Summer Institute 2013, 20 August

Focus Point in Gaugino Mediation

~Reconsideration of the fine-tuning problem~

Norimi Yokozaki (Kavli IPMU)

Tsutomu. T. Yanagida and N.Y. , Phys. Lett. B722, 355 (2013)

Tsutomu. T. Yanagida and N.Y. , 1308.0536

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(Rethinking)

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We got an evidence of SUSY?

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We finally discovered a spin-0 particle,
Higgs boson

Higgs boson

spin-0

Hagure metal

(To discover is also difficult)

Ref. Dragon Quest

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Higgs boson

SUSY particles are there!

Hagure metal

(To discover is also difficult)

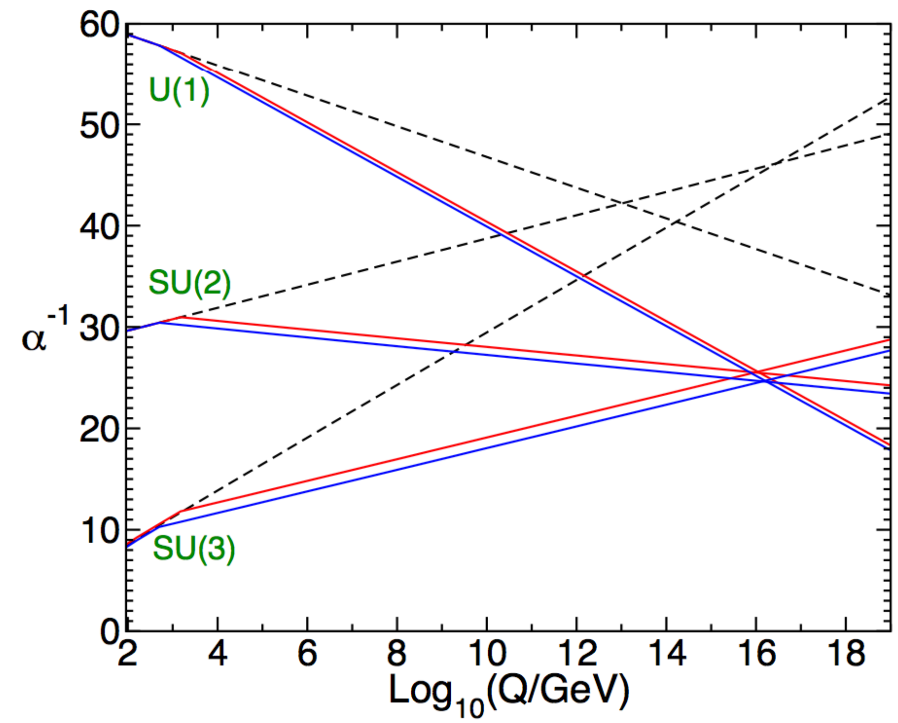
Ref. Dragon Quest

Outline

- Introduction
- Fine-tuning and original focus point scenario
- Focus point in gaugino mediation
- Summary

Benefits of SUSY

- Gauge coupling unification



SUSY primer, S. Martin

- Provide a candidate for dark matter

  gravitino, neutraino

Benefits of SUSY

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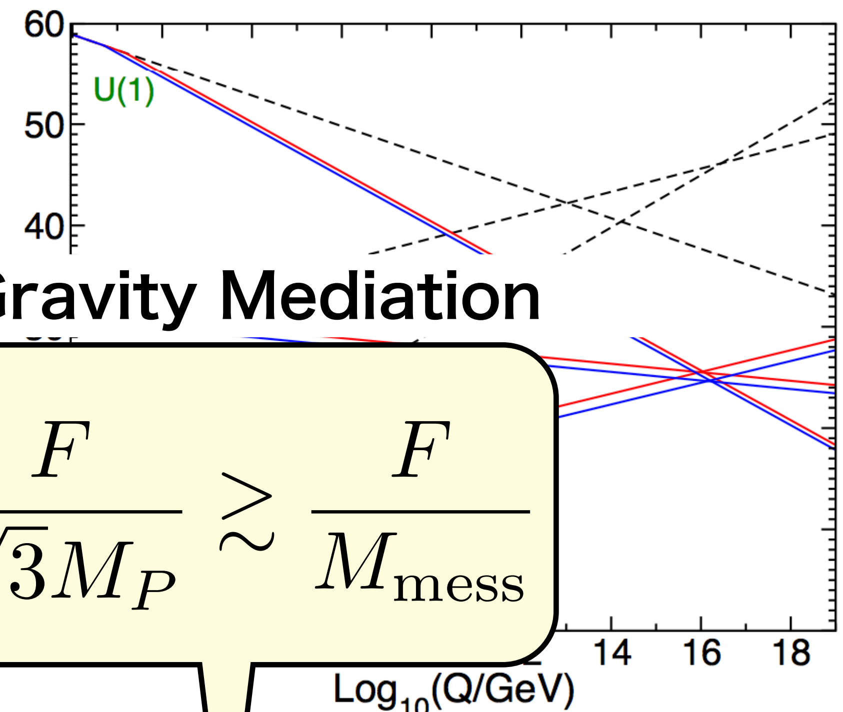

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e.g. Gauge Mediation

$$\frac{F}{\sqrt{3}M_P} < \frac{F}{M_{\rm mess}}$$

Gravity Mediation

$$\frac{F}{\sqrt{3}M_P} \gtrsim \frac{F}{M_{\rm mess}}$$

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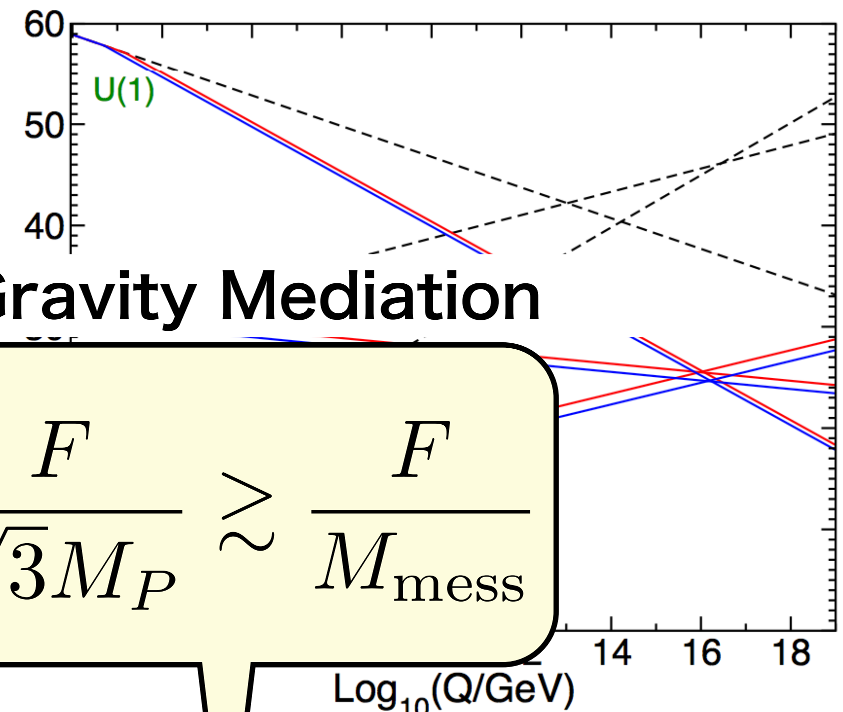

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- Stabilization of the electroweak symmetry breaking (EWSB) scale

Without SUSY, EWSB scale is not stabilized

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1, Destabilization at loop level

$$\Delta m_H^2 = -(6\lambda_{\mathrm{self}} - 6y_t^2 + \dots)\frac{\Lambda_{\mathrm{UV}}^2}{16\pi^2} + \dots$$

Well known quadratic divergence

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Well known quadratic divergence

2, Destabilization at tree level

$$V = \lambda_X |X_a|^2 |H|^2$$

e.g., PQ breaking scalar, B-L breaking scalar ...

$$X_a \sim 10^9 - 10^{12}\,\mathrm{GeV} \Rightarrow \lambda_X \sim 10^{-14} - 10^{-20}$$

better than tuning of $\theta < 10^{-10}$?

In SUSY

- **No quadratic divergence**

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- Coupling between intermediate scale, like PQ-scale, and EWSB scale can be controlled **by holomorphy**

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e.g., PQ case (SUSY KSVZ model)

protected by holomorphy

$$W = S(X_a \bar{X}_a - f_a^2) + \mu H_u H_d + \ldots$$

J. E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Nucl. Phys. B **166**, 493 (1980).

The PQ sector does't mixed with EWSB (or other) sector, if their charges are appropriately chosen

SUSY **was** a key ingredient to understand the electroweak symmetry breaking (EWSB)

SUSY is broken **dynamically** in hidden sector

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Gauge mediation
Gravity mediation
(Anomaly mediation)
Gaugino mediation

↓

Soft SUSY breaking masses of O(100) GeV

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SUSY is broken **dynamically** in hidden sector

Gauge mediation
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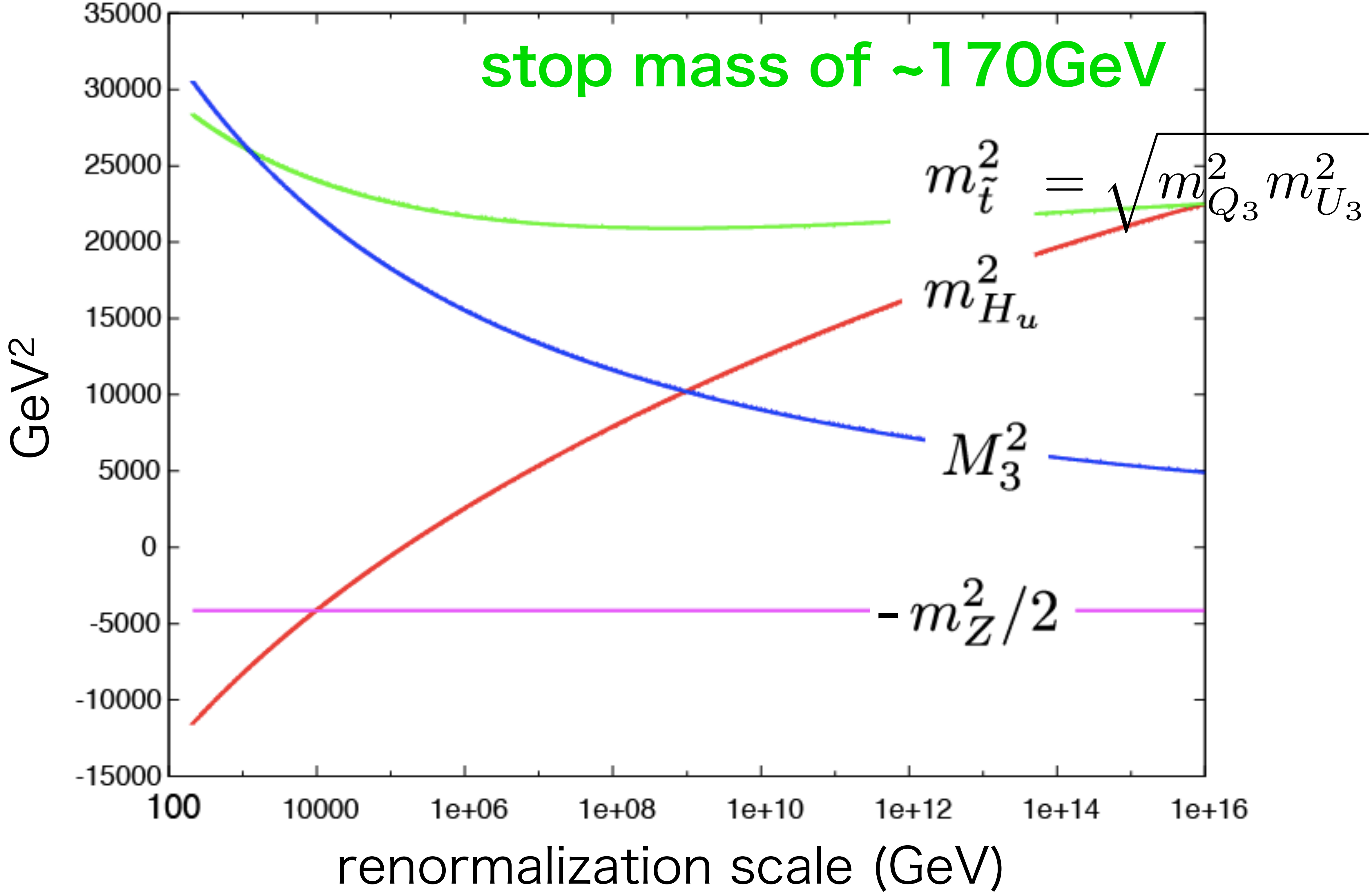
Soft SUSY breaking masses of O(100) GeV

The Fermi scale is obtained by radiative electroweak symmetry breaking

This picture works very well for low-energy SUSY



$$V = (m_{H_u}^2 + |\mu|^2)|H_u^0|^2 + (m_{H_d}^2 + |\mu|^2)|H_d^0|^2$$

$$-B\mu H_u^0 H_d^0 + h.c.$$

$$+\frac{g_Y^2 + g^2}{8}[|H_u^0|^2 - |H_d^0|^2]^2$$

$$+\Delta V \text{ (radiative correction)}$$

$\boxed{W = \mu H_u H_d}$

$$V = (m_{H_u}^2 + |\mu|^2)|H_u^0|^2 + (m_{H_d}^2 + |\mu|^2)|H_d^0|^2$$
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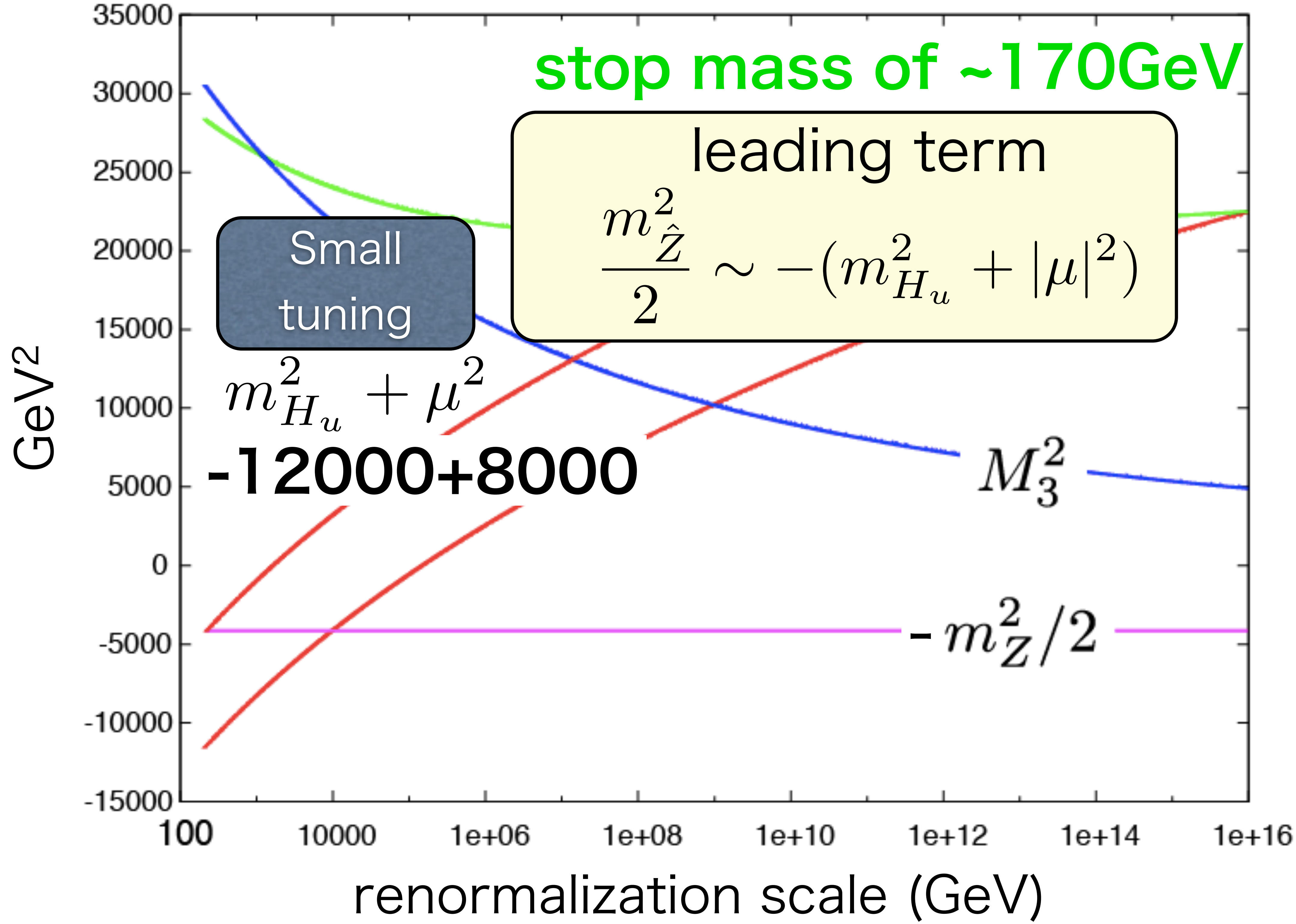
$$+\Delta V \text{ (radiative correction)}$$

