New Physics with Atmospheric Neutrinos

outline

1. New physics with atmospheric neutrinos
2. Sterile neutrinos
3. Non-standard Interaction
4. Neutrino decoherence
5. Neutrino Lorentz violation
6. Conclusion

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

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Teppei Katori for the IceCube collaboration
King's College London
PAHEN 2019
Humboldt-Universität Berlin, Germany,
September 27, 2019

1. **New physics with atmospheric neutrinos**
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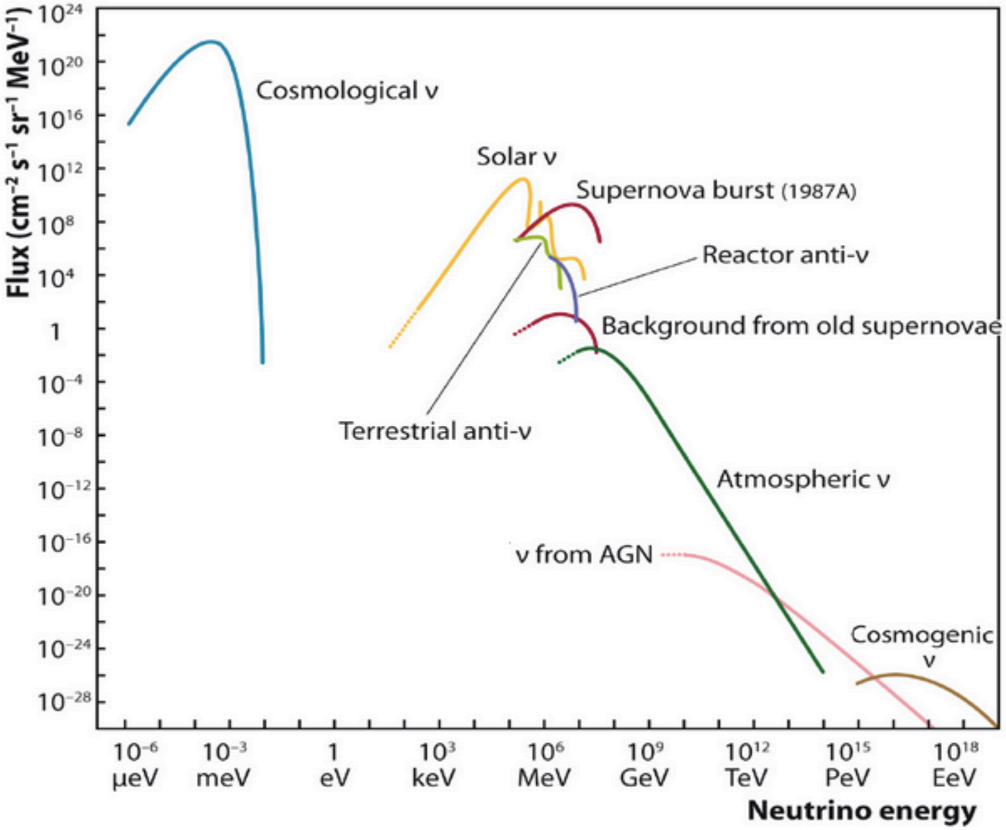
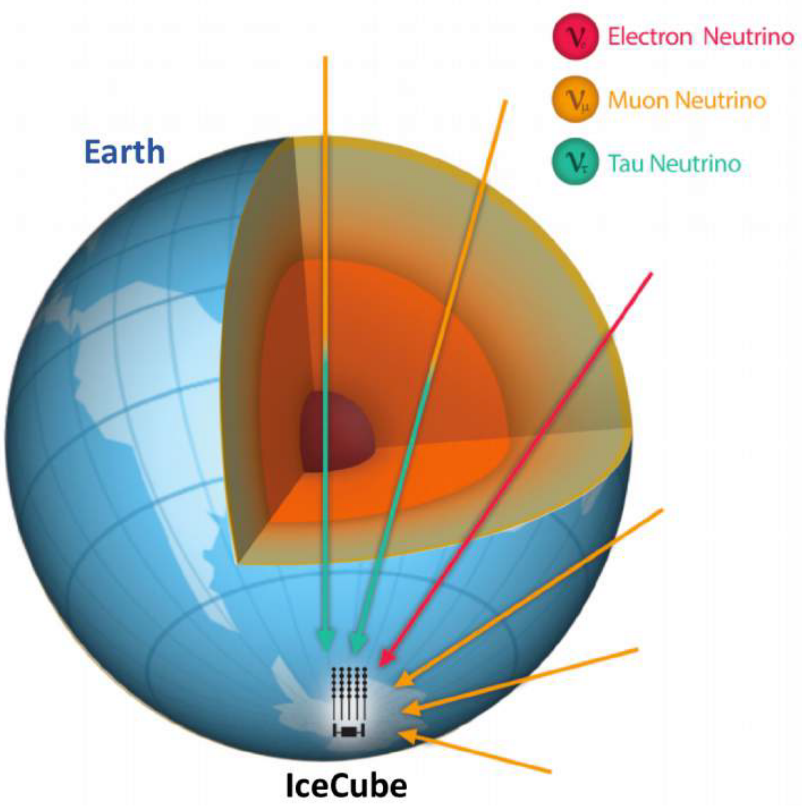
Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.

→ They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the high density material (~13g/cm^3) on Earth.





Super-Kamiokande, PRD94(2016)052001

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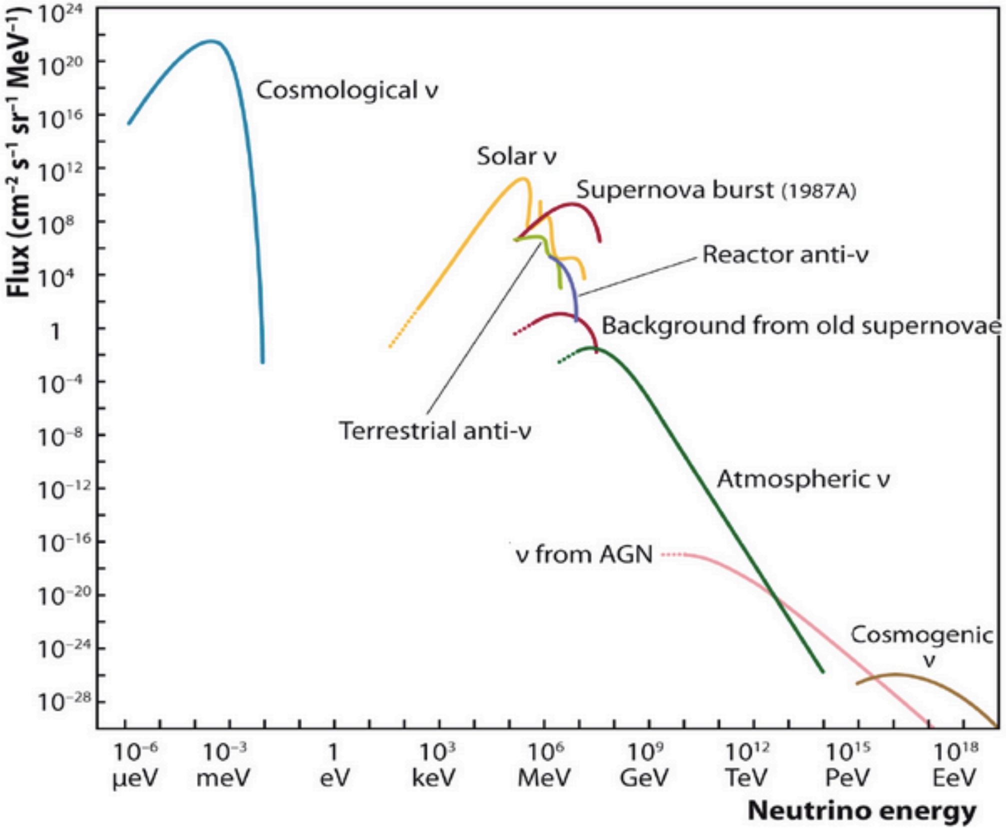

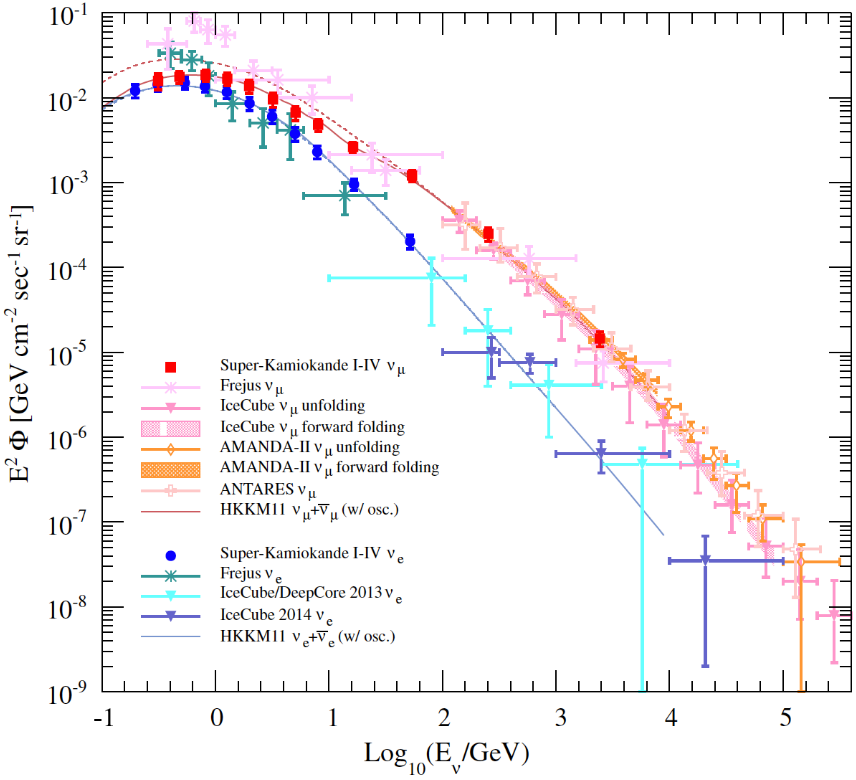

Atmospheric neutrinos are high statistics, but not as high as we hope

Super-Kamiokande,PRL93(2004)101801

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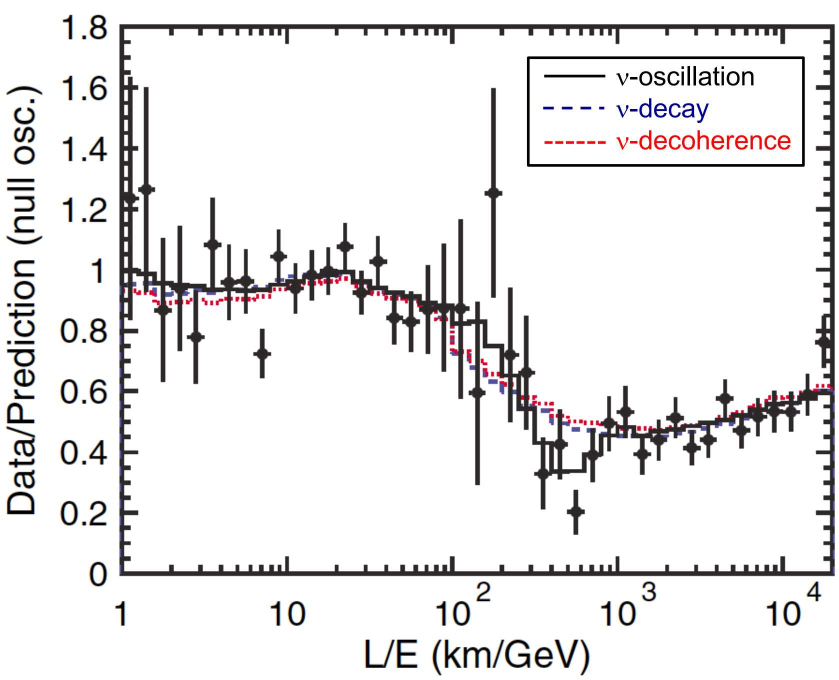

$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC}, \quad P_{\alpha\beta} = \left| \langle \nu_\alpha | U(h_{eff}, t) | \nu_\beta \rangle \right|^2$$

$$M^2 = \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 \\ (m_{e\mu}^2)^* & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ (m_{\tau e}^2)^* & (m_{\mu\tau}^2)^* & m_{\tau\tau}^2 \end{pmatrix}, V_{CC} = \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Massive neutrino oscillation describes atmospheric neutrino data

↓

BSM physics is second order effect of atmospheric neutrinos

IceCube, PRD97(2018)072009

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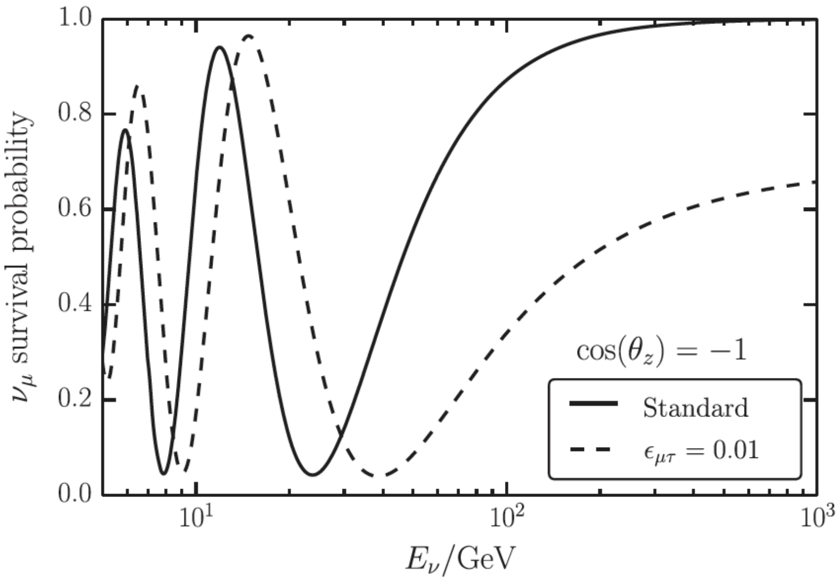

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Neutrino oscillation

- quantum interference
- macroscopic phase shift (=count of neutrinos) by microscopic effects

e.g.) Non-standard interaction (~10^{-24} GeV)

cf) The highest precision hydrogen 1S-2S transition (PRL107(2011)203001)

Fractional frequency uncertainty ~ 4x10^{-15} → new physics sensitivity ~10^{-23} GeV

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High energy + high density
→ 1eV sterile neutrino MSW resonance

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High energy + long baseline
- Open quantum system
→ Neutrino wave decoherence

High energy + long baseline
- Effective field theory
→ Lorentz violation (LV)

High energy + long baseline + high density
- Effective field theory
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$$M_s^2 = \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 & m_{es}^2 \\ \left(m_{e\mu}^2\right)^* & m_{\mu\mu}^2 & m_{\mu\tau}^2 & m_{\mu s}^2 \\ \left(m_{\tau e}^2\right)^* & \left(m_{\mu\tau}^2\right)^* & m_{\tau\tau}^2 & m_{\tau s}^2 \\ \left(m_{es}^2\right)^* & \left(m_{\mu s}^2\right)^* & \left(m_{\tau s}^2\right)^* & m_{ss}^2 \end{pmatrix}$$

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$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC}, \quad P_{\alpha\beta}^{OQS} = Tr\left|\rho_\alpha(t)\rho_\beta(0)\right|^2$$

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$$\frac{d\rho}{dt} = -i\left[h_{eff}, \rho\right] - D[\rho]$$

$$P_{\alpha\beta} = A \cdot \left[1 - e^{-\gamma_{ij}} cos\left(\frac{\Delta m_{ij}^2}{2E} L\right)\right]$$

damping of oscillation

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$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC} + a^{(3)} + Ec^{(4)} + E^2 a^{(5)} + E^3 c^{(6)} \dots$$

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$$a^{(3)} \sim \begin{pmatrix} a_{ee}^{(3)} & a_{e\mu}^{(3)} & a_{\tau e}^{(3)} \\ a_{e\mu}^{(3)*} & a_{\mu\mu}^{(3)} & a_{\mu\tau}^{(3)} \\ a_{\tau e}^{(3)*} & a_{\mu\tau}^{(3)*} & a_{\tau\tau}^{(3)} \end{pmatrix}$$

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$$P_{\alpha\beta} \sim sin^2\left(E^{d-3} a^{(d)} L\right)$$

high-energy limit oscillation phase

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$$NSI = V_{CC} \frac{n_f}{n_e} \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{\tau e} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

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- Effective field theory
→ Non-standard interaction NSI)

IceCube, Nature Physics14,961(2018), PRD97(2018)072009, Salvado et al., JHEP01(2017)141, Coloma et al.,EPJC(2018)78:614
Super-Kamiokande, PRD91(2015)052003, PRD84(2011)113008,

1. New physics search with neutrino interferometry

New physics sensitivity with atmospheric neutrino is limited by Δm^2_{atm}. In order to discover BSM physics, scale of BSM physics needs to be order ~ $\Delta m^2_{atm}/4E$

New physics operators without energy dependence

Decoherence and LV in IceCube (~20 TeV)

