Search for Quantum Gravity using Astrophysical Neutrino Flavour with IceCube

Teppei Katori for the IceCube collaboration
King's College London
SCAR scientific meeting, August 9, 2022

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

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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

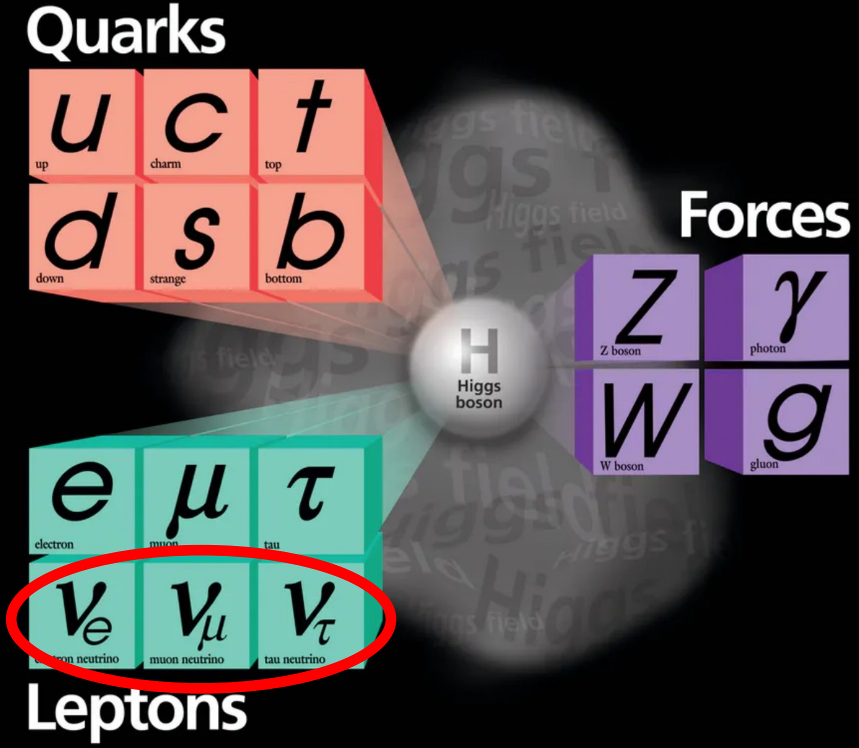

Lorentz Institute

1. Neutrinos are ghost particles!

1. Only interact through Weak nuclear force
2. With very tiny masses, travelling space almost speed of light
3. Neutrinos have 3 species (flavours), and they change flavours via propagation

Neutrino flavour changing process is very sensitive to small space-time effect on neutrinos

We compare neutrino flavours between data and simulation to look for any anomalous neutrino flavour conversion

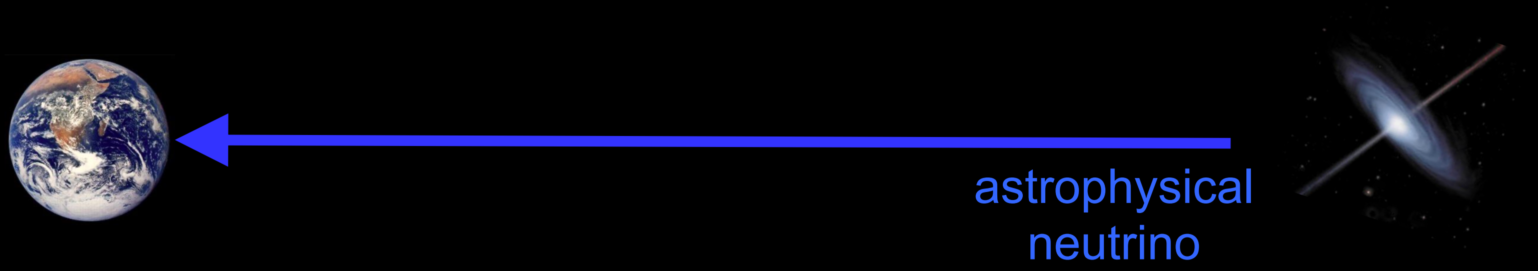


The Standard Model of Particle Physics

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



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

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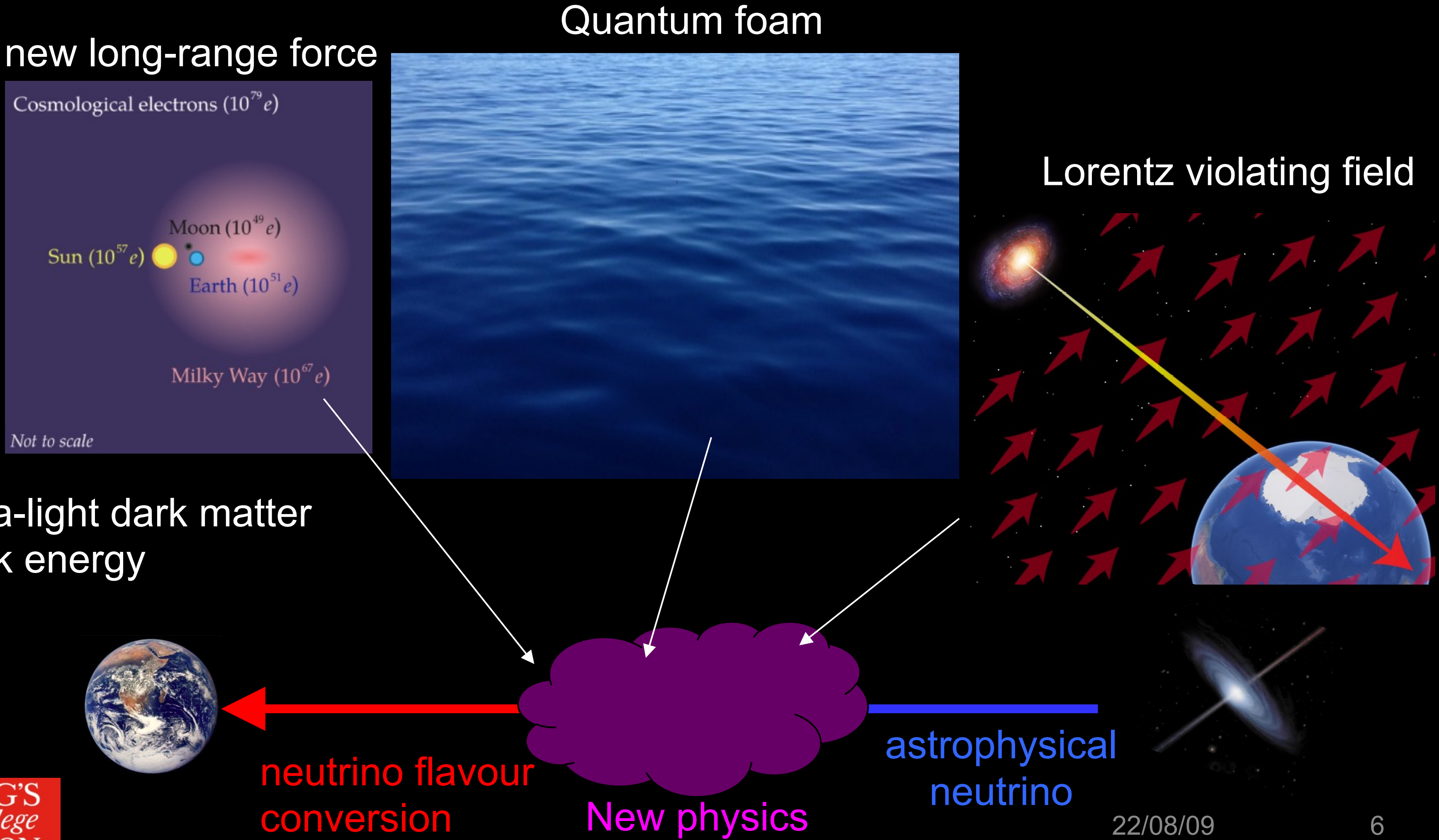


Quantum foam

new long-range force

Lorentz violating field

ultra-light dark matter
dark energy
etc

neutrino flavour conversion

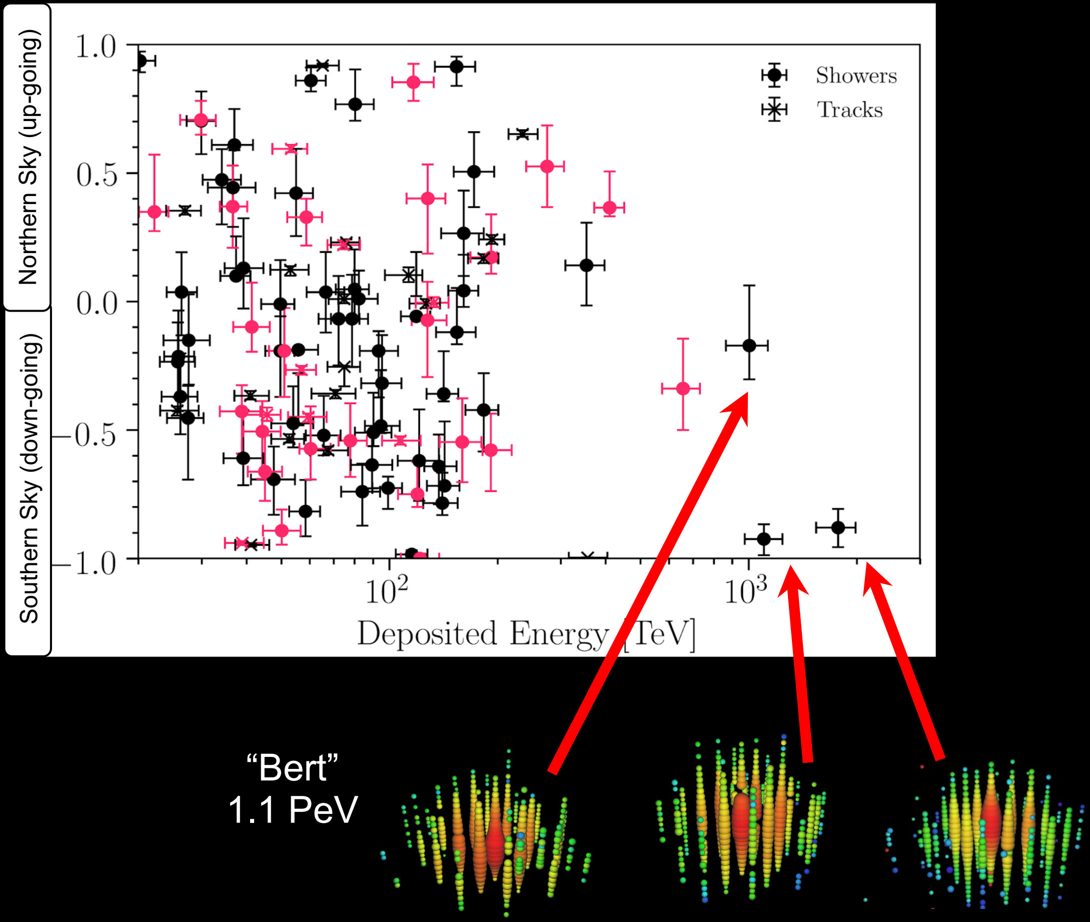
New physics

astrophysical neutrino

IceCube, PRD104(2021)022002

3. High-energy astrophysical neutrinos

60TeV- 2PeV astrophysical neutrinos are 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

