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

ArXiv:1709.03434

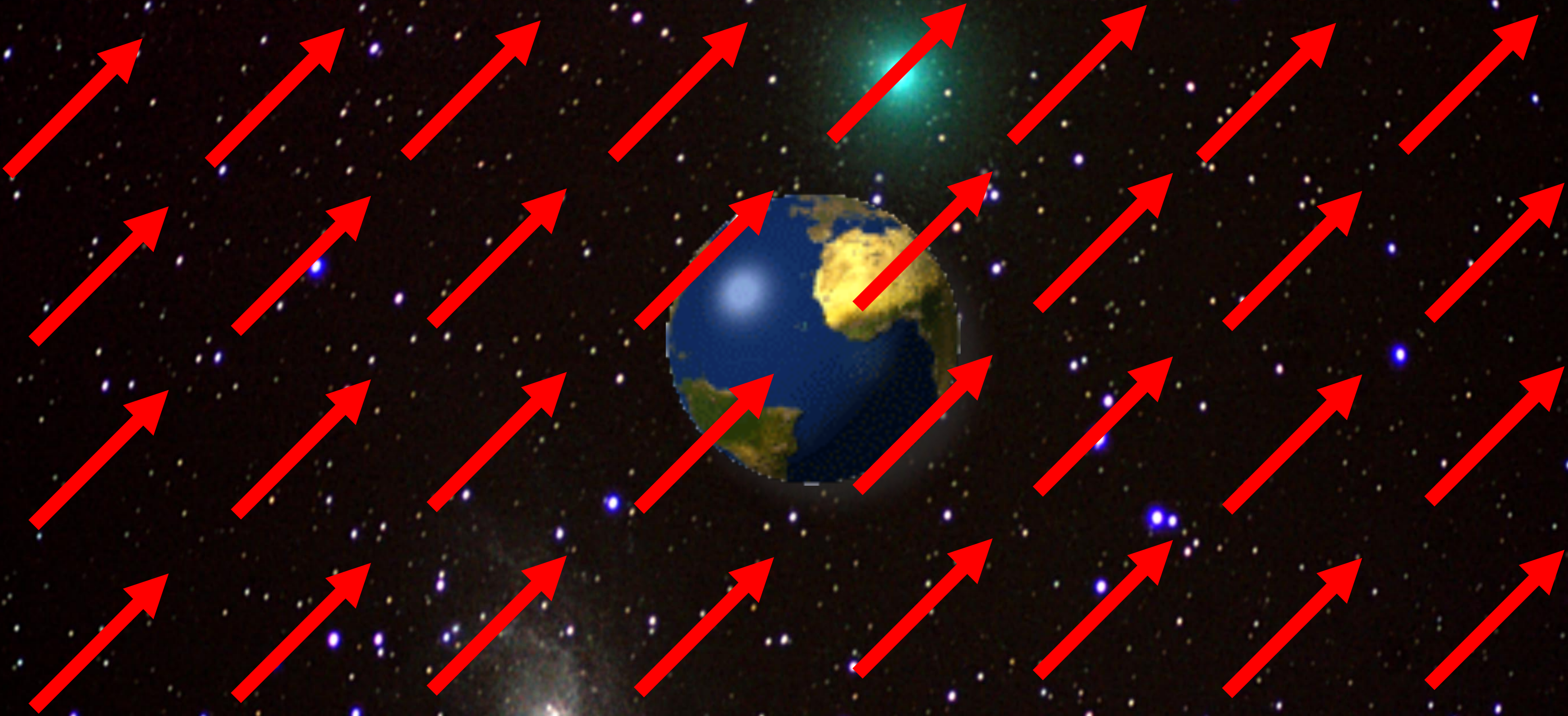
Find us on Facebook,
"Institute of Physics Astroparticle Physics"
https://www.facebook.com/IOPAPP

Teppei Katori for the IceCube collaboration
Queen Mary University of London
IoP APP-HEPP meeting, University of Bristol, Mar. 26, 2018

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

ArXiv:1709.03434

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

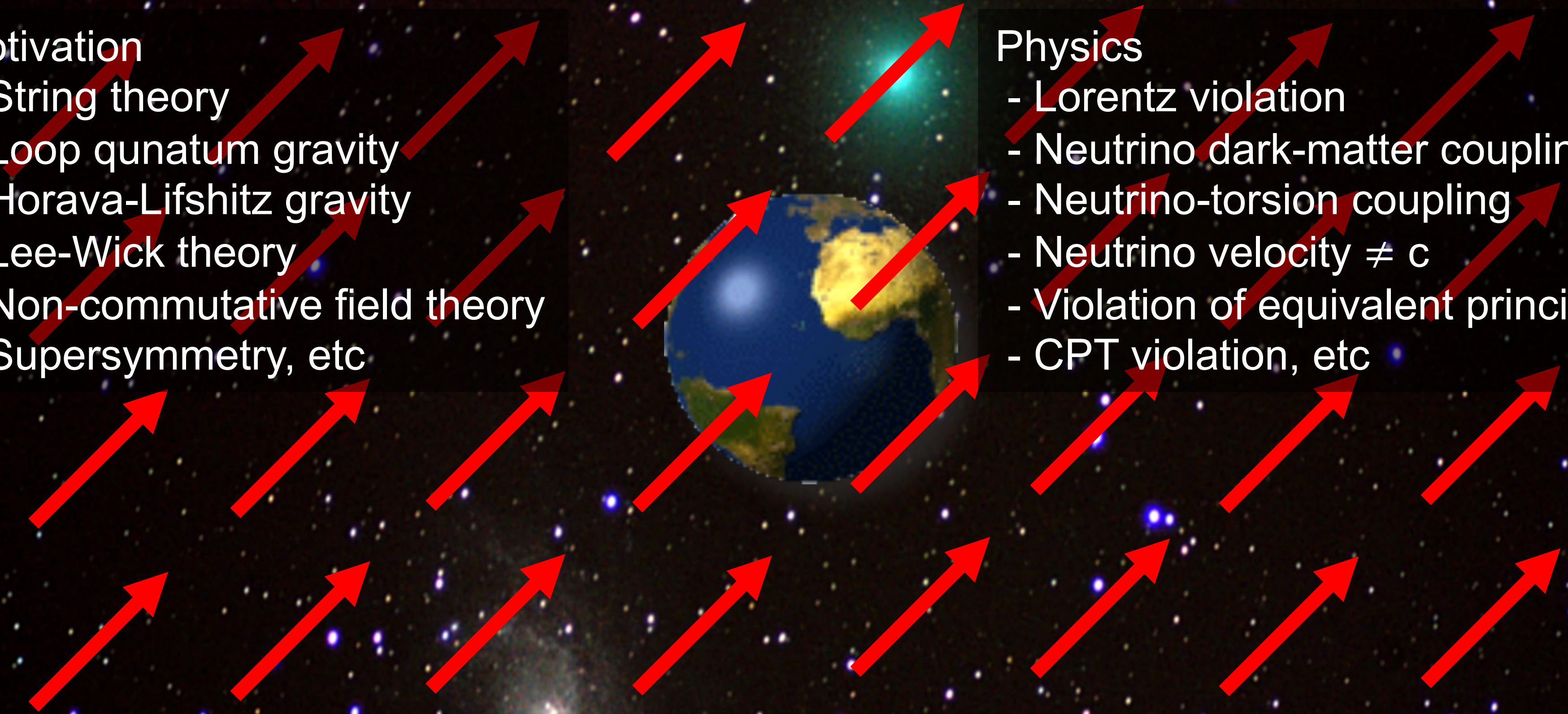


Teppei Katori for the IceCube collaboration
Queen Mary University of London
IoP APP-HEPP meeting, University of Bristol, Mar. 26, 2018

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

ArXiv:1709.03434

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



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

Teppei Katori for the IceCube collaboration
Queen Mary University of London
IoP APP-HEPP meeting, University of Bristol, Mar. 26, 2018

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

ArXiv:1709.03434

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

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

Teppei Katori for the IceCube collaboration
Queen Mary University of London
IoP APP-HEPP meeting, University of Bristol, Mar. 26, 2018

