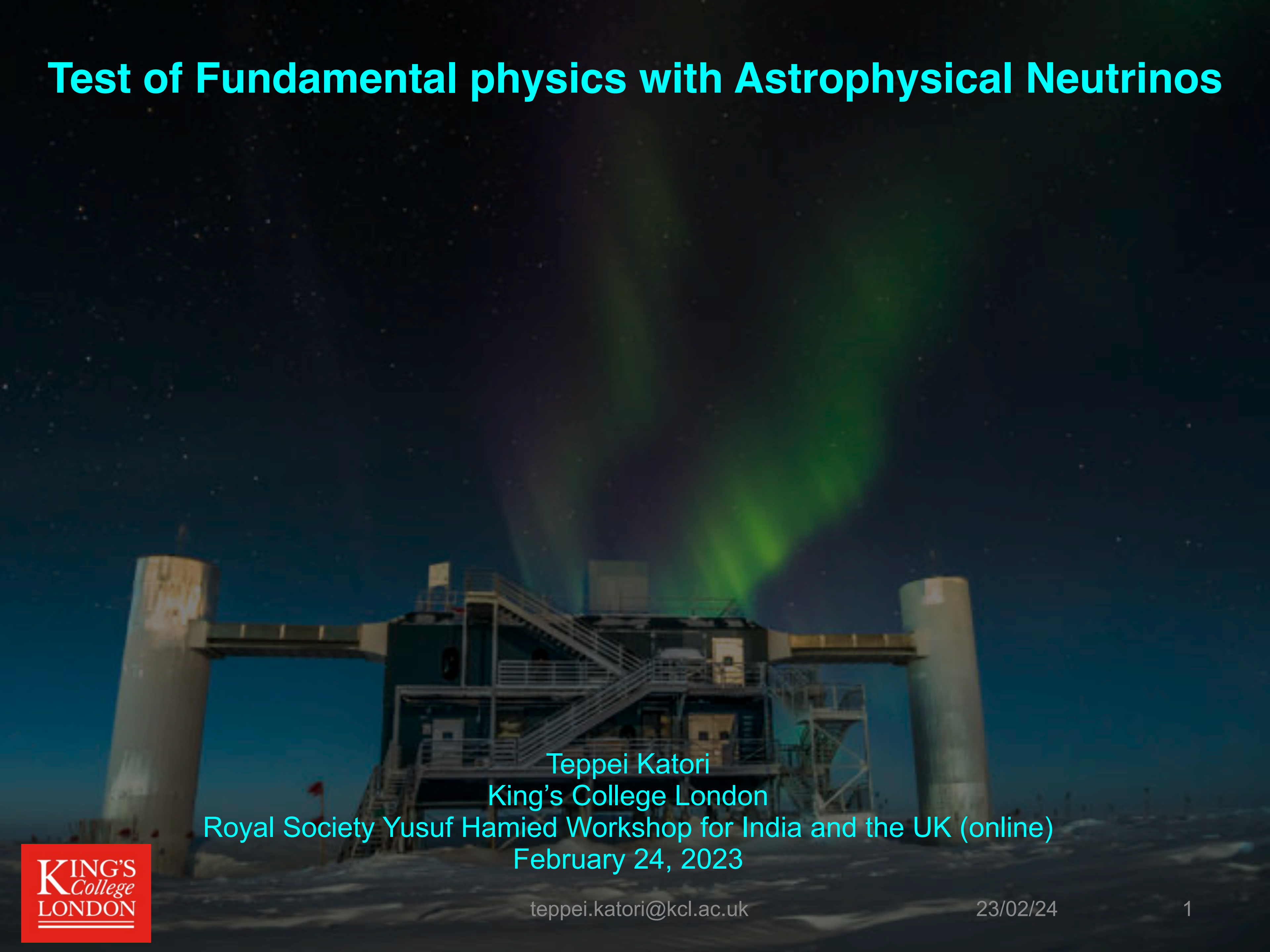

Test of Fundamental physics with Astrophysical Neutrinos

Teppei Katori
King's College London
Royal Society Yusuf Hamied Workshop for India and the UK (online)
February 24, 2023

1. Test of Fundamental Physics

2. Astrophysical High-Energy Neutrinos

3. Search of Lorentz violation in IceCube

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

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

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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

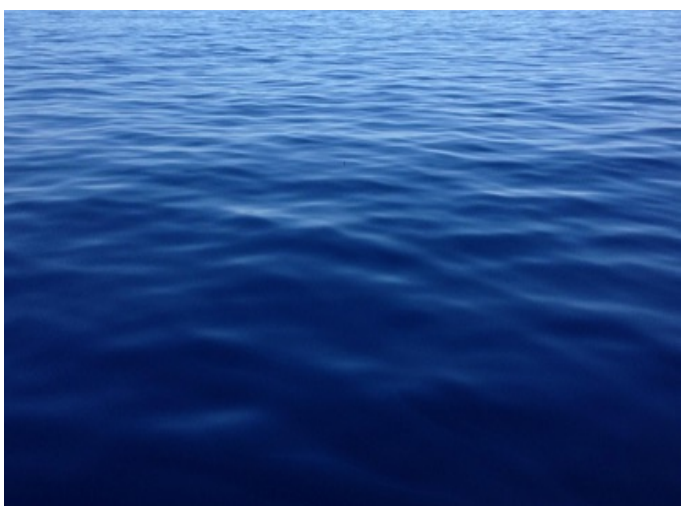
etc.

Standard Model | New physics

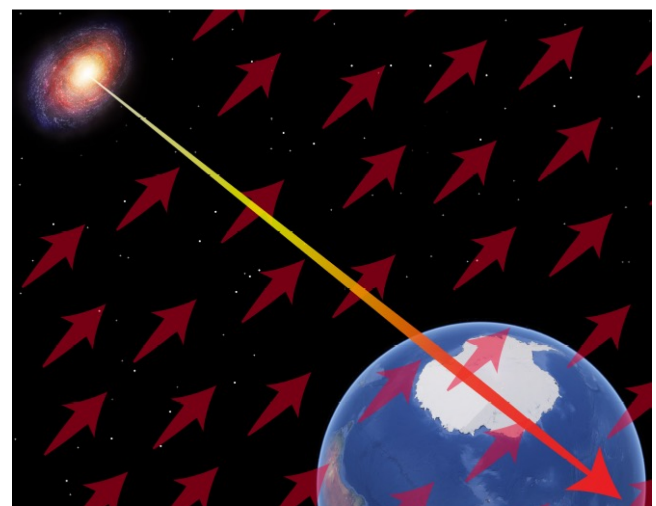
$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots$$

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

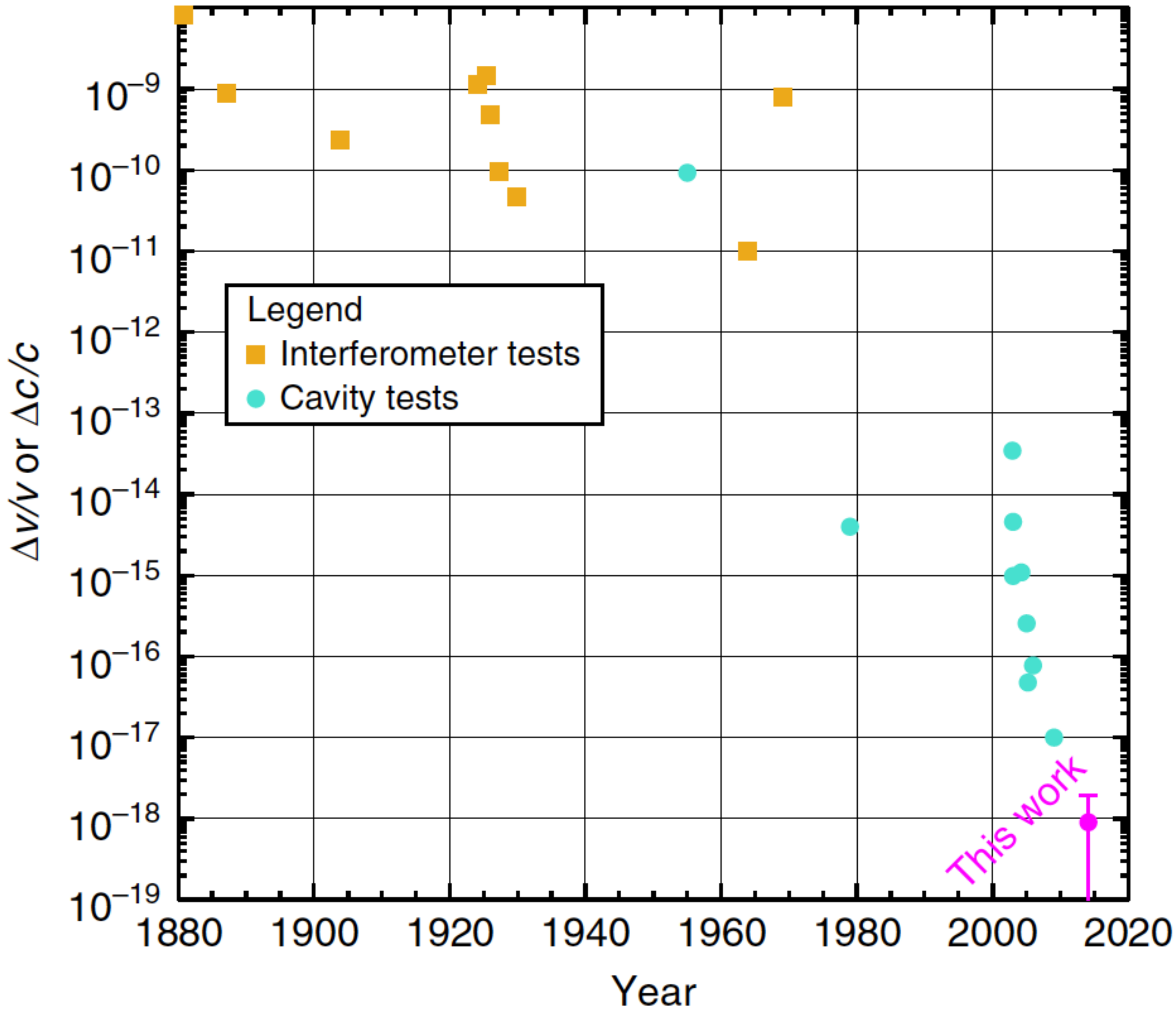
quantum foam
- quantum fluctuation of space-time