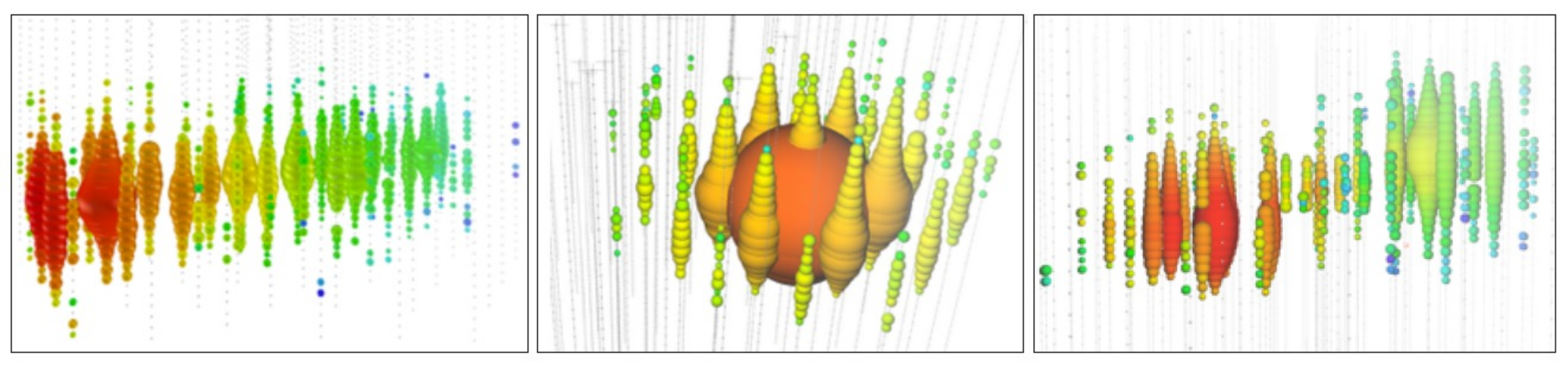
$$\nu_\mu + N \rightarrow \mu + X$$

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)

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



IceCube, ArXiv: 2111.04654

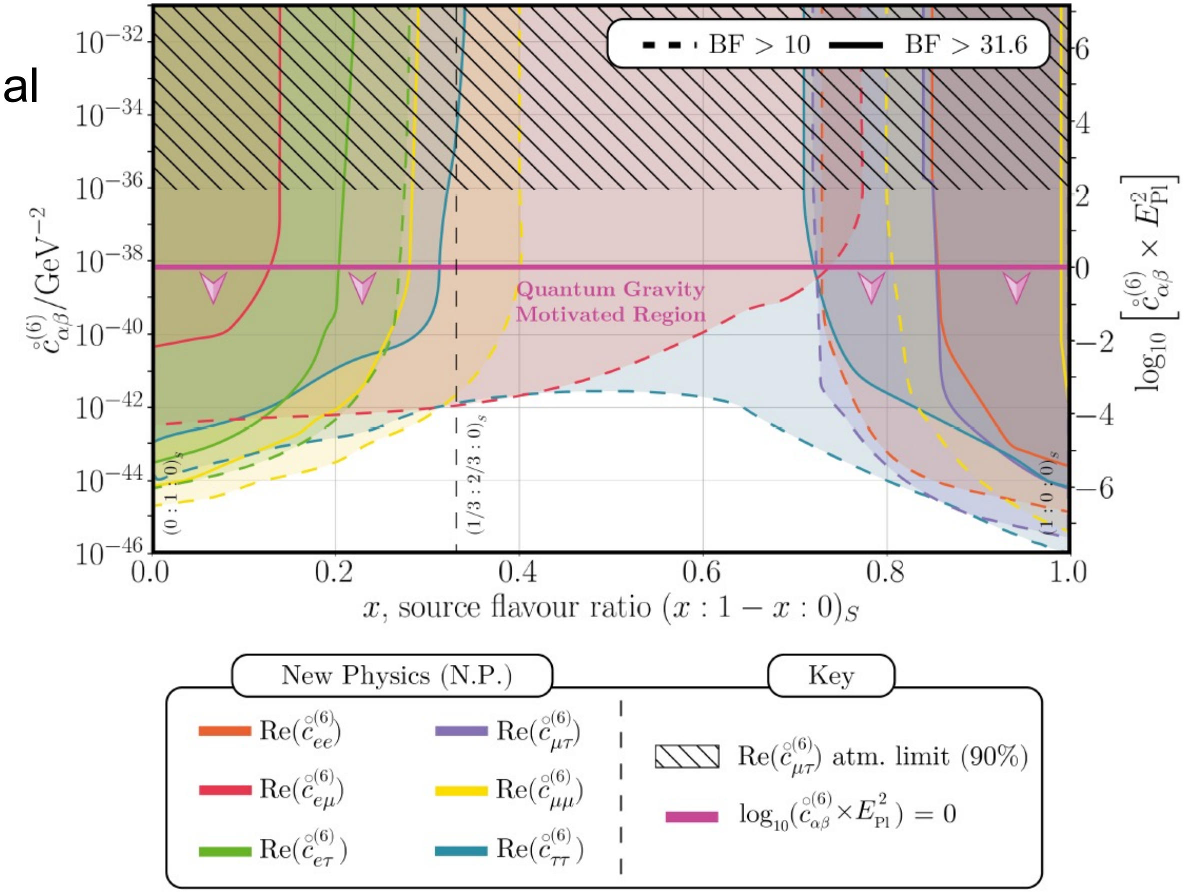
3. HESE 7.5-yr flavor new physics search

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



IceCube, ArXiv: 2111.04654

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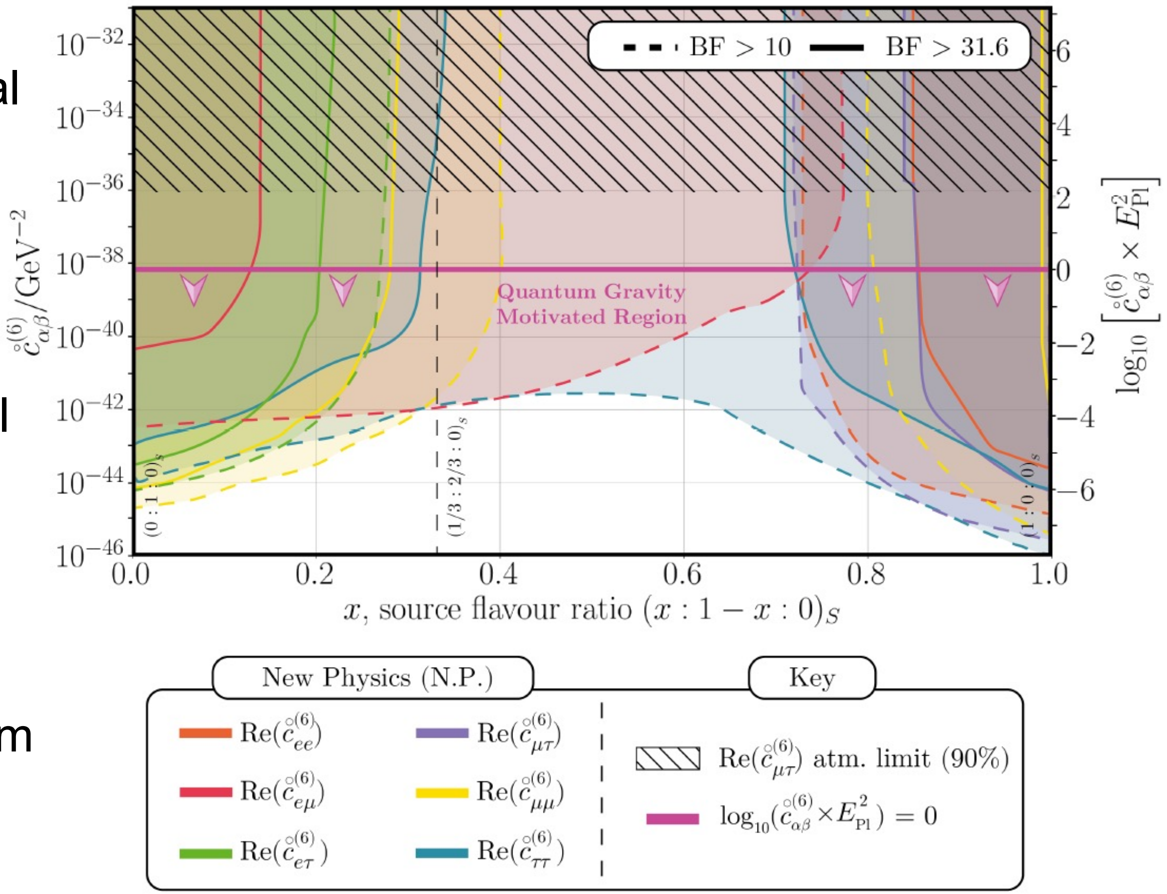
Results depend on astrophysical neutrino production models. We need to improve this;

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

dim-6 new physics operator limit



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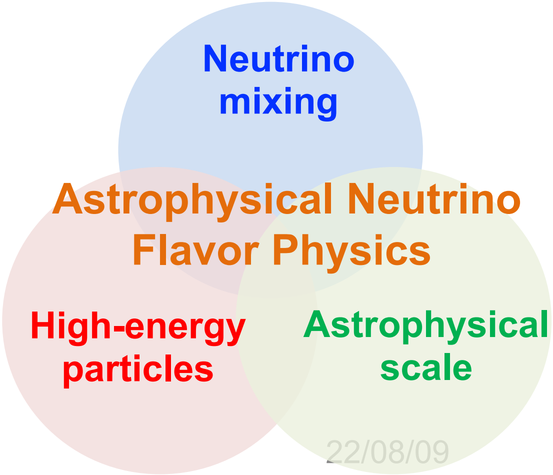
Results depend on astrophysical neutrino production models. We need to improve this;

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

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!



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!

