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

ArXiv:1709.03434
(to be published)

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Teppei Katori for the IceCube collaboration
Queen Mary University of London
Cavendish seminar, Univ. Cambridge, UK, May 1, 2018

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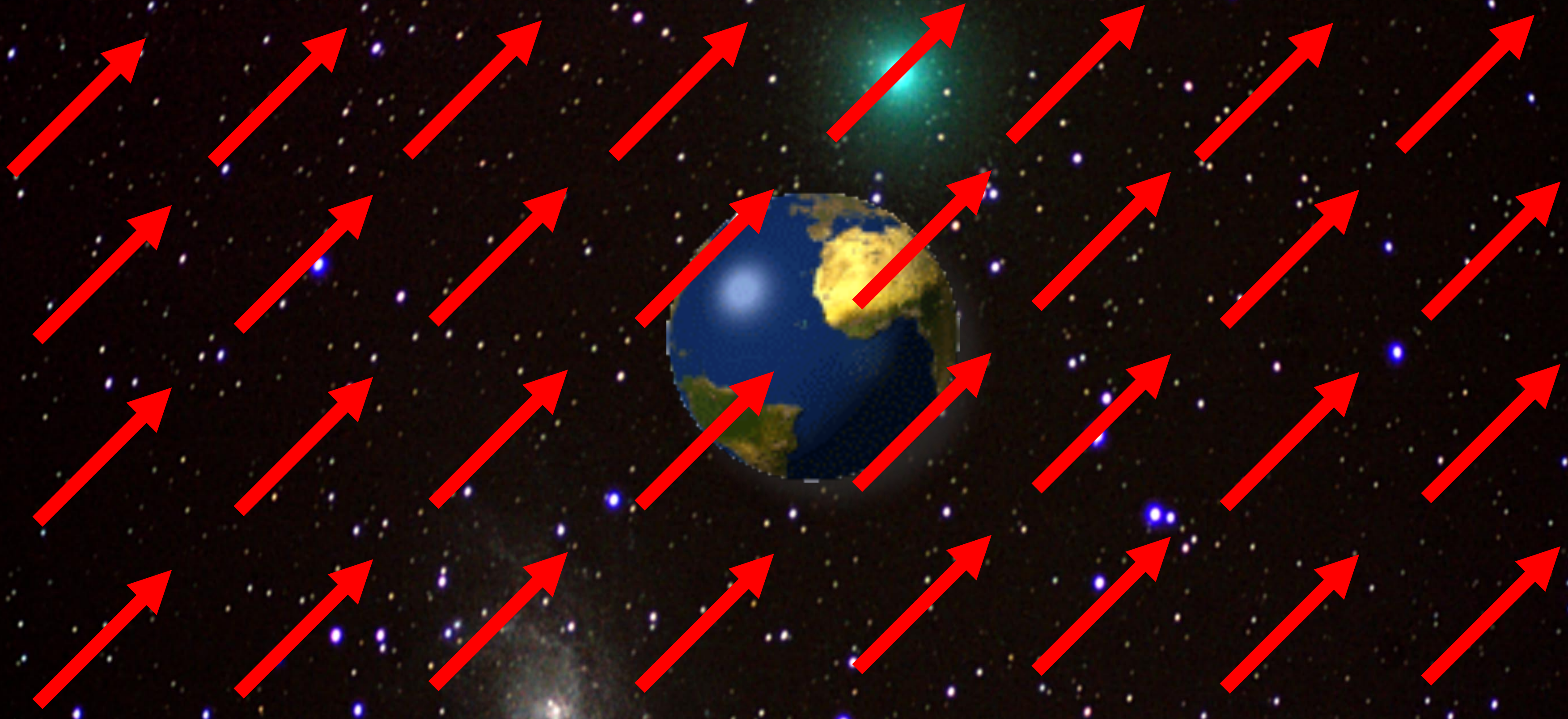
$$\bar{\psi}\gamma_{\mu}a^{\mu}\psi$$



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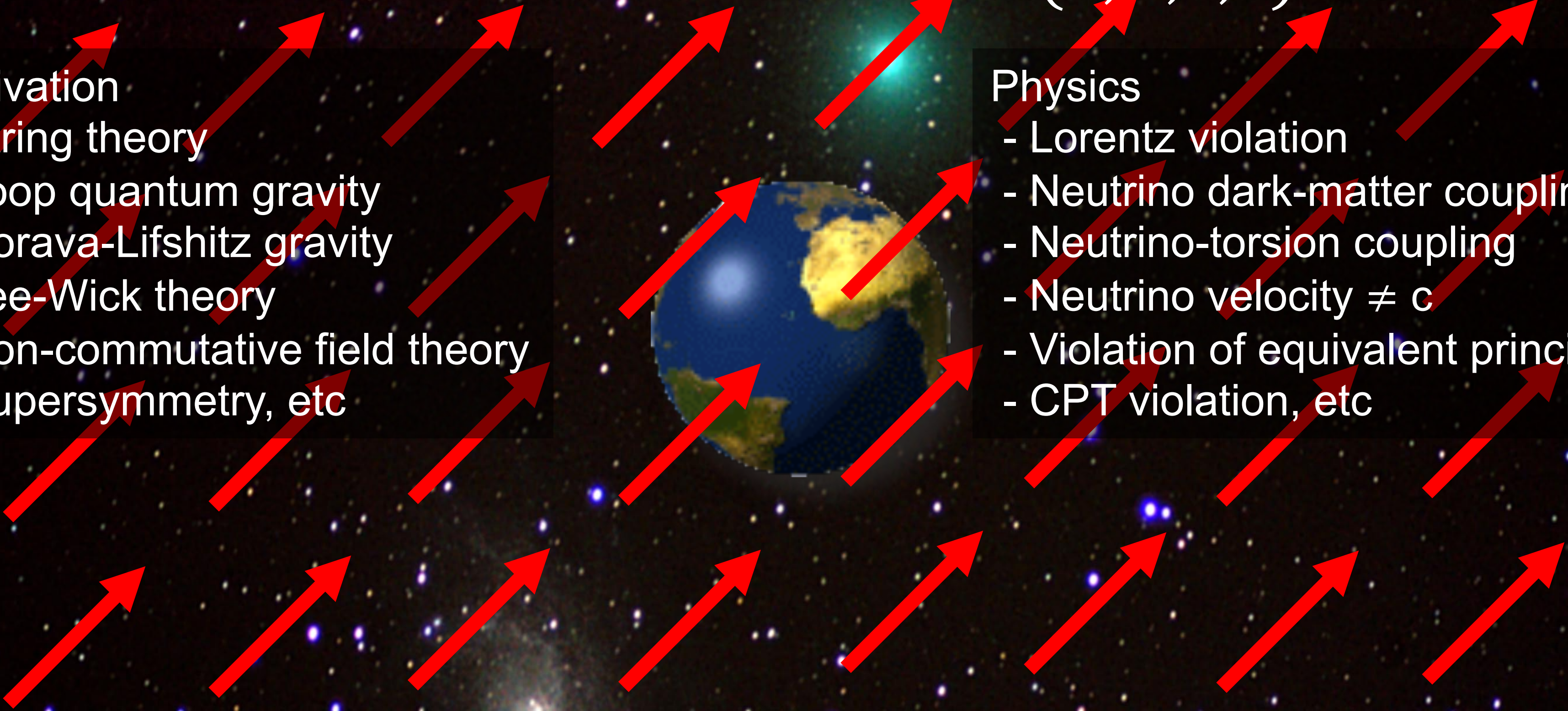
$$\bar{\psi}\gamma_{\mu}a^{\mu}\psi = a|\psi|^{2}$$

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



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

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

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THE ROYAL SOCIETY

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

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outline

1. Spontaneous Lorentz symmetry breaking
2. Modern test of Lorentz violation
3. Neutrino interferometry
4. IceCube Neutrino Observatory
5. Test for Lorentz violation with atmospheric neutrinos
6. Very-High-Energy (VHE) astrophysical neutrinos
7. Test for Lorentz violation with astrophysical neutrinos
8. Conclusion

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THE ROYAL SOCIETY

Collaborators

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Gabriel Collin

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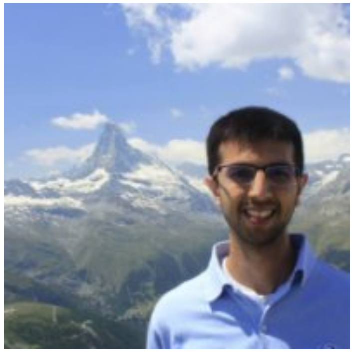
MIT

Ali Kheirandish

U. Wisconsin, Madison



Shivesh Mandalia

Queen Mary U. of London

1. **Spontaneous Lorentz symmetry breaking**
2. Modern test of Lorentz violation
3. Neutrino interferometry
4. IceCube Neutrino Observatory
5. Test for Lorentz violation with atmospheric neutrinos
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1. 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

1. Spontaneous Lorentz symmetry breaking (SLSB)

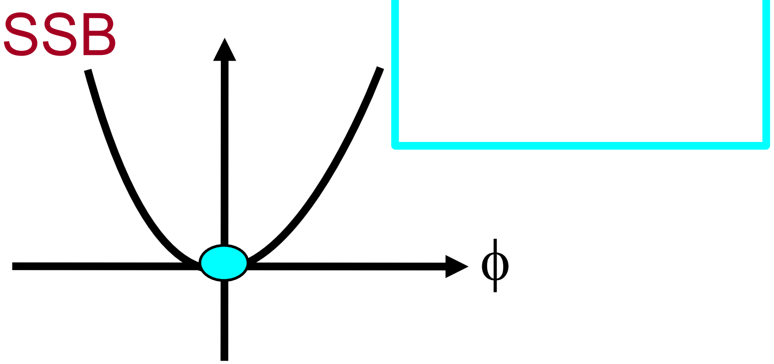
vacuum Lagrangian for fermion $L = i\overline{\Psi}\gamma_{\mu}\partial^{\mu}\Psi$

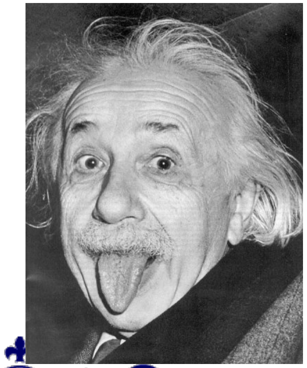
e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

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

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





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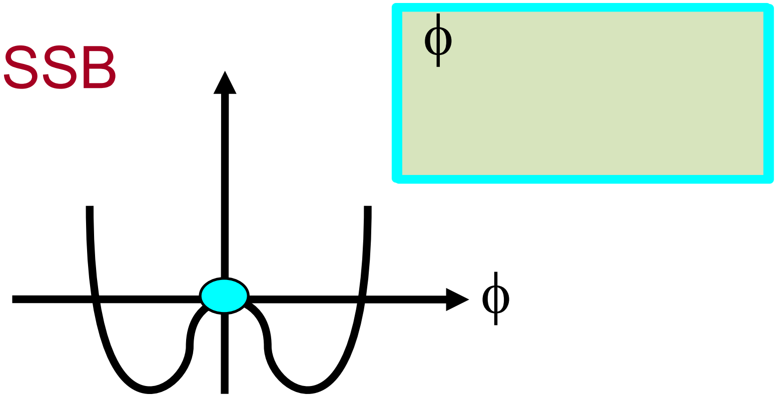
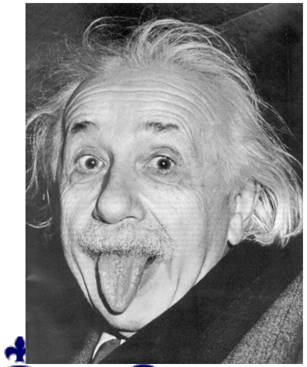
SSB





Particle acquires
mass term!

Kostelecký and Samuel,PRD39(1989)683

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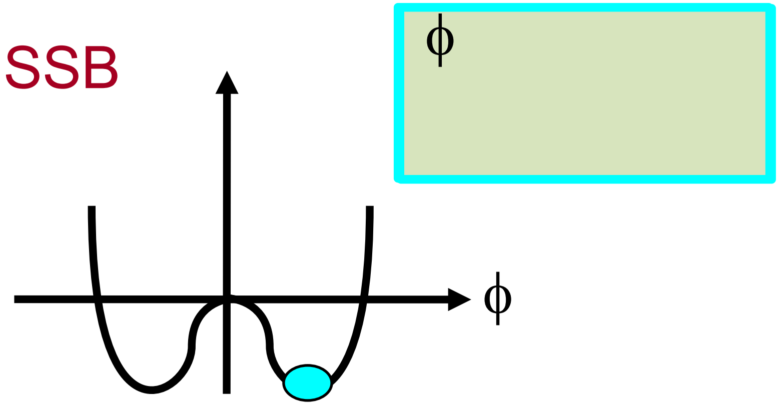
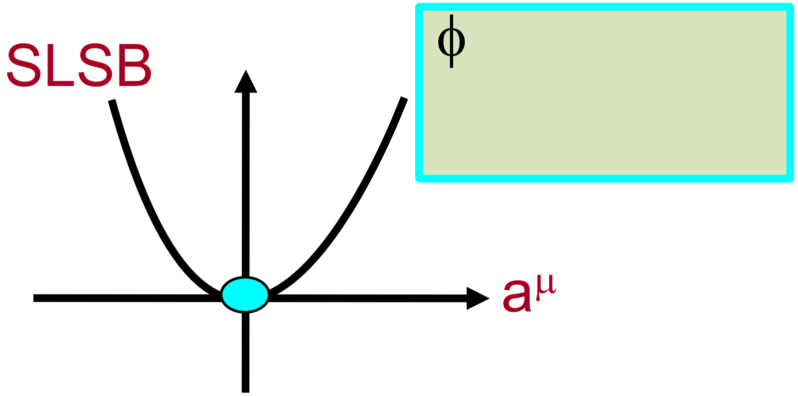
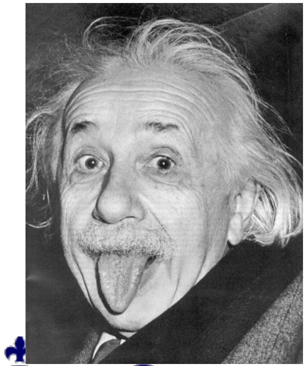
e.g.) SLSB in string field theory

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

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







Kostelecký and Samuel,PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking (SLSB)

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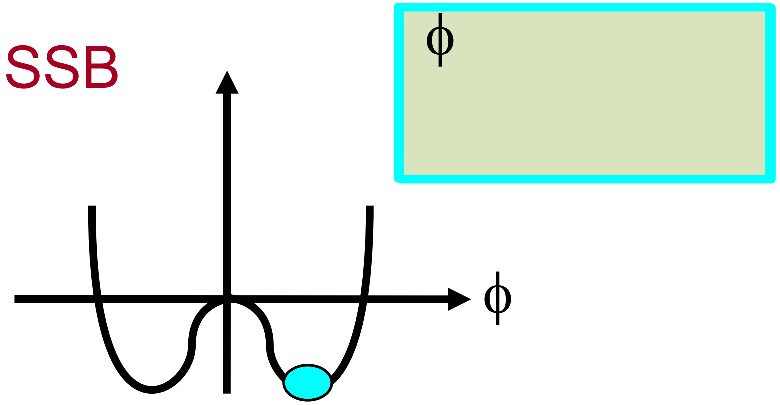

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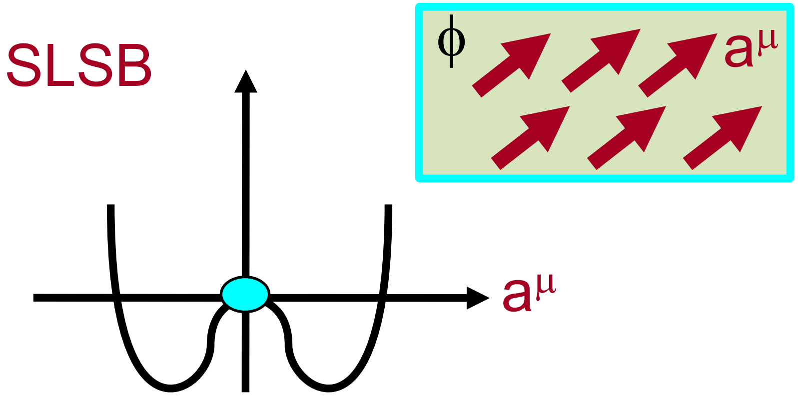
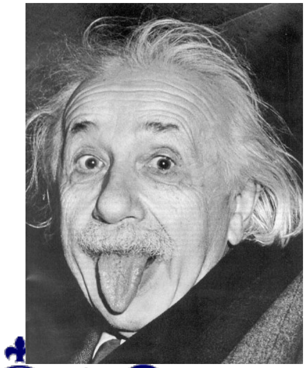




Lorentz symmetry is spontaneously broken!

1. String theory landscape

The universe was a hot fireball, but it cools down to this present form.

Every step universe cools down (phase transtion), the universe has a chance to “choose” its vacuum configuration.

It may be natural to assume the universe to generate more fields in the vacuum, other than Higgs field?

1. Search of Lorentz violation

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

kinetic term (SM)

mass term (SM)

background fields of the universe

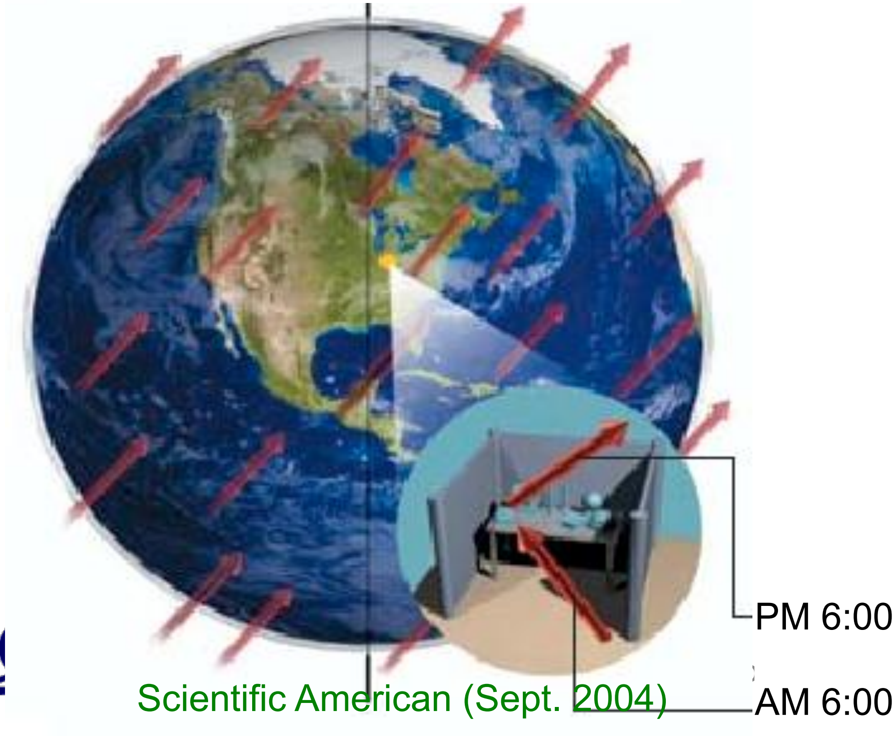
vacuum Lagrangian
for fermion

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

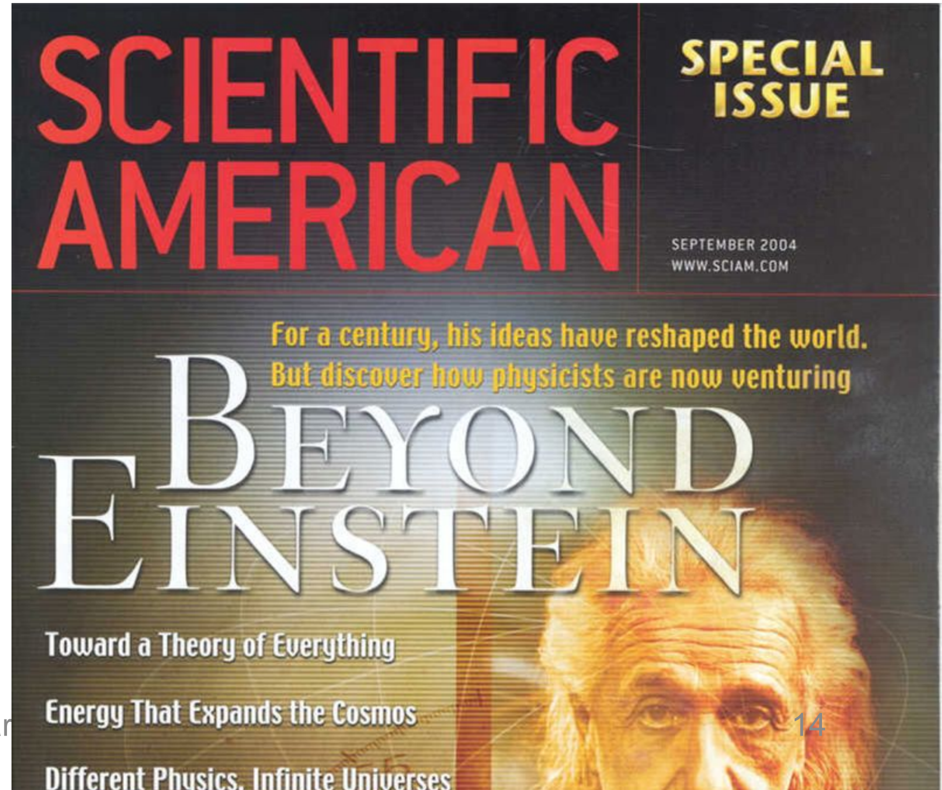
Sidereal time dependence

The smoking gun of Lorentz violation is the sidereal time dependence of the observables.

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



Scientific American (Sept. 2004)



SCIENTIFIC AMERICAN

SPECIAL ISSUE

SEPTEMBER 2004
WWW.SCIAM.COM

For a century, his ideas have reshaped the world. But discover how physicists are now venturing

BEYOND EINSTEIN

Toward a Theory of Everything

Energy That Expands the Cosmos

Different Physics, Infinite Universes

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Time independent tests of Lorentz violation

We assume only time components to be nonzero

- Simplify the formulation
- Useful when you don't know the source location of in coming neutrinos (averaged out)
- Some theoretical argument that the time components may be the largest

mass term (SM)

background fields of the universe

Effective Hamiltonian
for neutrino oscillation

$$\mathcal{H} \sim \frac{m^2}{2E} + a + c \cdot E \cdots$$

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

$$c^{\mu\nu} = \left(\begin{bmatrix} c & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c \end{bmatrix}\right)$$

1. Spontaneous Lorentz symmetry breaking

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8. Conclusion

Colladay and Kostelecký, Phys.Rev.D55(1997)6760, Kostelecký, Phys.Rev.D58(1998)116002;69(2004)105009

2. Standard Model-Extension (SME)

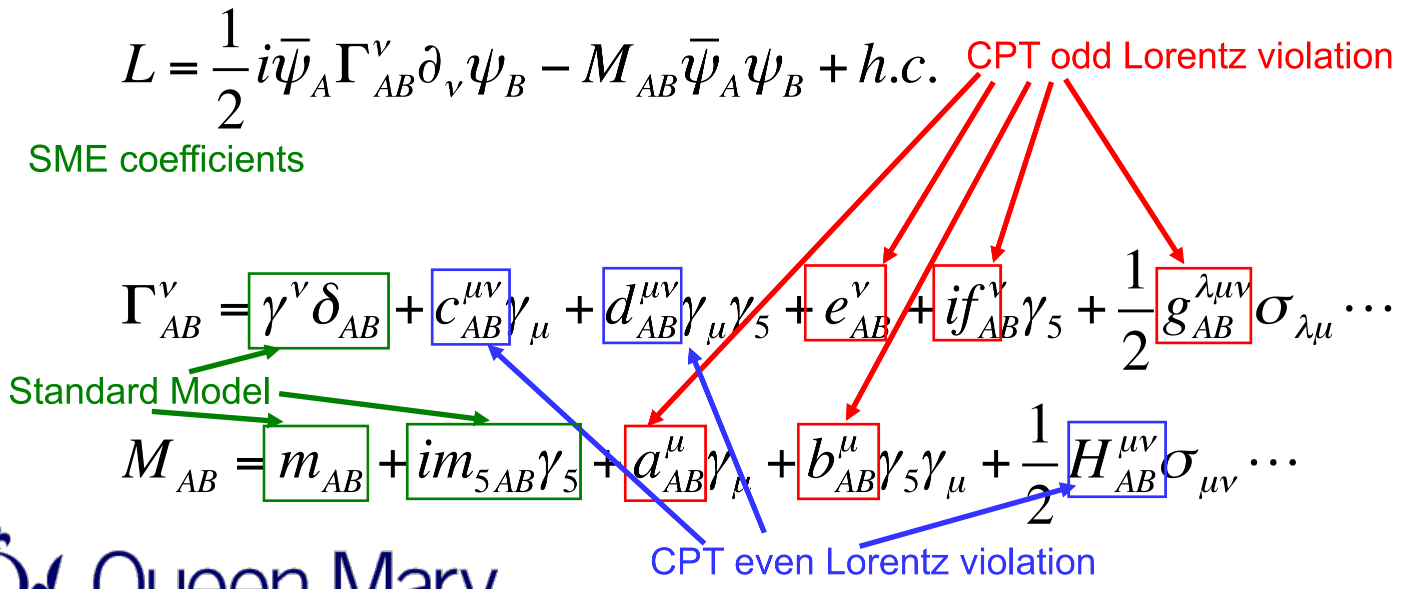
SME is a effective field theory framework to compare results of test of Lorentz violation.

Physics observables (energy level of atoms, presession of spins, neutrino oscillations, etc) can be written including Lorentz violation under SME langrangian.

By comparing with data, one can study Lorentz violation sytematically.

Limits of Lorentz violation are quoted in terms of limits on SME coefficients.

SME Lagrangian in neutrino sector



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

CPT odd Lorentz violation

SME coefficients

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

Standard Model

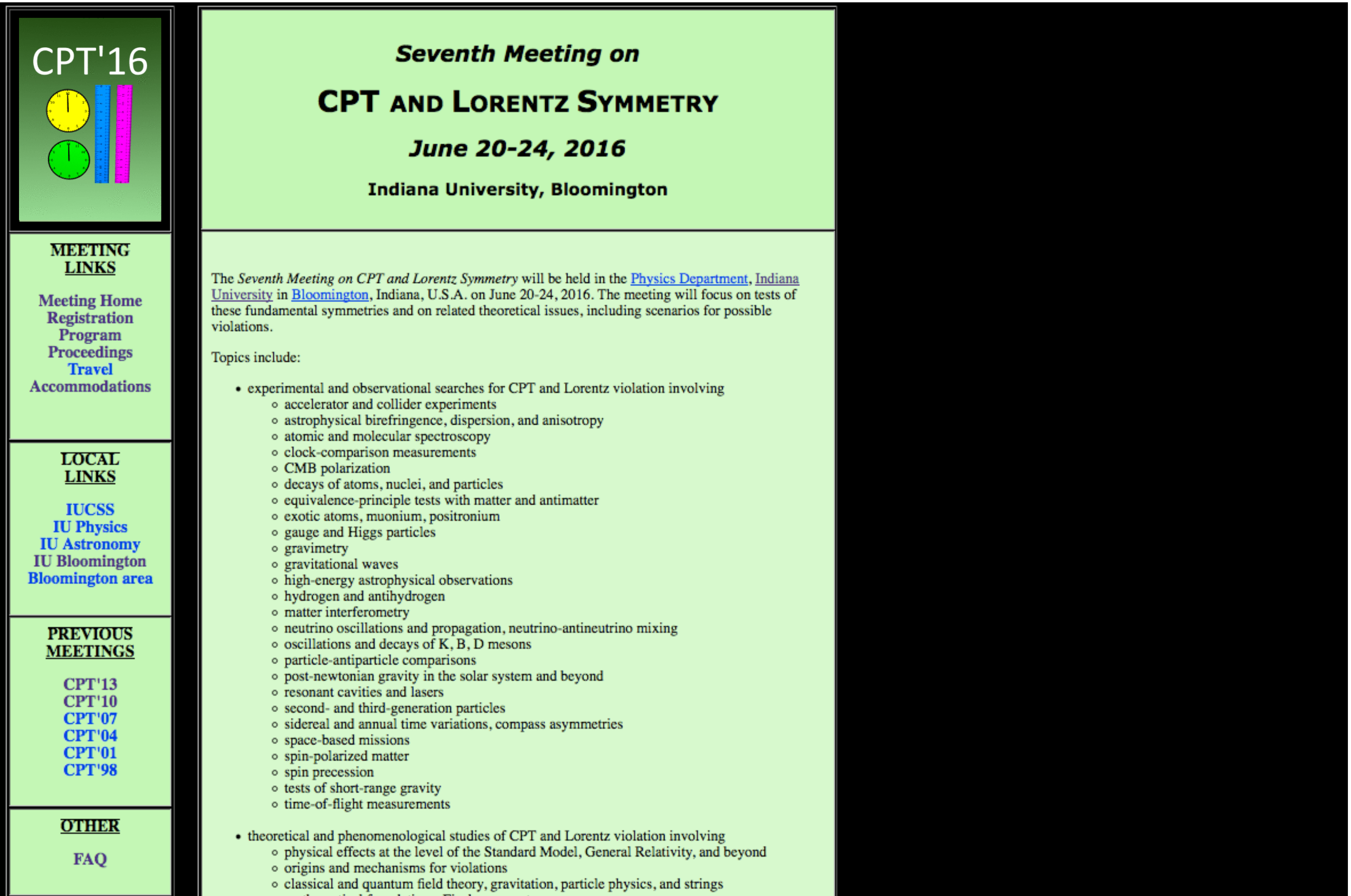
$$M_{AB} = \boxed{m_{AB}} + \boxed{im_{5AB}\gamma_5} + \boxed{a^{\mu}_{AB}}\gamma_{\mu} + \boxed{b^{\mu}_{AB}}\gamma_5\gamma_{\mu} + \frac{1}{2}\boxed{H^{\mu\nu}_{AB}}\sigma_{\mu\nu}\cdots$$

CPT even Lorentz violation

2. Modern tests of Lorentz violation

The latest meeting was in June 2016
(The next meeting will be 2019)

http://www.physics.indiana.edu/~kostelec/faq.html



MEETING LINKS

Meeting Home
Registration
Program
Proceedings
Travel
Accommodations

LOCAL LINKS

IUCSS
IU Physics
IU Astronomy
IU Bloomington
Bloomington area

PREVIOUS MEETINGS

CPT'13
CPT'10
CPT'07
CPT'04
CPT'01
CPT'98

OTHER

FAQ

Seventh Meeting on

CPT AND LORENTZ SYMMETRY

June 20-24, 2016

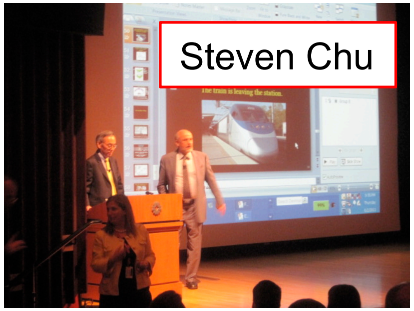
Indiana University, Bloomington

The *Seventh Meeting on CPT and Lorentz Symmetry* will be held in the Physics Department, Indiana University in Bloomington, Indiana, U.S.A. on June 20-24, 2016. The meeting will focus on tests of these fundamental symmetries and on related theoretical issues, including scenarios for possible violations.