- Naïve sensitivity ~ 10^{-26} GeV

→ Decoherence limit, $\gamma_0^{n=0} \sim 10^{-24}$ GeV

→ LV limit, $a^{(3)} \sim 10^{-24}$ GeV

Damping term (decoherence)

$$\gamma_{ij} = \gamma^0_{ij} \cdot \left(\frac{E}{GeV}\right)^n$$

Decoherence and NSI in DeepCore (~50 GeV)

- naïve sensitivity ~ 10^{-23} GeV

→ Decoherence limit, $\gamma_0^{n=0} \sim 10^{-23}$ GeV

→ NSI limit, $\varepsilon \sim 10^{-2}$ ($V_{cc} x \varepsilon \sim 10^{-24}$ GeV)

Effective LV new operator

$$a^{(d)} \cdot E^{d-3}$$

Due to suppression of mass term, higher energy neutrinos often have higher sensitivity to new physics

IceCube, Nature Physics14,961(2018), PRD97(2018)072009, Salvado et al., JHEP01(2017)141, Coloma et al.,EPJC(2018)78:614
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New physics operators with energy dependence

Decoherence with n=2 in IceCube (~20 TeV)
- Naïve sensitivity ~ 10^{-34} GeV

→ Decoherence limit, $\gamma_0^{n=2}$ ~ 10^{-33} GeV

Damping term (decoherence)

$$\gamma_{ij} = \gamma_{ij}^0 \cdot \left(\frac{E}{GeV}\right)^n$$

LV with dimension-6 operator in IceCube (~20 TeV)
- naïve sensitivity ~ 10^{-39} GeV^{-2}

→ LV limit, $c^{(6)}$ ~ 10^{-36} GeV^{-2}

Effective LV new operator

$$c^{(d)} \cdot E^{d-3}$$

Due to suppression of mass term, higher energy neutrinos often have higher sensitivity to new physics

Some new physics may show up only at high-energy, and IceCube is good at find them (=high-energy)

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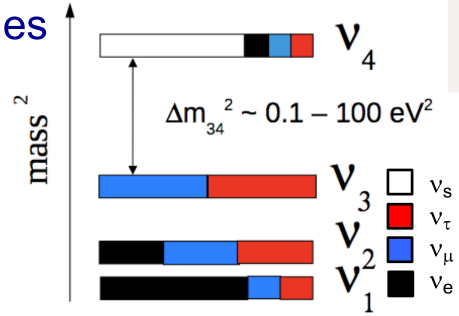
MiniBooNE,PRL121(2018)221801
Diaz et al., ArXiv:1906.00045

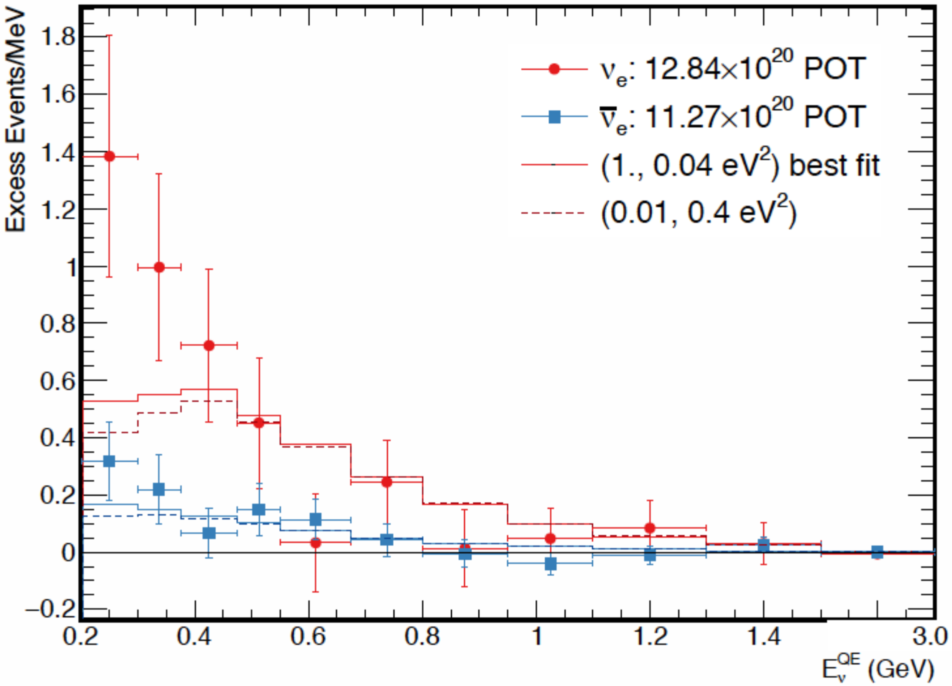
2. 1eV sterile neutrino

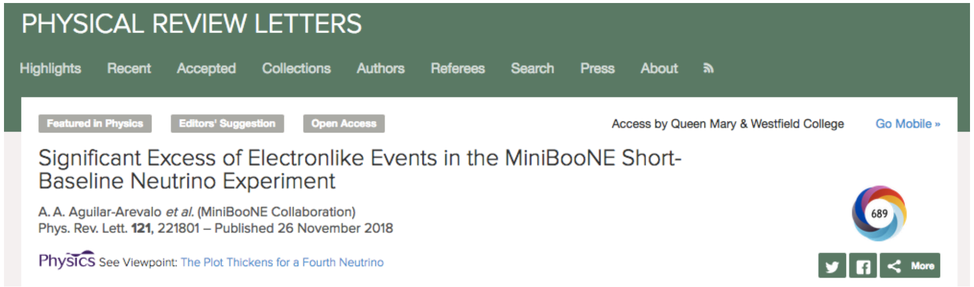
Short-baseline anomalies

- LSND excess
- MiniBooNE excess
- Gallium anomaly
- Reactor anomaly



MiniBooNE data excess



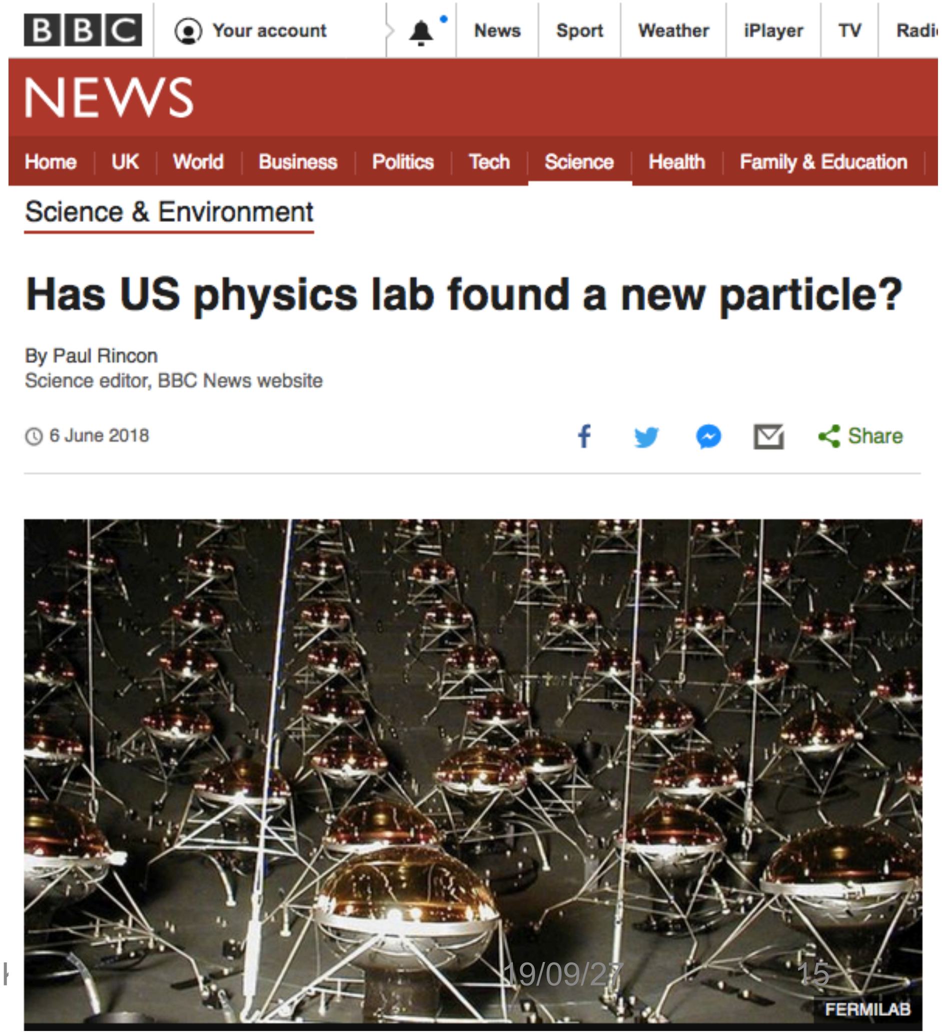


Access by Queen Mary & Westfield College

Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration)
Phys. Rev. Lett. **121**, 221801 – Published 26 November 2018

Physics See Viewpoint: The Plot Thickens for a Fourth Neutrino



Science & Environment

Has US physics lab found a new particle?

By Paul Rincon
Science editor, BBC News website

6 June 2018

IceCube, PRL117(2016)071801
Hignight, NuFact 2019

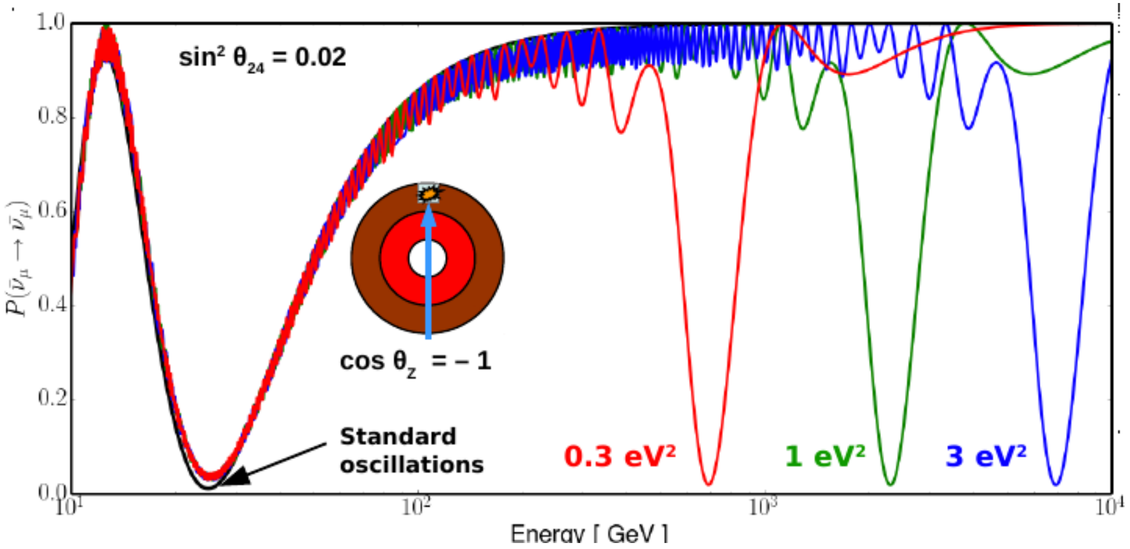
2. 1eV sterile neutrino

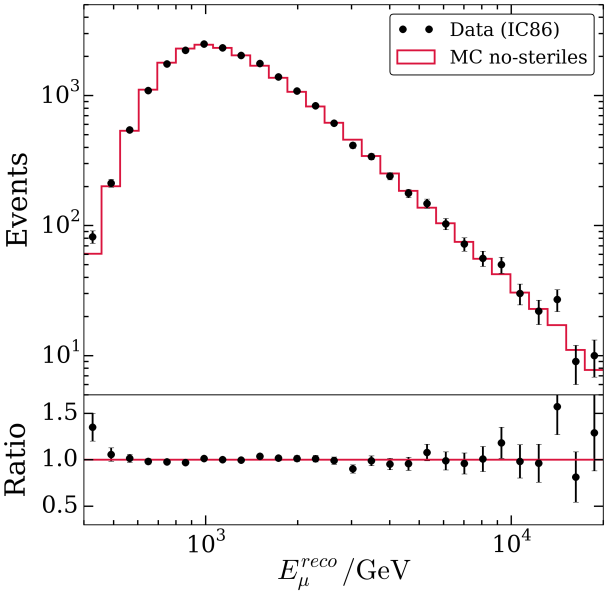
1eV sterile neutrino MSW resonance

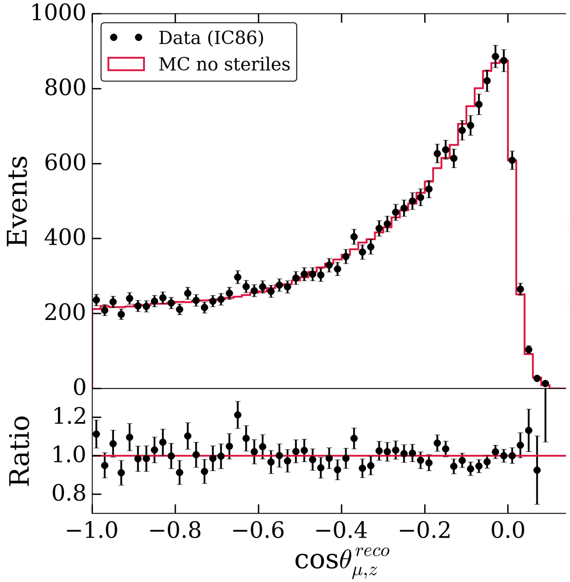
- TeV neutrinos undergo resonance

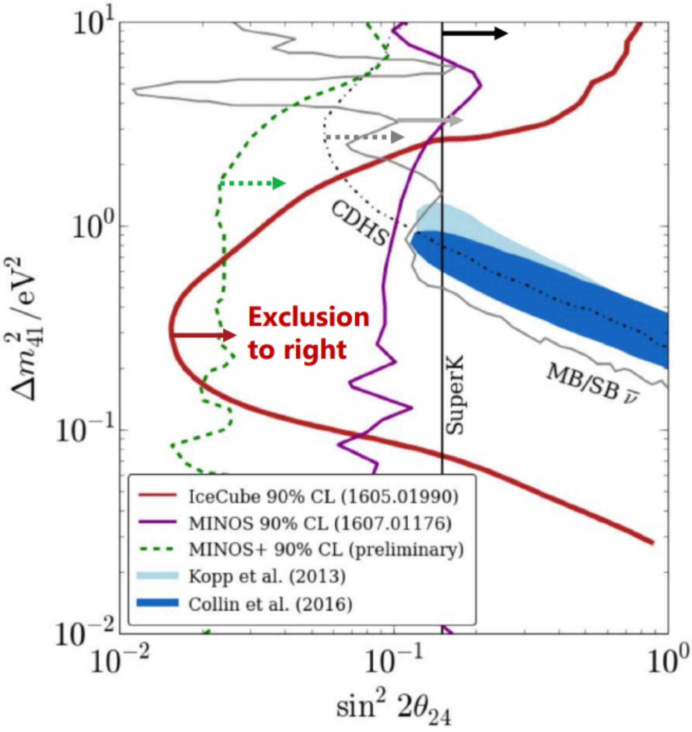
Through going muon sample

- pure ν_μ up-going muon
- up to 20 TeV
- Data-MC agree well, set limit









IceCube, PRL117(2016)071801
Hignight, NuFact 2019

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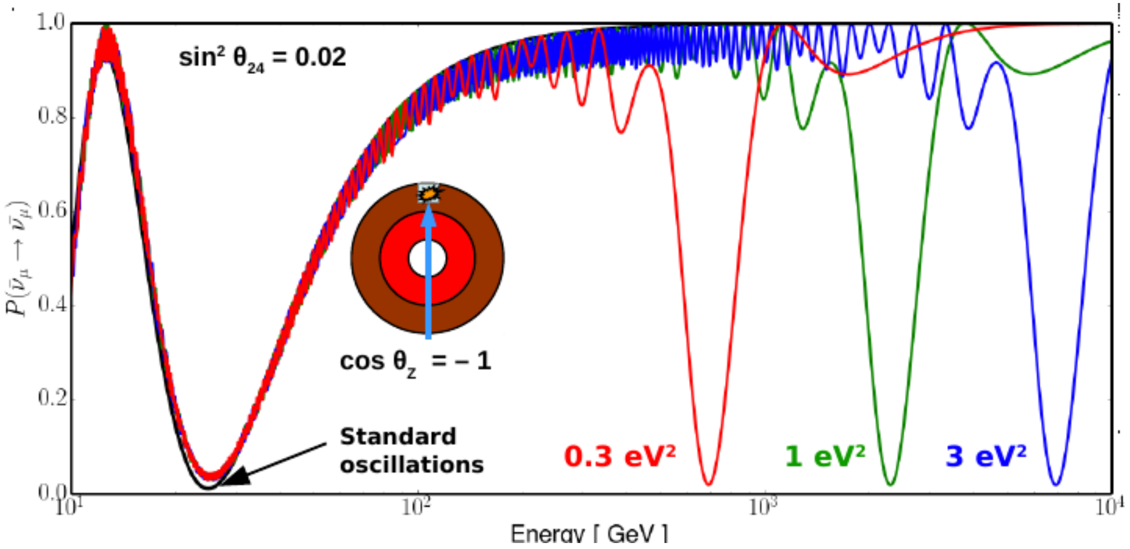

