Title: Supersymmetry breaking in gauge theory and string theory

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Abstract: TBA

Introduction

The vacuum structure and low energy dynamics of SUSY gauge theories were studied extensively in the last 25 years. Tools such as the NSVZ β–function, Seiberg duality, non-perturbative superpotentials and a-maximization were developed and used to analyze a wide variety of theories.

Spontaneous supersymmetry breaking was also studied, but was thought to be a rather esoteric phenomenon, not exhibited by generic supersymmetric theories.

This attitude began to change in 2006, when Intriligator, Seiberg and Shih (ISS) found a metastable supersymmetry breaking vacuum in supersymmetric QCD (SQCD) with a small mass for the quarks.

This suggests that there is much to be learned about non-supersymmetric meta-stable states in supersymmetric gauge theories. Indeed, in the first part of this talk we will see that a small deformation of SQCD leads to a rich landscape of metastable vacua with varying properties. Such vacua may provide natural models of supersymmetry breaking in nature.

In the second part of the talk I will discuss the embedding of the gauge theory problem in string theory, as the low energy theory on a system of Neveu-Schwartz fivebranes and D-branes.

Such systems were found in the past to be useful for studying SUSY gauge dynamics. They lead to a geometric realization of Seiberg-Witten curves in N=2 SYM, Seiberg duality in N=1 SYM, etc.

BUT...

Typically, the brane realization is useful in a regime of parameter space different from the one in which the gauge theory is valid. For protected quantities related to the vacuum structure this should not matter, but the possible existence and properties of metastable states might strongly depend on such parameters.

Thus, apriori it is unclear whether the brane picture is useful for studying SUSY breaking states. In fact we will find that the brane construction has the same rich structure of metastable states as the gauge theory. Furthermore, it provides a good qualitative picture of these states and can be used to perform quantitative calculations in a regime of parameter space of brane configurations that is inaccessible to gauge theory.

Gauge theory

The theory we will consider is N=1 SQCD with gauge group $SU(N_c)$ and $N_f > N_c$ flavors of chiral superfields in the fundamental representation of the gauge group:

$$Q_i^\alpha, \widetilde{Q}_\alpha^i \ (\alpha = 1, \cdots, N_c;\ i = 1, \cdots, N_f).$$

This theory is asymptotically free for $N_f < 3N_c$. We will be mostly interested in the regime $N_f < \frac{3}{2}N_c$ where the theory is strongly coupled in the infrared and there is a better description of its dynamics.

Seiberg dual (magnetic) theory

- **Gauge group**: $SU(N_f - N_c)$

- **Chiral superfields**:

  N_f fundamentals $q^i, \tilde{q}_i,\ i = 1, \cdots, N_f$

  Gauge singlets $M^i_j (= \tilde{Q}^i Q_j)$

- **Superpotential**: $W_{\rm mag} = \frac{1}{\Lambda} \tilde{q}_i M^i_j q^j$

The deformation

We add to the electric Lagrangian the superpotential

$$W_{\rm el} = \frac{\alpha}{2}{\rm Tr}(\tilde{Q}Q)^2 - m{\rm Tr}(\tilde{Q}Q) = \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

In the magnetic description this corresponds to deforming $W_{\rm mag}$ to

$$W_{\rm mag} = \frac{1}{\Lambda}\tilde{q}_i M^i_j q^j + \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

Integrating out M_j^i gives

$$W_{\rm mag} = -\frac{1}{\alpha\Lambda}\left[\frac{1}{2\Lambda}{\rm Tr}(\tilde{q}q)^2 - m{\rm Tr}(\tilde{q}q)\right]$$

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Supersymmetric vacua

There are two types of supersymmetric vacua in this theory:

- Mesonic branch: $\det M \neq 0.$
- Baryonic branch: $\det M = 0;\ \ b = q^{N_f - N_c} \neq 0.$

We will focus on the mesonic vacua.

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Since $\det M \neq 0$, the magnetic quarks $q^i, \tilde{q}_i$ are massive and can be integrated out in the infrared. The resulting superpotential for M is

$$W_{\rm mag} = {\rm Tr}\left(\frac{\alpha}{2}M^2 - mM\right) - (N_f - N_c)\left(\frac{\det M}{\Lambda_e^{3N_c-N_f}}\right)^{\frac{1}{N_f-N_c}}$$

The last term is the familiar non-perturbative superpotential of N=1 SYM.

Supersymmetric vacua correspond to solutions of the F-term equations of this superpotential:

$$\alpha M^2 - mM = \left(\frac{\det M}{\Lambda_e^{3N_c - N_f}} \right)^{\frac{1}{N_f - N_c}} I_{N_f}$$

Here I_{N_f} is the $N_f \times N_f$ identity matrix.

Including the D-terms constraints, one finds that M can be diagonalized and has at most two distinct eigenvalues, x and y. Denoting the degeneracy of y by k and that of x by $N_f - k$ one finds that x, y satisfy:

$$x + y = \frac{m}{\alpha}$$

$$x^{N_c - k} y^{k - N_f + N_c} = (-\alpha)^{N_f - N_c} \Lambda_e^{3N_c - N_f}$$

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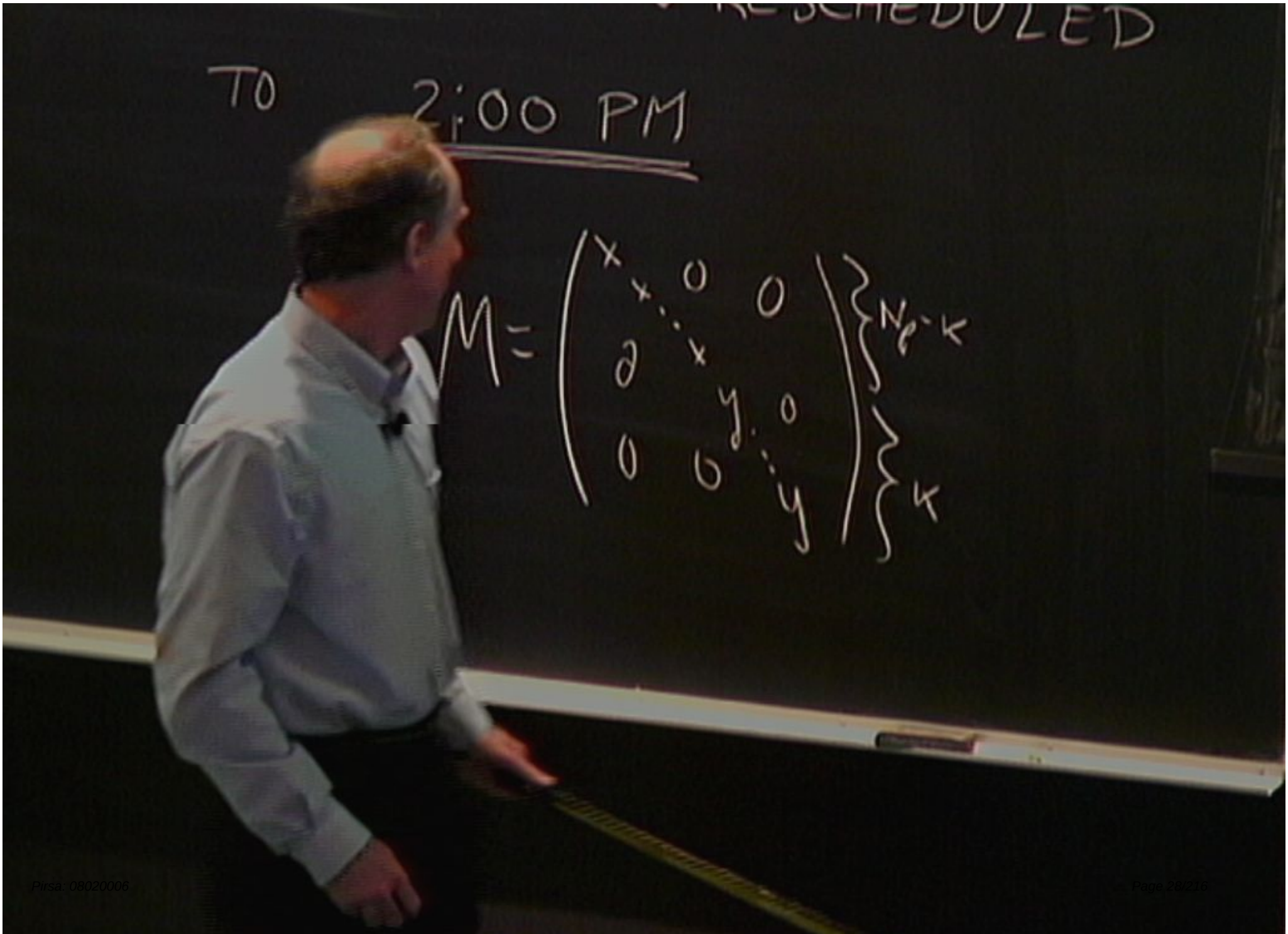
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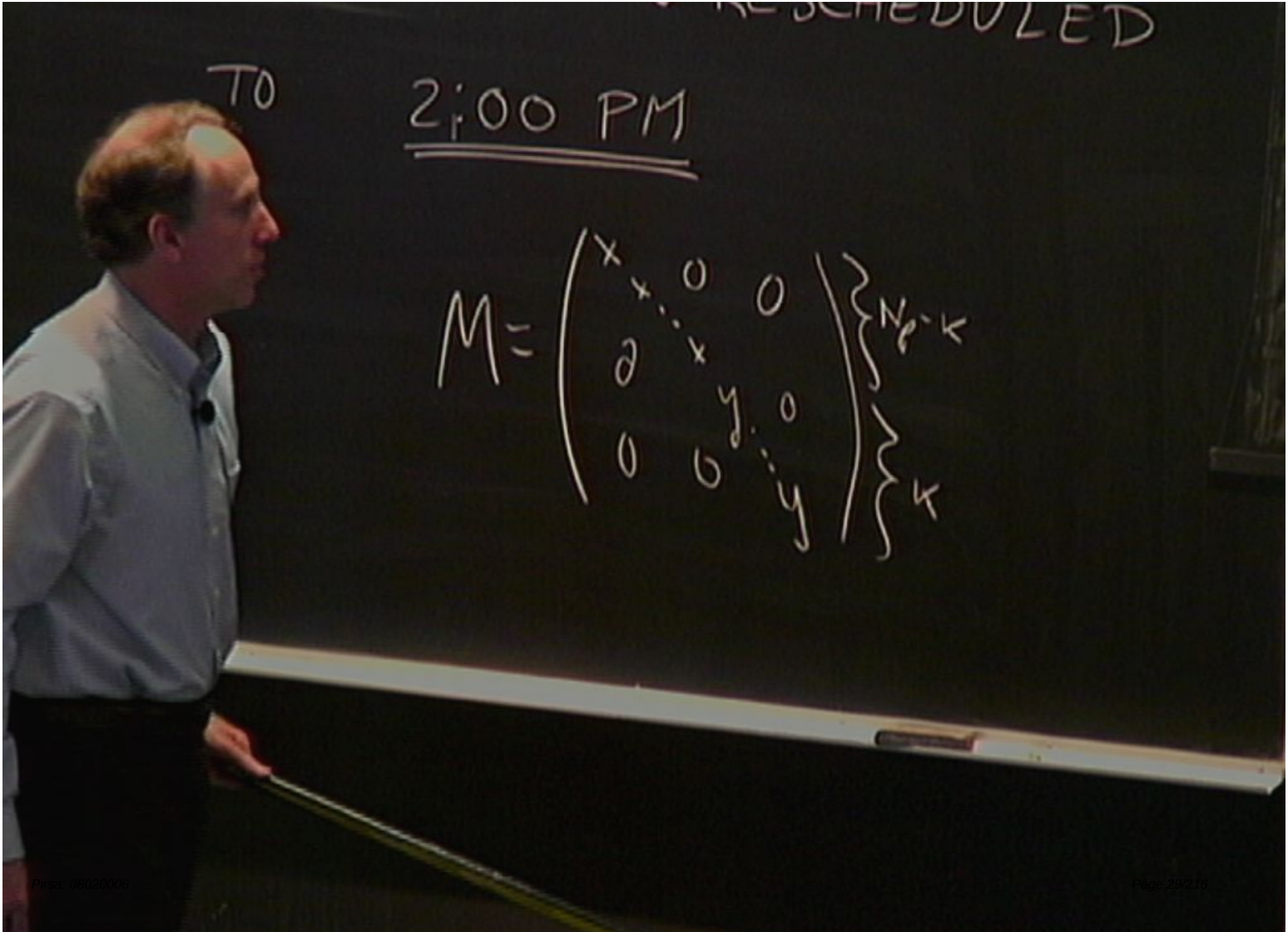
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for $N_f \geq 2N_c$, $\frac{1}{2}(N_f-N_c)(N_f-N_c+1)$ vacua.

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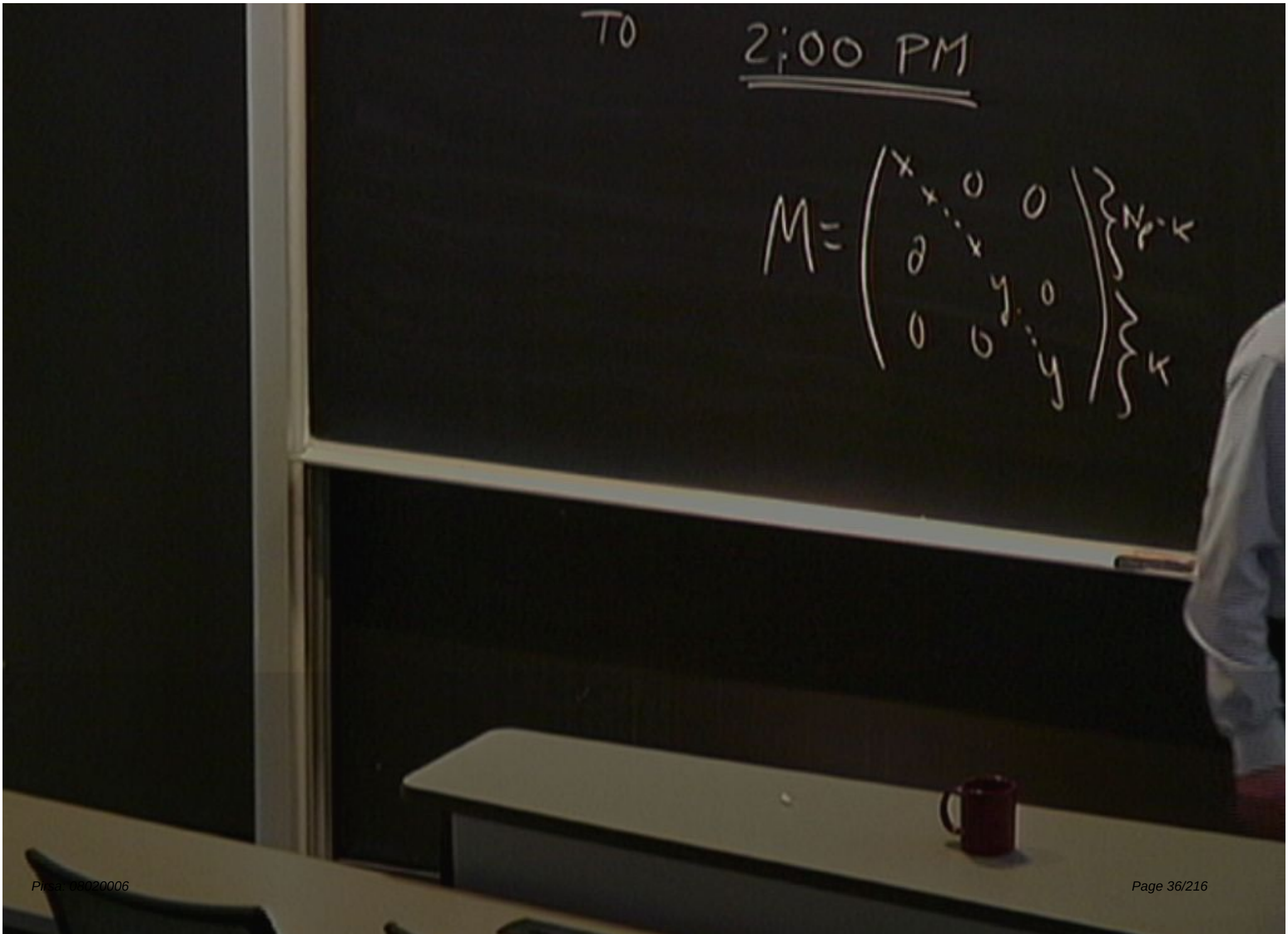
Metastable vacua

The theory described above is a small deformation of the one studied by ISS. Hence, it is natural to expect that it has non-supersymmetric metastable ground states as well.

