Test of Fundamental Physics with Neutrinos

outline

1. Test of Fundamental Physics
2. High-Energy Astrophysical Neutrinos
3. Search of Lorentz violation in IceCube
4. Conclusions

Teppei Katori
King's College London

Corfu 2021 Workshop on the Standard Model and Beyond, Greece, Sep. 3, 2021

1. **Test of Fundamental Physics**

2. **Astrophysical High-Energy Neutrinos**

3. **Search of Lorentz violation in IceCube**

4. **Conclusions**

1. Effective violation of fundamental physics

All fundamental physics phenomena must be experimentally tested

- Spin statistics (Fermion and Boson)
- Lorentz symmetry (rotation and Lorentz boost)
- Poincare symmetry (energy and momentum conservation)
- CPT symmetry (combination of above)

etc.

Fundamental physics laws are basis of all science, so the violation, if it exists, must be very small

Often people assume fundamental physics can be violated effectively, not intrinsic violation

Many Beyond-the-Standard-Model theories show it is possible to violate these fundamental physics laws

- string theory
- noncommutative field theory
- Horava-Lifshitz gravity

etc.

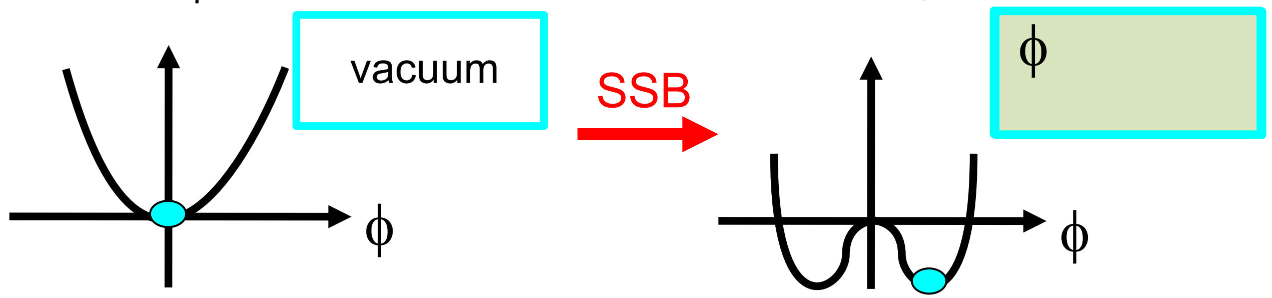
Kostelecký and Samuel,PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking (SLSB)

SSB of scalar field in Standard Model (SM)

- A scalar field generates vacuum expectation value (VEV), reason unknown
- Particle acquires mass term, spontaneously violating gauge invariance

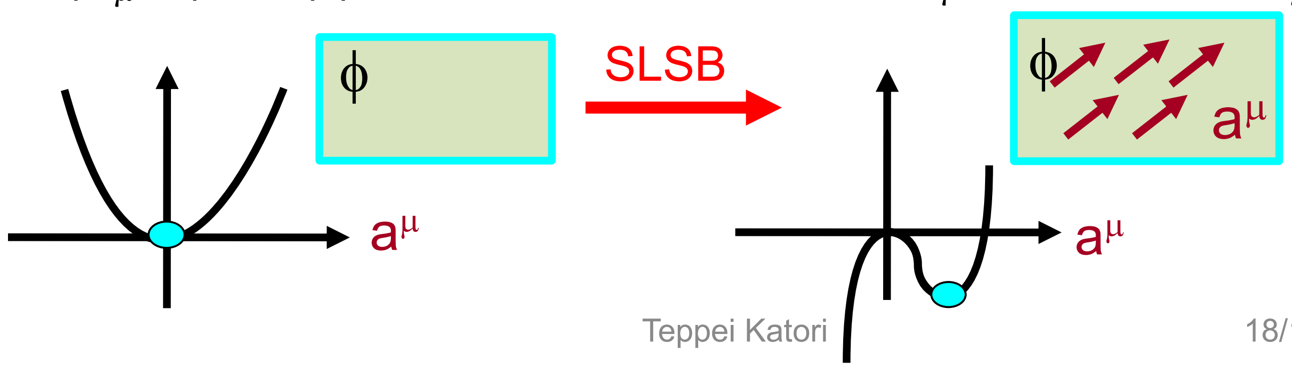
$L = i\bar{\psi}\gamma_\mu\partial^\mu\psi\cdots$ $\qquad$ $L = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi\cdots$



SLSB in string field theory

- Vector fields can generate VEVs
- Lorentz symmetry is spontaneously broken

$L = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi\cdots$ $\qquad$ $L = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi + \bar{\psi}\gamma_\mu a^\mu\psi\cdots$



1. Violation of fundamental physics

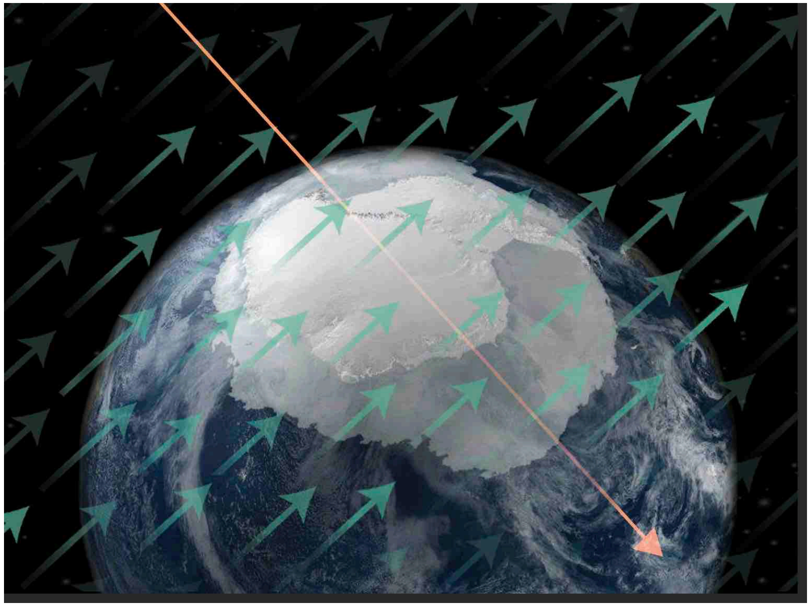
Coupling of SM particles and new physics might modify behaviour of SM physics in vacuum
- matter-antimatter asymmetry
- Direction dependent physics
- Modified dispersion

etc.

Expected effect is small. We need high-precision measurements to find such new physics

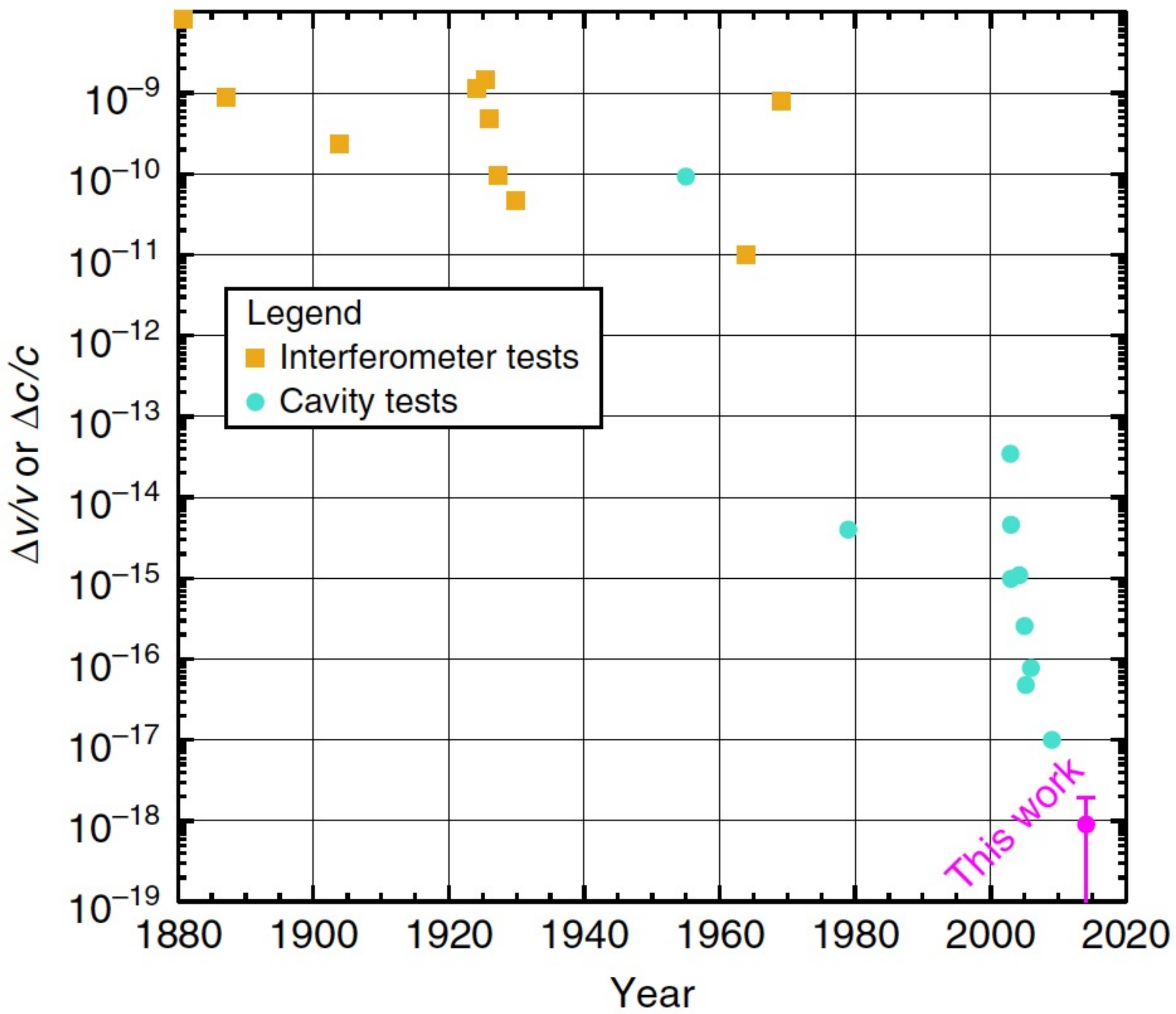
quantum foam
- quantum fluctuation of space time

Lorentz violating field
- new field saturating the universe (æther)



Nagel et al, Nature Comm., 6(2015)8174

1. History of Michelson-Morley experiment (2015)



1. Test of Fundamental Physics

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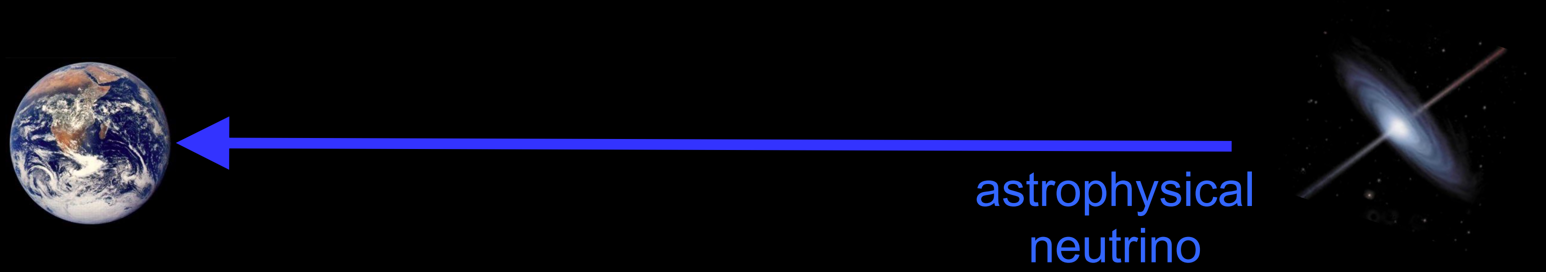
2. High-energy astrophysical neutrinos

High-energy particles (>100 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe



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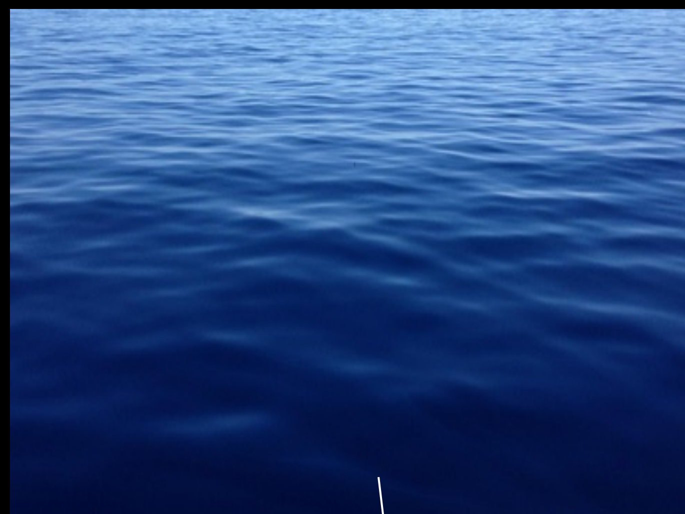
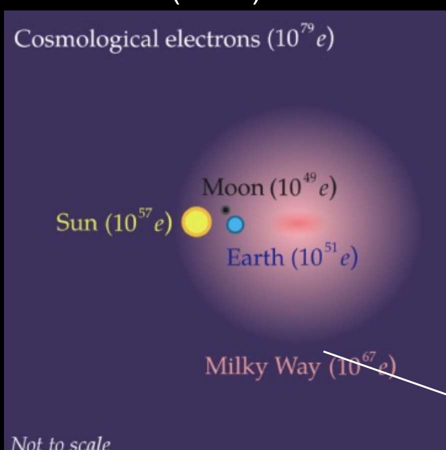
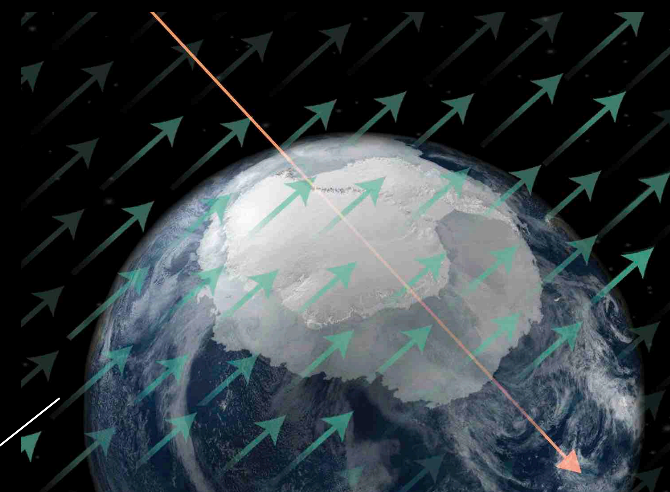
Quantum foam
Ellis,Mavromatos,NanopoulosPLB293(1992)37