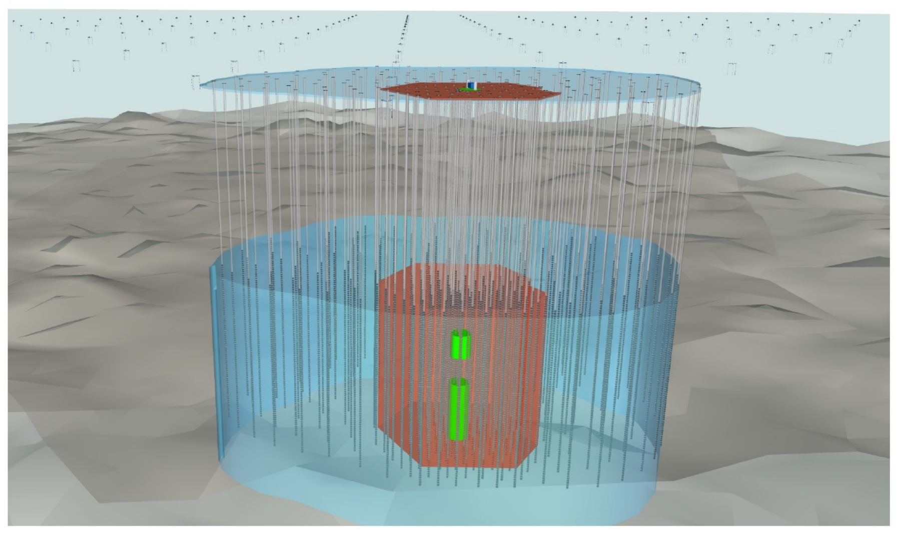
Backup

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

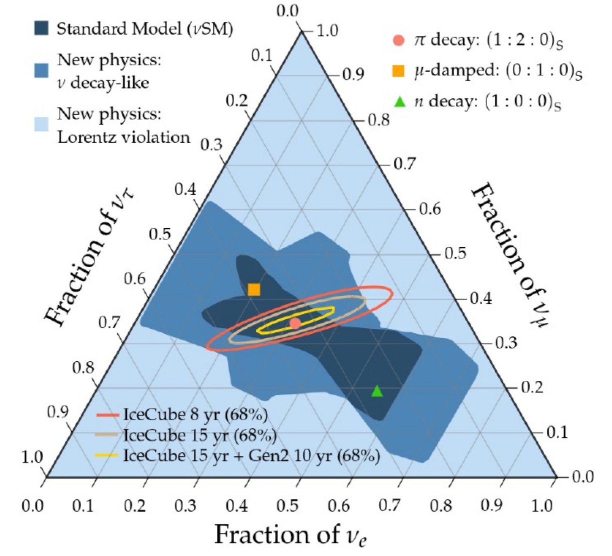
3. IceCube-Gen2

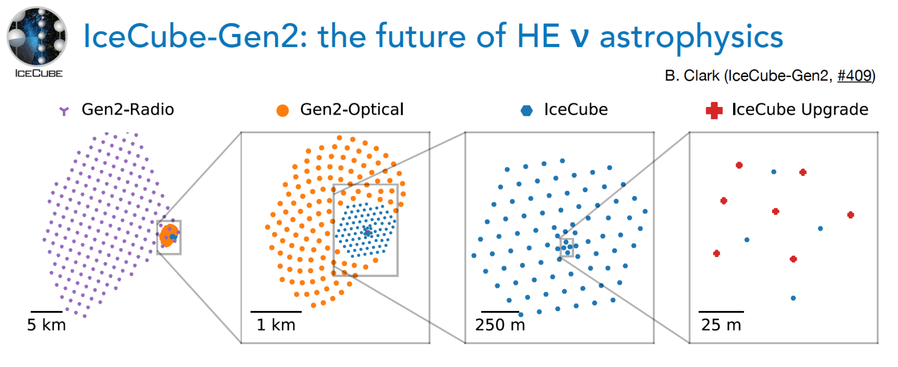
ICECUBE GEN2

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





IceCube-Gen2: the future of HE ν astrophysics

B. Clark (IceCube-Gen2, #409)

The first stage of Gen2 (IceCube upgrade) is ongoing

KING'S College LONDON

IceCube, PRD104(2021)022002

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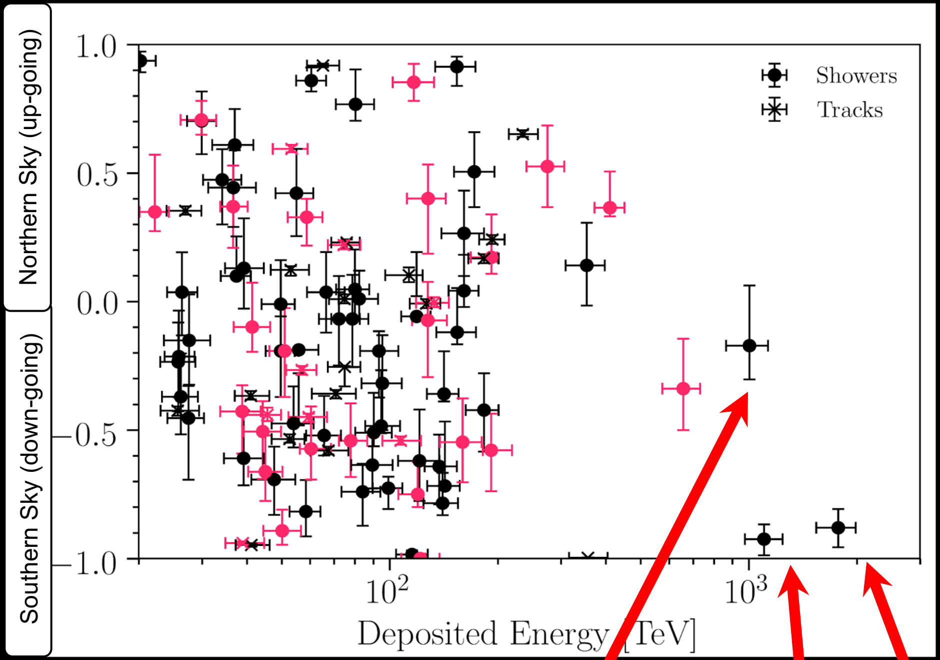
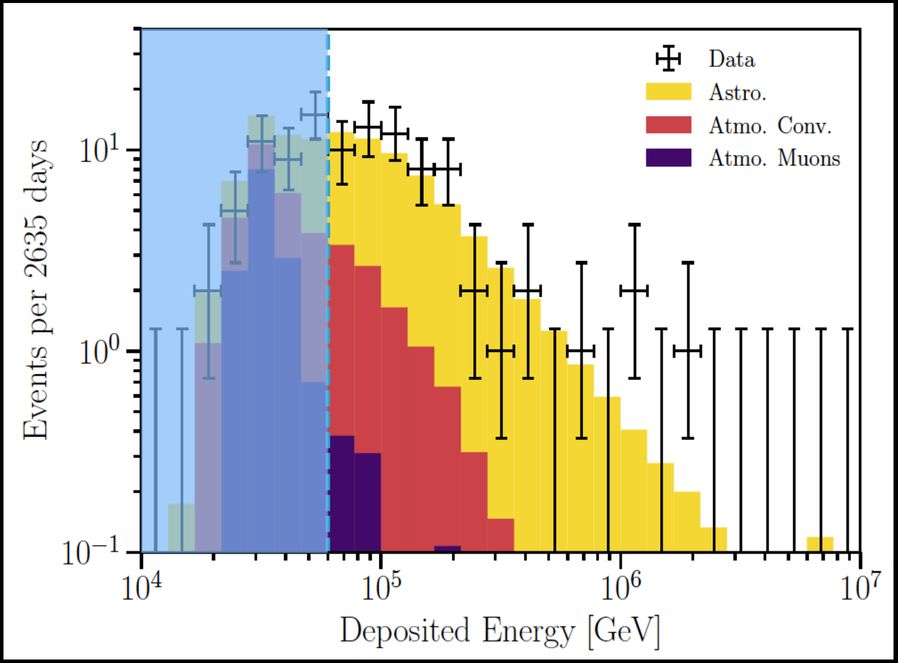
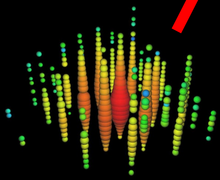
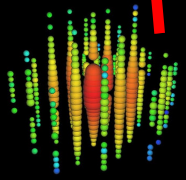


