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Enhanced Axion-Photon Coupling in GUT with Hidden Photon

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Fuminobu Takahashi, Masaki Yamada, **N.Y.** arXiv:1604.07145, PLB

Ryuji Daido, Fuminobu Takahashi, **N.Y.** arXiv:1610.00631, PLB

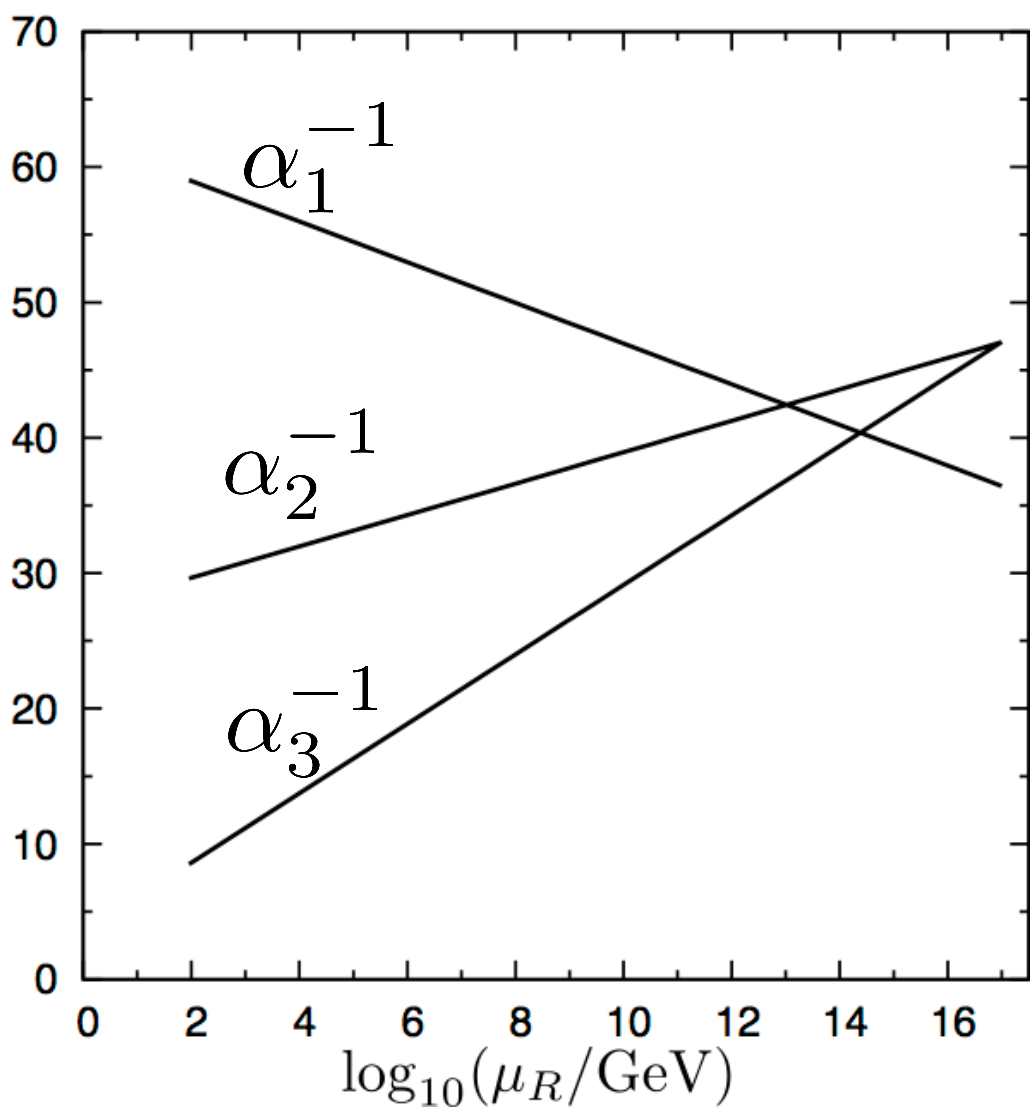
Ryuji Daido, Fuminobu Takahashi, **N.Y.** arXiv:1801.10344

Motivations to go beyond the SM

- Dark matter
- Strong CP problem

} Solved by QCD axion

Unification of SM gauge couplings and charge quantization



The figure shows the RG running of the SM gauge couplings

In SM, the unification fails

Motivations to go beyond the SM

- Dark matter
- Strong CP problem

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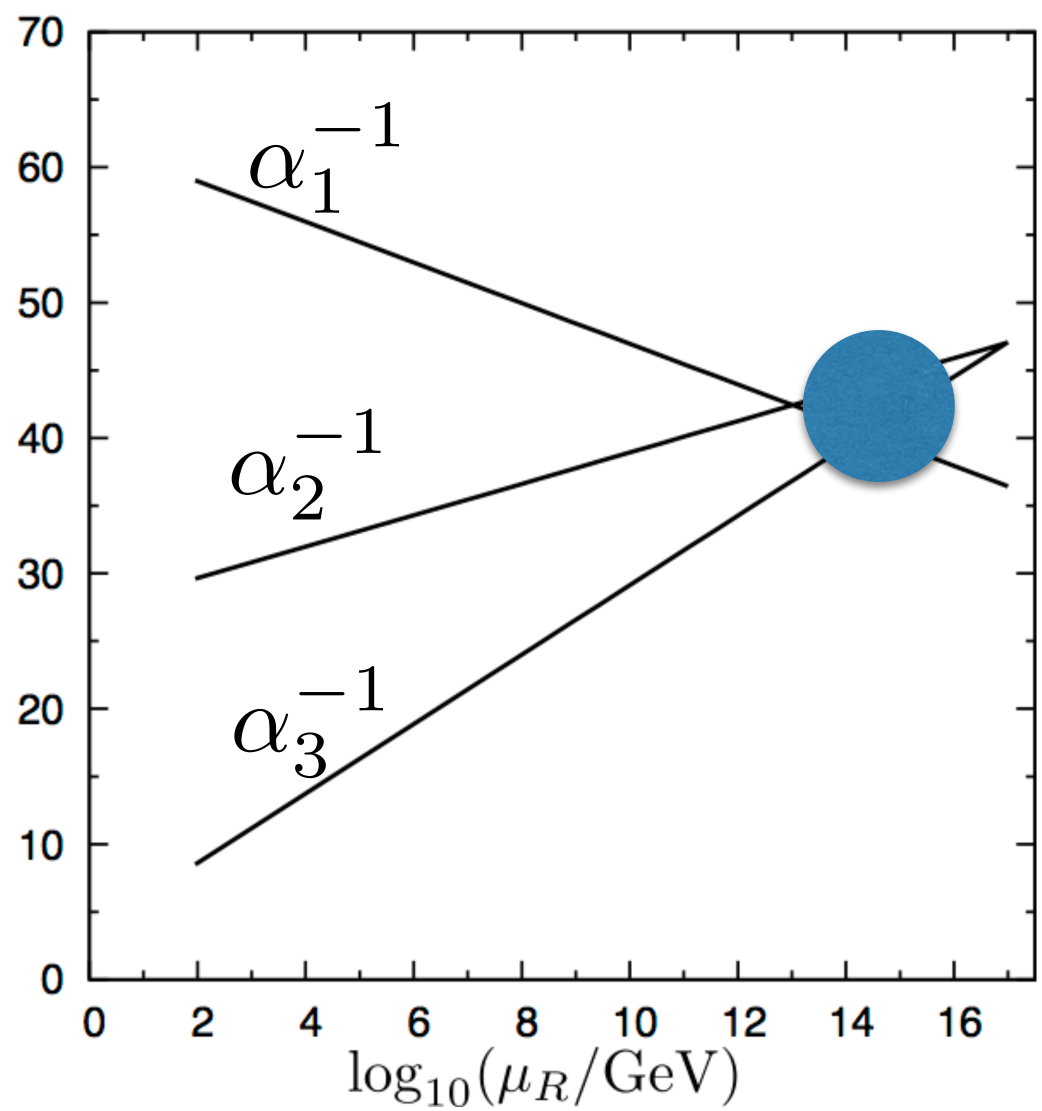
Unification of SM gauge couplings and charge quantization