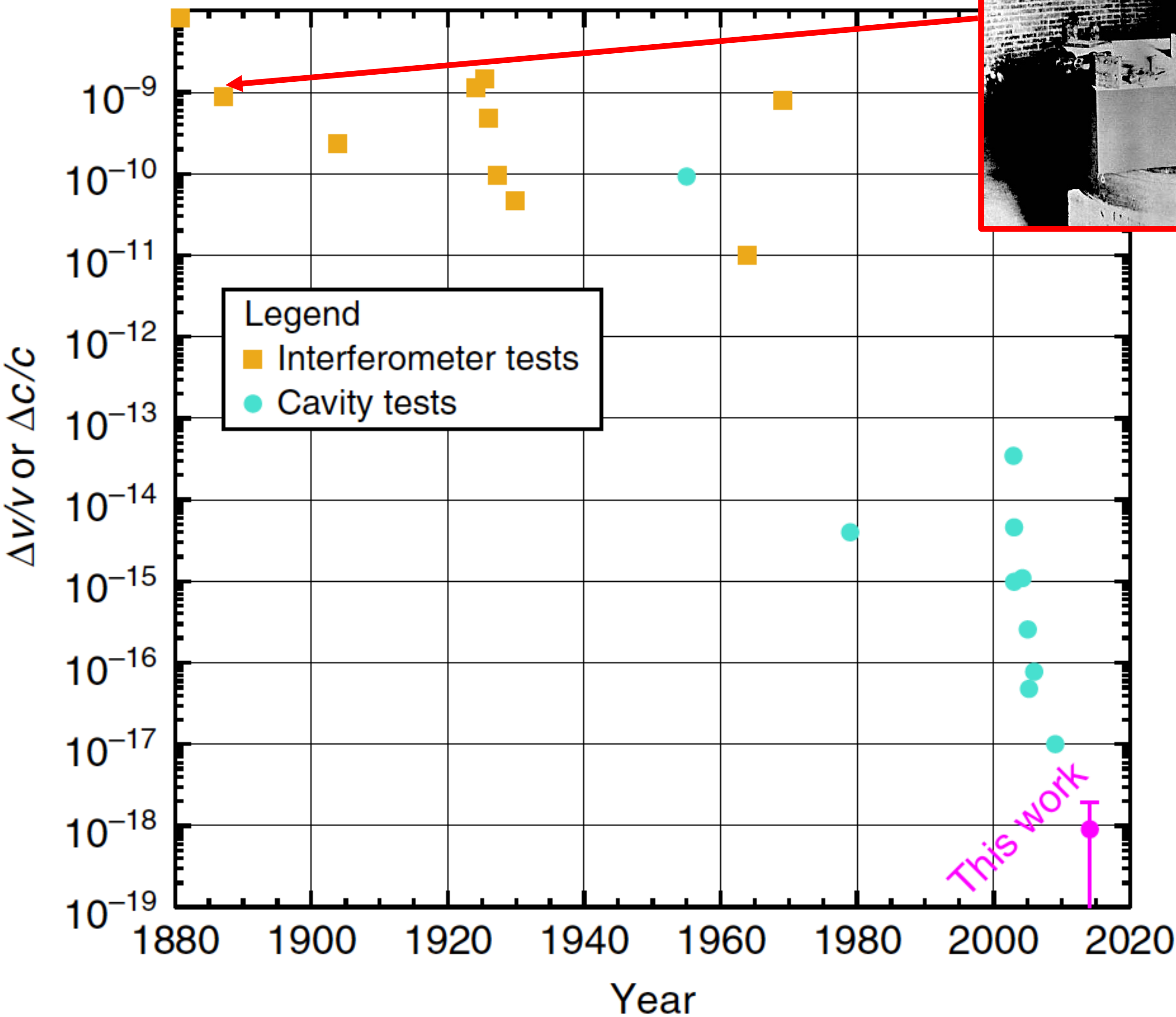
Lorentz violating field
- new field saturating the universe (æther)

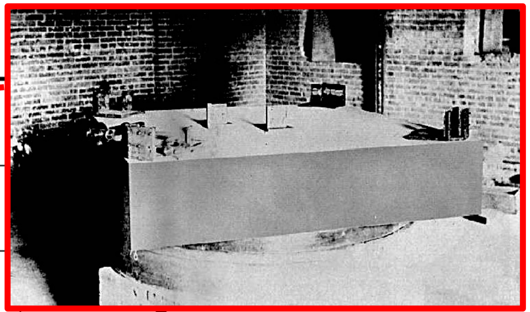


1. History of Michelson-Morley experiment

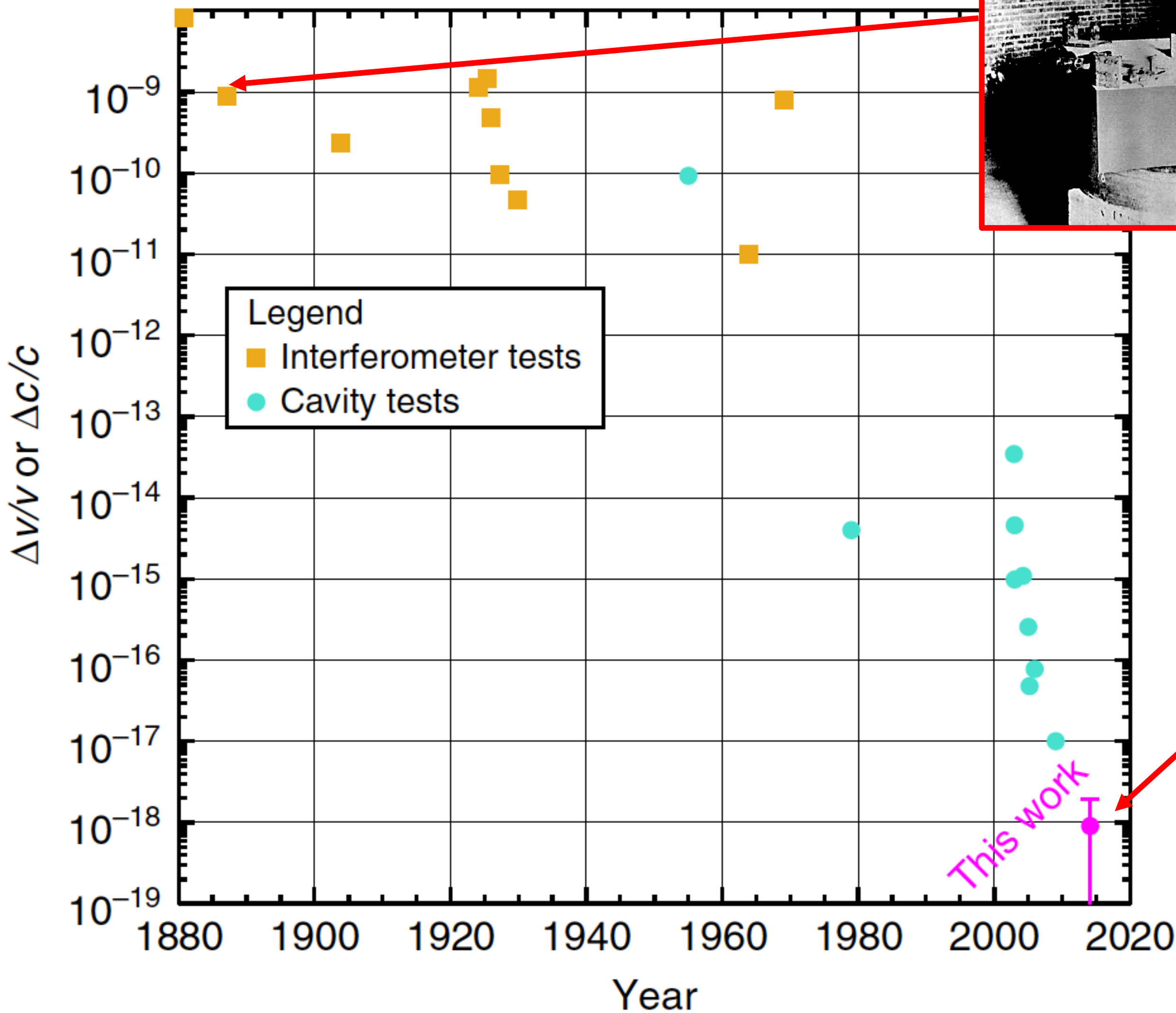


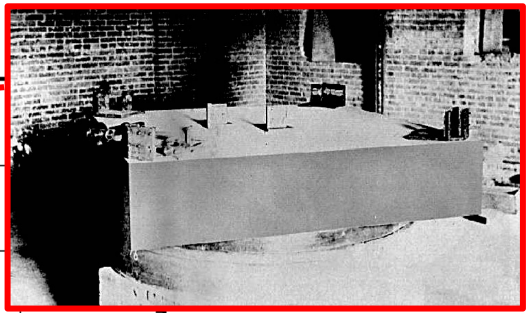
1. History of Michelson-Morley experiment (1887)





1. History of Michelson-Morley experiment (2015)





1. Test of Fundamental Physics

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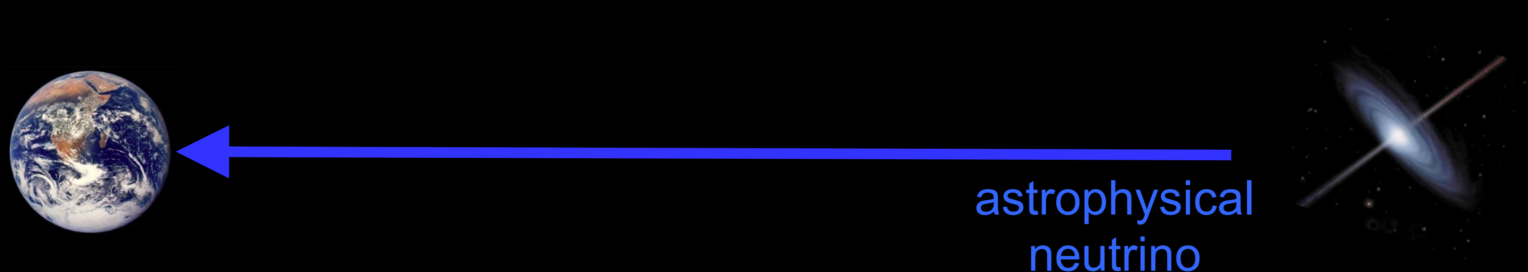
2. High-energy astrophysical neutrinos

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc) in vacuum
- Astrophysical neutrino flavour is sensitive to tiny space-time effect



