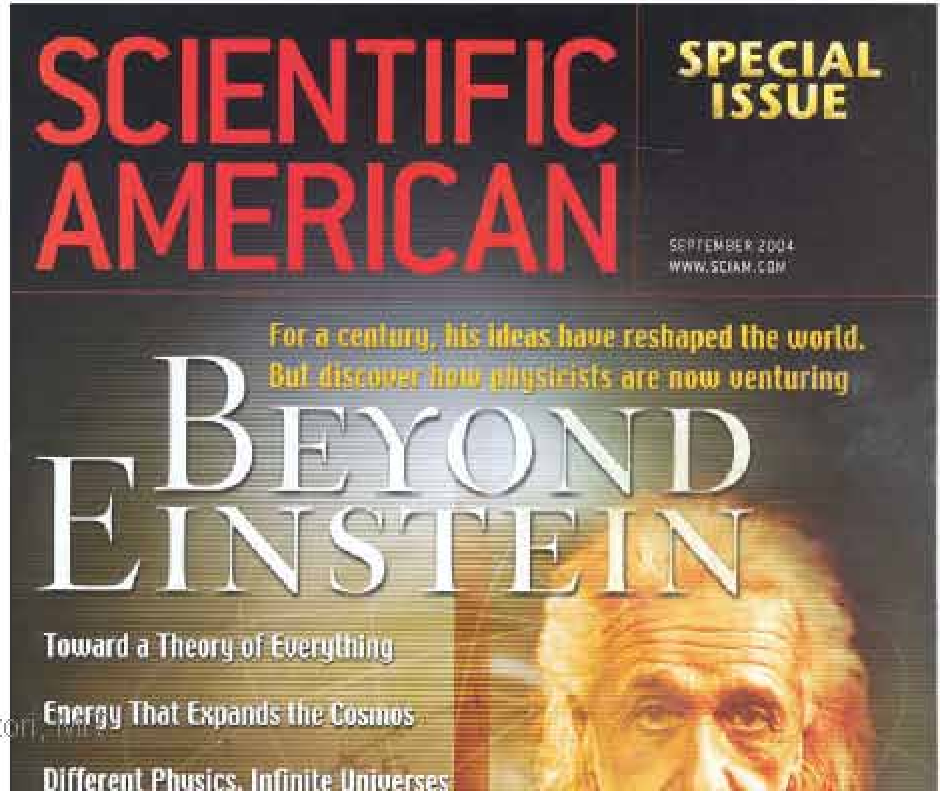
background field of the universe

vacuum Lagrangian for fermion

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

Scientific American (Sept. 2004)





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Sidereal time dependence

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?!

Target scale

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

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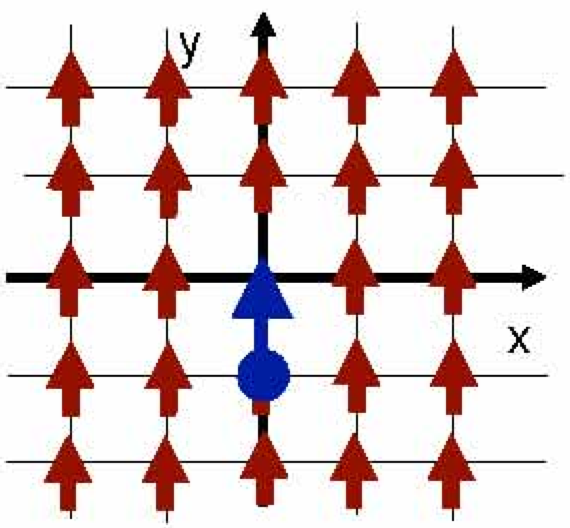
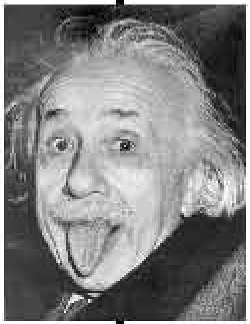
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)$$





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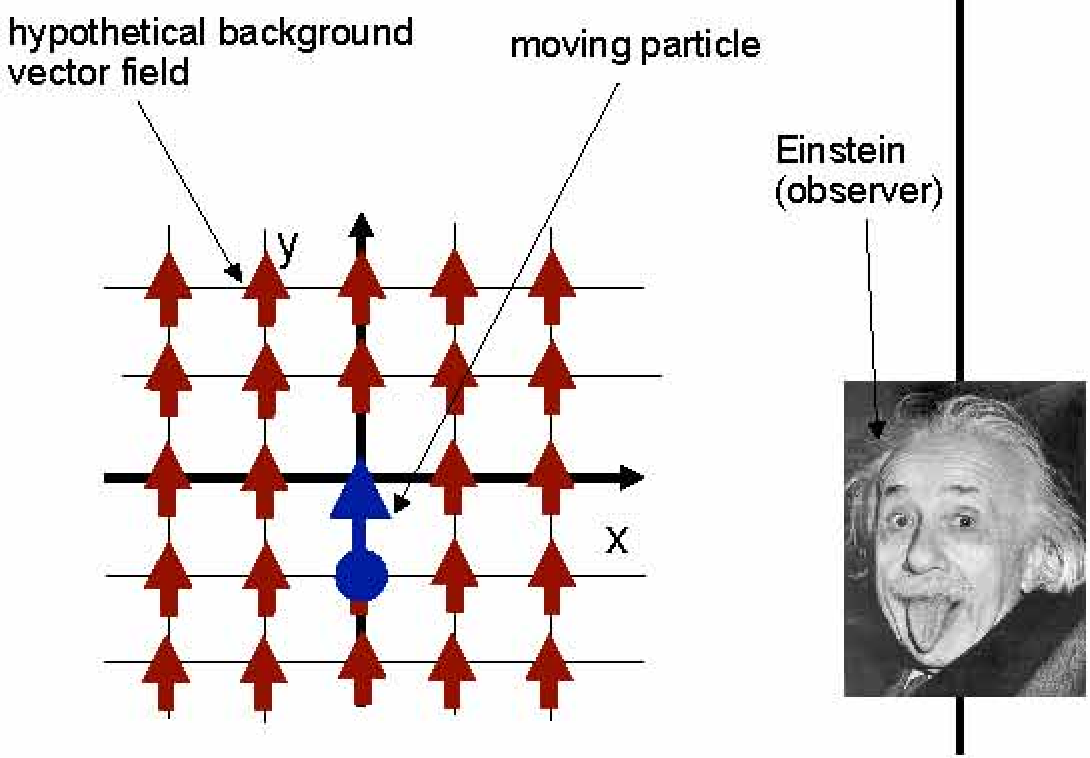
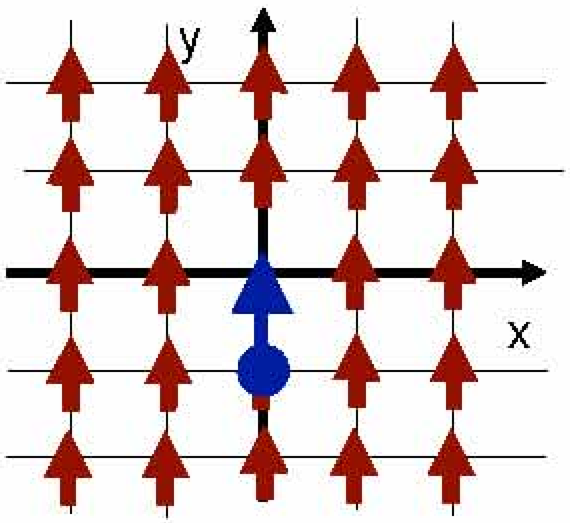
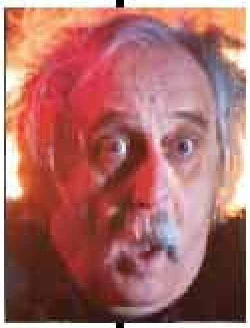


2. What is Lorentz violation?

Under the particle Lorentz transformation:

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





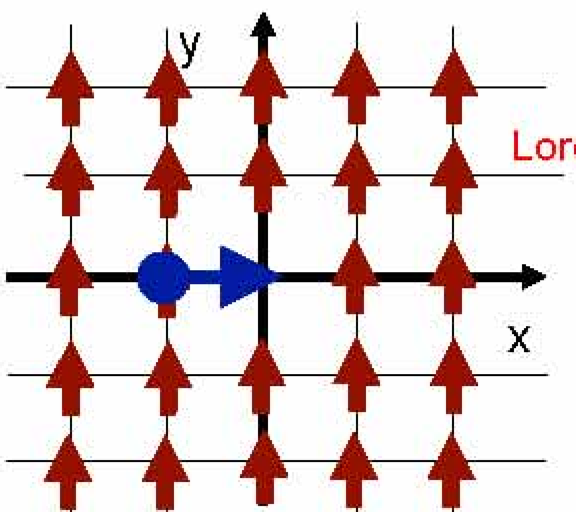
2. What is Lorentz violation?

Under the particle Lorentz transformation:

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

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

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



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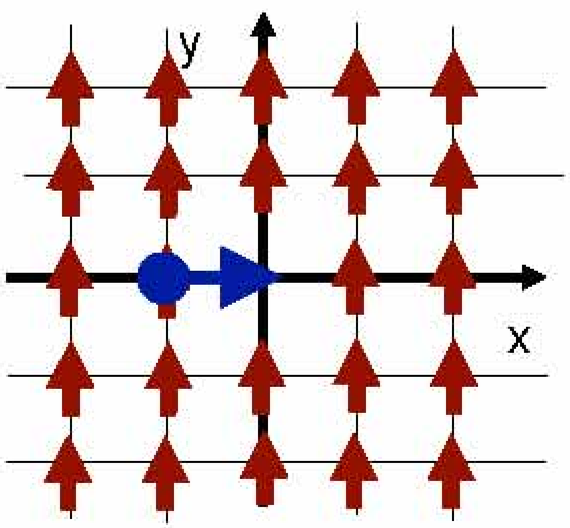
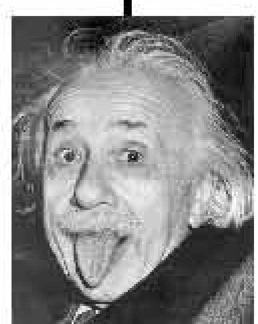
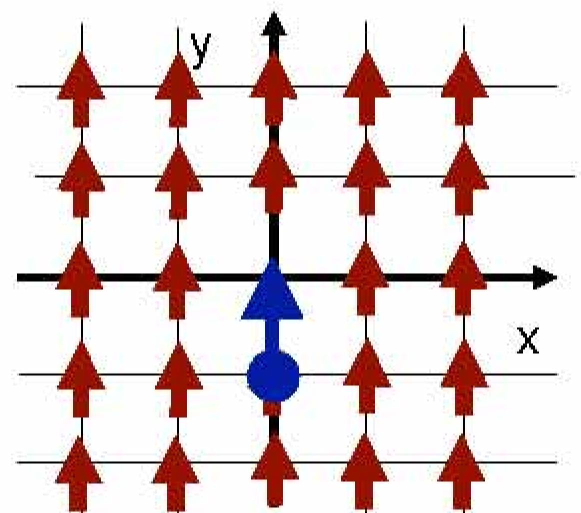




Under the observer Lorentz transformation:

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



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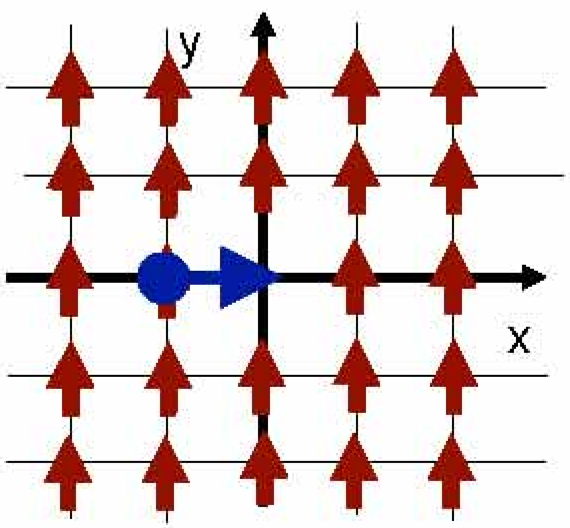
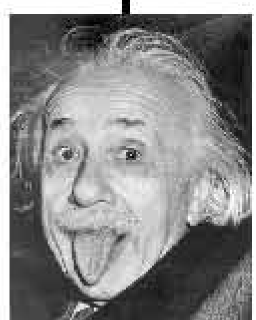
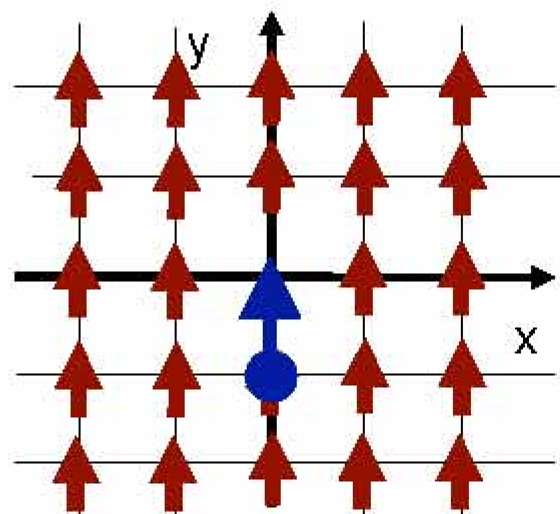




Under the observer Lorentz transformation:

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

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



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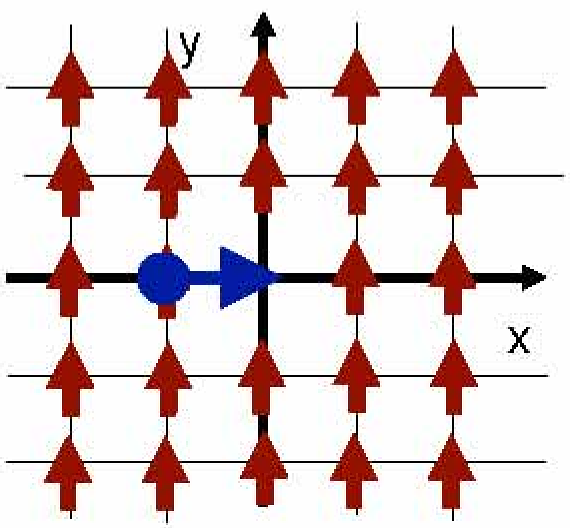
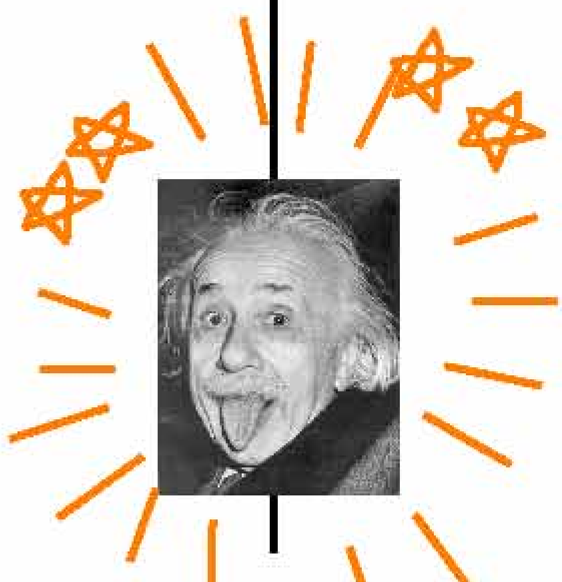


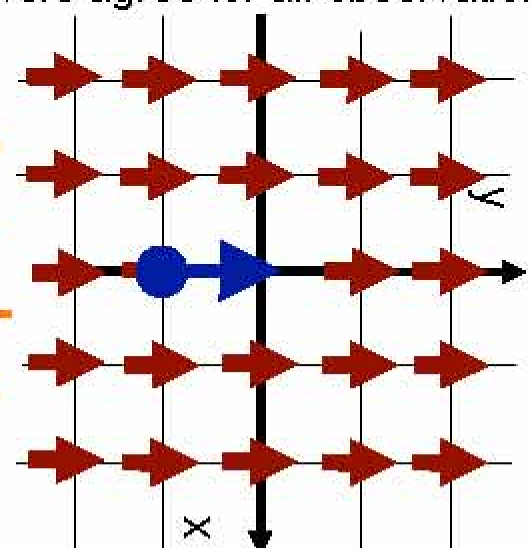
Under the observer Lorentz transformation:

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

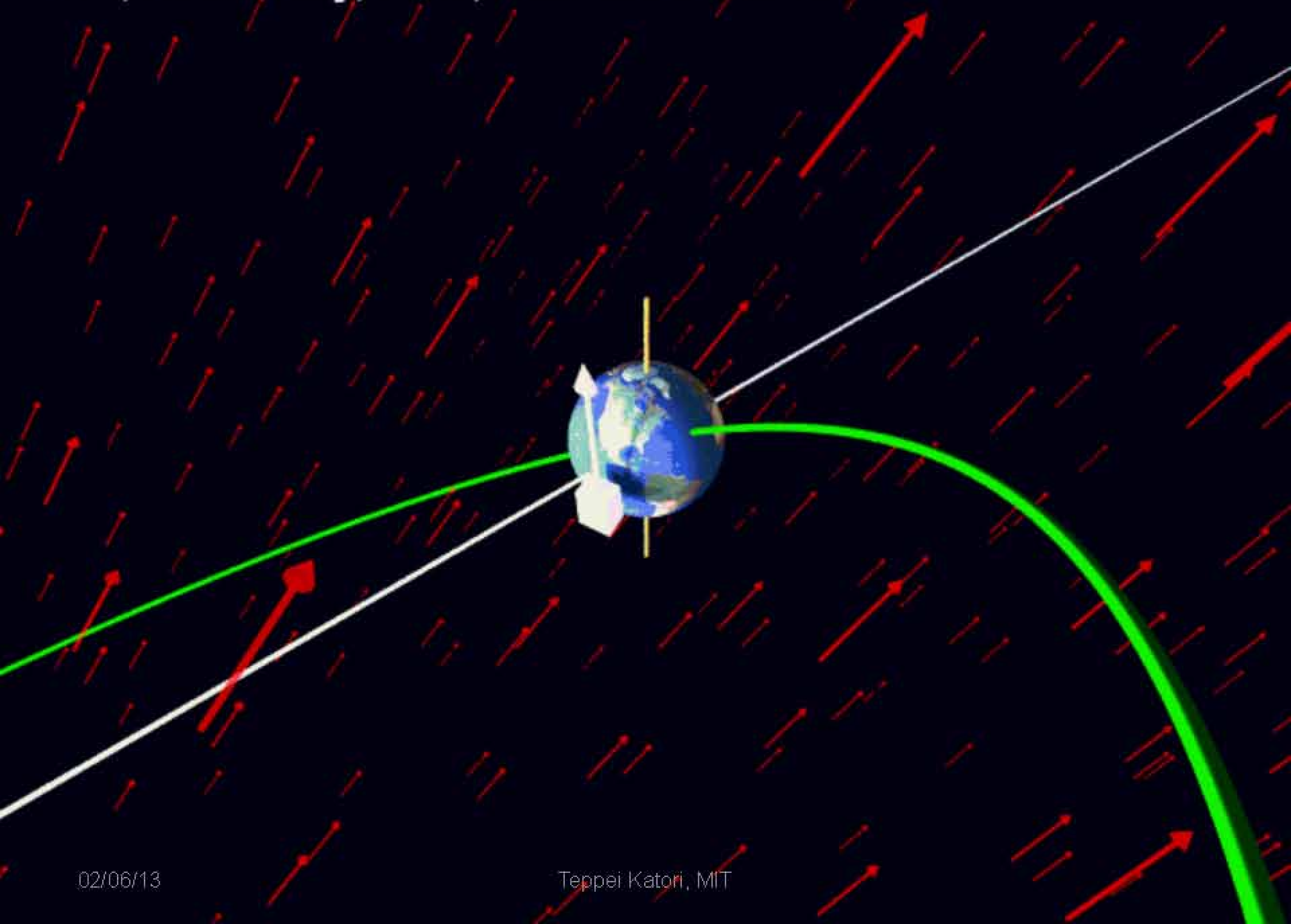
Lorentz violation cannot be generated by observers motion (coordinate transformation is unbroken)

all observers agree for all observations





Bluhm, Kostelecky, Lane, Russell PRL 2002



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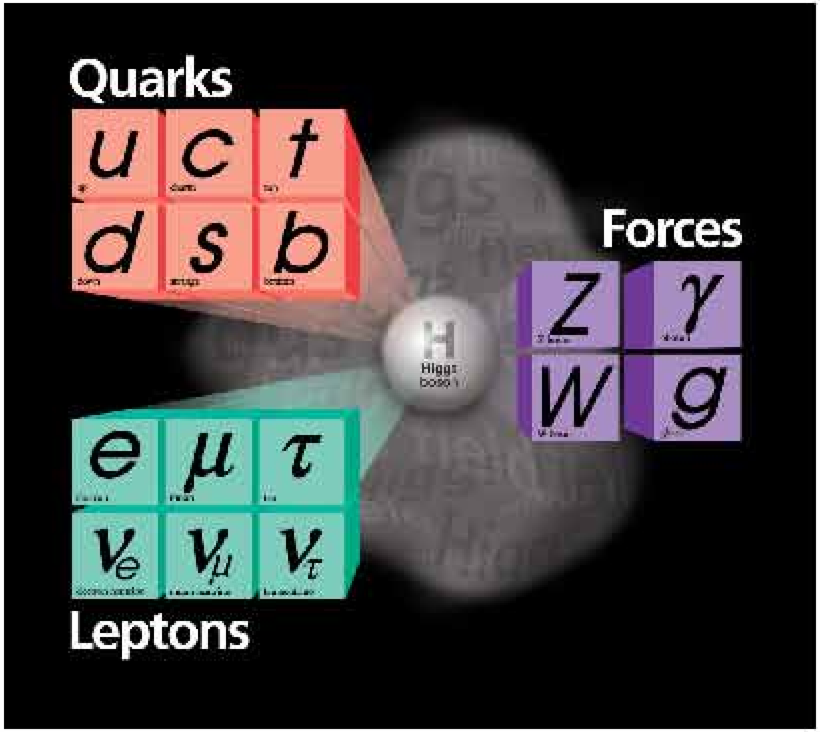
3. Neutrinos

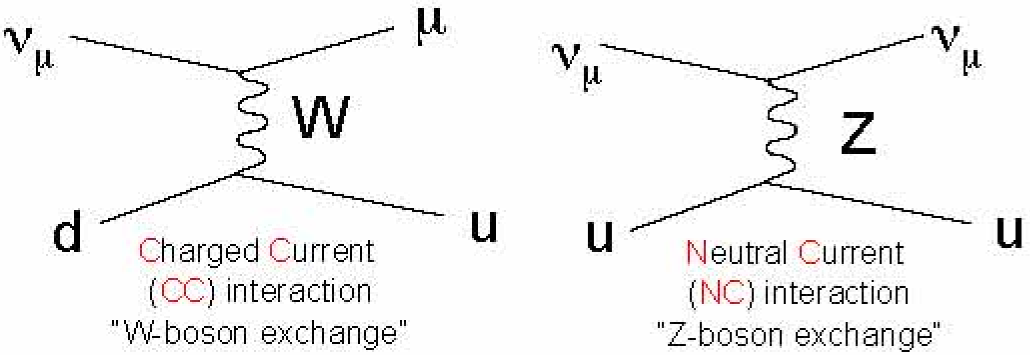
Neutrinos in the standard model

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



Neutrinos are special because,

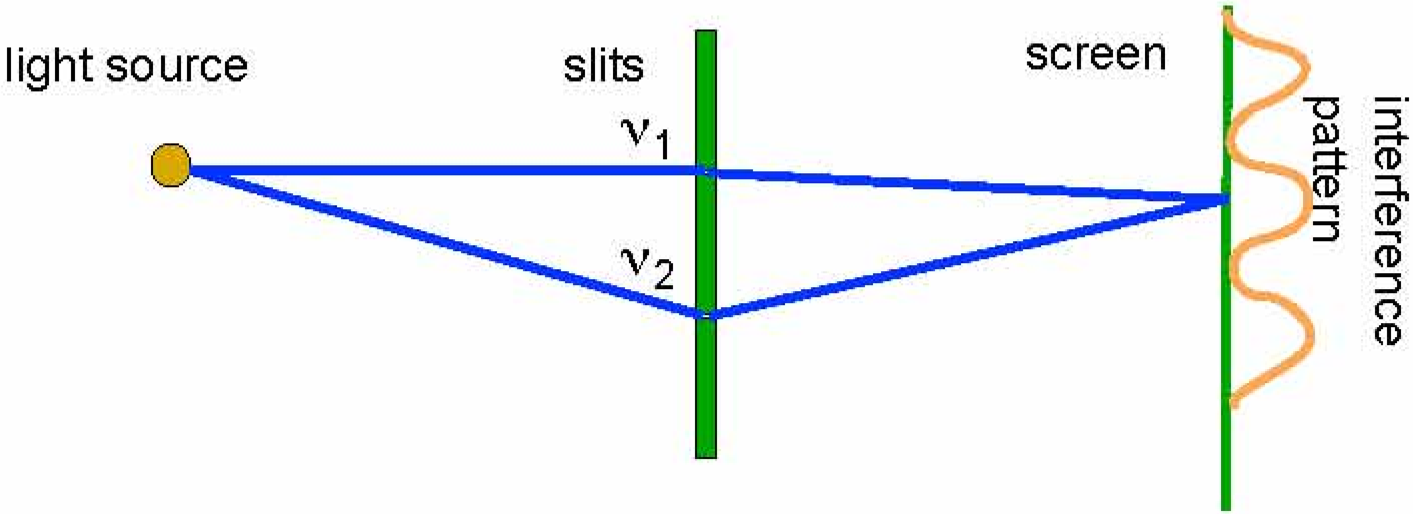
1. they only interact with weak nuclear force.



