Charge Breaking Minima in the NMSSM

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Based on arXiv:1703.05329
with M. E. Krauss & F. Staub

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Motivation

When the MSSM simply isn't enough

Stability of the electroweak vacuum disfavours low-scale supersymmetry breaking in the MSSM

Hollik (2016)
Camargo-Molina, Garbrecht, O'Leary, Porod, Staub (2014)
and many more....

Low $M_{\not{SUSY}}$
$+$
$m_h = 125\,\mathrm{GeV}$

→ Large stop mass splitting →

Large A_t & $\tan\beta$

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Large stop mass splitting $\longrightarrow$ **Large A_t & $\tan\beta$**

Toy Example: consider a D-flat direction with stop VEVs: $v_u = v_{\tilde{t}^r_L} = v_{\tilde{t}^r_R}$

$$V_{\text{tree}} \propto (\text{soft-mass})^2 v_X^2 + A_t v_X^3 + |Y_t|^2 v_X^4$$

Drives minima away from origin

<u>*Warning:*</u>
Approach is overly simplistic

Two Higgs Doublet Models

What are the physical VEVs?

CP-even and -odd scalar fields

$$H_u^0 = \frac{1}{\sqrt{2}}\left[v_u e^{i\varphi_u} + \ldots\right] \qquad H_d^0 = \frac{1}{\sqrt{2}}\left[v_d e^{i\varphi_d} + \ldots\right]$$

$$H_u^+ = \frac{1}{\sqrt{2}}\left[v_p e^{i\varphi_p} + \ldots\right] \qquad H_d^- = \frac{1}{\sqrt{2}}\left[v_m e^{i\varphi_m} + \ldots\right]$$

Charged Higgs fields

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Eliminate VEVs through:

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Physical VEVs: v_u , v_d , v_p , and $\varphi_\mathrm{p}/\varphi_\mathrm{u}$

Two Higgs Doublet Models

Possible symmetry breaking minima

$$\underbrace{v_u\,,\ v_d}\,,\ v_p\,,\ \text{and}\ \varphi_\mathrm{p}/\varphi_\mathrm{u}$$

Required electroweak (EW) breaking VEVs

Charge-breaking (CB) VEV

CP-violating VEVs (not considered here)

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Shown in THDMs:

Barroso, Ferreira, Santos (2014 & 2015)

$$V_{\text{tree}}^{\text{CB}} - V_{\text{tree}}^{\text{EW}} > 0 \quad \Longrightarrow$$

If an electroweak breaking vacuum exists then any possible charge-breaking vacuum will always be shallower

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Does not hold for further extended Higgs sectors

c.f. Muhlleitner, Sampaio, Santos, Wittbrodt (2016)

What about the NMSSM?

The role of the singlet

$$W_{\text{NMSSM}} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3 + W_Y$$

New F-term tree-level contributions to Higgs mass

MSSM vacuum structure plus:

$$\langle S \rangle = \frac{v_S}{\sqrt{2}} \qquad \Longrightarrow \qquad \mu_{\text{eff}} = \frac{\lambda v_S}{\sqrt{2}}$$

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But also new soft-terms in the game

$T_\lambda = \lambda A_\lambda$ $\quad$ $T_\kappa = \kappa A_\kappa$

$$-V_{\text{soft}} = \left(T_\lambda H_u H_d S + \frac{1}{3} T_\kappa S^3 + \text{h.c.} \right) + m_S^2 |S|^2 + \ldots$$

New non-trivial vacuum stability constraints

Ellwanger, Rausch de Traubenberg, Savoy (1997)
Ellwanger, Hugonie (1999)
Kanehata, Kobayashi, Konishi, Seto, Shimomura (2011)
Kobayashi, Shimomura, Takahashi (2012)
Agashe, Cui, Franceschini (2012)
Beuria, Chattopadhyay, Datta, Dey (2016)

Charge-breaking VEVs

Determining coexisting vacua

Large A-terms not required: neglect stop & sbottom VEVs

Here we consider 5 VEVs: $v_u, \; v_d, \; v_S, \; v_p, \; v_m$

Similar analysis appeared yesterday:
Beuria, Datta (2017)

can rotate this
VEV away

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Quick Recap:

