From Brave New Spacetime: Quantum Gravity

"Postcards from the Very Edge, With Love from IceCube"

outline

1. Test of Fundamental Physics
2. Neutrino interferometry with IceCube
3. Astrophysics neutrino flavour physics
4. Conclusions

LONDON
The Houses of Parliament & The London Eye
& King's College London

Greetings,
IceCube allows me to work on many topics from dinner skits to search of Lorentz Violation[1].
We are so close to beat Einstein and find Quantum Gravity!

IceCube since 2014

Ciao,
Teppei Katori
Reader (associate professor)
King's College London
WC2R 2LS London, UK

to: IceCube
222 W. Washington Ave.
Suite 500
Madison, WI 53703
U.S.A.

BY AIR MAIL par avion Royal Mail

[1] about Lorentz Violation. Astrophysical Neutrinos propagate long distance straight, and any tiny interaction with vacuum may change flavor. This is the way to look for the smallest effect in space-time.

Teppei Katori for the IceCube collaboration
King's College London
APS April meeting, NYC, USA, April 12, 2022

1. **Test of Fundamental Physics**

2. Neutrino interferometry with IceCube

3. Astrophysics neutrino flavour physics

4. Conclusions

1. Violation of fundamental physics

All fundamental physics phenomena must be experimentally tested including Lorentz symmetry, isotropy of the space-time

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

Einstein and Lorentz

Lorentz Institute

1. Violation of fundamental physics

All fundamental physics phenomena must be experimentally tested including Lorentz symmetry, isotropy of the space-time

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

However, quantum gravity theories show it is possible to violate fundamental physics laws
- string theory
- noncommutative field theory

etc.

Discovery of a new space-time structure is the breakthrough to understand quantum gravity theories!

Einstein and Lorentz

1. Violation of fundamental physics

Coupling of ordinary particles (photons, neutrinos, etc) and new space-time structure might modify behaviour of particles in vacuum

- Energy spectrum
- Neutrino flavour

etc.

Standard Model

New physics

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

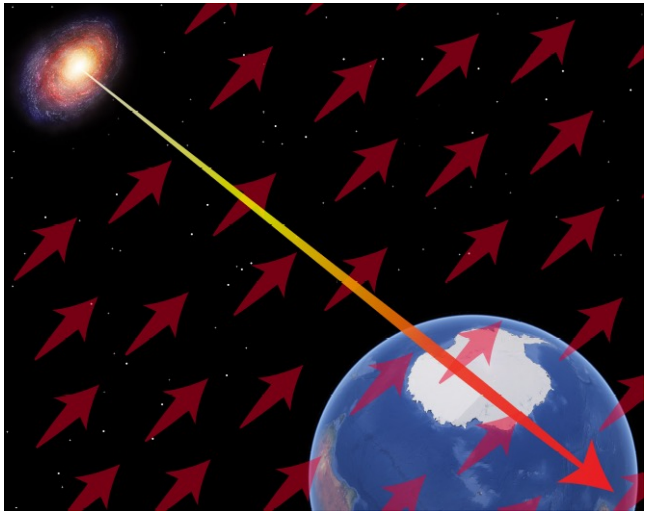
Expected effect is small. We need high-precision measurements to find such new physics

quantum foam

- quantum fluctuation of space-time

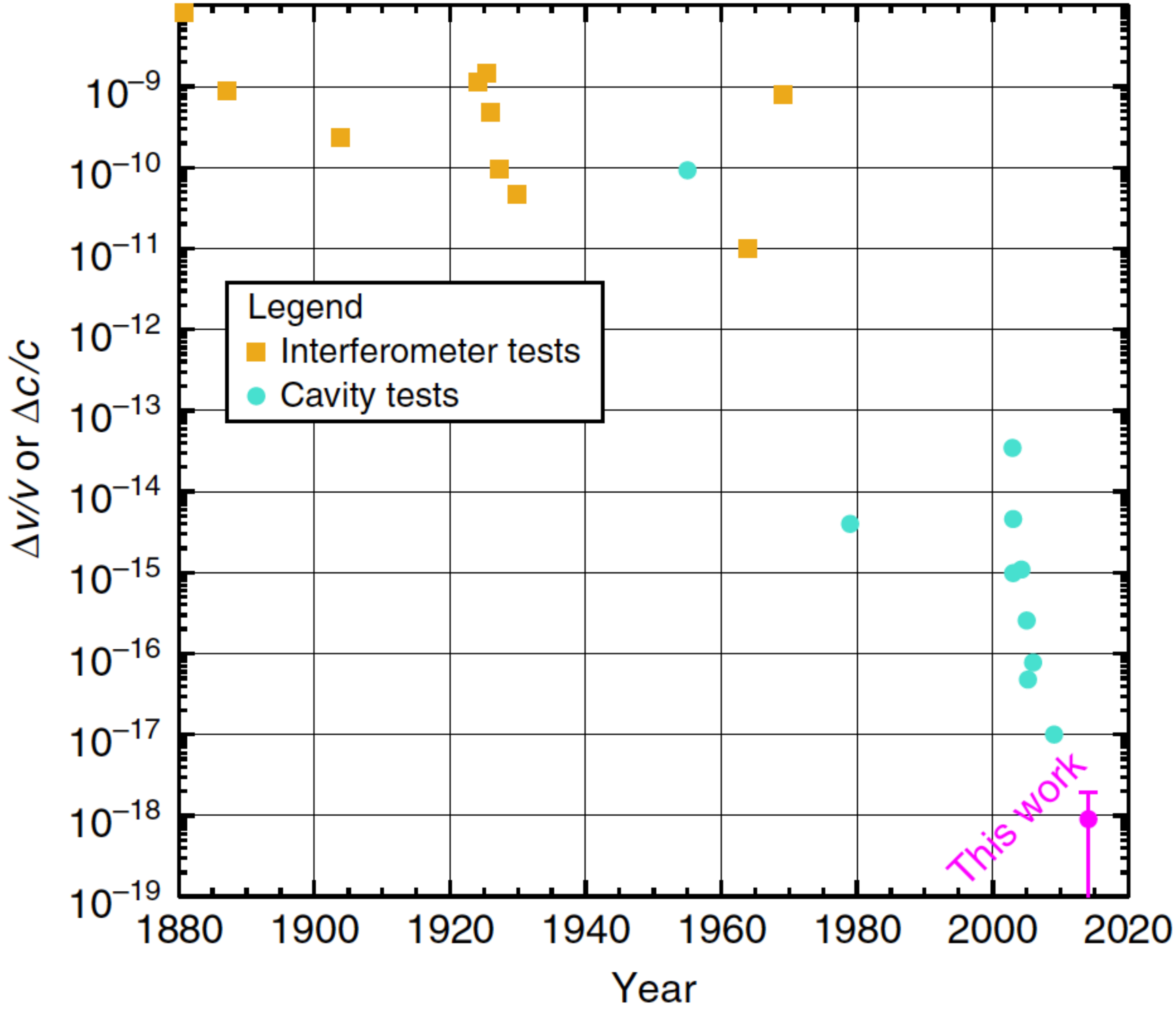
Lorentz violating field

- new field saturating the universe (æther)



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

1. History of Michelson-Morley experiment



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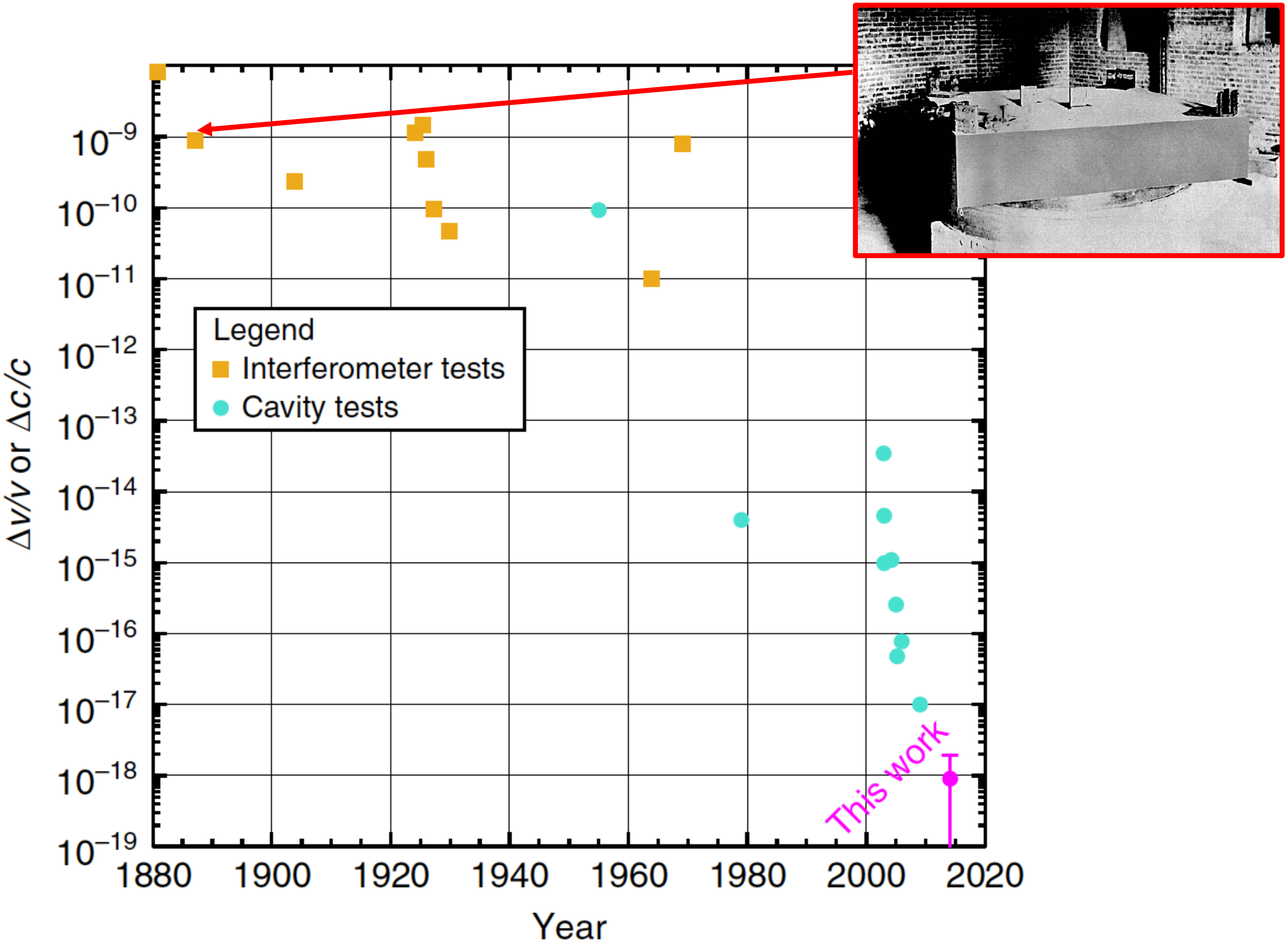

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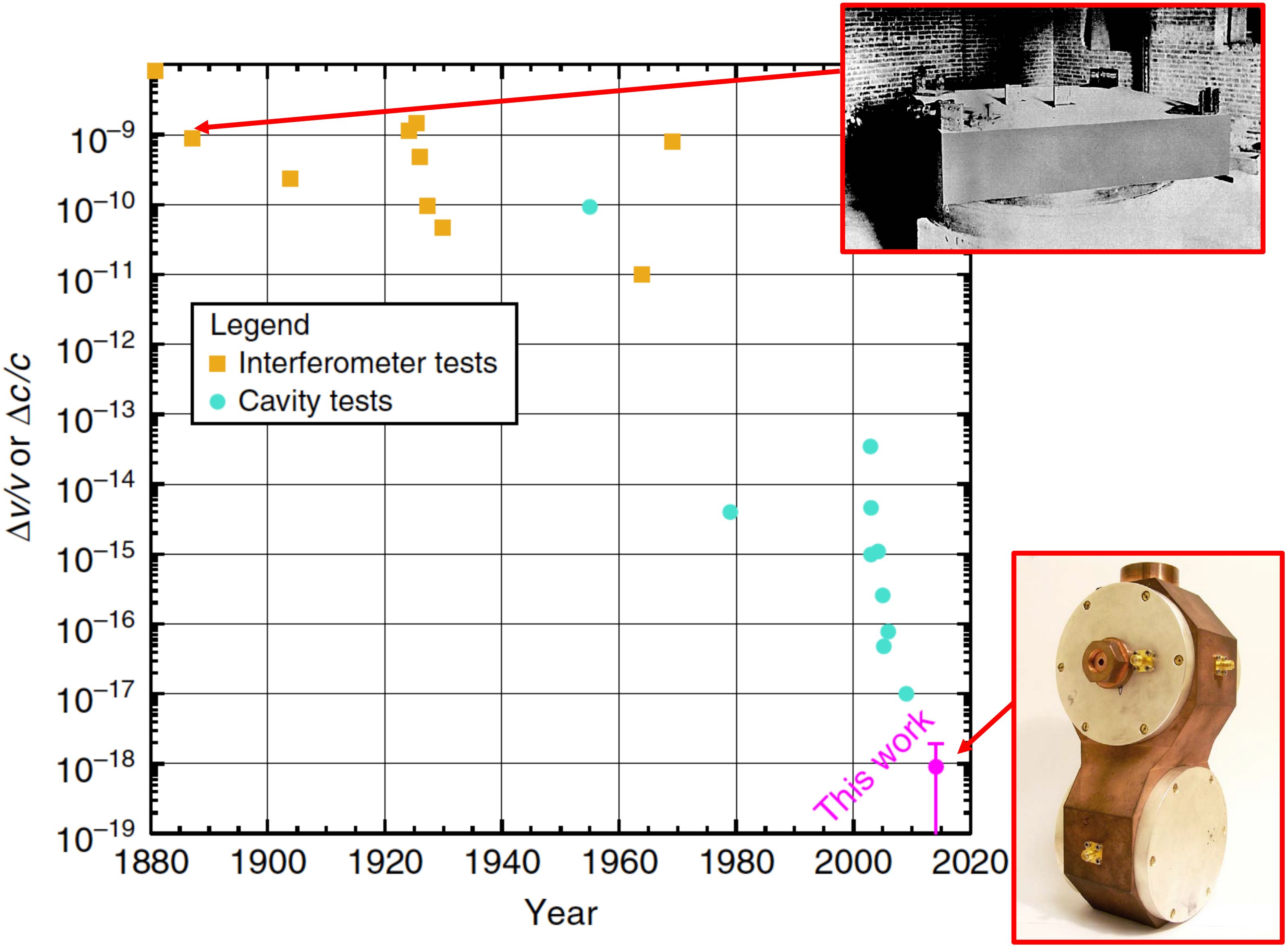

From King’s College London to IceCube

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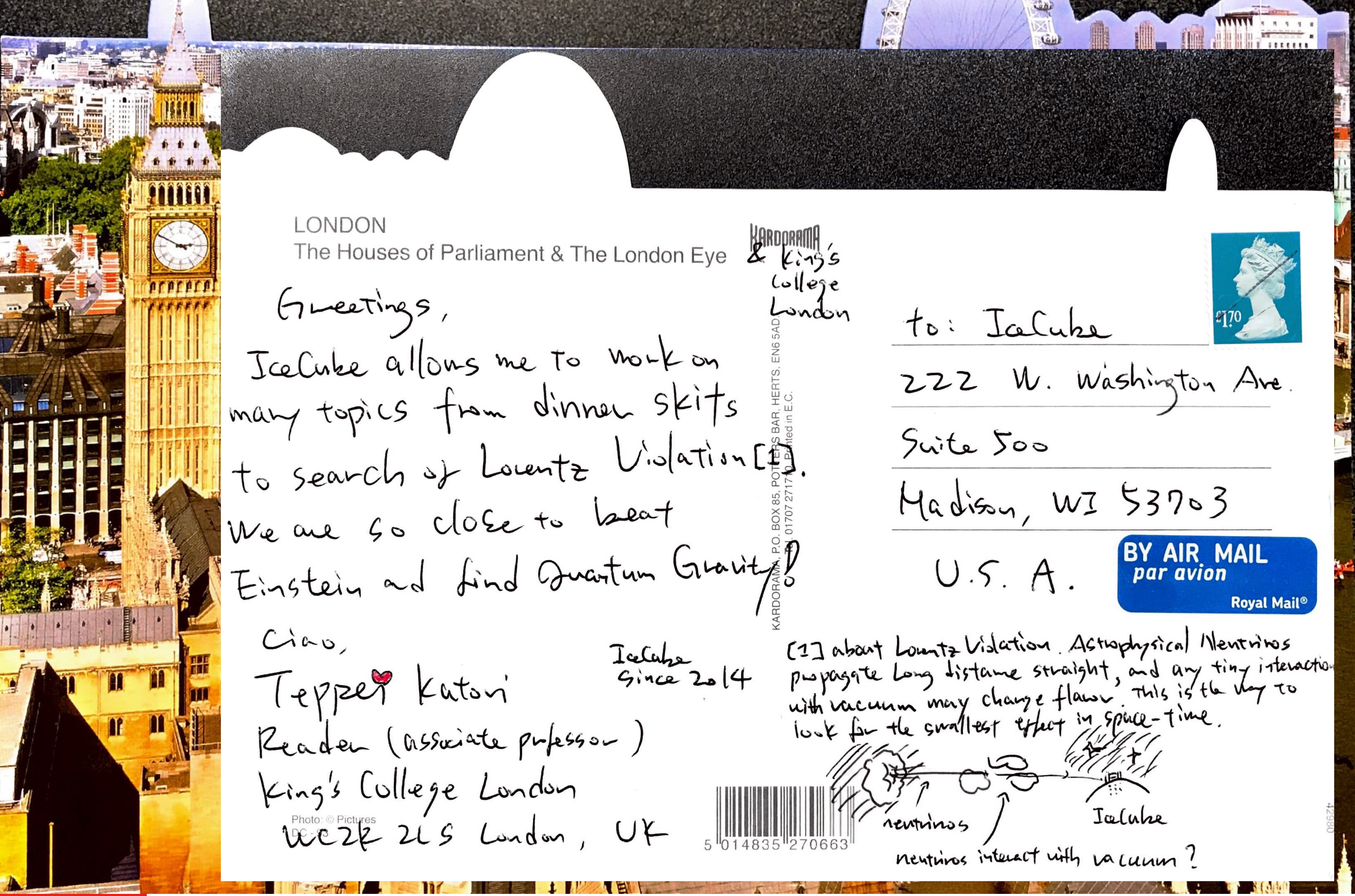

