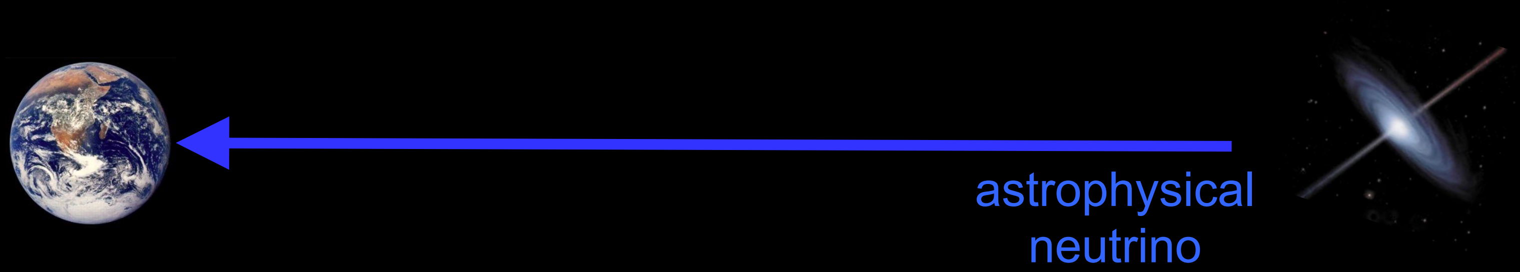
Search of Quantum Gravity with High-Energy Astrophysical Neutrino Flavour
高エネルギー天体ニュートリノフレーバーによる量子重力の探索

To be published (2021)

Teppei Katori (香取哲平), Carlos Argüelles, Kareem Farrag, Shivesh Mandalia
King’s College London, Harvard University, Queen Mary University of London
76th JPS annual meeting (日本物理学会第７６回 年次大会), Mar. 15, 2021

Astrophysical high-energy neutrinos

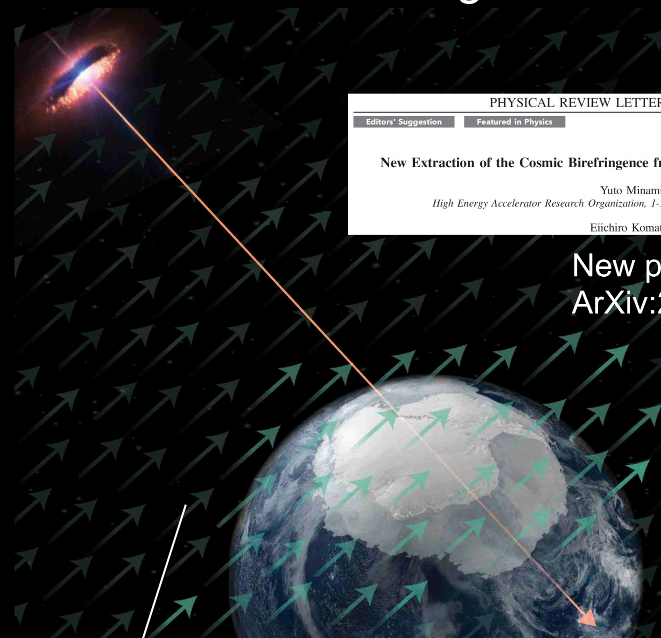
High-energy particles (~1PeV) propagating a long distance (~Gpc)
- Neutrinos can probe new physics in the universe



Astrophysical high-energy neutrinos

High-energy particles (~1PeV) propagating a long distance (~Gpc)
- Neutrinos can probe new physics in the universe

Lorentz violating field


PHYSICAL REVIEW LETTERS 125, 221301 (2020)

Editors' Suggestion | Featured in Physics

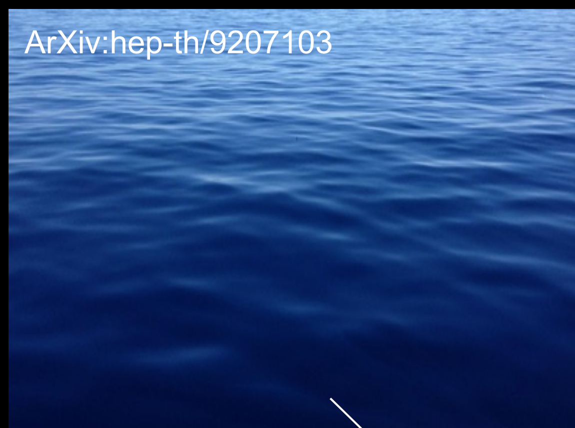
New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

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

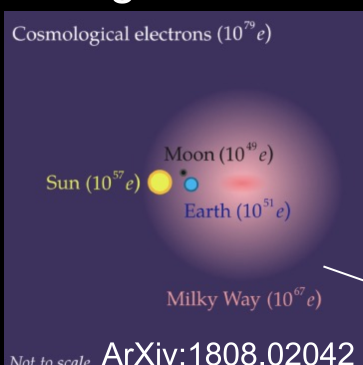
Eiichiro Komatsu

New pseudoscalar field?
ArXiv:2011.11254

Quantum foam



new long-range force



neutrino mixing

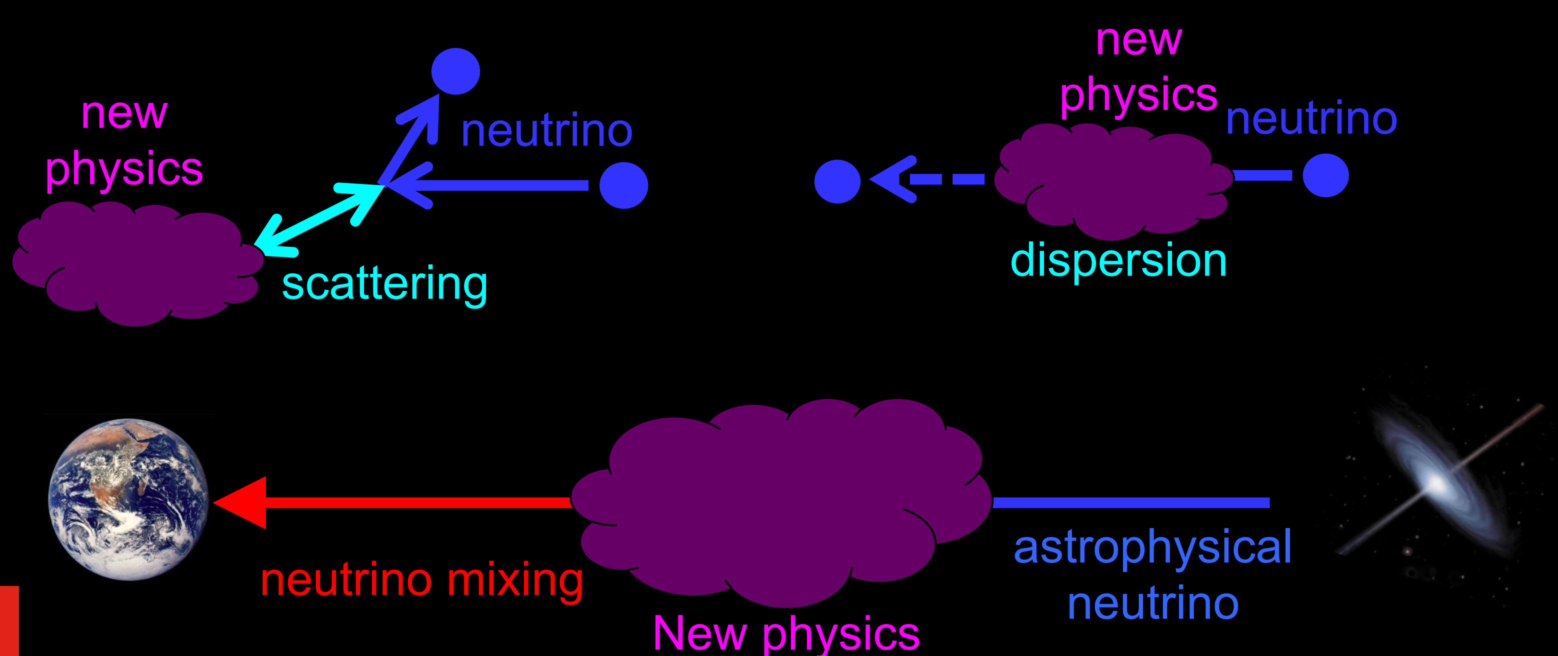
New physics

astrophysical neutrino

Astrophysical high-energy neutrinos

High-energy particles (~1PeV) propagating a long distance (~Gpc)
- Neutrinos can probe new physics in the universe

New physics search
- New scattering (=spectrum distortion)
- New dispersion (=spectrum distortion)
- New mixing → new flavour structure (high sensitivity by quantum effect)



KING'S College LONDON

Astrophysical high-energy neutrinos

High-energy particles (~1PeV) propagating a long distance (~Gpc)
- Neutrinos can probe new physics in the universe

New physics search
- New scattering (=spectrum distortion)
- New dispersion (=spectrum distortion)
- New mixing → new flavour structure (high sensitivity by quantum effect)