1. Minimise potential w.r.t desired EW VEVs: $v_u, \; v_d, \; v_S$

Allows soft-masses to be eliminated for other input parameters

$m^2_{H_u}, \; m^2_{H_d}, \; m^2_S \;\rightarrow\; (\mu_{\text{eff}})_{\text{min}}, \; \tan\beta_{\text{min}}, \; v_{\text{min}}$

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Quick Recap:

1. Minimise potential w.r.t desired EW VEVs: $v_u, \ v_d, \ v_S$

   Allows soft-masses to be eliminated for other input parameters

   $m_{H_u}^2, \ m_{H_d}^2, \ m_S^2$ → $(\mu_{\text{eff}})_{\text{min}}, \ \tan\beta_{\text{min}}, \ v_{\text{min}}$

2. Re-minimise potential now w.r.t *all* VEVs

Determines all additional minima that *coexist* with desired EW-breaking minimum

Tree-Level Potential

A first glance

Expect deeper CB minima

$$\Delta V = V_{\text{tree}} - V_{\text{tree}}\Big|_{v_m=v_p=0}$$
$$= \frac{1}{32} v_p^2 \Big(g_2^2 \left(2v_d^2 - 2v^2 + v_p^2 + 2v_u^2\right) - 16\mu_{\text{eff}}^2 + 8\lambda^2 v_S^2$$
$$+ g_1^2 \left(v_p^2 - 2v_d^2 + 2v_u^2\right) + 8m_{H^+}^2 \Big)$$

$\tan\beta \to 1$

$v_m \to 0$

Tree-Level Potential

F-flat directions

F-flat direction including CB VEVs: $v_m = v_u,\ v_p = v_d,\ v_S = 0$

Note: no *F*-flat directions when excluding CB VEVs

$$V\left(x^{\rm CB}_{\rm min}\right) = -\frac{\left(-4A_\lambda \lambda \mu_{\rm eff} + 4\mu_{\rm eff}^2(\lambda-\kappa) + \lambda^3 v^2\right)^2}{8 g_2^2 \lambda^2}$$

$$x^{\rm CB} = \sqrt{v_d^2 + v_u^2 + v_m^2 + v_p^2}$$

CB minima occur for:

- $|\lambda|$ and $|\mu_{\rm eff}|$ are large
- $|\kappa/\lambda| < 1$ with $\mathrm{sign}(\kappa) = \mathrm{sign}(\lambda)$
- $|A_\lambda/\mu_{\rm eff}| < 1$
- $\mathrm{sign}(A_\kappa) = -\mathrm{sign}(\mu_{\rm eff})$

Condition for positive mass squared of charged Higgs:

$$0 < \frac{1}{4} v^2 \left(g_2^2 - 2\lambda^2\right) + 2\frac{\kappa}{\lambda}\mu_{\rm eff}^2 + 2\mu_{\rm eff} A_\lambda$$

