Vacuum Selection in String Theory

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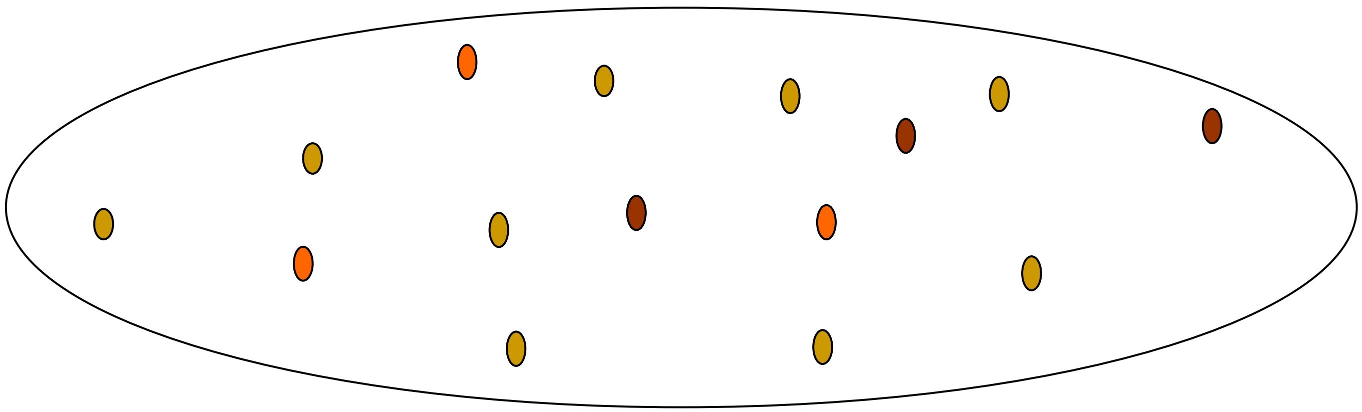
Motivation

- Landscape of vacua in string theory. Some may be supersymmetric, non-supersymmetric, (metastable, unstable) etc.



- Question: Does cosmology provide a vacuum selection principle?

Motivation

- That's a hard question! Why?
  - We don't know full vacuum structure of string theory
  - We don't really understand real-time dynamics in string theory
- Our approach: attack this question by studying some toy examples. Advantages: understanding vacuum structure is more accessible, as are real time dynamics
- Setting the scene:
  - $g_s \to 0$
  - Simple closed string background with branes.
  - Won't attempt to stabilise closed string moduli etc.
- Intersecting brane systems give a rich landscape of vacua. Can we understand real-time dynamics? Is there a selection principle?

Motivation

- Quasi-phenomenology: want to study systems that break supersymmetry in a controlled and realistic manner.
- Intriligator-Seiberg-Shih (ISS) realised how to do this naturally in massive SQCD. Compellingly simple.
- Exhibits a mini-landscape:
  - Metastable vacuum near origin of field space
  - Non-perturbative effects generate supersymmetric vacua at large field values
- Naturally embeds into string theory via intersecting branes. Brane systems exhibit a (richer) landscape & are phenomenologically improved
- We'll study dynamics of brane systems & compare with results attained in field theory

Outline

1. Motivation
2. ***Field Theory: Review ISS in cosmology***
3. String Theory: Review Brane Embedding ISS
4. Early Universe Dynamics in Brane Systems
5. Conclusion

Field theory: ISS

- SQCD in magnetic phase. N=1 SYM with gauge group $\mathrm{SU}(N_f - N_c)$
- Field content, chiral superfields
  - N_f fundamentals, $q^i, \widetilde{q}_i$
  - singlet $\Phi^i{}_j$
- Superpotential: $W = h\mathrm{Tr} q\Phi\widetilde{q} - h\mu^2 \mathrm{Tr}\Phi$
- Magnetic dual of massive $\mathrm{SU}(N_c)$ SQCD ("electric phase")
- $N_f < \frac{3}{2}N_c$ so theory is IR free
- Bosonic potential $V = h^2\left(\left|q\tilde{q} - \mu^2 I_{N_f}\right|^2 + |q\Phi| + |\Phi\tilde{q}|^2\right)$
- Classically supersymmetry is broken, as in the O'Raifeartaigh model. Pseudo-moduli space

$$(q\tilde{q}) = \begin{pmatrix} \mu^2 I_{N_f - N_c} & 0 \\ 0 & 0_{N_c} \end{pmatrix} \qquad (\Phi) = \begin{pmatrix} 0 & 0 \\ 0 & X \end{pmatrix}$$

