

# CP violation beyond the MSSM

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Blum, D, Hochberg – arXiv: [0905.1701](https://arxiv.org/abs/0905.1701)

Blum, D, Losada, Nir, Tulin – arXiv: [1001.soon](https://arxiv.org/abs/1001.0001)

# Outline

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- MSSM little hierarchy (little) problem
- No fine-tuning with a heavy (susy) threshold (BMSSM)
- BMSSM CP violation
- EDMs constraints
- Impact on Electroweak Baryogenesis

# MSSM little hierarchy

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- MSSM – The fine-tuning strikes back (no-mixing, degenerate stops)

$$(115 \text{ GeV})^2 < m_h^2 < m_Z^2 \cos^2(2\beta) + \frac{3g^2 m_t^4}{16\pi^2 m_W^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \mathcal{O}(t_\beta m_b/m_t)^4$$

- need large susy breaking scale  $(m_{\tilde{t}}^2 - m_t^2) \propto e^{m_h^2}$

$$m_U^2, m_Q^2 \gtrsim (500 \text{ GeV})^2 \quad (\tan \beta \gtrsim 10), \quad \text{TeV}^2 \quad (\tan \beta \simeq 1)$$

- back to quadratic running of scalar masses

fine – tuning  $\sim m_Z^2/m_Q^2 \simeq 1 - 5\%$  *there is a little hierarchy problem!*

- Electroweak baryogenesis requires a light (RH-) stop

$$m_U^2 \lesssim 0, \quad m_Q^2 > (10 - 10^4 \text{ TeV})^2 \quad (\tan \beta \lesssim 10), \quad \text{Review: Carena et al. '08}$$

*there is a **big** little hierarchy problem!*

# Going Beyond the MSSM

*Dine, Seiberg, Thomas '07*

- The MSSM is crying for new physics; what if it's heavy ?

$$\mathcal{W} \supset \mu H_u H_d + \frac{1}{M} (\lambda_1 + \lambda_2 \mathcal{Z}) (H_u H_d)^2, \quad \mathcal{K} = \mathcal{K}_{\text{MSSM}} + \mathcal{O}(1/M^2)$$

new susy threshold

Susy breaking spurion  $\mathcal{Z} = M_{\text{susy}} \theta^2$

- new quartic:  $V = V_{\text{MSSM}} + 2\epsilon_1 h_u h_d (|h_u|^2 + |h_d|^2) + \epsilon_2 (h_u h_d)^2 + \text{h.c.}$

$$(\epsilon_1 = \lambda_1 \mu^*/M, \quad \epsilon_2 = -\lambda_2 M_{\text{susy}}/M)$$

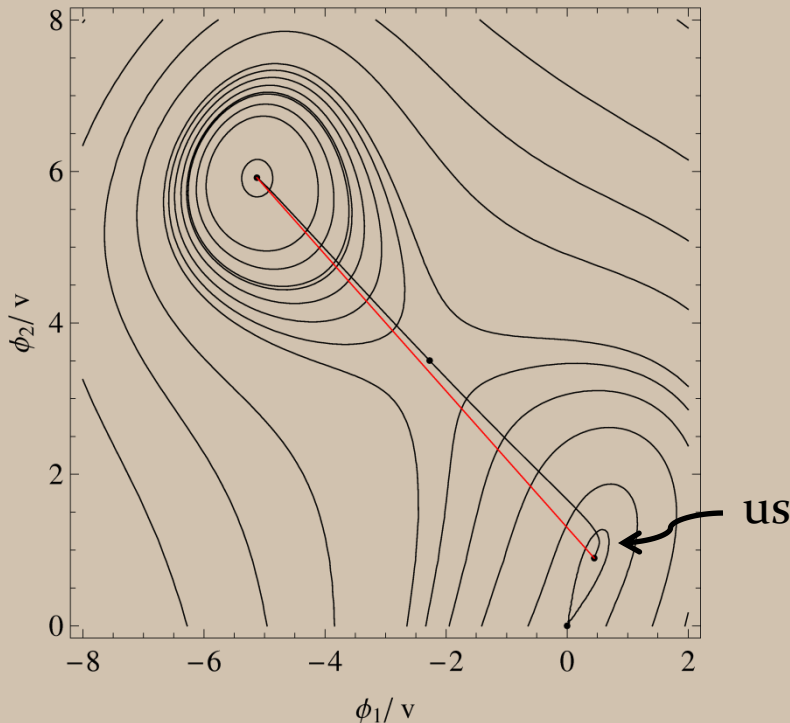
$$(115 \text{ GeV})^2 < m_h^2 \lesssim m_Z^2 \cos^2(2\beta) + 16v^2 \left( -\frac{\epsilon_{1r}}{\tan \beta} + \frac{\epsilon_{2r}}{2 \tan \beta^2} \right) + \text{loops}$$

$$|\epsilon_{1r}| \simeq 0.05 - 0.1 \quad \rightarrow \quad \text{sizable Higgs mass correction} \quad (\tan \beta \lesssim 1/\epsilon \sim 10)$$

