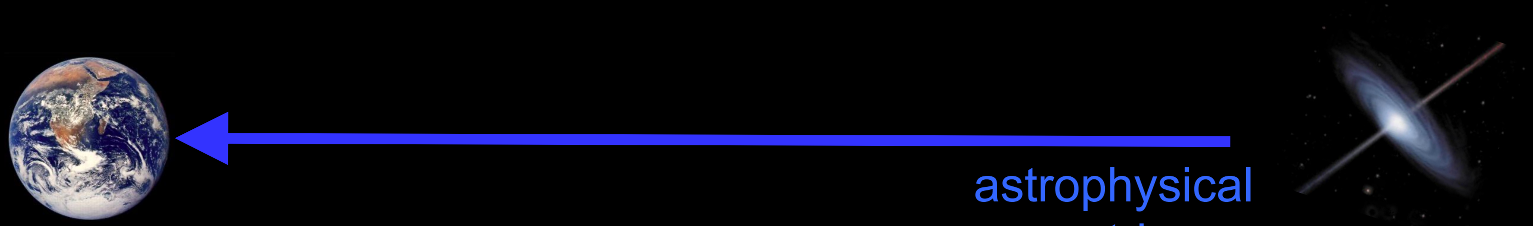
Search for Quantum Gravity Using Astrophysical Neutrino Flavour

IceCube, ArXiv:2111.04654

Teppei Katori for the IceCube collaboration
King's College London
Snowmass21 Neutrino BSM Physics workshop,
PITT PACC, Pittsburgh, Feb. 11, 2022

High-energy astrophysical neutrino flavour

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

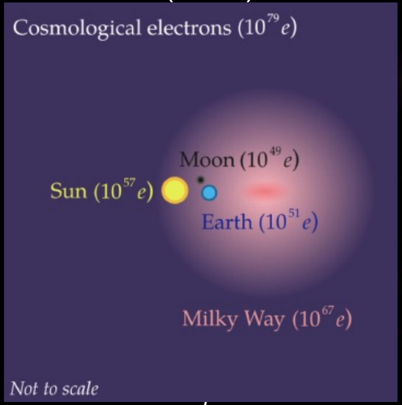


High-energy astrophysical neutrino flavour

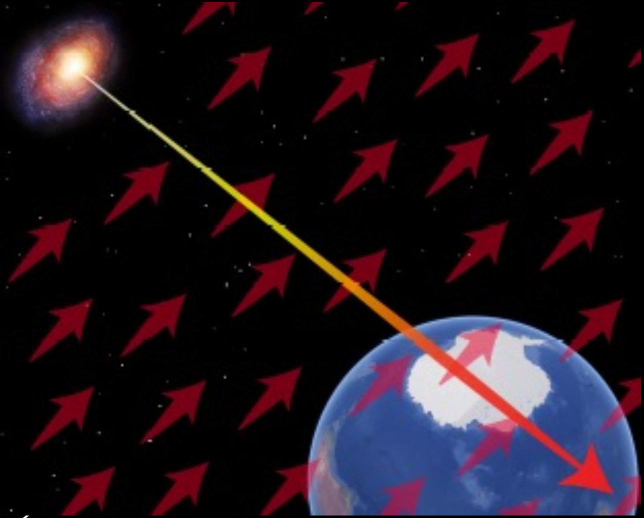
High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

Quantum foam
Ellis,Mavromatos,Nanopoulos
PLB293(1992)37

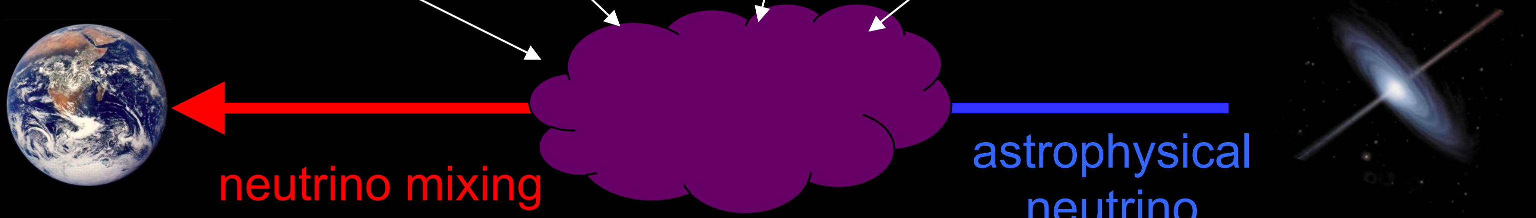
new long-range force
Bustamante,Agarwalla
PRL122(2019)061103



Lorentz violating field
Kostelecký Mewes,PRD69(2004)016005



Klop, Ando
PRD97(2018)063006
neutrino-dark energy coupling
etc...



neutrino mixing

New physics

astrophysical neutrino

Mewes and Kostelecký, PRD85(2012)096005

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

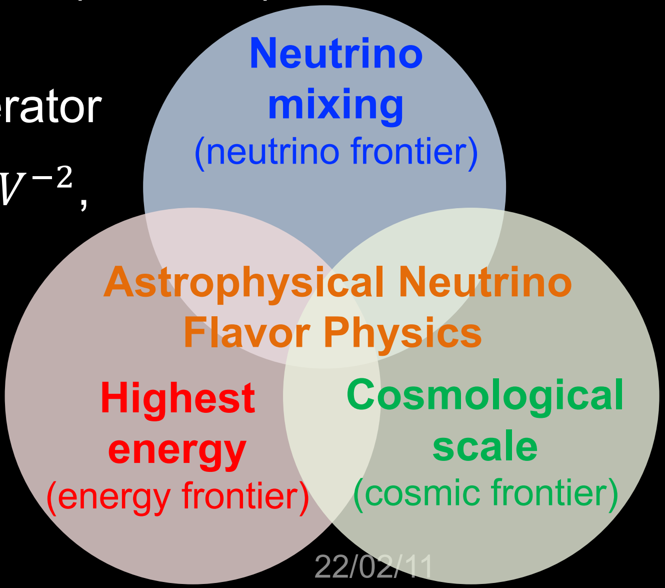
Standard Model

New physics (renormalizable)

higher dimension operator (non-renormalizable)

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

Astrophysical neutrino flavour sensitivity of dim-6 operator goes beyond the natural scale $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38}GeV^{-2}$, first time in any known scientific system



Neutrino mixing

(neutrino frontier)

Astrophysical Neutrino Flavor Physics

Highest energy

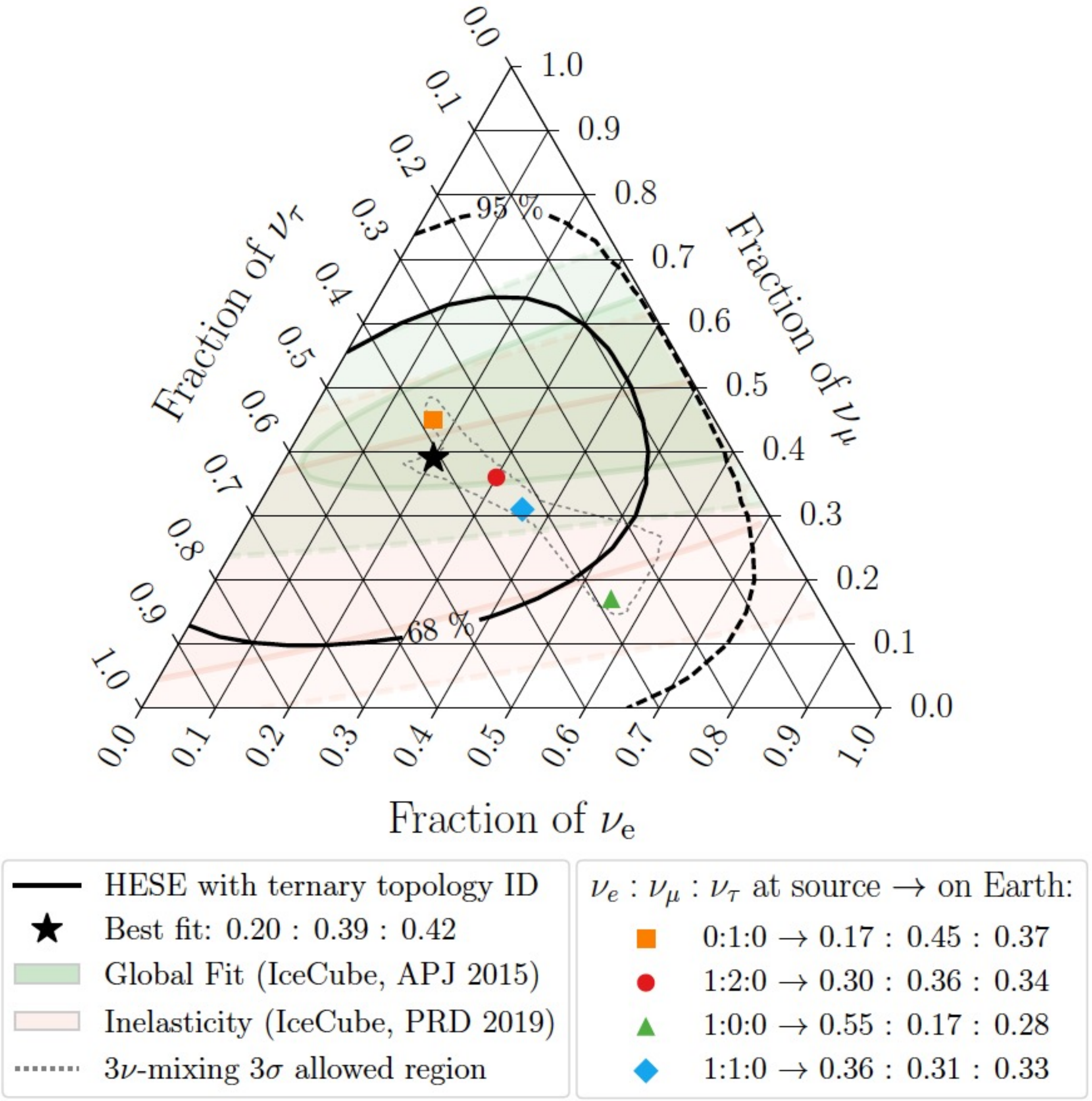
(energy frontier)

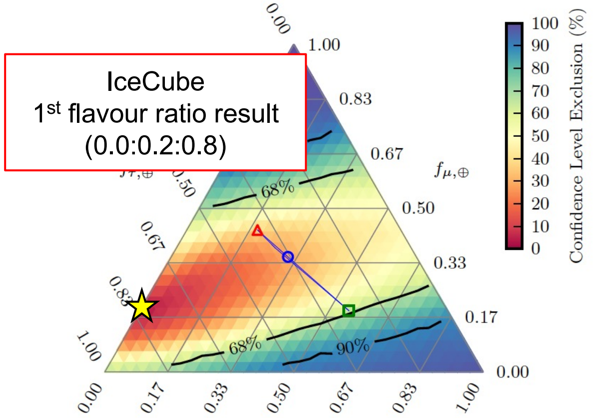
Cosmological scale

(cosmic frontier)

