Supersymmetric Dark Matter: CMSSM-like Models in the LHC era

1) With CMSSM-like models pushed to high mass scales, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC. Viable dark matter models in the CMSSM tend to lie in strips (co-annihilation, funnel, focus point), how far up in energy do these strips extend?

2) How detectable is DM along these strips

3) Generalization of the CMSSM

Why Supersymmetry (still)?

- Gauge Coupling Unification
- Gauge Hierarchy Problem
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter
- Improvement to low energy phenomenology?

but, $m_h \sim 125$ GeV, and no SUSY?

Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)

SUSY Superpotential + Soft terms

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

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

R-parity conservation assumed

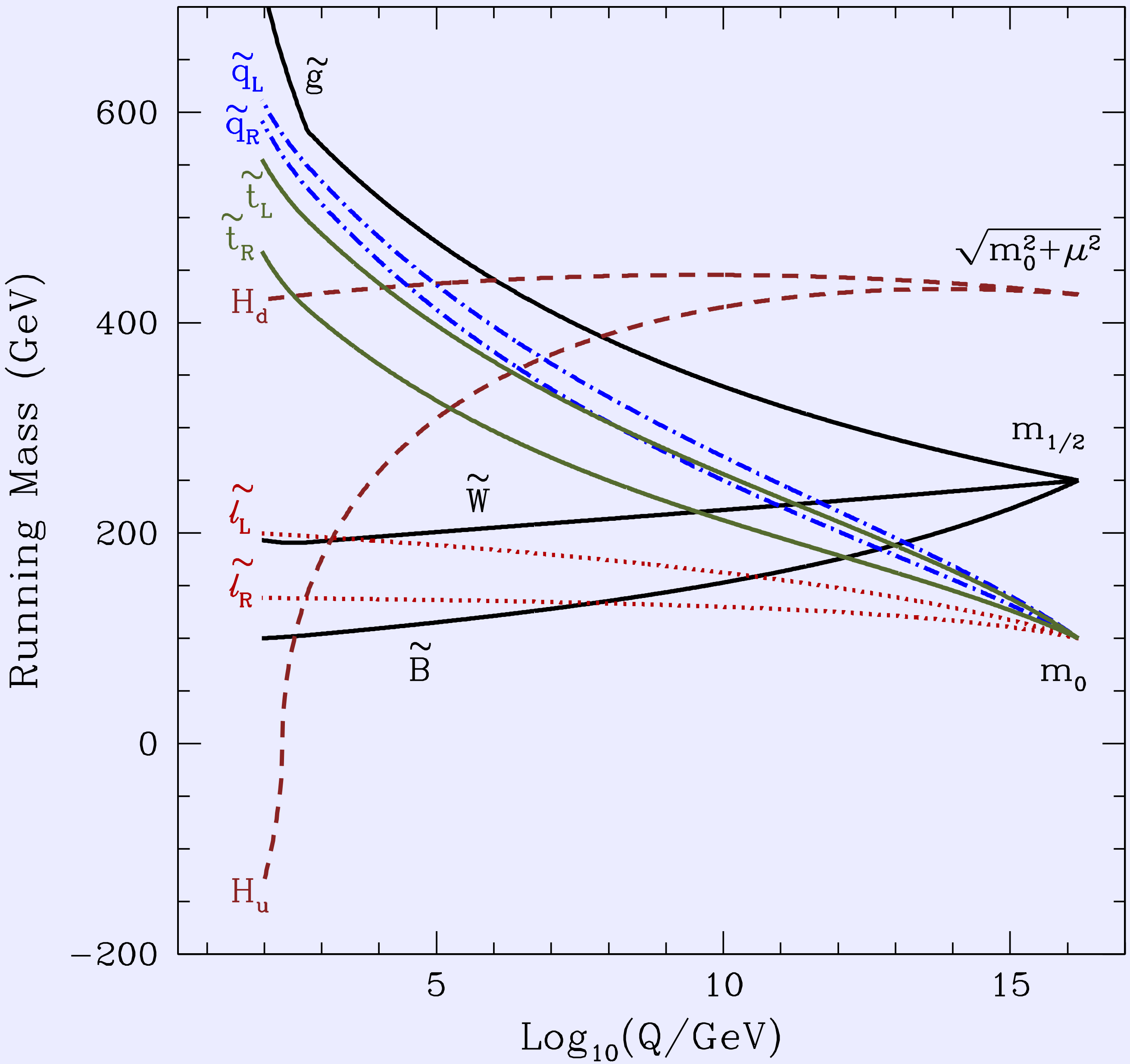
Which Supersymmetric Model?

- MSSM with R-Parity (still more than 100 parameters)

- Gaugino mass Unification
- A-term Unification
- Scalar 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 Spectra



Unification to rich spectrum
+
EWSB

Falk

Which Supersymmetric Model?

- **CMSSM (4+ parameters)**

Parameters: $m_{1/2}$, m_0, A_0, $\tan\beta$, $\mathrm{sgn}(\mu)$ {$m_{3/2}$}

- **Pure Gravity Mediation (PGM) (2+ parameters)**

Parameters: $m_{3/2}$, $\tan\beta$, $\mathrm{sgn}(\mu)$

- mSUGRA (3+ parameters)

Parameters: $m_{1/2}$, $m_{3/2}$, A_0, $\mathrm{sgn}(\mu)$

- **Anomaly mediation: mAMSB (3+ parameters)**

Parameters: $m_{3/2}$, m_0, $\tan\beta$, $\mathrm{sgn}(\mu)$

Which Supersymmetric Model?

- **CMSSM (4+ parameters)**

Parameters: $m_{1/2}$, m_0, A_0, tan β, sgn(μ)   {$m_{3/2}$}

- subGUT-CMSSM (5+ parameters)

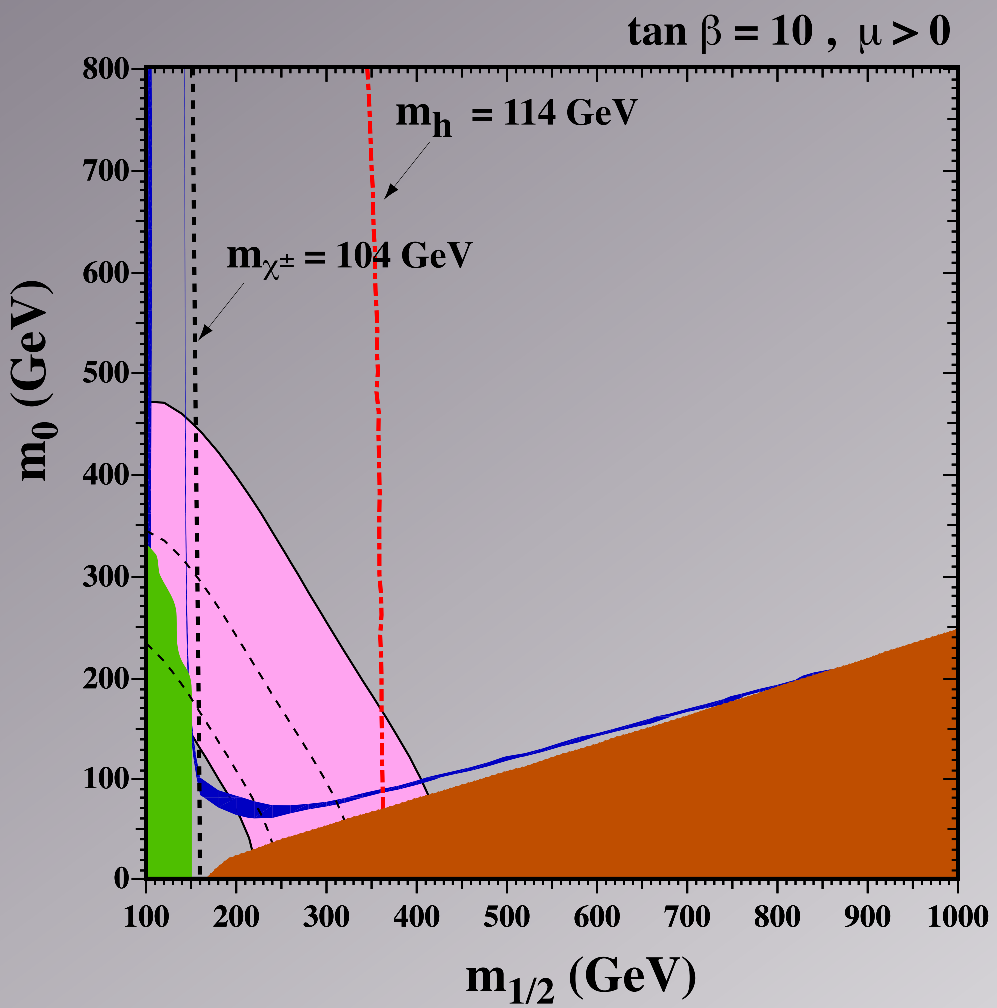
Parameters: $m_{1/2}$, m_0, A_0, tan β, M_{in}, sgn(μ)   {$m_{3/2}$}

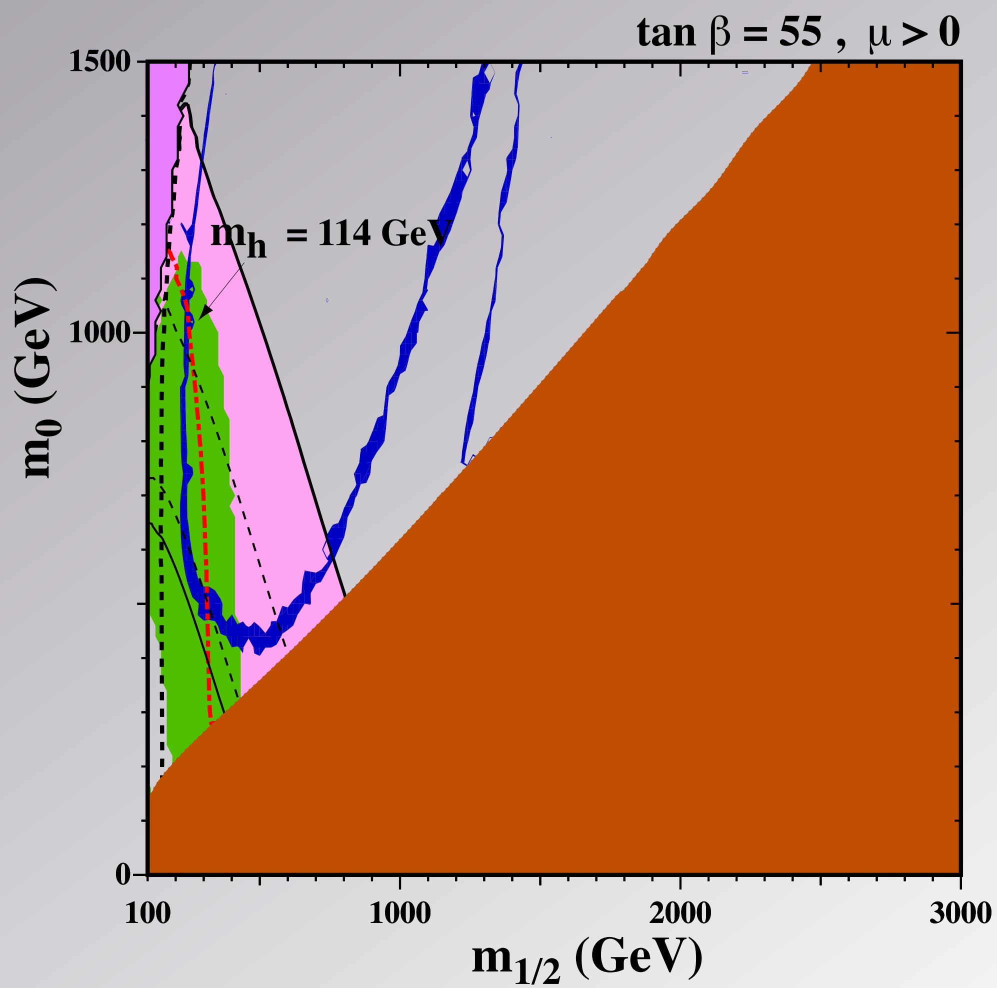
- **NUHM (5,6+ parameters)**

Parameters: $m_{1/2}$, m_0, m_1, m_2, A_0, tan β, sgn(μ) {$m_{3/2}$}

- **SU(5) models (7+ parameters)**

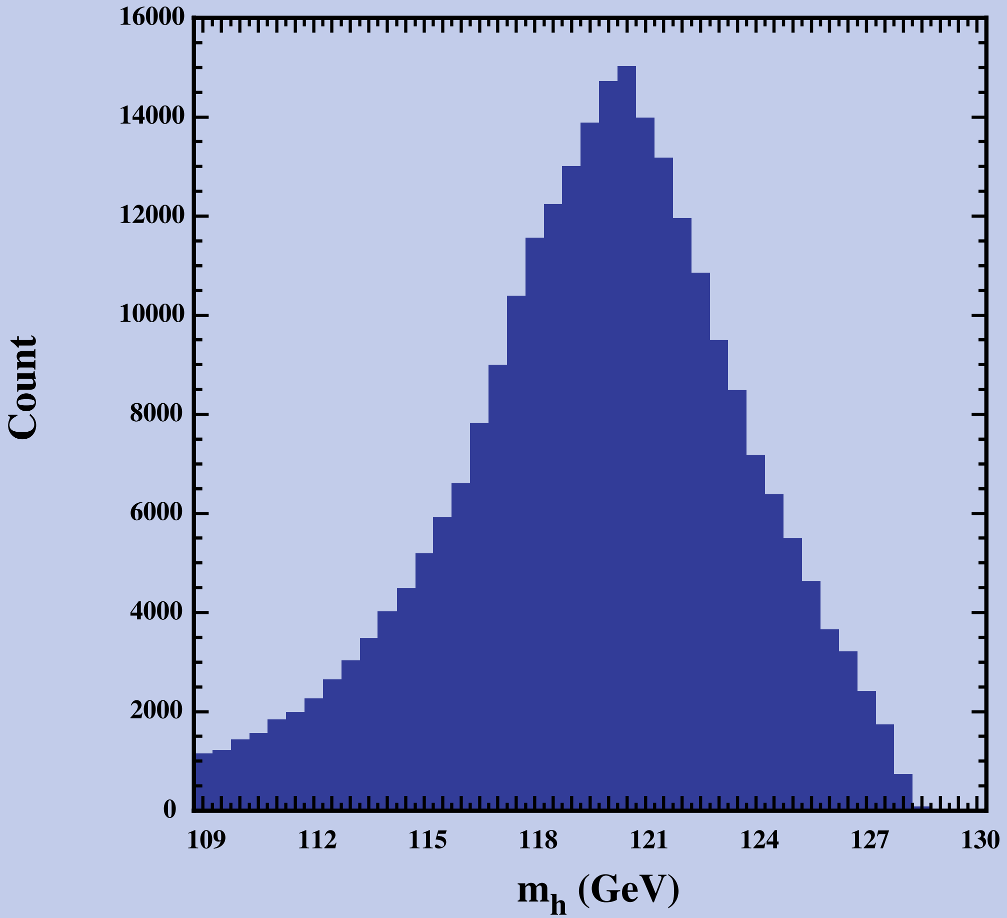
Parameters: $m_{1/2}$, m_5, m_{10}, m_1, m_2, A_0, tan β, sgn(μ) {$m_{3/2}$}