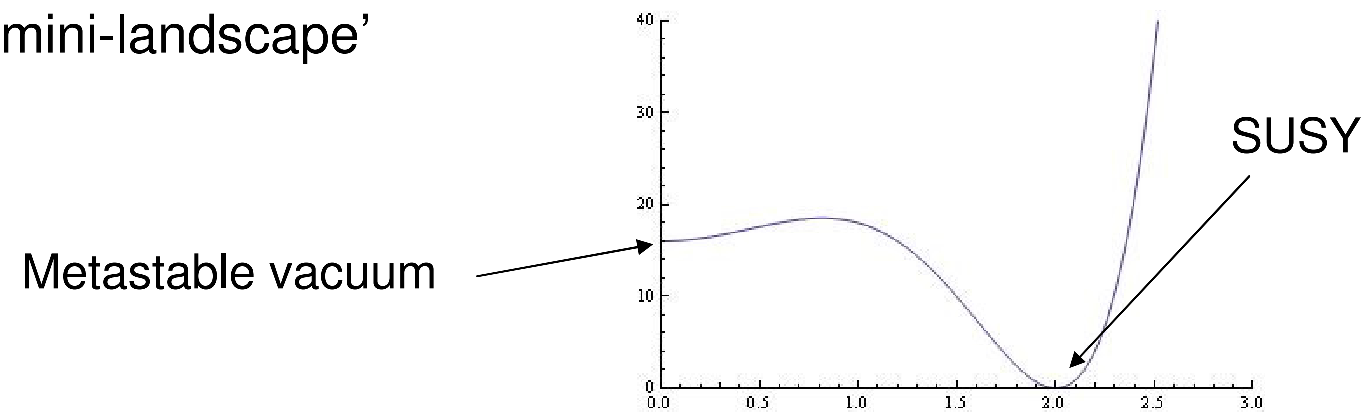
Psuedo-modulus X. $N_c \times N_c$ matrix

Field Theory: ISS

- SUSY is broken. Quantum corrections to the pseudo-moduli space. Leading correction comes from 1-loop Coleman-Weinberg potential

$$V = h^4\mu^2 \mathrm{Tr} X^2 + \ldots$$

- Stabilises the pseudo-modulus at the origin.
- Non-perturbative corrections generate supersymmetric vacua at large values of X.
- Exhibits a `mini-landscape'



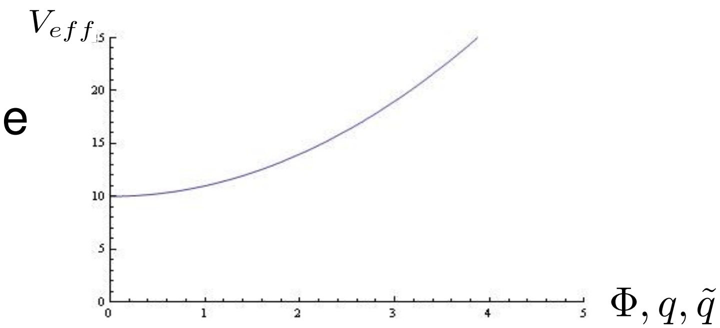
- ***Is there a dynamical selection principle?***

Field Theory: Thermal ISS

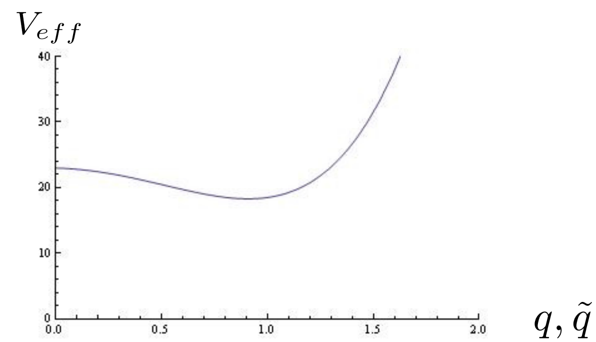
- Problem was studied by Abel et al. (061033), Craig et al (0611006) and Fischler et al (0611018) .
- Assume early universe is in a thermal state with adiabatic decreasing temperature.
- Determine its fate by evaluating finite T free energy and follow it with decreasing T

Field Theory: Thermal ISS

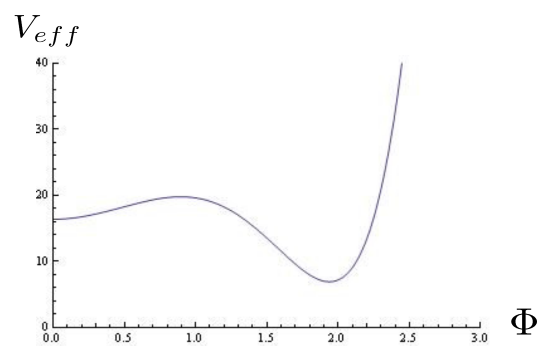
- $T > T_c \approx \mu$: energetically preferred state is at the origin, unbroken gauge symmetry. Only vacuum at origin.



- $T < T_c$: quarks condense; gauge symmetry broken & second order phase transition



- $T < h\, T_c$: SUSY vacuum appears with lower F than origin; but separated by wide potential barrier.



Field Theory: Thermal ISS

- Start at $T > T_c$,. Follow evolution of system as decrease T.
- System driven towards origin of field space (assuming equilibrium time << change in T etc.)
- As T decreases systems remains in metastable vacuum
- Simple example of vacuum selection.

Field Theory: Generalised ISS

- Phenomenologically want to break R-symmetry (i.e. metastable vacuum not at the origin of field space).
- Can do this by a small perturbation of ISS Superpotential

$$W = h\mathrm{Tr}q\Phi\widetilde{q} - h\mu^2\mathrm{Tr}\Phi + \tfrac{1}{2}h^2\mu_\phi\mathrm{Tr}\Phi^2$$