Collaborators

Carlos Argüelles

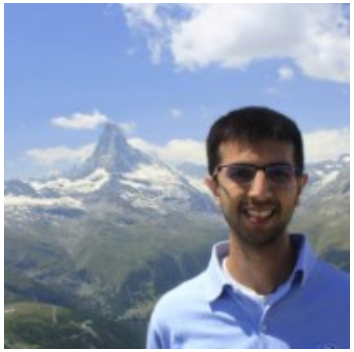
Gabriel Collin

Janet Conrad

MIT

Ali Kheirandish

U. Wisconsin, Madison



Shivesh Mandalia

Queen Mary U. of London

THE ROYAL SOCIETY

1. **Lorentz violating neutrino oscillation**

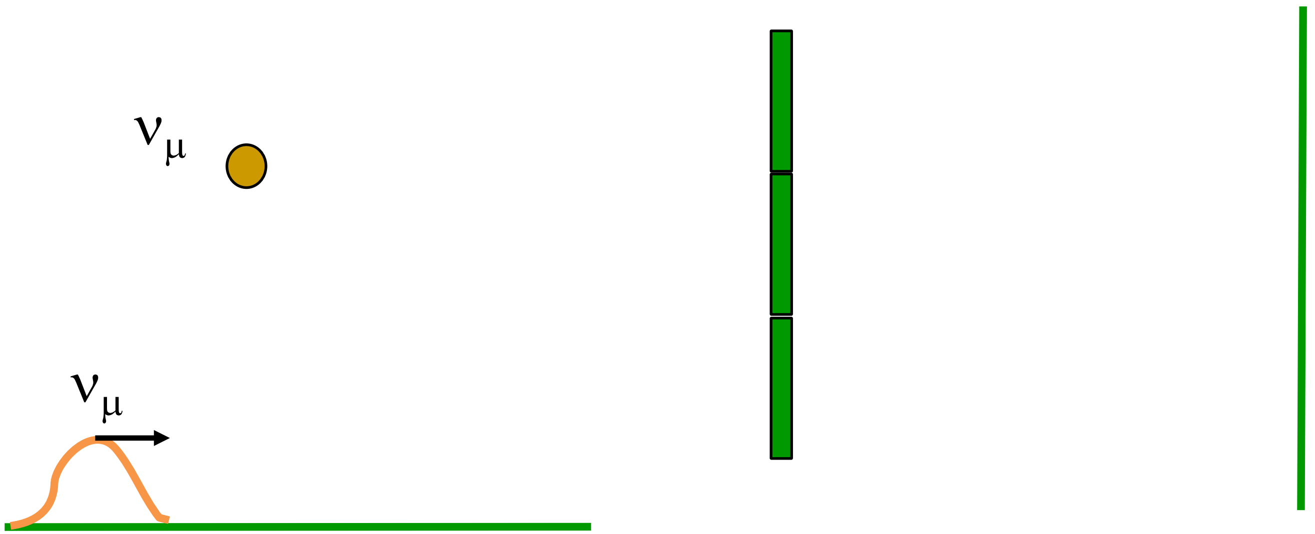
2. **Test for Lorentz violation with atmospheric neutrinos**

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

4. **Conclusion**

1. Neutrino interferometry as a probe of new physics

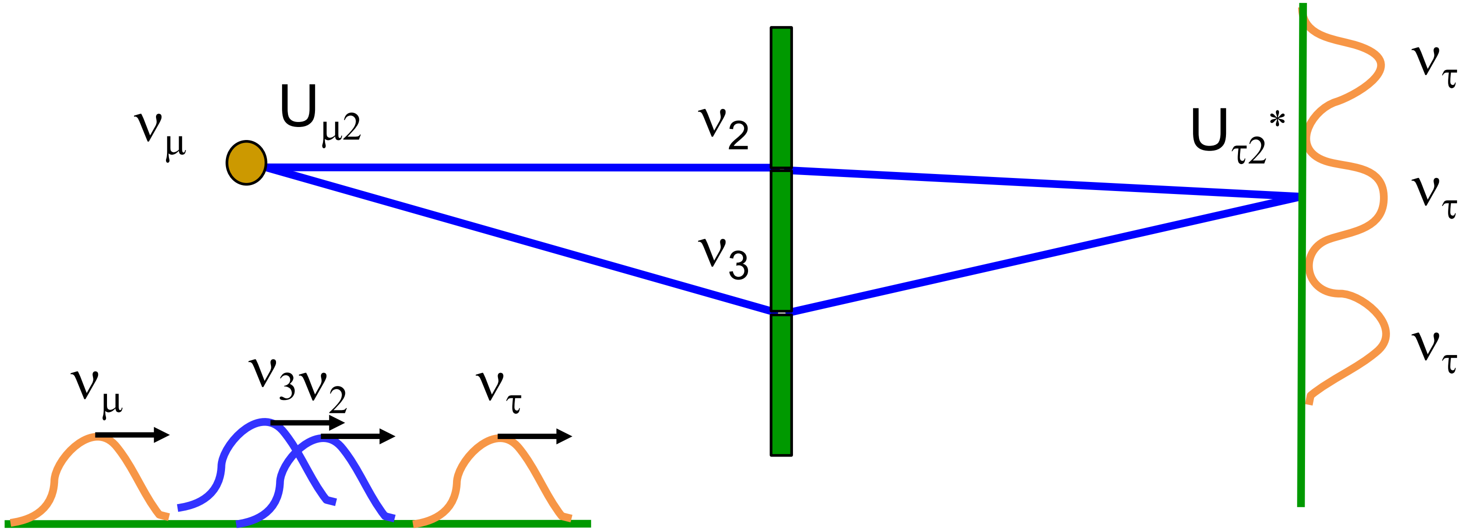
Neutrino oscillation is an interference experiment (cf. double slit experiment)



- 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

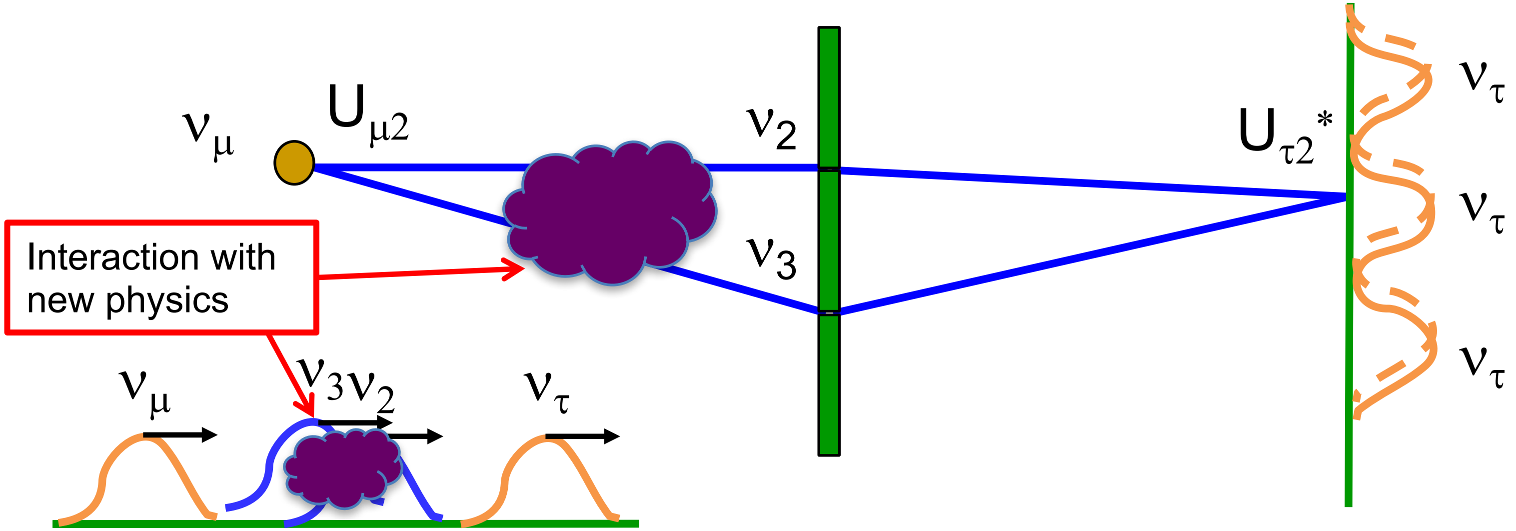
Neutrino oscillation is an interference experiment (cf. double slit experiment)



