Supersymmetric Dark Matter

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HUH????

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Is “low energy” susy DM still viable?

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yes

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What about high scale susy?

Supersymmetric Dark Matter

Is "low energy" susy DM still viable?

yes

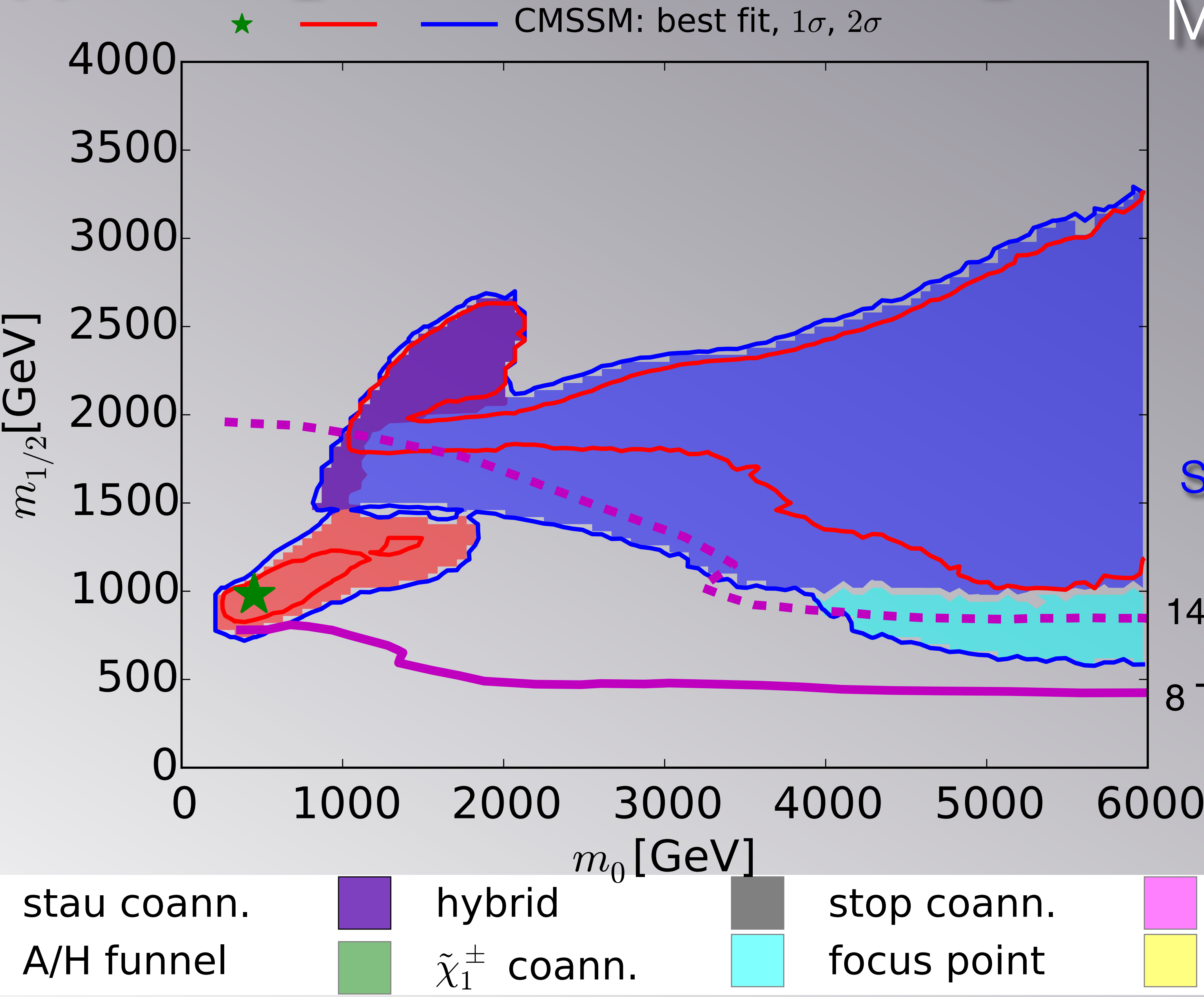
What about high scale susy?

No susy?

$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

Mastercode

2015



Low mass spectrum still observable at LHC

14 TeV 3000 fb^{-1}

8 TeV 20 fb^{-1}

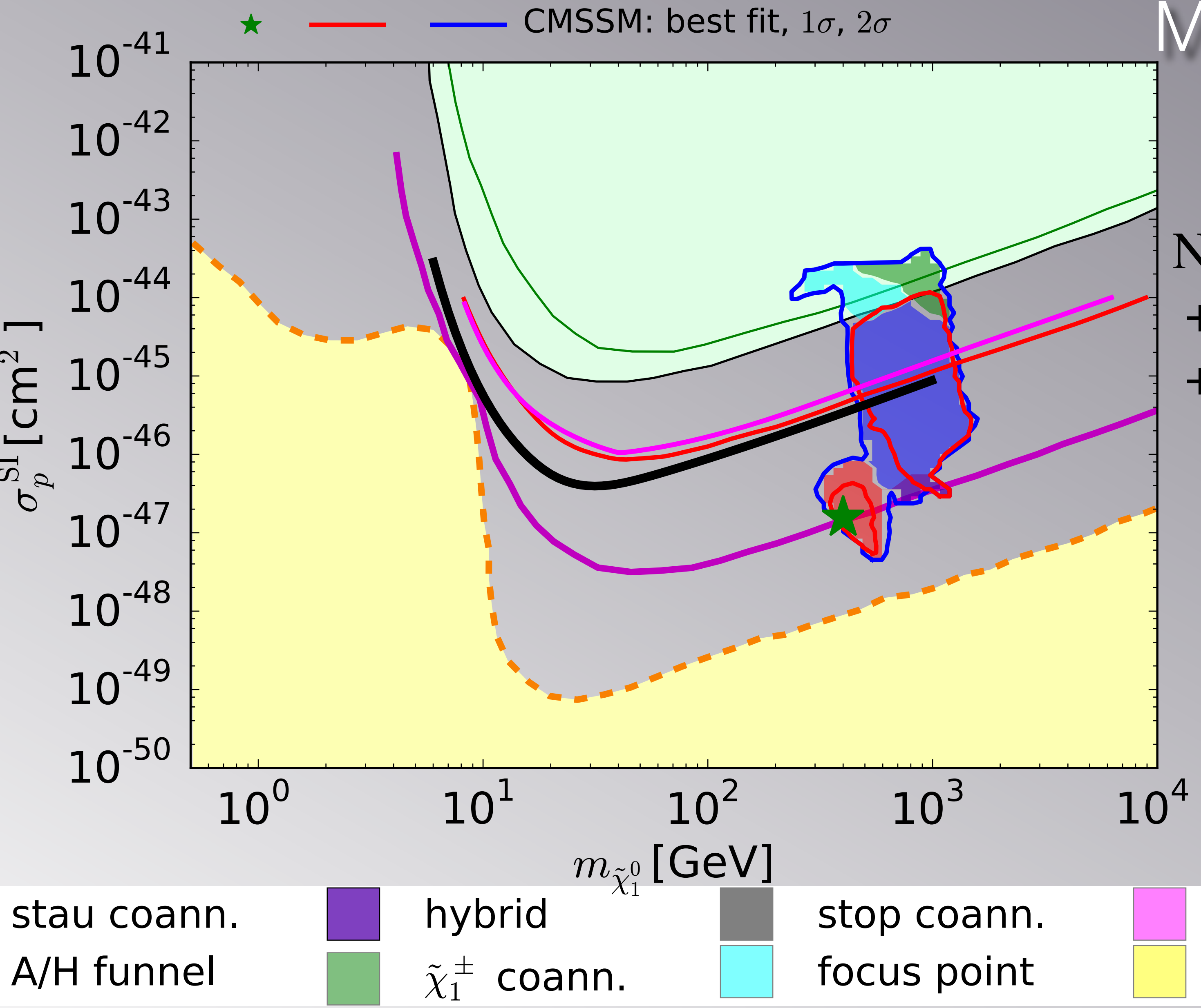
- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

