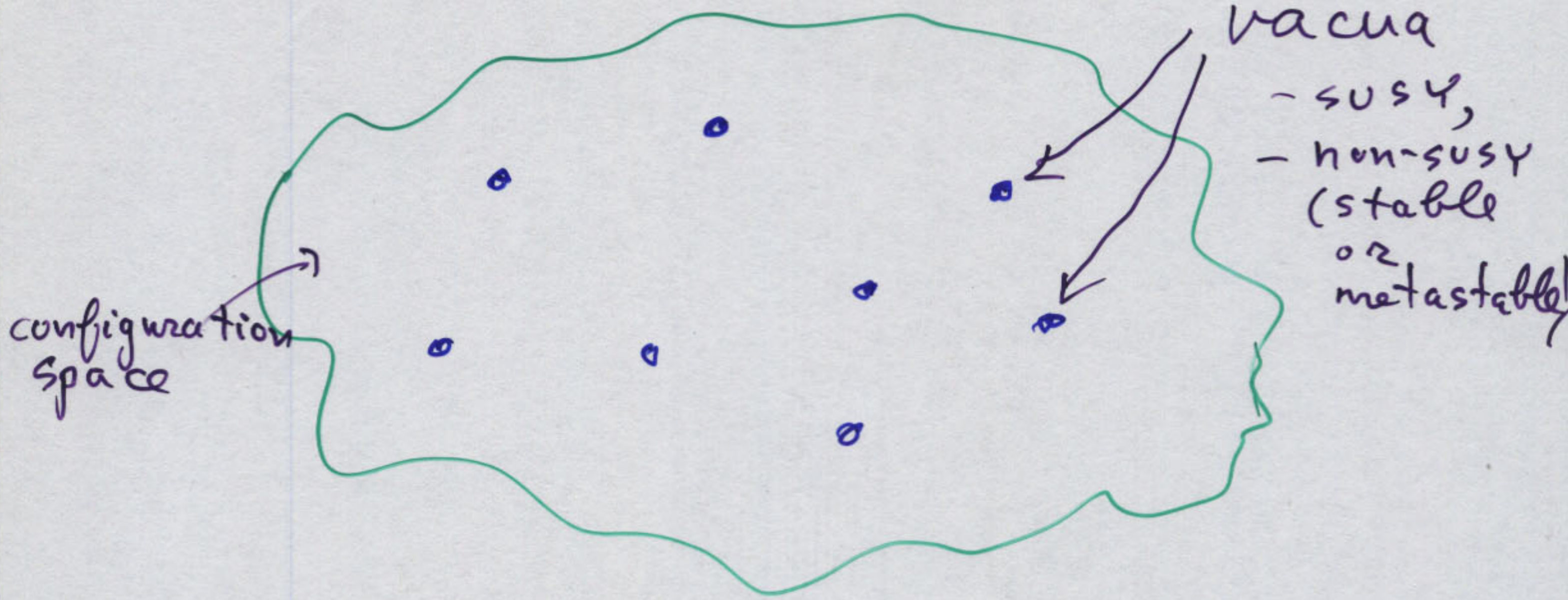
Dynamical Vacuum Selection in String Theory

DK, O. Lunin, J. McOrist, A. Royston

The problem

String landscape:



Question: does early universe dynamics give a selection mechanism among different vacua?

In general, this is a hard question:

- landscape?
- real-time dynamics?

The strategy

- small g_s.
- closed string background + branes.
- Take closed string background as given (will not attempt to stabilize closed string moduli, etc
- Branes give rich landscape of vacua

Does dynamics distinguish among them?

Setting: Brane embedding of ISS model of supersymmetry breaking.

Plan:

- Field theory:
  * ISS model
  * Early universe dynamics.
  * Generalized ISS.

- String theory:
  * Brane construction of ISS model.
  * brane construction of generalized ISS model.
  * Early universe dynamics.

Review of ISS model

* $G = SU(N_f - N_c)$ $\mathcal{N}=1$ SYM theory
* chiral superfields:
  - N_f fundamentals $q^i, \tilde{q}_i$, $i = 1 \ldots N_f$
  - singlet Φ^i_j
* superpotential: $W = h q \Phi \tilde{q} - h \mu^2 \mathrm{Tr}\,\Phi$
* Magnetic dual of $G = SU(N_c)$ SQCD with massive quarks.
* Take $N_f < \frac{3}{2} N_c$, so magnetic theory is IR free.

* Classical potential:

$$V_0 = h^2 \left(|q\tilde{q} - \mu^2 \cdot 1_{N_f}|^2 + |q\,\phi|^2 + |\phi\,\tilde{q}|^2 \right)$$

* No SUSY vacuum (like in O'Raifeartaigh model)

* $q, \tilde{q}$ tachyonic at the origin.

Vacuum manifold:

$$\underset{N_f \times N_f}{\left(q\tilde{q} \right)} = \begin{pmatrix} \mu^2 \cdot 1_{N_f - N_c} & 0 \\ 0 & 0_{N_c} \end{pmatrix}$$

$SU(N_f - N_c)$ completely broken

$$\left(\phi \right) = \begin{pmatrix} 0 & 0 \\ 0 & X \end{pmatrix}$$

$N_c \times N_c$ pseudo-moduli

Since SUSY is broken on pseudo-moduli space, small corrections to the dynamics may lift it.