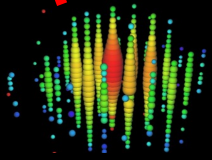


“Bert”
1.1 PeV





“Ernie”
1.0 PeV



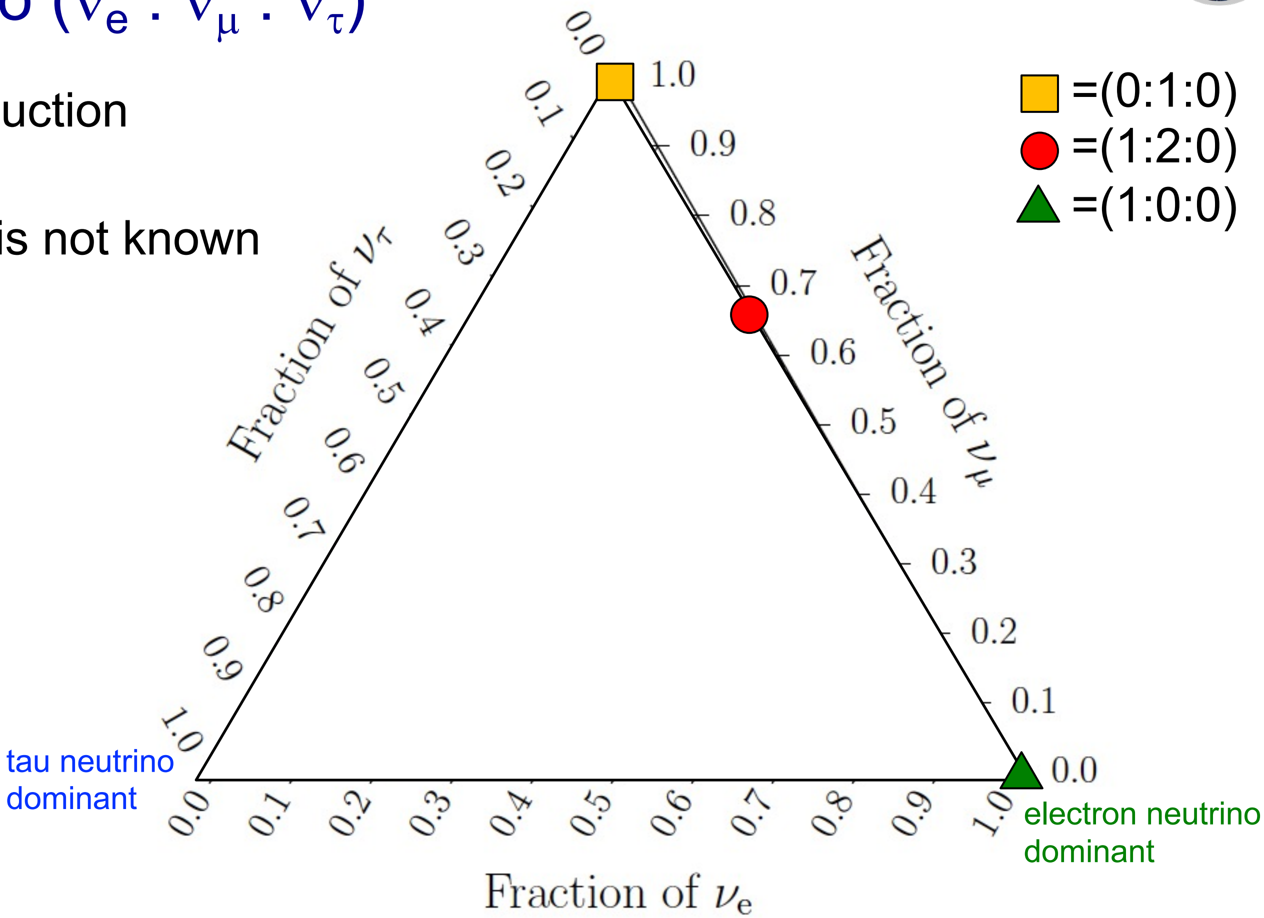
“Big Bird”
2.0 PeV

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


muon neutrino dominant

Argüelles, TK, Salvado, PRL115(2015)161303

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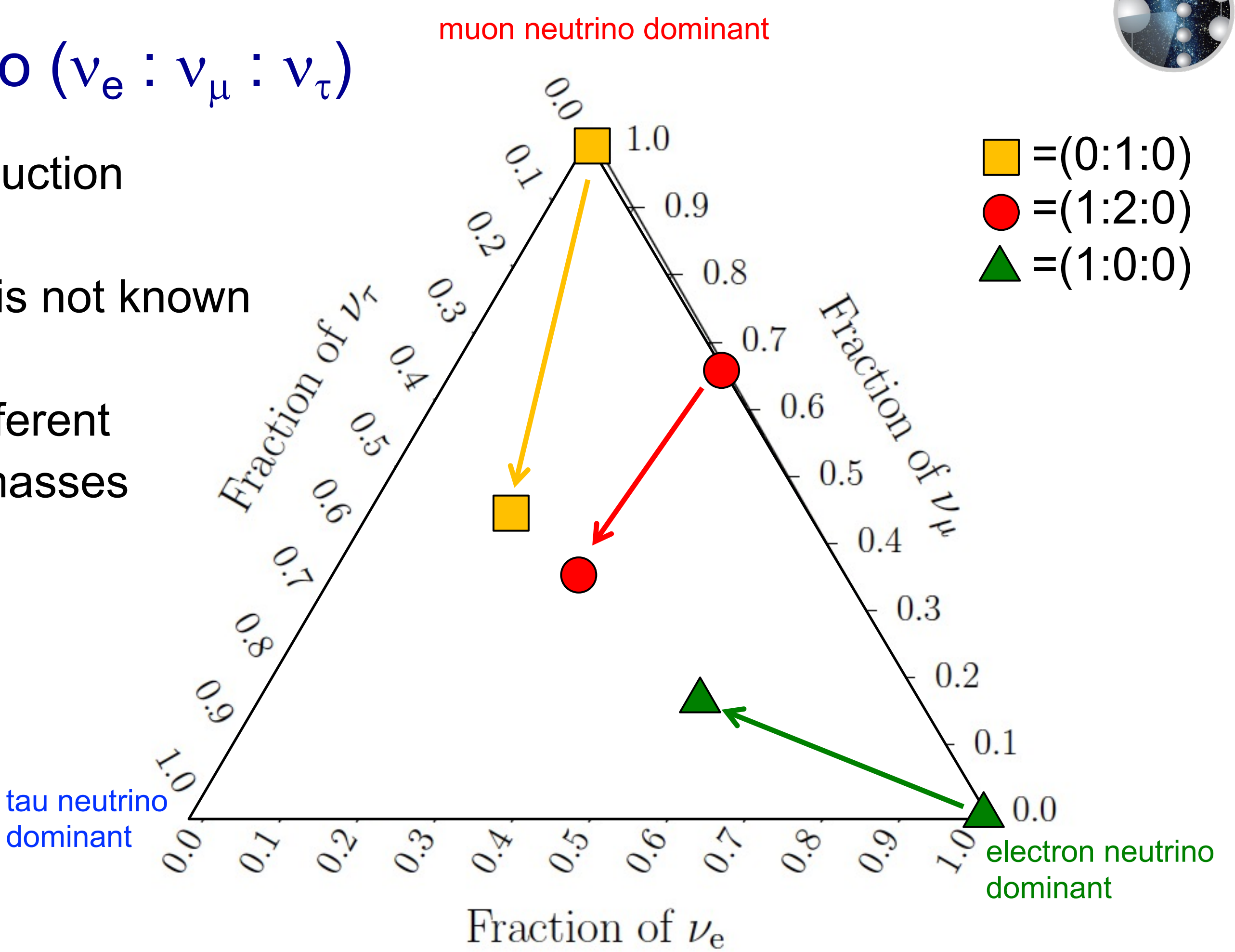
Flavour ratio on Earth is different due to mixing by neutrino masses



🟨 =(0:1:0)
● =(1:2:0)
▲ =(1:0:0)

$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:	
🟧	0:1:0 → 0.17 : 0.45 : 0.37
●	1:2:0 → 0.30 : 0.36 : 0.34
▲	1:0:0 → 0.55 : 0.17 : 0.28
◆	1:1:0 → 0.36 : 0.31 : 0.33

Argüelles, TK, Salvado, PRL115(2015)161303

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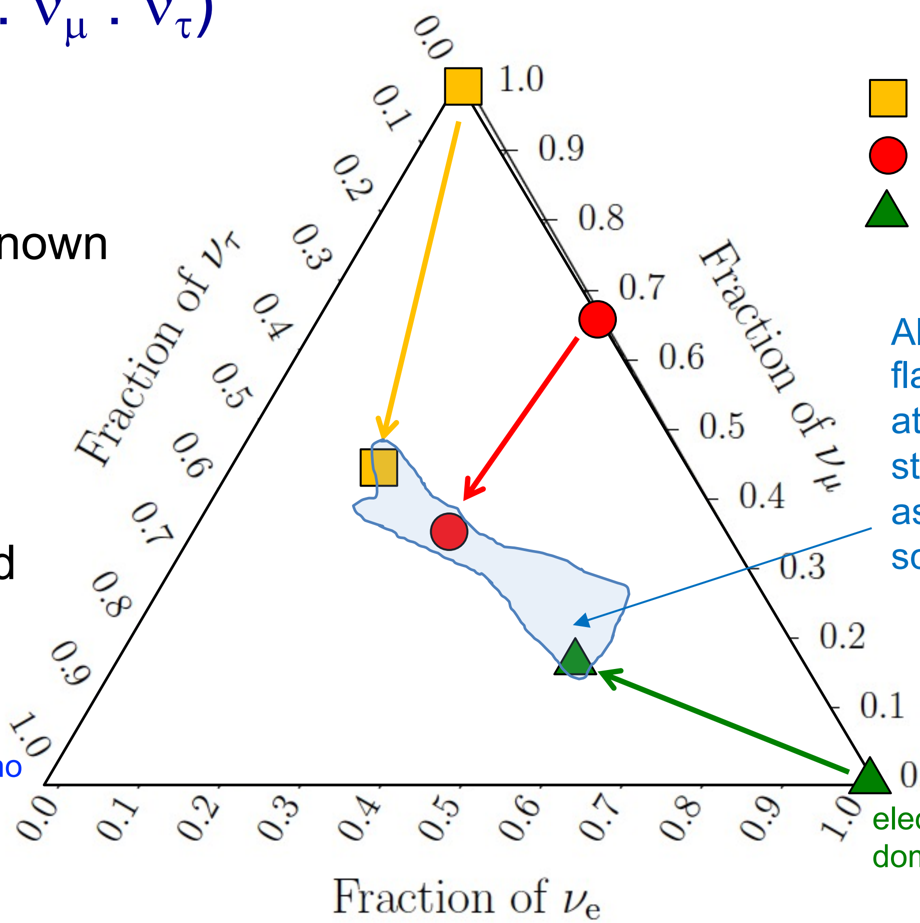
All possible flavour ratio is confined in a small space

muon neutrino dominant



🟧 =(0:1:0)
● =(1:2:0)
▲ =(1:0:0)

All possible flavour ratios at Earth by standard astrophysical scenario

tau neutrino dominant

electron neutrino dominant

$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:

🟧 0:1:0 → 0.17 : 0.45 : 0.37
● 1:2:0 → 0.30 : 0.36 : 0.34
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◆ 1:1:0 → 0.36 : 0.31 : 0.33

IceCube, ArXiv: 2011:03561

3. HESE 7.5-yr flavor ratio

60 HESE events in 60 TeV – 2 PeV

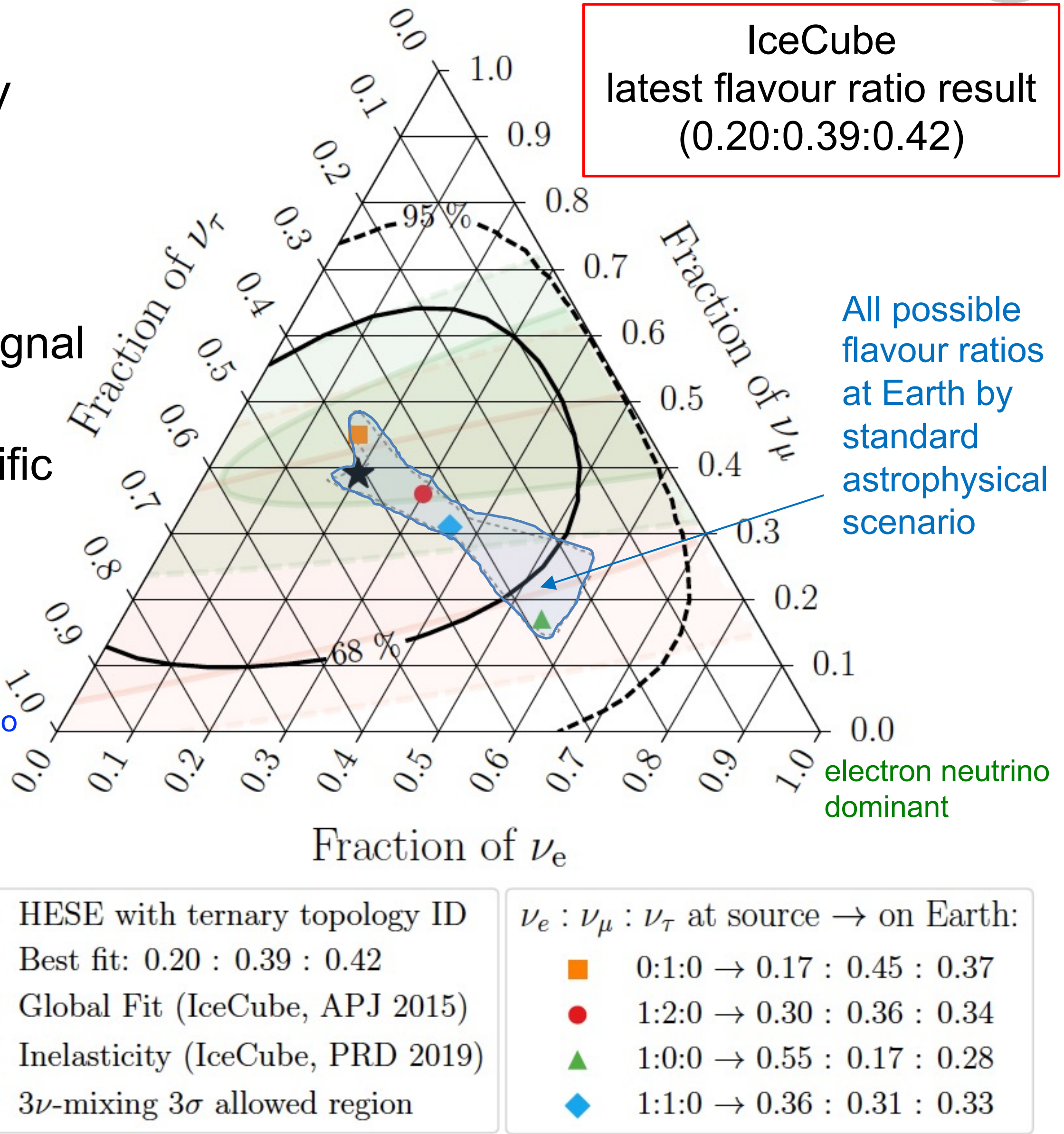
New flavour ratio measurement

- 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

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

muon neutrino dominant



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Argüelles, TK, Salvado, PRL115(2015)161303