The highest sensitivity to the dimension-6 operator

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

this guy

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

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

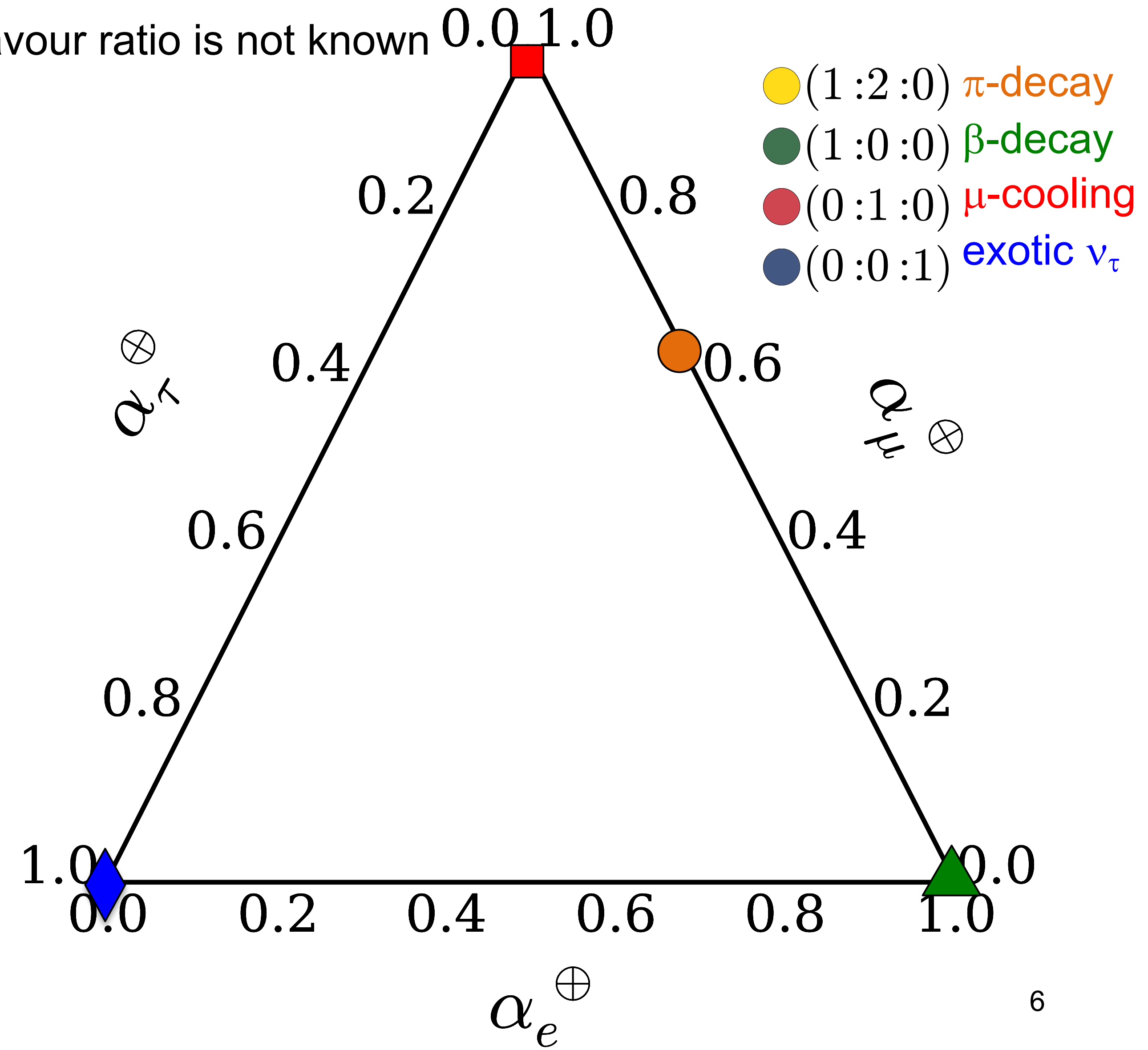
Previous limit (IceCube atmospheric neutrino), $c^{(6)} < 10^{-36} GeV^{-2}$
The sensitivity of this analysis can reach to the expected signal region

KING'S College LONDON

Argüelles, TK, Salvado, PRL115(2015)161303

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

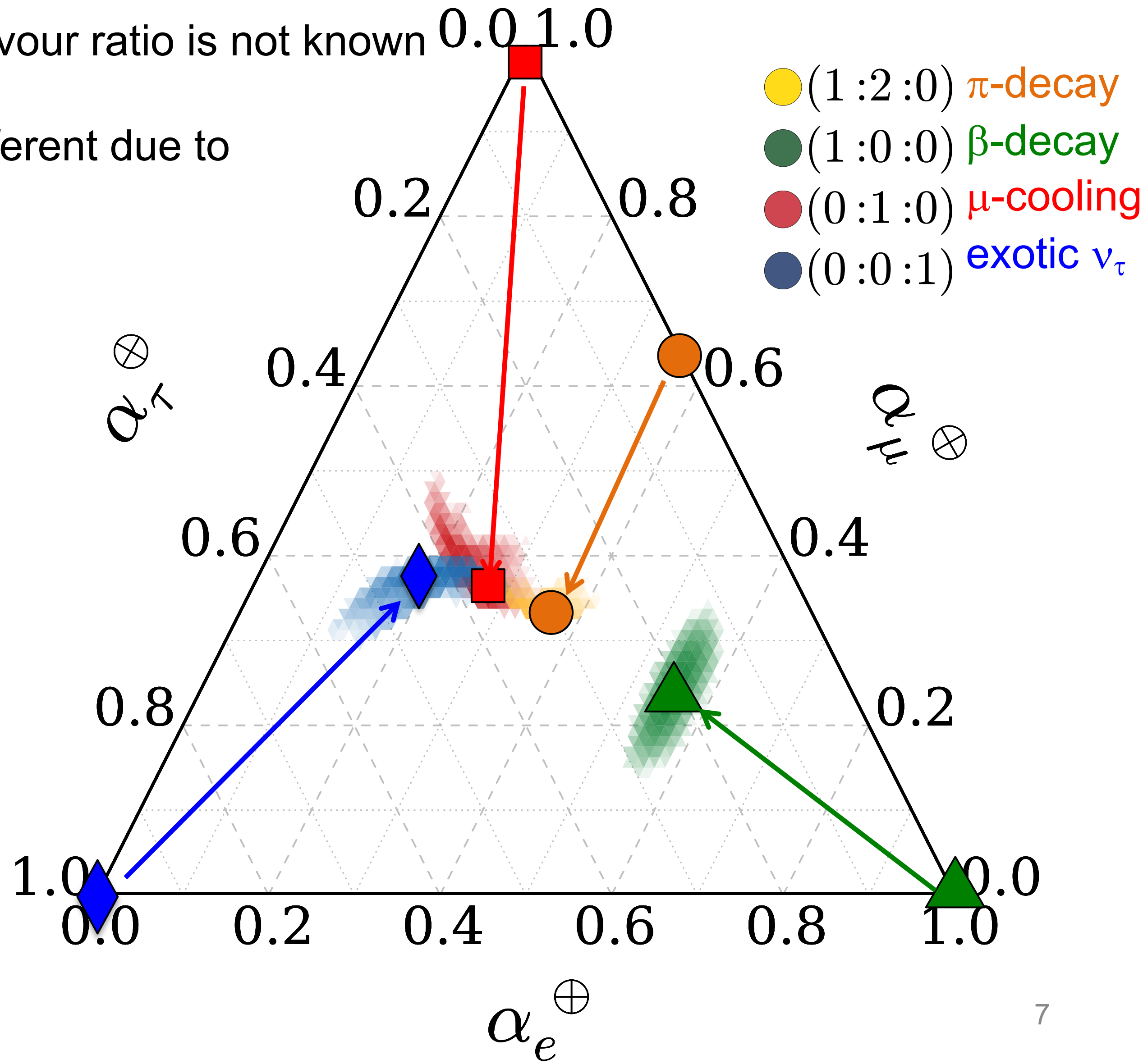
Astrophysical neutrino production mechanism is not known → production flavour ratio is not known



