Ultra-light Dark Matter Limits from Astrophysical Neutrino Flavour

Paper in preparation

outline

1. Astrophysical neutrino flavour physics
2. Ultra-light dark matter search
3. Time varying ultra-light dark matter search
4. Conclusions

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King's College London, Harvard University, Chiba University
ICRC2023, Nagoya University, Nagoya, Japan, Aug. 2, 2023

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KING'S College LONDON

VE RI TAS HARVARD

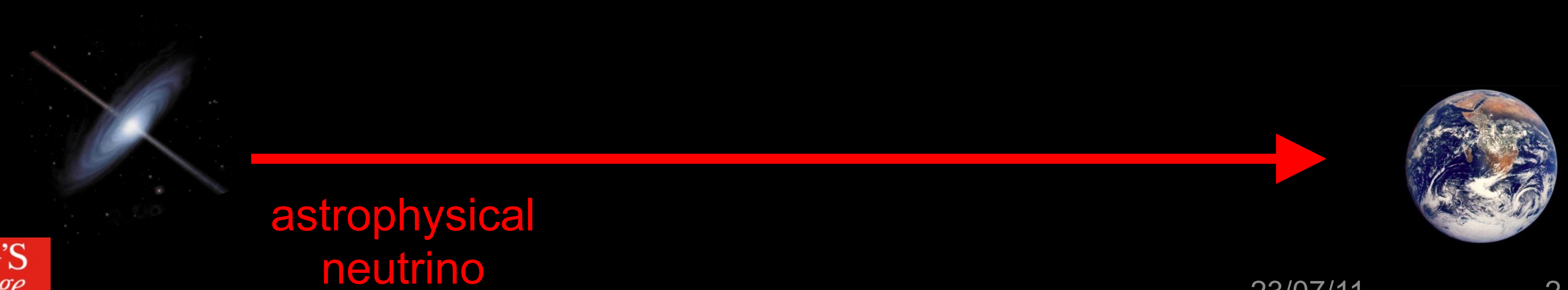
CHIBA UNIVERSITY

ICRC2023
The Astroparticle Physics Conference
Nagoya, Japan, Jul 26–Aug 3, 2023

Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, EPJC83(2023)15

1. Astrophysical neutrino flavour physics

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



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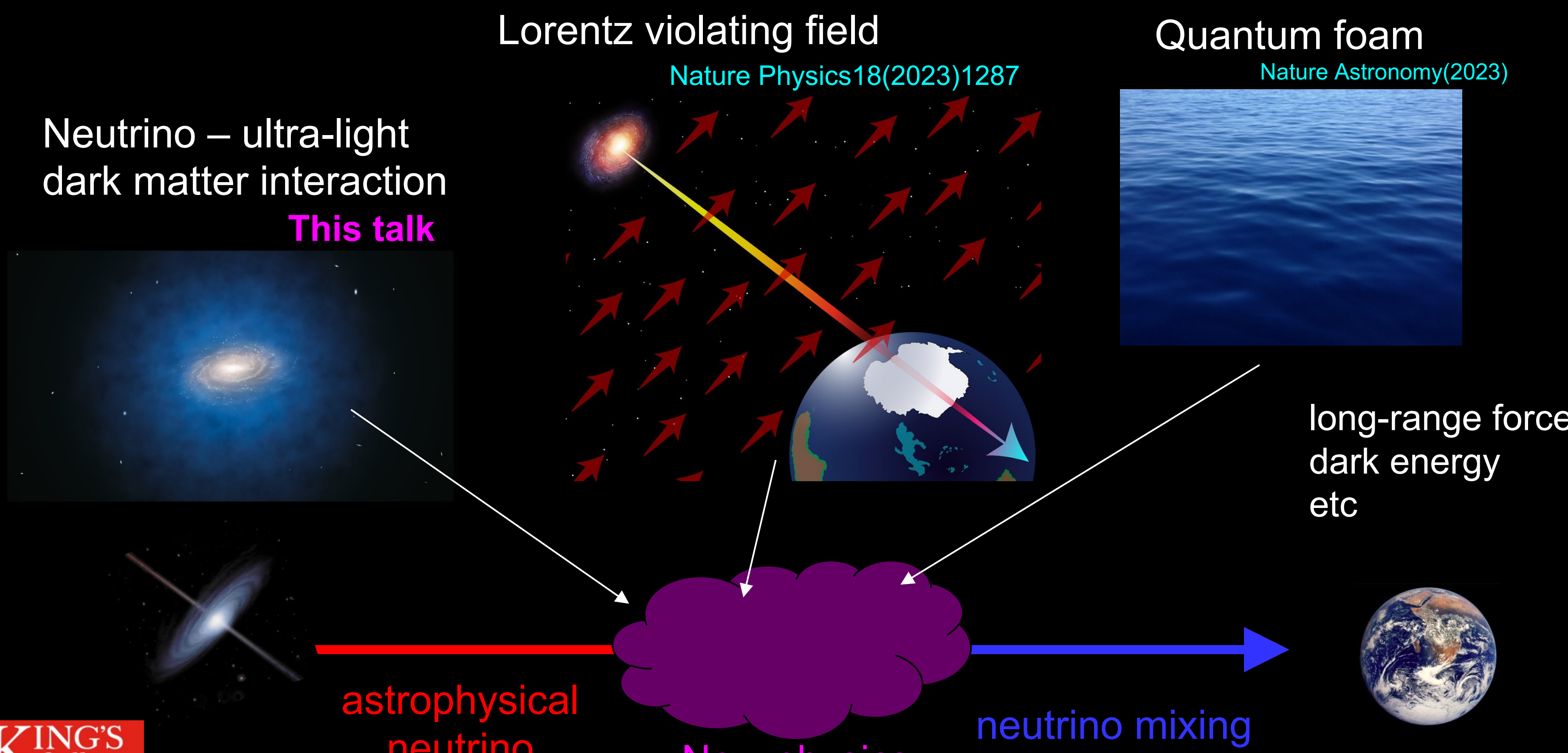


Ferreira, Astron Astrophys Rev (2021) 29:7
Marsh, Phys. Rep. 643 (2016) 1

1. Ultra-light dark matter

Ultra-light dark matter is a class of dark matter models with very light mass

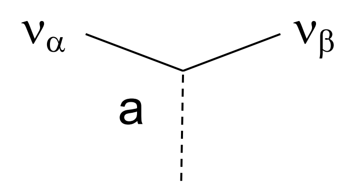
$$10^{-22}eV < m_{DM} < 1eV$$

They behave like waves, not particles

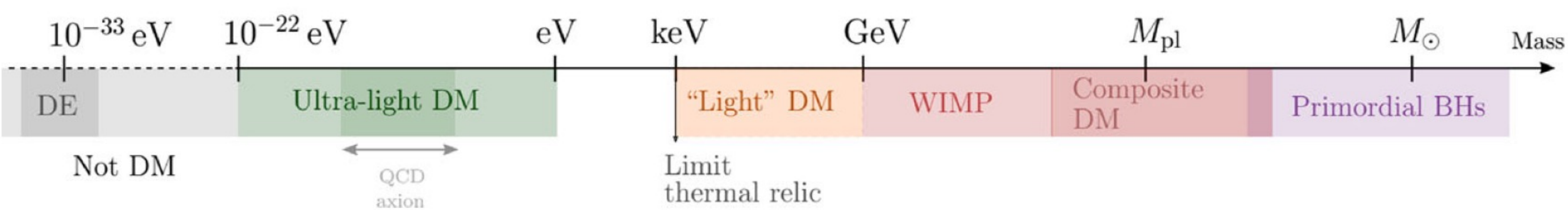
$$\phi(t) = \frac{\sqrt{2\rho_{DM}}}{m_{DM}} sin(m_{DM}t)$$

e.g.) axion dark matter – neutrino coupling

$$L_{int} = g_{\alpha\beta}\partial_\mu a\left(\bar{\nu}_\alpha\gamma^\mu\gamma_5\nu_\beta\right)$$



Neutrino interactions with dark matter field in the Milky Way make a matter potential for neutrinos in this galaxy



1. Astrophysical neutrino flavour physics

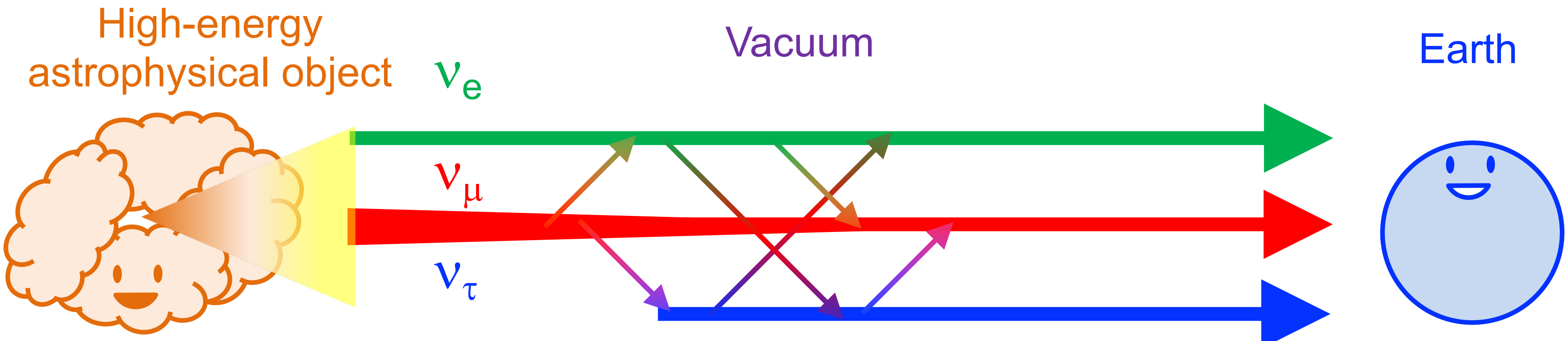
Neutrino mass term in the flavour basis is not diagonal

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U \cdots \sim \frac{1}{2E} \begin{pmatrix} m_{ee}^2 & m_{e\mu}^2 & m_{\tau e}^2 \\ m_{e\mu}^{2*} & m_{\mu\mu}^2 & m_{\mu\tau}^2 \\ m_{\tau e}^{2*} & m_{\mu\tau}^{2*} & m_{\tau\tau}^2 \end{pmatrix} \cdots$$

