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   How far up in energy do these strips extend?

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EeV Supersymmetric Dark Matter

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   How far up in energy do these strips extend?

2) How much better are CMSSM-like alternatives?

3) Gravitino Dark Matter in High Scale SUSY models

KBO Regular Season
Thursday, July 13, 6:30 PM
Daejeon Hanbat Baseball Stadium, Daejeon

Lotte **4 - 6** Hanwha

Final

	1	2	3	4	5	6	7	8	9	R	H	E
Lotte	0	0	1	0	2	1	0	0	0	4	12	0
Hanwha	1	1	0	0	0	0	4	0	x	6	8	0

Eagles 6
Giants 4

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CMSSM-Like Models

CMSSM-Like Models

- Gaugino mass Unification

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\rm soft} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad - A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

CMSSM-Like Models

- Gaugino mass Unification
- A-term Unification

$$
\begin{aligned}
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CMSSM-Like Models

- Gaugino mass Unification
- A-term Unification
- Scalar mass unification

$$
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\end{aligned}
$$

$+ \tan\beta$

Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

Multinest

- ~~MCMC~~ technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not on the distribution of sampled points.
- 400 million points sampled

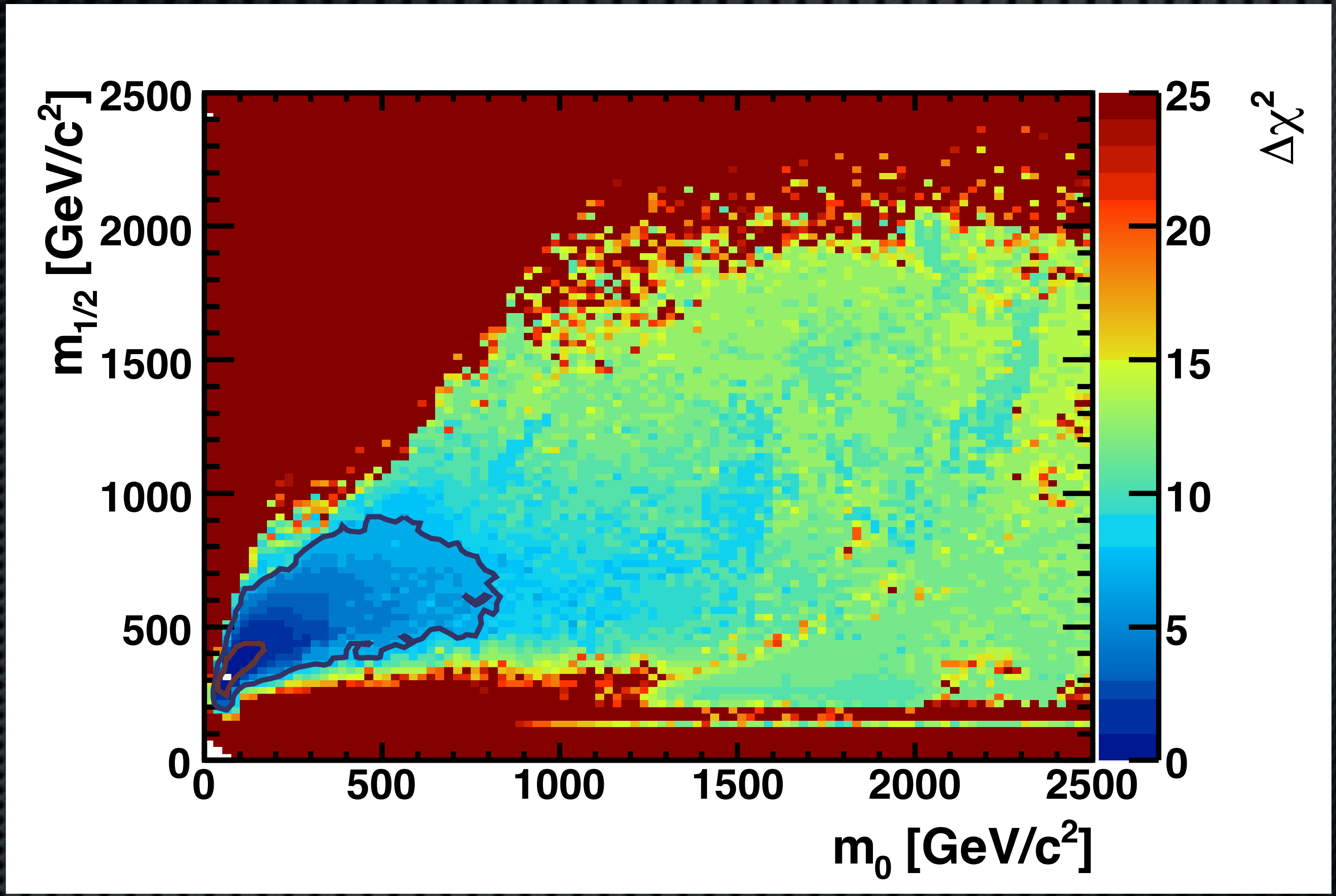
$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\mathrm{SUSY\ search\ limits})$$
$$+ \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

Bagnaschi, Buchmueller, Cavanaugh, Citron, Colling, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Marrouche, Nakach, Olive, Paradisi, Rogerson, Ronga, Sakurai, Martinez Santos, de Vries, Weiglein

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

Mastercode

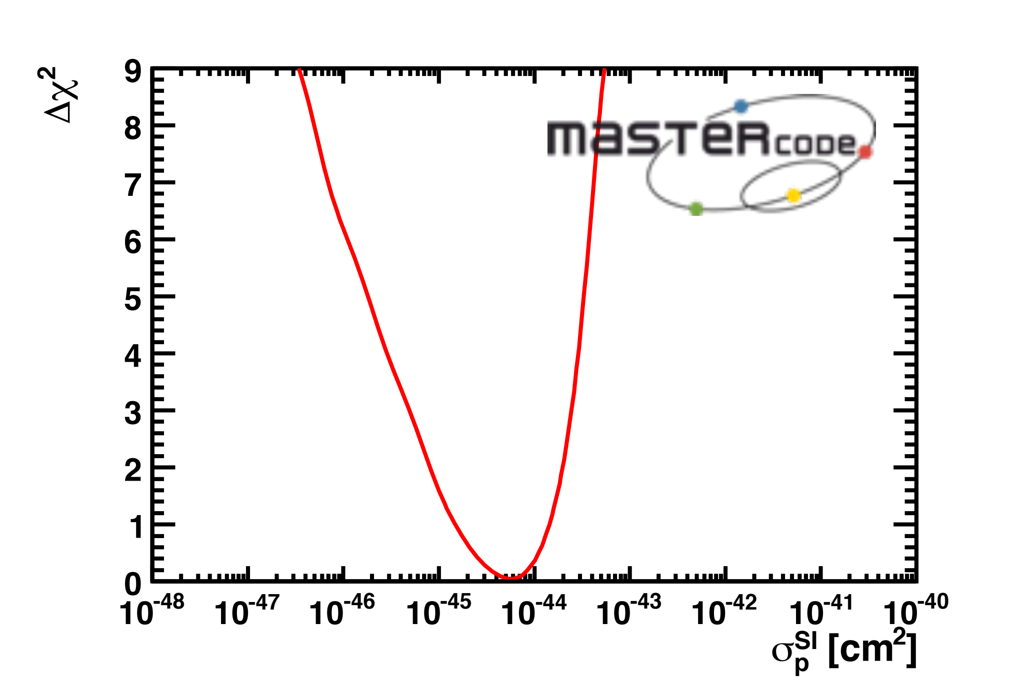
2009



- CMSSM

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer,
Isidori, Olive, Ronga, Weiglein