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

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

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

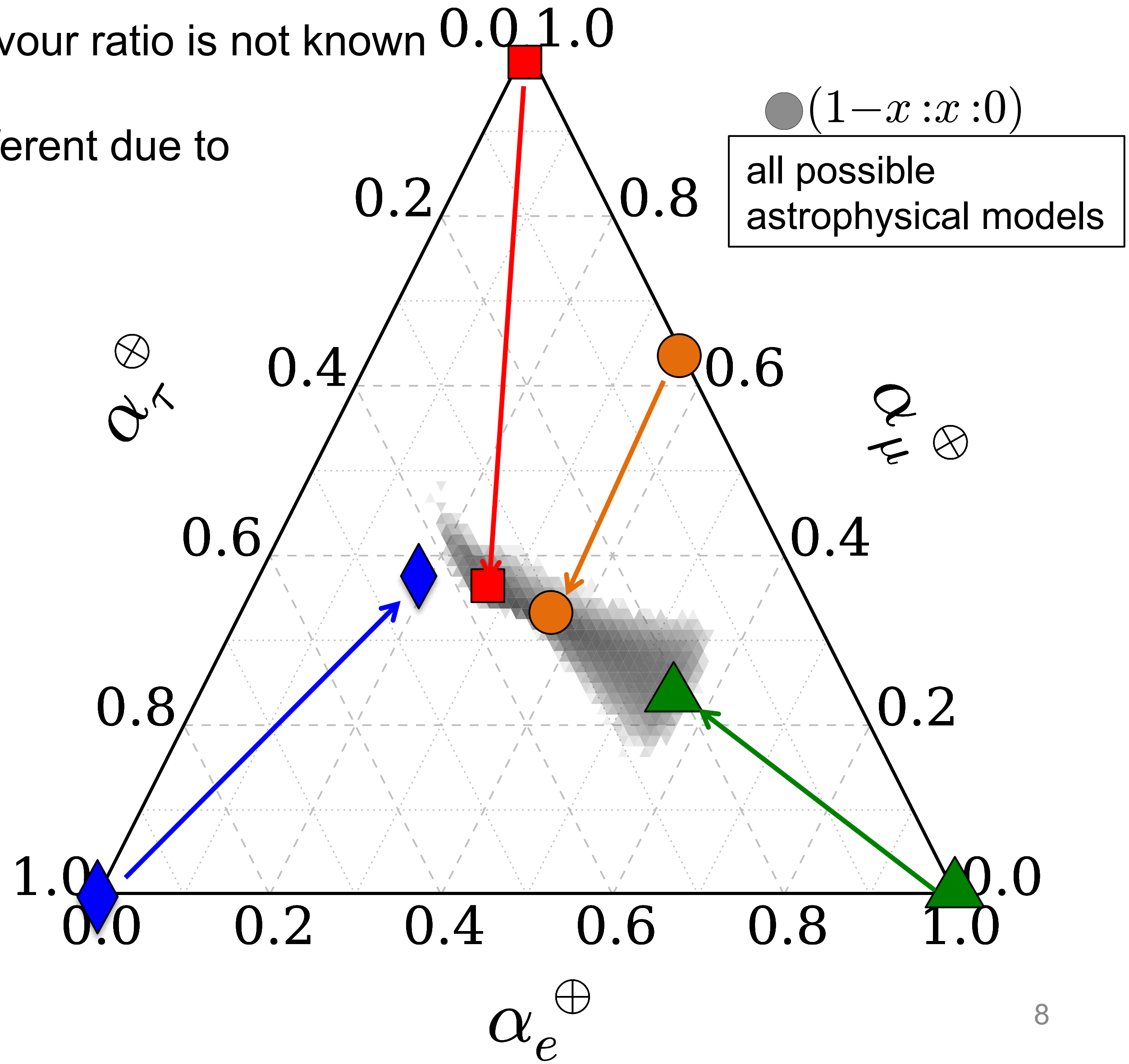


Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

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

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

All possible flavour ratio is confined in a small space



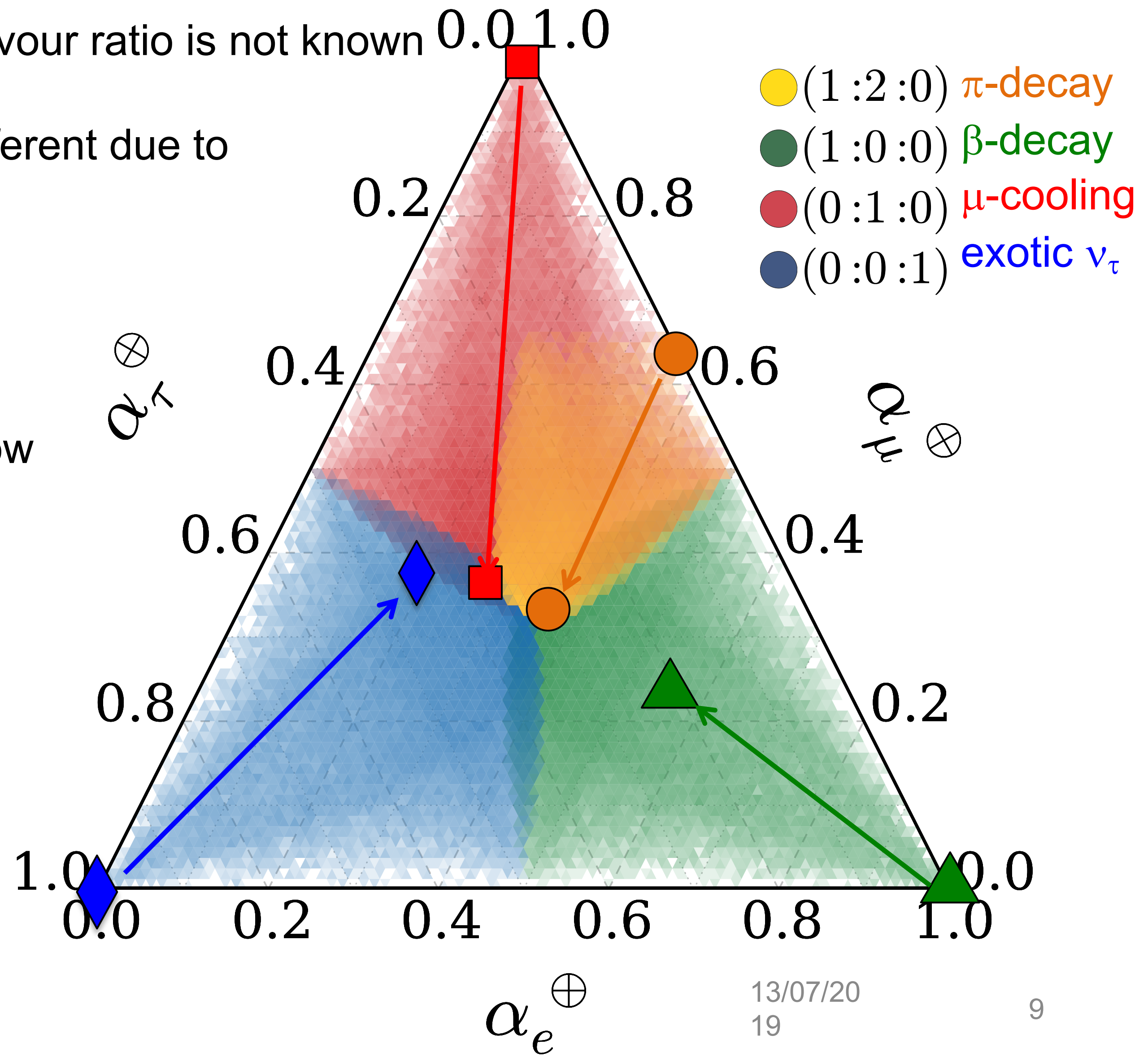
Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

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

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

All possible flavour ratio is confined in a small space

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



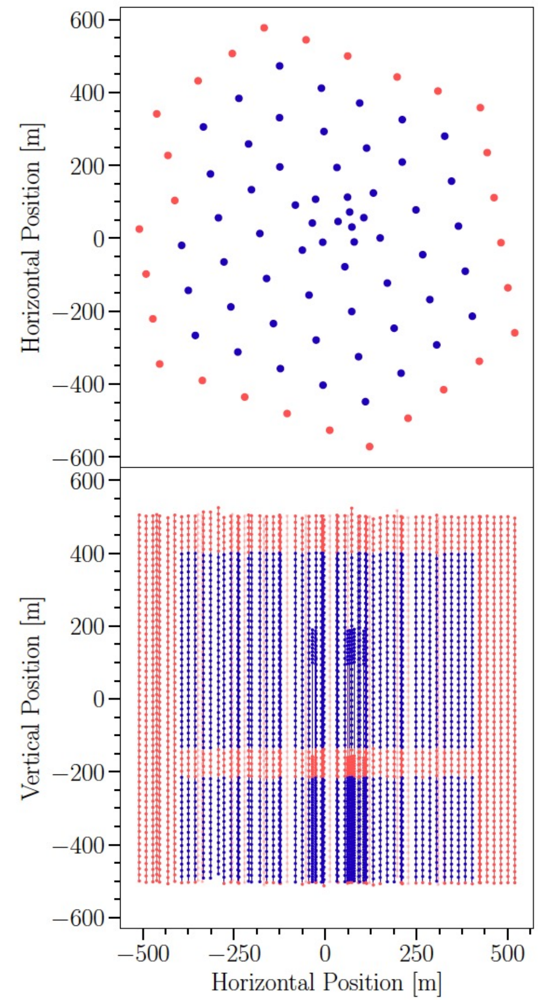
HESE 7.5-yr sample

60 HESE events in 60 TeV – 2 PeV

First identification of tau neutrinos

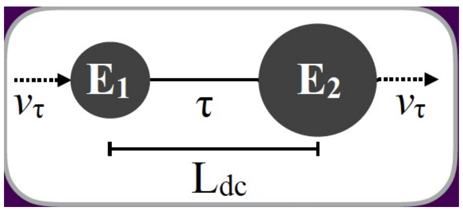
Parameter	Value
Event start time charge threshold	250 PE
Maximum veto charge	3.0 PE
Maximum DOMs with veto hits	2
Minimum total charge	6000 PE
Trigger time window	3 μs

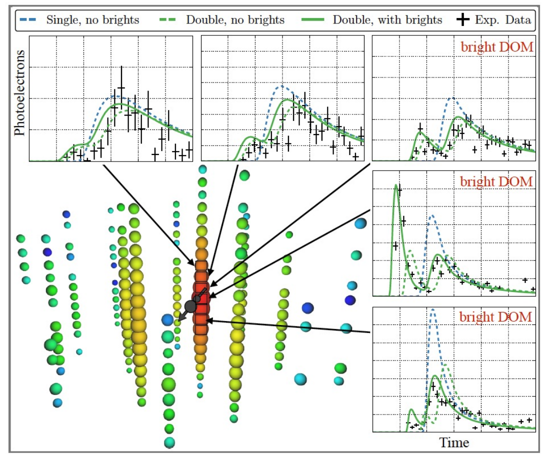
IceCube veto

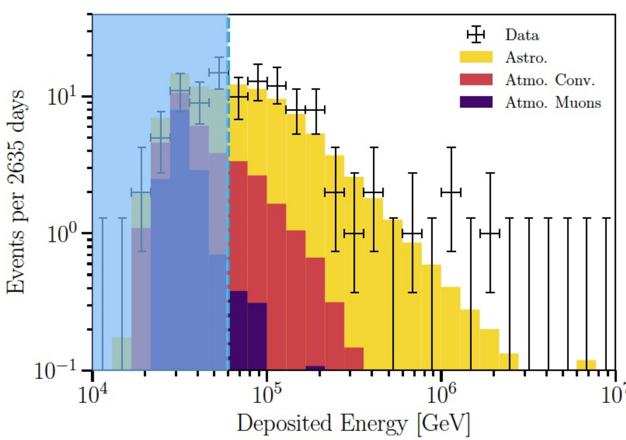


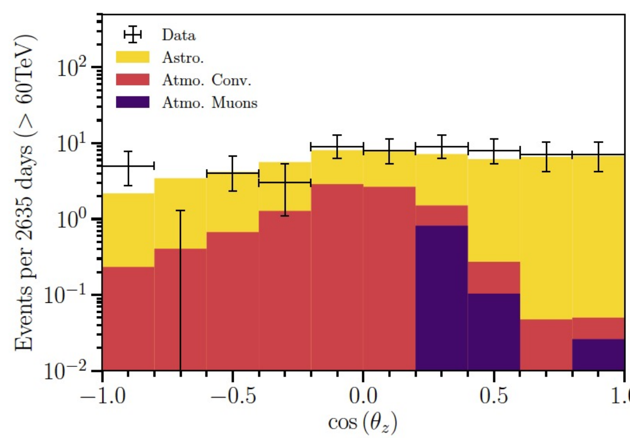
Astrophysical tau neutrino candidate event display

