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Brown University
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Indiana University Center for Spacetime Symmetries

Three-Parameter Lorentz-Violating Model for Neutrino Oscillations

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Indiana University

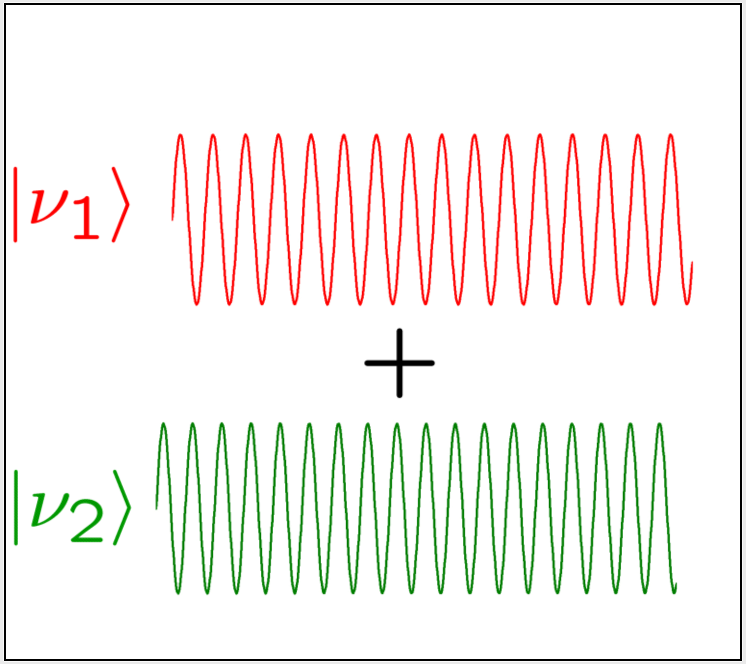
based on

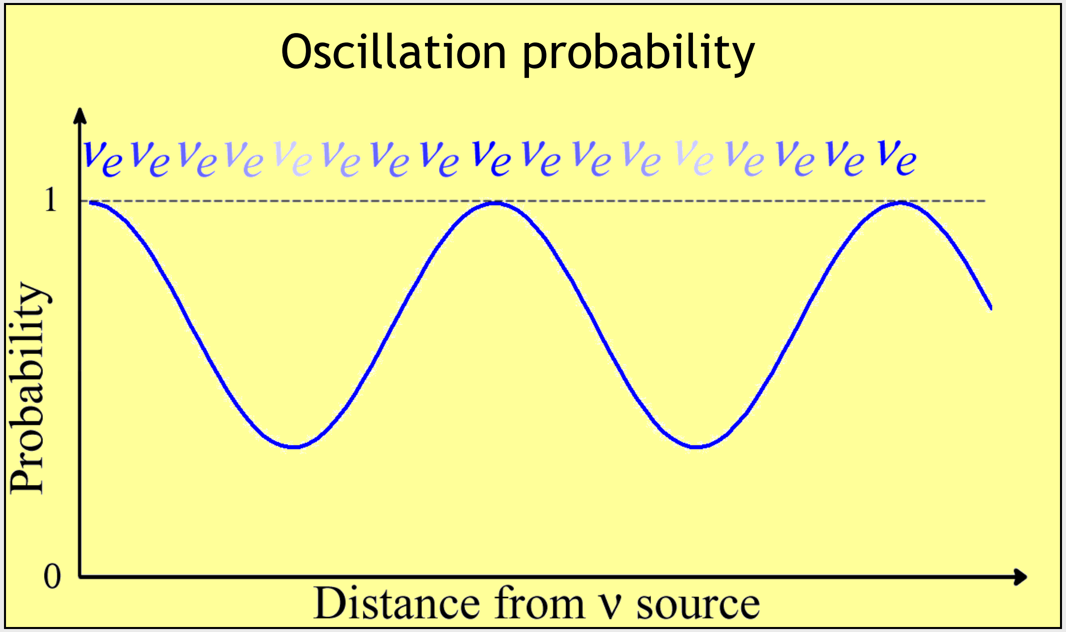
JSD and V.A. Kostelecký, Phys. Lett. B 700, 25 (2011)
JSD and V.A. Kostelecký, arXiv:1108.1799

Outline

- Neutrino oscillations
  - Established evidence
  - Conventional Lorentz-invariant model
- Lorentz and CPT violation
  - Motivation and framework: the Standard-Model Extension (SME)
- Lorentz-violating model for neutrino oscillations
  - Theory
  - Experimental data and predictions
- Summary

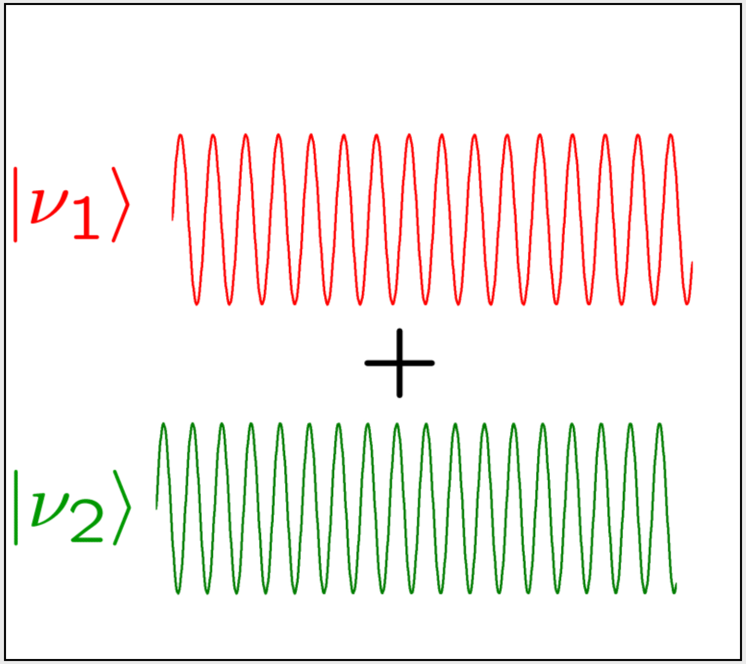
Neutrino Oscillations

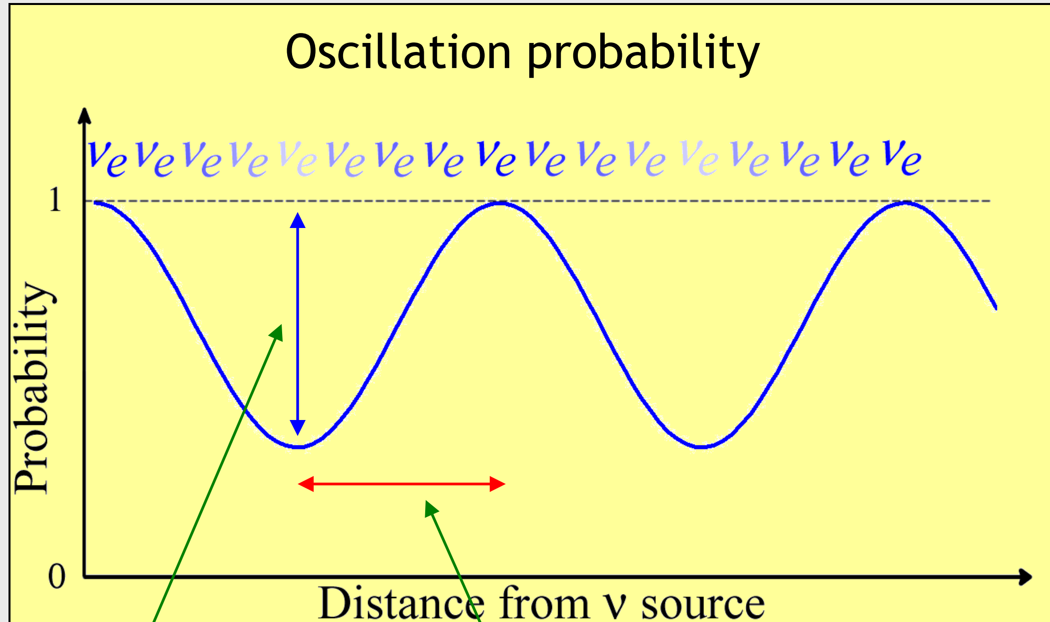




$$P_{\nu_a \to \nu_b}(L) = \sum_{jk} A_{jk}(U) \sin^2(\Delta_{jk} L/2)$$

Neutrino Oscillations





$$P_{\nu_a \to \nu_b}(L) = \sum_{jk} A_{jk}(U) \sin^2(\Delta_{jk} L/2)$$

Matrix that diagonalizes the hamiltonian

$\Delta_{jk} = \lambda_j - \lambda_k$ eigenvalues of the hamiltonian

Neutrino Oscillations: massive model $(3\nu\mathrm{SM})$

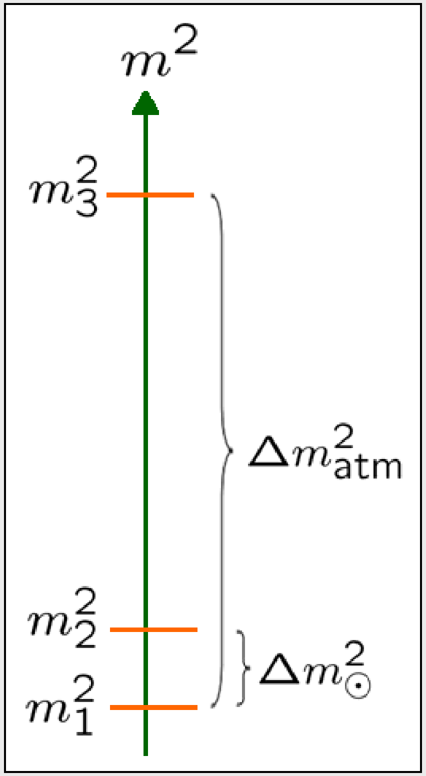
Effective hamiltonian

$$h_{\mathrm{eff}} = \frac{1}{2E} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_\odot & 0 \\ 0 & 0 & \Delta m^2_{\mathrm{atm}} \end{pmatrix} U$$

$$U = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix}$$

Properties:

- Lorentz and CPT invariant
- 3 massive neutrinos
- 5 parameters
- Energy-independent mixing



This model properly describes all the compelling results for neutrino oscillations

- atmospheric-neutrino disappearance (SK, K2K, MINOS, T2K)
- reactor-antineutrino disappearance (KamLAND)
- solar-neutrino deficit (SK, SNO, Borexino)

