Dark Matter Candidates in Supersymmetric Models

Dark Matter Candidates in Supersymmetric Models

Weak scale susy?

Dark Matter Candidates in Supersymmetric Models

Weak scale susy?

SU(5) GUT models and Missing Partners

Dark Matter Candidates in Supersymmetric Models

Weak scale susy?

SU(5) GUT models and Missing Partners

Dark Matter Candidates in Supersymmetric Models

Weak scale susy?

SU(5) GUT models and Missing Partners

Gravitino Dark Matter in High Scale susy

Constrained Models (CMSSM)

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

Constrained Models (CMSSM)

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

- Gaugino mass Unification

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

Constrained Models (CMSSM)

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

- Gaugino mass Unification
- A-term Unification

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

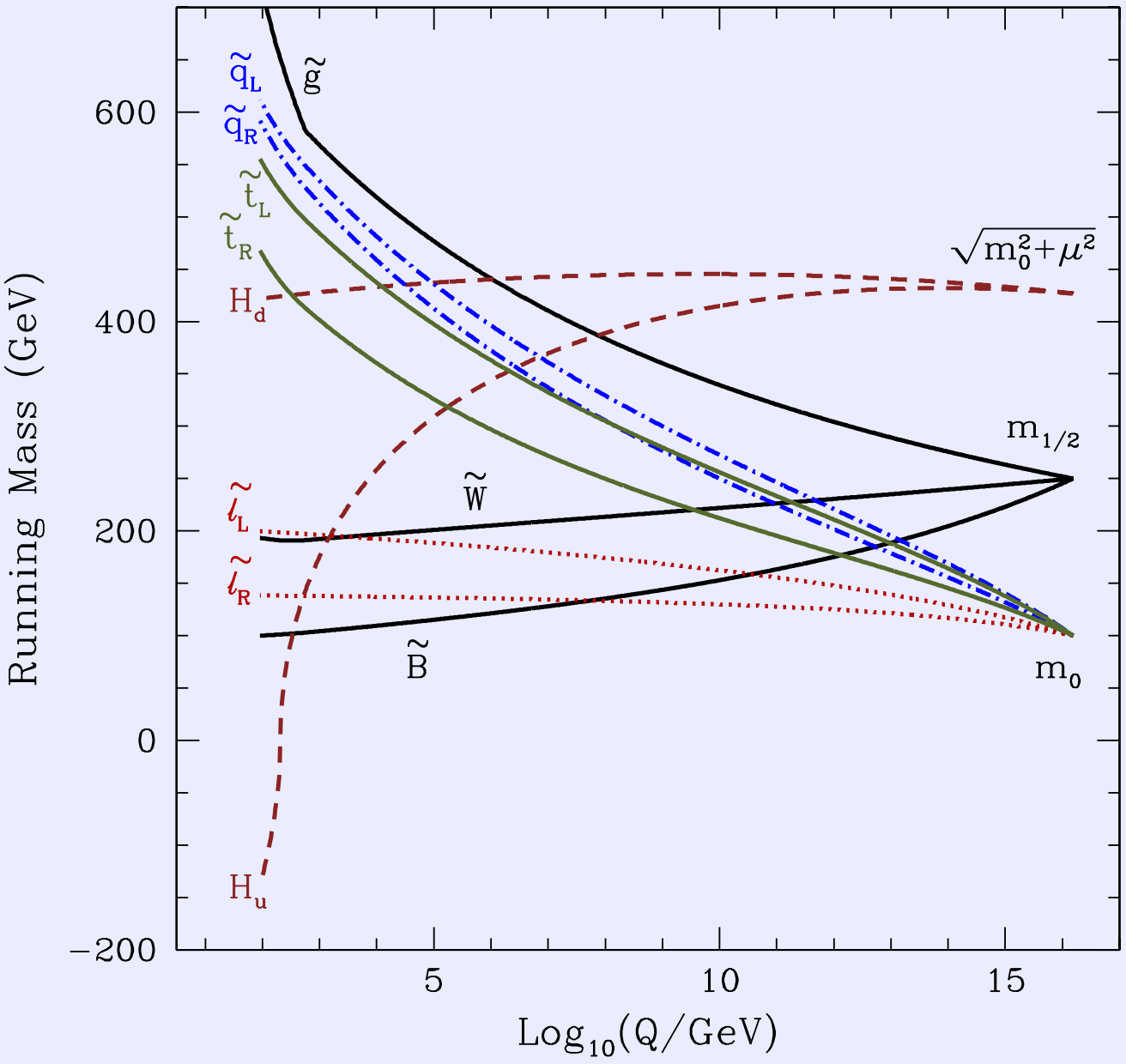
Constrained Models (CMSSM)

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

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

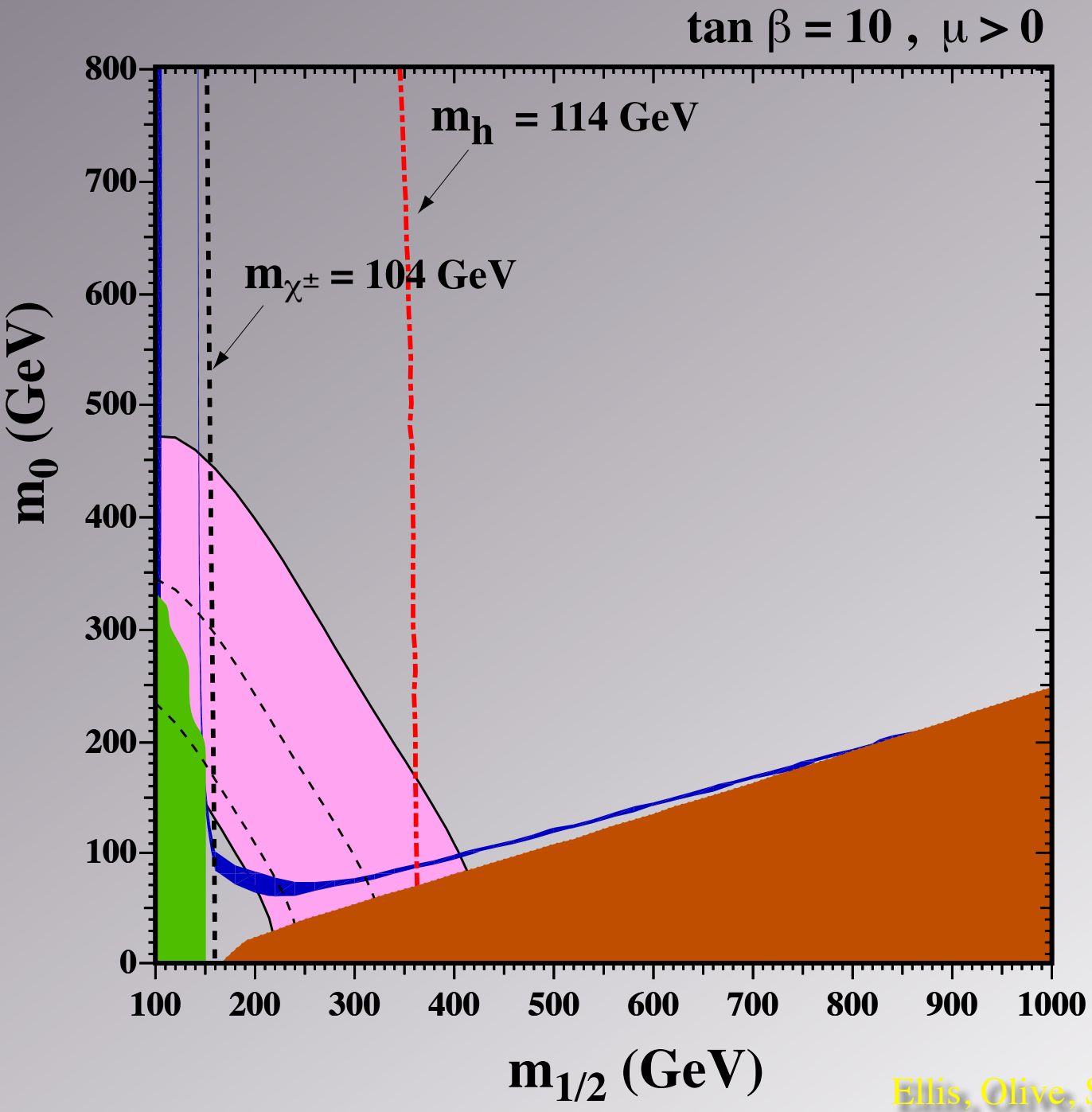
$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\text{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B \mu H_2 H_1 + h.c.
\end{aligned}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