Tree-Level Potential

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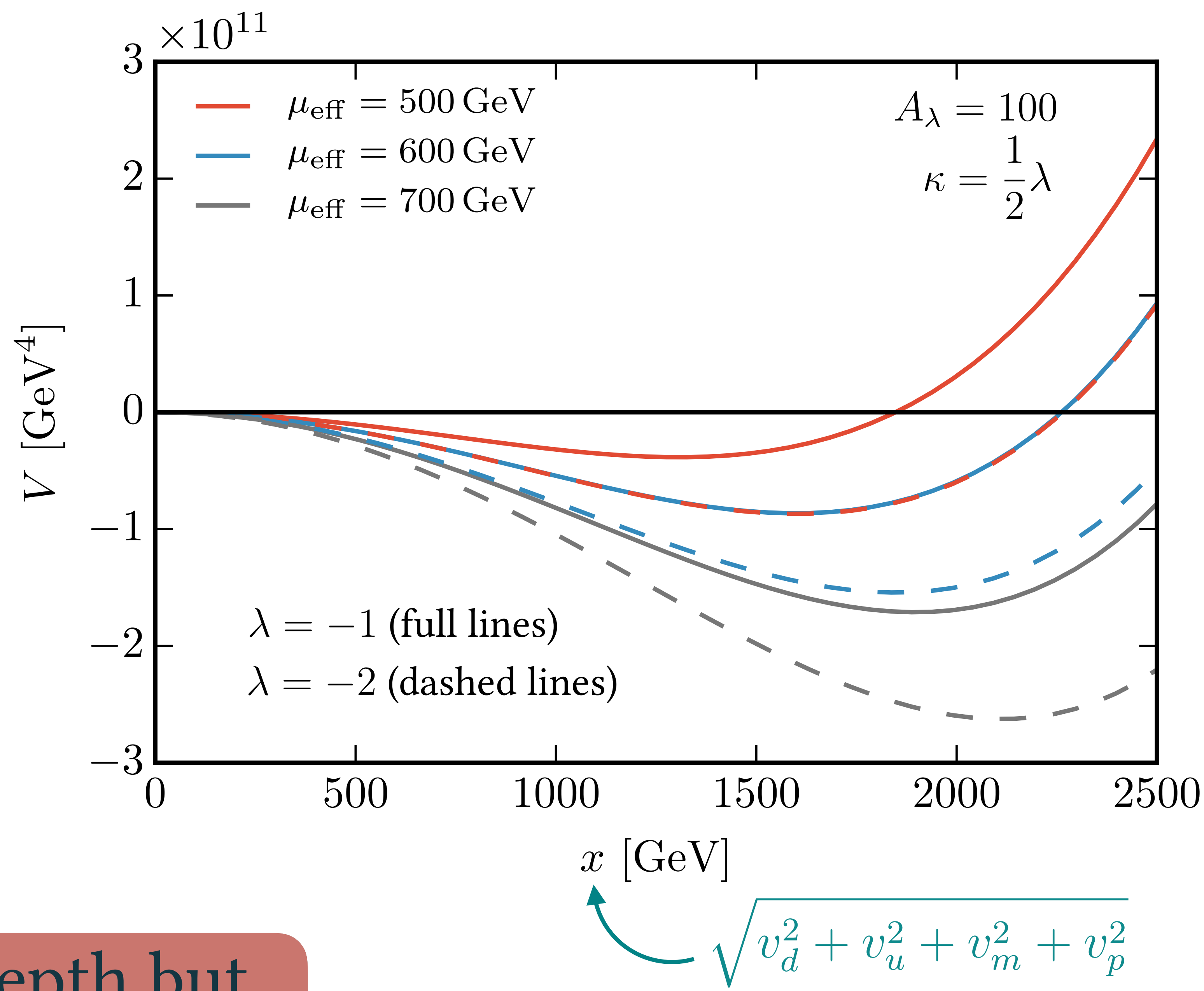