W= μ HuHd

leading term
$$\frac{m_{\hat{Z}}^2}{2} \sim -(m_{H_u}^2 + |\mu|^2)$$

$$\frac{m_{\hat{Z}}^2}{2} = \frac{(m_{H_d}^2 + \frac{1}{2v_d}\frac{\partial \Delta V}{\partial v_d}) - (m_{H_u}^2 + \frac{1}{2v_u}\frac{\partial \Delta V}{\partial v_u})\tan^2\beta}{\tan^2\beta - 1} - \mu^2,$$
$$(\tan\beta + \cot\beta)^{-1} = \frac{B\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 + \frac{1}{2v_d}\frac{\partial \Delta V}{\partial v_d} + \frac{1}{2v_u}\frac{\partial \Delta V}{\partial v_u}},$$

This picture works very well for low-energy SUSY



However, a generation of the EWSB scale seems more complicated

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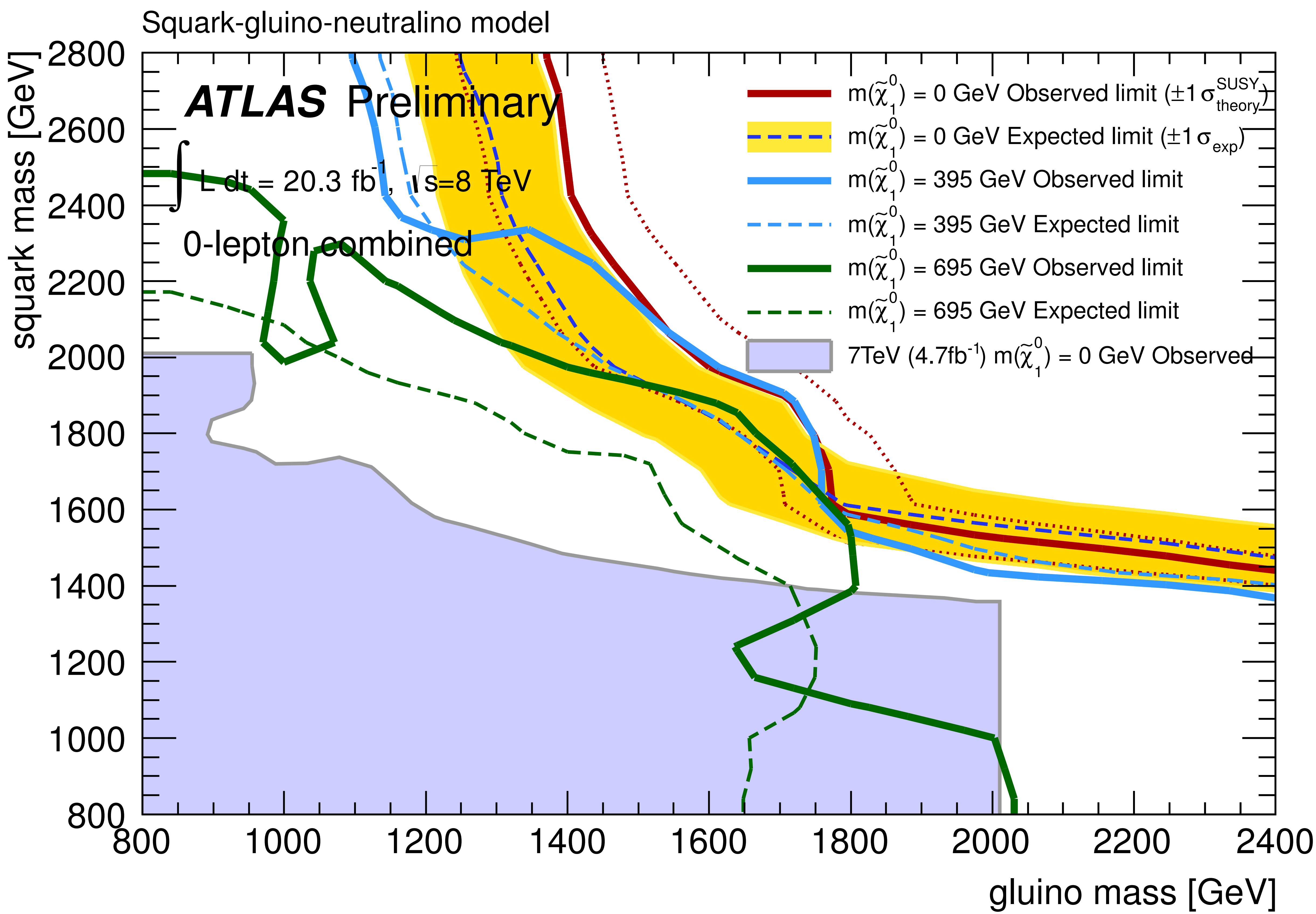
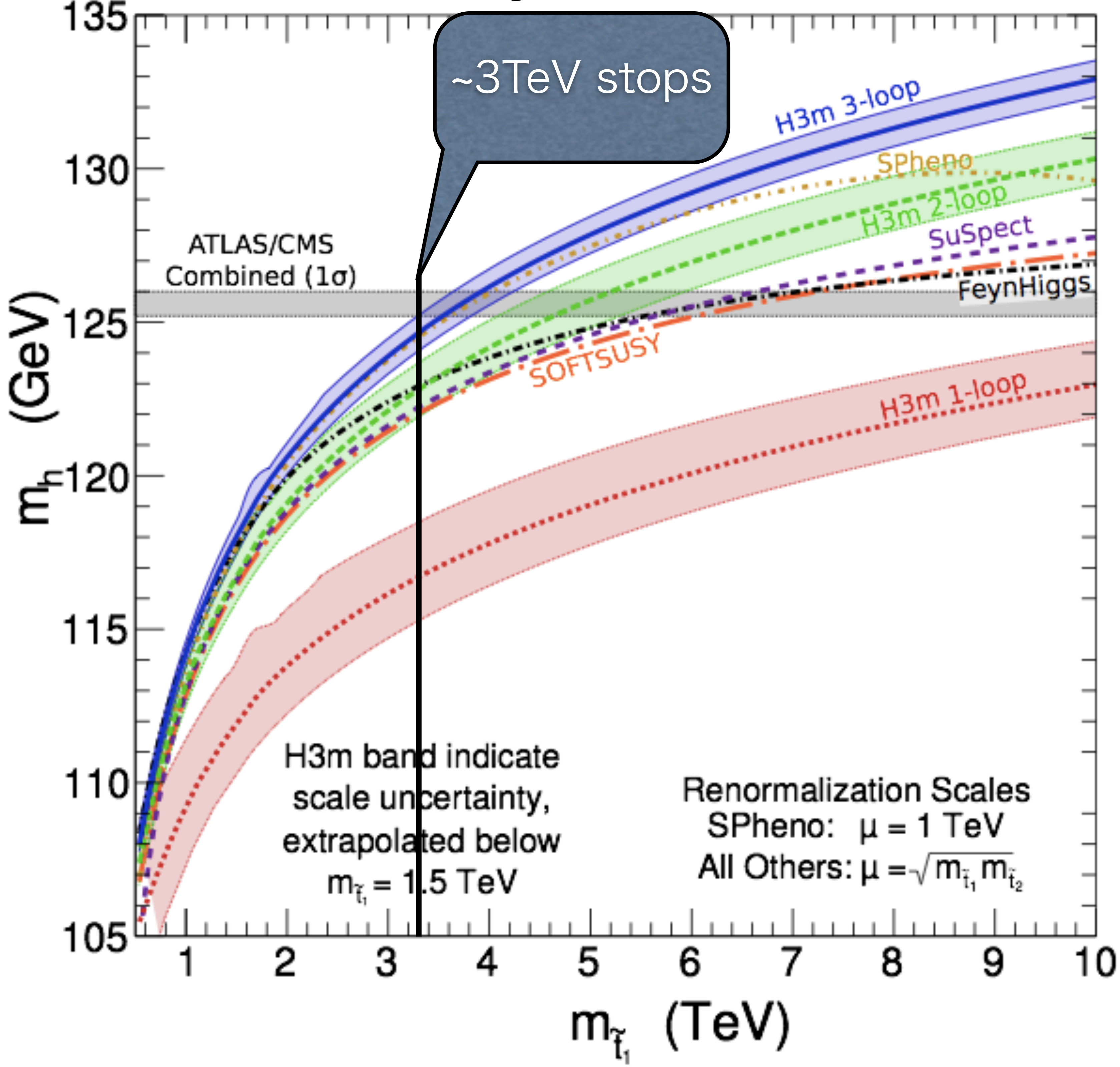
SUSY particles are heavier than we expected

Non-observation of SUSY signals



Moreover observed Higgs boson mass requires rather large radiative correction



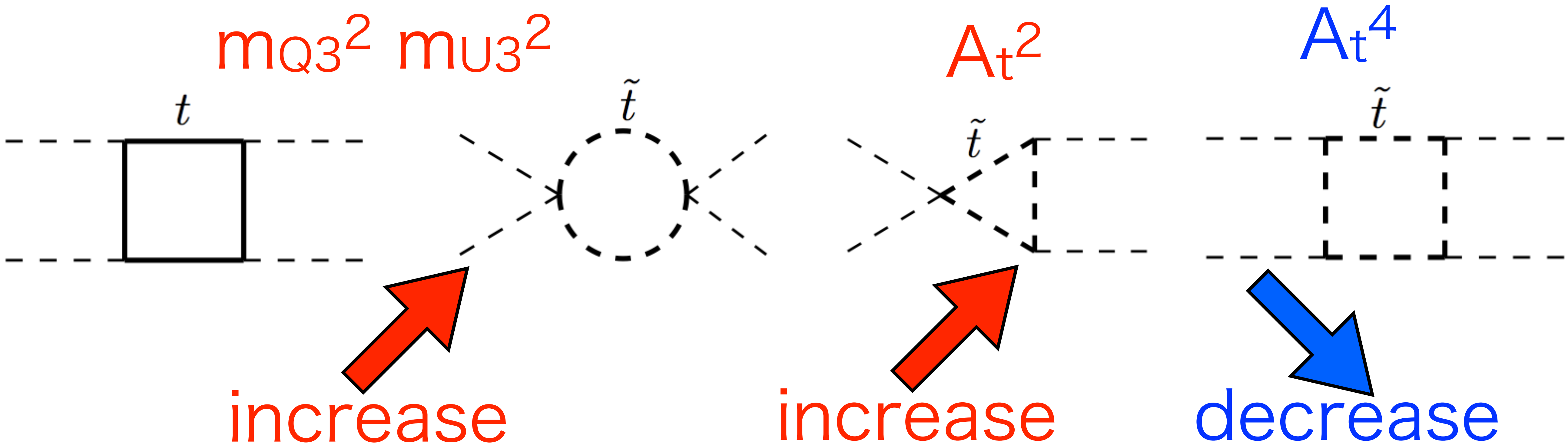
$O(\alpha_t\ \alpha_S^2)$

J.L. Feng, P. Kant, S. Profumo and D. Sanford, 1306.2318

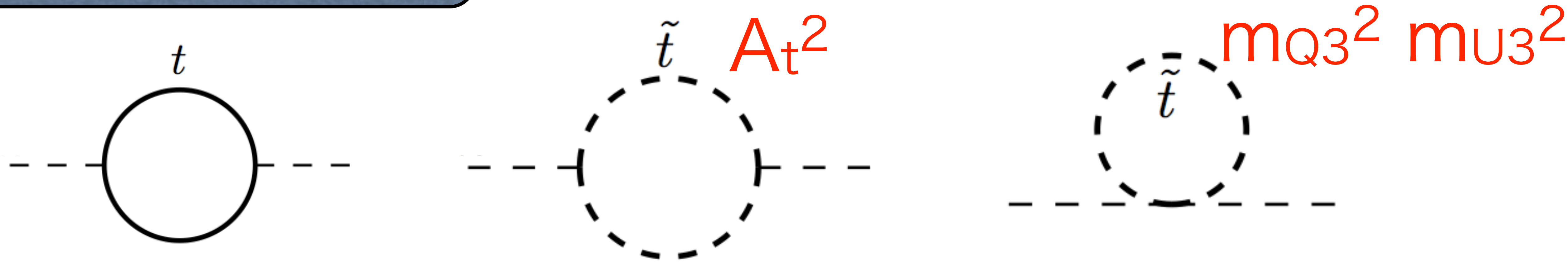
The H3m error corresponds to change of the renormalization scale from Ms/2 to 2Ms