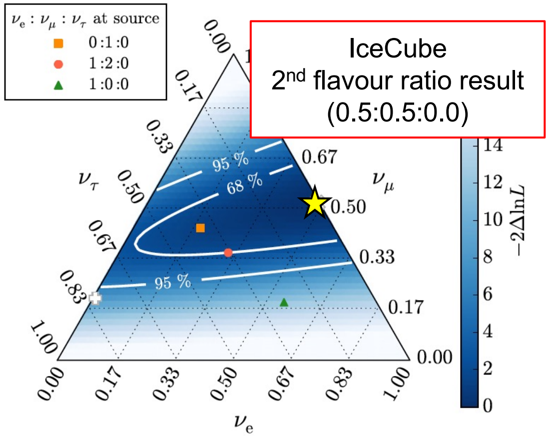
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, ArXiv:2011:03560

HESE 7.5-yr flavor ratio (2018)

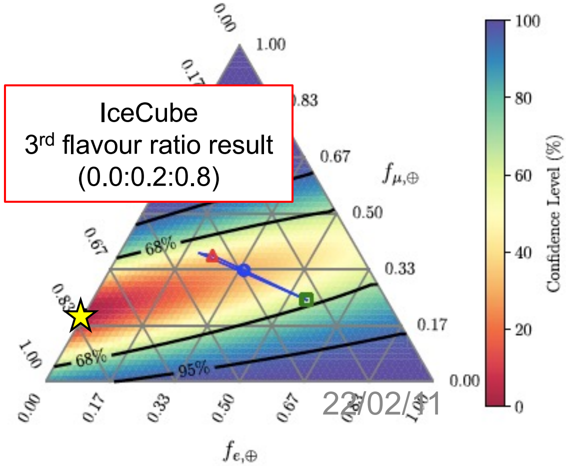




IceCube
1st flavour ratio result
(0.0:0.2:0.8)



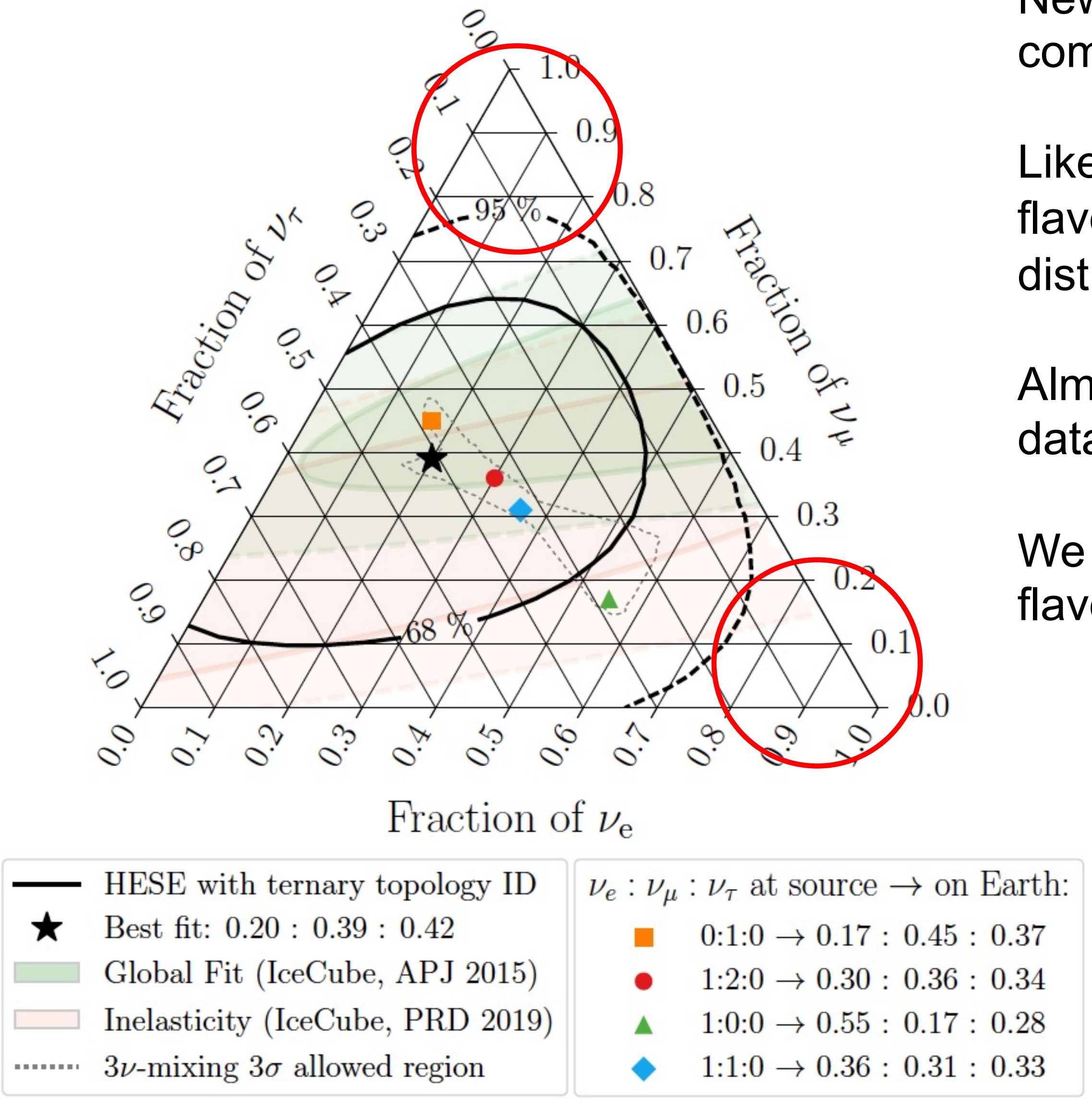
IceCube
2nd flavour ratio result
(0.5:0.5:0.0)



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

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

HESE 7.5-yr flavor ratio (2018)



New HESE analysis included more comprehensive systematic errors

Likelihood includes tau PID, new flavour ratio result has some power to distinguish ν_e and ν_τ

Almost all flavour ratio is allowed from data, except regions near 2 corners

We can test scenarios which predict flavour ratio in those regions

Search for Quantum Gravity Using Astrophysical Neutrino Flavour

Strong limits for many parameters depending on assumed initial flavour ratio

$a^{(3)}_{\alpha\beta}\sim10^{-27}$ GeV

$c^{(4)}_{\alpha\beta}\sim10^{-33}$

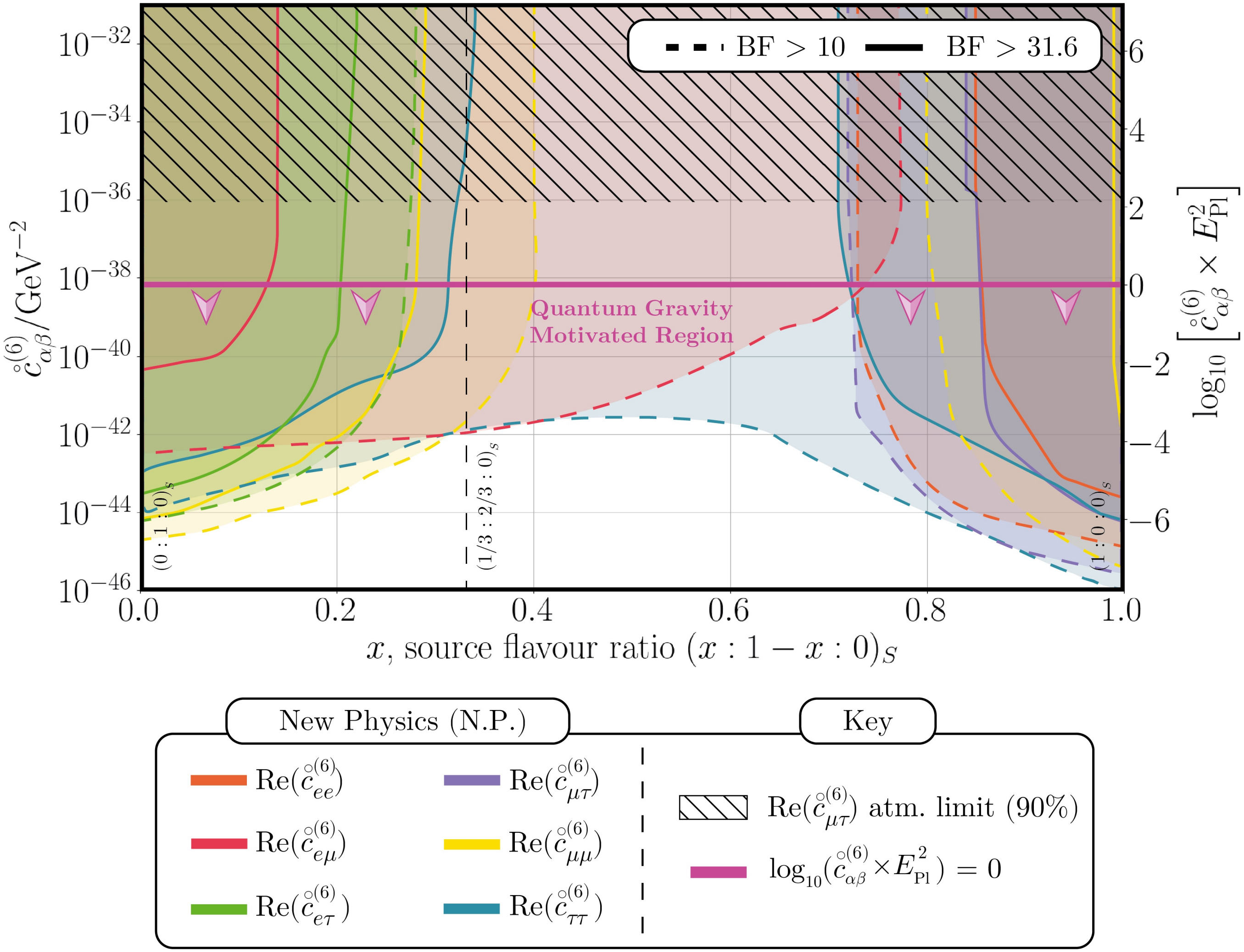
$a^{(5)}_{\alpha\beta}10^{-39}$ GeV^{-1}

$c^{(6)}_{\alpha\beta}\sim10^{-45}$ GeV^{-2}

$a^{(7)}_{\alpha\beta}\sim10^{-49}$ GeV^{-3}

$c^{(8)}_{\alpha\beta}\sim10^{-55}$ GeV^{-4}

But not many limits for standard flavour ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1/3:2/3:0)$



Search for Quantum Gravity Using Astrophysical Neutrino Flavour – Next step

Does quantum gravity-motivated physics exist? Do we have new structure in vacuum and space-time? Say YES!