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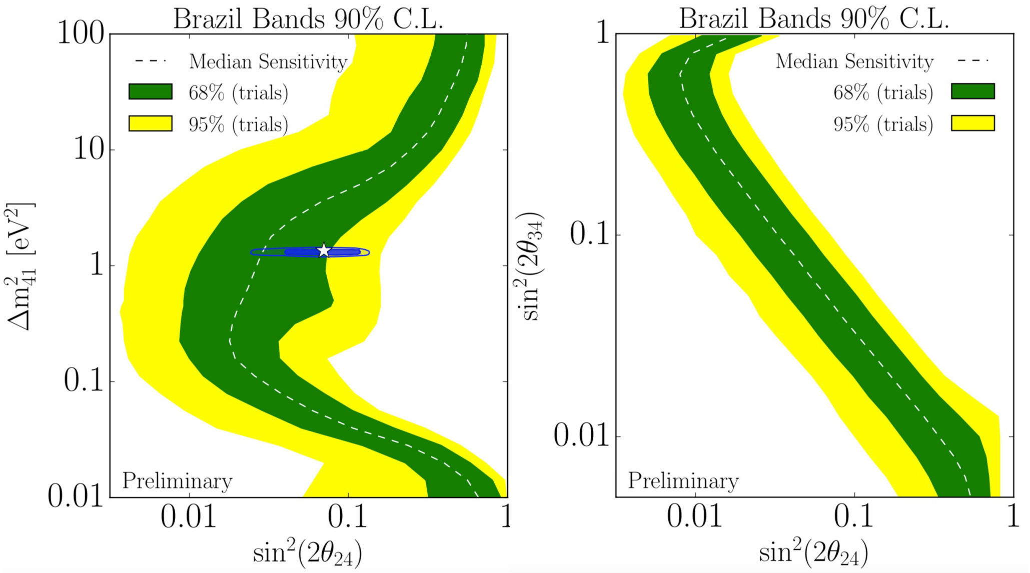
New IceCube analysis (Spencer Axani, MIT)

- 7 times more statistics
- better systematics (ice, flux)
- limits on both θ_{23} and θ_{34}



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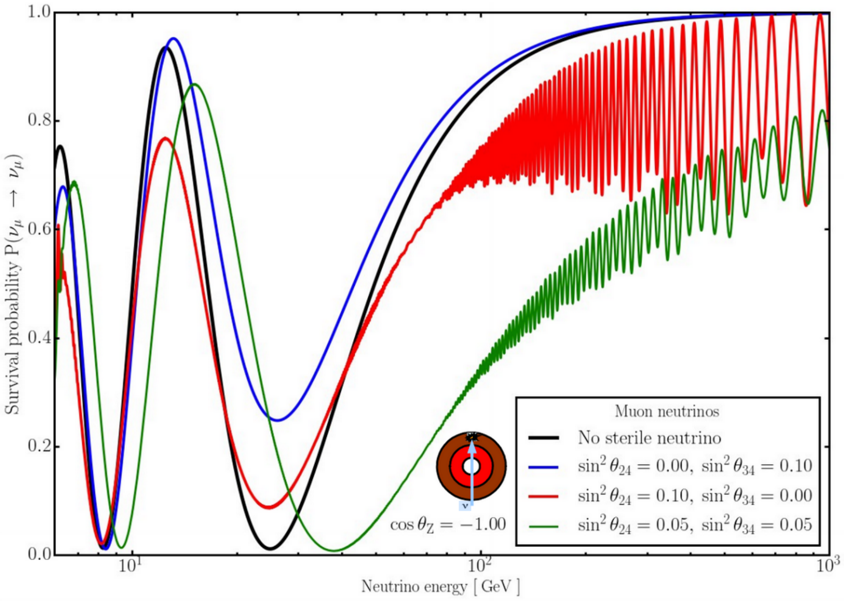

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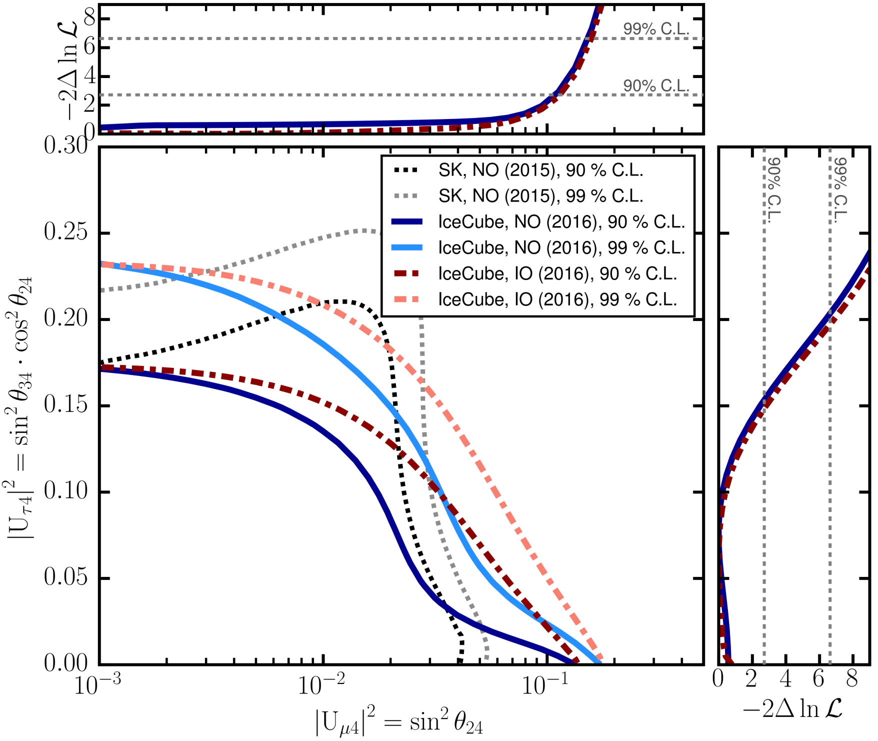
New DeepCore analysis (Andrii Terliuk, DESY)

- limits on both θ_{23} and θ_{34} through $U_{\tau 4}$ and $U_{\mu 4}$



Asaka and Watanabe, JHEP07(2012)112
Richard (SuperK), Neutrino 2014

2. Heavy neutrino decay

νMSM

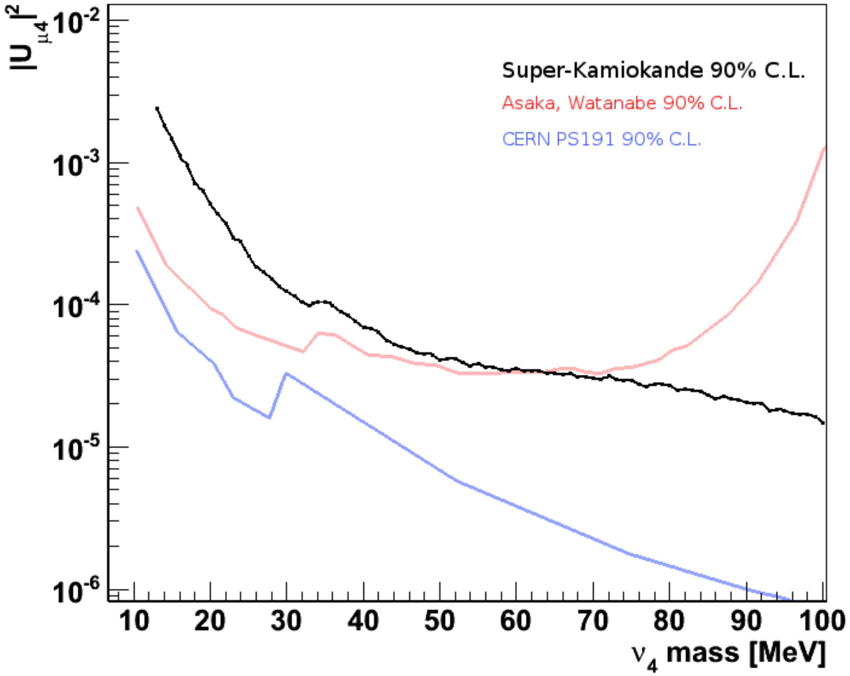
- MeV sterile neutrinos are theoretically motivated.

Trident event search in SuperK

- $N \rightarrow e^{+} + e^{-} + \nu$

Invariant mass and zenith angle distributions are used for the fit.

Atmospheric neutrinos look not competitive(?) compared with beam experiments.



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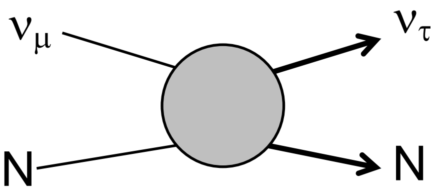
NSI in propagation

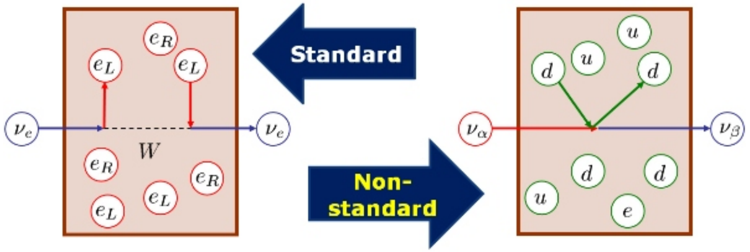
- Wolfenstein term Vcc = $\sqrt{2}G_F n_e \sim 4\times 10^{-22} GeV$
- expected sensitivity $\varepsilon \sim 10^{-2\text{-}3}$

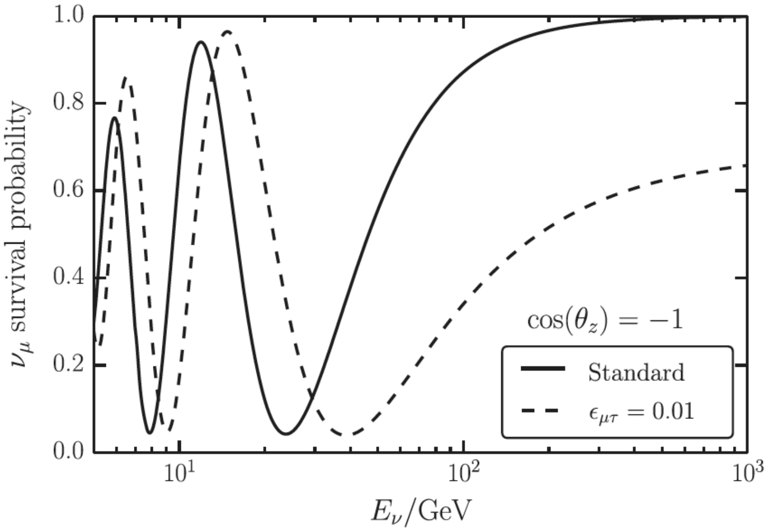
SuperK and DeepCore analyses

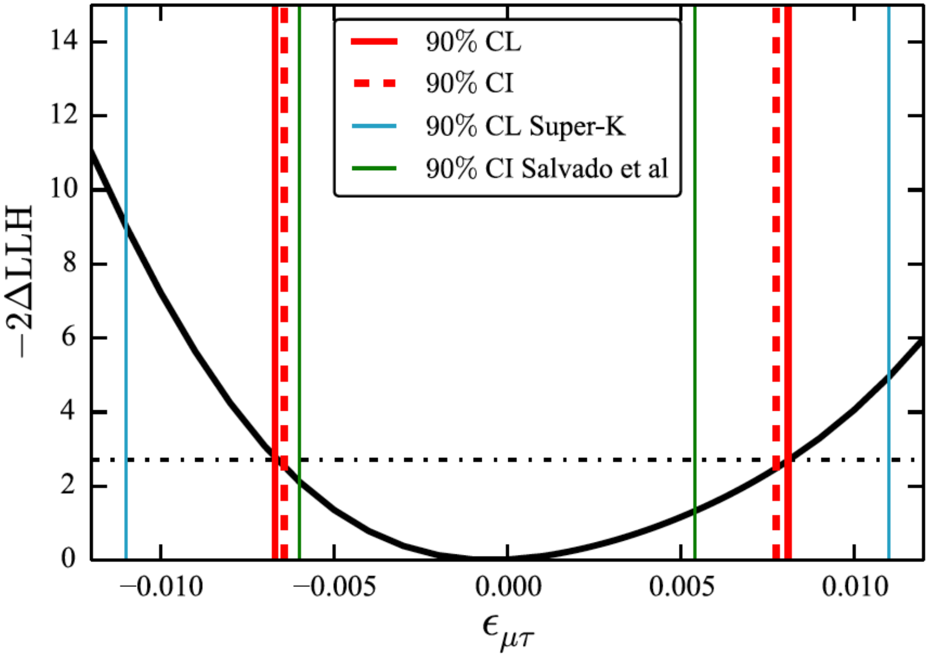
- Limits are set on $\varepsilon_{\mu\tau}$ coefficient



$$NSI = V_{CC} \frac{n_f}{n_e} \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{\tau e} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{\tau e} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$







IceCube, PRD97(2018)072009, Super-K, PRD84(2011)113008, Salvado et al., JHEP01(2017)141
Blot, TAUP2019

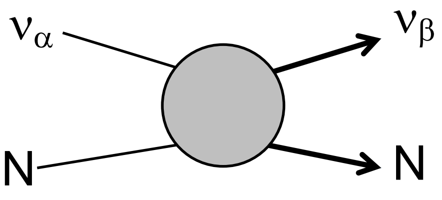
3. Non-standard interaction (NSI)

$$h_{eff} \sim \frac{1}{2E} M^2 + V_{CC} + NSI$$

$$M^2 = \begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{\tau e} \\ (m^2_{e\mu})^* & m^2_{\mu\mu} & m^2_{\mu\tau} \\ (m^2_{\tau e})^* & (m^2_{\mu\tau})^* & m^2_{\tau\tau} \end{pmatrix}, V_{CC} = \begin{pmatrix} \sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

NSI in propagation

- Wolfenstein term Vcc = $\sqrt{2} G_F n_e \sim 4 \times 10^{-22} GeV$
- expected sensitivity $\varepsilon \sim 10^{-2\text{-}3}$



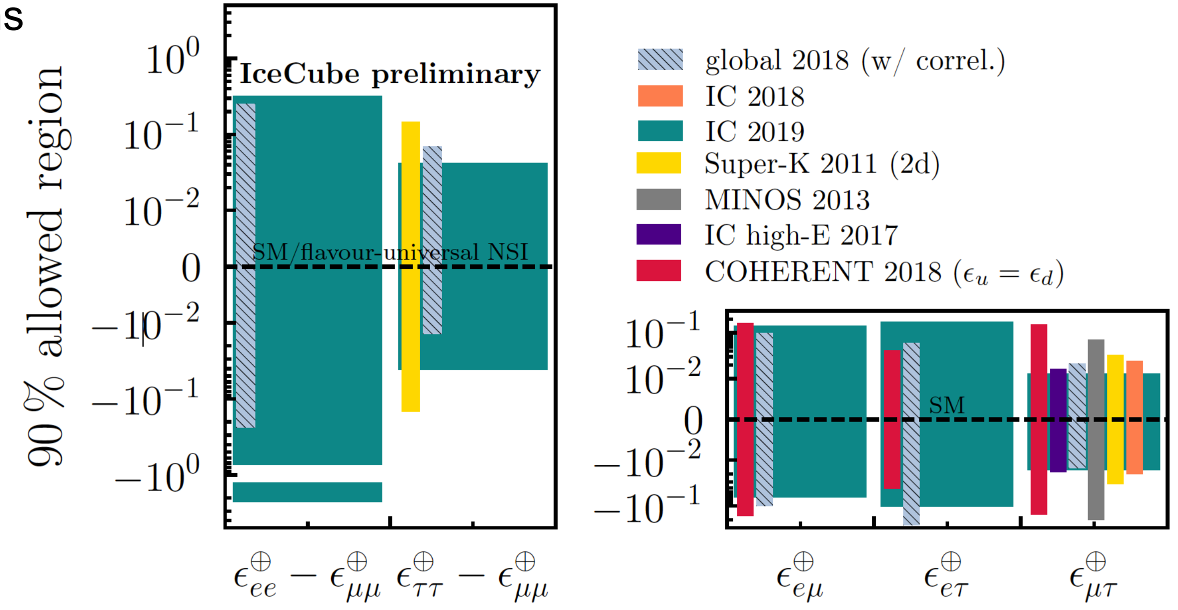
$$NSI = V_{CC} \frac{n_f}{n_e} \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{\tau e} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{\tau e} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

SuperK and DeepCore analyses

- Limits are set on $\varepsilon_{\mu\tau}$ coefficient

New DeepCore analysis (Thomas Ehrhardt, JGU Mainz)

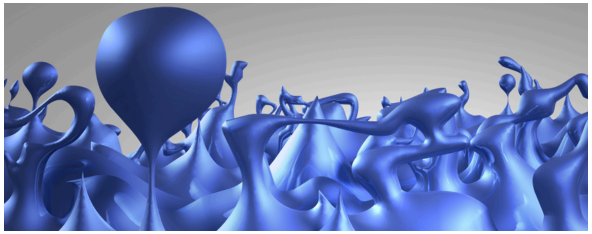
- 10 times more statistics
- Limits on all complex parameters
- Limits on parameter combinations



1. New physics with atmospheric neutrinos
2. Sterile neutrinos
3. Non-standard interaction
4. **Neutrino decoherence**
5. Neutrino Lorentz violation
6. Conclusion

Ellis, Mavromatos, Nanopoulos, MPLA12(1997)1759:1773

4. Neutrino decoherence



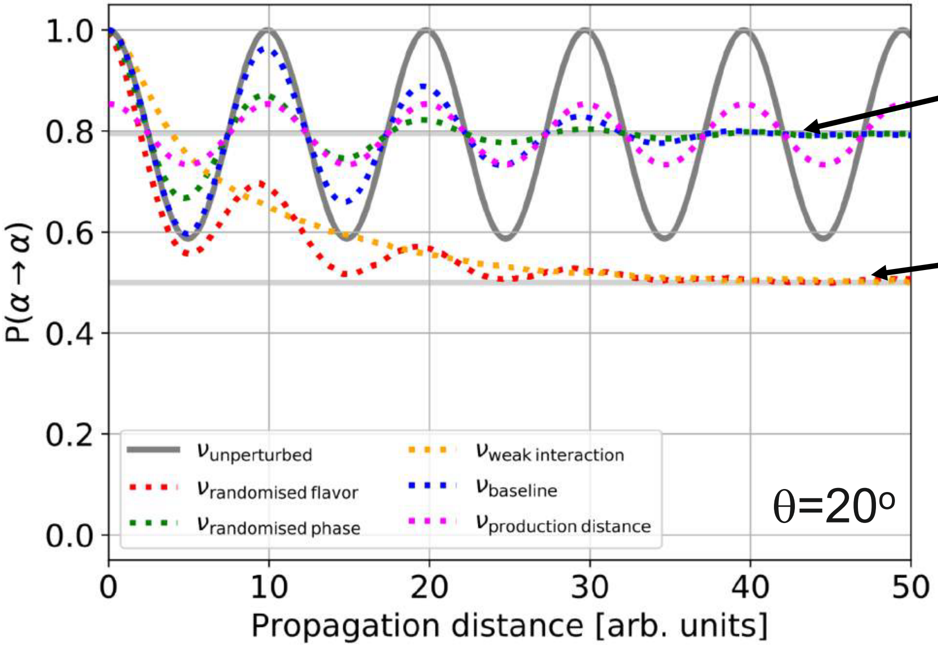
Space-time foam

Quantum gravity motivated quantum fluctuation of space-time.