Elastic cross section from MCMC analysis



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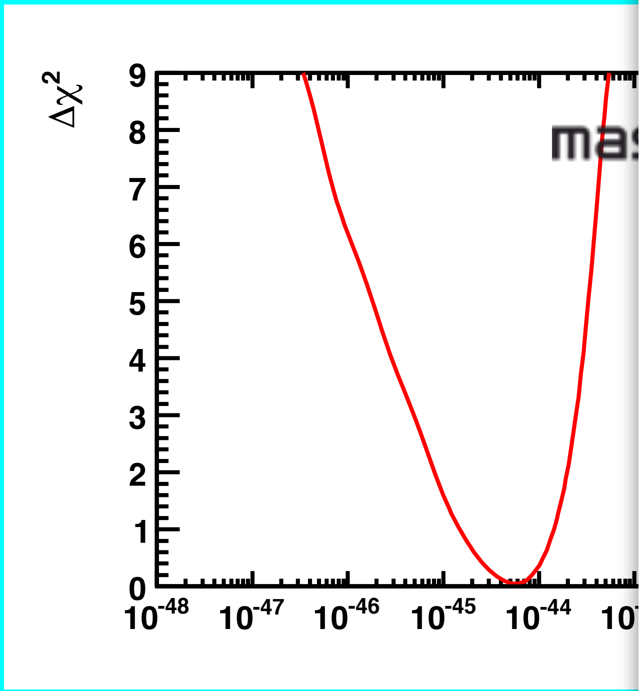
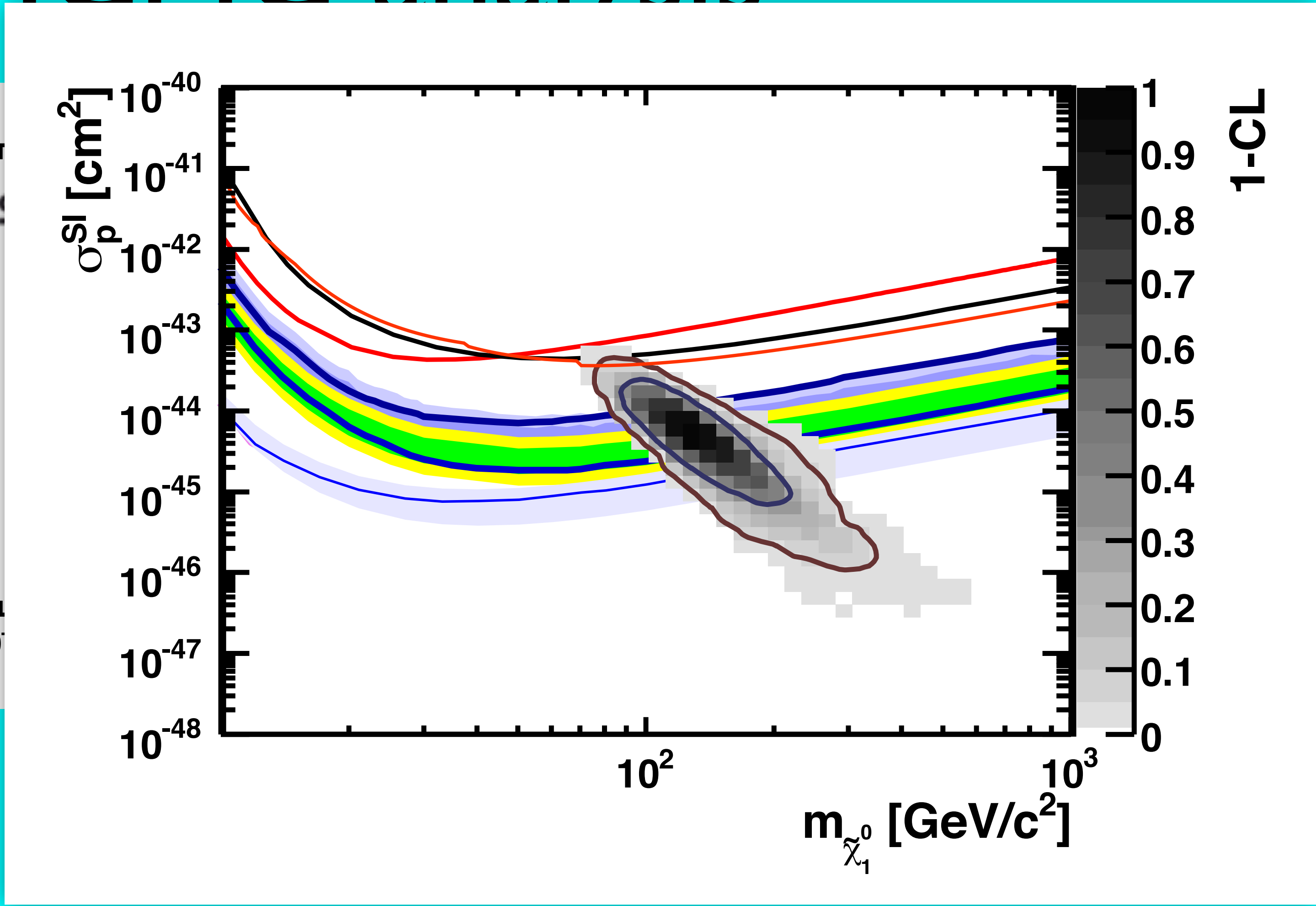