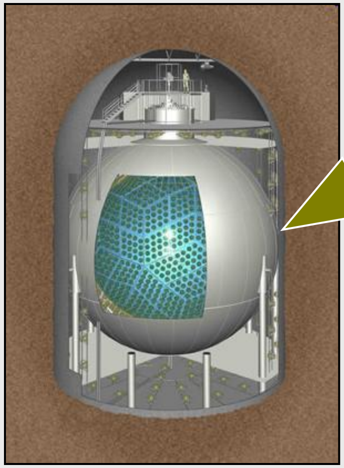
Neutrino Oscillations: massive model $(3\nu\mathrm{SM})$

Low energy: reactor antineutrinos

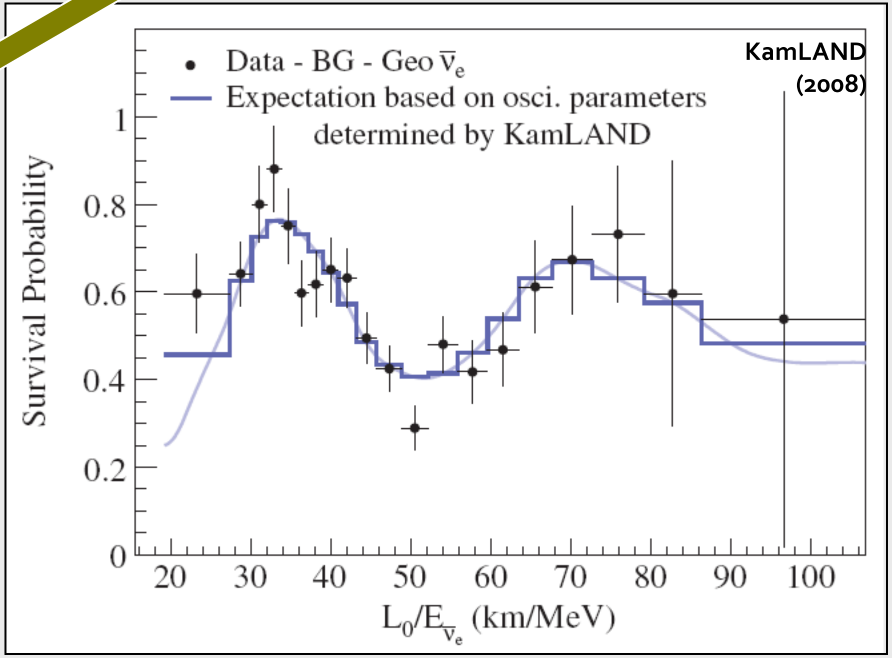
$$h_{\text{eff}} = \frac{1}{2E} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_\odot & 0 \\ 0 & 0 & \cancel{\Delta m^2_{\text{atm}}} \end{pmatrix} U$$

$$P_{\bar\nu_e \to \bar\nu_e} \simeq 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_\odot L}{4E}\right)$$

$\bar\nu_e$



KamLAND

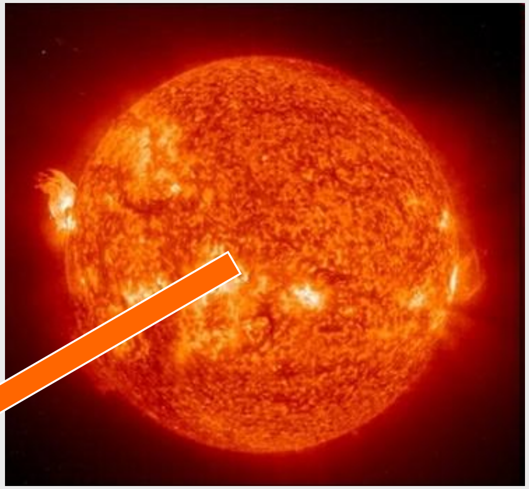


Neutrino Oscillations: massive model $(3\nu\mathrm{SM})$

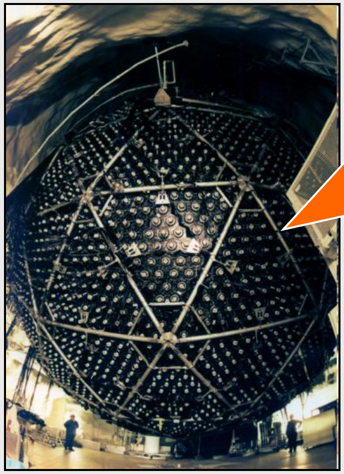
Low energy: solar neutrinos

$$h_{\text{eff}} = \frac{1}{2E} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_\odot & 0 \\ 0 & 0 & \cancel{\Delta m^2_{\text{atm}}} \end{pmatrix} U + \begin{pmatrix} V_{\text{CC}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

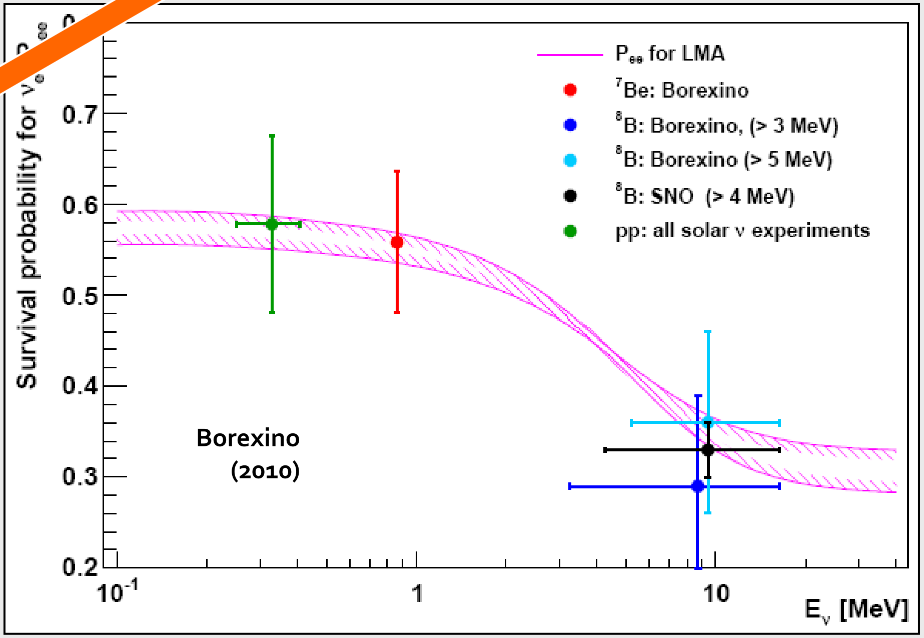
$$\langle P_{\nu_e \to \nu_e} \rangle \simeq \frac{1}{2} + \frac{1}{2} \cos 2\theta_{12} \cos 2\theta_{\text{M}} (\Delta m^2_\odot, E, V_{\text{CC}})$$



ν_e



SNO

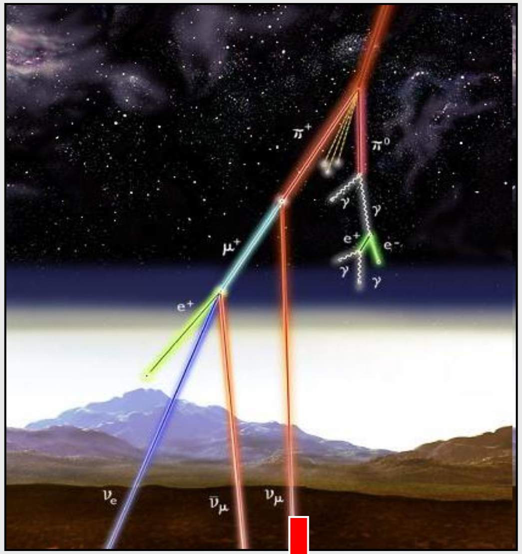


Neutrino Oscillations: massive model (3νSM)

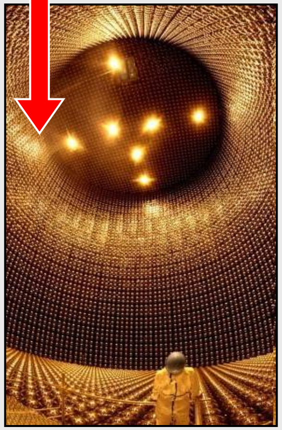
High energy: atmospheric neutrinos

$$h_{\text{eff}} = \frac{1}{2E} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cancel{\Delta m^2_\odot} & 0 \\ 0 & 0 & \Delta m^2_{\text{atm}} \end{pmatrix} U$$

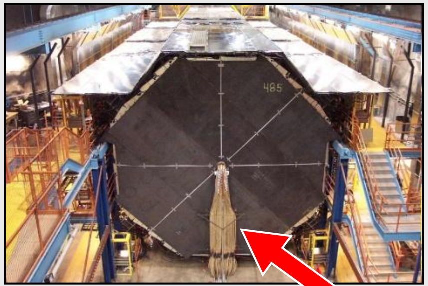
$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{\text{atm}} L}{4E} \right)$$