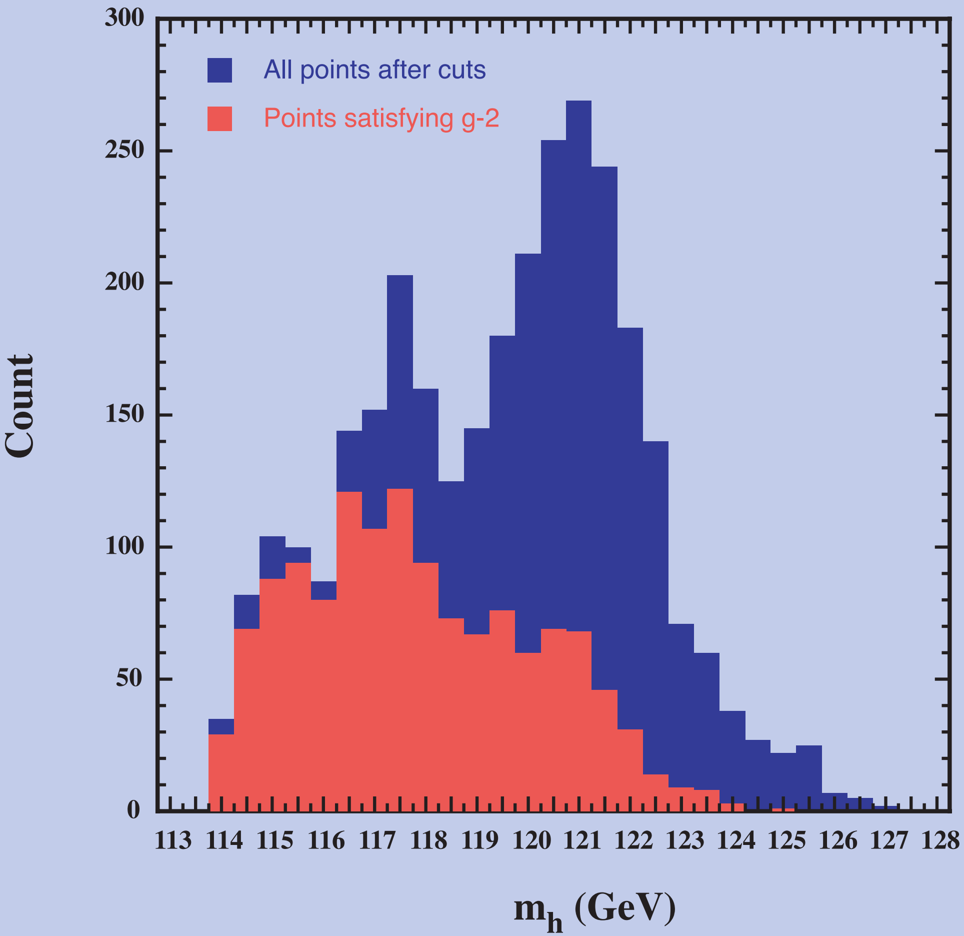




Ellis, Olive, Santoso, Spanos

The Higgs mass in the CMSSM





Ellis, Nanopoulos, Olive, Santoso

Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

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

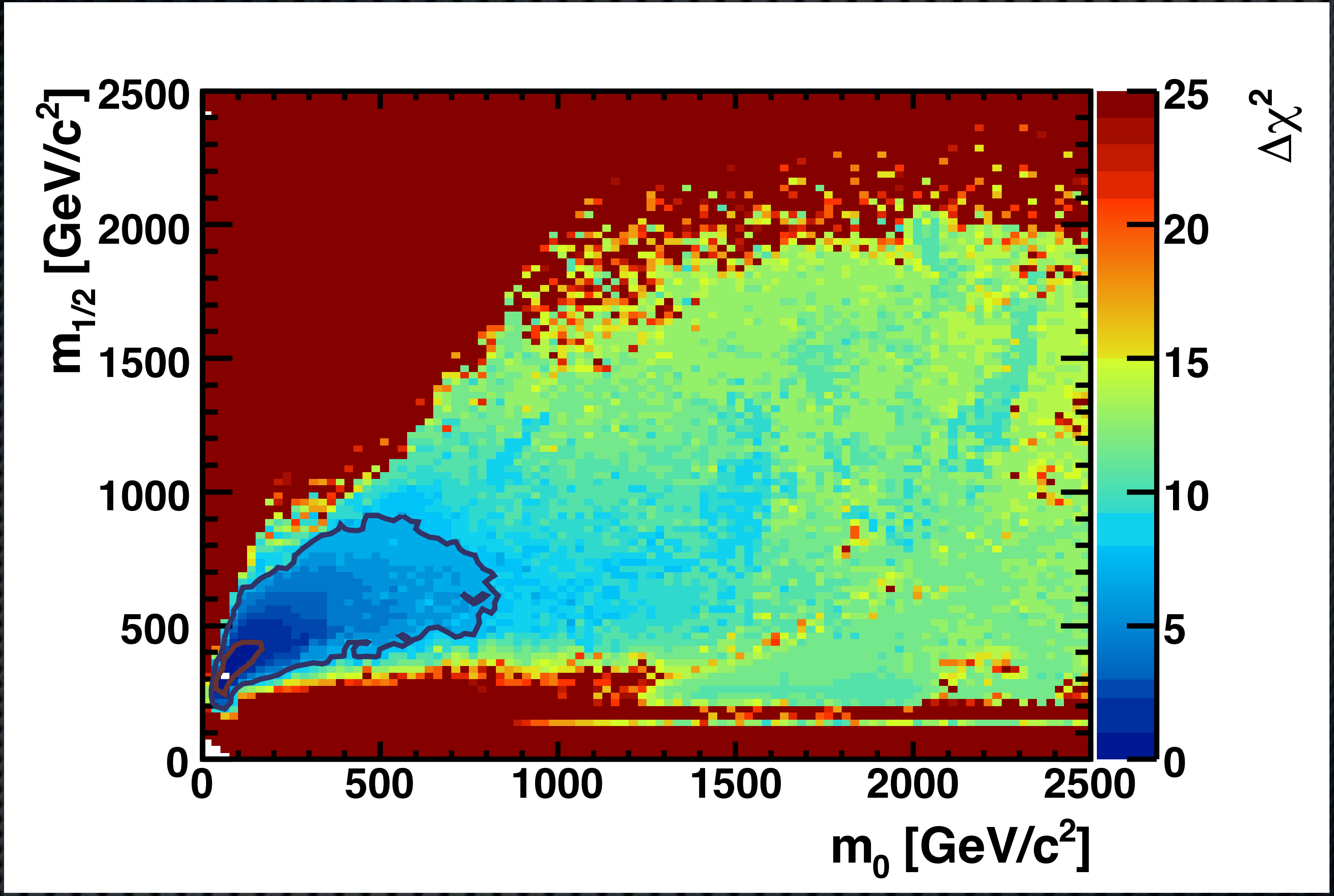
Multinest

- M~~C~~MC 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

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

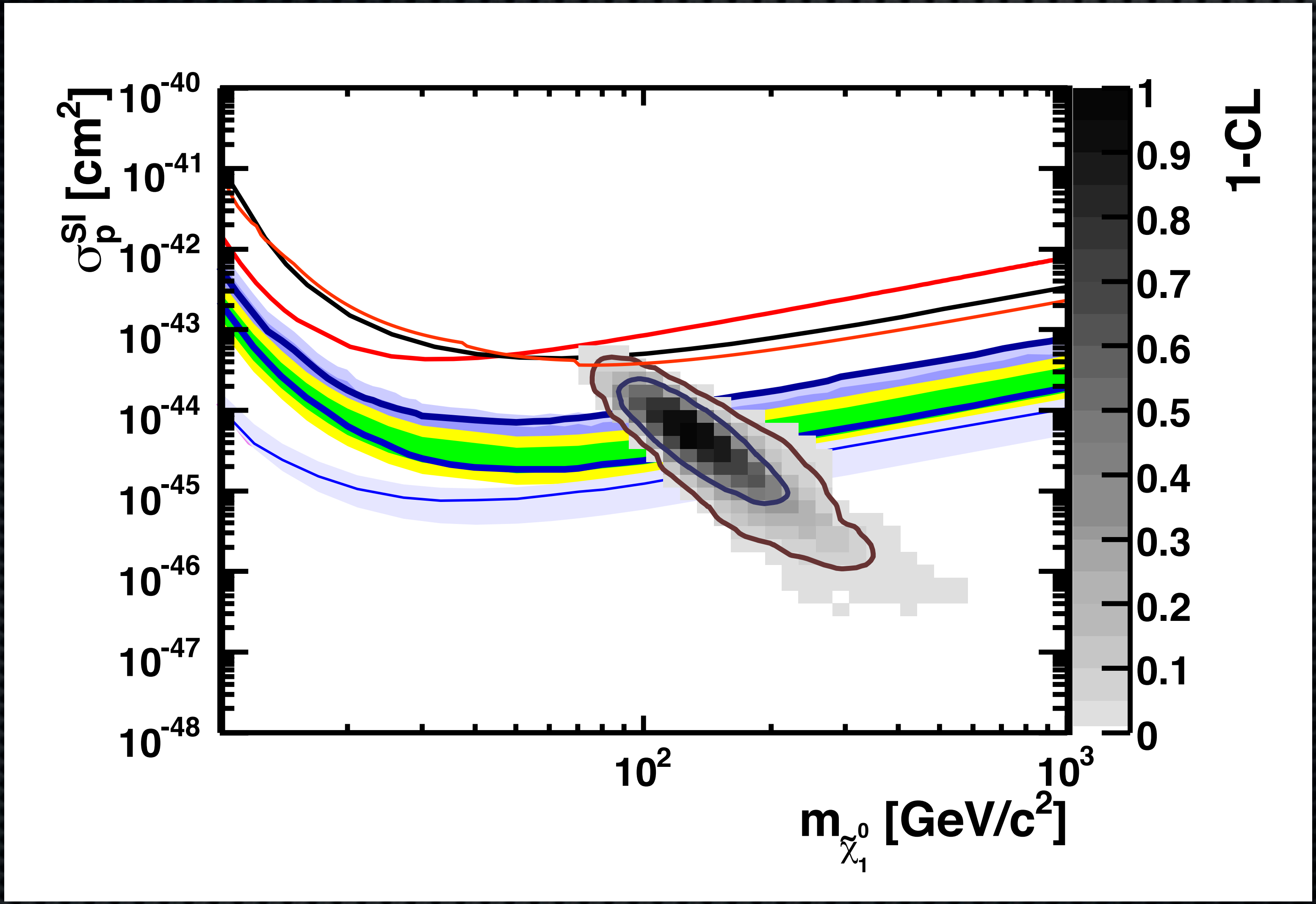
- CMSSM

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

Elastic scaterring cross-section

Mastercode

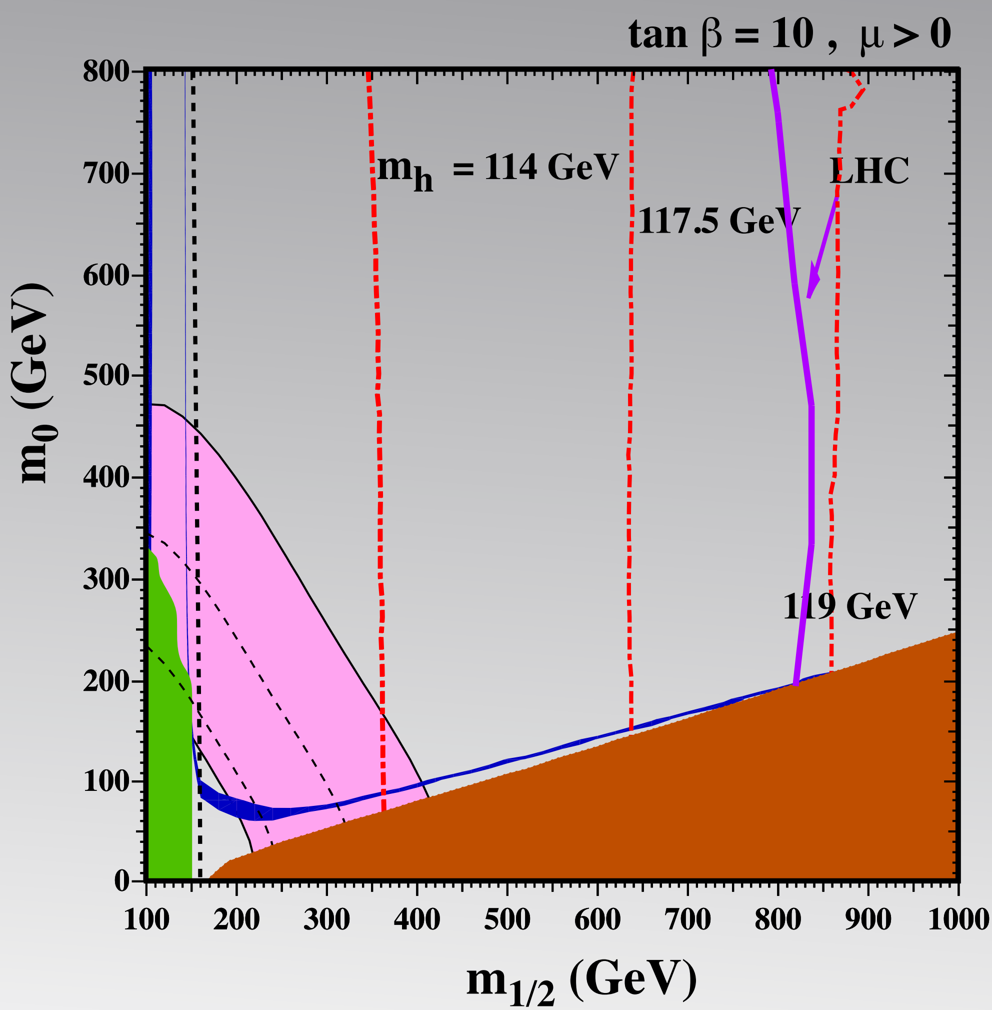
2009

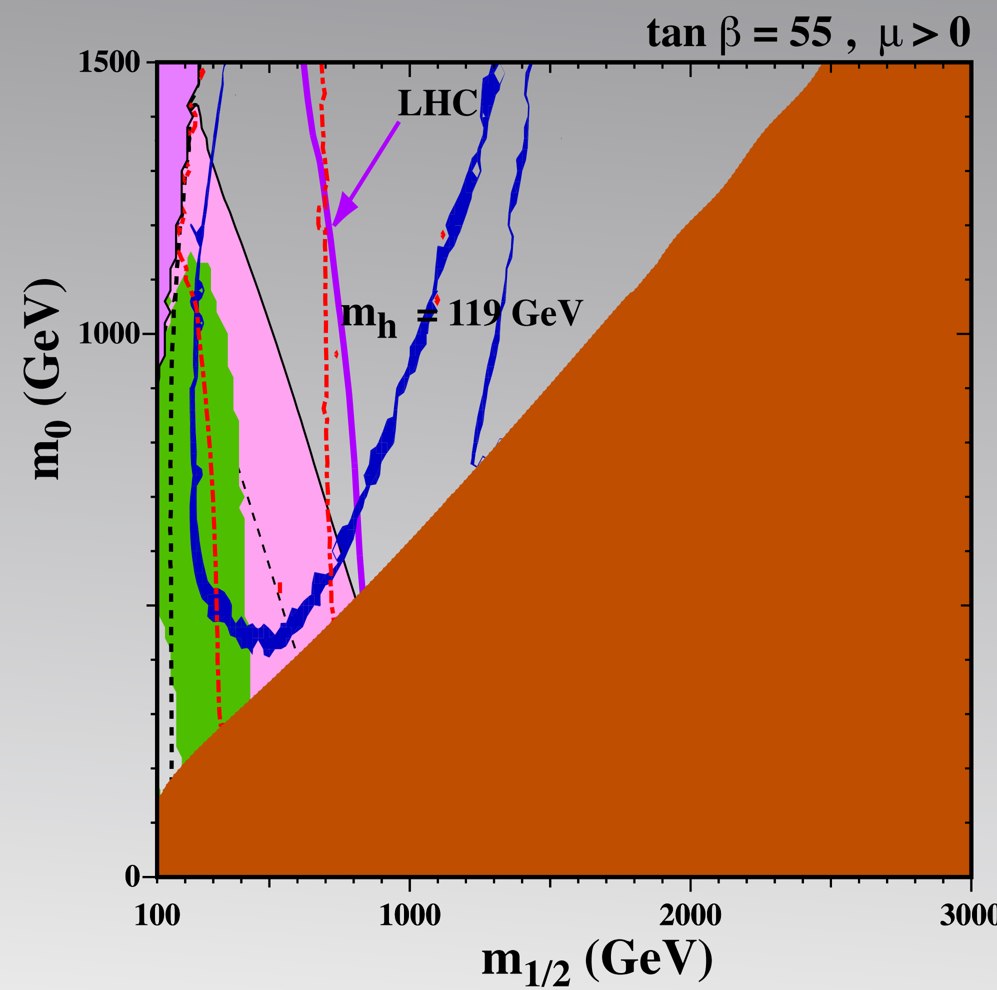