Larger m_{Q3} m_{U3} A_t increase both Higgs boson mass and Higgs soft mass

Higgs mass



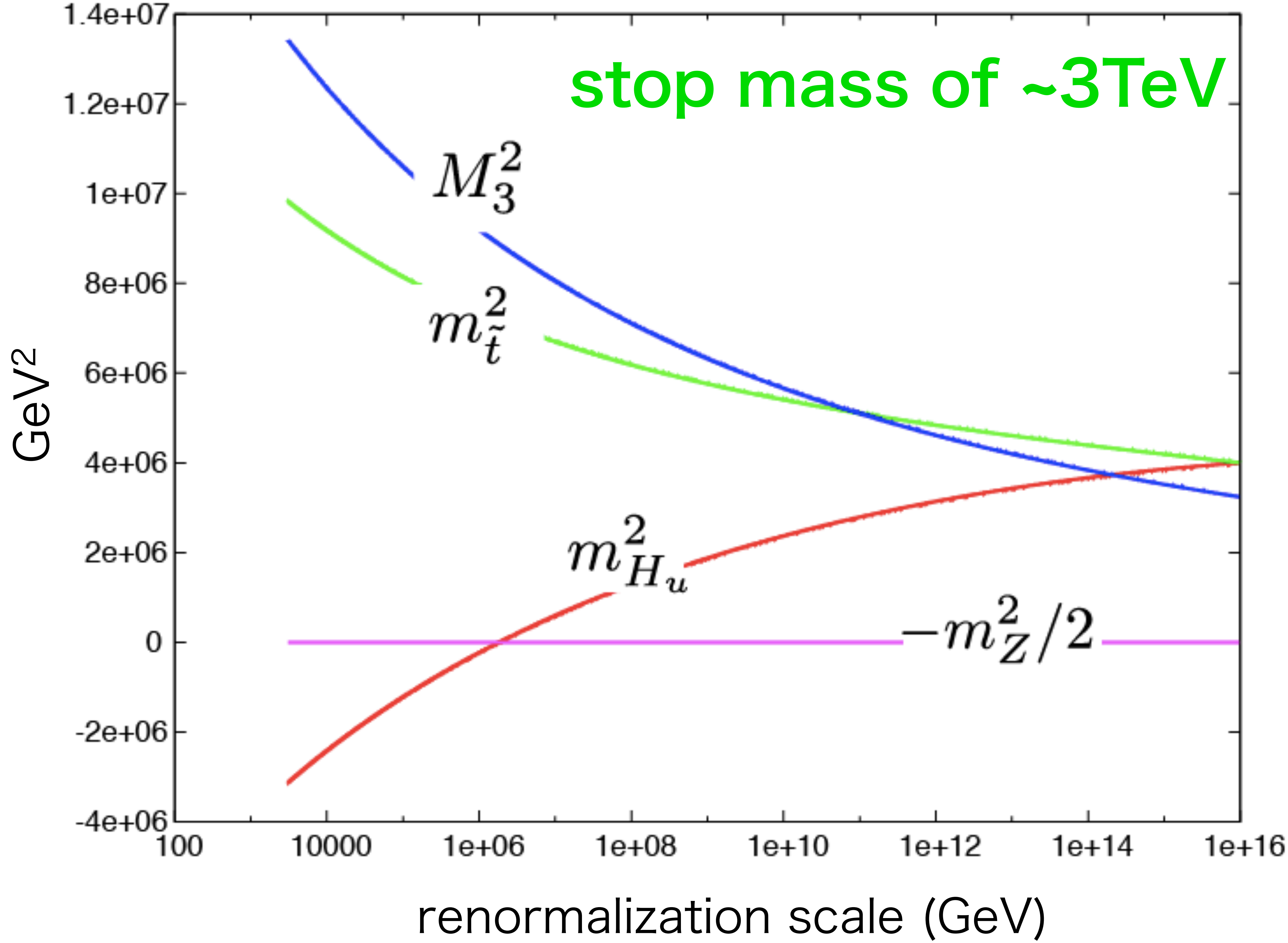
Higgs soft mass squared



+ wave function renormalization of H_u

Figures from "SUSY primer", S. Martin

We need an elaborate choice of μ-parameter



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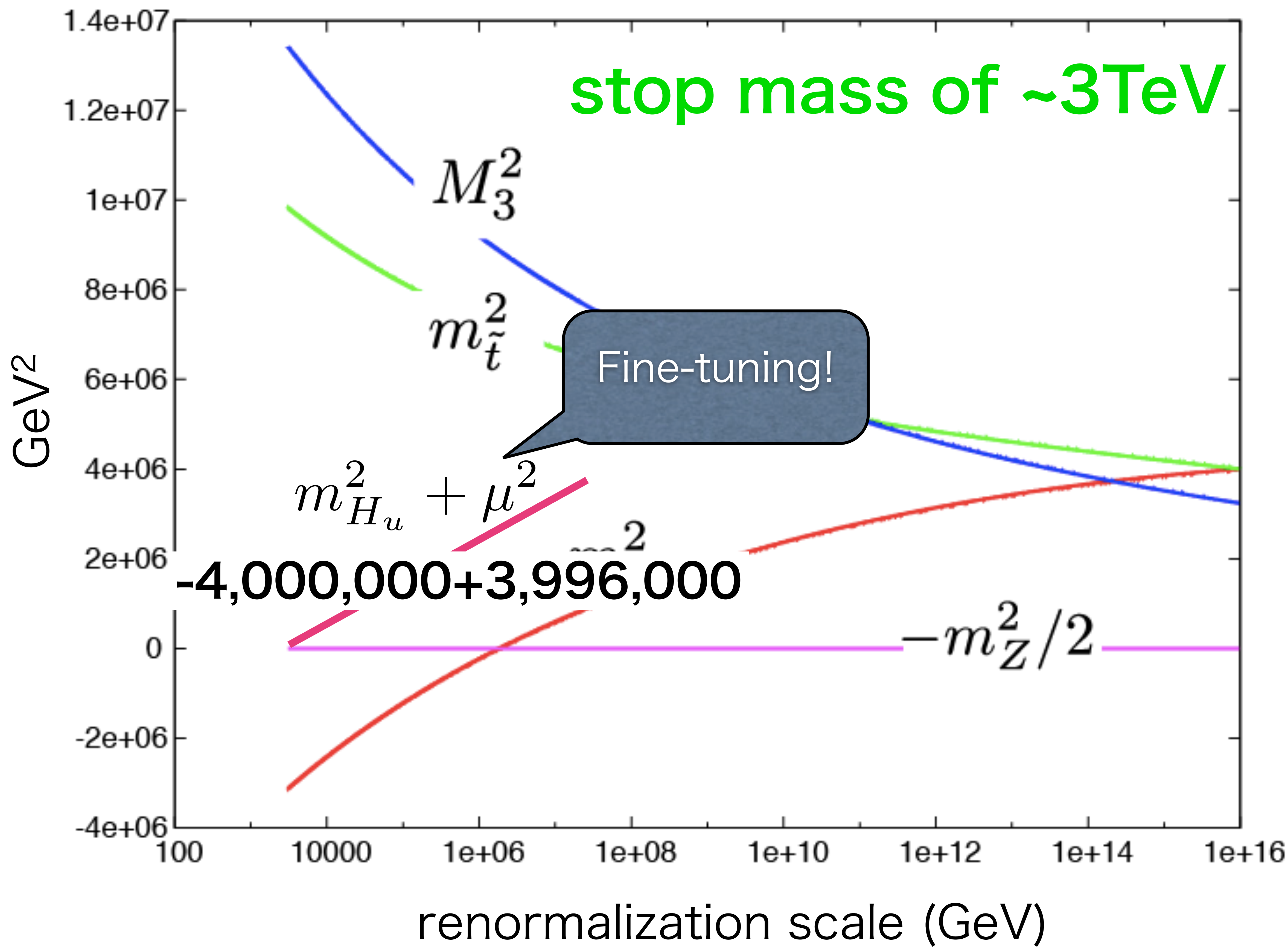

Approaches to the origin of the Fermi scale

Attractive but difficult in the current situation

- Low scale SUSY (and low messenger scale)
- Never mind (much better than the fine-tuning of the cosmological constant)

Approaches to the origin of the Fermi scale

$$V \sim |F|^2 - 3\frac{|W_0|^2}{M_P^2}$$

$$\sim m_{\rm soft}^2 M_{\rm mess}^2 - \frac{3|W_0|^2}{M_P^2}$$

$$(M_P^2)$$

$$10^{-120} M_P^4$$

$$m_{\rm soft}^2 \sim 10^{-30} M_P^2$$

(much better than the fine-tuning of the cosmological constant)

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- **Some relations among parameters at UV physics**

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Focus point!

Original Focus Point

universal scalar mass $\quad$ gaugino mass

$$m_0 \quad >> \quad M_{1/2}$$

Arises from minimal Kahler

input parameters at the GUT scale

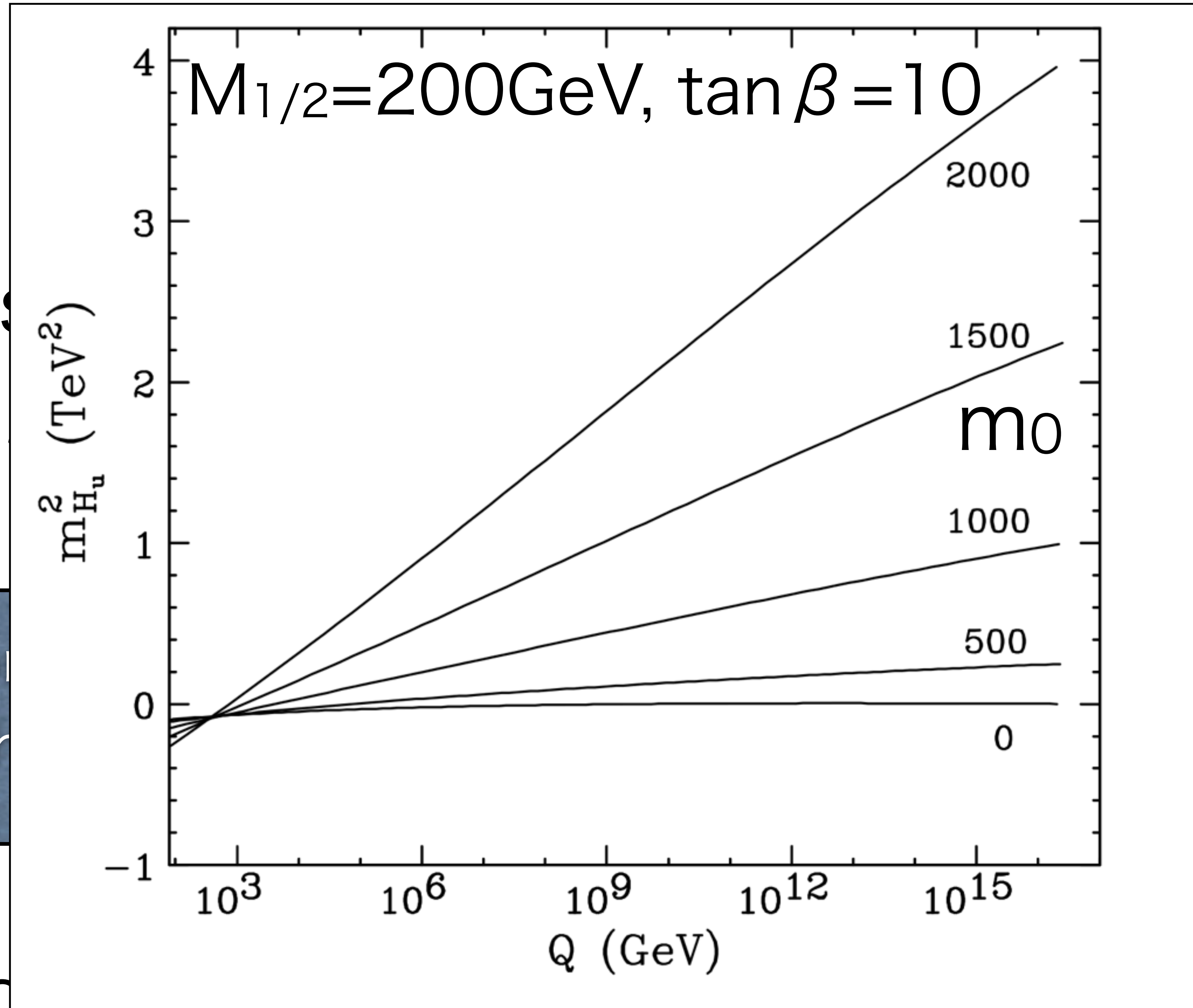
$m_{Hu}^2(m_Z)$ becomes much smaller than expected and does not sensitive to the change of m_0

[Feng, Matchev, Moroi, 1999]

Orig

universal

Arises fro
minimal Kah



$m_{Hu}{}^2(m_Z)$ bec ... cted
and does not sensitive to the change of m_0

[Feng, Matchev, Moroi, 1999]

Why $m_{Hu}^2(m_{soft})$ is small ?

Why $m_{H_u}{}^2(m_{soft})$ is small ?

looks like coincidence

$$\frac{dm_{H_u}^2}{dt} \simeq \frac{1}{16\pi^2}[6Y_t^2(m_{Q_3}^2 + m_{H_u}^2 + m_{U_3}^2 + A_t^2) - 6g_2^2|M_2|^2 + \ldots]$$

$$\frac{dm_{U_3}^2}{dt} \simeq \frac{1}{16\pi^2}[4Y_t^2(m_{Q_3}^2 + m_{H_u}^2 + m_{U_3}^2 + A_t^2)$$

$$-(32/3)g_3^2 M_3^2 + \ldots]$$

$$\frac{dm_{Q_3}^2}{dt} \simeq \frac{1}{16\pi^2}[2Y_t^2(m_{Q_3}^2 + m_{H_u}^2 + m_{U_3}^2 + A_t^2)$$

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$$-(32/3)g_3^2 M_3^2 - 6g_2^2 M_2^2 + \ldots]$$

~1

Taking $A_0=0$, $m_0^2=0$

$$\bar{m}_{H_u}^2(Q = m_{\rm stop}) = -|c_H|M_{1/2}^2$$

$$\bar{m}_{U_3}^2(Q = m_{\rm stop}) = +|c_u|M_{1/2}^2$$

$$\bar{m}_{Q_3}^2(Q = m_{\rm stop}) = +|c_Q|M_{1/2}^2$$

We want to make $M_{1/2}$ small

Let us shift boundary value m_0=0 to δm_0

$$\bar{m}^2_{H_u} \to \bar{m}^2_{H_u} + \delta m^2_{H_u}$$
$$\bar{m}^2_{U_3} \to \bar{m}^2_{U_3} + \delta m^2_{U_3}$$
$$\bar{m}^2_{Q_3} \to \bar{m}^2_{Q_3} + \delta m^2_{Q_3}$$

RGEs for A_t, M_1, M_2, M_3 do not change

(because of the mass dimension)

A_t, M_1, M_2, M_3 do not change

RGEs for δm_{Hu}^2, δm_{U3}^2, δm_{Q3}^2

$$\frac{d}{dt}\begin{bmatrix}\delta m_{H_u}^2\\ \delta m_{U_3}^2\\ \delta m_{Q_3}^2\end{bmatrix} = \frac{Y_t^2}{8\pi^2}\begin{bmatrix}3 & 3 & 3\\ 2 & 2 & 2\\ 1 & 1 & 1\end{bmatrix}\begin{bmatrix}\delta m_{H_u}^2\\ \delta m_{U_3}^2\\ \delta m_{Q_3}^2\end{bmatrix},$$

solving RGEs

$$\begin{bmatrix}\delta m_{H_u}^2\\ \delta m_{U_3}^2\\ \delta m_{Q_3}^2\end{bmatrix} = \frac{\delta m_0^2}{2}\left\{\begin{bmatrix}3\\ 2\\ 1\end{bmatrix}\exp\left[\int_0^t \frac{6Y_t^2}{8\pi^2}dt'\right] - \begin{bmatrix}1\\ 0\\ -1\end{bmatrix}\right\}.$$

$$t \equiv \ln(Q/M_{\rm GUT})$$

RGEs for δm_{Hu}^2, δm_{U3}^2, δm_{Q3}^2

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$$t \equiv \ln(Q/M_{\rm GUT})$$

