# Cosmological Axions Challenge String Theory

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2023/11/9 at Tsukuba

# Contents

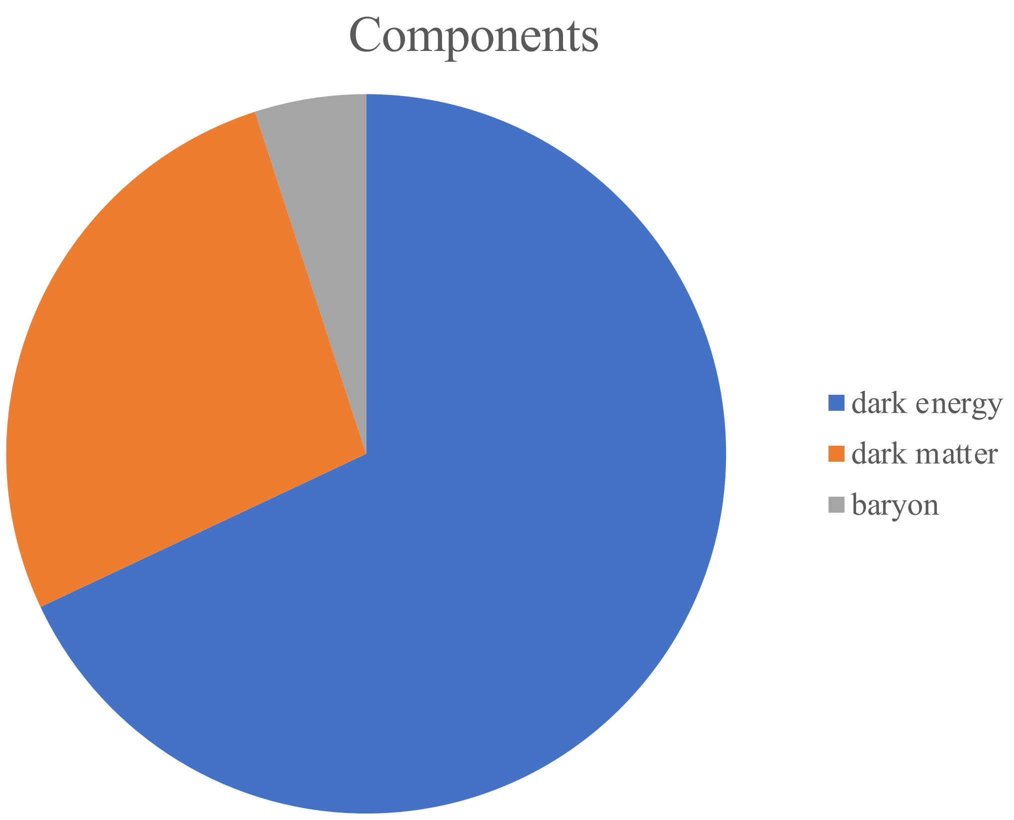
# ΛCDM model

- ΛCDM describes the expanding universe.

Λ : cosmological constant
CDM : cold dark matter

- Baryon is only 5%

- Although 95% of ΛCDM is unknown dark sector, it explains most of our universe.




ΛCDM works well! Unfortunately, there are still some problems!

# Problems of ΛCDM model

- $H_0$ tension … discrepancy of Hubble constant
- $S_8$ tension … discrepancy of growth parameter
- Cosmic birefringence … rotation of CMB polarization
- Dark sector … dark matter and dark energy

Cosmological axions can solve these problems!