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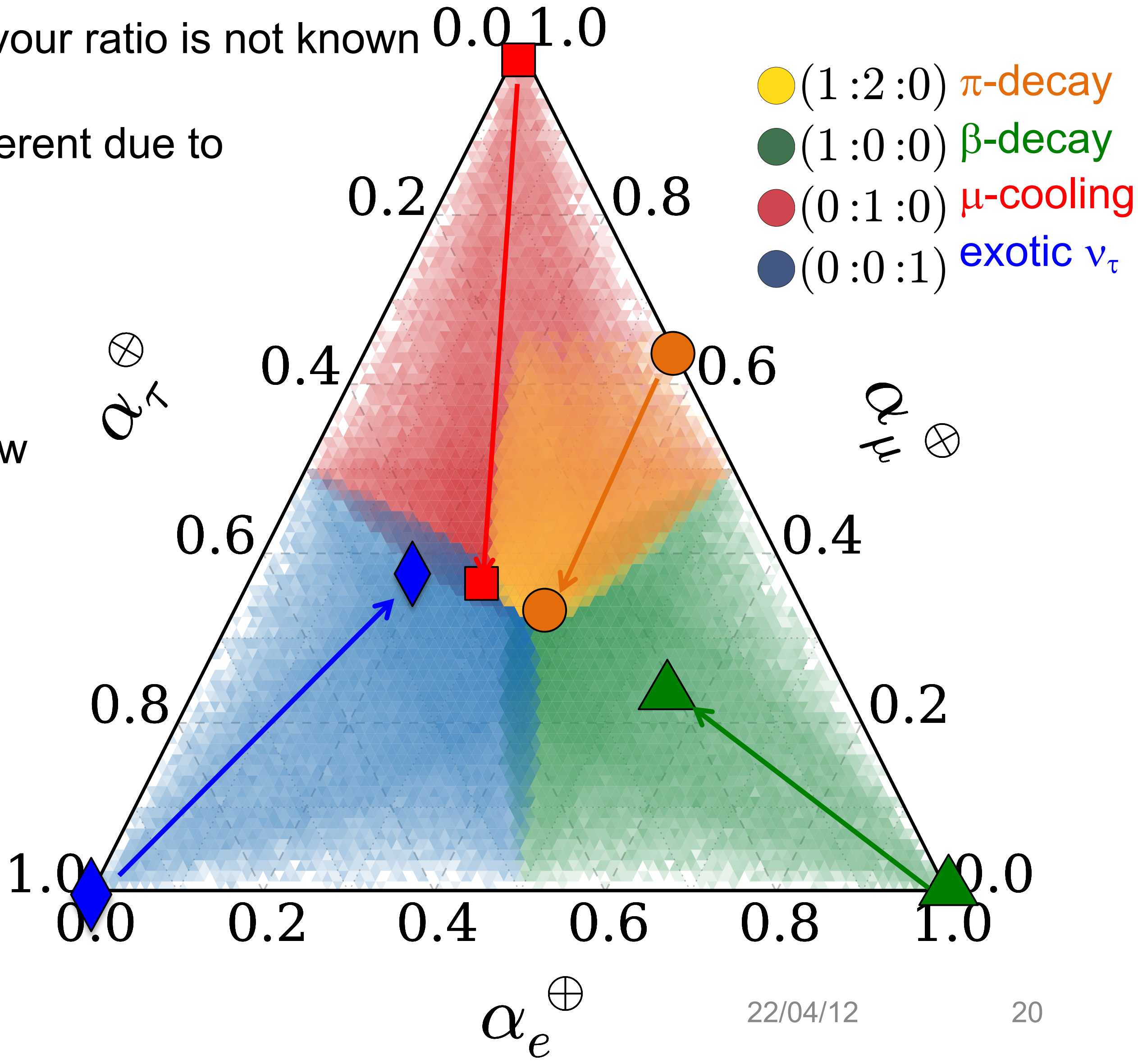
Astrophysical neutrino production mechanism is not known → production flavour ratio is not known

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



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)

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

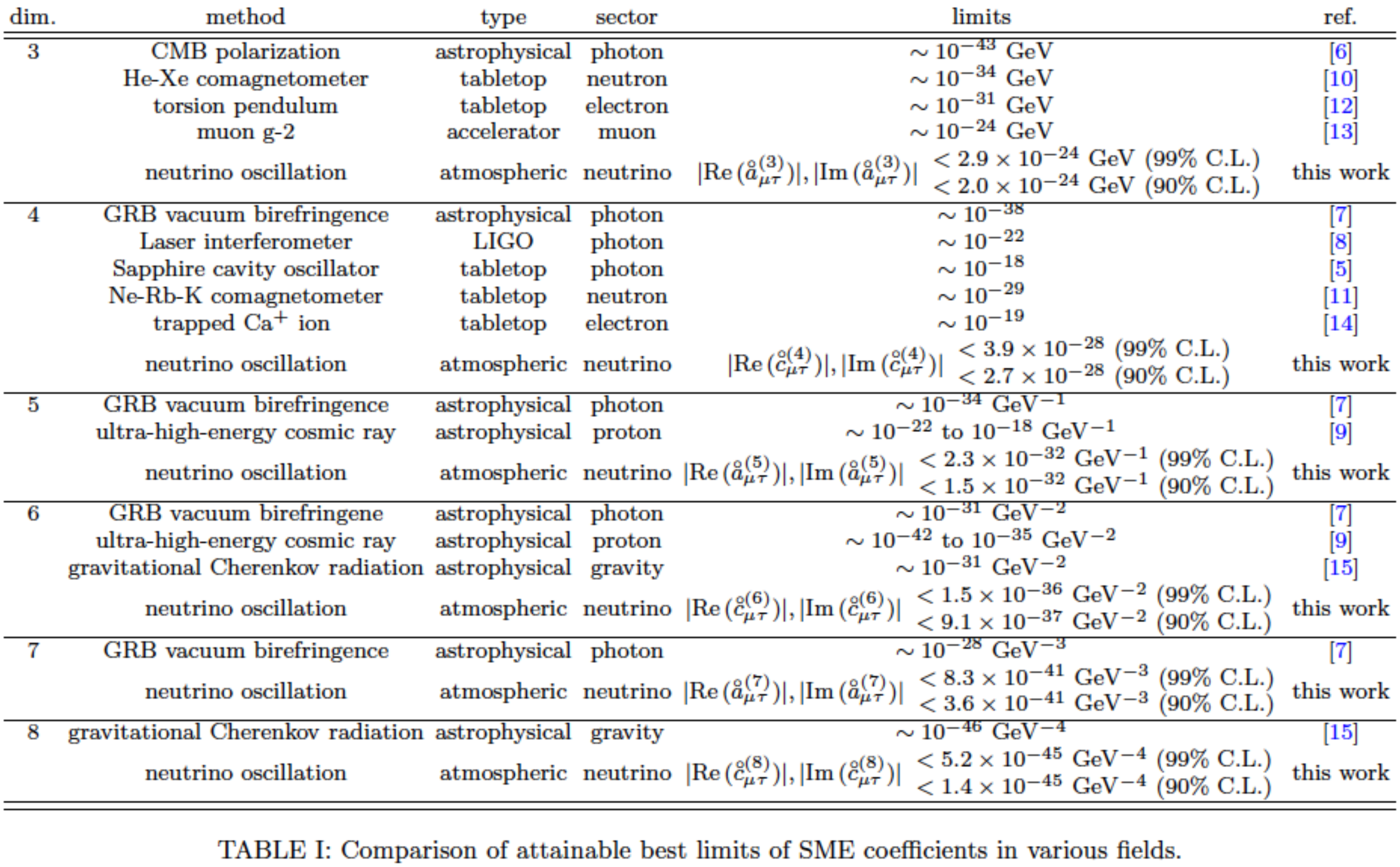
$$E^{3}c^{(6)}_{\alpha\beta} = E^{3}\begin{pmatrix} c^{(6)}_{ee} & c^{(6)}_{e\mu} & c^{(6)}_{\tau e} \\ c^{(6)*}_{e\mu} & c^{(6)}_{\mu\mu} & c^{(6)}_{\mu\tau} \\ c^{(6)*}_{\tau e} & c^{(6)*}_{\mu\tau} & c^{(6)}_{\tau\tau} \end{pmatrix}$$

IceCube is sensitive to higher dimension operators

dimension-6 operator natural scale: $c^{(6)}\sim\frac{1}{M^{2}_{Planck}}\sim10^{-38}GeV^{-2}$

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, $c^{(6)} \sim 10^{-38} GeV^{-2}$

Neutrino Standard Model (νSM) - Unknowns

SM + 3 active massive neutrinos

Neutrinos are least known particles!