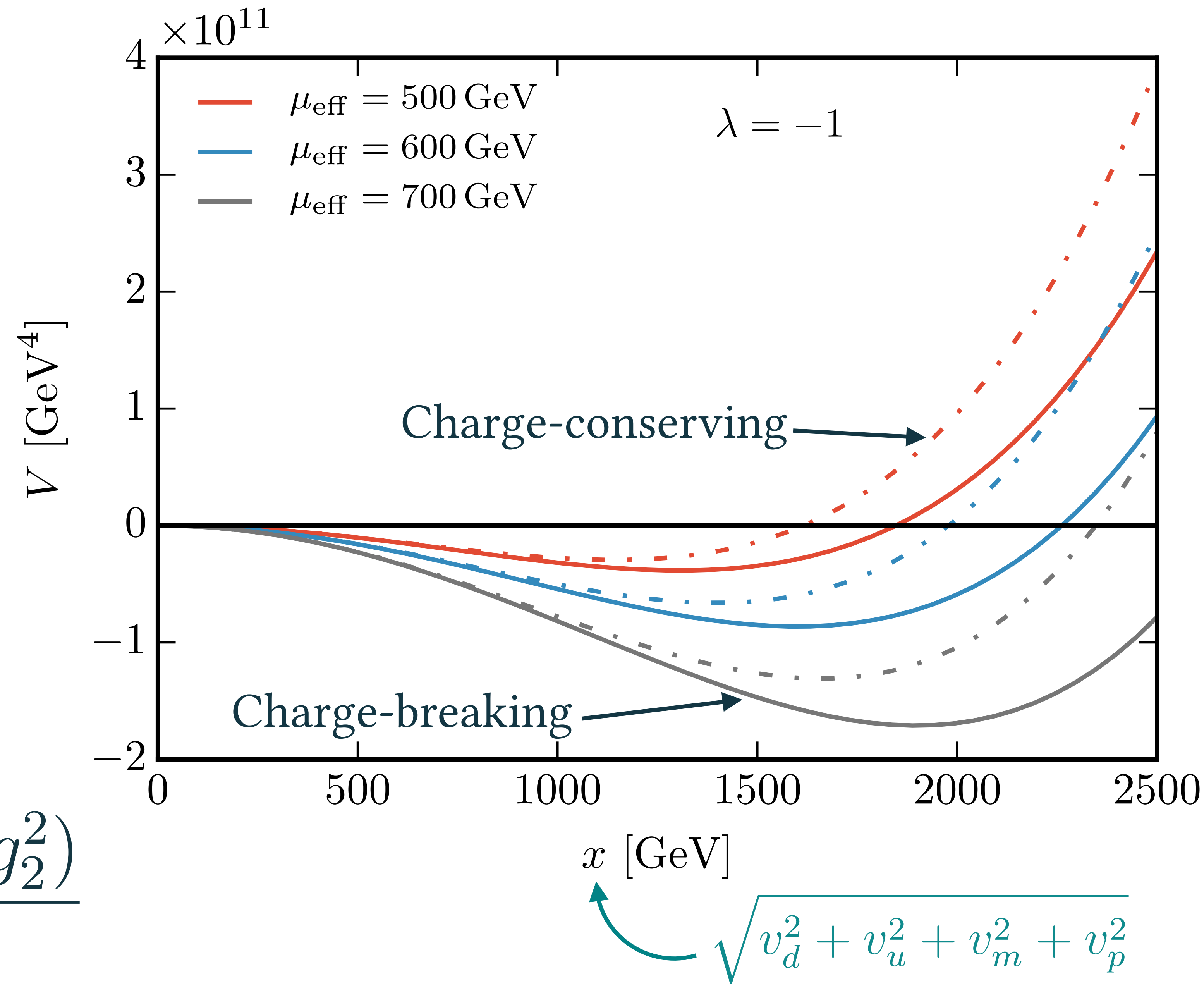
Increasing μ_{eff} increases depth but drives minima further away

Tree-Level Potential

Other directions

Another important direction in field space:

$$v_u = v_m = v_p = v_S = 0$$
$$v_d \equiv x^{\mathrm{CC}} \neq 0$$



Deeper by a factor: $\dfrac{(g_1^2 + g_2^2)}{g_2^2}$

Further away by a factor: $\dfrac{\sqrt{g_1^2 + g_2^2}}{g_2}$

Numerical Results

Methodology

Considering all minima and directions in field space requires a numerical approach

SARAH

Consider two models:
3 VEV (only neural)
4 VEV (one charged)

SPheno

Consider the following parameter space:
(no A-terms in the sfermion sectors)

- $\tan\beta \in [1, 4]$
- $\lambda \in [-2, 2]$
- $\kappa \in [-2, 2]$
- $A_\lambda \in [-5, 5]$ TeV
- $A_\kappa \in [-5, 5]$ TeV
- $\mu_{\text{eff}} \in [-2, 2]$ TeV