Standard astrophysical models predict astrophysical neutrinos are ν_e and ν_μ

Neutrinos mixings in vacuum produce ν_τ

$$P_{\alpha\to\beta}(E,\infty) \sim \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2$$



1. Astrophysical neutrino flavour physics

Any effective interactions in vacuum (=Lorentz violation) modify mixing pattern

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a^{(3)}_{\alpha\beta} \cdots \sim \frac{1}{2E} \begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{\tau e} \\ m^{2*}_{e\mu} & m^2_{\mu\mu} & m^2_{\mu\tau} \\ m^{2*}_{\tau e} & m^{2*}_{\mu\tau} & m^2_{\tau\tau} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a^{(3)}_{\tau\tau} \end{pmatrix} \cdots$$

Large diagonal term can modify the neutrino flavour ratio

IceCube set the strongest limit on $a^{(3)}_{\tau\tau}$

[NU10-07] Carlos Argüelles
"Search for quantum gravity using
astrophysical neutrino flavor with IceCube"

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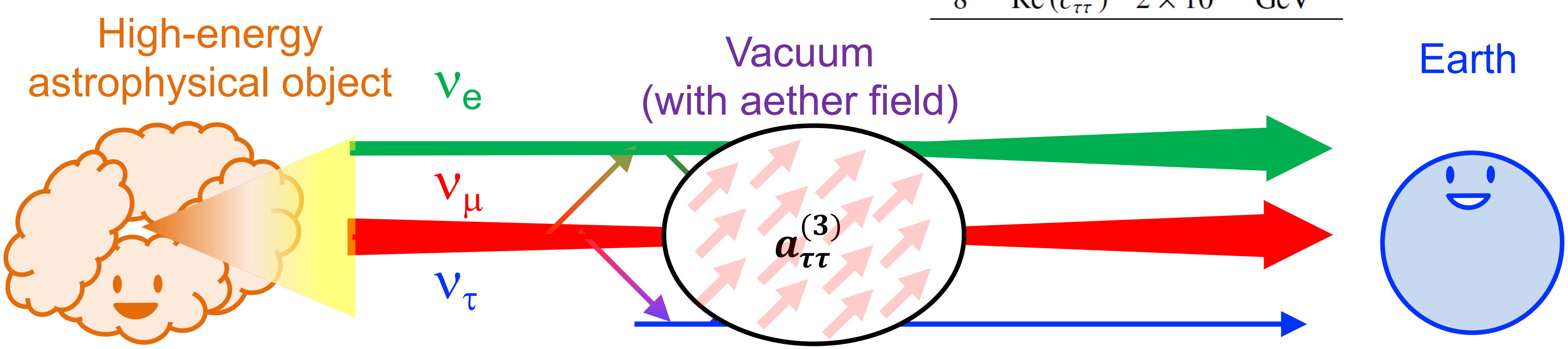

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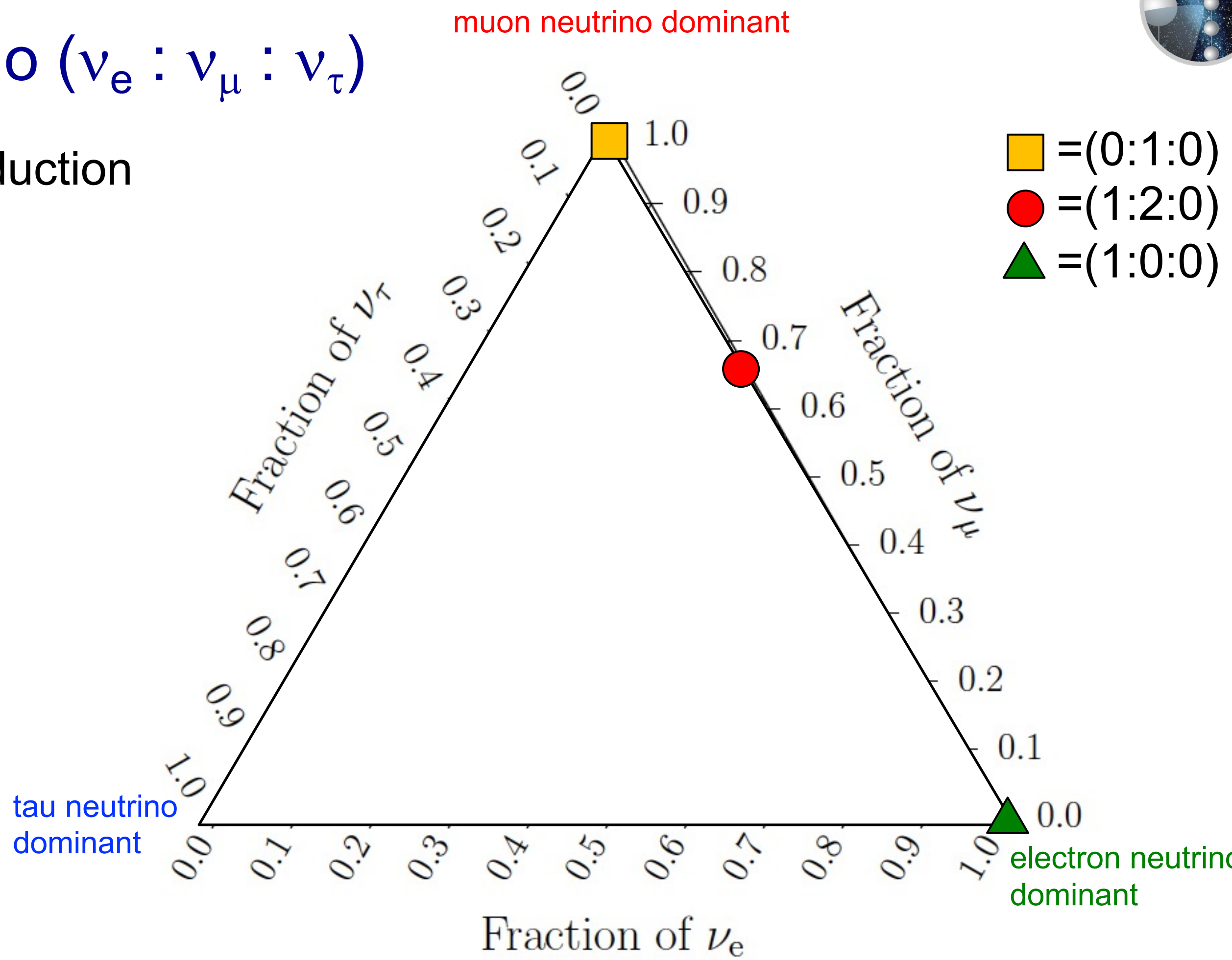
1. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

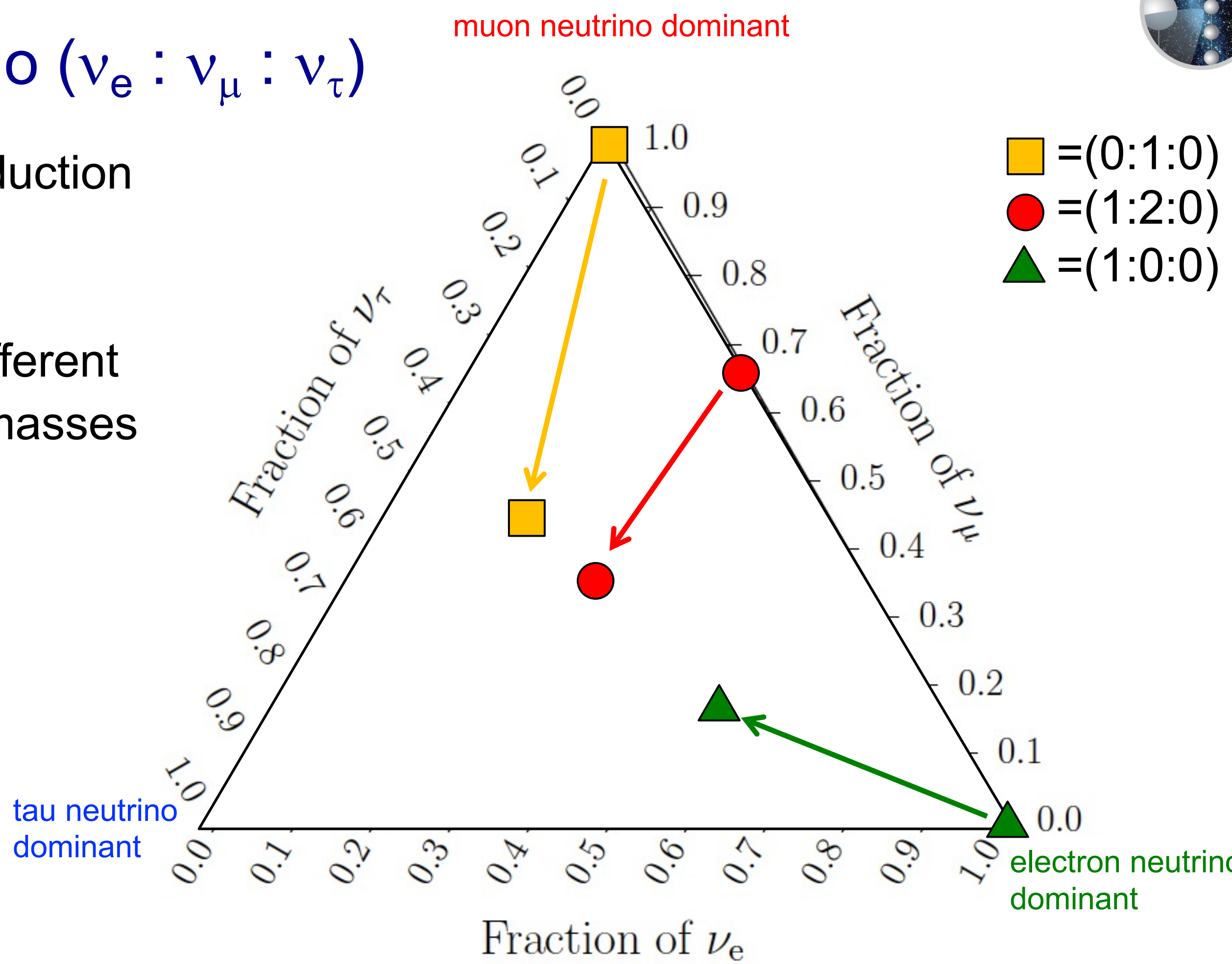
Astrophysical neutrino production mechanism is not known