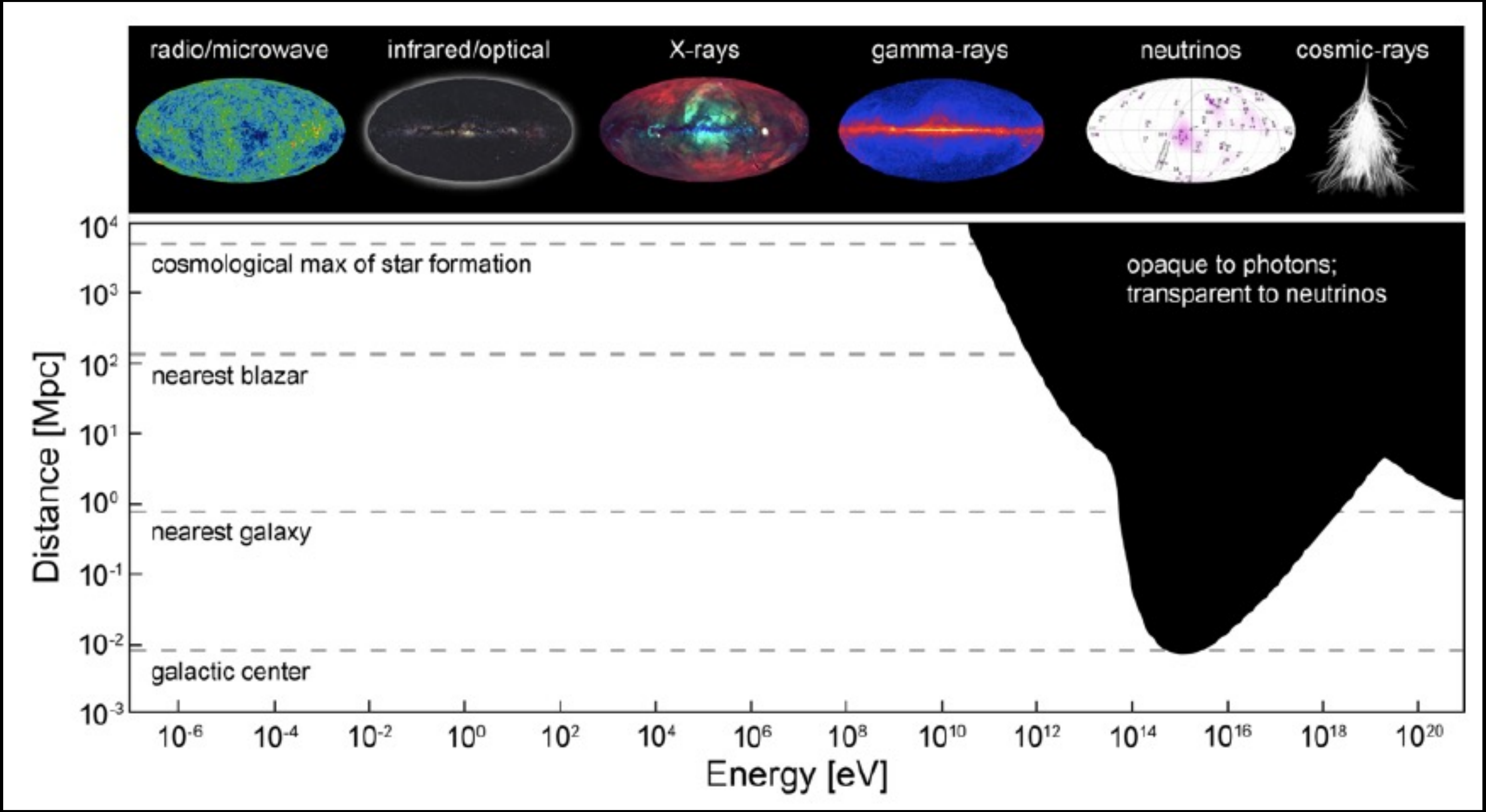
There are several unknowns and anomalies
→ Do they indicate new physics?

Unknown parameters of νSM

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

2. High-energy astrophysical neutrinos

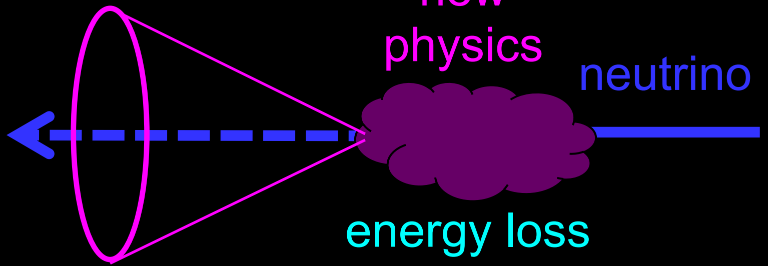
Above ~100 TeV, neutrinos are only particles pointing to their high-energy sources



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)



new physics

neutrino

energy loss

Z-boson

new physics

neutrino

photon

delay

mixing

neutrino mixing

New physics

astrophysical neutrino

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%)

