ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究 文部科学省 科学研究費助成事業 学術変革領域研究 （2020–2024）
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

Cosmological axions in light of quantum gravity

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Contents

Axion and axion-like particles

- Axion was introduced as a solution to the strong CP problem
  - Axion with a mass $\gtrsim 10^{-20}$ eV can be **Dark Matter**
- Ultra-light axion-like particles (ALPs) may be created by string theory
- Certain types of ALPs can explain **Dark Energy**
- They can also solve (or weaken) several **tensions in cosmology**

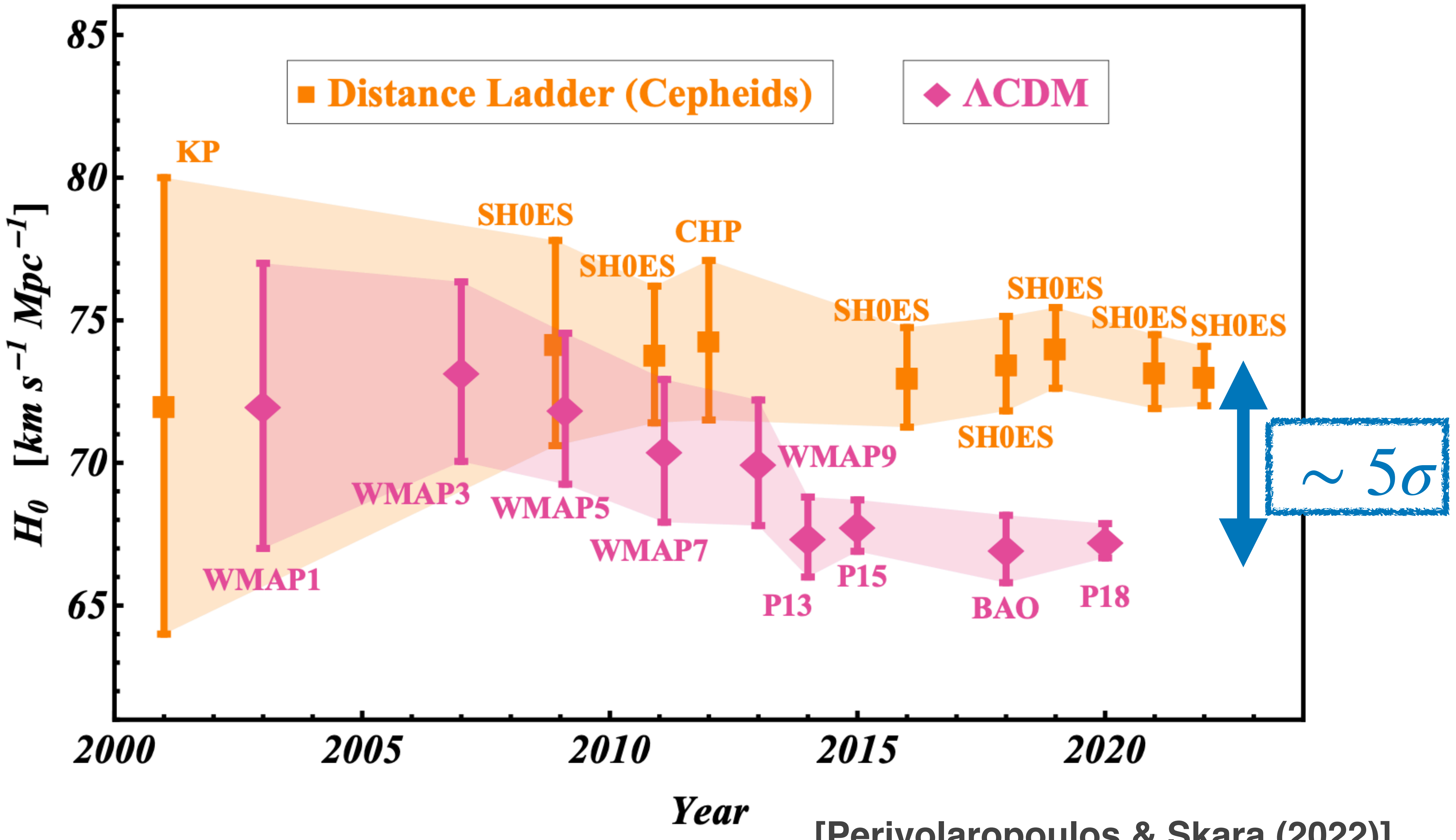
Tensions in cosmology: H_0 tension

- $\sim 5\sigma$ discrepancy between the values of Hubble constant H_0 measured in **the late Universe** and **the early Universe**

- Solution: Early Dark Energy
  - ALP with $m_{\rm EDE} \sim 10^{-27}$ eV can increase expansion rate before recombination

$$V_{\rm EDE}(\phi) = m_{\rm EDE}^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$

$(n \geq 2)$

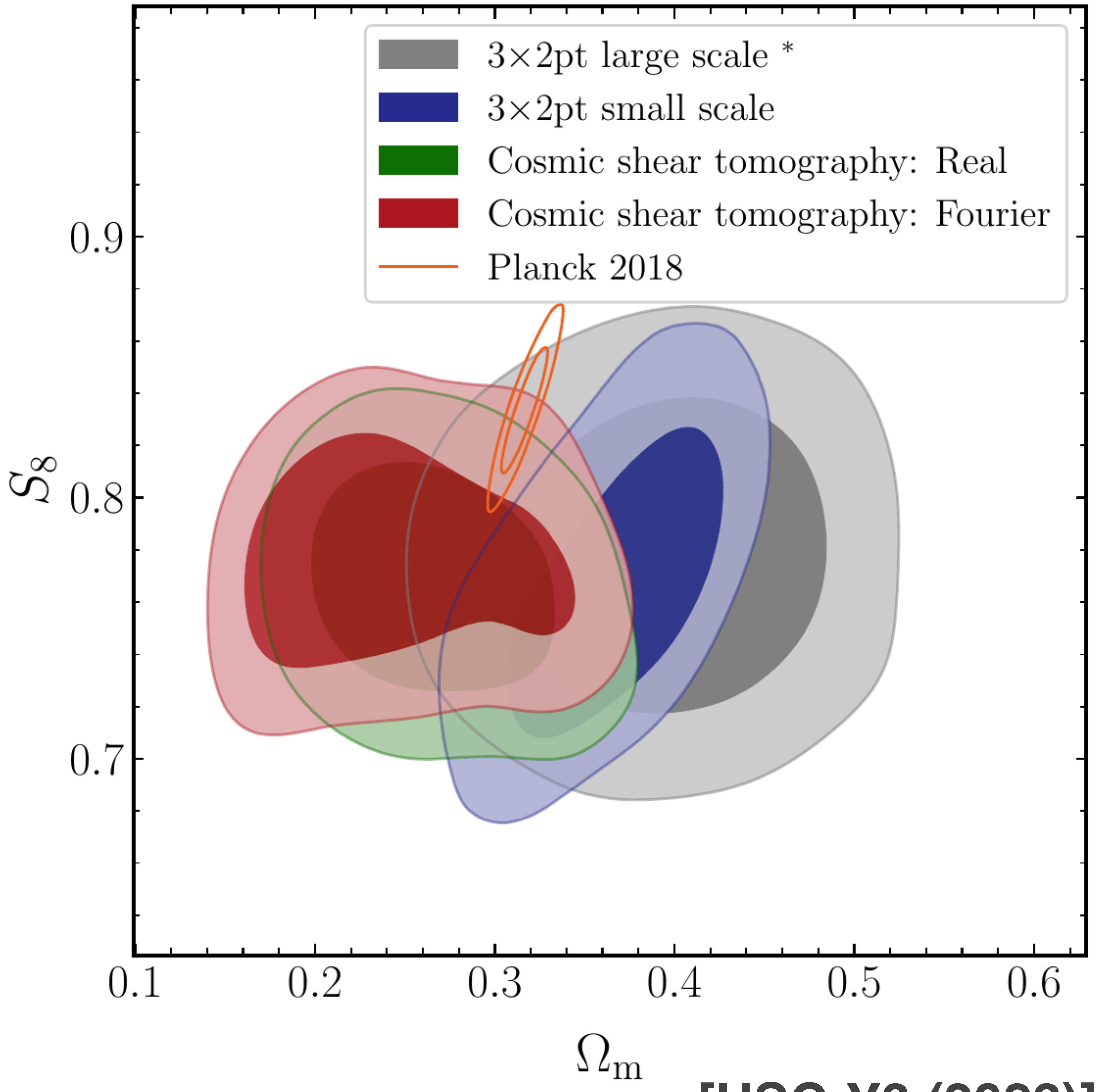


[Perivolaropoulos & Skara (2022)]

