Ultra-light Dark Matter Limits from Astrophysical Neutrino Flavour

ArXiv.2404.10926

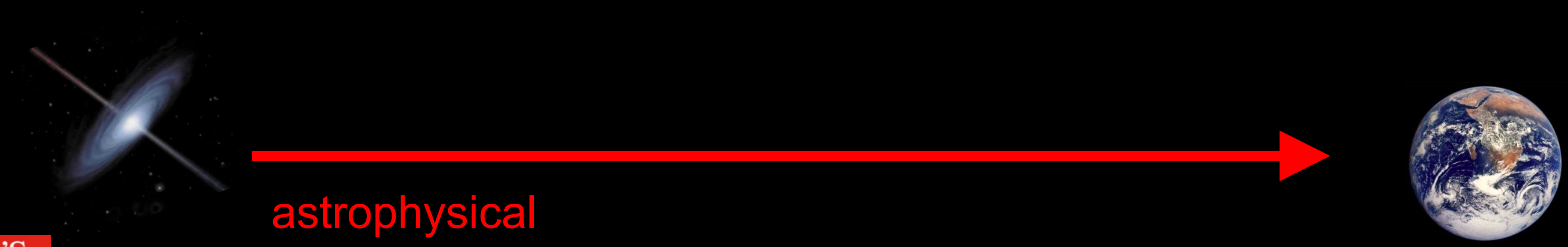
outline

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

Teppei Katori, Carlos Argüelles, Kareem Farrag
King's College London, Harvard University, Chiba University
DMUK meeting, London, UK, Jan. 7, 2025

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



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

Lorentz violating field

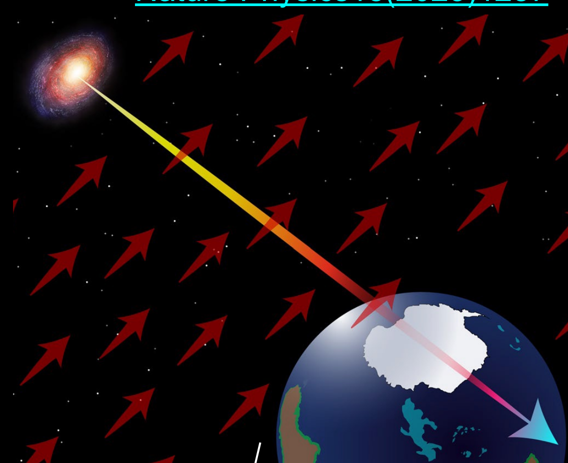
Nature Physics18(2023)1287

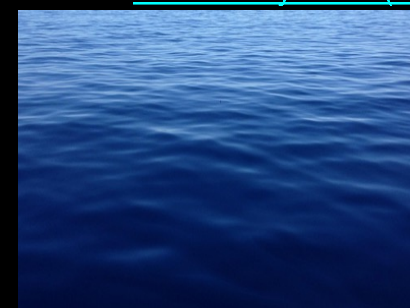
Quantum foam

Nature Physics20(2024)913

Neutrino – ultra-light dark matter interaction

This talk





long-range force
dark energy
etc

astrophysical neutrino

New physics

neutrino mixing

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

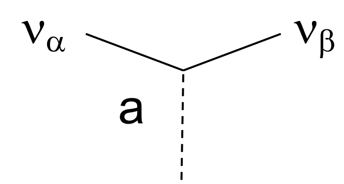
$$10^{-22}eV < m_{DM} < 1eV$$

They behave like waves, not particles

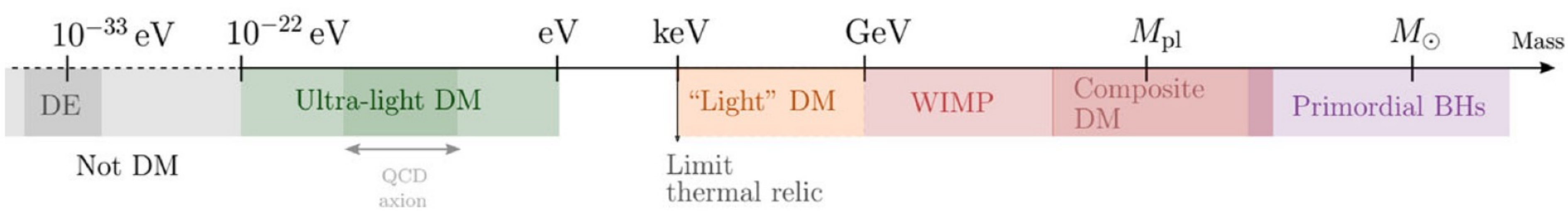
$$\phi(t) = g_{\alpha\beta}\frac{\sqrt{2\rho_{DM}}}{m_{DM}}sin(m_{DM}t)$$

e.g.) axion dark matter – neutrino coupling

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



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



1. Astrophysical neutrino flavour physics

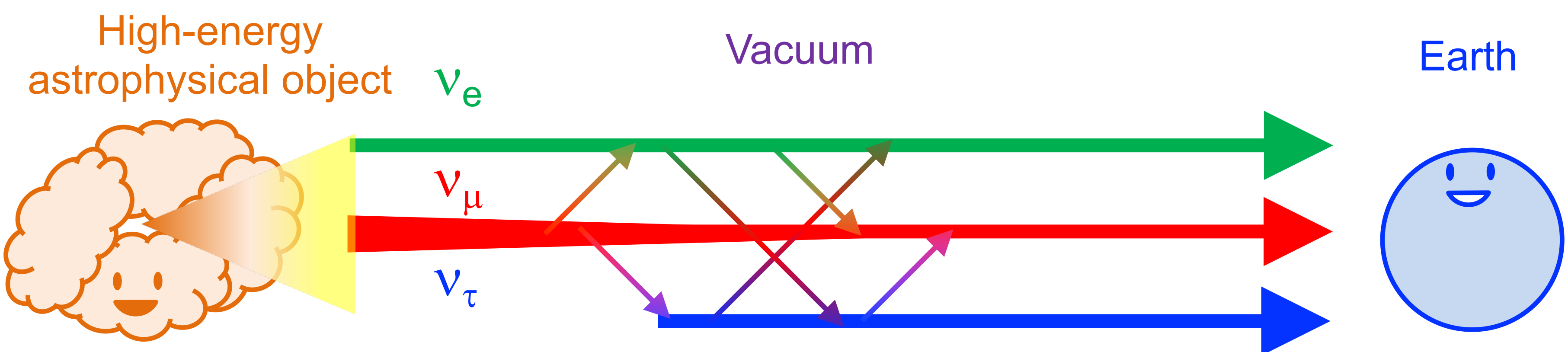
Neutrino mass term in the flavour basis is not diagonal

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

Standard astrophysical models predict astrophysical neutrinos are ν_e and ν_μ

Neutrinos mixings in vacuum produce ν_τ

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



IceCube, Nature Physics18(2023)1287

1. Astrophysical neutrino flavour physics

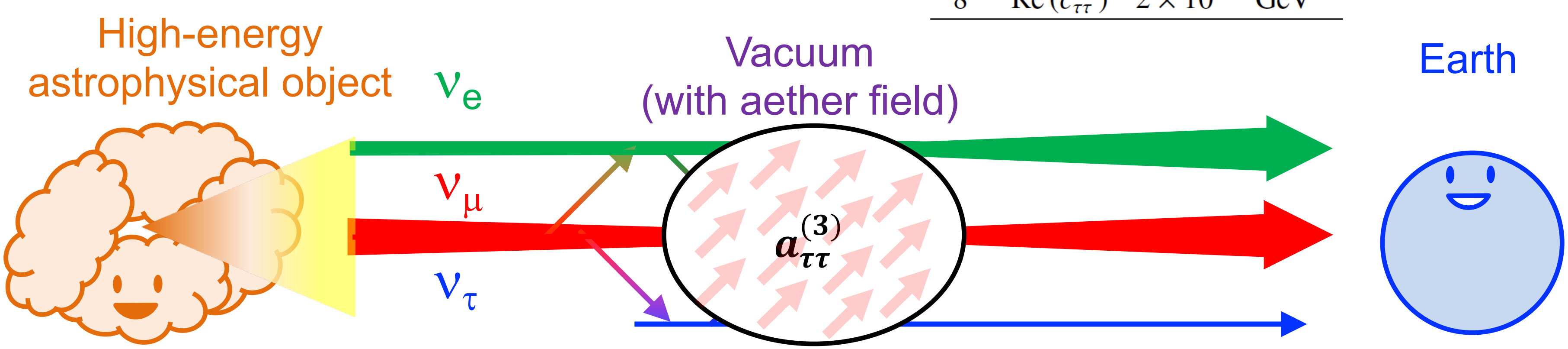
Any effective interactions in vacuum (=Lorentz violation) modify mixing pattern

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

Large diagonal term can modify the neutrino flavour ratio

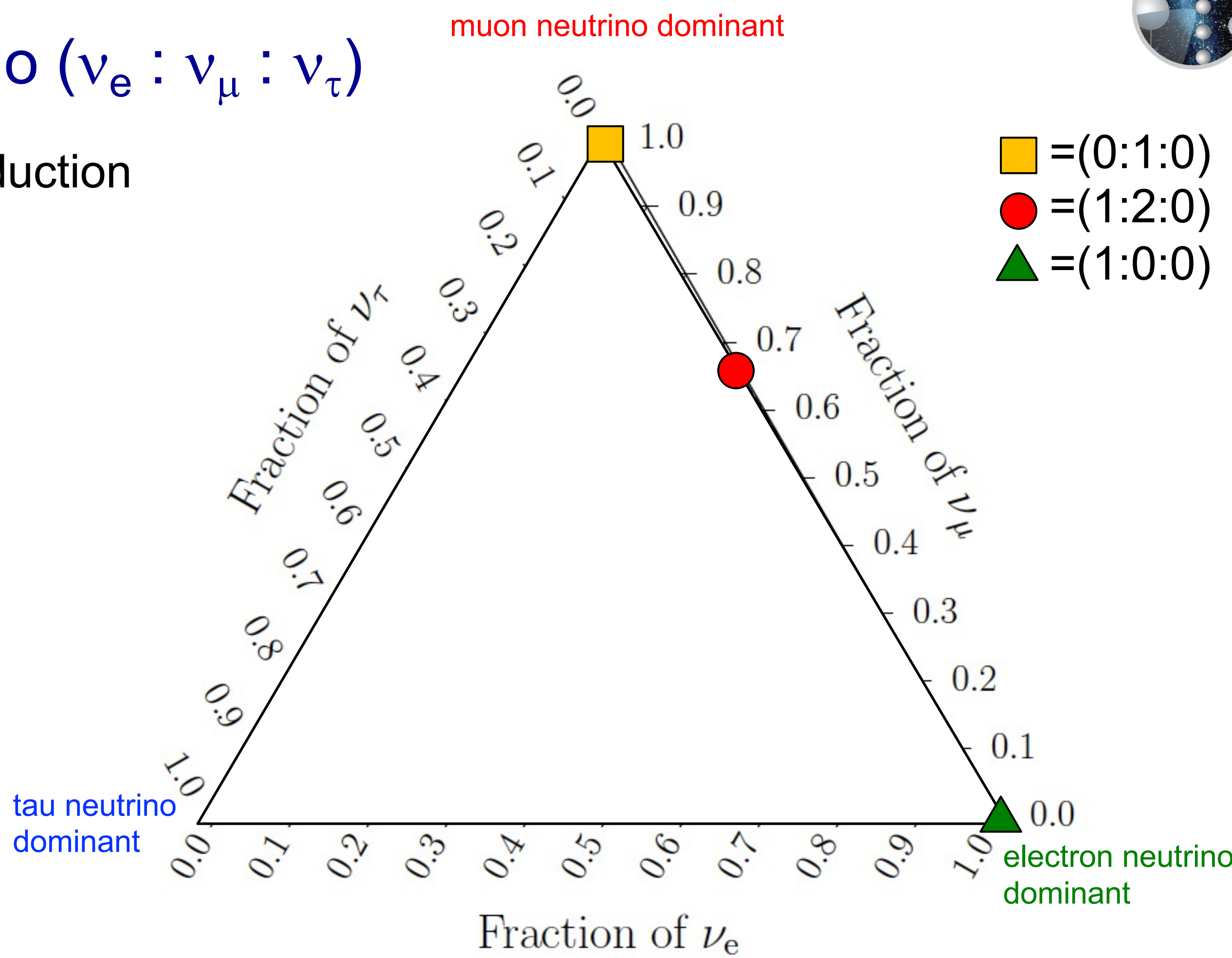
IceCube set the strongest limit on $a^{(3)}_{\tau\tau}$