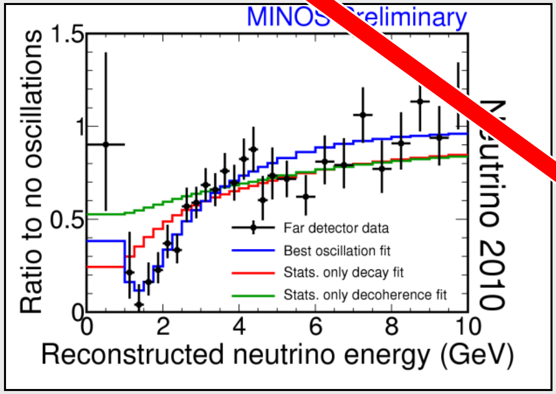
ν_μ



SK

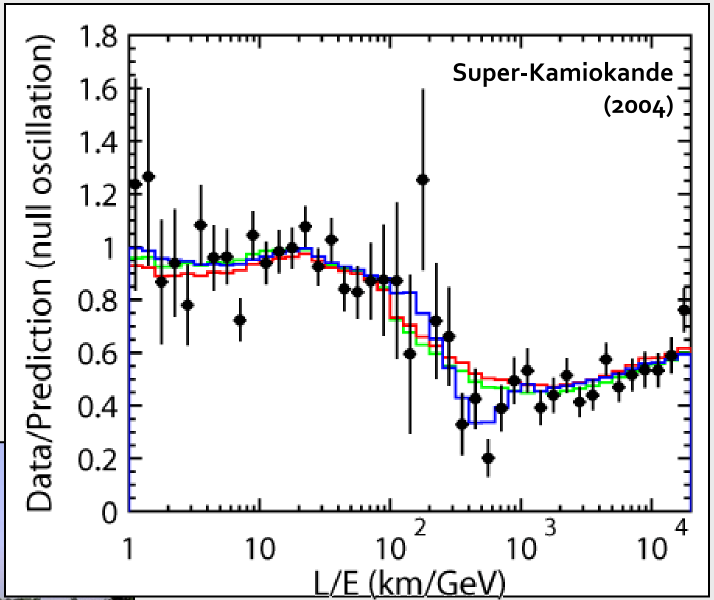


MINOS



ν_μ

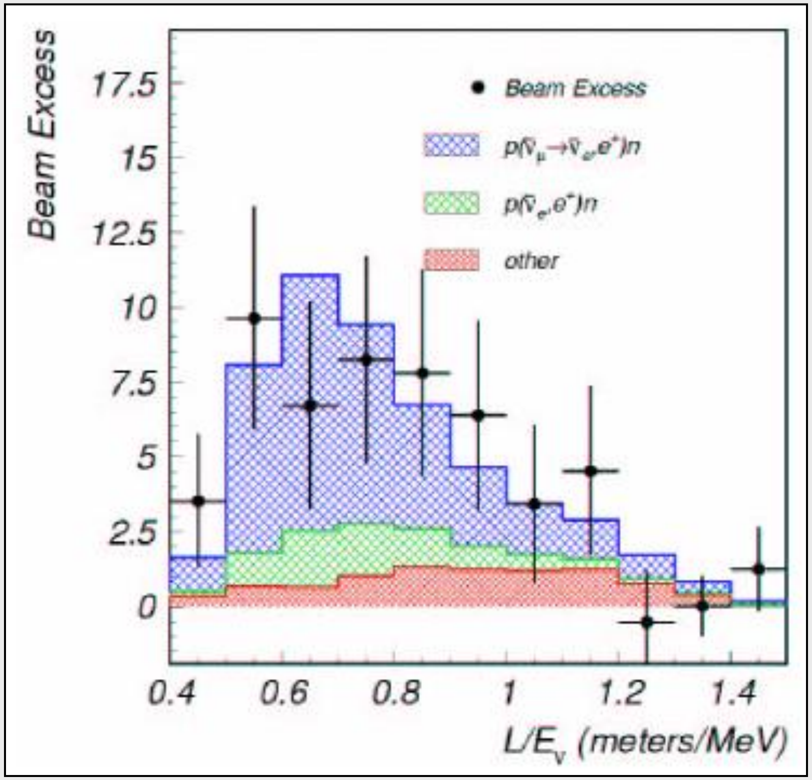
Fermilab



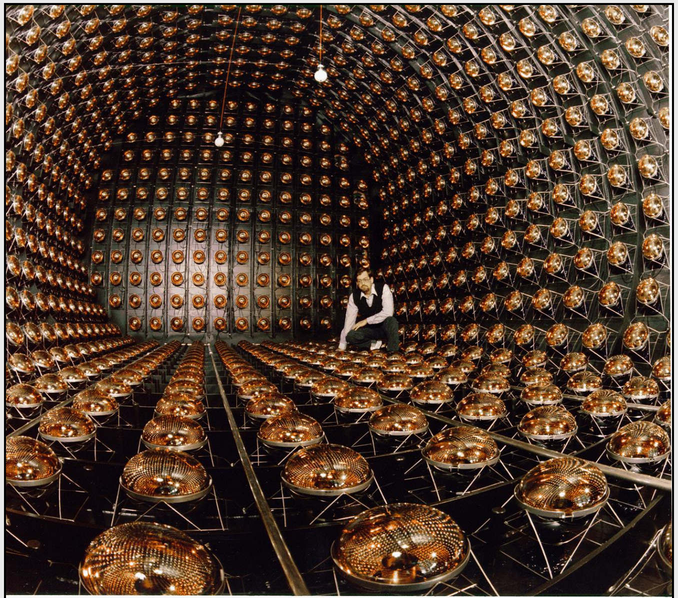
Neutrino Oscillations: anomalies

LSND (2001)

3.8σ evidence of oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



LSND 2001



Liquid Scintillator Neutrino Detector (LSND)

DNP

If excess is due to oscillations then extra neutrino flavors are needed (sterile neutrinos)

$$\Delta m^2_{\mathrm{LSND}} \gg \Delta m^2_{\mathrm{atm}}, \Delta m^2_{\odot}$$

Neutrino Oscillations: anomalies

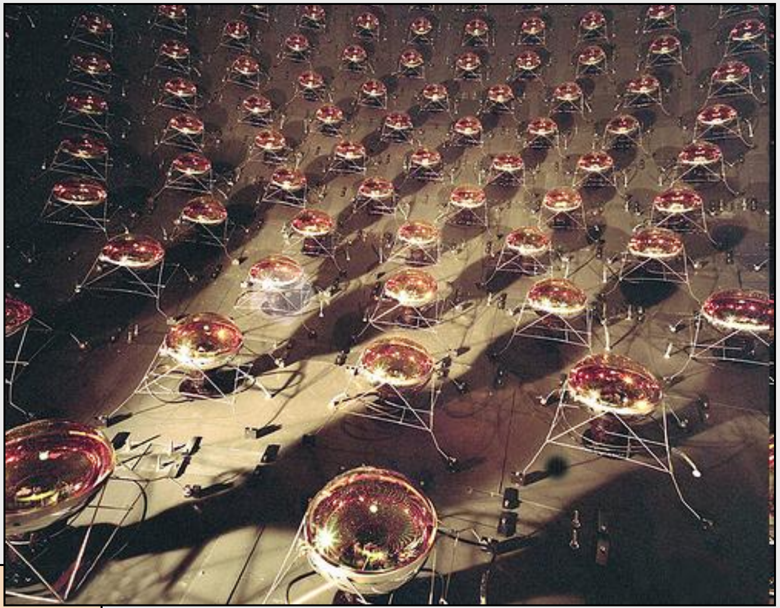
MiniBooNE (2007,2010)

$\nu_\mu \rightarrow \nu_e$

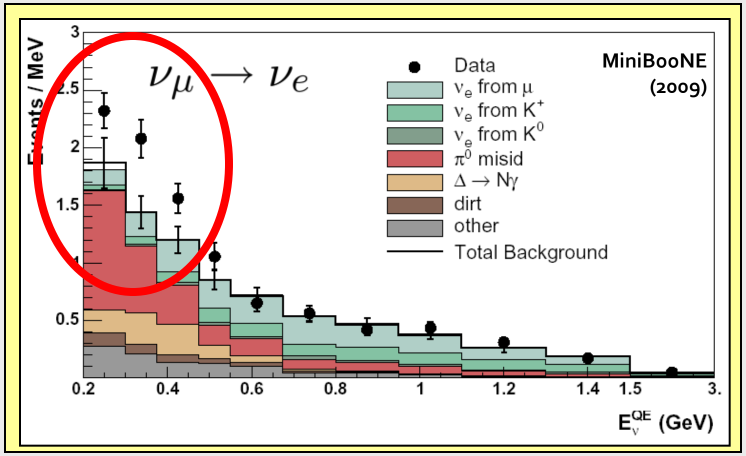
Neutrinos (2007):
- E<475 MeV: unexplained 3.0σ excess
- E>475 MeV: no signals of oscillations

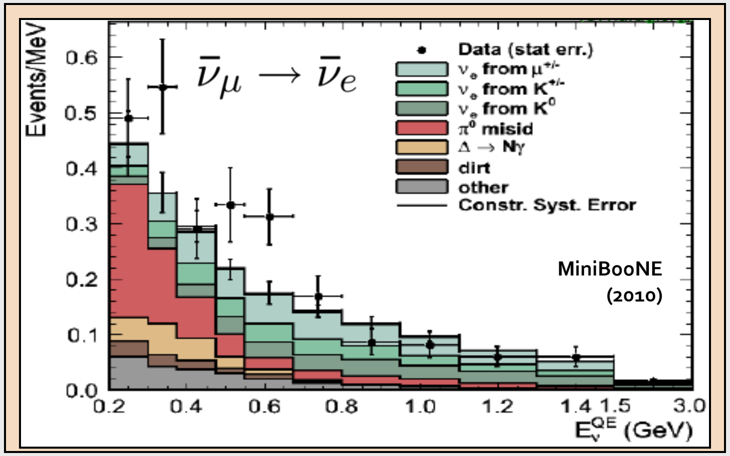
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Antineutrinos (2010):
- E<475 MeV: 1.3σ excess
- E>475 MeV: signal consistent with LSND (99.4%CL)



MiniBooNE

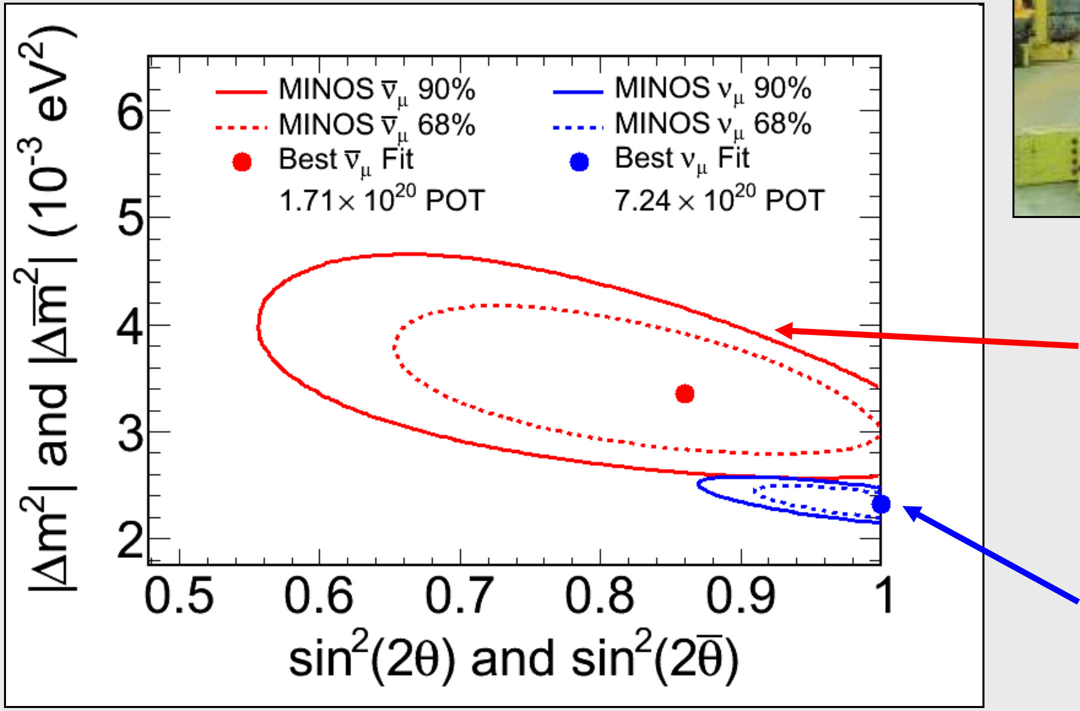




Neutrino Oscillations: anomalies

MINOS (2010)

Preliminary data is inconsistent with the 3νSM: oscillation parameters for neutrinos and antineutrinos must be equal.