1. Better particle ID (IceCube)
Next generation tau PID will improve the flavour ratio measurement

2. Combined analysis (IceCube)
Maximize statistical power, constrain systematics from different samples

3. Astrophysical neutrino production model constraints (astrophysics)
New constraints on flavour structure, power spectrum, normalization will improve this analysis

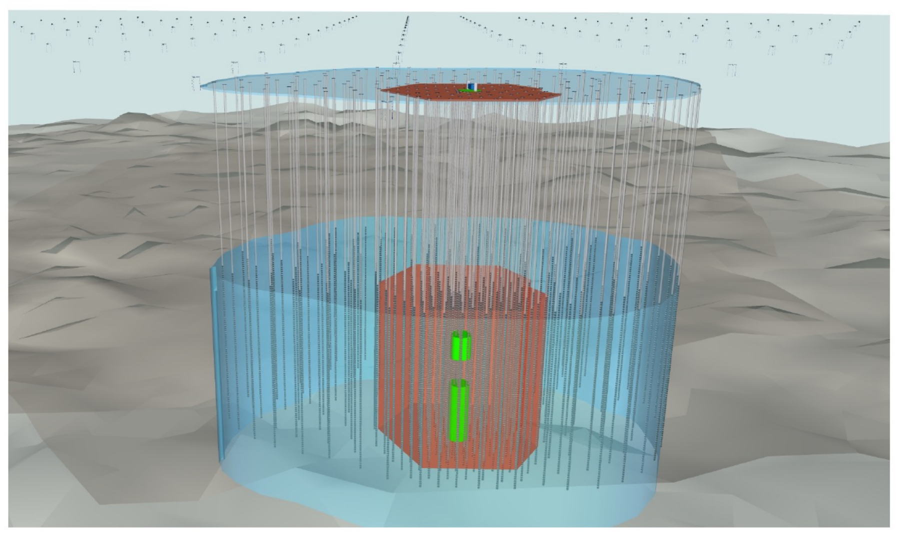
4. More precise oscillation parameter measurements (oscillation physics)
Smaller neutrino mass errors will improve this analysis

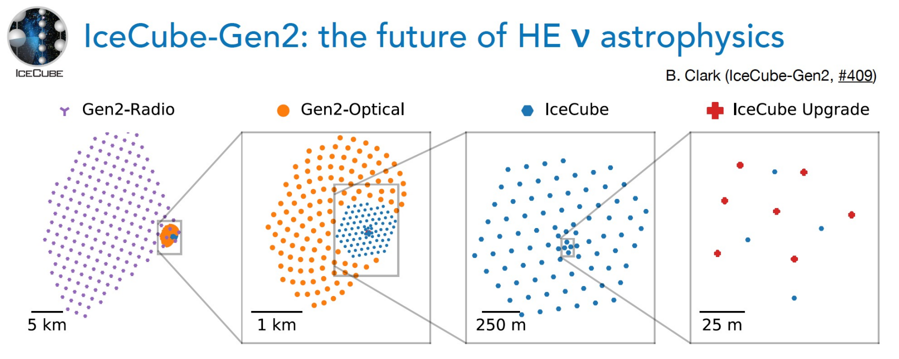
5. New experiments

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

IceCube-Gen2

IceCube-Gen2

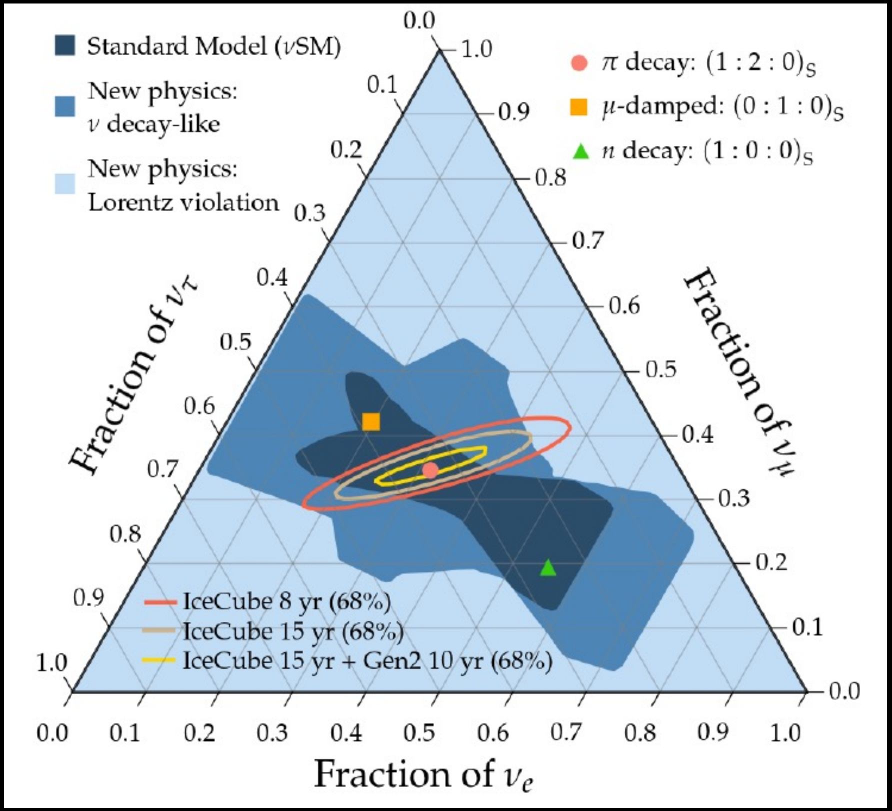




IceCube-Gen2: the future of HE ν astrophysics

B. Clark (IceCube-Gen2, #409)

IceCube-Gen2 flavour ratio sensitivity

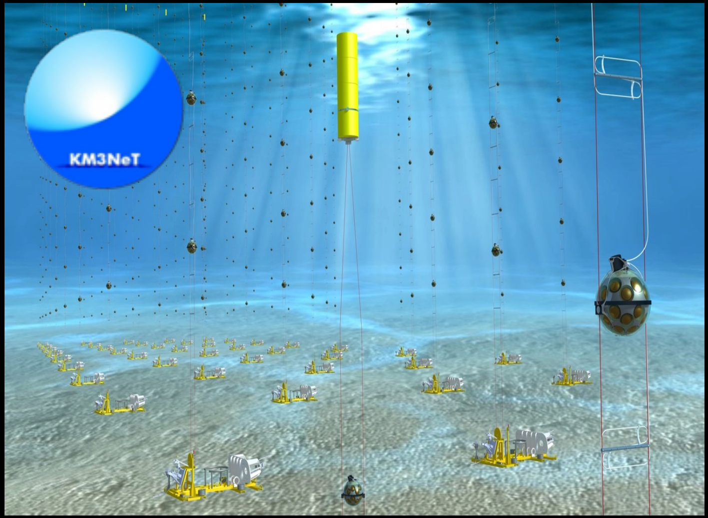


IceCube-Gen2, J.Phys.G48(2021)060501,P-ONE,Nature Astronomy 4(2020)913,Baikal-GVD,EPJC81(2021)1025
Song et al., JCAP04(2021)054

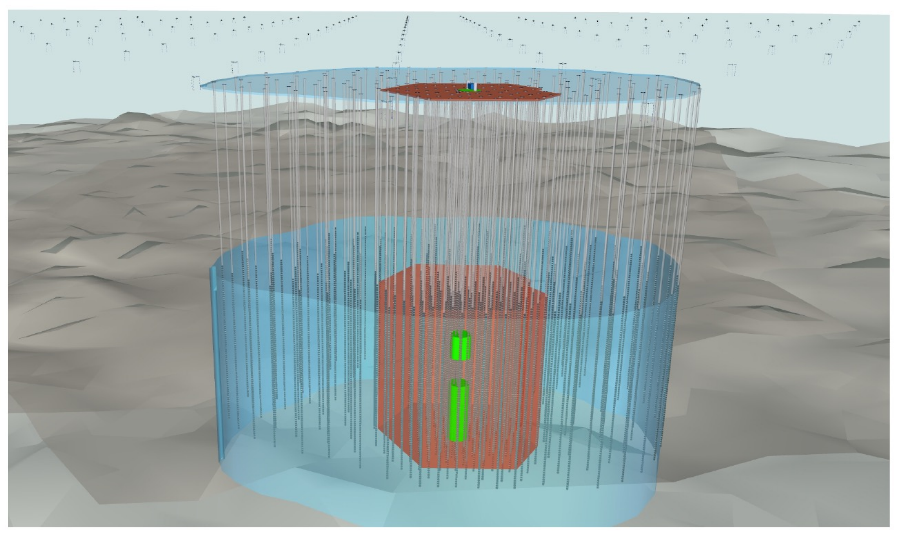
Future HENTs (high-energy neutrino telescopes)

GEN2

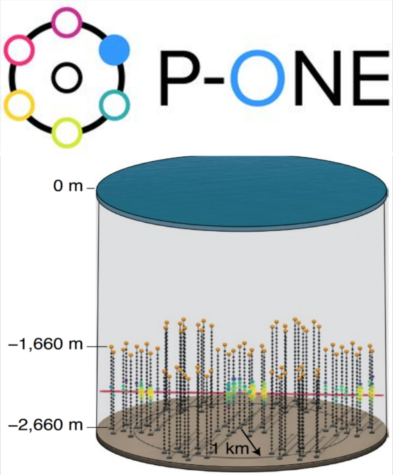
KM3NeT

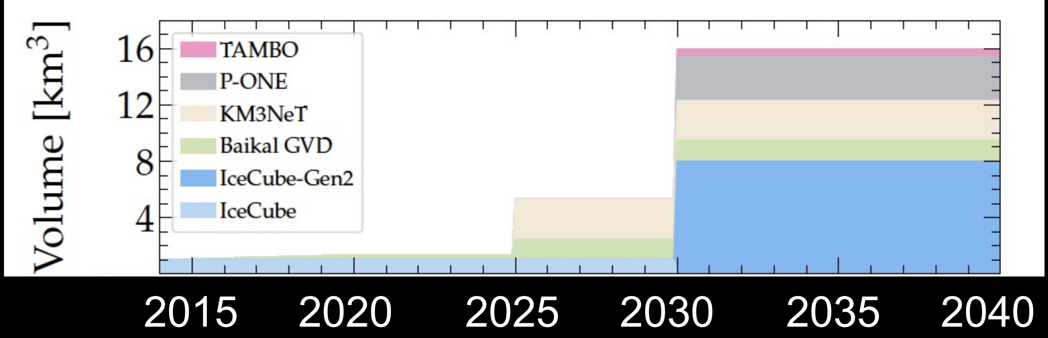


IceCube-Gen2



P-ONE



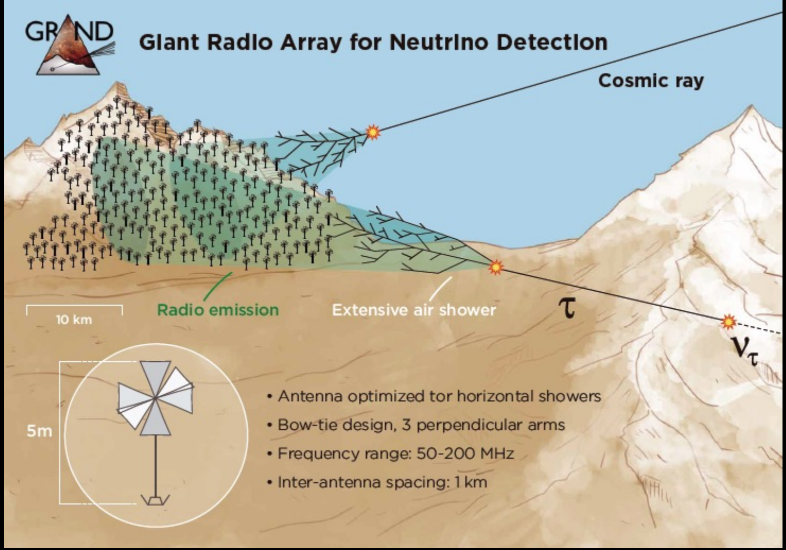


KING'S College LONDON

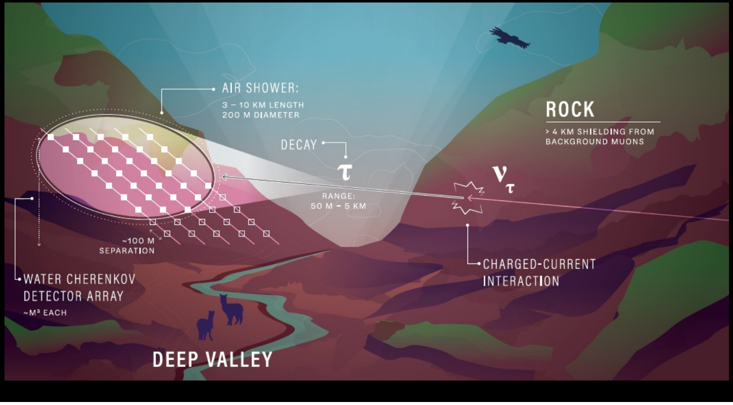
Argüelles et al, Rev. Mod. Phys. 93, 35007 (2021)

