Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

ArXiv:1709.03434

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Teppei Katori for the IceCube collaboration
Queen Mary University of London
NExT 2017 fall meeting, Royal Holloway University of London, Nov. 1, 2017

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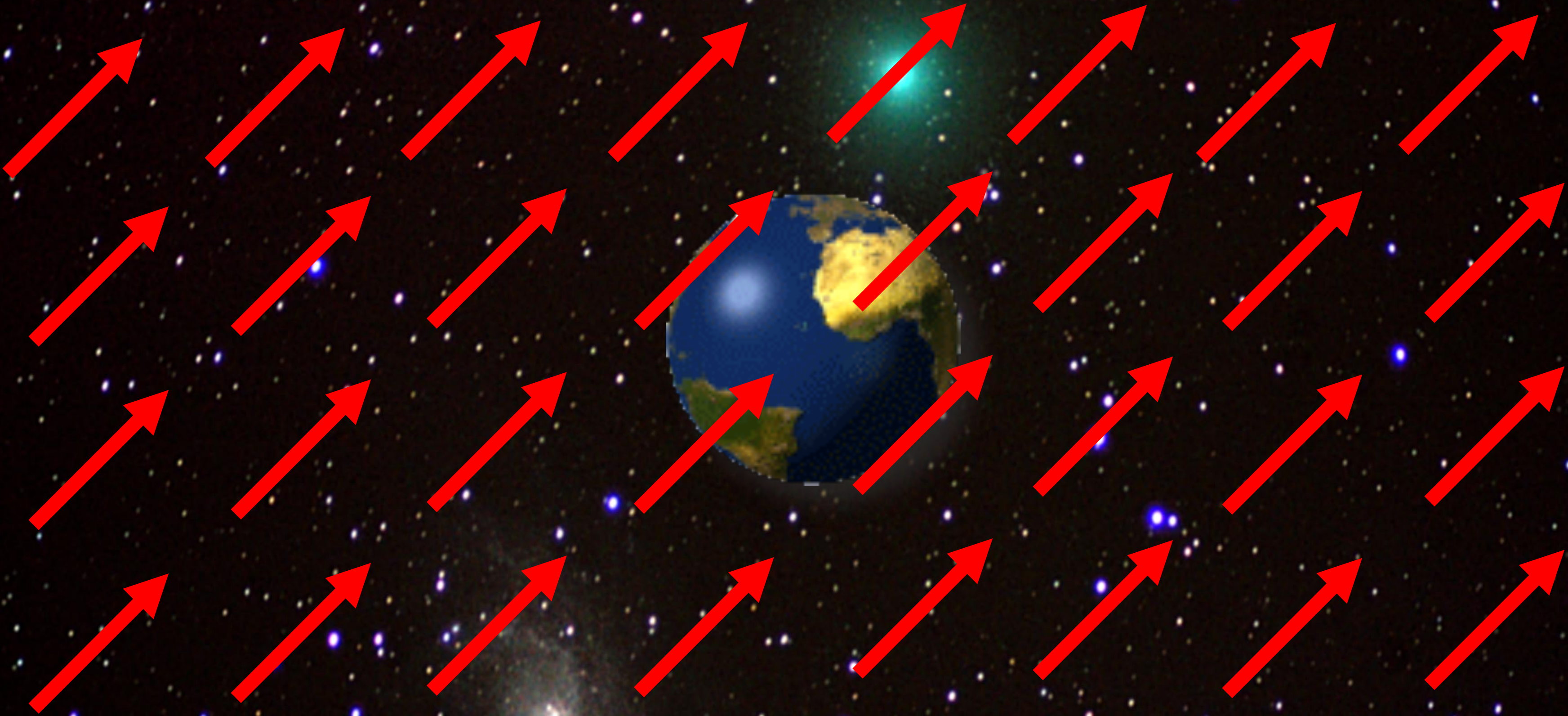
$$\bar{\psi}\gamma_\mu a^\mu \psi$$



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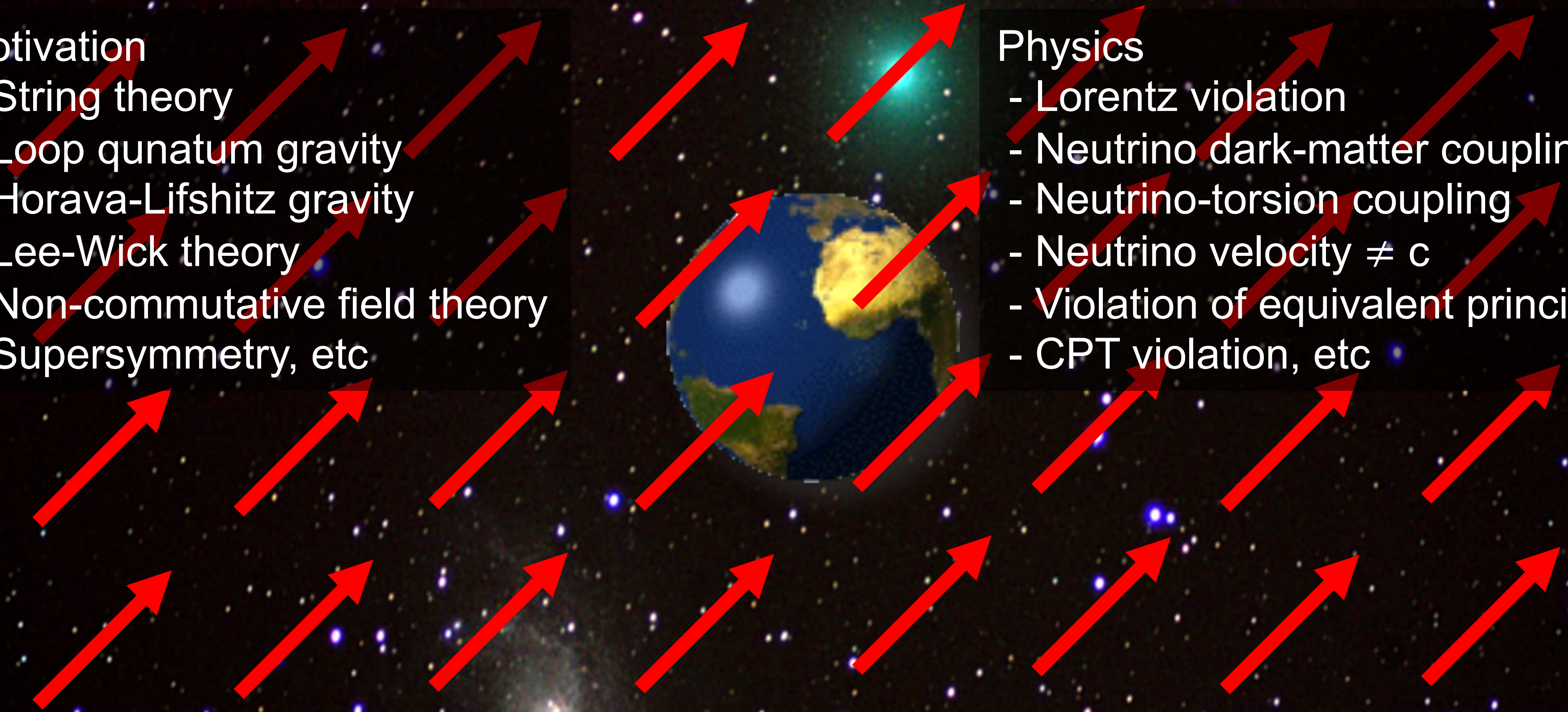

Motivation
- String theory
- Loop qunatum gravity
- Horava-Lifshitz gravity
- Lee-Wick theory
- Non-commutative field theory
- Supersymmetry, etc

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

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$$\bar{\psi}\gamma_{\mu}a^{\mu}\psi \qquad a^{\mu}=(a,0,0,0)$$

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Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube

outline

1. Lorentz violating neutrino oscillations
2. Test for Lorentz violation with atmospheric neutrinos
3. Test for Lorentz violation with astrophysical neutrinos
4. Conclusion

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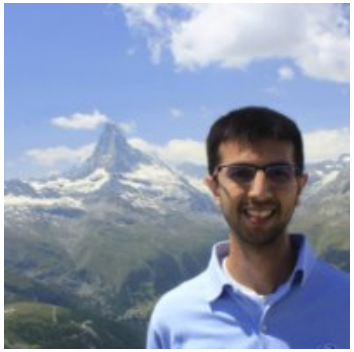

Shivesh Mandalia

Queen Mary U. of London

1. **Lorentz violating neutrino oscillation**

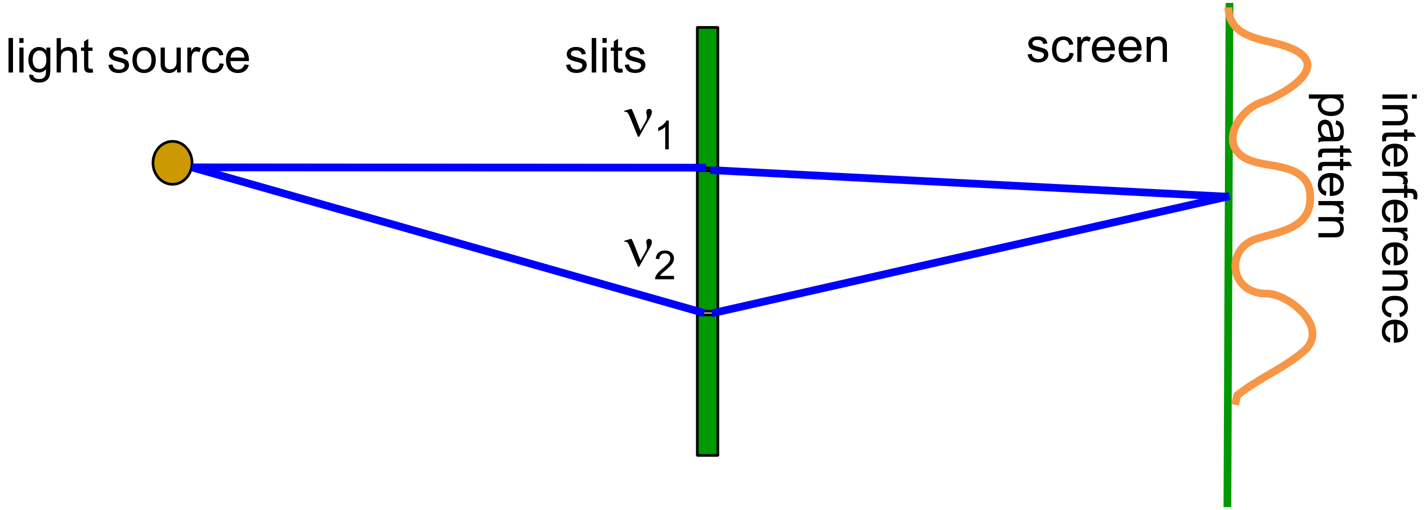
2. Test for Lorentz violation with atmospheric neutrinos

3. Test for Lorentz violation with astrophysical neutrinos

4. Conclusion

1. Neutrino interferometry

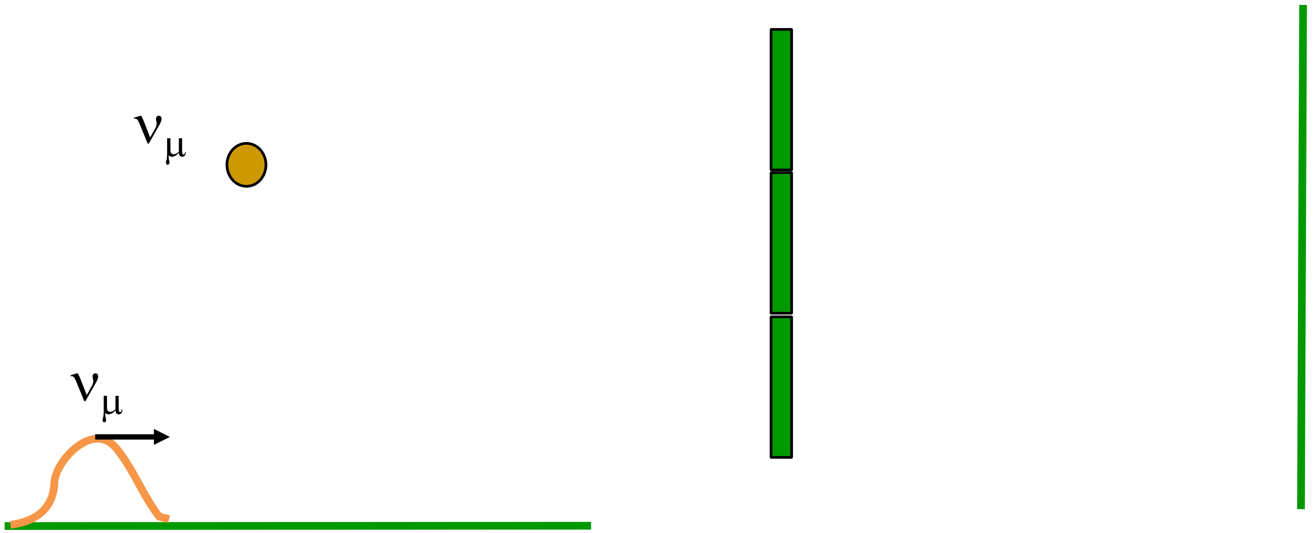
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

1. Neutrino interferometry as a probe of new physics

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



- If 2 neutrino Hamiltonian eigenstates, ν_2 and ν_3, have different phase rotation, they cause quantum interference.