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

Astrophysical neutrino production mechanism is not known

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



$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:	
■ (orange square)	0:1:0 → 0.17 : 0.45 : 0.37
● (red circle)	1:2:0 → 0.30 : 0.36 : 0.34
▲ (green triangle)	1:0:0 → 0.55 : 0.17 : 0.28
◆ (blue diamond)	1:1:0 → 0.36 : 0.31 : 0.33

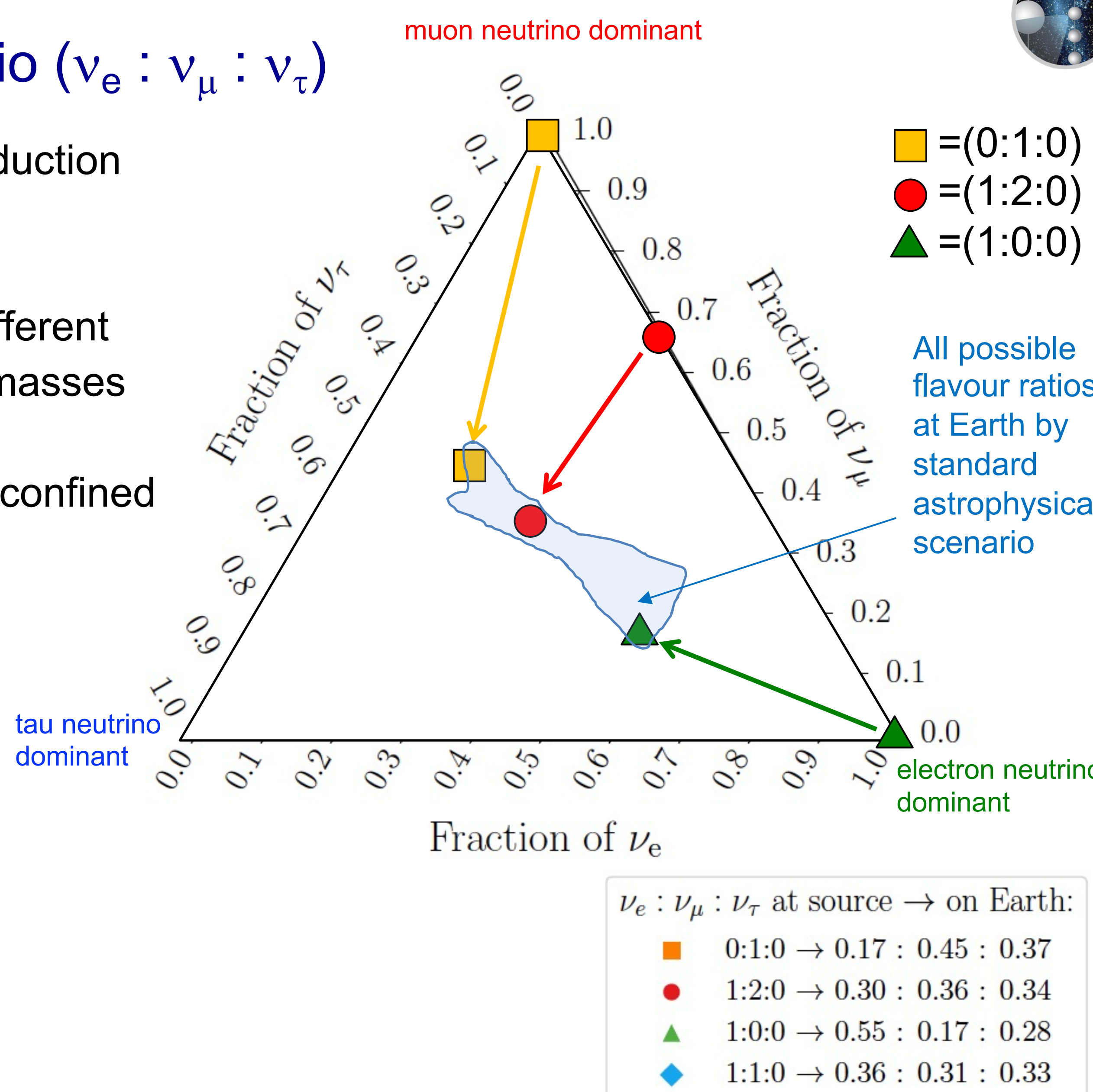
Argüelles, TK, Salvado, PRL115(2015)161303

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

Astrophysical neutrino production mechanism 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



IceCube, PRD104,(2021)022002, EPJC82(2022)1031

1. HESE 7.5-yr flavor ratio

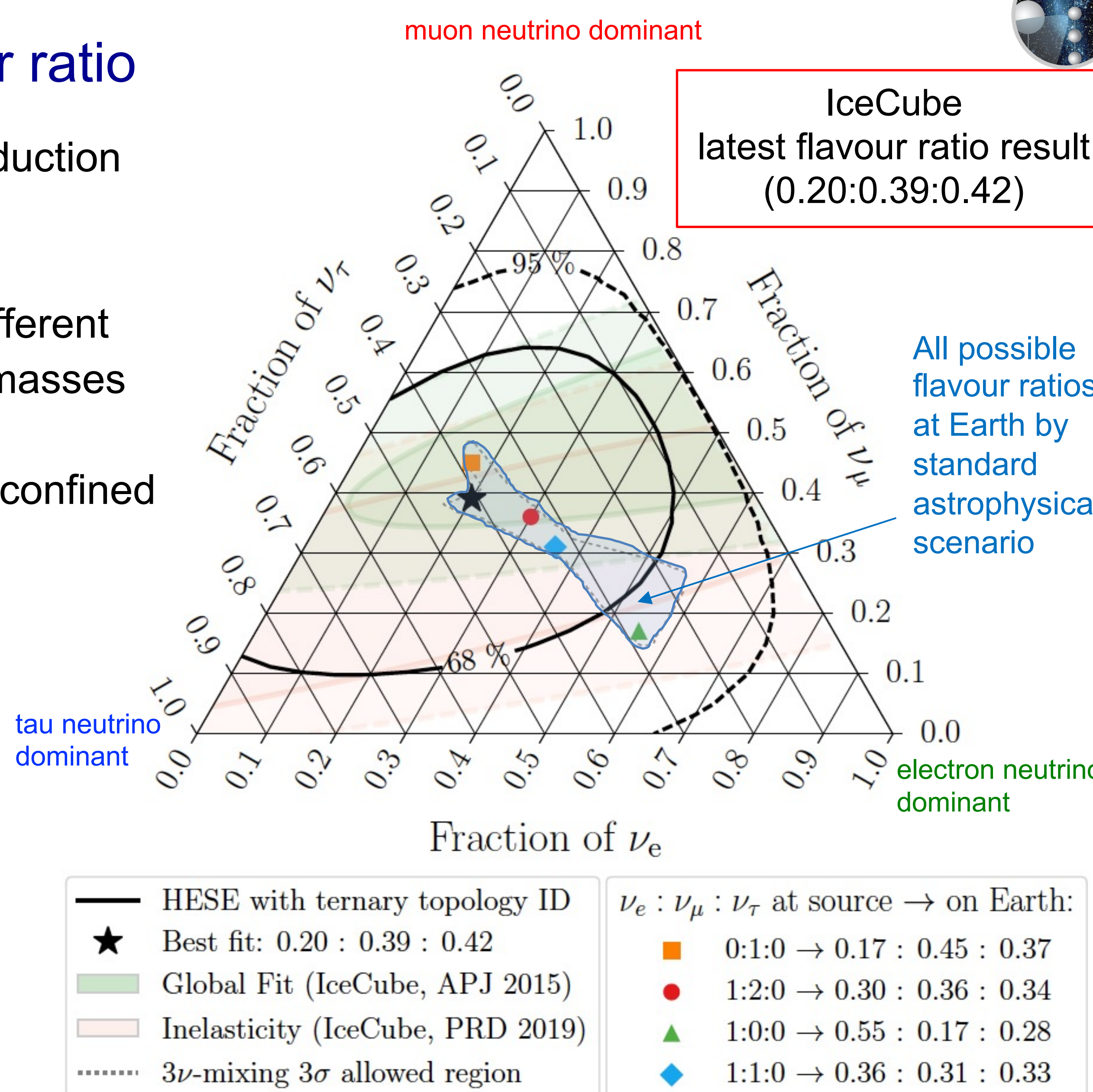
Astrophysical neutrino production mechanism is not known

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

All possible flavour ratio is confined in a small space

Data contours are big, but data can be statistically used to exclude some new physics models

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



IceCube, Nature Physics18(2023)1287

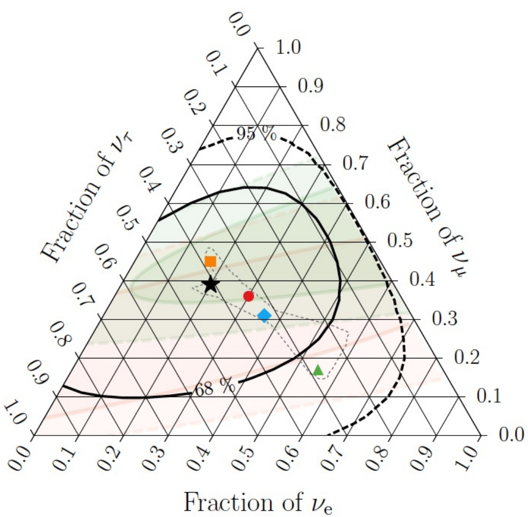
1. Astrophysical neutrino flavour physics

We expect improvement of flavour measurements by neutrino telescopes. Here, we focus on the new physics limit from the current flavour data