Topics include:

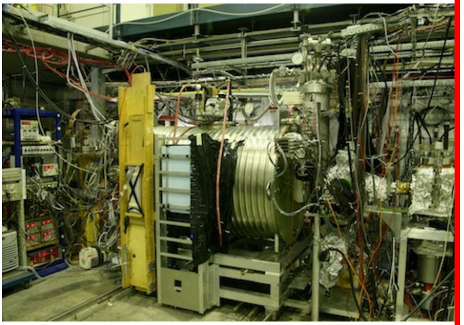
- experimental and observational searches for CPT and Lorentz violation involving
  - accelerator and collider experiments
  - astrophysical birefringence, dispersion, and anisotropy
  - atomic and molecular spectroscopy
  - clock-comparison measurements
  - CMB polarization
  - decays of atoms, nuclei, and particles
  - equivalence-principle tests with matter and antimatter
  - exotic atoms, muonium, positronium
  - gauge and Higgs particles
  - gravimetry
  - gravitational waves
  - high-energy astrophysical observations
  - hydrogen and antihydrogen
  - matter interferometry
  - neutrino oscillations and propagation, neutrino-antineutrino mixing
  - oscillations and decays of K, B, D mesons
  - particle-antiparticle comparisons
  - post-newtonian gravity in the solar system and beyond
  - resonant cavities and lasers
  - second- and third-generation particles
  - sidereal and annual time variations, compass asymmetries
  - space-based missions
  - spin-polarized matter
  - spin precession
  - tests of short-range gravity
  - time-of-flight measurements
- theoretical and phenomenological studies of CPT and Lorentz violation involving
  - physical effects at the level of the Standard Model, General Relativity, and beyond
  - origins and mechanisms for violations
  - classical and quantum field theory, gravitation, particle physics, and strings

Atomic Interferometer
$(a,c)^{n,p,e} < 10^{-8}$



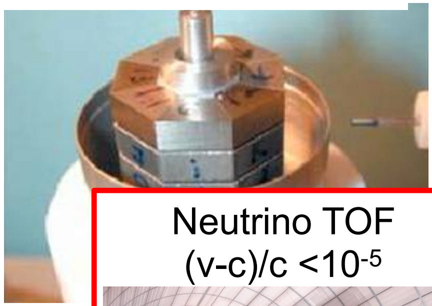
PRL106(2011)151102

CERN Antiproton Decelerat
$\Delta(S_1-S_2)<10^{-10}$



Nature541(2017)506

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



PRL9

Tevatron and LEP
$-5.8\times10^{-12}<\kappa_{tr}-4/3c_e^{00}<1.2\times10^{-11}$

PRL102(2009)170402

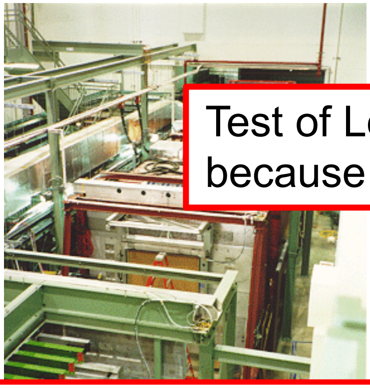
Neutrino TOF
$(v-c)/c<10^{-5}$

JHEP11(2012)049

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

PRL97(2006)140401

KTeV/KLOE (strange)
$\Delta a_K<10^{-22}$ GeV
FOCUS (charm)
$\Delta a_D<10^{-16}$ GeV
BaBar/Belle (bottom)
$\Delta m_B/m_B<10^{-14}$

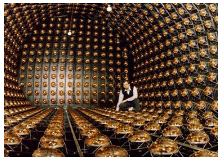


Limits from all these
experiments >80 page tables!
Rev.Mod.Phys.83(2011)11
ArXiv:0801.0287v11

- clock-comparison measurements
- laboratory and gravimetric tests of gravity
- matter interferometry
- ★ neutrino oscillations and propagation, neutrino-antineutrino mixing
- ★ oscillations and decays of K, B, D mesons
- space-based missions
- spectroscopy of hydrogen and a
- ★ spin-polarized matter
- ★ time-of-flight measurements

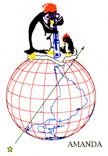
Test of Lorentz invariance with neutrino oscillation is very interesting, because neutrinos are the least known standard model particles!

uble gas maser
tation)$<10^{-33}$GeV
boost)$<10^{-27}$GeV

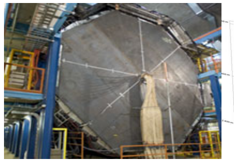
LSND

PRD72(2005)076004

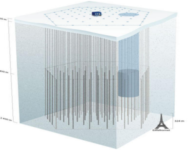
MINOS ND

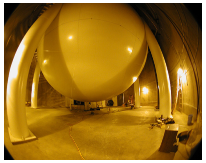
PRL101(2008)151601

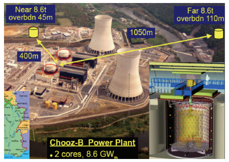
AMANDA


PRD79(2009)102005

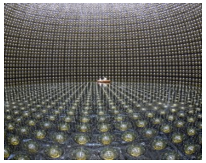
MINOS FD

PRL105(2010)151601

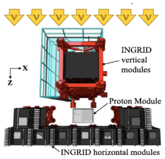
IceCube

PRD82(2010)112003

MiniBooNE

PLB718(2013)1303

Double Chooz


PRD86(2013)112009

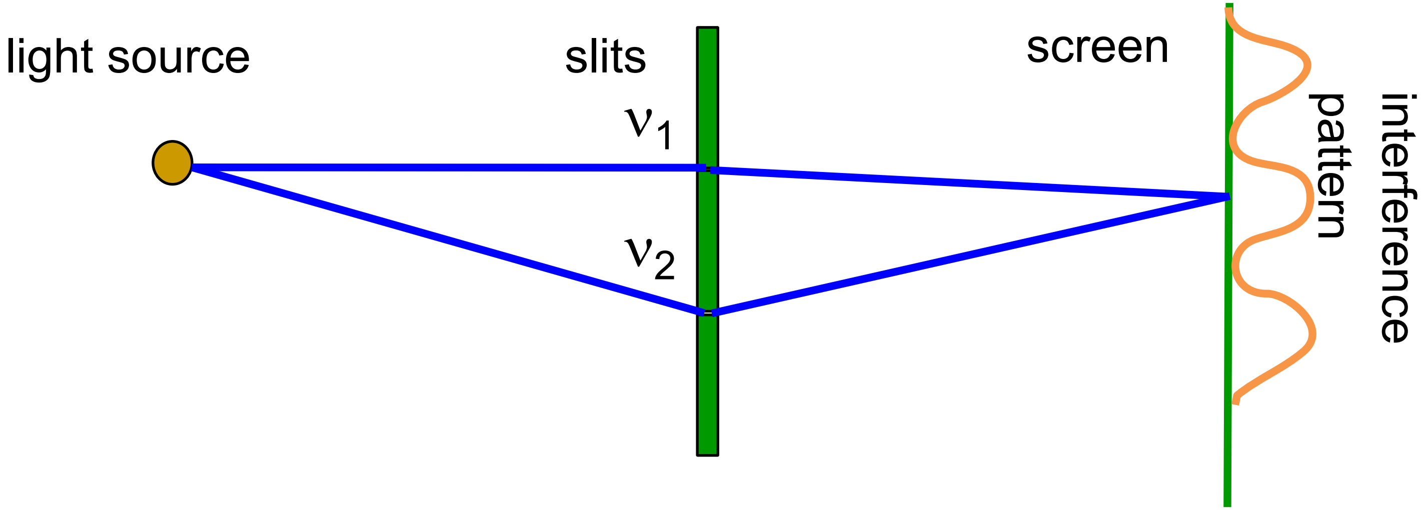
Super-Kamiokande

PRD91(2015)052003

T2K


PRD95(2017)111101

3. Neutrino interferometry as a probe of new physics

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



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

3. Neutrino interferometry as a probe of new physics

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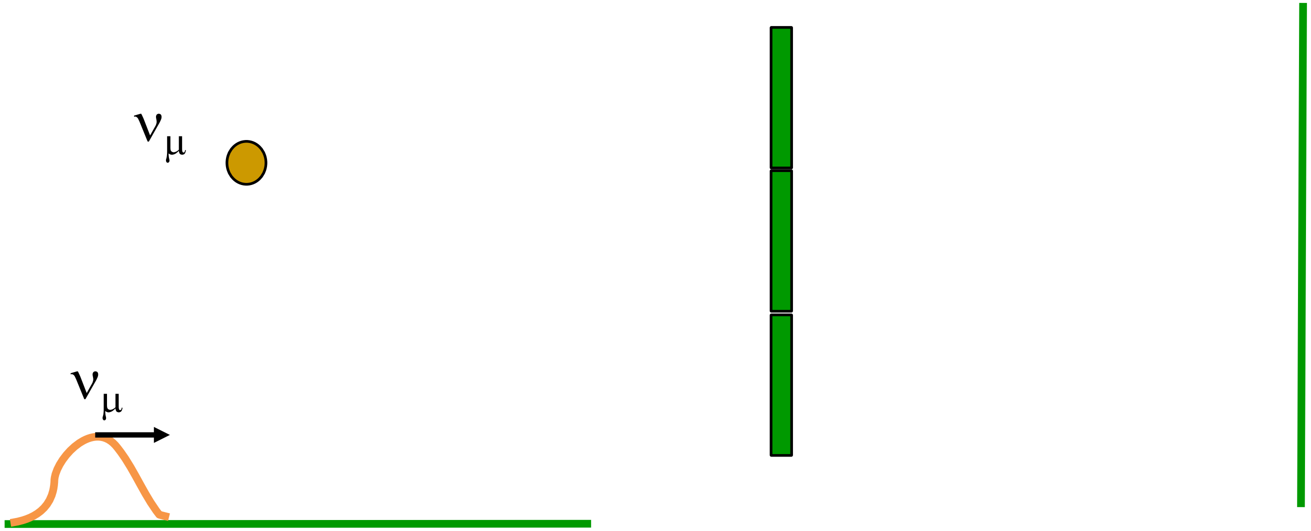

- If 2 neutrino Hamiltonian eigenstates, ν_2 and ν_3, have different phase rotation, they cause quantum interference.

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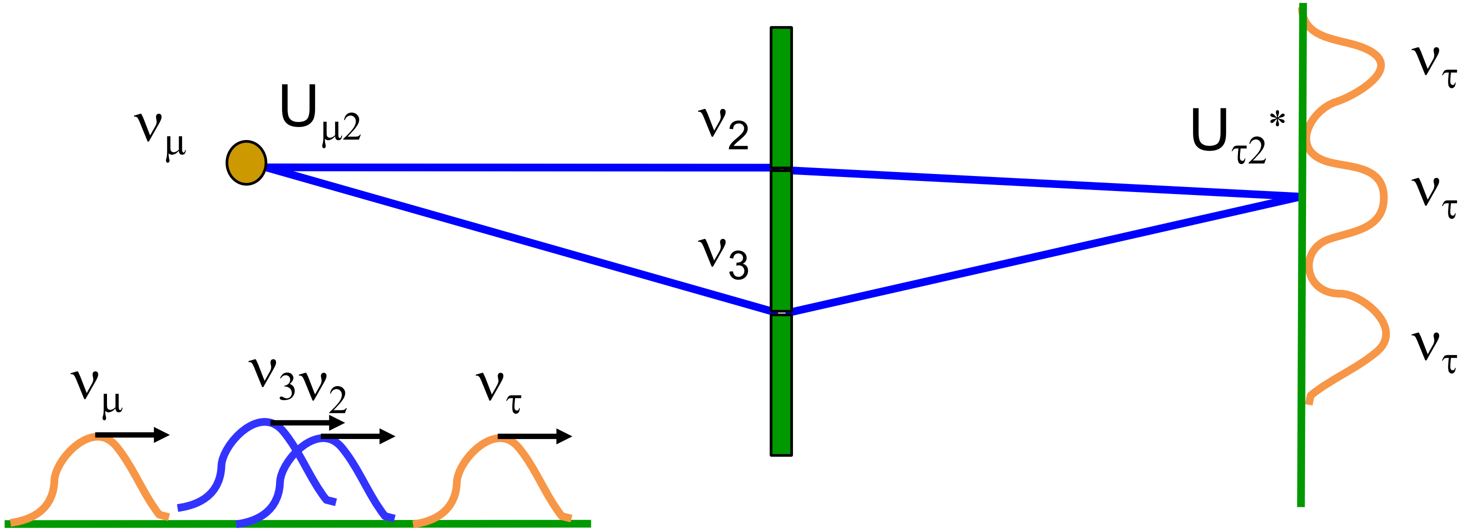

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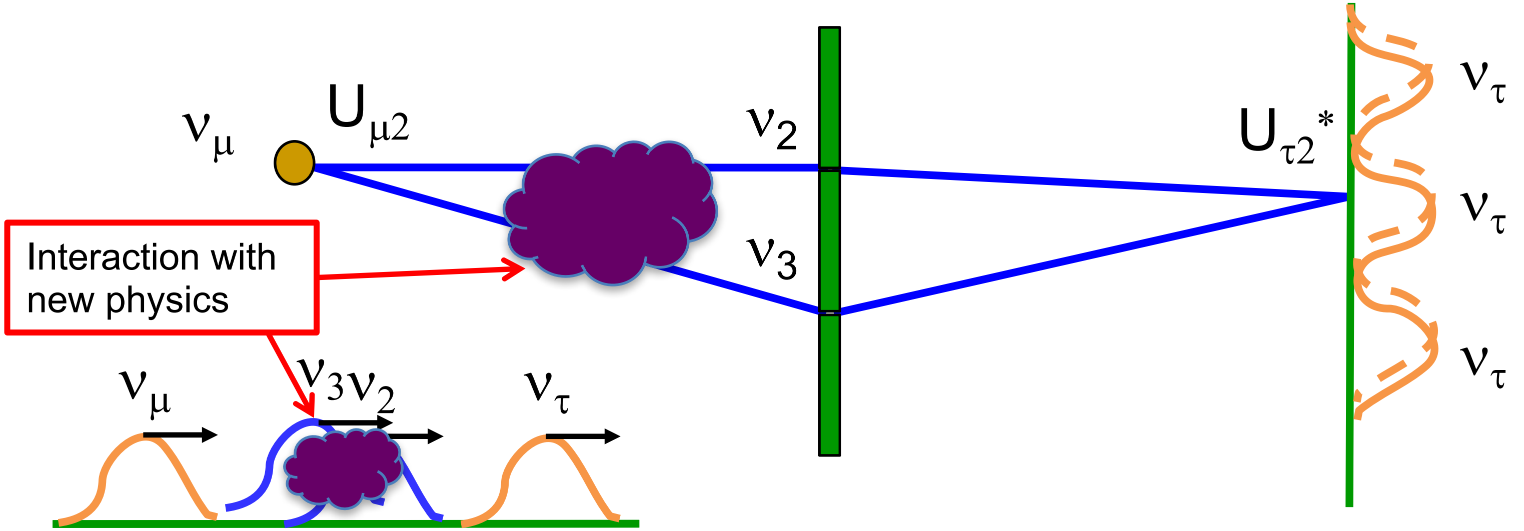

- If 2 neutrino Hamiltonian eigenstates, ν_2 and ν_3, have different phase rotation, they cause quantum interference (neutrino oscillation).
- Any BSM physics coupling to neutrinos can contribute the phase shift of neutrino oscillation, and it appears as spectrum distortion of atmospheric neutrino data.
- 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. Spontaneous Lorentz symmetry breaking

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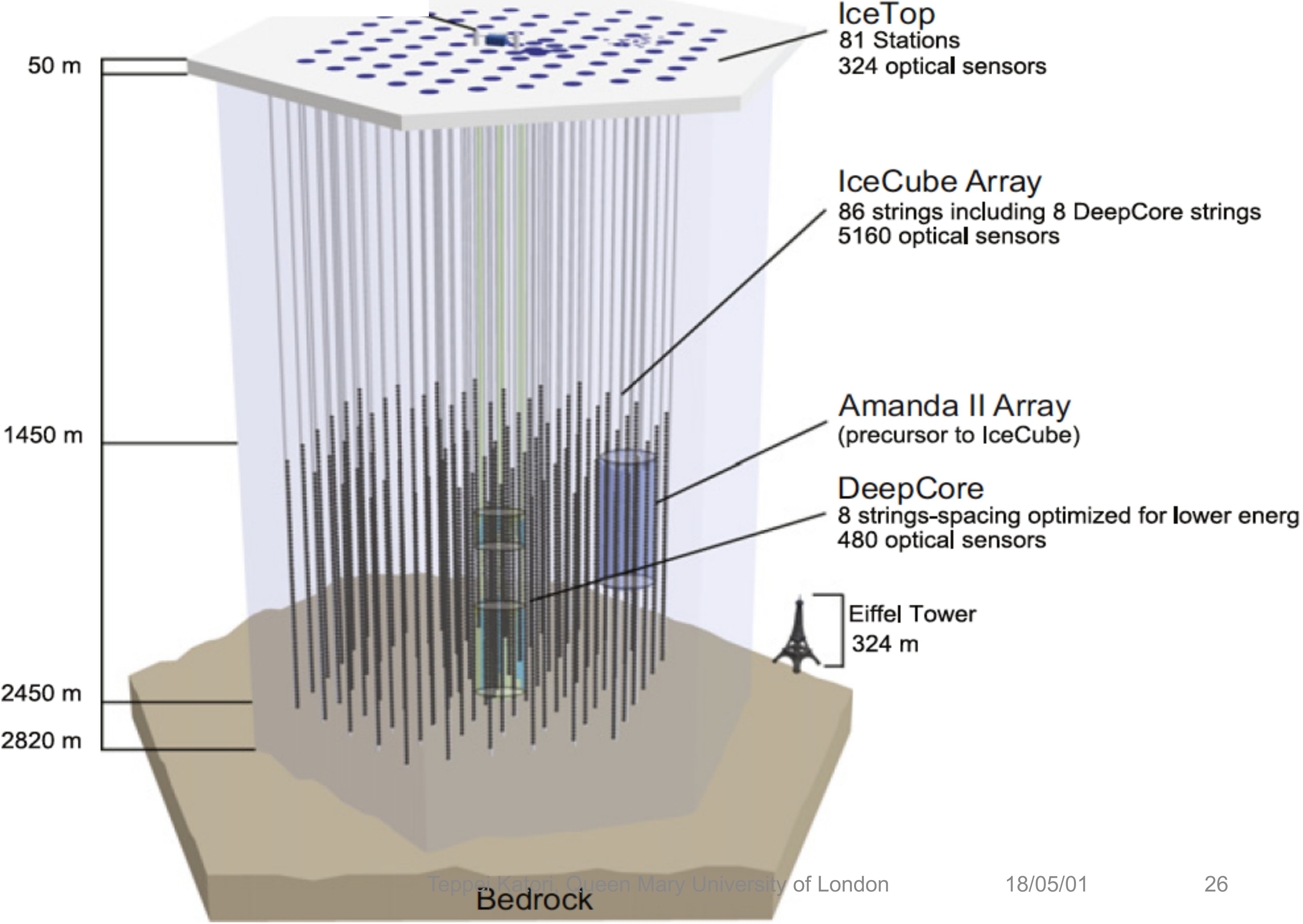
8. Conclusion

4. IceCube detector



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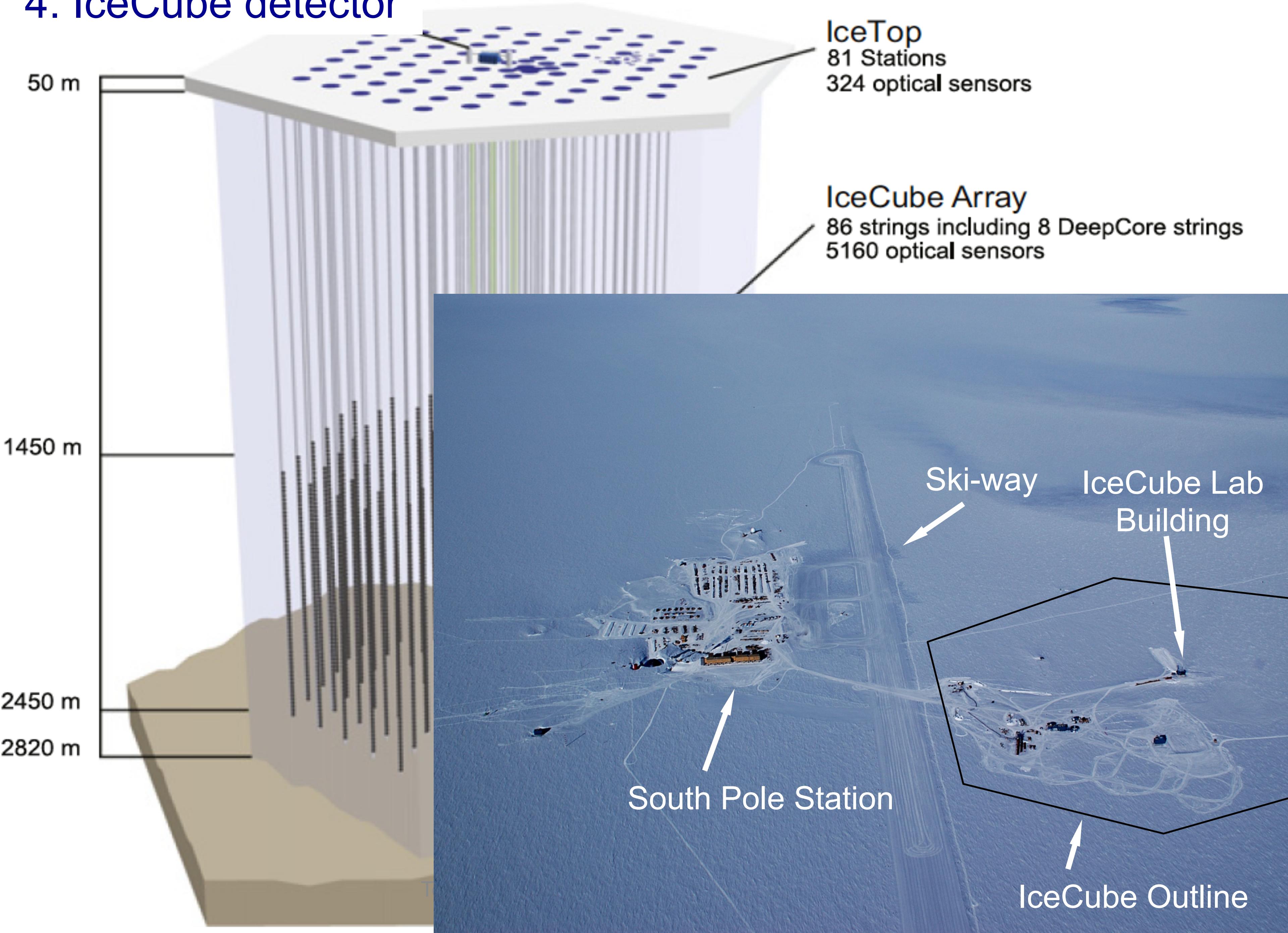