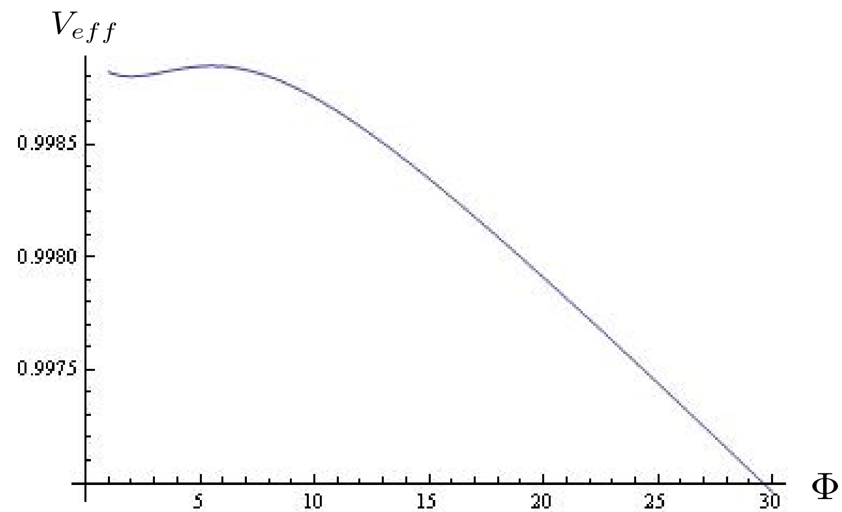
  where $\mu_\phi \ll \mu$
- Generalize the VeVs parameterising pseudo-moduli space

$$(q\tilde{q}) = \begin{pmatrix} \mu^2 I_k & 0 & 0 \\ 0 & \varphi\tilde{\varphi} & 0 \\ 0 & 0 & 0_{N_f-k-n} \end{pmatrix} \qquad (h\Phi) = \begin{pmatrix} 0_k & 0 & 0 \\ 0 & h\Phi_n & 0 \\ 0 & 0 & \frac{\mu^2}{\mu_\phi}1_{N_f-k-n} \end{pmatrix}$$

- There are now supersymmetric vacua in perturbation theory (as opposed to ISS, which involve instanton effects).
  - SUSY vacua: $n = 0,\ k = 0,1,2,\ldots,N_f - N_c$

Field Theory: Generalised ISS

- There are also non-supersymmetric metastable vacua $n > 0$
  - The classical potential pushes Φ towards the SUSY vacuum
  - The 1-loop potential provides an attractive force towards the origin.
  - Balancing the two gives additional non-SUSY vacua viz.



- [Caveat: unless $k = N_f - N_c$, the quarks are tachyonic. In string theory, not so…all metastable vacua exist.]

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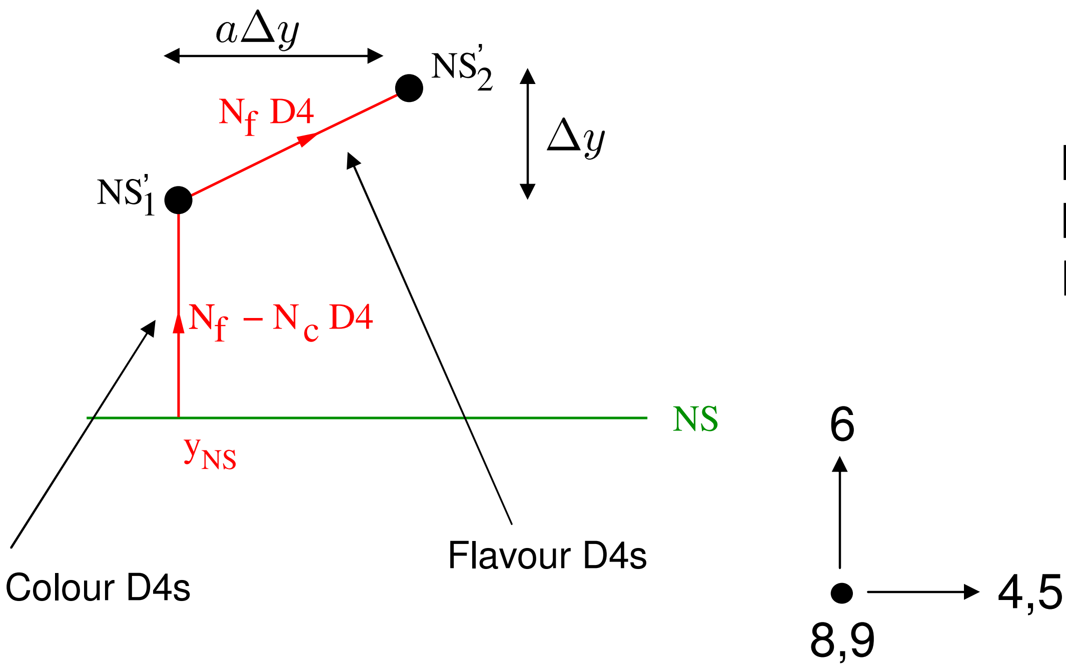
Brane Constructions of ISS

- Brane construction of ISS model:



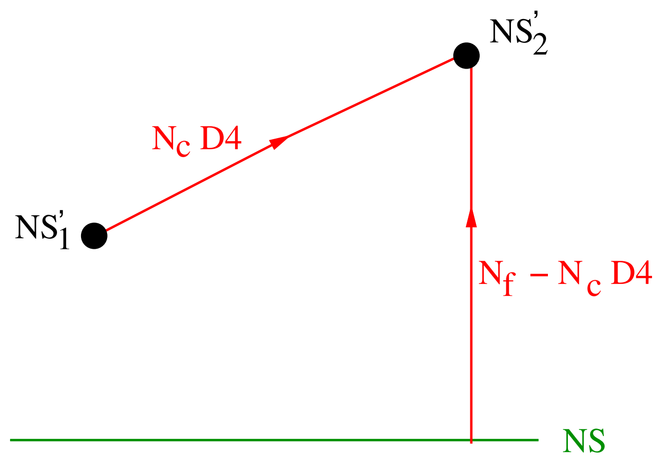
NS: 012345
NS': 012389
D4: 01236

- Realises ISS in the magnetic phase with gauged $U(N_f)$ flavour group
- Parameters

