Reviving SO(10) for Cosmology

Reviving SO(10) for Cosmology

1) Dark Matter:

Reviving SO(10) for Cosmology

1) Dark Matter:

Non-Supersymmetric SO(10) - Do we need low energy SUSY?

Reviving SO(10) for Cosmology

1) Dark Matter:
Non-Supersymmetric SO(10) - Do we need low energy SUSY?

2) Starobinsky-like inflation in no-scale supergravty:

Reviving SO(10) for Cosmology

1) Dark Matter:
Non-Supersymmetric SO(10) - Do we need low energy SUSY?

2) Starobinsky-like inflation in no-scale supergravty:
Supersymmetric SO(10) and the connection to neutrino masses

Why Supersymmetry?

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

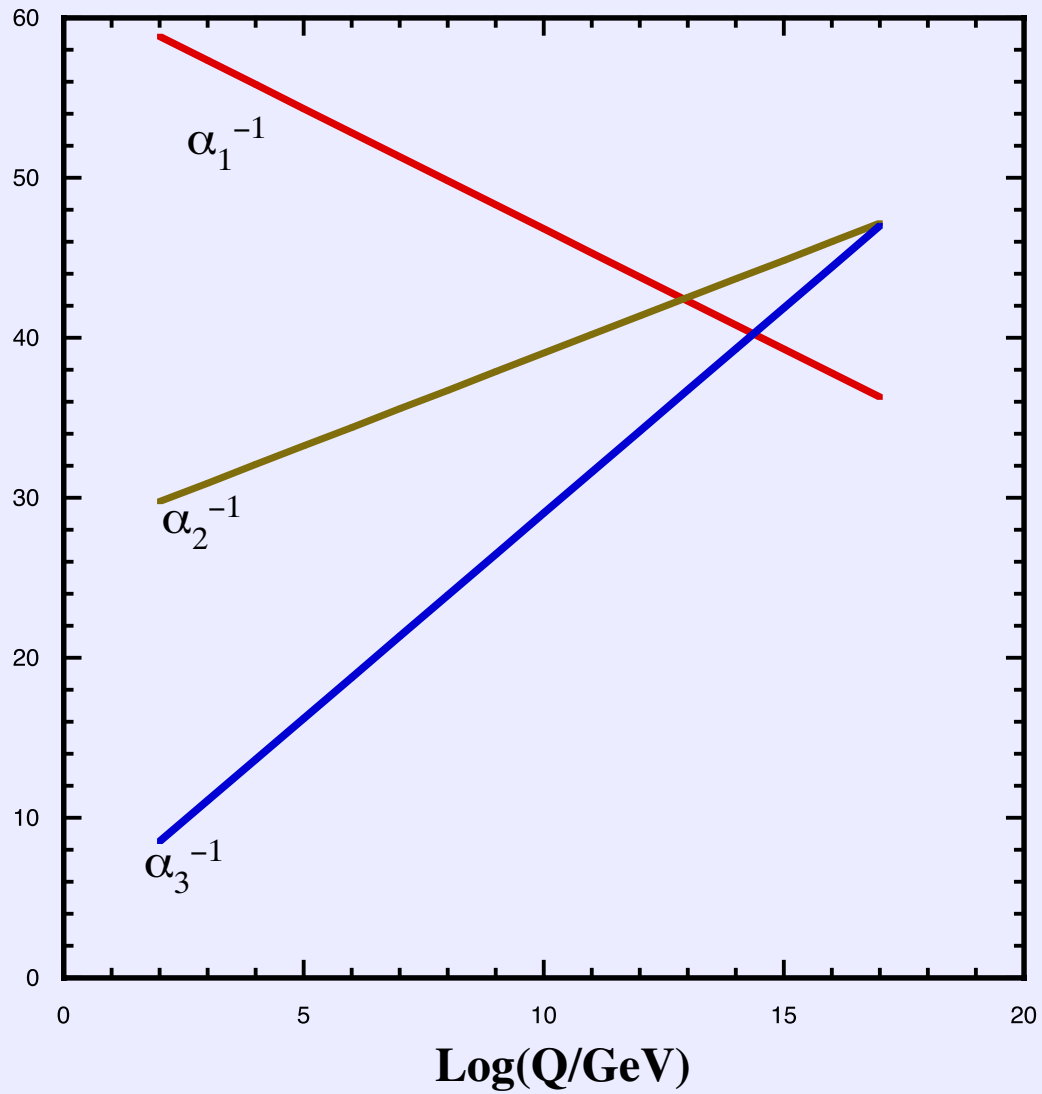
but, $m_h \sim 126$ GeV, and no SUSY?

GUTS

Supersymmetric SU(5) Grand Unified Theory

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

is really:

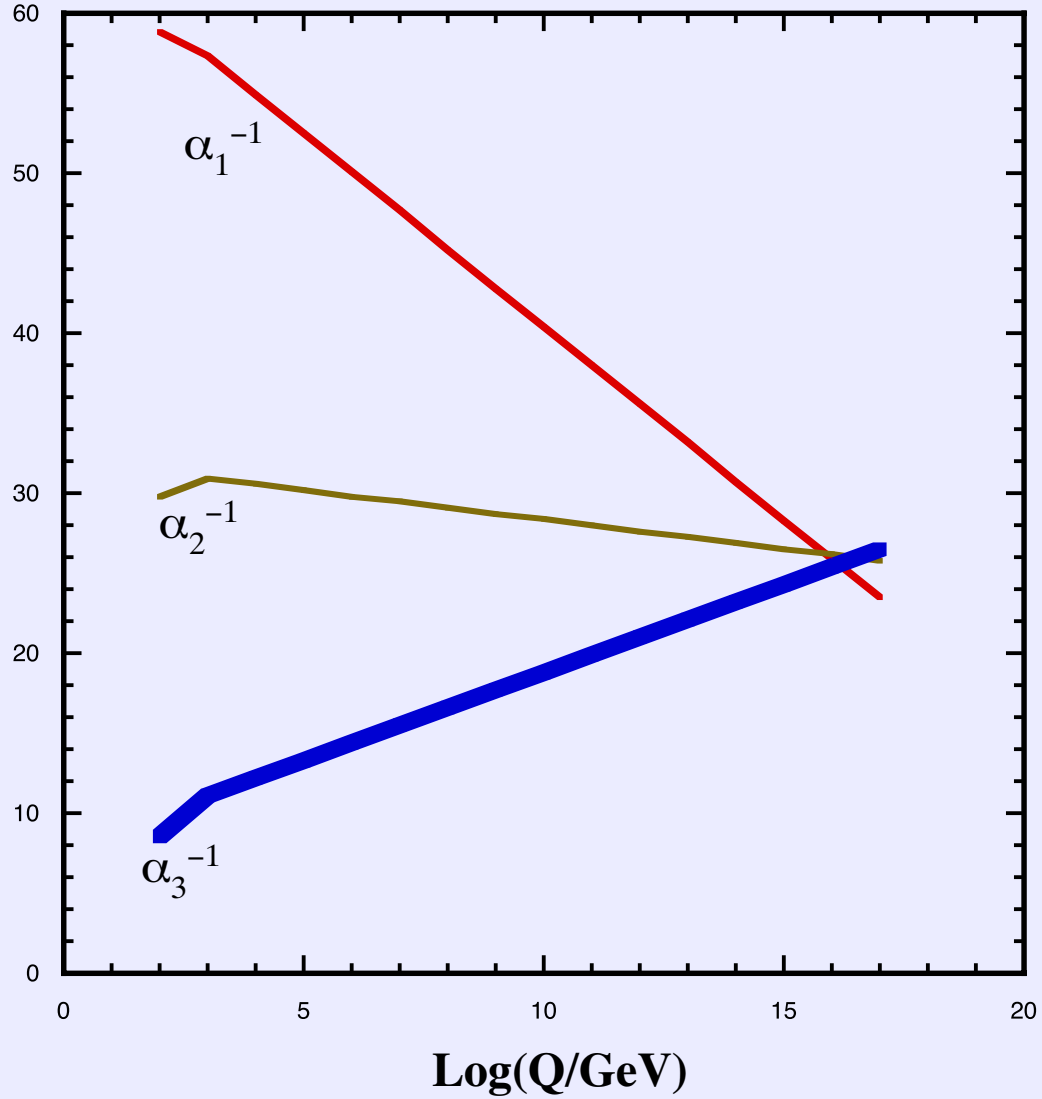


GUTS

Supersymmetric SU(5) Grand Unified Theory

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

is now



GUTS

Standard Model Higgs potential

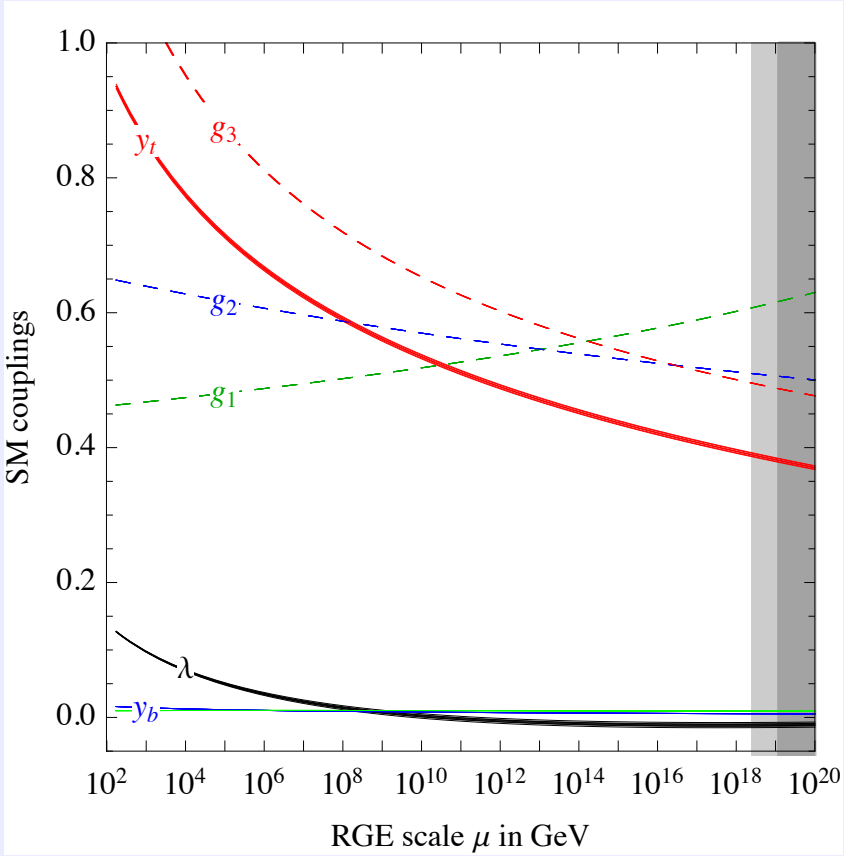
$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

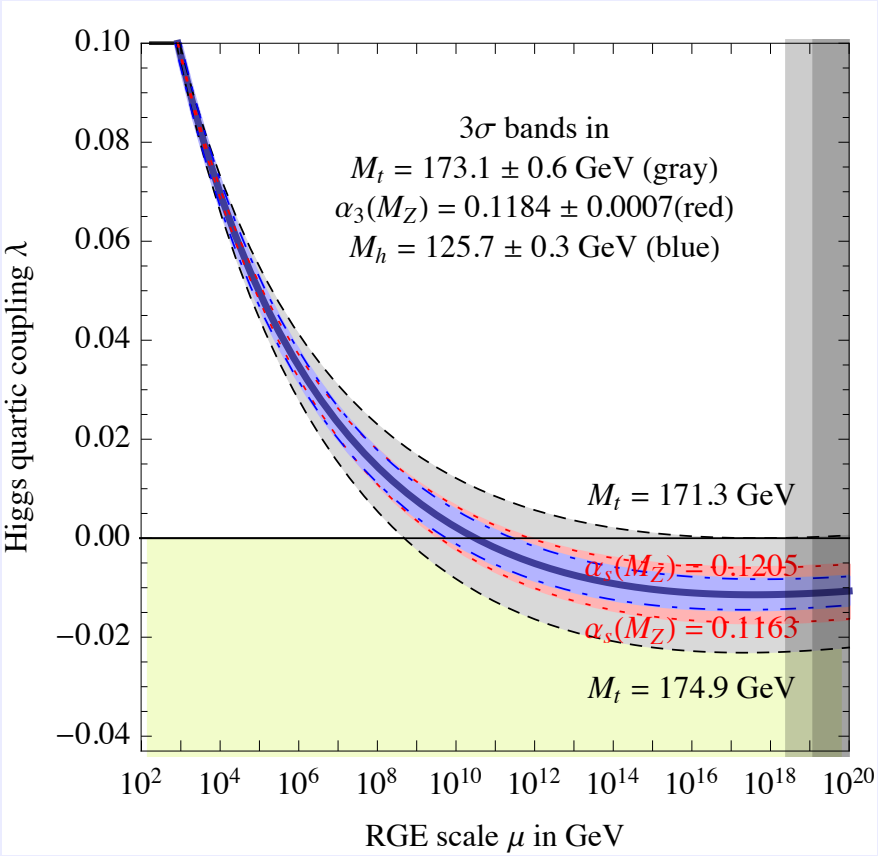
GUTS

Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

Running of the Higgs quartic coupling





Degrassi et al.