- CMSSM

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

$m_{1/2}$ - m_0 planes incl. LHC





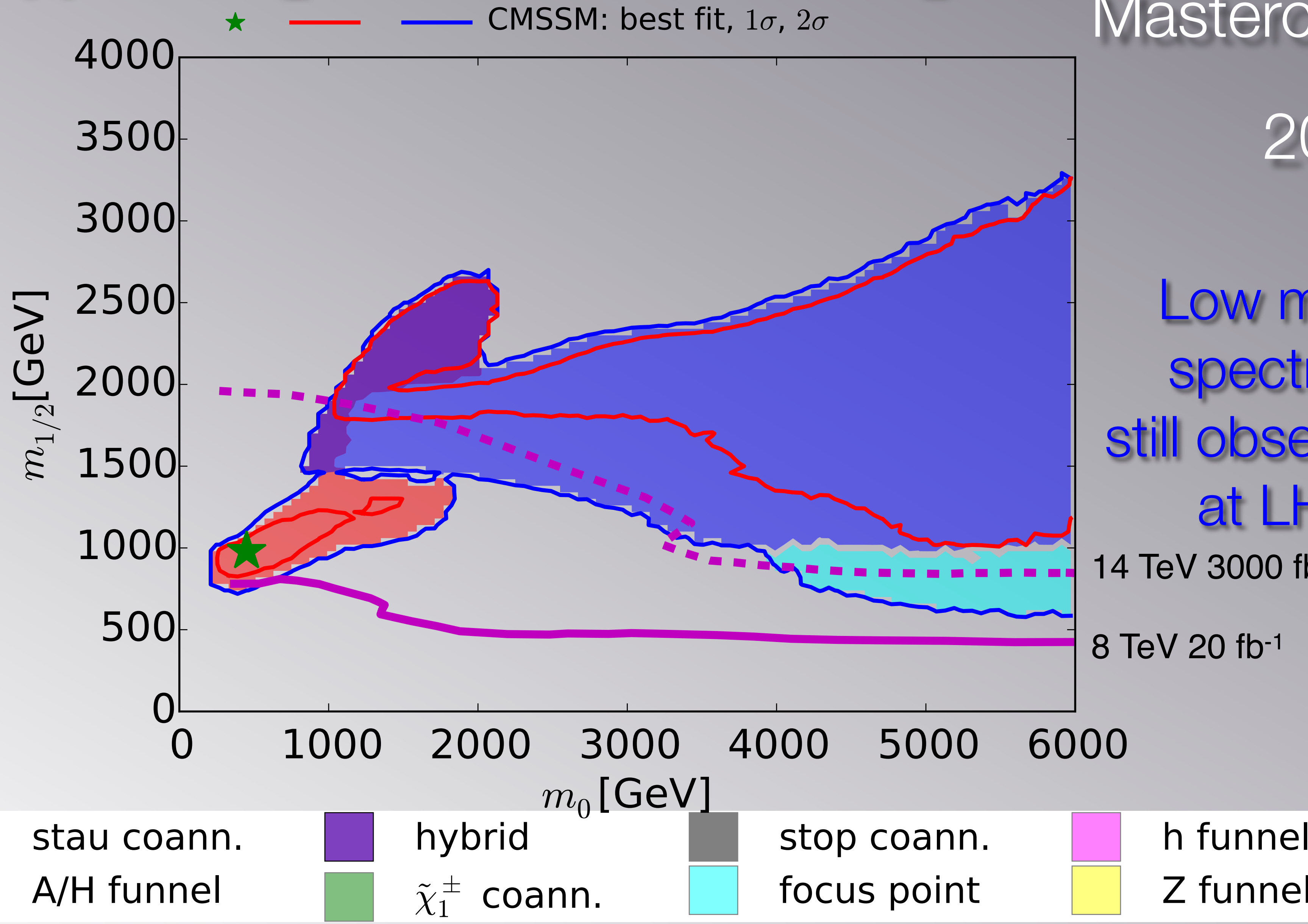
- CMSSM

Ellis, Olive, Santoso, Spanos

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

Mastercode

2015



Low mass spectrum still observable at LHC

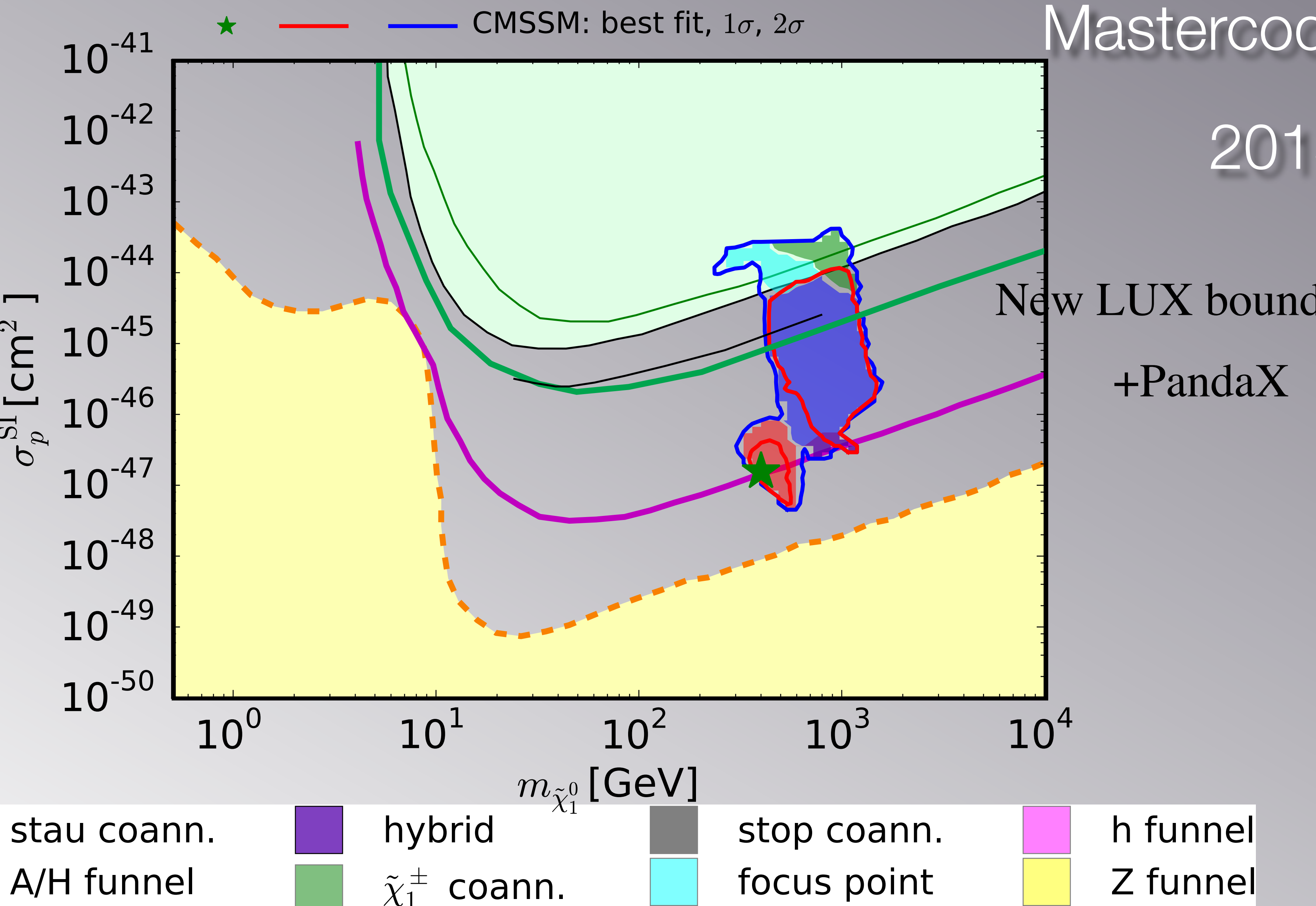
- CMSSM

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



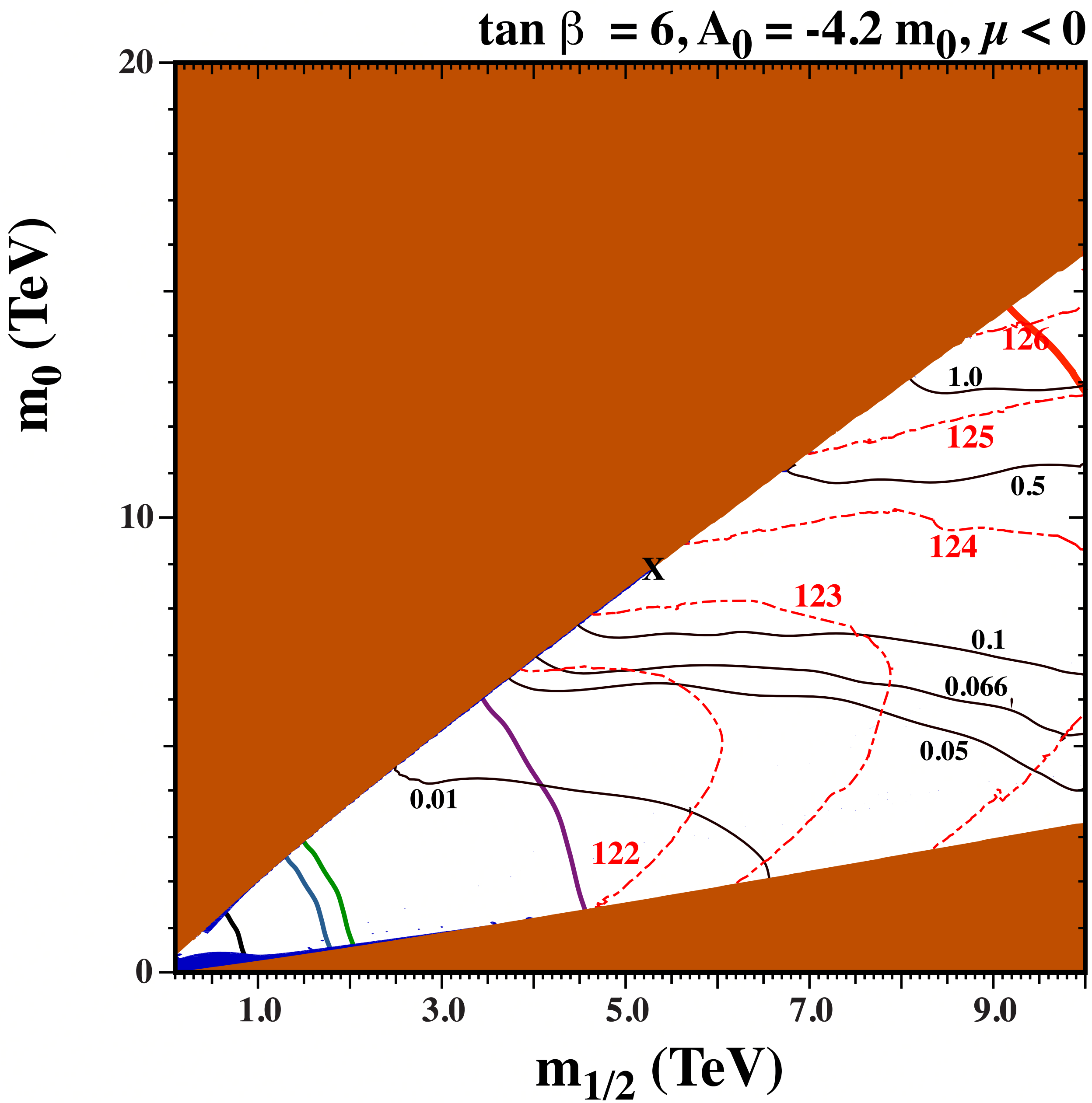
- CMSSM

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

The Strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip

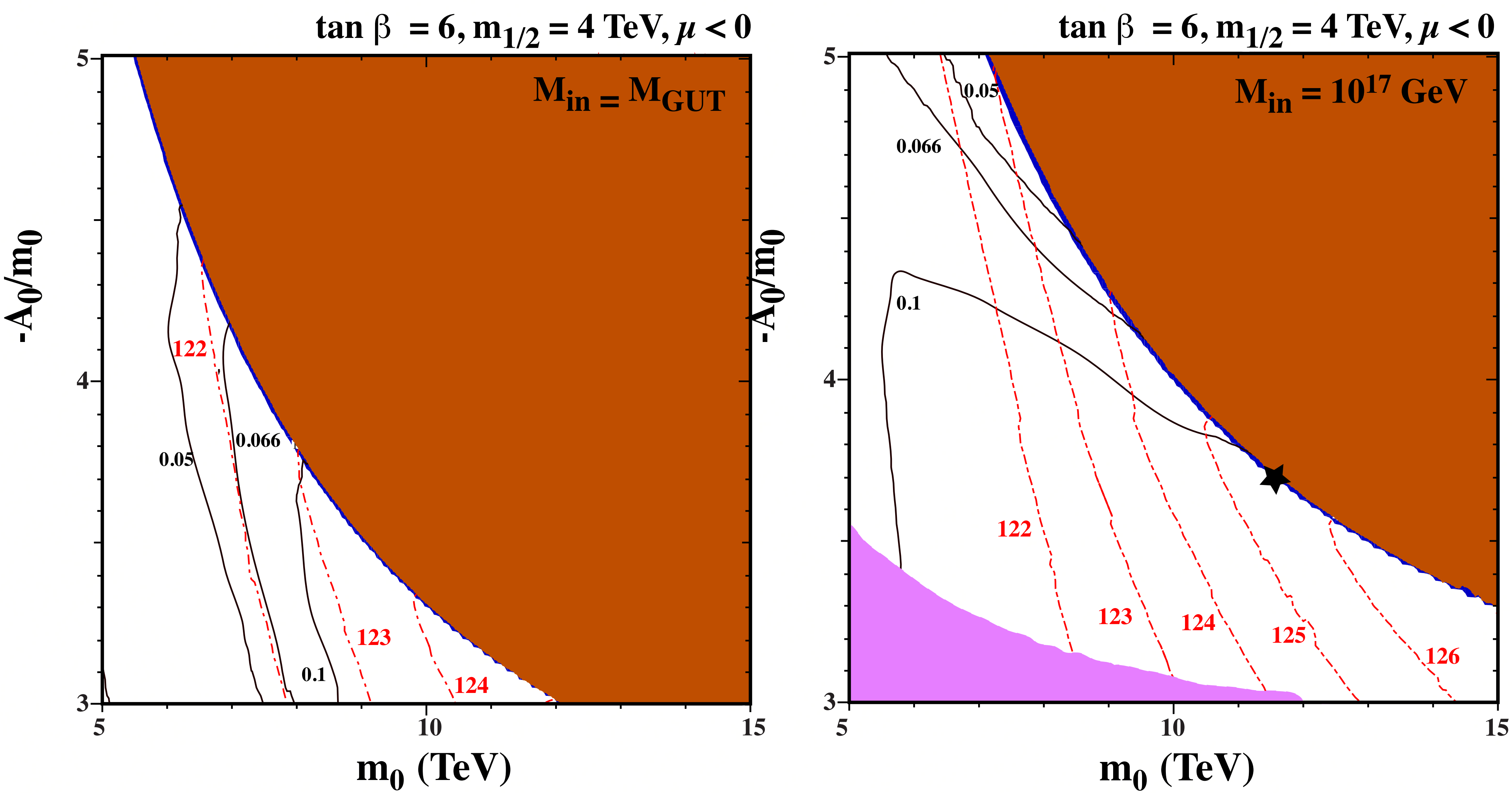
Stop strip



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}