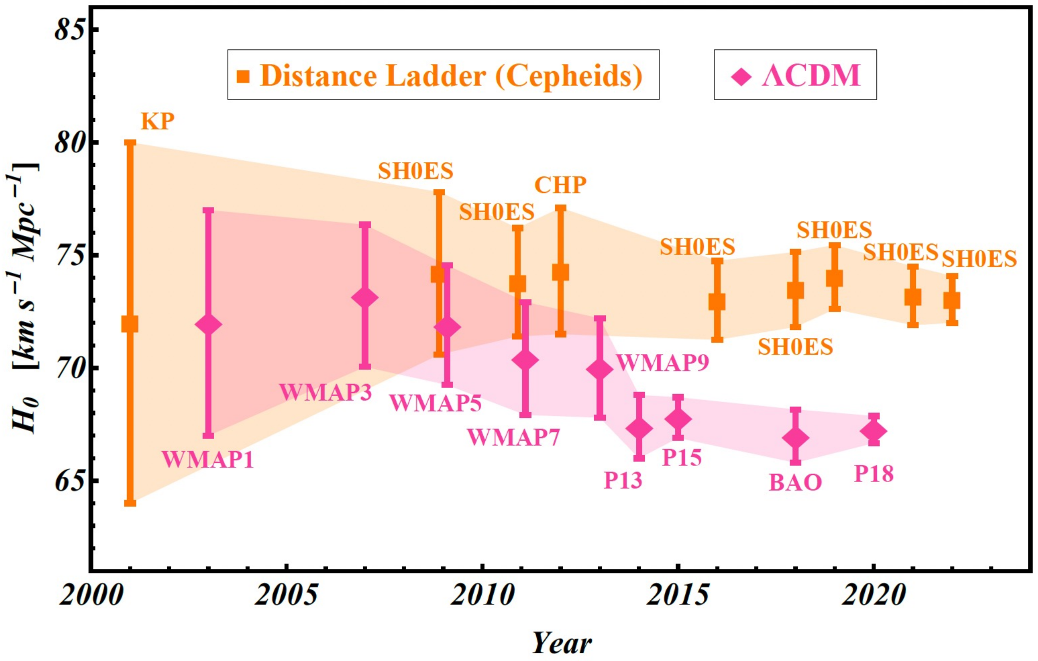
# Cosmological axion for $H_0$ tension

- $H_0$ tension is about $5\sigma$ discrepancy of Hubble constant between CMB and local distance ladder.

- Early dark energy can solve this, which behaves like a cosmological constant before recombination and dilutes away faster than radiation.

- Axion field : $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

Mass should be $m_a \approx H_{rec}$ (friction)




L. Perivolaropoulos et al. (2022)

Axion mass is expected in the range of $m_a \approx 10^{-27}$eV

# Cosmological axion for $S_8$ tension

- $S_8 \equiv \sqrt{\frac{\Omega_{0m}}{0.3}}\sigma_8$

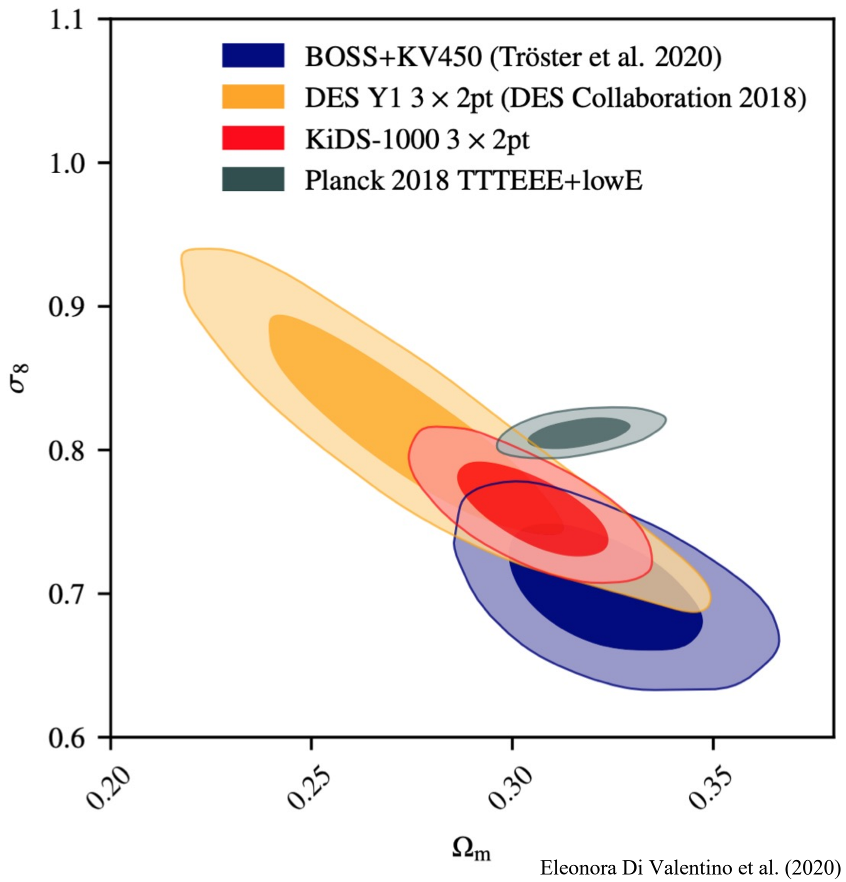
where $\sigma_8$ is the standard deviation of matter density fluctuation around $8h^{-1}$Mpc

- About $2\sigma$ discrepancy

BOSS : $S_8 = 0.723^{+0.041}_{-0.037}$

Planck18 : $S_8 = 0.834 \pm 0.016$

- This tension is softened by introducing cosmological axion.




