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Metastable Supersymmetry Breaking in a Cooling Universe[1]

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Abstract. I put metastable supersymmetry breaking in a cosmological context. I argue that under reasonable assumptions, the cooling down early Universe favors metastable SUSY-breaking vacua over the stable supersymmetric vacua. To illustrate the general argument, I analyze the early–Universe history of the Intriligator–Seiberg–Shih model.

Keywords: supersymmetry breaking, cosmology
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Let me start with a historical note. The metastable supersymmetry breaking (MSB) is actually quite old — Michael Dine and Willy Fischler [1] constructed interesting models with both SUSY and non-SUSY vacua back in 1981. But later, when people searched for SUSY breaking driven by strong interactions (in a UV-free but IR-strong hidden sector) but didn't have techniques for analyzing effective potential in strongly interacting theories, they focused on models where SUSY *had to break* because there were no SUSY vacua at all, and no runaway directions [2]. Although many new techniques for analyzing IR-strong gauge theories emerged in mid-nineties, the search for SUSY breaking remained focused on *true vacua* (lowest-energy states) without SUSY. It took the Intriligator–Seiberg–Shih paper [3] to bring the MSB back into limelight.

Following Intriligator, Seiberg and Shih, there was a flood [8]–[24][2] of metastable SUSY–breaking (MSB) models, many of them string based. Such models have multiple vacua, some supersymmetric and some SUSY-breaking; sometimes there also supersymmetric runaway directions. The physically-interesting non-SUSY vacua are metastable but very long lived. Given infinite time, they would eventually tunnel to a SUSY vacuum or a runaway state, but this takes much longer then the present age of the Universe. So if a model somehow ended in the metastable state soon after the Big Bang, it would stay there until today and long afterwards.

Naturally, this raises **the Big Question:** *Given an MSB model with multiple vacua, which vacuum would be selected by the cosmological history of the Early Universe?* In this talk I am presenting **Our Answer:** Under reasonable assumptions, *the Early Universe favors the metastable SUSY–breaking vacua.*

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[1] Plenary talk at Pascos–07 conference (Imperial College (London), July 2007), based on paper [4] by W. Fischler, myself, C. Krishnan, L. Manelli, and M. Torres, and on subsequent (not yet published) work by M. Torres and myself.
[2] As of this writing, the arXiv has over 130 papers on the subject, but I cannot quote them all because of space limitations. The papers [8]–[24] are just a small sample of this flood.

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Let me start by summarizing the common features of MSB models which can be used as SUSY-breaking hidden sectors of phenomenologically viable theories.

- For phenomenological reasons, the scale of SUSY breaking should be either 10^5–10^6 GeV (for the direct gauge mediation of SUSY breaking to the Standard Model), or 10^{10}–10^{11} GeV (for the indirect gauge mediation, or for the SUGRA+Kähler mediation). In any case, the SUSY breaking itself (as opposed to its mediation) does not depend on SUGRA effects and can be approximated by the rigid SUSY.
- The model must have an approximate $U(1)_{\mathrm{R}}$ symmetry to facilitate the spontaneous SUSY breakdown. I am not sure if this R-symmetry is quite as necessary as Seiberg *et al* claim [7], but it certainly helps, and thus far all known MSB models do have an approximate R–symmetry.
- In order to give masses to the Standard Model's gauginos, the R-symmetry must be broken. Usually, a small *explicit* breaking of the R-symmetry is amplified via spontaneous breaking. Alternatively, a small *explicit* breaking of the R-symmetry in the SUSY-breaking hidden sector is amplified in the mediator sector. But a purely spontaneous R-symmetry breaking would be bad because of exactly-massless Goldstone bosons.
- Explicit breaking of the R-symmetry leads to additional vacua with unbroken SUSY. For *small* R-symmetry breaking, those SUSY vacua are far away (in field space) from the non-SUSY vacua. That is, the scale σ of VEVs and masses in the SUSY vacuum is much bigger then the scale μ in the non-SUSY vacuum,

$$\frac{\sigma}{\mu} \sim \Big(\text{R-symmetry breaking}\Big)^{\text{some negative power}} \gg 1. \tag{1}$$

