March 8th@KEK

Minicharged Dark Matter from Gauge Coupling Unification

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

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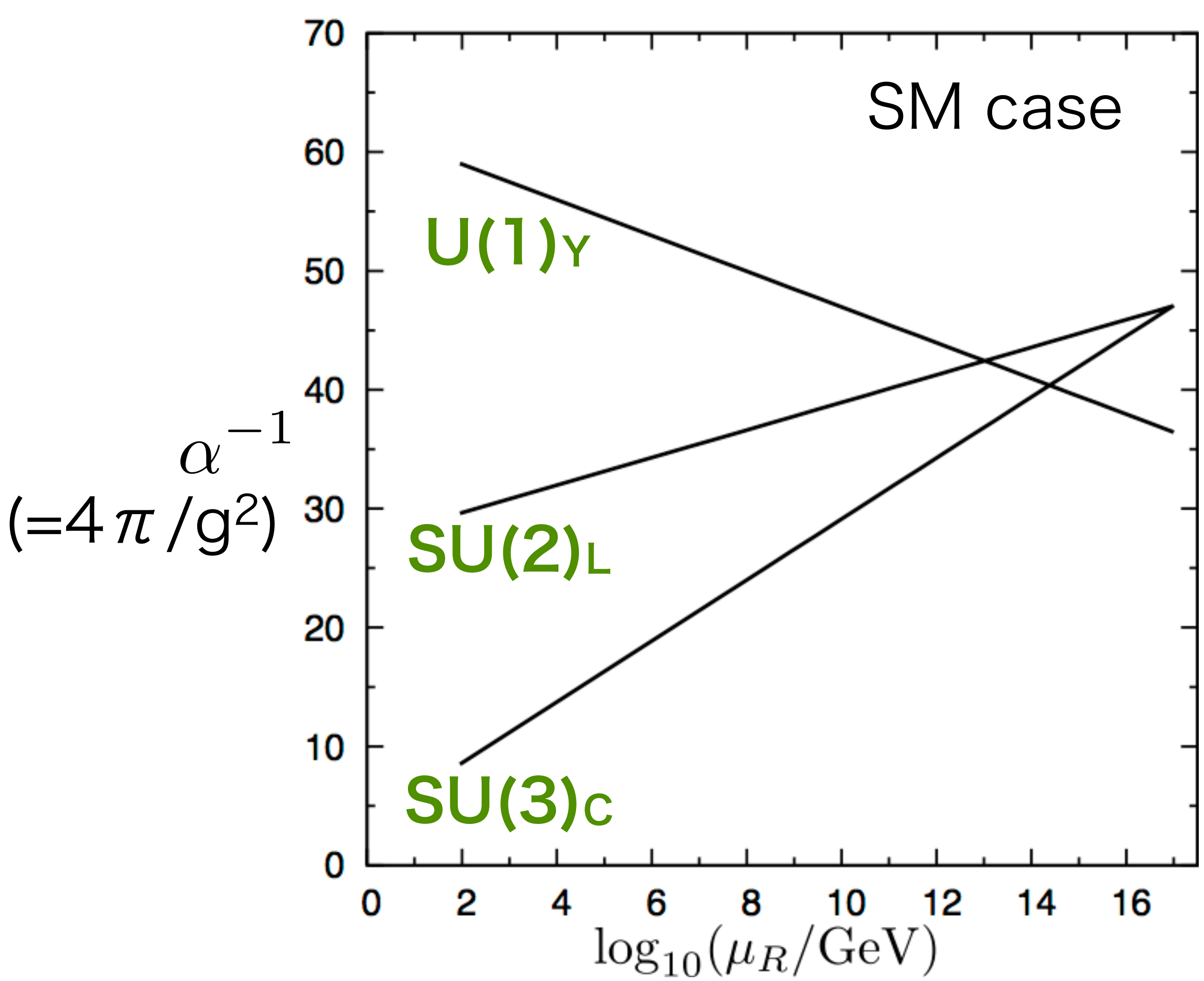
Motivations to go beyond the SM

- Dark matter

Unification of SM forces and matters, and charge quantization

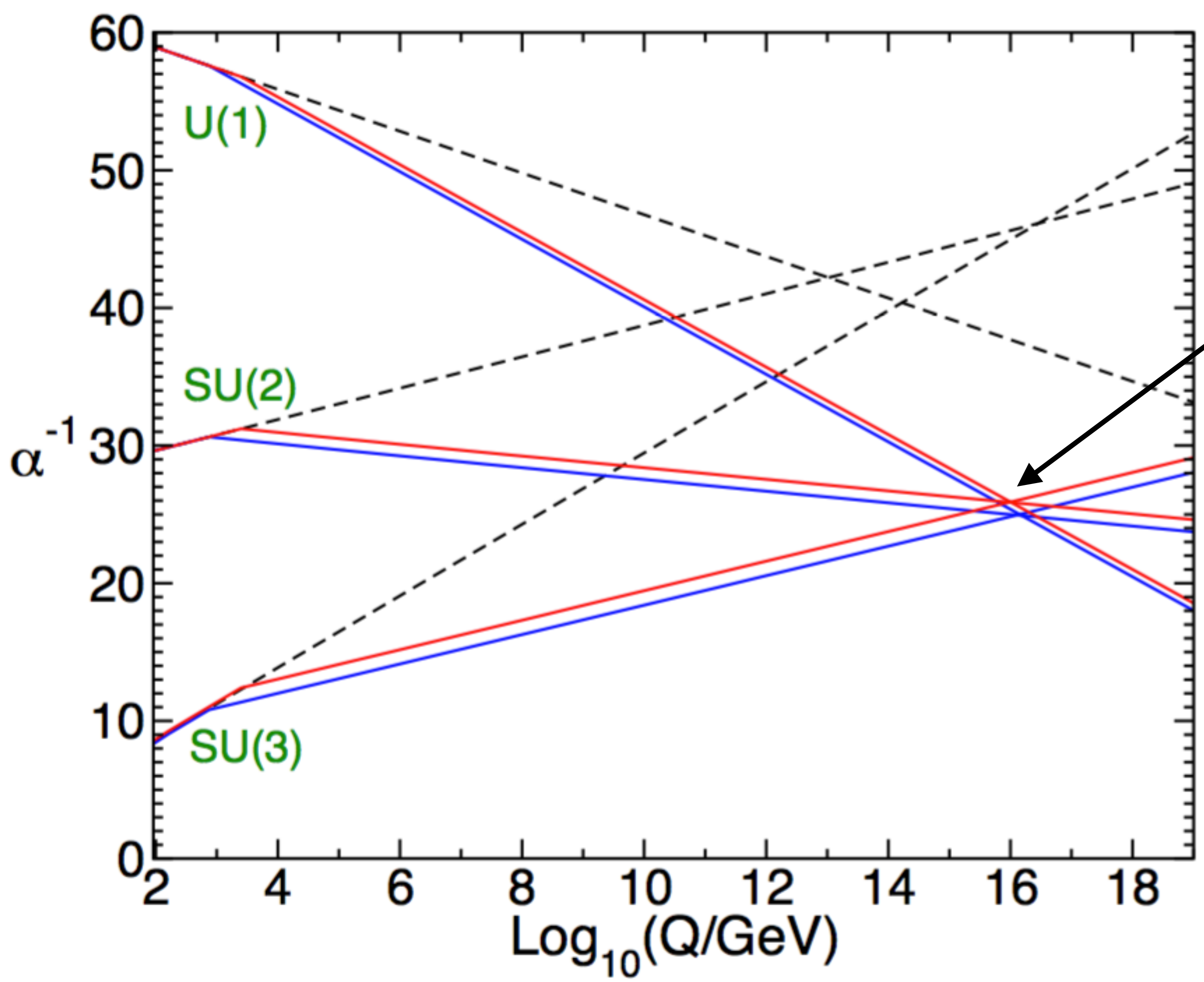


In SM, the unification of the gauge couplings fails apparently.

