Neutrino Interferometry for High-Precision Tests of Space-Time Symmetry

TK, MPLA27(2012)1230024
IceCube, Nature Physics 14(2018)961

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Teppei Katori for the IceCube collaboration
Queen Mary University of London
HEP seminar, University of Edinburgh, UK, Nov. 9, 2018

THE ROYAL SOCIETY

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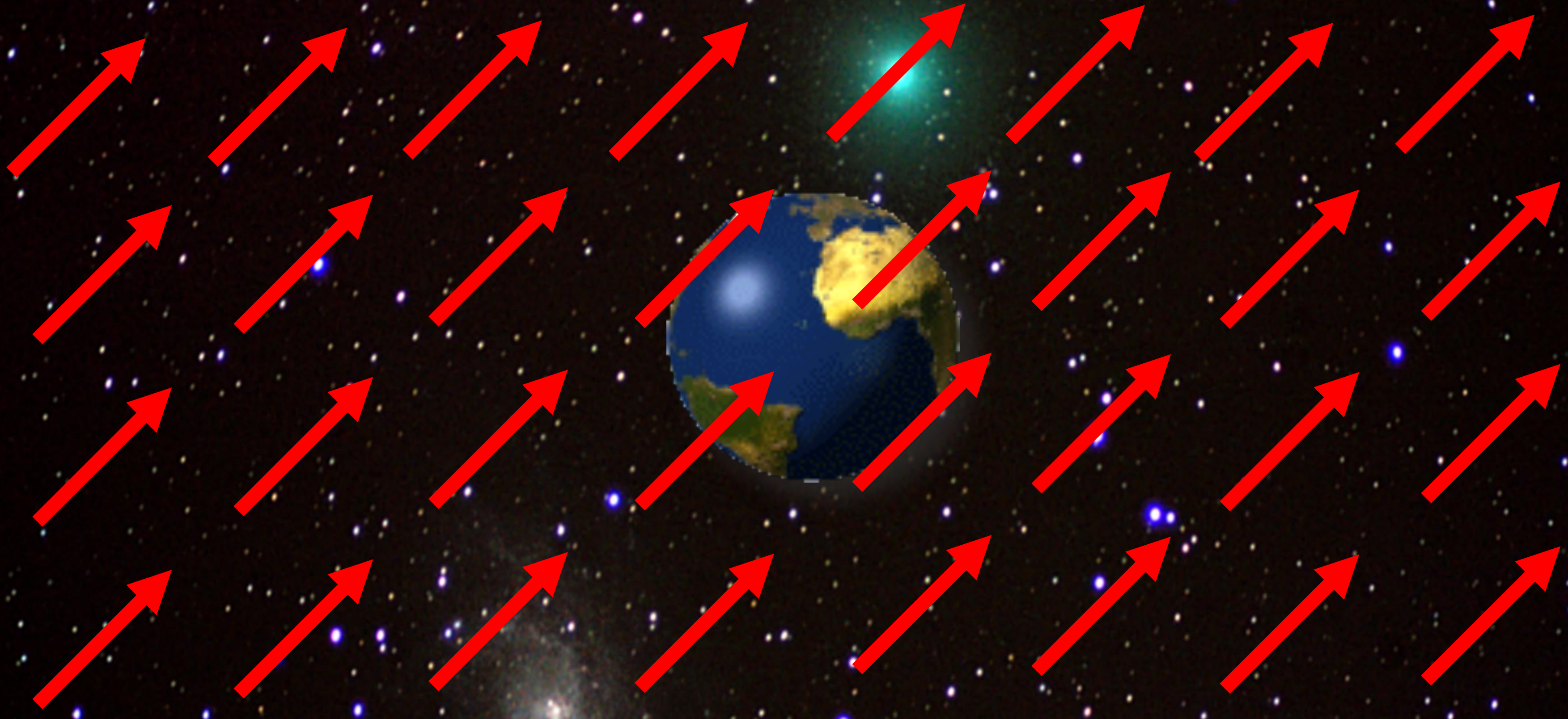
$$\bar{\psi}\gamma_{\mu}a^{\mu}\psi$$



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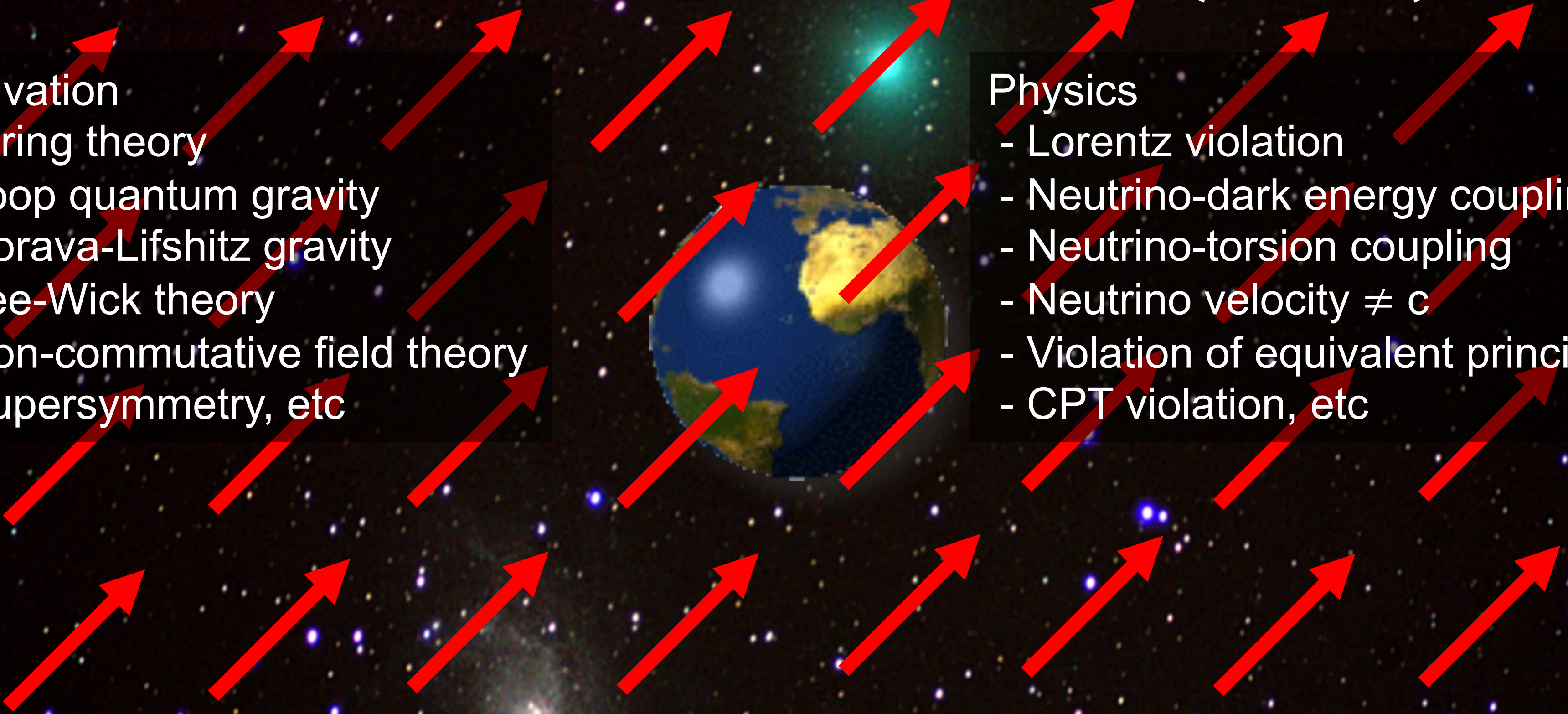
$$\bar{\psi}\gamma_{\mu}a^{\mu}\psi = a|\psi|^2$$

$$a^{\mu} = (a,0,0,0)$$



Motivation
- String theory
- Loop quantum gravity
- Horava-Lifshitz gravity
- Lee-Wick theory
- Non-commutative field theory
- Supersymmetry, etc

Physics
- Lorentz violation
- Neutrino-dark energy coupling
- Neutrino-torsion coupling
- Neutrino velocity ≠ c
- Violation of equivalent principle
- CPT violation, etc

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outline

1. Neutrino Interferometry
2. Spontaneous Lorentz symmetry breaking
3. Modern test of Lorentz violation
4. Test of Lorentz violation with neutrino data
5. Astrophysical very-high-energy neutrinos
6. Lorentz violation tests on astrophysical neutrinos
7. Conclusion

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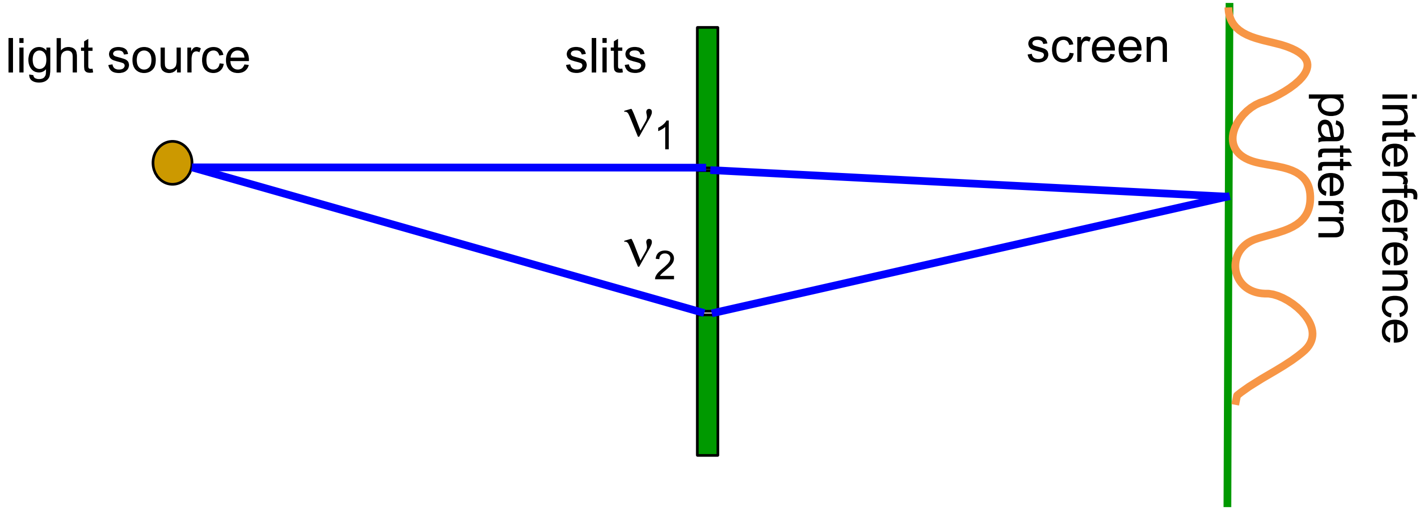
1. Neutrino oscillation - natural interferometer

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.

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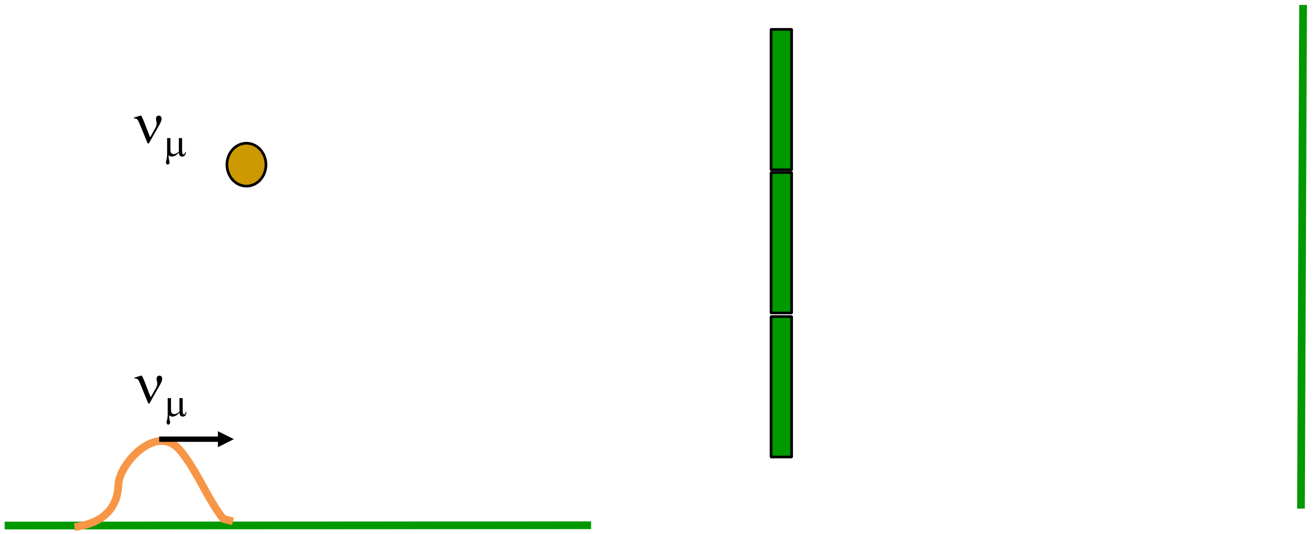

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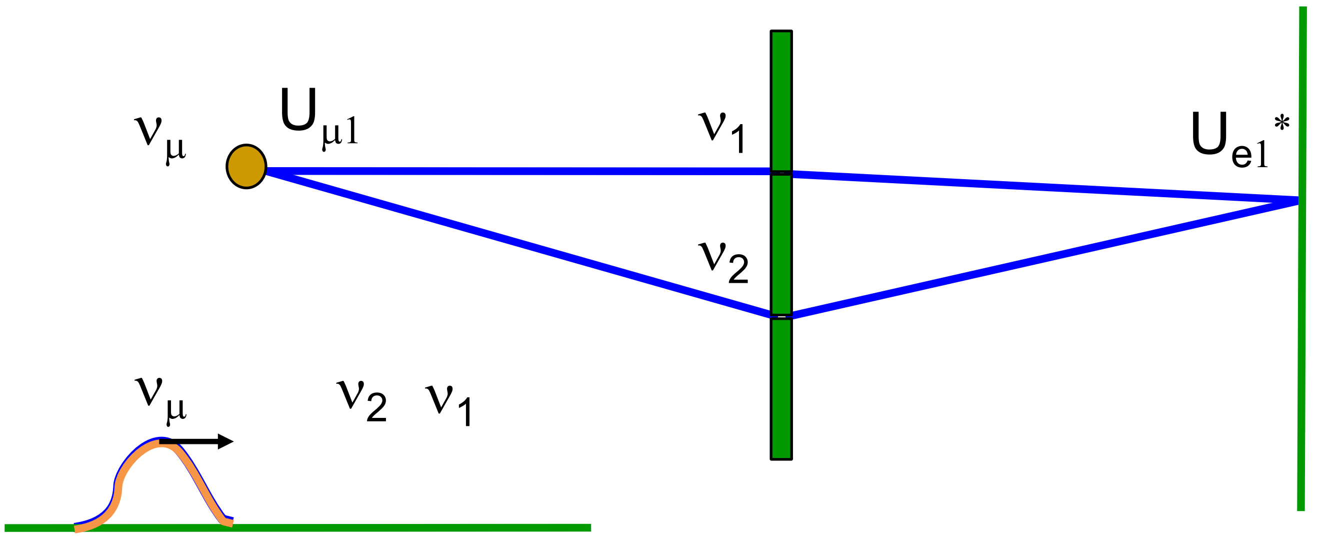

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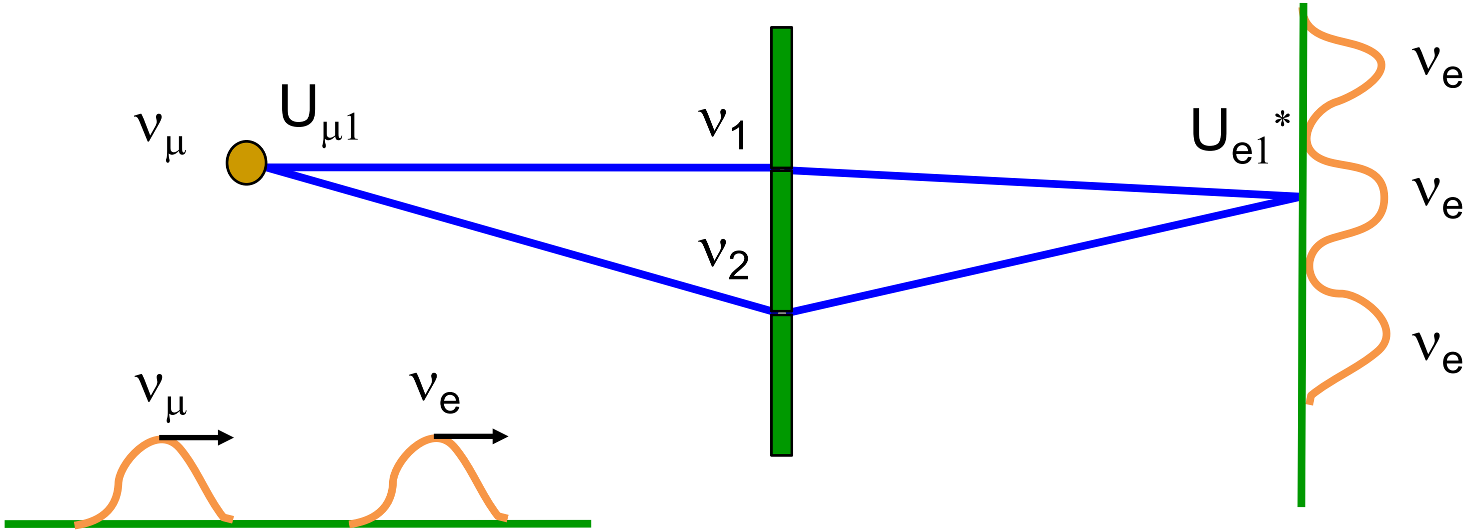

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

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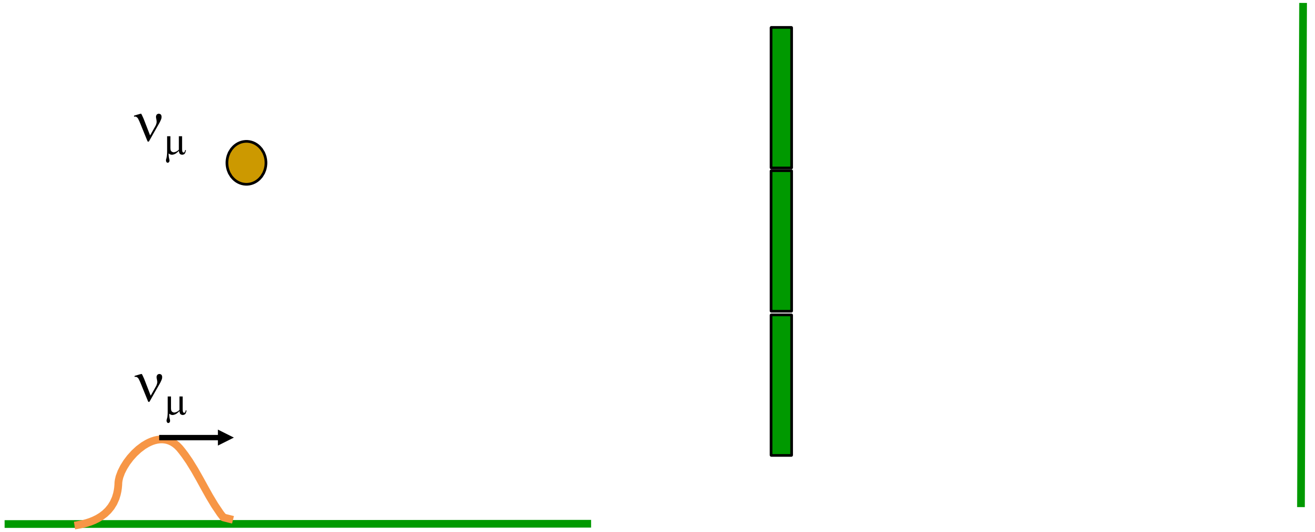
The detection may be different flavor (neutrino oscillations).

1. Neutrino oscillation as a probe of new physics

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



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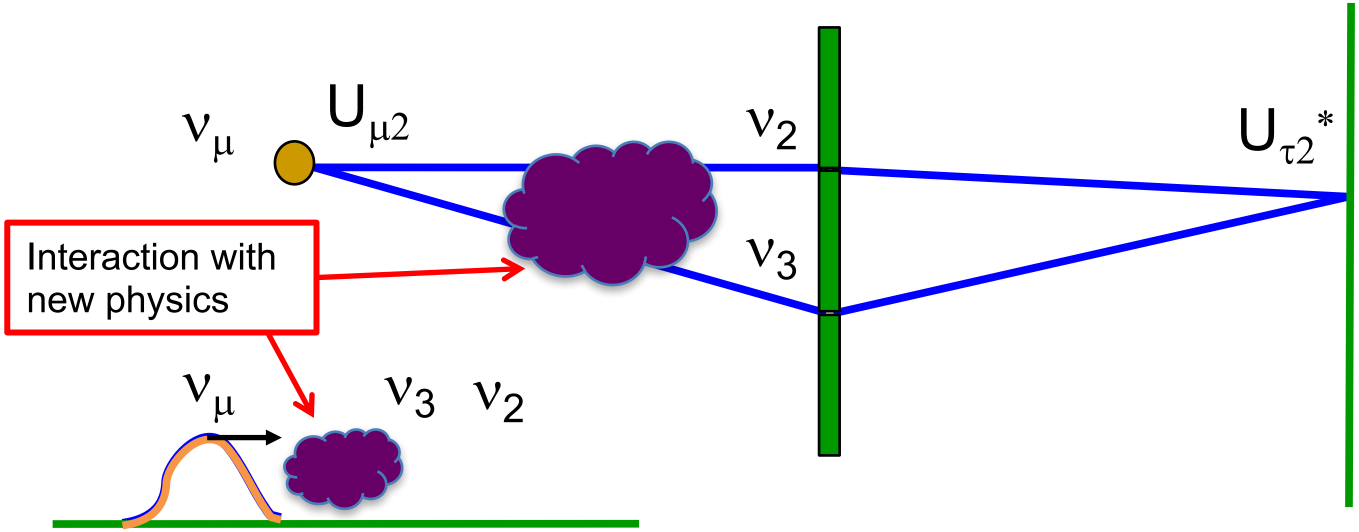

If 2 neutrino Hamiltonian eigenstates, ν_1 and ν_2, have different phase rotation, they cause quantum interference.

If ν_1 and ν_2, have different coupling with new physics field, neutrinos also oscillate. The sensitivity of "neutrino interferometer" can beyond precise atomic/optical interferometers.

- Longer propagation length (LIGO = 4km, Atmospheric neutrino = 12700 km)
- Higher energy (Gamma ray ~ 100 GeV, Astrophysical neutrino ~ 1 PeV)

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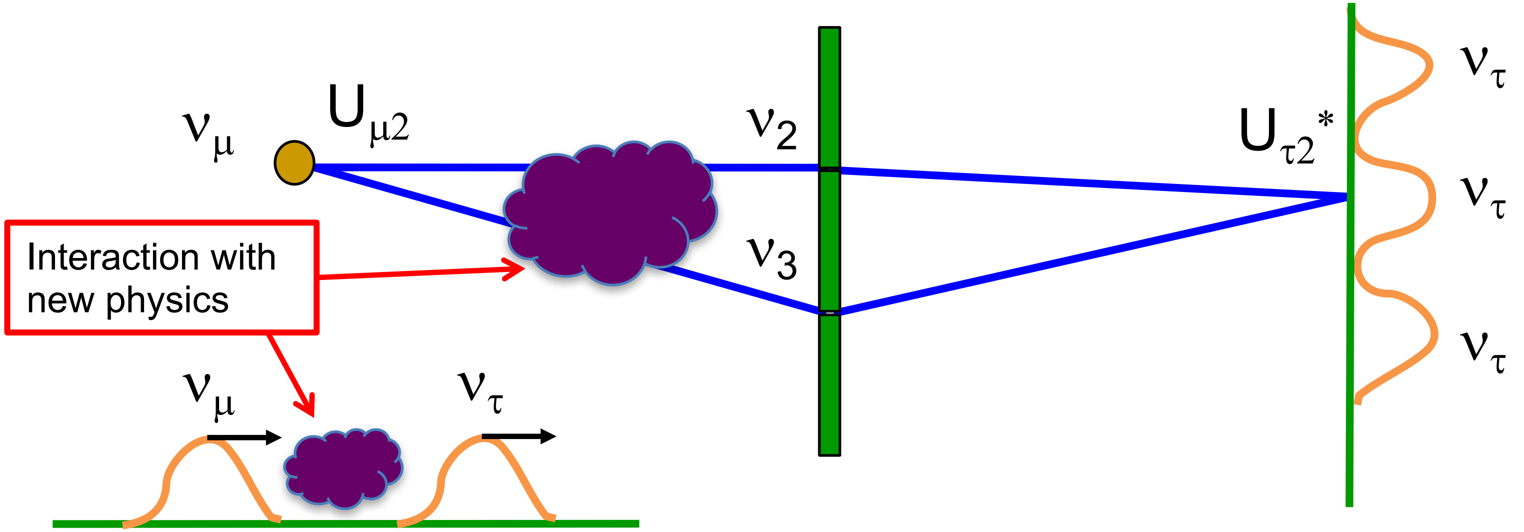

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1. Neutrino Interferometry

2. **Spontaneous Lorentz symmetry breaking**

3. Modern test of Lorentz violation

4. Test of Lorentz violation with neutrino data

5. Astrophysical very-high-energy neutrinos

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2. Spontaneous Lorentz symmetry breaking (SLSB)

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 from CPT04 at
Bloomington, IN

2. Spontaneous Lorentz symmetry breaking (SLSB)

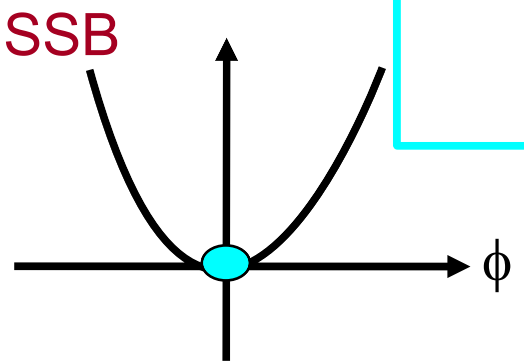
vacuum Lagrangian for fermion $L = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi$

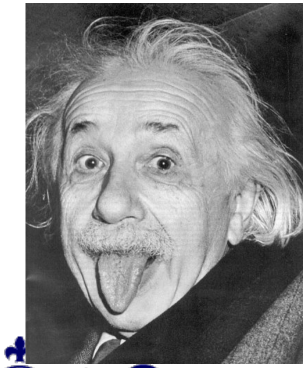
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

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





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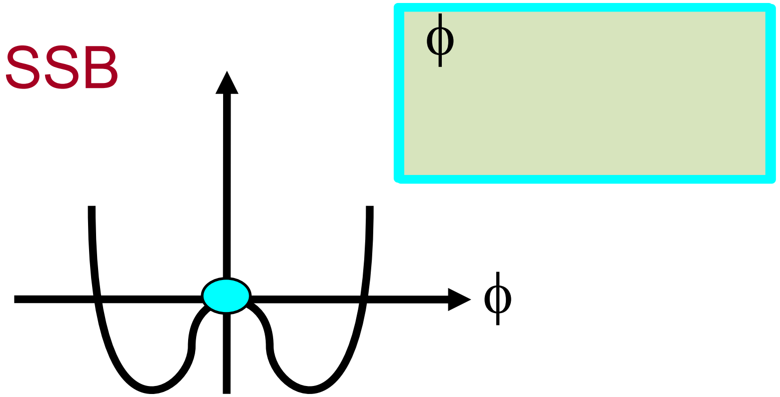

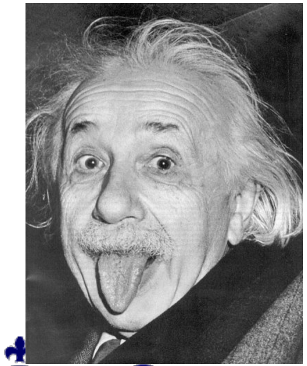

Particle acquires mass term!

Kostelecký and Samuel,PRD39(1989)683

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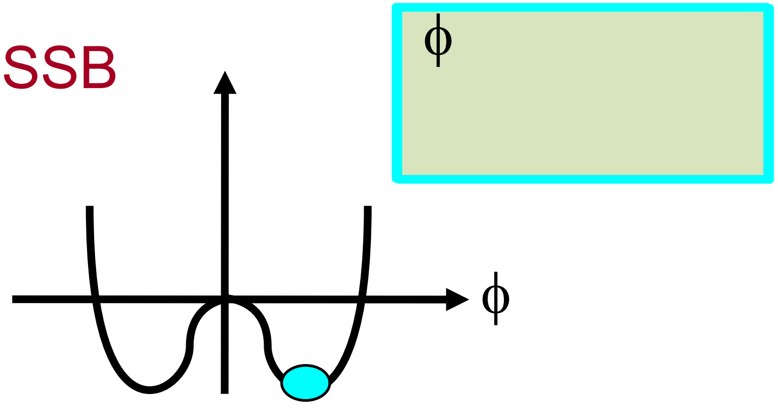
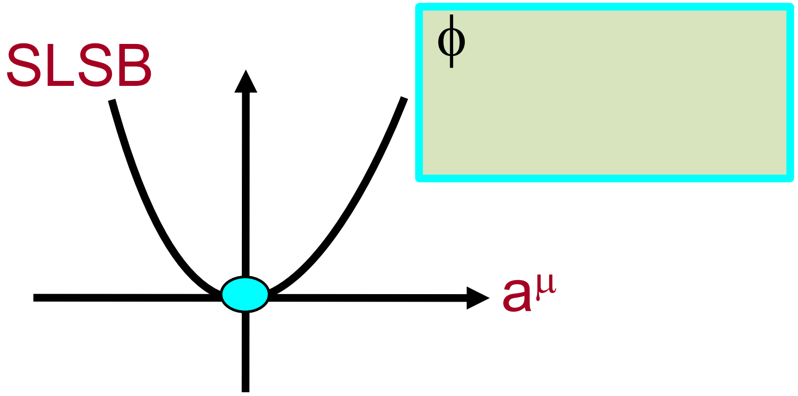
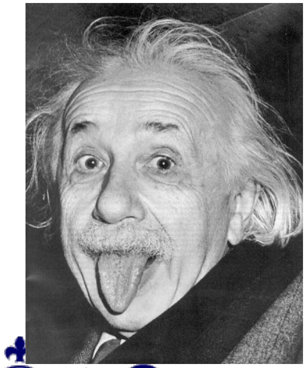


e.g.) SLSB in string field theory

- 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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2. 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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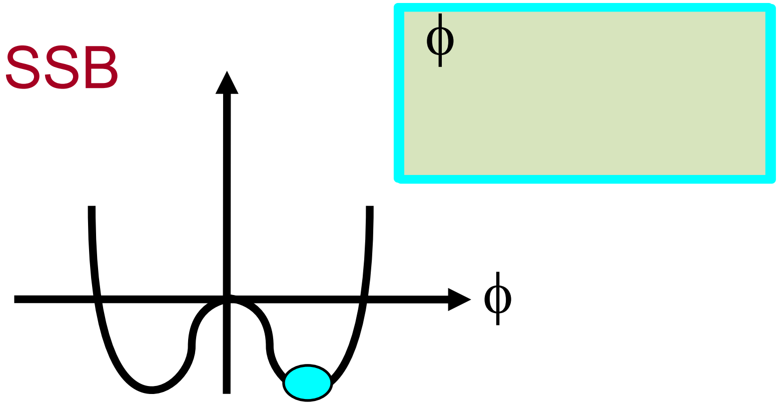
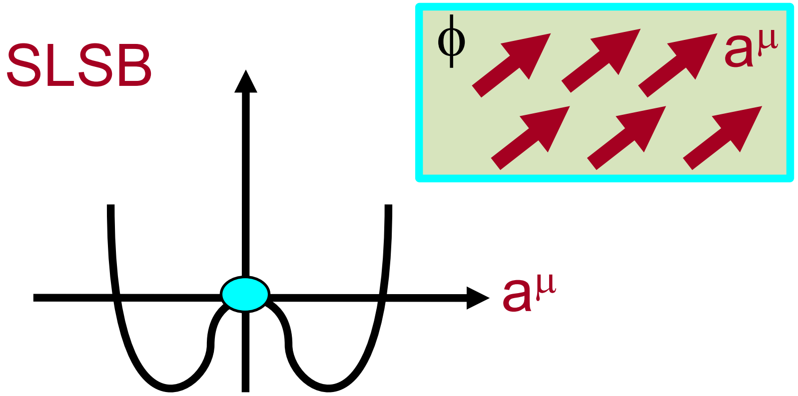
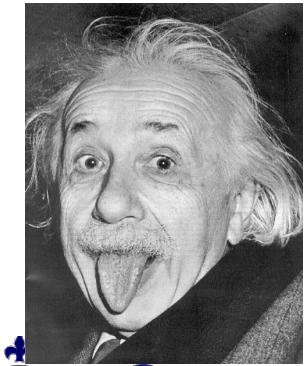






Lorentz symmetry is spontaneously broken!