This factor is accidentally ~1/3!

for Q~M_Z, M_{GUT}~10^{16}GeV, Yt~1

$\boxed{\text{Then} \quad \delta m_{H_u}^2 \sim 0}$

RGEs for δm_{Hu}^2, δm_{U3}^2, δm_{Q3}^2

$$\frac{d}{dt}\begin{bmatrix}\delta m_{H_u}^2\\ \delta m_{U_3}^2\\ \delta m_{Q_3}^2\end{bmatrix} = \frac{Y_t^2}{8\pi^2}\begin{bmatrix}3 & 3 & 3\\ 2 & 2 & 2\\ 1 & 1 & 1\end{bmatrix}\begin{bmatrix}\delta m_{H_u}^2\\ \delta m_{U_3}^2\\ \delta m_{Q_3}^2\end{bmatrix},$$

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for Q~M_Z, M_{GU}

Then δ

RGEs for δm_{Hu}^2, δm_{U3}^2, δm_{Q3}^2

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$$t \equiv \ln(Q/M_{\rm GUT})$$

Deep reason may be hidden

flavor symmetry breaking scale $\leftrightarrow$ $\boxed{Y_t \quad M_{\rm GUT}}$ $\leftarrow$ Λ

(more fundamental scale)

Fine-tuning measure

Defining a fine-tuning measure

$$\Delta_a = \left| \frac{\partial \ln m_{\hat{Z}}}{\partial \ln a} \right|_{m_{\hat{Z}} = m_Z} \qquad \boxed{\Delta = \max(\Delta_a)}$$

a is a fundamental parameter

J. R. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A **1**, 57 (1986); R. Barbieri and G. F. Giudice, Nucl. Phys. B **306**, 63 (1988).

e.g., mSUGRA

$$\{a_i\} = \{m_0, M_{1/2}, \mu_0, A_0, B_0\}$$

$$\Delta_{B_0} \sim (1/\tan\beta)\Delta_{\mu_0}$$

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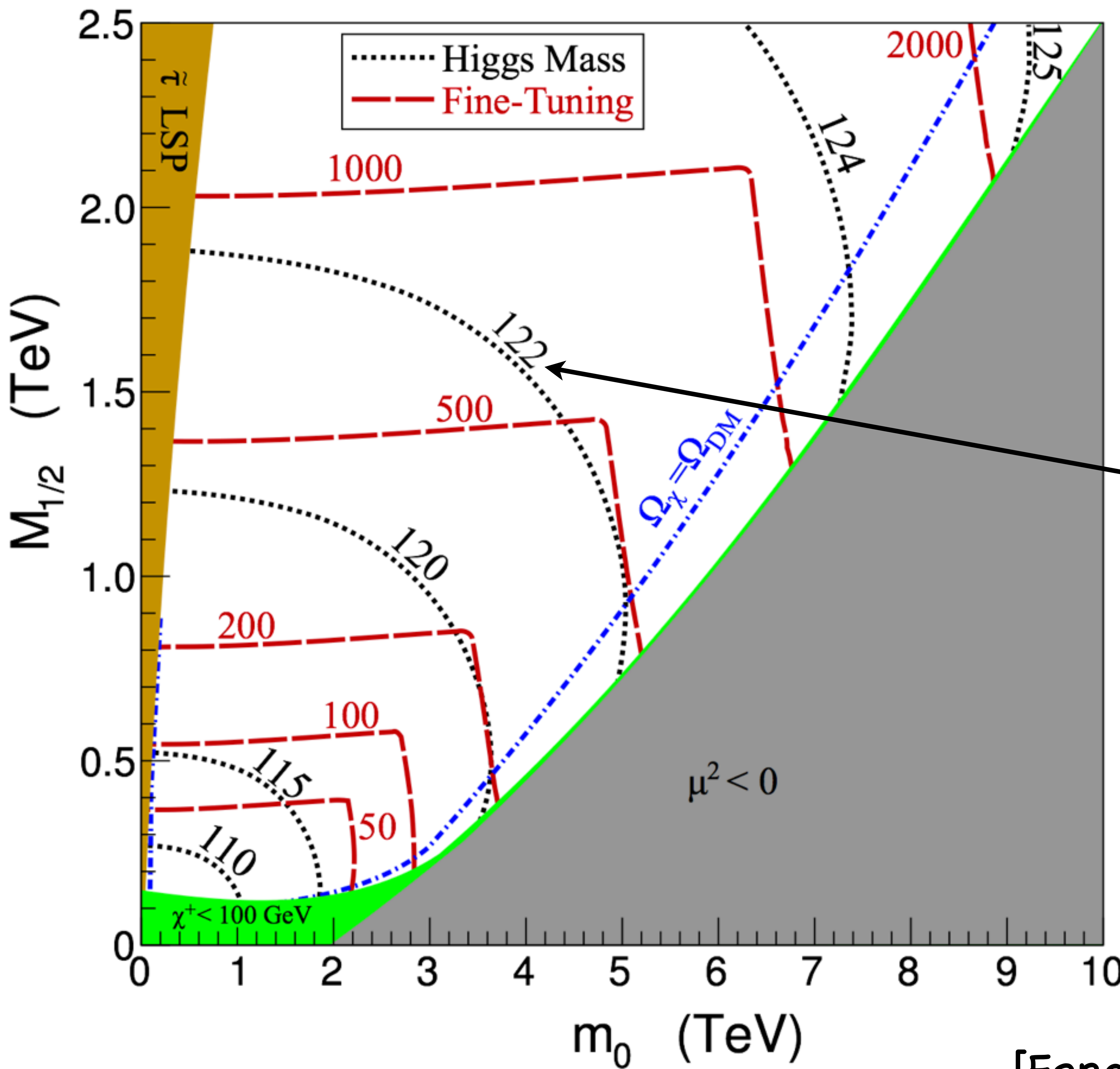
e.g., mSUGRA

$$\{a_i\} = \{m_0, M_{1/2}, \mu_0, A_0, B_0\}$$

$$\boxed{(\Delta_{\mu_0})^{-1} = \frac{m_Z^2}{\mu_0^2}\left(\frac{dm_Z^2}{d\mu^0}\right)^{-1} \sim \frac{m_Z^2}{2\mu^2}} \,\mu_0$$



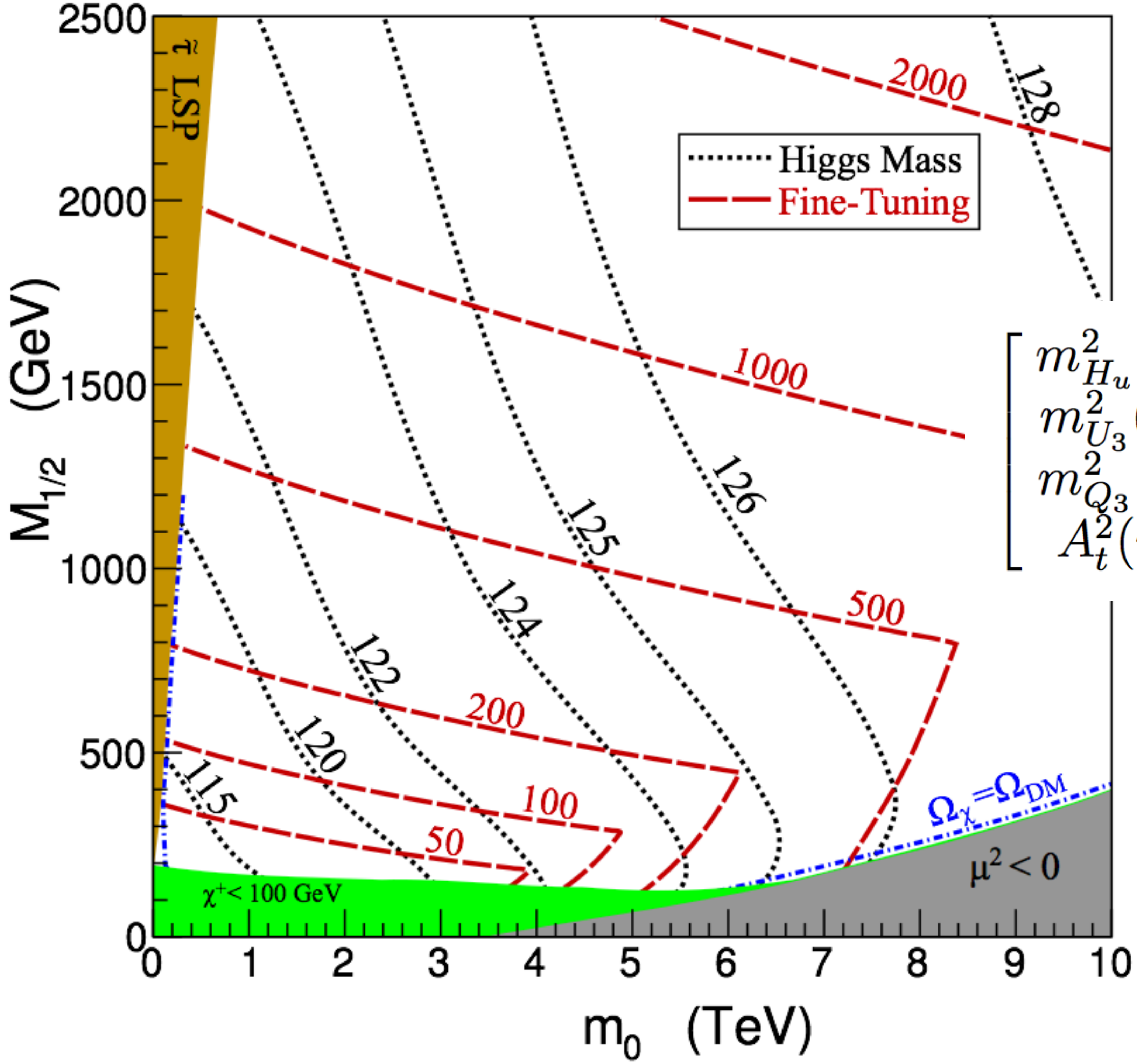
122 can be consistent with observed value

Δ~500

(Higgs mass is calculated using SoftSUSY, $\tan\beta = 10$, $A_0 = 0$)

[Feng, Sanford, 2012]

With A-term



$$\begin{bmatrix} m_{H_u}^2(m_{\mathrm{GUT}}) \\ m_{U_3}^2(m_{\mathrm{GUT}}) \\ m_{Q_3}^2(m_{\mathrm{GUT}}) \\ A_t^2(m_{\mathrm{GUT}}) \end{bmatrix} = m_0^2 \begin{bmatrix} 1 \\ 1+x-3y \\ 1-x \\ 9y \end{bmatrix}$$

$$(x, y) = \left(\frac{1}{4}, \frac{1}{6}\right)$$

(Higgs mass is calculated using SoftSUSY, $\tan\beta = 10$)

Fine-tuning is reduced to Δ~50-100

We would like to propose simpler model

Gaugino (dominated) mediation with fixed ratio of the gluino mass to wino mass M_2/M_3~0.4, e.g., 3/8

Focus point in Gaugino Mediation

- Fine-tuning can be reduced with a certain ratio of gluino mass to wino mass

(bino mass is not so important)

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GUT scale parameters

$$
\begin{aligned}
m_{H_u}^2(2.5\,\mathrm{TeV}) \quad &\simeq \quad -1.197M_3^2 + 0.235M_2^2 - 0.013M_1M_3 - 0.134M_2M_3 \\
&+ \quad 0.010M_1^2 - 0.027M_1M_2 + 0.067m_0^2,
\end{aligned}
$$

~m_{stop}

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~m_{stop}

non-universal

$$-0.006M_{1/2}^2 + 0.067m_0^2 \ \text{for}\ r_1 = r_3 = (3/8)$$

where $(M_1, M_2, M_3) = (r_1, 1, r_3)M_{1/2}.$

Focus point in Gaugino Mediation

Doublet-triplet splitting problem in SU(5)GUT

solve

- Fine-tuning ca… duced with a certain ratio of gluino mass to wino mass

GUT scale parameters

Product GUT/non-anomalous discrete R-symmetry(later)