Moreover, it predicts too rapid proton decay

For Mx=10^{15}GeV

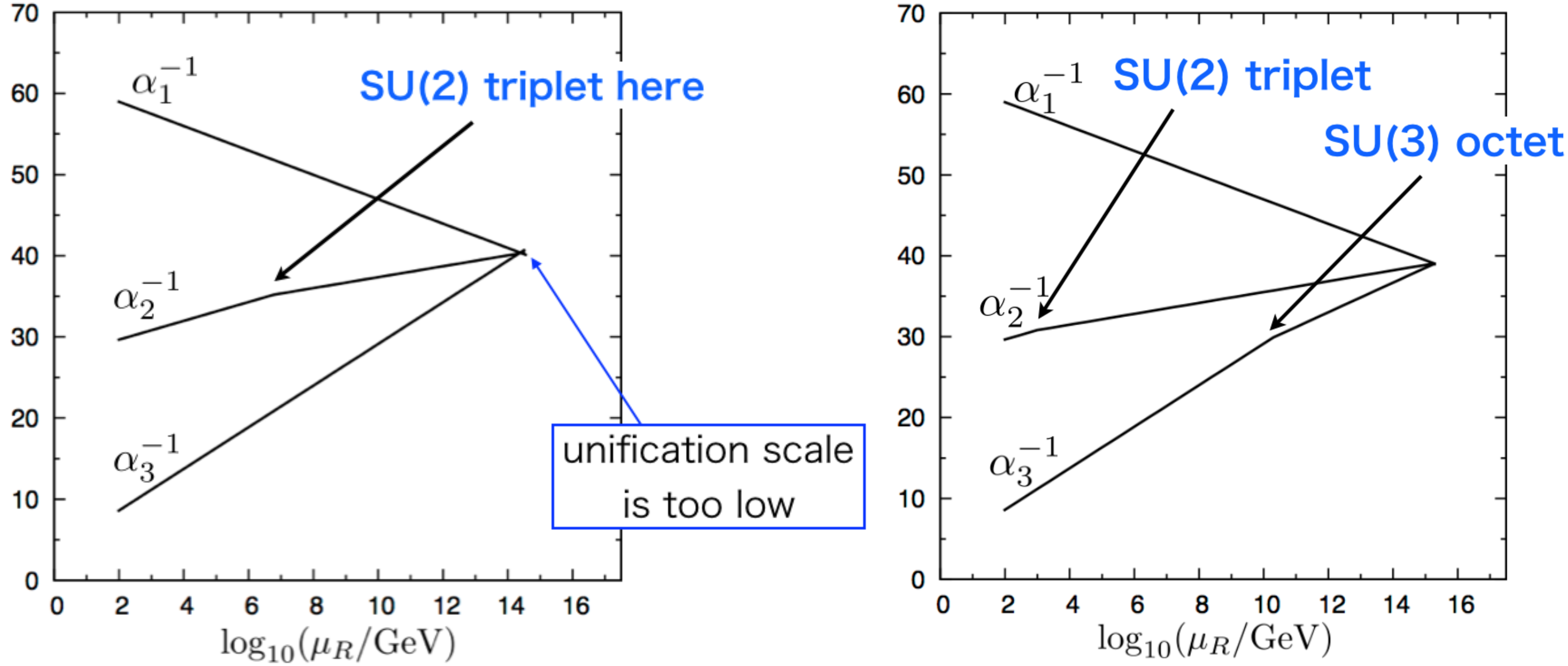
≒5×10^{31} years ($p \to \pi^0 e^+$)

exp: > 1.7 x 10^{34} years

[Takhistov, 2016]

Possible ways for unification

- Adding incomplete SU(5) multiplets



- Supersymmetry

- Unbroken hidden $U(1)_H$ symmetry, which mixies with $U(1)_Y$

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

A model with a hidden photon ($U(1)_H$ gauge boson)

unbroken

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

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

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

[Holdom, 1986]

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

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

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

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

$$\begin{aligned} A^{\mu\,\prime}_{Y} &= \frac{A^\mu_Y}{\sqrt{1-\chi^2}} \\ A^{\mu\,\prime}_{H} &= A^\mu_H - \frac{\chi}{\sqrt{1-\chi^2}} A^\mu_Y \end{aligned}$$

$$\Downarrow$$

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

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

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

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

Let's consider a matter field charged only under **$U(1)_H$**

$$\begin{aligned} & \bar{\Psi}_i \gamma_\mu (g'_H q_{H\,i} A'^\mu_H) \Psi_i \\ = \quad & \bar{\Psi}_i \gamma_\mu \left(-\frac{q_{H\,i} g_H \chi}{\sqrt{1-\chi^2}} A_Y^\mu + g_H q_{H\,i} A_H^\mu \right) \Psi_i \end{aligned}$$

The hidden matter obtains fractional $U(1)_Y$ charge in the canocnical basis

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

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

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

Let's consider a matter field charged only under **$U(1)_Y$**

$$\begin{aligned} & \bar{\Psi}_i\gamma_\mu(g'_Y Q_i A'^\mu_Y)\Psi_i \\ = \quad & \bar{\Psi}_i\gamma_\mu\left(\frac{g'_Y}{\sqrt{1-\chi^2}}Q_i A^\mu_Y\right)\Psi_i \\ = \quad & \bar{\Psi}_i\gamma_\mu\left(g_Y Q_i A^\mu_Y\right)\Psi_i \end{aligned}$$