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

1. Neutrino interferometry as a probe of new physics

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



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

Kostelecky and Mewes, PRD85(2012)096005

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

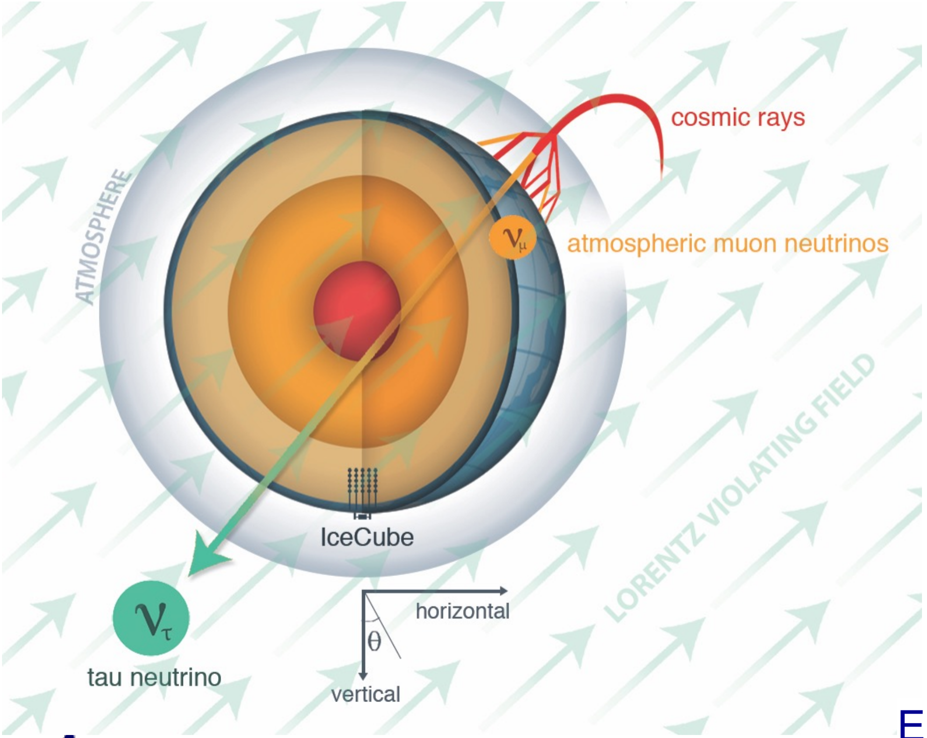
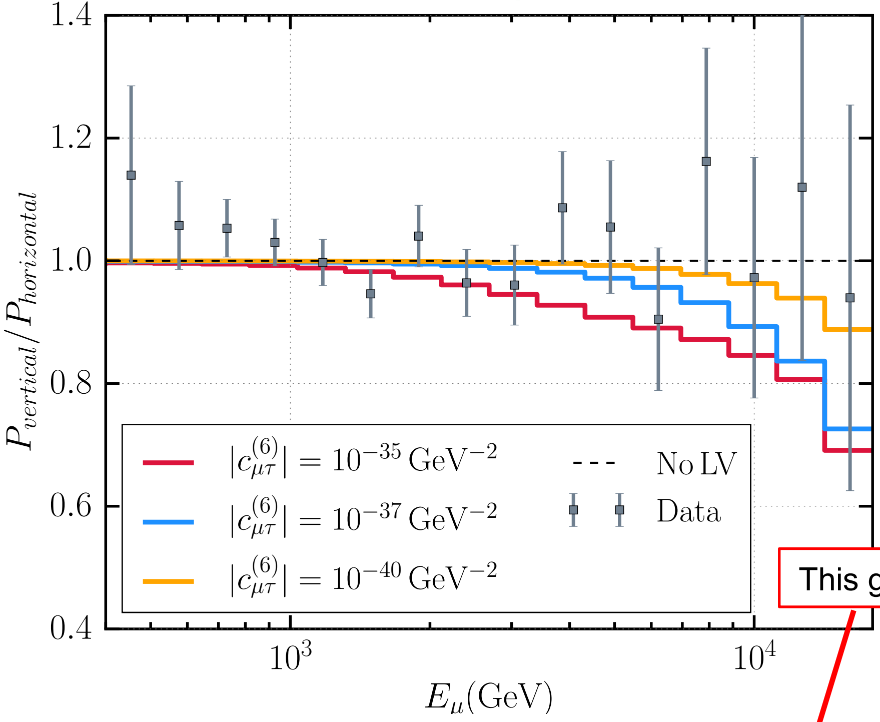


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator



This guy

Eq. 1: LV motivated new physics Hamiltonian

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

Kostelecky and Mewes, PRD85(2012)096005

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

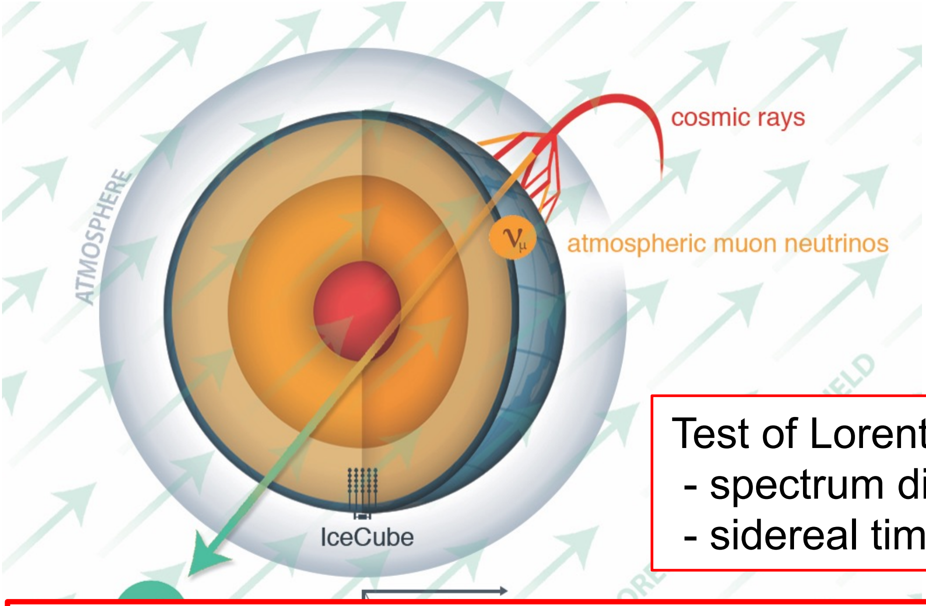
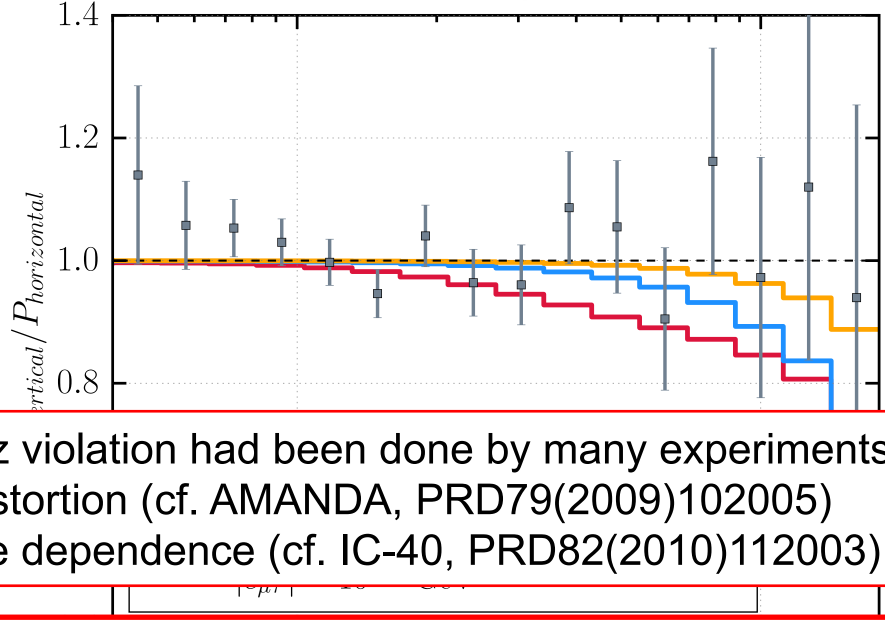
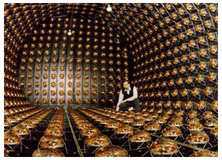