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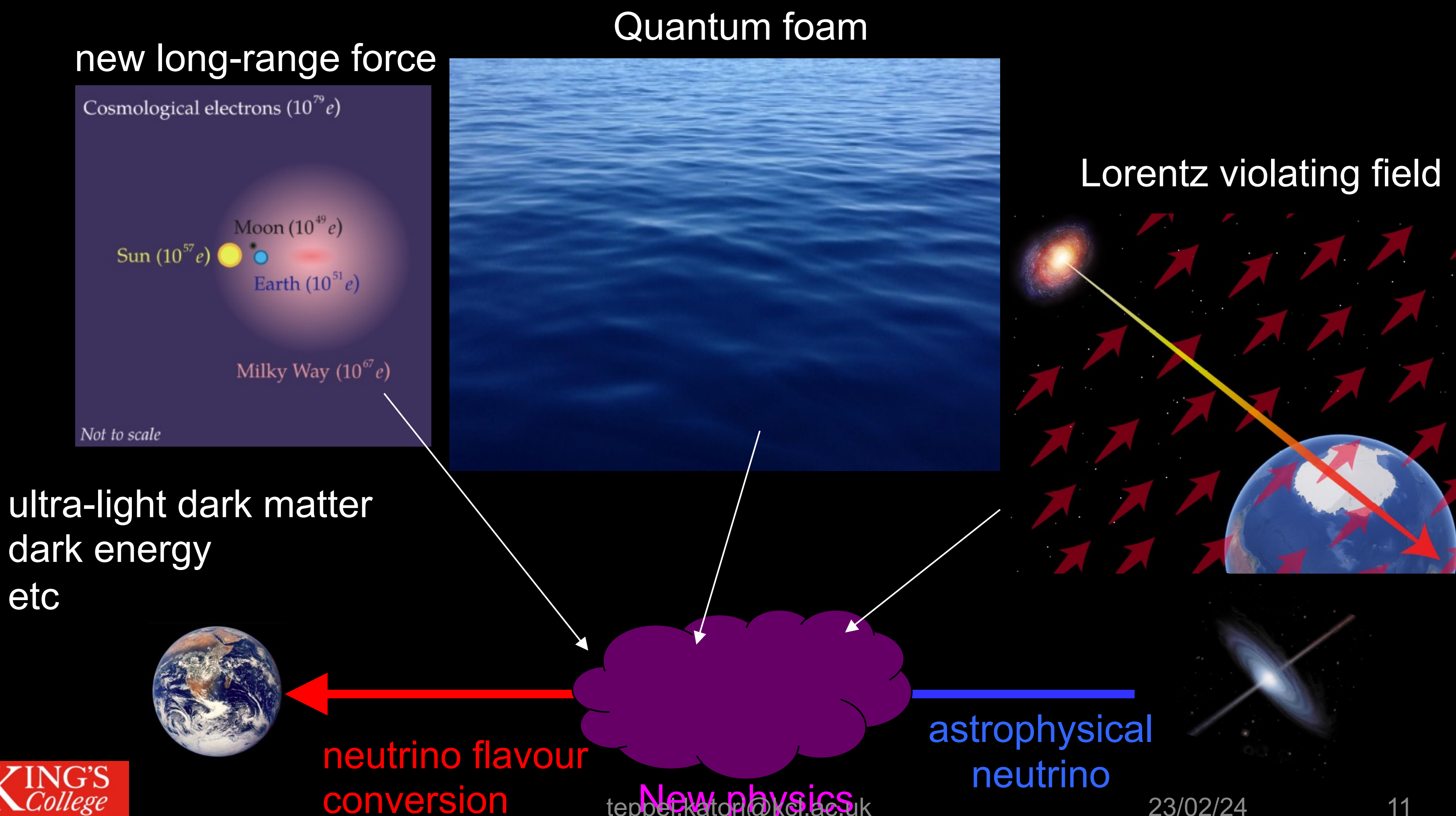
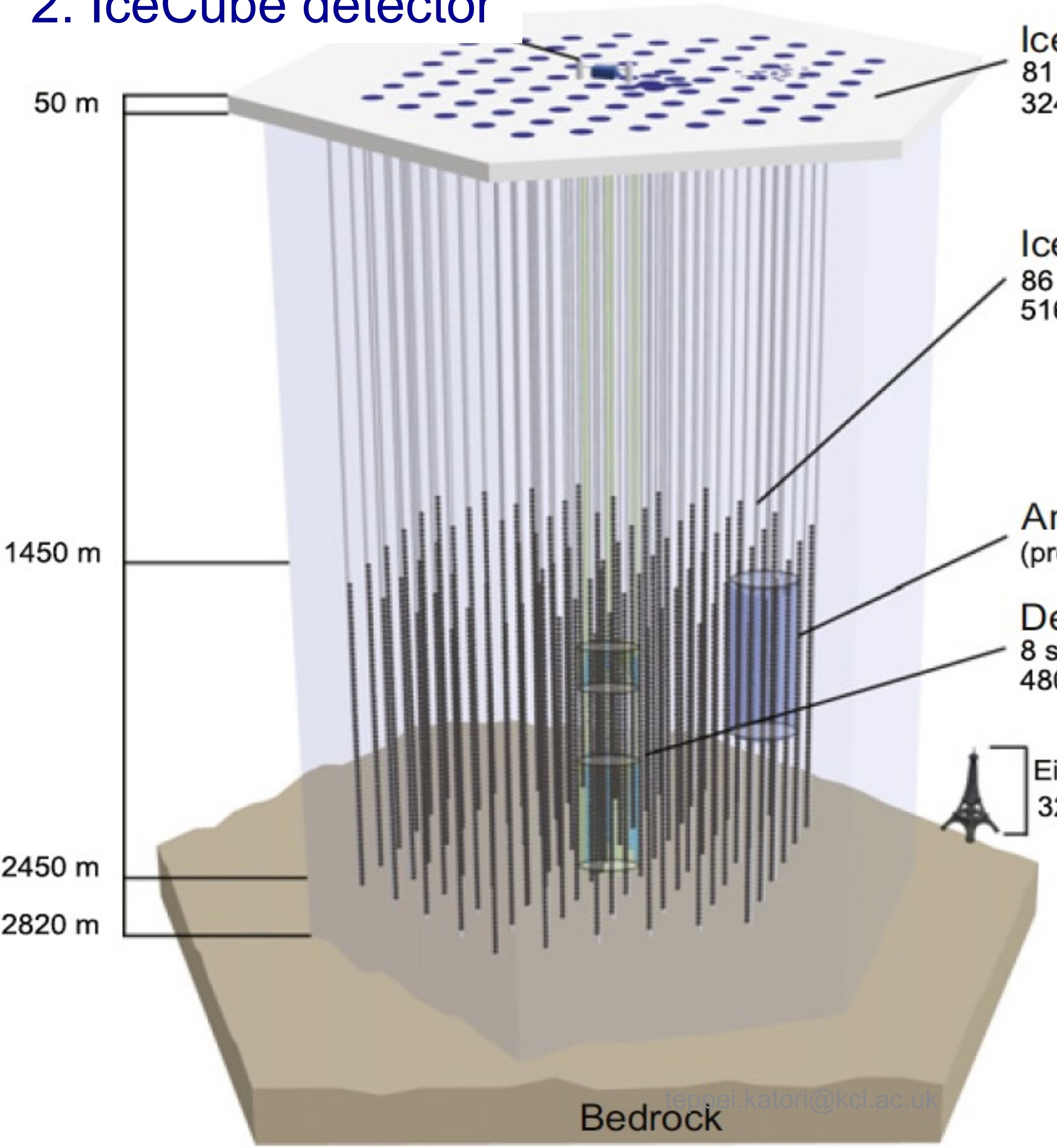
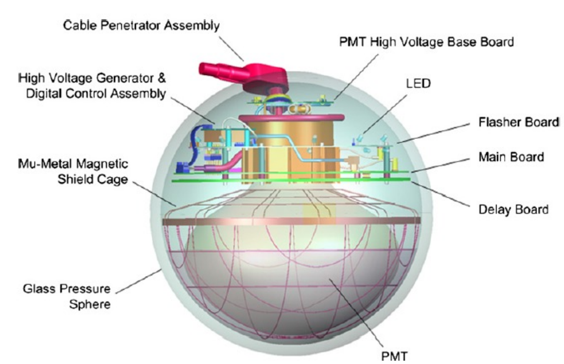


2. IceCube detector



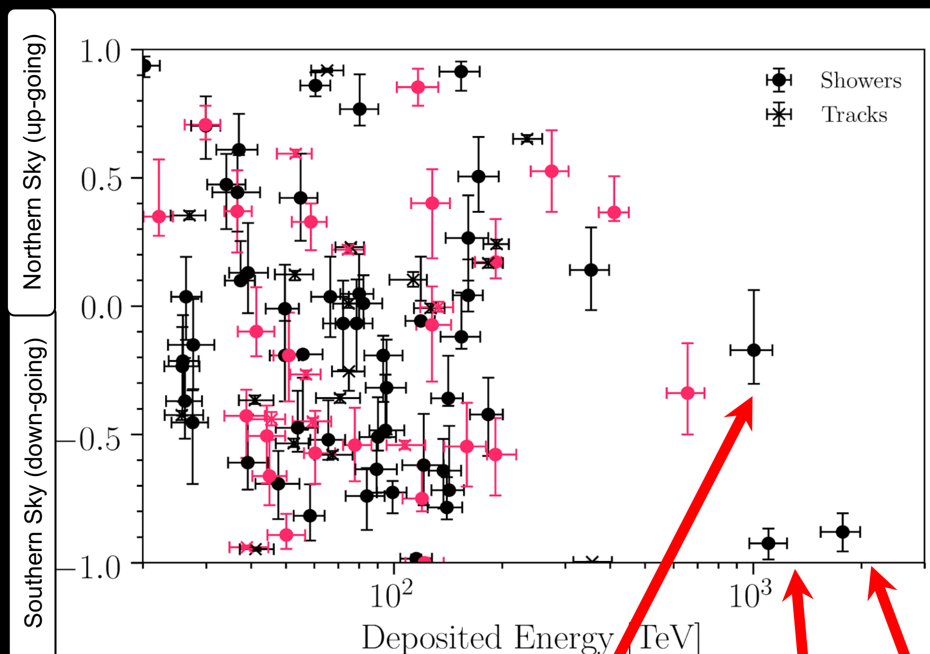
digital optical module (DOM)

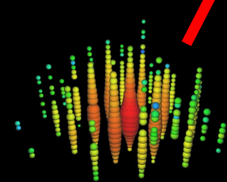


2. High-energy astrophysical neutrinos

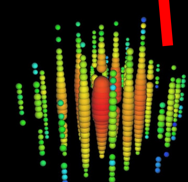
60TeV- 2PeV astrophysical neutrinos are observed by IceCube Neutrino Observatory

high-energy starting event (HESE) sample

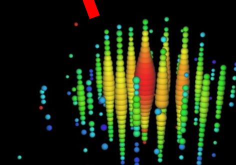




“Bert”
1.1 PeV



“Ernie”
1.0 PeV



“Big Bird”
2.0 PeV

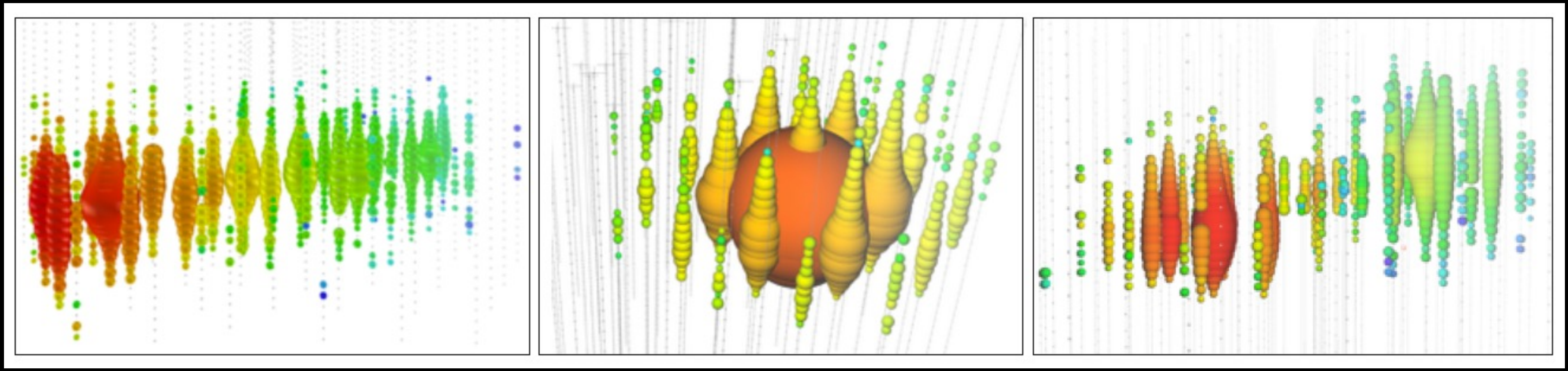
IceCube-Gen2, J.Phys.G48(2021)060501

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



1. Test of Fundamental Physics

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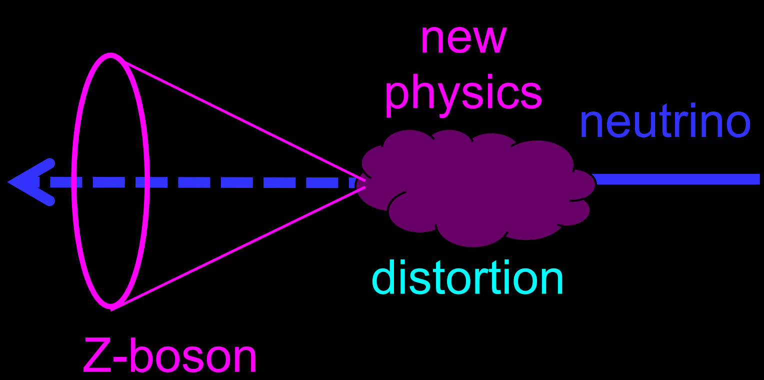
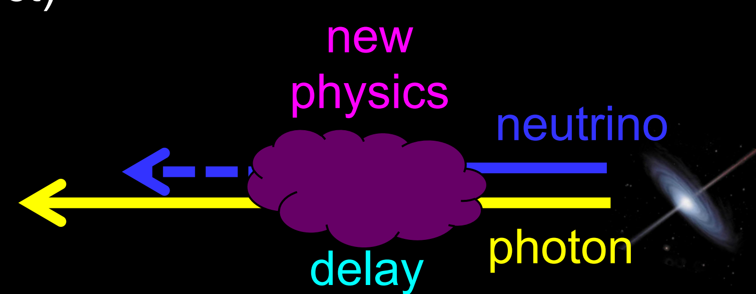
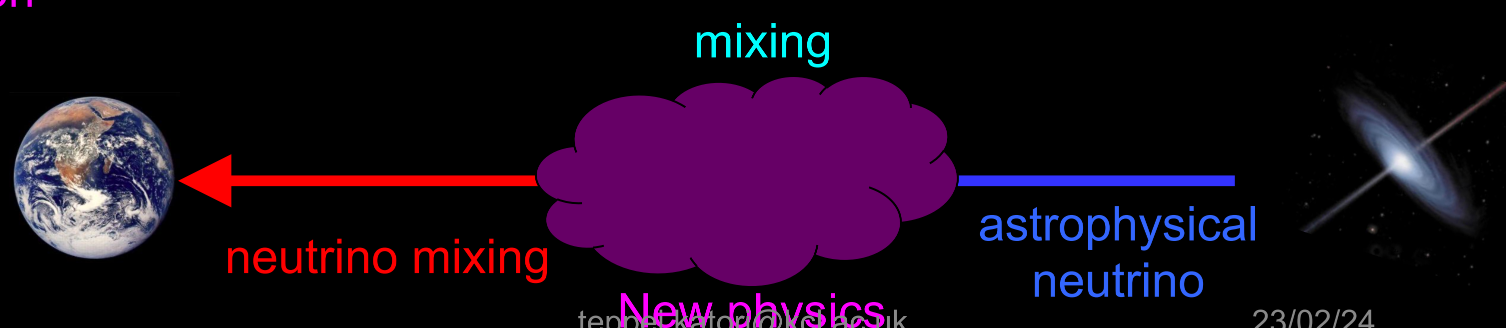
3. Search for Lorentz violation with astrophysical neutrinos