2. Spontaneous Lorentz symmetry breaking (SLSB)

Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos, etc)

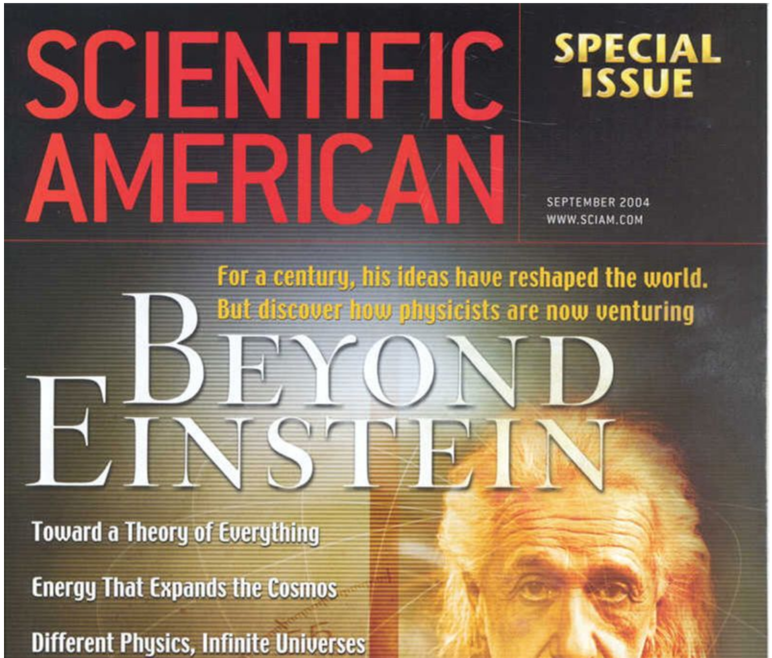
background fields of the universe

vacuum Lagrangian for fermion

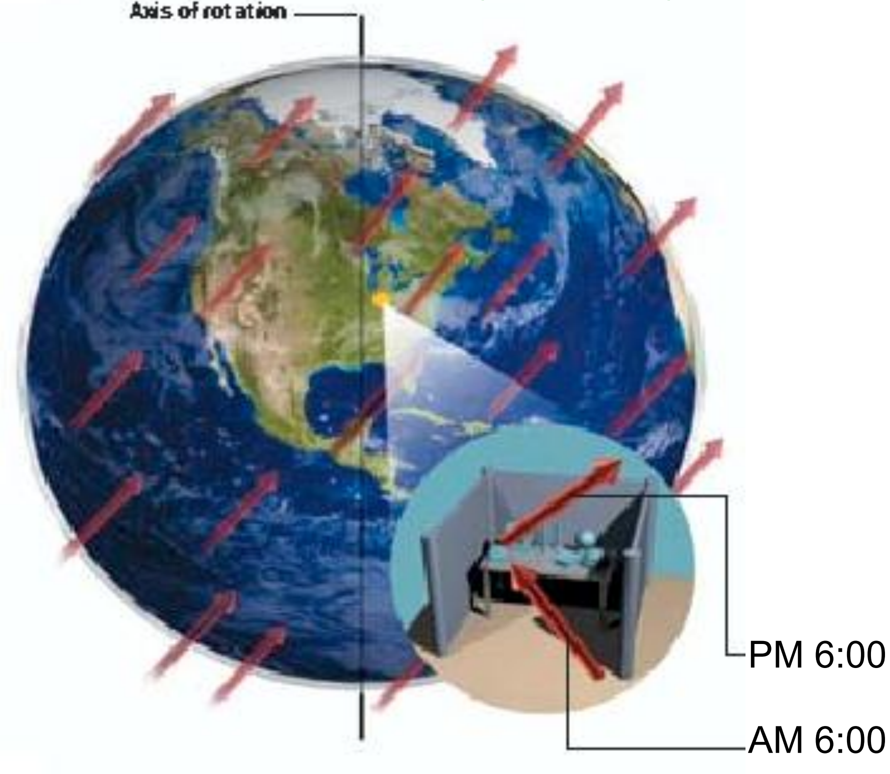
$$L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi + \bar{\Psi}\gamma_\mu\boxed{a^\mu}\Psi + \bar{\Psi}\gamma_\mu\boxed{c^{\mu\nu}}\partial_\nu\Psi \ldots$$

Physics of Lorentz violation

- Sidereal time dependence
- Spectrum distortion
- etc…



Scientific American (Sept. 2004)



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Physics of Lorentz violation

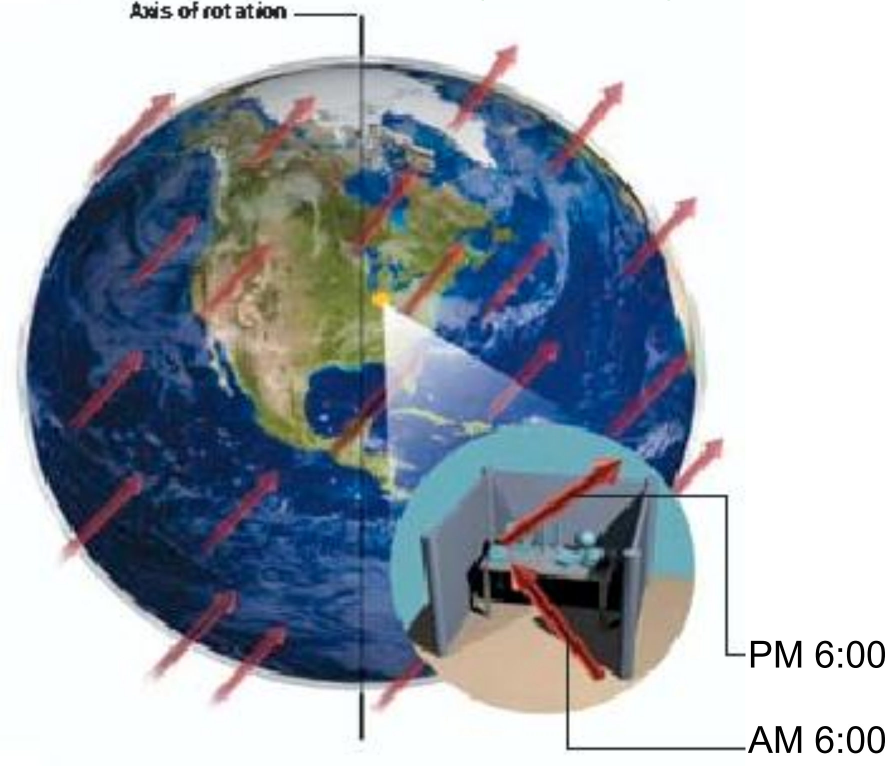
- Sidereal time dependence
- Spectrum distortion

MiniBooNE, PLB(2017)111101

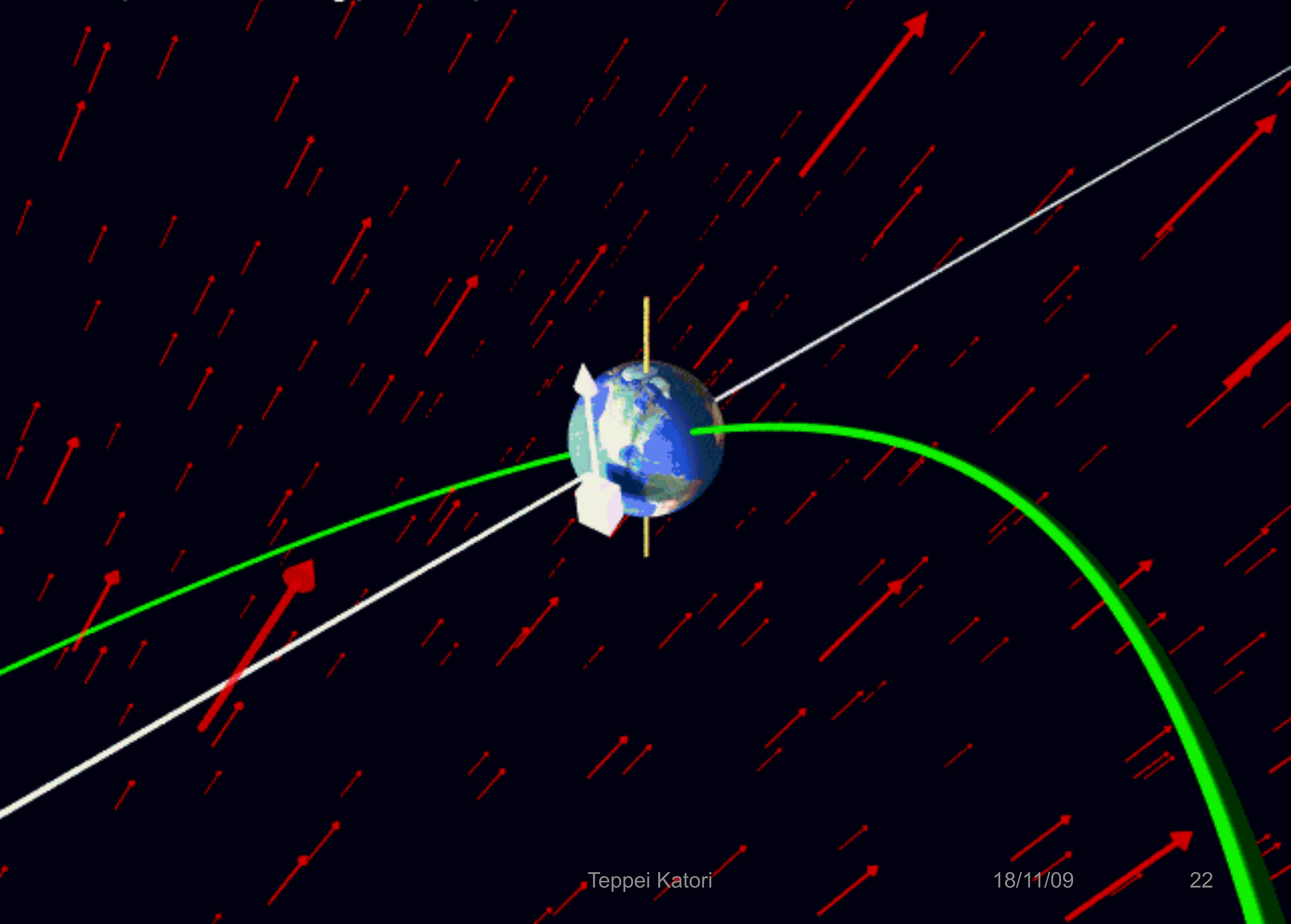
Solar time: 24h 00m 00.0s
sidereal time: 23h 56m 04.1s

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?!

Scientific American (Sept. 2004)



Bluhm, Kostelecky, Lane, Russell PRL 2002



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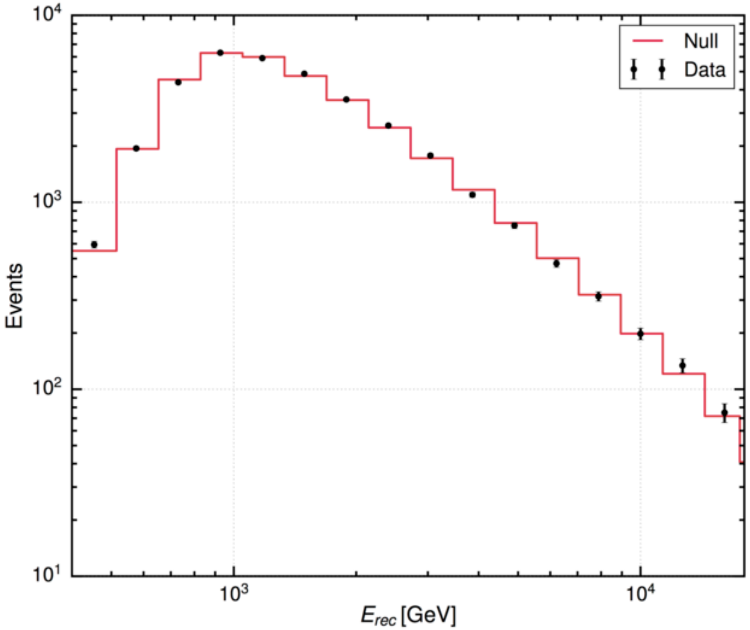
Physics of Lorentz violation

- Sidereal time dependence MiniBooNE, PLB(2017)111101
- Spectrum distortion IceCube, Nature Physics 14 (2018) 961

Oscillation phase may be shifted by Lorentz violation. This can be seen by distortion of the spectrum.



IceCube through going up-muon sample

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Kostelecký and Mewes, PRD69(2004)016005;70(2004)076002

3. Test of Lorentz violation

Lorentz violation is realized as a coupling of particle fields and background fields.

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

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

SME Lagrangian in neutrino sector

$$L = \frac{1}{2} i \bar{\psi}_A \Gamma^{\nu}_{AB} \partial_{\nu} \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.$$

SME coefficients

$$\Gamma^{\nu}_{AB} = \gamma^{\nu} \delta_{AB} + c^{\mu\nu}_{AB} \gamma_{\mu} + d^{\mu\nu}_{AB} \gamma_{\mu} \gamma_5 + e^{\nu}_{AB} + i f^{\nu}_{AB} \gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB} \sigma_{\lambda\mu} \cdots$$

$$M_{AB} = m_{AB} + i m_{5AB} \gamma_5 + a^{\mu}_{AB} \gamma_{\mu} + b^{\mu}_{AB} \gamma_5 \gamma_{\mu} + \frac{1}{2} H^{\mu\nu}_{AB} \sigma_{\mu\nu} \cdots$$

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Various physics are predicted under SME…

Lagrangian → Hamiltonian → Observables

MiniBooNE, PLB(2017)111101

e.g.) Neutrino oscillation probability with sidereal variation due to Lorentz violation

$$P_{\nu_\mu\to\nu_e}(L,T_\oplus) = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{e\mu} + (A_s)_{e\mu} sin\omega_\oplus T_\oplus + (A_c)_{e\mu} cos\omega_\oplus T_\oplus + (A_s)_{e\mu} sin2\omega_\oplus T_\oplus + (A_c)_{e\mu} cos2\omega_\oplus T_\oplus\right|^2$$

IceCube, Nature Physics 14 (2018) 961

e.g.)Neutrino oscillation probability with spectral distortion due to Lorentz violation

$$P_{\nu_\mu\to\nu_x} = P_{\nu_\mu\to\nu_x}\big(h_{eff}(E),L\big), \quad h_{eff}(E) = \frac{m^2}{2E} + a_3 - c_4E + a_5E^2 - c_6E^3 + a_5E^2 - c_6E^3 + \cdots$$

and more…

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

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MiniBooNE, PRL110(2013)161801;arXiv:1805.12028

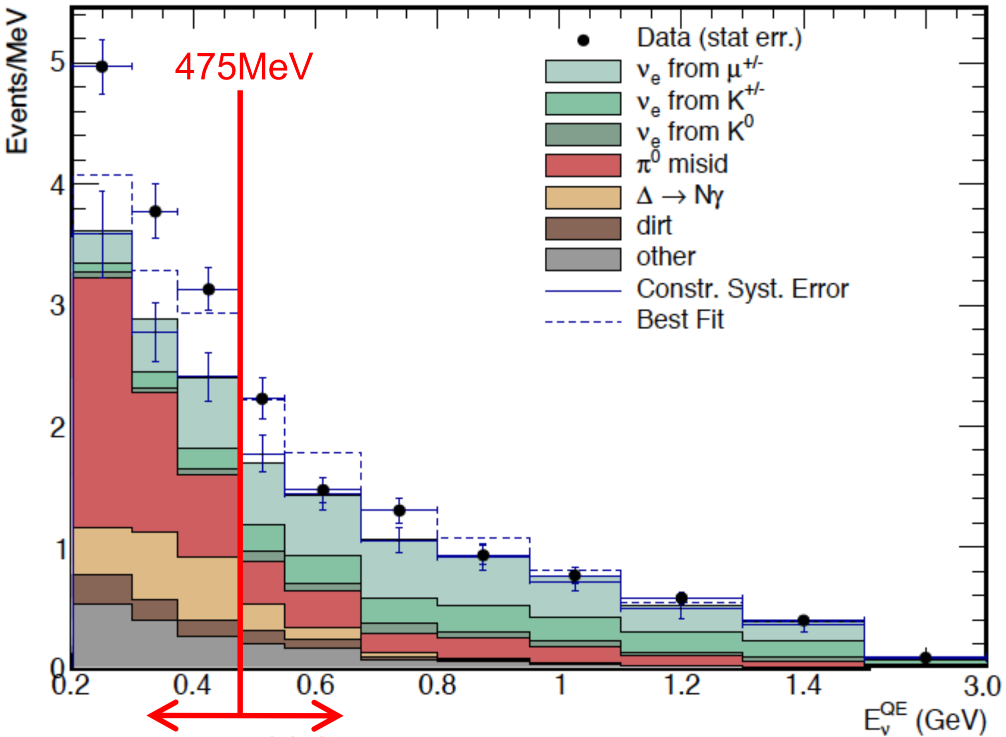
4. MiniBooNE ν_e appearance candidate data

Low energy excess

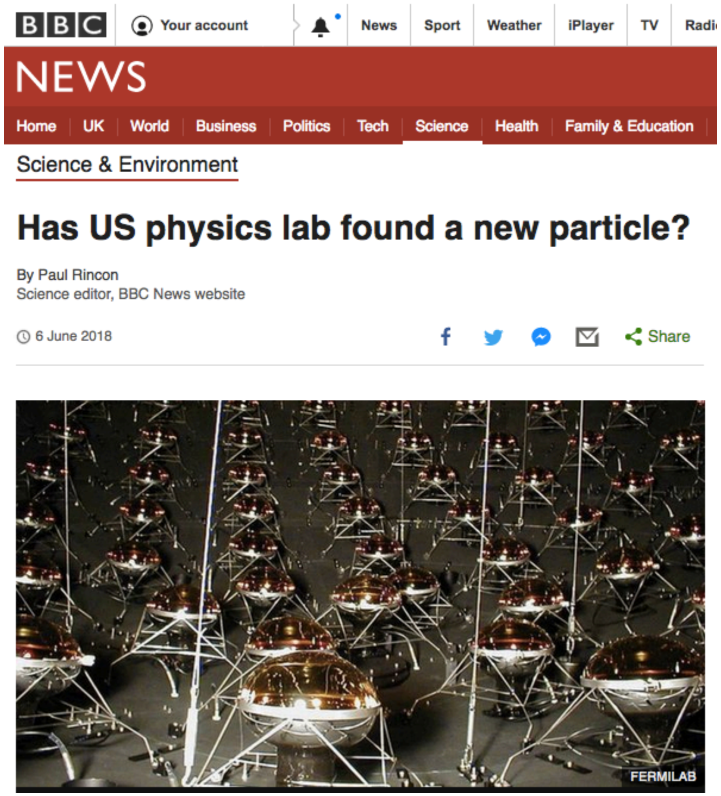
MiniBooNE excess is mostly low energy region where we don't expect excess from LSND.

This might be new physics such as Lorentz violation?

MiniBooNE low E ν_e excess



low energy high energy



Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

MiniBooNE, PLB718(2013)1303

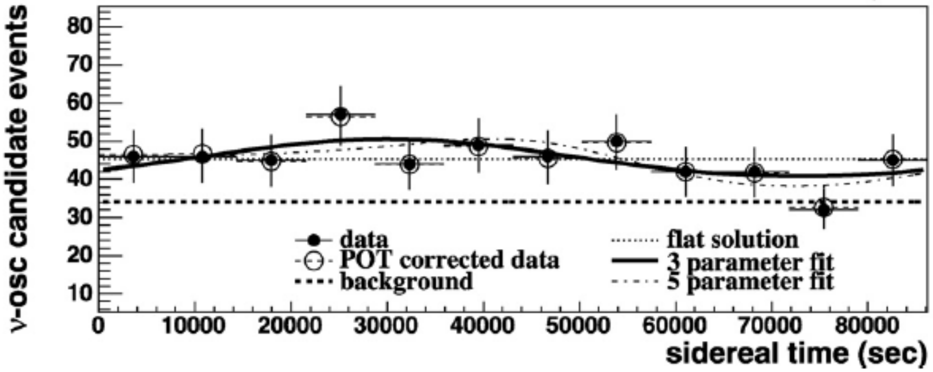
4. Lorentz violation with MiniBooNE neutrino data

MiniBooNE data has weak (~6%) day-night effect mainly due to accelerator operation

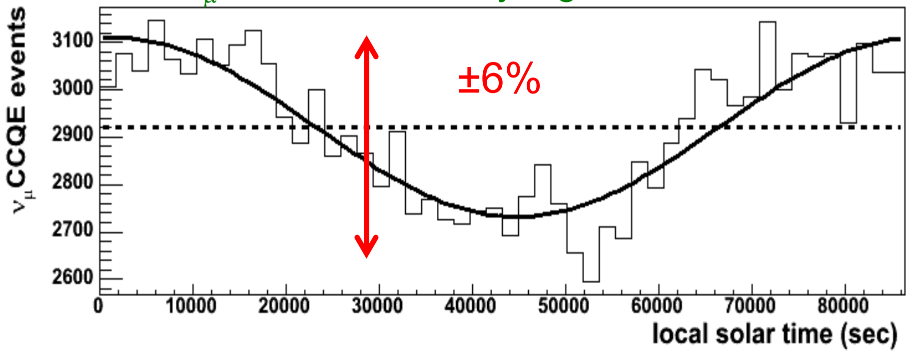
Both neutrino mode and anti-neutrino mode data are consistent with no sidereal time variation

We find no evidence of Lorentz violation

Neutrino mode electron candidate data sidereal time distribution



ν_μCCQE events day-night distribution



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

	ν-mode BF	2σ limit	$\bar{\nu}$-mode BF	2σ limit
$\lvert(\mathcal{C})_{e\mu}\rvert$	$3.1 \pm 0.6 \pm 0.9$	< 4.2	$0.1 \pm 0.8 \pm 0.1$	< 2.6
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$0.6 \pm 0.9 \pm 0.3$	< 3.3	$2.4 \pm 1.3 \pm 0.5$	< 3.9
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$0.4 \pm 0.9 \pm 0.4$	< 4.0	$2.1 \pm 1.2 \pm 0.4$	< 3.7

	SME coefficients combination (unit 10^{-20} GeV)
$\lvert(\mathcal{C})_{e\mu}\rvert$	$\pm[(a_L)^T_{e\mu} + 0.75(a_L)^Z_{e\mu}] - \langle E\rangle[1.22(c_L)^{TT}_{e\mu} + 1.50(c_L)^{TZ}_{e\mu} + 0.34(c_L)^{ZZ}_{e\mu}]$
$\lvert(\mathcal{A}_s)_{e\mu}\rvert$	$\pm[0.66(a_L)^Y_{e\mu}] - \langle E\rangle[1.33(c_L)^{TY}_{e\mu} + 0.99(c_L)^{YZ}_{e\mu}]$
$\lvert(\mathcal{A}_c)_{e\mu}\rvert$	$\pm[0.66(a_L)^X_{e\mu}] - \langle E\rangle[1.33(c_L)^{TX}_{e\mu} + 0.99(c_L)^{XZ}_{e\mu}]$

Queen Mary
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LSND, PRD72(2005)076004

4. Lorentz violation with LSND data

LSND experiment

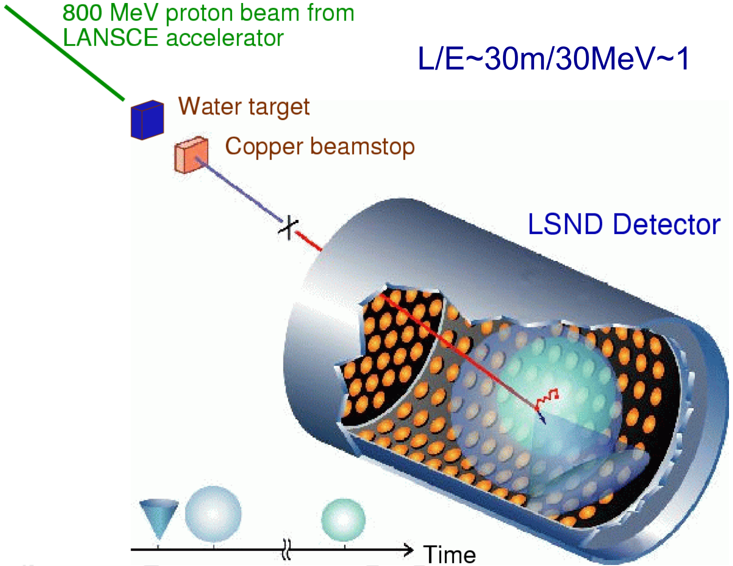
LSND is a short-baseline neutrino oscillation experiment at Los Alamos.

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

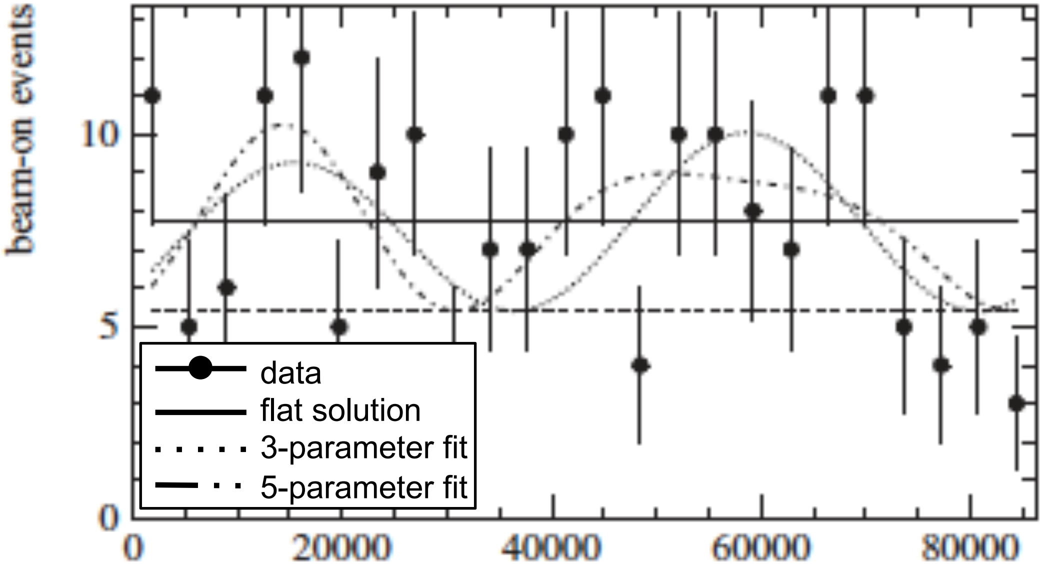
$$n + p \rightarrow d + \gamma$$

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

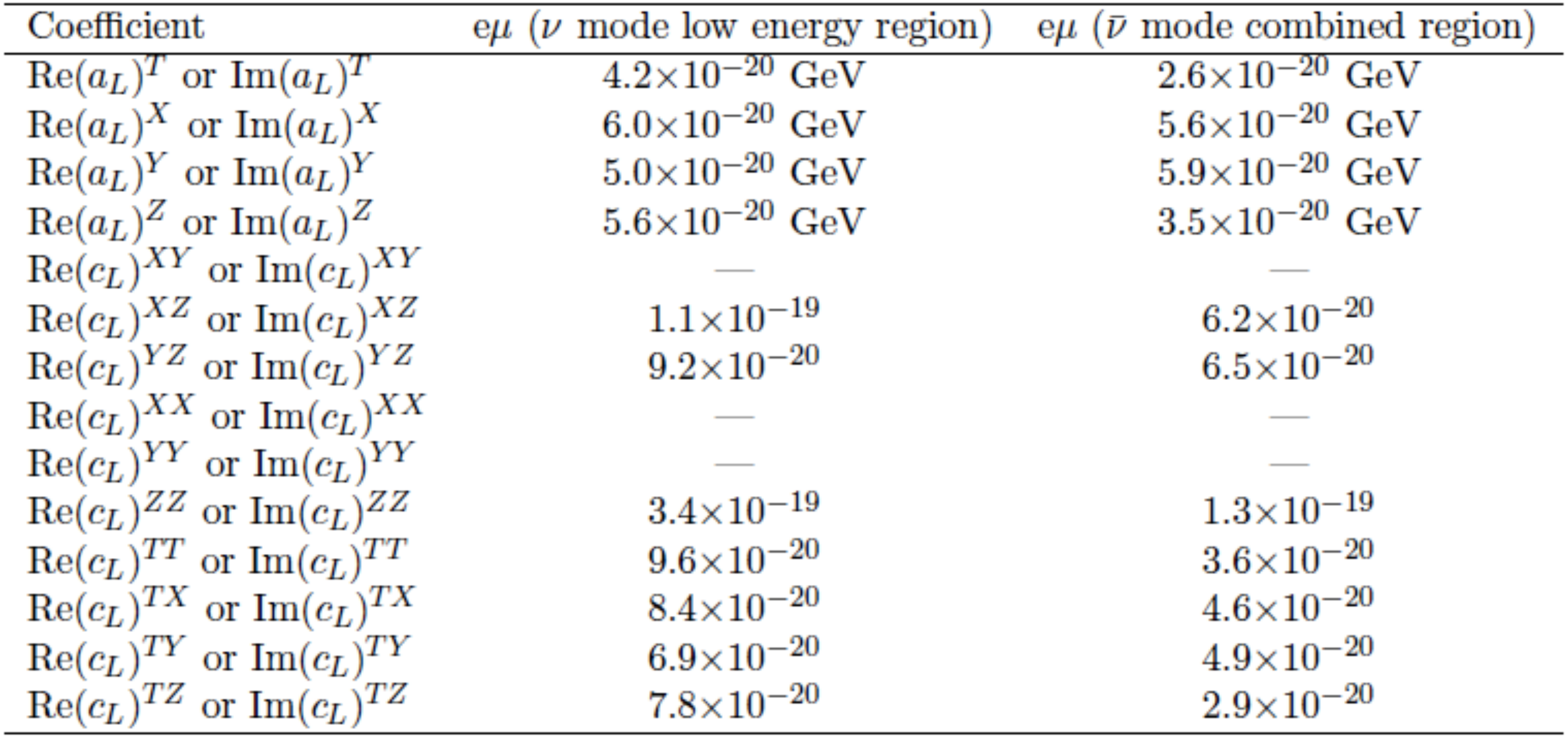
Queen Mary
University of London

TK, MPLA27(2012)1230024

4. MiniBooNE vs. LSND

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}

IceCube, Nature Physics 14 (2018) 961

4. Test of Lorentz violation with atmospheric neutrinos

We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.

The oscillation probability is different with energy and baseline (direction), so simultaneous fit with wide energy and all direction can fit Lorentz violation parameters.

Fig. 1 Concept of spectrum distortion

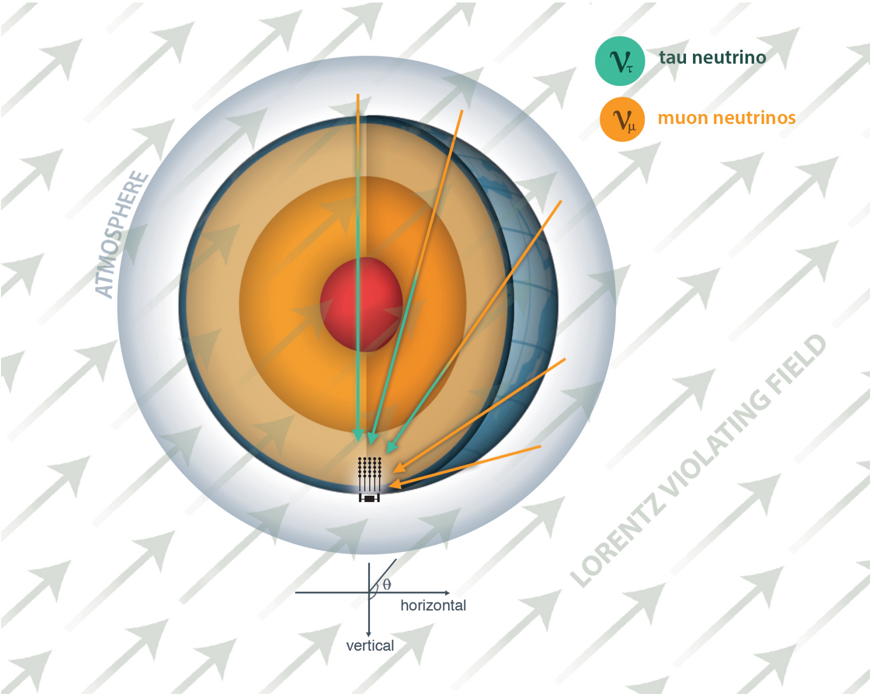
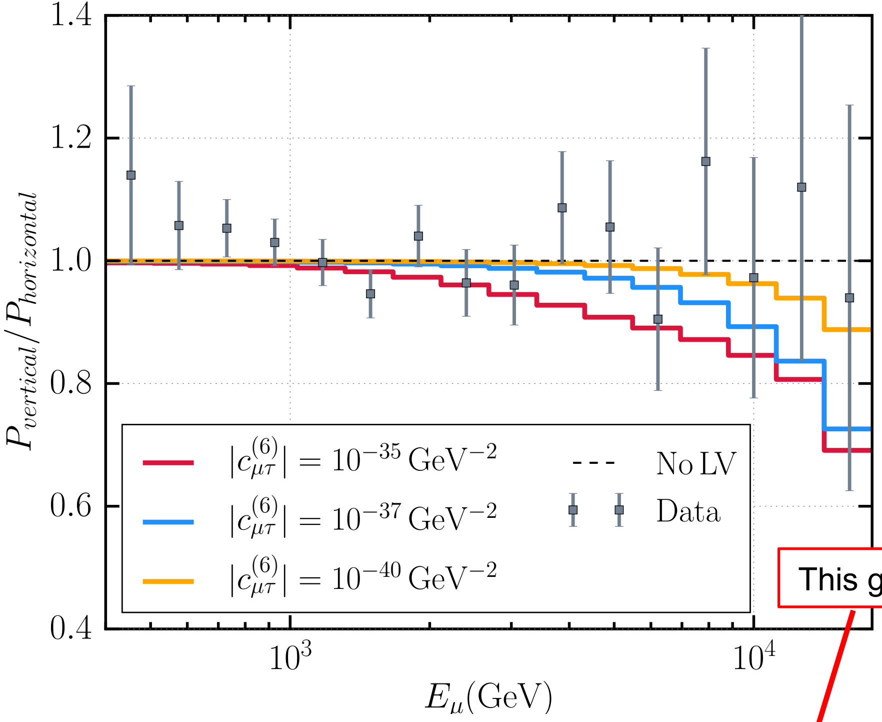


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator



This guy

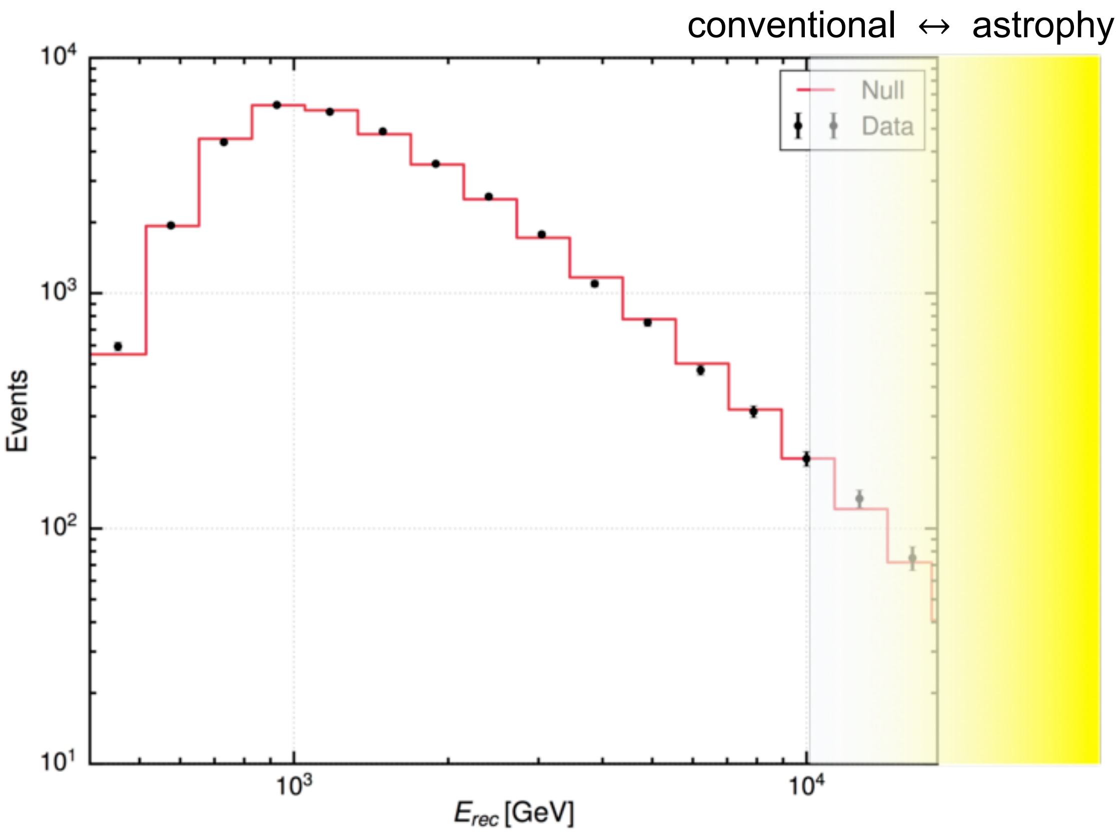
Eq. 1: LV motivated new physics Hamiltonian

Tep $$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E\cdot\mathring{c}^{(4)} + E^2\cdot\mathring{a}^{(5)} - E^3\cdot\mathring{c}^{(6)}\cdots. \quad (1)$$

IceCube, Nature Physics 14 (2018) 961

4. Test of Lorentz violation with atmospheric neutrinos

We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.



The longest baseline and highest energy neutrinos are most sensitive to Lorentz violation.

Longest → diameter of the earth
Highest → tail of conventional flux
↓
This analysis is the possible best analysis of Lorentz violation within terrestrial neutrinos.