CMSSM Spectra



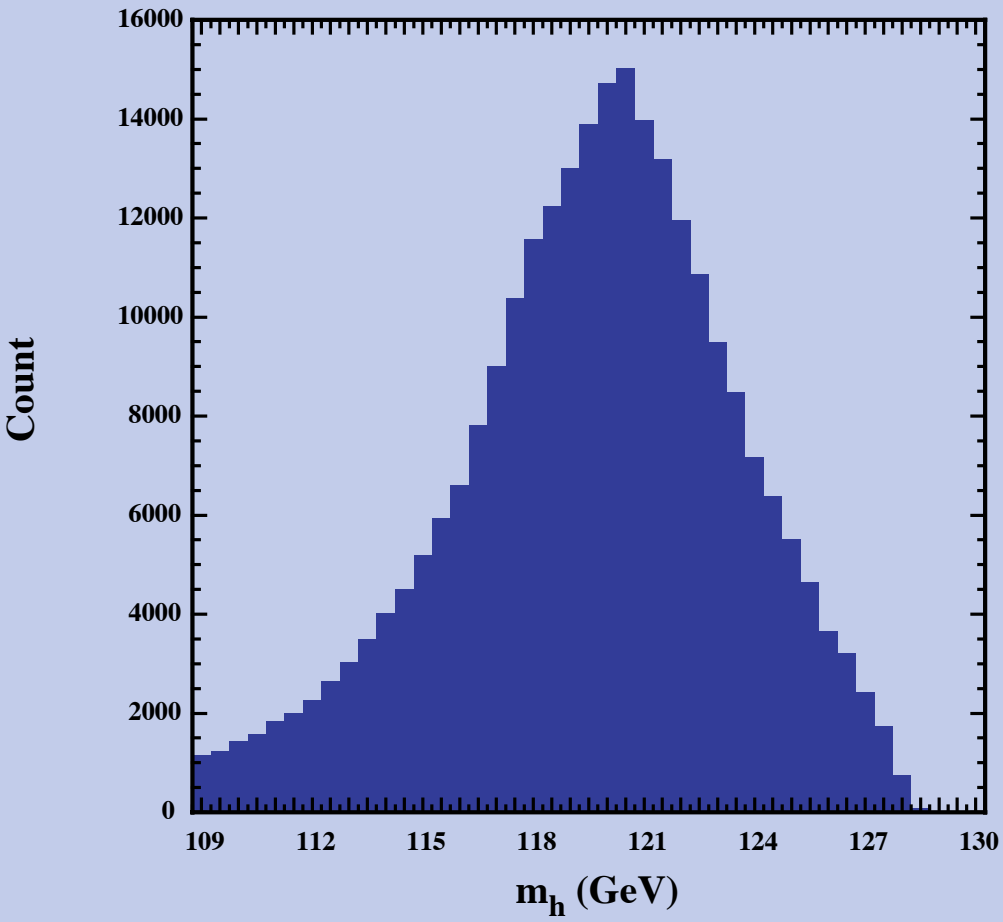
Unification to
rich spectrum
+
EWSB

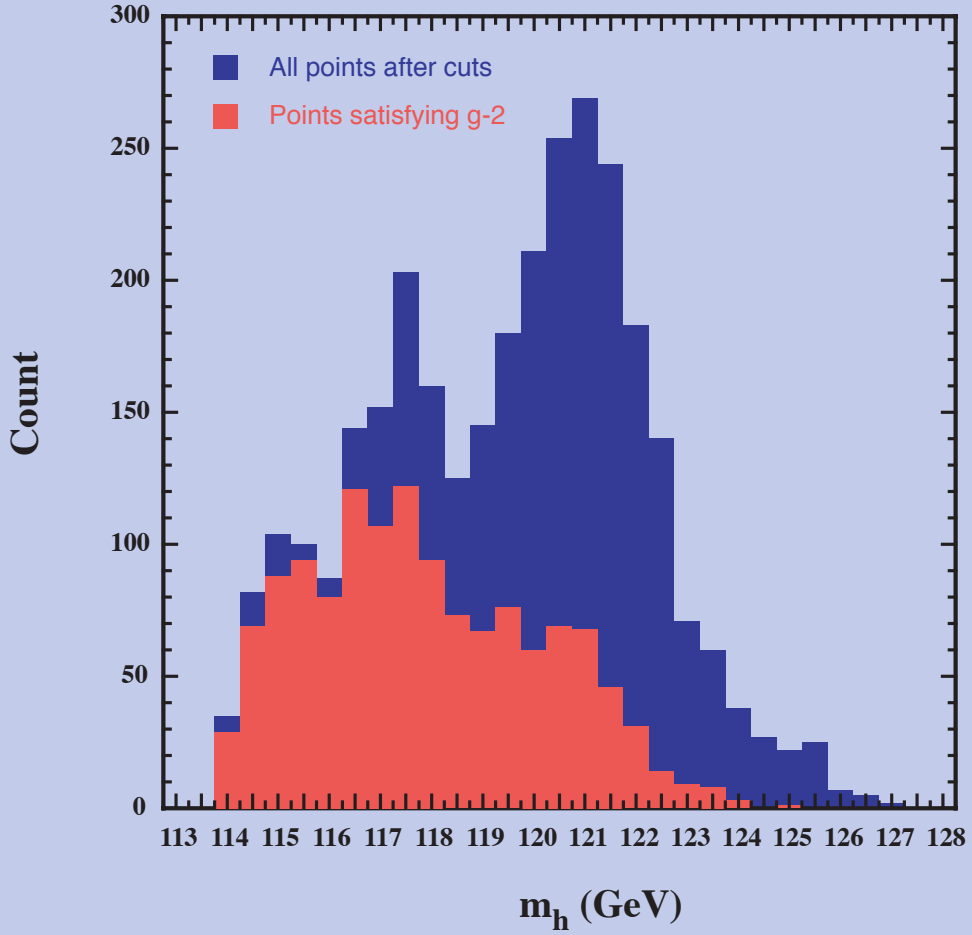
Falk



Ellis, Olive, Santoso, Spanos

The Higgs mass in the CMSSM



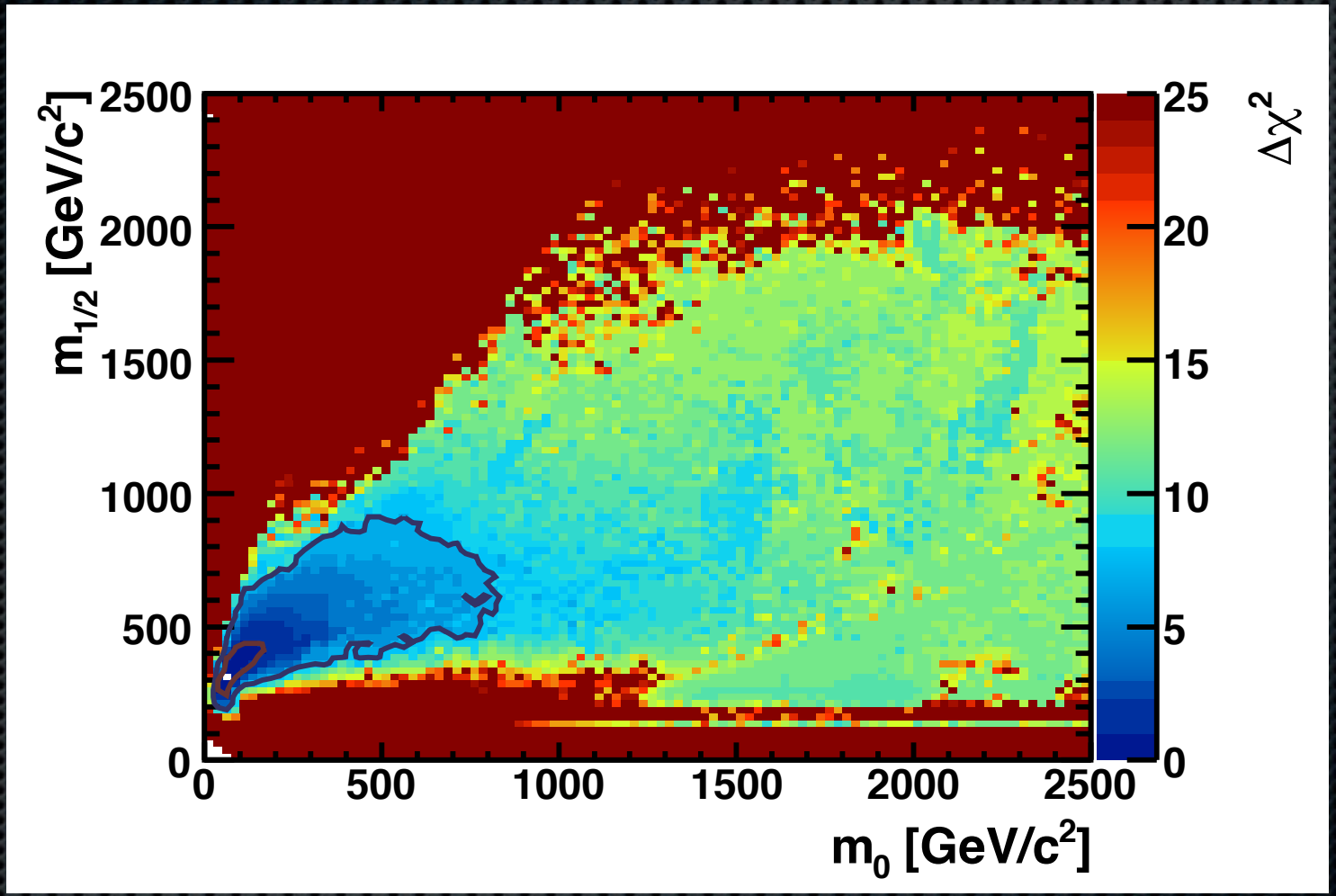


Ellis, Nanopoulos, Olive, Santoso

What happened to weak scale SUSY

Mastercode

2009



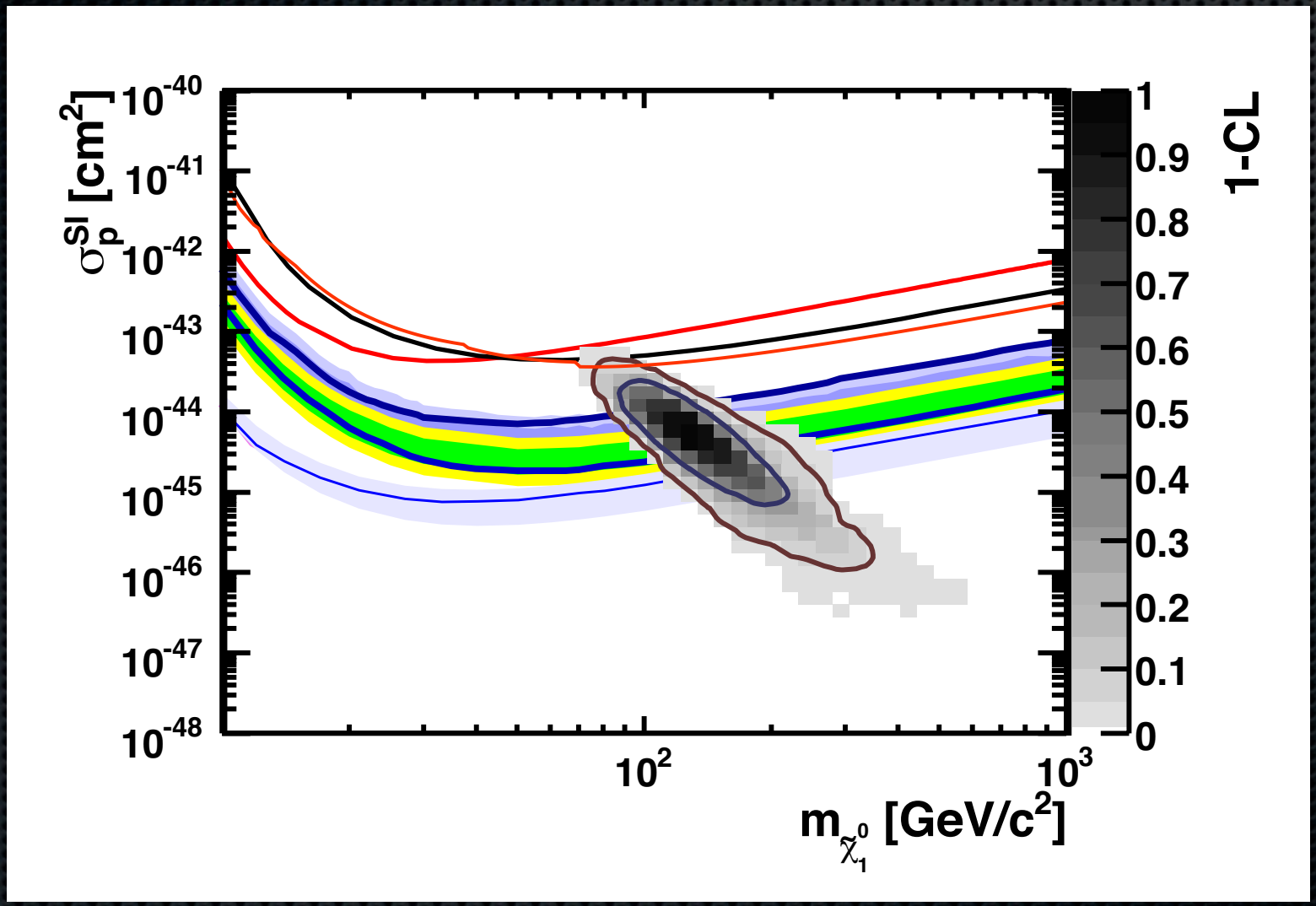
- CMSSM

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

Elastic scaterring cross-section

Mastercode

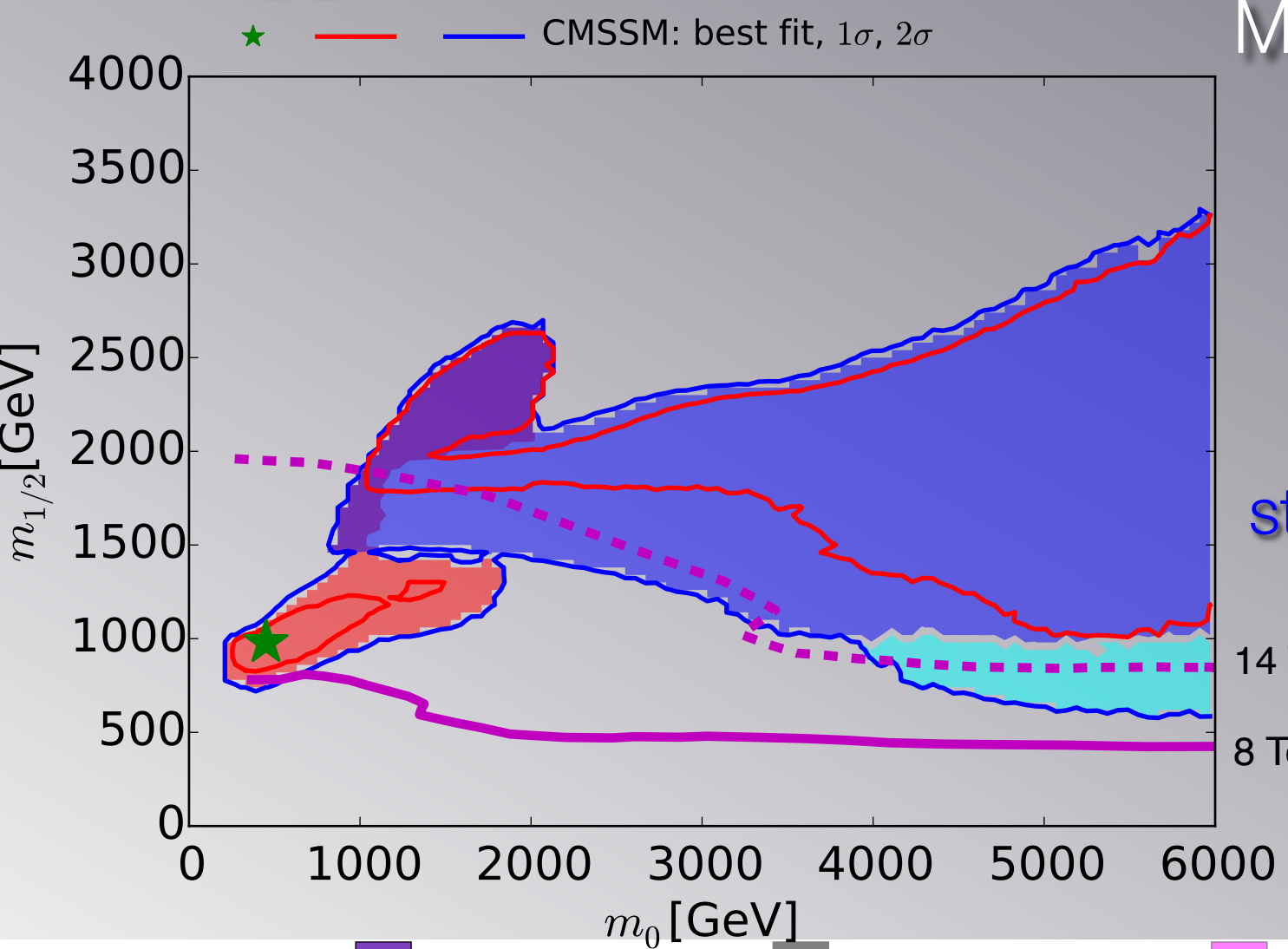
2009



- CMSSM

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

LHC Happened



Mastercode

2015

Low mass spectrum still observable at LHC

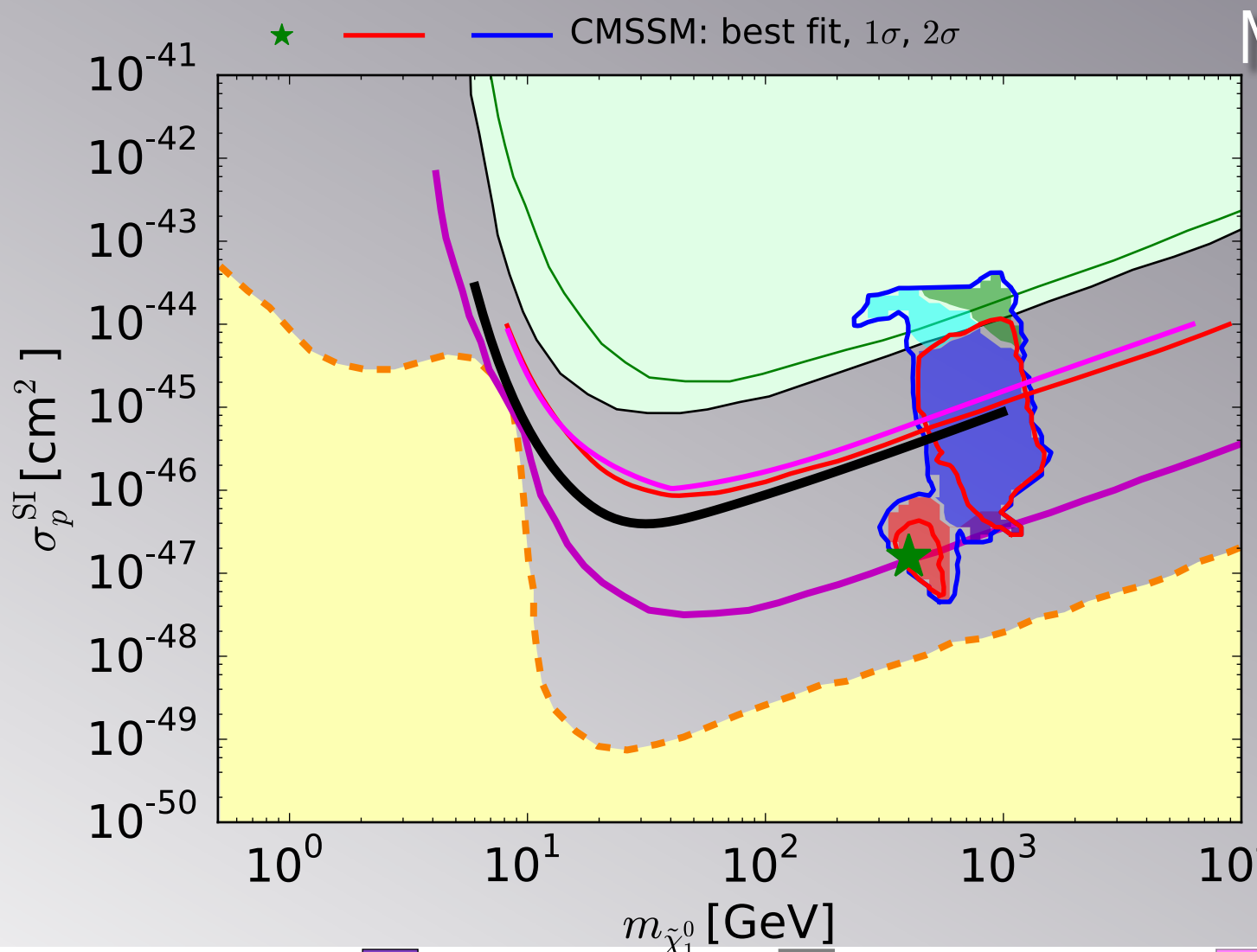
stau coann. | hybrid | stop coann. | h funnel