Slope: $a << 1$ EFT couplings: $h^2 = g_s l_s \Delta y, \qquad \mu^2 = \dfrac{a\Delta y}{g_s l_s^3}$

Reconnection

- Quarks $q, \tilde{q}$ tachyonic at the origin => instability for reconnection.
- Endpoint is slightly different configuration. Pseudo-modulus X is of rank N_c , describing location of the N_c flavour D4 branes

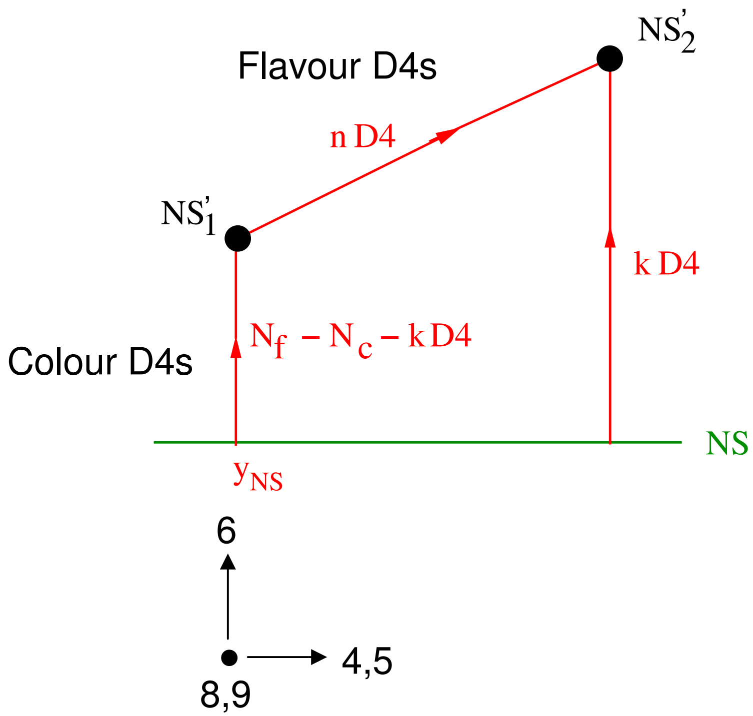


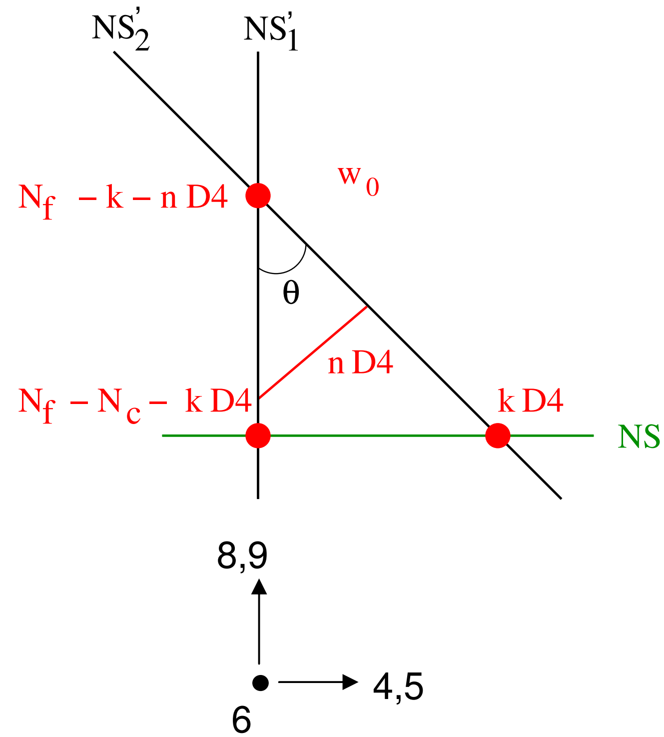
Brane Construction: ISS

- What are corrections to classical description of branes? Two qualitatively important ones:
  - ISS 1-loop effect ⇔ g_s effect. Dominates in ‘field theory regime’ $\mu \ll m_s$
  - Classical string interactions: gravitational attraction of the N_c D4’s to the NS-brane. Dominates in ‘string regime’ $\mu \gg m_s$
- In string regime, dominant corrections come from gravitational interactions between NS5-branes and D4-branes. Low energy effective theory gives a non-canonical Kahler potential for X. Stabilises the pseudo-modulus.

Brane Constructions: Generalised ISS

- Generalised ISS rotate the NS'_2 brane by a small angle θ





Brane Constructions: Generalised ISS

- n branes are stabilised by competition between geometric and gravitational interactions between branes
- Tachyon issue is visible in branes (and in field theory). Strings stretched between n and $N_f - N_c - k$ D4-branes are tachyonic if endpoints on NS_1' are close
- Can arrange parameters such that all vacua labelled by (n,k) are metastable
- Large breaking of R-symmetry (important for phenomenology)
- A landscape of vacua with a hierarchy of lifetimes
  - $n = 0$ & any k: SUSY & stable
  - $n > 0$ & $k = N_f - N_c$: metastable with longer lifetime than….
  - $n > 0$ & $k < N_f - N_c$: which have additional decay channels.

