Where we do not want to go: avoiding charge- or color-breaking vacua

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in collaboration with
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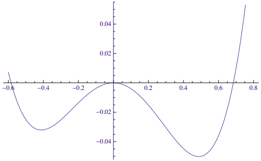
LHC Run1 Aftermath
Bad Honnef,
October 2nd, 2013

QFT potentials typically have multiple minima

Even tree-level potentials for single scalars have in general multiple minima:



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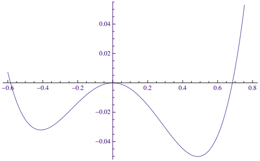
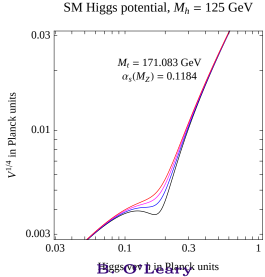
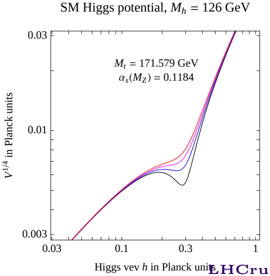


Top loops create extra minima for high Higgs field values in SM:





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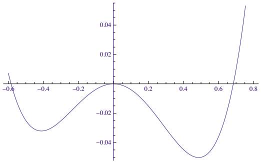
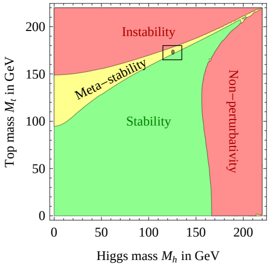


SM is probably metastable!



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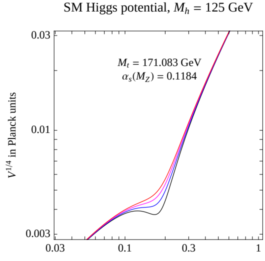
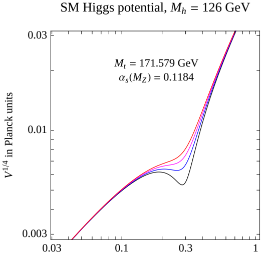
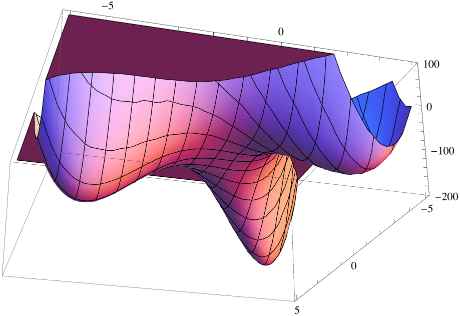




Figs. 2, 3, 4: Degrassi *et al.*, JHEP 1208 (2012)

More scalars ⇒ more minima in general

Multiple scalars in general yield many vacua:



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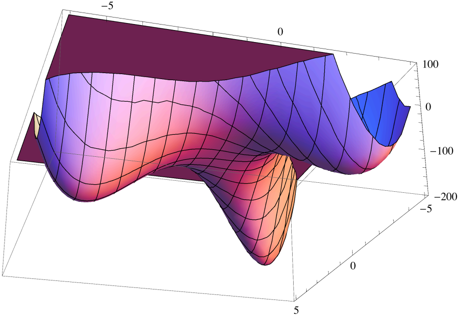

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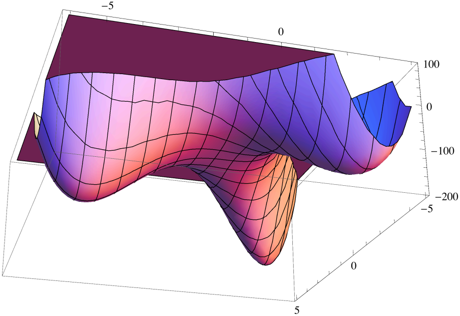

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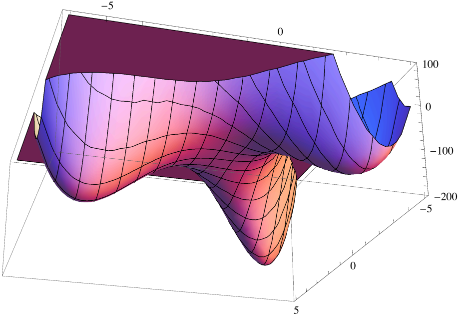

Finding the global minimum is not trivial!