Future EHENTs (extremely-high-energy neutrino telescopes

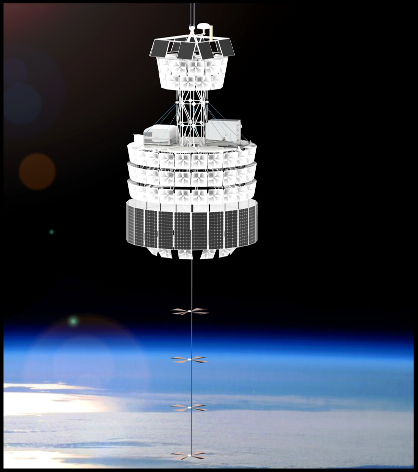
GRAND

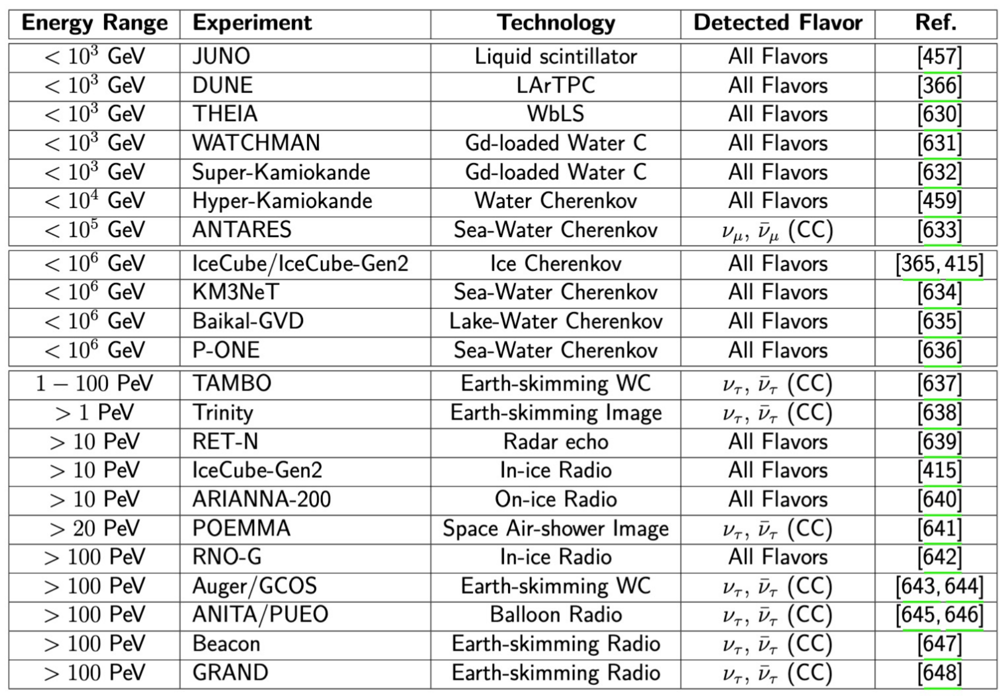


TAMBO



PUEO





Energy Range	Experiment	Technology	Detected Flavor	Ref.
$< 10^3$ GeV	JUNO	Liquid scintillator	All Flavors	[457]
$< 10^3$ GeV	DUNE	LArTPC	All Flavors	[366]
$< 10^3$ GeV	THEIA	WbLS	All Flavors	[630]
$< 10^3$ GeV	WATCHMAN	Gd-loaded Water C	All Flavors	[631]
$< 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors	[632]
$< 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors	[459]
$< 10^5$ GeV	ANTARES	Sea-Water Cherenkov	$\nu_\mu, \bar{\nu}_\mu$ (CC)	[633]
$< 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors	[365, 415]
$< 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors	[634]
$< 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors	[635]
$< 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors	[636]
$1 - 100$ PeV	TAMBO	Earth-skimming WC	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[637]
> 1 PeV	Trinity	Earth-skimming Image	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[638]
> 10 PeV	RET-N	Radar echo	All Flavors	[639]
> 10 PeV	IceCube-Gen2	In-ice Radio	All Flavors	[415]
> 10 PeV	ARIANNA-200	On-ice Radio	All Flavors	[640]
> 20 PeV	POEMMA	Space Air-shower Image	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[641]
> 100 PeV	RNO-G	In-ice Radio	All Flavors	[642]
> 100 PeV	Auger/GCOS	Earth-skimming WC	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[643, 644]
> 100 PeV	ANITA/PUEO	Balloon Radio	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[645, 646]
> 100 PeV	Beacon	Earth-skimming Radio	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[647]
> 100 PeV	GRAND	Earth-skimming Radio	$\nu_\tau, \bar{\nu}_\tau$ (CC)	[648]

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.

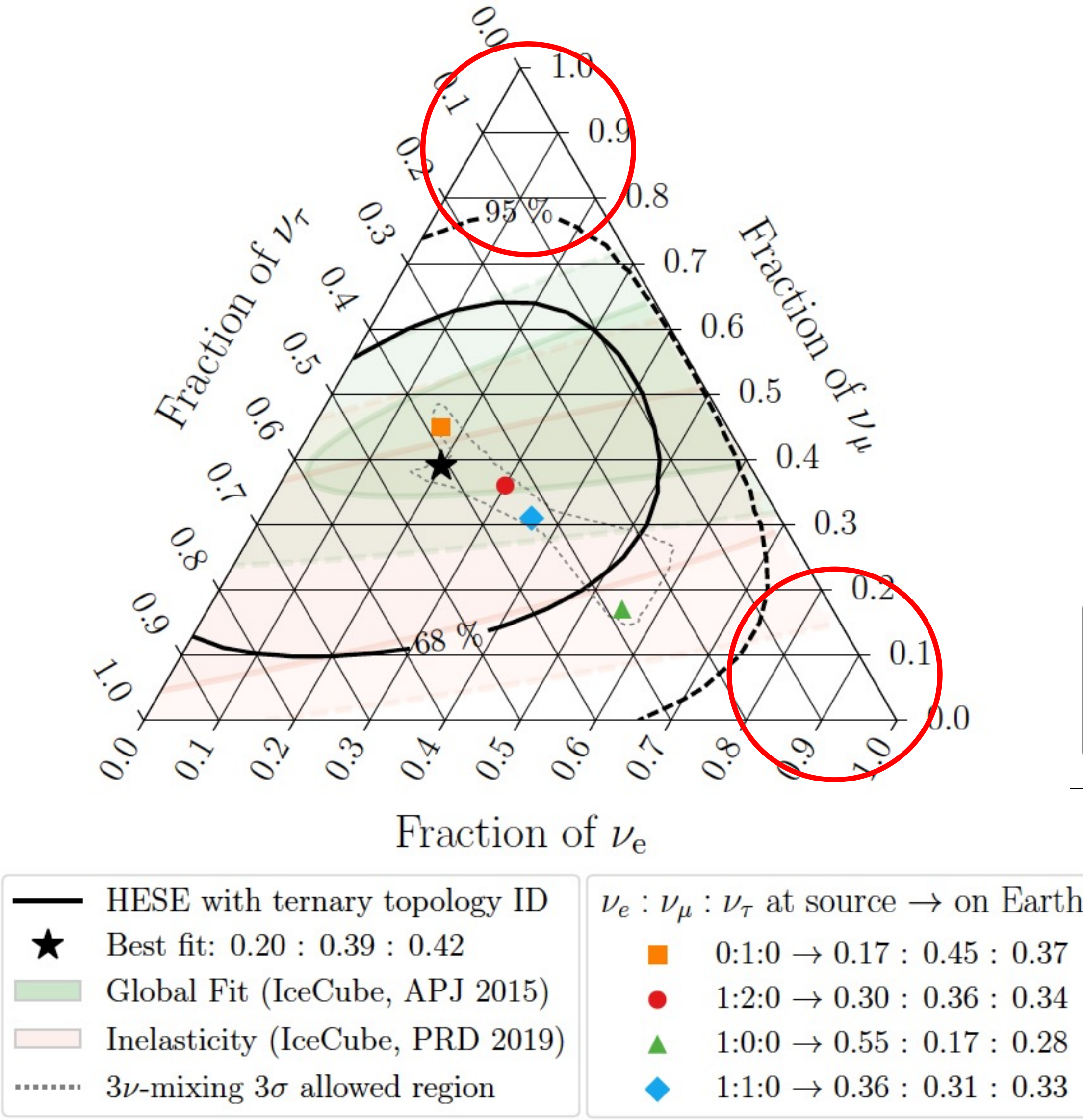
IceCube-Gen2 collaboration

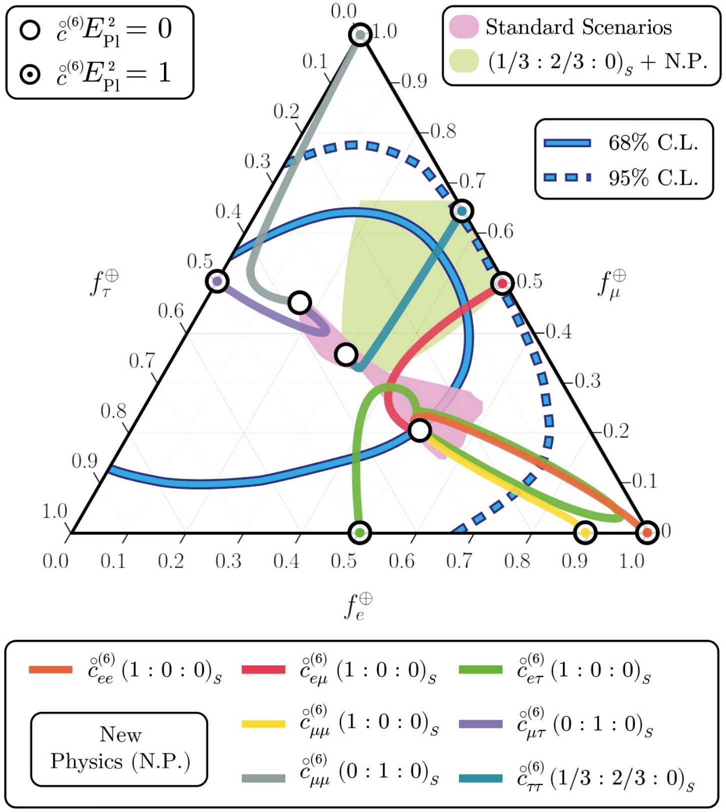
Thank you for your attention!