Brane Constructions: Generalised ISS

Question: What do early universe dynamics imply?

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Early Universe Dynamics

- At early times, universe is in a thermal state
  - Excess energy can go to exciting D-branes and/or NS5-branes
  - For small g_s , most of energy goes into exciting NS5-branes (massive & decay more slowly than D-branes)
  - Thus, consider above brane systems with NS, NS' branes taken to be non-extremal, and allow them to relax.
- The non-extremality modifies the landscape of vacua for the D4-branes; study D4-brane dynamics in the modified landscape as time evolves.
- In the extremal case, the gravitational attraction between D4-branes and NS5-branes played an important role. Will start by analyzing modification due to non-extremality.

Non-Extremal NS5-branes

- Non-extremal NS5-brane background

$$
\begin{aligned}
ds^2 &= -f(r)dt^2 + H(r)\left[\frac{dr^2}{f(r)} + r^2 d\Omega_3^2\right] + dx_i^2, \\
e^{2(\Phi-\Phi_0)} &= H(r), \\
f(r) &= 1 - \frac{r_h^2}{r^2}, \\
H(r) &= 1 + \frac{l_s^2}{r^2},
\end{aligned}
$$

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

  => evaporation time $T_{evap} \sim \frac{l_s}{g_s^2}$

Non-Extremal Massless ISS

- Start with simplest case $a = \mu = 0$
- In the extremal limit $r_h = 0$, no potential on the pseudo-moduli space. For $r_h \neq 0$ there is a potential. Only SUSY breaking is non-extremality. Analyse it by studying DBI action in the five-brane background

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

Pull back of metric to D-brane

- Evaluating the action and expanding to leading order in $\frac{r_h}{y_{NS}}, \frac{\Delta y}{y_{NS}}$

$$V(w) \approx \frac{T_4 \Delta y}{g_s} \left[1 - \frac{1}{2} \frac{r_h^2 |w|^2}{(y_{NS}^2 + |w|^2)^2} \right] \quad w = x^8 + ix^9$$

w is scalar parameterising location of flavour D4-brane

- Naively looks repulsive near the origin…..but wait! There's more…

Non-Extremal 5-branes Bend

- We implicitly assumed length of D4-branes Δy are independent of w. In fact, not the case. The NS' branes bend in the background of the NS-brane.
- To determine the shape of the NS'-branes, minimise a Nambu-Goto type action. After some work one finds

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

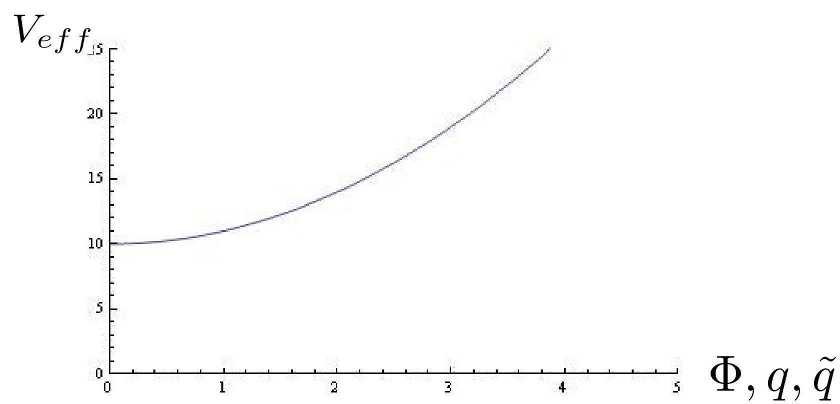
- Plugging into the potential we get

$$V(w) \approx \frac{T_4 \Delta y}{g_s}\left[1 + \frac{1}{4}\frac{r_h^2 |w|^2}{y_{NS}^4} + \mathcal{O}(|w|^4)\right]$$

- Note: the sign changed – D4-brane stabilised at the origin

Non-Extremal Massless ISS

- Repeating for multiple flavour D4-branes, find stack stabilises at origin, just like in the field theory analysis.



- D4-branes roll in this potential coming to rest at the origin on timescale of $\frac{l_s}{g_s}$
- But, two parallel non-extremal NS'-branes attract each other => merge on timescale $(g_s)^0 \ll$ hawking radiation