Eq. 1: LV motivated new physics Hamiltonian

Tep $$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots . \quad (1)$$

IceCube,PRL115(2015)081102;117(2016)071801, Nature551(2017)596

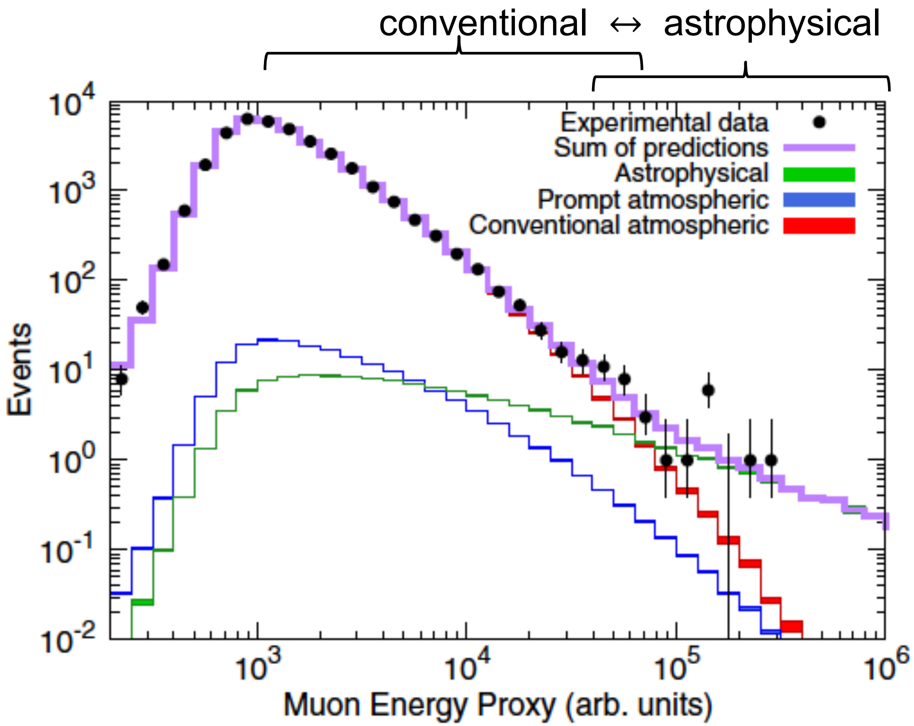
4. Analysis method

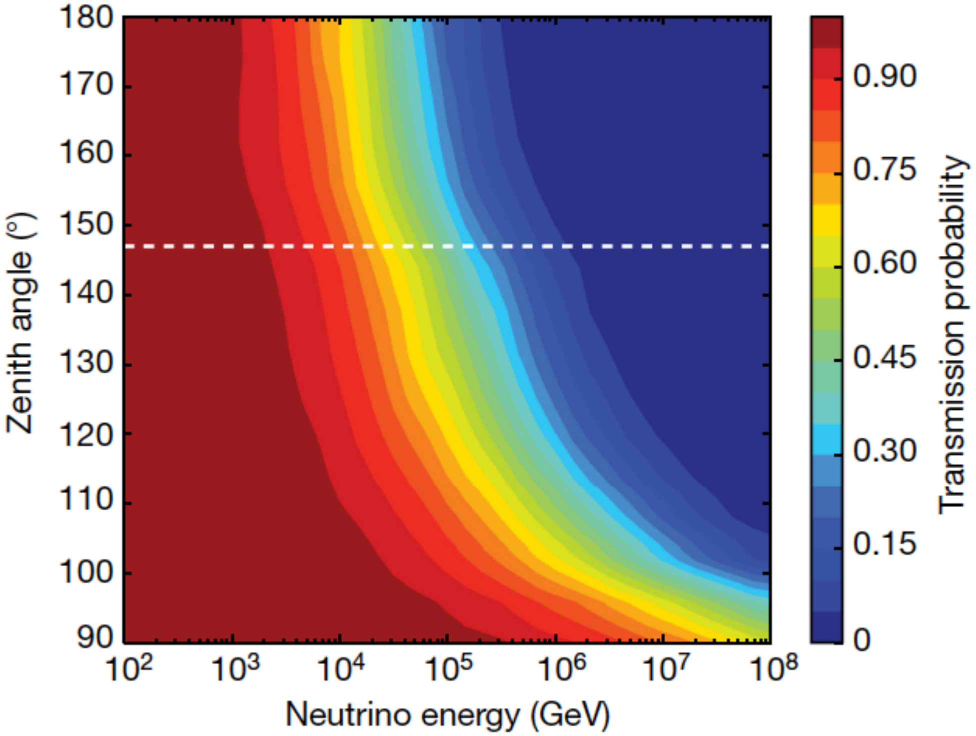
We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.

400 GeV<E<18 TeV (“conventional”)
Angle, -1<cosθ<0 (“through up-going”)

→ 2016 sterile ν analysis sample

ν_{atm} is complicated from ~20 TeV
- Prompt atmospheric neutrinos (=charm)
- Astrophysical neutrinos
- Earth absorption becomes significant





Fedynitch et al,EPJ.Web.Conf.99(2015)08001

4. Analysis method

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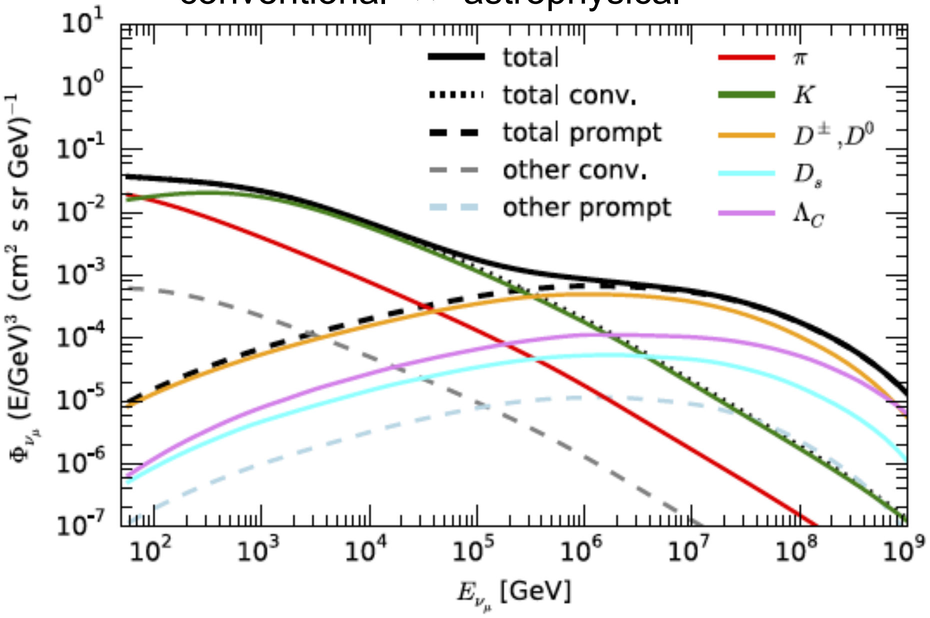
400 GeV<E<18 TeV (“conventional”)
Angle, -1<cosθ<0 (“through up-going”)

Simulation
- atmospheric neutrinos from MCEq https://github.com/afedynitch/MCEq

conventional ↔ astrophysical



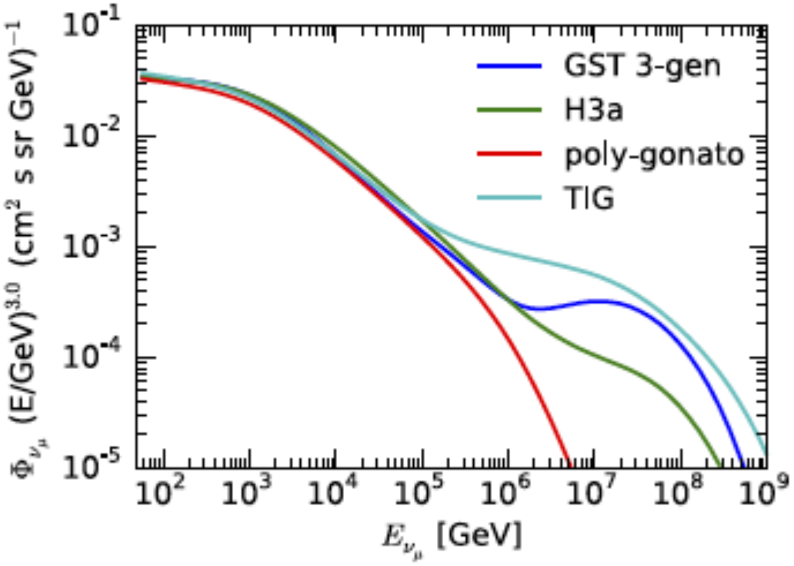


Figure 3. Primary model dependence of the atmospheric conventional + prompt neutrino flux. The model abbreviations are described in the caption of Fig. 2.

Vincent et al,PRD94(2016)023009
IceCube,PRL115(2015)081102

4. Analysis method

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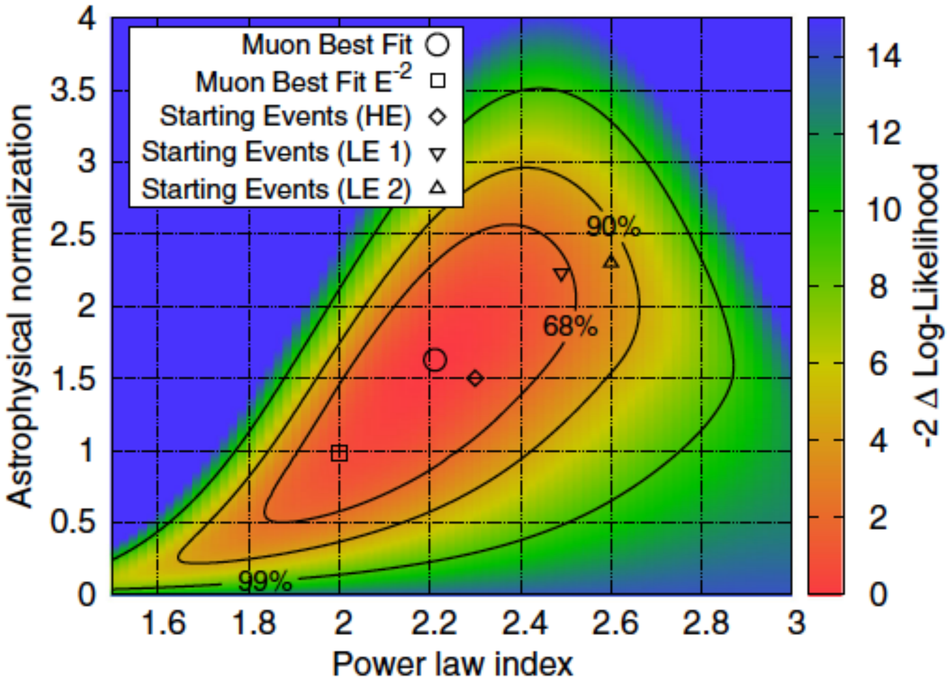
400 GeV<E<18 TeV (“conventional”)
Angle, $-1<\cos\theta<0$ (“through up-going”)

Simulation

- atmospheric neutrinos from MCEq https://github.com/afedynitch/MCEq
- simple power law astrophysical neutrinos

This moment, we don’t have a consistent flux model for astrophysical neutrinos. Spectrum index is highly correlated with normalization of the flux.

→ in this analysis, $\gamma=2$ ($\Phi\sim E^{-2}$) is used. We found in this analysis dependence on spectrum index is weak.



Cooper-Sarkar and Sarkar, JHEP01(2008)075
Gonzalez-Garcia et al., PRD71(2005)093010

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- simple power law astrophysical neutrinos
- DIS cross section from Cooper-Sarkar-Sarkar (CSS) paper
- Analytic oscillation formula

Systematics (6 nuisance parameters)

- normalization of flux : conventional (40%), prompt (free), and astrophysical (free)
- spectrum index : primary cosmic ray (2%) and astrophysical neutrinos (25%)
- π/K ratio for conventional flux (10%)
- Ice model : negligible
- DOM efficiency : constrained

Foreman-Mackey et al.,Publ.Astron.Soc.Pac.125(2013)306

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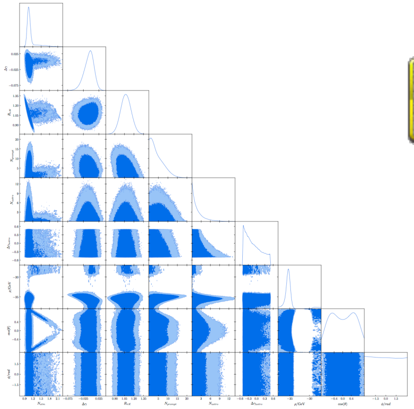

MARKOV

Fit methods

- Frequentist Wilk’s theorem (main results)
- Bayesian Markov Chain Monte Carlo (MCMC)

http://dan.iel.fm/emcee/current/

Foreman-Mackey et al.,Publ.Astron.Soc.Pac.125(2013)306

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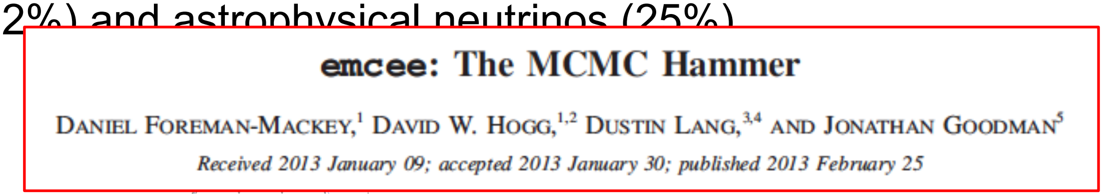

emcee: The MCMC Hammer

Daniel Foreman-Mackey,[1] David W. Hogg,[1,2] Dustin Lang,[3,4] and Jonathan Goodman[5]

Received 2013 January 09; accepted 2013 January 30; published 2013 February 25

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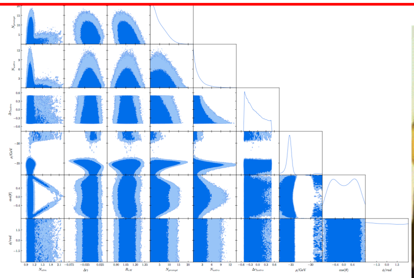
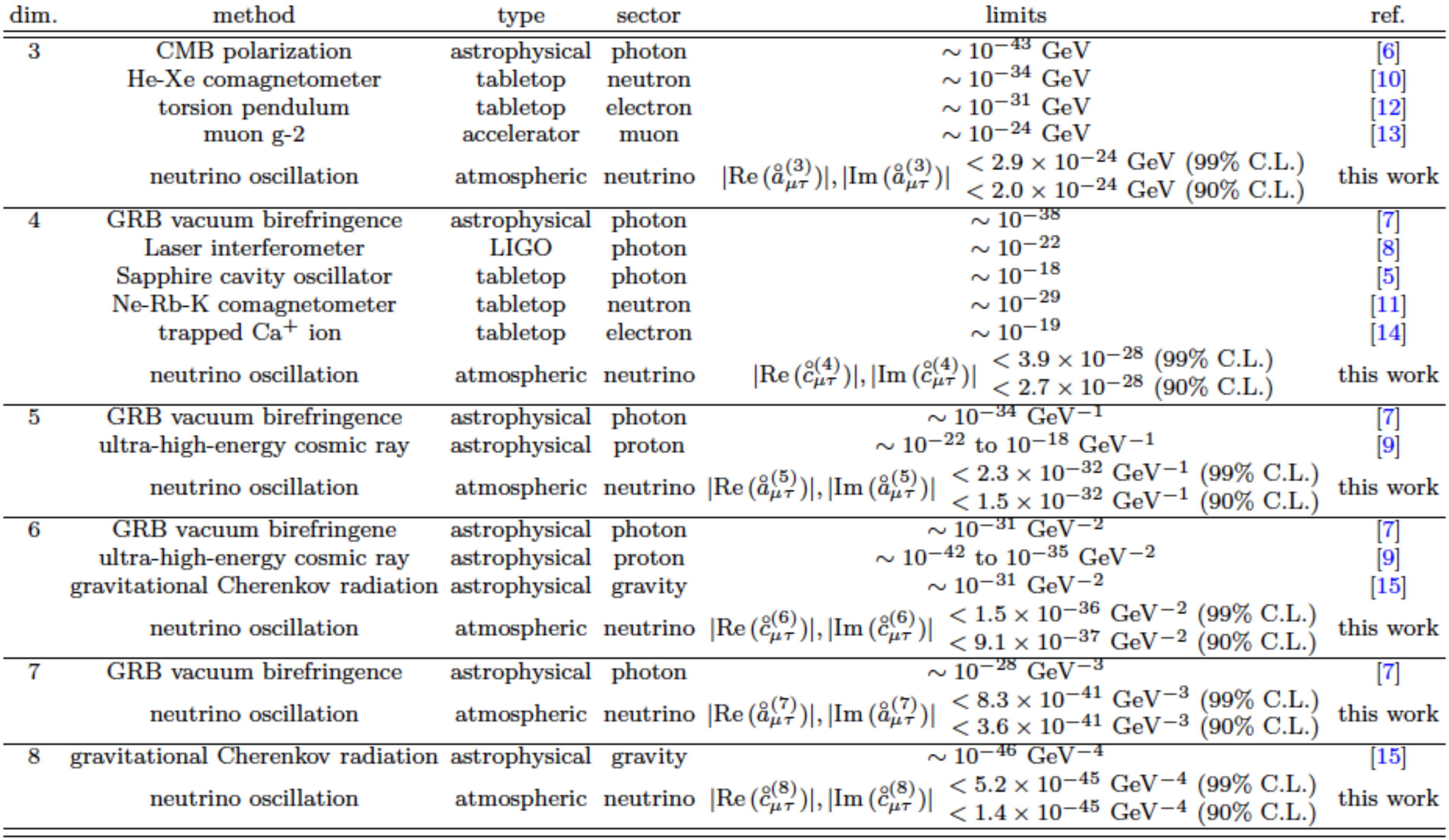


IceCube, Nature Physics 14 (2018) 961

4. Results

We don't find Lorentz violation

- we set new limits on Lorentz violation
- demonstrate the potential of neutrino interferometry



dim.	method	type	sector	limits		ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

IceCube, Nature Physics 14 (2018) 961

4. Results

Atomic physics results dominate LV test with low dimension operators (effective field theory approach)

dim.	method	type	sector		limits	ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
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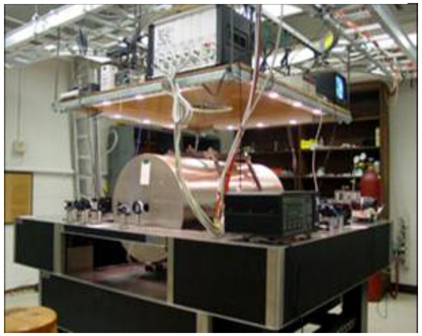
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca$^+$ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	
	u	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	
		atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(5)}_{\mu}$	$< 2.3 \times 10^{-32}$ GeV^{-1} (9 $< 1.5 \times 10^{-32}$ GeV^{-1} (9	
6		astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	
	u	ast				
	gra	ast				
		at		)|, |In	2 (9 2 (9	
7		ast				
		at		)|, |In	3 (99% C.L.) 3 (90% C.L.)	this work
8	gra	ast				[15]
		at		)|, |In	4 (99% C.L.) 4 (90% C.L.)	this work

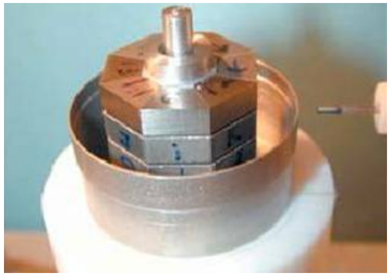
TABLE I: Comparison of attainable best limits of SM … lds.

Double gas maser
$b_n<10^{-34}$GeV
$c_n<10^{-29}$



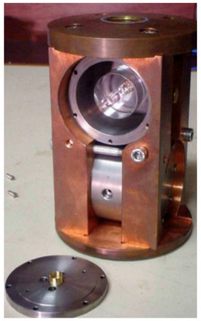
PRL107(2011)171604
PRL112(2014)110801

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



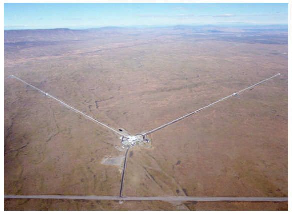
PRL97(2006)021603

Crystal oscillator
$\Delta c/c<10^{-18}$



Nature.Comm.6(2015)8174

LIGO
$c^{(4)}<10^{-22}$

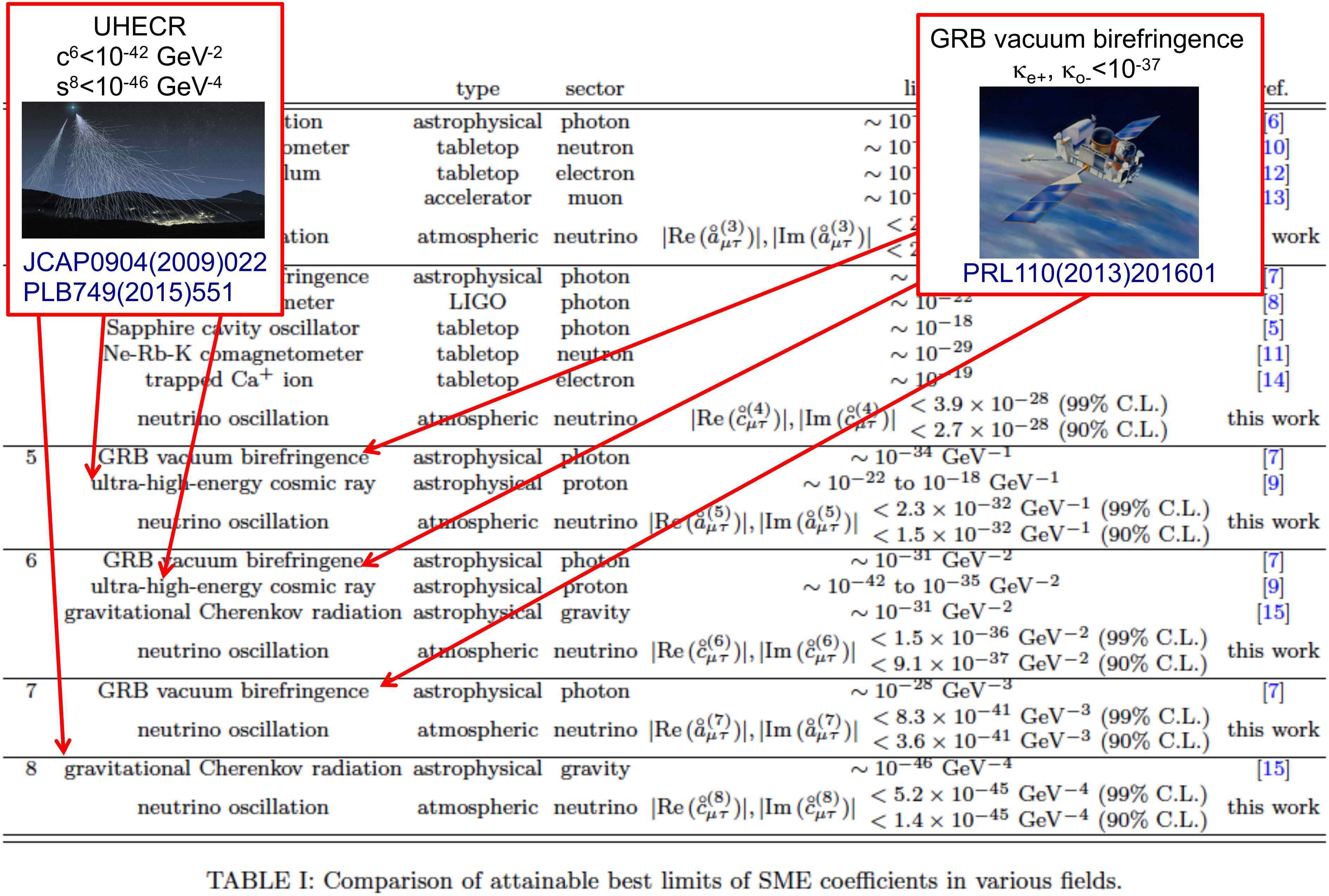


PLB761(2016)1

IceCube, Nature Physics 14 (2018) 961

4. Results

Astrophysical observations dominate LV test with high dimension operators (quantum gravity motivated models)



UHECR
$c^6<10^{-42}$ GeV^{-2}
$s^8<10^{-46}$ GeV^{-4}

JCAP0904(2009)022
PLB749(2015)551

GRB vacuum birefringence
$\kappa_{e+}, \kappa_{o-}<10^{-37}$

PRL110(2013)201601

		type	sector		li	ef.
	tion	astrophysical	photon		~ 10	[6]
	ometer	tabletop	neutron		~ 10	10]
	lum	tabletop	electron		~ 10	12]
		accelerator	muon		~ 10	13]
	ation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	< 2 < 2	work
	fringence	astrophysical	photon		$\sim$	[7]
	neter	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
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8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

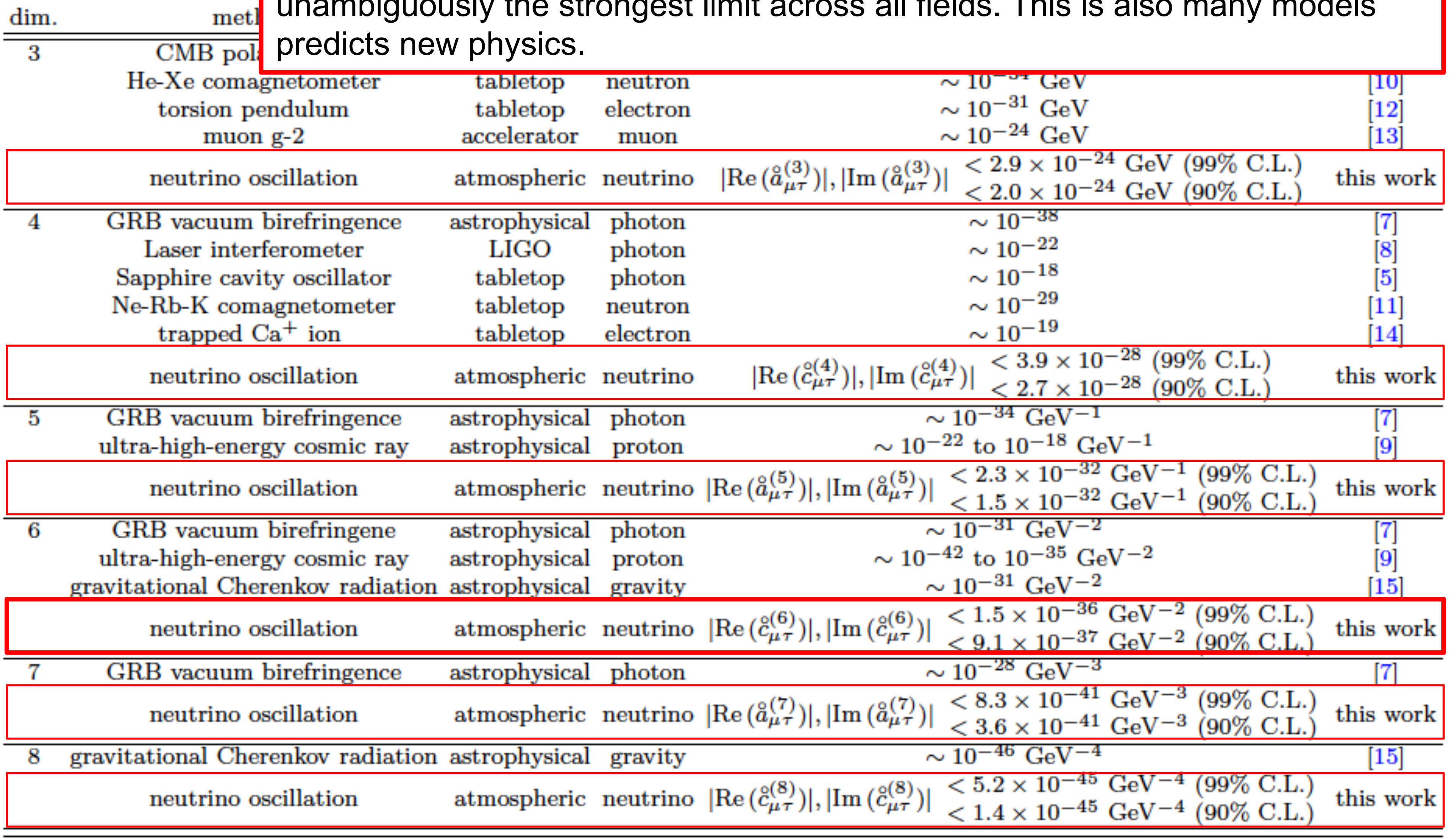
TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

IceCube, Nature Physics 14 (2018) 961

4. Results

This analysis set the strongest limits for any order operators in neutrino sector.

The limits are among the best in all sectors. In particular, dimension-six limit is unambiguously the strongest limit across all fields. This is also many models predicts new physics.



dim.	meth					
3	CMB pol					
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
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	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

Kostelecký and Russel, Rev.Mod.Phys.83(2011)11, ArXiv:0801.0287v11

4. Terrestrial neutrino LV limit summary

Lorentz violation is tested with all neutrino channels

Atmospheric neutrino oscillation is one of the best Lorentz violation tests on the Earth

Chance to see the Lorentz violation in terrestrial neutrino experiments is very small

		eμ	**eτ**	**μτ**
d=3	time indep	10^{-23} Super-K	10^{-23} Super-K	10^{-24} IceCube
	time dep	10^{-20} MB, MINOS	10^{-20} DoubleChooz	10^{-23} Super-K
d=4	time indep	10^{-26} Super-K	10^{-24} Super-K	10^{-28} IceCube
	time dep	10^{-21} MINOS	10^{-17} DoubleChooz	10^{-27} Super-K

1. Neutrino Interferometry

2. Spontaneous Lorentz symmetry breaking

3. Modern test of Lorentz violation

4. Test of Lorentz violation with neutrino data

5. **Astrophysical very-high-energy neutrinos**

6. Lorentz violation tests on astrophysical neutrinos

7. Conclusion

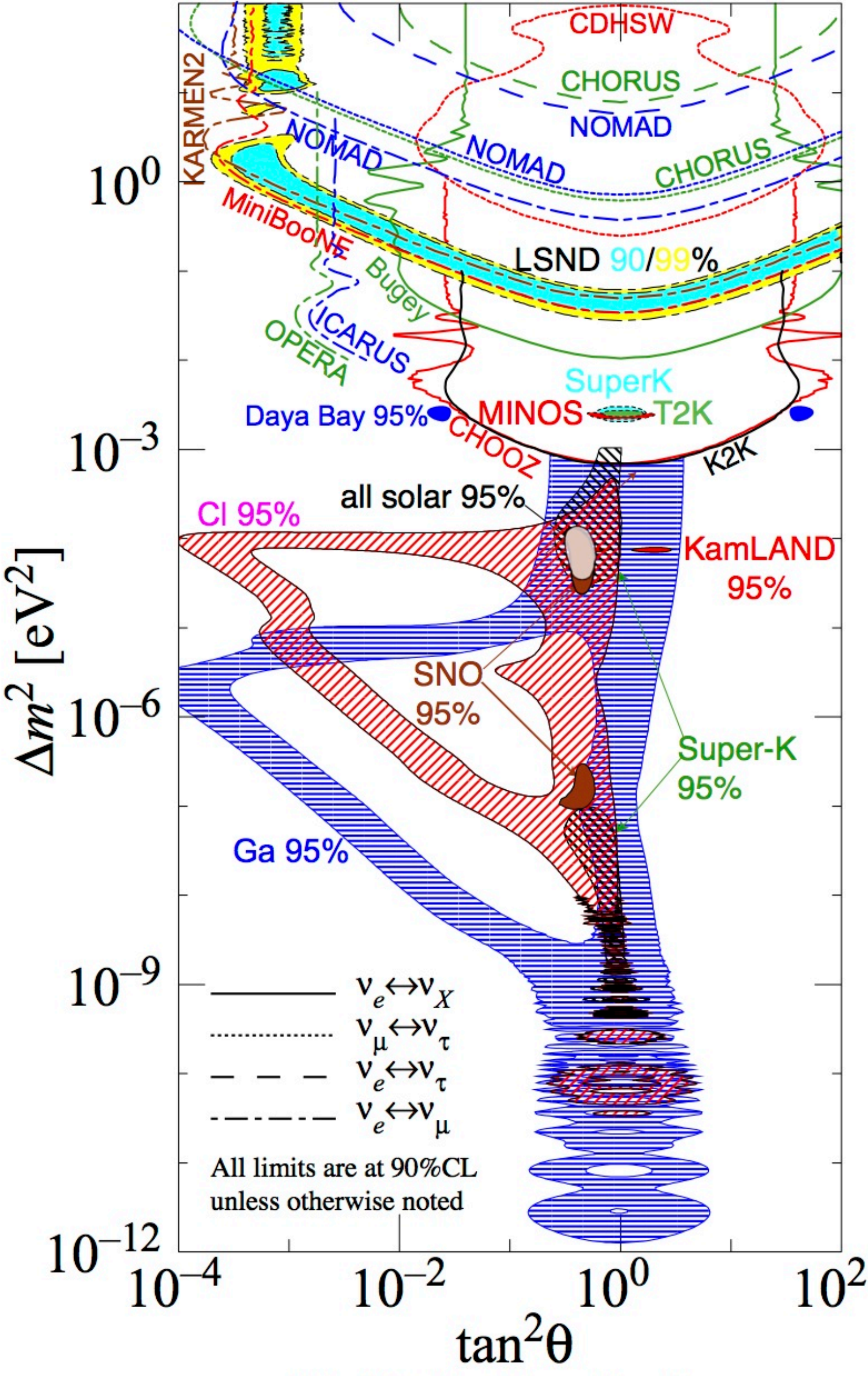
5. Neutrino standard Model (νSM)

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?