Motivations to go beyond the SM

- Dark matter

Unification of SM forces and matters, and charge quantization

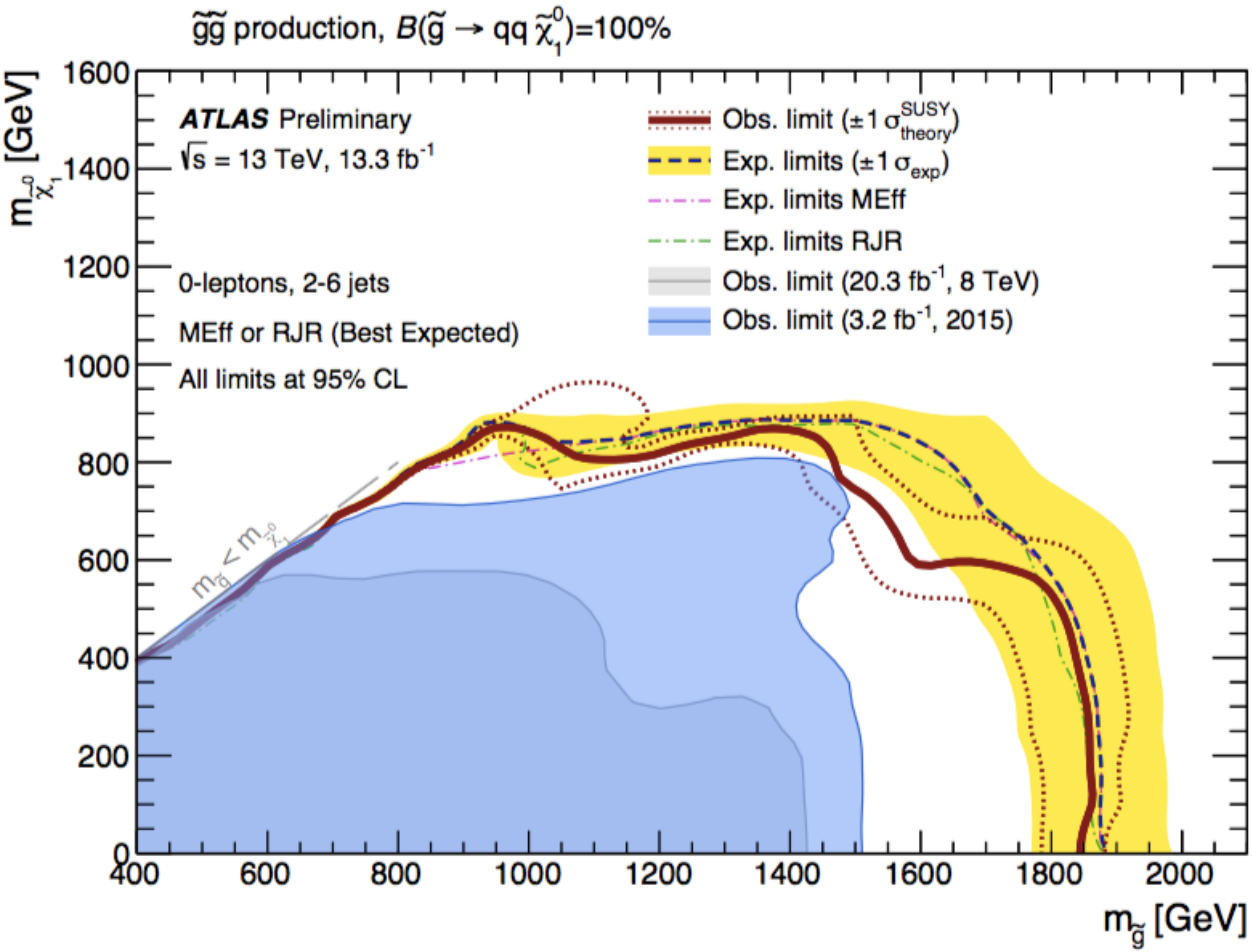


MSSM case

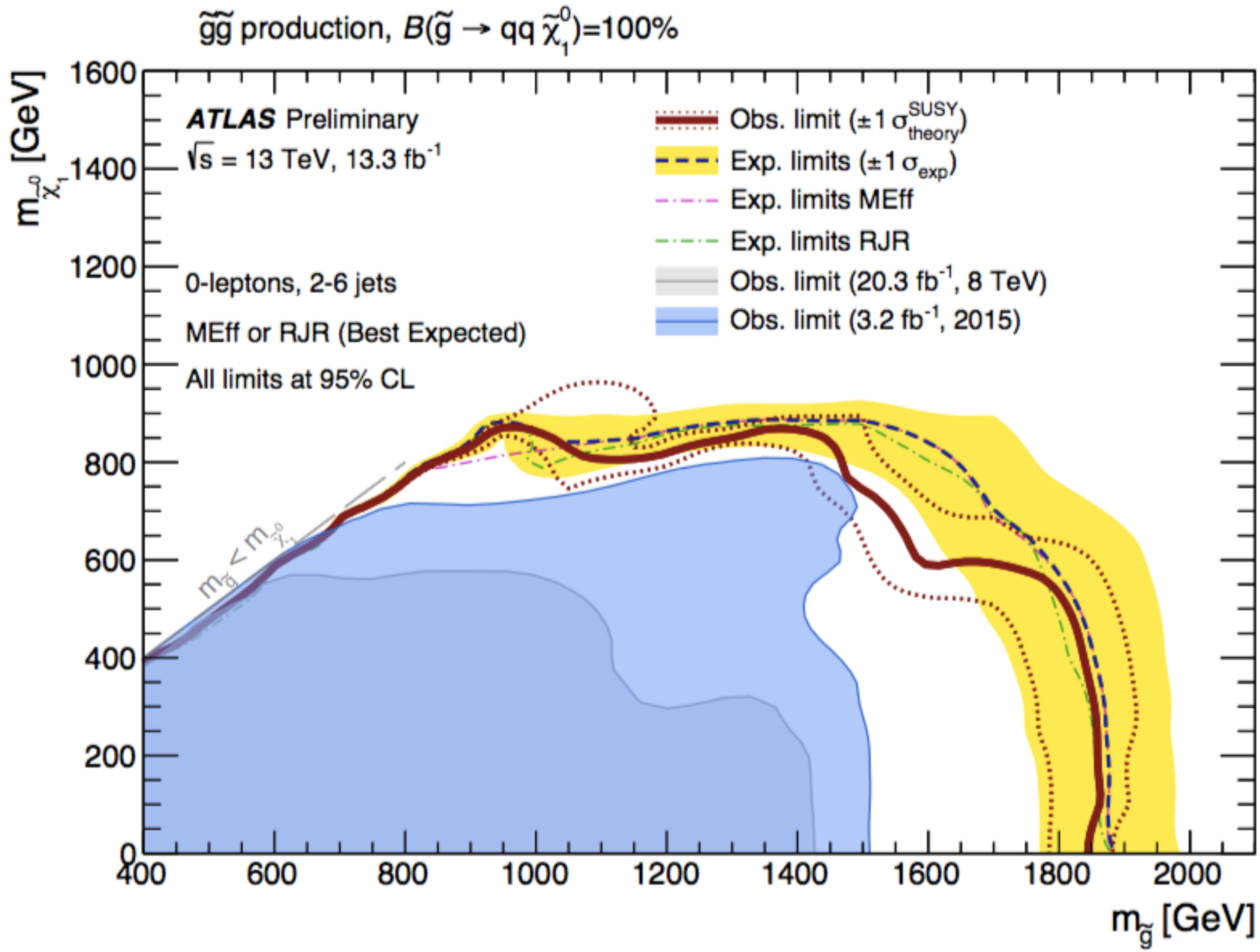
Supersymmetry might be a solution

[Fig. from SUSY primer, S. Martin]

However, SUSY particles have not been found



Colored SUSY particles should be heavier than 1.4-1.8 TeV.



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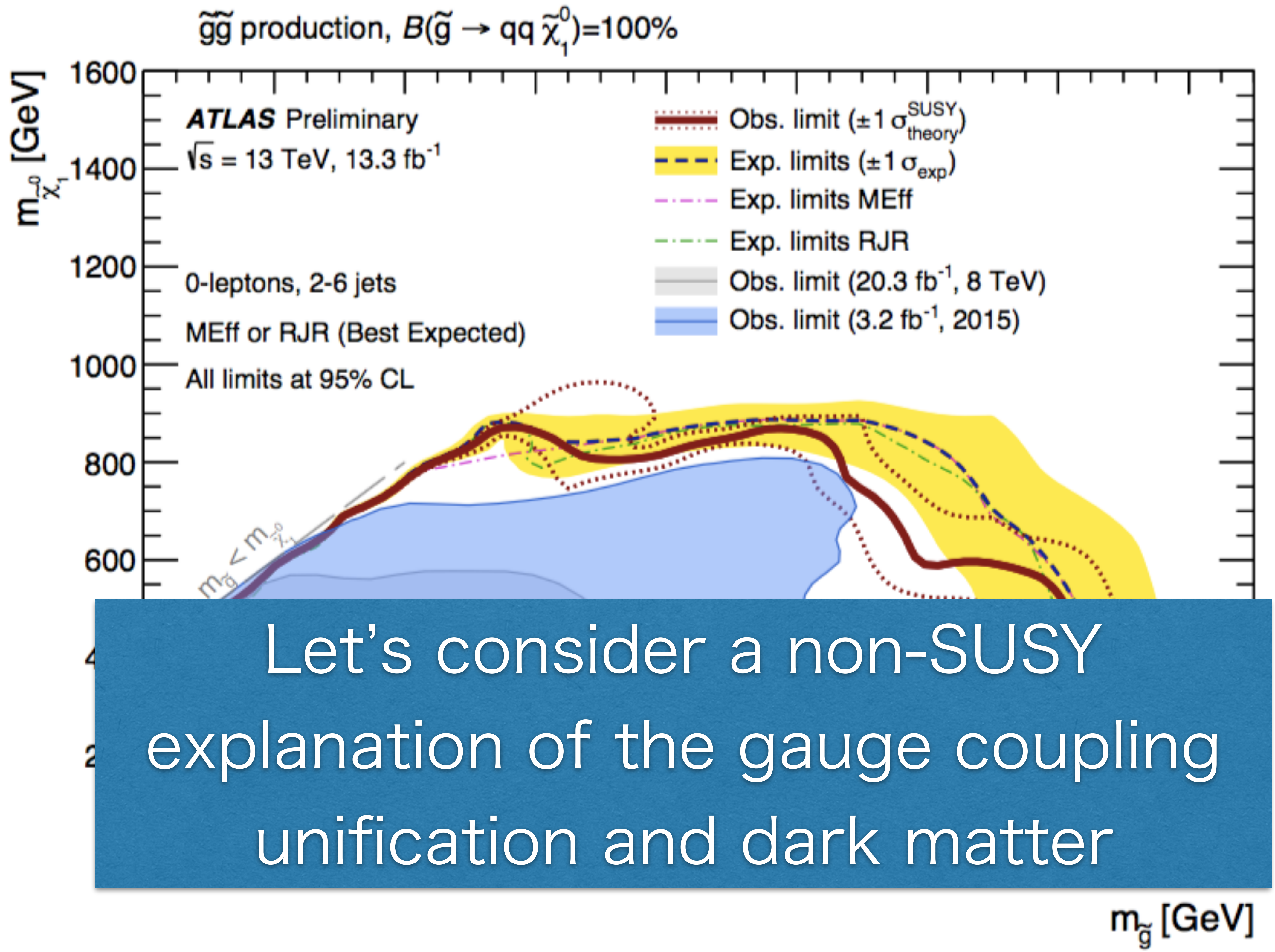
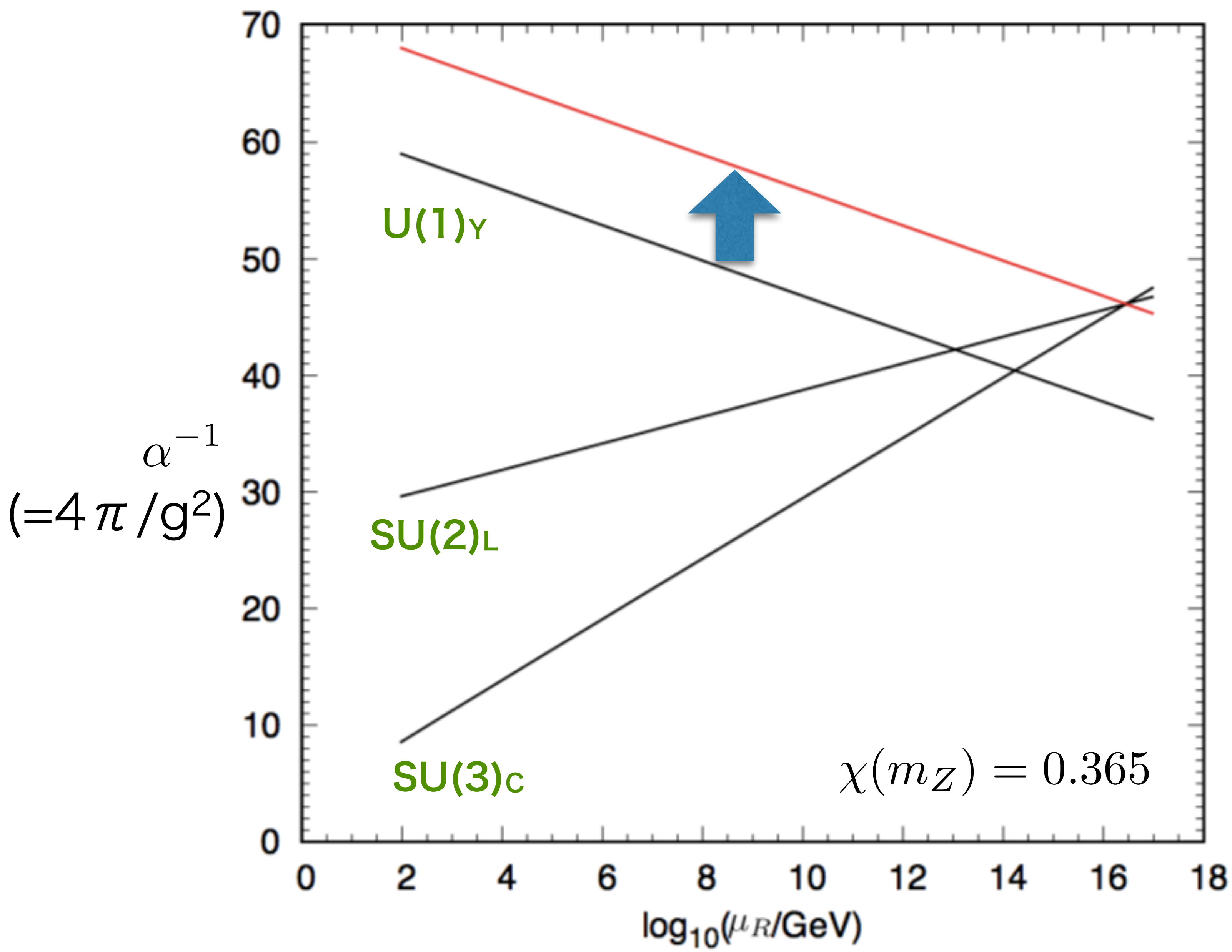


Let's consider a non-SUSY explanation of the gauge coupling unification and dark matter

We introduce a **massless hidden photon** and **hidden matter** to SM

The normalization of the U(1)Y gauge coupling is modified by the kinetic mixing with a massless hidden photon.



