Dark Matter after LHC Run I: Clues to Unification

1) After the results of Run I, can we still ‘guarantee’ Supersymmetry’s discovery at the LHC? Viable dark matter models in CMSSM-like tend to lie in strips (co-annihilation, funnel, focus point), how far up in energy do these strips extend?

2)Can we use Grand Unification to guide our SUSY searches?

3) Can Non-Supersymmetric GUTs such as SO(10) provide answers?

Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem

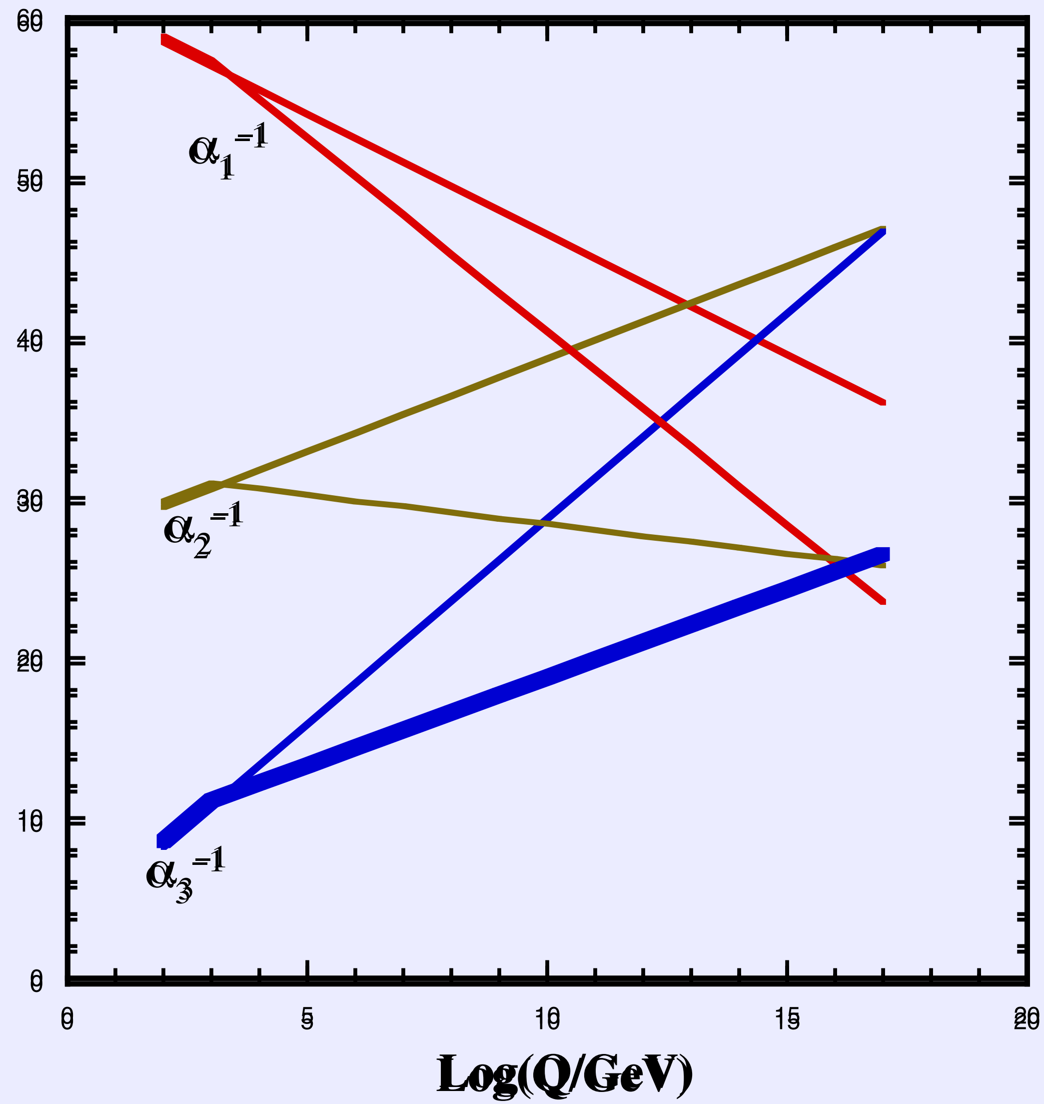
GUTS

Supersymmetric SU(5) Grand Unified Theory

$$b_i = \begin{pmatrix} 41/10 \\ -19/6 \\ -7 \end{pmatrix}$$

$$b_i = \begin{pmatrix} 33/5 \\ 1 \\ -3 \end{pmatrix}$$

is now / is really:



Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem

Among the Consequences:
R-parity conservation (to protect proton stability)
A stable Dark Matter candidate

Grand Unification as a guide

Among the motivations for SUSY:
Gauge coupling Unification
Gauge Hierarchy Problem

Boundary conditions set at renormalization scale given by gauge coupling Unification

- Common gaugino mass: $m_{1/2}$
- Common scalar mass: m_0 (= $m_{3/2}$ in mSUGRA)
- Common Trilinear mass: A_0
- Bilinear mass: B_0 (= A_0 - m_0 in mSUGRA)

Source of Supersymmetry breaking

Gravity mediation: mSUGRA/ CMSSM

$m_{1/2}$, m_0, A_0 / tan β

"Pure Gravity Mediation" with Anomaly mediation

$m_{3/2}$, tan β

Anomaly mediation: mAMSB

$m_{3/2}$, m_0, tan β

Other Possibilities

- NUHM1,2:
  - SO(10): $m_1^2 = m_2^2 \neq m_0^2$,
  - SU(5) $m_1^2 \neq m_2^2 \neq m_0^2$
  - μ and/or m_A free
- subGUT models: $M_{in} < M_{GUT}$
  - with or without mSUGRA
- superGUT models: $M_{in} > M_{GUT}$
  - with or without mSUGRA
- Relax gaugino mass universality

Mastercode - MCMC

Long list of observables to constrain CMSSM parameter space

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

Multinest

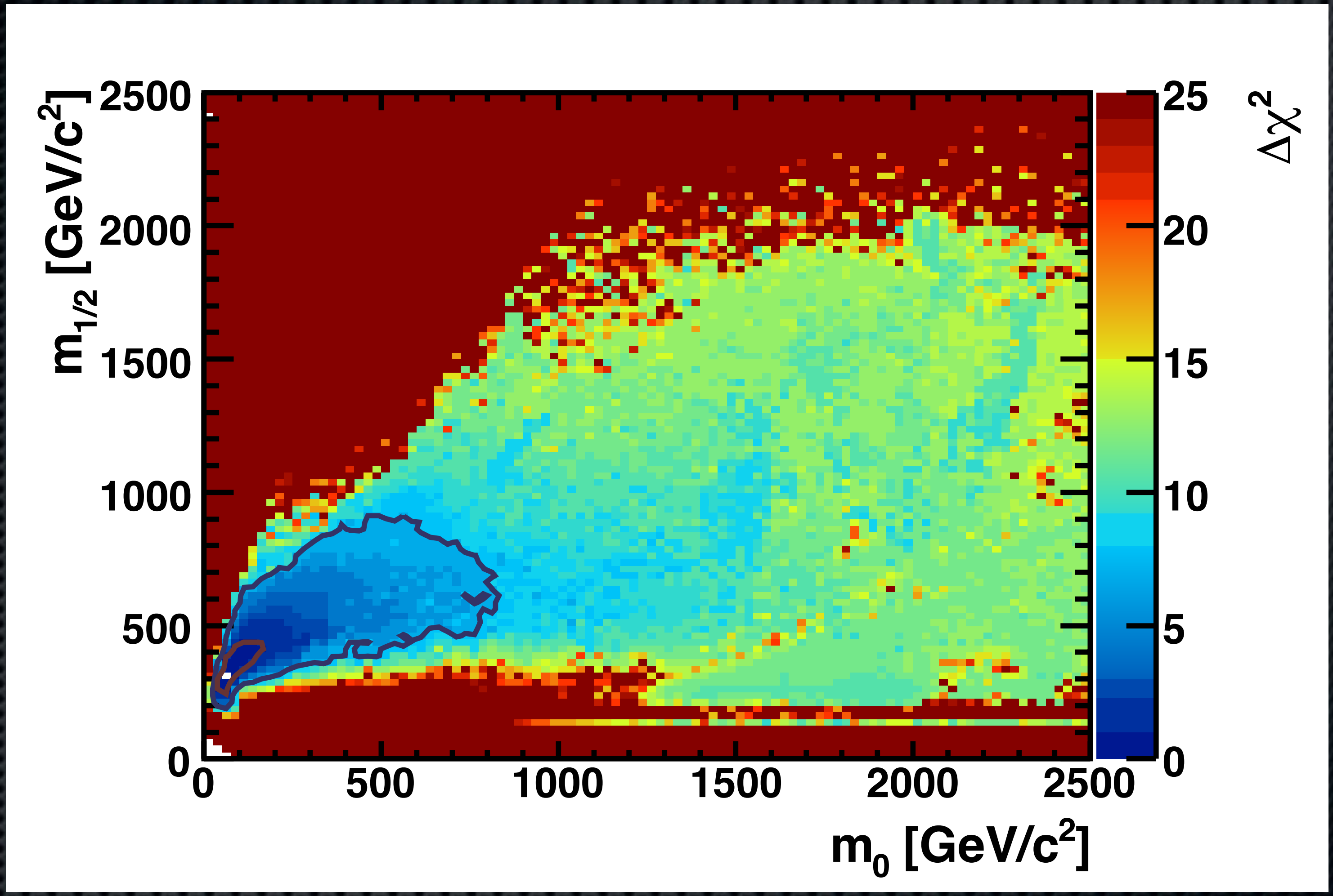
- ~~MCMC~~ technique to sample efficiently the SUSY parameter space, and thereby construct the χ^2 probability function
- Combines SoftSusy, FeynHiggs, SuperFla, SuperIso, MicrOmegas, and SSARD
- Purely frequentist approach (no priors) and relies only on the value of χ^2 at the point sampled and not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