- Charge- and/or color-breaking (CCB) minima (VEVs for charged or colored scalars)?
- Desired VEV combination may not be global minimum (even non-CCB if there are enough VEVs required)

Models with potentials that could develop CCB minima

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- $m^2_{\text{scalar}}(Q_{\text{GUT}}) = M_0^2$
- $m_{\text{gaugino}}(Q_{\text{GUT}}) = M_{1/2}$
- $[\text{scalar-scalar-scalar factor}](Q_{\text{GUT}}) = A_0$

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\begin{aligned}
&V^{\text{tree}}(H_d = v_d/\sqrt{2}, H_u = v_u/\sqrt{2}, \tilde{\tau}_L = v_{\tilde{\tau}_L}/\sqrt{2}, \tilde{\tau}_R = v_{\tilde{\tau}_R}/\sqrt{2}) \\
&= \tfrac{1}{32}\left(g_1^2(v_d^2 - v_u^2 + v_{\tilde{\tau}_L}^2 - 2v_{\tilde{\tau}_R}^2)^2 + g_2^2(v_d^2 - v_u^2 - v_{\tilde{\tau}_L}^2)^2\right) - B_\mu v_d v_u \\
&+ \tfrac{1}{2}\left(|\mu|^2(v_d^2 + v_u^2) + m_{H_d}^2 v_d^2 + m_{H_u}^2 v_u^2 + m_{\tilde{\tau}_L}^2 v_{\tilde{\tau}_L}^2 + m_{\tilde{\tau}_R}^2 v_{\tilde{\tau}_R}^2\right) + \\
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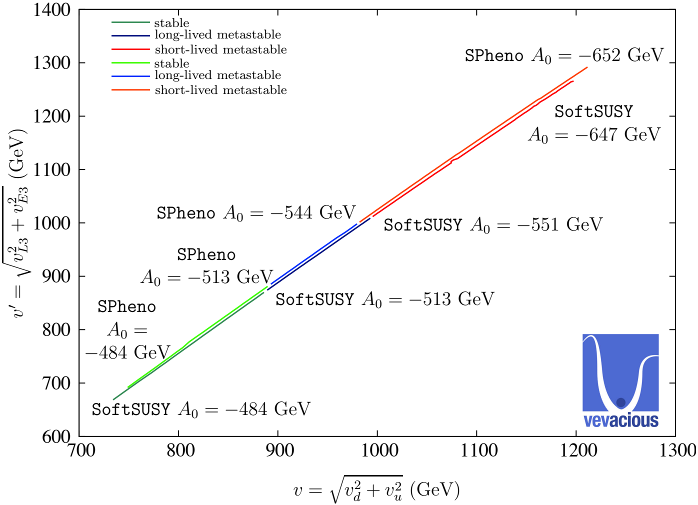
$$

Minima could develop where $v_{\tilde{\tau}_L} v_{\tilde{\tau}_R} (A_\tau v_d - \mu v_u)$ gets more negative than "$m^2 v^2 + \lambda v^4$" is positive

Evolution of a CCB minimum

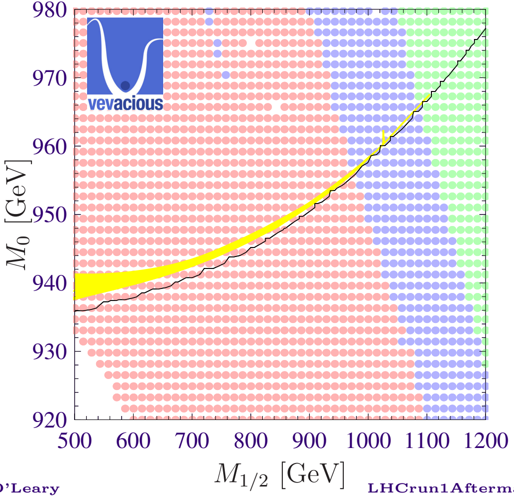
Camargo-Molina, BO'L, Porod, Staub, `arXiv:1309.7212`



$m_0 = 400$ GeV, $M_{1/2} = 300$ GeV, $\tan\beta = 50$, $\mu > 0$

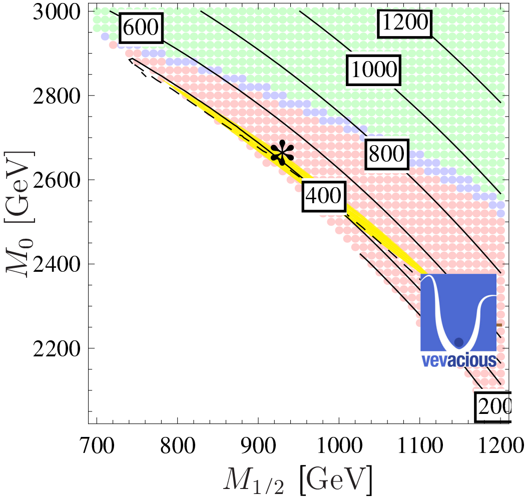
CCB restricts $\tilde{\tau}$ co-annihilation