MINOS (2011)

Neutrino Oscillations: results summary

Established data

3νSM

Atmospheric neutrinos	L/E oscillation signature	✓
Reactor antineutrinos	L/E oscillation signature	✓
Solar neutrinos	MSW-LMA signature (matter effects)	✓

Anomalies

LSND	Oscillation signal	✗
MiniBooNE 2007	Low-energy excess	✗
MiniBooNE 2010	Behavior $\nu \neq \bar{\nu}$	✗
MINOS	Behavior $\nu \neq \bar{\nu}$	✗

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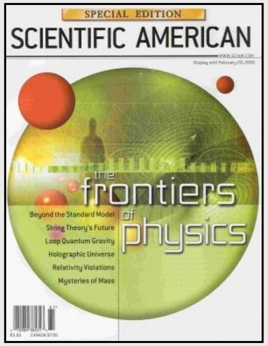
Lorentz violation

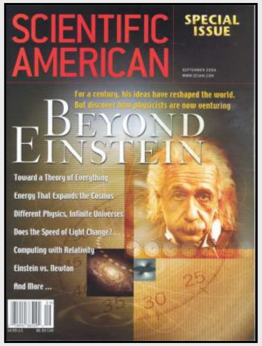
Last 20 years, growing interest in the possibility that Lorentz symmetry may not be exact.

- Quantum gravity candidates involve the breaking of Lorentz symmetry

Kostelecký & Samuel, PRD 1989
Kostelecký & Potting, NPB 1991

- Lorentz symmetry is a basic building block of both General Relativity (GR) and the Standard Model (SM). Anything this fundamental should be tested.

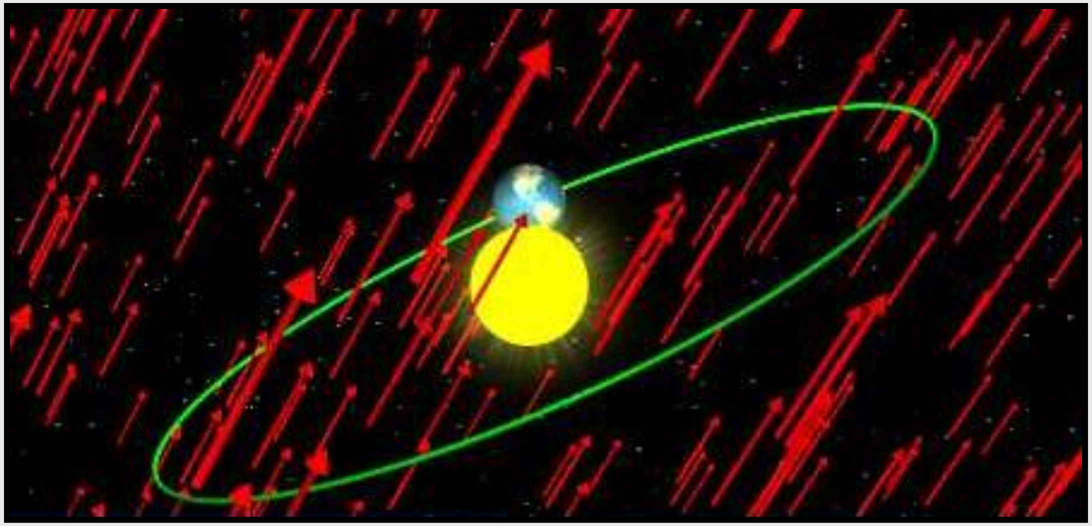




Standard-Model Extension

Colladay & Kostelecký, PRD 1997
Colladay & Kostelecký, PRD 1998
Kostelecký, PRD 2004

Standard-Model Extension = Standard Model coupled to Gravity + all possible Lorentz violations



- Standard fields
- Controlling coefficients
- Coordinate independent
- CPT violation included (no $\Delta m^2 \neq \Delta \bar{m}^2$ terms)

$$\mathcal{L}_{\text{LV}} \supset a_\mu \bar{\psi} \gamma^\mu \psi$$

SME: worldwide searches

K^0-$\bar{K}^0$ oscillations

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KTeV collaboration, H. Nguyen et al., in *CPT and Lorentz Symmetry II (2002);*
KTeV collaboration, Y.B. Hsiung et al., *Nucl. Phys. Proc. Suppl. 86, 312 (2000).*

D^0-$\bar{D}^0$ oscillations

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R. Mittleman et al., *Phys. Rev. Lett. 83, 2166 (1999);*
G. Gabrielse et al., *Phys. Rev. Lett. 82, 3198 (1999).*

Data Tables for Lorentz and CPT Violation,
Kostelecký & Russell, Rev. Mod. Phys. (2011).

Neutrino oscillations

MiniBooNE Collaboration, T. Katori, in *CPT and Lorentz Symmetry V (2011);*
IceCube Collaboration, R. Abbasi et al., *Phys. Rev. D 82, 112003 (2010);*
MINOS Collaboration, P. Adamson et al., *Phys. Rev. Lett. 105, 151601 (2010);*
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P. Antonini et al., *Phys. Rev. A 72, 066102 (2005);*
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C. Gemmel et al., *Phys. Rev. D 82, 111901 (R) (2010);*
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SME: the neutrino sector

Kostelecký & Mewes (PRD 2004a)
Kostelecký & Mewes (in preparation)

Effective hamiltonian for neutrinos (3x3 matrix) ← three left-handed neutrinos

$$(h_{\text{eff}})_{ab} = \underbrace{\frac{1}{2E}(\widetilde{m}^2)_{ab}}_{\text{Lorentz invariant}} + \underbrace{\overbrace{(a_L)^{\alpha}_{ab}\,\widehat{p}_{\alpha}}^{\text{CPT odd}} - \overbrace{(c_L)^{\alpha\beta}_{ab}\,p_{\alpha}\widehat{p}_{\beta}}^{\text{CPT even}} + (h_{\text{NR}})_{ab}}_{\text{Lorentz violating}}$$

$a, b = e, \mu, \tau$

Models based on this general effective hamiltonian

- bicycle model (Kostelecký et al., 2004)
- tandem model (Katori et al., 2006)
- BMW model (Barger et al., 2007)
- puma model (JSD et al., 2010) rest of this talk
- isotropic bicycle model (Barger et al., 2011) ← talk by K. Whisnant
- many others...

Search for key signals of Lorentz violation

- sidereal variations: LSND, MiniBooNE, MINOS (2), IceCube

Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

- Isotropic (no direction dependence)
- Includes nonrenormalizable terms
- Three real parameters

Puma model

$$h_{\text{eff}} = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + B \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A = m^2/2E, \quad B = aE^2, \quad C = cE^5$$

"[the model] was discovered by a systematic hunt through the jungle of possible SME-based models."

Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký
PLB 2011
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Low energy

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$$\begin{aligned} A &= m^2/2E, \\ B &= aE^2, \\ C &= cE^5 \end{aligned}$$

- mass term dominates
- L/E oscillation signature
- symmetries: Lorentz, CPT, S_3
- tri-bimaximal mixing
- consistent with KamLAND data
- consistent with solar data

$$\begin{aligned} \Delta m^2_{\odot} &\rightarrow m^2 \\ \theta_{12} &\rightarrow \text{given by texture} \end{aligned}$$

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- mass term dominates
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$$U \simeq \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\begin{aligned} \Delta m^2_{\odot} &\rightarrow m^2 \\ \theta_{12} &\rightarrow \text{given by texture} \end{aligned}$$

Lorentz-violating Neutrino Oscillations: puma model

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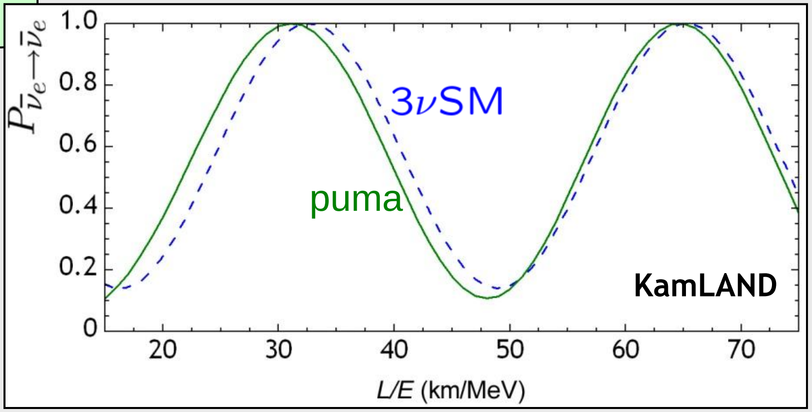

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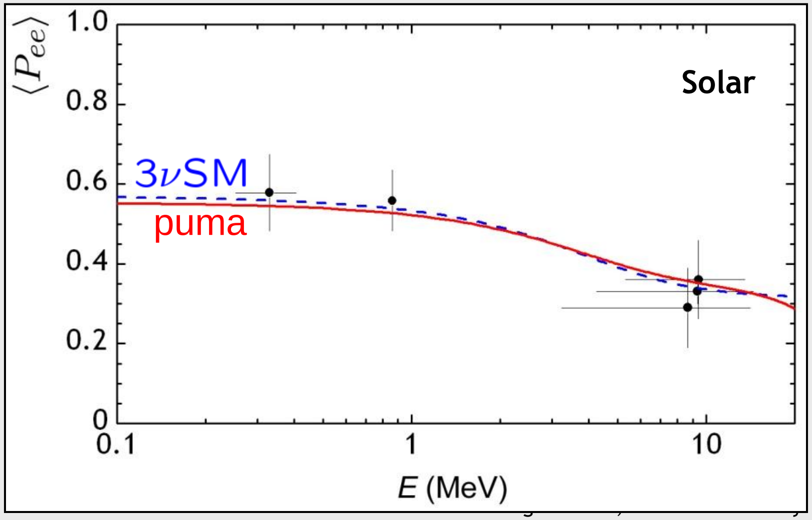
- consistent with KamLAND data
- consistent with solar data



$$\begin{aligned} \Delta m^2_{\odot} &\rightarrow m^2 \\ \theta_{12} &\rightarrow \text{given by texture} \end{aligned}$$

Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

High energy

$$h_{\text{eff}} = A\begin{pmatrix}1&1&1\\1&1&1\\1&1&1\end{pmatrix} + B\begin{pmatrix}1&1&1\\1&0&0\\1&0&0\end{pmatrix} + C\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}$$

$$\begin{aligned} A &= m^2/2E, \\ B &= aE^2, \\ C &= cE^5 \end{aligned}$$

- no masses
- Lorentz-violating see-saw mechanism
- *L*/*E* oscillation signature
- symmetries: S_2
- maximal mixing
- consistent with SK, K2K, MINOS, T2K

Lorentz-violating see-saw mechanism

$$\begin{aligned} \lambda_1 &= \frac{1}{2}\left(B + C - \sqrt{(B+C)^2 + 8B^2}\right) \\ &\approx -\frac{2B^2}{C} = -\frac{2a^2}{cE} \end{aligned}$$

$$\Delta m^2_{\text{atm}} \;\rightarrow\; a^2/c$$

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$$h_{\text{eff}} \approx B \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \end{array} + C \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \end{array}$$

$\mu\tau$ symmetry produces maximal mixing

Lorentz-violating seesaw mechanism

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$$\begin{aligned} \Delta m^2_{\text{atm}} &\rightarrow a^2/c \\ \theta_{23} &\rightarrow \text{given by texture} \end{aligned}$$

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$$h_{\text{eff}} = A\begin{pmatrix}1&1&1\\1&1&1\\1&1&1\end{pmatrix} + B\begin{pmatrix}1&1&1\\1&0&0\\1&0&0\end{pmatrix} + C\begin{pmatrix}1&0&0\\0&0&0\\0& & \end{pmatrix}$$

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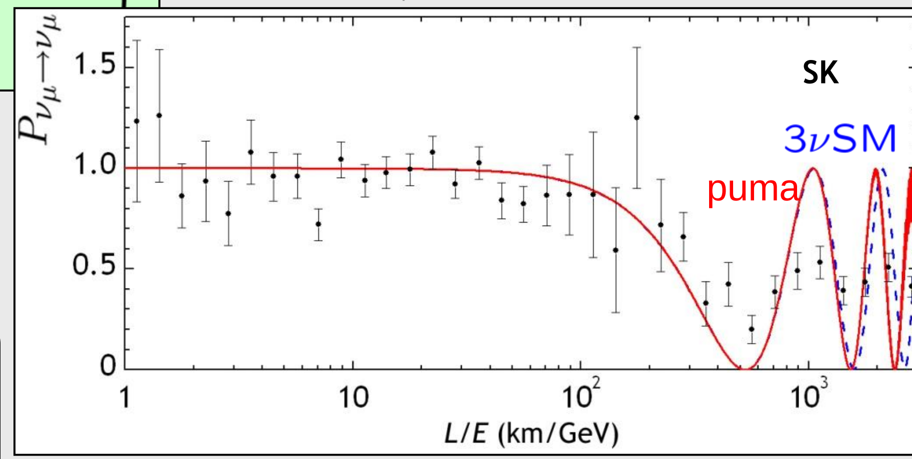

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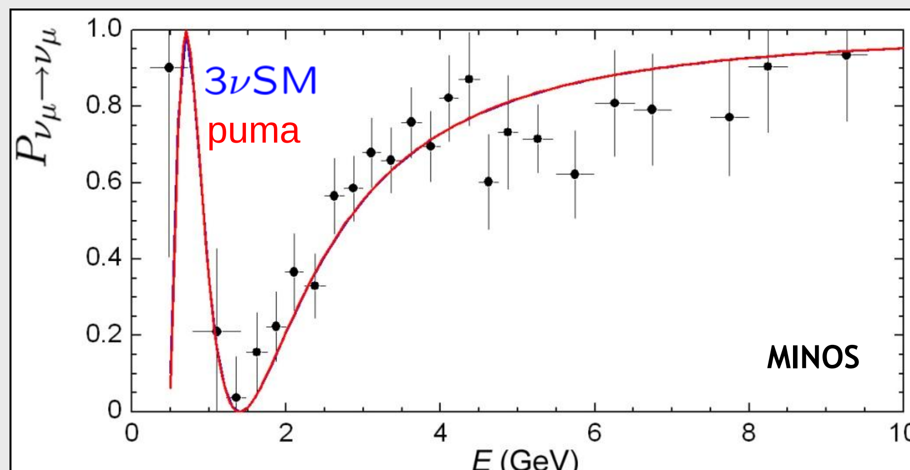

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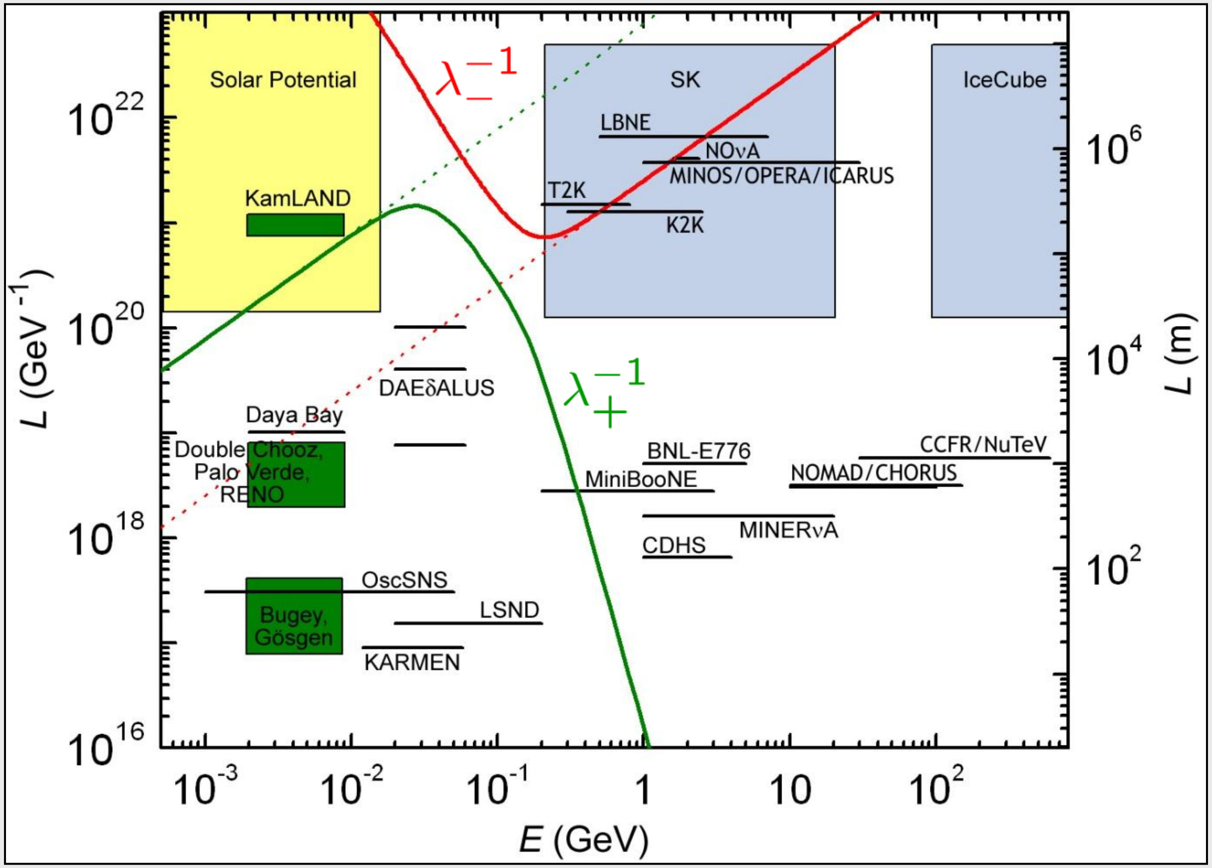
Remarkable natural feature:

Low-energy signal in MiniBooNE

$$P_{\nu_\mu\to\nu_e} \simeq A_{21}(U)\ \sin^2(\lambda_+ L/2)$$

Kostelecký & Mewes, PRD 2004

MiniBooNE



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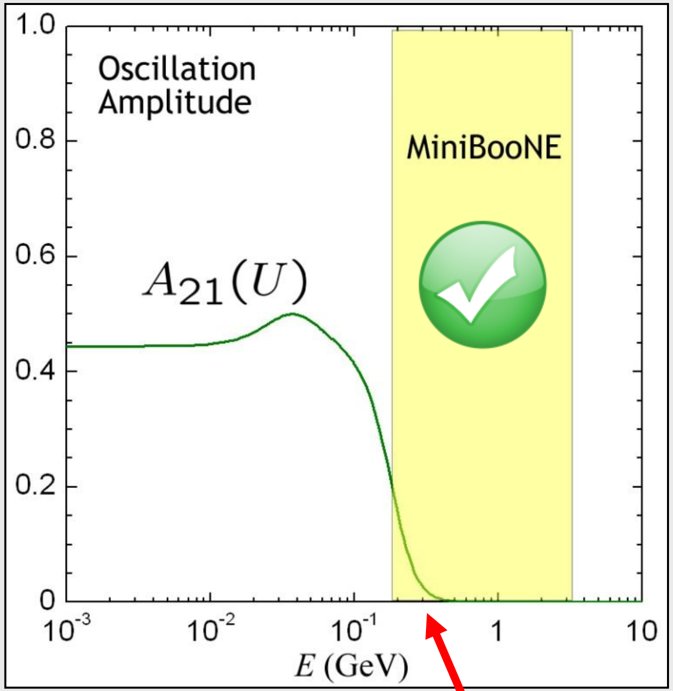
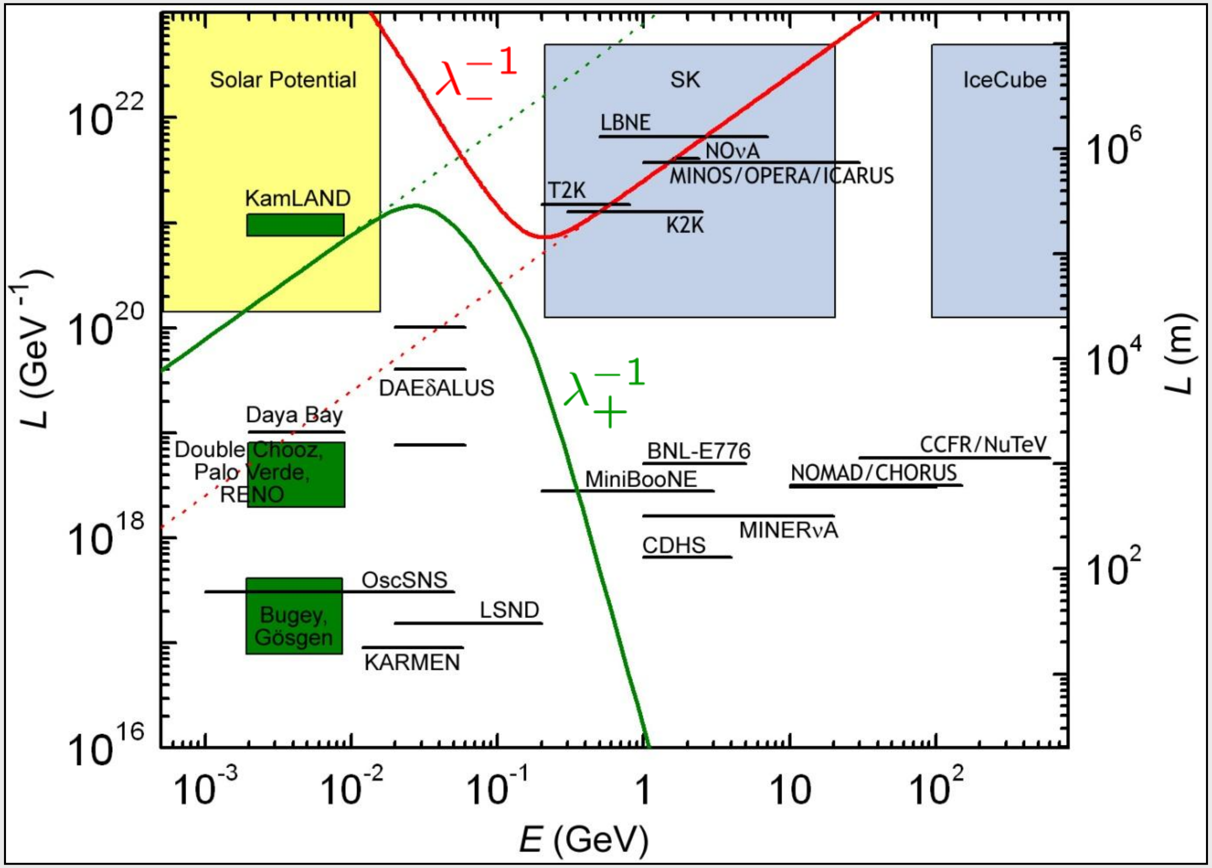


signal at low energy only



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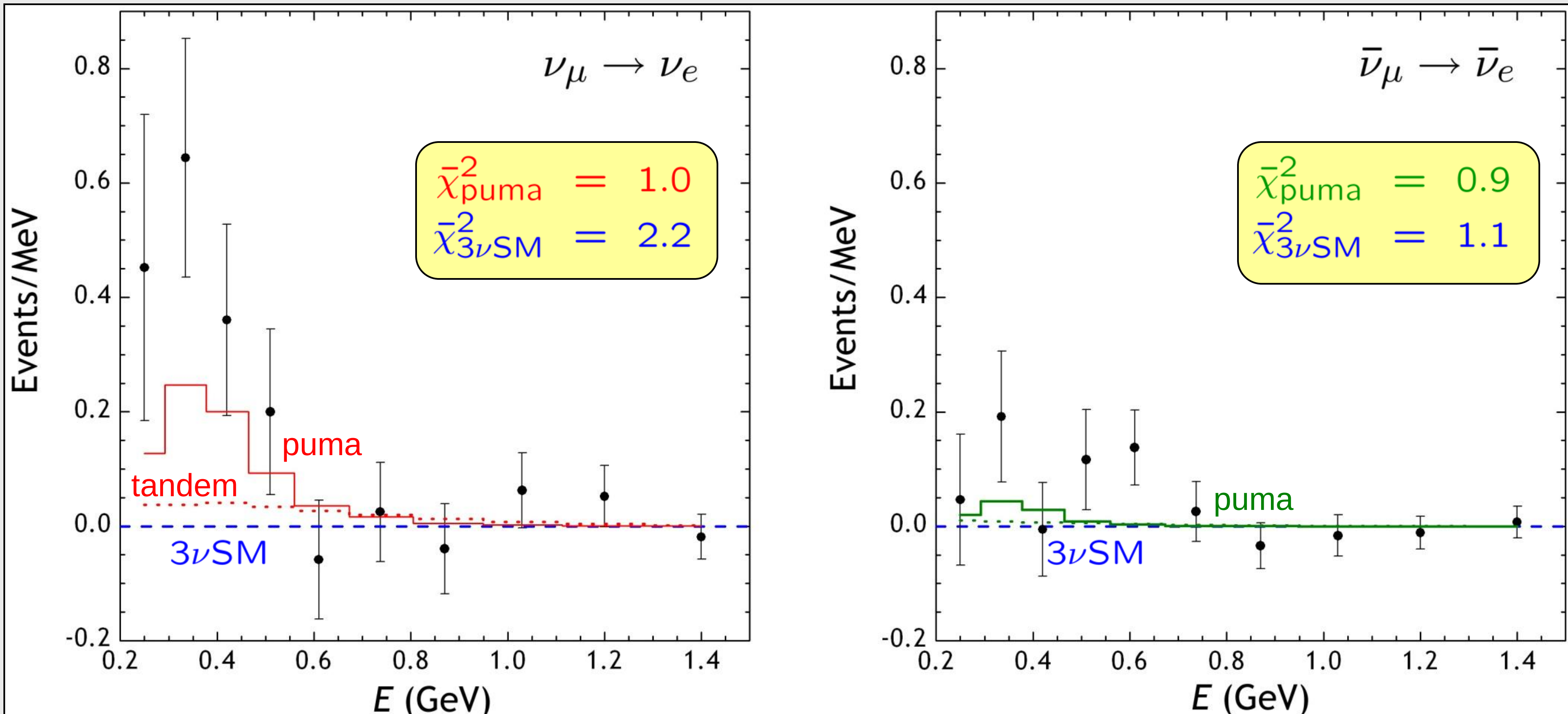


Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

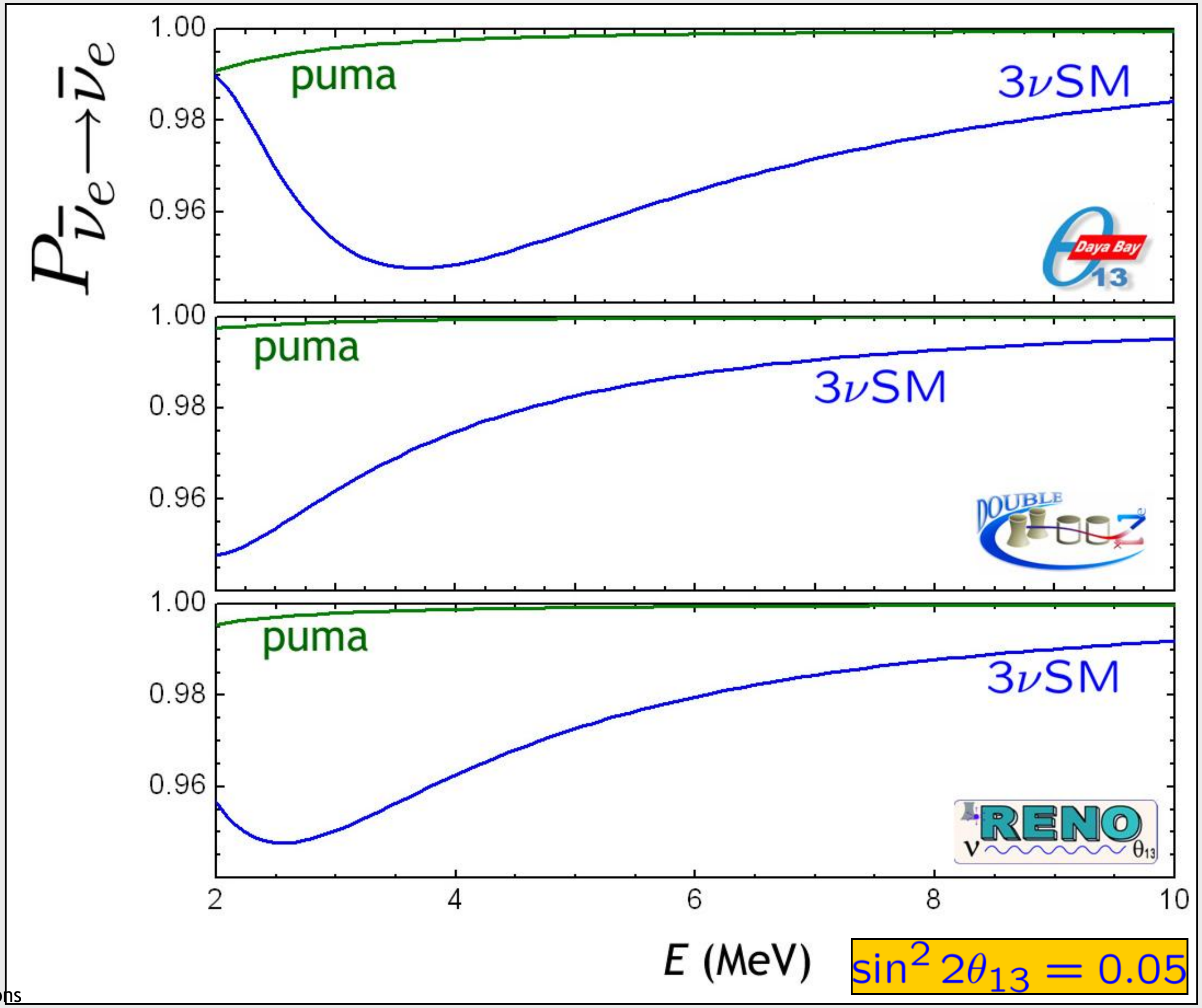
Predictions: new reactor experiments

Oscillation signals in Daya Bay, Double Chooz, and RENO driven by the solar mass term

Tribimaximal mixing at low energy

$$U \simeq \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$\sin\theta_{13}$