1. Neutrino interferometry as a probe of new physics

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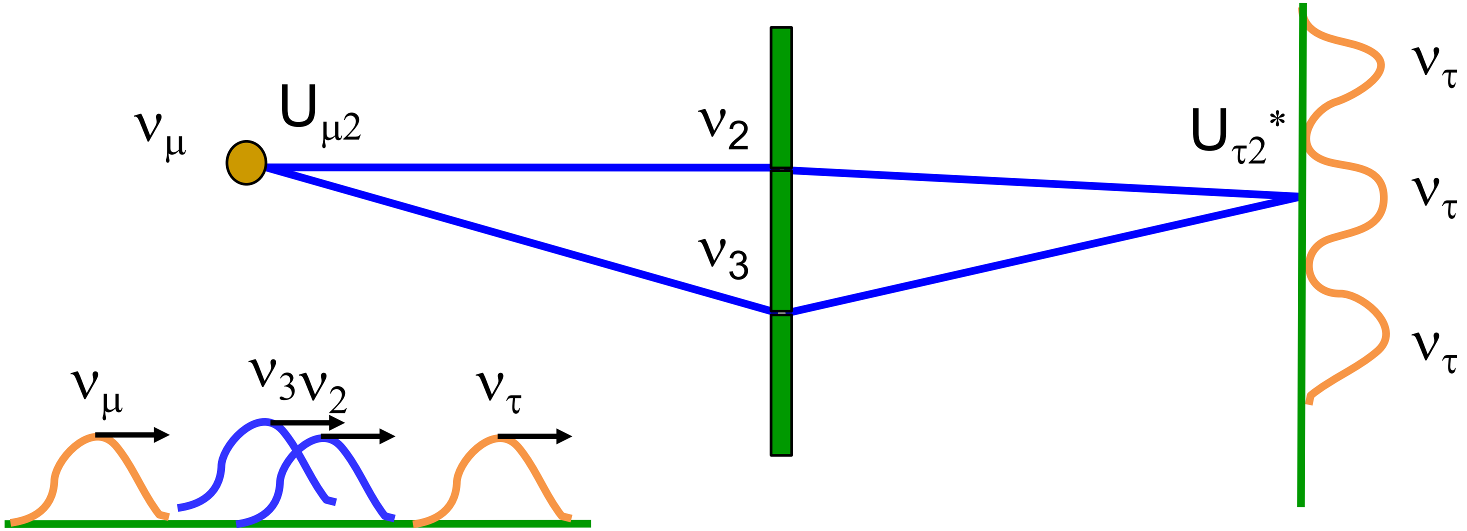

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1. Neutrino interferometry as a probe of new physics

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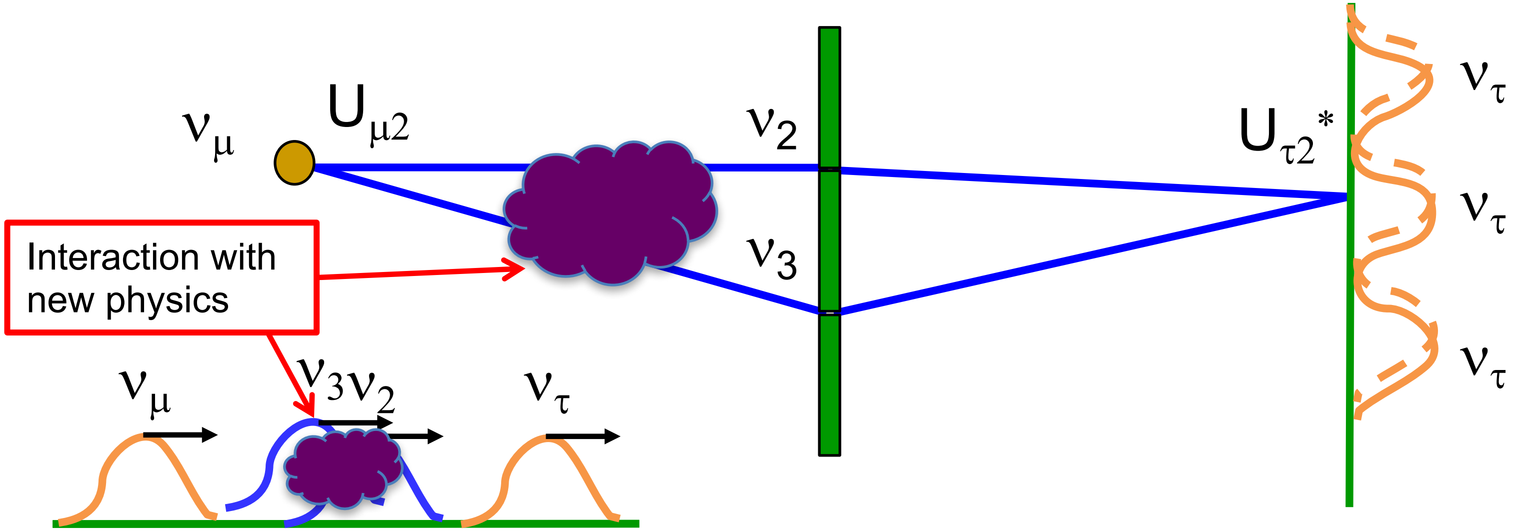


Interaction with new physics

- If 2 neutrino Hamiltonian eigenstates, ν_2 and ν_3, have different phase rotation, they cause quantum interference (neutrino oscillation).
- Any BSM physics coupling to neutrinos can contribute the phase shift of neutrino oscillation, and it appears as spectrum distortion of atmospheric neutrino data.
- The BSM effect is different with energy and baseline, so simultaneous fit of zenith and energy to find it.

Atmospheric neutrinos are the best source to test Lorentz violation within terrestrial neutrinos.

1. Lorentz violating neutrino oscillation

2. **Test for Lorentz violation with atmospheric neutrinos**

3. Test for Lorentz violation with astrophysical neutrinos

4. Conclusion

2. 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

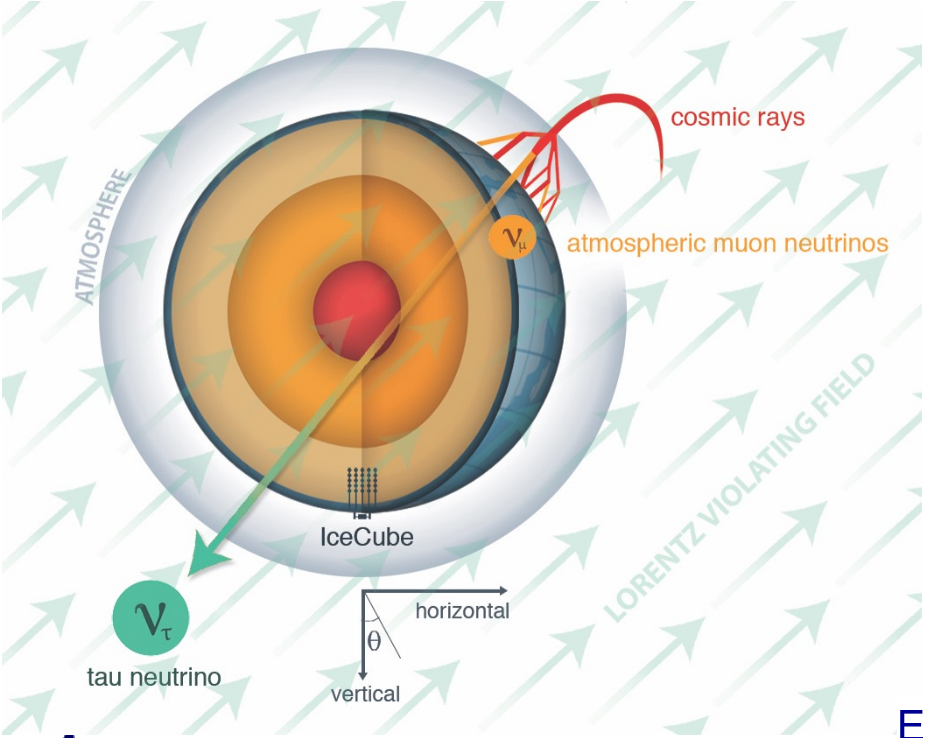
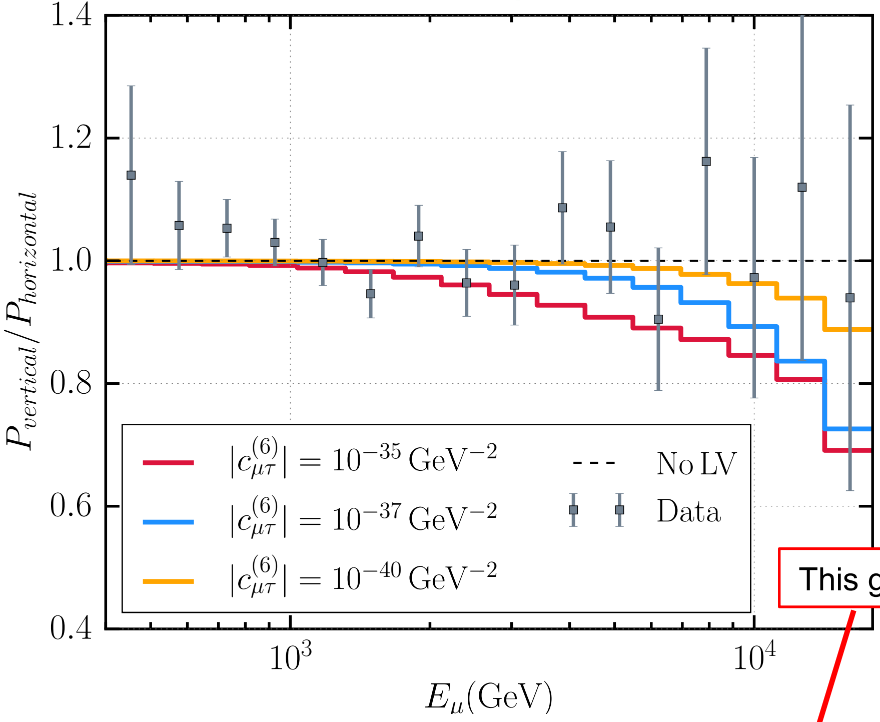


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator



This guy

Eq. 1: LV motivated new physics Hamiltonian

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

2. Test of Lorentz violation with atmospheric neutrinos

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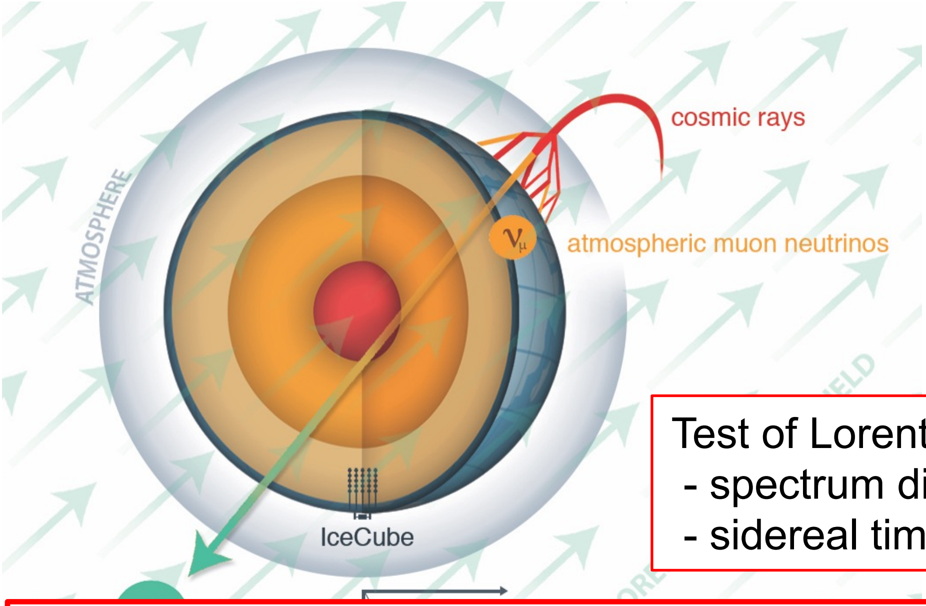
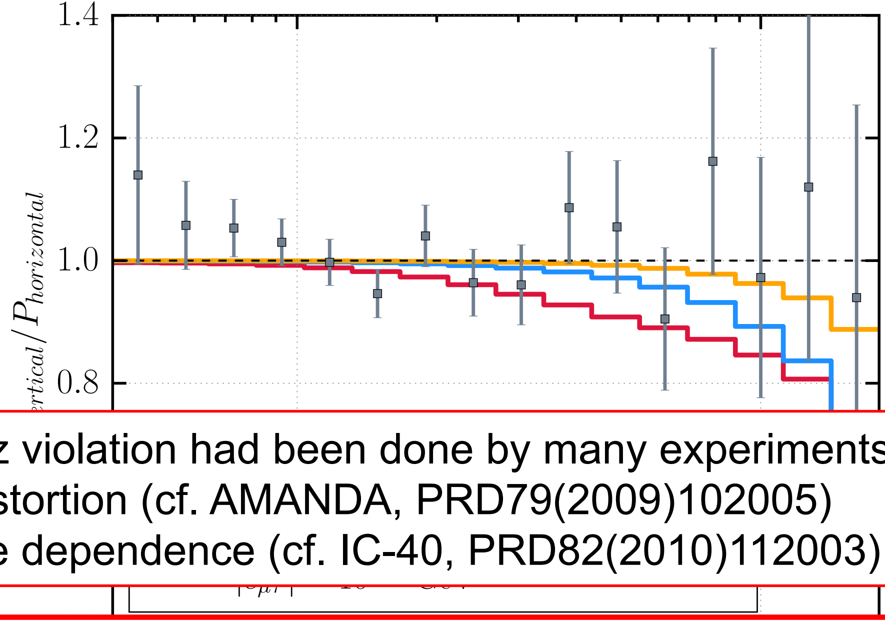
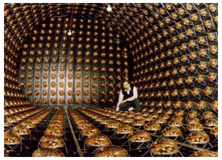
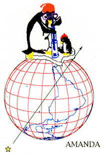
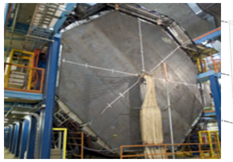
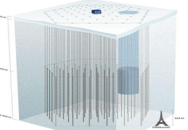
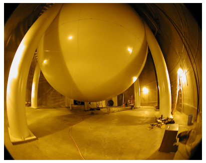
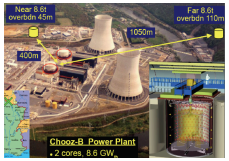
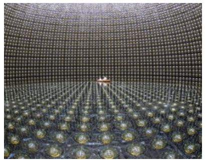
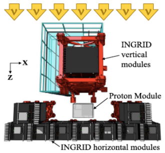


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator



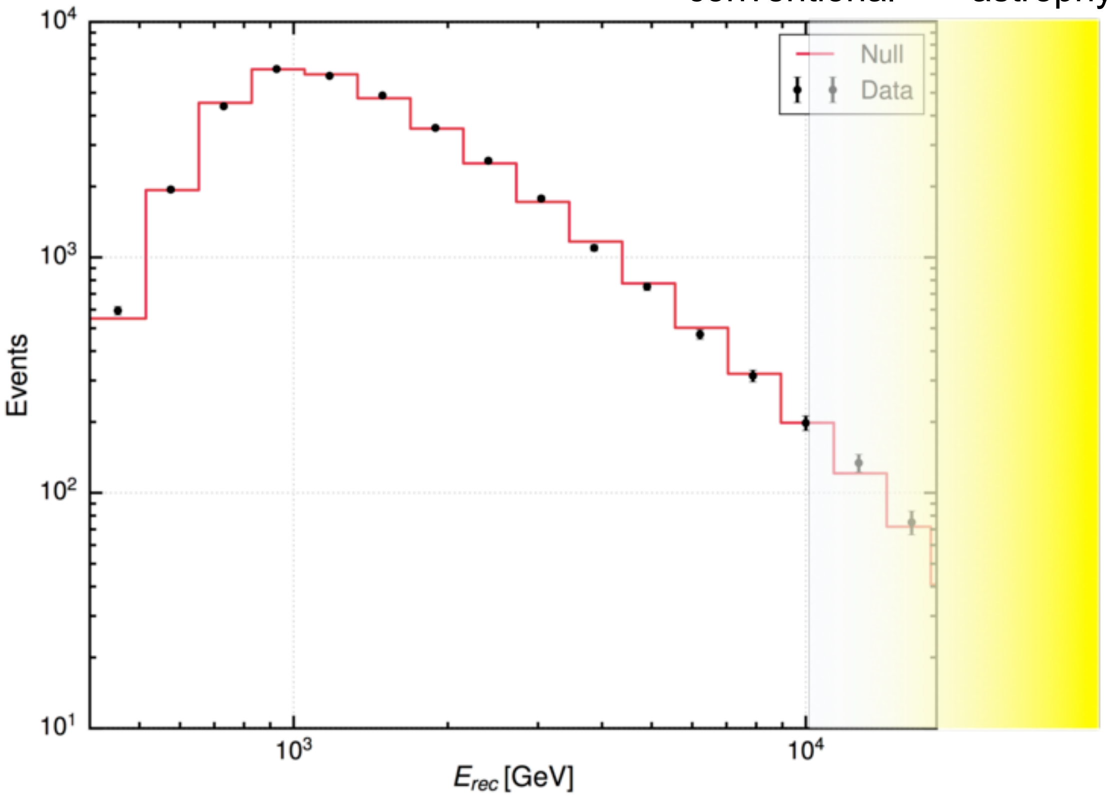
Test of Lorentz violation had been done by many experiments
- spectrum distortion (cf. AMANDA, PRD79(2009)102005)
- sidereal time dependence (cf. IC-40, PRD82(2010)112003)

LSND	MINOS ND	AMANDA	MINOS FD	IceCube	MiniBooNE	Double Chooz	Super-Kamiokande	T2K
								
PRD72(2005)076004	PRL101(2008)151601	PRD79(2009)102005	PRL105(2010)151601	PRD82(2010)112003	PLB718(2013)1303	PRD86(2013)112009	PRD91(2015)052003	PRD95(2017)111101

2. Test of Lorentz violation with atmospheric neutrinos

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

conventional ↔ astrophysical



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.