[Redondo, 2008; Takahashi, Yamada, **N.Y.**, 2016; Daido, Takahashi, **N.Y.**, 2016]

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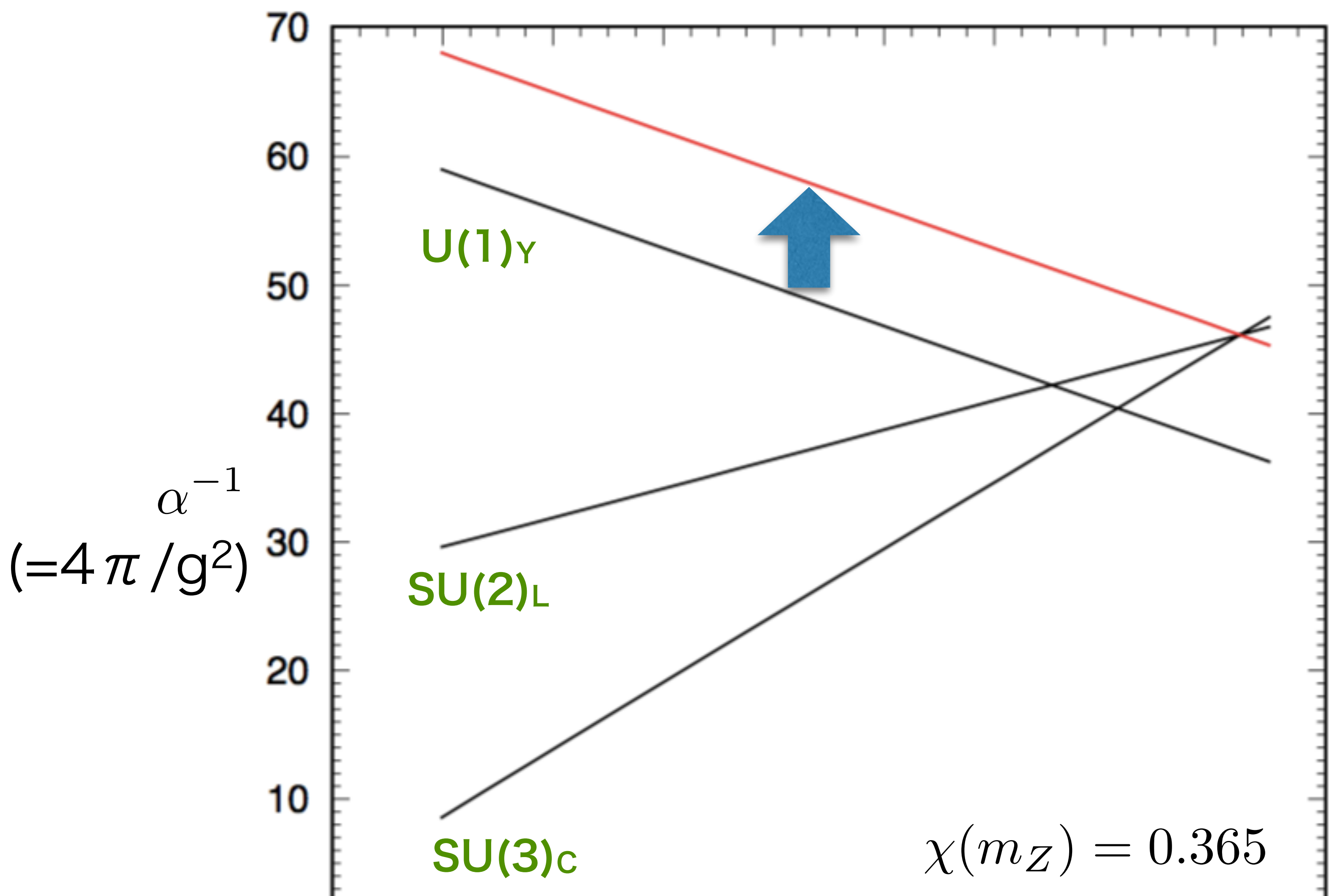
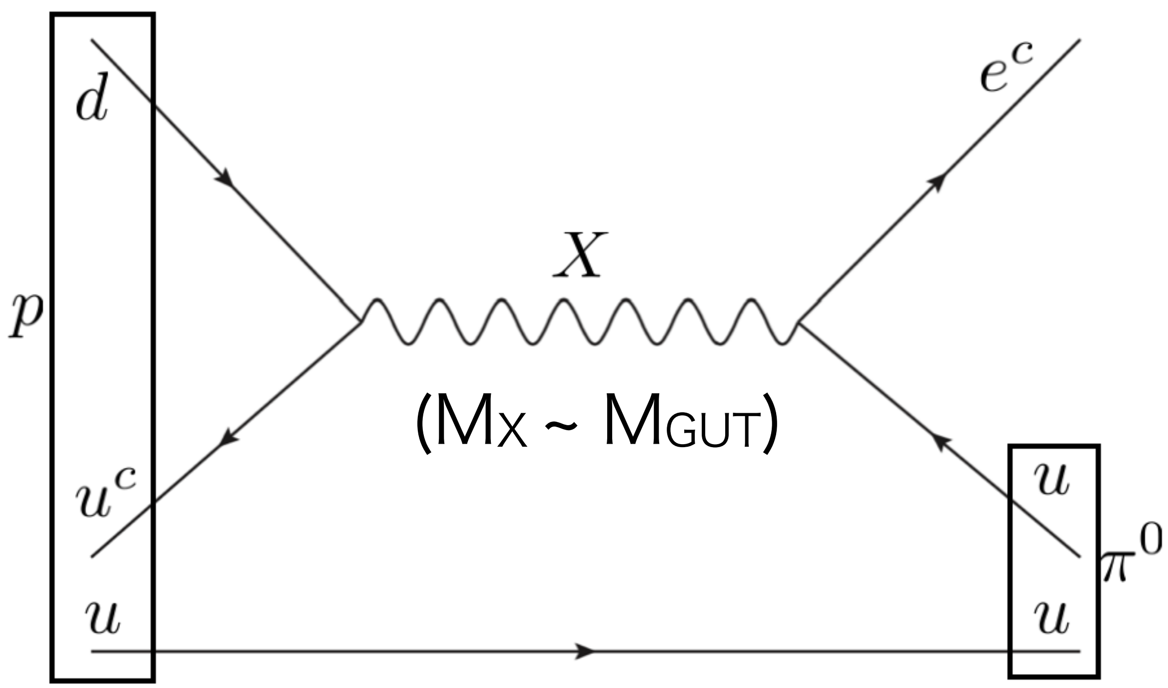


The gauge coupling unification is achieved without Supersymmetry

[Redond … 016]

- The unification scale is ~$10^{16.5}$ GeV, avoiding the rapid proton decay



(M$_X$ ~ M$_{GUT}$)

~10^{37} years ($p \rightarrow \pi^0 e^+$)

exp: > 1.7 x 10^{34} years

[Takhistov, 2016]

The unbroken U(1)$_H$ explains the stability of the DM (hidden matter)

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

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

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

[Holdom, 1986]

Here, we consider unbroken $U(1)_H$

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

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

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

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

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

$$\Downarrow$$

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

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

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

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

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

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

The hidden matter obtains fractional $U(1)_Y$ charge proportional to g_H and χ

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

Couplings are related to

observed value

$$\boxed{\begin{aligned} g_Y \\ g_H \end{aligned}} \begin{aligned} &= \frac{g'_Y}{\sqrt{1-\chi^2}} \\ &= g'_H \end{aligned}$$

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

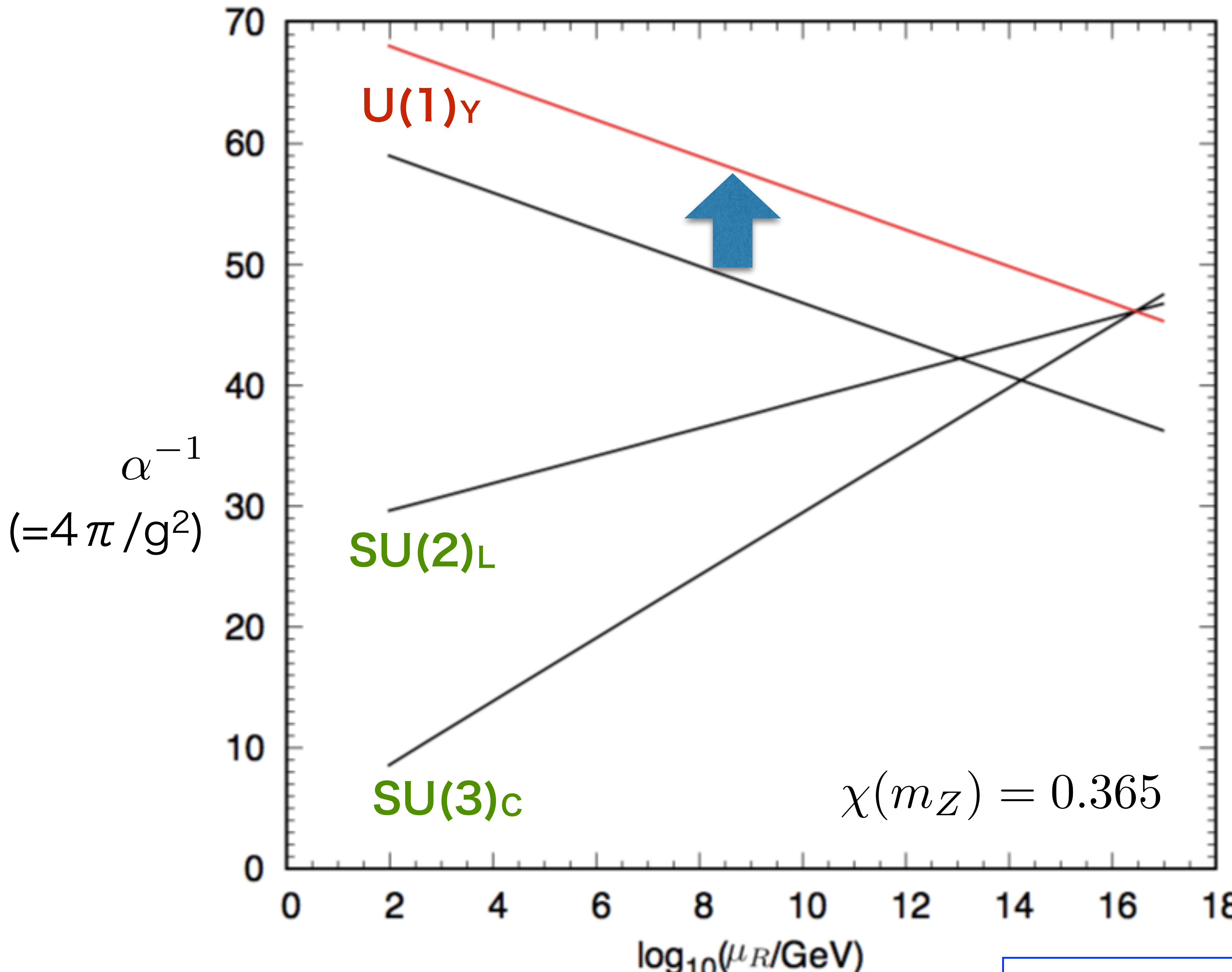
$$A_H^{\mu\,\prime} = A_H^\mu - \frac{\chi}{\sqrt{1-\chi^2}}A_Y^\mu$$