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

3. Neutrino oscillations, natural interferometers

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



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

3. Neutrino oscillations, natural interferometers

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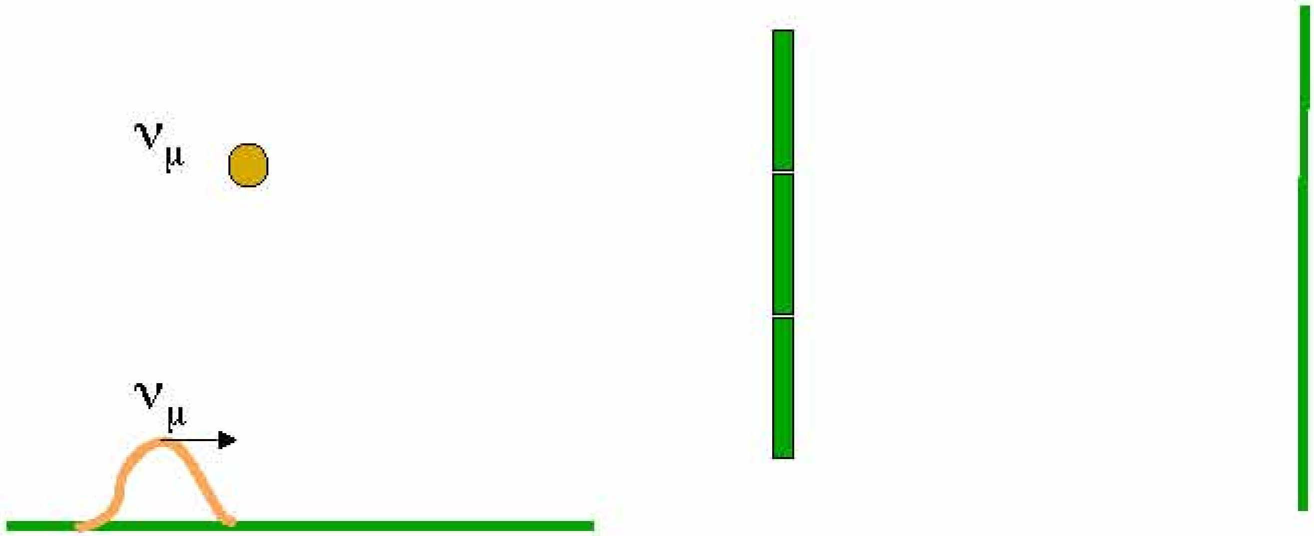

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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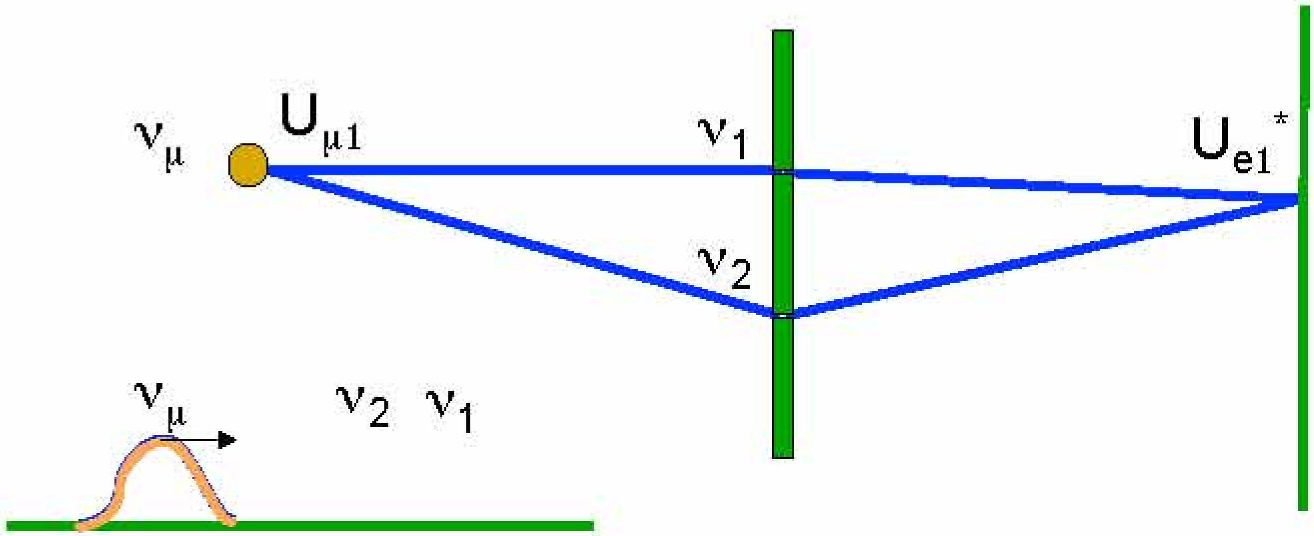

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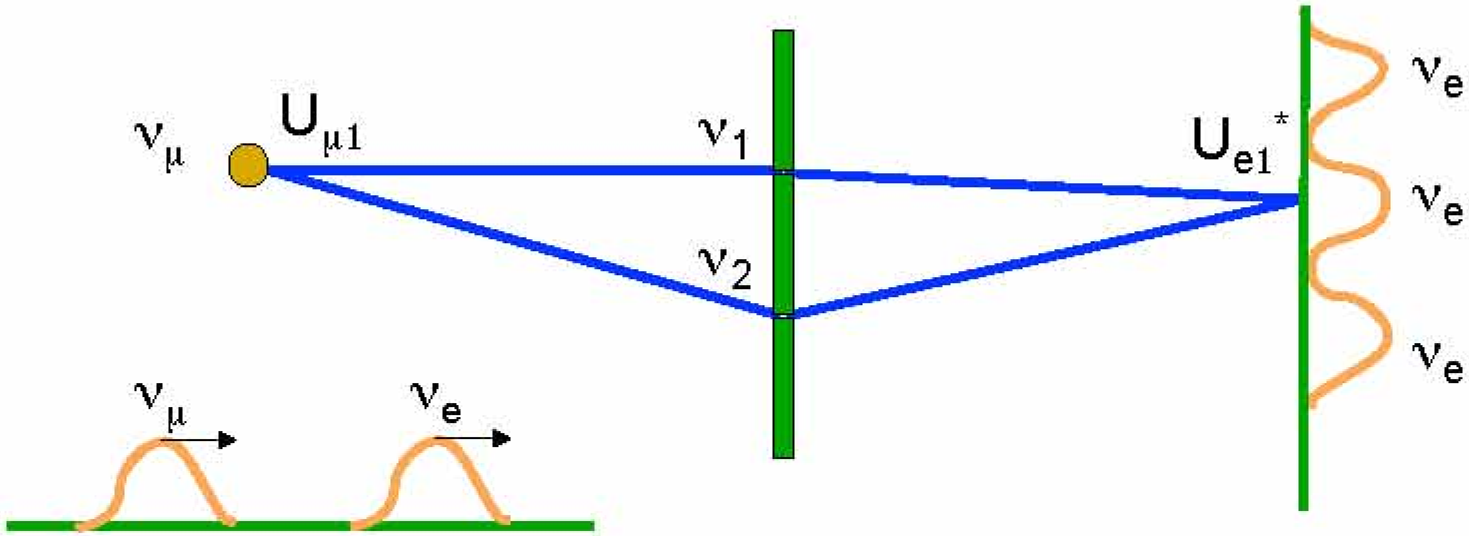

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The detection may be different flavor (neutrino oscillations).

3. Neutrino oscillations

2 neutrino mixing

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

$$|\nu_\mu\rangle = U_{e1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle$$

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

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

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

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

3. Neutrino oscillations

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

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is

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

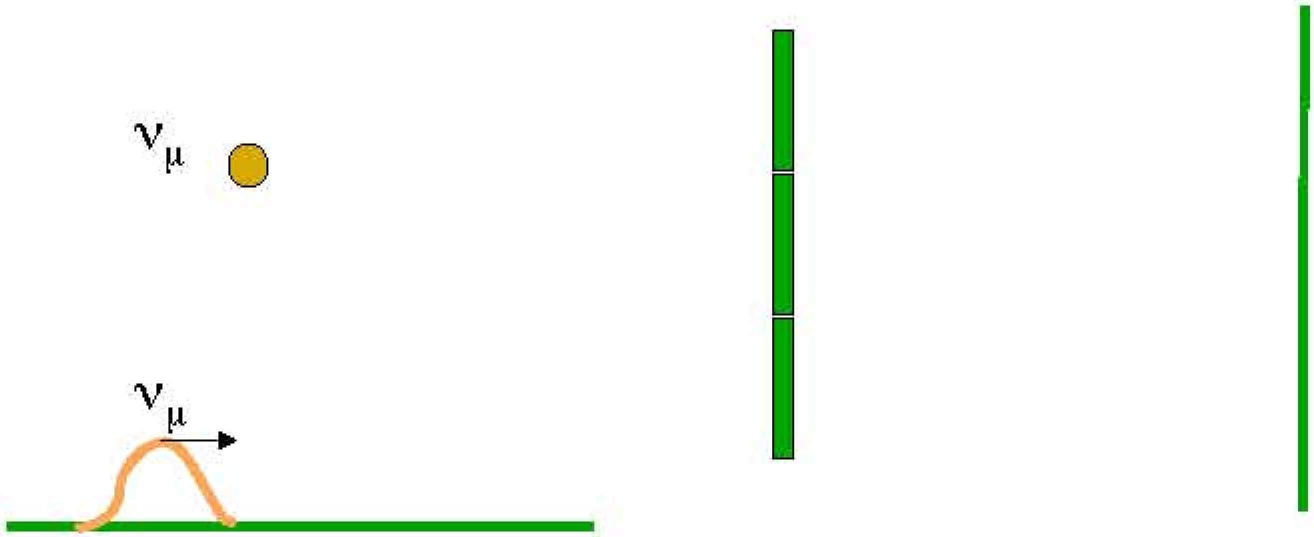
Oscillation maximum is described

$$L = \left(\frac{\pi}{2.54\Delta m^2}\right)\cdot E$$

$L \propto E$ straight line is the signature of neutrino mass

3. Lorentz violation with neutrino oscillation

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



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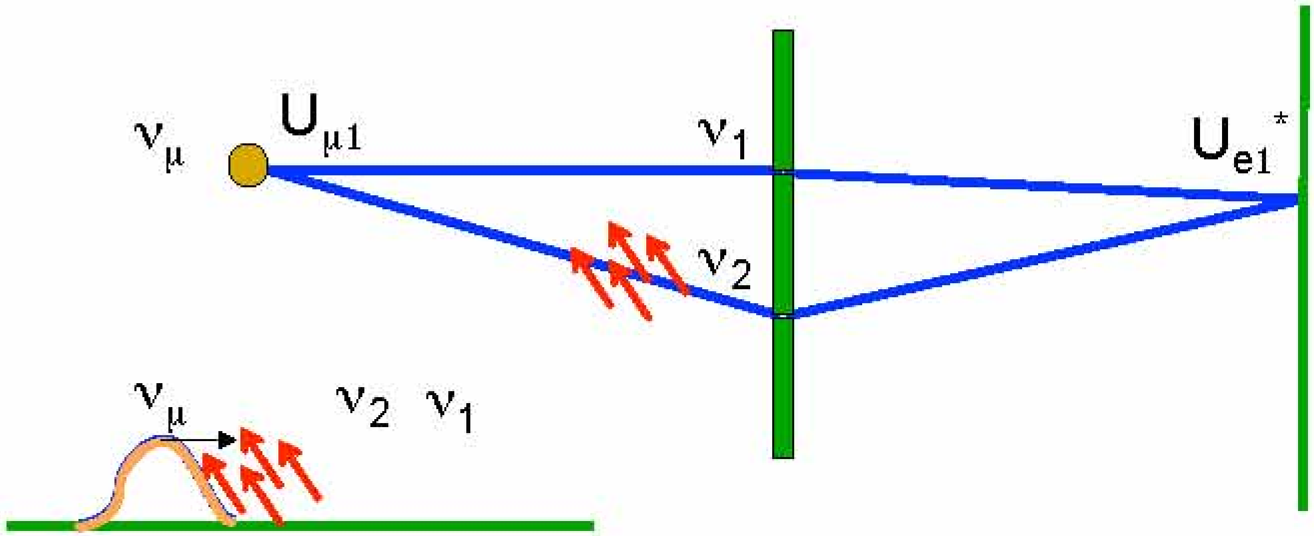

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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).

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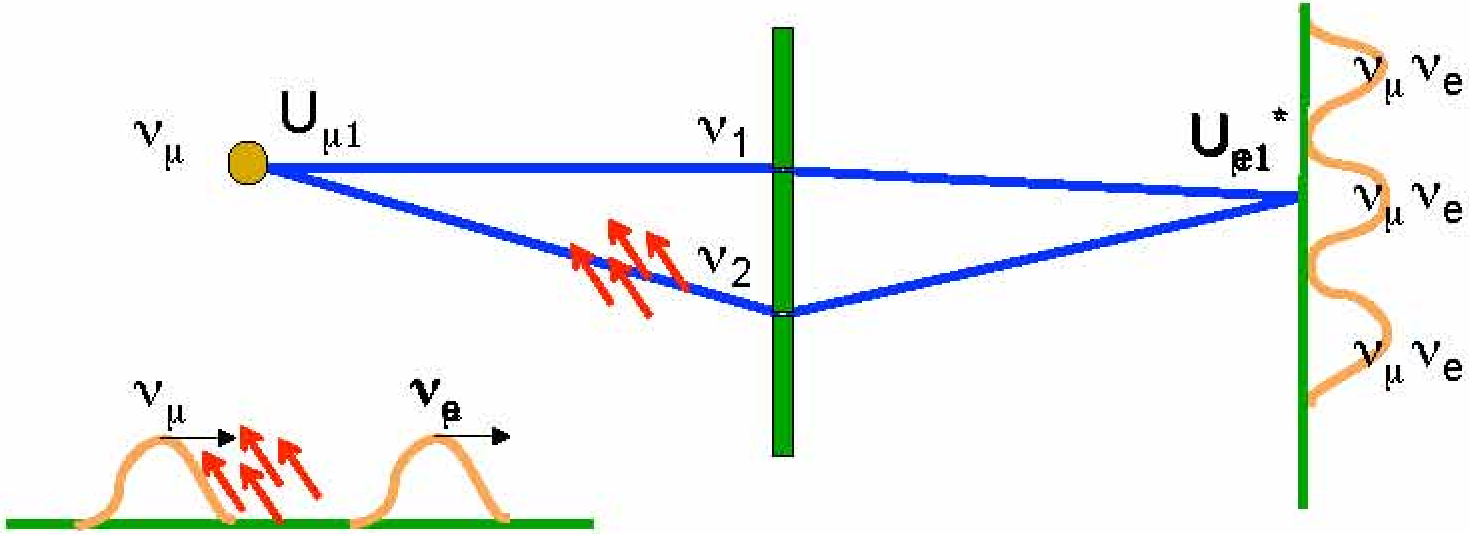

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If neutrino oscillation is caused by Lorentz violation, it may have sidereal time dependence

3. Lorentz violation with neutrino oscillation

In the vacuum, arbitrary 2 neutrino effective Hamiltonian,

$$H_{eff} \to \begin{pmatrix} h_{ee}(E) & h_{e\mu}(E) \\ h_{e\mu}(E) & h_{\mu\mu}(E) \end{pmatrix} = \begin{pmatrix} U_{e1}(E) & U_{e2}(E) \\ U_{\mu1}(E) & U_{\mu2}(E) \end{pmatrix} \begin{pmatrix} \lambda_1(E) & 0 \\ 0 & \lambda_2(E) \end{pmatrix} \begin{pmatrix} U_{e1}(E) & U_{e2}(E) \\ U_{\mu1}(E) & U_{\mu2}(E) \end{pmatrix}$$

Therefore, 2 neutrino oscillation formula is

$$P_{\mu\to e}(L,E) = -4\left[U_{e1}U_{e2}U_{\mu1}U_{\mu2}\right](E)\cdot\sin^2\left(\frac{\lambda_1(E)-\lambda_2(E)}{2}L\right)$$

Oscillation maximum is described

$$L = \left(\frac{\pi}{\lambda_1(E)-\lambda_2(E)}\right)$$

The solution of neutrino oscillation is arbitrary function of E.

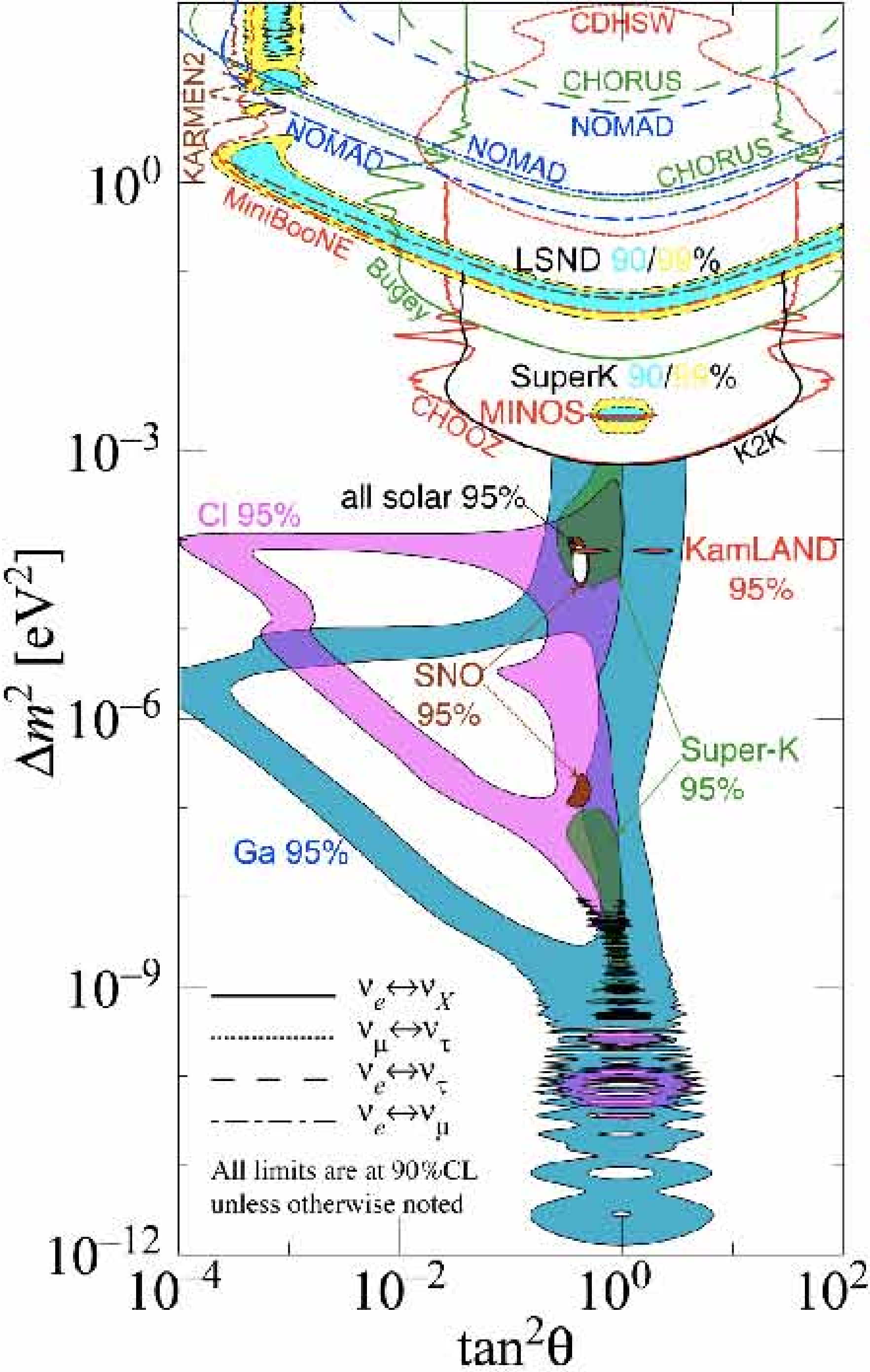
3. Neutrino standard Model (νSM)

This is the world data of neutrino oscillation

It looks majority of region is either accepted (positive signals) or excluded

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

What is model independent diagram look like?

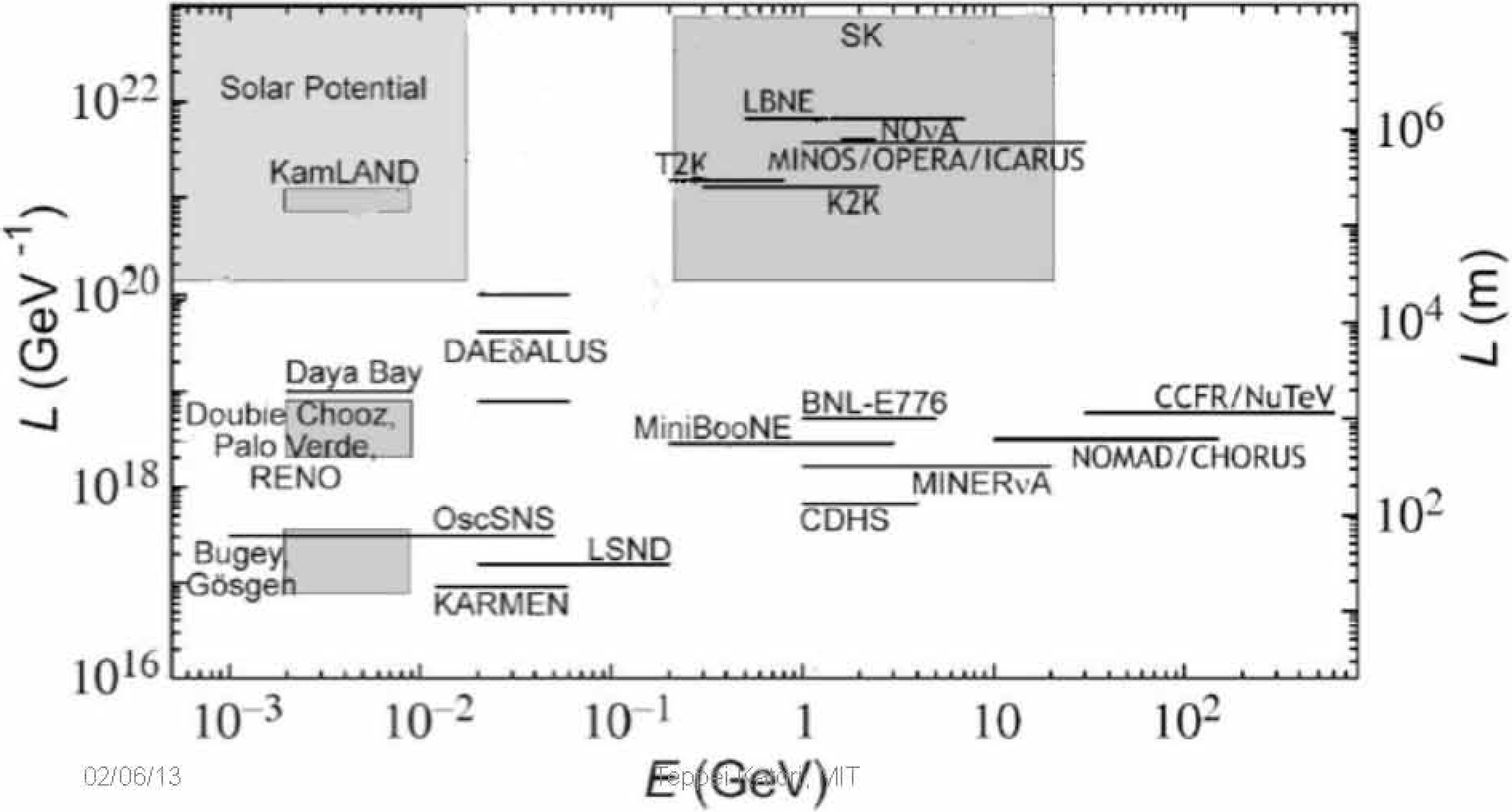


http://hitoshi.berkeley.edu/neutrino

Kostelecký and Mewes
PRD69(2004)016005

3. Lorentz violation with neutrino oscillation

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



Kostelecký and Mewes
PRD69(2004)016005

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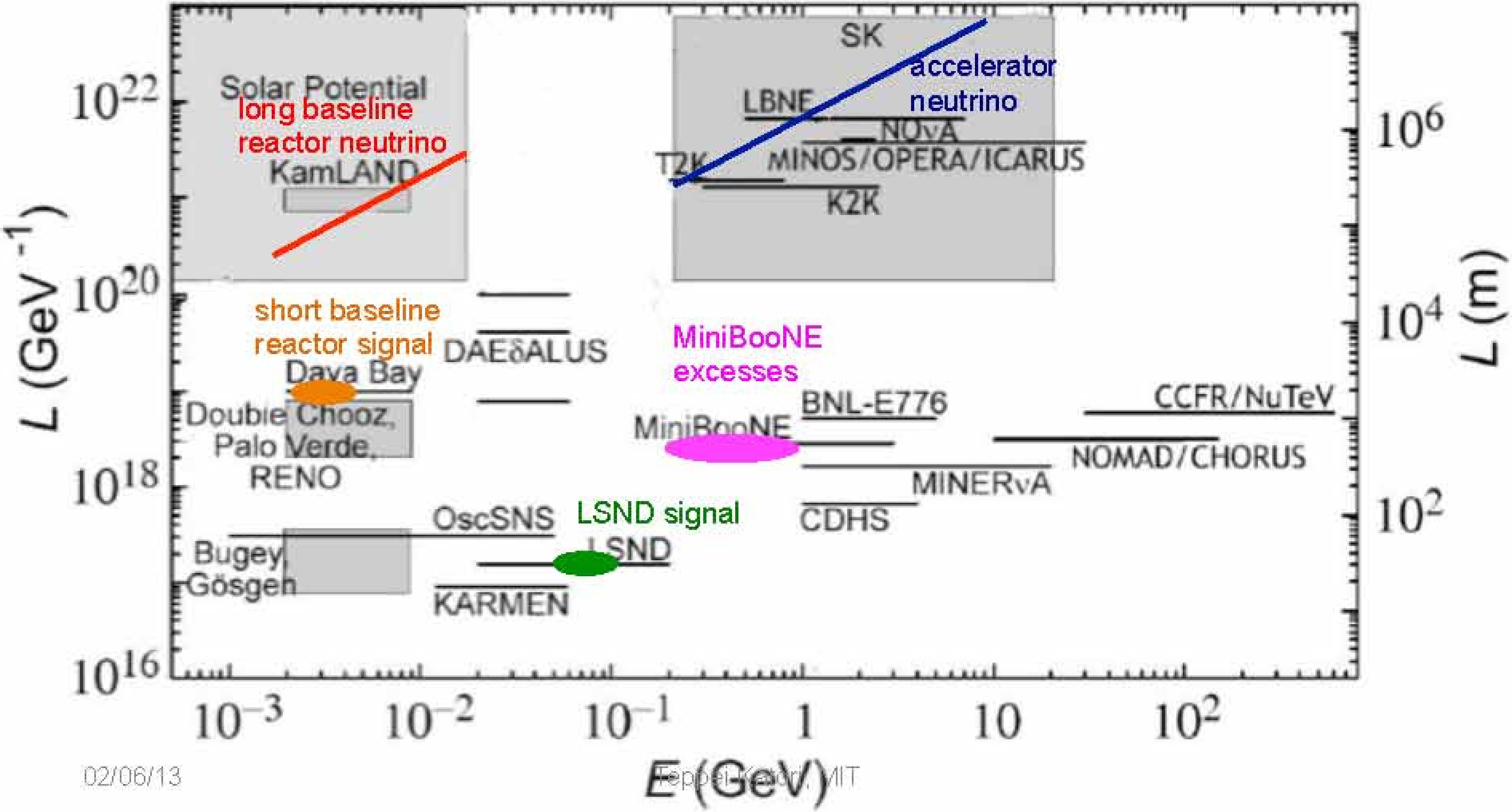

Kostelecký and Mewes
PRD69(2004)016005

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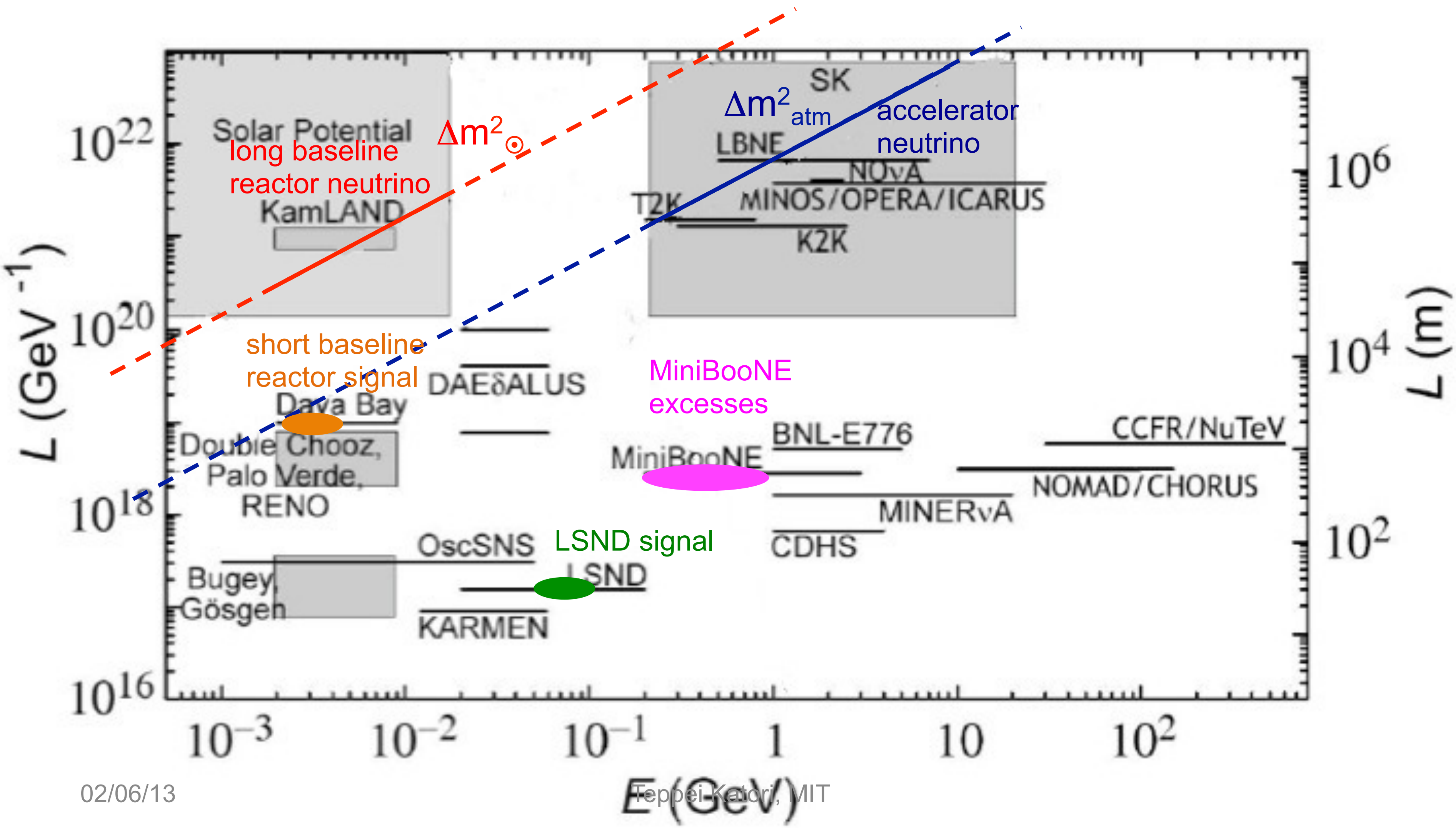