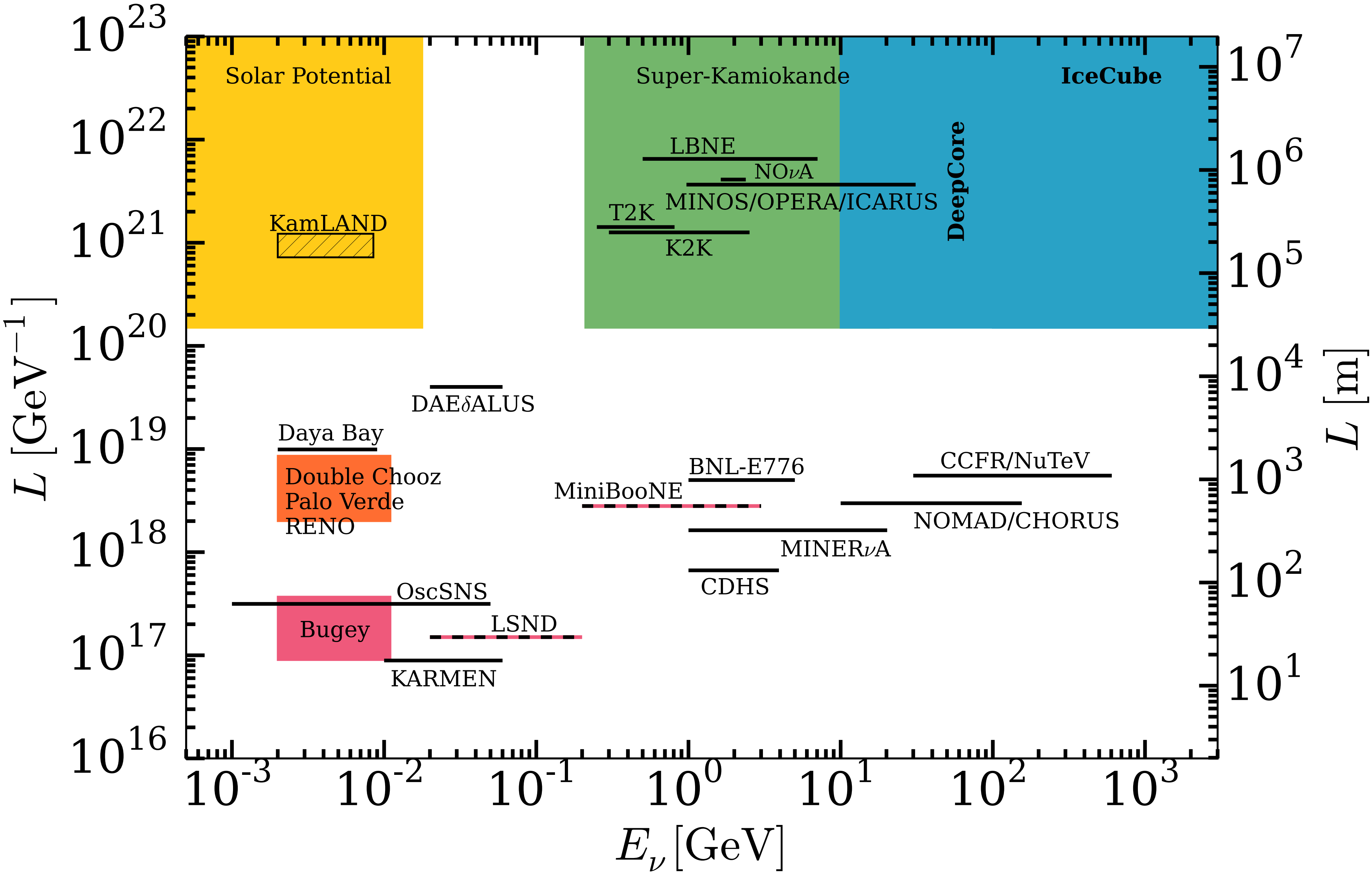


All limits are at 90%CL unless otherwise noted

http://hitoshi.berkeley.edu/neutrino

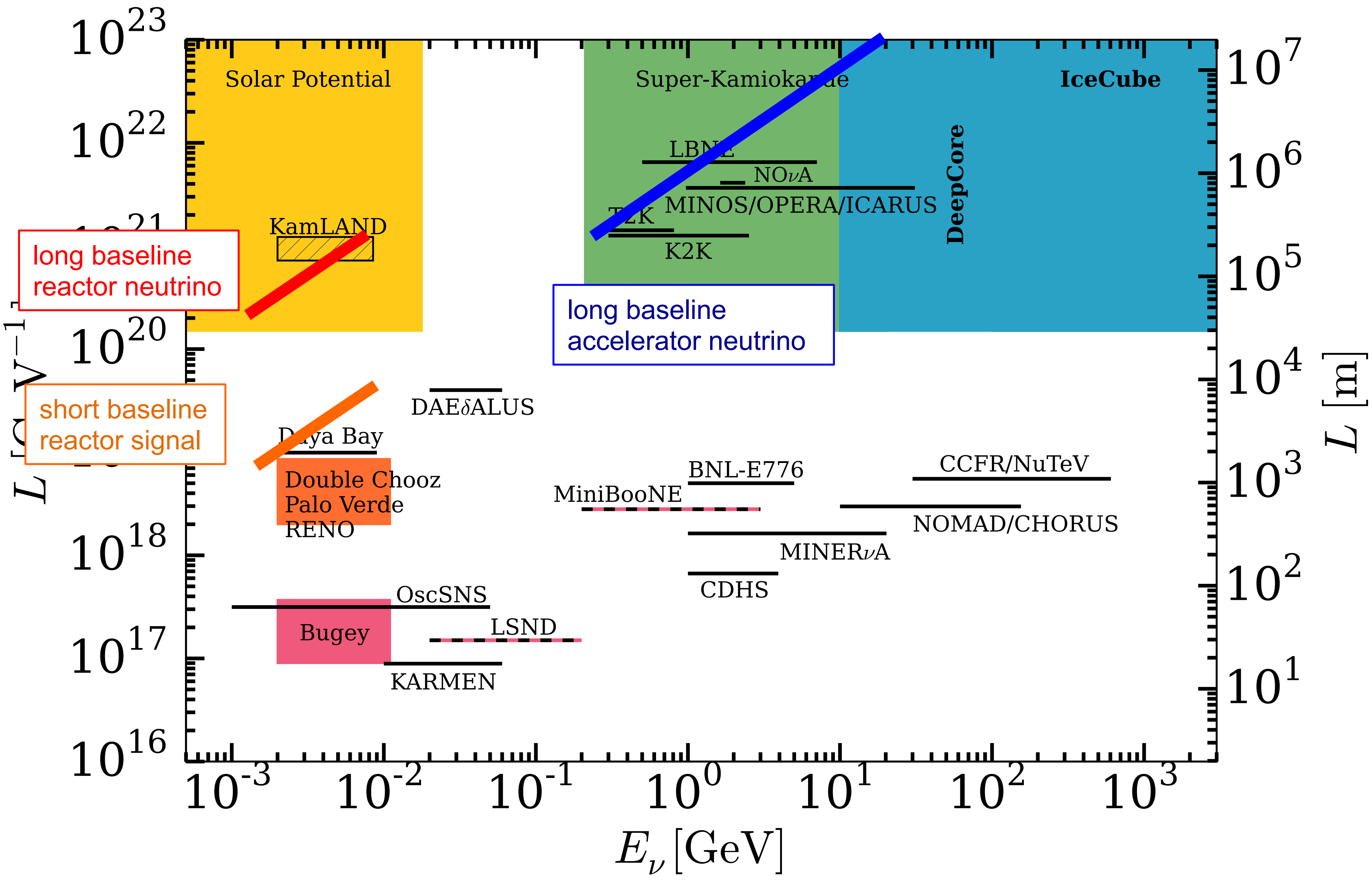
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

5. Lorentz violation with neutrino oscillation



Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

5. Lorentz violation with neutrino oscillation



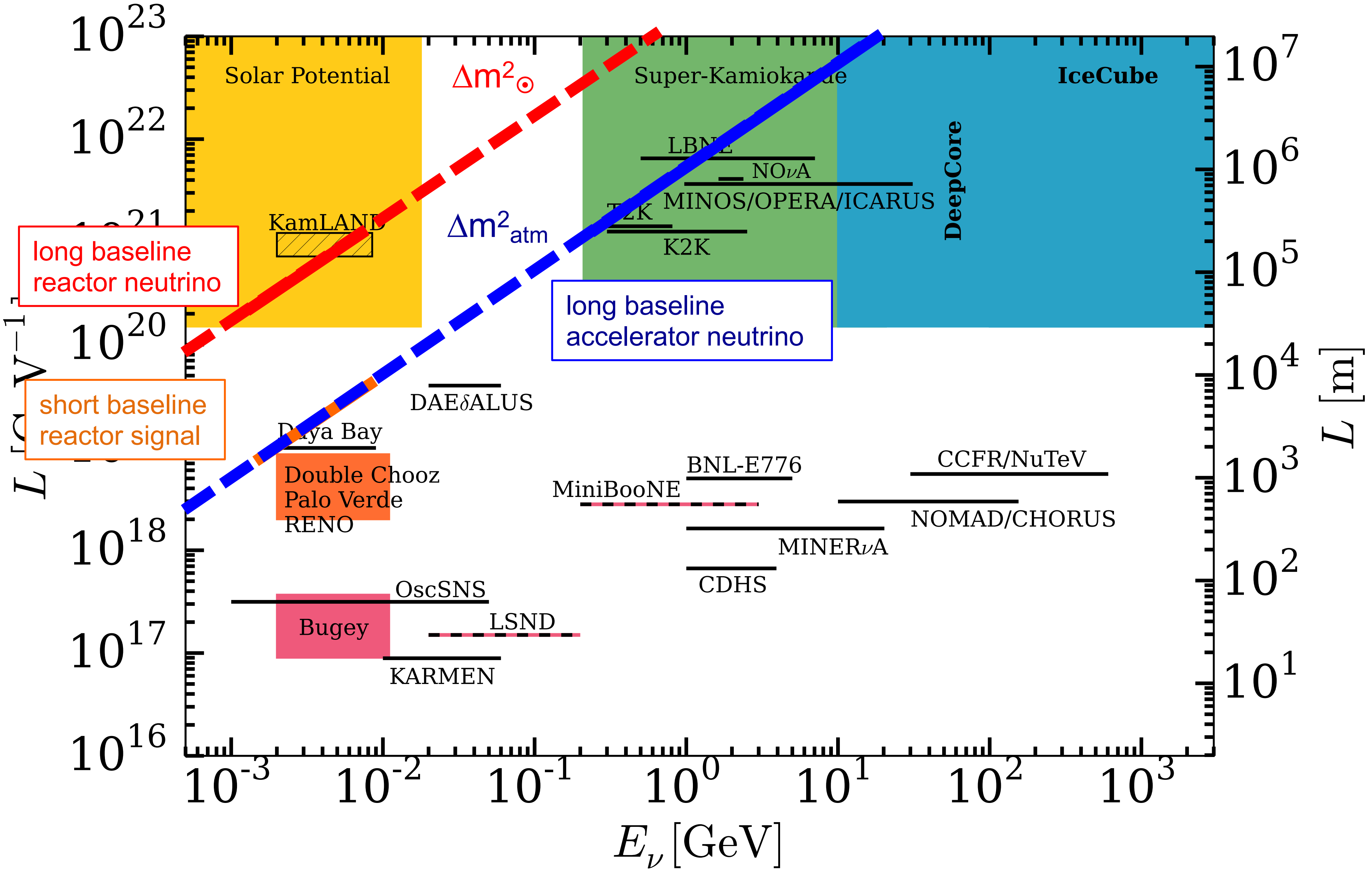
long baseline
reactor neutrino

long baseline
accelerator neutrino

short baseline
reactor signal

Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

5. Lorentz violation with neutrino oscillation



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Argüelles, INVISIBLE2015

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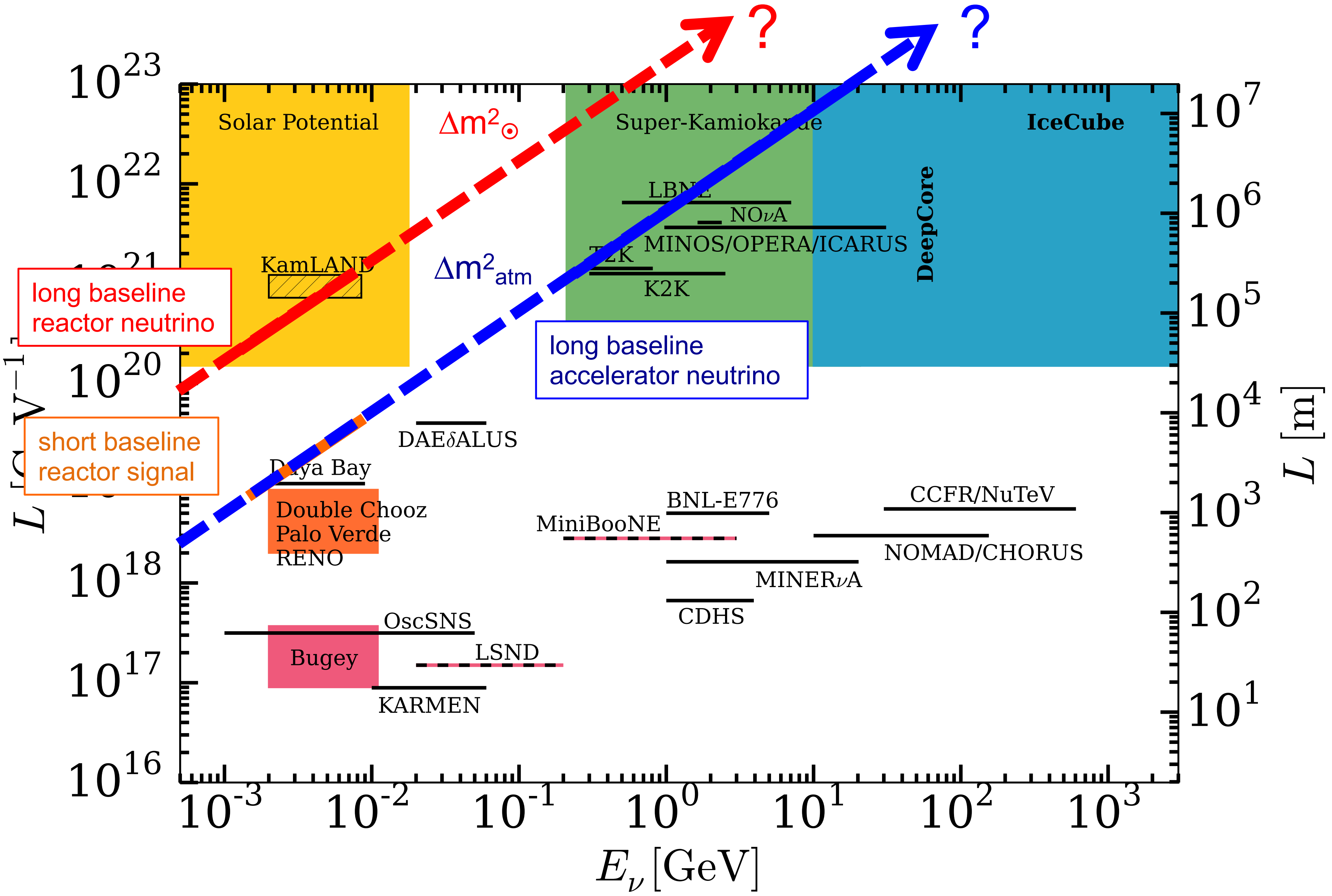

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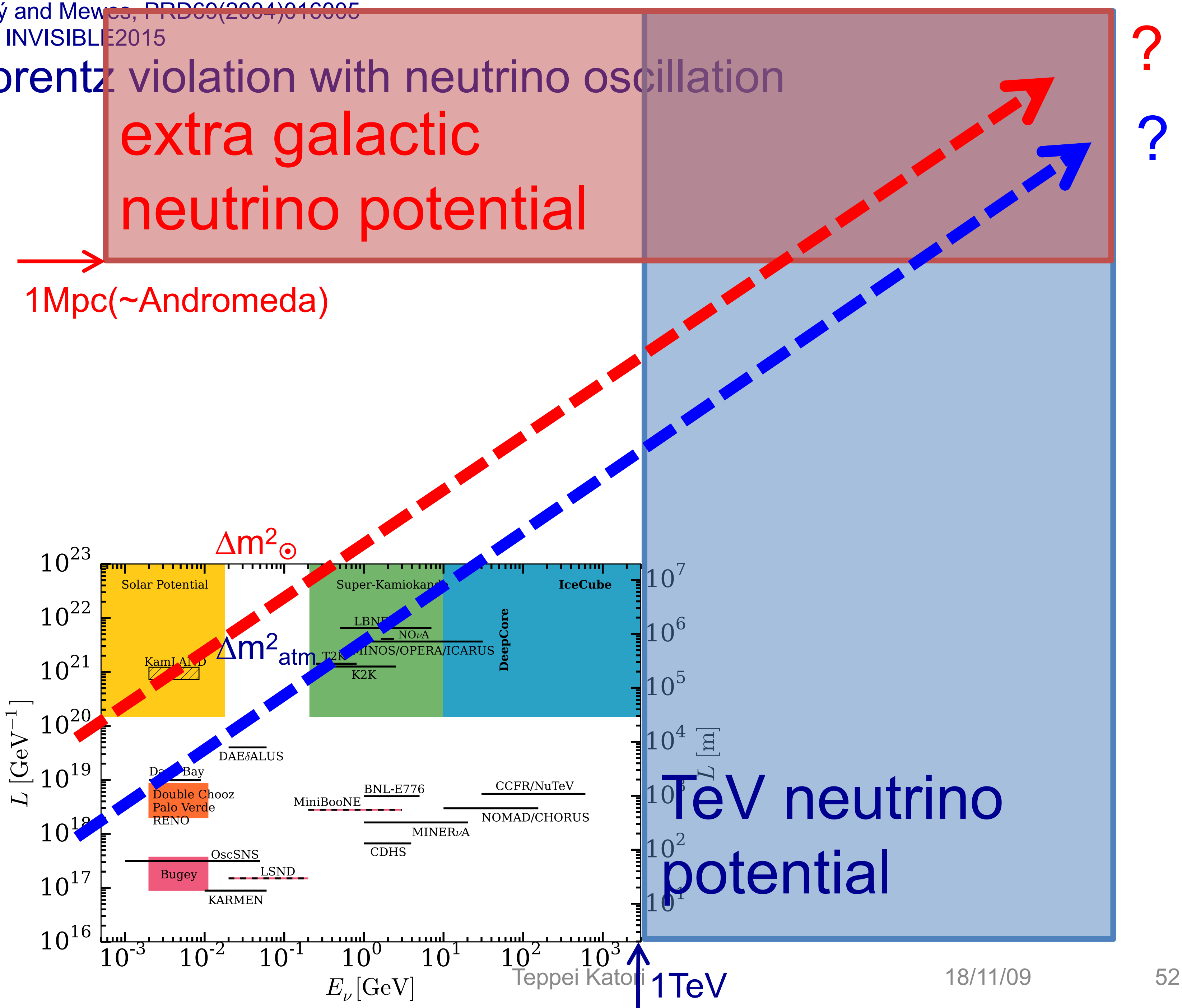
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

5. Lorentz violation with neutrino oscillation



extra galactic
neutrino potential

1Mpc(~Andromeda)

$\Delta m^2_{\odot}$

Δm^2_{atm}

?

?

TeV neutrino
potential

1TeV

Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

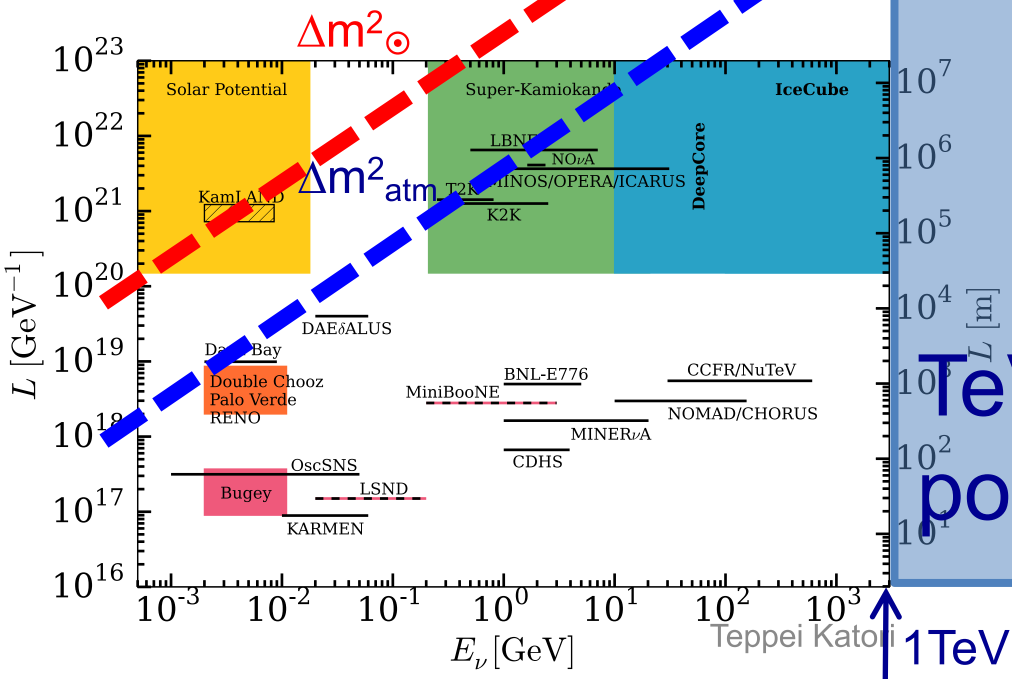
5. Lorentz violation with neutrino oscillation

extra galactic
neutrino potential

1Mpc(~Andromeda)

?

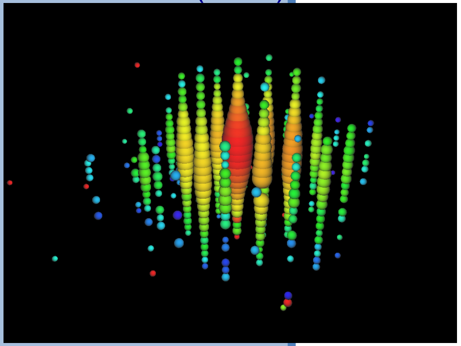
?



TeV neutrino
potential

1TeV

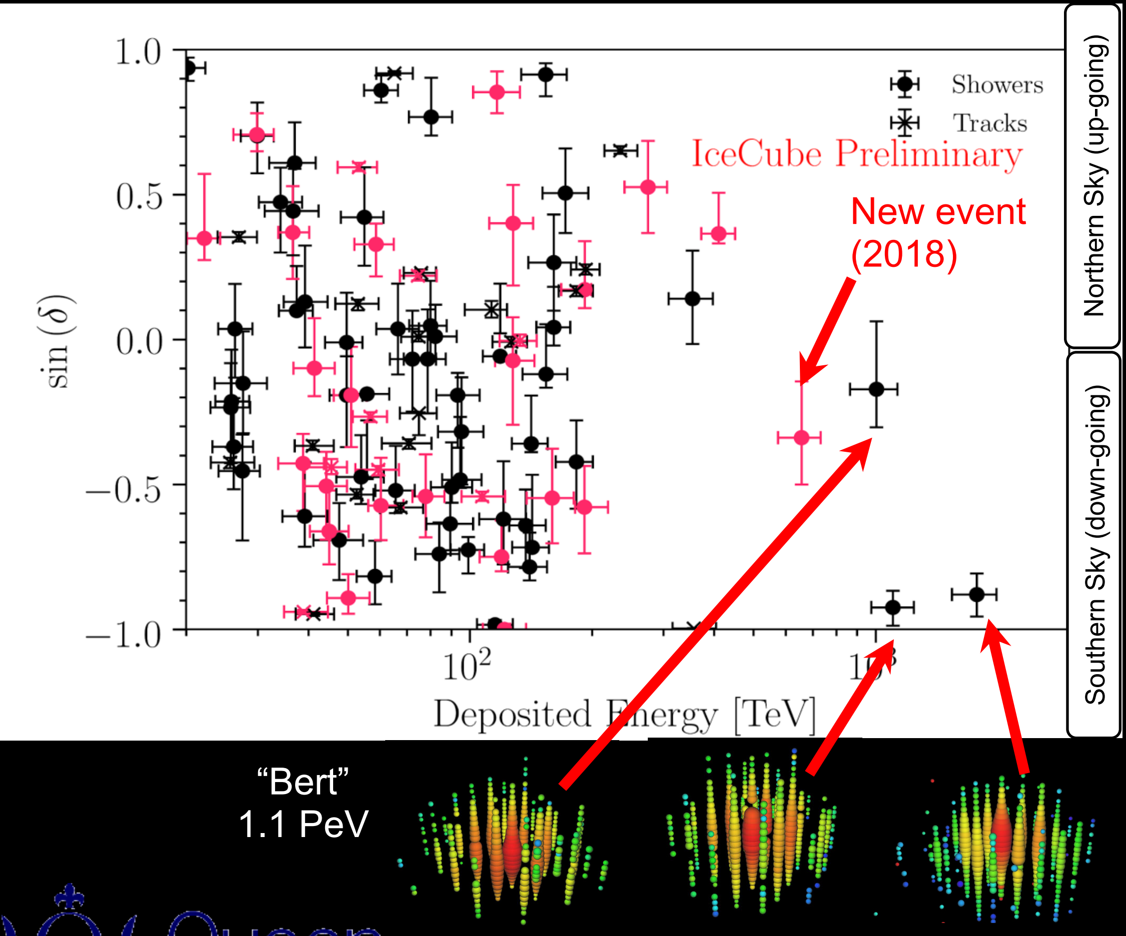
IceCube collaboration
PRL111(2013)021103



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

5. Astrophysical Very-High-Energy Neutrinos

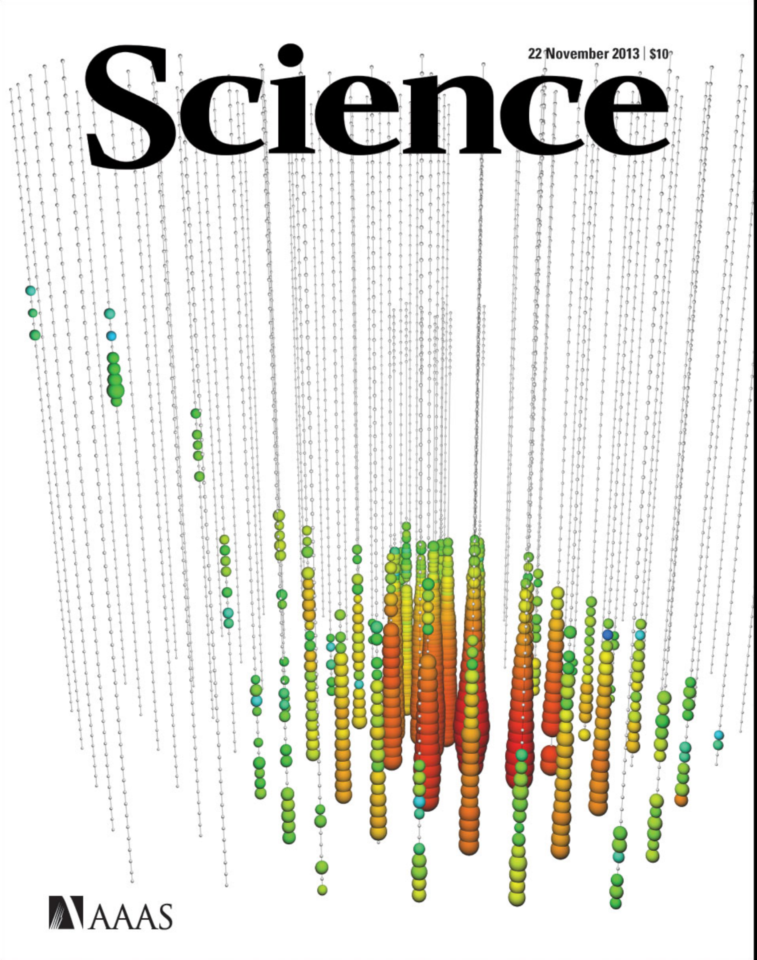
First observation (2013)
- 30-2000 TeV neutrinos



"Bert"
1.1 PeV

"Ernie"
1.0 PeV

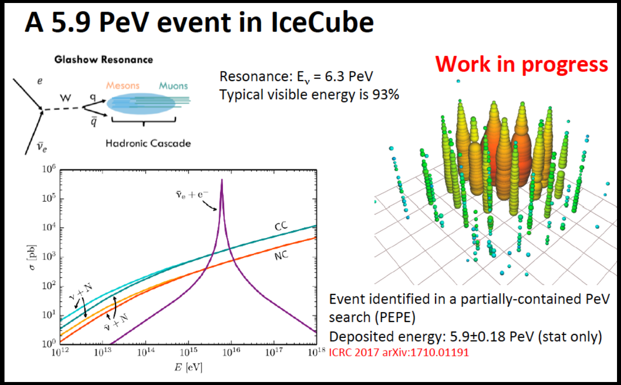
"Big Bird"
2.0 PeV



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

5. Astrophysical Very-High-Energy Neutrinos

First Glashow resonance?
(Taboada, Neutrino 2018)



A 5.9 PeV event in IceCube

Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

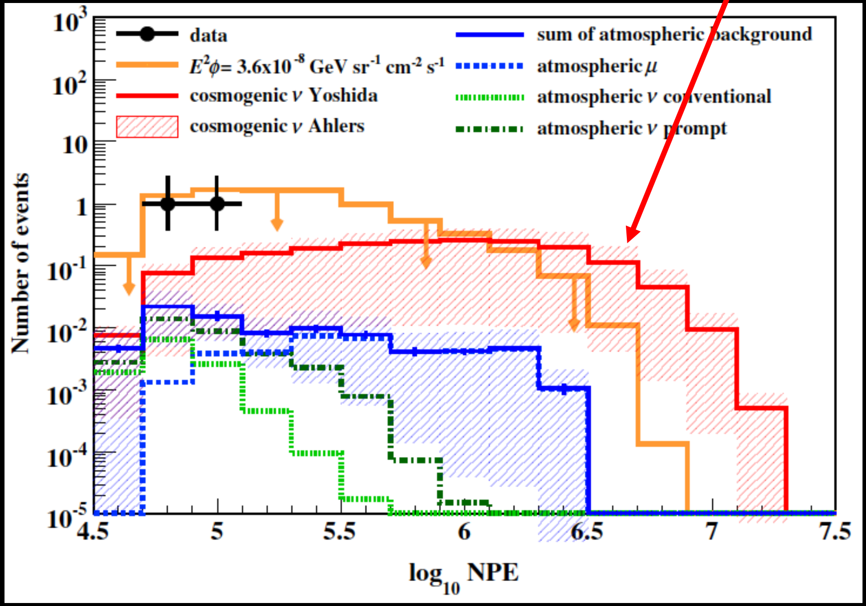
Work in progress

Event identified in a partially-contained PeV search (PEPE)
Deposited energy: 5.9±0.18 PeV (stat only)
ICRC 2017 arXiv:1710.01191

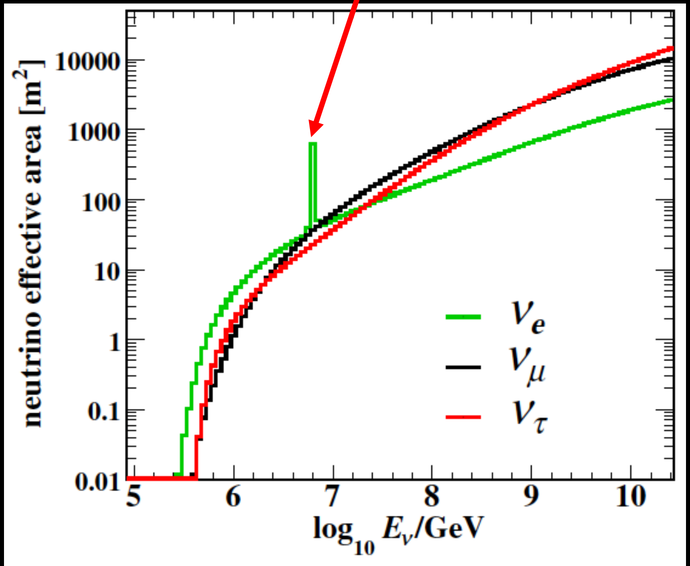
First observation (2013)

- 30-2000 TeV neutrinos
- Unlikely from GZK neutrinos or Glashow resonance

$$p + \gamma \to \Delta \to \pi \to \nu$$



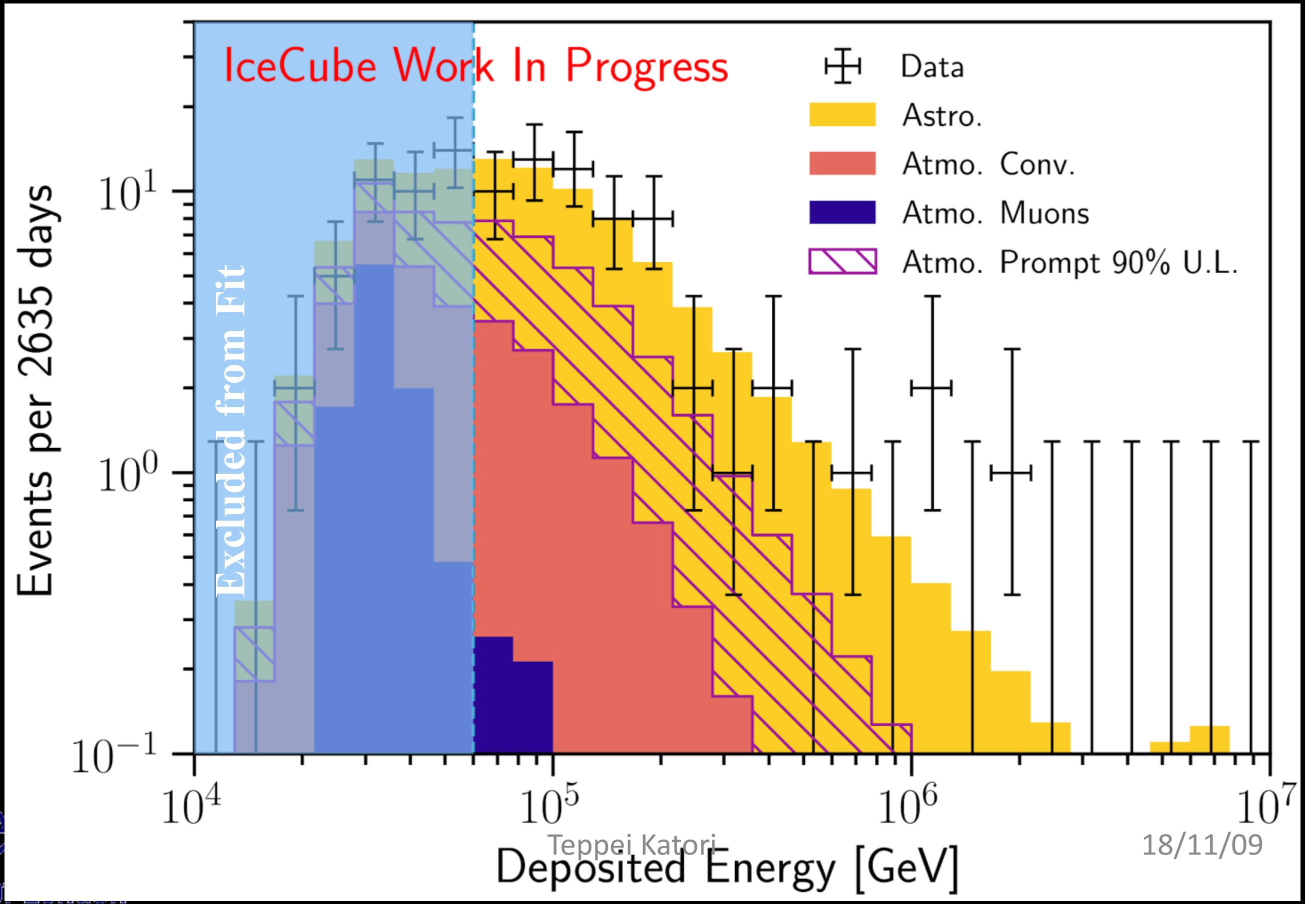
$$\bar{\nu}_e(6.2PeV) + e \to W$$



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

5. Astrophysical Very-High-Energy Neutrinos

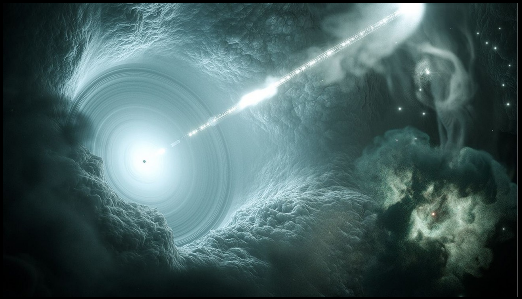
First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

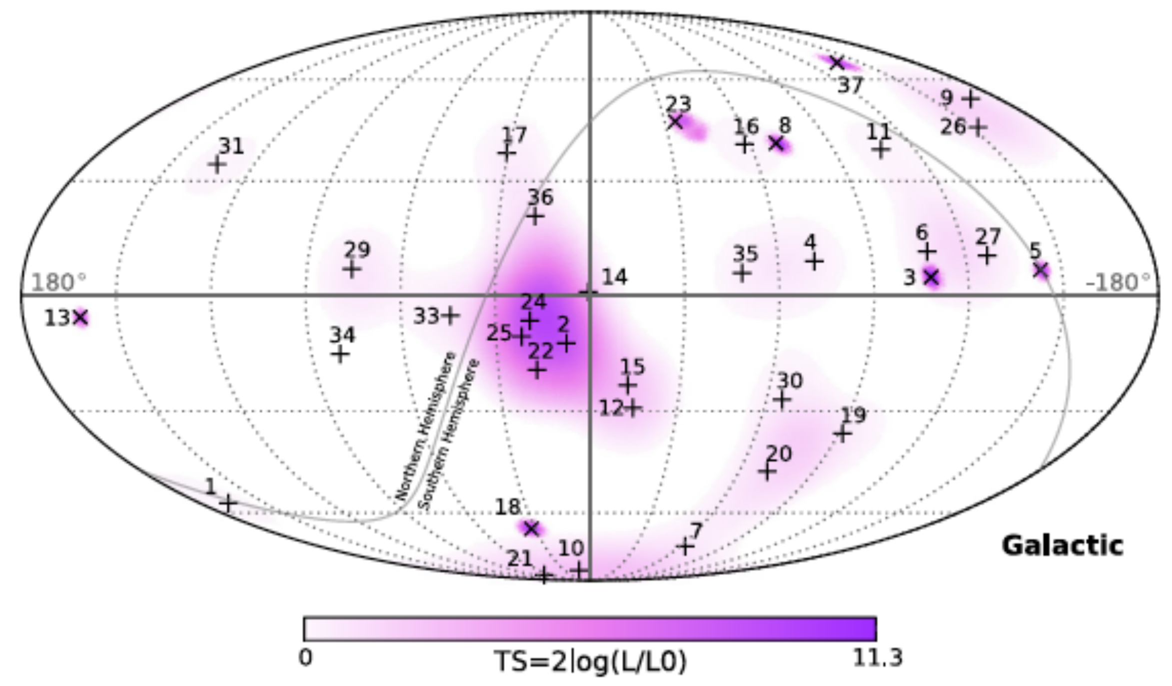
5. Astrophysical Very-High-Energy Neutrinos