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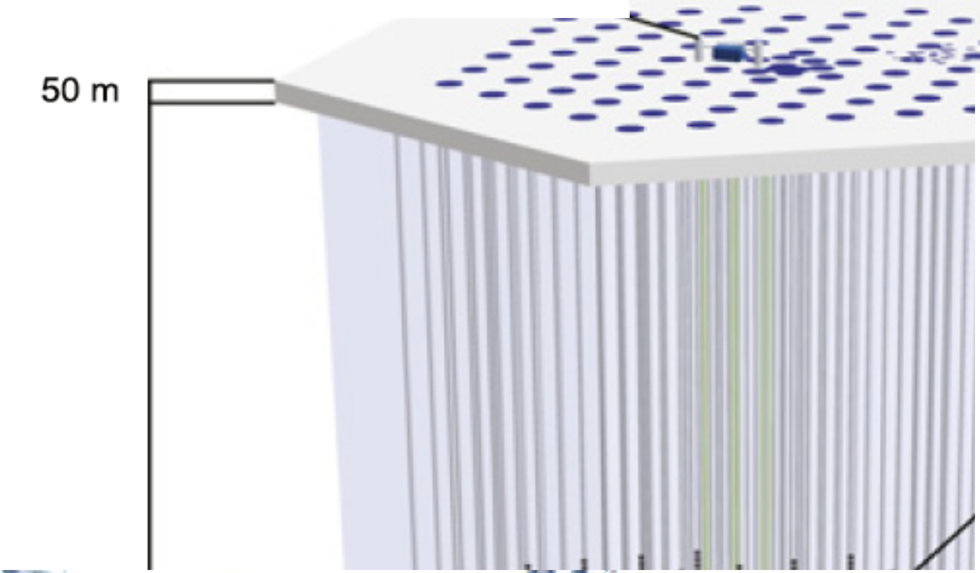
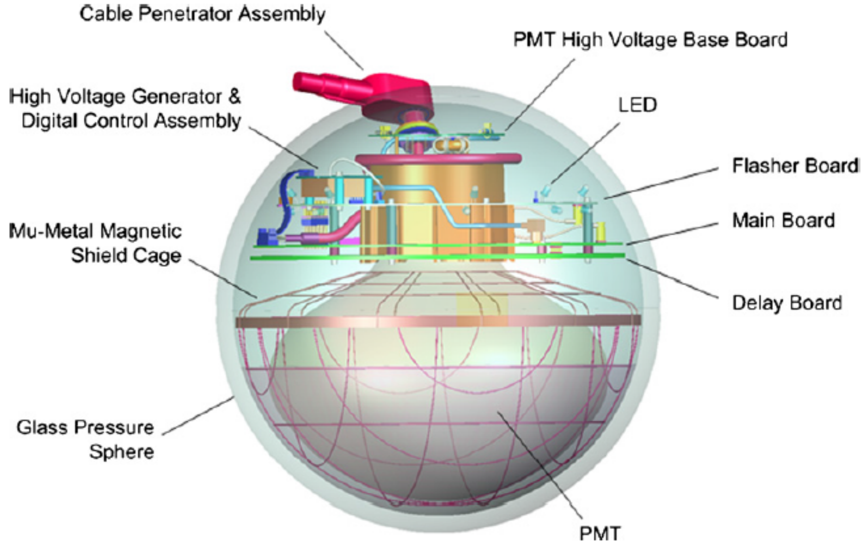
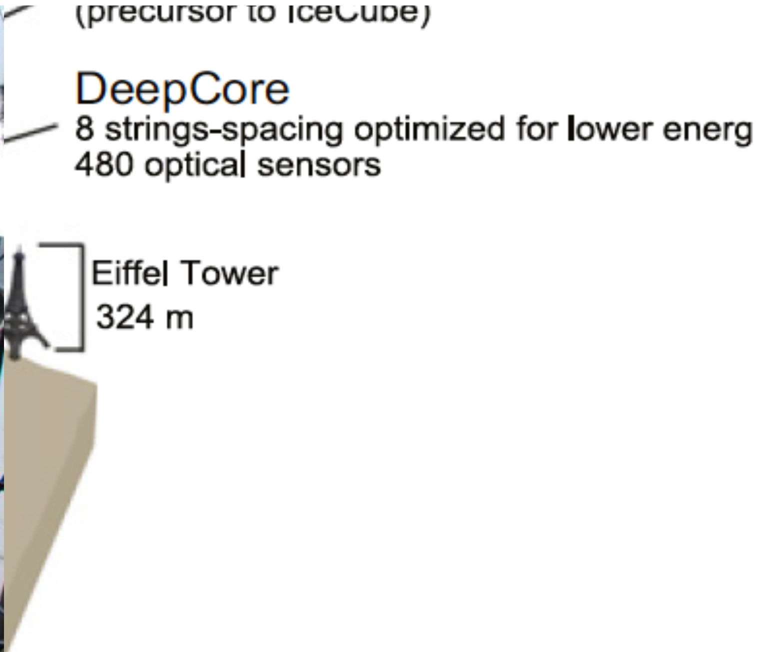
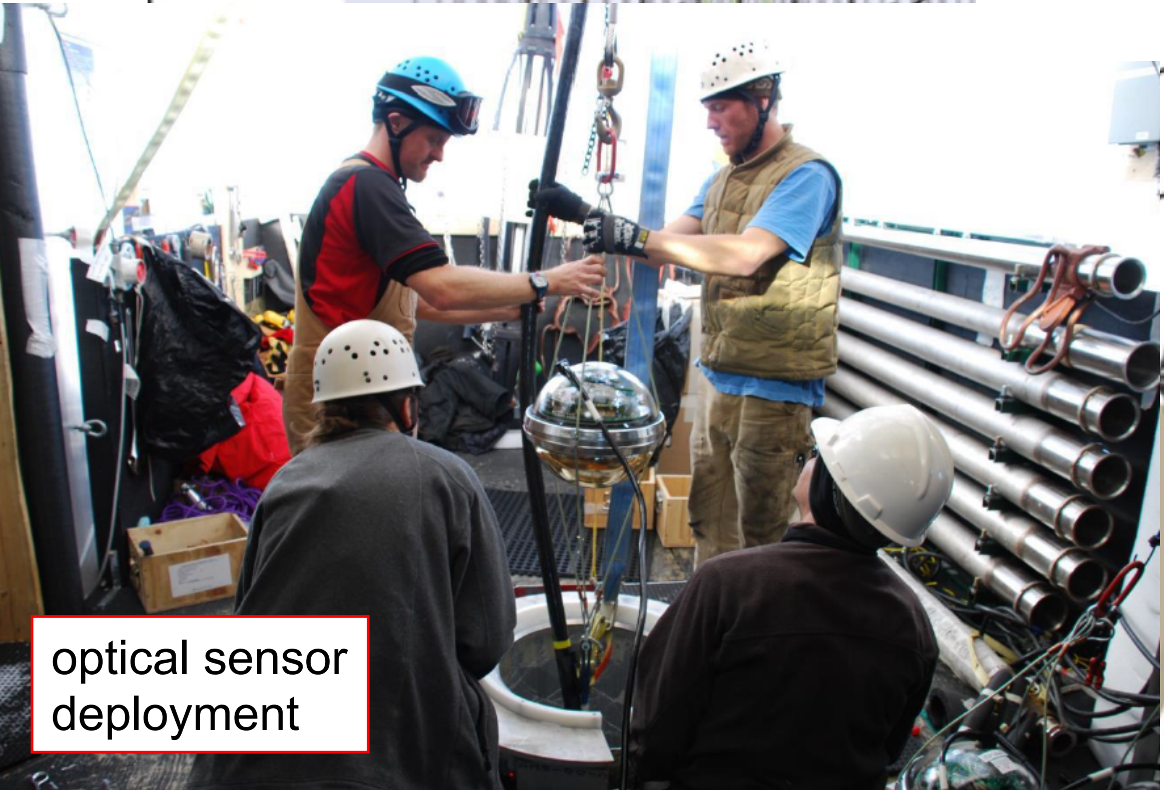


digital optical module (DOM)

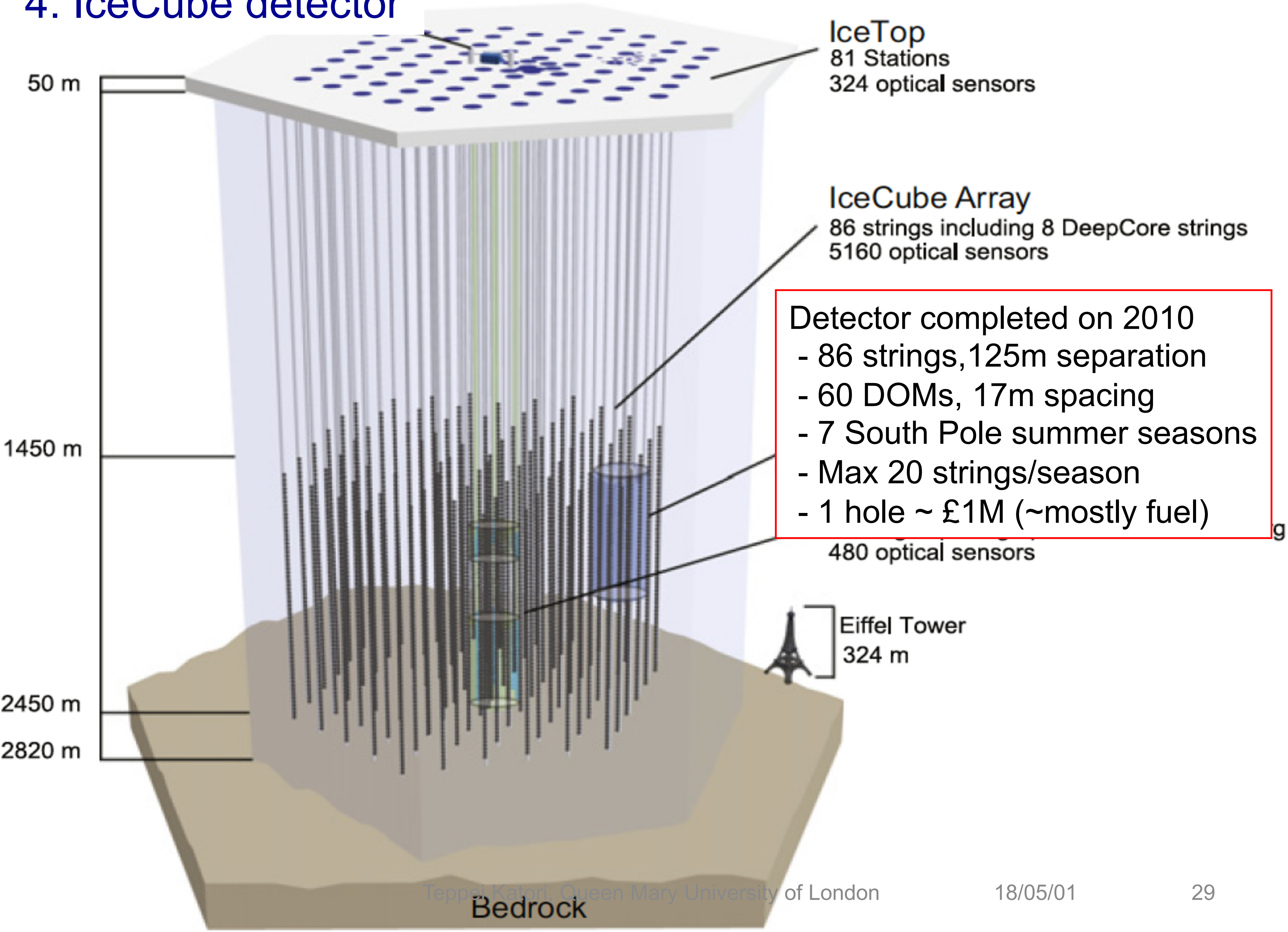






optical sensor deployment

4. IceCube detector



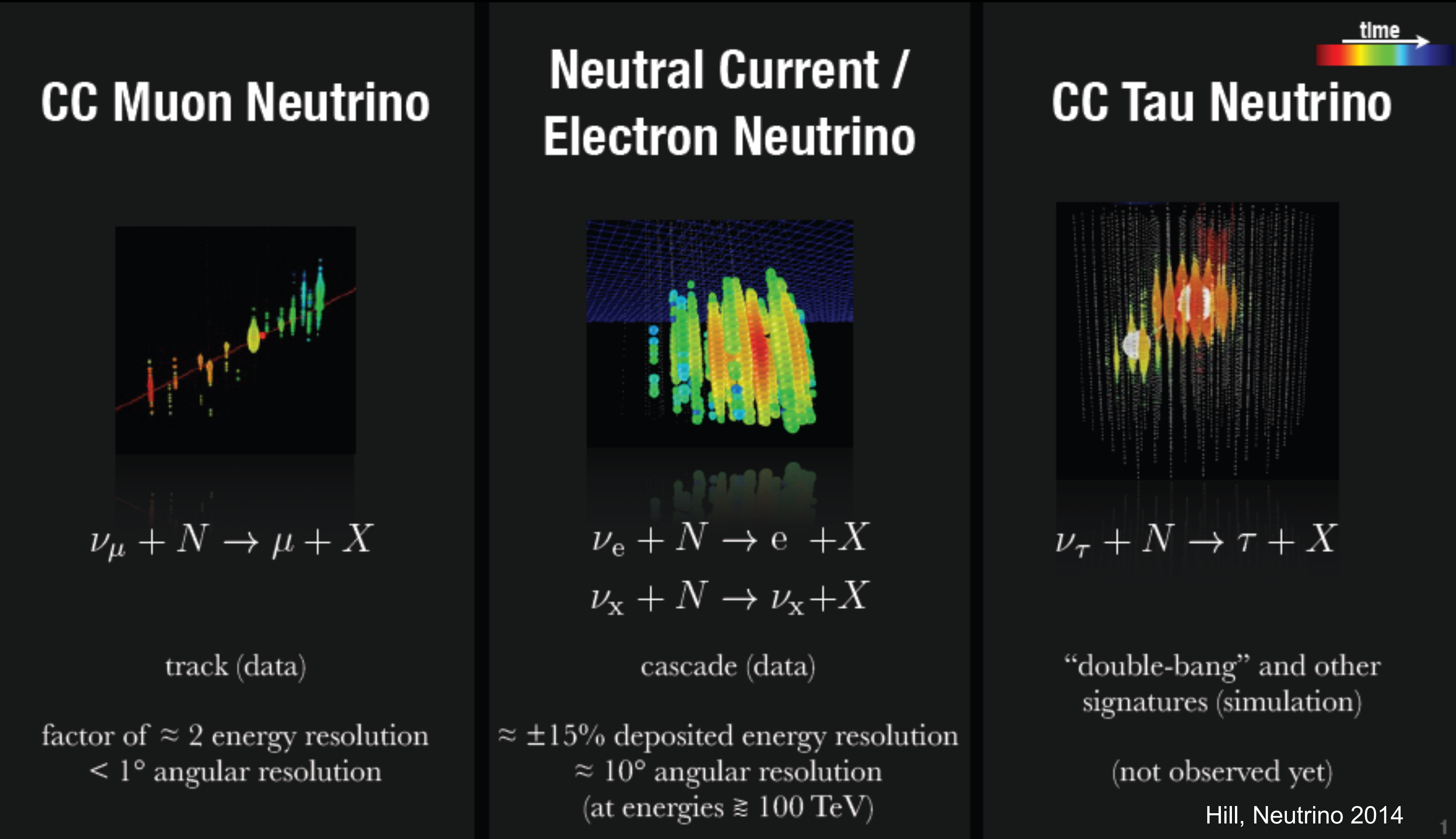
Detector completed on 2010

- 86 strings,125m separation
- 60 DOMs, 17m spacing
- 7 South Pole summer seasons
- Max 20 strings/season
- 1 hole ~ £1M (~mostly fuel)

5. IceCube detector

Topology

- Track = muon (~ν_μCC)
- Shower (cascade) = electron, tau, hadrons (~, ν_eCC, ν_τCC, NC)



CC Muon Neutrino

$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current / Electron Neutrino

$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

CC Tau Neutrino

$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

(not observed yet)

Hill, Neutrino 2014

1. Spontaneous Lorentz symmetry breaking
2. Modern test of Lorentz violation
3. Neutrino interferometry
4. IceCube Neutrino Observatory
5. **Test for Lorentz violation with atmospheric neutrinos**
6. Very-High-Energy (VHE) astrophysical neutrinos
7. Test for Lorentz violation with astrophysical neutrinos
8. Conclusion

Kostelecky and Mewes, PRD85(2012)096005

5. 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

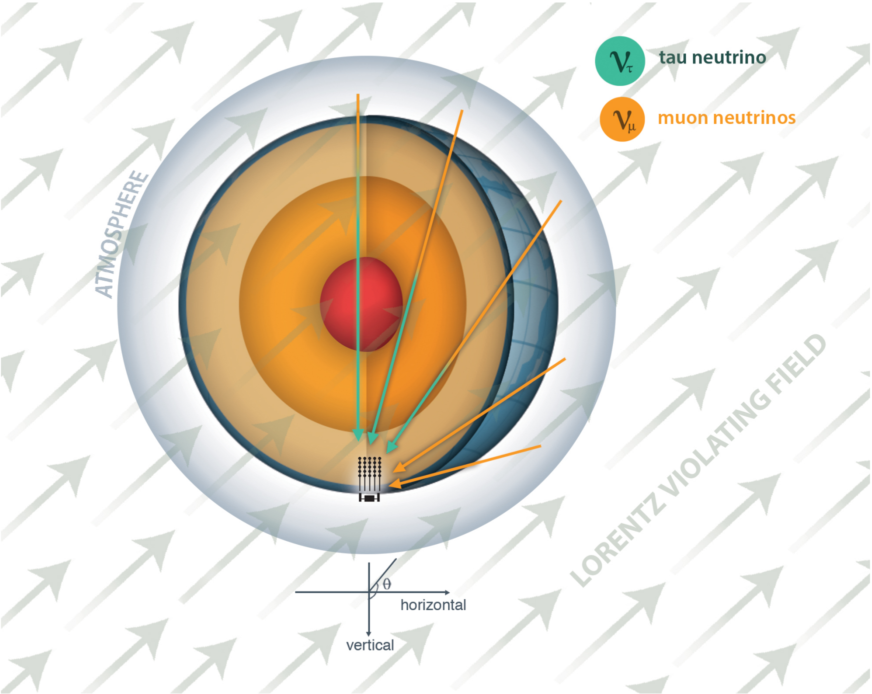
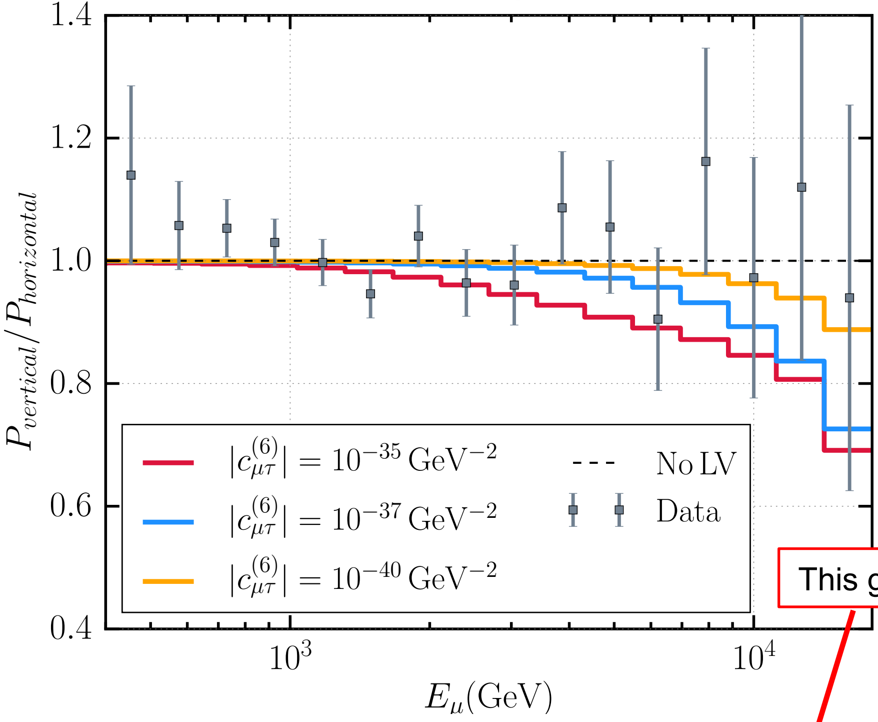


Fig2. Expected P(vertical)/P(horizontal) with dimension 6 LV operator



This guy

Eq. 1: LV motivated new physics Hamiltonian

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

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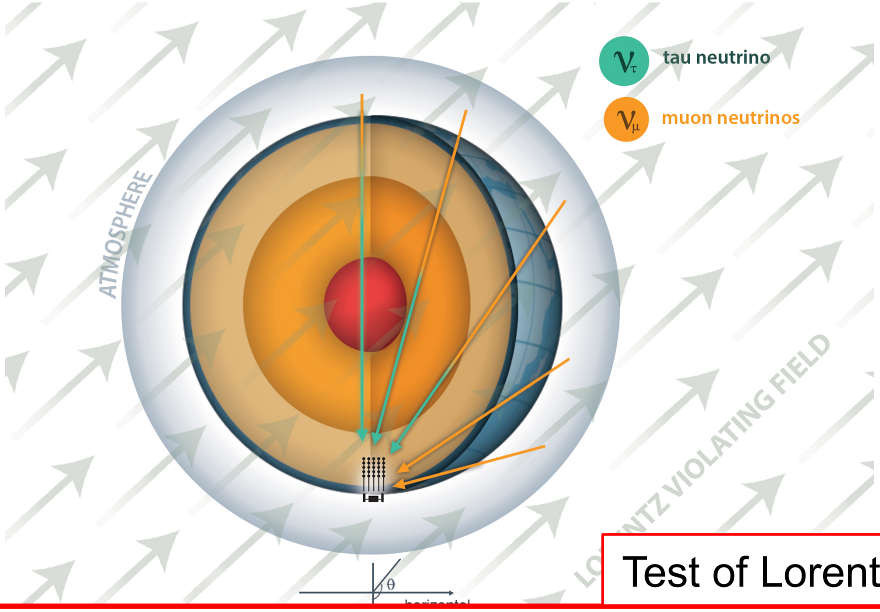

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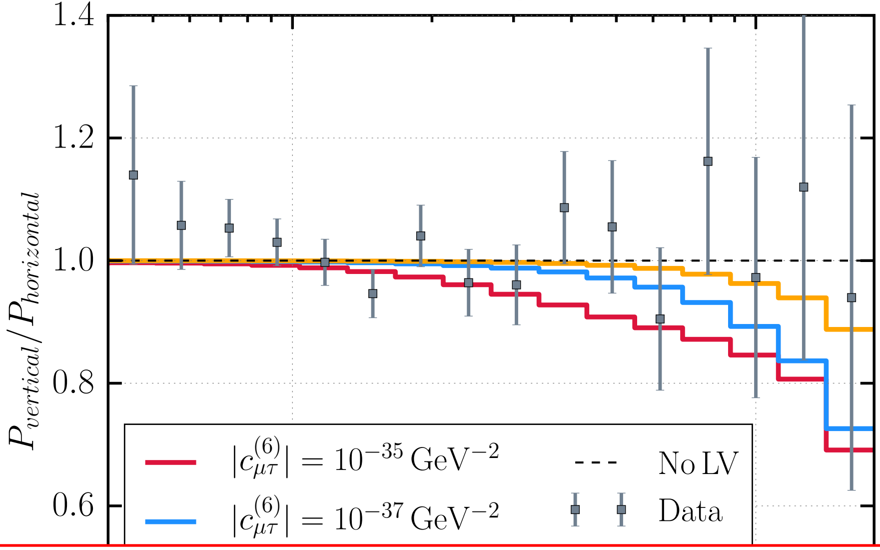
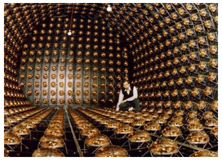


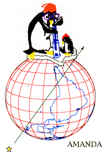
Test of Lorentz violation had been done by many experiments…

LSND

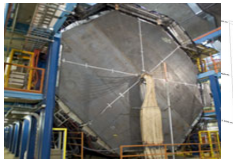


MINOS ND

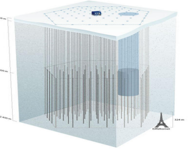
AMANDA



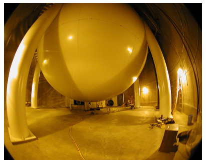
MINOS FD



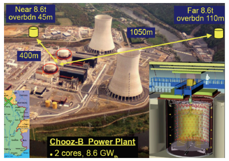
IceCube



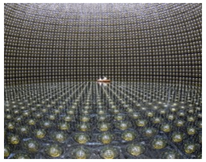
MiniBooNE



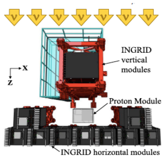
Double Chooz



Super-Kamiokande



T2K

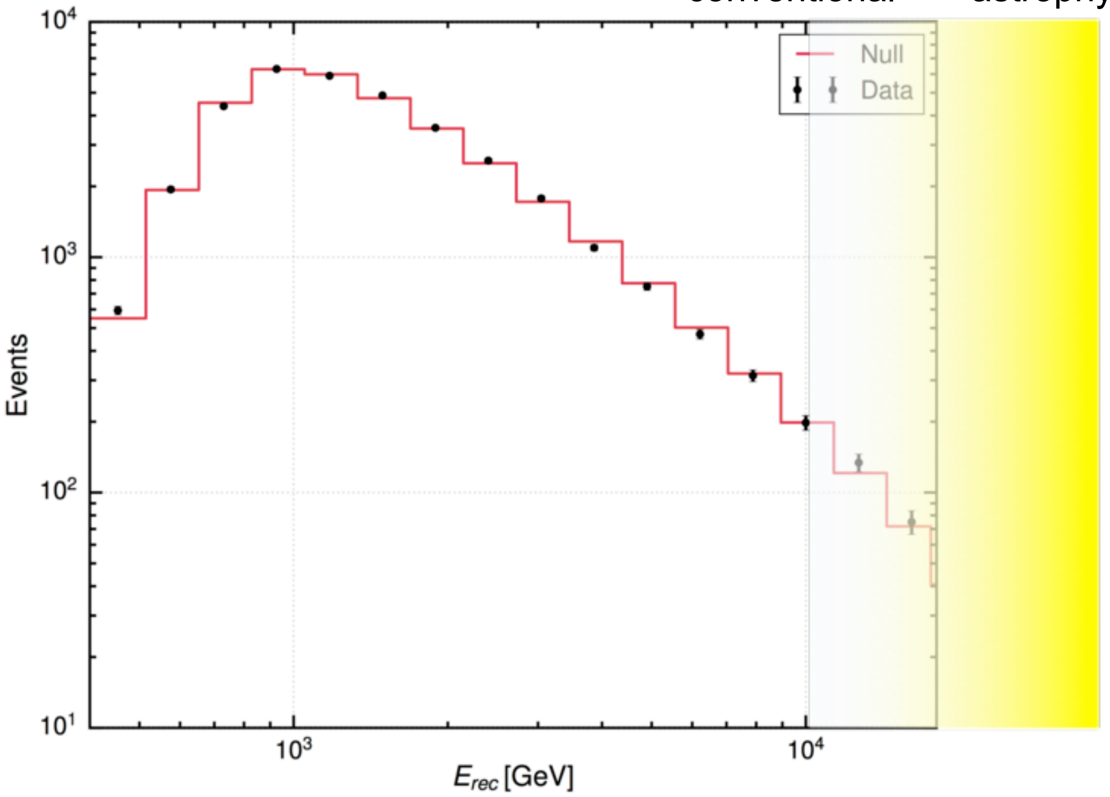


PRD72(2005)076004 PRL101(2008)151601 PRD79(2009)102005 PRL105(2010)151601 PRD82(2010)112003 PLB718(2013)1303 PRD86(2013)112009 PRD91(2015)052003 PRD95(2017)111101

5. 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.

Eq. 1: LV motivated new physics Hamiltonian

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

IceCube,PRL115(2015)081102, Nature551(2017)596

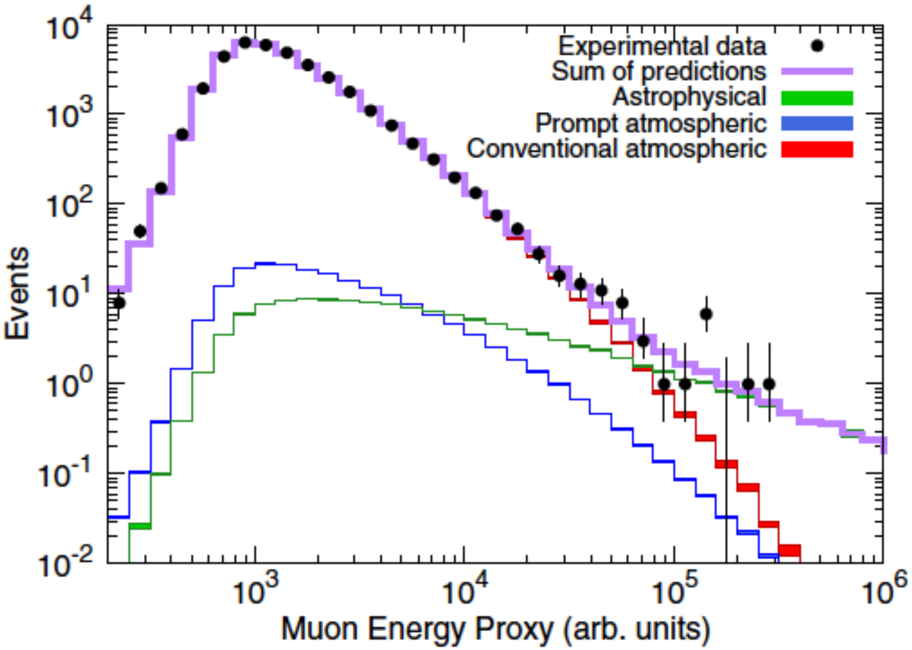
5. Test of Lorentz violation with atmospheric neutrinos

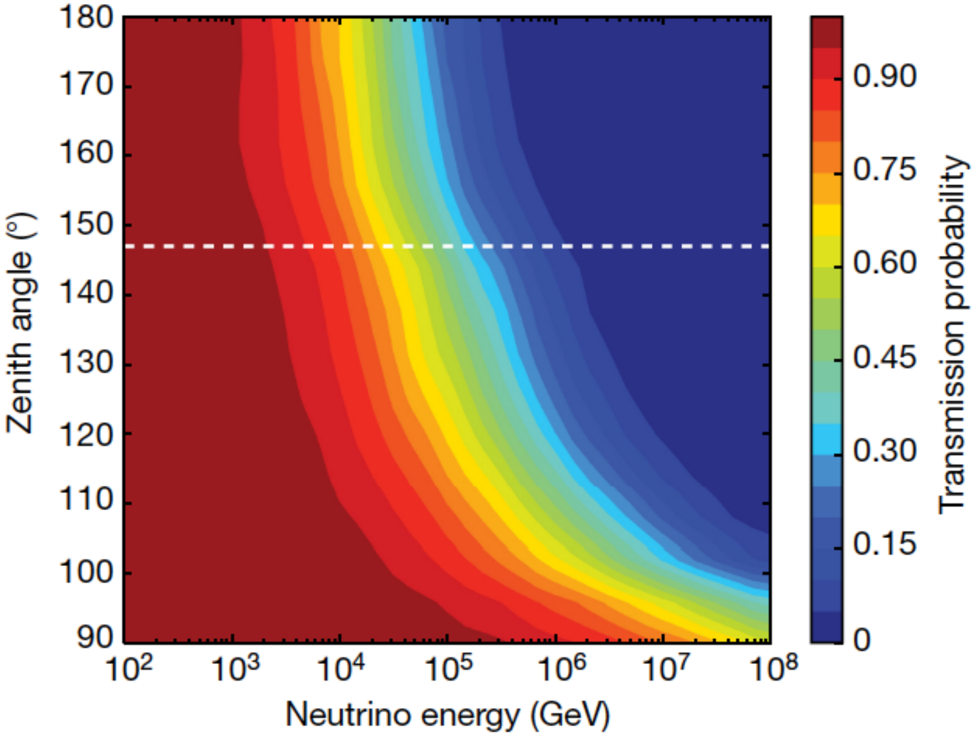
We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.

