New physics model constraints derived from SME coefficient limits using IceCube astrophysical neutrino flavour data

CPT'22

outline

1. IceCube constraints on SME coefficients
2. BSM effects on Neutrino Flavour
3. Test of new physics models and SME
4. Conclusions

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CPT and Lorentz symmetry 22, Bloomington, IN, USA (online), May 23, 2022

1. **IceCube constraints on SME coefficients**
2. **BSM effects on neutrino flavour**
3. **Test of new physics models and SME**
4. **Conclusions**

IceCube, ArXiv:2011:03561

1. IceCube flavor ratio data (2018)

60 high-energy starting events in
60 TeV – 2 PeV

New flavour ratio measurement, but contour is big and any flavor ratio models are accepted by data

IceCube
latest flavour ratio result
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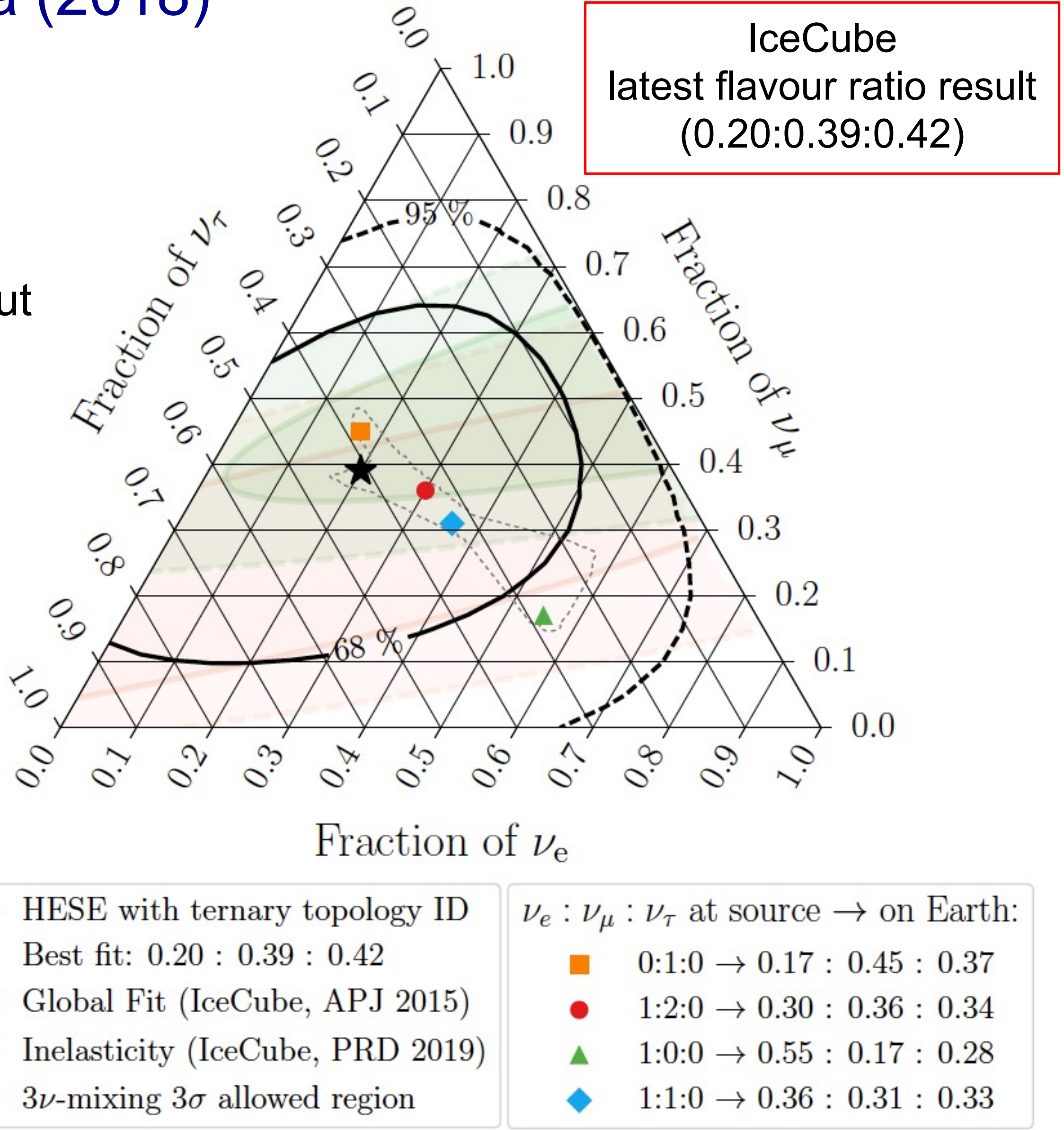
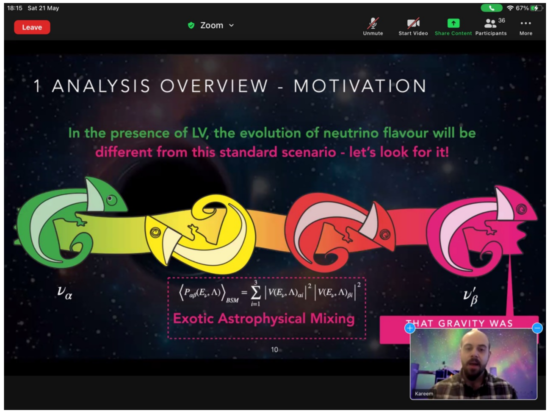




1 ANALYSIS OVERVIEW - MOTIVATION

In the presence of LV, the evolution of neutrino flavour will be different from this standard scenario - let's look for it!

$$\left\langle P_{\alpha\beta}(E_\nu,\Lambda)\right\rangle_{BSM} = \sum_{i=1}^{3} \left|V(E_\nu,\Lambda)_{\alpha i}\right|^2 \left|V(E_\nu,\Lambda)_{\beta i}\right|^2$$

Exotic Astrophysical Mixing

Kareem Farrag (May 21)

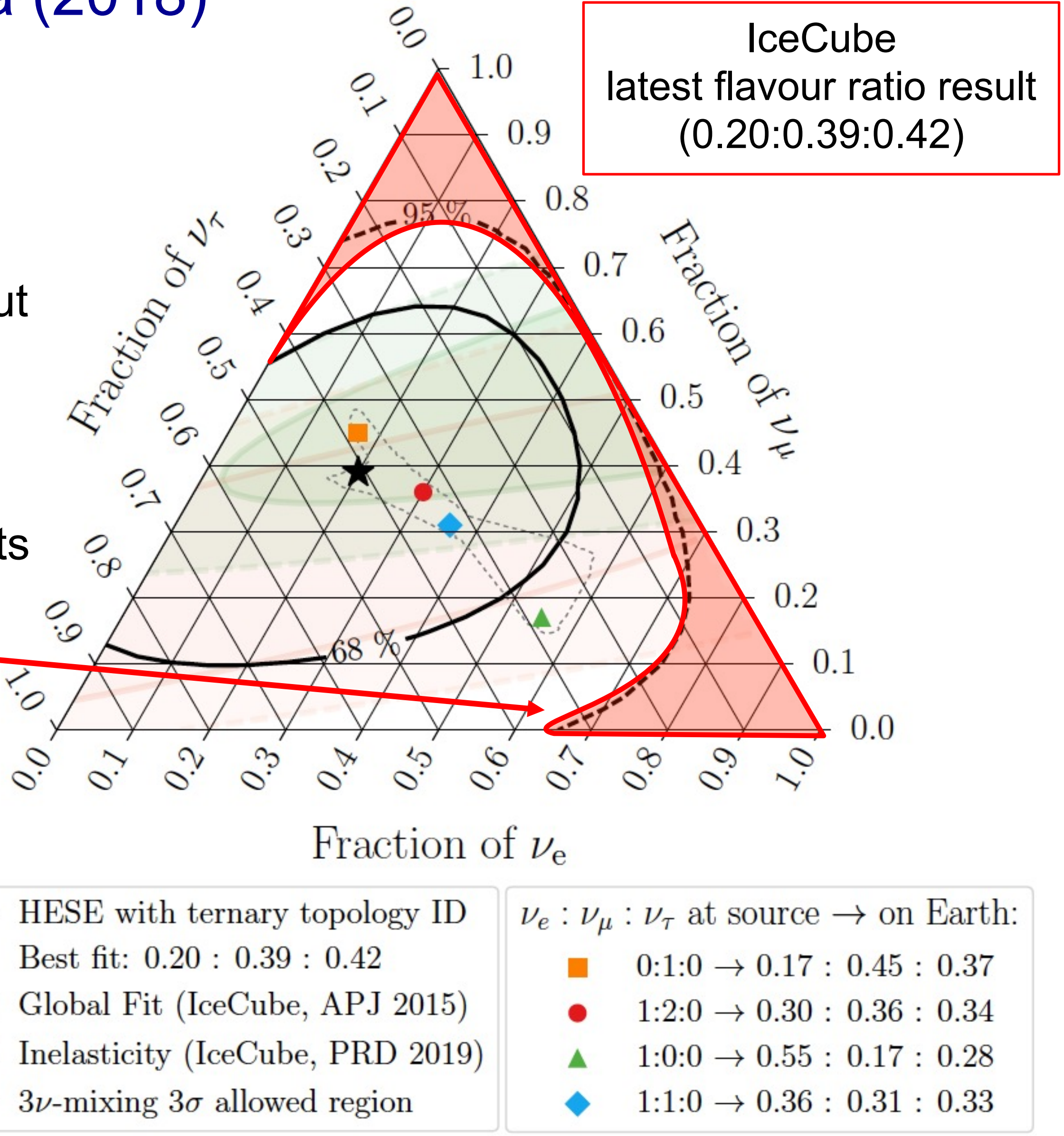
IceCube, ArXiv:2011:03561

1. IceCube flavor ratio data (2018)

60 high-energy starting events in 60 TeV – 2 PeV

New flavour ratio measurement, but contour is big and any flavor ratio models are accepted by data