Evidence of Blazar Neutrino
- IC170922A
- TXS 0506+056



IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown

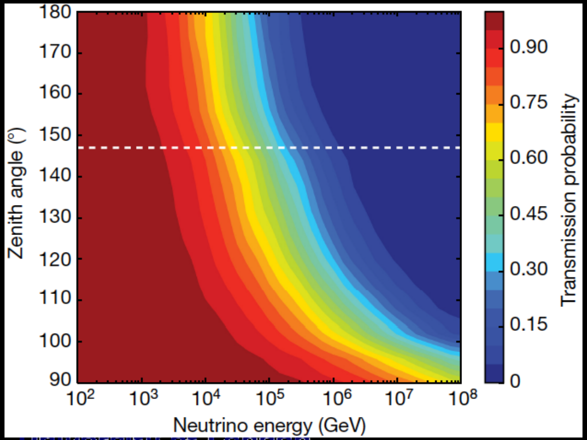


IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

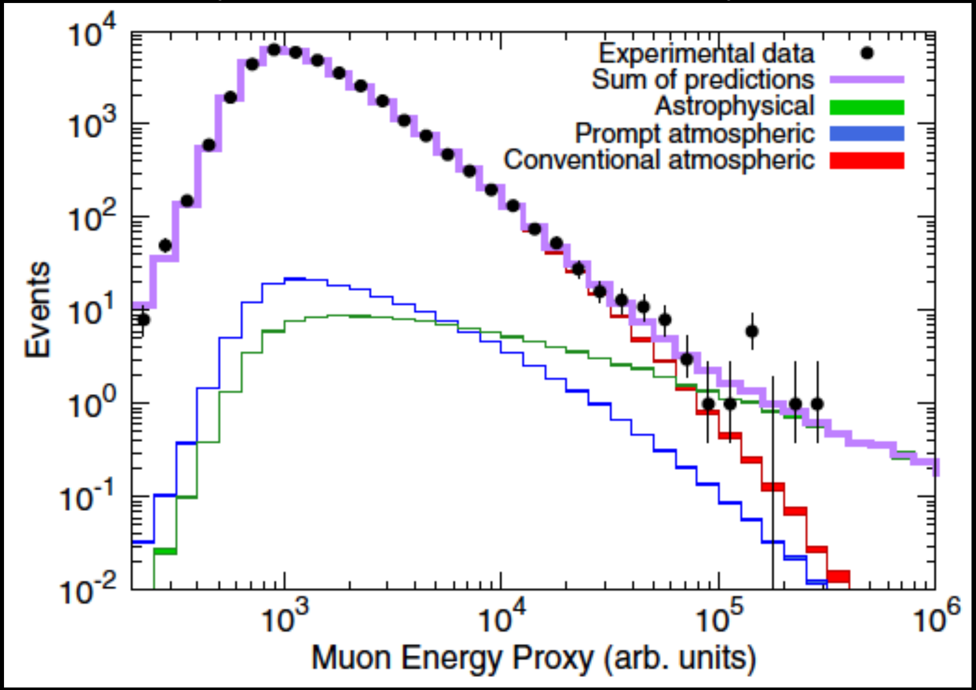
5. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown
- From both southern and northern sky

IceCube is not 4π measurement
- Southern sky (above) has high atmospheric muon background
- Northern neutrinos (bottom) are attenuated by the earth (>50 TeV)



Northern sky track sample with E^{-2} astrophysical spectrum

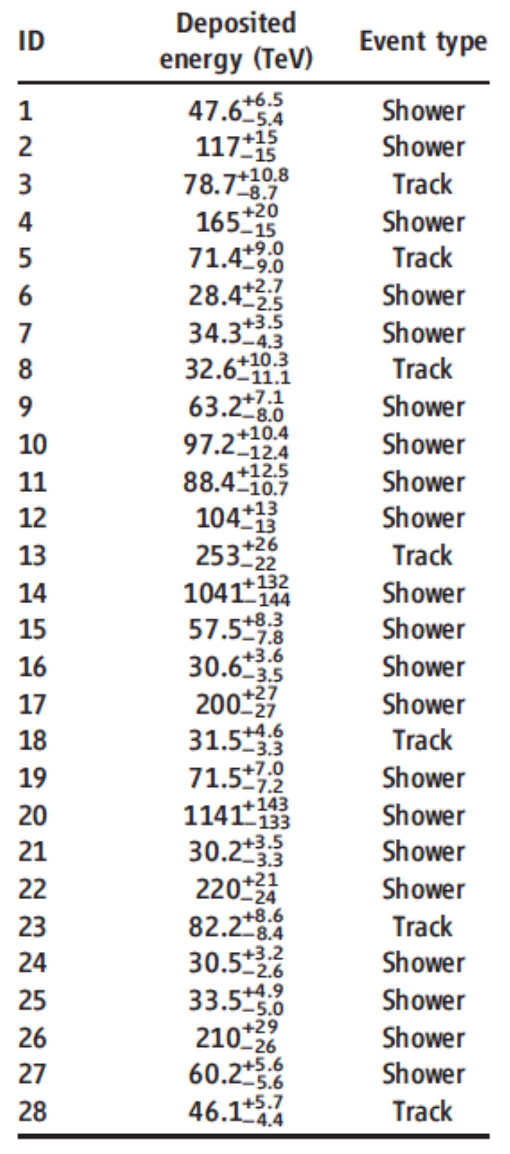


IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

5. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown
- From both southern and northern sky
- Shower topology is dominant

Naively
- Astrophysical flavor ratio of $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$
- At very high energy, $\sigma(CC) \sim 3\sigma(NC)$
- Track : Shower ~ 1 : 3 ($N_T/N_S \sim 0.33$)

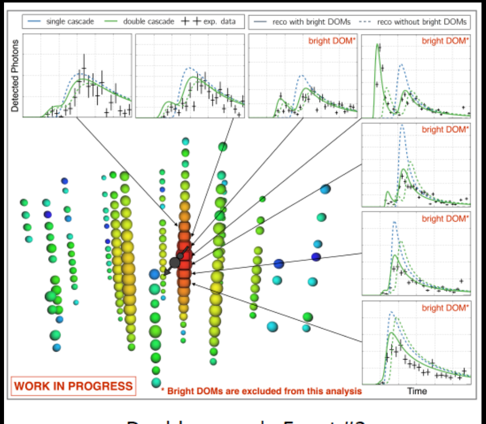


ID	Deposited energy (TeV)	Event type
1	$47.6^{+6.5}_{-5.4}$	Shower
2	117^{+15}_{-15}	Shower
3	$78.7^{+10.8}_{-8.7}$	Track
4	165^{+20}_{-15}	Shower
5	$71.4^{+9.0}_{-9.0}$	Track
6	$28.4^{+2.7}_{-2.5}$	Shower
7	$34.3^{+3.5}_{-4.3}$	Shower
8	$32.6^{+10.3}_{-11.1}$	Track
9	$63.2^{+7.1}_{-8.0}$	Shower
10	$97.2^{+10.4}_{-12.4}$	Shower
11	$88.4^{+12.5}_{-10.7}$	Shower
12	104^{+13}_{-13}	Shower
13	253^{+26}_{-22}	Track
14	1041^{+132}_{-144}	Shower
15	$57.5^{+8.3}_{-7.8}$	Shower
16	$30.6^{+3.6}_{-3.5}$	Shower
17	200^{+27}_{-27}	Shower
18	$31.5^{+4.6}_{-3.3}$	Track
19	$71.5^{+7.0}_{-7.2}$	Shower
20	1141^{+143}_{-133}	Shower
21	$30.2^{+3.5}_{-3.3}$	Shower
22	220^{+21}_{-24}	Shower
23	$82.2^{+8.6}_{-8.4}$	Track
24	$30.5^{+3.2}_{-2.6}$	Shower
25	$33.5^{+4.9}_{-5.0}$	Shower
26	210^{+29}_{-26}	Shower
27	$60.2^{+5.6}_{-5.6}$	Shower
28	$46.1^{+5.7}_{-4.4}$	Track

Palladino et al,PRL114(2015)171101

5. Astrophysical Very-High-Energy Neutrinos

First astrophysical tau neutrino?
(Taboada, Neutrino 2018)



Double cascade Event #2

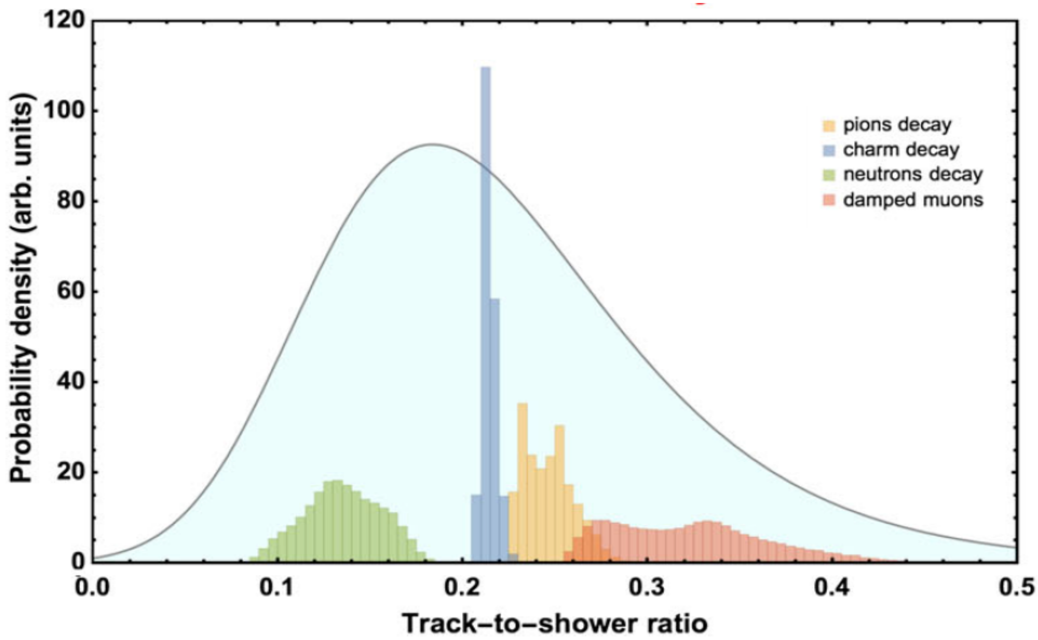
First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are mostly unknown
- From both southern and northern sky
- Production flavor structure unknown

This moment, any production models are compatible with data

Data: Track (N_T) and Shower (N_S)
→ $N_T/N_S \sim 0.15 - 0.3$

Naively, data of flavor ratio
$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$

$$N_S = 8.4F_e + 0.9F_\mu + 6.3F_\tau, \qquad N_T = 3.7F_\mu.$$



Queen Mary
University of London

1. Neutrino Interferometry

2. Spontaneous Lorentz symmetry breaking

3. Modern test of Lorentz violation

4. Test of Lorentz violation with neutrino data

5. Astrophysical very-high-energy neutrinos

6. Lorentz violation tests on astrophysical neutrinos

7. Conclusion

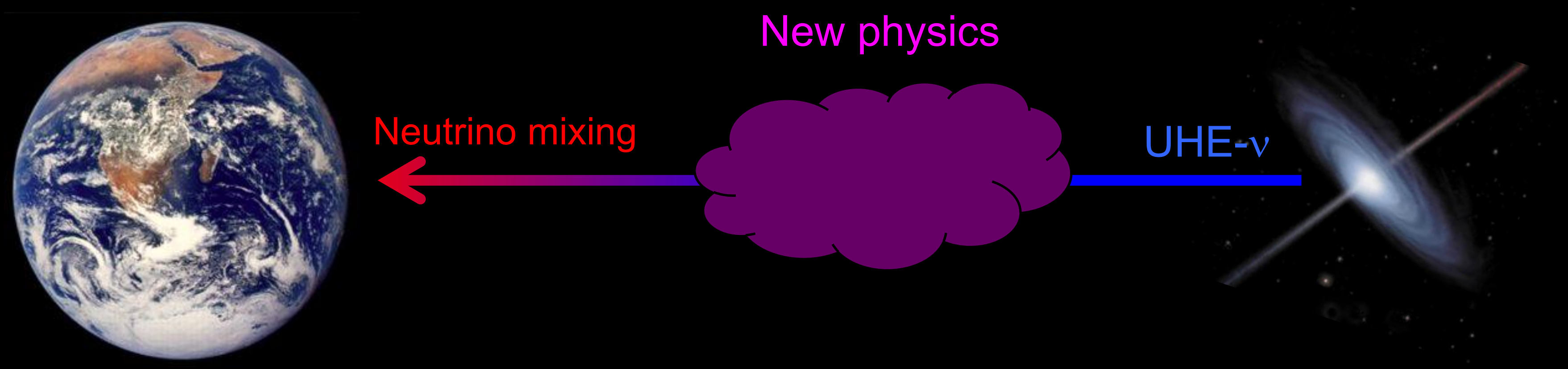
Diaz, Kostelecký, Mewes, PRD85(2013)096005;89(2014)043005, Ellis et al, arXiv:1807.05155
Arugüelles, TK, Salvado,PRL115(2015)161303

6. Lorentz violation with extra-terrestrial neutrinos

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Vacuum Cherenkov radiation can limit new physics of neutrino up to 10^{-20}
Blazar neutrino ToF can limit new physics of neutrino up to 10^{-12}

Neutrino mixing properties of UHE neutrinos can push this limit further ($\sim 10^{-34}$). It is the most sensitive test of new physics (including Lorentz violation) with neutrinos.



6. Neutrino flavour with new physics

Any new physics can end up in the effective Hamiltonian

$$h_{eff} = \frac{1}{2E} U^{\dagger} M^{2} U + \sum_{n} \left(\frac{E}{\Lambda_{n}} \right)^{n} \tilde{U}_{n}^{\dagger} O_{n} \tilde{U}_{n} = V^{\dagger} \Delta V$$

neutrino oscillation formula

$$P_{\alpha \to \beta}(L) = 1 - 4 \sum_{i>j} \mathrm{Re}(V_{\alpha i}^{*} V_{\beta i}^{*} V_{\alpha j} V_{\beta j}) \sin^{2}\left(\frac{\Delta_{ij}}{2} L \right) + 2 \sum_{i>j} \mathrm{Im}(V_{\alpha i}^{*} V_{\beta i}^{*} V_{\alpha j} V_{\beta j}) \sin\left(\Delta_{ij} L \right)$$

neutrino mixing formula

$$P_{\alpha \to \beta}(L \to \infty) \sim 1 - 2 \sum_{i>j} \mathrm{Re}(V_{\alpha i}^{*} V_{\beta i}^{*} V_{\alpha j} V_{\beta j}) = \sum_{i} \left| V_{\alpha i} \right|^{2} \left| V_{\beta i} \right|^{2}$$

Information of small contamination of new physics appears on neutrino flavours

At high energy, neutrino mass term is suppressed
→ (probably) mixing properties of the UHE neutrinos are the most sensitive method to look for new physics within particle physics

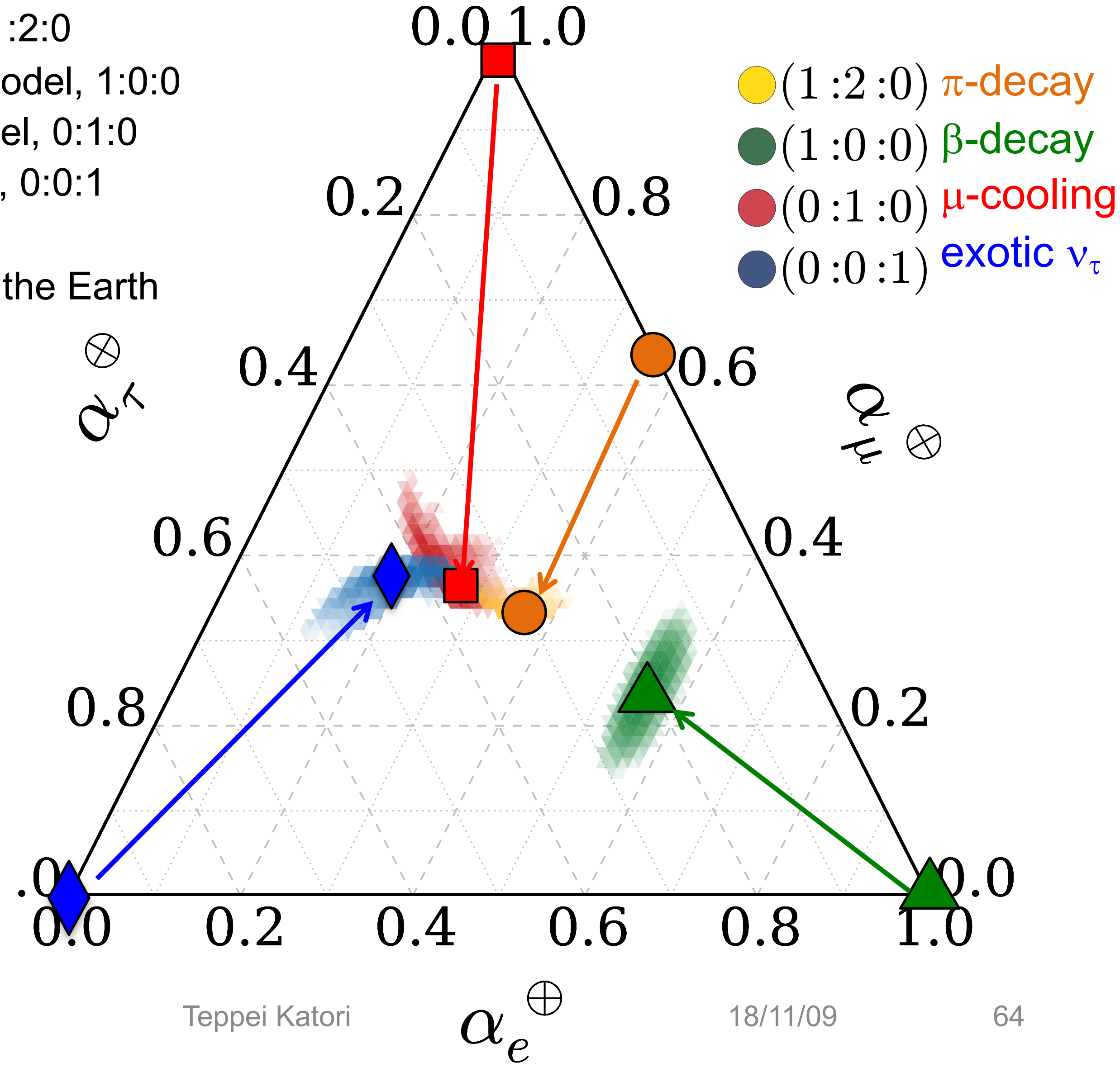
Arugüelles, TK, Salvado, PRL115(2015)161303

6. Standard flavour triangle diagram

There are 3 UHE neutrino production models

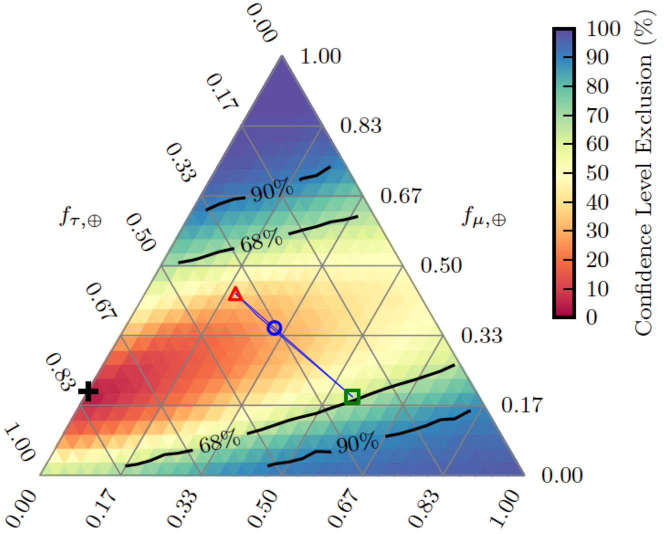
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1

Initial flavour ratio is modified on the Earth due to neutrino mixing



IceCube collaboration
PRL114(2015)171102

IceCube flavour triangle diagram



Arugüelles, TK, Salvado, PRL115(2015)161303

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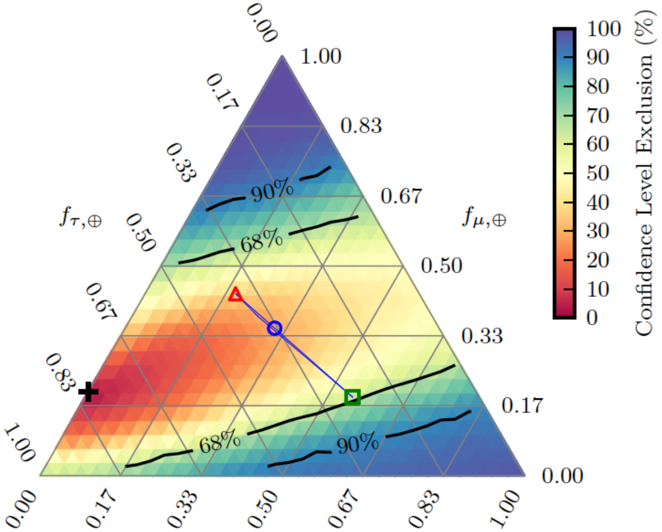
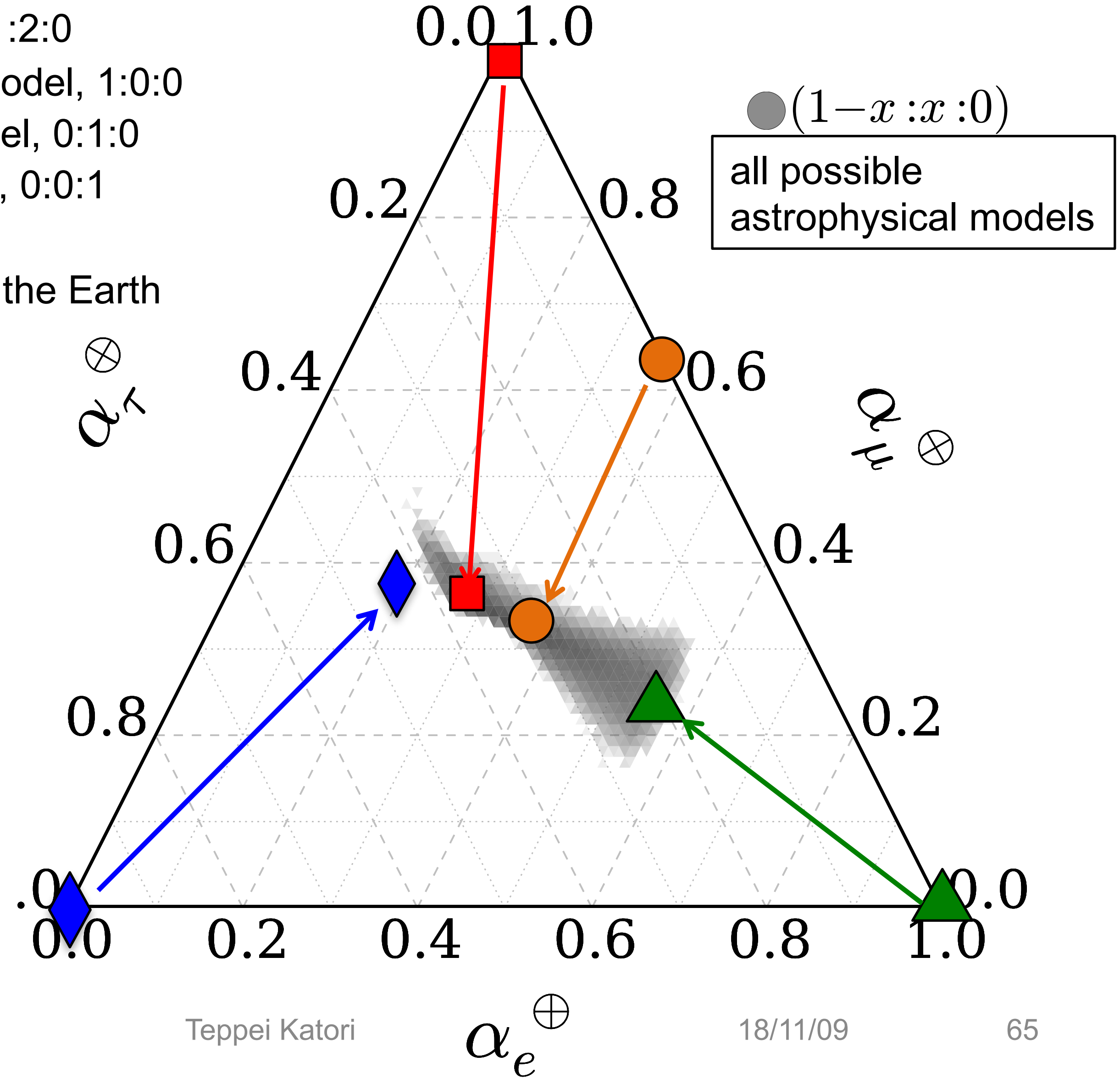
IceCube collaboration
PRL114(2015)171102

IceCube flavour triangle diagram





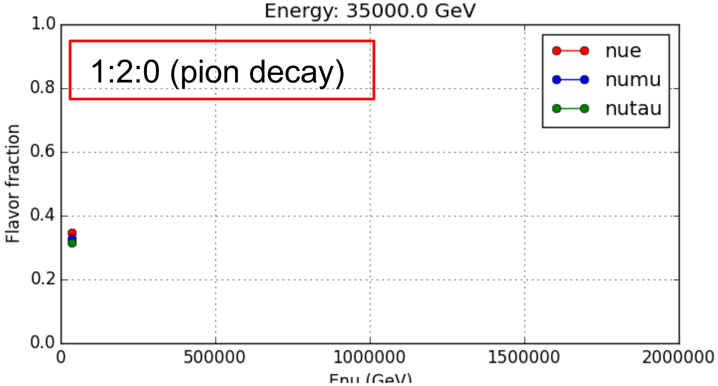
Arugüelles, TK, Salvado, PRL115(2015)161303

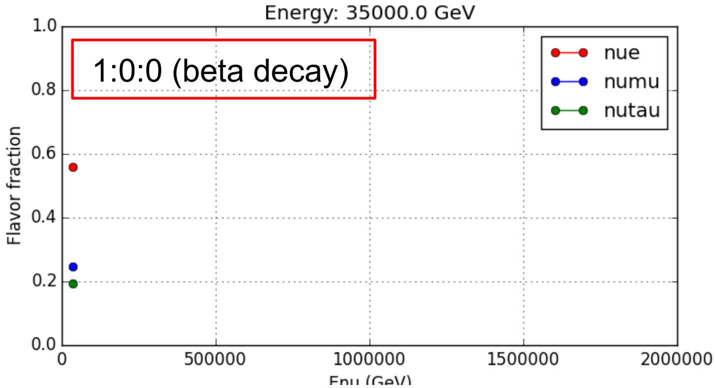
6. Neutrino flavour ratio with new physics

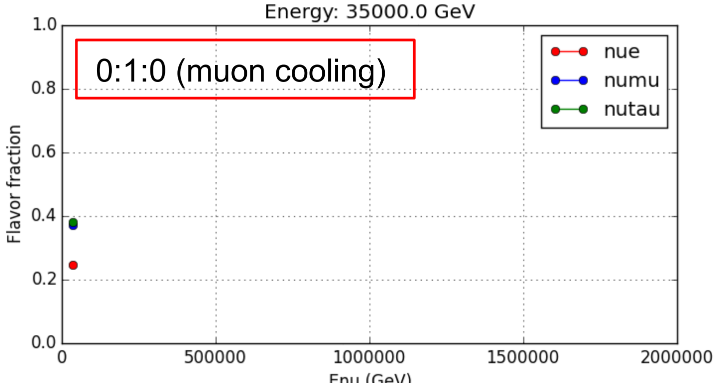
Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

An example Hamiltonian with new physics term
(~10^{-26} GeV CPT odd Lorentz violation)

$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{e\tau}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{e\tau}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} + E \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & c_{\mu\tau} \\ 0 & c_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$







Arugüelles, TK, Salvado, PRL115(2015)161303

6. Neutrino flavour ratio with new physics

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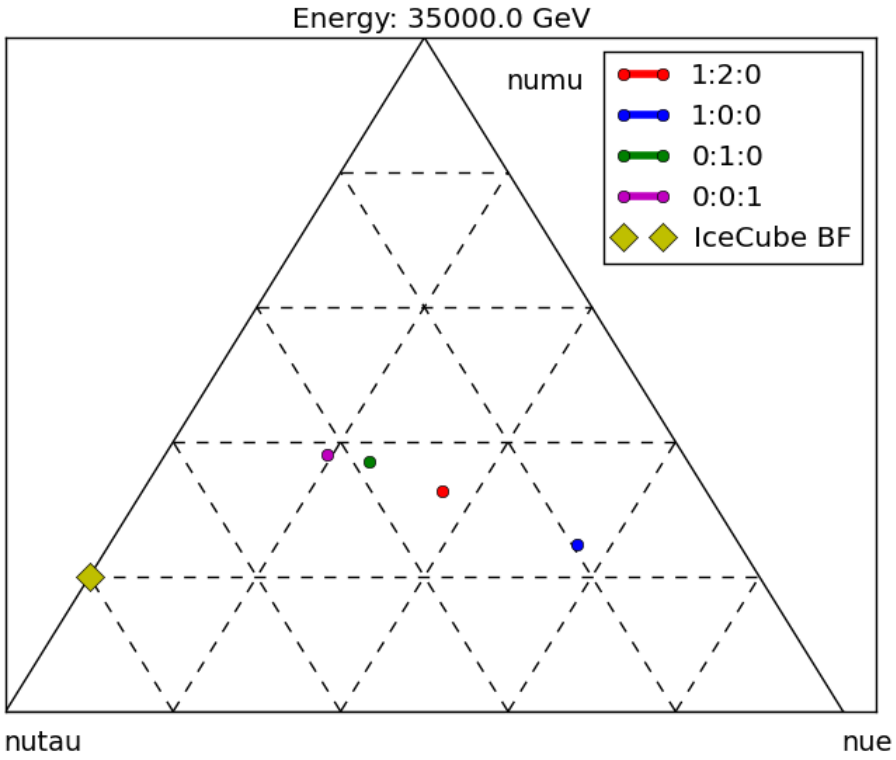
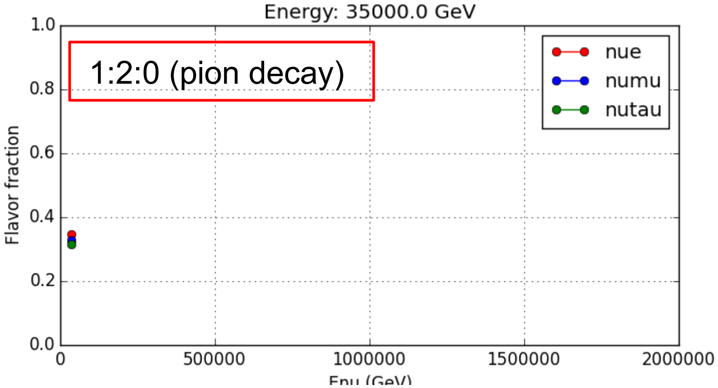
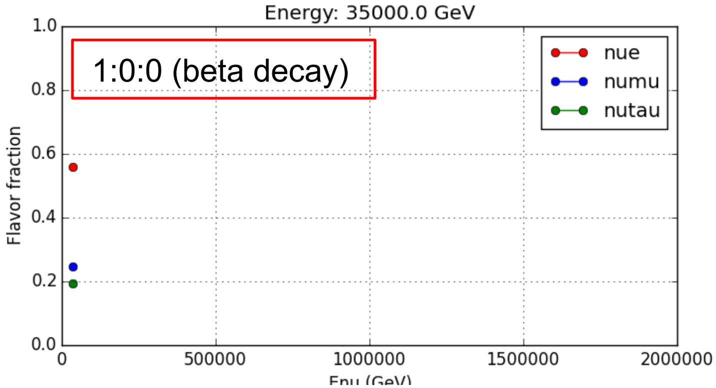
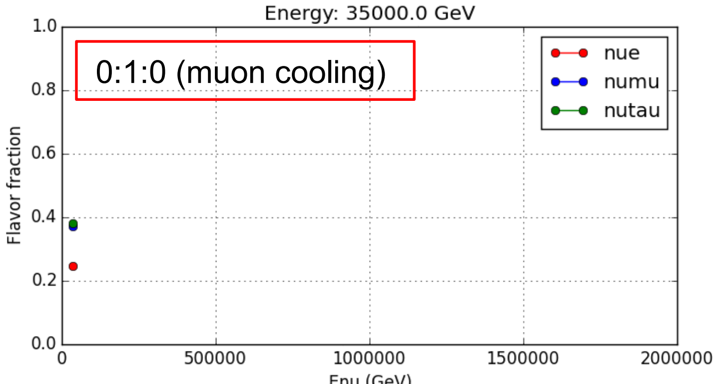
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

Flavor triangle diagram is a convenient way to show these models.









Arugüelles, TK, Salvado, PRL115(2015)161303

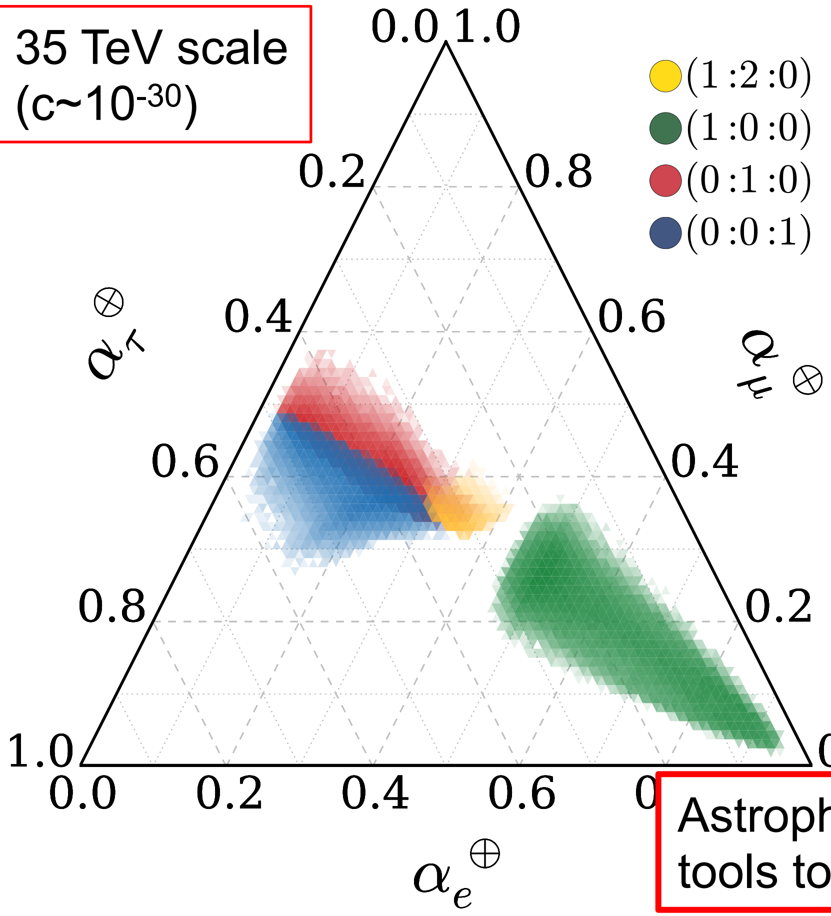
6. Flavour triangle histogram

Exotic models can make variety of flavour ratios, but not every flavour ratio is possible.