A/H funnel | $\tilde{\chi}_1^{\pm}$ coann. | focus point | Z funnel

- 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

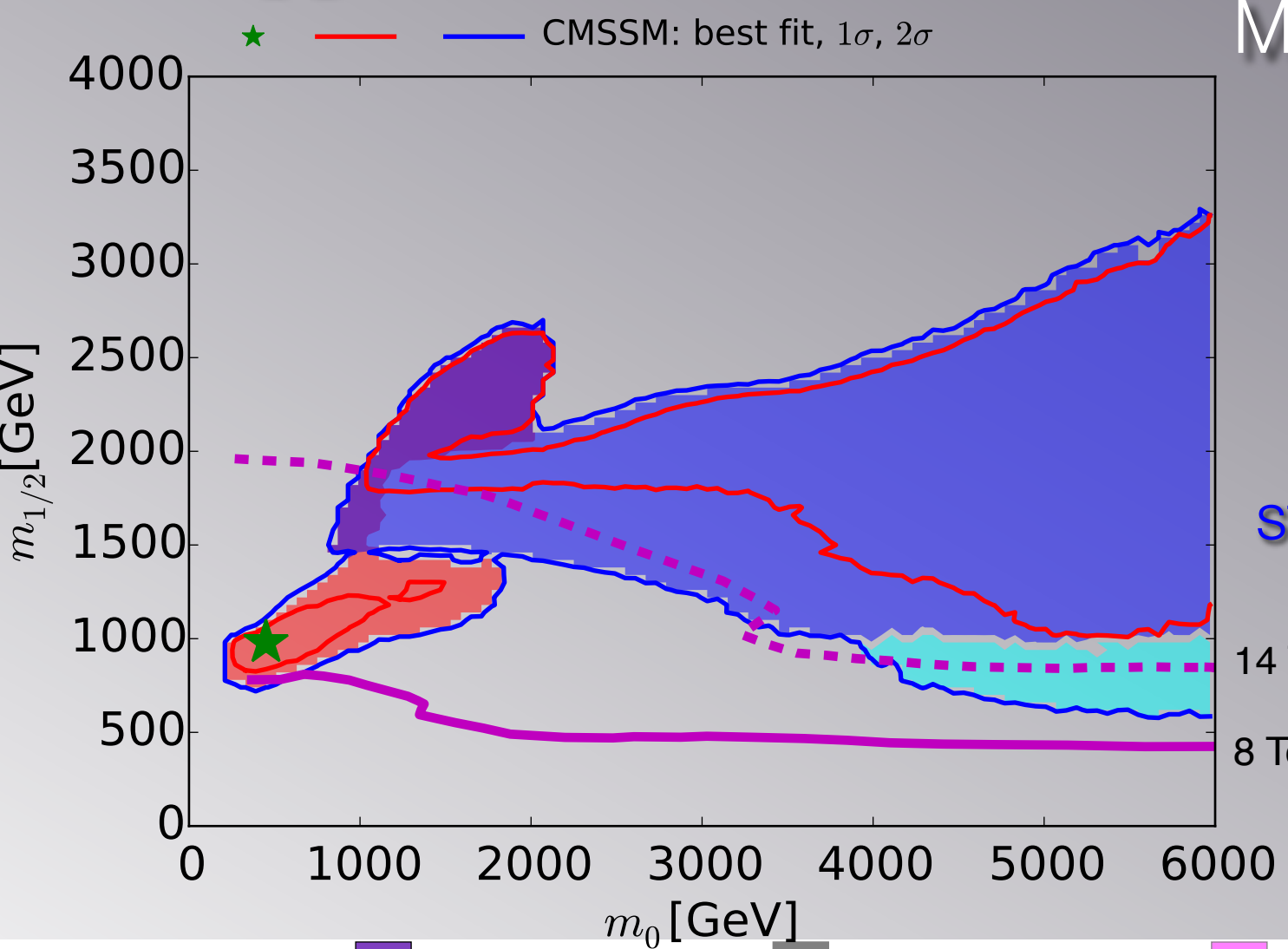
LZ

stau coann.
hybrid
stop coann.
h funnel
A/H funnel
$\tilde{\chi}_1^{\pm}$ coann.
focus point
Z funnel

- CMSSM

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

LHC Happened



Mastercode

2015

Low mass spectrum still observable at LHC

stau coann. | hybrid | stop coann. | h funnel

A/H funnel | $\tilde{\chi}_1^{\pm}$ coann. | focus point | Z funnel

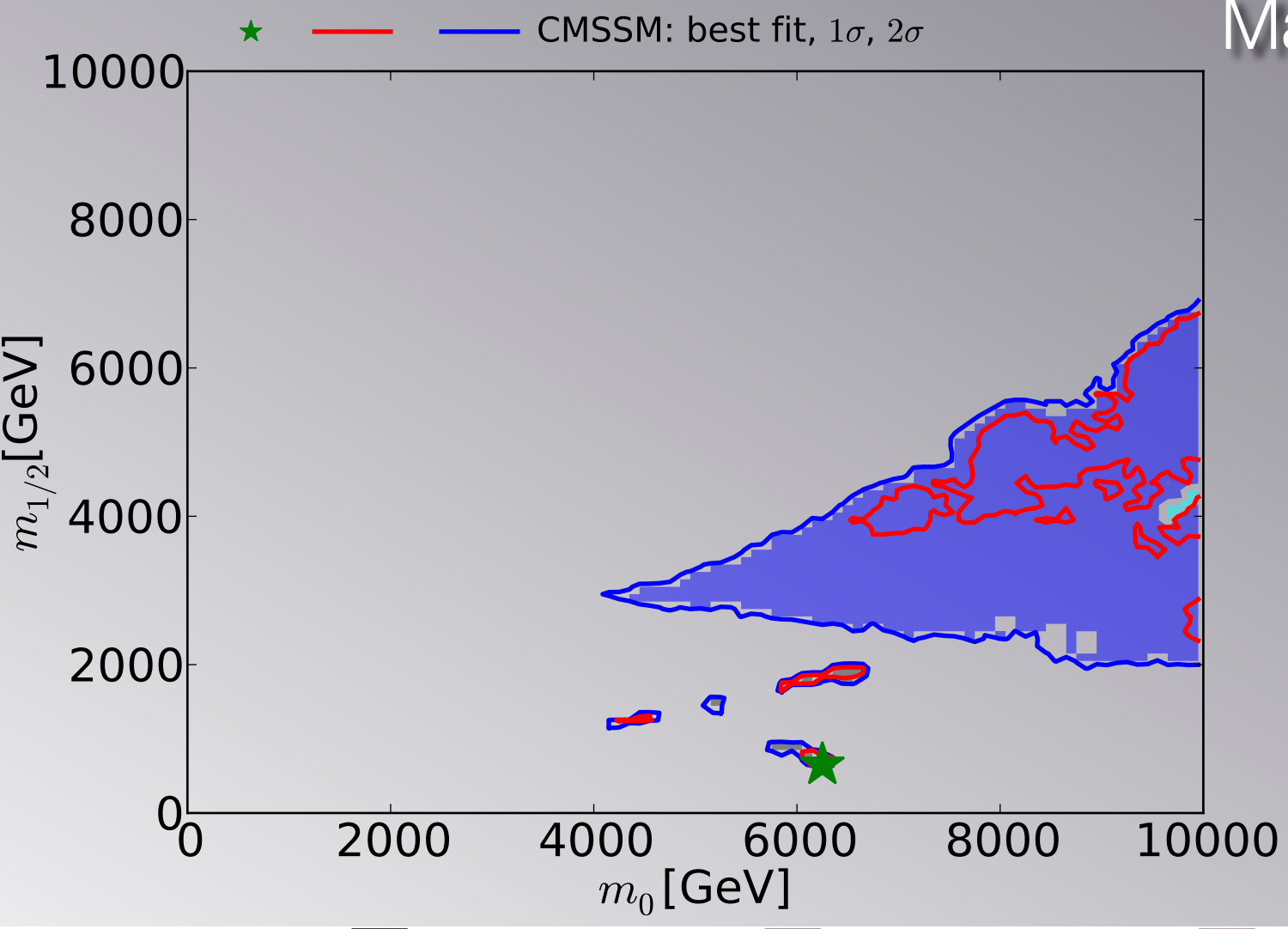
- CMSSM

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

LHC Happened

Mastercode

2021



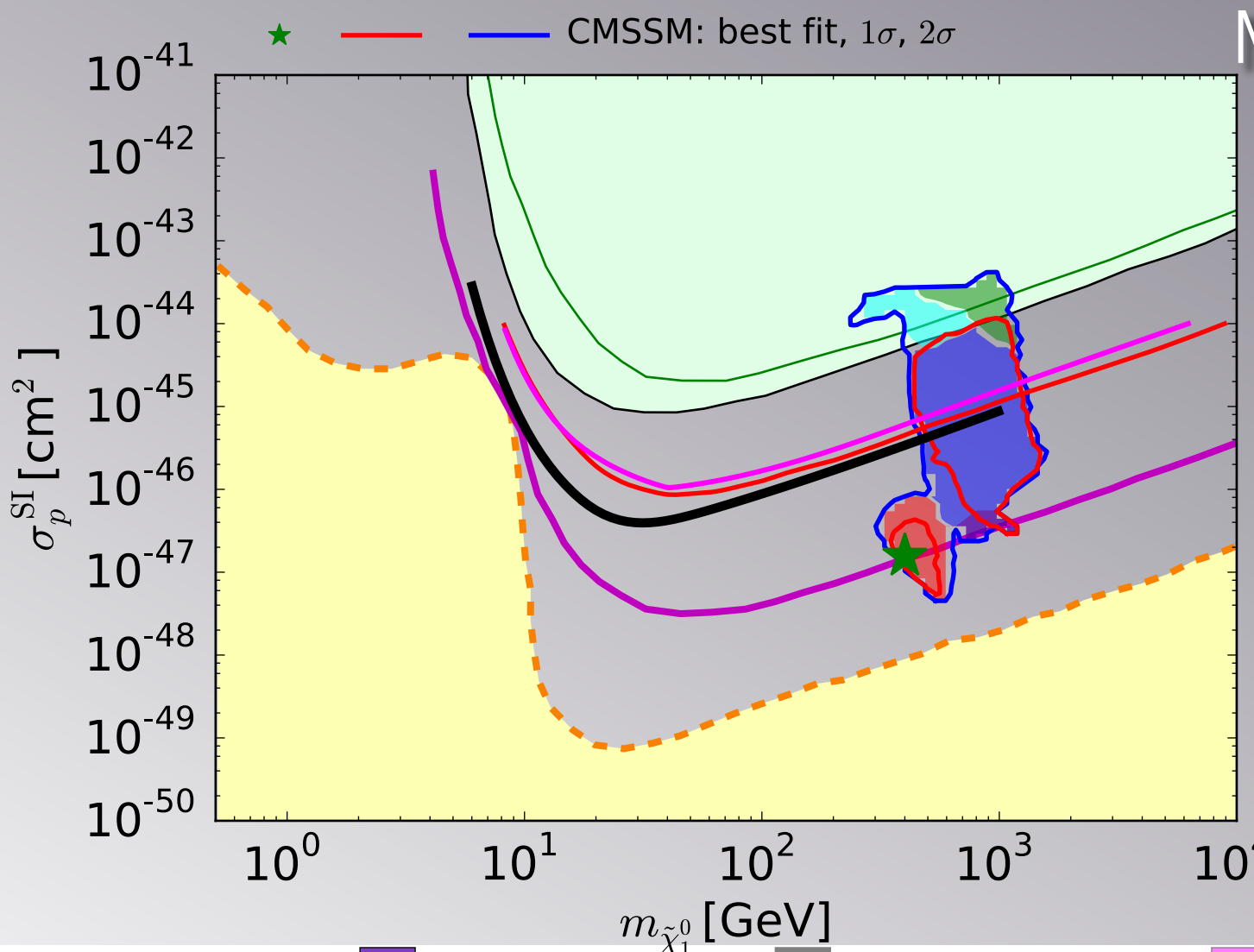
stau coann. | hybrid | stop coann. | h funnel