To study these states we restrict to the regime $N_f < \frac{3}{2} N_c$ where the magnetic theory is infrared free and one can neglect its gauge interactions.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It is also convenient to rescale the magnetic meson M and write the Lagrangian in terms of a field Φ, which has a canonical kinetic term near the origin of field space,

$$K = \mathrm{Tr}\Phi^\dagger\Phi + \cdots$$

The magnetic superpotential takes now the form

$$W_{\mathrm{mag}} = h\tilde{q}_i\Phi^i_j q^j - \mathrm{Tr}\left(h\mu^2\Phi - \frac{1}{2}h^2\mu_\phi\Phi^2\right)$$

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where h is a free dimensionless parameter and μ, μ_ϕ are mass scales. We will work in the regime

$$h, \frac{\mu_\phi}{\mu} \ll 1$$

in which we can study the O'Raifeartaigh model for $q, \tilde{q}, \Phi$, as in ISS. The small parameters above will be responsible for the long lifetime of the metastable vacua that we will find.

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These vacua exhibit diverse patterns of global symmetries and low lying excitations and might be interesting candidates for the supersymmetry breaking sector in nature.

String theory

If string theory is realized in nature, particle physics models that naturally arise from it are more likely to play a role in beyond the standard model physics. Therefore, it is interesting to ask whether the supersymmetry breaking dynamics described above can be naturally embedded in a string construction. In the remainder of the talk I will argue that this is indeed the case.

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There are two ways of realizing it as a low energy theory on D-branes:

- Near conical singularities of Calabi-Yau manifolds.
- In the vicinity of Neveu-Schwartz fivebranes.

The two descriptions are related by a version of T-duality.

We will use the NS5-brane picture, which was found to be more useful than the CY one in studying supersymmetric vacua. It turns out to be more useful for studying metastable vacua as well.

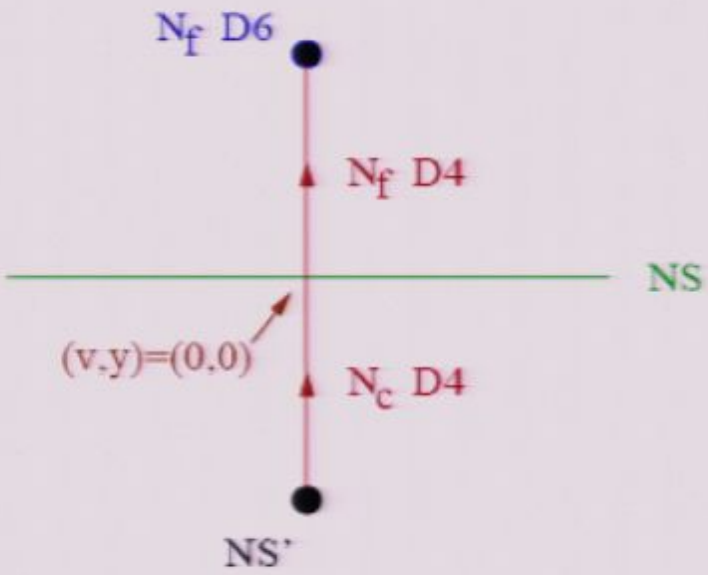
In particular, this description provides a nice geometric picture of the vacua that we found in the gauge theory before.

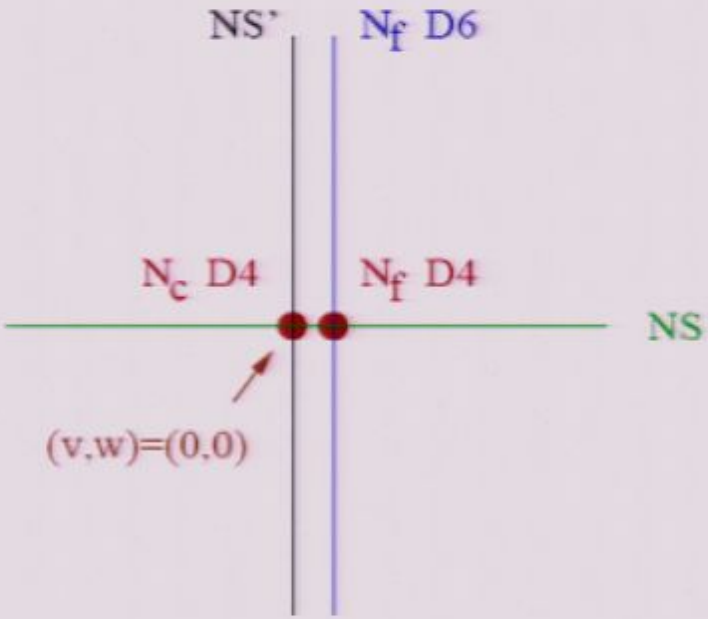
Brane realization of SQCD

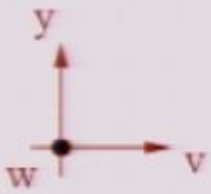
The electric SQCD described above can be realized in string theory as the low energy theory corresponding to a brane configuration containing two kinds of NS5-branes, which we will denote by NS and NS', as well as D4 and D6-branes.

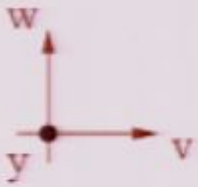
All the branes are stretched in the 3+1 directions (0123). The NS-branes are also stretched in the directions (45), the NS'-branes in (89), the D4-branes in 6 and the D6-branes in (789). One can check that any configuration containing all these branes preserves N=1 supersymmetry in the 3+1 common dimensions (0123).

The branes are arranged in the extra dimensions as follows:



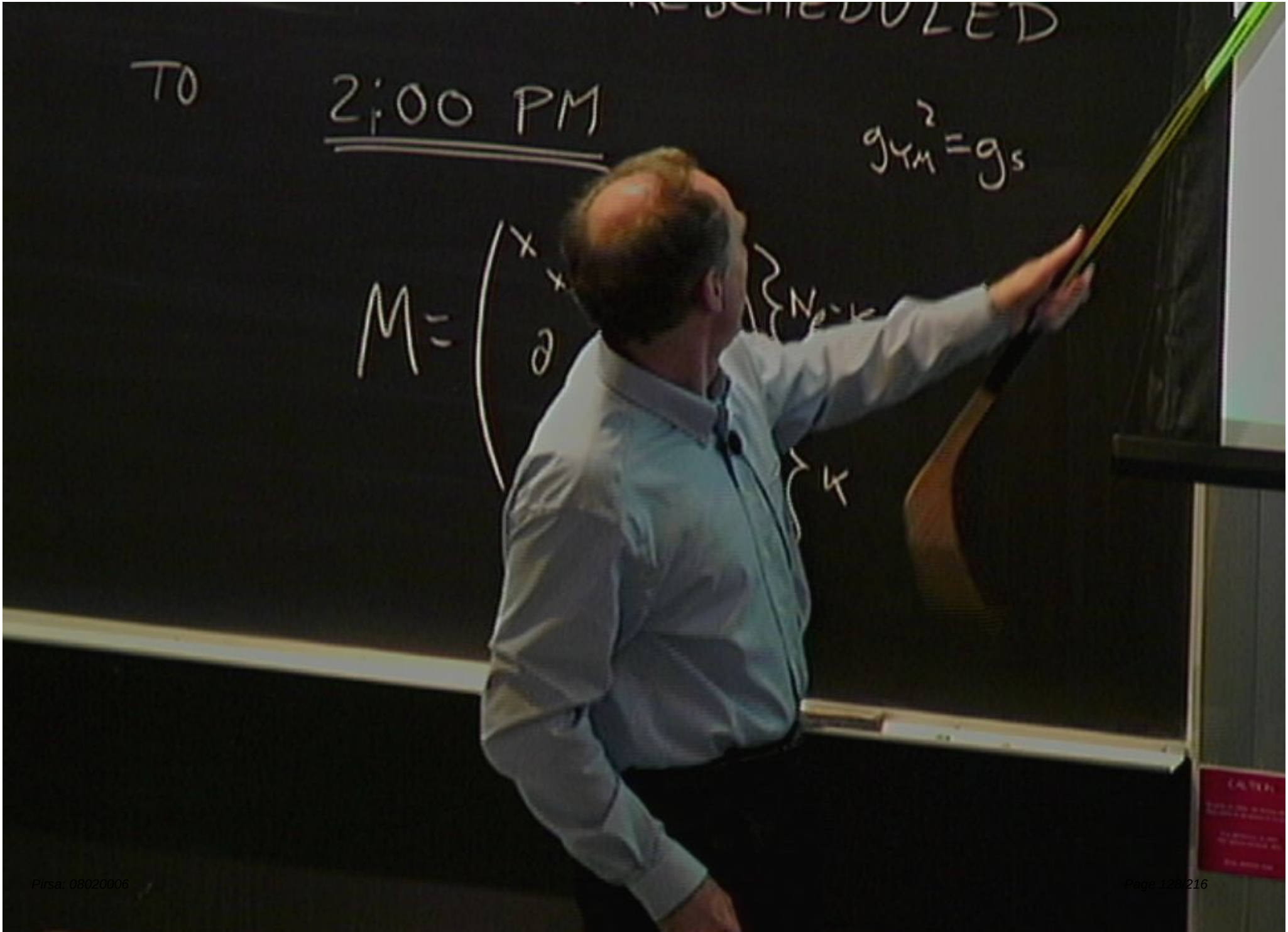






$$v = x^4 + ix^5 \,, \qquad w = x^8 + ix^9 \,, \qquad y = x^6$$

- Field content, gauge coupling, moduli space.