$m_{H_u}^2(2.5\,\mathrm{TeV}$ … $-\,0.134 M_2 M_3$

~mstop

$$-0.006 M_{1/2}^2 + 0.067 m_0^2 \;\; \text{for } r_1 = r_3 = (3/8)$$

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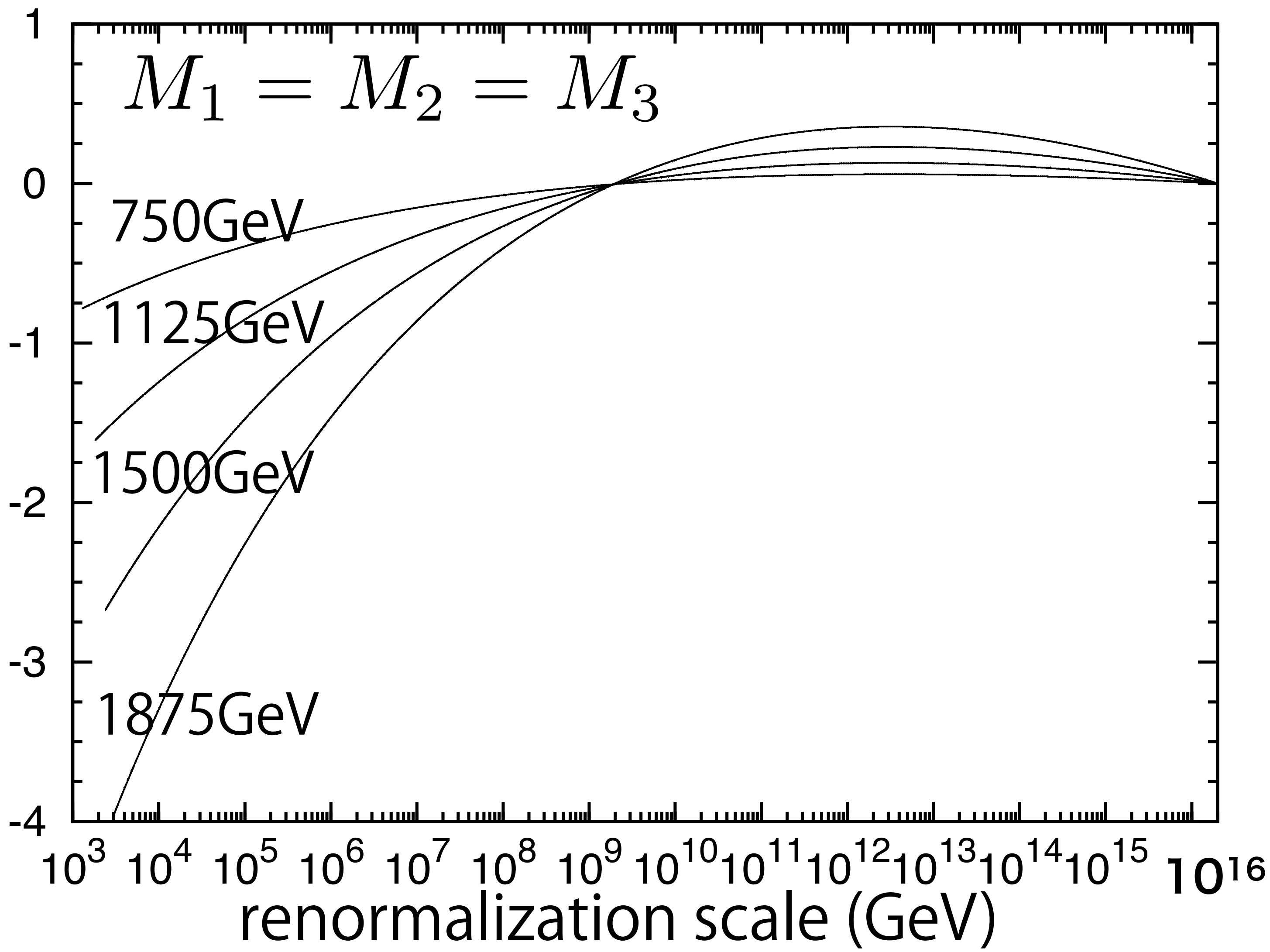
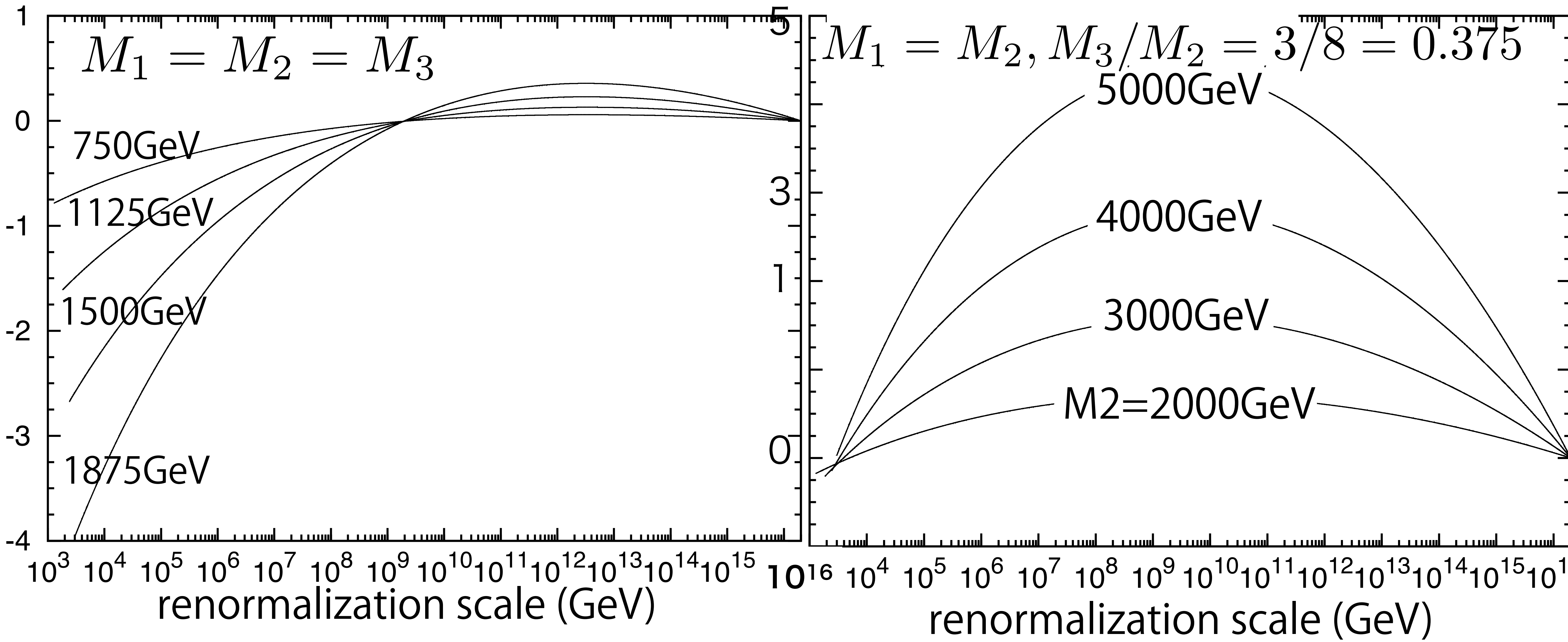
The running of $m_{Hu}{}^2$ (TeV^2)



universal case

For almost same gluino mass

The running of m_{Hu}^2 (TeV^2)



universal case

M_2:M_3=8:3 case

For almost same gluino mass

Higgs boson mass @ three loop level

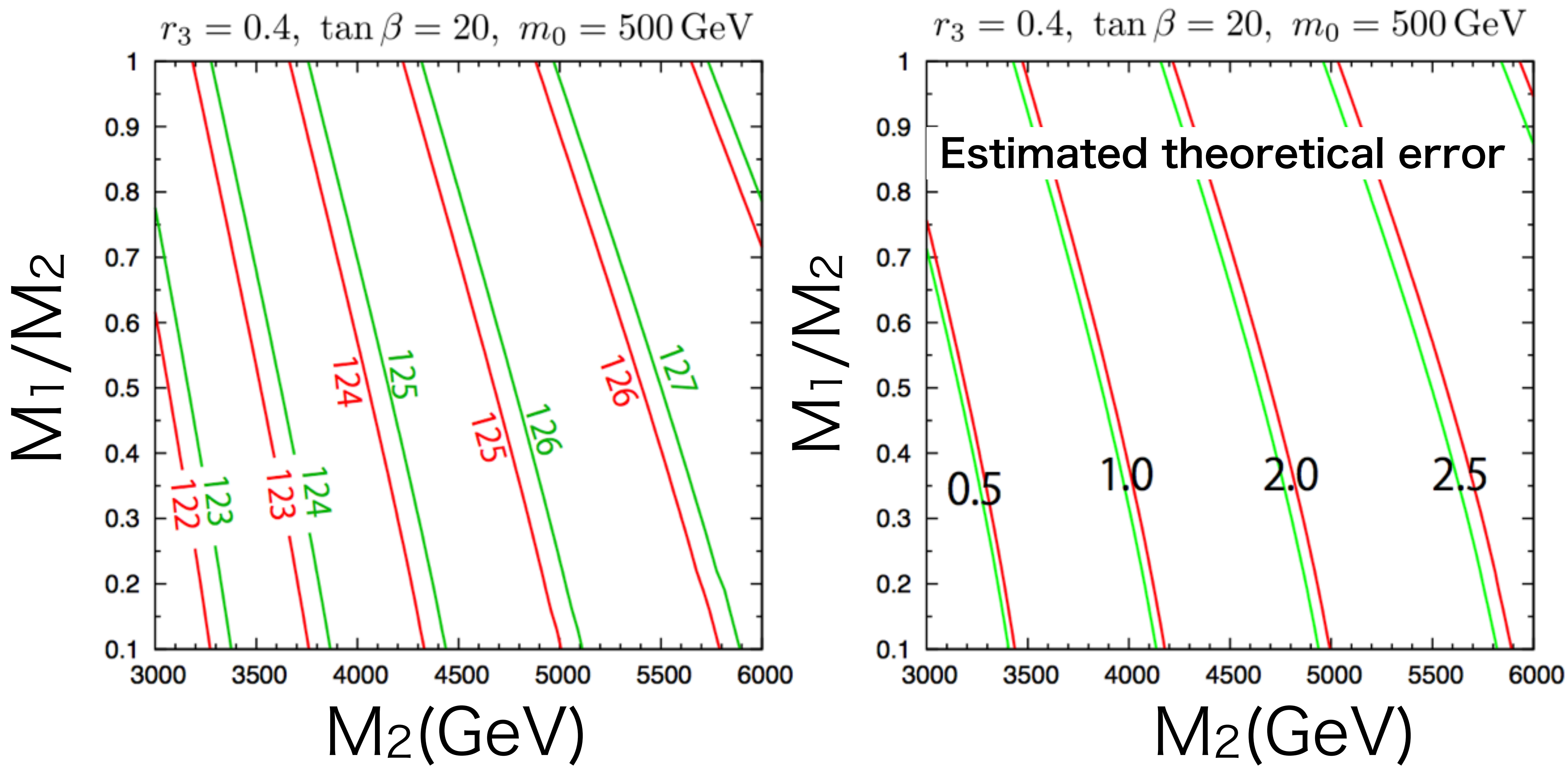
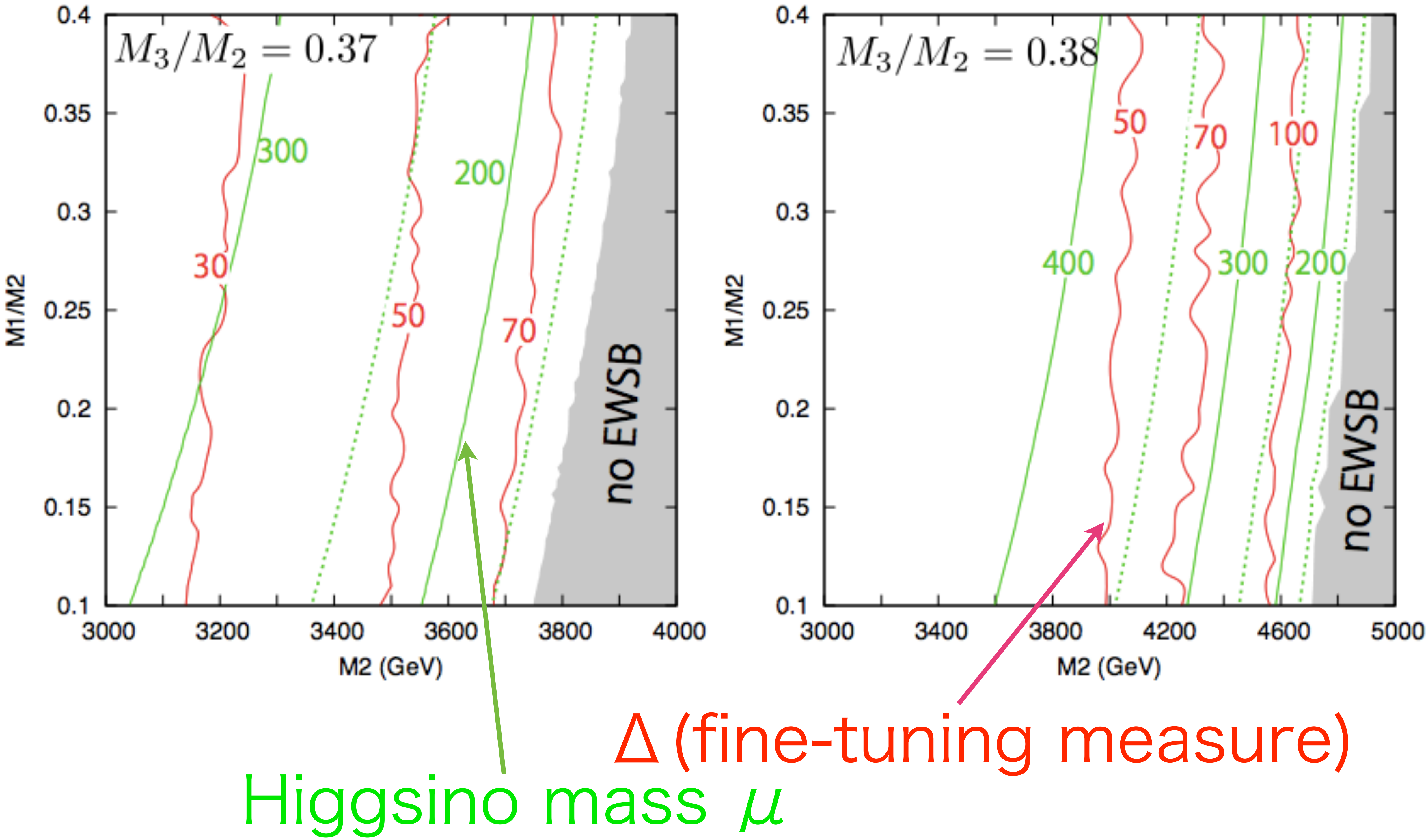


Figure 2: Contours of the Higgs boson mass (left panel) and Δm_h (right panel) in the unit of GeV. The red (green) lines drawn with the top mass of $m_t = 173.2$ GeV (174.2 GeV). Here, $\alpha_S(m_Z) = 0.1184$.

red: m_t=173.2 GeV green: m_t=174.2 GeV

Fine-tuning and Higgsino mass



Prediction

- At least Higgsino is light, which can be target at the ILC
- Bino-Higgsino dark matter if the gravitino is heavier than the neutralino

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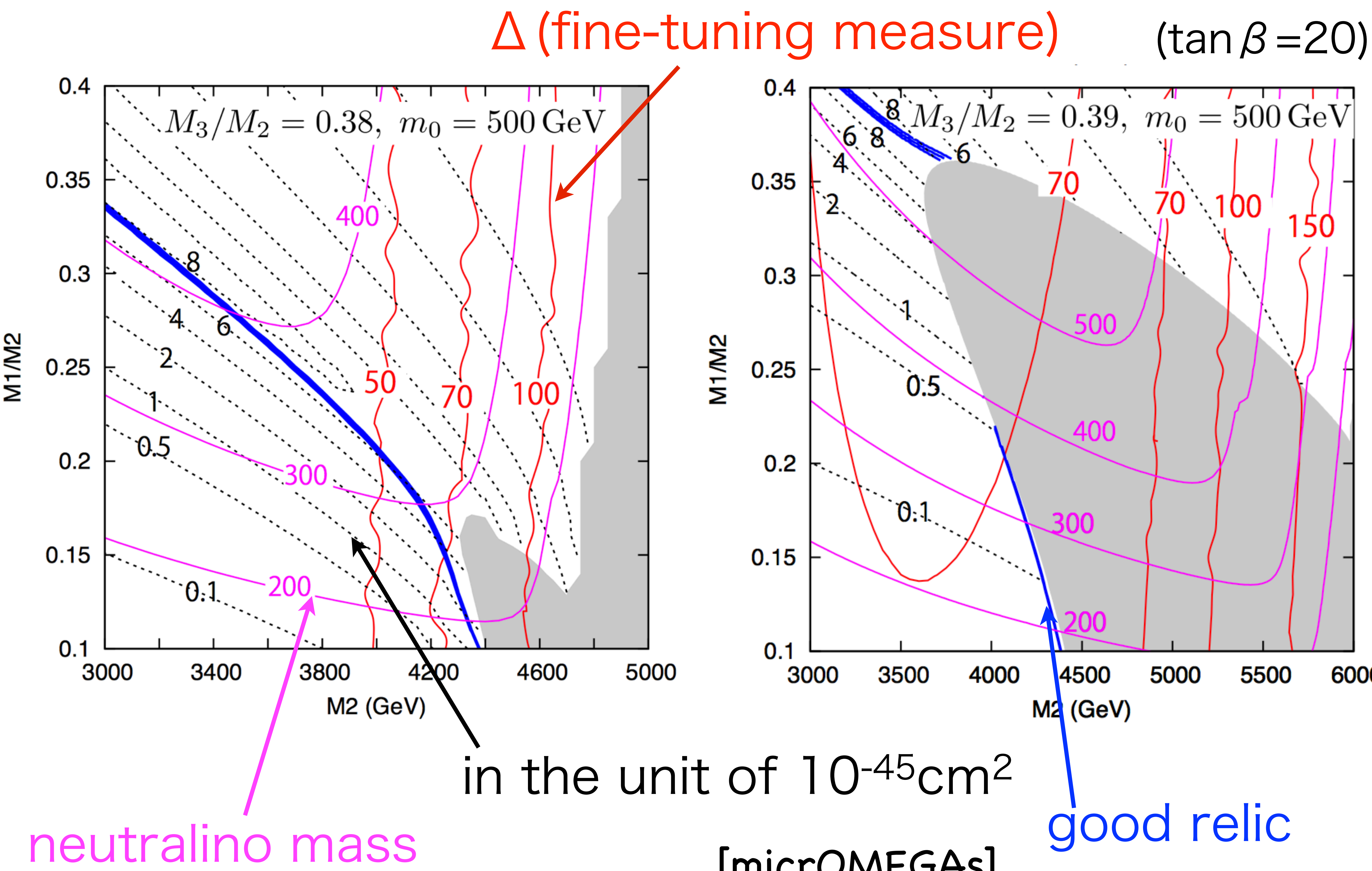
Strong constraint from XENON100