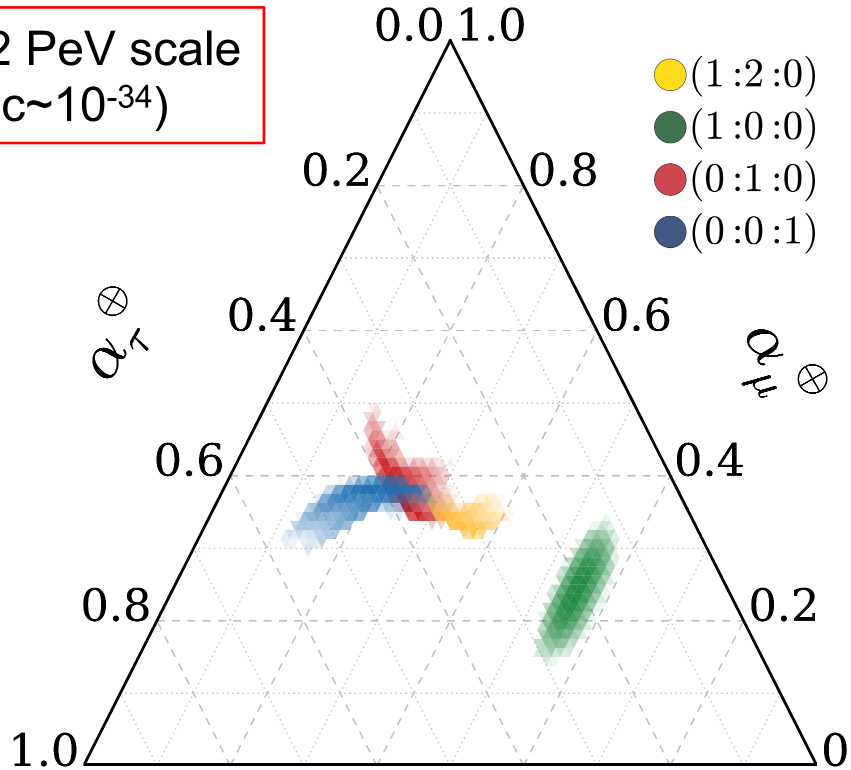
$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{e\tau} \\ m^{2*}_{e\mu} & m^2_{\mu\mu} & m^2_{\mu\tau} \\ m^{2*}_{e\tau} & m^{2*}_{\mu\tau} & m^2_{\tau\tau} \end{pmatrix} + E\cdot\begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

Dimension-4 operator new physics

35 TeV scale
(c~10^{-30})



2 PeV scale
(c~10^{-34})



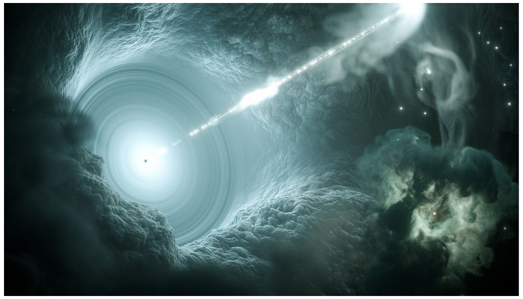
Astrophysical neutrino flavor is one of the most powerful tools to look for new physics in particle physics!

Taboada (IceCube), Neutrino 2018

6. New IceCube data (2018)

Blazar neutrino

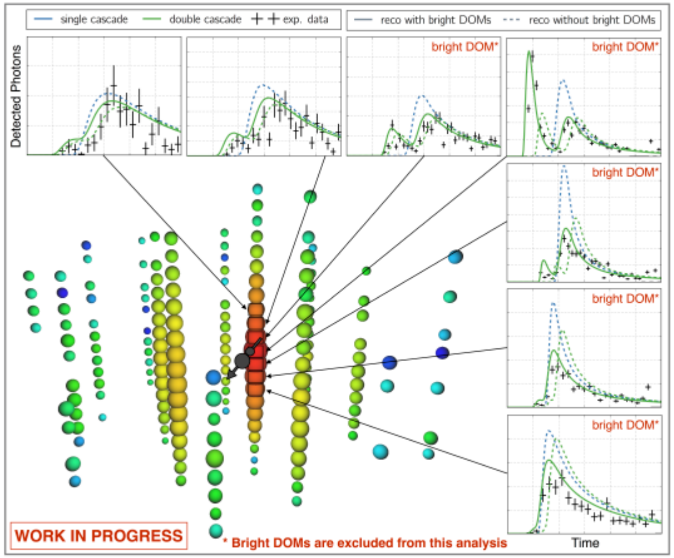
- IC170922A and TXS 0506+056
- Optical coincidence, clustering from this direction



IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378

First astrophysical tau neutrino?

- double pulse of τ-production & decay



Double cascade Event #2

SHOP ICECUBE
OFFICAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

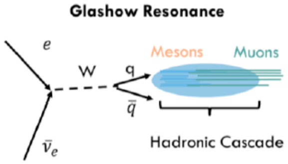
https://charge.wisc.edu/icecube/wipac_store.aspx

IceCube IC170922 t-shirt (Crew-Neck)
$18.00
The front side features an image of "IC170922" and the IceCube logo on the back Heathered navy, crewneck, rinspun cotton/polyester, Available in unisex sizes S-2XL. Runs small.

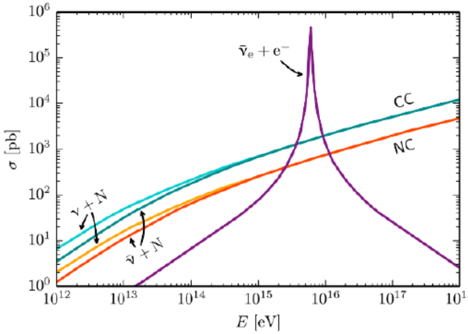
Support IceCube!

First Glashow resonance?

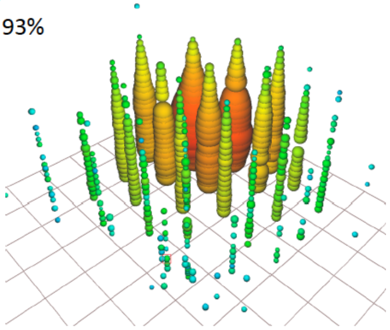
A 5.9 PeV event in IceCube



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%



Work in progress



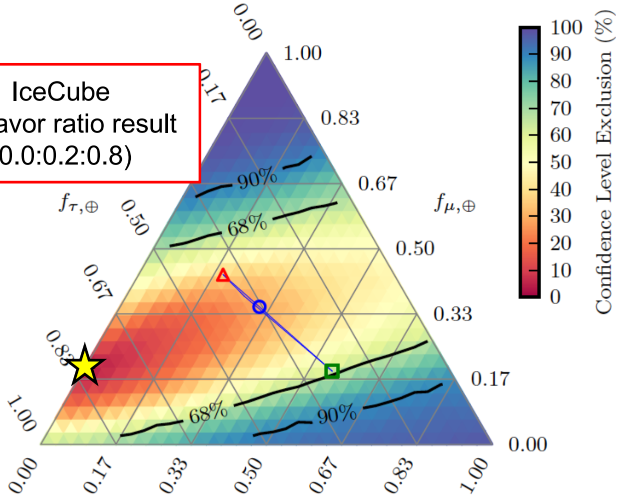
Event identified in a partially-contained PeV search (PEPE)
Deposited energy: 5.9±0.18 PeV (stat only)
ICRC 2017 arXiv:1710.01191

Queen Mary
University of London

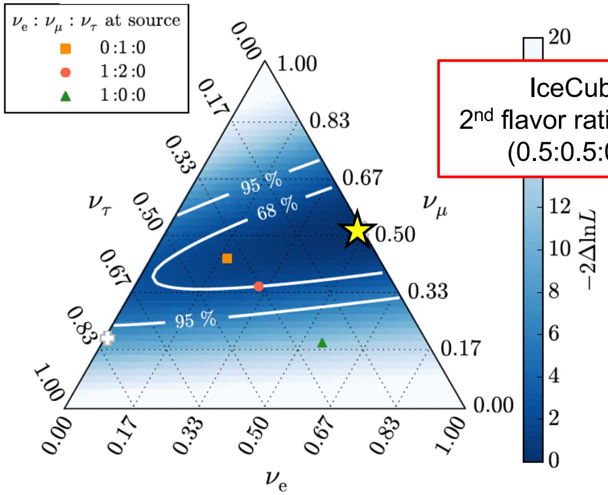
Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015)

6. New flavor ratio data (2018)

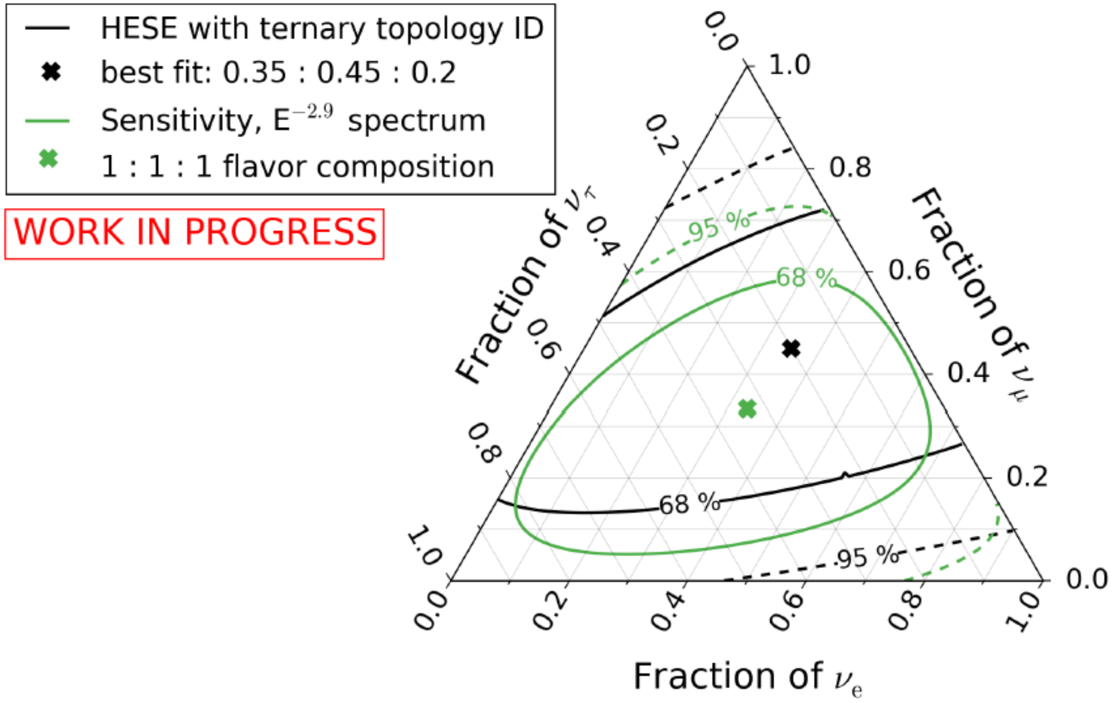
IceCube preliminary



IceCube
1st flavor ratio result
(0.0:0.2:0.8)



IceCube
2nd flavor ratio result
(0.5:0.5:0.0)



WORK IN PROGRESS

Likelihood is very shallow and fit confuse between ν_e and ν_τ

New flavour ratio result has some power to distinguish between ν_e and ν_τ

Taboada (IceCube), Neutrino 2018
IceCube, PRL114(2015)171102, Astro.J.809:98(2015)

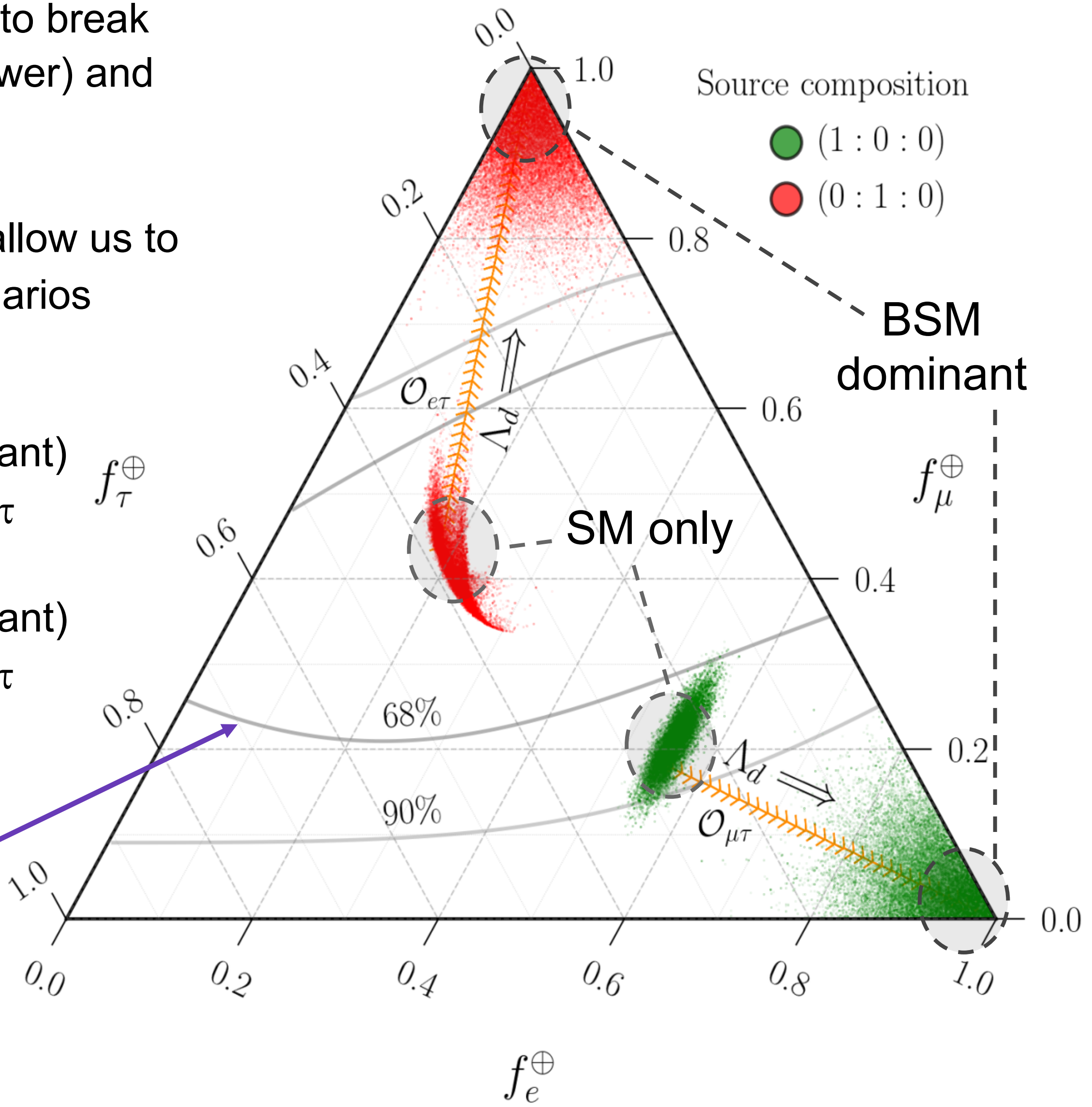
6. New flavor ratio data (2018)

IceCube preliminary

Improved tau-neutrino PID allows to break the degeneracy of ν_e shower (shower) and ν_τ shower (double shower)

However, large contour does not allow us to exclude most of new physics scenarios

We focus on 2 scenarios;
1. Source ratio is 1:0:0 (ν_e dominant) and new physics is dominate $\mu\leftrightarrow\tau$ mixing
2. Source ratio is 0:1:0 (ν_μ dominant) and new physics is dominate $e\leftrightarrow\tau$ mixing



BSM dominant

SM only

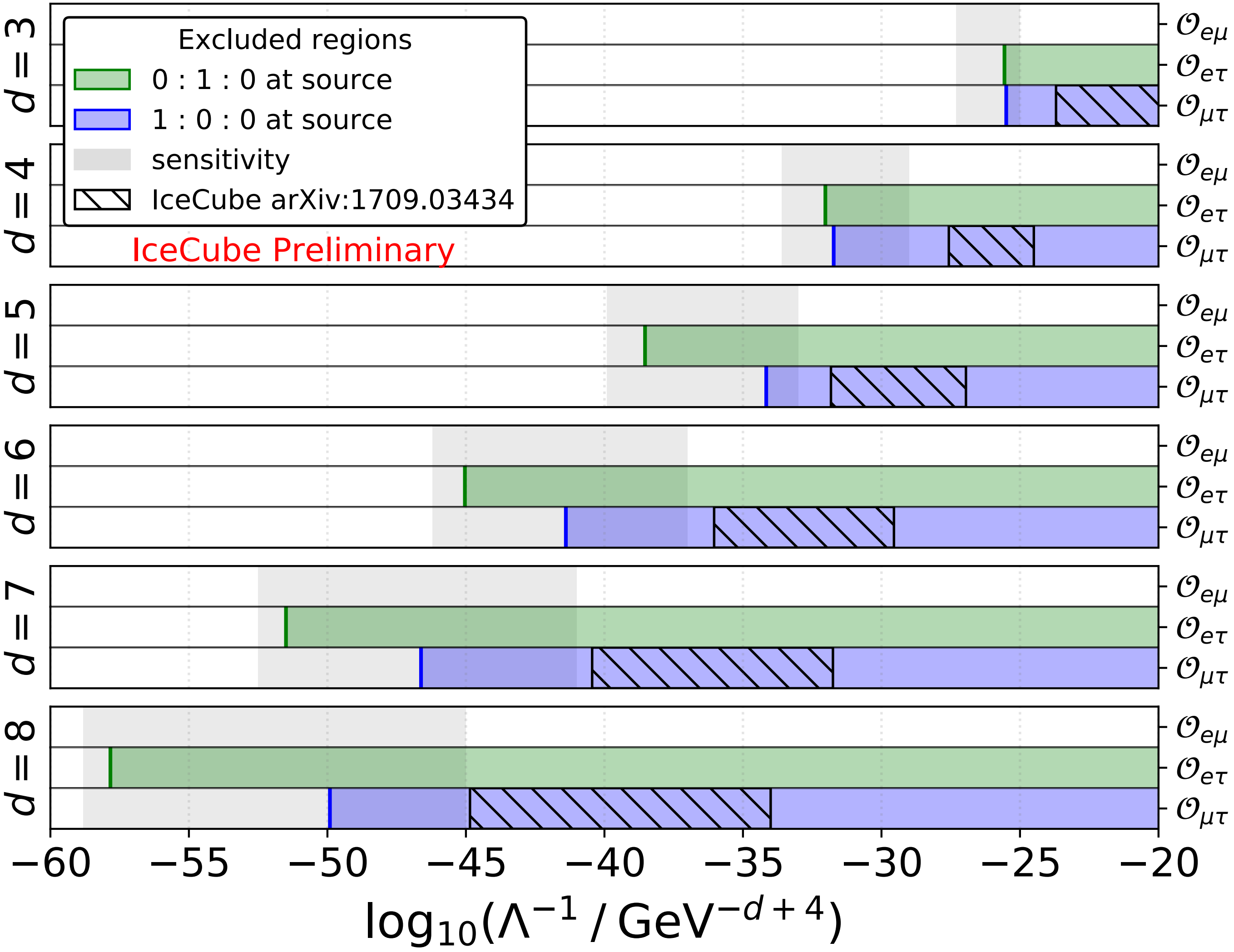
2018 flavour ratio contour (preliminary)

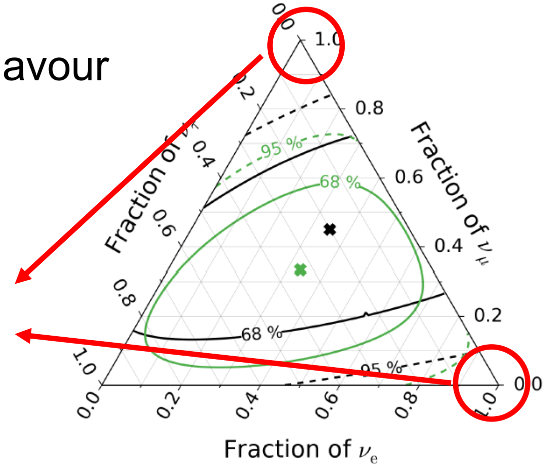
IceCube preliminary

6. First Lorentz violation test from astrophysical neutrinos

We start to exclude possible SME values from astrophysical neutrino flavour

- This moment, we can exclude only extreme scenarios
- dimension-6 new physics operator limit reaches to 10^{-45}-10^{-42} GeV^{-2}





Argüelles (IceCube), Neutrino 2018

IceCube preliminary

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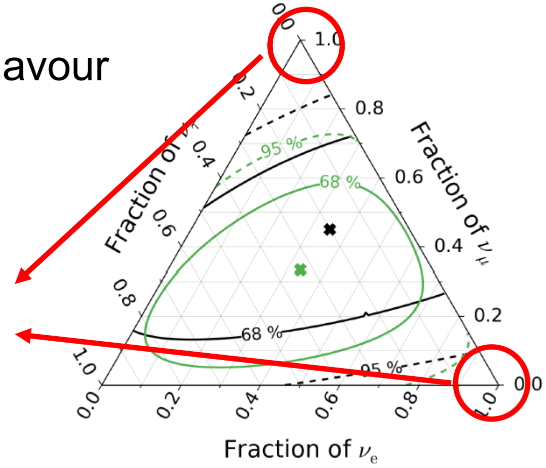
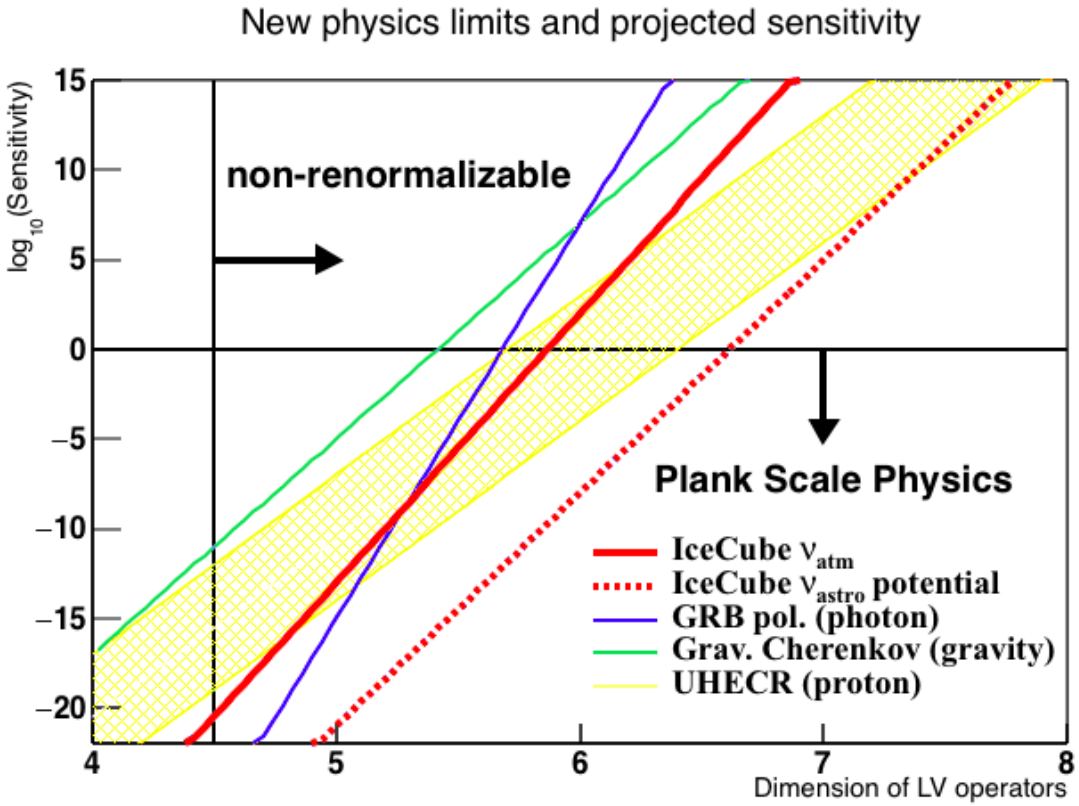




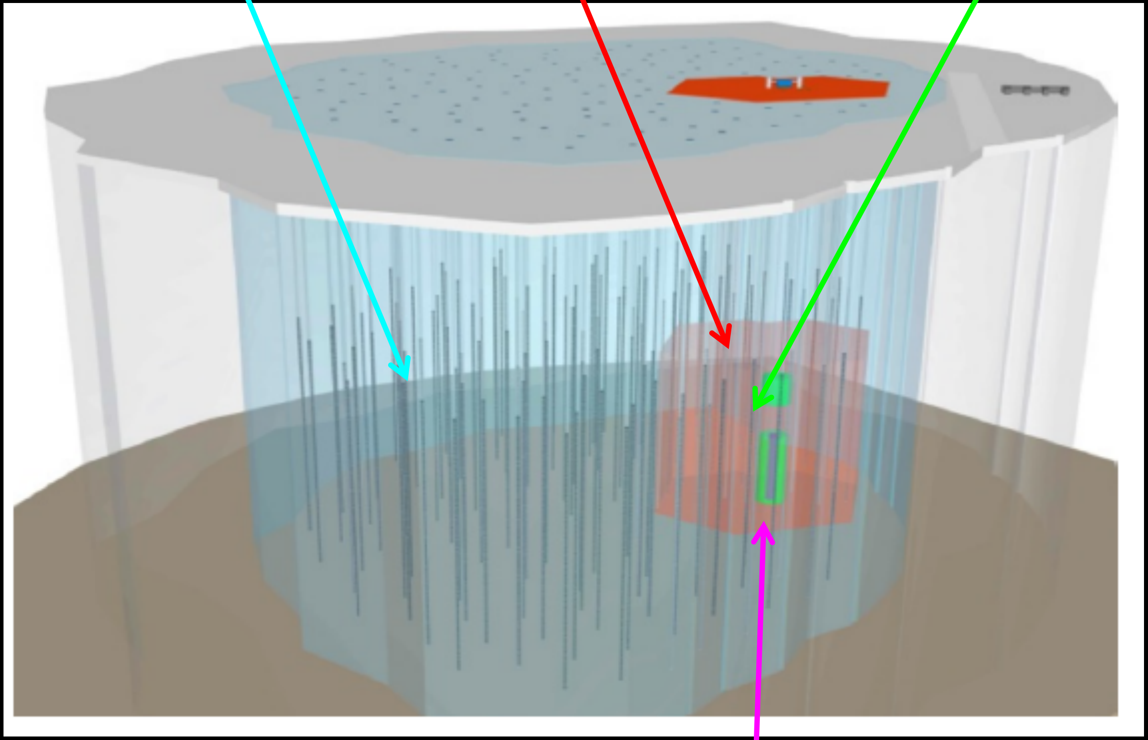
If, quantum gravity-motivated new interaction existed, we would expect the leading effect $1/M_P^2 \sim 10^{-38}$ GeV^{-2}

Astrophysical neutrino flavor is one of the most powerful tools to look for new physics in particle physics!

What's next?

IceCube-Gen2, arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

7. IceCube-Gen2



Bigger IceCube and denser DeepCore can push their physics

Gen2
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

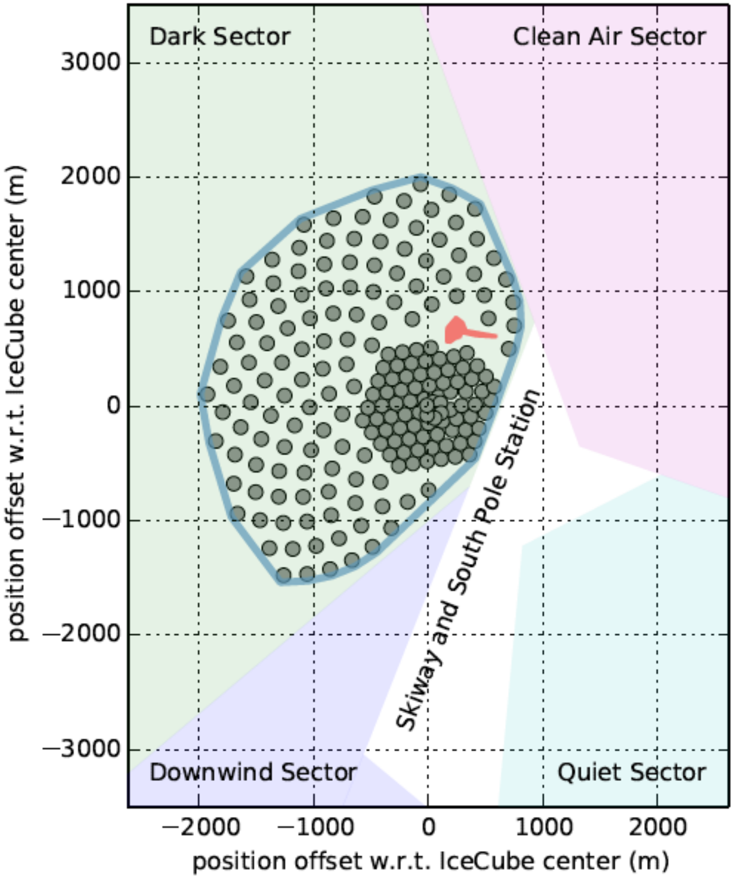
IceCube-Gen2 collaboration meeting (May 1, 2015)

IceCube is working on the first stage of this (IceCube upgrade)

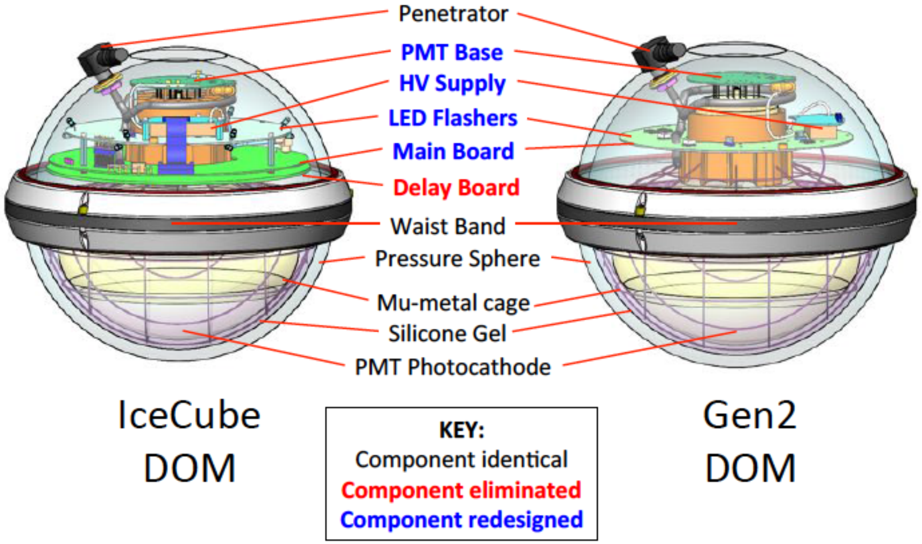
IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

7. IceCube-Gen2

Ice is clear than we thought
 → larger separation (125m → ~200-300m) to cover larger volume
 - 120 new strings with 80 DOMs, 240 m separation, x10 coverage



pDOM
 - Improved IceCube DOM
 - baseline design



IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

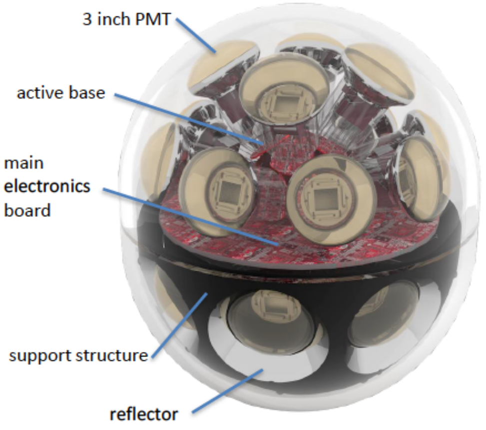
7. IceCube-Gen2

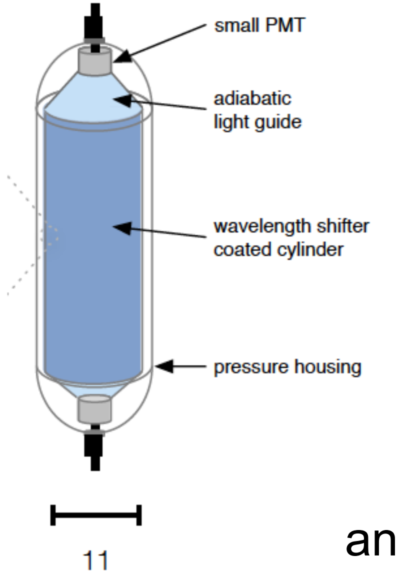
Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 80 DOMs, 240 m separation, x10 coverage
- Variety of new detectors are under development

mDOM
- KM3NeT style
- direction sensitive
- Collaboration in HyperK

D-Eggs
- 8-inch high-QE PMTs
- cleaner glass window
- Chiba-U initiative

WOM
- Scintillator light guide
- cheaper per coverage
- small diameter





and more...