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Photo: © Pictures DC

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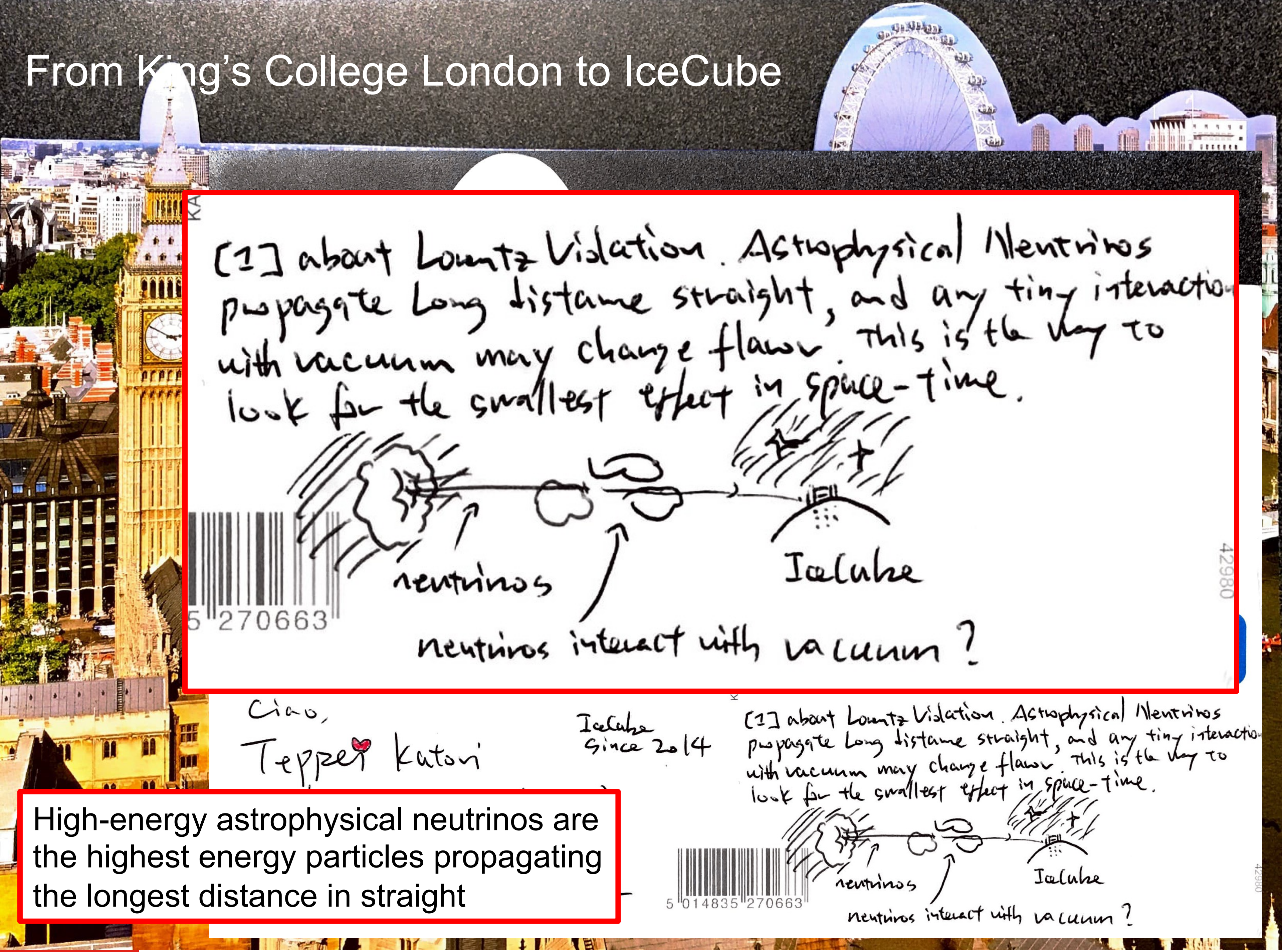
From King's College London to IceCube



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High-energy astrophysical neutrinos are the highest energy particles propagating the longest distance in straight

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2. **Neutrino interferometry with IceCube**

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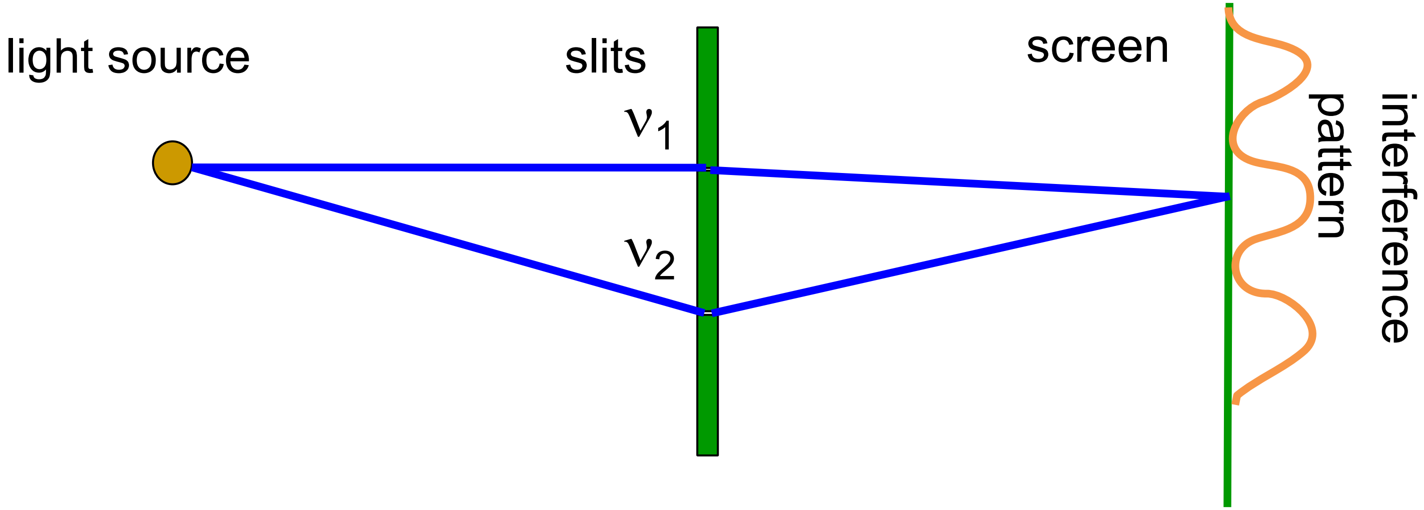
4. Conclusions

2. Double slit experiment

Neutrino flavour conversion is an interference experiment

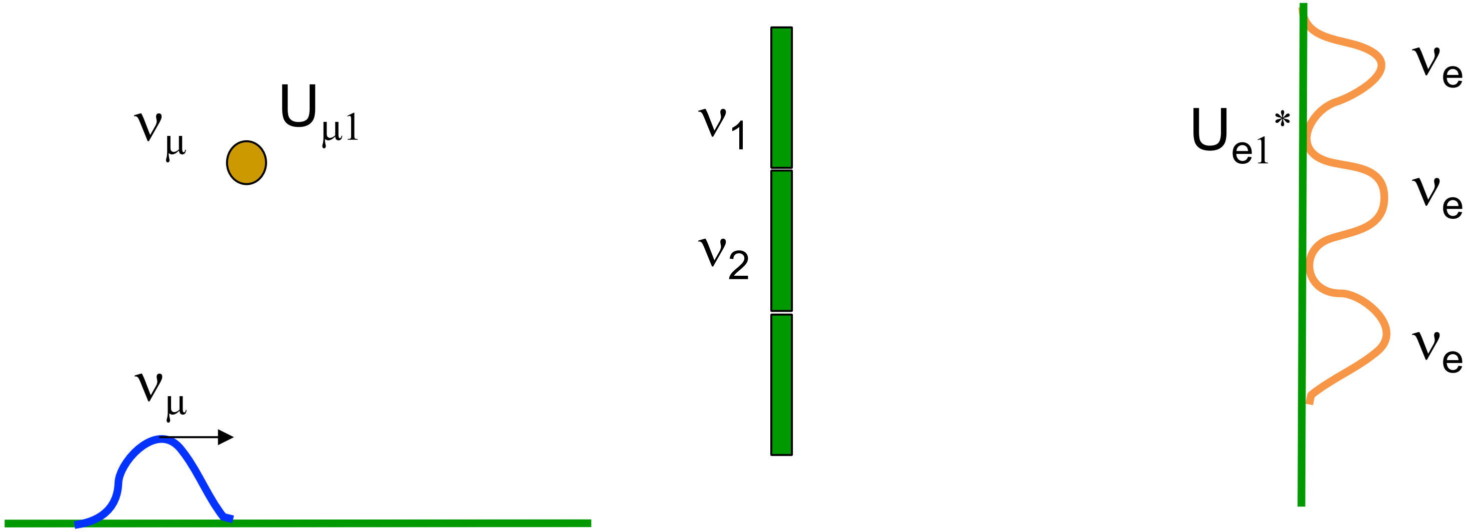


For double slit experiment, if path ν_1 and path ν_2 have different length, they have different phase rotations and it causes interference.

Interference pattern carries the information of an invisibly small slit size

2. Neutrino interferometry for neutrino mass measurement

Neutrino flavour conversion is an interference experiment



Neutrinos are produced in flavour eigenstates, but they propagate as Hamiltonian eigenstates, then detected in flavour eigenstates

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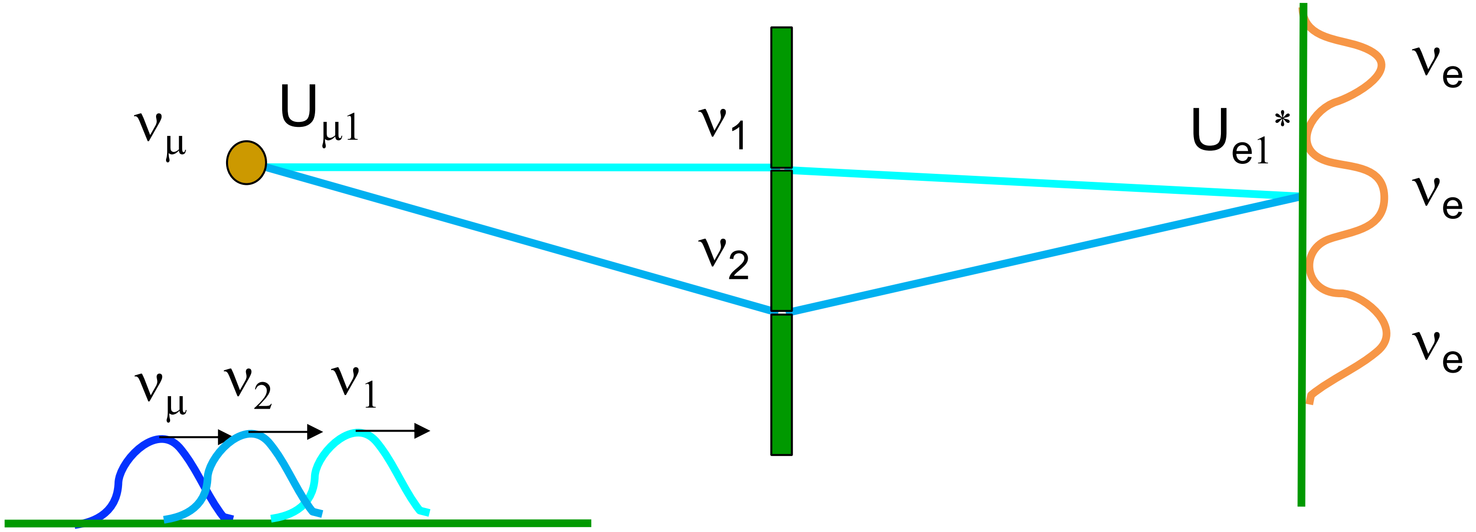

Neutrinos are produced in flavour eigenstates, but they propagate as Hamiltonian eigenstates, then detected in flavour eigenstates

If ν_1 and ν_2, have different masses, they have different velocity and they don't overlap exactly at the detection

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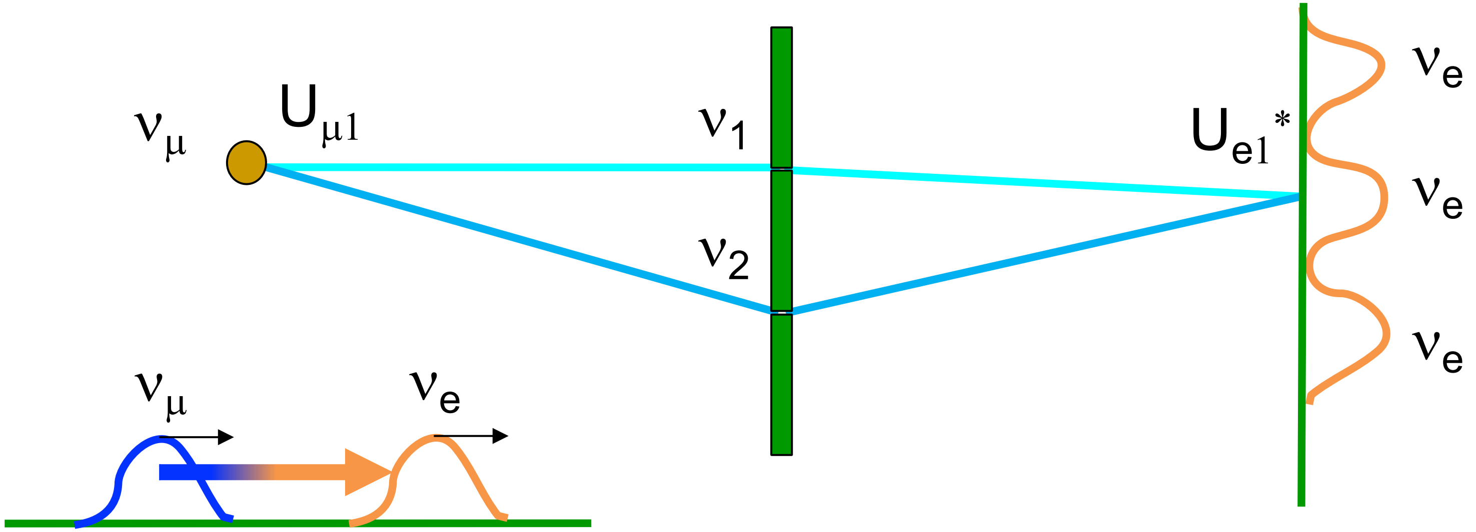


Neutrinos are produced in flavour eigenstates, but they propagate as Hamiltonian eigenstates, then detected in flavour eigenstates

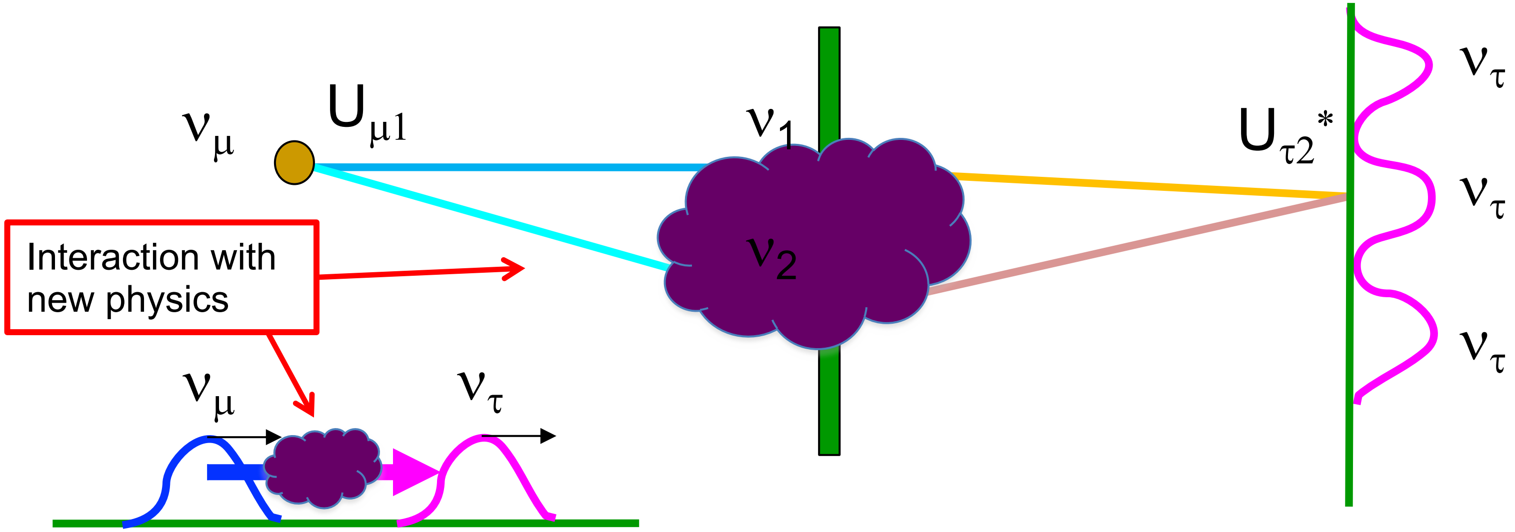
If ν_1 and ν_2, have different masses, they have different velocity and they don't overlap exactly at the detection

Neutrino flavour carries an information of immeasurably tiny neutrino masses

katori@fnal.gov

2. Neutrino interferometry for new physics search

Neutrino flavour conversion is an interference experiment



Interaction with new physics

Neutrinos are produced in flavour eigenstates, and they propagate as Hamiltonian eigenstates, then detected in flavour eigenstates

If neutrinos couple with new physics in vacuum, this modifies neutrino flavour. The sensitivity of "neutrino interferometry" can go beyond precise atomic and optical interferometers.

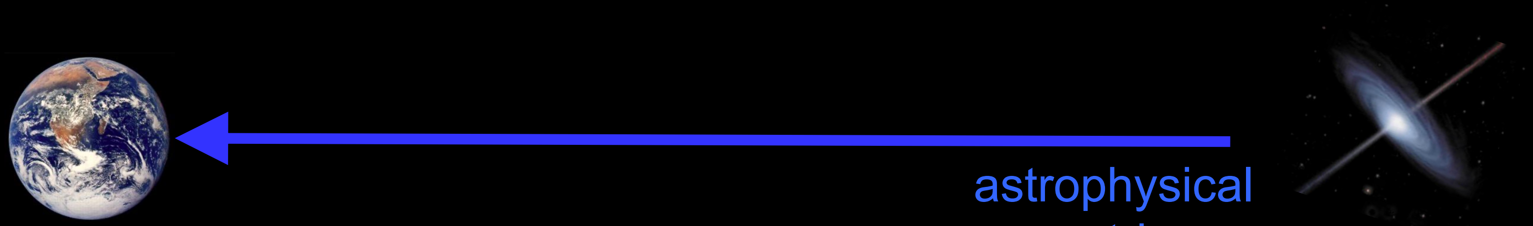
Longer propagation length
- LIGO = 4km,
- Astrophysical neutrinos >100Mpc

Higher energy
- LHC ~ 7 TeV
- Astrophysical neutrinos ~ 1000 TeV

2. High-energy astrophysical neutrinos

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)

- Neutrinos can probe brave new spacetime!



astrophysical neutrino

Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, ArXiv:2203.10811

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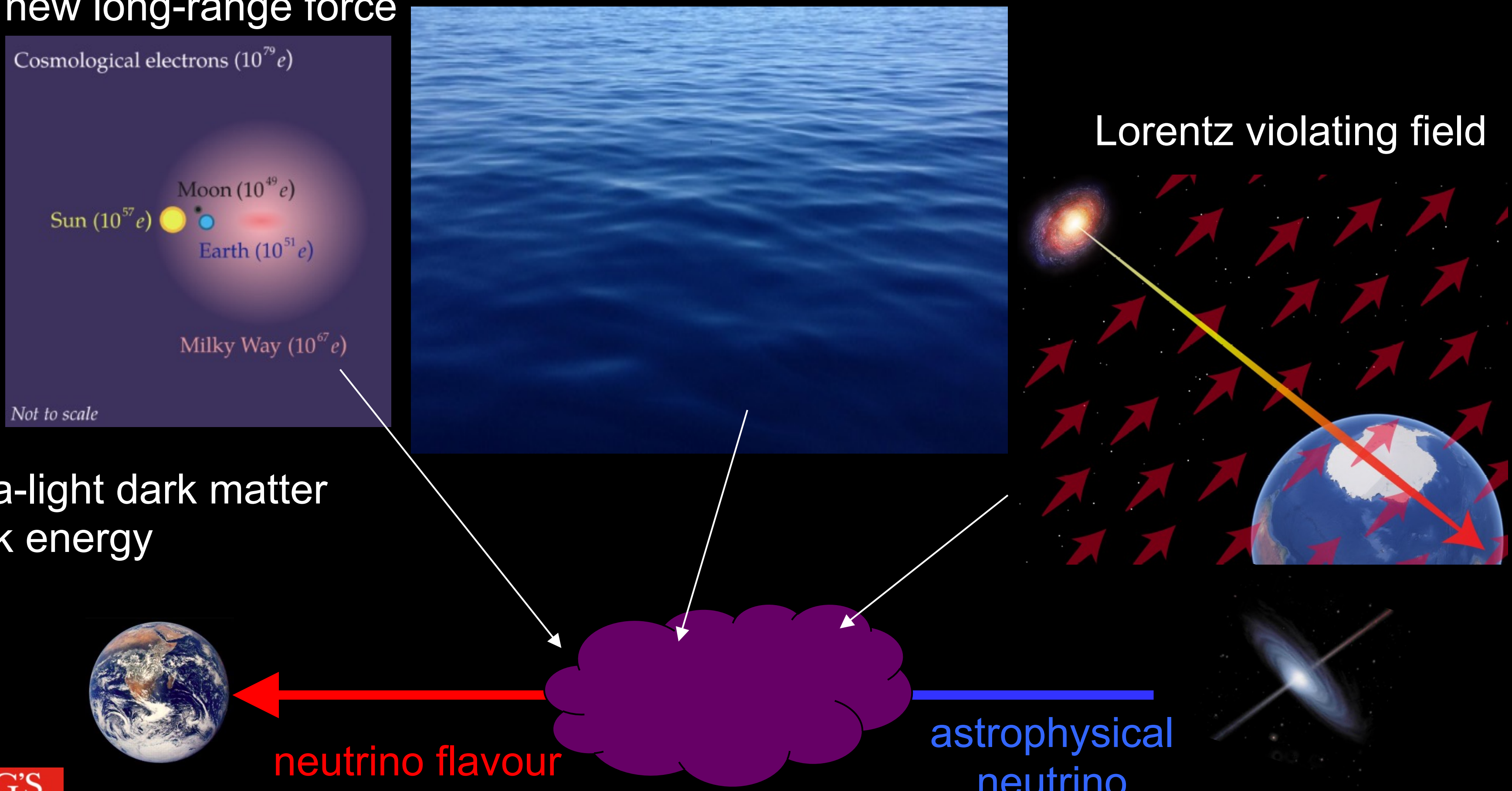