TO
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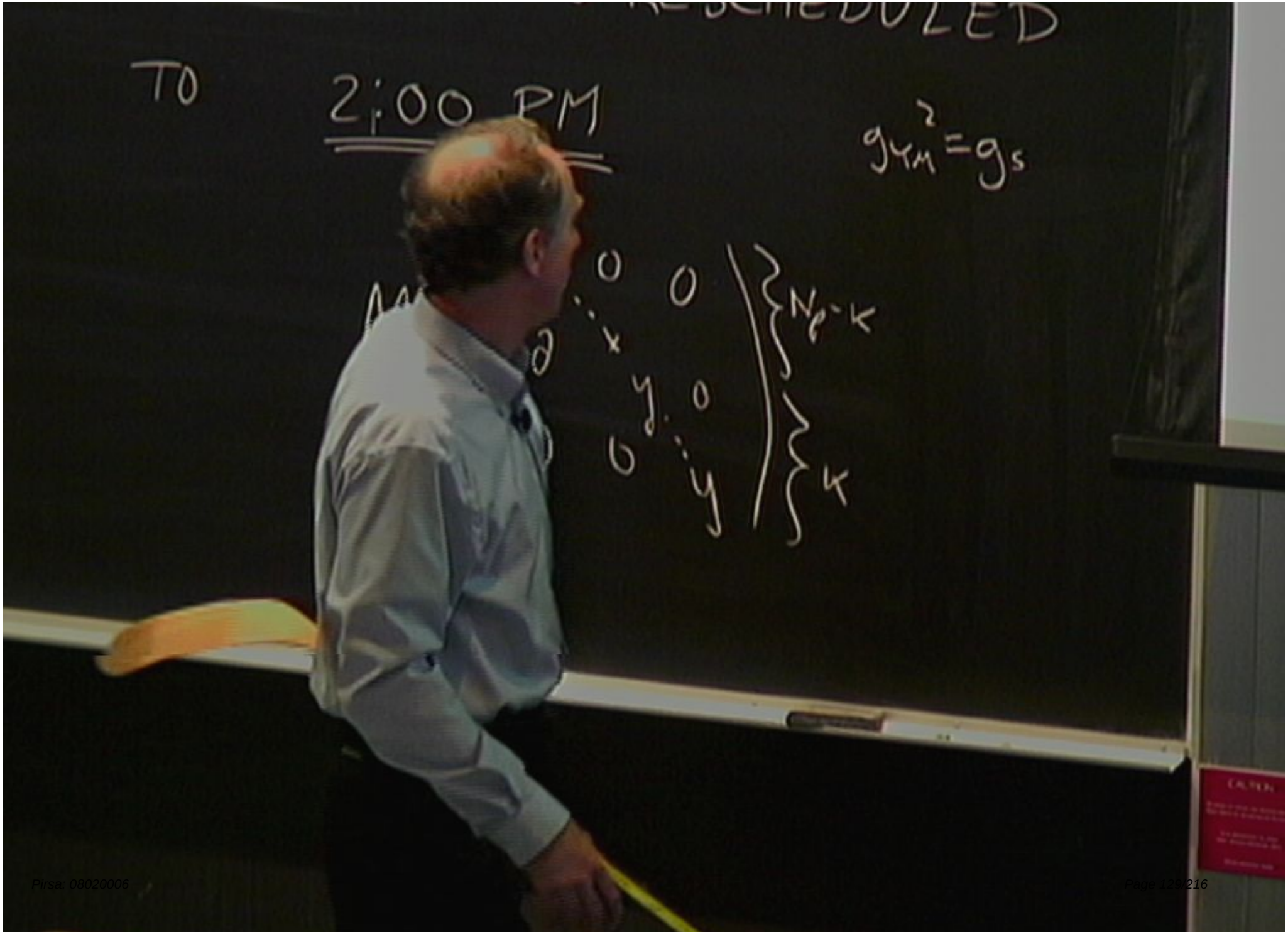
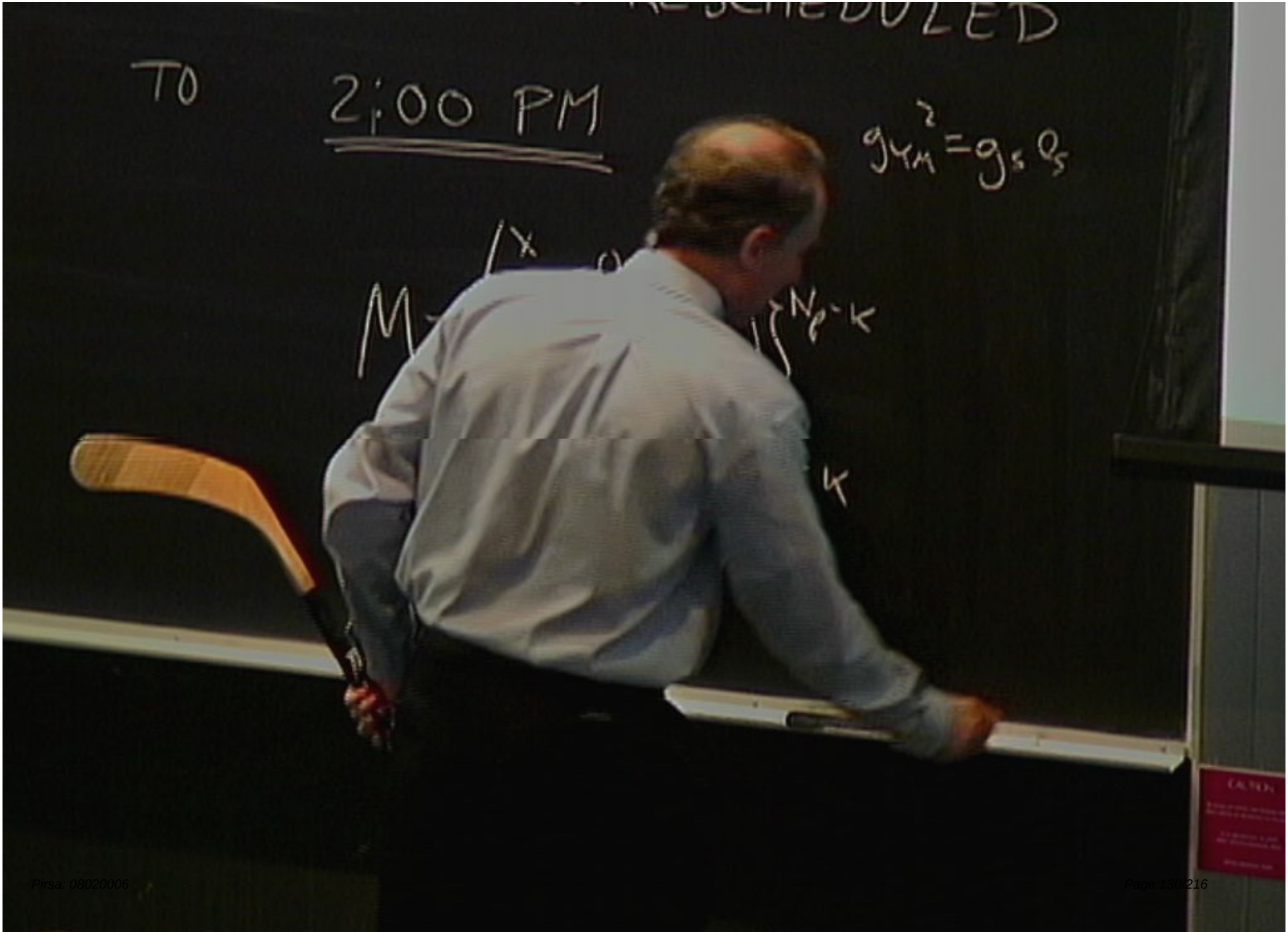
$g_{YM}^2 = g_s$
$M =$


TO
2:00 PM
$g_{YM}^2 = g_s$
$N_p - k$
k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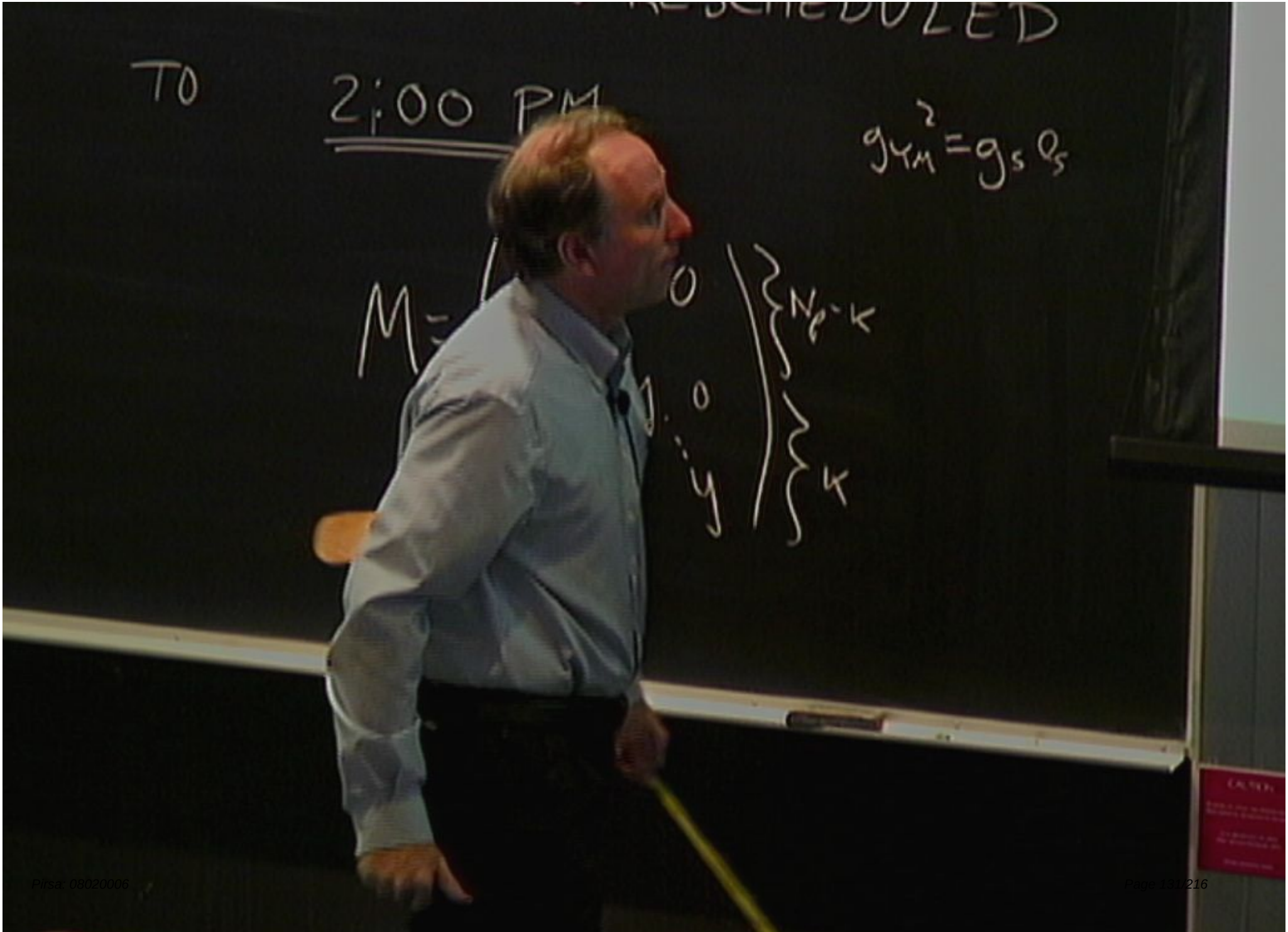
$g_{YM}^2 = g_s \ell_s$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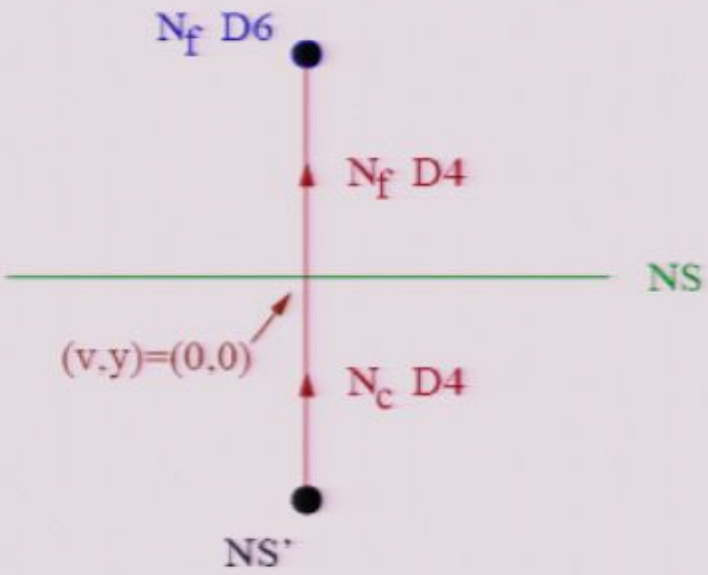

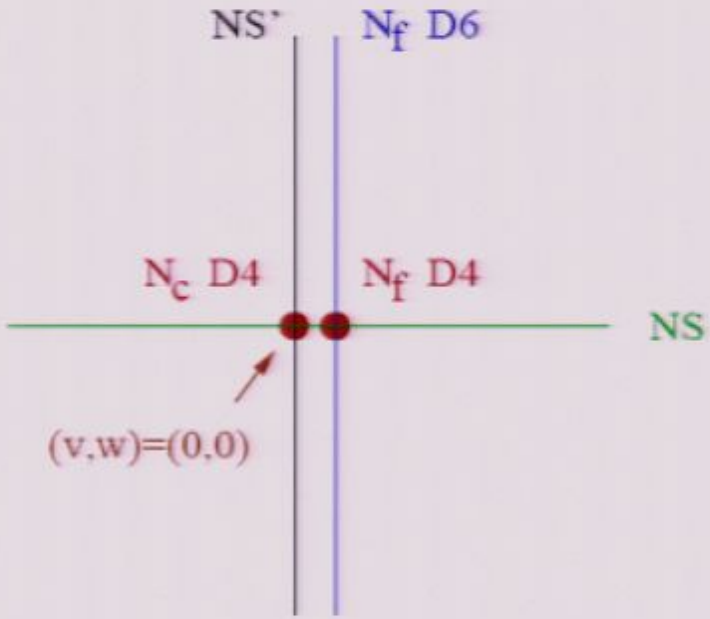

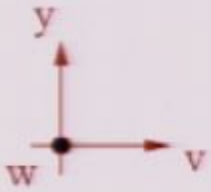

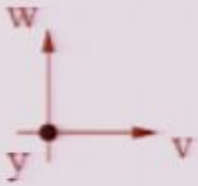

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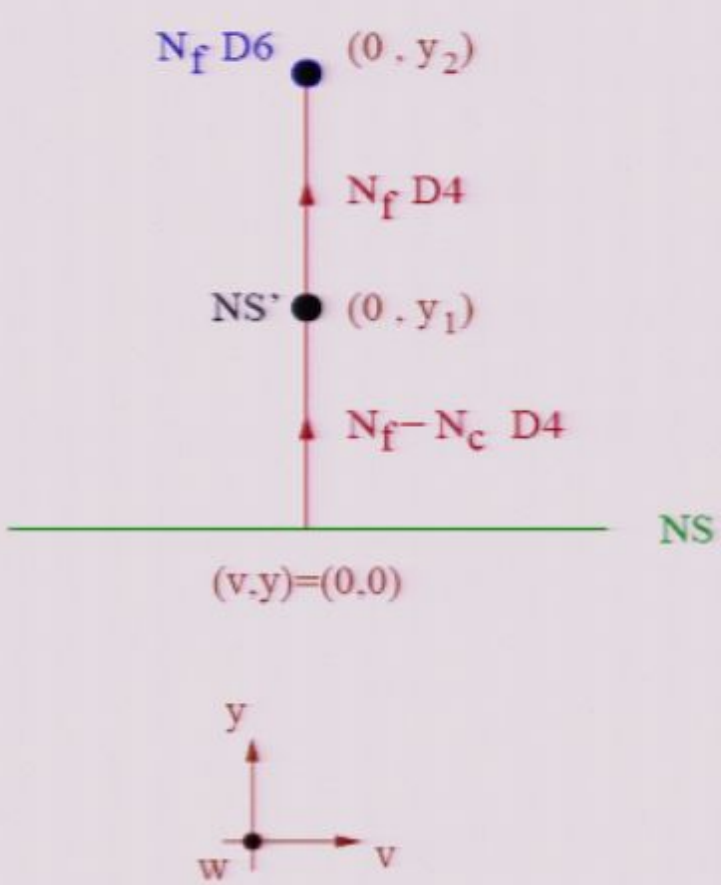
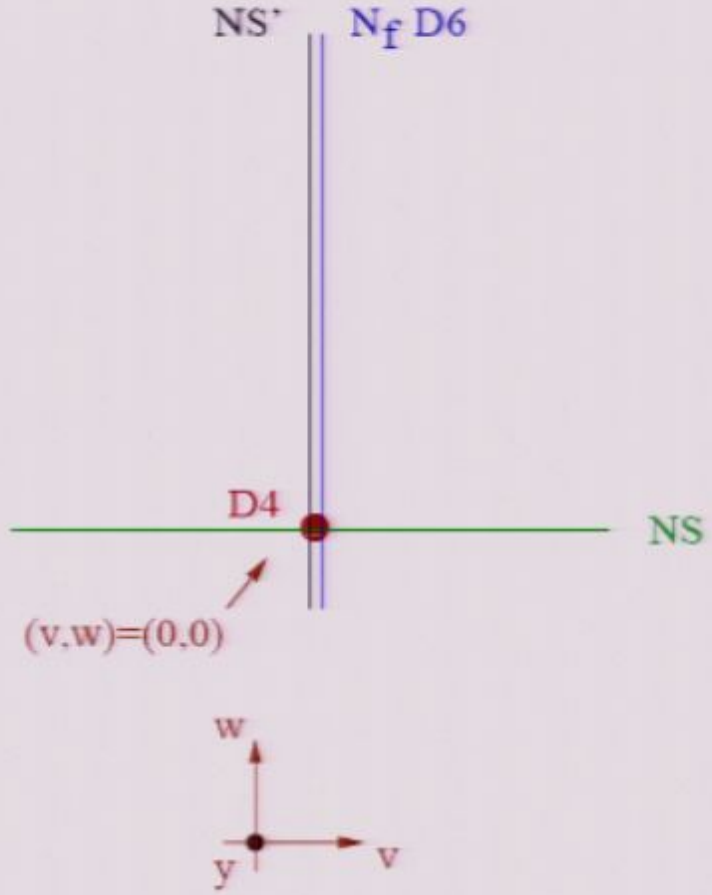
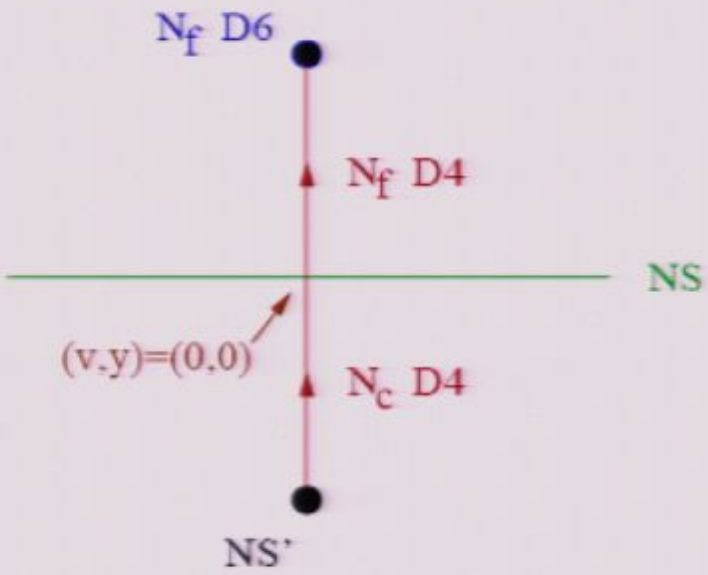
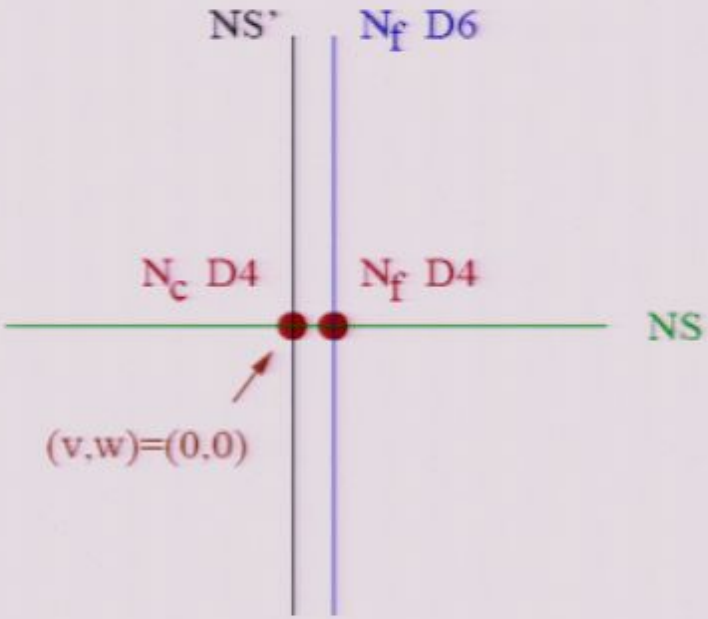
- Field content, gauge coupling, moduli space.