IceCube-Gen2,arXiv:1412.5106, JPhysG.44 (2017) 054006
ICRC2017 proceedings, arXiv:1710.01207

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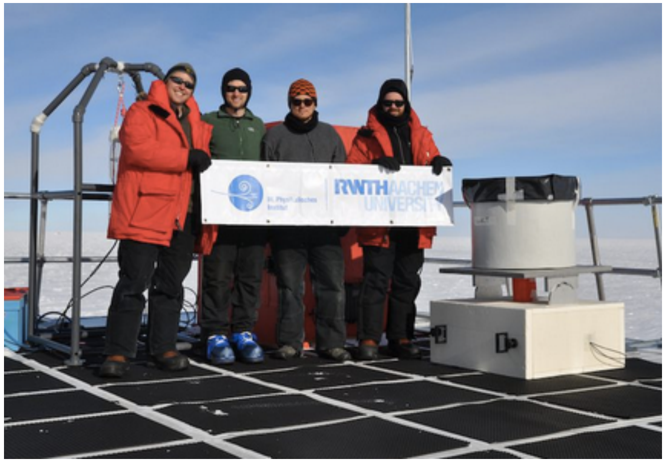
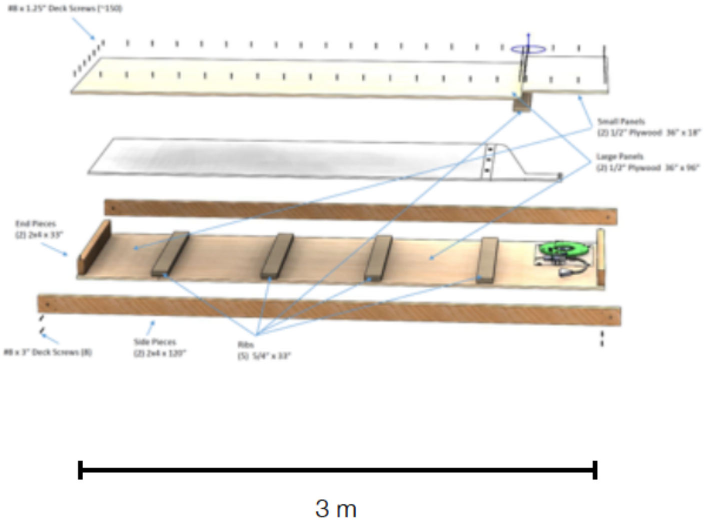
Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 80 DOMs, 240 m separation, x10 coverage
- Variety of new detectors are under development
- Variety of new surface array are under development

IceACT
- air Cherenkov telescope
- larger coverage with fewer stations
- prototype is installed at South Pole



Scintillator panels
- cheaper coverage per area
- easy deployment



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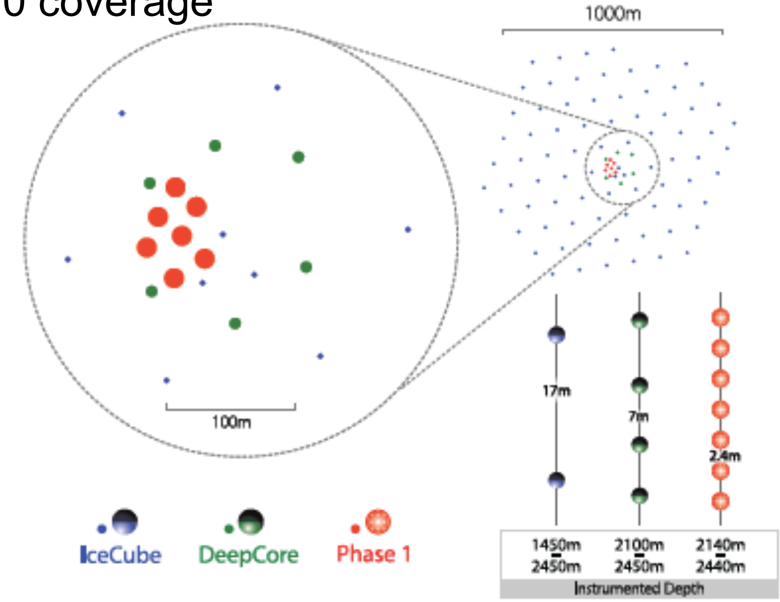
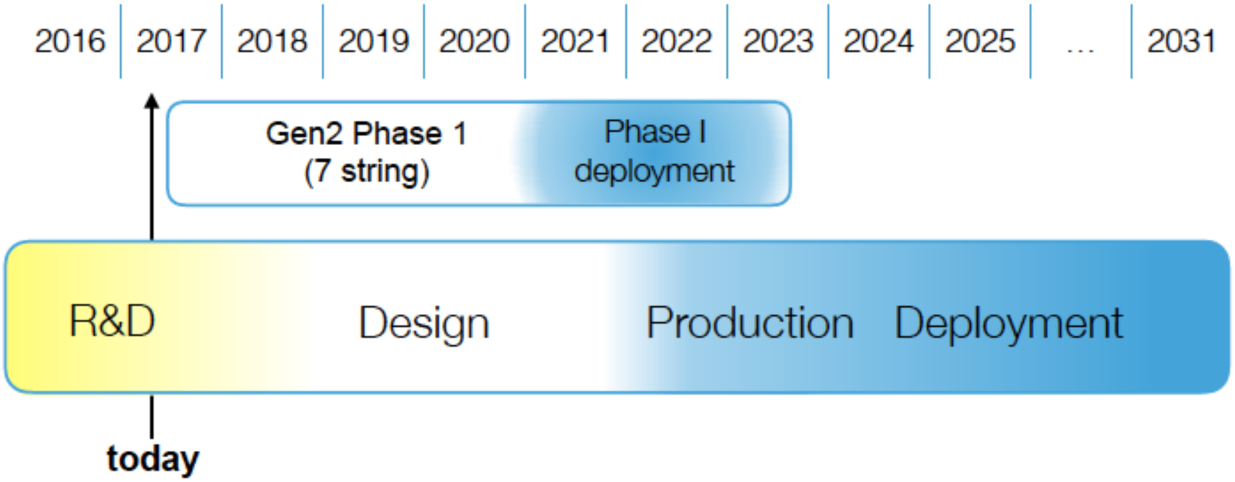
- Variety of new surface array are under development

IceCube-Upgrade
- Proposal accepted
- 7 new strings (part of PINGU array)
- Test new calibration device for high energy physics
- ν_τ appearance to constrain unitary triangle




2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | … | 2031

Gen2 Phase 1
(7 string)

Phase I
deployment

R&D

Design

Production

Deployment

today

Conclusion

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

There is a world wide effort to test Lorentz violation with various state-of-the-art technologies.

MiniBooNE, MINOS, IceCube, Double Chooz, T2K, and Super-Kamiokande set stringent limits on Lorentz violation in neutrino sector in terrestrial level.

Extra-terrestrial neutrinos from IceCube are one of the most sensitive tool to test fundamental physics, such as Lorentz violation.

Thank you for your attention!

backup

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)

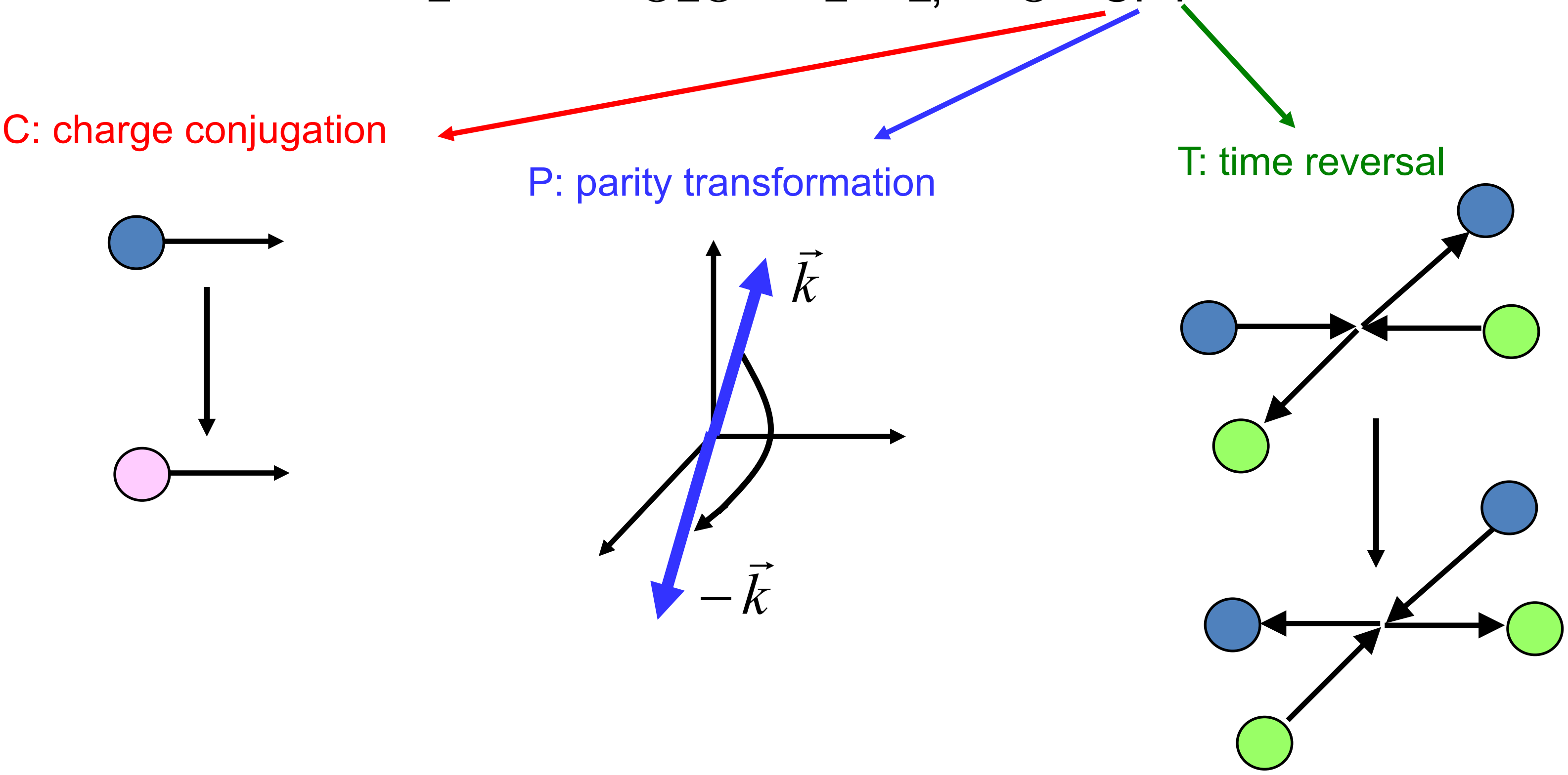
But there is a frame where universe looks isotropic even with a Lorentz violating vector field. You may call that is the "preferred frame", and people often speculate the frame where CMB looks isotropic is such a frame (called "CMB frame").

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.

3. What is CPT violation?

CPT symmetry is the invariance under the CPT transformation

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


C: charge conjugation

P: parity transformation

T: time reversal

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

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

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

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

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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.

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

number of Lorentz indices
→ always even number

3. What is CPT violation?

CPT phase = $(-1)^n$
n = # Lorentz indices

CPT symmetry is the invariance under the CPT transformation

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

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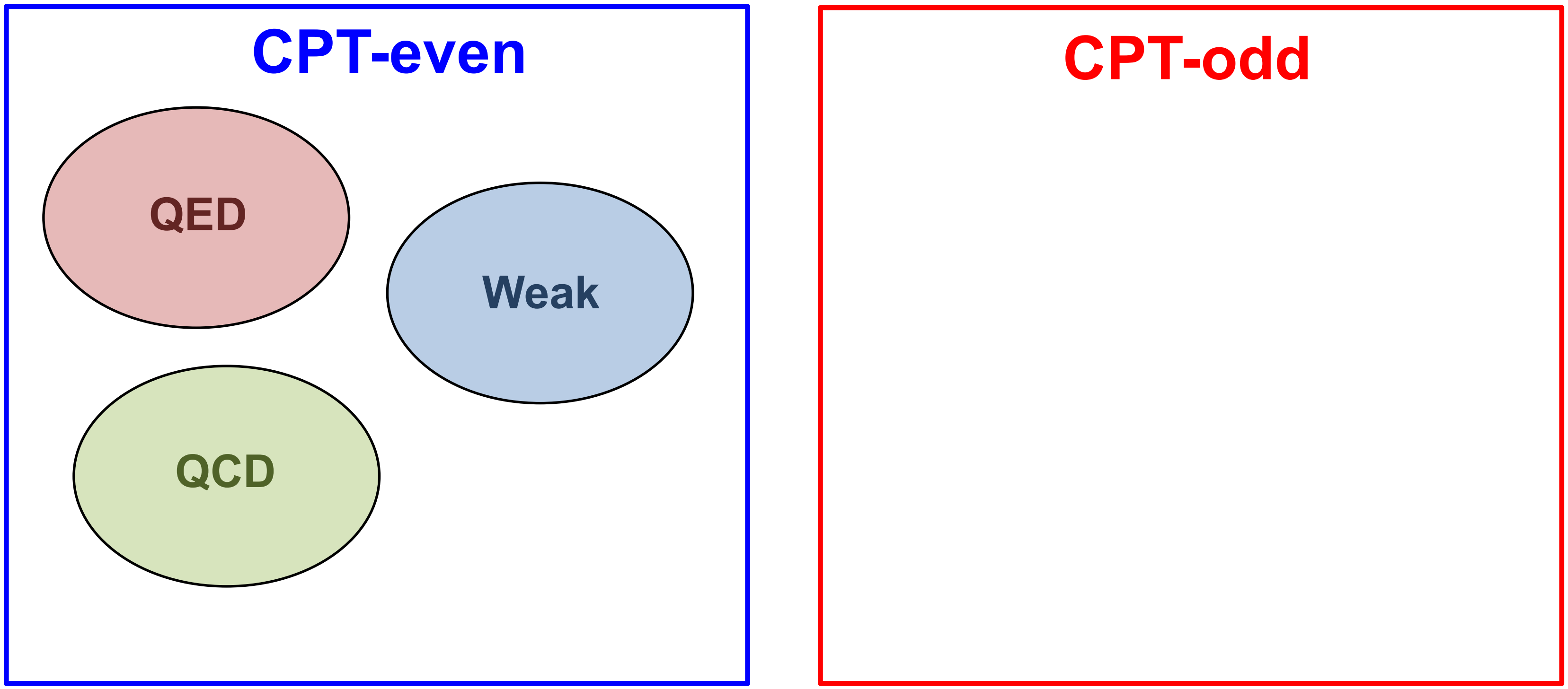

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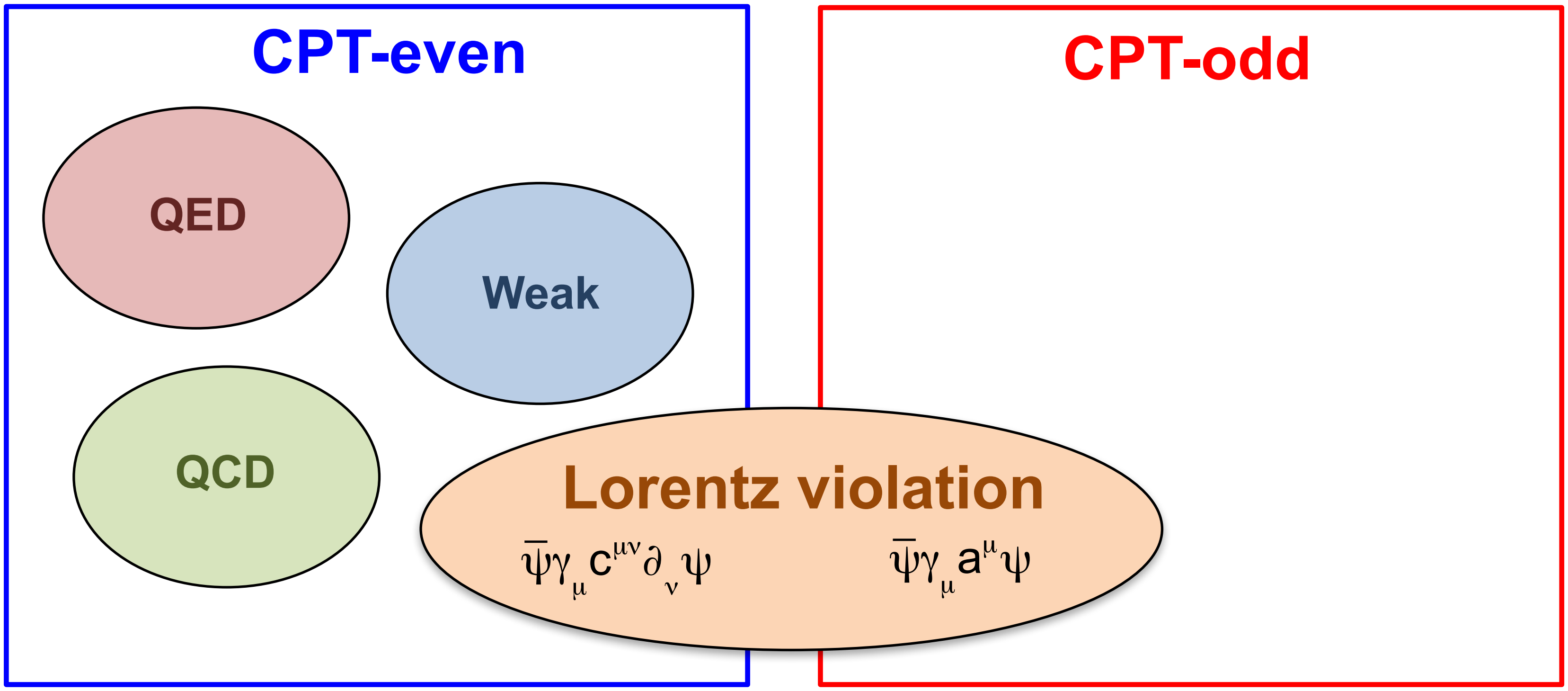


CPT-even

QED

Weak

QCD

CPT-odd

Lorentz violation

$\bar{\psi}\gamma_\mu c^{\mu\nu}\partial_\nu\psi$

$\bar{\psi}\gamma_\mu a^\mu\psi$

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

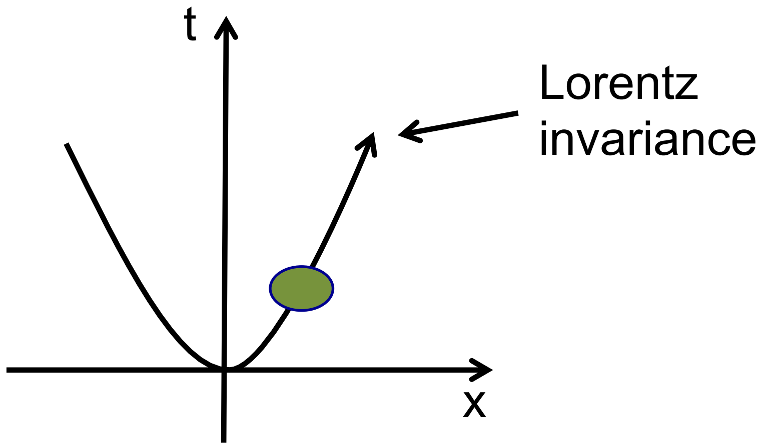
CPT-even Lorentz violating coefficients (even number Lorentz indices, e.g., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

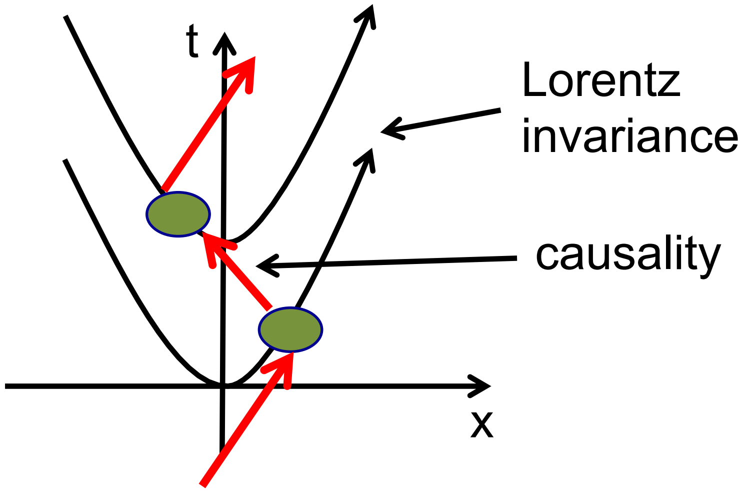
Greenberg, PRL(2002)231602

3. CPT violation implies Lorentz violation

Lorentz invariance → CPT → Lorentz invariance of quantum field theory

CPT violation implies Lorentz violation in interactive quantum field theory.





3. Test of Lorentz violation

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

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

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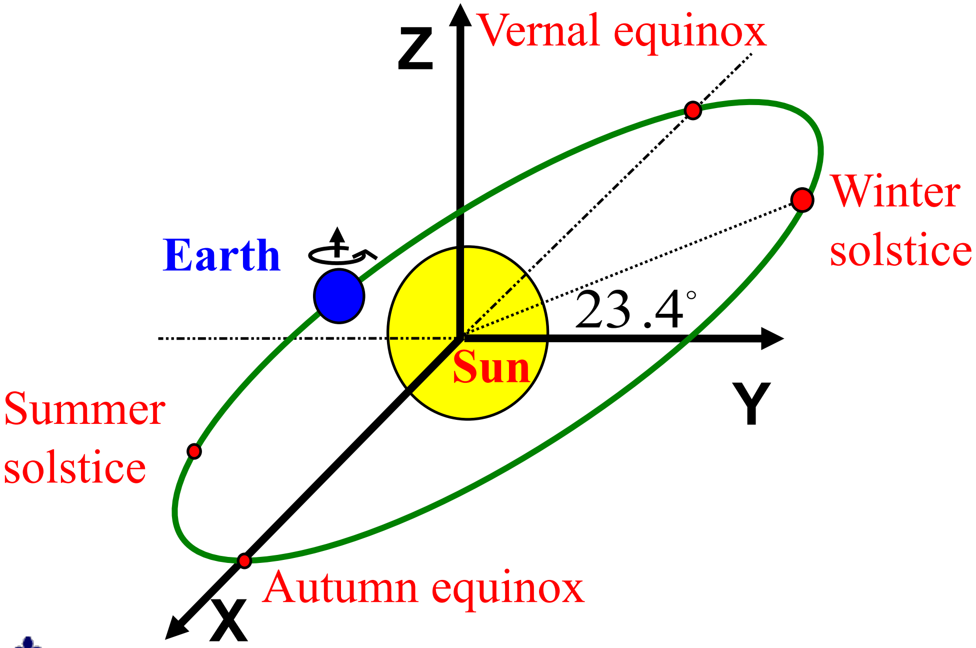
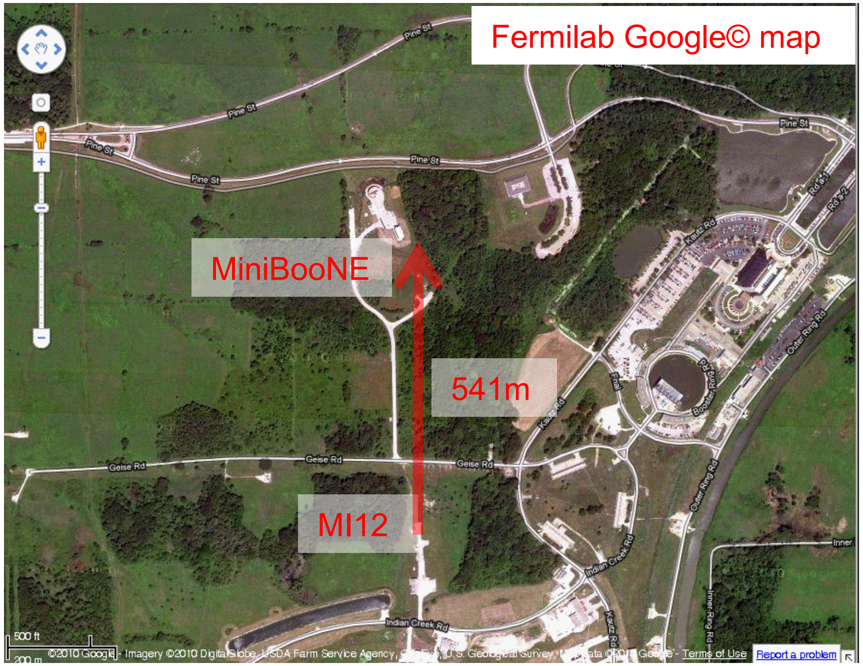
- Neutrino beamline is described in Sun-centred coordinates





MiniBooNE beamline

Kostelecký and Mewes, PRD69(2004)016005

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

SME Lagrangian in neutrino sector

$$L = \frac{1}{2} i \bar{\psi}_A \Gamma^{\nu}_{AB} \partial_{\nu} \psi_B - M_{AB} \bar{\psi}_A \psi_B + h.c.$$

SME coefficients

$$\Gamma^{\nu}_{AB} = \gamma^{\nu} \delta_{AB} + c^{\mu\nu}_{AB} \gamma_{\mu} + d^{\mu\nu}_{AB} \gamma_{\mu} \gamma_5 + e^{\nu}_{AB} + i f^{\nu}_{AB} \gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}_{AB} \sigma_{\lambda\mu} \cdots$$

$$M_{AB} = m_{AB} + i m_{5AB} \gamma_5 + a^{\mu}_{AB} \gamma_{\mu} + b^{\mu}_{AB} \gamma_5 \gamma_{\mu} + \frac{1}{2} H^{\mu\nu}_{AB} \sigma_{\mu\nu} \cdots$$

Kostelecký and Mewes, PRD70(2004)076002

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Various physics are predicted under SME…

Lagrangian → Hamiltonian → Observables

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

sidereal time $T_\oplus$

Neutrino oscillation probability with sidereal variation due to Lorentz violation

$$P_{\nu_\mu\rightarrow\nu_e}(L,T_\oplus) = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{e\mu} + (A_s)_{e\mu} sin\omega_\oplus T_\oplus + (A_c)_{e\mu} cos\omega_\oplus T_\oplus + (A_s)_{e\mu} sin2\omega_\oplus T_\oplus + (A_c)_{e\mu} cos2\omega_\oplus T_\oplus\right|^2$$

Neutrino oscillation probability with spectral distortion due to Lorentz violation

$$P_{\nu_\mu\rightarrow\nu_x} = P_{\nu_\mu\rightarrow\nu_x}\left(h_{eff}(E), L\right), \quad h_{eff}(E) = \frac{m^2}{2E} + a_3 - c_4 E + a_5 E^2 - c_6 E^3 + a_5 E^2 - c_6 E^3 + \cdots$$

Queen Mary
University of London

Kostelecký and Mewes, PRD70(2004)076002

3. Test of Lorentz violation

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

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(3) write down the observables using this Lagrangian

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

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

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

sidereal time $T_\oplus$

Lorentz-violating neutrino oscillation probability for short-baseline experiments

time independent amplitude

sidereal time dependent amplitude

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

Sidereal variation analysis for short baseline neutrino oscillation is 5-parameter fitting problem

Kostelecký and Mewes
PRD70(2004)076002

6. Lorentz violation with MiniBooNE

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

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

Expression of 5 observables (14 SME parameters)

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

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

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

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

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

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

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

MiniBooNE, PRD79(2009)072002, NIM.A599(2009)28

5. MiniBooNE experiment

MiniBooNE is a short-baseline neutrino oscillation experiment at Fermilab.

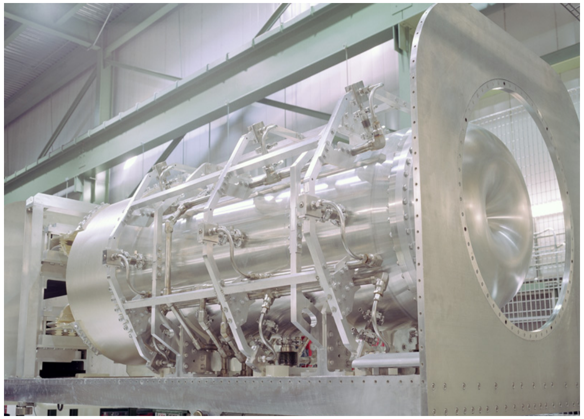
$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \to e^- + p$$

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

Booster Neutrino Beamline (BNB) creates ~800(600)MeV neutrino(anti-neutrino) by pion decay-in-flight. Cherenkov radiation from the charged leptons are observed by MiniBooNE Cherenkov detector to reconstruct neutrino energy.

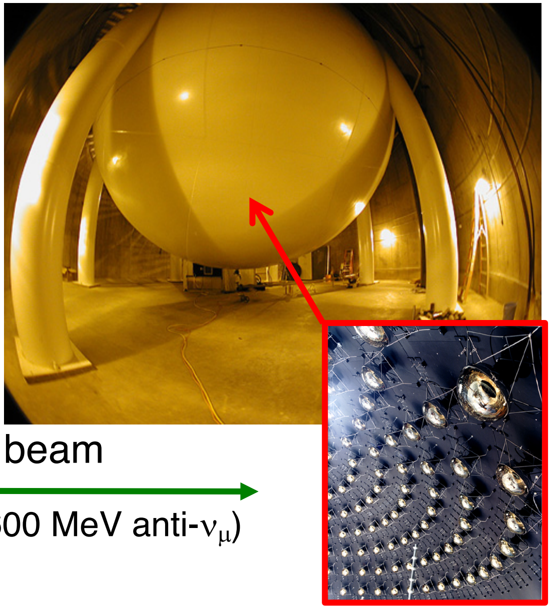
FNAL Booster

Magnetic focusing horn



~520m →

MiniBooNE detector



1280 of 8” PMT

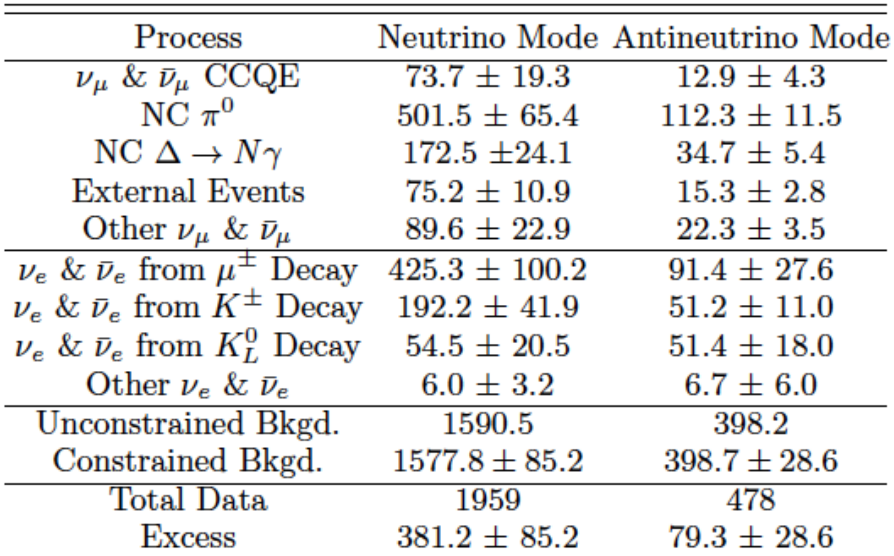
primary beam → (8 GeV protons)

secondary beam → (1-2 GeV pions)

tertiary beam → (800 MeV ν_μ , 600 MeV anti-ν_μ)

4. Internal background constraints

All backgrounds are internally constrained
→ intrinsic (beam ν_e) = flat
→ misID (gamma) = accumulate at low E

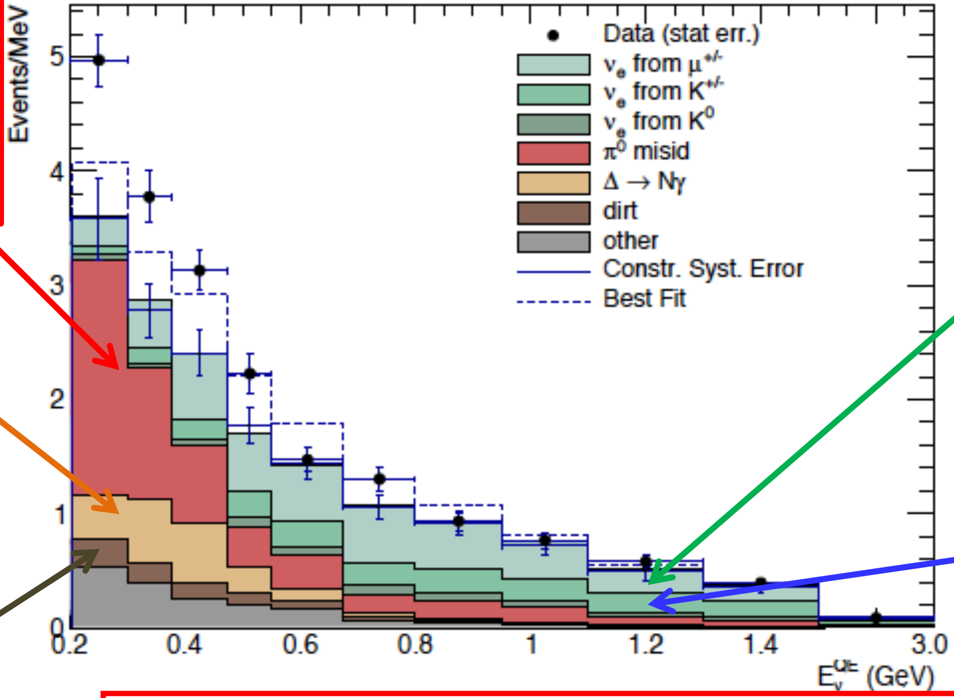


Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.5	398.2
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6

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

Δ resonance rate is constrained from measured $NC\pi^o$ rate

dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

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

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

Kostelecký, Mewes, PRD70(2004)031902, TK, Kostelecký, Tayloe, PRD74(2006)105009
Díaz, Kostelecký, PLB700(2011)25, PRD85(2012)016013

5. LV-motivated alternative oscillation model

LV can provide many exotic texture of Hamiltonian. This allows to construct models for neutrino oscillation, including CPT violation.

Puma model Hamiltonian

$$h_{eff} = \frac{m^2}{2E}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + aE^2\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + cE^5\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

e.g.) Puma model

Non-trivial Hamiltonian can reproduce all oscillation data (circa 2011) including MiniBooNE ν and $\bar{\nu}$-data

If LV is really the solution of MiniBooNE anomaly, do data exhibit sidereal variation?

Puma model predictions

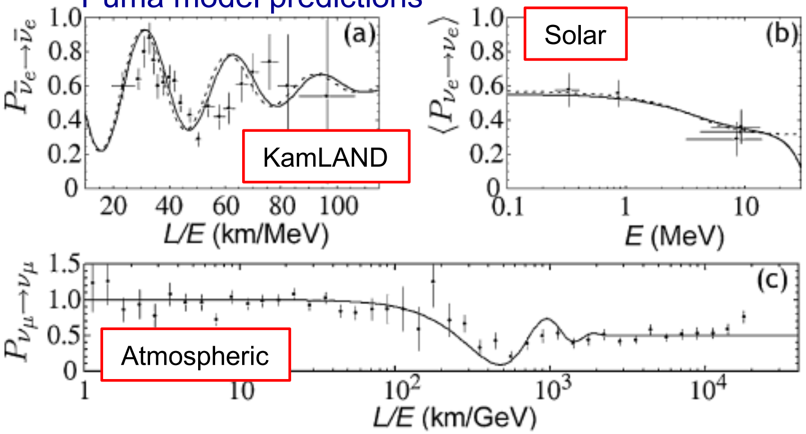
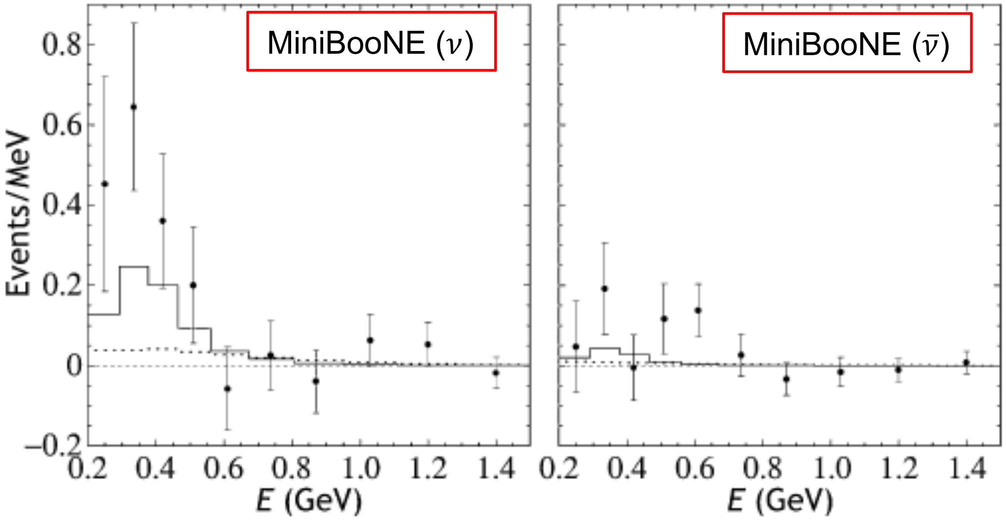
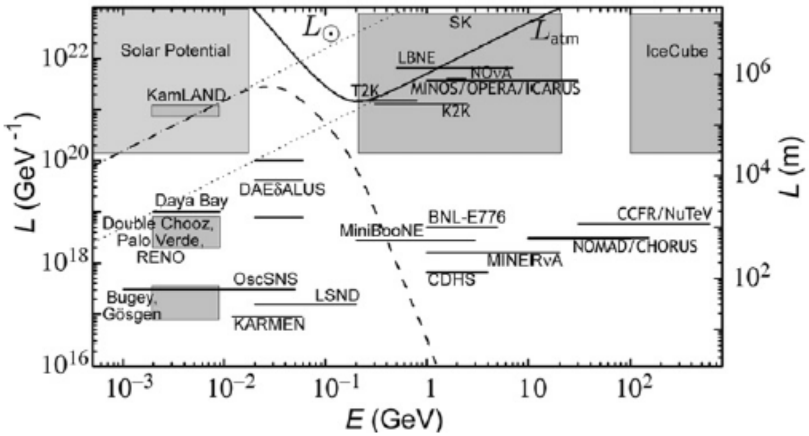


Fig. 1. Puma model (solid) and 3νSM (dashed) compared to (a) KamLAND [31], (b) solar [33], and (c) SK [34] data.