# Vacuum stability constraint

Blum, D, Hochberg '09

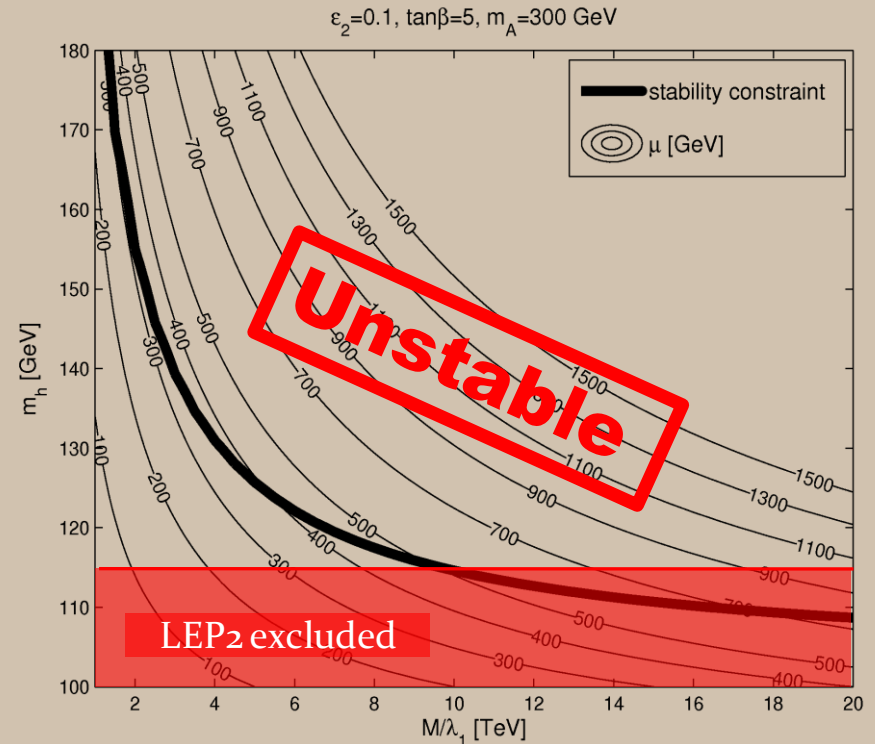
- another vacuum forms at  $|h| \sim \sqrt{m_Z M} < M$



*classical* Higgs mass  
as large as 170 GeV  
(for  $M \sim \text{TeV}$ )

our vacuum stable if:

$$\frac{|(1 + \epsilon_{2r}/4\epsilon_{1r})\mu|^2}{2m_A^2(1 + s_{2\beta})} \leq 1 + \mathcal{O}(m_Z^2/m_A^2)$$



# CP violation in the BMSSM

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- 7 MSSM CPV phases + 2 new phases from  $\epsilon_{1,2} \in \mathbb{C}$   
but not all physical, thanks to  $U(1)_{PQ,R}$  field redefinitions
- invariant phases:

MSSM phases		BMSSM phases		VEV phase
$\phi_i$	$\phi_f$	$\vartheta_1$	$\vartheta_2$	$\theta$
$\arg(M_i \mu / b)$	$\arg(A_f \mu / b)$	$\arg(\epsilon_1 / b)$	$\arg(\epsilon_2 / b^2)$	$\arg(b H_u H_d)$

- in BMSSM the VEV phase is non-zero at tree-level,  $\partial V / \partial \theta = 0$

$$\tan \theta = \frac{2 v^2 (\epsilon_{2i} s_{2\beta} - 2 \epsilon_{1i})}{s_{2\beta} (m_{H_{\pm}}^2 - m_W^2) + 2 v^2 (\epsilon_{2r} s_{2\beta} - 2 \epsilon_{1r})}$$

$$\epsilon_{1i} \equiv |\epsilon_1| \sin(\vartheta_1 + \theta), \text{ etc } \dots$$