- The non-SUSY vacuum is metastable because it has higher energy density then the SUSY vacua. *But for $\sigma \gg \mu$, its lifetime is very long.* Indeed, the potential barrier between the SUSY and non-SUSY vacua is very wide, $\Delta\Phi = O(\sigma)$, while the potential difference is only $\Delta V = O(\mu^4)$. The tunneling action of a Euclidean bubble of the true vacuum inside the false vacuum is

$$S \sim \frac{V^2(\Delta\Phi)^4}{(\Delta V)^3} \gtrsim \frac{(\Delta\Phi)^4}{\Delta V} \sim \left(\frac{\sigma}{\mu}\right)^4 \gg 1. \tag{2}$$

  Thus, *for $\sigma \gtrsim 10\mu$, the metastable SUSY-breaking vacuum would easily survive until the present age of the Universe.*

To place an MSB model in a broader context, I make the following **assumptions**:

⋆ The SUSY-breaking hidden sector has nothing to do with inflating the Universe. The Inflation happens due to dynamics of a completely separate sector of the overall theory.

⋆ The overall theory has yet another sector, which cancels the cosmological constant due to SUSY breaking in the metastable vacuum.

⋆ After the Inflation, the reheating temperature is high enough for the high-temperature phase of the SUSY-breaking sector,

$$T_{\text{reheat}} > O(\sigma) \gg \mu. \tag{3}$$

I claim that under these assumptions, the cosmological evolution of the MSB sector during the early Universe tends to end up in the metastable non-SUSY vacuum state. Here is the **basic argument**:

After the Inflation is over, the Hubble expansion of the Universe is slow ($H \ll T$) and the temperature decreases slowly enough for the quasistatic approximation: At any given time, the fields and particles are in thermal equilibrium for the appropriate temperature, and the free energy is minimized. Or rather, the free energy density $\mathscr{F}$ is always in a *local* minimum.

Multiple local minima of $\mathscr{F}$ correspond to multiple phases: one stable (the global minimum), the others metastable. Transitions between the phases require tunneling or thermal activation, and can be very slow. If they take longer then the Hubble time, they never happen, and the SUSY-breaking sector stays in a metastable phase.

The non-SUSY phase has higher potential energy then the "SUSY" phase[3] but also higher entropy (because it has lighter particles, $\mu \ll \sigma$). At higher temperatures, the entropy wins over the potential energy, which favors the non-SUSY phase. And at very high temperatures ($T > O(\sigma)$) the SUSY phase disappears altogether, because the slope of the entropy function overwhelms the minimum of the scalar potential.

I assume the Universe reheats to $T \gg \sigma$ and then slowly cools down. At first, the MSB sector has only the non-SUSY phase. As the temperature drops below $O(\sigma)$, other phases develop, but the non-SUSY phase has lowest free energy, and the sector remains in that phase.

Much later, for $T = O(\mu)$, the scalar potential wins over entropy, and the non-SUSY phase becomes metastable, while the SUSY phase becomes thermodynamically stable. But the first-order transition from the metastable to the stable phase requires either tunneling or thermal activation of a bubble, and both processes are very slow for $\sigma \gg \mu$:

$$\Gamma_{\text{tunneling}} \sim \exp(-S[\text{Eucl. 4D bubble}]) \ll \exp\left(-O(1) \times \left(\frac{\sigma}{\mu}\right)^4\right), \tag{4}$$

$$\Gamma^{\text{thermal}}_{\text{activation}} \sim \exp\left(-\frac{E[\text{3D bubble}]}{T}\right) \ll \exp\left(-O(1) \times \left(\frac{\sigma}{\mu}\right)^3\right). \tag{5}$$

Thus today, 13.5 gigayears since the temperature crossed the transition point, the theory remains in the metastable SUSY-breaking phase, and will stay there for many more gigayears.

To illustrate this general argument with a specific example, let us consider the **Intriligator–Seiberg–Shih model** [3]. In that model, the **UV** theory is simply SQCD with massive but light quarks, $m_q \ll \Lambda$, and $N_c < N_f < \frac{3}{2}N_c$. The **IR** theory at energies below Λ follows by Seiberg duality: it's SQCD with $N = N_f - N_c$ colors, $N_f > 3N$ flavors, and N_f^2 extra gauge singlets $\Phi_{ff'}$. The singlets originate from the mesons of the UV theory, $\Phi_{ff'} = \Lambda^{-1}\langle \tilde{q}_f q_{f'} \rangle$; their flavor quantum numbers are $\mathbf{Adj} + \mathbf{1}$. The IR quarks Q_f and antiquarks $\tilde{Q}_f$ and the IR gauge fields do not have clear UV origins. The

[3] By "SUSY" phase I mean the phase which for zero temperature reduces to the SUSY vacuum. At finite temperatures SUSY is broken, hence the quote marks.

superpotential is

$$W = h\,\mathrm{tr}(\Phi\tilde{Q}Q) - h\mu^2\,\mathrm{tr}(\Phi) + hNC\Big(\det(\Phi)\Big)^{1/N} \tag{6}$$

where $\mu^2 \simeq \Lambda m_q \ll \Lambda^2$, and $C \simeq \Lambda^{3-(N_f/N)}$. The Kähler function is approximately canonical (modulo perturbative renormalization), because the theory is IR free, $\beta_h, \beta_g > 0$.