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)







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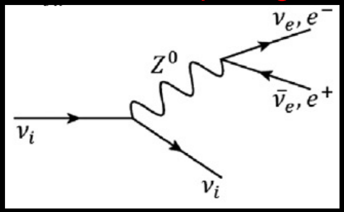
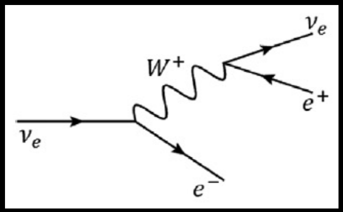
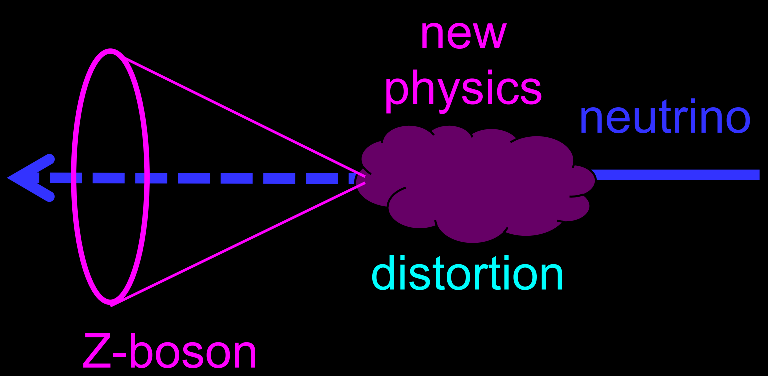
neutrino splitting

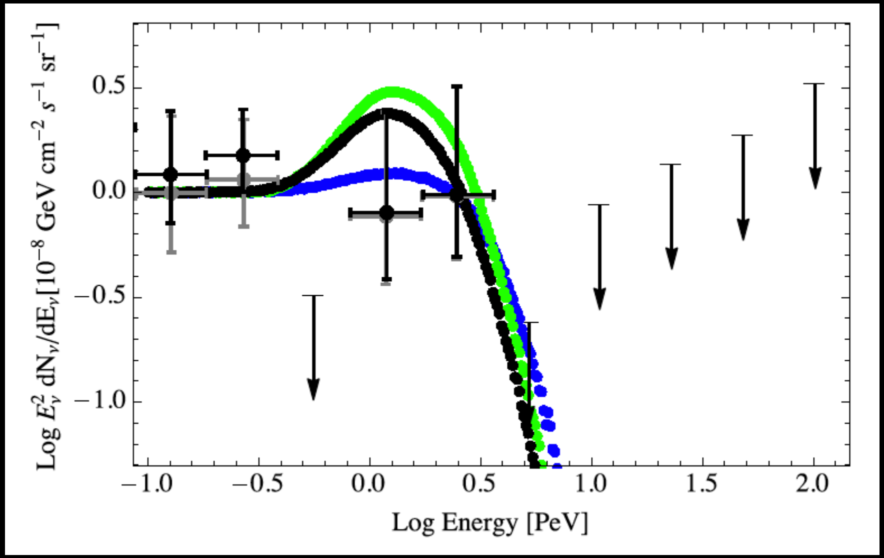


vacuum pair emission





Lorentz violating field cause
Cherenkov radiation in vacuum



Neutrino spectrum with new physics

3. Search for Lorentz violation with astrophysical neutrinos

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New physics search
- Spectrum distortion (vacuum Cherenkov radiation)
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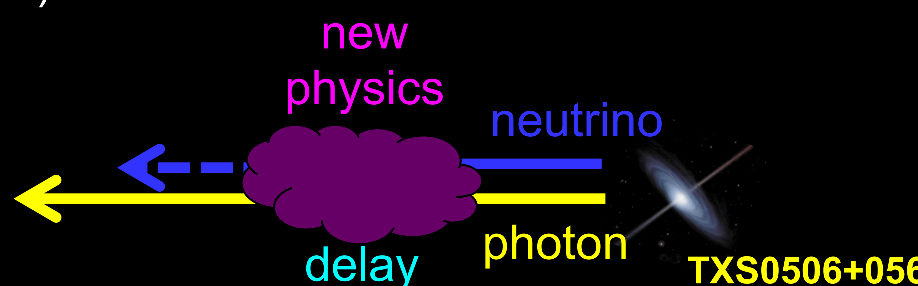
Modified dispersion due to quantum foam cause unexpected delay/advance for neutrinos

$$E^2 = p^2 + m^2 \pm \left(\frac{E}{M_{QG,n}}\right)^n$$



$$\frac{|v-c|}{c} \lesssim 4.2 \times 10^{-12} \left(\frac{\Delta t}{7\ \text{days}}\right)$$

Argüelles, TK, Salvado, PRL115(2015)161303

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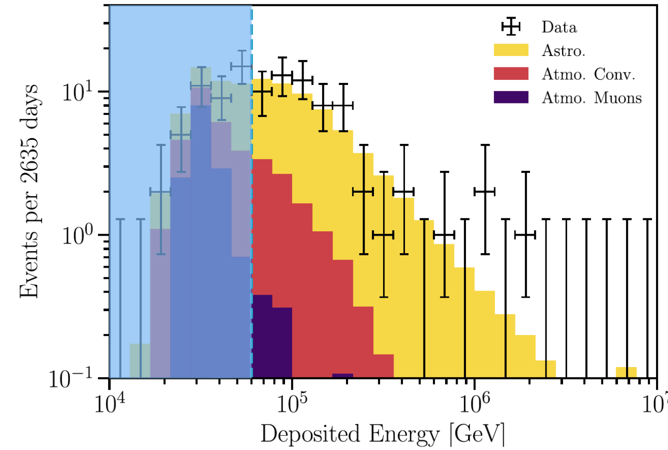
Flavour effect
- Macroscopic quantum effect and sensitive to small effects

IceCube, Nature Physics 18(2022)1287

HESE 7.5-yr Flavor new physics search



Data

IceCube, PRD104(2021)022002

- 2635 days high-energy starting event (HESE) sample

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)

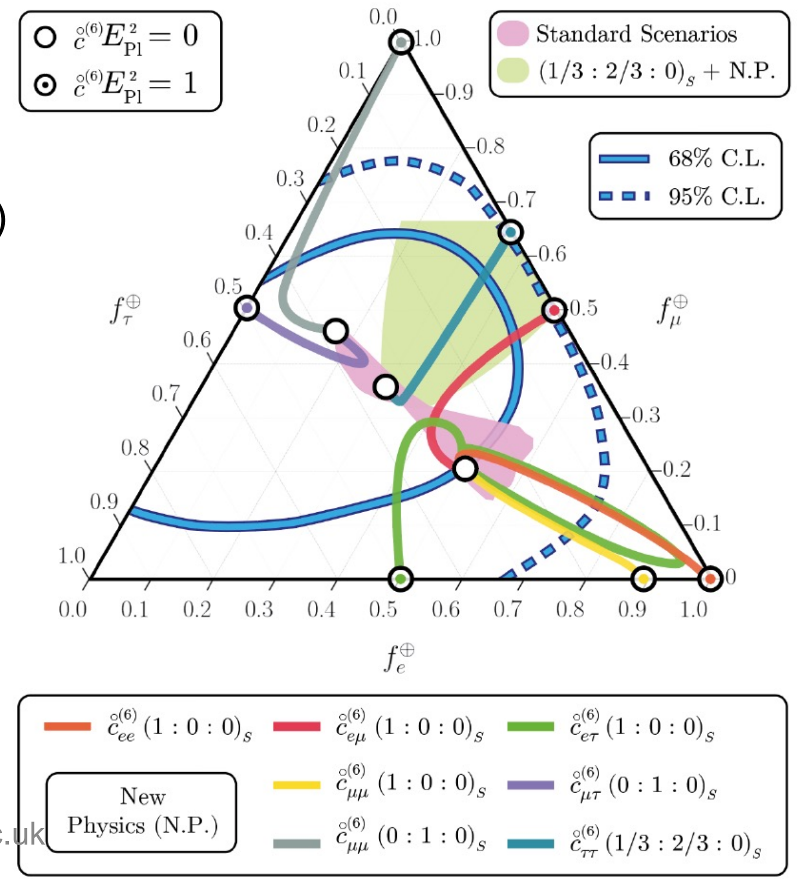
Cooper-Sarkar et al., JHEP08(2011)042

Systematics

- 15 nuisance parameters (oscillations, flux, detector)

Limits

- Bayesian analysis (BF>10)
- Production model dependent



KING'S College LONDON

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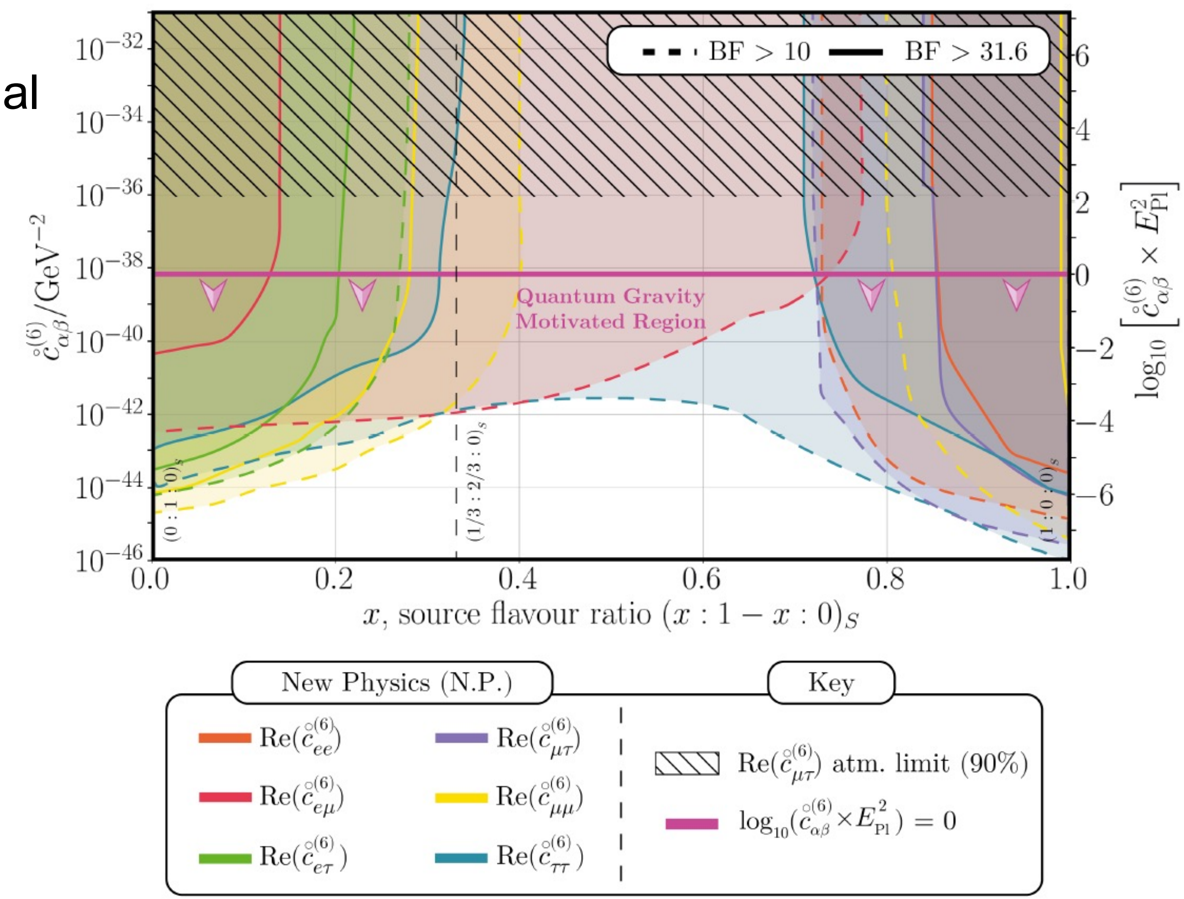
3. HESE 7.5-yr flavor new physics search

