Grand unification with hidden photon, and implications for the axion-photon coupling

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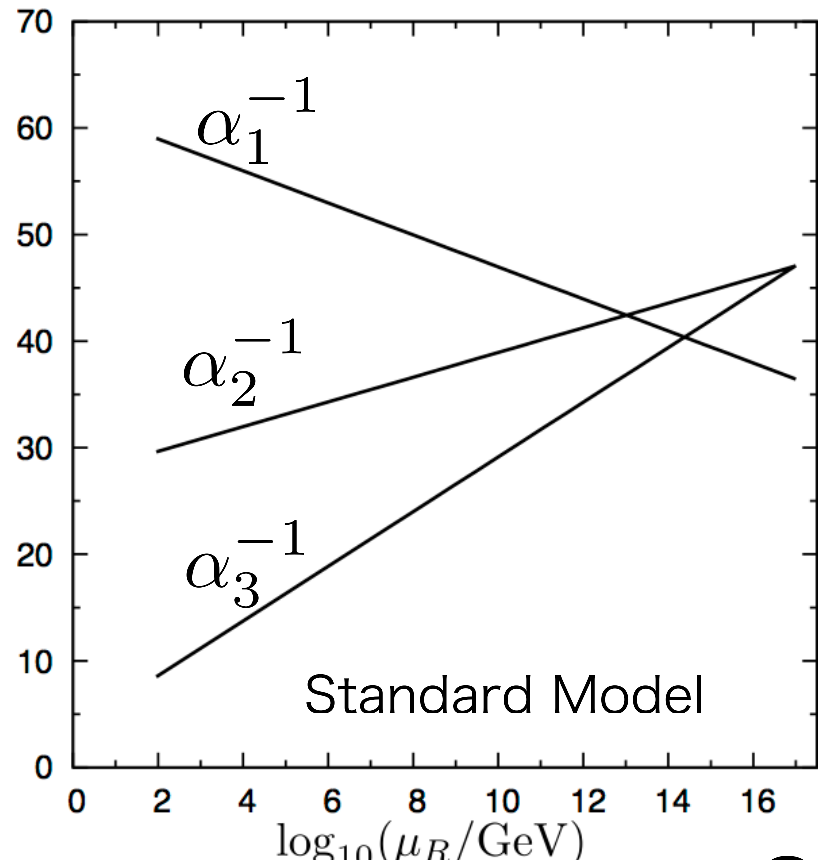
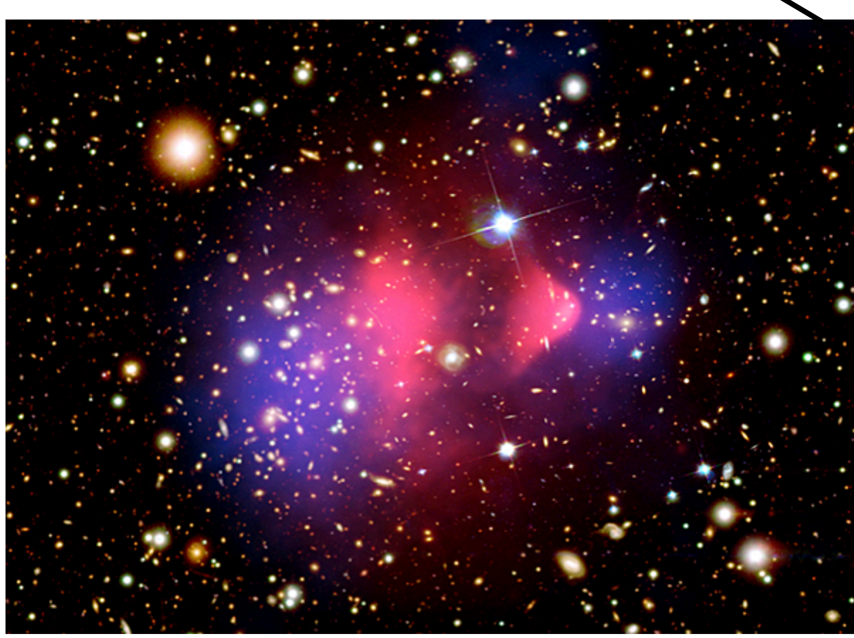
Evidences for physics beyond SM