Lorentz-violating Neutrino Oscillations: puma model

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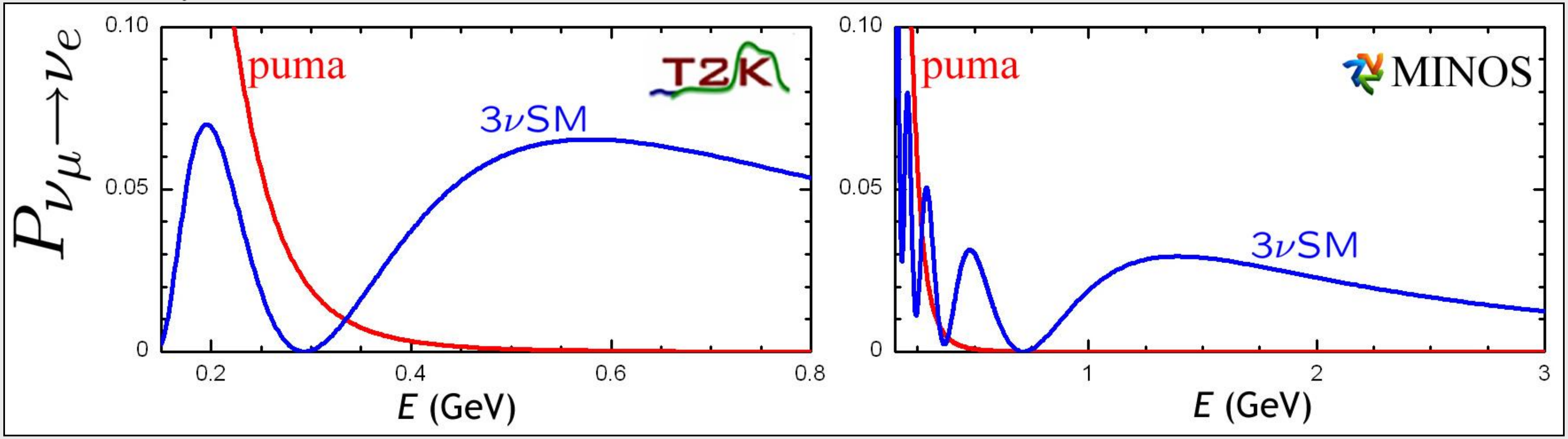
Predictions: long-baseline experiments

$$\nu_\mu \longrightarrow \nu_e$$



Appearance signal decreases with energy → $\sin^2 2\theta_{13}$ will be smaller in MINOS compared to T2K

Lorentz-violating Neutrino Oscillations: puma model

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PLB 2011
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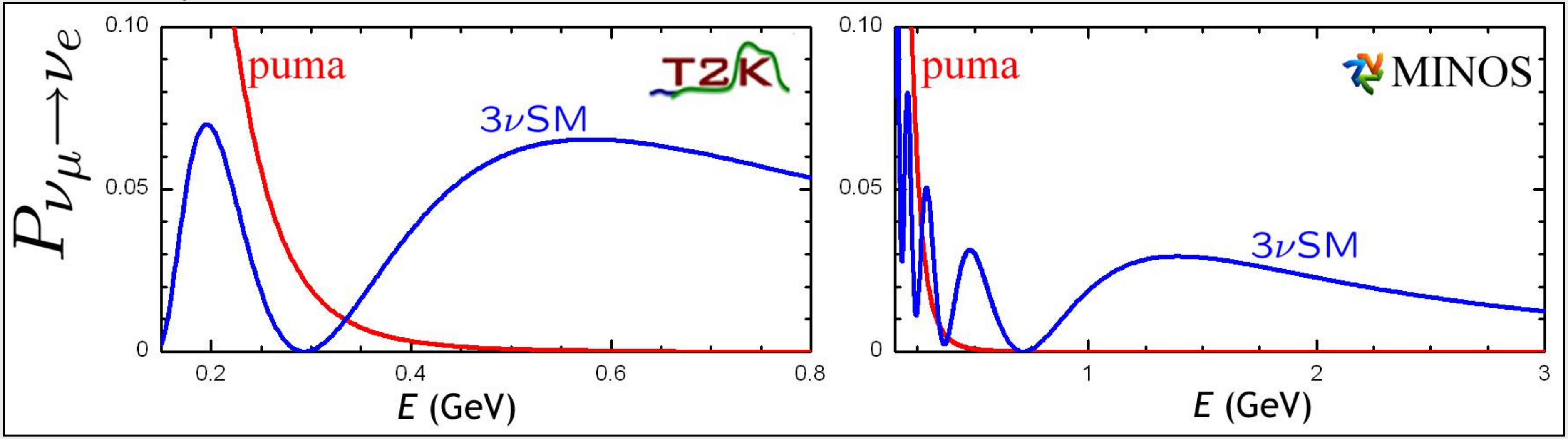

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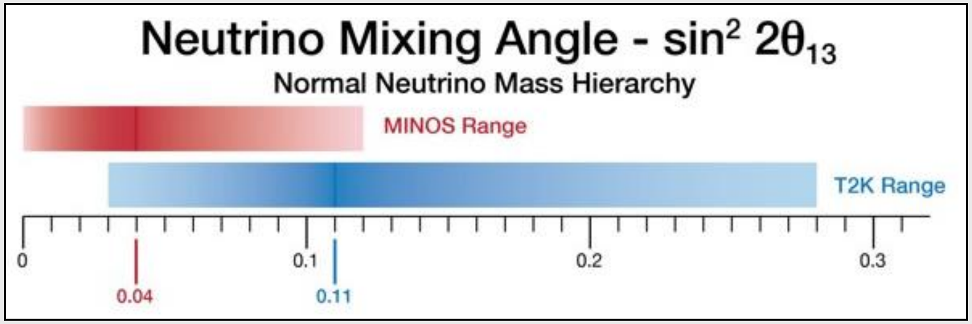
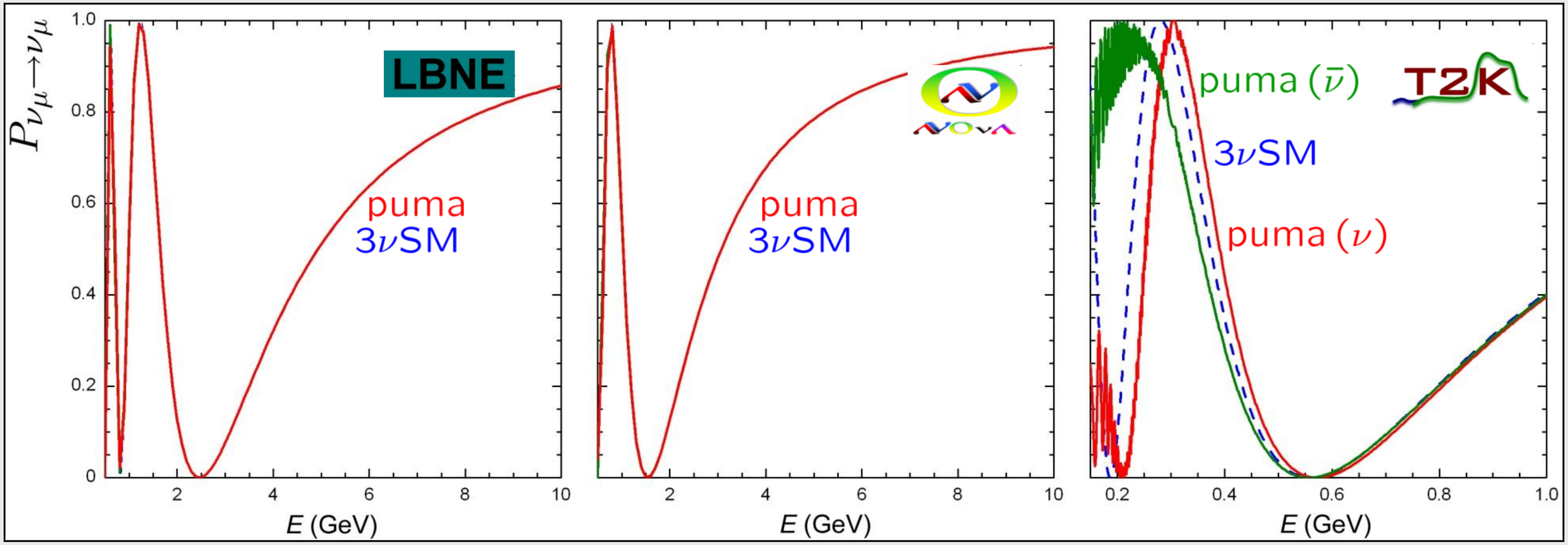


Lorentz-violating Neutrino Oscillations: puma model

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

Predictions: new long-baseline experiments

$$\nu_\mu \longrightarrow \nu_\mu$$



Conventional signal | Conventional signal | Unconventional signal

LSND: enhanced puma

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

- Our model does not include LSND
- We should explore possible extensions

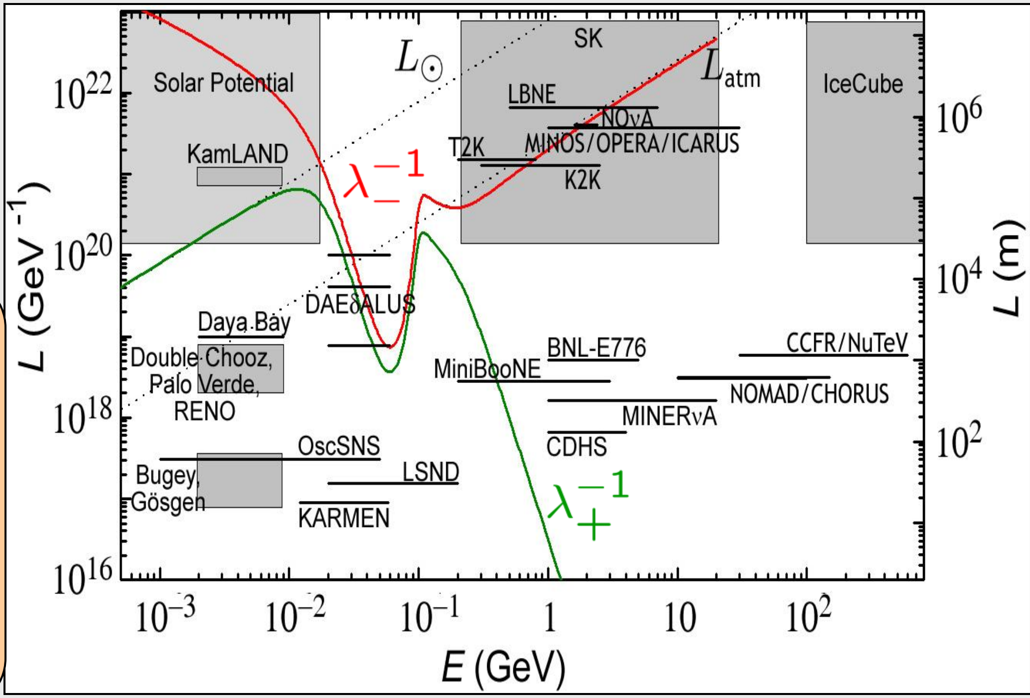
$$h^{\bar{\nu}}_{\text{eff}} = A \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \bar{B} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + \bar{C} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\bar{f}(E) = \alpha\, e^{-\beta(E-E_0)^2}$$

$$\begin{aligned} A &= m^2/2E, \\ \bar{B} &= -aE^2 + c'E + \bar{f}(E), \\ \bar{C} &= cE^5 - c'E - \bar{f}(E). \end{aligned}$$