Kostelecký and Mewes
PRD69(2004)016005

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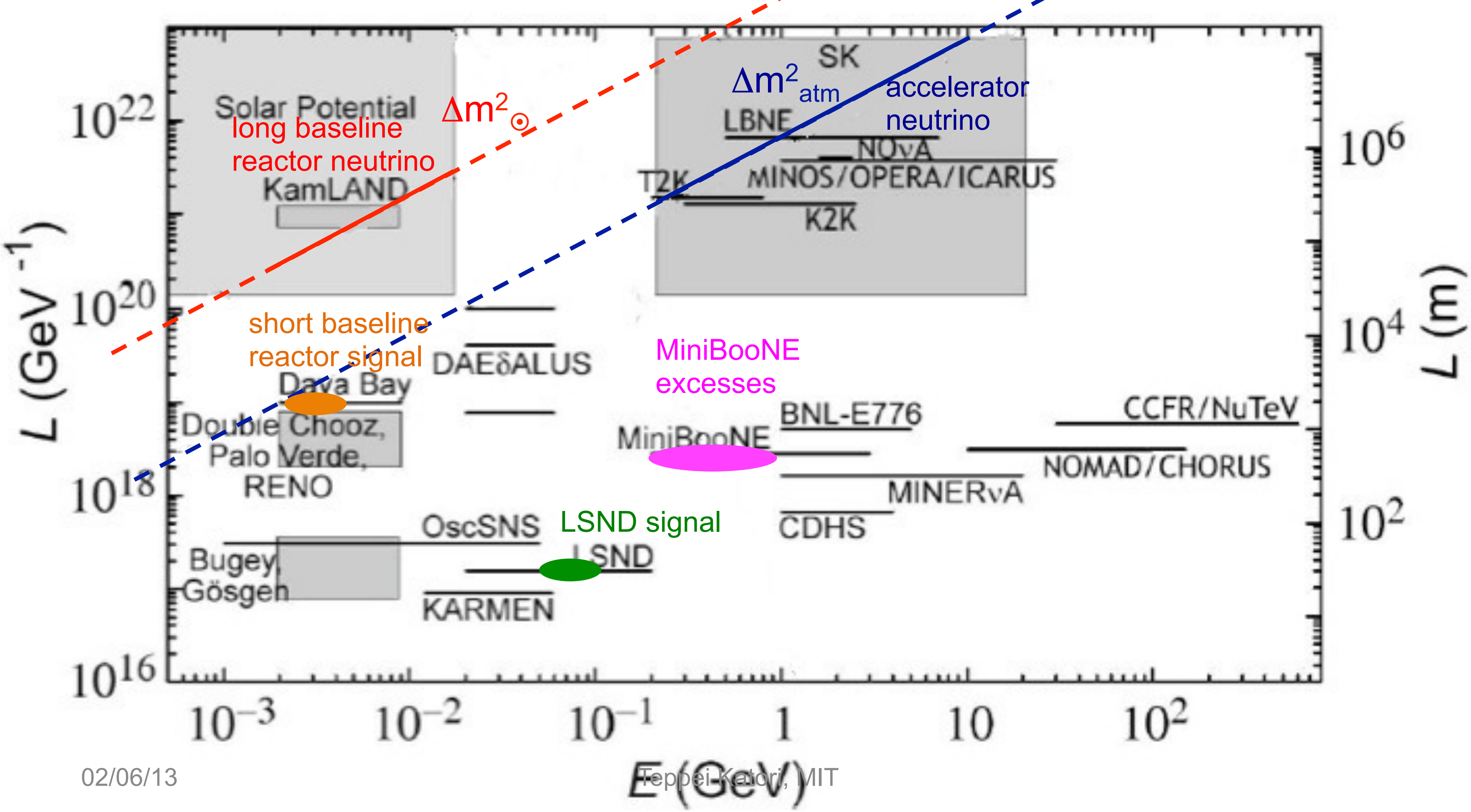

Kostelecký and Mewes
PRD69(2004)016005

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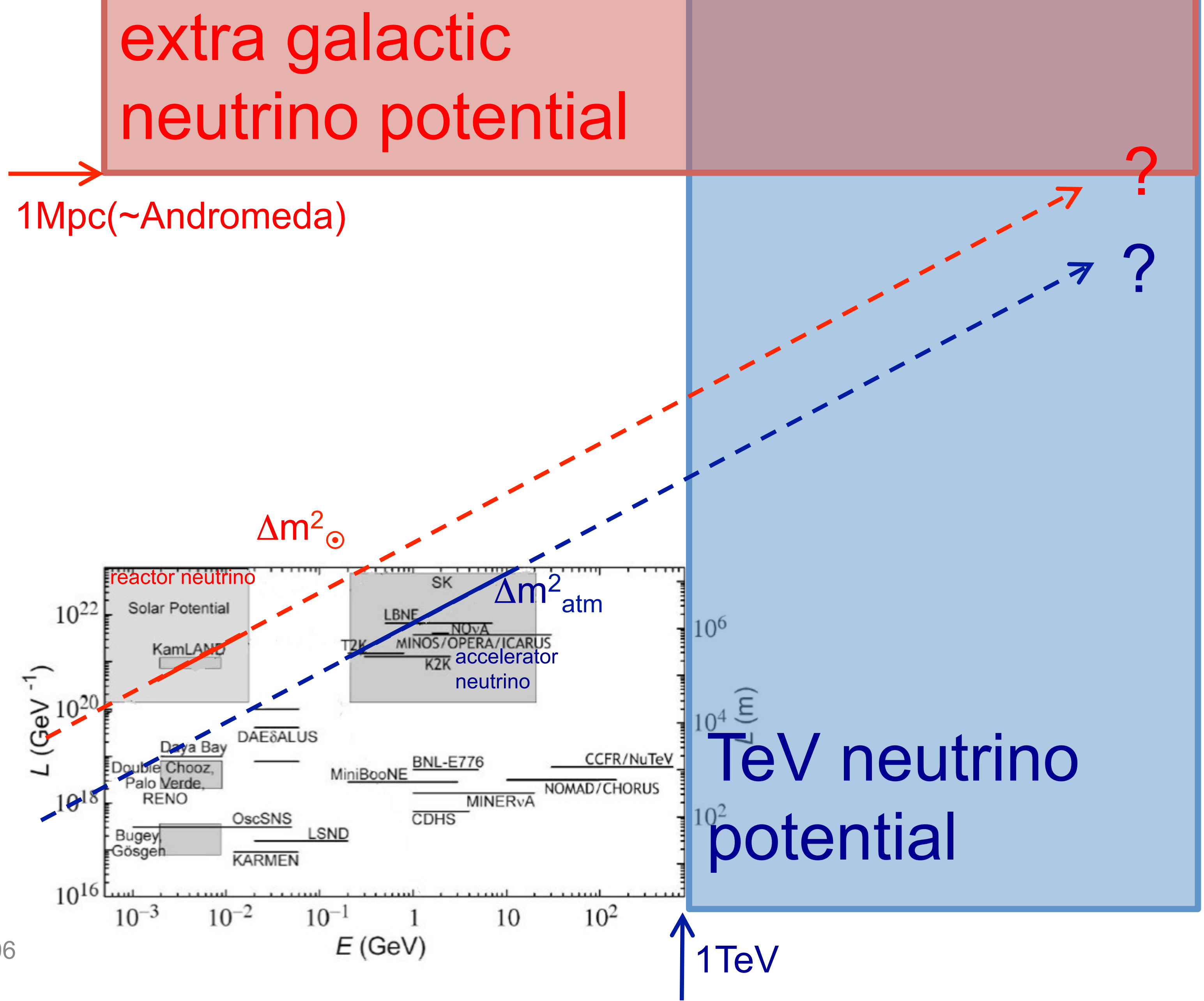

Kostelecký and Mewes
PRD69(2004)016005

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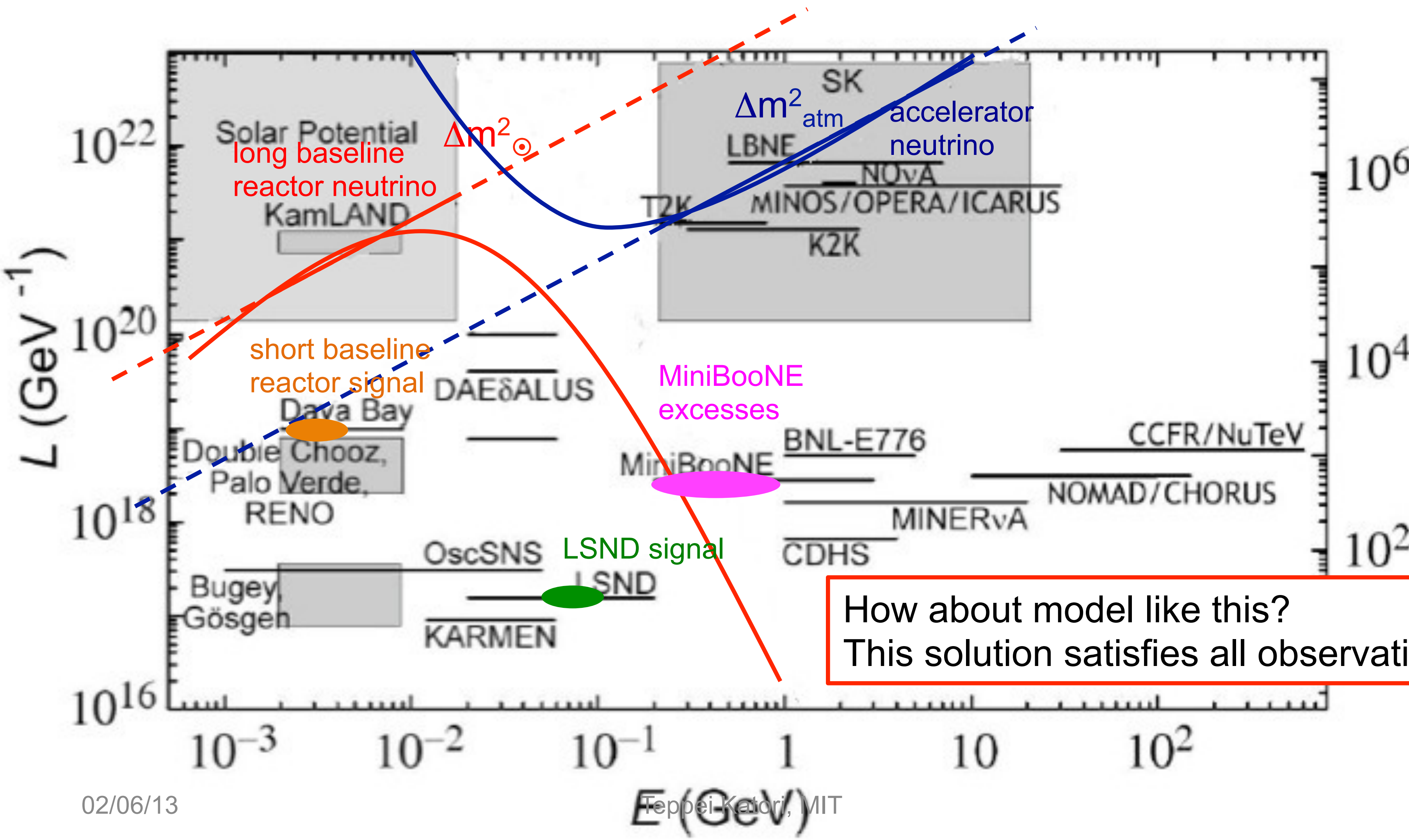
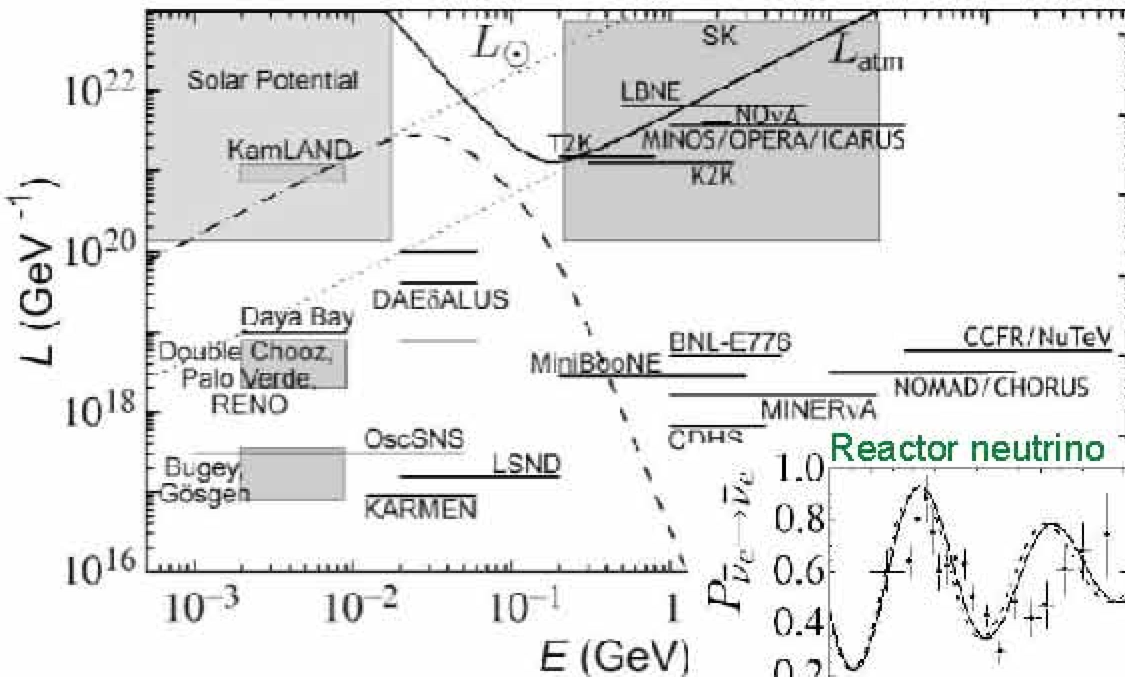


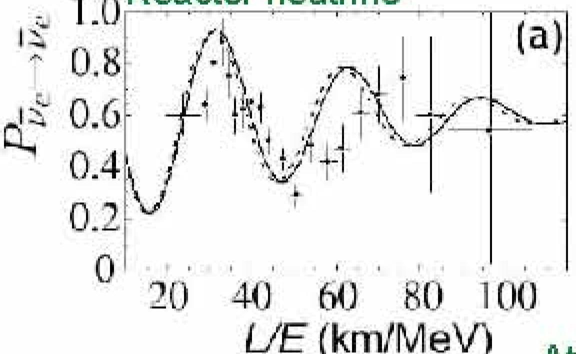
How about model like this?
This solution satisfies all observation

3. Puma model

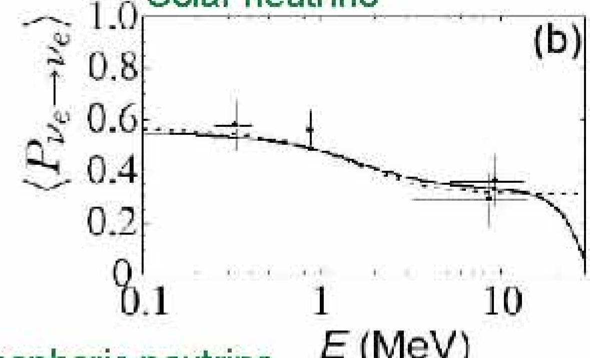
Puma model has only 3 parameters, and perfectly describe all neutrino oscillation signal, including MiniBooNE low energy excess (neutrino mode only!)



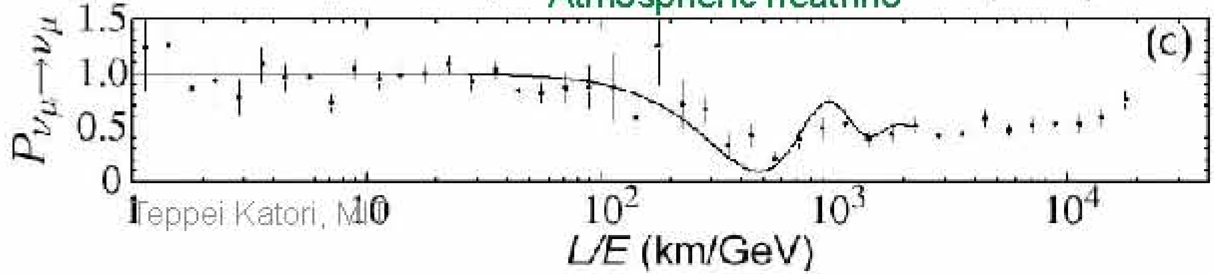
Reactor neutrino



Solar neutrino



Atmospheric neutrino



Diaz and Kostelecký
PLB700(2011)25

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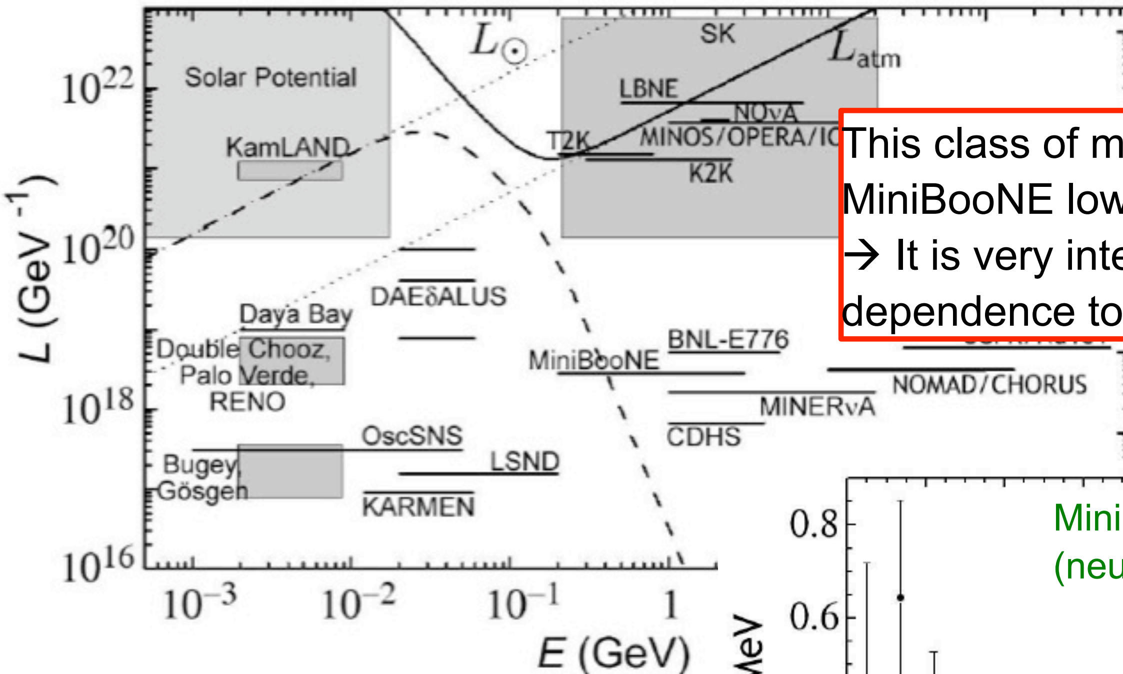
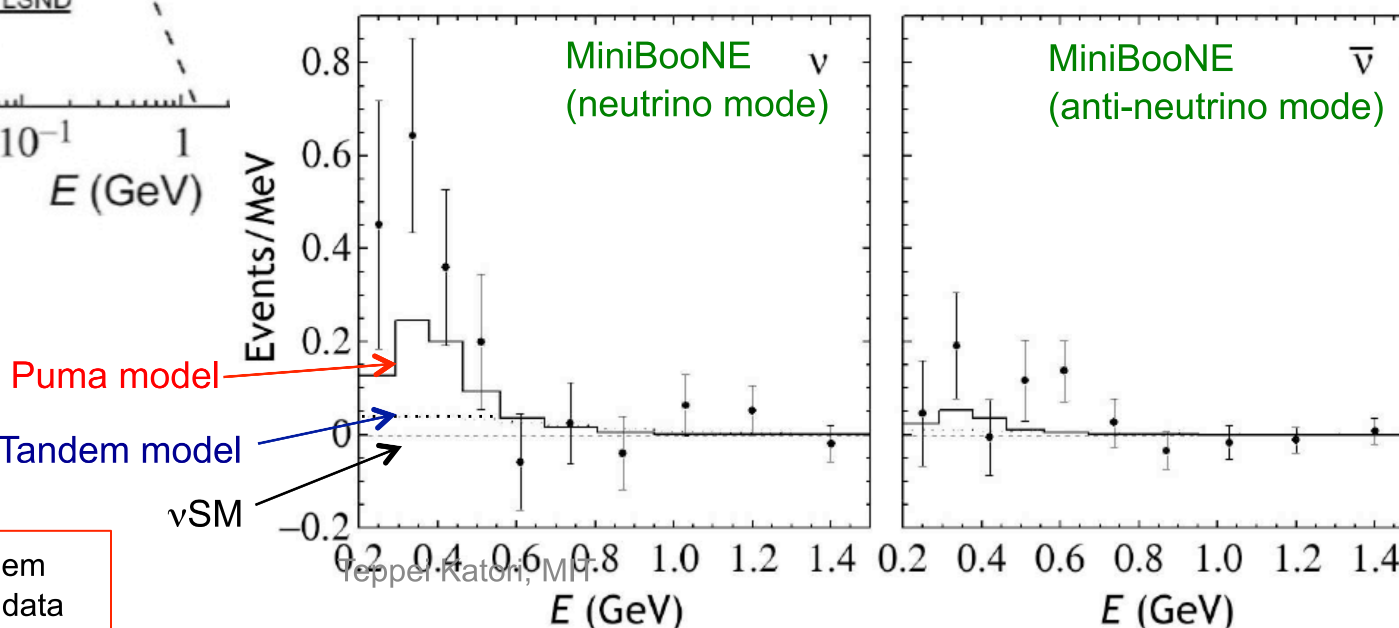


This class of models predict non-zero signal for MiniBooNE low energy or LSND high energy region.
→ It is very interesting to test sidereal time dependence to MiniBooNE excesses!



TK, Kostelecký, Tayloe
PRD(2006)105009 → Tandem model

Note: both Puma model and Tandem model conflict with recent reactor data

1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Lorentz violation with neutrino oscillation

4. MiniBooNE experiment

5. Test for Lorentz violation with MiniBooNE data

6. Test for Lorentz violation with Double Chooz data

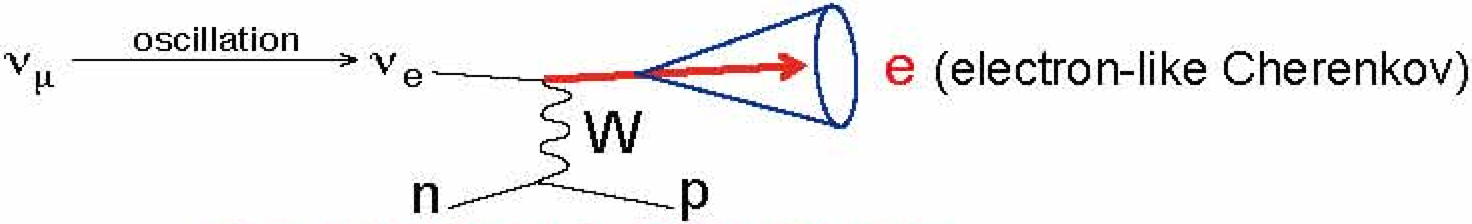
7. Future of neutrino physics

8. Conclusion

MiniBooNE collaboration,
PRD79(2009)072002

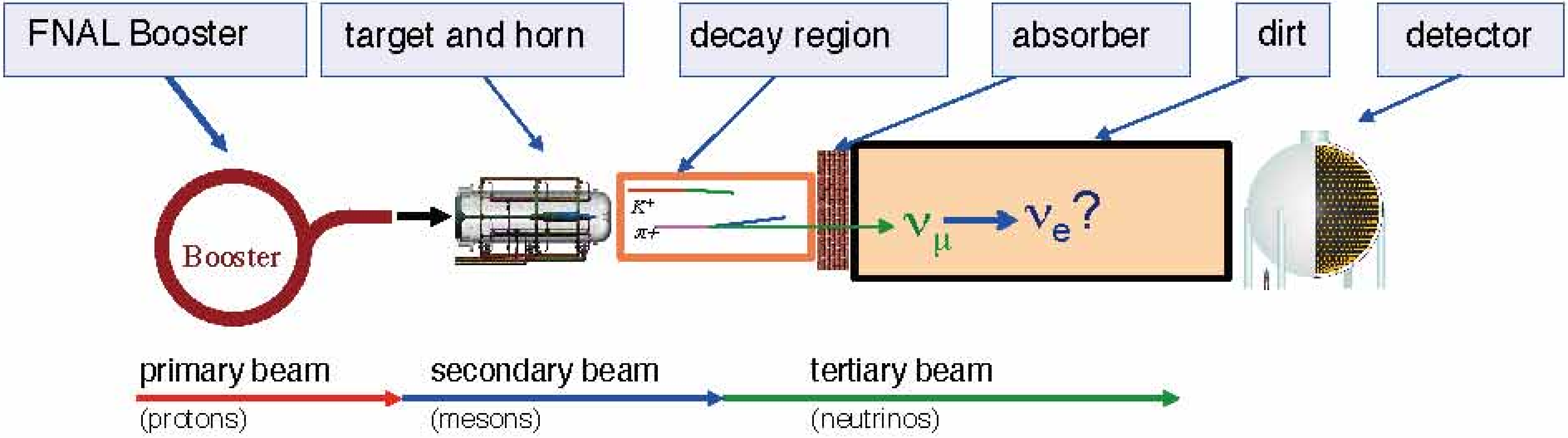
4. MiniBooNE experiment

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

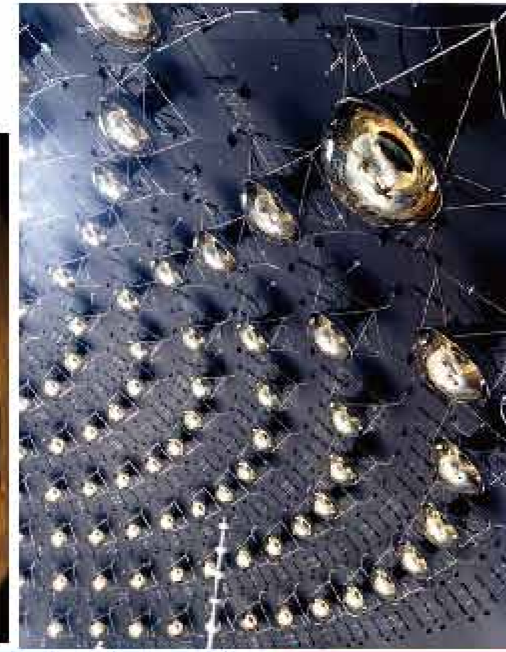
Booster Neutrino Beamline (BNB) creates ~800(600)MeV neutrino(anti-neutrino) by pion decay-in-flight from 8GeV Booster protons on Be-target in the magnetic focusing horn.