Backup

IceCube, ArXiv:2011:03560

HESE 7.5-yr flavor ratio (2018)

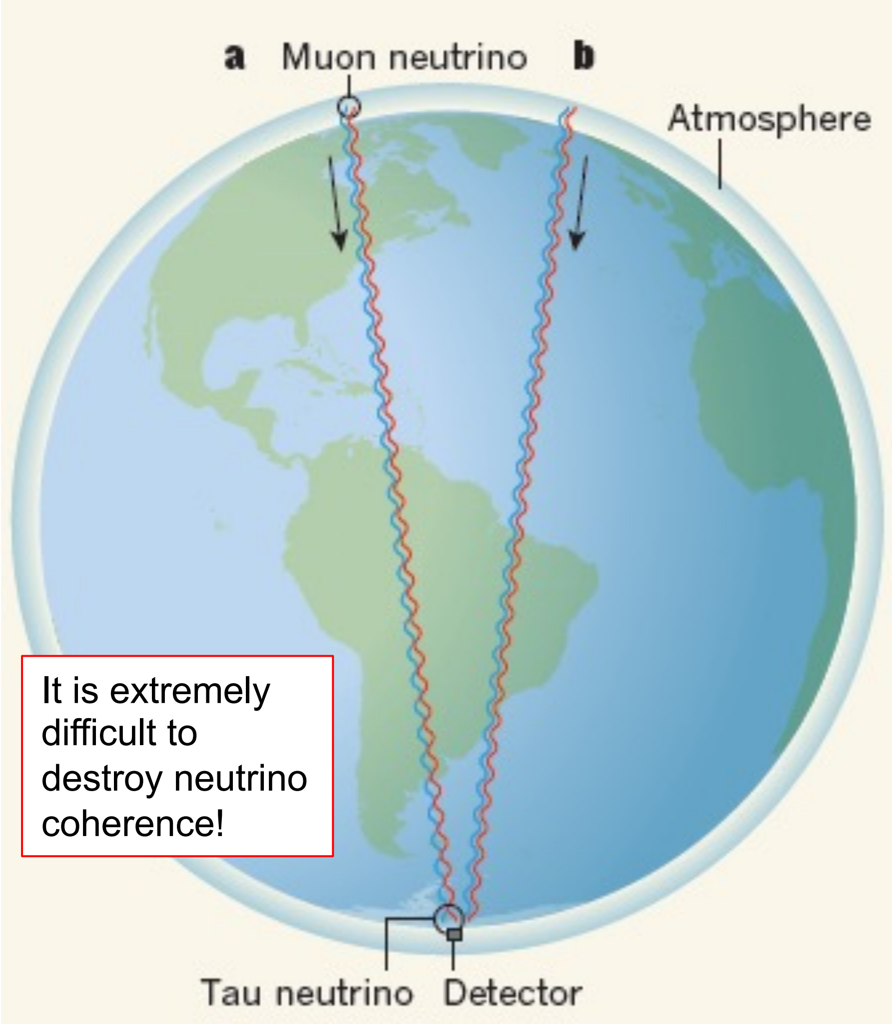




We are mainly testing scenarios where we assume astrophysical neutrino productions are dominated by ν_e or ν_μ

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

Neutrino interferometry – Atmospheric neutrinos

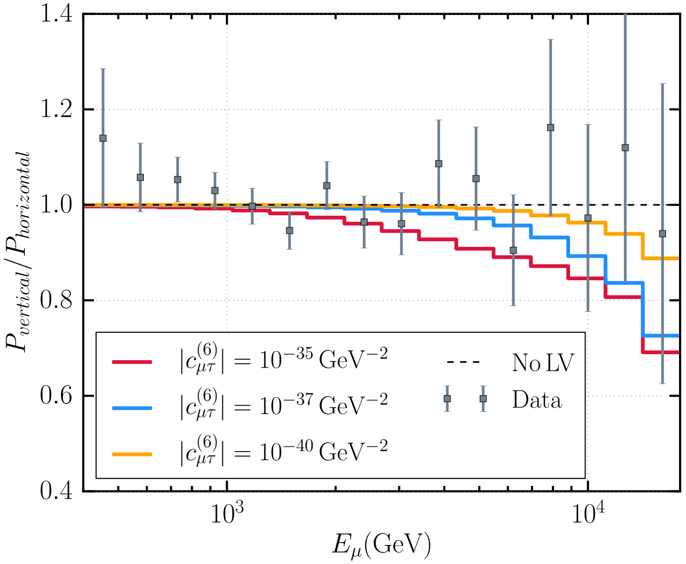


It is extremely difficult to destroy neutrino coherence!

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

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

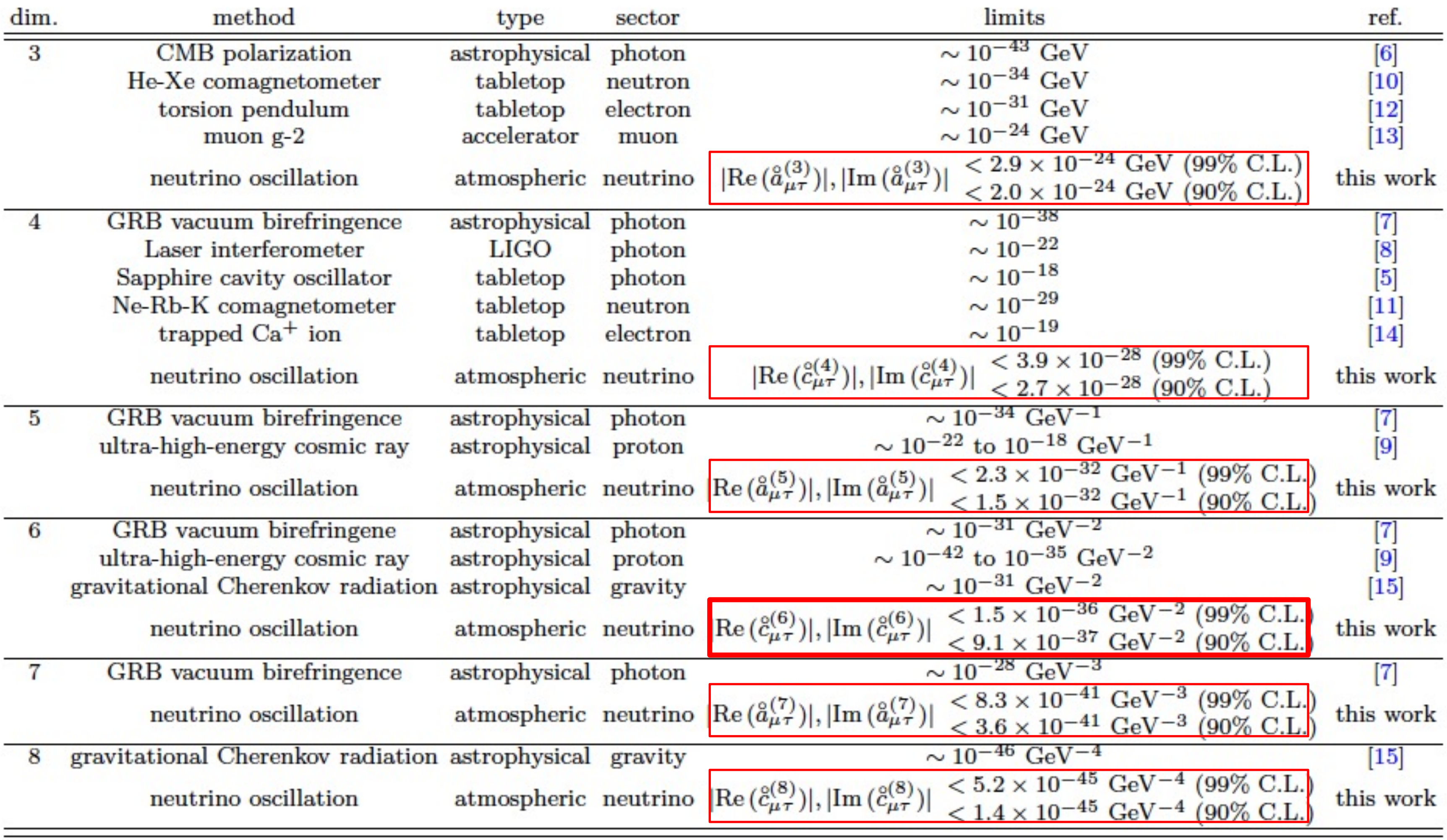
If anomalous coupling with neutrinos in vacuum cause a phase shift in similar order, we can see it from spectrum distortion of atmospheric neutrinos



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

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

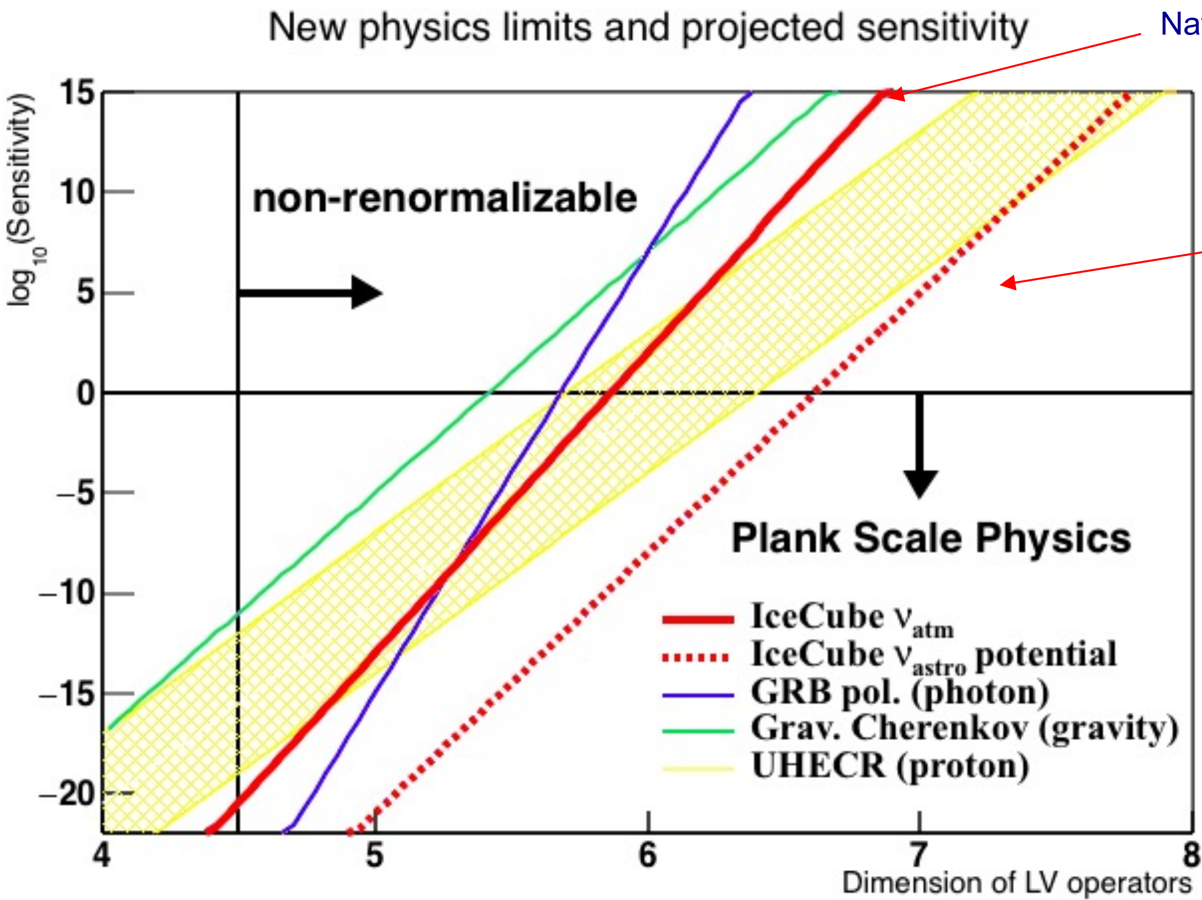
TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

