3/8@PPAP2018

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

Outline

- Motivations to go beyond the SM
- Unbroken $U(1)_H$ mixing with $U(1)_Y$
- Grand unification with $U(1)_H$
- Enhanced axion-photon coupling in GUT axion models with $U(1)_H$

Motivations to go beyond the SM

- Strong CP problem
- Dark matter

Unification of SM gauge couplings and matter fields, and charge quantization

Strong CP problem

In QCD, θ-term breaks P and CP symmetry

$$\mathcal{L} \supset \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$G^a_{\mu\nu}$: gluon field strength $\tilde{G}^{a\mu\nu}$: dual

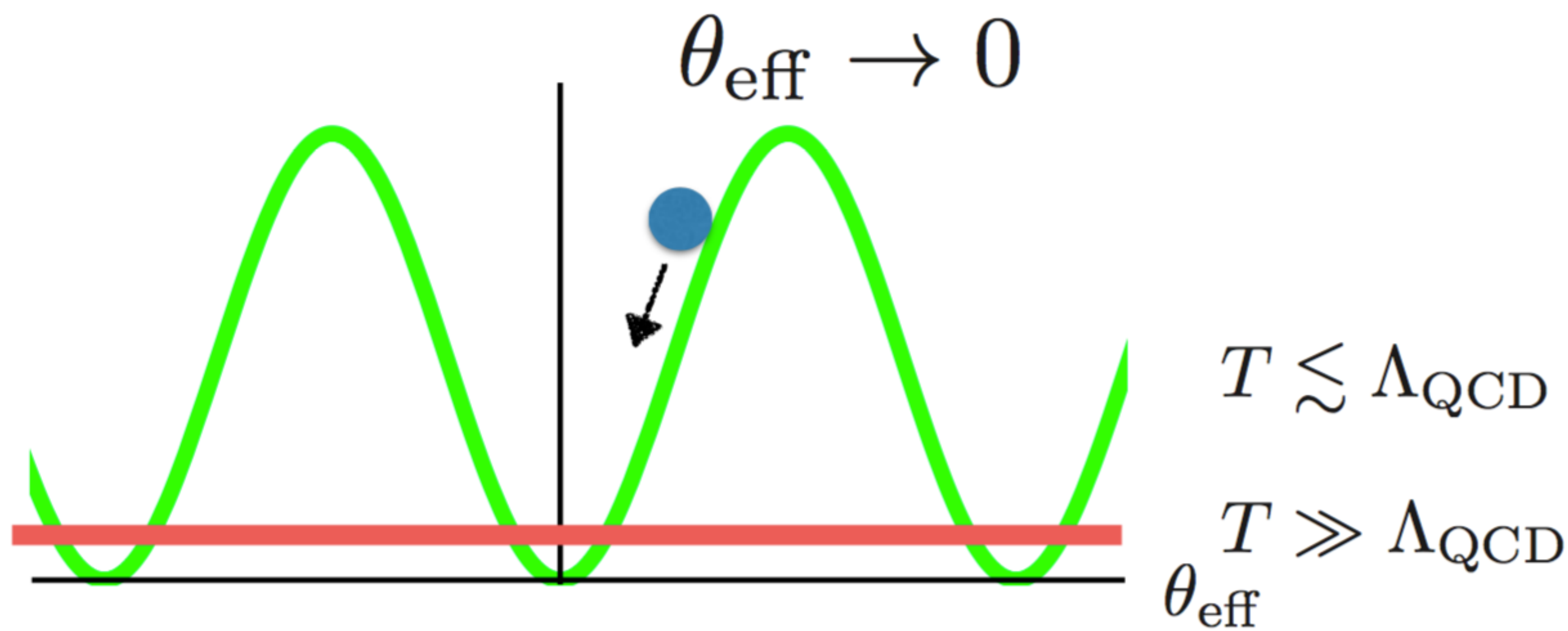
The size of θ is severely constrained from the neutron EDM experiment

$$|\theta| \lesssim 10^{-10}\text{-}10^{-11}$$

Why θ is so small? This is **strong CP problem**

Peccei-Quinn introduced a (anomalous) global symmetry, which makes θ parameter a dynamical field

$$\underbrace{\left(\theta + \frac{a}{f_a}\right)}_{=\,\theta_{\rm eff}} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



[fig. from R. Daido's slide]

$$m_a \simeq 5.7 \times 10^{-6}\,{\rm eV}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)$$ for $T \ll \Lambda_{\rm QCD}$

Axion as dark matter

The axion is produced as coherent oscillation
[misalignment mechanism]

Axion field starts to oscillate when $m_a(T) \sim H$

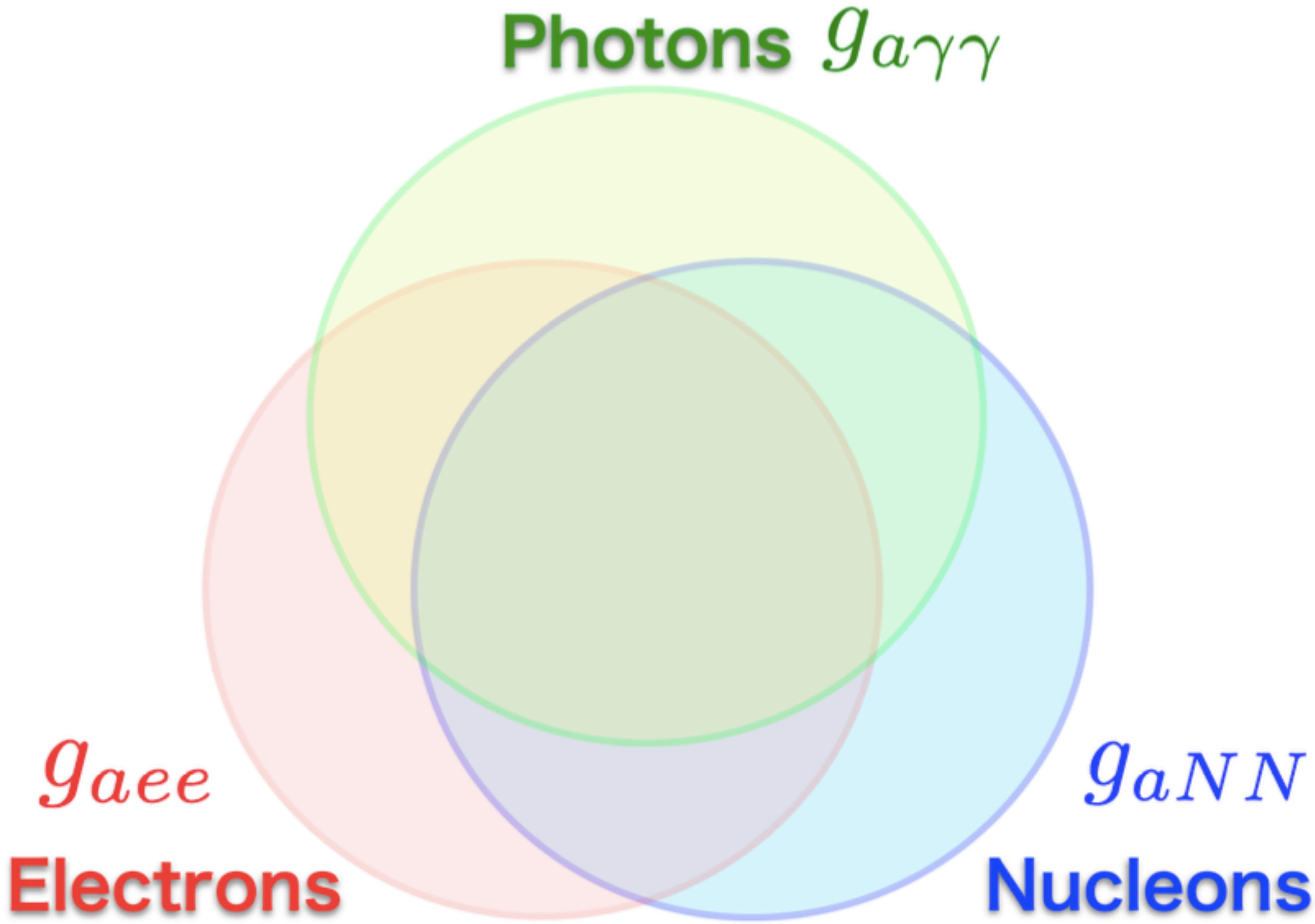
$$\Omega_a h^2 \approx 0.18\,\theta_I^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19}$$