L_{dc}~50m/PeV









HESE 7.5-yr energy and angular distribution

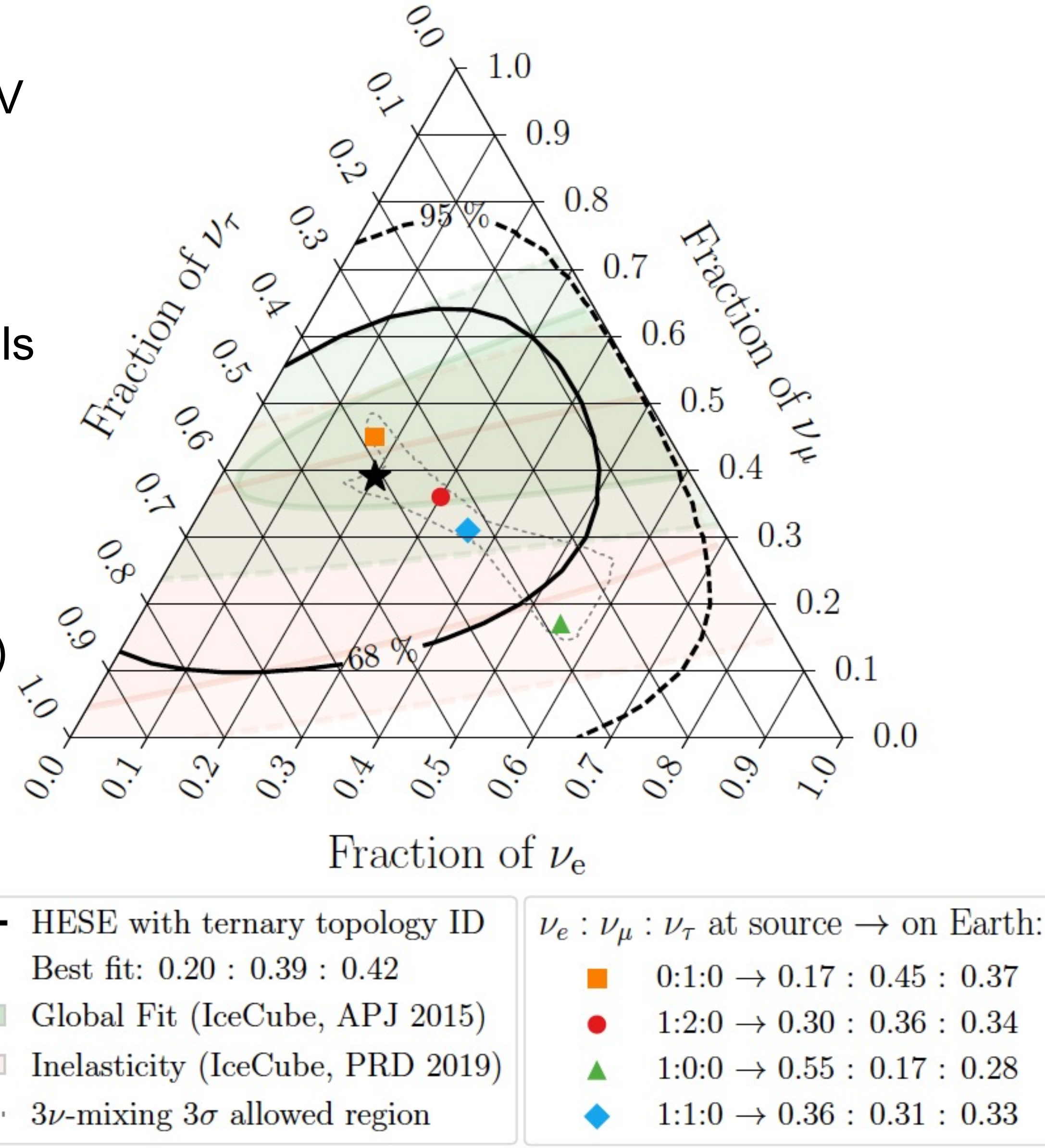
KING'S College LONDON

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)



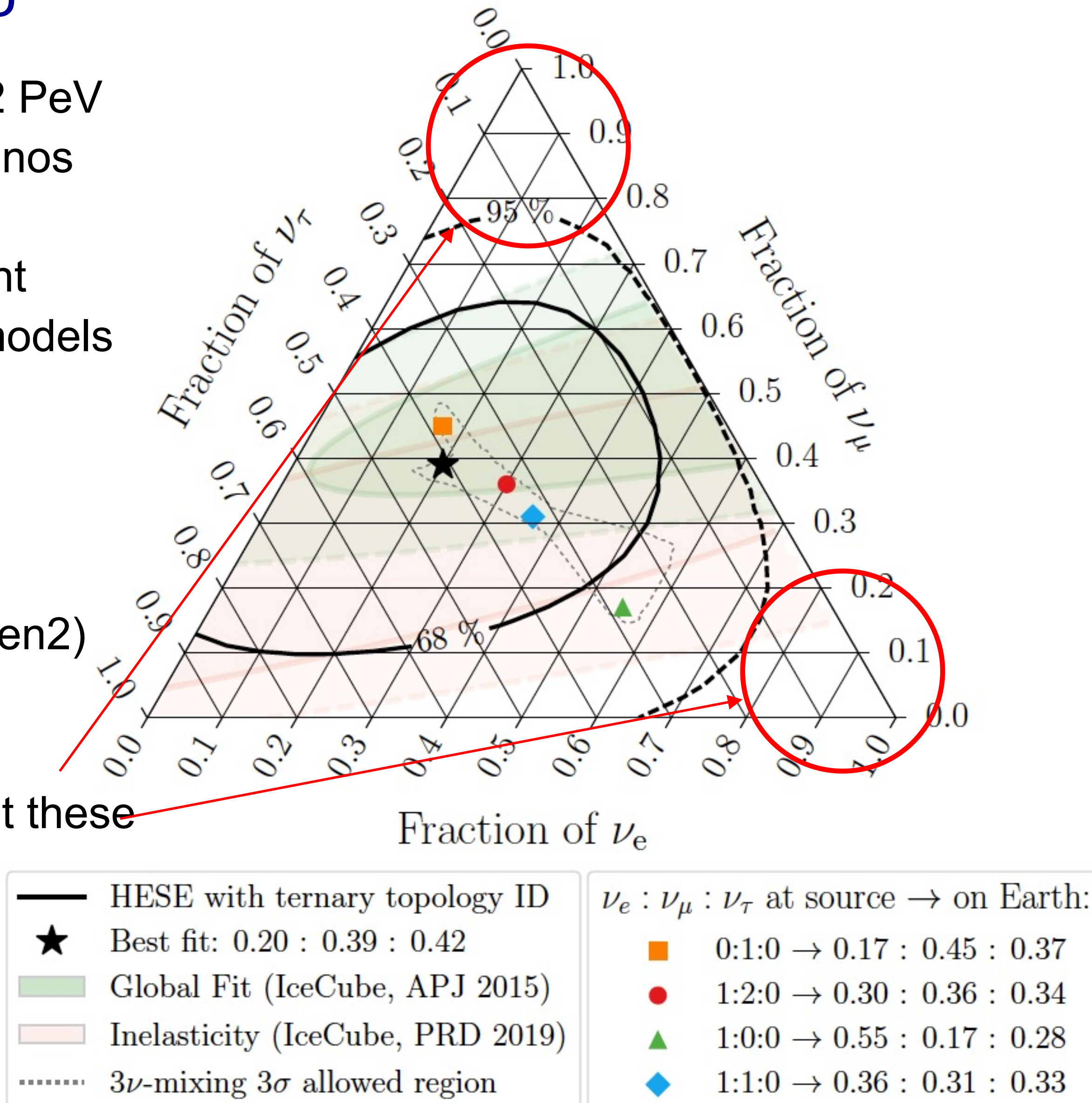
HESE 7.5-yr flavor ratio

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)