However, isotropic SME coefficients which predict flavour ratios at this region can be tested



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

IceCube, ArXiv:2111.04654

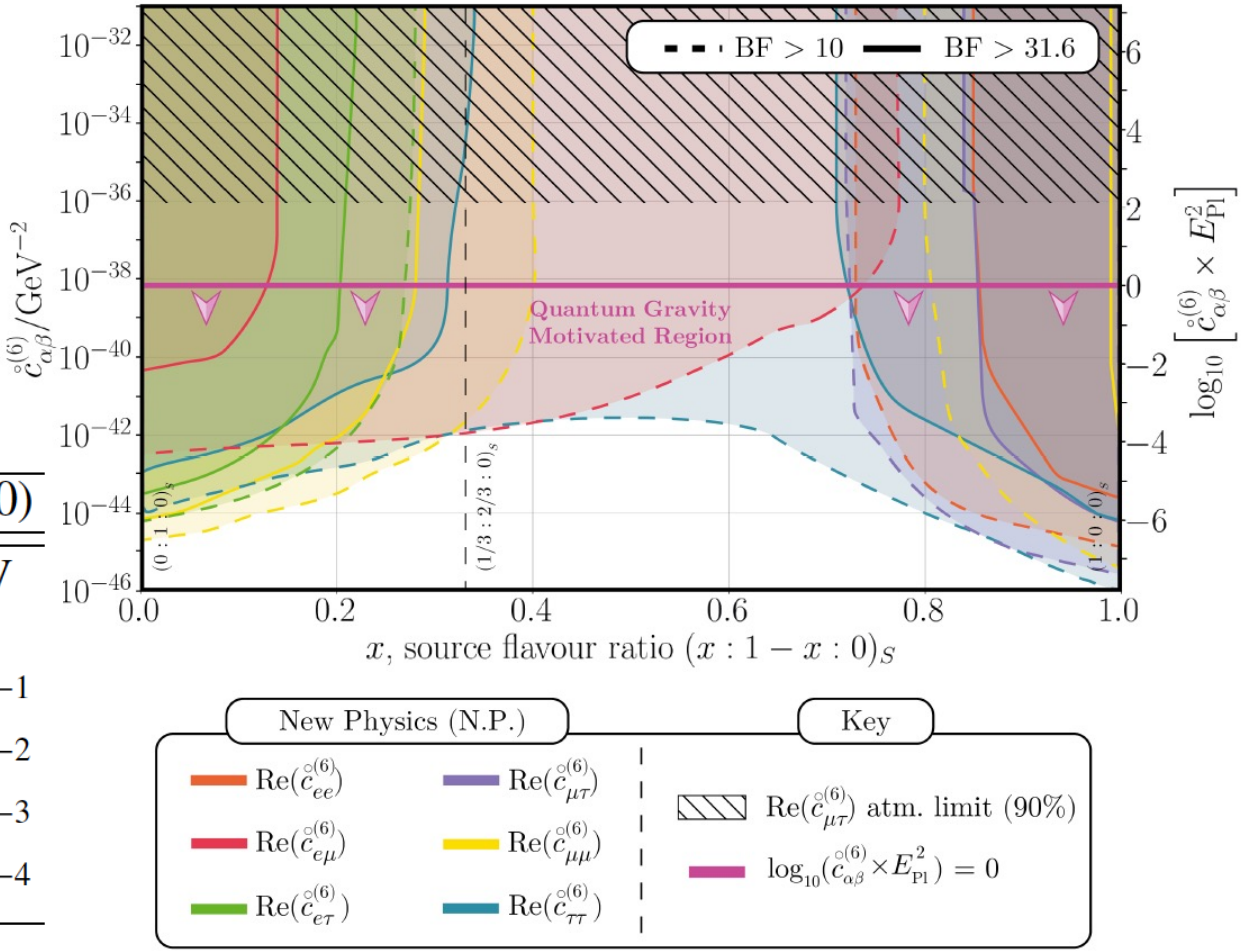
1. Search for Lorentz violation using astrophysical neutrino flavor

Many isotropic SME limits depend on astrophysical neutrino production model assumption

The model-independent limits are $a_{\tau\tau}^{(d)}$ and $c_{\tau\tau}^{(d)}$

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



Stodolsky, PRD36(1984)2273

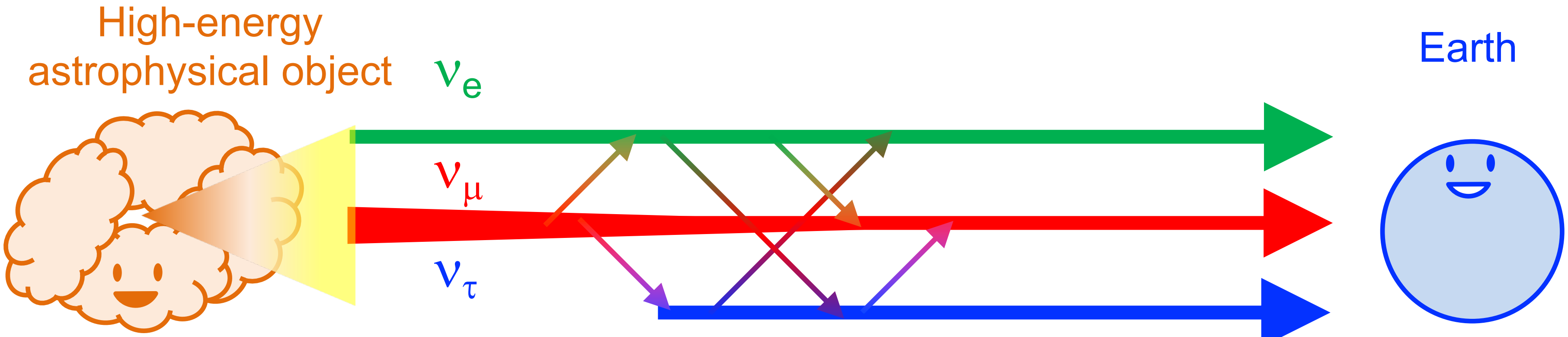
1. Quantum Zeno effect

Neutrino mass term is not flavour eigenstate

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

Standard astrophysical models predict astrophysical neutrinos are ν_e and ν_μ

Neutrinos mixings in vacuum produce ν_τ



Stodolsky, PRD36(1984)2273

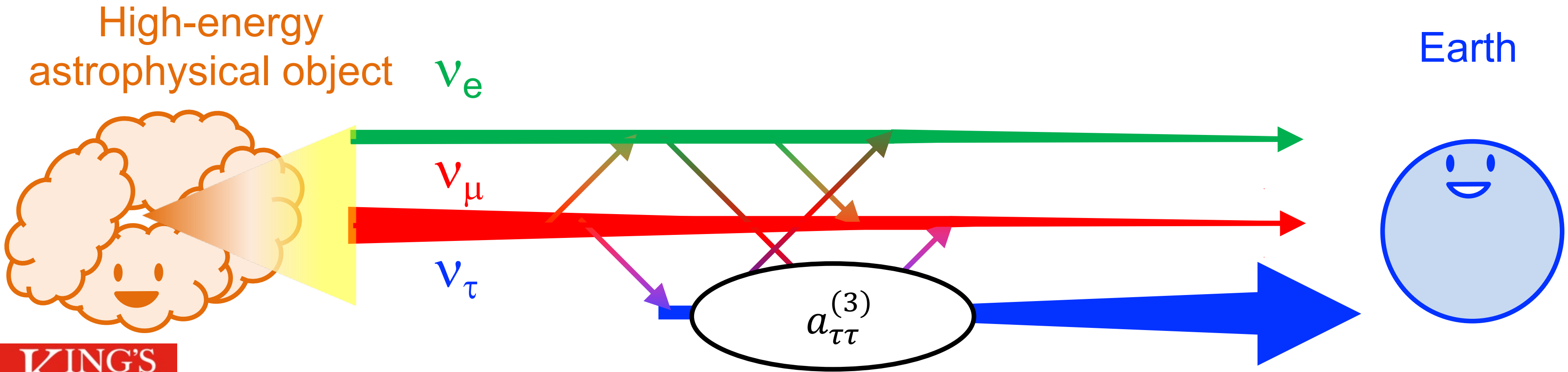
1. Quantum Zeno effect

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

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

Large diagonal term can modify the neutrino mixing pattern

In our analysis, we set the strongest limit on $a^{(3)}_{\tau\tau}$



1. Limitation of astrophysical neutrino interferometry

Neutrino mass term limits the sensitivity on SME coefficients

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

The highest energy observed astrophysical neutrino is ~ 1 PeV

$$\frac{\Delta m^{2}_{23}}{2E} \sim 10^{-27} GeV$$

This is the intrinsic limit of dim-3 operator by this approach.