IceCube, PRL115(2015)081102, Cooper-Sarkar and Sarkar, JHEP01(2008)075
Fedynitch et al,EPJ.Web.Conf.99(2015)08001, Foreman-Mackey et al.,Publ.Astron.Soc.Pac.125(2013)306

2. 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, $-1<\cos\theta<0$ ("up-going")

} very similar to 2016 sterile ν analysis sample
https://icecube.wisc.edu/science/data/HE_NuMu_diffuse

Simulation

- atmospheric neutrinos from MCEq https://github.com/afedynitch/MCEq
- 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 : posterior values from sterile ν analysis (new central value w/ constrained error)

Fit methods

- Likelihood with Wilk's theorem (our main results)
- Bayesian Markov Chain Monte Carlo http://dan.iel.fm/emcee/current/

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

2. Results

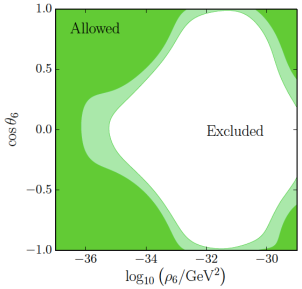
Eq. 2: An example of Lorentz violation operator matrix

These 3 parameters

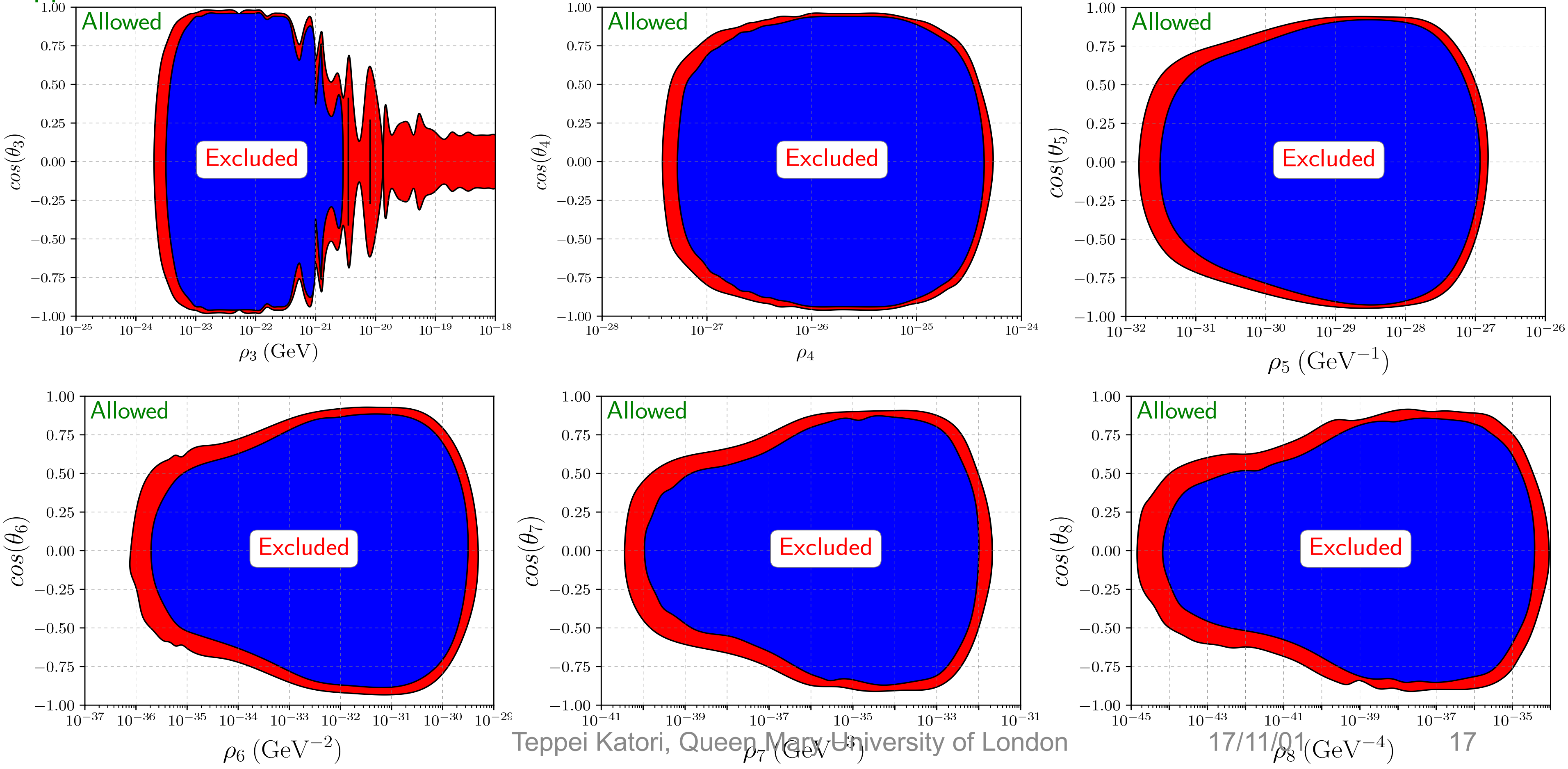
$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

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



2. Results

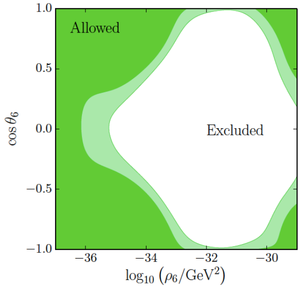
$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots . \quad (1)$$

Eq. 2: An example of Lorentz violation operator matrix

Make these 0 by hand

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

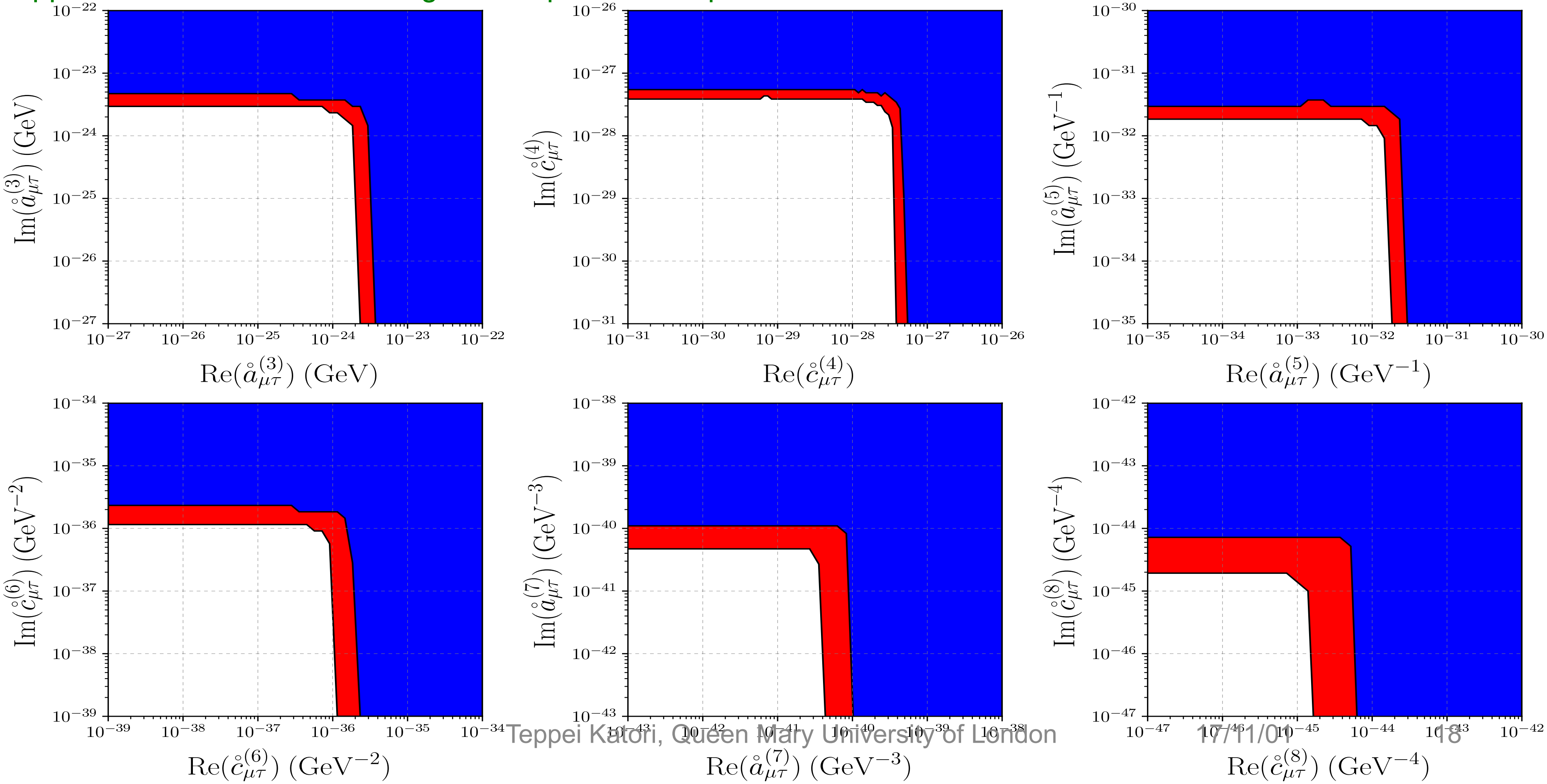
Appendix 2: MCMC result



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

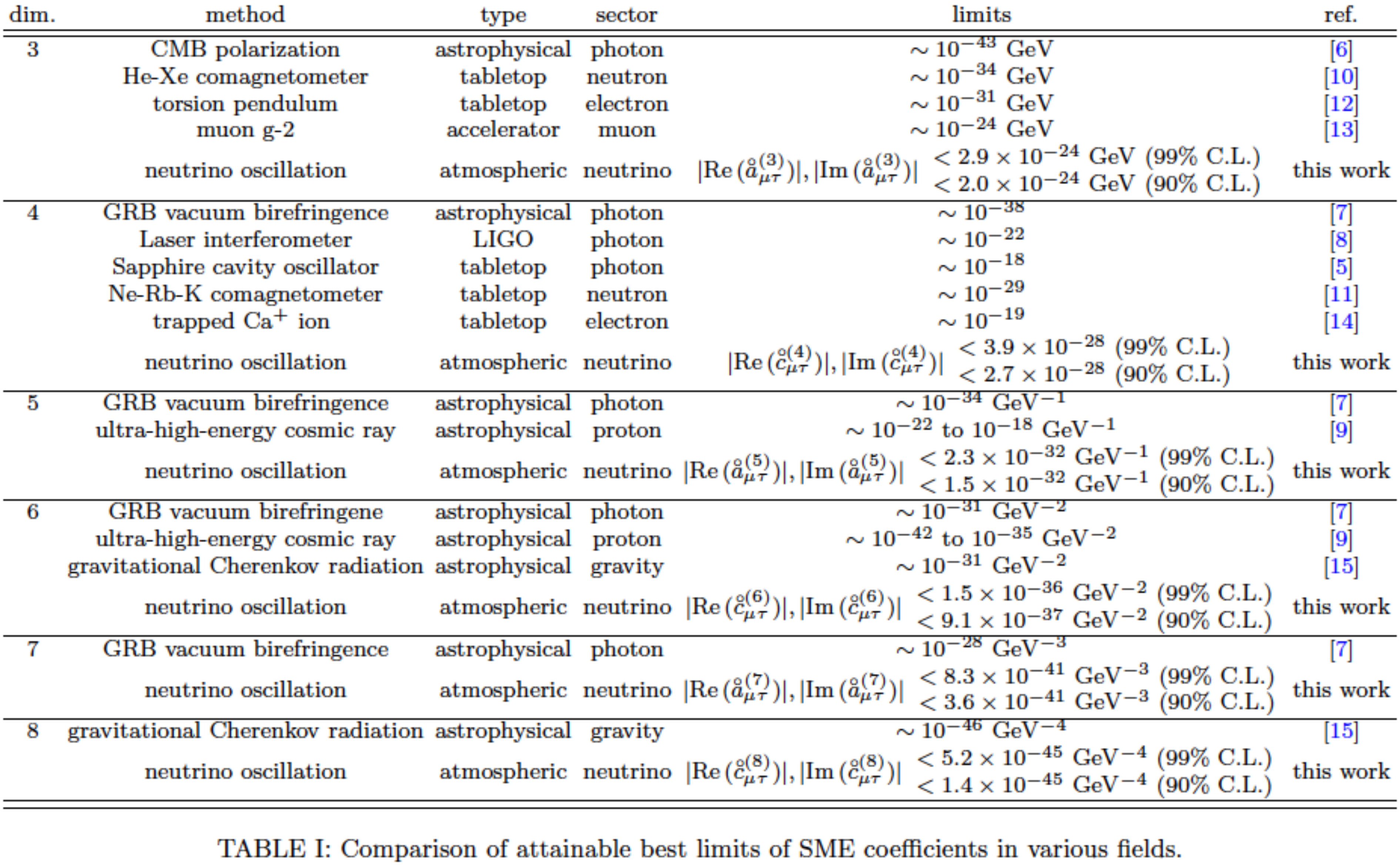
- additionally, we set all parameters=0 but one to match community standard
→ we report these as our main results

Appendix 4: Contour on off-diagonal LV parameter space



2. Results

The main results of this paper are new limits on Lorentz violation and to demonstrate the potential of neutrino interferometry. Note, we don't know which sector has Lorentz violation, so there is no straightforward way to compare results from different sectors.



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.