Non-Extremal ISS

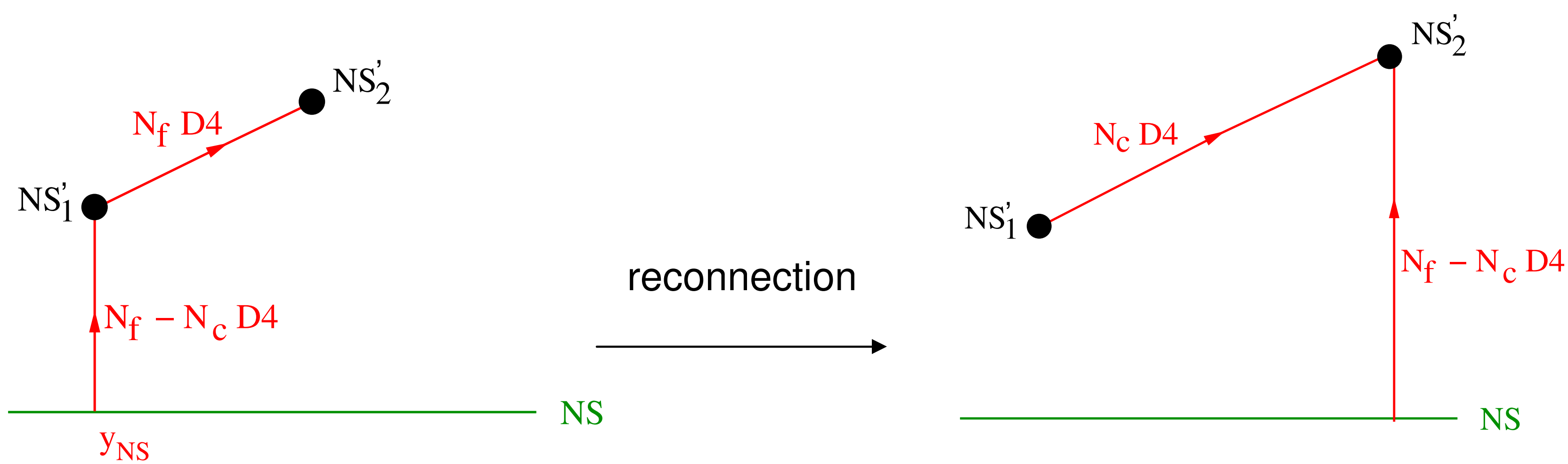
- What happens when $a, \mu \neq 0$? (i.e. the ISS system)
- Recall when $r_h = 0$ there is a pseudo-moduli space of rank N_c that is lifted by classical gravitational interactions (confined to origin)
- For $r_h \neq 0$, find potential is given by

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

- Potential is sum of attractive contributions from two sources of SUSY breaking ($r_h \neq 0$ and $a \neq 0$). For $r_h \gg l_s$, non-extremality dominates.

Reconnection Revisited

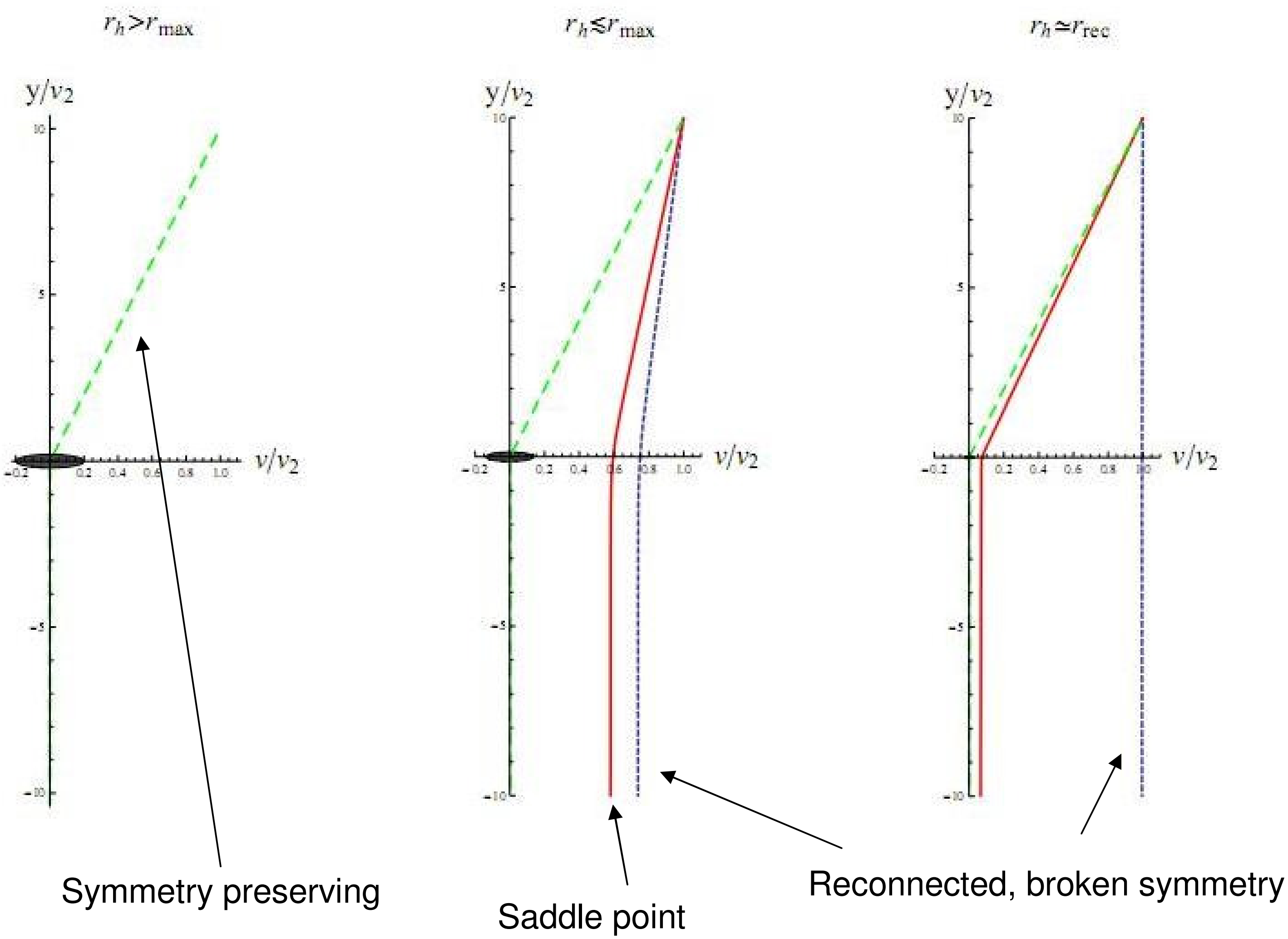
- Recall the ISS system had an instability to reconnect. Need to re-examine this in presence of non-extremality