- Planck scale black hole background
- D-brane fluctuation

Propagating particles lose coherence with interactions with these background

- New damping terms in oscillation



Toy model (Tom Stuttard, NBI)

- Space-time foam baseline variation damp oscillations.

- Flavor basis interaction with Space-time foam may randomize flavor basis

Different physics collapse wave functions differently.

Ellis, Mavromatos, Nanopoulos, MPLA12(1997)1759:1773
Farzan, Schwetz, Smirnov, JHEP07(2008)067

4. Neutrino decoherence

Open quantum system

$$P_{\alpha\beta}^{OQS} = Tr\left|\rho_\alpha(t)\rho_\beta(0)\right|^2$$

- Model independent search of decoherence
- Density matrix formalism and decoherence term

$$\frac{d\rho}{dt} = -i[h_{eff},\rho] - D[\rho], \quad D[\rho] = \begin{pmatrix} 0 & \rho_{12}\gamma_{12} & \rho_{31}\gamma_{31} \\ \rho_{12}\gamma_{12} & 0 & \rho_{23}\gamma_{23} \\ \rho_{31}\gamma_{31} & \rho_{23}\gamma_{23} & 0 \end{pmatrix}$$

Damping term

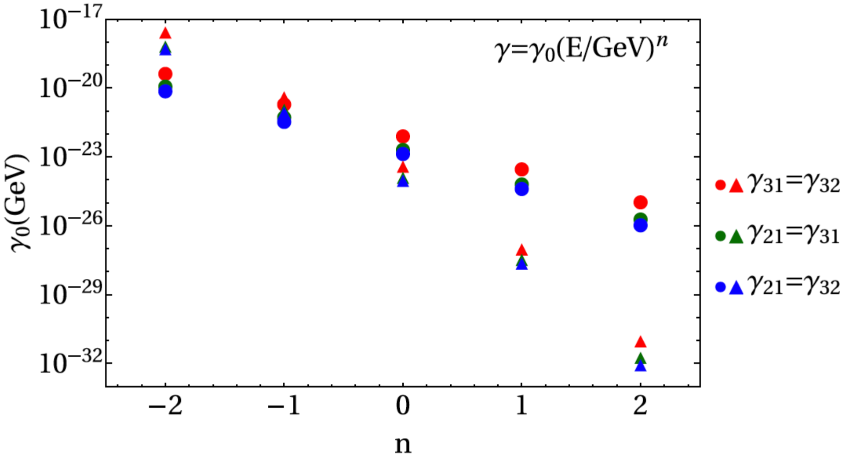
$$\gamma_{ij} = \gamma_{ij}^0 \cdot \left(\frac{E}{GeV}\right)^n$$

- Analysis can be designed to find nonzero γ_{ij}^0.
- Experimental sensitivity is many order far away than expected Planck scale physics region?

(naturalness: decoherence length of neutrino with E~M_{Planck} is Planck length)

Coloma et al, EPJC(2018)78:614

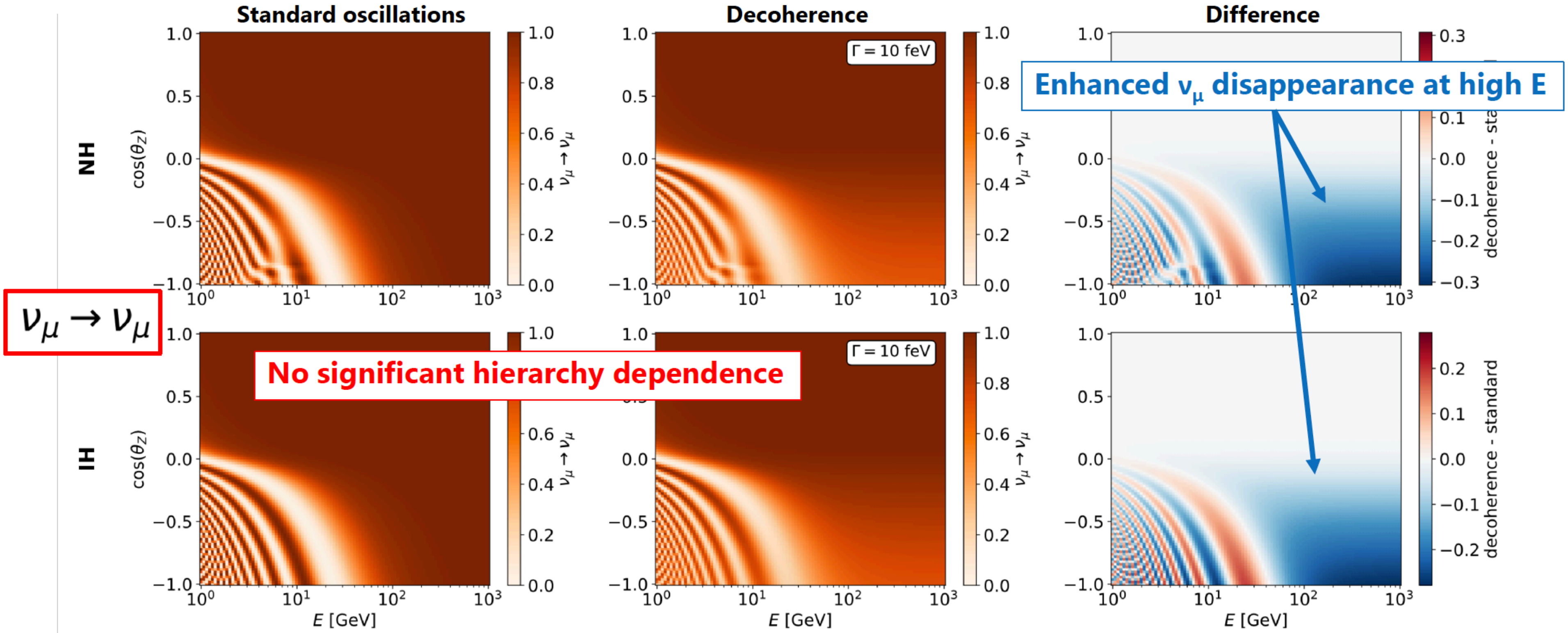
4. Neutrino decoherence



Stronger sensitivity on γ_0 (damping term scale) can be obtained by assuming larger n

New analysis (Tom Stuttard, NBI)

- DeepCore data
- Weak dependence on mass ordering
- Exotic ν_μ disappearance (different pattern, new structure)



Enhanced ν_μ disappearance at high E

$\nu_\mu \to \nu_\mu$

No significant hierarchy dependence

1. BSM physics with atmospheric neutrinos
2. Sterile neutrinos
3. Non-standard interaction
4. Neutrino decoherence
5. **Neutrino Lorentz violation**
6. Conclusion

Kostelecký and Samuel, PRD39(1989)683
Kostelecký and Mewes, PRD69(2004)016005;70(2004)076002

5. Lorentz violation

Particle Lorentz violation

Quantum gravity motivated physics could generate vacuum expectation values with Lorentz indices (spontaneous Lorentz symmetry violation)

Standard Model Extension (SME)

Effective field theory to study Lorentz violation

- Sidereal time variation
- Spectrum distortion
- CPT violation, etc

SME Lagrangian

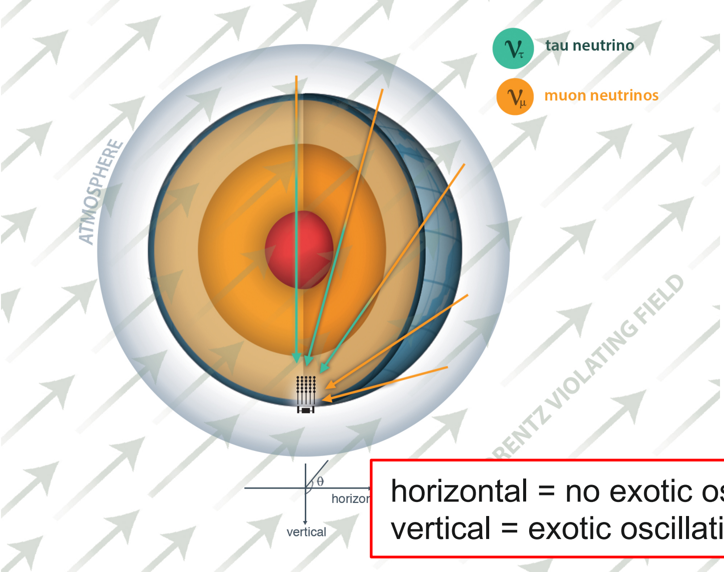
nonrenormalizable →

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a^{(3)}_{\mu}\psi + \bar{\psi}\gamma^{\mu}a^{(3)}_{\mu\nu}\partial^{\nu}\psi\cdots$$

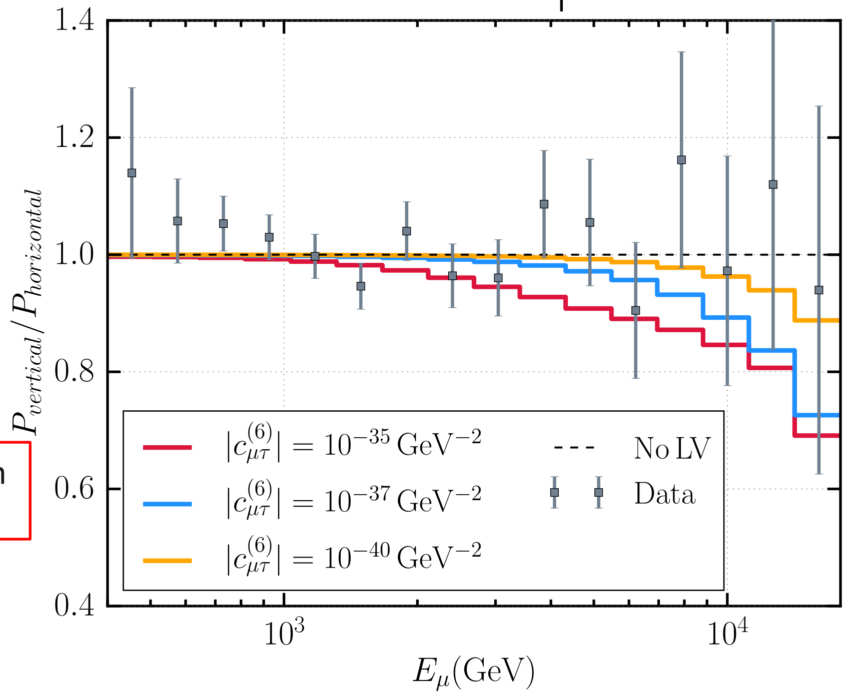
SME motivated effective Hamiltonian for neutrinos

$$h_{eff}\sim\frac{1}{2E}M^{2}+V_{CC}+a^{(3)}+Ec^{(4)}+\boldsymbol{E^{2}a^{(5)}}+\boldsymbol{E^{3}c^{(6)}}\cdots$$

→ nonrenormalizable



horizontal = no exotic oscillation
vertical = exotic oscillation



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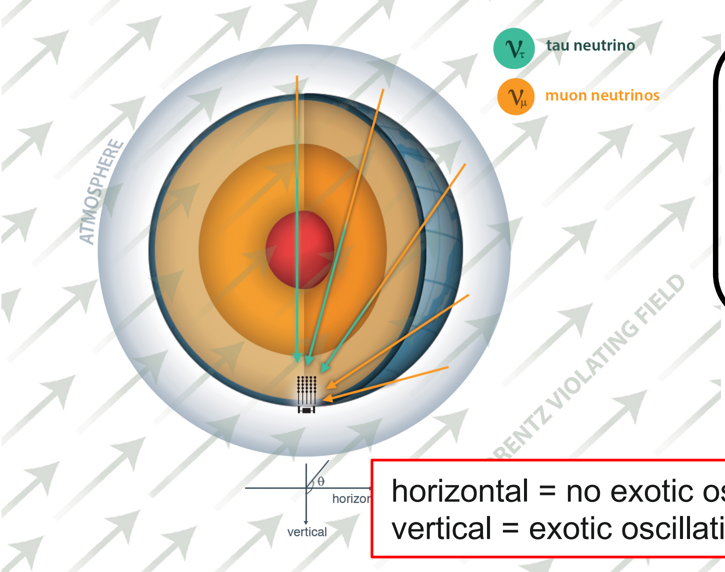
SME motivated effective Hamiltonian for neutrinos

$$h_{eff} \sim \frac{1}{2E}M^2 + V_{CC} + a^{(3)} + Ec^{(4)} + \boldsymbol{E^2 a^{(5)}} + \boldsymbol{E^3 c^{(6)}} \cdots$$

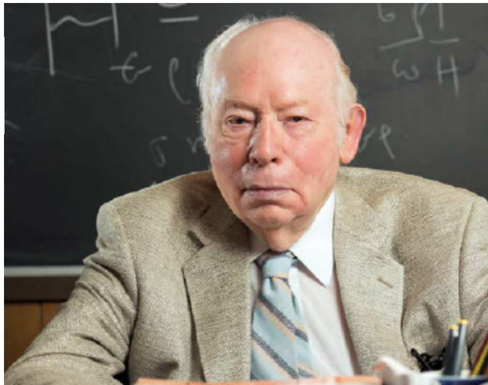
→ nonrenormalizable



horizontal = no exotic oscillation
vertical = exotic oscillation

> "In a sense it is beyond the SM, but I would rather say it is beyond the leading terms – the renormalisable, unsuppressed part of the SM," says Weinberg. "But hell – so is gravity! The symmetries of general relativity don't allow any renormalisable interactions of massless spin-2 particles called gravitons."

Steve Weinberg
(CERN Courier, Nov 2017)



Higher-dimension operator search is interesting, and IceCube is good at that (=high energy)

IceCube,PRL115(2015)081102;117(2016)071801
Fedynitch et al,EPJ.Web.Conf.99(2015)08001

5. Analysis method

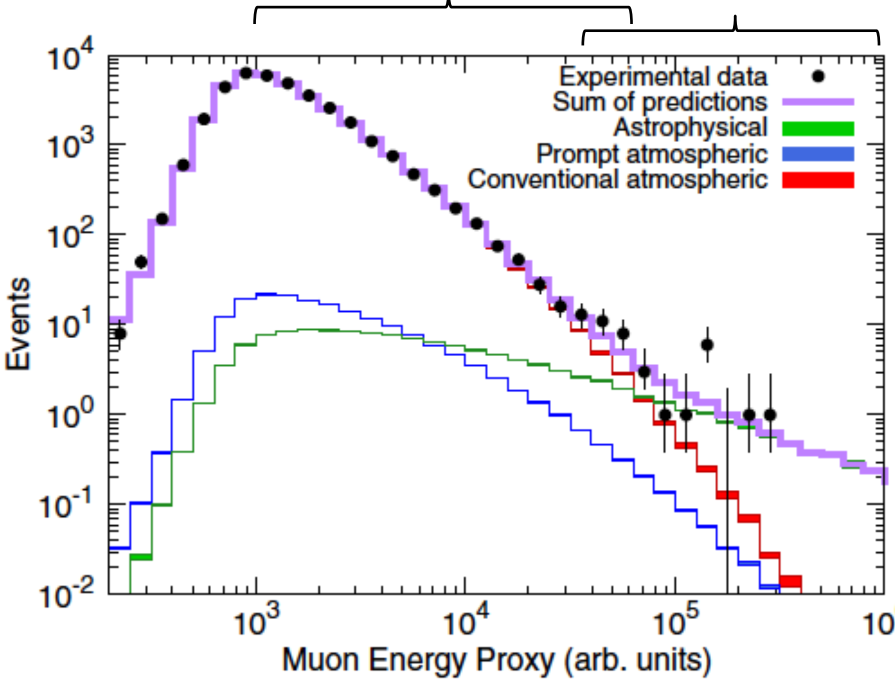
We use 2yrs northern sky muon data to look for spectrum distortion due to Lorentz violation.