The visible matter does not couple to $U(1)_H$

The normalization of $U(1)_Y$ coupling changes

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

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

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

The gauge couplings in the two basis are related as

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

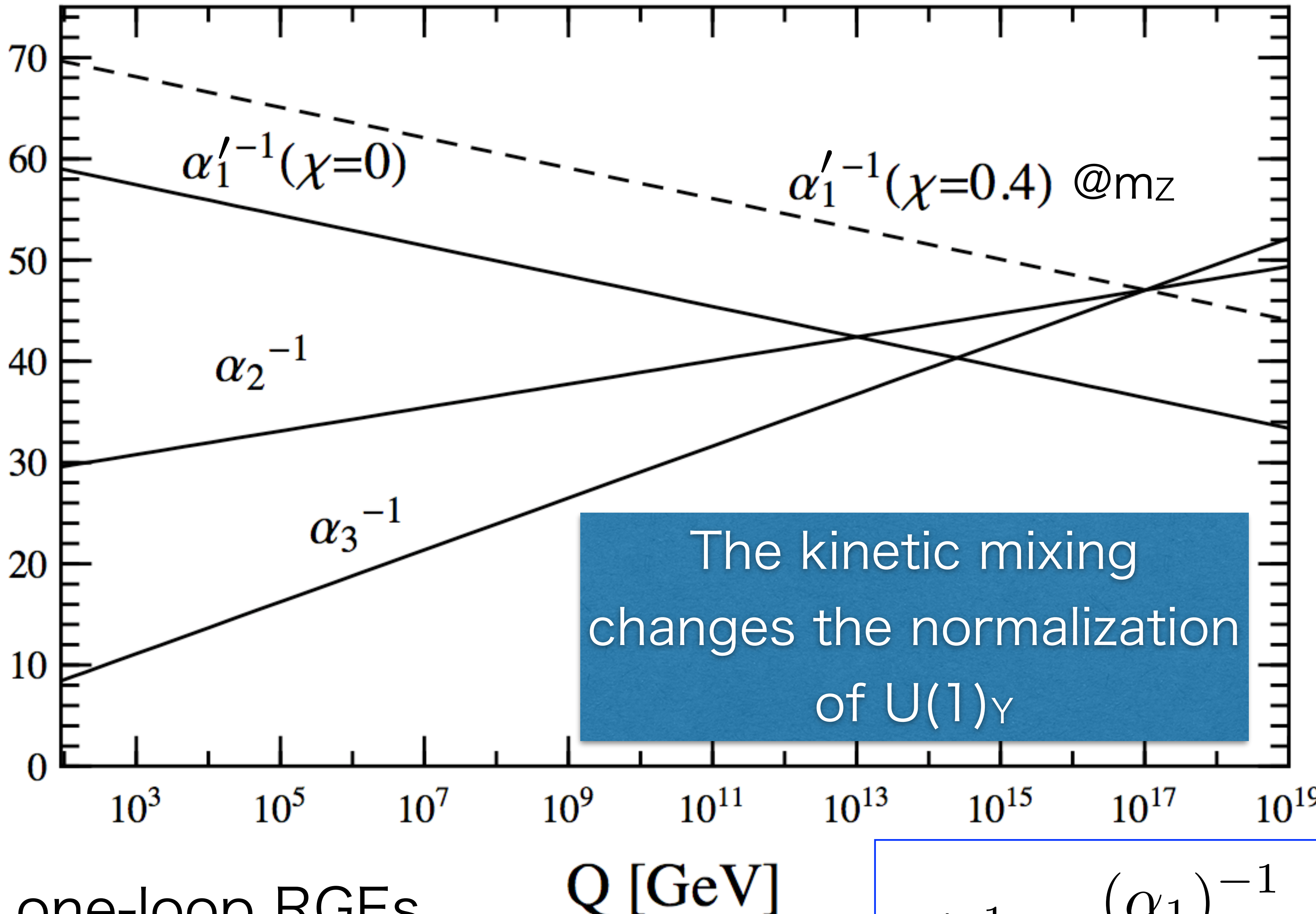
$$g_H = g'_H$$

observed value

couplings in the canonical basis

Grand unification with $U(1)_H$

Without matter fields



With one-loop RGEs

[J. Redondo, 2008]

$$\alpha_1'^{-1} = \frac{(\alpha_1)^{-1}_{\text{canonical}}}{(1-\chi^2)}$$

Case with a hidden matter which is a singlet of SU(5)

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

$$-M_0\bar{\Psi}_0\Psi_0$$

1TeV $\quad q_H(\Psi_0) = 1$

one-loop RGEs are

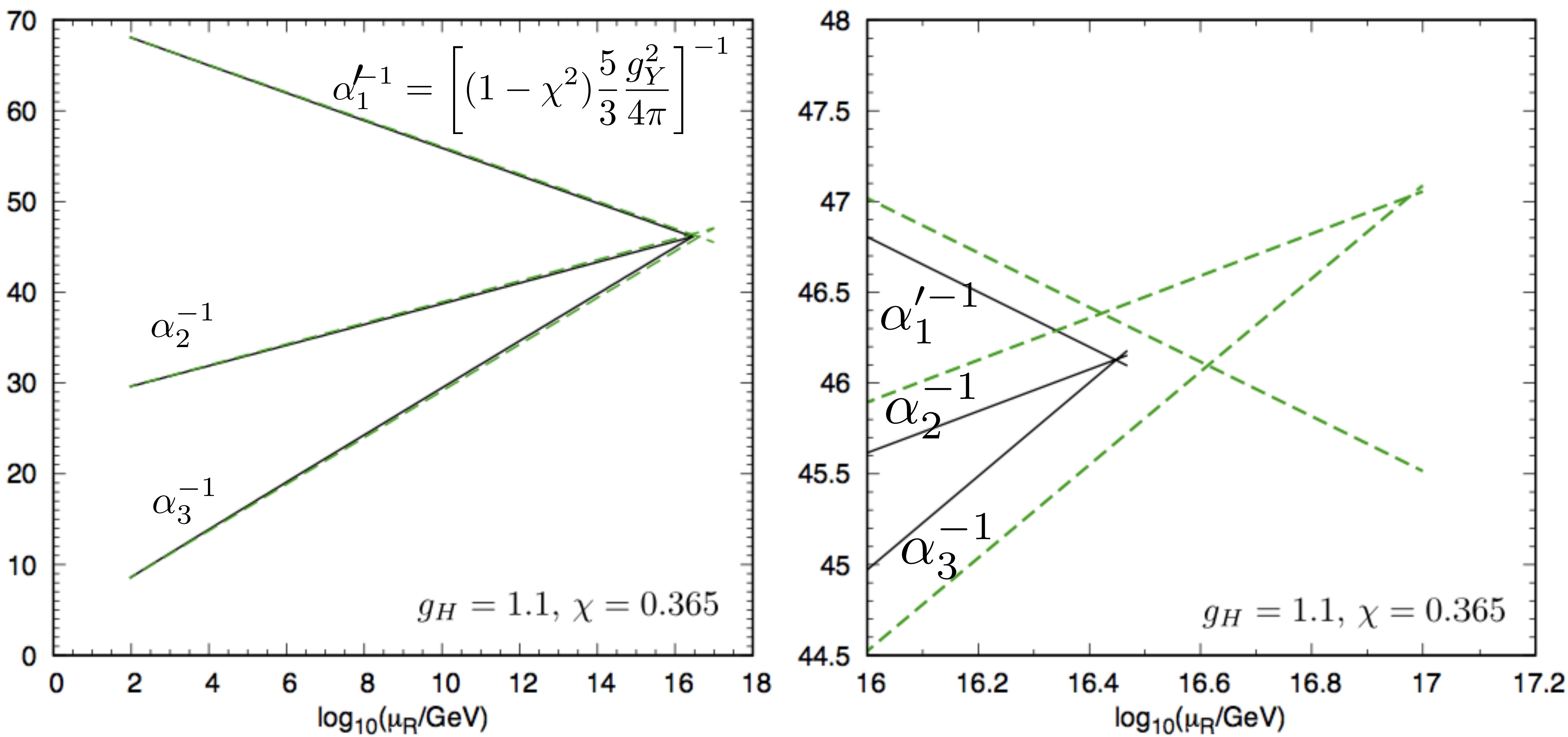
$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2}\left(\frac{41}{6}\right)g'^3_Y,$$