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator

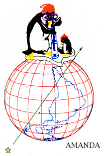


Test of Lorentz violation had been done by many experiments
- spectrum distortion (cf. AMANDA, PRD79(2009)102005)
- sidereal time dependence (cf. IC-40, PRD82(2010)112003)

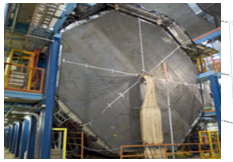
LSND

PRD72(2005)076004

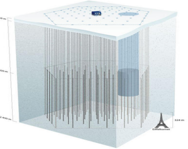
MINOS ND

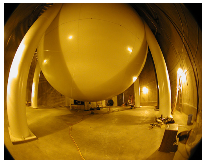
PRL101(2008)151601

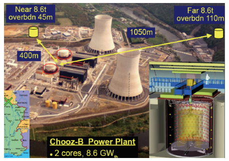
AMANDA


PRD79(2009)102005

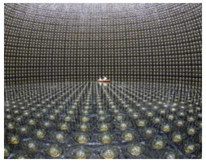
MINOS FD

PRL105(2010)151601

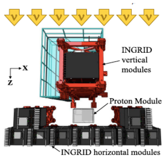
IceCube

PRD82(2010)112003

MiniBooNE

PLB718(2013)1303

Double Chooz


PRD86(2013)112009

Super-Kamiokande

PRD91(2015)052003

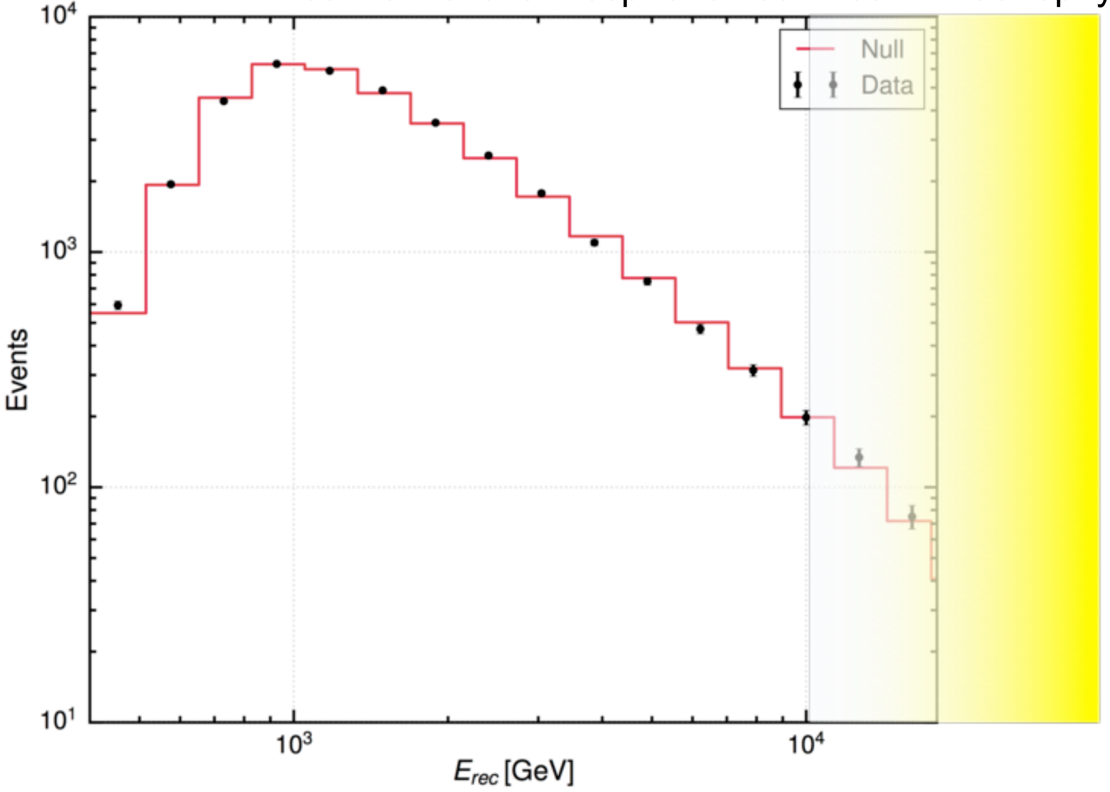
T2K


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 atmospheric neutrinos ↔ astrophysical neutrinos



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

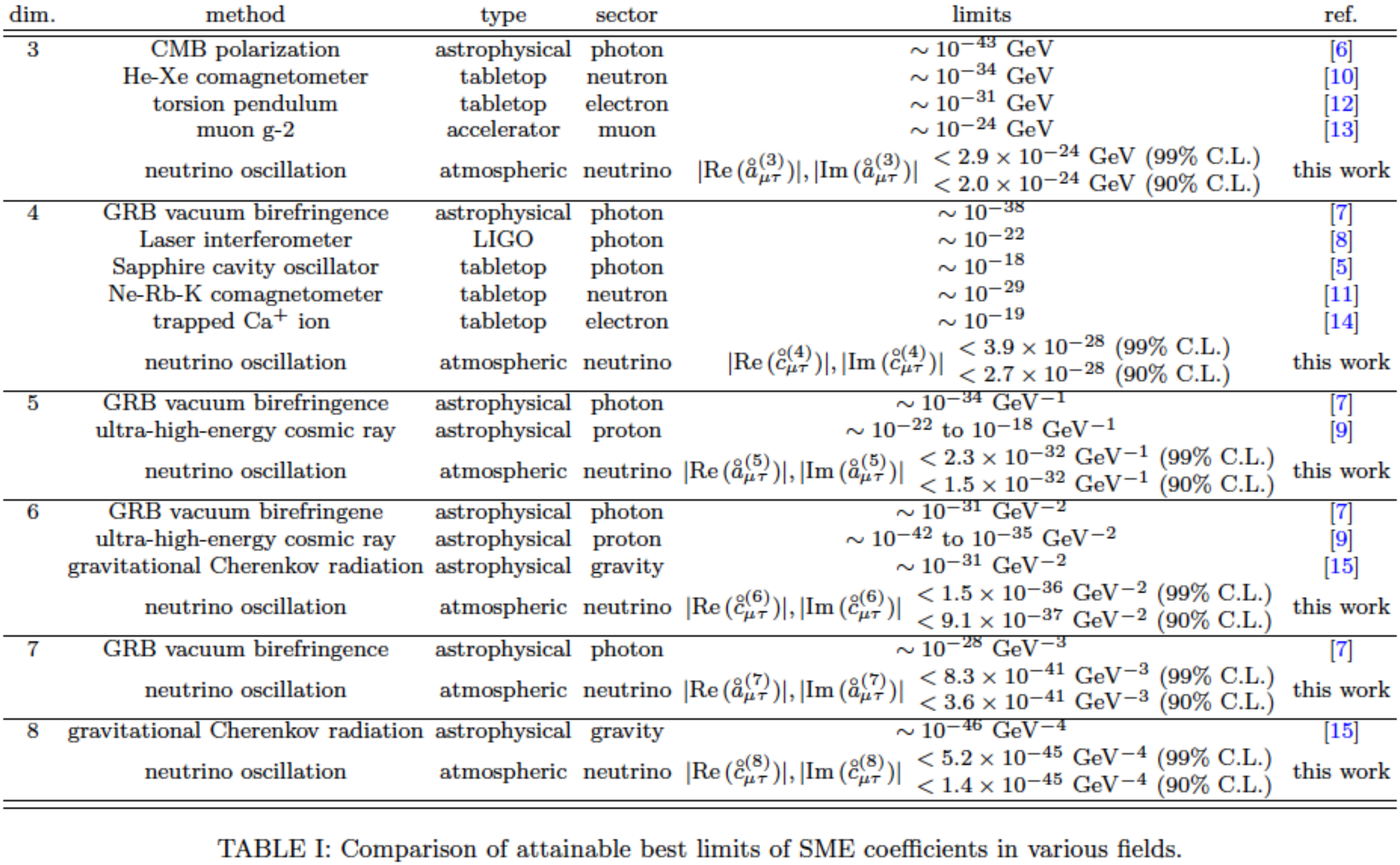
↓

This analysis is the possible best analysis of Lorentz violation within terrestrial neutrinos.