SusyGUTS

Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

$$\lambda = \frac{g_1^2 + g_2^2}{2}$$

Positive definite

Stability of the vacuum ensured

SusyGUTS

Standard Model Higgs potential

$$V = \frac{\lambda}{4}\phi^4 + \frac{m^2}{2}\phi^2$$

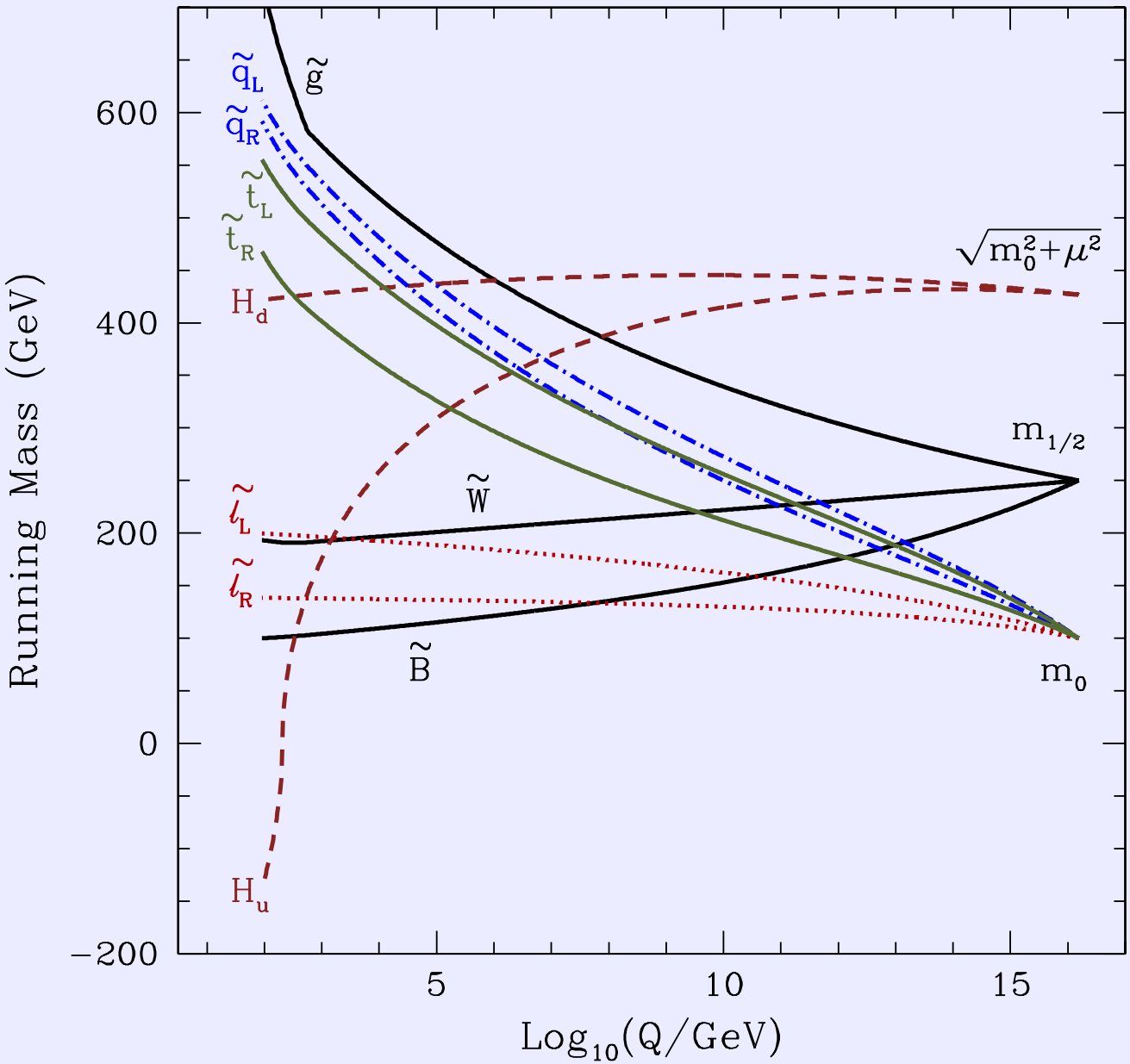
$$\lambda = \frac{g_1^2 + g_2^2}{2}$$

Positive definite

Stability of the vacuum ensured

Also for free: radiatively induced symmetry breaking

CMSSM Spectra



Unification to rich spectrum

+

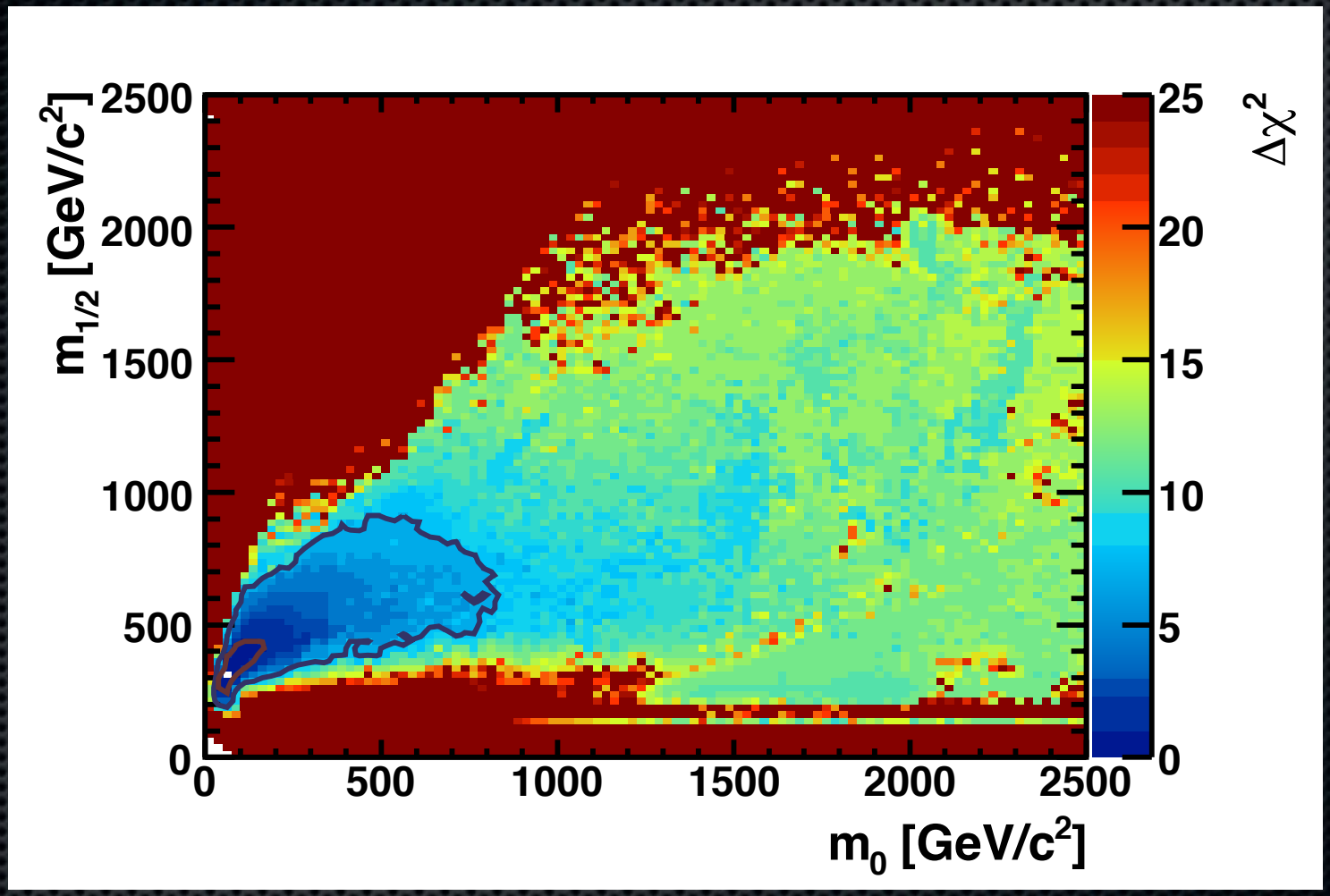
EWSB

Falk

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

Mastercode

2009



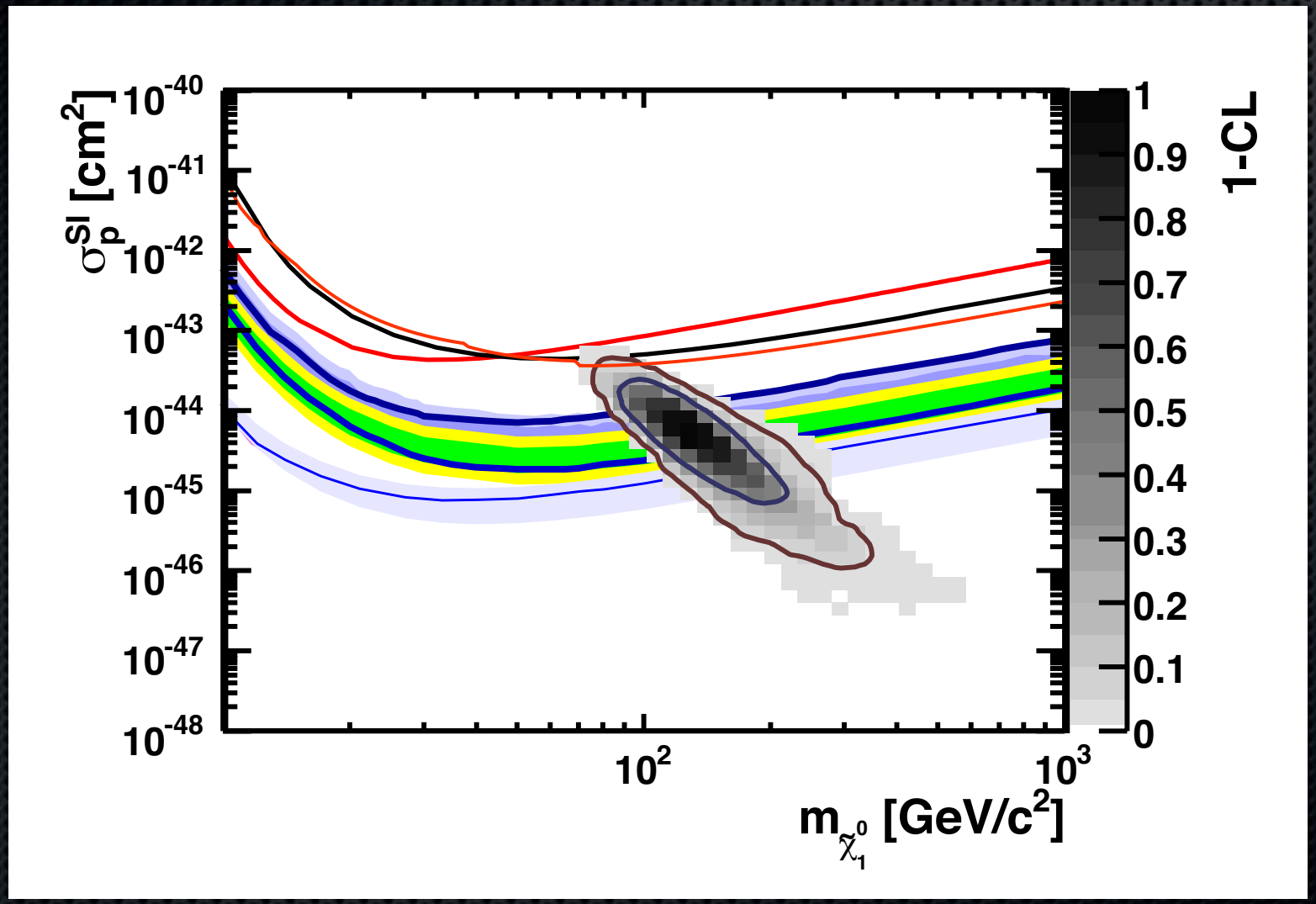
- CMSSM

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

Elastic scaterring cross-section

Mastercode

2009



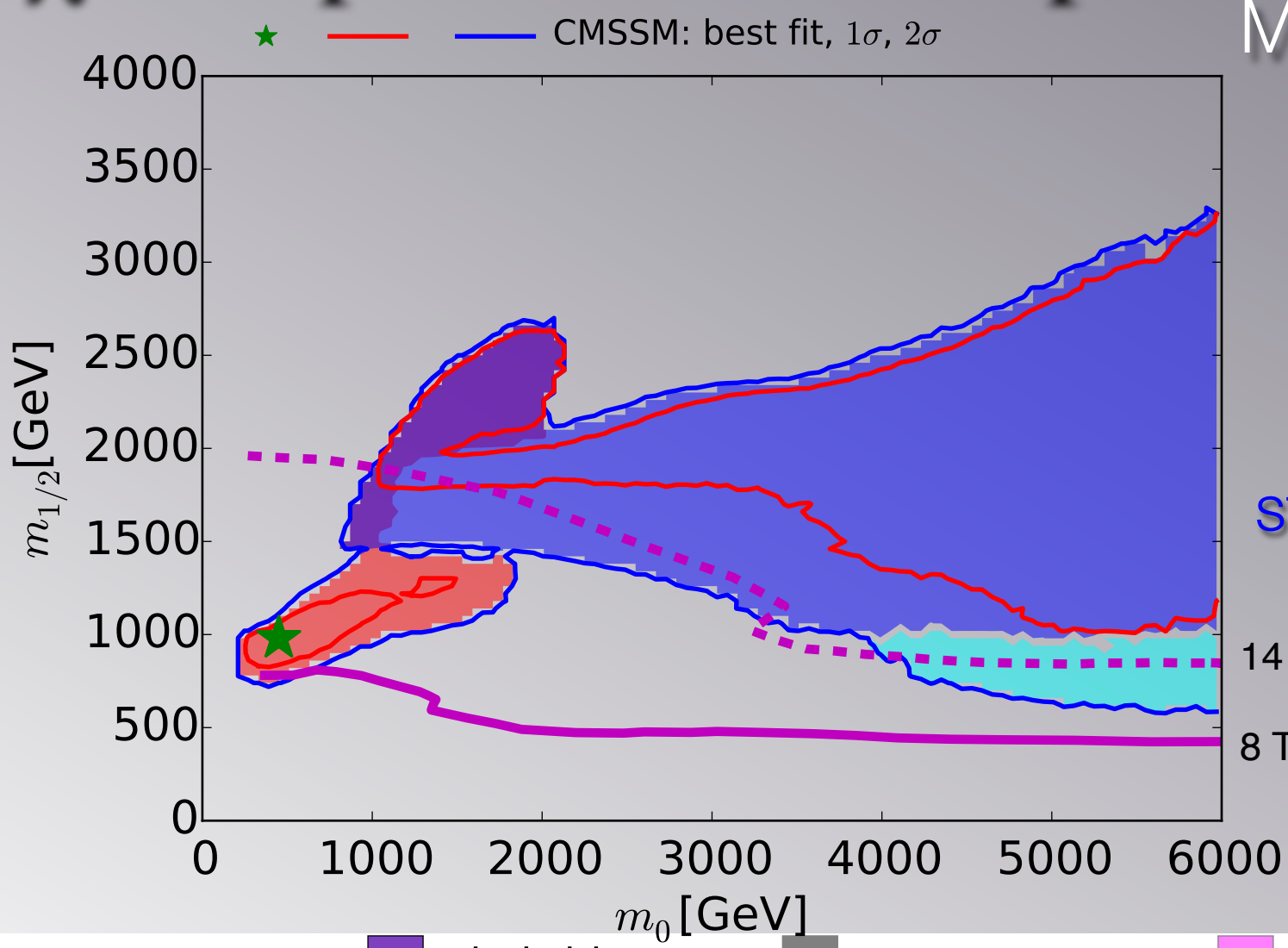
- CMSSM

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

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

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

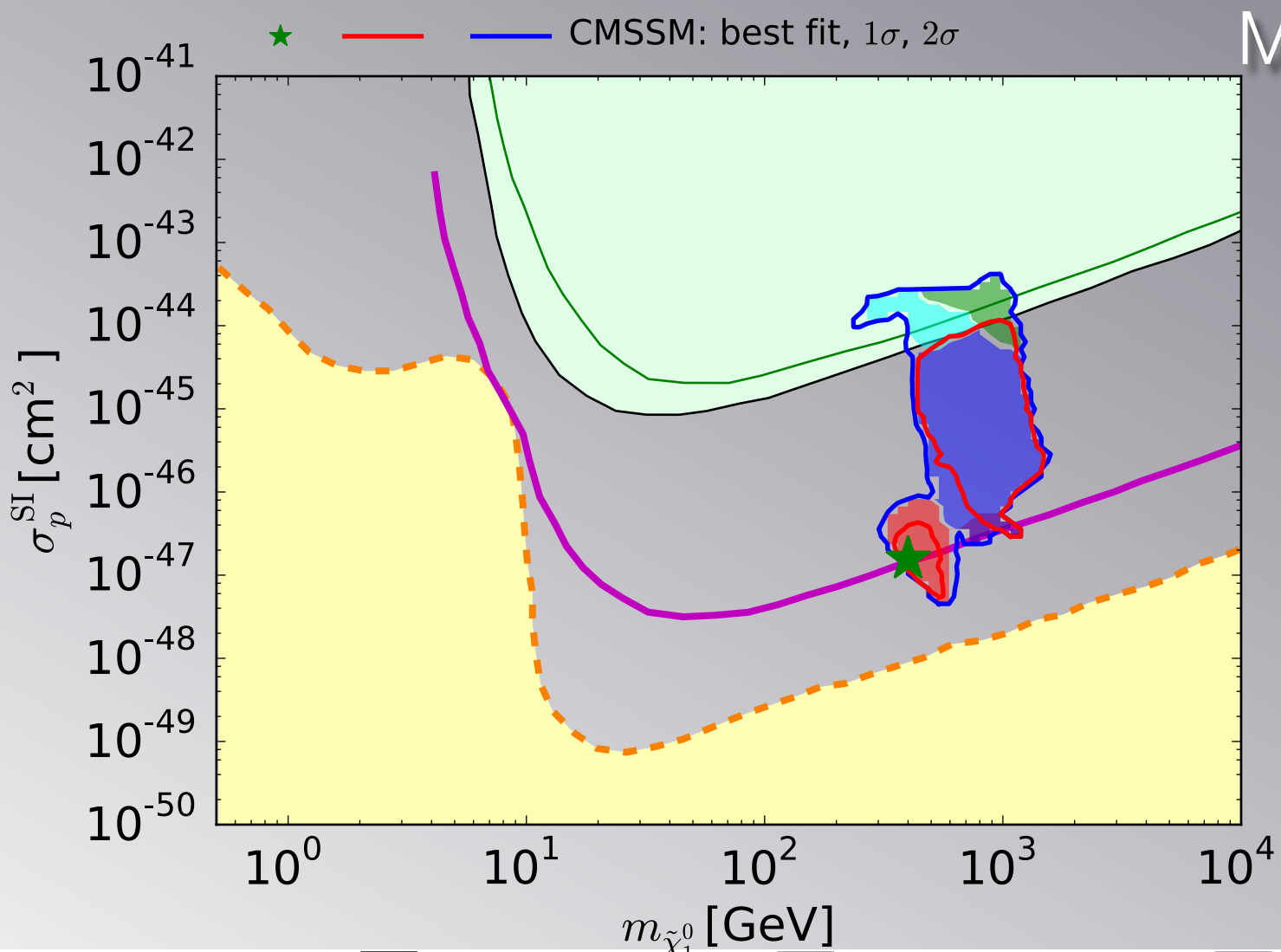
- CMSSM

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



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

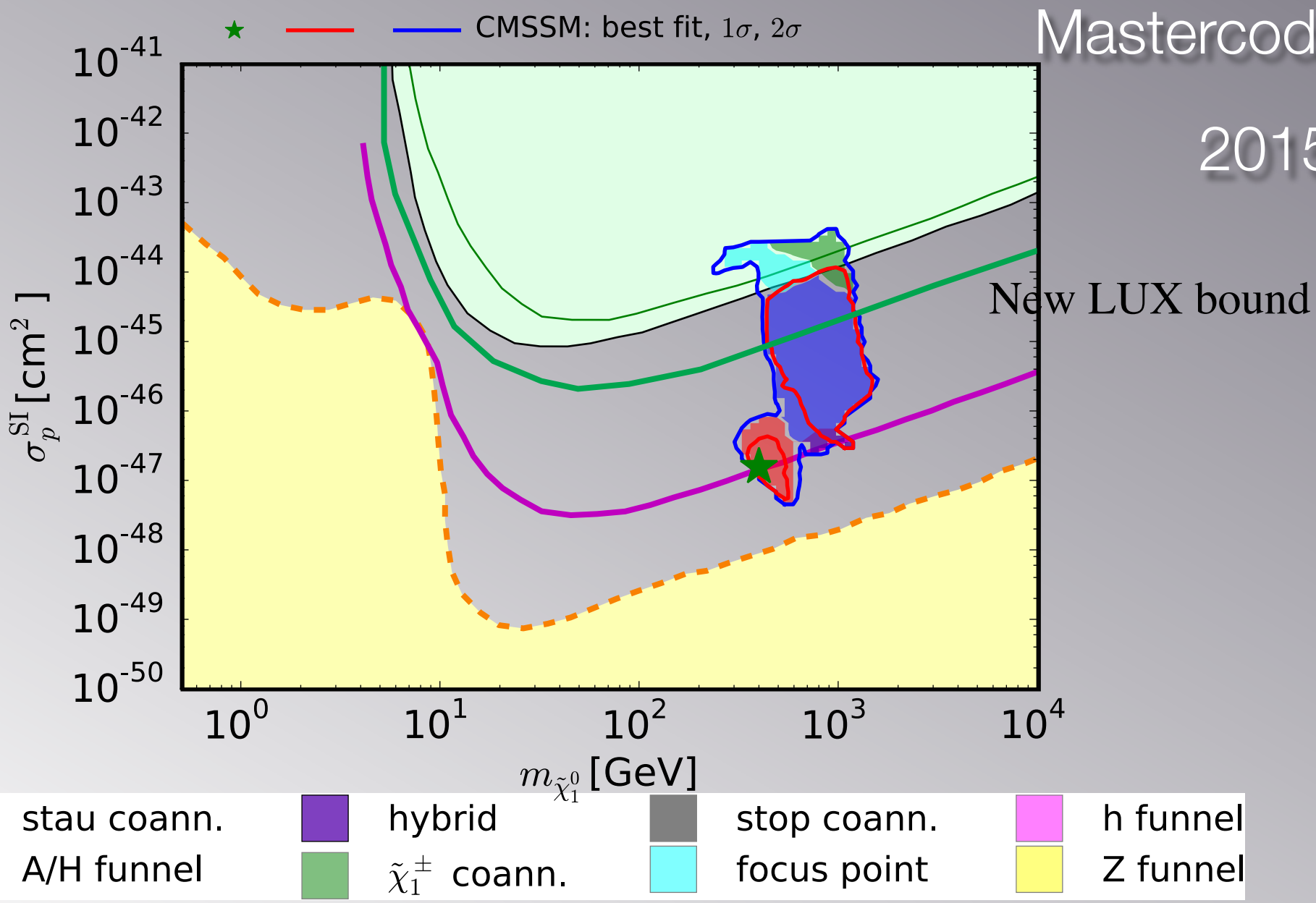
- CMSSM

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



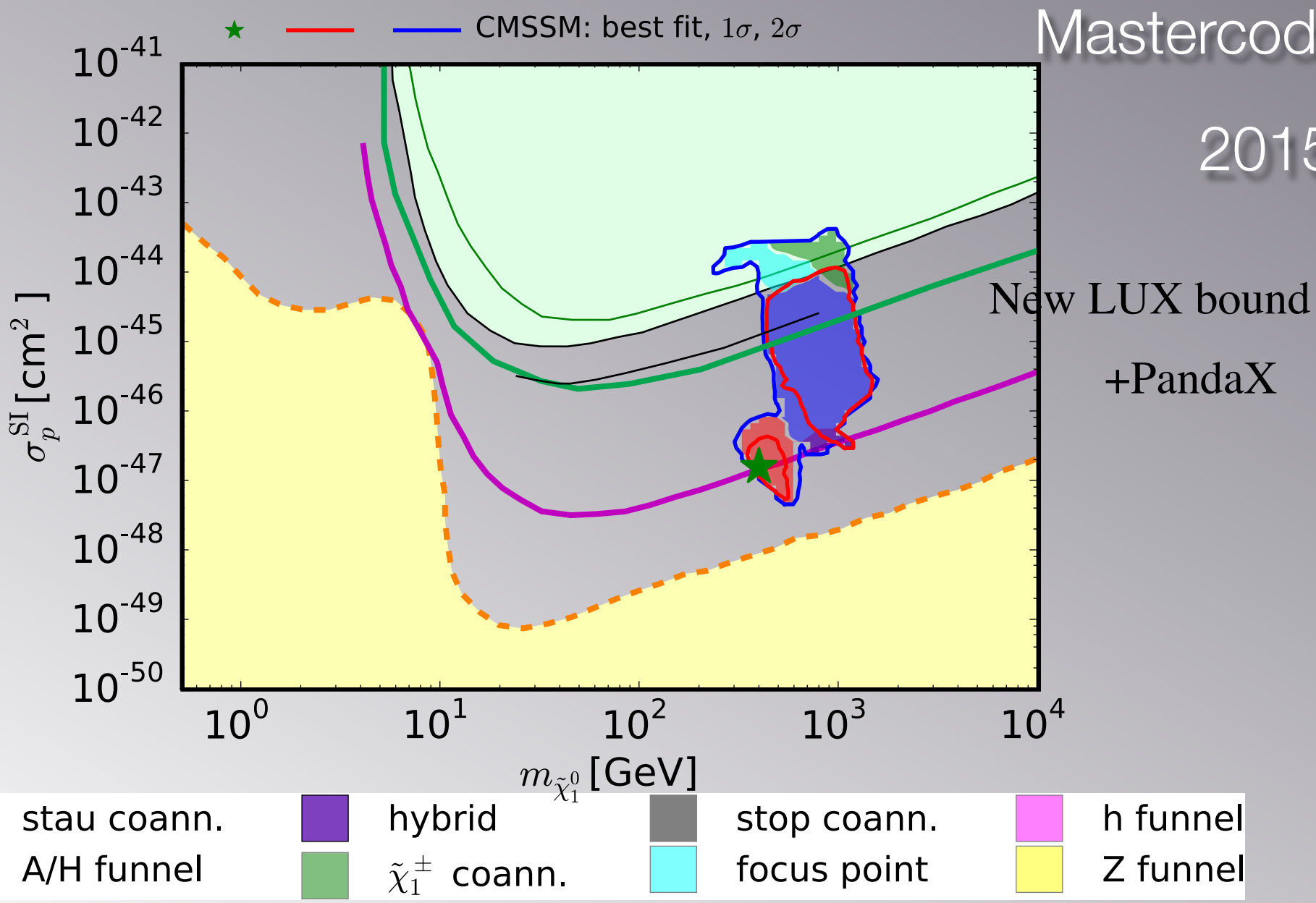
- CMSSM

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



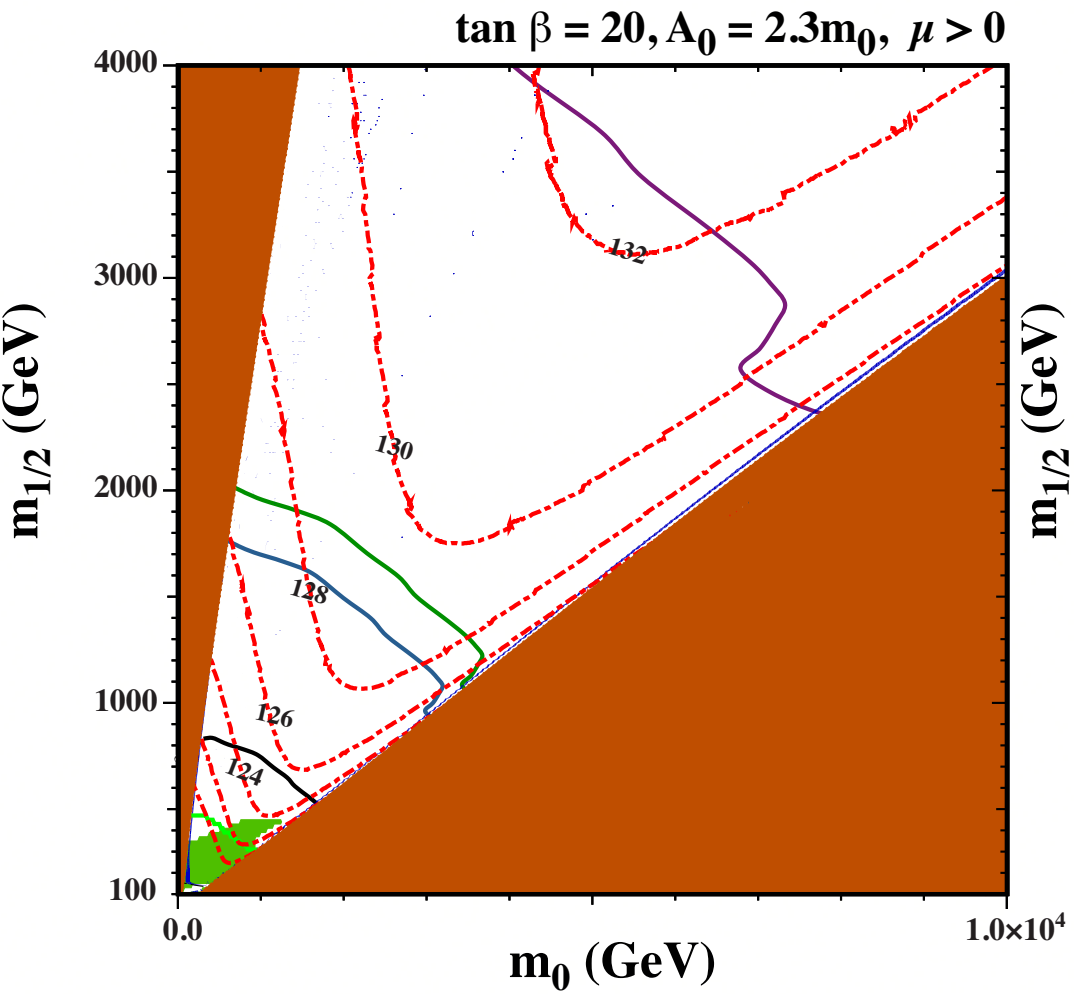
- CMSSM

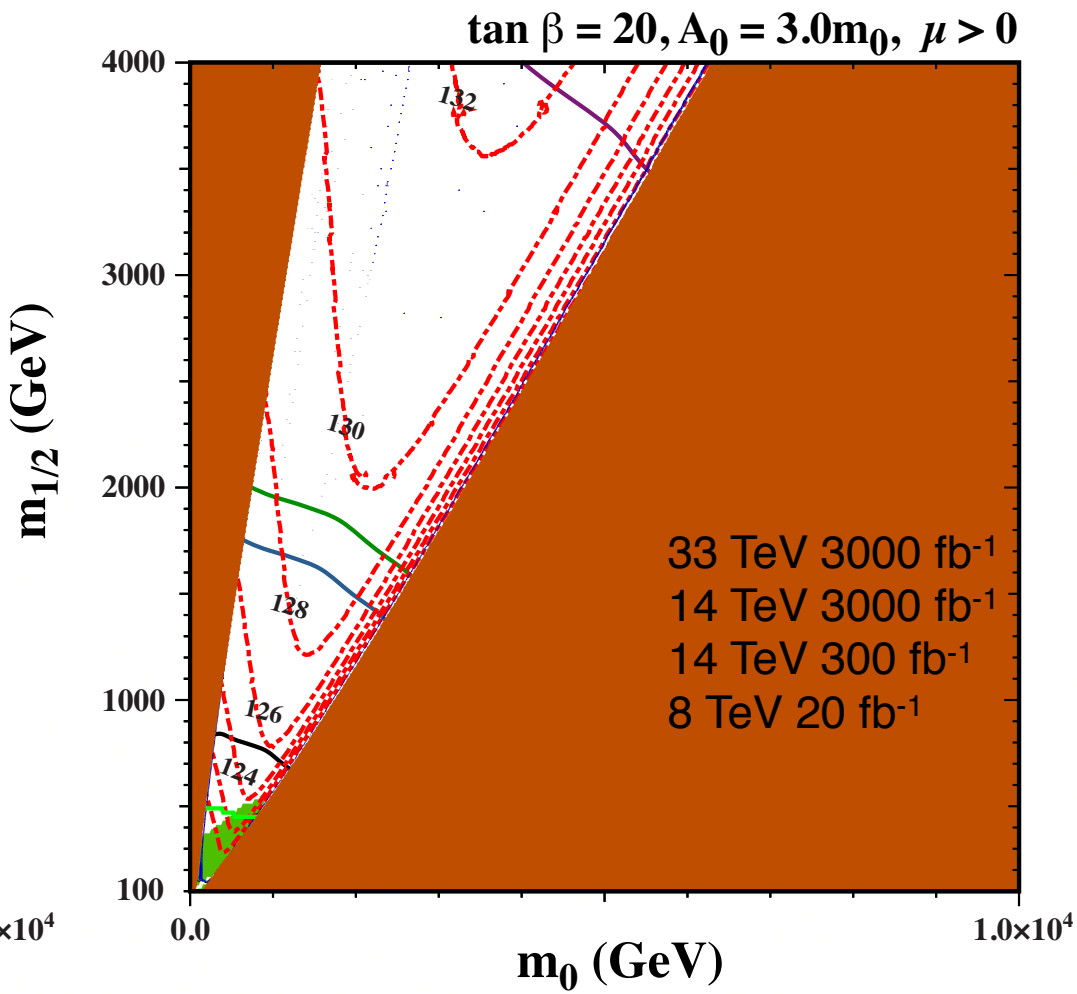