Quantum foam

new long-range force

Lorentz violating field

ultra-light dark matter
dark energy
etc

neutrino flavour conversion

New physics

astrophysical neutrino

Mewes and Kostelecký, PRD85(2012)096005

2. 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)

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

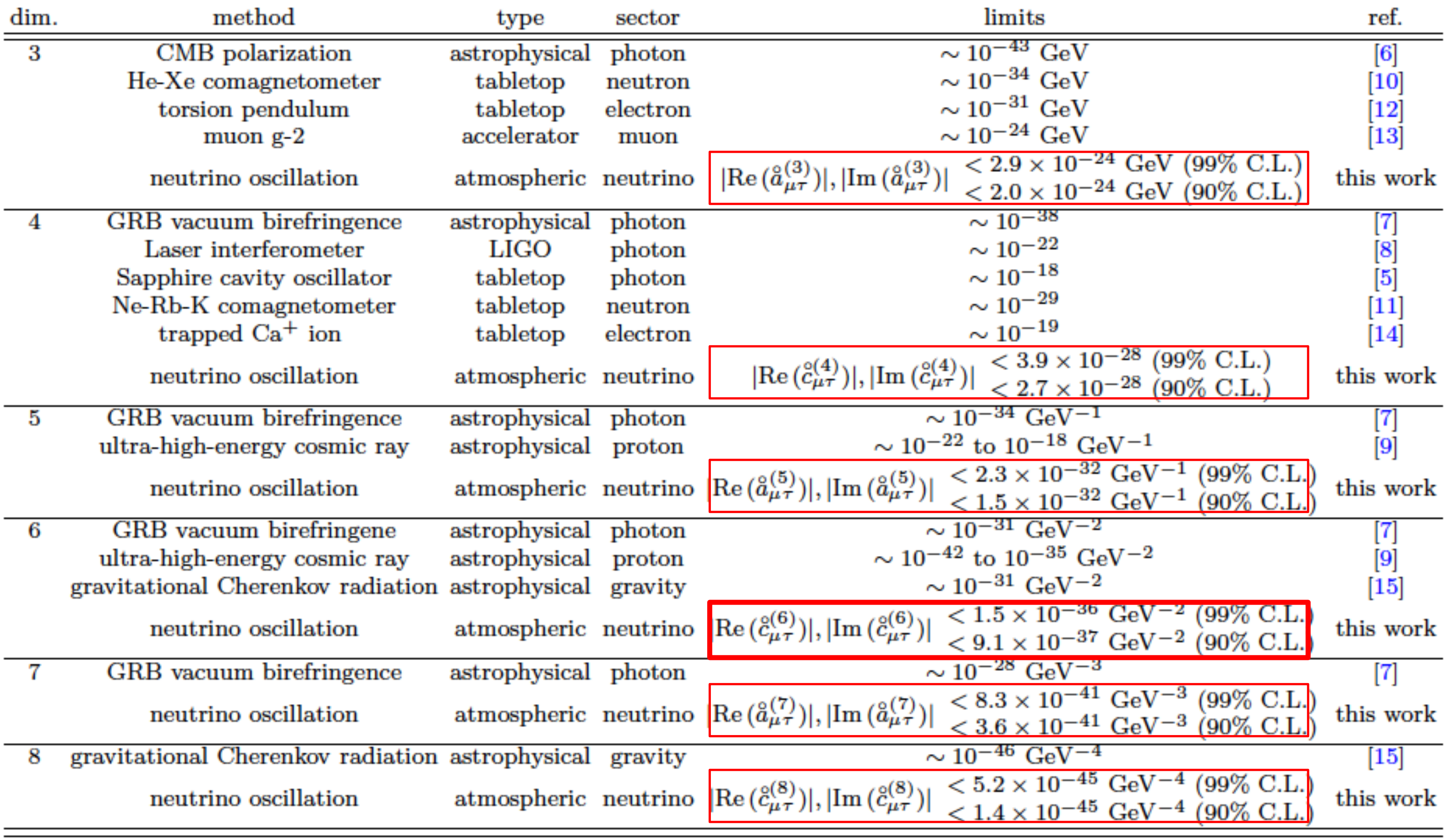
$$E^{3}c^{(6)}_{\alpha\beta} = E^{3}\begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix}$$

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

2. 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, $c^{(6)} < 10^{-36} GeV^{-2}$
Astrophysical neutrino sensitivity reach the benchmark value, $c^{(6)} \sim 1/M_P^2 \sim 10^{-38} GeV^{-2}$

IceCube, Nature Physics 14 (2018) 961
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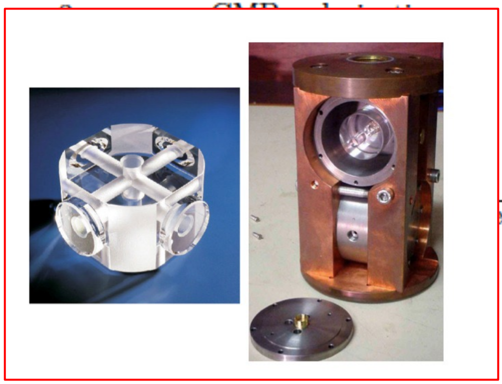
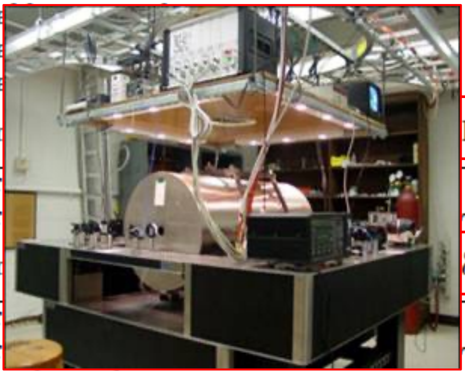
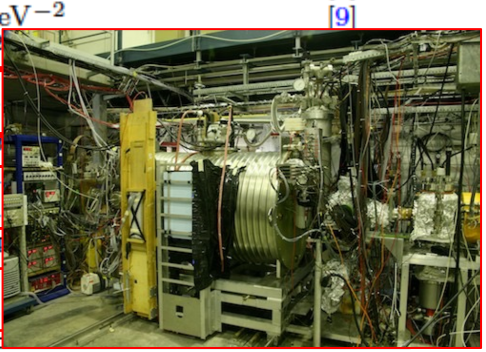
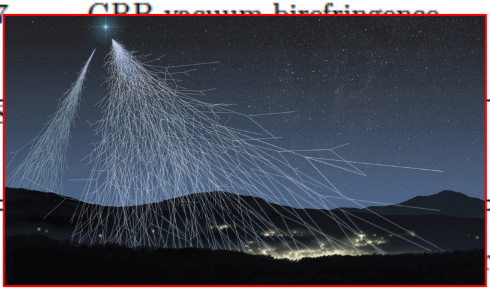
2. Neutrino interferometry – Atmospheric neutrinos

Physics MMA









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		astrophysica		$\sim 10^{-43}$ GeV	
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		ta			[5]
		ta			[11]
		ta			[14]
	neutrino oscillation	atm	$\mathrm{Im}\,(\mathring{c}_{\mu}$		s work
5		astr		$\sim$	[7]
		astr		$\sim 10^{-}$	[9]
		atm	$\mathring{a}^{(5)}_{\mu\tau})\|$		s work
6		astr		$\sim$	[7]
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	g n	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	
		atmospheric		$< 1.5 \times 10^{-36}$ $< 9.1 \times 10^{-37}$	
7		astrophysical		10^{-28} GeV^{-3}	
		atmospheric		$< 8.3 \times 10^{-41}$ $< 3.6 \times 10^{-41}$	
8		astrophysical		10^{-46} GeV^{-4}	
		atmospheric		$< 5.2 \times 10^{-45}$ $< 1.4 \times 10^{-45}$	

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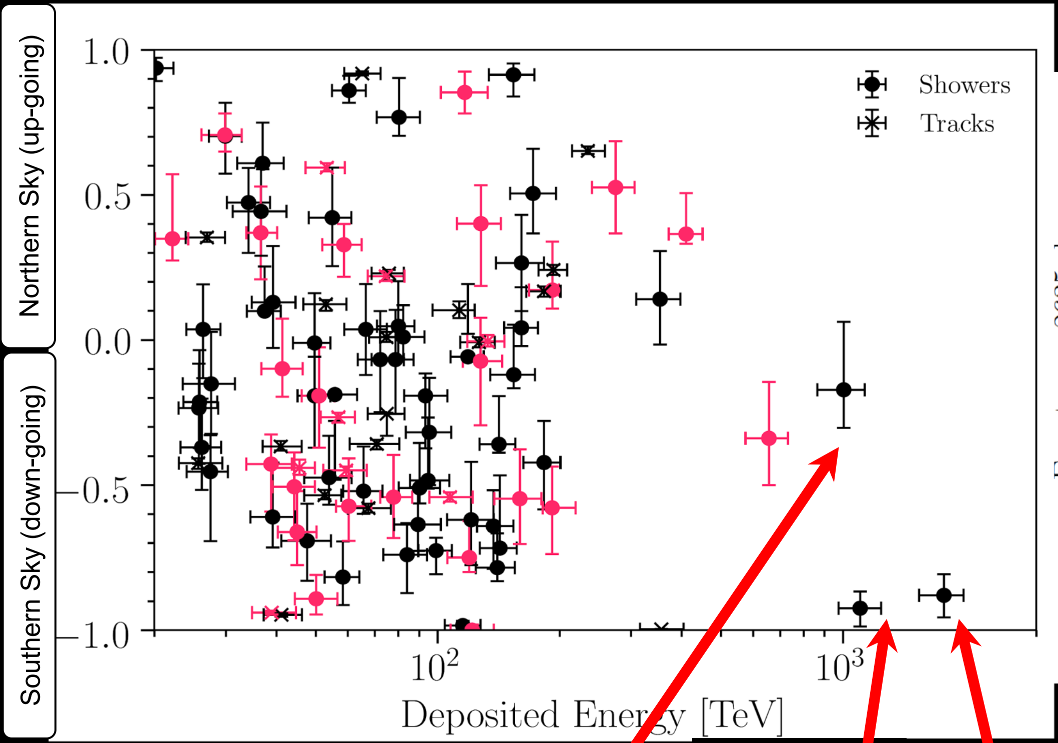
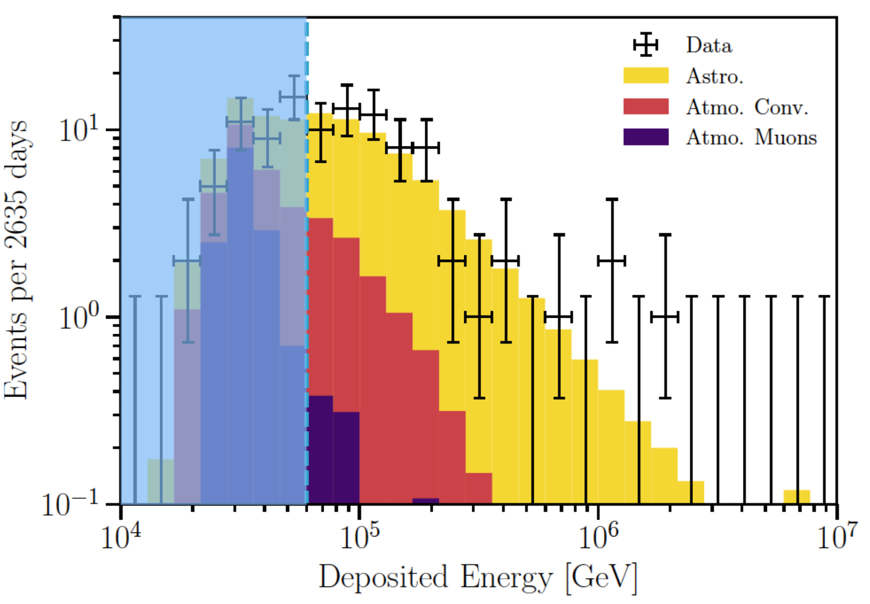
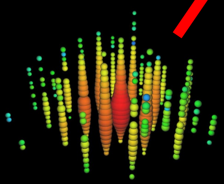
IceCube, PRD104(2021)022002

3. High-energy astrophysical neutrinos

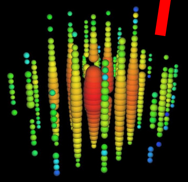
60-2000 TeV astrophysical neutrinos have been observed by IceCube Neutrino Observatory



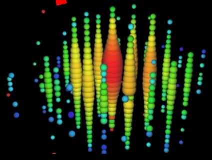




"Bert"
1.1 PeV



"Ernie"
1.0 PeV



"Big Bird"
2.0 PeV

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

3. IceCube event morphology

Track

ν_μCC

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

Cascade

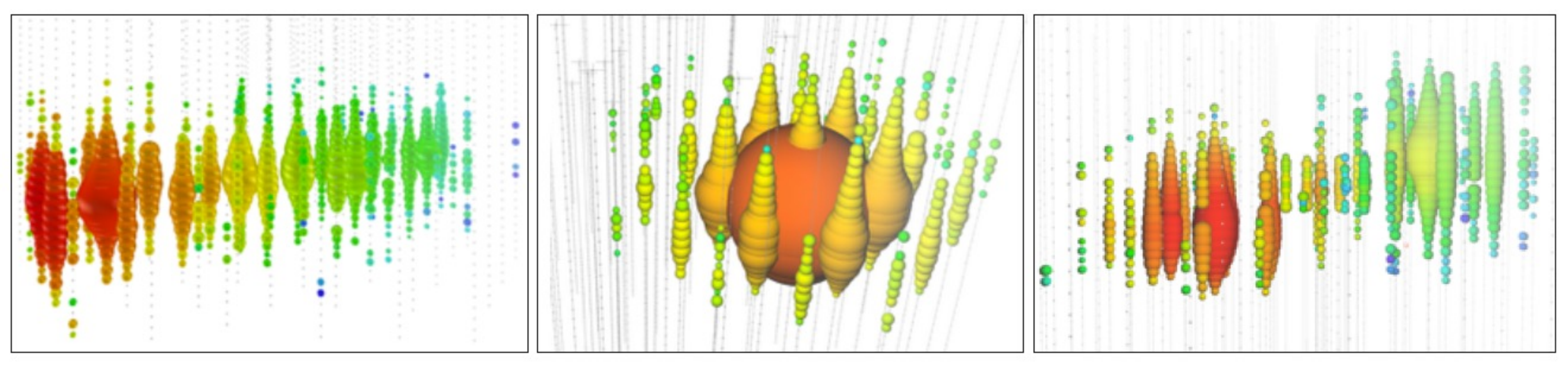
ν_eCC, ν_τCC, NC

$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade

ν_τCC (L~50m•E/PeV)

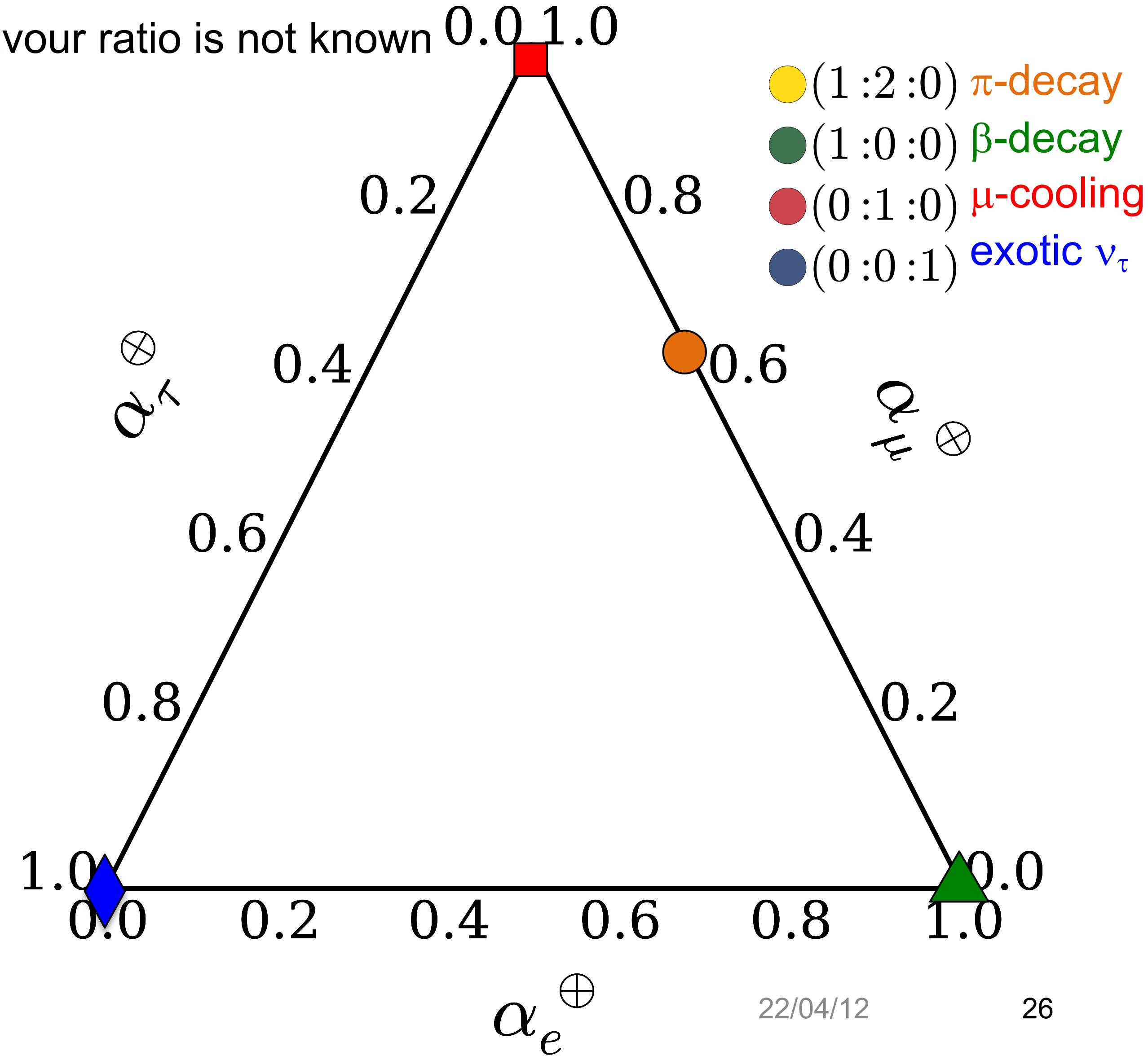
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X'$$