Grand Unification



BSM is needed

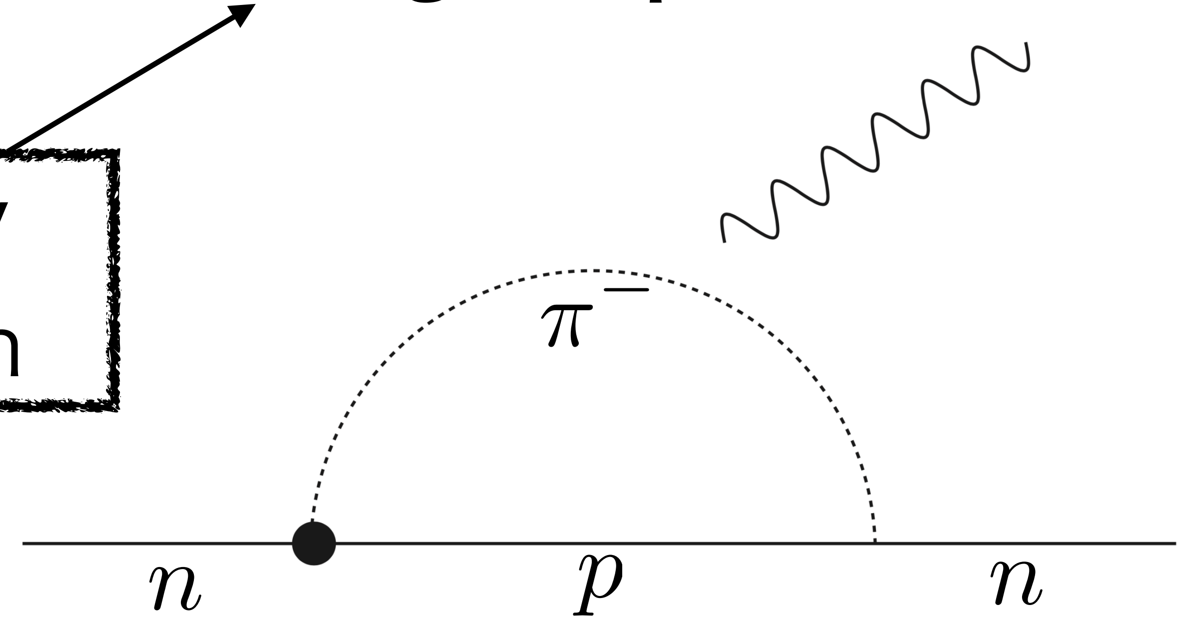
Dark matter



[NASA]

Solved by QCD axion

Strong CP problem



SU(5) GUT

Simplest GUT is SU(5) GUT (because of the rank)

The matter multiplets are unified into **5*** and **10**

The charge quantization is explained

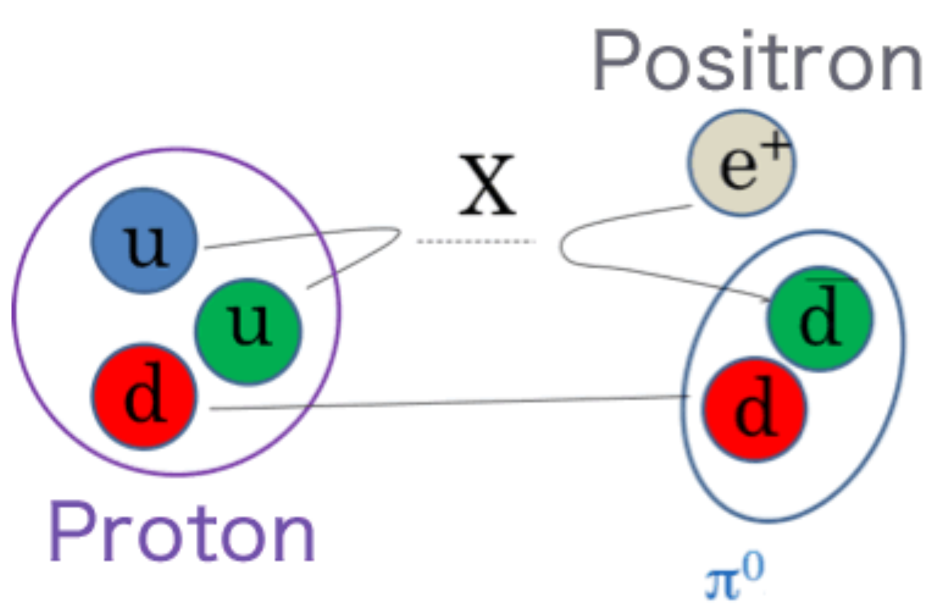
However…

- **Coupling unification**

  Gauge couplings do not unify precisely

- **Proton decay**

  The proton decays too quickly



[hyper-K:HP]

For $M_X = 10^{15}$ GeV

$\tau(p \to \pi^0 e^+) \approx 5 \times 10^{31}$ years

$\tau(p \to \pi^0 e^+)_{\rm exp} > 1.7 \times 10^{34}$ years

[Super-K, 2016]

Grand unification with massless hidden photon

[Redondo, 2008; Takahashi, Yamada, NY, 2016; Daido, Takahashi, NY, 2016, 2018]

Consider U(1)$_Y$ x U(1)$_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F'^{\mu\nu}_{Y}F'_{Y\mu\nu} - \frac{1}{4}F'^{\mu\nu}_{H}F'_{H\mu\nu} - \frac{\chi}{2}F'^{\mu\nu}_{Y}F'_{H\mu\nu}$$

$$F'^{\mu\nu}_{i} \equiv \partial^{\mu}A'^{\nu}_{i} - \partial^{\nu}A'^{\mu}_{i} \;\; (i = Y, H)$$

By the field redefinitions, we can go to the canonical basis

$$A^{\mu\,\prime}_{Y} = \frac{A^{\mu}_{Y}}{\sqrt{1-\chi^2}}$$

$$A^{\mu\,\prime}_{H} = A^{\mu}_{H} - \frac{\chi}{\sqrt{1-\chi^2}}A^{\mu}_{Y}$$

⇓

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}_{Y}F_{Y\mu\nu} - \frac{1}{4}F^{\mu\nu}_{H}F_{H\mu\nu}$$

Consider $U(1)_Y \times U(1)_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F'^{\mu\nu}_{Y}F'_{Y\mu\nu} - \frac{1}{4}F'^{\mu\nu}_{H}F'_{H\mu\nu} - \frac{\chi}{2}F'^{\mu\nu}_{Y}F'_{H\mu\nu}$$

$$F'^{\mu\nu}_{i} \equiv \partial^\mu A'^{\nu}_{i} - \partial^\nu A'^{\mu}_{i} \;\; (i = Y, H)$$