Models predict flavour ratios at these corners would be rejected



KING'S College LONDON

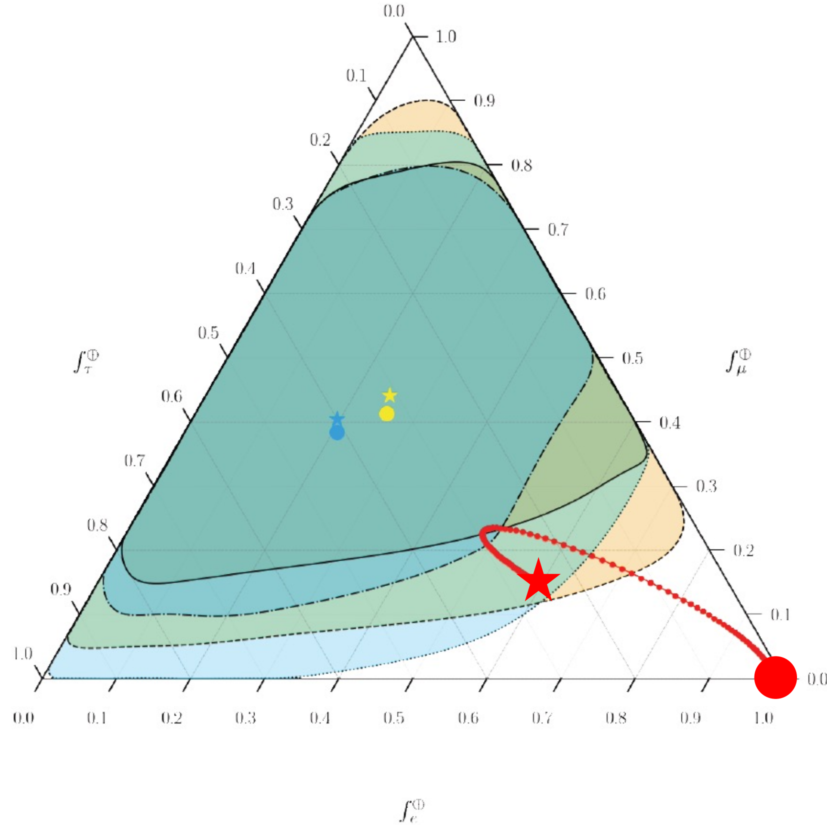
HESE 7.5-yr flavor new physics search

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)

Models predict flavour ratios at these corners would be rejected



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

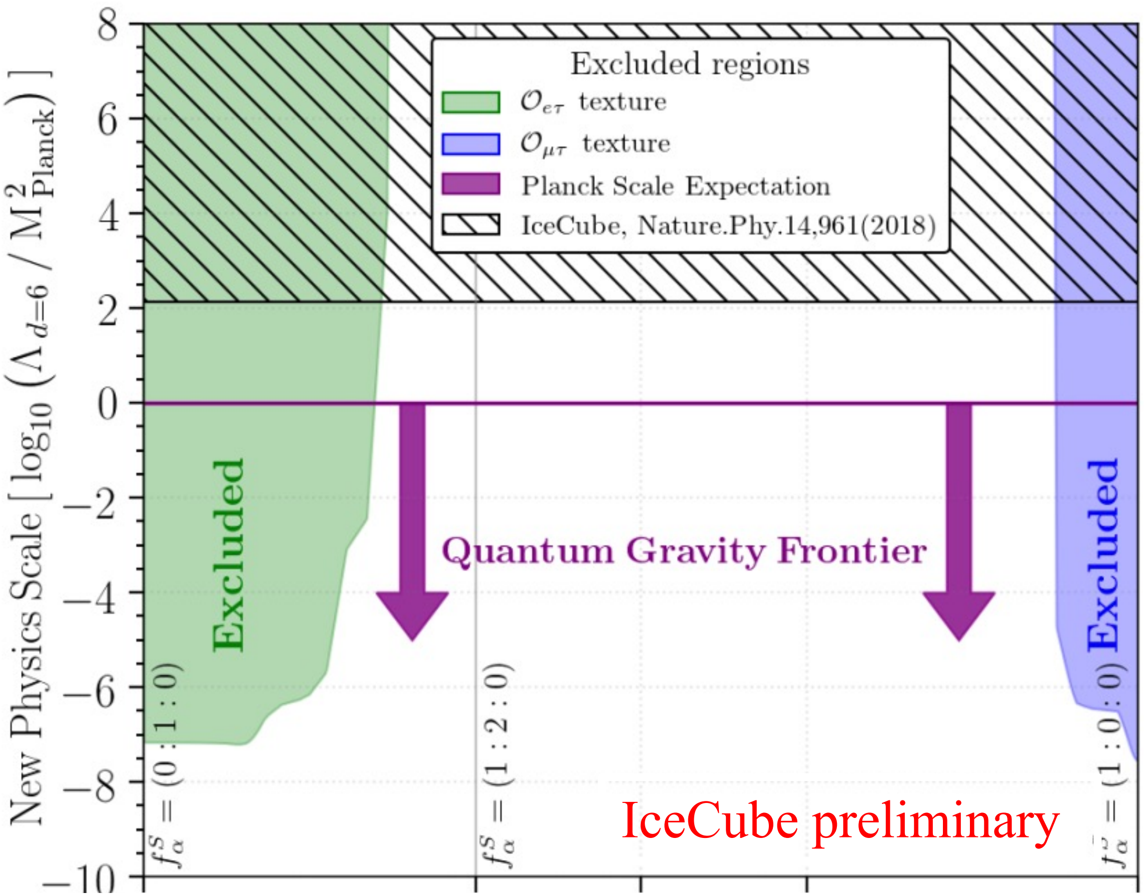
HESE 7.5-yr flavor new physics search

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

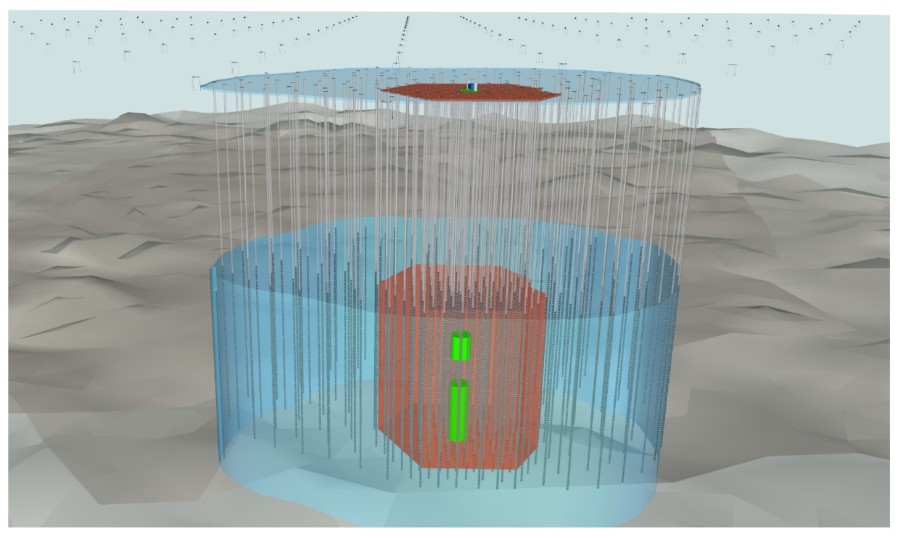
Paper in preparation (2021)



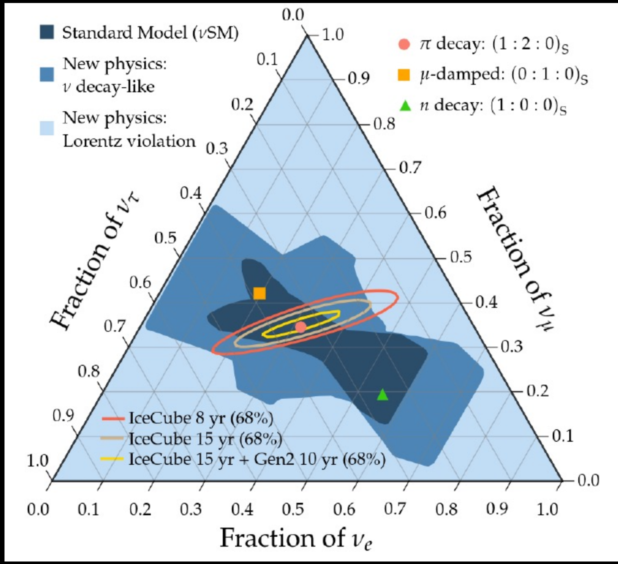
IceCube-Gen2, arXiv:2008.04323
Santarder (Neutrino2020)

