TeV scale Mirage Mediation in Next-to-MSSM

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based on

T. Kobayashi, T. S., T. Takahashi, arXiv:1203.4328

T. Kobayashi, H. Makino, K-I. Okumura, T. S., T. Takahashi, arXiv:1204.3561

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Introduction

The Standard Model (SM) has been successful to explain almost all of experimental results so far.

In particular, the gauge interactions of the electroweak sector agree with precise measurements very well.

The only mysterious part of the SM is the physics of

ElectroWeak Symmetry Breaking (EWSB)

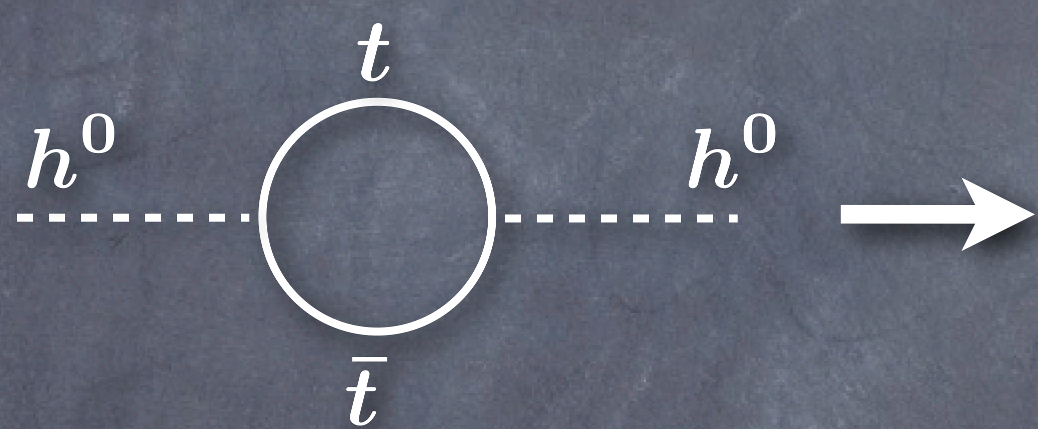
How is the EW symmetry broken?
Probably the (fundamental) Higgs mechanism

Why is the EWSB scale O(100) GeV?
New Physics...

Fine-tuning in the Standard Model

In the SM, the EW symmetry is broken by spontaneous symmetry breaking, i.e. the Higgs mechanism.

The mass of the Higgs receives large quadratic radiative corrections from UV physics (e.g. Planck/GUT)



$$\mu_{eff}^2 = \mu^2 + \frac{3Y_t^2}{8\pi^2}\Lambda^2$$

Λ : cutoff scale

A very strong fine-tuning is required to stabilize the EW scale.

$$(100)^2(\mathrm{GeV}^2) \sim (10^{16})^2 - (10^{16})^2\ (\mathrm{GeV}^2)$$ hierarchy problem

Such fine-tuning is "unnatural" and
new physics is required to stabilize the scale

Supersymmetry

Supersymmetry (SUSY) is a very attractive candidate of new physics for the hierarchy problem.

Each of the SM particles has a SUSY partner which has the same quantum charge but a different spin.

e.g.) MSSM

	SM particles	SUSY particles	
quarks	$Q,\ q$	$\tilde{Q},\ \tilde{q}$	squarks
leptons	$L,\ e$	$\tilde{L},\ \tilde{e}$	sleptons
Higgses	$H_1,\ H_2$	$\tilde{H}_1,\ \tilde{H}_2$	Higgsinos
gauge bosons	$B,\ W,\ G$	$\tilde{B},\ \tilde{W},\ \tilde{G}$	gauginos

Higgses

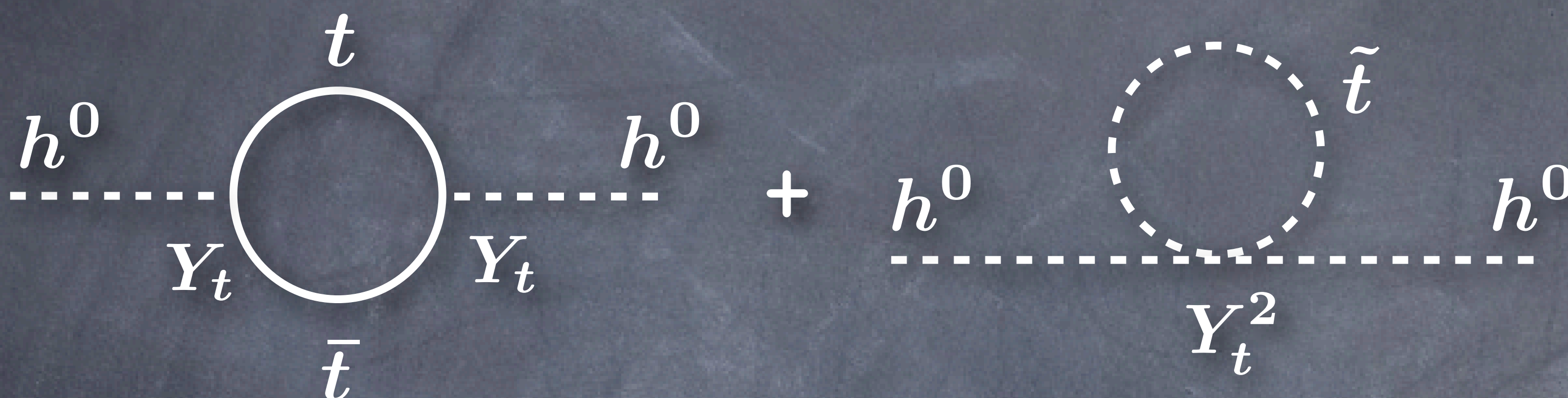
$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

charged Higgs

neutral Higgs

Supersymmetry

The quadratic divergences cancel due to SUSY partner contributions, and only log divergence remains.



$$\sim \frac{3|Y_t|^2}{16\pi^2} m_{\tilde{t}}^2 \log\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)$$

Λ : cutoff scale

The hierarchy problem can be solved if SUSY scale is around TeV.

SUSY also provides

- Dark Matter candidate (if R-parity is conserved)
- Grand Unification of the gauge interactions
- Quantum Gravity (?) (superstring)

Single sector SUSY breaking

Suppose SUSY breaking is transferred directly like

$$\mathcal{L} = F\Phi\Phi \rightarrow \langle F \rangle \Phi\Phi = m\Phi\Phi$$

F : SUSY breaking field
Φ : SM particles or their partners

The supertrace formula predicts the very light SUSY particles.