Bagnaschi, Buchmueller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flacher, Heinemeyer, Isidori, Malik, Martinez Santos, Olive, Sakurai, de Vries, Weiglein

The Strips:

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

Stop strip





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

Ellis, Olive, Zheng

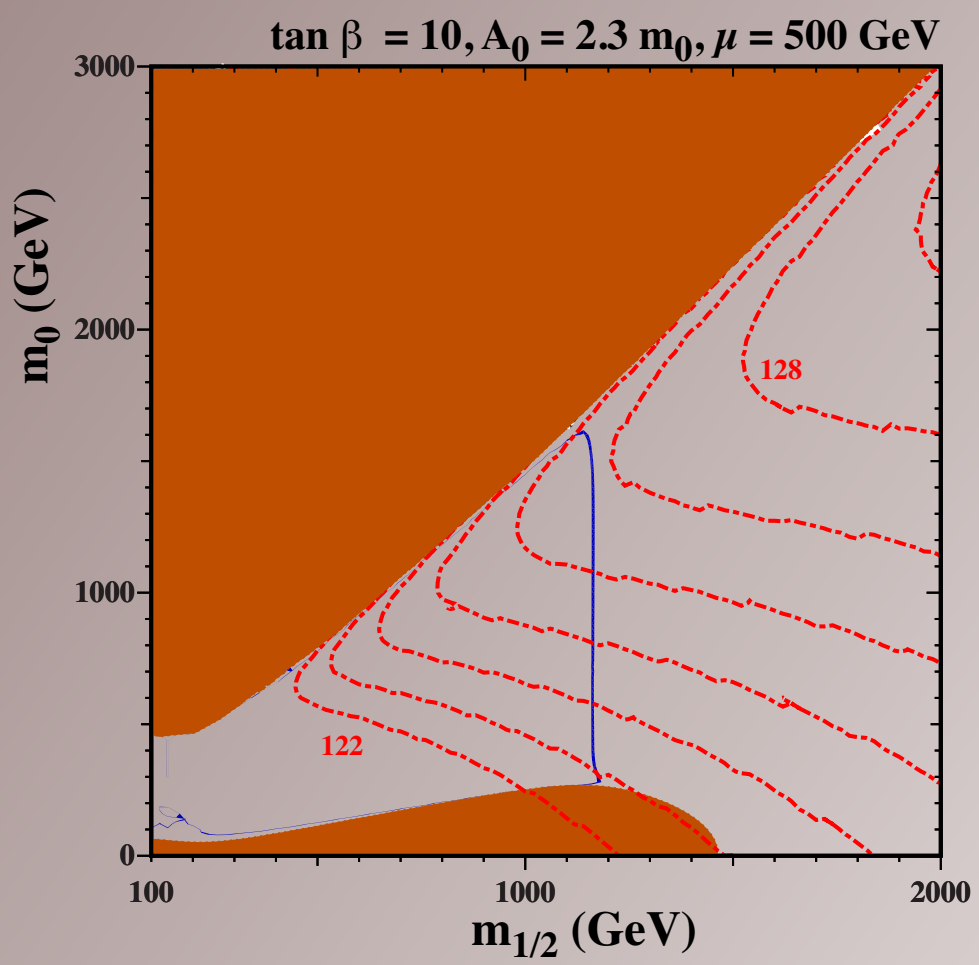
May require more general models which are concordant with LHC MET; Higgs; and $B_s \to \mu^+\mu^-$; and Dark Matter

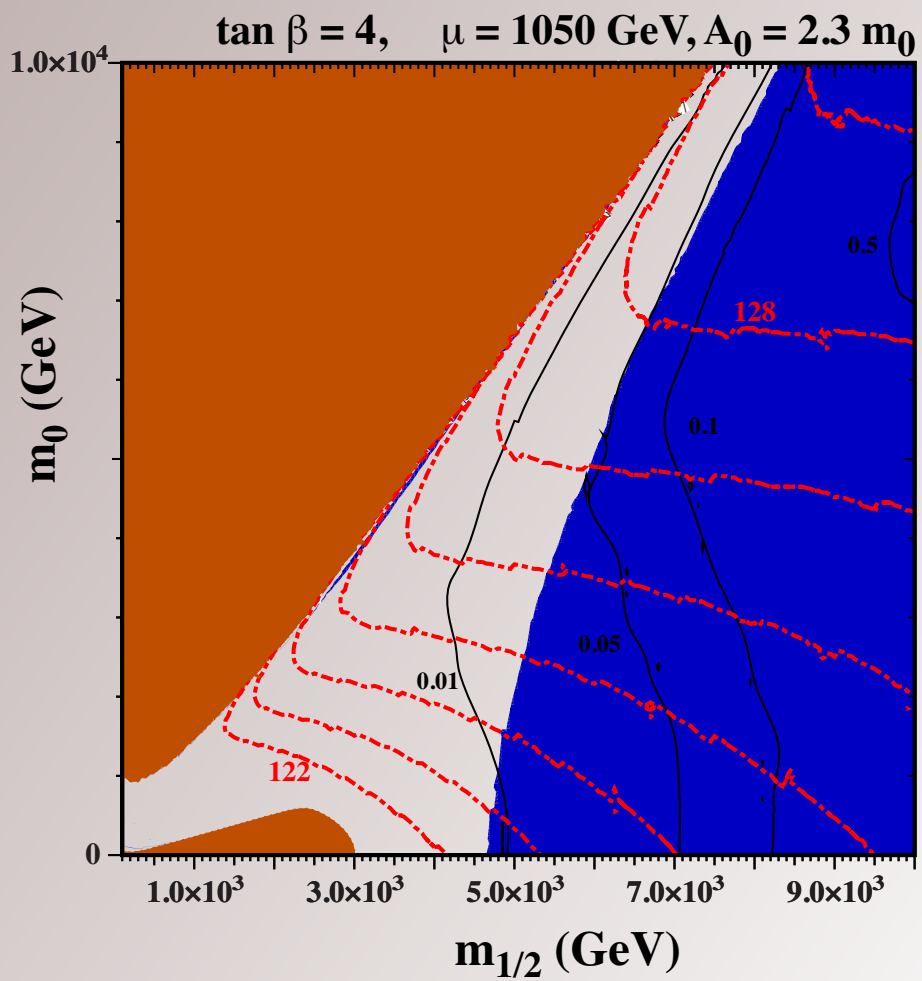
Other Possibilities

- 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
- subGUT models: $M_{in} < M_{GUT}$
  - with or without mSUGRA
- Pure Gravity Mediation
  - 2 parameter model with very large scalar masses

Ibe,Moroi,Yanagida
Ibe,Yanagida
Ibe,Matsumoto,Yanagida
Evans,Ibe,Olive,Yanagida

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





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

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…

What is SO(10)

Georgi
Fritzsch,Minkowski

$$\begin{aligned} SO(10) &\supset SU(5) \times U(1) \\ &\supset SU(4) \times SU(2) \times SU(2) \\ &\supset \text{others} \end{aligned}$$

Gauge degrees of freedom: 45

decomposition of the **45**

SU(5) × U(1): $\mathbf{45 = (24,0) + (10,4) + (\overline{10},-4) + (1,0)}$

SU(4) × SU(2) × SU(2): $\mathbf{45 = (15,1,1) + (6,2,2) + (1,1,0) + (1,3,1) + (1,1,3)}$

(SU(4) decomposition in terms of SU(3): $\mathbf{15 = 8 + 3 + \overline{3} + 1;\ 6 = 3 + \overline{3}}$)

What is SO(10)

$$SO(10) \supset SU(5) \times U(1)$$