Elastic scaterring cross-section

Mastercode

2015

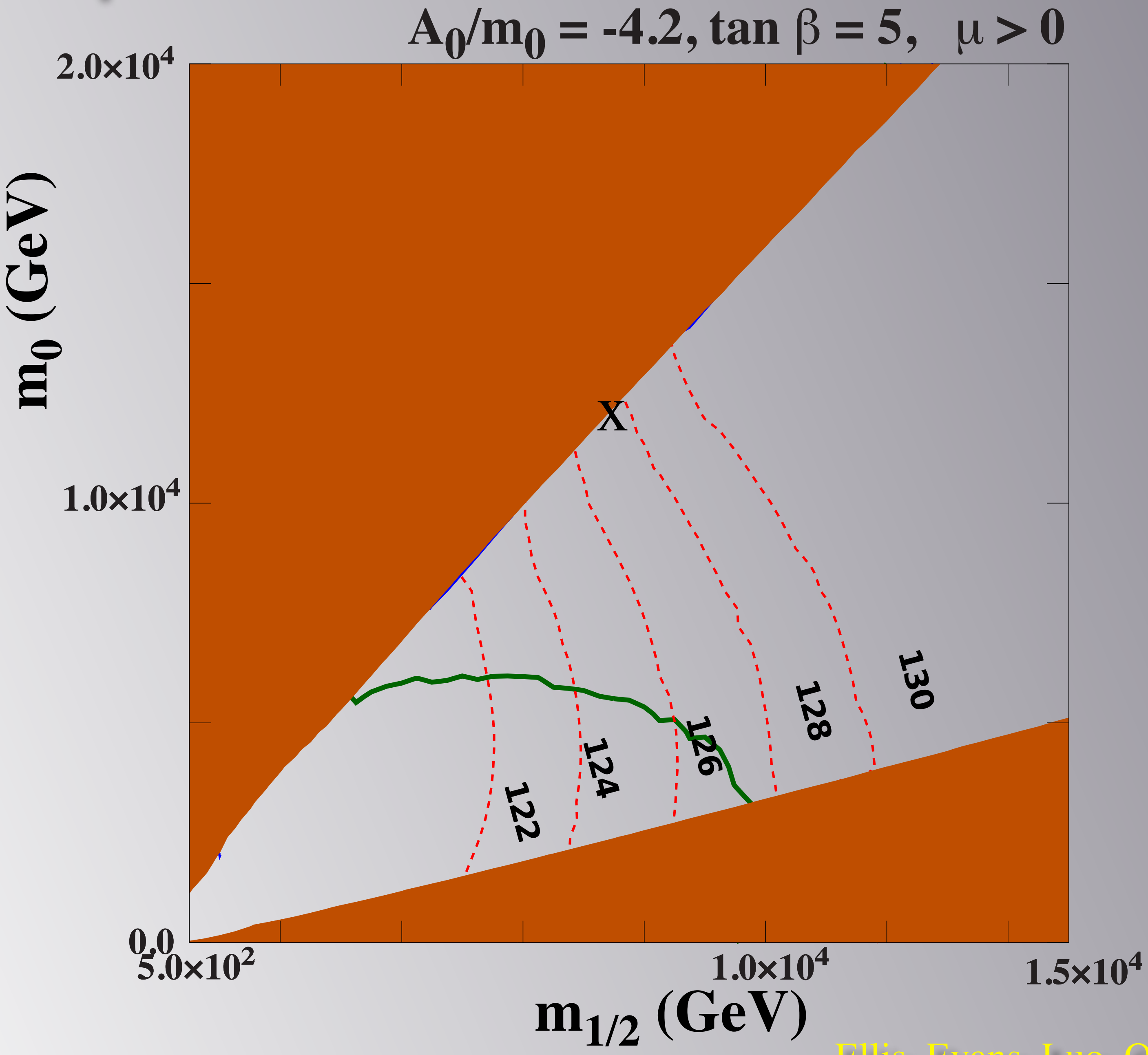


New LUX bound
+ PandaX
+ XENON1t

- CMSSM

Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

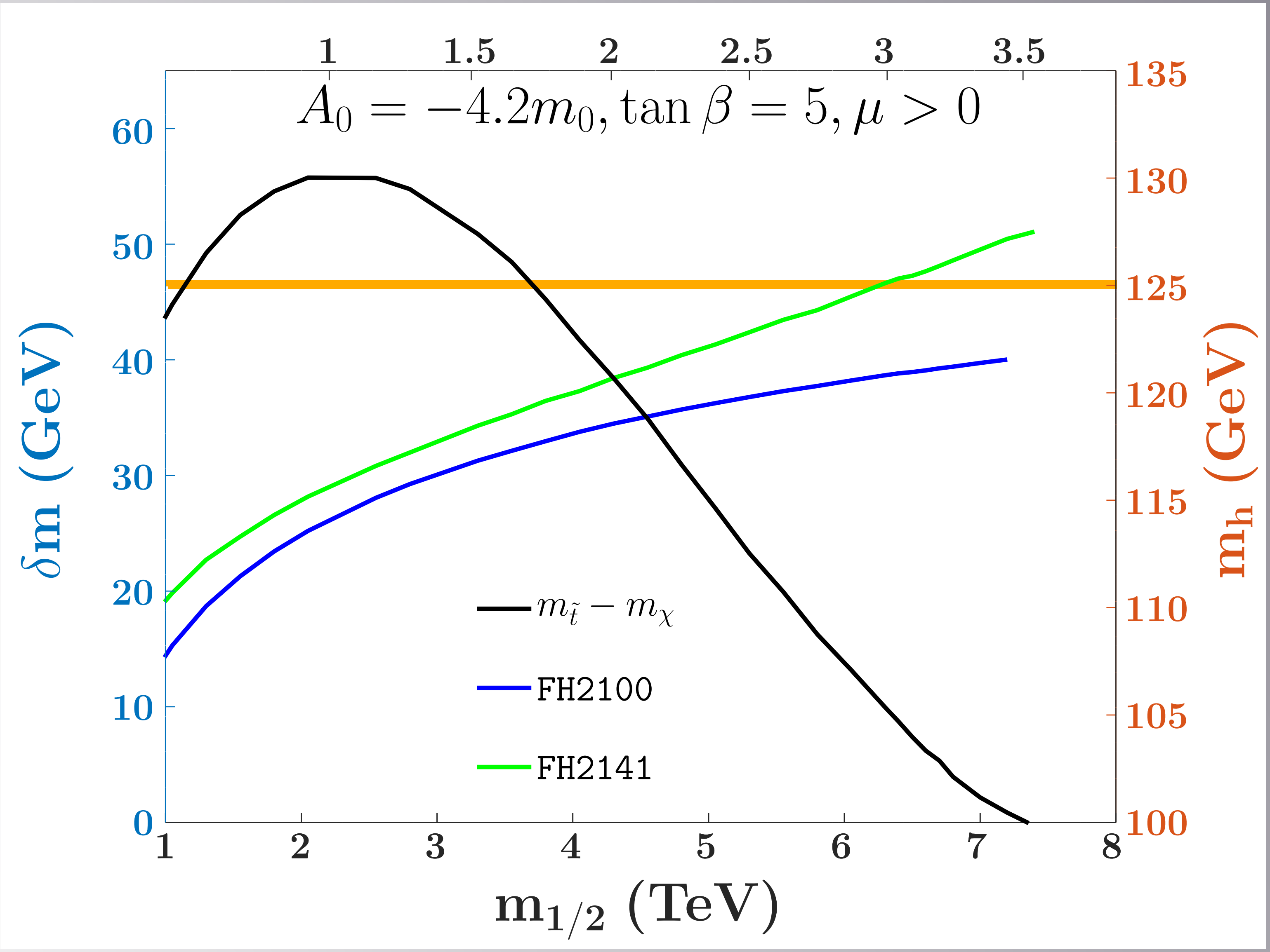
Stop strip



Ellis, Evans, Luo, Olive, Zheng

Bagnaschi et al.

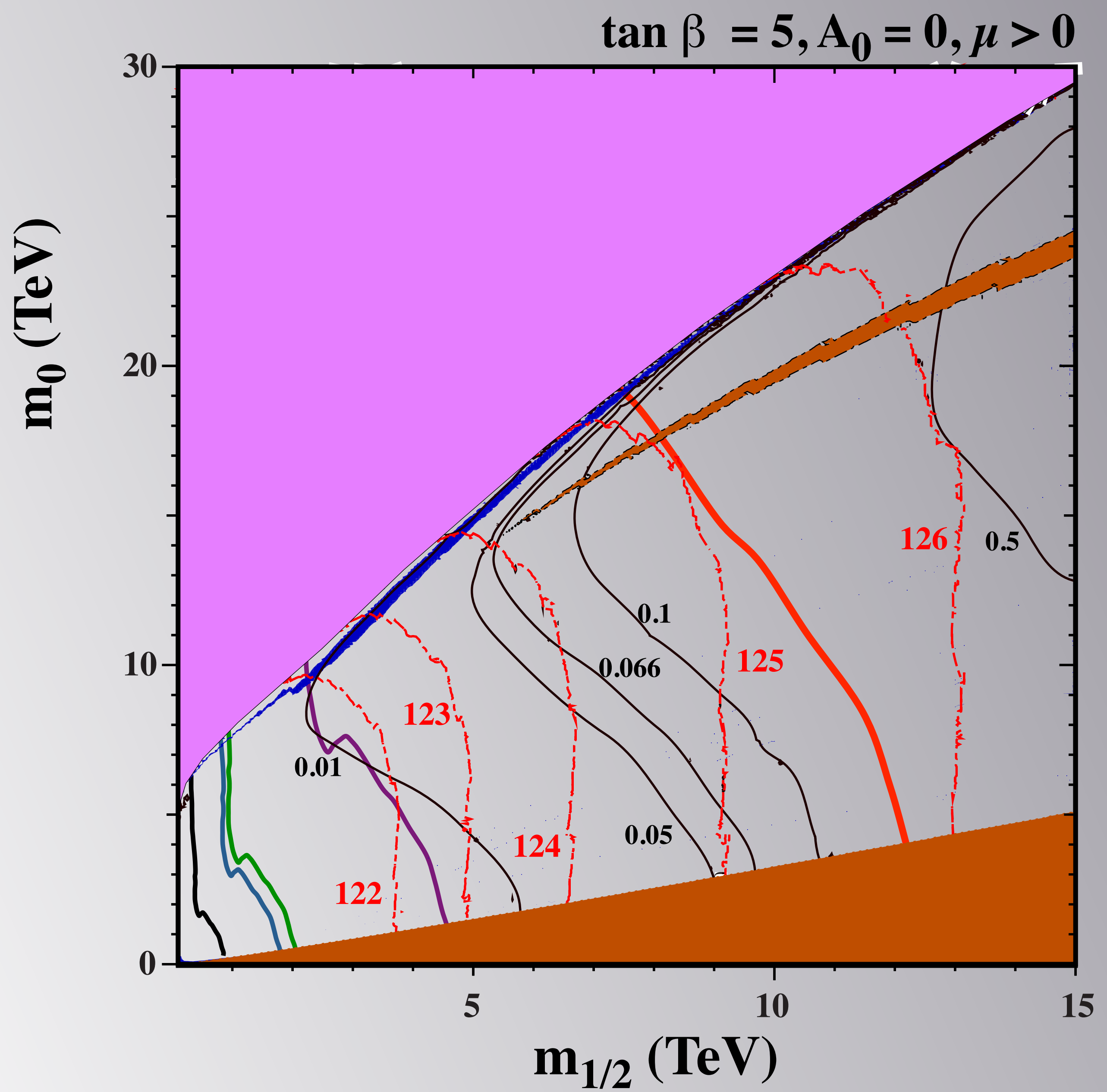
Stop strip



Ellis, Evans, Luo, Olive, Zheng

Bagnaschi et al.