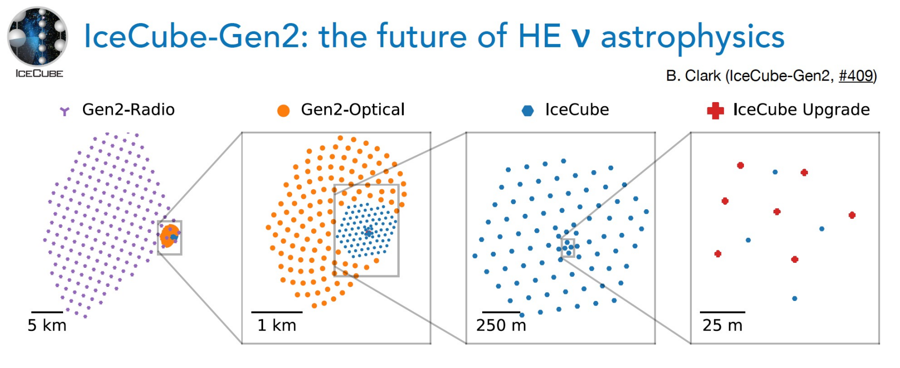
7. IceCube-Gen2

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

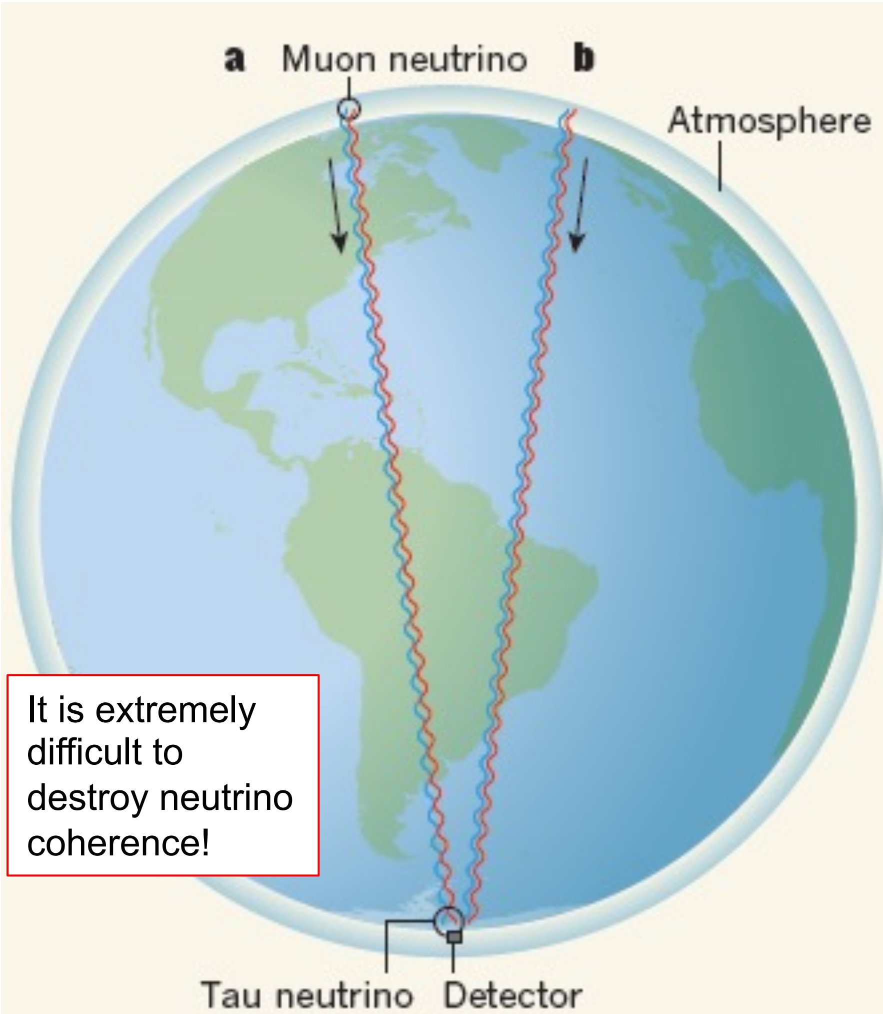
Thank you for your attention!

Backup

KING'S College LONDON

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

Neutrino interferometry – Atmospheric neutrinos



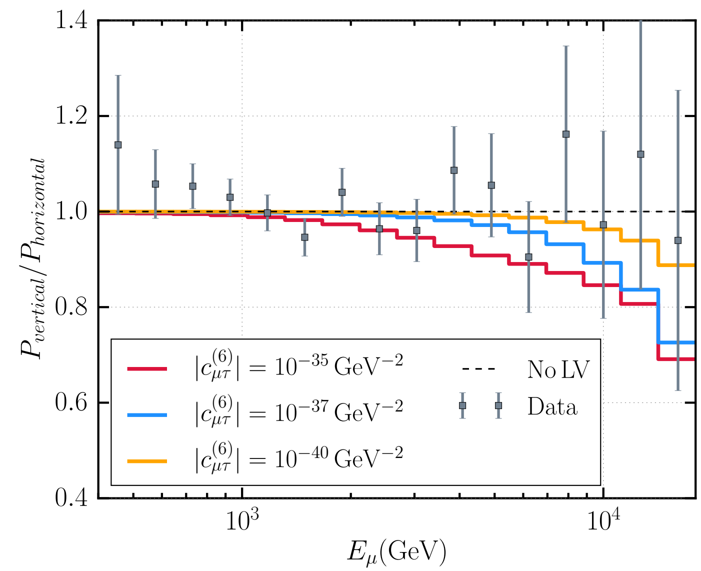
It is extremely difficult to destroy neutrino coherence!

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

For 20 TeV up-going atmospheric neutrinos (L~12700km), detectable phase shift by neutrino is

$$\bar{\psi} a^{\mu} \gamma_{\mu} \psi \ , \qquad a \sim 10^{-24}\ GeV$$

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



Effective Hamiltonian with new physics operators

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

KING'S College LONDON

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

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.

Effective Hamiltonian with new physics operators

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

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)

nonrenormalizable

SME Lagrangian

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

We focus on higher-dimension Lorentz violating operator search

SME motivated effective Hamiltonian for neutrinos

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

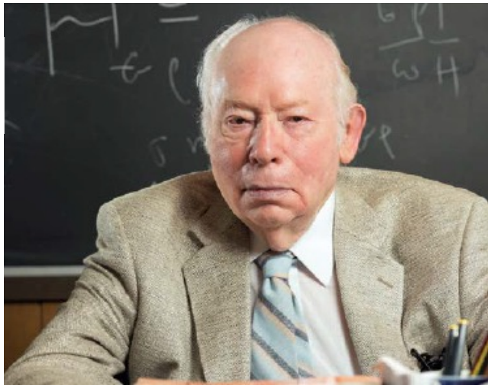
nonrenormalizable

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

"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)

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

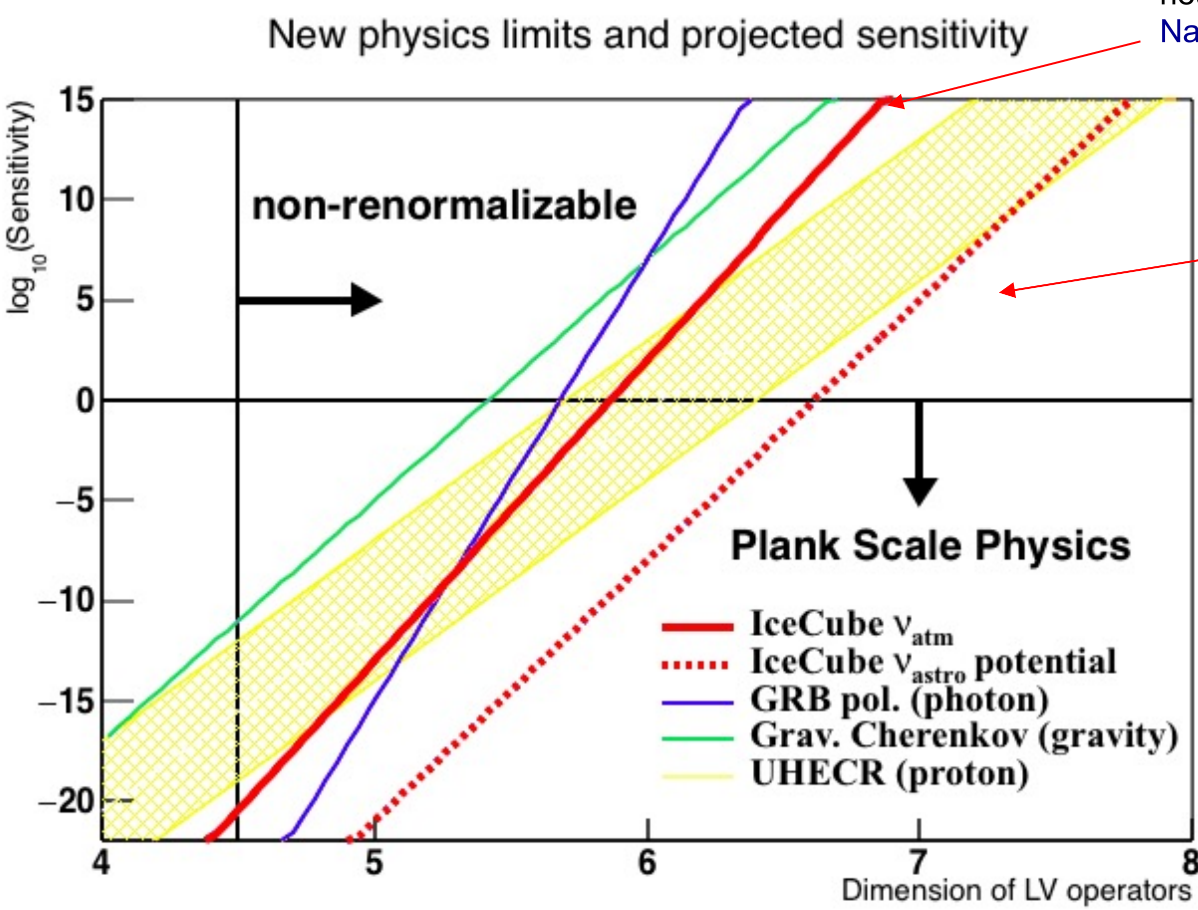


KING'S College LONDON

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)