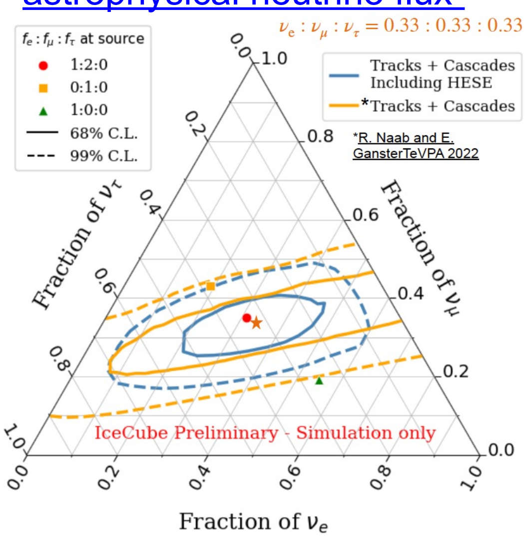
$$a_{\tau\tau}^{(3)} = 2\times10^{-26}\ GeV$$

This can be interpreted as the tau neutrino – ultra-light dark matter coupling limit

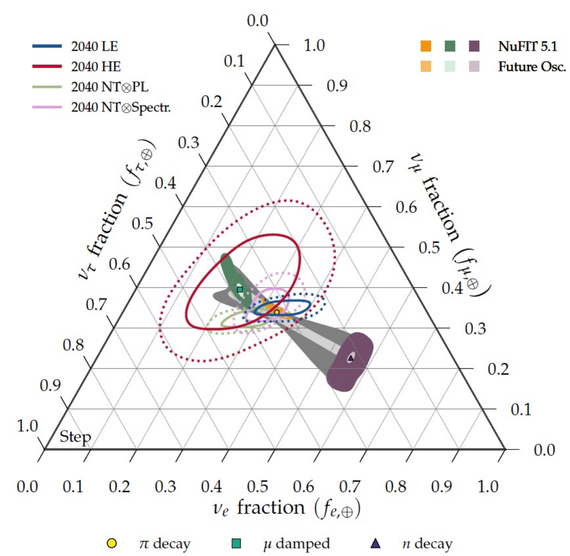
[NU10-07] Carlos Argüelles "Search for quantum gravity using astrophysical neutrino flavor with IceCube"



[NU3-06] Neha Lad "Summary of IceCube tau neutrino searches and flavor composition measurements on the diffuse astrophysical neutrino flux"



[PNU1-44] Qinrui Liu "Energy-dependent flavor ratios of High-energy Astrophysical Neutrinos"



2. Ultra-light dark matter coupling with neutrinos

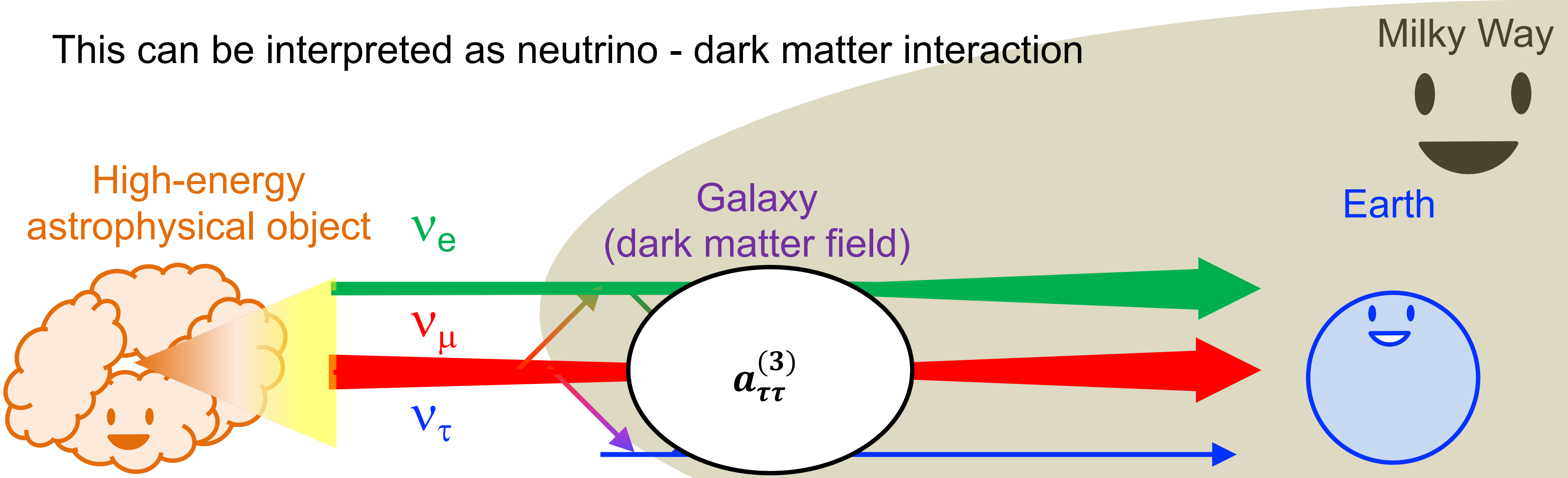
Any effective interaction in vacuum (=Lorentz violation) modify mixing pattern

$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + a^{(3)}_{\alpha\beta} \cdots \sim \frac{1}{2E} \begin{pmatrix} m^2_{ee} & m^2_{e\mu} & m^2_{\tau e} \\ m^{2*}_{e\mu} & m^2_{\mu\mu} & m^2_{\mu\tau} \\ m^{2*}_{\tau e} & m^{2*}_{\mu\tau} & m^2_{\tau\tau} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a^{(3)}_{\tau\tau} \end{pmatrix} \cdots$$

Large diagonal term can modify the flavour ratio

IceCube set the strongest limit on $a^{(3)}_{\tau\tau}$

This can be interpreted as neutrino - dark matter interaction



Salas, Lineros, Tórtola, PRD94(2016)123001

2. Ultra-light dark matter coupling with neutrinos

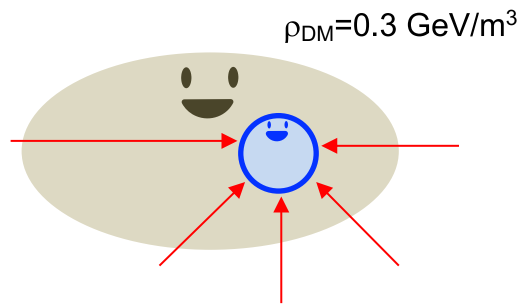
Different dark matter models provide different effective Hamiltonian

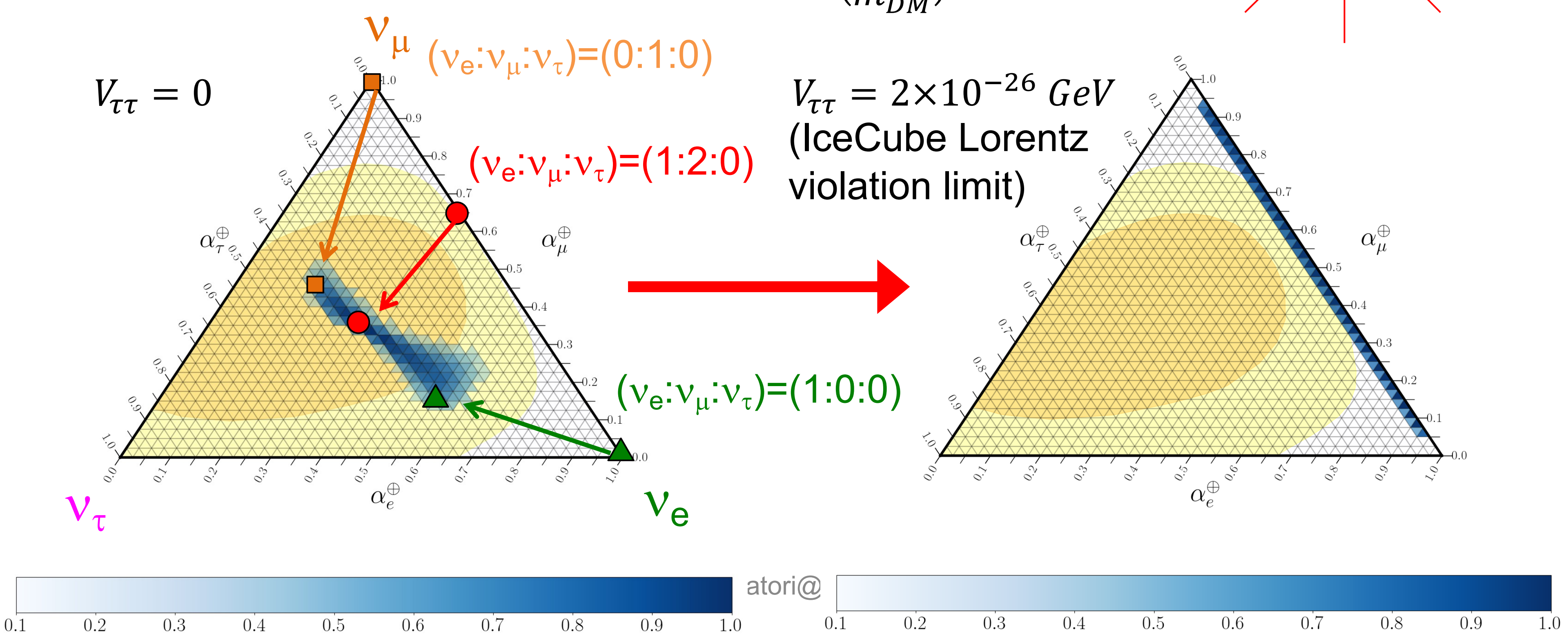
ex) Generic dark matter model

Dark matter makes matter potential in galactic halo

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + V_{\tau\tau}$$

$$V_{\tau\tau} = G'_{\tau\tau} \left(\frac{\rho_{DM}}{m_{DM}} \right)$$





2. Ultra-light dark matter coupling with neutrinos

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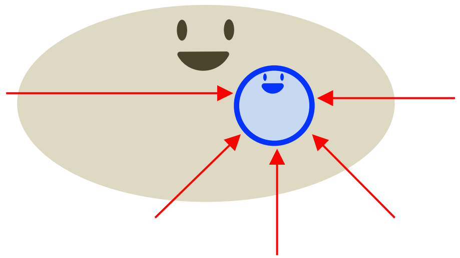
$$h_{eff} \sim \frac{1}{2E} U^\dagger M^2 U + V_{\tau\tau}$$

$$V_{\tau\tau} = G'_{\tau\tau} \left(\frac{\rho_{DM}}{m_{DM}} \right)$$

ρ_{DM}=0.3 GeV/m^3



IceCube Lorentz violation limit: $a^{(3)}_{\tau\tau} < 2\times10^{-26}\ GeV$

Dark matter potential limit: $V_{\tau\tau} < 2\times10^{-26}\ GeV$

From here, we extract the effective Fermi coupling limit: $G'_{\tau\tau} < 10^{-13} GeV^{-2} \left(\frac{m_{DM}}{10^{-20} eV} \right)$