$\mathrm{Str}(-1)^F m^2$ = (boson mass)^2 - (fermion mass)^2 = 0

SUSY particles   the SM particles

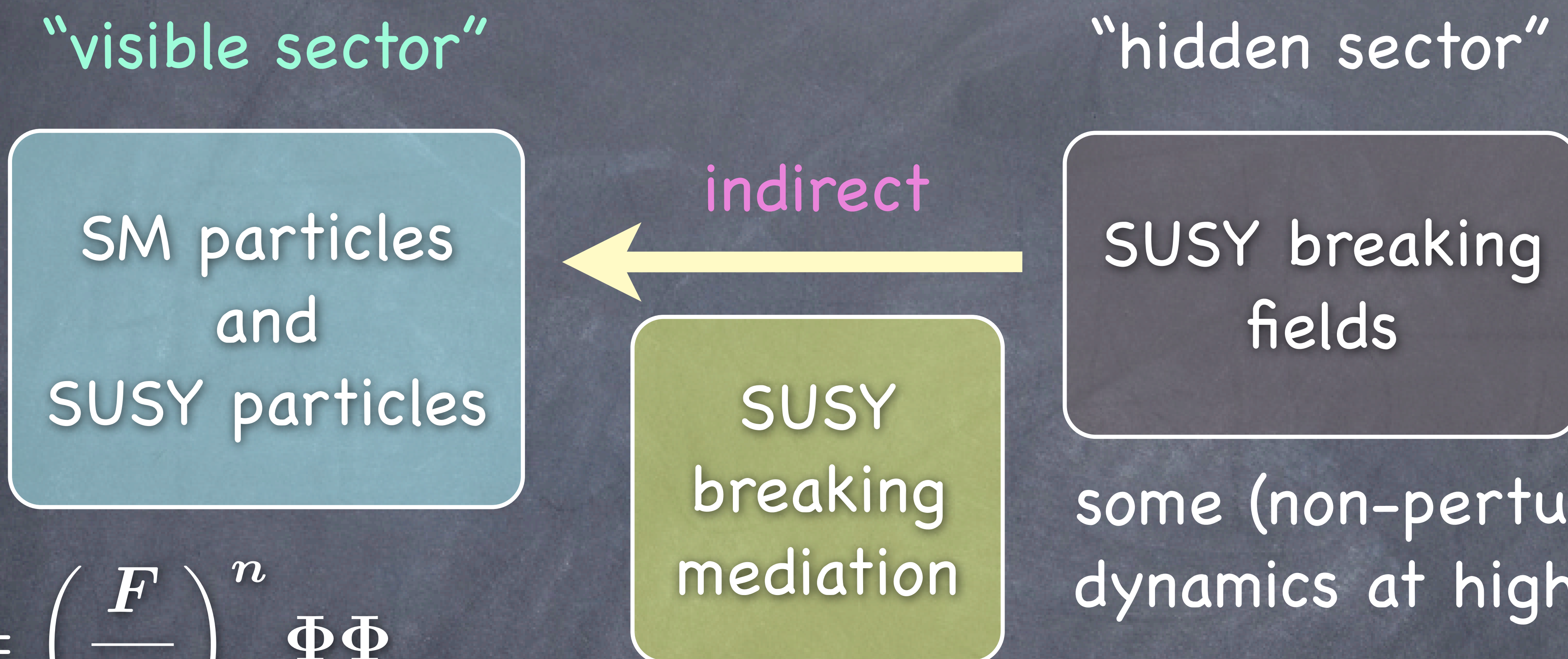
→ SM fermion mass = SUSY particle mass

Such light SUSY particles already excluded

SUSY breaking must be mediated indirectly

Two Sector Paradigm

SUSY world requires two sector and (some) mediation mechanism.



some (non-perturbative) dynamics at high energy

$$\mathcal{L} = \left(\frac{F}{M}\right)^n \Phi\Phi$$

Supertrace does not hold anymore.

soft SUSY br. terms are generated

Mediation mechanism

- supergravity (Planck scale)
- gauge interaction (intermediate scale)
- superconformal anomaly (Planck scale)

The little hierarchy problem

Kim and Nilles, '84

If SUSY scale is much above the TeV scale, another new fine-tuning is introduced.

In the MSSM, the EWSB scale is determined by

$$-\frac{1}{2}m_Z^2 \simeq m_{H_2}^2 + \mu^2, \quad \text{(for large } \tan\beta \text{)}$$

$m_{H_2}^2$:soft SUSY br. mass

The little fine-tuning is needed if

$$|m_{H_2}^2|,\ \mu^2 \gg m_Z^2$$

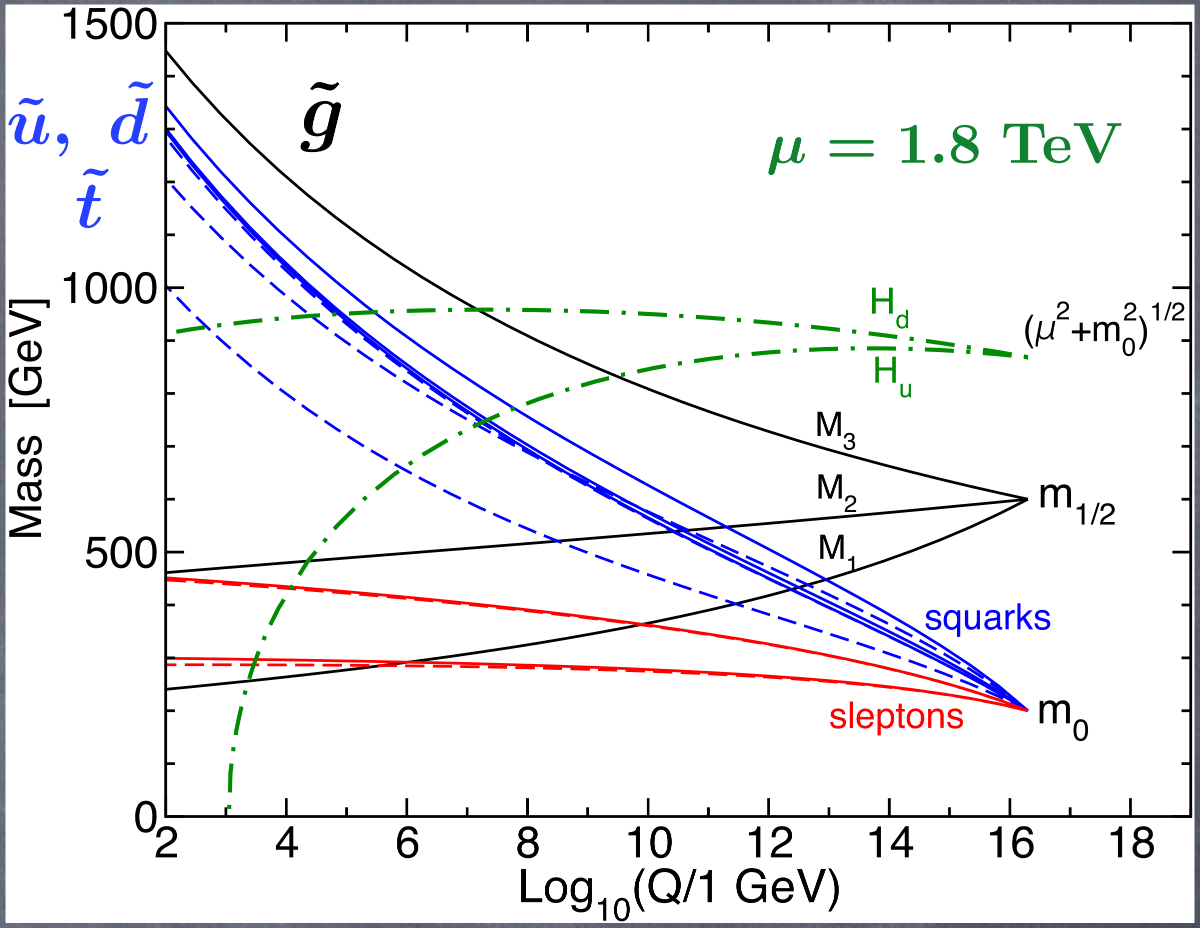
the little hierarchy problem

SUSY suffers this problem because the LHC has been pushing up the bound on SUSY scale.

This is a problem of mediation mechanisms, not SUSY!

The little hierarchy problem

(Martin, "susy primer")



ex) mSUGRA mediation

- Universal soft masses at GUT scale
- RG running to the EWSB scale
- Heavy SUSY particles at the EWSB scale