The axion can be cold dark matter

(Almost) Stable due to very weak interaction and small mass

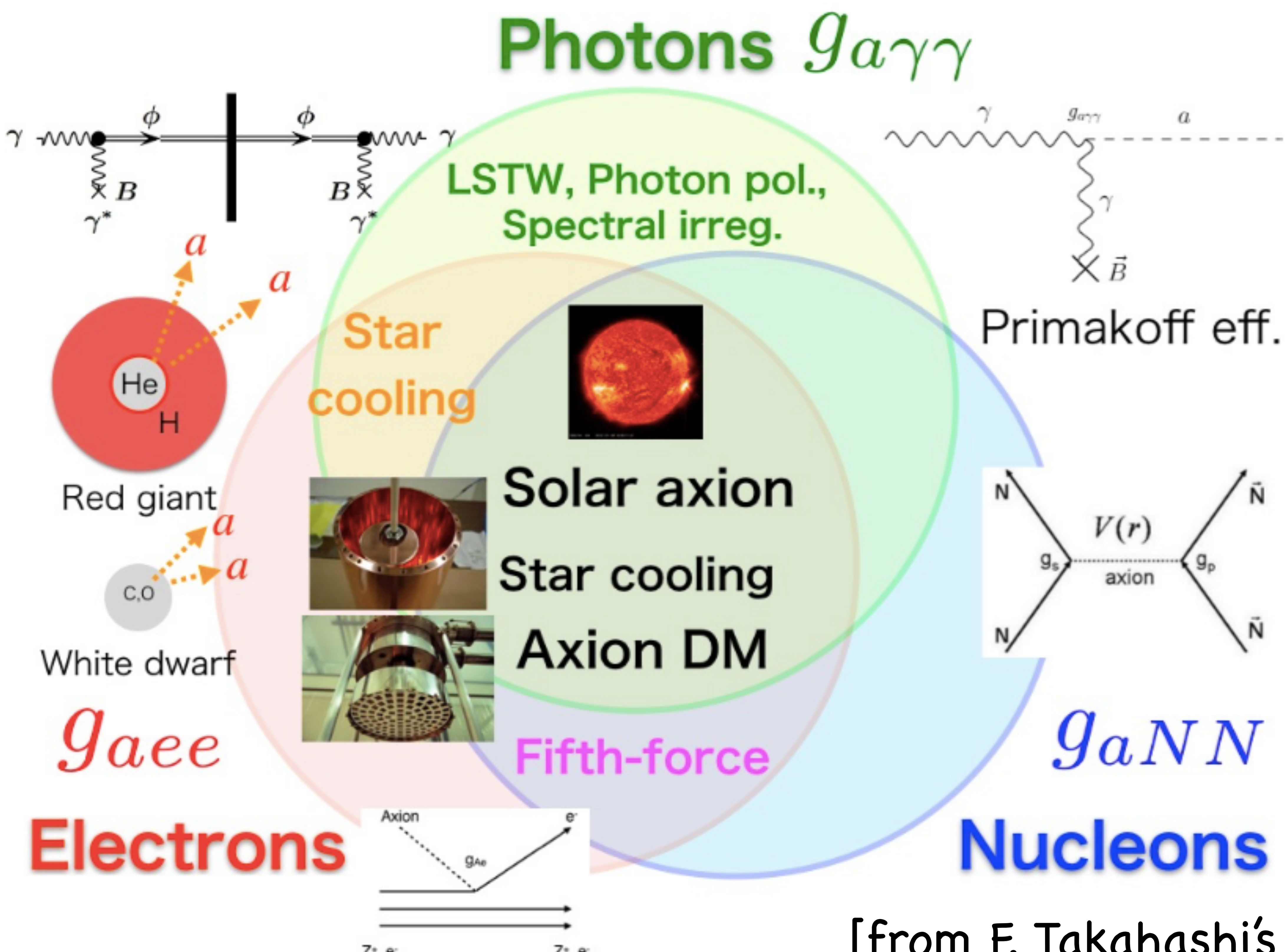
Behave as non-relativistic matter

Axion couplings

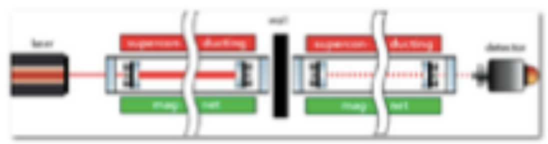
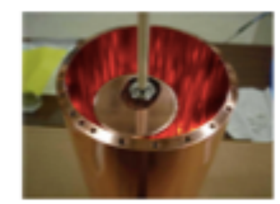
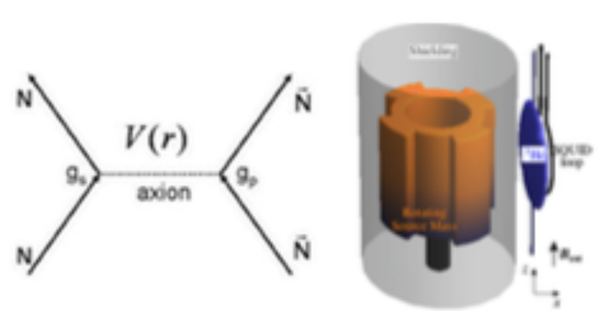
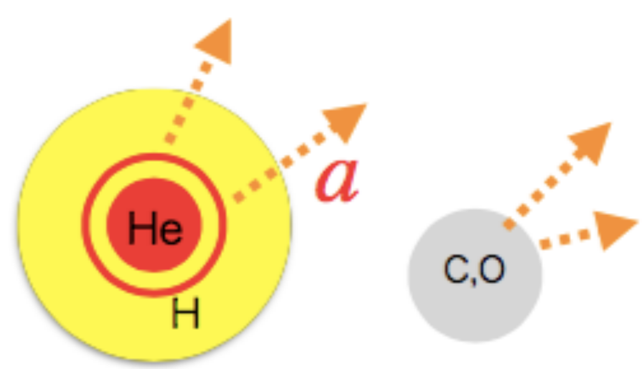
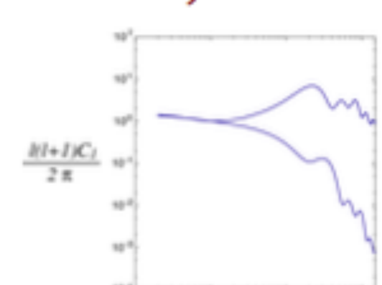


[from F. Takahashi's slide]

Axion couplings



[from F. Takahashi's slide]

		Production		
		Terrestrial	Celestial	Cosmological
Detection	Direct	LSTW, Photon pol. ALPS, PVLAS, SAPPHIRES 	Solar axion CAST, IAXO, TASTE  	Axion DM ADMX, CAPP,ORPHEUS MADMAX, LC-circuits, ABRACADABRA, CASPEr, LUX,XMASS, EDELWISE,XENON100  
	Indirect	Fifth force ARIADNE 	Excessive cooling of WD, RGB, HB, and NS 	Isocurvature, DR, HDM, caustics, Spectral irreg. transparency Fermi, Chandra, IACT CMB, lensing, shear  

[from F. Takahashi's slide]

Axion photon coupling

As an example, let's consider KSVZ axion model:

PQ field: $\phi = \frac{v_{PQ} + \rho(x)}{\sqrt{2}} \exp\left(i\frac{a(x)}{v_{PQ}}\right)$

Interaction: $\mathcal{L} \supset \lambda\phi\bar{\psi}_L\psi_R + h.c.$

with $Q_{\rm PQ}(\psi_L) = 1,\ Q_{\rm PQ}(\Psi_R) = 0$

↓

$$N\frac{g_s^2}{32\pi^2}\frac{a}{v_{\rm PQ}}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \equiv \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$N = {\rm Tr}(Q_{PQ}{\rm T}^a{\rm T}^a)\times 2$$

$$E\frac{e^2}{32\pi^2}\frac{a}{v_{\rm PQ}}F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{E}{N}\frac{e^2}{32\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$E = {\rm Tr}(Q_{PQ}Q^2_{\rm EM})\times 2$$

Axion photon coupling

As an example, let's consider KSVZ axion model:

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Interaction: $$\mathcal{L} \supset \lambda \phi \bar{\psi}_L \psi_R + h.c.$$

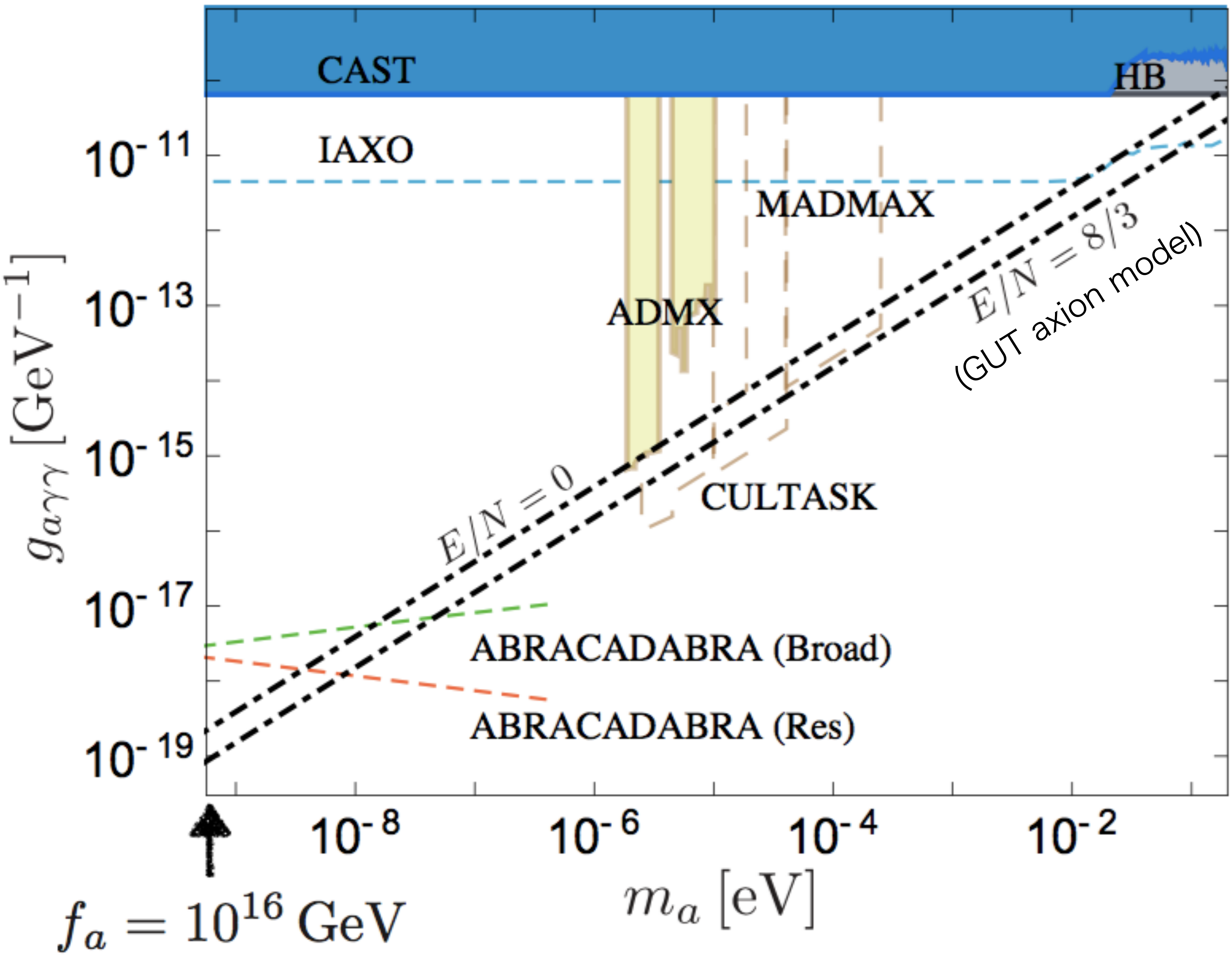
with $$Q_{\rm PQ}(\psi_L) = 1, \; Q_{\rm PQ}(\Psi_R) = 0$$

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

$$g_{\phi\gamma\gamma} = \frac{\alpha_{\rm EM}}{2\pi f_a} \left(\frac{E}{N} - 1.92 \right).$$

from axion-meson mixing

Current and future experiments



Motivations to go beyond the SM

- Strong CP problem
- Dark matter

} Solved by QCD axion

Unification of SM gauge couplings and matter fields, and charge quantization

known quarks and leptons nicely fit into $\mathbf{5}$ and $\mathbf{10}$ in SU(5)

$$\bar{\mathbf{5}} = \begin{pmatrix} (d^1)^c \\ (d^2)^c \\ (d^3)^c \\ e^- \\ -\nu_e \end{pmatrix} \qquad \mathbf{10} = \begin{pmatrix} 0 & (u^3)^c & -(u^2)^c & -u^1 & -d^1 \\ -(u^3)^c & 0 & (u^1)^c & -u^2 & -d^2 \\ (u^2)^c & -(u^1)^c & 0 & -u^3 & -d^3 \\ u^1 & u^2 & u^3 & 0 & -e^+ \\ d^1 & d^2 & d^3 & e^+ & 0 \end{pmatrix}$$