Things become more complicated (more interesting?) around 10-100 TeV
- Astrophysical neutrinos kick in
- Earth absorption becomes significant

→ 400 GeV to 18 TeV region for this analysis

conventional ↔ astrophysical





IceCube,PRL115(2015)081102;117(2016)071801

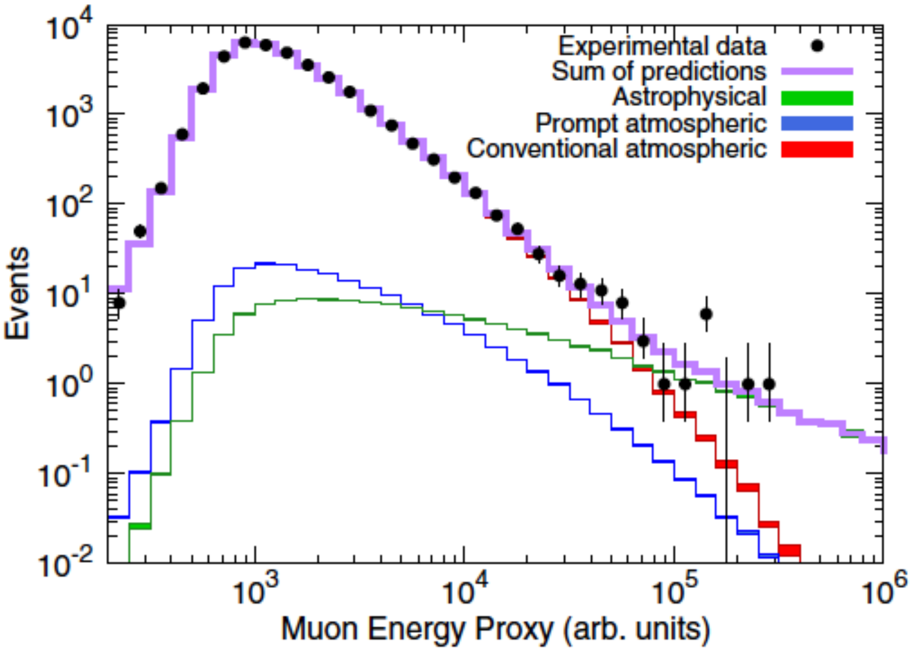
5. Analysis method

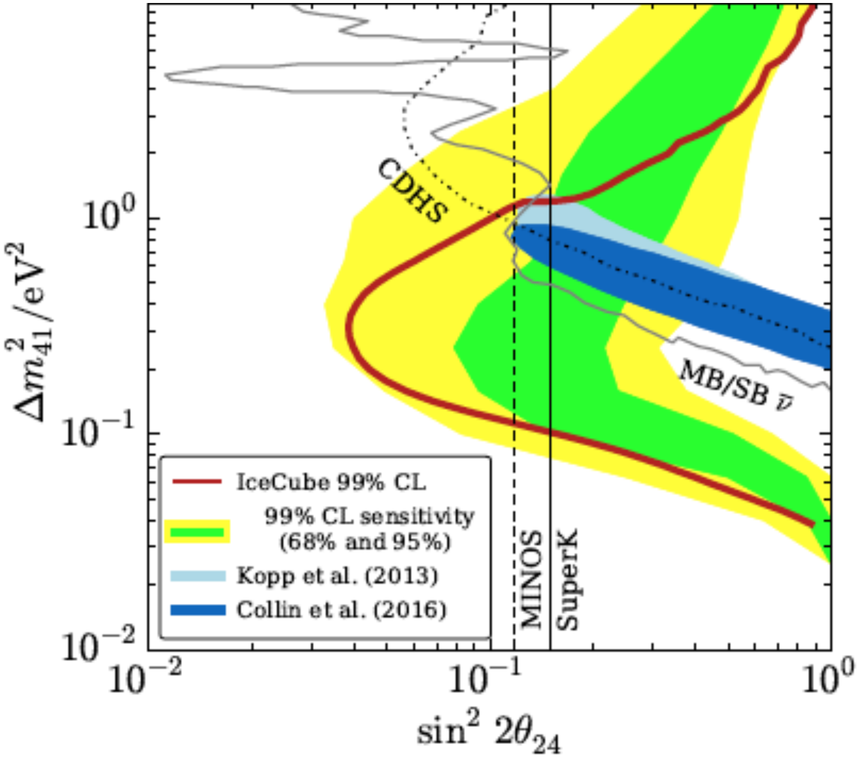
We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.

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

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

conventional ↔ astrophysical





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

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Simulation

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

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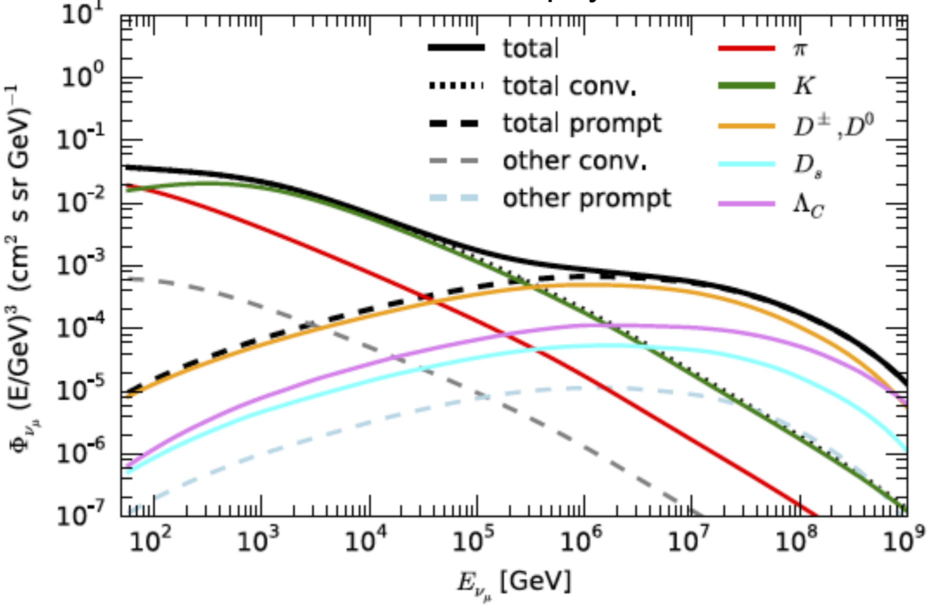

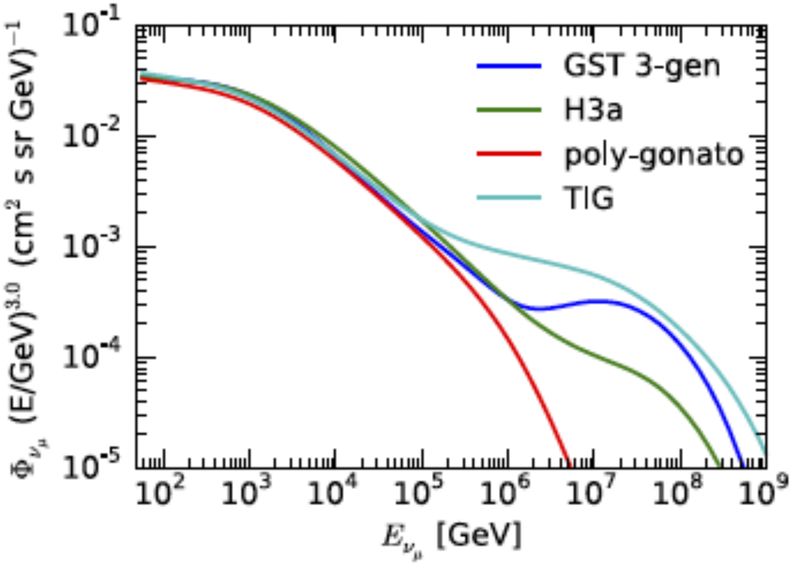

Figure 3. Primary model dependence of the atmospheric conventional + prompt neutrino flux. The model abbreviations are described in the caption of Fig. 2.

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

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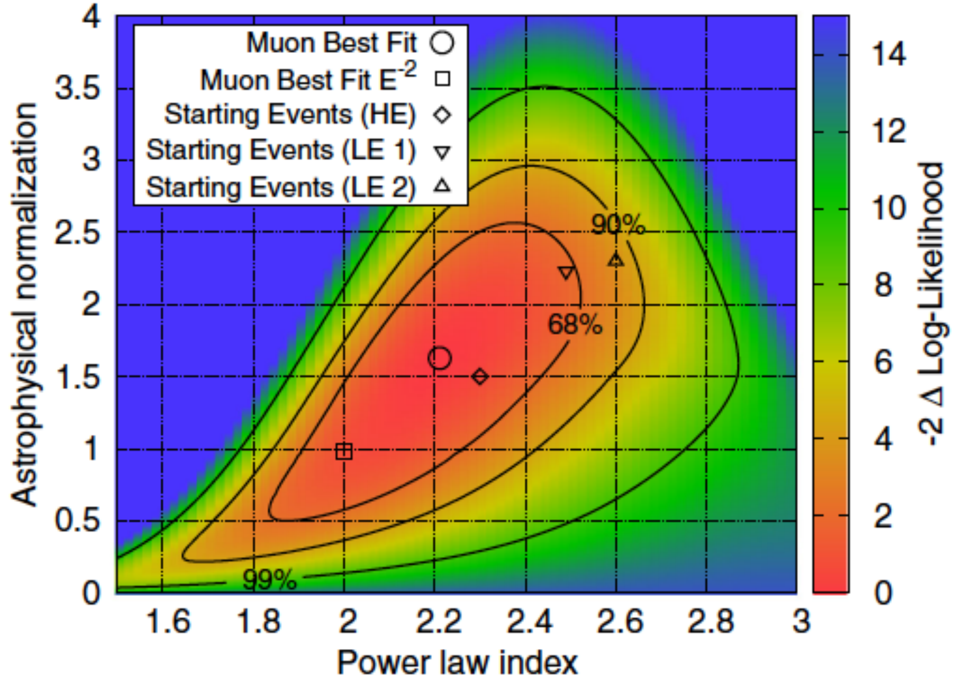
- simple power law astrophysical neutrinos

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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- 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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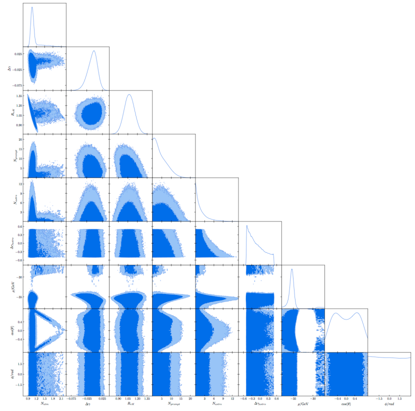

MARKOV

Fit methods

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

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

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

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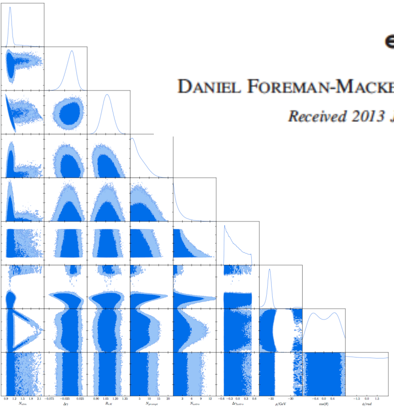


emcee: The MCMC Hammer

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

IceCube, arXiv:1709.03434

5. Results

Eq. 2: An example of Lorentz violation operator matrix

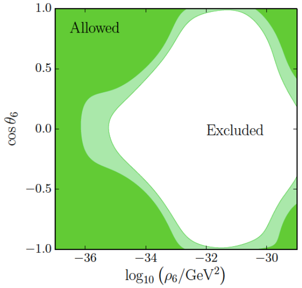
$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots . \tag{1}$$

These 3 parameters

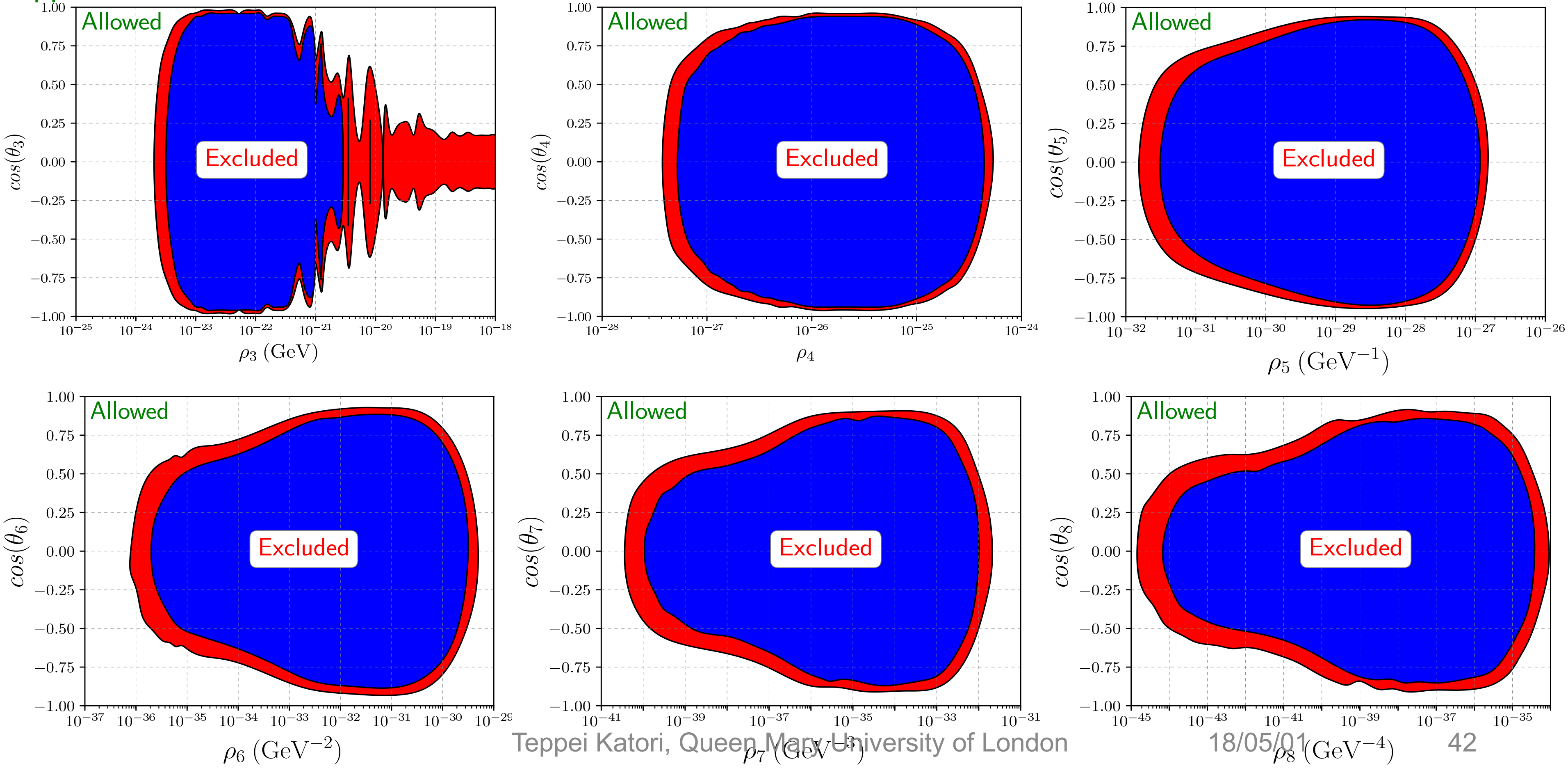
$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

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

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Eq. 2: An example of Lorentz violation operator matrix

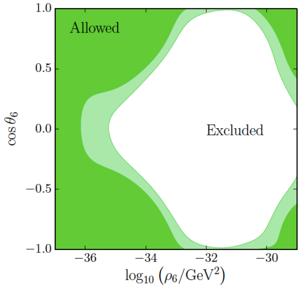
Make these 0 by hand

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

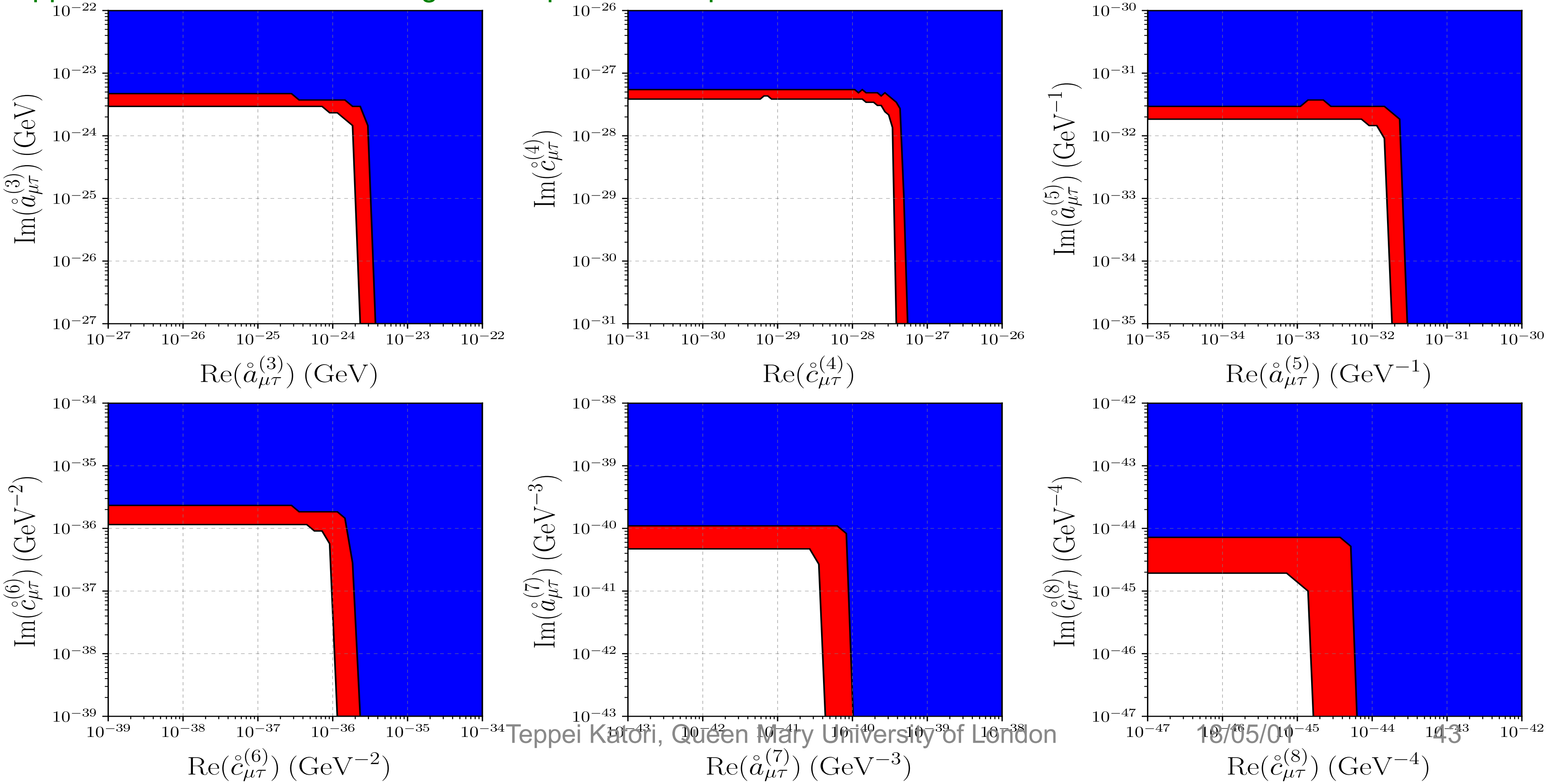
We performed fits for 3 LV parameters for each dimension LV operator → no LV, draw 99% exclusion contours

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

Appendix 2: MCMC result



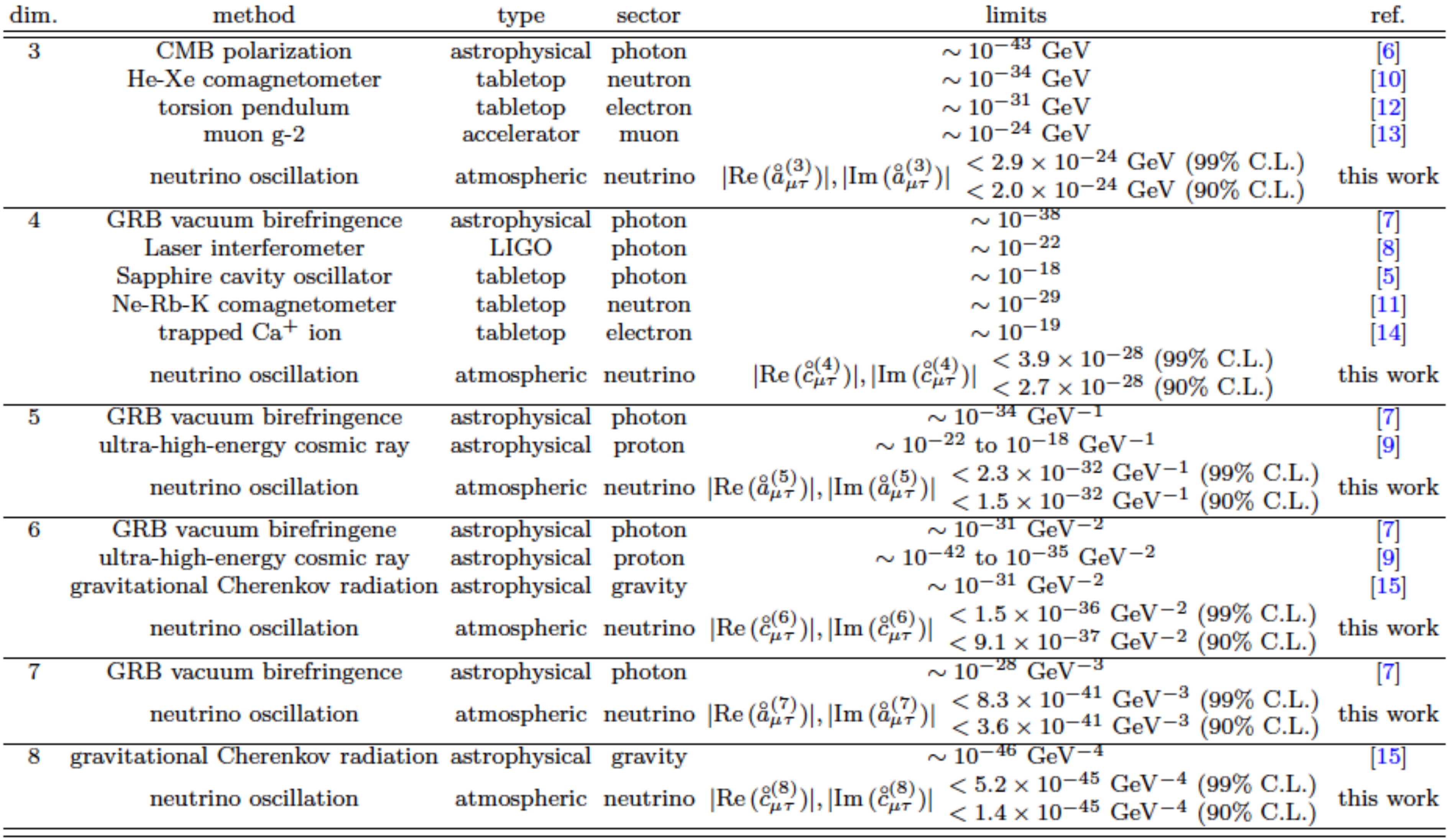
Appendix 4: Contour on off-diagonal LV parameter space



IceCube, arXiv:1709.03434

5. 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.

IceCube, arXiv:1709.03434

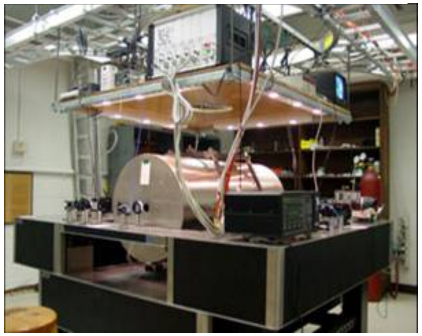
5. Results

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} (9 $< 1.5 \times 10^{-32}$ GeV^{-1} (9	
6		astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	
		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

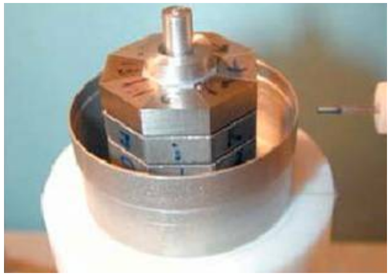
TABLE I: Comparison of attainable best limits of SM … lds.