A/H funnel | $\tilde{\chi}_1^{\pm}$ coann. | focus point | Z funnel

- 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

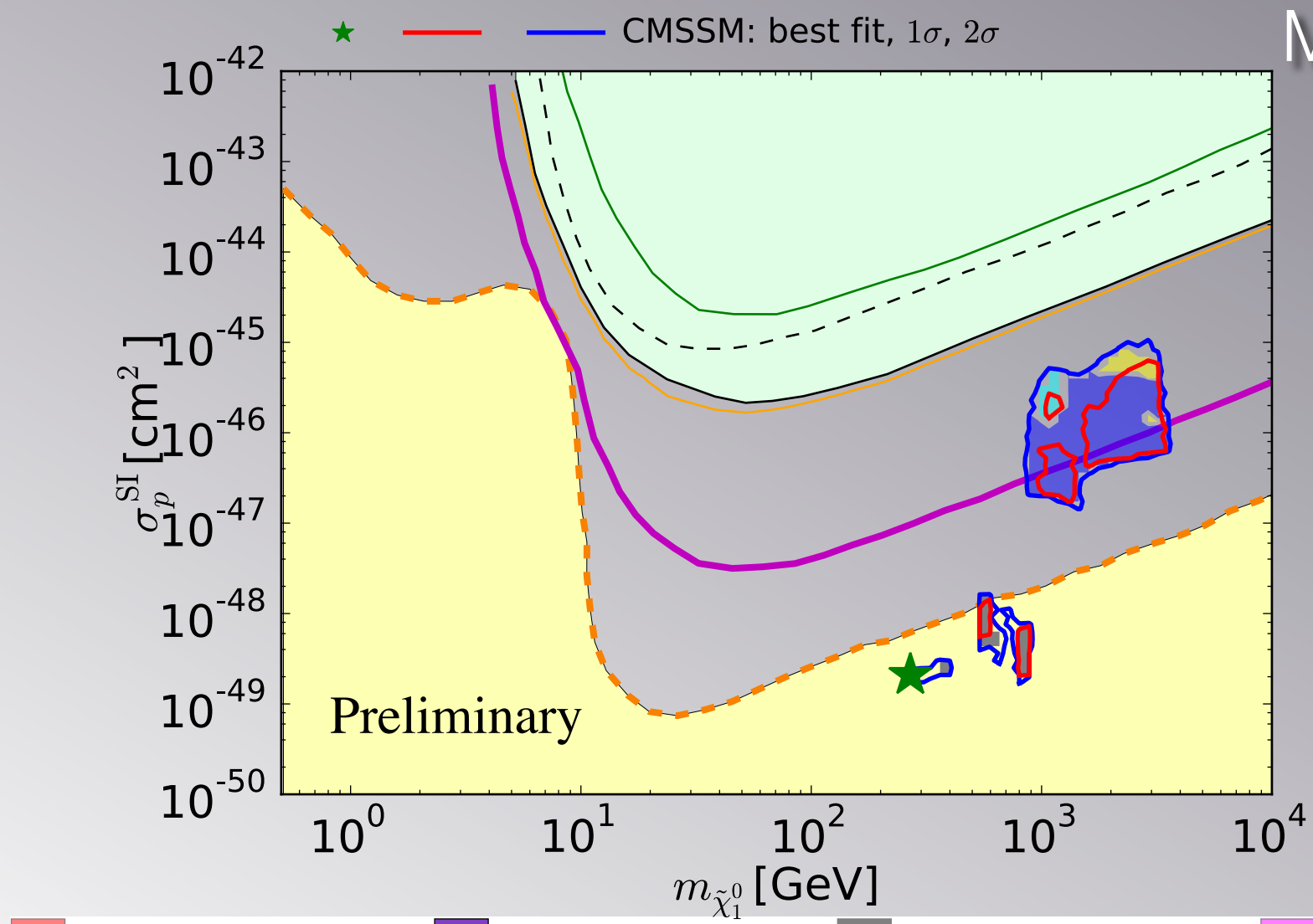
LZ

stau coann.
hybrid
stop coann.
h funnel
A/H funnel
$\tilde{\chi}_1^{\pm}$ coann.
focus point
Z funnel

- CMSSM

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

Elastic scaterring cross-section



stau coann.	hybrid	stop coann.	h funnel
A/H funnel	$\tilde{\chi}_1^{\pm}$ coann.	focus point	Z funnel

- CMSSM

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

Weak (?) scale supersymmetric dark matter

Weak (?) scale supersymmetric dark matter

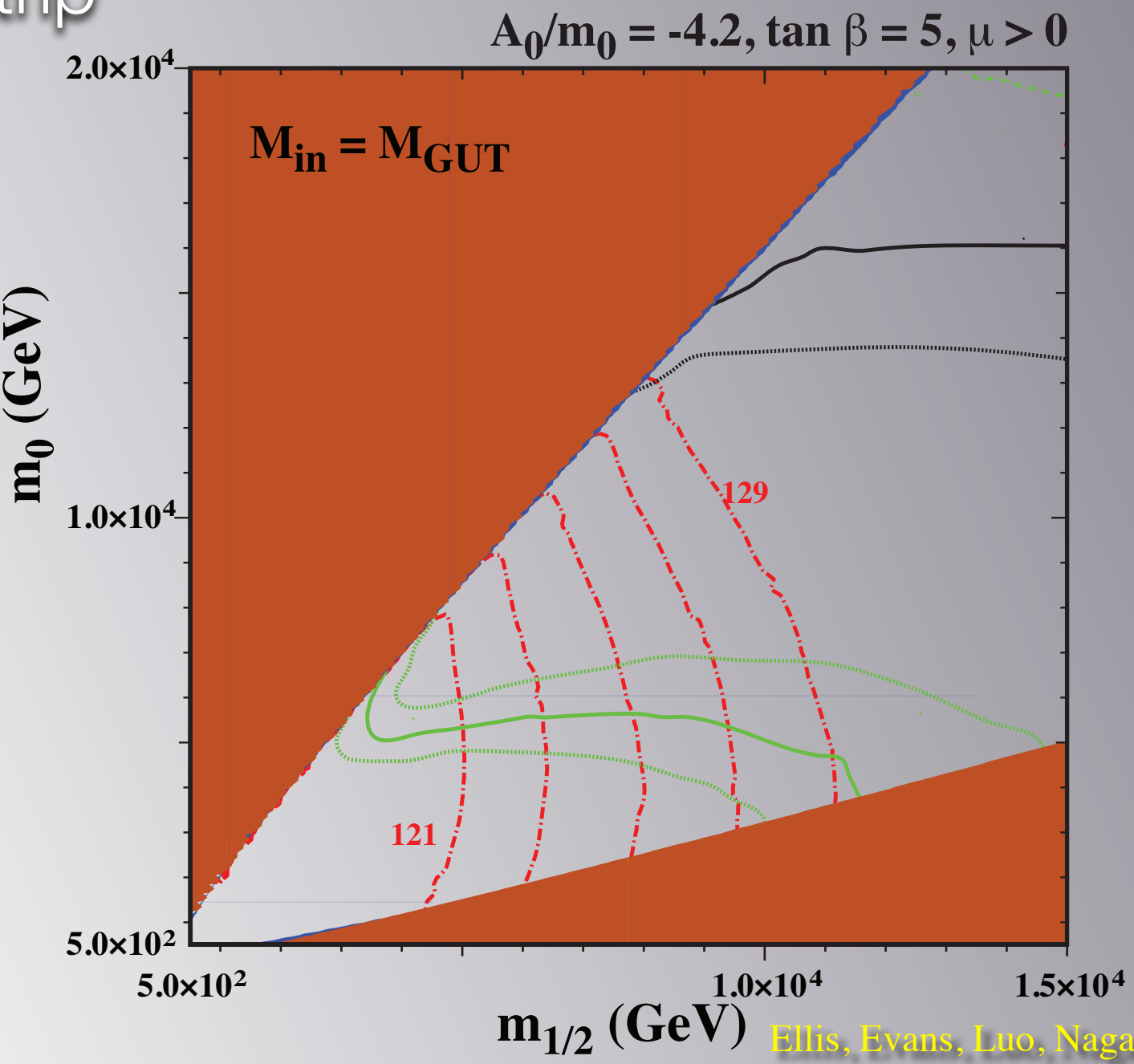
Viable regions of parameter space with dark matter is found along strips:

Weak (?) scale supersymmetric dark matter

Viable regions of parameter space with dark matter is found along strips:

- Stau-coannhilation Strip
  - extends only out to ~1 TeV
- Stop-coannihilation Strip
- Higgs Funnel
- Focus Point

Stop strip



Ellis, Evans, Luo, Nagata, Olive, Sandick
Ellis, Evans, Luo, Olive, Zheng
Bagnaschi et al.
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Three Requirements

- Relic Density*
- Higgs Mass
- Proton Decay Lifetime

*Assuming no late entropy production

Proton Decay

Dominant Mode: $p \rightarrow K^{+}\overline{\nu}.$

Current Limit: 6.6×10^{33} yr SuperK

Proton Decay

Dominant Mode: $p \rightarrow K^{+}\overline{\nu}.$

Current Limit: 6.6×10^{33} yr SuperK

Expected update (8.2×10^{33} yr)

Proton Decay

Dominant Mode: $p \rightarrow K^{+}\overline{\nu}.$

Current Limit: 6.6×10^{33} yr SuperK

Expected update (8.2×10^{33} yr)

Future Limits: $1.9\ (4.0) \times 10^{34}$ yr JUNO

10 years (20 years)

Proton Decay

Dominant Mode: $p \rightarrow K^{+}\overline{\nu}.$

Current Limit: 6.6×10^{33} yr SuperK

Expected update (8.2×10^{33} yr)

Future Limits: $1.9\ (4.0) \times 10^{34}$ yr JUNO

$3.3\ (6.5) \times 10^{34}$ yr DUNE

10 years (20 years)

Proton Decay

Dominant Mode: $p \rightarrow K^{+}\overline{\nu}.$

Current Limit: 6.6×10^{33} yr SuperK

Expected update (8.2×10^{33} yr)

Future Limits: $1.9\ (4.0) \times 10^{34}$ yr JUNO

$3.3\ (6.5) \times 10^{34}$ yr DUNE

$3.2\ (5.0) \times 10^{34}$ yr HyperK

10 years (20 years)

Minimal SU(5) GUT

$$W_5 = \mu_\Sigma \mathrm{Tr}\,\Sigma^2 + \frac{1}{6}\lambda' \mathrm{Tr}\,\Sigma^3 + \mu_H \overline{H} H + \lambda \overline{H} \Sigma H$$
$$+ (h_{\mathbf{10}})_{ij}\, \epsilon_{\alpha\beta\gamma\delta\zeta}\, \Psi_i^{\alpha\beta} \Psi_j^{\gamma\delta} H^\zeta + \left(h_{\overline{\mathbf{5}}}\right)_{ij} \Psi_i^{\alpha\beta} \Phi_{j\alpha} \overline{H}_\beta,$$

$$\Psi_i \ni \{Q_i,\ e^{-i\varphi_i}\overline{U}_i,\ V_{ij}\overline{E}_j\}, \qquad \Phi_i \ni \{\overline{D}_i,\ L_i\},$$

$$W_{\rm eff}^{\Delta g} = \frac{c}{M_P}\mathrm{Tr}\,[\Sigma \mathcal{W}\mathcal{W}], \quad \mathcal{W} \equiv \mathcal{W}^A T^A \qquad \epsilon \equiv 8cV/M_P.$$

$$\langle\Sigma\rangle = V \cdot \mathrm{diag}(2,2,2,-3,-3), \qquad V = 4\mu_\Sigma/\lambda'$$

$$M_{H_C} = 5\lambda V \qquad M_\Sigma = 5\lambda' V/2 \qquad M_X = 5 g_5 V$$

$$\mu_H \approx 3\lambda V$$

Ellis, Evans, Luo, Nagata, Olive, Sandick
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Minimal SU(5) GUT

$$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{3}{2\pi^2}\ln\left(\frac{Q^3}{M_X^2 M_\Sigma}\right),$$

$$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = -\frac{3}{10\pi^2}\ln\left(\frac{Q}{M_{H_C}}\right) - \frac{96cV}{M_P},$$

$$\frac{5}{g_1^2(Q)} + \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{15}{2\pi^2}\ln\left(\frac{Q}{M_X}\right) + \frac{6}{g_5^2(Q)} - \frac{144cV}{M_P},$$