IceCube sensitivity goes beyond terrestrial experiments

- Higher energy suppresses neutrino mass term

Berlin, PRL117(2016)231801
Huang and Nath, EPJC78(2018)922

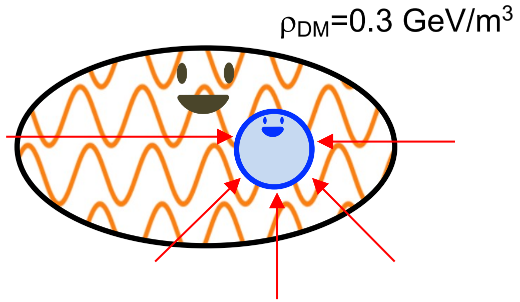
3. Time varying ultra-light dark matter coupling with neutrinos

Different dark matter models provide different effective Hamiltonian

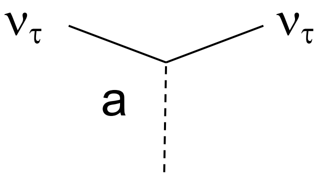
ex) Axion dark matter model

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + V_{\tau\tau}$$

$$V_{\tau\tau} = g_{\tau\tau} \sqrt{2\rho_{DM}} sin(m_{DM} t)$$



Axion dark matter is coherently oscillating in the galaxy halo
→ oscillation of the dark matter field is important

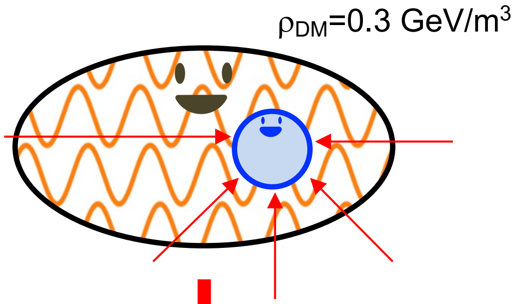


Losada,et al, JHEP04(2022)030.
Hamaide,Müller,Marsh,PRD106(2022)123509

3. Time varying ultra-light dark matter coupling with neutrinos

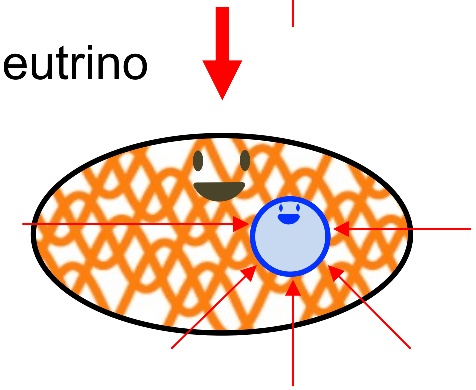
Since we do not know the exact propagation length of each neutrino in our galaxy and the phase of dark matter oscillation, oscillation is averaged out

$$V_{\tau\tau} = g_{\tau\tau}\sqrt{2\rho_{DM}}sin(m_{DM}t) \xrightarrow{t\to\infty} 0$$



On average, dark matter potential is zero

However, dark matter potential smear flavour ratio for each neutrino



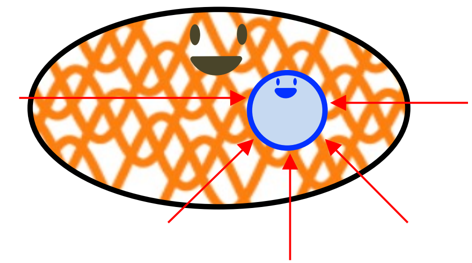
We monitor the smearing effect to look for ultra-light dark matter

Berlin, PRL117(2016)231801
Huang and Nath, EPJC78(2018)922

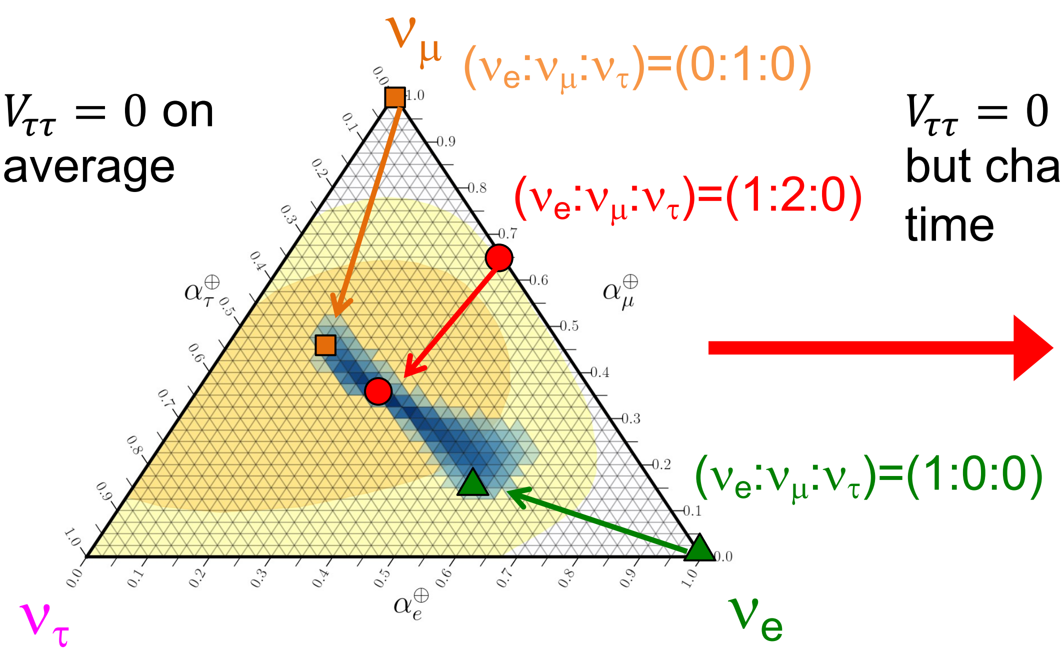
3. Time varying ultra-light dark matter coupling with neutrinos

We calculate flavour prediction points with oscillating dark matter potential which smears predicted flavour ratio

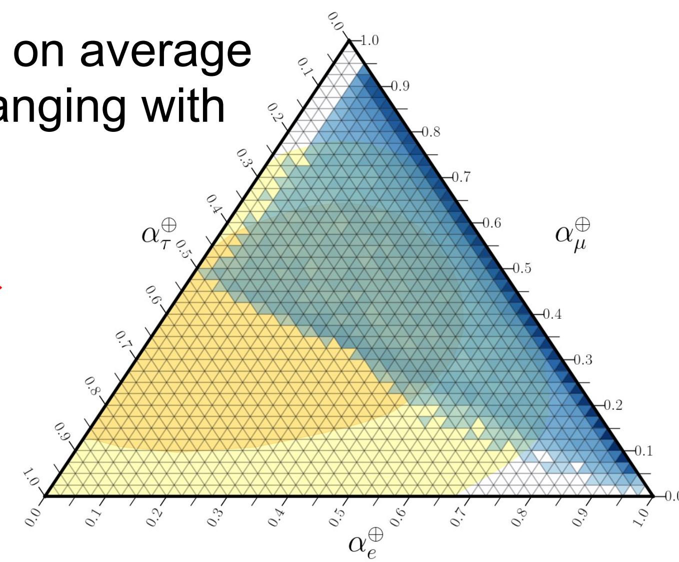
Many calculated flavour ratio points become compatible with the data contours