Tensions in cosmology: S_8 tension

(Talks by B02 group)

- S_8 : a measure of how much the structure formation progresses
- 2 - 3σ discrepancy between CMB & low-redshift observations
- ALP with 10^{-27} - 10^{-25} eV mass can suppress the growth of structure formation and weaken S_8 tension [Rogers et al. (2023)]



[HSC-Y3 (2023)]

Tensions in cosmology: Cosmic birefringence

(talks by B06 group and Andrew Long)

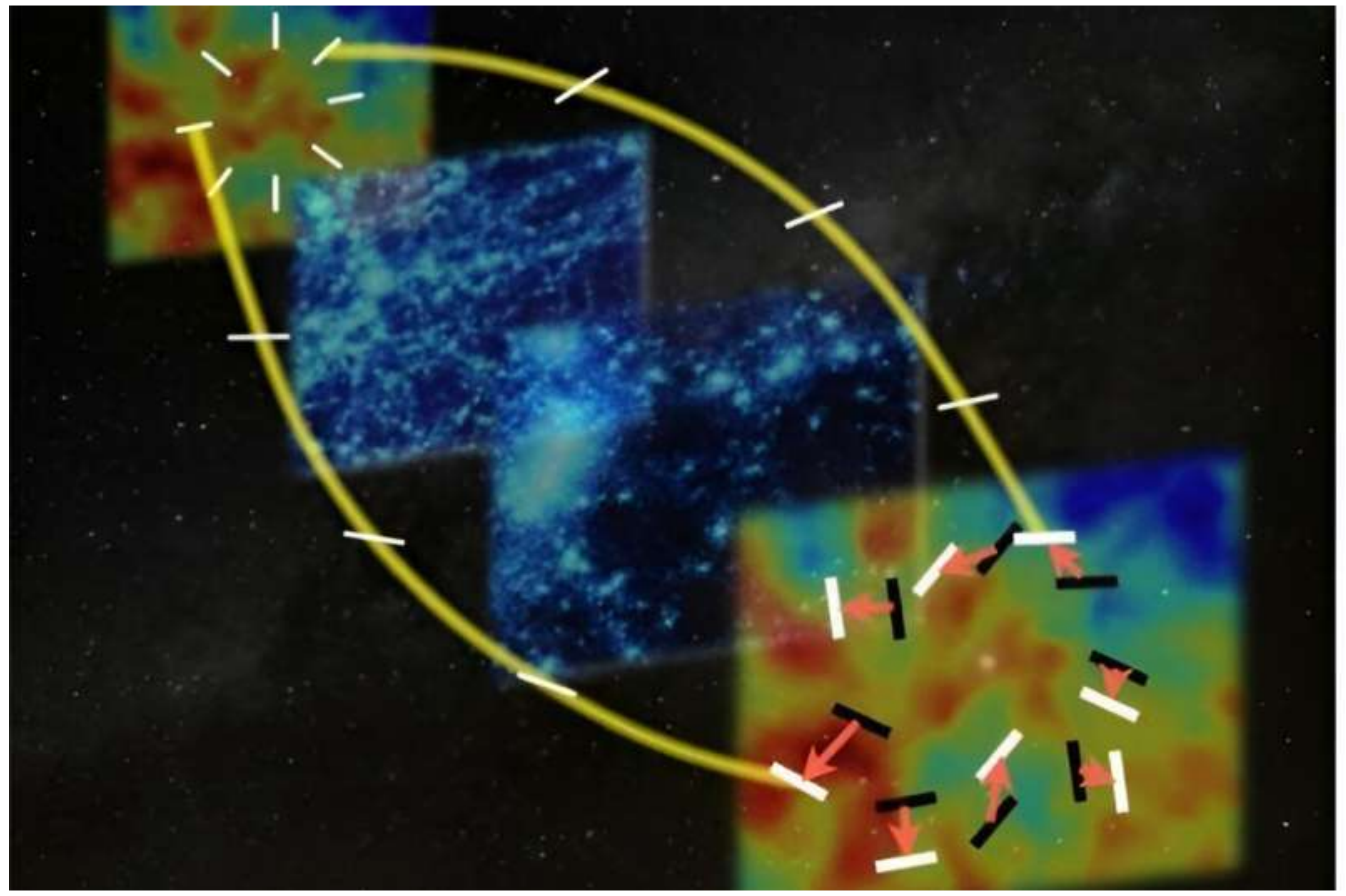
- Rotation of the polarization plane of CMB has been observed at 3.6σ

[Eskilt & Komatsu (2023)]

- This can be caused by the interaction between ALP and photon

$$-\frac{1}{4}g\phi F\tilde{F}$$

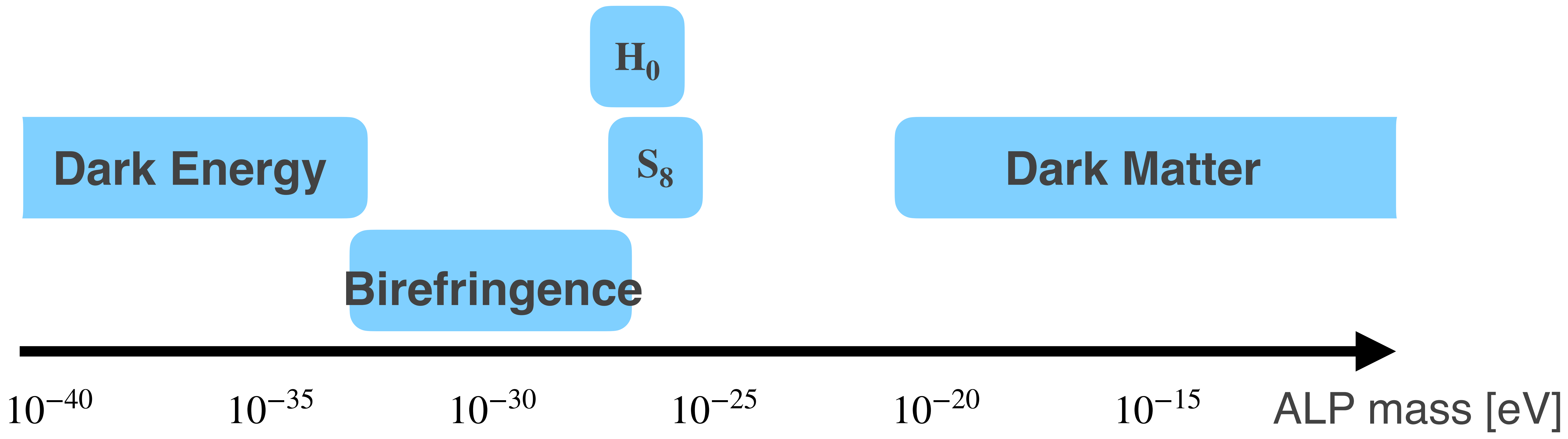
- ALP with a mass ~ 10^{-32} - 10^{-28} eV can cause cosmic birefringence



[Naokawa & Namikawa (2023)]