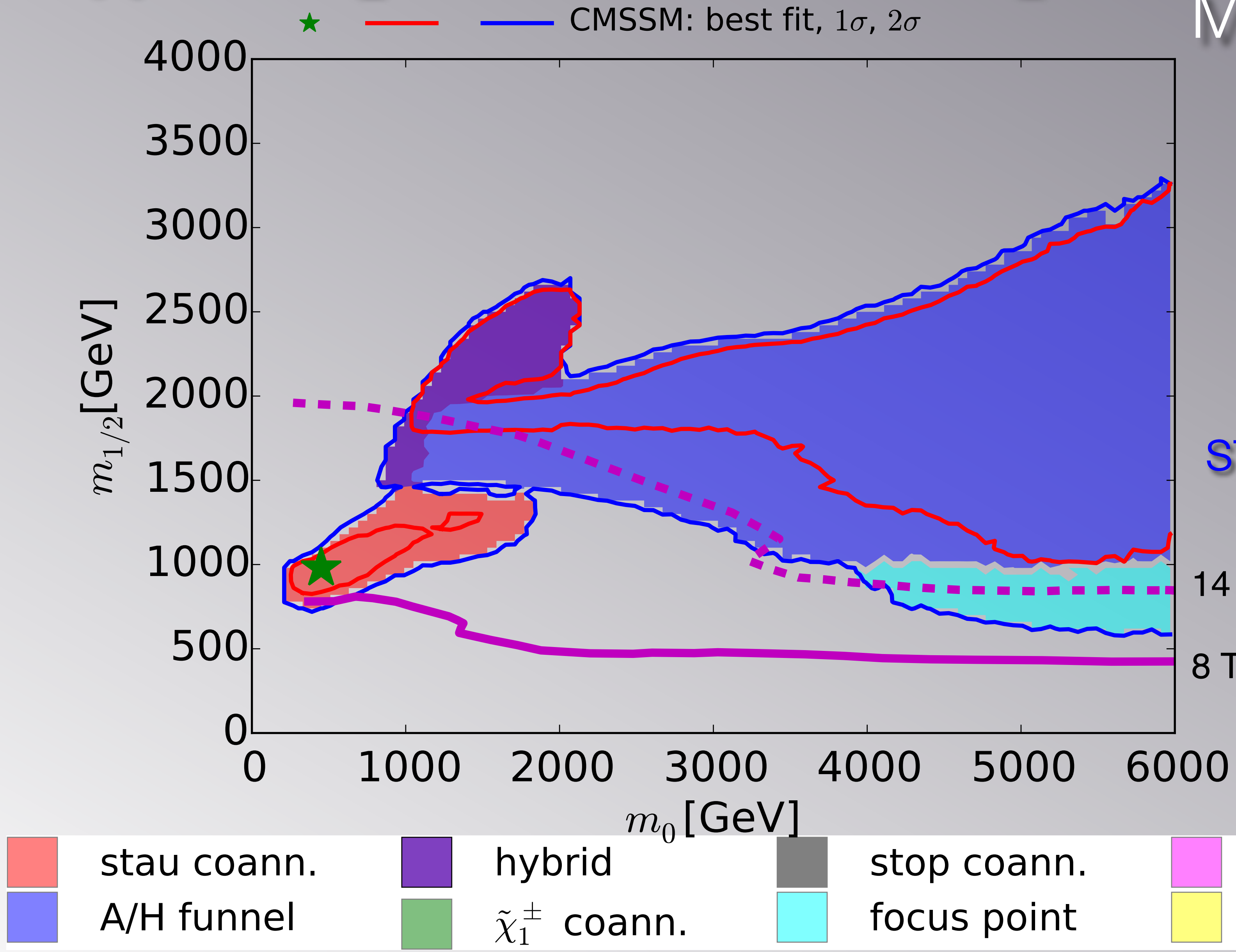


Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

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

Mastercode

2015



14 TeV 3000 fb^{-1}

8 TeV 20 fb^{-1}

Low mass spectrum still observable at LHC

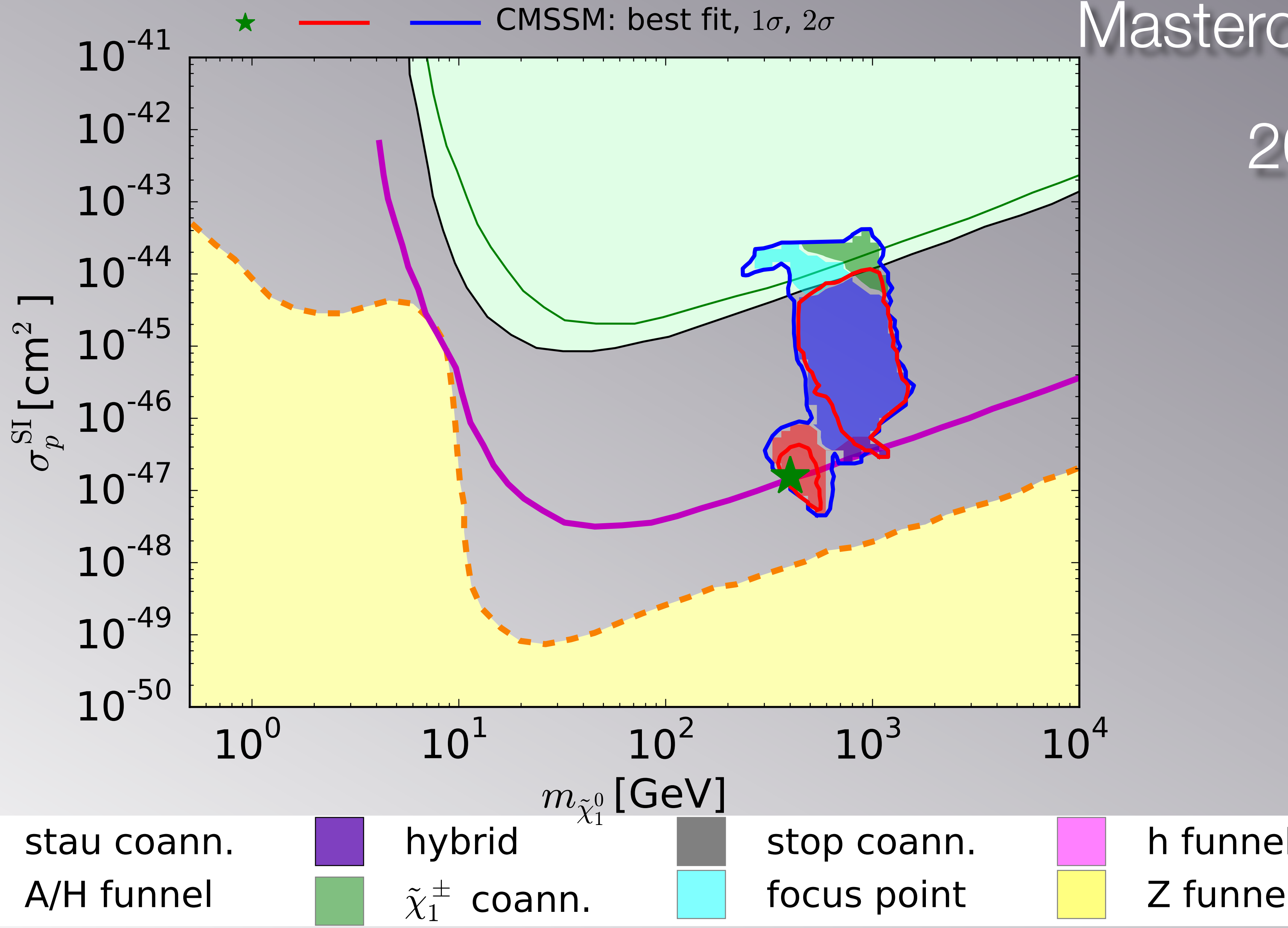
- CMSSM