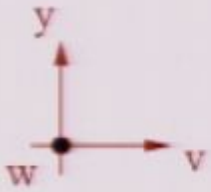
Seiberg dual (magnetic) brane configuration

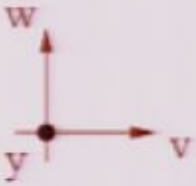












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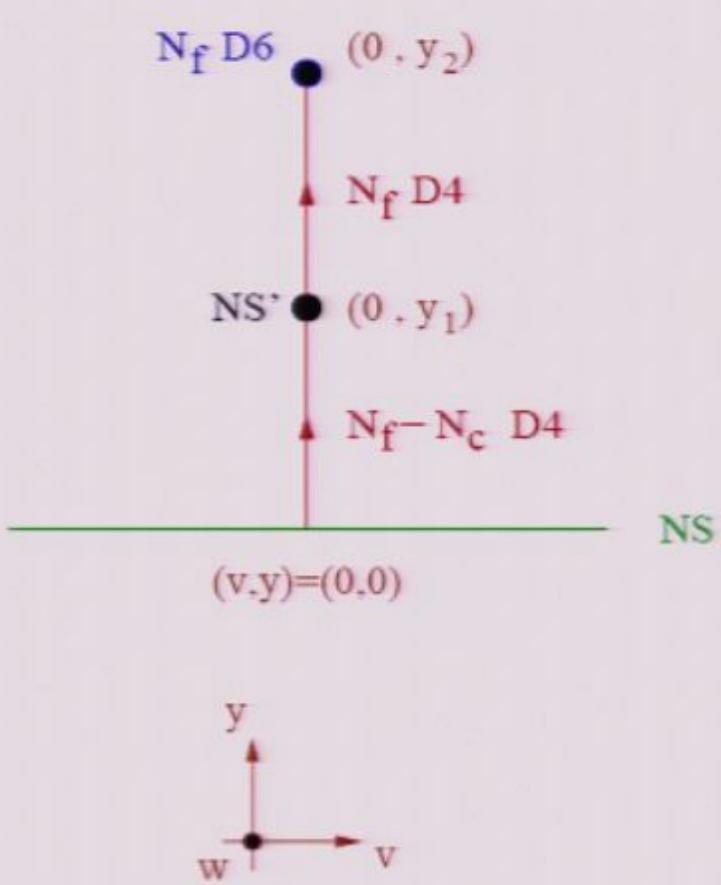

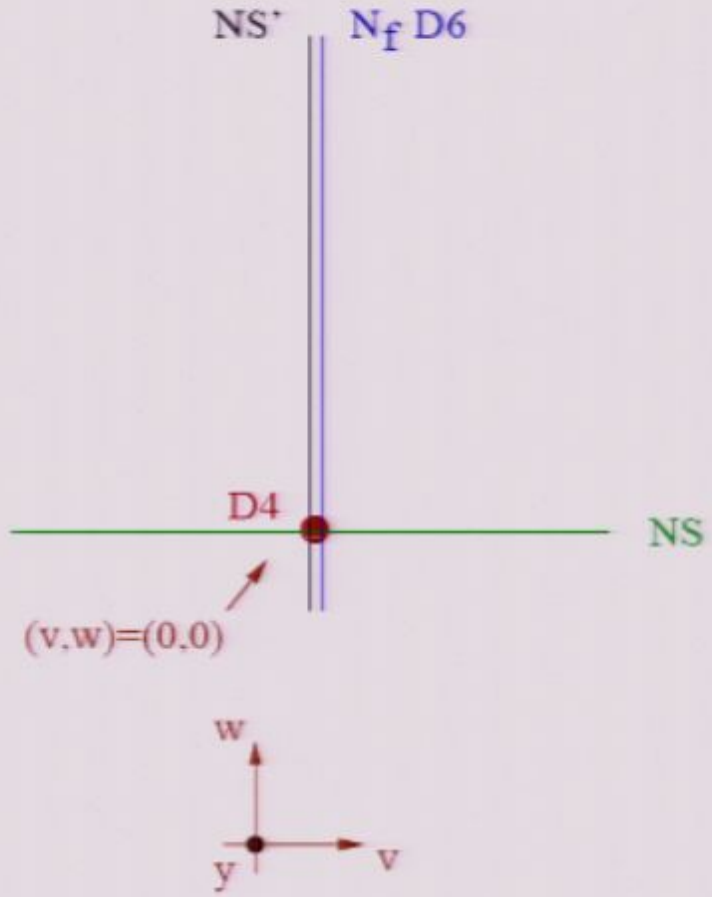

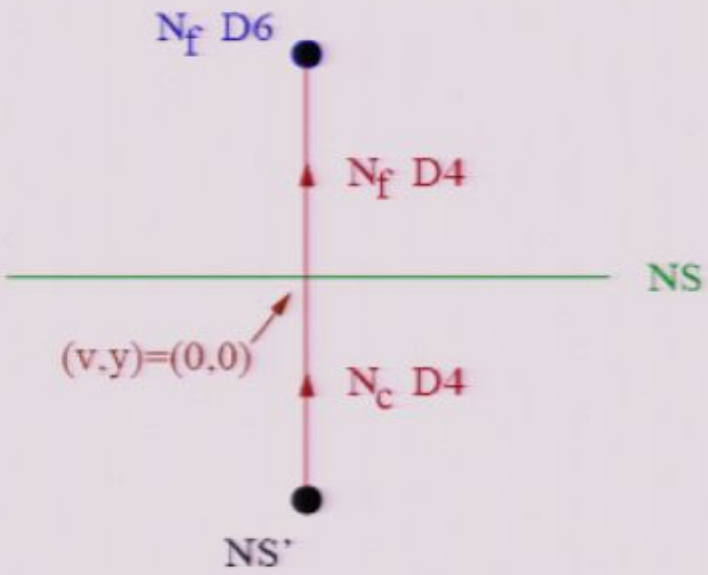

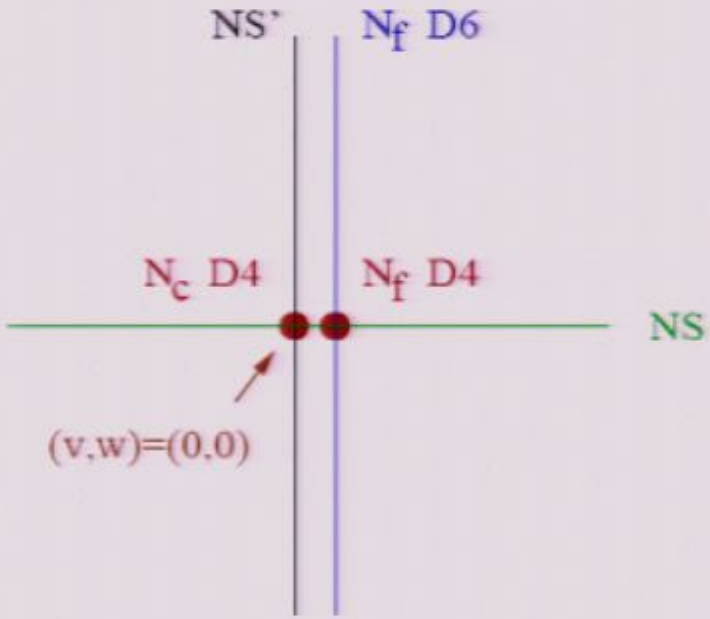

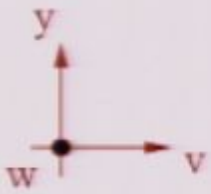

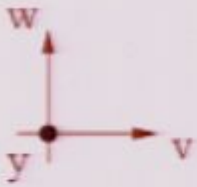

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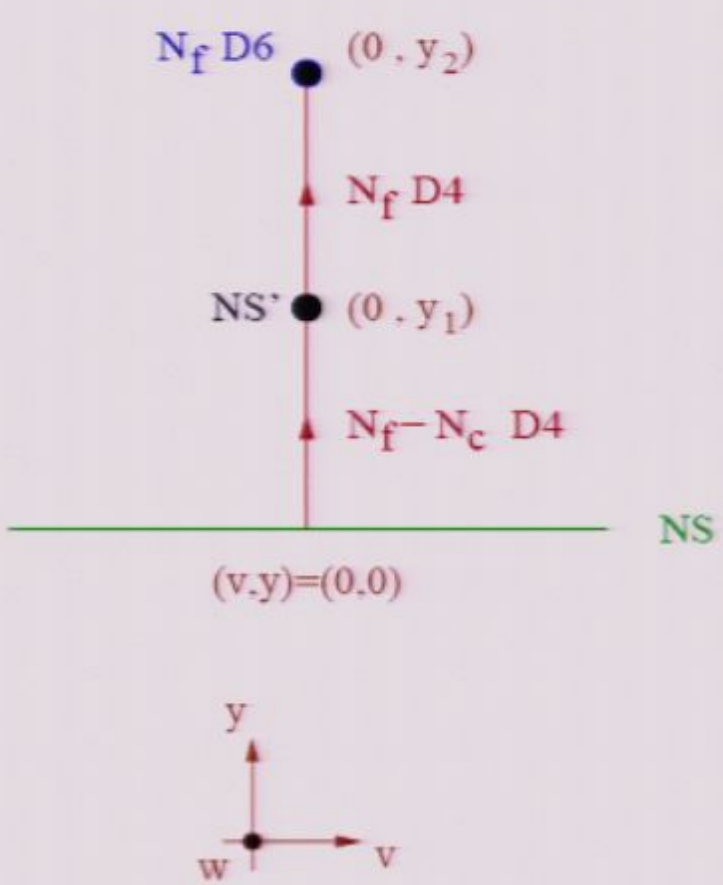