ISS Branes: Reconnection & Energetics

- Re-examining reconnection:
  - In the early universe expect all the NS-brane and the two NS'-branes to be non-extremal with same r_h.
  - Thus take NS_1' to be non-extremal, and examine solutions to DBI-action.
- Find a number of different phases:
  1. For $r_h > r_{max} \simeq \frac{4}{3\sqrt{3\pi}}\sqrt{a}v_2$ no reconnection occurs. Only solution exhibits unbroken gauge symmetry
  2. For $r_{max} \geq r_h \geq r_{rec} \simeq \frac{a^2}{4}\Delta y$ additional solutions of DBI appear, but are higher energy configurations. Reconnection not energetically favourable
  3. For $r_h \leq r_{rec}$ the reconnected solution energetically preferred; only be reached by tunnelling (non-perturbative in g_s) & time scale exponentially suppressed.
  4. For $r_h \leq l_s$ DBI analysis not valid. Two possibilities: barrier disappears (2nd order phase transition) or remains (1st order phase transition) in limit $r_h \to 0$

Non-Extremal Reconnection

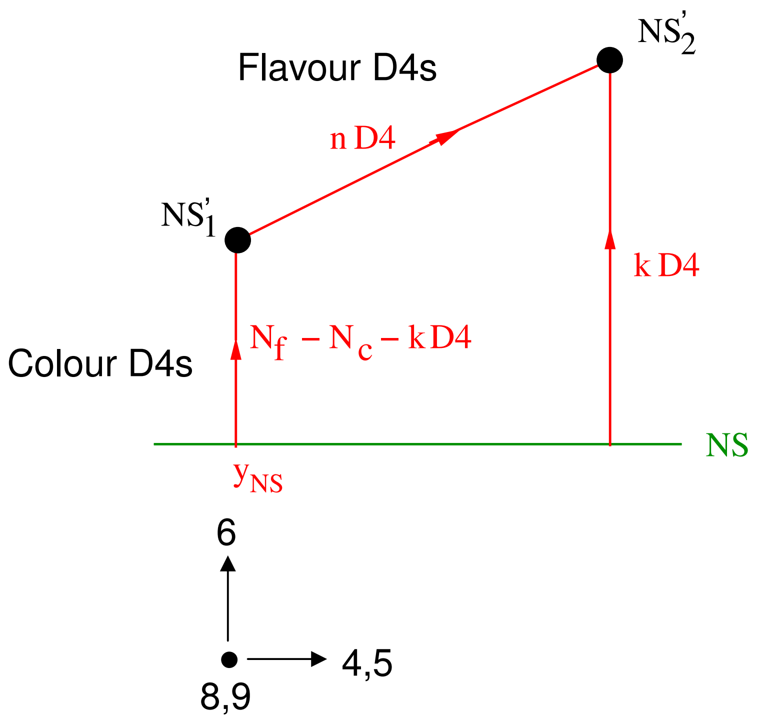


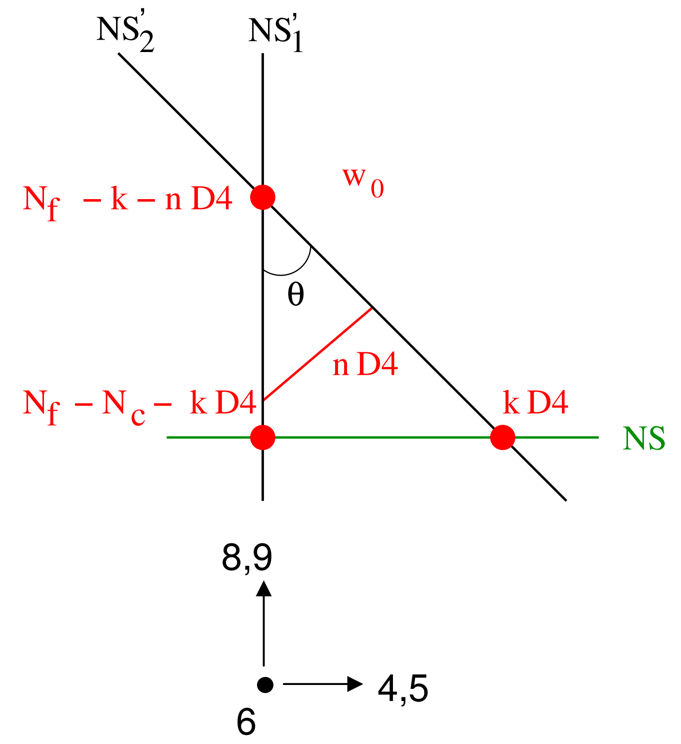
The Collapse of ISS

- Issue: so far assumed a static non-extremal five-brane background. Generically not true; five-branes gravitationally attract each other leading to collapse
  - As before: Time scale for collapse is very fast relative to Hawking radiation
  - Endpoint of time evolution is a system with coincident NS'-branes
  - ISS type system is not a likely endpoint of universe evolution
- Nonetheless, the previous analysis useful. Applies to the generalized ISS system (does not suffer from the instability problem)