large soft mass of the Higgs

$$m^2_{H_u} \sim -m^2_{\tilde{t}} \sim -M^2_{\tilde{g}} \gg 1.5\ \mathrm{TeV},$$

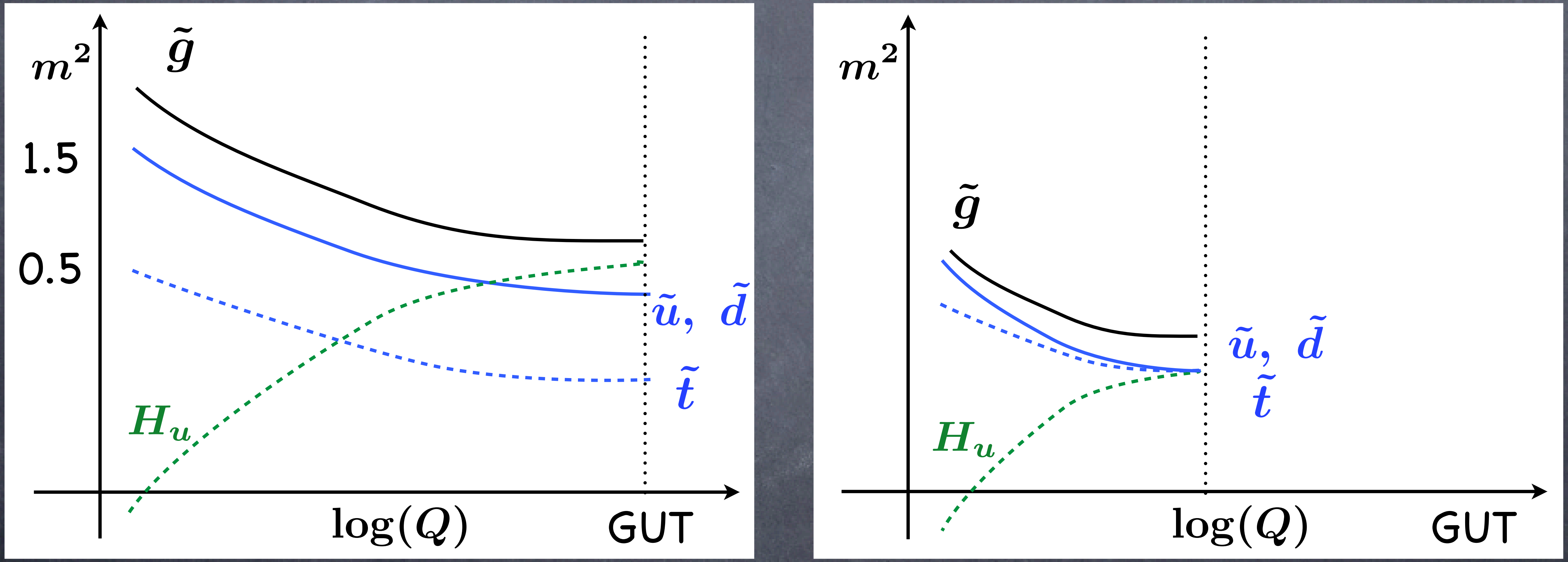
then, the little fine-tuning is needed

$$-\frac{1}{2}m_Z^2 \simeq m_{H_2}^2 + \mu^2, = (1\ \mathrm{TeV})^2 - (1\ \mathrm{TeV})^2$$

Mediations

We need another mediation mechanism in which

- The soft masses are different in each particles.
- The soft masses evolve over short scale.



One of such possibilities is Mirage Mediation.

Naturalness of the MSSM

The MSSM Lagrangian is given by three potentials

$$\mathcal{L} = K|_D + W|_F + V_{soft},$$

soft SUSY breaking terms

$$V_{soft} = m^2\phi^2 + A\phi^3 + M\tilde{B}^2,$$

scalar soft A-term gaugino soft

m,A,M are EWSB or TeV scale

supersymmetic interactions

$$W = Y\Phi_1\Phi_2 H + \mu H_1 H_2,$$

μ can be the Planck/GUT scale or keV scale, whatever...

There are no reason why μ is around the EWSB scale, but it must be...

Next-to-Minimal SSM

Fayet, '75, '76, '77; Nilles, Srednicki, Wyler, '83
Frere, Jones, Saby, '83; See review by Ellwaner'10

The NMSSM is an extension of the MSSM with a singlet and Z_3 parity.

$$\mathcal{W} \supset \mu \hat{H}_1 \cdot \hat{H}_2 \longrightarrow \mathcal{W} \supset \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \frac{\kappa}{3} \hat{S}^3,$$

No dimensionful parameter in the SUSY int.

Only dimensionful parameters are soft breaking terms.

$$V_{soft} = m^2 \phi^2 + A \phi^3 + M \tilde{B}^2,$$

- The EWSB occurs when the three Higgses develop vevs.
- μ term is generated by the EWSB.

$$\mu_{eff} = \lambda \langle S \rangle$$

- The vevs are determined by the soft breaking terms.

SUSY breaking scale determines the EWSB scale!

The Higgs mass

In the SM,

$$V = -m^2 H^2 + \frac{\lambda}{4} H^4 \longrightarrow m_h^2 \sim \lambda v^2$$

In the MSSM,

$$V = m_{H_1}^2 H_1^2 + m_{H_2} H_2^2 + B\mu H_1 H_2 + \frac{1}{8}(g_1^2 + g_2^2)(H_1^2 - H_2^2)^2$$

$$\longrightarrow m_{h_1}^2 \sim (g_1^2 + g_2)^2 v^2 \cos^2 2\beta = M_Z^2 \cos^2 2\beta$$

125 GeV Higgs mass needs large radiative corrections

$$\Delta m_{h_1}^2 = \frac{3m_t^4}{4\pi^2 v^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + X_t\left(1 - \frac{1}{6}X_t^2\right)\right) \quad X_t = A_t^2/m_{\tilde{t}}^2$$

the heavy stops/large A-term increase the little hierarchy

The Higgs mass in the NMSSM

In the NMSSM,

$$\mathcal{W} \supset \lambda \hat{S}\hat{H}_1 \cdot \hat{H}_2 + \frac{\kappa}{3}\hat{S}^3,$$

This superpotential gives a new quartic coupling

$$V \supset (kS^2 - \lambda H_1 H_2)^2 + \lambda^2 S^2 (H_1^2 + H_2^2)$$

then the Higgs mass becomes

$$m_{h_1}^2 = M_Z^2 \cos^2 2\beta + \underline{\lambda^2 v^2 \sin^2 2\beta - \lambda^2/\kappa^2 v^2 \cdots}$$

+ (radiative corrections)

the Higgs mass can be heavier than in the MSSM

the little hierarchy becomes milder in the NMSSM

short summary

Why is the EWSB scale O(100) GeV?

This is one of the most important questions at this time.

- tachyonic Higgs mass is very sensitive to UV physics

  the EWSB scale is unstable to radiative corrections

  SUSY can solve this problem

- the LHC has been pushing the bound up and up

  The little hierarchy problem?

  This is a problem of mediations

  It can be solved by the Mirage Mediation

- the naturalness problem?

  tension between the Higgs mass and the little hierarchy?

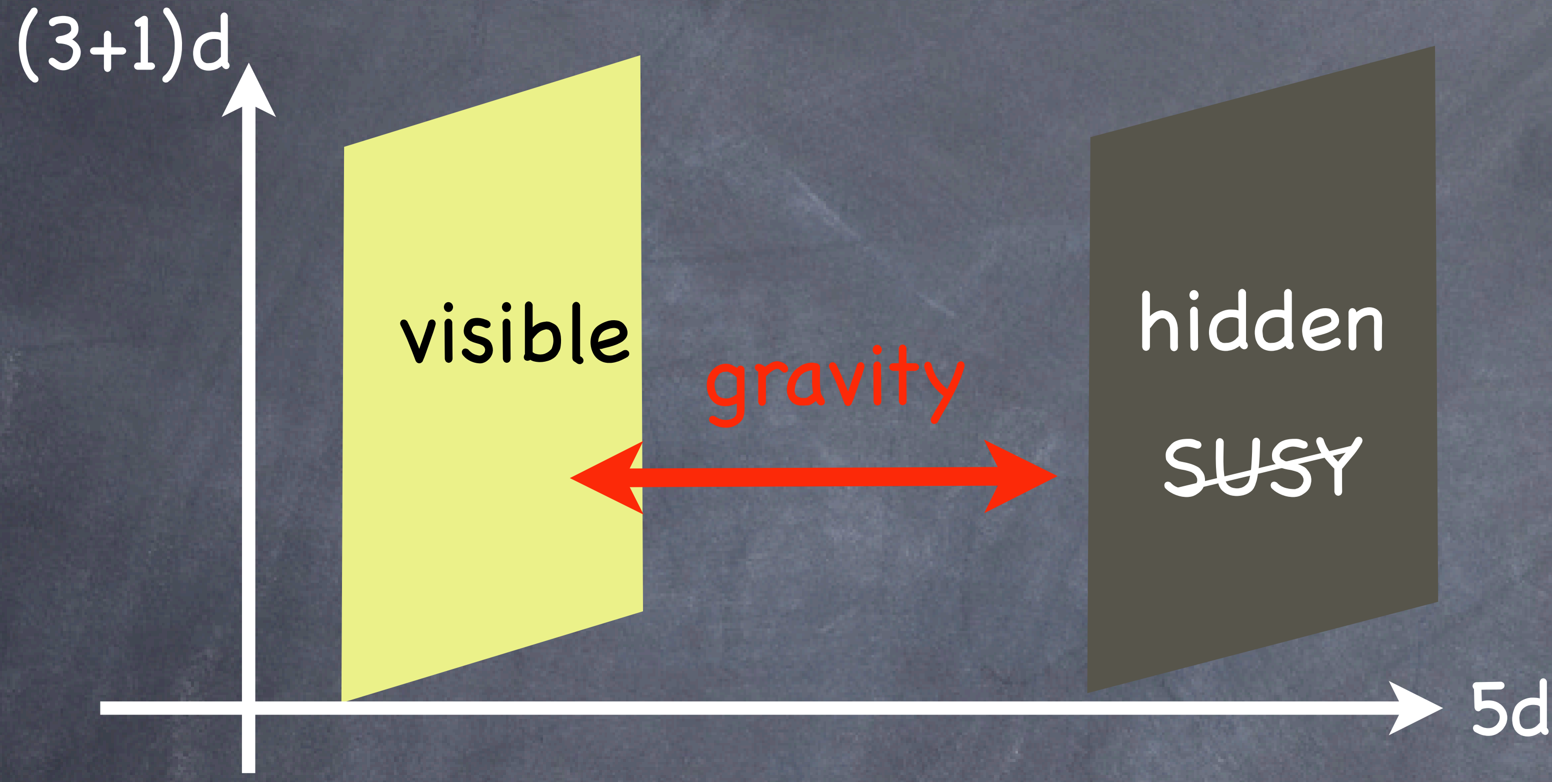
  Don't worry. the NMSSM can solve it.