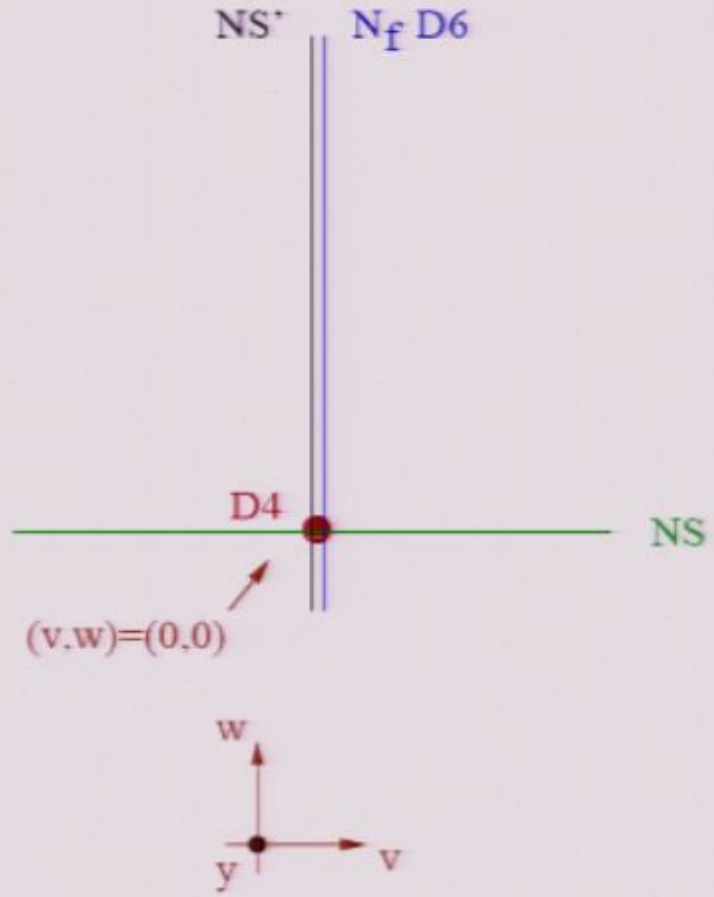

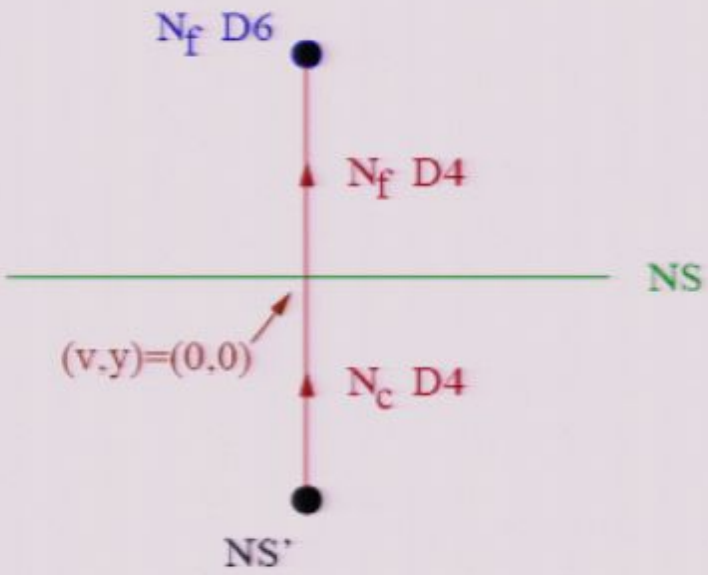

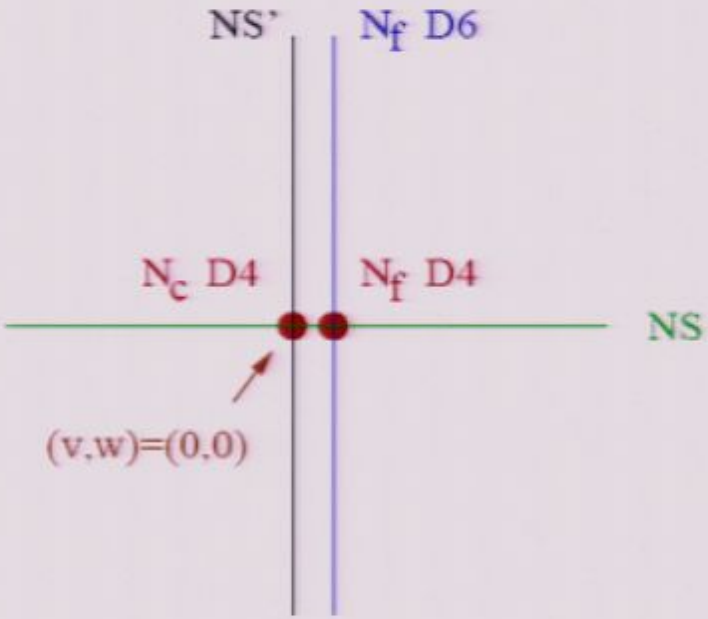

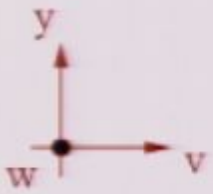

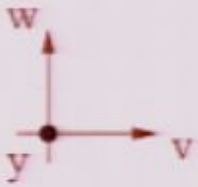

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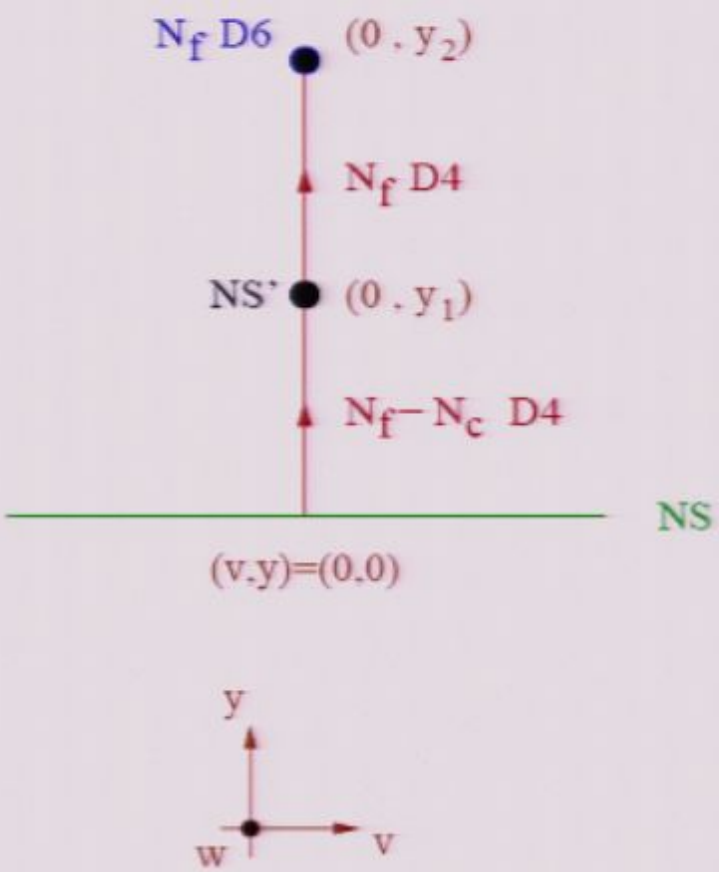
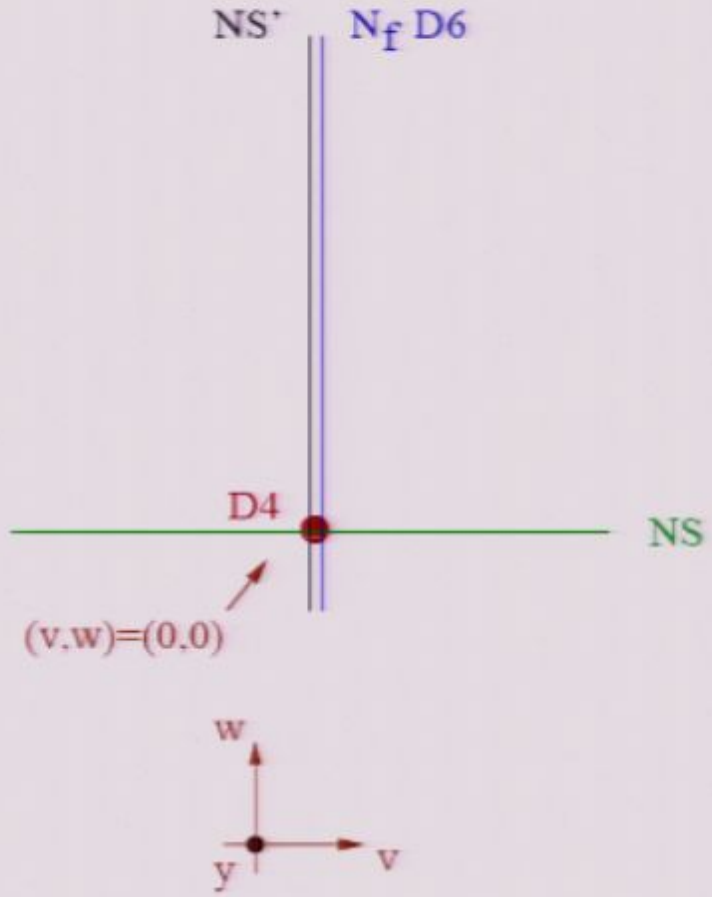


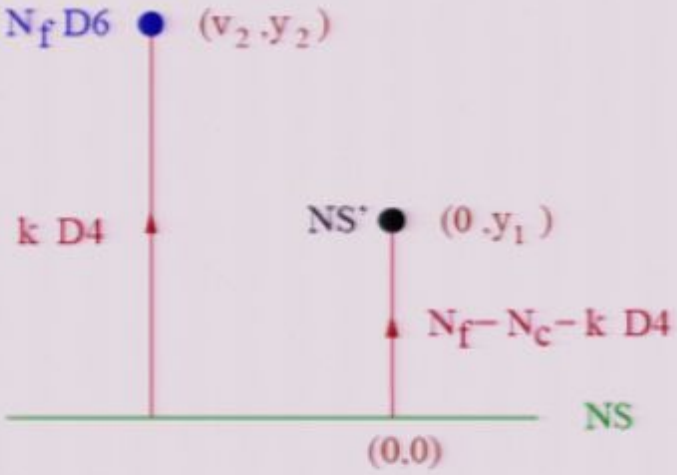


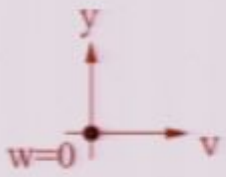
The deformation

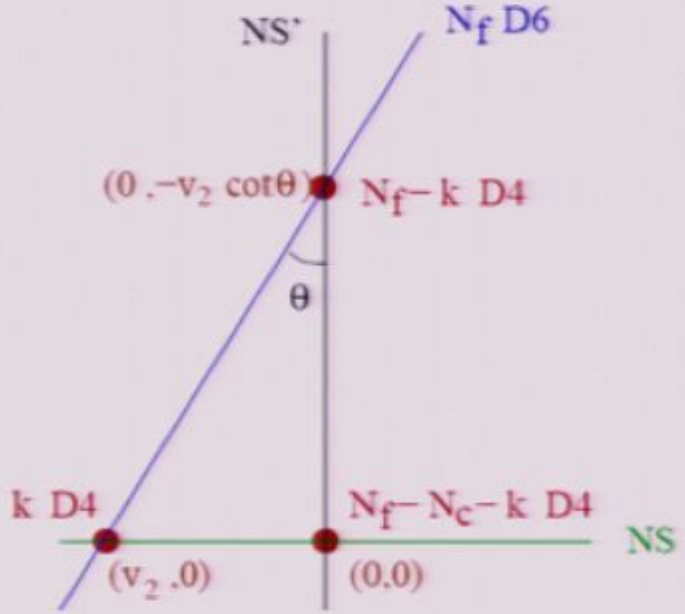
Deforming the superpotential to

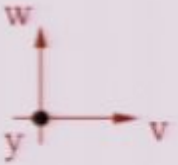
$$W_{\rm mag} = \frac{1}{\Lambda}\tilde{q}_i M^i_j q^j + \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

corresponds geometrically to a translation (m) and rotation (α) of the D6-branes:





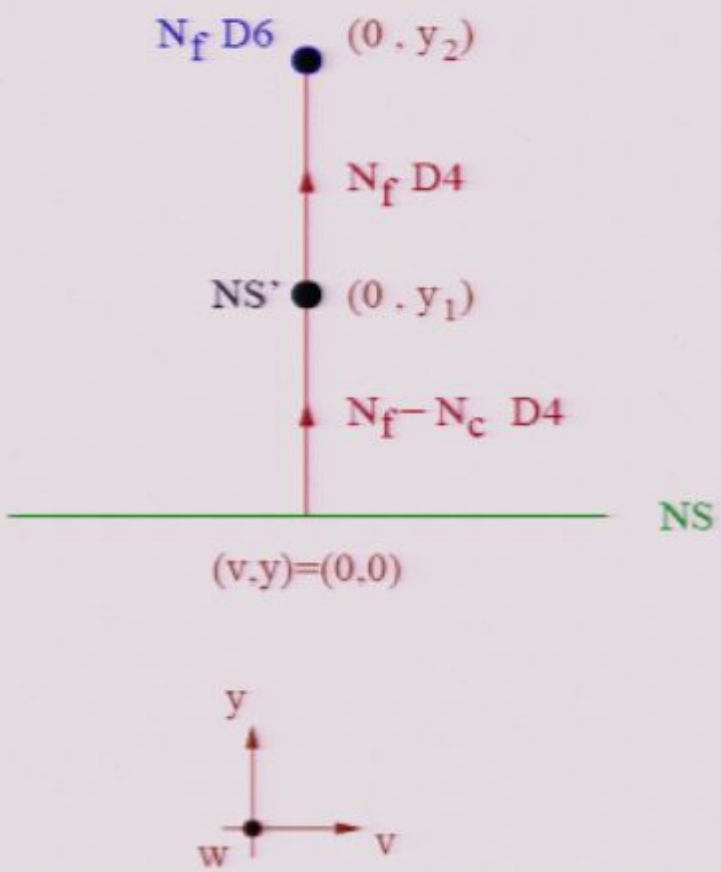


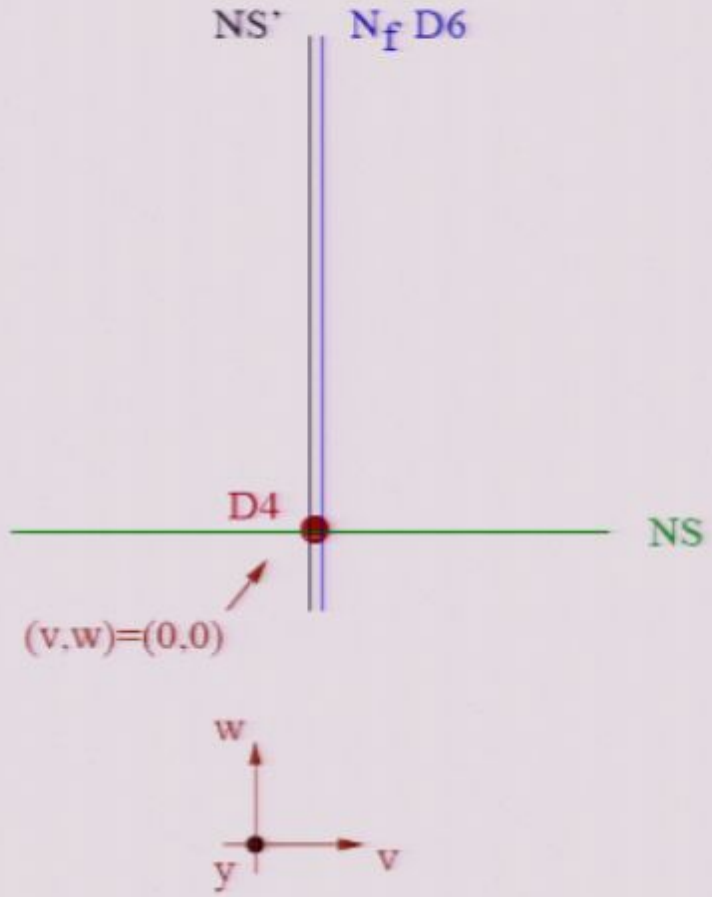


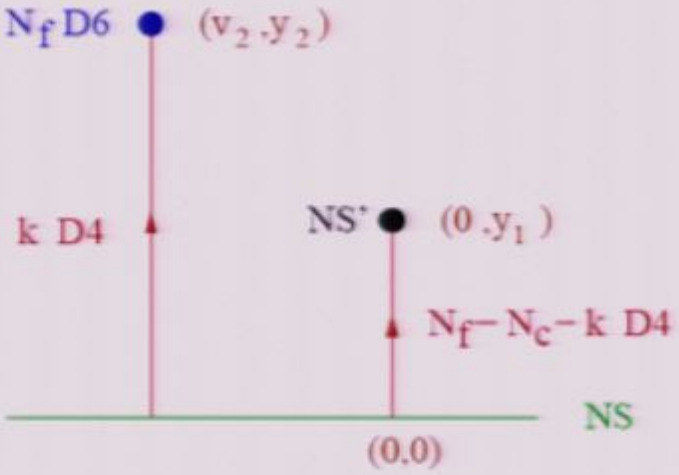
where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

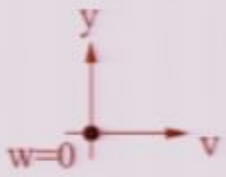
k labels supersymmetric vacua (as before).