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

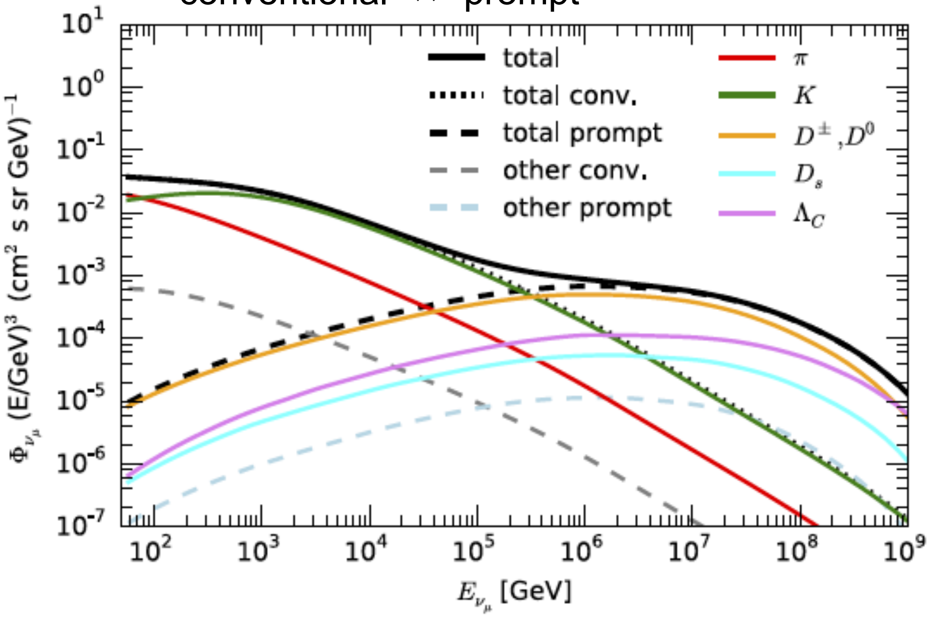
ν_{atm} is complicated from ~20 TeV
- Prompt atmospheric neutrinos (=charm)
- Astrophysical neutrinos
- Earth absorption becomes significant

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

conventional ↔ astrophysical



conventional ↔ prompt



IceCube,PRL115(2015)081102;117(2016)071801
Fedynitch et al,EPJ.Web.Conf.99(2015)08001

5. Analysis method

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

Simulation

- atmospheric neutrinos from MCEq https://github.com/afedynitch/MCEq
- simple power law astrophysical neutrinos (=background)
- DIS cross section from Cooper-Sarkar-Sarkar (CSS) paper Cooper-Sarkar and Sarkar, JHEP01(2008)075
- Analytic oscillation formula to test exotic ν_μ-ν_τ oscillation Gonzalez-Garcia et al., PRD71(2005)093010

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

- Frequentist Wilk’s theorem (main results)
- Bayesian Markov Chain Monte Carlo (MCMC) http://dan.iel.fm/emcee/current/

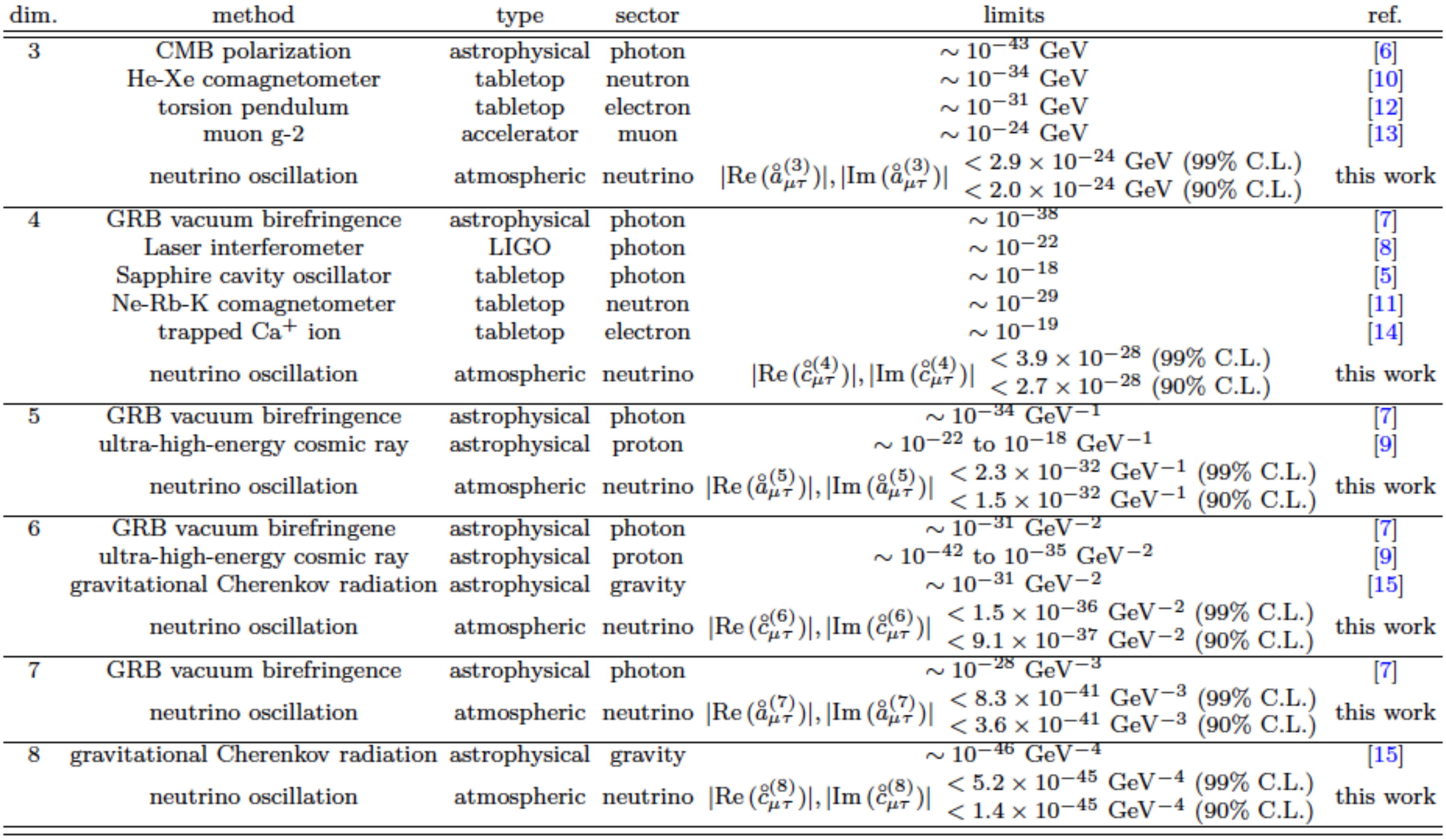
IceCube, Nature Physics 14 (2018) 961

5. Results

We don't find Lorentz violation

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

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



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
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	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

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

IceCube, Nature Physics 14 (2018) 961

5. Results

Atomic physics results dominate LV tests with renormalizable operators (effective field theory approach)

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

dim.	method	type	sector		limits	ref.
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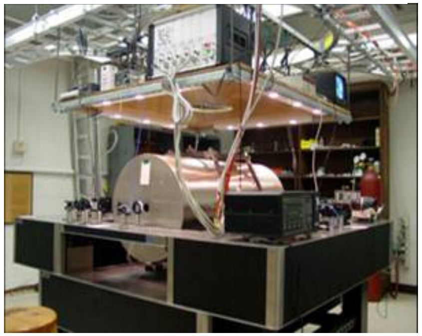
	u	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	
		atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (9 $< 1.5 \times 10^{-32}$ GeV^{-1} (9	
6		astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	
	u	ast				
	gra	ast				
		at		)|, |In	2 (9 2 (9	
7		ast				
		at		)|, |In	3 (99% C.L.) 3 (90% C.L.)	this work
8	gra	ast				[15]
		at		)|, |In	4 (99% C.L.) 4 (90% C.L.)	this work

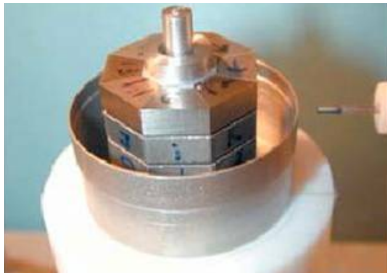
TABLE I: Comparison of attainable best limits of SM … lds.

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



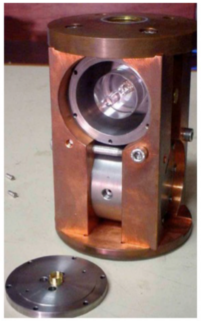
PRL107(2011)171604
PRL112(2014)110801

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



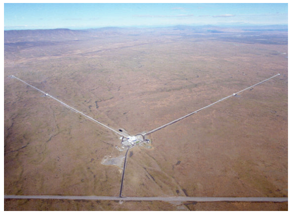
PRL97(2006)021603

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



Nature.Comm.6(2015)8174

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



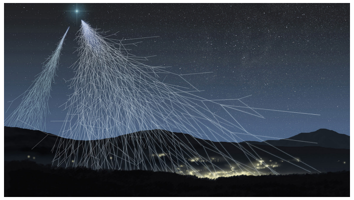
PLB761(2016)1

IceCube, Nature Physics 14 (2018) 961

5. Results

Astrophysical observations dominate LV test with non-renormalizable operators (quantum gravity motivated models)

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

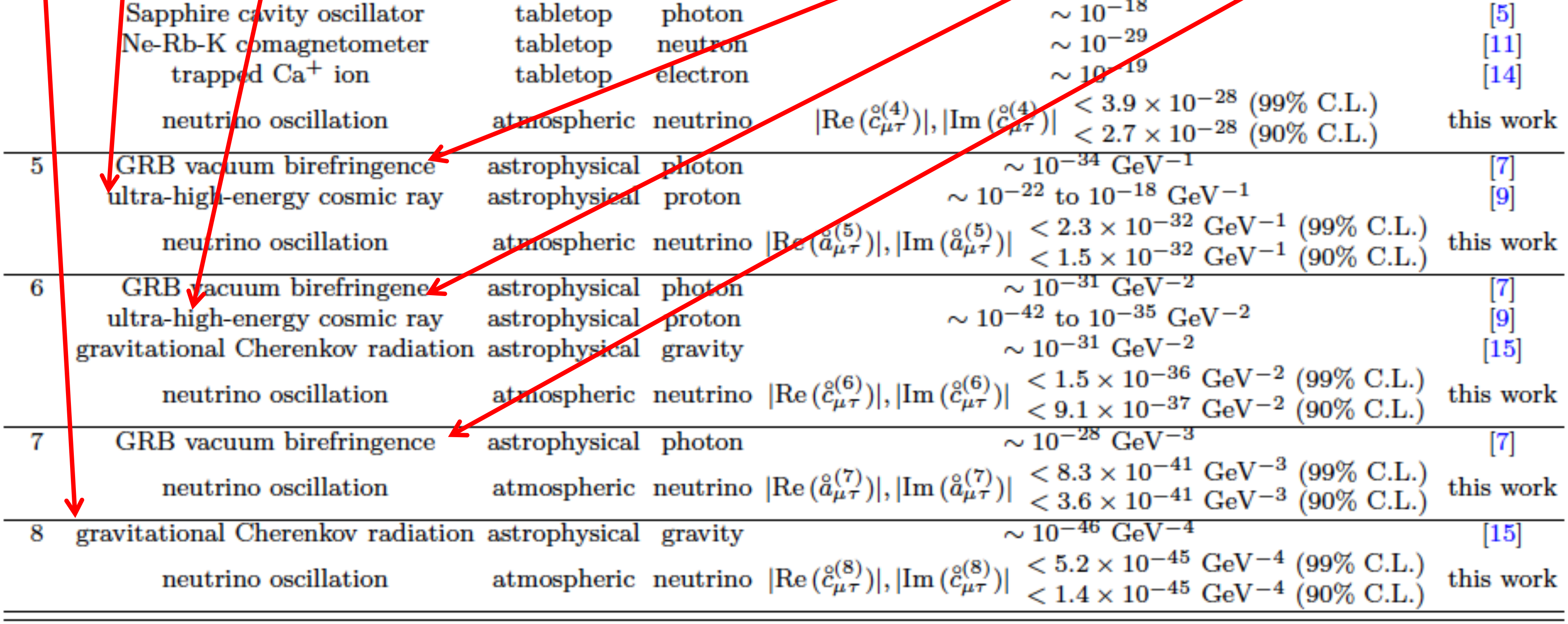


JCAP0904(2009)022
PLB749(2015)551

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

PRL110(2013)201601

$\mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots .$ (1)



		type	sector		li	ef.
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	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]
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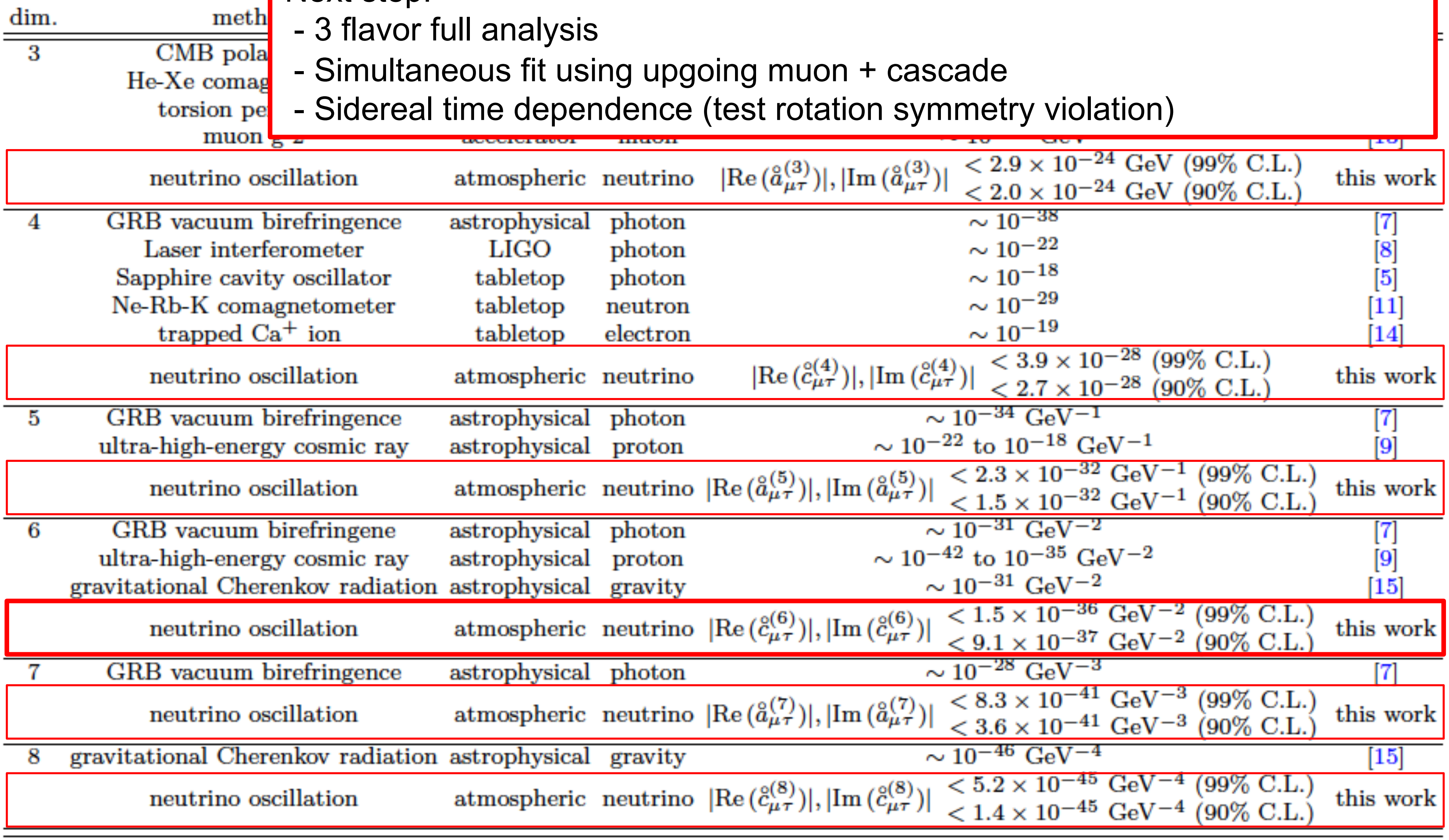
TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

IceCube, Nature Physics 14 (2018) 961

5. Results

This analysis set the strongest limits for any operators in the neutrino sector.
Limits are also among the strongest from atomic experiments to cosmology.