couplings in the canonical basis

Normalization of U(1)$_Y$ changes

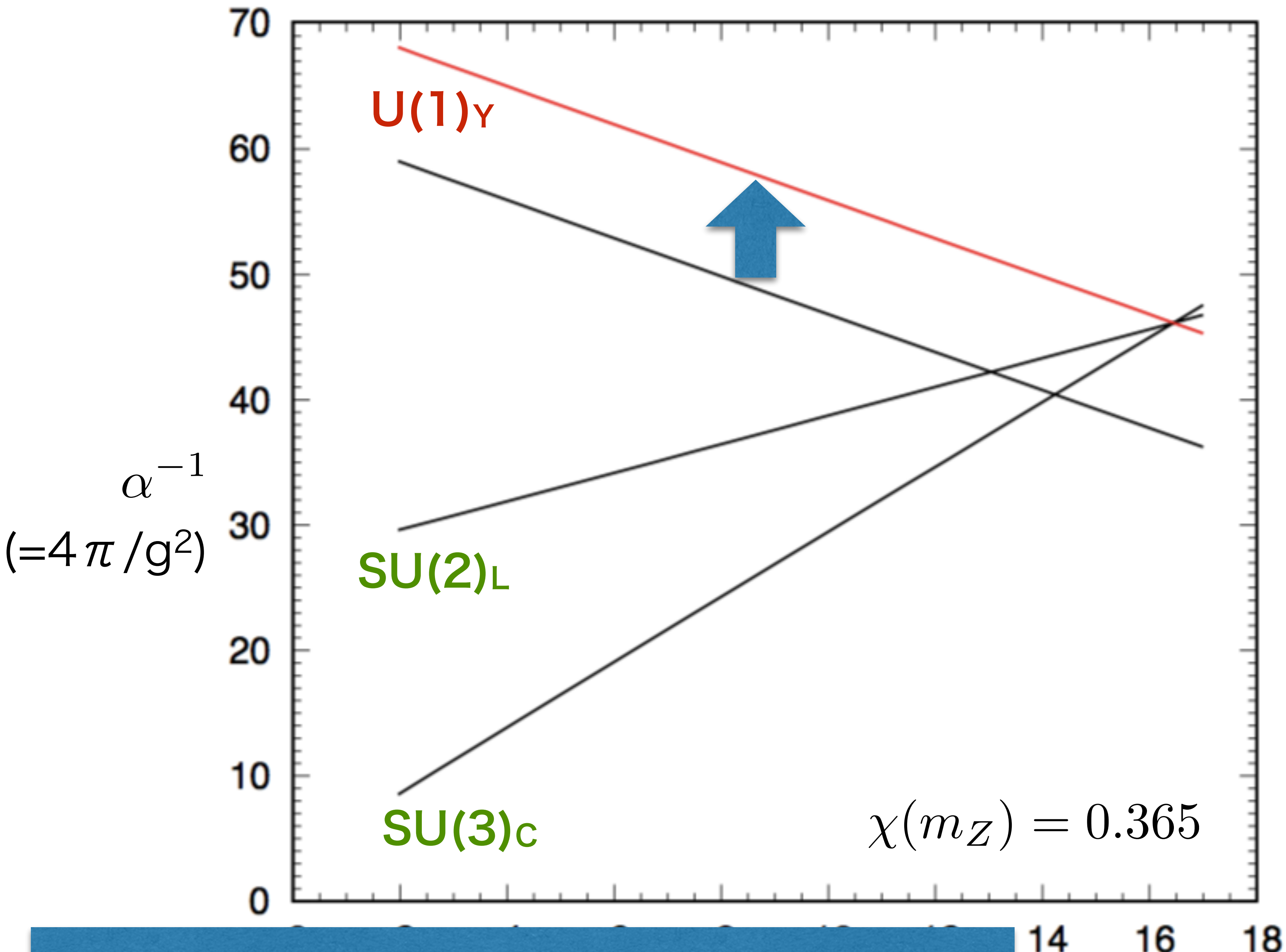
Gauge coupling unification

Without hidden matters



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

Without hidden matters



This is just the change of the normalization of U(1)Y

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

In other words, there are no phenomenological implications at the low-energy

$$\bar{\Psi}_i \gamma_\mu (g'_Y Q_i A'^{\mu}_Y) \Psi_i = \bar{\Psi}_i \gamma_\mu (g_Y Q_i A^{\mu}_Y) \Psi_i$$

(original basis)

(canonical basis)

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

with

$$\begin{aligned} A^{\mu}_Y{}' &= \frac{A^{\mu}_Y}{\sqrt{1-\chi^2}} \\ A^{\mu}_H{}' &= A^{\mu}_H - \frac{\chi}{\sqrt{1-\chi^2}} A^{\mu}_Y \end{aligned}$$

The hyperchages are identical: the basis of GUT is not fixed.

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(original basis)

(canonical basis)

$$g_Y = \frac{g'_Y}{\sqrt{1-\chi^2}}, \quad \text{with} \quad \begin{aligned} A^{\mu\,\prime}_Y &= \frac{A^\mu_Y}{\sqrt{1-\chi^2}} \\ A^{\mu\,\prime}_H &= A^\mu_H - \frac{\chi}{\sqrt{1-\chi^2}}A^\mu_Y \end{aligned}$$

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Once we have a hidden matter ⋯

The unification basis is fixed.

We have a dark matter candidate!

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Once we have a hidden matter ⋯

The unification basis is fixed.

We have a dark matter candidate!

Does it spoil the unification?

No. We have checked it using 2-loop RGEs.

Results with 2-loop RGEs

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

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

$$-M_0\bar{\Psi}_0\Psi_0$$ + (other terms in SM Lagrangian)

No SM charges

With a hidden charge of unity

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

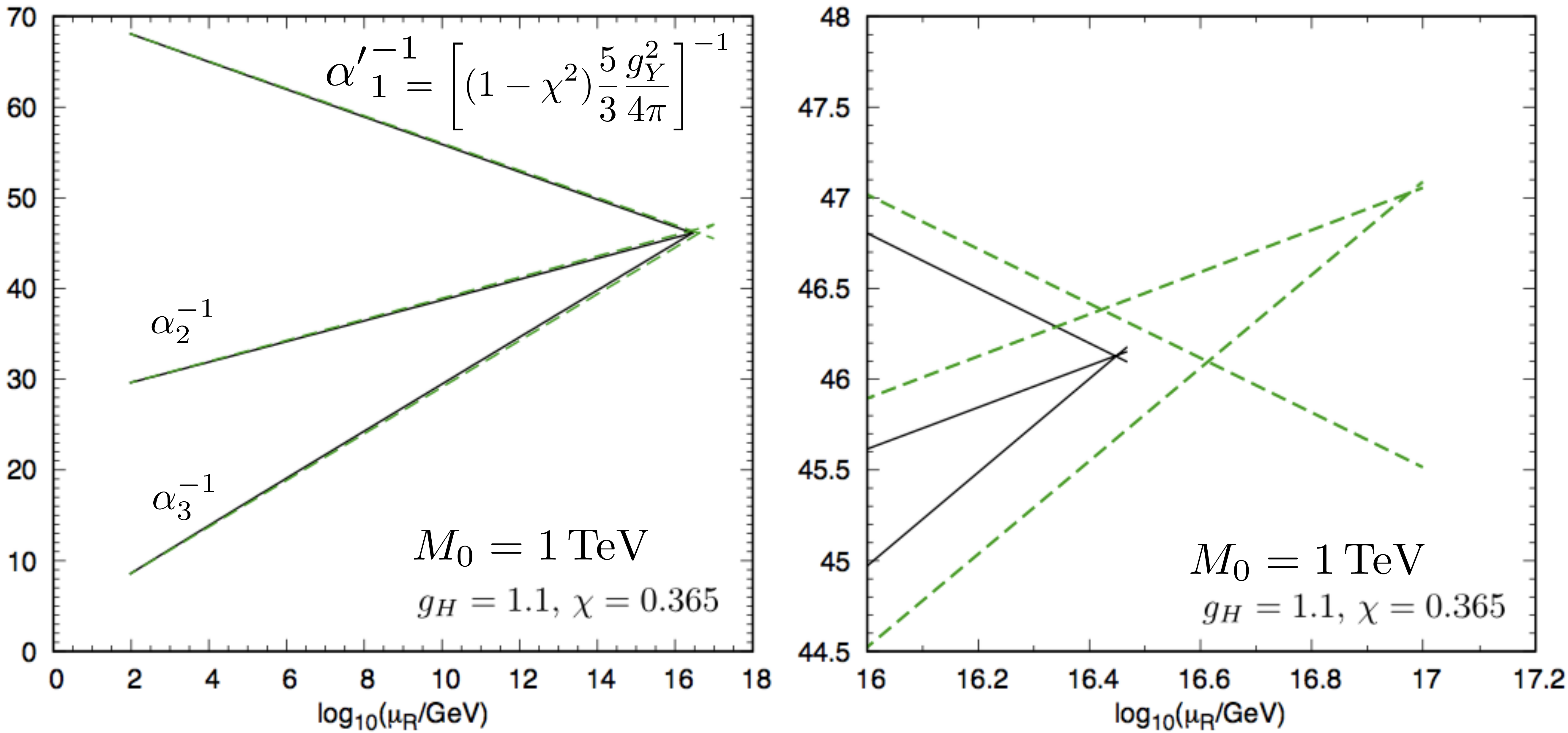
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F'_{H\mu\nu}F'^{\mu\nu}_{H} - \frac{\chi}{2}F'_{H\mu\nu}F'^{\mu\nu}$$

$$-M_0\bar{\Psi}_0\Psi_0$$ + (other terms in SM Lagrangian)

$$\frac{dg_Y}{d\ln\mu_R} = \frac{1}{16\pi^2}\left(\frac{41}{6}g_Y^3 + \frac{4}{3}g_Y g_H^2\frac{\chi^2}{1-\chi^2}\right)$$ canonical basis

$$\frac{dg'_Y}{d\ln\mu_R} = \frac{1}{16\pi^2}\left(\frac{41}{6}{g'_Y}^3\right)$$ original basis