2. 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]
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	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]
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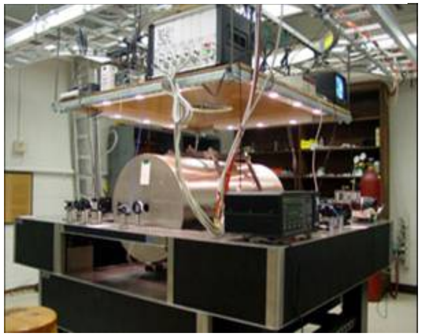
	trapped Ca$^+$ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	
	u	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	
		atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}$	$< 2.3 \times 10^{-32}$ 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

$c_n<10^{-29}$

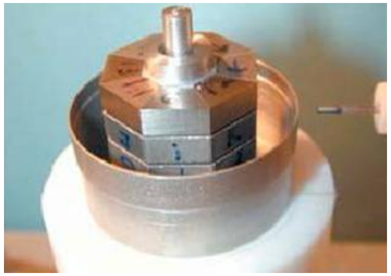


PRL107(2011)171604

PRL112(2014)110801

Spin torsion pendulum

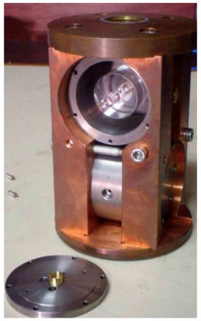
$b_e<10^{-30}$ GeV



PRL97(2006)021603

Crystal oscillator

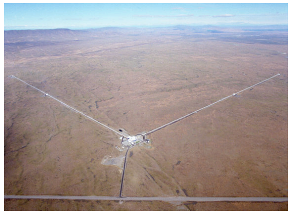
$\Delta c/c<10^{-18}$



Nature.Comm.6(2015)8174

LIGO

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

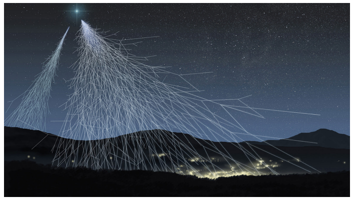


PLB761(2016)1

2. 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

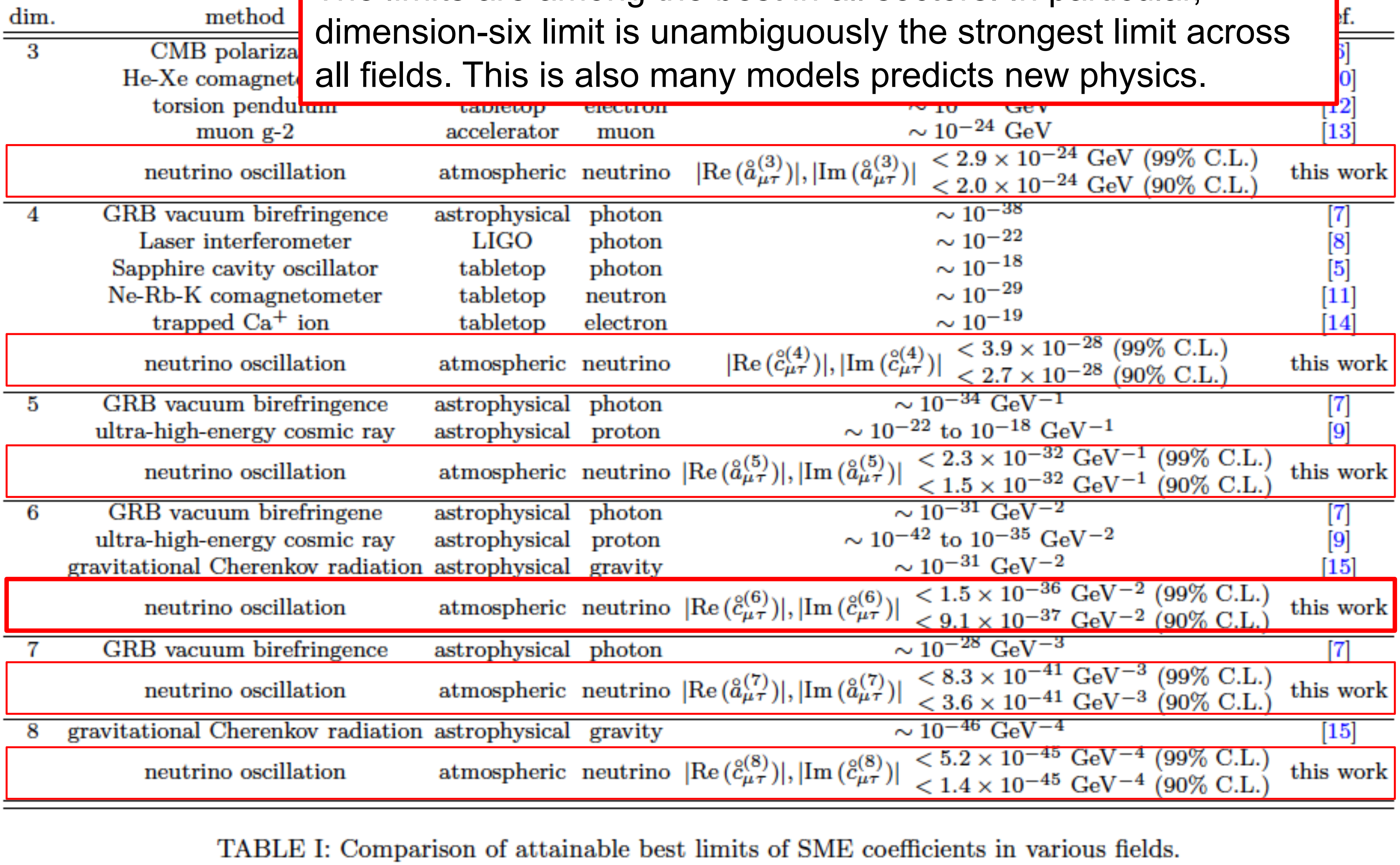
		type	sector		li	ef.
	tion	astrophysical	photon		~ 10	[6]
	ometer	tabletop	neutron		~ 10	[10]
	lum	tabletop	electron		~ 10	[12]
		accelerator	muon		~ 10	[13]
	ation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	< 2 < 2	work
	fringence	astrophysical	photon		$\sim$	[7]
	meter	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 birefringence	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.

2. 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.	method					f.
3	CMB polariza					6]
	He-Xe comagnet					0]
	torsion pendu	tabletop	electron		~ 10 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
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	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
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	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.

1. Lorentz violating neutrino oscillation

2. Test for Lorentz violation with atmospheric neutrinos

3. **Test for Lorentz violation with astrophysical neutrinos**

4. Conclusion

3. Test of Lorentz violation with astrophysical neutrinos

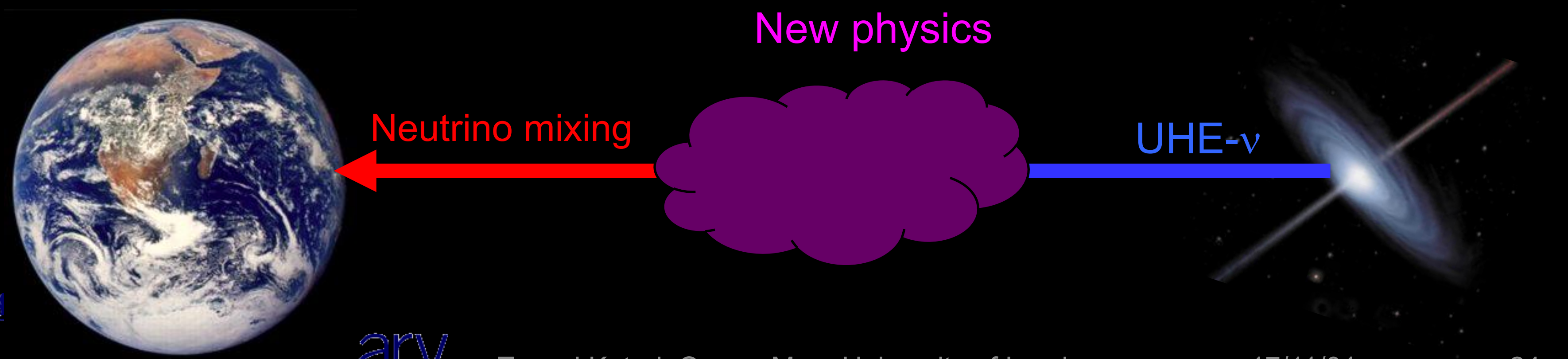
Combination of longer baseline and higher energy makes astrophysical neutrino to be the most sensitive source of fundamental physics.

Astrophysical neutrinos are not coherent and we cannot study Lorentz violation using neutrino oscillations (cf. atmospheric neutrinos).

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

However, incoherent neutrino mixings of astrophysical neutrinos also carry information of tiny Lorentz violation. This is a different type of neutrino interferometry.

$$P_{\alpha\rightarrow\beta}(L\rightarrow\infty, E) = \sum_{i>j}|V_{\alpha i}|^{2}\left|V_{\beta i}\right|^{2}$$



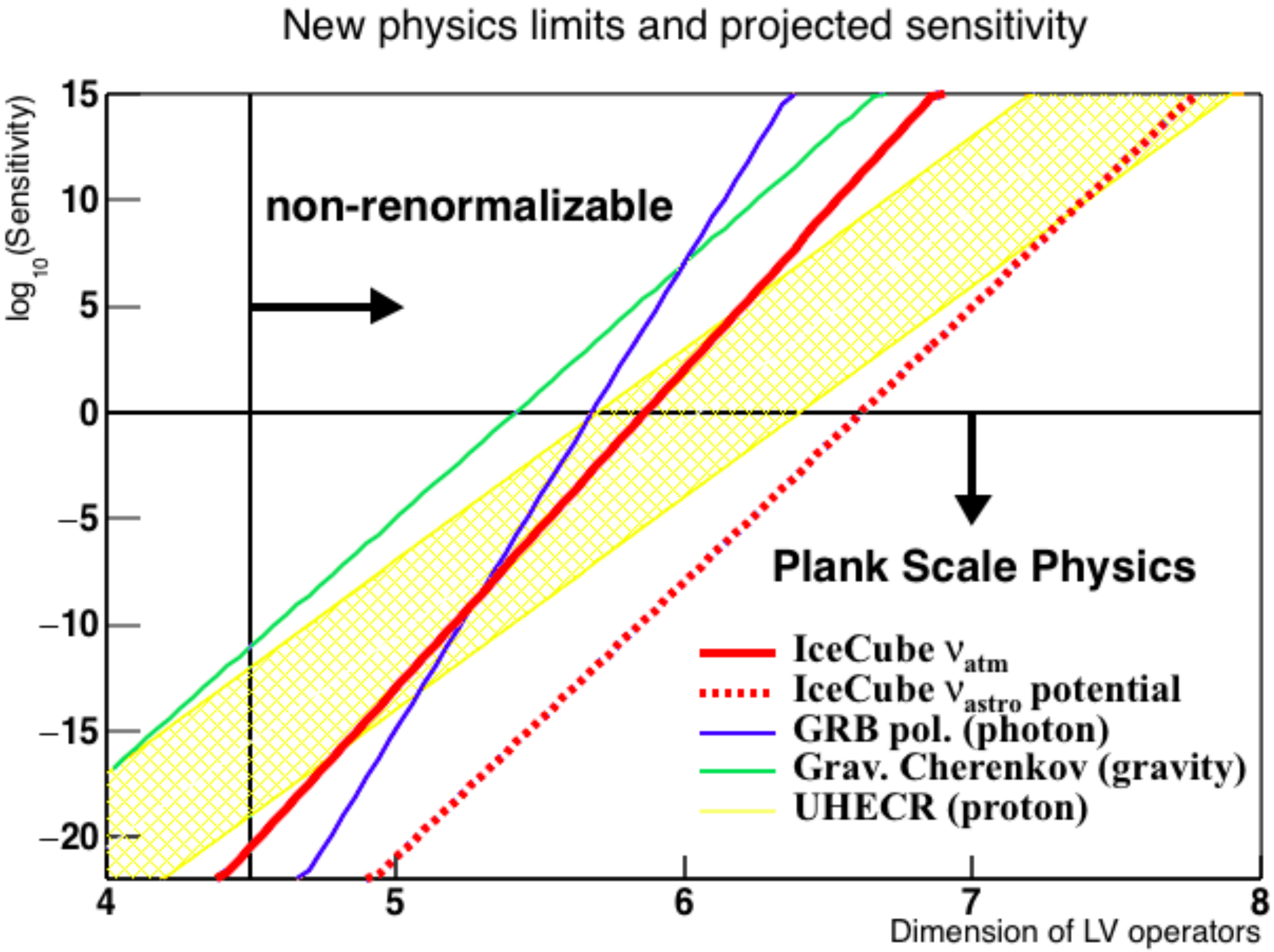
New physics

Neutrino mixing

UHE-ν

3. Astrophysical neutrino new physics sensitivity

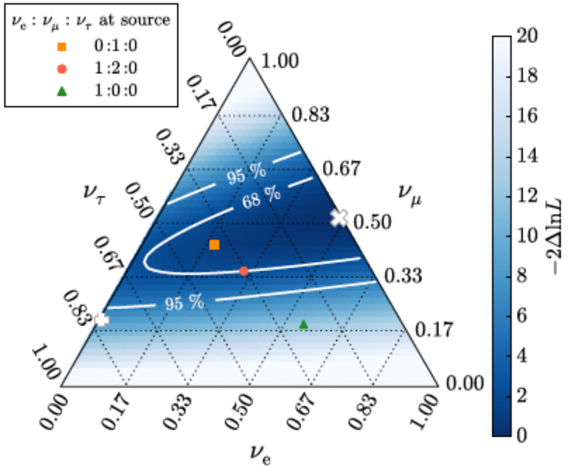
Astrophysical neutrinos have the best new physics sensitivity to dimension 5, 6, 7 operators across all fields. Moreover, for dimension 5 and 6 operators, the sensitivity reaches the scale expected from Planck scale physic.



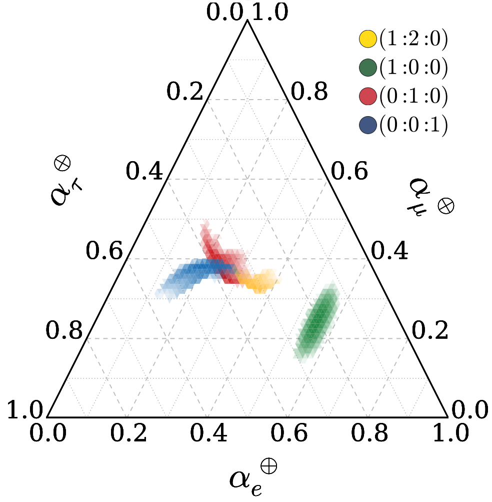
IceCube, Ap.J.(2015)809:98
Argüelles, TK, Salvado, PRL115(2015)161303

3. Neutrino flavour ratio with new physics

Astrophysical neutrinos are more sensitive to new physics than atmospheric neutrinos, and the sensitivity is at least order 2 higher.