Argüelles, TK, Salvado, PRL115(2015)161303

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

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



Argüelles, TK, Salvado, PRL115(2015)161303

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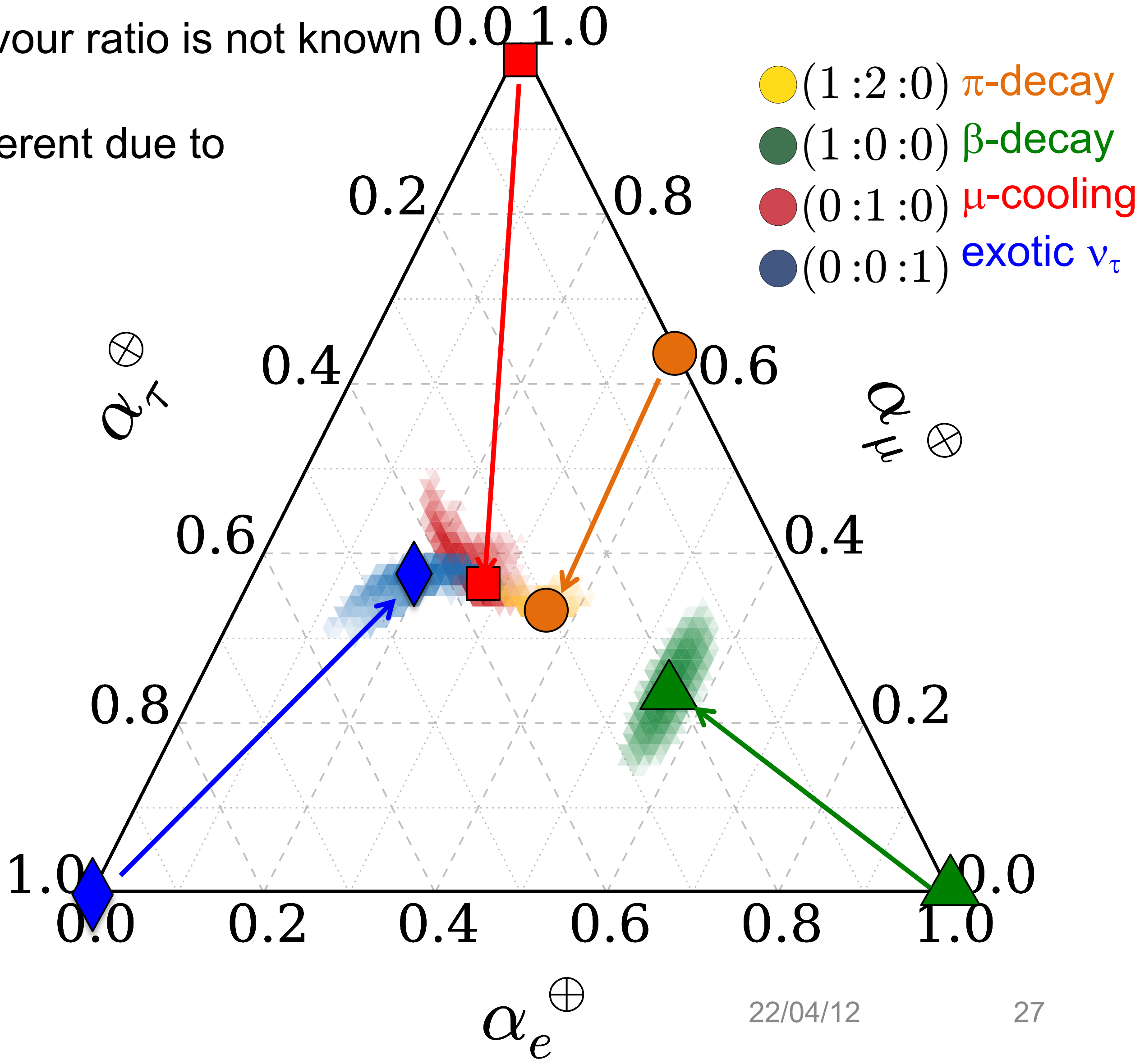
Flavour ratio on Earth is different due to mixing by neutrino masses



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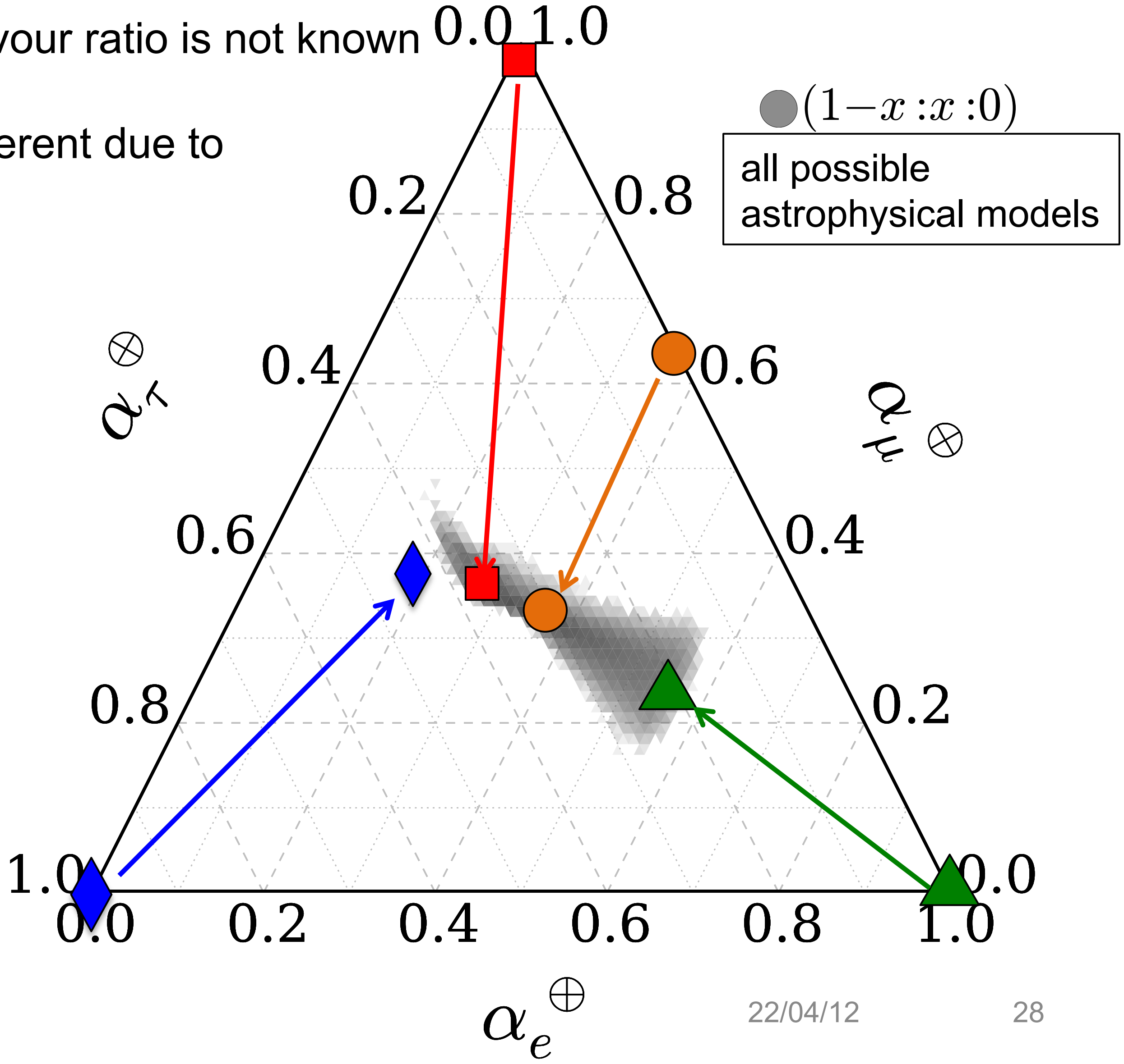

all possible astrophysical models

Argüelles, TK, Salvado, PRL115(2015)161303

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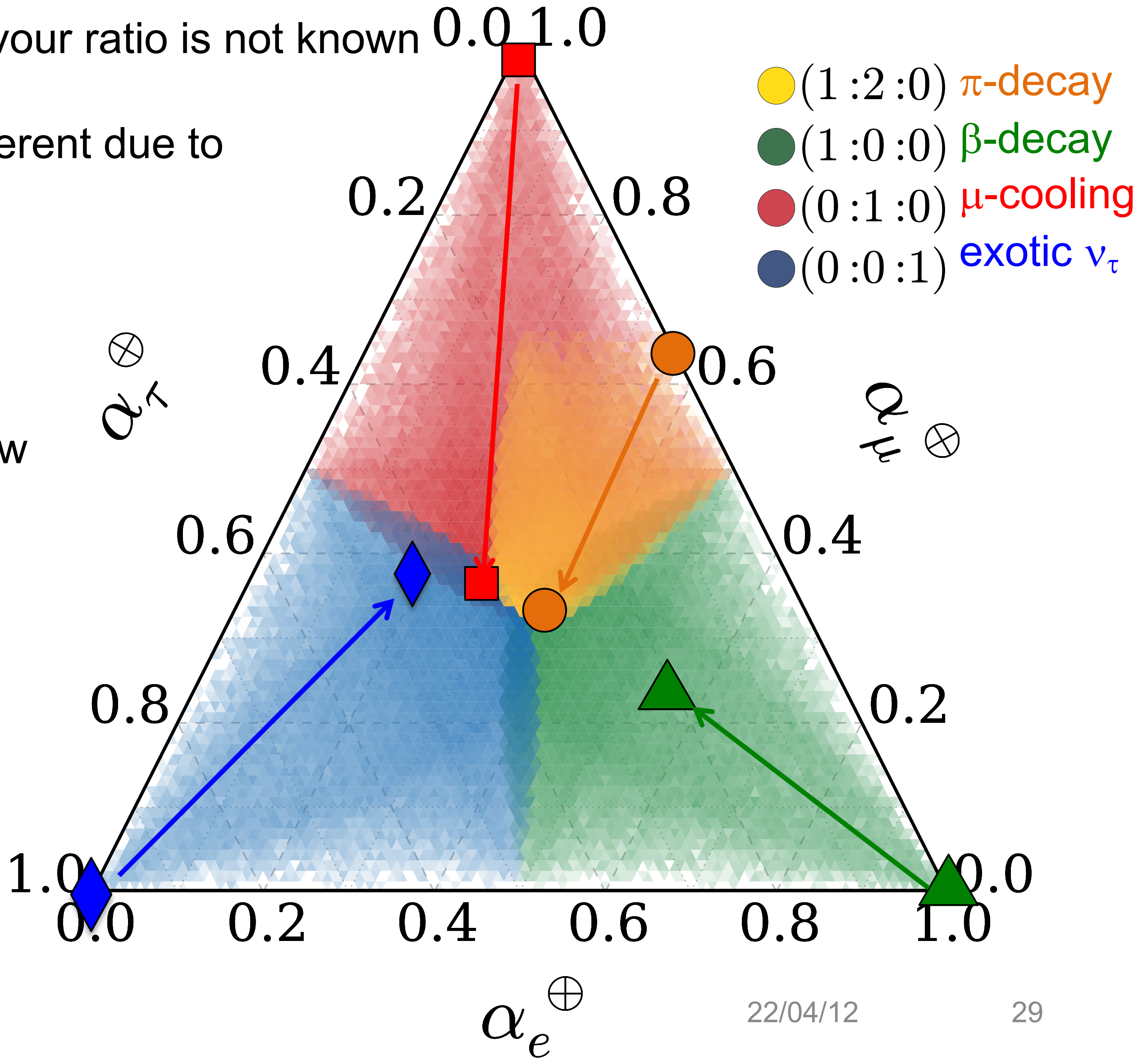
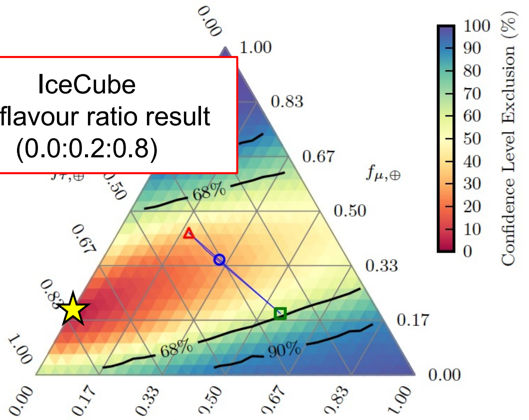
e.g.) New physics just below the limit can produce any flavour ratio

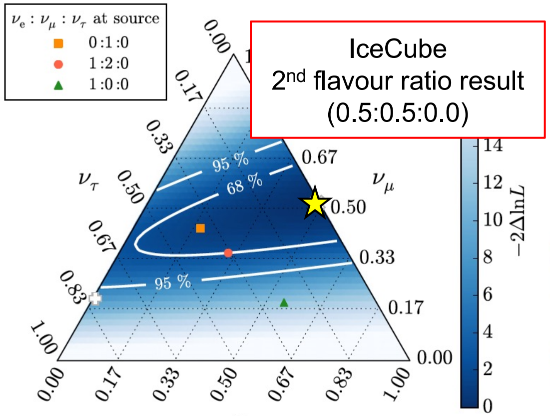


IceCube, ArXiv: 2011:03561, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004

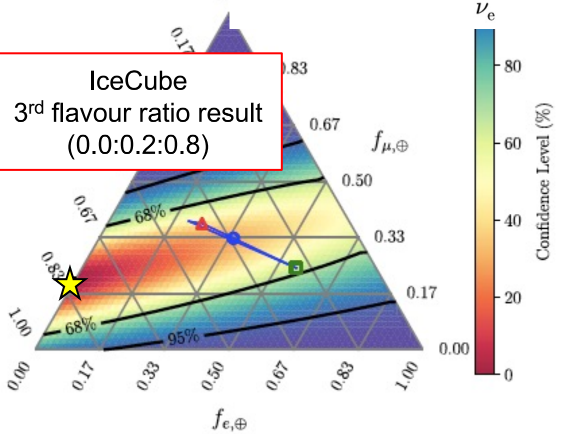
3. HESE 7.5-yr flavor ratio



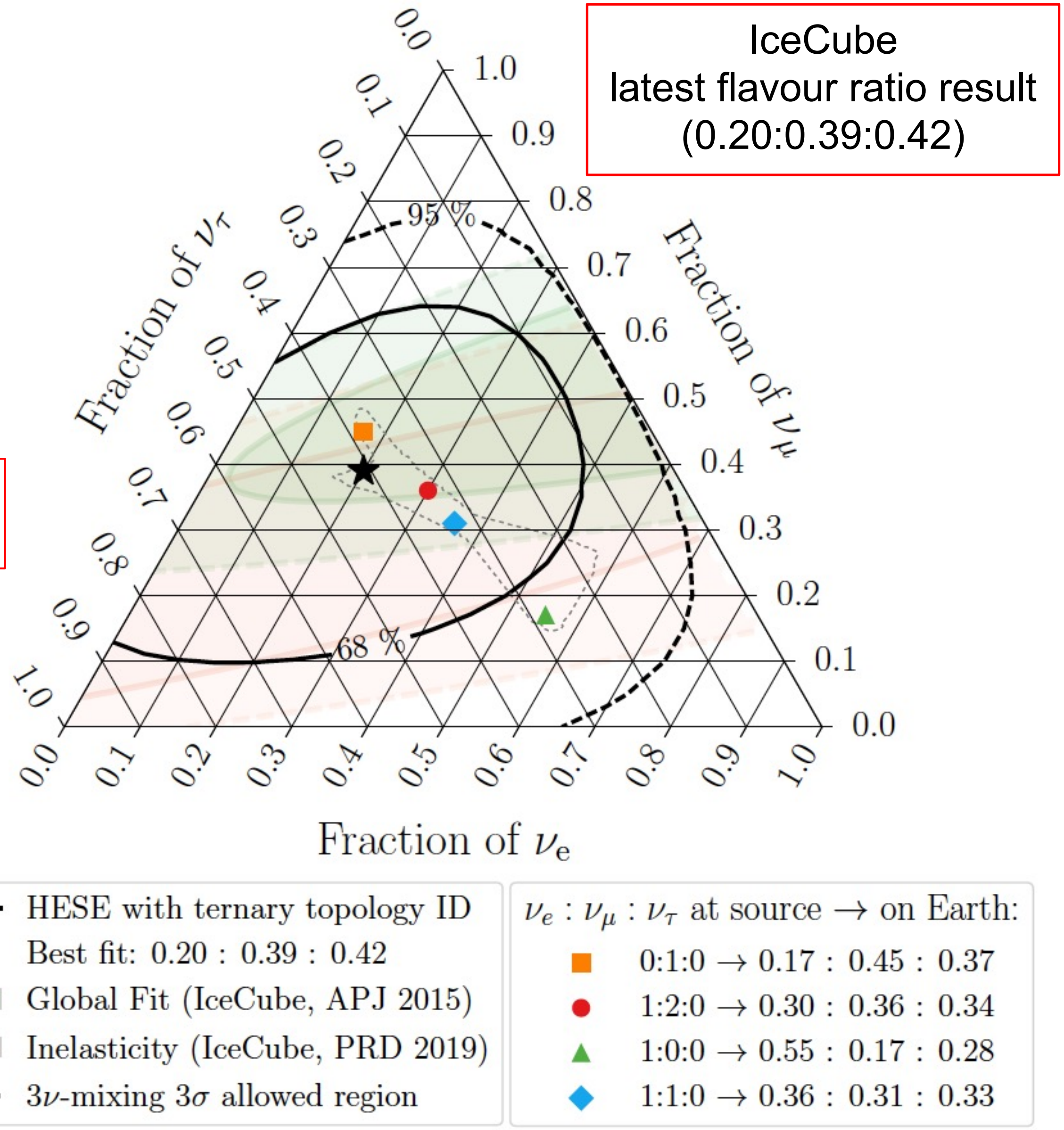
IceCube
1st flavour ratio result
(0.0:0.2:0.8)



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



IceCube
3rd flavour ratio result
(0.0:0.2:0.8)



IceCube
latest flavour ratio result
(0.20:0.39:0.42)