$$\frac{dg_2}{dt} = \frac{1}{16\pi^2}\left(-\frac{19}{6}\right)g_2^3,$$

$$\frac{dg_3}{dt} = \frac{1}{16\pi^2}(-7)\,g_3^3$$

$$\frac{dg_H}{dt} = \frac{1}{16\pi^2}\left(\frac{4}{3}\right)g_H^3$$

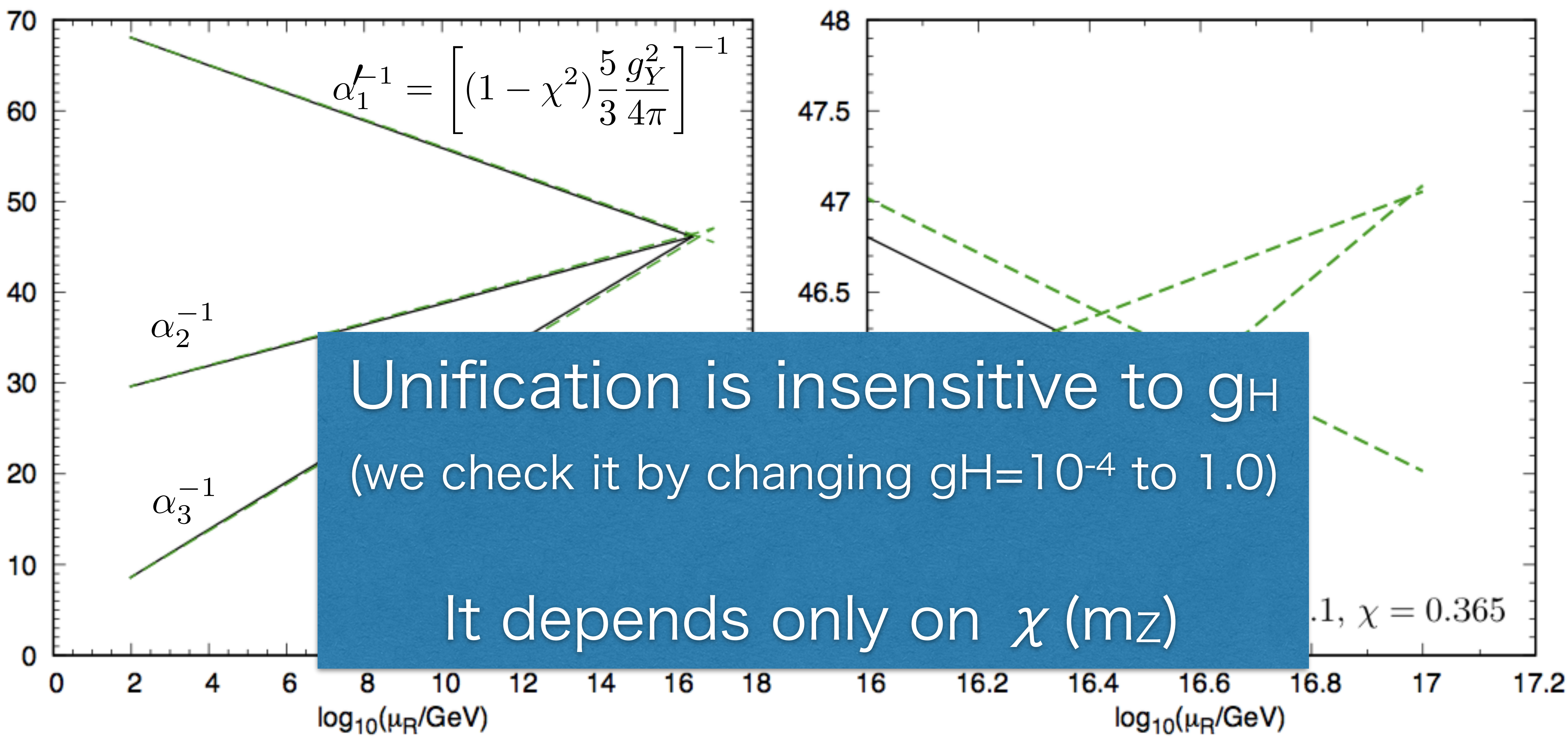
Running of the gauge couplings



green dashed: one-loop

black solid: two-loop

Running of the gauge couplings



Unification is insensitive to g_H

(we check it by changing $g_H=10^{-4}$ to 1.0)

It depends only on $\chi\,(m_Z)$

green dashed: one-loop

black solid: two-loop

With SU(5) multiplets charged under U(1)$_H$

$$\mathcal{L} = -M_V \sum_{i=1}^{N_b} (\bar{\Psi}_{L,i}\Psi_{L,i} + \bar{\Psi}_{\bar{D},i}\Psi_{\bar{D},i}),$$

$\Psi_{L,i}$ ($\Psi_{\bar{D},i}$) is **2** of SU(2)$_L$ ($\bar{\mathbf{3}}$ of SU(3)$_C$);

$(Q_{L,i}, q_{H\,L,i}) = (-1/2, 1)$ and $(Q_{\bar{D},i}, q_{H\,\bar{D},i}) = (1/3, 1)$.