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



- CMSSM

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

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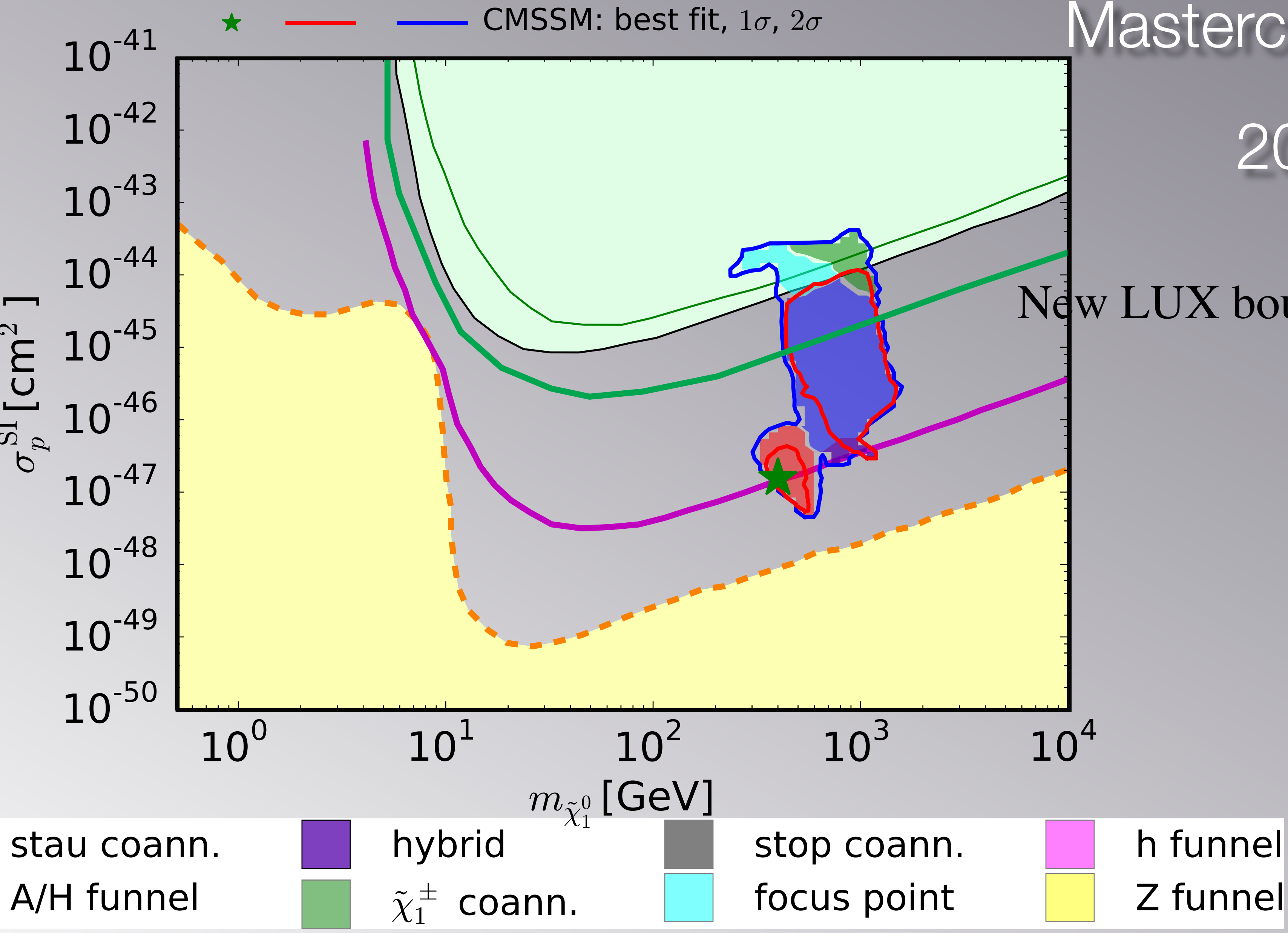


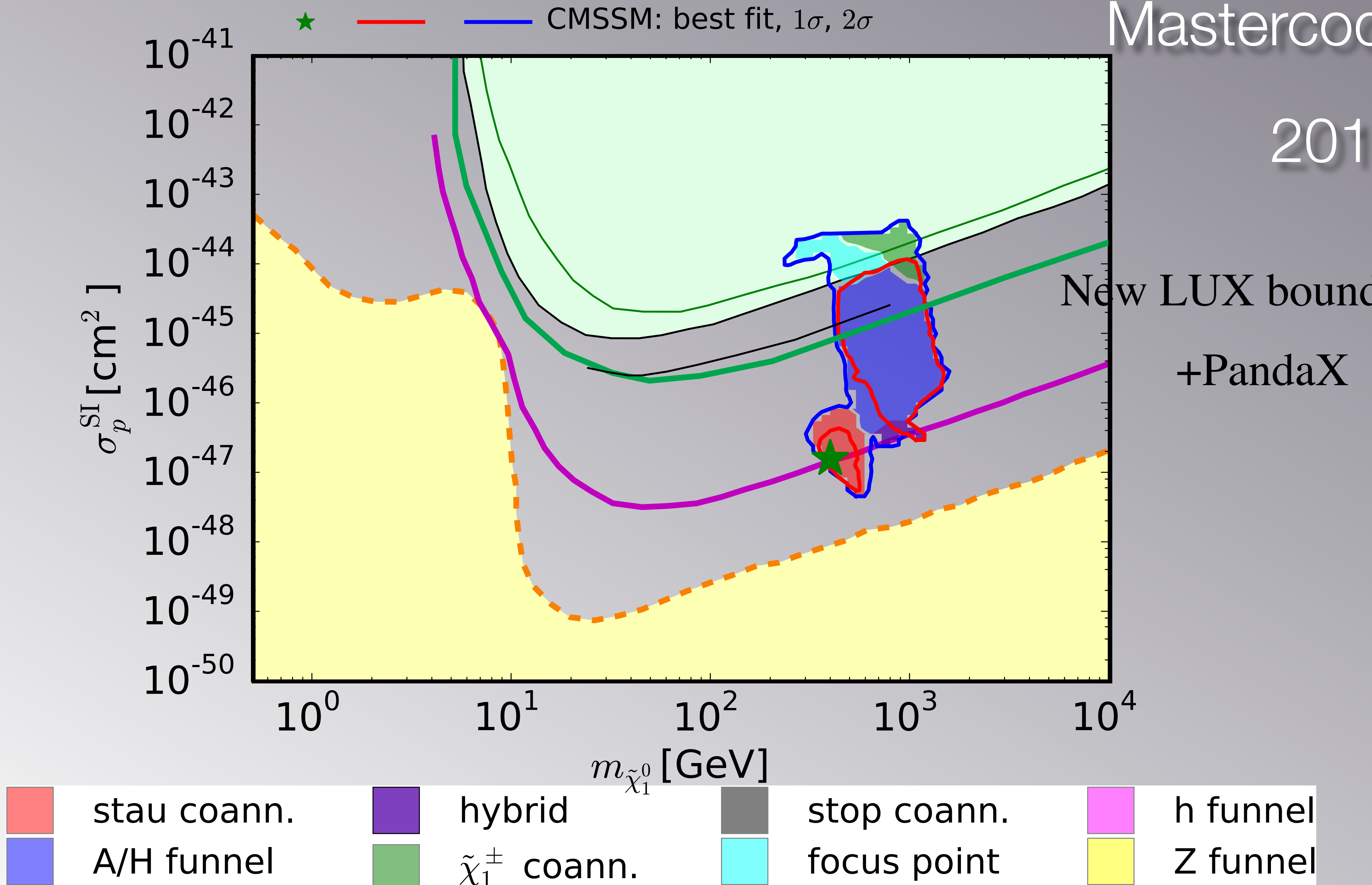
Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