Properties

- model fits LSND data better than 3νSM
- requires three new parameters
- clear oscillation signals in future experiments:
    - OscSNS
    - DAEδALUS



LSND: enhanced puma

JSD & V.A. Kostelecký
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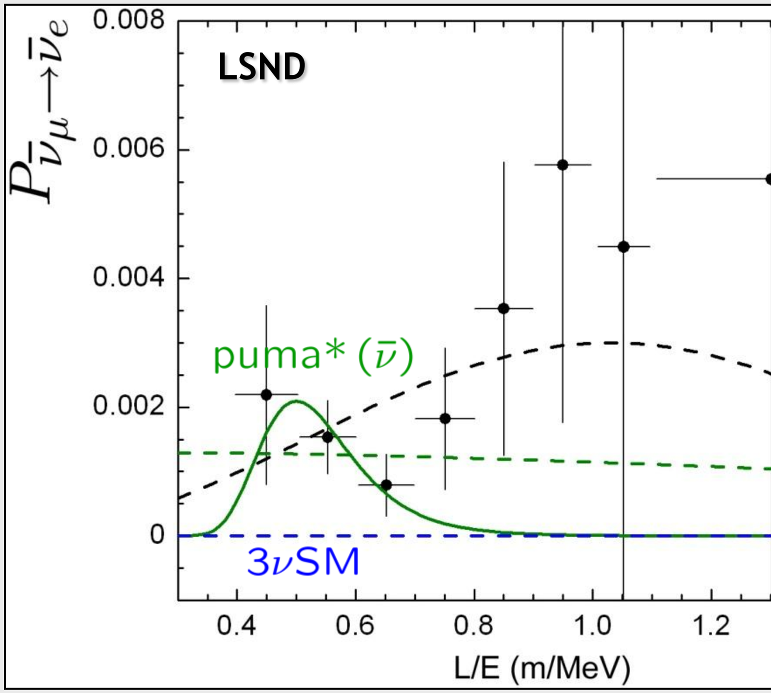
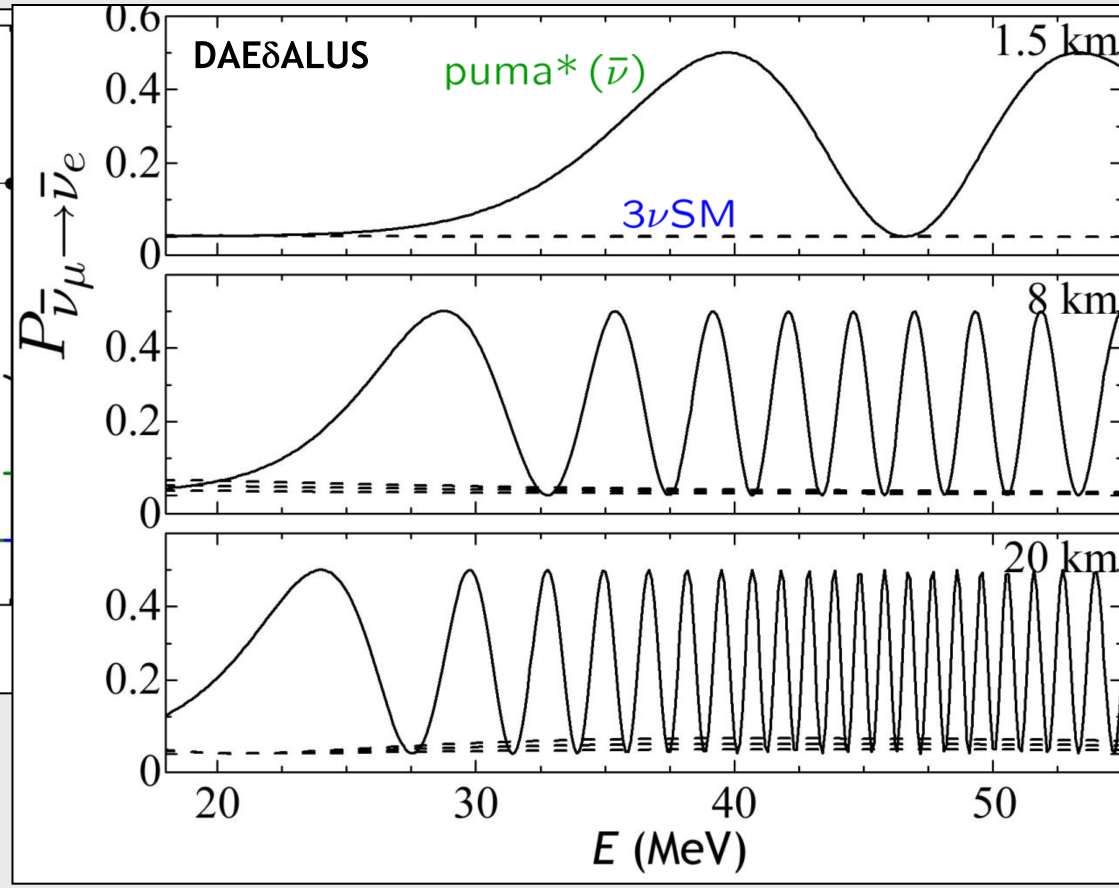
extension could be tested in future experiments





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Possible extension of the puma model

JSD & V.A. Kostelecký
PLB 2011
& arXiv:1108.1799

Addition of one more coefficient preserving the texture

Puma* model

$$h_{\text{eff}} = A\begin{pmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{pmatrix} + B\begin{pmatrix}1 & 1 & 1\\ 1 & 0 & 0\\ 1 & 0 & 0\end{pmatrix} + C\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$A = m^2/2E, \quad B = aE^2 + c'E, \quad C = cE^5 - c'E$$

Possible extension of the puma model

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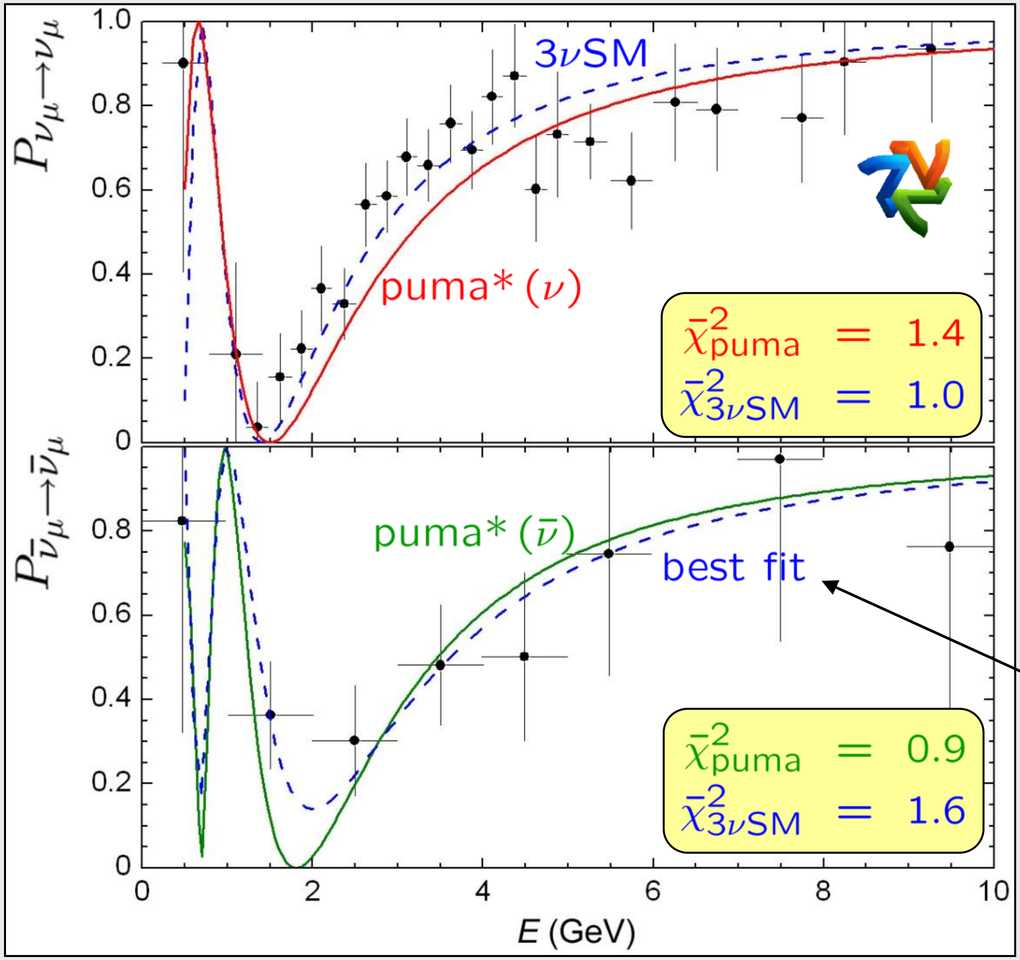
New features: $\nu \neq \bar{\nu}$ at high energies

MINOS



Neutrino-antineutrino difference is produced by a CPT-odd coefficient.

There are **no masses** at high energies.

best fit $\neq 3\nu$SM

Description of anomalies: parameters

3νSM	puma*
5	7
It does not explain - MiniBooNE 2007 - MiniBooNE 2010 - MINOS - LSND	consistent with everything

(*): extension

To my knowledge no other existing model is consistent with all compelling data and all the anomalies with 7 parameters. The puma is an economical model...

Summary

Puma model

• based on Lorentz and CPT violation;

• uses a total of 3 parameters (instead of 5 as the 3νSM);

• consistent will all established data (atmospheric, reactor, and solar neutrinos);

• naturally reproduces the two MiniBooNE anomalies;

• simple extensions produce signals of the LSND and MINOS type;

• predictions for $\nu_\mu \rightarrow \nu_e$ in agreement with recent results from MINOS and T2K;

• realistic possible solution to some anomalies without extra particles or interactions;

• more details can be found in arXiv:1108.1799.