$$\supset SU(4) \times SU(2) \times SU(2)$$
$$\supset \text{others}$$

Matter degrees of freedom: fundamental 16

new: right-handed neutrino

decomposition of the **16**

$SU(5) \times U(1)$: $\mathbf{16 = (10,-1) + (\bar{5},3) + (1,-5)}$

$SU(4) \times SU(2) \times SU(2)$: $\mathbf{16 = (4,1,2) + (\bar{4},2,1)}$

(SU(4) decomposition in terms of SU(3): $\mathbf{4 = 3 + 1}$

What is SO(10)

$$
\begin{aligned}
SO(10) &\supset SU(5) \times U(1) \\
&\supset SU(4) \times SU(2) \times SU(2) \\
&\supset \text{others}
\end{aligned}
$$

Higgs: see below

Recipe for constructing an SO(10) DM model

1. Pick an Intermediate Scale Gauge Group

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

$G_{\rm int}$	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 $\mathrm{SU}(5) \otimes \mathrm{U}(1)$	$\mathbf{45}, \mathbf{210}$

Georgi, Nanopoulos; Vayonakis; Masiero; Shafi, Sondermann, Wetterich; del Aguila, Ibanez; Mohapatra, Senjanovic; 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

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

R_2 = **126** + …

Neutrino see-saw: Majorana mass for ν_R
from 16 16 126 → $m_{\nu R} \sim M_{int}$ and $m_\nu \sim v^2/M_{int}$

Z_2 related to matter parity and B-L

Unlike SUSY R-parity, this Z_2 is not put in by hand!

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

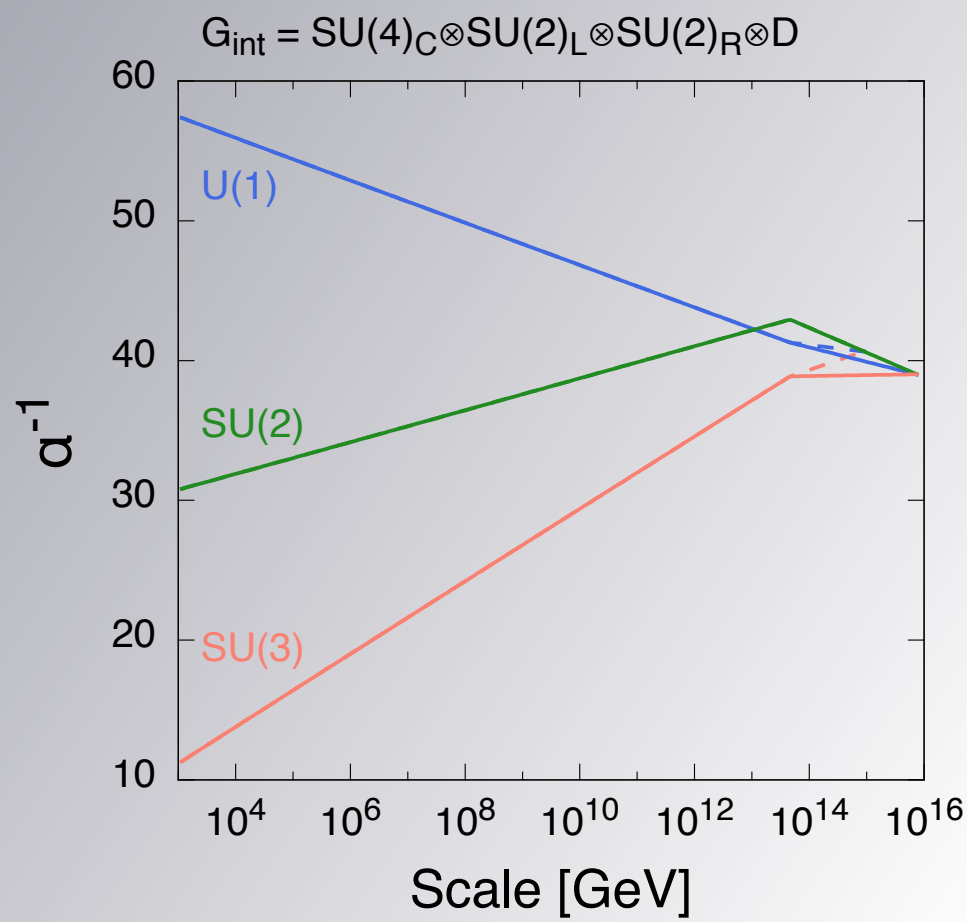
3. Pick DM representation and insure proper splitting within the multiplet, and pick low energy field content