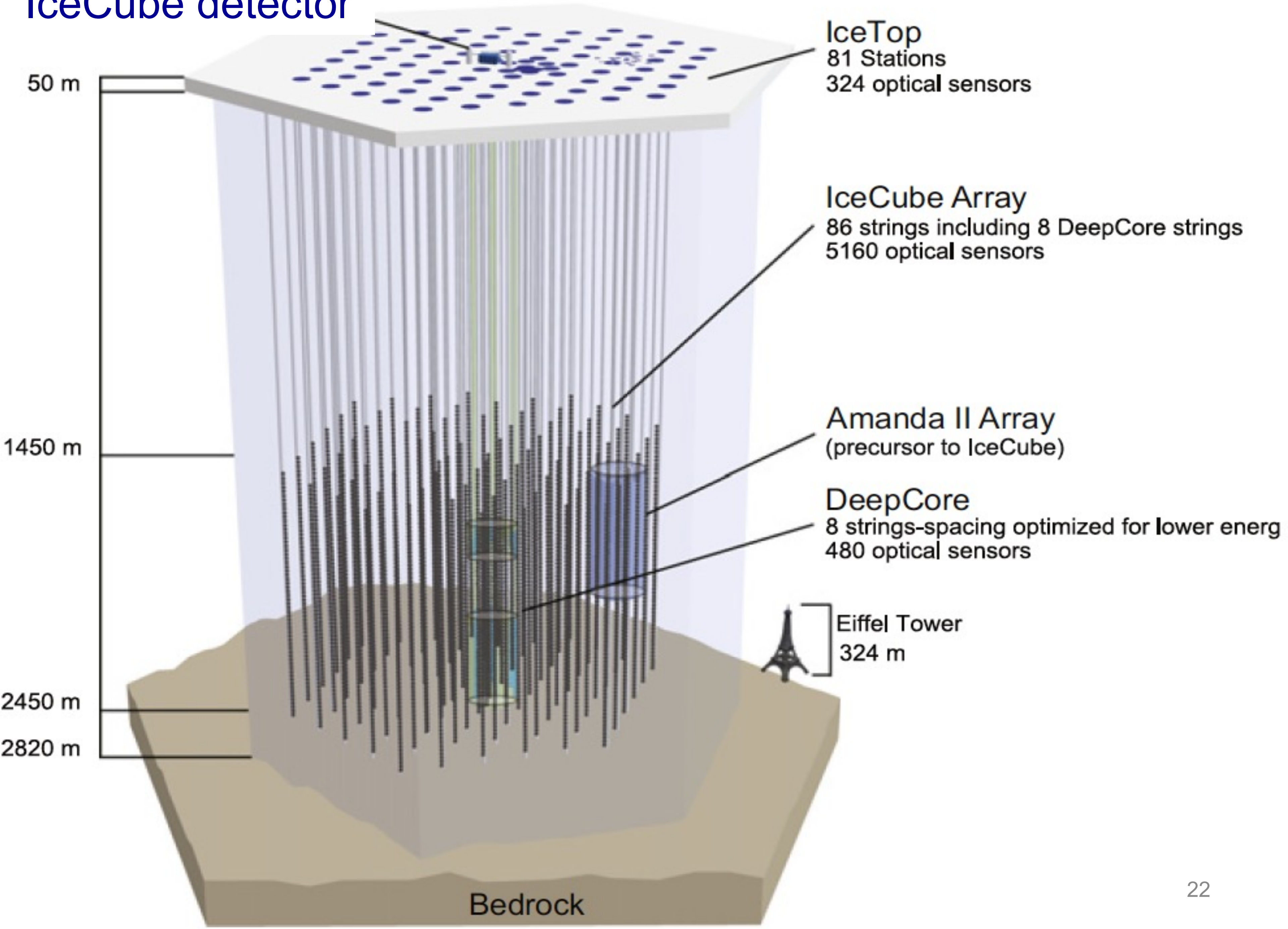
IceCube atmospheric neutrino LV sensitivity
Nature Physics 14(2018)961



IceCube astrophysical neutrino LV sensitivity

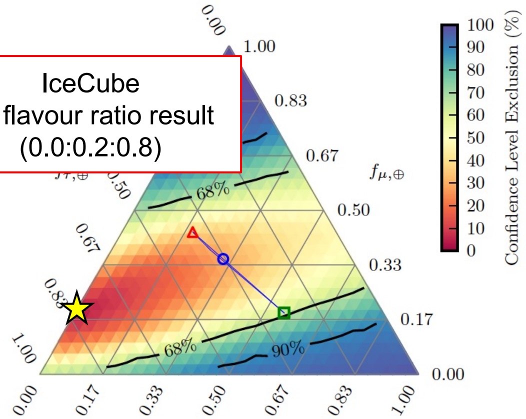
Astrophysical neutrino dim-6 LV operator search can reach quantum gravity motivated region ($\sim 1/M_{Planck}^2 \sim 10^{-38}$ GeV^{-2})

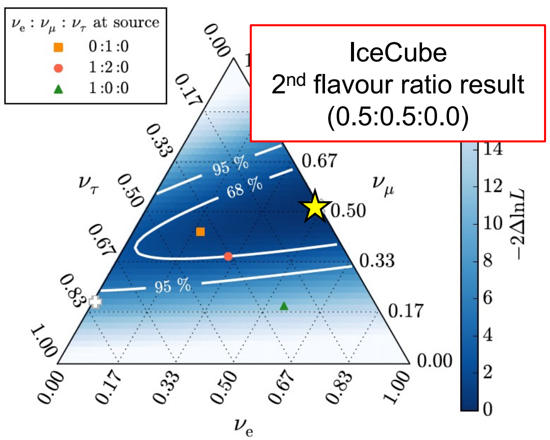
IceCube detector

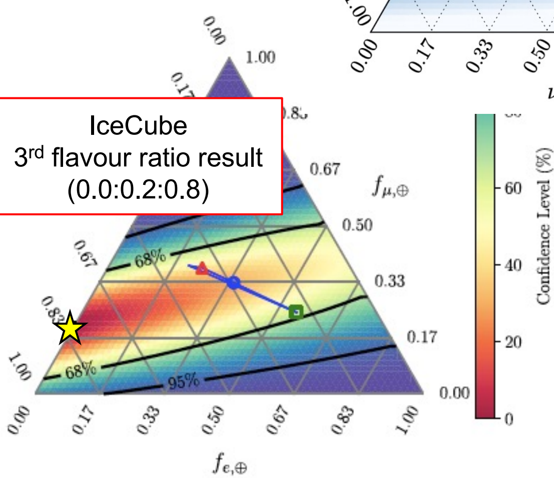


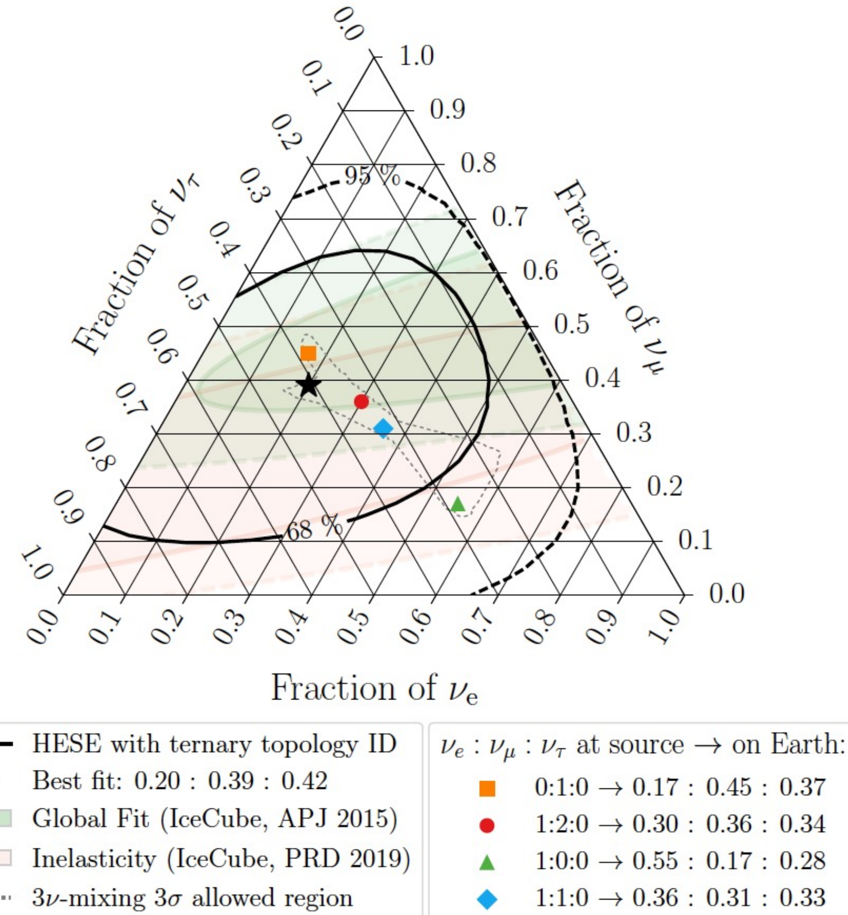
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, ArXiv:2011:03560

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)

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

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

KING'S College LONDON

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 $\phi^p_\alpha(E)\sim\phi^P_\alpha\cdot E^{-\gamma}$. Since it's low statistics, we consider energy-averaged flavor composition β on Earth

$$\bar{\phi}^\oplus_\beta = \frac{1}{\Delta E}\int_{\Delta E}\sum_\alpha P_{\alpha\to\beta}(E,\infty)\,\phi^p_\alpha(E)dE$$

We take the fraction of this for each flavor.

$$f^\oplus_\beta = \frac{\bar{\phi}^\oplus_\beta}{\sum_{e,\mu,\tau}\bar{\phi}^\oplus_\gamma}$$

KING'S College LONDON

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

- Foregrounds, conventional (Honda flux), prompt (BERSS model), muon (CORSIKA) Bhattacharya et al.,JHEP06(2015)110
- 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