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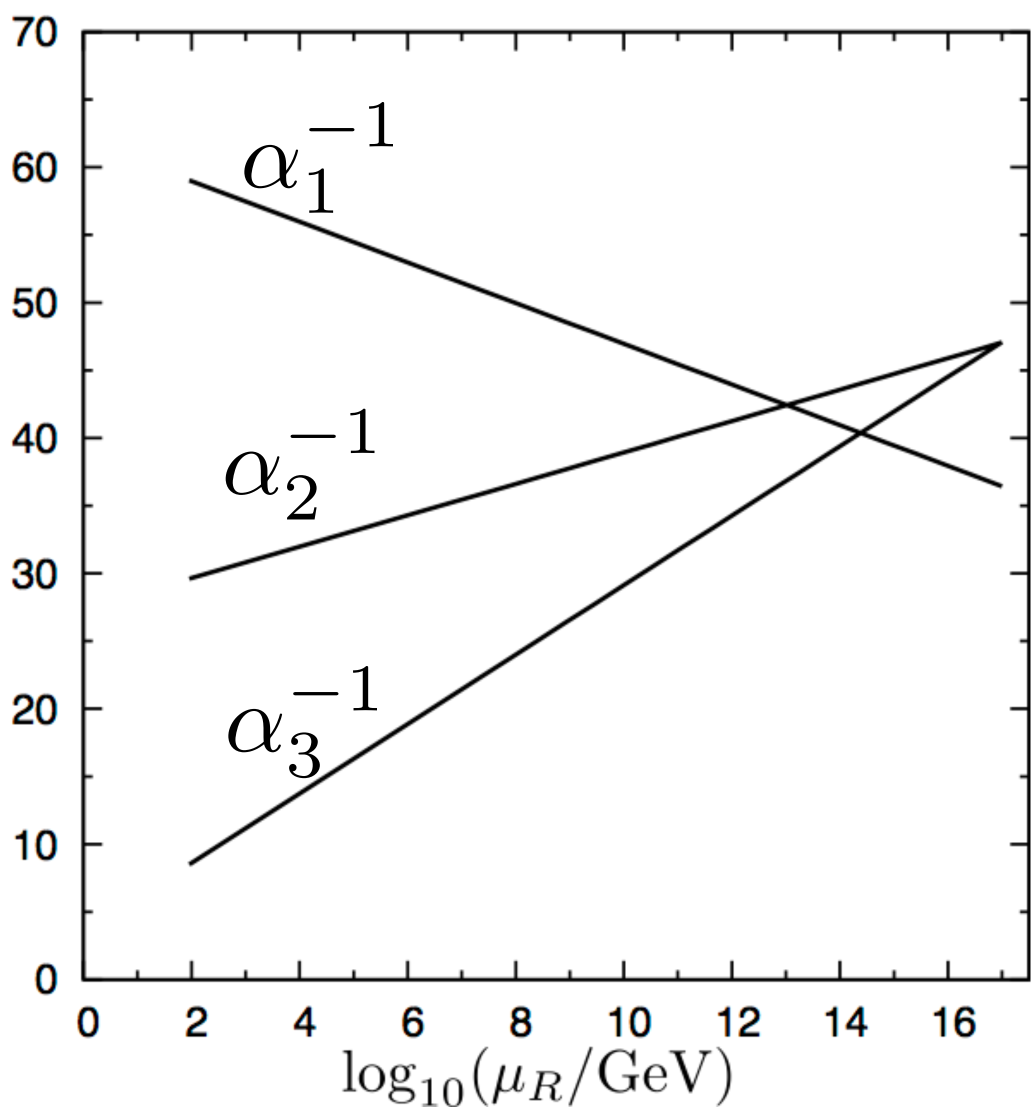
Explains the charge quantization

Motivations to go beyond the SM

- Strong CP problem
- Dark matter

} Solved by QCD axion

Unification of SM gauge couplings and matter fields, and charge quantization



However, for the couplings ···

The figure shows the RG running of the SM gauge couplings

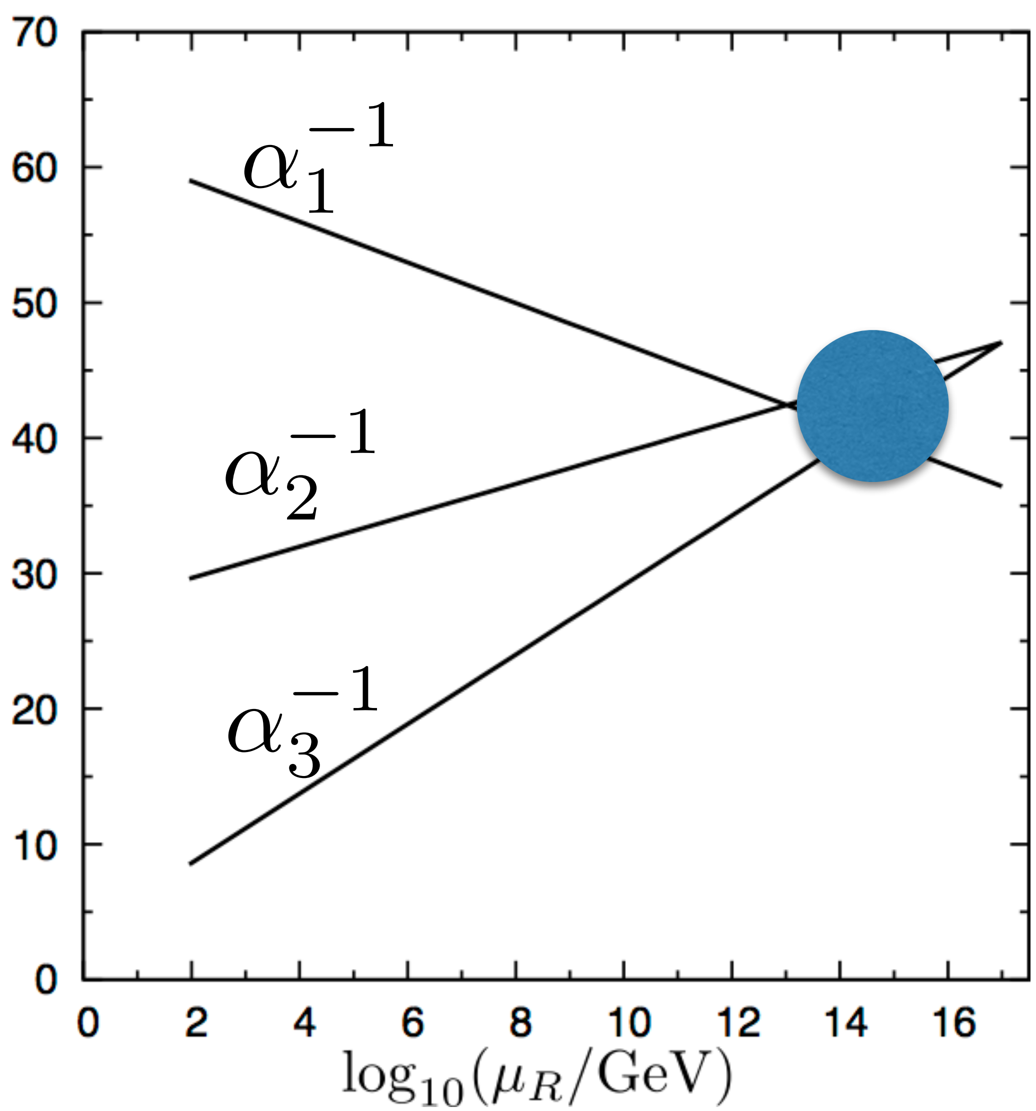
In SM, the unification fails

Motivations to go beyond the SM

- Strong CP problem
- Dark matter

} Solved by QCD axion

Unification of SM gauge couplings and matter fields, and charge quantization



Moreover, it predicts too rapid proton decay

For Mx=10^{15}GeV

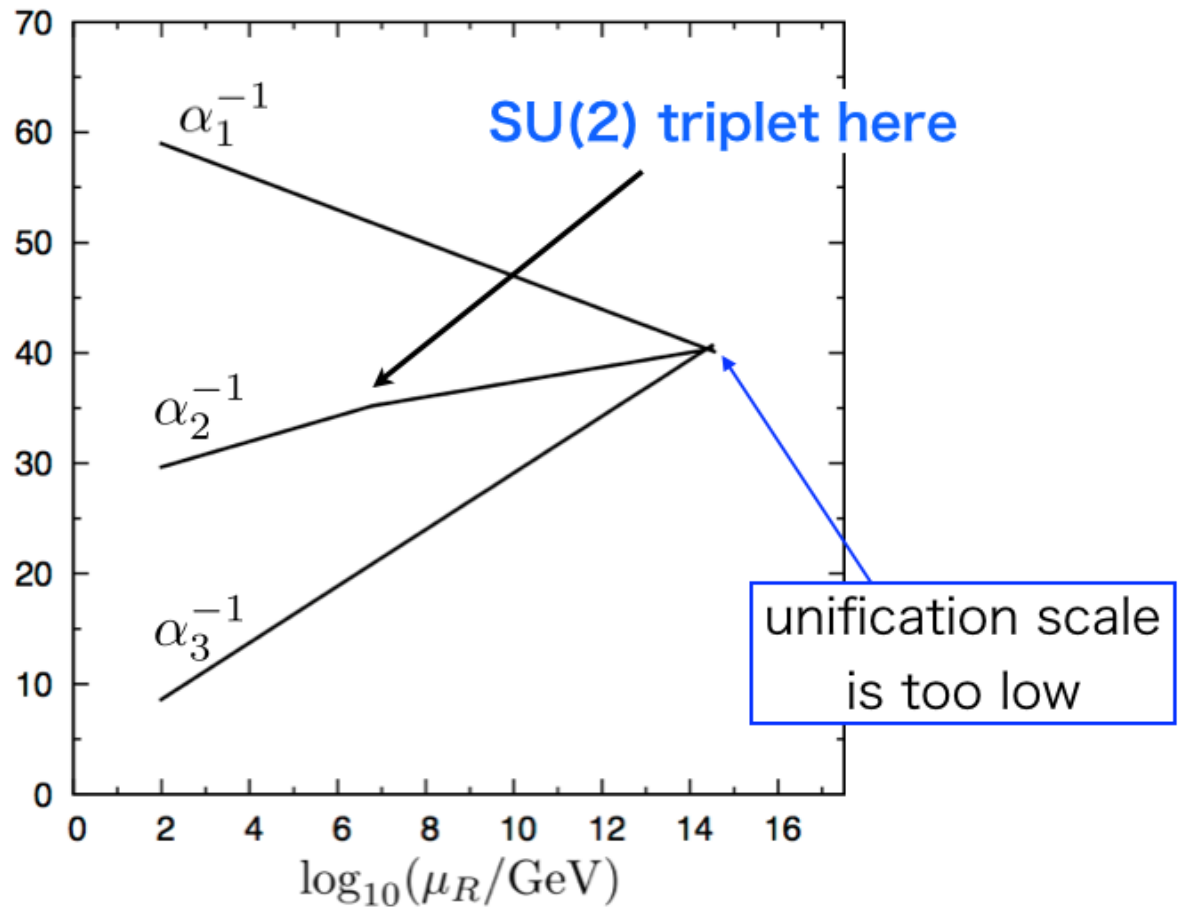
≒5×10^{31} years ($p \to \pi^0 e^+$)