To reach this, experimental errors need to be reduced

1. More data (=bigger experiment)
2. Precise flavor measurement (=better algorithm)
3. Reduce neutrino mass parameter error (=synergy with oscillation experiments)

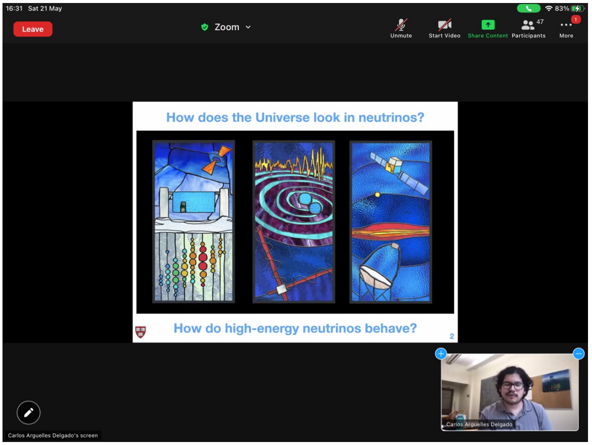
To go beyond this intrinsic limit;

4. Measure higher energy neutrinos (=different technology)
5. searches of higher dimension operators are easier

Song et al, JCAP04(2021)054

2. Limitation of astrophysical neutrino interferometry

Kareem Farrag (May 21)

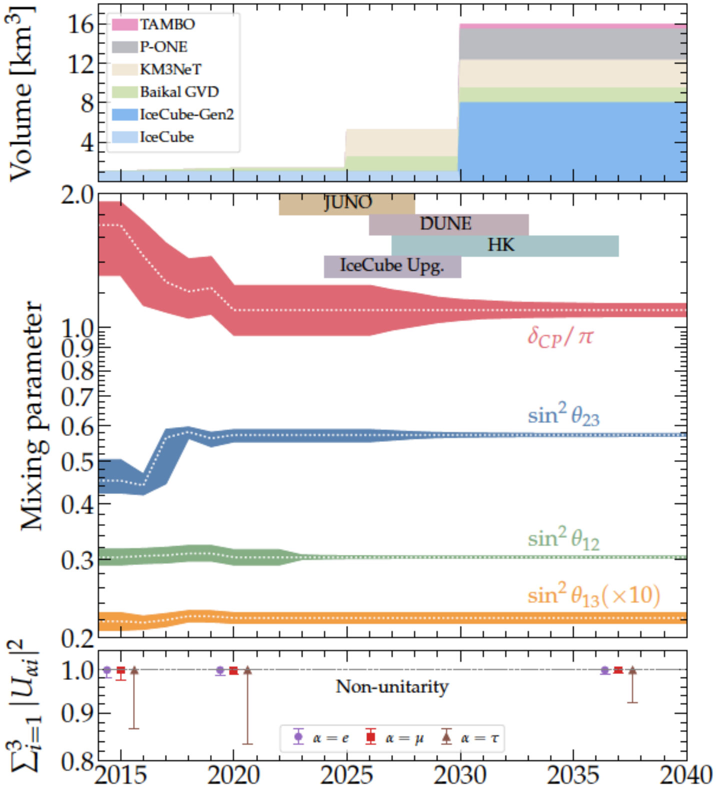


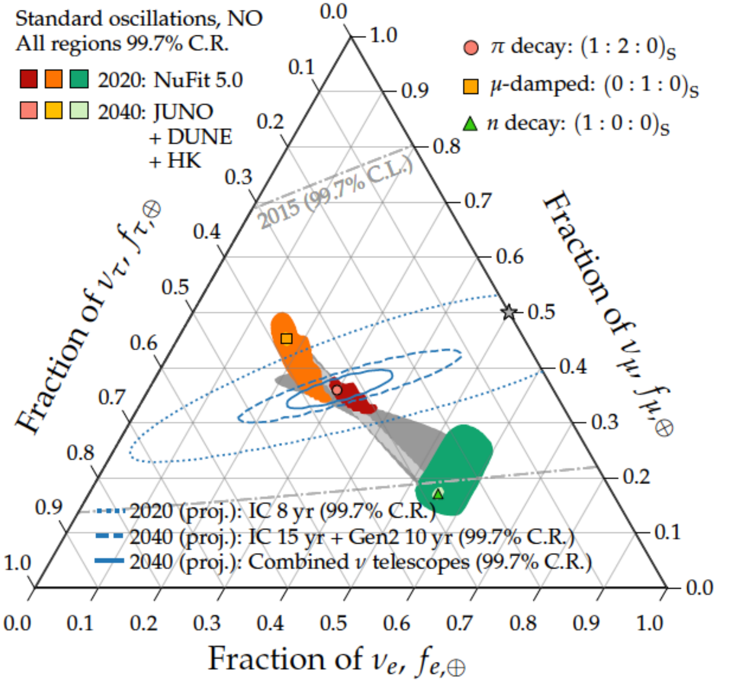
How does the Universe look in neutrinos?

How do high-energy neutrinos behave?

Future of neutrino astronomy

1. More data (=bigger experiment)
2. Precise flavor measurement (=better algorithm)
3. Small neutrino mass error (=synergy with osc. expts)
4. Measure higher energy neutrinos (=different technology)
5. searches of higher dimension operators are easier





1. IceCube constraints on SME coefficients

2. **BSM effects on neutrino flavour**

3. Test of new physics models and SME

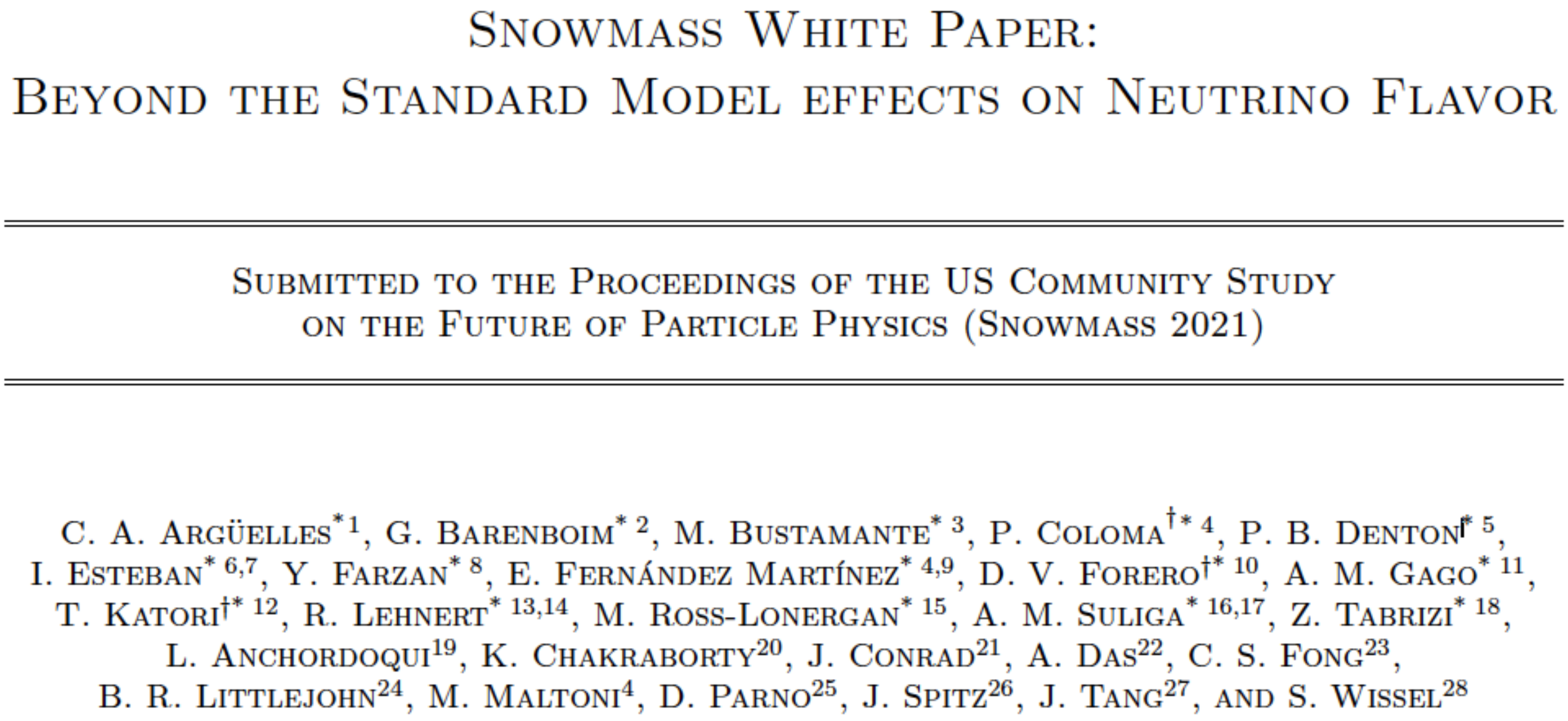
4. Conclusions

Argüelles et al, ArXiv:2203.10811

1. Beyond the Standard Model effects on Neutrino Flavor

Snowmass 21 (https://snowmass21.org)