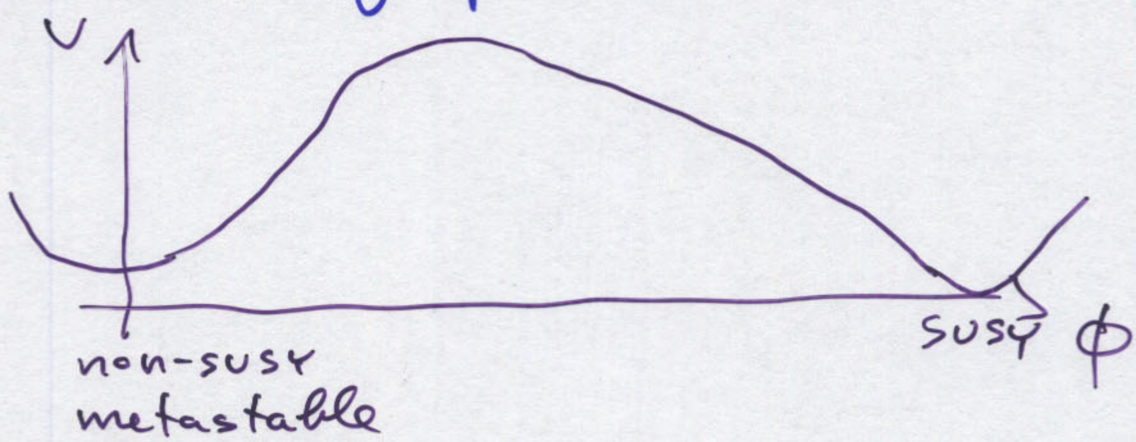
Leading effect in field theory: Coleman-Weinberg potential. Near the origin:

$$V_1 \sim h^4 \mu^2 \, \mathrm{Tr}\,|X|^2 + \ldots$$

pseudo-moduli stabilized at the origin.

Non-perturbative gauge dynamics gives additional contribution to V
$\Rightarrow$ SUSY vacua at large ϕ.

Caricature of potential:



Question: which of the vacua (if any) is dynamically prefered?

Finite temperature ISS

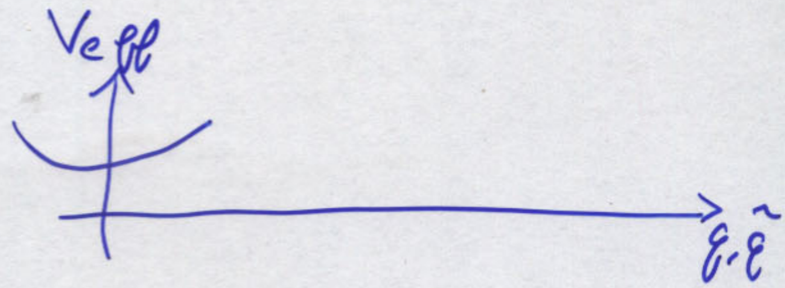
Assume that at early times, the universe is in a thermal state with adiabatically decreasing temperature.

To determine its fate, need to evaluate finite T free energy and follow it, with decreasing T. This was done by:

Abel et al
Craig et al (2006)
Fischler et al

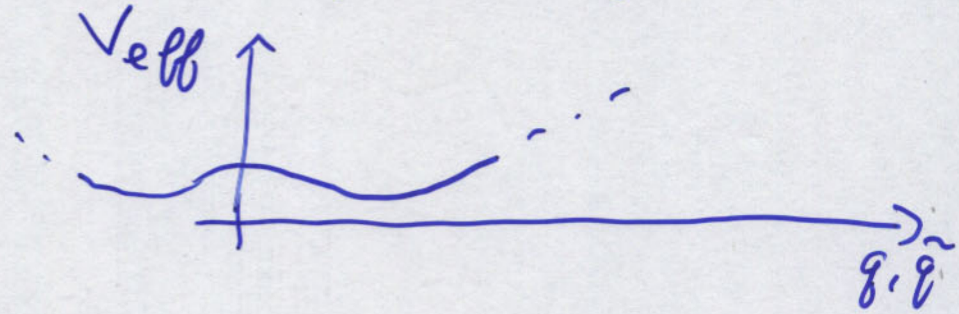
They found:

* $T > T_c \approx \mu$



The system is in a phase with unbroken gauge symmetry

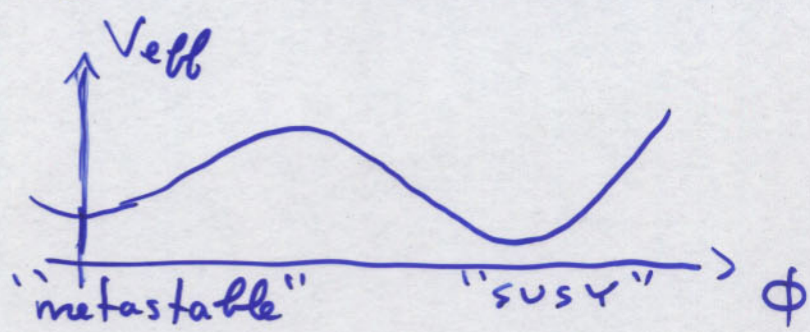
* $T < T_c$:



$q, \tilde{q}$ condense; $SU(N_f - N_c)$ broken.

Second order phase transition at T_c.

* $T < \sqrt{h}\, T_c$:



SUSY vacuum has lower F than metastable one. But, the two are separated by a wide potential barrier.

Early universe vacuum selection

Start at early times with $T > T_c$. The system is driven to the origin of field space (assuming thermal equilibration time $\ll$ rate of change of T, etc)

T decreases, system remains in metastable vacuum.

$$\Downarrow$$

Simple example of dynamical vacuum selection.

Generalized ISS model

For phenomenology, it is useful to break R-symmetry, e.g. by modifying the superpotential:

$$W = h q \Phi \tilde{q} - h \mu^2 \mathrm{Tr}\,\Phi + \frac{1}{2} h^2 \mu_\phi \mathrm{Tr}\,\Phi^2$$

For $\mu_\phi \ll \mu$, Φ^2 term is small perturbation.