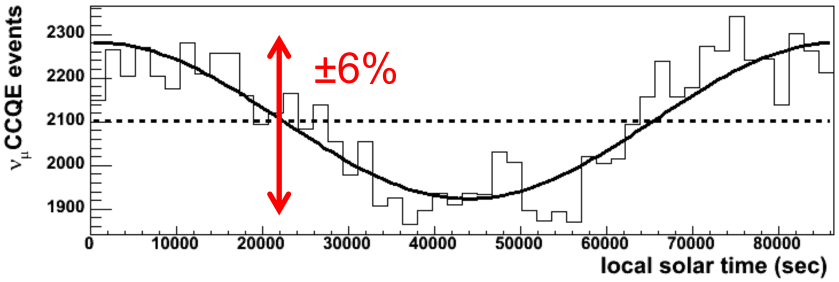
MiniBooNE, PLB718(2013)1303

3. Lorentz violation with MiniBooNE neutrino data

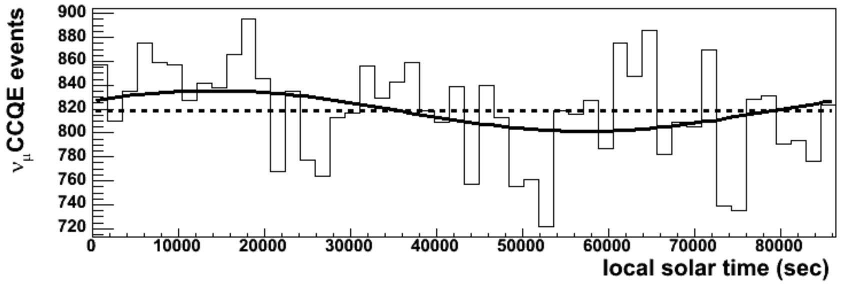
Time dependent systematics

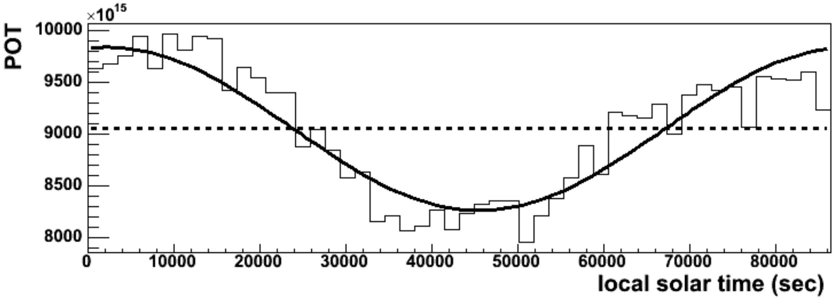
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)

ν_μCCQE events distribution, Monday to Friday

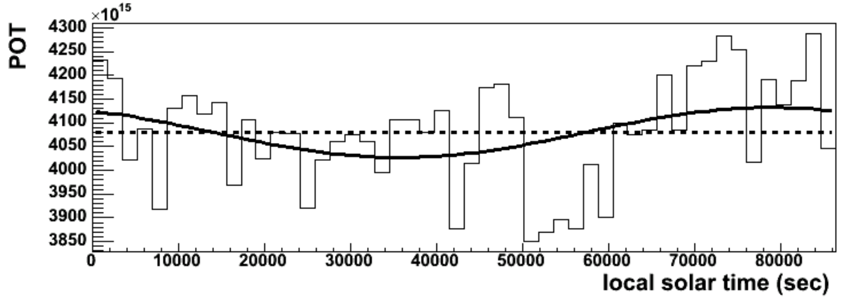


ν_μCCQE events distribution, Saturday and Sunday





POT distribution, Monday to Friday



POT distribution, Saturday and Sunday

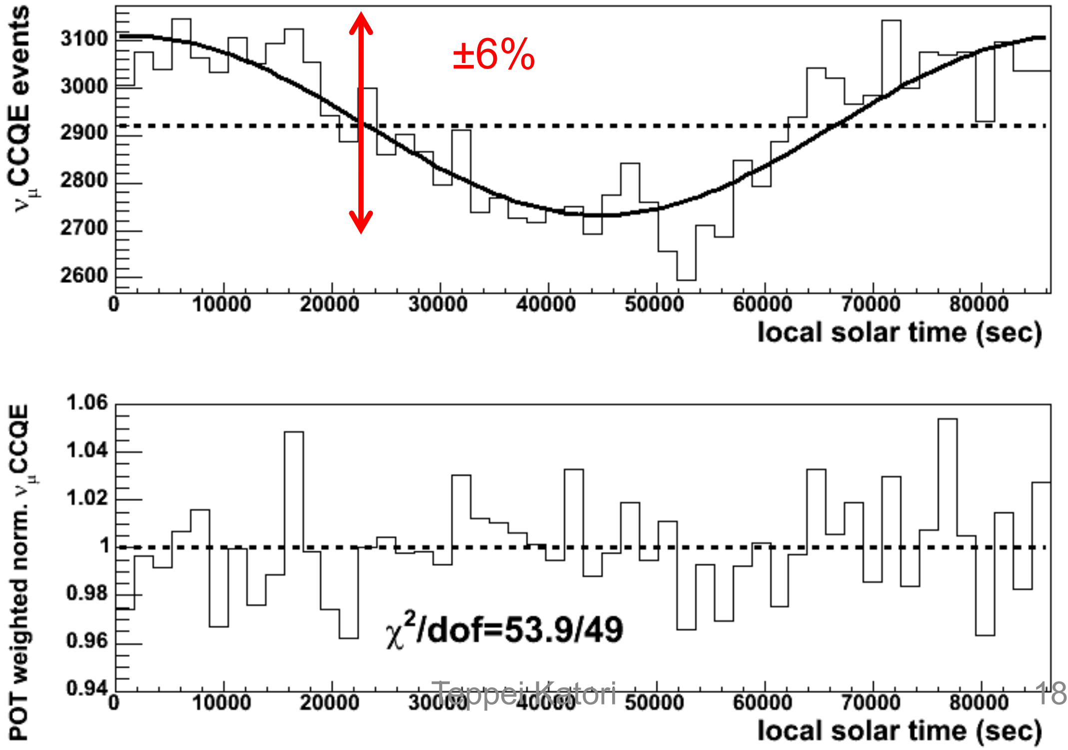
MiniBooNE, PLB718(2013)1303

3. Lorentz violation with MiniBooNE neutrino data

Time dependent systematics

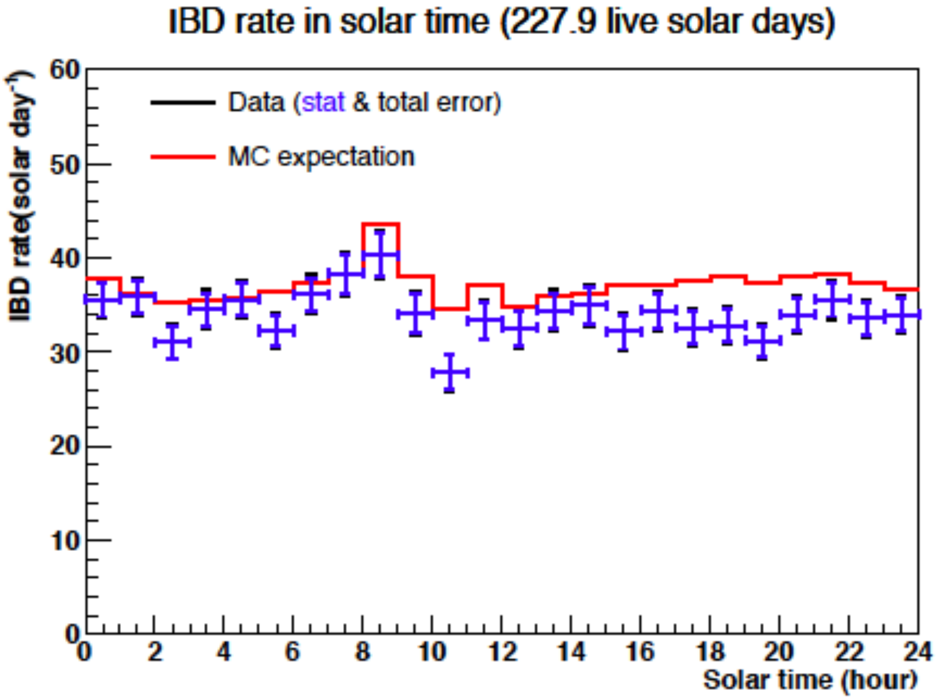
- Beam and detector day night effect is evaluated from high statistics ν_μCCQE sample
- ν_μCCQE events show ±6% day-night variation
- Furthermore, neutrinos know when the weekend is!
- day-night variation of protons on target (POT)
- After correcting this, ν_μCCQE events exhibit flat

ν_μCCQE events day-night distribution

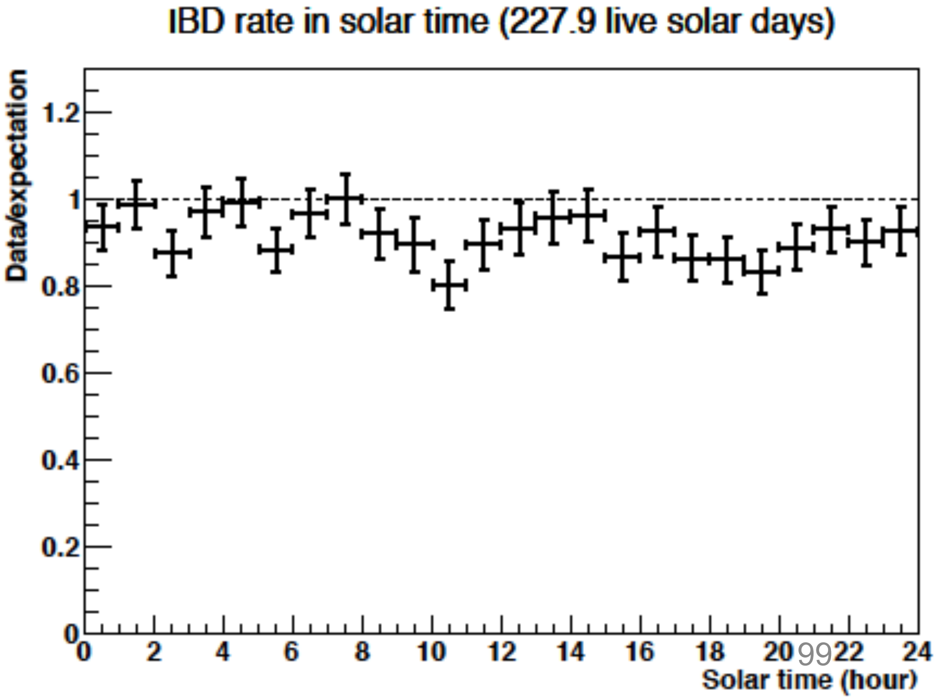


6. Inverse beta decay (IBD) rate

IBD rate is affected by day-night effect of reactor cycle. However, this feature is precisely simulated.



IBD rate in solar time (227.9 live solar days)

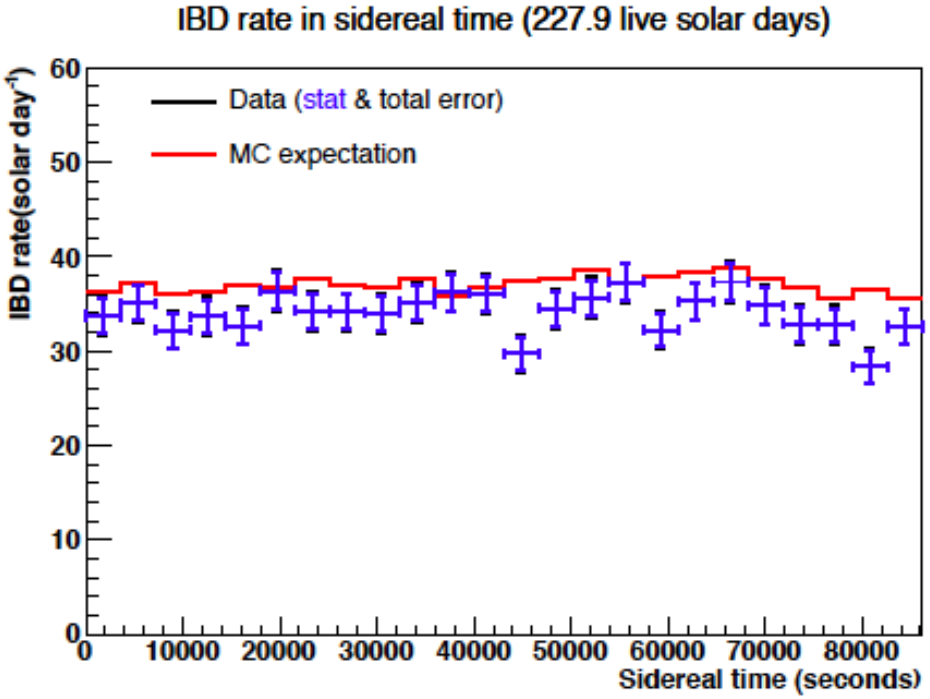


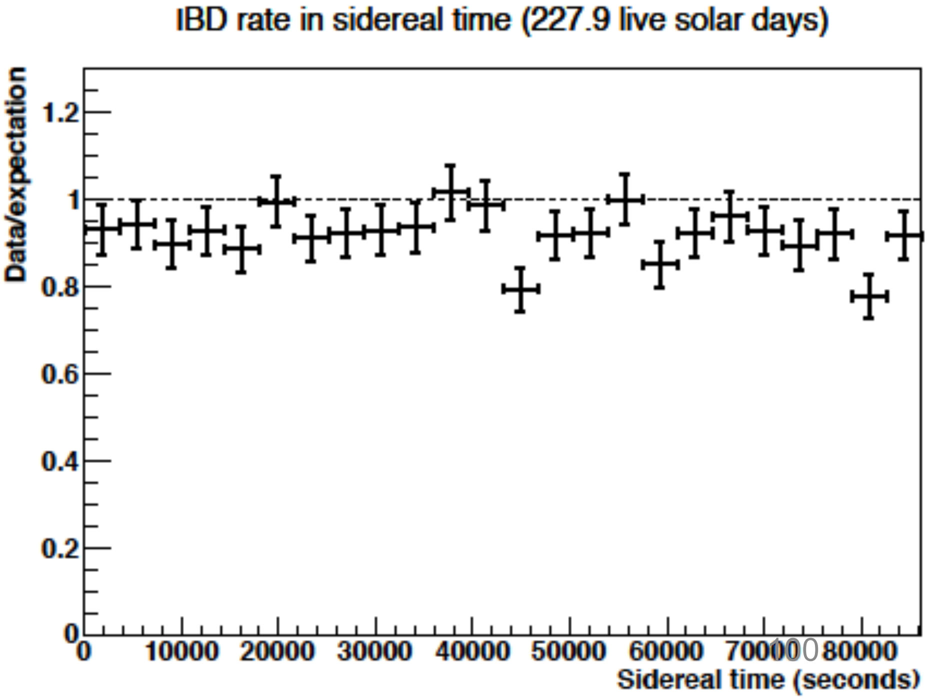
IBD rate in solar time (227.9 live solar days)

6. Inverse beta decay (IBD) rate

IBD rate is affected by day-night effect of reactor cycle. However, this feature is precisely simulated.

Although we simulate this effect, majorities are smeared out in sidereal distribution.

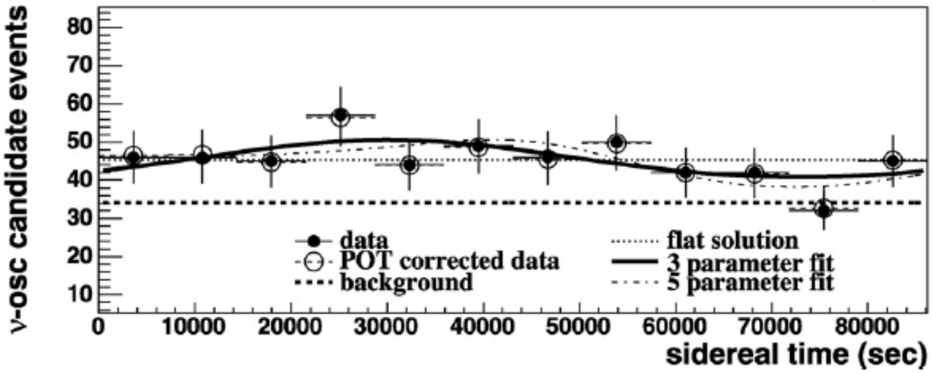




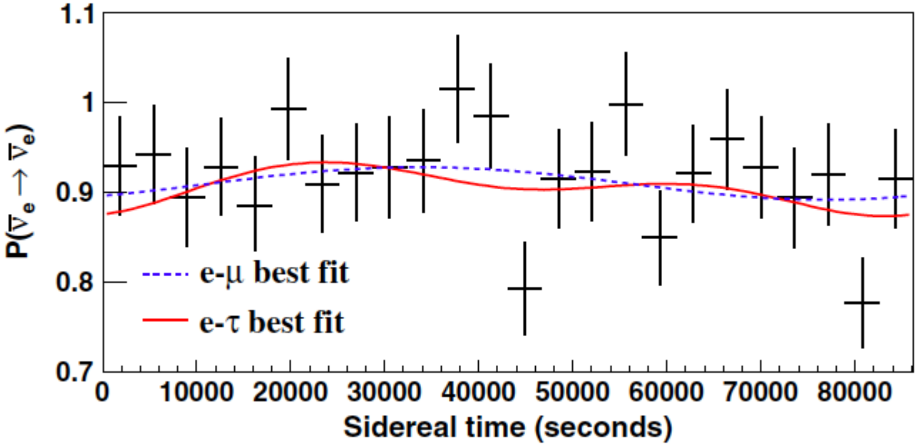
MiniBooNE, PLB718(2013)1303
Double Chooz, PRD86(2012)112009

5. Lorentz violation with neutrino sidereal time data

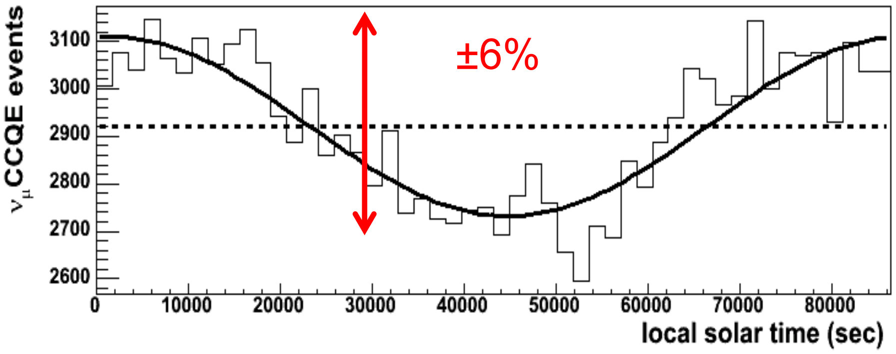
MiniBooNE neutrino mode data



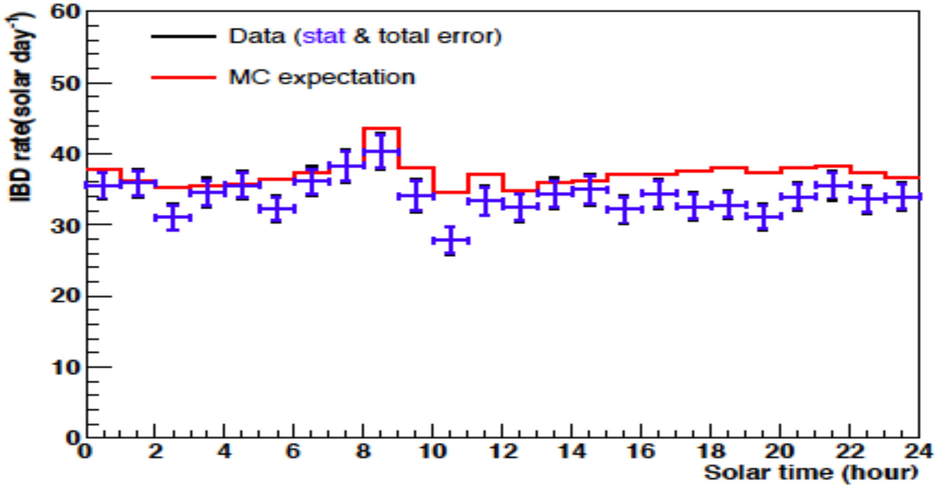
Double Chooz reactor neutrino data/prediction ratio



MiniBooNE ν_μCCQE events day-night distribution



Reactor neutrino data day-night distribution



Neutrino data usually have day-night effect

Double Chooz collaboration,
PRD86(2012)112009

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 $\nu_e \leftrightarrow \nu_\tau$

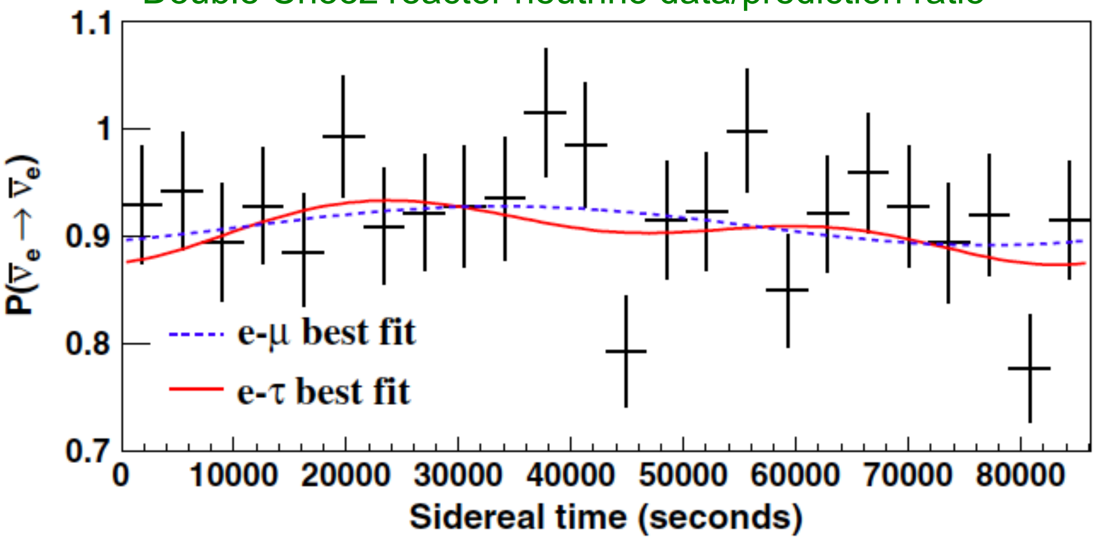
It is possible to limit $\nu_e \leftrightarrow \nu_\tau$ channel from reactor ν_e disappearance experiment

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

Small disappearance signal prefers sidereal time independent solution (flat)

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

Double Chooz reactor neutrino data/prediction ratio



IceCube, arXiv:1709.03434

5. Results

Eq. 2: An example of Lorentz violation operator matrix

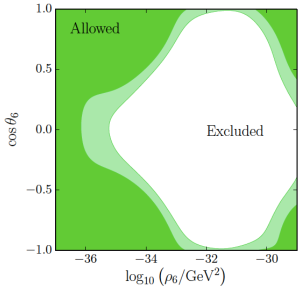
$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E\cdot\mathring{c}^{(4)} + E^2\cdot\mathring{a}^{(5)} - E^3\cdot\mathring{c}^{(6)}\cdots . \quad (1)$$

These 3 parameters

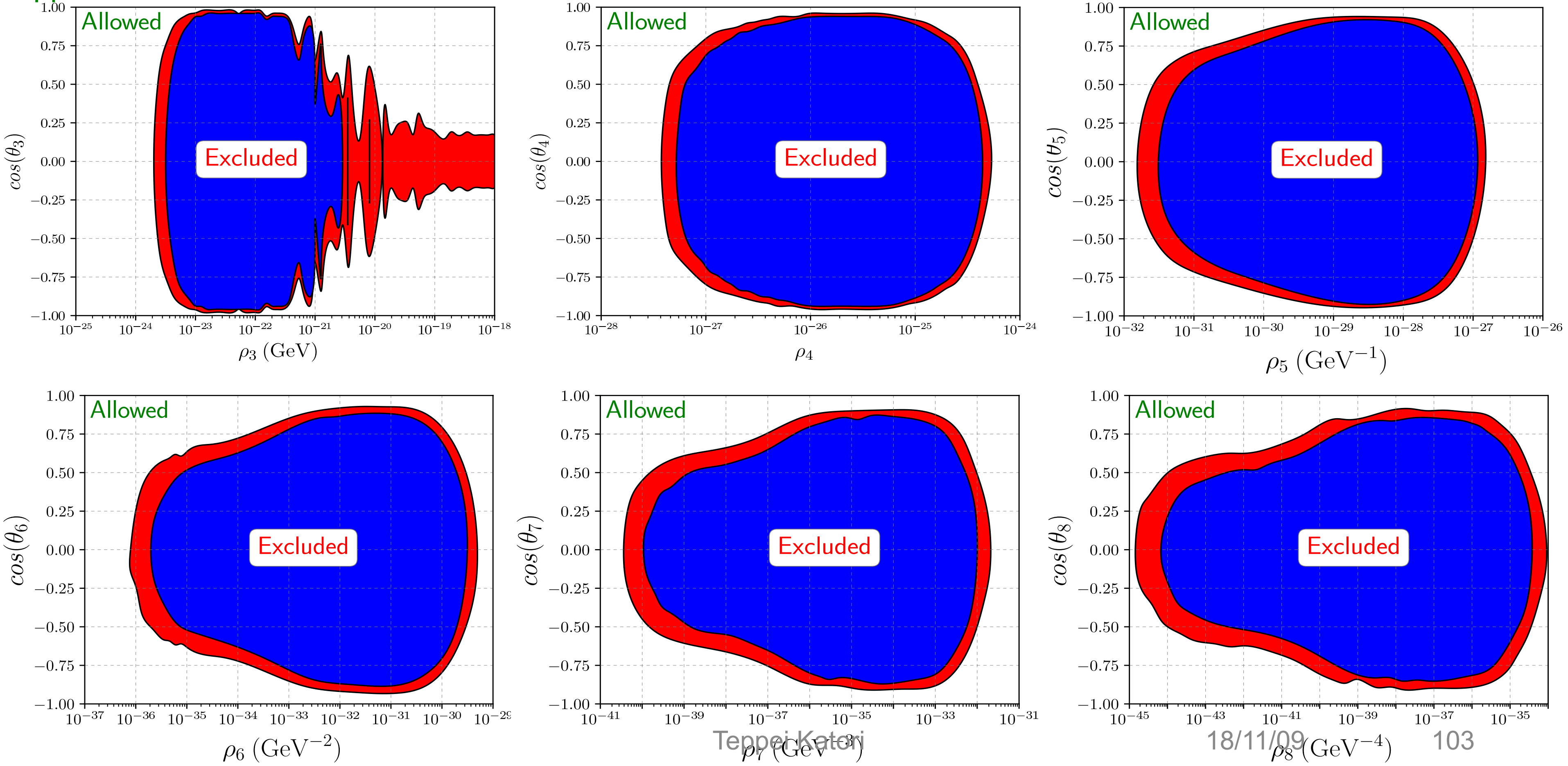
$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

We performed fits for 3 LV parameters for each dimension LV operator → no LV, draw 99% exclusion contours

Appendix 2: MCMC result



Appendix 3: Wilk's theorem based results



IceCube, arXiv:1709.03434

5. Results

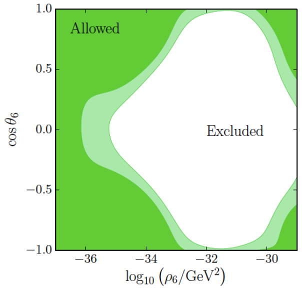
Eq. 2: An example of Lorentz violation operator matrix

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots . \quad (1)$$

Make these 0 by hand

$$\mathring{c}^{(6)} = \begin{pmatrix} \sim 0 & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & \sim 0 \end{pmatrix}$$

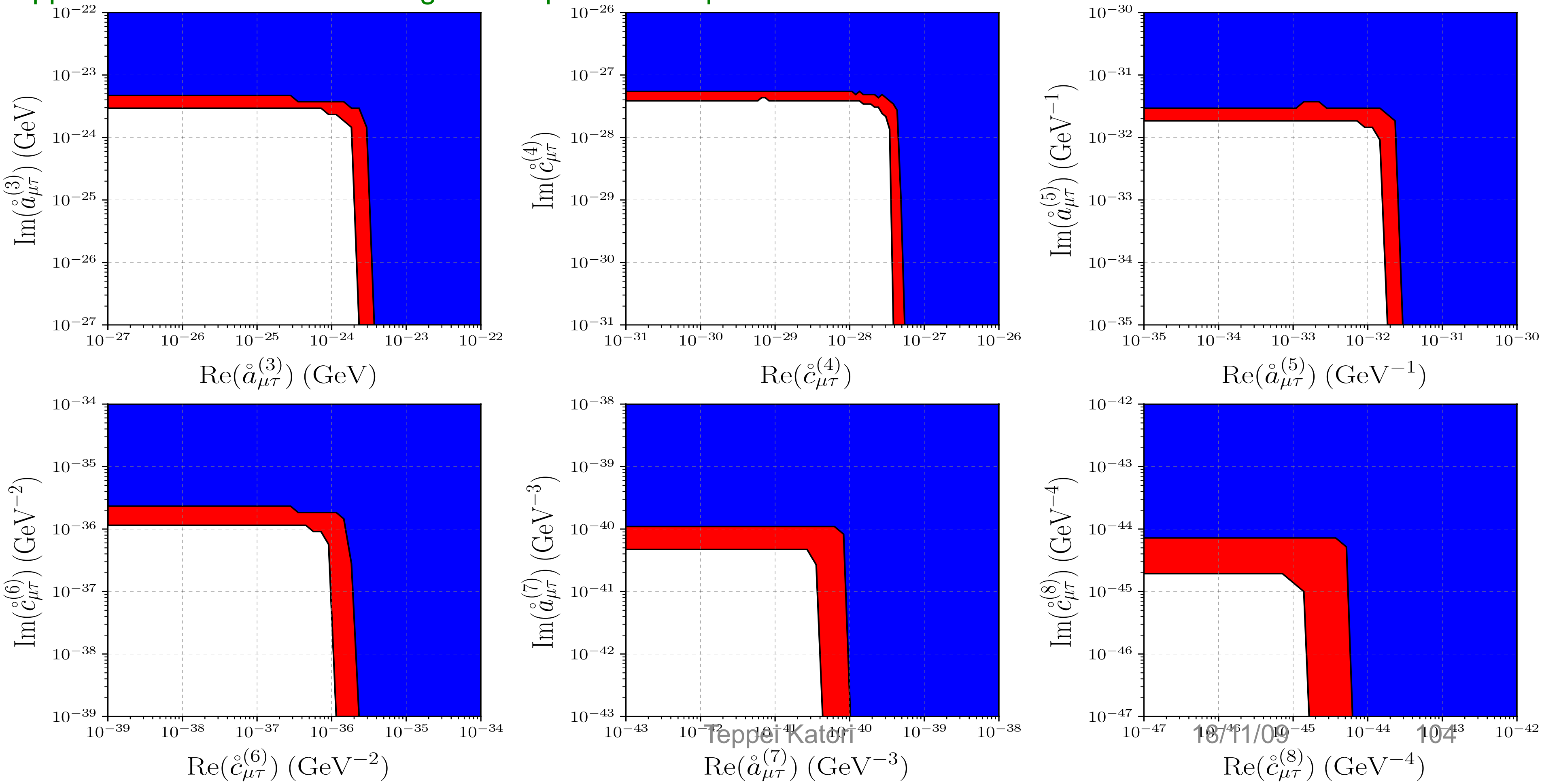
Appendix 2: MCMC result



We performed fits for 3 LV parameters for each dimension LV operator → no LV, draw 99% exclusion contours

- additionally, we set all parameters=0 but one to match community standard
→ we report these as our main results

Appendix 4: Contour on off-diagonal LV parameter space



Arugüelles, TK, Salvado, PRL115(2015)161303

Haba, Murayama,
PRD63(2001)053010

7. Flavour triangle histogram

However, we don't observe flavour ratio with function of energy
→ neutrino flux model (~E^{-2}) is convoluted

Also, there are many possible models
→ flavour triangle histogram

We follow the anarchic sampling scheme to choose the new physics model, and the model density is shown as a histogram on the triangle diagram.

$$d\tilde{U} = ds_{12}^2 \wedge dc_{13}^4 \wedge ds_{23}^2 \wedge d\delta$$

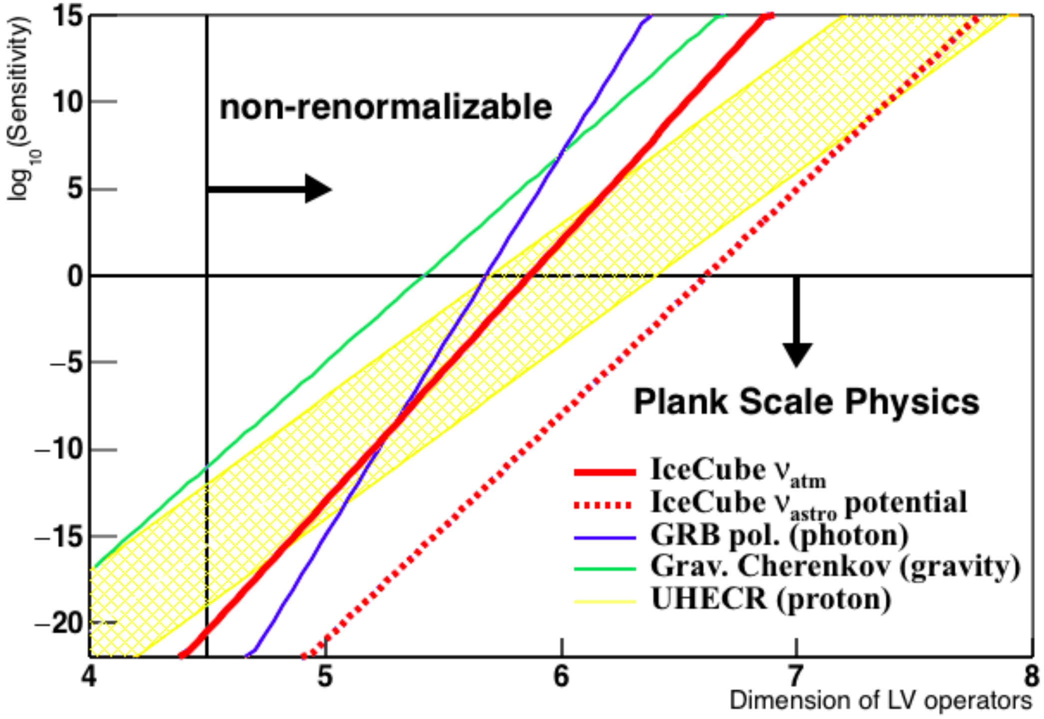
Large Lorentz violation → observed flavour ratio can be many option
Small Lorentz violation → only tiny deviation from the standard value is possible

6. Astrophysical neutrino new physics sensitivity

Combination of longer baseline and higher energy makes extra-terrestrial neutrino to be the most sensitive source of fundamental physics.

Astrophysical neutrinos have the best new physics sensitivity to dimension 5, 6, 7 operators across all fields. Moreover, for dimension 5 and 6 operators, the sensitivity reaches the scale expected from Planck scale physic.

New physics limits and projected sensitivity



OPERA collaboration,
ArXiv:1109.4897

8. 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) PRD85(2012)096005
- no indication of Lorentz violation from any neutrino oscillation experiments Rev.Mod.Phys.83(2011)11
- superluminal neutrino is unstable (vacuum Cherenkov radiation) ArXiv:1109.6562
- pion phase space is limited to create such neutrinos ArXiv:1109.6630
- SN1987A neutrinos provide severe limit to superluminal neutrinos PRL58(1987)1490
- etc...

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