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



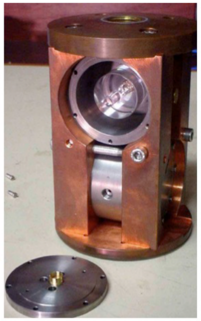
PRL107(2011)171604
PRL112(2014)110801

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



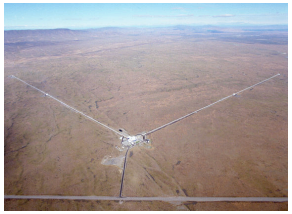
PRL97(2006)021603

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



Nature.Comm.6(2015)8174

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

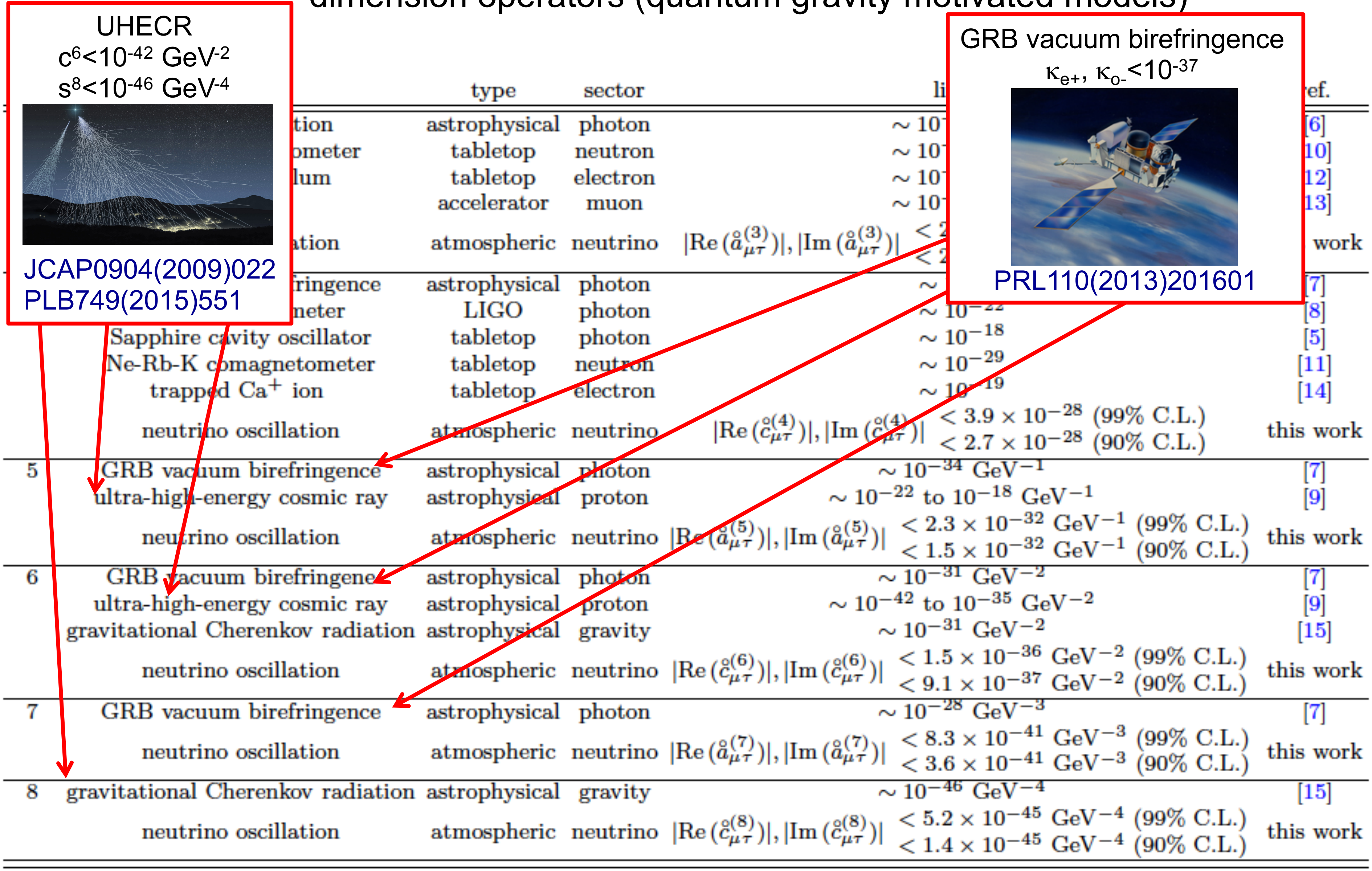


PLB761(2016)1

IceCube, arXiv:1709.03434

5. 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

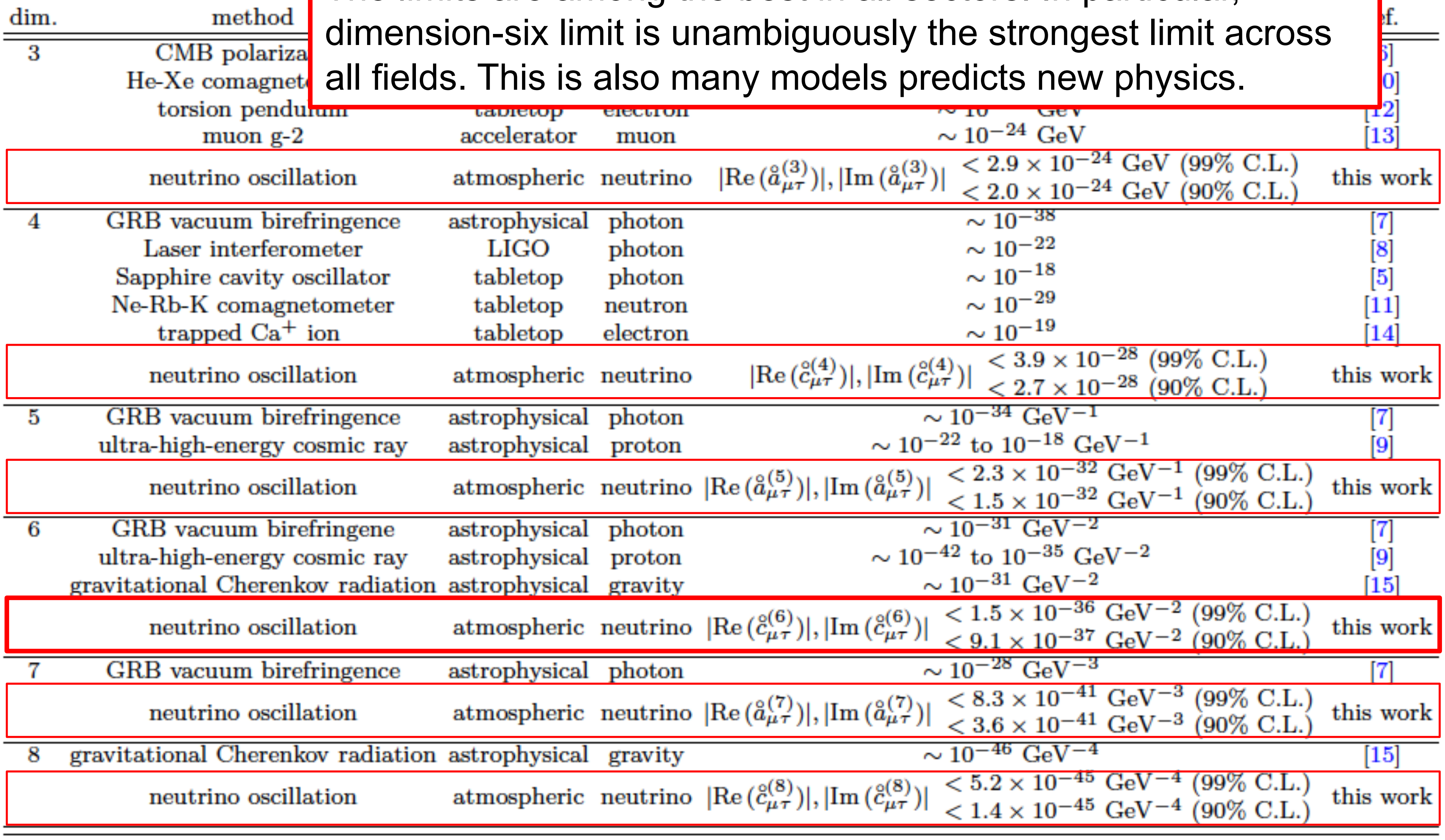
TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

IceCube, arXiv:1709.03434

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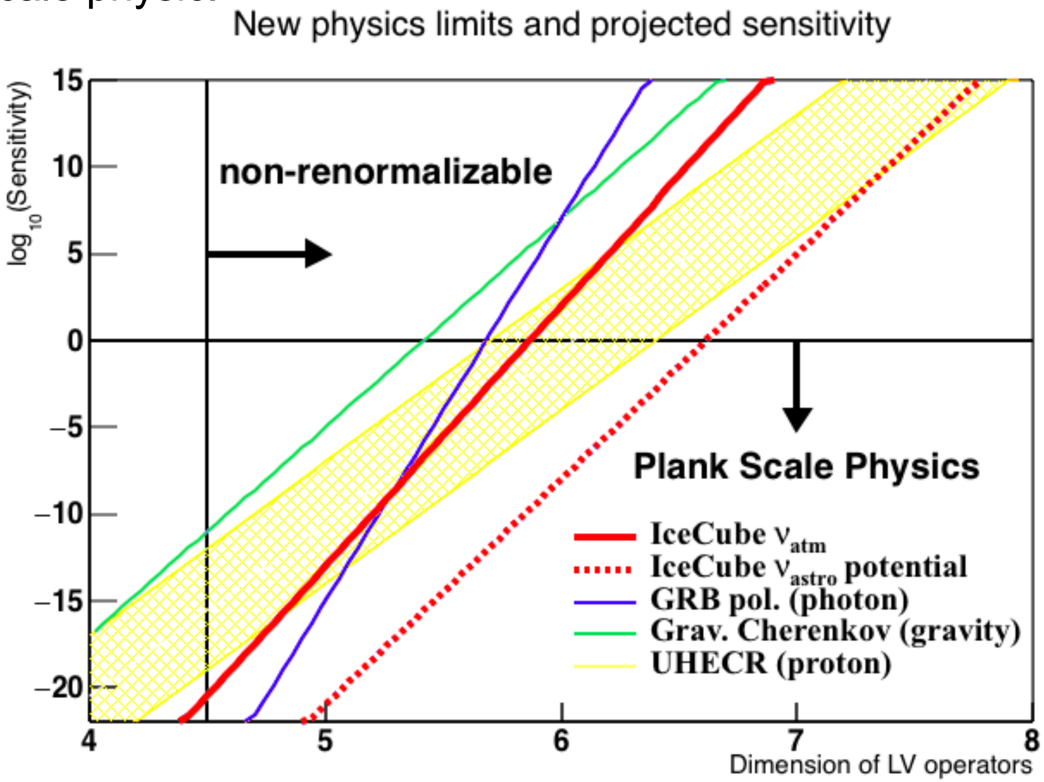
TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

5. 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.



1. Spontaneous Lorentz symmetry breaking
2. Modern test of Lorentz violation
3. Neutrino interferometry
4. IceCube Neutrino Observatory
5. Test for Lorentz violation with atmospheric neutrinos
6. **Very-High-Energy (VHE) astrophysical neutrinos**
7. Test for Lorentz violation with astrophysical neutrinos
8. Conclusion

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

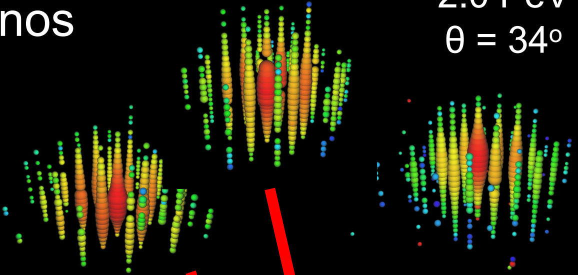
6. Astrophysical Very-High-Energy Neutrinos

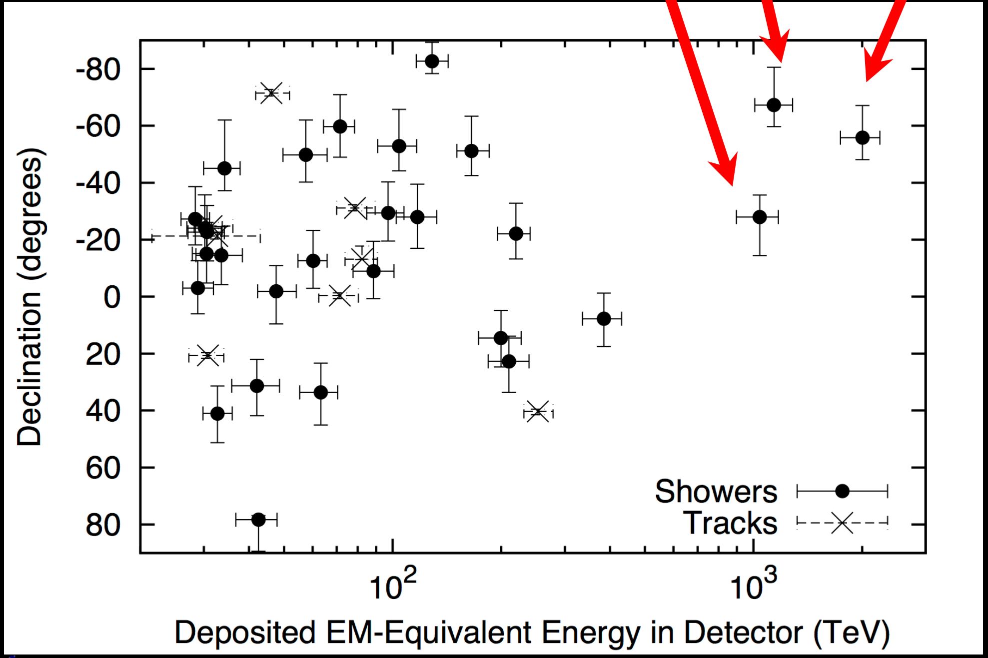
First observation (2013)
- 30-2000 TeV neutrinos

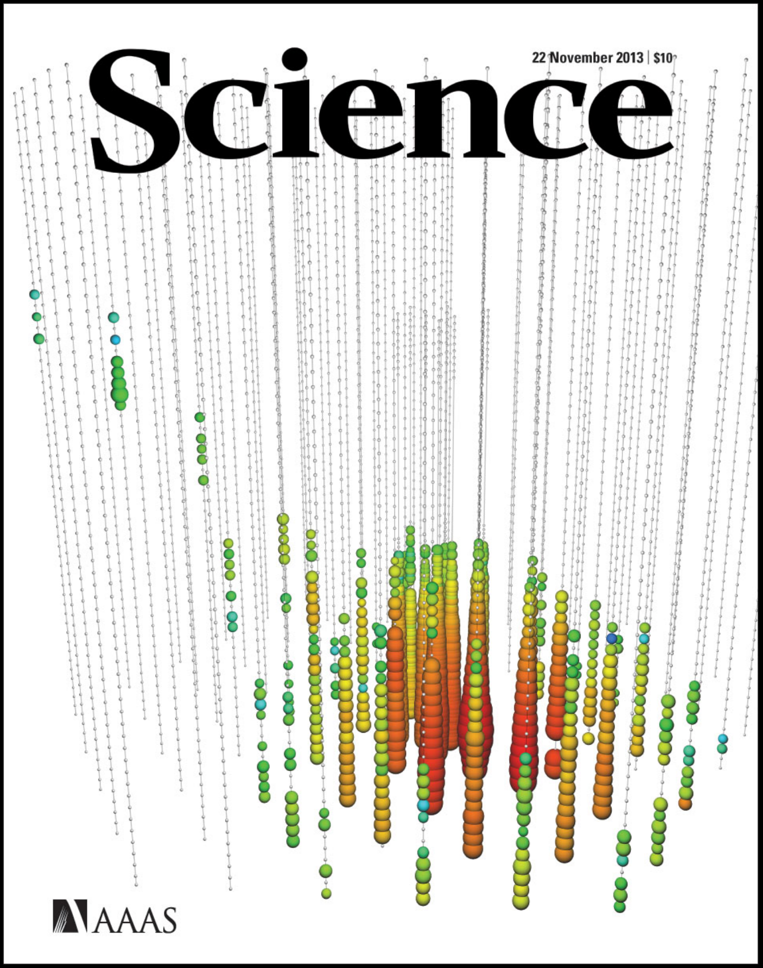
“Bert”
1.1 PeV
θ = 23º

“Ernie”
1.0 PeV
θ = 62º

“Big Bird”
2.0 PeV
θ = 34º







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

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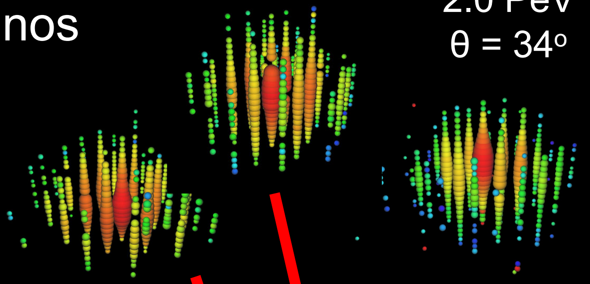
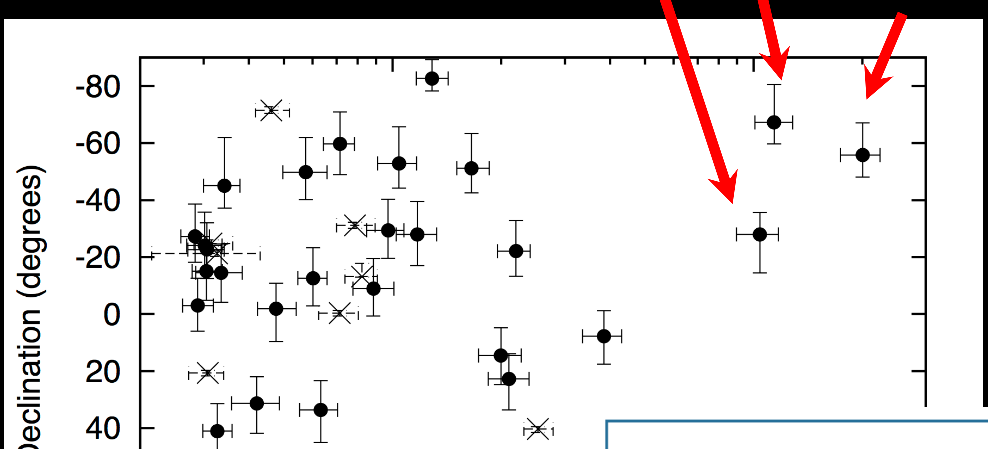
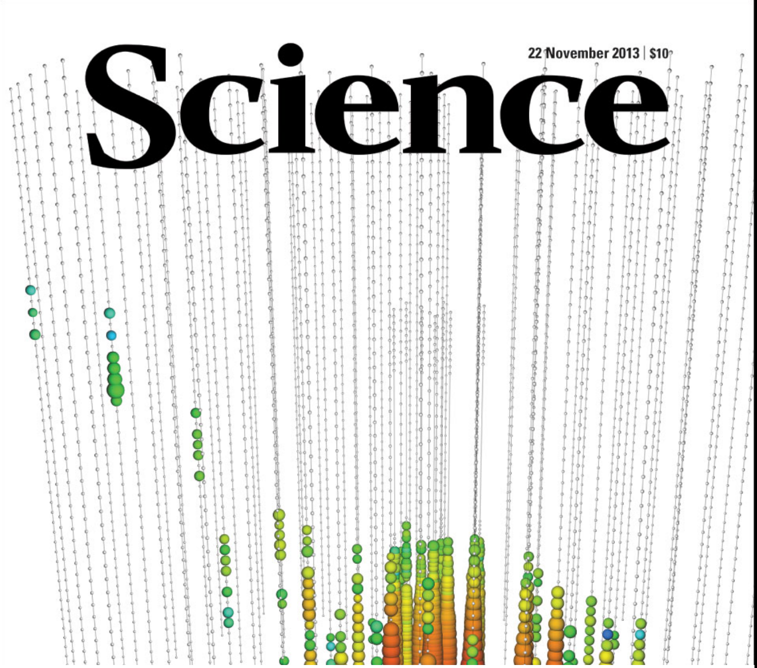






IceCube V-neck high energy neutrino t-shirt

$15.00

The "Bertshirt" in V-neck style. Soft, 100% ring spun cotton with a longer torso length makes it comfortable for all wearers. IceCube logo on the back. Black, V-neck, pre-shrunk 3.2 oz cotton. Available in sizes S-2XL.

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

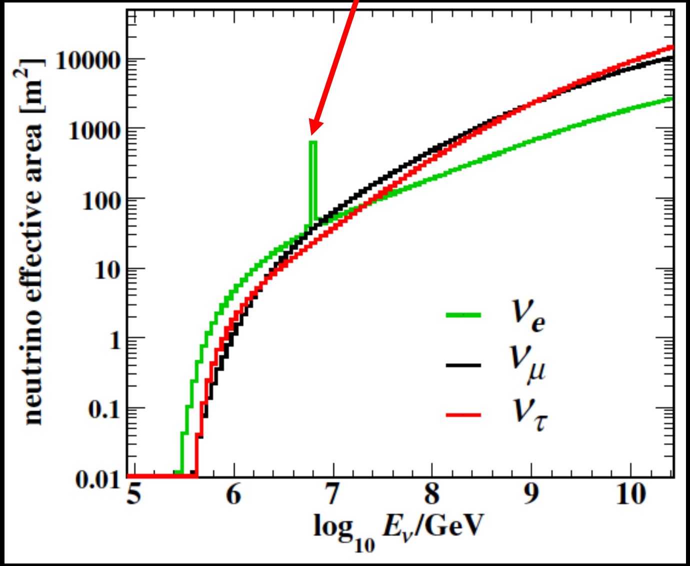
Support IceCube!

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

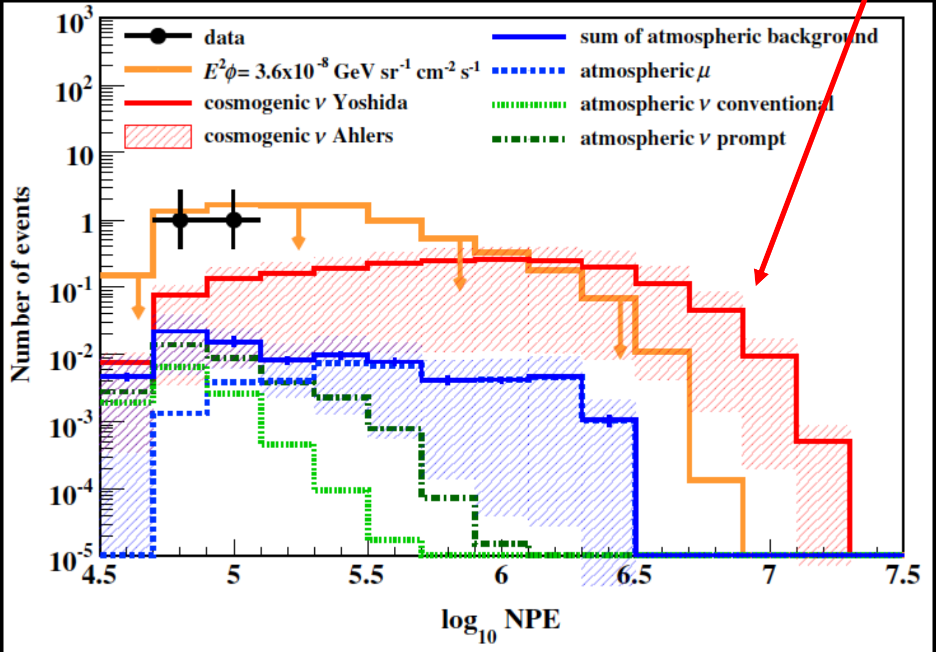
6. Astrophysical Very-High-Energy Neutrinos

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

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



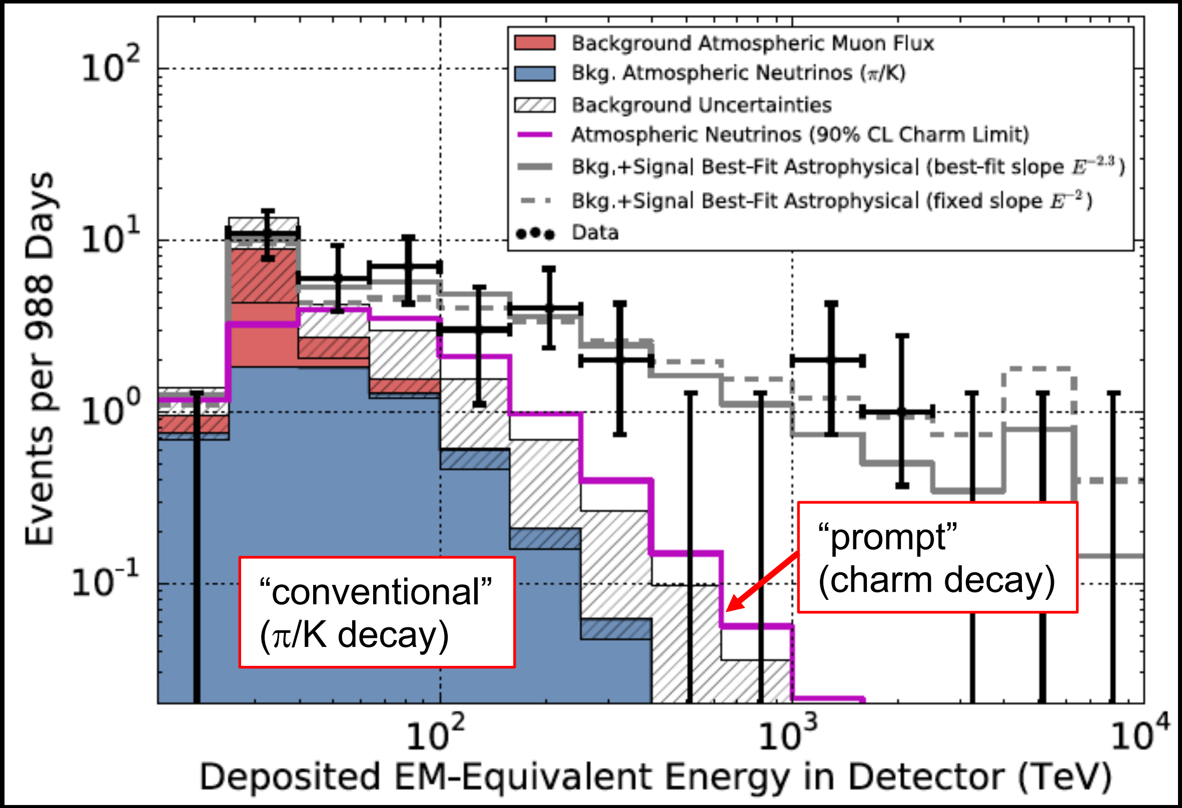
$p + \gamma \rightarrow \Delta \rightarrow \pi \rightarrow \nu$



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

6. Astrophysical Very-High-Energy Neutrinos

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



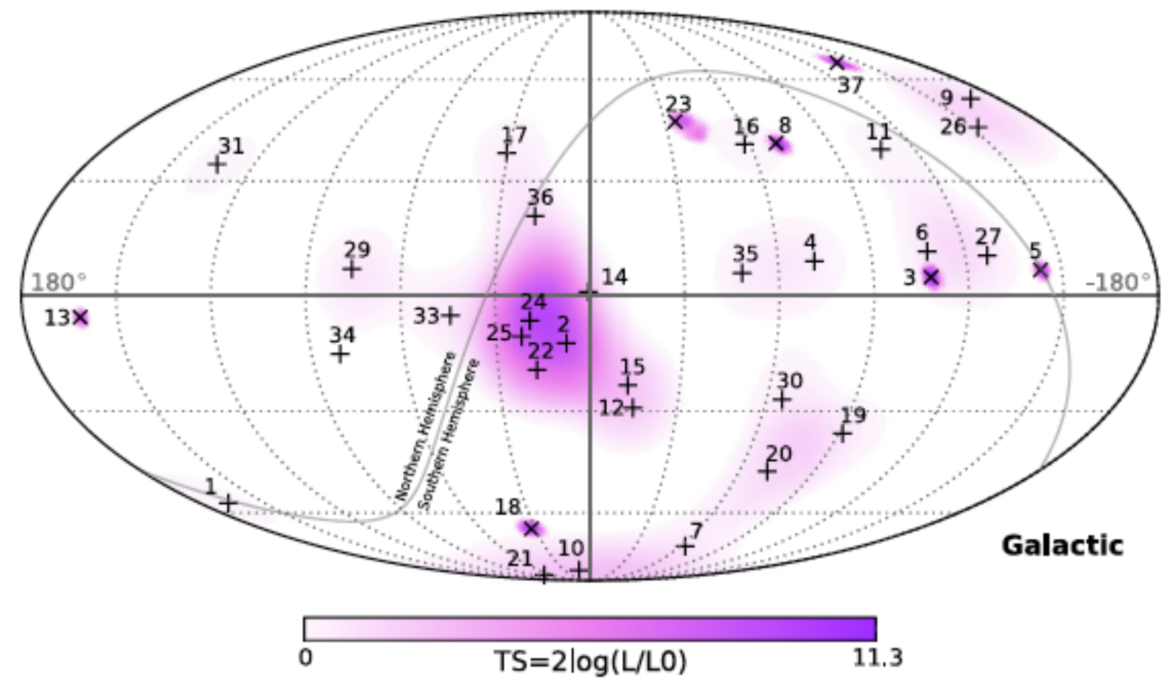
"conventional"
(π/K decay)

"prompt"
(charm decay)

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

6. 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 not known



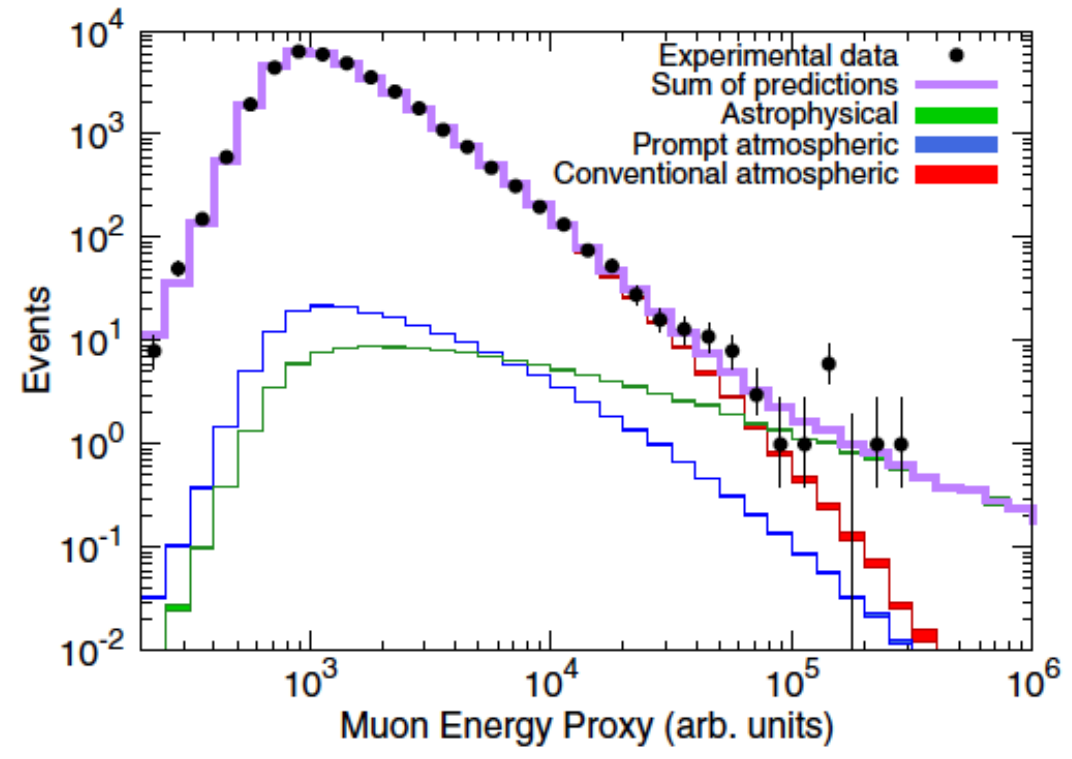
IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

6. 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 not known
- From both southern and northern sky

IceCube is not 4π measurement
- efficiency is not uniform
- 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

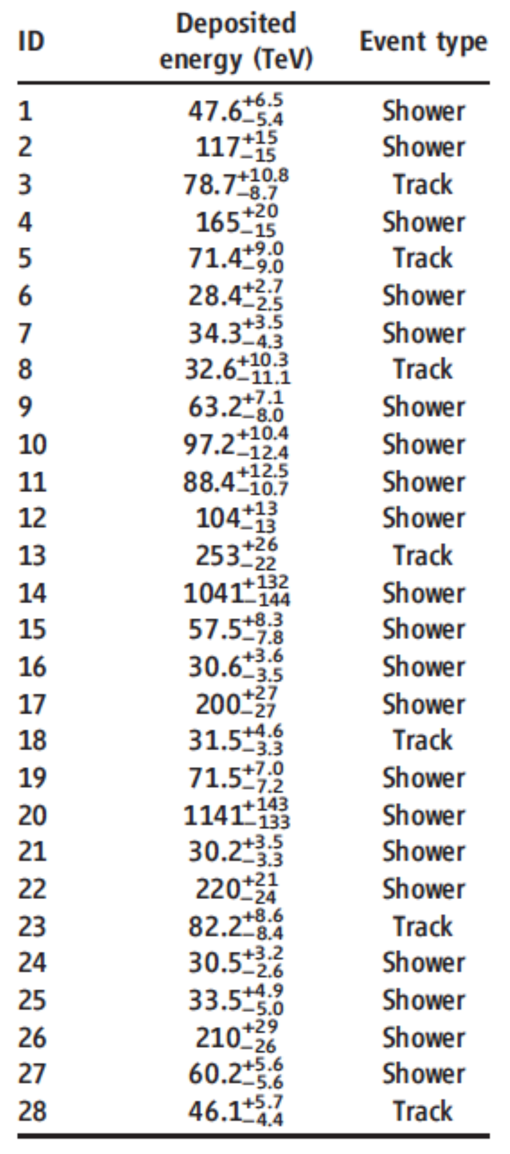


IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102

6. 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 not known
- 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

7 years data will
be released soon!