Without the non-renormalizable third term, there is exact $U(1)_{\mathrm{R}}$ symmetry, and SUSY has to break:

$$F_\Phi \propto \tilde{Q}Q - \mu^2 \times \mathbf{1}_{N_f \times N_f} \neq 0 \quad \text{because } \mathrm{rank}(\tilde{Q}Q) \leq N < N_f. \tag{7}$$

In the non-SUSY vacuum,

$$\langle\Phi\rangle = 0, \qquad \langle Q\rangle = \langle\tilde{Q}\rangle^\top = \mu \times \begin{pmatrix} \mathbf{1}_{N\times N} \\ \mathbf{0}_{N\times(N_f-N)} \end{pmatrix}. \tag{8}$$

The determinant term in W breaks the R-symmetry, and leads to an additional SUSY vacuum (or rather $N_f - N = N_c$ vacua) with

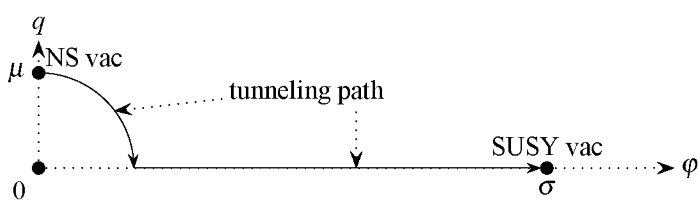
$$\langle Q\rangle = \langle\tilde{Q}\rangle = 0, \qquad \langle\Phi\rangle = \sigma \times \mathbf{1}_{N_f\times N_f}, \tag{9}$$

$$\sigma = (\mu^2/C)^{N/(N_f-N)} \simeq \left(\mu^{2N}\Lambda^{N_f-3N}\right)^{1/(N_f-N)} \gg \mu. \tag{10}$$

To analyze and depict various phase transitions in this model, I am restricting its fieldscape to a two-parameter ansatz:

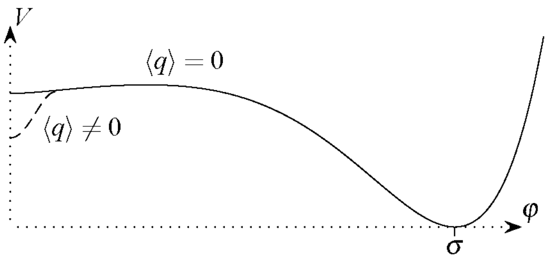
$$\Phi = \varphi \times \mathbf{1}_{N_f\times N_f}, \qquad Q = \tilde{Q}^\top = q \times \begin{pmatrix} \mathbf{1}_{N\times N} \\ \mathbf{0}_{N\times(N_f-N)} \end{pmatrix}, \tag{11}$$

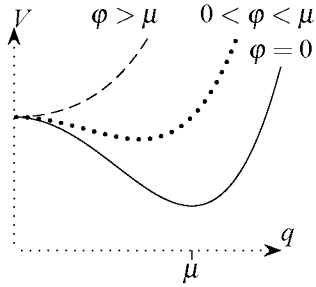
and real φ and q (for real σ and μ). In this ansatz, the tunneling from the non-SUSY to the SUSY vacuum happens along the following path:



At zero temperature, the effective potential of the model is approximately

$$V(\varphi,q) \approx \frac{N_f h^2\mu^4}{Z_\Phi(\varphi)} \times \left(1 - (\varphi/\sigma)^{(N_f/N)-1}\right)^2 + Nh^2\left(q^4 - 2\mu^2 q^2 + 2\varphi^2 q^2\right) \tag{12}$$