Let's consider a matter field charged under $U(1)_Y/U(1)_H$

$$\begin{aligned}
& \bar{\Psi}_i\gamma_\mu(g'_Y Q_i A'^{\mu}_{Y} + g'_H q_{H\,i} A'^{\mu}_{H})\Psi_i \\
= \;& \bar{\Psi}_i\gamma_\mu\left(\frac{g'_Y}{\sqrt{1-\chi^2}}Q_i A^\mu_Y - \frac{q_{H\,i}g_H\chi}{\sqrt{1-\chi^2}}A^\mu_Y + g_H q_{H\,i}A^\mu_H\right)\Psi_i \\
= \;& \bar{\Psi}_i\gamma_\mu\left[g_Y\left(Q_i - \frac{g_H q_{H\,i}}{g_Y}\frac{\chi}{\sqrt{1-\chi^2}}\right)A^\mu_Y + g_H q_{H\,i}A^\mu_H\right]\Psi_i
\end{aligned}$$

Consider $U(1)_Y \times U(1)_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4}F_Y'^{\mu\nu}F'_{Y\mu\nu} - \frac{1}{4}F_H'^{\mu\nu}F'_{H\mu\nu} - \frac{\chi}{2}F_Y'^{\mu\nu}F'_{H\mu\nu}$$

$$F_i'^{\mu\nu} \equiv \partial^\mu A_i'^\nu - \partial^\nu A_i'^\mu \quad (i = Y, H)$$

Let's consider a matter field charged under $U(1)_Y/U(1)_H$

$$\begin{aligned}
&\bar{\Psi}_i\gamma_\mu(g'_Y Q_i A'^\mu_Y + g'_H q_{H i} A'^\mu_H)\Psi_i \\
=\;& \bar{\Psi}_i\gamma_\mu\left(\frac{g'_Y}{\sqrt{1-\chi^2}}Q_i A^\mu_Y - \frac{q_{H i} g_H \chi}{\sqrt{1-\chi^2}}A^\mu_Y + g_H q_{H i} A^\mu_H\right)\Psi_i \\
=\;& \bar{\Psi}_i\gamma_\mu\left[g_Y\left(Q_i - \frac{g_H q_{H i}}{g_Y}\frac{\chi}{\sqrt{1-\chi^2}}\right)A^\mu_Y + g_H q_{H i} A^\mu_H\right]\Psi_i
\end{aligned}$$