Vevacious

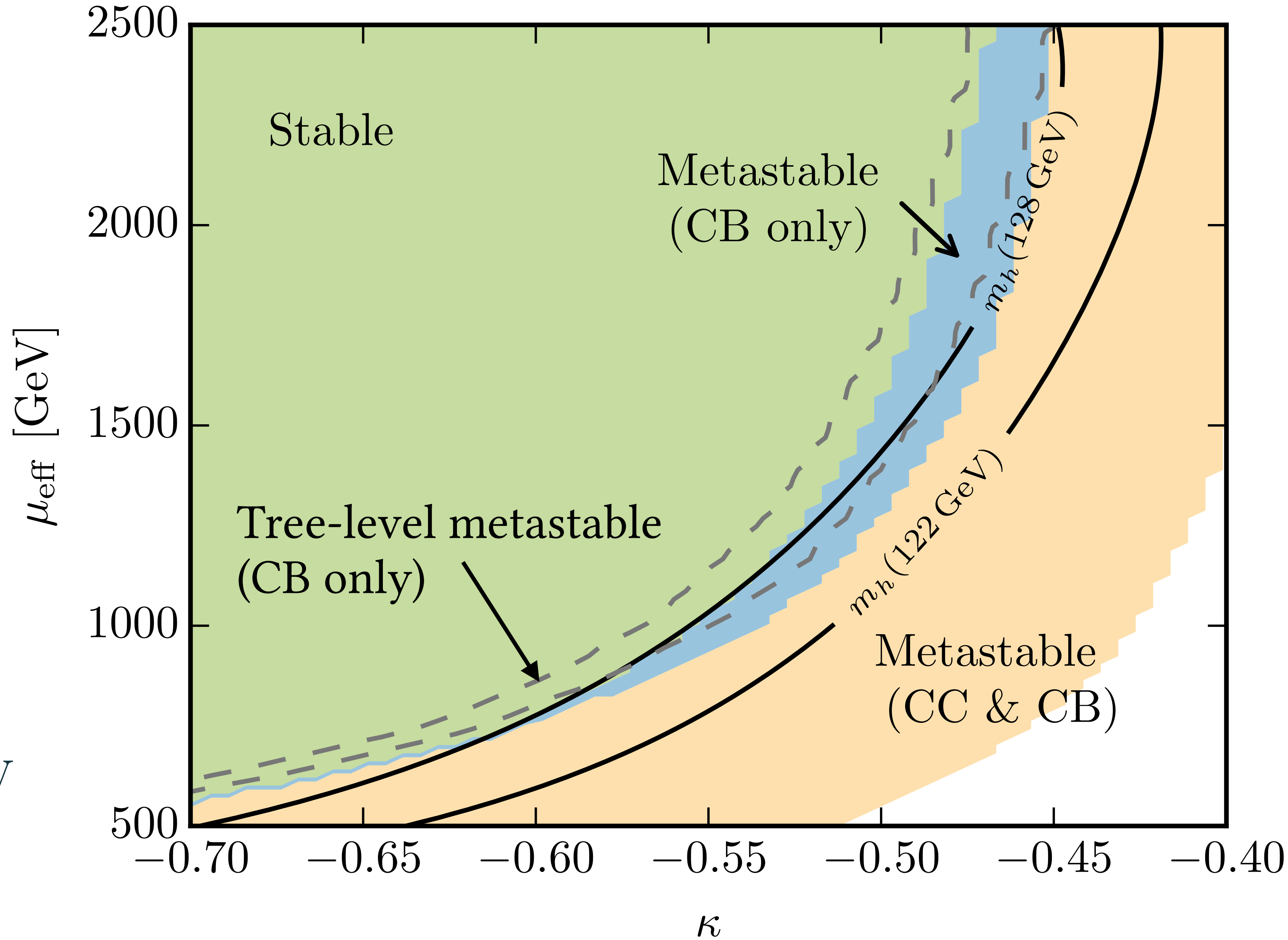
- Determines all tree-level minima
- Minima of one-loop eff. potential found by allowing tree-level minima to roll
- CosmoTransitions used to calculate tunnelling rate to the panic vacuum

Must check *all* minima!