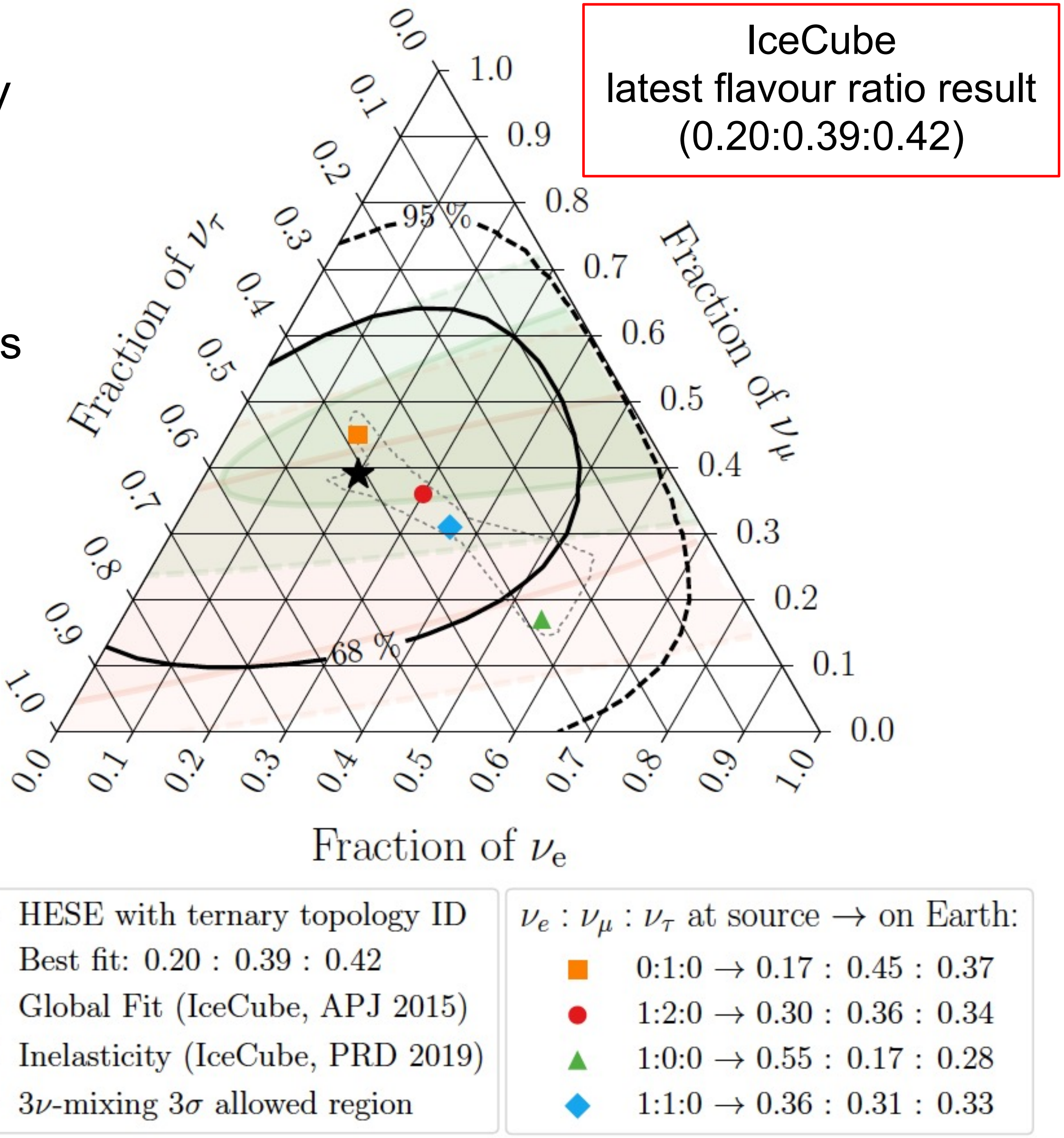
IceCube, ArXiv: 2011:03561

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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We will not find new physics
We need;
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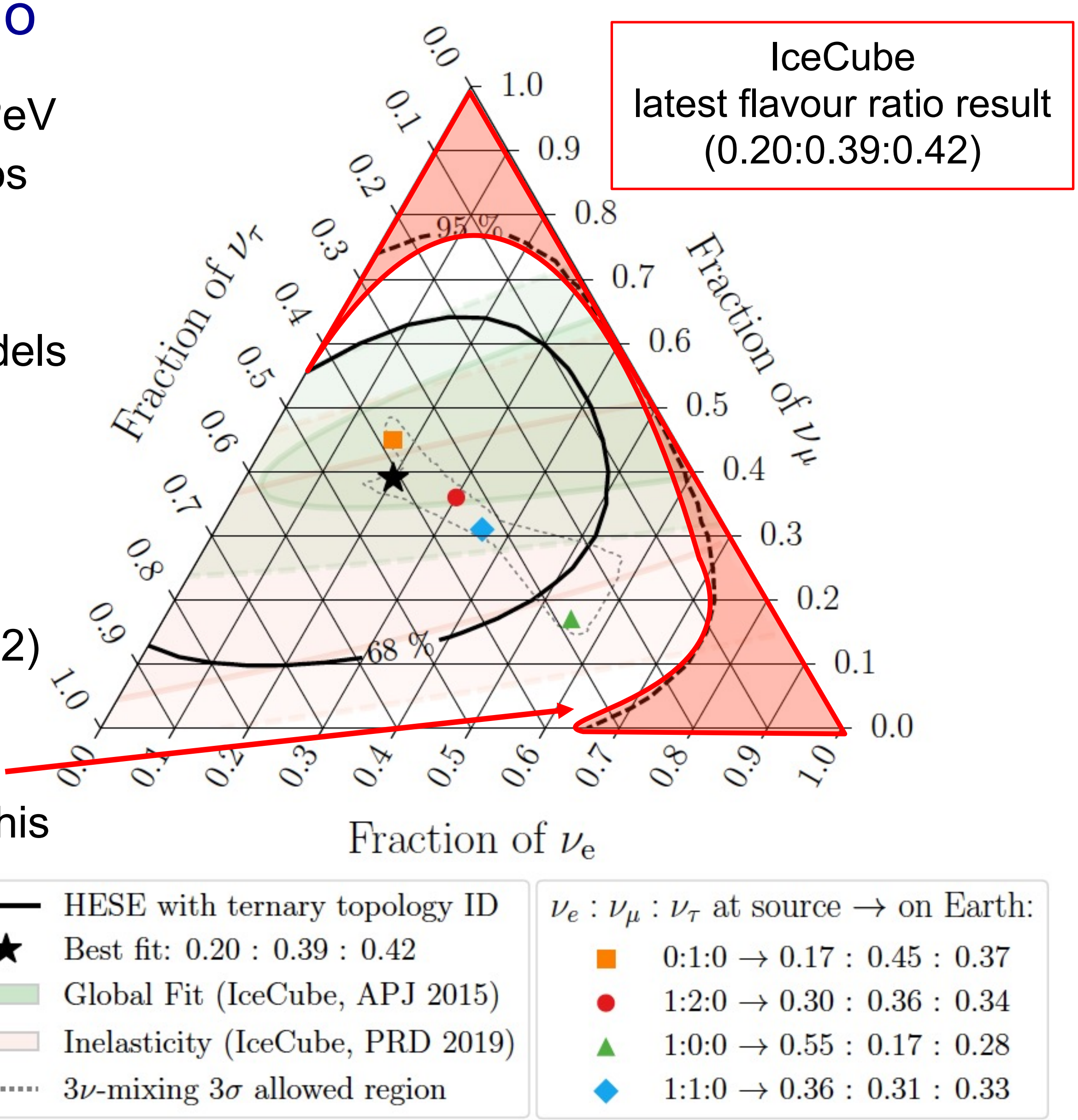
 - better PID (software)

Models predict flavour ratios at this region can be rejected



IceCube
latest flavour ratio result
(0.20:0.39:0.42)

IceCube, ArXiv: 2111.04654

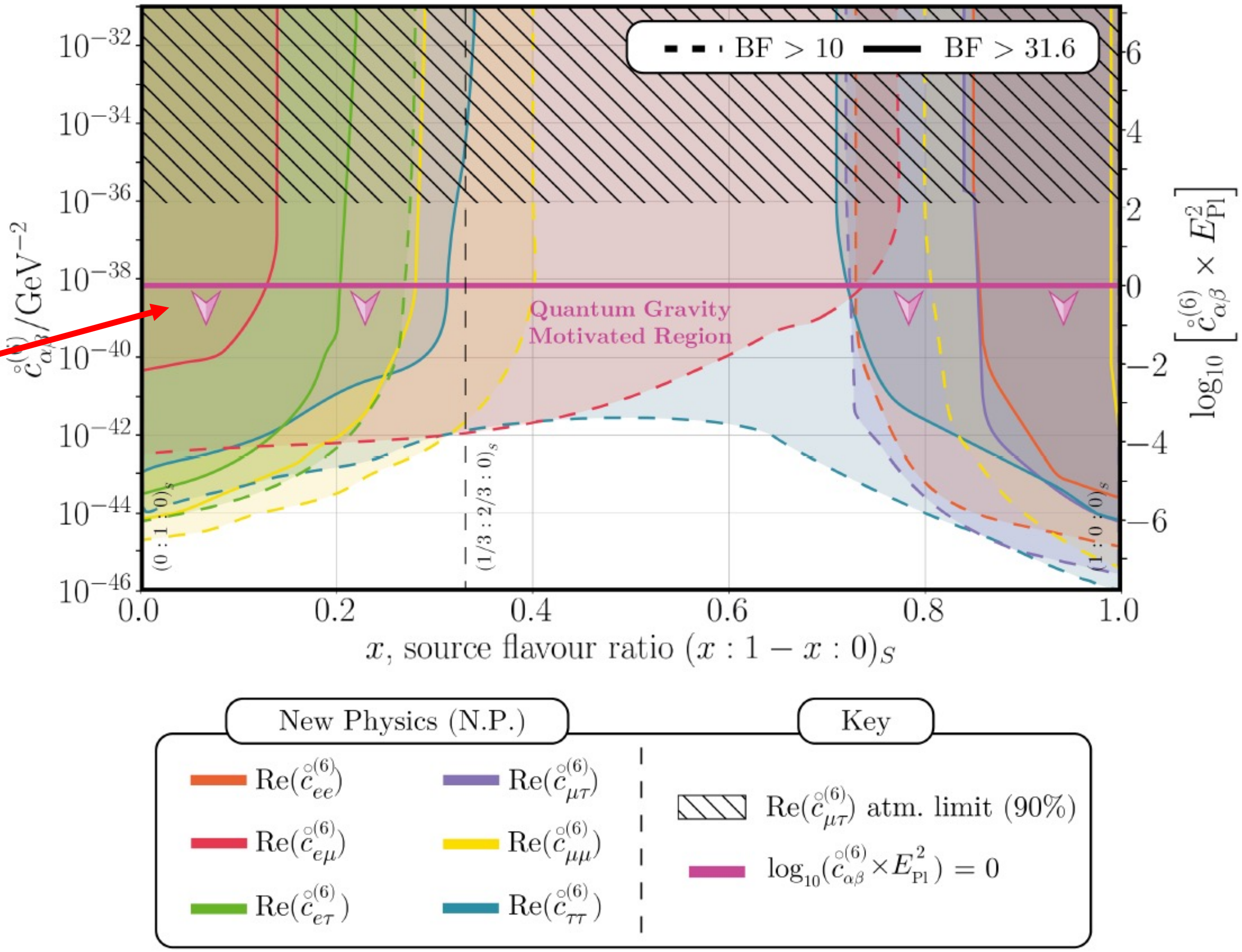
3. HESE 7.5-yr flavor new physics search

60 HESE events in 60 TeV – 2 PeV

First identification of tau neutrinos

Strong limits for many parameters depending on assumed initial flavour ratio

dim-6 new physics operator limit



$1/M_P^2 \sim 10^{-38} GeV^{-2}$

IceCube, ArXiv: 2111.04654

3. HESE 7.5-yr flavor new physics search

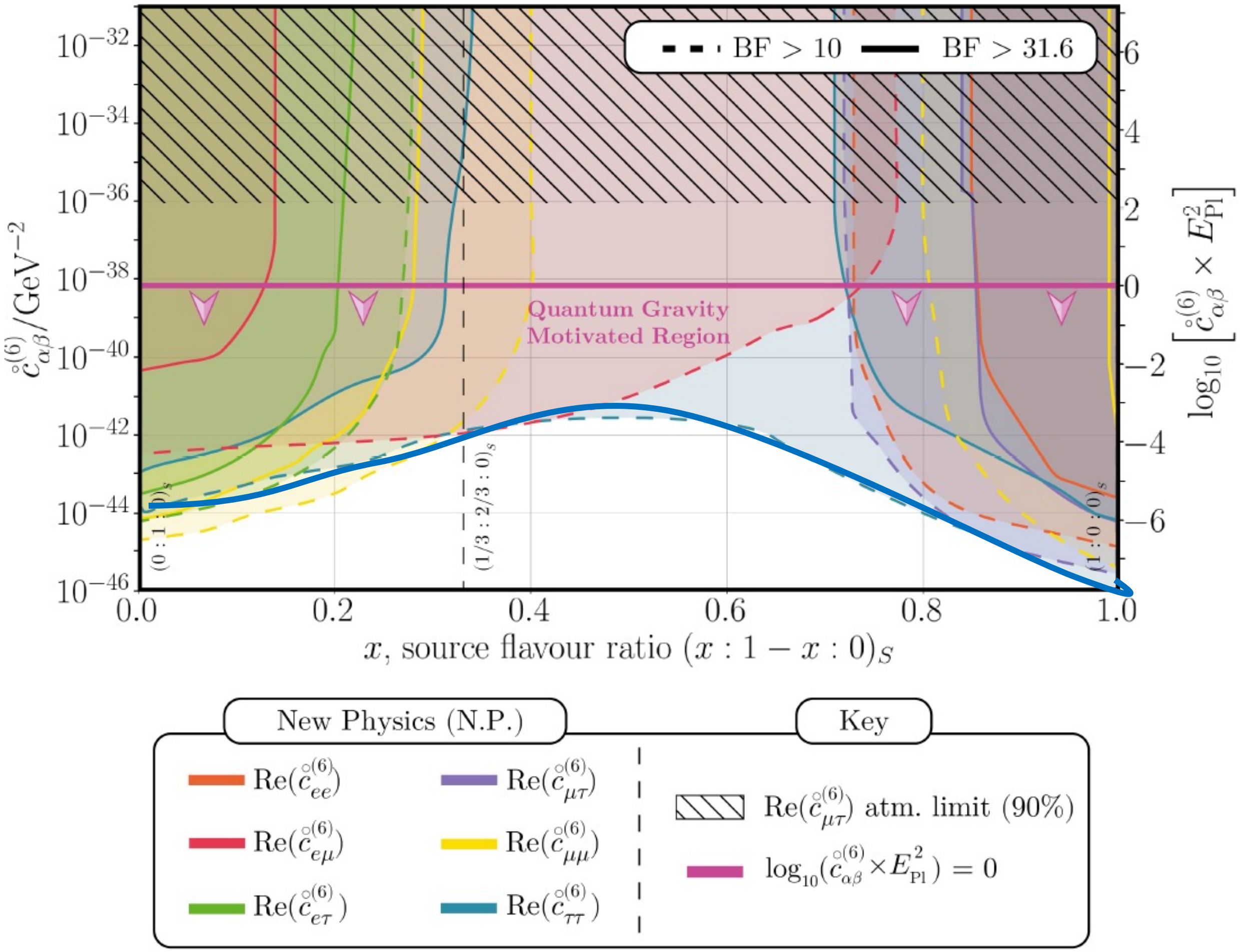
60 HESE events in 60 TeV – 2 PeV

First identification of tau neutrinos

Strong limits for many parameters depending on assumed initial flavour ratio

We obtain model-independe limits for $c_{\tau\tau}$

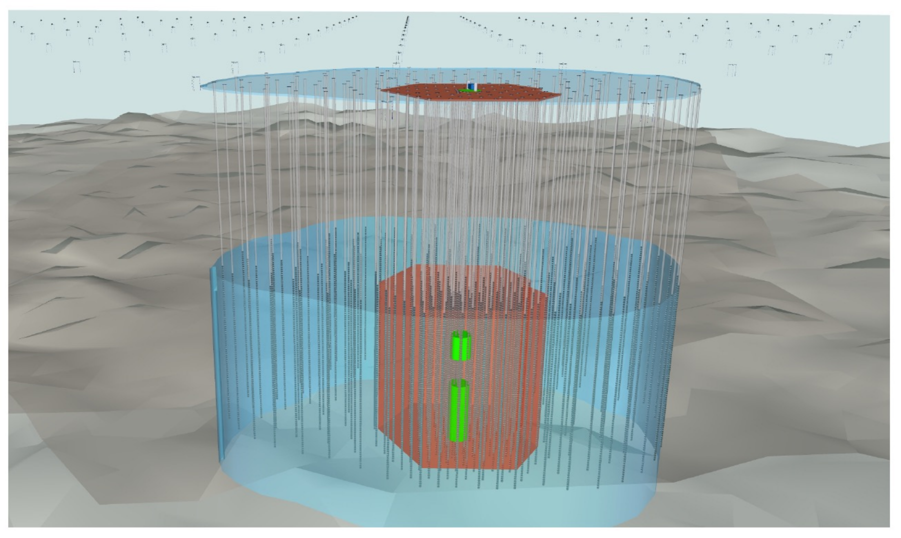
dim	coefficient	limit (BF> 10.0)
3	$\mathrm{Re}\,(\mathring{a}^{(3)}_{\tau\tau})$	2×10^{-26} GeV
4	$\mathrm{Re}\,(\mathring{c}^{(4)}_{\tau\tau})$	2×10^{-31}
5	$\mathrm{Re}\,(\mathring{a}^{(5)}_{\tau\tau})$	2×10^{-37} GeV^{-1}
6	$\mathrm{Re}\,(\mathring{c}^{(6)}_{\tau\tau})$	3×10^{-42} GeV^{-2}
7	$\mathrm{Re}\,(\mathring{a}^{(7)}_{\tau\tau})$	3×10^{-47} GeV^{-3}
8	$\mathrm{Re}\,(\mathring{c}^{(8)}_{\tau\tau})$	2×10^{-52} GeV^{-4}

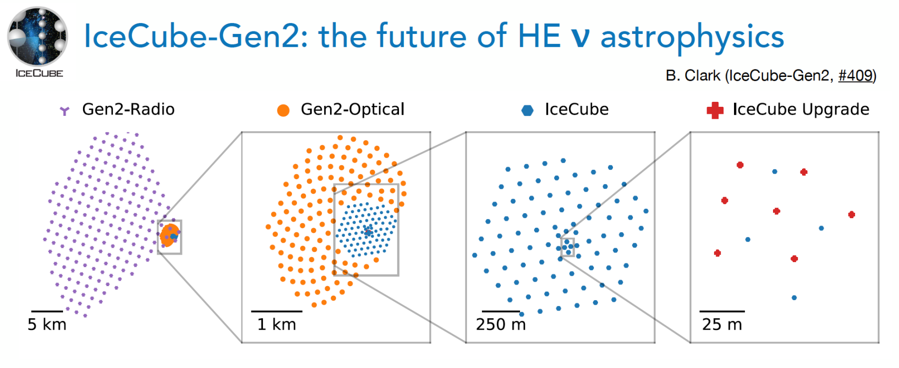

dim-6 new physics operator limit

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

3. IceCube-Gen2

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

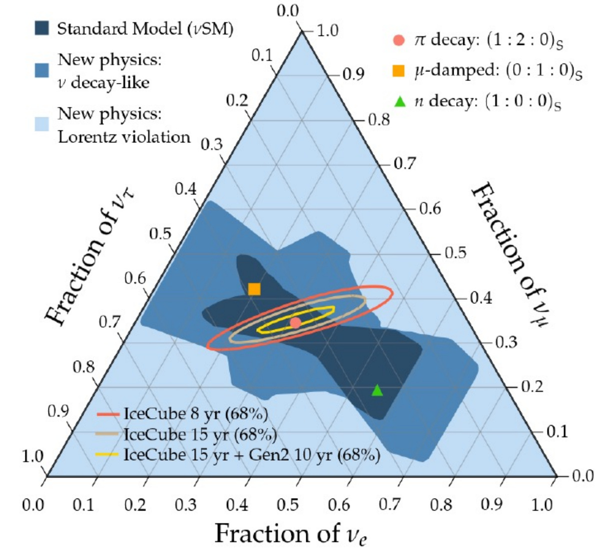




IceCube-Gen2: the future of HE ν astrophysics

B. Clark (IceCube-Gen2, #409)

IceCube-Gen2 flavour ratio sensitivity



The first stage of Gen2
(IceCube upgrade) is ongoing

Conclusion

Quantum gravity may create a new space-time 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

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} ($\theta_{23}=40^{o}$ and 50^{o} are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
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

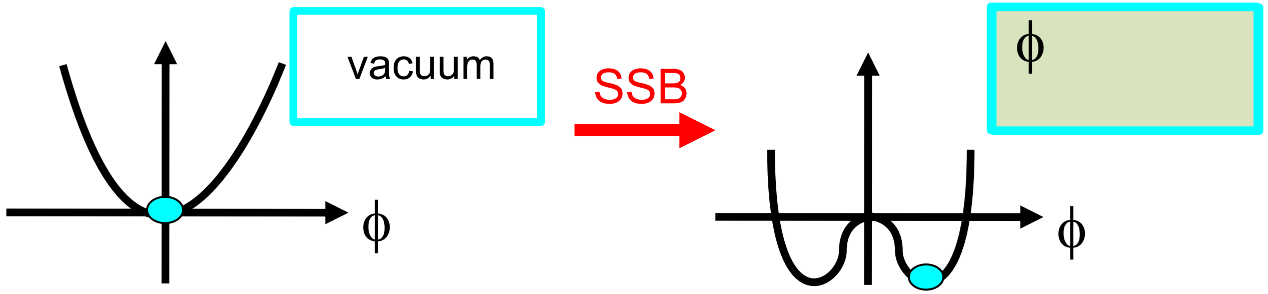
Kostelecký and Samuel,PRD39(1989)683

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

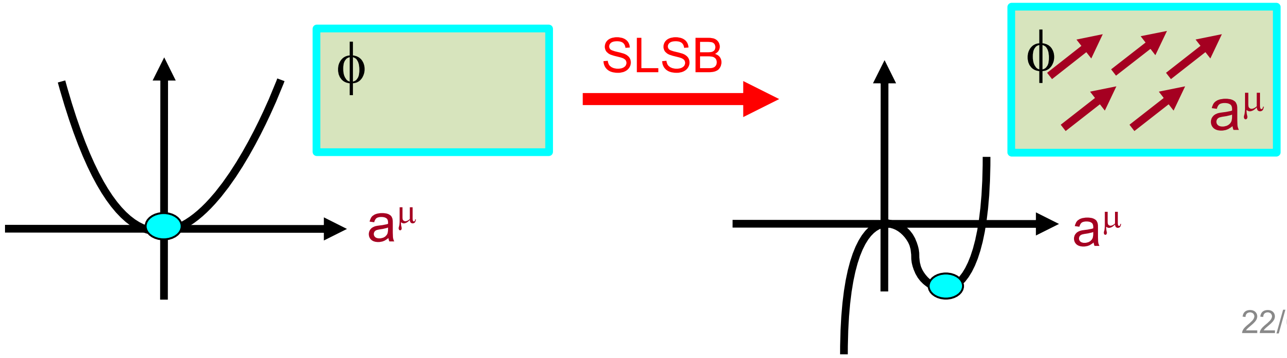
$L = i\bar{\psi}\gamma_\mu\partial^\mu\psi\cdots$ $\quad$ $L = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi\cdots$