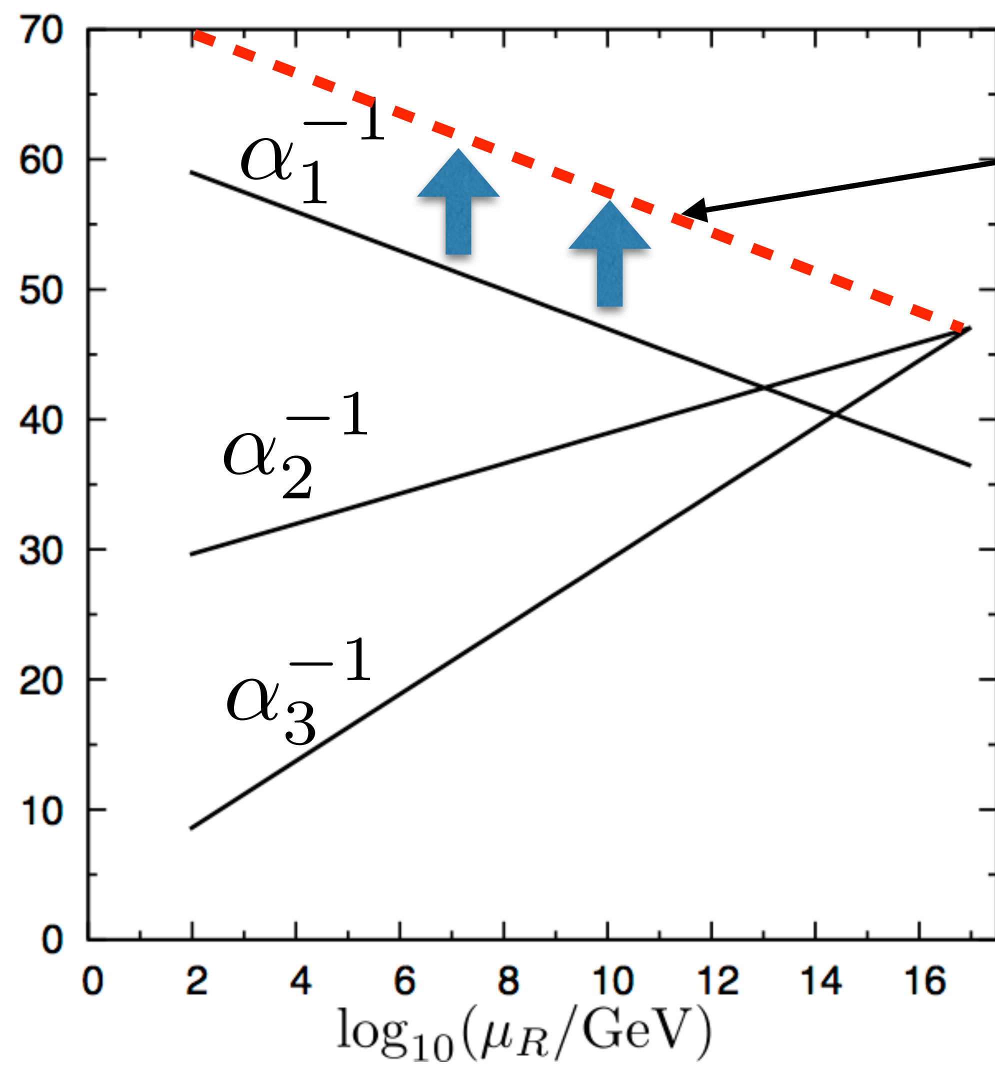
Fractional $U(1)_Y$ charge

The gauge couplings in the two basis are related as

$$g_Y = \frac{g'_Y}{\sqrt{1-\chi^2}}$$

$$g_H = g'_H$$

observed value



$$\alpha'^{-1}_1 = \frac{\alpha_1^{-1}}{1-\chi^2}$$

We may achieve the gauge coupling unification in the original basis

With SU(5) multiplets charged under U(1)H

$$-\mathcal{L} \supset M_V \sum_i^{N_b} \overline{\psi}^b_{5,i} \psi^b_{5,i}$$

bi-charged

$q_H(\psi^b_5) = -1$

one-loop RGEs are

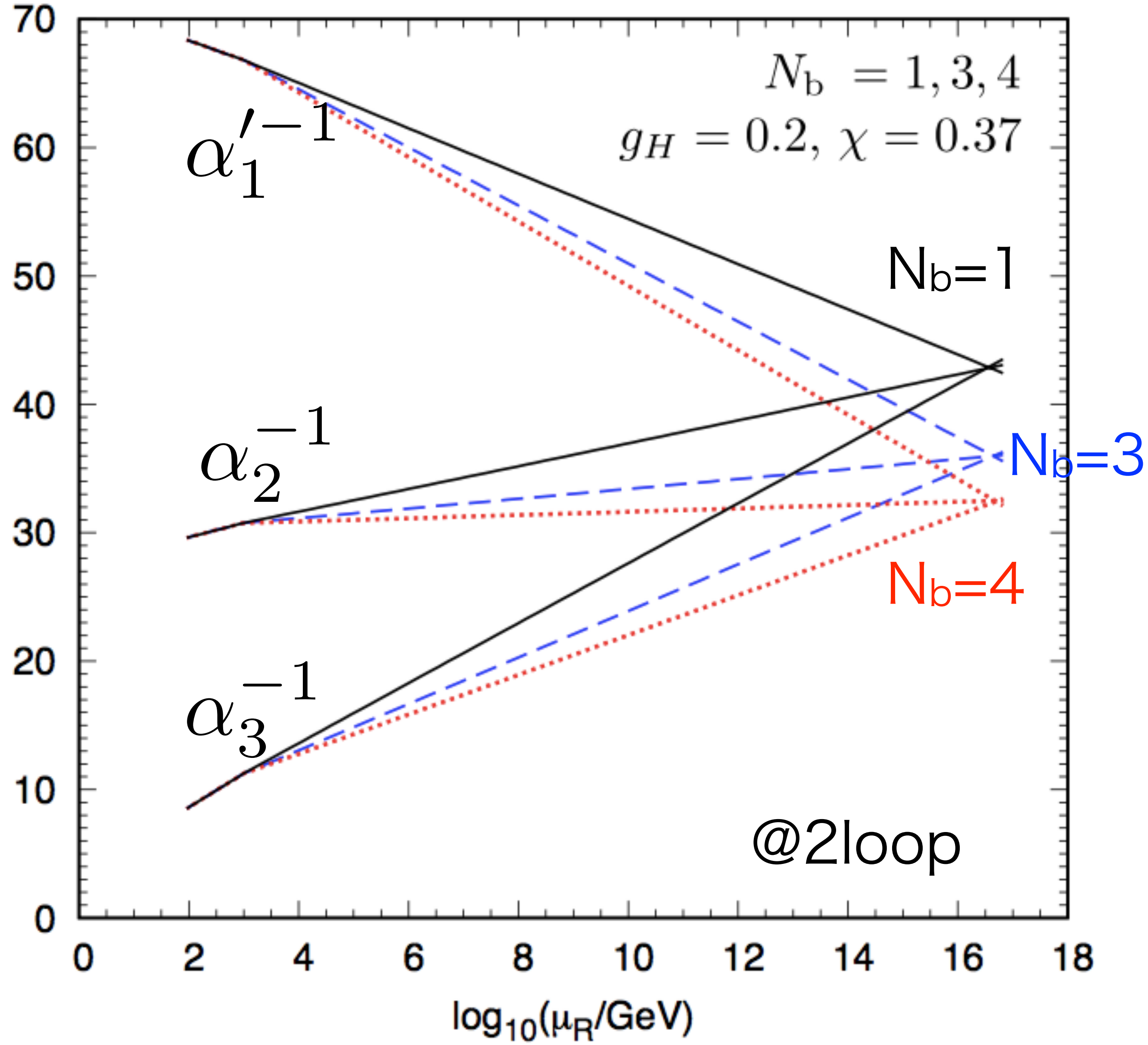
$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2}\left(\frac{41}{6} + \frac{10}{9}N_\mathrm{b}\right) g'^3_Y,$$

$$\frac{dg_2}{dt} = \frac{1}{16\pi^2}\left(-\frac{19}{6} + \frac{2}{3}N_\mathrm{b}\right) g^3_2,$$