Focus Point



100 TeV 3000 fb^{-1}
33 TeV 3000 fb^{-1}
14 TeV 3000 fb^{-1}
14 TeV 300 fb^{-1}
8 TeV 20 fb^{-1}

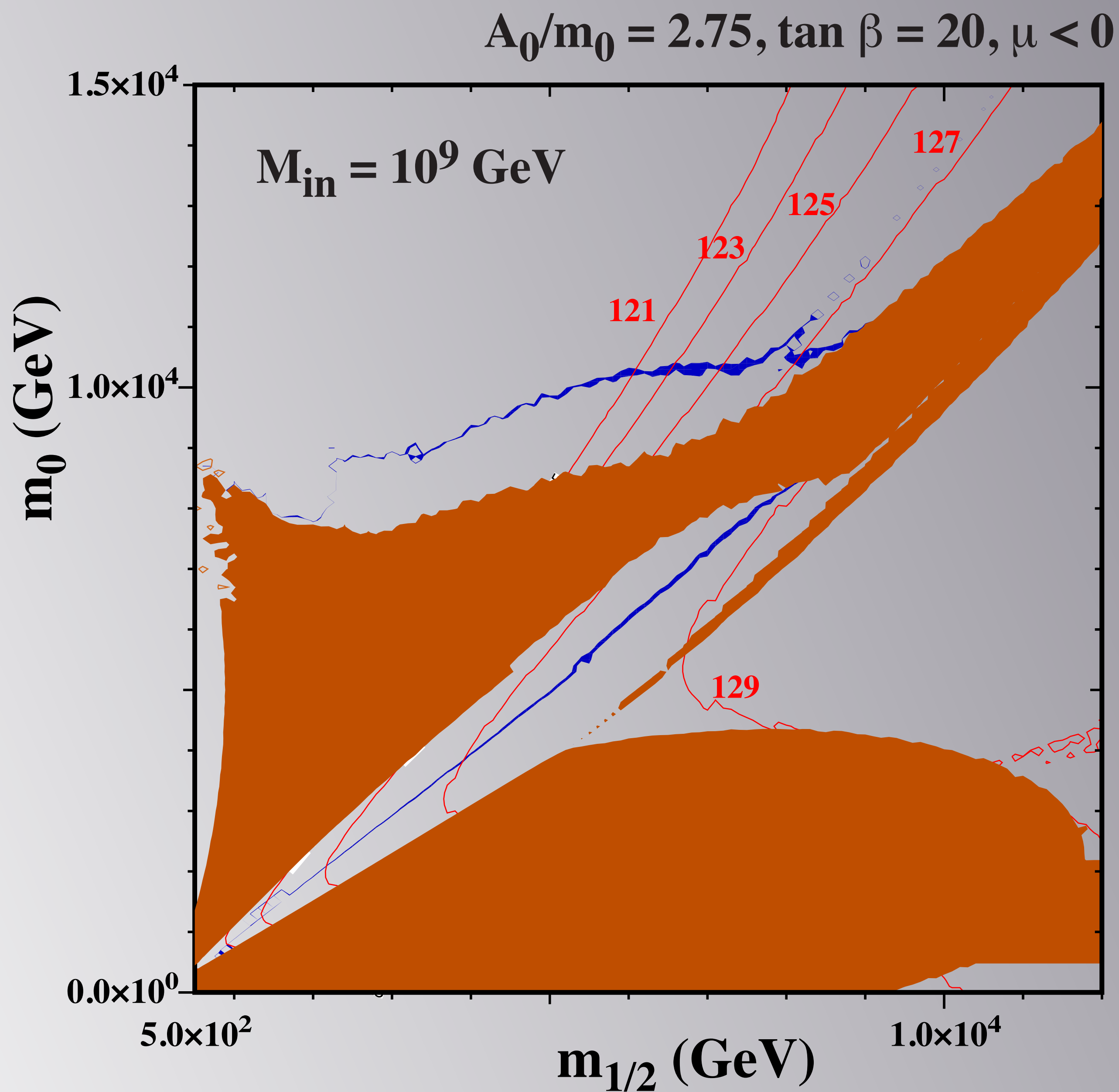
Ellis, Evans, Mustafayev, Nagata, Olive

Other Possibilities

Less Constrained (more parameters)

- NUHM1,2: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - μ and/or m_A free
- NUGM
  - gluino coannihilation
- subGUT models: $M_{in} < M_{GUT}$
  - new parameter M_{in}
- SuperGUT models: $M_{in} > M_{GUT}$
  - requires SU(5) input couplings

SubGUT Stop strip



Ellis, Evans, Luo, Olive, Zheng

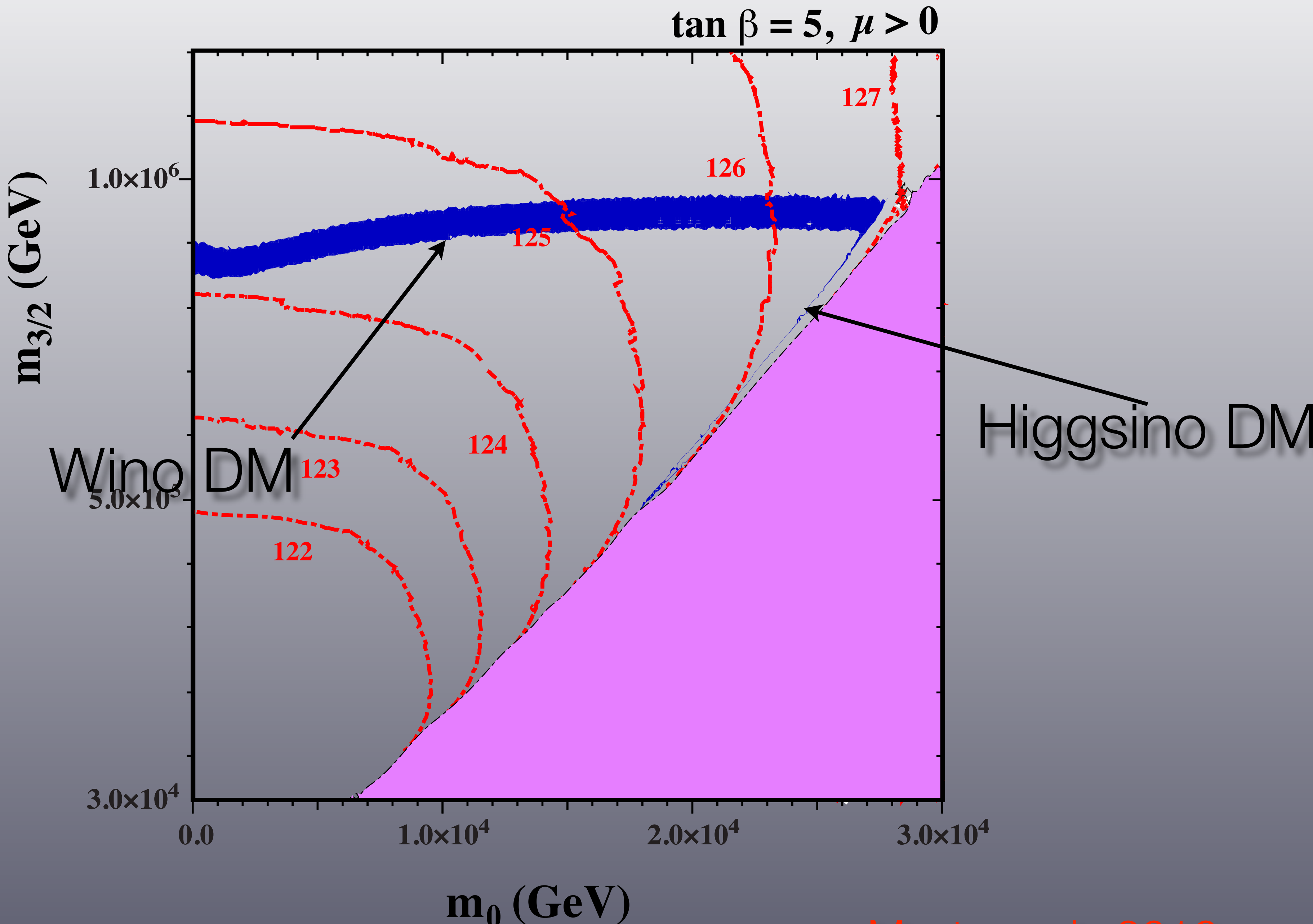
Bagnaschi et al.