one-loop RGEs are

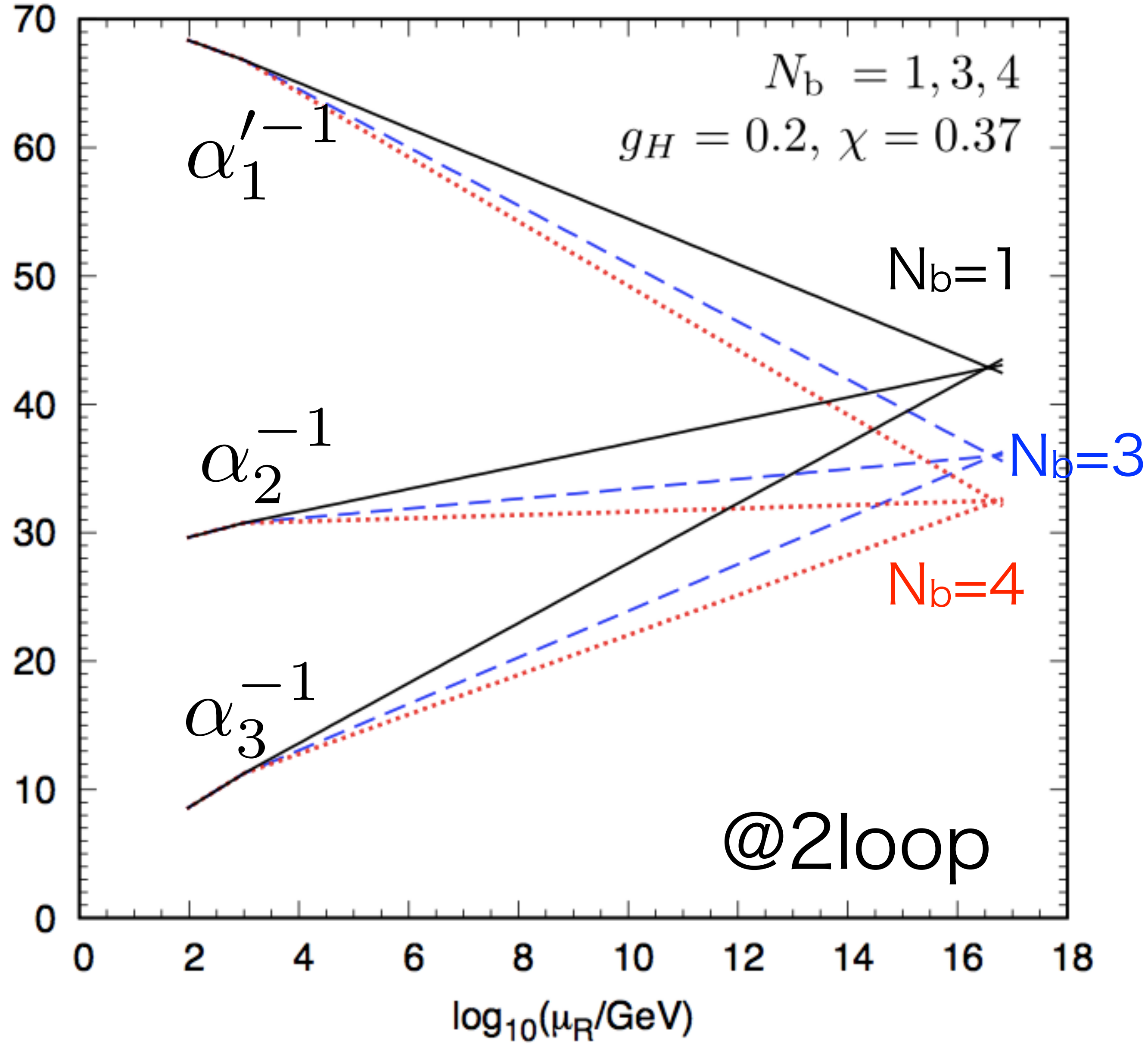
$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2}\left(\frac{41}{6} + \frac{10}{9}N_b\right) g'^3_Y,$$

$$\frac{dg_2}{dt} = \frac{1}{16\pi^2}\left(-\frac{19}{6} + \frac{2}{3}N_b\right) g_2^3,$$

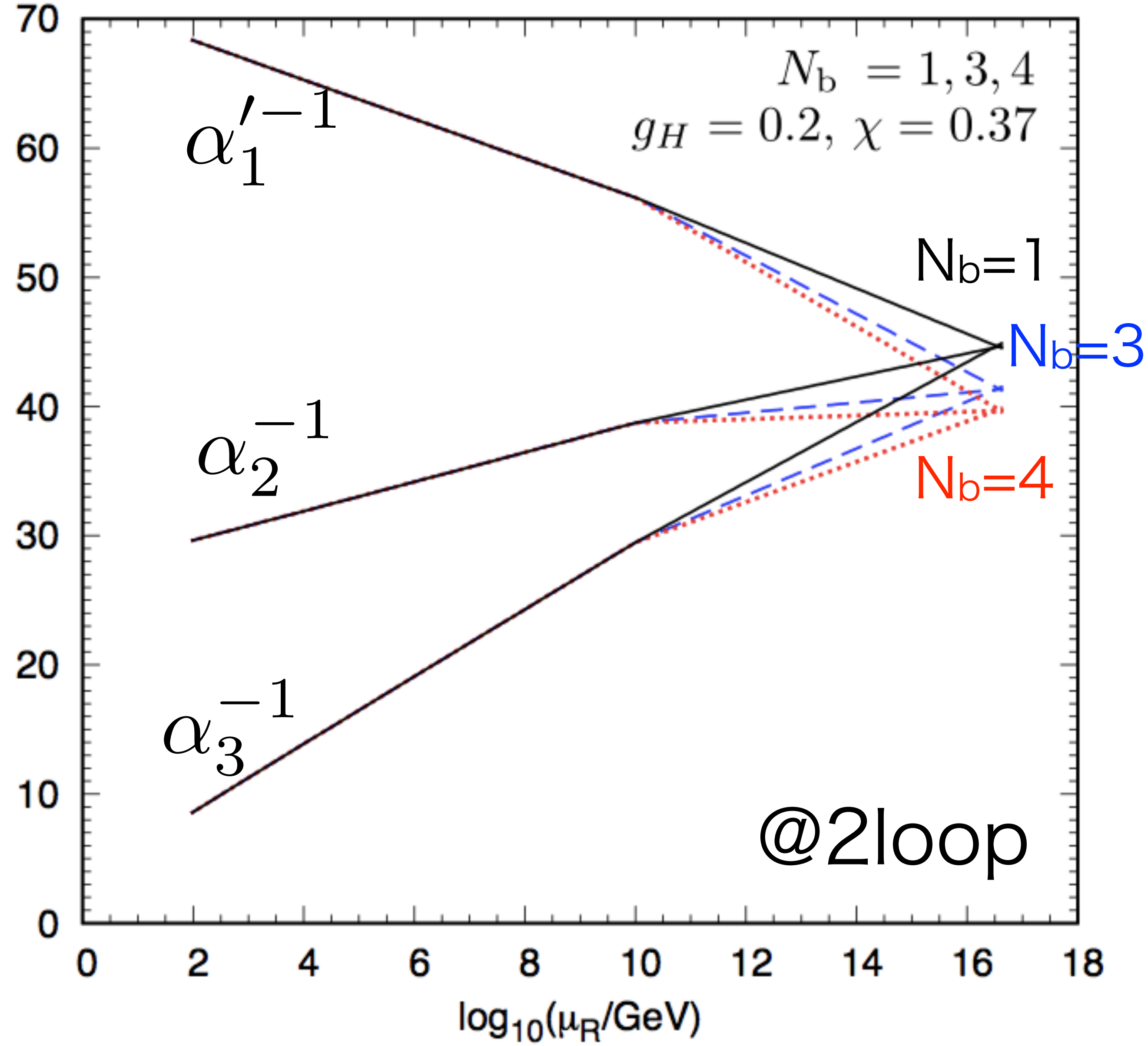
$$\frac{dg_3}{dt} = \frac{1}{16\pi^2}\left(-7 + \frac{2}{3}N_b\right) g_3^3,$$