Cosmological axions

5 types of light ALPs appear to be desirable



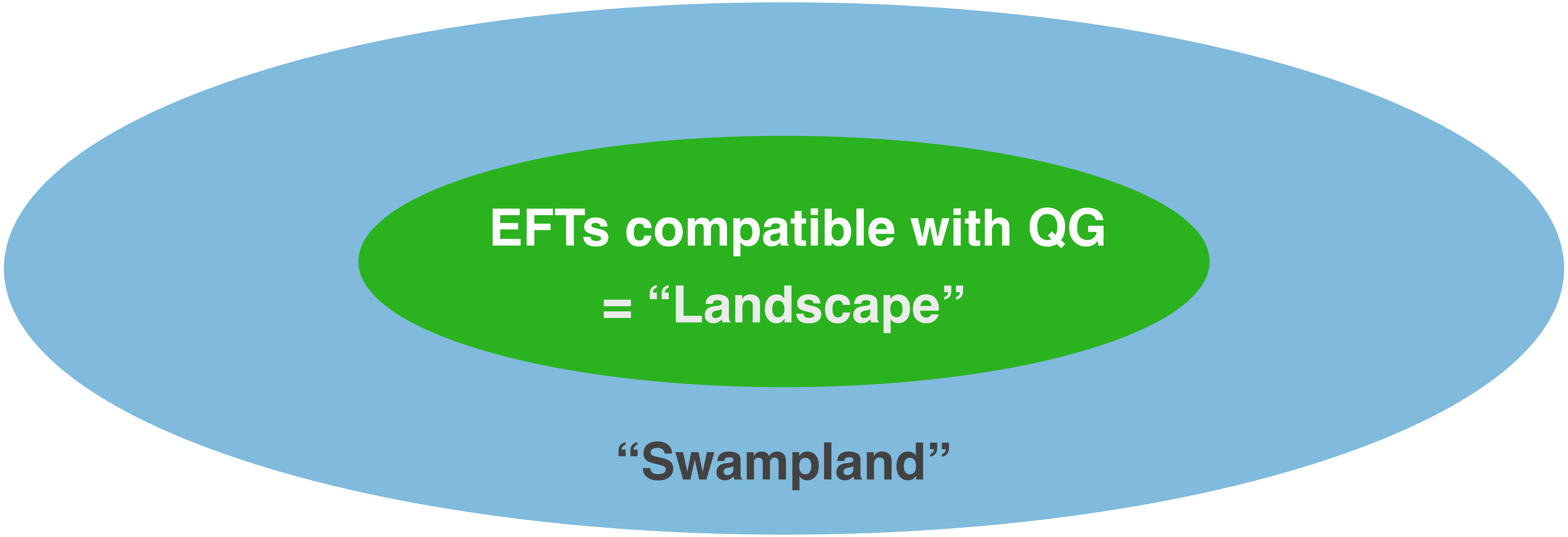
Q. Is there any constraint on # of species of ALPs?

A. Quantum Gravity (QG)?

Contents

Swampland conjecture

- Constraints for low-energy EFTs to be compatible with Quantum Gravity
  - No global sym. , Weak gravity conj. , Distance conj. , …



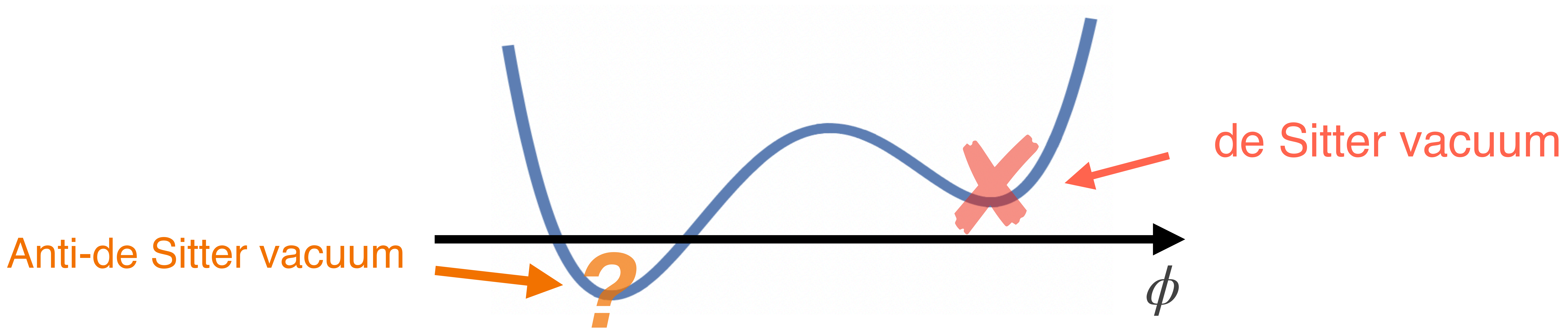
"Refined" de Sitter conjecture

[Lüst et al. (2019)]

- It is difficult to obtain de Sitter vacua in string theory
- Any potential for scalar fields should satisfy either

$$|\nabla V| \geq c \cdot |V| \,/\, M_{\rm Pl} \quad \textbf{or} \quad \min(\nabla_i \nabla_j V) \leq -c' \cdot V \,/\, M_{\rm Pl}^2$$

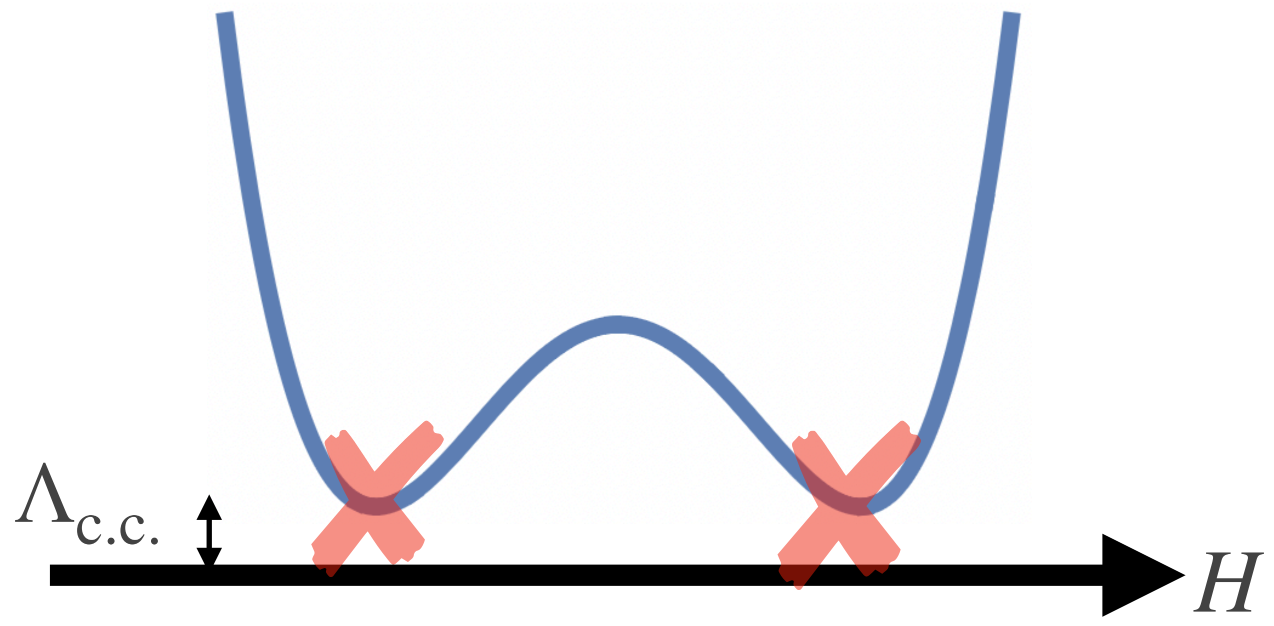
where c, c' are $\mathcal{O}(1)$ positive constants