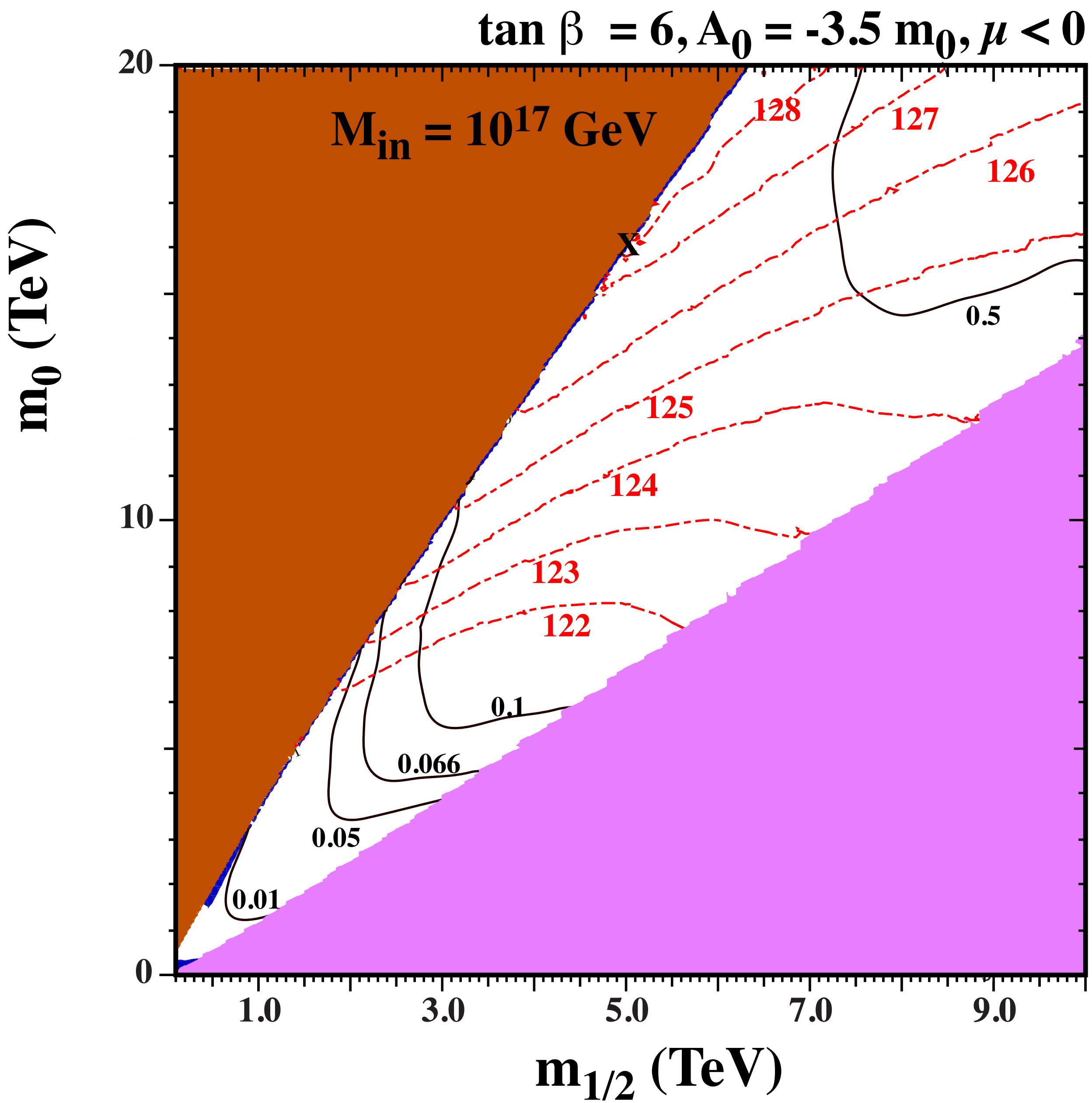
Ellis, Evans, Mustafayev, Nagata, Olive

Improved in an SU(5) superGUT extension



Ellis, Evans, Mustafayev, Nagata, Olive

Improved in an SU(5) superGUT extension

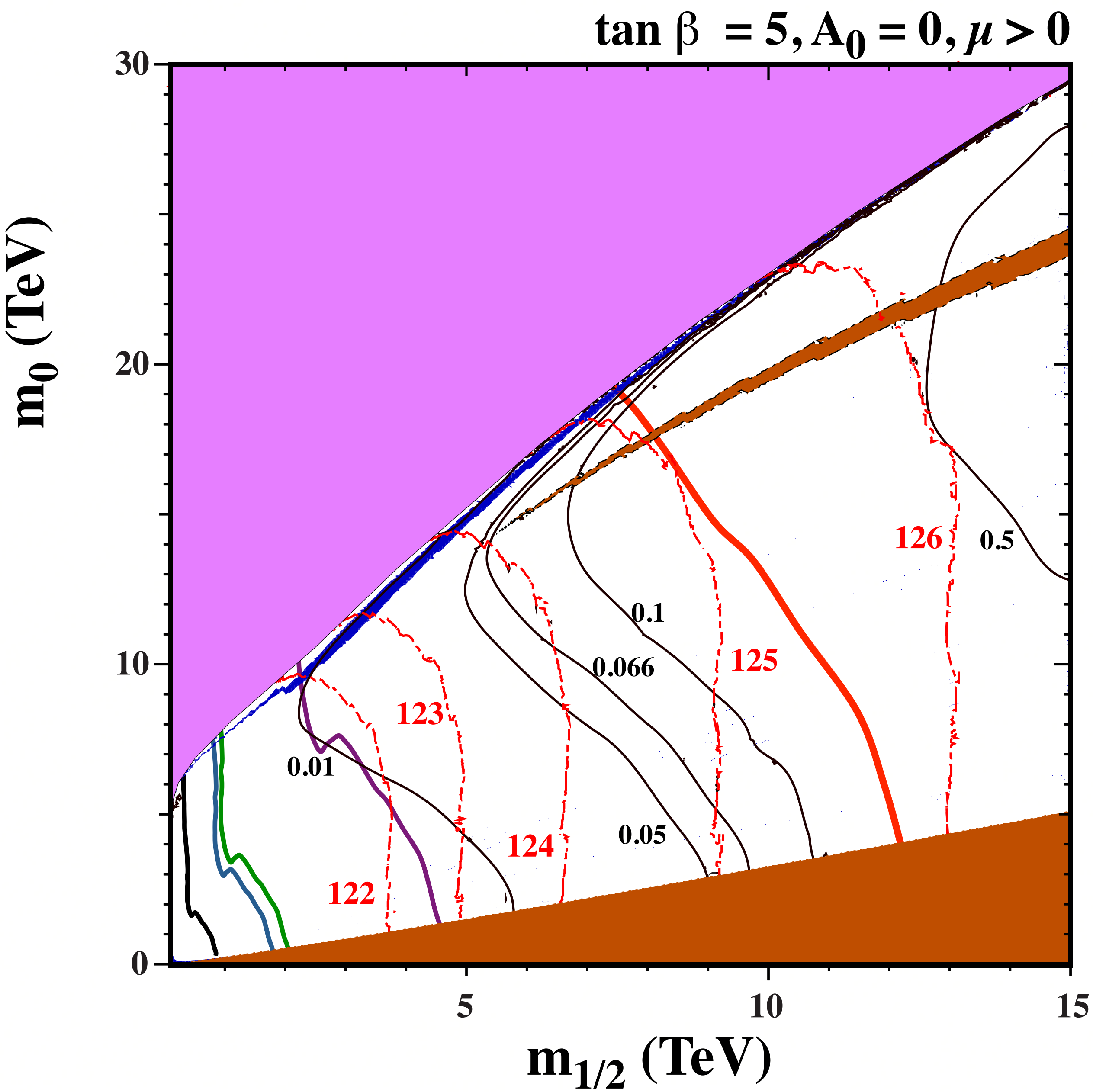


Ellis, Evans, Mustafayev, Nagata, Olive

The Strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Funnel
  - associated with high tan β, problems with $B \to \mu\mu$
- Focus Point

Focus Point



100 TeV 3000 fb^{-1}
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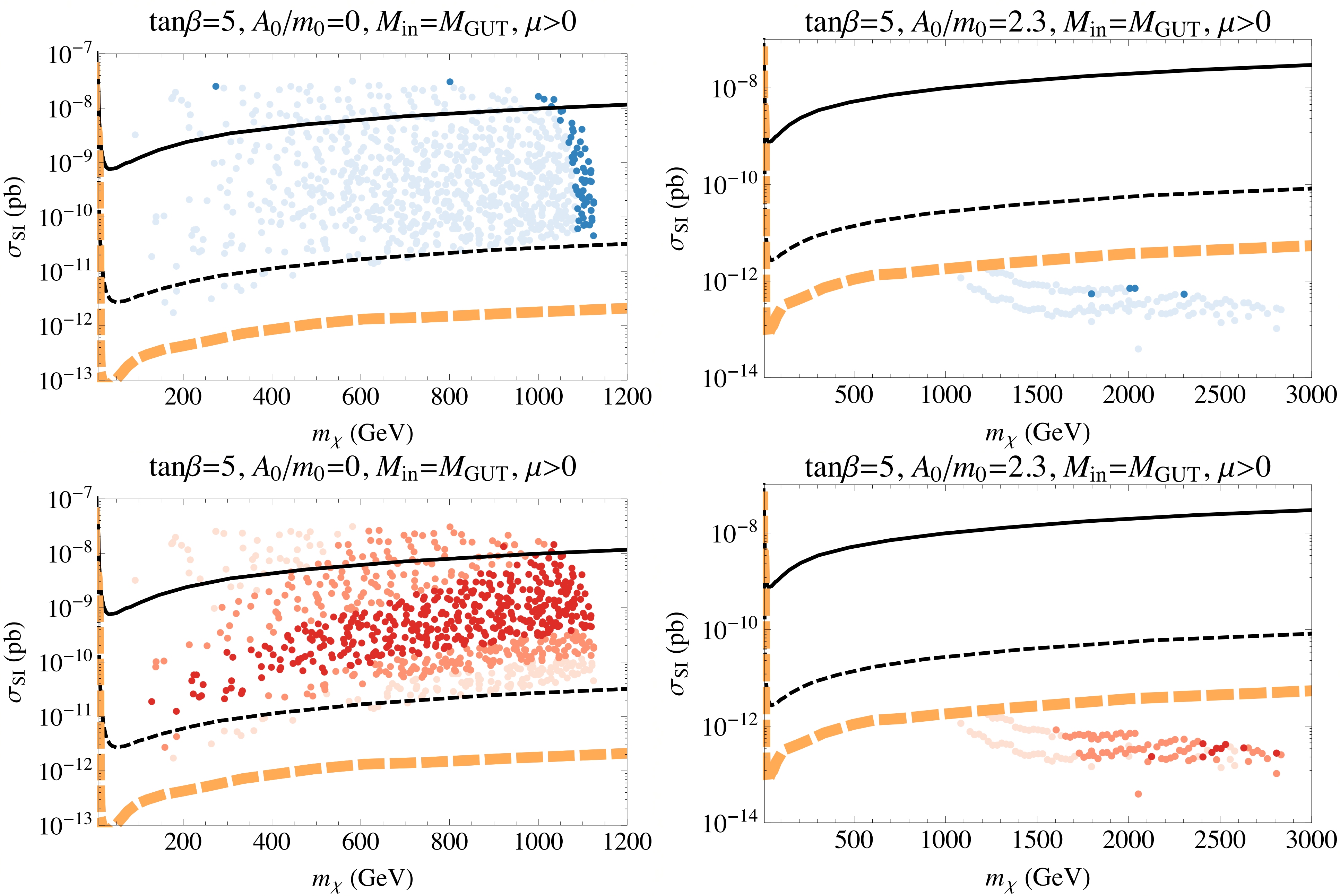
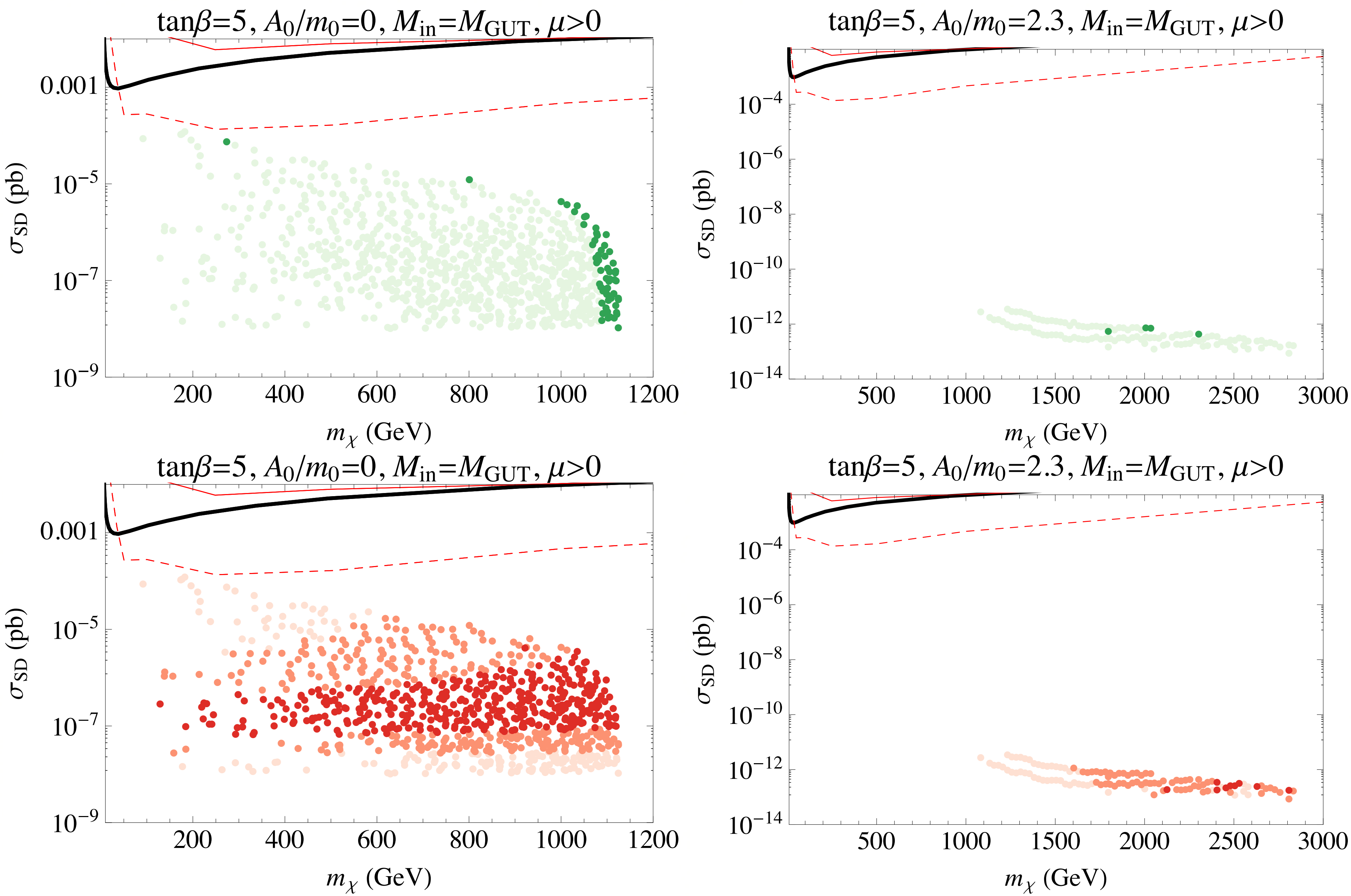
Ellis, Evans, Mustafayev, Nagata, Olive