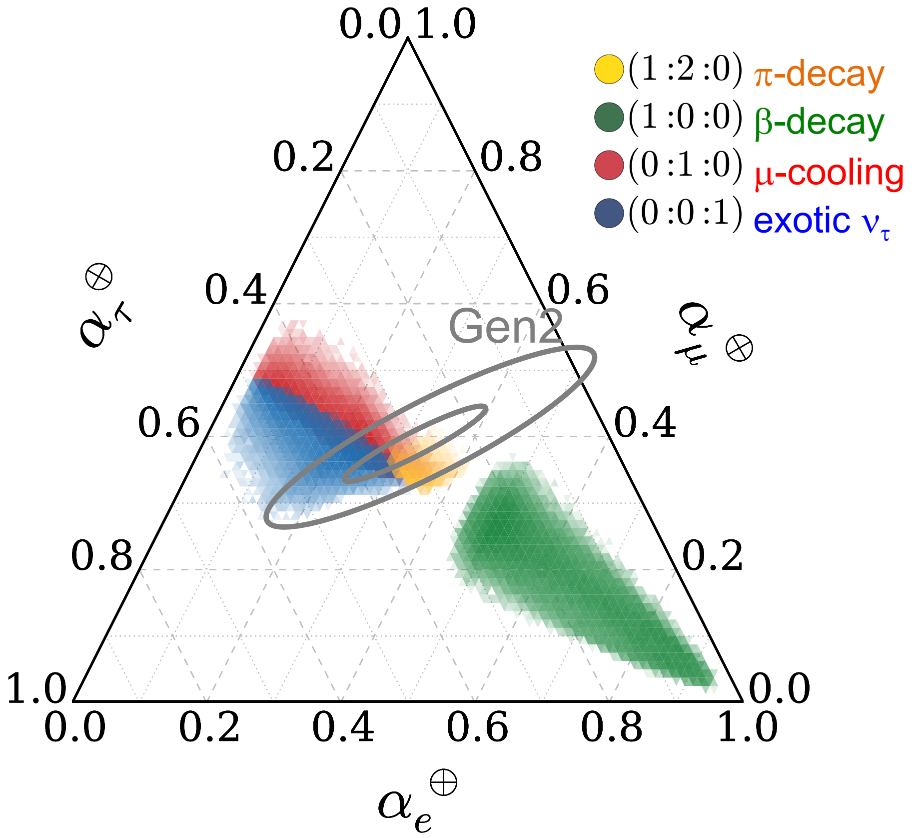


IceCube flavour ratio measuremen



Standard flavour triangle (NuFit2014)

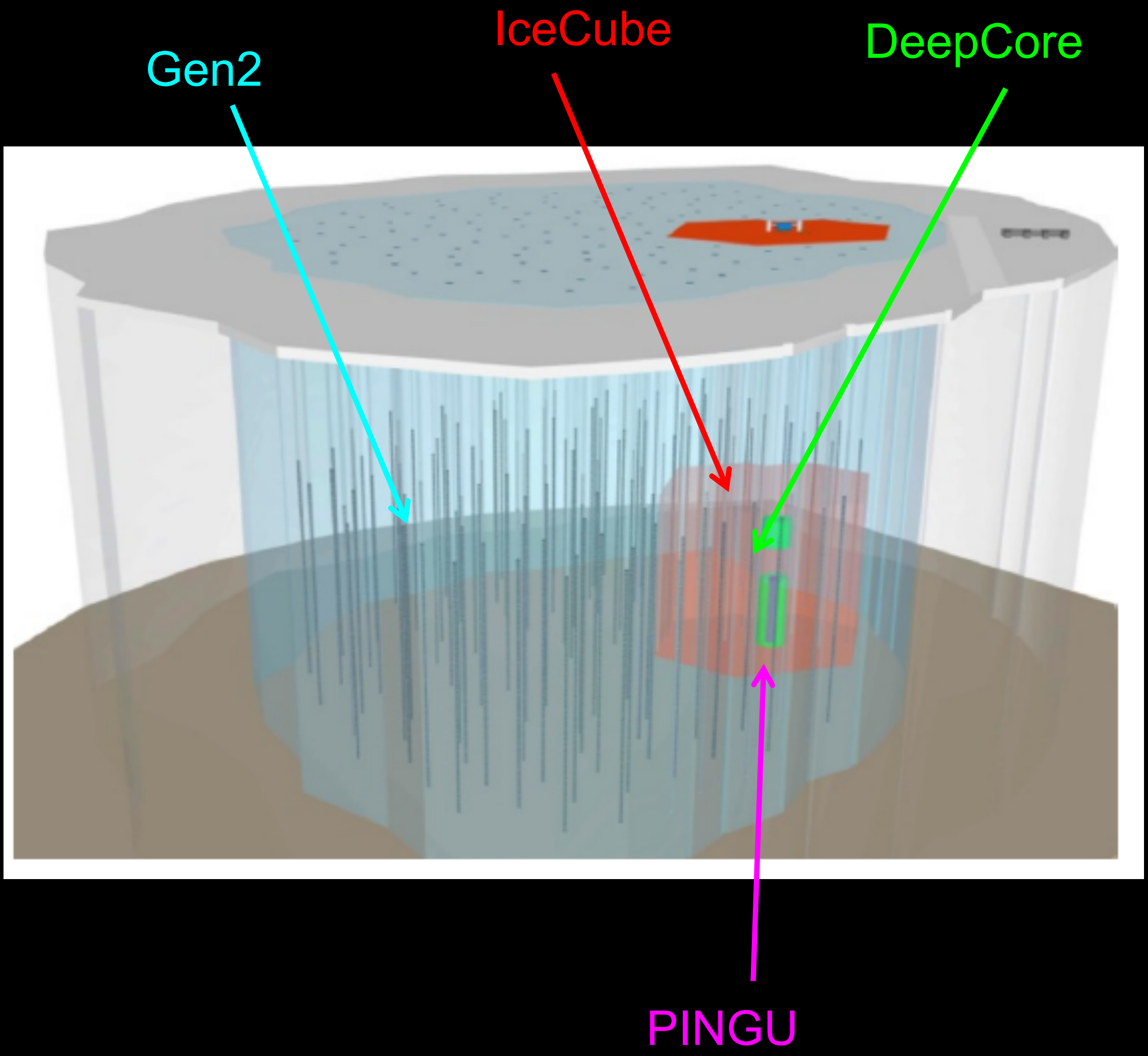
Dimension-4 ($c^{(4)}$~10^{-30}) operator new physics



Astrophysical neutrino flavour has a real discovery potential of new physics!

IceCube-Gen2,arXiv:1412.5106;1510.05228

3. 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

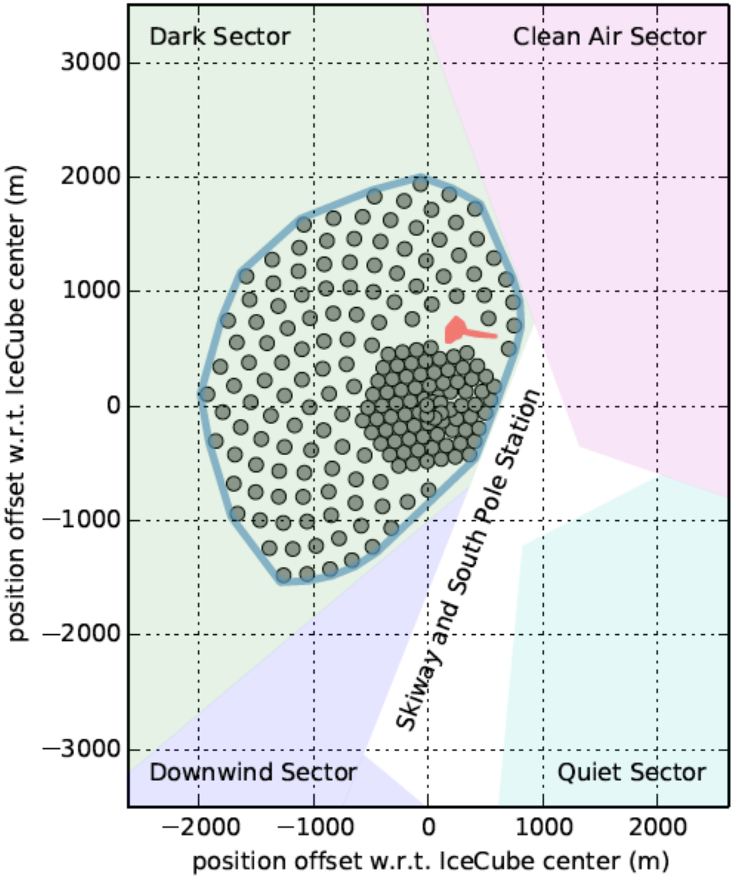
IceCube-Gen2,arXiv:1412.5106;1510.05228

3. IceCube-Gen2

Ice is clear than we thought

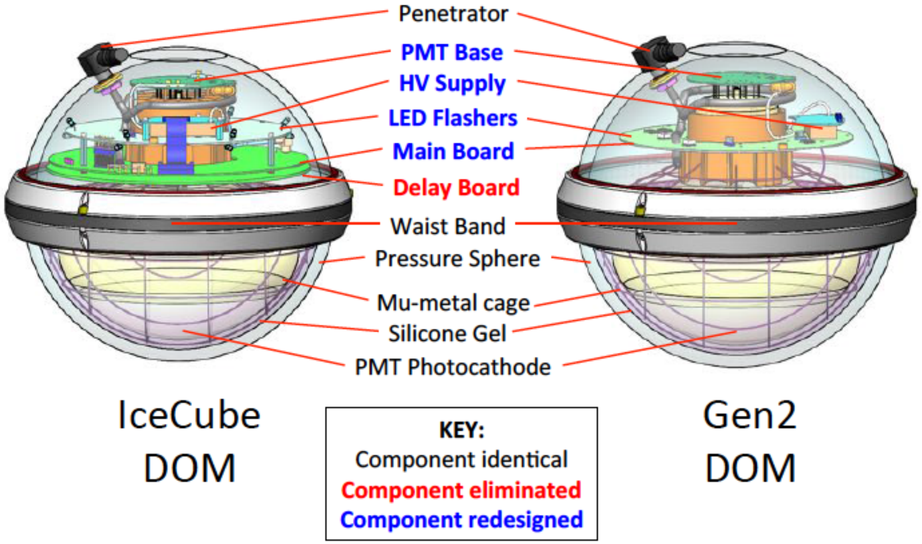
→ larger separation (125m → ~200-300m) to cover larger volume

- 120 new strings with 80 DOMs, 240 m separation, x10 coverage



pDOM

- Improved IceCube DOM
- baseline design

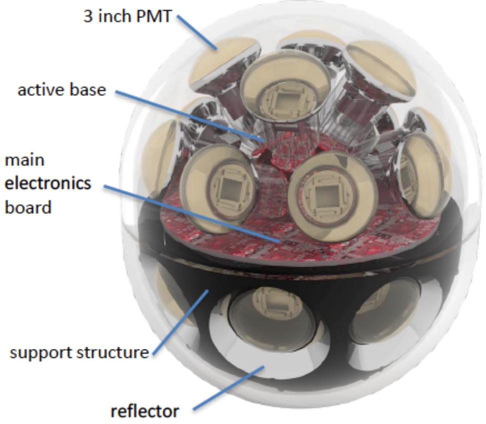


IceCube-Gen2,arXiv:1412.5106;1510.05228
Kowalski (Gen2), IPA2017

3. IceCube-Gen2

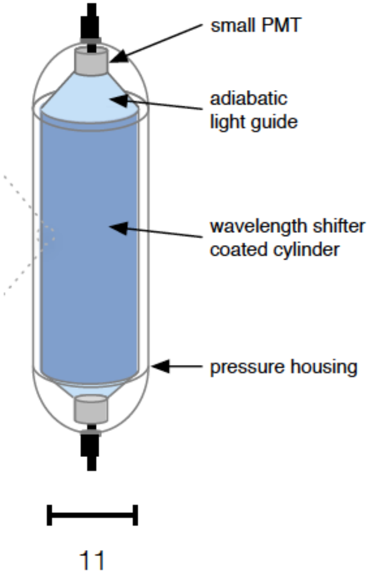
Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 80 DOMs, 240 m separation, x10 coverage
- Variety of new detectors are under development

mDOM
- KM3NeT style
- direction sensitive



D-Eggs
- 8-inch high-QE PMTs
- cover both sky
- cleaner glass window

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



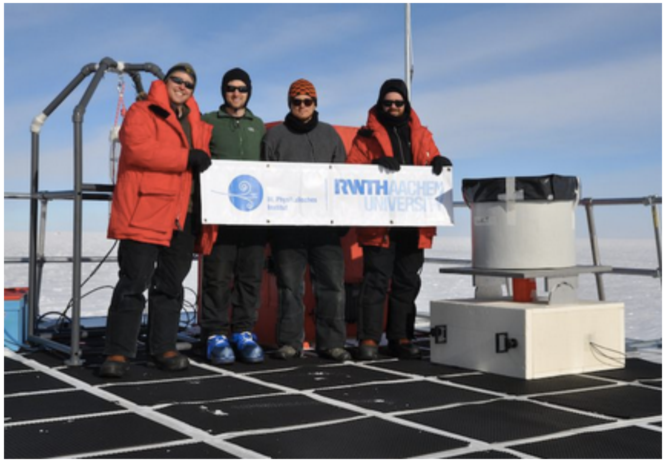
and more…

IceCube-Gen2,arXiv:1412.5106;1510.05228
Kowalski (Gen2), IPA2017

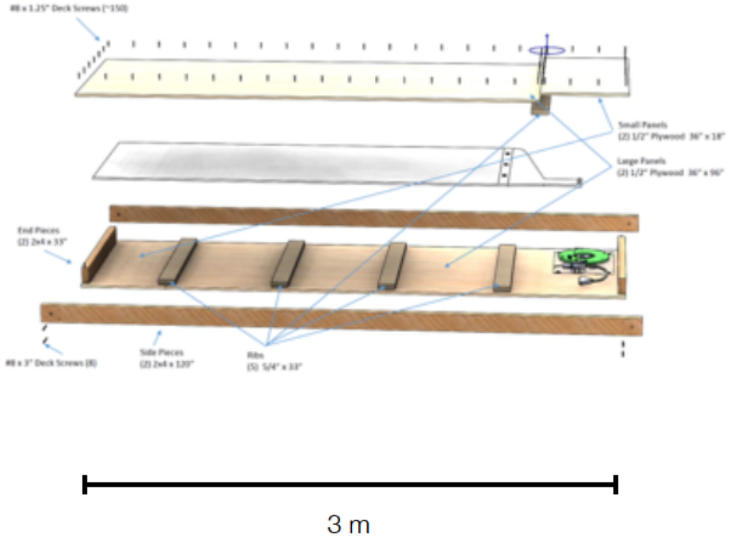
8. IceCube-Gen2

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
- 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



IceCube-Gen2,arXiv:1412.5106;1510.05228
Kowalski (Gen2), IPA2017

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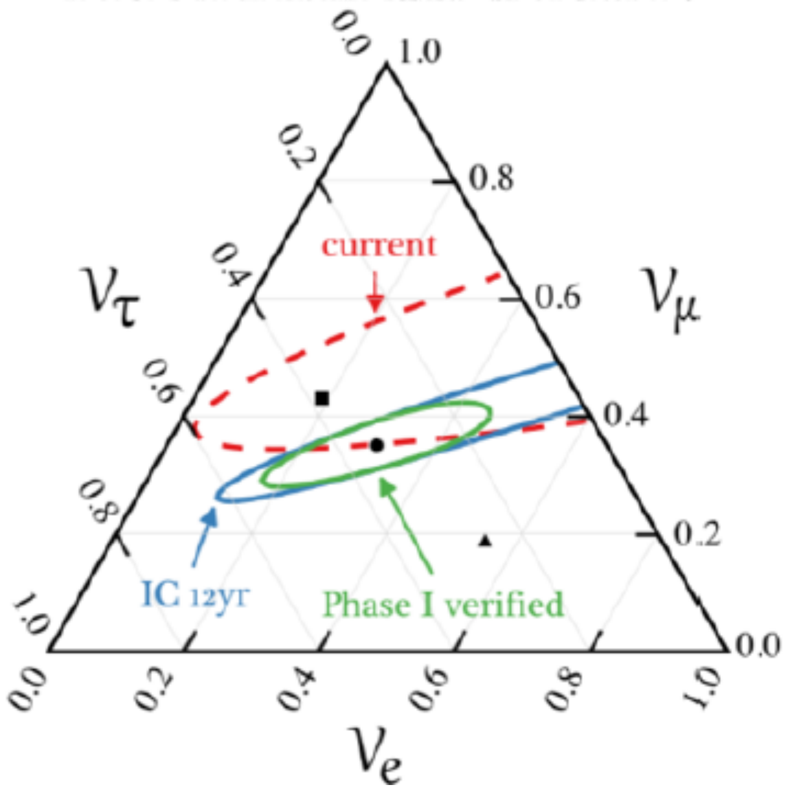
Prediction of Gen2 flavour ratio



Physics
- ν_τ appearance, PMNS matrix unitary
- Neutrino mass ordering (PINGU)
- WIMP search
- Point source
- UHE tau-neutrino
- Nail down production mechanism, etc…

…and, discover new physics!

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.

.

Future IceCube-Gen2 may dramatically improve the astrophysical neutrino flavour information, and has a real discovery potential of new physics.