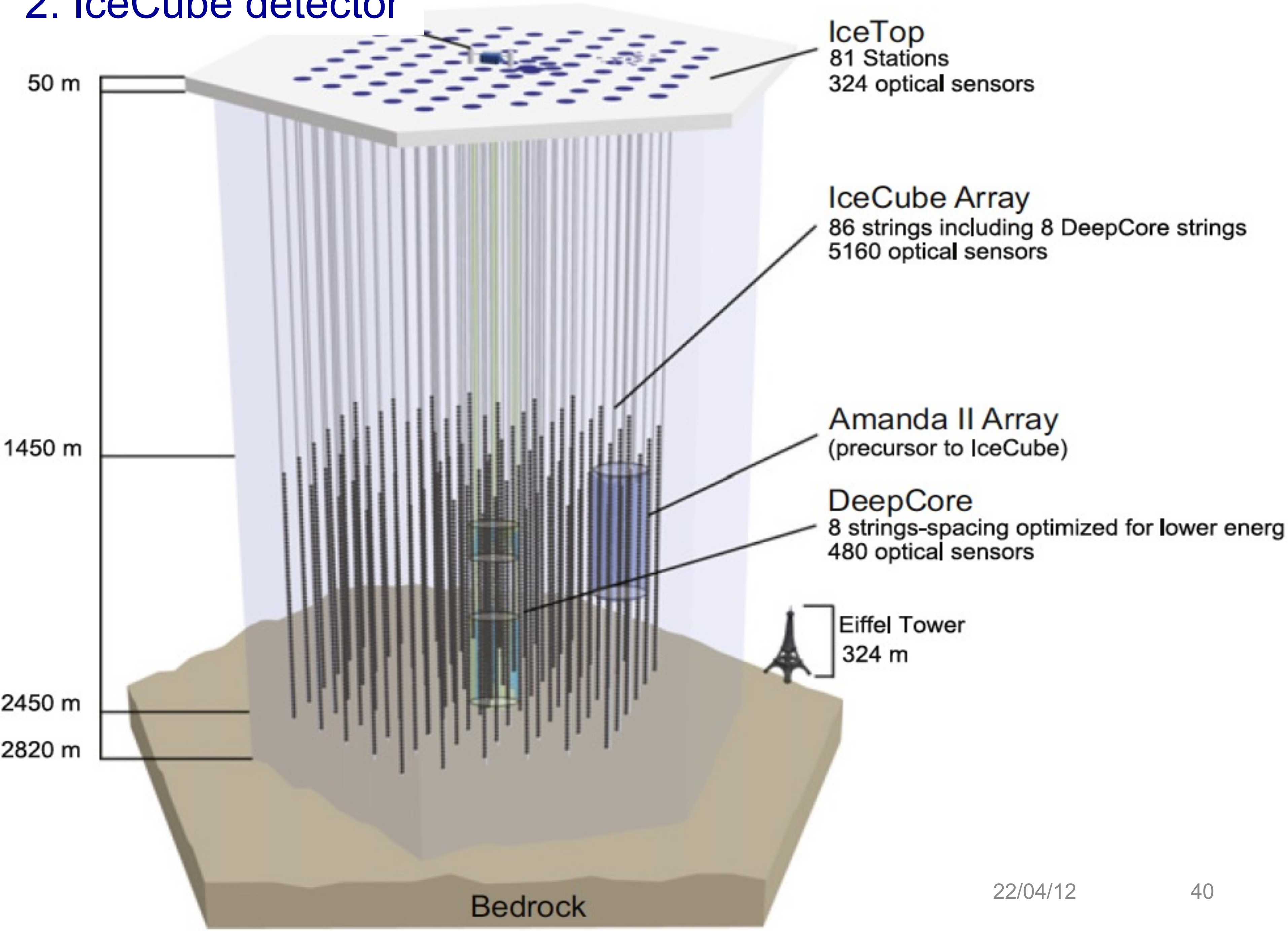
SLSB in string field theory

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

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

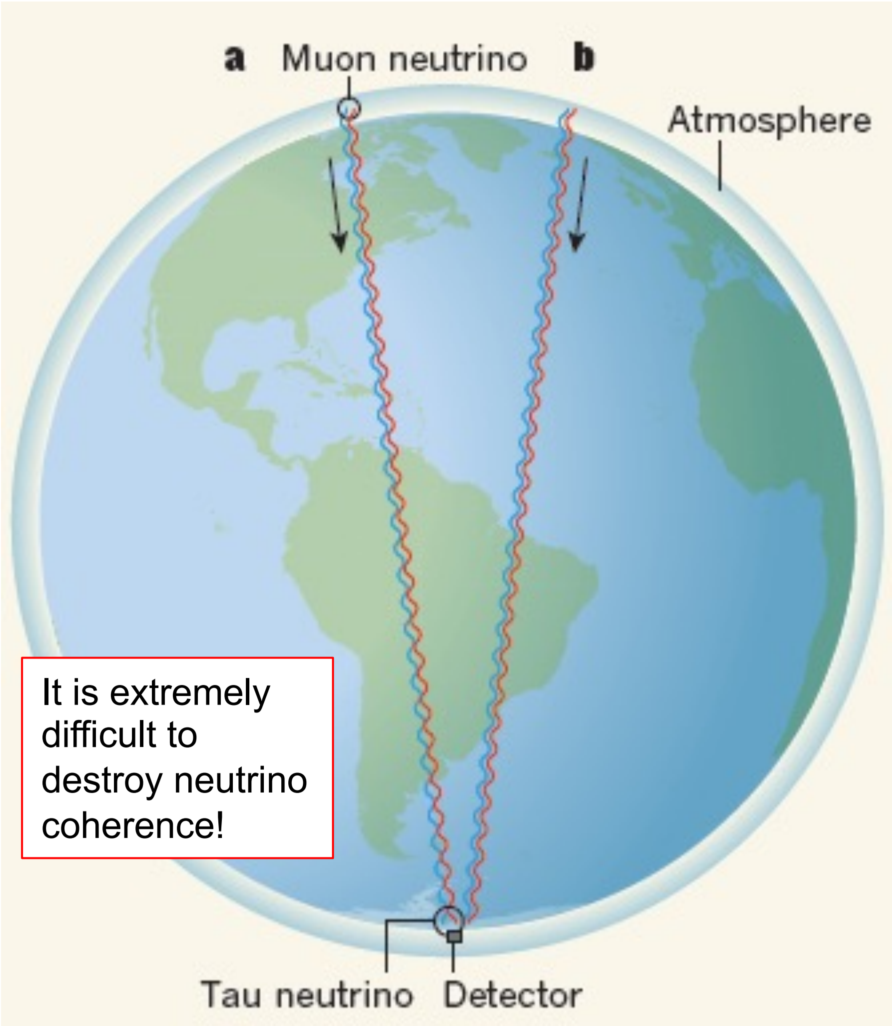


2. IceCube detector



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

3. Neutrino interferometry – Atmospheric neutrinos

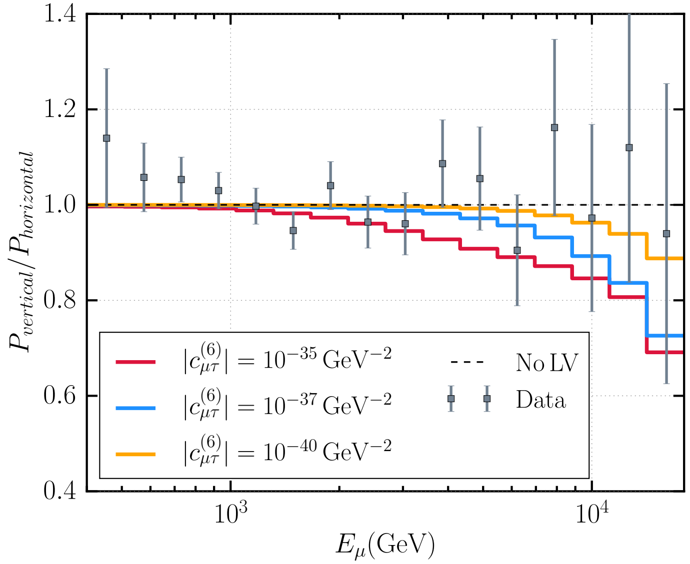


It is extremely difficult to destroy neutrino coherence!

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

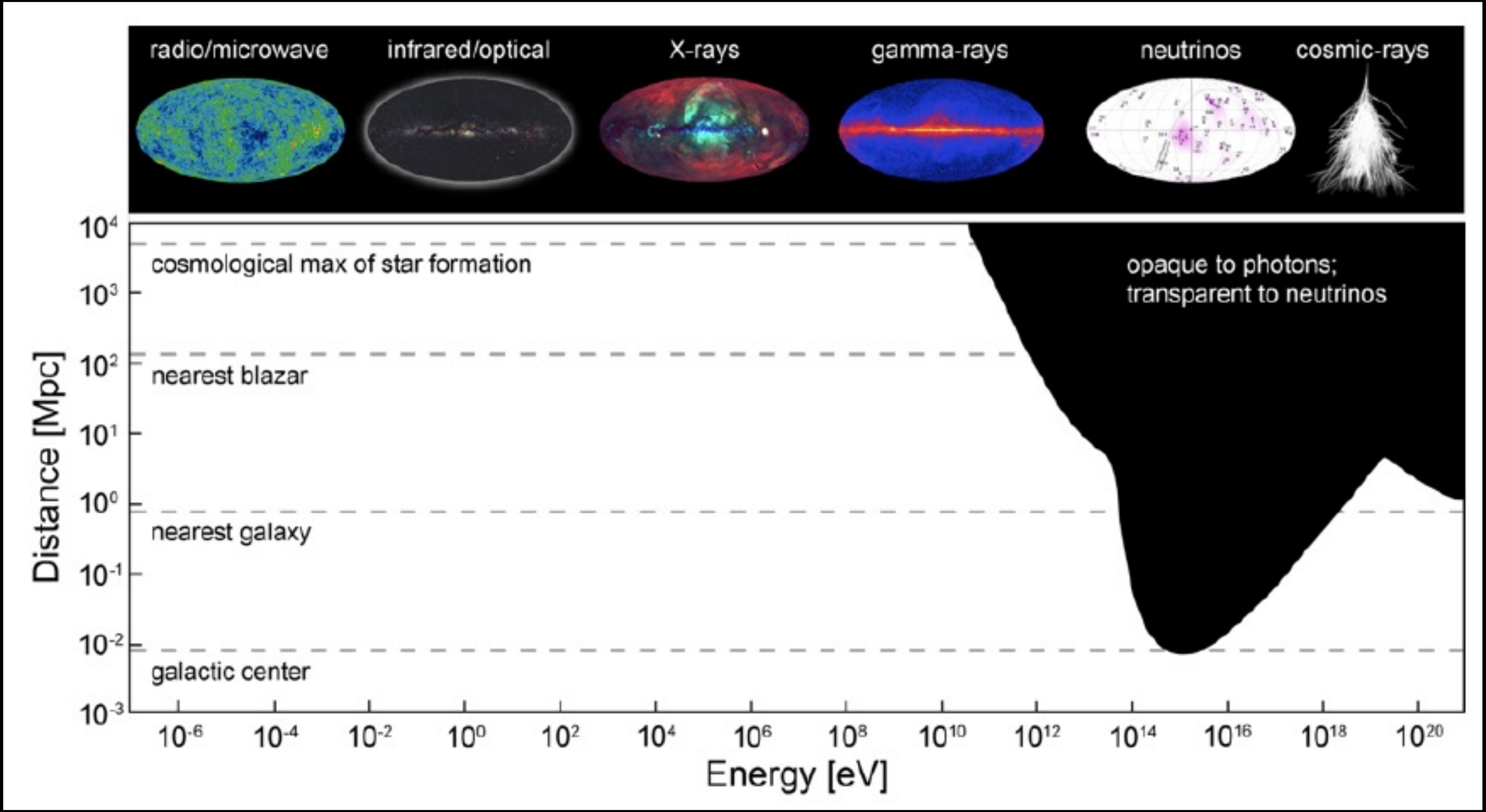
If anomalous coupling with neutrinos in vacuum cause a phase shift in similar order, we can see it from spectrum distortion of atmospheric neutrinos



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

2. High-energy astrophysical neutrinos

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



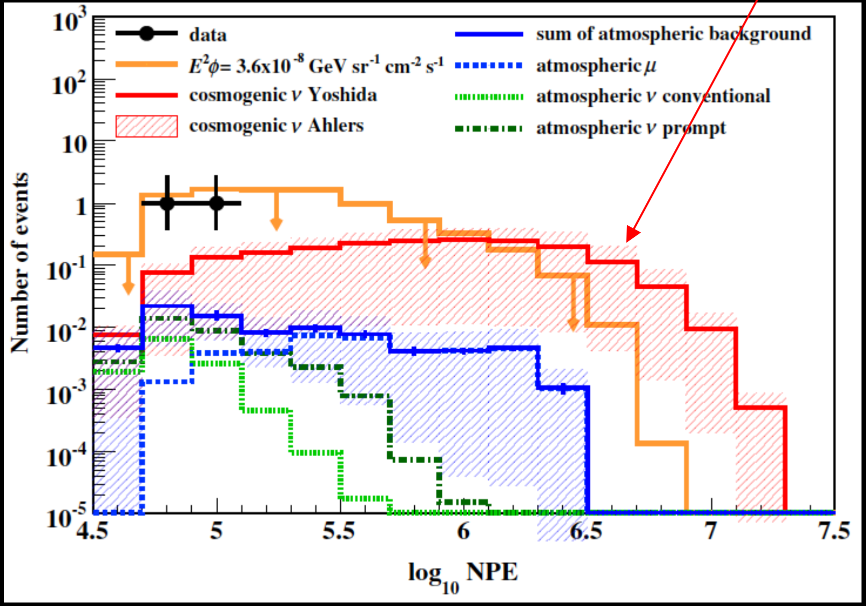
IceCube, PRD104(2021)022002

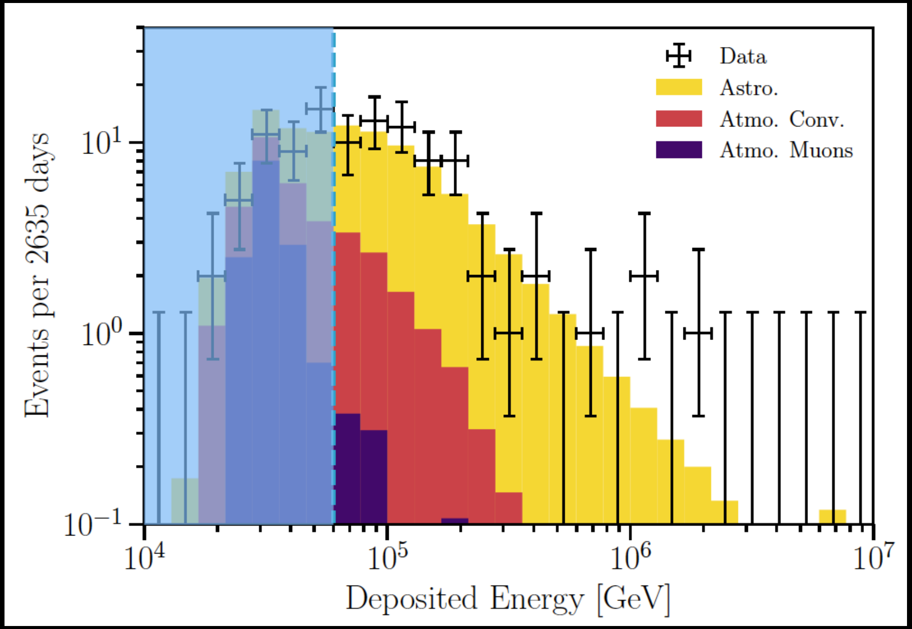
2. Astrophysical Very-High-Energy Neutrinos

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, PRD104(2021)022002

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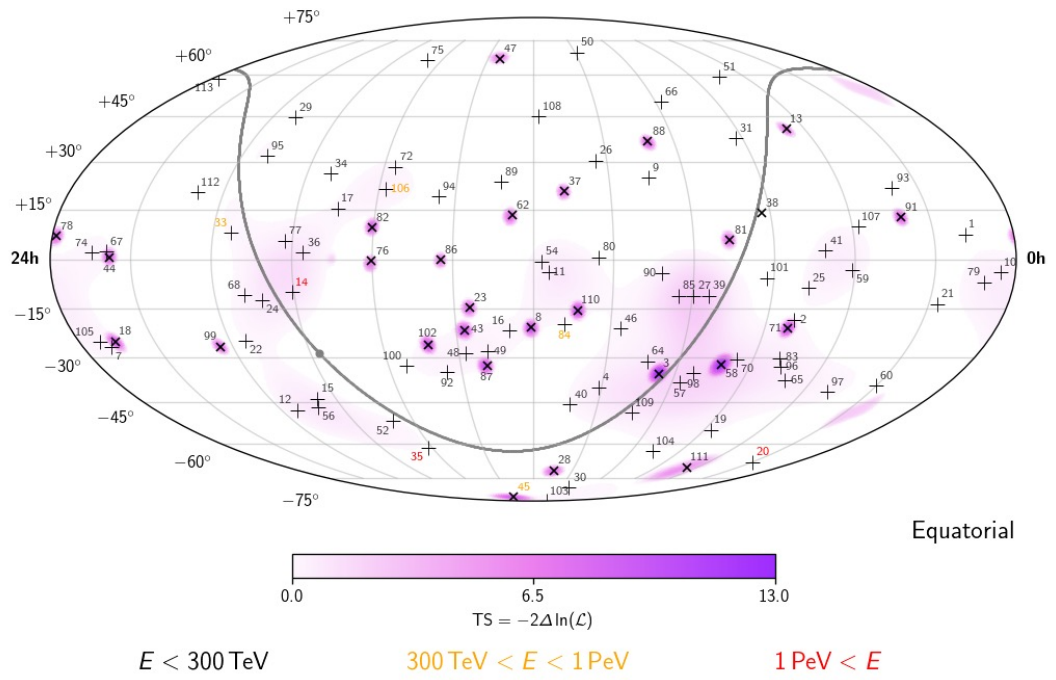
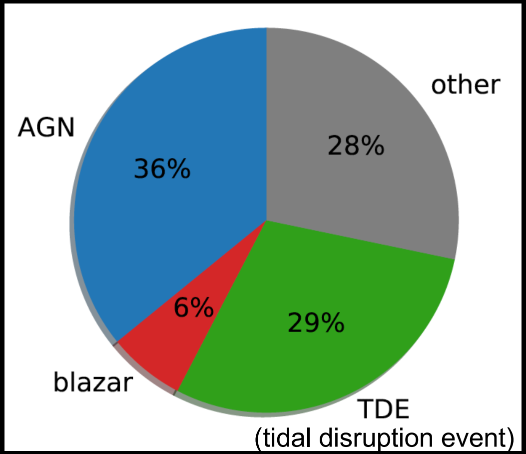