Eleonora Di Valentino et al. (2020)

Axion mass is expected in the range of $10^{-27}\text{eV} \lesssim m_a \lesssim 10^{-25}\text{eV}$

# Cosmological axion for cosmic birefringence

- Cosmic birefringence needs parity violating physics.

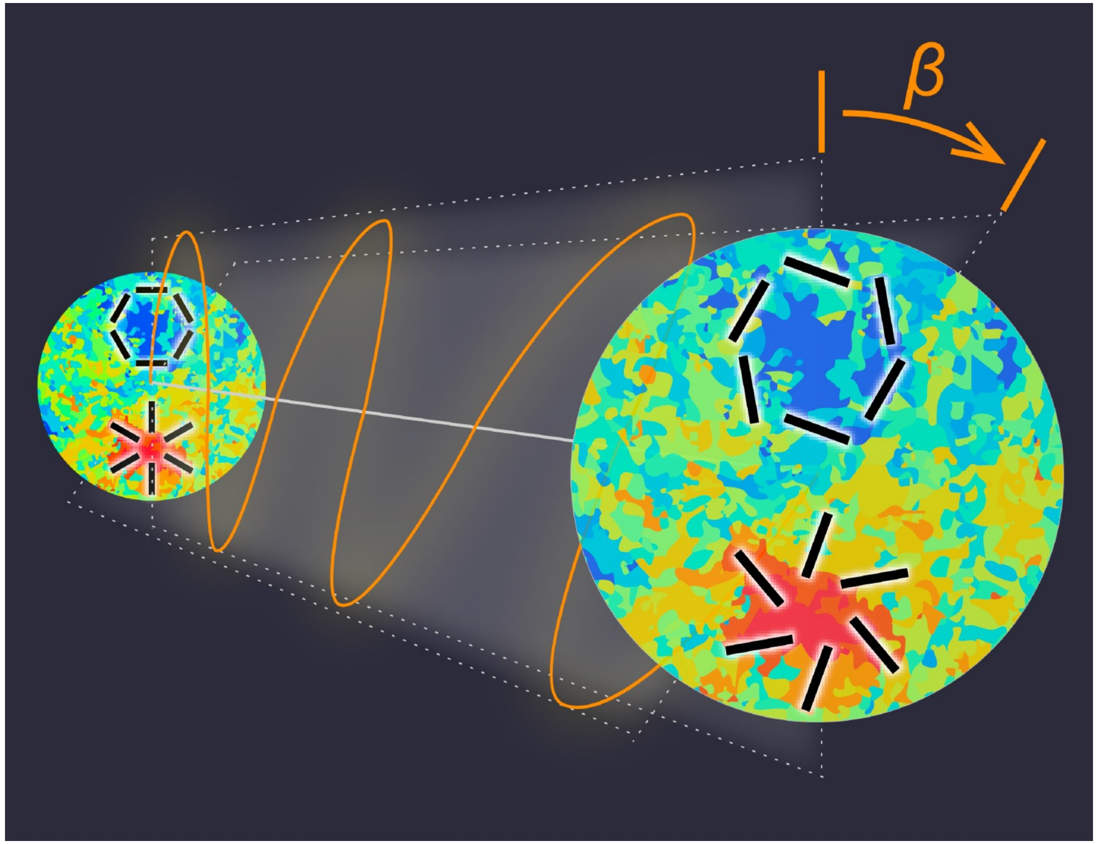
$\mathcal{L}_{CS} = -\frac{1}{4} g\phi F\tilde{F}$

Introduce axion photon coupling by Chern-Simons term

- Rotating angle is $\beta = \frac{g}{2}\Delta\phi$

- Observed value is

$\beta = 0.35 \pm 0.14\text{deg}\ (2\sigma)$




Komatsu (2022)

Axion mass is expected in the range of $10^{-38}\text{eV} \lesssim m_a \lesssim 10^{-27}\text{eV}$

# Is dark sector axion?

- Mass of fuzzy dark matter is restricted by Lyman $\alpha$, subhalo mass function and heating.

$$m_a \gtrsim 10^{-19}\text{eV}$$

- Mass of dark energy should be smaller than today's Hubble constant.

$$m_a \lesssim 10^{-33}\text{eV}$$

Axion mass for DE is expected in the range of $m_a \lesssim 10^{-33}$eV
Axion mass for DM is expected in the range of $m_a \gtrsim 10^{-19}$eV

# Summary of Cosmological axions

- To solve the tensions of ΛCDM by axions, multi-axions are needed.