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

Model	$R_{\rm DM}$	$\mathtt{S}^{\mathtt{Y}}_{\mathbf{n}}$	SO(10) representation
$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R (\otimes D)$			
$\mathtt{SA}_{422(\mathtt{D})}$	$\mathbf{4}, \mathbf{1}, \mathbf{2}$	$\mathtt{S}^{0}_{\mathbf{1}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SB}_{422(\mathtt{D})}$	$\mathbf{4}, \mathbf{2}, \mathbf{1}$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SC}_{422(\mathtt{D})}$	$\mathbf{4}, \mathbf{2}, \mathbf{3}$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{144}$
$\mathtt{SD}_{422(\mathtt{D})}$	$\mathbf{4}, \mathbf{3}, \mathbf{2}$	$\mathtt{S}^{1}_{\mathbf{3}}$	$\mathbf{144}$
$\mathtt{SE}_{422(\mathtt{D})}$	$\mathbf{4}, \mathbf{3}, \mathbf{2}$	$\mathtt{S}^{0}_{\mathbf{3}}$	$\mathbf{144}$
$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm U}(1)_R$			
$\mathtt{SA}_{421}$	$\mathbf{4}, \mathbf{1}, -1/2$	$\mathtt{S}^{0}_{\mathbf{1}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SB}_{421}$	$\mathbf{4}, \mathbf{2}, 0$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SC}_{421}$	$\mathbf{4}, \mathbf{2}, 1$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{144}$
$\mathtt{SD}_{421}$	$\mathbf{4}, \mathbf{3}, 1/2$	$\mathtt{S}^{1}_{\mathbf{3}}$	$\mathbf{144}$
$\mathtt{SE}_{421}$	$\mathbf{4}, \mathbf{3}, -1/2$	$\mathtt{S}^{0}_{\mathbf{3}}$	$\mathbf{144}$
$G_{\rm int} = {\rm SU}(3)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R \otimes {\rm U}(1)_{B-L} (\otimes D)$			
$\mathtt{SA}_{3221(\mathtt{D})}$	$\mathbf{1}, \mathbf{1}, \mathbf{2}, 1$	$\mathtt{S}^{0}_{\mathbf{1}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SB}_{3221(\mathtt{D})}$	$\mathbf{1}, \mathbf{2}, \mathbf{1}, -1$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{16}$, $\mathbf{144}$
$\mathtt{SC}_{3221(\mathtt{D})}$	$\mathbf{1}, \mathbf{2}, \mathbf{3}, -1$	$\mathtt{S}^{1/2}_{\mathbf{2}}$	$\mathbf{144}$
$\mathtt{SD}_{3221(\mathtt{D})}$	$\mathbf{1}, \mathbf{3}, \mathbf{2}, 1$	$\mathtt{S}^{1}_{\mathbf{3}}$	$\mathbf{144}$
$\mathtt{SE}_{3221(\mathtt{D})}$	$\mathbf{1}, \mathbf{3}, \mathbf{2}, 1$	$\mathtt{S}^{0}_{\mathbf{3}}$	$\mathbf{144}$

Nagata, Olive, Zheng

Examples:

Scalars

Higgs portal models
Inert Higgs doublet models

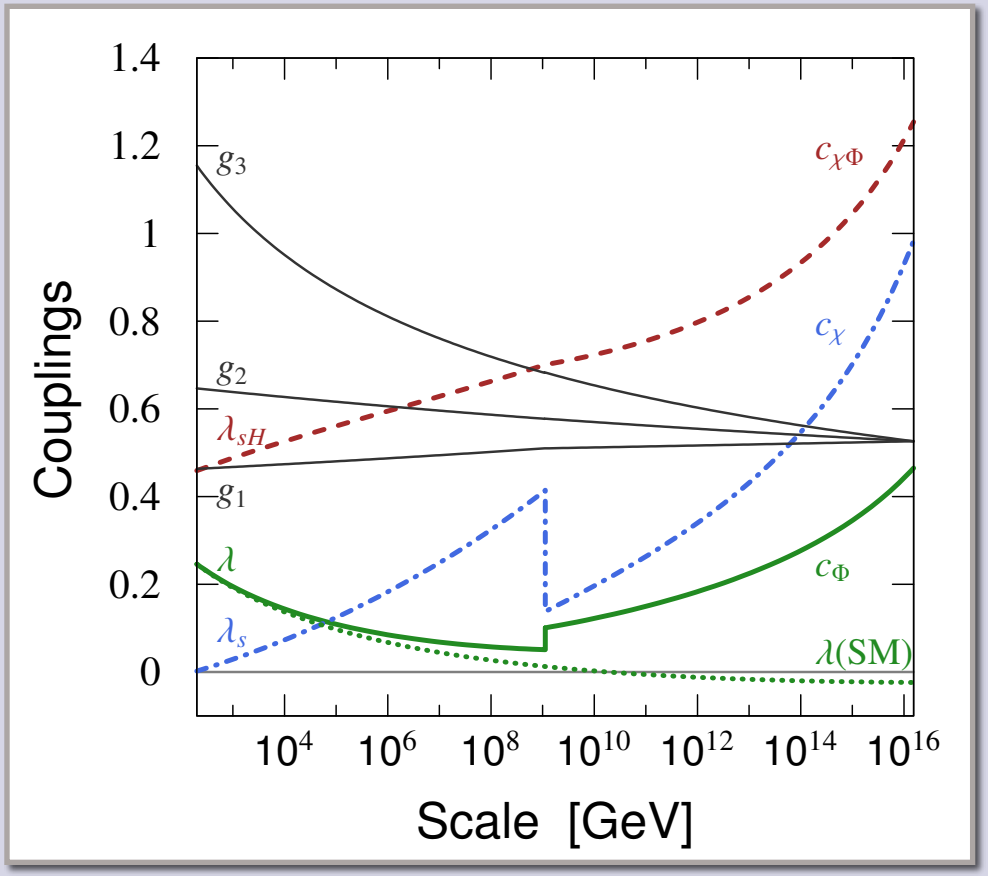
Model	$\log_{10} M_{\rm GUT}$	$\log_{10} M_{\rm int}$	$\alpha_{\rm GUT}$	$\log_{10} \tau_p(p \to e^+\pi^0)$
$G_{\rm int} = {\rm SU}(4)_C \otimes {\rm SU}(2)_L \otimes {\rm SU}(2)_R$				
$\mathtt{SA}_{422}$	16.33	11.08	0.0218	36.8 ± 1.2
$\mathtt{SB}_{422}$	15.62	12.38	0.0228	34.0 ± 1.2
$G_{\rm int} =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

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

mass splitting:

$$
\begin{aligned}
-\mathcal{L}_{\rm int} = {} & M^2 |R_{\rm DM}|^2 + \kappa_1 R^*_{\rm DM} R_{\rm DM} R_1 + \{\kappa_2 R_{\rm DM} R_{\rm DM} R_2^* + {\rm h.c.}\} \\
& + \lambda_1^{\mathbf{1}} |R_{\rm DM}|^2 |R_1|^2 + \lambda_2^{\mathbf{1}} |R_{\rm DM}|^2 |R_2|^2 + \left\{\lambda_{12}^{\mathbf{126}} \left(R_{\rm DM} R_{\rm DM}\right)_{\mathbf{126}} \left(R_1 R_2^*\right)_{\overline{\mathbf{126}}} + {\rm h.c.}\right\} \\
& + \lambda_1^{\mathbf{45}} \left(R^*_{\rm DM} R_{\rm DM}\right)_{\mathbf{45}} \left(R_1^* R_1\right)_{\mathbf{45}} + \lambda_1^{\mathbf{210}} \left(R^*_{\rm DM} R_{\rm DM}\right)_{\mathbf{210}} \left(R_1^* R_1\right)_{\mathbf{210}} \\
& + \lambda_2^{\mathbf{45}} \left(R^*_{\rm DM} R_{\rm DM}\right)_{\mathbf{45}} \left(R_2^* R_2\right)_{\mathbf{45}} + \lambda_2^{\mathbf{210}} \left(R^*_{\rm DM} R_{\rm DM}\right)_{\mathbf{210}} \left(R_2^* R_2\right)_{\mathbf{210}} \ ,
\end{aligned}
$$

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

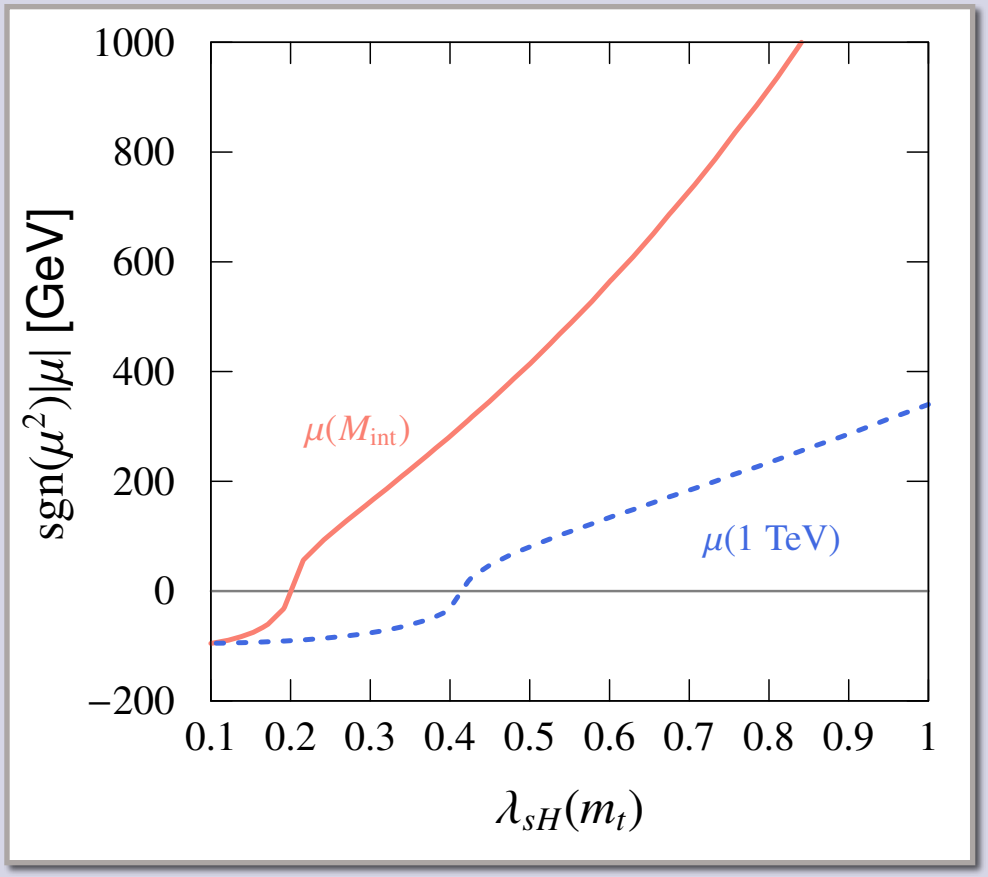
$$V_{\rm blw} = \mu^2|H|^2 + \frac{1}{2}\mu_s^2 s^2 + \frac{\lambda}{2}|H|^4 + \frac{\lambda_{sH}}{2}|H|^2 s^2 + \frac{\lambda_s}{4!}s^4 .$$

Additional fields appear at the intermediate scale.