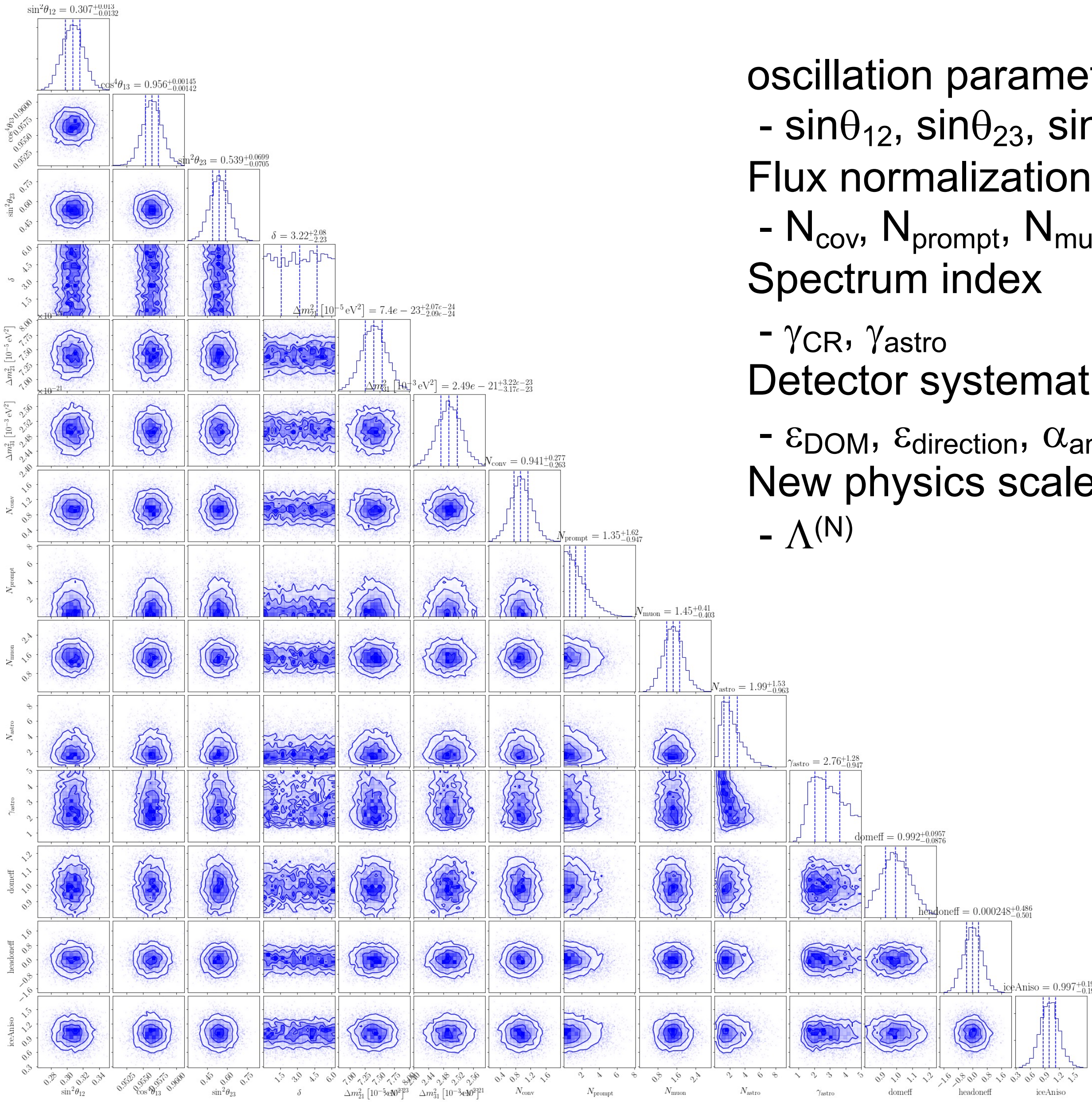
- Bayesian: MCMC with Multinest, Bayes factor with Jefferey' scale "strong" limit
- Frequentist: Wilks' theorem

KING'S College LONDON

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

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}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

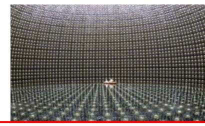
New physics scale

- $\Lambda^{(N)}$

KING'S College LONDON

Test of Lorentz violation with neutrinos

Spectral distortion

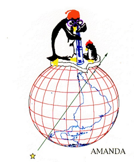


Super-Kamiokande

PRD91(2015)052003

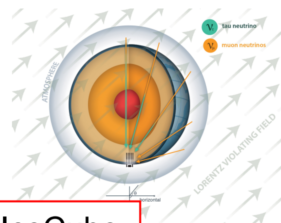
Daya Bay

PRD98(2018)092013



AMANDA

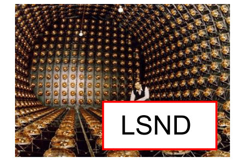
PRD79(2009)102005



IceCube

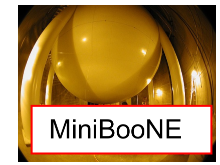
Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004



MiniBooNE

PLB718(2013)1303

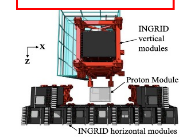
MINOS ND

PRL101(2008)151601

MINOS FD

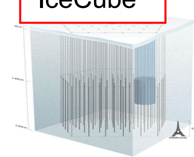
PRL105(2010)151601

T2K ND



PRD95(2017)111101

IceCube

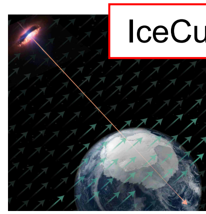


PRD82(2010)112003

Double Chooz

PRD86(2013)112009

Flavor ratio

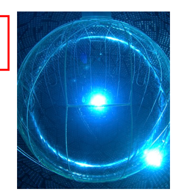


IceCube

To be published

Seasonal variation

SNO



PRD98(2018)112013

KING'S College LONDON

HESE 7.5-yr data (2018)

New data release of high-energy starting event (HESE) data set.
- 60 events in 60 TeV to 2 PeV (big bird)
  - 41 track, 17 cascade, and 2 double cascades

Kareem Farrag
(Queen Mary→JSPS)

Shivesh Mandalia
(Queen Mary, UK)

Hrvoje Dujmovic
(Sungkyunkwan, S.Korea)

Nancy Wandkowsky
(UW-Madison)

Austin Schneider
(UW-Madison→MIT)

Juliana Stachurska
(DESY, Germany)

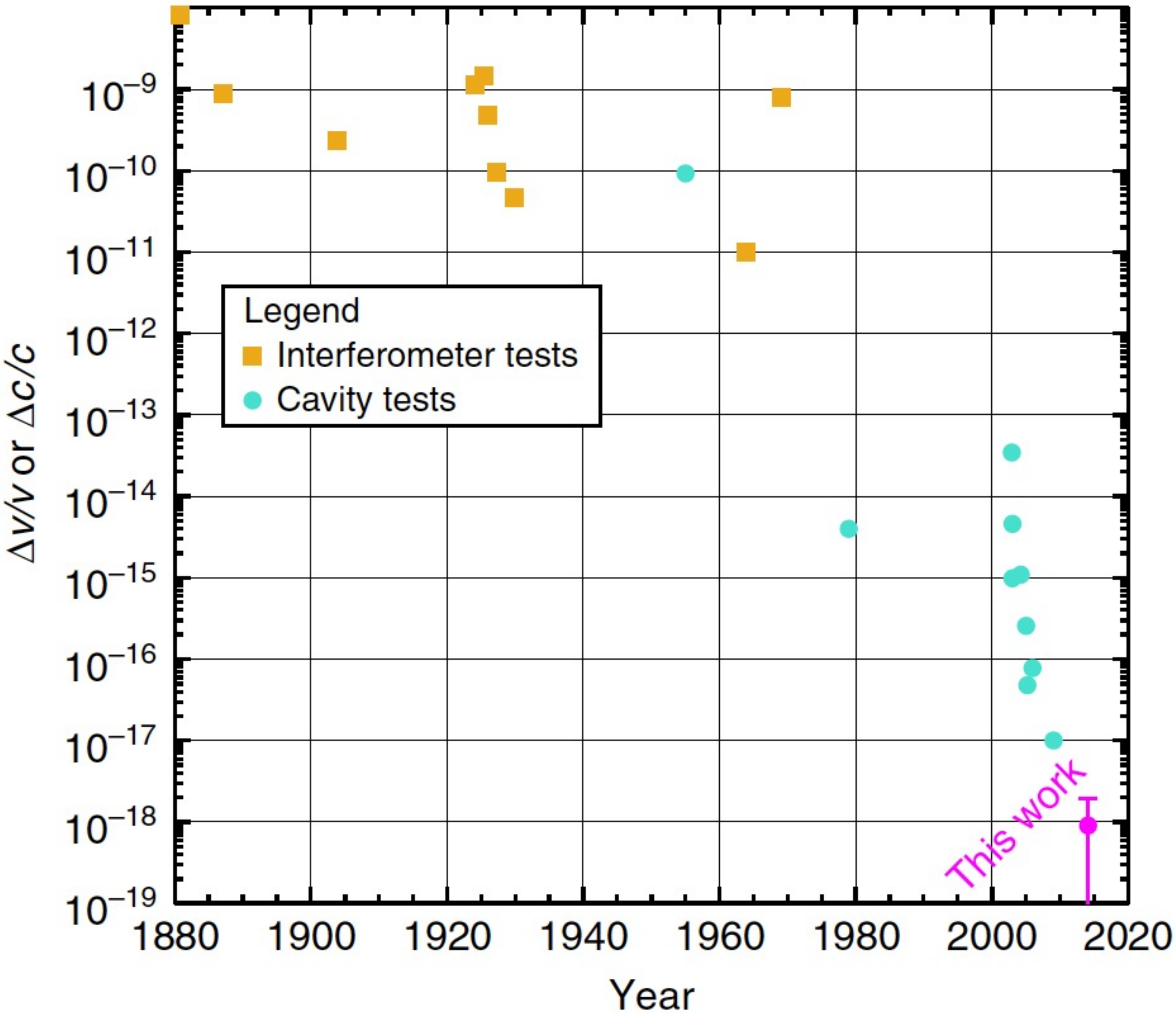
Carlos Argüelles
(MIT→Harvard)

Tianlu Yuan
(UW-Madison)

KING'S College LONDON

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

History of Michelson-Morley experiment



IceCube-Gen2, arXiv:2008.04323

Energy dependence of flavor ratio