- at leading order :  $\theta \simeq \mathcal{O}(\epsilon_i)$

# EDMs constraints on BMSSM phases

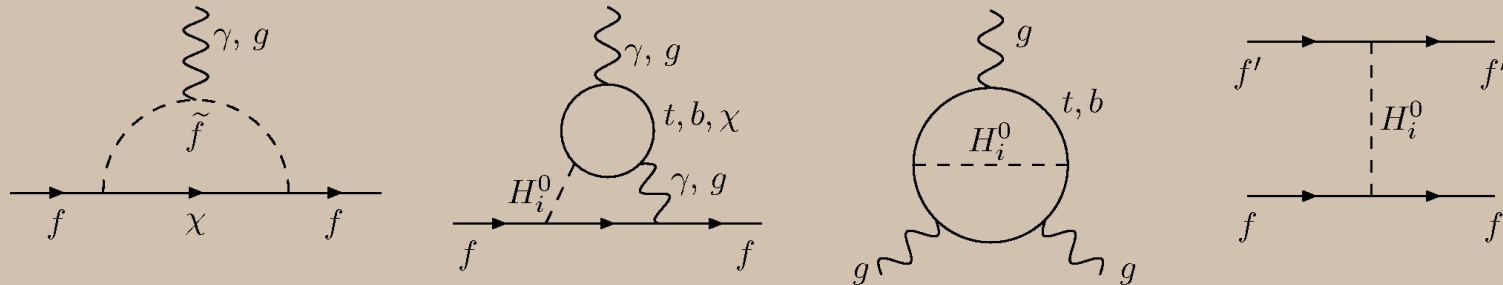
- BMSSM induces **new** CPV sources in

- tree-level Higgs scalar-pseudoscalar mixing (via  $\vartheta_{1,2}$ )

$$m_{h_A}^2 \approx 4v^2 \epsilon_{1i} - 2v^2 \epsilon_{2i} \sin 2\beta \propto \theta, \quad m_{H_A}^2 \approx 2v^2 \epsilon_{2i} \cos 2\beta$$

- Stop, chargino and neutralino mass matrices (mostly via  $\theta$ )

- leads to EDMs at zero-T :



which constrain the BMSSM phases (essentially  $\theta$ )

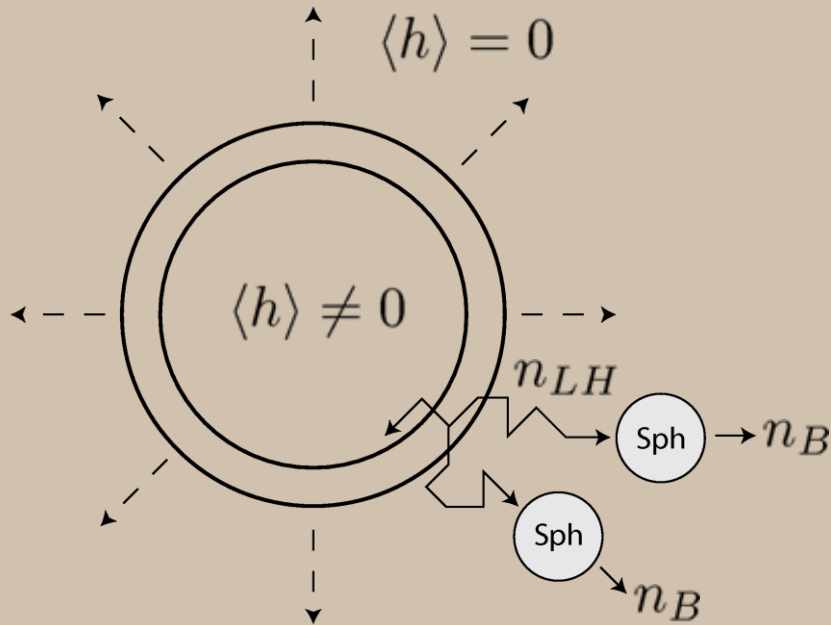
current bounds:  $|d_{n, Tl, Hg}| < 3 \times 10^{-26}, 9 \times 10^{-25}, 2 \times 10^{-29} \text{ ecm}$

$$d_{Tl} \simeq -585 d_e$$

strongest bound on BMSSM

# Electroweak Baryogenesis

Cohen, Kaplan, Nelson '92-94



$$\eta \equiv n_B/n_\gamma \simeq 6 \times 10^{-10} \gg 10^{-18}$$

Sakharov conditions:

- B violation (weak sphaleron)
- C, CP violation (complex phases)
- out of eq. (first-order transition)

- QBEs from « Closed-Time Path » formalism (for out-of equilibrium, finite T QFT) :

$$\partial_t n_a - D_a \nabla^2 n_a = \sum_b \Gamma_{ab} n_b + S_a^{CPV}, \quad (a = t_{L,R}, \tilde{t}_{L,R}, \tilde{H}, H)$$

diffusion approx.