- CMSSM

Elastic scaterring cross-section

Mastercode

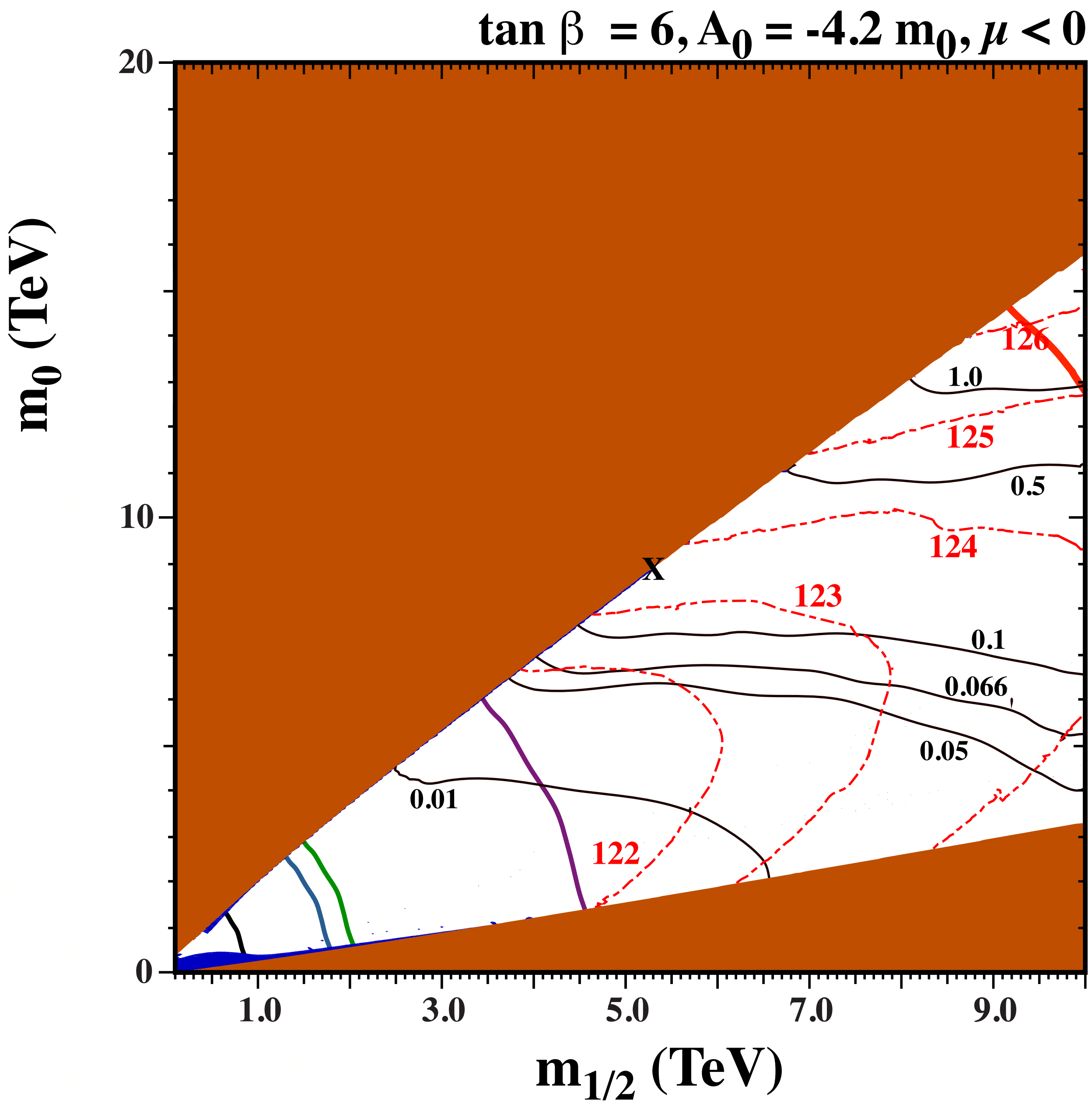
2015



- CMSSM

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

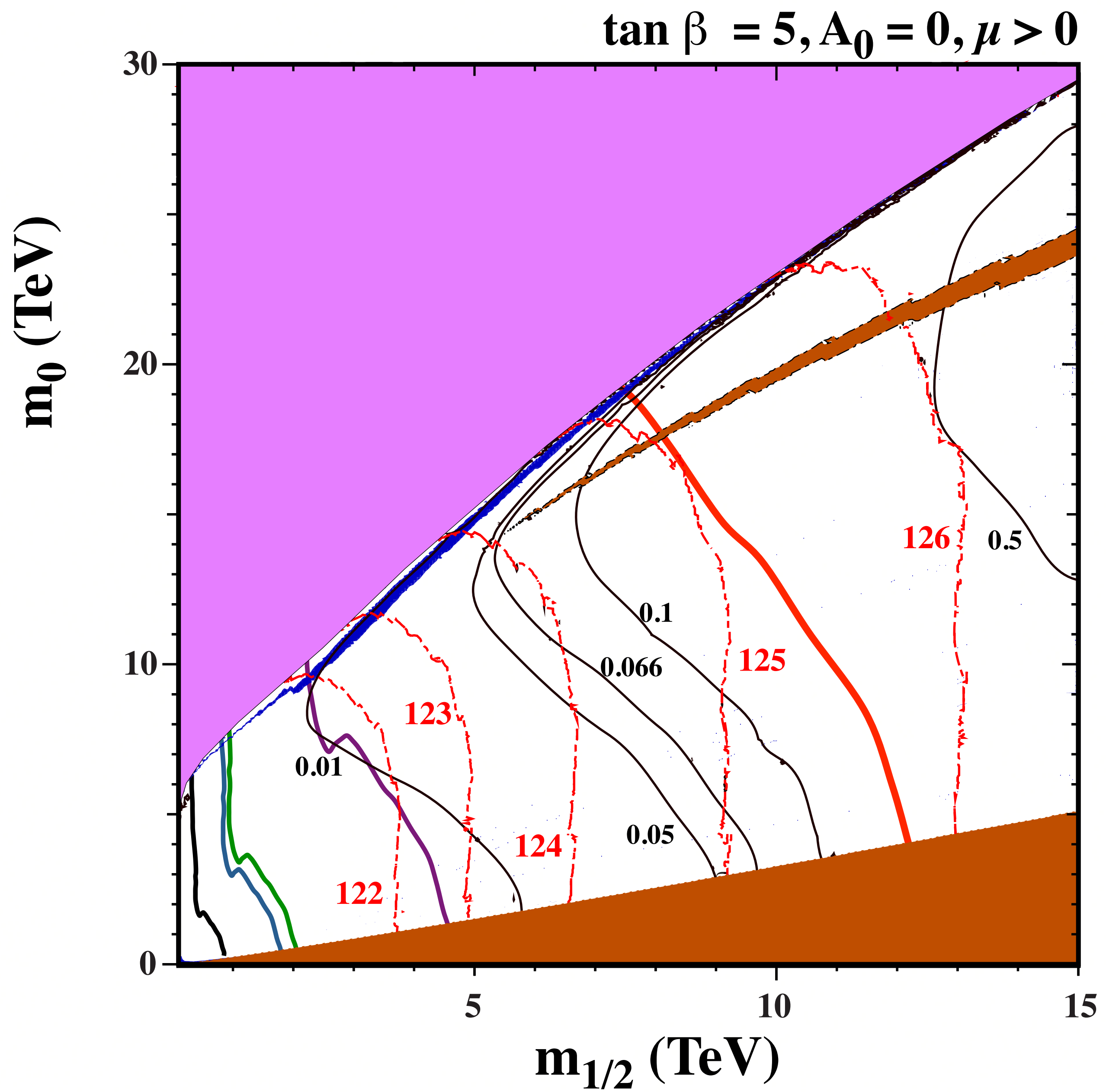
Stop strip



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

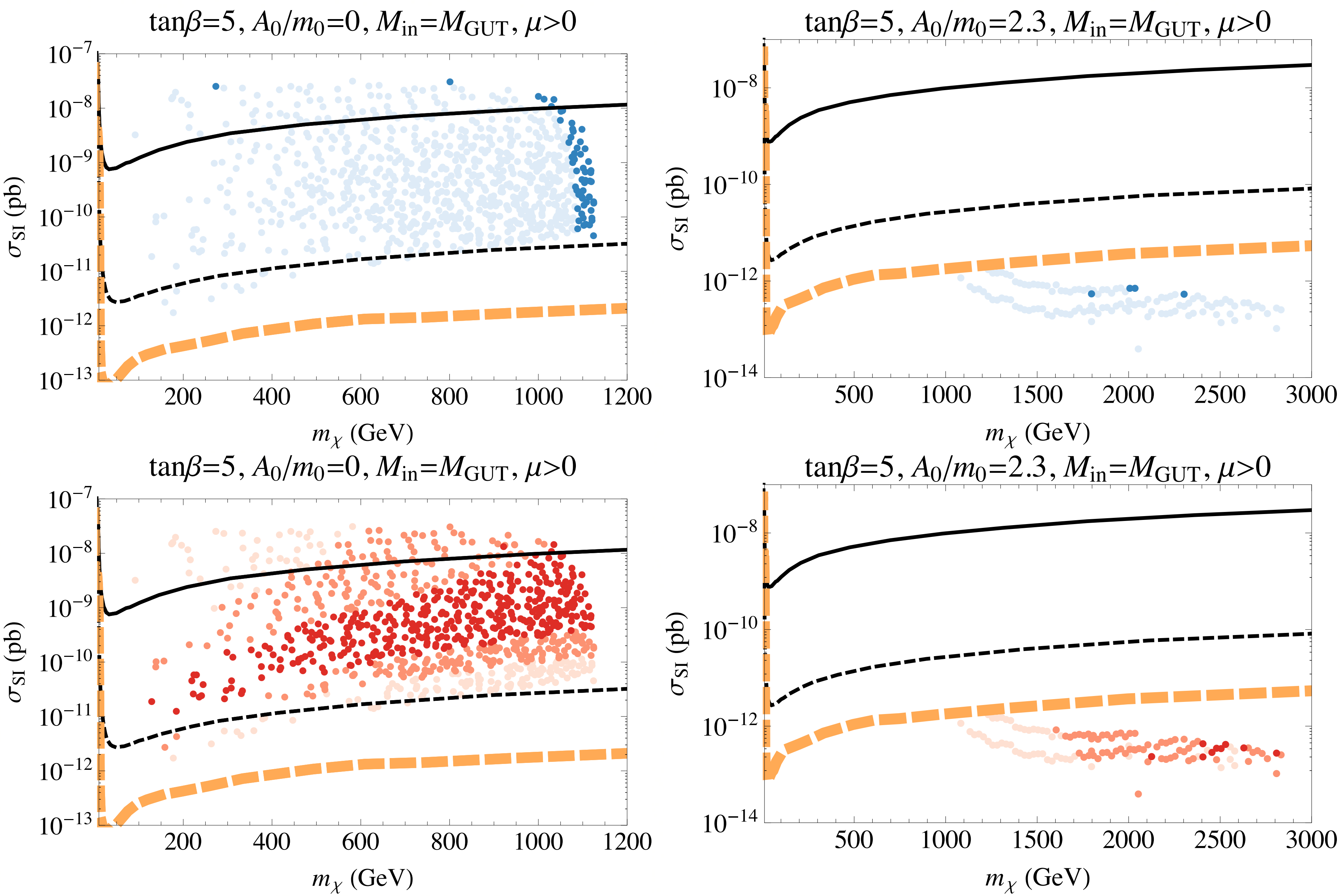
Focus Point



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

Direct detectability



Ellis,Evans, Nagata, Olive, Sandick, Zheng

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

Talk by Jason Evans

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
  - $B_0 = A_0 - m_0 \Rightarrow \tan\beta$ no longer free

Pure Gravity Mediation

Ibe,Moroi,Yanagida
Ibe,Yanagida
Ibe,Matsumoto,Yanagida

- Two parameter model!
  - $m_0 = m_{3/2}$; $\tan\beta$ (requires GM term to insure $B_0 = -m_0$)
  - gaugino masses (and A-terms) generated through loops

$$
\begin{aligned}
M_1 &= \frac{33}{5}\frac{g_1^2}{16\pi^2} m_{3/2}\ , \\
M_2 &= \frac{g_2^2}{16\pi^2} m_{3/2}\ , \\
M_3 &= -3\frac{g_3^2}{16\pi^2} m_{3/2}\ .
\end{aligned}
$$