60 HESE events in 60 TeV – 2 PeV

IceCube data start to explore quantum gravity-motivated signal region for some parameters

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

dim-6 new physics operator limit



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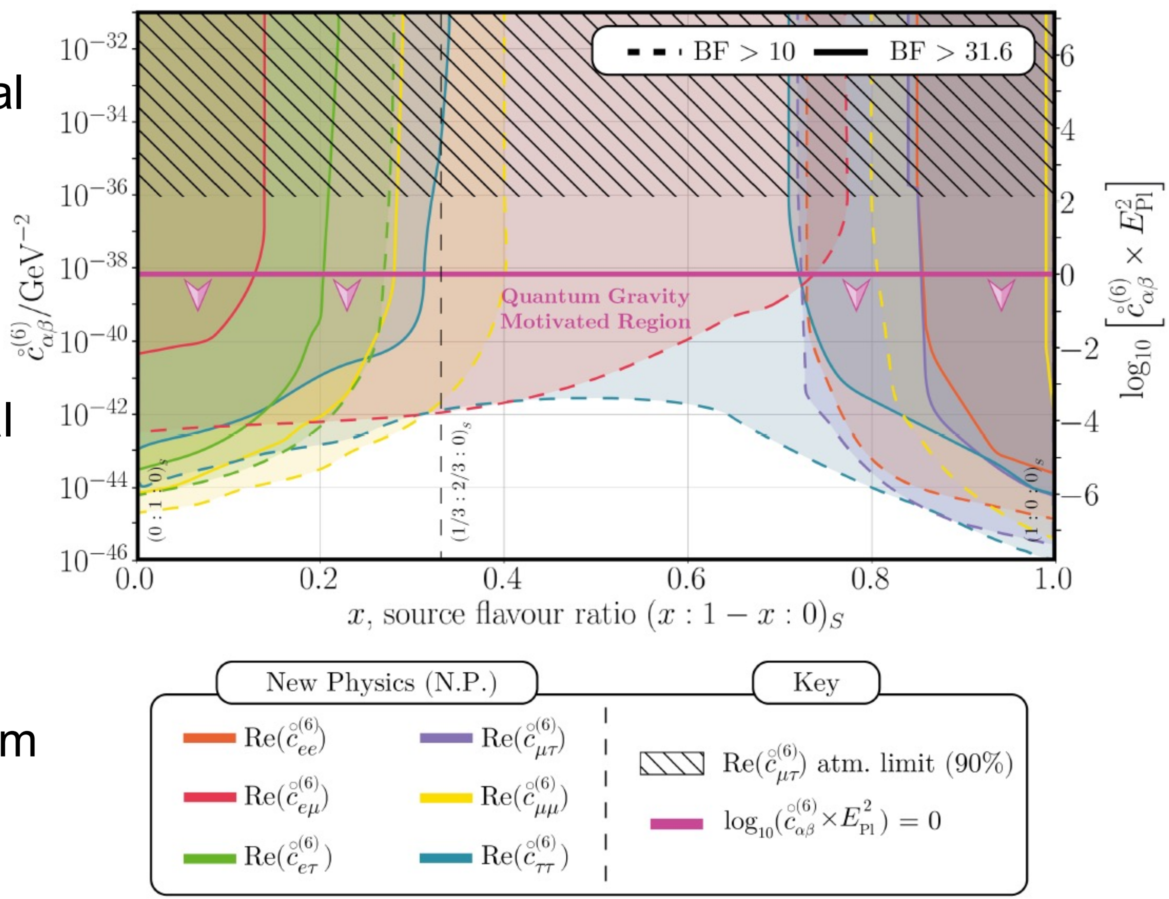
Results depend on astrophysical neutrino production models. We need to improve this;

1. Multi-messenger astronomy
2. More data
3. Flavour identification algorithm

dim-6 new physics operator limit



IceCube, Nature Physics 18(2022)1287

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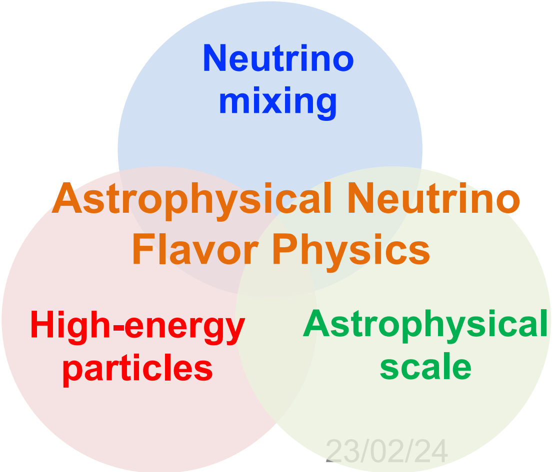
1. Multi-messenger astronomy
2. More data
3. Flavour identification algorithm

Results have significant implications on many new physics models

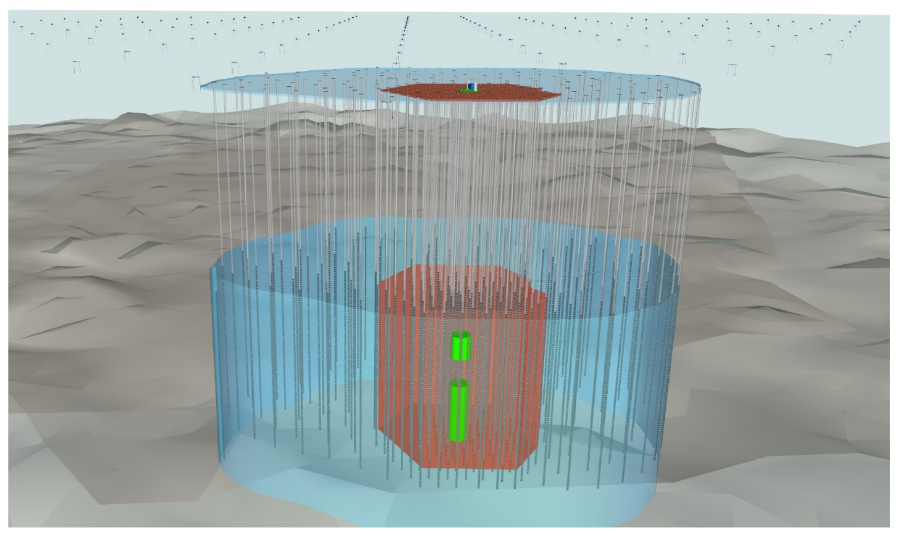
- Ultralight dark matter, PRD99(2019)051702
- Dark energy (quintessence), PRD97(2018)063006
- New long-range force, etc PRL122(2019)061103

Astrophysical neutrino flavour is a new tool to explore a variety of new physics beyond ordinary matter and spacetime!

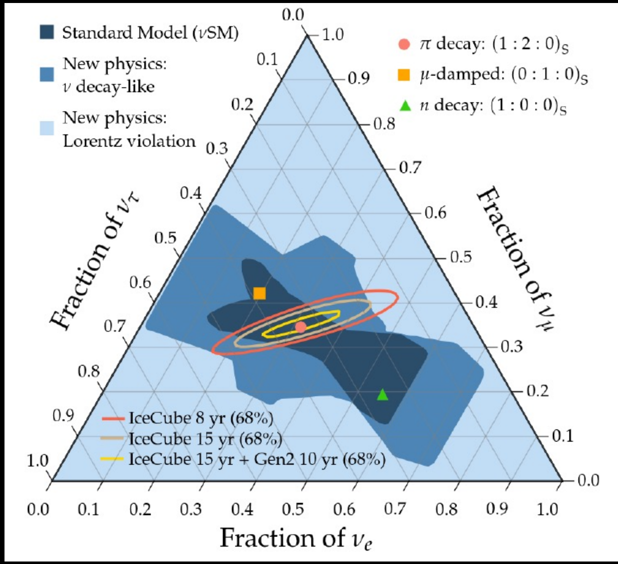


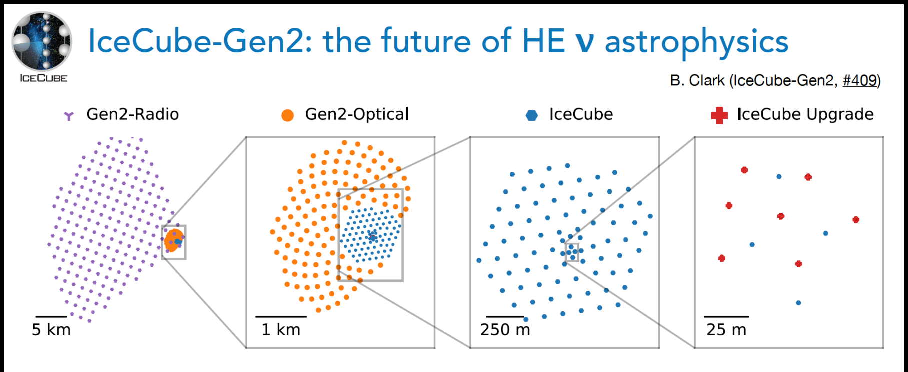
3. IceCube-Gen2

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 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. The results can be improved in near future.

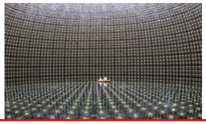
IceCube-Gen2 collaboration

Thank you for your attention!