$V_{\tau\tau} = 0$ on average



$V_{\tau\tau} = 0$ on average but changing with time



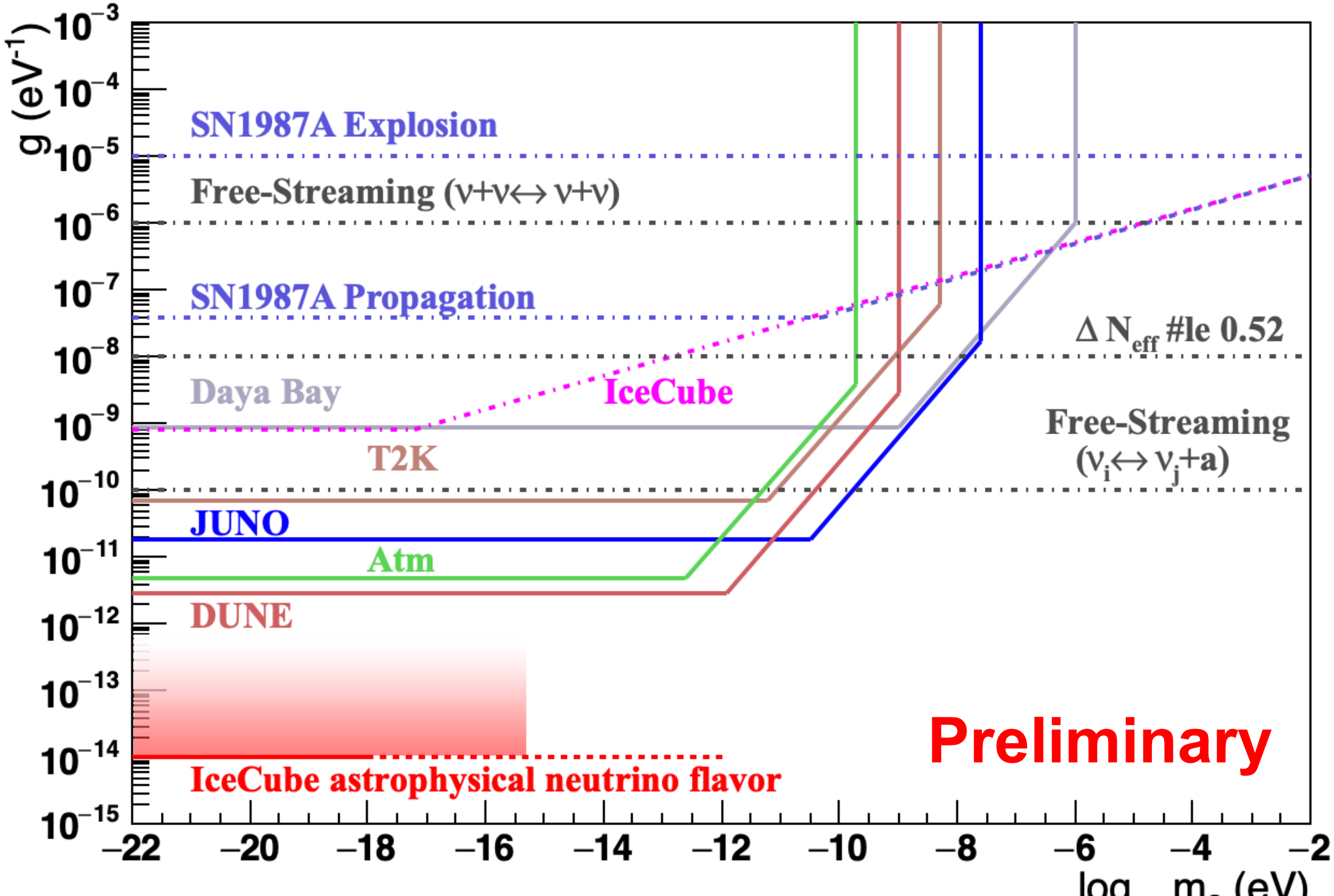
atori@I

Berlin, PRL117(2016)231801
Huang and Nath, EPJC78(2018)922

3. Time varying ultra-light dark matter coupling with neutrinos

Axion dark matter limit from astrophysical neutrino flavour is the strongest in neutrino sector, similar limits are obtained for other ultra-light dark matter models

Caveat
- Dark matter distribution is constant
- Smearing weakens our limit order 1-2
- Adiabaticity is broken at some point for larger axion mass



Conclusion

Ultra-light dark matter is a class of dark matter models which is oscillating like a classical field

IceCube set the strongest limit on Lorentz violating vector field in vacuum through astrophysical neutrino flavour

We investigate to recast IceCube LV limits to set limits on ultra-light dark matter coupling with neutrinos. Our limit is likely to be the strongest among current and future neutrino experiments

These limits will be improved by future astrophysical neutrino flavour data

Thank you for your attention!

Backup

Mewes and Kostelecký, PRD85(2012)096005
IceCube, Nature Physics18(2023)1287

1. Neutrino - dark matter field coupling

Different dark matter models provide different effective Hamiltonian

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

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

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

IceCube sensitivity goes beyond terrestrial experiments
- Higher energy suppresses neutrino mass term
- Higher energy enhances new physics term

These parameters can be interpreted for many new physics

Kostelecký and Mewes, PRD85(2012)096005
Argüelles, TK, Salvado, PRL115(2015)161303

3. HESE 7.5-yr flavor Lorentz violation search

We start from isotropic model of nonminimal SME

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a_{\alpha\beta}^{(3)} - E c_{\alpha\beta}^{(4)} + E^2 a_{\alpha\beta}^{(5)} - E^3 c_{\alpha\beta}^{(6)} + E^4 a_{\alpha\beta}^{(7)} - E^5 c_{\alpha\beta}^{(8)} \cdots$$

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

$$P_{\alpha\to\beta}(E,\infty) \sim 1 - 2\sum_{i>j} Re\left(V_{\alpha i}^* V_{\beta i}^* V_{\alpha j} V_{\beta j}\right) = \sum_i |V_{\alpha i}|^2 \left|V_{\beta i}\right|^2$$

Finally, fraction of neutrino flavour β on the earth is

$$\alpha_\beta^{\oplus} \sim \int_{Emin}^{Emax} \sum_\alpha P_{\alpha\to\beta}(L\to\infty, E)\phi_\alpha(E) dE$$

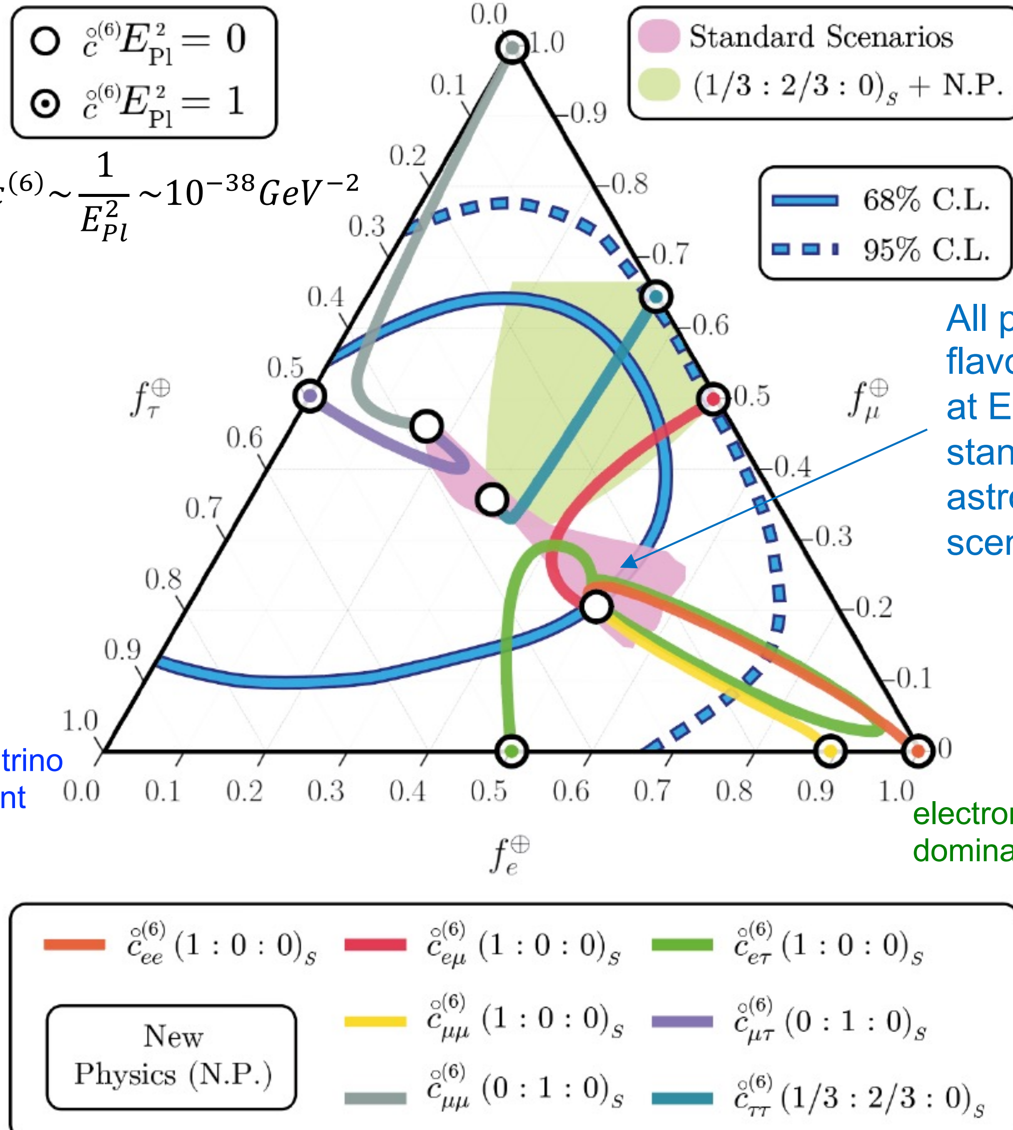
→ Information of small Lorentz violation is encoded on neutrino mixing probability, so by measuring (tasting) astrophysical neutrino flavours, you can explore Lorentz violation

3. Flavor ratio – Astrophysical neutrinos

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

$$c^{(6)} \sim \frac{1}{E_{Pl}^2} \sim 10^{-38} GeV^{-2}$$



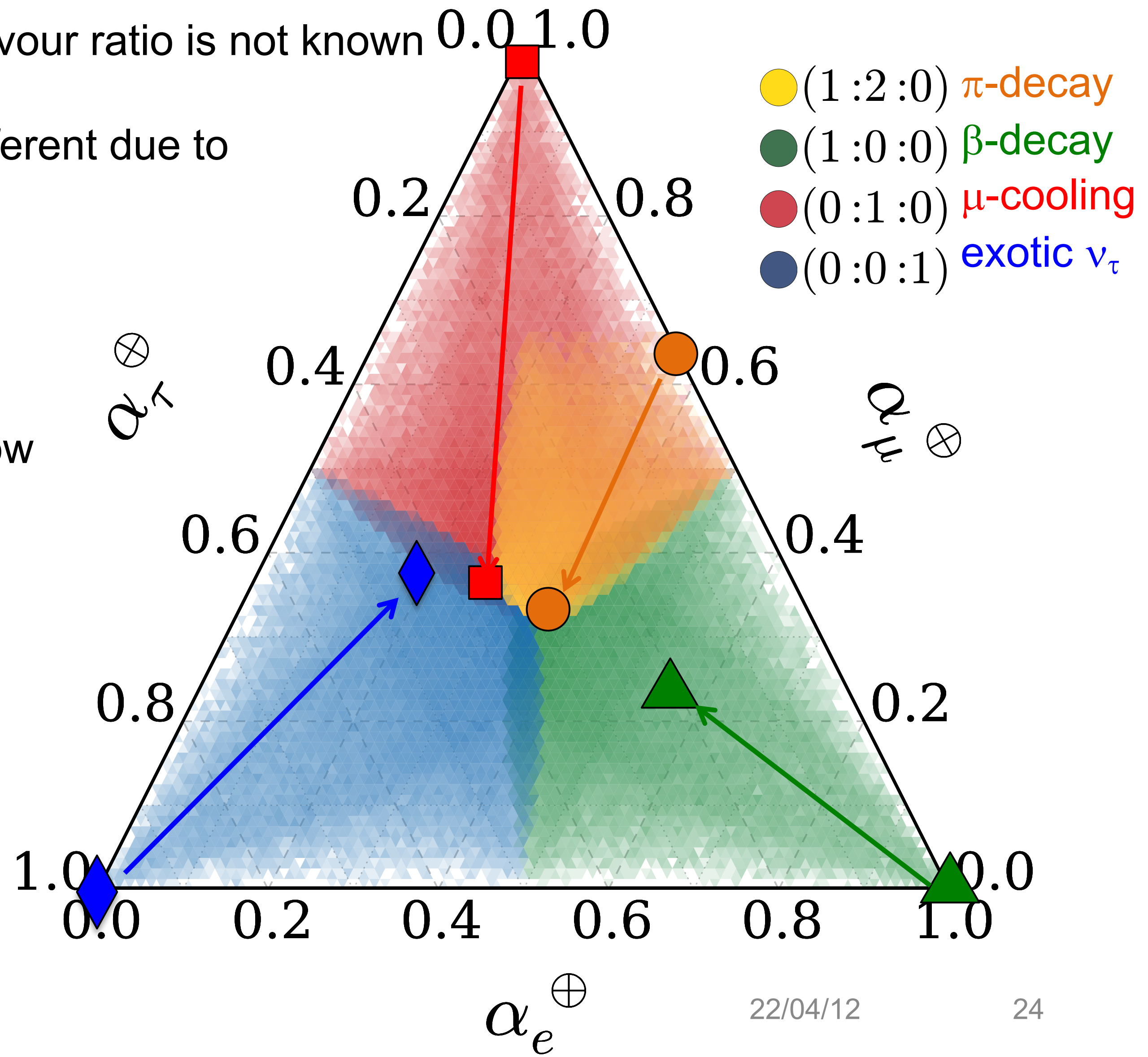
3. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