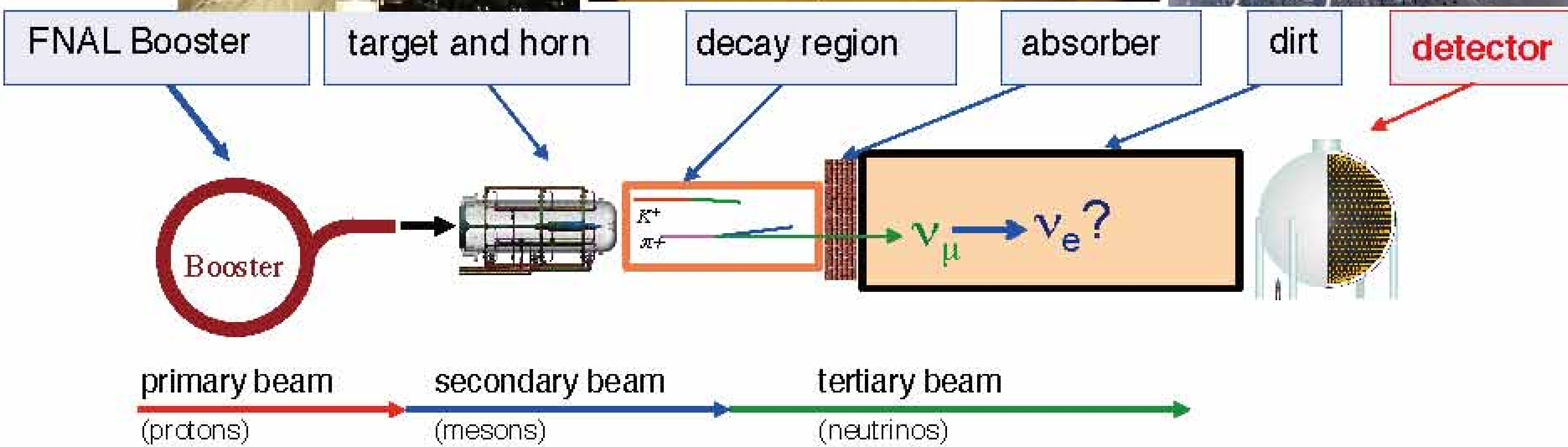


MiniBooNE collaboration, NIM.A599(2009)28

4. 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

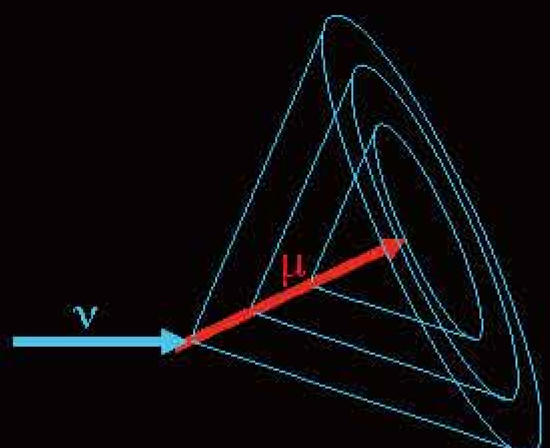


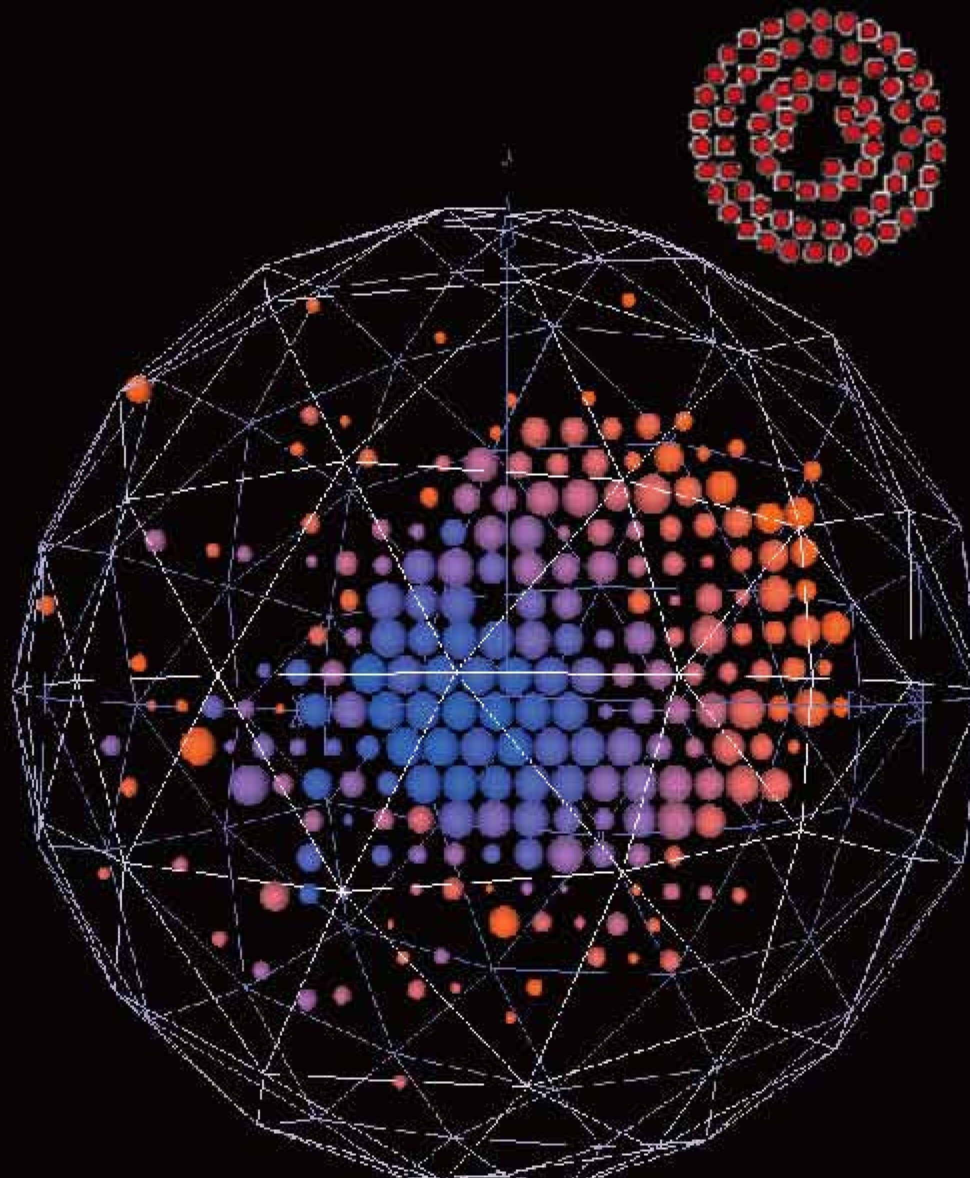


MiniBooNE collaboration, NIM.A599(2009)28

4. 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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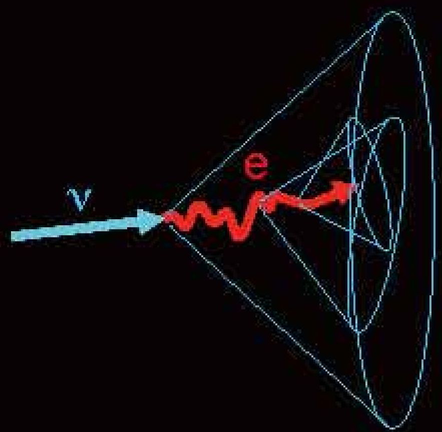
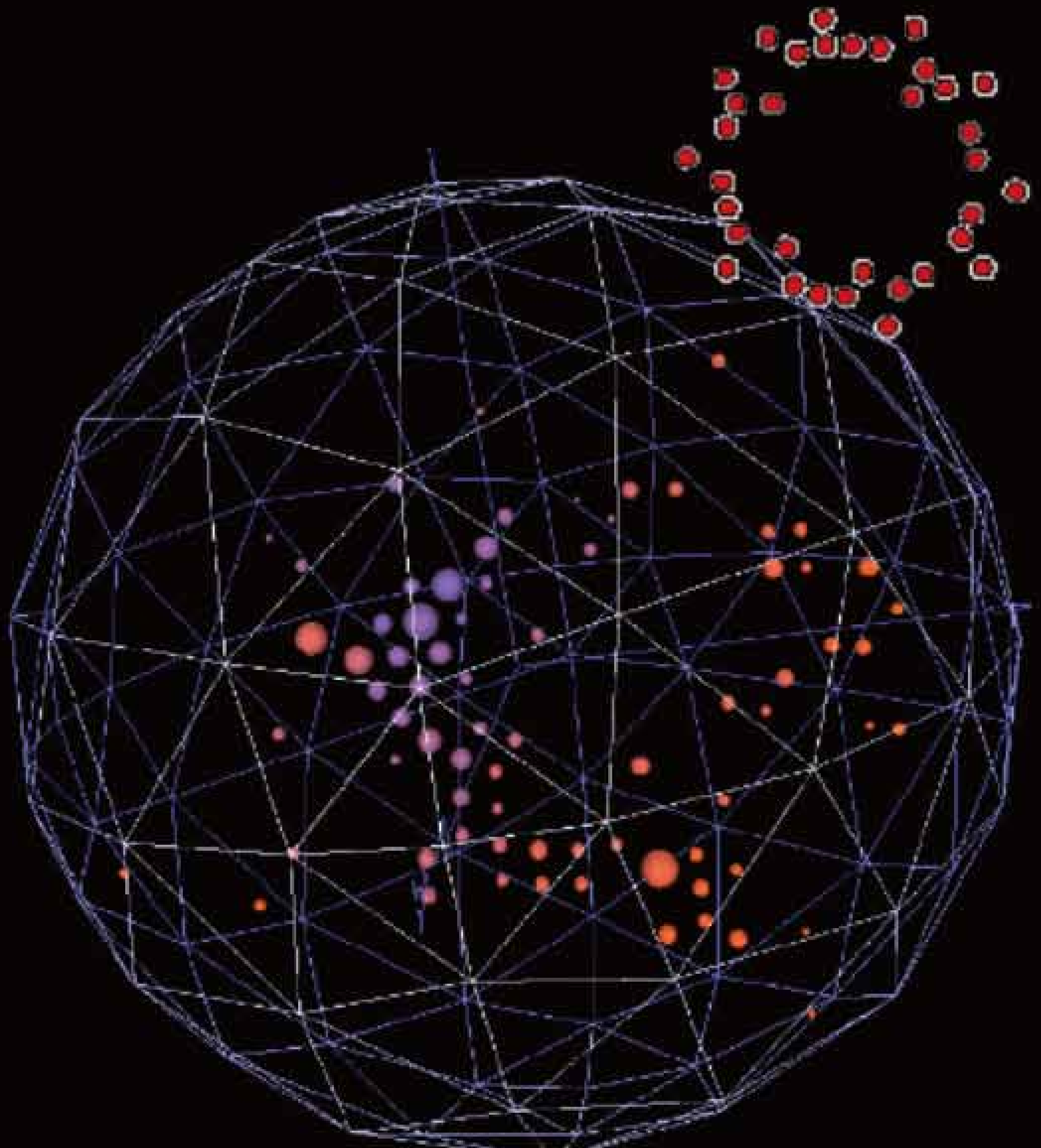


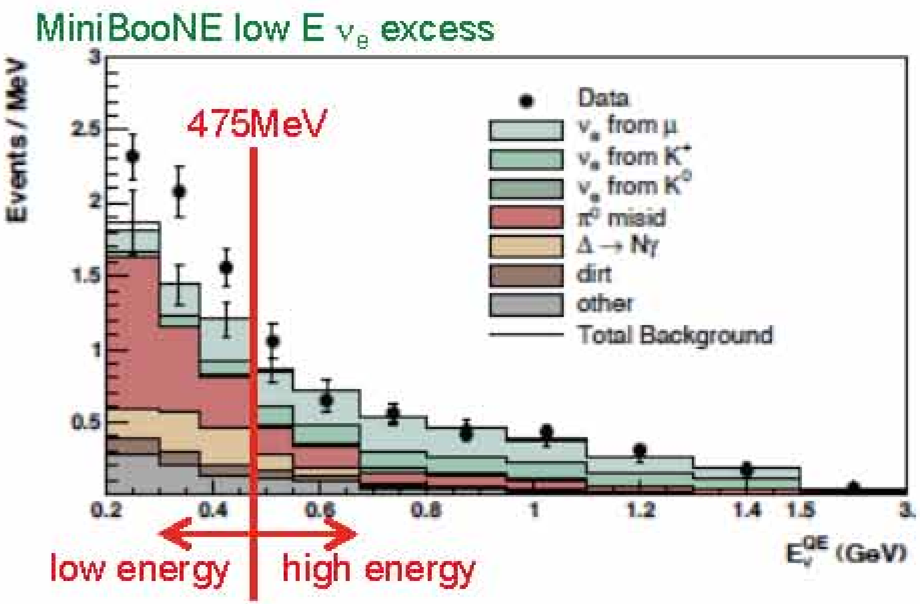


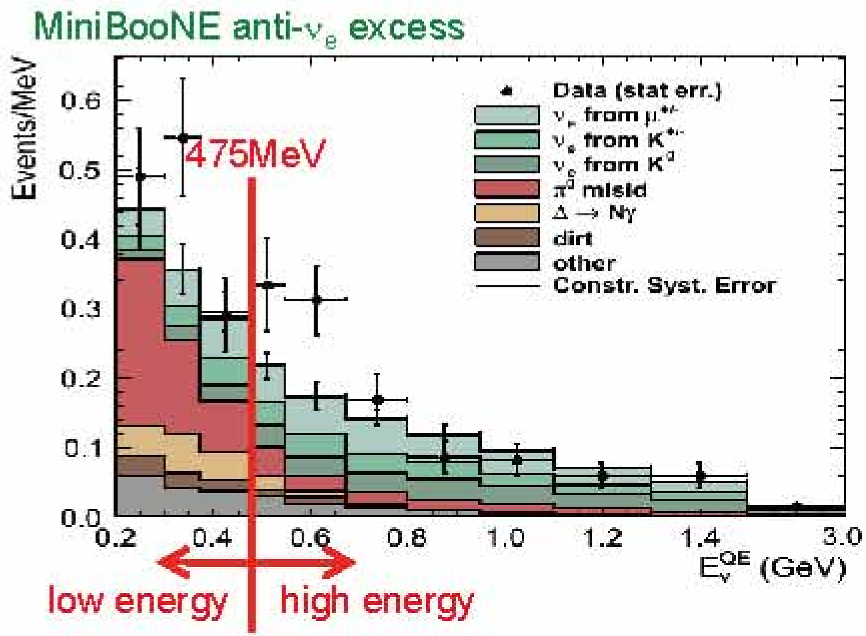
MiniBooNE collaboration,
PRL102(2009)101802,
PRL105(2010)181801

4. MiniBooNE oscillation analysis result

Neutrino mode low energy excess
MiniBooNE see the excess at low energy region.

Antineutrino mode excess
MiniBooNE see the excess at combined region.





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

1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

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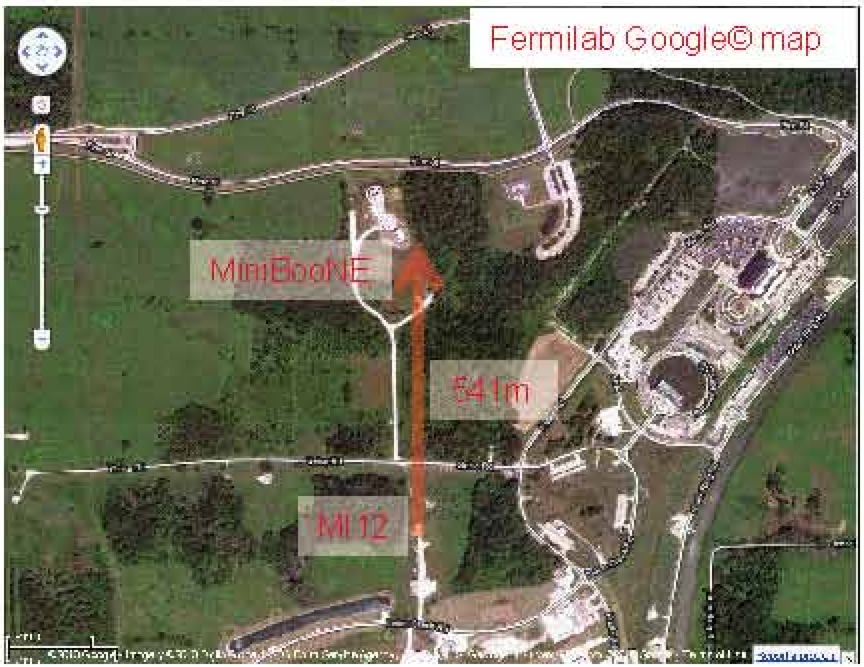
5. Lorentz violation with MiniBooNE

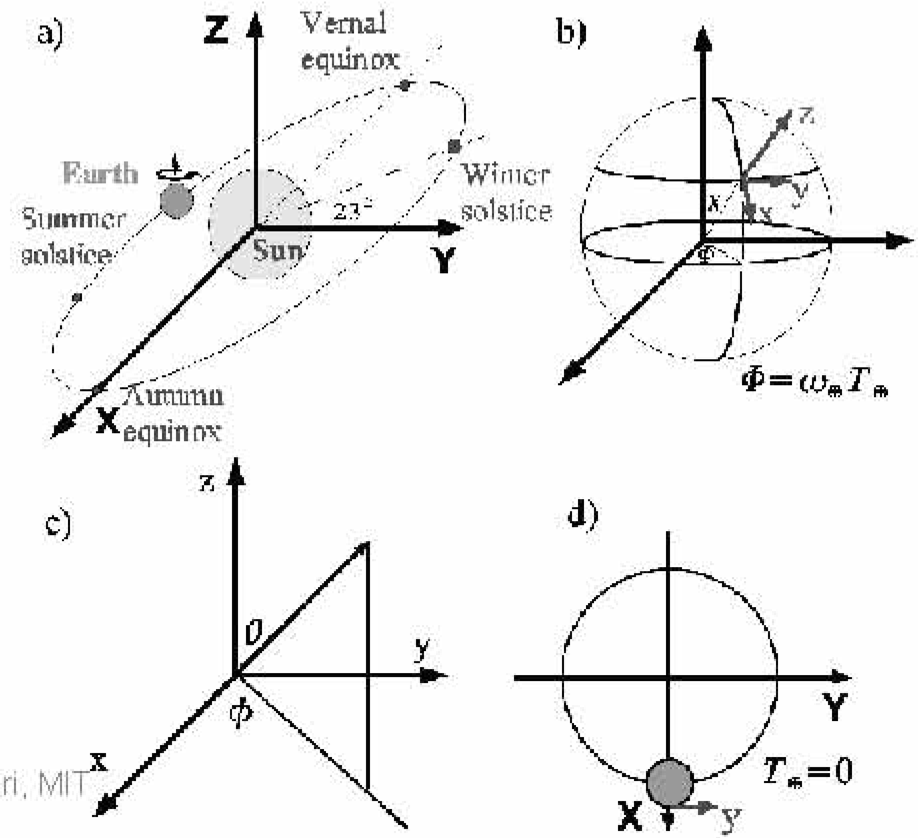
Test for Lorentz violation in MiniBooNE data;

(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

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- 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

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CPT odd: e^{ν}_{AB}, f^{ν}_{AB}, $g^{\lambda\mu\nu}_{AB}$, a^{μ}_{AB}, b^{μ}_{AB}

CPT even: $c^{\mu\nu}_{AB}$, $d^{\mu\nu}_{AB}$, $H^{\mu\nu}_{AB}$

Kostelecký and Mewes
PRD70(2004)076002

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(1) fix the coordinate system
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(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

Lorentz violating oscillation probability for MiniBooNE

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

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

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

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

sidereal time $T_\oplus$

Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

5. 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

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

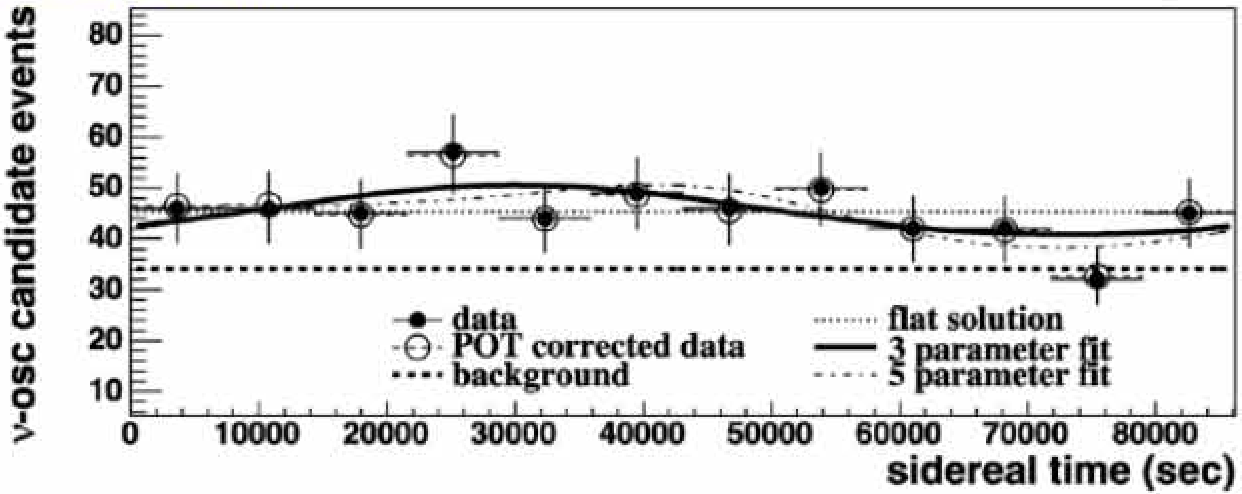
MiniBooNE collaboration,
PLB718(2013)1303

5. MiniBooNE Lorentz violation analysis results

Neutrino mode result, low energy region

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

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



MiniBooNE collaboration, PLB718(2013)1303

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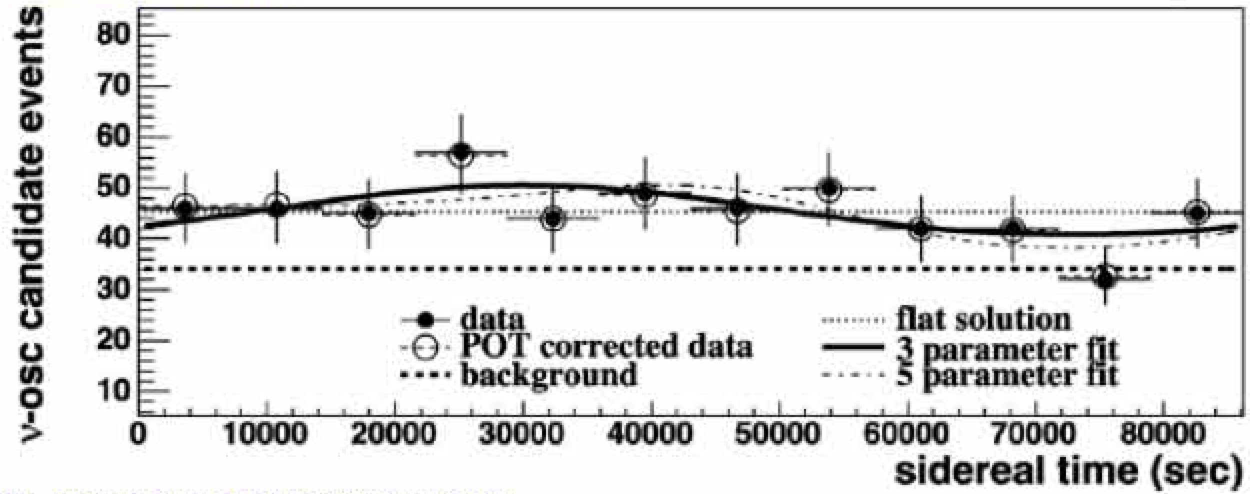
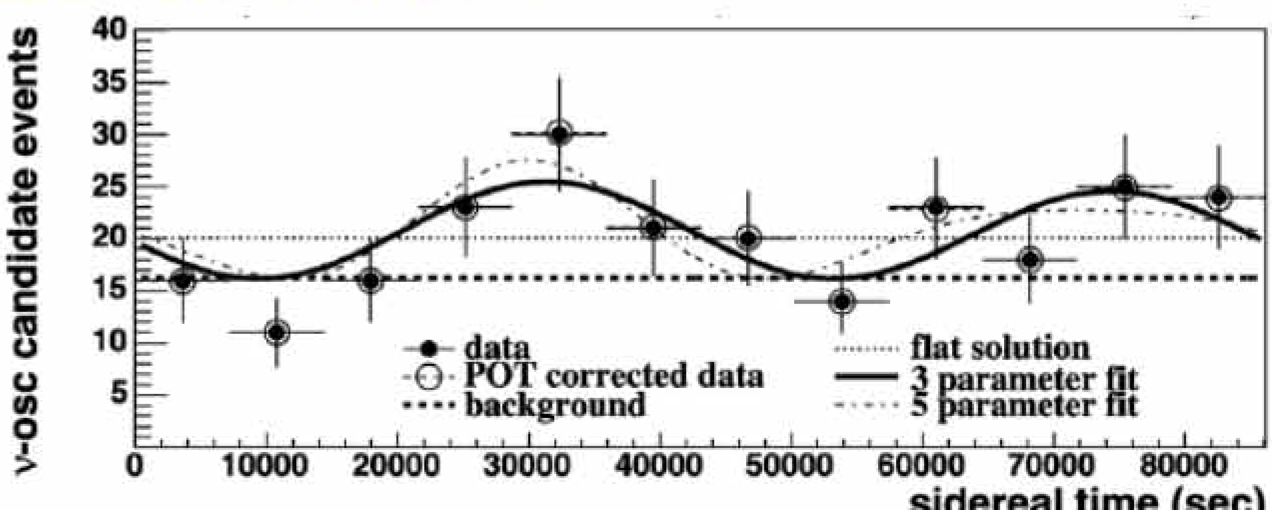


Anti-neutrino mode result, combined energy region

The anti-neutrino mode combined energy region excess prefer sidereal time dependent solution

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

...but not statistically significant level.



5. 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)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$3.1 \pm 0.6 \pm 0.9$	< 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	$\pm[0.66(a_L)^X_{e\mu}] - < E > [1.33(c_L)^{TX}_{e\mu} + 0.99(c_L)^{XZ}_{e\mu}]$

LSND collaboration,
PRD72(2005)076004

5. Summary of results

LSND experiment

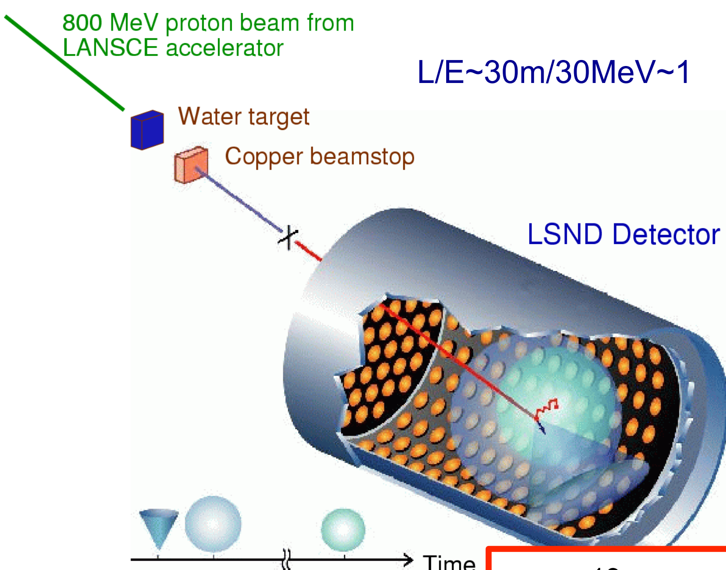
LSND is a short-baseline neutrino oscillation experiment at Los Alamos.

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

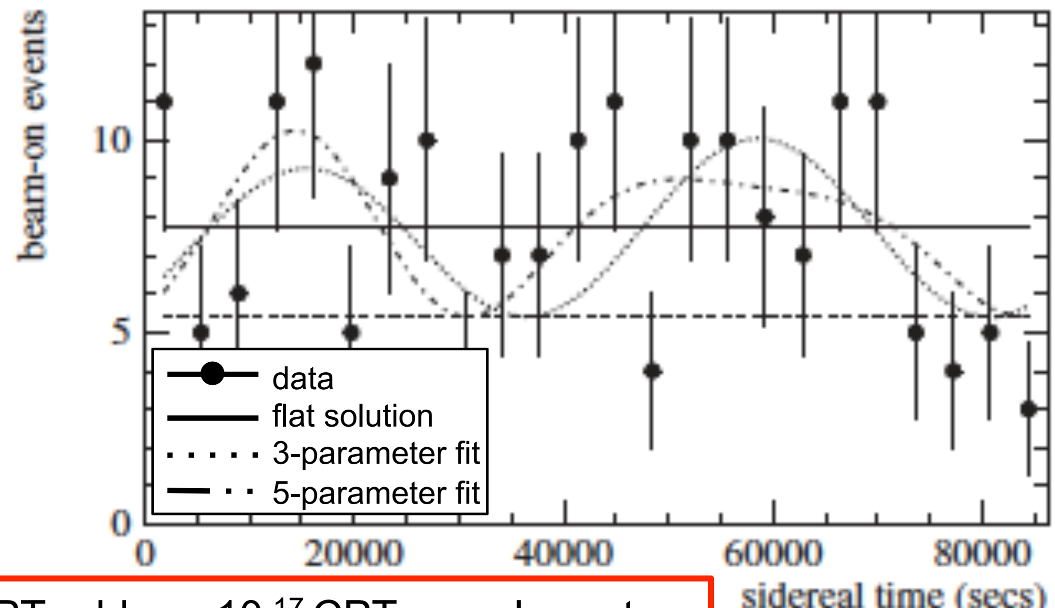
$$n + p \rightarrow d + \gamma$$

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

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



LSND oscillation candidate sidereal time distribution



~10^{-19} GeV CPT-odd or ~10^{-17} CPT-even Lorentz violation could be the solution of LSND excess

TK,
MPLA27(2012)1230024

5. Summary of results

Since we find no evidence of Lorentz violation from MiniBooNE analysis, we set limits on the SME coefficients.

These limits exclude SME values to explain LSND data, therefore there is no simple Lorentz violation motivated scenario to accommodate LSND and MiniBooNE results simultaneously

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

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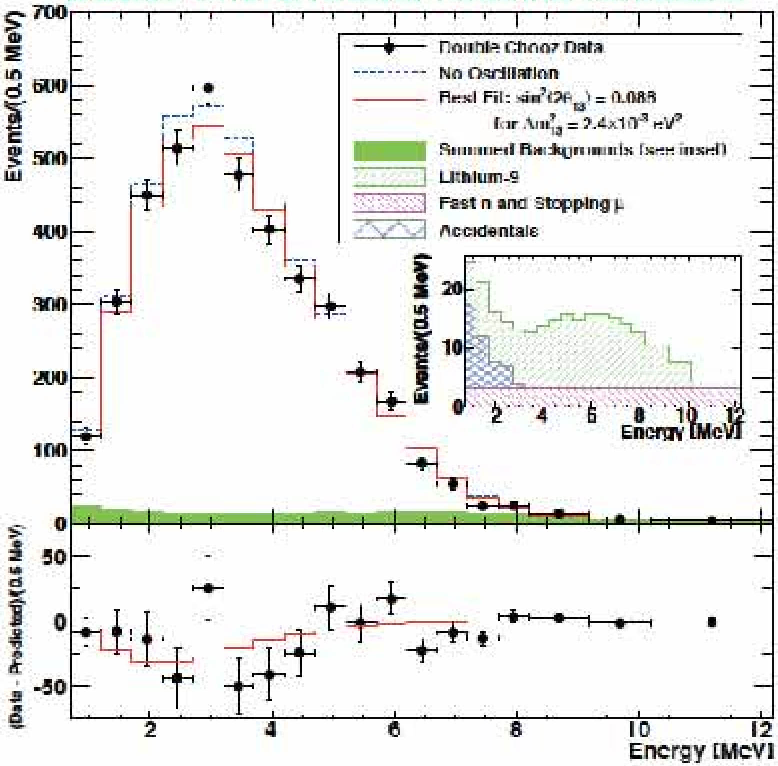
Double Chooz collaboration
PRL108(2012)131801

6. Double Chooz experiment

Reactor electron antineutrino disappearance experiment
- The first result shows small anti-ν_e disappearance!