Next step:
- 3 flavor full analysis
- Simultaneous fit using upgoing muon + cascade
- Sidereal time dependence (test rotation symmetry violation)



dim.	meth					
3	CMB pola					
	He-Xe comag					
	torsion pe					
	muon g-2					
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	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^+ ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[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.

TK, Argüelles, Farrag, Mandalia, ArXiv:1906.09204

5. New physics search with neutrino interferometry

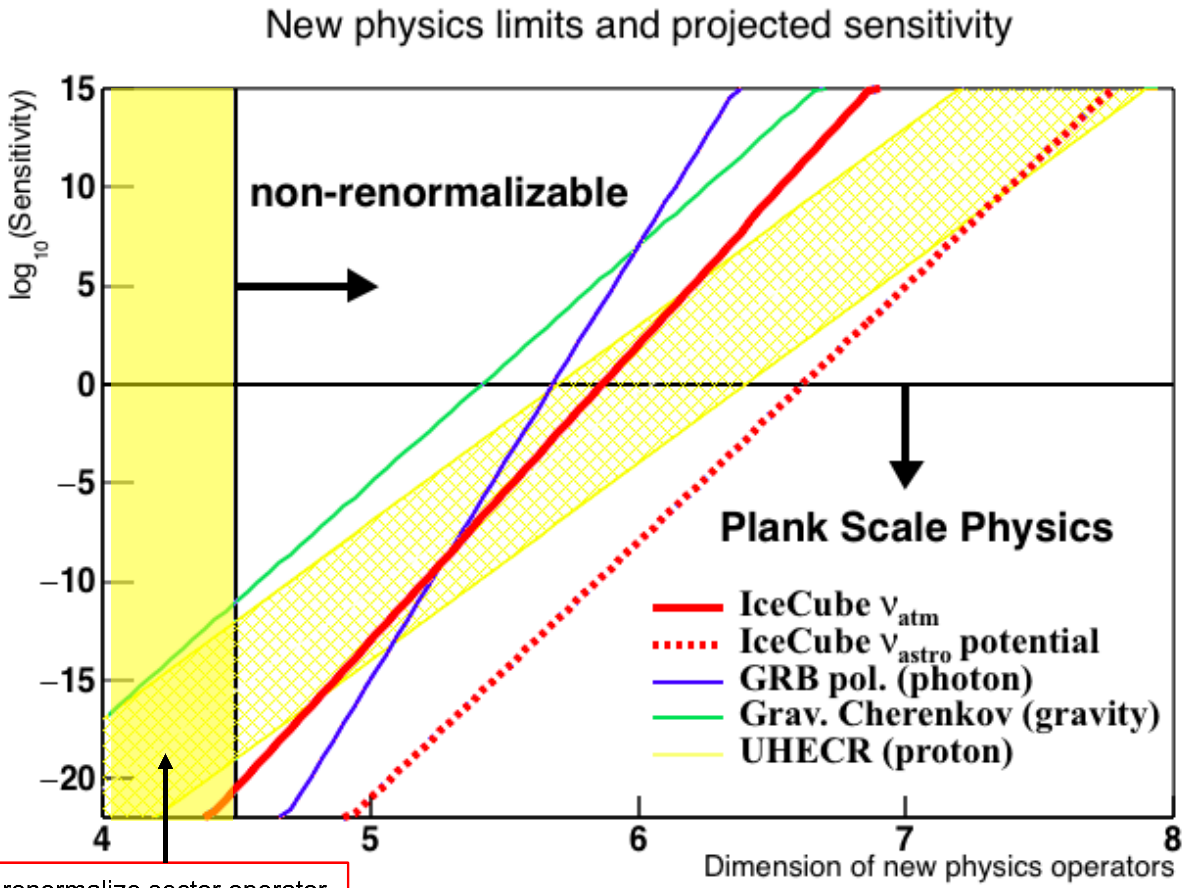
Quantum Gravity-motivated new physics operator search

Sensitivity is normalized with Planck mass (M_{Planck}~10^{19} GeV)

New physics sensitivity of atmospheric neutrinos is competitive to astrophysical sources

It looks sensitivity exceed naïve expectation of Planck scale

- dim-5 ~ $1/M_{Planck}$ ~ 10^{-19} GeV^{-1}
- dim-6 ~ $1/M_{Planck}^2$ ~ 10^{-38} GeV^{-2}



renormalize sector operator (dimension-3 and -4) have many very strong limits from atomic physics

Conclusion

Atmospheric neutrinos offers unique laboratories of new physics.
- Highest energy particles (~20 TeV)
- Longest baseline (12700km)
- Traveling through high density material (~13g/cm^3)

Neutrinos make natural quantum system (neutrino interferometry) and sensitive to small effect.
- Sterile neutrinos
- Non-standard interaction
- Quantum decoherence
- Lorentz violation

Atmospheric neutrino system has one of the highest sensitivity to quantum gravity motivated physics, but astrophysical neutrino system has even higher sensitivity.

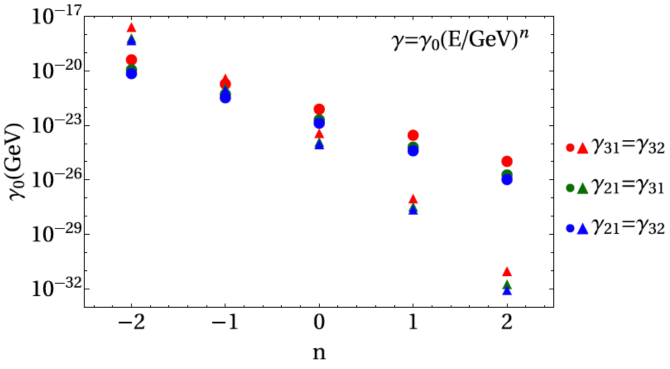
Thank you for your attention!

1. Atmospheric neutrinos, natural laboratories of new physics

Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.

→ They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the highest density material (~13g/cm^3) on Earth.

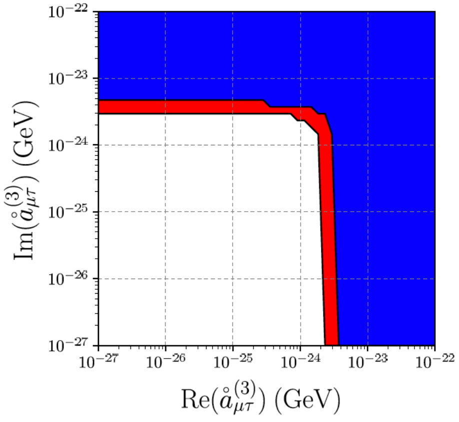
In order to discover BSM physics, scale of BSM physics needs to be ~ $\Delta m^2_{atm}/4E \sim 10^{-26}$ GeV ~20TeV) → Sensitivity limit of energy independent new physics



Decoherence limit

$\gamma_0 \sim 10^{-24}$ GeV

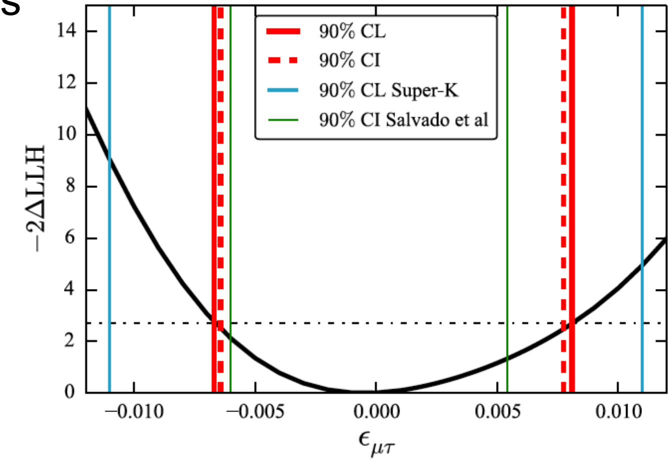
Coloma et al.,EPJC(2018)78:614



Lorentz violation limit

$a^{(3)} \sim 10^{-24}$ GeV

IceCube,Nature Physics14,961(2018)
Super-Kamiokande, PRD91(2015)052003



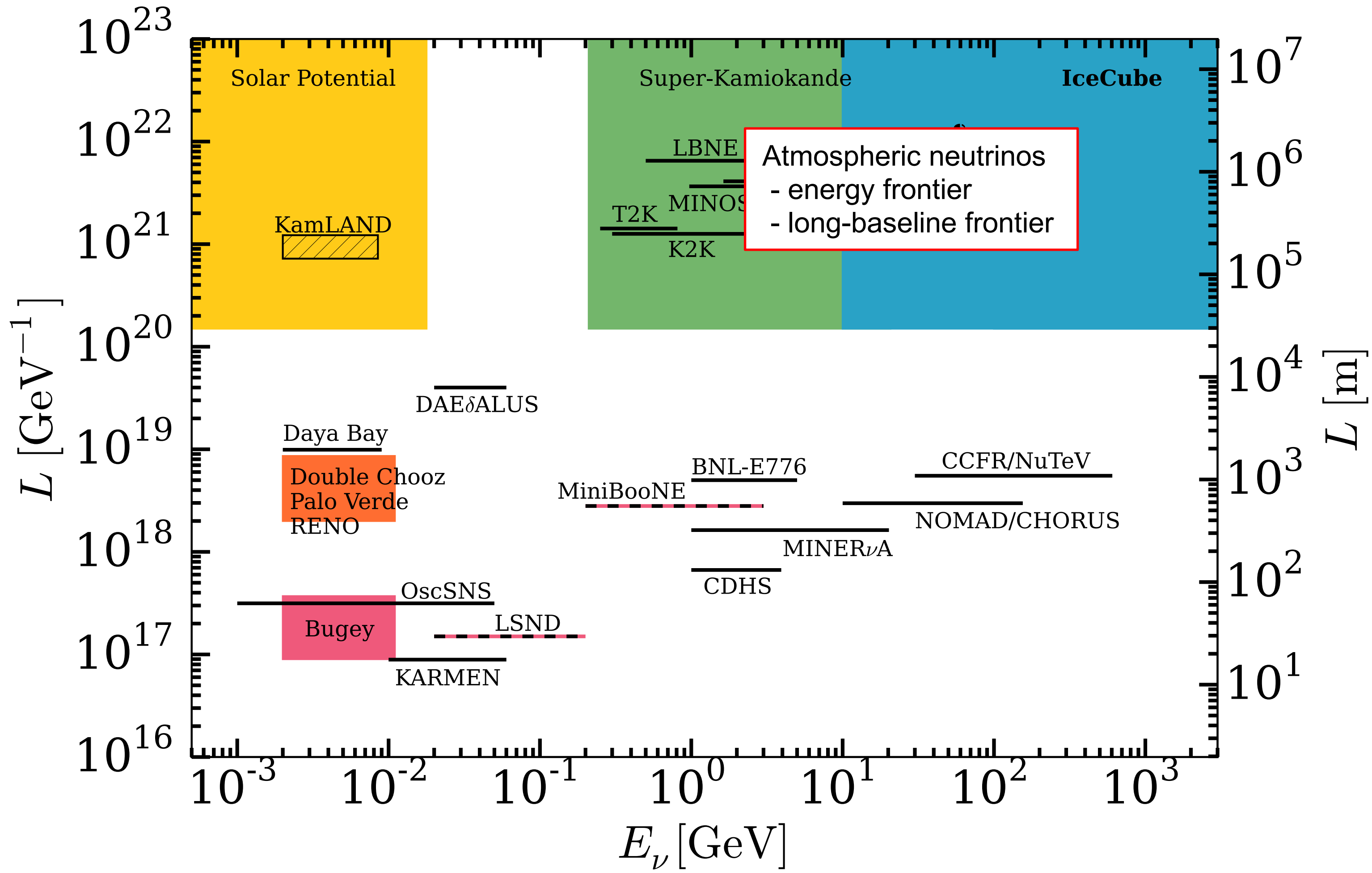
Non-standard interaction limit

$V_{cc} x \varepsilon \sim 10^{-19}$ GeV

IceCube,PRD97(2018)072009
Super-Kamiokande, PRD84(2011)113008
Salvado et al., JHEP01(2017)141

1. Atmospheric neutrinos, natural laboratories of new physics

Phase space of atmospheric neutrinos are largely unexplored.



Atmospheric neutrinos
- energy frontier
- long-baseline frontier

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

1. Atmospheric neutrinos, natural laboratories of new physics

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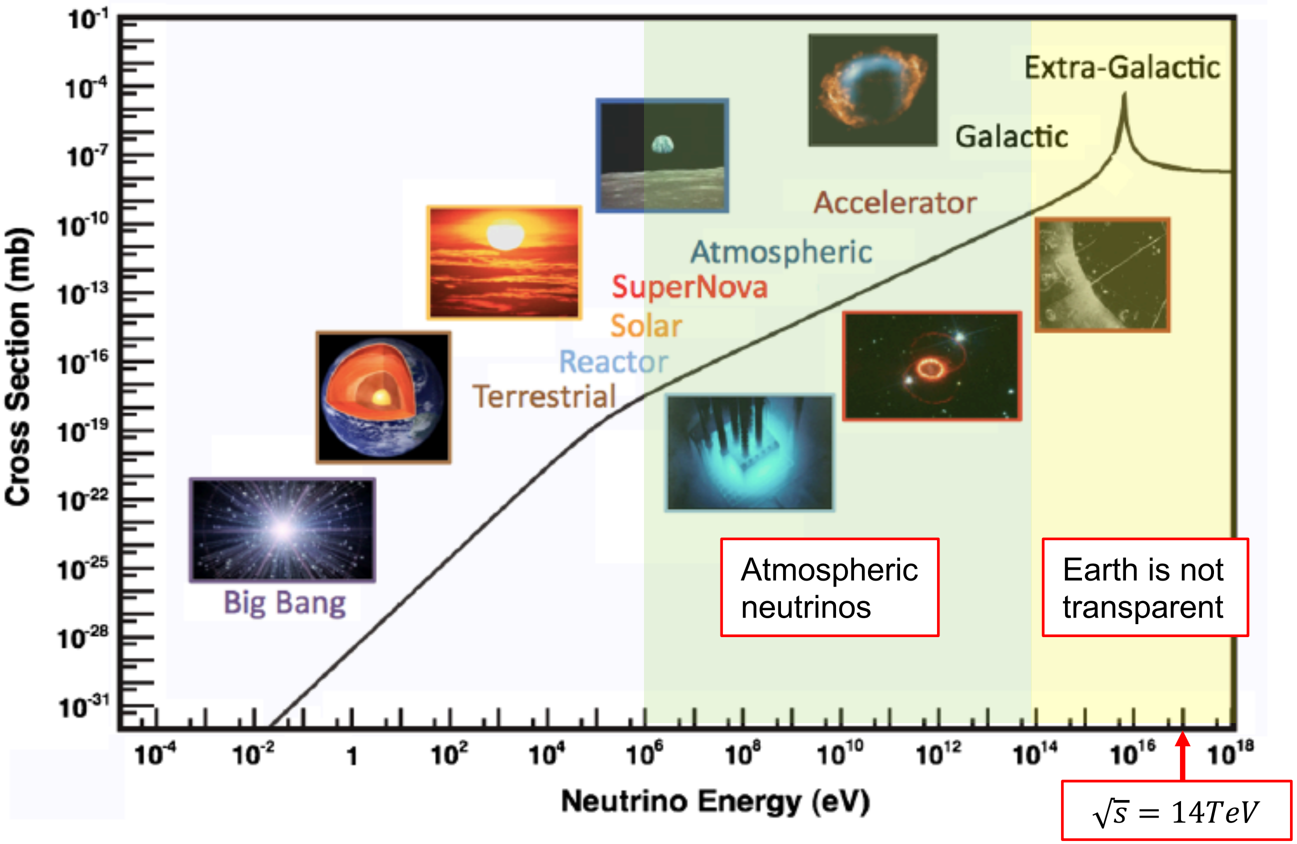
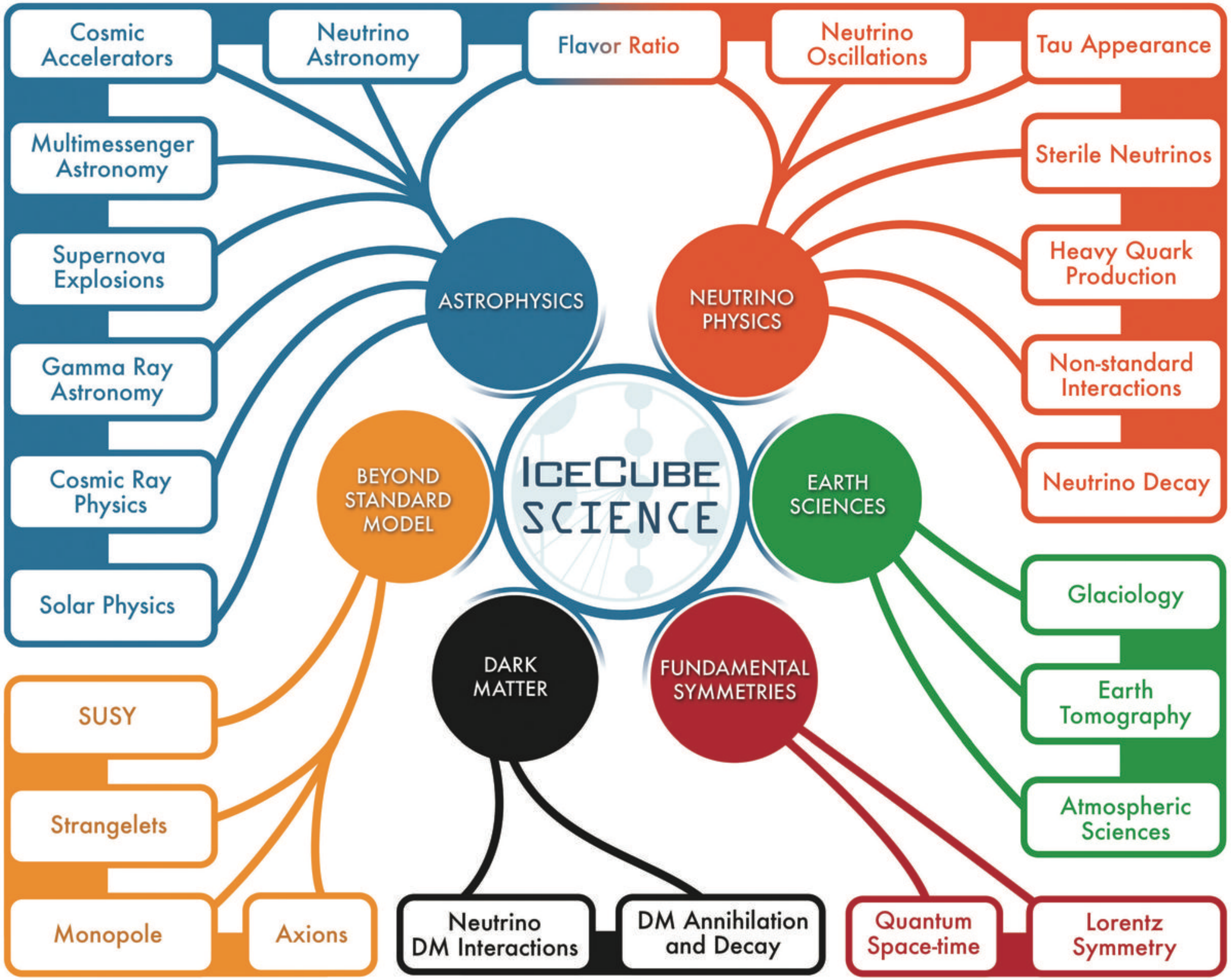