- Review of community activities around particle physics
- DOE prioritization process of particle physics projects for the next decade
- Dedicated to neutrino flavour effect with new physics, including Lorentz violation



Snowmass White Paper:
Beyond the Standard Model effects on Neutrino Flavor

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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L. Anchordoqui[19], K. Chakraborty[20], J. Conrad[21], A. Das[22], C. S. Fong[23],
B. R. Littlejohn[24], M. Maltoni[4], D. Parno[25], J. Spitz[26], J. Tang[27], and S. Wissel[28]

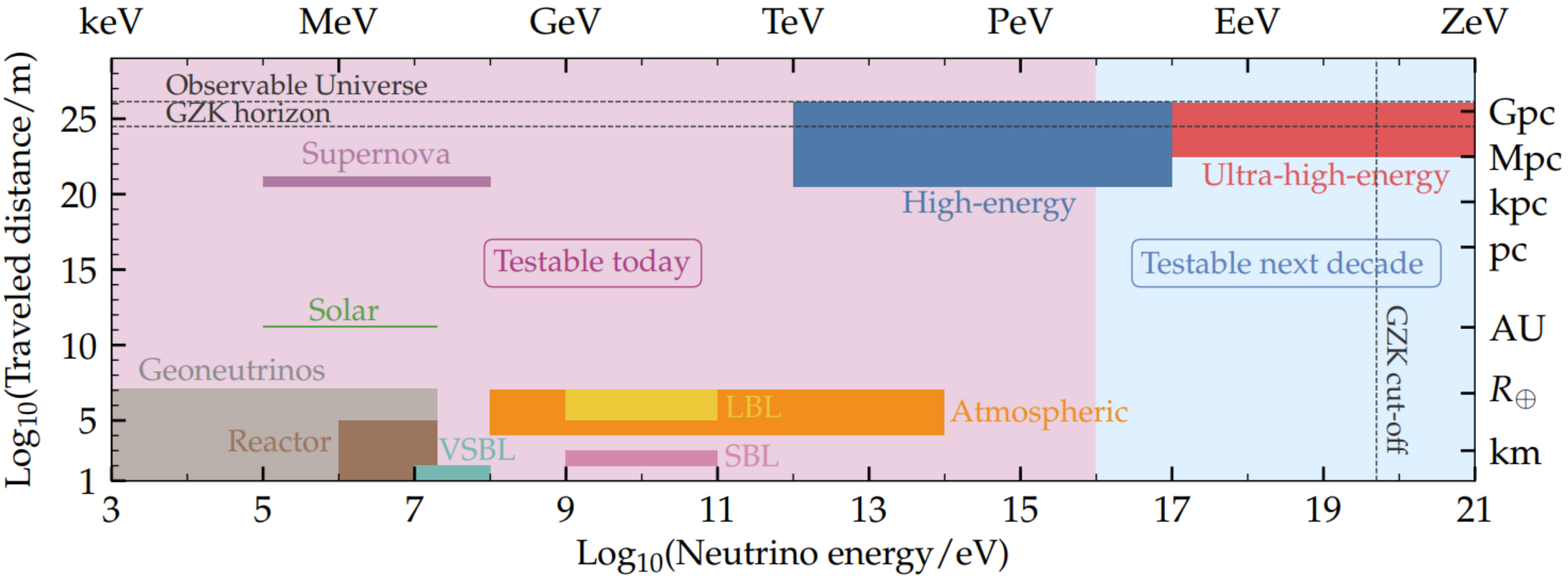
Argüelles et al, ArXiv:2203.10811,1903.04333

1. Beyond the Standard Model effects on Neutrino Flavor

Fundamental physics with high-energy cosmic neutrinos today and in the future

- Natural place to look for new physics

1. Longest propagation distance (>100 Mpc)
2. Direct highest energy particles (>60 TeV)
3. Quantum mixing



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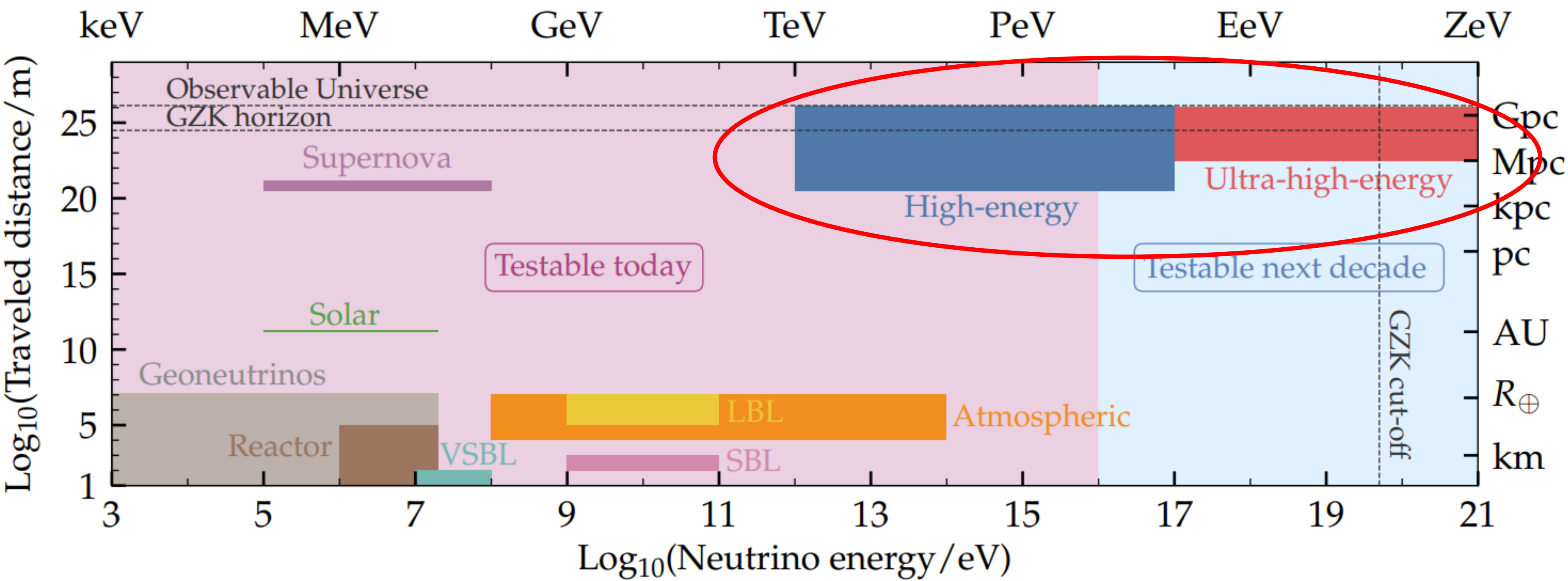