Double Chooz reactor neutrino candidate



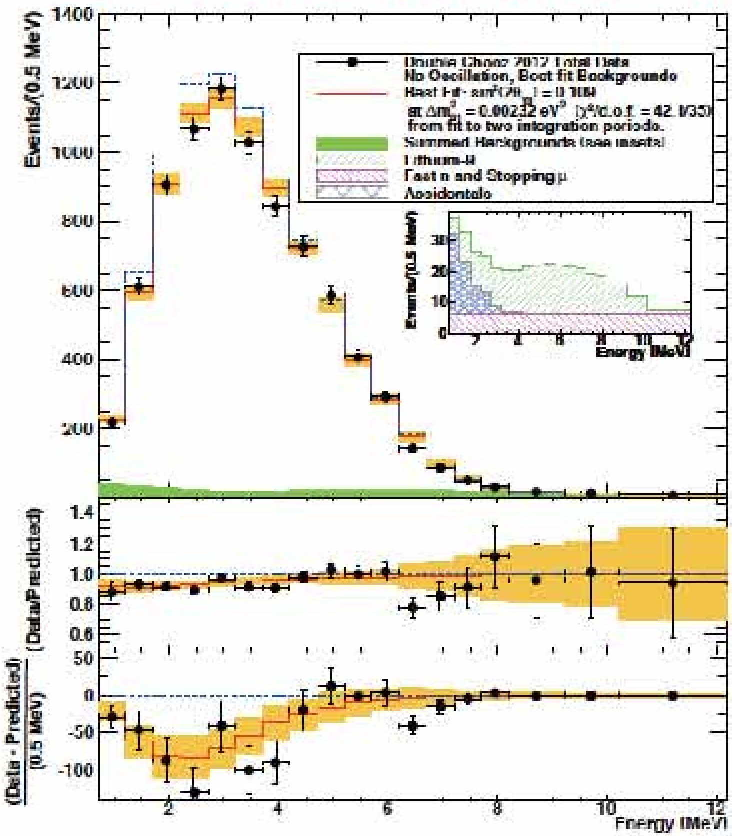
6. Double Chooz experiment

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



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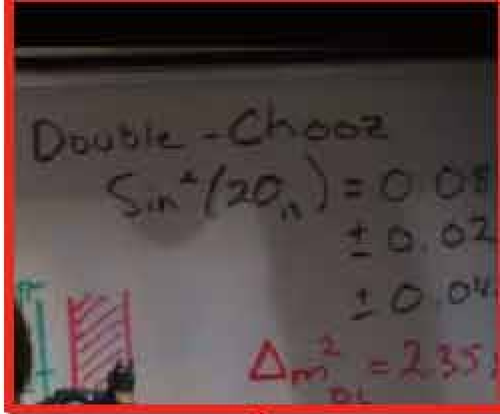

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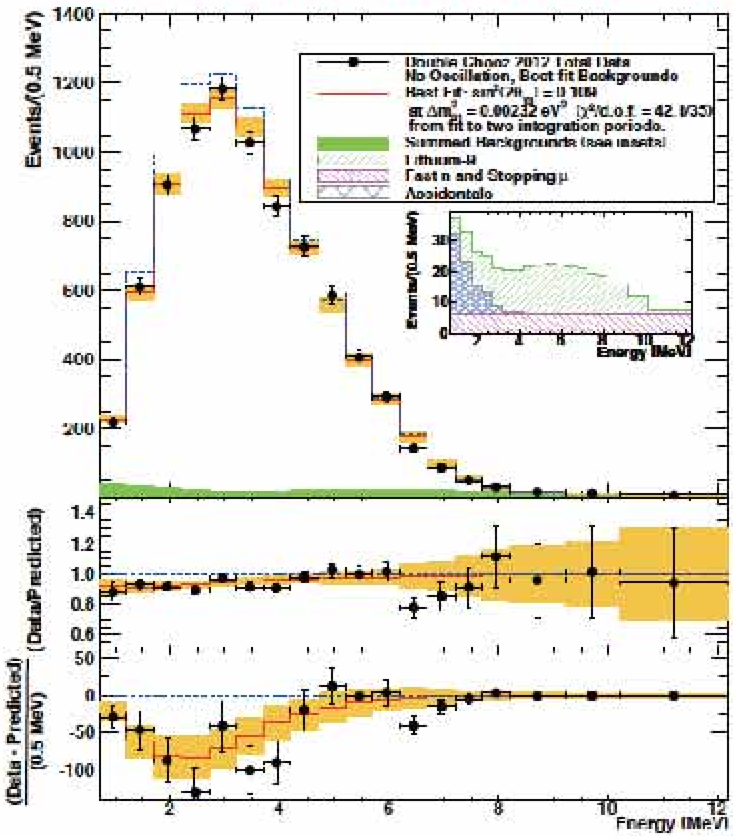

Teppei Katori, MIT

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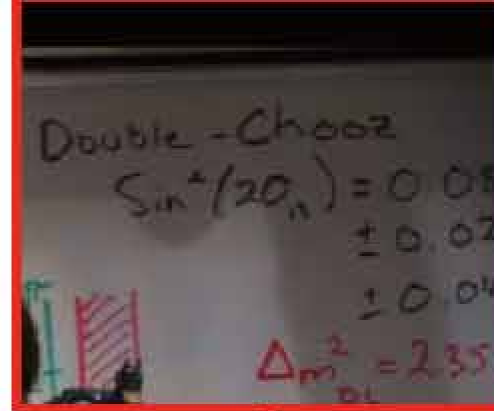
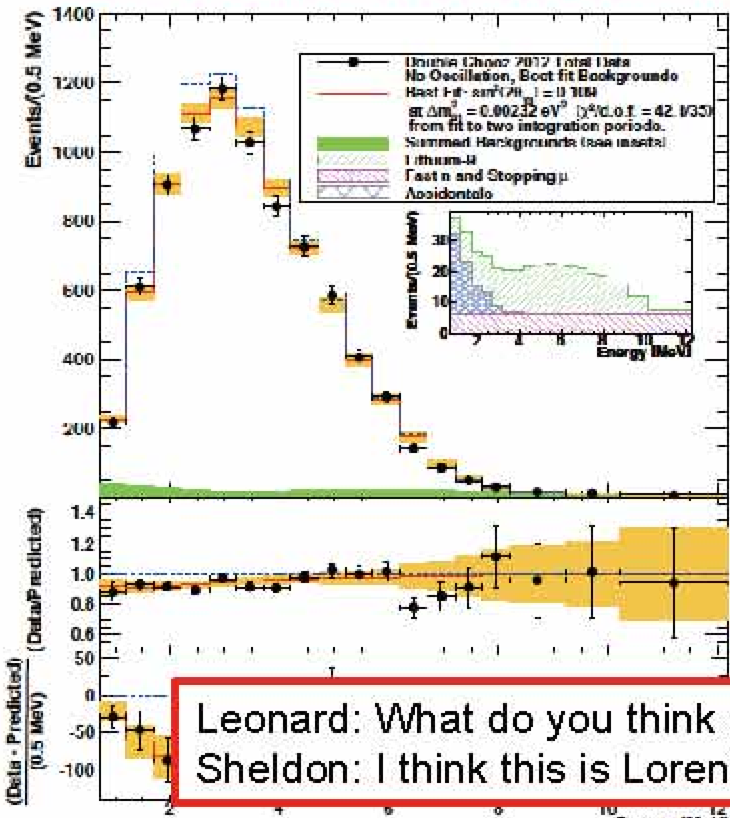
Reactor electron antineutrino disappearance experiment

- 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



Double Chooz reactor neutrino candidate



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

6. Double Chooz experiment

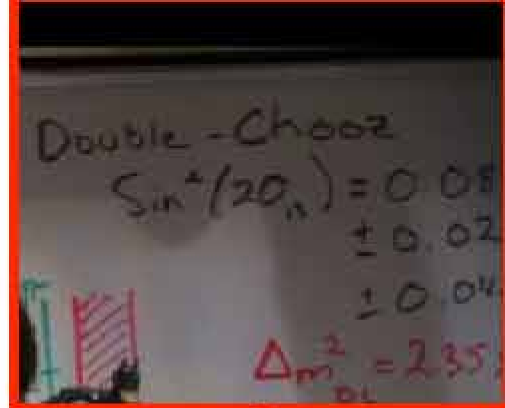
So far, we have set limits on

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

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




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

Double Chooz collaboration,
PRD86(2012)112009

6. Double Chooz experiment

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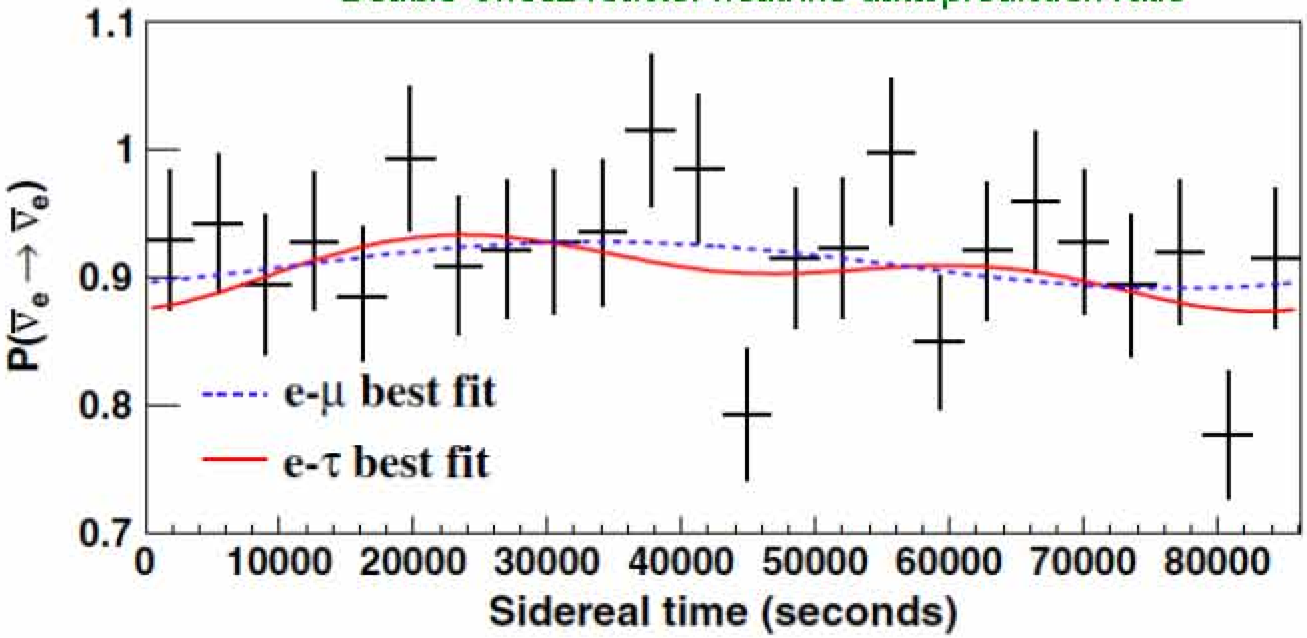
Small disappearance signal prefers sidereal time independent solution (flat)

We set limits in the e-τ sector for the first time; $\nu_e \leftrightarrow \nu_\tau$ ($<10^{-19}$ GeV)

Double Chooz reactor neutrino data/prediction ratio



Kostelecký and Russel
Rev.Mod.Phys.83(2011)11
ArXiv:0801.0287v6

6. Double Chooz experiment

By this work, Lorentz violation is tested with all neutrino channels

Chance to see the Lorentz violation in terrestrial experiments will be very small

MiniBooNE / MINOS ND → $e\mu$; Double Chooz → $e\tau$; IceCube / MINOS FD → $\mu\tau$

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Y$	10^{-21} GeV	10^{-19} GeV	10^{-23} GeV
	$\mathrm{Re}\,(a_L)^Z$	10^{-19} GeV	10^{-19} GeV	–
$d=4$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(c_L)^{XY}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XZ}$	10^{-21}	10^{-17}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YZ}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{XX}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{YY}$	10^{-21}	10^{-16}	10^{-23}
	$\mathrm{Re}\,(c_L)^{ZZ}$	10^{-19}	10^{-16}	–
	$\mathrm{Re}\,(c_L)^{TT}$	10^{-19}	10^{-17}	–
	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TY}$	10^{-22}	10^{-17}	10^{-27}
	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	10^{-16}	–

Kostelecký and Russel
Rev.Mod.Phys.83(2011)11
ArXiv:0801.0287v6

6. Double Chooz experiment

By this work, Lorentz violation is tested with all neutrino channels

Chance to see the Lorentz violation in terrestrial experiments will be very small

Possible improvements from existing data:
- T2K
$\nu_e \leftrightarrow \nu_\mu$ parameters, order 2
- KamLAND
$\nu_e \leftrightarrow \nu_\tau$ parameters, order 2

Super-K/Hyper-K
- Galactic neutrinos (~1Mpc)
order least order 10 improvement

$e\mu$: T2K, MiniBooNE, MINOS ND
$e\tau$: KamLAND, Double Chooz
$\mu\tau$: IceCube, MINOS FD

$d=3$	Coefficient	$e\mu$	$e\tau$	$\mu\tau$
	$\mathrm{Re}\,(a_L)^T$	10^{-20} GeV	10^{-19} GeV	–
	$\mathrm{Re}\,(a_L)^X$	10^{-20} GeV	10^{-19} GeV	10^{-23} GeV
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	$\mathrm{Re}\,(c_L)^{TX}$	10^{-22}	10^{-17}	10^{-27}
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	$\mathrm{Re}\,(c_L)^{TZ}$	10^{-20}	10^{-16}	–

1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Lorentz violation with neutrino oscillation

4. MiniBooNE experiment

5. Test for Lorentz violation with MiniBooNE data

6. Test for Lorentz violation with Double Chooz data

7. Future of neutrino physics

8. Conclusion

Futurama (Comedy Central)

7. Superluminal neutrinos

OPERA collaboration,
JHEP1210(2012)093

7. Superluminal neutrinos

OPERA

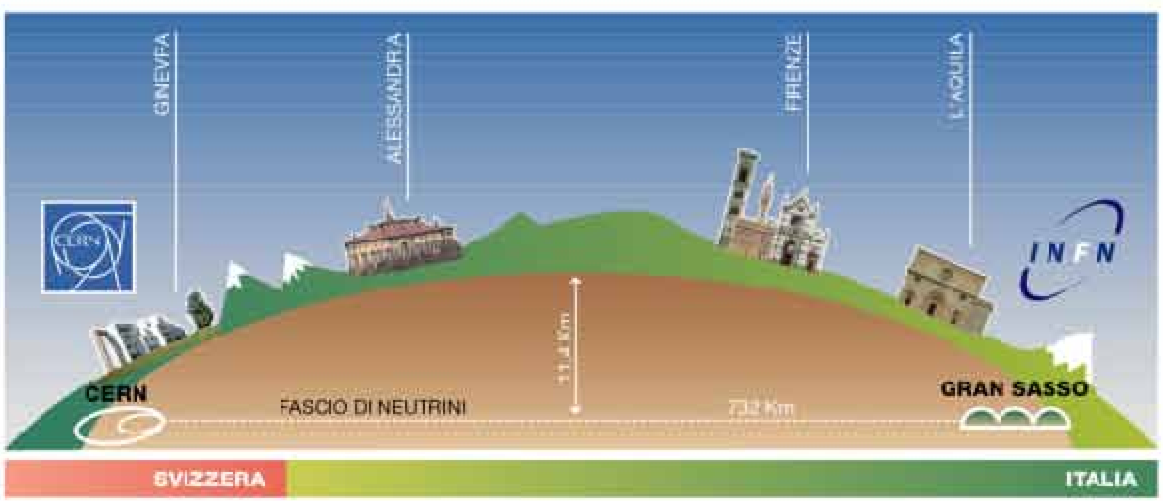
$v(\text{neutrino}) = c + (2.37 \pm 0.32) \times 10^{-5}\, c$

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

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
- etc

It is very difficult to interpret superluminal neutrinos at OPERA by Lorentz violation...



OPERA collaboration, JHEP1210(2012)093

7. Superluminal neutrinos

The New York Times — **Science**

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPI

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

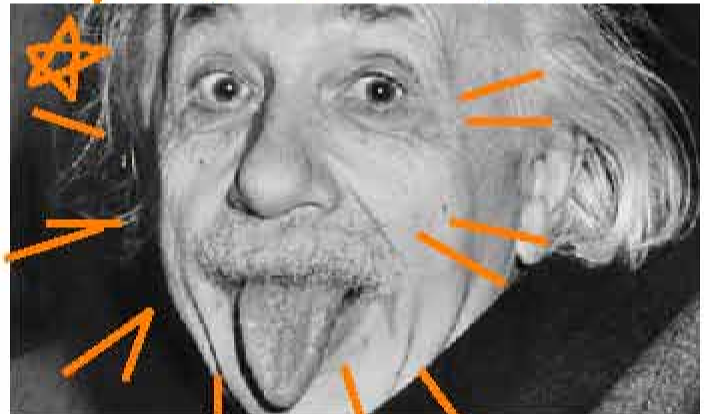
News | US | World | Sports | Comment | Culture | Business | Enviro

News › Science › Cern

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

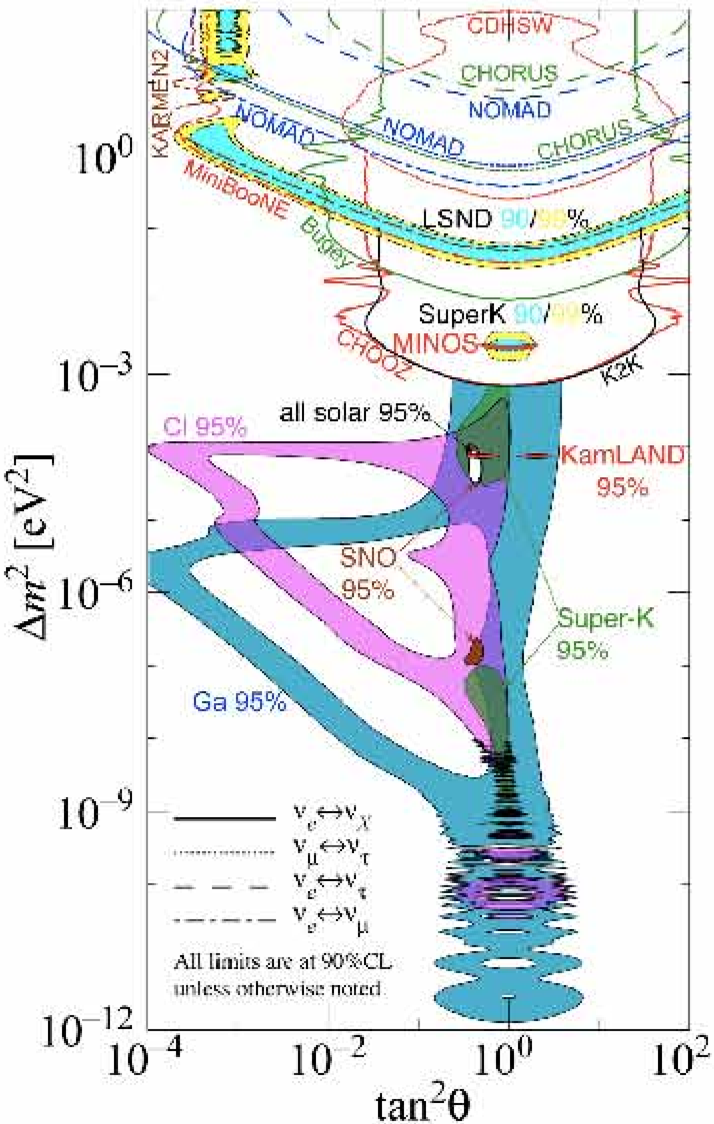
Alok Jha, science correspondent
guardian.co.uk, Thursday 23 February 2012 17.06 EST
Article history



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

It is hard to topple the giant...

7. Future of neutrino physics



http://hitoshi.berkeley.edu/neutrino

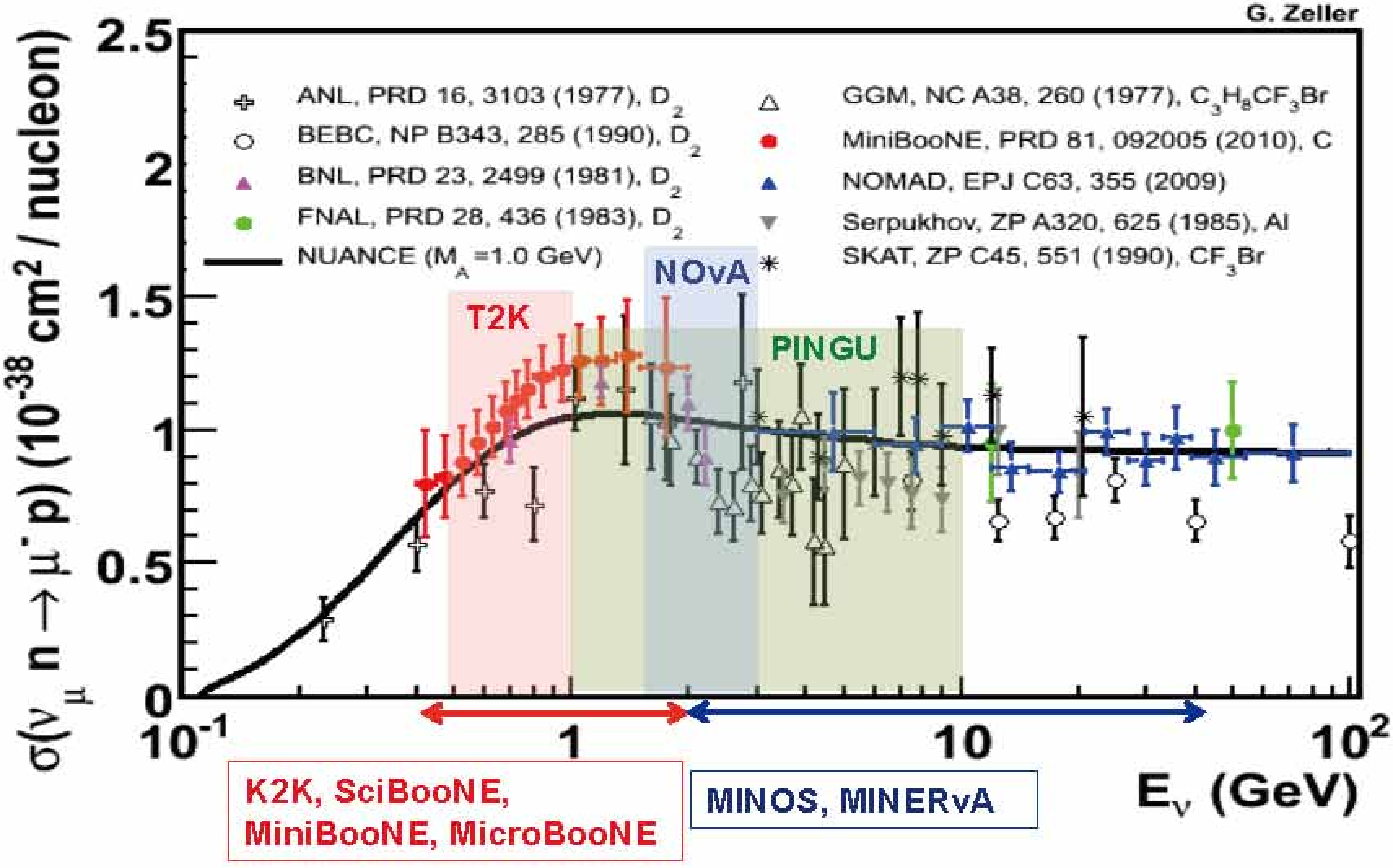
Neutrino Standard Model (νSM)

3 active massive neutrino model is quite successful, and we came into the "precision measurement era"

- The next generation oscillation experiments, including T2K, allow very small cross section errors.
- 1 GeV neutrino cross section is tricky because of the interplay of CC quasi-elastic (CCQE), meson exchange current (MEC), CC resonance pion production (CC1π), and final state interaction (FSI).

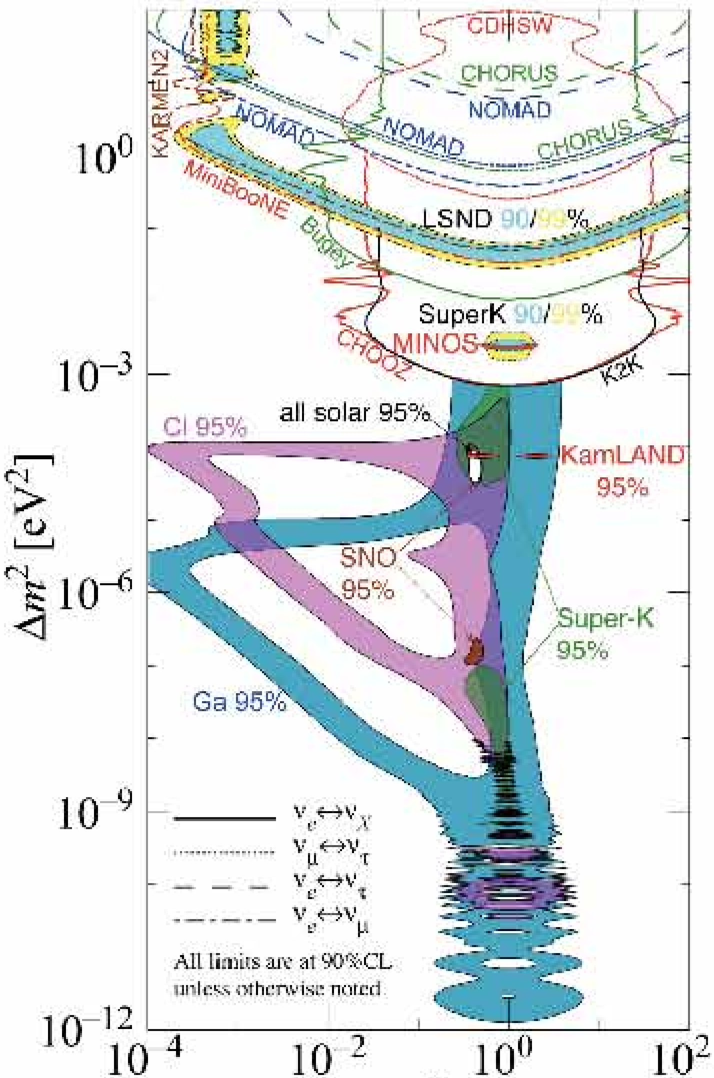
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

7. CCQE world data



Formaggio and Zeller,
Rev.Mod.Phys.84(2012)1307

7. Neutrino cross sections

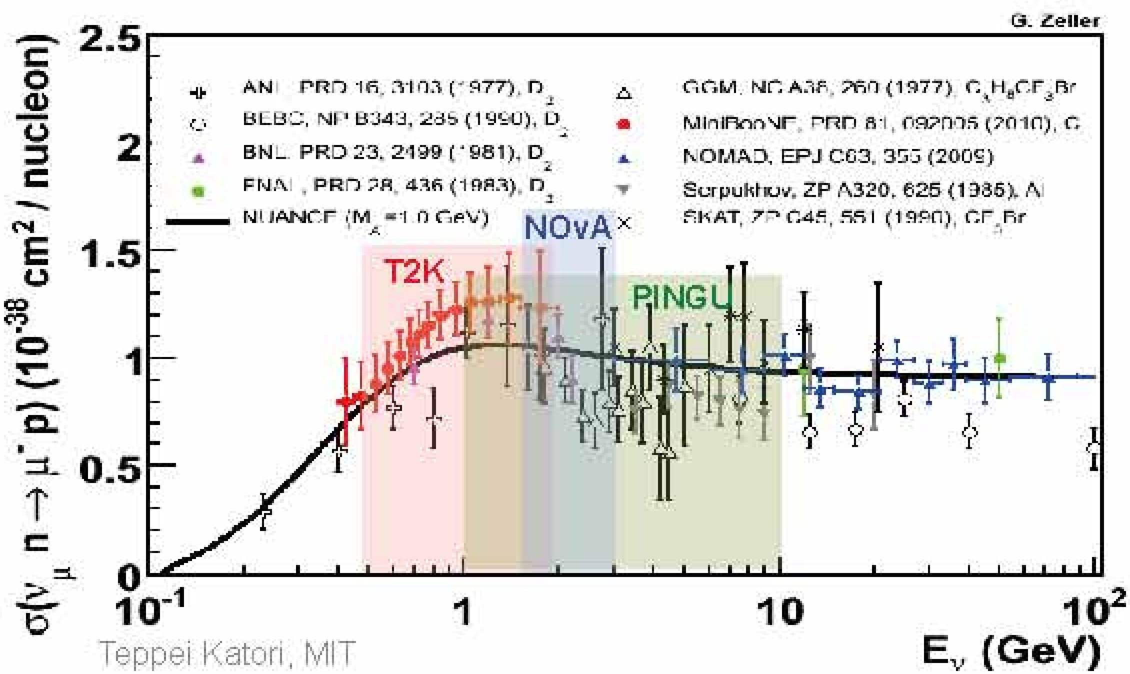


http://hitoshi.berkeley.edu/neutrino

Neutrino cross section measurement

There is a world-wide effort to understand neutrino cross section around 1-10 GeV

- Our understanding is not ready for future high precision measurement
- There are tons of cross section work for near future
  - hadronic simulation of MEC, CC1π, transition region
  - understanding of FSI



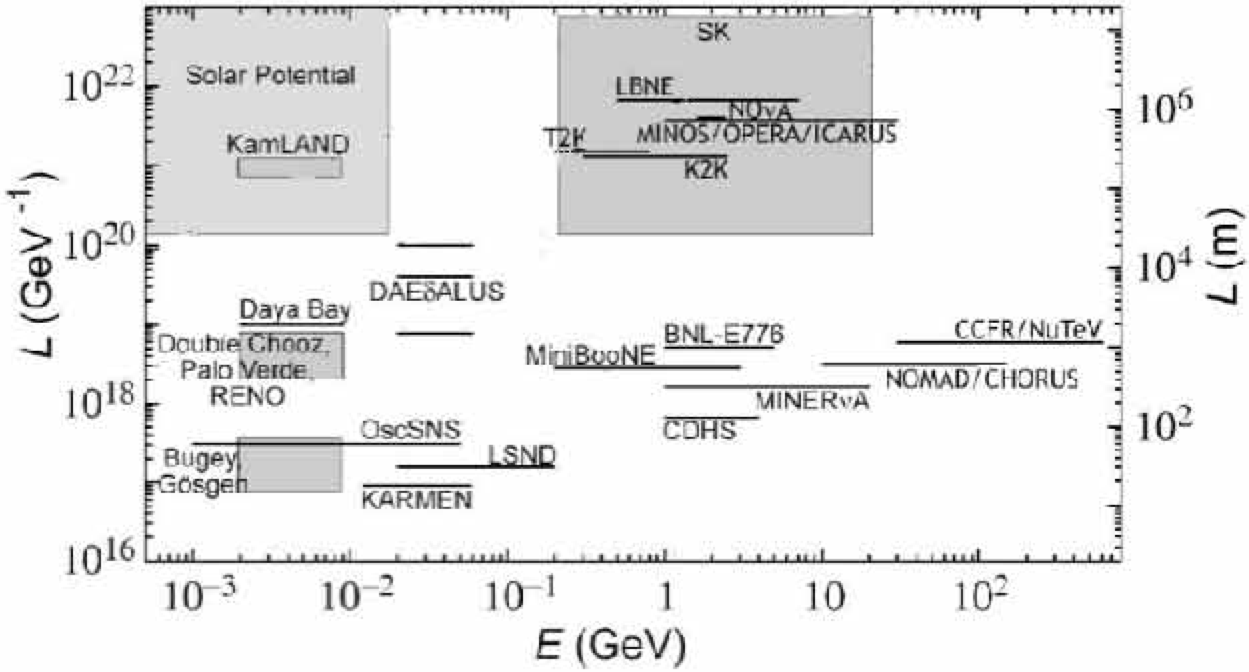
7. Future of neutrino physics

Beyond neutrino Standard Model (BνSM)

L-E plot shows the model independent phase space of neutrino oscillation physics.