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

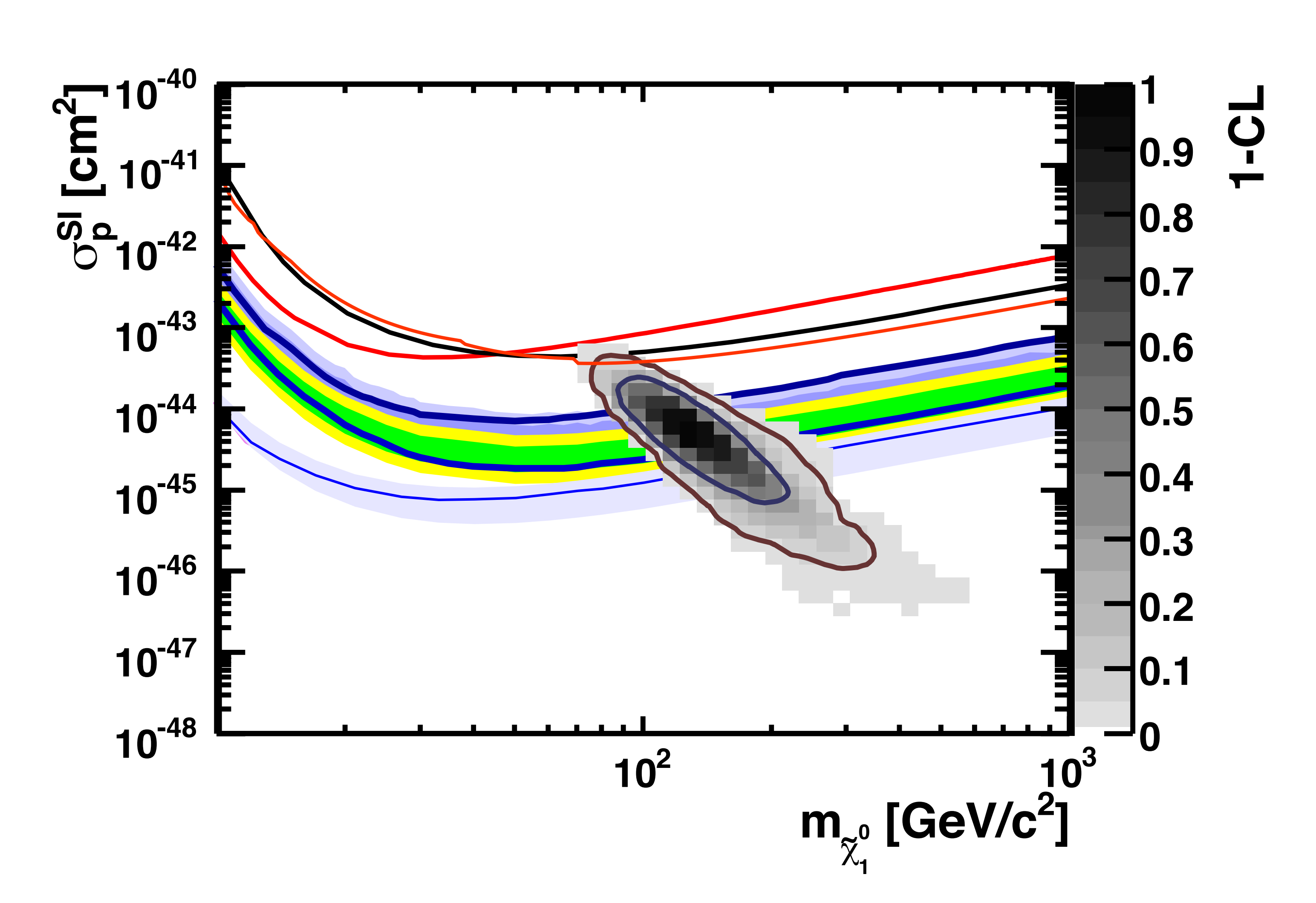


- CMSSM

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

Elastic scaterring cross-section

Mastercode
2009



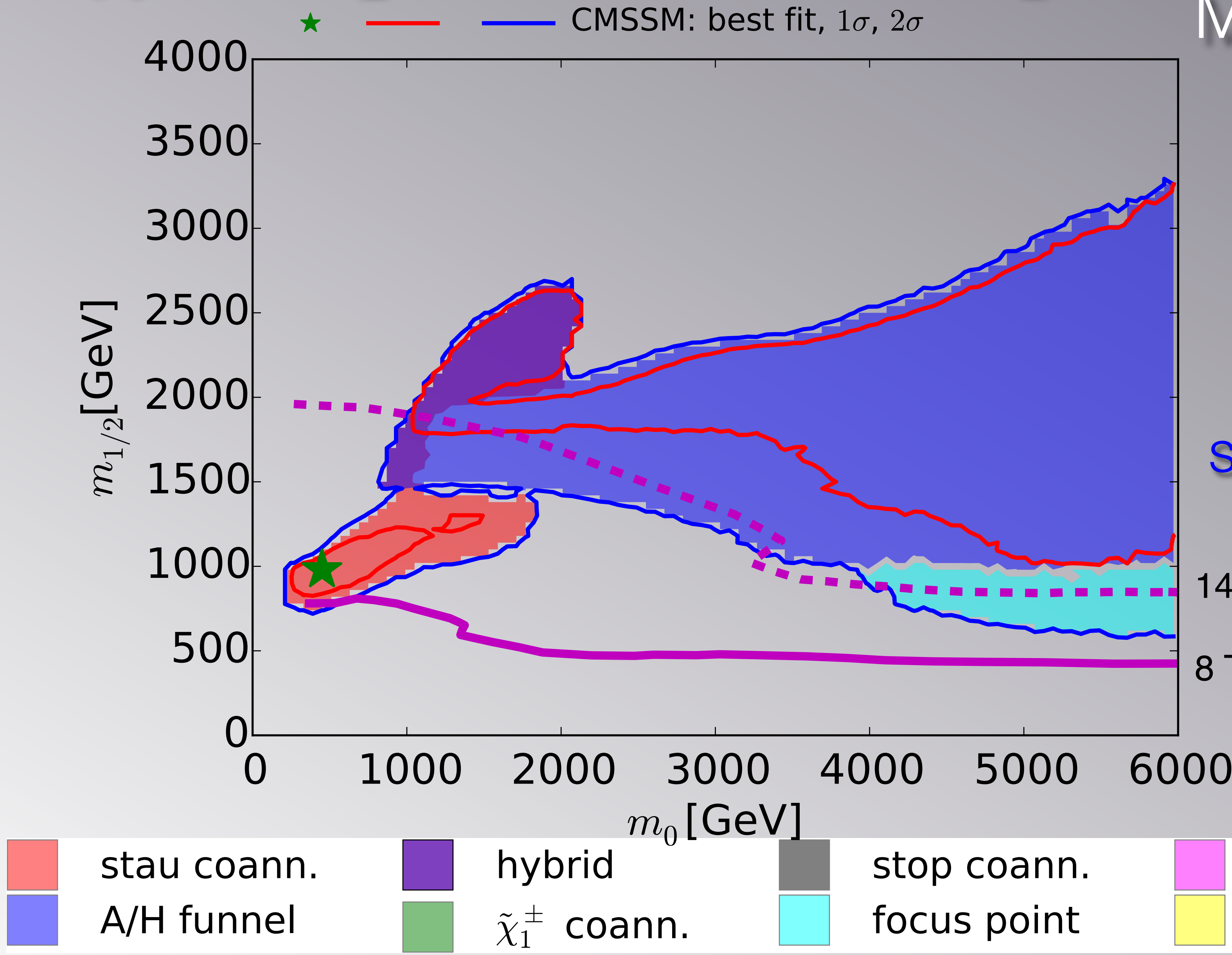
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