$$\frac{dg_H}{dt} = \frac{1}{16\pi^2}\left(\frac{20}{3}N_b\right) g_H^3$$

and two-loop corrections…



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



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

(Almost) insensitive to N_b, g_H and M_V

Again, the unification depends only on $\chi\,(m_Z)$

A GUT axion model

Setup

$$\mathcal{L} \supset -\left[\sqrt{2}\phi(\overline{\psi}_{5L}\psi_{5R} + \overline{\psi}_{HL}\psi_{HR}) + h.c.\right]$$

PQ breaking field including axion

SU(5) complete multiplet

Hidden matter with charge of q_H

$$\phi = \frac{v_{PQ} + \rho(x)}{\sqrt{2}} \exp\left(i\frac{a(x)}{v_{PQ}}\right) \qquad f_a = \frac{v_{PQ}}{N_{DW}} = v_{PQ}$$

ϕ contains the axion in its phase component

A GUT axion model

Setup

$$\mathcal{L} \supset -\left[\sqrt{2}\phi(\overline{\psi}_{5L}\psi_{5R} + \overline{\psi}_{HL}\psi_{HR}) + h.c.\right]$$

PQ breaking field including axion

SU(5) complete multiplet

Hidden matter with charge of q_H

In the canonical basis, hidden matter gets an effective electric charge:

$$q_{\text{eff}} = -q_H \frac{\chi}{\sqrt{1-\chi^2}} \frac{g_H}{g_Y}$$

Then, axion-photon coupling gets an additional contribution from the hidden matter field through the electromagnetic anomaly

E/N

$$\mathcal{L} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{a\gamma\gamma} \simeq \frac{\alpha_{\mathrm{EM}}}{2\pi f_a} \left(\frac{8}{3} + \frac{2 q_H^2 g_H^2}{g_Y^2} \frac{\chi^2}{1-\chi^2} - 1.92 \right)$$

from SU(5) complete multiplet

For large g_H and χ, the enhancement is significant.

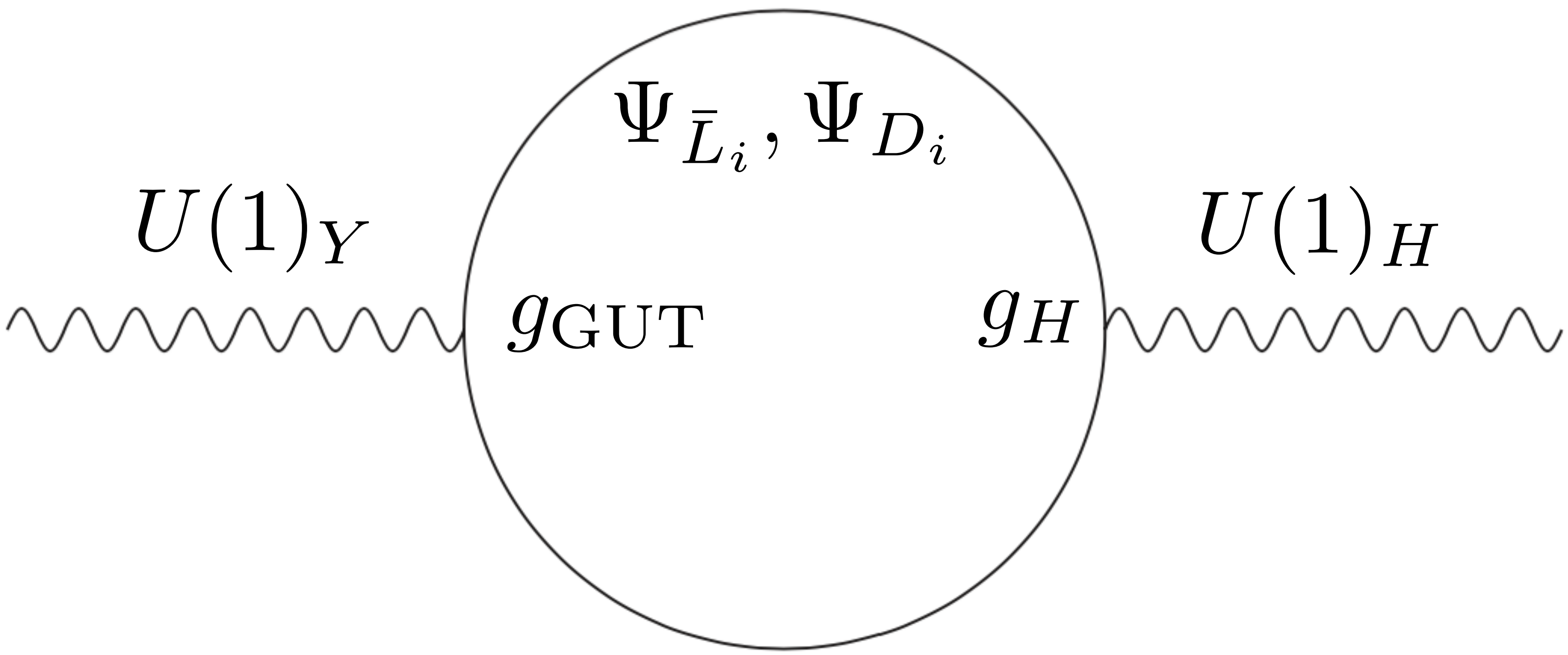
Large χ and g_H are required for consistency with GUT