α^{-1} $(=4\pi/g^2)$

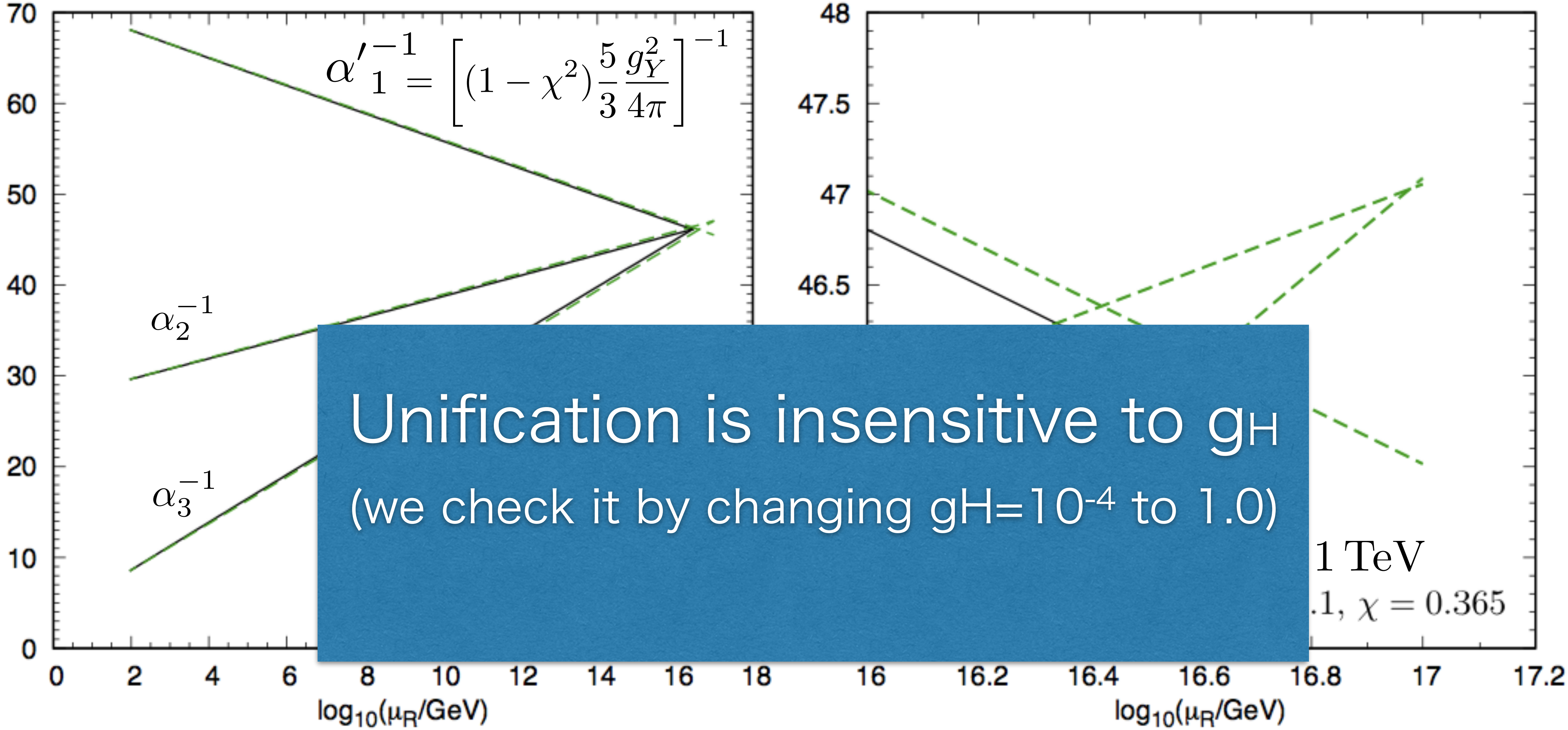


green dashed: one-loop

black solid: two-loop

The unification is fixed by $\chi(m_Z)$

α^{-1} ($=4\pi/g^2$)



Unification is insensitive to g_H

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

green dashed: one-loop

black solid: two-loop

The unification is fixed by $\chi(m_Z)$

With $N_{\rm bi}$ pairs of SU(5) multiplets having $U(1)_H$ charges

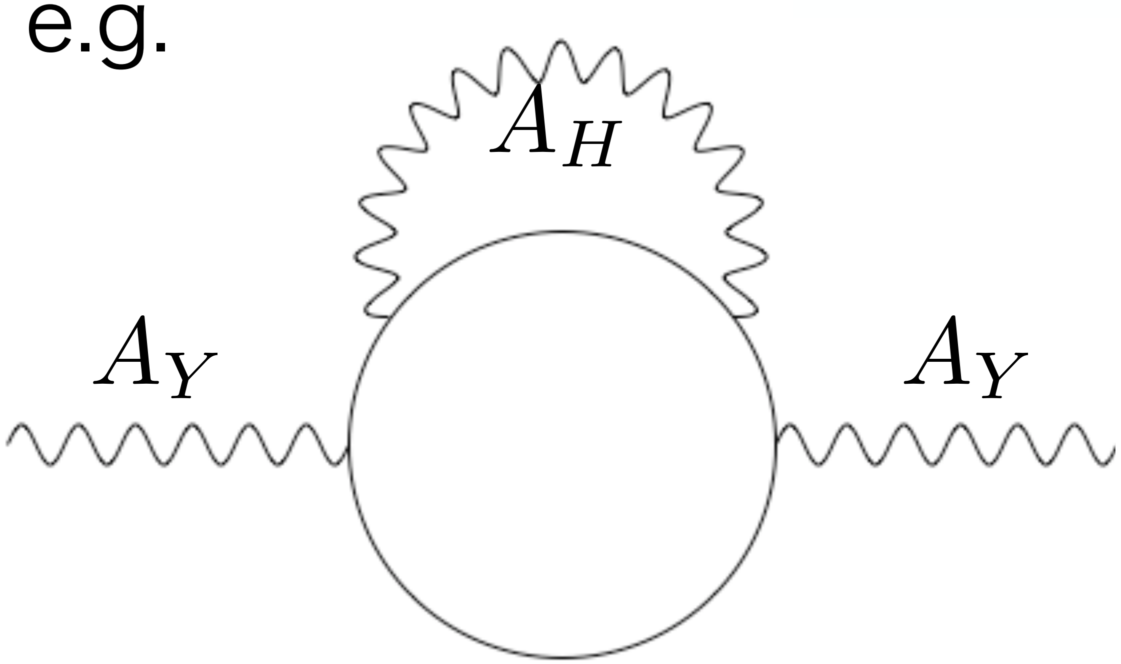
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F'_{H\mu\nu}F'^{\mu\nu}_{H} - \frac{\chi}{2}F'_{H\mu\nu}F'^{\mu\nu}$$

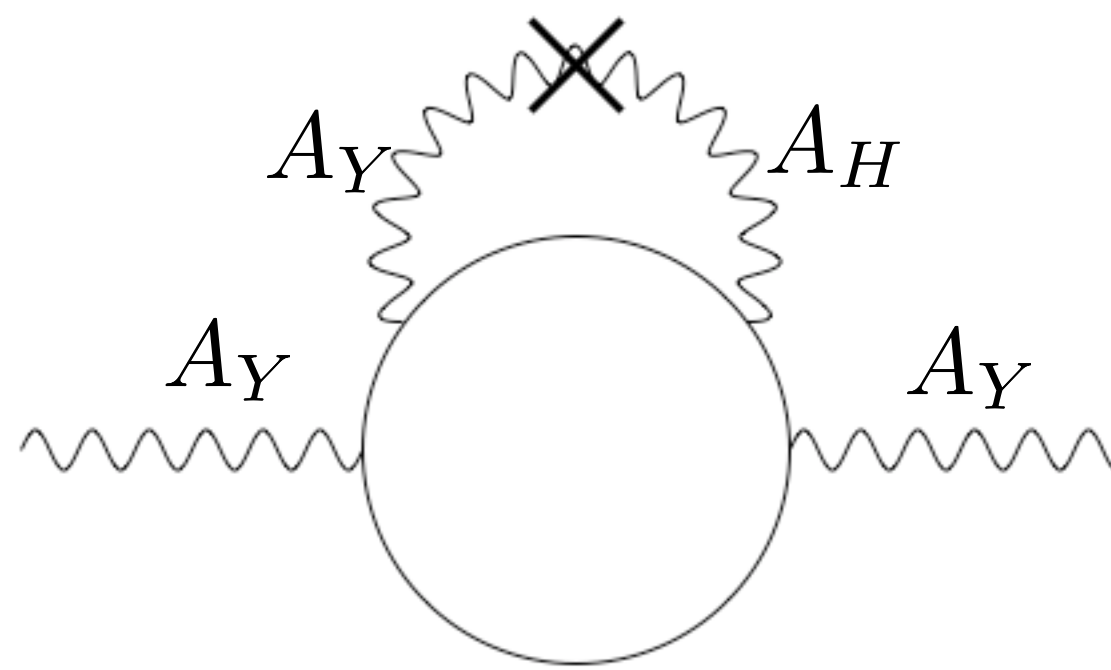
$$-M_V \sum_{i=1}^{N_{\rm bi}} (\bar{\Psi}_{L,i}\Psi_{L,i} + \bar{\Psi}_{\bar{D},i}\Psi_{\bar{D},i}),$$

bi-charged fields

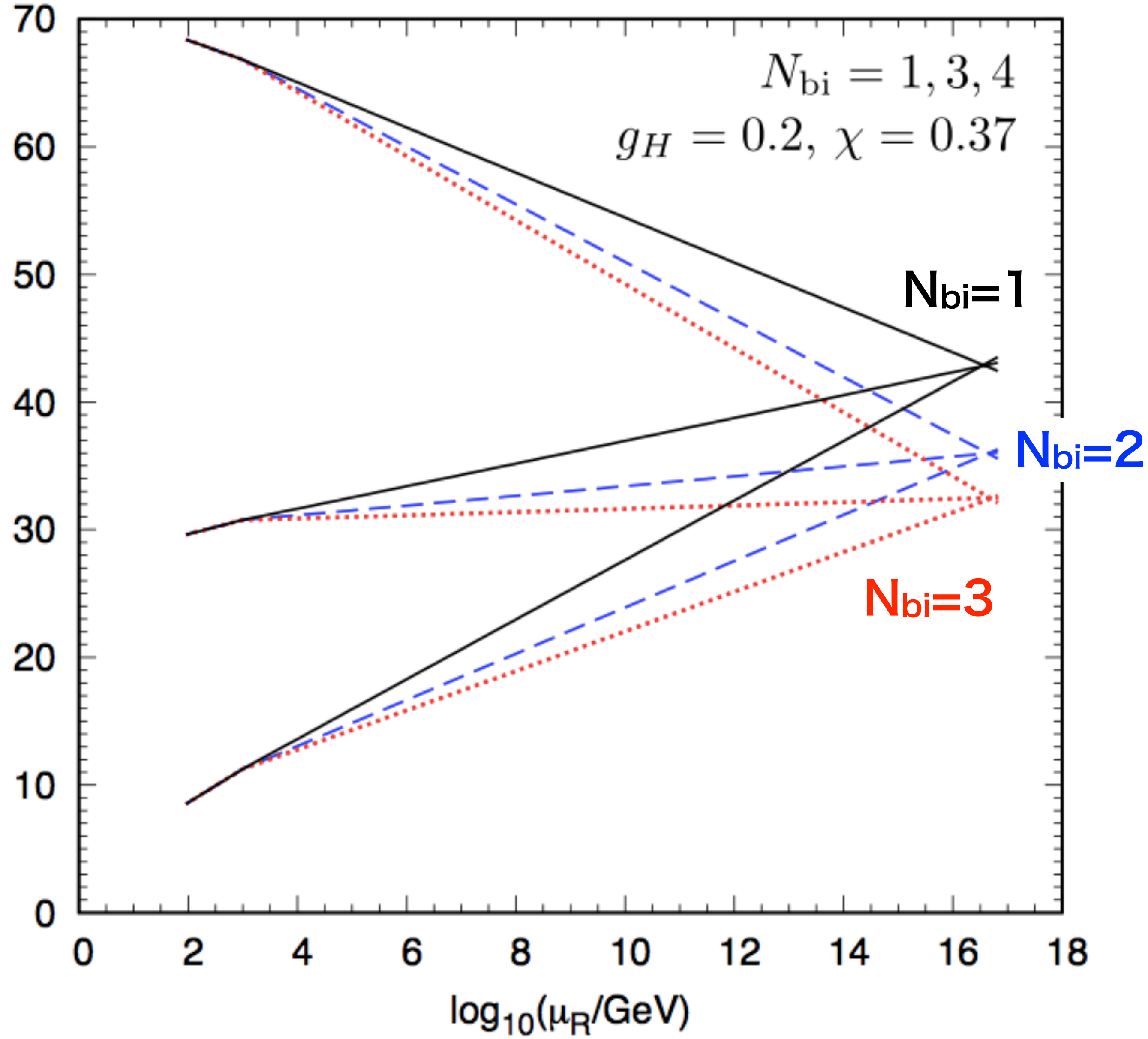
with $$(Q_Y, q_H) = \begin{cases} \left(-\frac{1}{2}, 1\right) & \text{for } \Psi_{L,i} \\ \left(\frac{1}{3}, 1\right) & \text{for } \Psi_{\bar{D},i} \end{cases}$$

e.g.