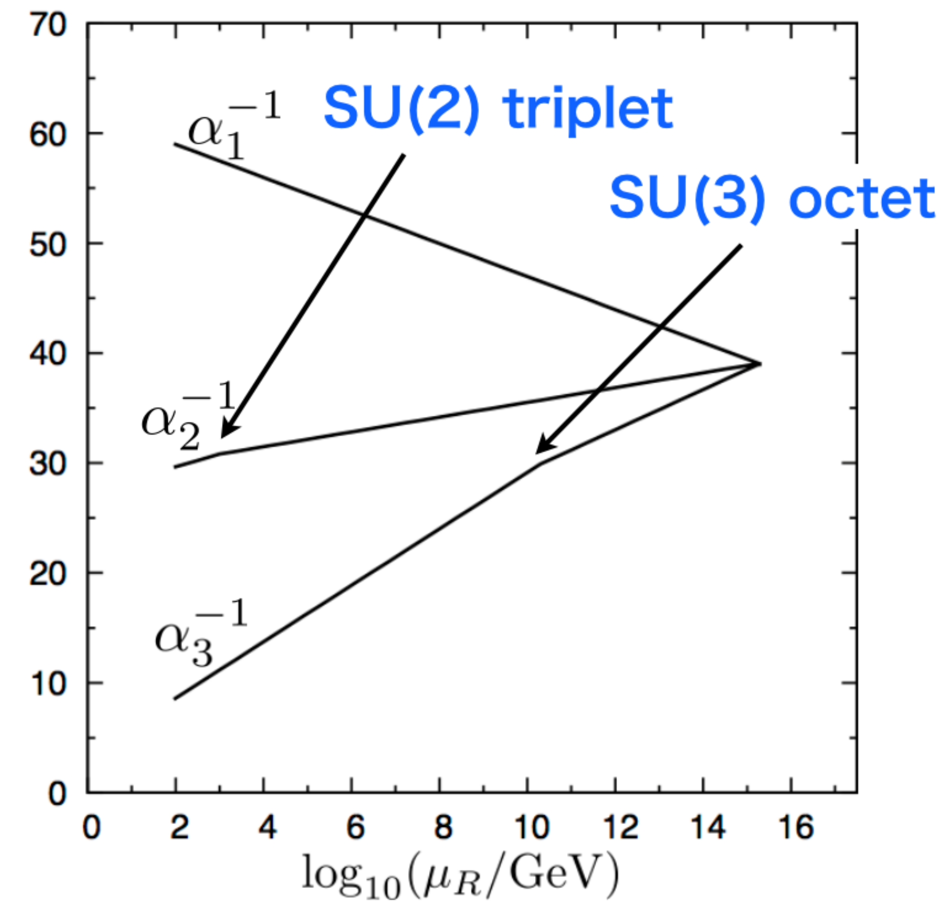
exp: > 1.7 x 10^{34} years

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

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

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

[Holdom, 1986]

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

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

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

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

$$A_Y^{\mu\,\prime} = \frac{A_Y^\mu}{\sqrt{1-\chi^2}}$$

$$A_H^{\mu\,\prime} = A_H^\mu - \frac{\chi}{\sqrt{1-\chi^2}} A_Y^\mu$$

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

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

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

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

Let's consider a matter field charged 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

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

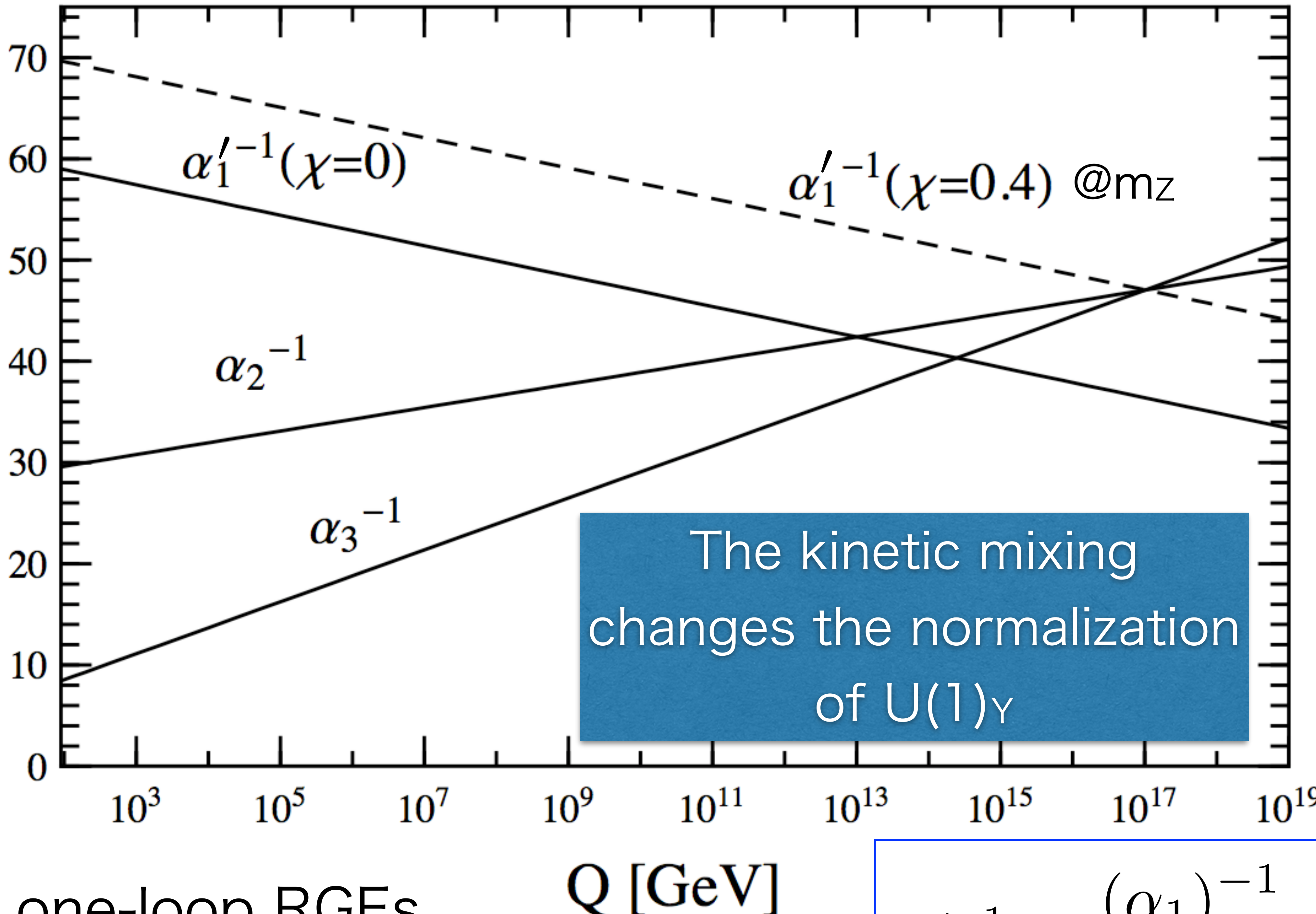
$$g_H = g'_H$$

observed value

couplings in the canonical basis

Grand unification with $U(1)_H$

Without matter fields



With one-loop RGEs

[J. Redondo, 2008]

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

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)

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?

With matter fields

Let's consider the Lagrangian including matter fields charged under U(1)H

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

$$-\sum_i M_\Psi \bar{\Psi}_i \Psi_i$$

Ψ_i has a hypercharge of Q_i and a $\mathrm{U}(1)_H$ charge of $q_{H\,i}$.

$$Q_i \to Q_i - \frac{g_H q_{H\,i}}{g_Y}\frac{\chi}{\sqrt{1-\chi^2}}$$

$$q_{H\,i} \to q_{H\,i}$$

In the canonical basis, the field gets a fractional U(1)Y charge

The RG equations

RGEs in the canonical basis

$$\frac{dg_Y}{dt} = \frac{1}{16\pi^2}(b_Y g_Y^3 + b_H g_Y g_{\rm mix}^2 + 2b_{\rm mix} g_Y^2 g_{\rm mix}),$$

$$\frac{dg_H}{dt} = \frac{1}{16\pi^2} b_H g_H^3,$$

$$\frac{dg_{\rm mix}}{dt} = \frac{1}{16\pi^2}(b_Y g_{\rm mix} g_Y^2 + 2b_H g_{\rm mix} g_H^2 + b_H g_{\rm mix}^3 + 2b_{\rm mix} g_Y g_H^2 + 2b_{\rm mix} g_Y g_{\rm mix}^2),$$

[Babu, Kolda, March-Russell, 1996]

$t = \ln \mu_R$ (μ_R is a renormalization scale)

$$b_Y = \frac{41}{6} + \frac{4}{3}\sum_i Q_i^2, \quad b_H = \frac{4}{3}\sum_i {q_H}_i^2, \quad b_{\rm mix} = \frac{4}{3}\sum_i Q_i {q_H}_i$$

$$g_{\rm mix} = -\frac{g_H \chi}{\sqrt{1-\chi^2}}$$

It looks like GUT is non-trivial.