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}
7	$\mathrm{Re}\,(\mathring{a}^{(7)}_{\tau\tau})$	3×10^{-47} GeV^{-3}
8	$\mathrm{Re}\,(\mathring{c}^{(8)}_{\tau\tau})$	2×10^{-52} GeV^{-4}



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

Astrophysical neutrino production mechanism is not known

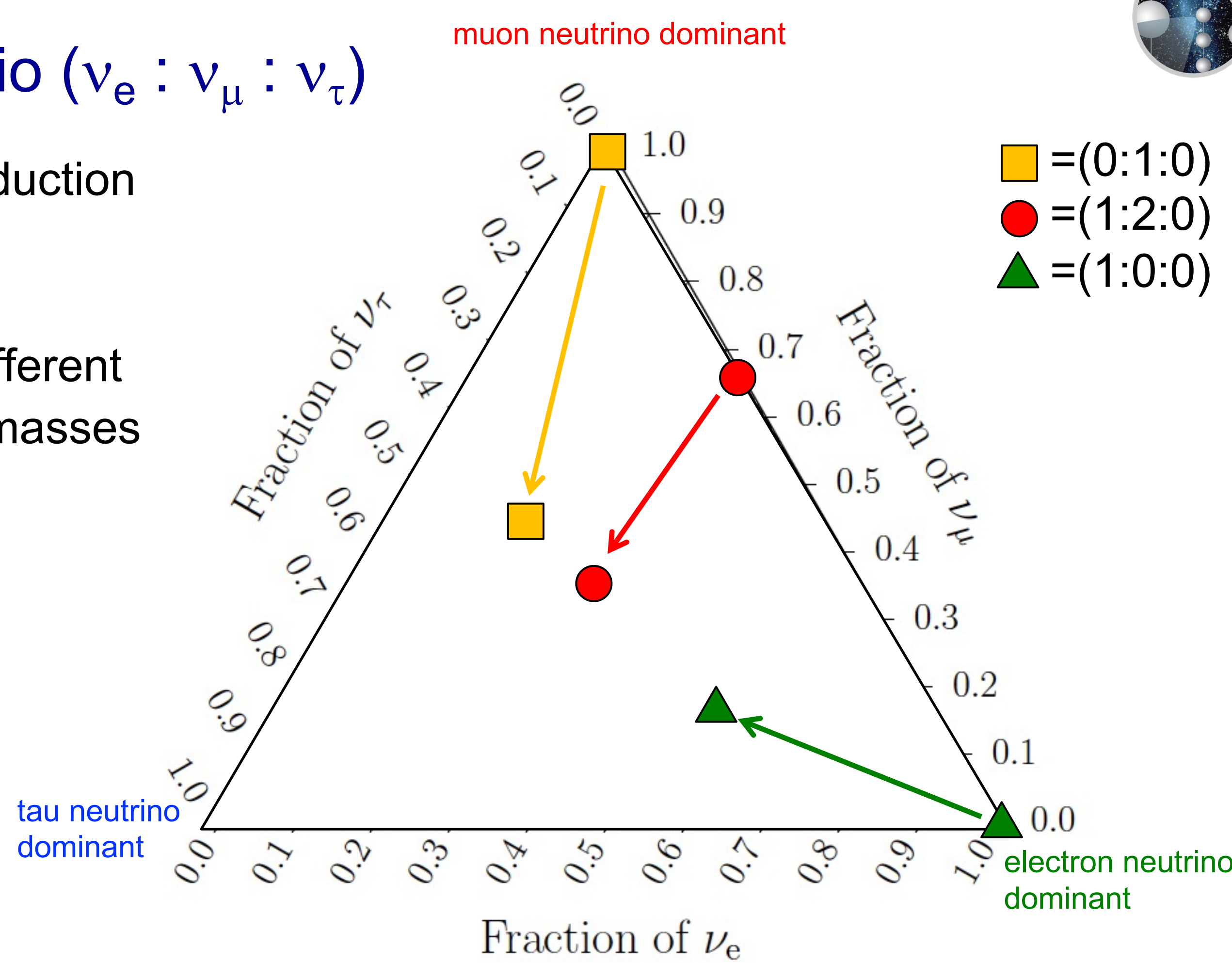


[Argüelles, TK, Salvado, PRL115(2015)161303](#)

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



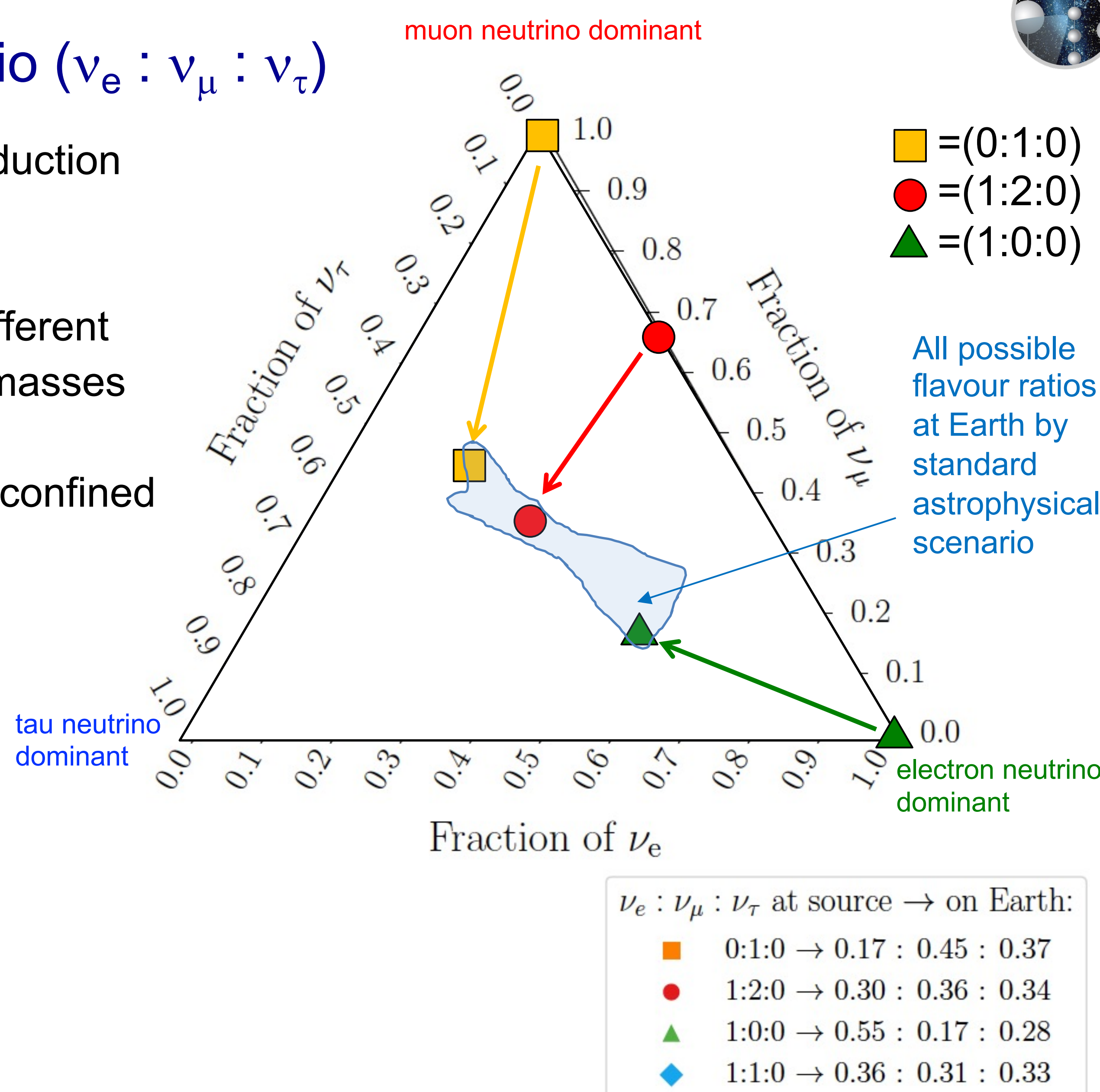
$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:	
■	0:1:0 → 0.17 : 0.45 : 0.37
●	1:2:0 → 0.30 : 0.36 : 0.34
▲	1:0:0 → 0.55 : 0.17 : 0.28
◆	1:1:0 → 0.36 : 0.31 : 0.33