IceCube-Gen2 collaboration

Thank you for your attention!

backup

1. Spontaneous Lorentz symmetry breaking (SLSB)

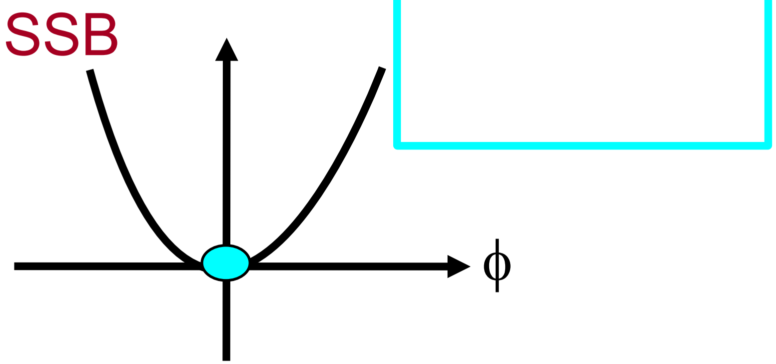
vacuum Lagrangian for fermion $L = i\overline{\Psi}\gamma_\mu\partial^\mu\Psi$

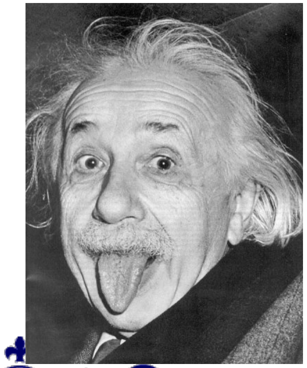
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

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





1. Spontaneous Lorentz symmetry breaking (SLSB)

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

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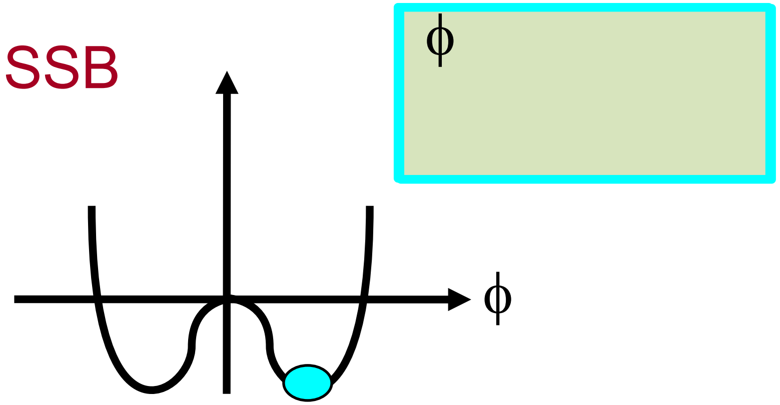

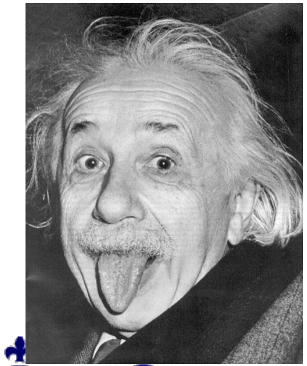

Particle acquires
mass term!

Kostelecký and Samuel,PRD39(1989)683

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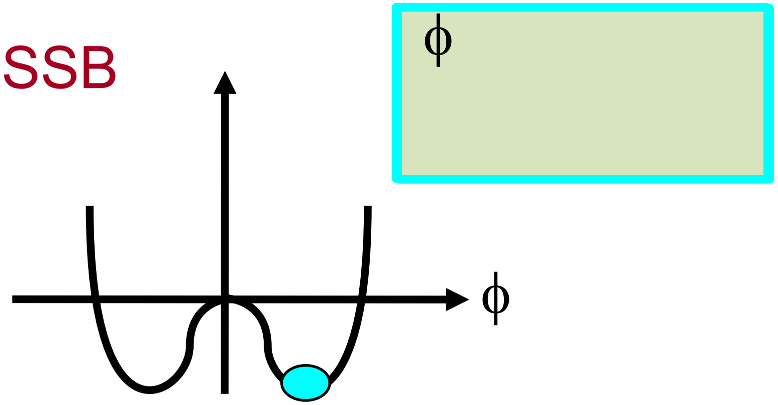
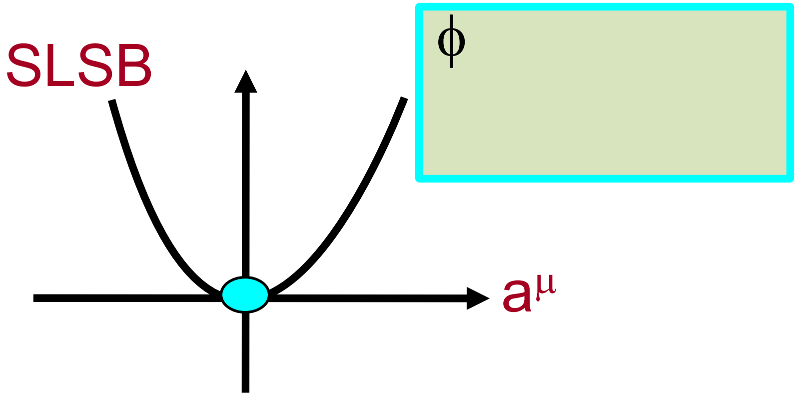
$$M(\varphi) = \mu^{2} < 0$$

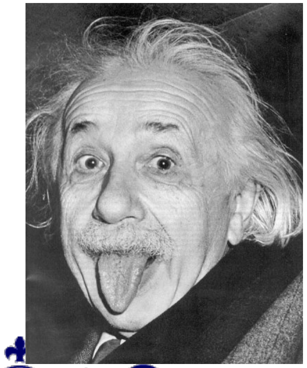
e.g.) SLSB in string field theory

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

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







Kostelecký and Samuel,PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking (SLSB)

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

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

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

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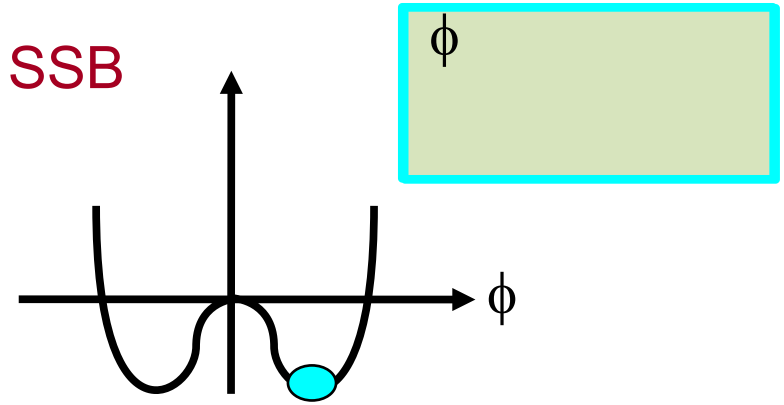

e.g.) SLSB in string field theory

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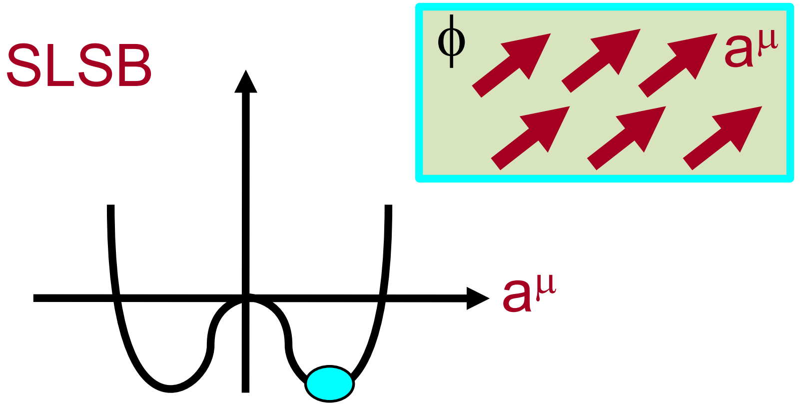
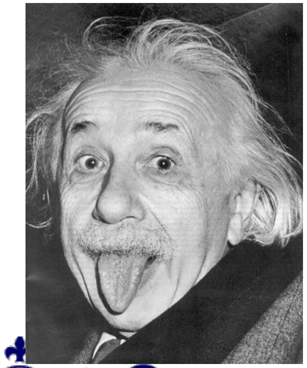




Lorentz symmetry
is spontaneously
broken!

1. Spontaneous Lorentz symmetry breaking

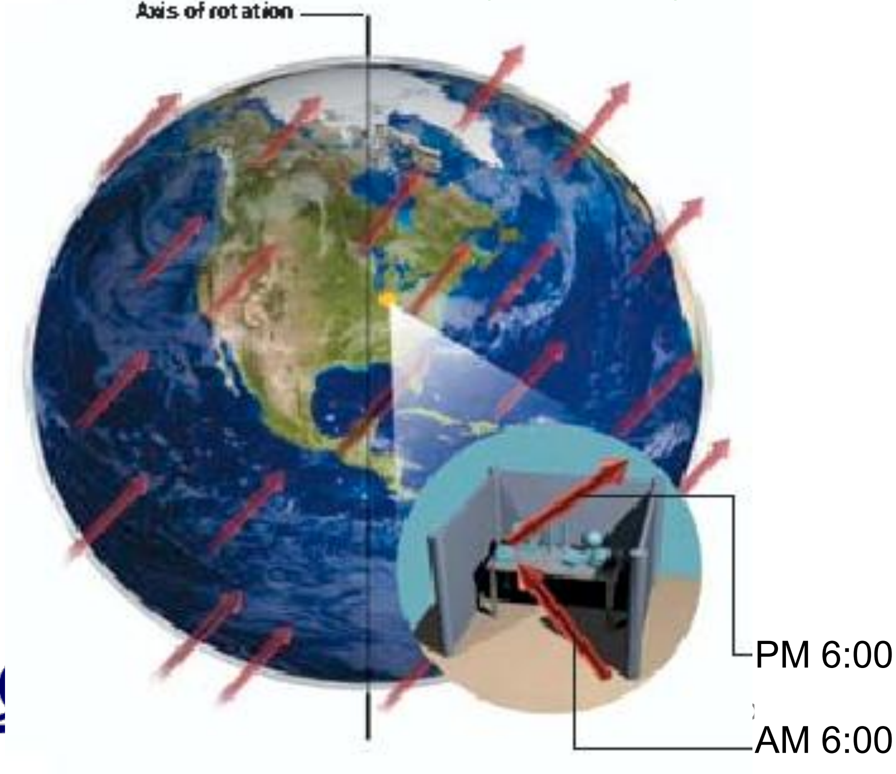
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos, etc); then the physical quantities may be modified (oscillation probability, etc)

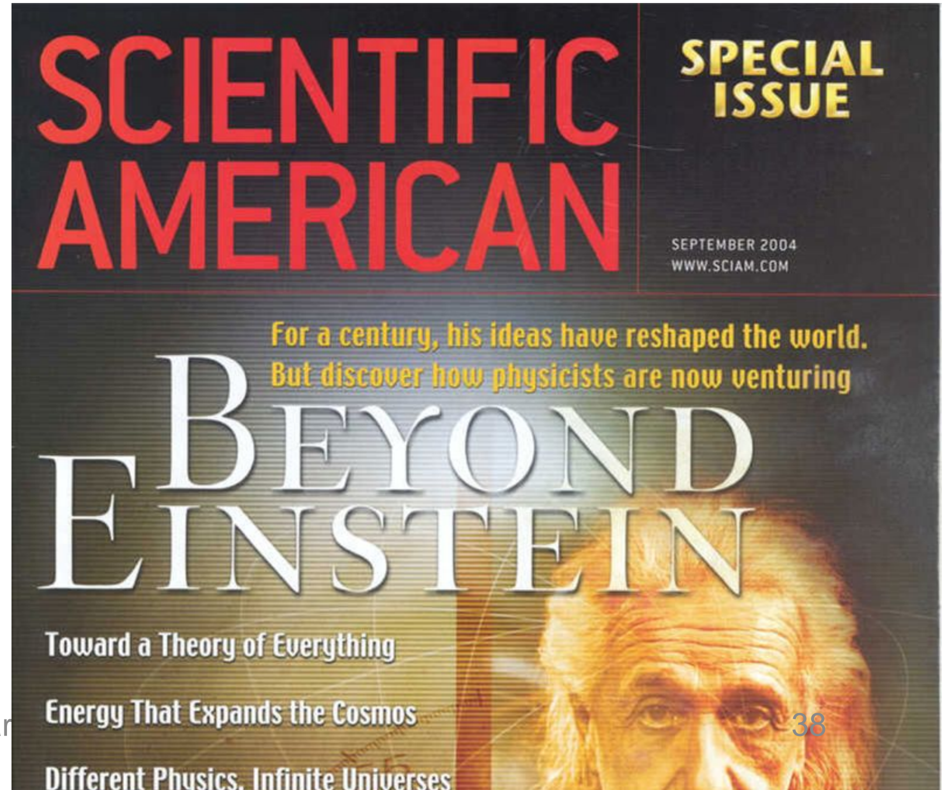
background fields of the universe

vacuum Lagrangian for fermion

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

Scientific American (Sept. 2004)

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SPECIAL ISSUE

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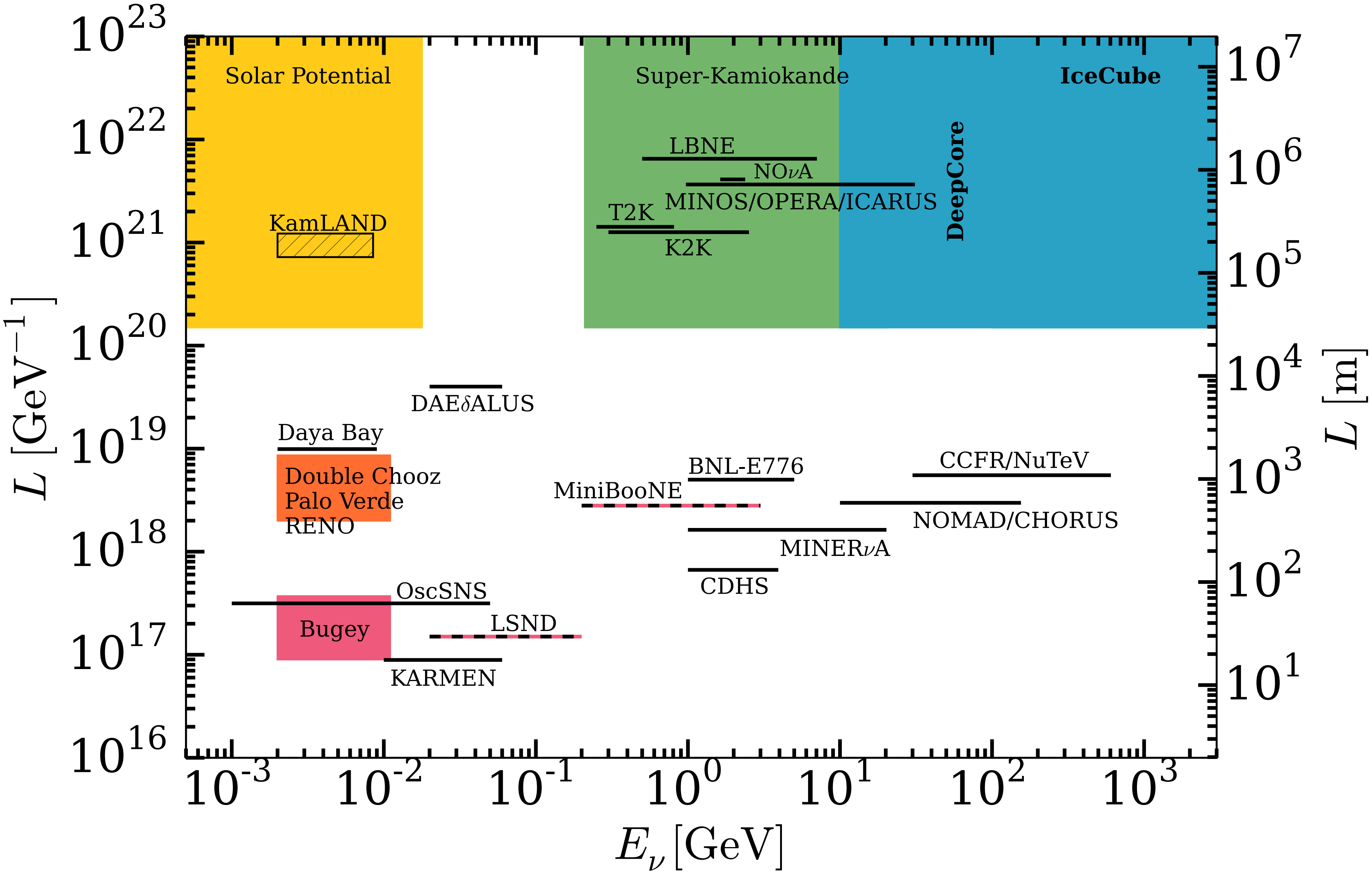
Energy That Expands the Cosmos