perturbatitivity implies $m_{DM} < 2$ TeV

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

Vacuum stability and radiative EWSB

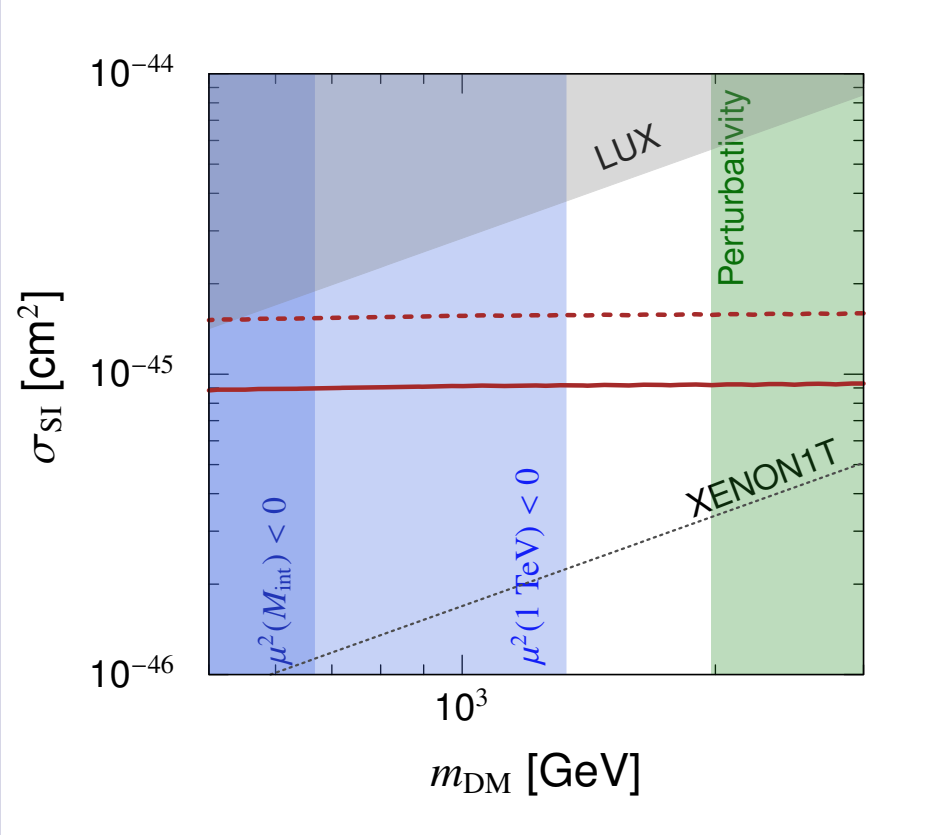


Higgs mass term runs negative and depends on λ_{sH}

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

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

Vacuum stability and radiative EWSB



Direct Detection of this candidate can be probed at XENON1T

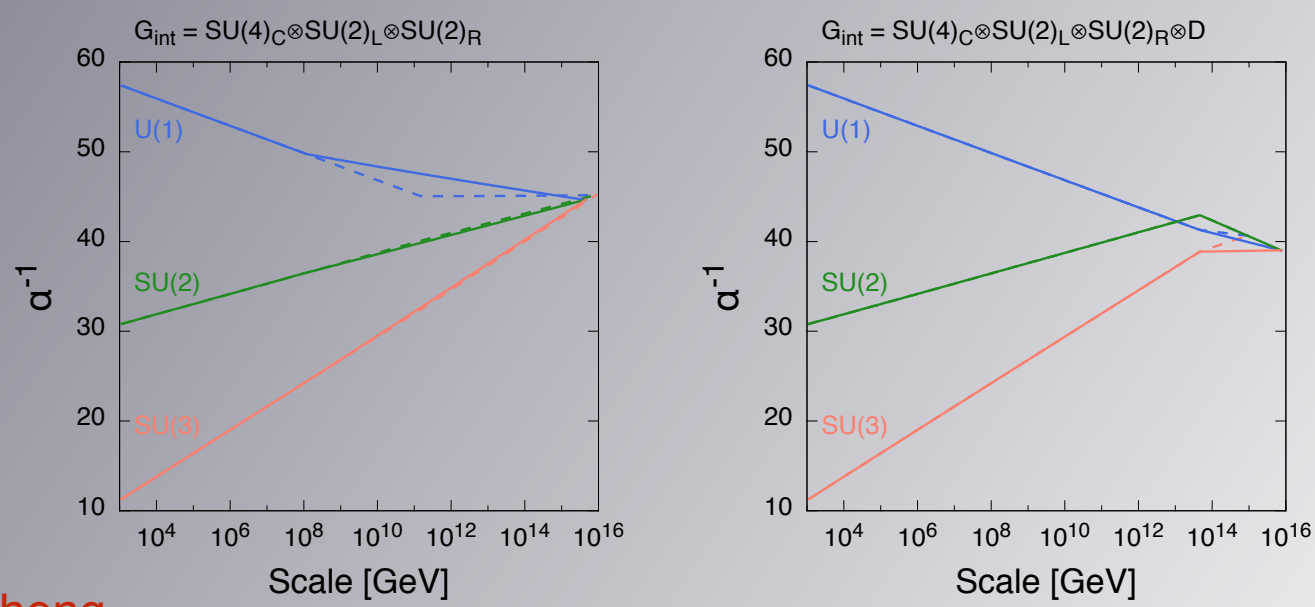
Mambrini, Nagata, Olive, Zheng

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

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

Nagata, Olive, Zheng

Summary: Part 1

- LHC susy and Higgs searches have pushed CMSSM-like models to “corners” or strips
- SO(10) models contain almost all of the benifits of SUSY models:
  - gauge coupling unification, radiative EWSB, stable Higgs vacuum, stable DM candidate….
- Several possibilities in non-SUSY SO(10) models which are phenomenologically consistent with p-decay limits
- Challenge lies in detection strategies

Inflation

- Supersymmetry
- Supergravity
- No-Scale Supergravity
- Storbinsky Model
- SO(10)

No-Scale Supergravity

Natural vanishing of cosmological constant (tree level) with the supersymmetry scale not fixed at lowest order. (Also arises in generic 4d reductions of string theory.)

Cremmer, Ferrara, Kounnas, Nanopoulos; Ellis, Kounnas, Nanopoulos; Lahanas, Nanopoulos

$$K = -3\ln(T + T^* - \phi^i {\phi_i}^*/3)$$

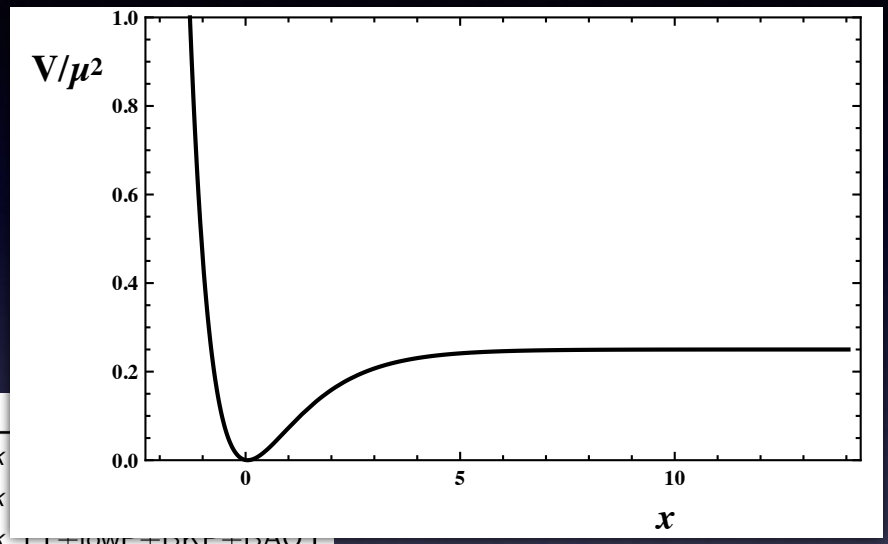
$$V = e^{\frac{2}{3}K} \left|\frac{\partial W}{\partial \phi^i}\right|^2$$

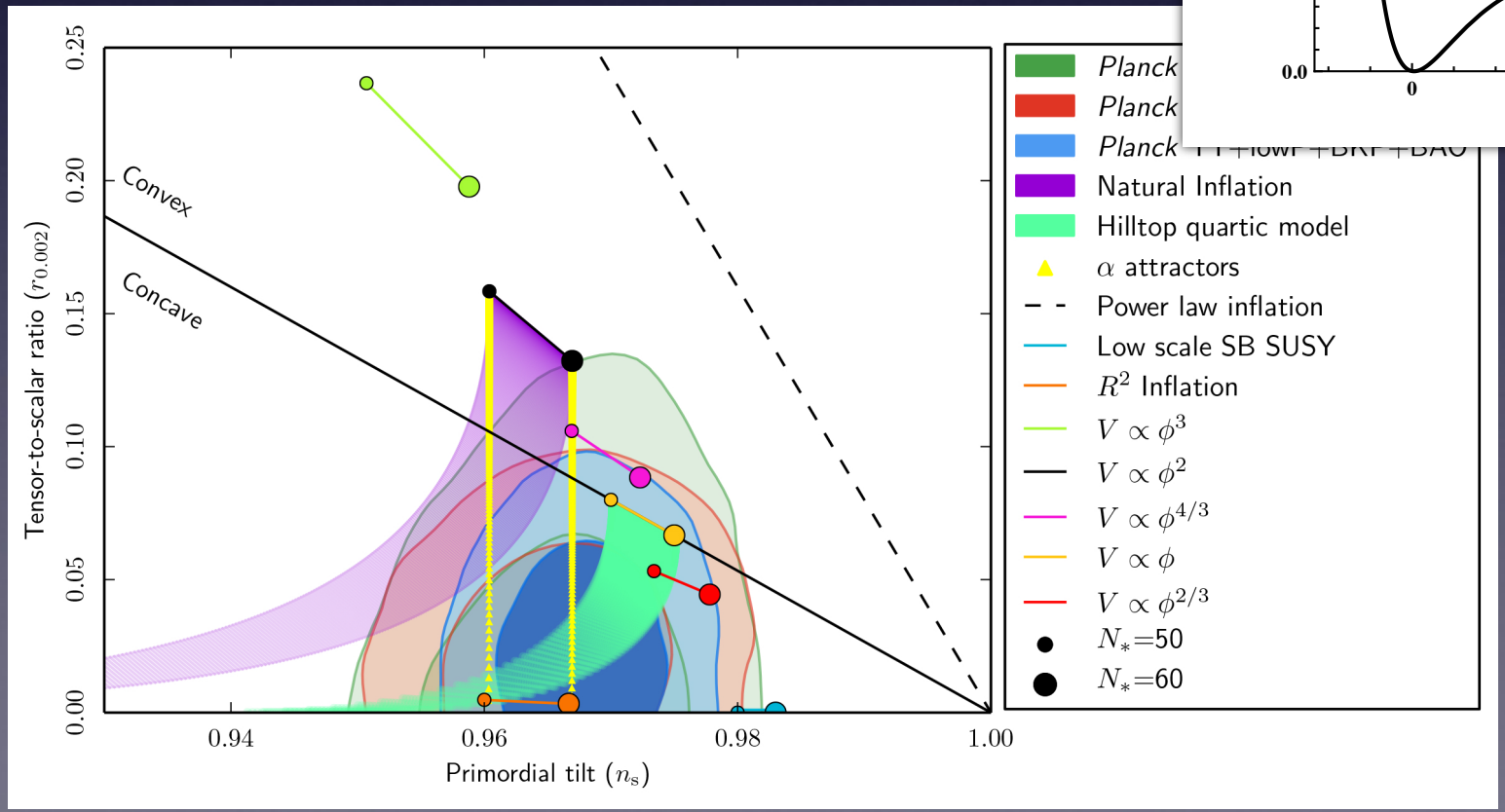
Globally supersymmetric potential once K (canonical) picks up a vev

Planck-friendly Models

R+R^2 Inflation

For N=55, n_s = 0.965; r = .0035





R+R^2 Inflation

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)\,,$$

Starobinsky

where $M \ll M_P$

With $\tilde{g}_{\mu\nu} = (1 + \varphi/3M^2)g_{\mu\nu}$

and $\varphi' = \sqrt{\frac{3}{2}}\ln\left(1 + \frac{\varphi}{3M^2}\right)$

conformally equivalent to:

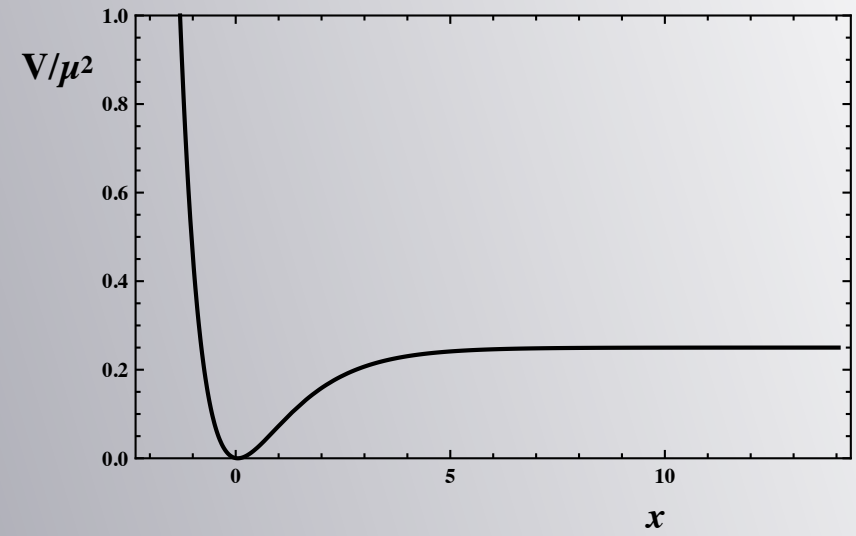
$$S - \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

$$V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$$

R+R^2 Inflation

$$V = \frac{3}{4}M^2(1-e^{-\sqrt{2/3}\varphi'})^2$$
$$= \mu^2 e^{-\sqrt{2/3}x}\sinh^2(x/\sqrt{6})$$

$x=\varphi/M_P$, $\mu^2 = 3M^2$



Slow Roll parameters:

$$\epsilon = \frac{1}{3}\mathrm{csch}^2(x/\sqrt{6})e^{-\sqrt{2/3}x},$$
$$\eta = \frac{1}{3}\mathrm{csch}^2(x/\sqrt{6})\left(2e^{-\sqrt{2/3}x}-1\right)$$

μ is again set by the normalization of the quadrupole

$$A_s = \frac{V}{24\pi^2\epsilon} = \frac{\mu^2}{8\pi^2}\sinh^4(x/\sqrt{6})$$

$\Longrightarrow$ $\mu = 2.2 \times 10^{-5}$ for $N = 55$

$x_i = 5.35$

No-Scale realization of Starobinsky

Can we find a model consistent with Planck?

Ellis, Nanopoulos, Olive

Start with WZ model: $$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

Assume now that T picks up a vev: 2<Re T> = c

$$\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$$

Redefine inflaton to a canonical field χ

$$\hat{V} = |W_\Phi|^2$$

$$\phi = \sqrt{3c}\tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

No-Scale models revisited

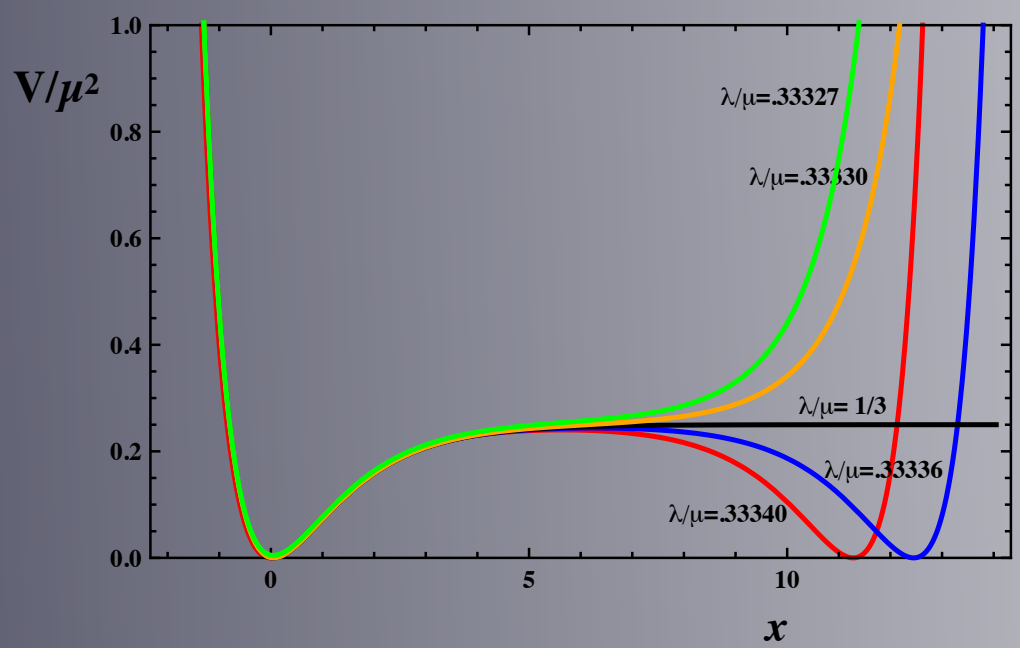
The potential becomes:

$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

$$\hat{\mu} = \mu\sqrt{(c/3)}$$

For λ=μ/3, this is exactly the R + R^2 potential and Starobinsky model of inflation