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

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

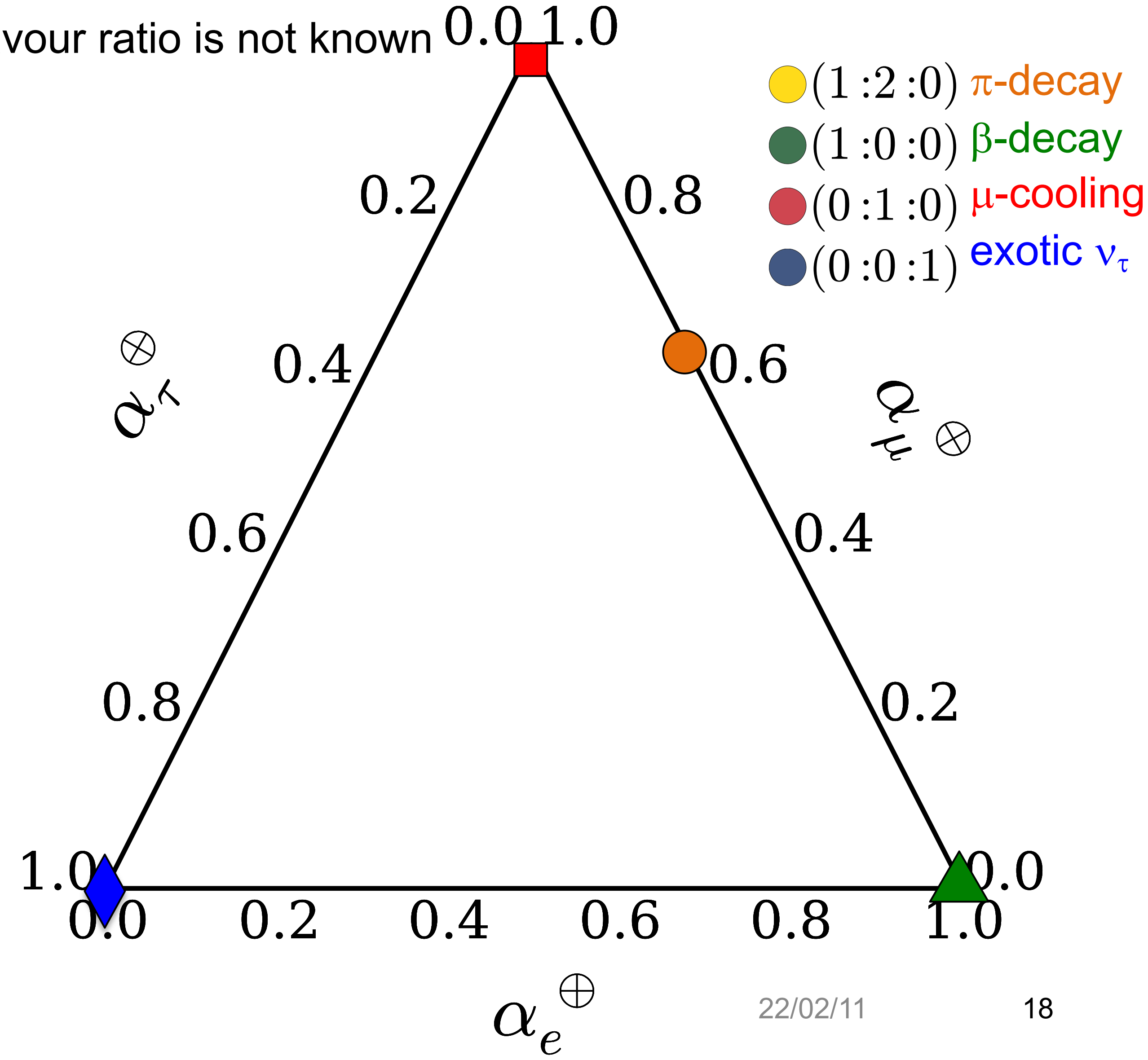
IceCube astrophysical neutrino LV sensitivity

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

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

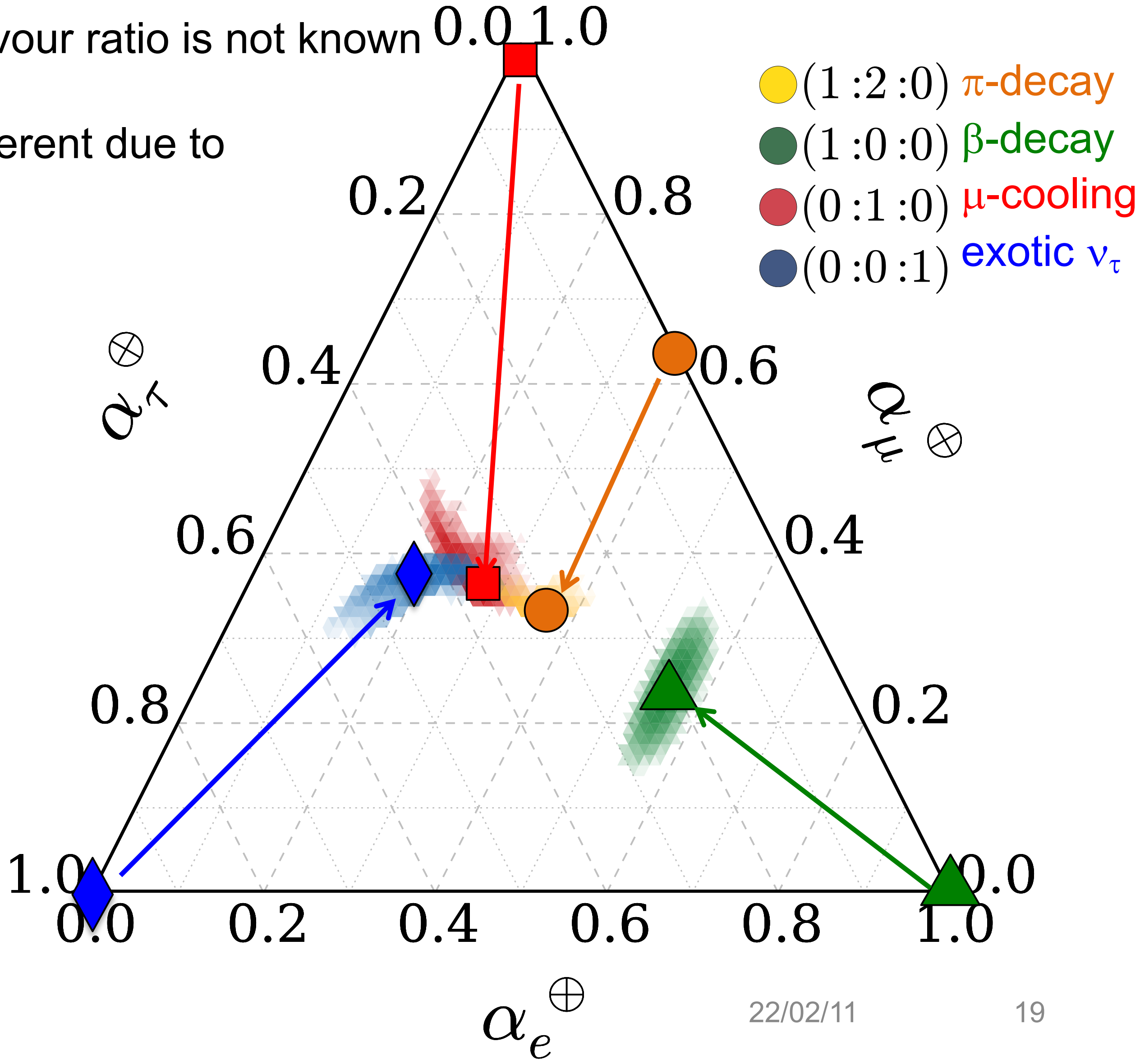


Argüelles, TK, Salvado, PRL115(2015)161303

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



Argüelles, TK, Salvado, PRL115(2015)161303

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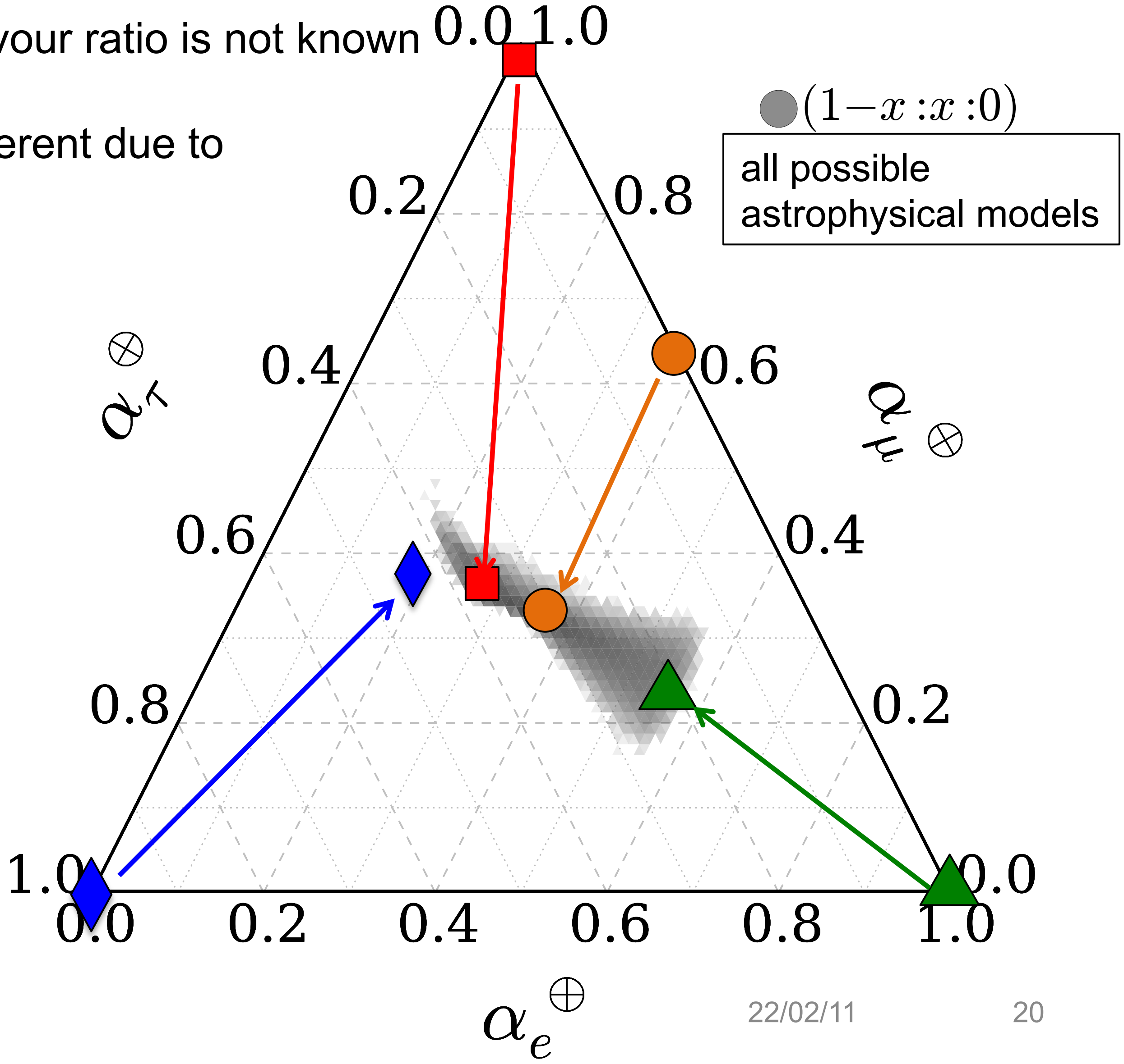
All possible flavour ratio is confined in a small space