- The L-E phase space is sparse, unlike Δm^2-θ space.
- Extra galactic neutrinos and TeV neutrinos have the highest potential to discover the new physics, including Lorentz violation.

Wide range of available baseline and energy by Super-K/Hyper-K is naturally sensitive to vast area of L-E plot (=new physics).



7. Future of neutrino physics

Beyond BνSM

Super-K/Hyper-K itself is a multi purpose detector and sensitive to unexpected physics

Pospelov et al., PRL110(2013)021803

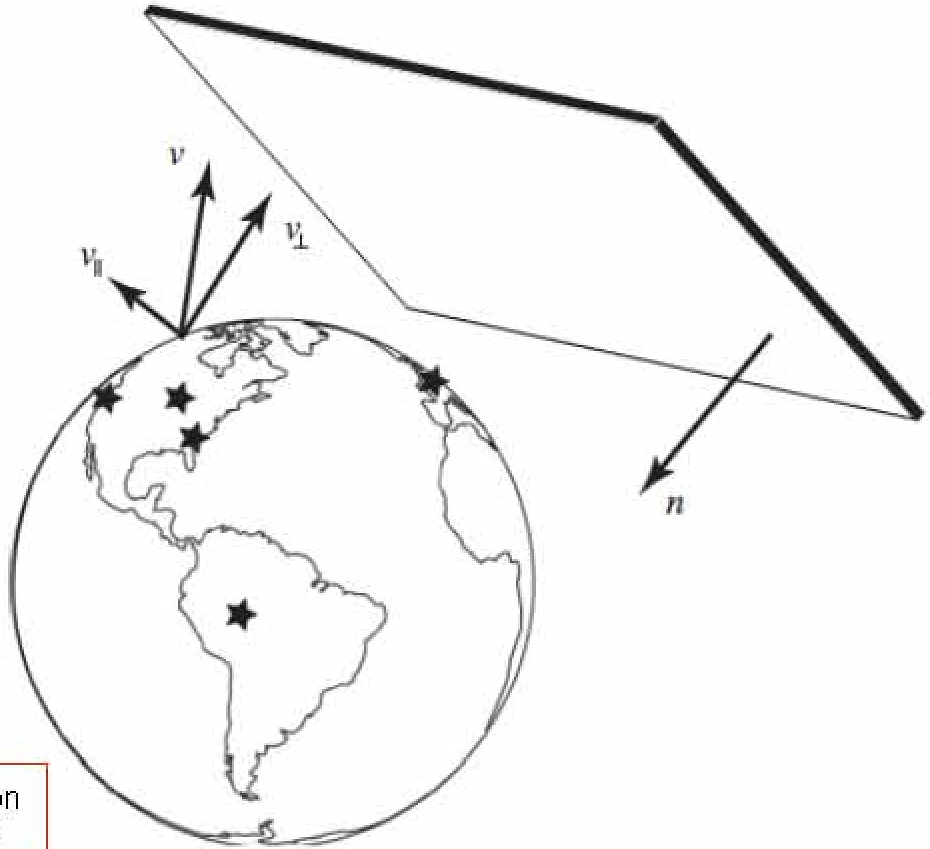
7. Future of neutrino physics

Beyond BνSM

Super-K/Hyper-K itself is a multi purpose detector and sensitive to unexpected physics

Domain Wall crossing

Domain wall crossing the detector may cause temperature fluctuation on the photo-cathode of PMTs which might be detectable as a correlated noise like events



Note: estimated temperature fluctuation is 10^{-11} K or 10^{-11} T and not detectable

Gninenko,
ArXiv:0802.1315

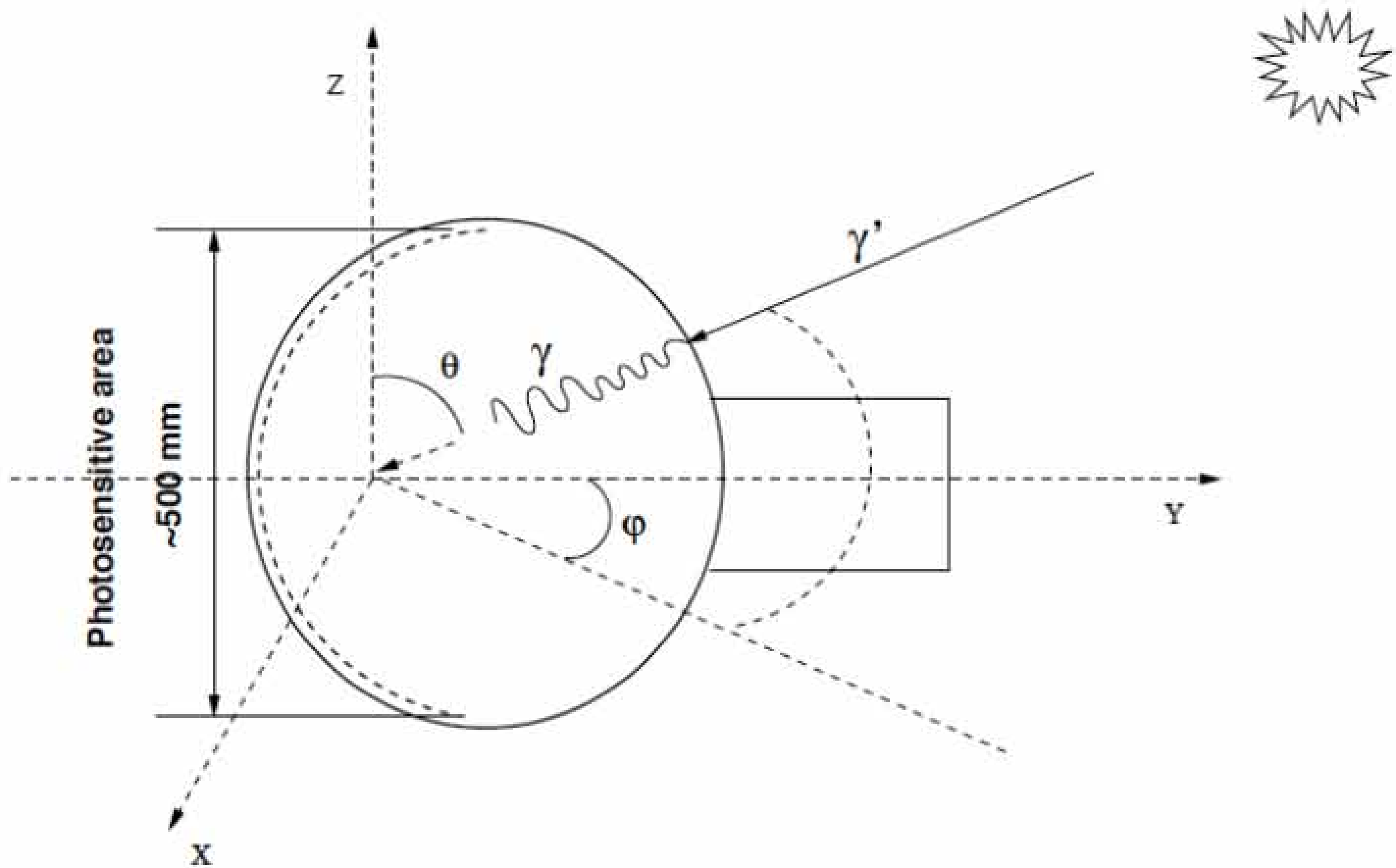
7. Future of neutrino physics

Beyond BνSM

Super-K/Hyper-K itself is a multi purpose detector and sensitive to unexpected physics

Hidden sector photon

Hidden sector photon to real photon conversion may contribute additional noise of PMTs



7. Future of neutrino physics

Beyond BνSM

Super-K/Hyper-K itself is a multi purpose detector and sensitive to unexpected physics

Clever analysis ideas provide potential discovery of new physics!
(Super-K is not a neutrino detector, but large array of PMTs in a large water tank)

7. Future of neutrino physics

Beyond BνSM
Super-K/Hyper-K itself is a multi purpose detector and sensitive to unexpected physics

Clever analysis ideas provide potential discovery of new physics!
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Kamiokande
Kamioka Nucleon Decay Experiment

7. Future of neutrino physics

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Kamiokande

Kamioka Nucleon Decay Experiment

Super-Kamiokande

Super-Kamioka Neutrino Detection Experiment

7. Future of neutrino physics

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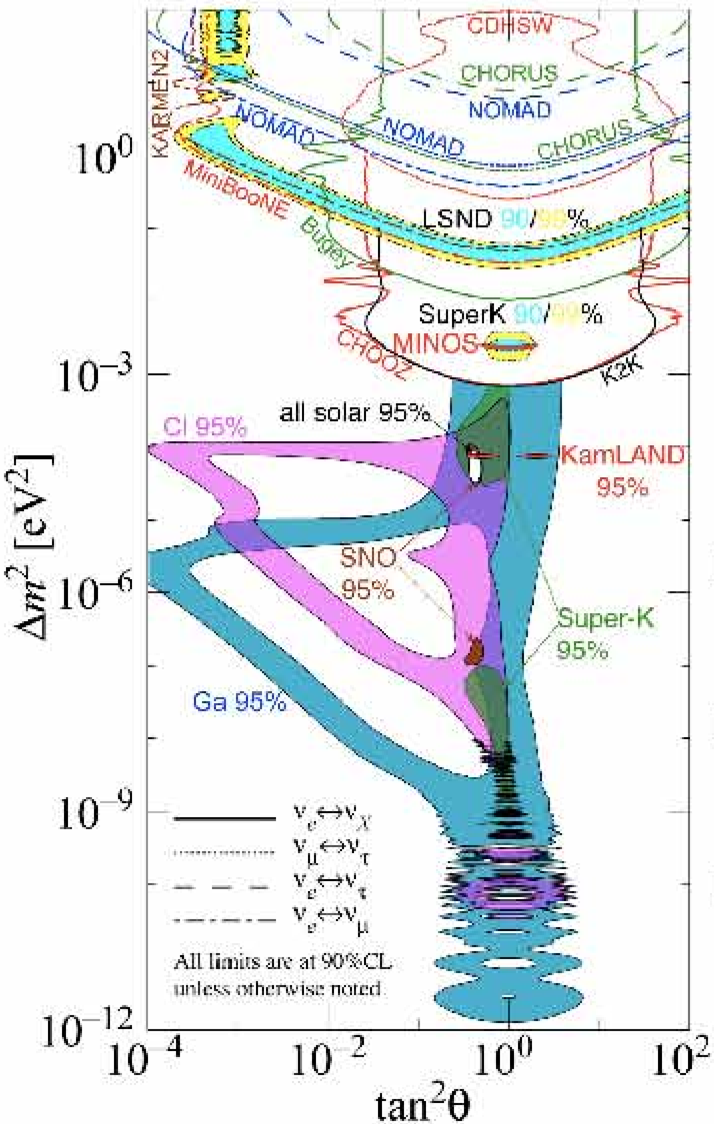
Kamiokande
Kamioka Nucleon Decay Experiment

Super-Kamiokande
Super-Kamioka Neutrino Detection Experiment

Hyper-Kamiokande
Hyper-Kamioka Nobody can preDict what will happen in this Experiment
(=we need to invent more physics)

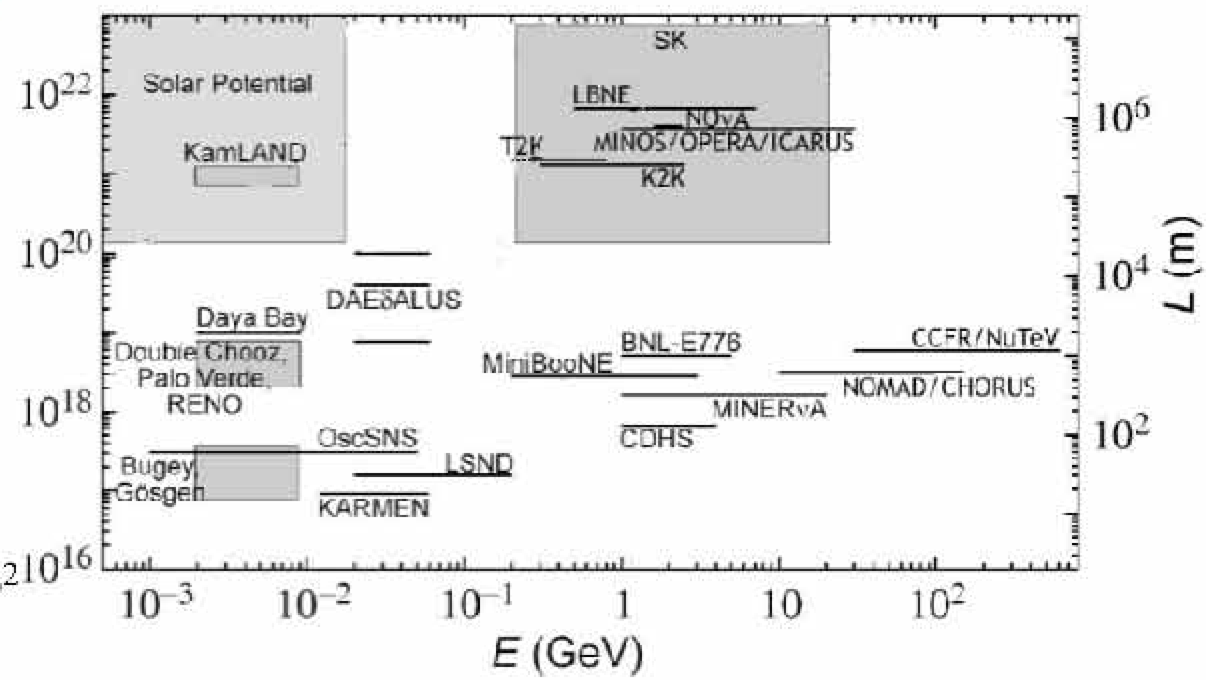
7. Future of neutrino physics



http://hitoshi.berkeley.edu/neutrino

Super-K/Hyper-K+JPARC neutrino programs

They have a good position to contribute both νSM and BνSM and BBνSM physics
- neutrino cross sections
- exotics



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.

Double Chooz reactor neutrino disappearance signal prefers time independent solution. By this work, Lorentz violation is tested with all oscillation channels.

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!

Backup

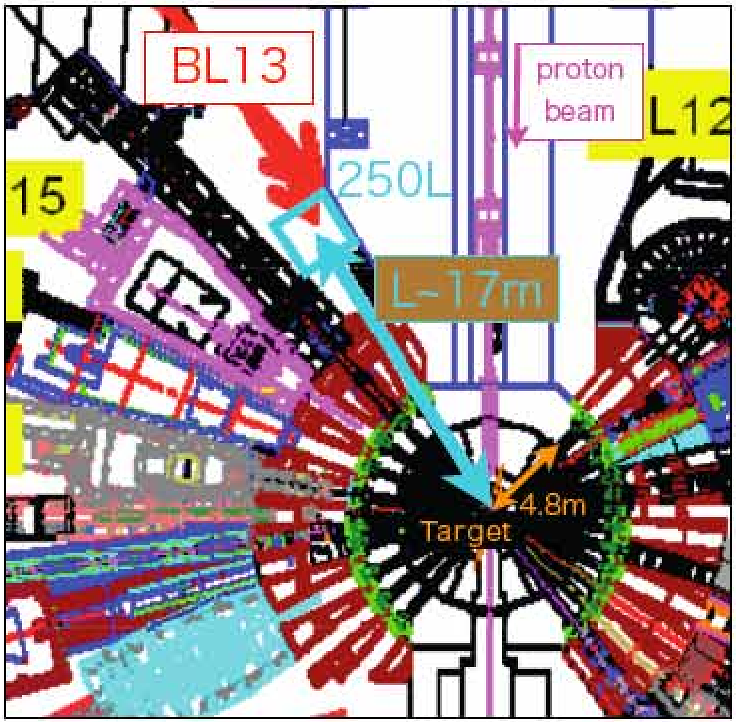
7. Future of neutrino physics

J-PARC MLF kaon decay-at-rest neutrino measurement
- MLF 3GeV neutron source
- 250L liquid argon TPC detector
- muon neutrinos from KDAR
- ~200 events/yr after cut

These mono-energetic neutrinos are useful for number of new studies
- test neutrino energy reconstruction
- full kinematics reconstruction (~e-scattering)
- etc

LoI is being prepared

Candidate locations of the detector



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").

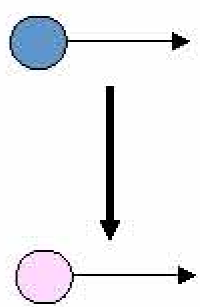
However, we are not on CMB frame (e.g., dipole term of WMAP is nonzero), so we expect anisotropy by lab experiments even CMB frame is the preferred frame.

2. What is CPT violation?

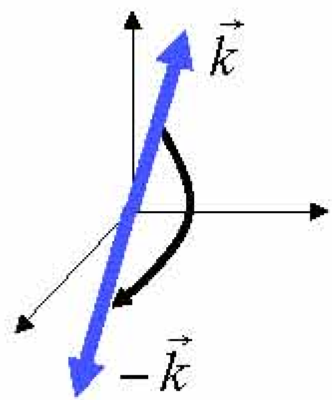
CPT symmetry is the invariance under the CPT transformation

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

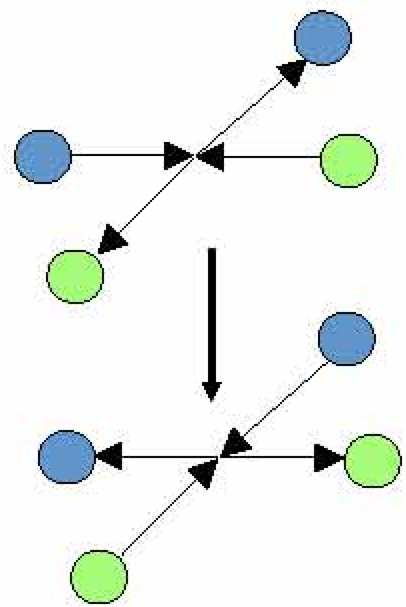
C: charge conjugation



P: parity transformation



T: time reversal



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

2. What is CPT violation?

CPT symmetry is the invariance under the CPT transformation

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

CPT 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.

↓

number of Lorentz indices
→ always even number

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

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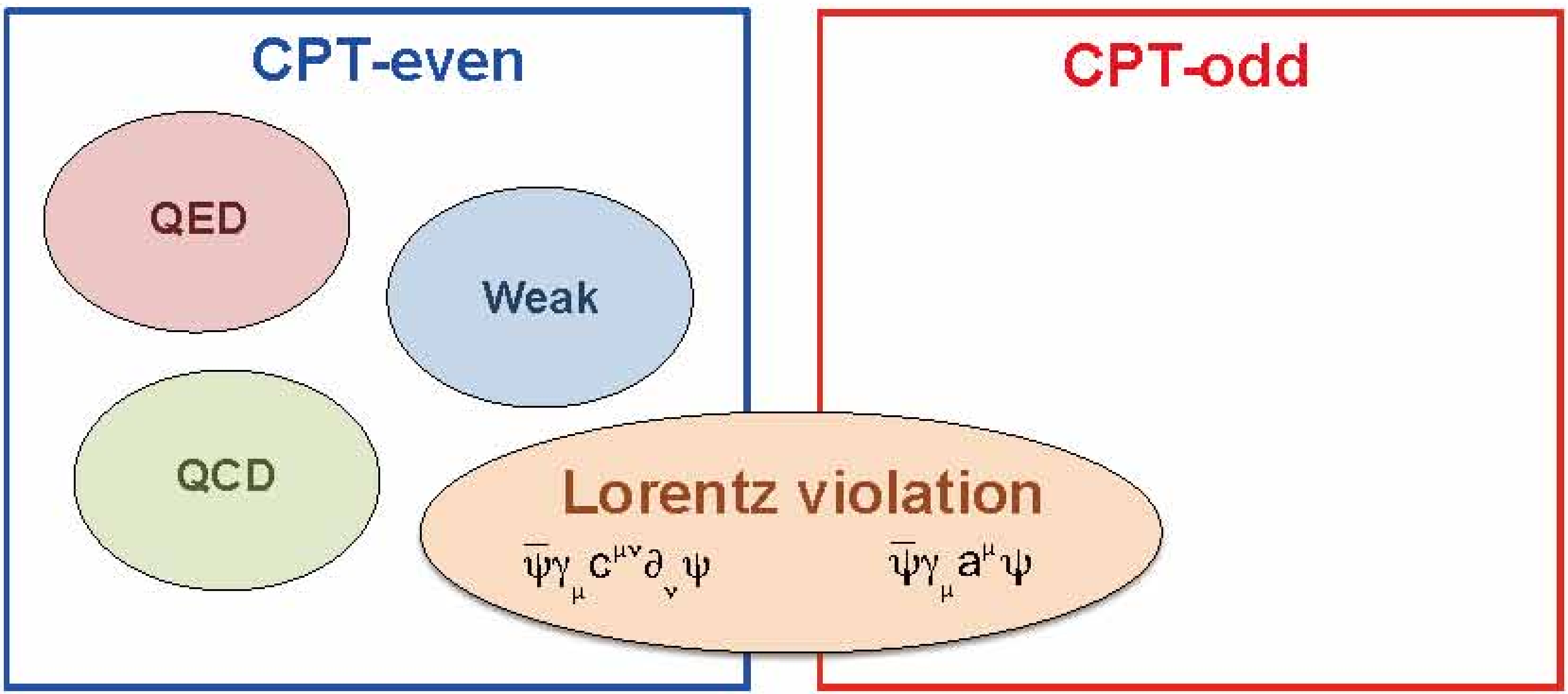


CPT-odd Lorentz violating coefficients (odd number Lorentz indices, e.g., a^μ , $g^{\lambda\mu\nu}$)

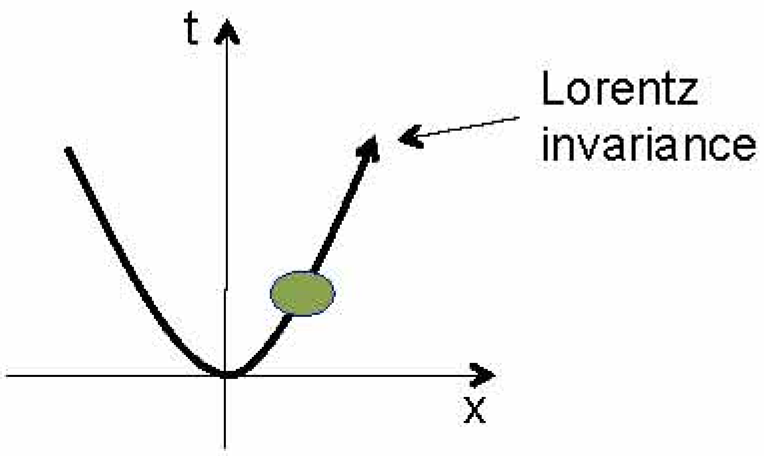
CPT-even Lorentz violating coefficients (even number Lorentz indices, e.g., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

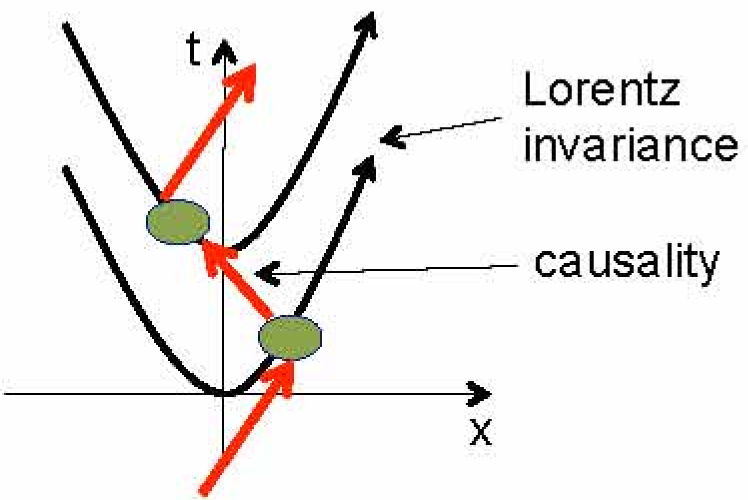
Greenberg, PRL(2002)231602

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.