2. Mirage Mediation

Anomaly Mediation (AMSB)

Landall, Sundrum, '99;
Giudice, Luty, Murayama, Rattazzi, '98

the visible and the hidden sectors are physicaly separated.



- only gravity propagates in the bulk.
- Interactions are purely gravitational.
- Scale invariant if no SUSY mass terms

The scale inv. is broken by super-Weyl anomaly

gaugino: $$M_a = \frac{b_a g_a^2}{16\pi^2}\frac{\langle F\rangle}{M_{pl}}$$ $$\frac{\langle F\rangle}{M_{pl}} = m_{3/2}$$

scalar: $$m_q^2 = -\frac{1}{4}(\beta_g \gamma'_g + \beta_y \gamma'_y)\frac{\langle F\rangle^2}{M_{pl}^2}$$

12年7月4日水曜日

Modulus Mediation

Kaplunovsky, Luis, '93; Brignole, Ibanez, Munoz, '94
Kobayashi, Suematsu, et al, '95

- String theory is consistently defined in 10 dimensions.
- Superfluous 6 dimensions should be compactified in small size.
- moduli appear which parameterize shape and size of the extra-dimensions.
- In KKLT setup, moduli can be stabilized, then SUSY is broken.

Kachru, Kallosh, Linde, Trivedi, '03

- F-term of modulus fields are suppressed and comparable to the AMSB contributions.

the AMSB and the MMSB can contribute together

Mirage Mediation

Choi, Falkowski, Nilles, Olechowski, Pokorski '04
Choi,Falkowski,Nilles,Olechowski, '05
Endo, Yamaguchi, Yoshioka, '05

The mirage mediation is a mixture of the modulus mediation and the anomaly mediation.

gaugino soft mass

$$M_a(M_{GUT}) = M_0 + \frac{b_a}{16\pi^2} g^2(M_{GUT}) m_{3/2}$$

Mirage scale : special energy scale in the mirage med.

$$M_{\rm mir} = \frac{M_{GUT}}{(M_{pl}/m_{3/2})^{\alpha/2}}$$

M_{pl}: Planck scale

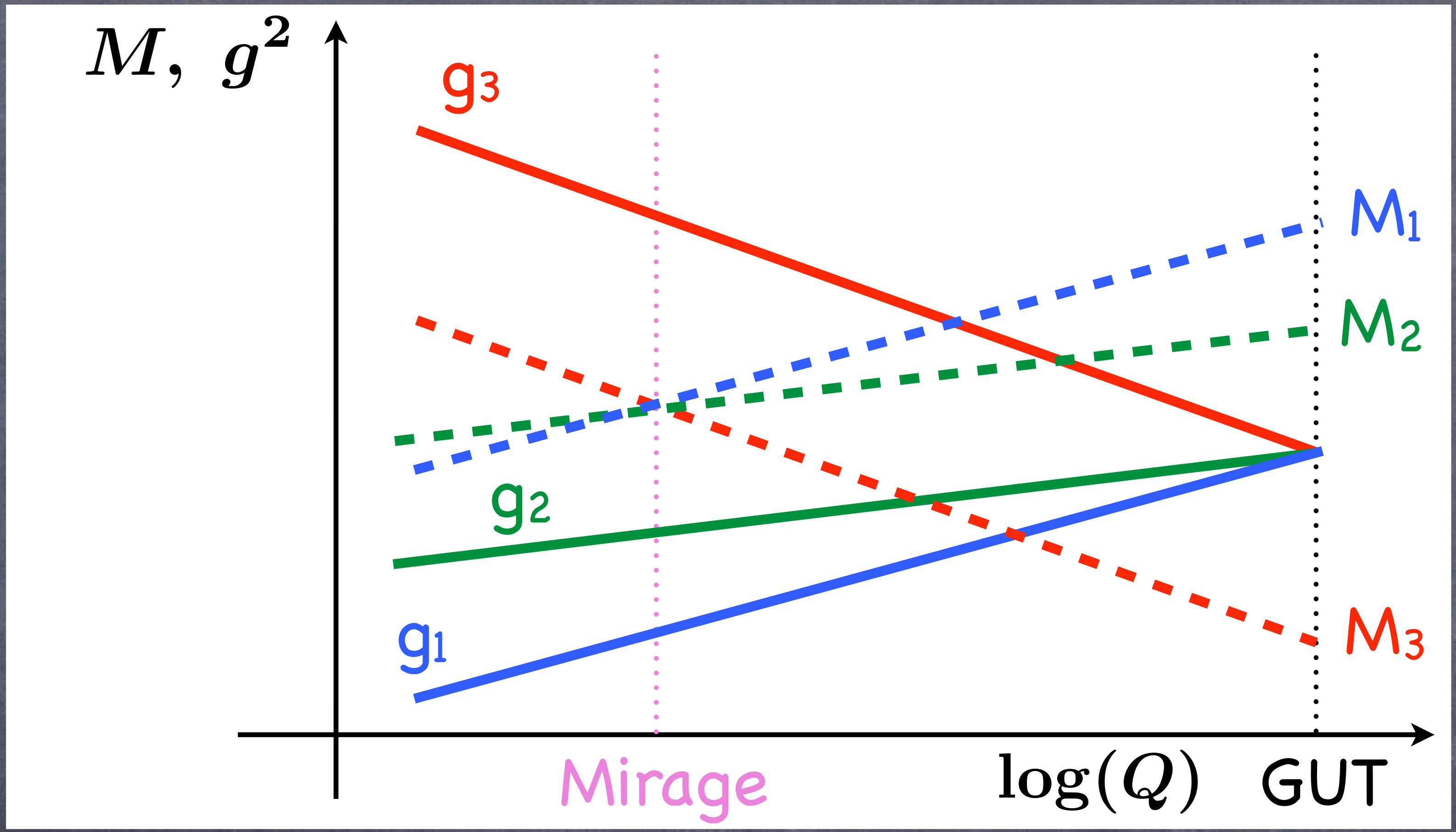
the ratio of the anomaly med. to the modulus med.

$$\alpha \equiv \frac{m_{3/2}}{M_0 \log(M_{pl}/m_{3/2})}$$

the gaugino masses are unified at the mirage scale

$$M_a(M_{\rm mir}) = M_0 \qquad \text{@ 1-loop}$$

This result is independent of α.



This unification is just due to a cancellation between the anomaly med. and RGE's contributions.

A terms and scalar soft masses

$$A_{ijk}(M_{GUT}) = a_{ijk}M_0 - (\gamma_i + \gamma_j + \gamma_k)\frac{m_{3/2}}{8\pi^2}$$

$$m_i^2(M_{GUT}) = c_i M_0^2 - \dot{\gamma}_i(\frac{m_{3/2}}{8\pi^2})^2 - \frac{m_{3/2}}{8\pi^2}M_0\theta_i,$$

where

a_{ijk} & c_i : modular weight

γ_i, θ_i : functions of gauge and Yukawa coupl.