Direct detectability



Ellis,Evans, Nagata, Olive, Sandick, Zheng

Direct detectability



Ellis,Evans, Nagata, Olive, Sandick, Zheng

Other Possibilities

- Pure Gravity Mediation (PGM) (2+ parameters)

Parameters: $m_{3/2}$, $\tan\beta$, $\mathrm{sgn}(\mu)$

- Anomaly mediation: mAMSB (3+ parameters)

Parameters: $m_{3/2}$, m_0, $\tan\beta$, $\mathrm{sgn}(\mu)$

Pure Gravity Mediation

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

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

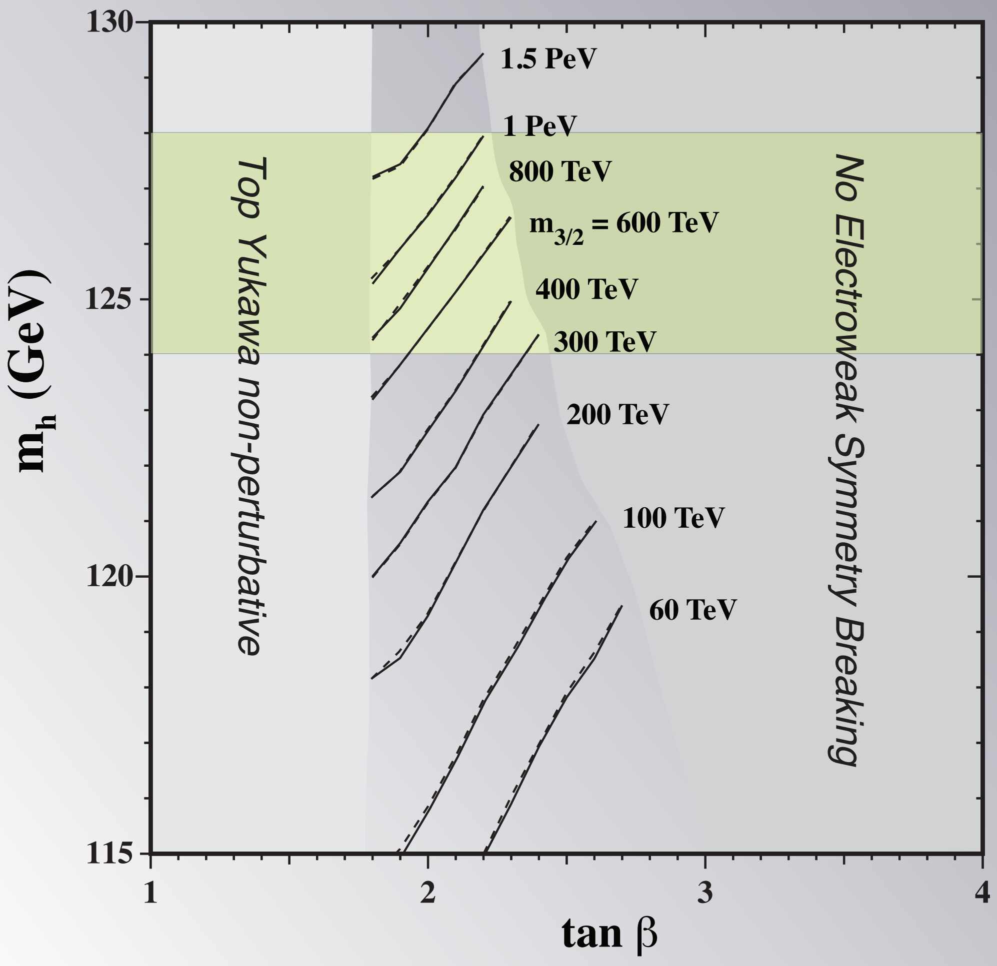
$$
\begin{aligned}
M_1 &= \frac{33}{5}\frac{g_1^2}{16\pi^2} m_{3/2} \,, \\
M_2 &= \frac{g_2^2}{16\pi^2} m_{3/2} \,, \\
M_3 &= -3\frac{g_3^2}{16\pi^2} m_{3/2} \,.
\end{aligned}
$$

- ⇒ Push towards very large masses

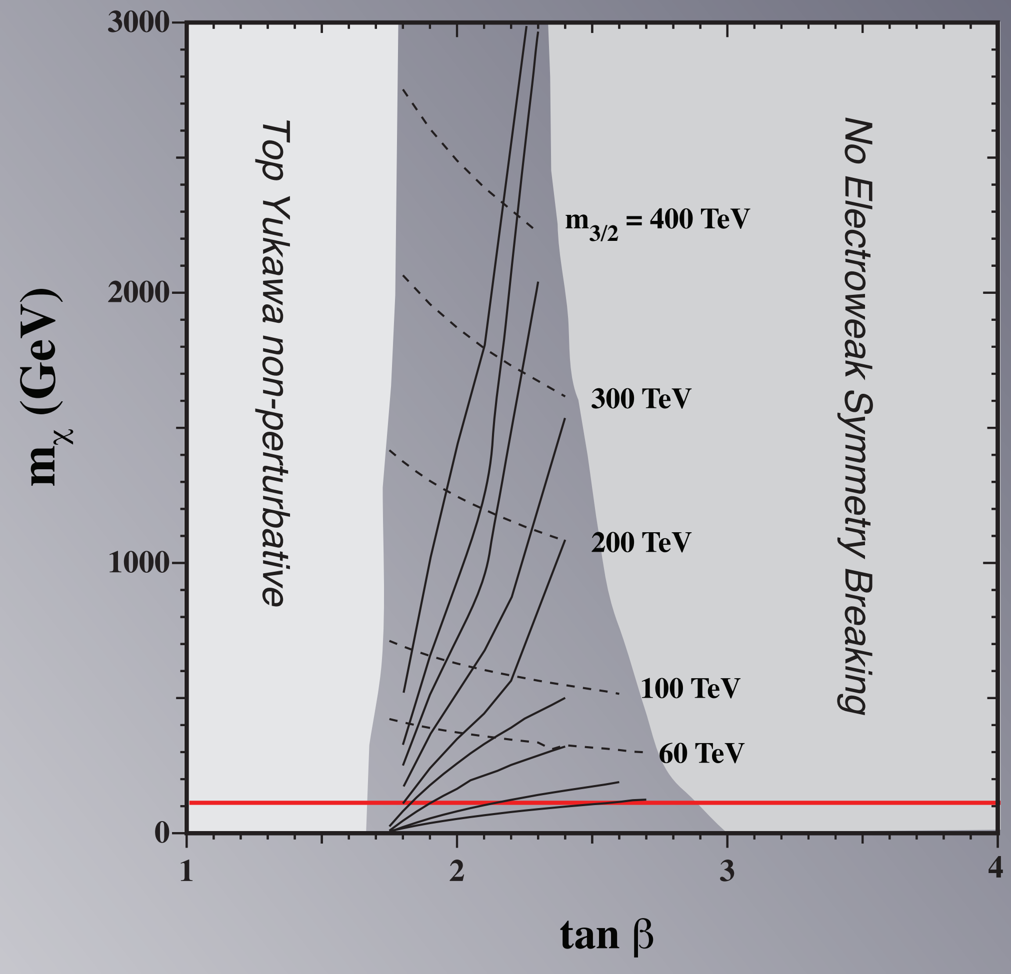
Evans,Ibe,Olive,Yanagida

Phenomenological Aspects

Higgs Mass

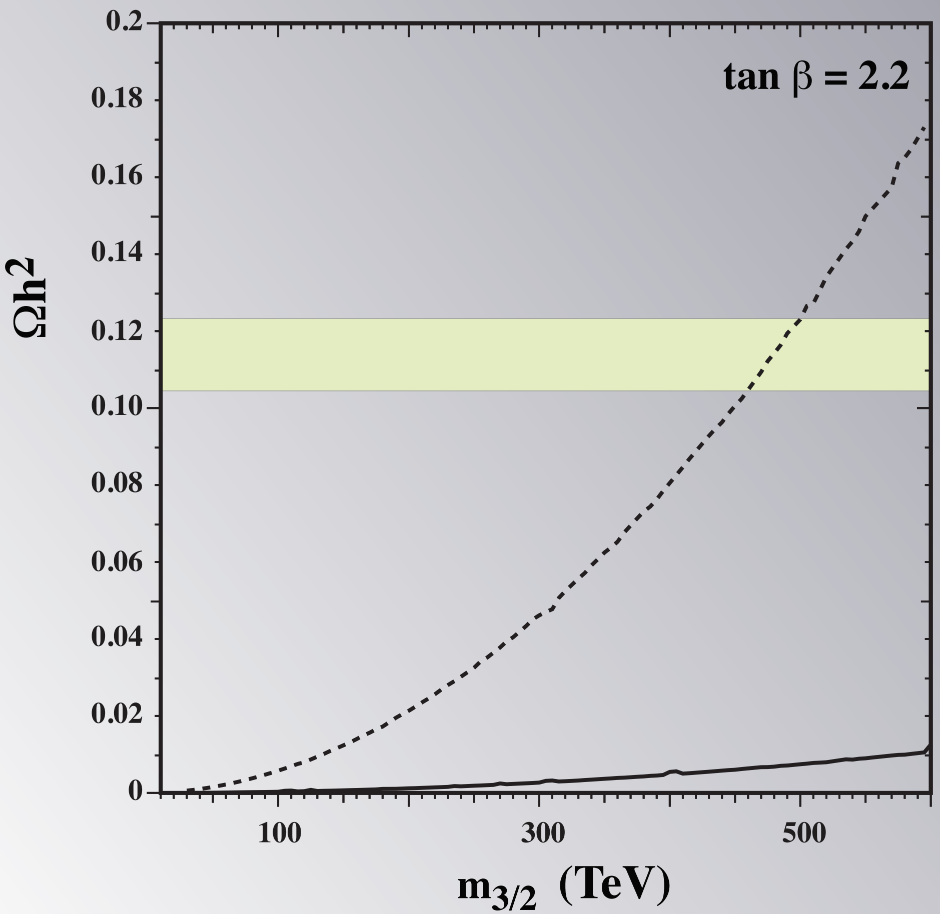


Neutralino mass



Evans, Ibe, Olive, Yanagida

Dark Matter:
LSP is a wino



Potential problem for wino dark matter from Fermi/HESS

(Fan + Reese;
Cohen, Lianti, Pierce, Slatyer)

PGM with small μ
Higgsino DM

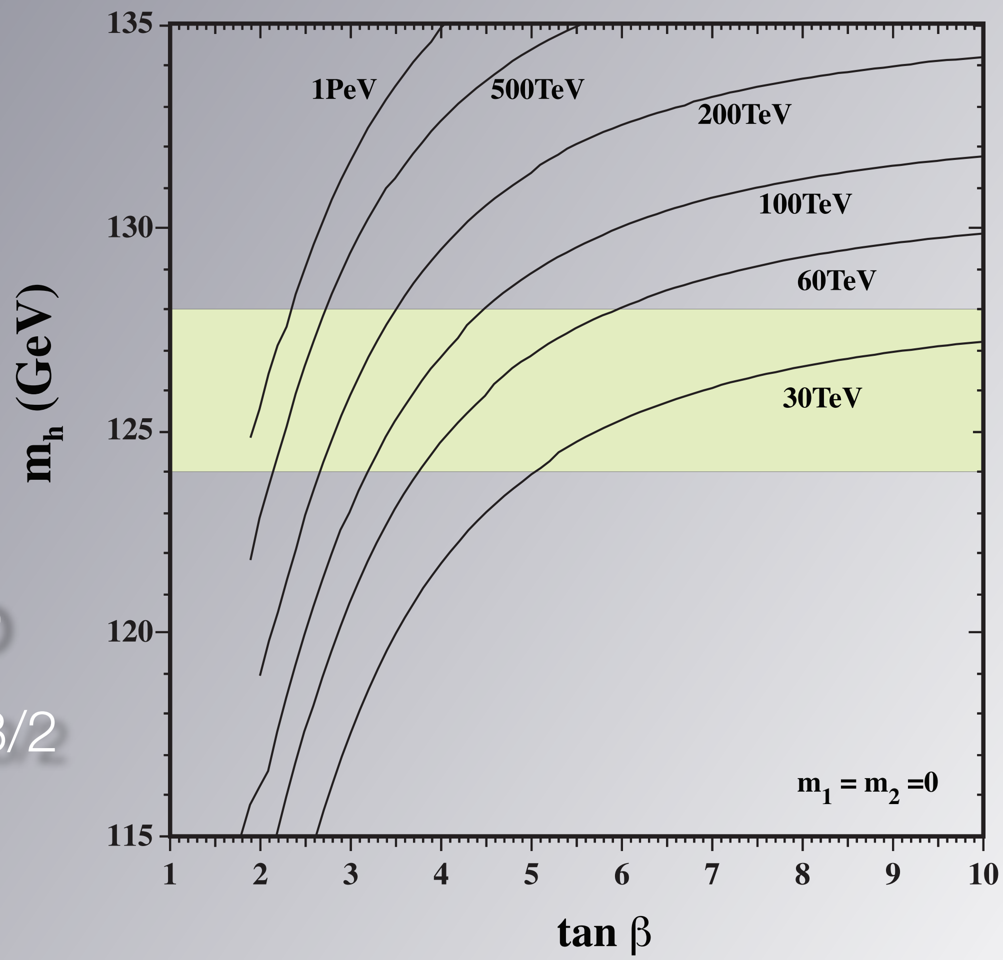
NUHM1-like model; use EWSB conditions to determine $m_1 = m_2 \neq m_{3/2}$

μ, $\tan\beta$, $m_{3/2}$ free;