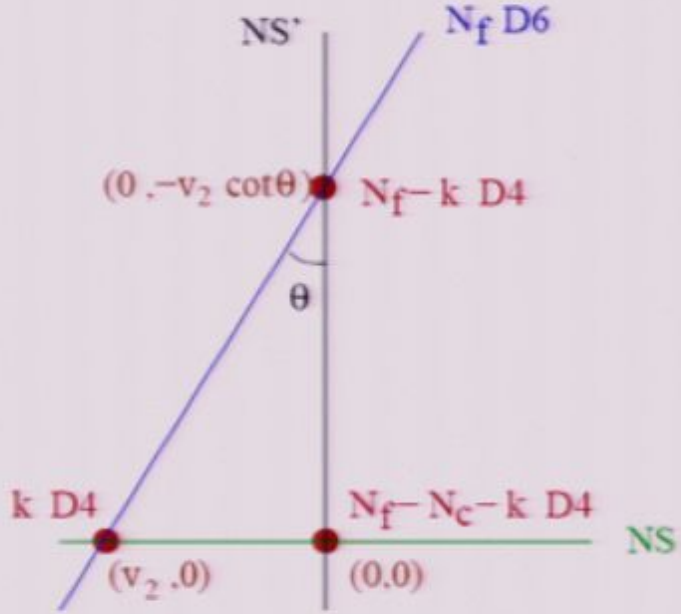
Seiberg dual (magnetic) brane configuration

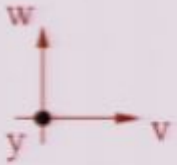












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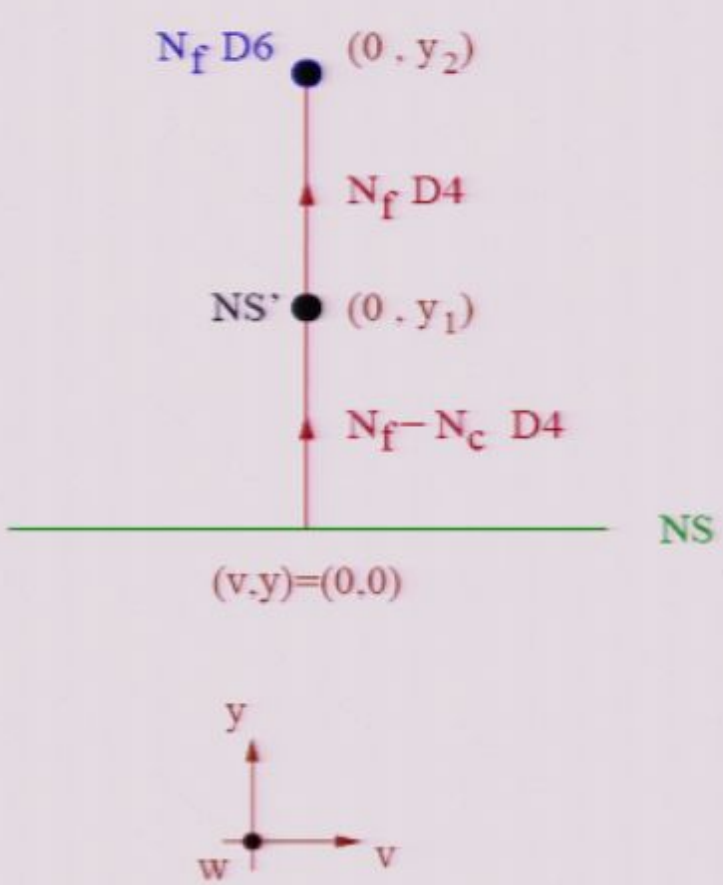

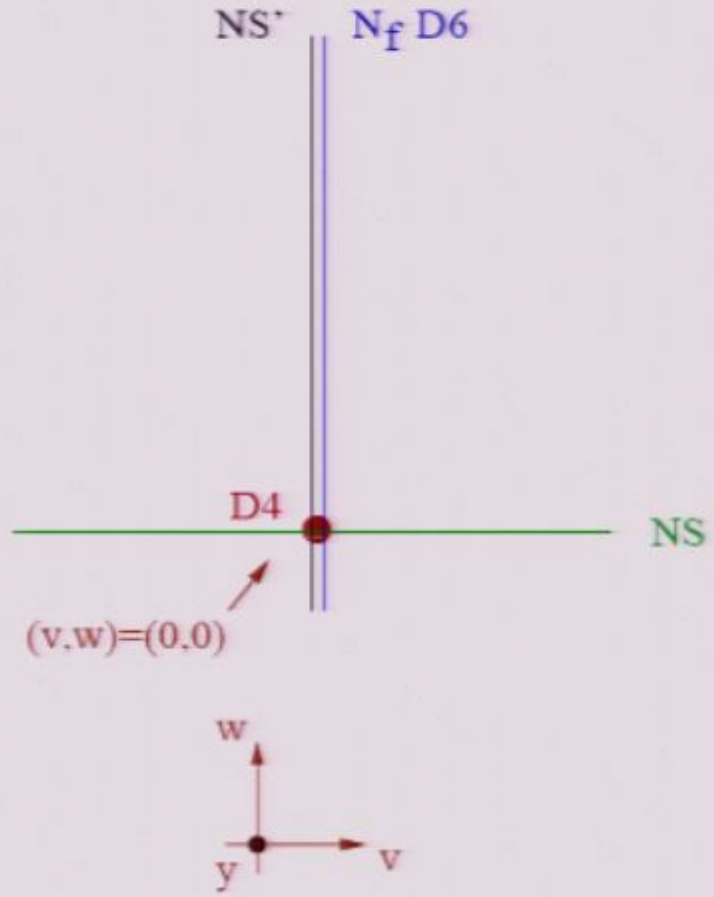

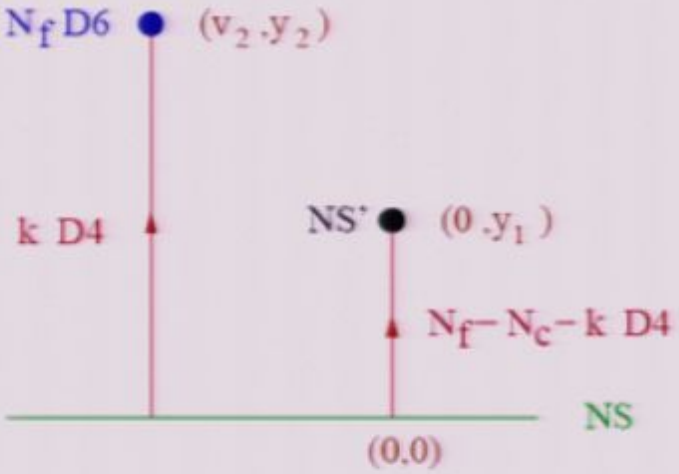

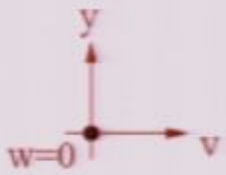

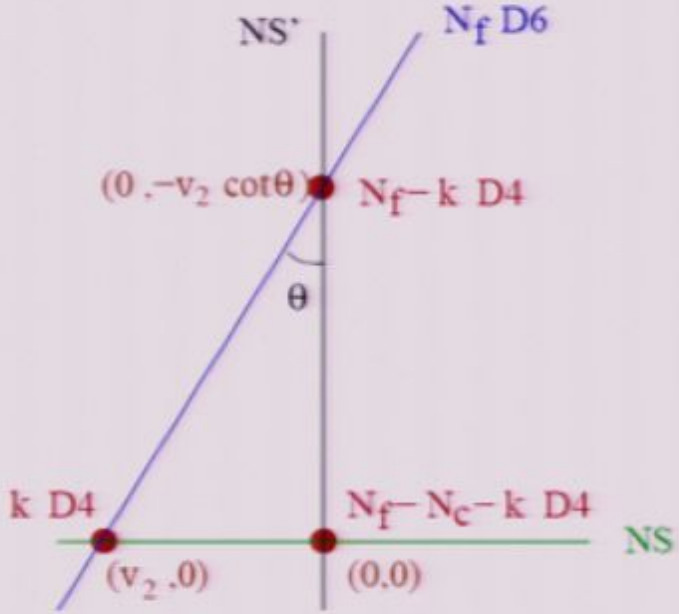

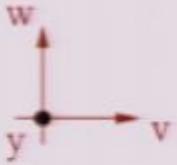

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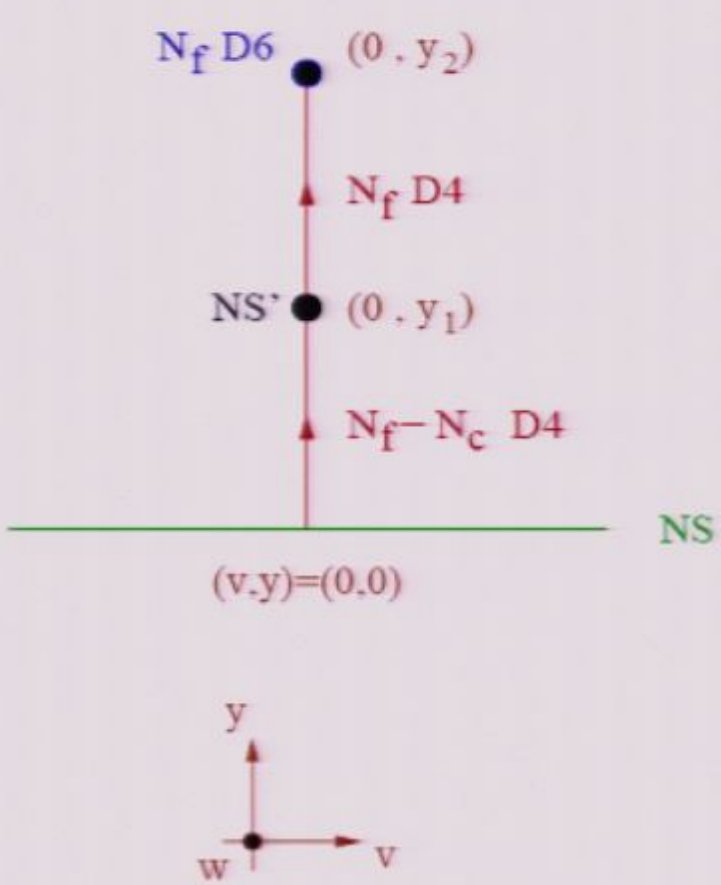
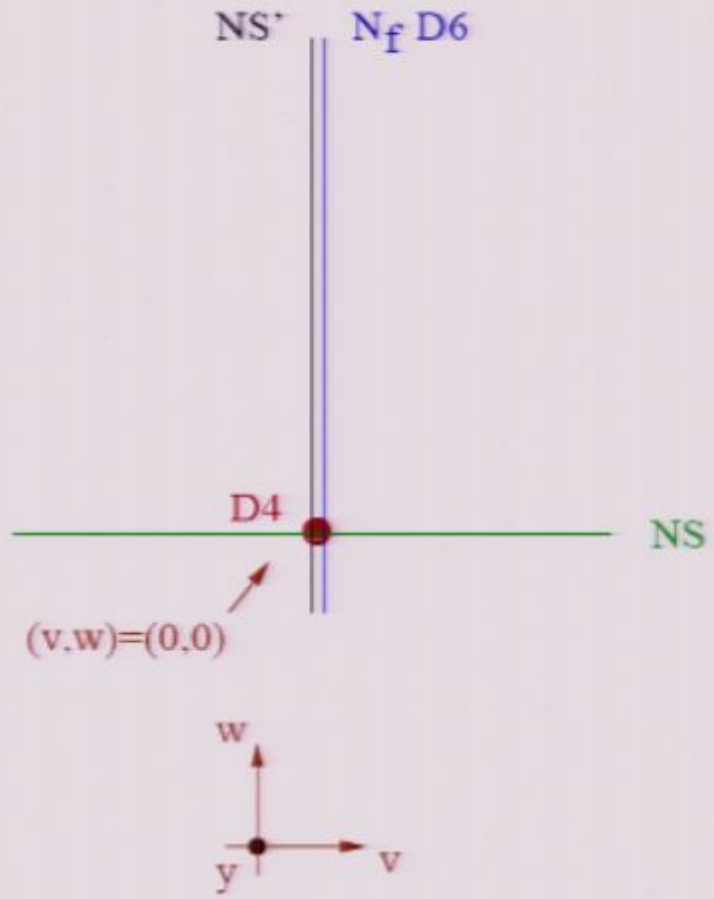
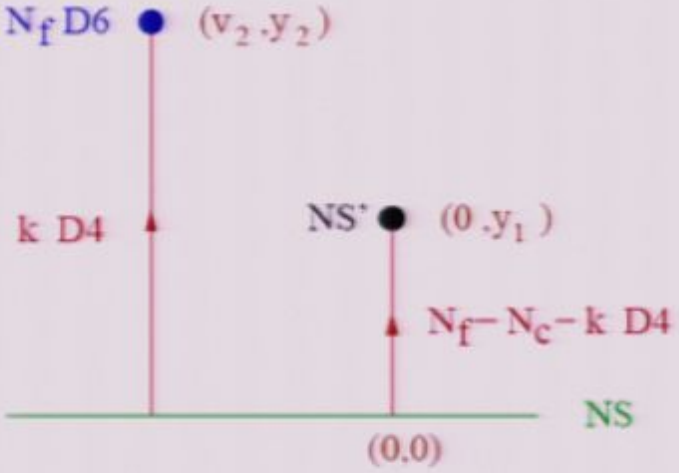
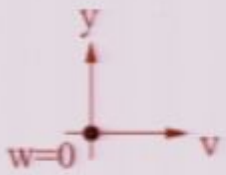
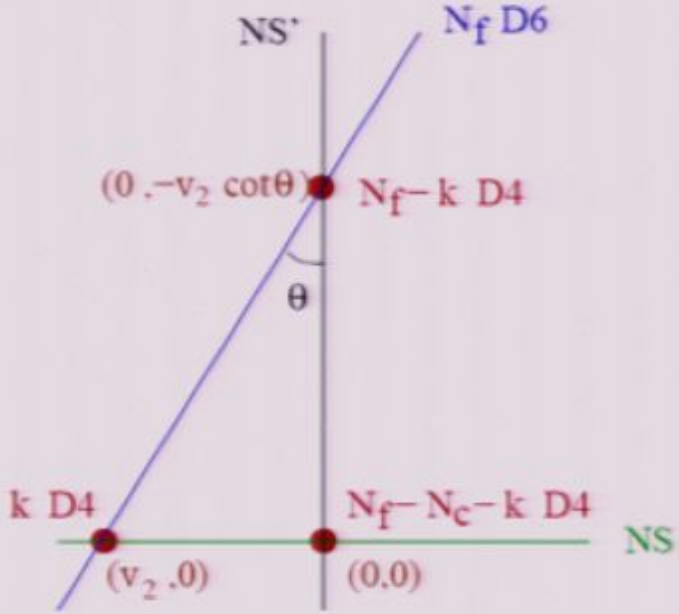
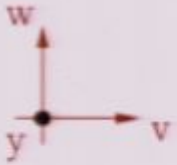