Longest baseline → diameter of the earth (12000km)
Highest energy → conventional flux (~20TeV)

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.

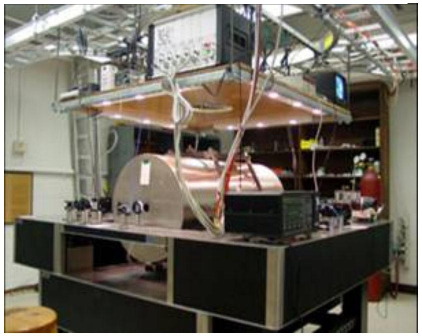
2. Results

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]
	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}	
		astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	
		atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} $< 1.5 \times 10^{-32}$ GeV^{-1}	
6		astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	
					(99% C.L.) (90% C.L.)	this work
7						
					(99% C.L.) (90% C.L.)	this work
8						[15]
					(99% C.L.) (90% C.L.)	this work

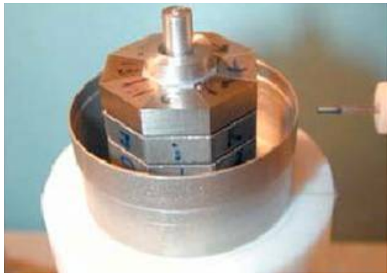
TABLE I: Comparison of attainable best limits of SM … lds.

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



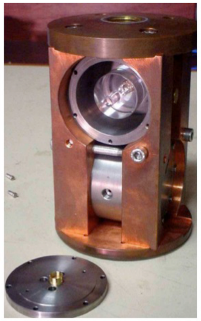
PRL107(2011)171604
PRL112(2014)110801

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



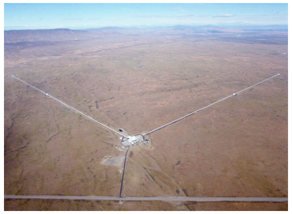
PRL97(2006)021603

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



Nature.Comm.6(2015)8174

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

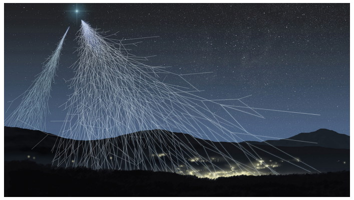


PLB761(2016)1

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

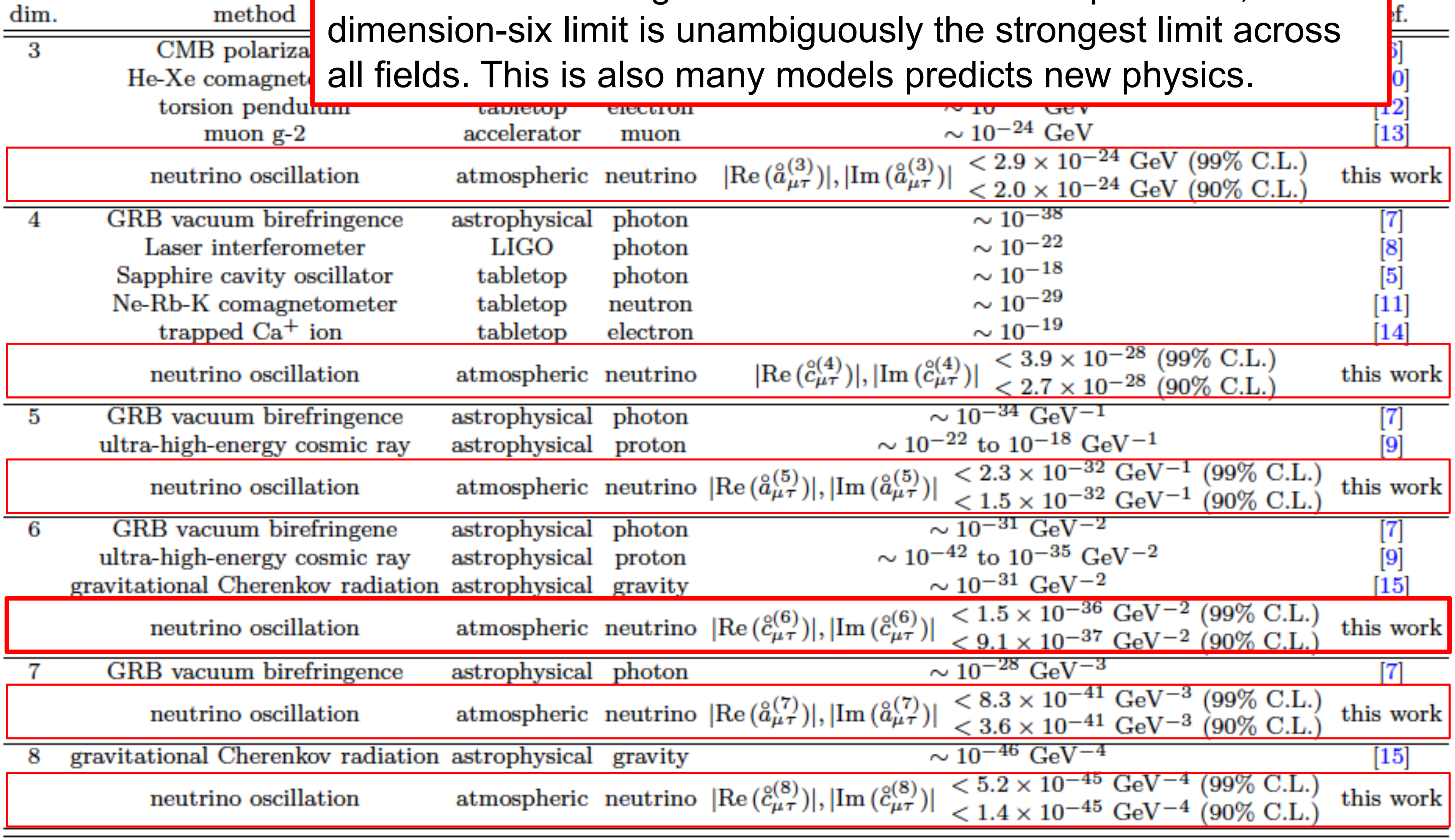
		type	sector		li	ef.
	tion	astrophysical	photon		~ 10	[6]
	ometer	tabletop	neutron		~ 10	[10]
	lum	tabletop	electron		~ 10	[12]
		accelerator	muon		~ 10	[13]
	ation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$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

1. Lorentz violating neutrino oscillation

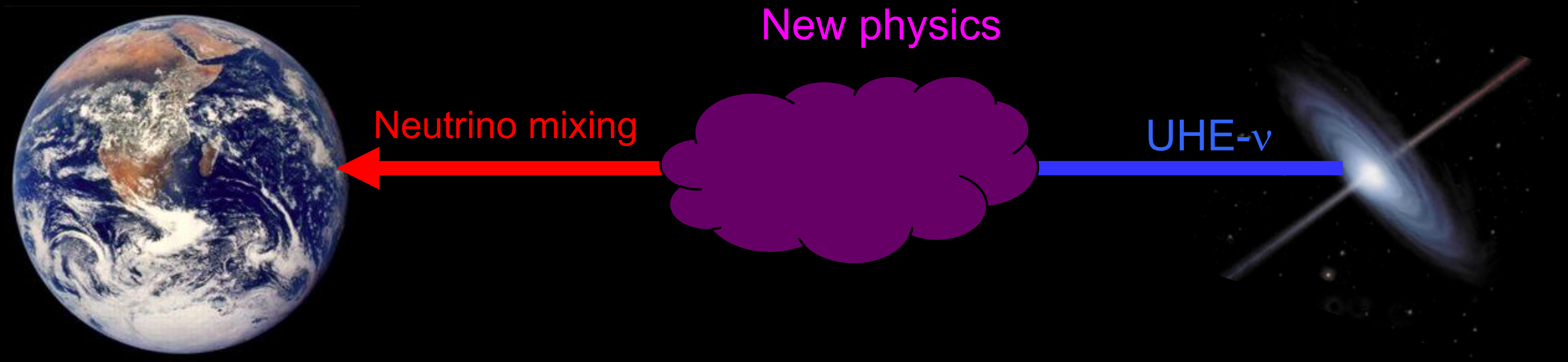
2. Test for Lorentz violation with atmospheric neutrinos