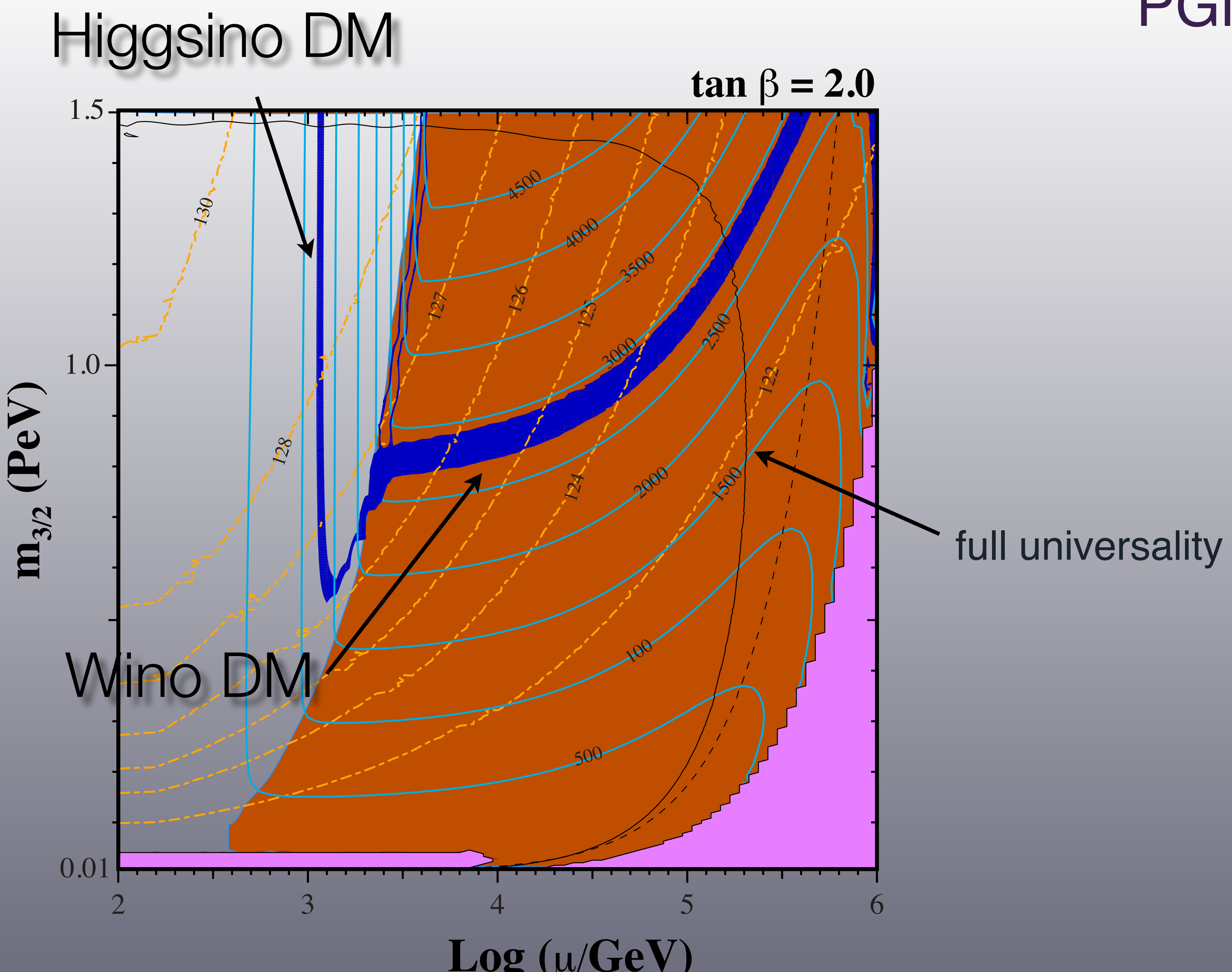
Somewhat more freedom with non-universal Higgs masses

Can also choose
μ, $\tan\beta$, $m_{3/2}$ free;

NUHM1-like model;
use EWSB conditions to determine $m_1 = m_2 \neq m_{3/2}$ and c_H (GM term)



Evans, Ibe, Olive, Yanagida



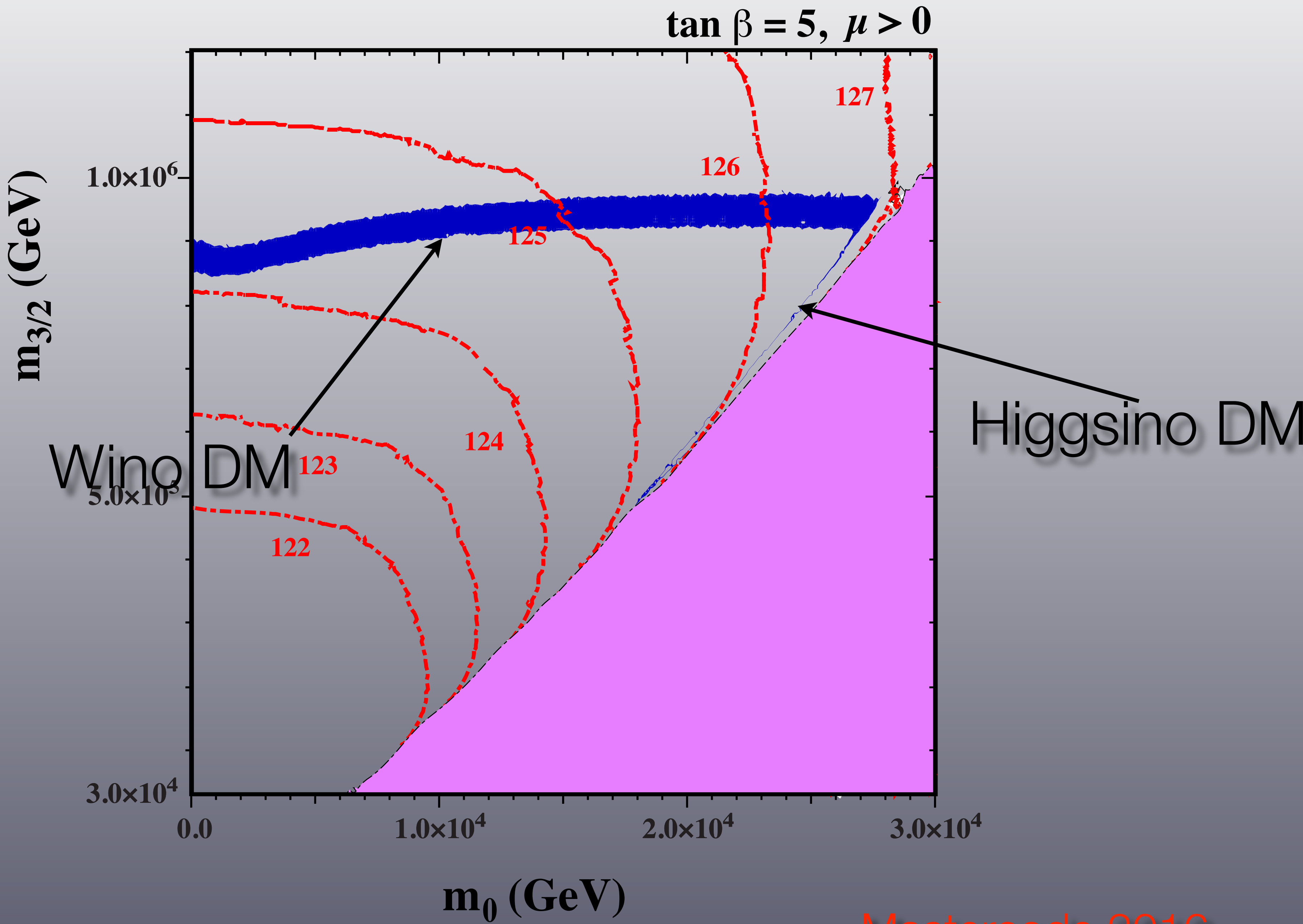
Evans, Ibe, Olive, Yanagida

mAMSB

Similar to PGM, but allow $m_0 \neq m_{3/2}$

m_0, $\tan\beta$, $m_{3/2}$ free;

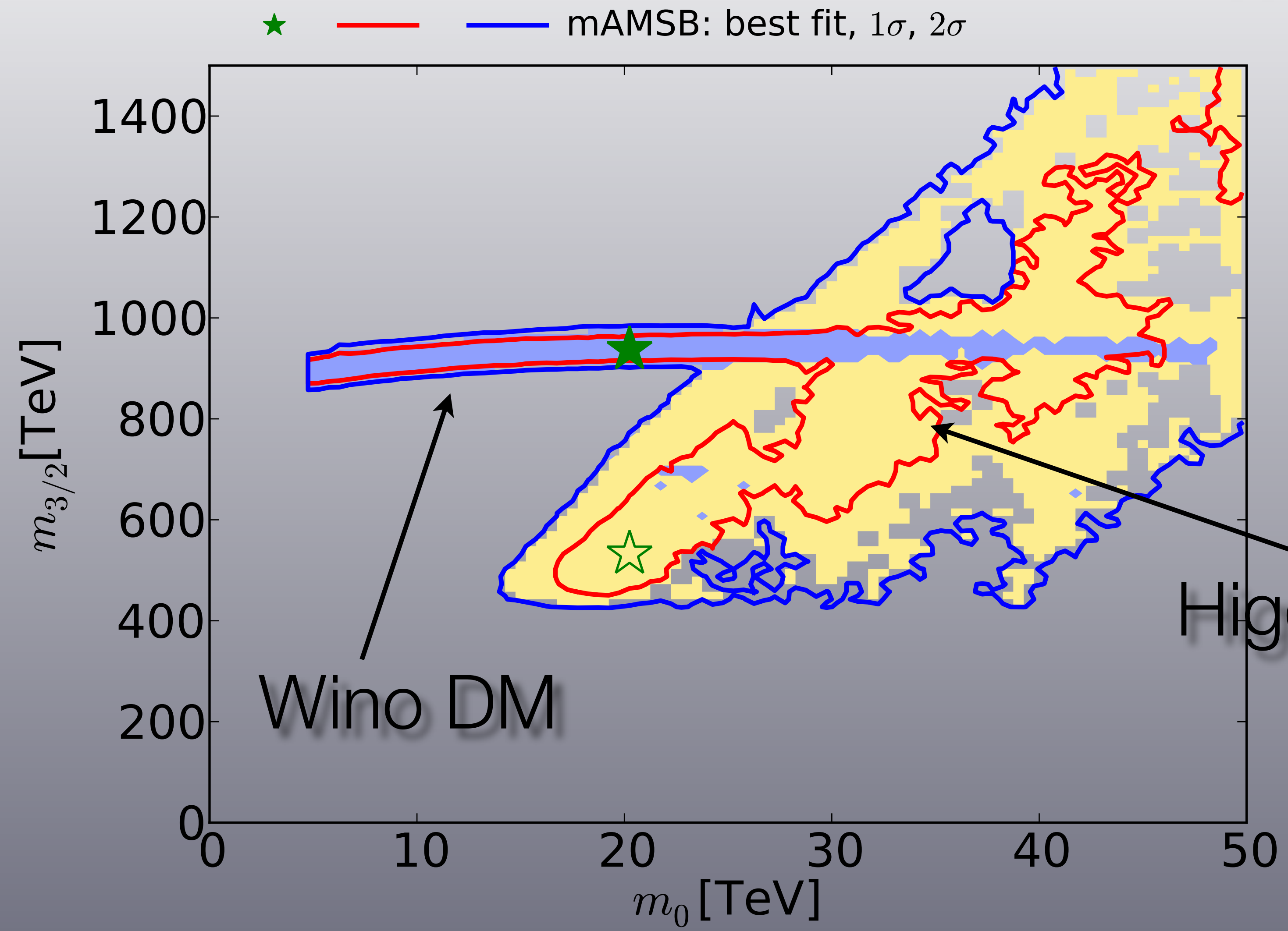
mAMSB



Mastercode 2016

mAMSB

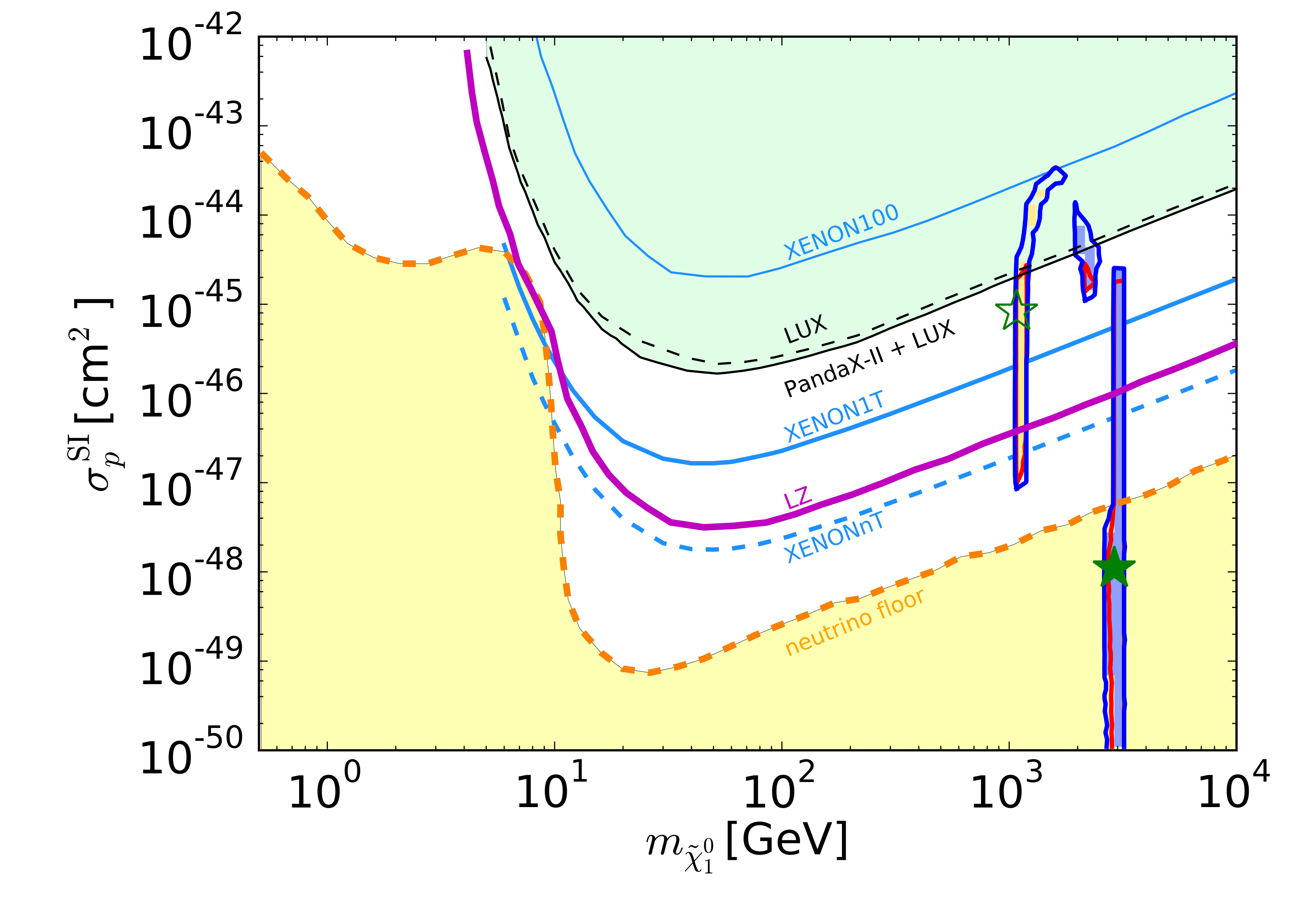
Mastercode 2016



Preliminary

Bagnaschi, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Luo, Martinez Santos, Olive, Riochards,Sakurai, Weiglein