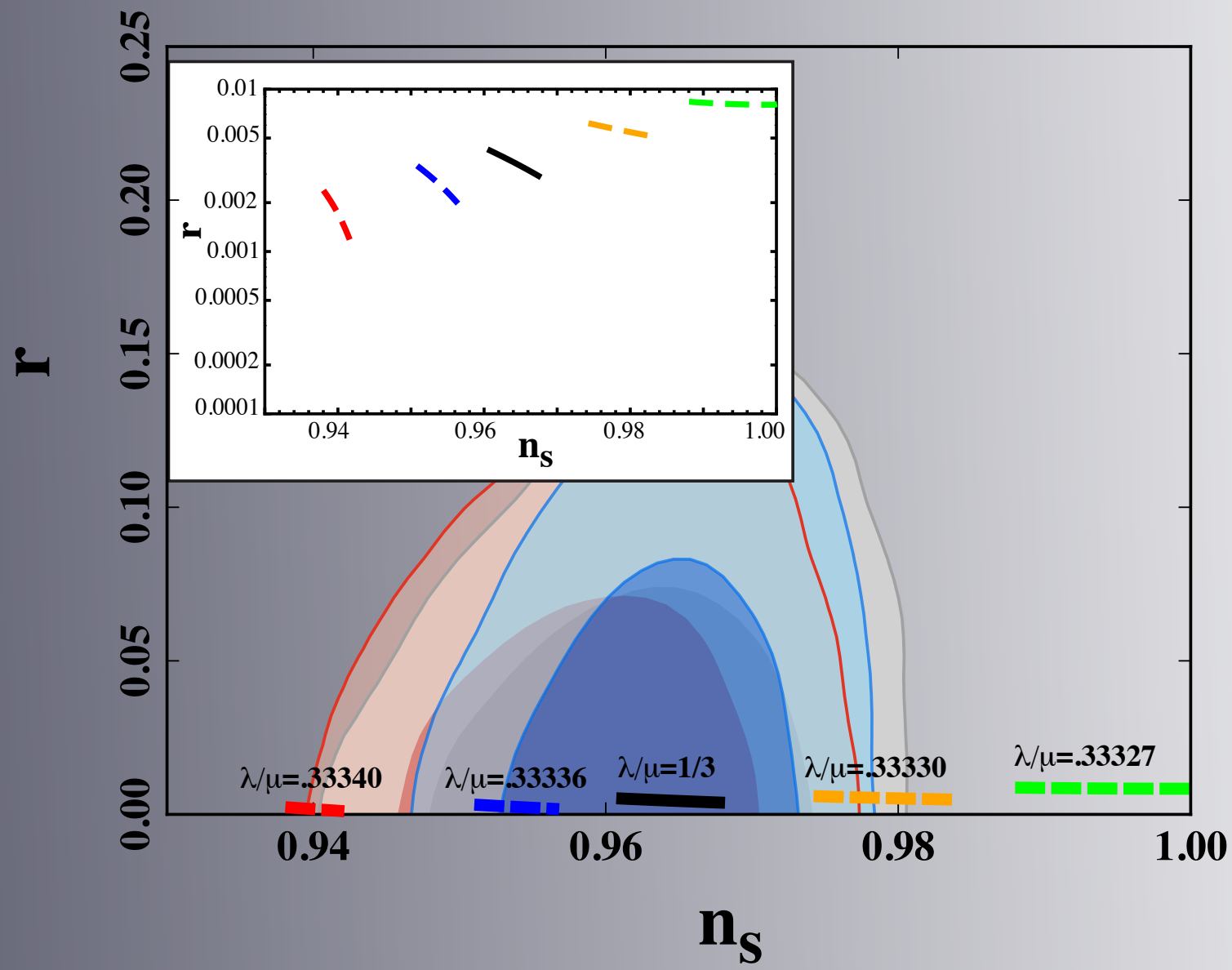
$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$



$$\chi = (x + iy)/\sqrt{2}$$

No-Scale models revisited

How well does this do vis a vis Planck?



What is the inflation

Let's rewrite

$$K = -3\ln\left(1 - \frac{|y_1|^2 + |y_2|^2}{3} + \frac{|y_2|^4}{\Lambda^2}\right)$$

$$W = M\left[\frac{y_1^2}{2}\left(1 + \frac{y_2}{\sqrt{3}}\right) - \frac{y_1^3}{3\sqrt{3}}\right]$$

Ellis, Nanopoulos, Olive

Lets rewrite

$$W_Y = \lambda H_2^i L_i y_1$$

Interpret y_1 as a right handed neutrino

Inflaton mass term, M, provides intermediate scale majorana mass term for "ν_R"

Reheating

$$T_R \simeq \left(\frac{5}{\pi^3 N}\right)^{1/4} \left(\frac{\lambda^2 M M_P}{\sqrt{32\pi}}\right)^{1/2} \sim 2 \times 10^{14} \lambda \mathrm{GeV}$$

but $$\frac{n_{3/2}}{s} \simeq 2.4 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)$$

and to avoid overproduction of neutralinos from graviton decay:

$$\lambda \lesssim 10^{-5} \, .$$

typical Yukawa for electron

lightest neutrino with mass of 10^{-10} - 10^{-9} eV

Susy breaking and matter

Ellis, Nanopoulos, Olive

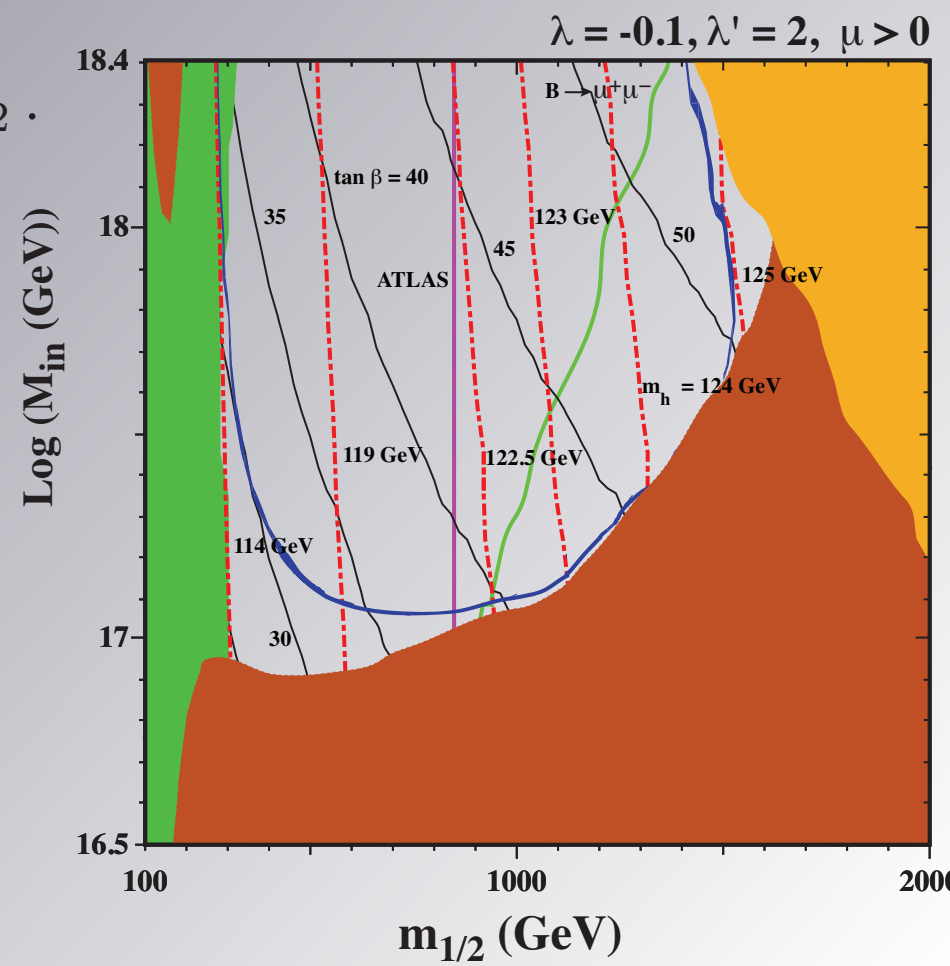
$$W_{SSB} = r\left(1+\frac{y_2}{\sqrt{3}}\right)^3$$

$$W_{SM} = W_2(y_{SM})\left(1+\frac{y_2}{\sqrt{3}}\right)^{\beta} + W_3(y_{SM})\left(1+\frac{y_2}{\sqrt{3}}\right)^{\alpha}$$

$$m_0 = 0,\ B_0 = (\beta-1)m_{3/2},\ A_0 = \alpha m_{3/2}\,.$$

$\alpha = 0$, $\beta=1 \Rightarrow$ no scale boundary conditions

Require $M_{in} > M_{GUT}$



In SO(10)?

Ellis, Garcia, Nagata, Nanopoulos, Olive

- Can not use ν_R as the inflation - no $\mathbf{16}^2$ or $\mathbf{16}^3$ coupling
- There is a $\mathbf{210}^2$ and $\mathbf{210}^3$ coupling, but scale is wrong
- Add a singlet (inflaton) coupled to matter.

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

S - inflaton

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

Yukawa coupling of
Higgs (H) **10** and matter (ψ) **16**

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

Neutrino Masses through Higgs (Φ) **16**

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

SUSY breaking

Georgi-Nanopoulos model

Ellis, Garcia, Nagata, Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

Remainder: Higgs potential involving (Σ) **210**
and terms allowed by gauge invariance

Georgi-Nanopoulos model

Ellis, Garcia, Nagata,
Nanopoulos, Olive

$$W = \frac{m}{2}S^2 - \frac{\lambda}{3}S^3 + yH\psi\psi + (M + bS)\bar{\Phi}\psi + m_\Phi\bar{\Phi}\Phi + \frac{\eta}{4!}\bar{\Phi}\Phi\Sigma + \frac{m_\Sigma}{4!}\Sigma^2 + \frac{\Lambda}{4!}\Sigma^3$$

$$+ m_H H^2 + \lambda_{SH} S H^2 + H(\alpha\Phi\Phi + \bar{\alpha}\bar{\Phi}\bar{\Phi} + \alpha'\Phi\psi) + cS\bar{\Phi}\Phi + \frac{\beta}{4!}\bar{\Phi}\psi\Sigma + \frac{\gamma}{4!}S\Sigma^2 + \kappa$$

Remainder: Higgs potential involving (Σ) **210**
and terms allowed by gauge invariance

Directions of interest:

$$p = \langle\Sigma(\mathbf{1},\mathbf{1},\mathbf{1})\rangle\ , \qquad a = \langle\Sigma(\mathbf{15},\mathbf{1},\mathbf{1})\rangle\ , \qquad \omega = \langle\Sigma(\mathbf{15},\mathbf{1},\mathbf{3})\rangle\ ,$$

$$\phi_R = \langle\Phi(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})\rangle\ , \qquad \bar{\phi}_R = \langle\bar{\Phi}(\mathbf{4},\mathbf{1},\mathbf{2})\rangle\ , \qquad \widetilde{\nu}_R = \langle\psi(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})\rangle\ ,$$

Resulting potential

$$V \simeq \frac{\hat{V}}{\left[1 - \frac{1}{3}(|S|^2 + |p|^2 + 3|a|^2 + 6|\omega|^2 + 2|\phi|^2)\right]^2},$$

where

$$\hat{V} = |mS - \lambda S^2|^2 + |S|^2\Big[|b\phi|^2 + 2|c\phi|^2 + |2\gamma p|^2 + |6\gamma a|^2 + |12\gamma\omega|^2\Big].$$