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

4. Conclusion

3. Test of Lorentz violation with astrophysical neutrinos

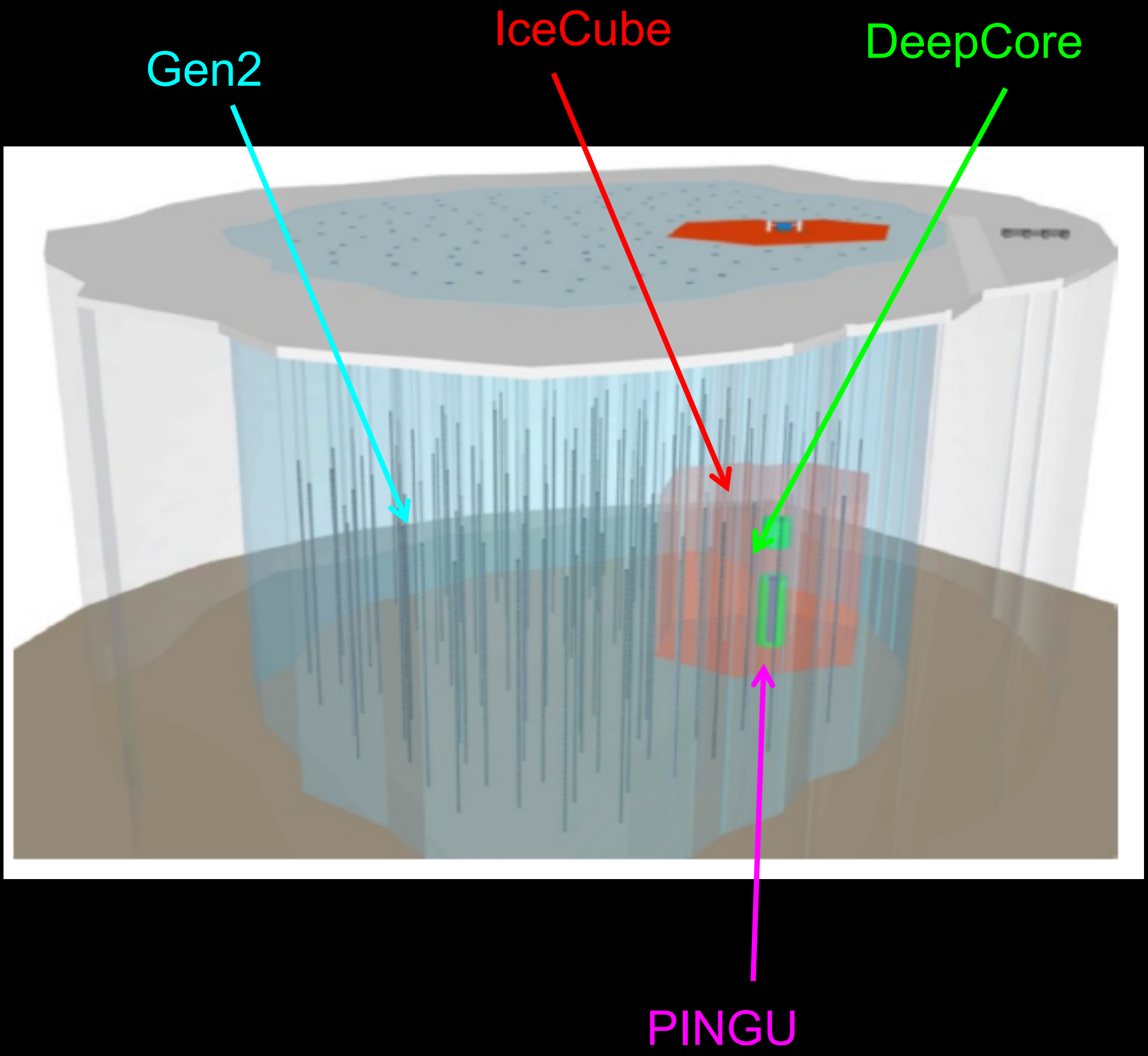
Combination of longer baseline and higher energy makes astrophysical neutrino to be the most sensitive source of fundamental physics. For this, flavors of astrophysical neutrinos are very important and we are working on that.



Shivesh Mandalia (Next talk)
"Search for New Physics in Astrophysical neutrino Flavor at IceCube"

IceCube-Gen2,arXiv:1412.5106;1510.05228

3. IceCube-Gen2



Bigger IceCube and denser DeepCore can push their physics

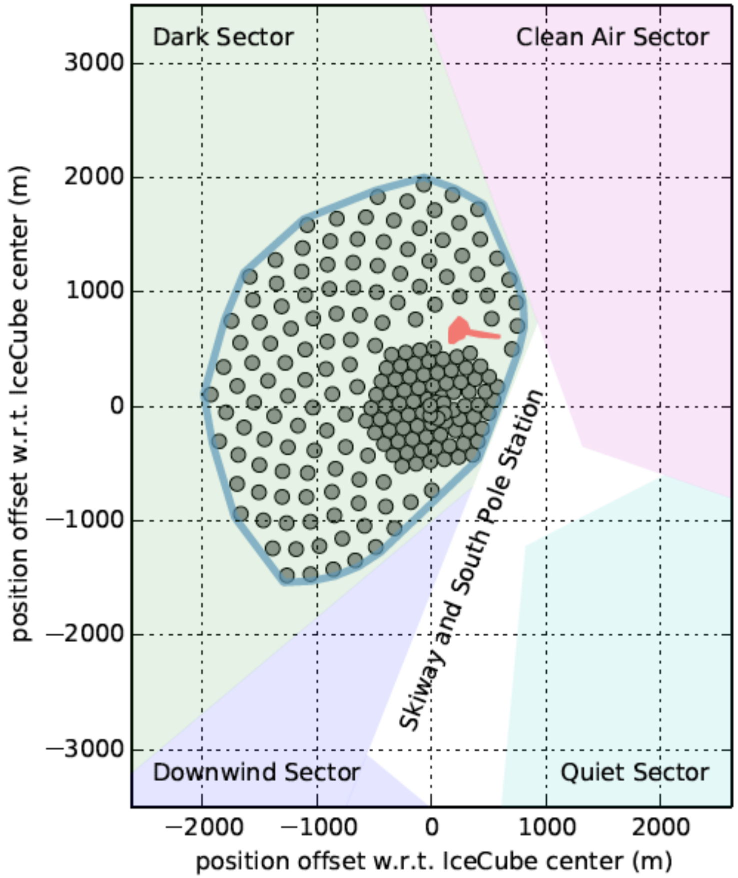
Gen2
Larger string separations to cover larger area

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

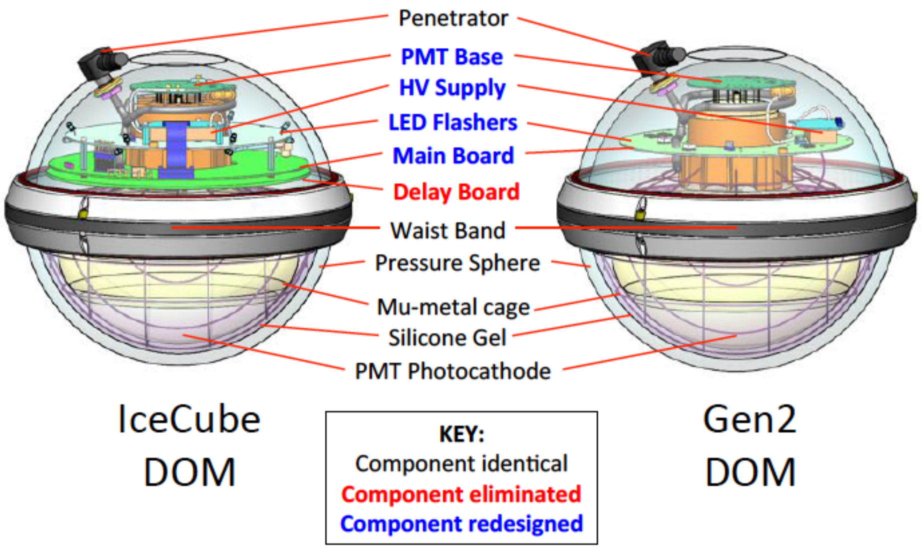
IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