The RG equations

However, RGEs in the original basis are simple:

$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2} b_Y g'^3_Y \,, \qquad g'_Y = g_Y\sqrt{1-\chi^2}$$

$$\frac{dg_H}{dt} = \frac{1}{16\pi^2} b_H g^3_H \,,$$

$$\frac{d\chi}{dt} = \frac{1}{16\pi^2}\left[\chi(b_Y g'^2_Y + b_H g^2_H) - 2b_{\rm mix} g'_Y g_H\right]$$

$$t = \ln\mu_R \ (\mu_R \text{ is a renormalization scale})$$

$$b_Y = \frac{41}{6} + \frac{4}{3}\sum_i Q_i^2, \quad b_H = \frac{4}{3}\sum_i {q_H}_i^2, \quad b_{\rm mix} = \frac{4}{3}\sum_i Q_i {q_H}_i$$

RGE running is trivial at the one-loop level in this basis.

How does it affect if two-loop RGEs are considered?

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

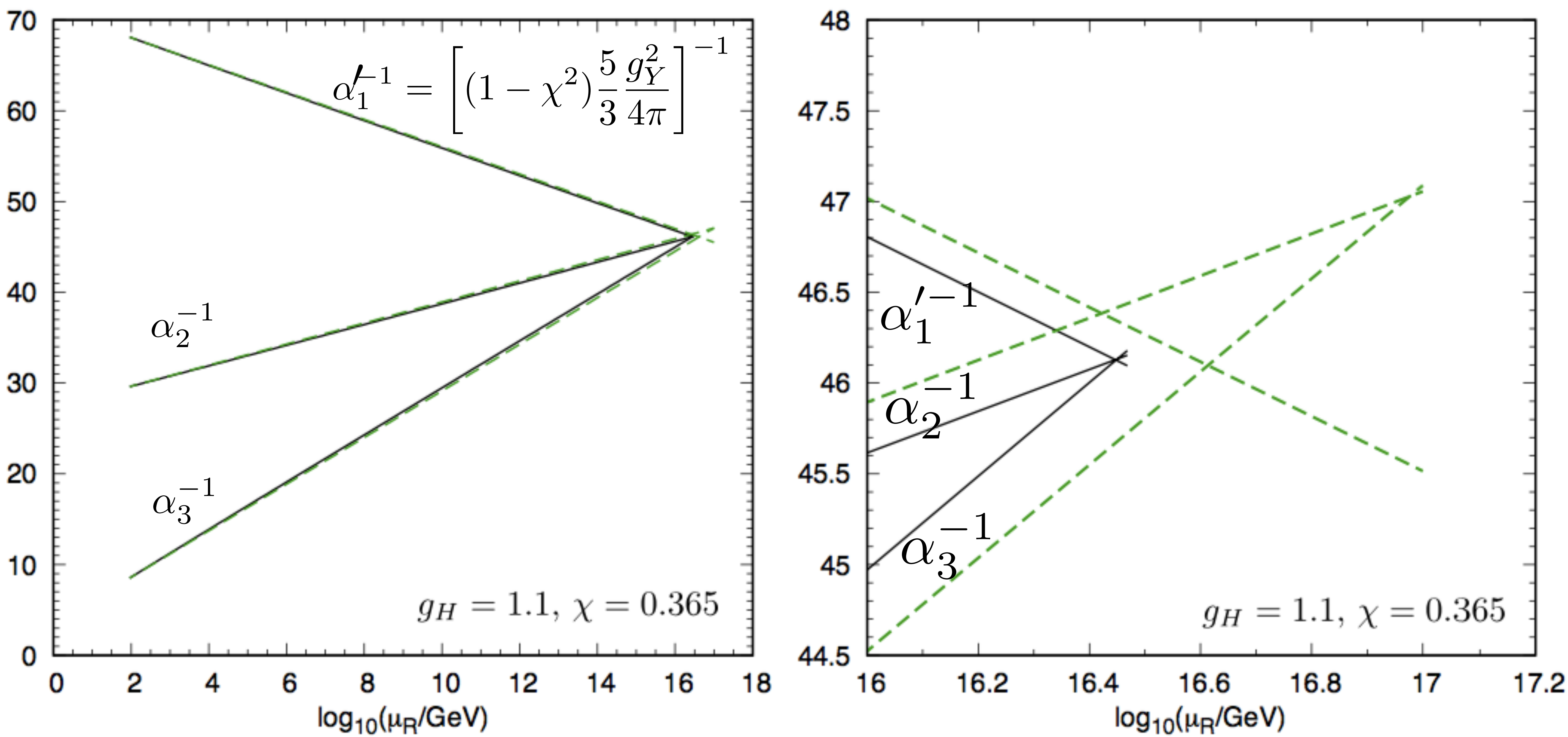
$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2}\left(\frac{41}{6}\right)g'^3_Y,$$

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

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

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

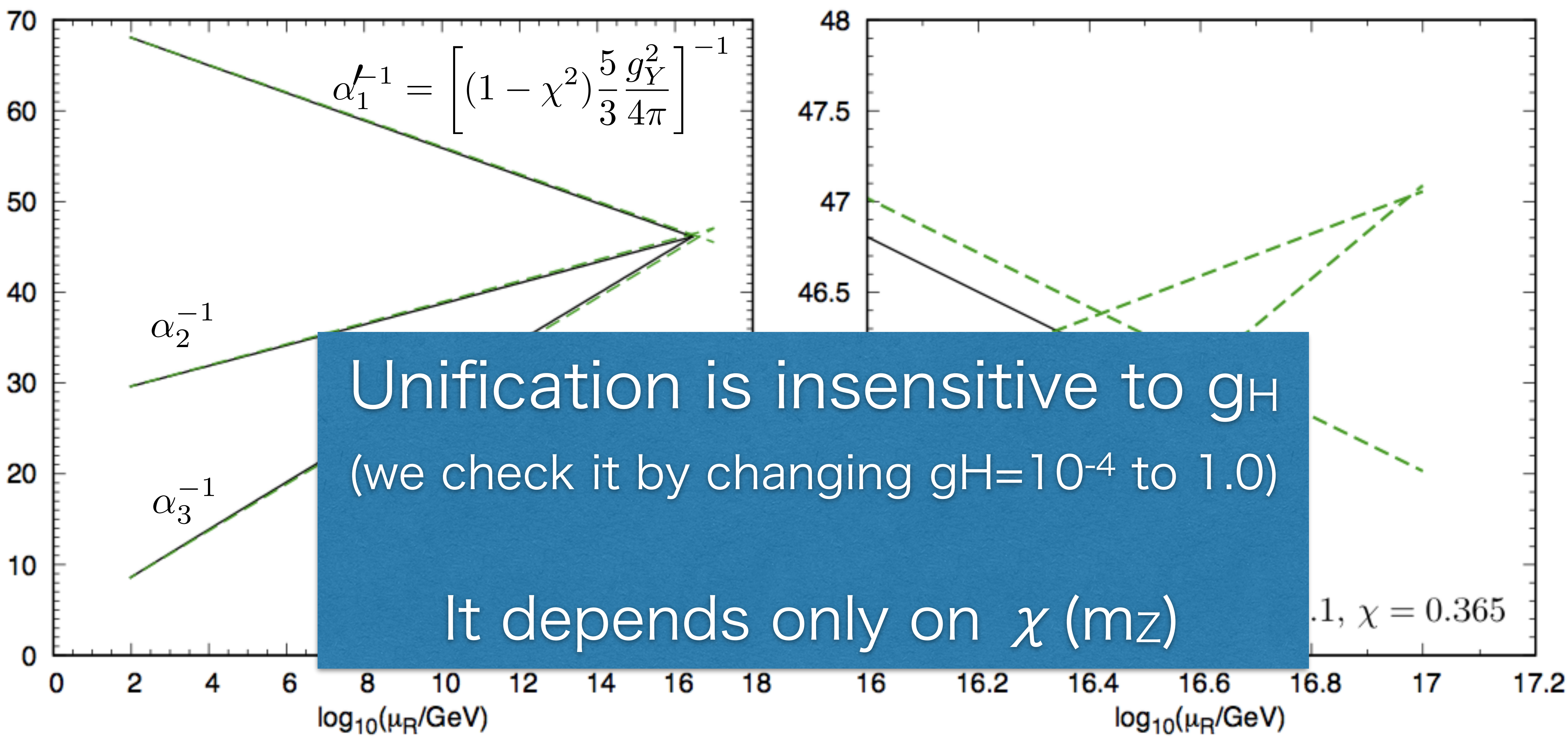
Running of the gauge couplings



green dashed: one-loop

black solid: two-loop

Running of the gauge couplings



Unification is insensitive to g_H

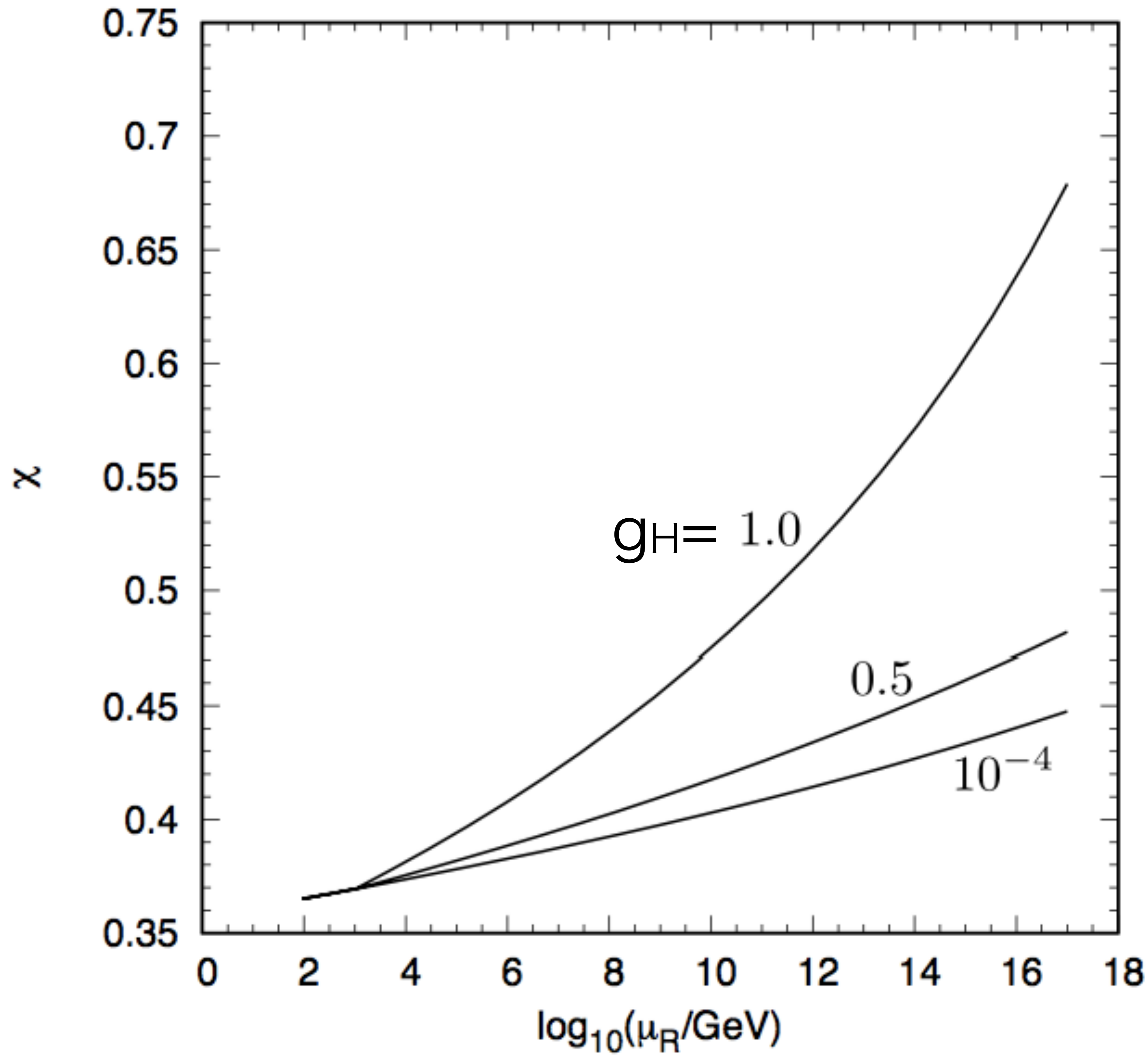
(we check it by changing gH=10^{-4} to 1.0)