At the mirage scale, the same cancellation works

$$A_{ijk}(M_{\rm mir}) = a_{ijk}M_0$$

$$m_i^2(M_{\rm mir}) = c_i M_0^2$$

if the corresponding Yukawa coupling is small or
the following condition is satisfied,

$$a_{ijk} = c_i + c_j + c_k = 1$$

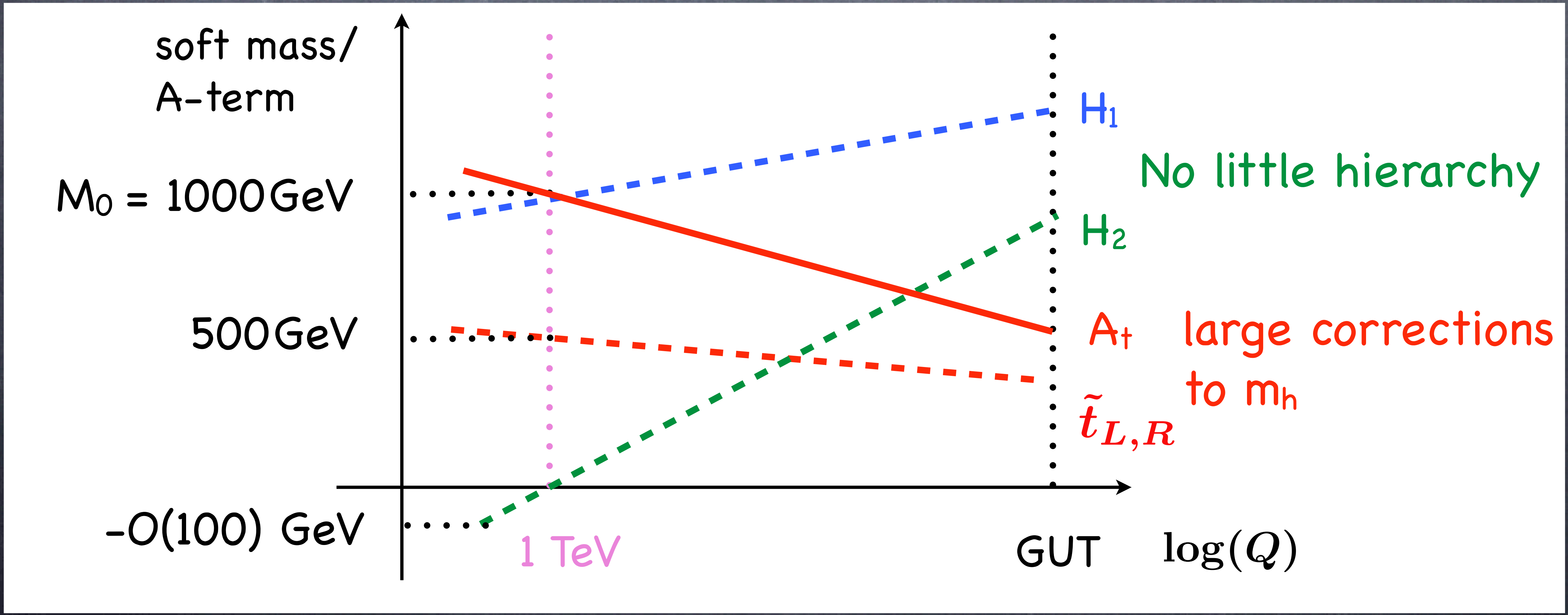
TeV scale Mirage

Choi, Jeong, Kobayashi, Okumura, '06 & '07
Kitano, Nomura, '05

When we take c_i and α as

$$c_{H_1} = 1, \; c_{H_2} = 0, \quad c_{t_L} = c_{t_R} = \frac{1}{2},$$

$$M_{\rm mir} = \left. \frac{M_{GUT}}{(M_{pl}/m_{3/2})^{\alpha/2}} \right|_{\alpha=2} \simeq 1 \text{ TeV}$$



TeV scale Mirage in NMSSM

Kobayashi, Makino, Okumura, T.S., Takahashi; '12
Asano, Higaki; '12

The Higgs sector is extended in the NMSSM

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \qquad S$$

The soft SUSY breaking terms are

$$V_{soft} = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + m_S^2 S^\dagger S - \left(\lambda A_\lambda S H_1 H_2 - \frac{1}{3} \kappa A_\kappa S^3 \right)$$

For the TeV scale mirage, the modular weights are assigned

$$c_{H_1} = 1,\ c_{H_2} = c_S = 0$$

and for stops

$$c_{t_L} = c_{t_R} = 1/2$$

TeV scale Mirage in NMSSM

At the TeV mirage scale,

$$A_\lambda = A_t = M_0$$

$$m^2_{H_1} = M_0^2, \quad m^2_{\tilde{t}_L} = m^2_{\tilde{t}_R} = \frac{1}{2} M_0^2$$

and

$$A_\kappa = m_S^2 = m^2_{H_2} = 0 \qquad \text{@ 1-loop}$$

Ambiguity comes from a Kahler metric of UV theory

$$\delta A_\kappa \simeq \mathcal{O}(M_0/8\pi^2)$$

$$\delta m_{S,H_2} \simeq \mathcal{O}(\kappa^2 M_0^2/8\pi^2)$$

which can not be determined without UV theory.

TeV scale Mirage in NMSSM

At low energy, we can determine by requiring the EWSB

$$\frac{\partial V}{\partial H_{1,2}} = \frac{\partial V}{\partial S} = 0,$$

which lead

$$\mu = \lambda\langle S\rangle \sim \frac{m_{H_1}^2}{A_\lambda \tan\beta}$$

$$m_S^2 \sim -2\left(\frac{\kappa}{\lambda}\right)^2\left(\frac{m_{H_1}^2}{A_\lambda \tan\beta}\right)^2 - \left(\frac{\kappa}{\lambda}\right)A_\kappa\left(\frac{m_{H_1}^2}{A_\lambda \tan\beta}\right)$$

$$+2\frac{\lambda^2}{g^2}\frac{A_\lambda^2}{m_{H_1}^2}m_Z^2$$

$$m_{H_2}^2 \sim \frac{m_{H_1}^2}{\tan^2\beta} - \frac{m_{H_1}^4}{A_\lambda^2 \tan^2\beta} - \frac{m_Z^2}{2}$$

TeV scale Mirage in NMSSM

The little hierarchy is ameliorated because

$$A_\lambda \simeq m_{H_1} \simeq M_0$$

then,

$$m_{H_2}^2 \sim \frac{m_{H_1}^2}{\tan^2\beta} - \frac{m_{H_1}^4}{A_\lambda^2 \tan^2\beta} - \frac{m_Z^2}{2} \simeq -\frac{m_Z^2}{2}$$

cancel each other

The EWSB scale is almost determined by m_{H2} and insensitive to μ paramter

- tanβ=3 is enough for the little hierarchy, which increase the Higgs mass.
- μ can be as heavy as O(400) GeV