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

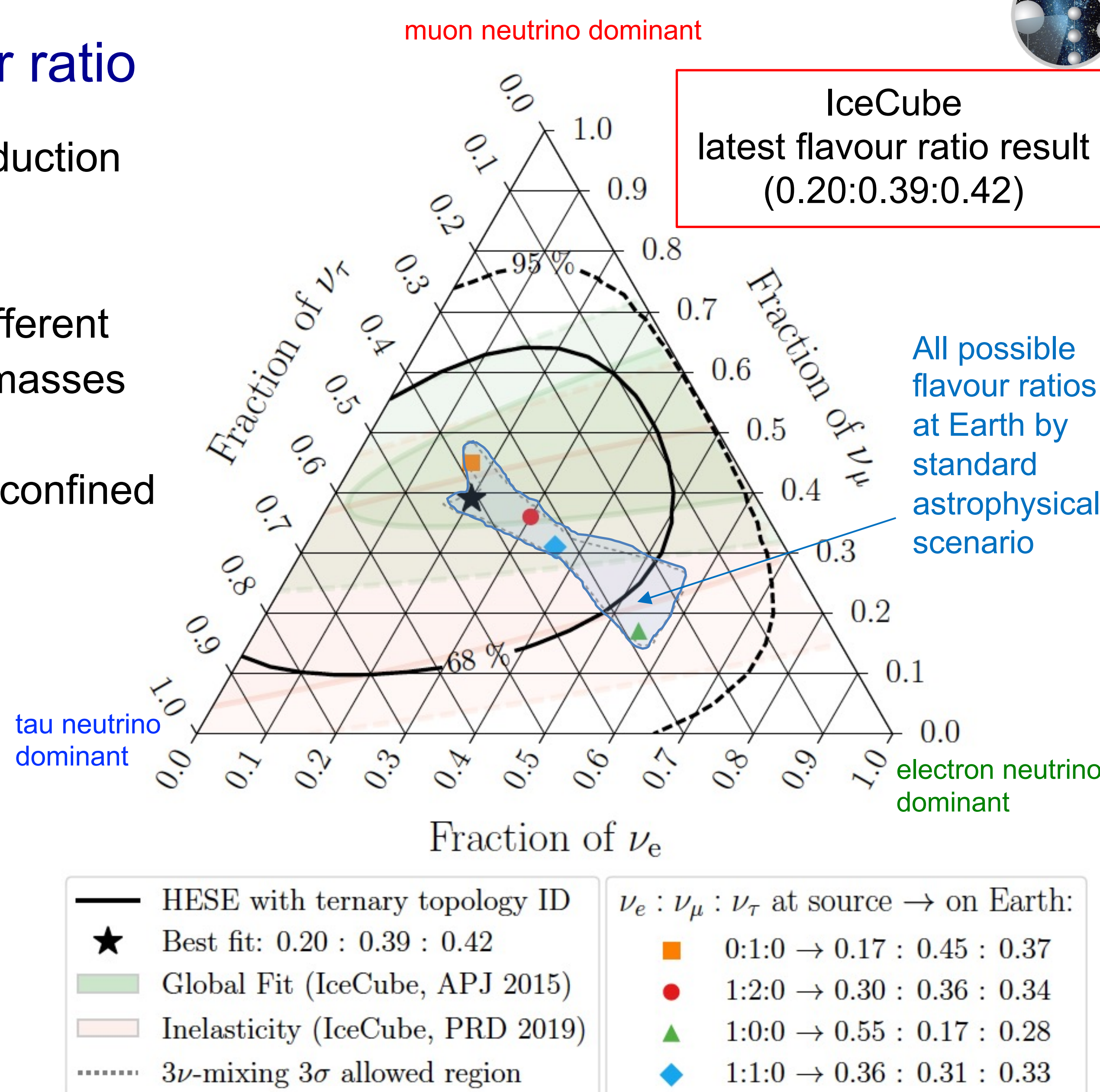
1. HESE 7.5-yr flavor ratio

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



2. Ultra-light dark matter coupling with neutrinos

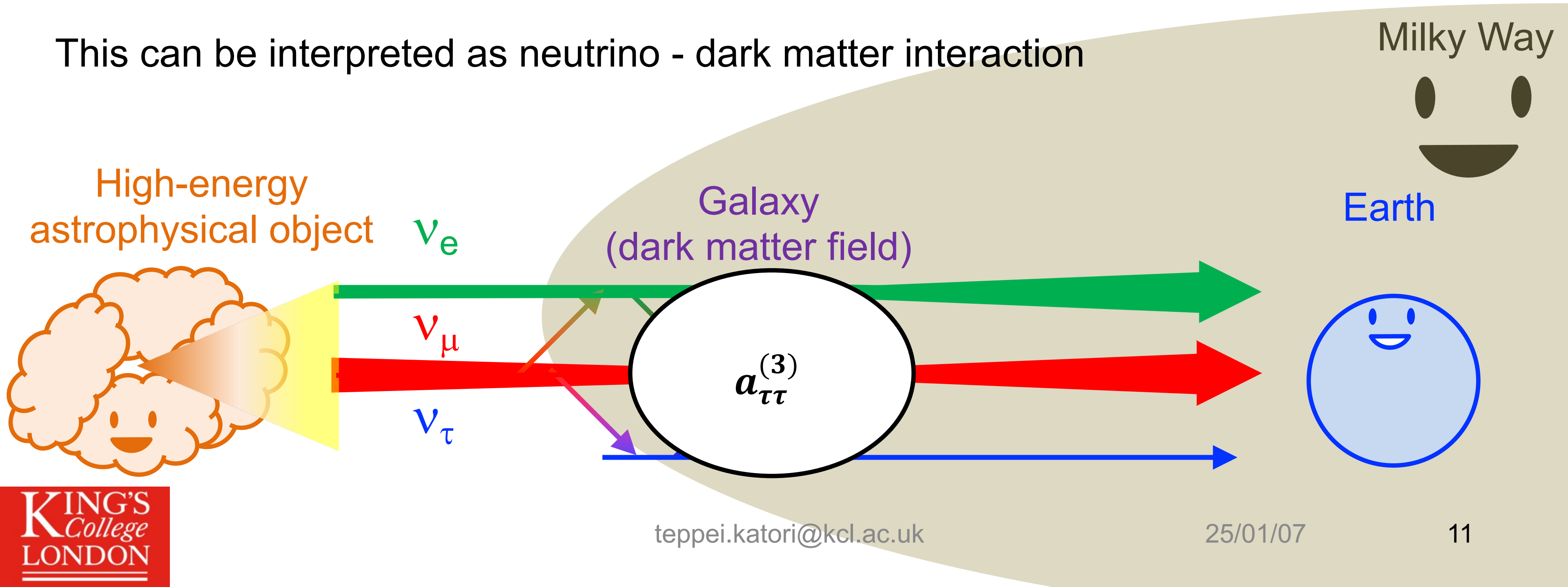
Any effective interaction in vacuum (=Lorentz violation) modify mixing pattern

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

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

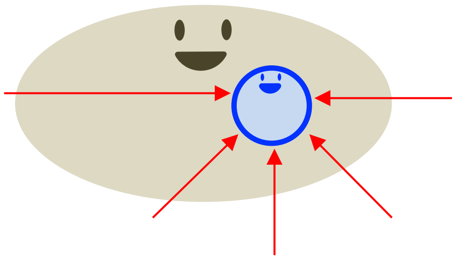
ex) Generic dark matter model

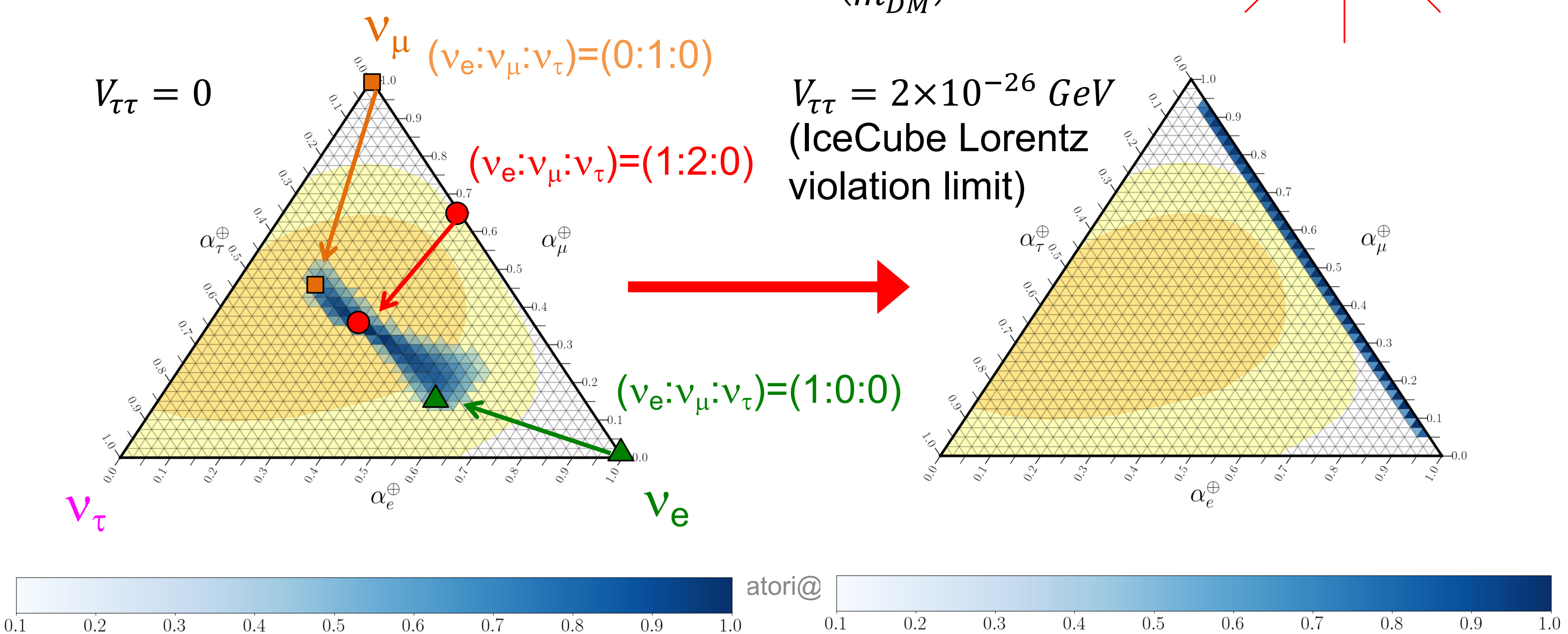
Dark matter makes matter potential in galactic halo

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

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

ρ_{DM}=0.3 GeV/m^3





Salas, Lineros, Tórtola, PRD94(2016)123001
Karmakar, Pandey, Rakshit, JHEP10(2021)004(2021)

2. Ultra-light dark matter coupling with neutrinos

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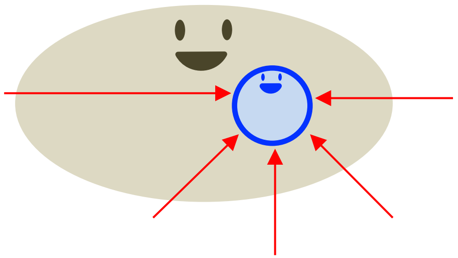


Dark matter potential limit: $V_{\tau\tau} < 2\times10^{-26}\ GeV$

Dark matter effective Fermi coupling limit: $G'_{\tau\tau} < 10^{-13} GeV^{-2} \left(\frac{m_{DM}}{10^{-20} eV} \right)$

Dark matter non-standard interaction limit: $\epsilon_{\tau\tau} < 8\times10^{-9} \left(\frac{m_{DM}}{10^{-20} eV} \right)$

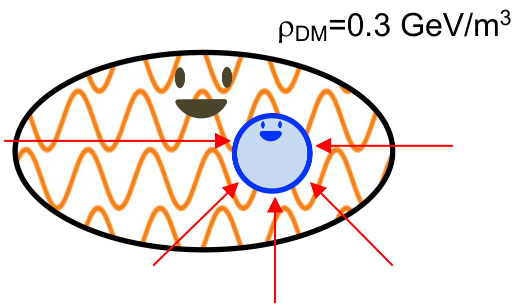
IceCube sensitivity goes beyond terrestrial experiments
- Higher energy suppresses neutrino mass term

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

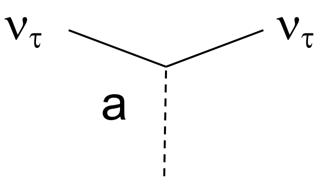
Different dark matter models provide different effective Hamiltonian

ex) Axion dark matter model

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + V_{\tau\tau}$$
$$V_{\tau\tau}(t) = g_{a\tau\tau} m_a a_0 sin(m_a t)$$