Atmospheric neutrinos

Earth is not transparent

$\sqrt{s} = 14TeV$

1. Atmospheric neutrinos, natural laboratories of new physics



Kostelecký and Mewes, PRD85(2012)096005

5. Neutrino flavour with Lorentz violation

We start from isotropic model of nonminimal SME

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

dim-6 isotropic SME (d=6)

scale

O(1) diagonal element

$$E^3 c^{(6)}_{\alpha\beta} = E^3 \frac{1}{\sqrt{4\pi}} \left(c^{(6)}_{\alpha\beta} \right)_{00} = E^3 \begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix} = E^3 c^{(6)} \widetilde{U}^{\dagger}_6 O_6 \widetilde{U}_6$$

mixing matrix

and so on…

We test dim-3 to dim-8 operators one by one to find nonzero scale (or set limit on scale)

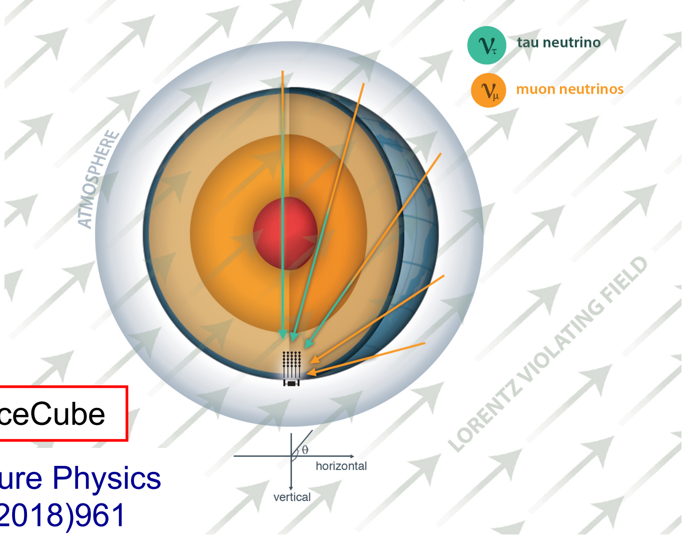
$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U - E^3 c^{(6)}_{\alpha\beta} = V^{\dagger}(E) \Delta V(E)$$

$$V(E) = \begin{pmatrix} V_{e1}(E) & V_{e2}(E) & V_{e3}(E) \\ V_{\mu 1}(E) & V_{\mu 2}(E) & V_{\mu 3}(E) \\ V_{\tau 1}(E) & V_{\tau 2}(E) & V_{\tau 3}(E) \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \lambda_1(E) & 0 & 0 \\ 0 & \lambda_2(E) & 0 \\ 0 & 0 & \lambda_3(E) \end{pmatrix}$$

5. Test of Lorentz violation with neutrinos

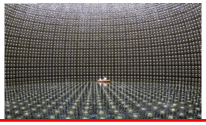
Test of Lorentz violation with neutrinos can be classified to 2 groups.
→ We test spectral distortion of atmospheric neutrino spectrum due to Lorentz violation.

Spectral distortion vs. Sidereal variation



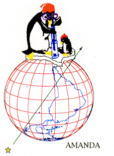
IceCube

Nature Physics 14(2018)961



Super-Kamiokande

PRD91(2015)052003



AMANDA

PRD79(2009)102005

MINOS ND

PRL101(2008)151601

MINOS FD

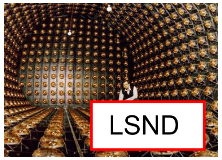
PRL105(2010)151601

MiniBooNE

PLB718(2013)1303

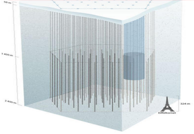
Daya Bay

PRD98(20 8)092013



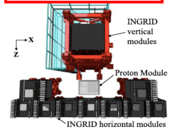
LSND

PRD72(2005)076004



IceCube-40

PRD82(2010)112003



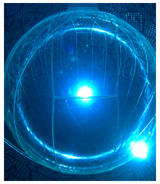
T2K ND

PRD95(2017)111101

Double Chooz

PRD86(2013)112009

Seasonal variation



SNO

PRD98(2018)112013

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

5. Analysis method

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

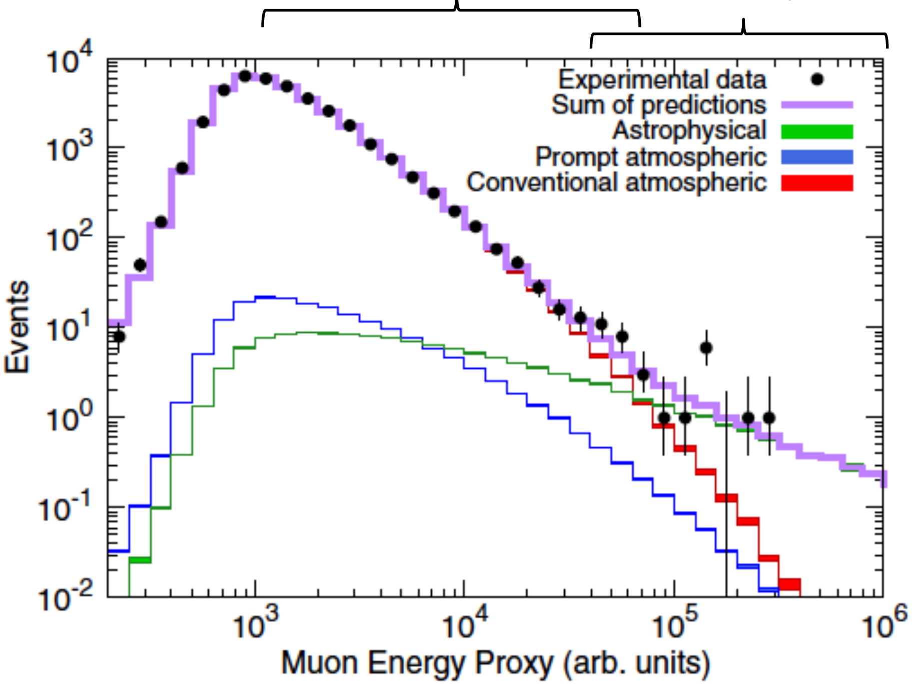
400 GeV<E<18 TeV (“conventional”)
Angle, -1<cosθ<0 (“through up-going”)

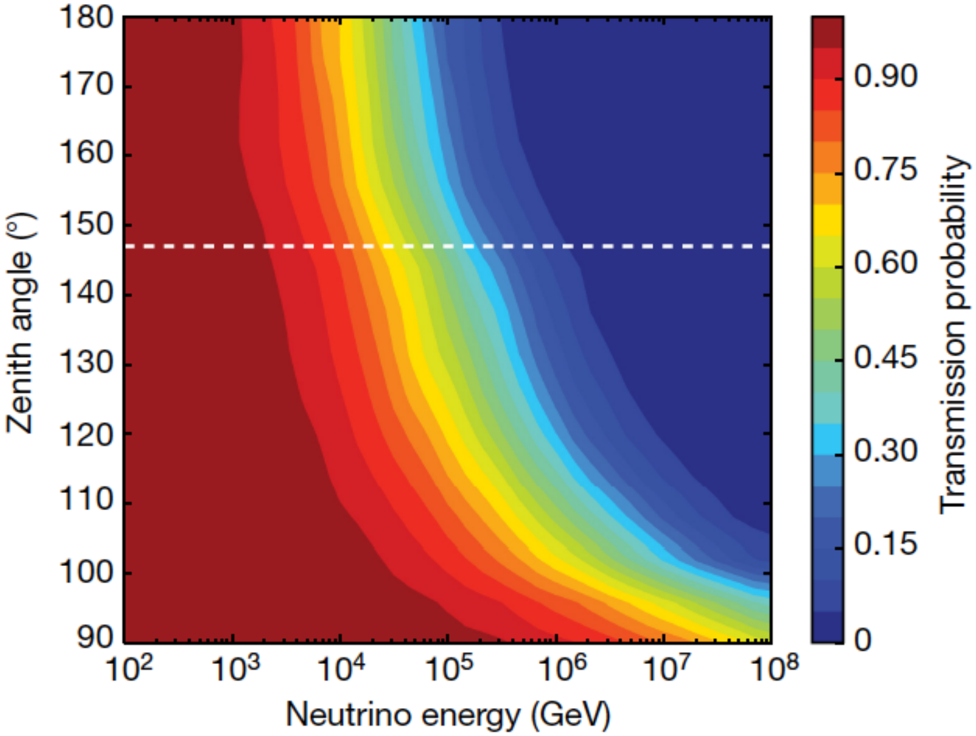
→ 2016 sterile ν analysis sample

ν_{atm} is complicated from ~20 TeV

- Prompt atmospheric neutrinos (=charm)
- Astrophysical neutrinos
- Earth absorption becomes significant

conventional ↔ astrophysical





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

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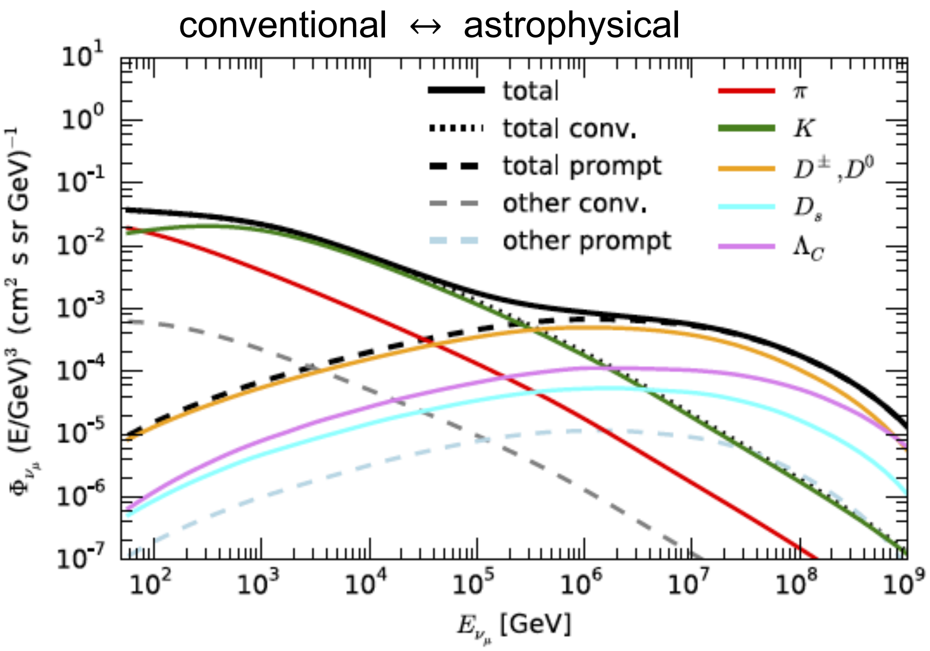
400 GeV<E<18 TeV ("conventional")
Angle, -1<cosθ<0 ("through up-going")

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



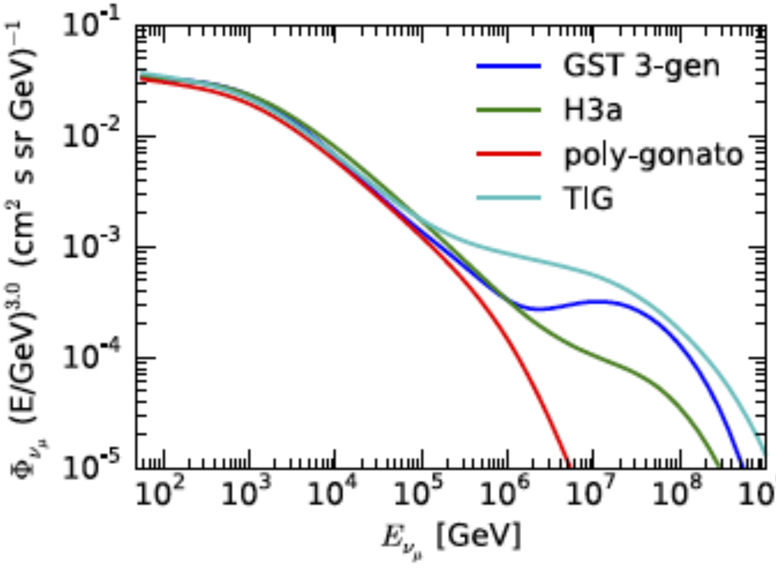


Figure 3. Primary model dependence of the atmospheric conventional + prompt neutrino flux. The model abbreviations are described in the caption of Fig. 2.