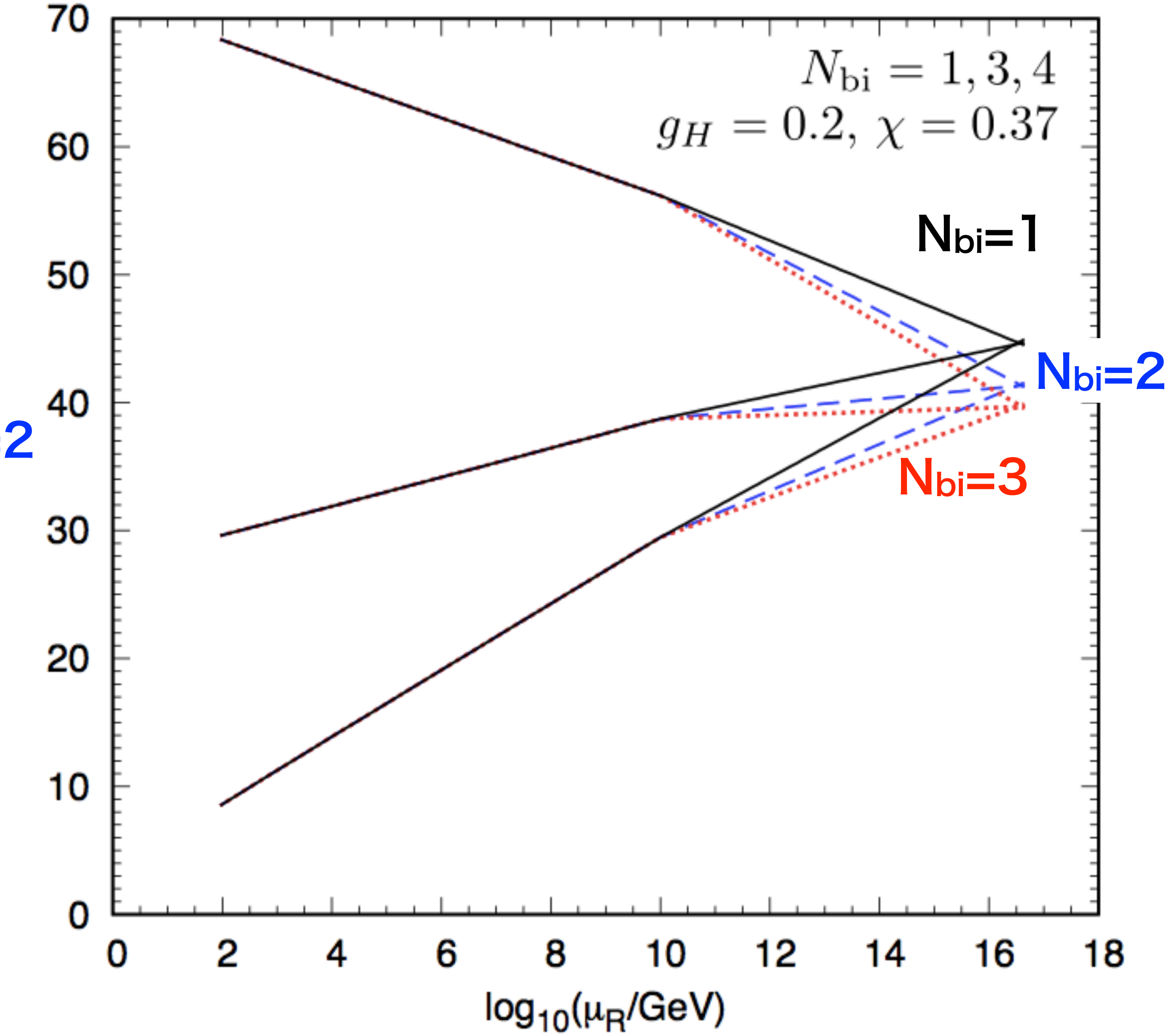




α^{-1} $(=4\pi/g^2)$



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



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

Almost insensitive to N_{bi}, g_H and M_V

Outcomes

- The gauge coupling unification is achieved with the kinetic mixing between $U(1)_Y$ and $U(1)_H$ of ~0.37.
- The unification behavior does not depend on the size of hidden gauge coupling
- Also, the existence of matter fields charged under SU(5) and/or $U(1)_H$ does not affect the unification.
- We can simply includes the SU(5) multiplets at an arbitrary scale.
- For instance, we can accommodate the PQ symmetric solution to the strong CP problem.

Outcomes

- Due to the kinetic mixing of ~0.37, a hidden matter has an electric charge.
- For small hidden gauge coupling
  $\rightarrow$ **Minicharged dark matter** **(having tiny electric charge)**
- **The stability of the DM** is ensured by the unbroken $U(1)_H$.

Minicharged Dark Matter

- For tiny g_H, the hidden matter with Q_Y=0 has a non-zero but tiny electric charge in the canonical basis

$$\bar{\Psi}\gamma_\mu (g'_H A'^\mu_H)\Psi = \bar{\Psi}\gamma_\mu \left(-\frac{g_H \chi}{\sqrt{1-\chi^2}} A_Y + g_H A^\mu_H \right) \Psi$$

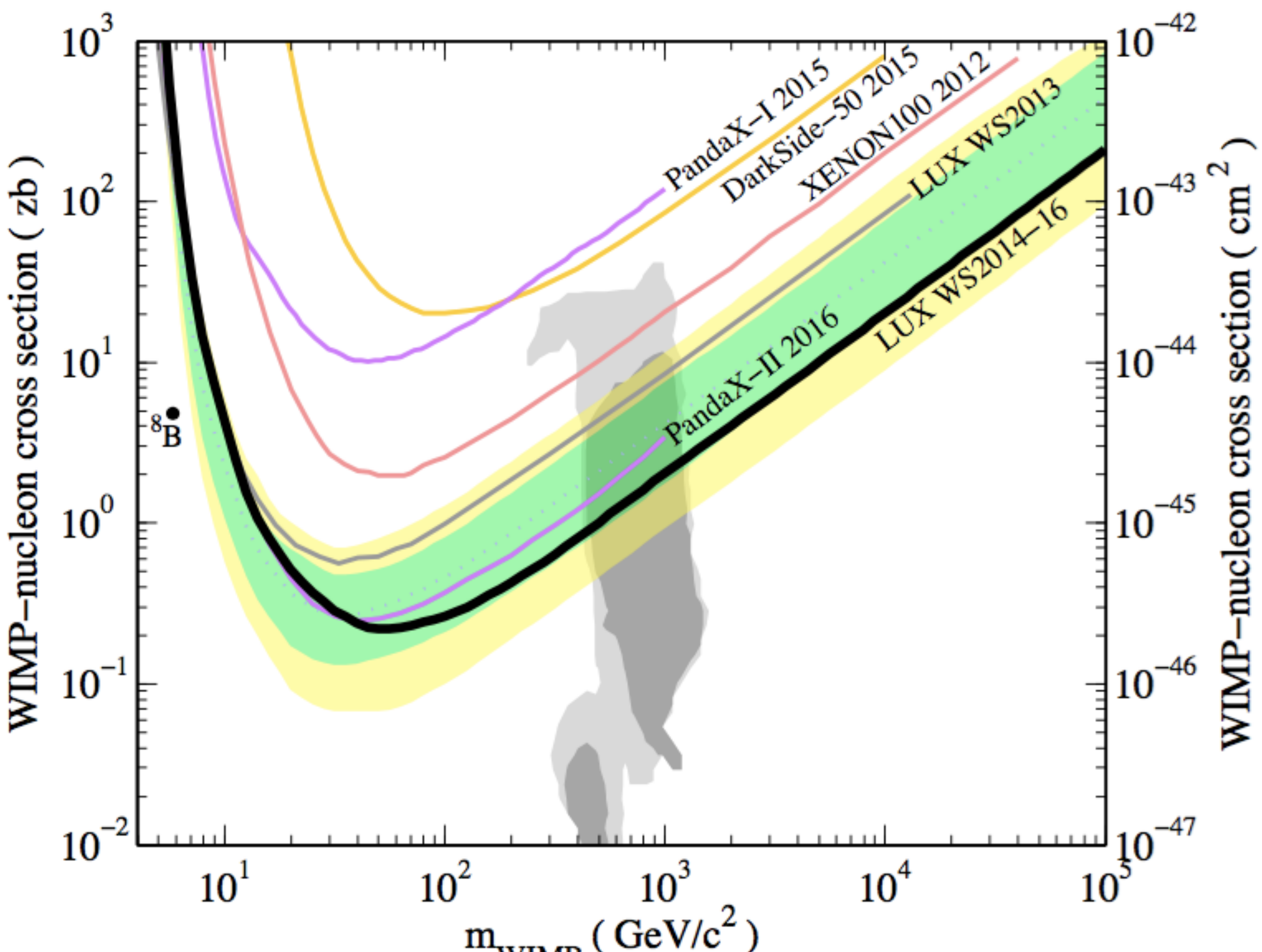
$$\boxed{q_e = -\frac{g_H}{g_Y}\frac{\chi}{\sqrt{1-\chi^2}}}$$

$\rightarrow$ Stable; a candidate for dark matter (minicharged dark matter)

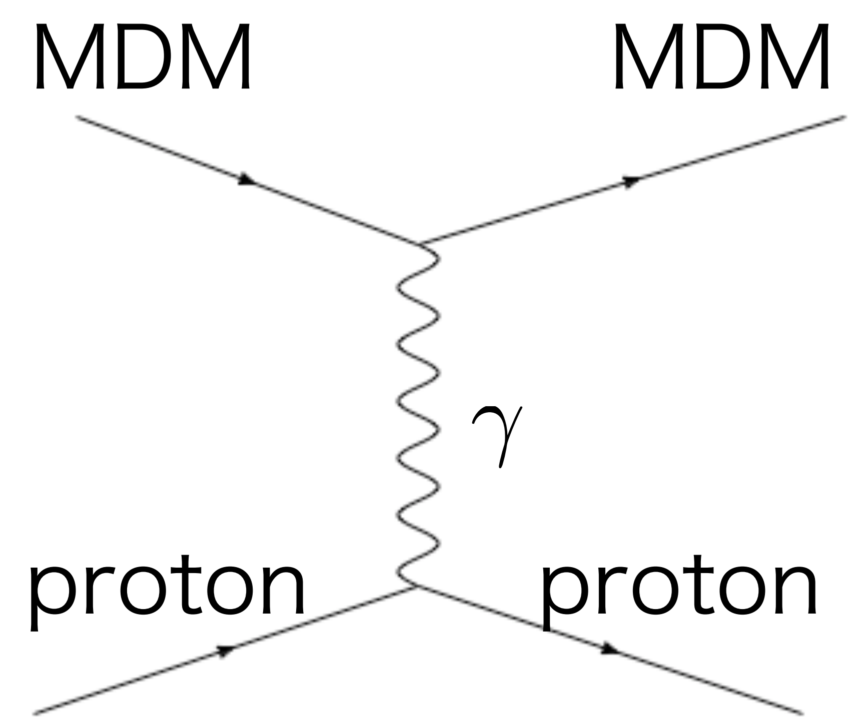
This minicharged DM is constrained by cosmological and astrophysical observations.

Constraints on minicharged DM

Stringent constraint comes from the direct detection experiment.