To generalize the ISS analysis to this case, useful to parameterize

$$h\Phi = \begin{pmatrix} 0_k & 0 & 0 \\ 0 & h\phi_n & 0 \\ 0 & 0 & \frac{\mu^2}{\mu_\phi}\mathbb{1}_{N_f-k-n} \end{pmatrix}$$

$N_f \times N_f$

$$q\tilde{q} = \begin{pmatrix} \mu^2 \cdot \mathbb{1}_k & 0 & 0 \\ 0 & \varphi\tilde{\varphi} & 0 \\ 0 & 0 & 0_{N_f-k-n} \end{pmatrix}$$

$\varphi, \tilde{\varphi}$: $n \times (N_f - N_c - k)$

ϕ_n : $n \times n$

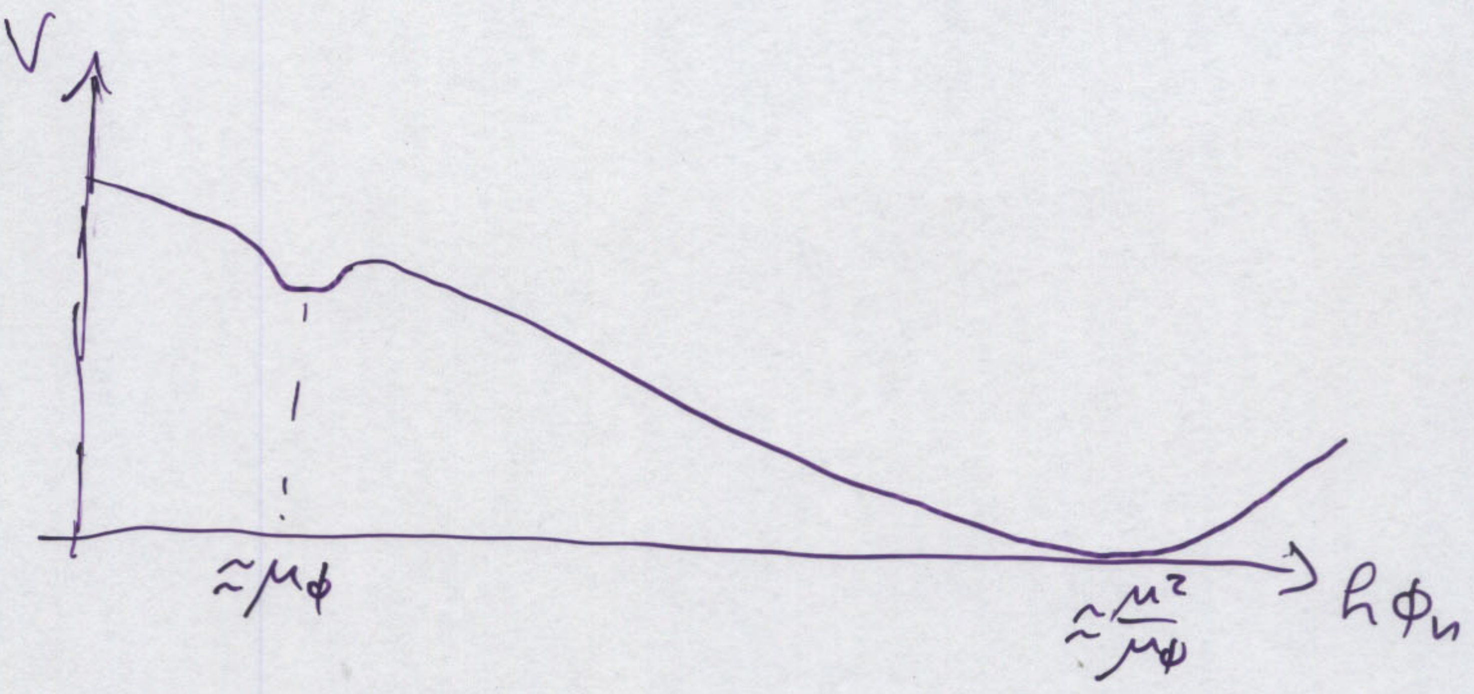
SUSY vacua: $n=0$, $k=0,1,2,\ldots N_f - N_c$

Non-SUSY vacua

* Classical potential pushes ϕ_n toward SUSY vacuum at $\Phi_n = \frac{\mu^2}{\mu_\phi} \cdot \mathbb{1}_n$

* One loop potential pushes it towards 0.

* One may hope that balancing the two will give additional, non-SUSY, vacua. Indeed one finds:



(assuming $\mu_\phi \ll h\mu$)

Q: Is this a metastable vacuum?

A: In general no, since $\varphi, \tilde{\varphi}$ are tachyonic unless $\langle \Phi_n \rangle > \mu$.

This is not the case for the vacua we found. Thus, only metastable vacua are those in which $\varphi, \tilde{\varphi}$ are absent, i.e. those with $k = N_f - N_c$.

Summary

Generalized ISS model has SUSY vacua labeled by $k = 0, 1, 2, \ldots, N_f - N_c$. It also has non-SUSY (metastable) vacua with $k = N_f - N_c$, $n = 1 \ldots N_c$. These are simple generalizations of the ISS ones.

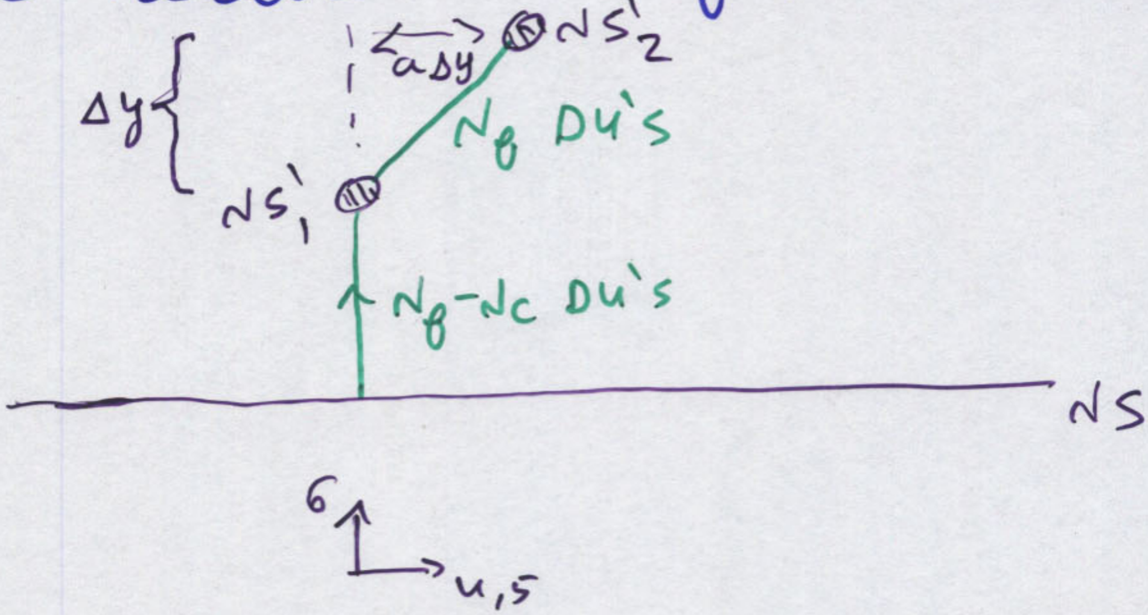
In particular, they are close to the origin of field space (i.e. ϕ_n is small). This is a problem for phenomenological applications.