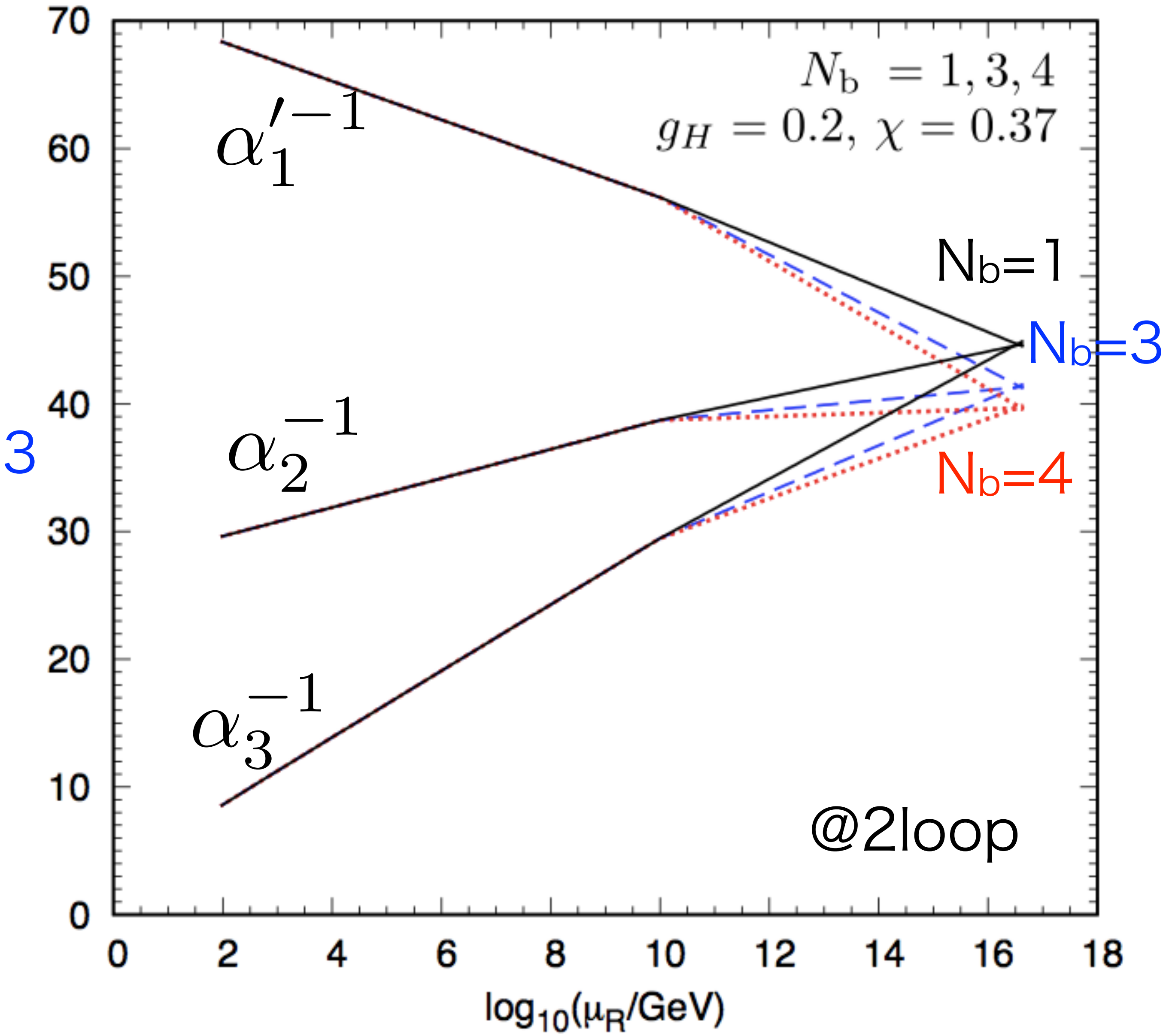
$$\frac{dg_3}{dt} = \frac{1}{16\pi^2}\left(-7 + \frac{2}{3}N_\mathrm{b}\right) g^3_3,$$

$$\frac{dg_H}{dt} = \frac{1}{16\pi^2}\left(\frac{20}{3}N_\mathrm{b}\right) g^3_H$$