[Lux, 2016]

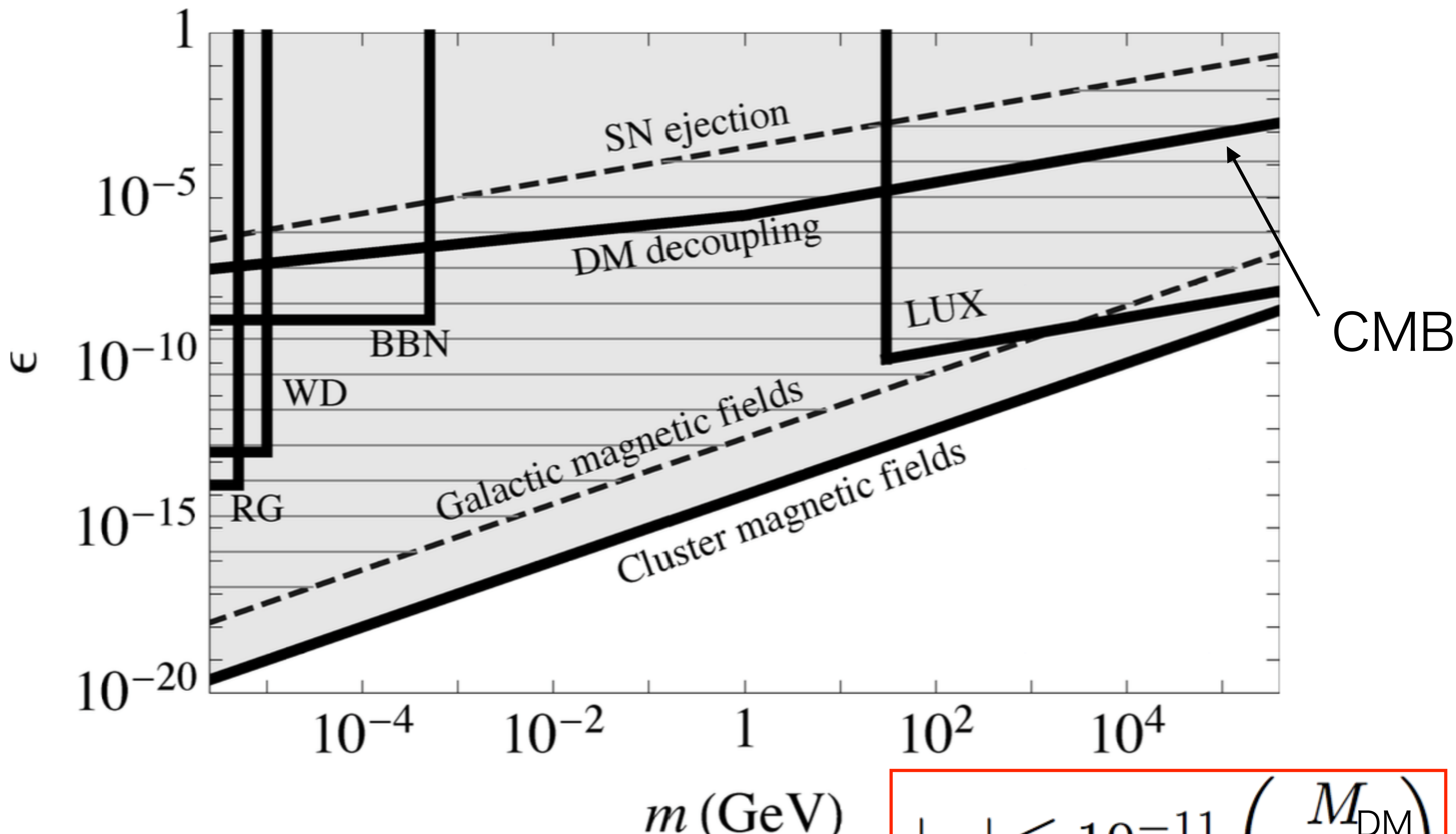


$$\boxed{|q_e| \lesssim 3.6 \times 10^{-10} \left(\frac{M_{\rm DM}}{1\,{\rm TeV}}\right)^{1/2}}$$

g_H should be tiny as 10^{-10}

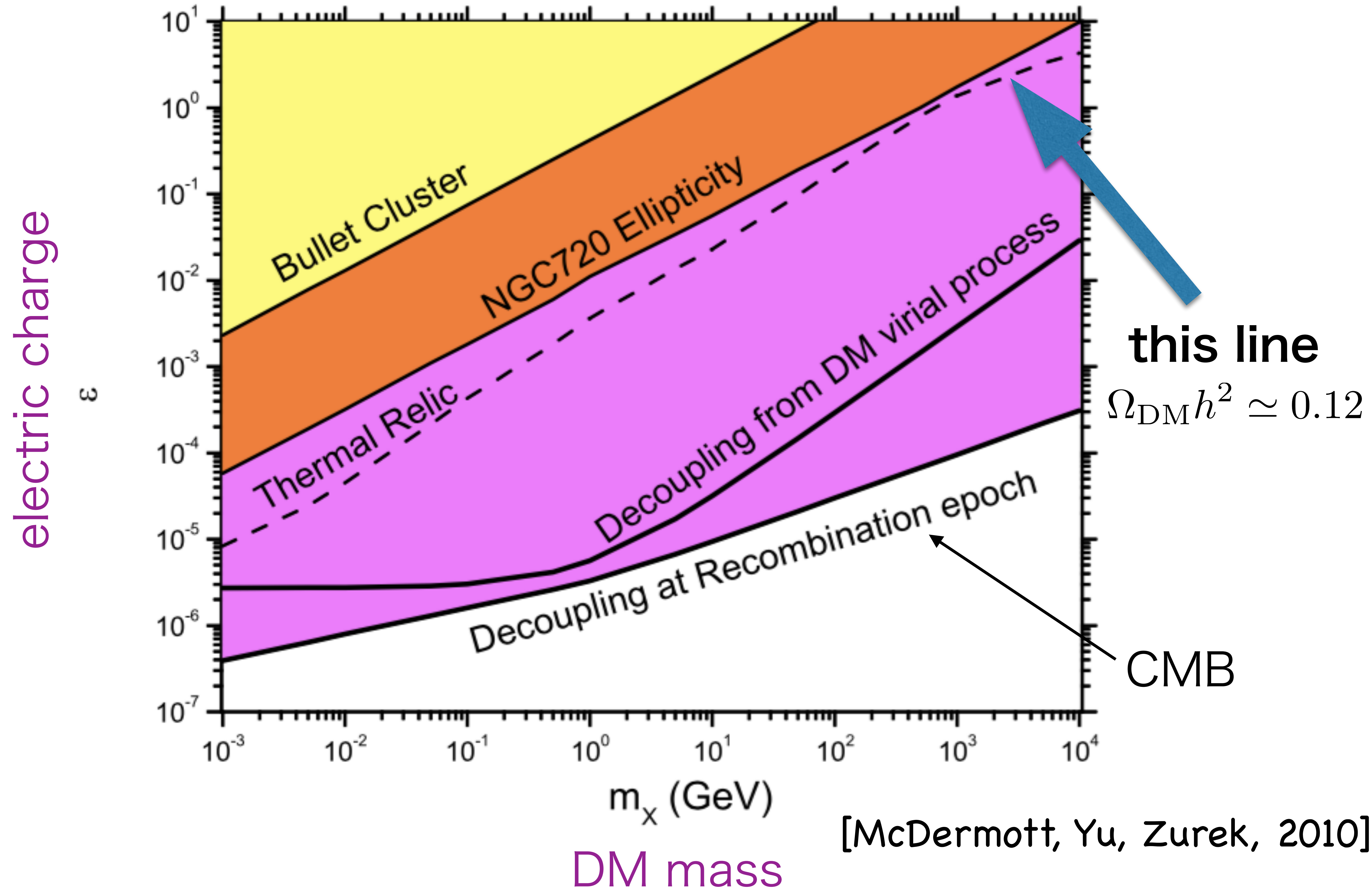
[Nobile, Nardecchia, Panci, 2015]

Magnetic fields in galaxy clusters provide more stringent constraint for the small mass region. (changing DM profile)



$$\boxed{|q_e| \lesssim 10^{-11} \left(\frac{M_{\rm DM}}{\rm TeV}\right)}$$

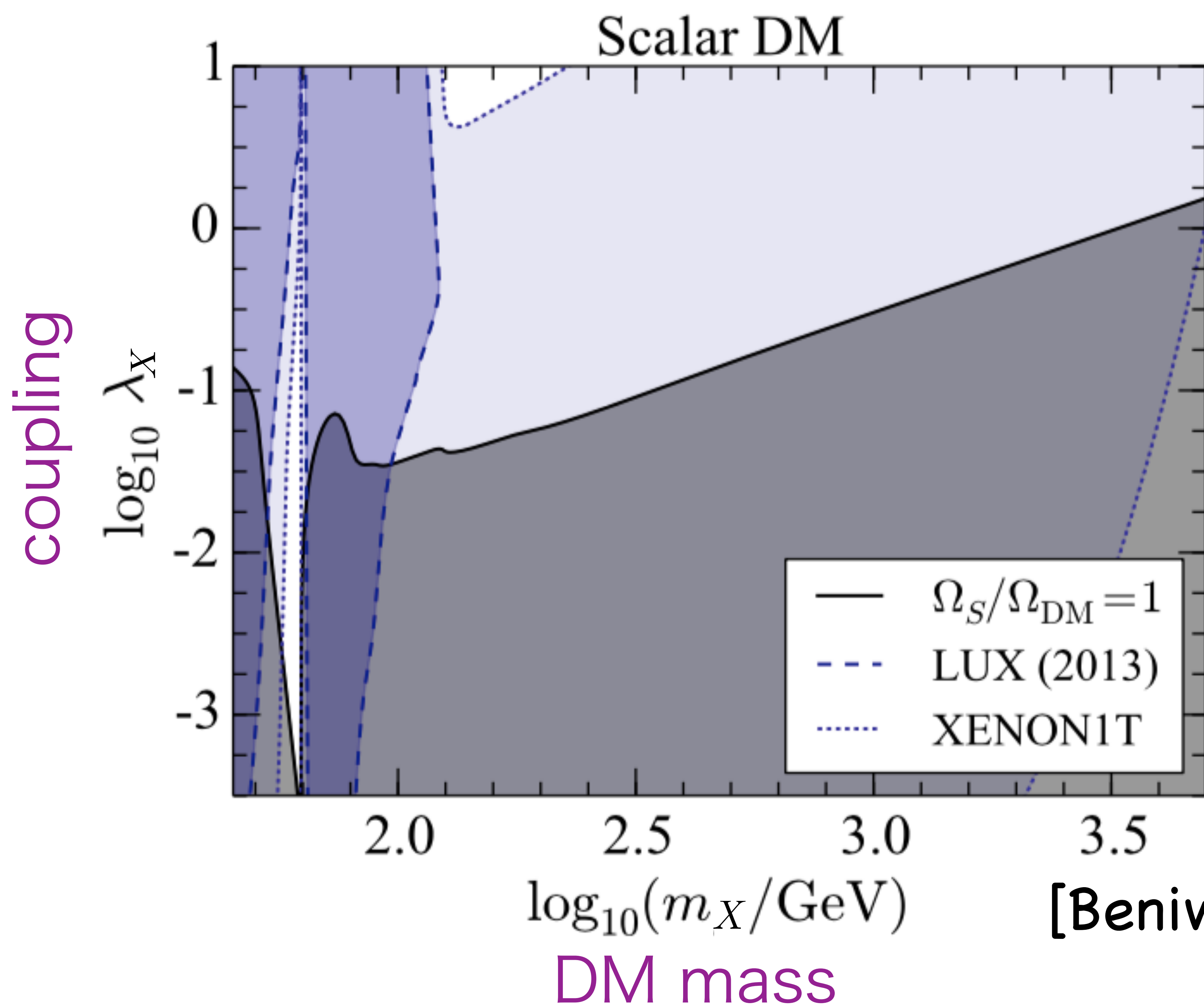
[Kadota, Sekiguchi, Tashiro, 1602.04009]



Required size of the electric charge is much larger than the constraints from LUX, CMB and cluster magnetic fields.