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

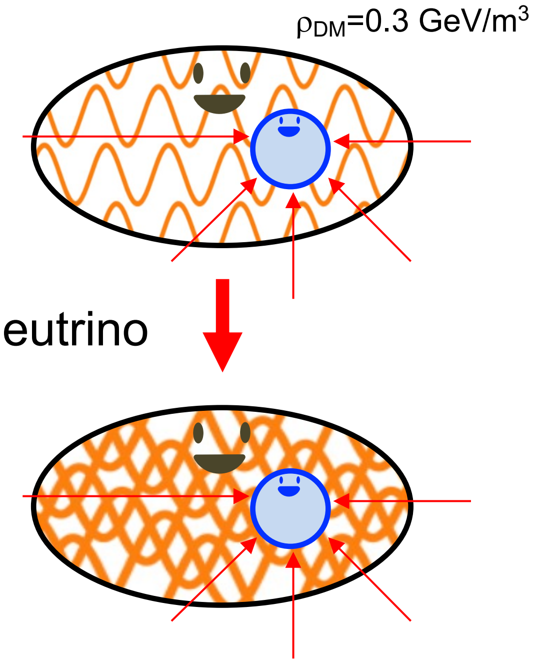


Losada,et al, JHEP04(2022)030.
Hamaide,Müller,Marsh,PRD106(2022)123509

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

$$V_{\tau\tau}(t) = g_{a\tau\tau} m_a a_0 sin(m_a t) \xrightarrow{t\to\infty} 0$$



On average, dark matter potential is zero

However, dark matter potential smear flavour ratio for each neutrino

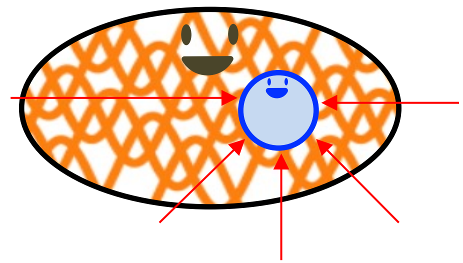
We monitor the smearing effect to look for ultra-light dark matter

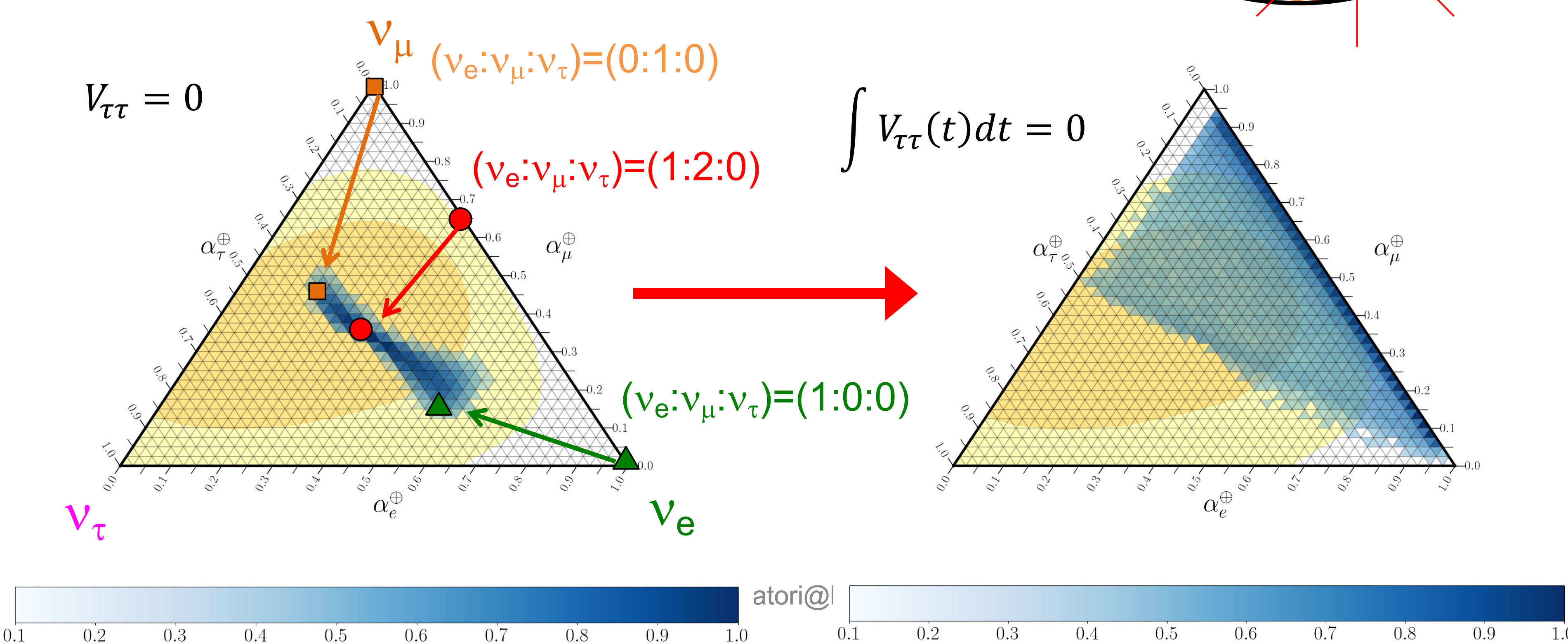
Berlin, PRL117(2016)231801,
Huang and Nath, EPJC78(2018)922

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

Choose field amplitude where 95% of parameter space is rejected by data

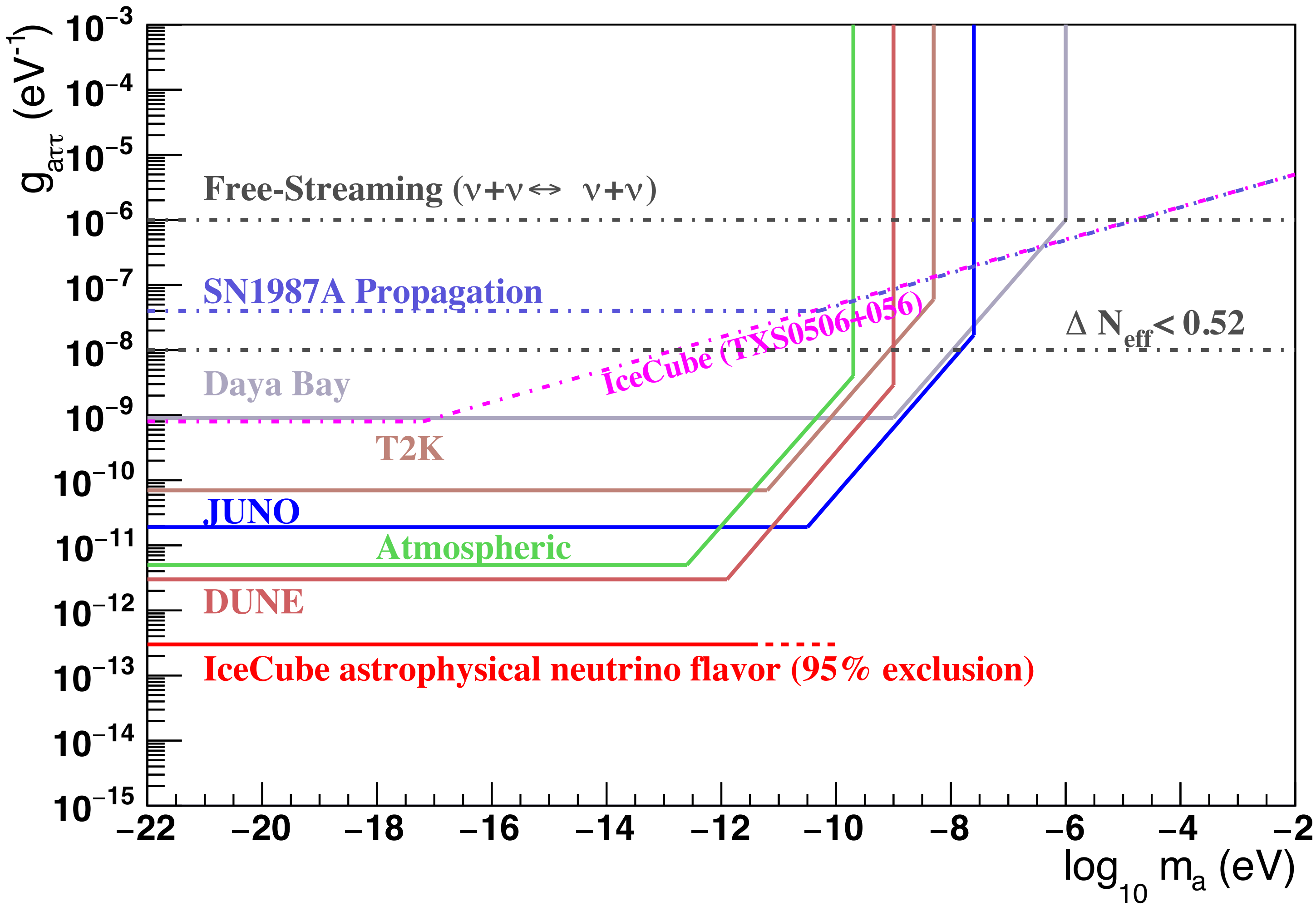




Argüelles, TK, Farrag, ArXiv.2404.10926
Huang and Nath, EPJC78(2018)922

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

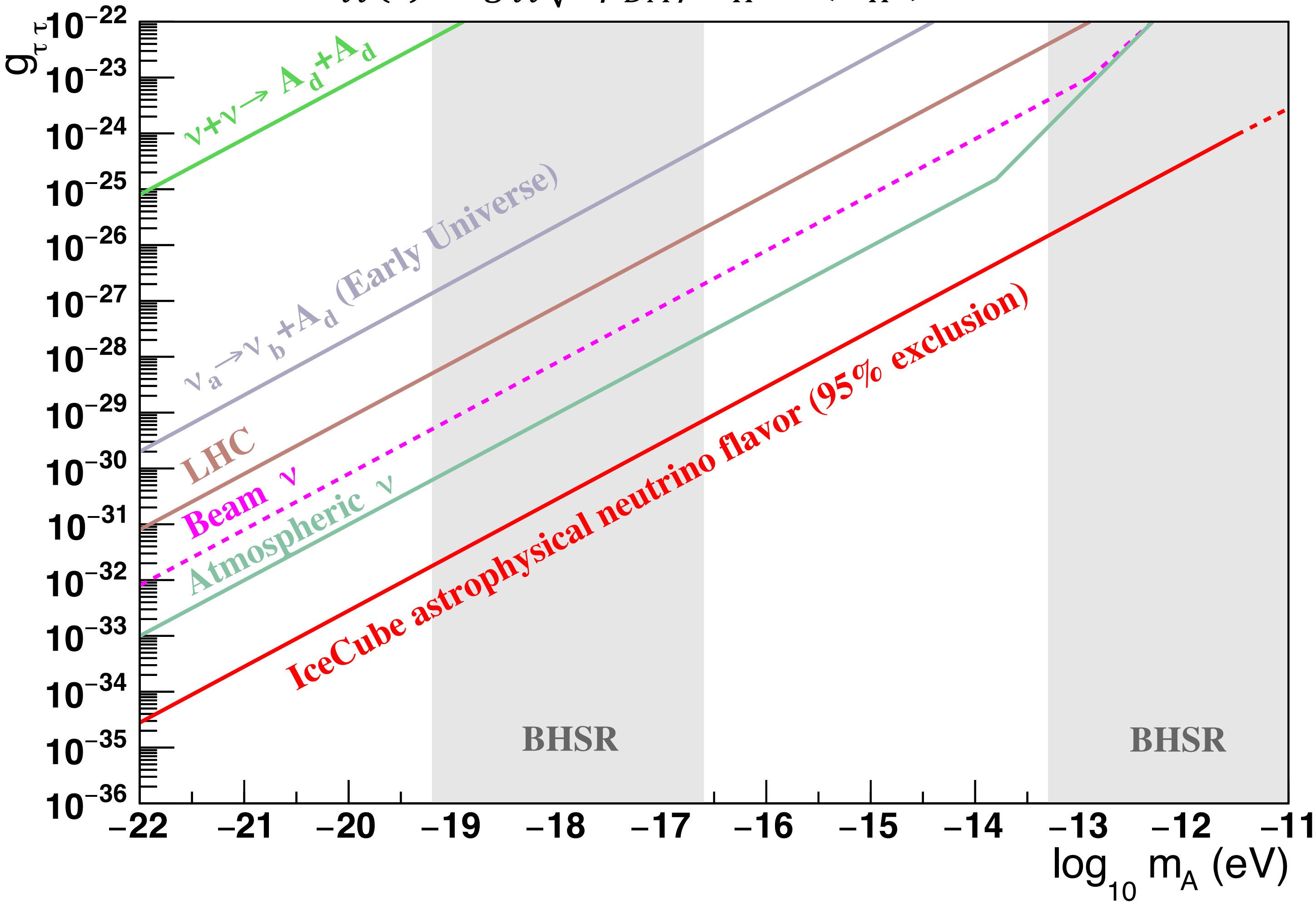
Axion dark matter limit: $V_{\tau\tau}(t) = g_{a\tau\tau} m_a a_0 sin(m_a t)$