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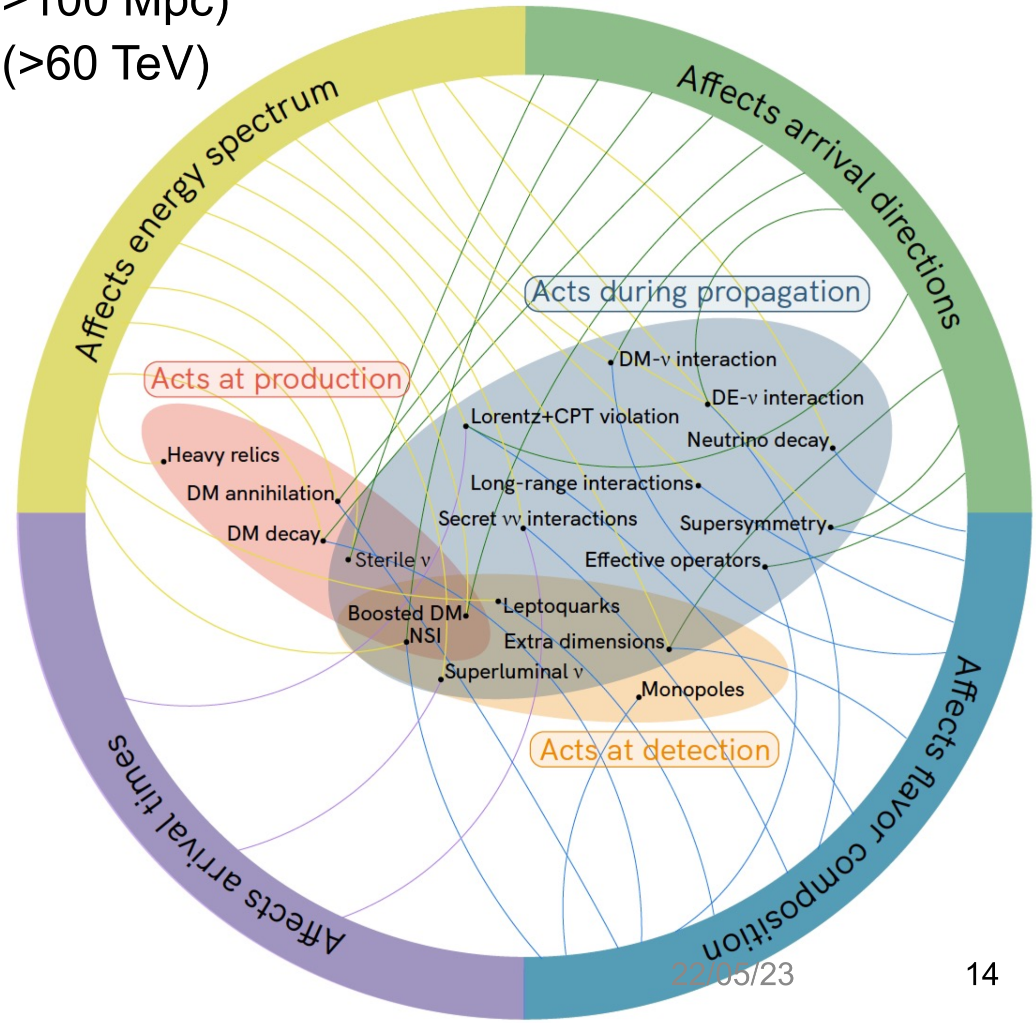
“Neutrino flavour conversion during propagation” is the natural place to look for BSM physics (and related to SME framework)



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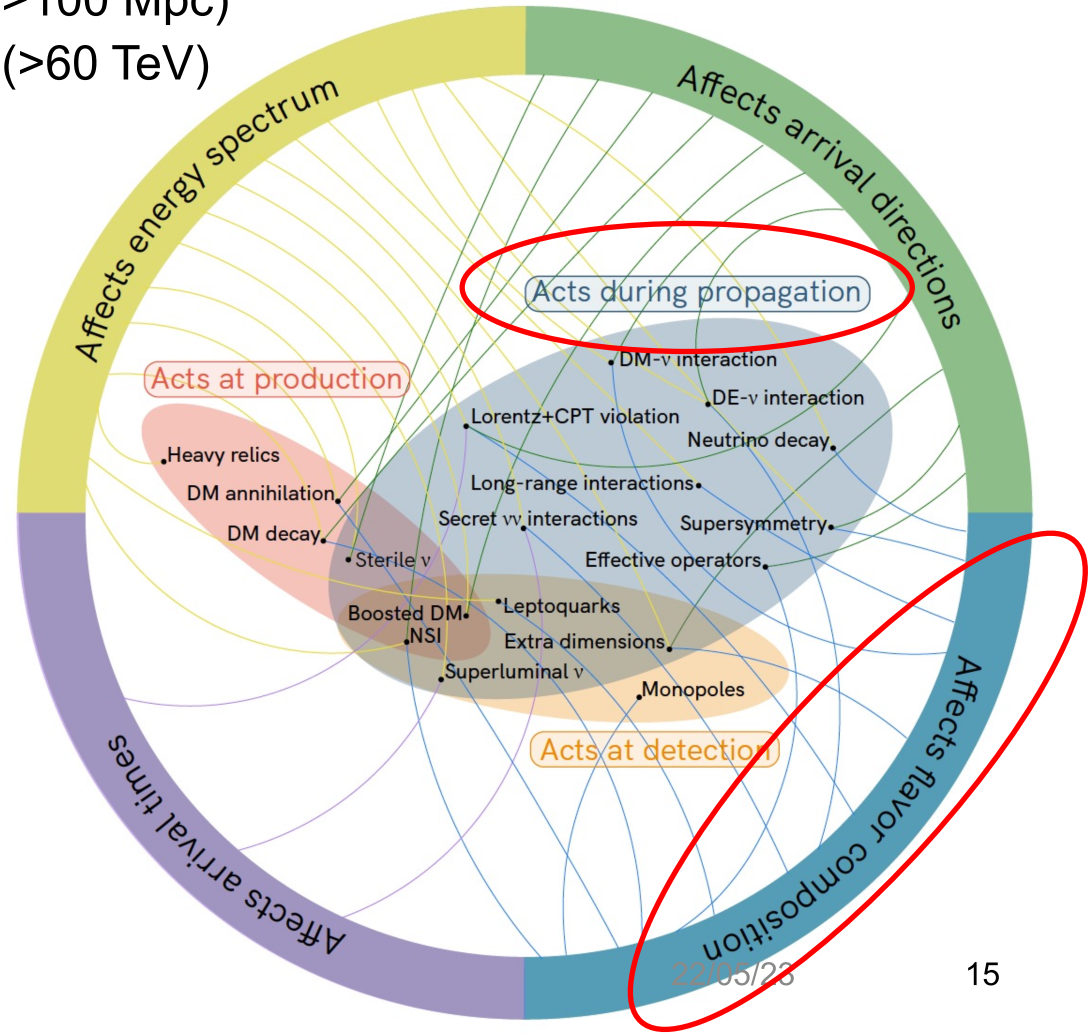
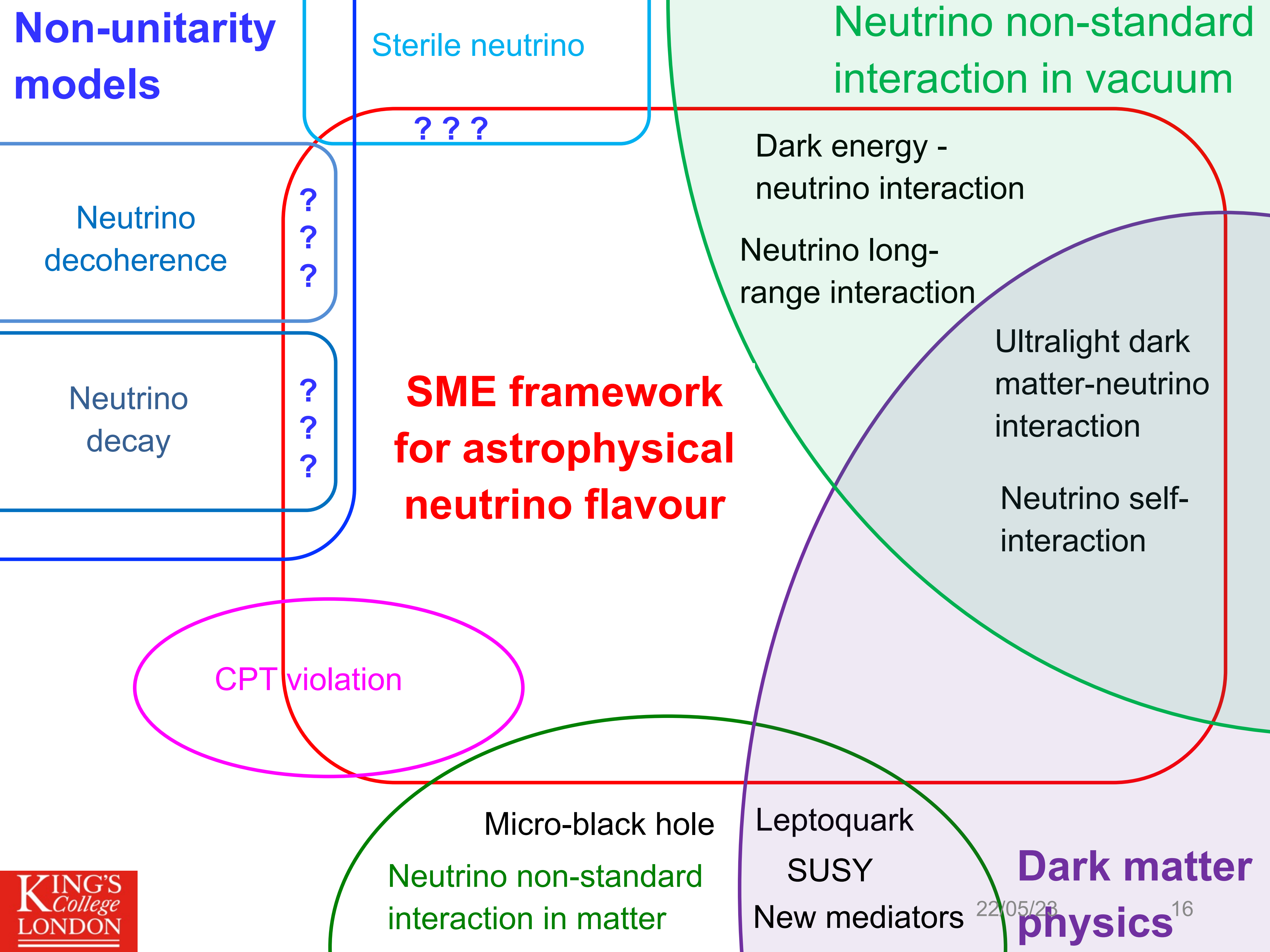
Lorentz and CPT violation
Dark matter-neutrino interaction
Dark energy-neutrino interaction
Long range neutrino interaction
Neutrino self-interaction
Neutrino decay
Neutrino decoherence