  More than there axions, or more if dark sectors are so.

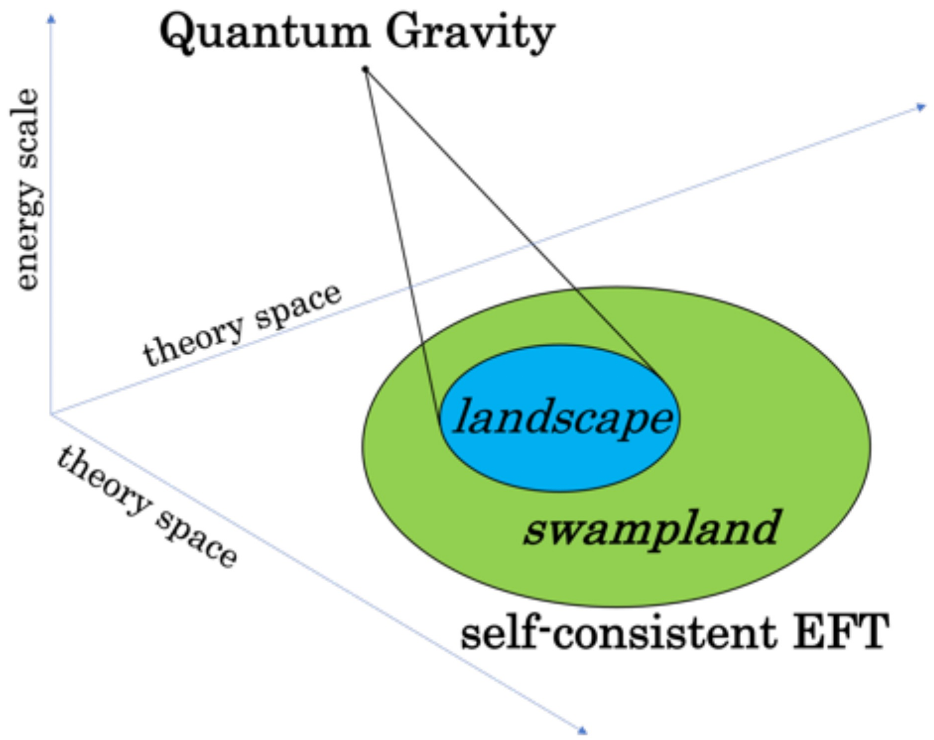
- Are multi-axions allowed

# Swampland program

- It aims to distinguish effective theory which is consistent with QG in UV region.

- It is possible to impose constraints on EFT.

- We use this method for cosmological axions.



# Swampland conjecture

- de Sitter conjecture

A potential $V$ for scalar field of any consistent theory of QG should satisfies

$$|\nabla V| \geq c \cdot V$$

where $c$ is a positive one order constant in the Planckian unit.

# Swampland conjecture

- refined de Sitter conjecture

A potential $V$ for scalar field of any consistent theory of QG should satisfies

$$|\nabla V| \geq c \cdot V$$

or

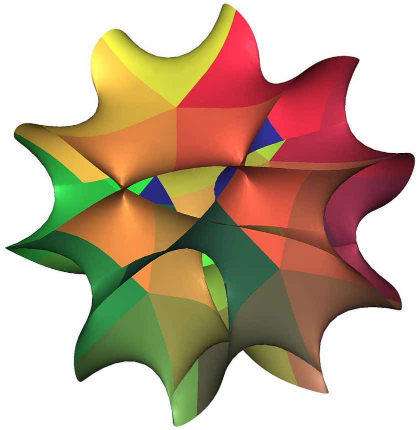
$$min\left(\nabla_i \nabla_j V\right) \leq -c' \cdot V$$