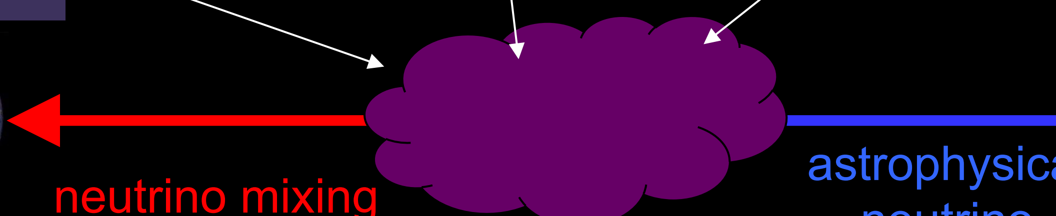


new long-range force
Bustamante,Agarwalla
PRL122(2019)061103

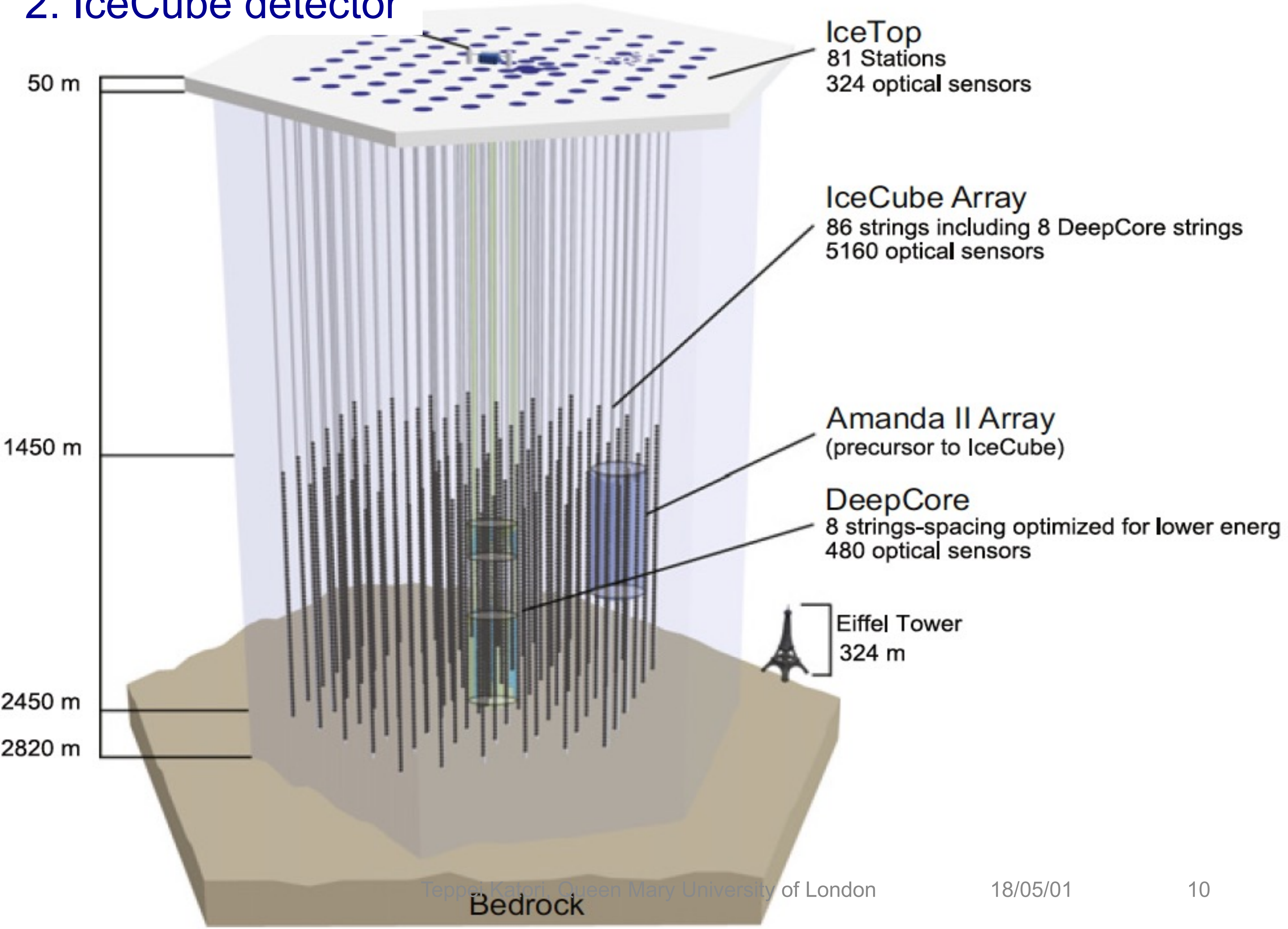


Lorentz violating field
Argüelles,TK,Salvado,PRL115(2015)161303





2. IceCube detector



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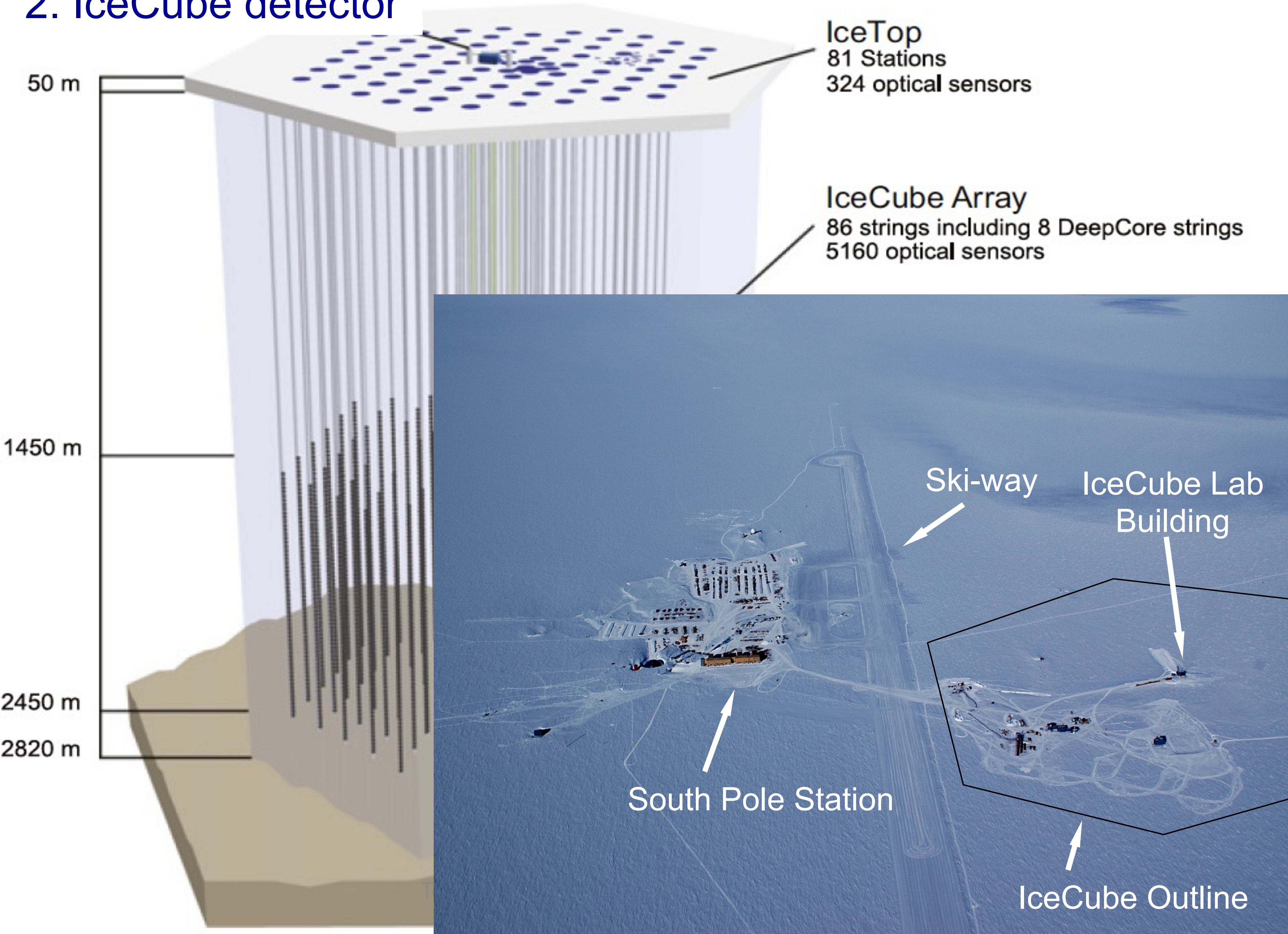

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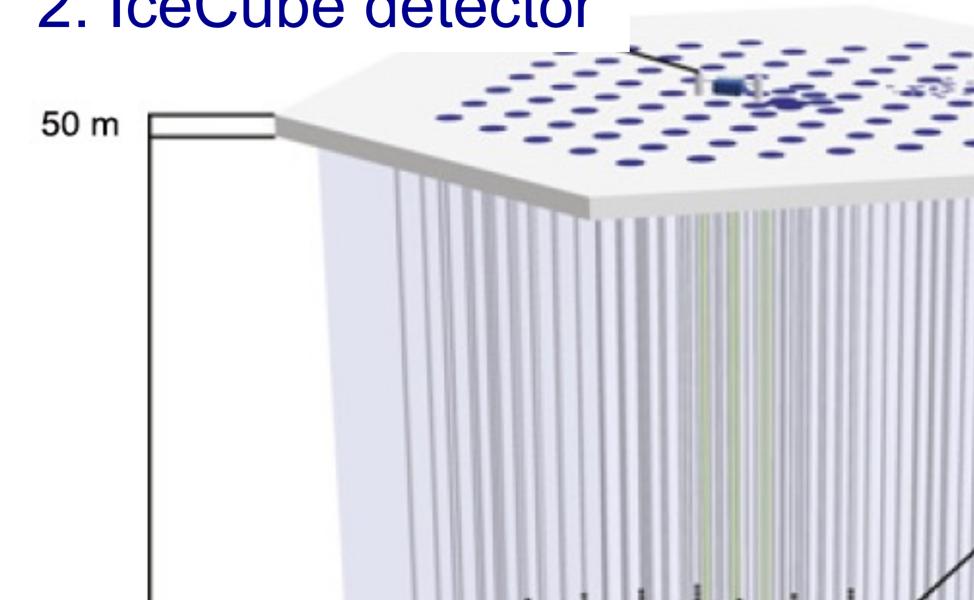
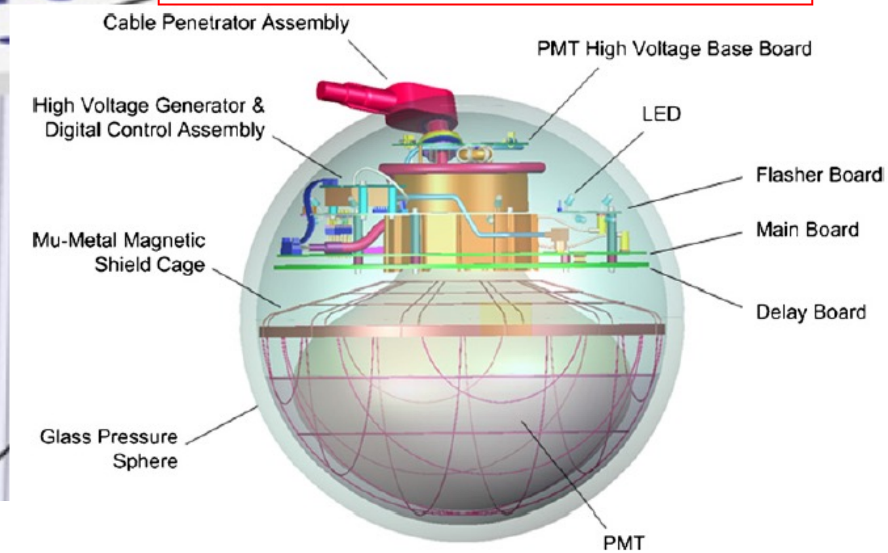
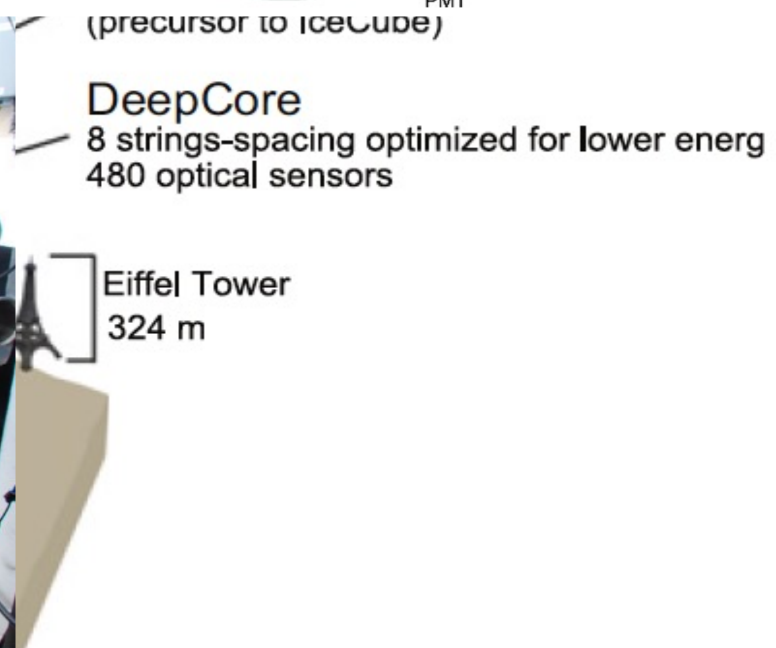


digital optical module (DOM)



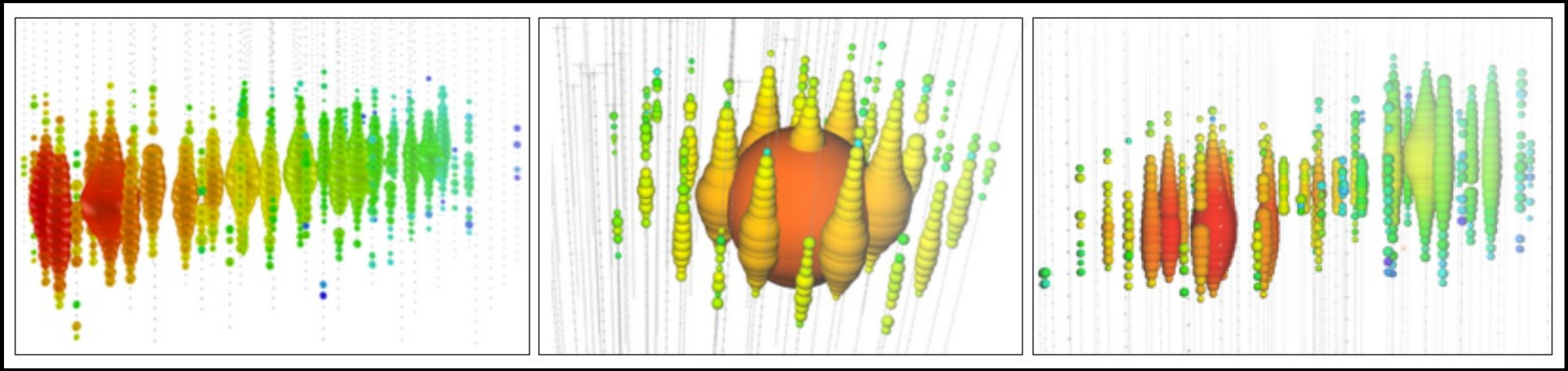


2. IceCube event morphology

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

Cascade
ν_eCC, ν_τCC, NC
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

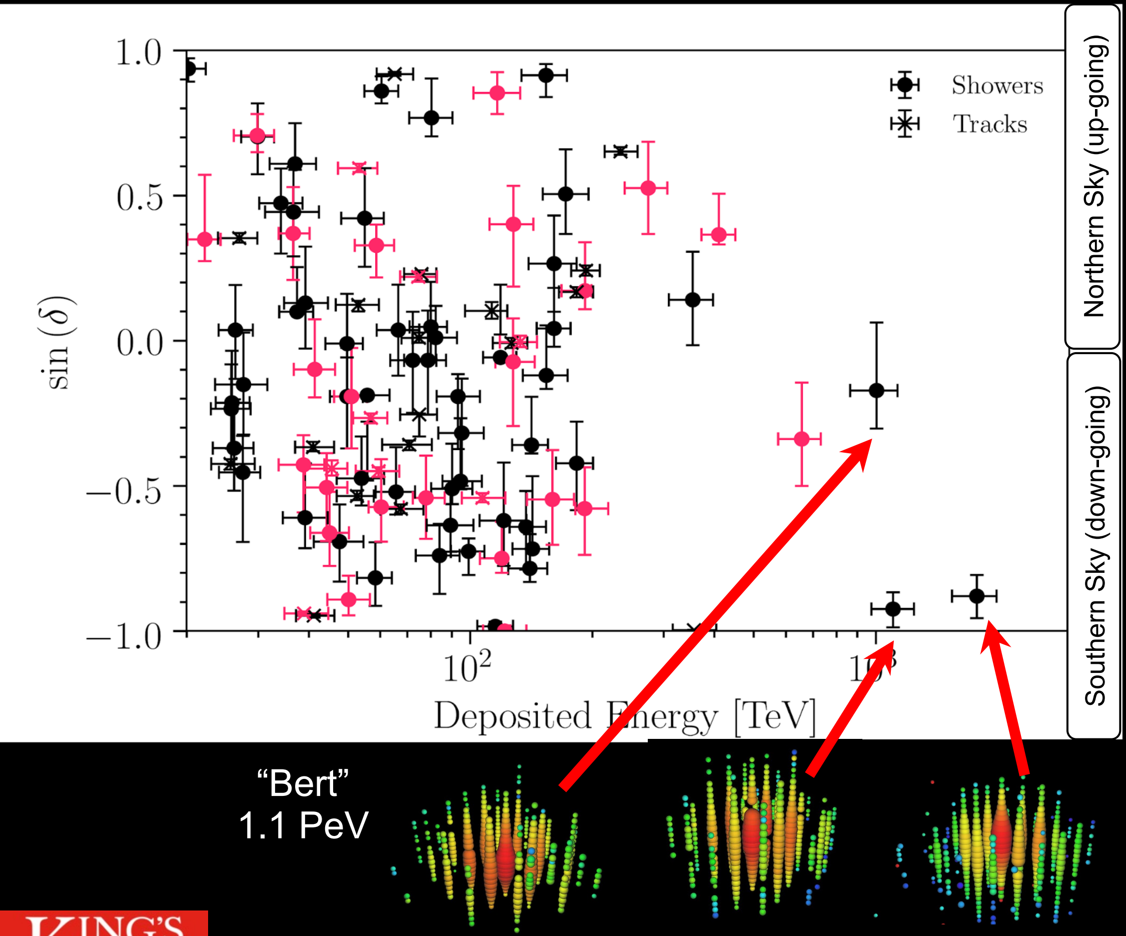
Double cascade
ν_τCC (L~50m•E/PeV)
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X'$$



IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102
ArXiv:2011.03545,2011.03560,2011.03561

2. Astrophysical Very-High-Energy Neutrinos

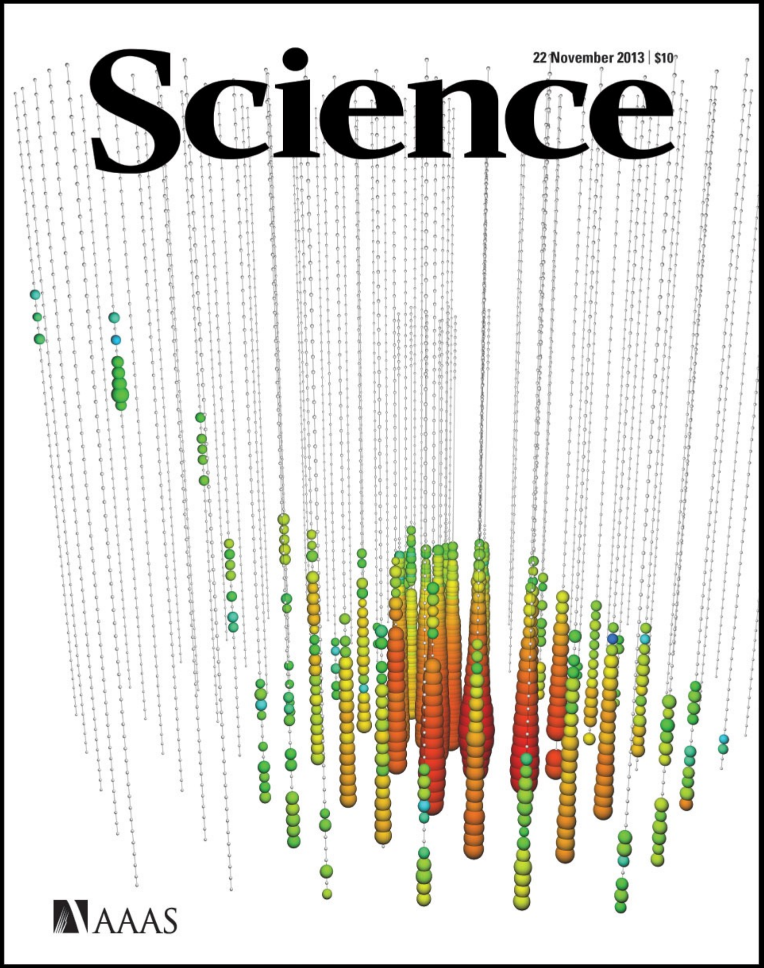
First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos



"Bert"
1.1 PeV

"Ernie"
1.0 PeV

"Big Bird"
2.0 PeV



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3. Search for Lorentz violation with astrophysical neutrinos

High-energy particles (>100 TeV) propagating a long distance (>100 Mpc)
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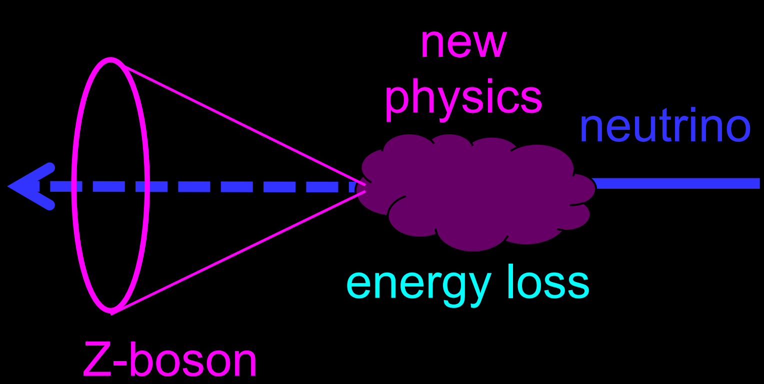
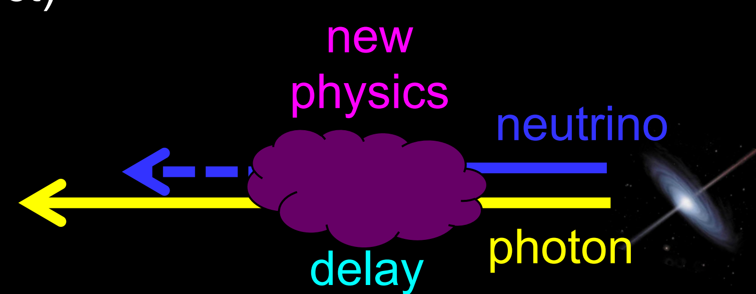
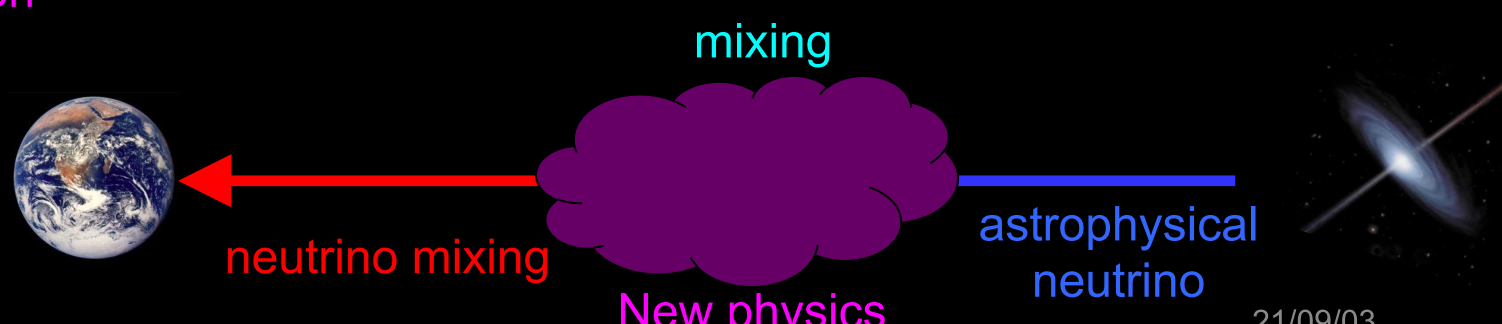
New physics search
- Spectrum distortion (vacuum Cherenkov radiation)
- Time of Flight (modified dispersion)
- New flavour structure (new vacuum effect)







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Diaz et al, PRD89(2014)043005, Borriello et al, PRD87(2013)116009

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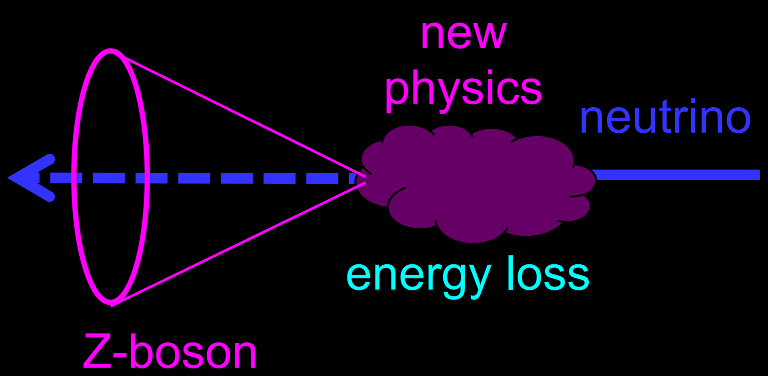

Lorentz violating field cause
Cherenkov radiation in vacuum

Diaz et al, PRD89(2014)043005, Borriello et al, PRD87(2013)116009
Minami and Komatsu, PRL125(2020)221302

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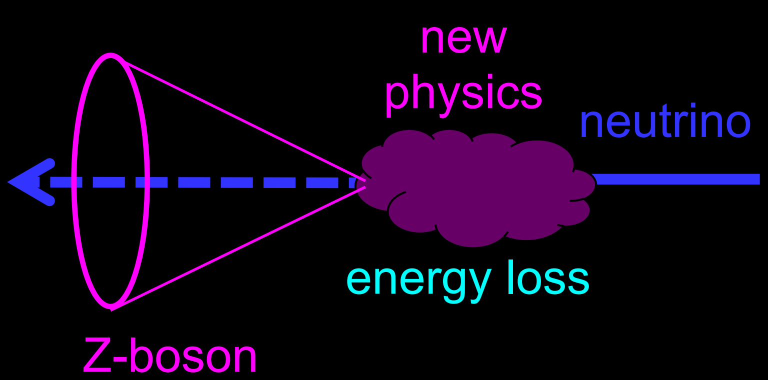

Lorentz violating field cause Cherenkov radiation in vacuum

PHYSICAL REVIEW LETTERS **125,** 221301 (2020)

Editors' Suggestion | Featured in Physics

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami*
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Eiichiro Komatsu†

CMB polarization data may indicate nonzero vacuum birefringence $k^{(3)}_{00} \sim 10^{-43}$ GeV

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3. Search for Lorentz violation with astrophysical neutrinos

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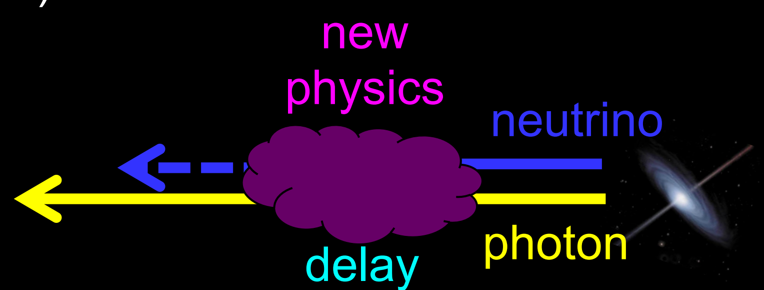
Modified dispersion due to quantum foam cause unexpected delay/advance for neutrinos



Ellis et al, PLB789(2019)352, Laha PRD100(2109)103002, Wei et al, JHEA22(2019)1, Ma et al.,PRD99(2019)123018

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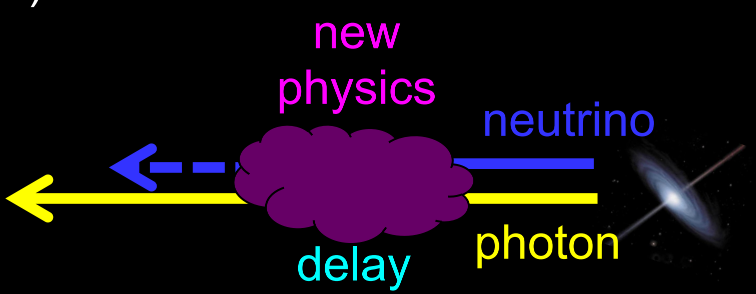

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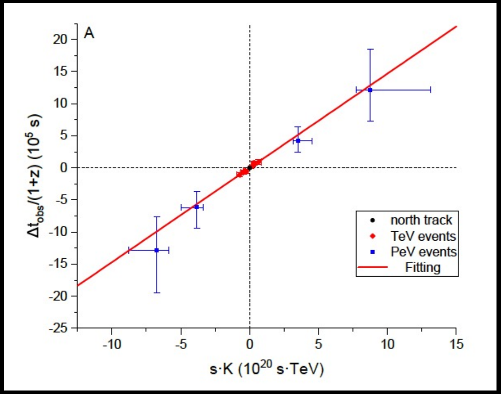

nonzero LV
$E_{LV} \sim 10^{17}$ GeV

$$\frac{\Delta t_{\mathrm{obs}}}{1+z} = \Delta t_{\mathrm{in}} + s \cdot \frac{K}{E_{\mathrm{LV}}}.$$

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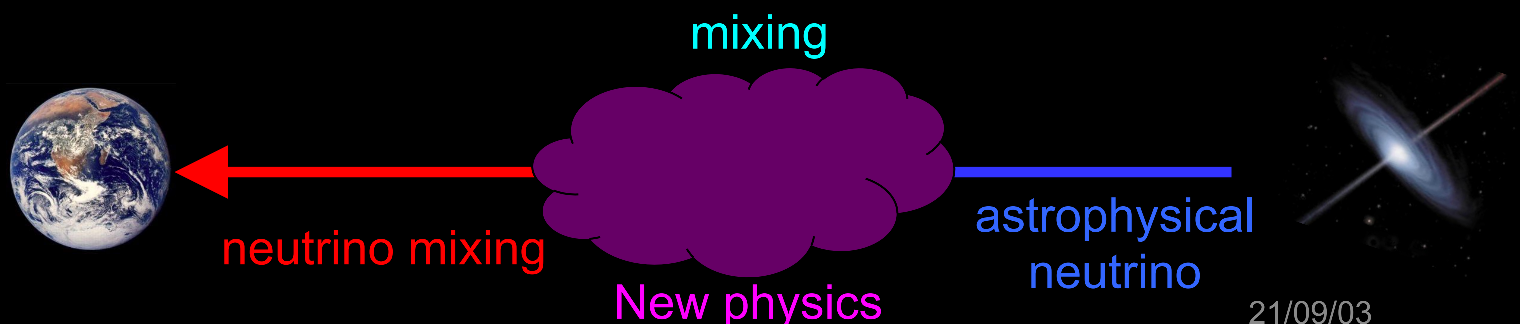
Flavour effect
- Macroscopic quantum effect and sensitive to small effects
- Today's topic



Mewes and Kostelecký, PRD85(2012)096005

3. Flavor new physics search with effective operators

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

Standard Model | New physics

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots$$

Effective Hamiltonian can be written from here

Standard Model | New physics (renormalizable) | higher dimension operator (non-renormalizable)

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

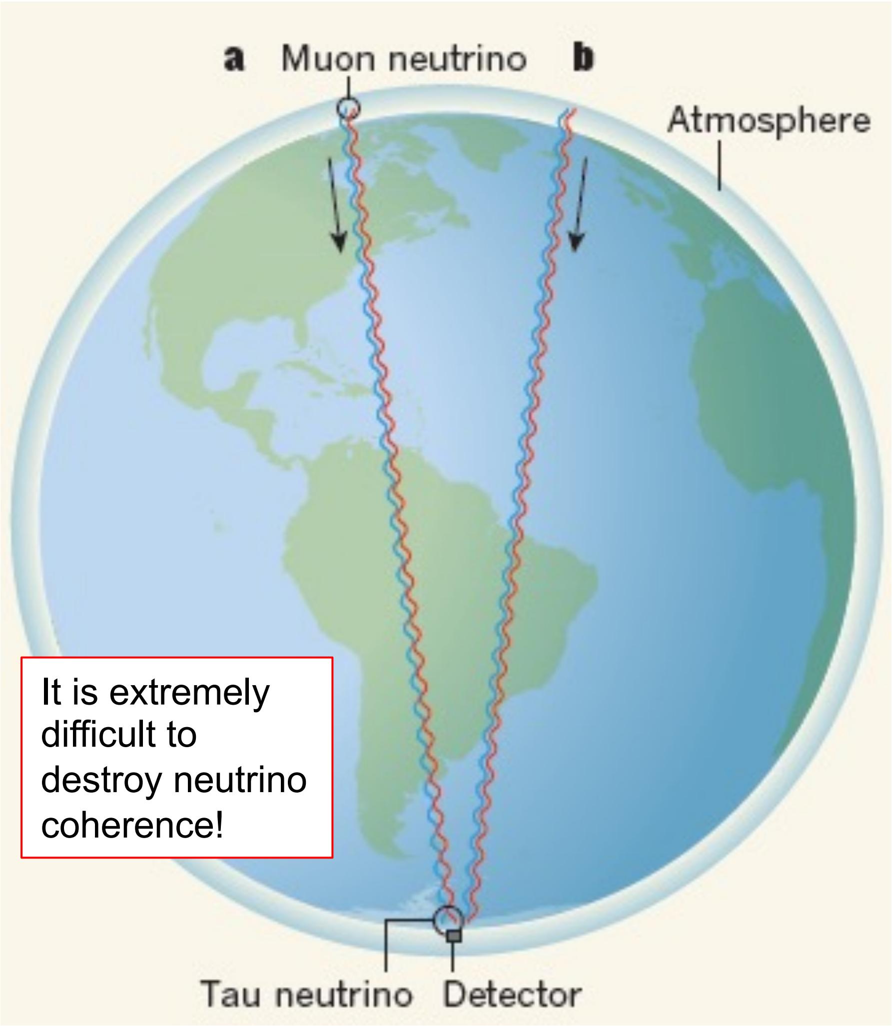
$$E^{3}c^{(6)}_{\alpha\beta} = E^{3}\begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix}$$

IceCube is sensitive to higher dimension operators

dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38}GeV^{-2}$

IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

3. Neutrino interferometry – Atmospheric neutrinos

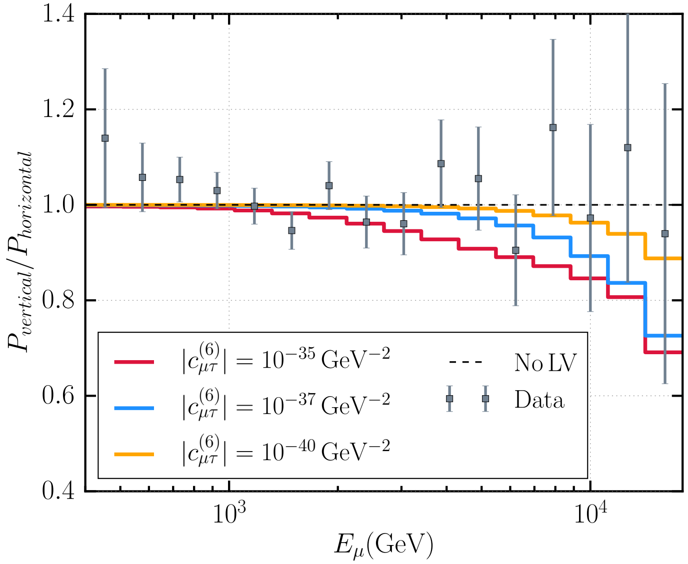


It is extremely difficult to destroy neutrino coherence!