Spin-independent cross section

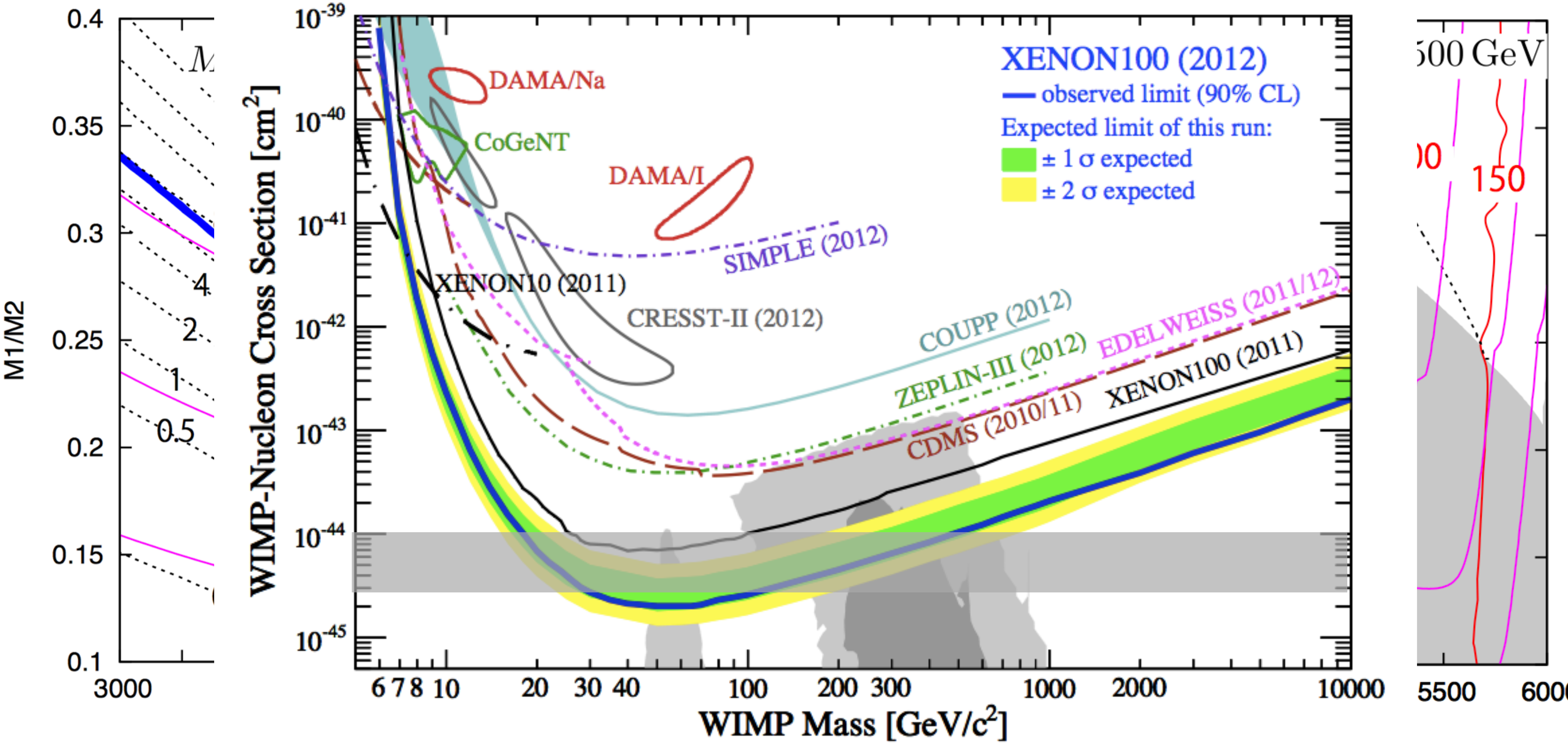


[micrOMEGAs]

Spin-independent cross section

Δ (fine-tuning measure)

(tan β =20)



in the unit of 10^{-45}cm^2

neutralino mass

good relic

[micrOMEGAs]

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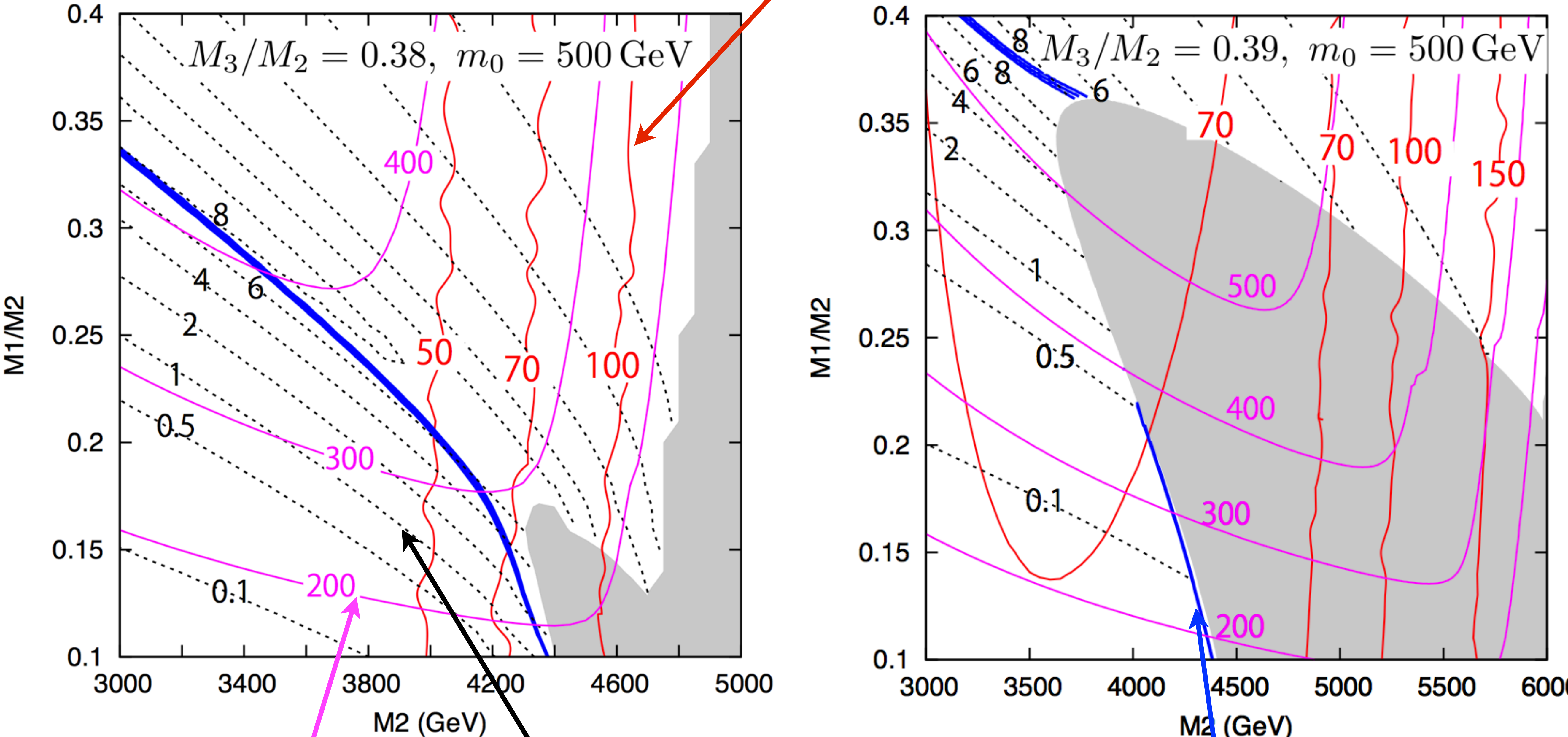


neutralino mass

in the unit of $10^{-45}\mathrm{cm}^2$

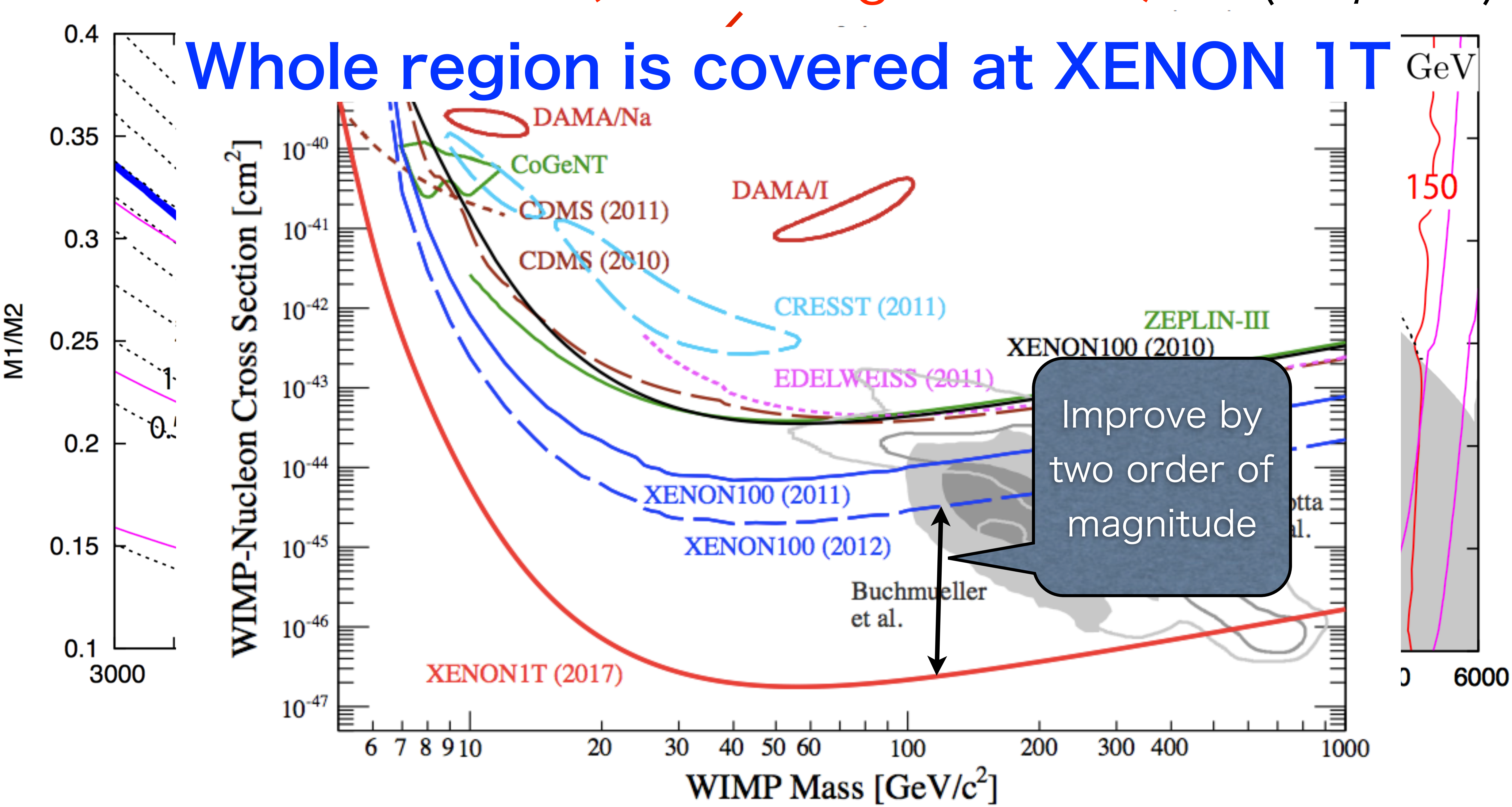
good relic

[micrOMEGAs]

Spin-independent cross section

Δ (fine-tuning measure) (tan β =20)

Whole region is covered at XENON 1T



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[micrOMEGAs]