Apply refined de Sitter conjecture to the 4D Standard Model

- Potential for scalar fields

$$V(H) = V_{\mathrm{Higgs}}(H) + \Lambda_{\mathrm{c.c.}}$$

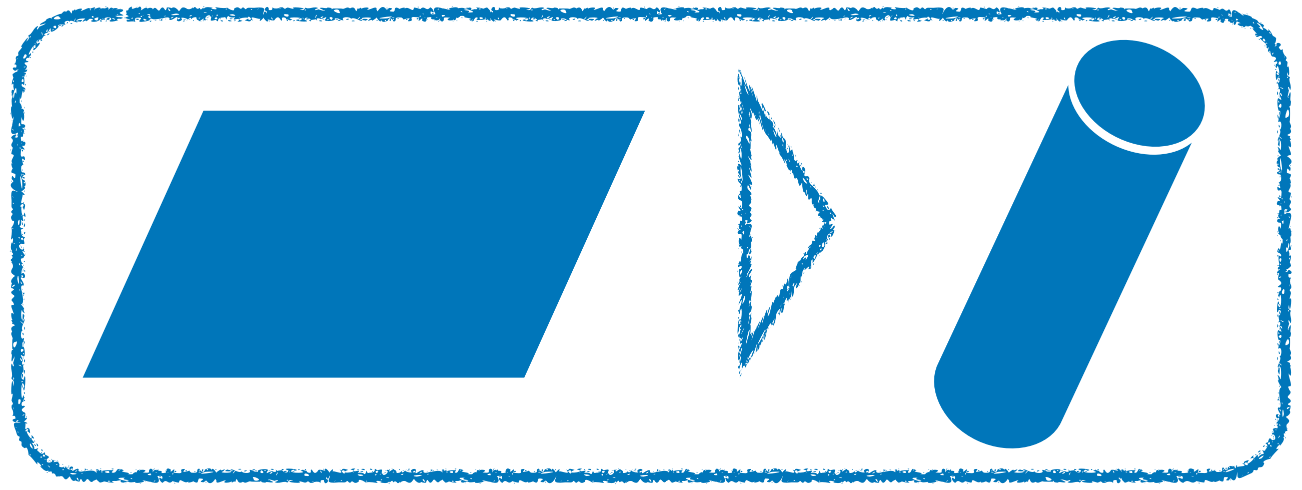


▷ ~~de Sitter vacua~~

- Solution: introduce a light scalar, **quintessence** Q [Agrawal et al. (2018)]

$$\Lambda_{\mathrm{c.c.}} \to V_Q(Q) \propto \exp[-\lambda Q/M_{\mathrm{Pl}}] \quad (\lambda : \mathcal{O}(1) \text{ constant})$$

Compactification of 4D spacetime to 3D



- We can consider compactification from 4D to 3D (cf. string theory: extra dimensions → Calabi-Yau manifold)
  - 4D → 3D + a **radion** field $R(x)$
- The size of compactification is determined by Casimir energy
  - Casimir energy from a particle with mass m: $\propto \exp[-2\pi\, m\, R]$
  - Only massless or light particles contribute to Casimir energy (photon, graviton, neutrinos, ALPs)

Potential for scalar fields in 3D

$$V(\{\phi_i\}, H, R) \propto R^{-2}\left[\sum_i \boxed{V_i(\phi_i)} + V_{\text{Higgs}}(H) + V_{\text{Casimir}}(R)\right]$$

Potential of ALP ϕ_i in 4D

Remarks

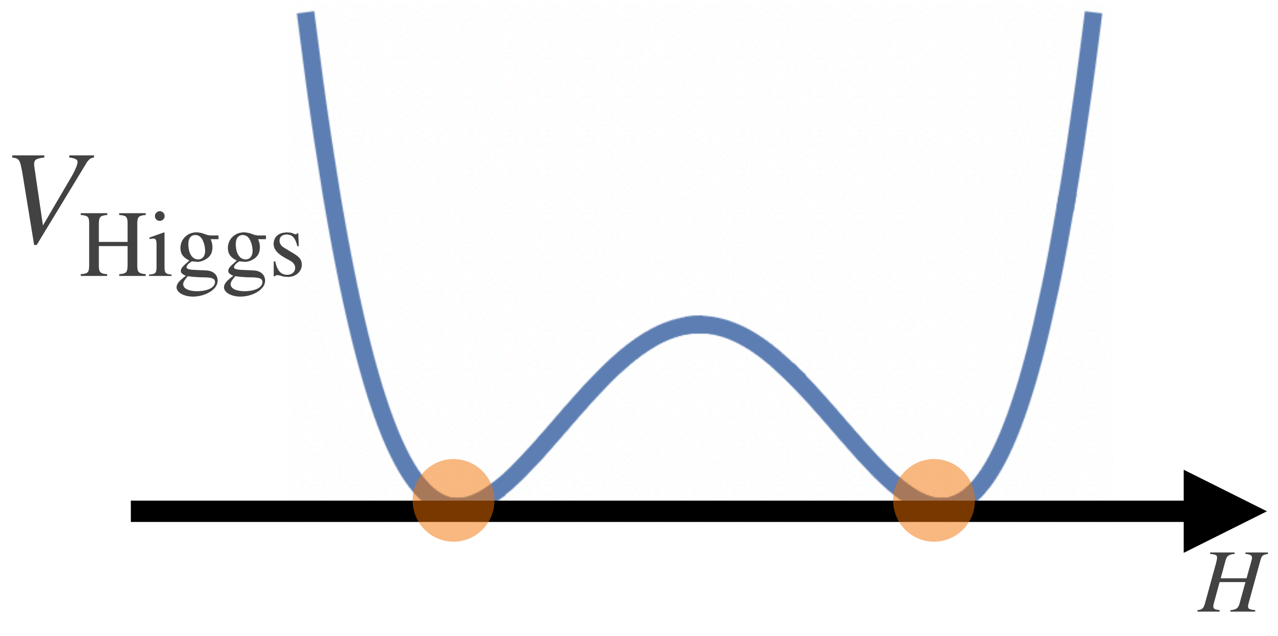
- We assume that different ALPs do not interact with each other
- ALPs are regarded as massless
  - V_{Casimir} is determined by **neutrino nature** and **# of ALPs**

Apply refined de Sitter conjectures to 3D spacetime

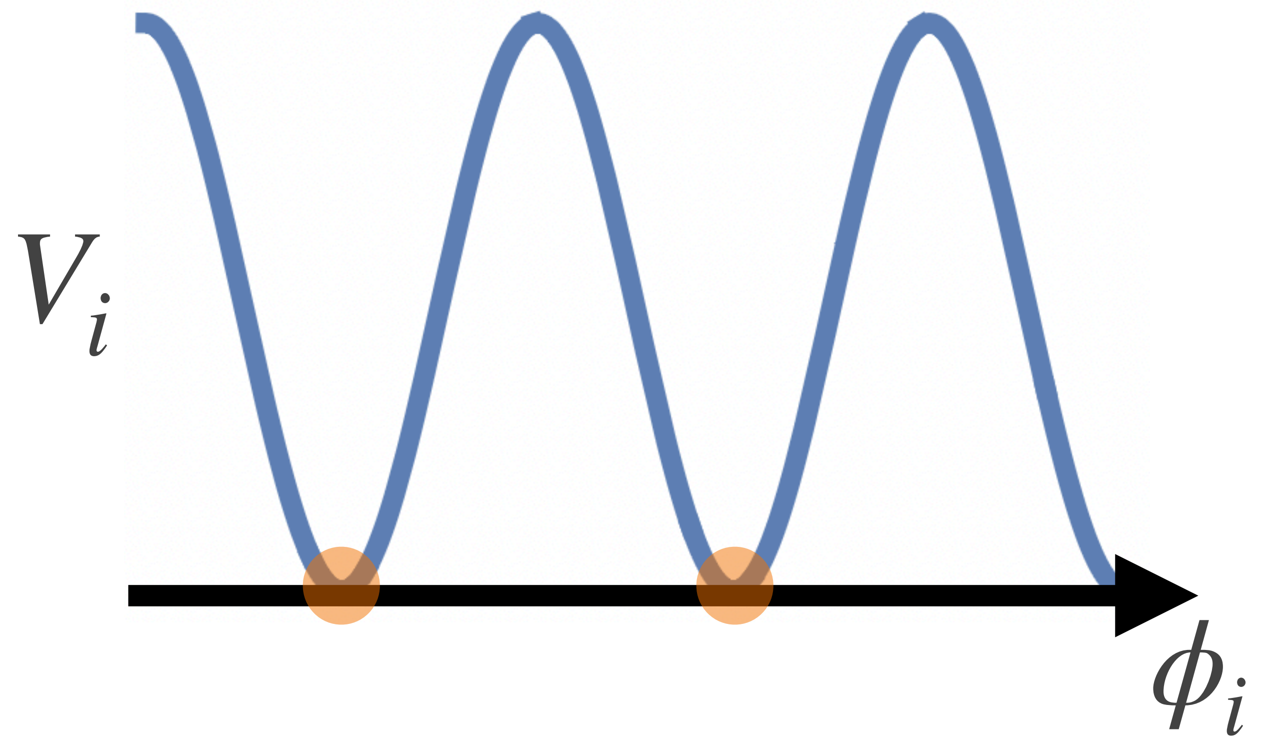
- We only consider special points where

$$\frac{\partial V_{\mathrm{Higgs}}}{\partial H} = V_{\mathrm{Higgs}} = 0 \quad \text{and} \quad \frac{\partial V_i}{\partial \phi_i} = V_i = 0$$