where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

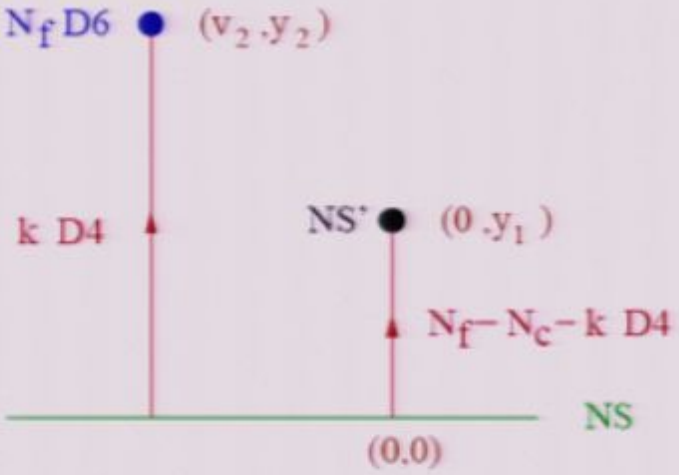
k labels supersymmetric vacua (as before).

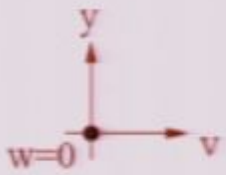
The deformation

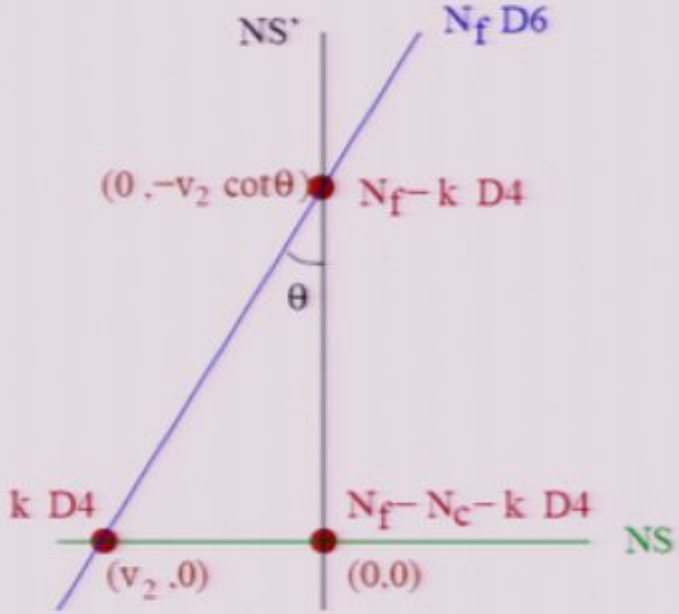
Deforming the superpotential to

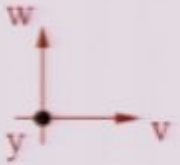
$$W_{\rm mag} = \frac{1}{\Lambda}\tilde{q}_i M^i_j q^j + \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

corresponds geometrically to a translation (m) and rotation (α) of the D6-branes:









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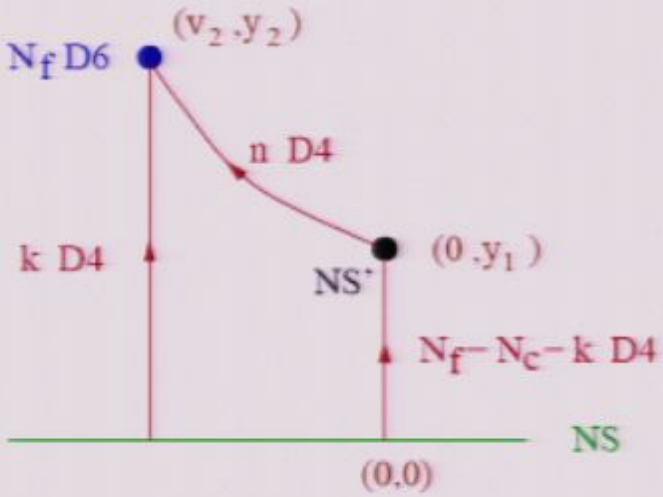
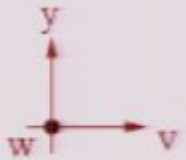
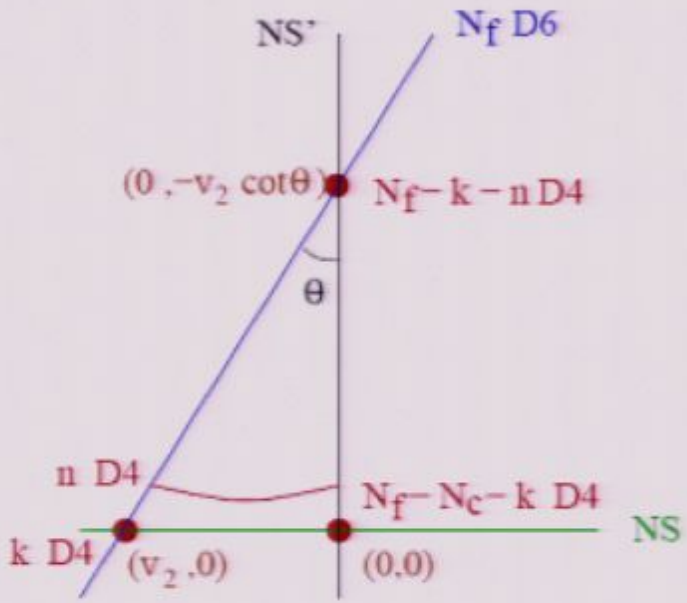
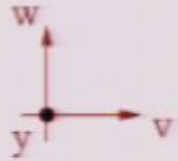
Metastable vacua

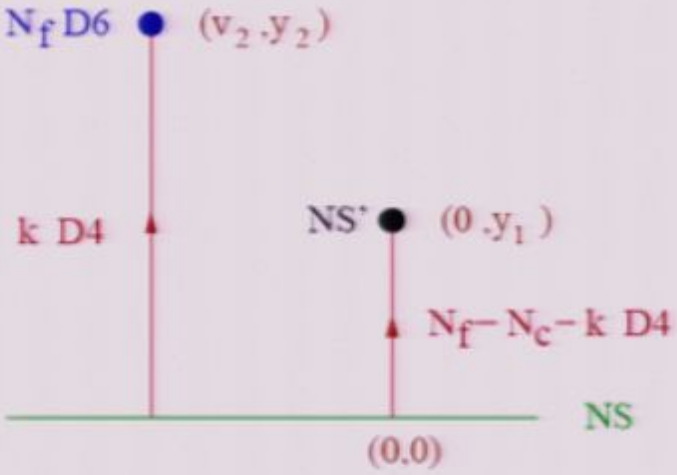
correspond to the following brane configurations:

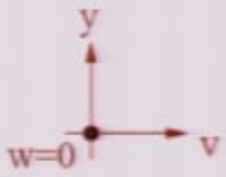


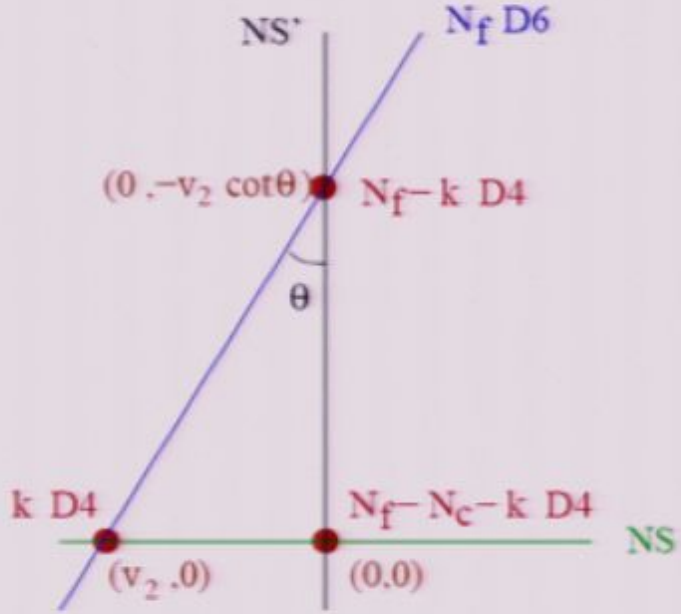


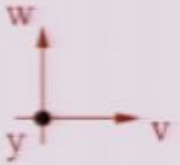












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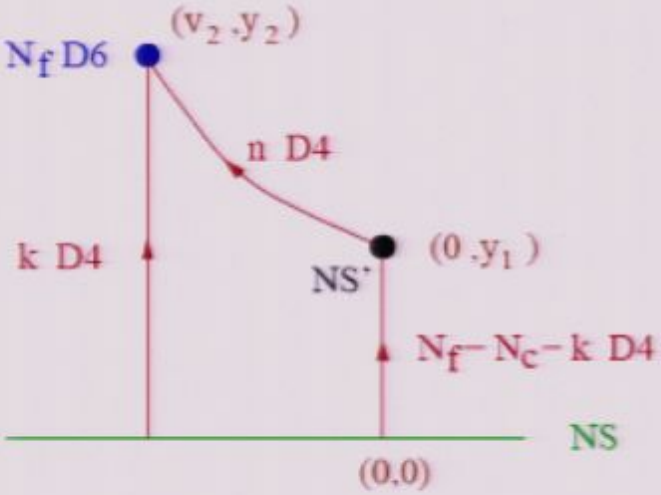

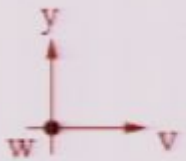

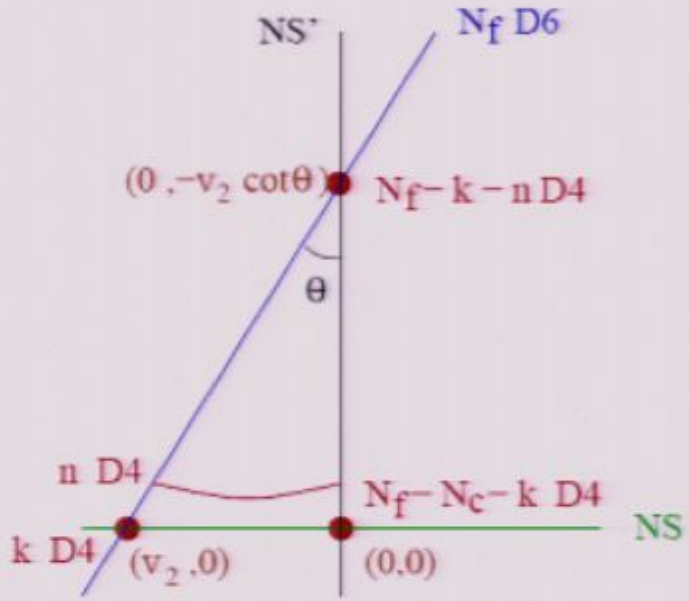

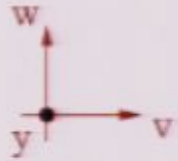

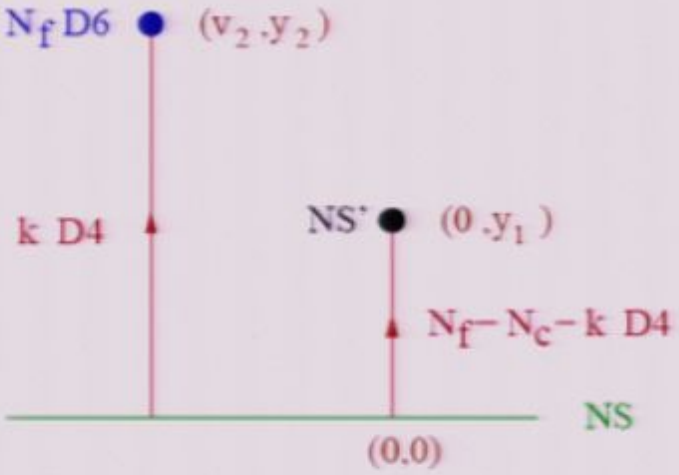

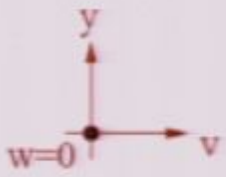

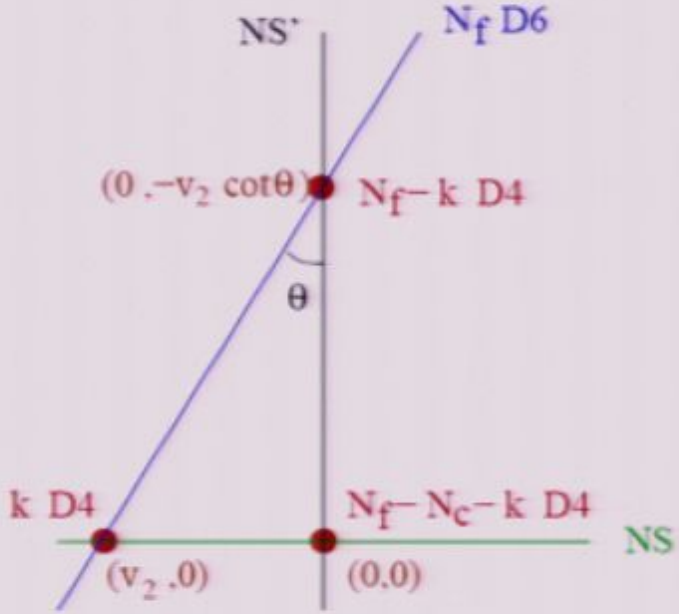

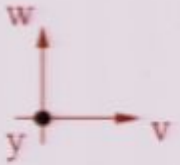

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To summarize, we see that N=1 SQCD with the deformation described above has in addition to its supersymmetric vacua a rather rich spectrum of metastable supersymmetry breaking states, which can be made arbitrarily long-lived by tuning the parameters of the model.