Palladino et al,PRL114(2015)171101

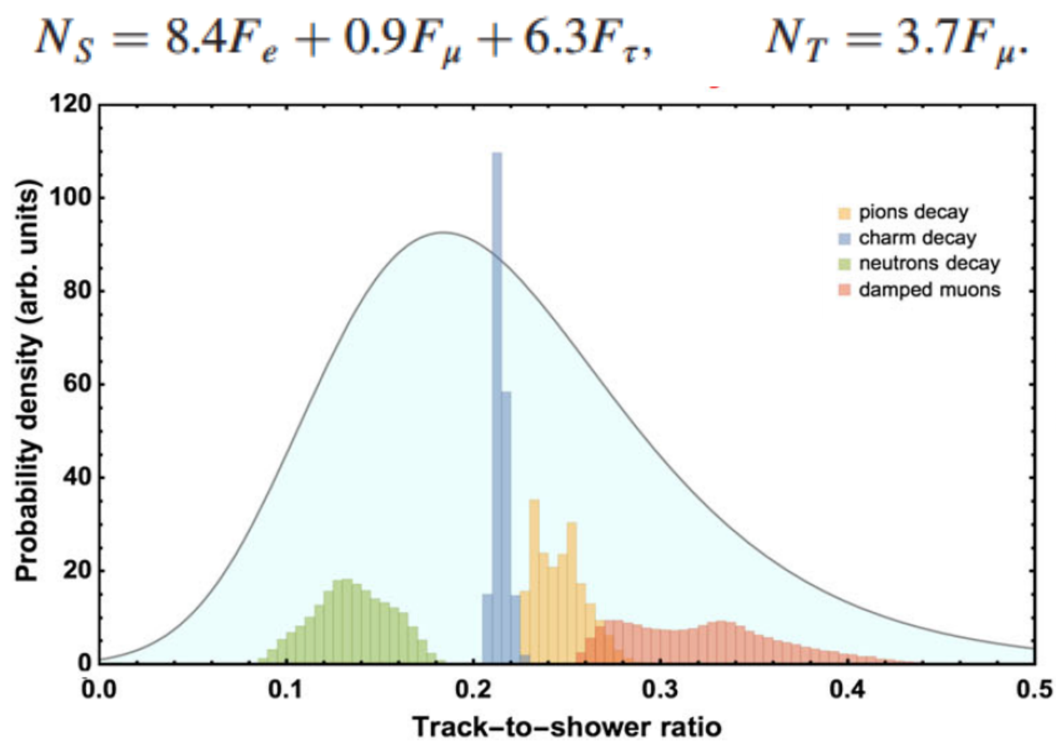
6. Astrophysical Very-High-Energy Neutrinos

First observation (2013)
- 30-2000 TeV neutrinos
- Unlikely from Glashow resonance or GZK neutrinos
- Unlikely from atmospheric neutrinos
- Sources are not known
- From both southern and northern sky
- Shower topology is dominant

Precise calculation shows
$N_T/N_S \sim 0.15 – 0.3$

This moment, any production models are compatible with data

It is tricky to treat ν_τCC interaction
- Naively it’s shower
- High chance to make high energy muon → track



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

1. Spontaneous Lorentz symmetry breaking

2. Modern test of Lorentz violation

3. Neutrino interferometry

4. IceCube Neutrino Observatory

5. Test for Lorentz violation with atmospheric neutrinos

6. Very-High-Energy (VHE) astrophysical neutrinos

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

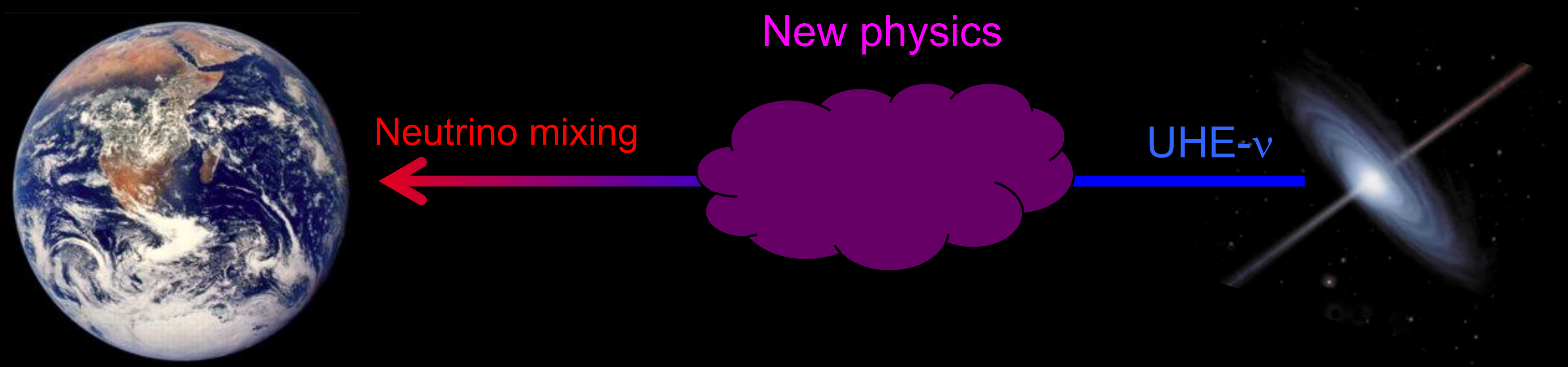
8. Conclusion

Arugüelles, TK, Salvado,PRL115(2015)161303

7. 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.

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.



Arugüelles, TK, Salvado, PRL115(2015)161303

7. Standard flavour triangle diagram

There are 3 UHE neutrino production models

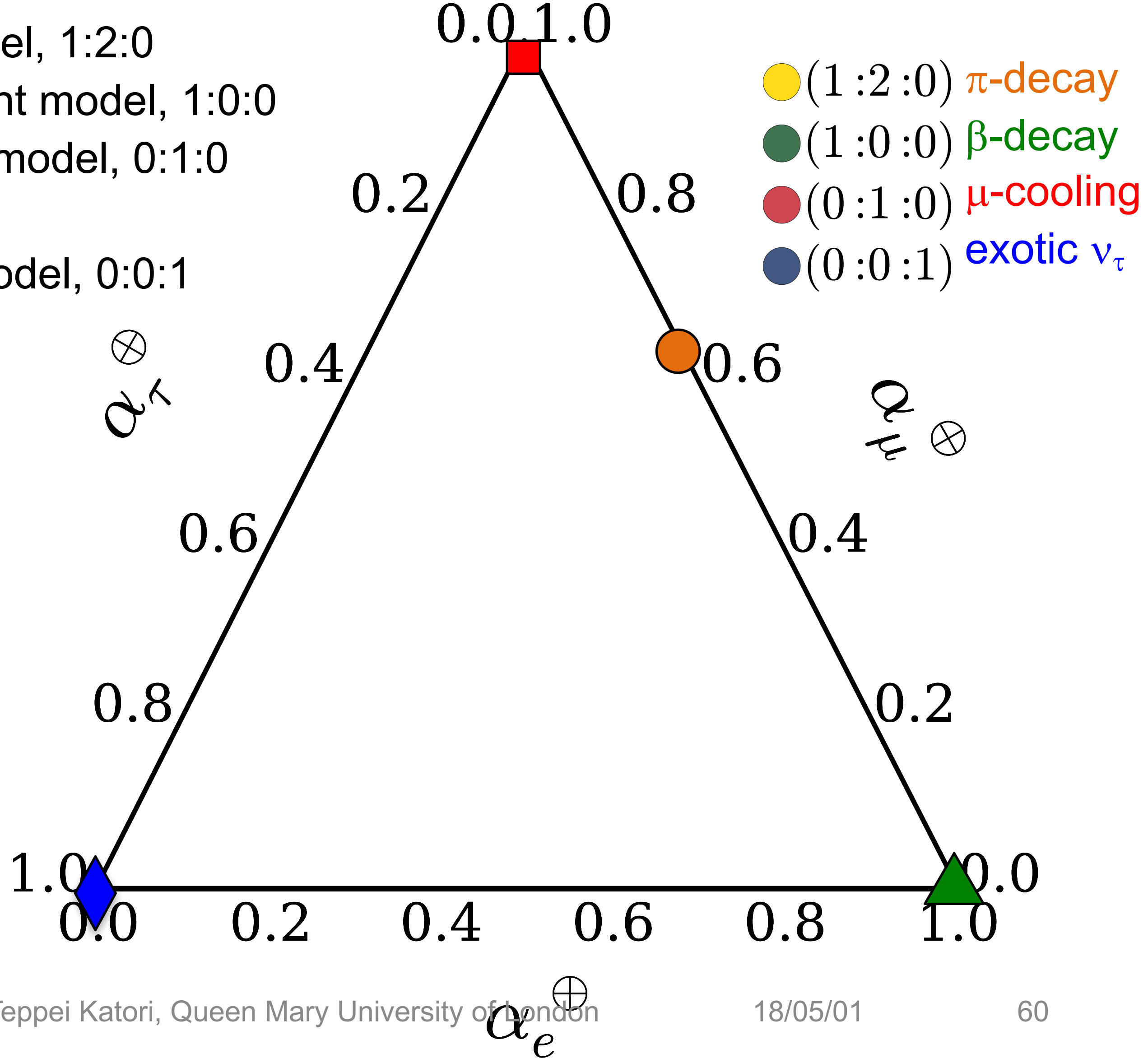
i. pion decay dominant model, 1:2:0

ii. electron neutrino dominant model, 1:0:0

iii. muon neutrino dominant model, 0:1:0

…and 1 exotic model,

iv. tau neutrino dominant model, 0:0:1



Arugüelles, TK, Salvado, PRL115(2015)161303

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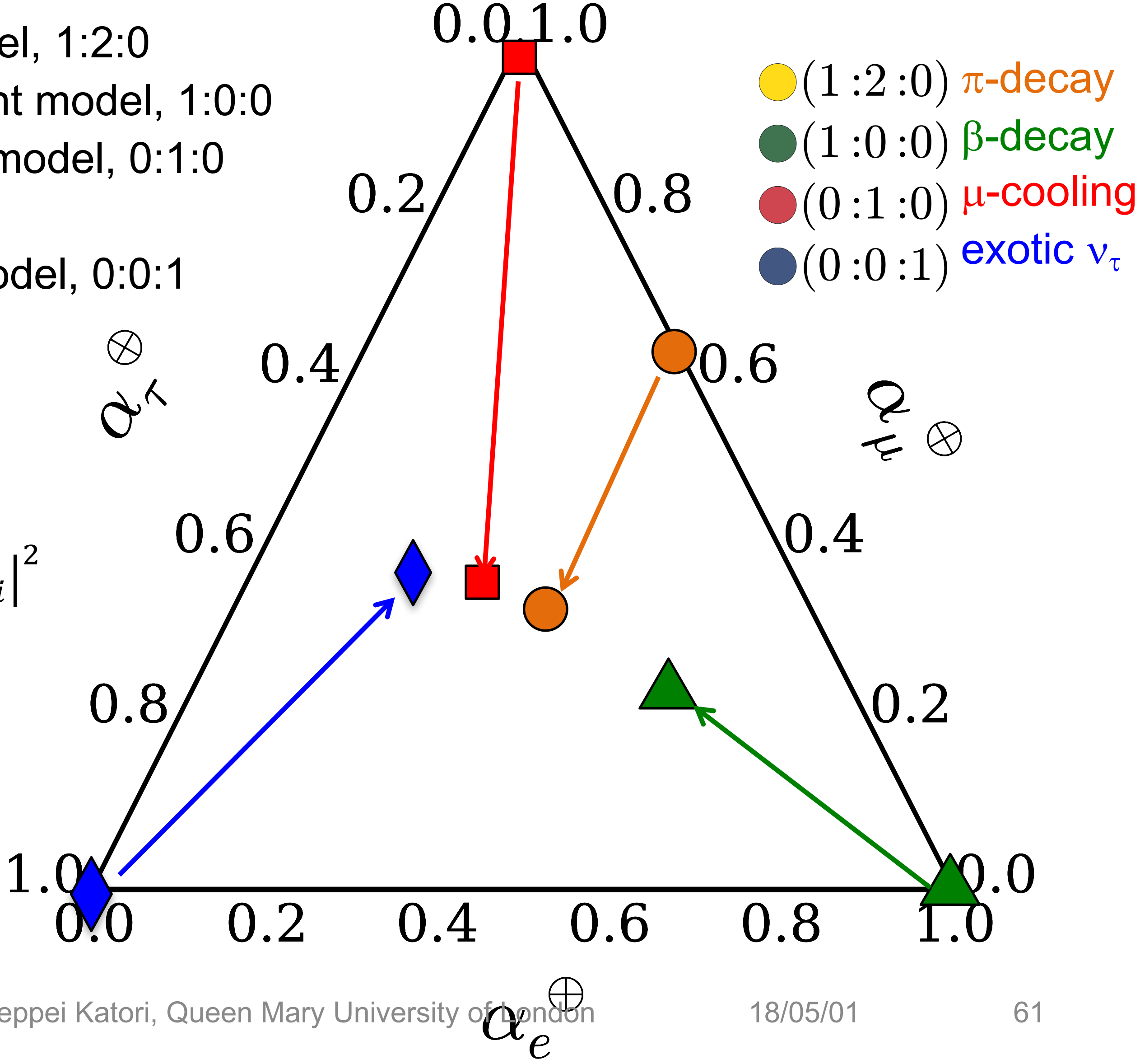
Due to neutrino mixing, flavours on the earth are different

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



Arugüelles, TK, Salvado, PRL115(2015)161303

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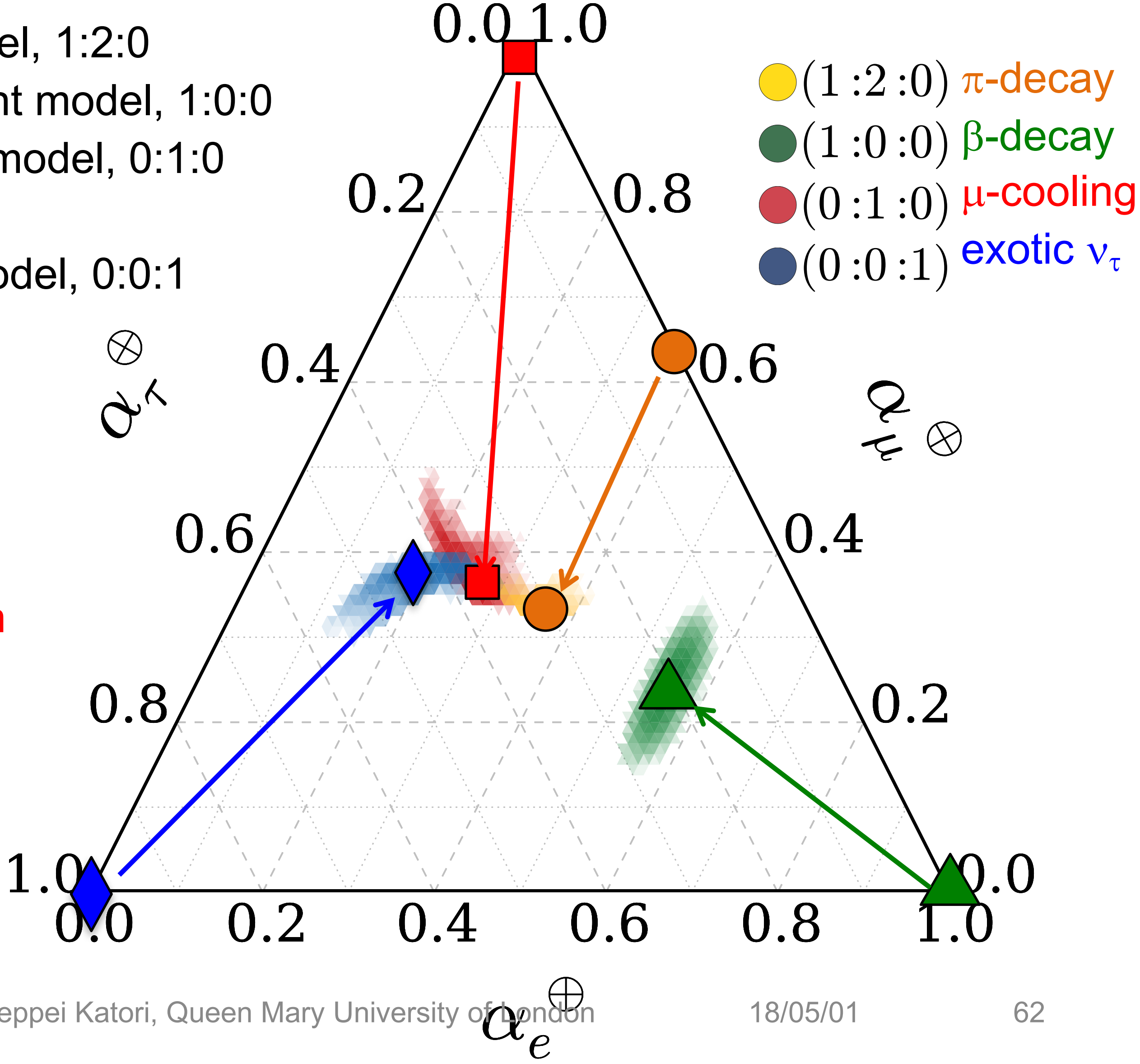
Due to neutrino mixing, flavours on the earth are different

Flavour ratio on the earth, including errors of oscillation parameter



Arugüelles, TK, Salvado, PRL115(2015)161303

7. 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

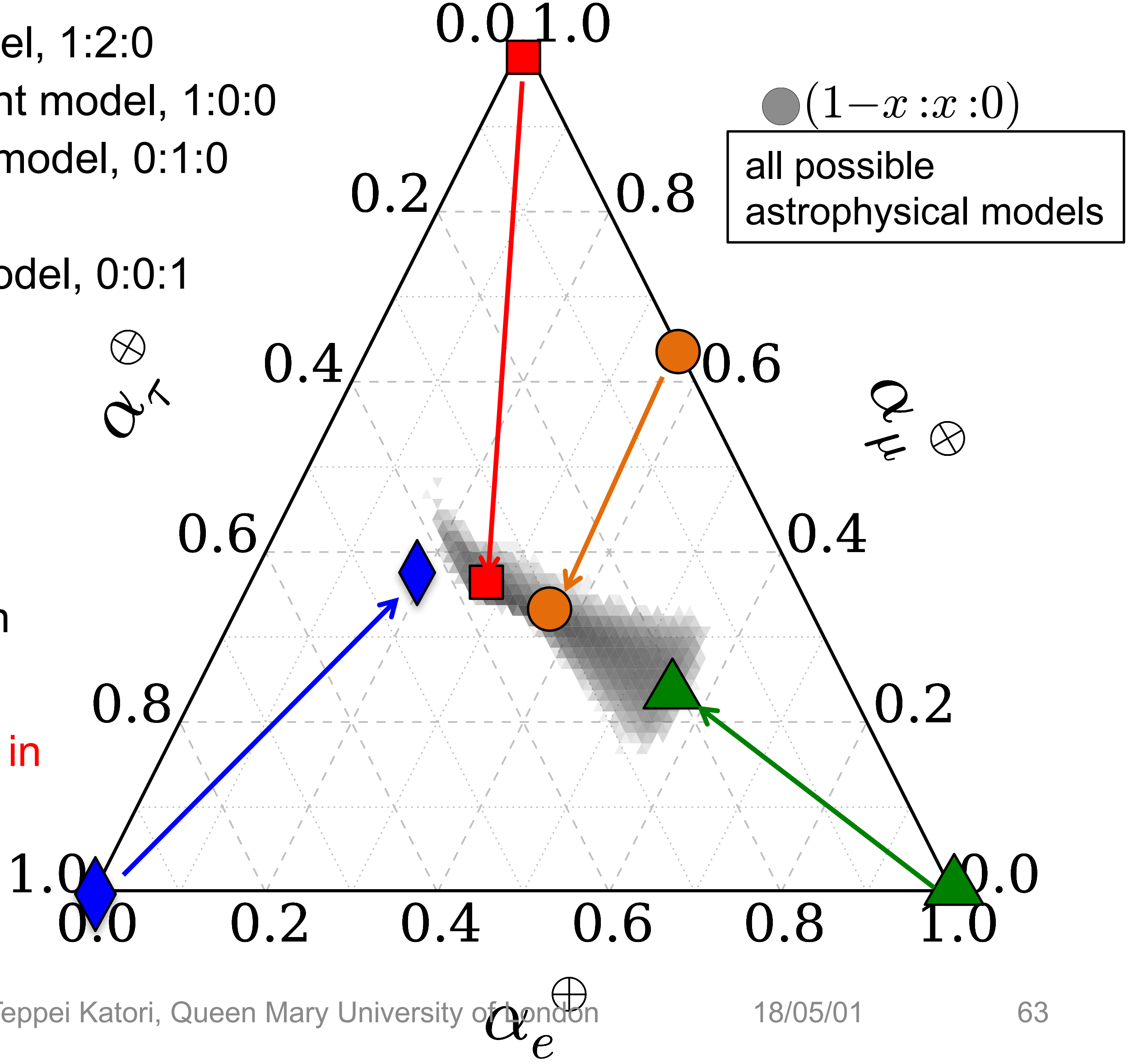
…and 1 exotic model,

- iv. tau neutrino dominant model, 0:0:1

Due to neutrino mixing, flavours on the earth are different

Flavour ratio on the earth, including errors of oscillation parameter

All possible flavour ratio are in this tiny band!



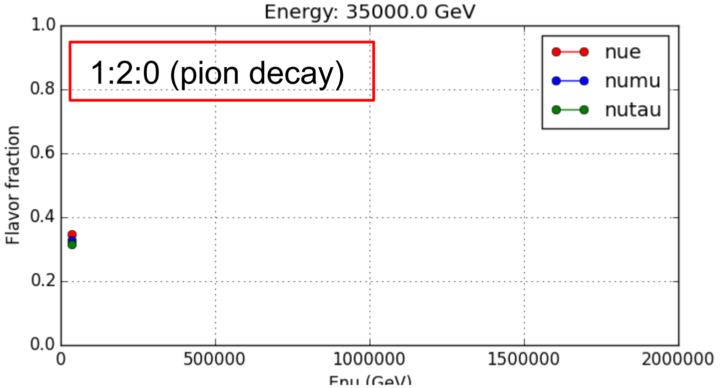
Arugüelles, TK, Salvado, PRL115(2015)161303

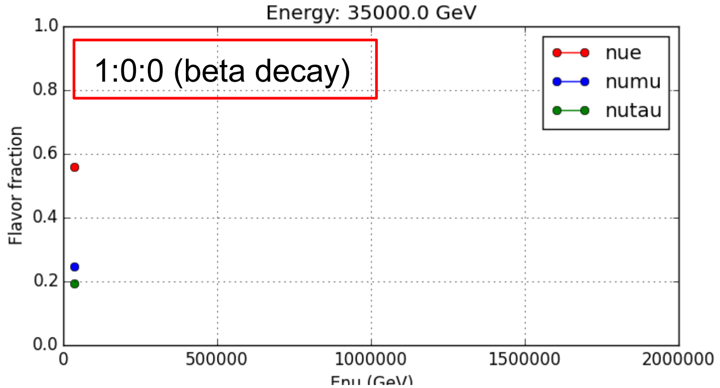
7. Neutrino flavour ratio with new physics

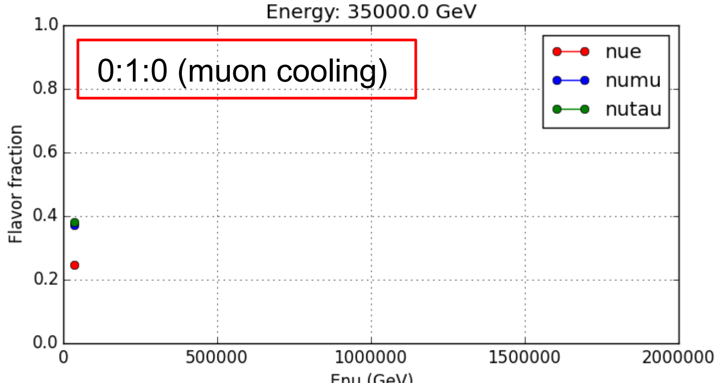
Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

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

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





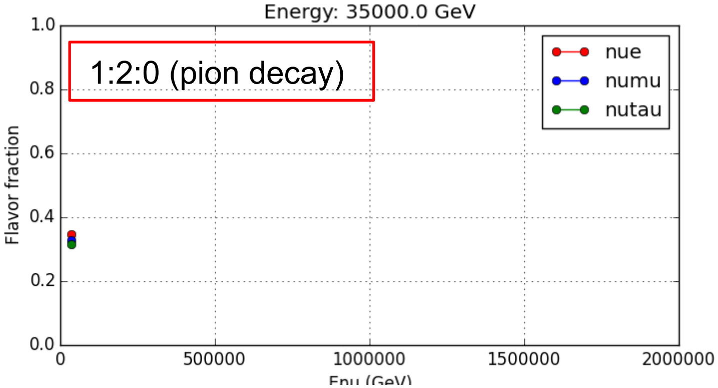


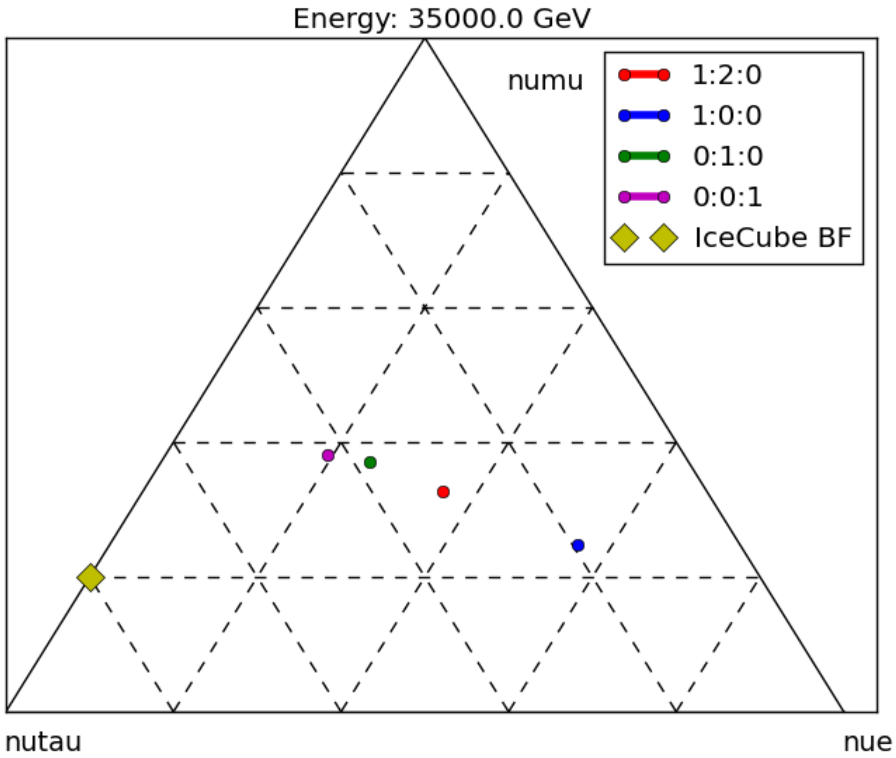
Arugüelles, TK, Salvado, PRL115(2015)161303