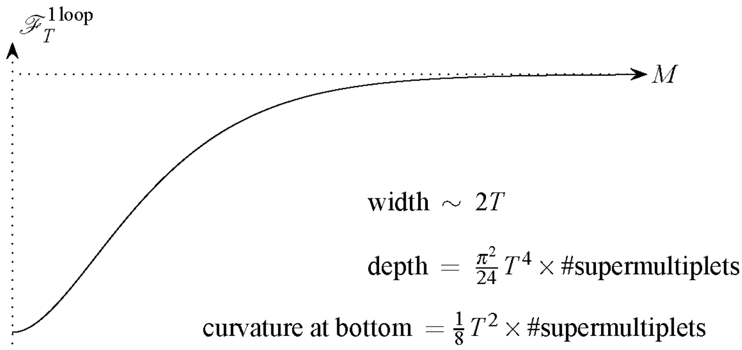


At finite temperatures, the effective potential — *i.e.*, the free energy density — comprises

$$\mathscr{F}(\varphi,q) \;=\; V(\varphi,q) + \mathscr{F}_T^{1\,\mathrm{loop}}(\varphi,q) + \text{higher order corrections}, \qquad (13)$$

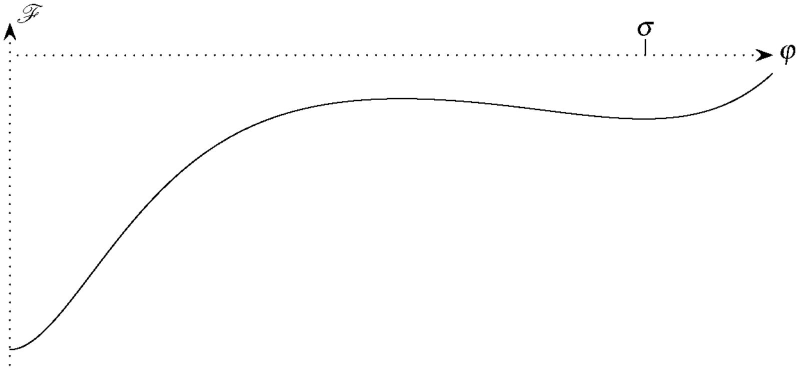
$$\mathscr{F}_T^{1\,\mathrm{loop}} \;=\; T\times\int\frac{d^3p}{8\pi^3}\,\mathrm{Str}\Big(1-(-1)^F\exp\Big(-\sqrt{p^2+M^2}/T\Big)\Big), \qquad (14)$$

where the spectrum of M^2 depends on φ and q.



For high temperatures, $T \gg \sigma$, the thermal energy $\mathscr{F}_T^{1\,\mathrm{loop}}$ completely overwhelms the scalar potential V. Consequently, the net free energy $\mathscr{F}(\varphi,q)$ has only one minimum at $\varphi = q = 0$, which means there is a unique high-temperature phase HT. Note that this phase is distinct from the non-SUSY phase at low temperatures because of different squark expectation values ($\langle q\rangle = 0$ in the HT phase versus $\langle q\rangle = \mu$ in the low-temperature NS phase).

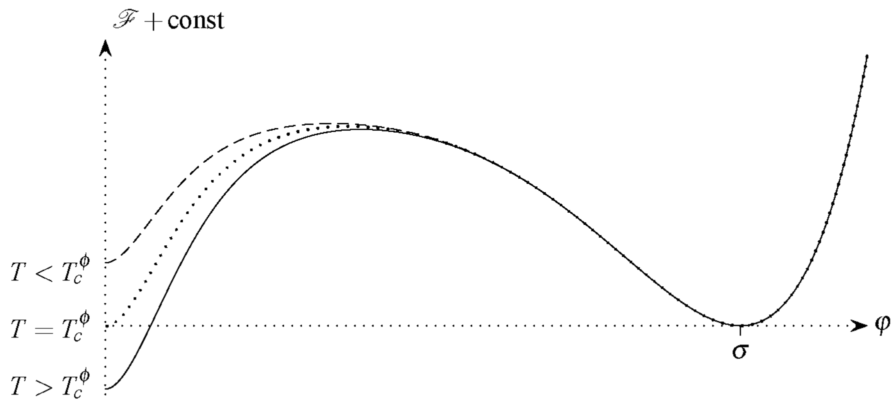
For medium temperatures, $\mu \ll T \ll \sigma$, the thermal energy overwhelms the scalar potential for $q,\varphi \lesssim \mu \ll T$. But for $h\varphi \gg T$, the $\mathscr{F}_T^{1\,\mathrm{loop}}(\varphi)$ flattens out (because all masses are either much larger or much smaller than T), so the minimum of V at $\varphi = \sigma$ becomes visible in the overall free energy:



This gives us two phases: the stable HT phase with $\langle q\rangle = \langle\varphi\rangle = 0$, and the metastable NS (non-SUSY) phase with $\langle q\rangle = 0$ and $\langle\varphi\rangle \approx \sigma$. *In the cooling Universe, the system is in the HT phase before temperature drops below $O(\sigma)$, and afterwards it remains in the HT phase because it's stable.*

As the Universe cools down further, the energy difference between the HT and the SUSY phases becomes smaller, and eventually changes sign at the critical temperature

$$T_c^\phi \approx \frac{2\mu}{\sqrt{N}} \times \sqrt[4]{6\frac{Nh^2}{8\pi^2}} \tag{15}$$

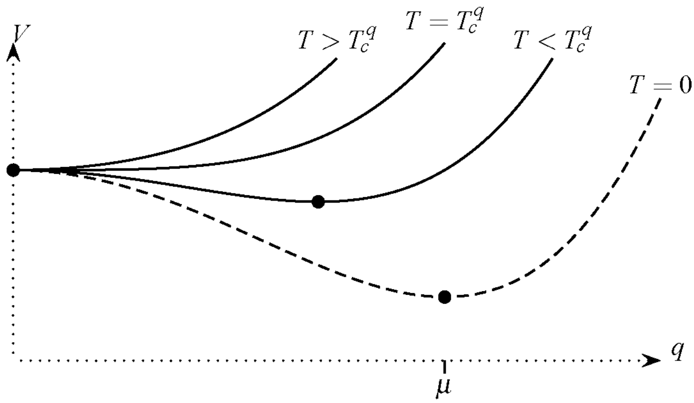


For temperatures below T_c^ϕ, the HT phase becomes metastable while the SUSY phase becomes thermodynamically stable. *Nevertheless, the model remain in the now-metastable HT phase because the first order transition between the two phases is extremely slow.*

At somewhat lower temperature

$$T_c^q \approx \frac{2\mu}{\sqrt{N_f + 2N}} \sim (0.4 \text{ to } 0.75) \times T_c^\phi \tag{16}$$

there is another phase transition in the squark direction:



This transition is second order, and proceeds without delay. As soon as the Universe cools down to T_c^q, the HT phase with $\langle q\rangle = \langle\varphi\rangle = 0$ disappears, and the model enters the low-temperature non-SUSY phase NS with $\langle\varphi\rangle = 0$ but $\langle q\rangle \neq 0$.

Similar to the HT phase below T_c^ϕ, *the NS phase is metastable.* Given infinite time, it would eventually decay into the SUSY phase with $\langle q\rangle = 0$ and $\langle\varphi\rangle \approx \sigma$. But for $\sigma \gtrsim 20\mu$, the tunneling and the thermal activation are both very slow — *cf.* eqs. (4–5) — and the decay takes longer then the present age of the Universe.

Instead of decay, the model remains in the metastable NS phase. As the temperature drops, the squark VEV grows toward $\langle q\rangle = \mu$, and *the model cools down to the non-SUSY vacuum.*

Besides the Intriligator–Seiberg–Shih model, M. Torres and I have analyzed similar models with weakly gauged flavor symmetries (the whole $SU(N_f)_V$ or its subgroups). Such models have spontaneously broken R-symmetry at $T = 0$ and more complicated phase structures at $t > 0$. But of the end of the evolution, they too end up in metastable non-SUSY vacuum states.

<u>To summarize our results</u>, **Metastable SUSY breaking is OK**. In models with both non-SUSY and SUSY vacua where the latter have much larger VEVs and masses then the former, this little hierarchy not only keeps the metastable SUSY-breaking vacua very long lived, but also leads the cosmological evolution of the model toward those vacua. **But the devil is in details**:

- Above all, the model must work! And mediation of SUSY breaking to the SSM should also work.
- There should be no way *around* the potential barrier between the vacua. The pseudo-moduli directions are particularly dangerous.
- The phase diagram of the model should direct its thermal evolution toward the desired non-SUSY vacuum. In models with several distinct vacua, this could be quite a challenge.
- The mediators should not screw things up.
- *Etc., etc. ...*

Acknowledgements: Simultaneously with our paper [4] on which this talk is based, two other groups published independent papers [5, 6] with similar conclusions.
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REFERENCES