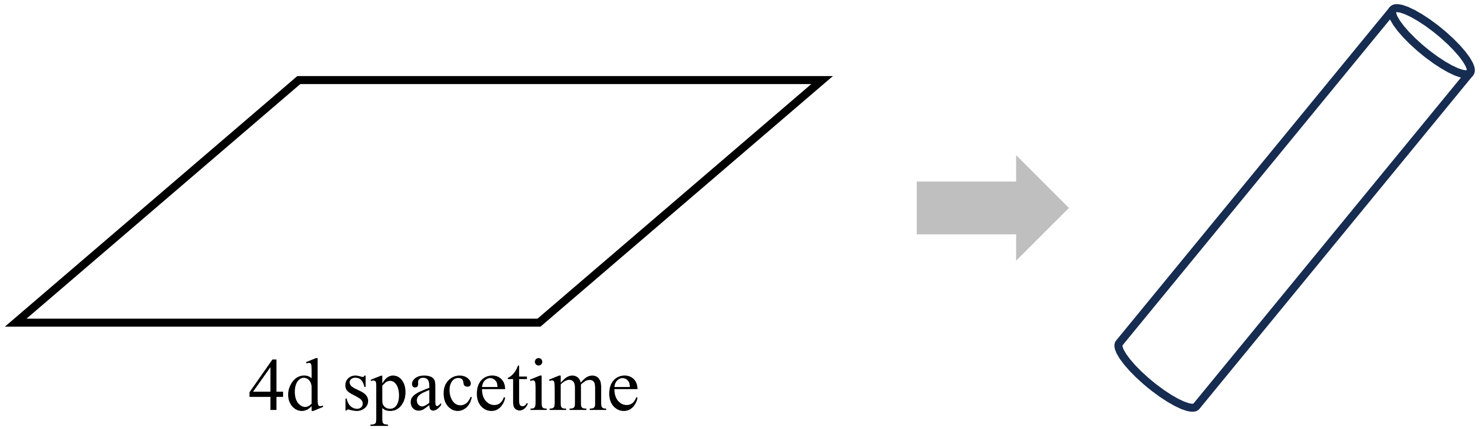
where $c, c'$ are positive one order constants in the Planckian unit.

# Compactifying the SM

In the string theory, to obtain 4d Minkowski spacetime,
higher dimensional spacetime is compactified to Calabi-Yau manifold.

Not to obtain lower dimensional theory,
we consider the possibility of $S^1$ compactification of 4d SM.





# Calculating vacuum energy

- Casimir energy contributes to vacuum energy.

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

$$\rho_i(R) = \sum_{k=0}^{\infty} \frac{2{m_i}^4}{(2\pi)^2} \frac{K_2(2\pi R m_i k)}{(2\pi R m_i k)^2}$$

where $R$ is size of compactified dimension.

- The potential of vacuum energy depends on the size of compactified dimension.

# For light sectors

- Vacuum energy of massive sector decreases exponentially

$$\rho(R) \propto e^{-2\pi m R}, R \to \infty$$

For this reason, light sectors determine the effective potential.