Neutrino oscillation is a nature interferometer. Any extra interactions in the Lagrangian contribute the phase shift

The highest energy - 20 TeV
The longest baseline - 12700km

If anomalous coupling with neutrinos in vacuum cause a phase shift in similar order, we can see it from spectrum distortion of atmospheric neutrinos



IceCube atmospheric neutrino limit, $c^{(6)} < 10^{-36} GeV^{-2}$
This is close to the target signal region, $c^{(6)} \sim 10^{-38} GeV^{-2}$

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IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

3. Neutrino interferometry – Atmospheric neutrinos

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 atmospheric neutrino limit, $c^{(6)} < 10^{-36} GeV^{-2}$
This is close to the target signal region, $c^{(6)} \sim 10^{-38} GeV^{-2}$

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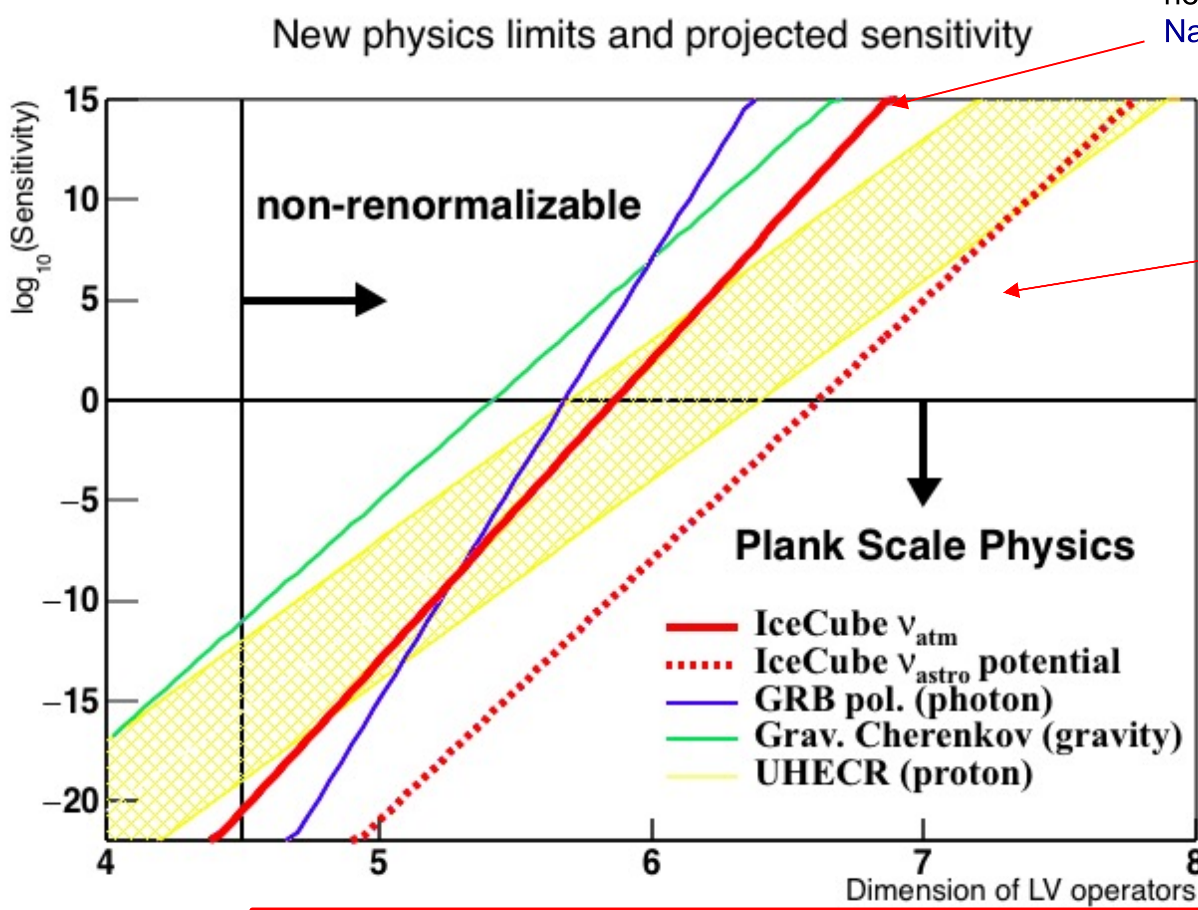
3. Neutrino interferometry – Astrophysical neutrinos

Higher-dimension operators may be related to new physics

- Dimension-5 operator (unit: GeV^{-1}), example: Majorana mass
- Dimension-6 operator (unit: GeV^{-2}), example: Fermi constant (G_F)

IceCube atmospheric neutrino LV sensitivity Nature Physics 14(2018)961

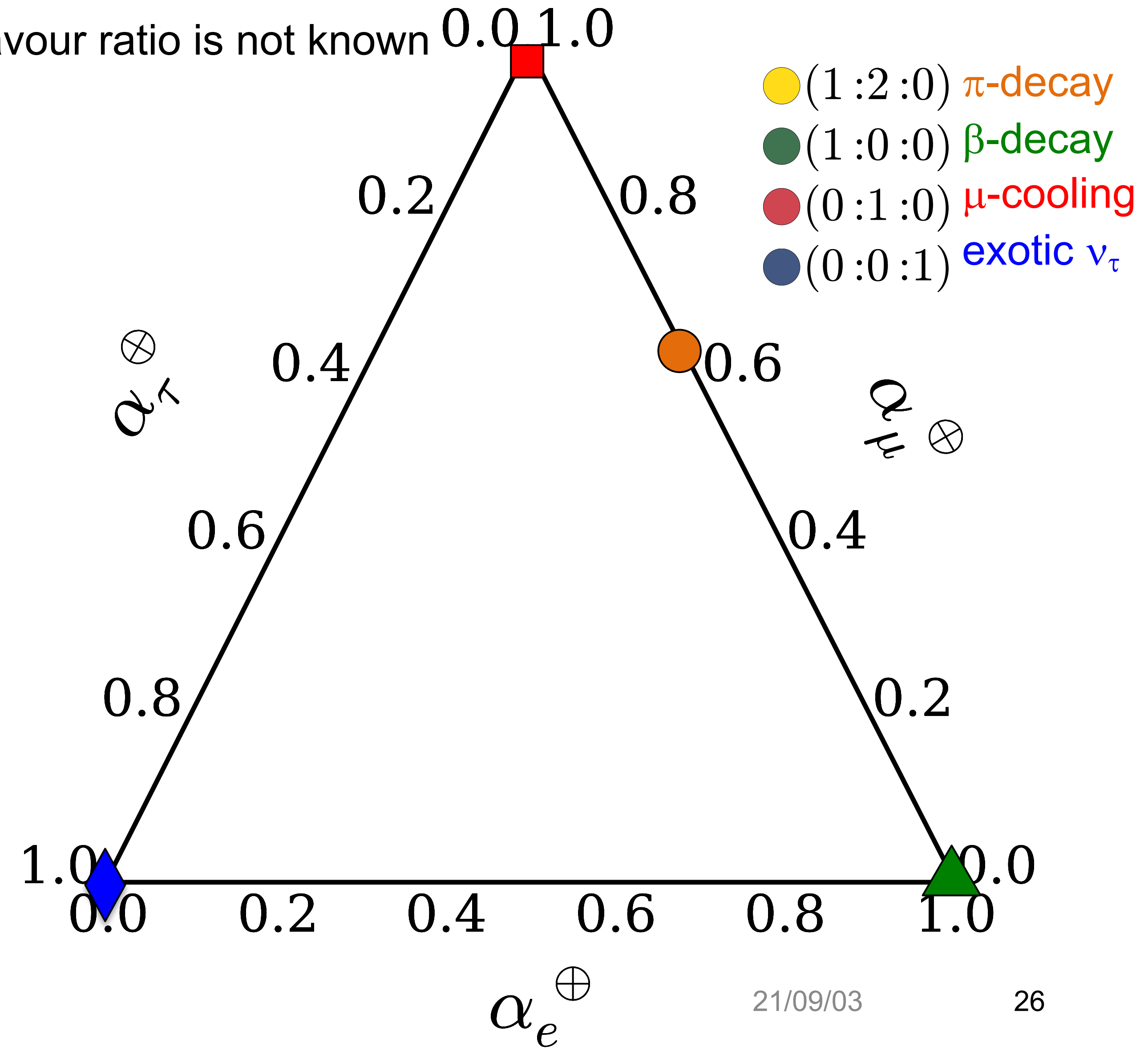


IceCube astrophysical neutrino LV sensitivity

Astrophysical neutrino dim-6 LV operator search can reach quantum gravity motivated region (~$1/M_{Planck}^2$~10^{-38} GeV^{-2})

3. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

Astrophysical neutrino production mechanism is not known → production flavour ratio is not known



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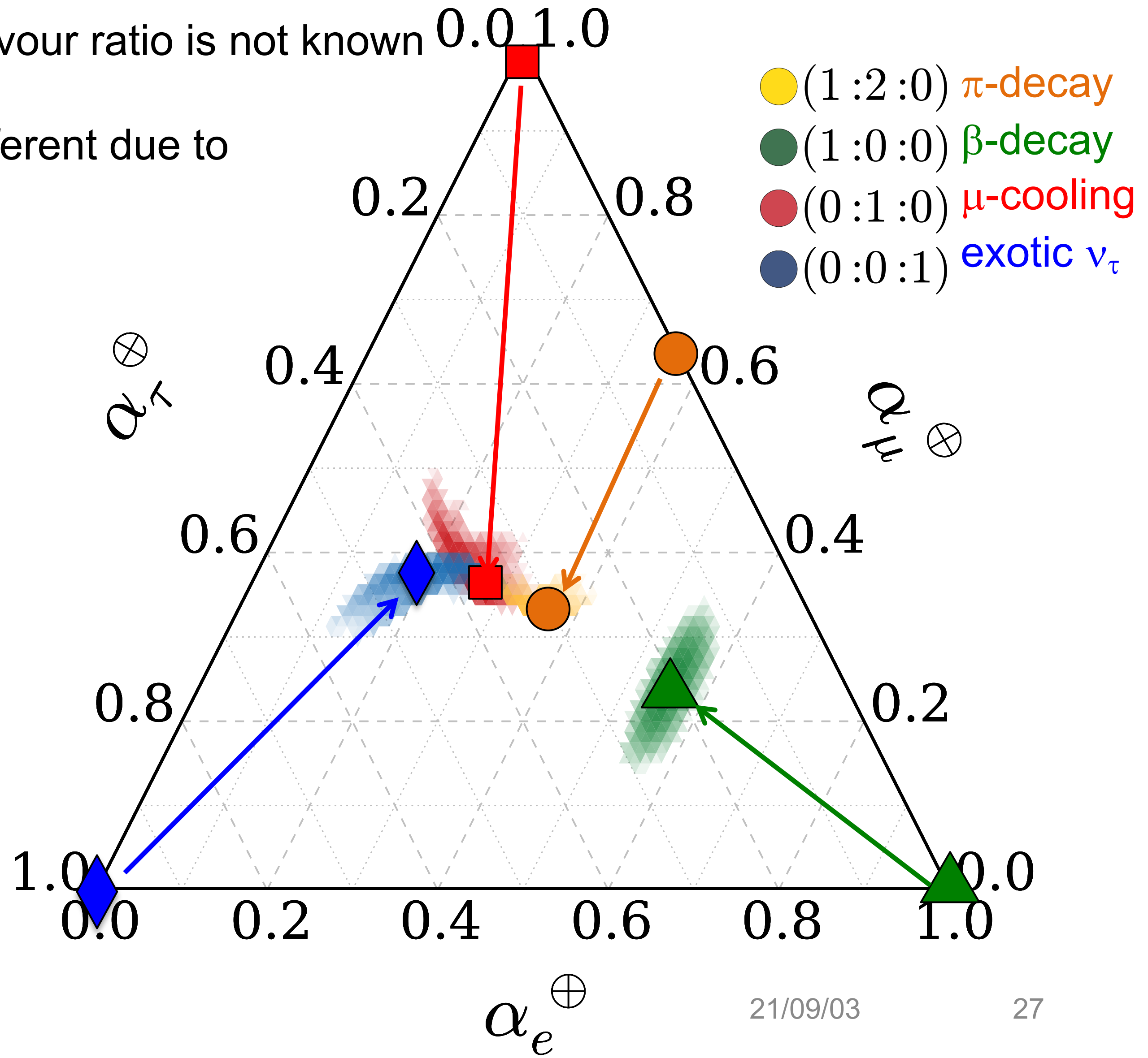
Flavour ratio on Earth is different due to mixing by neutrino masses



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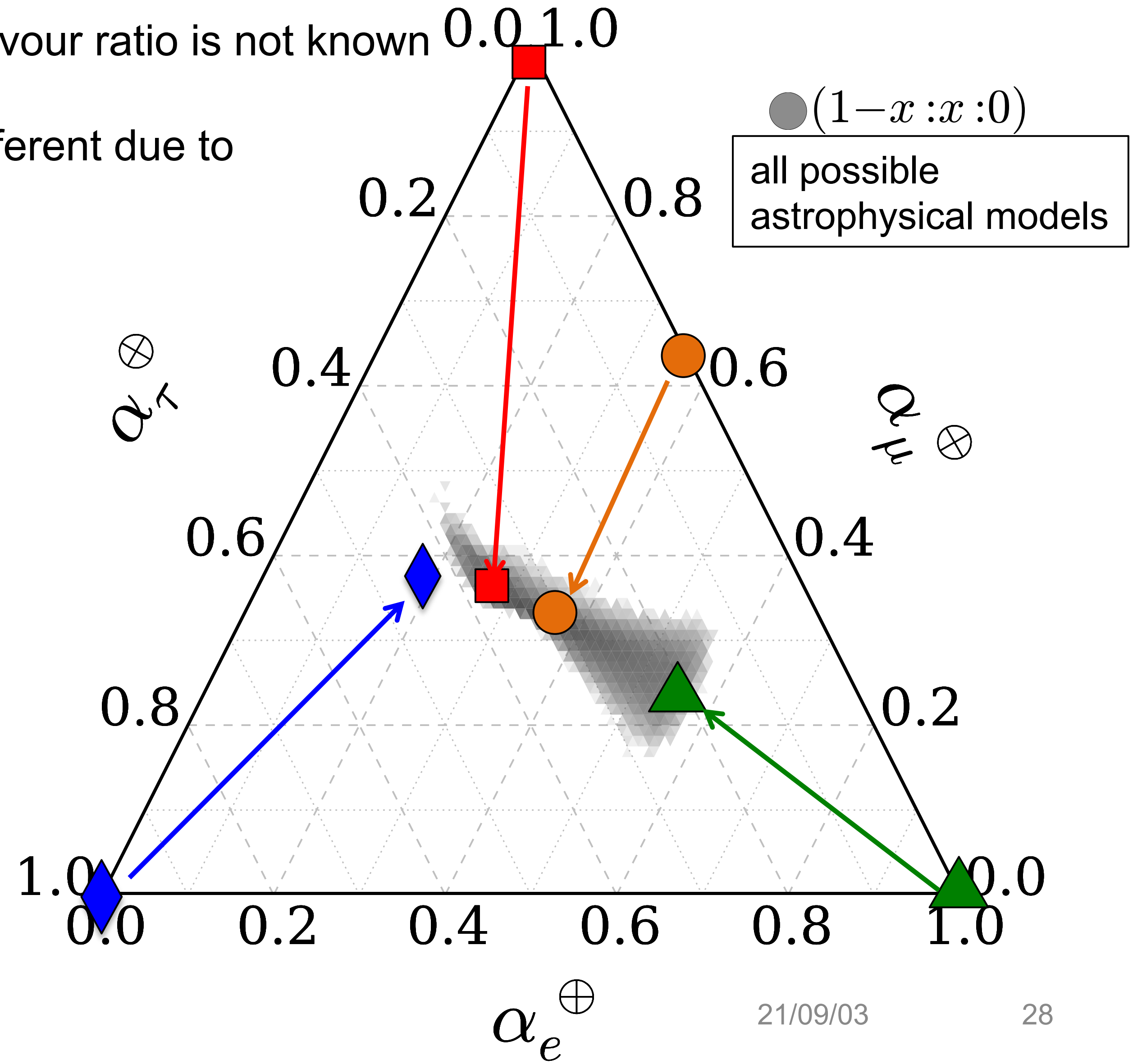
All possible flavour ratio is confined in a small space



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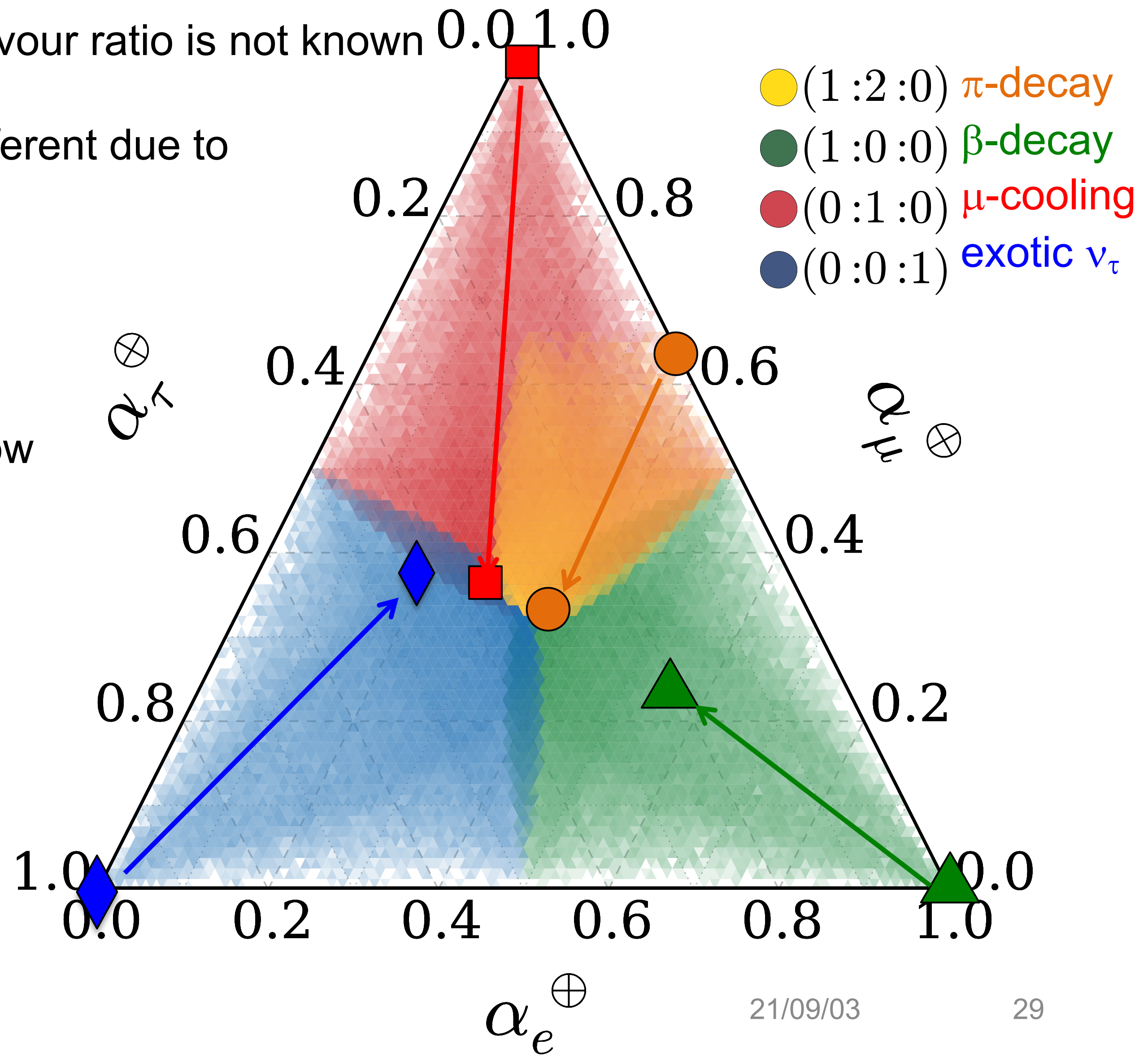
e.g.) New physics just below the limit can produce any flavour ratio