- $\Rightarrow$ Push towards very large masses

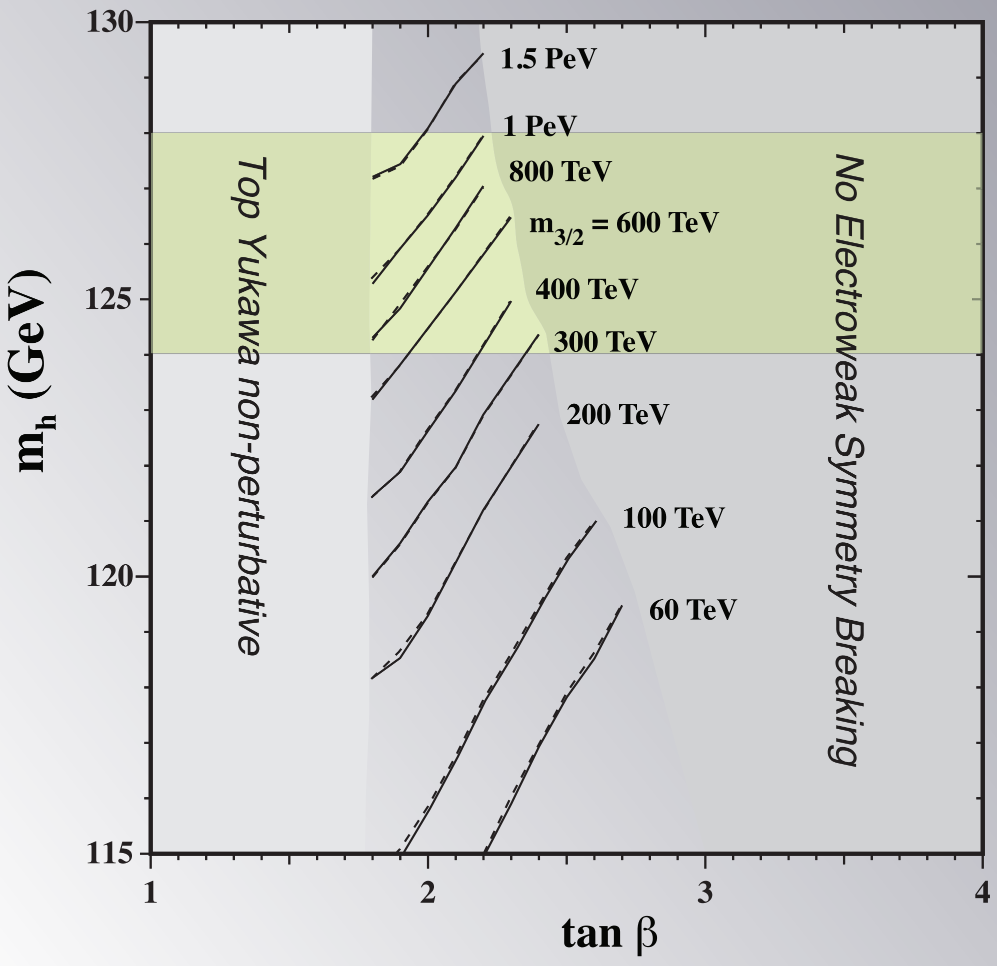
Evans,Ibe,Olive,Yanagida

Pure Gravity Mediation

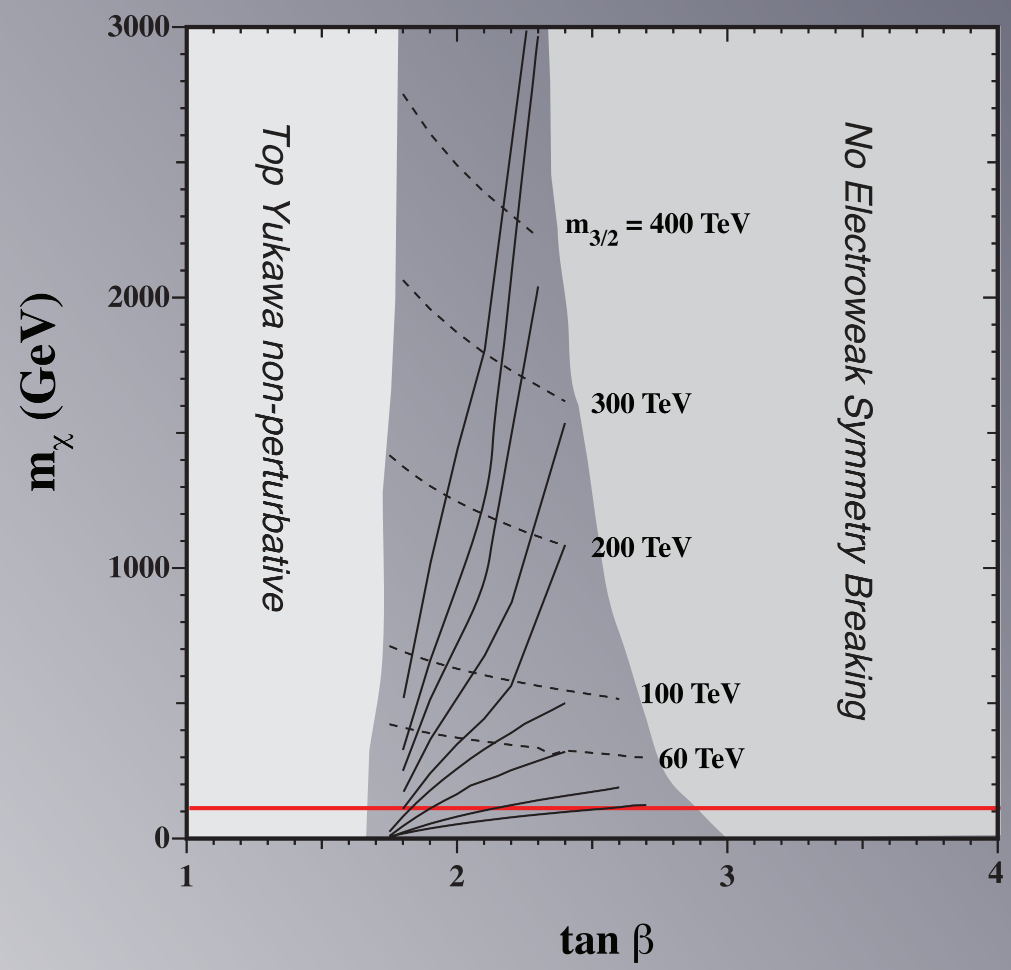
- The sfermion and gravitino have masses O(100) TeV.
- The higgsino and the heavier Higgs boson also have masses O(100) TeV.
- The gaugino masses are in the range of hundreds to thousands of GeV.
- The LSP is the neutral wino which is nearly degenerate with the charged wino.
- The lightest Higgs boson mass is consistent with the observed Higgs-like boson, i.e. $m_h \sim 125 - 126$ GeV.

Pure Gravity Mediation

Higgs Mass



Neutralino mass



Evans, Ibe, Olive, Yanagida

PGM with small μ
Higgsino DM

NUHM1-like model; use EWSB conditions to determine $m_1 = m_2 \neq m_{3/2}$

μ, tan β, $m_{3/2}$ free;

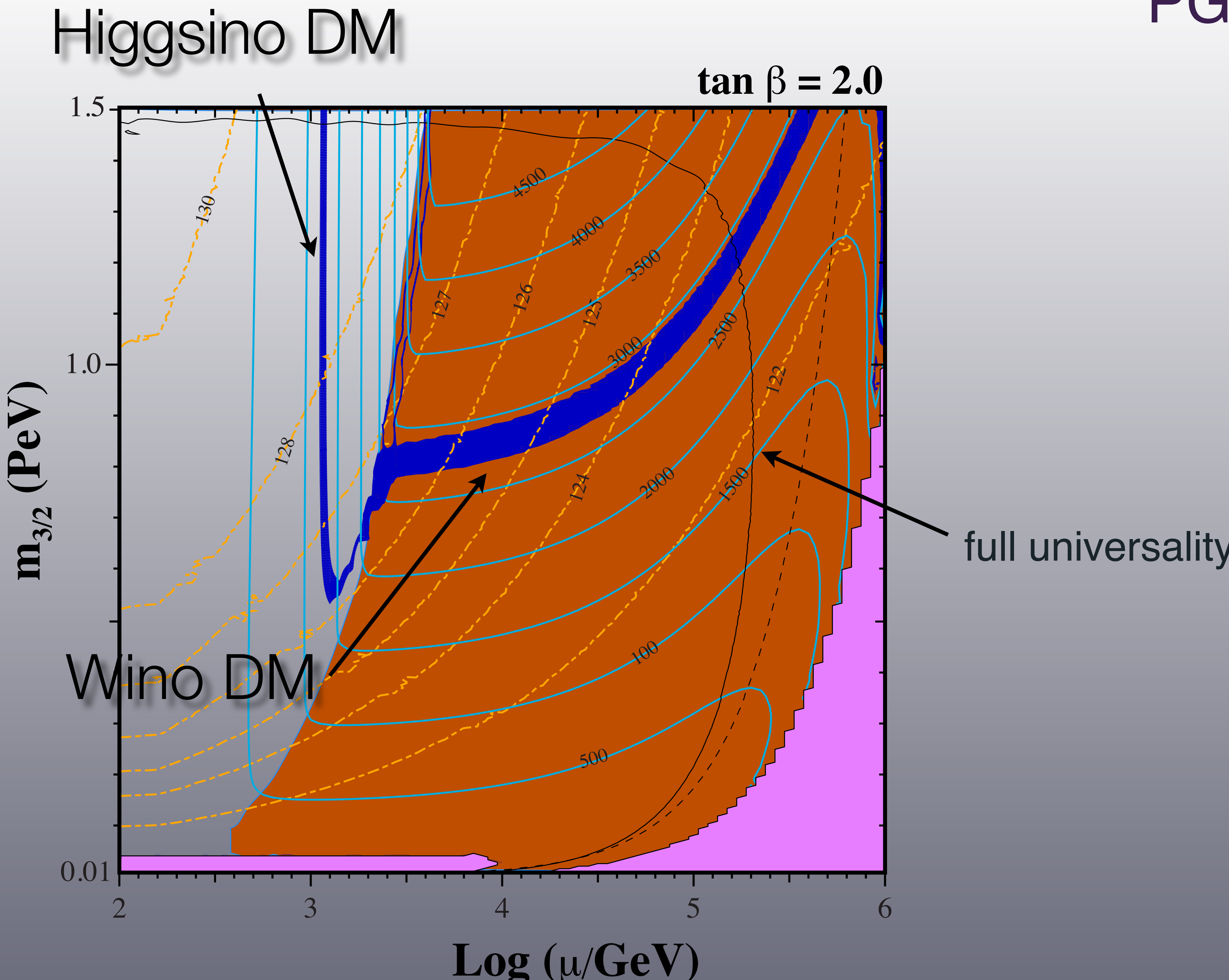
$m_1 = m_2$, c_H (GM term) fixed by EWSB

Can drop c_H, and allow $m_1 \neq m_2$, but no viable Higgsino DM

Can drop μ, and allow $m_1 \neq m_2$, ($\mu = c_H\, m_{3/2}$, $B0 = 2\, m_{3/2}$) but no viable Higgsino DM