- CMSSM

$\Delta\chi^2$ 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

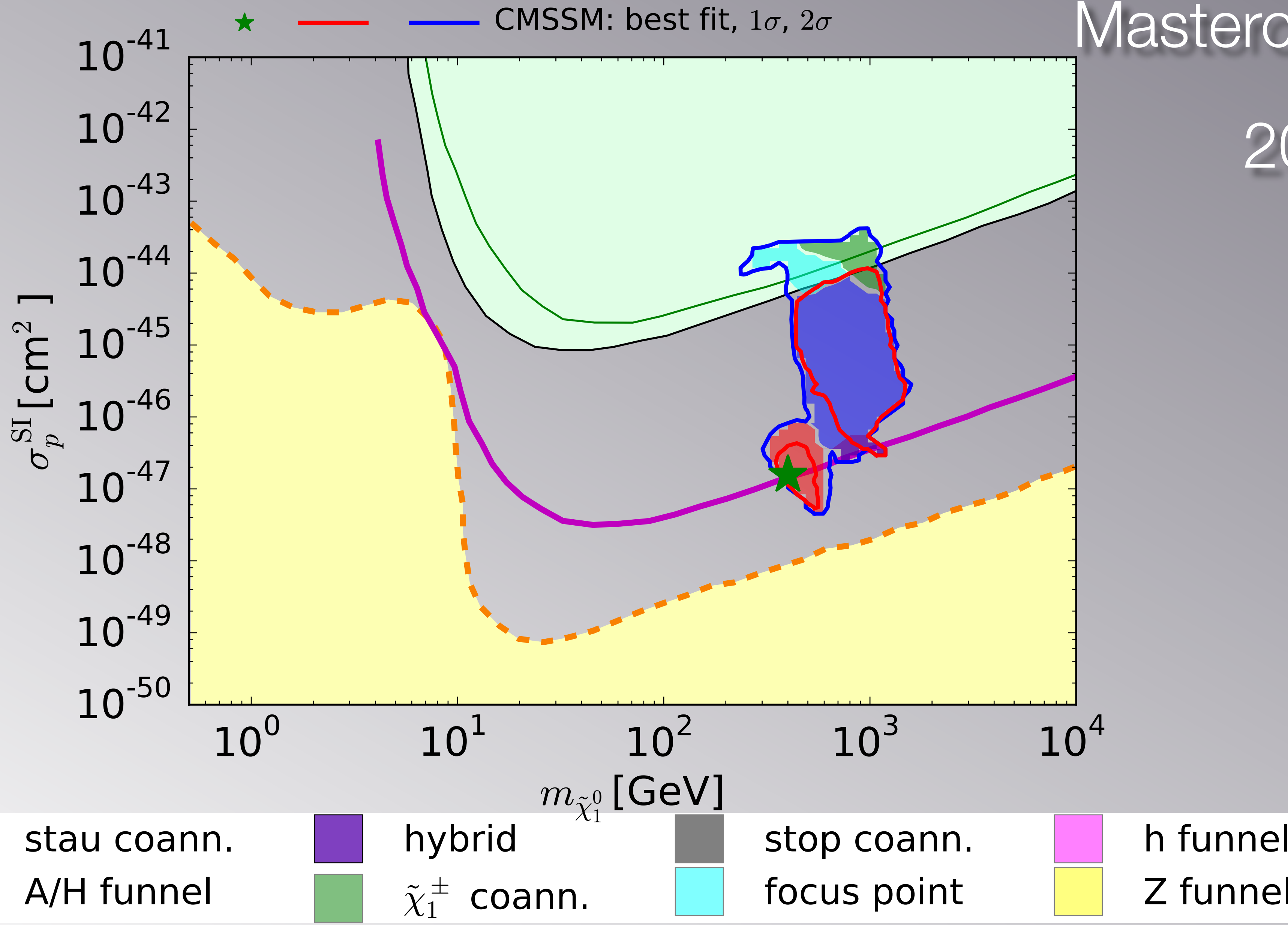
- CMSSM

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



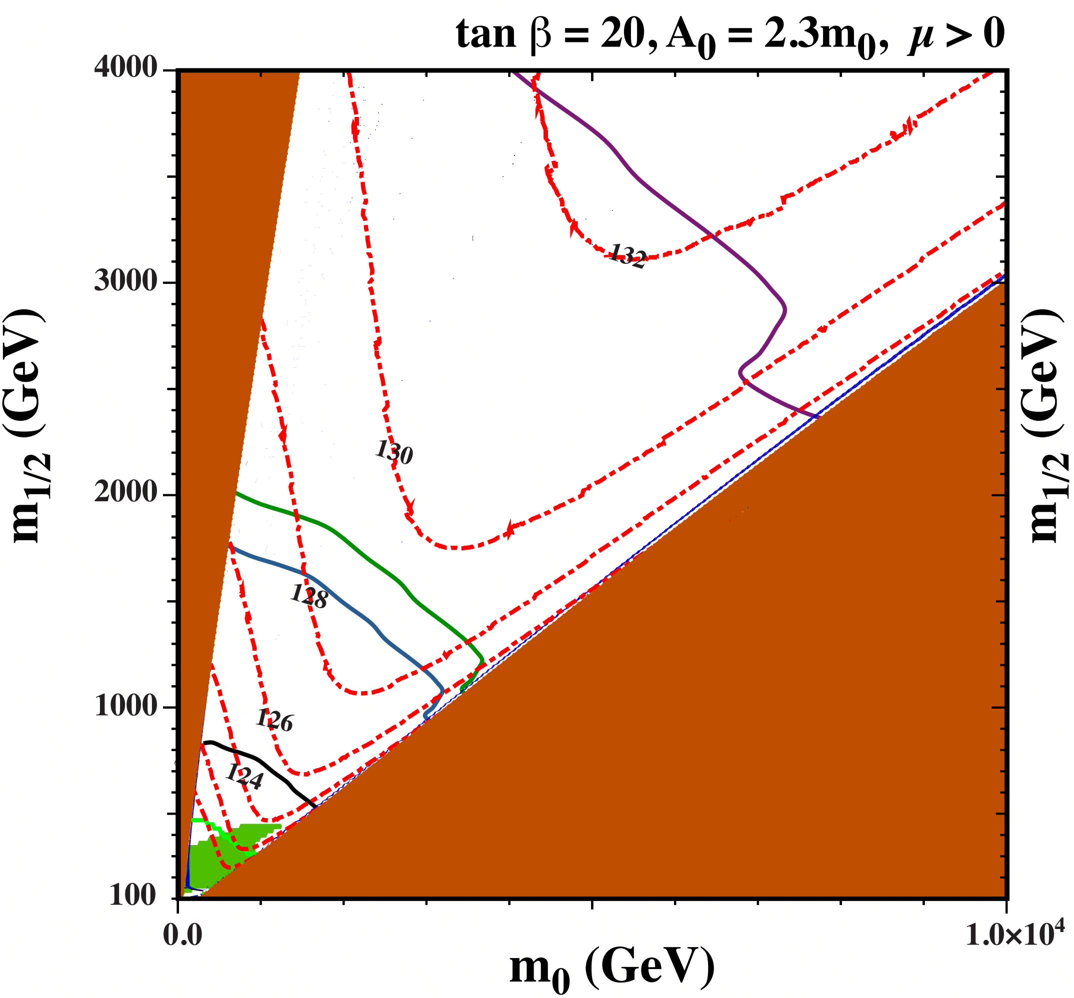
- CMSSM

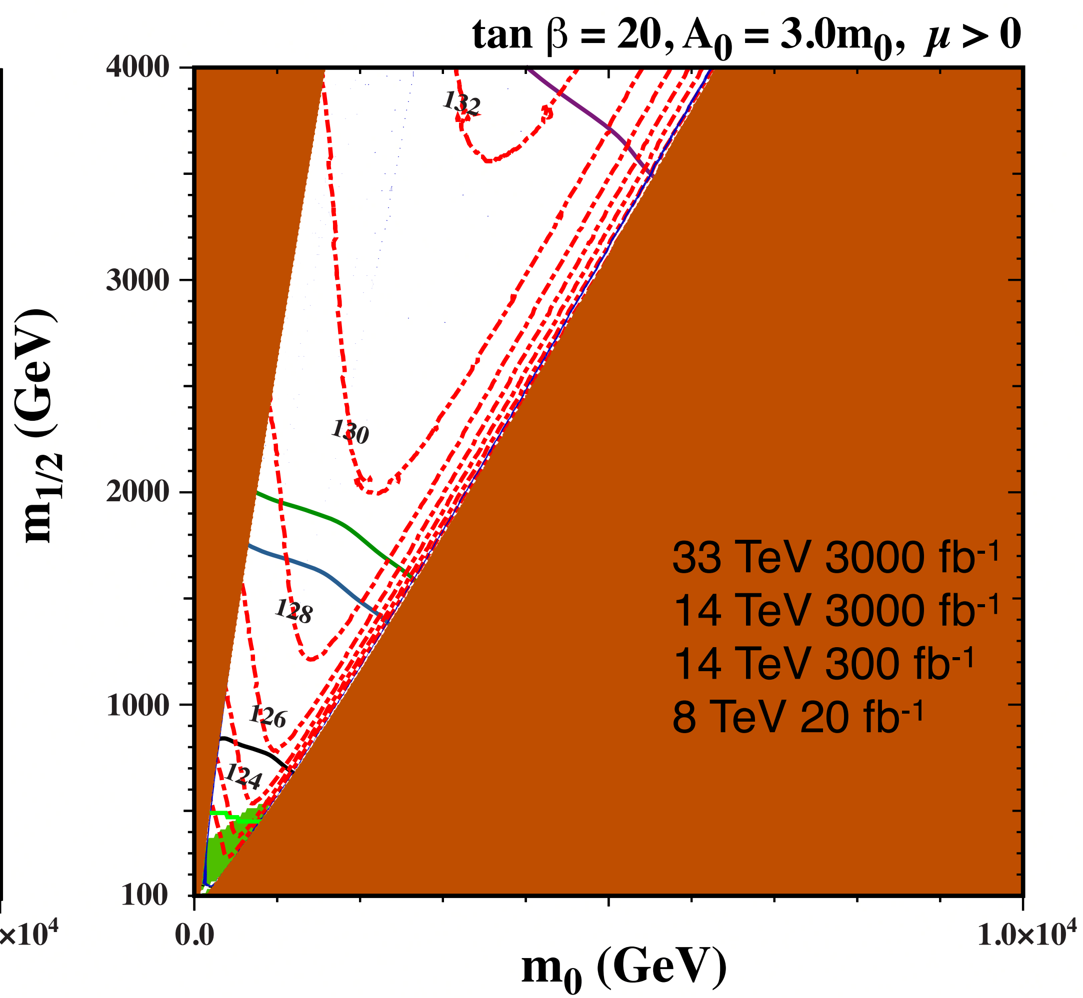
Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

The Strips:

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

Stop strip

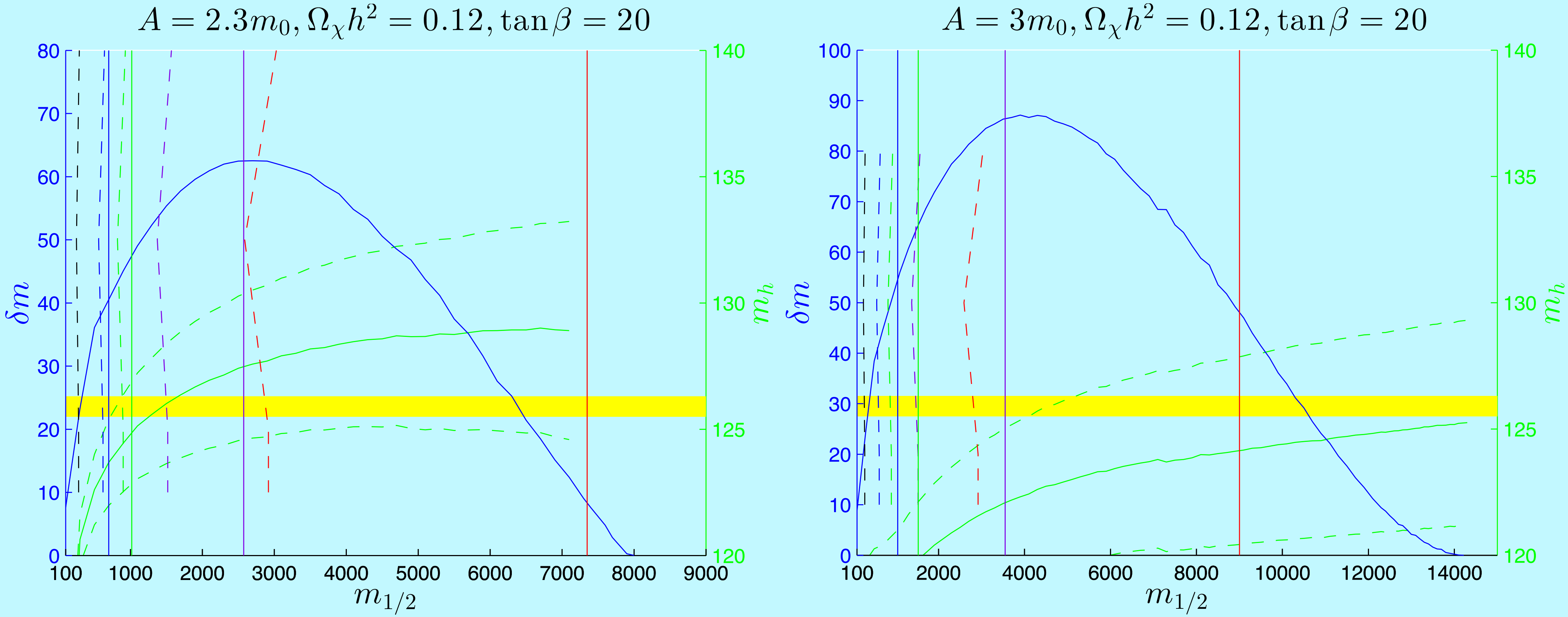




Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng

Stop strip



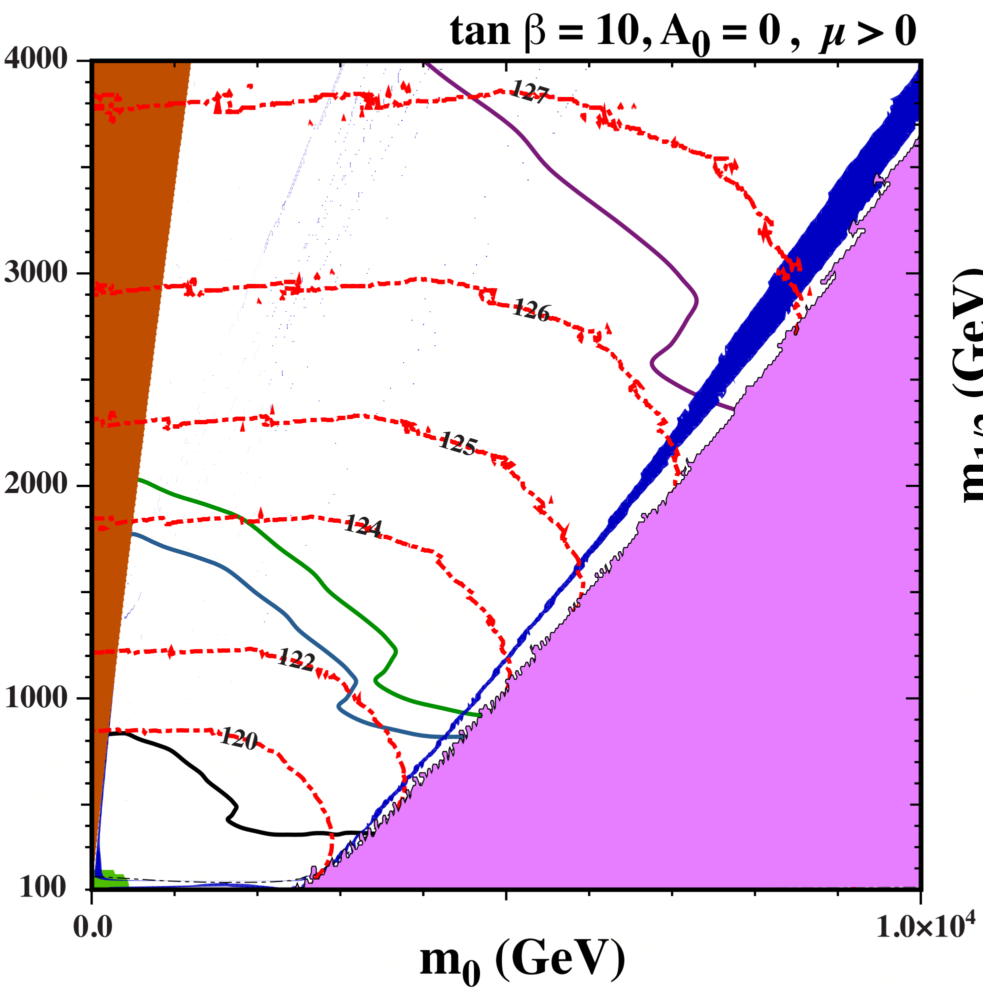
Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

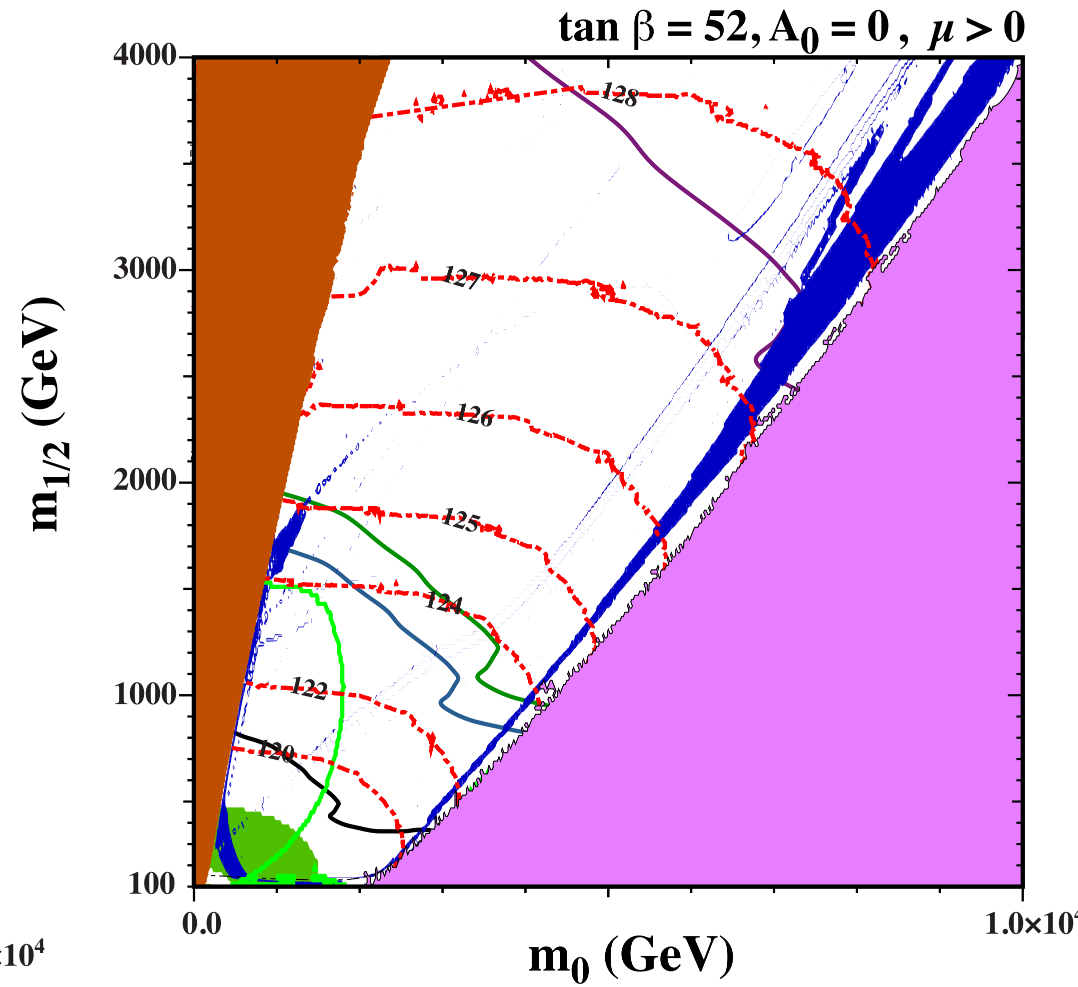
Ellis, Olive, Zheng

The Strips:

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

Focus Point

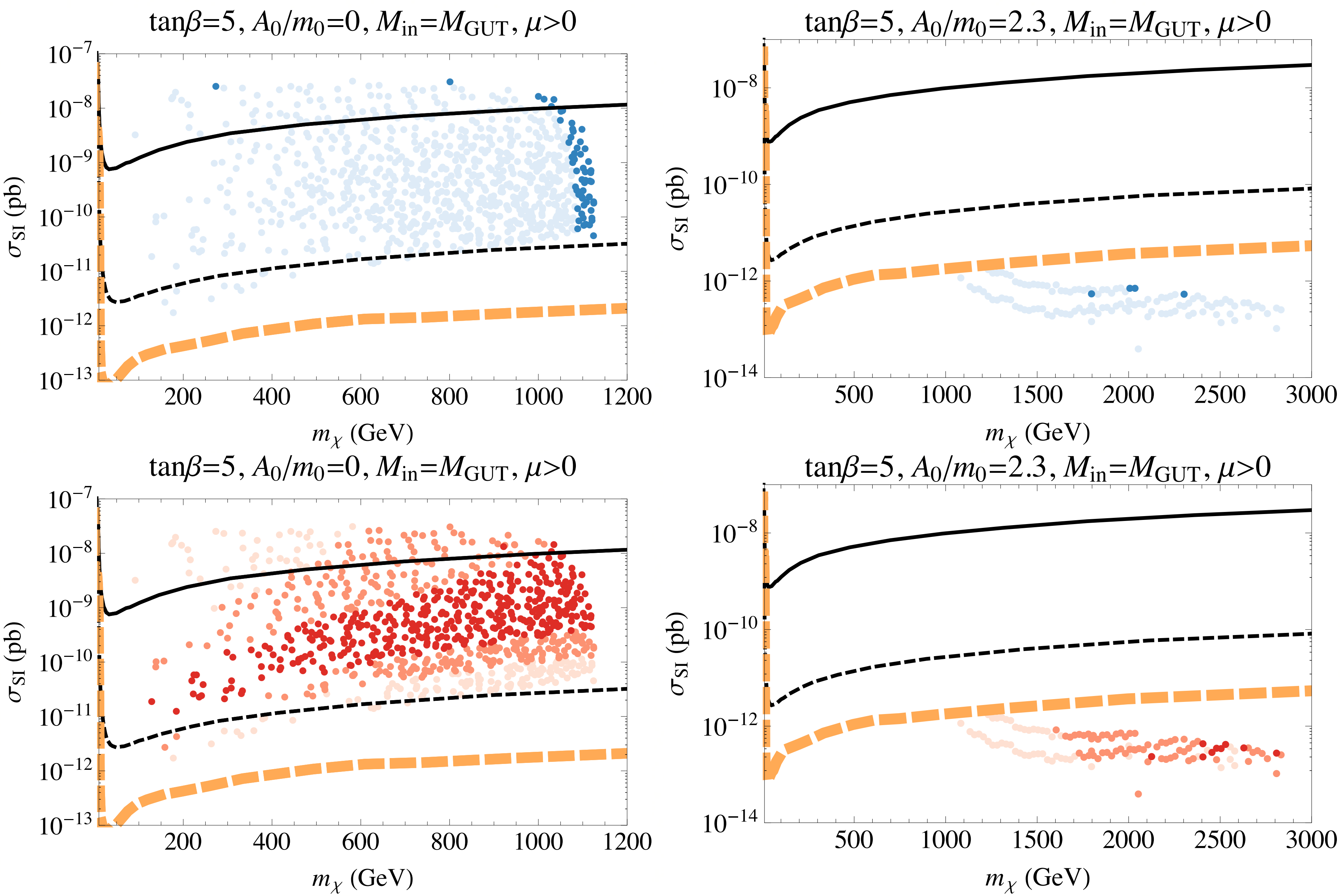




Buchmueller, Citron, Ellis, Guha, Marrouche, Olive, de Vries, Zheng

Ellis, Olive, Zheng

Direct detectability



Ellis,Evans, Nagata, Olive, Sandick, Zheng

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

$$M_1 = \frac{33}{5}\frac{g_1^2}{16\pi^2}m_{3/2} ,$$

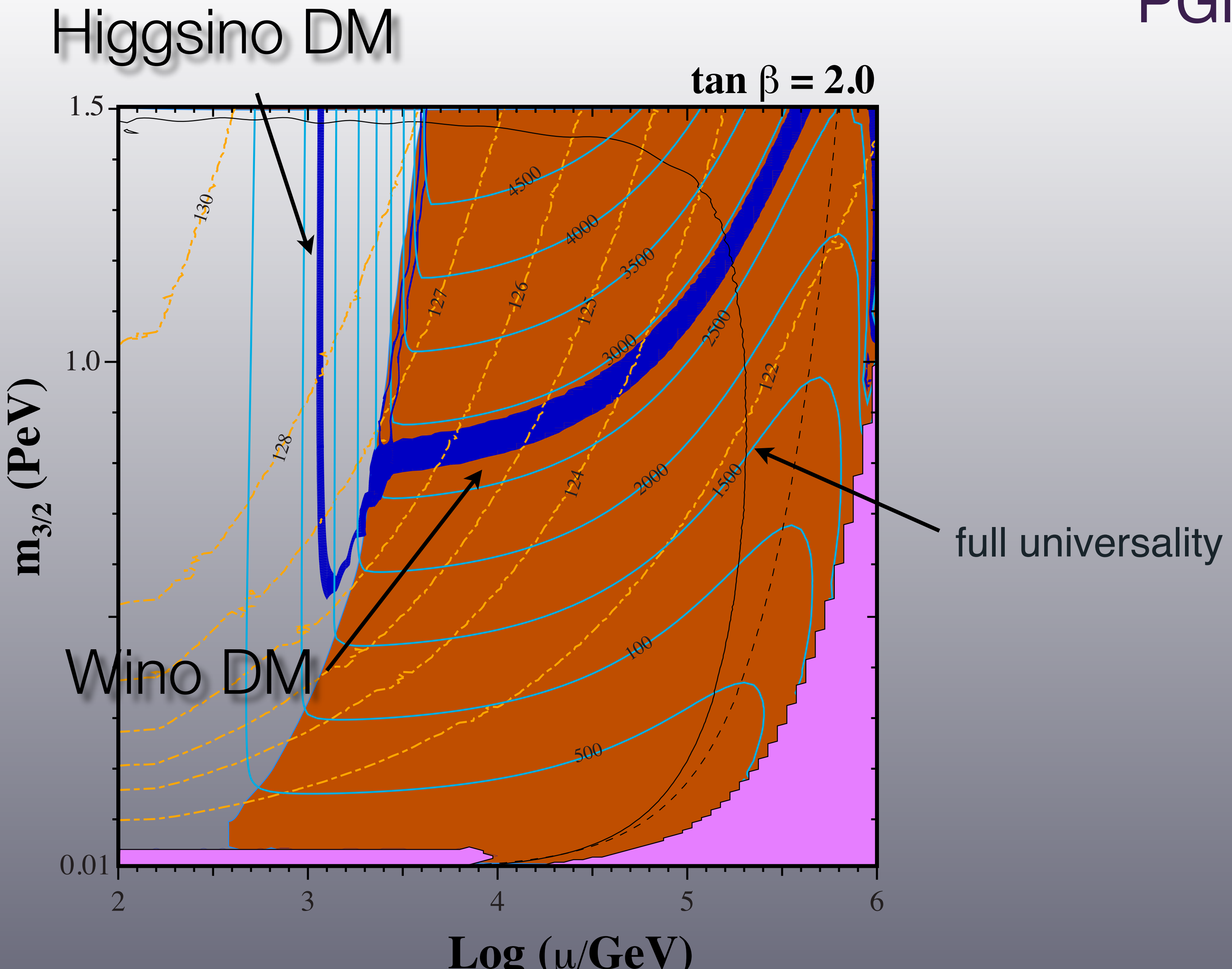
$$M_2 = \frac{g_2^2}{16\pi^2}m_{3/2} ,$$