$$\eta \propto \sum_a S_a^{CPV}$$



# Electroweak Baryogenesis + EDMs

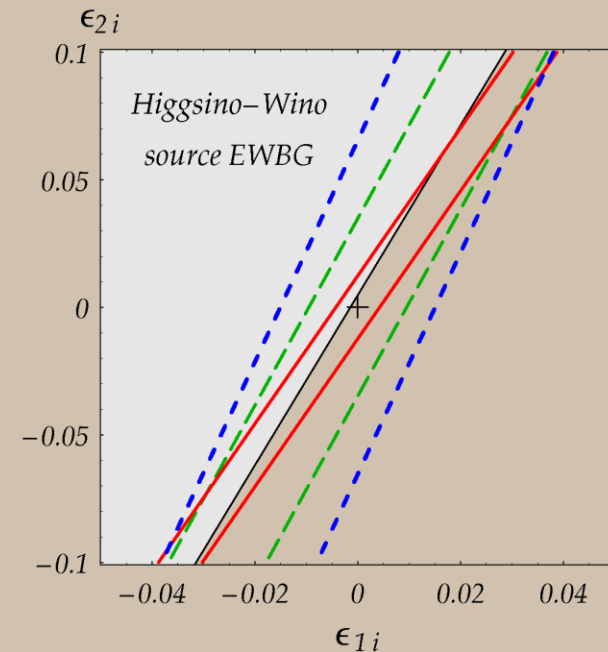
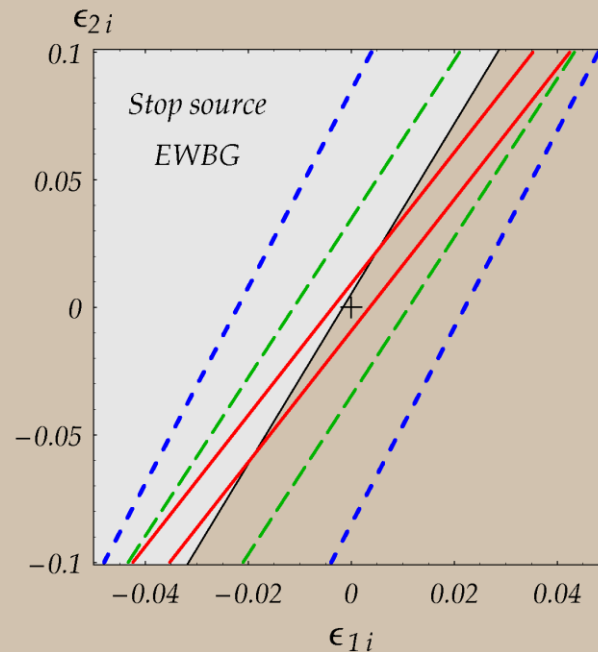
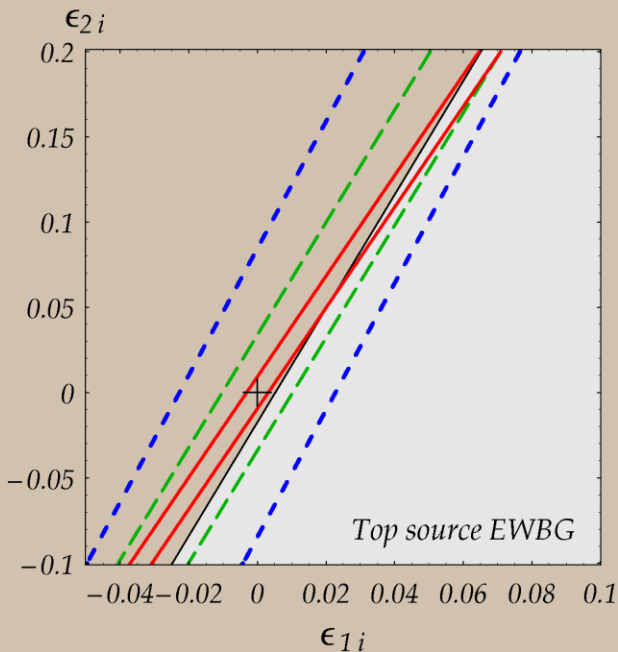
- in BMSSM, EWBG can be (s)top-, or higgs(ino)-driven!
- at leading order in the VEV (in the wall-frame):

$$S_{i=\tilde{t},t,\tilde{H}}^{CPV}(z) \sim v_w v^2(z) \left[ A_i \dot{\beta}(z) + B_i \dot{\theta}(z) \right] \quad \dot{\beta}(z) \simeq \Delta\beta/L_w, \quad \dot{\theta}(z) \simeq \Delta\theta/L_w$$

$$\Delta\theta \simeq \theta(v_c/v)^2 \sim (0.2 - 0.5)\theta$$

$\phi_{\text{MSSM}} = 0$   
**e-, n-, Hg-EDMs**

T=0 phase



# what to take back home?

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- the MSSM is a bit (lot?) fine-tuned! but this is not a big problem
- a heavy new physics (BMSSM) solves it (for  $\tan\beta \lesssim 10$ ) and seems to make EWBG much more natural as well
- if BMSSM is the correct susy theory of the weak scale/era, one should measure EDMs soon!

LHC ?

- a Higgs + 2 light stops would be a first hint

More anything?