Redefine

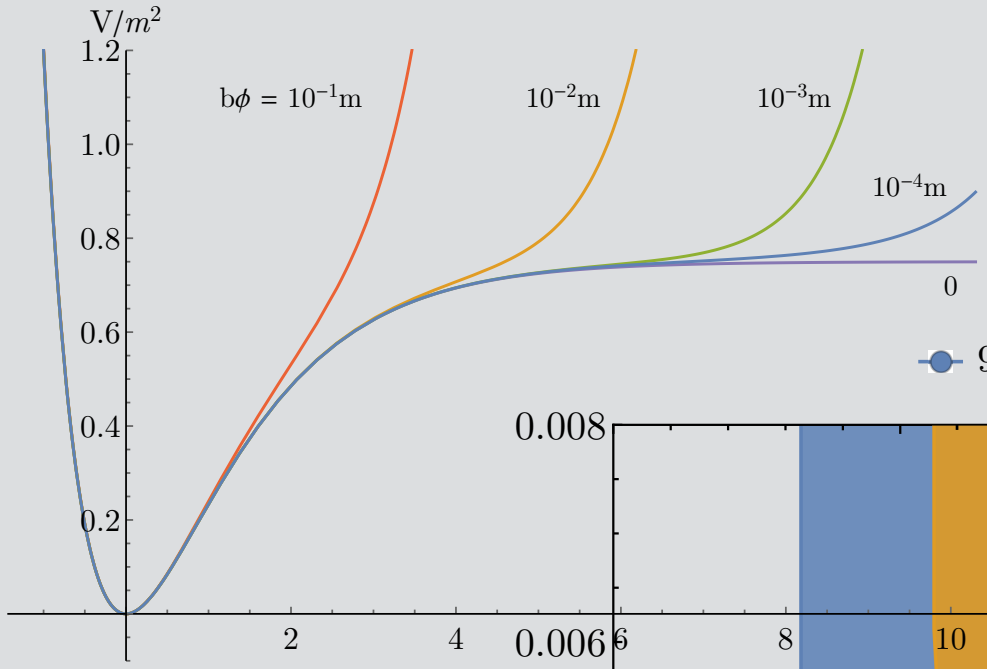
$$S \equiv \sqrt{3}\tanh(s/\sqrt{6}),$$

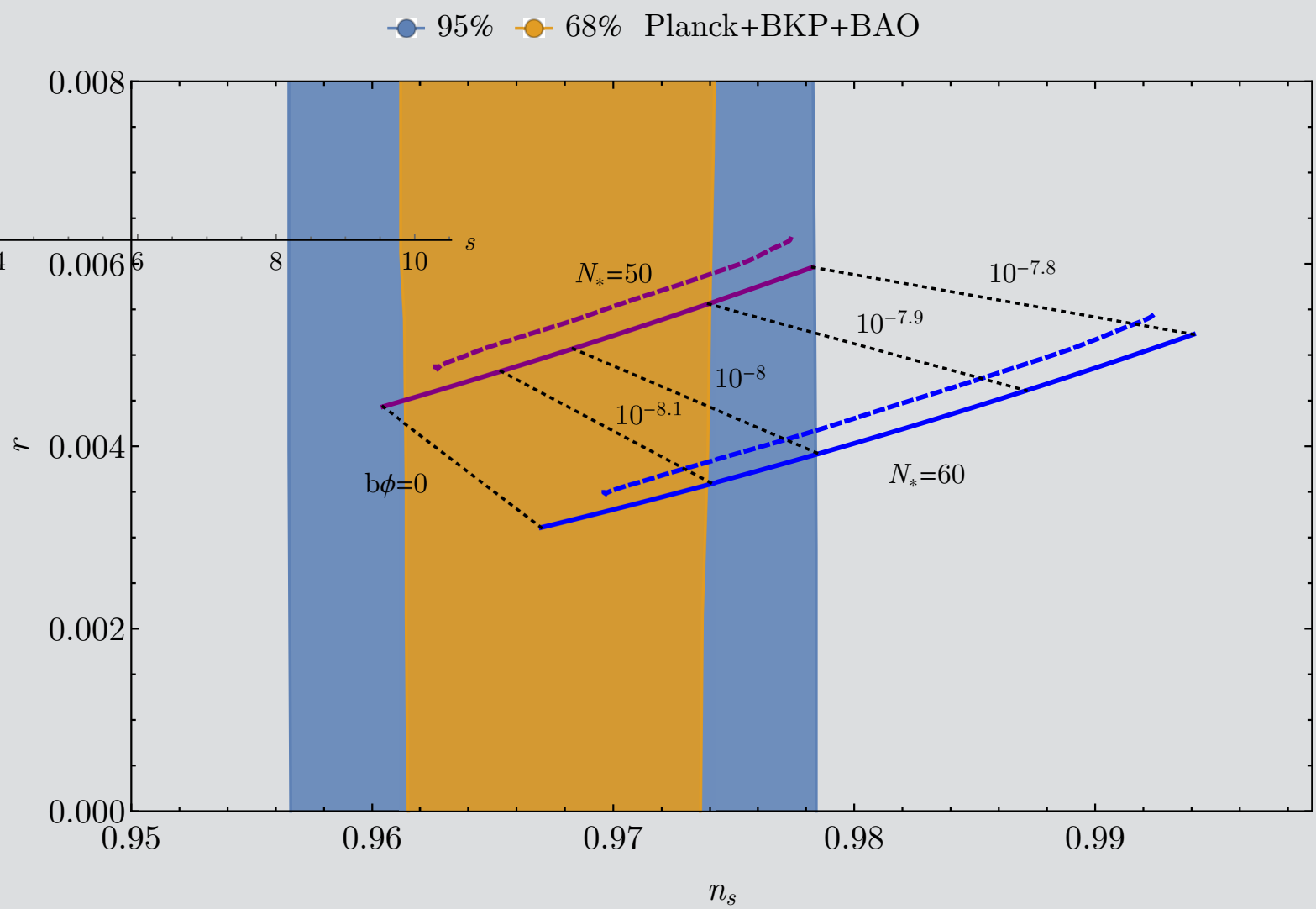
$$V \simeq \frac{3}{4}m^2\left(1 - e^{-\sqrt{2/3}\,s}\right)^2 + \Delta V$$

$$\Delta V = \left[\frac{3}{4}|b\phi|^2 + \frac{1}{2}m^2 e^{-\sqrt{2/3}\,s}\Delta K\right]\sinh^2(\sqrt{2/3}\,s)$$

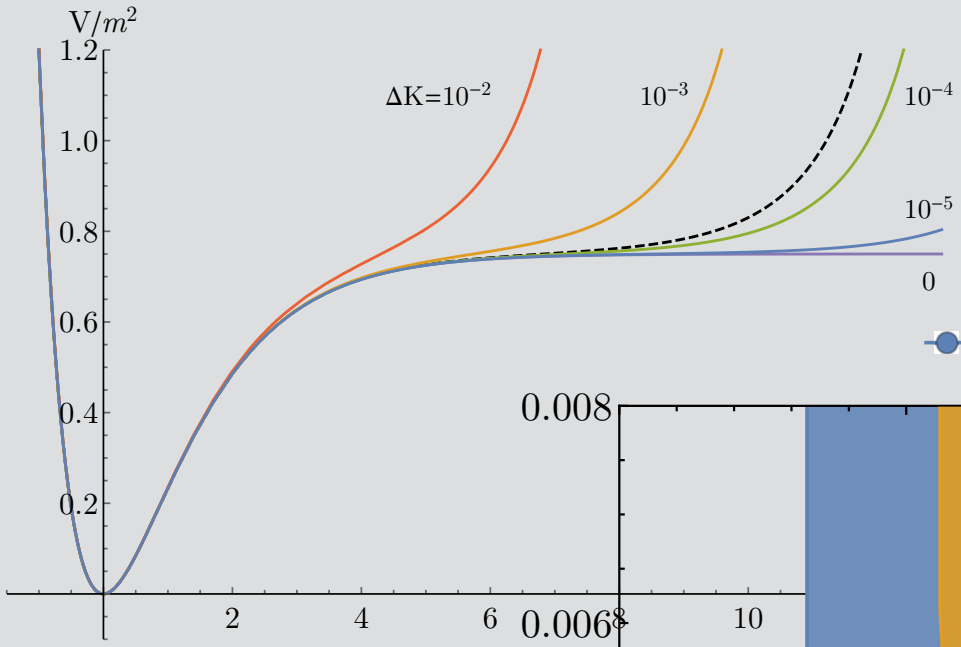
$$\Delta K \equiv |p|^2 + 3|a|^2 + 6|\omega|^2 + 2|\phi|^2$$

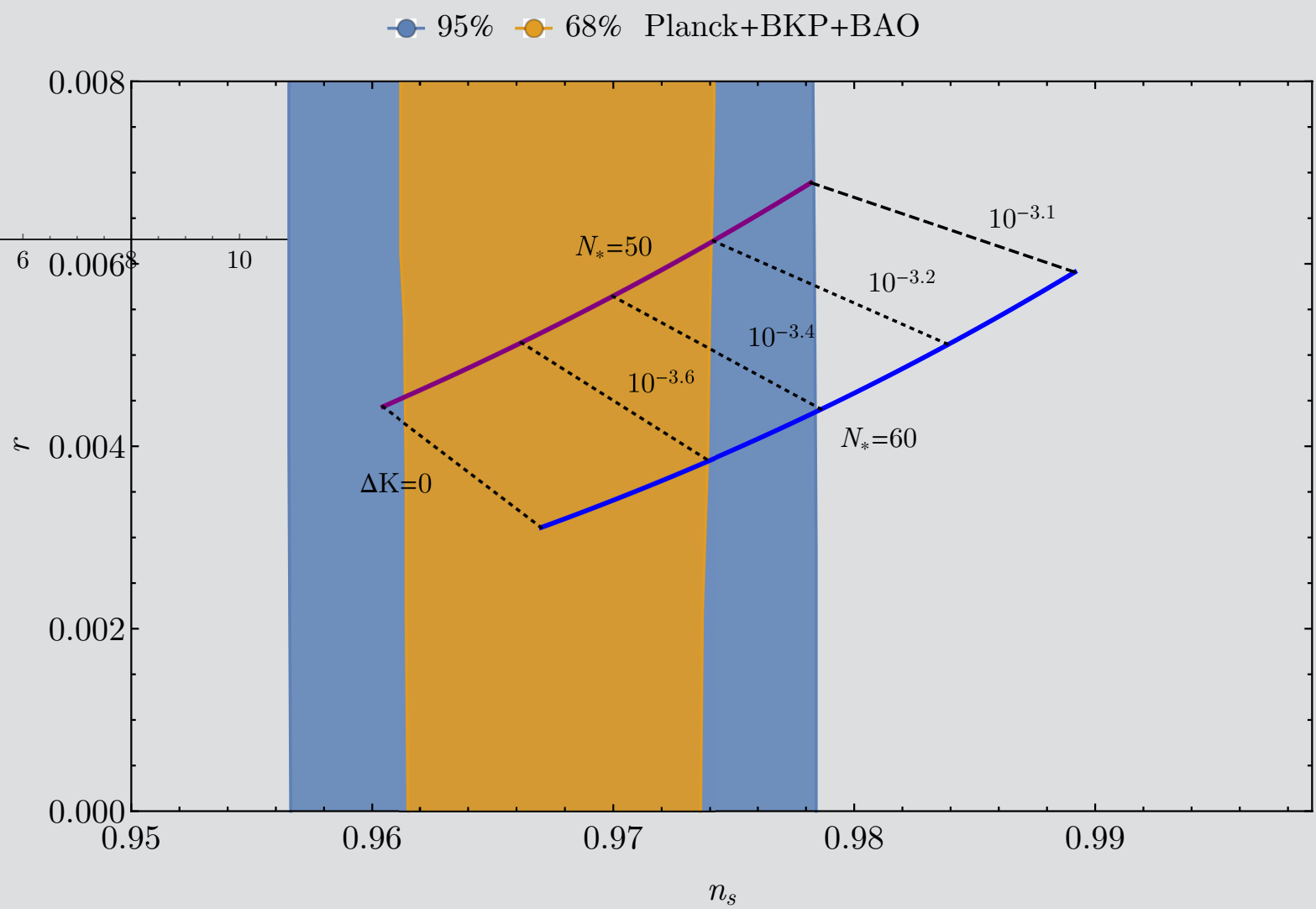
Resulting potential





Resulting potential





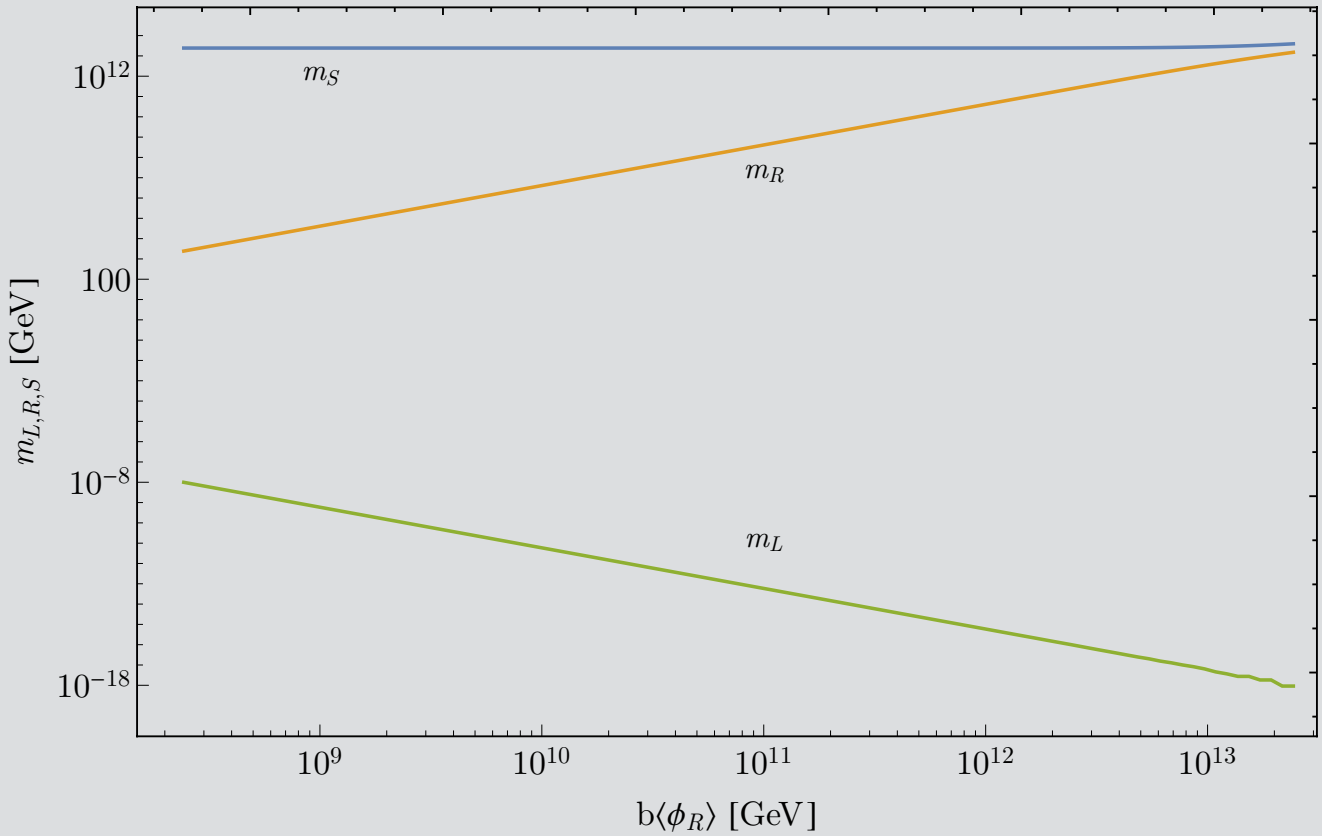
Neutrino Masses:

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R & \bar{\tilde{S}} \end{pmatrix} \begin{pmatrix} 0 & -y\,v\sin\beta & 0 \\ -y\,v\sin\beta & 0 & -b\phi \\ 0 & -b\phi & m \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \tilde{S} \end{pmatrix}$$

double seesaw

$$\begin{pmatrix} \bar{\nu}_L^M & \bar{\nu}_R^M & \bar{\tilde{S}}^M \end{pmatrix} \begin{pmatrix} m\left(\frac{y\,v\sin\beta}{b\phi}\right)^2 & 0 & 0 \\ 0 & -\frac{(b\phi)^2}{m} - m\left(\frac{y\,v\sin\beta}{b\phi}\right)^2 & 0 \\ 0 & 0 & m + \frac{(b\phi)^2}{m} \end{pmatrix} \begin{pmatrix} \nu_L^M \\ \nu_R^M \\ \tilde{S}^M \end{pmatrix}$$

$$\begin{aligned} \nu_L^M &\simeq \nu_L - \frac{m\,yv\sin\beta}{(b\phi)^2}\,\nu_R - \frac{yv\sin\beta}{b\phi}\,\tilde{S}\,, \\ \nu_R^M &\simeq \nu_R + \frac{b\phi}{m}\,\tilde{S} + \frac{m\,yv\sin\beta}{(b\phi)^2}\,\nu_L\,, \\ \tilde{S}^M &\simeq \tilde{S} - \frac{b\phi}{m}\,\nu_R + \frac{b\phi\,yv\sin\beta}{m^2}\,\nu_L\,. \end{aligned}$$



Reheating:

$$\Gamma(S \to H_u^0 \tilde{\nu}_L, \tilde{H}_u^0 \nu_L) = \frac{m}{8\pi} \left| y \frac{b\phi}{m} \right|^2 .$$

$$\left| y \frac{b\phi}{m} \right| \lesssim 10^{-5} .$$

Summary: Part 2

- The Starobinsky model of inflation can be realized with either modulus T or 'matter' field ϕ with a simple WZ superpotential.
- The latter lends itself nicely to equating the inflaton with a right-handed sneutrino
- Can easily integrate low energy susy phenomenology
- In SO(10) inflaton reverts back to a singlet, but may still be involved in the generation of neutrino masses.