for each ALP ϕ_i except for quintessence Q



- Overall potential depends only on R and Q at such points
  - Compute $|\nabla V|/|V|$ and $-\min(\nabla_i \nabla_j V)/V$ in (R, Q), and verify the refined dS conjecture



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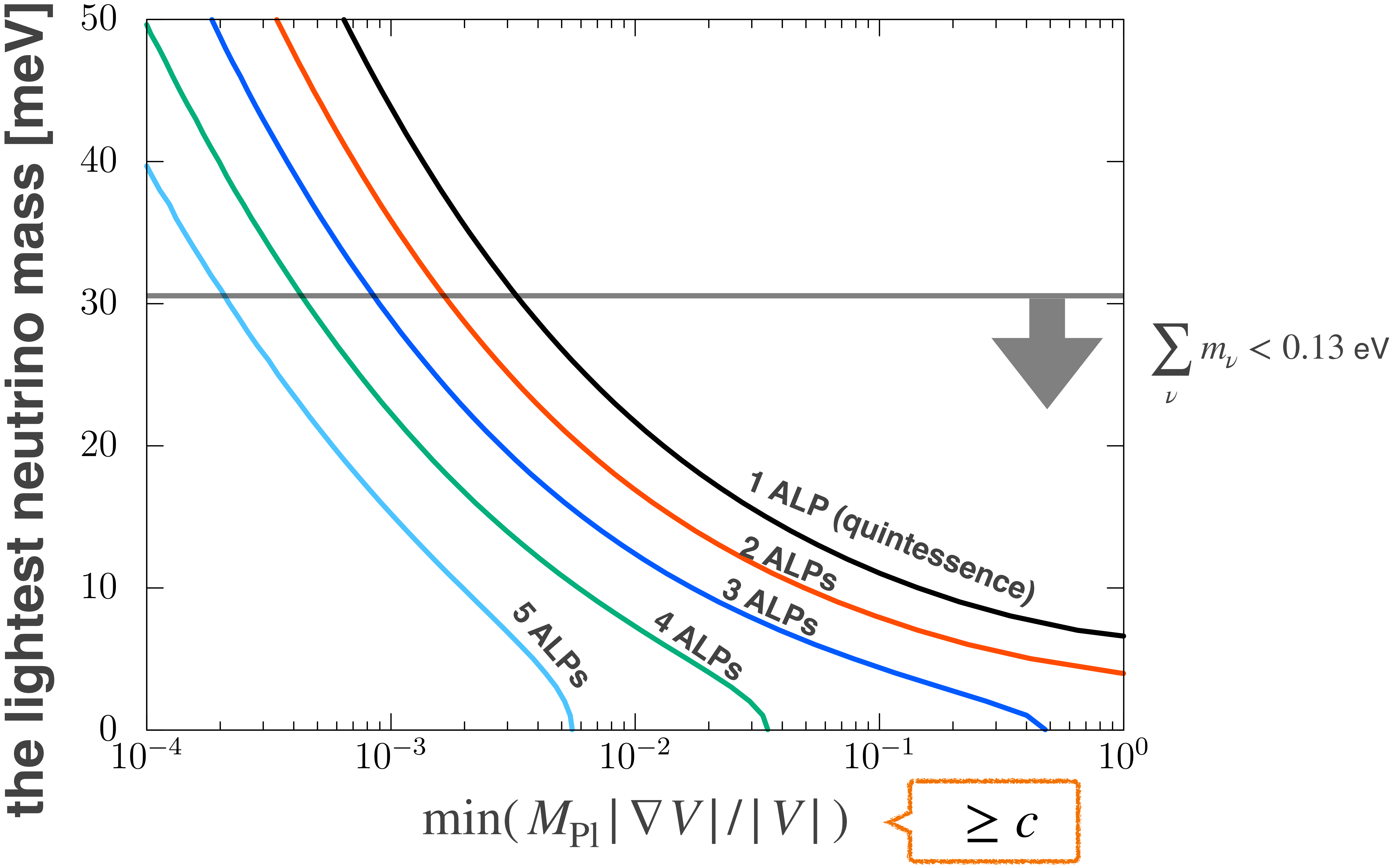
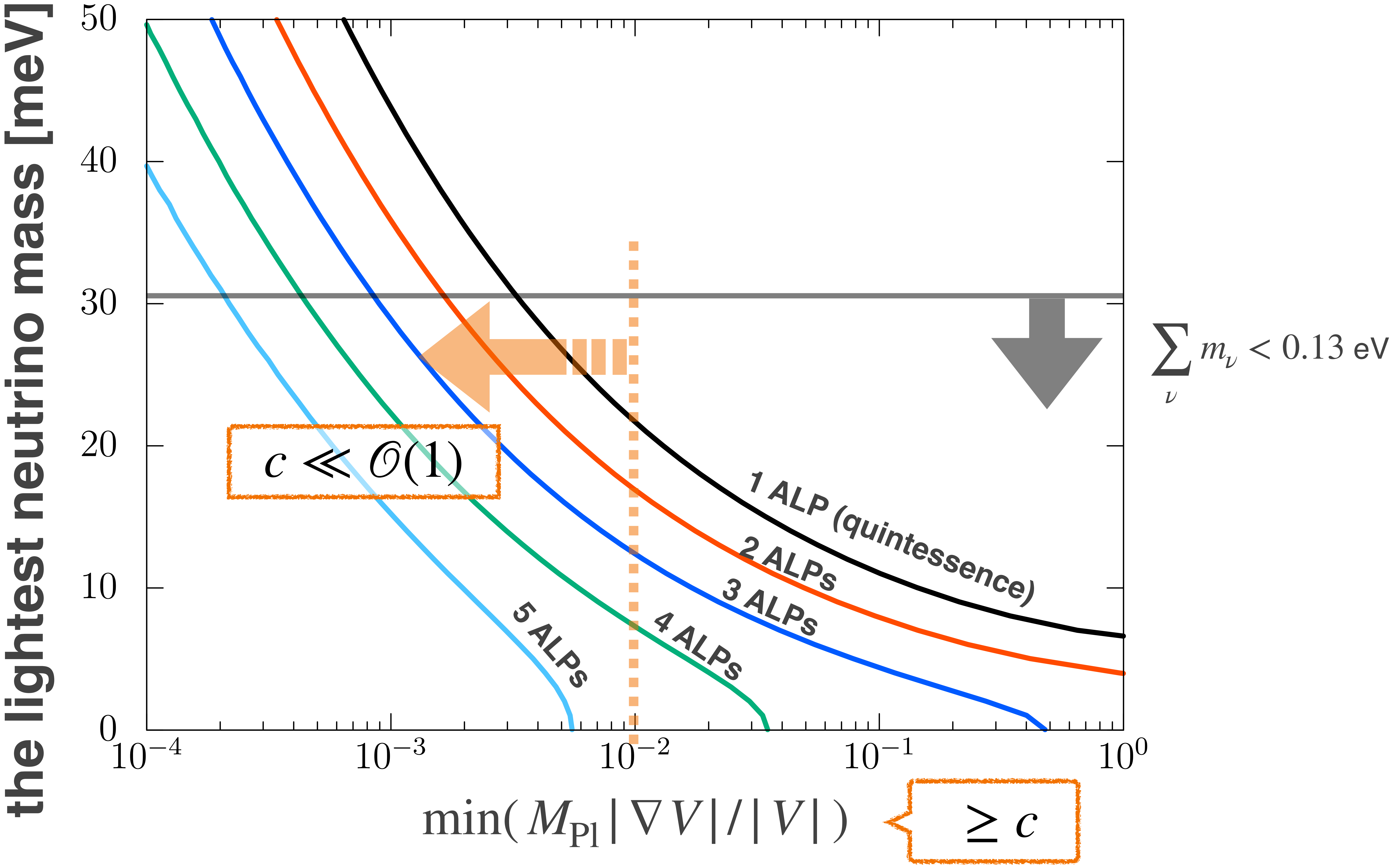
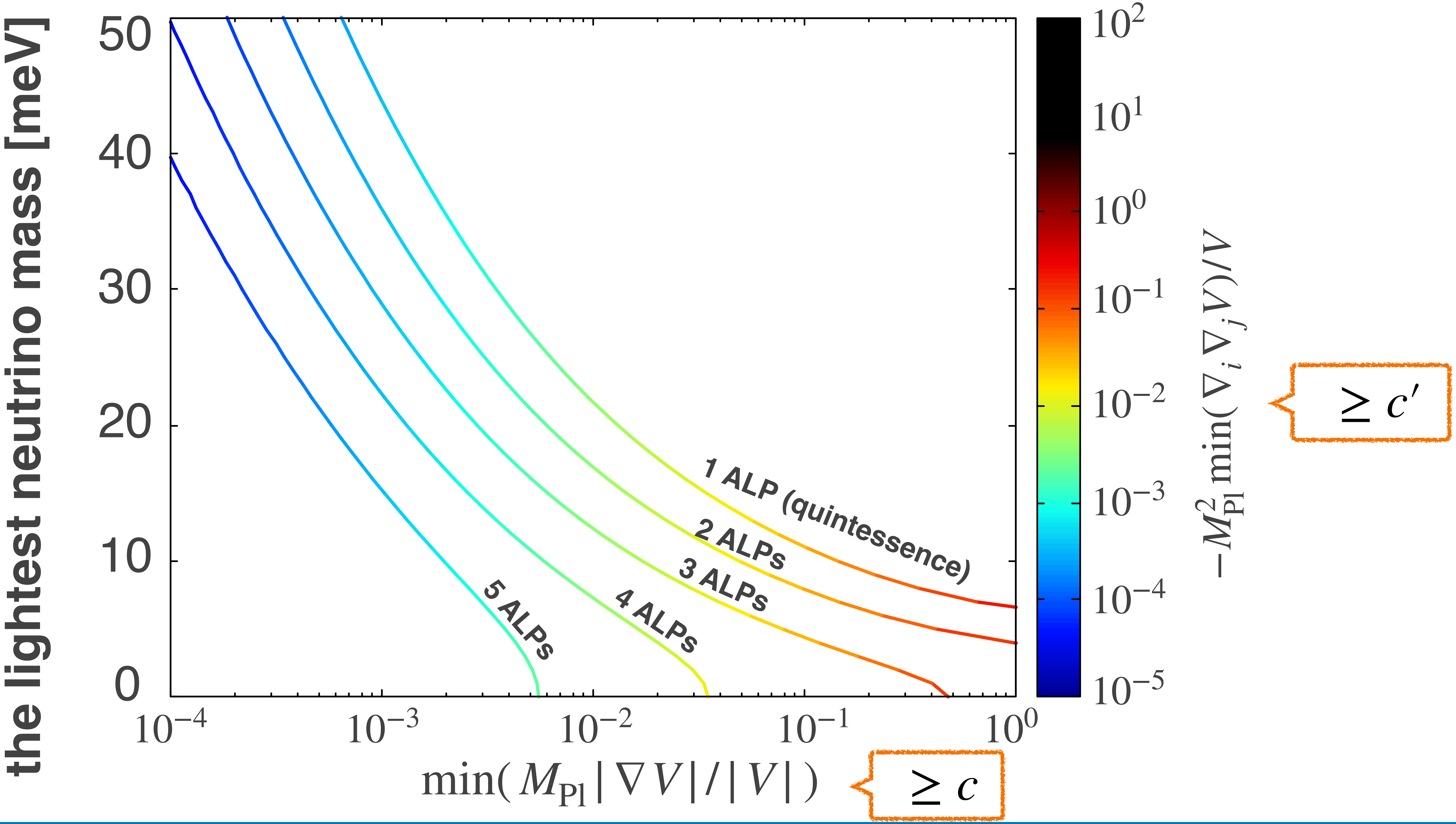
Dirac neutrino of Normal Ordering