Gauge coupling unification → $\chi(m_Z) \approx 0.37$

large χ of O(0.1) → large g_H

Generation of large χ

Around the GUT scale



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

$$\chi(M_{\mathrm{GUT}}) \approx 0.12 N_f \left(\frac{g_{\mathrm{GUT}}}{0.53}\right) \times \left[\frac{g_H(M_{\mathrm{GUT}})}{4\pi}\right] \left[\frac{\ln(M_{D'}/M_{L'})}{\ln 4}\right]$$

large g_H is required

Enhanced Axion-Photon Coupling

We take the possibly large g_H avoiding the Landau Pole

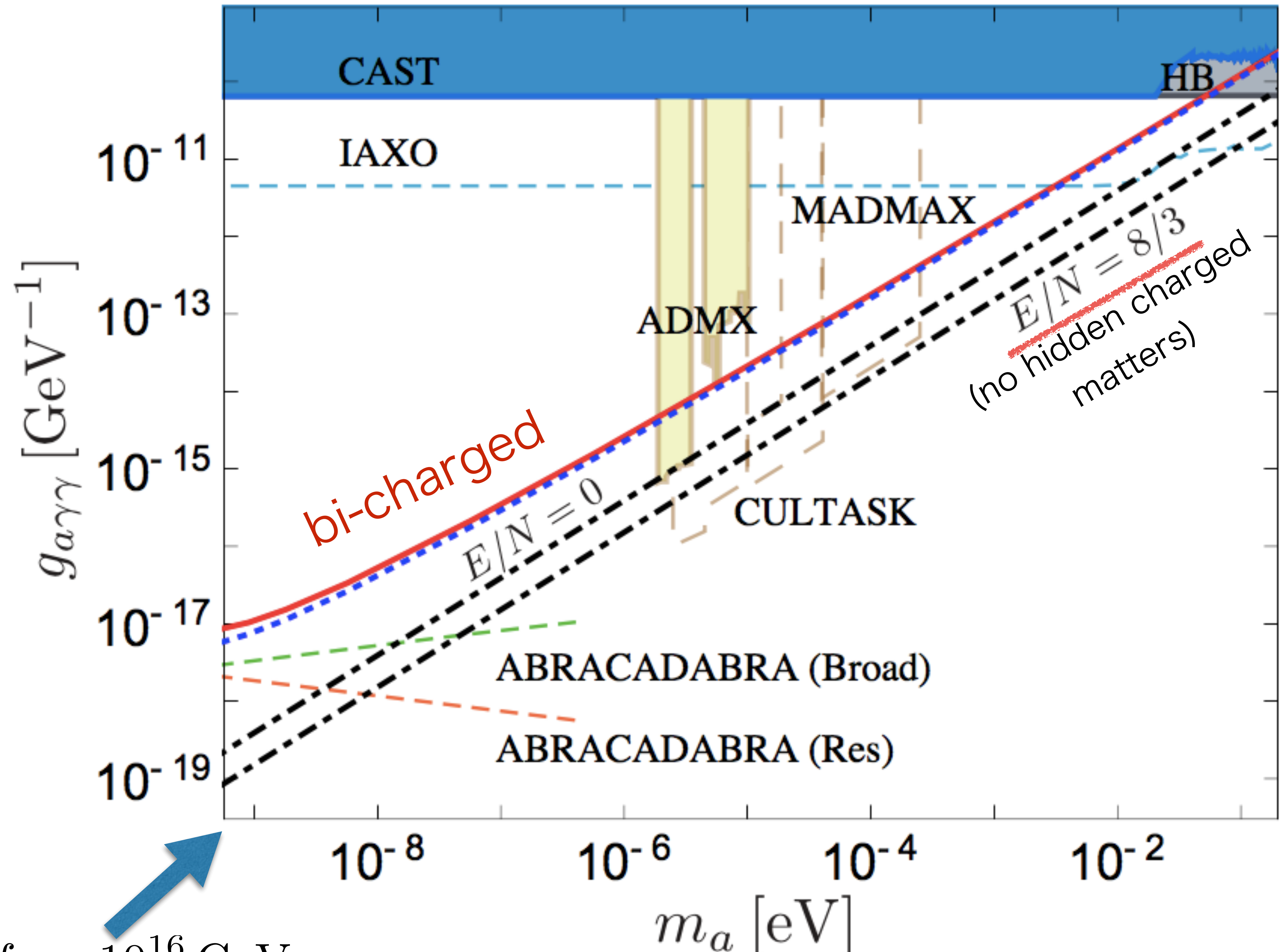
The kinetic mixing is taken as $\chi(m_Z) = 0.365$ required for GUT

$$\text{Case (i)} : \mathcal{L} \supset -\left[\sqrt{2}\phi(\overline{\psi}_{5L}\psi_{5R} + \overline{\psi}_{HL}\psi_{HR}) + h.c.\right],$$

$$\text{Case (ii)} : \mathcal{L} \supset -\left[\sqrt{2}\phi\overline{\psi}^{\mathrm{b}}_{5L}\psi^{\mathrm{b}}_{5R} + h.c.\right],$$