Argüelles, TK, Farrag, ArXiv.2404.10926
Brzeminski et al, JHEP08(2023)181

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

Vector dark matter limit: $V_{\tau\tau}(t) = g_{\tau\tau}\sqrt{2\rho_{DM}}/m_A sin(m_A t)$



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

Ultra-light dark matter limit from astrophysical neutrino flavour is the strongest in neutrino sector

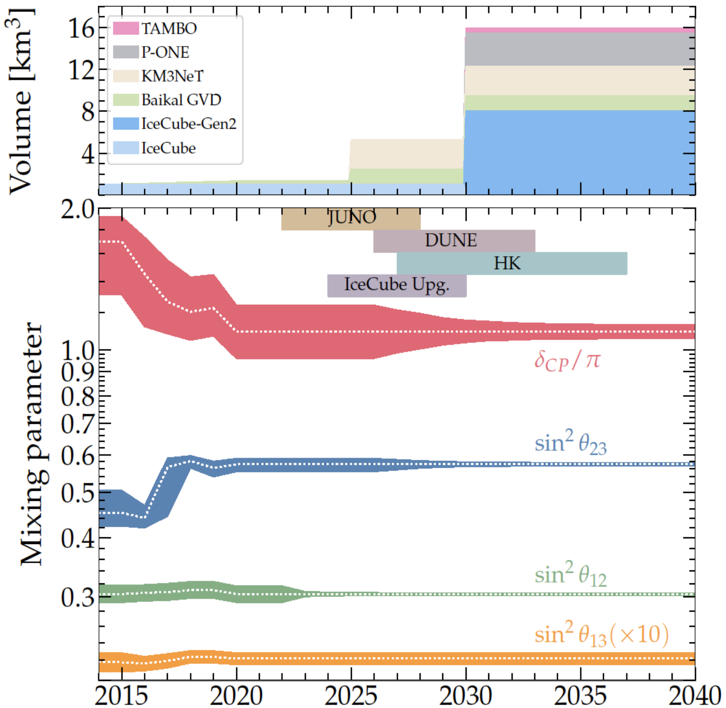
Limits can be further improved by new astrophysical neutrino flavour data
- Improved neutrino PID algorithm (tau neutrinos)
- Higher statistics data from IceCube
- New neutrino telescopes

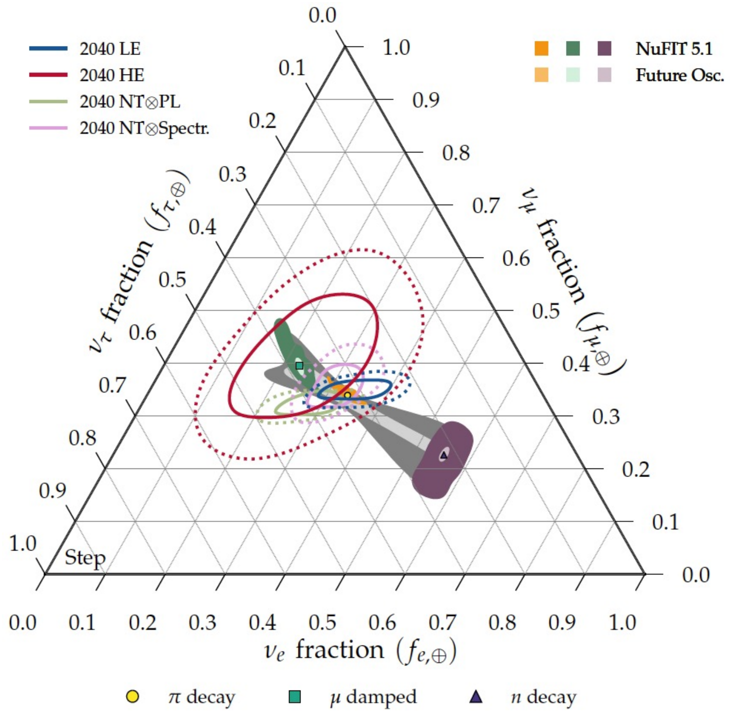
Model	Limits
IceCube Lorentz violation limit	$\mathring{a}^{(3)}_{\tau\tau} < 2 \times 10^{-26}\text{GeV}$
Dark matter potential	$V_{\tau\tau} < 2 \times 10^{-26}\text{GeV}$
Dark matter effective Fermi coupling	$G'_F < 10^{-13}\text{GeV}^{-2}(m_\phi/10^{-20}\text{eV})$
Dark matter non-standard interaction	$\epsilon_{\tau\tau} < 8 \times 10^{-9}(m_\phi/10^{-20}\text{eV})$
Vector dark matter coupling	$g_{\tau\tau} < 3 \times 10^{-33}(m_\phi/10^{-20}\text{eV})$
Axion dark matter coupling	$g_{a\tau\tau} < 3 \times 10^{-13}\text{eV}^{-1}$

Astrophysical neutrino flavour physics - future

Smaller flavour ratio contour will allow to find any anomalous effects

- Improved neutrino PID algorithm (tau neutrinos)
- Higher statistics data from IceCube
- New neutrino telescopes
- Improved oscillation parameter data

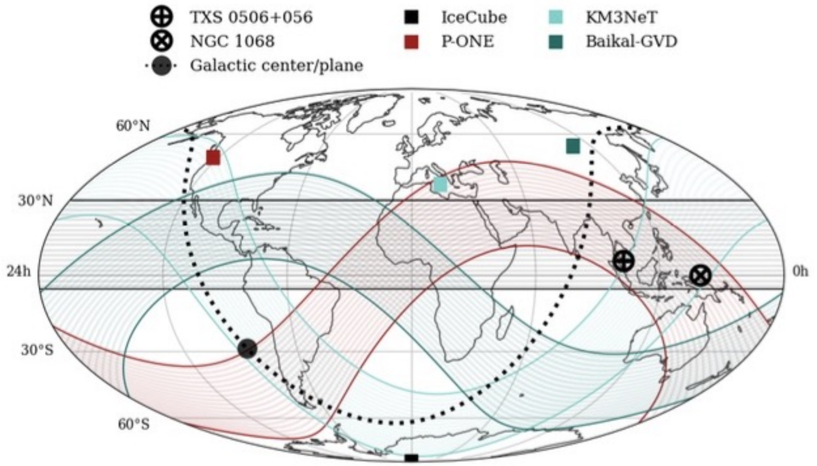


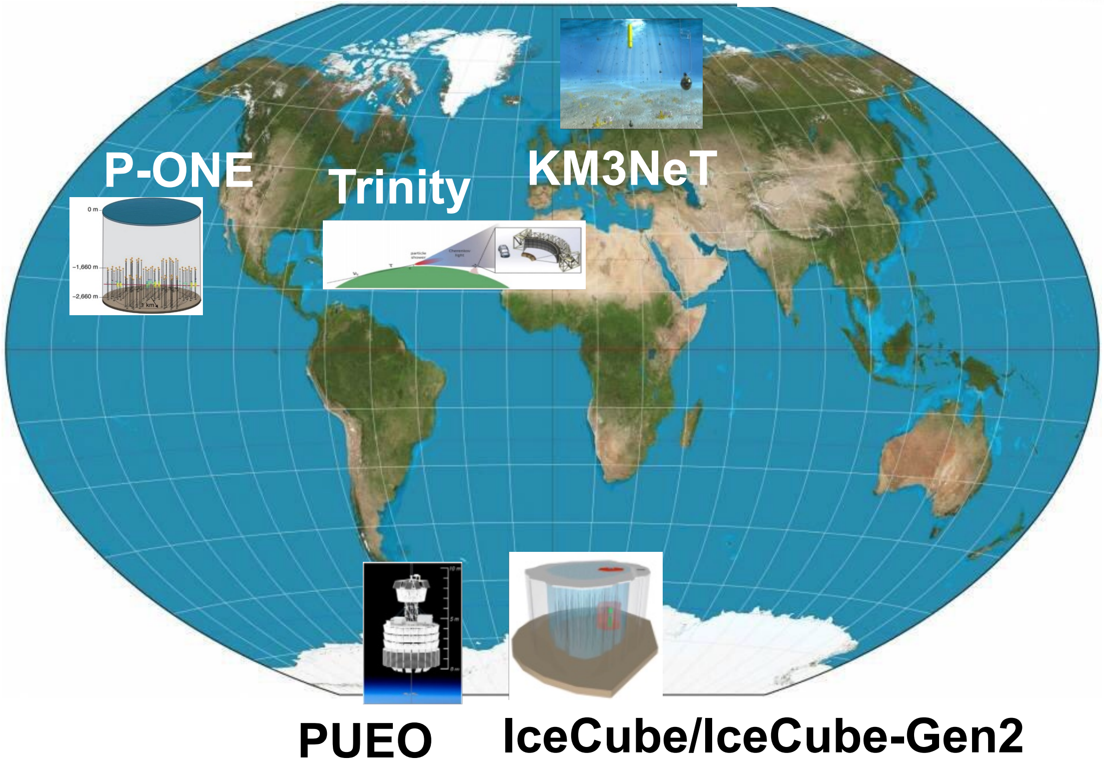


teppei.katori@kcl.ac.uk

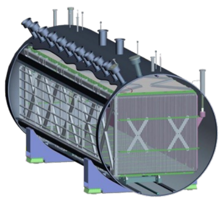
UK High-Energy Astrophysical Neutrino Consortium

- **IceCube, PUEO, P-ONE, KM3NeT, Trinity**
- Experimental submission to PPGP
  (IceCube, PUEO, P-ONE)
  Near term plan:
  Exploit science from **IceCube** and **PUEO**
  Long term plan:
  P-ONE as a baseline UK project

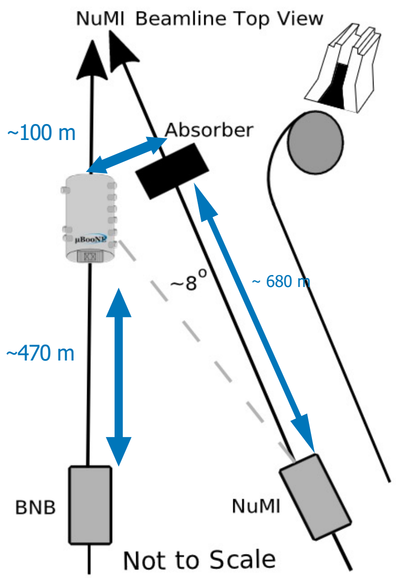




Dark sector searches with the MicroBooNE neutrino detector



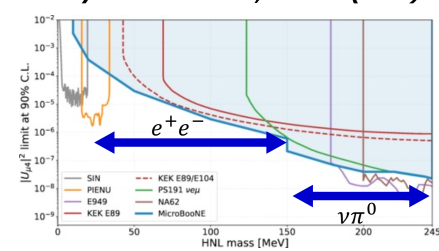
85-tonne **Liquid Argon Time Projection Chamber**