Brane construction of ISS

Geometry $\Rightarrow$ NS5-branes

D-branes $\Rightarrow$ D4-branes stretched between NS5-branes.

Brane realization of ISS model:



NS: 012345

NS': 012389

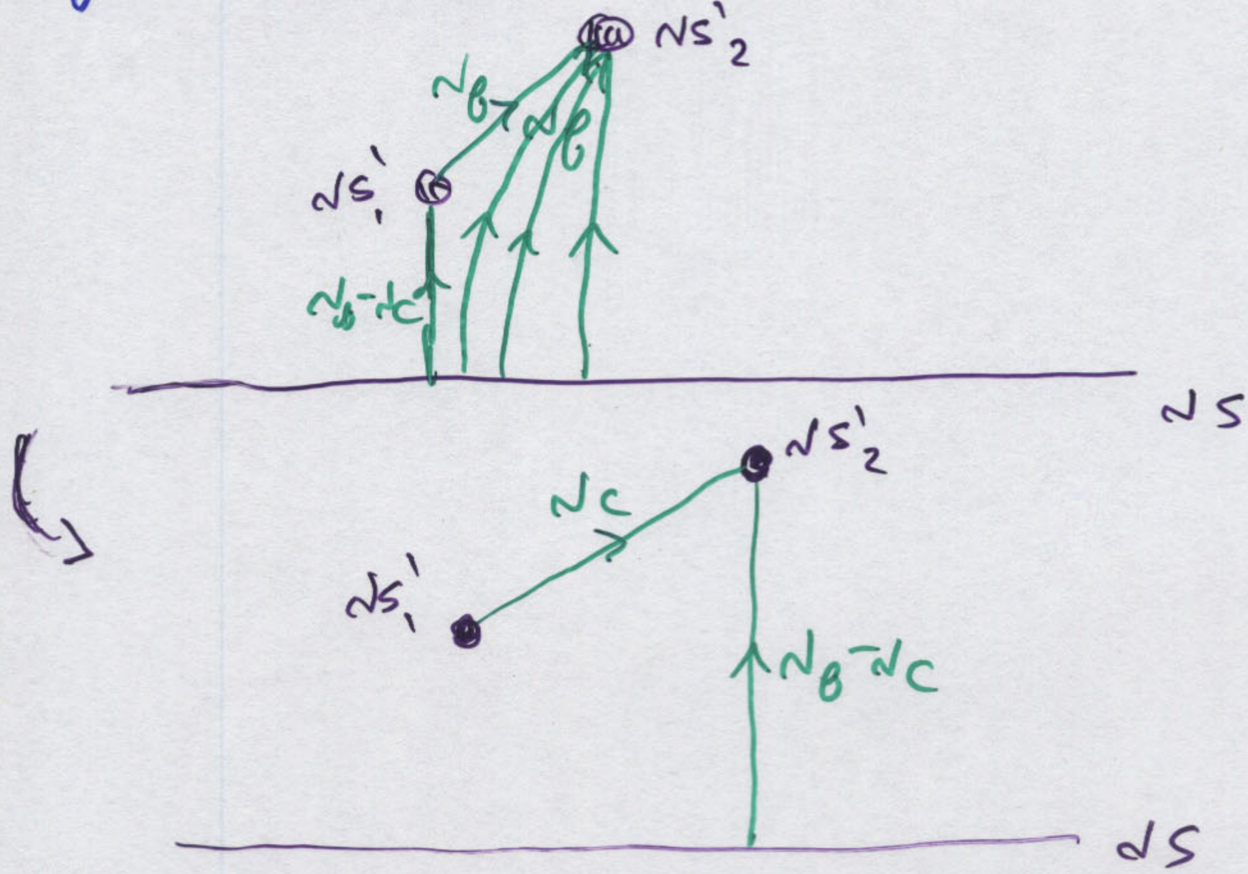
D4: 01236

Parameters: $\quad h^2 = \dfrac{g_s \ell_s}{\Delta y}$; $\mu^2 = \dfrac{a \Delta y}{g_s \ell_s^3}$

slope $a \ll 1$.

* This brane configuration realizes magnetic SQCD with gauged $U(N_f)$ flavor group.

* $q, \tilde{q}$ tachyonic at origin => instability for reconnection:



pseudo-moduli X = positions of N_c D4's in (8,9) plane.

* pseudo-moduli space: no potential for N_c flavor branes.