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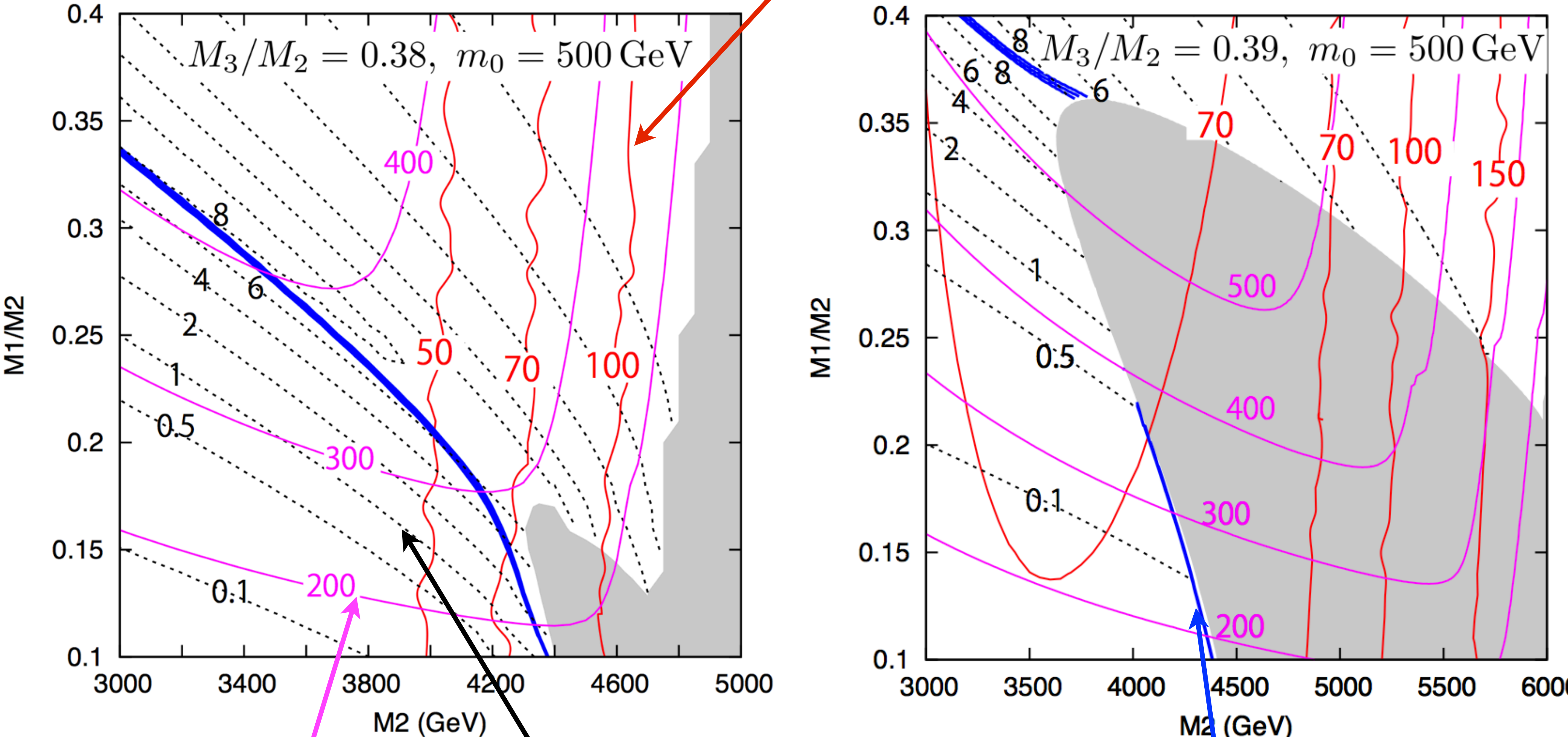

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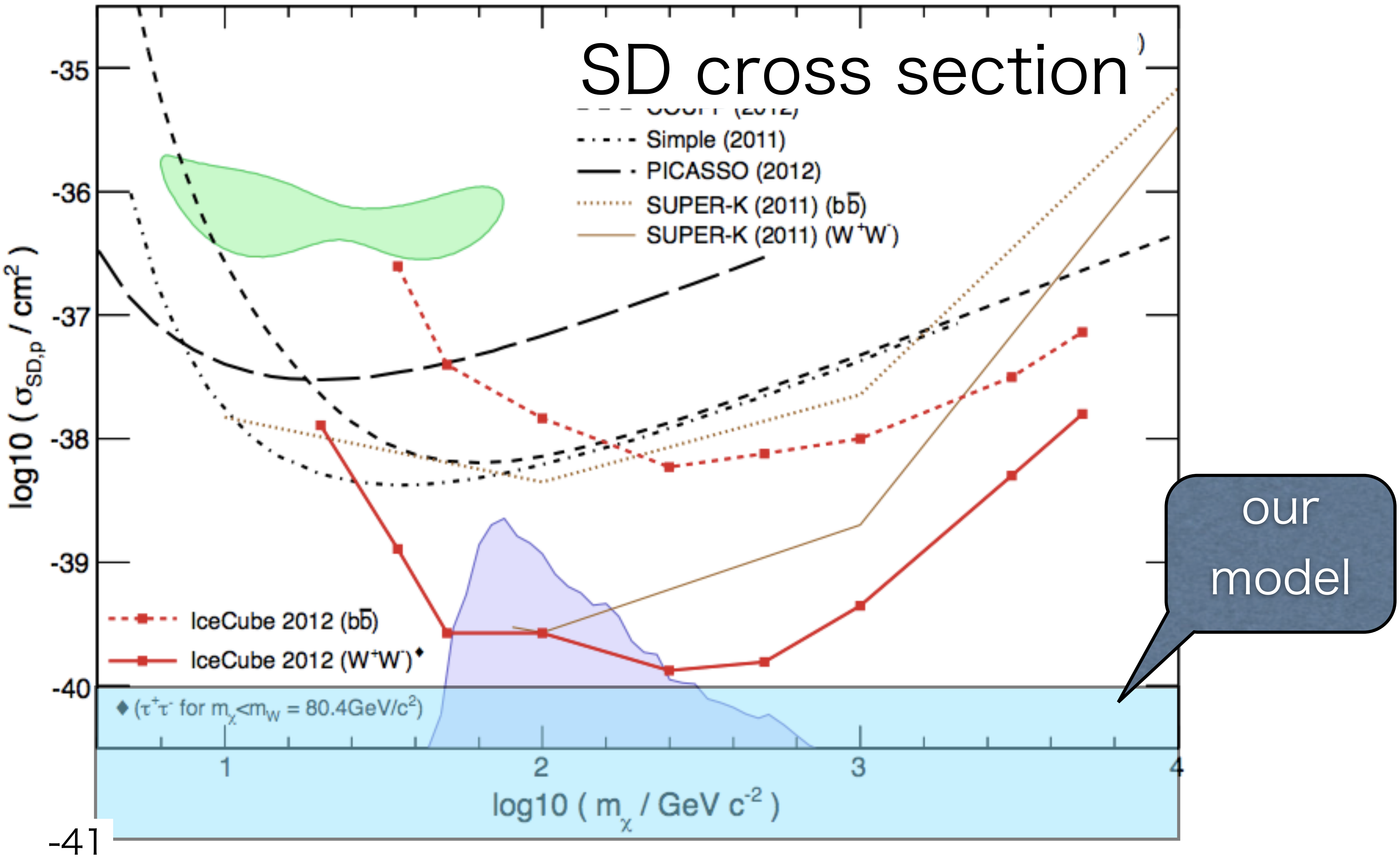
Ice Cube Experiment



(but χ_1^0 does not decays into WW exclusively)

[micrOMEGAs]

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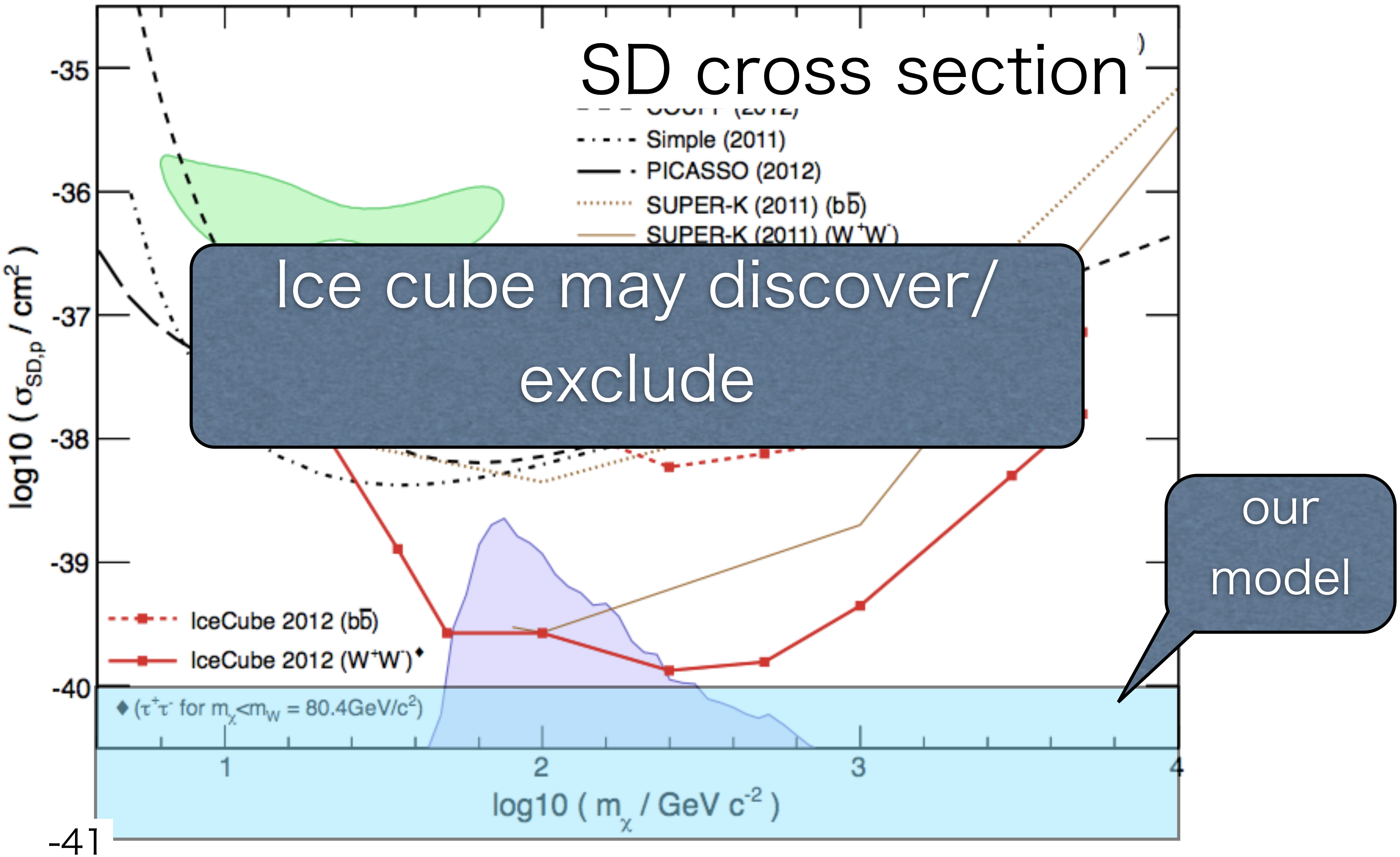

(but $\chi_1{}^0$ does not decays into WW exclusively)

[micrOMEGAs]

The origin of 8:3(~0.4)

- Product GUT $SU(5)_{GUT} \times U(2)_H$

bi-fundamental field $\Rightarrow$ $SU(3)_C \times SU(2)_L \times U(1)_Y$

The origin of 8:3(~0.4)

- Product GUT $SU(5)_{GUT} \times U(2)_H$

bi-fundamental field ⇒ $SU(3)_C \times SU(2)_L \times U(1)_Y$

Doublet-triplet splitting problem is solved

Approximate gauge coupling unification is satisfied

small enough (strong coupling)

$$\alpha_1^{-1} = \alpha_{GUT}^{-1} + \alpha_{1H}^{-1}$$

$$\alpha_2^{-1} = \alpha_{GUT}^{-1} + \alpha_{2H}^{-1} \qquad \alpha_3^{-1} = \alpha_{GUT}^{-1}$$

The origin of 8:3(~0.4)

- Product GUT $SU(5)_{GUT} \times U(2)_H$

bi-fundamental field $\Rightarrow$ $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\boxed{\begin{aligned} M_1 &\simeq M_{\rm GUT} + \qquad g^2_{\rm GUT} M_{H1}/g^2_{H1}, \\ M_2 &\simeq M_{\rm GUT} + g^2_{\rm GUT} M_{H2}/g^2_{H2}, \\ M_3 &\simeq M_{\rm GUT}, \end{aligned}}$$

if $(g^2_{\rm GUT}/g^2_{H_2}) M_{H2}$ ~ M_{GUT}

Then M_3/M_2~3/8 may arise

The origin of 8:3

- May be determined by dim($SU(2)_{adj}$): dim($SU(3)_{adj}$)

$$M_2 = M_5/\dim(SU(2)_{\rm adj})$$

$$M_3 = M_5/\dim(SU(3)_{\rm adj})$$

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- **Anomaly free condition of Z_{NR}**

Suppose that there exist non-anomalous discrete R-symmetry

R parity can not forbid dim 5 proton decay operators

$$\boxed{W \ni \frac{QQQL}{M_P} \;,\; \frac{\bar{U}\bar{U}\bar{D}\bar{E}}{M_P}}$$

very dangerous!

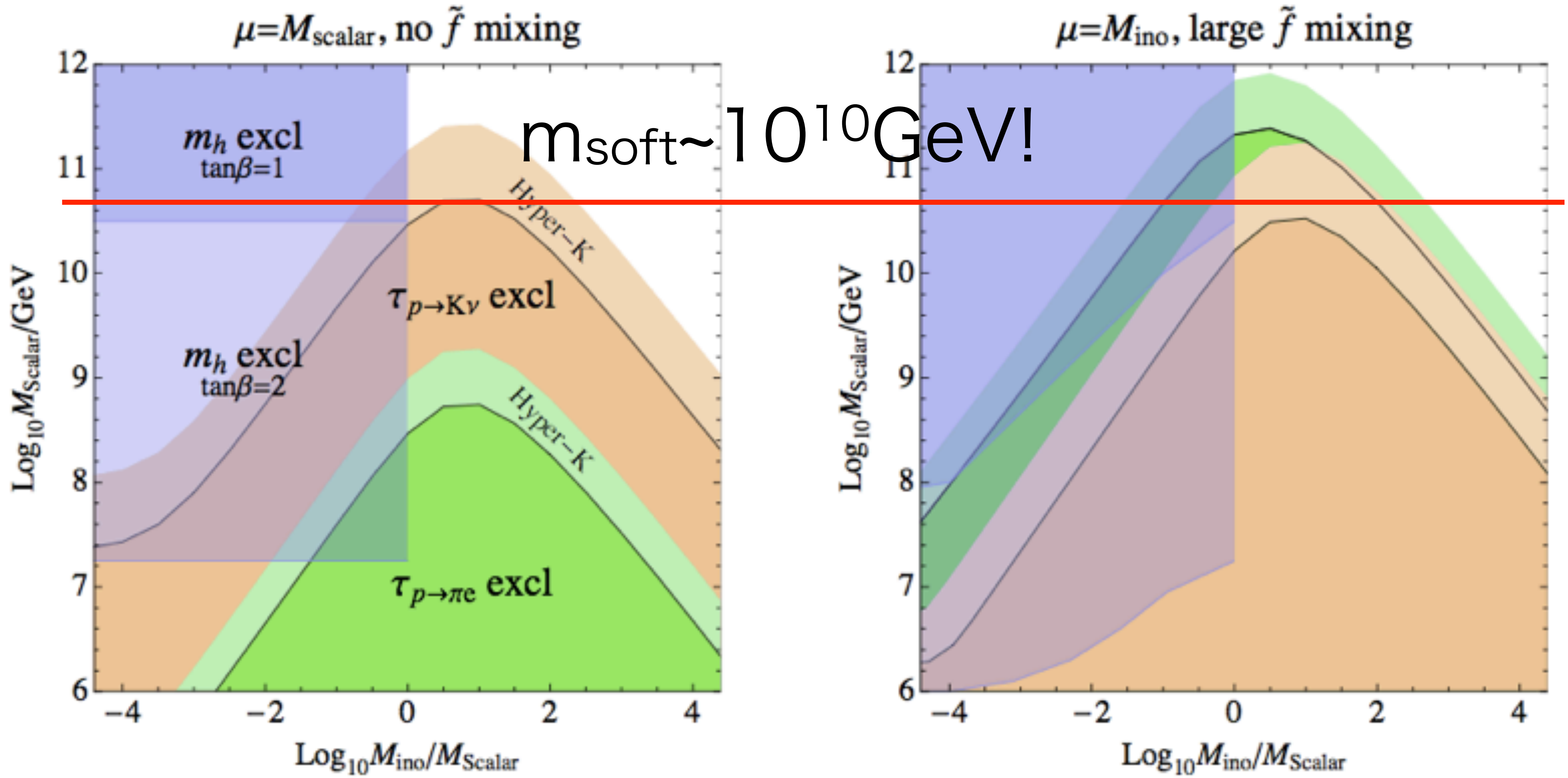
For N=even, constant term breaks Z_{NR} to R-parity

(For N=odd, R-Parity is broken by constant term)

Let us focus on even number of N

Z_{4R}, Z_{6R}, Z_{8R} ...

m_{soft}~10^{10}GeV!