Backup

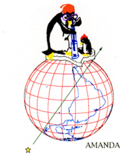
3. Test of Lorentz violation with neutrinos

Spectral distortion

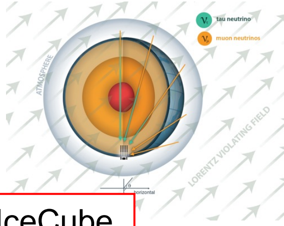


Super-Kamiokande
PRD91(2015)052003

Daya Bay
PRD98(2018)092013

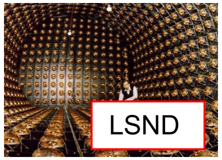


AMANDA
PRD79(2009)102005



IceCube
Nature Physics 14(2018)961

Sidereal variation

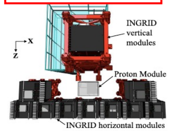


LSND
PRD72(2005)076004

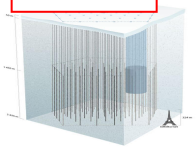
MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

MINOS FD
PRL105(2010)151601



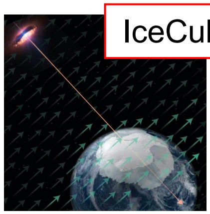
T2K ND
PRD95(2017)111101



IceCube
PRD82(2010)112003

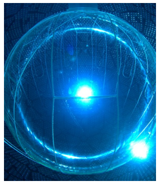
Double Chooz
PRD86(2013)112009

Flavor ratio



IceCube
ArXiv: 2111.04654

Seasonal variation



SNO
PRD98(2018)112013

3. HESE 7.5-yr flavor ratio

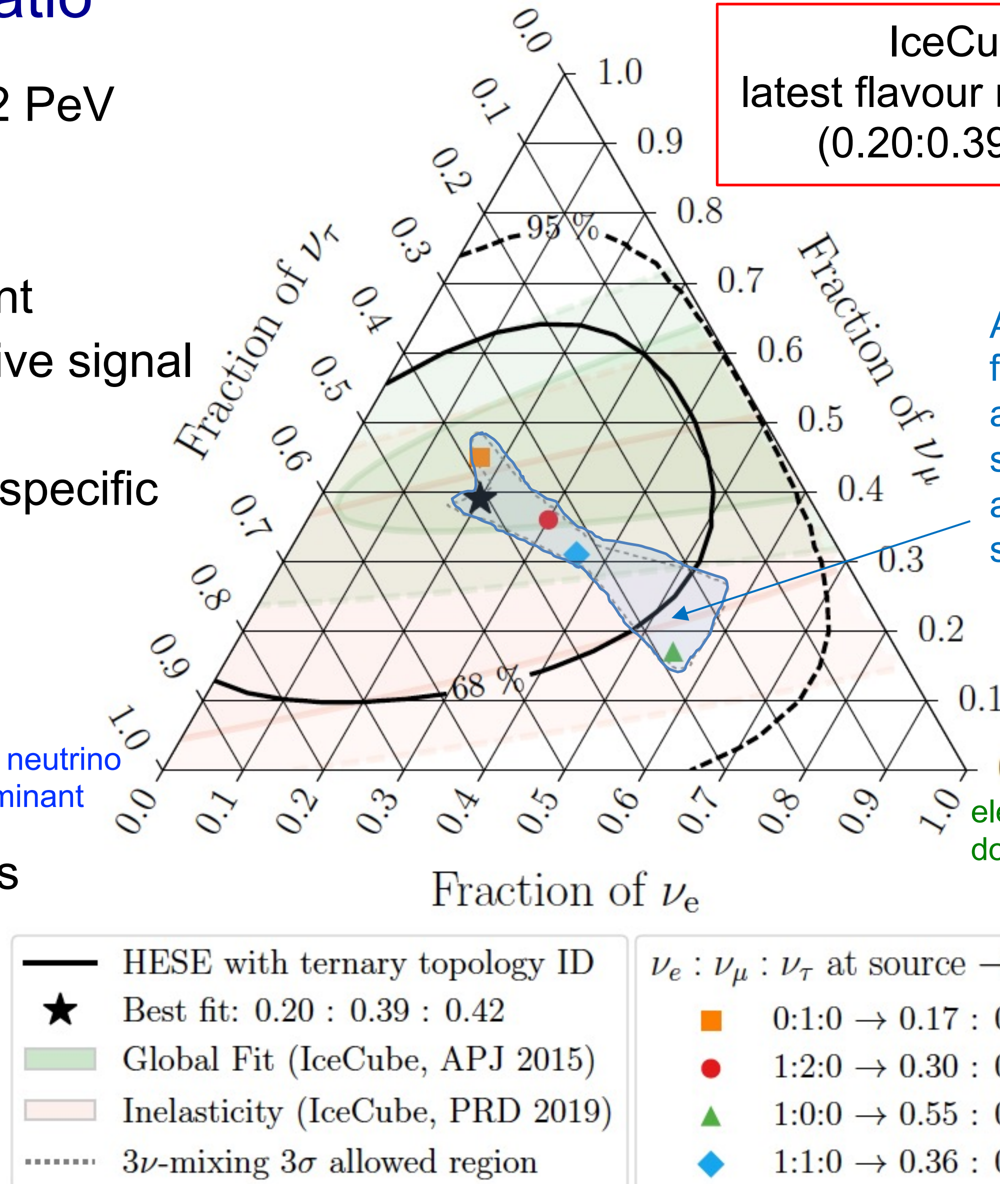
60 HESE events in 60 TeV – 2 PeV

New flavour ratio measurement
- contour is very big, no positive signal of new physics
- Data are used to test some specific new physics models

We focus on setting limits on certain new physics models

muon neutrino dominant

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



All possible flavour ratios at Earth by standard astrophysical scenario

tau neutrino dominant

electron neutrino dominant

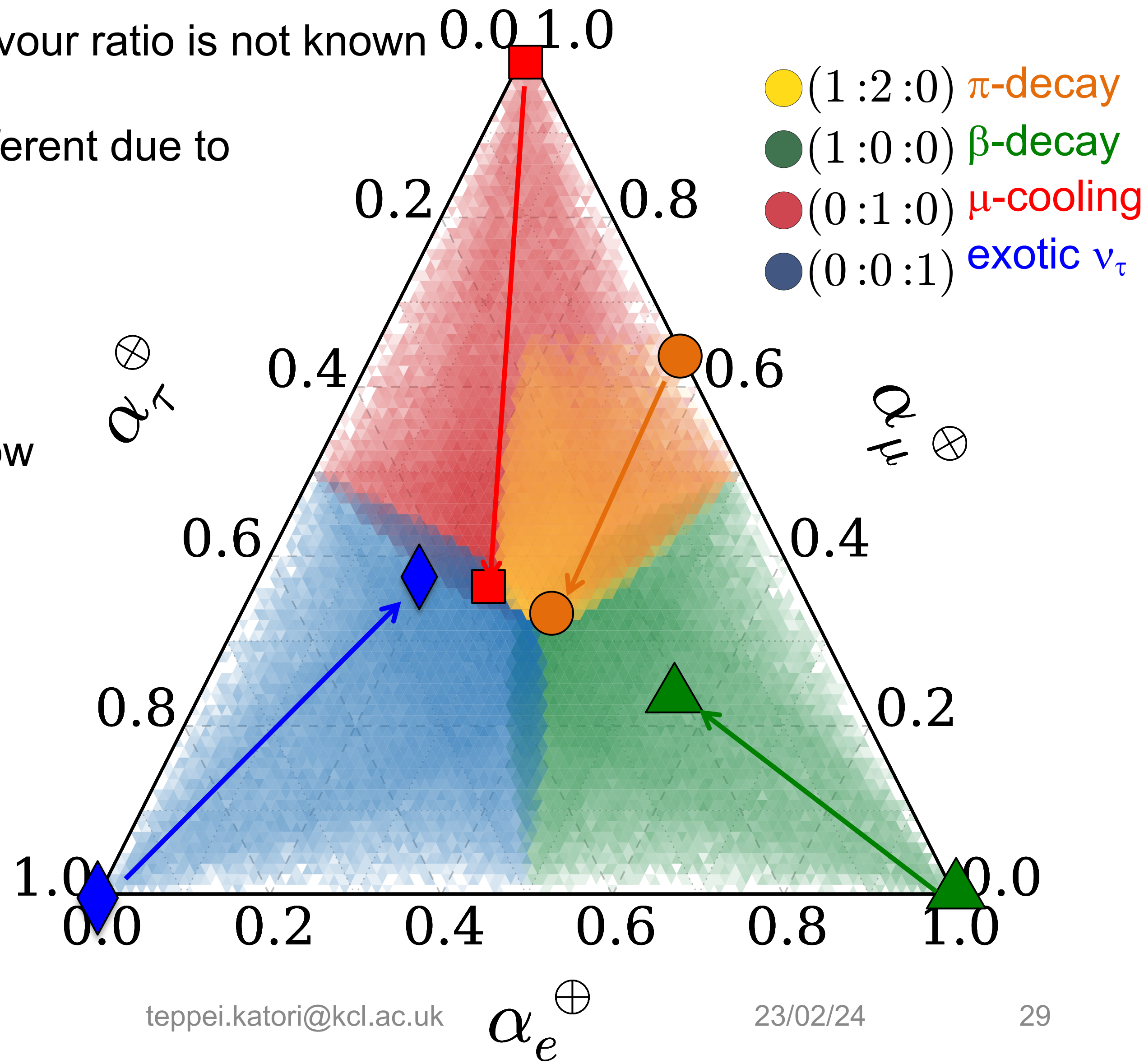
3. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

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



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

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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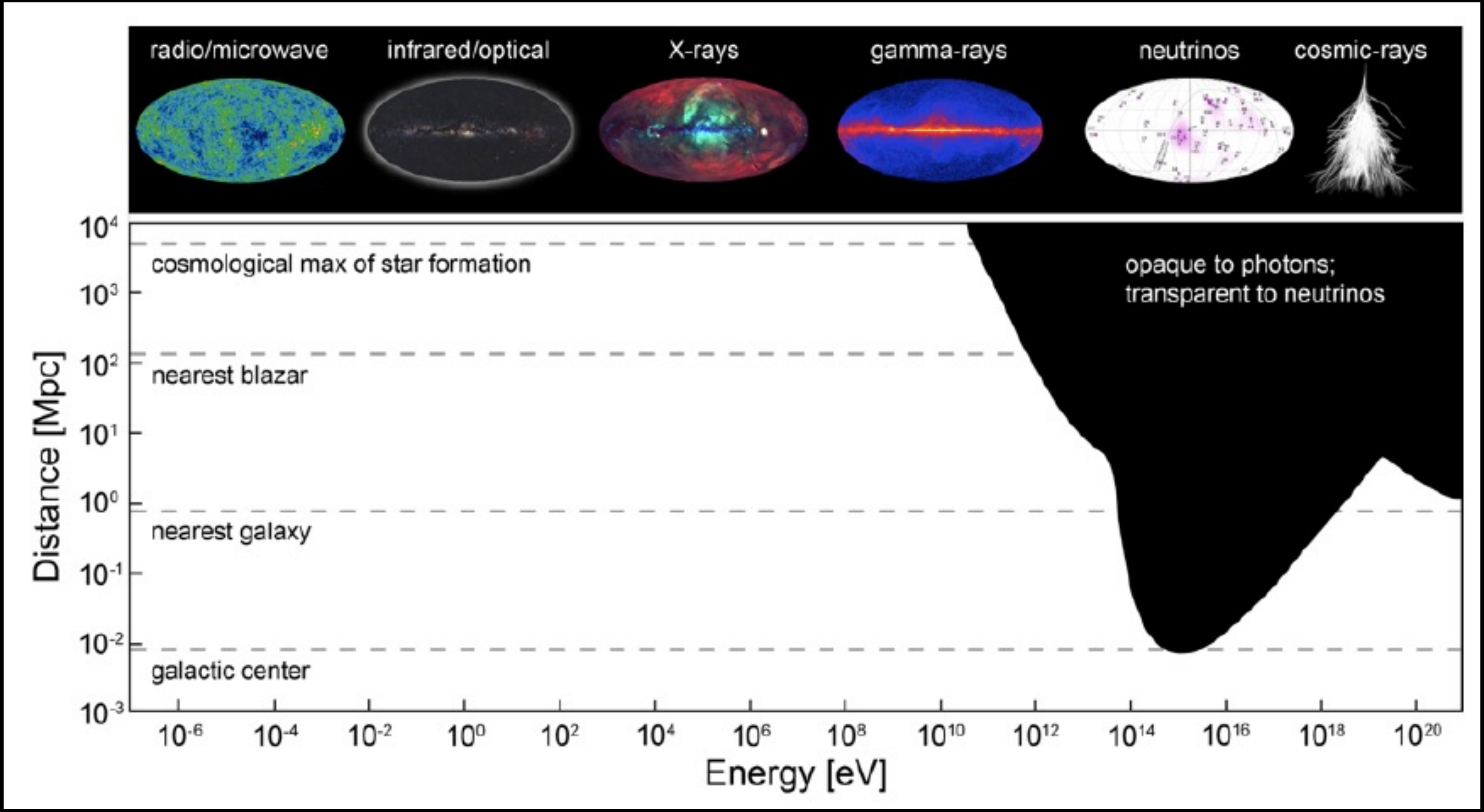
2. High-energy astrophysical neutrinos