Other Possibilities

More Constrained (fewer parameters)

- Pure Gravity Mediation
  - 2 parameter model with very large scalar masses
  - $m_0 = m_{3/2}$, tan β
- mAMSB
  - similar to PGM, but allow $m_0 \neq m_{3/2}$
- mSUGRA
  - $B_0 = A_0 - m_0 \Rightarrow$ tan β no longer free

mAMSB



Mastercode 2016

Even Larger Mass Scales

What if the entire SUSY matter spectrum were very large

with only the gravitino remaining "light"

Benakli, Chen, Dudas, Mambrini
Dudas, Mambrini, Olive

Supersplit Supersymmetry

- 1 parameter model: $m_{3/2}$

Gravitino Mass Limits

For $m_{3/2} \sim$ 10-1000 GeV

Gravitino decays to the LSP/NLSP decays to the gravitino:

Lifetimes 100-10^8 s $\Rightarrow$ BBN limits

$$\Gamma_{\rm decay} \simeq \frac{C^2}{16\pi} \frac{m_\chi^5}{m_{3/2}^2 M_P^2}$$

NLSP $\rightarrow$ gravitino + γ

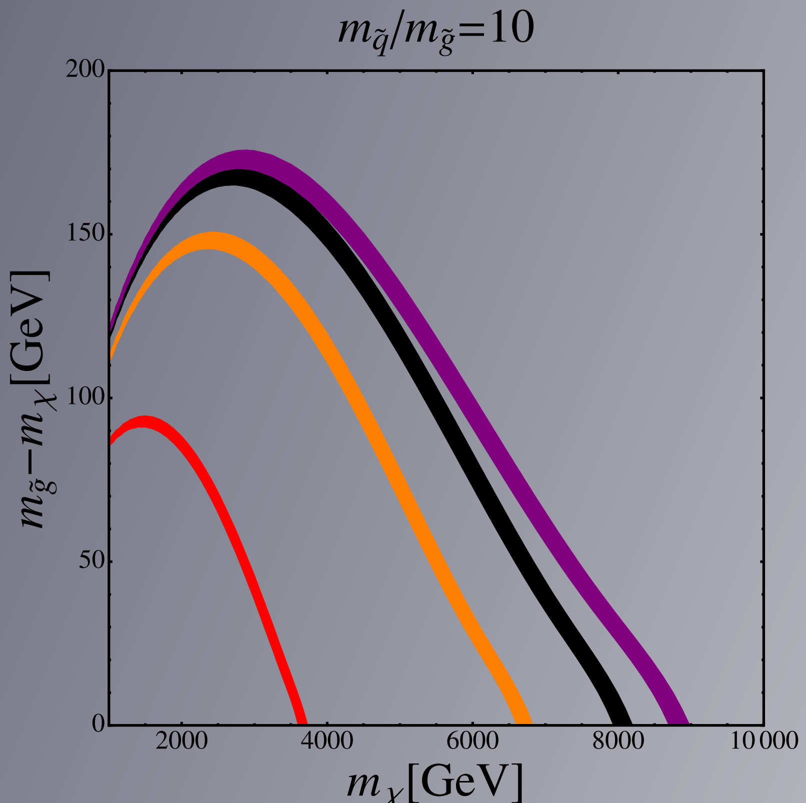
$\tau_\chi \lesssim 100$ s $\Rightarrow m_\chi > 300$ GeV $(m_{3/2}/\mathrm{GeV})^{2/5}$

Gravitino Mass Limits

$\tau_\chi \lesssim 100$ s $\Rightarrow m_\chi > 300$ GeV $(m_{3/2}/\text{GeV})^{2/5}$

Relic Density: $\Omega_{3/2}h^2 = \frac{m_{3/2}}{m_\chi}\Omega_\chi h^2$ or $\Omega_\chi h^2 \lesssim 0.12\frac{m_\chi}{m_{3/2}}$

Gluino coannihilation



$m_\chi < 8$ TeV $\Rightarrow m_{3/2} < 4$ TeV

heavier gravitino → heavier neutralino

→ $\Omega_\chi h^2$ too large → $\Omega_{3/2}h^2$ too large

Ellis, Luo, Olive

Gravitino Mass Limits

$m_{3/2} < 4$ TeV unless(!) the susy spectrum lies above the inflationary scale.

For $M_{susy} \sim F^{1/2} > m_{infl} \sim 3 \times 10^{13}$ GeV

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2 \text{ EeV}$$

Toy Model

Dudas, Gherghetta, Mambrini, Olive

No Scale Model:

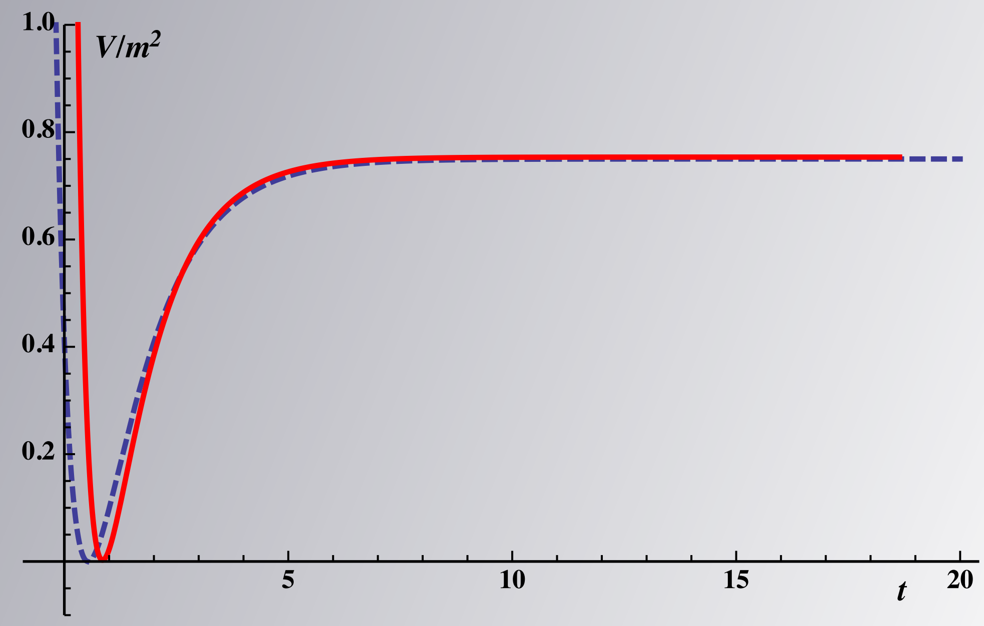
$$K = -3\ln\left(T + \bar{T} - \frac{1}{3}\sum_i |\phi_i|^2\right) + |z|^2 - \frac{|z|^4}{\Lambda_z^2}$$

Inflaton   Matter   Polonyi

$$W = \sqrt{3}m\phi(T - 1/2), \quad + \; \tilde{m}^2(z + b)$$

Starobinsky Inflation

Polonyi Model



Toy Model

for small Λ_z

$$m_{3/2} = m\frac{4\tilde{m}^6 + 2\tilde{m}^2 m^3 M_P}{2\sqrt{3}(m^2 M_P^2 + \tilde{m}^4)^{3/2}} \to \tilde{m}^2/\sqrt{3}M_P$$

for small $\tilde{m}^2/mM_P$

For $\tilde{m} = m$

$$m_{3/2} = \frac{m^2}{\sqrt{3}M_P} \approx 0.2 \text{ EeV}.$$

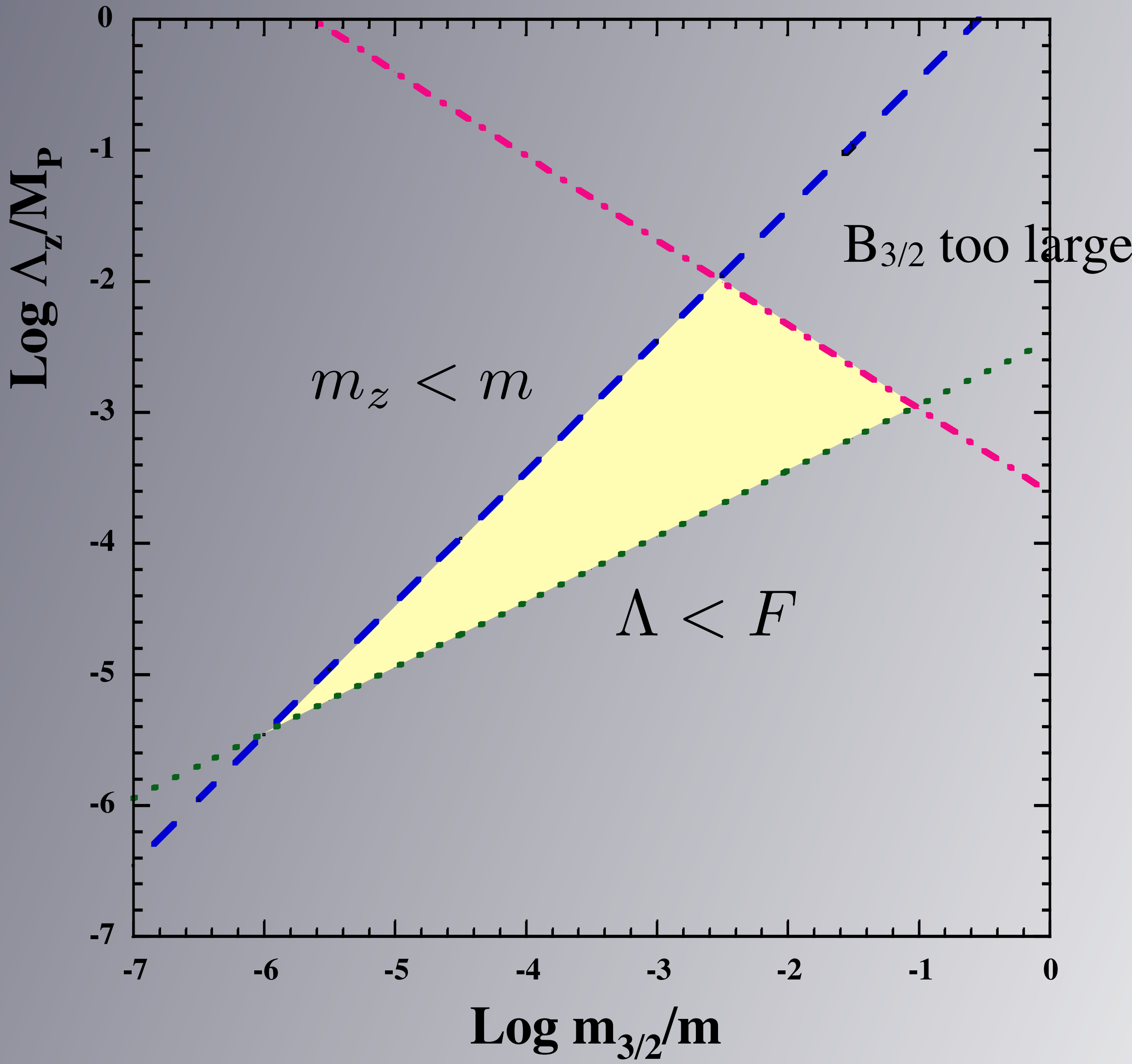
$$m_{1/2} \sim m_{3/2}\frac{M_P^2}{\Lambda_z^2}$$