$$M_3 = -3\frac{g_3^2}{16\pi^2}m_{3/2} .$$

- ⇒ Push towards very large masses

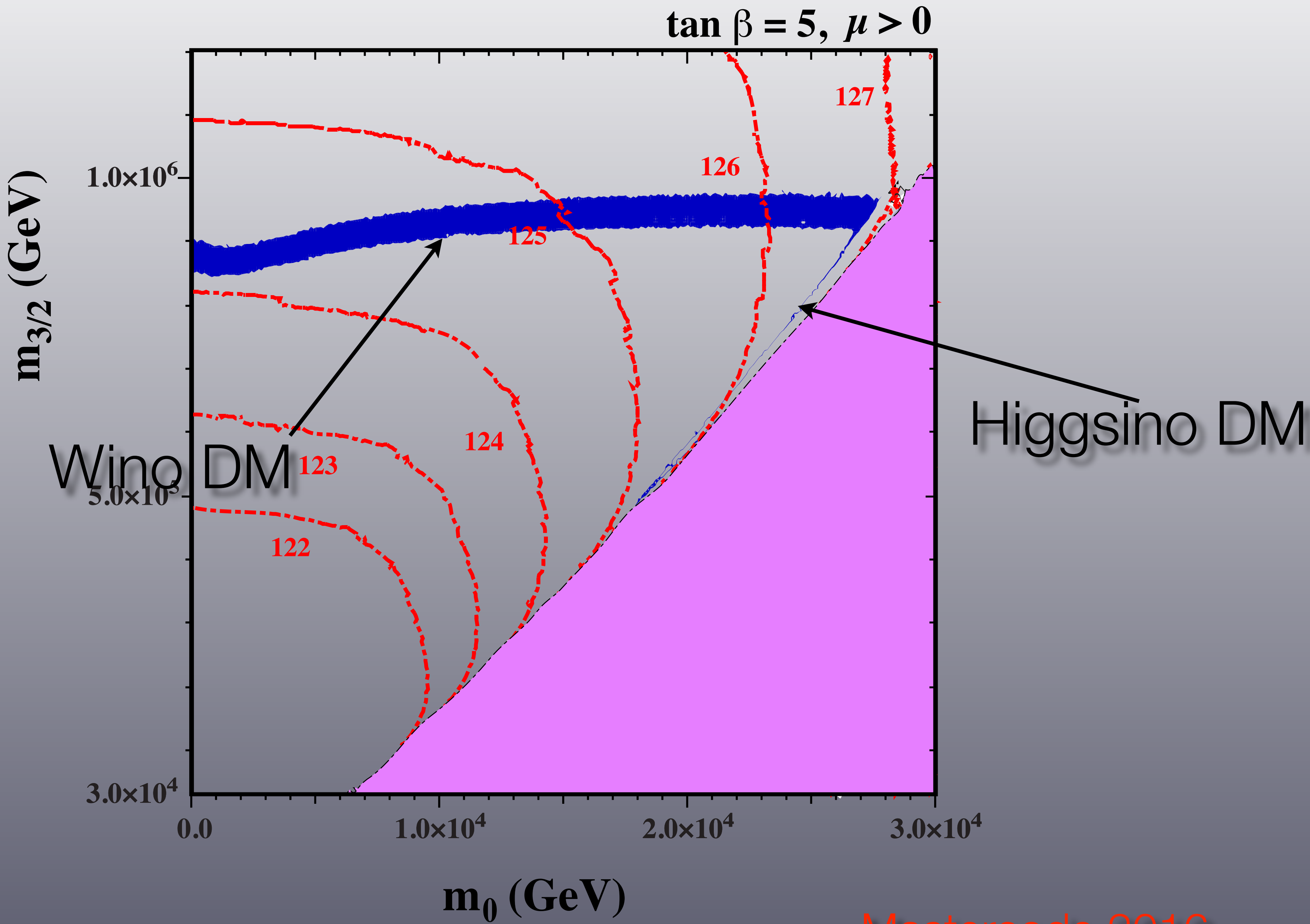
Evans,Ibe,Olive,Yanagida

PGM



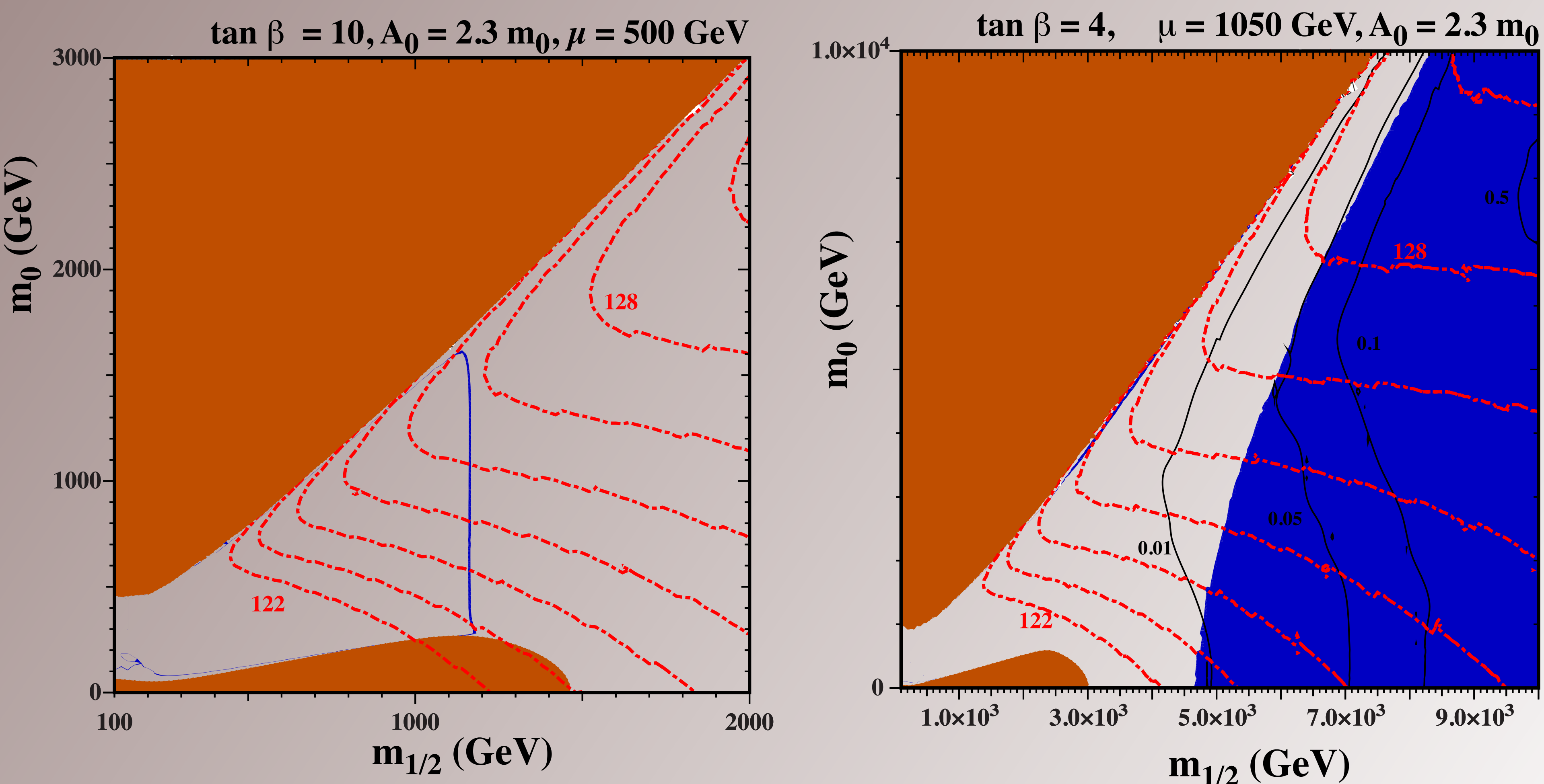
Evans, Ibe, Olive, Yanagida

mAMSB



Mastercode 2016

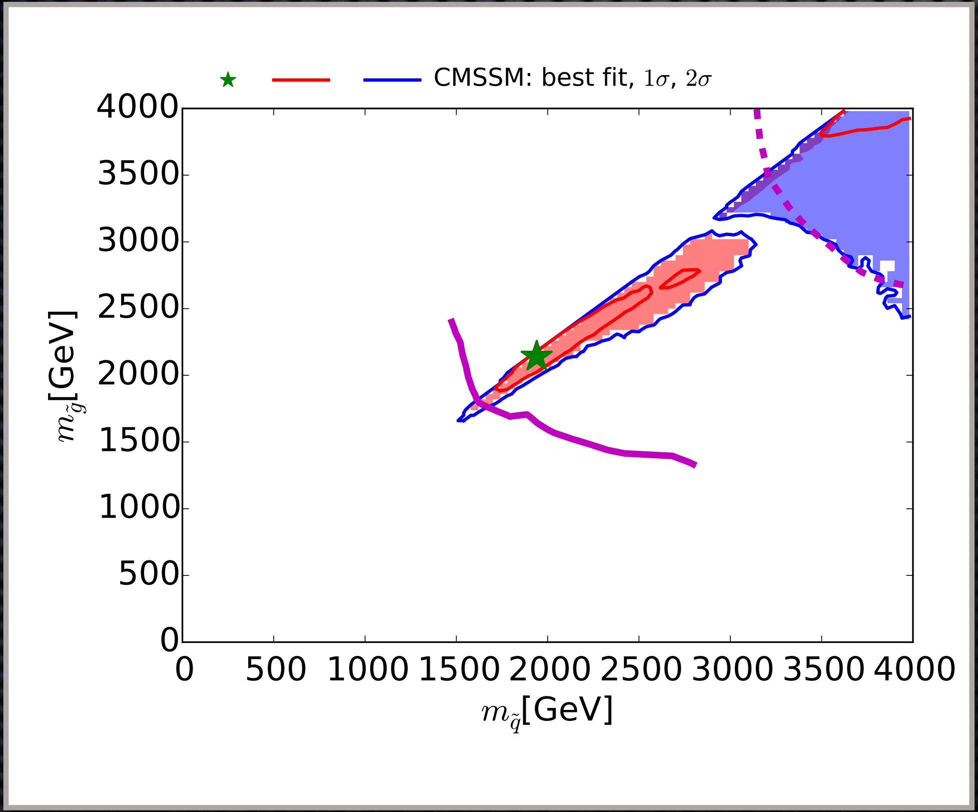
NUHM1 models with μ free ($m_1 = m_2$)



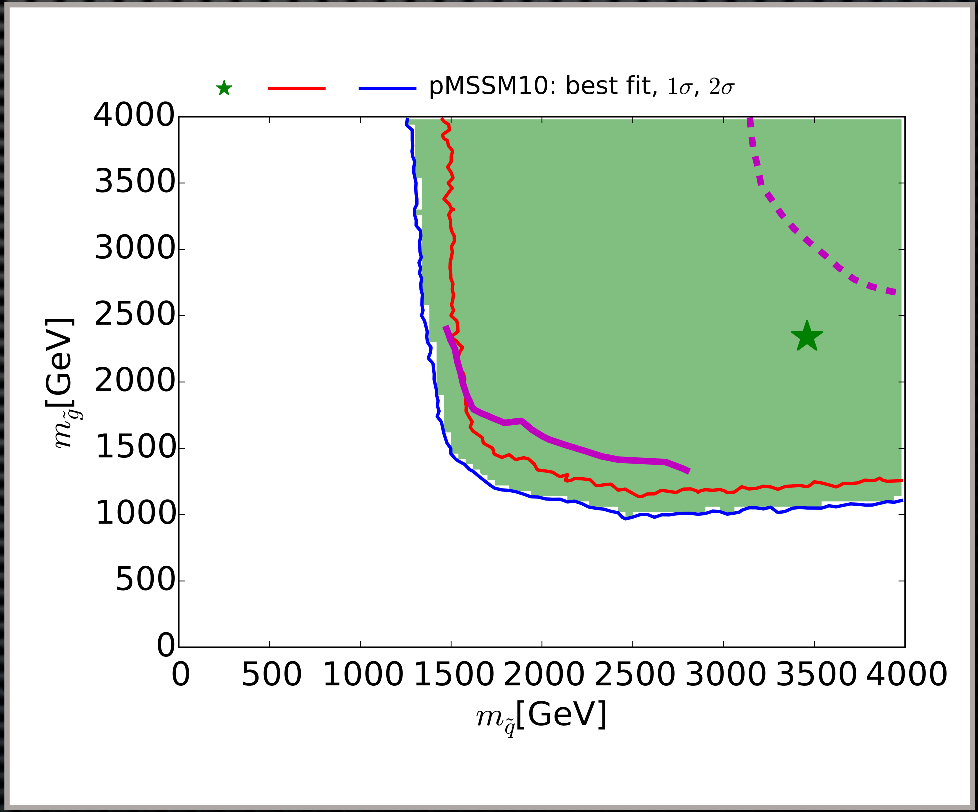
Ellis, Luo, Olive, Sandick;
Ellis, Evans, Luo, Nagata, Olive, Sandick

Relaxing GUT conditions

CMSSM



pMSSM



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

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, $m_h \sim 126$ GeV, and no SUSY?