Correct thermal relic abundance can be obtained if there is a Higgs portal interaction (or non-thermal production)

$$\mathcal{L} \ni -m_X^2|X|^2 + \lambda_X|H|^2|X|^2 \quad \text{or} \quad -m_Y\bar{\Psi}_Y\Psi_Y + \frac{\lambda_Y}{\Lambda_Y}|H|^2\bar{\Psi}_Y\left(\frac{1-\gamma_5}{2}\right)\Psi_Y + h.c.,$$



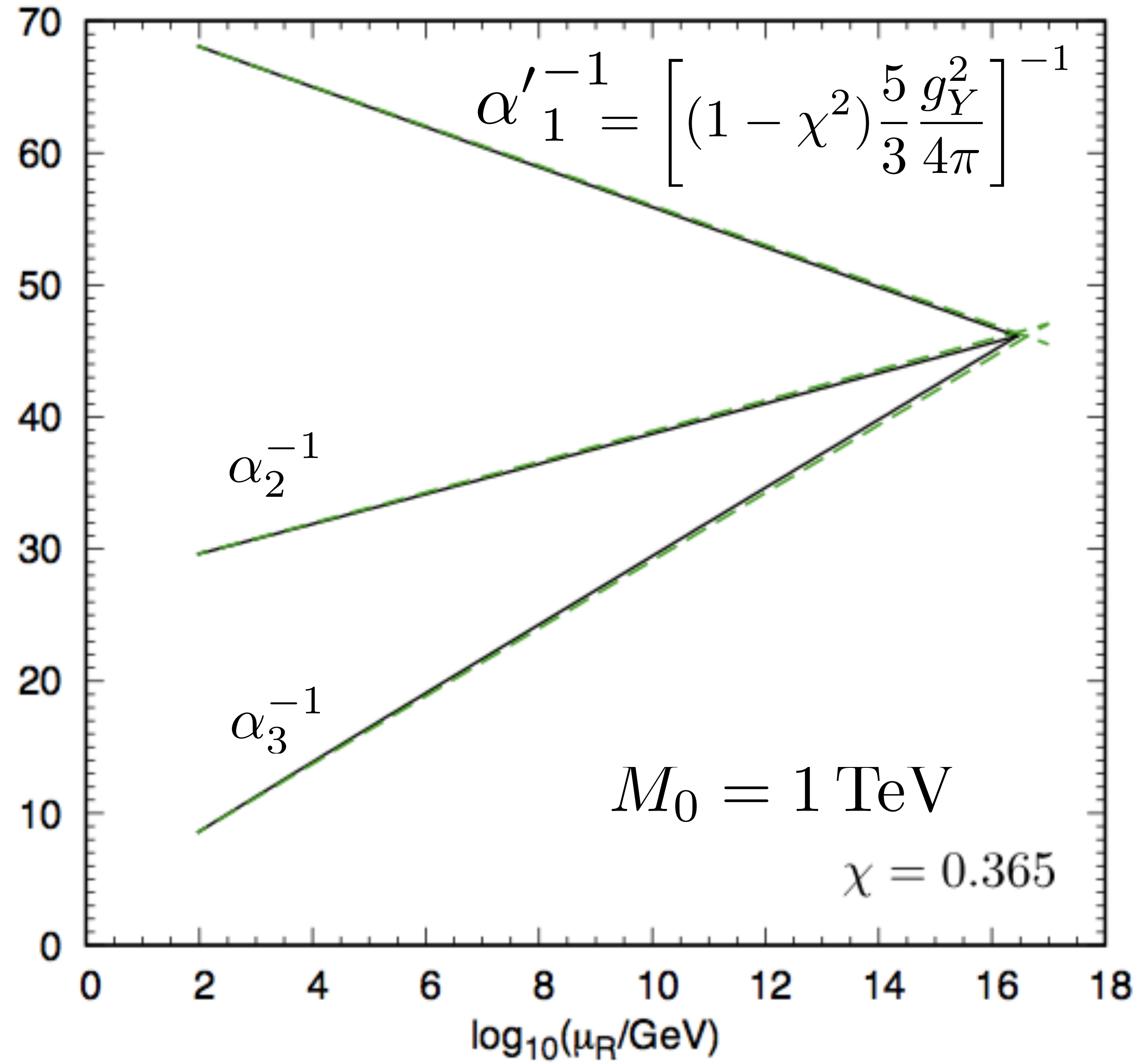
m_X > ~0.6 TeV with Lux2016

[Beniwal et.al. 2015]

Summary

- Massless hidden photon with the kinetic mixing term can achieve the gauge coupling unification **without Supersymmetry**
- The unification scale is rather high as $10^{16.5}$ GeV (no rapid proton decay)
- For tiny g_H, we have the interesting dark matter candidate: **minicharged dark matter**
- Stability is ensured by the hidden gauge symmetry
- The correct relic abundance is obtained via the Higgs portal.

SM + hidden photon + kinetic mixing
→ GUT + minicharged dark matter!



green dashed: one-loop

black solid: two-loop

Thank you for your attention!

The RG equations

RGEs in the canonical basis

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

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

[Babu, Kolda, March-Russell, 1996]

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

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

RGE of $U(1)_Y$ is trivial only if $b_H=0$ and $b_{\rm mix}=0$

i.e. if there are no hidden matters

The RG equations

RGEs in the original basis are very simple:

$$\frac{dg'_Y}{dt} = \frac{1}{16\pi^2} b_Y g'^3_Y \,,$$

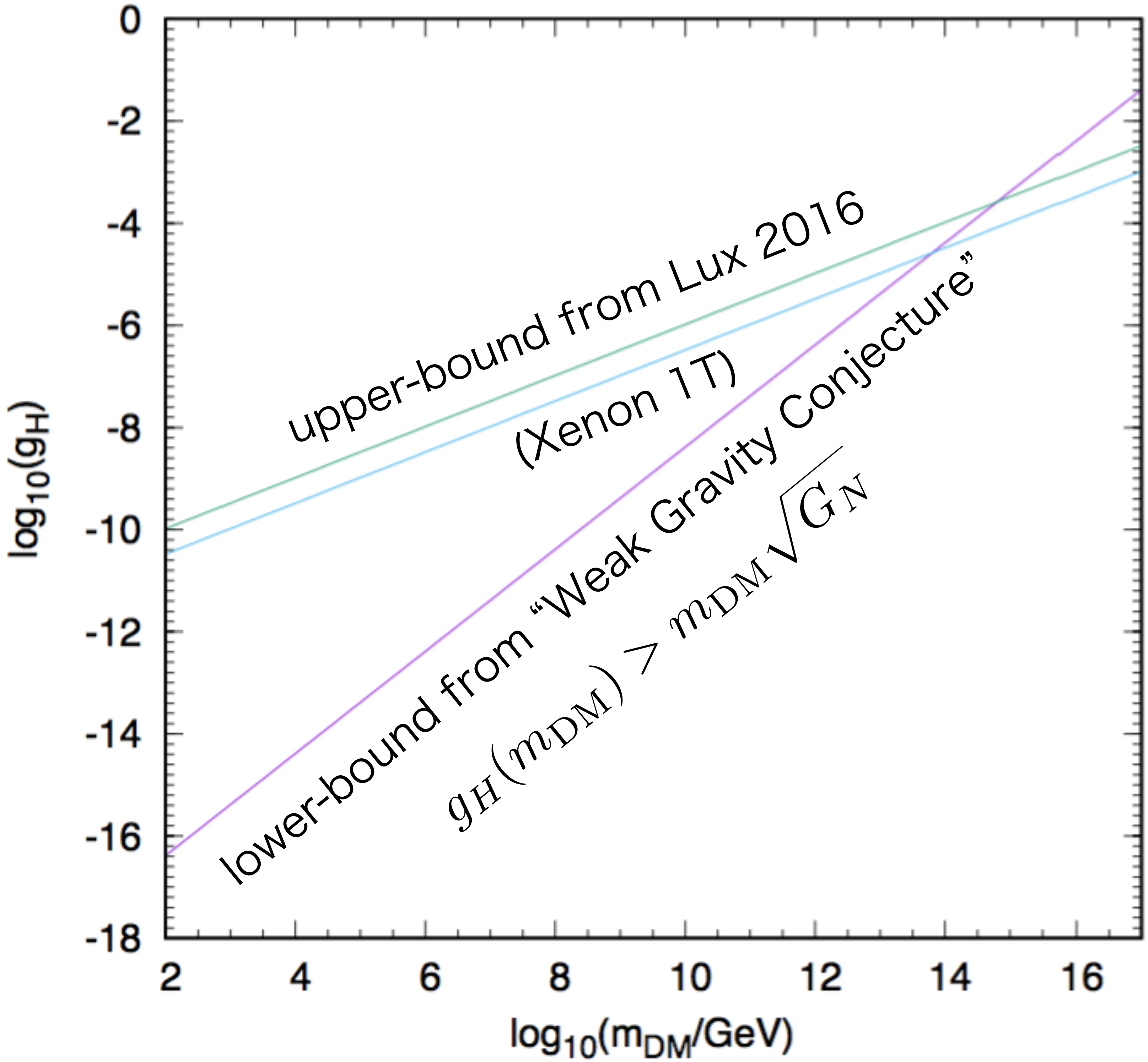
$$\frac{dg_H}{dt} = \frac{1}{16\pi^2} b_H g_H^3 \,,$$

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

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

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

Bound from WGC



The small coupling is close to the lower-bound from the WGC.

[WGC: Arkani-Hamed, Motl, Nicolis, Vefa, 2006]

Origin of the Kinetic mixing

The kinetic mixing arises via a higher dimensional operator

$$\mathcal{L} \ni \frac{k_0}{M_*} \mathrm{Tr}(\langle \Sigma_{24} \rangle F_{5\mu\nu}) F_H^{\mu\nu},$$

$$\langle \Sigma_{24} \rangle = \frac{v_{24}}{2\sqrt{15}} \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix}$$

$$\chi = -k_0 \frac{v_{24}}{M_*},$$

There may exists an operator

$$\mathcal{L} \ni \frac{k_1}{2M_*} \mathrm{Tr}(\langle \Sigma_{24} \rangle F_{5\mu\nu} F_5^{\mu\nu}),$$

$$\frac{\Delta\alpha_1^{-1}}{\alpha_5^{-1}} = \sqrt{\frac{1}{60}} \frac{k_1}{k_0} \chi, \quad \frac{\Delta\alpha_2^{-1}}{\alpha_5^{-1}} = \sqrt{\frac{3}{20}} \frac{k_1}{k_0} \chi, \quad \frac{\Delta\alpha_3^{-1}}{\alpha_5^{-1}} = -\sqrt{\frac{1}{15}} \frac{k_1}{k_0} \chi,$$

We can not realize the consistent GUT only with the above threshold correction, due to the proton decay constraint

$$k_1/k_0 \lesssim 6 \quad \Rightarrow \quad (\Delta\alpha_2^{-1} - \Delta\alpha_3^{-1})/\alpha_5^{-1}, \text{ is within } 5\% \text{ level}$$