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



HESE 7.5-yr Flavor new physics search

Data, 2635 days HESE sample IceCube, PRD104(2021)022002
- 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%)

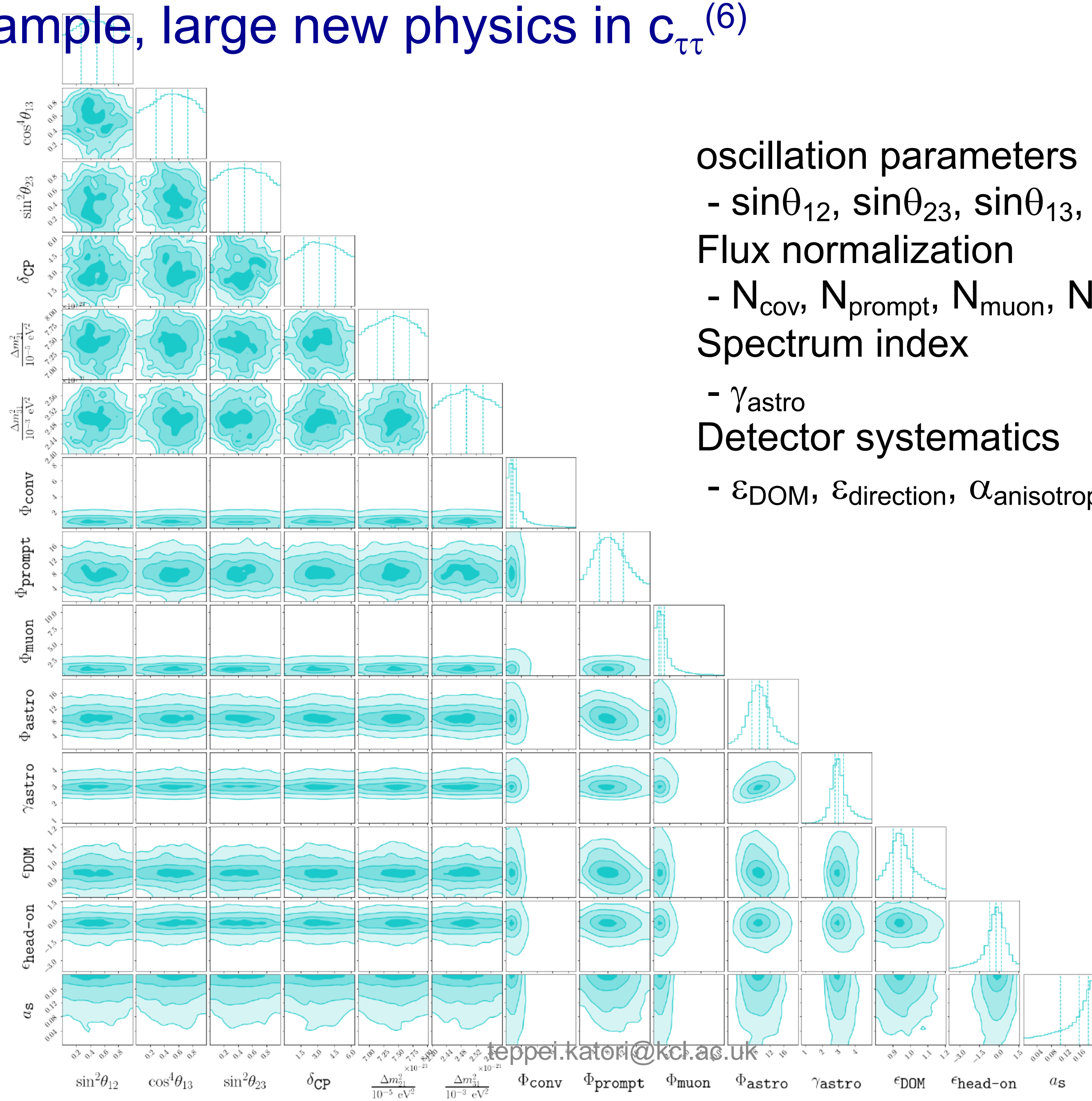
Limits

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

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}

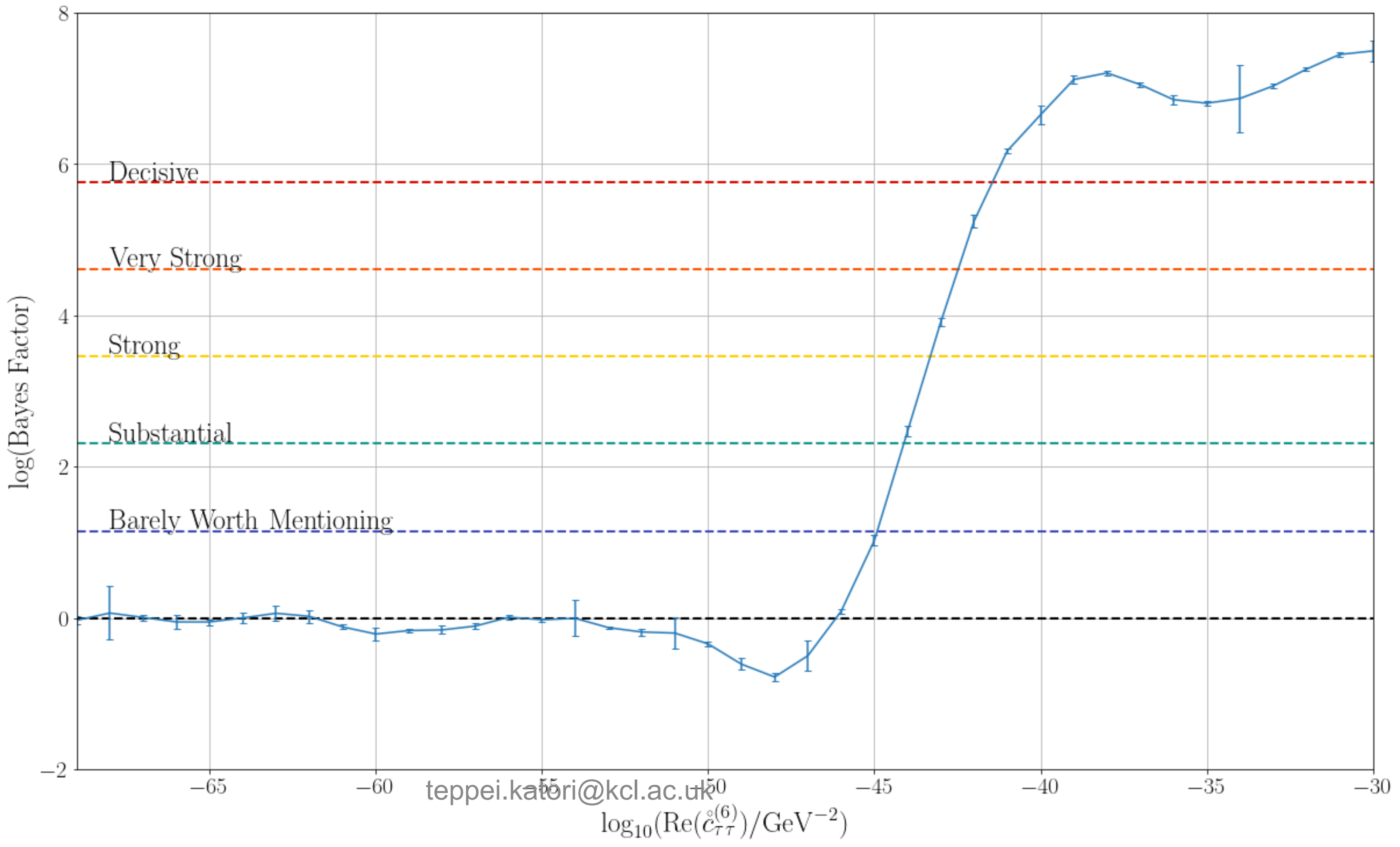
Spectrum index
- γ_{astro}

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

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



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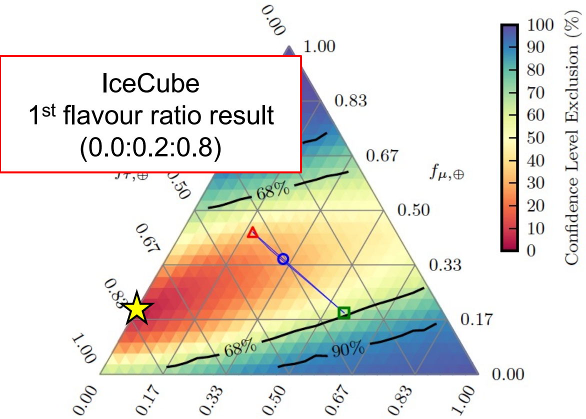
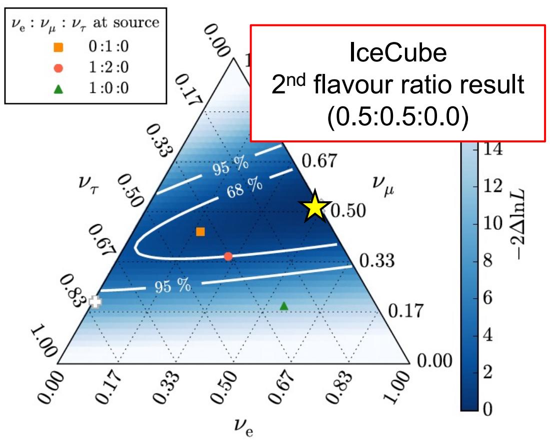
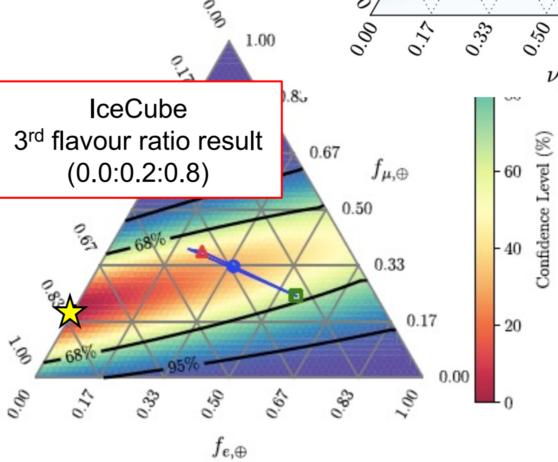
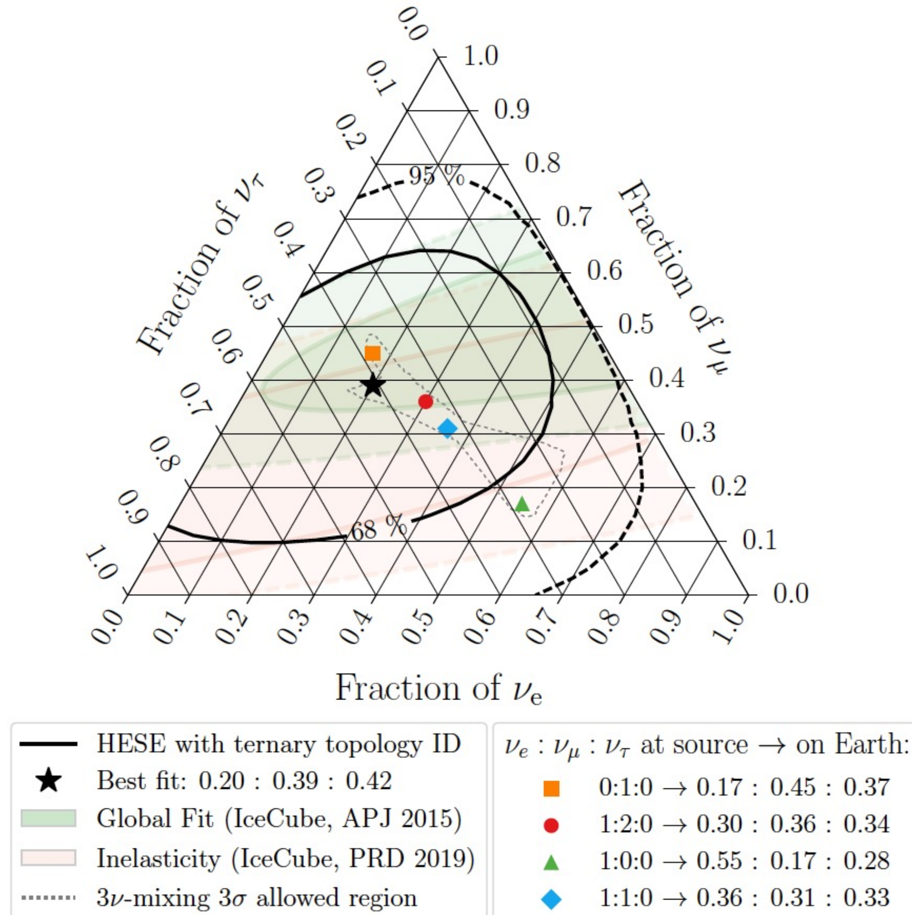
HESE 7.5-yr data (2018)