SO(10) GUT?

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

Neutrino masses…

Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

$$\mathrm{SO}(10) \xrightarrow{R_1} G_{\mathrm{int}}$$

G_{int}	R_1
$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$	$\mathbf{210}$
$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes D$	$\mathbf{54}$
$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_R$	$\mathbf{45}$
$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}$	$\mathbf{45}$
$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \otimes D$	$\mathbf{210}$
$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_R \otimes \mathrm{U}(1)_{B-L}$	$\mathbf{45}, \mathbf{210}$
$\mathrm{SU}(5) \otimes \mathrm{U}(1)$	$\mathbf{45}, \mathbf{210}$
Flipped $\mathrm{SU}(5) \otimes \mathrm{U}(1)$	$\mathbf{45}, \mathbf{210}$

Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

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

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

R_2 = **126** + …

Neutrino see-saw: Majorana mass for ν_R from 16 16 126 → $m_{\nu R} \sim M_{int}$

Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

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

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

Remnant Z_2 symmetry

Fermions from **10**,**45**, **54**, **120**, **126**, or **210** representations;

Scalars from **16**, **144**

Model	$B-L$	$SU(2)_L$	Y	SO(10) representations
$F_{\mathbf{1}}^{0}$		$\mathbf{1}$	0	$\mathbf{45}$, $\mathbf{54}$, $\mathbf{210}$
$F_{\mathbf{2}}^{1/2}$		$\mathbf{2}$	1/2	$\mathbf{10}$, $\mathbf{120}$, $\mathbf{126}$, $\mathbf{210'}$
$F_{\mathbf{3}}^{0}$	0	$\mathbf{3}$	0	$\mathbf{45}$, $\mathbf{54}$, $\mathbf{210}$
$F_{\mathbf{3}}^{1}$		$\mathbf{3}$	1	$\mathbf{54}$
$F_{\mathbf{4}}^{1/2}$		$\mathbf{4}$	1/2	$\mathbf{210'}$
$F_{\mathbf{4}}^{3/2}$		$\mathbf{4}$	3/2	$\mathbf{210'}$
$S_{\mathbf{1}}^{0}$		$\mathbf{1}$	0	$\mathbf{16}$, $\mathbf{144}$
$S_{\mathbf{2}}^{1/2}$	1	$\mathbf{2}$	1/2	$\mathbf{16}$, $\mathbf{144}$
$S_{\mathbf{3}}^{0}$		$\mathbf{3}$	0	$\mathbf{144}$
$S_{\mathbf{3}}^{1}$		$\mathbf{3}$	1	$\mathbf{144}$
$\widehat{F}_{\mathbf{1}}^{0}$		$\mathbf{1}$	0	$\mathbf{126}$
$\widehat{F}_{\mathbf{2}}^{1/2}$	2	$\mathbf{2}$	1/2	$\mathbf{210}$
$\widehat{F}_{\mathbf{3}}^{1}$		$\mathbf{3}$	1	$\mathbf{126}$

Kadastik, Kannike, Raidal;
Frigerio, Hambye;
Mambrini, Nagata,
Olive, Quevillon, Zheng;
Nagata, Olive, Zheng

Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

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

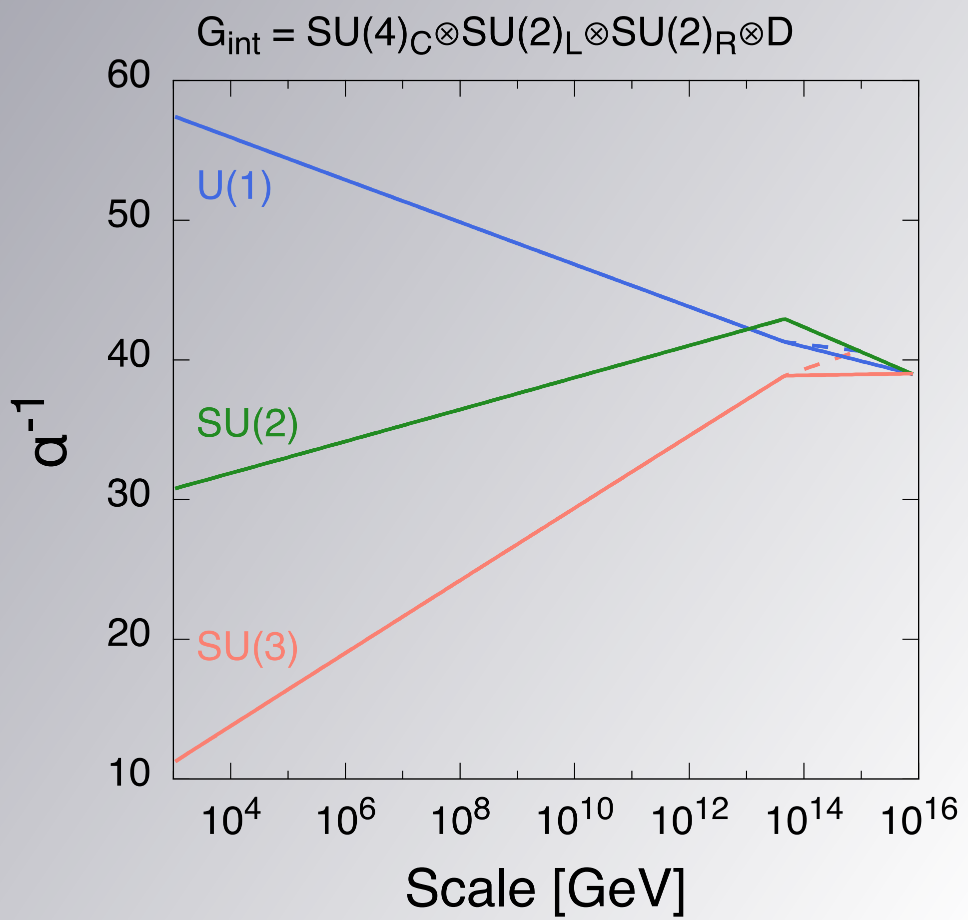
3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

4. Use RGEs to obtain Gauge Coupling Unification

Recipe for constructing an SO(10) DM model

4. Use RGEs to obtain Gauge Coupling Unification

Fixes M_{GUT}, M_{int}, α_{GUT}



Examples:

Scalars

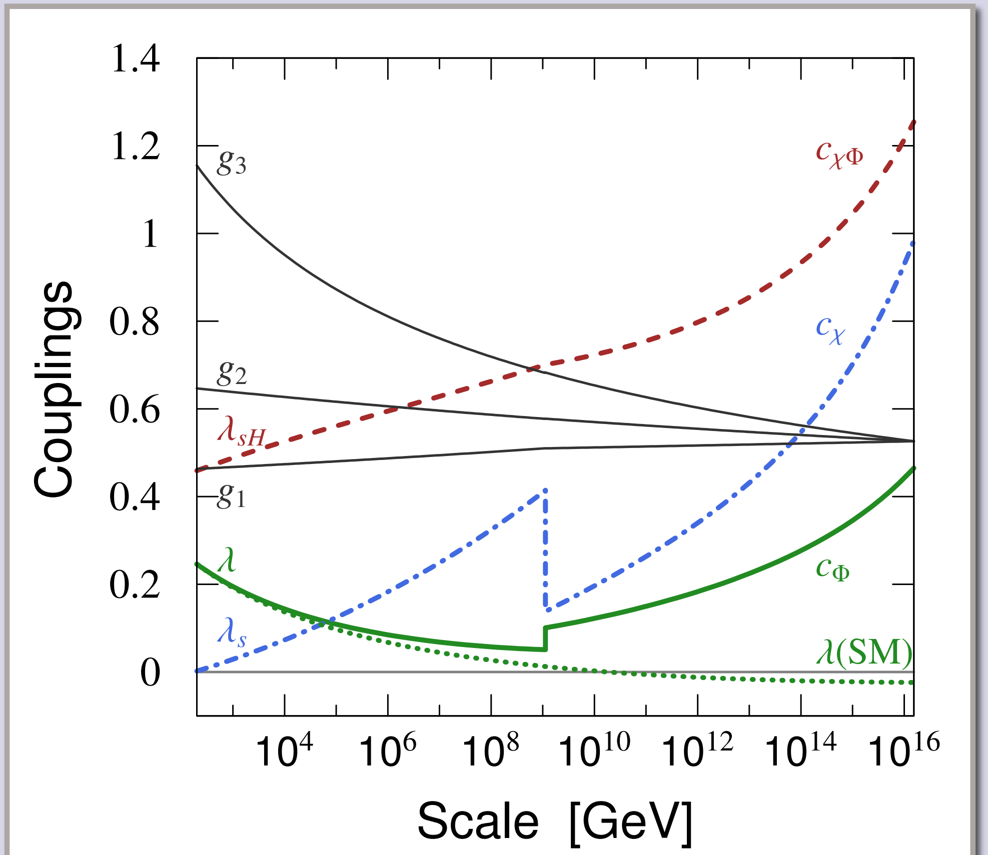
Higgs portal models
Inert Higgs doublet models