$\epsilon = 0$ $\qquad \epsilon \equiv 8cV/M_P.$

$M_{H_C} = 5\lambda V$ $\qquad M_\Sigma = 5\lambda' V/2$ $\qquad M_X = 5g_5 V$

Only λ or λ' free

Ellis, Evans, Luo, Nagata, Olive, Sandick
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Minimal SU(5) GUT

$$\epsilon = \frac{1}{6g_3^2(M_{\rm GUT})} - \frac{1}{6g_1^2(M_{\rm GUT})} - \frac{1}{40\pi^2}\ln\left(\frac{M_{\rm GUT}}{M_{H_C}}\right),$$

Both λ or λ' free

Allows larger M_{HC} and longer proton lifetime

Free Parameters:

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu).$

$M_{\rm in},\ \lambda,\ \lambda'.$

Ellis, Evans, Luo, Nagata, Olive, Sandick
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Proton Decay

$$p \rightarrow K^+ \overline{\nu}.$$

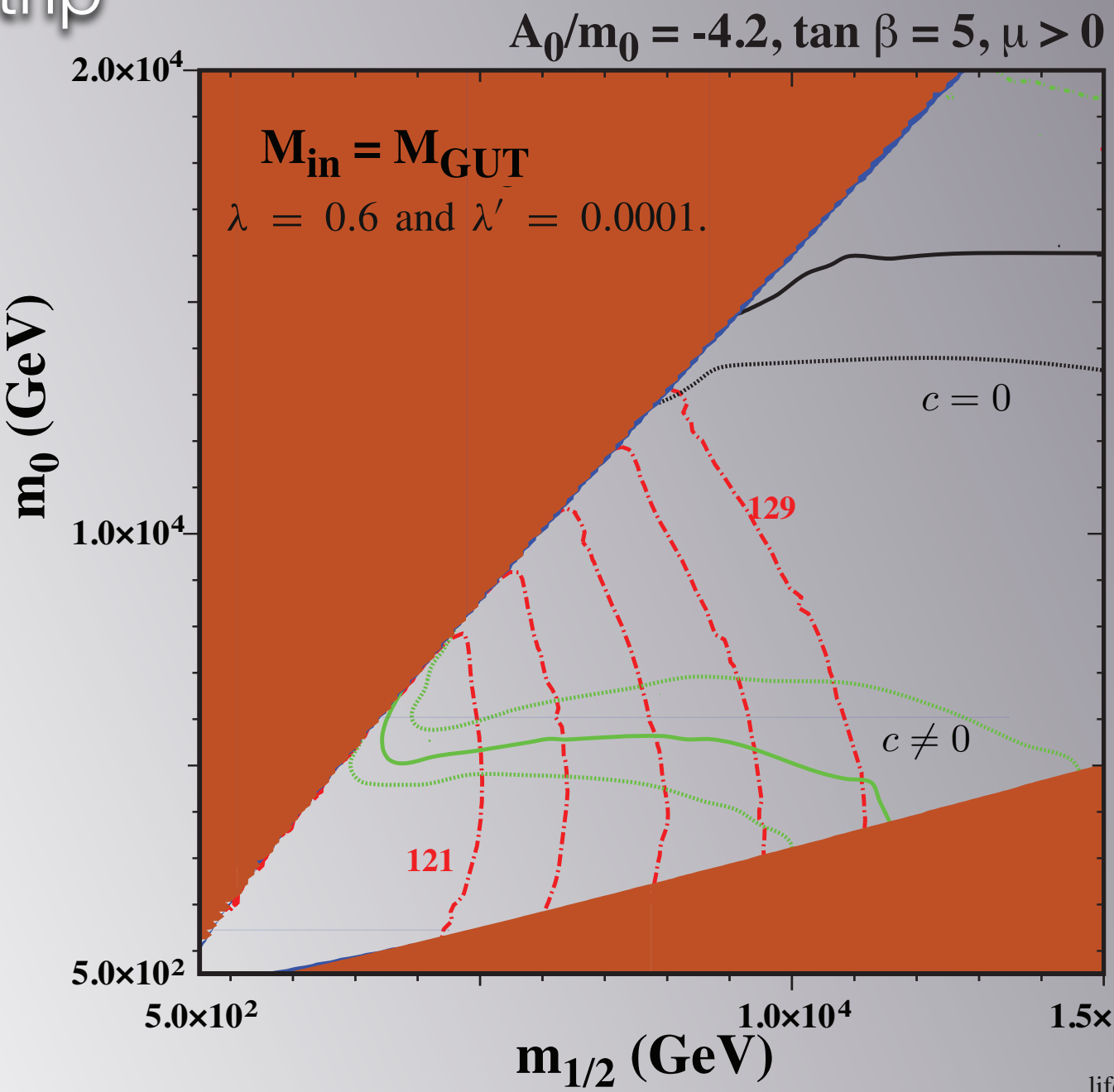
$$\Gamma(p \to K^+ \bar{\nu}_i) = \frac{m_p}{32\pi}\left(1 - \frac{m_K^2}{m_p^2}\right)^2 |\mathcal{A}(p \to K^+ \bar{\nu}_i)|^2,$$

$$\begin{aligned}\mathcal{A}(p \to K^+ \bar{\nu}_i) = & C_{RL}(usd\nu_i)\langle K^+|(us)_R d_L|p\rangle \\ & + C_{RL}(uds\nu_i)\langle K^+|(ud)_R s_L|p\rangle \\ & + C_{LL}(usd\nu_i)\langle K^+|(us)_L d_L|p\rangle \\ & + C_{LL}(uds\nu_i)\langle K^+|(ud)_L s_L|p\rangle.\end{aligned}$$

Wilson coefficients C are determined from RGE running

Matrix elements from lattice simulations Aokim Izubuchi, Shintani, Soni (2017)

Stop strip



20yr DUNE 3σ discovery range

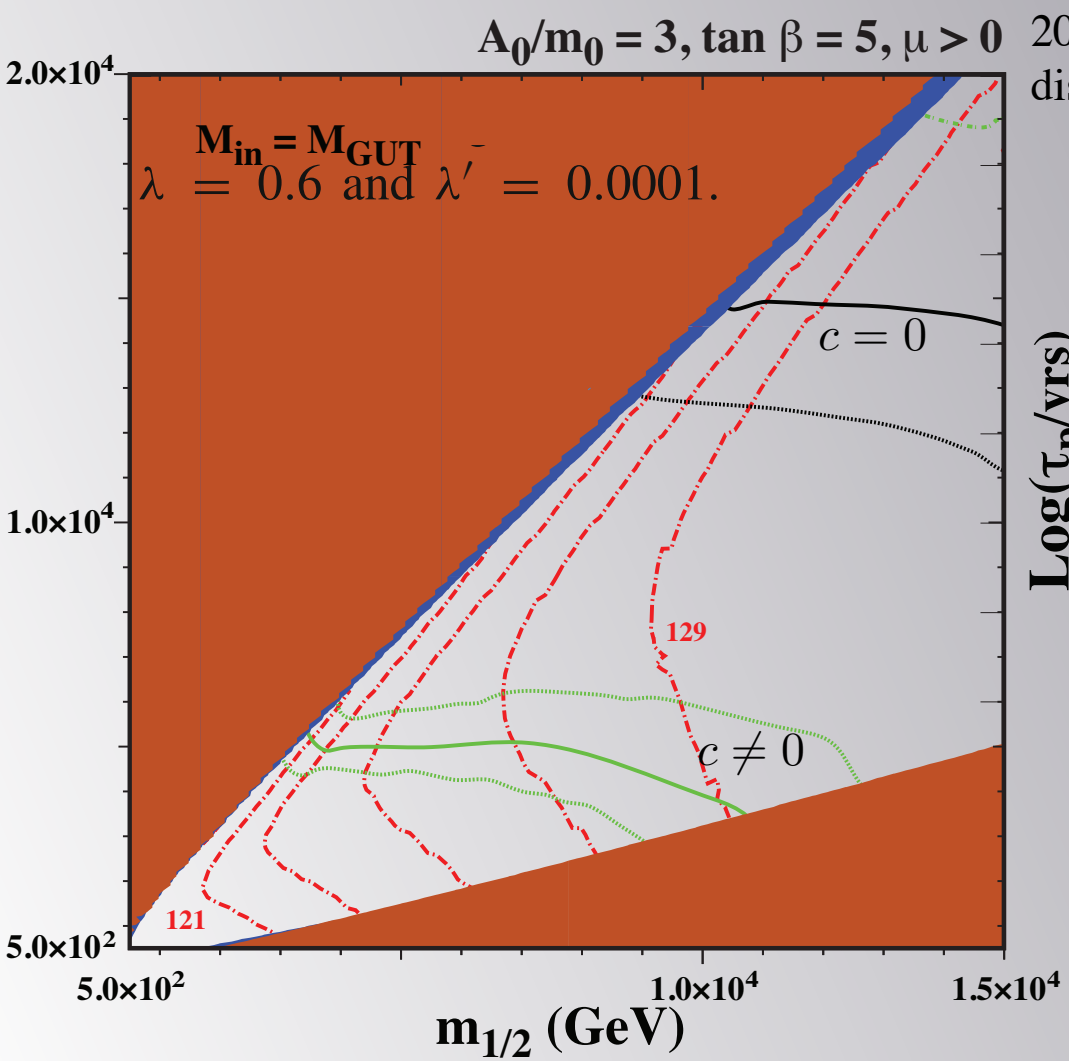
$\pm1\sigma$ Uncertainty in α_s and hadronic matrix elements

lifetimes in units of 10^{33} years

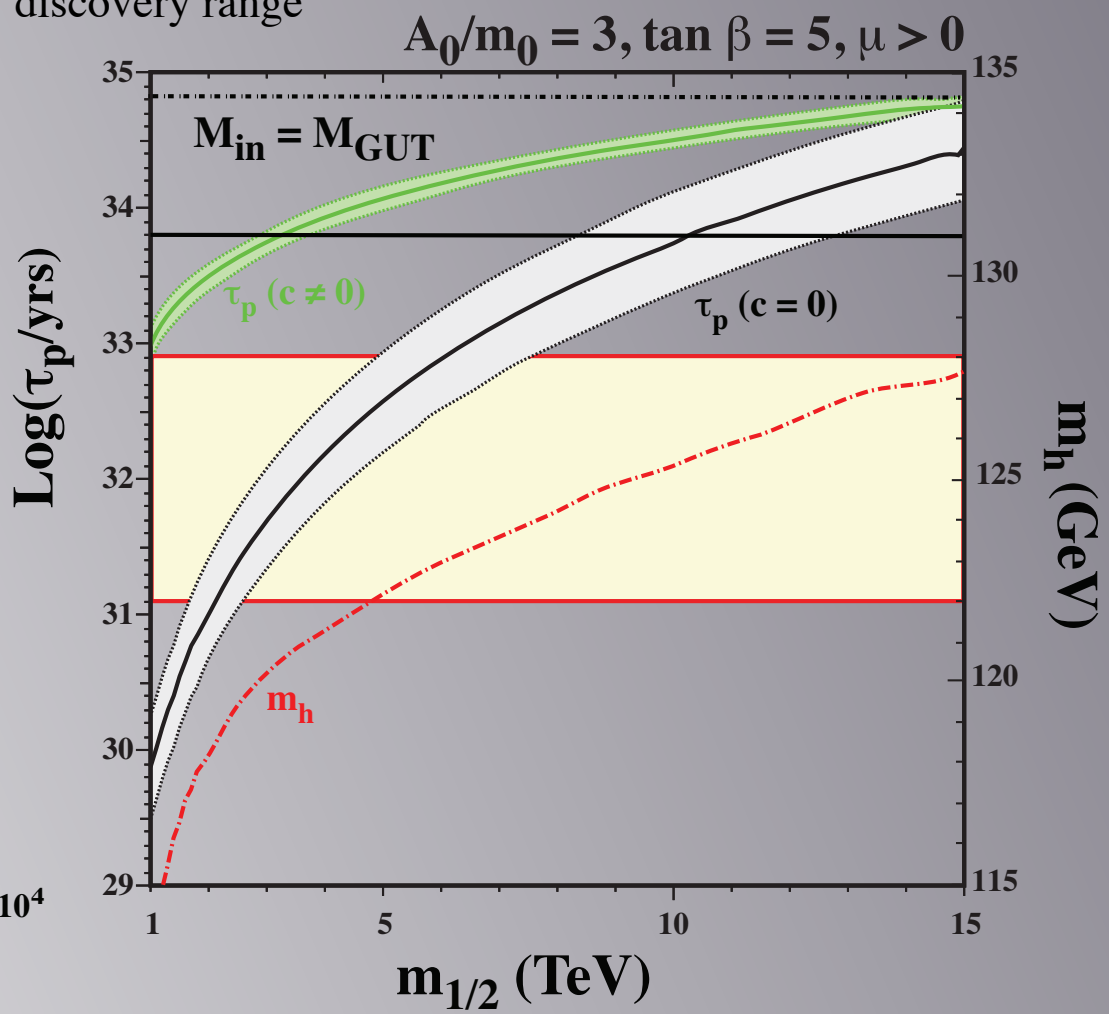
$m_{1/2}$	m_0	m_χ	$\tau_p(c=0)$	ϵ	$\tau_p(c\neq0)$
6.4	10.6	3.0	1.5 ± 1.3	0.0030	16 ± 4

Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Stop strip



20yr DUNE 3σ discovery range

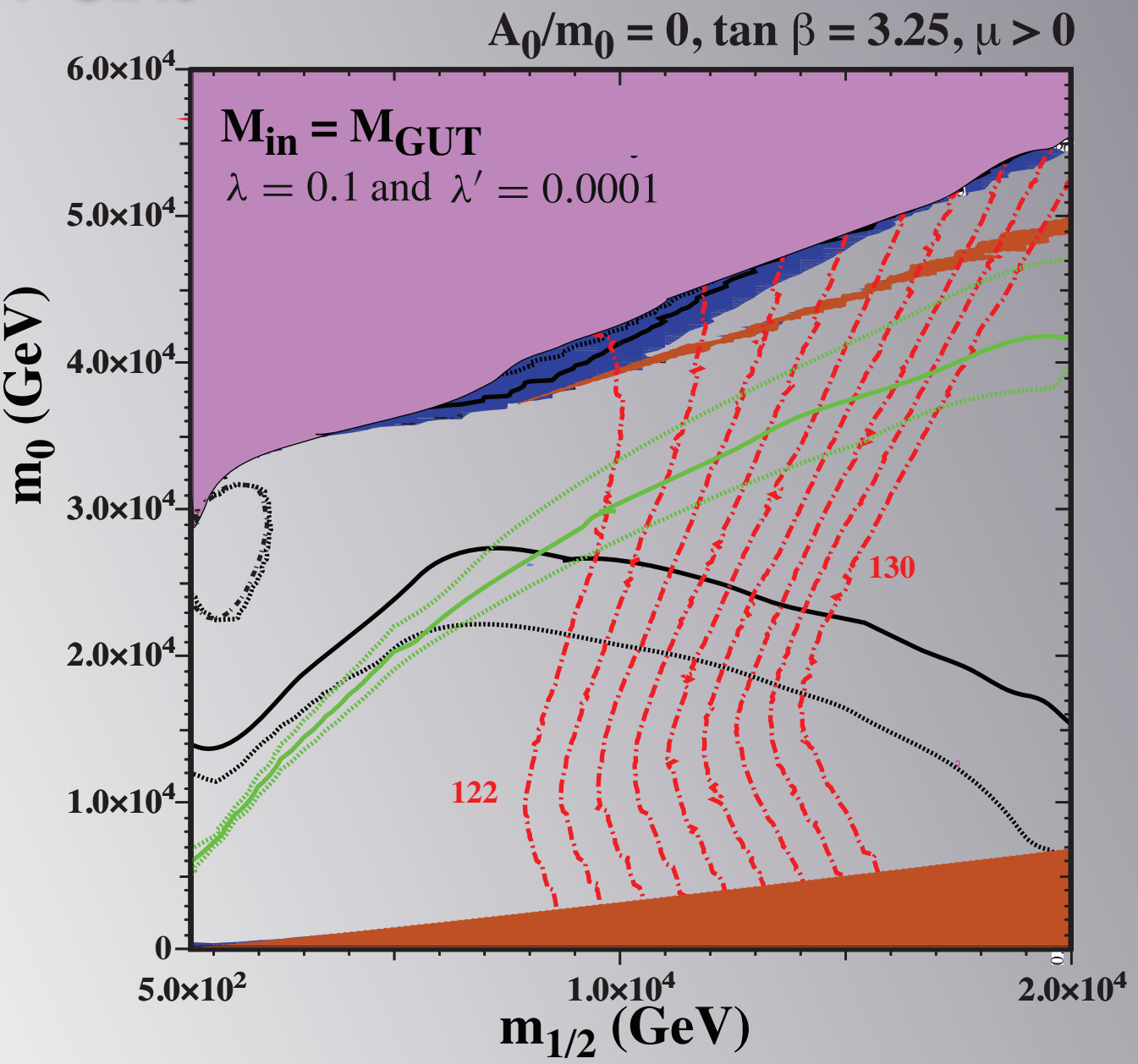


lifetimes in units of 10^{33} years

$m_{1/2}$	m_0	m_χ	$\tau_p(c=0)$	ϵ	$\tau_p(c\neq 0)$
9.8	14.1	4.8	5.4 ± 4.6	0.0024	33 ± 6

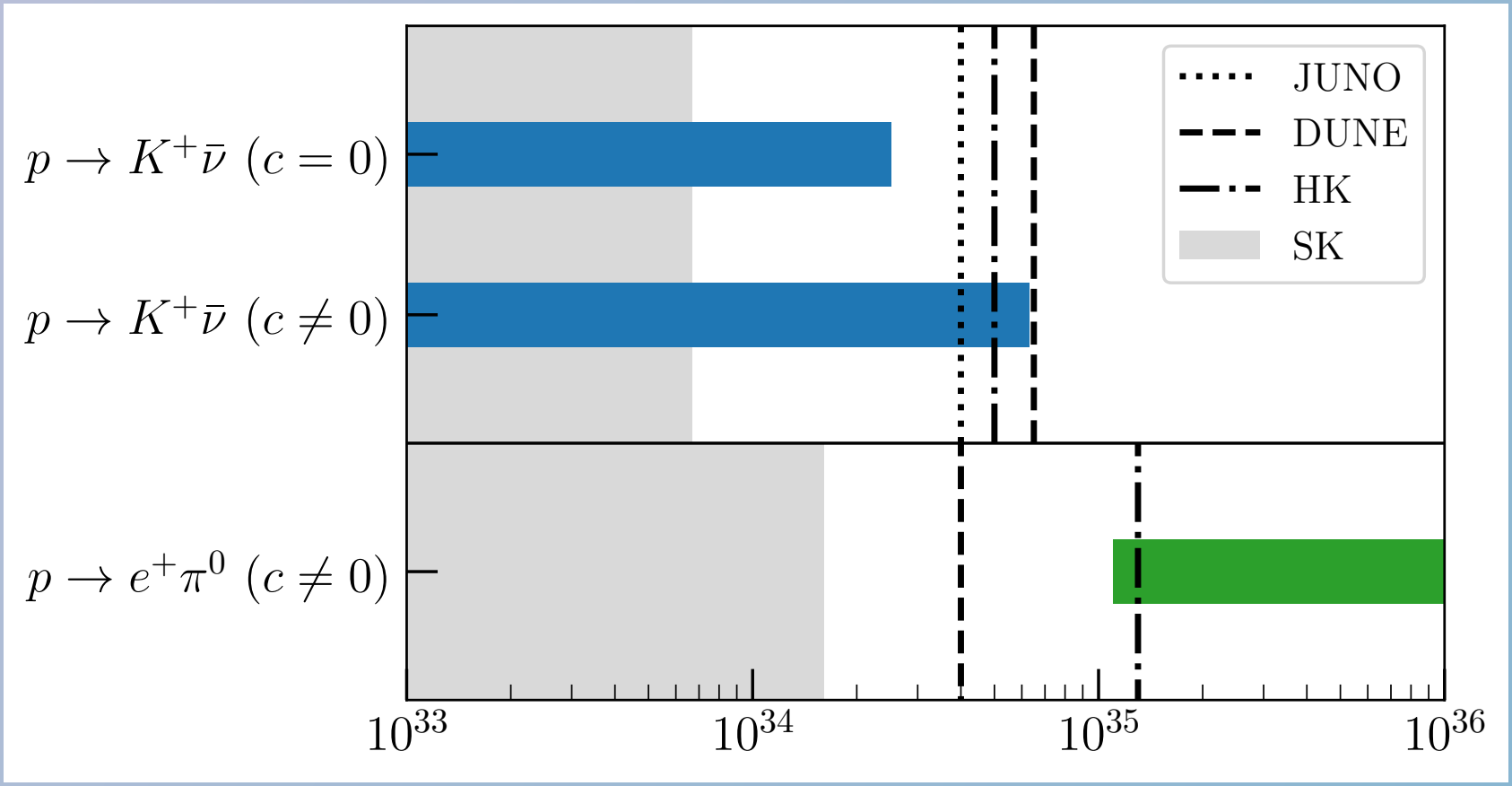
Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Focus Point



Ellis, Evans, Nagata, Olive, Velasco-Sevilla

Proton Decay



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

Missing Partner Models

Dimopoulos, Wilczek
Masiero, Nanopoulos,
Tamvakis, Yanagida

Avoids fine-tuning: $\mu_H \approx 3\lambda V$

75 **50**

$$W_5 = \frac{\mu_\Sigma}{2}\,\Sigma^{AB}_{CD}\Sigma^{CD}_{AB} - \frac{1}{3}\lambda'\,\Sigma^{AB}_{CD}\Sigma^{CD}_{EF}\Sigma^{EF}_{AB} + \lambda_\Theta \overline{H}_A \Sigma^{DE}_{BC}\Theta^{ABC}_{DE} + \lambda_{\bar\Theta} H^A \Sigma^{BC}_{DE}\bar\Theta^{DE}_{ABC}$$
$$+ M_\Theta \Theta^{ABC}_{DE}\bar\Theta^{DE}_{ABC} + (h_{\mathbf{10}})_{ij}\,\epsilon_{ABCDE}\Psi^{AB}_i\Psi^{CD}_j H^E + (h_{\bar{\mathbf{5}}})_{ij}\,\Psi^{AB}_i \Phi_{jA}\overline{H}_B\,,$$

$$\Psi_i \ni \{Q_i,\ e^{-i\varphi_i}\overline{U}_i,\ V_{ij}\overline{E}_j\}, \qquad \Phi_i \ni \{\overline{D}_i,\ L_i\},$$

$$W^{\Delta g}_{\rm eff} = \frac{d}{M_P}\mathcal{W}^C_A \mathcal{W}^D_B \Sigma^{AB}_{CD}\,, \qquad \mathcal{W} \equiv \mathcal{W}^A T^A$$

$$\langle \Sigma^{\alpha\beta}_{\gamma\delta}\rangle_0 = \frac{3}{2}V\left(\delta^\alpha_\gamma\delta^\beta_\delta - \delta^\alpha_\delta\delta^\beta_\gamma\right),$$
$$\langle \Sigma^{ab}_{cd}\rangle_0 = \frac{1}{2}V\left(\delta^a_c\delta^b_d - \delta^a_d\delta^b_c\right),$$
$$\langle \Sigma^{\alpha b}_{\gamma d}\rangle_0 = \langle \Sigma^{b\alpha}_{d\gamma}\rangle_0 = -\langle \Sigma^{b\alpha}_{\gamma d}\rangle_0 = -\langle \Sigma^{\alpha b}_{d\gamma}\rangle_0 = -\frac{1}{2}V\delta^\alpha_\gamma\delta^a_d\,,$$

$$V = \frac{3}{4}\frac{\mu_\Sigma}{\lambda'}\,.$$

Ellis, Evans, Nagata, Olive

Missing Partner Models

$$M_X = \sqrt{24} g_5 V$$

$$M_{\Sigma_{(\mathbf{1},\mathbf{1},0)}} = -\frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{1},5/3)}} = -\frac{8}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{2},-5/6)}} = 0 \ ,$$

$$M_{\Sigma_{(\mathbf{6},\mathbf{2},5/6)}} = \frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{1},0)}} = \frac{2}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{3},0)}} = \frac{10}{3}\lambda' V \ .$$

Hisano, Moroi, Tobe, Yanagida
Pokorski, Rolbiecki, Ross, Sakurai
Hisano, Nomura, Yanagida

Ellis, Evans, Nagata, Olive

Missing Partner Models

$$M_X = \sqrt{24} g_5 V$$

$$M_{\Sigma_{(\mathbf{1},\mathbf{1},0)}} = -\frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{1},5/3)}} = -\frac{8}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{2},-5/6)}} = 0 \ ,$$

$$M_{\Sigma_{(\mathbf{6},\mathbf{2},5/6)}} = \frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{1},0)}} = \frac{2}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{3},0)}} = \frac{10}{3}\lambda' V \ .$$

$$W_{\text{eff}} \supset -\lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} H_C^a \bar{H}_{Ca} \ , \qquad M_{H_C} = \lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} \ .$$

Hisano, Moroi, Tobe, Yanagida

Pokorski, Rolbiecki, Ross, Sakurai

Hisano, Nomura, Yanagida

Ellis, Evans, Nagata, Olive

Missing Partner Models

$$M_X = \sqrt{24} g_5 V$$

$$M_{\Sigma_{(\mathbf{1},\mathbf{1},0)}} = -\frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{1},5/3)}} = -\frac{8}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{2},-5/6)}} = 0 \ ,$$

$$M_{\Sigma_{(\mathbf{6},\mathbf{2},5/6)}} = \frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{1},0)}} = \frac{2}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{3},0)}} = \frac{10}{3}\lambda' V \ .$$

$$W_{\text{eff}} \supset -\lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} H_C^a \bar{H}_{Ca} \ , \qquad M_{H_C} = \lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} \ .$$

$$C(\mathbf{5}) = C(\bar{\mathbf{5}}) = \frac{1}{2} \ , \qquad C(\mathbf{10}) = \frac{3}{2} \ ,$$

$$C(\mathbf{50}) = C(\overline{\mathbf{50}}) = \frac{35}{2} \ , \qquad C(\mathbf{75}) = 25 \ .$$

Hisano, Moroi, Tobe, Yanagida
Pokorski, Rolbiecki, Ross, Sakurai
Hisano, Nomura, Yanagida