3. (Old) Numerical Results

Setup for the mirage mediation

free parameters

$$\lambda, \ \kappa, \ \tan\beta, \ M_0, \ A_\kappa$$

the stationary conditions determine

$$m_{H_2}, \ m_S, \ \mu = \lambda\langle S\rangle$$

illustrating examples

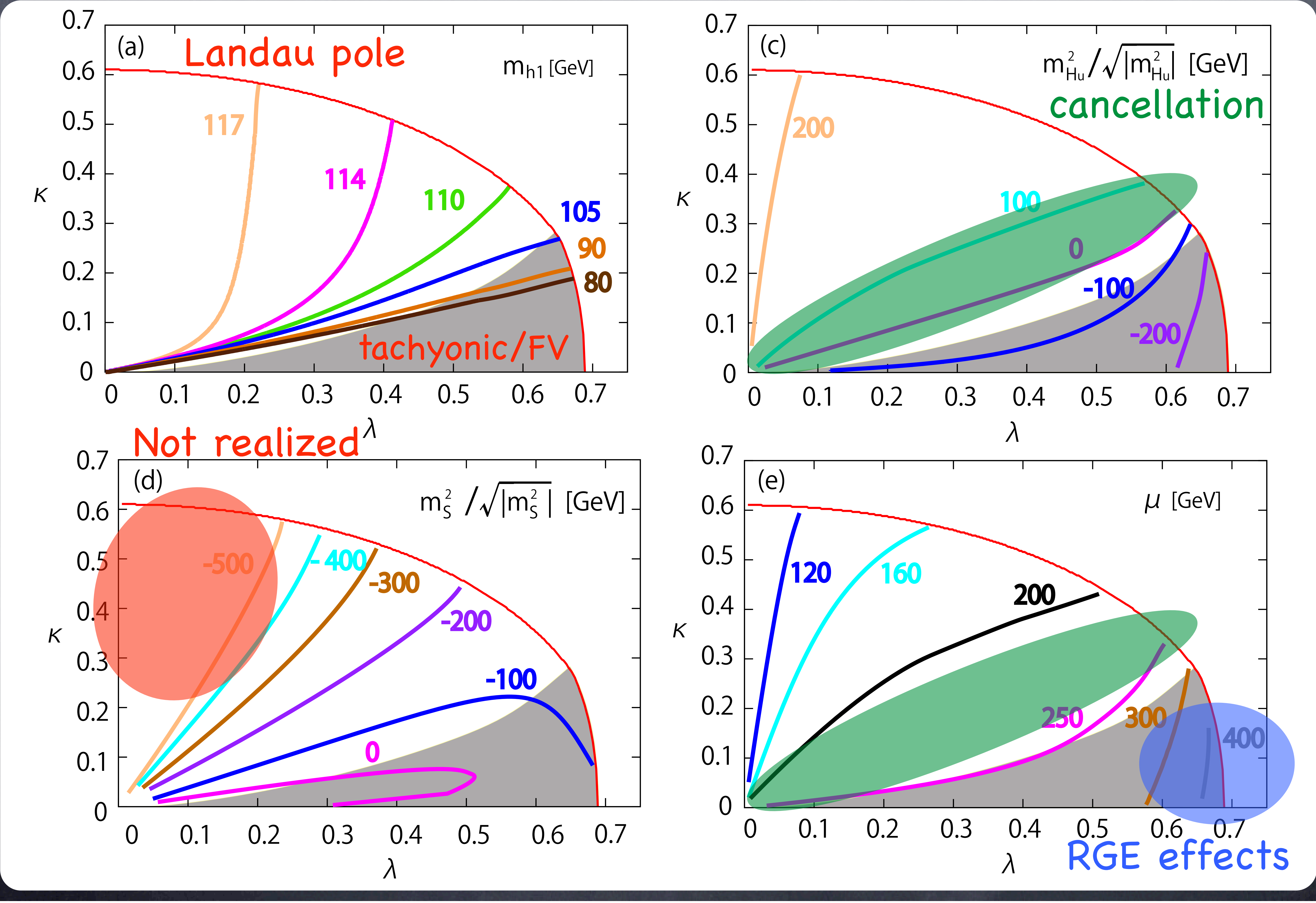
$$A_\kappa = -100 \text{ GeV}$$

$$\tan\beta = 3, \ 5$$

$$M_0 = 1.2, \ 1.5 \text{ TeV}$$

The higgs mass is evaluated at pole m_t
and should be +5 GeV at m_Z

$\tan\beta = 5,\ M_0 = 1.2\ \mathrm{TeV} \quad \mu = M_0/\tan\beta = 100 - 300\ \mathrm{GeV}$



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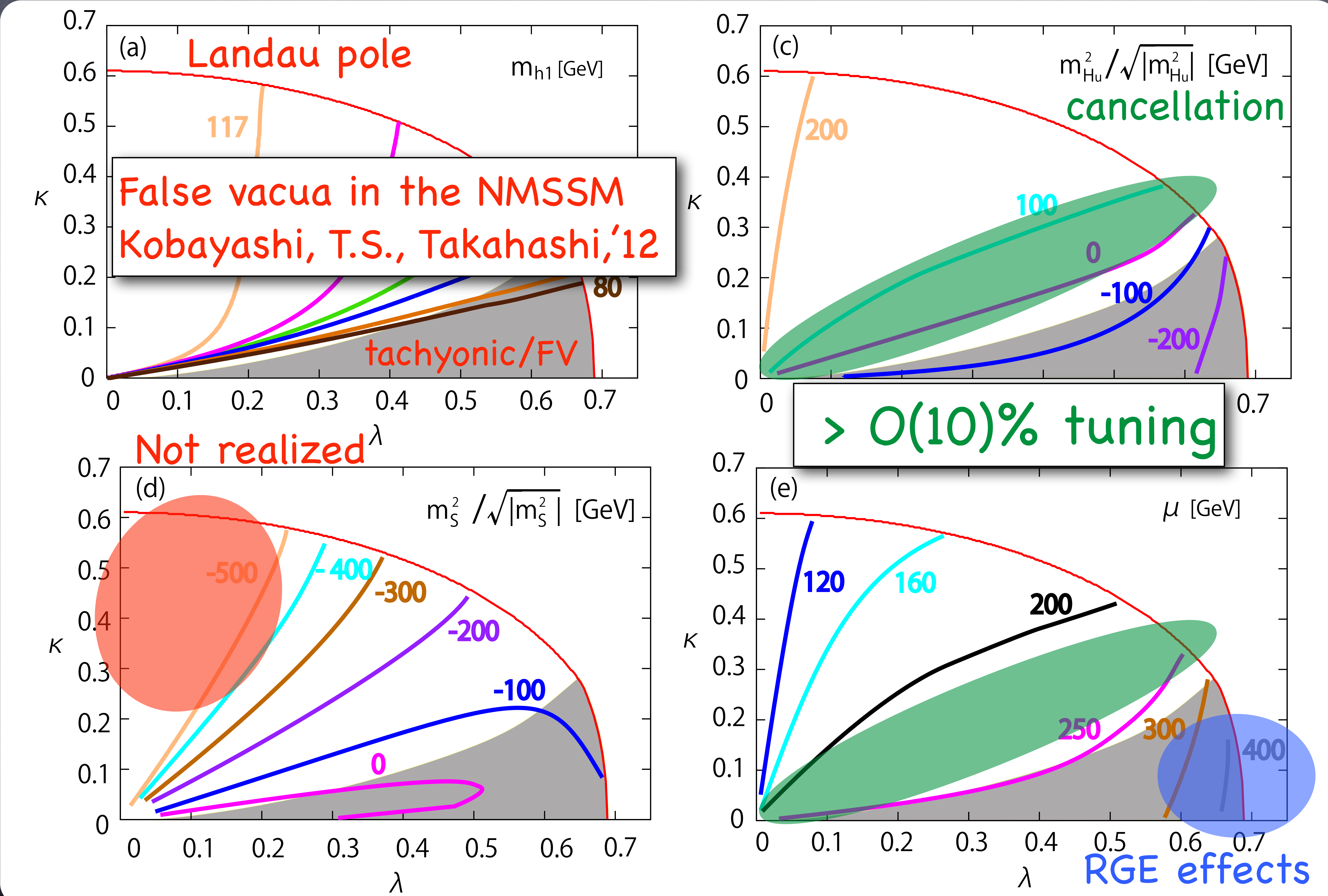
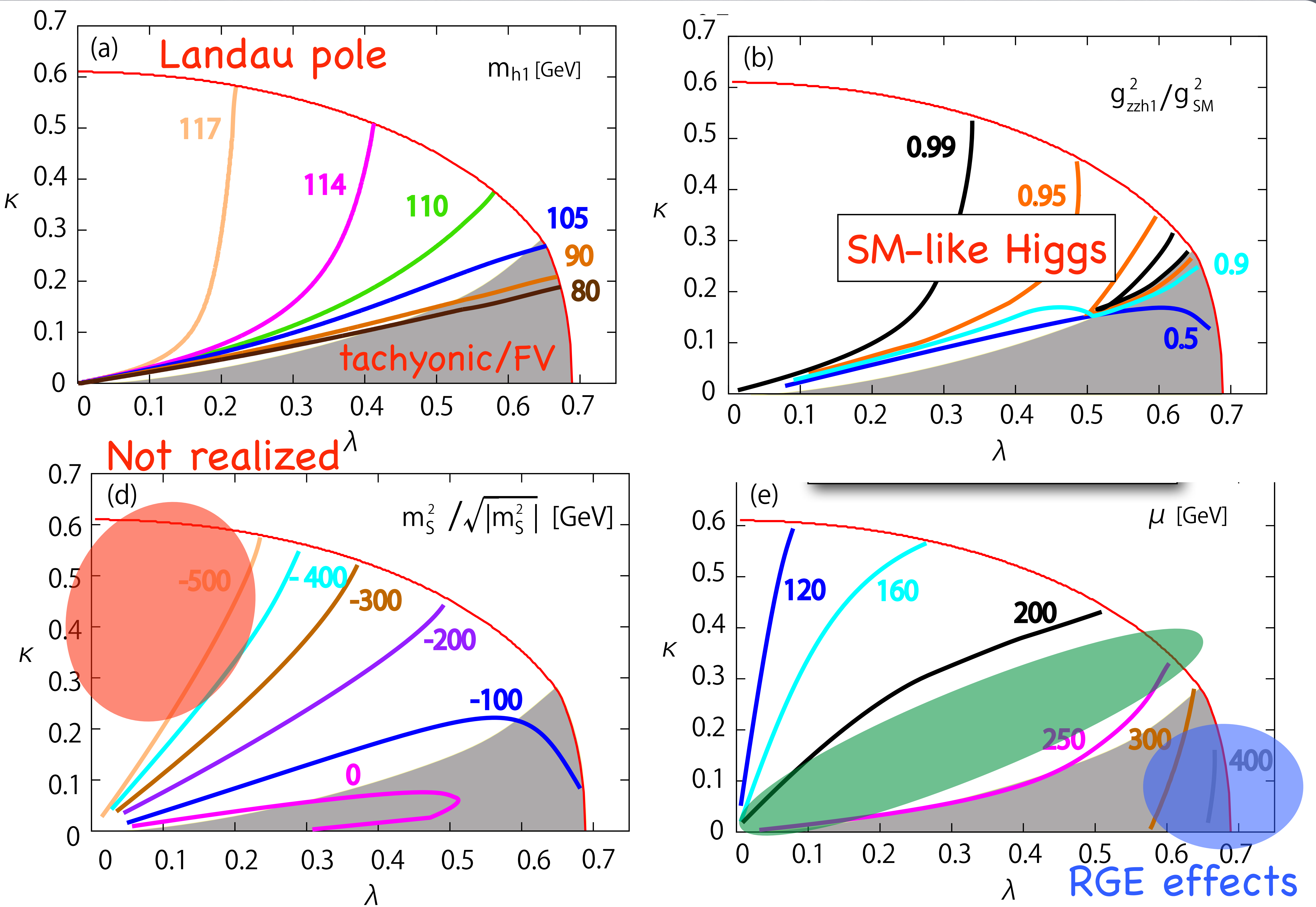
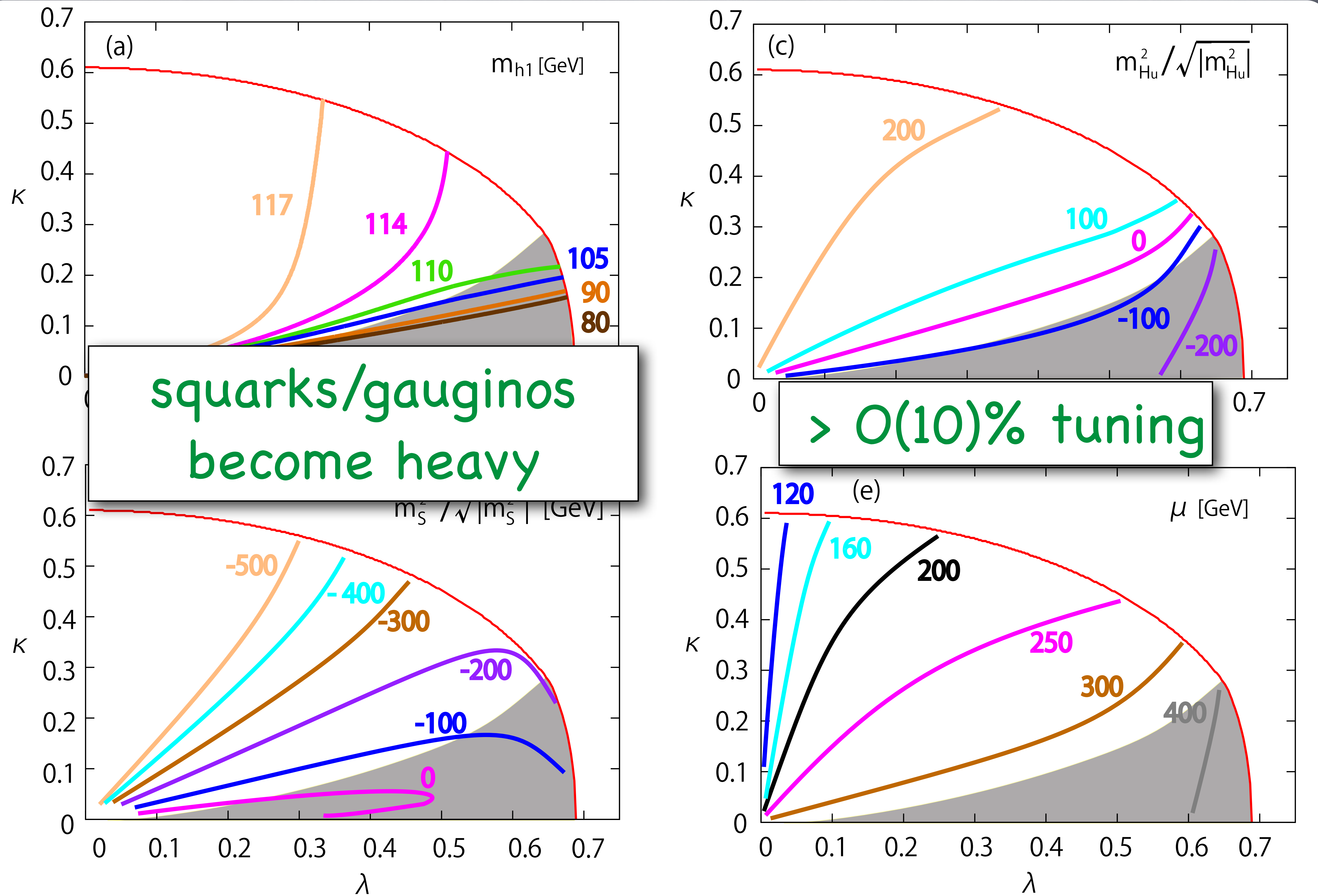