Preliminary Mastercode 2016 mAMSB



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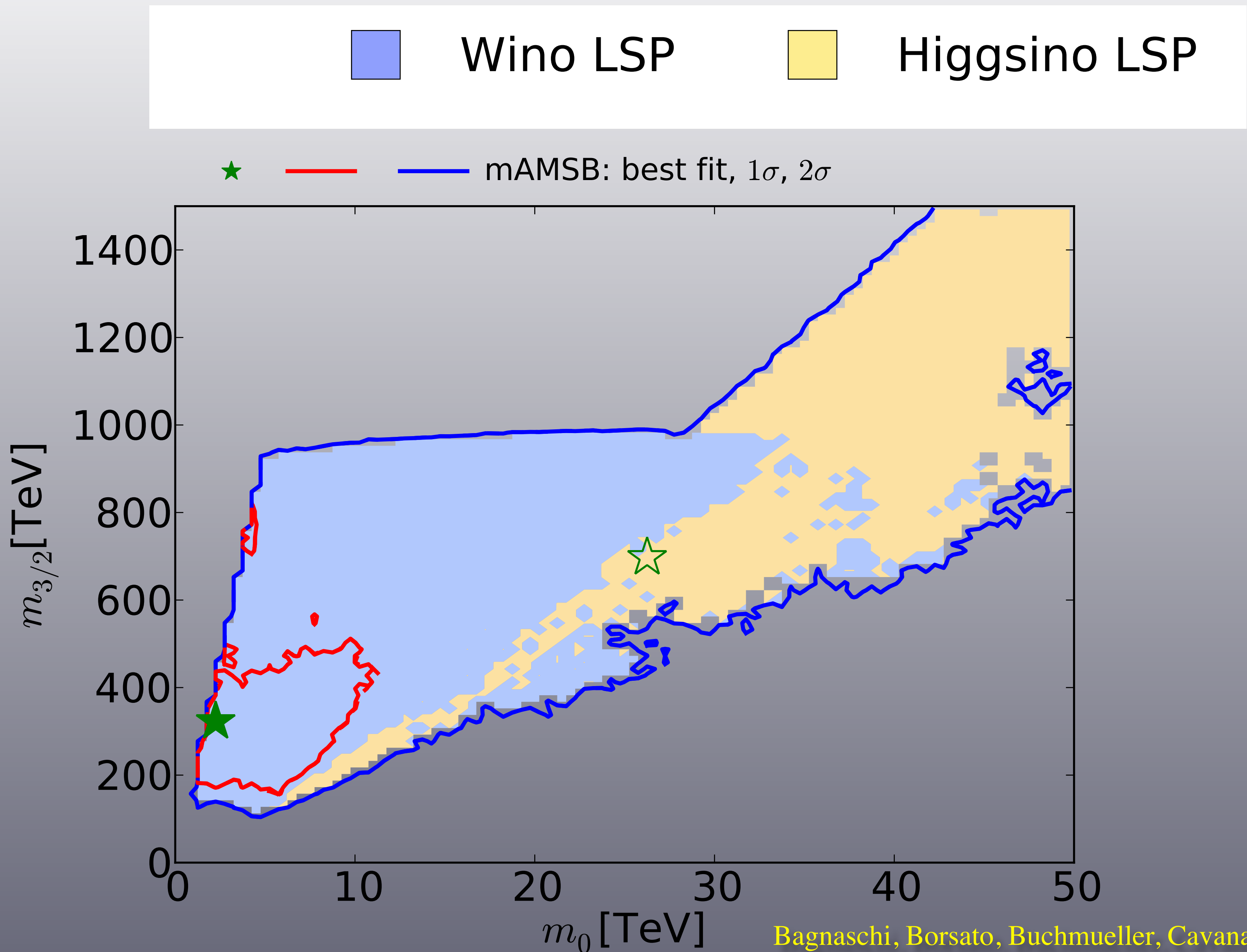

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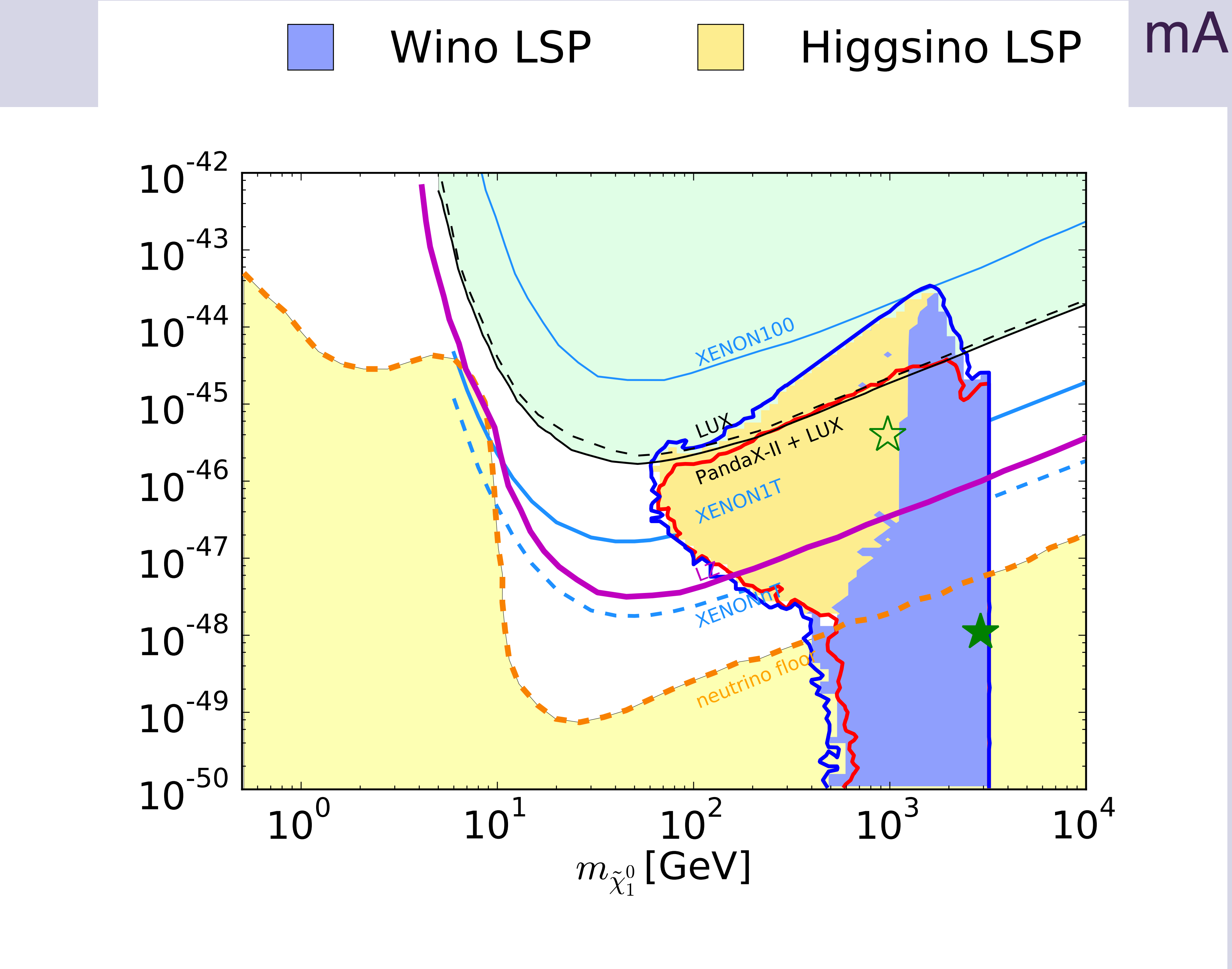

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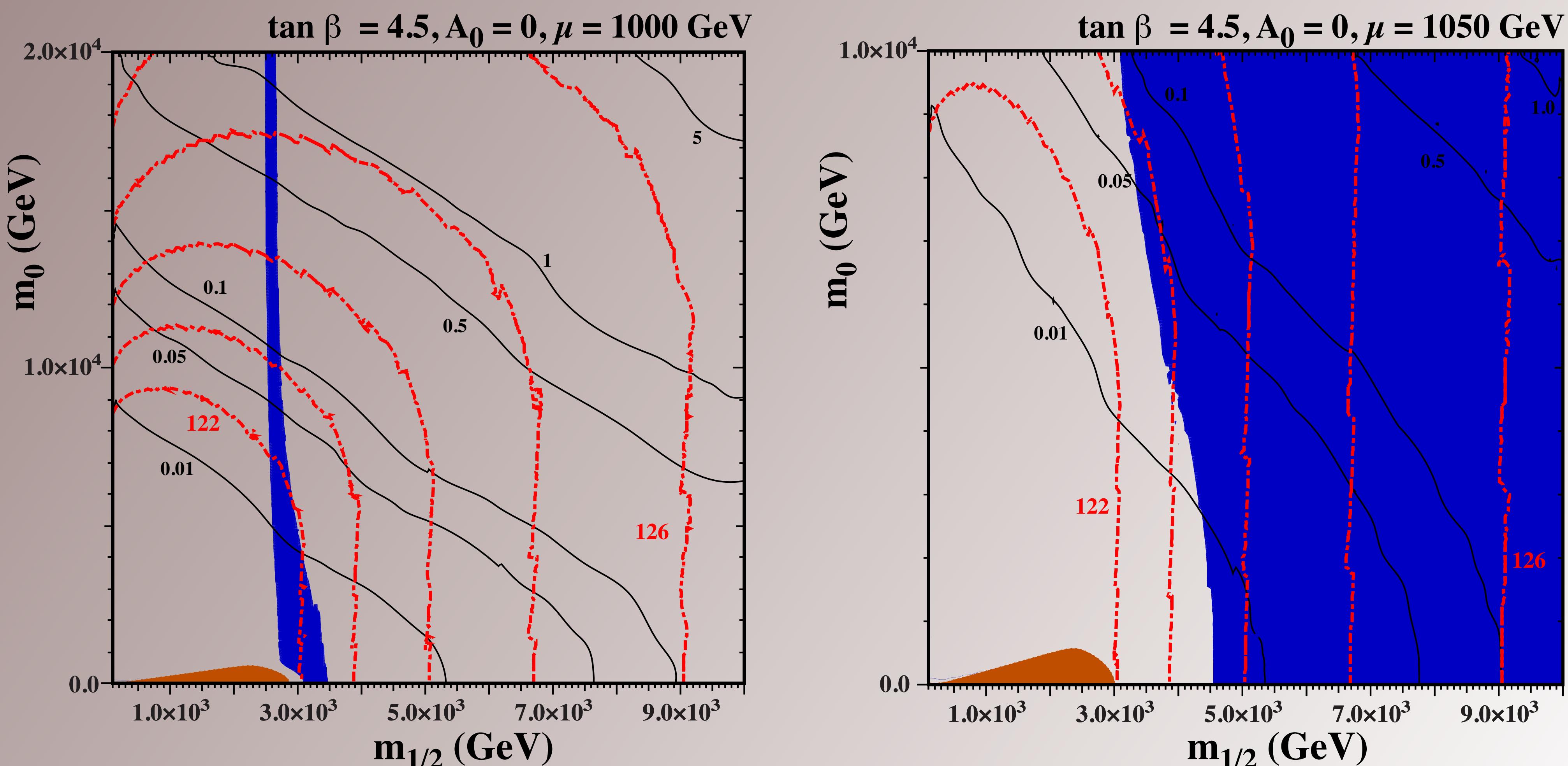
Other Possibilities

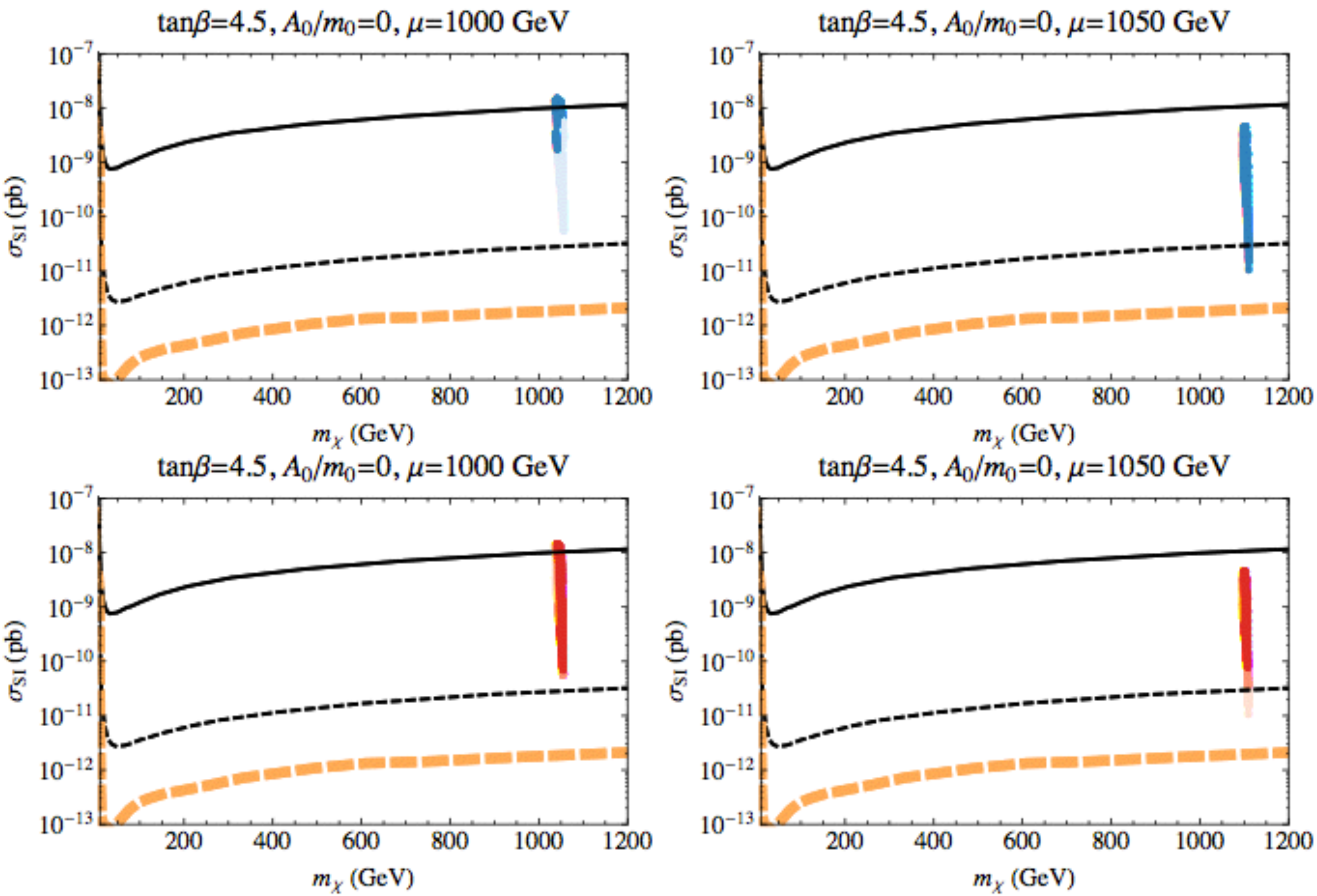
- NUHM1,2: $m_1^2 = m_2^2 \neq m_0^2$, $m_1^2 \neq m_2^2 \neq m_0^2$
  - μ and/or m_A free

NUHM1 models with μ free ($m_1 = m_2$)