Evans, Ibe, Olive, Yanagida

PGM



Evans,Ibe,Olive,Yanagida

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 $m_{3/2}$ ~ 10-1000 GeV

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

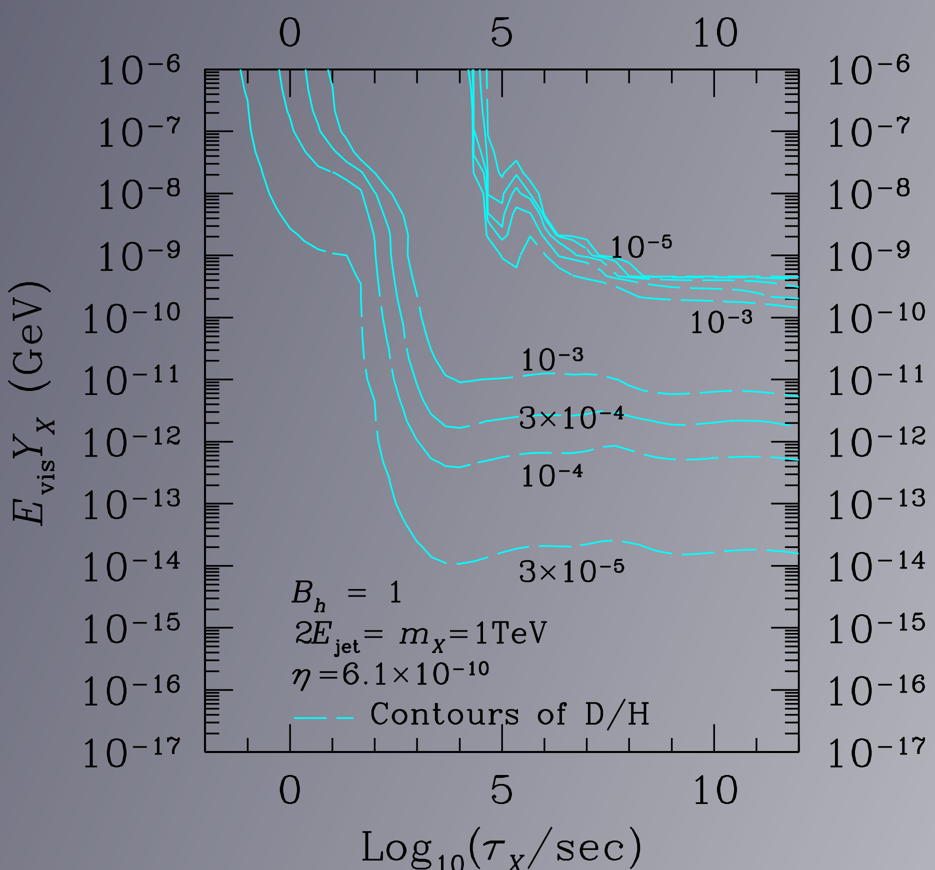
Lifetimes 100-10^8 s $\Rightarrow$ BBN limits

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

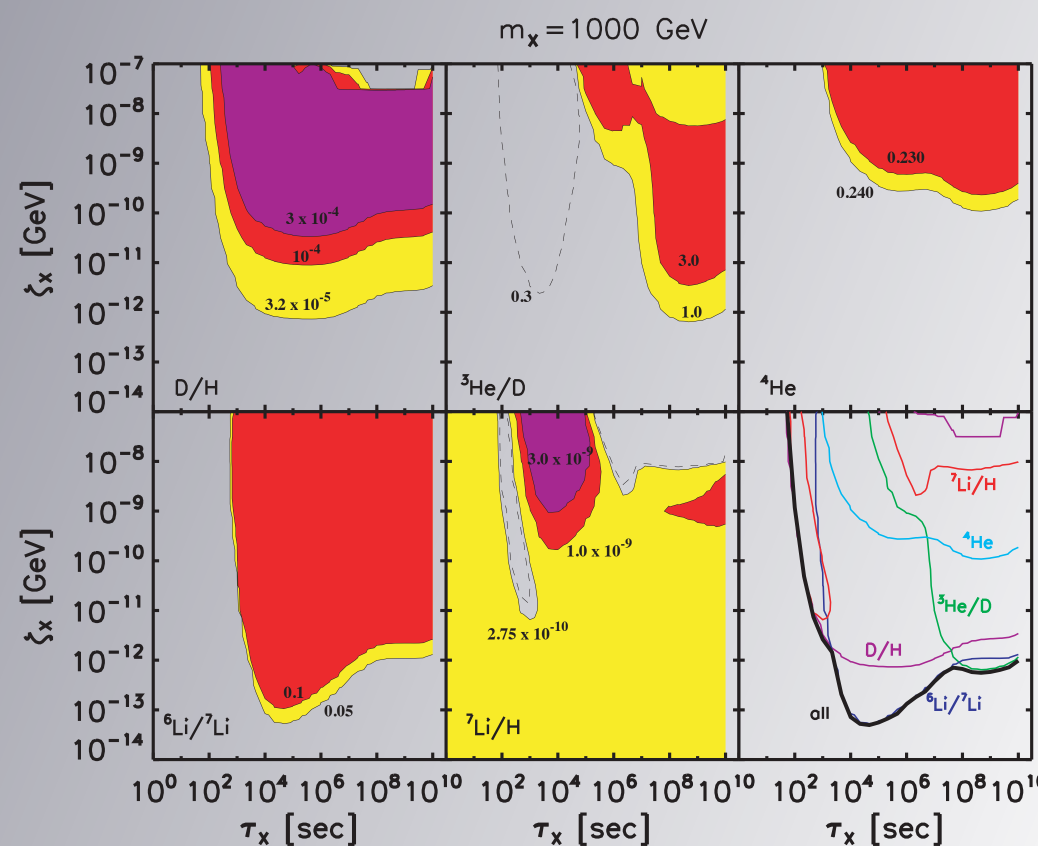
NLSP → gravitino + γ

Gravitino Mass Limits

Kawasaki, Kohri, Moroi



Cyburt, Ellis, Fields, Luo, Olive, Spanos



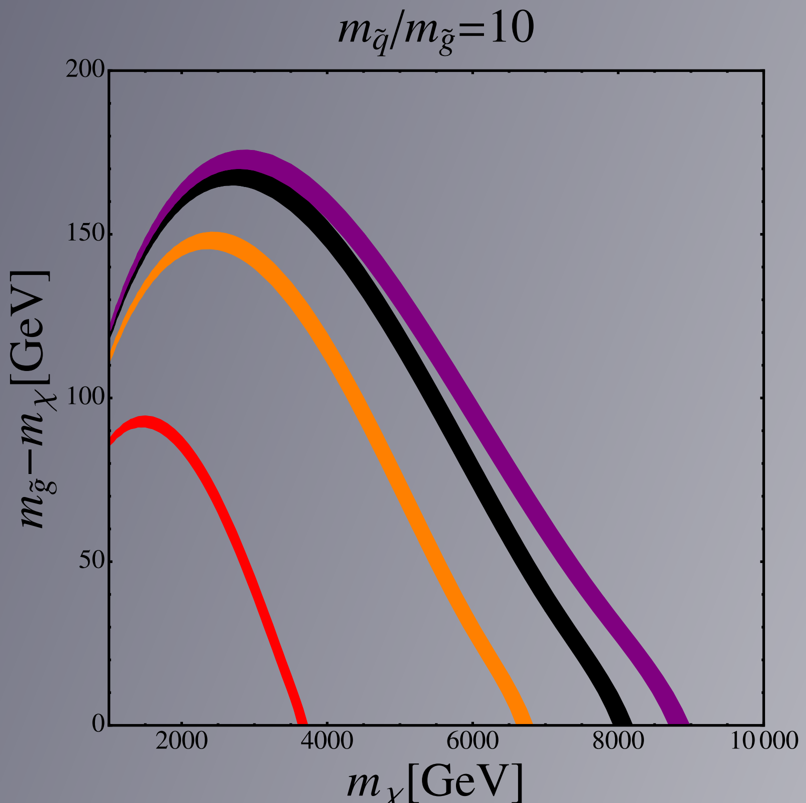
$$\tau_\chi \lesssim 100 \text{ s} \Rightarrow m_\chi > 300 \text{ GeV } (m_{3/2}/\text{GeV})^{2/5}$$

Gravitino Mass Limits

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

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



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

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

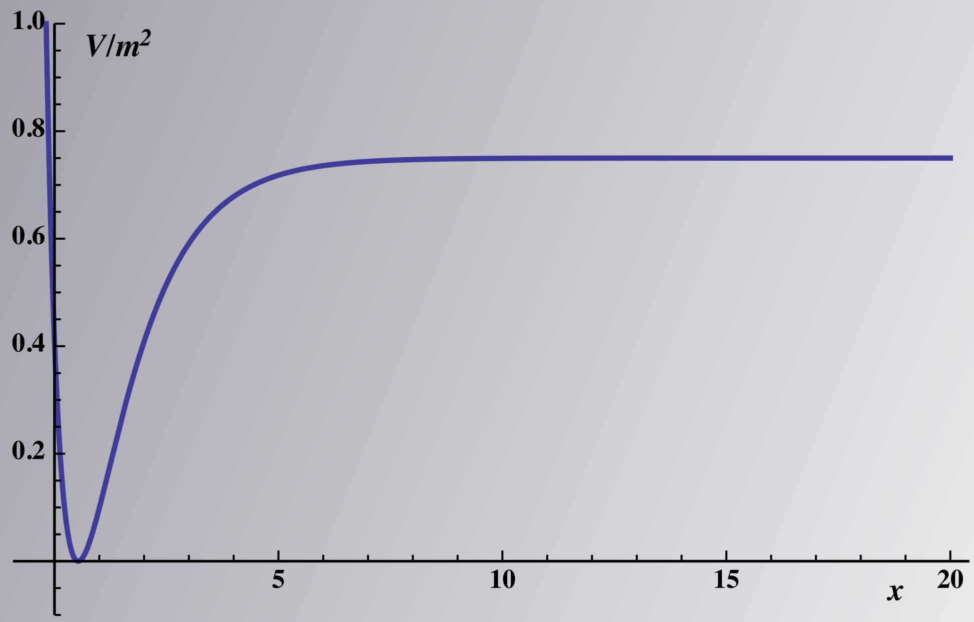
No Scale Model:

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

Inflaton | Matter | Polonyi

$$W = \sqrt{3}m\phi(T-1/2),$$ Starobinsky Inflation

$$+\ \mu(z+\nu)$$ Polonyi Model



Toy Model

for small Λ_z

$$m_{3/2} = m\frac{5\mu^3 + 6\mu m^2 M_P^2}{2(3m^2M_P^2 + \mu^2)^{3/2}} \quad \rightarrow \quad \mu/\sqrt{3}M_P.$$

for small μ/mM_P

For $\mu = m^2$

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

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

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

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

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 → gravitino + gravitino

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

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

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

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

see talk of Yann Mambrini

Reheating

Parametrize inflaton decays: $\Gamma_\phi = \frac{y_\phi^2}{8\pi} m_\phi$

$$T_{RH} = \left(\frac{10}{g_s}\right)^{1/4} \left(\frac{2\Gamma_\phi\, M_P}{\pi\, c}\right)^{1/2} = 0.55 \frac{y_\phi}{2\pi} \left(\frac{m_\phi\, M_P}{c}\right)^{1/2}$$

$g_s = 427/4 \quad c \simeq 1.2$

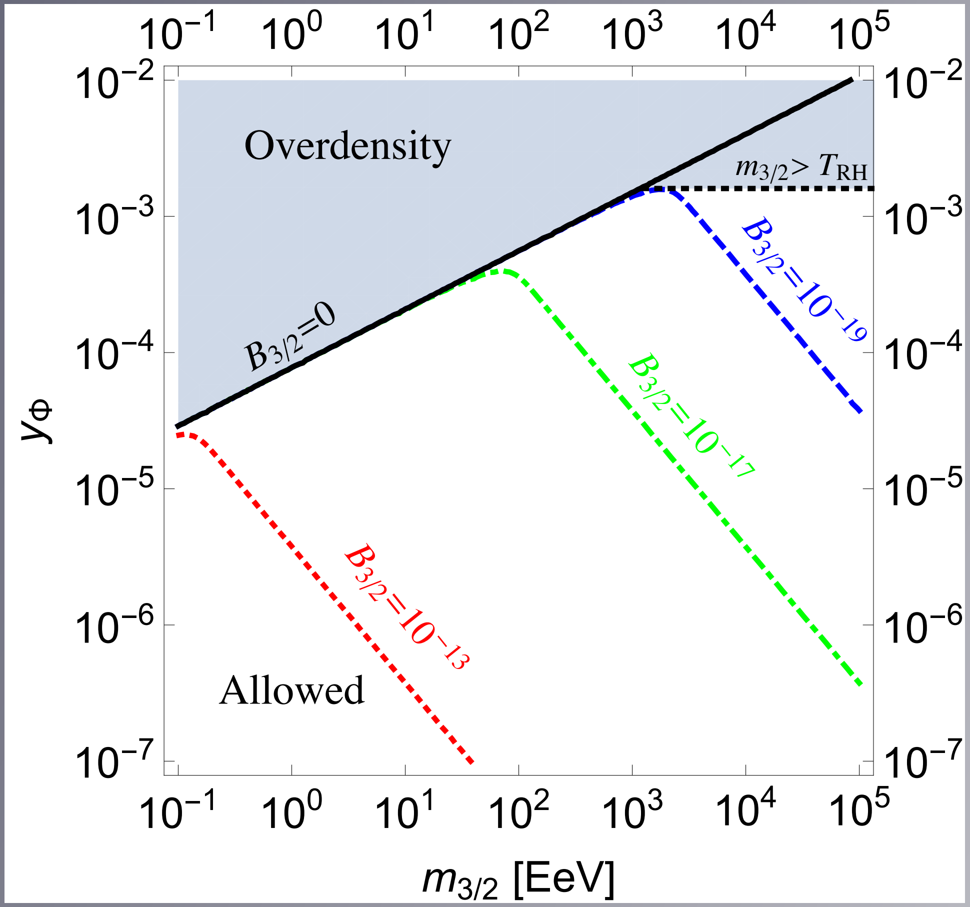
$$\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{0.1 \text{ EeV}}{m_{3/2}}\right)^3 \left(\frac{m_\phi}{3 \times 10^{13} \text{GeV}}\right)^{7/2} \left(\frac{y_\phi}{2.9 \times 10^{-5}}\right)^7$$

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

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

Reheating

Limit on inflaton decay coupling



Reheating

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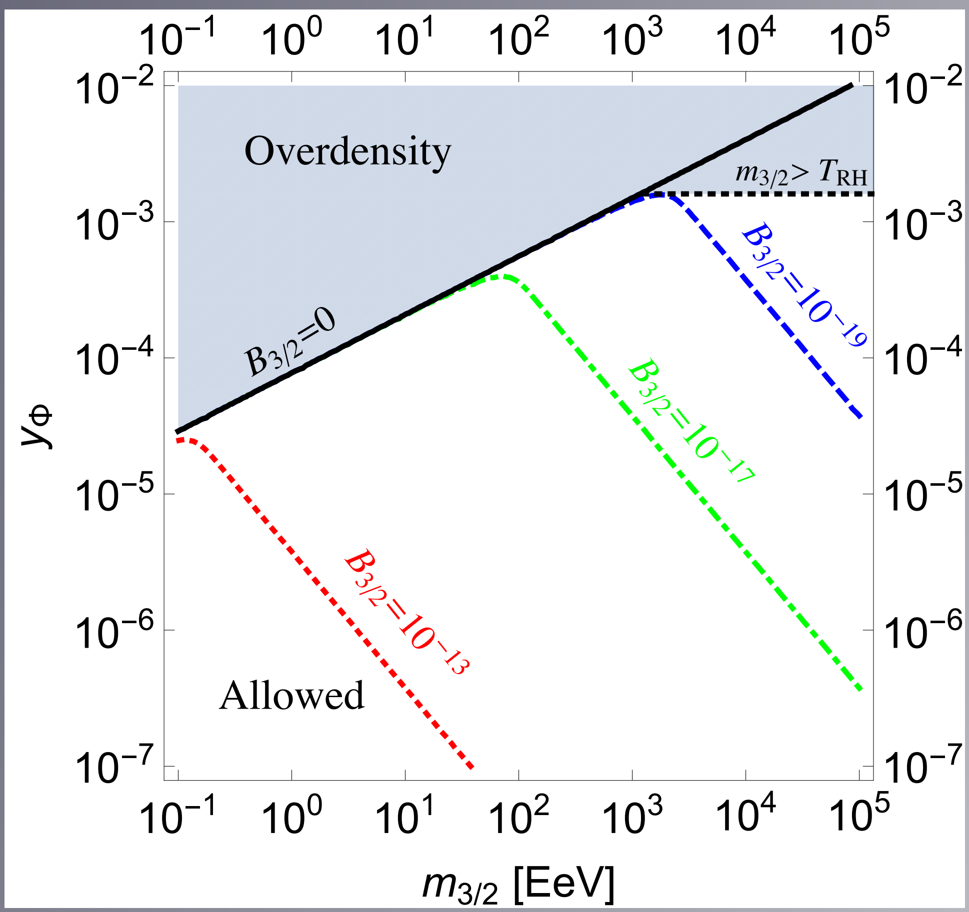

inflaton decays to gravitinos

$$\Gamma_{3/2} = m_\phi \frac{y_{3/2}^2}{72\pi}$$

$$B_{3/2} = \Gamma_{3/2}/\Gamma_\phi = \frac{|y_{3/2}|^2}{9y_\phi^2}.$$

$$\Omega_{3/2}^{decay} h^2 = 0.11 \left(\frac{B_{3/2}}{1.3\times10^{-13}}\right)\left(\frac{y_\phi}{2.9\times10^{-5}}\right) \times \left(\frac{m_{3/2}}{0.1\ \mathrm{EeV}}\right)\left(\frac{3\times10^{13}\ \mathrm{GeV}}{m_\phi}\right)^{1/2}$$

$$B_{3/2} y_\phi = \frac{|y_{3/2}|^2}{9|y_\phi|} \lesssim 1.9\times10^{-18}\left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)$$

Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to "corners" or strips
- There remain several beyond the CMSSM-like models
  - PGM at the PeV scale
- 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!
  - at the EeV scale