and two-loop corrections…



$M_V = 1\,\mathrm{TeV}$



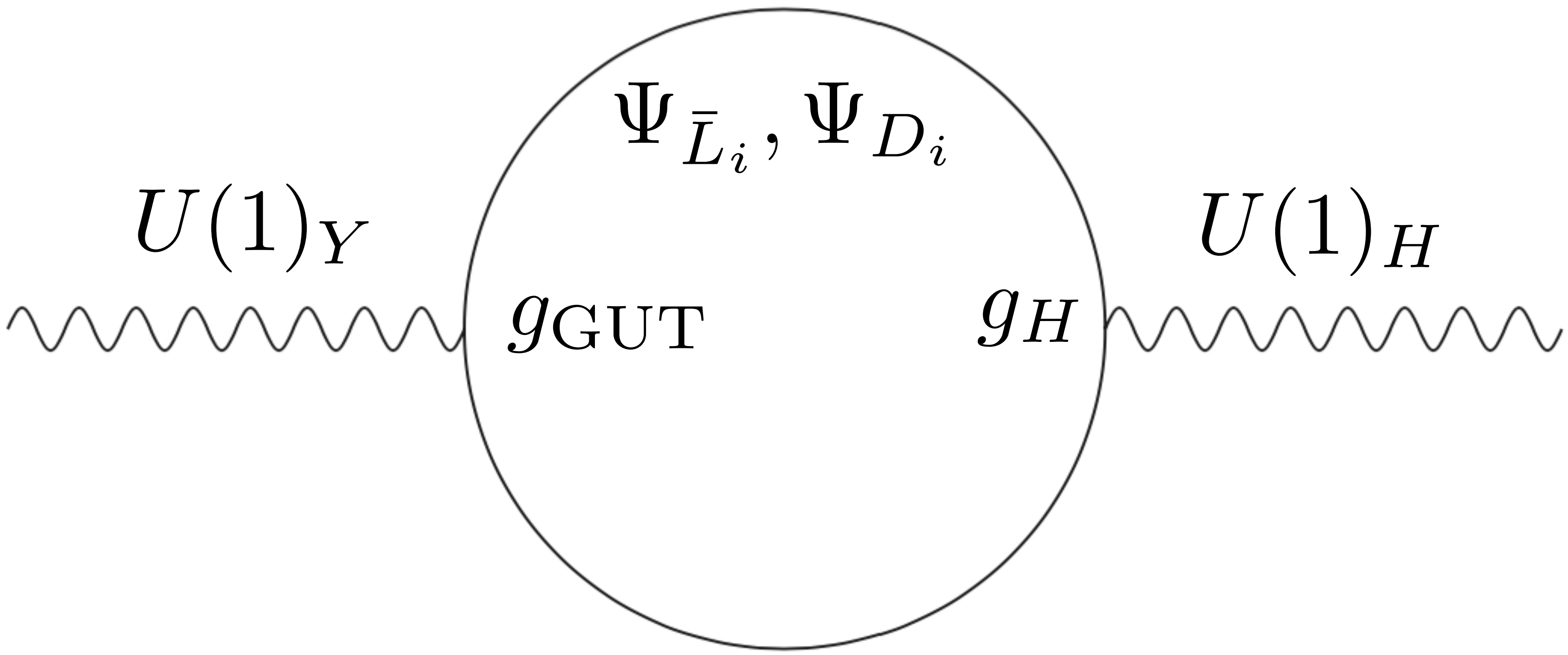
$M_V = 10^{10}\,\mathrm{GeV}$

Unification is solely determined by the kinetic mixing χ (m_Z) and rather robust against varying N_b, g_H and M_V

(This GUT scheme is insensitive to the physics at the intermediate scale)

Generation of large χ

Around the GUT scale



With the GUT breaking mass induced by Σ_{24}:

$$\chi(M_{\rm GUT}) \sim 0.12 N_f \left(\frac{g_{\rm GUT}}{0.53}\right) \times \left[\frac{g_H(M_{\rm GUT})}{4\pi}\right]\left[\frac{\ln(M_D/M_L)}{\ln 4}\right]$$

large g_H is required

Enhanced Axion-Photon Coupling

We can couple the bi-charged field to the axion without spoiling gauge coupling unification

$$\mathcal{L} \supset -\left[\sqrt{2}\phi\overline{\psi}^{\rm b}_{5L}\psi^{\rm b}_{5R} + h.c.\right]$$

PQ breaking field including axion

bi-charged $q_H(\psi_5^b) = -1$

We take the largest possible g_H avoiding the Landau Pole

The kinetic mixing is taken as $\chi(m_Z) = 0.365$ required for GUT

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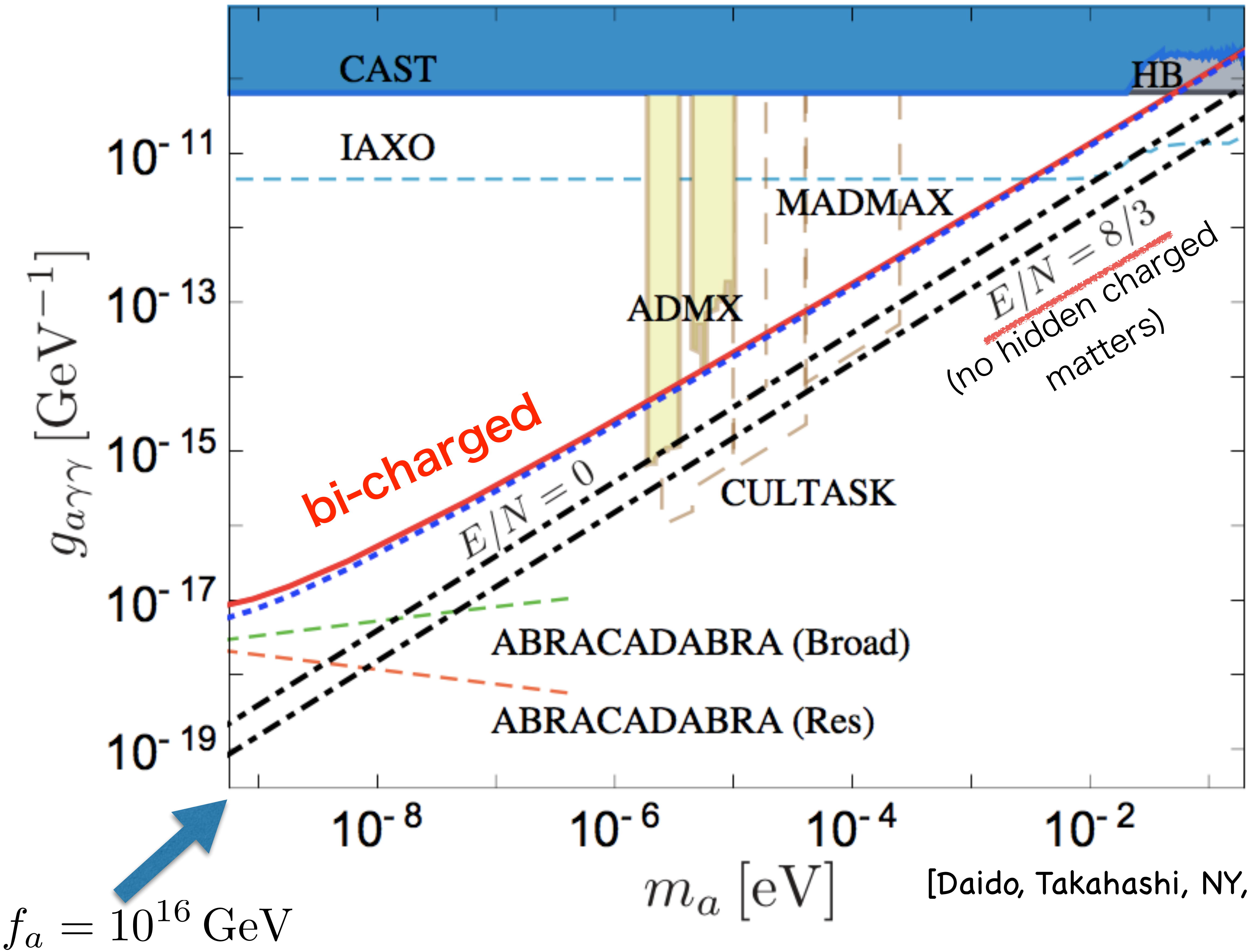
PQ breaking field including axion