$$m_z^2 = \frac{12 m_{3/2}^2 M_P^2}{\Lambda_z^2}$$

$$m_0 \sim m_{1/2}\frac{g^2}{16\pi^2}$$

$$\Rightarrow \quad \frac{\Lambda_z}{M_P} < \frac{g}{4\pi}\left(\frac{m}{M_P}\right)^{1/2} \sim \text{few} \times 10^{-3}$$

Toy Model



Gravitino Production

Standard Picture:

gluon + gluon → gluino + gravitino

$$\langle \sigma v \rangle \sim \frac{1}{M_P^2}\left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)$$

$$\Gamma \sim T^3 \frac{m_{\tilde{g}}^2}{M_P^2 m_{3/2}^2}$$

$m_{\tilde{g}} > m_{3/2}$

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim T \frac{m_{\tilde{g}}^2}{M_P m_{3/2}^2}$$

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Not possible if $m_{\tilde{g}} > m_\phi$

Gravitino Production

$$m_{\tilde{g}} > m_\phi$$

gluon + gluon $\rightarrow$ gravitino + gravitino

$$\langle \sigma v \rangle \sim \frac{T^6}{M_P^4 m_{3/2}^4}$$

$$\Gamma \sim \frac{T^9}{M_P^4 m_{3/2}^4}$$

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim \frac{T^7}{M_P^3 m_{3/2}^4}$$

$$\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{0.1 \text{ EeV}}{m_{3/2}} \right)^3 \left(\frac{T_{RH}}{2.0 \times 10^{10} \text{ GeV}} \right)^7$$

Reheating

Inflaton decays (dominant channel):

$$\mathcal{L}_{\rm eff} \ni \frac{{\rm Re}T}{\sqrt{3}}(n_I + n_L - 3)W^{IL}\bar{W}_{LJ}\Phi_I\bar{\Phi}^J \, ,$$

$$\sim \mu^2 e^{\sqrt{\frac{2}{3}}t}(|h_u|^2 + |h_d|^2) \, ,$$

Ellis, Garcia, Nanopoulos, Olive

$$\Gamma_{2h} = \frac{\mu^4}{384\pi m M_P^2}\sin^2 2\beta$$

$$T_{RH} = \left(\frac{10}{g_s}\right)^{1/4}\left(\frac{2\Gamma_{2h}\, M_P}{\pi\, c}\right)^{1/2} = 0.5\frac{y_I}{2\pi}\,(m\, M_P)^{1/2}$$

$$y_I = \mu^2/(4\sqrt{3}mM_P) \qquad g_s = 427/4 \qquad c \simeq 1.2$$

$$2.7 \times 10^{10}\ {\rm GeV} \lesssim T_{RH} \lesssim 1.1 \times 10^{12}\ {\rm GeV}$$

$m_{3/2} > .2{\rm EeV}$ $\qquad$ $m_{3/2} < T_R$

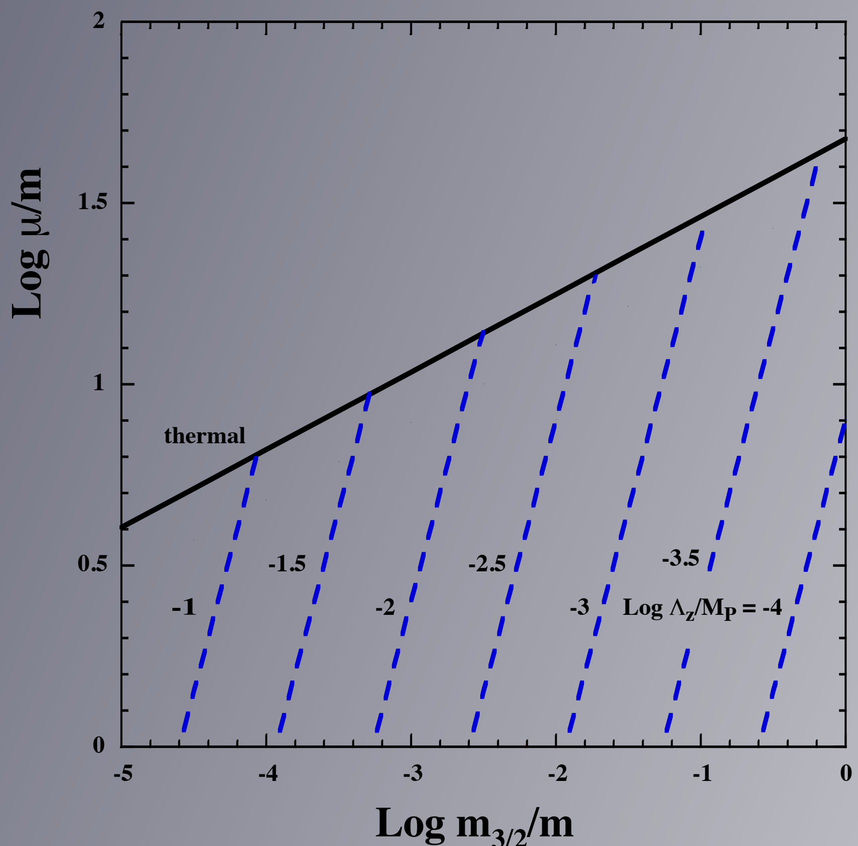
Reheating

Thermal production

$$\Omega_{3/2}h^2 \simeq 0.11\, r_{3/2} \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{3\times 10^{13}\,\mathrm{GeV}}{m}\right)^{7/2} \times \left(\frac{\mu}{1.2\times 10^{14}\,\mathrm{GeV}}\right)^{14}$$

gravitinos from inflaton decay

$$\Omega_{3/2}^{decay}h^2 = 0.11 \left(\frac{B_{3/2}}{1.3\times 10^{-13}}\right)\left(\frac{y_I}{2.9\times 10^{-5}}\right)$$



$$B_{3/2} = \frac{9}{2}\left(\frac{\Lambda_z}{M_P}\right)^4 \left(\frac{m_{3/2}}{m}\right)^2 \left(\frac{m}{\mu}\right)^4$$

UV Completion -SO(10)

Ellis, Gherghetta, Kaneta, Olive

$$W \supset \frac{\mu_\Phi}{4!}\Phi^2 + \frac{\mu_\Sigma}{5!}\Sigma\overline{\Sigma} + \frac{\lambda}{4!}\Phi^3 + \frac{\eta}{4!}\Phi\Sigma\overline{\Sigma} + \mu_H H^2 + \frac{1}{4!}\Phi H(\alpha\Sigma + \overline{\alpha}\overline{\Sigma})$$

$$\Phi(\mathbf{210}); \quad \Sigma(\mathbf{126}); \quad \overline{\Sigma}(\overline{\mathbf{126}}); \quad H(\mathbf{10})$$

Vanishing F- and D- terms fixes the vevs

$$v_{1,1,1} = -\frac{\mu_\Phi}{\lambda}\frac{x(1-5x^2)}{(1-x)^2}; \quad v_{1,1,15} = -\frac{\mu_\Phi}{\lambda}\frac{(1-2x-x^2)}{(1-x)}; \quad v_{1,3,15} = -\frac{\mu_\Phi}{\lambda}x;$$

$$\sigma_{1,3,\overline{10}}\sigma_{1,3,10} = \frac{2\mu_\Phi^2}{\eta\lambda}\frac{x(1-3x)(1+x^2)}{(1-x)^2}; \quad -8x^3 + 15x^2 - 14x + 3 = (x-1)^2\frac{\lambda\mu_\Sigma}{\eta\mu_\Phi}$$

choice of $x \sim 0.63$ leaves one state (in addition to the Higgs) light

$$S = (1,3,0) \subset (1,3,15) \subset 210$$

gauge coupling unification

Threshold corrections:

$$\left(\frac{1}{g_i^2(\mu_*)}\right) = \left(\frac{1}{g_U^2(\mu_*)}\right) - \left(\frac{\lambda_i}{48\pi^2}\right)$$