$A_0 = +3$ TeV, $\tan\beta = 40$, $\mu > 0$; (arXiv:1309.7212)
red/blue: metastable ($\tau_{\text{tunnel}} < / > 3$ Gy); green: stable
yellow region: correct relic density; black: $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$



CCB restricts $\tilde{t}$ co-annihilation

$A_0 = -6.444$ TeV, $\tan\beta = 8.52$, $\mu < 0$; $m_{\tilde{t}_1}$ (GeV) contours colors as before, but dashed black for $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$ (1309.7212)



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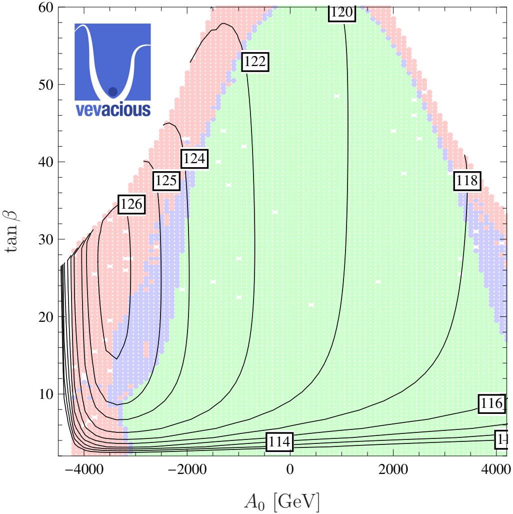
$M_0 = M_{1/2} = 1$ TeV, $\mu > 0$; m_h (GeV) contours colors as before (1309.7212)



Analytic conditions

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- $|(Y_\tau v_u \mu)/(\sqrt{2} m_\tau)| < 56.9\sqrt{m_{\tilde{\tau}_L} m_{\tilde{\tau}_R}} + 57.1(m_{\tilde{\tau}_L} + 1.03 m_{\tilde{\tau}_R}) - 1.28 \times 10^4\text{GeV} + \frac{1.67\times10^6\text{GeV}^2}{m_{\tilde{\tau}_L} + m_{\tilde{\tau}_R}} - 6.41 \times 10^6\text{GeV}^3(\frac{1}{m_{\tilde{\tau}_L}^2} + \frac{0.983}{m_{\tilde{\tau}_R}^2})$ [“numeric”]

(“GUT”: Ellwanger, Rausch de Traubenberg, Savoy, Nucl. Phys. B**492**
“A_τ”, “A_t”: Alvarez-Gaumé, Polchinski, Wise, Nucl. Phys. B**221**;
“numeric”: Kitahara, Yoshinaga, arXiv:1303.0461, JHEP)

SPS4 ($M_0 = 400\text{GeV}, M_{1/2} = 300\text{GeV}, \tan\beta = 50, |\mu| > 0$, $A_0 = 0\text{GeV}$) but with $A_0 \rightarrow$ ...

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-484	SPheno	184	726	409	558
-484	SoftSUSY	181	712	394	540
-513	SPheno	269	851	540	701
-513	SoftSUSY	274	846	532	694
-544	SPheno	326	927	620	787
-551	SoftSUSY	342	935	626	795
-652	SPheno	485	1110	819	999
-647	SoftSUSY	481	1097	800	981

$v_d : v_{\tilde{\tau}_L} : v_{\tilde{\tau}_R} \neq 1:1:1$ at CCB minimum

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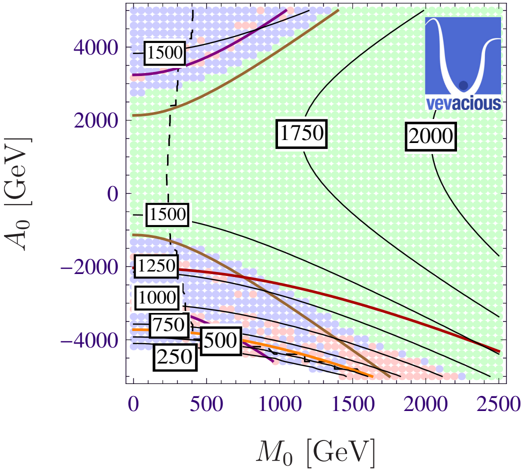
$v_d : v_{\tilde{\tau}_L} : v_{\tilde{\tau}_R} \neq 1 : 1 : 1$ at CCB minimum
$\Rightarrow$ not on line of "A_τ"!