bi-charged $q_H(\psi_5^b) = -1$

Effective electric charge becomes large:

$$\delta Q_e = \frac{g_H}{g_Y}\frac{\chi}{\sqrt{1-\chi^2}}$$

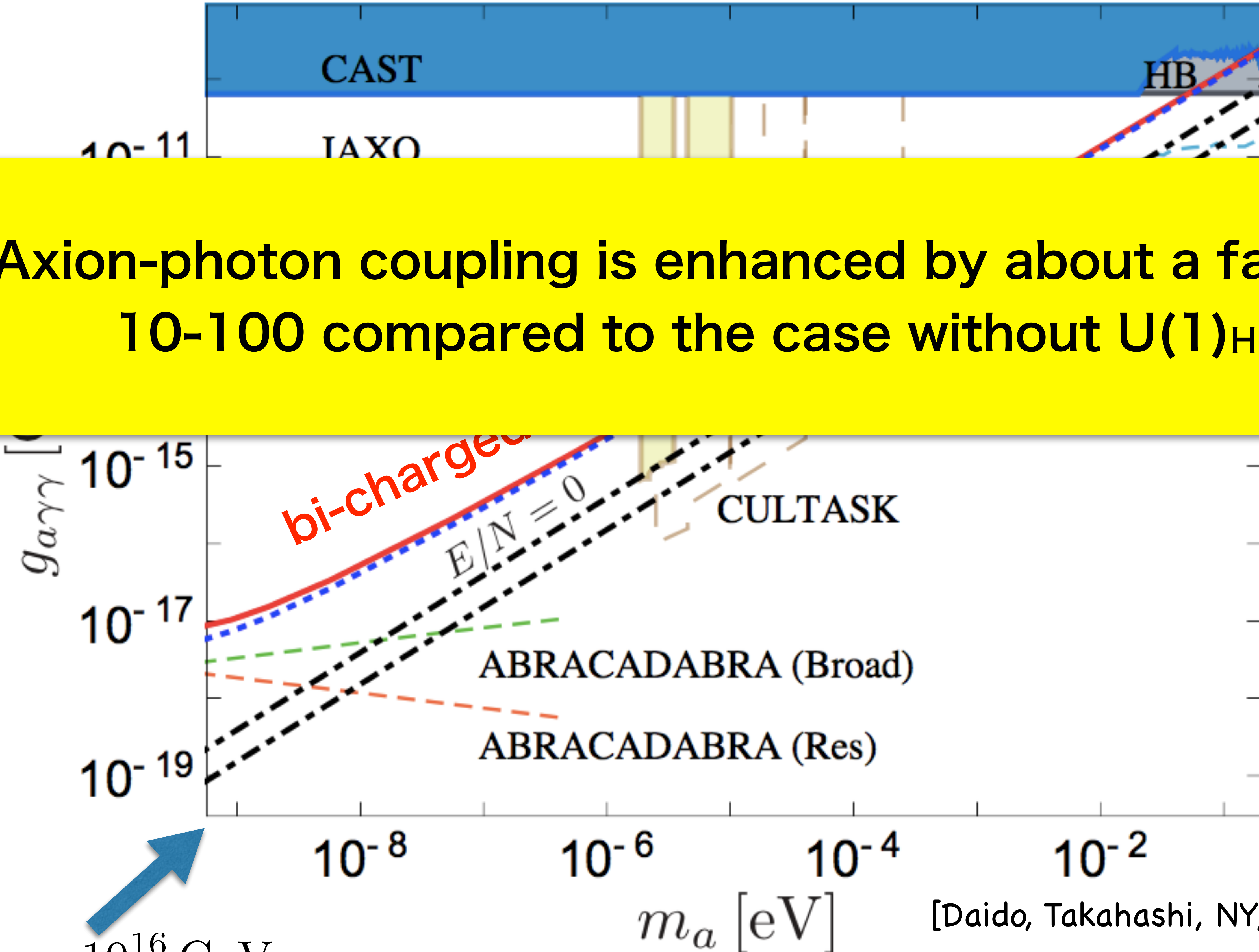
This charge makes the axion-photon coupling very large