Non-unitarity models

Sterile neutrino

? ? ?

Neutrino decoherence

?
?
?

Neutrino decay

?
?
?

SME framework for astrophysical neutrino flavour

CPT violation

Neutrino non-standard interaction in vacuum

Dark energy - neutrino interaction

Neutrino long-range interaction

Ultralight dark matter-neutrino interaction

Neutrino self-interaction

Micro-black hole

Neutrino non-standard interaction in matter

Leptoquark

SUSY

New mediators

Dark matter physics

1. BSM effects on neutrino flavour

2. IceCube constraints on SME coefficients

3. **Test of new physics models and SME**

4. Conclusions

Caldwell and Kamionkowski,Annu.Rev.Nucl.Part.Sci.59(2009)397
Klop and Ando, PRD97(2018)063006 (2018)

3. Dark energy – neutrino interaction

Time dependent scalar field can be dark energy (quintessence), and that may couple with neutrinos

Lagrangian of astrophysical neutrinos and dark energy interaction is

$$L = -\lambda_{\alpha\beta} \frac{\partial_\mu \phi}{M_*} \bar{\nu}_\alpha \gamma^\mu (1 - \gamma_5) \nu_\beta$$

This has an exact connection with SME

$$\lambda_{\alpha\beta} \frac{\dot{\phi}(t)}{M_*} l^\mu \sim a^{\mu(3)}_{\alpha\beta}$$

The time component in CMB frame is nonzero. We choose cosmic expansion is isotropic in CMB frame ($l^\mu = (1,0,0,0)$), however, we also assume our local frame is close to the CMB frame

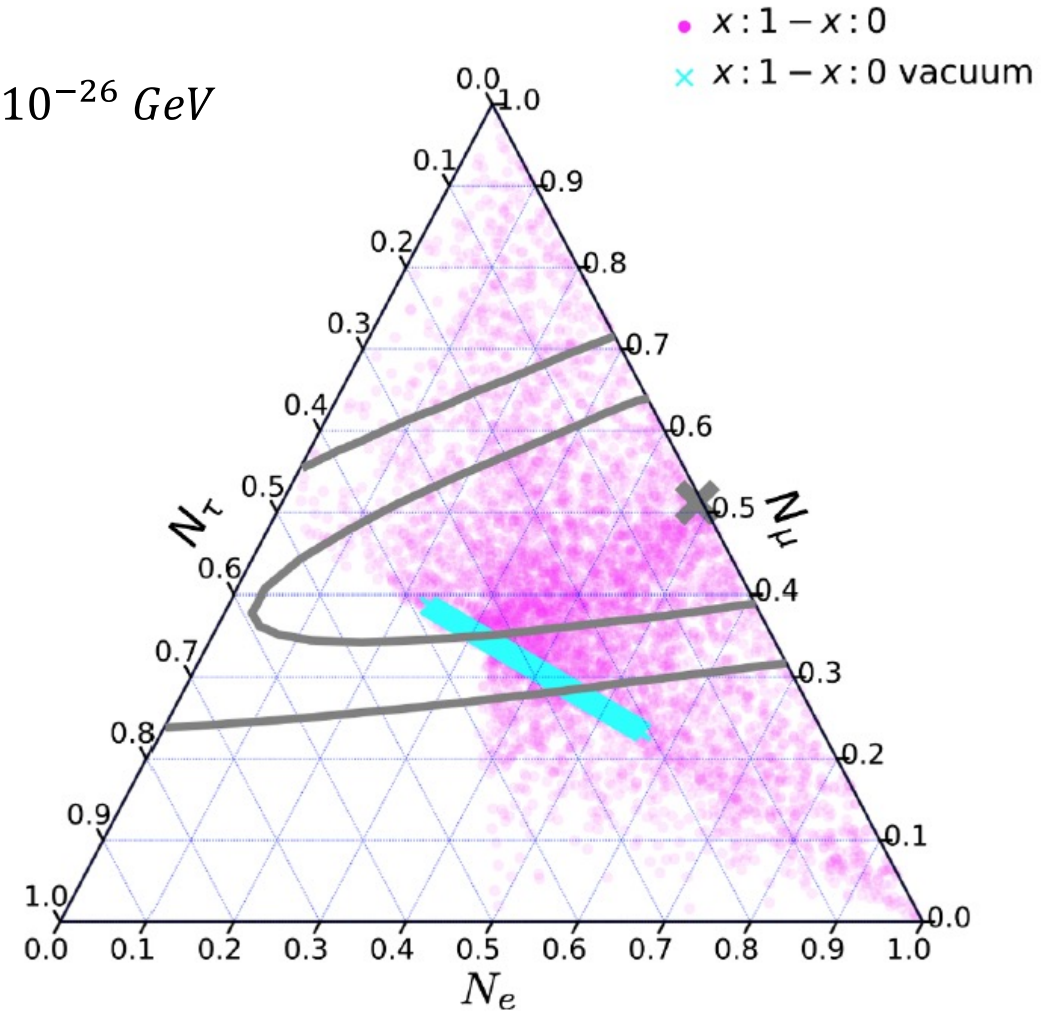
$$\lambda_{\alpha\beta} \frac{\dot{\phi}(t)}{M_*} \sim a^{0(3)}_{\alpha\beta} \sim \mathring{a}^{(3)}_{\alpha\beta}$$

Caldwell and Kamionkowski,Annu.Rev.Nucl.Part.Sci.59(2009)397
Klop and Ando, PRD97(2018)063006 (2018)

3. Dark energy – neutrino interaction

Dark energy-neutrino interaction model predicts any flavor ratio allowed by astrophysical neutrino production models with ν_e and ν_μ

We set limit on $\lambda_{\tau\tau}\frac{\dot{\phi}(t)}{M_*}\sim\mathring{a}_{\tau\tau}^{(3)}\leq 2\times10^{-26}\ GeV$



3. Neutrino self-interaction (“secret” interaction)

Many models are motivated by dark matter physics

1. New mediator to enhance neutrino self-interaction
2. Ultra-light dark matter – neutrino interaction

Barenboim et al, PRD99(2019)083515 etc

3. Neutrino self-interaction (“secret” interaction)

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1. New mediator to enhance neutrino self-interaction
2. Ultra-light dark matter – neutrino interaction

Stronger neutrino self-interaction is motivated, IceCube neutrinos may interact with cosmic neutrino background (CvB)

Interaction Lagrangian of astrophysical neutrinos and cosmic neutrinos is

$$L = g_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi$$

This can make an effective neutrino matter potential in vacuum $V_{\alpha\beta} \sim \text{å}^{(3)}_{\alpha\beta}$ which is the combination of 3 things

- mediator coupling
- mediator mass scale
- assumed cosmic neutrino density

Barenboim et al, PRD99(2019)083515 etc
Díaz and Klinkhamer, PRD93(2016)053004

3. Neutrino self-interaction (“secret” interaction)

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1. New mediator to enhance neutrino self-interaction
2. Ultra-light dark matter – neutrino interaction

We set $V_{\tau\tau} \sim \mathring{a}^{(3)}_{\tau\tau} \leq 2\times10^{-26}\ GeV$

The standard IceCube neutrino – CvB scattering depends on the assumption of CvB model (=Lepton asymmetry).