Numerical Results

Stable versus metastable vacua

Strips of parameter space where not including CB minima gives wrong result

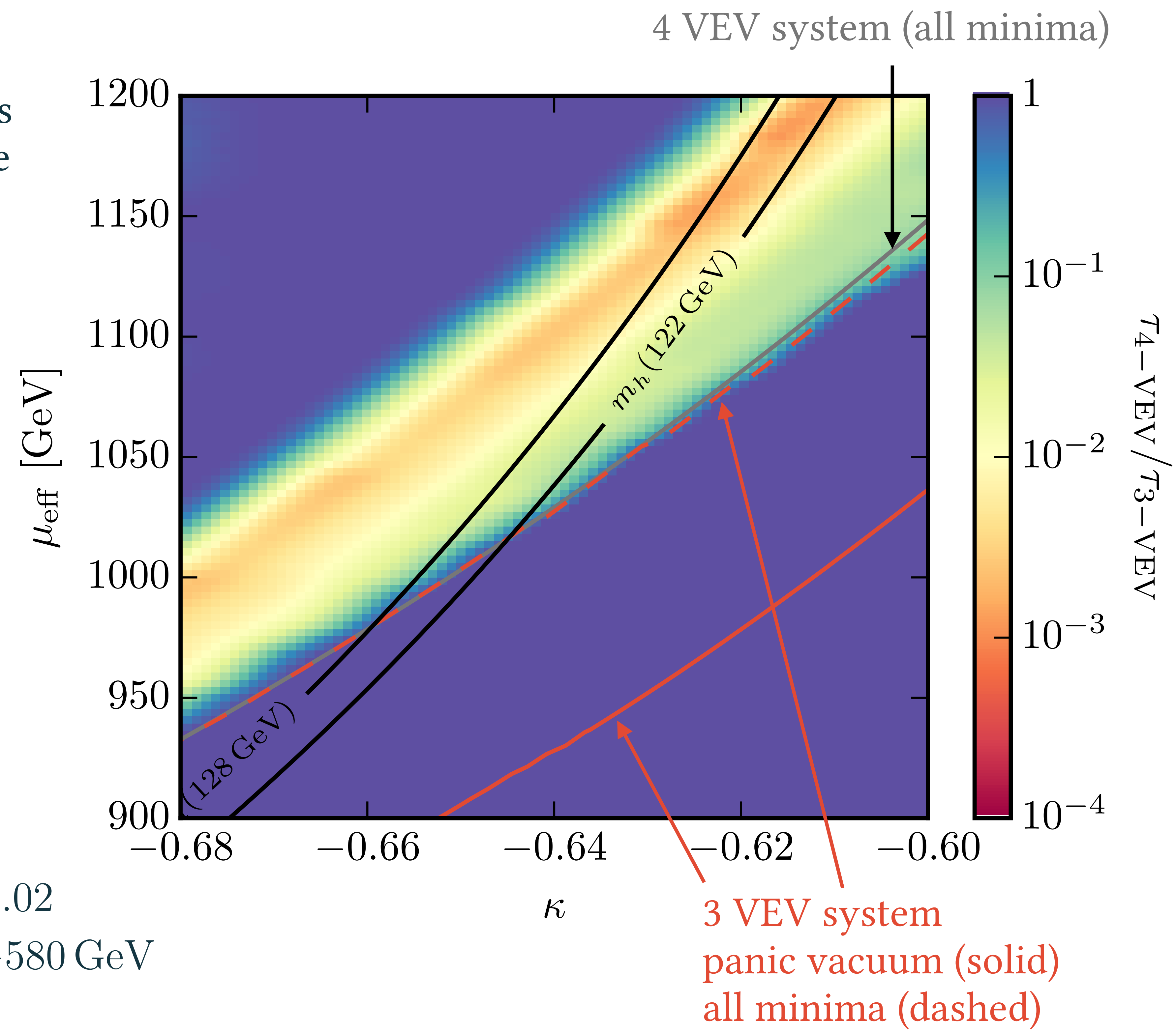


Here $\lambda = -0.68$, $\tan\beta = 1.02$
$A_\kappa = -700\,\mathrm{GeV}$, $A_\lambda = -300\,\mathrm{GeV}$

Numerical Results

Long-lived versus short-lived vacua

Regions *below* red/grey lines have lifetimes below the age of the universe



Here $\lambda = -0.81$, $\tan\beta = 1.02$

$A_\kappa = -1400\,\text{GeV}$, $A_\lambda = -580\,\text{GeV}$

Conclusion

1. If you want a stable EW vacuum in your BSM model:

Charge-breaking VEVs are important!

Conclusion

1. If you want a stable EW vacuum in your BSM model:

Charge-breaking VEVs are important!

2. If you are content with a metastable EW vacuum:

Charge-breaking VEVs are phenomenologically uninteresting

Caveats:
- thermal tunnelling neglected
- checked order 50,000 points
- not considered sfermion VEVs
- `CosmoTransitions` does not always find optimum tunnelling path