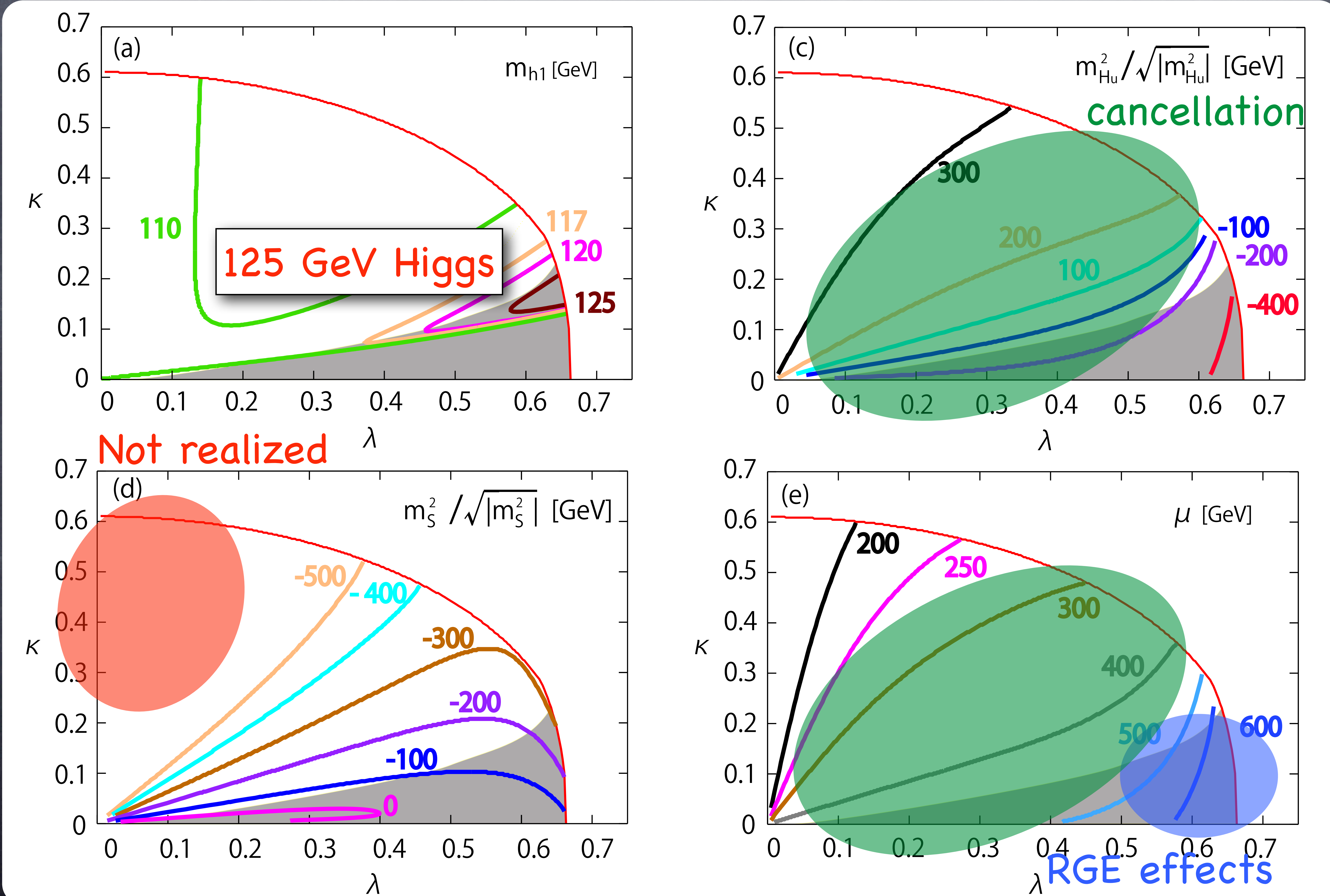
$\tan\beta = 5, \; M_0 = 1.2 \text{ TeV} \quad \mu = M_0/\tan\beta = 100 - 300 \text{ GeV}$