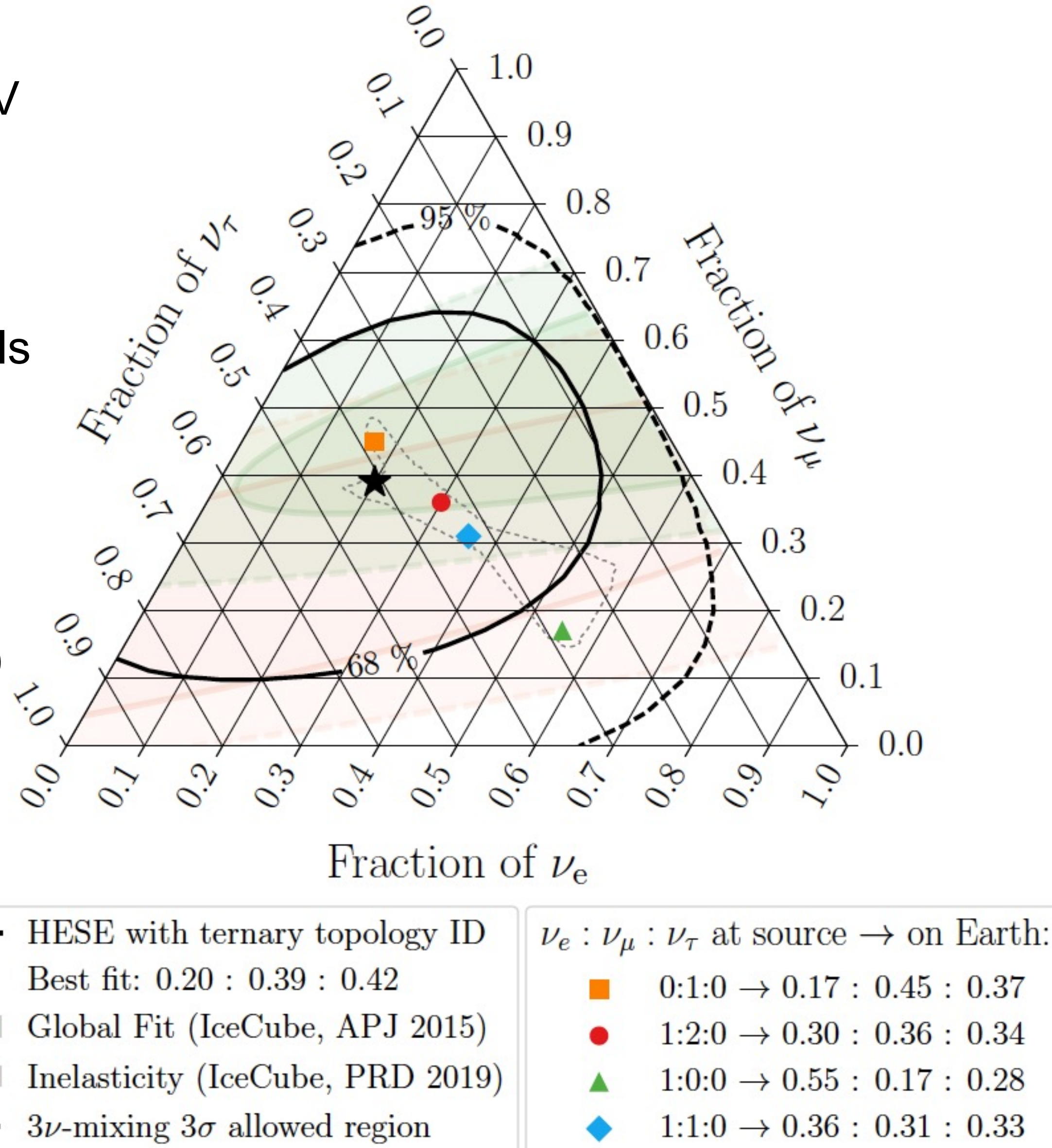


3. HESE 7.5-yr flavor ratio

60 HESE events in 60 TeV – 2 PeV
First identification of tau neutrinos

New flavour ratio measurement
- contour is too big, most of models are accepted by data

We will not find new physics
We need;
- higher statistics (IceCube-Gen2)
- better PID (software)



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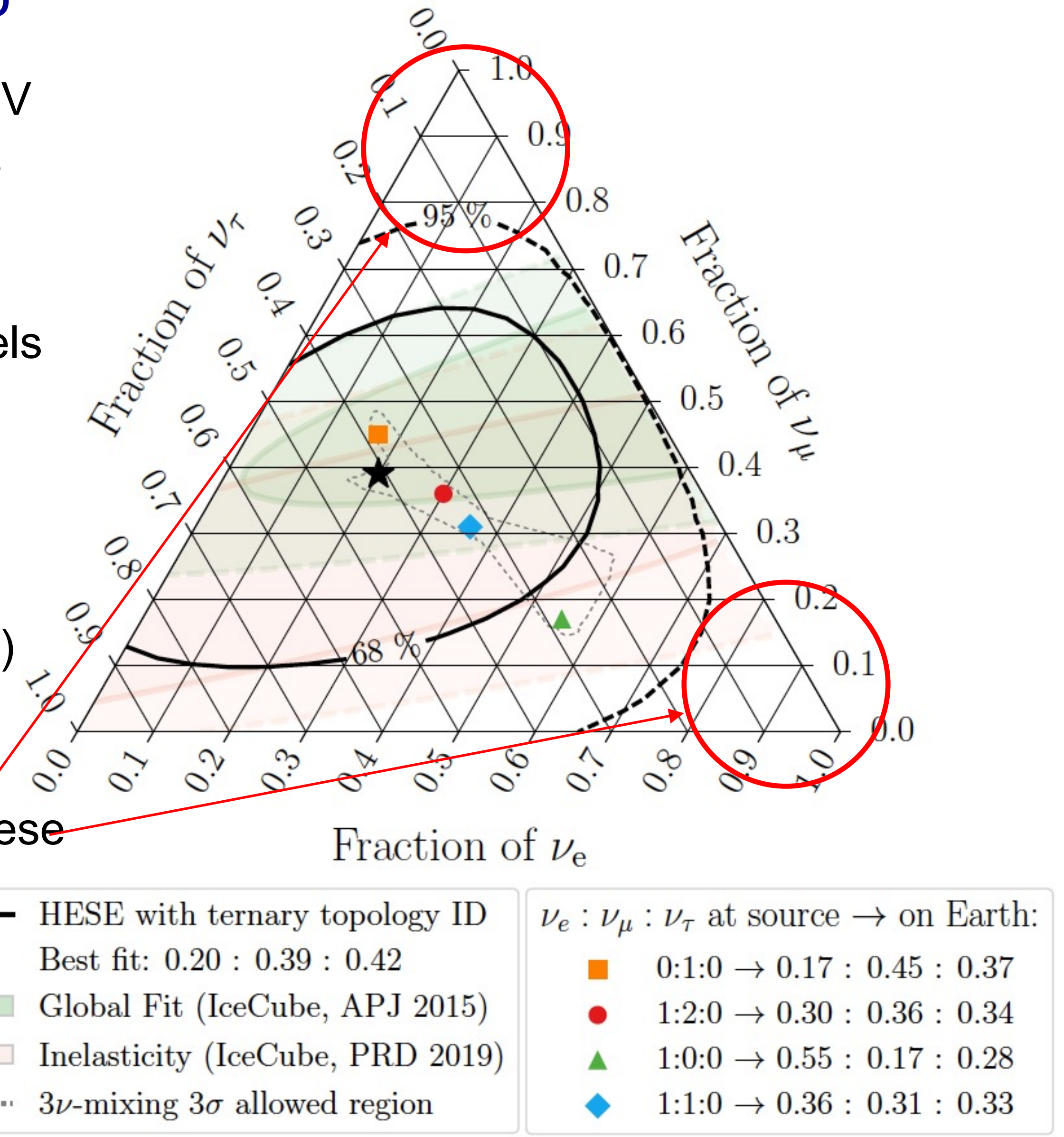
Models predict flavour ratios at these corners would be rejected



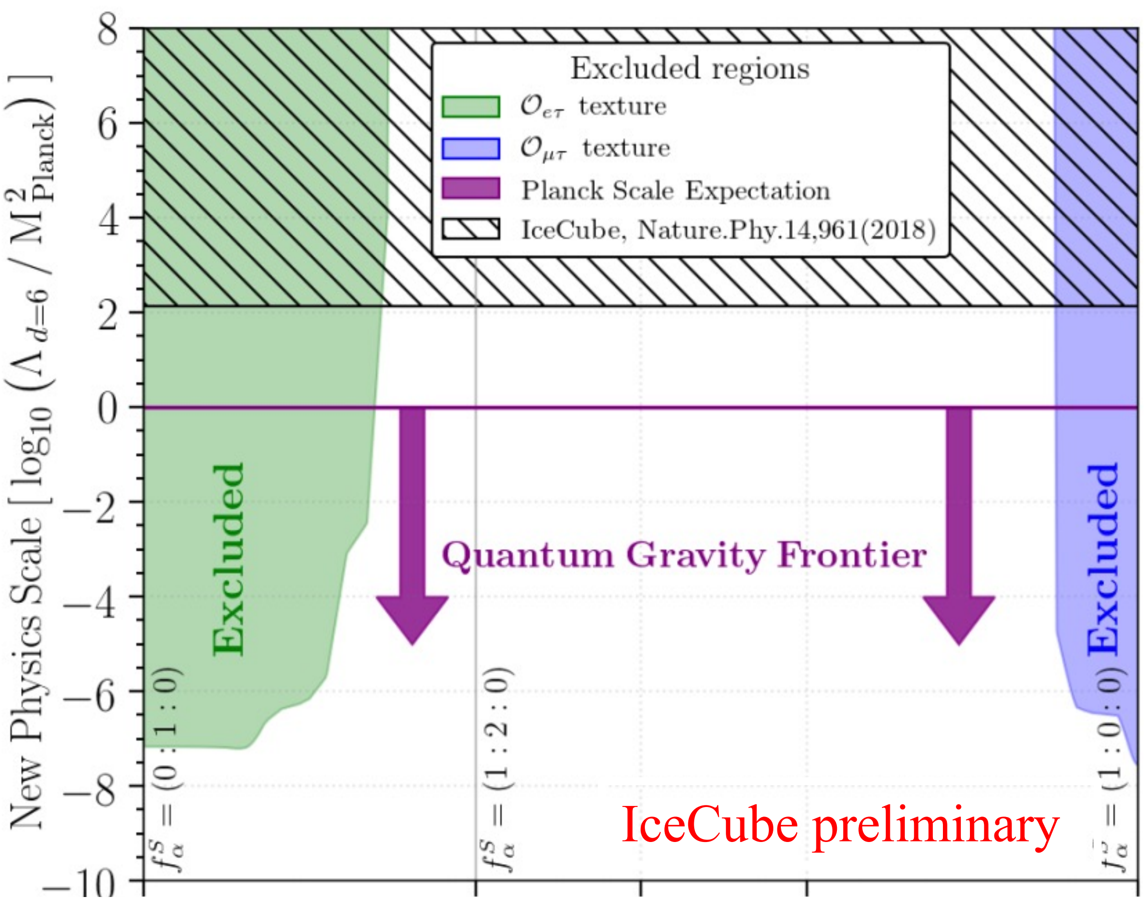
3. HESE 7.5-yr flavor new physics search

60 HESE events in 60 TeV – 2 PeV
First identification of tau neutrinos

Strong limits for many parameters depending on assumed initial flavour ratio

- 10^{-26} GeV ~ dim-3 LV limit
- 10^{-32} ~ dim-4 LV limit
- 10^{-40} GeV^{-1} ~ dim-5 LV limit
- 10^{-46} GeV^{-2} ~ dim-6 LV limit
- 10^{-51} GeV^{-3} ~ dim-7 LV limit
- 10^{-58} GeV^{-4} ~ dim-8 LV limit

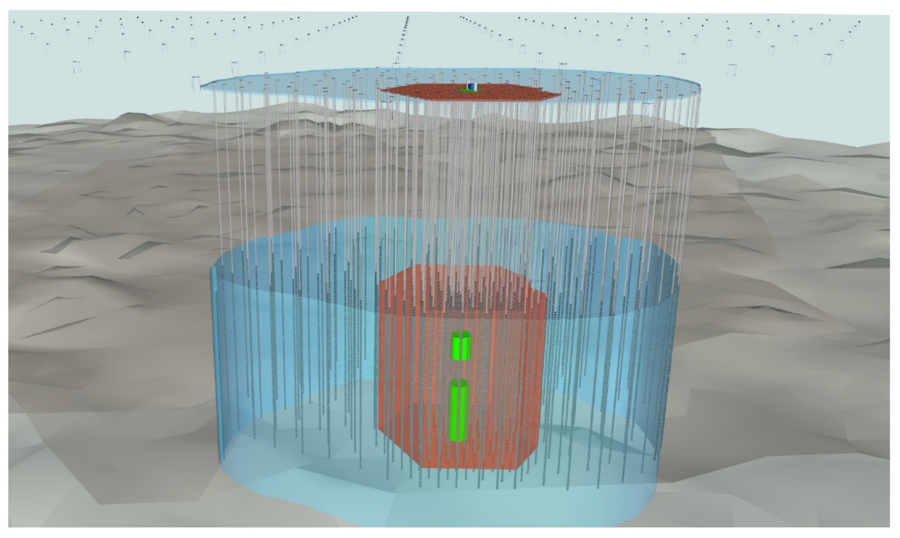
Paper in preparation (2021)

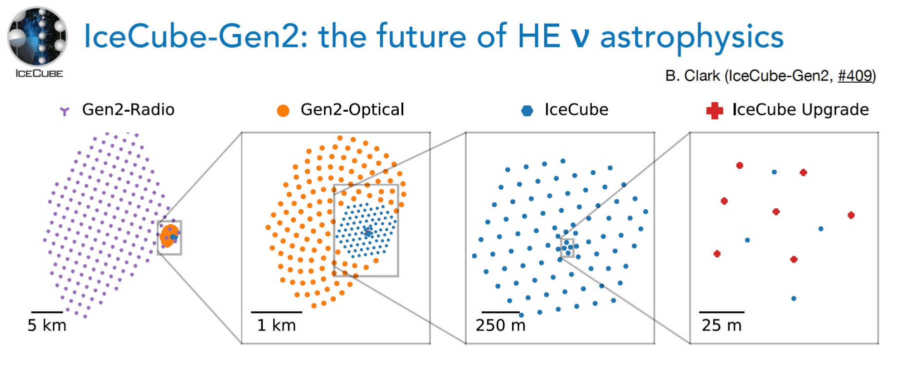


IceCube-Gen2, J.Phys.G48(2021)060501
Santarder (Neutrino2020)

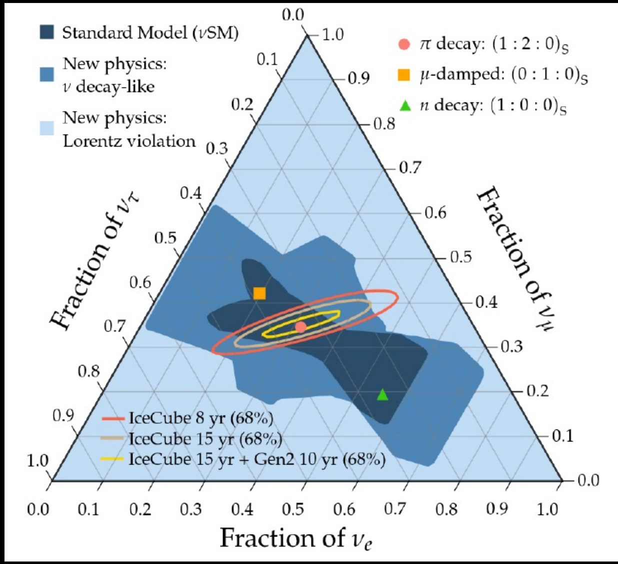
3. IceCube-Gen2

Larger separation (125m → ~200-300m) to cover larger volume
 - 120 new strings with 100 sensors, 240 m separation, x10 coverage





IceCube-Gen2 flavour ratio sensitivity



The first stage of Gen2 (IceCube upgrade) is approved and ongoing

Conclusion

Quantum gravity may create a new structure in vacuum.

Neutrino interferometry is a powerful technique to look for new physics.