Evidence of Blazar Neutrino
- IC170922A
- TXS 0506+056

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

IceCube astrophysical high-energy neutrino source contribution



ArXiv:2105.03792

KING'S College LONDON

IceCube, PRD104(2021)022002, ArXiv: 2011:03561

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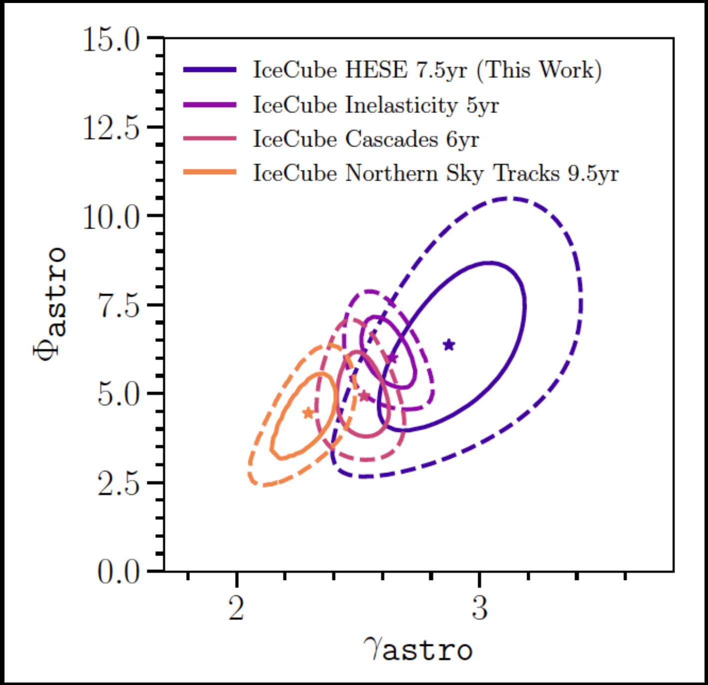
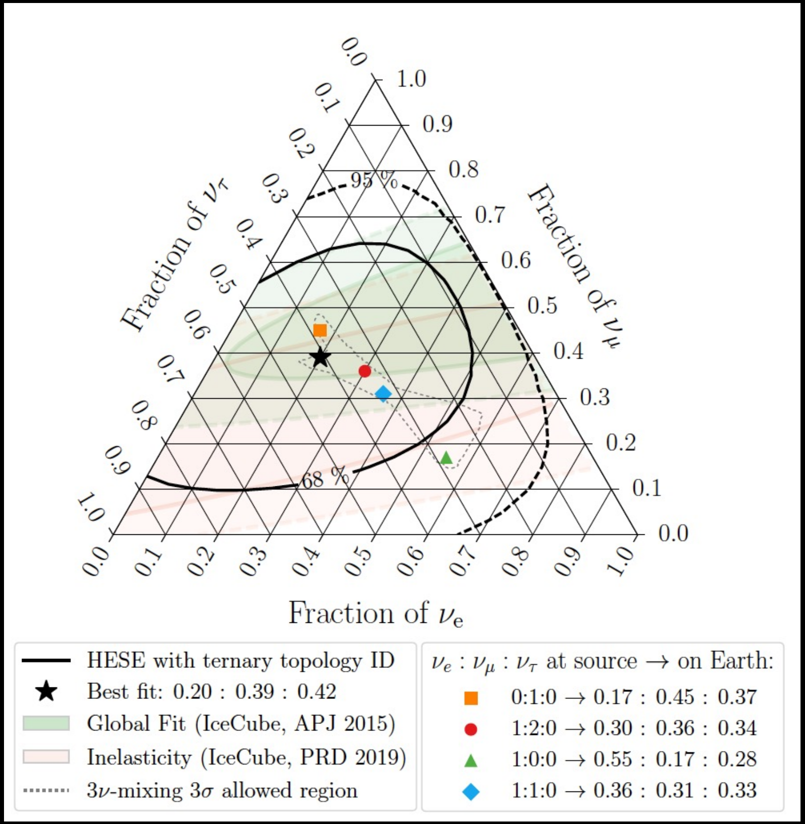
- 60-2000 TeV neutrinos
- Too high-energy as atmospheric neutrinos
- Too low-energy as GZK neutrinos
- Sources are mostly unknown (diffuse)
- Large uncertainty on spectrum and flavor structure

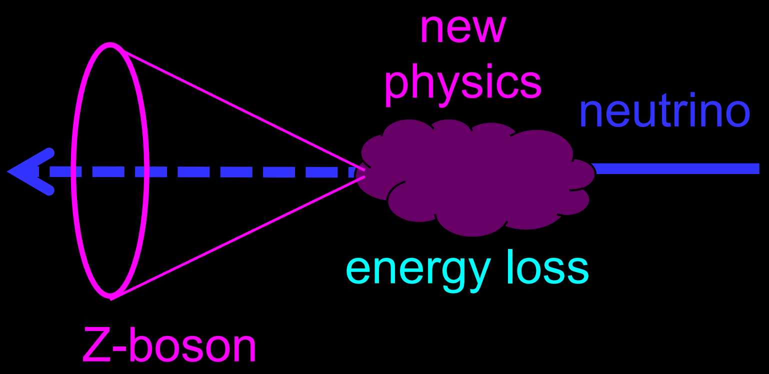


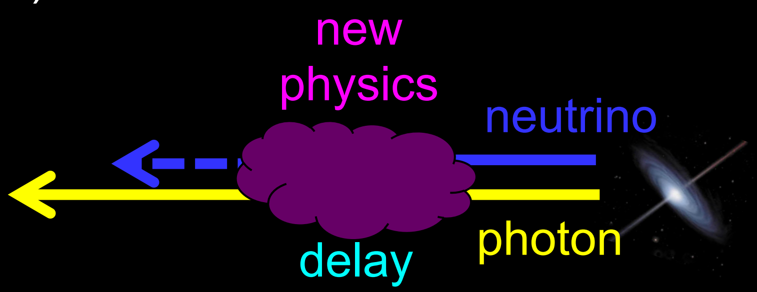


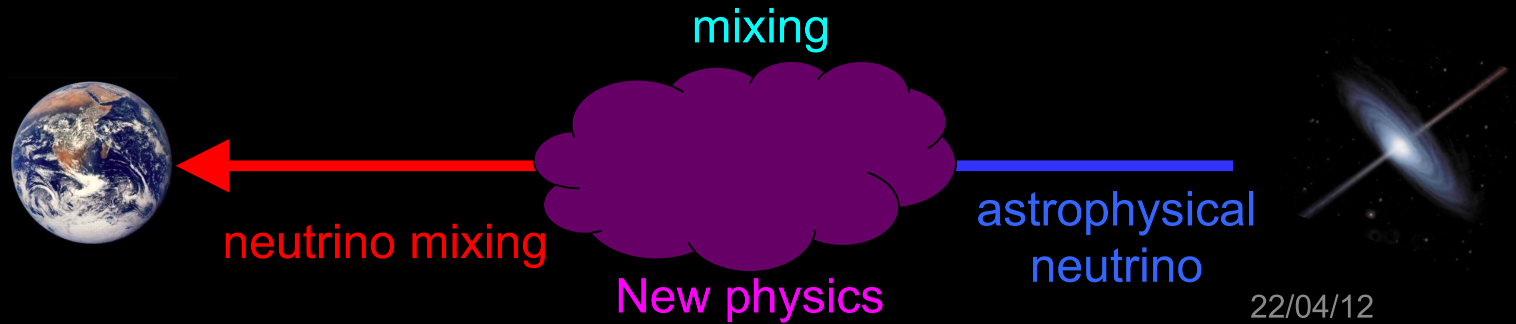
2. Search for Lorentz violation with astrophysical neutrinos

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

New physics search
- Spectrum distortion (vacuum Cherenkov radiation)
- Time of Flight (modified dispersion)
- New flavour structure (new vacuum effect)







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

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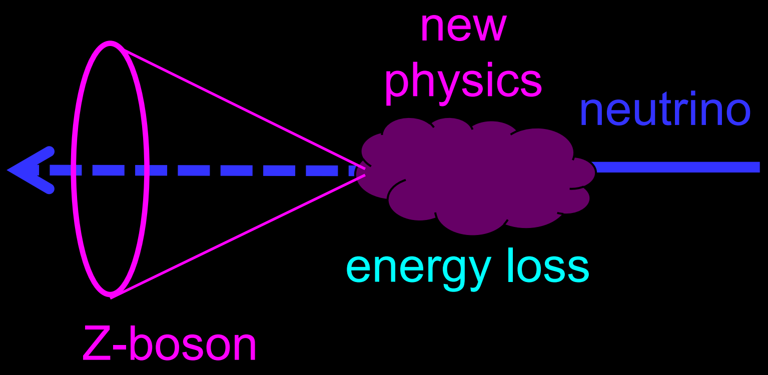
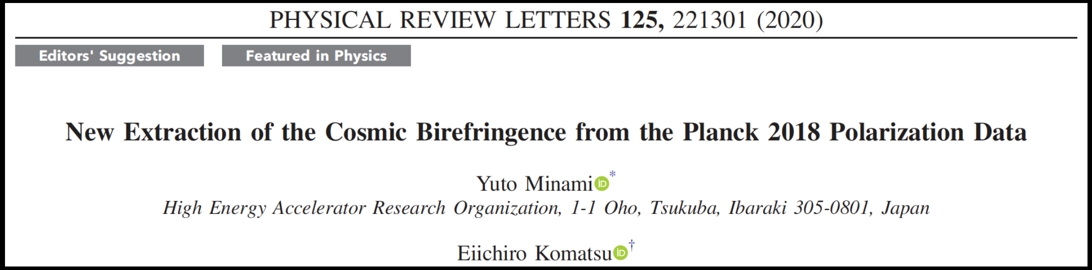


Lorentz violating field cause
Cherenkov radiation in vacuum

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


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†

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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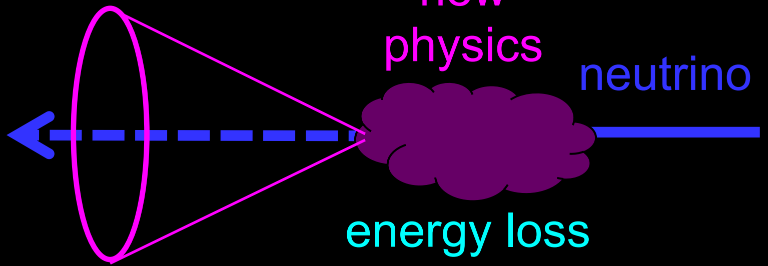
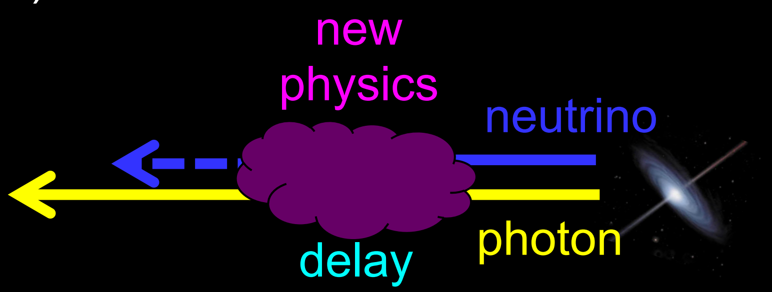
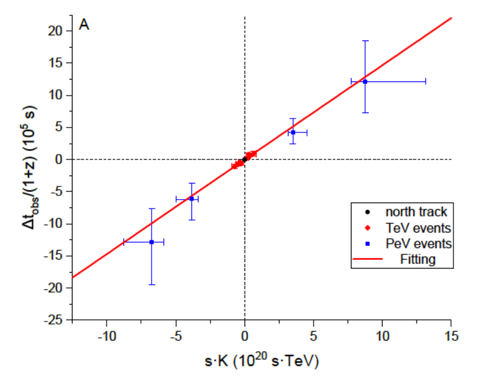


Z-boson



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



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

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

Argüelles, TK, Salvado, PRL115(2015)161303

2. 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
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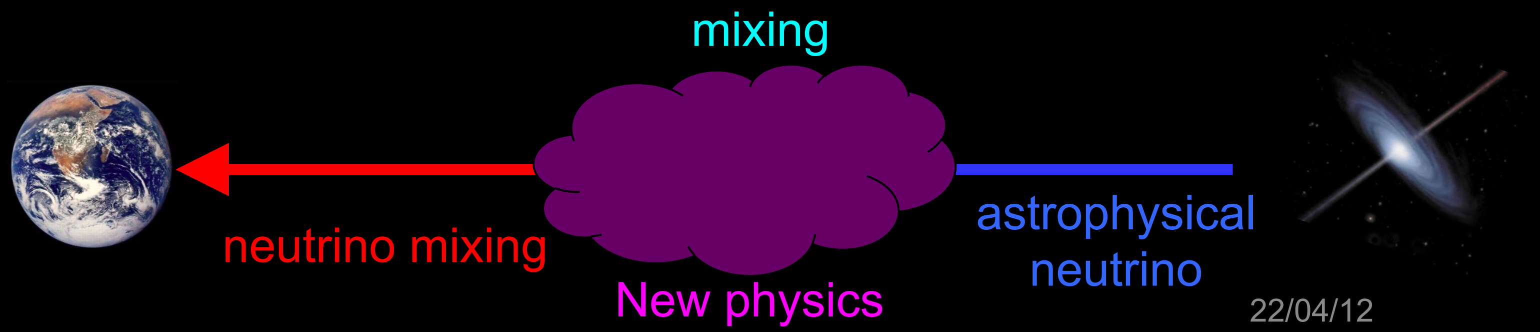
- Time of Flight (modified dispersion)
- New flavour structure (new vacuum effect)

Neutrino interferometry
- Macroscopic quantum effect and sensitive to small effects



Higher order operators in effective field theory (EFT)

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

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

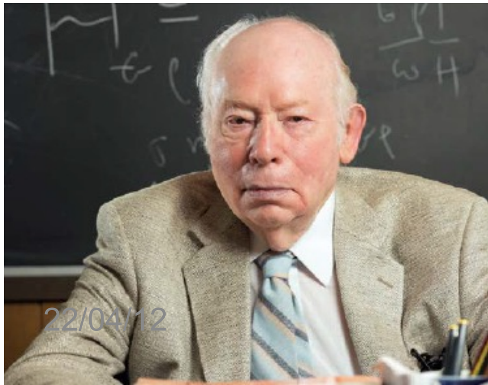
SME motivated effective Hamiltonian for neutrinos

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

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)



Kostelecký and Mewes, PRD85(2012)096005

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)

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

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

Argüelles, TK, Salvado, PRL115(2015)161303

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.

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

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

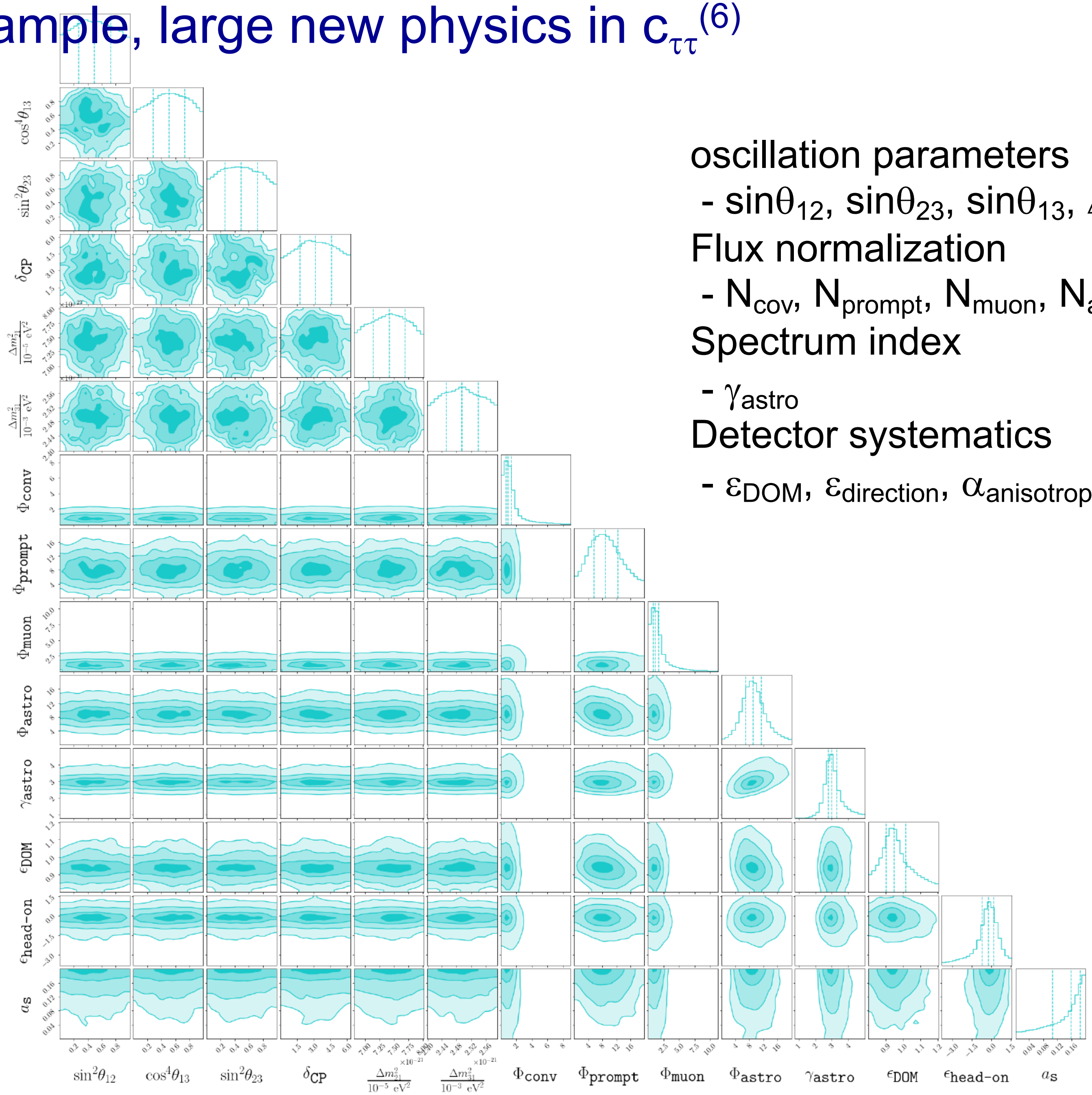
IceCube, ArXiv: 2011.03545, 2011:03560, 2011:03561

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
$2\nu/\left(\nu + \bar{\nu}\right)_{\texttt{atmo}}$	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

IceCube, ArXiv: 2111.04654

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



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_{astro}

Detector systematics

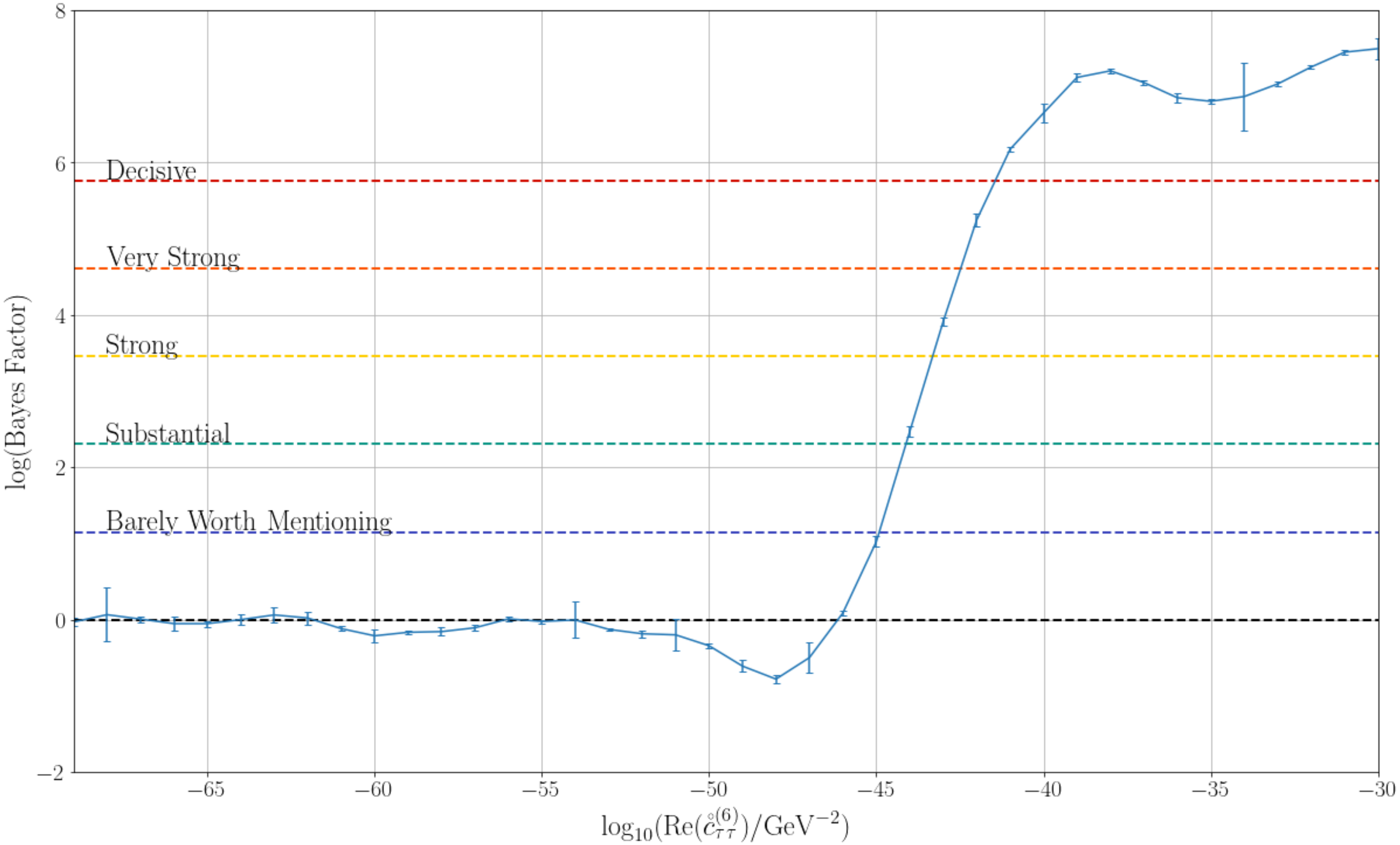
- ε_{DOM}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