Sometimes it looks like analytic conditions do well

$M_{1/2} = 1$ TeV, $\tan\beta = 10$, $\mu > 0$; $m_{\tilde{t}_1}$ (GeV) contours (1309.7212)



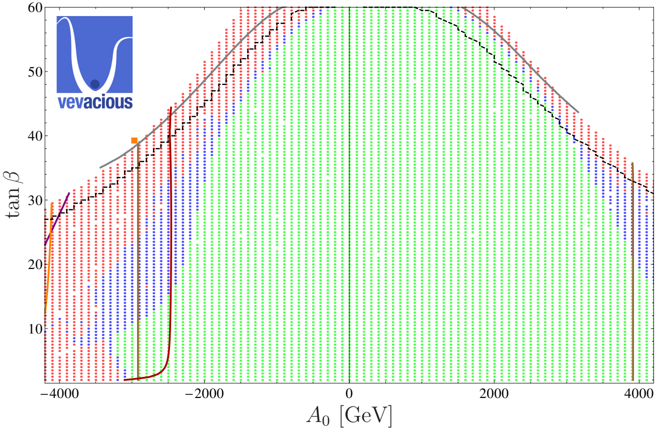
Brown: "GUT"; Purple: "A_τ"; Orange: "A_t"

Dark red: improved "A_t" (Casas, Lleyda, Munoz, Nucl. Phys. B**471**)

Dashed black: $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$

Analytic conditions do not always do well

$M_{1/2} = 1000$ GeV, $m_0 = 1000$ GeV, $\mu > 0$ (1309.7212)



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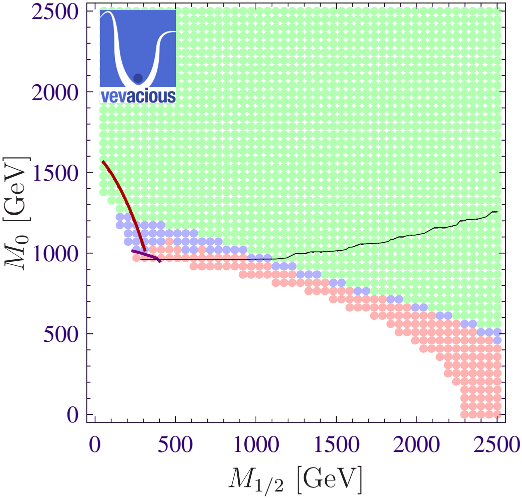
Dashed black: $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$

Analytic conditions can completely fail

$A_0 = +3$ TeV, $\tan\beta = 40$, $\mu > 0$ (1309.7212)



Purple: "A_τ"; Dark red: improved "A_t"; Black: $m_{\tilde{\tau}_1} = m_{\tilde{\chi}_1^0}$

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http://vevacious.hepforge.org/

vevacious

Vevacious: based on recent progress

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Before `Vevacious`: only implemented on a model-by-model basis, at tree-level!

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- Creating model file with `SARAH` takes minutes: `MakeVevacious[]`

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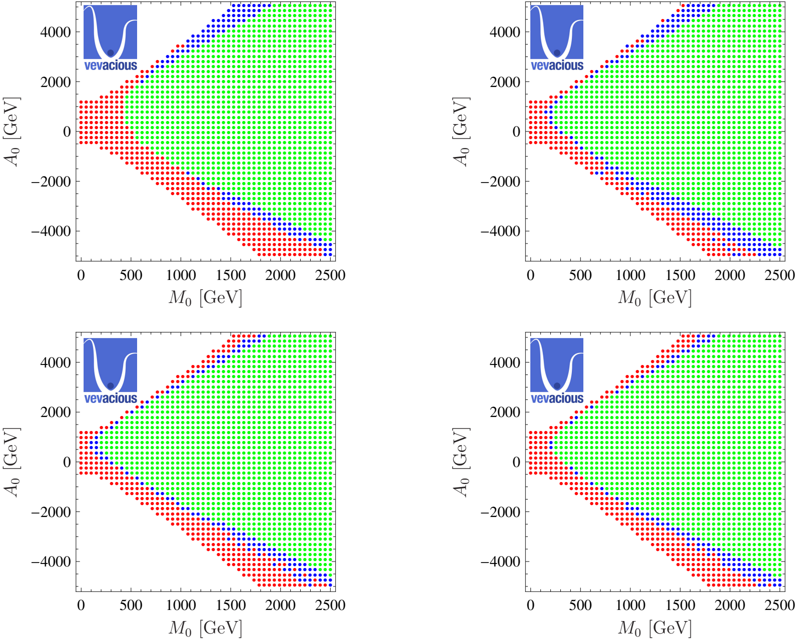
Thank you for your attention!

Backup slides

Tunneling times

- $\Gamma/$ volume $= Ae^{-B/\hbar}(1+\mathcal{O}(\hbar))$
- A is solitonic solution, should be $\sim$ energy scale of potential
- $B \sim$ ([surface tension]/[energy density difference]$)^3$
- typically TeV-scale energy barriers, energy depth differences $\Rightarrow$ roughly tunneling times of (factors of $16\pi^2$ *etc.*)/TeV $\ll$ age of Universe

Scale and loop order dependence: halving Q



Scale and loop order dependence: doubling Q