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

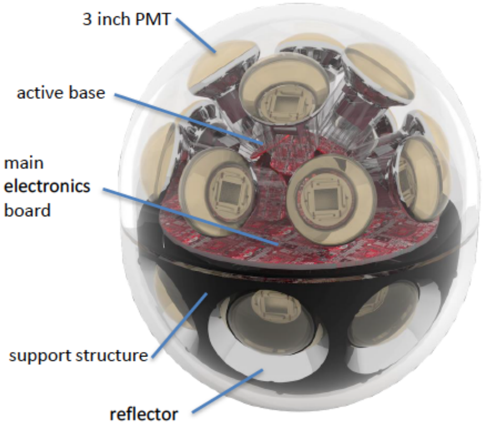


IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

3. IceCube-Gen2

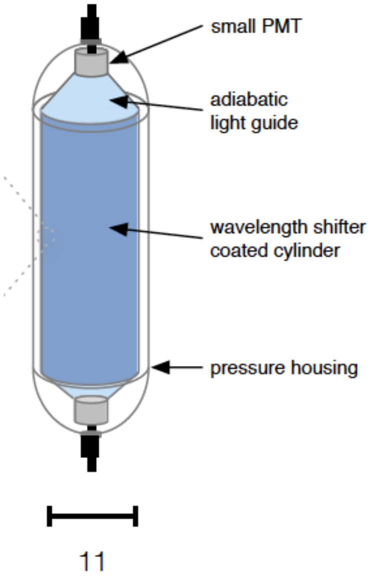
Ice is clear than we thought
→ larger separation (125m → ~200-300m) to cover larger volume
- 120 new strings with 80 DOMs, 240 m separation, x10 coverage
- Variety of new detectors are under development

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



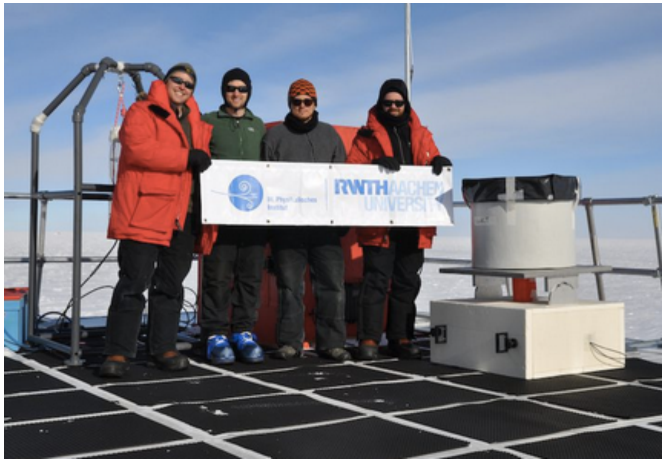
and more…

IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

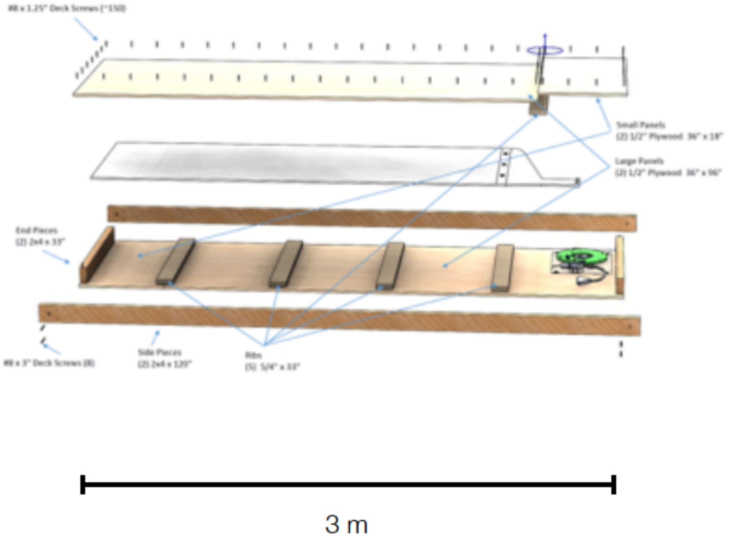
3. IceCube-Gen2

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
- 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

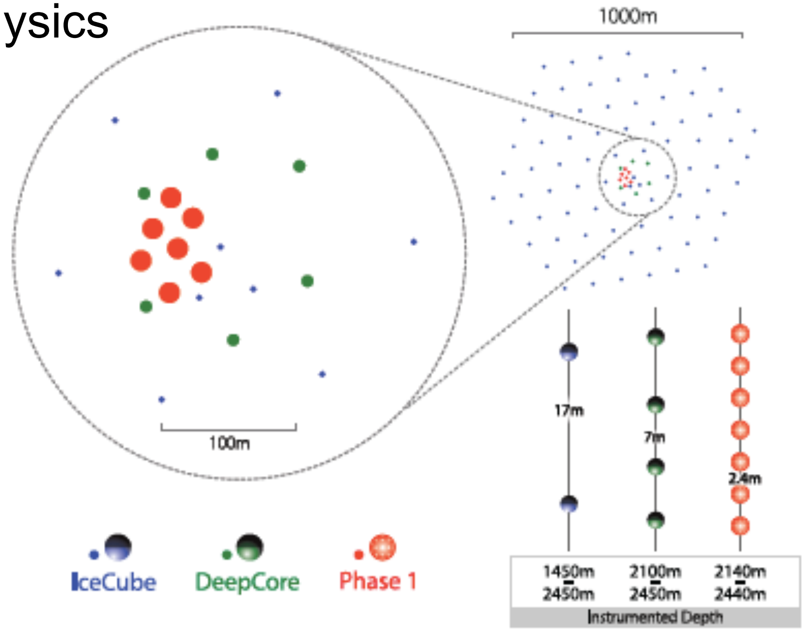


IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

3. IceCube-Gen2 Phase-1

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

Phase 1 proposal will be submitted in Fall 2018
 - 7 new strings for low energy physics
 - Test new calibration device for high energy 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

3. Test of Lorentz violation with astrophysical neutrinos

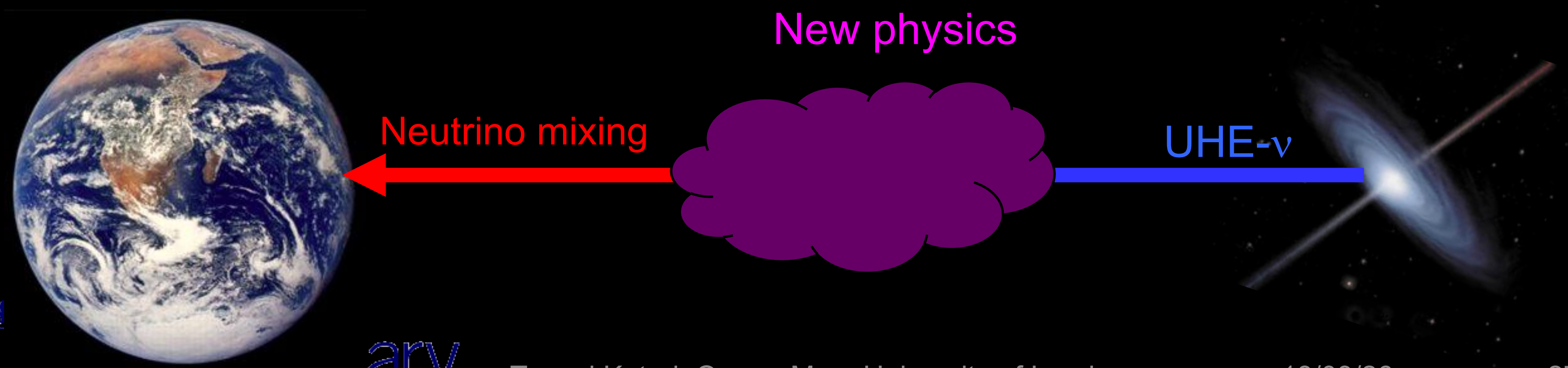
Combination of longer baseline and higher energy makes astrophysical neutrino to be the most sensitive source of fundamental physics.