It depends only on χ (m_Z)

green dashed: one-loop

black solid: two-loop

Running of the kinetic mixing



Large kinetic mixing at the GUT scale

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

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

$\Psi_{L,i}$ ($\Psi_{\bar{D},i}$) 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

$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2}\left(\frac{41}{6} + \frac{10}{9}N_\mathrm{b}\right) g'^3_Y, \qquad \frac{dg_H}{dt} = \frac{1}{16\pi^2}\left(\frac{20}{3}N_\mathrm{b}\right) g^3_H$$

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

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

and two-loop corrections…

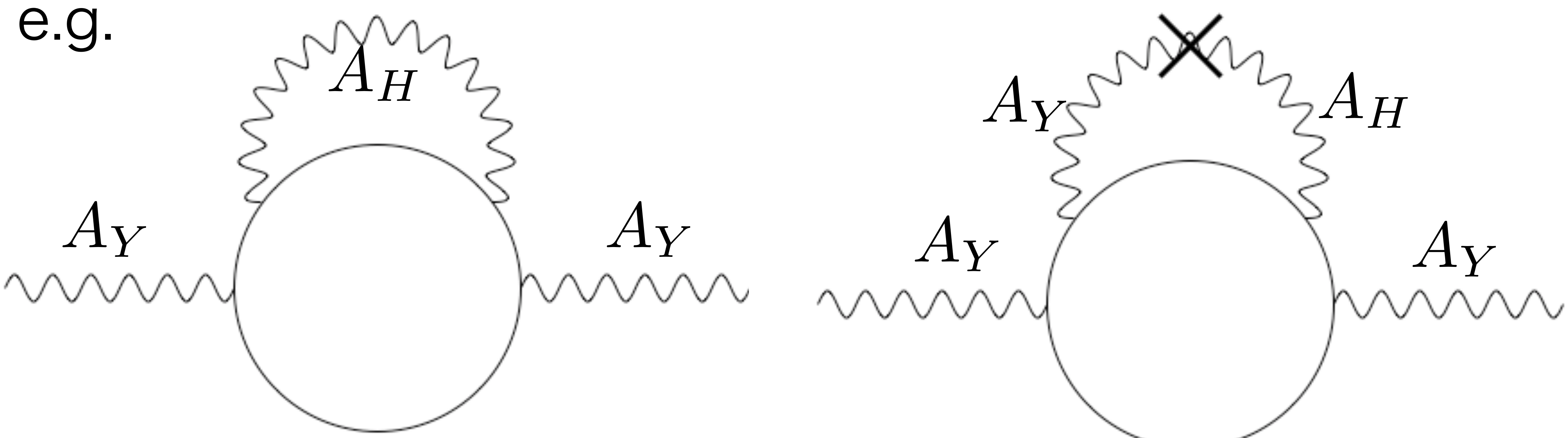
With SU(5) multiplets charged under U(1)$_H$

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

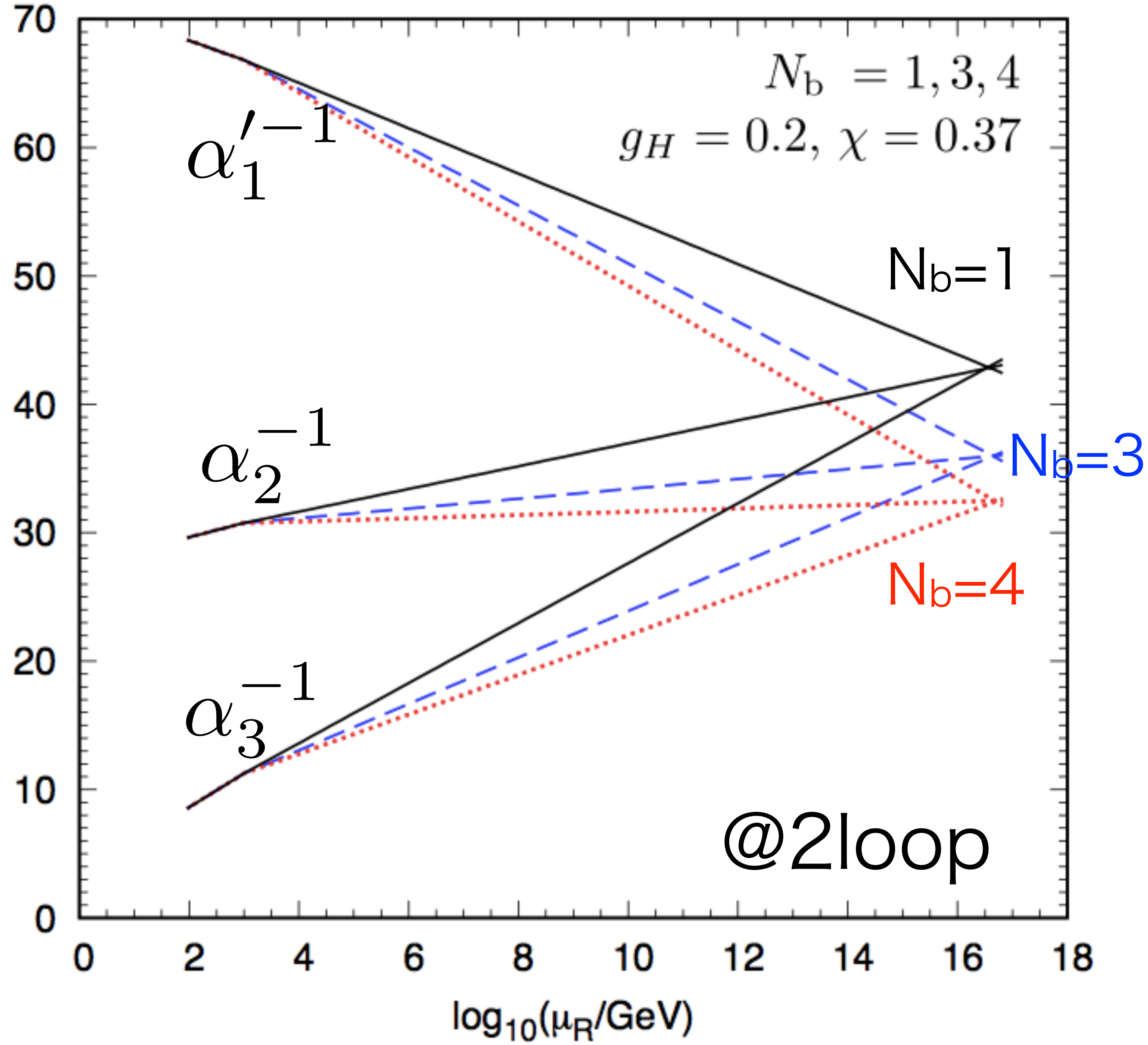
$\Psi_{L,i}$ ($\Psi_{\bar{D},i}$) is **2** of SU(2)$_L$ ($\bar{\mathbf{3}}$ of SU(3)$_C$);

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

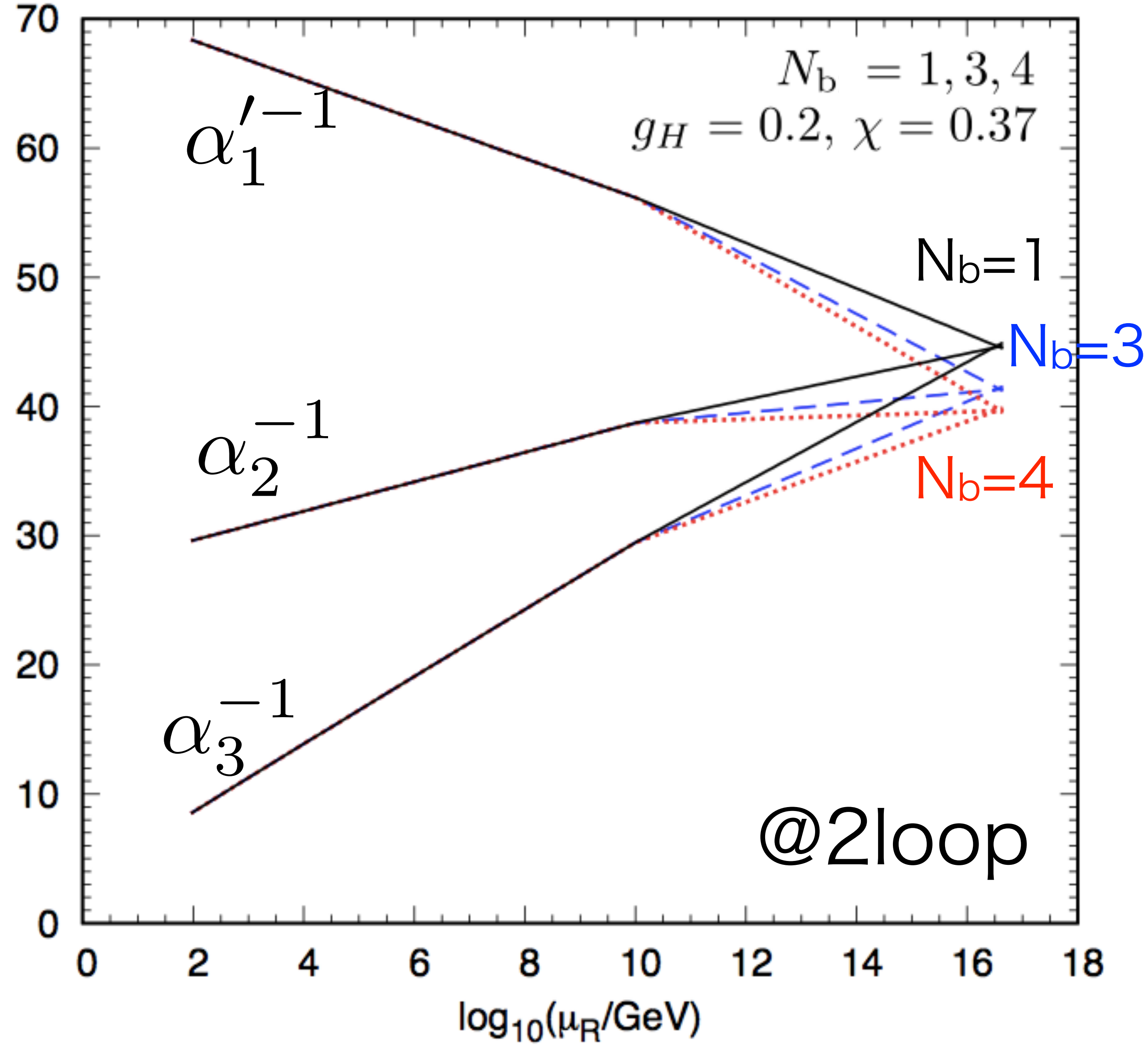
e.g.