Astrophysical neutrino mixing sensitivity reaches to naïve expectation of Planck scale physics. We need more statistics and better particle identification algorithm to find quantum gravity motivated physics.

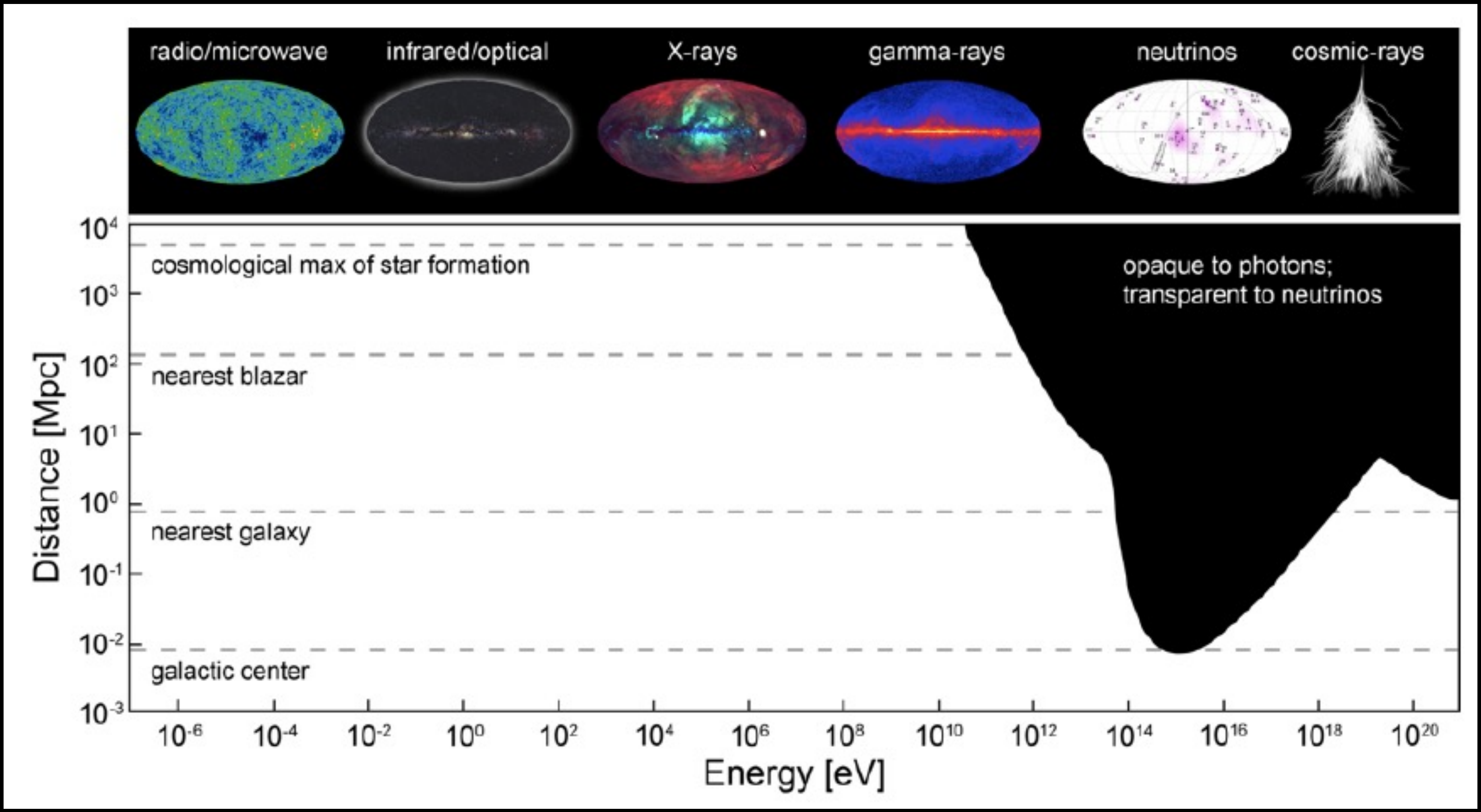
IceCube-Gen2 collaboration

Thank you for your attention!

Backup

2. High-energy astrophysical neutrinos

Above ~100 TeV, neutrinos are only particles pointing to their high-energy sources

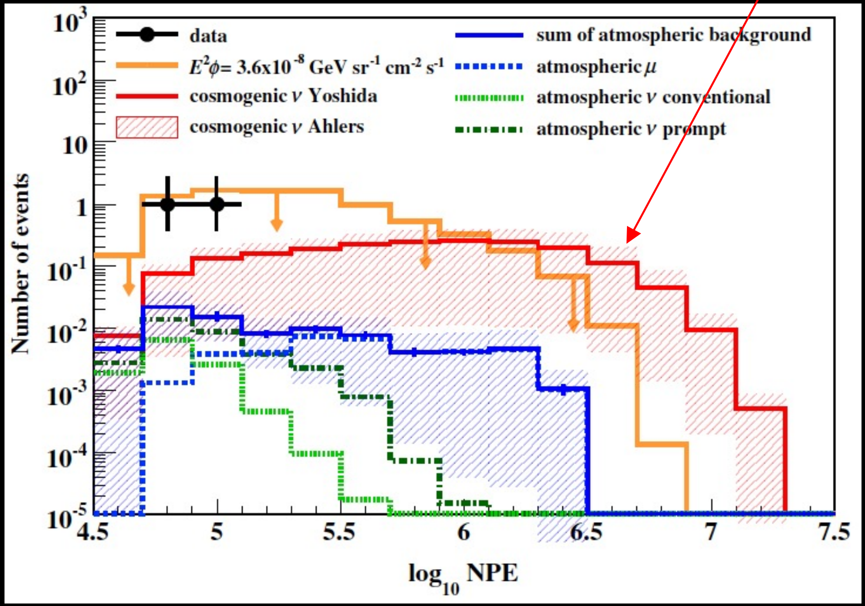


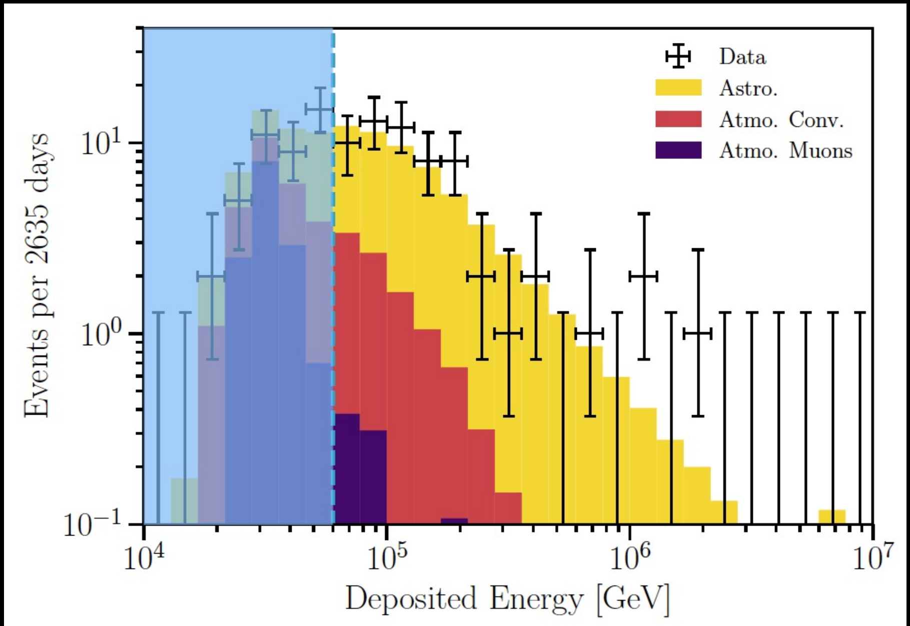
IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102
ArXiv:2011.03545,2011.03560,2011.03561

2. Astrophysical Very-High-Energy Neutrinos

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Too high-energy as atmospheric neutrinos
- Too low-energy as GZK neutrinos

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





IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102
ArXiv:2011.03545,2011.03560,2011.03561

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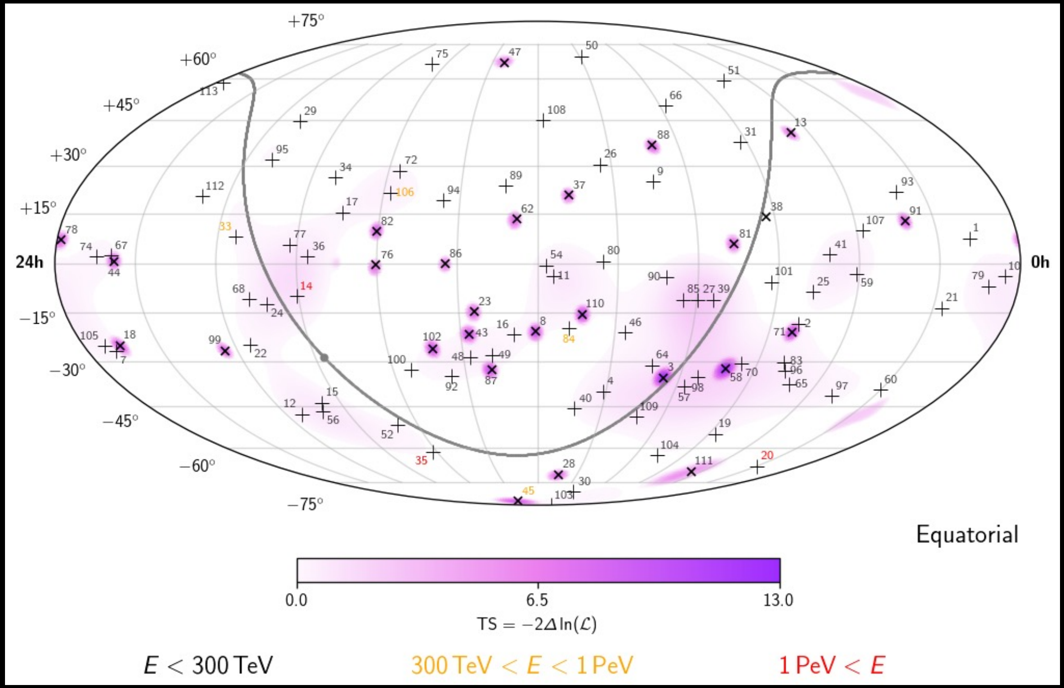
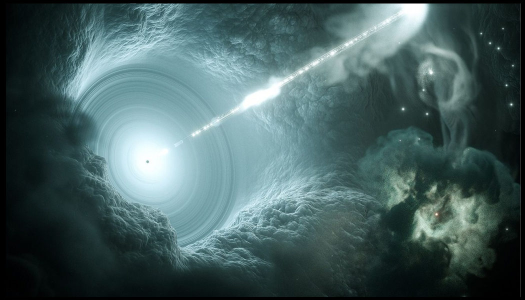
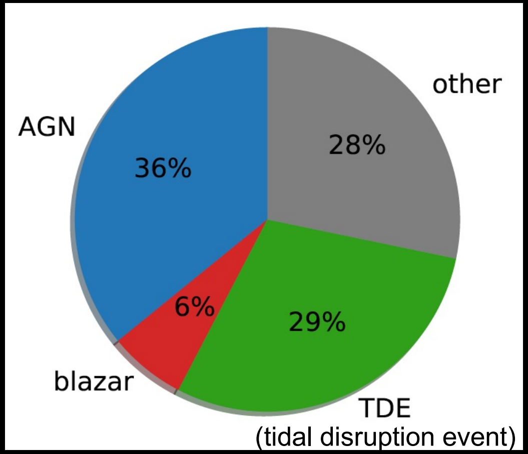


Evidence of Blazar Neutrino
- IC170922A
- TXS 0506+056



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

IceCube astrophysical high-energy neutrino source contribution

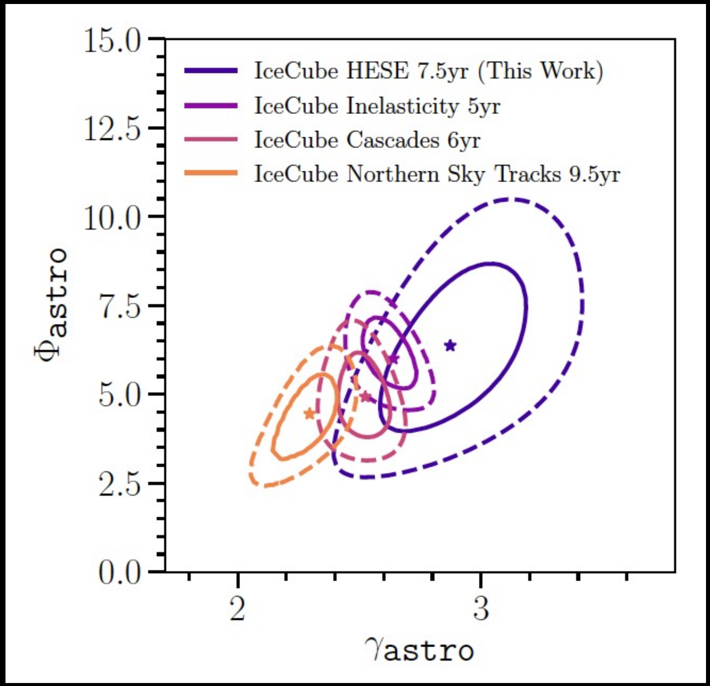


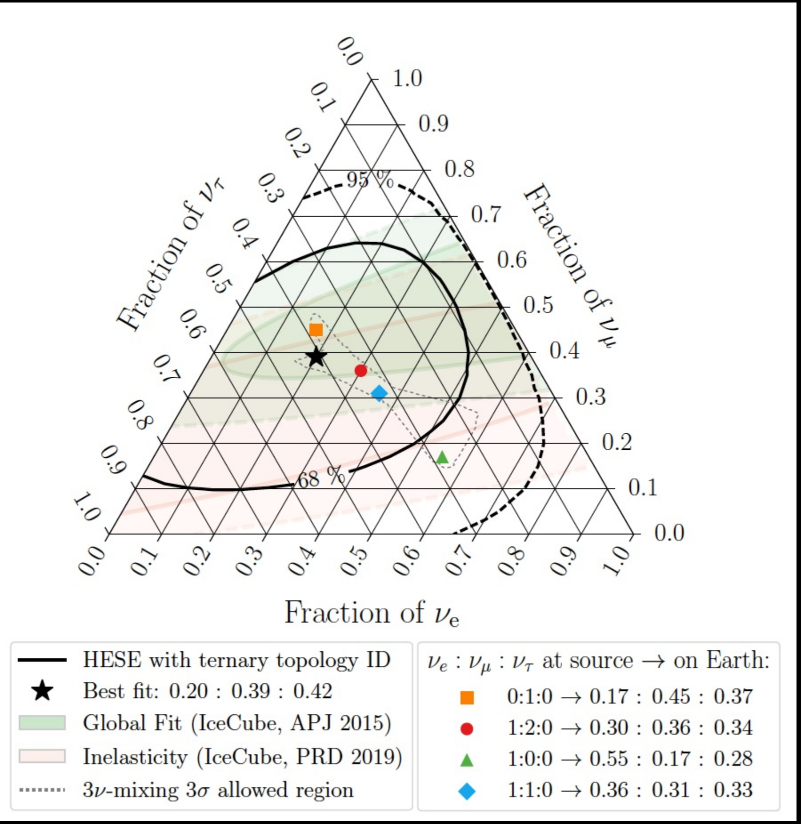
ArXiv:2105.03792

IceCube,Science.342(2013)1242856,PRL113(2014)101101:115(2015)081102
ArXiv:2011.03545,2011.03560,2011.03561

2. Astrophysical Very-High-Energy Neutrinos

First observation (2013) by IceCube Neutrino Observatory
- 60-2000 TeV neutrinos
- Too high-energy as atmospheric neutrinos
- Too low-energy as GZK neutrinos
- Sources are mostly unknown (diffuse)
- Large uncertainty on spectrum and flavor structure





When do we find Lorentz violation???