In the standard model, $V_{\alpha\beta} \leq 10^{-46}\ \ GeV$
(assuming large lepton asymmetry)

Farzan and Palomares-Ruiz, PRD99(2019)051702
Salas, Lineros, Tórtola, PRD94(2016)123001

3. Dark matter – neutrino interaction

Many models are motivated by dark matter physics

1. New mediator to enhance neutrino self-interaction
2. Ultra-light dark matter – neutrino interaction

Ultra-light dark matter behave as a field, and interactions will modify the flavor

Astrophysical neutrinos and dark matter background interaction can be written

$$L = i\frac{g_\alpha}{\Lambda^2}(\phi^*\partial_\mu\phi - \phi\partial_\mu\phi^*)(\bar{\nu}_\alpha\gamma^\mu\nu_\alpha)$$

This can make an effective neutrino matter potential in vacuum

$$V_{\alpha\beta}\sim\left(\frac{\rho_{DM}}{m_{DM}}\right)\left(\frac{g_\alpha}{\Lambda^2}\right)\sim\mathring{a}^{(3)}_{\alpha\beta}$$

Farzan and Palomares-Ruiz, PRD99(2019)051702
Salas, Lineros, Tórtola, PRD94(2016)123001

3. Dark matter – neutrino interaction

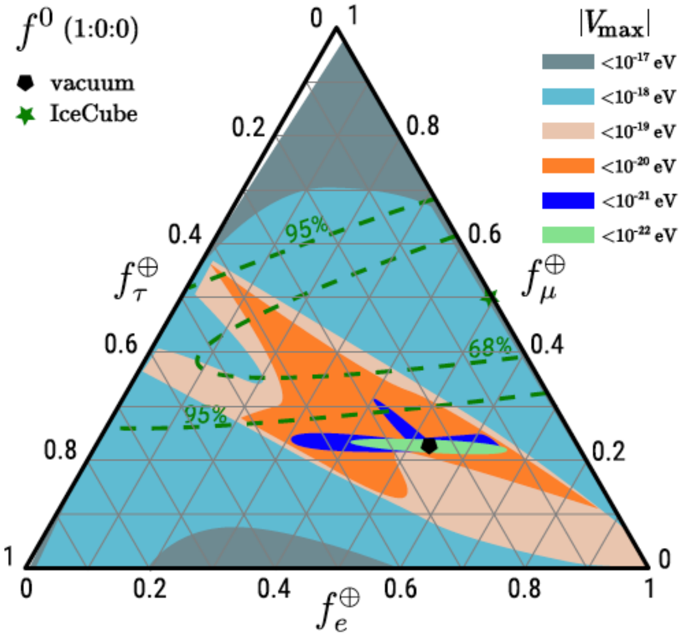
Many models are motivated by dark matter physics

1. New mediator to enhance neutrino self-interaction
2. Ultra-light dark matter – neutrino interaction

We set $V_{\tau\tau} \sim \left(\frac{\rho_{DM}}{m_{DM}}\right)\left(\frac{g_{\tau}}{\Lambda^{2}}\right) \sim \mathring{a}_{\tau\tau}^{(3)} \leq 10^{-26}\ GeV$

However, dark matter density in vacuum (extra galactic dark matter) is

$$\rho_{DM}^{extra-galactic} < 10^{-6} \times \rho_{DM}^{galactic}$$



Bustamante and Agarwalla, PRL122(2019)061103

3. Long-range force

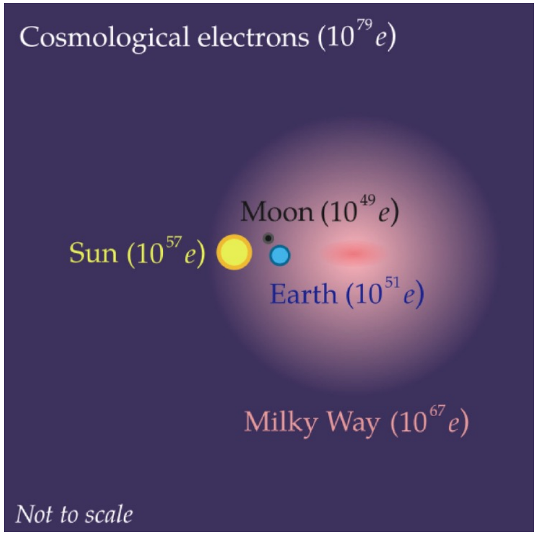
New weak long-range force from all electron in the universe affect neutrinos

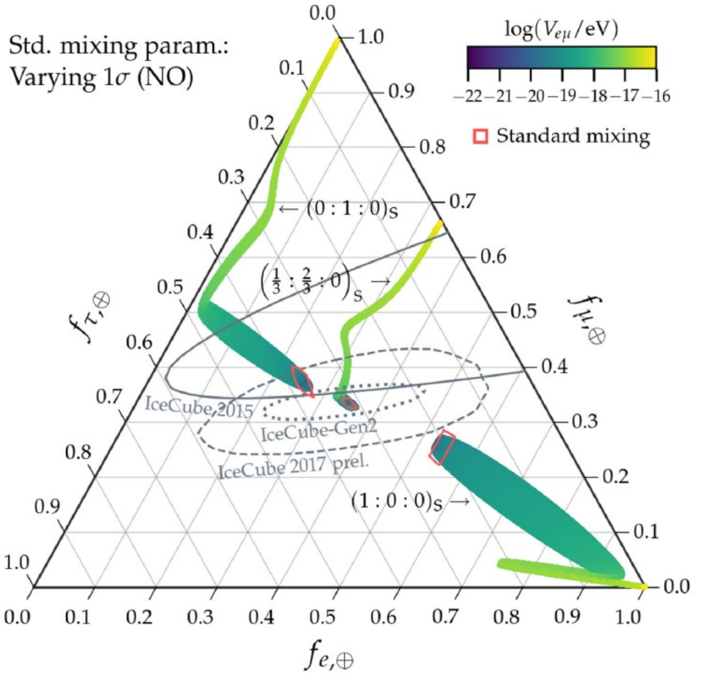
$$V_{e\alpha} = g'^2_{e\alpha} N_e \frac{e^{-d/m'_{e\alpha}}}{4\pi d}$$

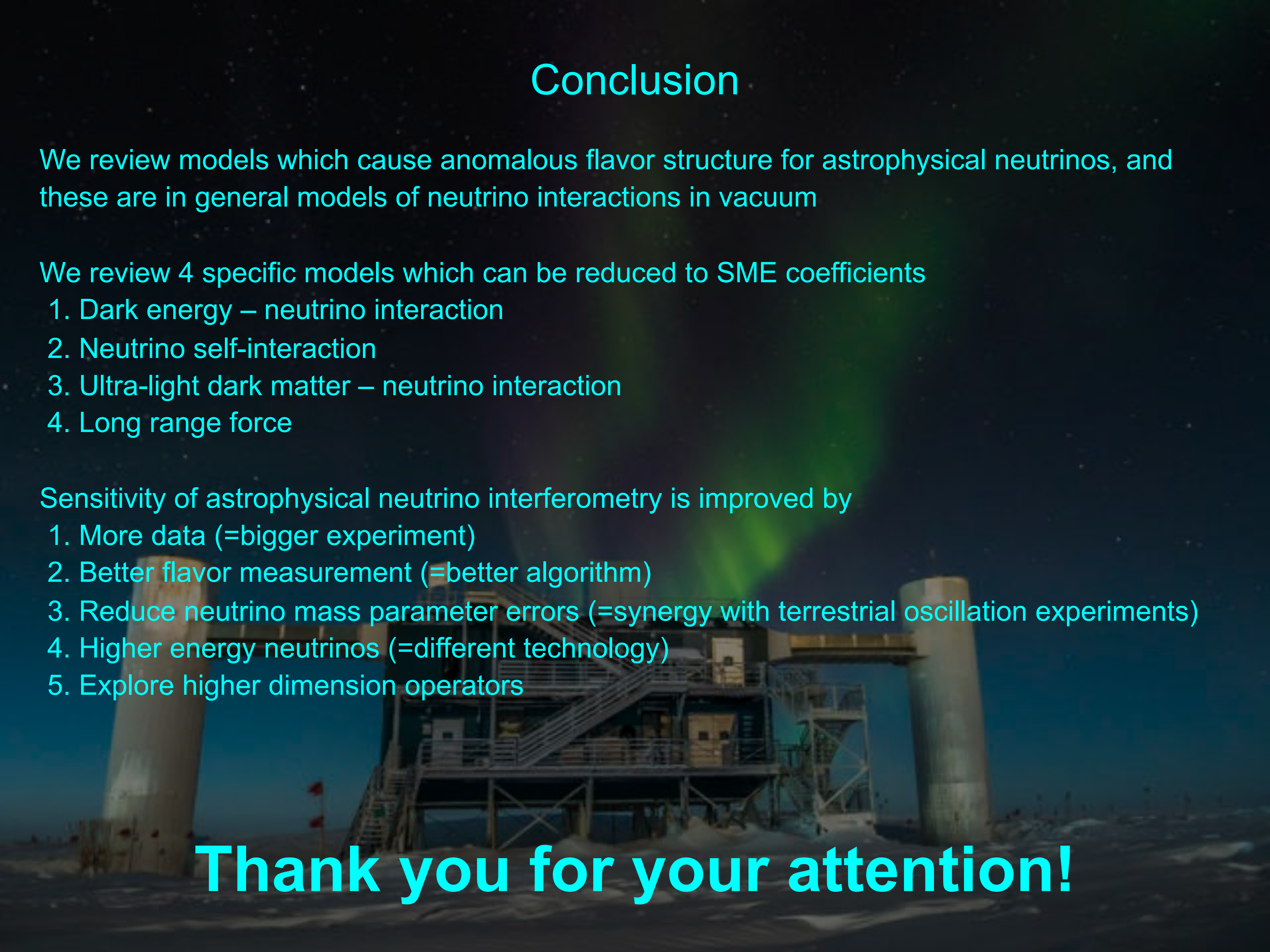
This potential can be related to $V_{e\alpha} \sim a^{(3)}_{\alpha\alpha}$