However, the effects are loop suppressed and small



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



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

(Almost) insensitive to N_b, g_H and M_V

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

Short summary

- The unification depends only on $\chi(m_Z)$
- We need a hidden charged field to fix the unification basis
- The unification does not depend on the hidden gauge coupling nor matter fields charged under SU(5) and/or $U(1)_H$.
- **The above statement implies that we can easily accommodates the PQ symmetric solution to the strong CP problem.**

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

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

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

from SU(5) complete multiplet

For large g_H and χ, the enhancement is significant.

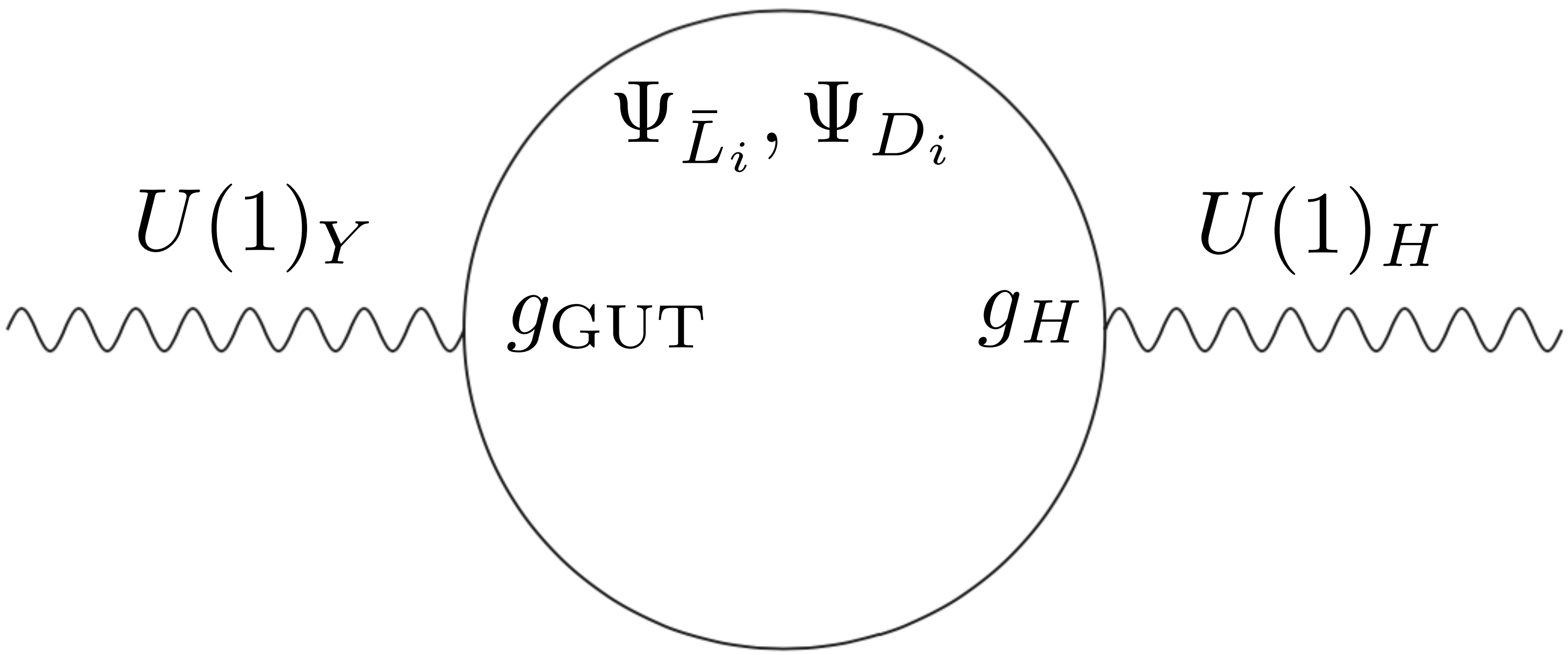
Large χ and g_H are required for consistency with GUT

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



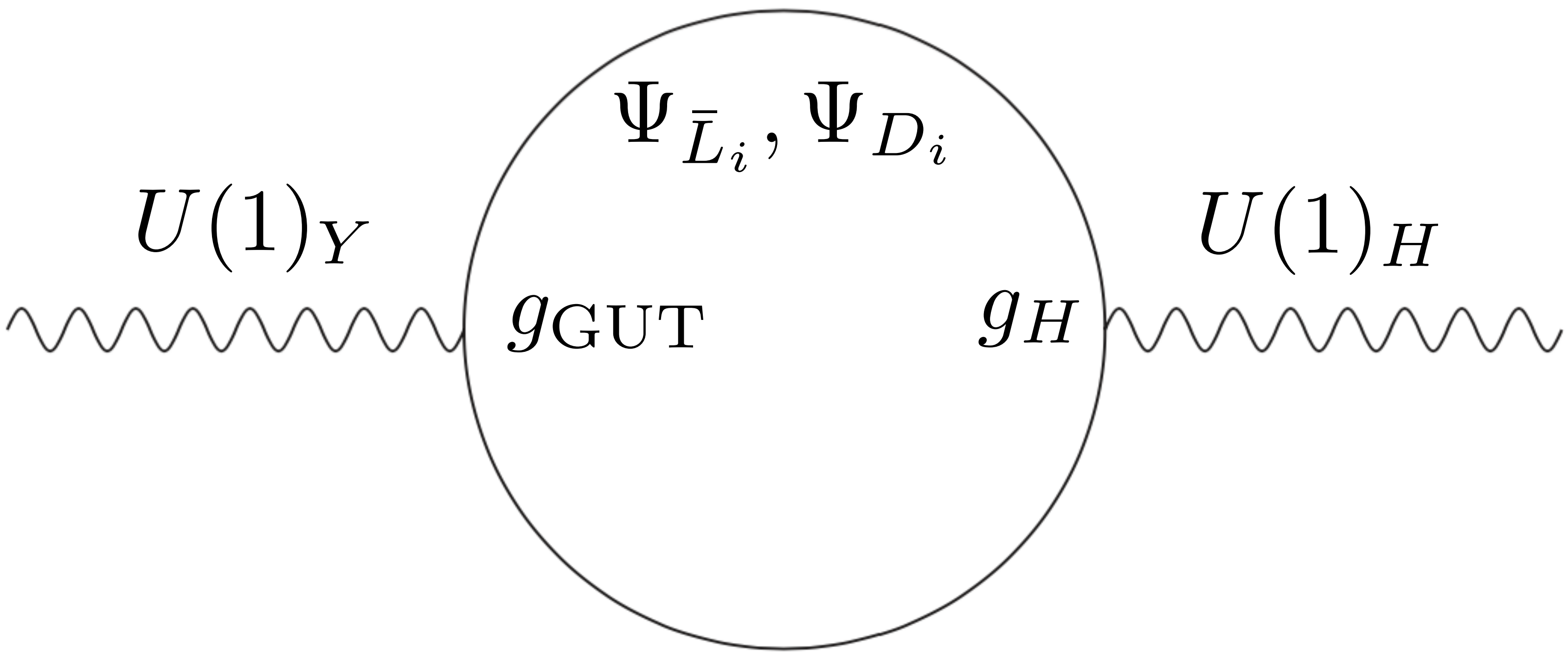
With the GUT breaking mass induced by Σ_{24}:

$$-\mathcal{L} \supset \sum_{i=1}^{N_f} \left(M_5 \overline{\Psi}_{5_i} \Psi_{5_i} + k \overline{\Psi}_{5_i} \langle \Sigma_{24} \rangle \Psi_{5_i} \right) \qquad q_H(\Psi_{5_i}) = -1$$

$$= \sum_{i=1}^{N_f} \left(M_D \overline{\Psi}_{D_i} \Psi_{D_i} + M_L \overline{\Psi}_{\bar{L}_i} \Psi_{\bar{L}_i} \right),$$