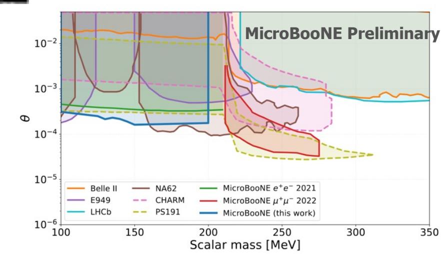
- Located at **Fermilab, USA**
- Exposed to **two neutrino beams** (NuMI & BNB)
- Search for **dark particles produced via meson decays** in the beam(s)

Heavy Neutral Leptons
- **One new right handed singlet state**
- Mixing with active neutrinos via **extended PMNS matrix**
- Produced from **charged kaon decays**
- **Decay to e^+e^- or $\nu\pi^0$**

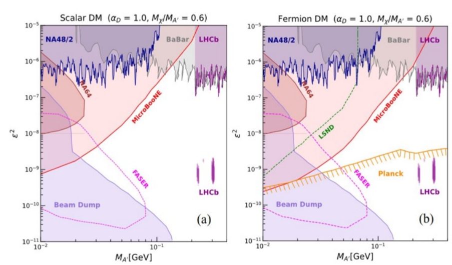
Phys. Rev. Lett. 132, 041801 (2024)



Higgs Portal Scalars
- **Neutral scalar singlet S,** mixing angle θ with the Higgs boson
- Production from **charged kaon decays**
- **Decay to lepton or pion pairs**



Light dark matter
- **Dark matter** produced in the neutrino beam via **dark photon mixing**
- Produced via **neutral meson decay**
- **Scatter off argon nucleus,** accompanied by a dark photon radiation subsequently decaying to e^+e^-



Phys.Rev.Lett. 132 (2024) 24, 241801

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 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

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

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

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

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

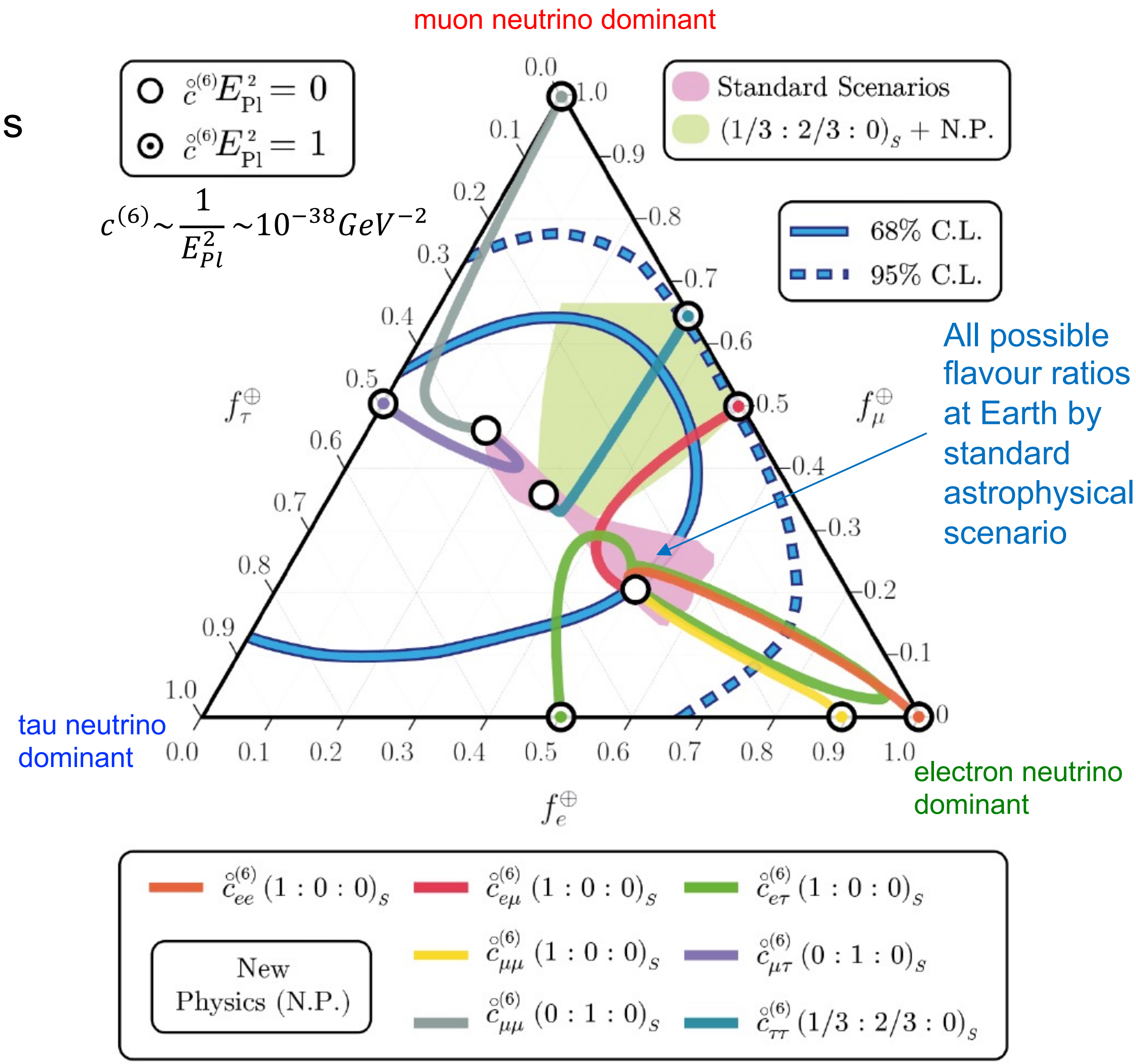
→ Information of small Lorentz violation is encoded on neutrino mixing probability, so by measuring (tasting) astrophysical neutrino flavours, you can explore Lorentz violation

IceCube, Nature Physics18(2023)1287

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



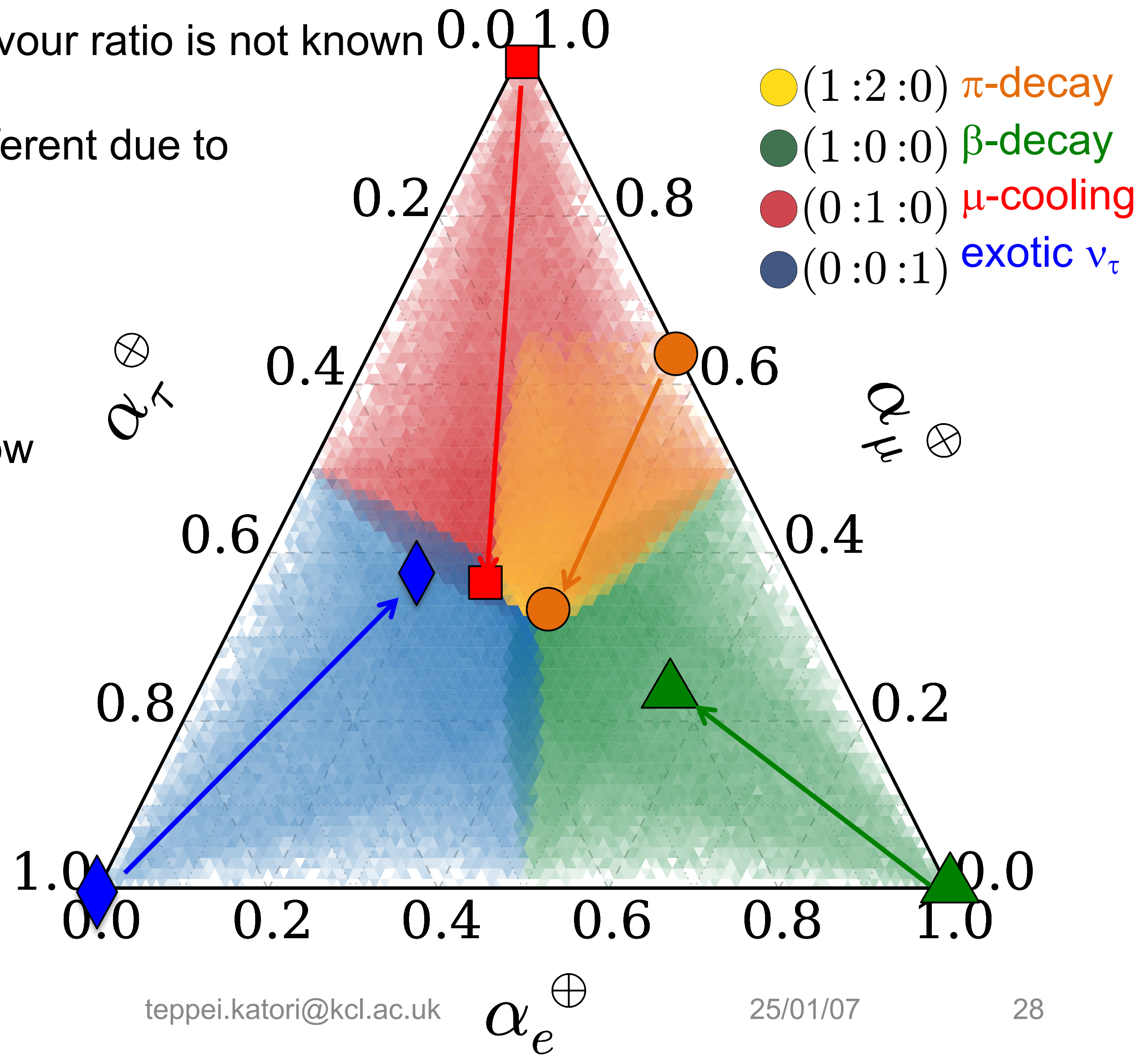
3. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