→ photon, graviton, neutrino, axion

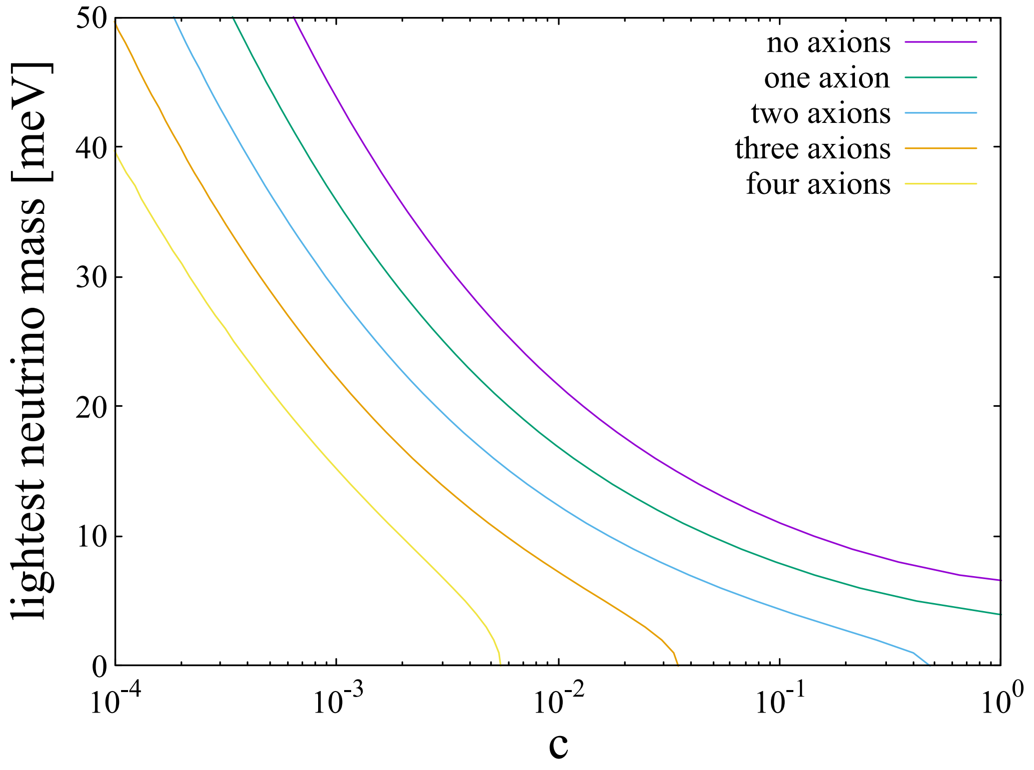
# For neutrinos

- In the SM, some properties of neutrinos are not determined.
    1. type (Dirac or Majorana)
    2. hierarchy (Normal or Inverted)
    3. lightest neutrino mass

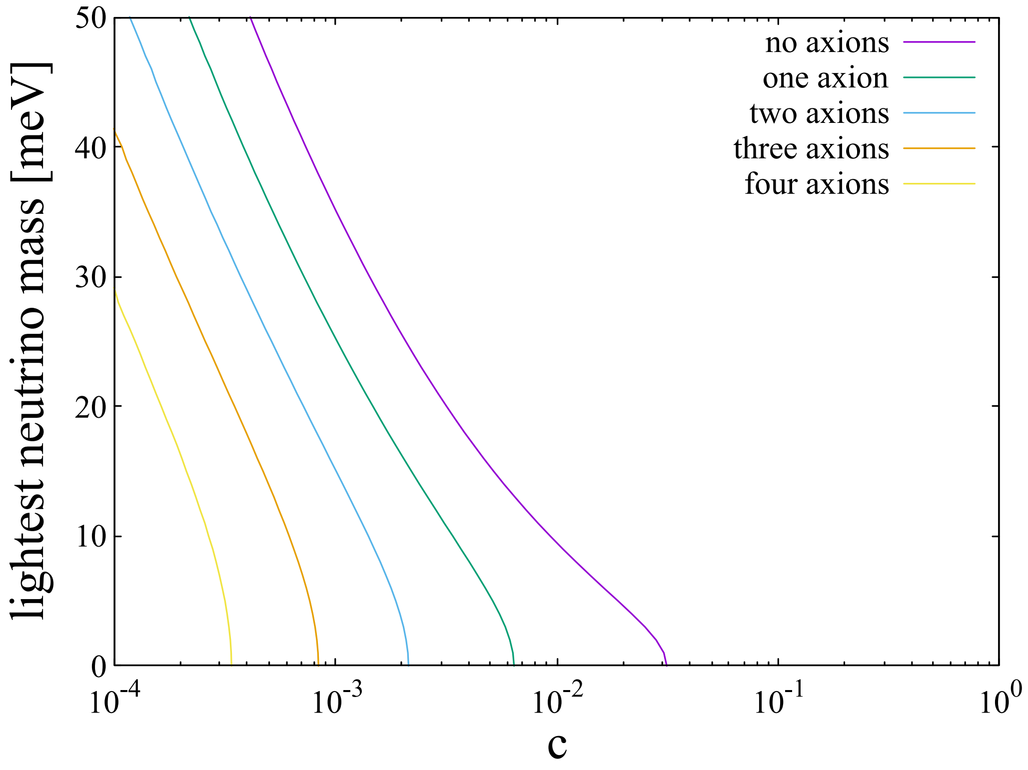
Analysis depends on these parameters.

# Result

Dirac neutrino of normal hierarchy




Dirac neutrino of inverted hierarchy




In the case of Dirac neutrino of normal hierarchy, up to two axions are allowed.

# Summary

- $\Lambda$CDM has some tensions.
- Cosmological axions can help to solve them.
- Such multi-axion picture conflict with string theory.

Thank you for listening!