$U(1)_H$ charges are

$$q_H(\psi_H) = 1 \quad q_H(\psi_5) = 0 \quad q_H(\psi_5^b) = -1$$

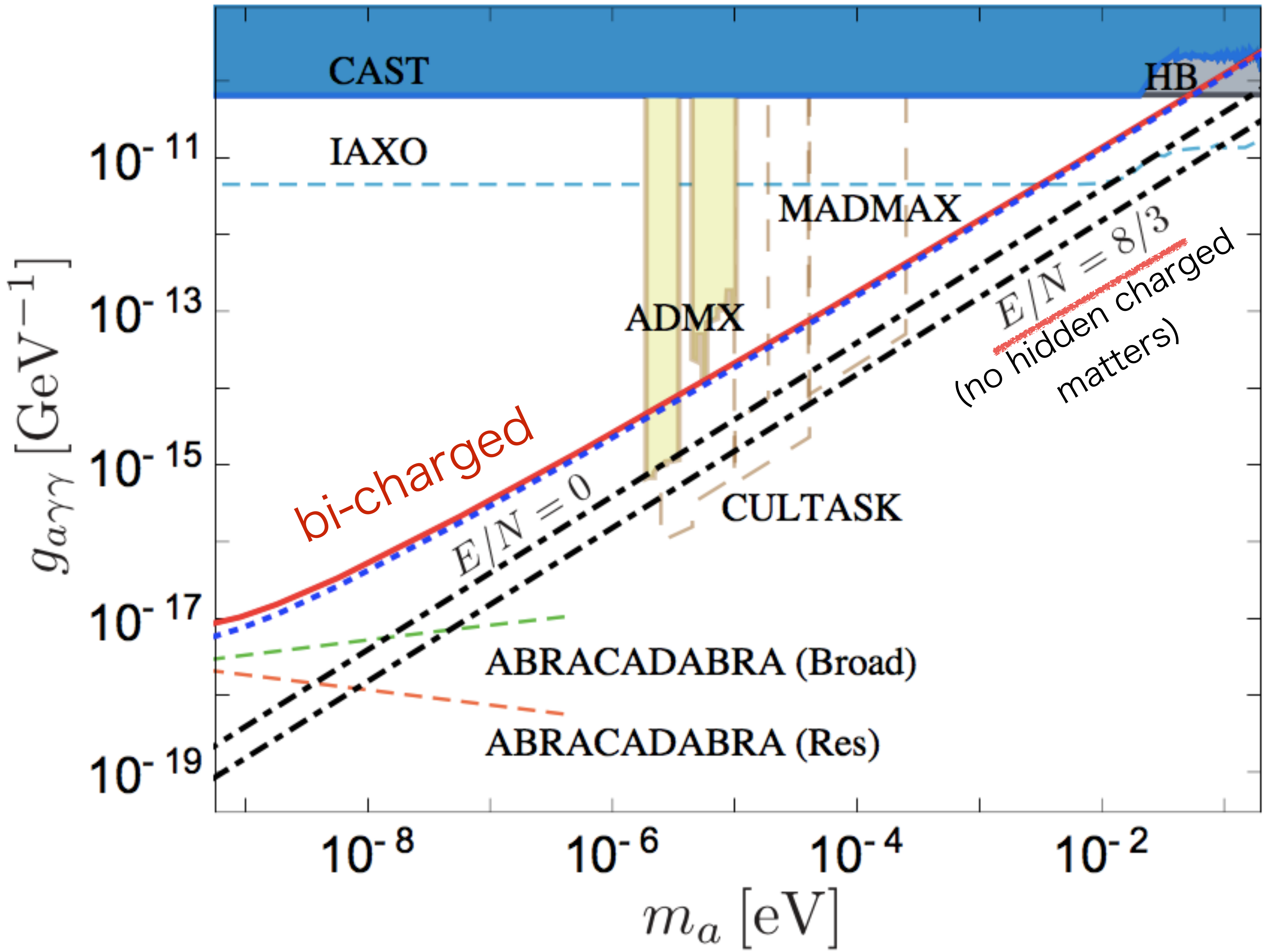


$f_a = 10^{16}$ GeV

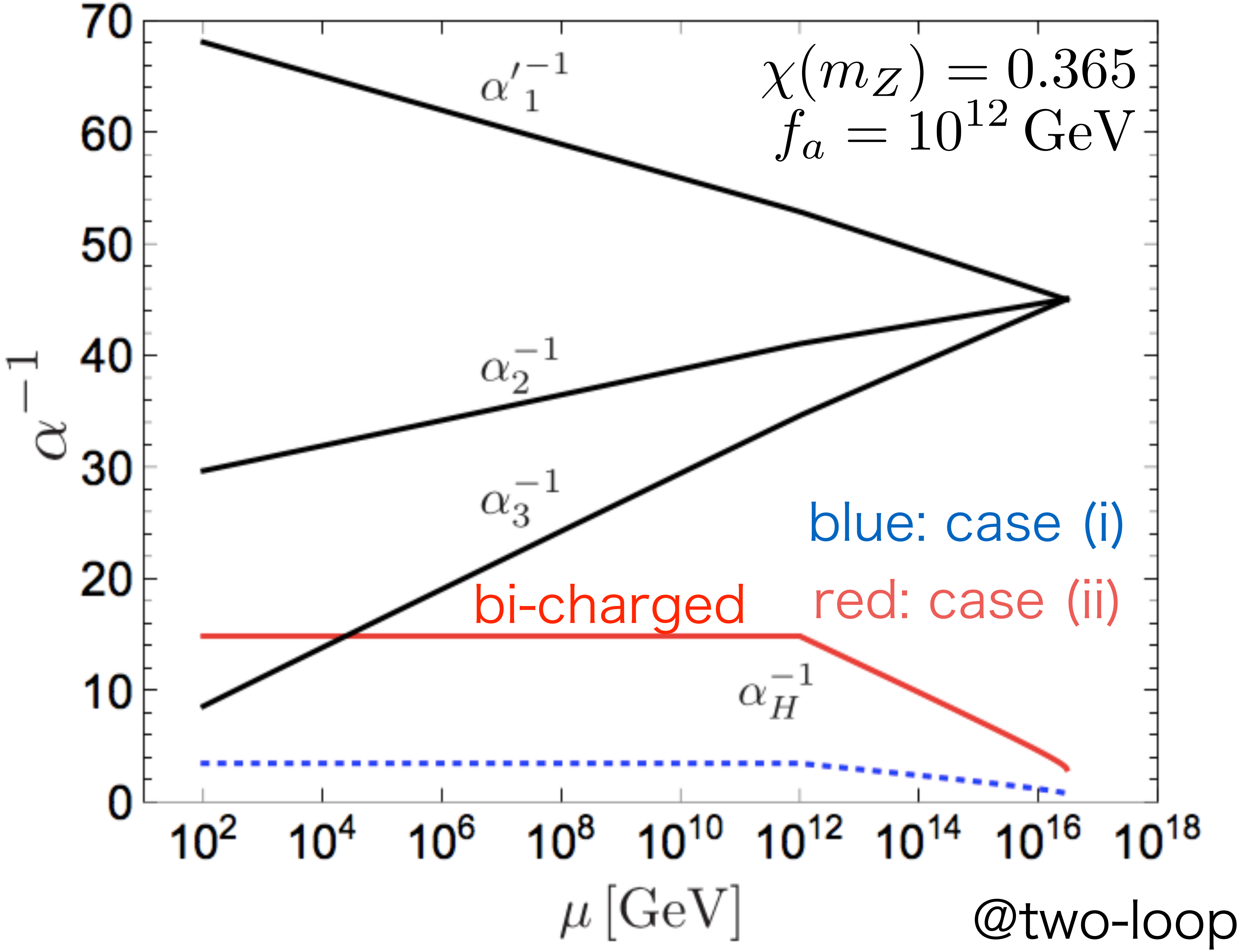
$$m_a = 5.70\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

blue: case (i)

red: case (ii)



Axion-photon coupling is enhanced by about a factor 10-100 for fa=10^{10}GeV-10^{16}GeV compared to the case without $U(1)_H$



Of course, the gauge coupling unification is maintained.

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

Thank you for your attention!

Once we have the hidden charged field

$$\bar{\Psi}\gamma_\mu(g'_Y Q_Y A'^\mu_Y + g_H q_H A'^\mu_H)\Psi = \bar{\Psi}\gamma_\mu(g_Y(\underline{Q_Y + \delta Q_Y})A^\mu_Y + g_H q_H A^\mu_H)\Psi$$

(original basis)

(canonical basis)

This basis is not ready to be embedded into SU(5)

(There is a fractional charge)

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

$$\frac{1}{2\sqrt{15}}\begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

The basis of the unification becomes manifest

Does the hidden charged field affect the unification?

However, without a hidden charged field, unification basis is not fixed

$$\bar{\Psi}\gamma_\mu(g'_Y Q_Y A'^{\mu}_Y)\Psi = \bar{\Psi}\gamma_\mu(g_Y Q_Y A^\mu_Y)\Psi$$

(original basis)

(canonical basis)

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

$$A^{\mu\,\prime}_H = A^\mu_H - \frac{\chi}{\sqrt{1-\chi^2}}A^\mu_Y$$

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

$$\frac{1}{2\sqrt{15}}\begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

A generator of SU(5)