Ellis, Evans, Nagata, Olive

Missing Partner Models

$$M_X = \sqrt{24} g_5 V$$

$$M_{\Sigma_{(\mathbf{1},\mathbf{1},0)}} = -\frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{1},5/3)}} = -\frac{8}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{3},\mathbf{2},-5/6)}} = 0 \ ,$$

$$M_{\Sigma_{(\mathbf{6},\mathbf{2},5/6)}} = \frac{4}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{1},0)}} = \frac{2}{3}\lambda' V \ , \qquad M_{\Sigma_{(\mathbf{8},\mathbf{3},0)}} = \frac{10}{3}\lambda' V \ .$$

$$W_{\text{eff}} \supset -\lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} H_C^a \bar{H}_{Ca} \ , \qquad M_{H_C} = \lambda_\Theta \lambda_{\bar{\Theta}} \frac{(2V)^2}{M_\Theta} \ .$$

$$C(\mathbf{5}) = C(\bar{\mathbf{5}}) = \frac{1}{2} \ , \qquad C(\mathbf{10}) = \frac{3}{2} \ ,$$

$$C(\mathbf{50}) = C(\overline{\mathbf{50}}) = \frac{35}{2} \ , \qquad C(\mathbf{75}) = 25 \ .$$

Hisano, Moroi, Tobe, Yanagida
Pokorski, Rolbiecki, Ross, Sakurai
Hisano, Nomura, Yanagida

$$M_\Theta > M_{\text{GUT}} \left(\frac{M_{\text{in}}}{M_{\text{GUT}}} \right)^{\frac{52}{35}} \exp\left(\frac{-8\pi^2}{g_5^2(M_{\text{GUT}})} \frac{1}{35} \right) \simeq 2 \times 10^{17} \text{ GeV} \ ,$$

Ellis, Evans, Nagata, Olive

Missing Partner Models

$$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = -\frac{3}{10\pi^2}\ln\left(\frac{Q}{M_{H_C}}N_{H_C}\right) - \frac{48dV}{M_P}\ ,$$

$$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{3}{2\pi^2}\ln\left(\frac{Q^3}{M_X^2 M_{\Sigma_{(\mathbf{8},\mathbf{1},0)}}}N_X\right) + \frac{144dV}{M_P}\ ,$$

$$\frac{5}{g_1^2(Q)} + \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{15}{2\pi^2}\ln\left(N_{g_5}\frac{M^2_{\Sigma_{(\mathbf{8},\mathbf{1},0)}}}{M_X Q}\right) + \frac{6}{g_5^2(Q)} + \frac{72dV}{M_P}\ ,$$

$N_{H_C} = \frac{5^{\frac{25}{2}}}{2^{15}}\ ,$

$N_X = \frac{2^9}{5^{\frac{11}{2}}}\ ,$

$N_{g_5} = 2^{\frac{12}{5}}5^{\frac{1}{2}}$

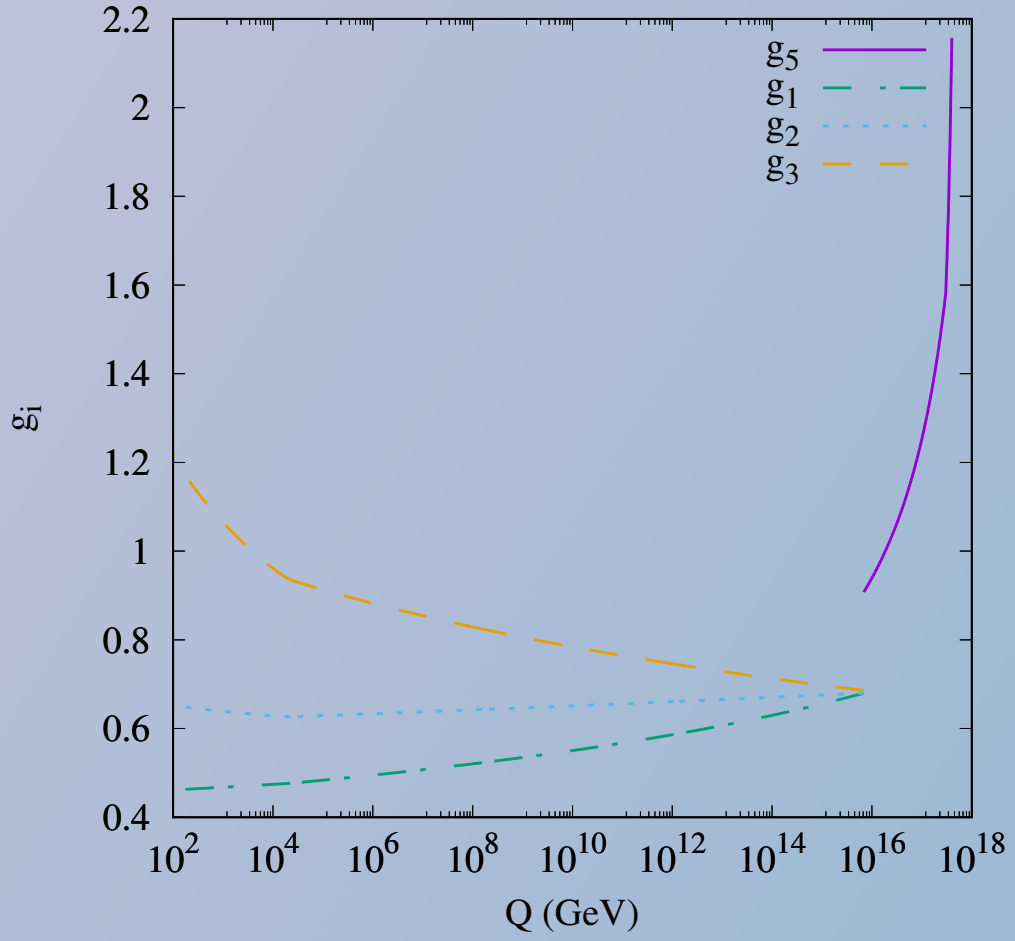
Free Parameters:

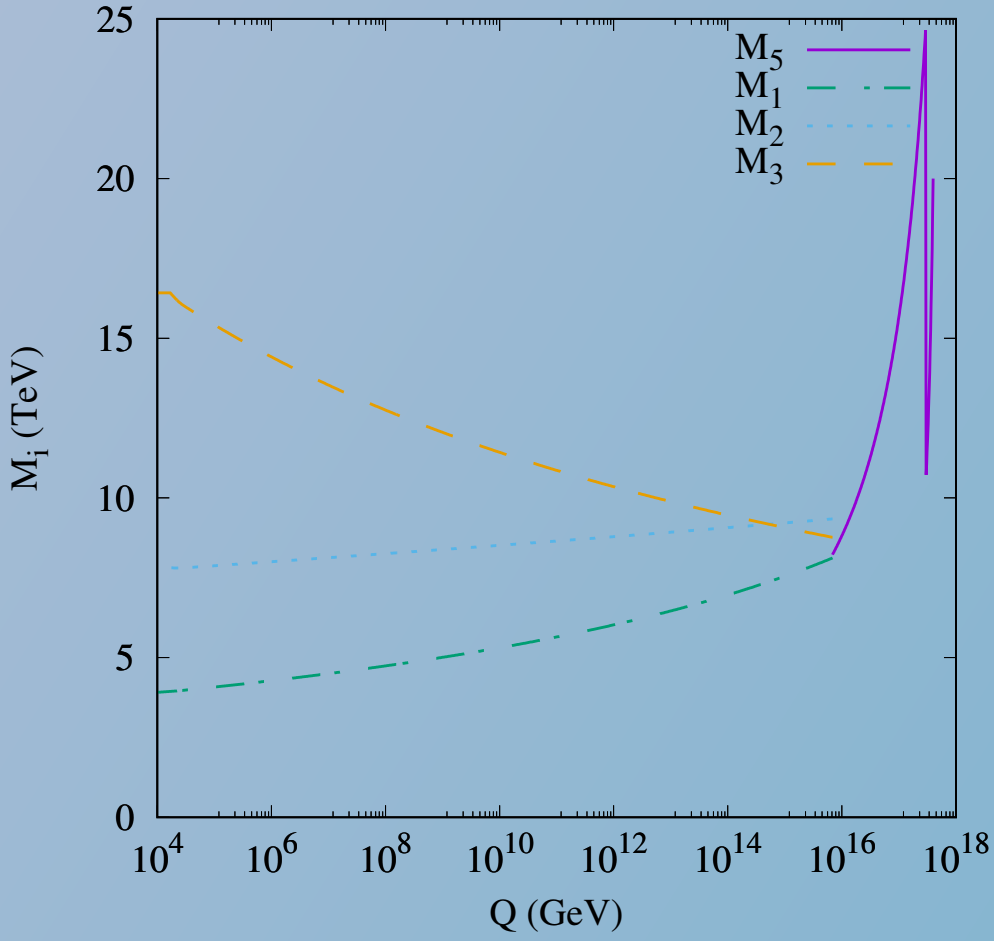
$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu).$