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



KING'S College LONDON

IceCube, Nature Physics18(2023)1287

3. HESE 7.5-yr flavor Lorentz violation search

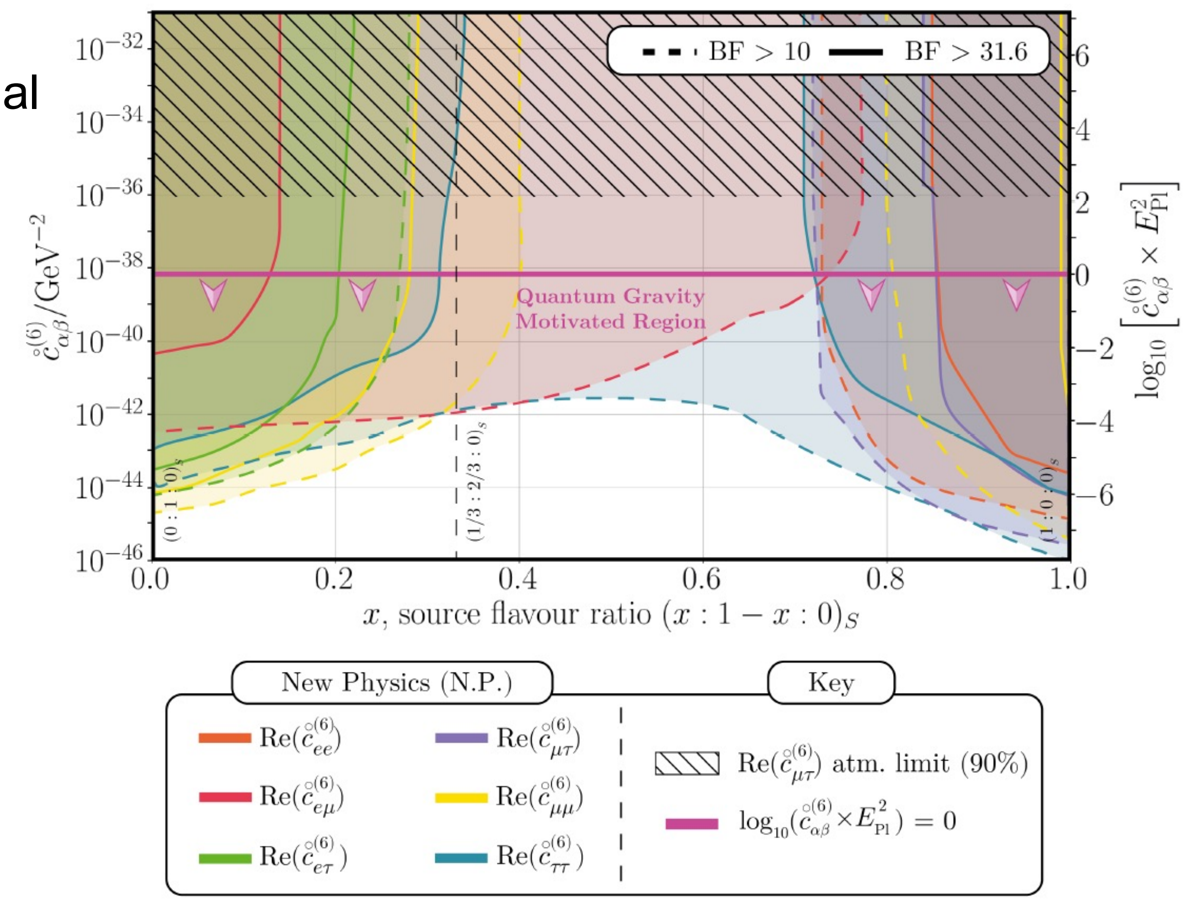
60 HESE events in 60 TeV – 2 PeV

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

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

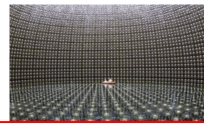
dim	coefficient	limit (BF> 10.0)
3	$\mathrm{Re}\,(\mathring{a}^{(3)}_{\tau\tau})$	2×10^{-26} GeV
4	$\mathrm{Re}\,(\mathring{c}^{(4)}_{\tau\tau})$	2×10^{-31}
5	$\mathrm{Re}\,(\mathring{a}^{(5)}_{\tau\tau})$	2×10^{-37} GeV^{-1}
6	$\mathrm{Re}\,(\mathring{c}^{(6)}_{\tau\tau})$	3×10^{-42} GeV^{-2}
7	$\mathrm{Re}\,(\mathring{a}^{(7)}_{\tau\tau})$	3×10^{-47} GeV^{-3}
8	$\mathrm{Re}\,(\mathring{c}^{(8)}_{\tau\tau})$	2×10^{-52} GeV^{-4}

dim-6 new physics operator limit



3. Test of Lorentz violation with neutrinos

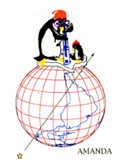
Spectral distortion



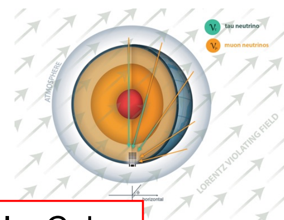
Super-Kamiokande
PRD91(2015)052003

Daya Bay

PRD98(2018)092013

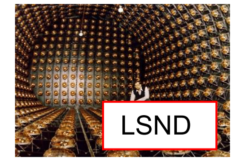


AMANDA
PRD79(2009)102005



IceCube
Nature Physics 14(2018)961

Sidereal variation



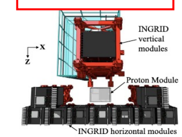
LSND
PRD72(2005)076004

MiniBooNE
PLB718(2013)1303

MINOS ND
PRL101(2008)151601

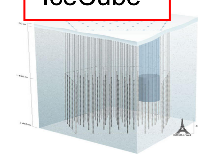
MINOS FD
PRL105(2010)151601

T2K ND



PRD95(2017)111101

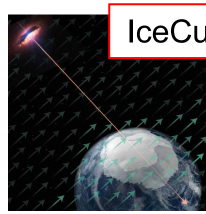
IceCube



PRD82(2010)112003

Double Chooz
PRD86(2013)112009

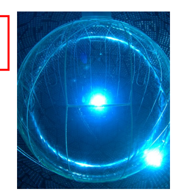
Flavor ratio



IceCube
Nature Physics, 18(2022)1287

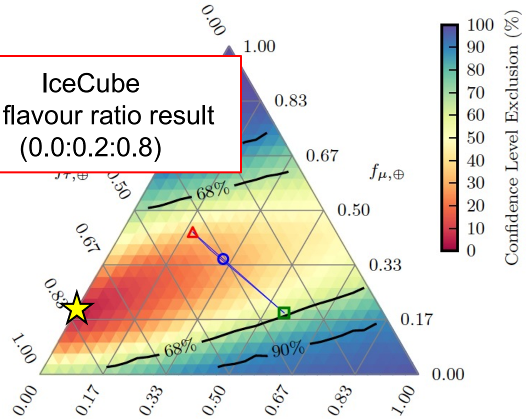
Seasonal variation

SNO

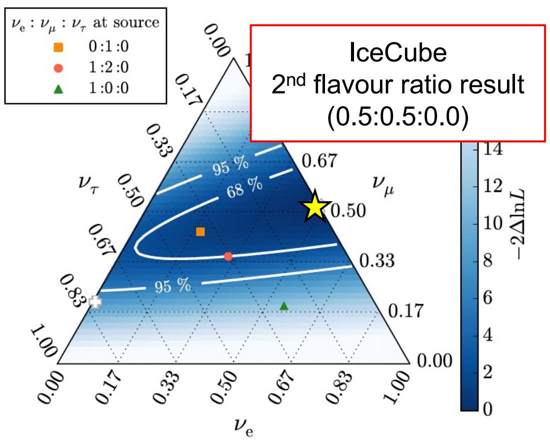


PRD98(2018)112013

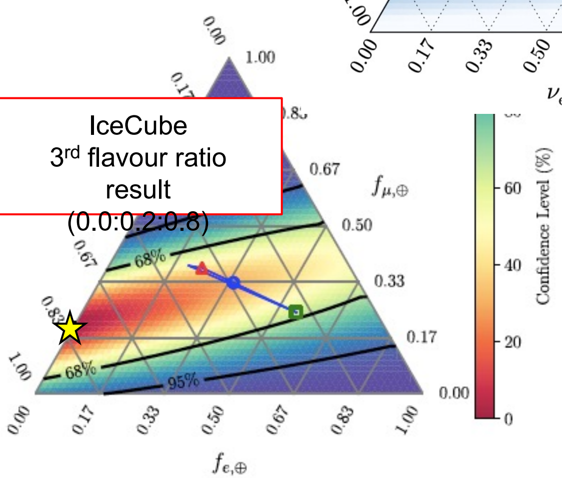
3. HESE 7.5-yr data (2018)



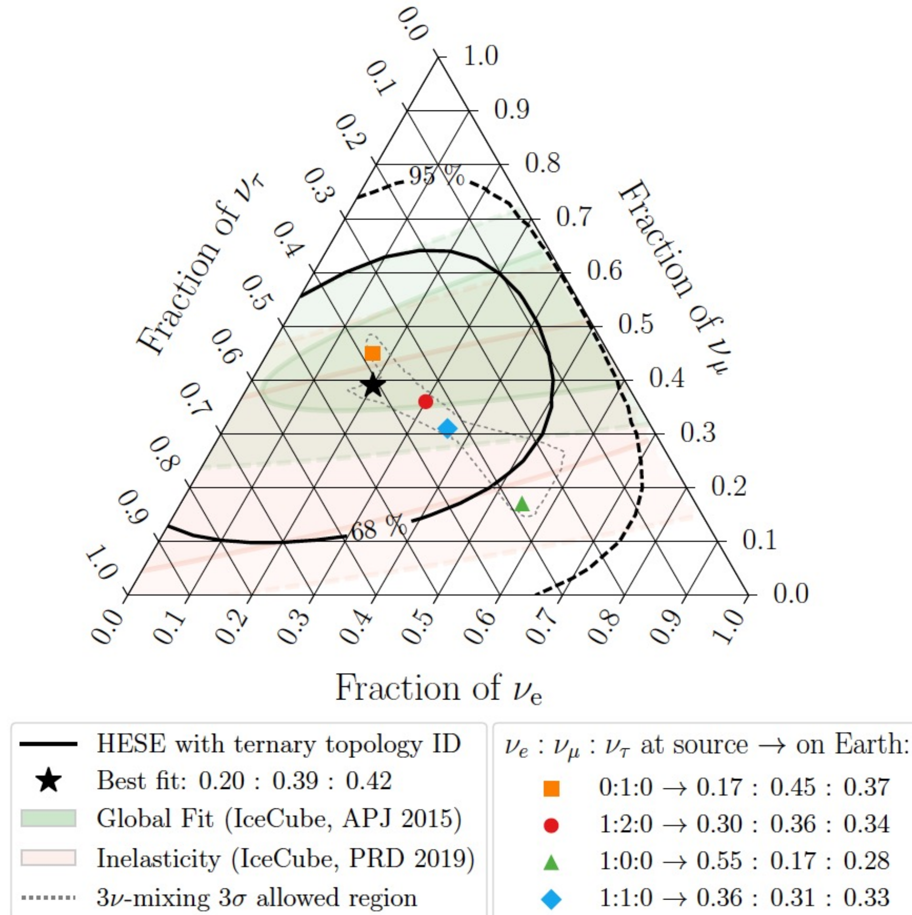
IceCube
1st flavour ratio result
(0.0:0.2:0.8)