Higher-dimension operators may be related to new physics
- Dimension-5 operator (unit: GeV^{-1}), example: Majorana mass
- Dimension-6 operator (unit: GeV^{-2}), example: Fermi constant (G_F)

We focus on higher-dimension Lorentz violating operator search

If, Lorentz violation is related to Planck scale physics, it is suppressed inverse of Planck energy, $1/E_{Planck}^2 \sim 10^{-38}$ GeV^{-2} → natural scale of dimension-6 Lorentz violating operator

Limits from this operator by atmospheric neutrino is $\sim 10^{-36}$ GeV^{-1}

nonrenormalizable

SME Lagrangian

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}^{(3)}\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}^{(4)}\partial^{\nu}\psi \cdots$$

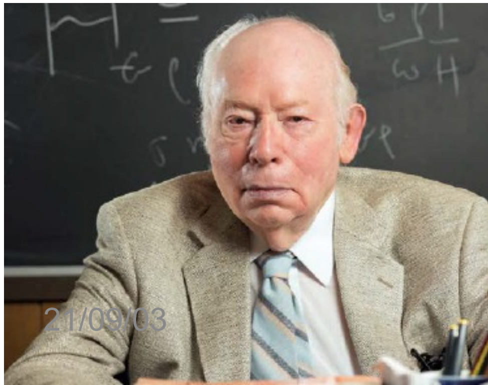
SME motivated effective Hamiltonian for neutrinos

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

nonrenormalizable

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

Steve Weinberg
(CERN Courier, Nov 2017)



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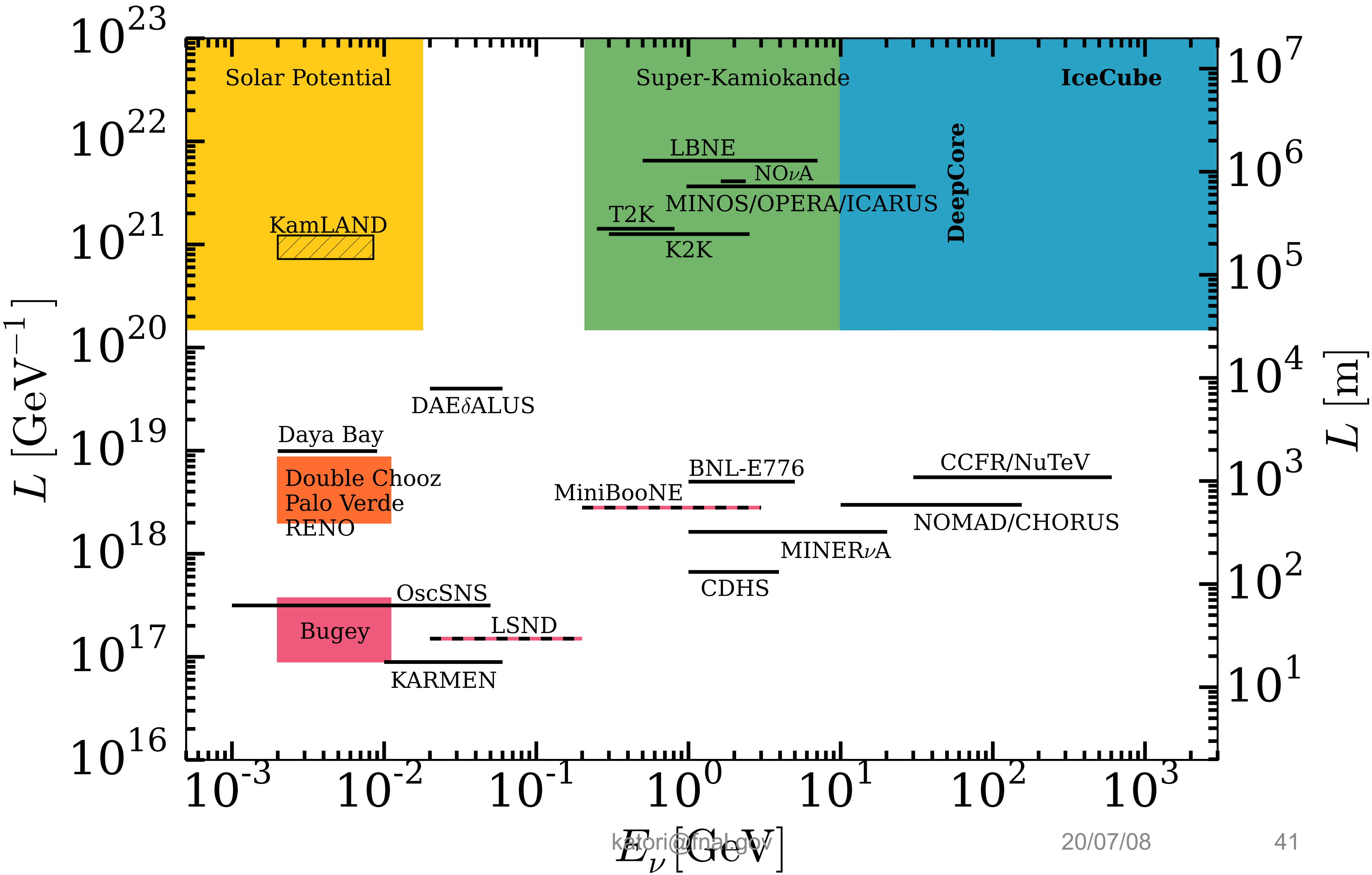
Kostelecký and Mewes, PRD69(2004)016005
Argüelles, INVISIBLE2015

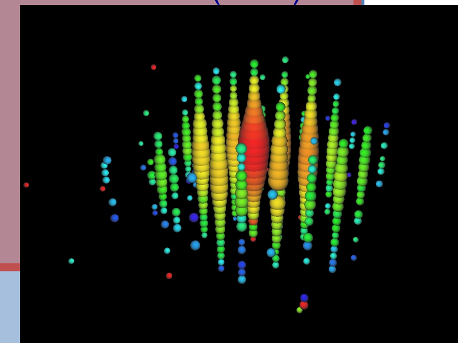
Lorentz violation with neutrino oscillations



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

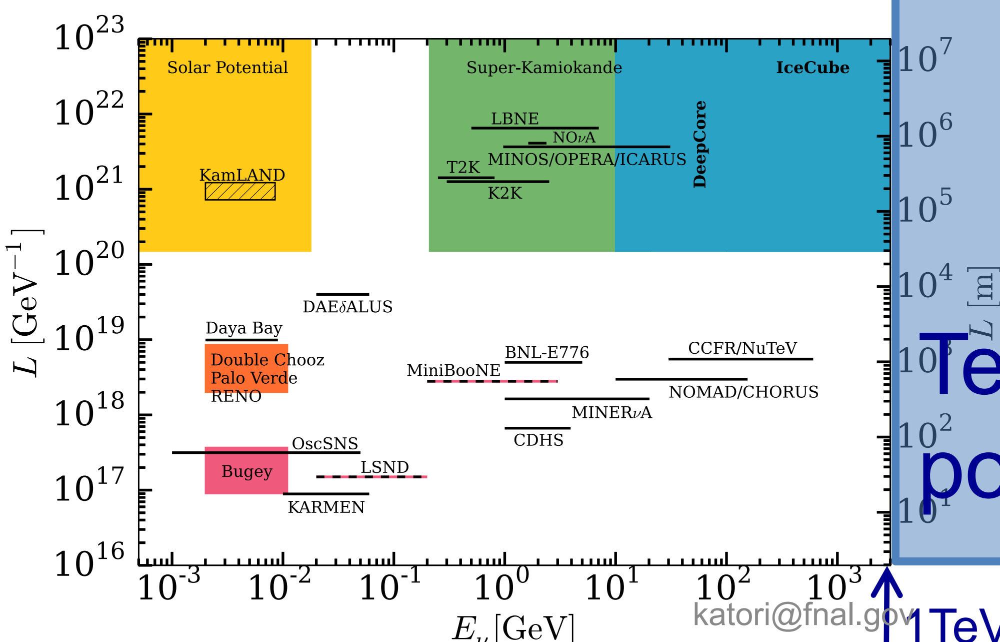
Lorentz violation with neutrino oscillation

IceCube collaboration
PRL111(2013)021103



extra galactic
neutrino potential

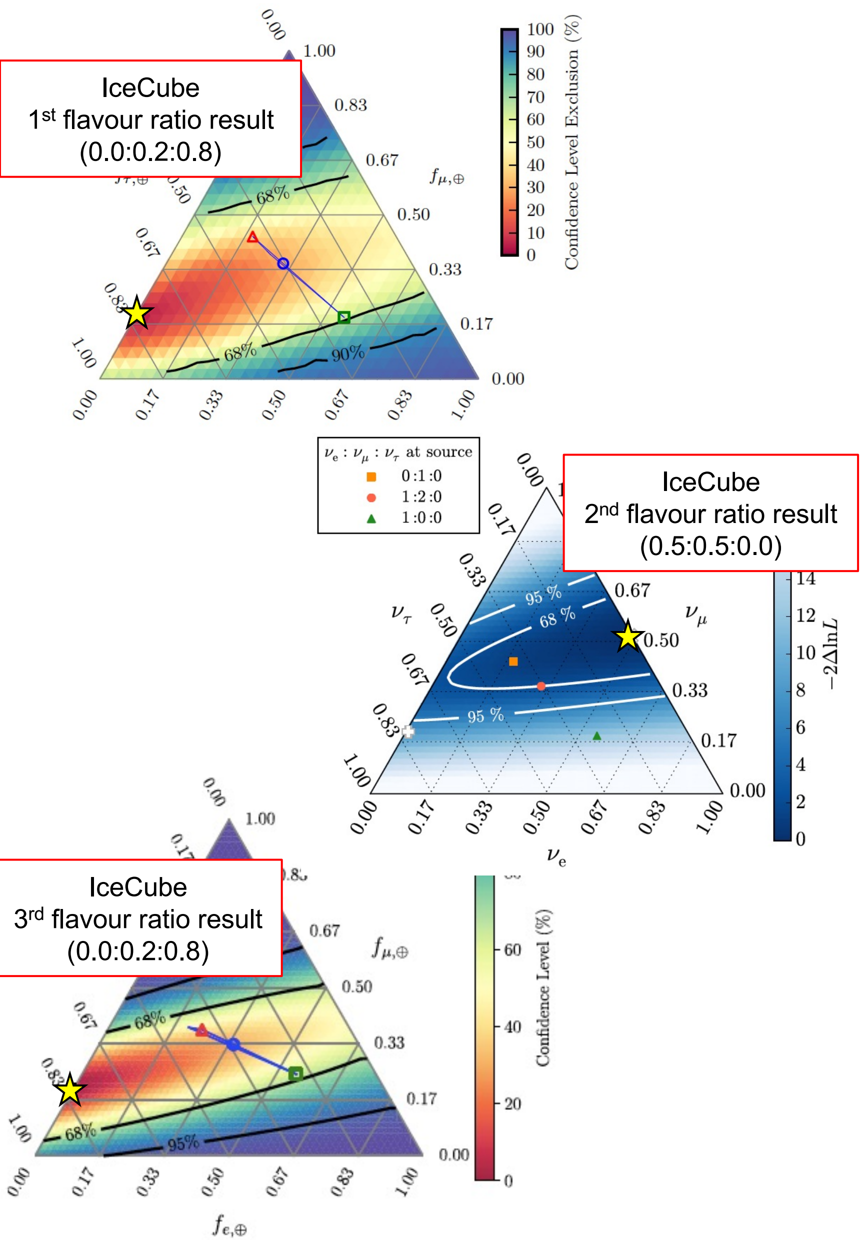
1Mpc(~Andromeda)

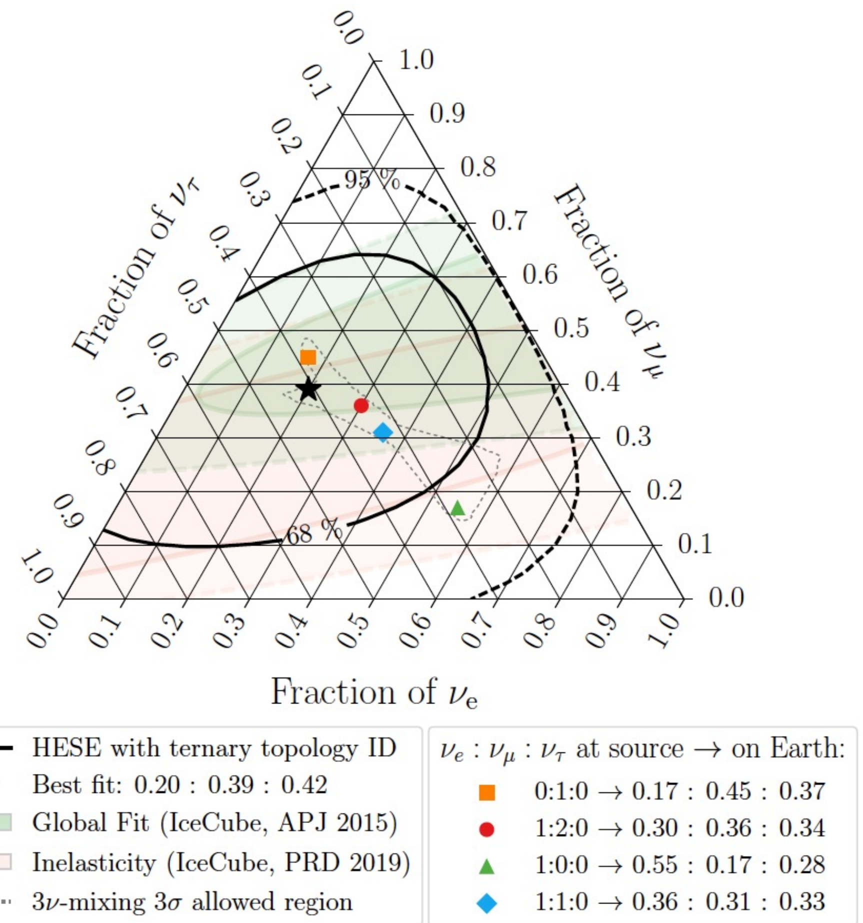


TeV neutrino
potential

1TeV

HESE 7.5-yr data (2018)





New flavour ratio measurement

- Likelihood is very shallow and fit often confuses between ν_e and ν_τ
- New flavour ratio result has some power to distinguish ν_e and ν_τ

Astrophysical neutrino flavor 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)

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

and so on…

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

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

$$V(E) = \begin{pmatrix} V_{e1}(E) & V_{e2}(E) & V_{e3}(E) \\ V_{\mu1}(E) & V_{\mu2}(E) & V_{\mu3}(E) \\ V_{\tau1}(E) & V_{\tau2}(E) & V_{\tau3}(E) \end{pmatrix}, \qquad \Delta = \begin{pmatrix} \lambda_1(E) & 0 & 0 \\ 0 & \lambda_2(E) & 0 \\ 0 & 0 & \lambda_3(E) \end{pmatrix}$$

Astrophysical neutrino flavor with Lorentz violation

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

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

However, astrophysical neutrinos propagate O(100Mpc) → lost coherence

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

Astrophysical neutrino flux of flavor α at production is $\phi_\alpha^p(E) \sim \phi_\alpha^P \cdot E^{-\gamma}$. Since it's low statistics, we consider energy-averaged flavor composition β on Earth

$$\bar{\phi}_\beta^{\oplus} = \frac{1}{\Delta E}\int_{\Delta E}\sum_{\alpha} P_{\alpha\to\beta}(E,\infty)\,\phi_\alpha^p(E)dE$$

We take the fraction of this for each flavor.

$$f_\beta^{\oplus} = \frac{\bar{\phi}_\beta^{\oplus}}{\sum_{e,\mu,\tau}\bar{\phi}_\gamma^{\oplus}}$$

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HESE 7.5-yr Flavor new physics search

Data, 2635 days HESE sample IceCube, ArXiv: 2011.03545

- 17 track events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 41 cascade events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 2 double cascades, 20 log(E) bins [60 TeV, 10 PeV], 10 log(L) bins [10m, 100m]

Simulation

Bhattacharya et al.,JHEP06(2015)110

- Foregrounds, conventional (Honda flux), prompt (BERSS model), muon (CORSIKA)
- Astrophysical neutrinos, simple power law
- Interaction, NLO PDF DIS (CSMS model) Cooper-Sarkar et al., JHEP08(2011)042

Systematics (15 nuisance parameters)

- oscillation parameters (6)
- normalization of flux : conventional (40%), prompt (free), muon (50%), astrophysical (free)
- spectrum index : primary cosmic ray (5%) astrophysical neutrinos (free)
- Ice model : (20%)
- DOM efficiency : overall (10%), angular dependence (50%)

Limits

Feroz et al., Mon. Not. Roy. Astron. Soc. 398,1601(2009)1601

- Bayesian: MCMC with Multinest, Bayes factor with Jefferey' scale "strong" limit
- Frequentist: Wilks' theorem

Systematic errors

Parameter	Prior (constraint)	Range	Description
Astrophysical neutrino flux:			
$\Phi_{\texttt{astro}}$	-	$[0, \infty)$	Normalization scale
$\gamma_{\texttt{astro}}$	-	$(-\infty, \infty)$	Spectral index
Atmospheric neutrino flux:			
$\Phi_{\texttt{conv}}$	1.0 ± 0.4	$[0, \infty)$	Conventional normalization scale
$\Phi_{\texttt{prompt}}$	-	$[0, \infty)$	Prompt normalization scale
$R_{K/\pi}$	1.0 ± 0.1	$[0, \infty)$	Kaon-Pion ratio correction
$2\nu / (\nu + \bar{\nu})_{\texttt{atmo}}$	1.0 ± 0.1	$[0, 2]$	Neutrino-anti-neutrino ratio correction
Cosmic-ray flux:			
$\Delta\gamma_{\texttt{CR}}$	0.0 ± 0.05	$(-\infty, \infty)$	Cosmic-ray spectral index modification
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$	Muon normalization scale
Detector:			
$\epsilon_{\texttt{DOM}}$	0.99 ± 0.1	$[0.80, 1.25]$	Absolute energy scale
$\epsilon_{\texttt{head-on}}$	0.0 ± 0.5	$[-3.82, 2.18]$	DOM angular response
$a_{\texttt{s}}$	1.0 ± 0.2	$[0.0, 2.0]$	Ice anisotropy scale