Different Physics, Infinite Universes

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

3. Lorentz violation with neutrino oscillation



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

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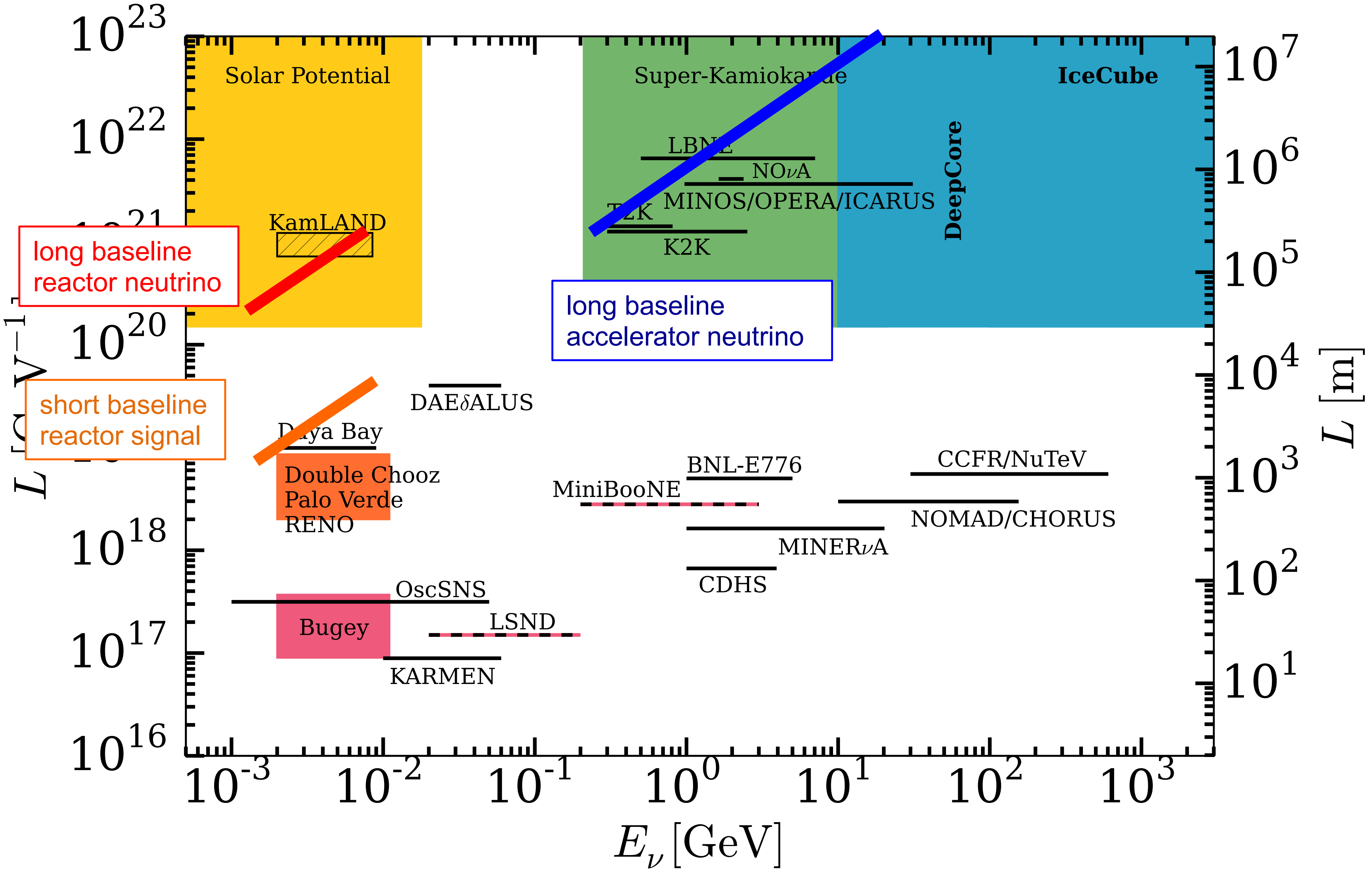

long baseline
reactor neutrino

short baseline
reactor signal

long baseline
accelerator neutrino

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

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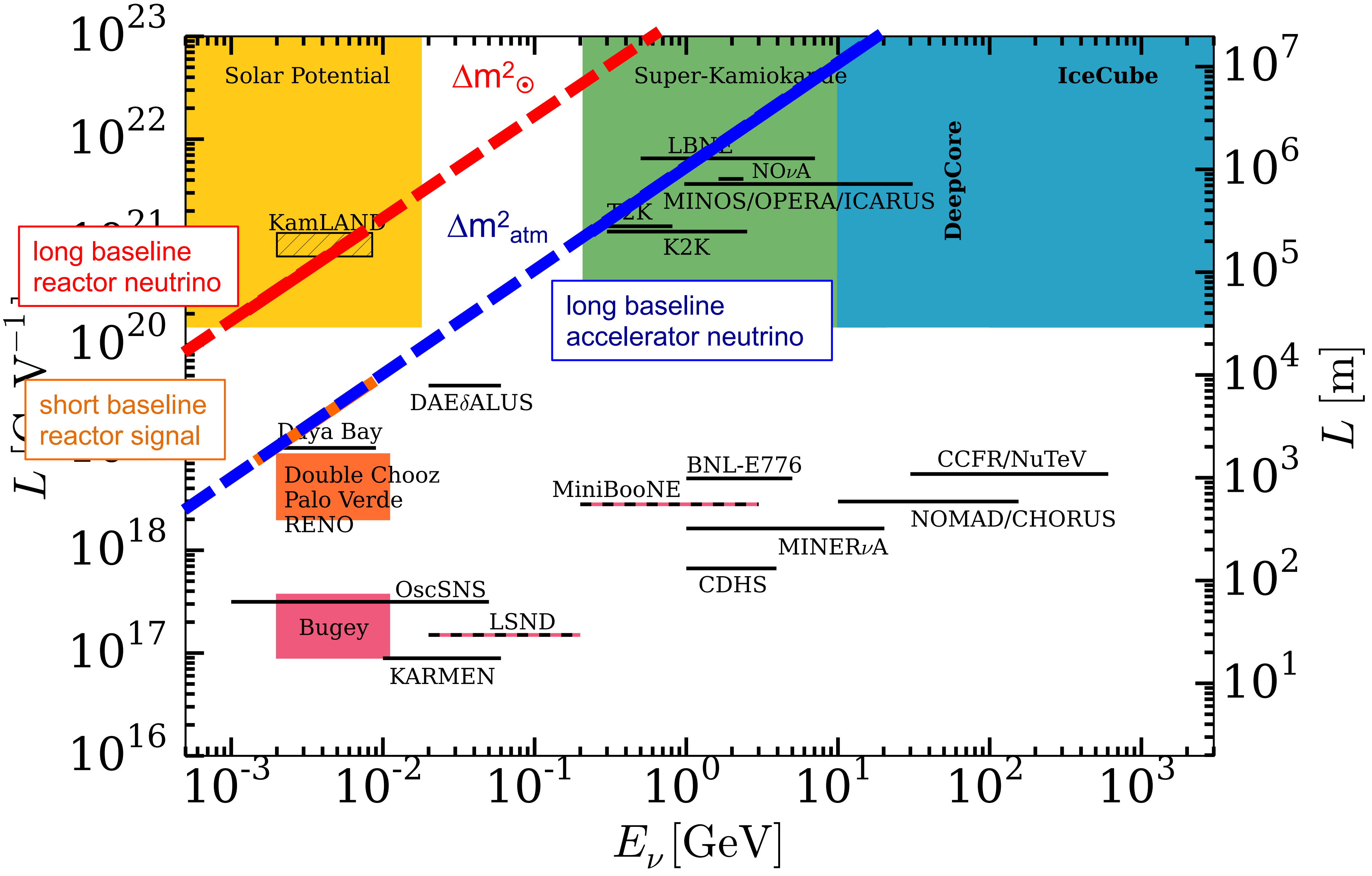

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Kostelecký and Mewes, PRD69(2004)016005
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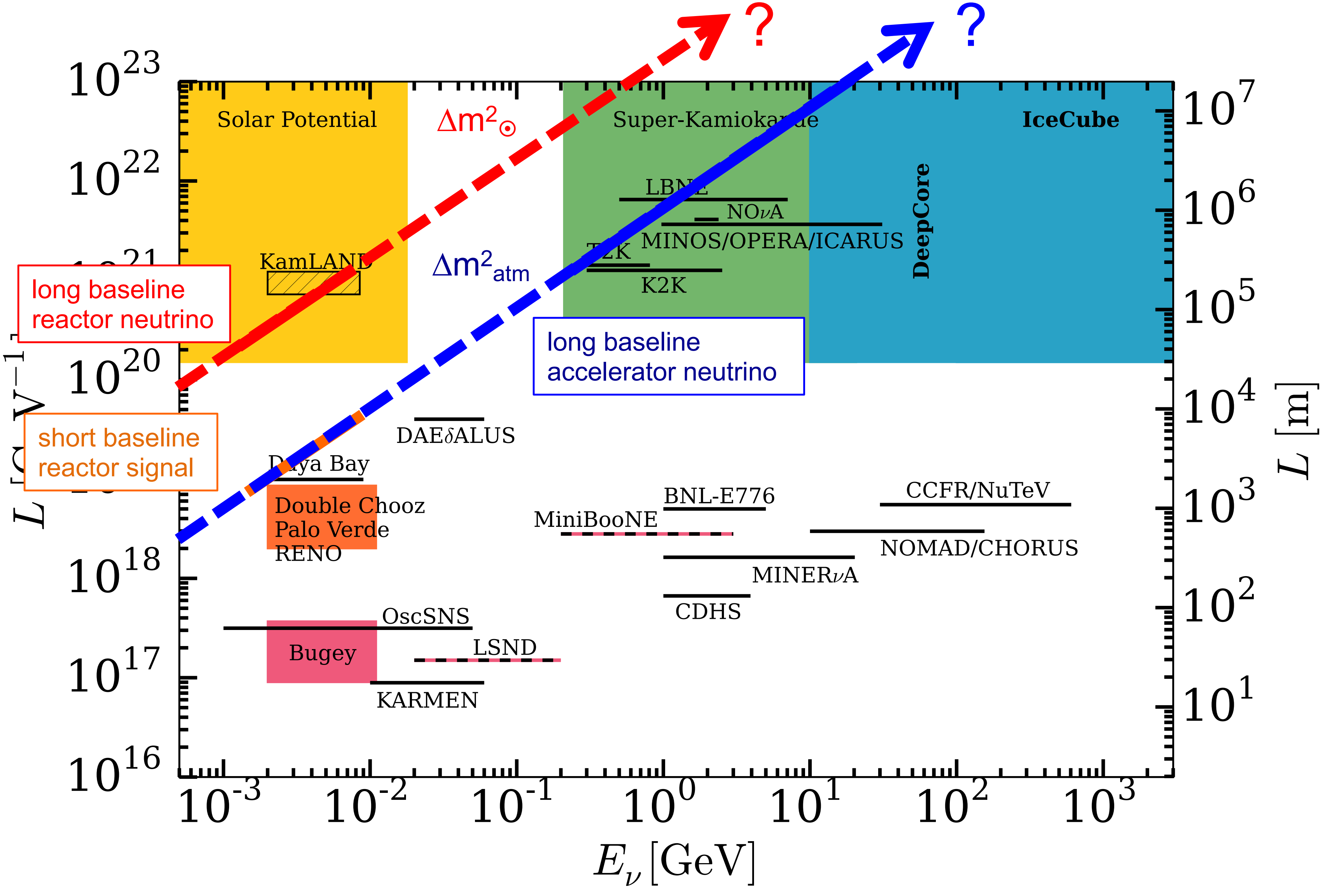

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Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLES2015

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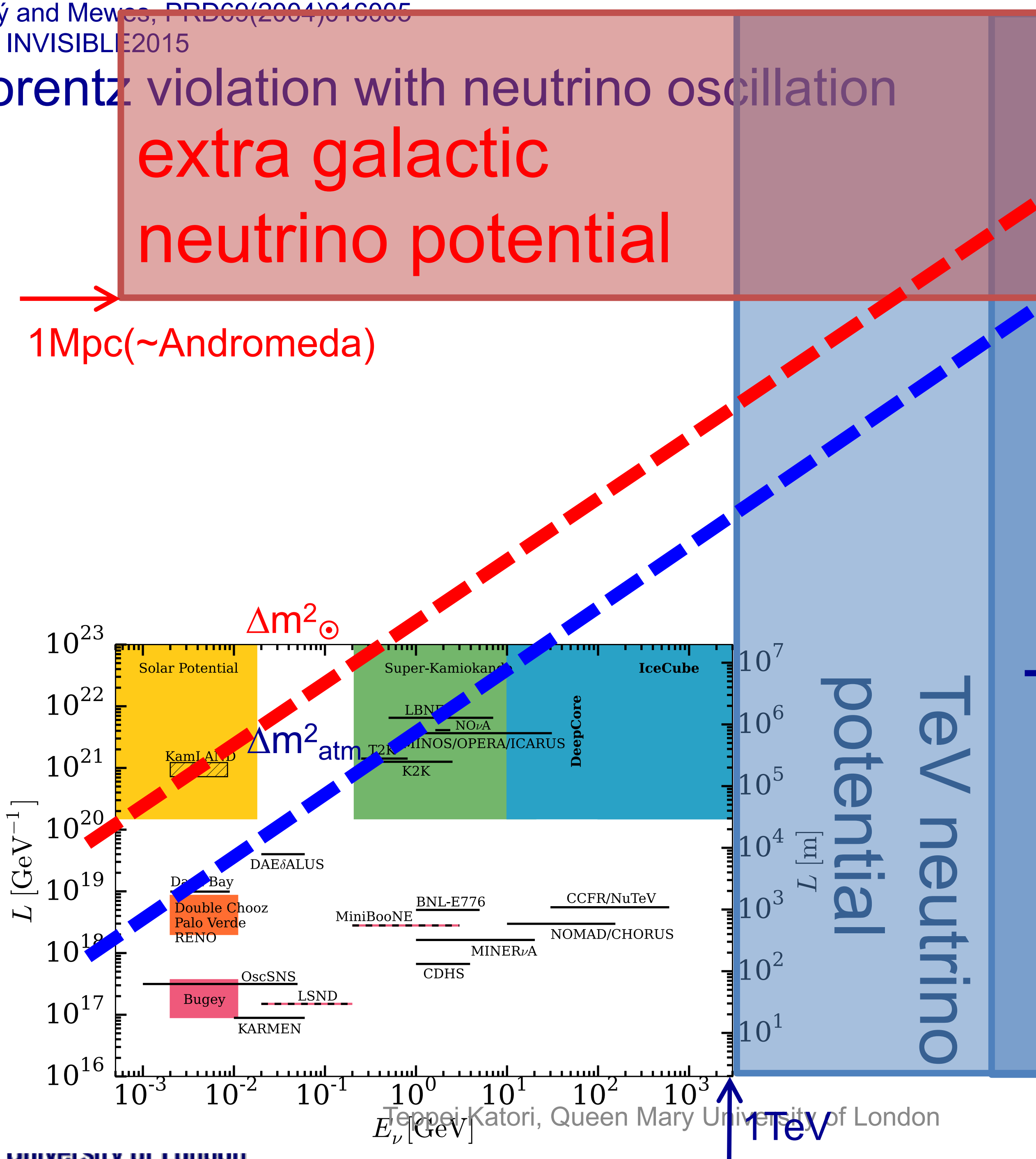


extra galactic
neutrino potential

1Mpc(~Andromeda)

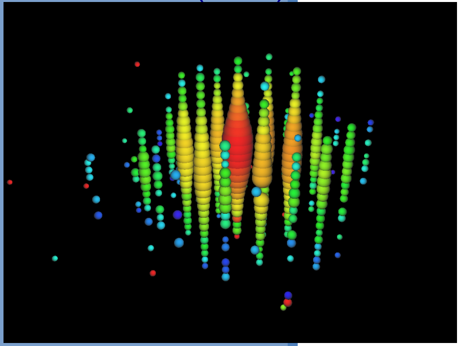
?
?