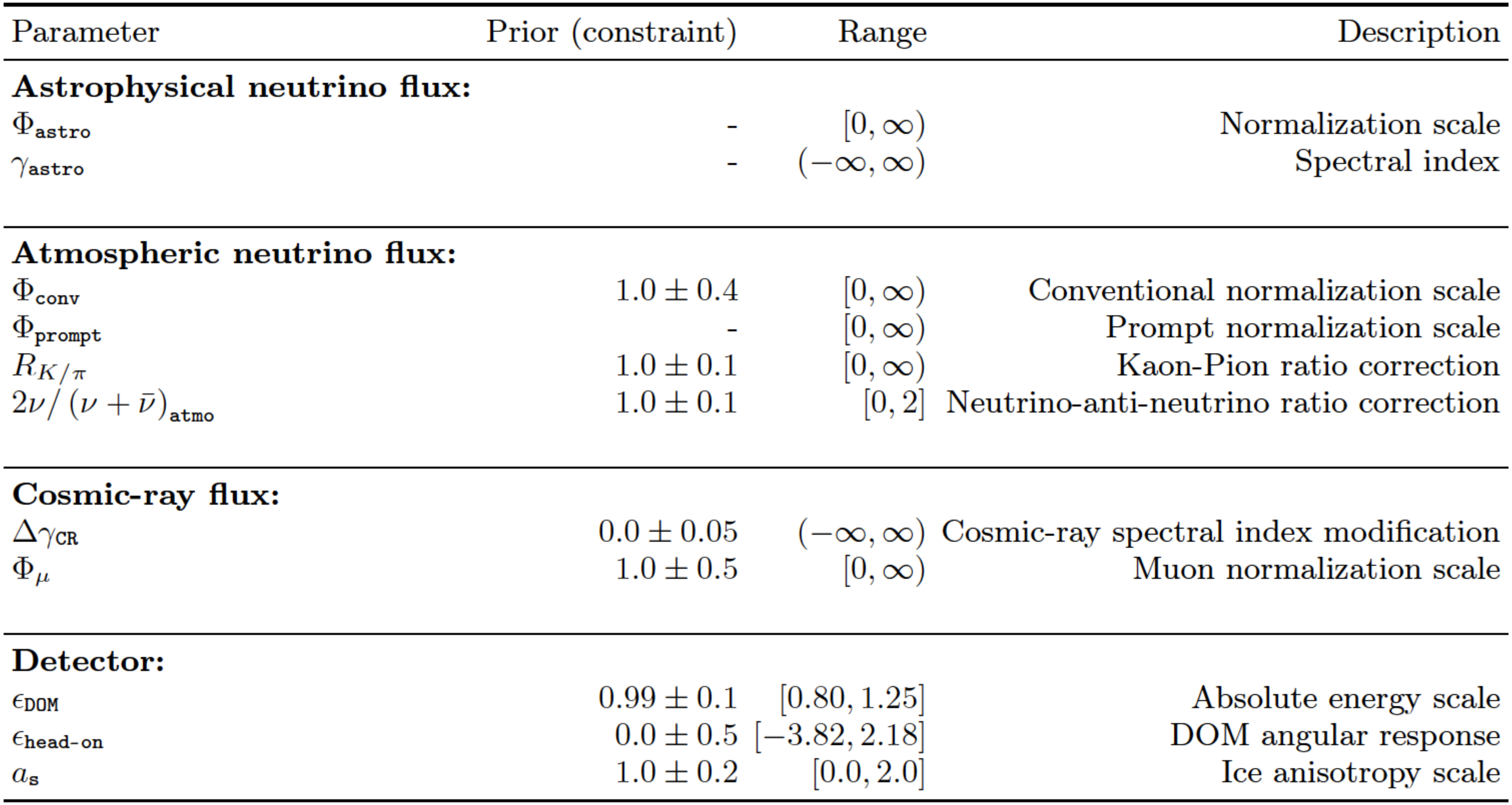
Limits

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

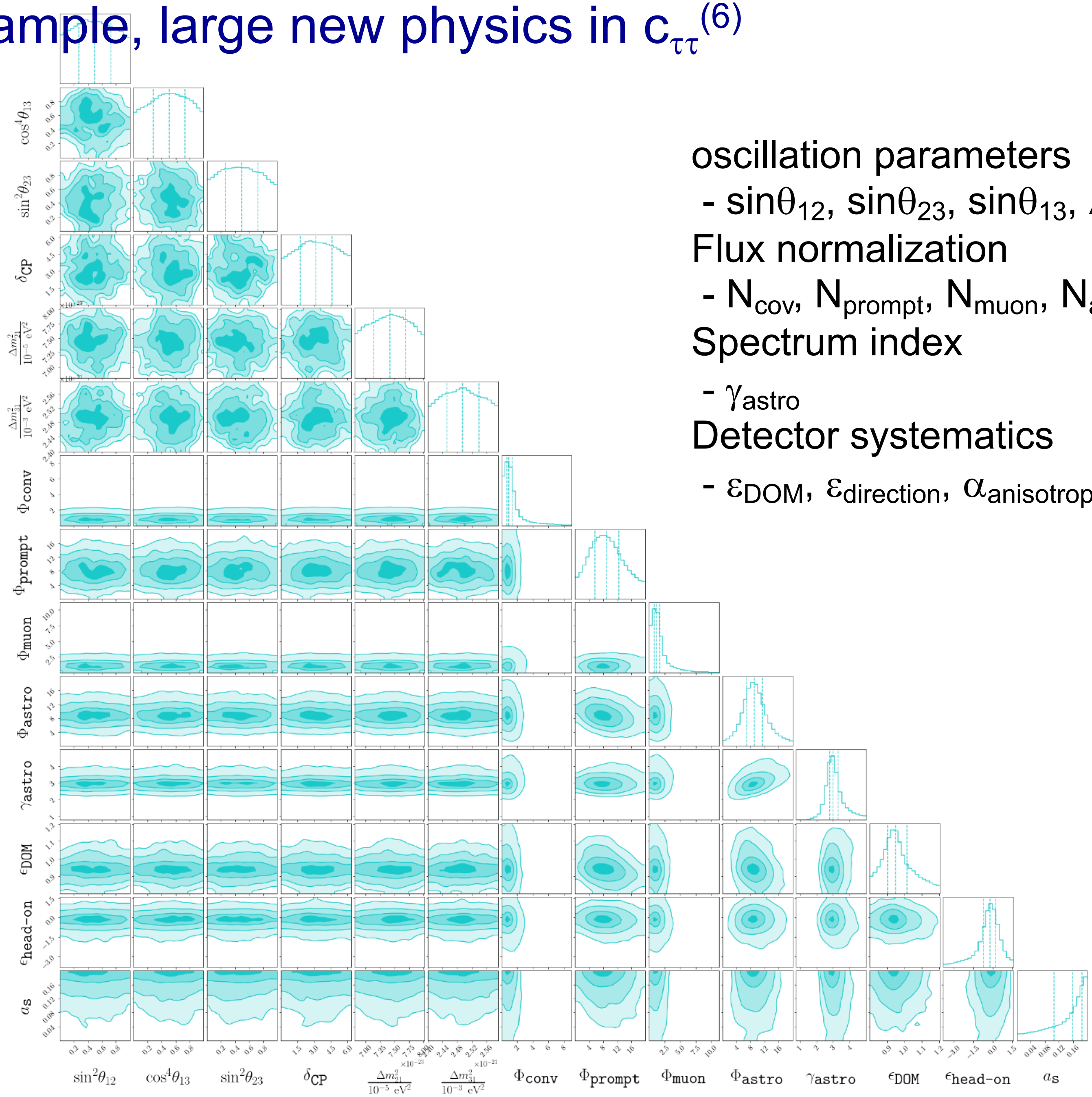
Systematic errors



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

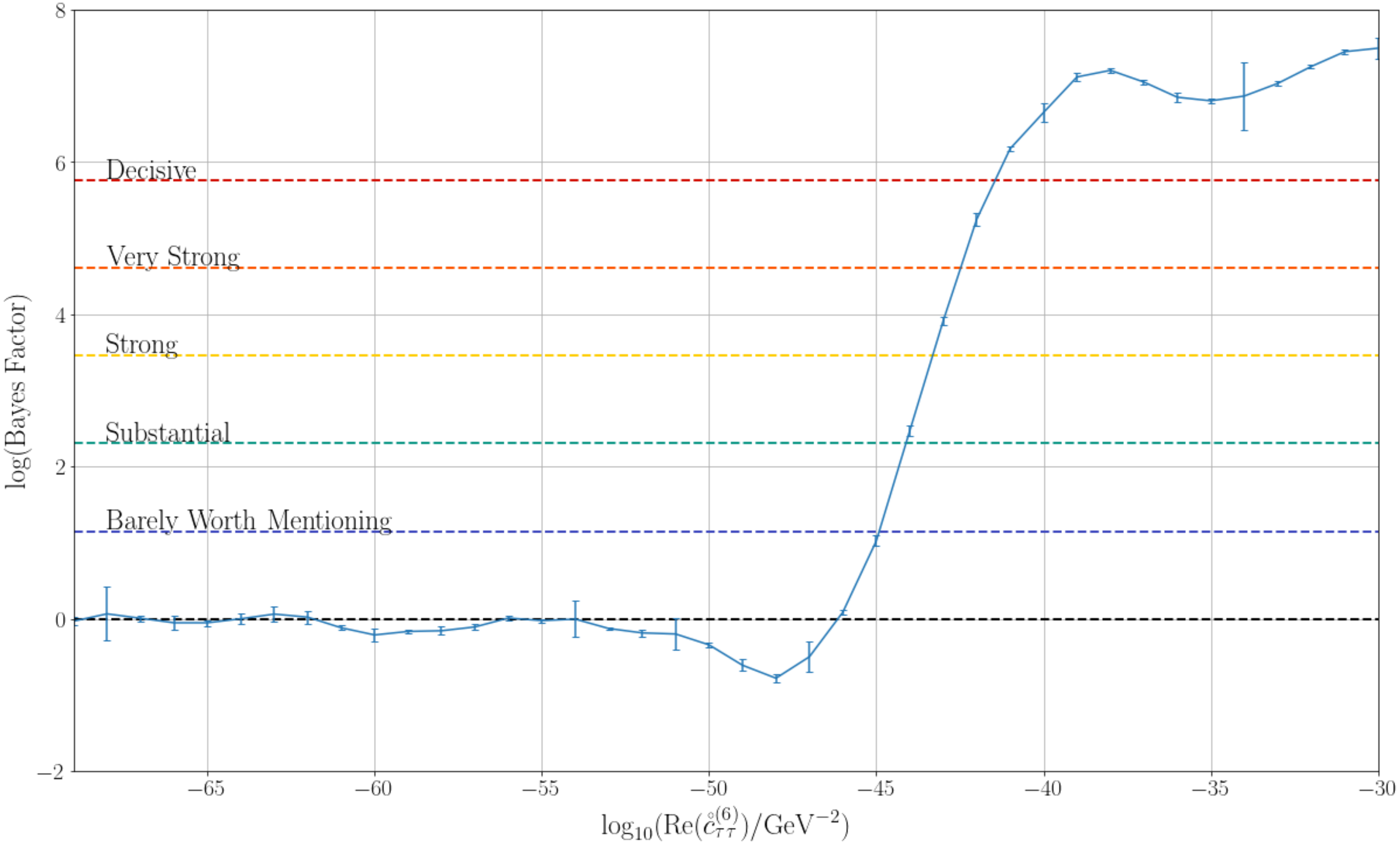
- ε_{DOM}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

09

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

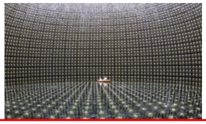
Bayesian analysis

- 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

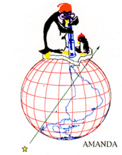


Super-Kamiokande

PRD91(2015)052003

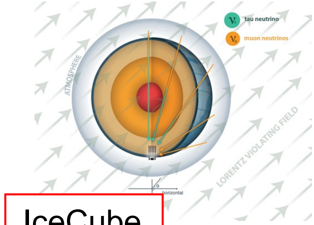
Daya Bay

PRD98(2018)092013



AMANDA

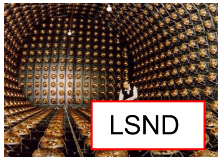
PRD79(2009)102005



IceCube

Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004

MiniBooNE

PLB718(2013)1303

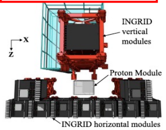
MINOS ND

PRL101(2008)151601

MINOS FD

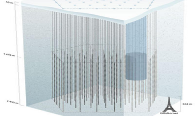
PRL105(2010)151601

T2K ND



PRD95(2017)111101

IceCube

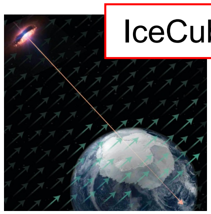


PRD82(2010)112003

Double Chooz

PRD86(2013)112009

Flavor ratio

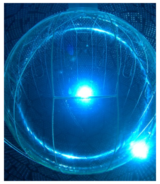


IceCube

ArXiv: 2111.04654

Seasonal variation

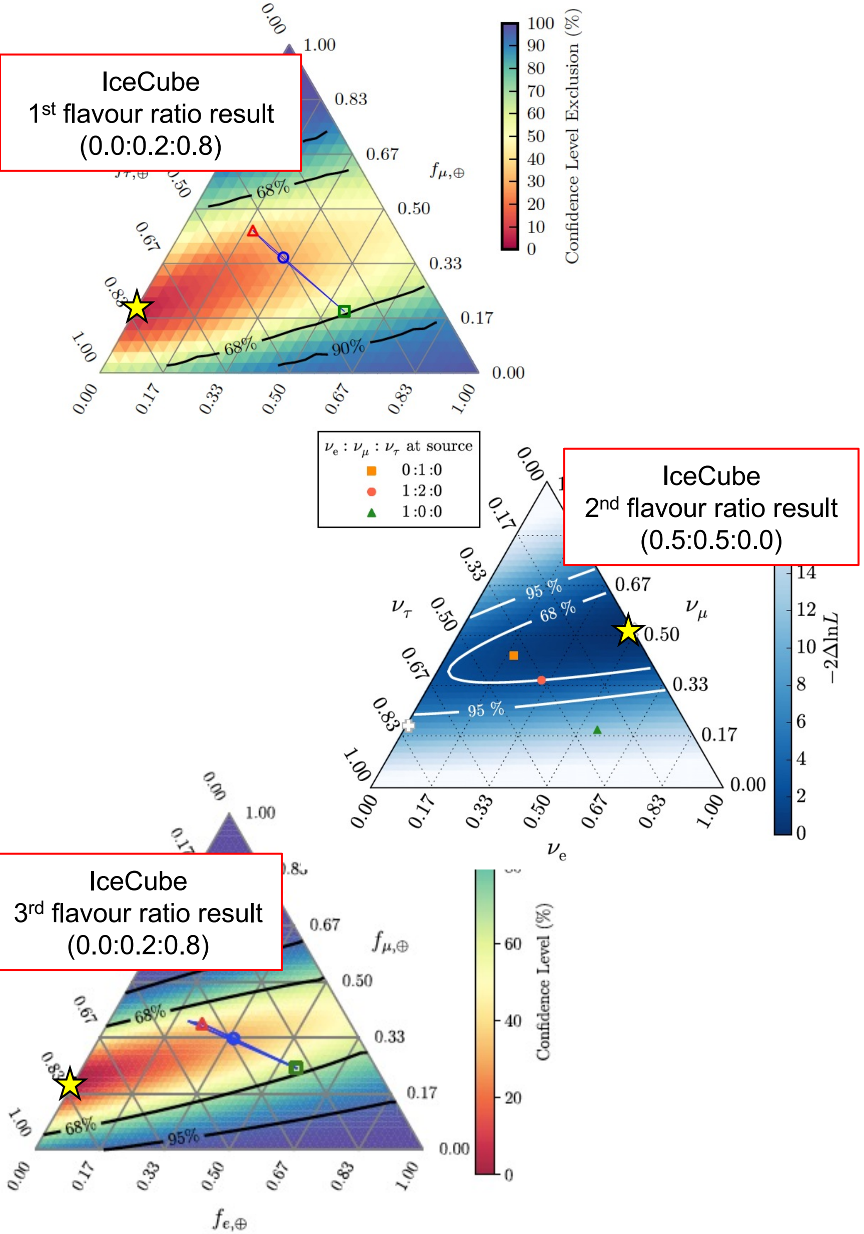
SNO



PRD98(2018)112013

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

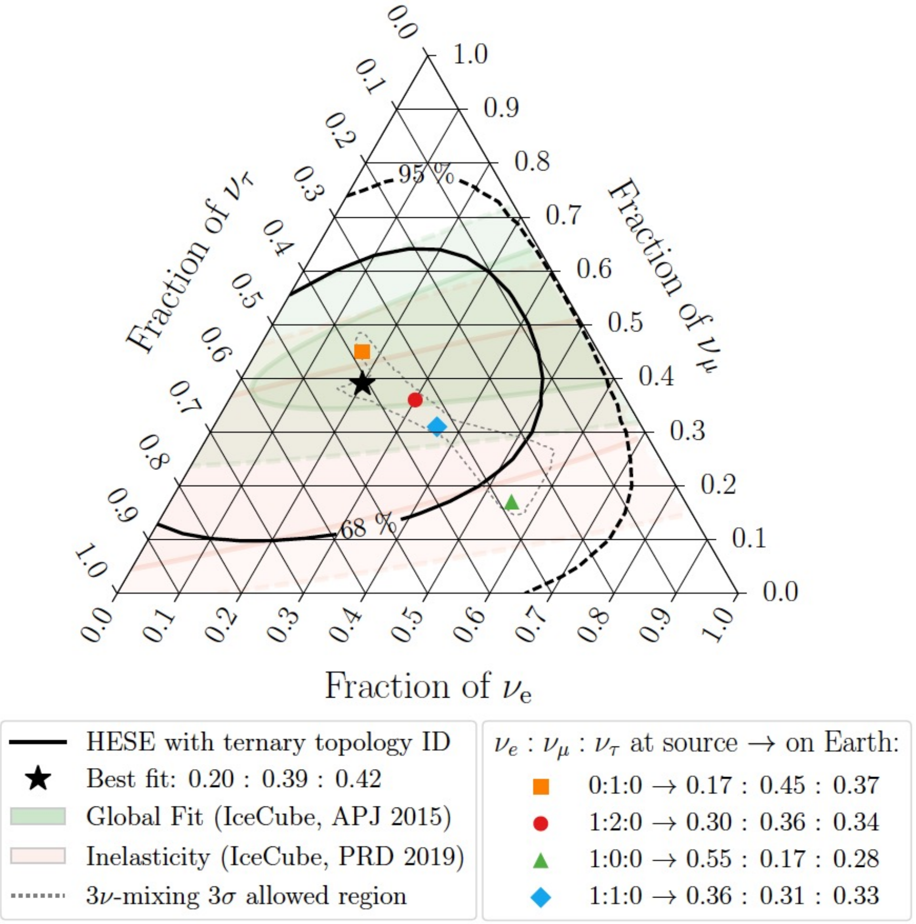
HESE 7.5-yr data (2018)