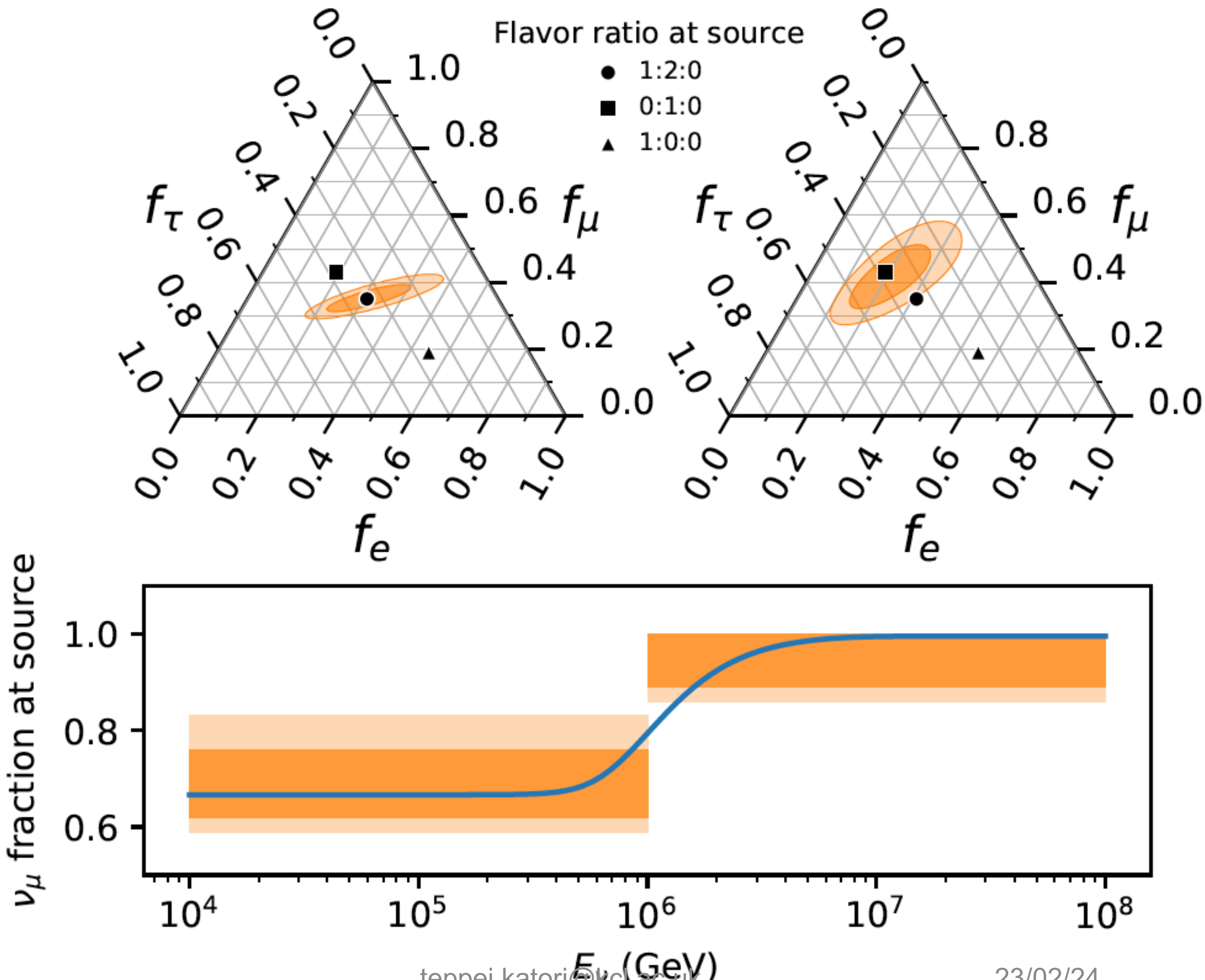




New flavour ratio measurement

- 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

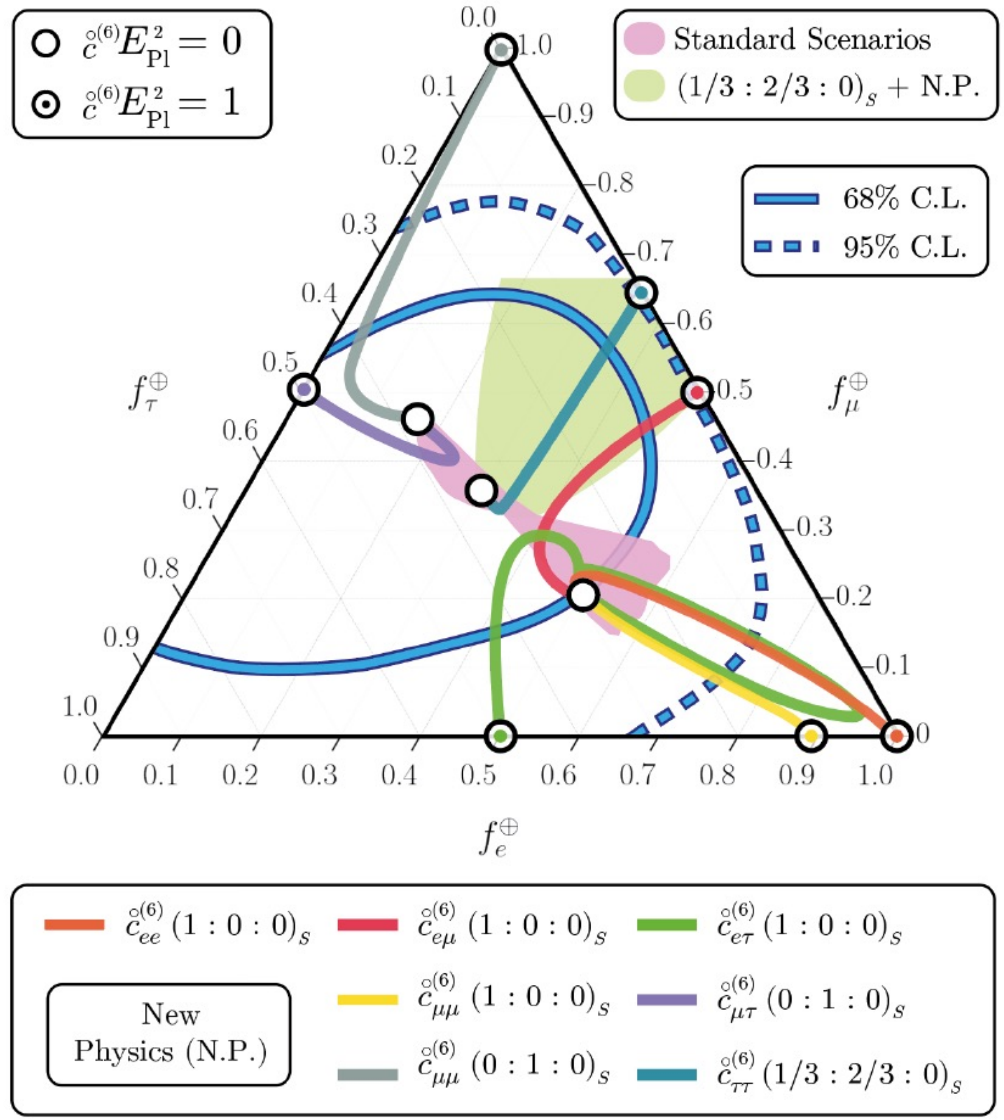
Energy dependence of flavor ratio



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.

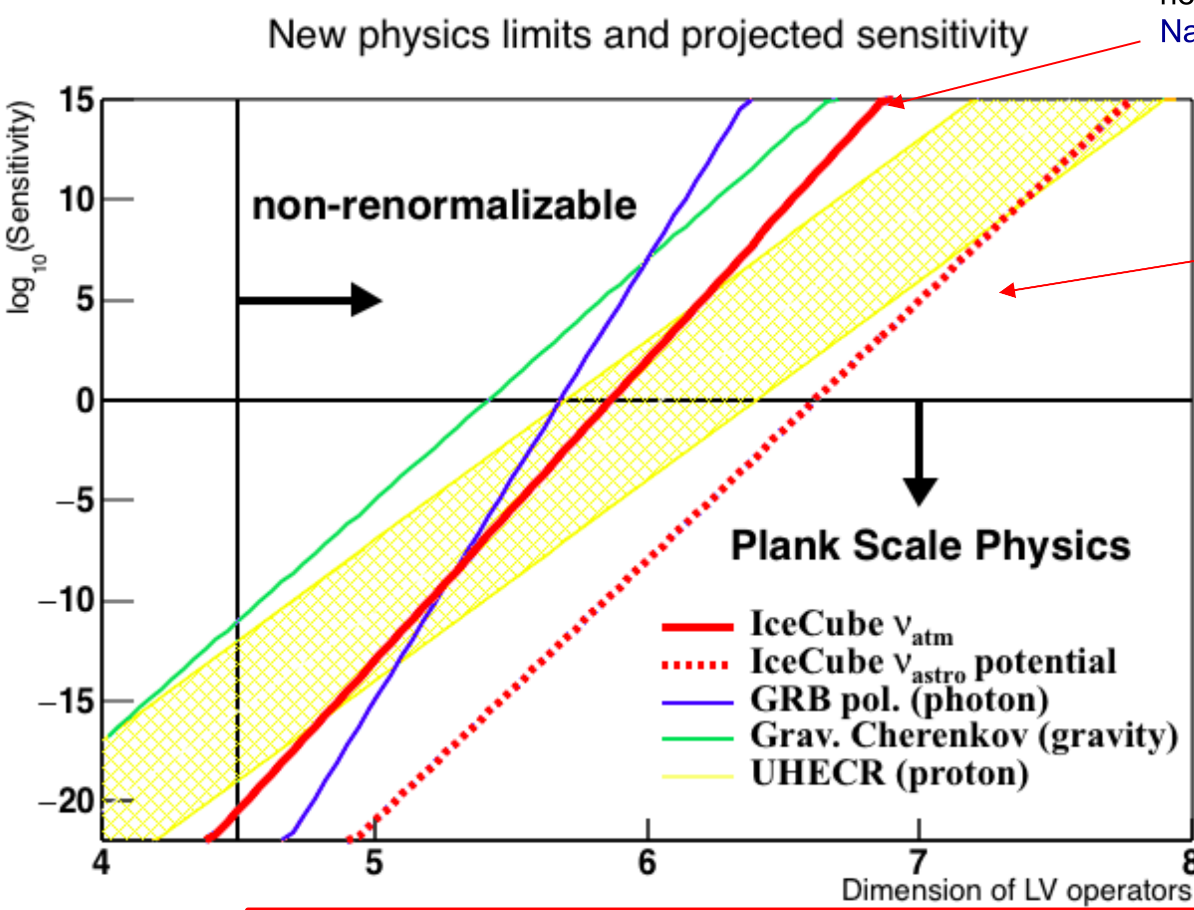
If the new physics models bring the standard predictions outside of the data contour, such model can be rejected by current data



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 ($\sim 1/M_{Planck}^2 \sim 10^{-38}$ GeV^{-2})