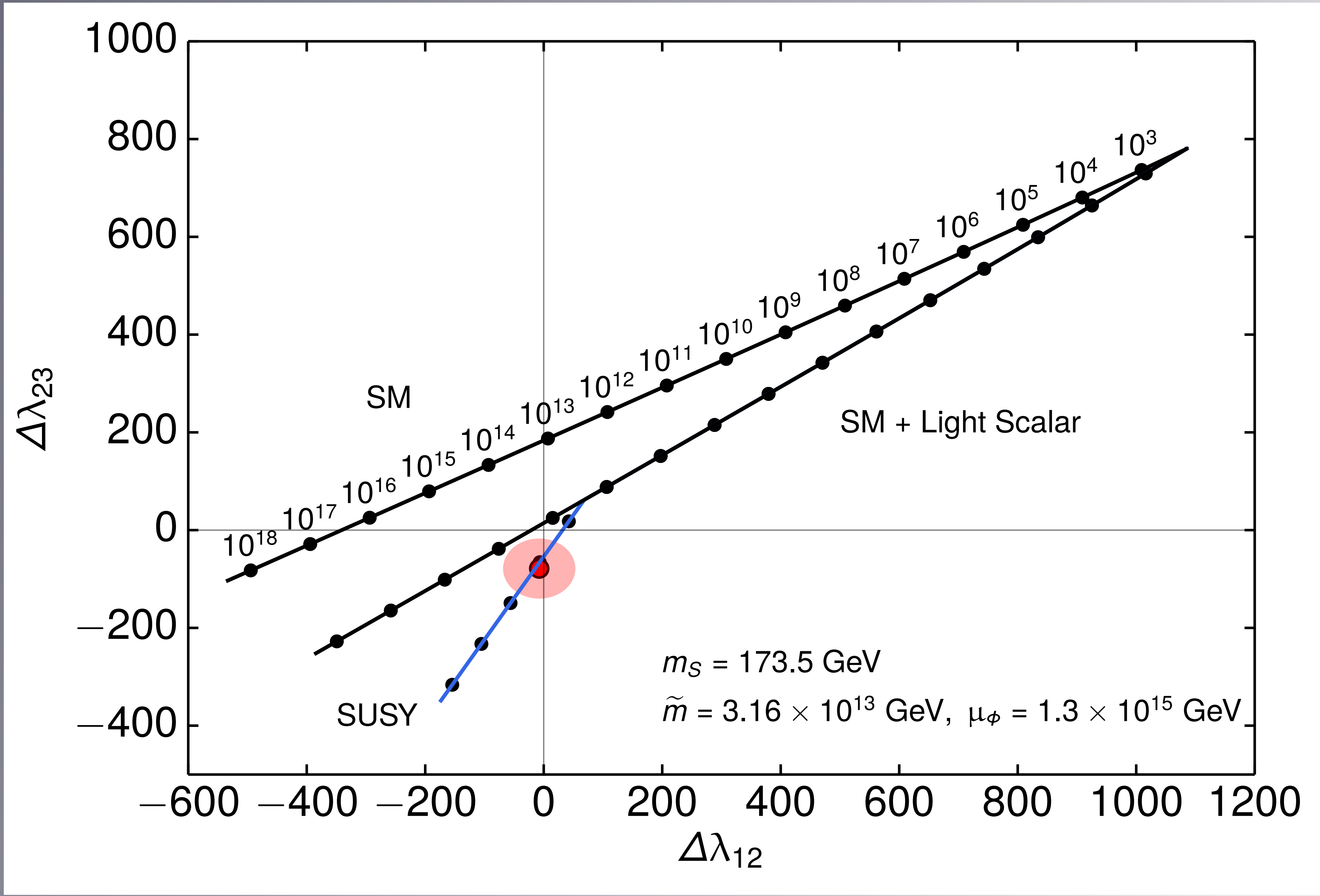
λ_i computable because spectrum is determined

$$\left(\frac{\Delta\lambda_{ij}(\mu)}{48\pi^2}\right) \equiv \left(\frac{1}{g_i^2(\mu)} - \frac{1}{g_j^2(\mu)}\right) = \left(\frac{\lambda_j(\mu) - \lambda_i(\mu)}{48\pi^2}\right)$$

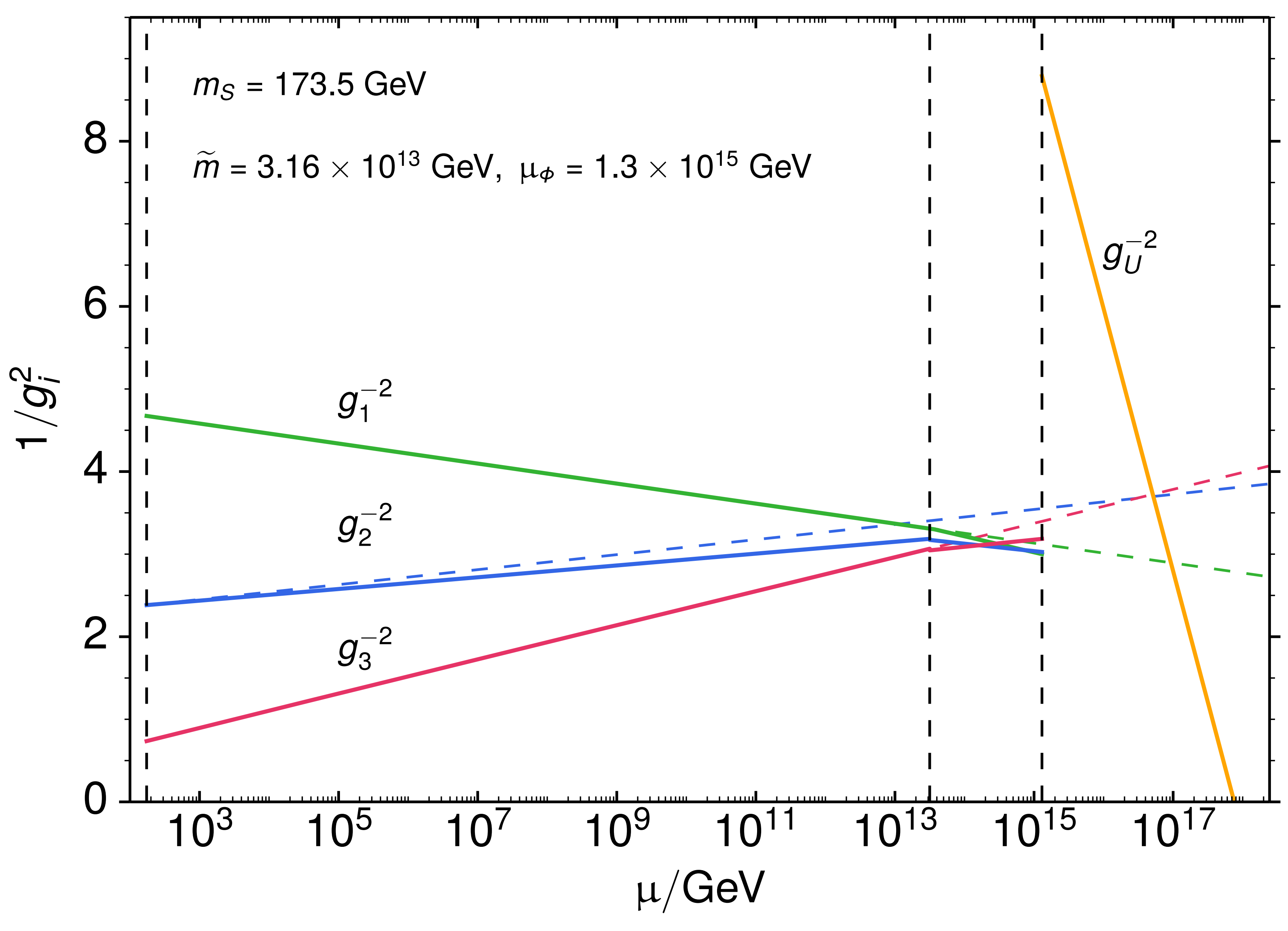
for each λ,η

$$\chi^2(g_U, \mu_\Phi, \tilde{m}, m_\chi) \equiv \sum_{i=1}^{3} \left[g_i^{-2}(\mu_\Phi) - (g_U^{-2} - \frac{\lambda_i(g_U, \mu_\Phi, \tilde{m}, m_\chi)}{48\pi^2}) \right]^2 / \sigma_i^2 ;$$