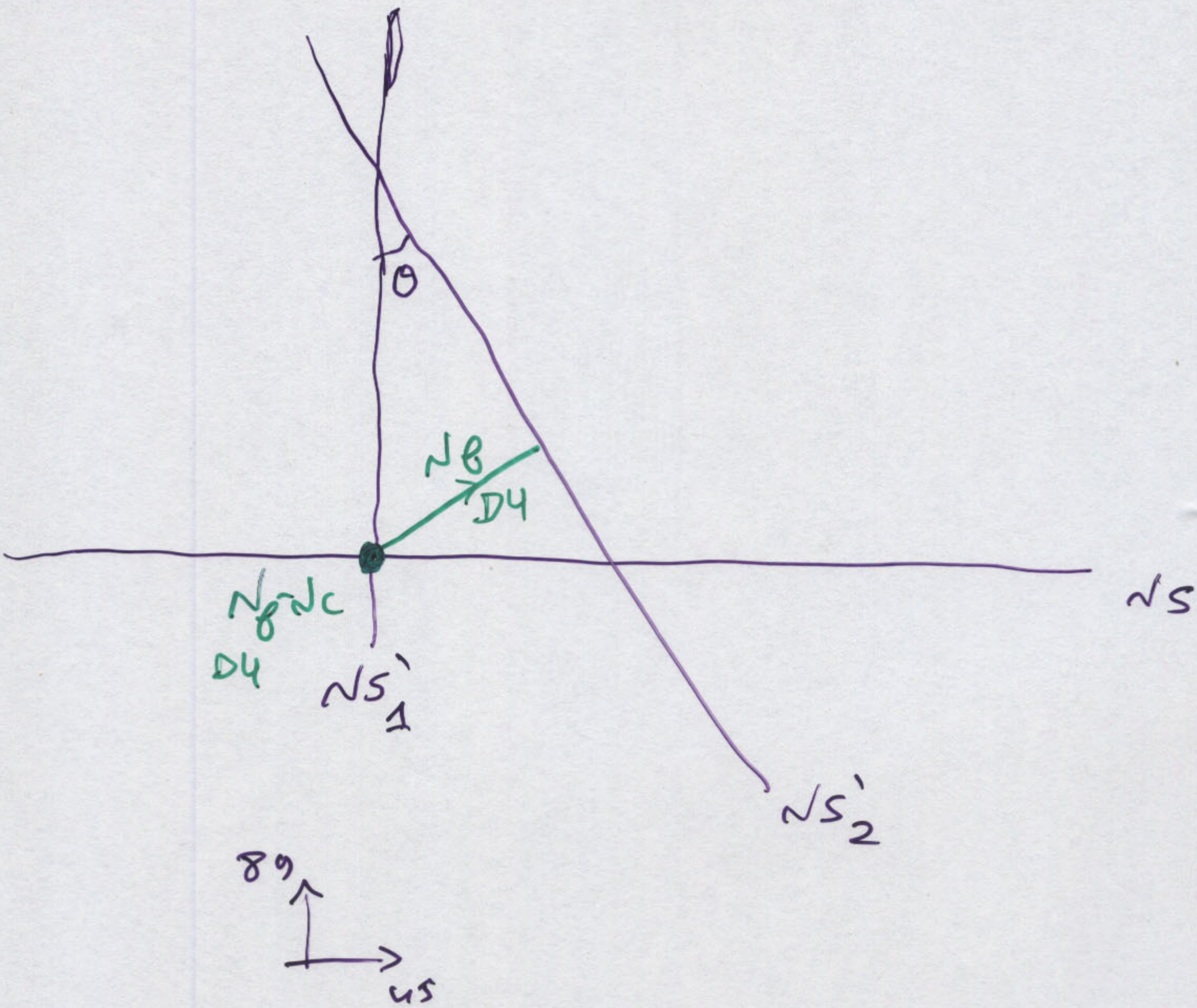
* Corrections: - ISS one loop potential: g_s effect.
  - classical correction: attraction of N_c D4's to NS.

Dominant in classical brane regime. In low energy theory corresponds to non-canonical Kahler potential for Φ.

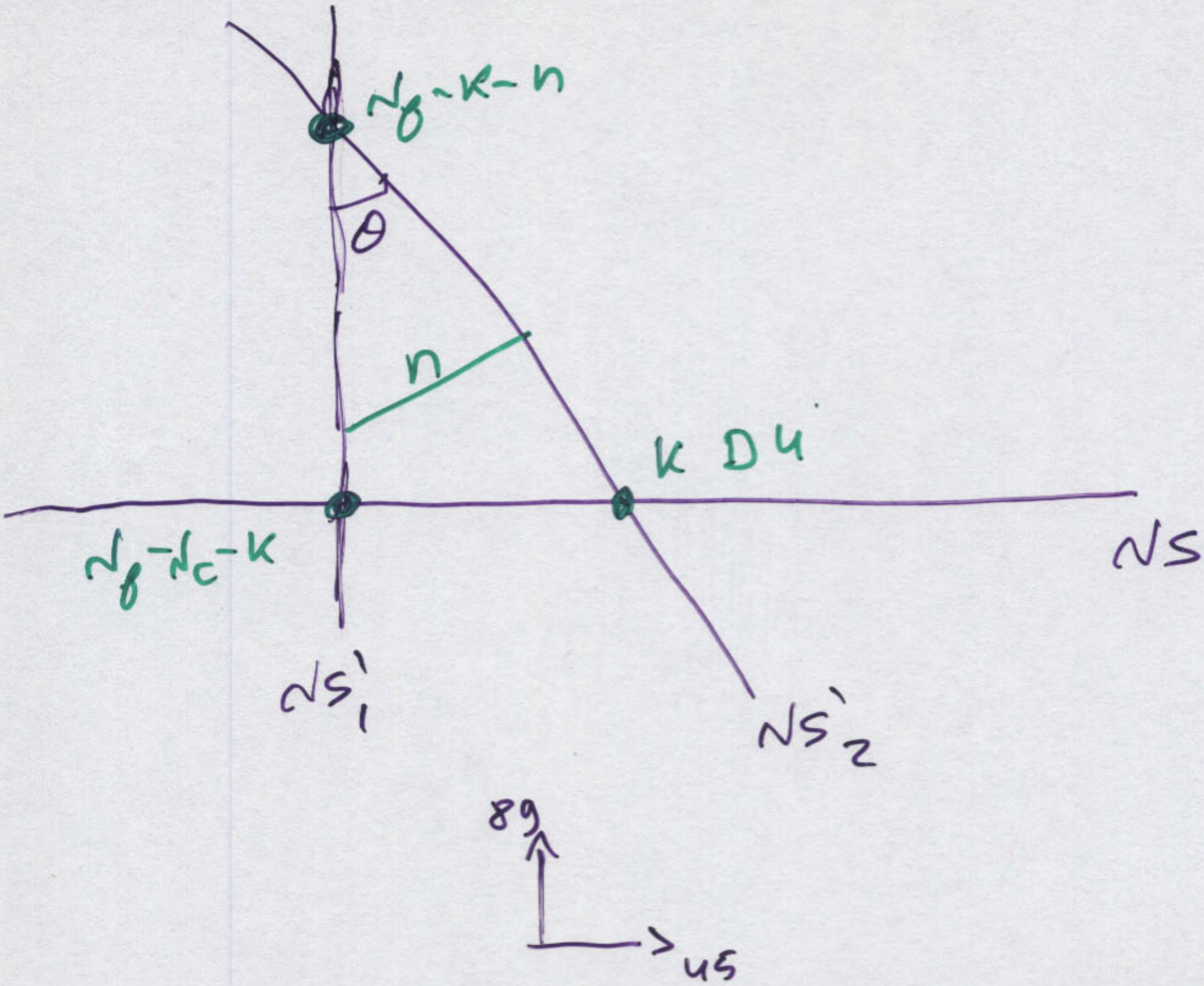
So, in string theory, pseudo-moduli are stabilized at origin, but mechanism is different from ISS