Kostelecký and Mewes
PRD69(2004)016005

5. Lorentz violation with neutrino oscillation

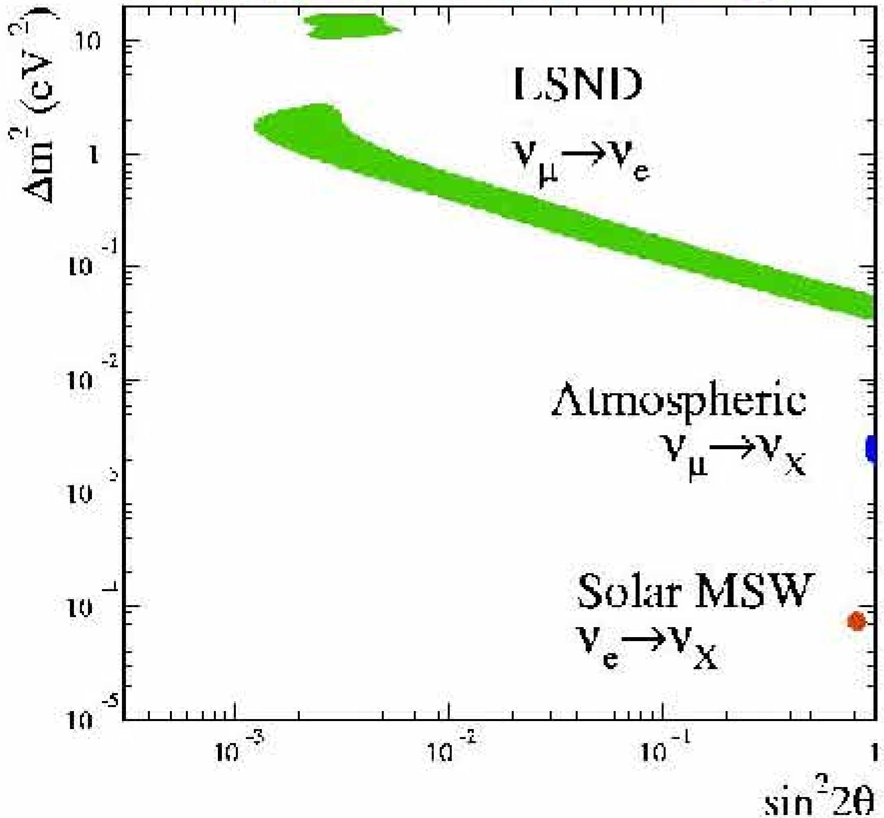
The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

(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



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

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  - 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
<κ_tr-4/3c_e^{00}<1.2x10^{-11}
(2009)170402
GRB vacuum birefringence
κ_{e+}, κ_{o-}<10^{-37}
PRL97(2006)140401
Double gas maser
b_n(rotation)<10^{-33}GeV
<10^{-27}GeV
optical resonator
c/c<10^{-16}
FOCUS
BaBar/Bell
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
second- and third-gener
LSND
MINOS ND
MINOS FD
IceCube
MiniBooNE
Double Chooz
PRD72(2005)076004
PRL101(2008)151601
PRL105(2010)151601
PRD82(2010)112003
PLB718(2013)1303
PRD86(2012)112009

Kostelecký and Mewes
PRD69(2004)016005

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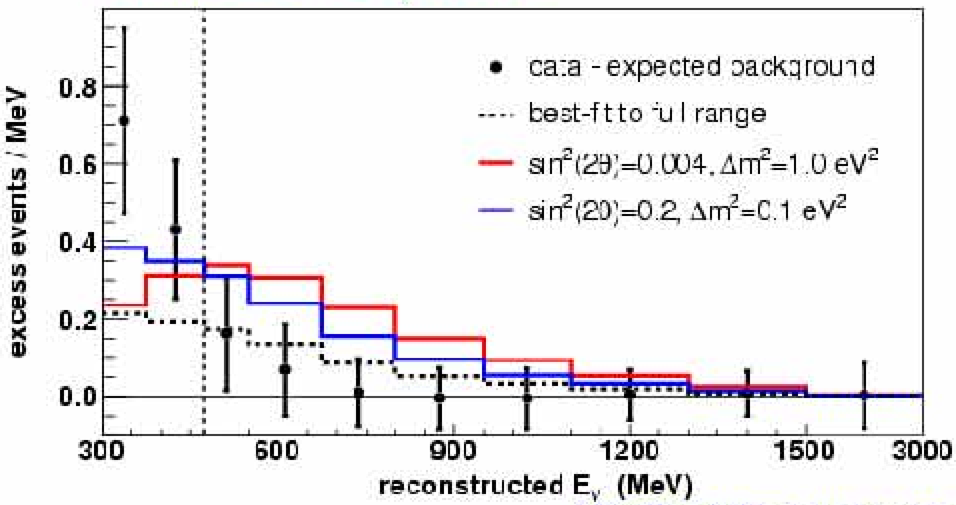
(2) L-E conflict
(3) Sidereal variation
(4) Compass asymmetries
(5) neutrino-antineutrino mixing
(6) classic CPT test

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

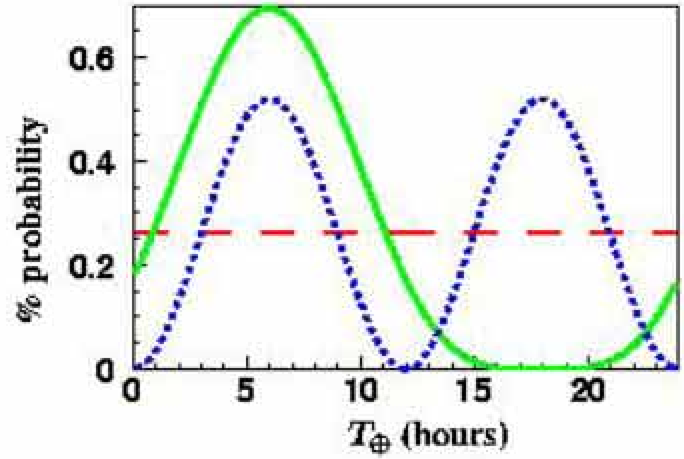
The examples of model independent features that represent characteristic signals of Lorentz violation for neutrino oscillation

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

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

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

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

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

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

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

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

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

5. Oscillation analysis background summary

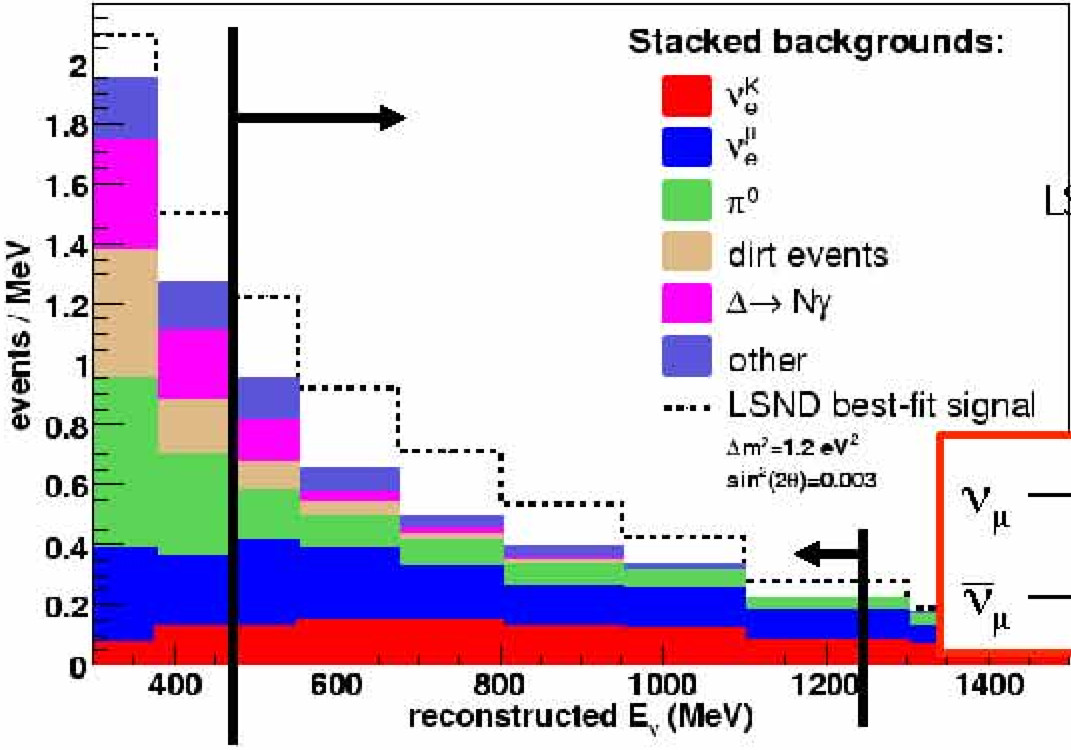
Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

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



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

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

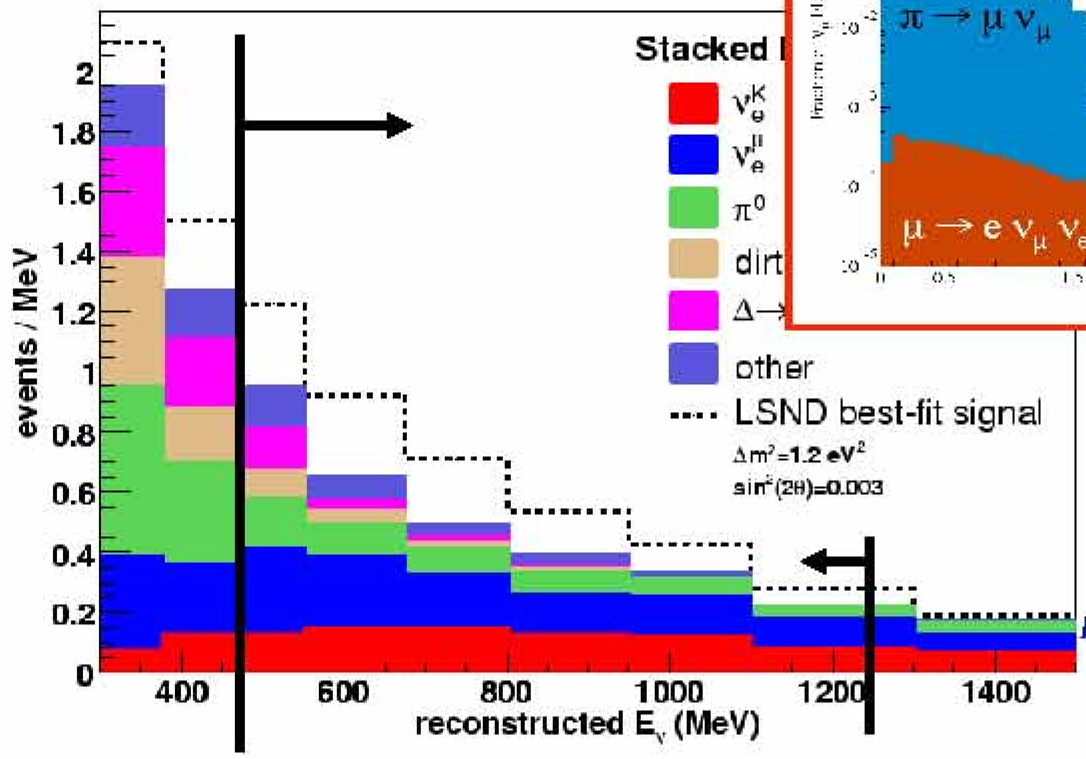
5. Oscillation analysis background summary

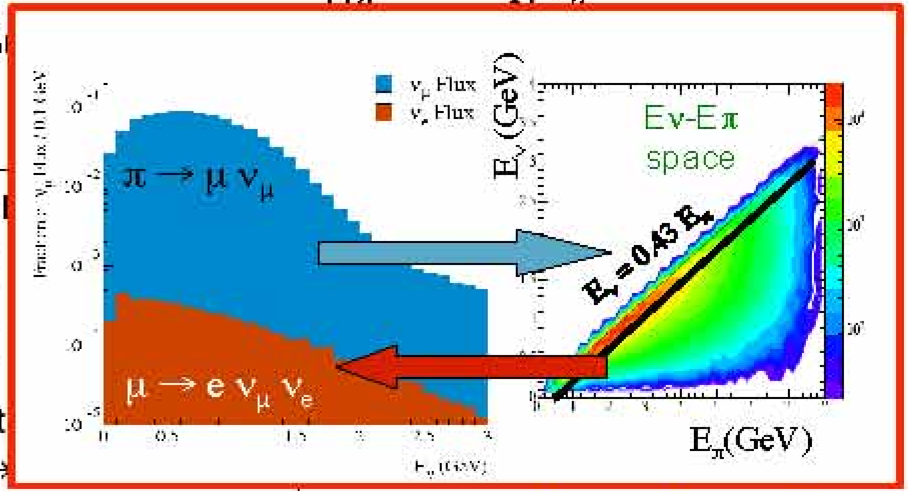
475 MeV - 1250 MeV

ν_e^K

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<125



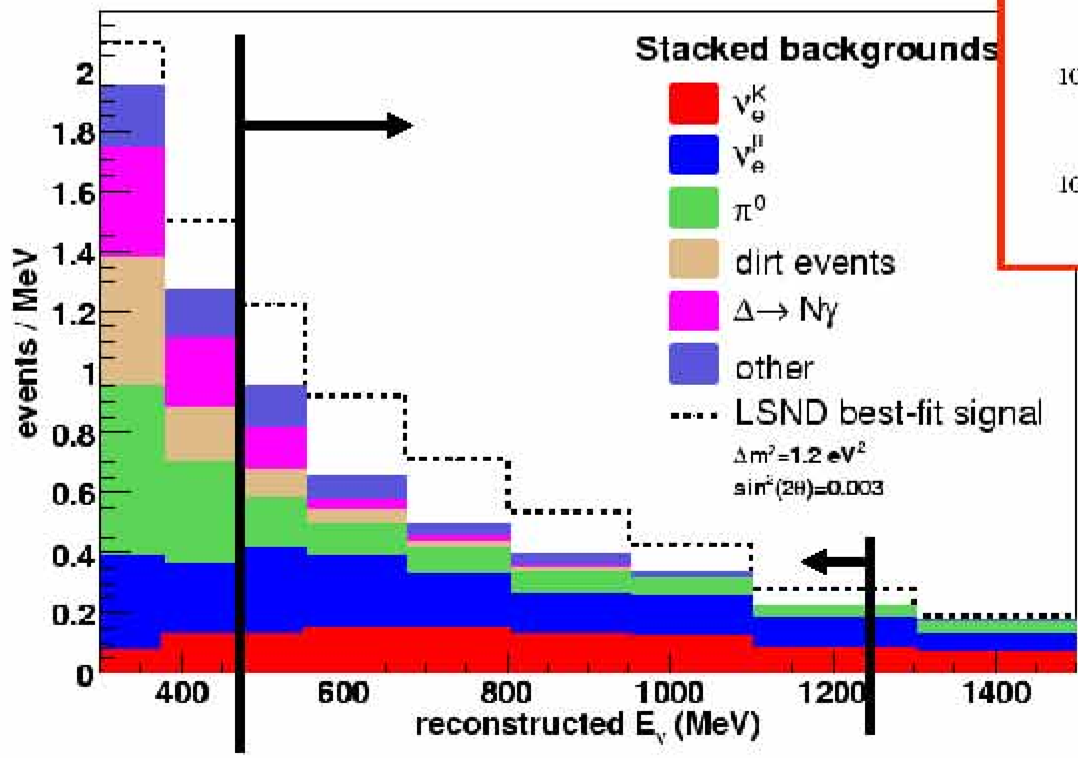


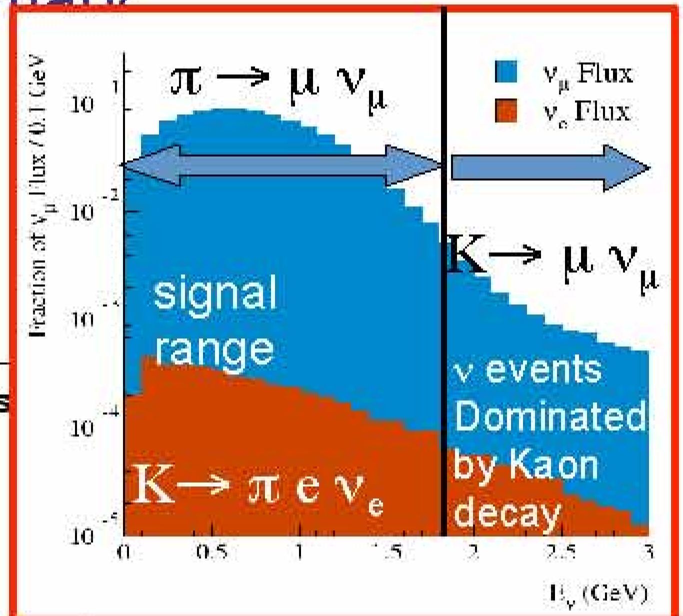
ν_e from μ decay is constrained from ν_μCCQE measurement

5. Oscillation analysis background summary

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV





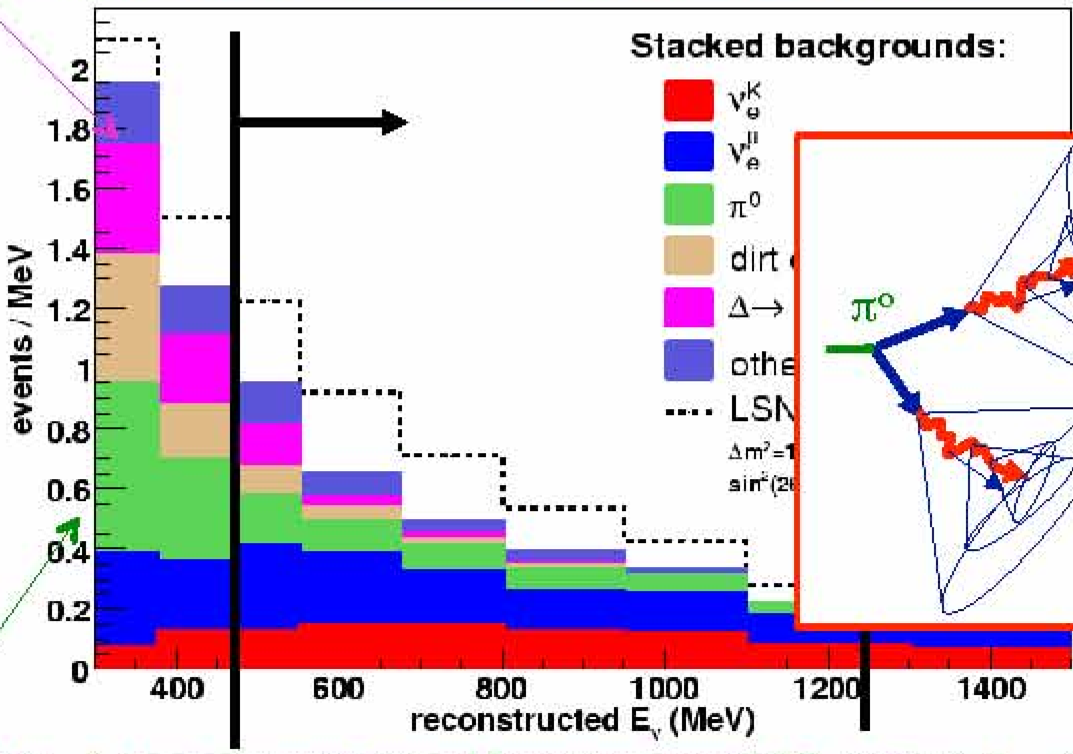
ν_e from μ decay is constrained from ν_μCCQE measurement

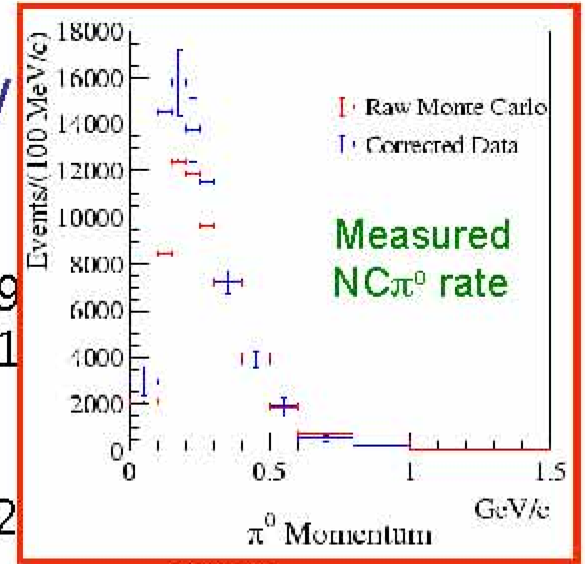
ν_e from K decay is constrained from high energy ν_e event measurement

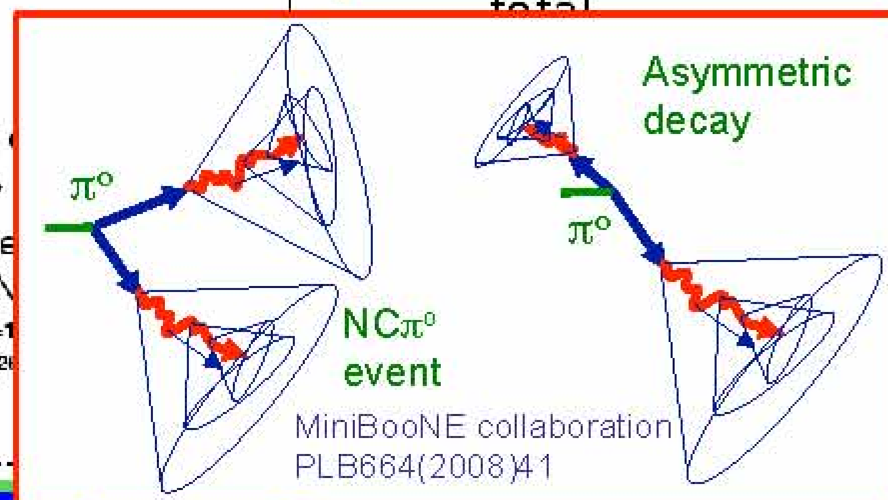
5. Oscillation analysis background summary

Oscillation analysis summary
- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured CCπ⁰ rate







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

Asymmetric π^0 decay is constrained from measured CCπ^0 rate ($\pi^0 \to \gamma$)

5. Oscillation analysis background summary

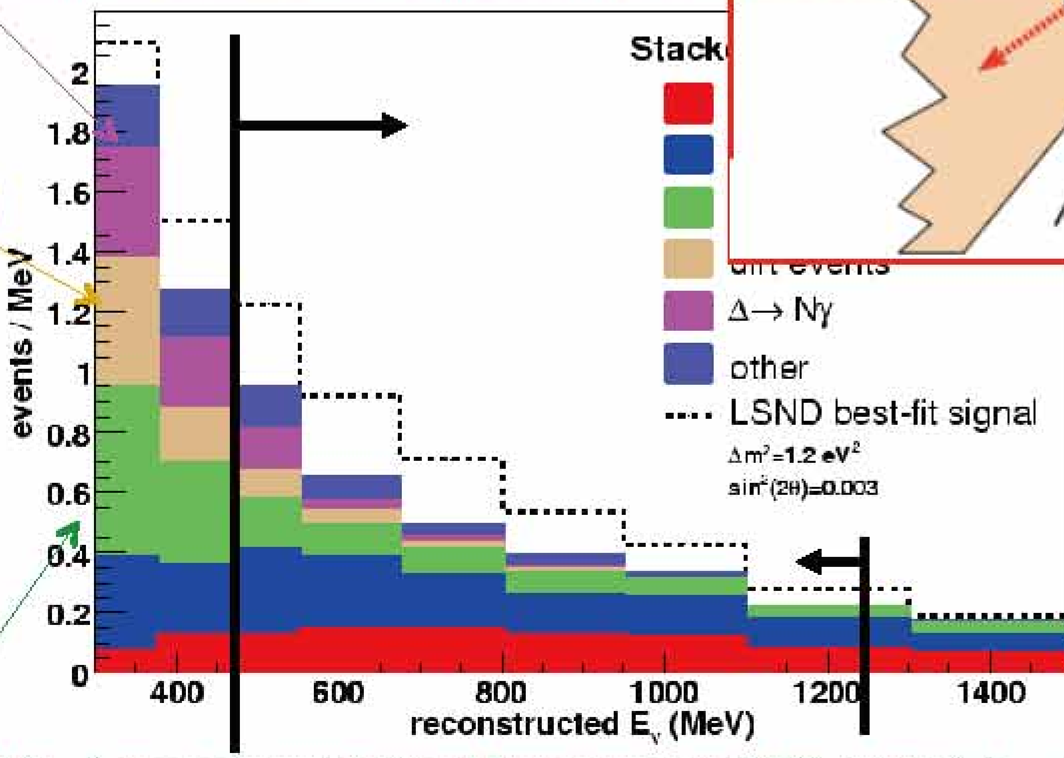
475 MeV - 1250 MeV

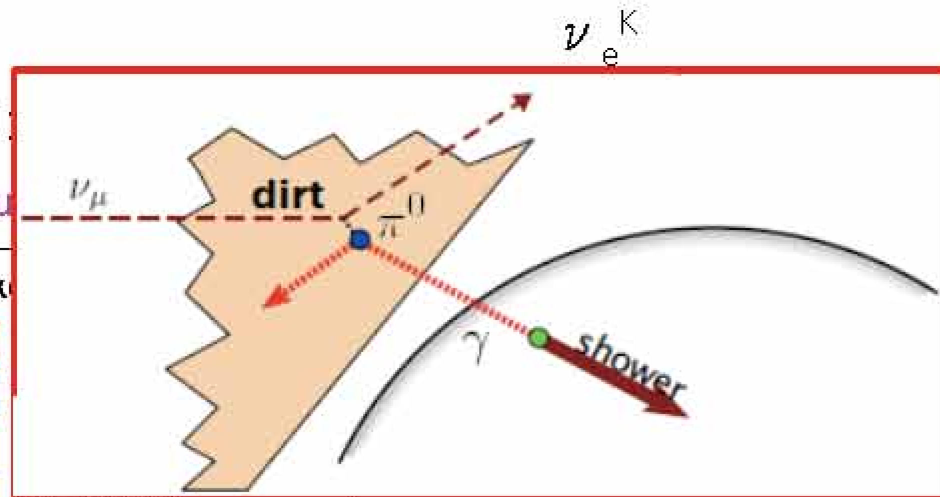
Oscillation analysis summary

- 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^0 decay is constrained from measured CCπ^0 rate ($\pi^0 \rightarrow \gamma$)

5. Oscillation analysis background summary

Oscillation analysis summary
- Oscillation analysis uses 475MeV<E<1250MeV

475 MeV - 1250 MeV

ν_e^K	94
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$\Delta \rightarrow N\gamma$	20
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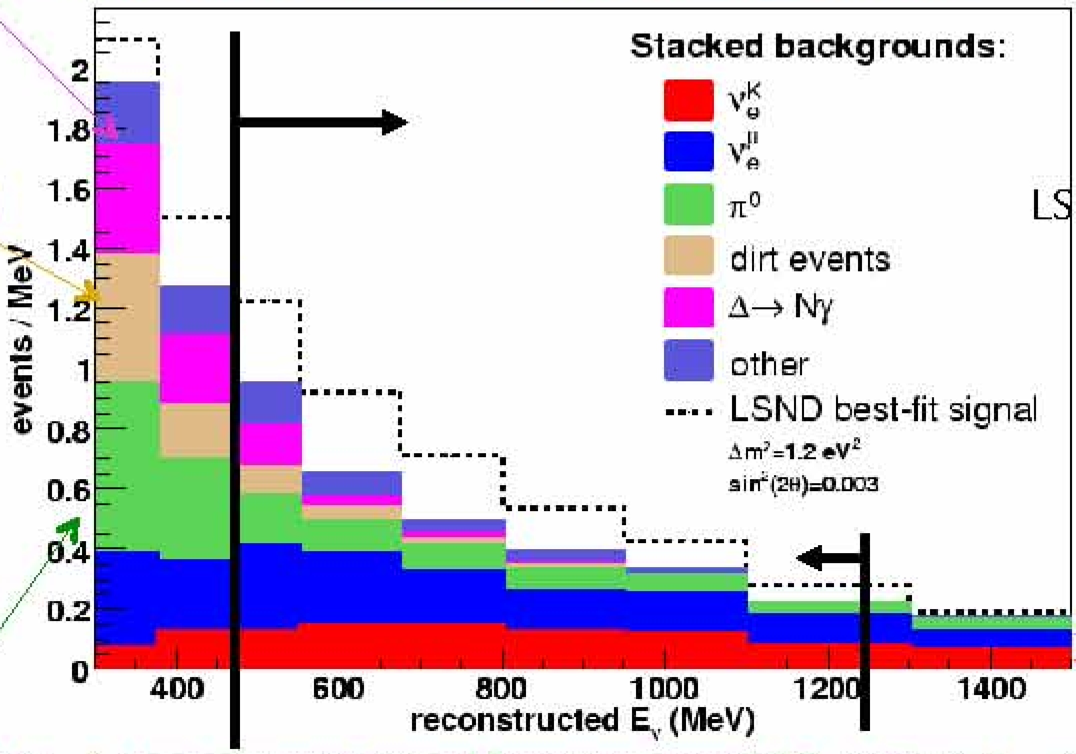
total	358

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

Δ resonance rate is constrained from measured $CC\pi^0$ 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^0 decay is constrained from measured $CC\pi^0$ rate ($\pi^0 \rightarrow \gamma$)