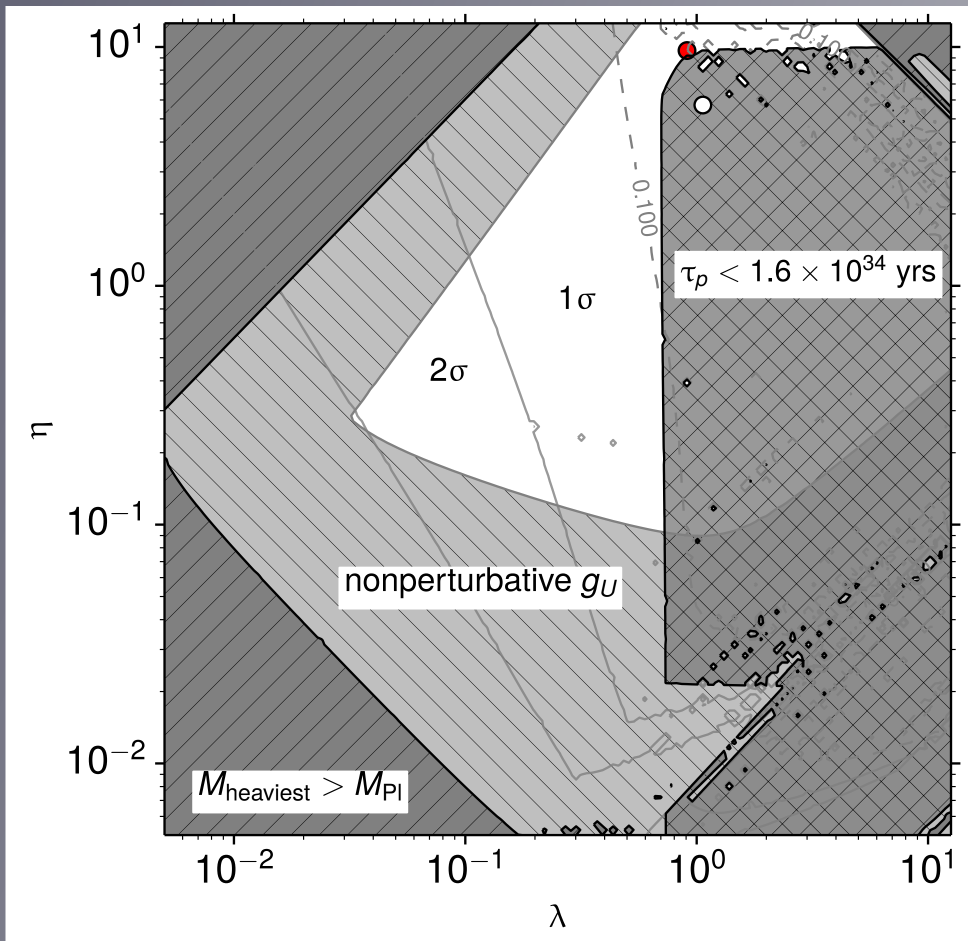
gauge coupling unification



gauge coupling unification



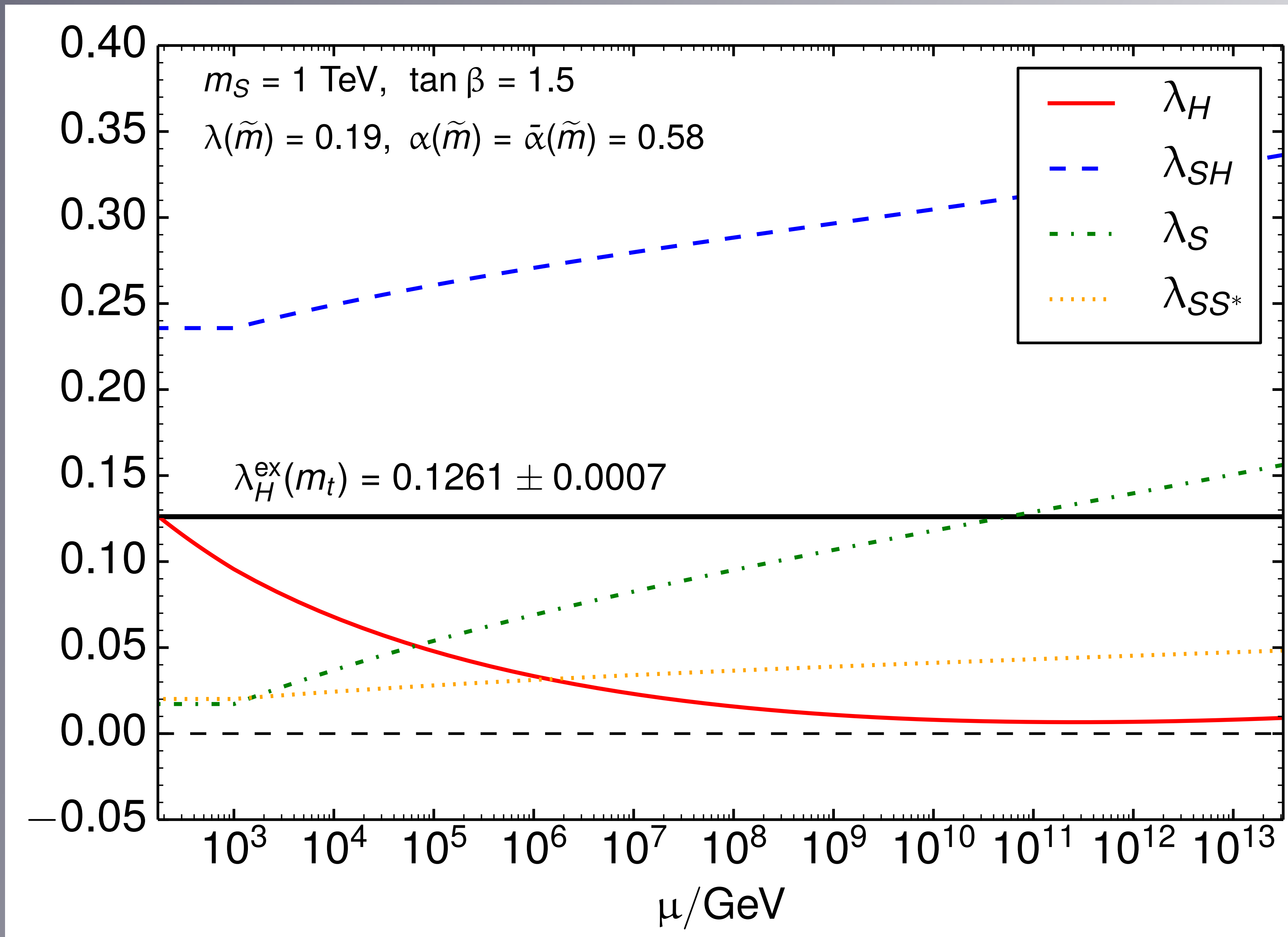
gauge coupling unification



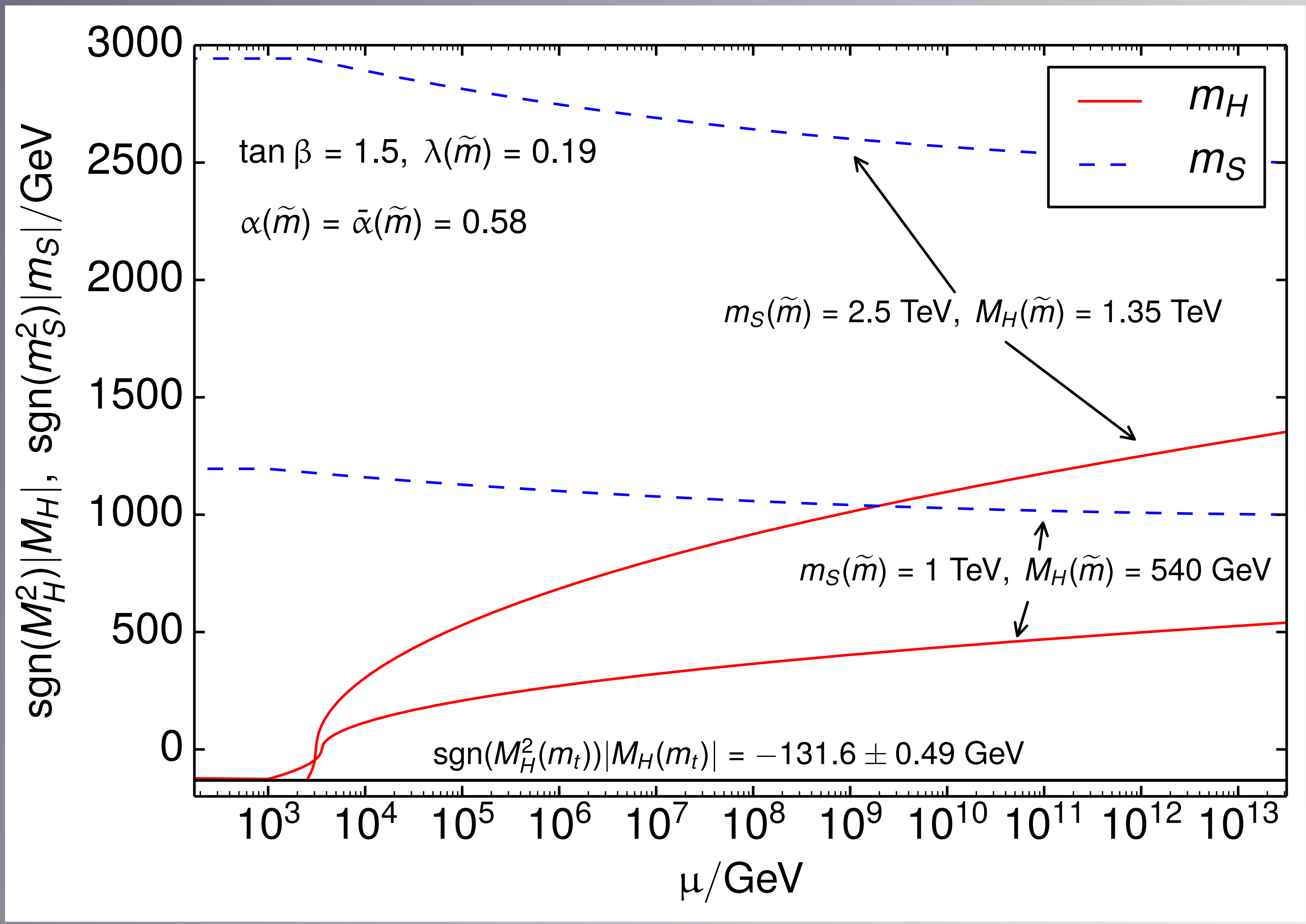
Higgs vacuum stability achieved through coupling of S (weak triplet) to H

Radiative EW symmetry breaking

Higgs vacuum stability



Radiative Electroweak Symmetry Breaking



Detection?