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

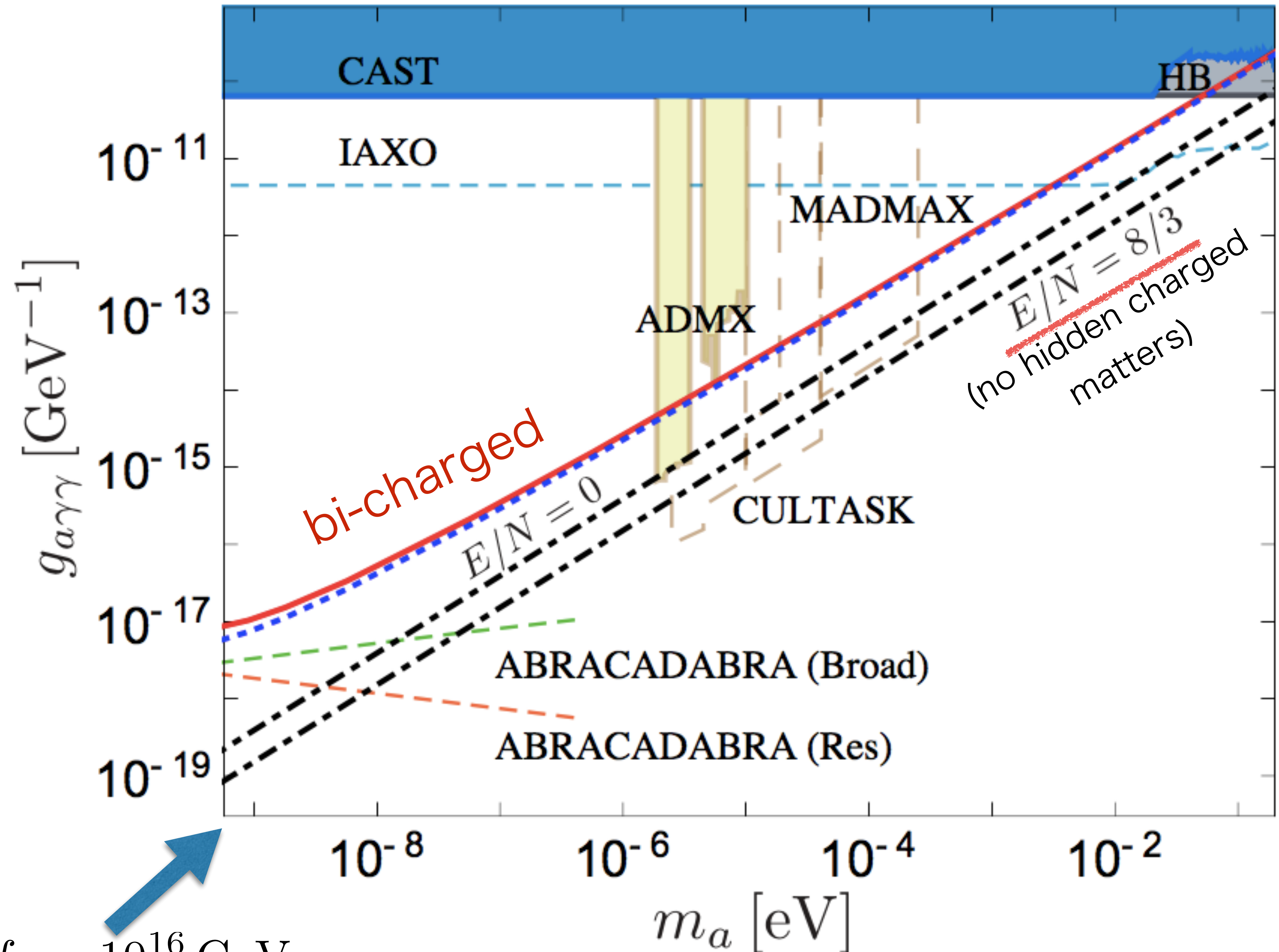
The kinetic mixing is taken as $\chi(m_Z) = 0.365$ required for GUT

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

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

$U(1)_H$ charges are

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

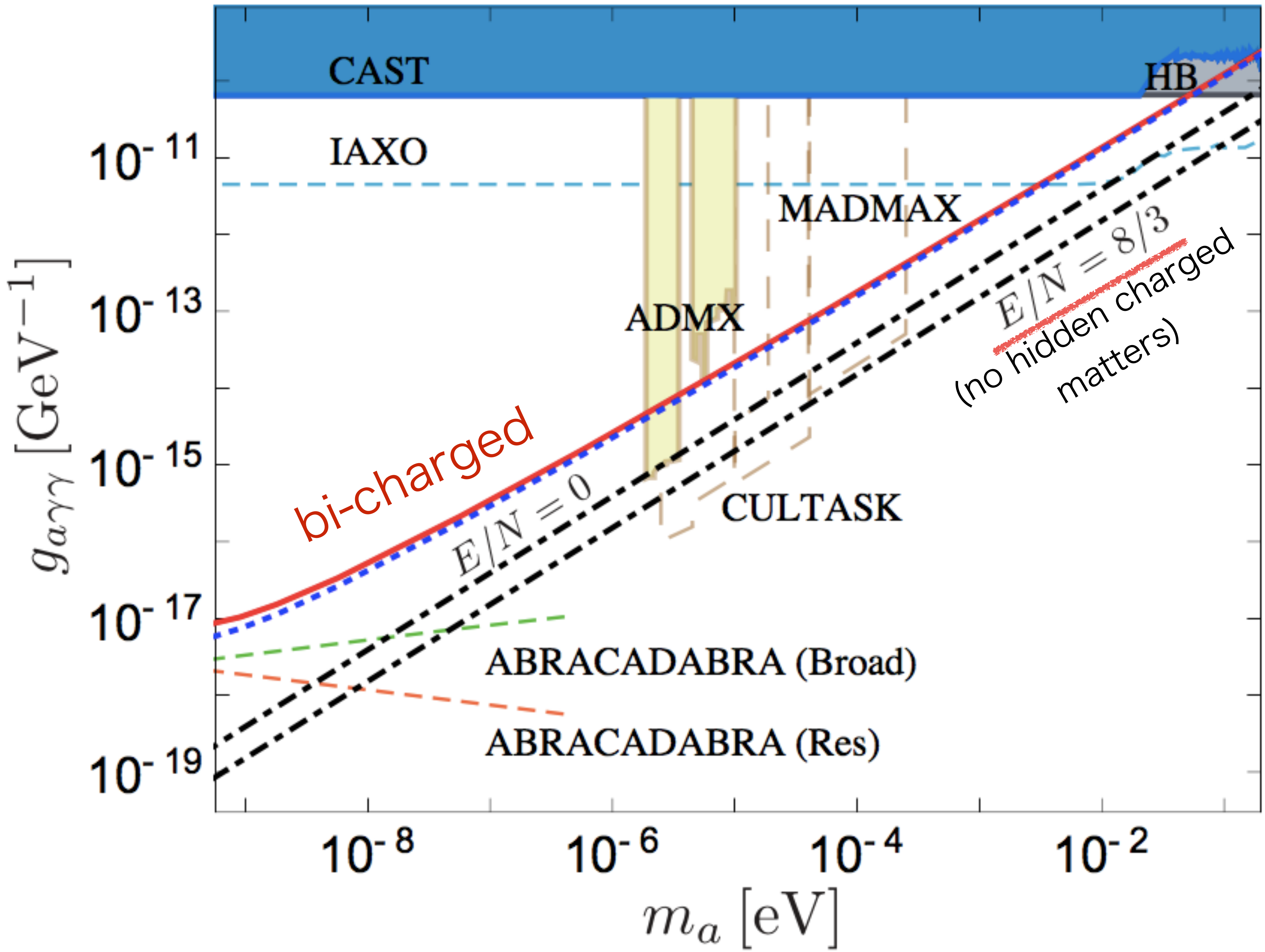


$f_a = 10^{16}$ GeV

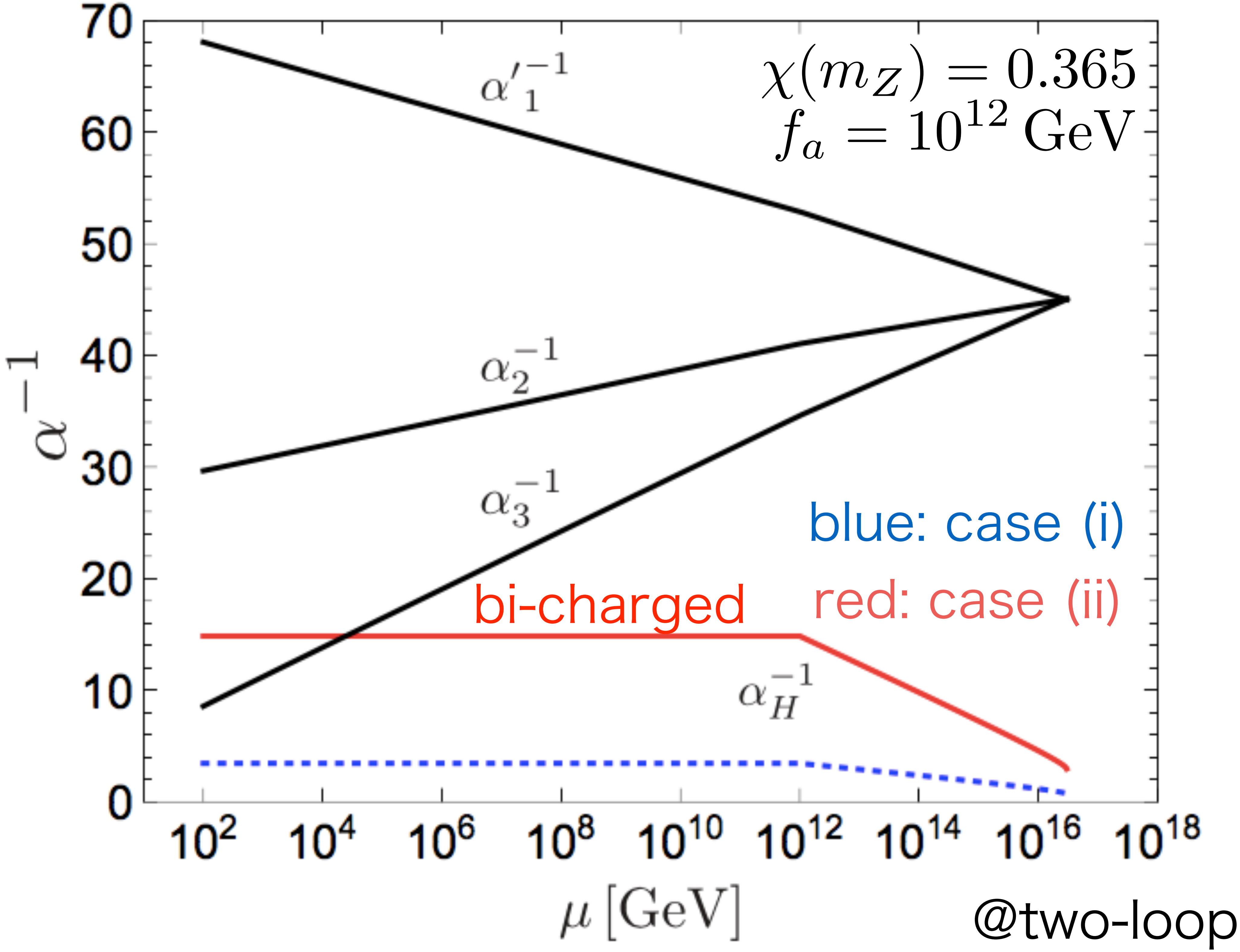
$$m_a = 5.70\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

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!