IceCube, ArXiv: 2111.04654

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

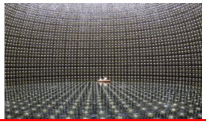
Bayesian analysis

- Bayes factor is computed with new physics parameter
- Repeat this to find the threshold to set the limit



Test of Lorentz violation with neutrinos

Spectral distortion

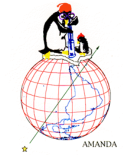


Super-Kamiokande

PRD91(2015)052003

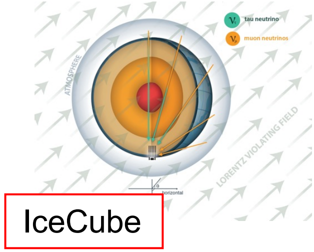
Daya Bay

PRD98(2018)092013



AMANDA

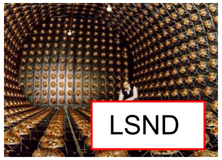
PRD79(2009)102005



IceCube

Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004

MiniBooNE

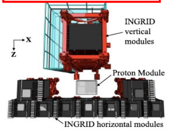
PLB718(2013)1303

MINOS ND

PRL101(2008)151601

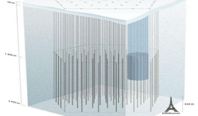
MINOS FD

PRL105(2010)151601



T2K ND

PRD95(2017)111101



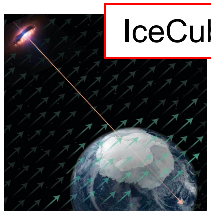
IceCube

PRD82(2010)112003

Double Chooz

PRD86(2013)112009

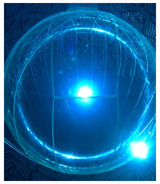
Flavor ratio



IceCube

ArXiv: 2111.04654

Seasonal variation

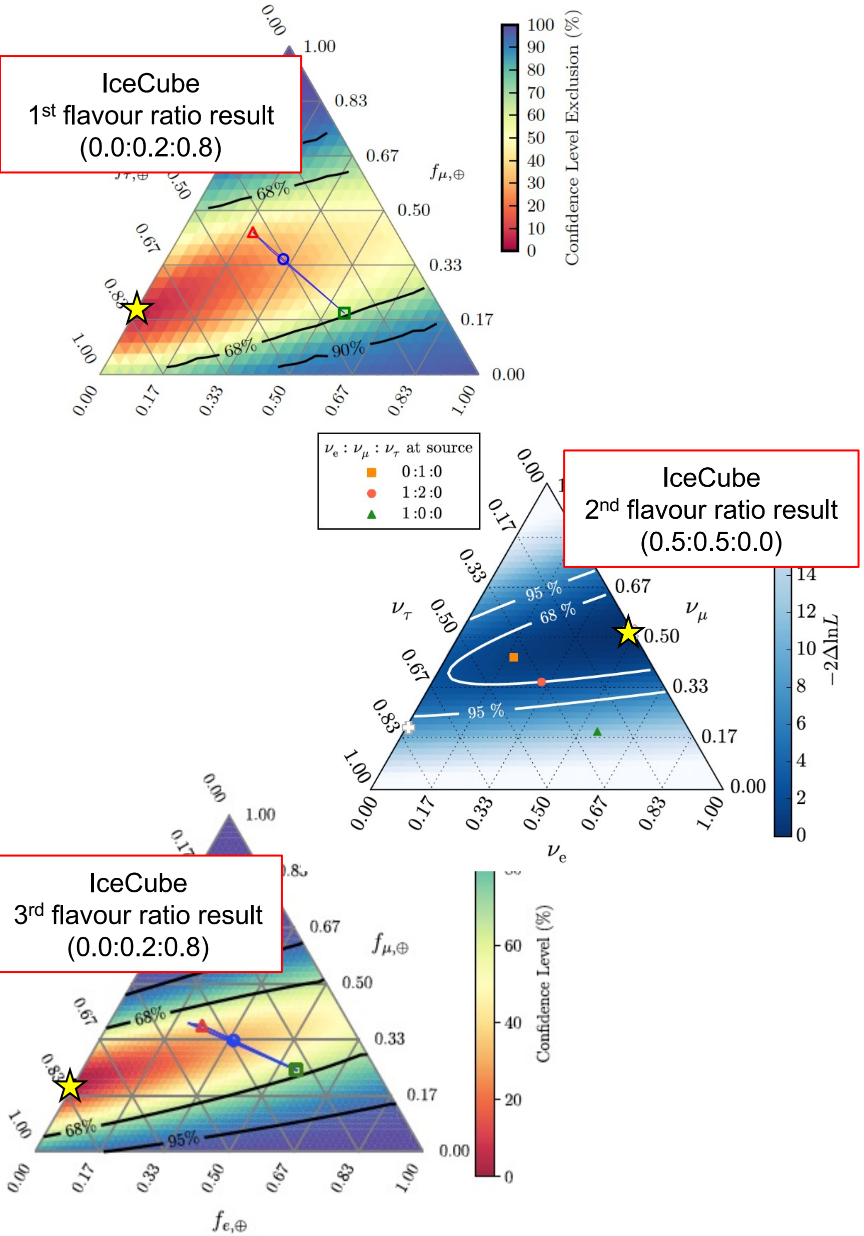


SNO

PRD98(2018)112013

IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, ArXiv:2011:03560

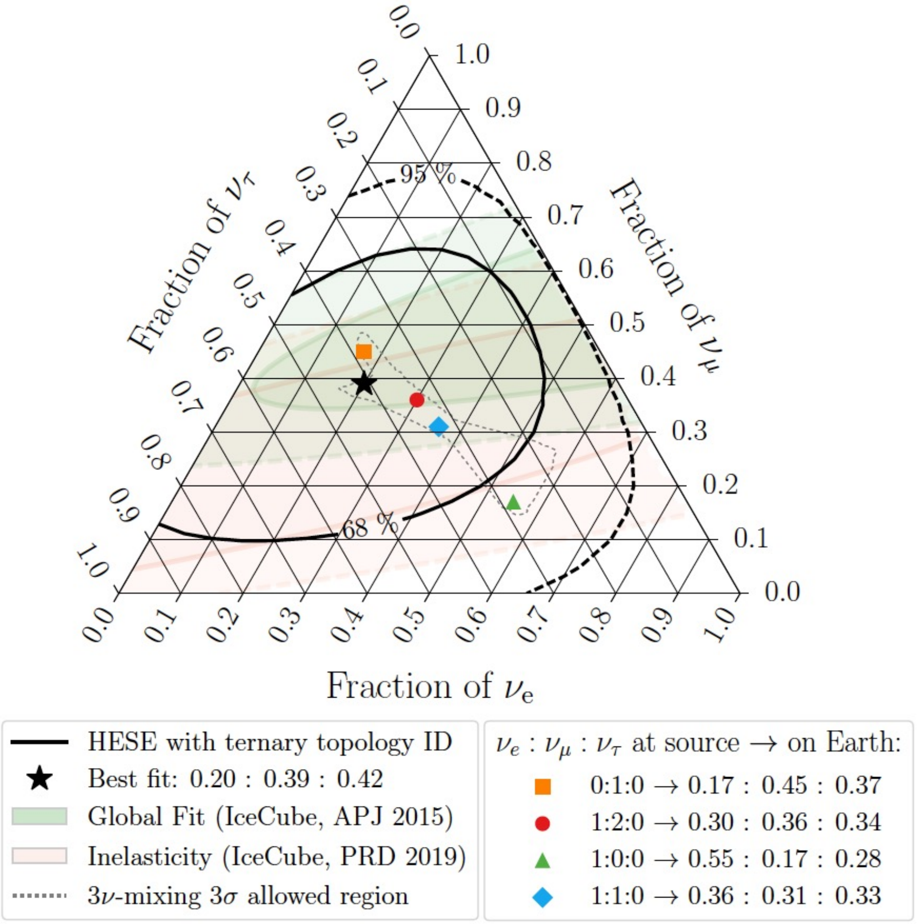
HESE 7.5-yr data (2018)



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

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

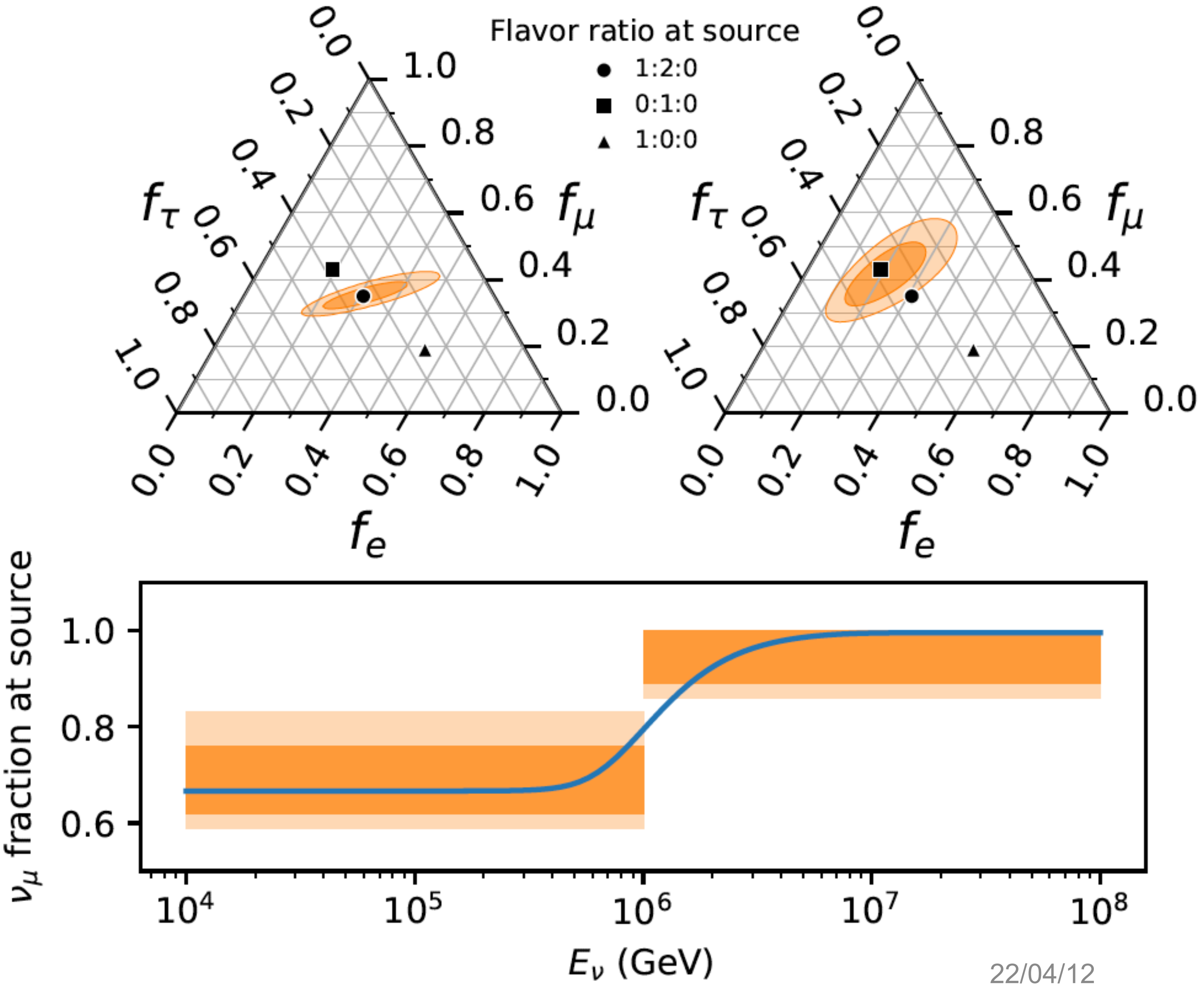
IceCube
3rd flavour ratio result
(0.0:0.2:0.8)



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

Energy dependence of flavor ratio

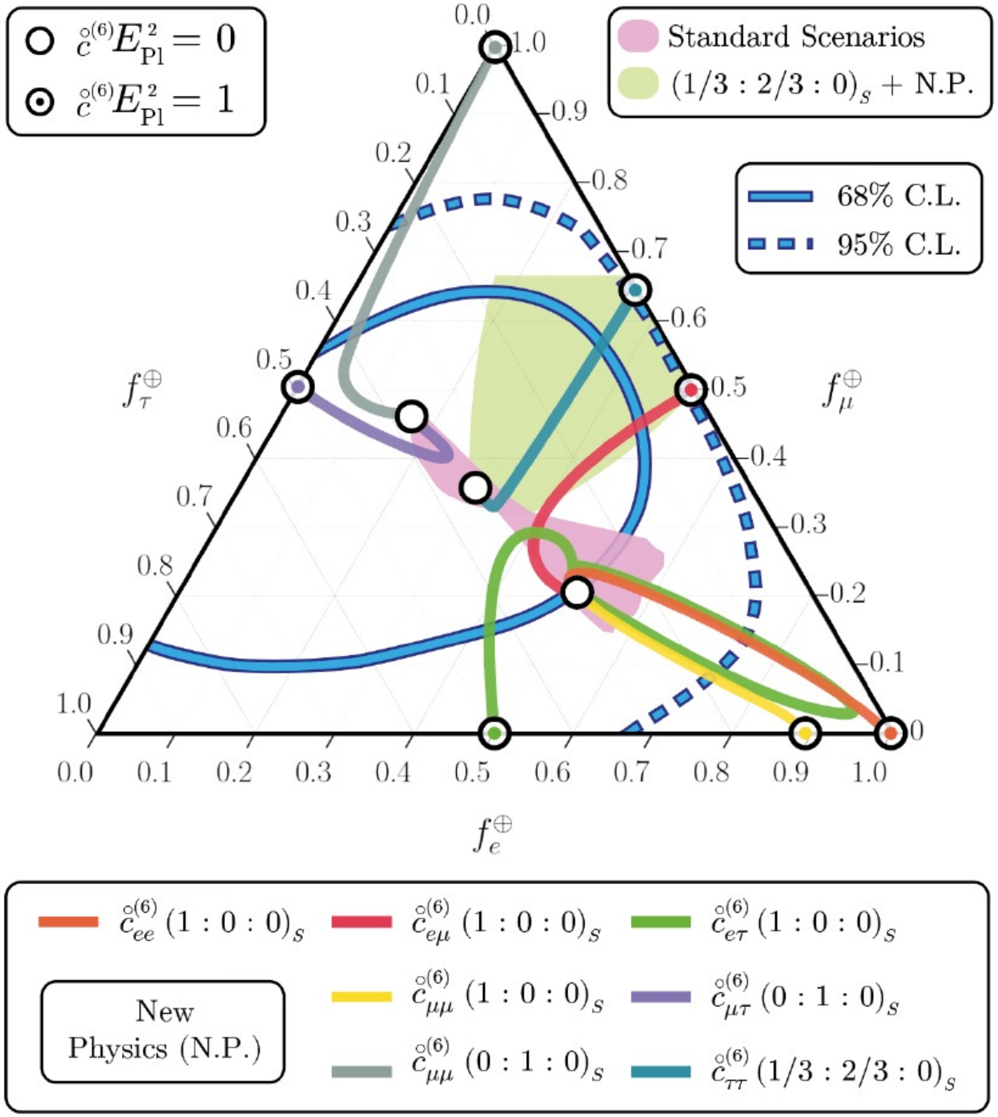


IceCube, ArXiv: 2111.04654

HESE 7.5-yr flavor new physics search

Various standard astrophysical neutrino production models predict different neutrino flavour ratios, however, they all end up in the pink region. ○ indicated characteristic model predictions. Nonzero new physics moves standard predictions ○ to different locations ⊙ depending on the types of new physics operators.

If the new physics models bring the standard predictions outside of the data contour, such model can be rejected by current data

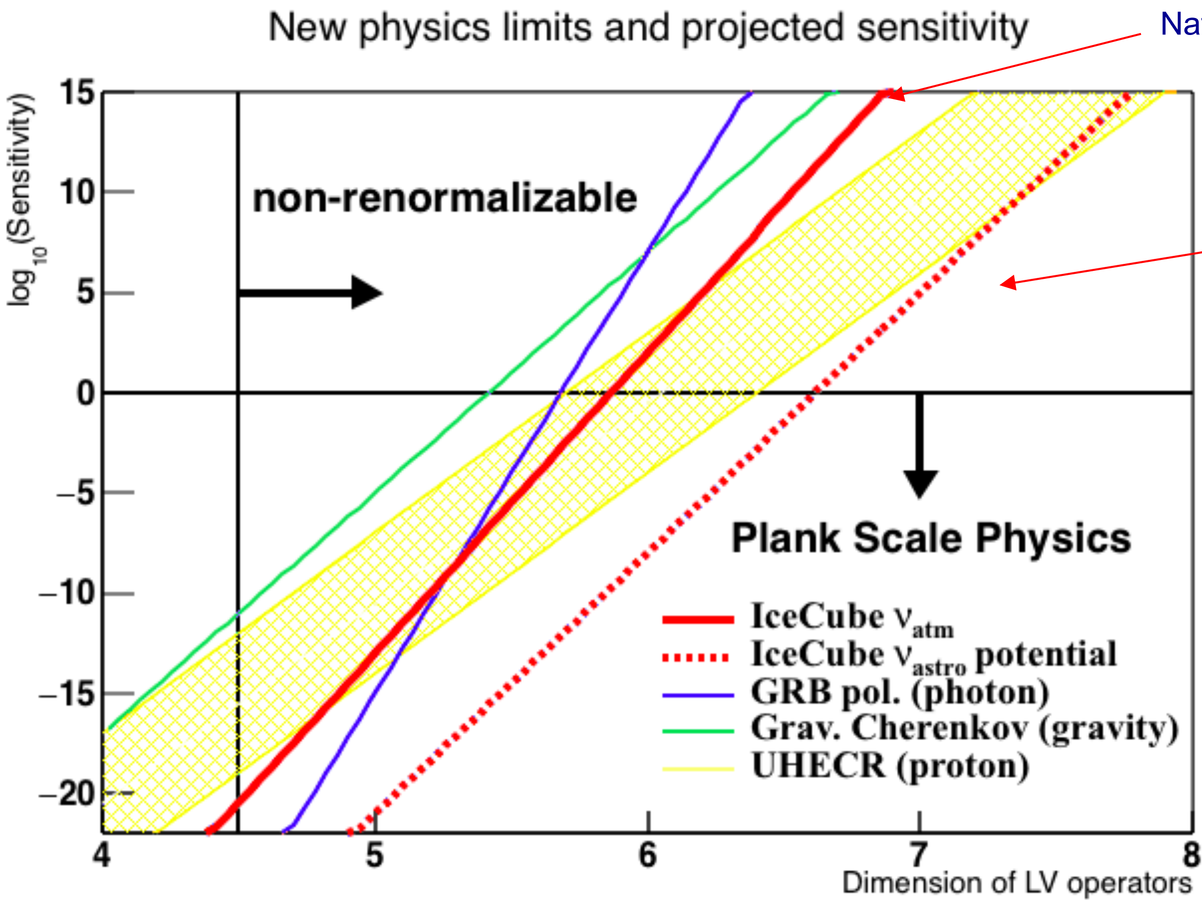


TK, arXiv:1906.09240

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)


New physics limits and projected sensitivity

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})