[Daido, Takahashi, NY, 2018]

$$m_a \simeq 6 \times 10^{-6}\text{eV}\left(\frac{f_a}{10^{12}\text{GeV}}\right)$$

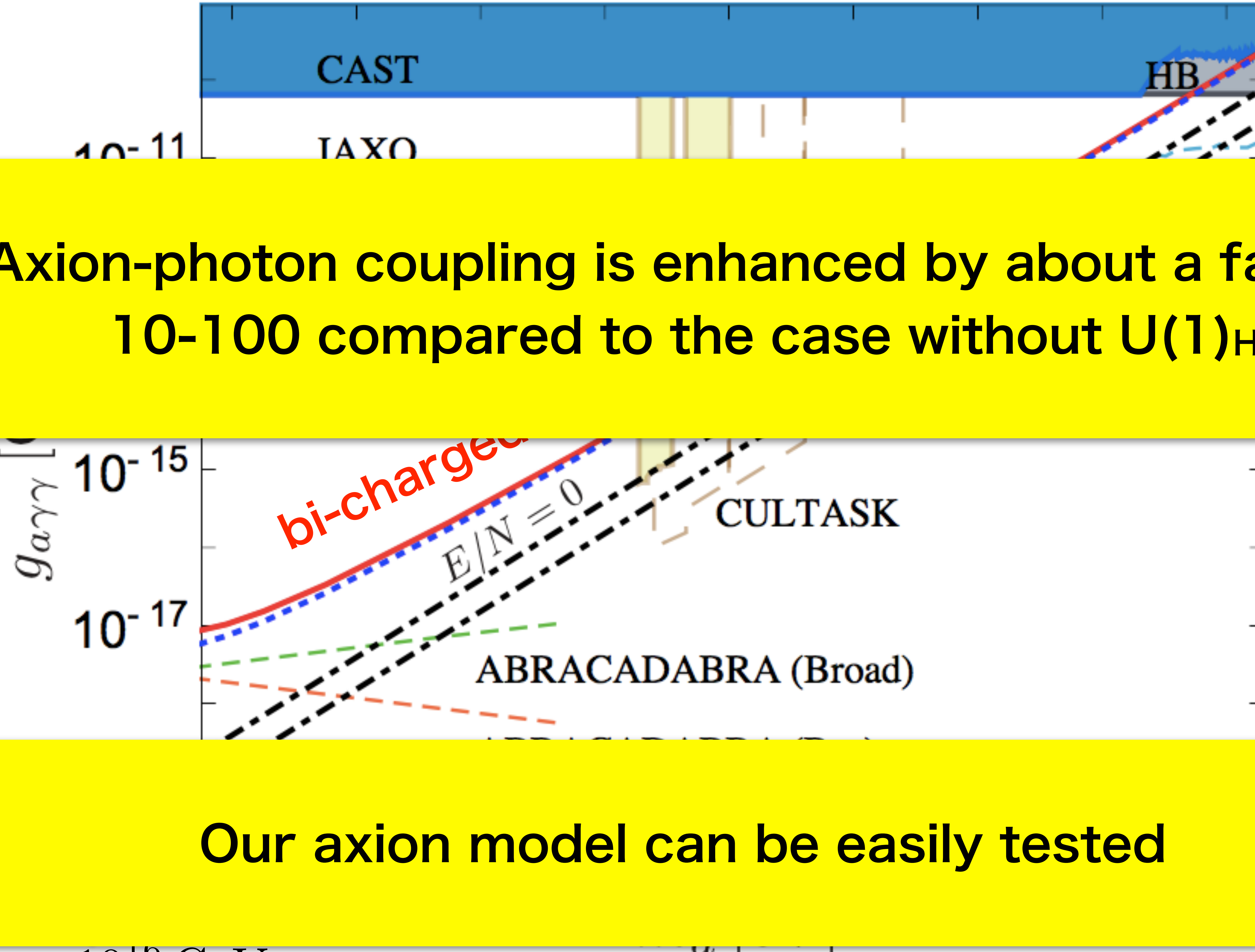
Axion-photon coupling is enhanced by about a factor 10-100 compared to the case without $U(1)_H$



[Daido, Takahashi, NY, 2018]

$f_a = 10^{16}$ GeV

$$m_a \simeq 6 \times 10^{-6}\mathrm{eV}\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)$$



Axion-photon coupling is enhanced by about a factor 10-100 compared to the case without $U(1)_H$

Our axion model can be easily tested

$f_a = 10^{16}$ GeV

$$m_a \simeq 6 \times 10^{-6}\mathrm{eV} \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)$$

Summary

- Massless hidden photon can achieve the gauge coupling unification
- The unification is rather robust, allowing the existence of matter fields charged under $SU(5)/U(1)_H$
- No rapid proton decay problem
- If the QCD axion is accommodated, axion-photon coupling is significantly enhanced (by about a factor 10-100)
- With the enhancement, the QCD axion is more easily tested in future experiments