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

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

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

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



New physics

Neutrino mixing

UHE-ν

2. Results

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

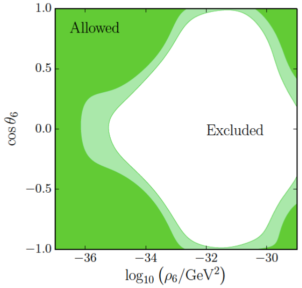
Eq. 2: An example of Lorentz violation operator matrix

These 3 parameters

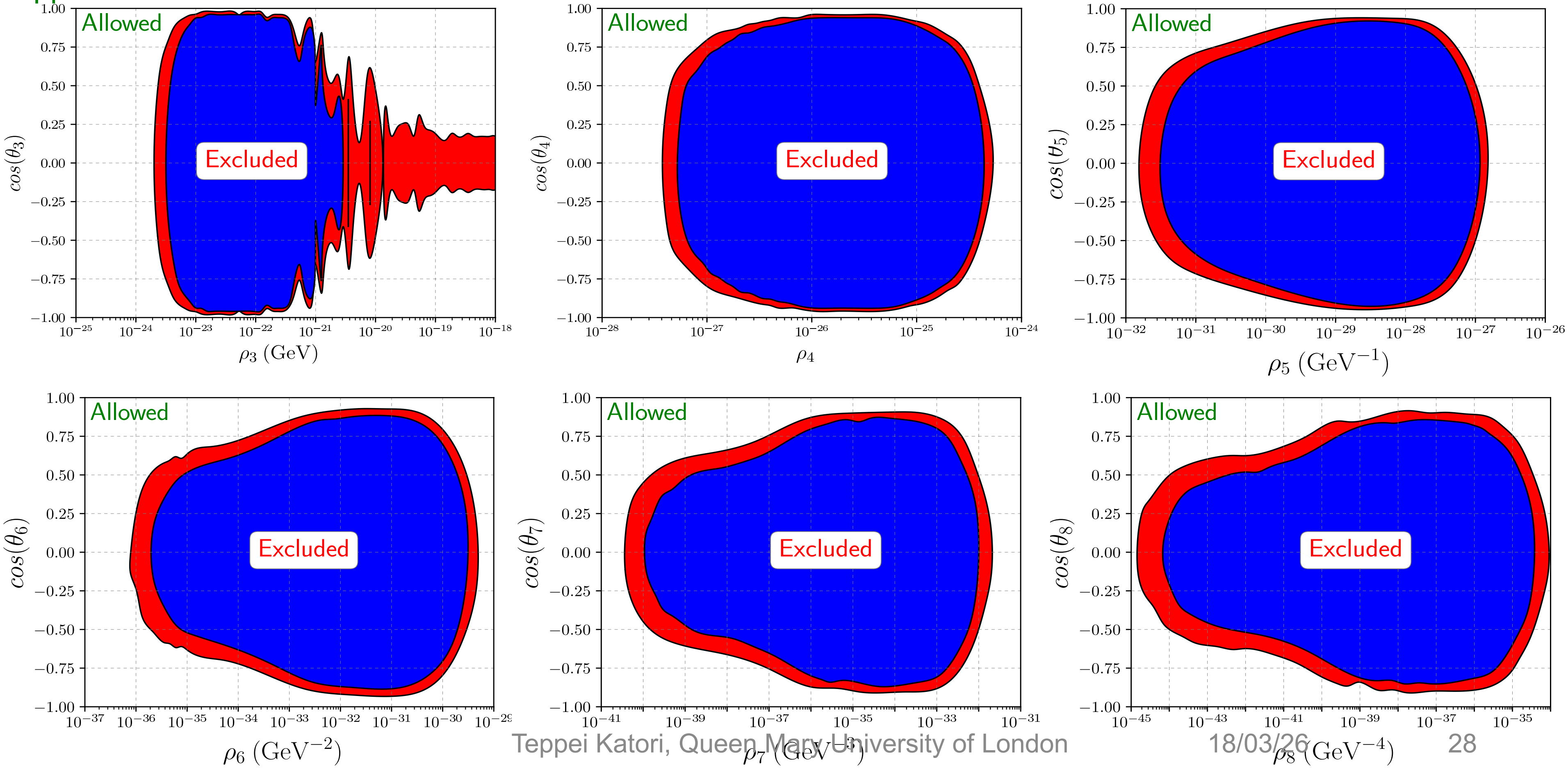
$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

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



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

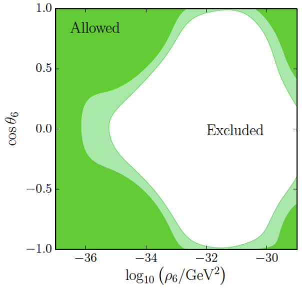
2. Results

Eq. 2: An example of Lorentz violation operator matrix

Make these 0 by hand

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

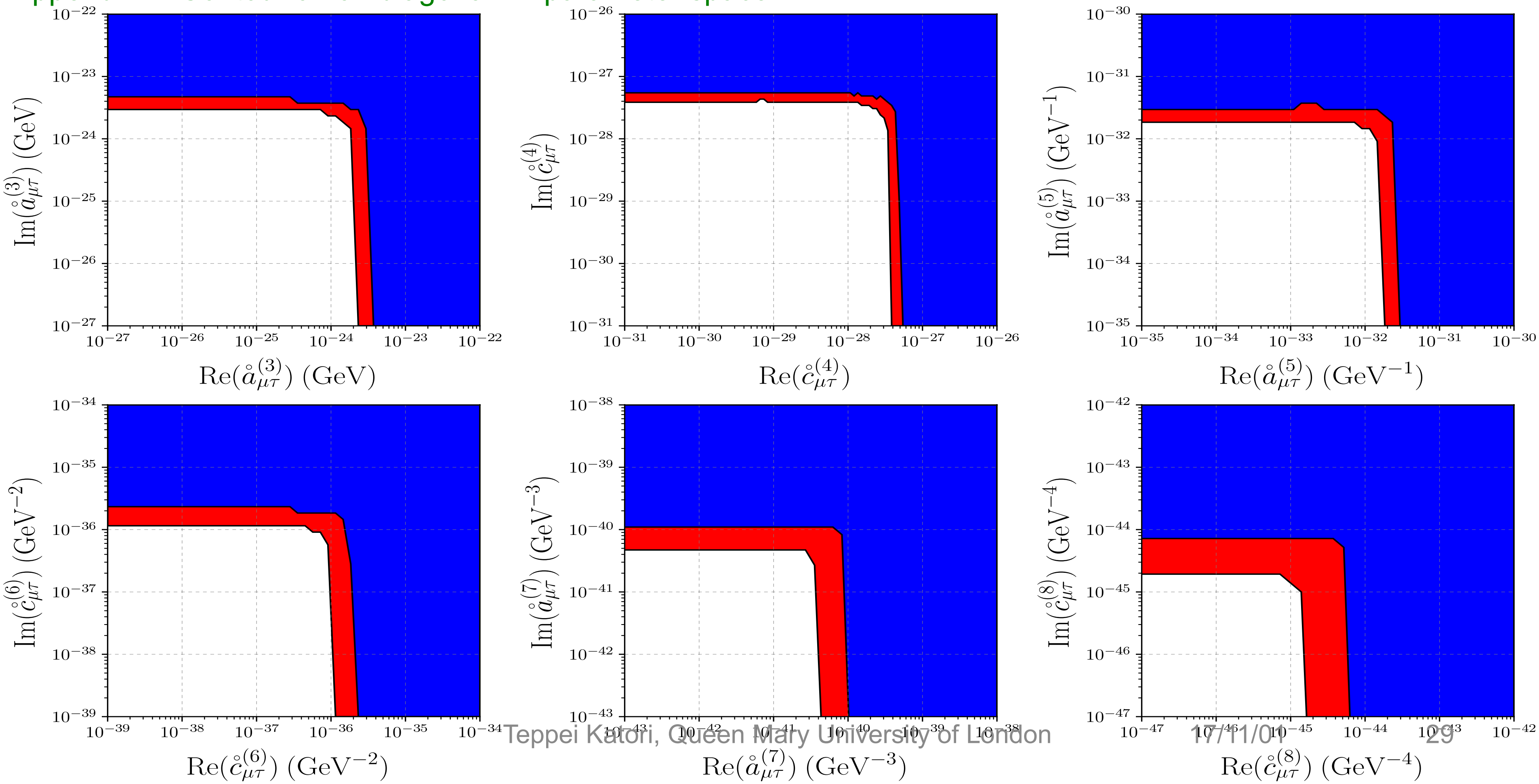
Appendix 2: MCMC result



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



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

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!

Prediction of Gen2 flavour ratio