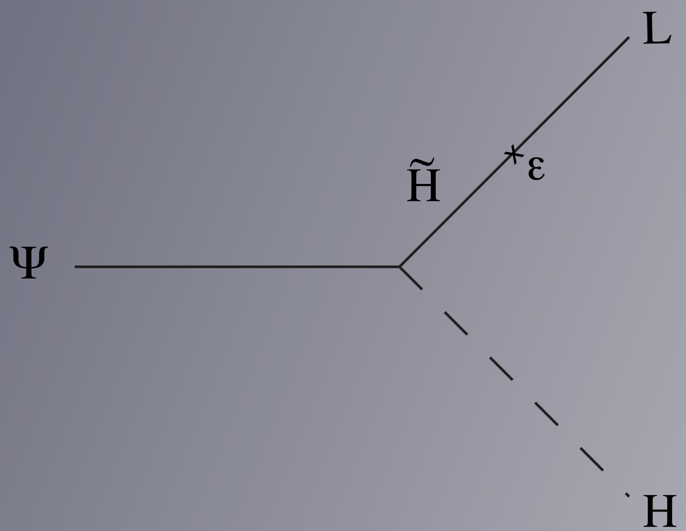
Dudas, Gherghetta, Kaneta, Mambrini, Olive

Signatures of decay with R-parity violation

$$W_{\rm RPV} = \mu' L H_u.$$

Normally, $\mu' < 2 \times 10^{-5}$GeV from L-violating interactions

High Scale Susy: $\mu' < 2 \times 10^{-7} \left(\frac{\mu \tilde{m}^{1/2}}{\text{GeV}^{3/2}} \right)$ GeV



$$\Gamma_{\rm tot} \simeq \frac{\epsilon^2 c_\beta^2 m_{3/2}^3}{16\pi M_P^2} \qquad \epsilon = \mu'/\mu$$

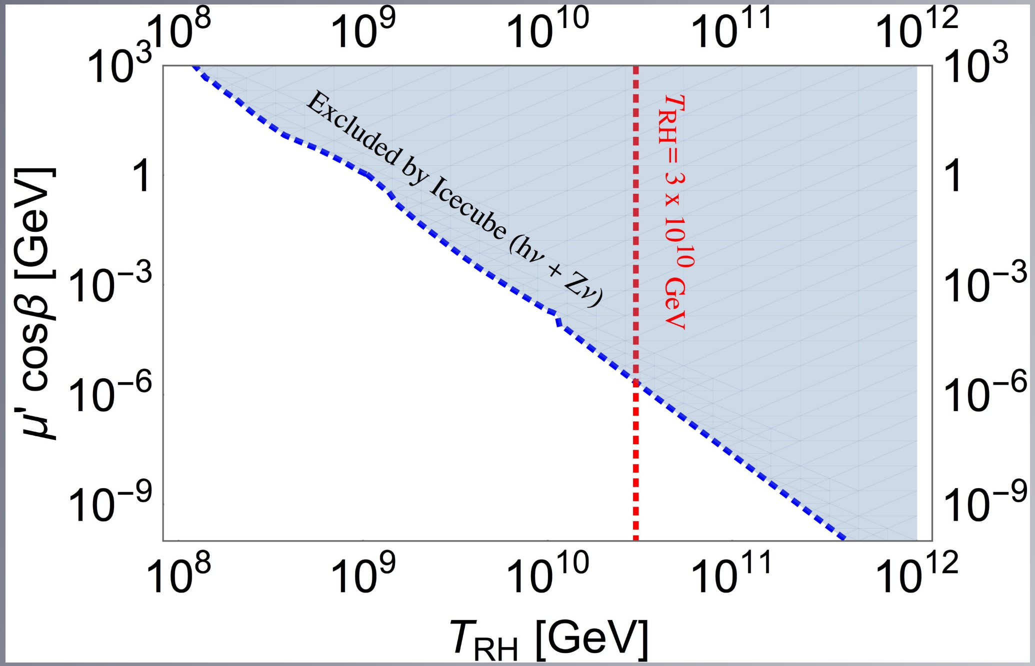
$$\tau_{3/2} \simeq 10^{28} \left(\frac{0.44 \times 10^{-20}}{\epsilon c_\beta} \right)^2 \left(\frac{1\ \text{EeV}}{m_{3/2}} \right)^3 \text{s.}$$

Detection?

Dudas, Gherghetta, Kaneta, Mambrini, Olive

$$\tau_{3/2} \simeq 10^{28} \left(\frac{\widetilde{m}}{10^{14}\ \mathrm{GeV}} \right)^2 \left(\frac{0.44\ \mathrm{keV}}{\mu' c_\beta} \right)^2 \left(\frac{1\ \mathrm{EeV}}{m_{3/2}} \right)^3 \mathrm{s} \qquad \mu \sim \widetilde{m} \gg \mu'$$

$$\mu' c_\beta = 14\ \mathrm{keV} \left(\frac{\Omega_{3/2} h^2}{0.11} \right)^{1/2} \left(\frac{10^{28}\ \mathrm{s}}{\tau_{3/2}} \right)^{1/2} \left(\frac{\widetilde{m}}{10^{14}\ \mathrm{GeV}} \right) \left(\frac{2.0 \times 10^{10}\ \mathrm{GeV}}{T_{\mathrm{RH}}} \right)^{7/2}$$



Expect about 1 event at ANITA every 137 years.

ANITA has seen 2 O(EeV) events in 3 years

Even Larger Mass Scales

Planck Scale SUSY $\equiv$ no susy at low energy

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Planck Scale SUSY $\equiv$ no susy at low energy

SO(10) GUT?

Even Larger Mass Scales

Planck Scale SUSY $\equiv$ no susy at low energy

SO(10) GUT?

- Gauge Coupling Unification
-
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Neutrino masses…

SO(10) DM models

Mambrini, Nagata, Olive, Zheng

1. Pick an Intermediate Scale Gauge Group

R$_1$ $\quad \mathrm{SO}(10) \longrightarrow G_{\mathrm{int}}$

2. Use **126** to break G_{int} to SM

$$\mathrm{SO}(10) \xrightarrow{R_1} G_{\mathrm{int}} \xrightarrow{R_2} G_{\mathrm{SM}} \otimes \mathbb{Z}_2$$

R_2 = **126** + …

3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

4. Use RGEs to obtain Gauge Coupling Unification

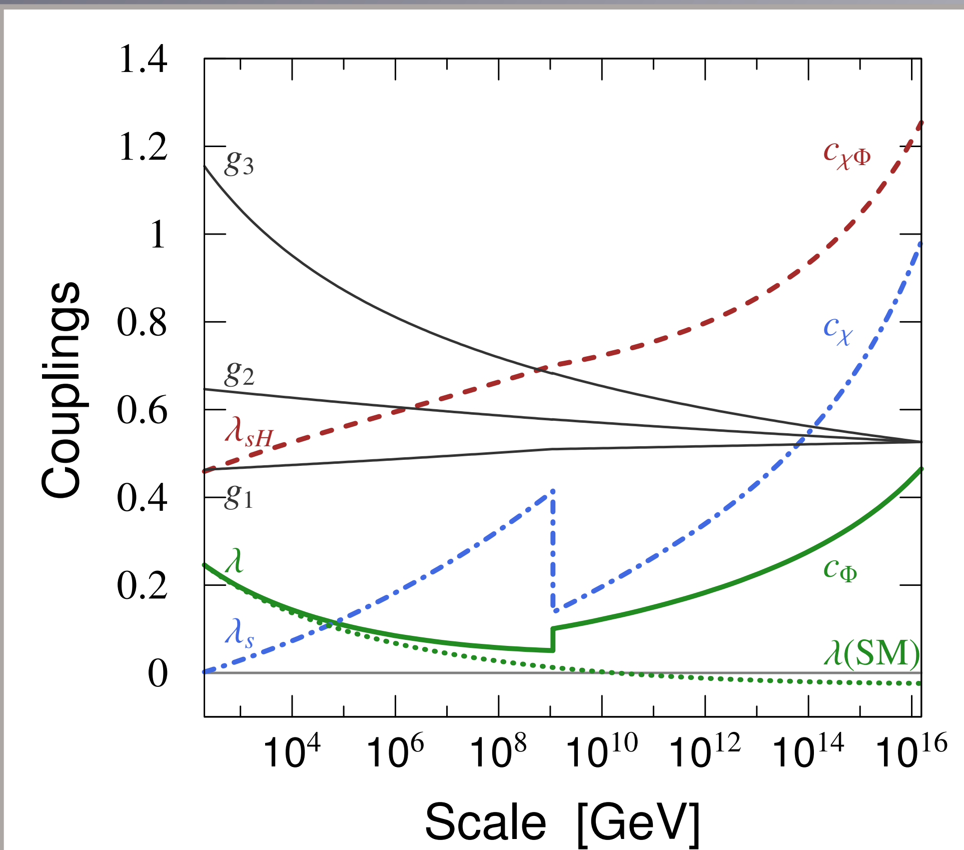
Examples:

Nagata, Olive, Zheng

Scalars

Higgs portal models
Inert Higgs doublet models

Model	$\log_{10} M_{\rm GUT}$	$\log_{10} M_{\rm int}$	$\alpha_{\rm GUT}$	$\log_{10} \tau_p(p \to e^+\pi^0)$
$G_{\rm int} = SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$				
SA_{422}	16.33	11.08	0.0218	36.8 ± 1.2
SB_{422}	15.62	12.38	0.0228	34.0 ± 1.2
$G_{\rm int} = SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$				
SA_{3221}	16.66	8.54	0.0217	38.1 ± 1.2
SB_{3221}	16.17	9.80	0.0223	36.2 ± 1.2
SC_{3221}	15.62	9.14	0.0230	34.0 ± 1.2
$G_{\rm int} = SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes D$				
SA_{3221D}	15.58	10.08	0.0231	33.8 ± 1.2
SB_{3221D}	15.40	10.44	0.0233	33.1 ± 1.2



Example based on scalar singlet DM (SA_{3221}) with

$$G_{\rm int} = SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Kadastik, Kannike, Raidal;
Mambrini, Nagata, Olive, Zheng

Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- However, still viable and more so beyond the CMSSM
- But maybe the susy spectrum is very heavy, and was never part of the thermal background, yet the gravitino may still be the dark matter!
- Can we learn more from a UV completion?
- Signatures at the EeV scale?