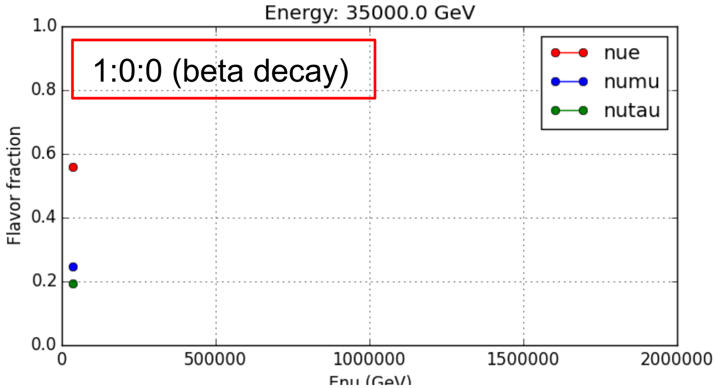
7. Neutrino flavour ratio with new physics

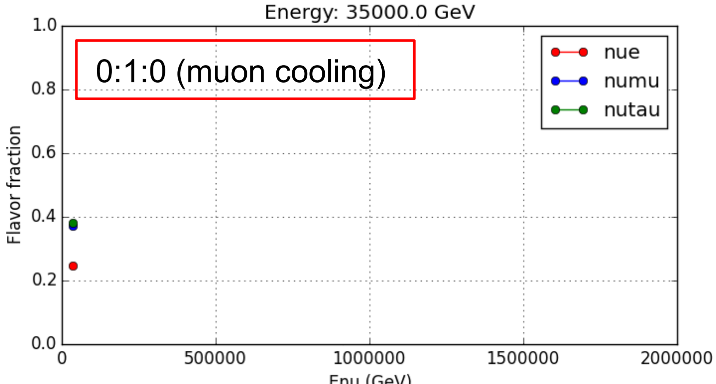
Any new physics can end up in the effective Hamiltonian
- neutrino mixing depends on energy
- there is strong initial flavour ratio dependency

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









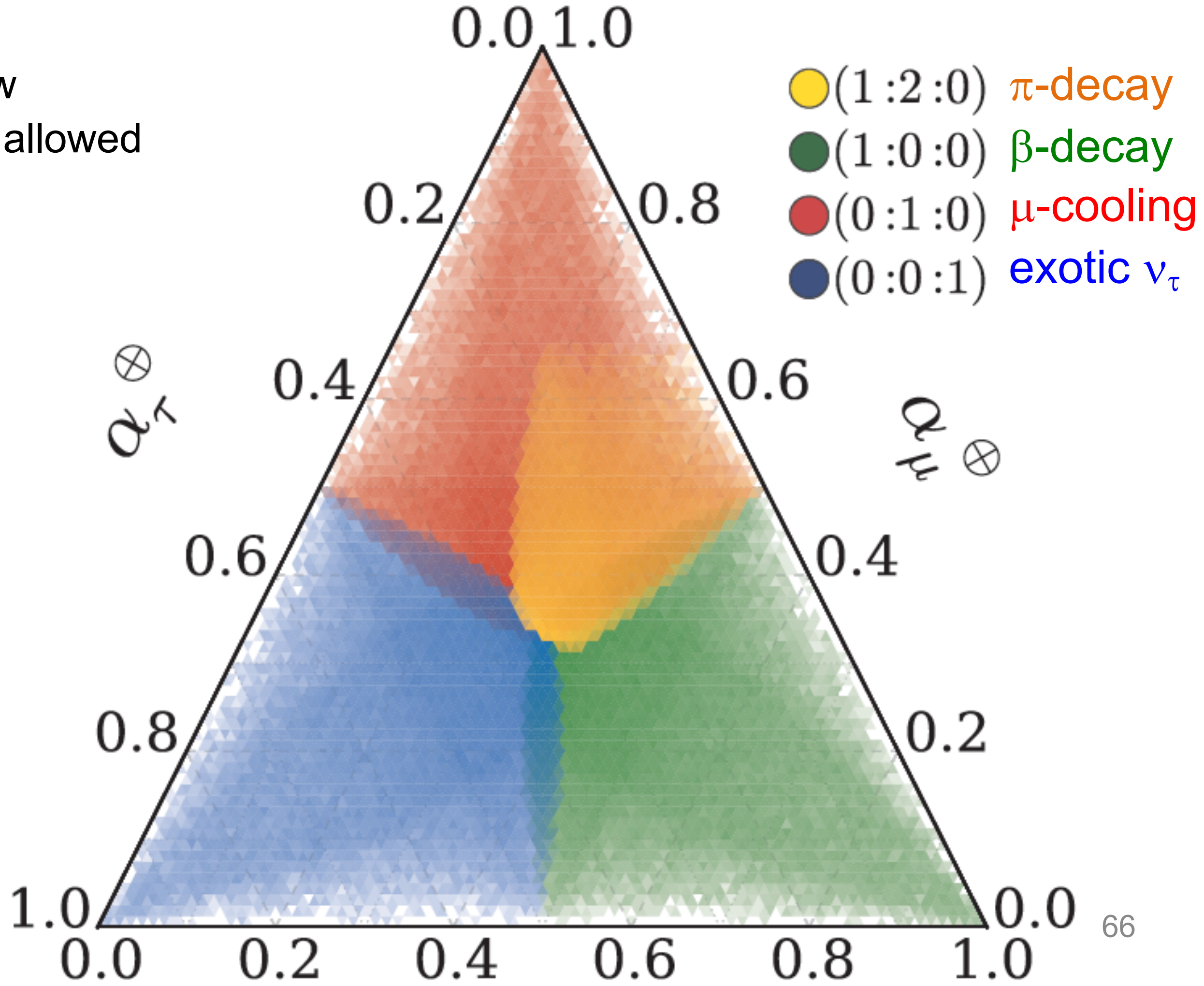
Arugüelles, TK, Salvado, PRL115(2015)161303

7. Flavor triangle histogram

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

Under the current limits on new physics, any flavour ratios are allowed

current best limits on new physics (a~10^{-24} GeV and c~10^{-28})



Arugüelles, TK, Salvado, PRL115(2015)161303

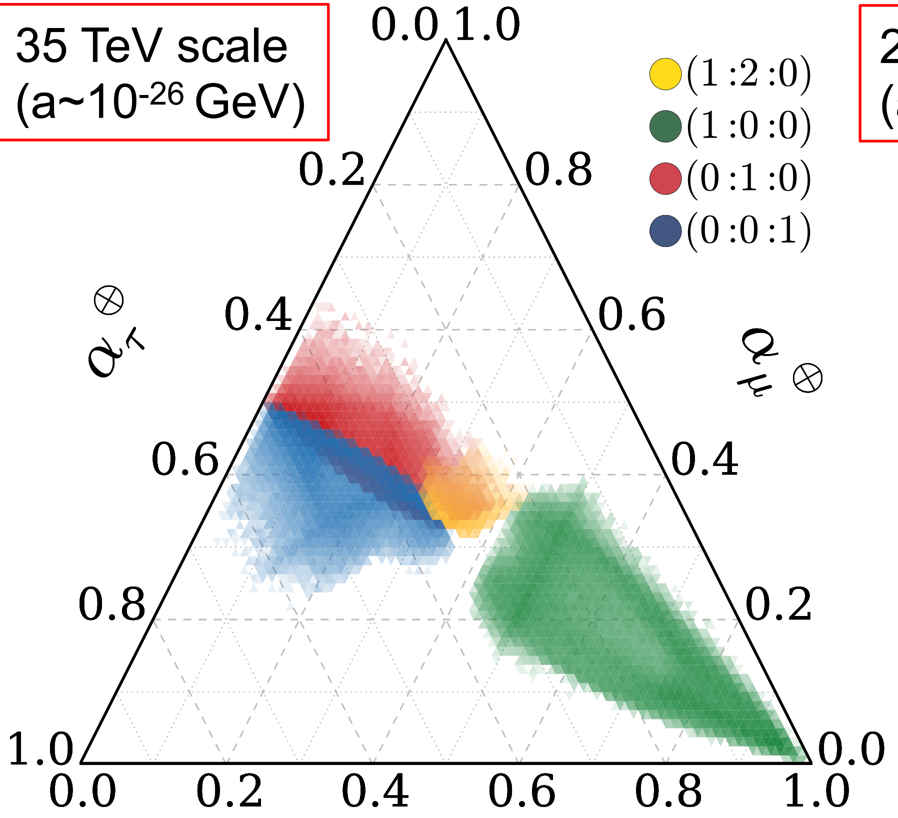
7. Flavor triangle histogram

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

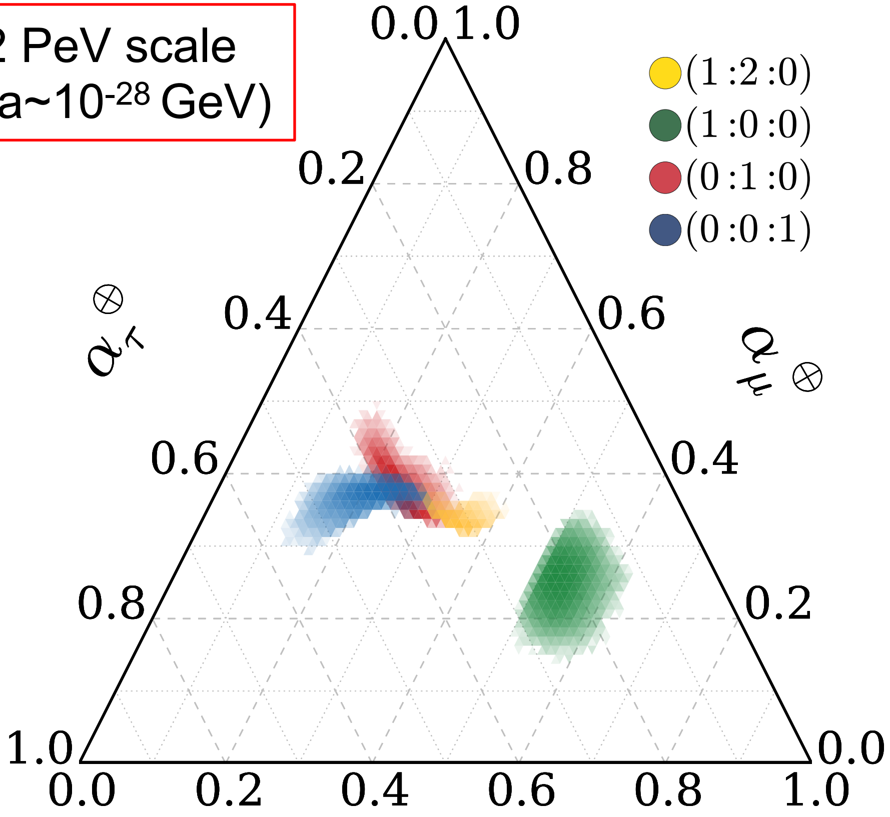
$$h_{eff}=\frac{1}{2E}\begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{e\tau} \\ m^{2*}_{e\mu} & m^2_{\mu\mu} & m^2_{\mu\tau} \\ m^{2*}_{e\tau} & m^{2*}_{\mu\tau} & m^2_{\tau\tau} \end{pmatrix}+\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau}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

d=3 operator new physics

35 TeV scale
(a~10^{-26} GeV)



2 PeV scale
(a~10^{-28} GeV)



The flavour ratio is the most powerful tool to explore any new physics

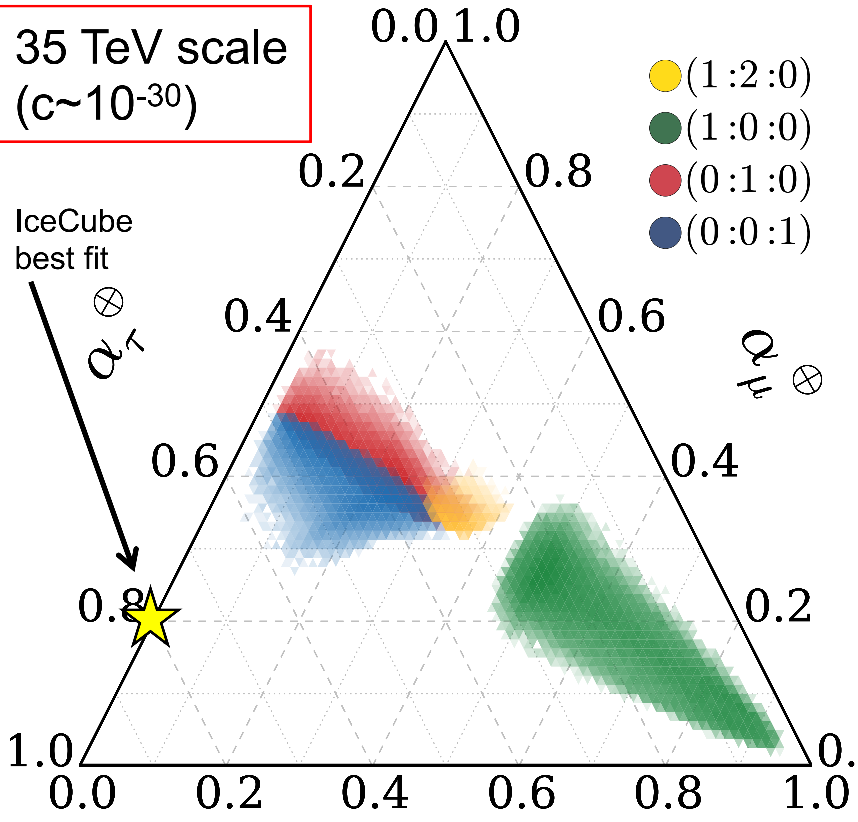
Arugüelles, TK, Salvado, PRL115(2015)161303

7. Flavor triangle histogram

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

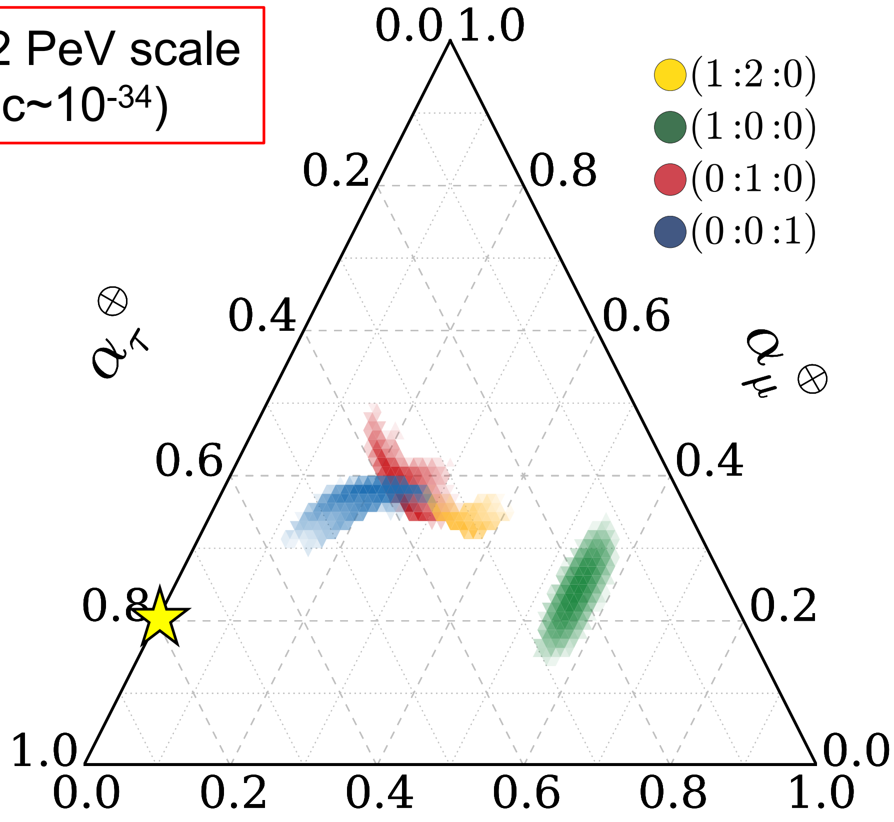
$$h_{eff} = \frac{1}{2E}\begin{pmatrix} m^{2}_{ee} & m^{2}_{e\mu} & m^{2}_{e\tau} \\ m^{2*}_{e\mu} & m^{2}_{\mu\mu} & m^{2}_{\mu\tau} \\ m^{2*}_{e\tau} & m^{2*}_{\mu\tau} & m^{2}_{\tau\tau} \end{pmatrix} + E\cdot\begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^{*}_{e\mu} & c_{\mu\mu} & c_{\mu\tau}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

d=4 operator new physics



35 TeV scale ($c \sim 10^{-30}$)

IceCube best fit



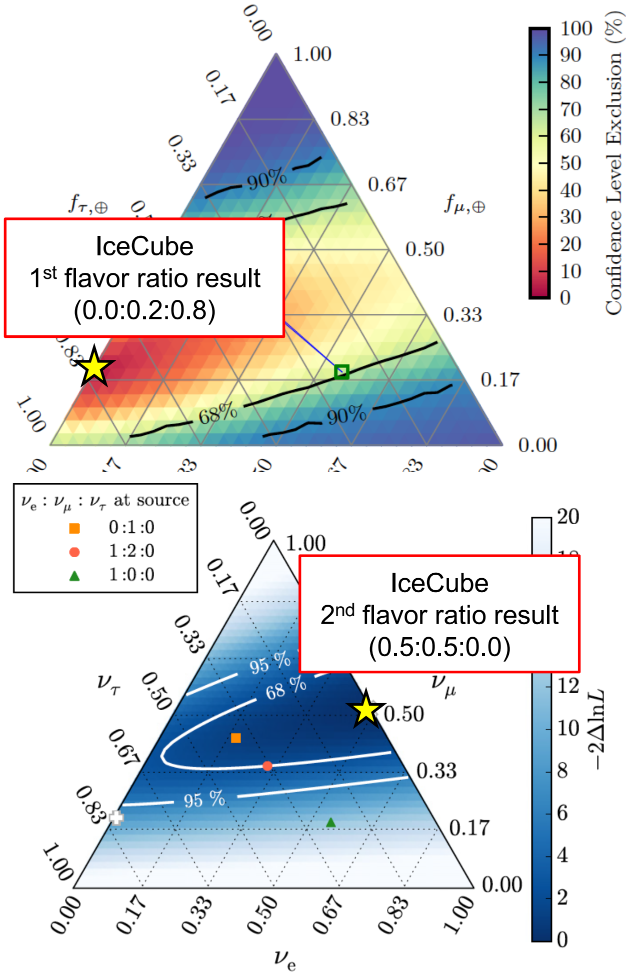
2 PeV scale ($c \sim 10^{-34}$)

The flavour ratio is the most powerful tool to explore any new physics

IceCube collaboration, PRL114(2015)171102, Astro.J.809:98(2015)
Argüelles, TK, Salvado, PRL115(2015)161303

7. Neutrino flavour ratio with new physics

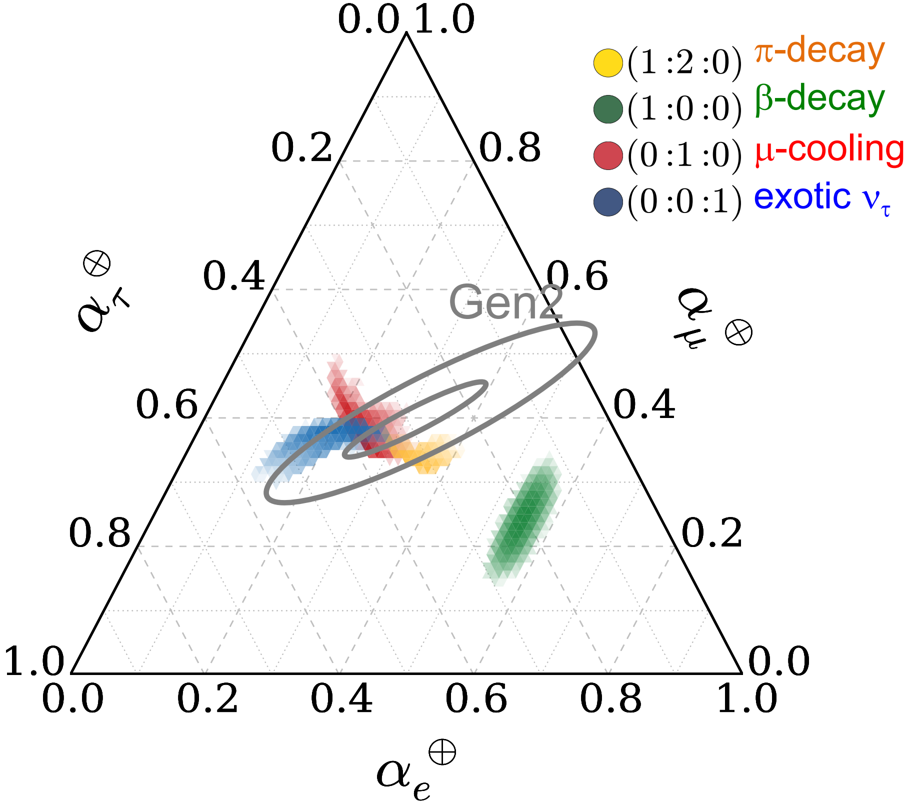
Astrophysical neutrinos are more sensitive to new physics than atmospheric neutrinos, and the sensitivity is at least order 2 higher.



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

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

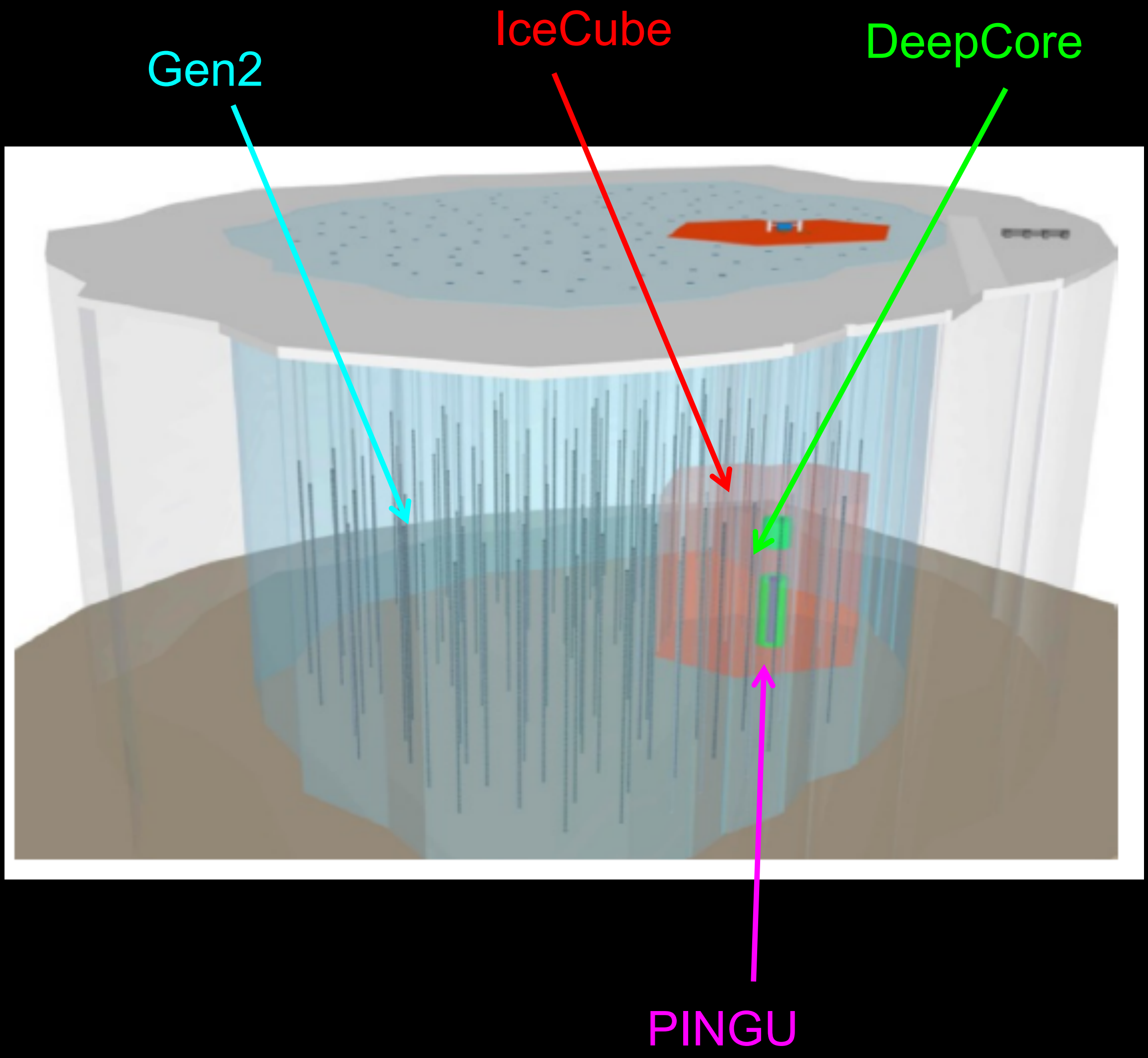
Standard flavour triangle (NuFit2014) and Gen2 potential



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

IceCube-Gen2,arXiv:1412.5106;1510.05228

7. IceCube-Gen2



Bigger IceCube and denser DeepCore can push their physics

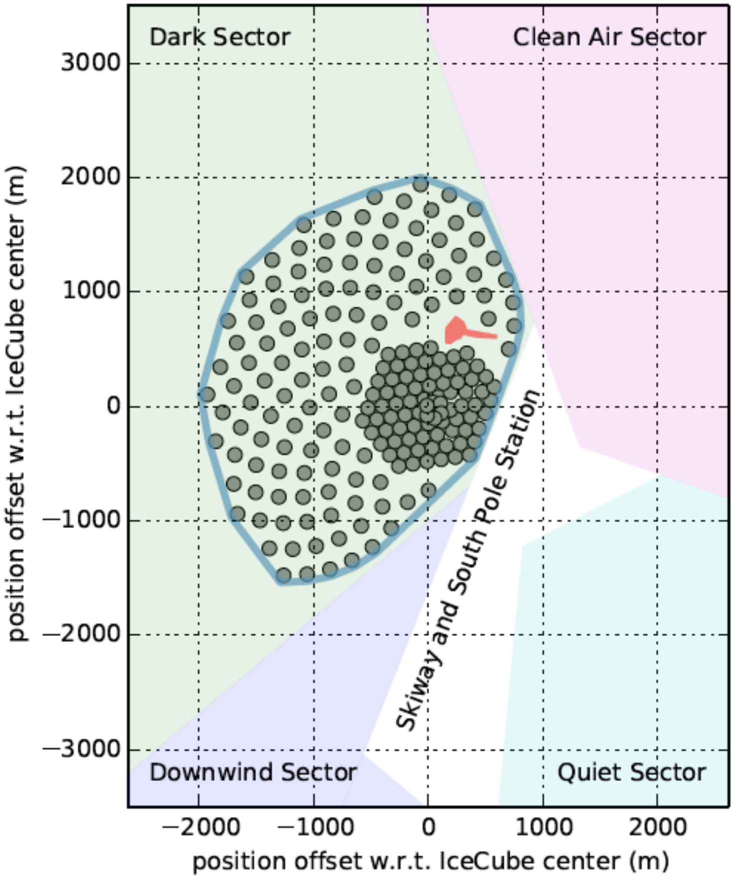
Gen2
Larger string separations to cover larger area

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

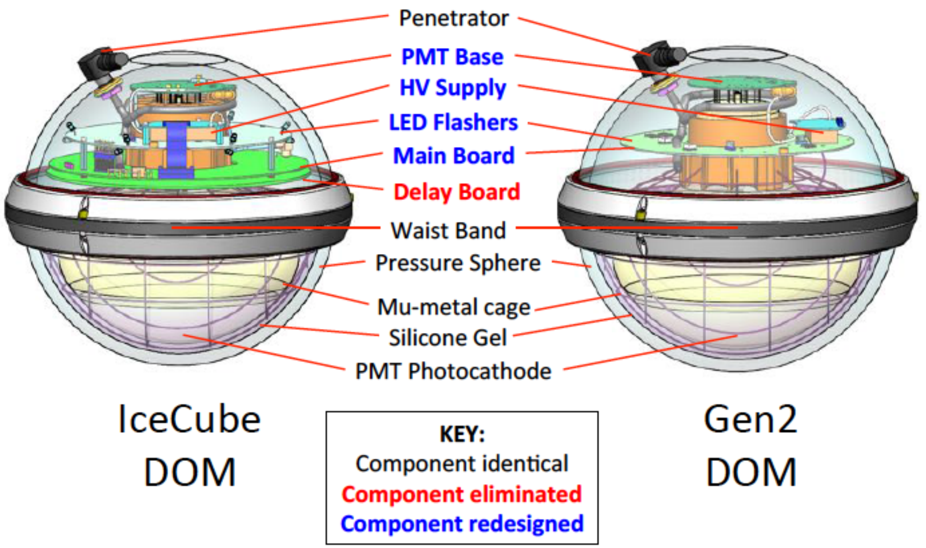
IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