[Dine, Draper, Shepherd, 2013]

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...ry

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Let us focus on even number of N

Z_{4R}, Z_{6R}, Z_{8R} ...

μ-term is generated by Giudice Masiero mechanism

Forbid bare Hu Hd

$$r_u + r_d = 0 \mod N \text{ (and } r_u + r_d \neq 2).$$

$$\mathbf{A}_2 = 2 \mod N, \quad \mathbf{A}_3 = 6 \mod N.$$

Z_{NR}-$SU(2)_L$-$SU(2)_L$ Z_{NR}-$SU(3)_C$-$SU(3)_C$

Z_{NR} transformation

$$\mathrm{Im}(Z/M_*) \to \mathrm{Im}(Z/M_*) + (2\pi l'/N)$$

$$\psi_i \to \psi_i \exp\left[i(r_i - 1)(2\pi l'/N)\right)$$

r_i: charge of matter fermion and Higgsino

$$\frac{k_2}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_2(W^{a\,\alpha})_2,$$ wino mass

$$\frac{k_3}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_3(W^{a\,\alpha})_3,$$ gluino mass

conjecture

Shift of Im(Z/M*) cancels the anomaly

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$$\psi_i \to \psi_i \exp\left[i(r_i - 1)(2\pi l'/N)\right)$$

r_i:

May be consistent with SU(5) x $U(2)_H$

$$\frac{k_5 \cos^2\theta + k_{2H}\sin^2\theta}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_2(W^a_\alpha)_2$$

$$\frac{k_5}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_3(W^a_\alpha)_3$$

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Shift of Im(Z/M*) cancels the anomaly

$$\mathbf{A}_2 = 2 \bmod N, \quad \mathbf{A}_3 = 6 \bmod N.$$

$$A_2 = 2 + k_2 \bmod N, \quad A_3 = 6 + k_3 \bmod N$$

Anomaly cancellation: $A_2 = A_3 = 0 \bmod N$

No solution with $k_2/k_3 = 8/3$ for Z_{4R}

$k_2 = 16$, $k_3 = 6$ for Z_{6R}

$$\frac{k_2}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_2(W^{a\,\alpha})_2,$$ wino mass

$$\frac{k_3}{32\pi^2}\int d^2\theta \frac{Z}{M_*}(W^a_\alpha)_3(W^{a\,\alpha})_3,$$ gluino mass

$k_2=16$, $k_3=6$

$M_{\mathrm{wino}} : M_{\mathrm{gluino}} = 8 : 3$

Summary

- Focus point in Gaugino Mediation is attractive
- If $M_3/M_2 \sim 0.4$ (say 3/8), the fine-tuning is significantly reduced
- The model is testable at ILC/XENON1T

Another interesting thing of gaugino mediation

Adding vector-like matters enhance the Higgs boson mass even when the gluino mass is small

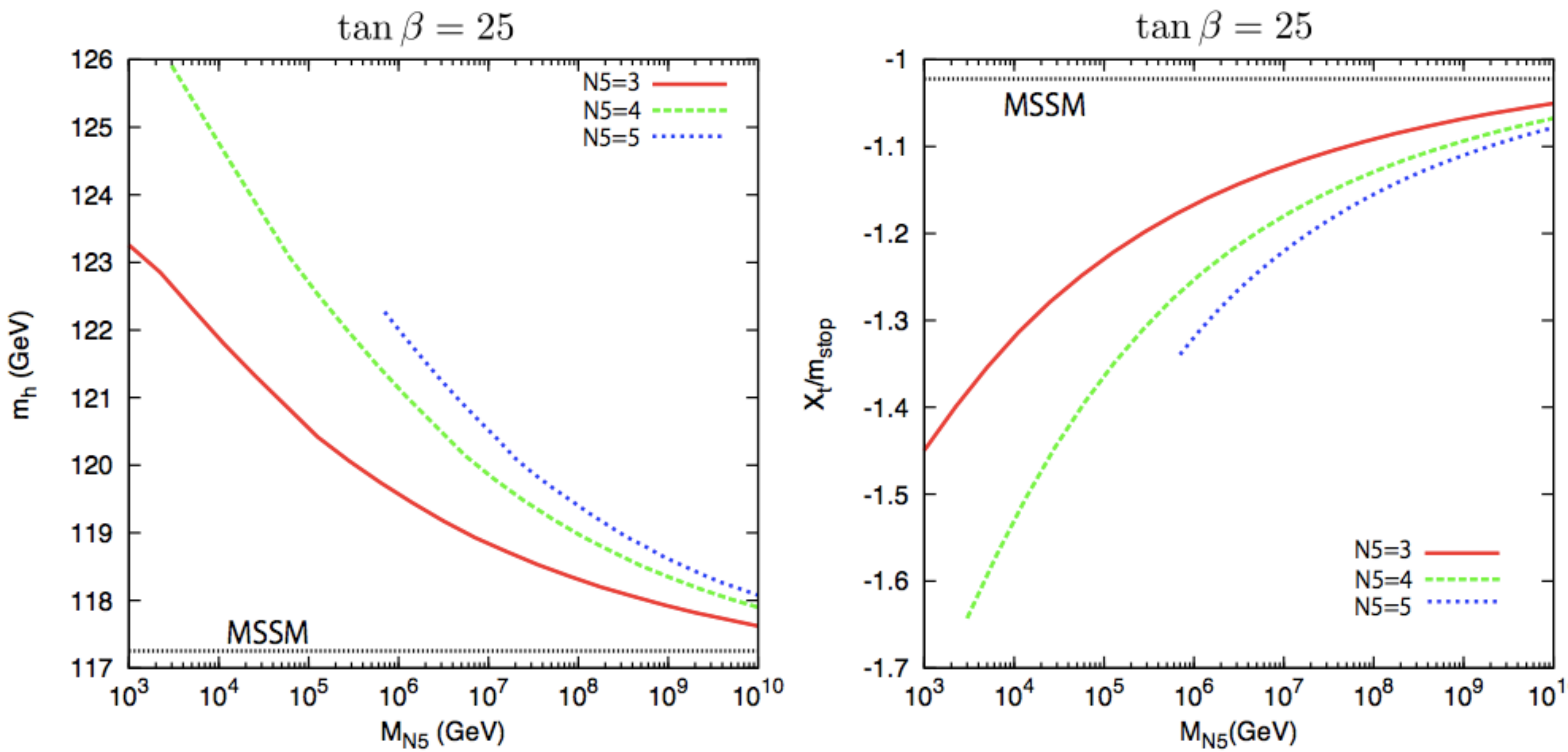

Figure 2: The Higgs boson mass and the normalized trilinear coupling of the stop as a function of the decoupling scale of the extra matter. The gluino mass is fixed to be $\boxed{m_{\tilde{g}} = 1.2\,\mathrm{TeV}}$. Here, $\tan\beta = 25$.

Moroi. T. Yanagida and N.Y. , 1211.4676 (PLB)

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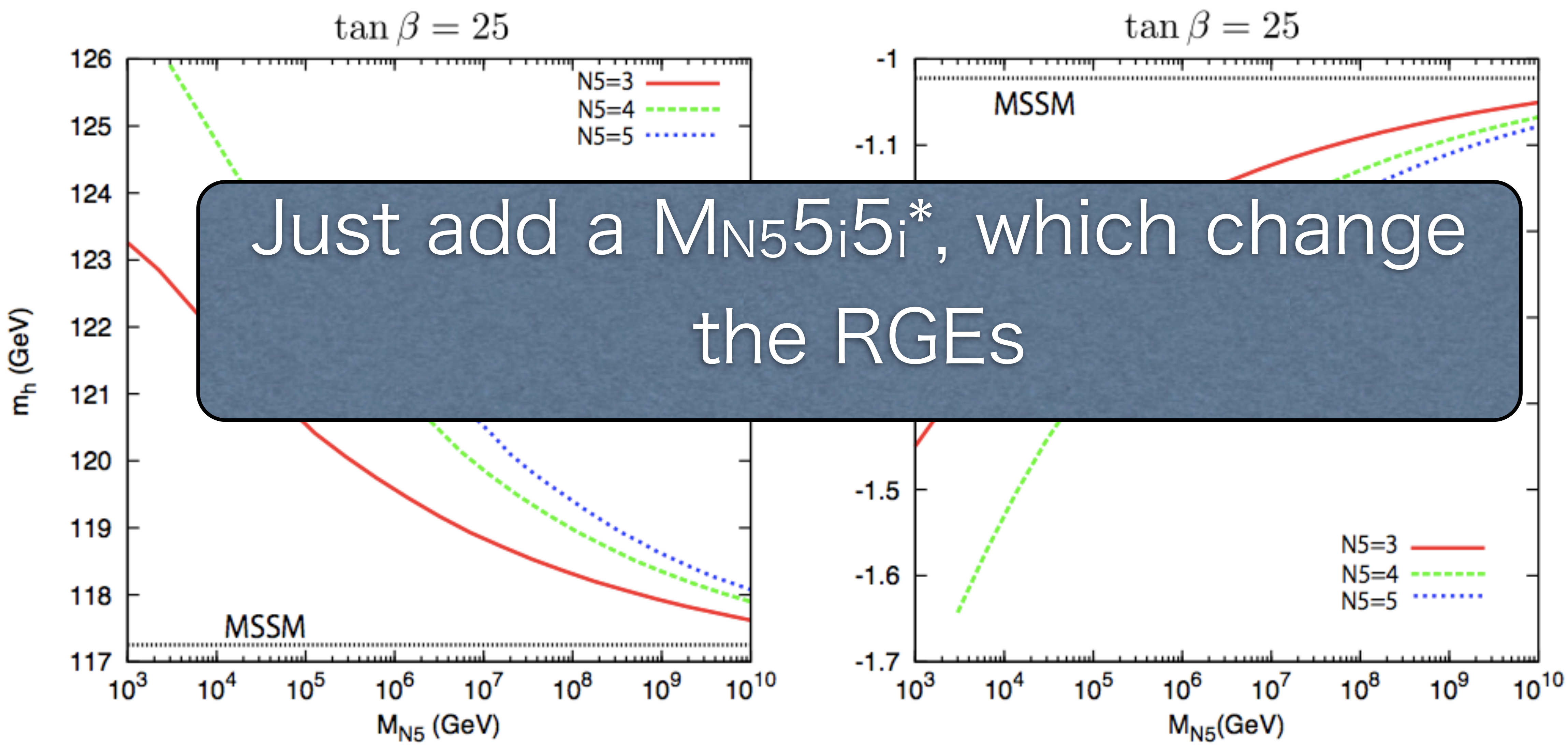

Just add a $M_{N5} 5_i 5_i^*$, which change the RGEs

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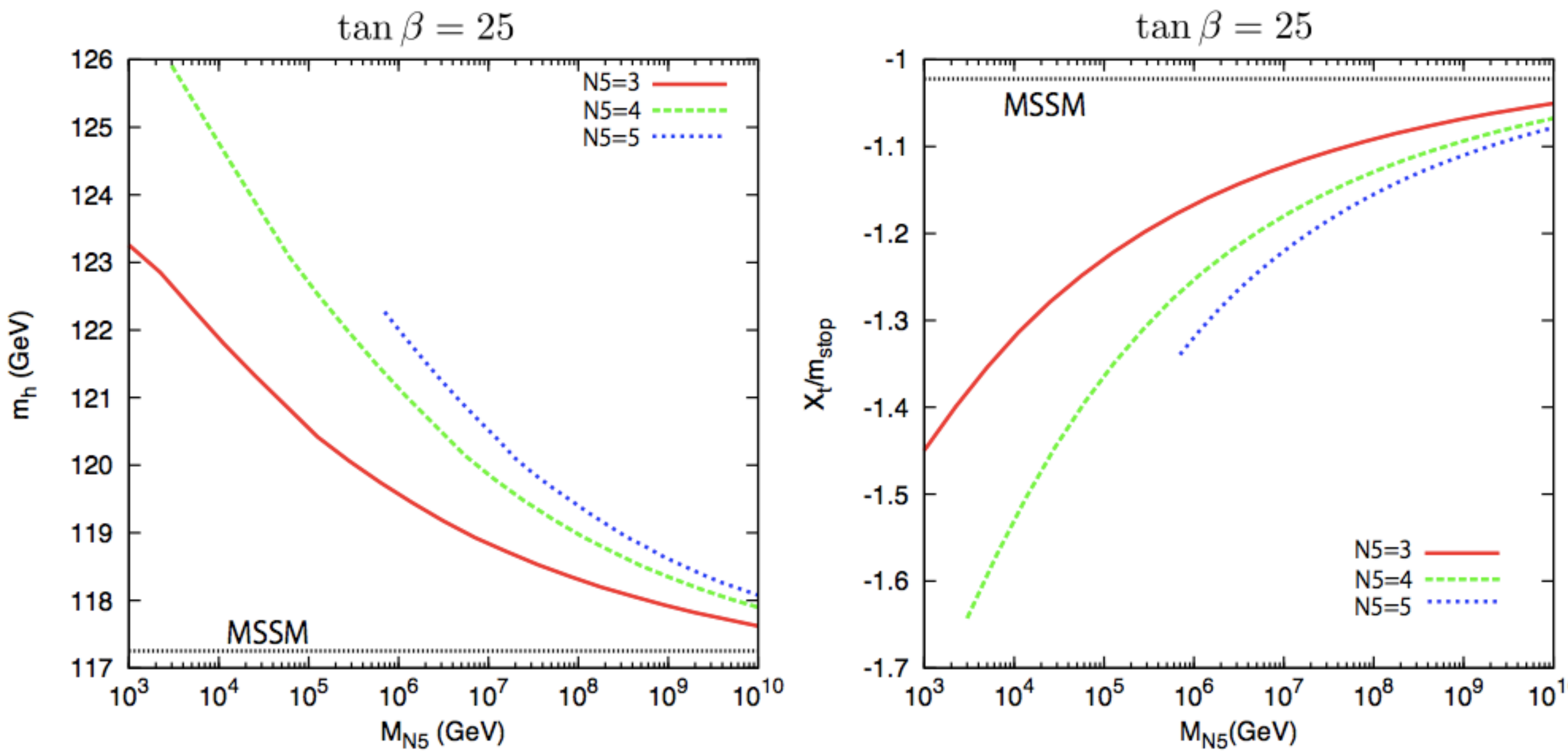

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Thank you