Extremal Generalised ISS

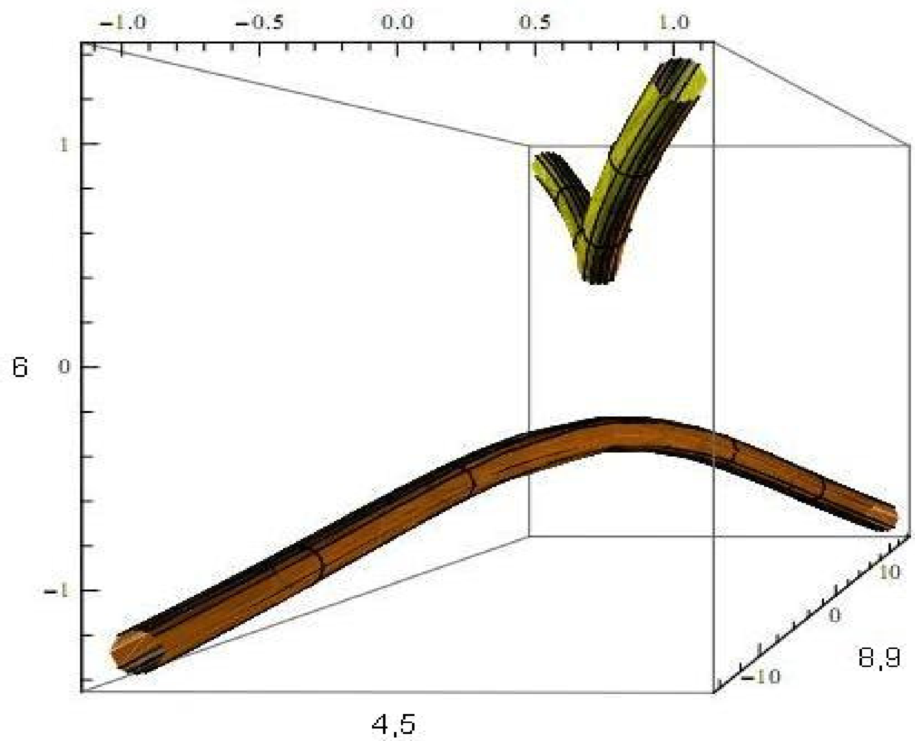
- Recall the extremal case $r_h = 0$. Multiple vacua labelled by (n,k). Ones with $n = 0$ are supersymmetric; of the remaining ones only $k = N_f - N_c$ are locally stable in field theory regime.





Non-Extremal Generalised ISS: bendy branes

- Two NS'-branes no longer parallel. Implies no gravitational collapse! Instead branes take a static shape with a dip towards each other



- To analyse time evolution, study the energetics of the system

Non-Extremal Generalised ISS

- Repeating the calculation in the ISS context one can show

$$V(w_1) \simeq \frac{T_4 \Delta y}{g_s}\left[1 - \frac{a^2 w_1}{w_0} + \frac{r_h^2 + 2a^2 l_s^2}{4 y_{NS}^4} w_1^2 + \dots\right]$$

  Here w_0 is the location of the supersymmetric vacuum, while w_1 is the location of the D4-branes.

- This has a metastable minimum at

$$w_{min} = \frac{(y_{NS}^4/l_s^2 w_0)}{1 + r_h^2/2a^2 l_s^2},$$

- Near w_0 (SUSY point) the NS'-branes bend towards each other. When $r_h \sim \theta \Delta y \ll a l_s$ the NS'-branes merge (horizons touch). Any D4-branes there disappear into black hole
- Thus typically area near w_0 is surrounded by horizon, and any time evolution endpoint has $N_f = k + n$

Generalised ISS: Time Evolution

- We can now analyse early universe dynamics with time
- Start with early times, assuming all NS5-branes have $r_h \gg \theta\Delta y$
- Any branes near w_0 fall into the black hole. Hence, any branes that survive at late times must be near the origin of field space.
- We now analyse the energetics near the origin of field space. Proceeds as in the ISS case, find a number of phase transitions.
- Large r_h preferred solution is one with unbroken gauge symmetry. As r_h decreases, a symmetry breaking minimum appears, separated by a large potential barrier.
- Generically, reconnection is exponentially suppressed; the preferred vacuum state is one with unbroken symmetry $k = 0$, $n = N_f$.
- This vacuum exists in string theory but not in field theory (requires higher derivative terms in effective field theory language)

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Summary & Comments

- The picture in string theory closely related to that in field theory. Some analogues:
  - Finite temperature ⇔ non-extremal five-branes
  - phase transition associated with condensation of quarks ⇔ reconnection of flavour & colour branes
  - Metastable vacuum energetically preferred
- Some features not seen in field theory:
  - R-symmetry breaking. In field theory desirable for phenomenological reasons; string theory needed for dynamical stability reasons;
  - Couplings evolve with time (in addition to usual RG flow)
  - ISS system unnatural endpoint of evolution (unstable)
  - Generalised ISS is stable! Also, has many metastable vacua not seen in field theory. Dynamics drives one to the most stringy of these.

Some Future Directions

- Future directions:
  - Use brane models to describe inflation (this scenario imagined post-inflation)
  - Couple to a sector that realises the MSSM
  - Compactify these models, stabalise closed string moduli etc.