$M_{\rm in},\ M_\Theta, \lambda', \lambda_{\Theta,\bar\Theta}, B_0 = A_0 - m_0$

Ellis, Evans, Nagata, Olive

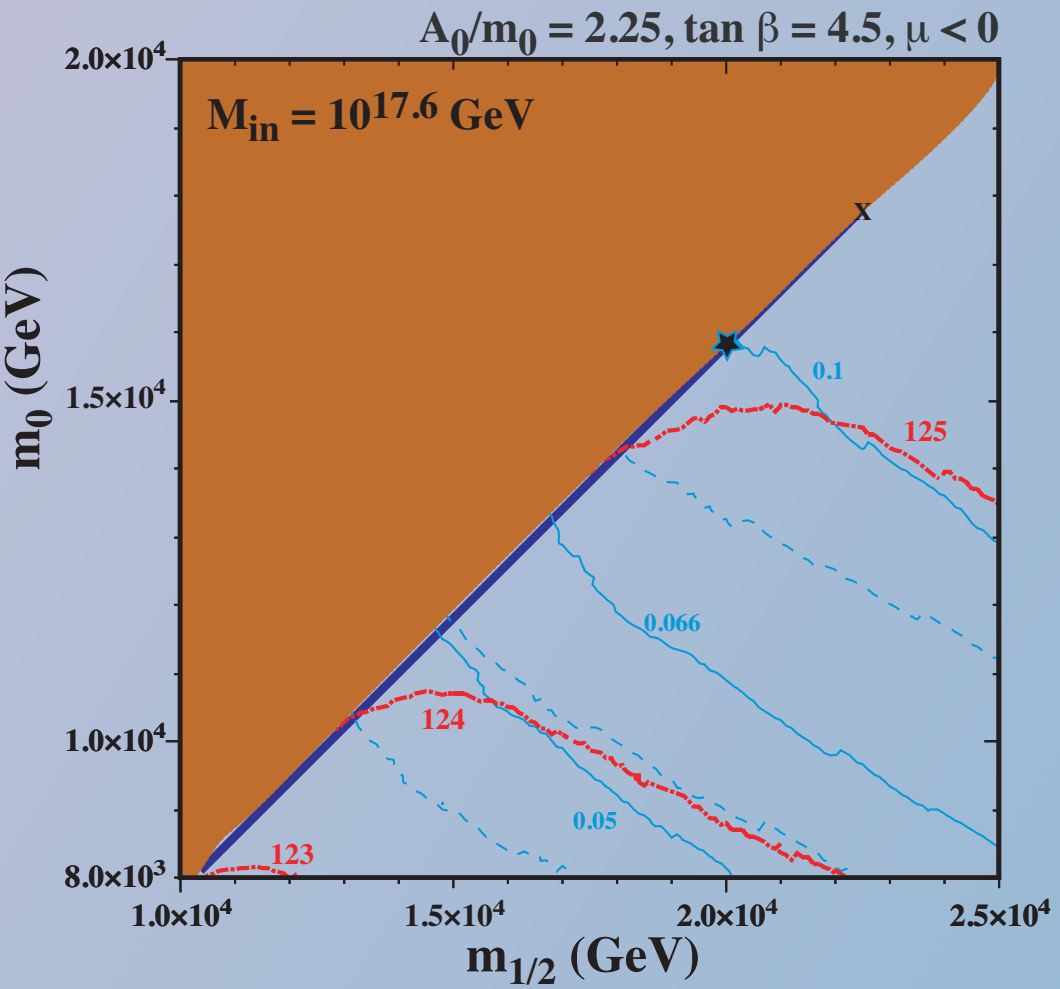
Missing Partner Models

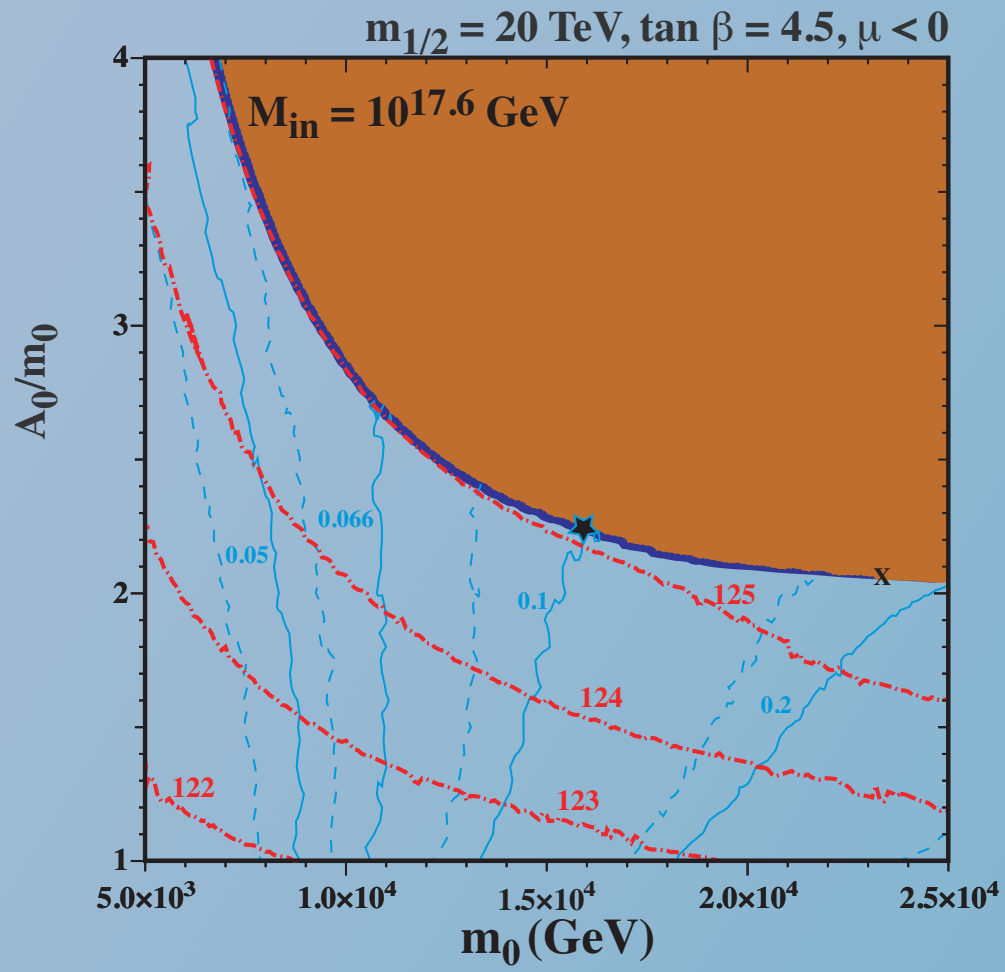




Ellis, Evans, Nagata, Olive

Missing Partner Models





Ellis, Evans, Nagata, Olive

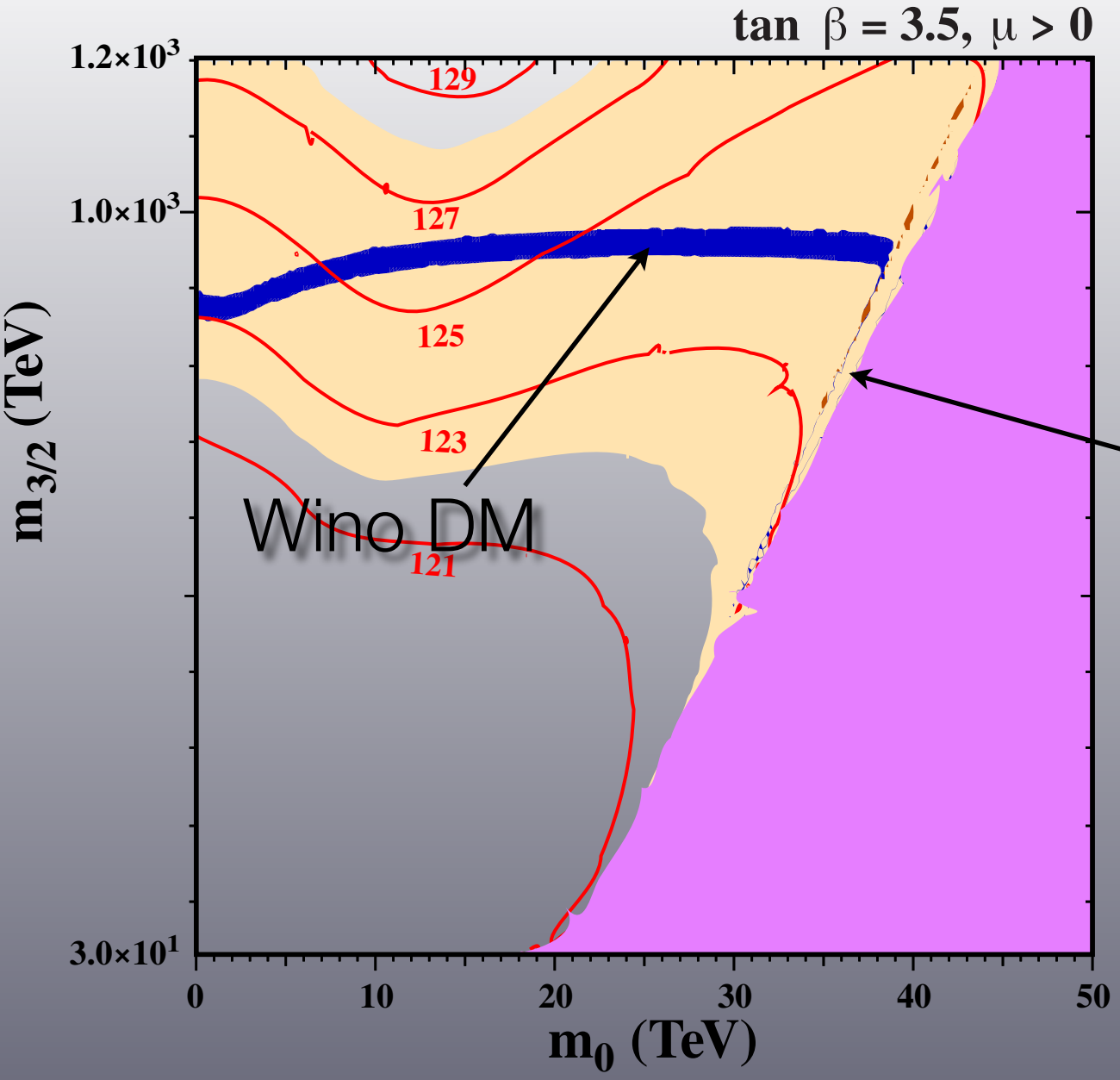
DM density/Higgs mass saturate for m_{SUSY} ~ O(10) TeV

Other Possibilities
(with PeV scales)

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 allows $m_0 \neq m_{3/2}$

mAMSB



Scalar masses: $m_0 \neq m_{3/2}$

Mastercode 2016

Bagnaschi et al.

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 ⇒ BBN 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 $\Omega_\chi h^2 \lesssim 0.12\frac{m_\chi}{m_{3/2}}$

$m_\chi < 8$ TeV ⇒ $m_{3/2} < 4$ TeV heavier gravitino → heavier neutralino → $\Omega_\chi h^2$ too large → $\Omega_{3/2}h^2$ too large

unless(!) the susy spectrum lies above the inflationary scale $m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2$ EeV

Gravitino Production

Standard Picture:

gluon + gluon → gluino + gravitino

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

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

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

Gravitino Production

Standard Picture:

gluon + gluon → gluino + gravitino

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

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

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

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

Gravitino Production

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

gluon + gluon → gravitino + gravitino

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

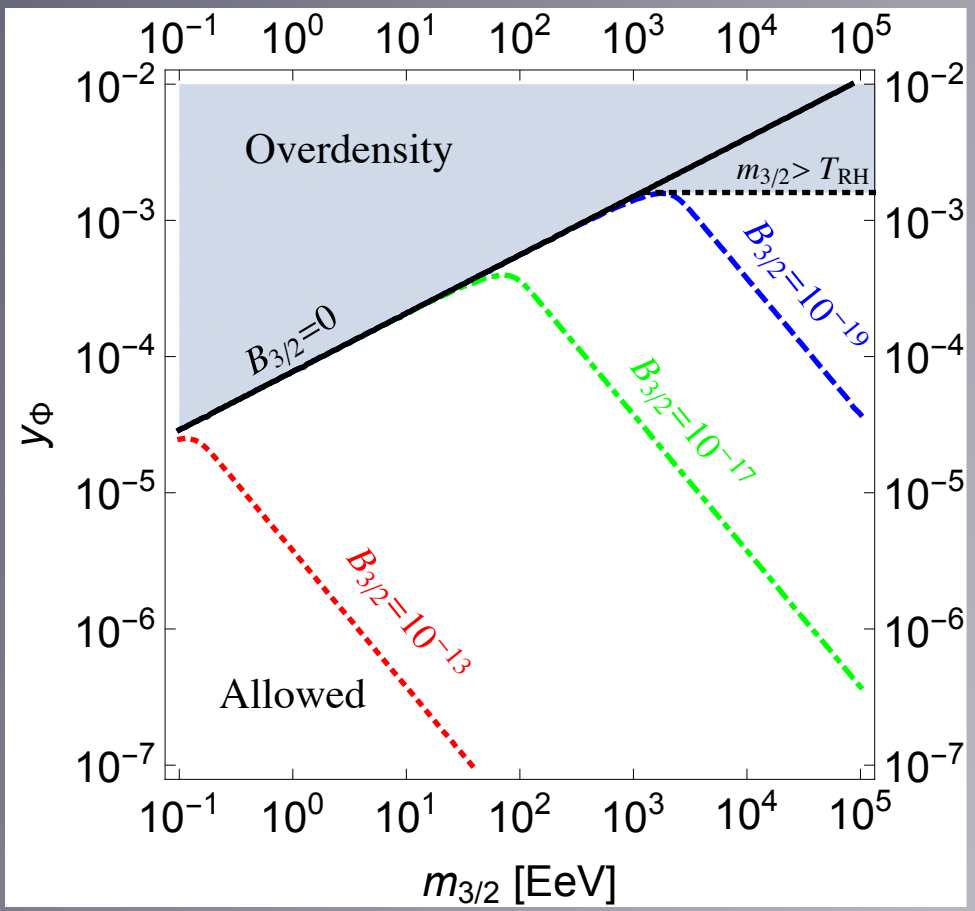
$$\Gamma \sim \frac{T^9}{M_P^4 m_{3/2}^4} \qquad \frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim \frac{T^7}{M_P^3 m_{3/2}^4}$$

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

Reheating

$$\Gamma_\phi = \frac{y_\phi^2}{8\pi} m_\phi$$

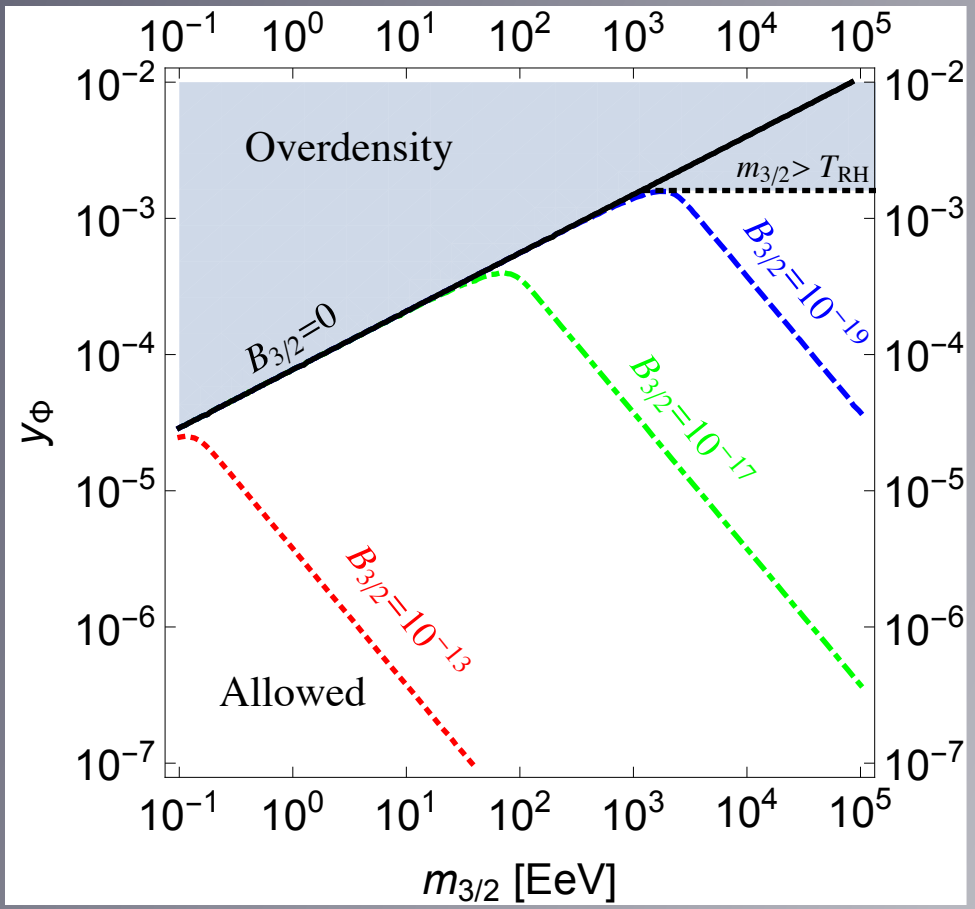
Limit on inflaton decay coupling



Reheating

$$\Gamma_\phi = \frac{y_\phi^2}{8\pi} m_\phi$$

Limit on inflaton decay coupling



inflaton decays to gravitinos

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

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

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

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

Can motivations for Supersymmetry still be addressed

- Gauge Hierarchy Problem -No
- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter -Yes

Even Larger Mass Scales

Planck Scale SUSY ≡ no susy at low energy

Even Larger Mass Scales

Planck Scale SUSY ≡ no susy at low energy

SO(10) GUT?

Even Larger Mass Scales

Planck Scale SUSY ≡ no susy at low energy

SO(10) GUT?

- Hierarchy Problem - No
- Gauge Coupling Unification
- Stabilization of the Electroweak Vacuum
- Radiative Electroweak Symmetry Breaking
- Dark Matter -Yes
- Neutrino masses…

Summary

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- However, still viable and more so beyond the CMSSM
- Proton decay may be a visible signature of these models
- Maybe the susy spectrum is very heavy
  - Is Susy at the multi-TeV or PeV or EeV scale?
- Perhaps sparticles were 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?