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

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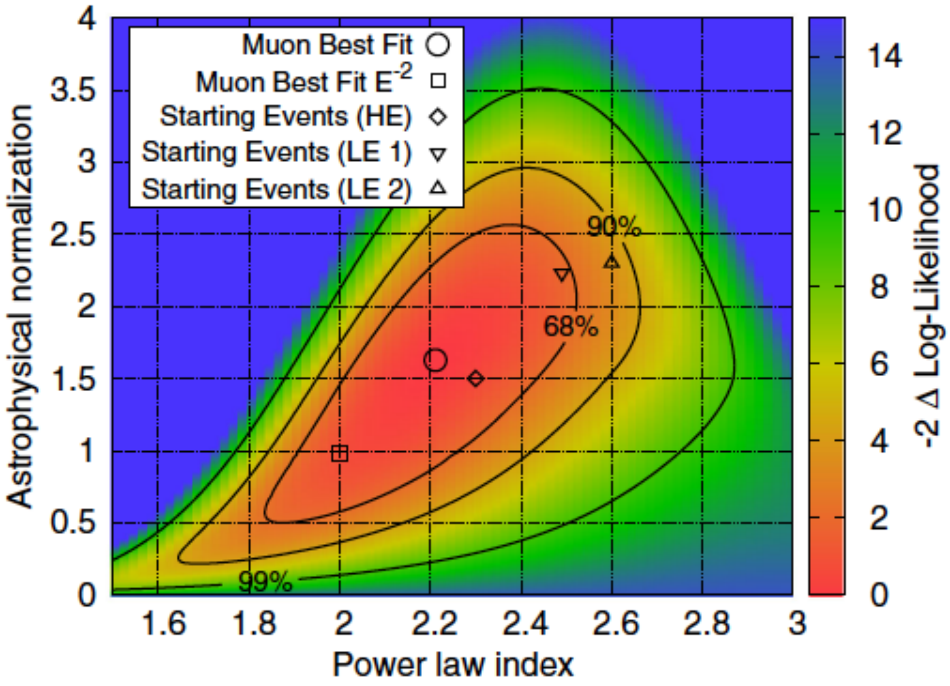
Angle, -1<cosθ<0 (“through up-going”)

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

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

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



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

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

Systematics (6 nuisance parameters)
- normalization of flux : conventional (40%), prompt (free), and astrophysical (free)
- spectrum index : primary cosmic ray (2%) and astrophysical neutrinos (25%)
- π/K ratio for conventional flux (10%)
- Ice model : negligible
- DOM efficiency : constrained

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

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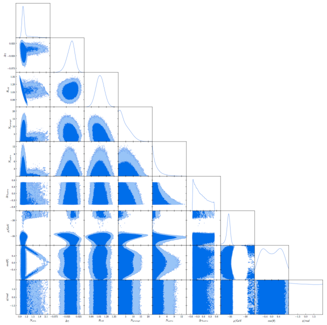
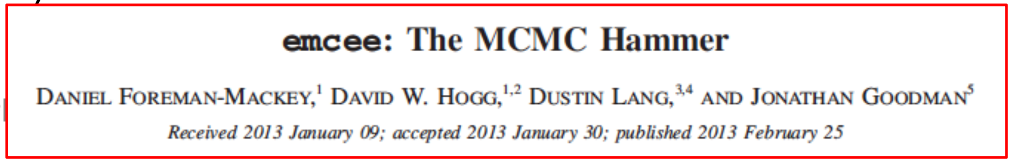


Fit methods

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

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



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, Nature Physics 14 (2018) 961

5. Results

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

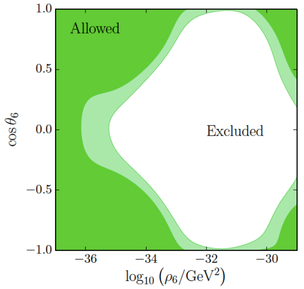
$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots . \quad (1)$$

Eq. 2: An example of Lorentz violation operator matrix

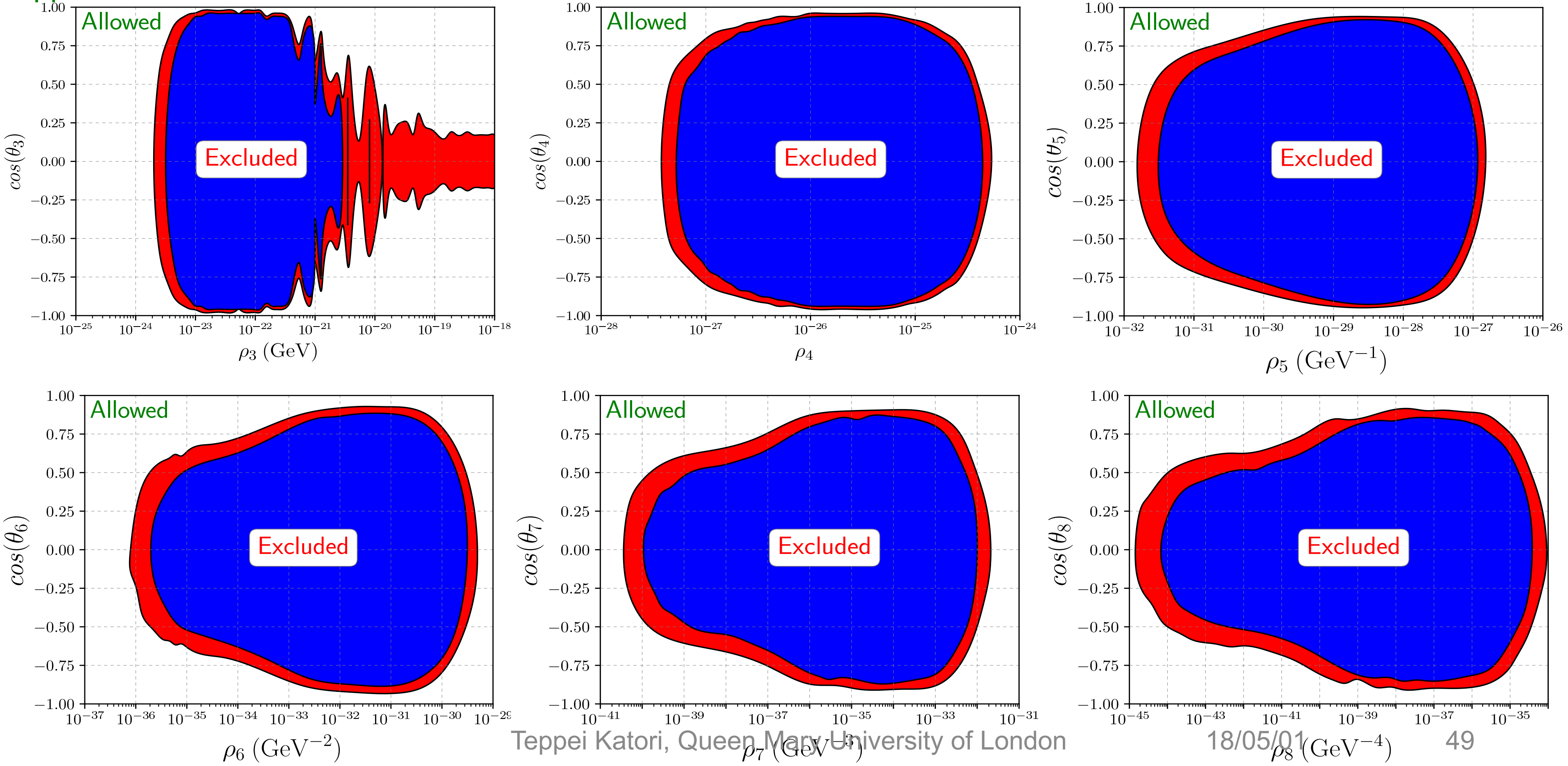
These 3 parameters

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

Appendix 2: MCMC result



Appendix 3: Wilk's theorem based results



IceCube, Nature Physics 14 (2018) 961

5. Results

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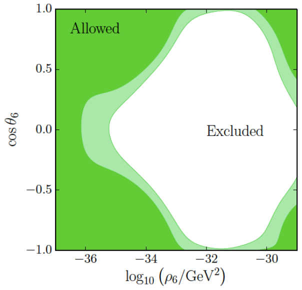
Eq. 2: An example of Lorentz violation operator matrix

Make these 0 by hand

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

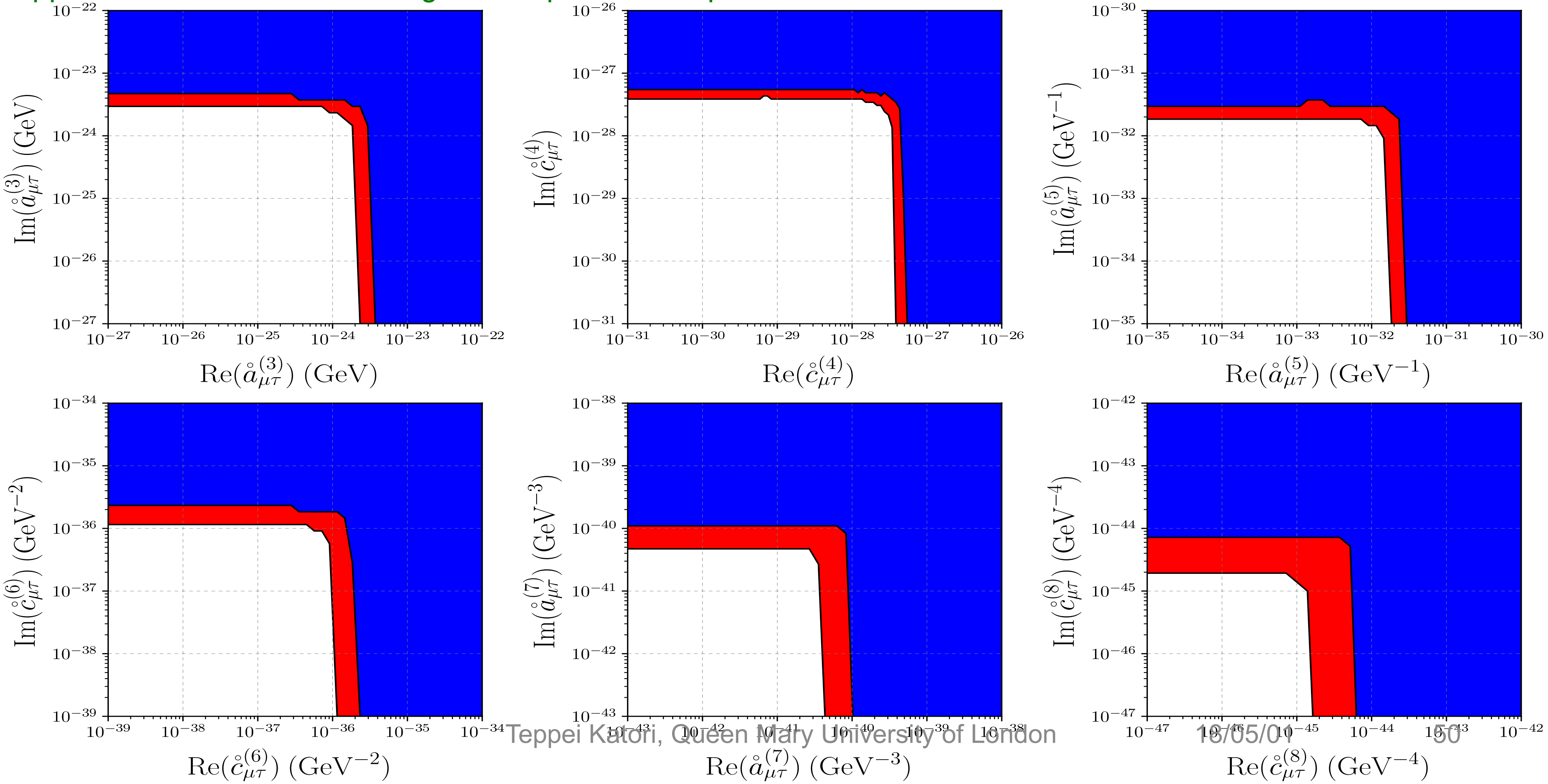
Appendix 2: MCMC result



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

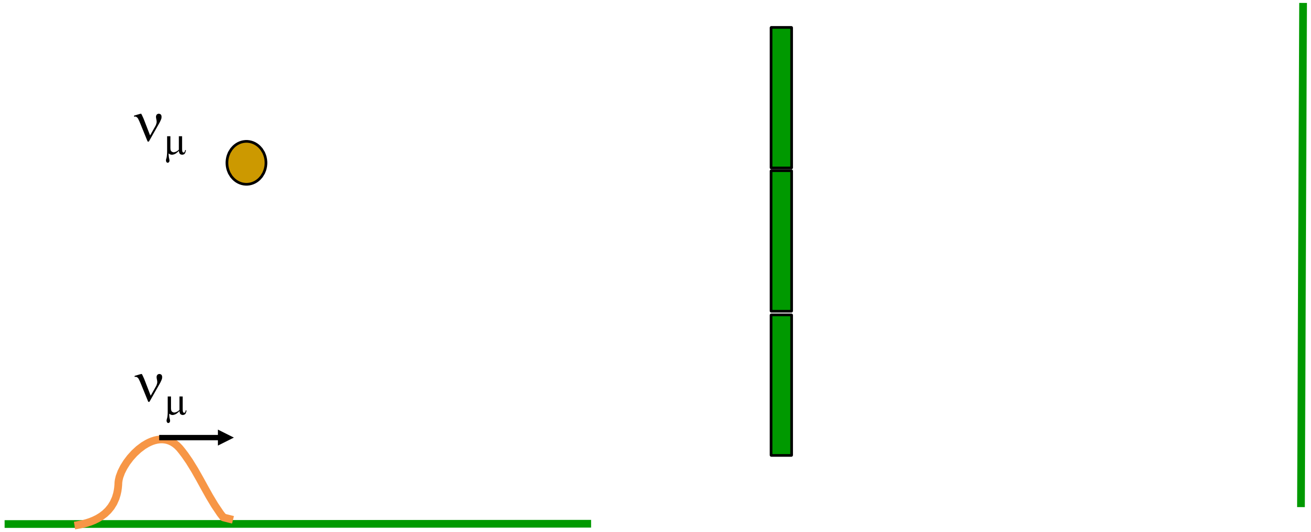
- additionally, we set all parameters=0 but one to match community standard → we report these as our main results

Appendix 4: Contour on off-diagonal LV parameter space



1. Neutrino oscillation as a probe of new physics

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



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

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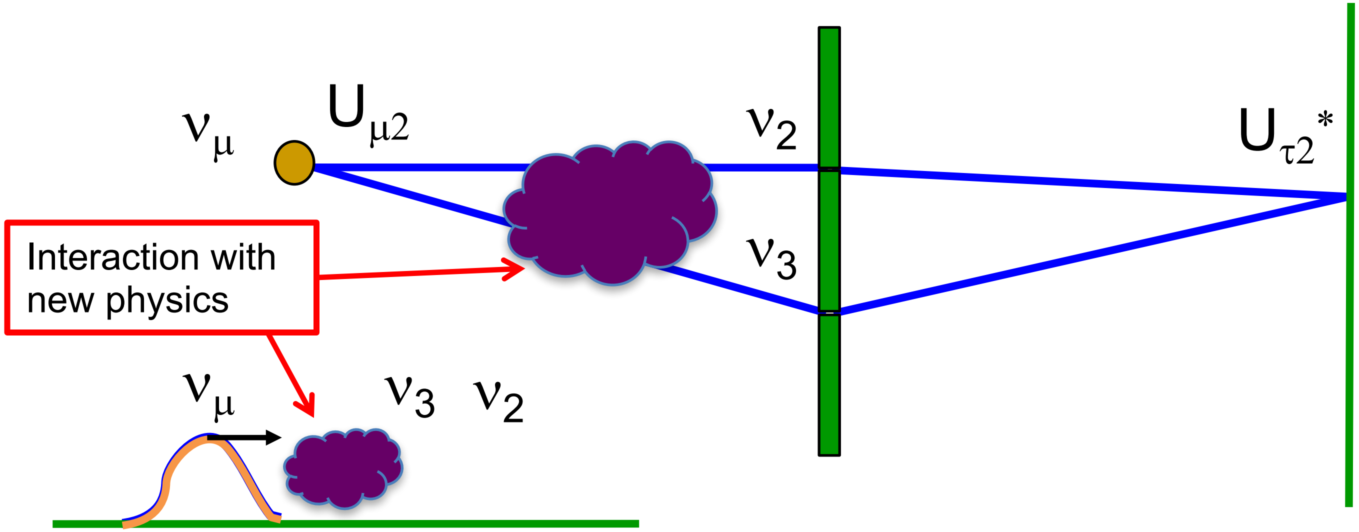

Interaction with new physics

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

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

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

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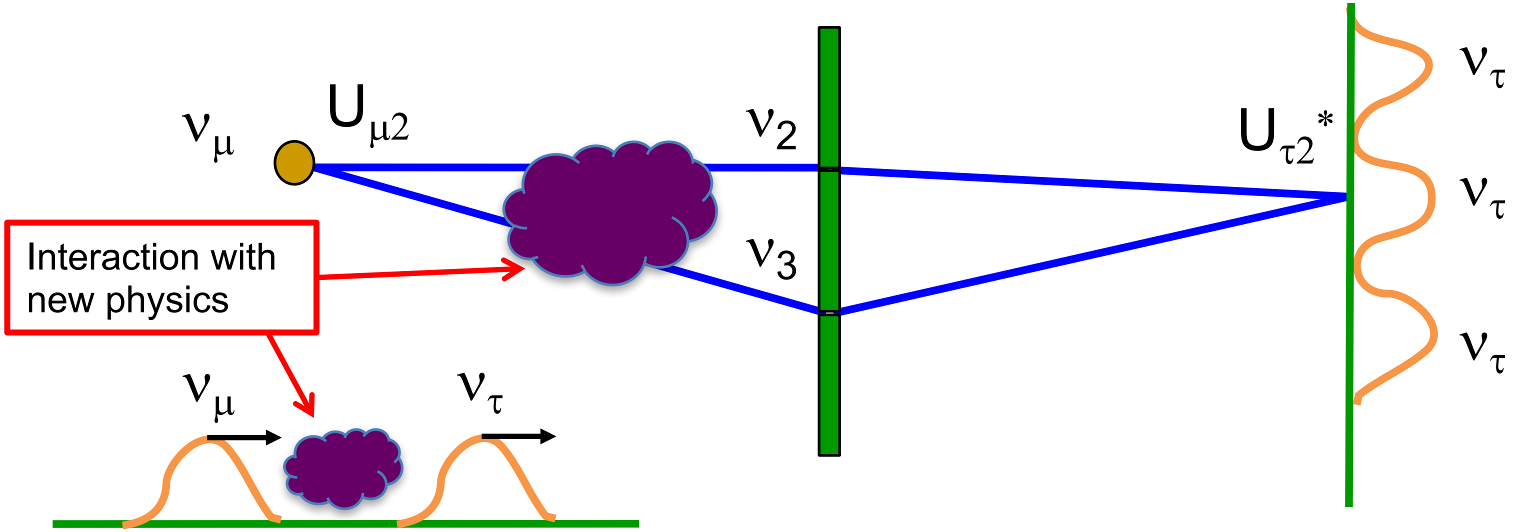

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