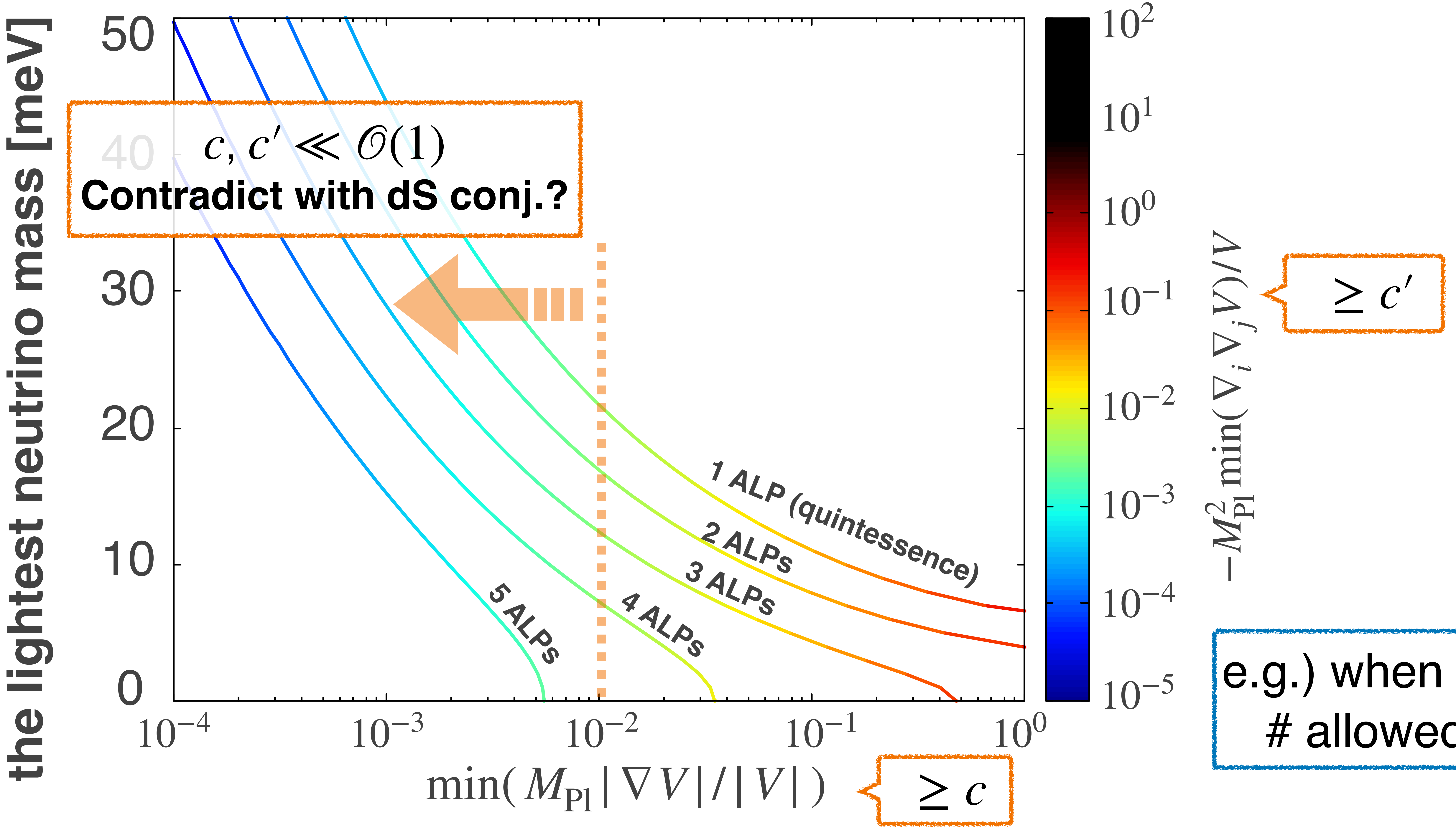
Dirac neutrino of Normal Ordering



Dirac neutrino of Normal Ordering

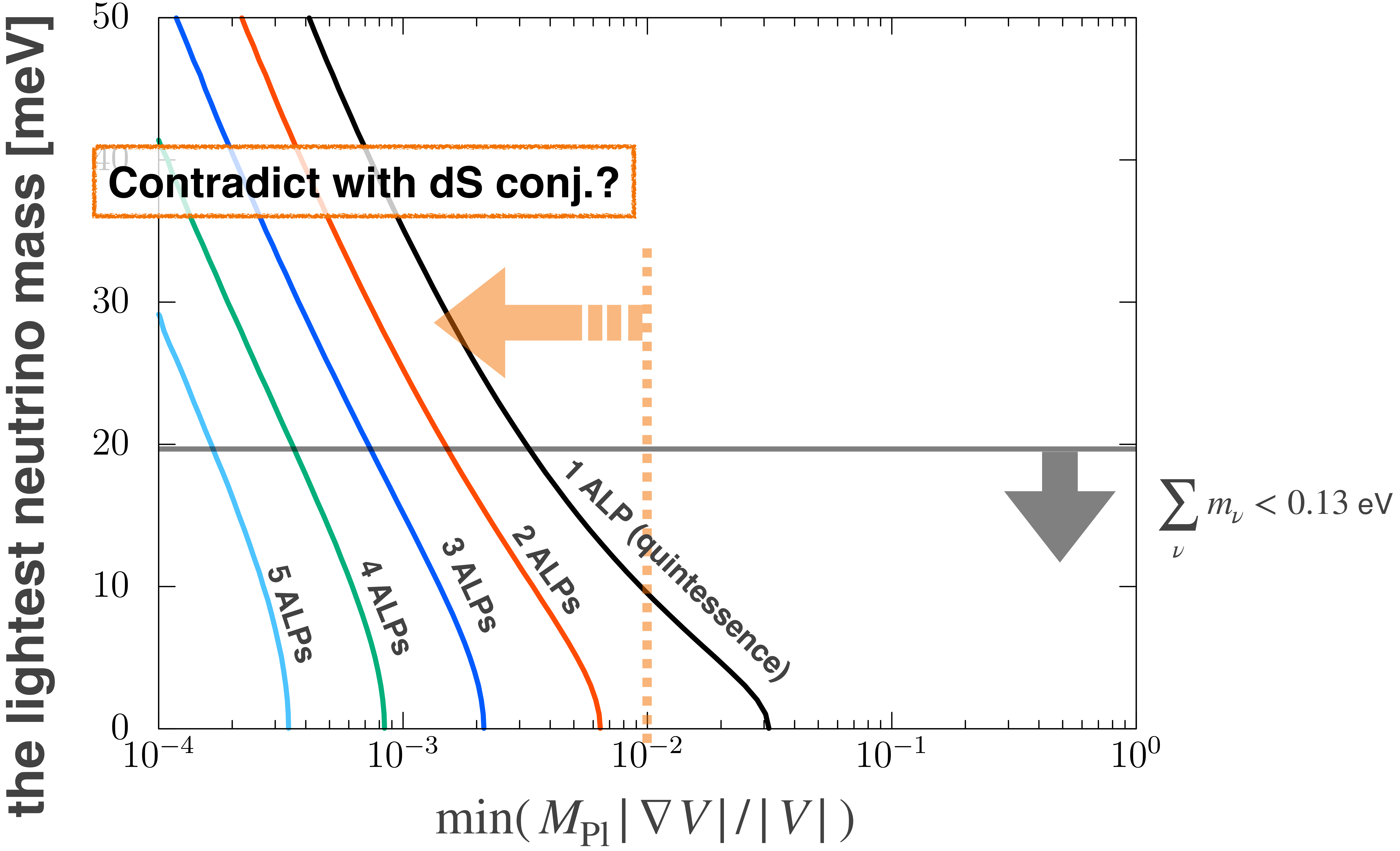


Dirac neutrino of Normal Ordering



e.g.) when $c, c' = 10^{-1}$,
allowed ALPs ≤ 3

Dirac neutrino of Inverted Ordering



Contents

Summary & Discussion

- Axion and ALP are motivated by cosmology
- Multi-ALPs may contradict with the refined de Sitter conjecture
  - "ALPs more than **3** (**1**) + quintessence" may be disfavored for Dirac NO (IO) neutrino
  - (Majorana neutrino is unfavorable regardless of NO and IO)
- Possible loopholes
  - Introduce ultra-light fermions, which compensate for ALPs' contribution to V_{Casimir}
  - Consider other forms for ALP potential
  - Mitigate swampland conjectures

Exploring (multi-)ALPs leads to verification of Quantum Gravity!

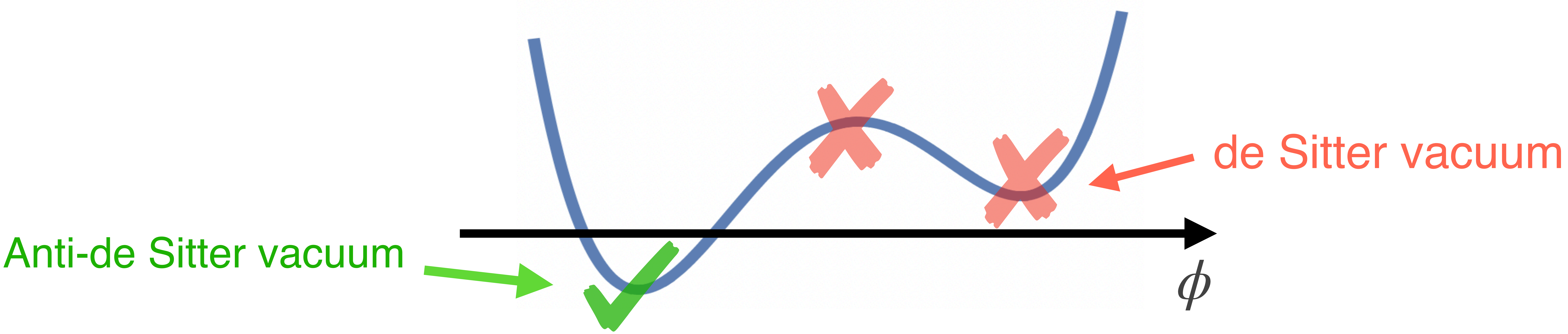
Back up

de Sitter conjecture [Obied et al. (2018)]