We set $V_{e\tau} \sim a^{(3)}_{\tau\tau} \le 10^{-26}\ GeV$

This limit is comparable with their estimation







Conclusion

We review models which cause anomalous flavor structure for astrophysical neutrinos, and these are in general models of neutrino interactions in vacuum

We review 4 specific models which can be reduced to SME coefficients

1. Dark energy – neutrino interaction
2. Neutrino self-interaction
3. Ultra-light dark matter – neutrino interaction
4. Long range force

Sensitivity of astrophysical neutrino interferometry is improved by

1. More data (=bigger experiment)
2. Better flavor measurement (=better algorithm)
3. Reduce neutrino mass parameter errors (=synergy with terrestrial oscillation experiments)
4. Higher energy neutrinos (=different technology)
5. Explore higher dimension operators

Thank you for your attention!

Backup

Argüelles et al, JCAP02(2020)015

3. Non-unitarity models

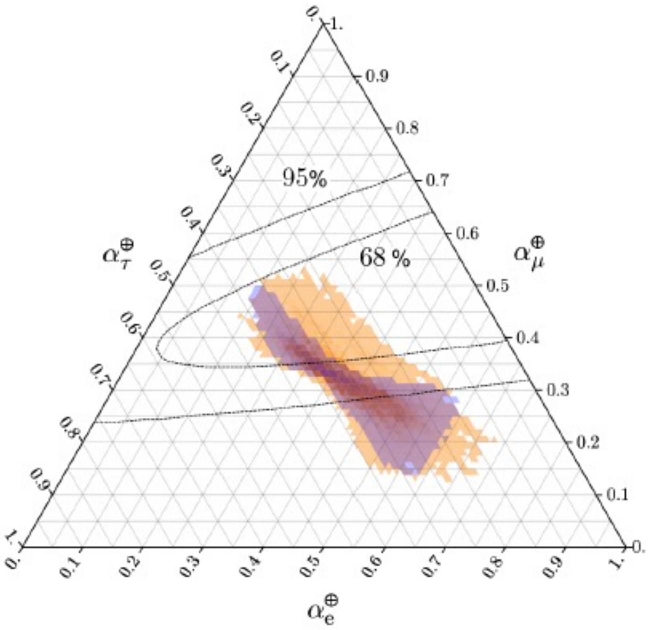
SME describes unitary evolution of neutrino flavours. It is not easy how to translate Propagation effects inducing non-unitarity (sterile neutrinos, decoherence, neutrino decay) can be written in terms of SME or not

e.g.) Sterile neutrino model

- motivated with short-baseline neutrino data anomalies
- Additional neutrino flavour modifies astrophysical neutrino flavour
- Data can set limit on such scenario, but one cannot translate SME limit to this

We focus on following 4 models

1. Neutrino self-interaction (secret interaction)
2. Ultralight dark matter – neutrino interaction
3. Dark energy – neutrino interaction
4. Long range force



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^o and 50^o 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

Mewes and Kostelecký, PRD85(2012)096005

3. Flavor new physics search with effective operators

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

Standard Model

New physics

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

Effective Hamiltonian can be written from here

Standard Model

New physics (renormalizable)

higher dimension operator (non-renormalizable)

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

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

IceCube is sensitive to higher dimension operators

dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{M^{2}_{Planck}} \sim 10^{-38} GeV^{-2}$

Mewes and Kostelecký, PRD85(2012)096005
Wei et al., JCAP08(2016)031

3. Flavor new physics search with effective operators

A common form of modified dispersion is

Standard Model

New physics

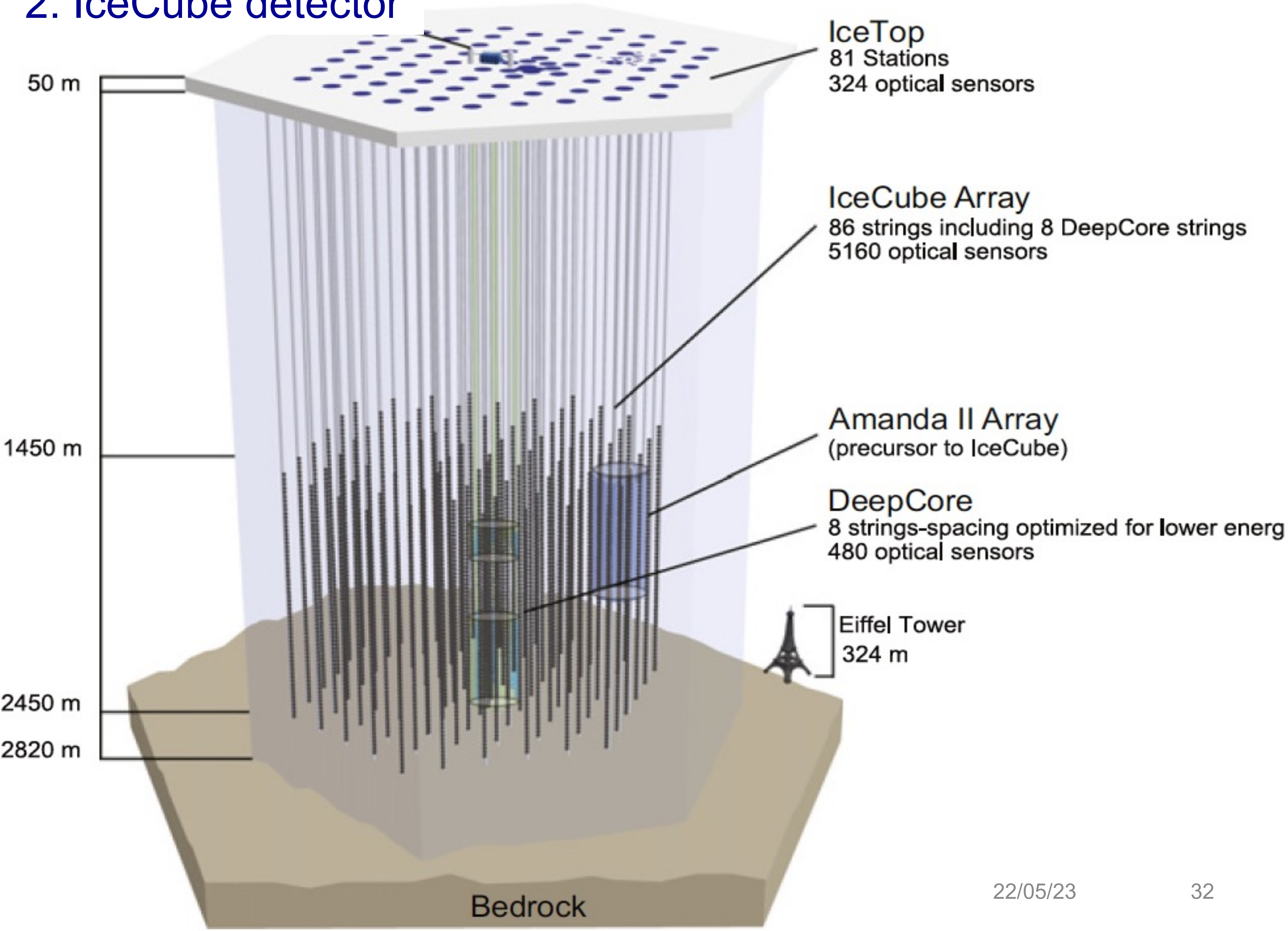
$$E^2 = p^2 + m^2 \pm E^2\left(\frac{E}{E_{QG,n}}\right)^n$$

$$\to E \sim p + \frac{m^2}{2E} + E^2\left(\frac{1}{E_{QG,1}}\right) + E^3\left(\frac{1}{E_{QG,2}}\right)$$

So, one can relate

$$a^{(5)} \sim \frac{1}{E_{QG,1}} \sim \frac{\xi_1}{M_{Planck}}, c^{(6)} \sim \frac{1}{\left(E_{QG,2}\right)^2} \sim \frac{\xi_2}{M_{Planck}^2}$$

2. IceCube detector



2. TAMBO experiment