Generalized ISS brane configuration

* Rotate NS'_2-brane by angle θ from $(8,9) \to (4,5)$



Here there is a very rich vacuum structure:



* n, k are as in field theory discussion

* n branes stabilized by competition between geometric & gravitational forces.

* Tachyon issue is visible in brane picture strings stretched between n and $N_f - N_c - k$ D4's are tachyonic if endpoints on D6's close.

* In brane regime can arrange parameters such that all vacua labeled by (n, k) are (meta)stable.

* Large breaking of R-symmetry possible in brane regime is useful for phenomenology.

* Hierarchy of lifetimes:

- $n=0$; any k : SUSY, stable.
- $n>0$; $k=N_f-N_c$: metastable, more long-lived than:
- $n>0$, $k<N_f-N_c$; which have additional decay channels.

Question: What does early universe dynamics lead to?

Early universe dynamics

* At early times, universe is in excited state.
* Excess energy can go to exciting D-branes and/or NS5-branes.
* For small g_s, most of energy goes to exciting NS5's (since they decay slowly)
* Thus, need to consider above brane systems with NS, NS'-branes taken to be non-extremal.

* Non-extremality of NS5's changes energy landscape for D4's. Need to map out modified landscape, and study D4-brane dynamics in it.

* In extremal case, important role played by gravitational interaction between NS and D4's. Will start by analyzing modification due to non-extremality.

Near-extremal NS background:

$$ds^2 = -f(r)dt^2 + H(r)\left[\frac{dr^2}{f(r)} + r^2 d\Omega_3^2\right] + dx^{i\,2} \quad i=1..5$$

$$e^{2(\phi-\phi_0)} = H(r)$$

$$f(r) = 1 - \frac{r_h^2}{r^2}$$

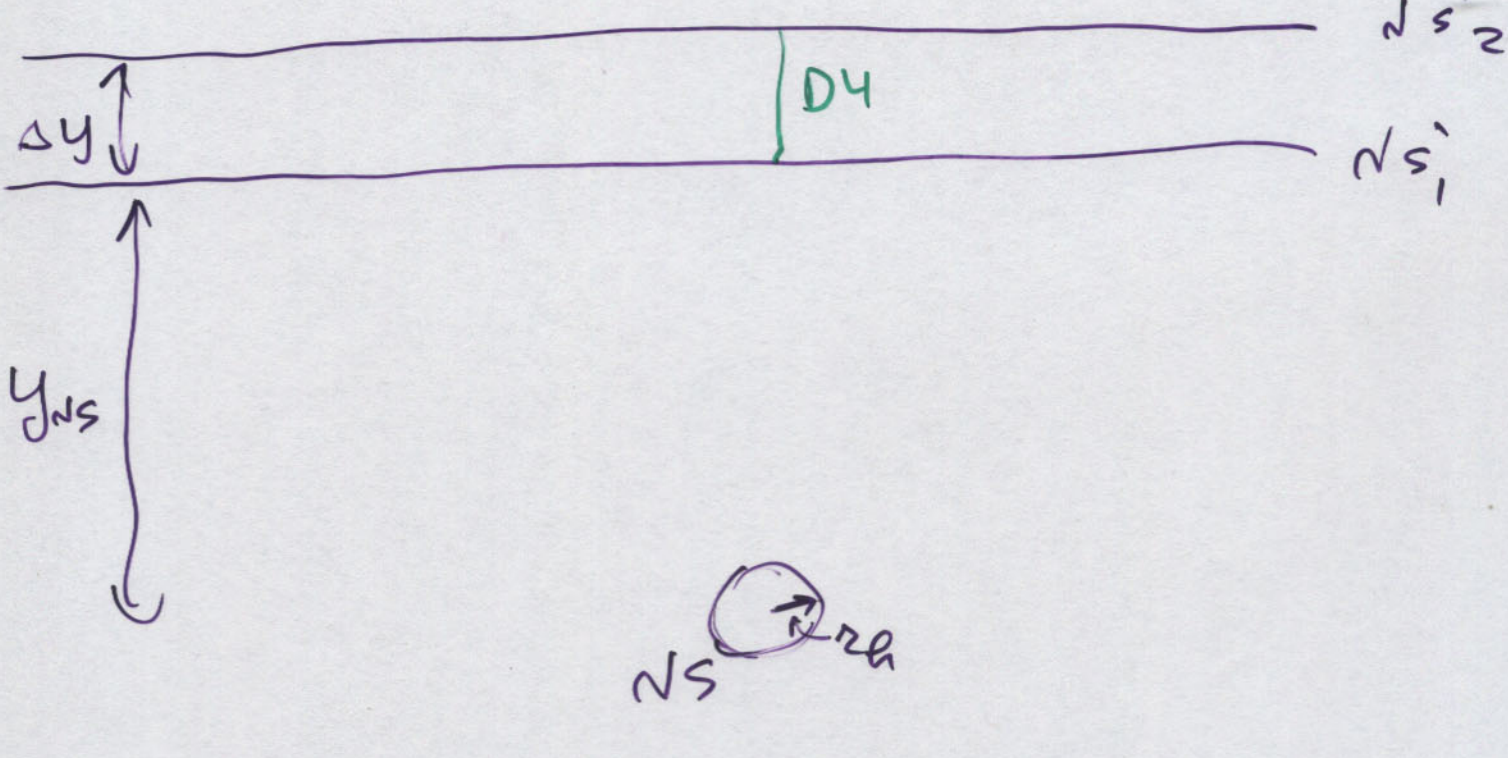
$$H(r) = 1 + \frac{\ell_s^2}{r^2}$$

* r_h = horizon size
* Energy density: $\mathcal{E} = \frac{1}{(2\pi)^5 \ell_s^6 g_s^2}\left(1 + \frac{r_h^2}{\ell_s^2}\right)$
* Hawking effect: $\frac{d}{dt}(r_h^2) = -g_s^2 \ell_s$

$\Longrightarrow$ Evaporation time $T_{evap} \sim \frac{\ell_s}{g_s^2}$

What happens to ISS brane configuration for $r_h \neq 0$?