1. M. Dine and W. Fischler, *"A Phenomenological Model Of Particle Physics Based On Supersymmetry"*, Phys. Lett. B **110**, 227 (1982).
2. I. Affleck, M. Dine and N. Seiberg, *"Supersymmetry Breaking By Instantons"*, Phys. Rev. Lett. **51**, 1026 (1983).
   Also, five more papers by the same authors in 1983–84, and great many subsequent papers by others.
3. K. Intriligator, N. Seiberg and D. Shih, *"Dynamical SUSY breaking in meta-stable vacua"*, JHEP **0604**, 021 (2006) [arXiv:hep-th/0602239].
4. W. Fischler, V. Kaplunovsky, C. Krishnan, L. Mannelli and M. A. C. Torres, *"Meta-Stable Supersymmetry Breaking in a Cooling Universe"*, JHEP **0703** (2007) 107 [arXiv:hep-th/0611018].
5. N. J. Craig, P. J. Fox and J. G. Wacker, *"Reheating metastable O'Raifeartaigh models"*, Phys. Rev. D **75**, 085006 (2007) [arXiv:hep-th/0611006].
6. S. A. Abel, C. S. Chu, J. Jaeckel and V. V. Khoze, *"SUSY breaking by a metastable ground state: Why the early universe preferred the non-supersymmetric vacuum"*, JHEP **0701**, 089 (2007) [arXiv:hep-th/0610334].
7. See for example: A. E. Nelson and N. Seiberg, *"R symmetry breaking versus supersymmetry breaking"*, Nucl. Phys. B **416**, 46 (1994) [arXiv:hep-ph/9309299].
8. S. Franco and A. M. Uranga, *"Dynamical SUSY breaking at meta-stable minima from D-branes at obstructed geometries"*, JHEP **0606**, 031 (2006) [arXiv:hep-th/0604136].
9. I. Garcia-Etxebarria, F. Saad and A. M. Uranga, *"Local models of gauge mediated supersymmetry breaking in string theory"*, JHEP **0608**, 069 (2006) [arXiv:hep-th/0605166].
10. H. Ooguri and Y. Ookouchi, *"Landscape of supersymmetry breaking vacua in geometrically realized gauge theories"*, Nucl. Phys. B **755**, 239 (2006) [arXiv:hep-th/0606061].
11. M. Aganagic, C. Beem, J. Seo and C. Vafa, *"Geometrically induced metastability and holography"*, arXiv:hep-th/0610249.
12. M. Dine and J. Mason, *"Gauge mediation in metastable vacua"*, arXiv:hep-ph/0611312.
13. R. Kitano, H. Ooguri and Y. Ookouchi, Phys. Rev. D **75**, 045022 (2007) [arXiv:hep-ph/0612139].
14. H. Murayama and Y. Nomura, *"Gauge mediation simplified"*, Phys. Rev. Lett. **98**, 151803 (2007) [arXiv:hep-ph/0612186].
15. C. Csaki, Y. Shirman and J. Terning, *"A simple model of low-scale direct gauge mediation"*, JHEP **0705**, 099 (2007) [arXiv:hep-ph/0612241].
16. O. Aharony and N. Seiberg, *"Naturalized and simplified gauge mediation"*, JHEP **0702**, 054 (2007) [arXiv:hep-ph/0612308].
17. S. A. Abel and V. V. Khoze, *"Metastable SUSY breaking within the standard model"*, [arXiv:hep-ph/0701069].
18. S. A. Abel, J. Jaeckel and V. V. Khoze, *"Naturalised supersymmetric grand unification"*, [arXiv:hep-ph/0703086].
19. D. Shih, *"Spontaneous R-symmetry breaking in O'Raifeartaigh models"*, [arXiv:hep-th/0703196].
20. K. Intriligator, N. Seiberg and D. Shih, *"Supersymmetry Breaking, R-Symmetry Breaking and Metastable Vacua"*, JHEP **0707**, 017 (2007) [arXiv:hep-th/0703281].
21. H. Ooguri, Y. Ookouchi and C. S. Park, *"Metastable Vacua in Perturbed Seiberg-Witten Theories"*, [arXiv:0704.3613 (hep-th)].
22. K. van den Broek, *"Vscape V1.1.0: An interactive tool for metastable vacua"*, [arXiv:0705.2019 (hep-ph)].
23. E. Dudas, J. Mourad and F. Nitti, *"Metastable Vacua in Brane Worlds"*, [arXiv:0706.1269 (hep-th)].
24. H. Y. Cho and J. C. Park, *"Dynamical $U(1)_R$ Breaking in the Metastable Vacua"*, [arXiv:0707.0716 (hep-ph)].