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

other models have $M_{\rm GUT}$ too low

Nagata, Olive, Zheng

Vacuum stability and radiative EWSB



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

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

with scalar potential

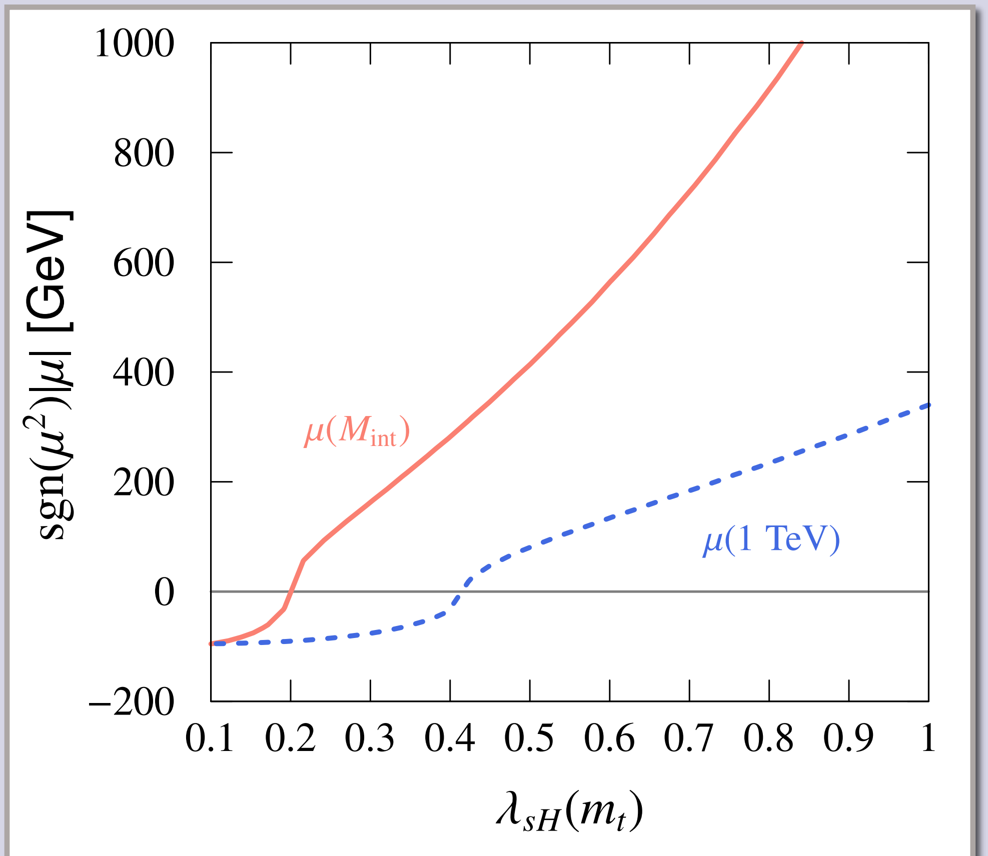
$$V_{\rm blw} = \mu^2|H|^2 + \frac{1}{2}\mu_s^2 s^2 + \frac{\lambda}{2}|H|^4 + \frac{\lambda_{sH}}{2}|H|^2 s^2 + \frac{\lambda_s}{4!}s^4 .$$

Additional fields appear at the intermediate scale.

perturbatitivity implies $m_{DM} \lesssim 2$ TeV

Mambrini, Nagata, Olive, Zheng

Vacuum stability and radiative EWSB



Higgs mass term runs negative and depends on λ_{sH}

$\mu^2 < 0$ @ $Q < 1$ TeV requires $\lambda_{sH} > .4$ or $m_{DM} > 1.35$ TeV

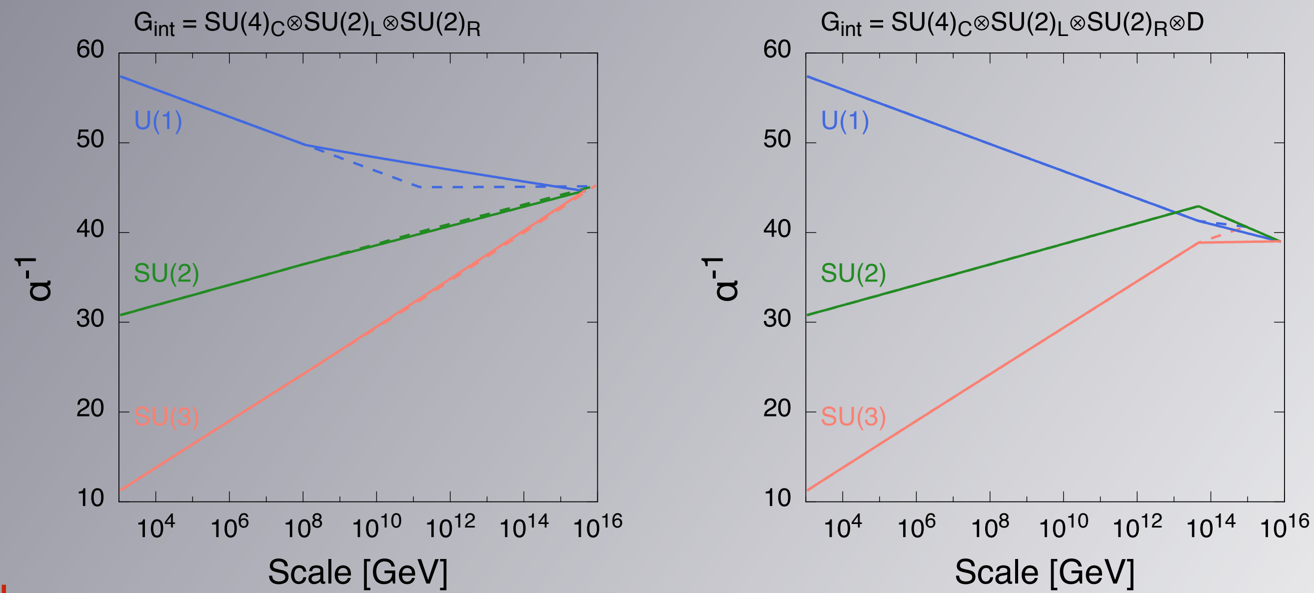
Mambrini, Nagata, Olive, Zheng

Examples:

SM Fermion Singlets: Produced thermally out of equilibrium
$\Rightarrow$ Fermionic candidates (NETDM)

Mambrini, Olive, Quevillon, Zaldivar

	Model I	Model II
$G_{\rm int}$	$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$	$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes D$
$R_{\rm DM}$	$(\mathbf{1},\mathbf{1},\mathbf{3})_D$ in $\mathbf{45}_D$	$(\mathbf{15},\mathbf{1},\mathbf{1})_W$ in $\mathbf{45}_W$
R_1	$\mathbf{210}_R$	$\mathbf{54}_R$
R_2	$(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{1},\mathbf{1},\mathbf{3})_R$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{10},\mathbf{3},\mathbf{1})_C \oplus (\mathbf{15},\mathbf{1},\mathbf{1})_R$
$\log_{10}(M_{\rm int})$	8.08(1)	13.664(5)
$\log_{10}(M_{\rm GUT})$	15.645(7)	15.87(2)
$g_{\rm GUT}$	0.53055(3)	0.5675(2)



(a) Model I (b) Model II

Mambrini, Nagata, Olive, Quevillon, Zheng

Examples:

Non-Singlets: Fermions

$R_{\rm DM}$	Additional Higgs in R_1	$\log_{10} M_{\rm int}$	$\log_{10} M_{\rm GUT}$	$\alpha_{\rm GUT}$	$\log_{10}\tau_p(p \to e^+\pi^0)$
	$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$				
$(\mathbf{1},\mathbf{3},\mathbf{1})$	$(\mathbf{15},\mathbf{1},\mathbf{1})$ $(\mathbf{15},\mathbf{1},\mathbf{3})$	6.54	17.17	0.0252	39.8 ± 1.2

Model	$R_{\rm DM}$	$R'_{\rm DM}$	Higgs	$\log_{10} M_{\rm int}$	$\log_{10} M_{\rm GUT}$	$\alpha_{\rm GUT}$	$\log_{10}\tau_p$
			$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm U}(1)_R$				
$\mathtt{FA}_{421}$	$(\mathbf{1},\mathbf{2},1/2)_D$	$(\mathbf{15},\mathbf{1},0)_W$	$(\mathbf{15},\mathbf{1},0)_R$ $(\mathbf{15},\mathbf{2},1/2)_C$	3.48	17.54	0.0320	40.9 ± 1.2
			$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$				
$\mathtt{FA}_{422}$	$(\mathbf{1},\mathbf{2},\mathbf{2})_W$	$(\mathbf{1},\mathbf{3},\mathbf{1})_W$	$(\mathbf{15},\mathbf{1},\mathbf{1})_R$ $(\mathbf{15},\mathbf{1},\mathbf{3})_R$	9.00	15.68	0.0258	34.0 ± 1.2
$\mathtt{FB}_{422}$	$(\mathbf{1},\mathbf{2},\mathbf{2})_W$	$(\mathbf{1},\mathbf{3},\mathbf{1})_W$	$(\mathbf{15},\mathbf{1},\mathbf{1})_R$ $(\mathbf{15},\mathbf{2},\mathbf{2})_C$ $(\mathbf{15},\mathbf{1},\mathbf{3})_R$	5.84	17.01	0.0587	38.0 ± 1.2

Nagata, Olive, Zheng

Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to "corners"
- Though some phenomenological solutions are still viable typically along "strips" in parameter space
- NUHM models with "low" μ still promising as are subGUT models; PGM/mAMSB (with wino DM or Higgsino DM)
- Several possibilities in non-SUSY SO(10) models
- Challenge lies in detection strategies