Argüelles, TK, Salvado, PRL115(2015)161303

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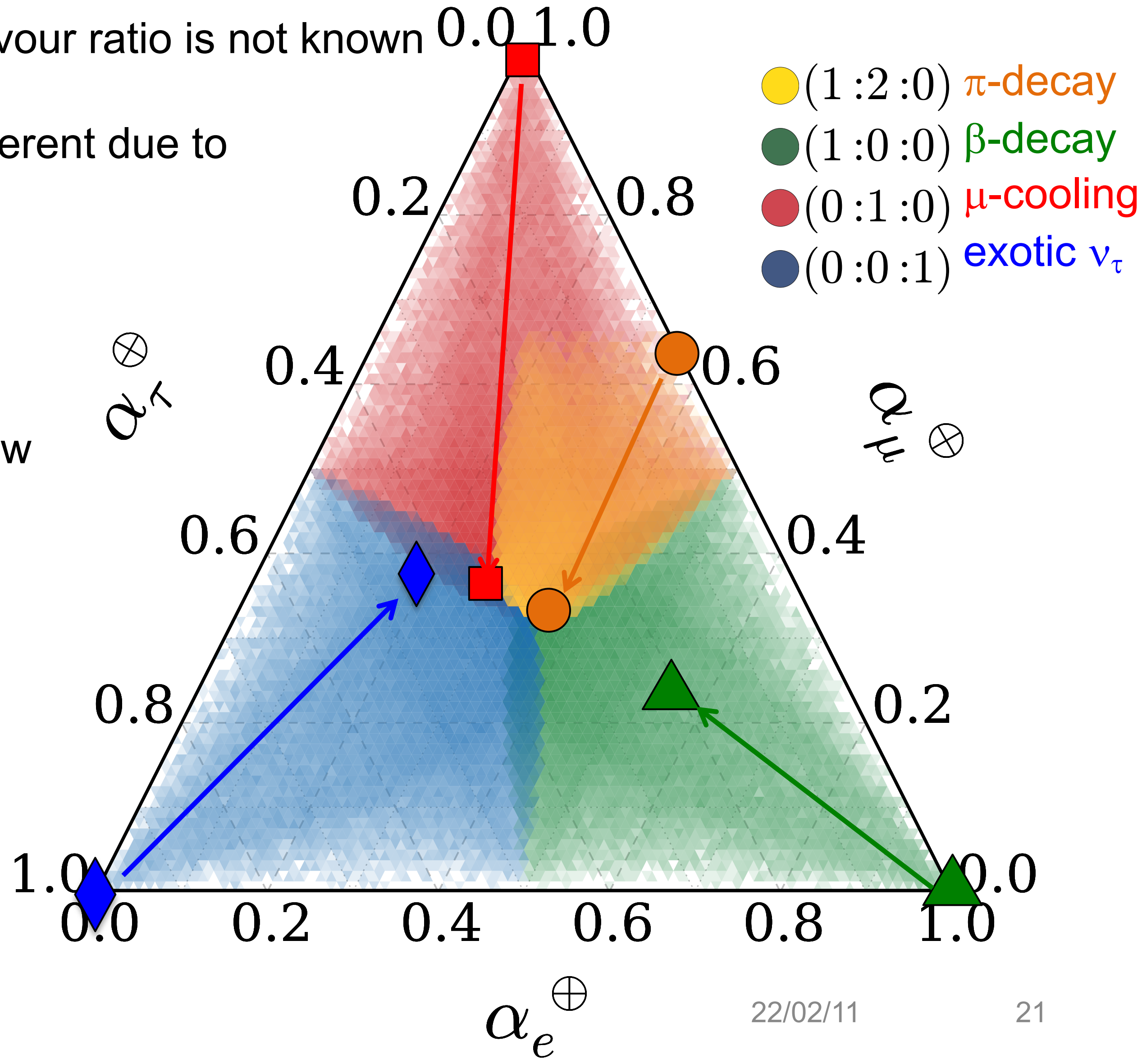
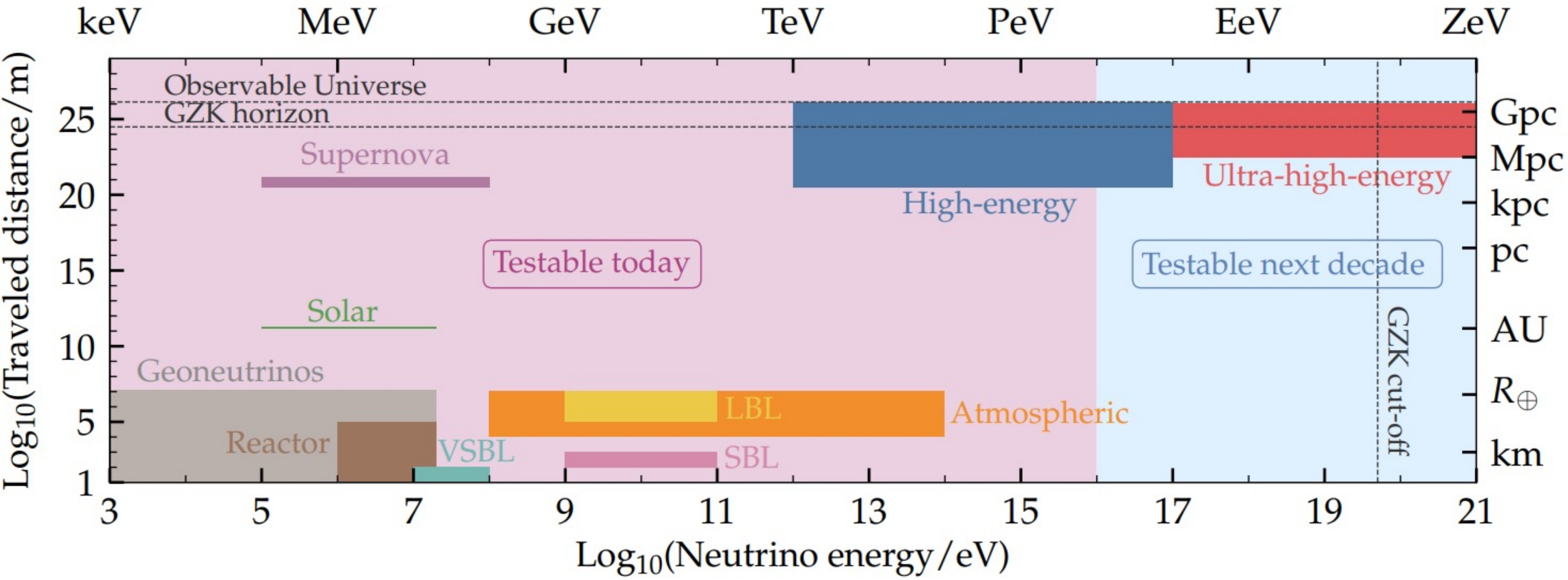
e.g.) New physics just below the limit can produce any flavour ratio



Argüelles et al, ArXiv:1907.08690

Fundamental Physics with High-Energy Cosmic Neutrinos Today and in the Future



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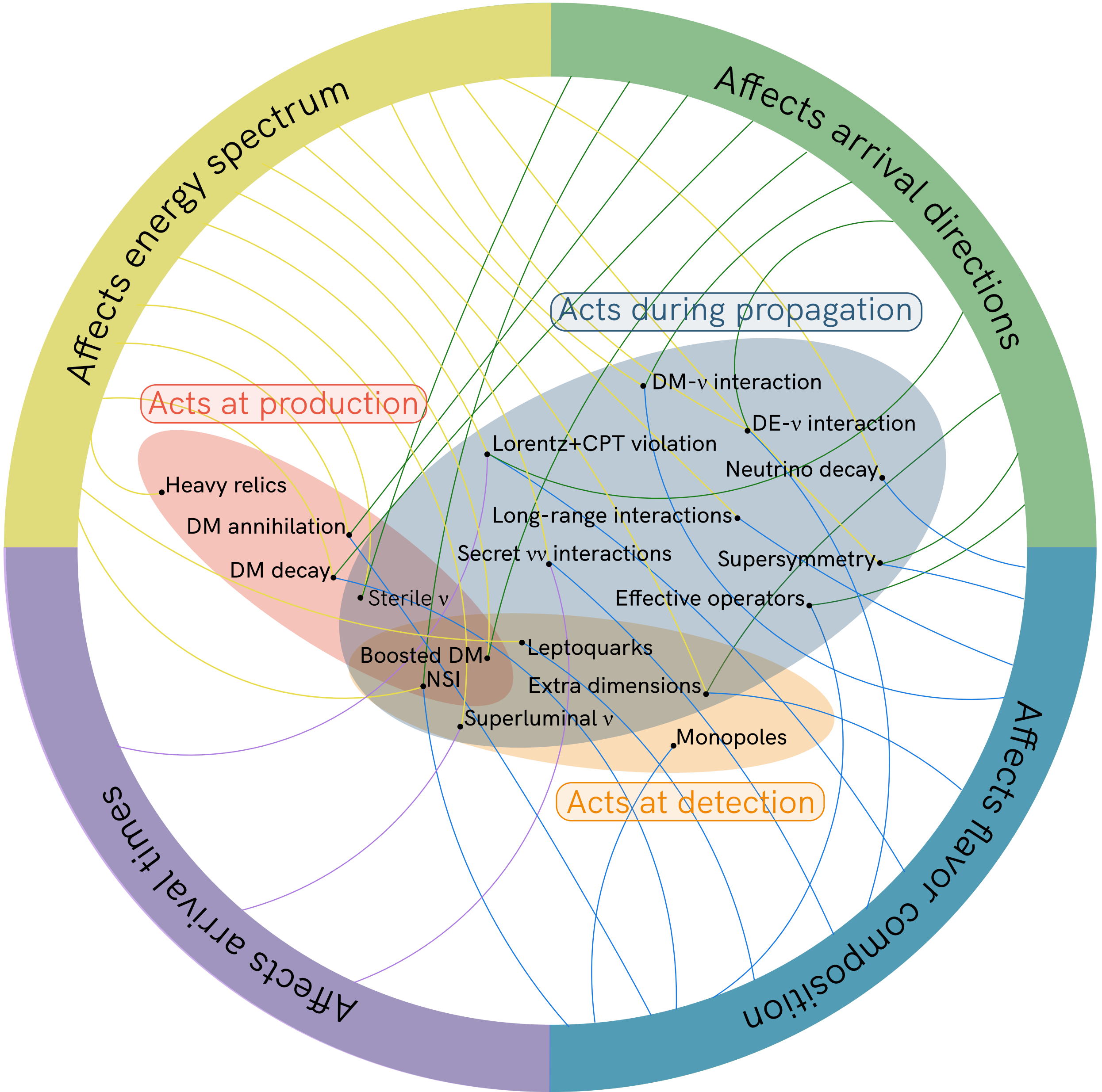
Fundamental Physics with High-Energy Cosmic Neutrinos Today and in the Future



Argüelles, TK, Salvado, PRL115(2015)161303

Flavor new physics search with effective operators

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

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

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 flavour α at production is $\phi_\alpha^p(E)\sim\phi_\alpha^P\cdot E^{-\gamma}$. Since it's low statistics, we consider energy-averaged flavour 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 flavour.