There are 2 main effects. One is a modification of potential on pseudo-moduli space. This is non-trivial already at $\mu = 0$:



For $r_h = 0$: no potential for D4; SUSY moduli space.

For $r_h \neq 0$ there is a potential on moduli space: Need to examine DBI action

$$S_{DBI} = -T_4 \int d^4x \int_{y_1}^{y_2} dy \, e^{-\Phi} \sqrt{-\det G}$$

induced metric

Plugging in fivebrane geometry, get (to leading order in $\frac{r_h}{y_{NS}}, \frac{\Delta y}{y_{NS}}$)

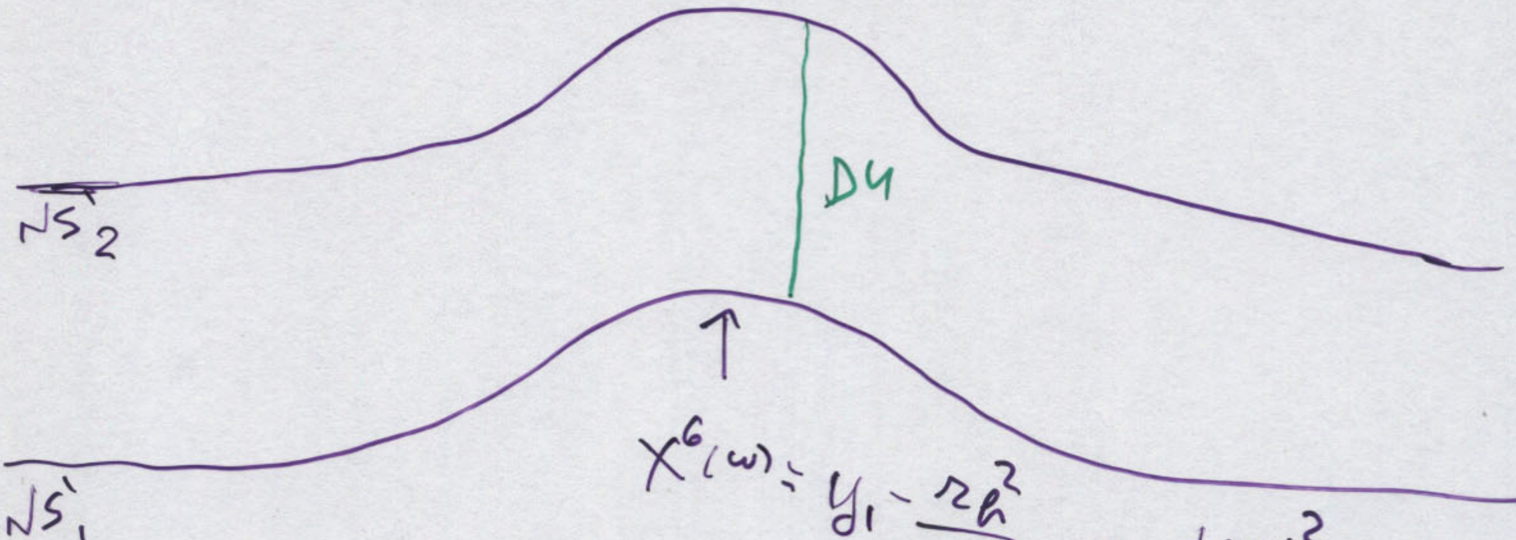
$$V(\omega) \approx \frac{T_4 \Delta y}{g_s} \left[1 - \frac{1}{2} \frac{r_h^2 |\omega|^2}{(y_{NS}^2 + |\omega|^2)^2} \right]$$

$\omega = x^8 + i x^9$

Looks repulsive near origin!

But, we are not done...

The NS'-branes are curved by NS background as well. Solving for their shape, find:



$$X^6(w) \simeq y_1 - \frac{r_h^2}{4(y_1 - y_{NS})^3}|w|^2 + \dots$$

NS

$$\Rightarrow \Delta y(w) \simeq \Delta y\left[1 + \frac{3 r_h^2}{4 y_{NS}^4}|w|^2 + \dots\right]$$

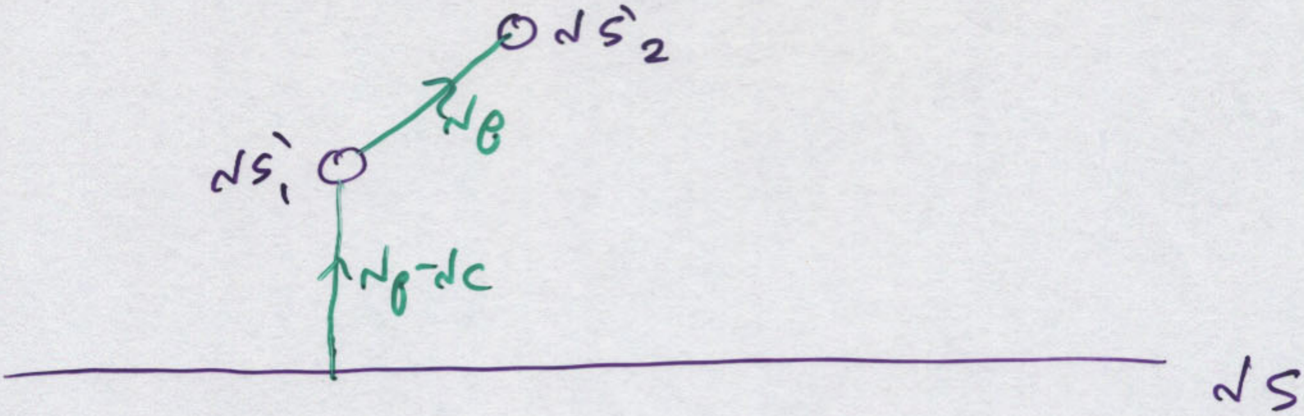
Altogether, potential on moduli space is:

$$V(\omega) \simeq \frac{T_4 \Delta y}{g_s}\left[1 + \left(\frac{3}{4}-\frac{1}{2}\right)\frac{z_h^2 |\omega|^2}{y_{NS}^4} + \cdots\right]$$

Stabilizes moduli at $\omega = 0$.