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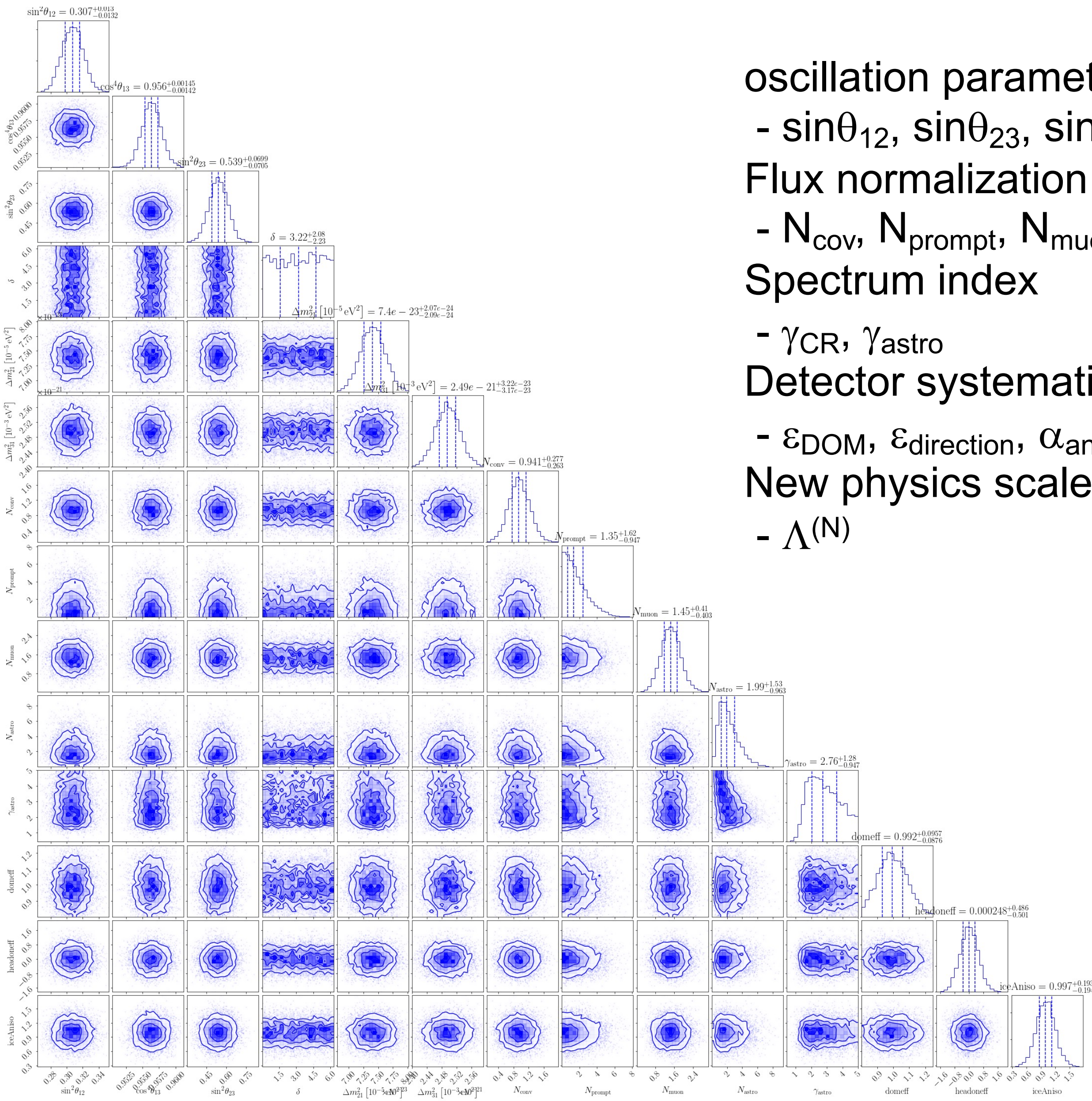
Fit example, large new physics in $c_{e\tau}^{(6)}$



oscillation parameters

- $\sin\theta_{12}$, $\sin\theta_{23}$, $\sin\theta_{13}$, Δm_{12}, Δm_{23}, δ

Flux normalization

- N_{cov}, N_{prompt}, N_{muon}, N_{astro}

Spectrum index

- γ_{CR}, γ_{astro}

Detector systematics

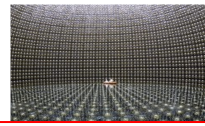
- ε_{DOM}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

New physics scale

- $\Lambda^{(N)}$

Test of Lorentz violation with neutrinos

Spectral distortion

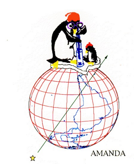


Super-Kamiokande

PRD91(2015)052003

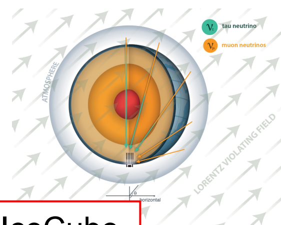
Daya Bay

PRD98(2018)092013



AMANDA

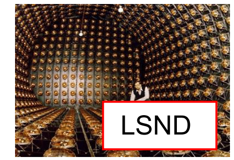
PRD79(2009)102005



IceCube

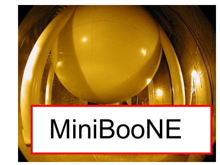
Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004



MiniBooNE

PLB718(2013)1303

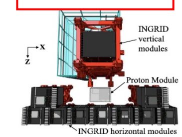
MINOS ND

PRL101(2008)151601

MINOS FD

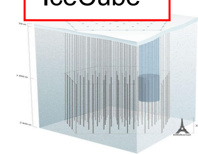
PRL105(2010)151601

T2K ND



PRD95(2017)111101

IceCube

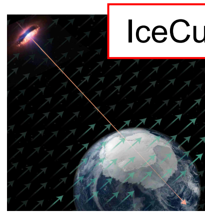


PRD82(2010)112003

Double Chooz

PRD86(2013)112009

Flavor ratio

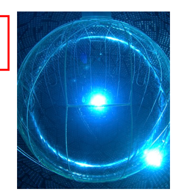


IceCube

To be published

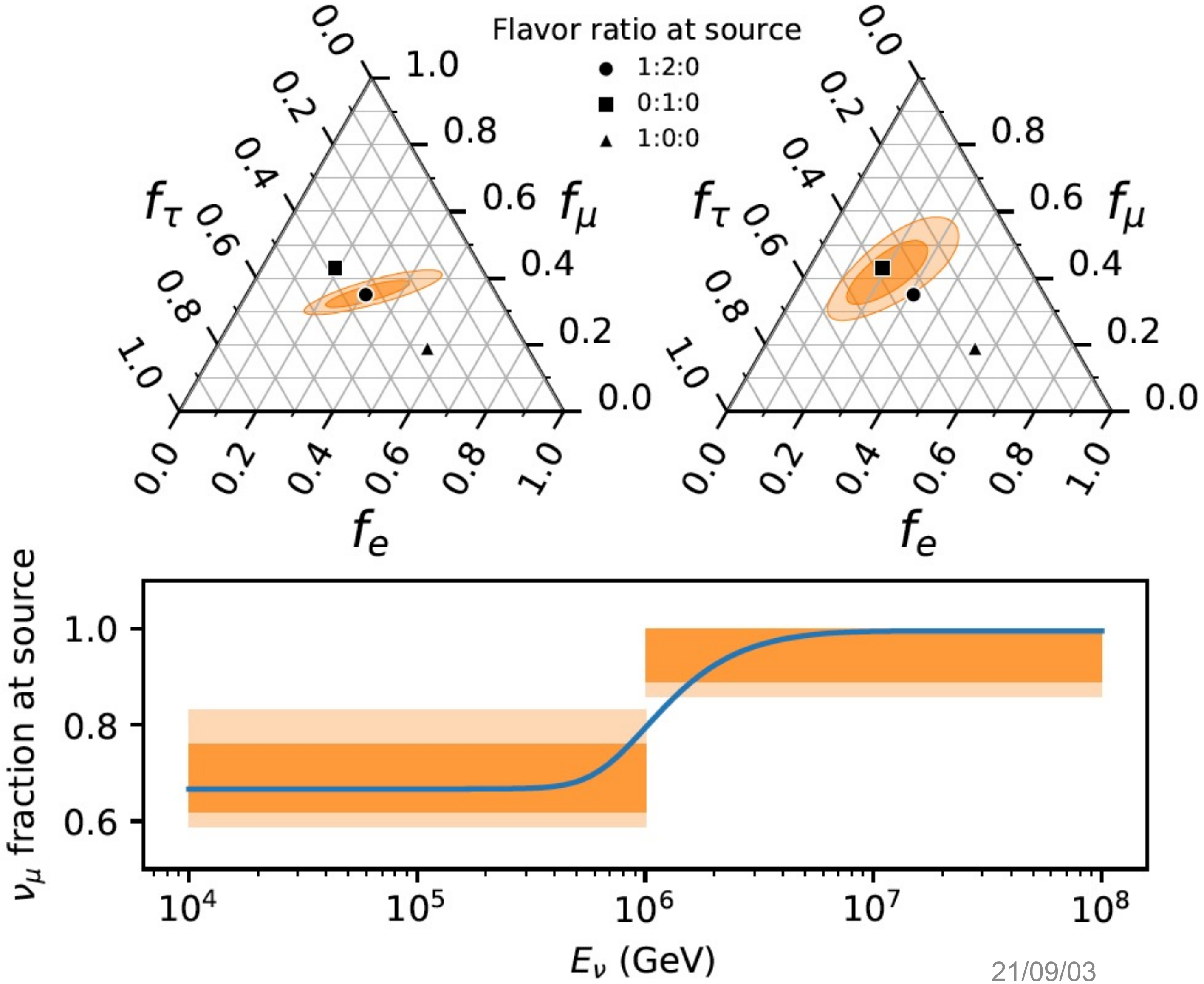
Seasonal variation

SNO



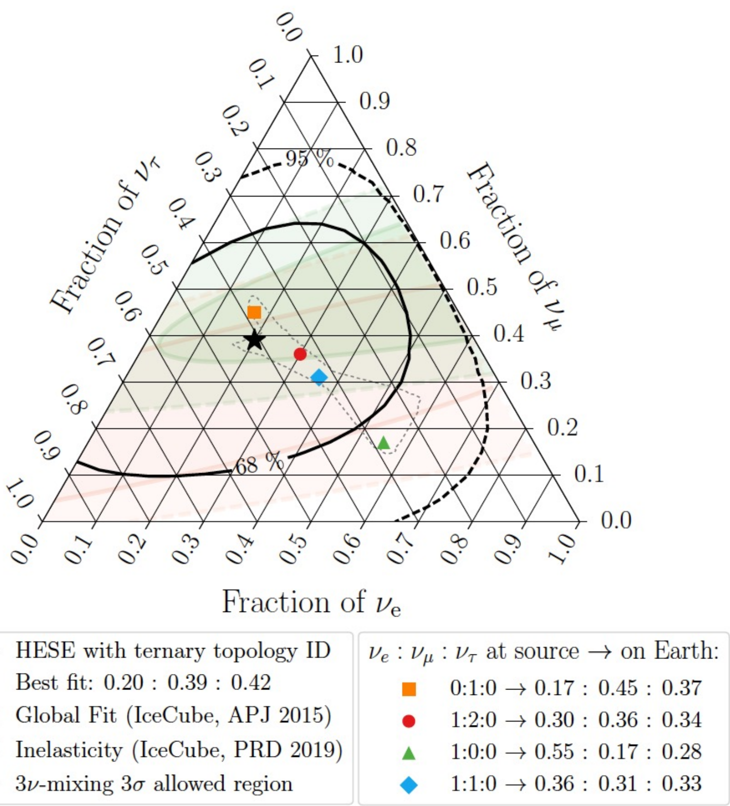
PRD98(2018)112013

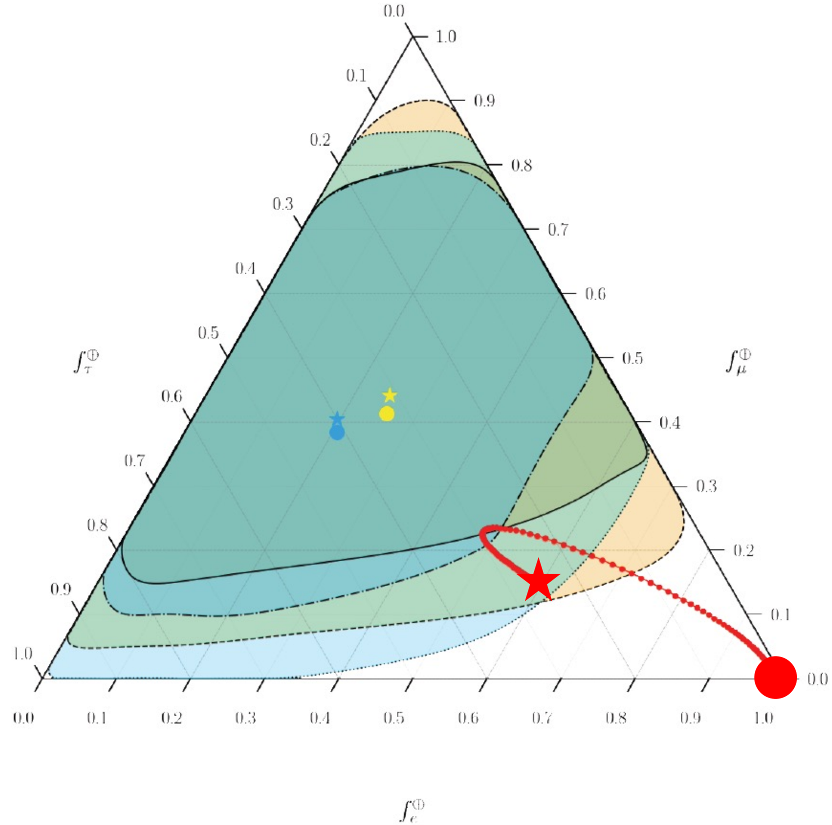
Energy dependence of flavor ratio



IceCube, ArXiv: 2011:03561, TK, ArXiv:1906.09240, Farrag, ArXiv:1908.07602

HESE 7.5-yr flavor new physics search





e.g.) Initial flavour ratio ★ is (1:0:0), and there is nonzero new physics $c_{\mu\tau}^{(6)}$ term (exotic ν_μ-ν_τ mixing). If the new physics term is big, the flavour ratio on Earth is ●

Such model is rejected by current data

Neutrino Standard Model (νSM) - Unknowns

SM + 3 active massive neutrinos

Neutrinos are least known particles!

There are several unknowns and anomalies
→ Do they indicate new physics?

Unknown parameters of νSM
1. Dirac CP phase
2. θ_{23} (θ_{23}=40^o and 50^o are same for sin2θ_{23}, but not for sinθ_{23})
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase
6. Absolute neutrino mass

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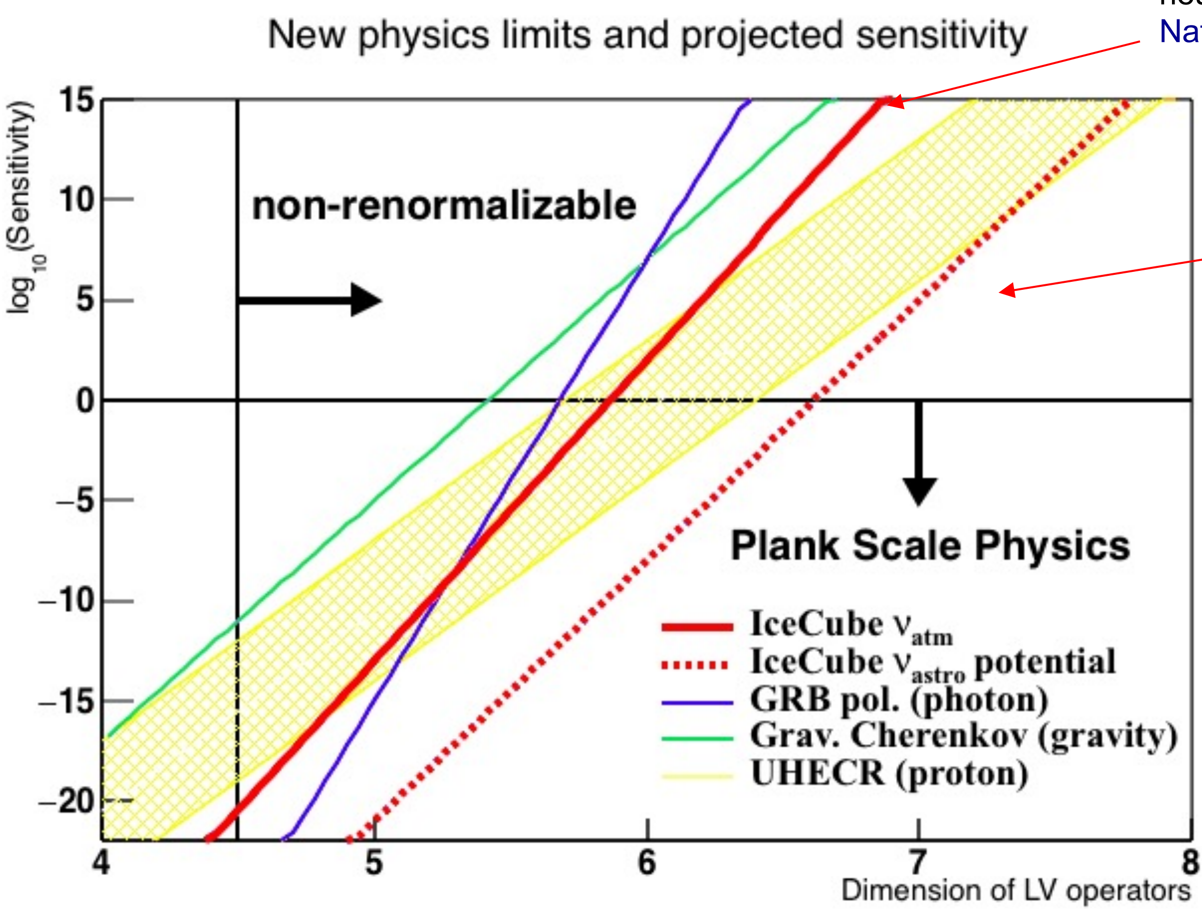
When do we find Lorentz violation???

Higher-dimension operators may be related to new physics
- Dimension-5 operator (unit: GeV^{-1}), example: Majorana mass
- Dimension-6 operator (unit: GeV^{-2}), example: Fermi constant (G_F)

IceCube atmospheric neutrino LV sensitivity
Nature Physics 14(2018)961



IceCube astrophysical neutrino LV sensitivity

Astrophysical neutrino dim-6 LV operator search can reach quantum gravity motivated region ($\sim 1/M_{Planck}^2 \sim 10^{-38}$ GeV^{-2})

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