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



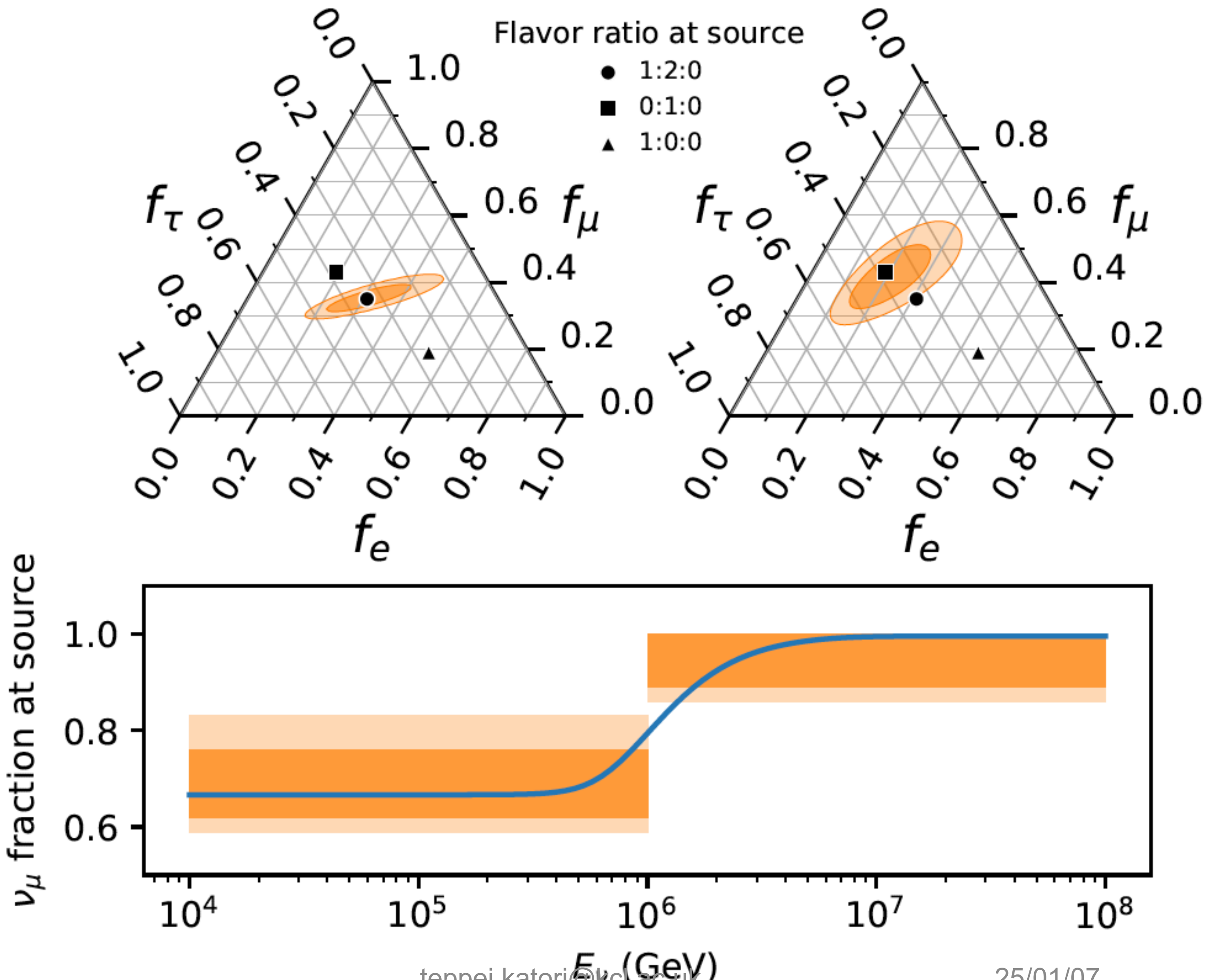
IceCube
3rd flavour ratio result
(0.0:0.2:0.8)



New flavour ratio measurement

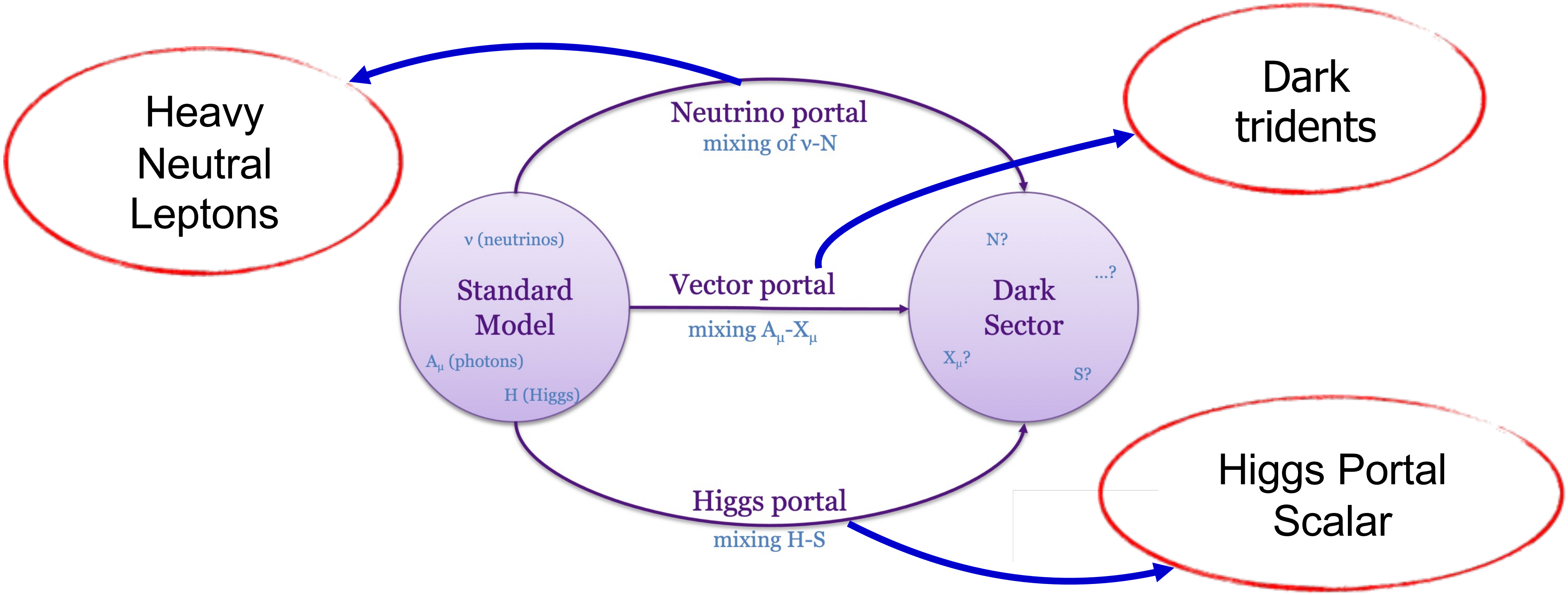
- Likelihood is very shallow and fit often confuses between ν_e and ν_τ
- New flavour ratio result has some power to distinguish ν_e and ν_τ

3. Energy dependence of flavor ratio



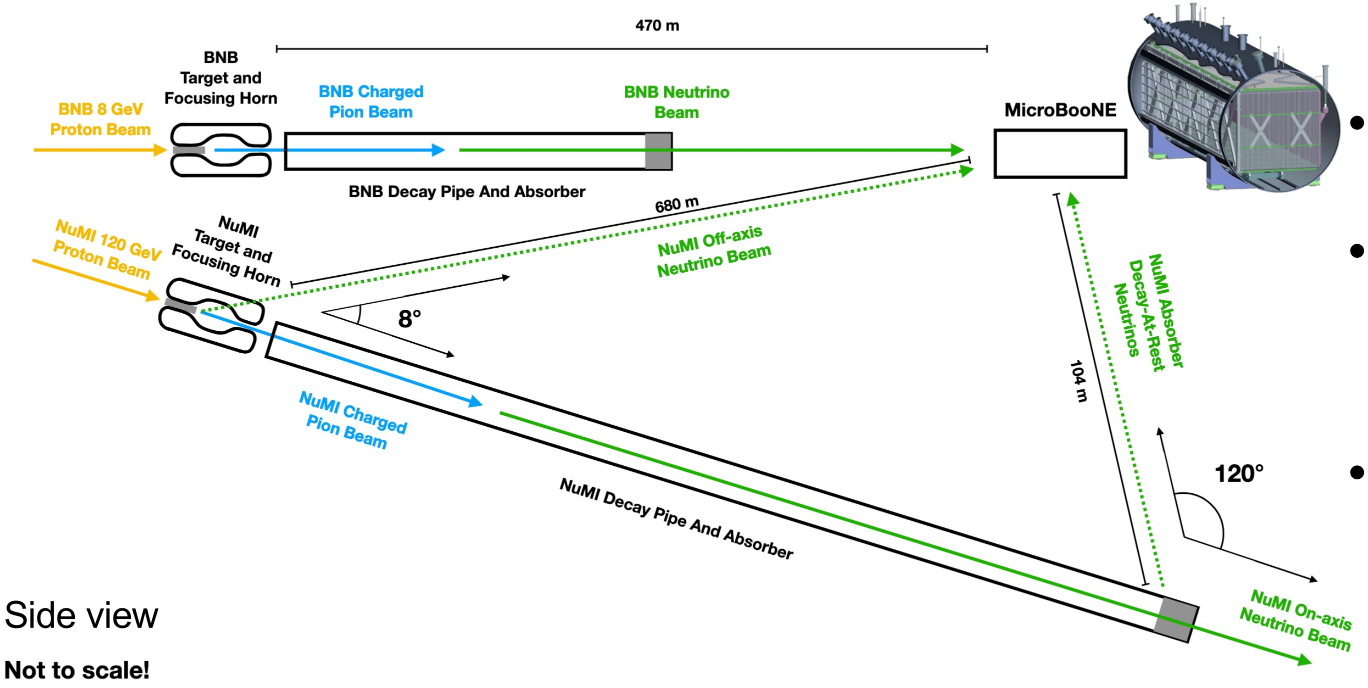
The MicroBooNE Experiment

Strategy: explore the different portals to the dark sector



The MicroBooNE Experiment

85-tonne **Liquid Argon Time Projection Chamber**

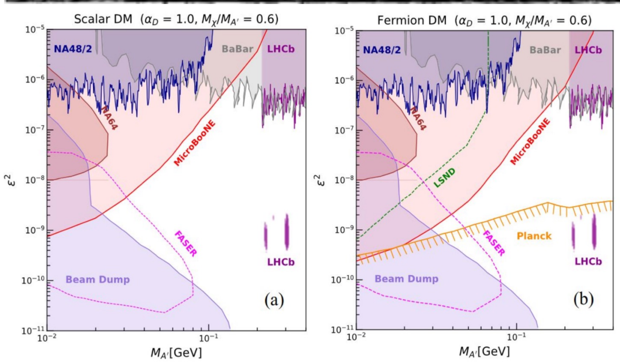


- Located at **Fermilab, USA**
- Exposed to **two neutrino beams** (NuMI & BNB)
- Search for **dark particles produced via meson decays** in the beam(s)

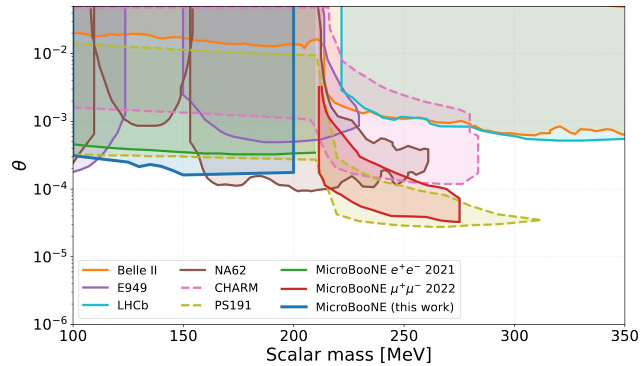
Recent BSM results from MicroBooNE

Light dark matter

- **Dark matter** produced in the neutrino beam via **dark photon mixing**
- Produced via **neutral meson decay**
- **Scatter off argon nucleus,** accompanied by a dark photon radiation subsequently decaying to e^+e^-



Phys.Rev.Lett. 132 (2024) 24, 241801



Higgs Portal Scalars

- **Neutral scalar singlet S**, mixing angle θ with the Higgs boson
- Production from **charged kaon decays**
- **Decay to lepton or pion pairs**

Heavy Neutral Leptons

- **One new right handed singlet state**
- Mixing with active neutrinos via **extended PMNS matrix**
- Produced from **charged kaon decays**
- **Decay to e^+e^- or $\nu\pi^0$**

Phys. Rev. Lett. 132, 041801 (2024)