D4's roll in this potential & come to rest at origin on timescale $\sim \frac{\ell_s}{g_s}$.

ISS brane system in early universe



Potential for N_f flavor D4's:

$$V(w) \sim \frac{T_4 \Delta y}{g_s}\left[1 + \frac{r_h^2 + 2a^2 \ell_s^2}{4 y_{NS}^4} |w|^2 + \dots\right]$$

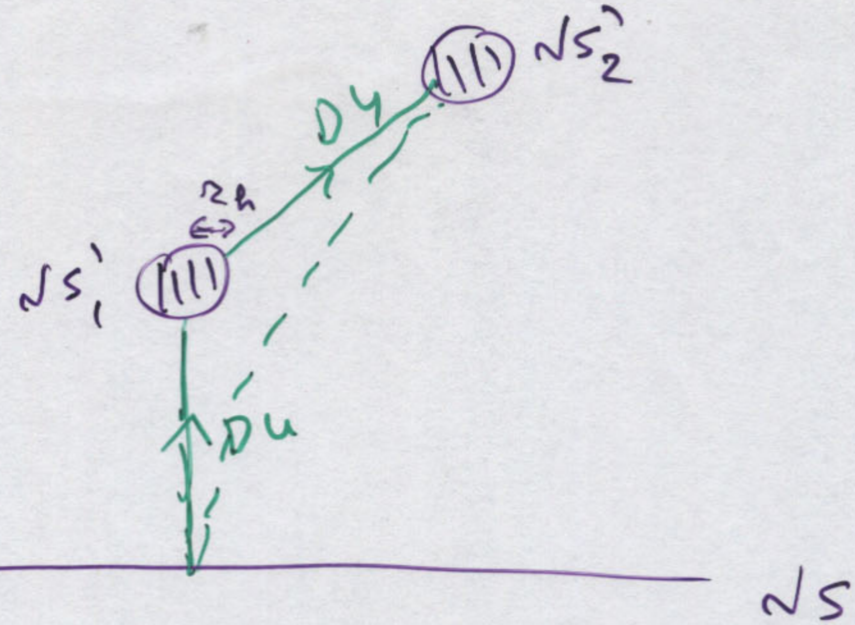
Receives contributions from both sources discussed above (a, r_h). Pseudo-moduli driven to $w=0$, which is true vacuum at large r_h.

As $r_h \to 0$, system approaches metastable state.

What about finite temperature phase transition mentioned in field theory discussion?

It turns out that it has a brane analog as well. To see it one has to take NS'-branes to be non-extremal as well. This is very reasonable: the origin of non-extremality in early universe presumably does not distinguish between the two.

We have:

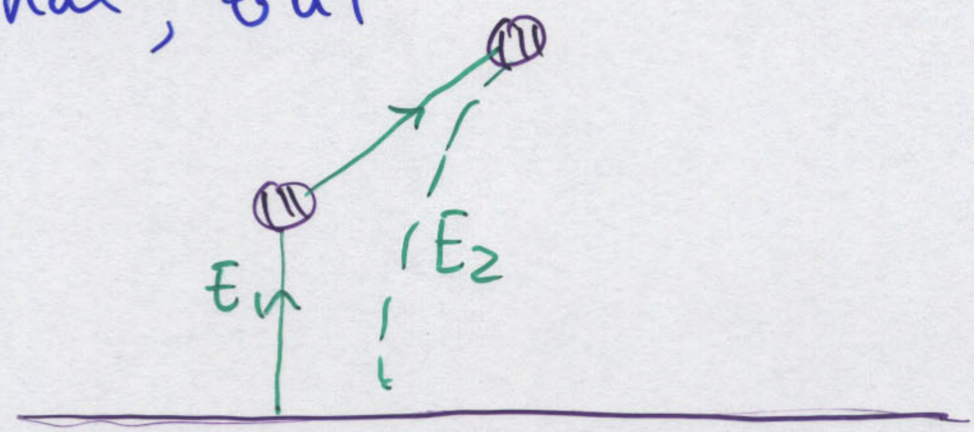


Need to check whether reconnection is possible, and if so whether it is energetically favorable.

DBI analysis gives:

* For $r_h > a^{3/2} \Delta y$, there is no static connected solution.

* For $a^{3/2} \Delta y > r_h > a^2 \Delta y$, there is a connected solution which is a local minimum of energy functional, but



$E_2 > E_1$

* For $r_h < a^2 \Delta y$, connected configuration becomes true minimum ($E_2 < E_1$) but the two are separated by a finite potential barrier.

Thus if r_h starts at a value $> a^{\frac{3}{2}} \Delta y$ the gauge symmetry is unbroken. As r_h decreases, system remains in unbroken phase, even for $r_h < a^2 \Delta y$.

Eventually, when $r_h \lesssim l_s$, DBI calculation breaks down, system likely to make transition to broken phase as in field theory analysis (but mechanism different).

Comments

* Can repeat discussion for generalized ISS brane system. Find that dynamics drives system to most stringy (and most symmetric) vacuum: $k=0$, $n=N_f$.
* Perhaps surprising, since this is the least stable of the 3 kinds of vacua of extremal system.

* General conclusion: systems with rich vacuum structure can exhibit dynamical vacuum selection. Would be interesting to understand more generally.