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



3. HESE 7.5-yr flavor Lorentz violation 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	coefficient	limit (BF> 10.0)
3	$\mathrm{Re}\,(\mathring{a}^{(3)}_{\tau\tau})$	2×10^{-26} GeV
4	$\mathrm{Re}\,(\mathring{c}^{(4)}_{\tau\tau})$	2×10^{-31}
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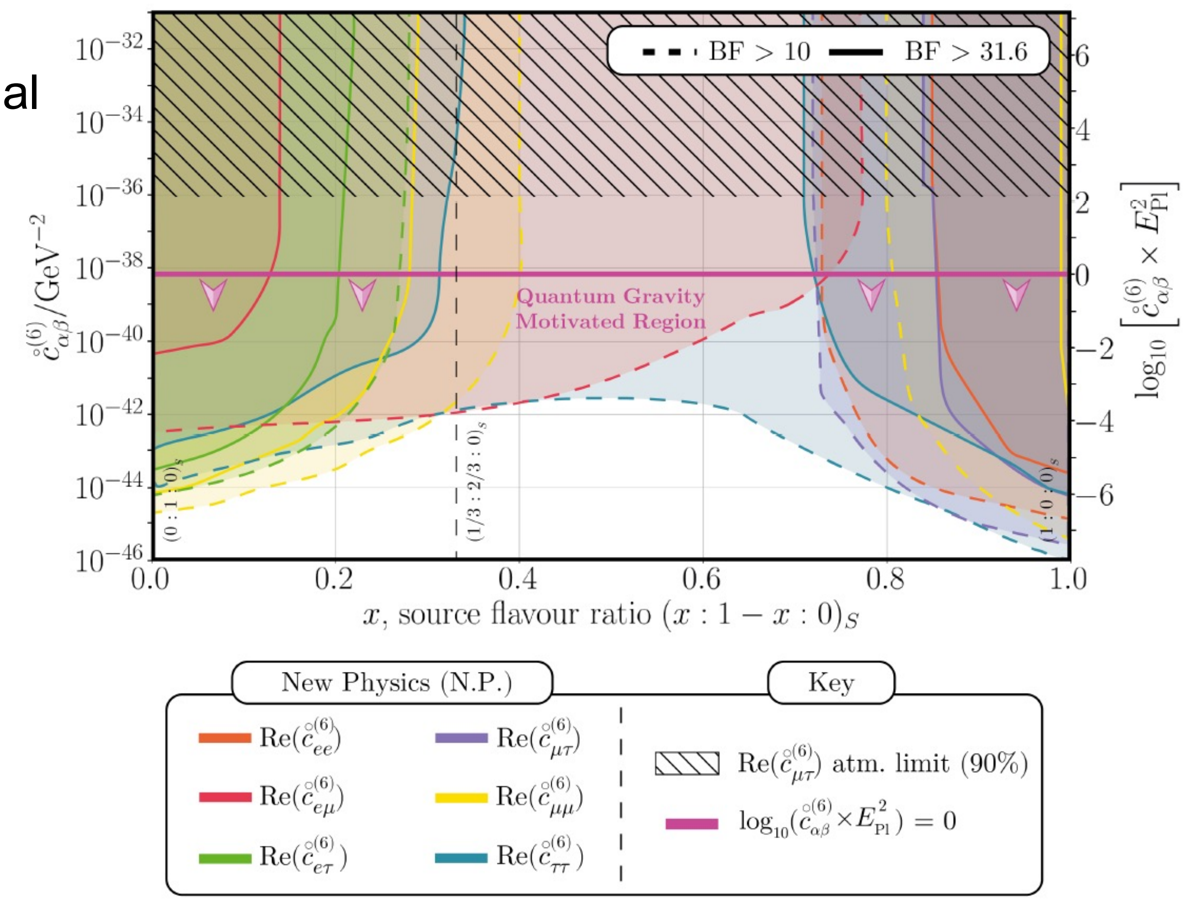
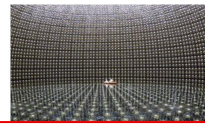
dim-6 new physics operator limit