TeV neutrino potential

PeV neutrino potential

1TeV

IceCube collaboration
PRL111(2013)021103



Argüelles, TK, Salvado, PRL115(2015)161303

3. Standard flavour triangle diagram

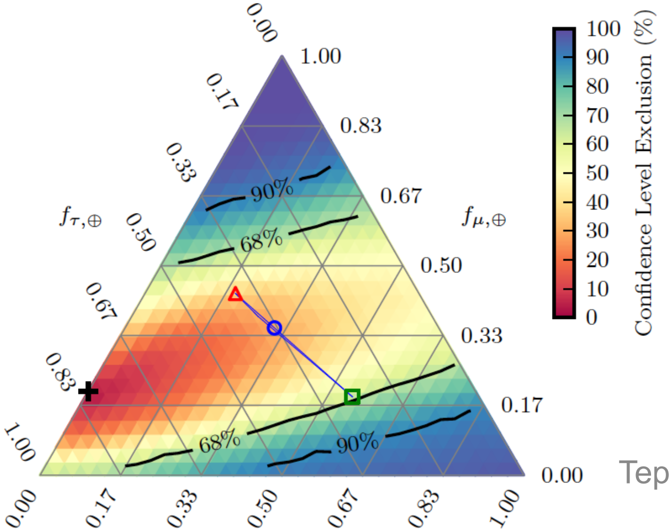
There are 3 UHE neutrino production models

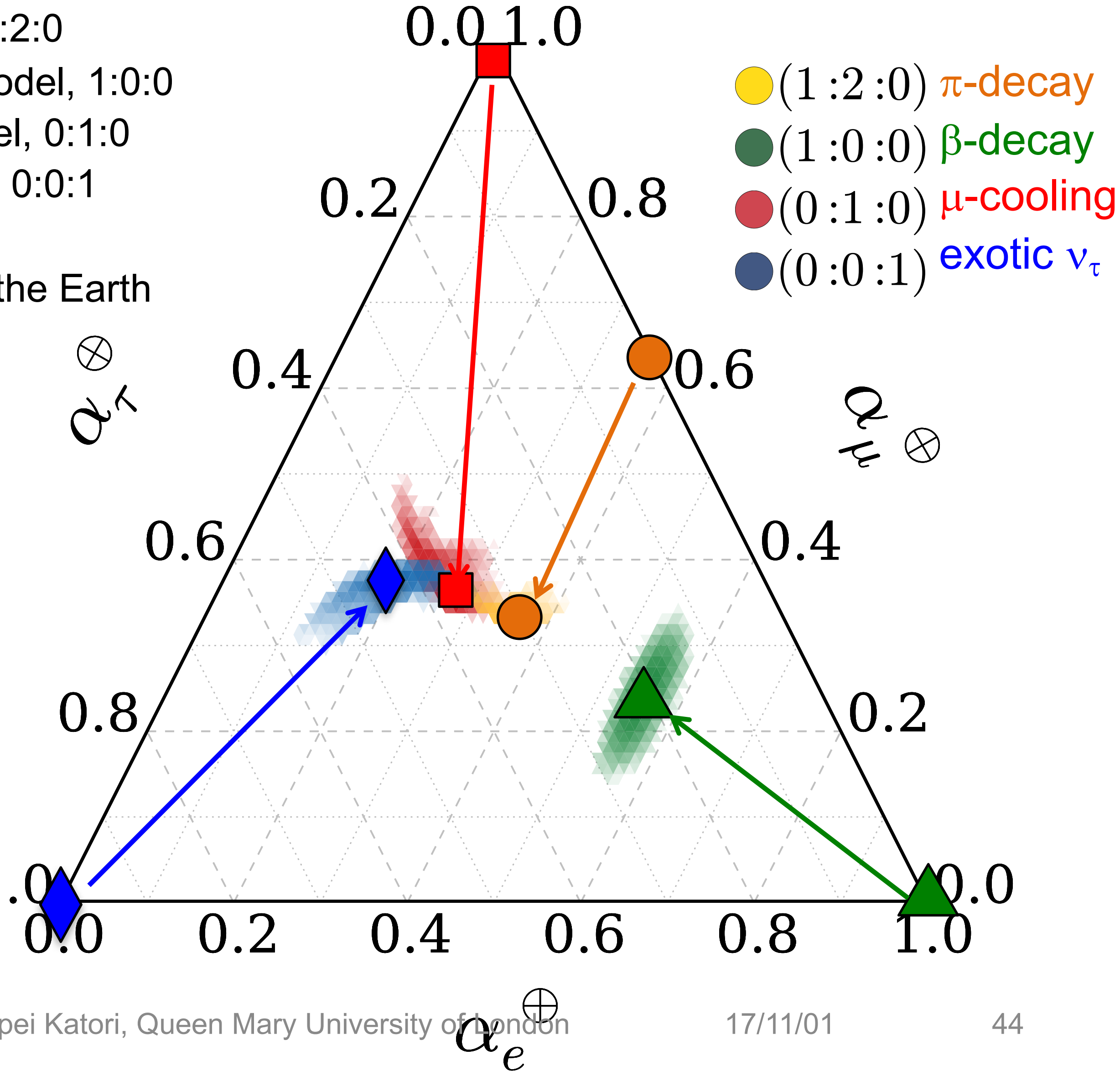
i. pion decay dominant model, 1:2:0
ii. electron neutrino dominant model, 1:0:0
iii. muon neutrino dominant model, 0:1:0
iv. tau neutrino dominant model, 0:0:1

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

IceCube collaboration
PRL114(2015)171102

IceCube flavour triangle diagram





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3. 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
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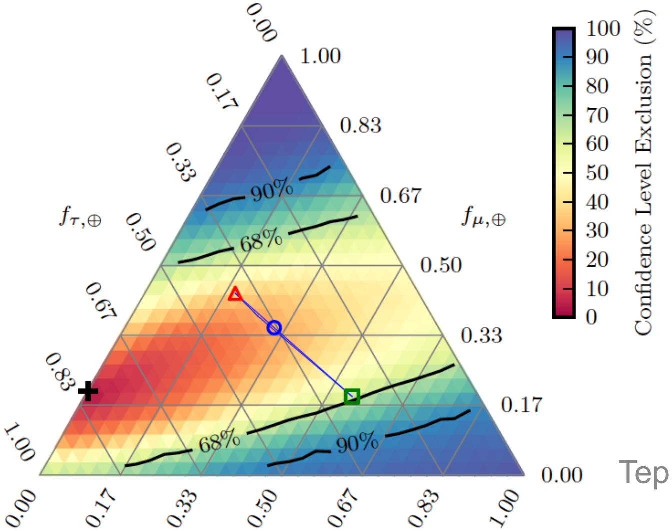
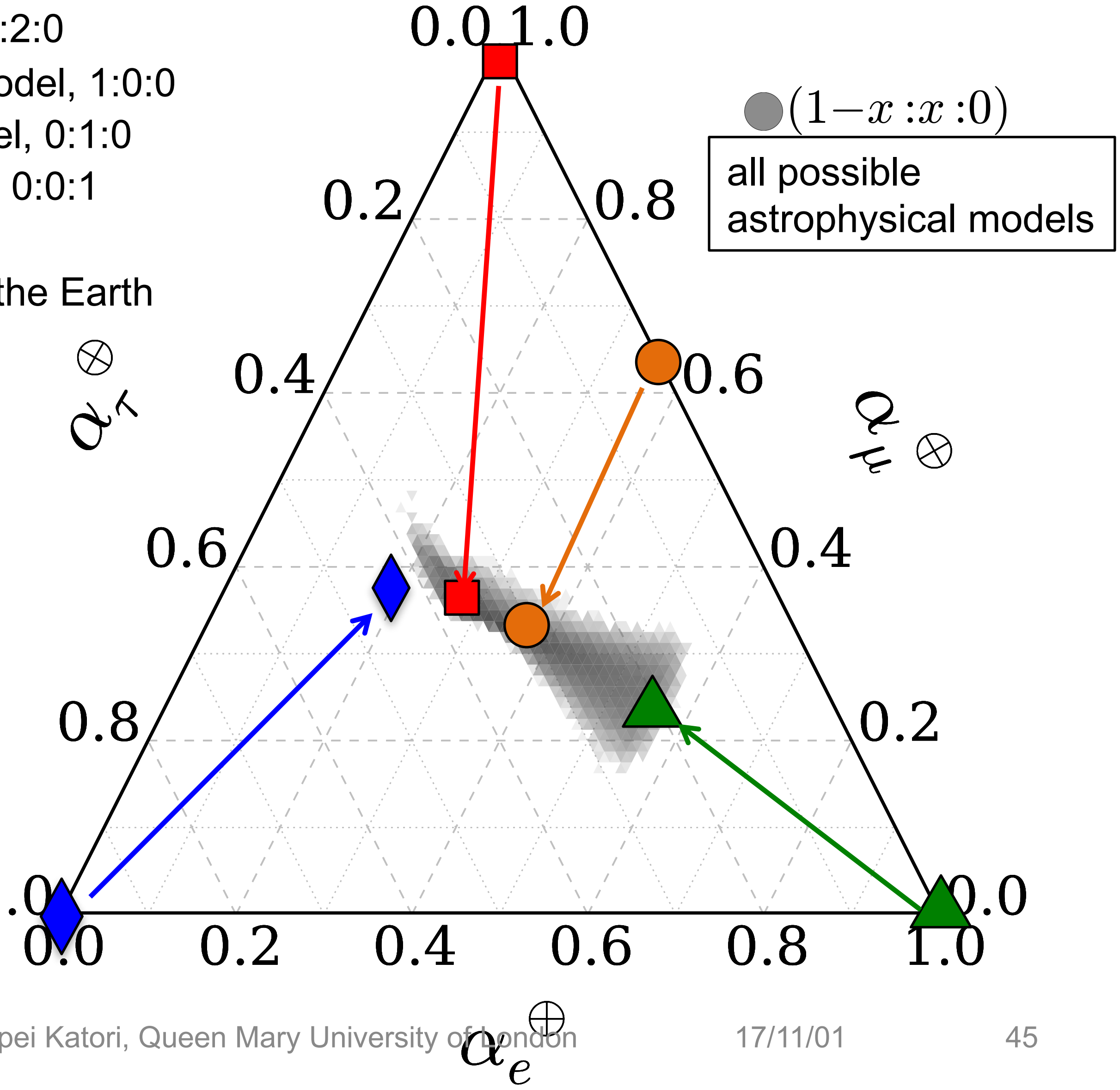
IceCube flavour triangle diagram





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3. New physics operator

Arbitrary new physics are described in terms of effective operators

$$\sum_n \left(\frac{E}{\Lambda_n}\right)^n \widetilde{U}_n O_n \widetilde{U}_n^\dagger = \widetilde{U}_0 O_0 \widetilde{U}_0^\dagger + \left(\frac{E}{\Lambda_1}\right)^1 \widetilde{U}_1 O_1 \widetilde{U}_1^\dagger + \cdots = a + c \cdot E + \cdots$$

- Lorentz violation
- cosmic torsion
- Non-Standard interaction

etc

- Lorentz and CPT violation
- Violation of equivalent principle

etc

Effective Hamiltonian is the combination of mass term and new physics term

$$h_{eff} = \frac{1}{2E} U^\dagger M U + \sum_n \left(\frac{E}{\Lambda_n}\right)^n \widetilde{U}_n O_n \widetilde{U}_n^\dagger = V^\dagger(E) \Delta V(E)$$

Then, equation is solved to find the neutrino mixing

$$P_{\alpha\to\beta}(L\to\infty, E) = \sum_{i>j} |V_{\alpha i}|^2 \left|V_{\beta i}\right|^2$$

Finally, fraction of neutrino flavour β on the earth is

$$\alpha_\beta^\oplus \sim \int_{Emin}^{Emax} \sum_\alpha P_{\alpha\to\beta}(L\to\infty, E)\phi_\alpha(E) dE$$

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IceCube,PRD82(2010)112003, SuperKamiokande,PRD91(2015)052003

3. Scale of new physics

a+c·E+…

First, we need to set the scale of new physics

$$h_{eff} = \frac{1}{2E}\,U^{\dagger}MU + \sum_{n}\left(\frac{E}{\boxed{\Lambda_n}}\right)^{n}\tilde{U}_n\boxed{O_n}\tilde{U}_n^{\dagger} = V^{\dagger}(E)\Delta V(E)$$

There are 3 choices

1. current limits on new physics (a~10^{-23} GeV and c~10^{-27})
 → We use the best limits on SME from Super-Kamiokande and IceCube-40

2. lowest energy observed astrophysical neutrino(a~10^{-26} GeV and c~10^{-30})
 → New physics is just above current limits

3. highest energy observed astrophysical neutrino(a~10^{-28} GeV and c~10^{-34})
 → Maximum sensitivity of new physics by IceCube

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3. Anarchy sampling

We need to scan the phase space of new physics parameter

$$h_{eff} = \frac{1}{2E} U^{\dagger} M U + \sum_{n} \left(\frac{E}{\Lambda_n}\right)^{n} \boxed{\widetilde{U}_n} O_n \boxed{\widetilde{U}_n^{\dagger}} = V^{\dagger}(E) \Delta V(E)$$

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

3. Neutrino oscillations vs. Neutrino mixings

Effective Hamiltonian

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

neutrino oscillation formula

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

neutrino mixing formula

$$P_{\alpha\to\beta}(L \to \infty, E) = \sum_{i>j} |V_{\alpha i}|^{2} \left|V_{\beta i}\right|^{2}$$