- It is difficult to obtain de Sitter vacua in string theory
  - Any potential V for scalar fields should satisfy

$$|\nabla V| \geq c \cdot V / M_{\mathrm{Pl}}$$

where c is an $\mathcal{O}(1)$ positive constant



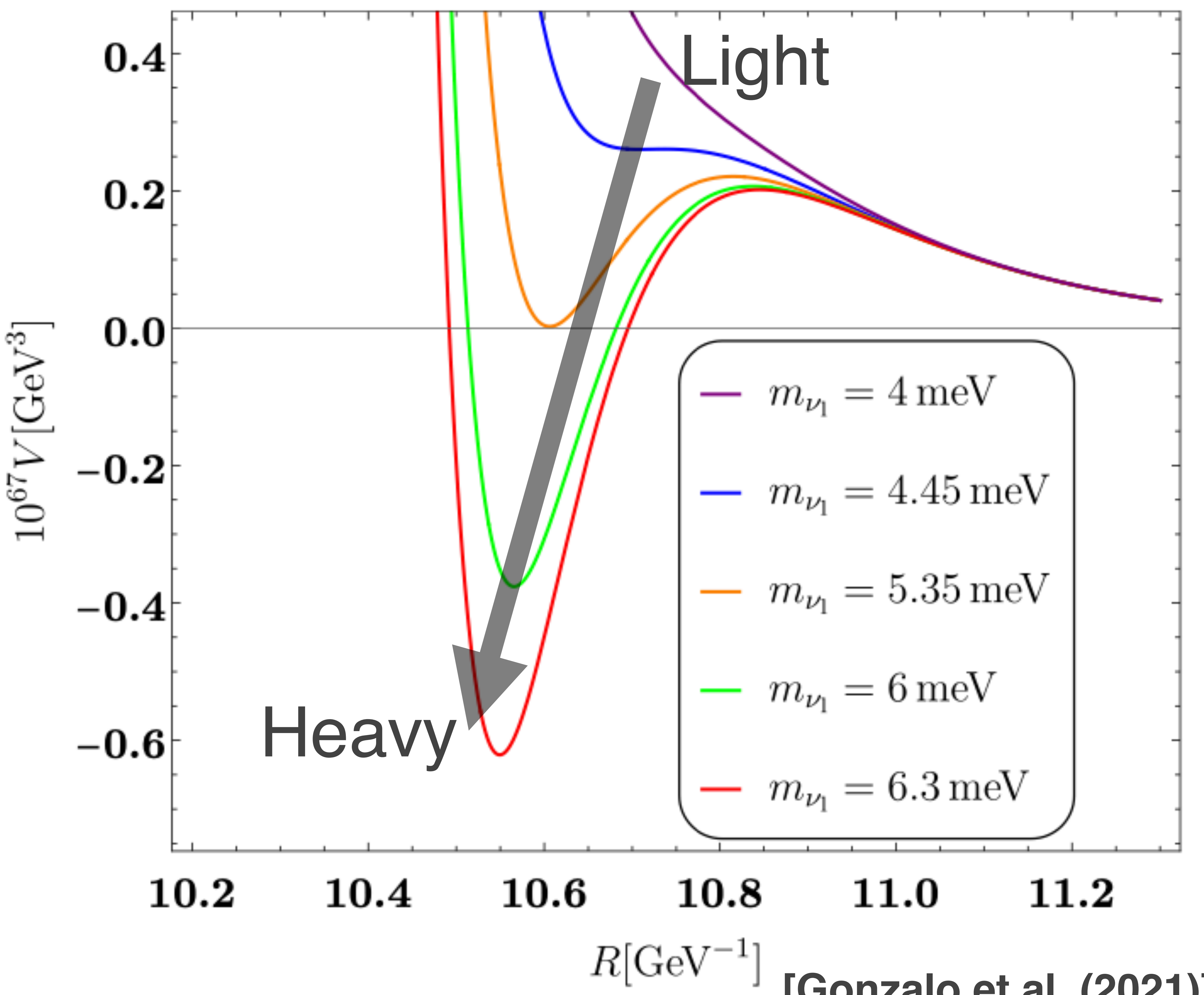
Casimir energy

$$V_{\text{Casimir}}(R) = \sum_i (-1)^{s_i} n_i \rho_i(R),$$

$$\rho_i(R) = \begin{cases} \dfrac{r^3 m_i^2}{4\pi^3 R^4} \displaystyle\sum_{n=1}^{\infty} \dfrac{K_2(2\pi R m_i n)}{n^2} \cos(n\theta) & (m_i \neq 0) \\ \dfrac{r^3}{720\pi R^6} & (m_i = 0) \end{cases}$$

- Boson: decrease V_{Casimir}

  Fermion: increase V_{Casimir}



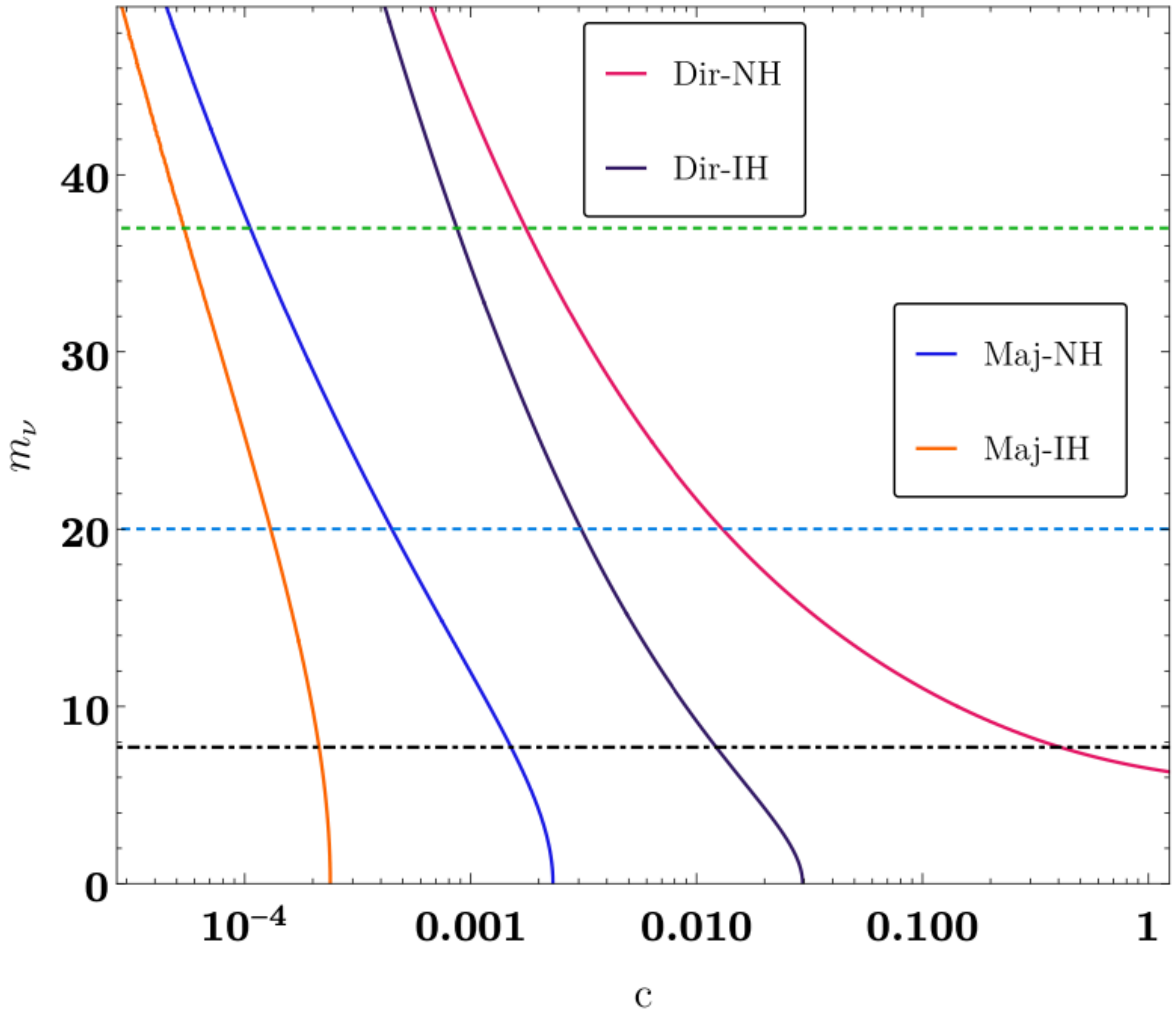
[Gonzalo et al. (2021)]

Majorana neutrino

- For Majorana neutrino, the constraint from dS conjecture is stronger

- Even if we don't introduce additional ALPs,

$$c \ll \mathcal{O}(1)$$



[Gonzalo et al. (2021)]