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

MiniBooNE collaboration,
PLB718(2013)1303

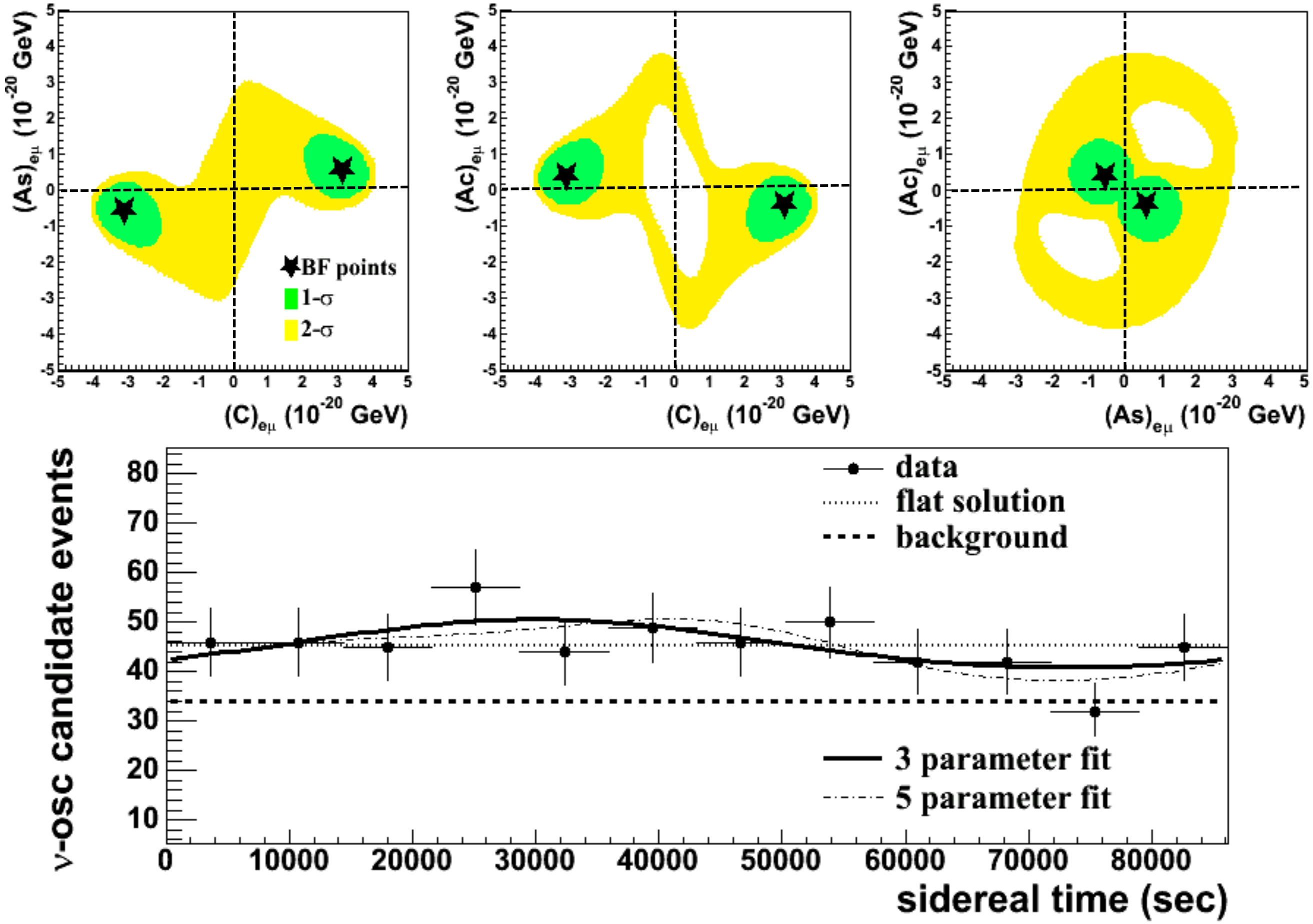
5. Lorentz violation with MiniBooNE neutrino data

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,
PLB718(2013)1303

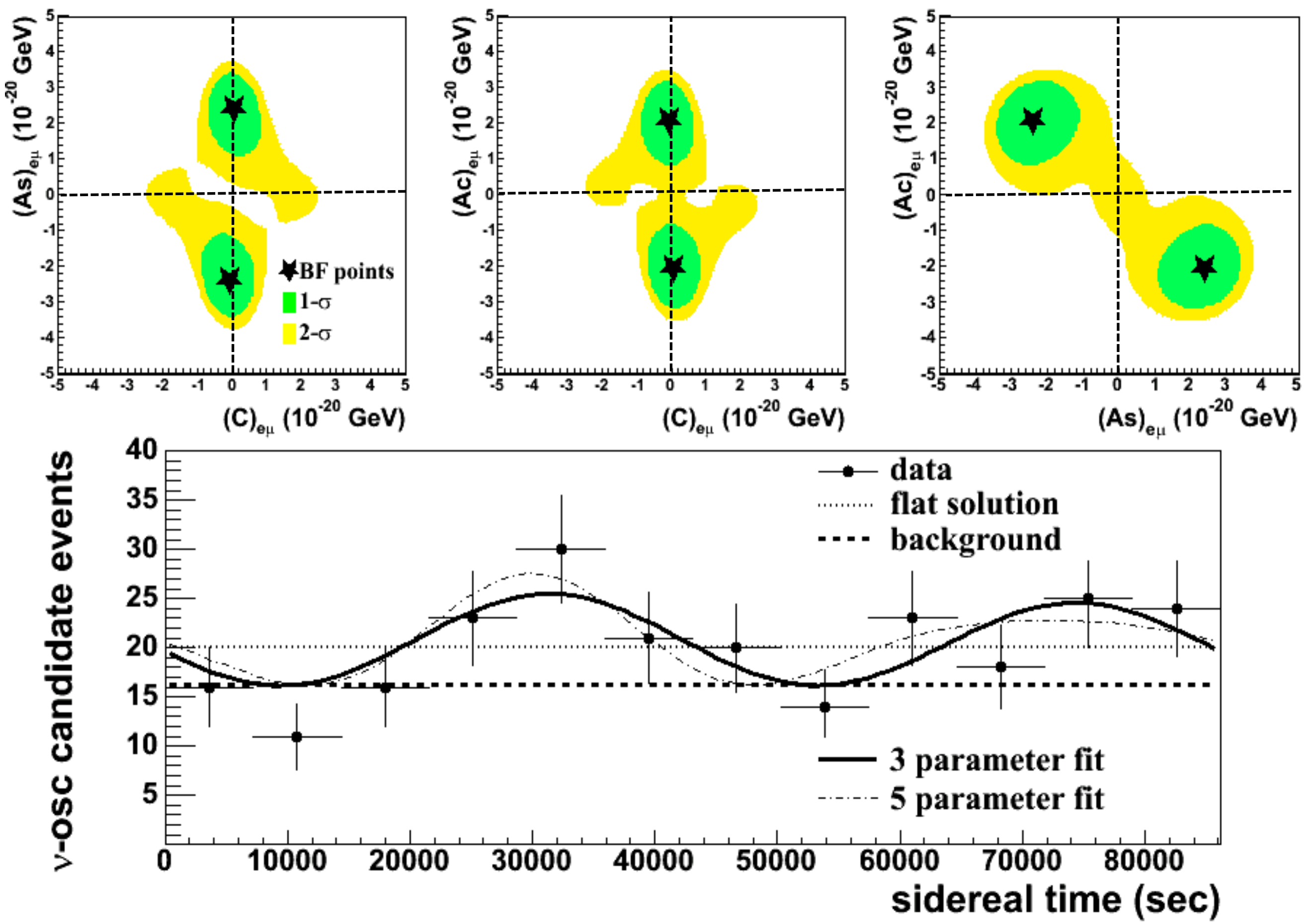
5. Lorentz violation with MiniBooNE anti-neutrino data

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.

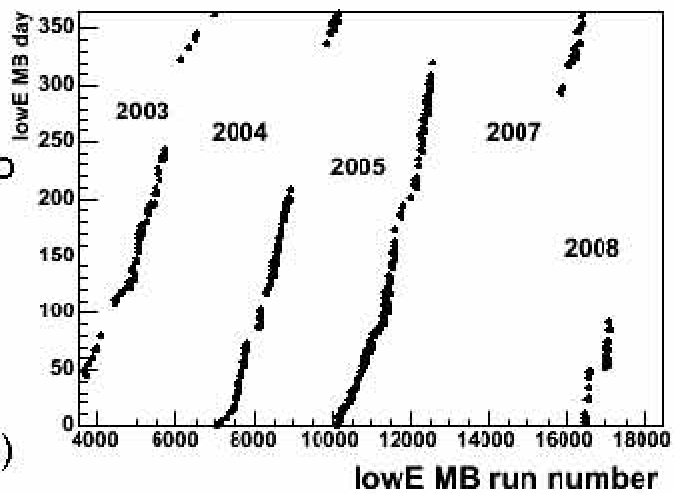


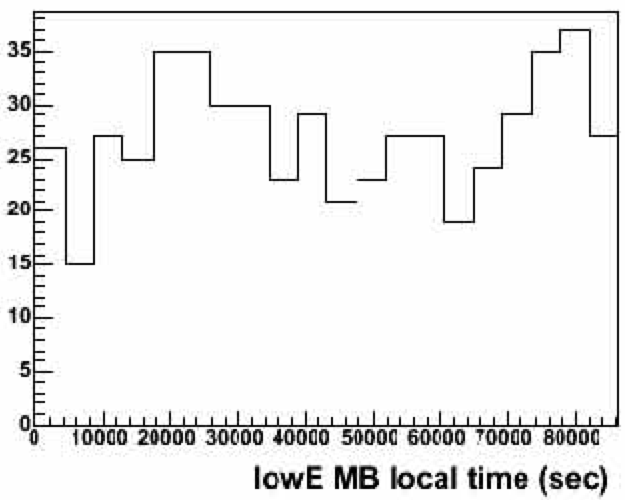
6. Lorentz violation with MiniBooNE neutrino data

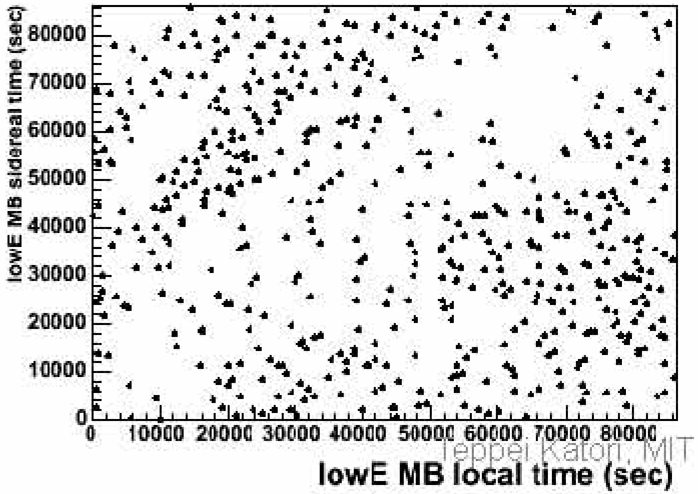
Time distribution of MiniBooNE neutrino mode low energy region

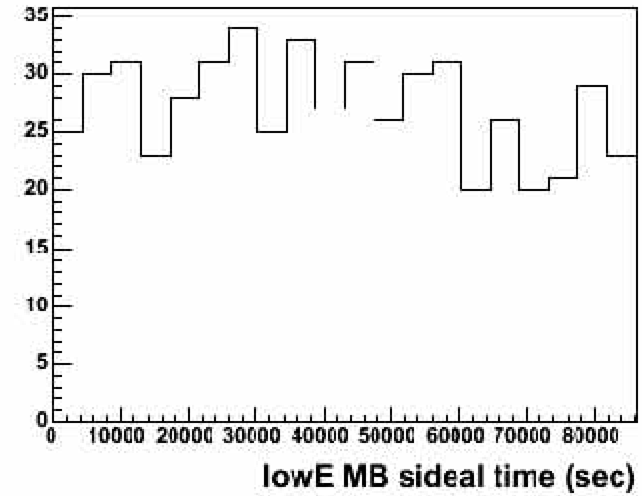
MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

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









6. Null hypothesis test

Unbinned Kolomogorov-Smirnov test (K-S test)

The flatness hypothesis is tested by 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.

	low energy		high energy		combined	
	solar	sidereal	solar	sidereal	solar	sidereal
	Neutrino mode					
$< E_\nu >$	0.36 GeV		0.82 GeV		0.71 GeV	
#cvt	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

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)

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

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

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

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

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

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

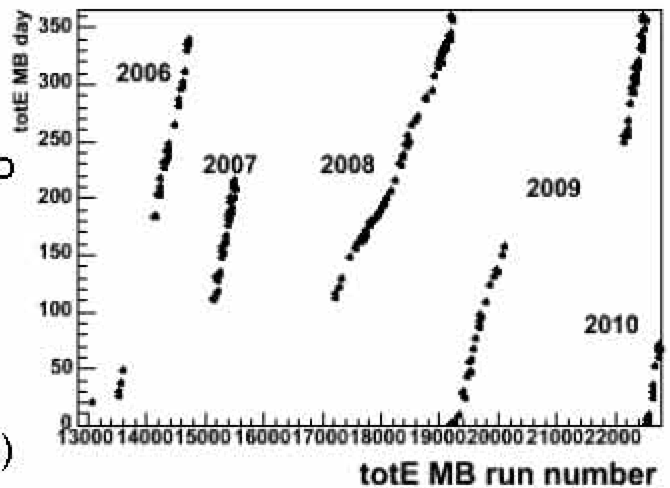
coordinate dependent direction vector
(depends on the latitude of FNAL, location of BNB and MiniBooNE detector)

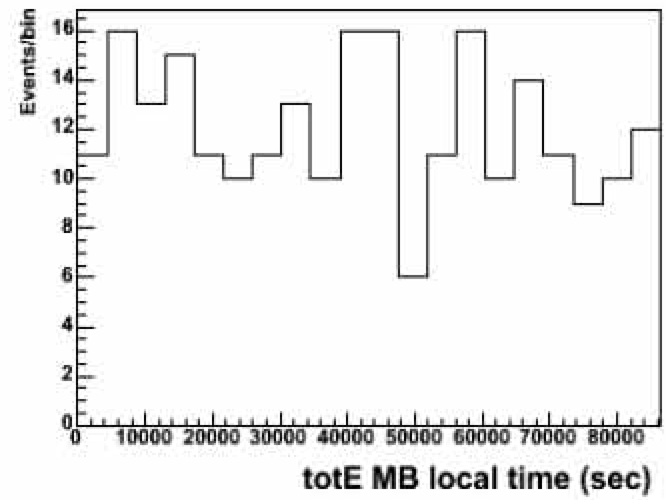
7. Lorentz violation with MiniBooNE anti-neutrino data

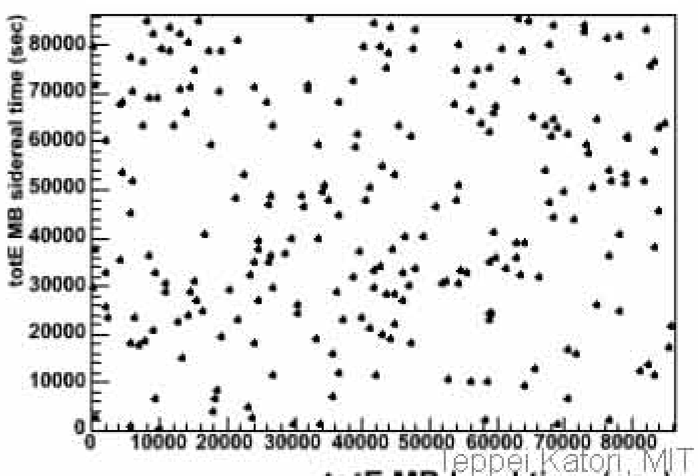
Time distribution of MiniBooNE antineutrino mode oscillation region

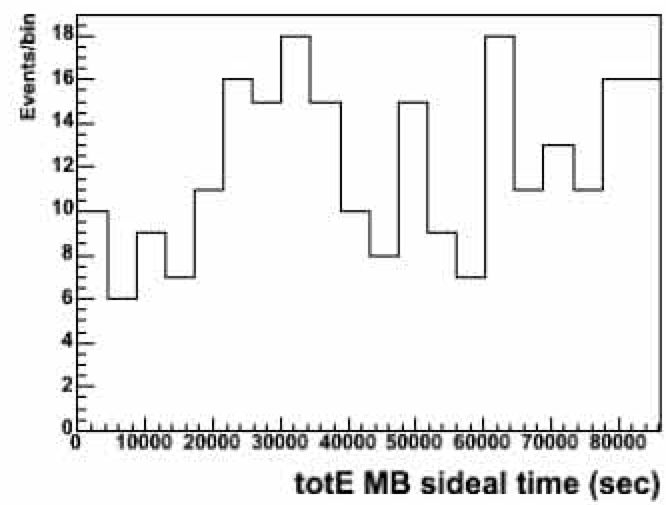
MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

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









7. Superluminal neutrinos

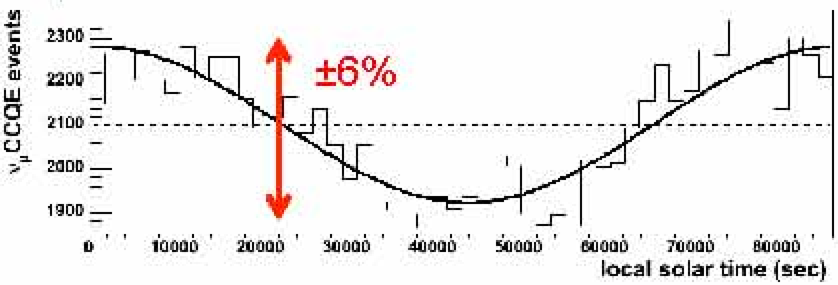
What about..., OPERA result?

6. Time dependent systematics

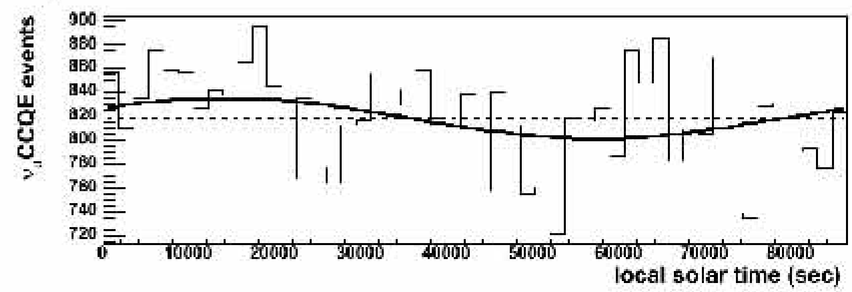
MiniBooNE CCQE data day-night distribution

- 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

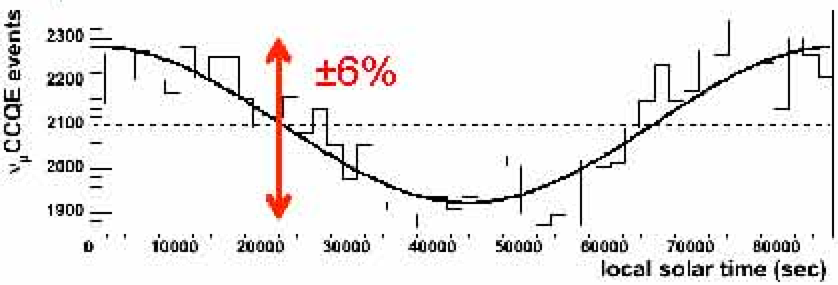


6. Time dependent systematics

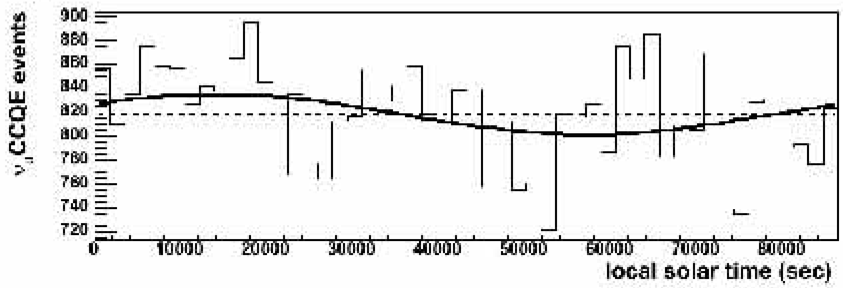
MiniBooNE CCQE data day-night distribution

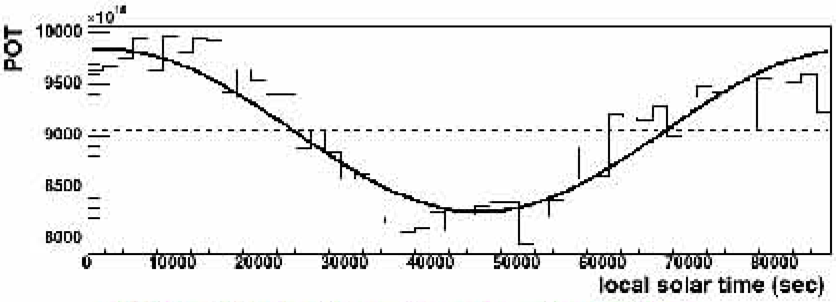
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show $\pm 6\%$ day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)

ν_μCCQE events distribution, Monday to Friday

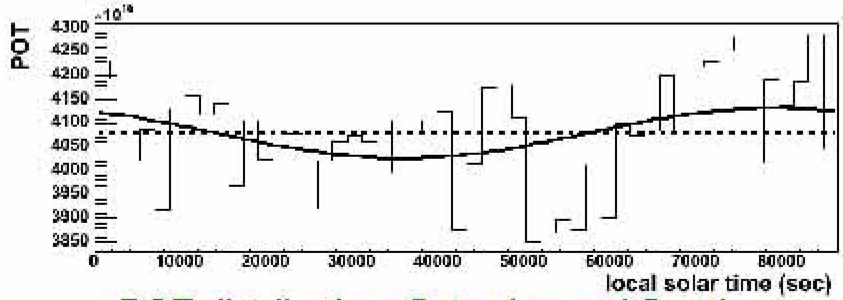


ν_μCCQE events distribution, Saturday and Sunday





POT distribution, Monday to Friday



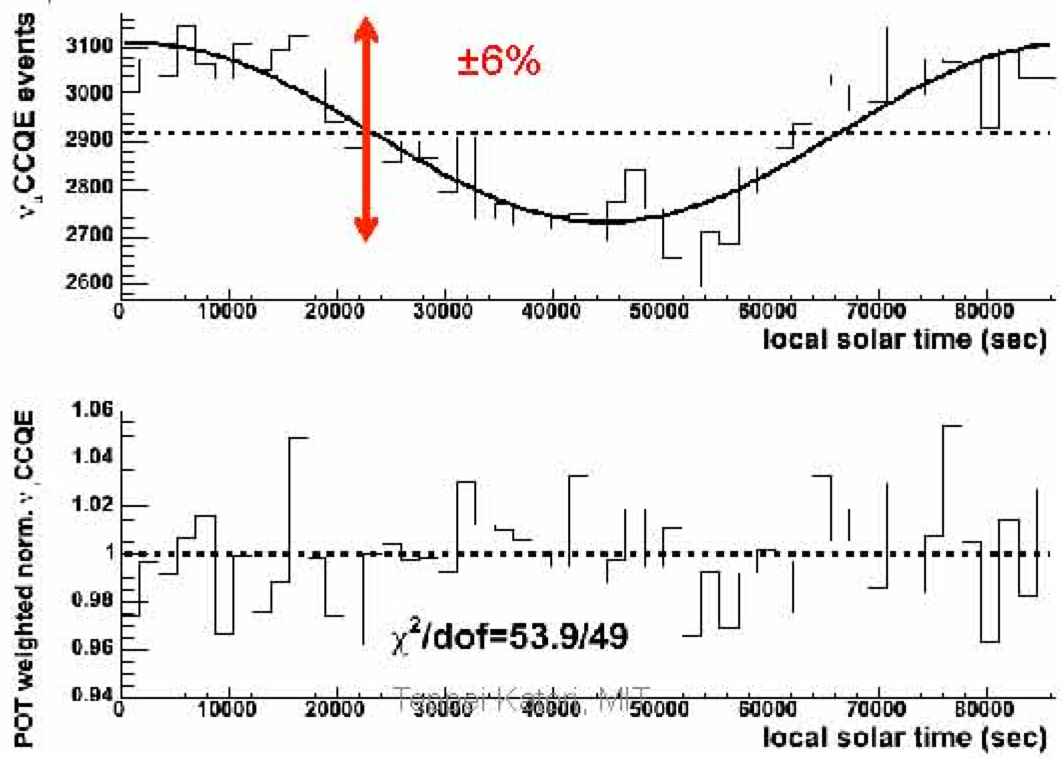
POT distribution, Saturday and Sunday

6. Time dependent systematics

MiniBooNE CCQE data day-night distribution

- 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. Time dependent systematics

MiniBooNE CCQE data day-night distribution

- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show $\pm$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.

We made event weight to correct this effect
- turns out negligible effect for oscillation candidates
  - 6% day-night effect → 3% sidereal time effect
  - statistical error, ~15%

We can safely ignore POT variation

Same study is repeated to MiniBooNE anti-ν_μCCQE data
- smaller day-night effect (3%)
- larger statistical error (20%)

→ POT variation is negligible

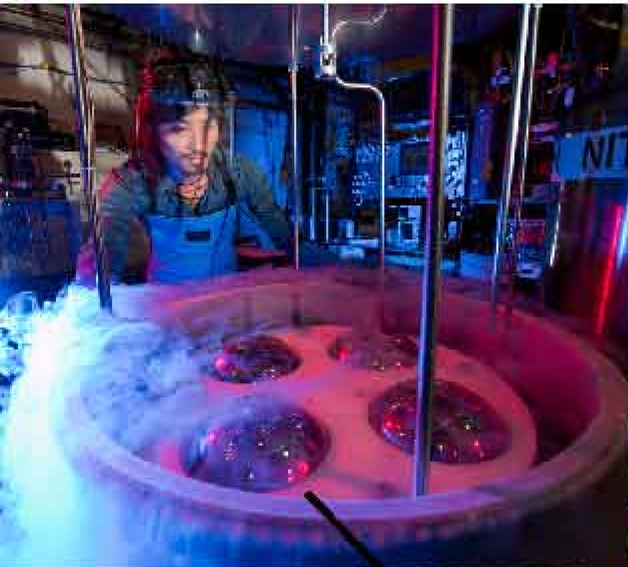
Therefore, we don't use an event weight to correct this in further analysis.

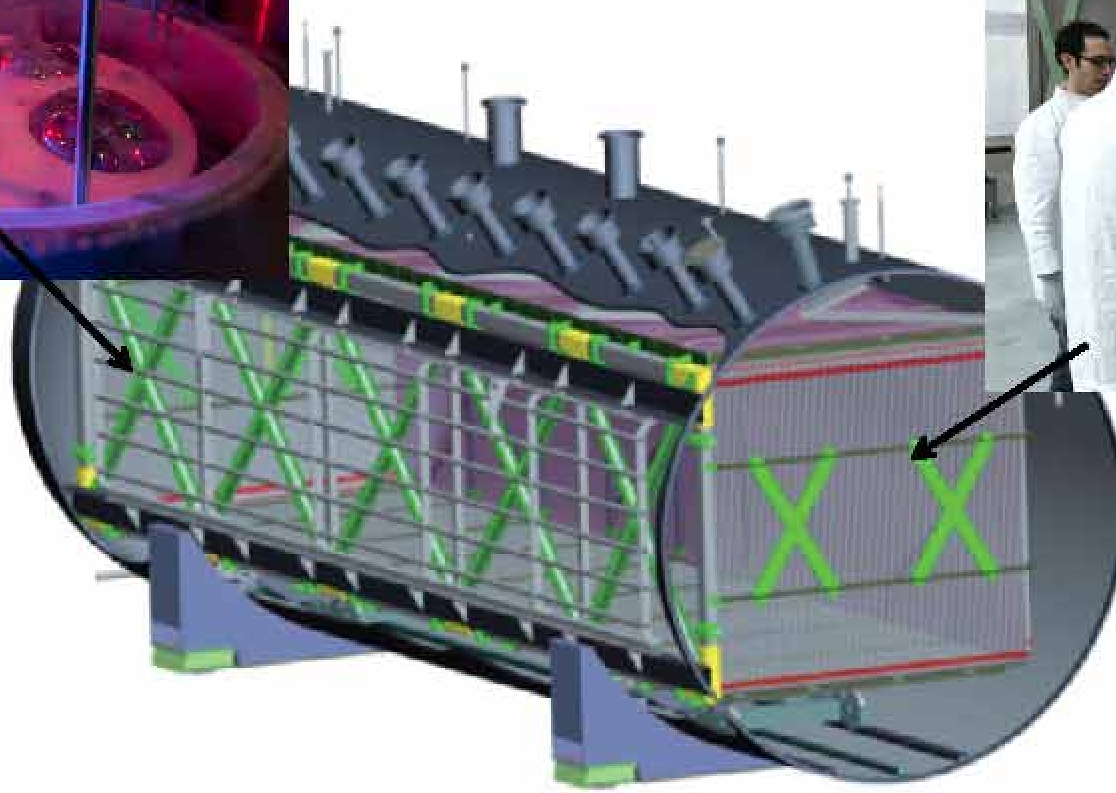
TK,
ArXiv:1107.5112

7. MicroBooNE experiment

Liquid Argon Time Projection Chamber (LArTPC)
- on the path to the future large LArTPC for LBNE
- data taking starts from 2014
- test MiniBooNE low energy excess
- precise neutrino cross section measurement

cryogenic PMT light collection system





LArTPC construction