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

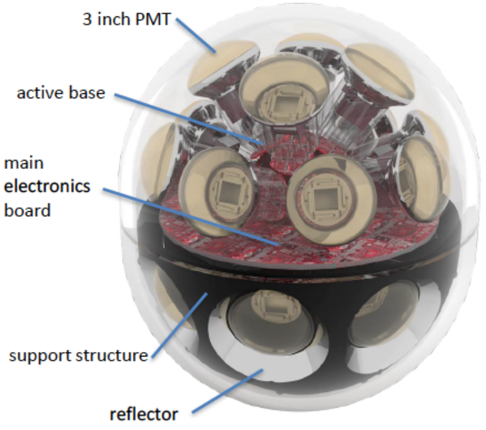
3. IceCube-Gen2

Ice is clear than we thought

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

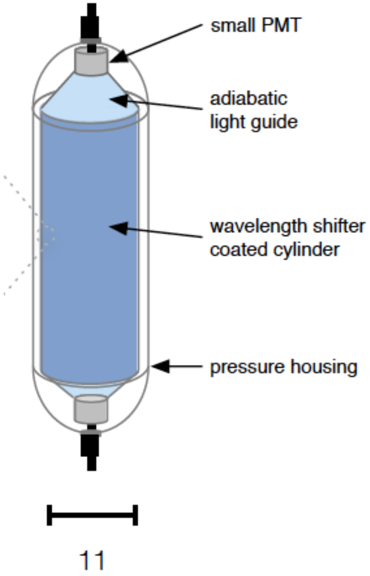
- 120 new strings with 80 DOMs, 240 m separation, x10 coverage
- Variety of new detectors are under development

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



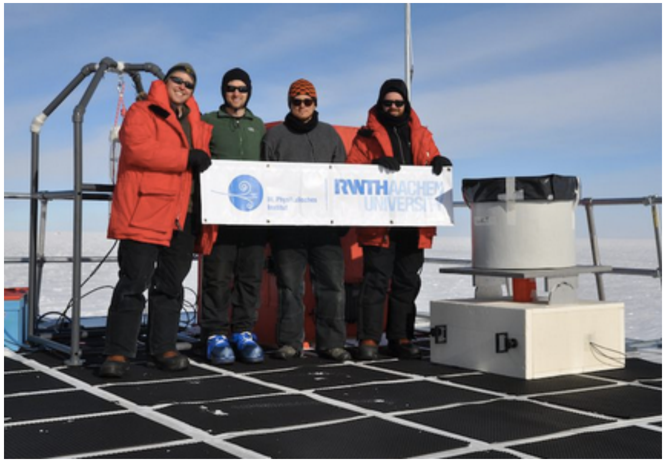
and more…

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

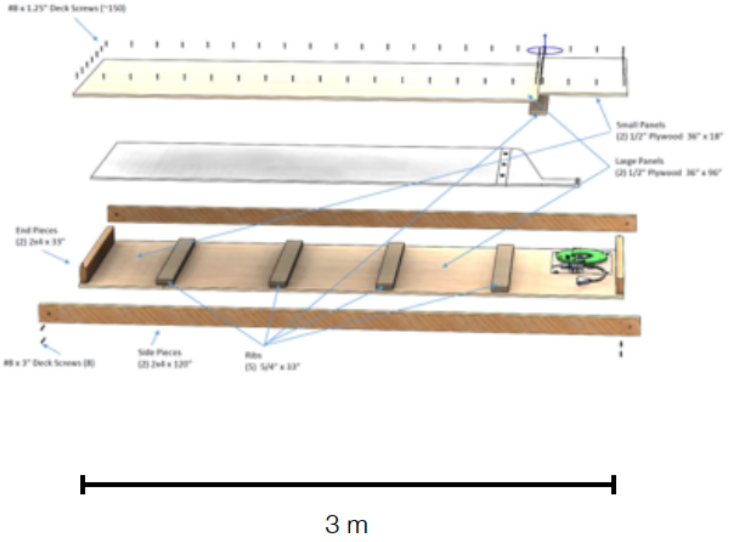
3. IceCube-Gen2

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

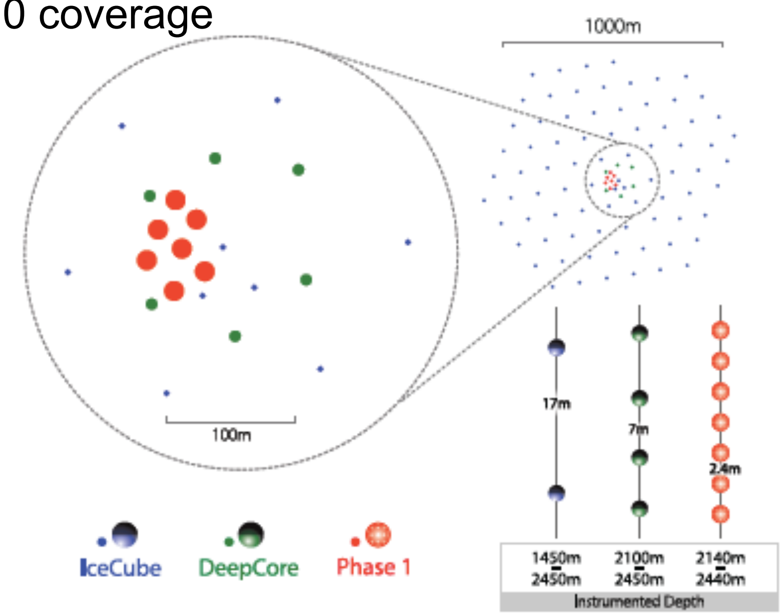


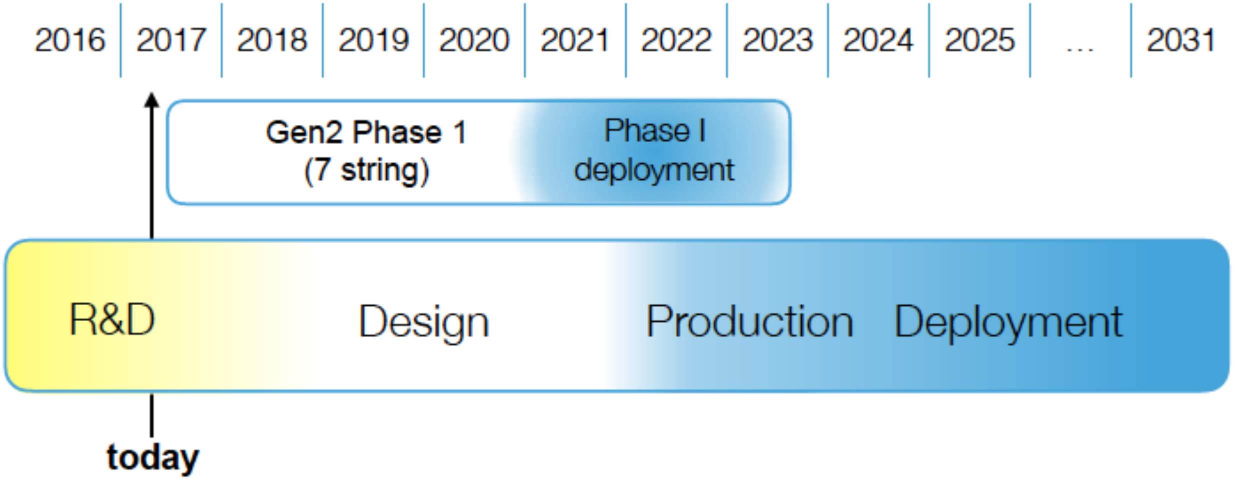
IceCube-Gen2,arXiv:1412.5106;1510.05228
ICRC2017 proceedings, arXiv:1710.01207

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

Staged approach
- Phase 1 proposal will be submitted in Fall 2018
- 7 new strings for low energy physics
- 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

IceCube-Gen2 in UK

Manchester: J. Evans, S. Söldner-Rembold, S. Wren
Oxford: S. Sarkar
Queen Mary: K. Farrag, T. Katori, S. Mandalia

IceCube data analysis
- Mass ordering analysis on DeepCore
- Test of quantum gravity arXiv:1709.03434

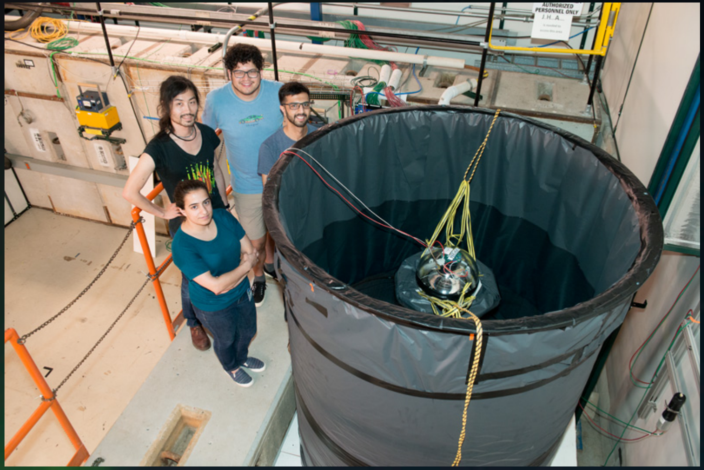
Software development
- Atmospheric flux systematics Evans et al, PRD95(2017)023012
- Hadronization systematics Katori et al, JPhysG42(2015)115004
- PINGU fast oscillation analysis code arXiv:1803.05390

Hardware
- FEB firmware development
- DOM Fermilab beam test paper in preparation

Analysis coordination
- Gen2 low E convener (Justin Evans)

On top of these, there is a large theory contribution from Oxford (Subir Sarkar)

LHCb for prompt-ν production, JHEP02(2016)130
High energy neutrino cross section, JHEP08(2011)042
etc



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.

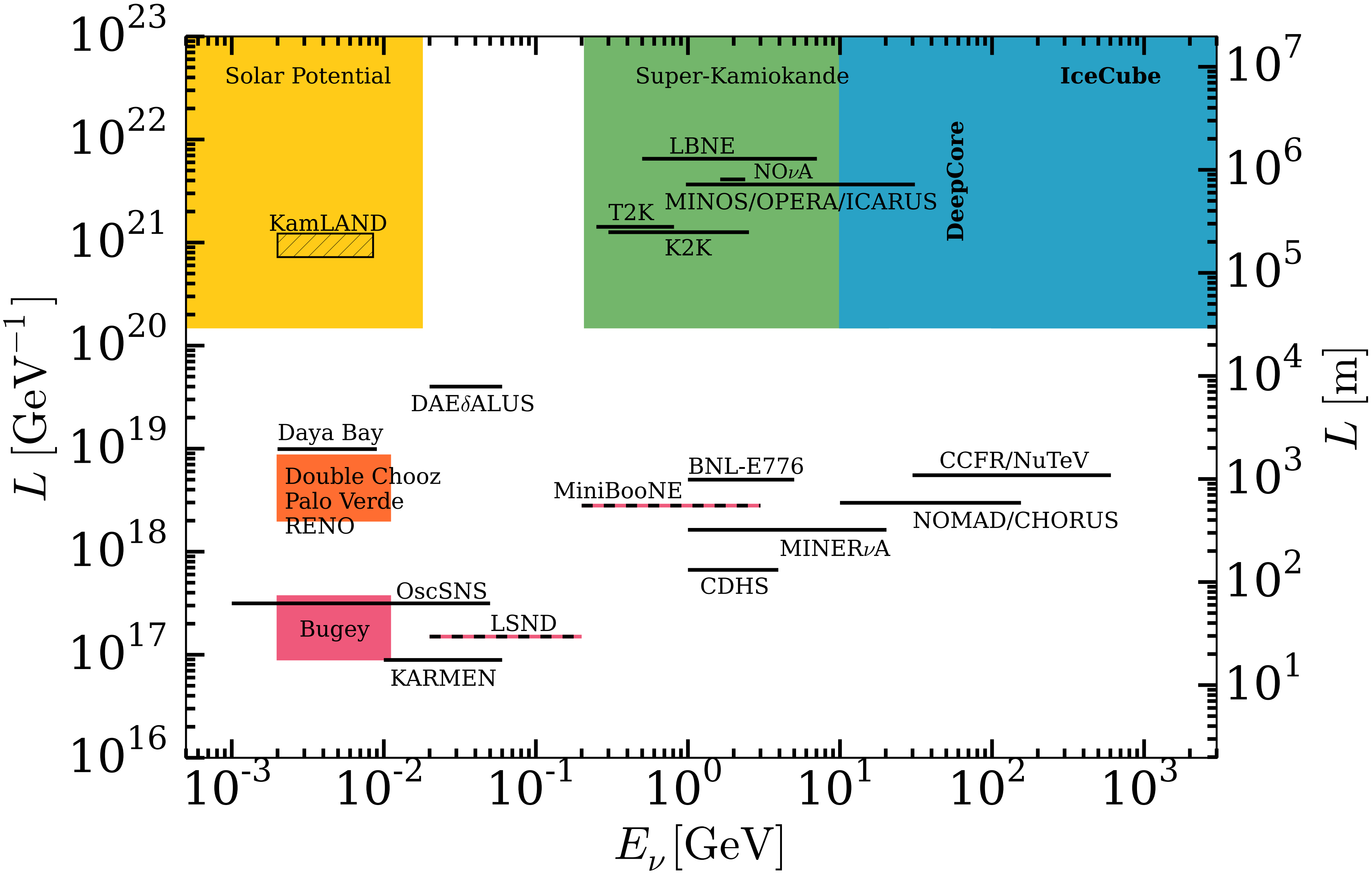

IceCube-Gen2 collaboration

Thank you for your attention!

backup

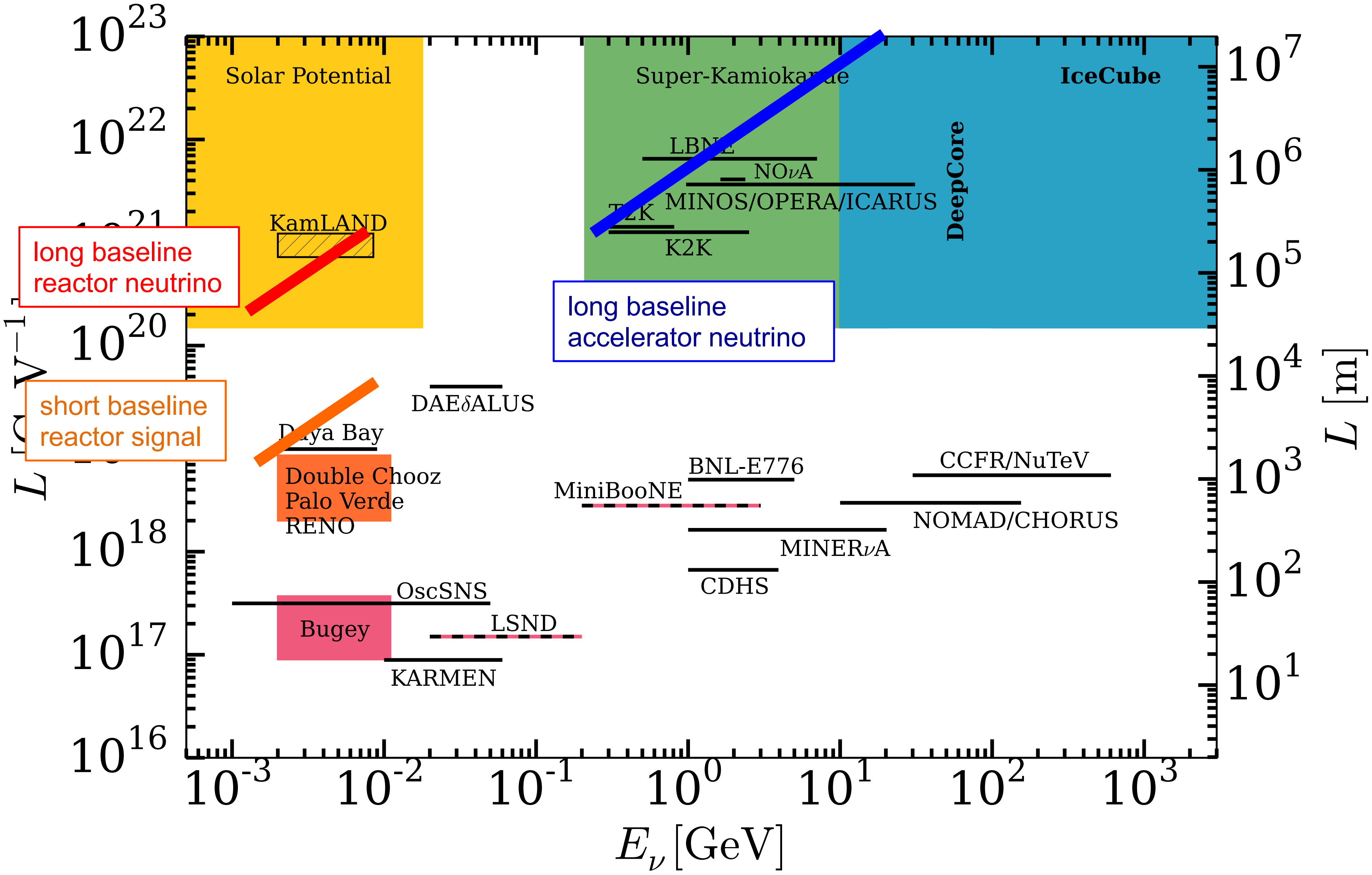
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

3. Lorentz violation with neutrino oscillation



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

3. Lorentz violation with neutrino oscillation



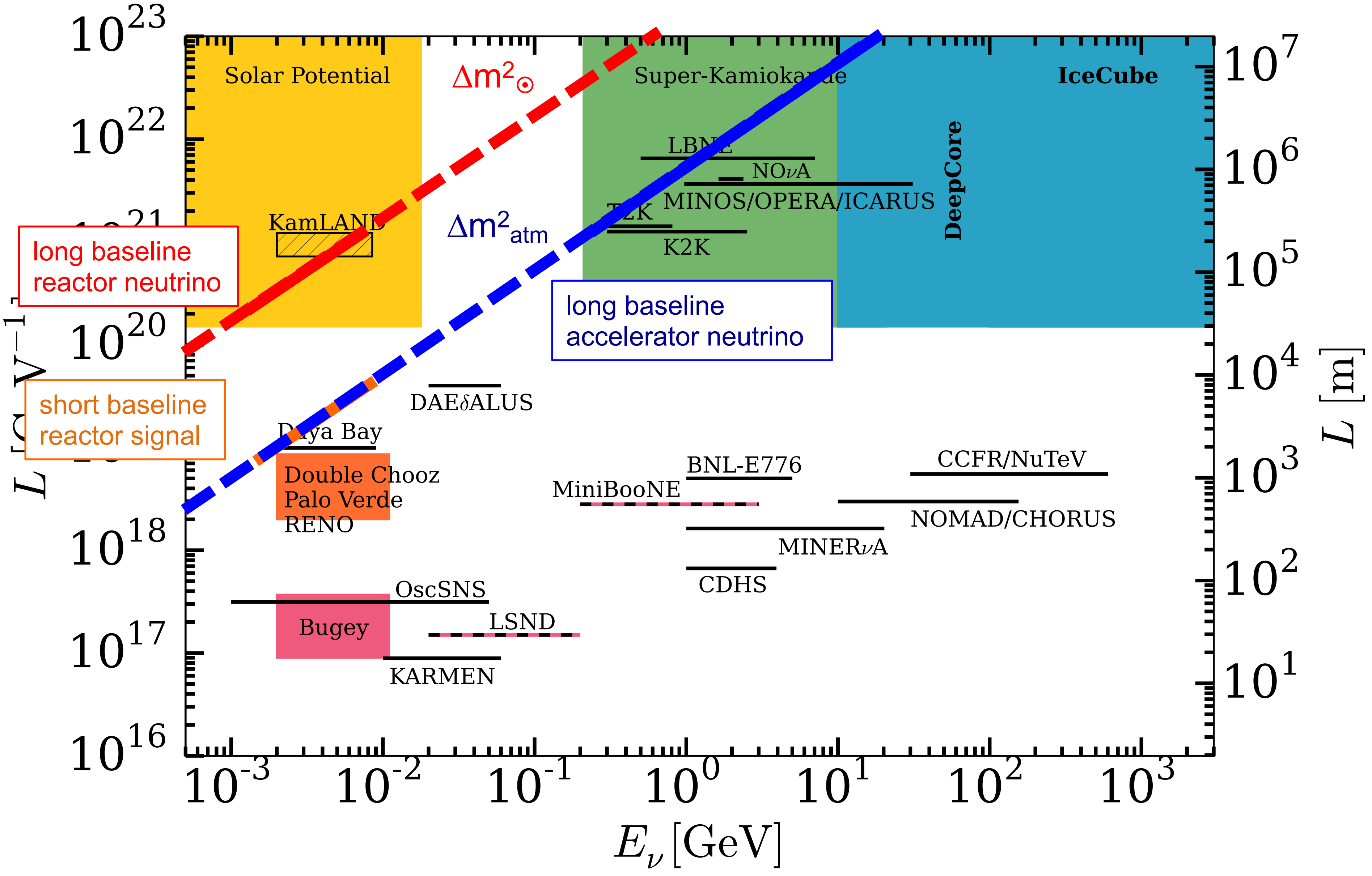
long baseline
reactor neutrino

long baseline
accelerator neutrino

short baseline
reactor signal

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

3. Lorentz violation with neutrino oscillation



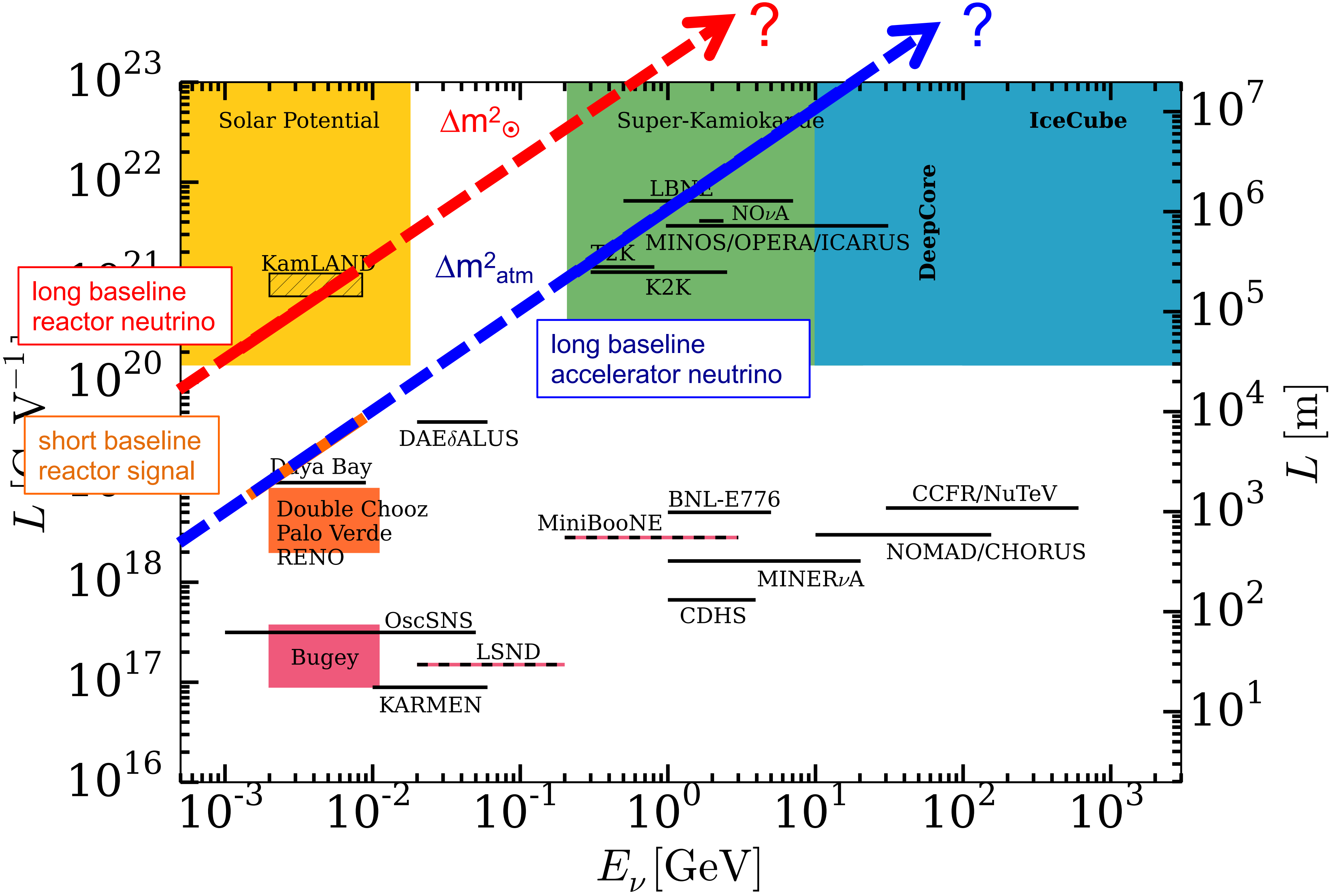
long baseline
reactor neutrino

short baseline
reactor signal

long baseline
accelerator neutrino

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

3. Lorentz violation with neutrino oscillation



long baseline
reactor neutrino

short baseline
reactor signal

long baseline
accelerator neutrino

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

3. Lorentz violation with neutrino oscillation

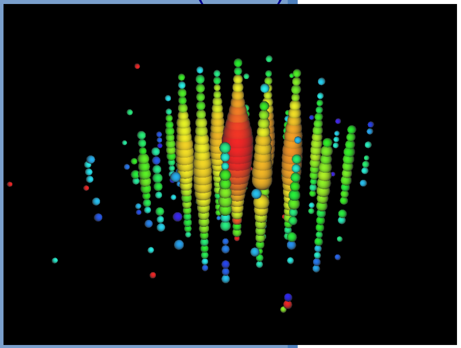
extra galactic
neutrino potential

?

?

1Mpc(~Andromeda)

IceCube collaboration
PRL111(2013)021103

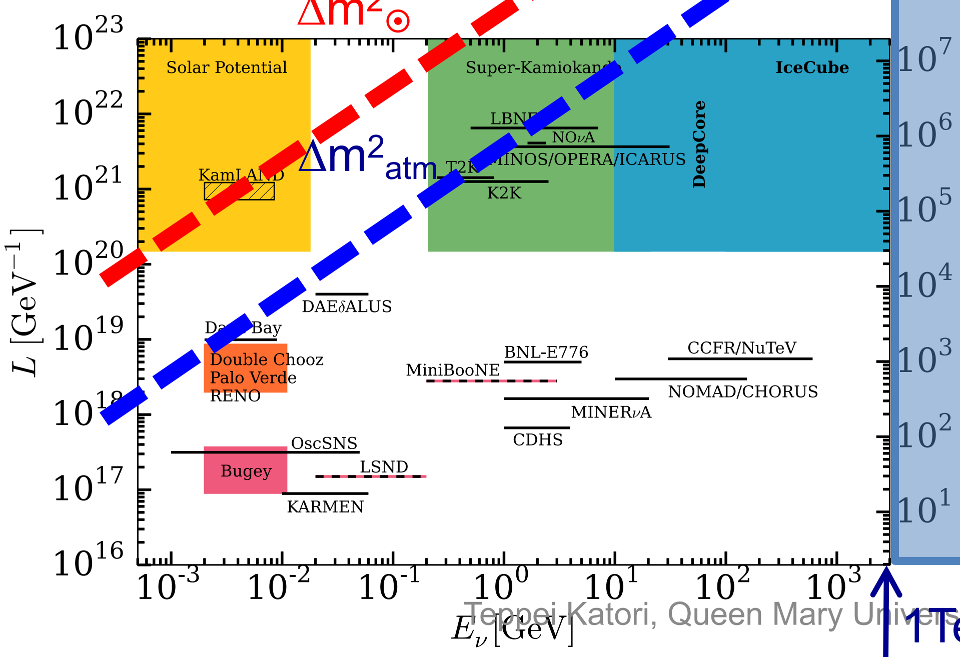


TeV neutrino
potential

PeV neutrino
potential

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

Δm^2_{atm}



1TeV

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

5. 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 : constrained

Fit methods

- Frequentist Wilk's theorem
- Bayesian Markov Chain Monte Carlo

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

Arugüelles, TK, Salvado, PRL115(2015)161303

7. New physics operator

Arbitrary new physics are described in terms of effective operators

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

- 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

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

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

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

Arugüelles, TK, Salvado, PRL115(2015)161303
IceCube,PRD82(2010)112003, SuperKamiokande,PRD91(2015)052003

7. Scale of new physics

a+c·E+…

First, we need to set the scale of new physics

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

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

Arugüelles, TK, Salvado, PRL115(2015)161303
Haba, Murayama, PRD63(2001)053010

7. 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

7. 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

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

Parke and Ross-Lonergan, PRD93(2016)113009

7. τ-appearance to complete lepton mixing matrix

If we want to look for new physics from unitarity, we need τ-appearance oscillation experiment
→ atmospheric neutirno oscillation