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

IceCube,PRD104(2021)022002

HESE 7.5-yr data 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 $\cos\theta$ bins [-1.0, +1.0]
- 41 cascade events, 20 log(E) bins [60 TeV, 10 PeV], 10 $\cos\theta$ 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%)

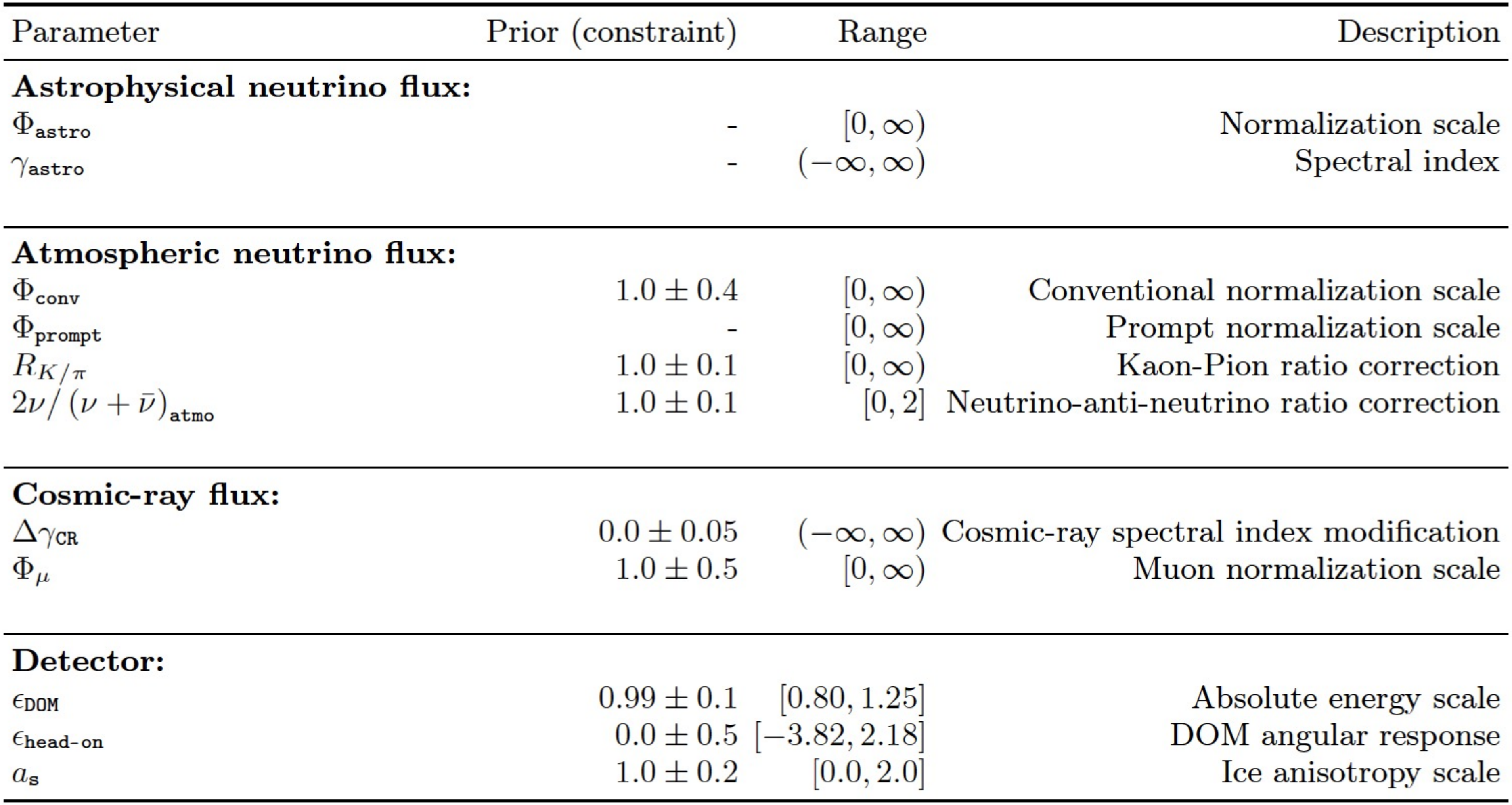
Limits

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

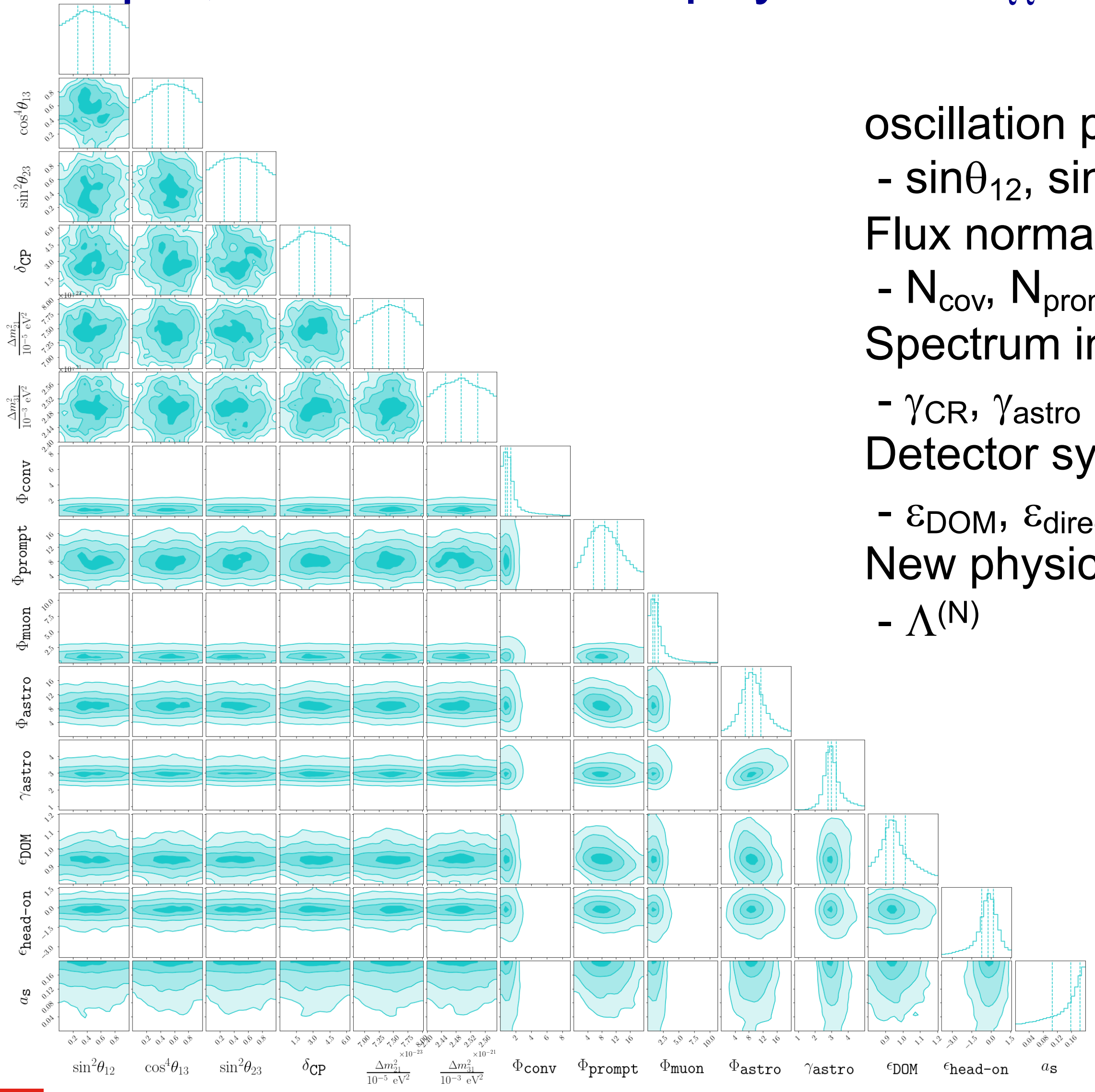
IceCube,PRD104(2021)022002

HESE 7.5-yr data 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, 10^{-44} GeV^{-2} 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_{CR}, γ_{astro}

Detector systematics

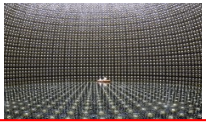
- ε_{DOM}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

New physics scale

- $\Lambda^{(N)}$

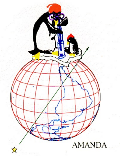
Test of Lorentz violation with neutrinos

Spectral distortion



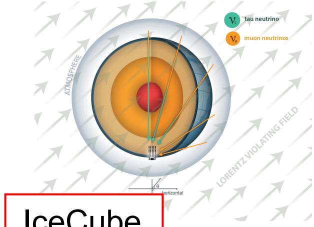
Super-Kamiokande

PRD91(2015)052003



AMANDA

PRD79(2009)102005



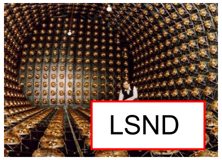
IceCube

Nature Physics 14(2018)961

Sidereal variation

Daya Bay

PRD98(2018)092013



LSND

PRD72(2005)076004

MiniBooNE

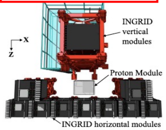
PLB718(2013)1303

MINOS ND

PRL101(2008)151601

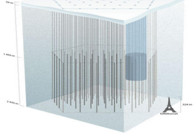
MINOS FD

PRL105(2010)151601



T2K ND

PRD95(2017)111101



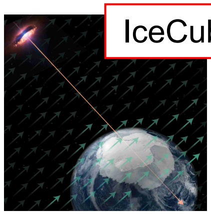
IceCube

PRD82(2010)112003

Double Chooz

PRD86(2013)112009

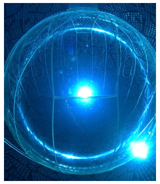
Flavor ratio



IceCube

ArXiv:2111.04654

Seasonal variation



SNO

PRD98(2018)112013

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

Energy dependence of flavor ratio