$\tan\beta = 5,\ M_0 = 1.5$ TeV



$\tan\beta = 3,\ M_0 = 1.2\ \mathrm{TeV} \qquad \mu = M_0/\tan\beta = 400 - 700\ \mathrm{GeV}$



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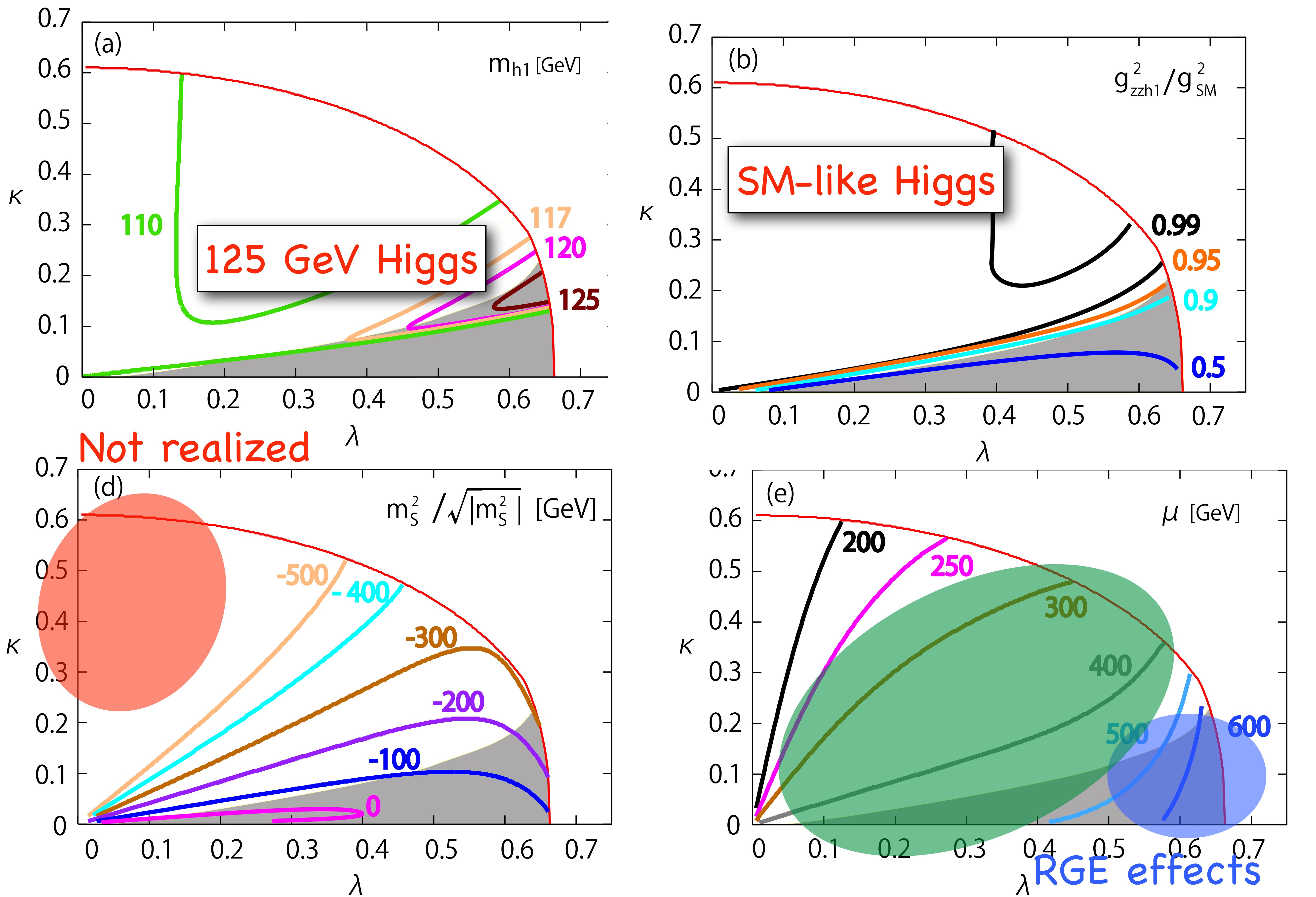

$\tan\beta = 5,\ M_0 = 1.2$ TeV

(λ, κ)	$(0.10, 0.30)$	$(0.41, 0.15)$	$(0.61, 0.20)$
m_{h1}	117 GeV	105 GeV	94 GeV
m_{h2}	997 GeV	149 GeV	136 GeV
m_{h3}	1237 GeV	1250 GeV	1256 GeV
m_{a1}	389 GeV	190 GeV	210 GeV
m_{a2}	1235 GeV	1249 GeV	1255 GeV
$g^2_{ZZh}/g^2_{\rm SM}$	1.00	0.91	0.89
m^2_{Hd}	$1.44 \times 10^6\mathrm{GeV}^2$	$1.45 \times 10^6\mathrm{GeV}^2$	$1.71 \times 10^6\mathrm{GeV}^2$
m^2_{Hu}	$2.64 \times 10^4\mathrm{GeV}^2$	$-1.56 \times 10^4\mathrm{GeV}^2$	$-1.43 \times 10^4\mathrm{GeV}^2$
m^2_S	$-4.42 \times 10^5\mathrm{GeV}^2$	$-6.89 \times 10^3\mathrm{GeV}^2$	$-9.25 \times 10^3\mathrm{GeV}^2$
$m_{\tilde{t}_1}$	839 GeV	839 GeV	807 GeV
$m_{\tilde{t}_2}$	1080 GeV	1078 GeV	1058 GeV
μ	168 GeV	240 GeV	286 GeV

$\tan\beta = 5,\ M_0 = 1.2$ TeV

(λ, κ)	$(0.10, 0.30)$	$(0.41, 0.15)$	$(0.61, 0.20)$
m_{h1}	117 GeV	105 GeV	singlet 94 GeV
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$\tan\beta = 3,\ M_0 = 1.2$ TeV

(λ, κ)	$(0.1, 0.3)$	$(0.41, 0.15)$	$(0.61, 0.20)$
m_{h1}	110 GeV	113 GeV	122 GeV
m_{h2}	1293 GeV	261 GeV	234 GeV
m_{h3}	1484 GeV	1339 GeV	1346 GeV
m_{a1}	478 GeV	246 GeV	273 GeV
m_{a2}	1293 GeV	1337 GeV	1345 GeV
$g^2_{ZZh}/g^2_{\rm SM}$	1.00	1.00	0.96
m^2_{Hd}	$1.44 \times 10^6 {\rm GeV}^2$	$1.45 \times 10^6 {\rm GeV}^2$	$1.87 \times 10^6 {\rm GeV}^2$
m^2_{Hu}	$9.97 \times 10^4 {\rm GeV}^2$	$4.97 \times 10^3 {\rm GeV}^2$	$-5.69 \times 10^4 {\rm GeV}^2$
m^2_S	$-1.04 \times 10^6 {\rm GeV}^2$	$-3.05 \times 10^4 {\rm GeV}^2$	$-4.70 \times 10^4 {\rm GeV}^2$
$m_{\tilde{t}_1}$	840.2 GeV	842.6 GeV	788 GeV
$m_{\tilde{t}_2}$	1073.5 GeV	1067.9 GeV	1032 GeV
μ	251 GeV	414 GeV	542 GeV

μ increases for small tanβ

Summary

We have studied the NMSSM with TeV scale mirage mediation.
We showed

- The cancellation mechanism works well between m_{H1} and μ parameter.
- The little hierarchy can be ameliorated to O(10) % with large μ parameter.
- The lightest Higgs mass can be 115-130 GeV for M_0=1.2-1.5 TeV.
- The lightest Higgs boson is almost the SM-like.
- The lightest CP-odd Higgs boson is relatively light.
- The heaviest CP-even/odd Higgs bosons has mass close to M_0.

Future Works

We have showed only illustrating examples.
More detailed analyses should be done.

- allowed region search with experimental constraints as well as false vacua constraints.
- Dark matter physics for singlino/higgsino LSP.
- more concrete analysis on the Higgs sector.

Some of works are in progress but you are welcome to join in the collaboration.

Danke Schön!