3. Test of Lorentz violation with neutrinos

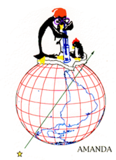
Spectral distortion



Super-Kamiokande
PRD91(2015)052003

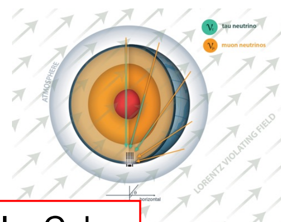
Daya Bay

PRD98(2018)092013



AMANDA

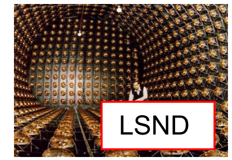
PRD79(2009)102005



IceCube

Nature Physics 14(2018)961

Sidereal variation



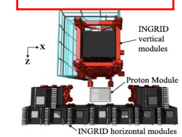
LSND
PRD72(2005)076004

MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

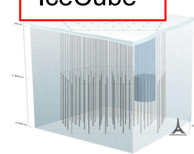
MINOS FD
PRL105(2010)151601

T2K ND



PRD95(2017)111101

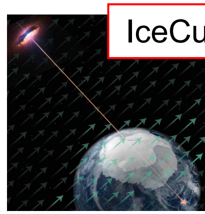
IceCube



PRD82(2010)112003

Double Chooz
PRD86(2013)112009

Flavor ratio

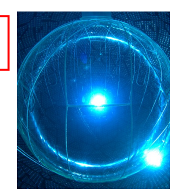


IceCube

Nature Physics, 18(2022)1287

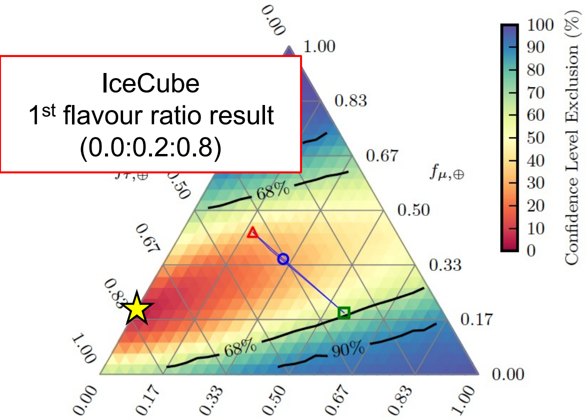
Seasonal variation

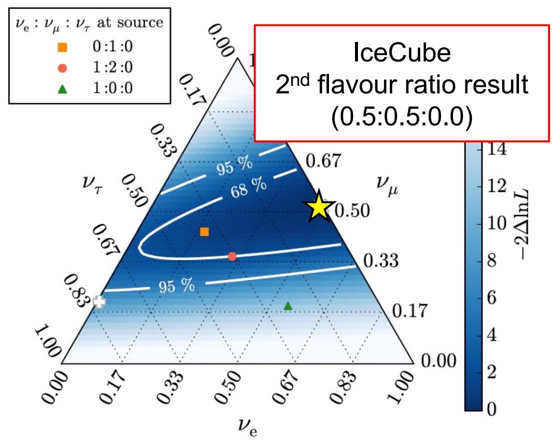
SNO

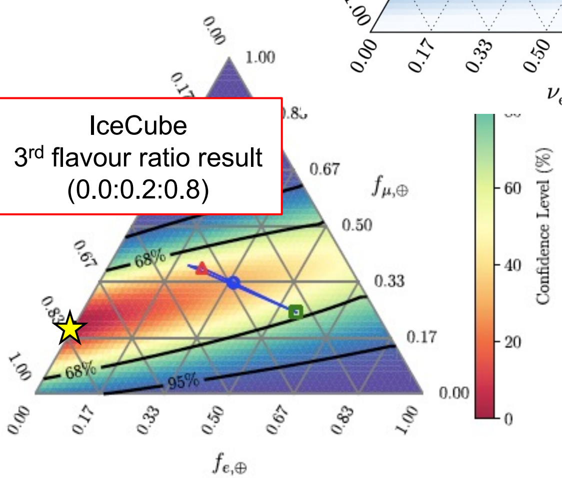


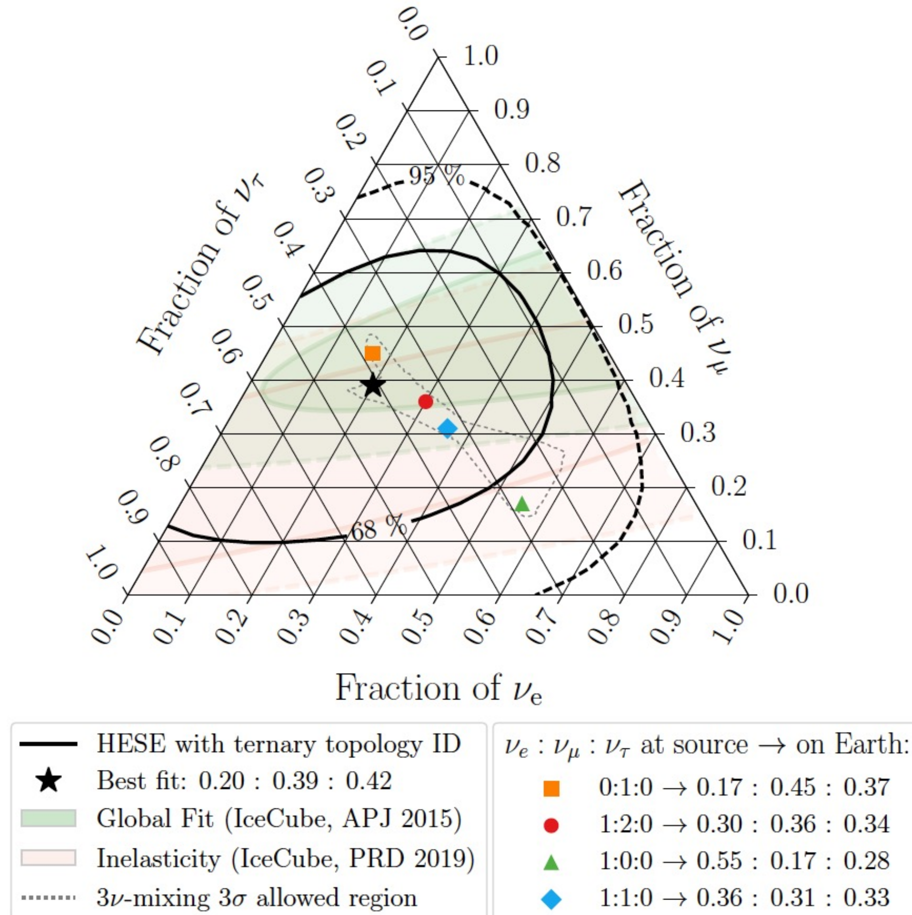
PRD98(2018)112013

3. HESE 7.5-yr data (2018)





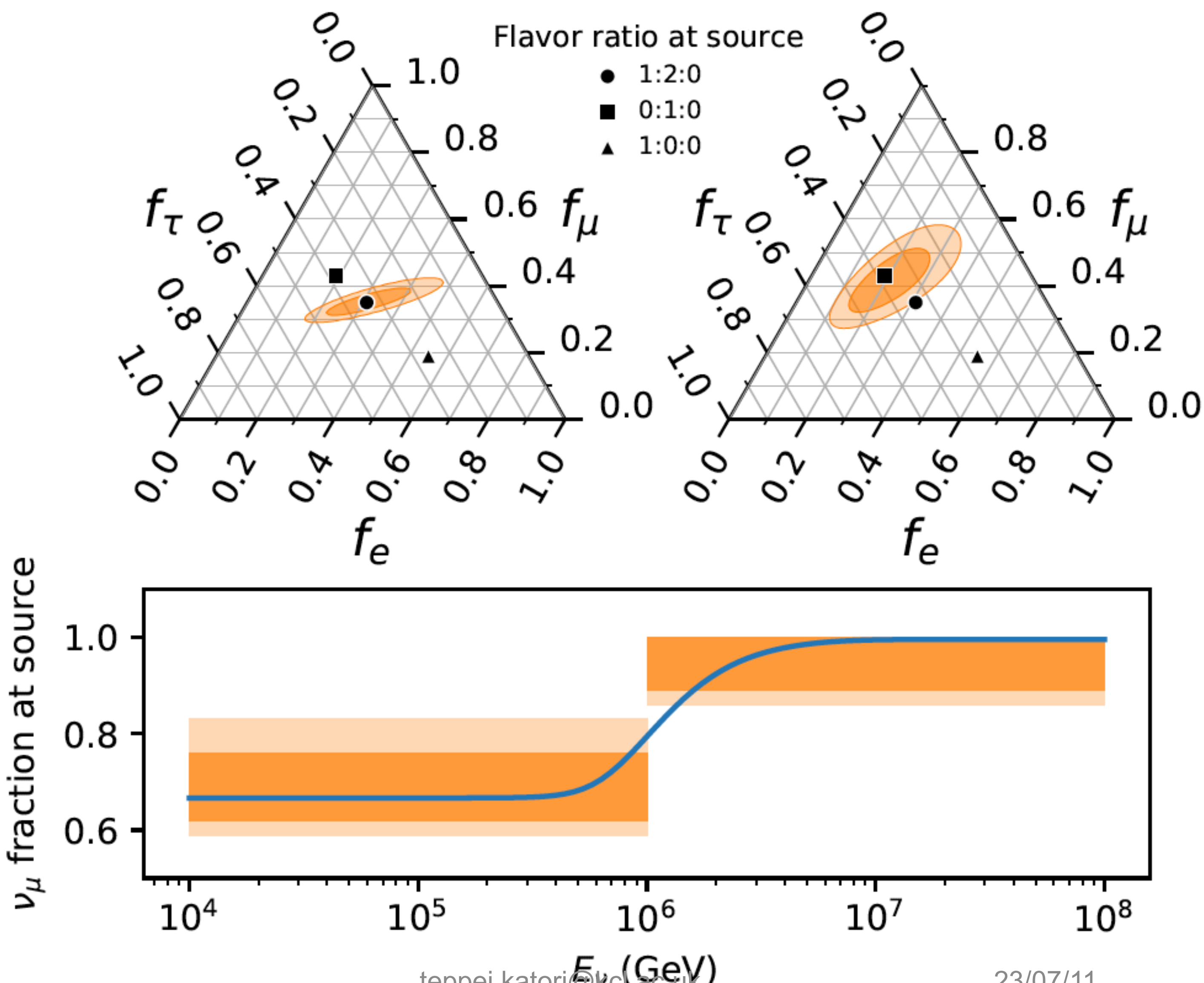




New flavour ratio measurement

- 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

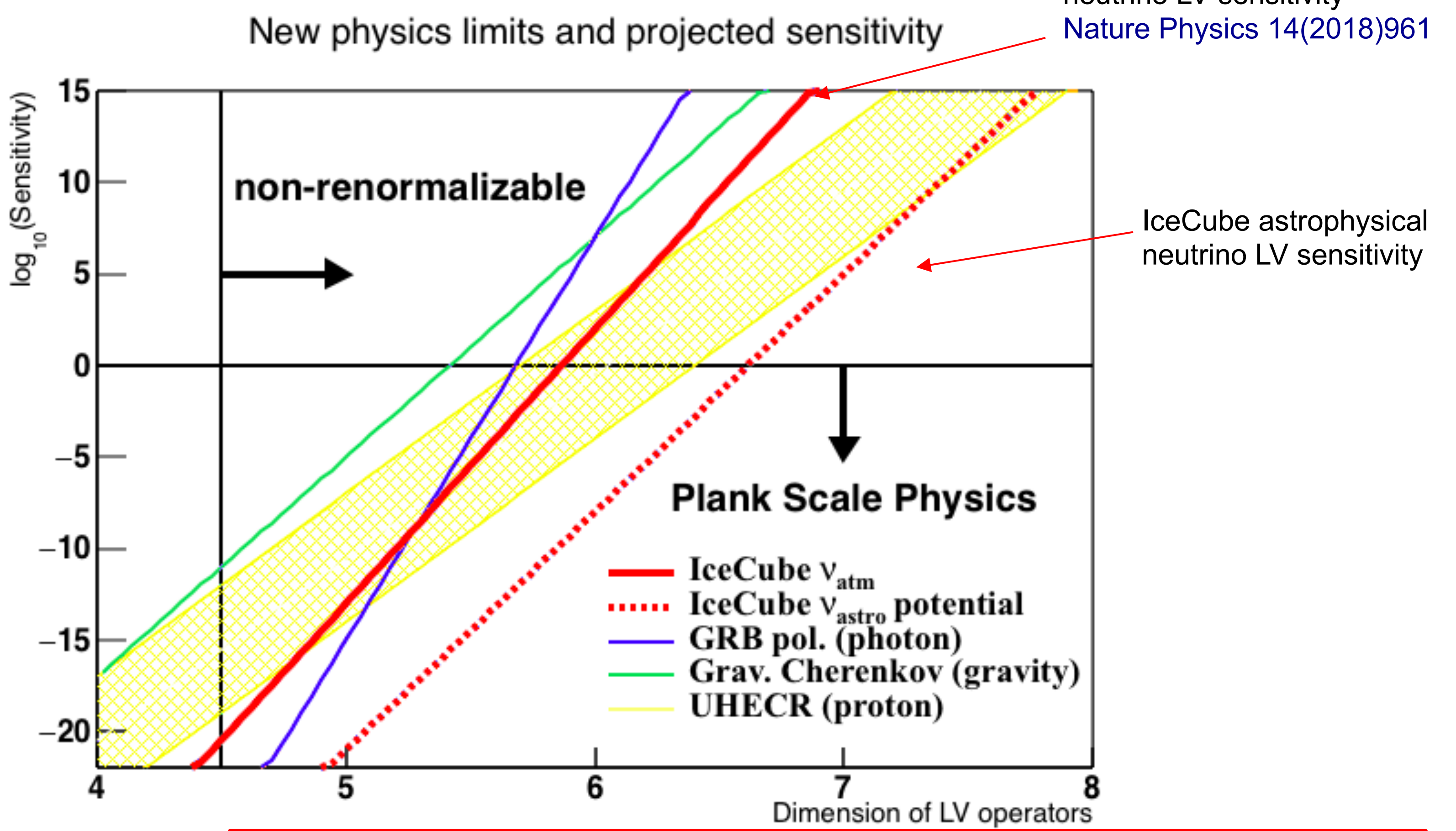
3. Energy dependence of flavor ratio



3. 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)



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

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