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)

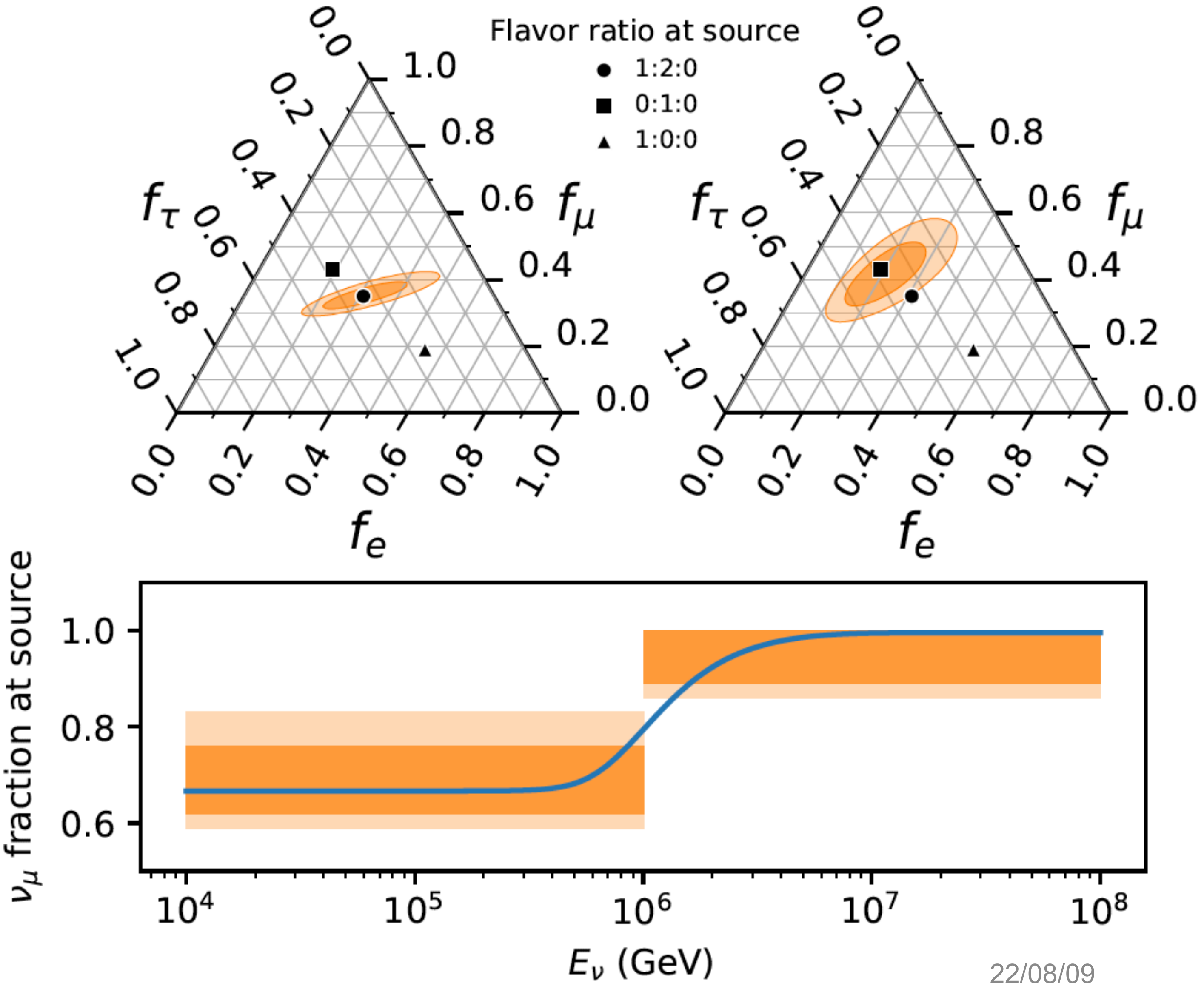


New flavour ratio measurement

- 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

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

Energy dependence of flavor ratio

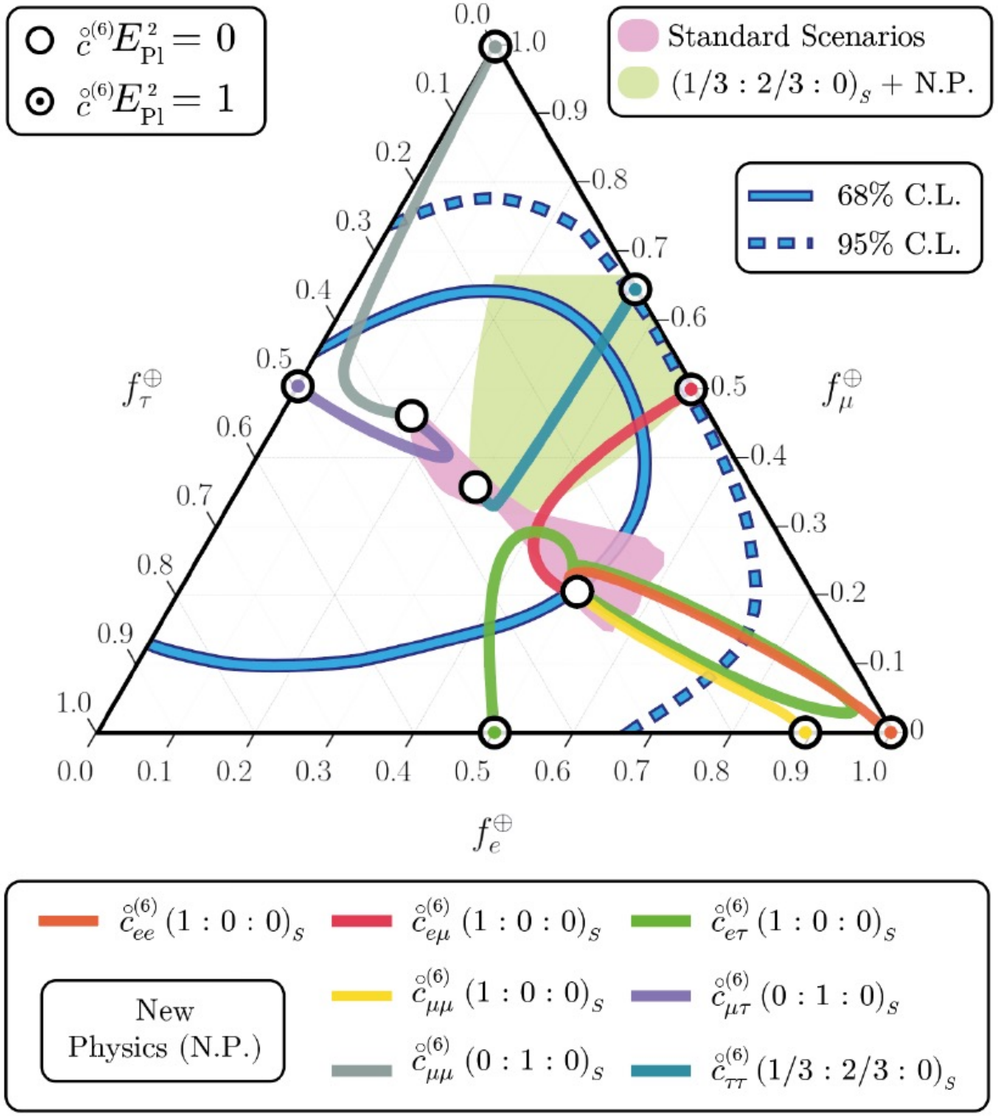


IceCube, ArXiv: 2111.04654

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

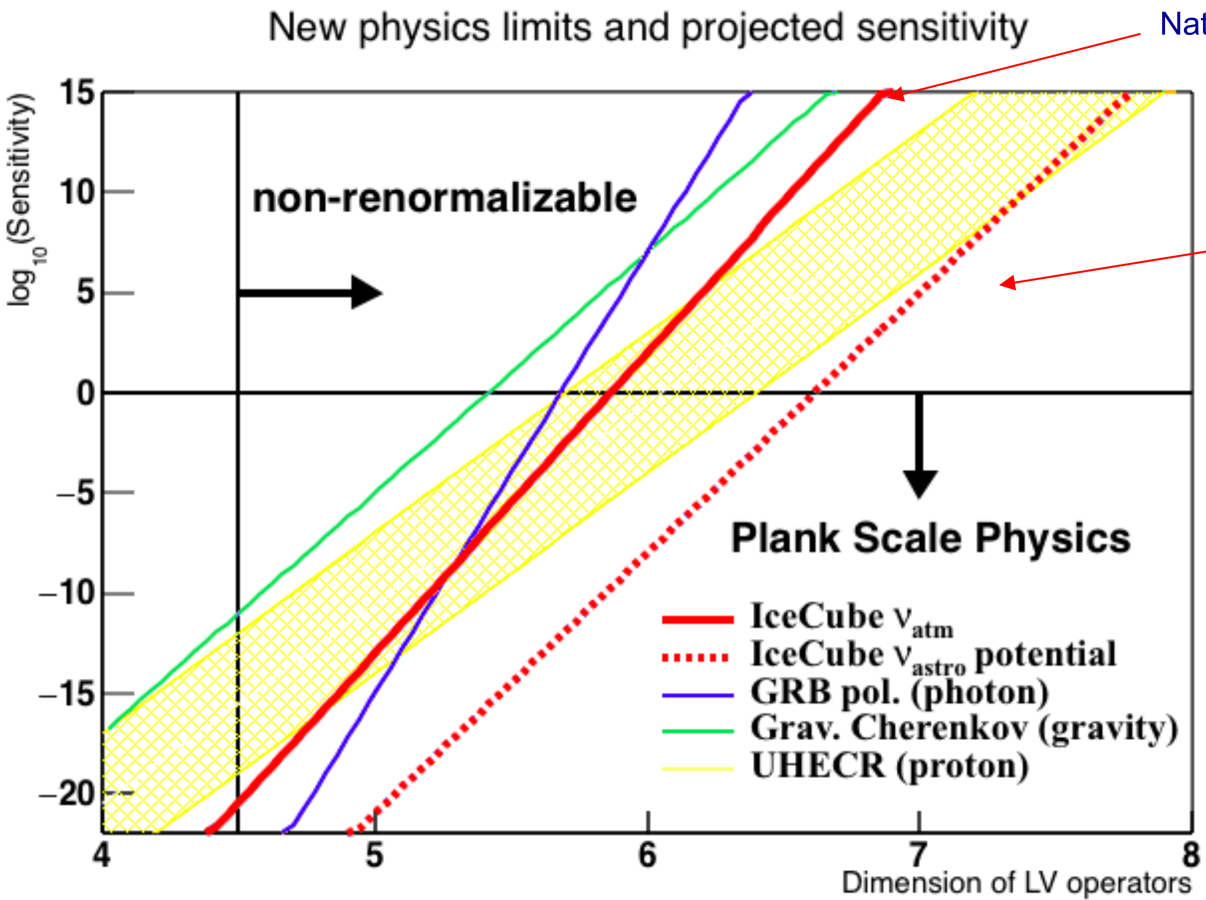


TK, arXiv:1906.09240

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)



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})