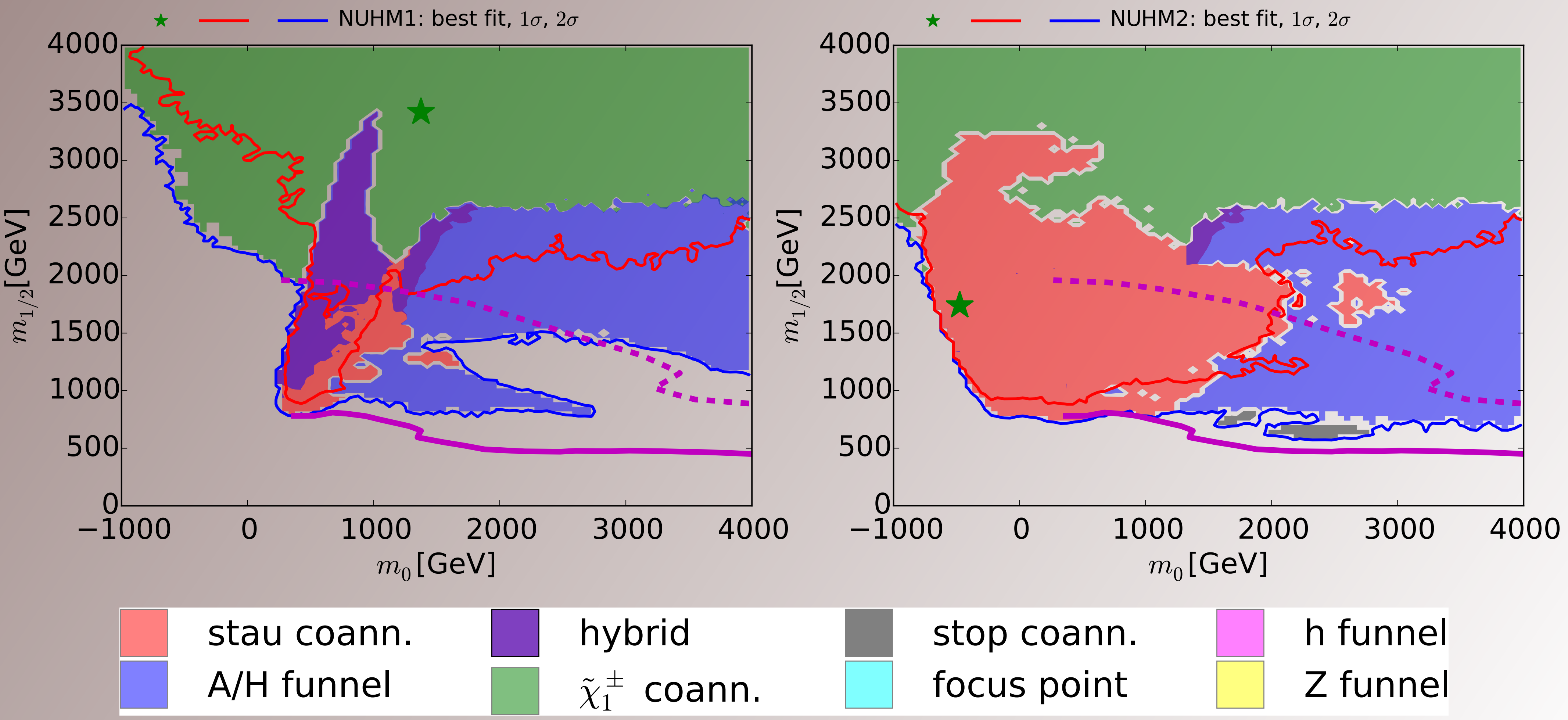
Ellis, Luo, Olive, Sandick;
Ellis, Evans, Luo, Nagata, Olive, Sandick

Direct detectability



Ellis,Evans, Nagata, Olive, Sandick, Zheng

NUHM1/NUHM2 mastercode results (2015)



Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck,
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Martinez Santos, Olive, Sakurai, de Vries, Weiglein

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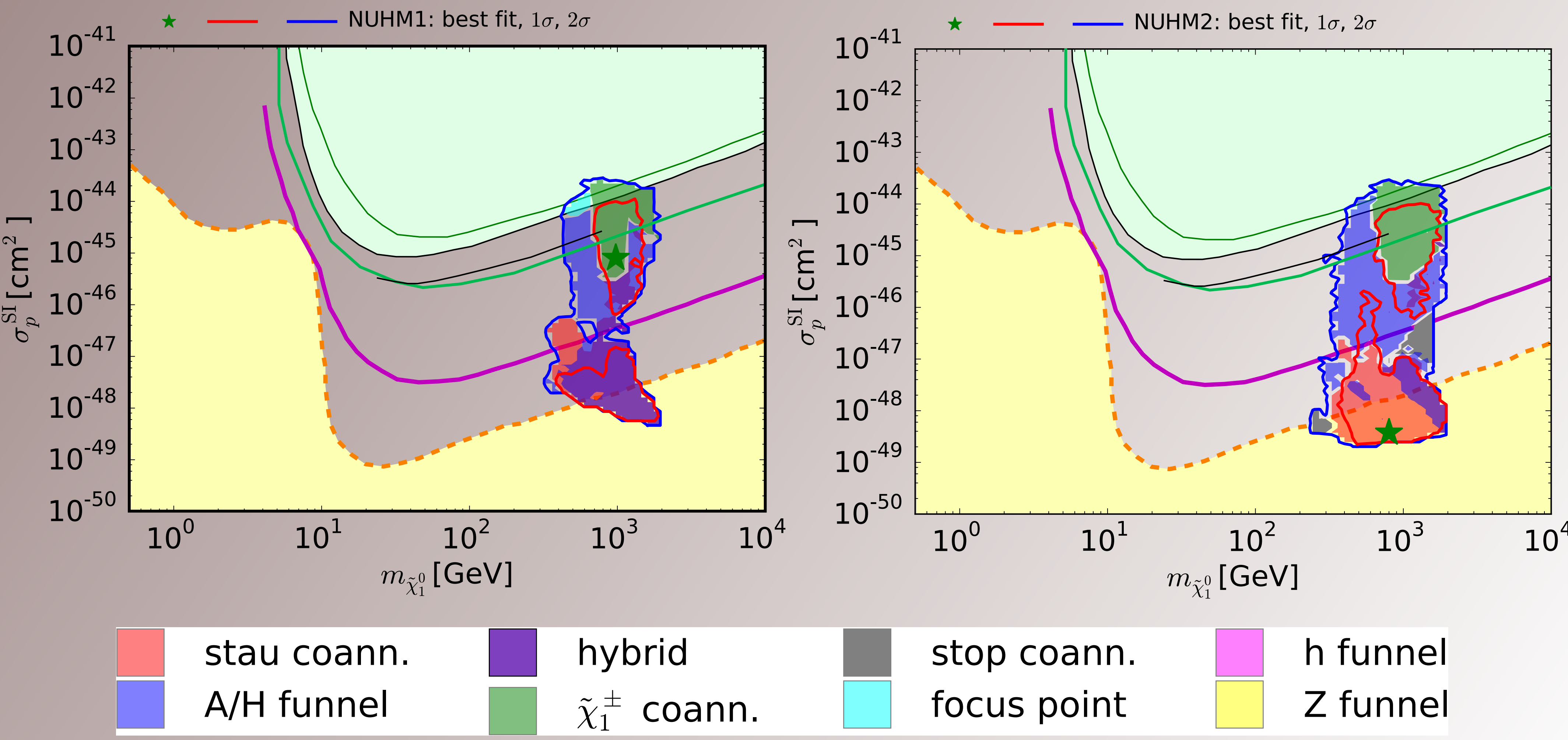

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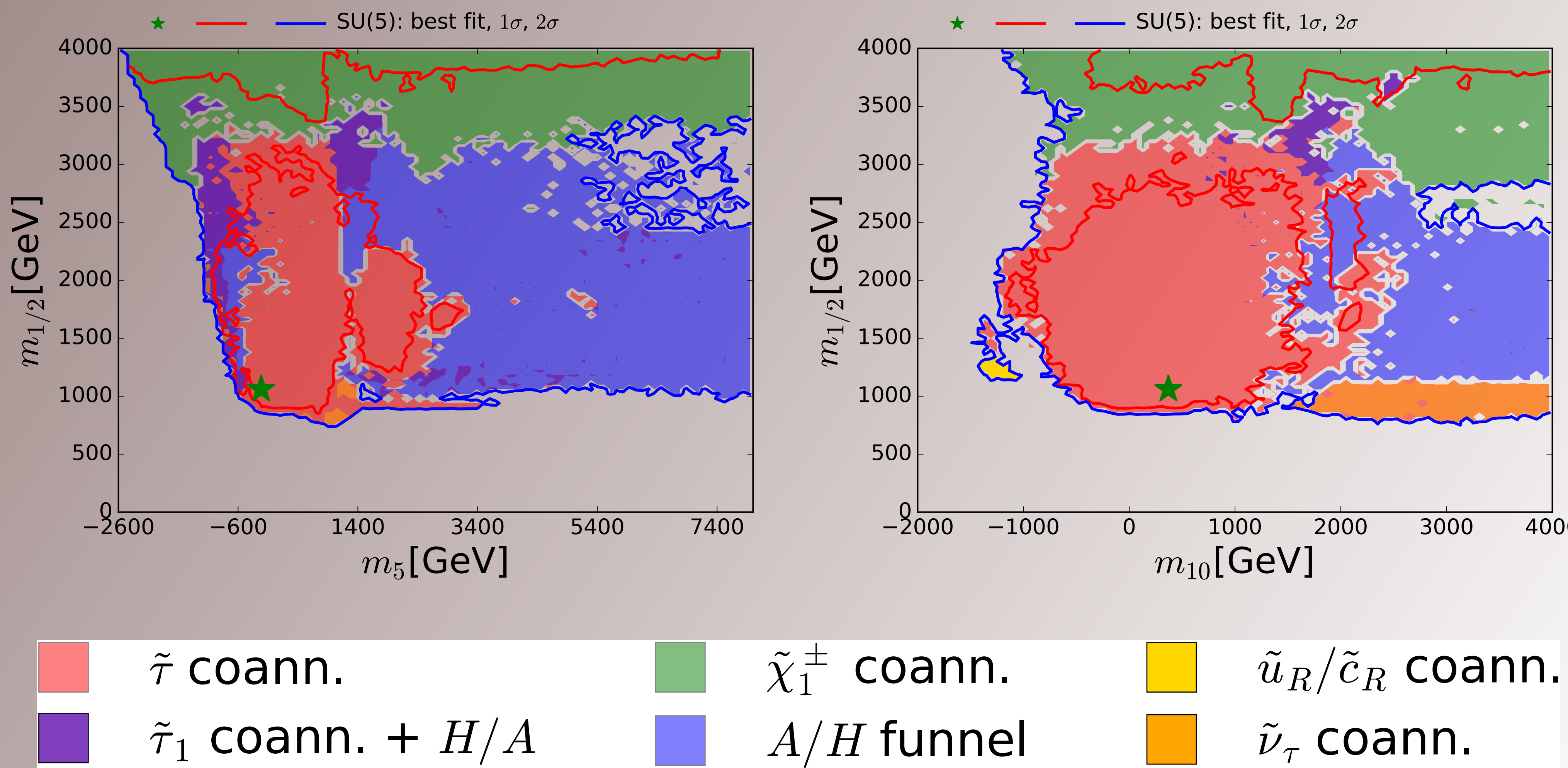
- **SU(5) models (7+ parameters)**

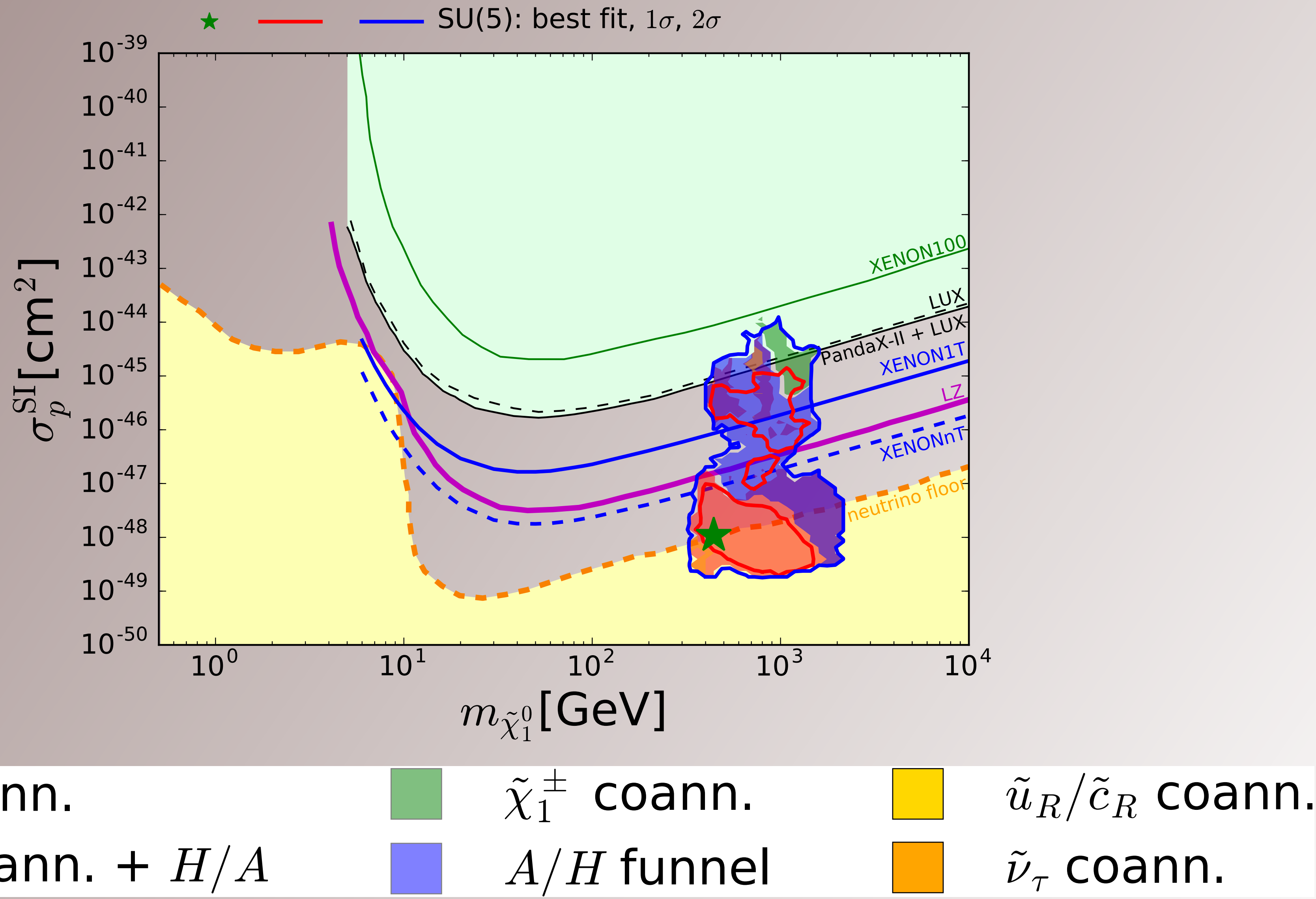
Parameters: $m_{1/2}$, m_5, m_{10}, m_1, m_2, A_0, tan β, sgn(μ) {$m_{3/2}$}

SU(5) mastercode results (2016)



Bagnaschi, Costa, Sakurai, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Martinez Santos, Olive, Riochards, de Vreis, Weiglein

SU(5) mastercode results (2016)



Bagnaschi, Costa, Sakurai, Borsato, Buchmueller, Cavanaugh, Chobanova, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Lucio, Martinez Santos, Olive, Riochards, de Vreis, Weiglein

Summary

- SUSY Dark Matter ALIVE and well (?)
- CMSSM generally confined to strips in parameter space: stop strips below neutrino background; focus point fully detectable
- Higgsino Dark Matter quite generic in the focus point; NUHM1,2, and parts of mAMSB with m~1 TeV.
- extended models offer wider range of possibilities

Need to Discover DM!