These vacua exhibit diverse patterns of global symmetries and low lying excitations and might be interesting candidates for the supersymmetry breaking sector in nature.

It is convenient to parametrize the light fields in $\Phi, q, \tilde{q}$ as follows:

$$h\Phi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & h\Phi_n & 0 \\ 0 & 0 & \frac{\mu^2}{\mu_\phi} I_{N_f-k-n} \end{pmatrix}$$

$$\tilde{q}q = \begin{pmatrix} \mu^2 I_k & 0 & 0 \\ 0 & \tilde{\varphi}\varphi & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Indeed, the full one loop potential takes the form

$$\frac{V}{|h|^2} = |\Phi_n \varphi|^2 + |\tilde{\varphi}\Phi_n|^2 + |\tilde{\varphi}\varphi - \mu^2 I_n + h\mu_\phi \Phi_n|^2 + b|h\mu|^2 \mathrm{Tr}\Phi_n^\dagger \Phi_n$$

where b is a numerical coefficient computed in ISS,

$$b = \frac{\ln 4 - 1}{8\pi^2}(N_f - N_c).$$

In addition to the supersymmetric minimum, this potential has a non-supersymmetric extremum at which the tree level and one loop terms balance each other.

- At this extremum, one has $\varphi = \tilde{\varphi} = 0$ and

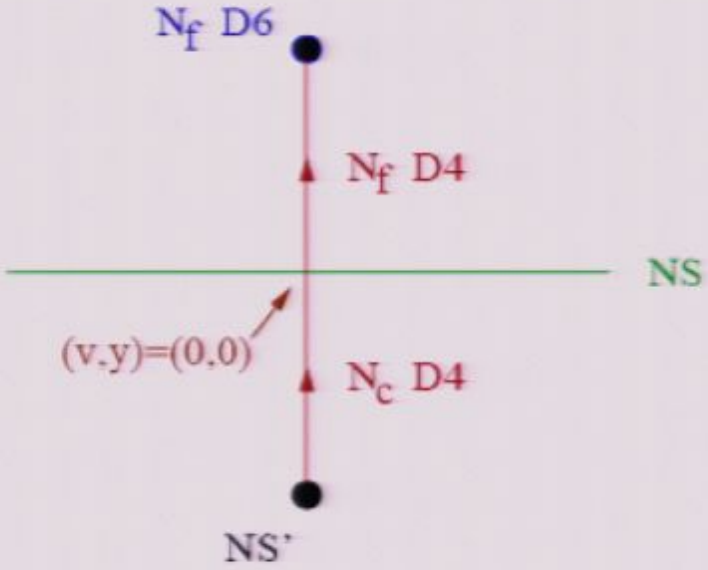
$$h\Phi_n = \frac{\mu^2 \mu_\phi^*}{|\mu_\phi|^2 + b|\mu|^2} I_n \simeq \frac{\mu^2 \mu_\phi^*}{b|\mu|^2} I_n$$

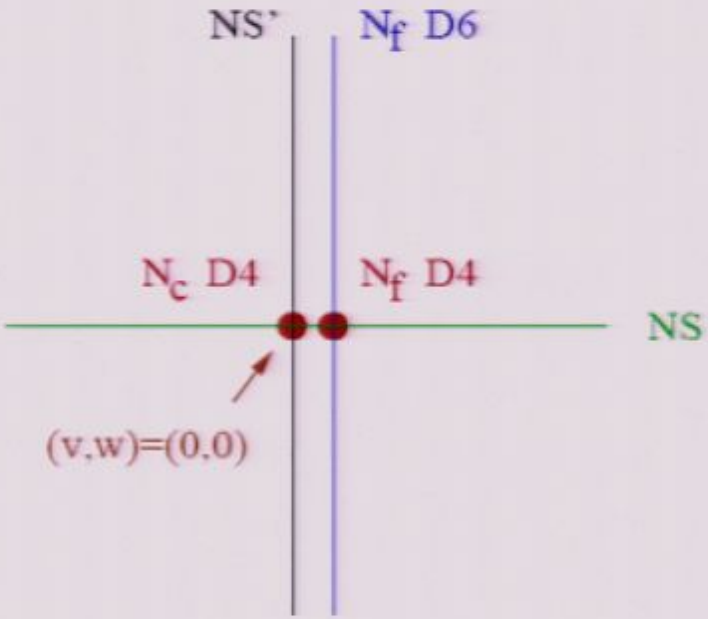
- The vacuum energy is given by: $V \simeq n|h\mu^2|^2$

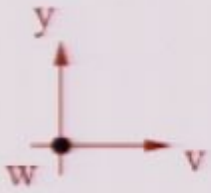
- Expanding around this solution one finds that the mass matrix for $\varphi, \tilde{\varphi}$ has eigenvalues: $m_\pm^2 \simeq \frac{1}{b^2}\left(|\mu_\phi|^2 \pm |bh\mu|^2\right)$

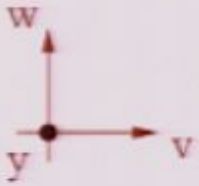
Thus, to avoid infrared instabilities one must have

$$\left|\frac{\mu_\phi}{\mu}\right|^2 > \frac{|bh|^2}{1 - b|h|^2} \simeq |bh|^2$$



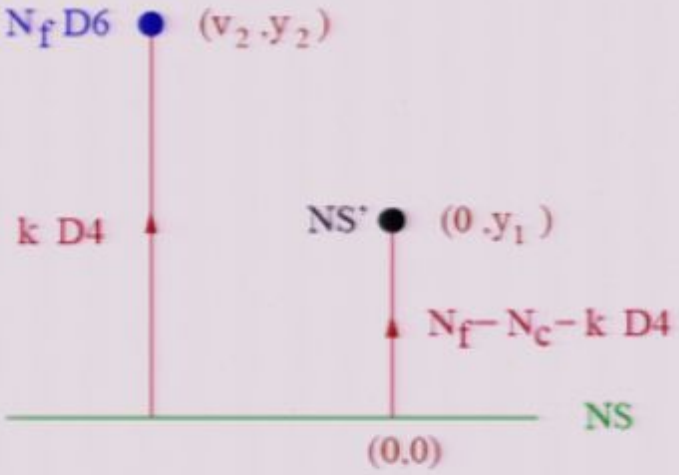


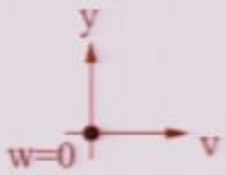


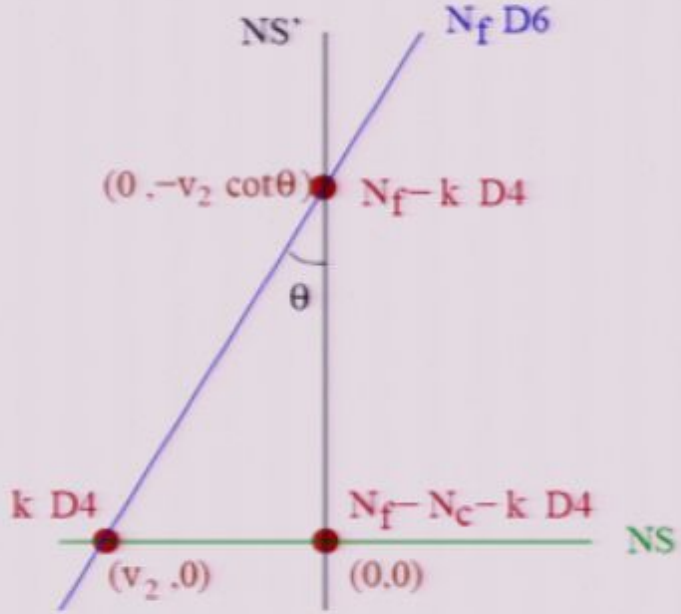


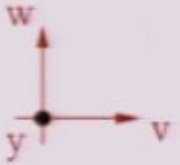
$$v = x^4 + ix^5 \,, \qquad w = x^8 + ix^9 \,, \qquad y = x^6$$

- Field content, gauge coupling, moduli space.









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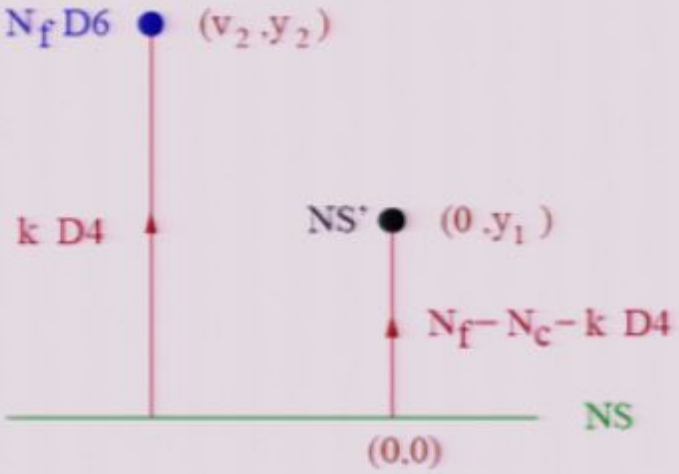

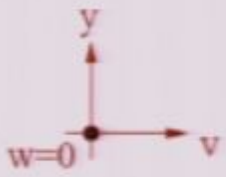

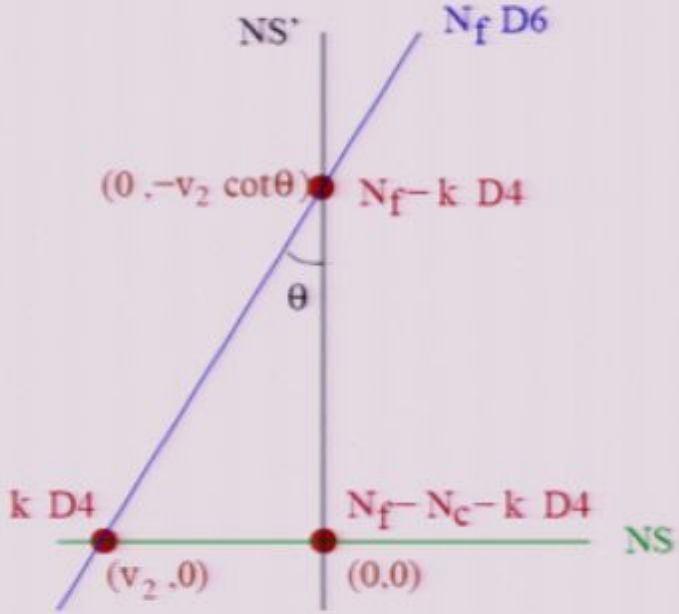

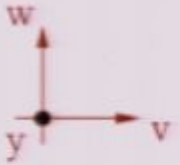

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Metastable vacua

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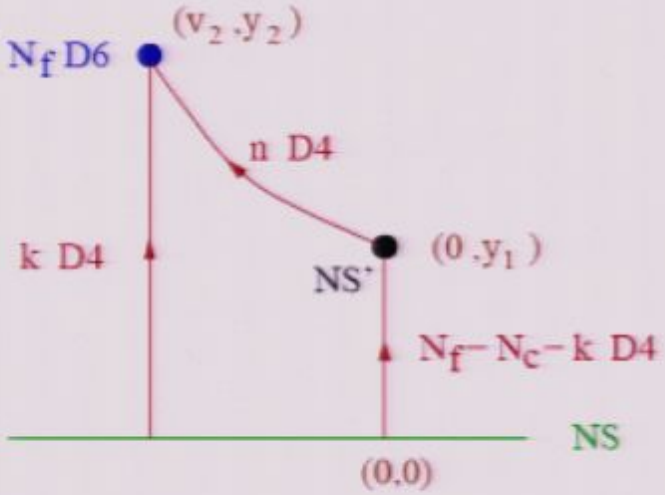

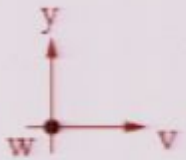

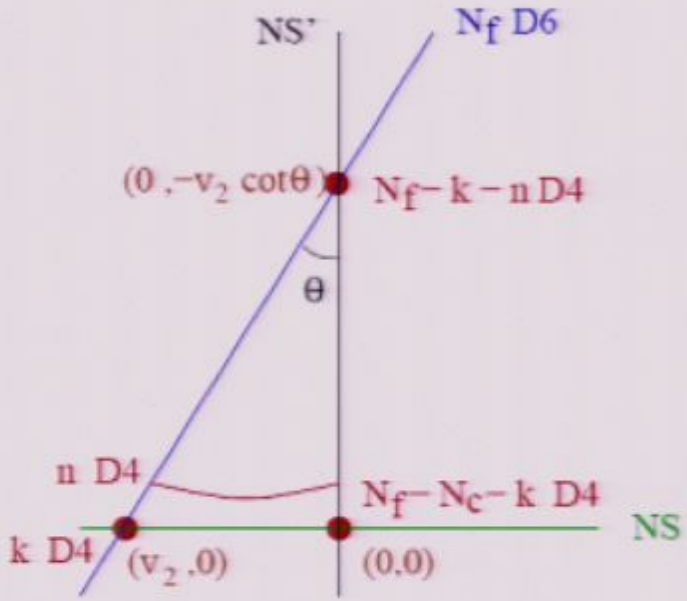

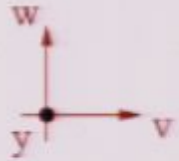

They are locally stable due to a competition between two effects:

1) The tension of the D4-branes attracts them to the D6-NS' intersection.

2) The gravitational attraction of the D4-branes towards the NS-brane pulls them in the opposite direction.

For small θ, one can show that there is a locally stable equilibrium in which the D4-branes remain close to the NS-brane.

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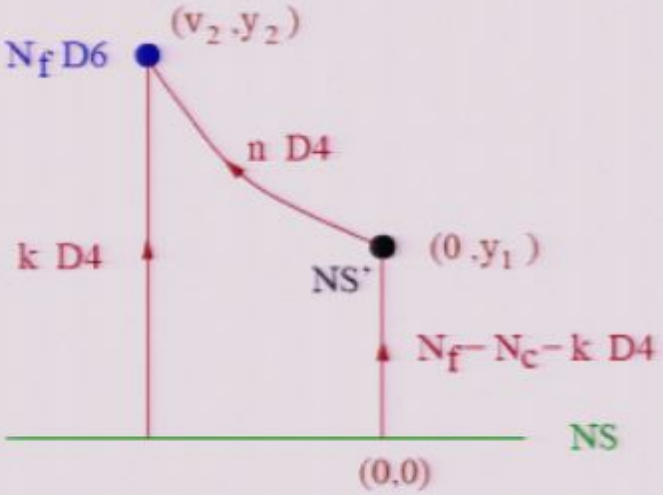

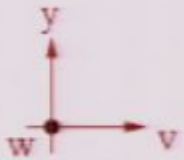

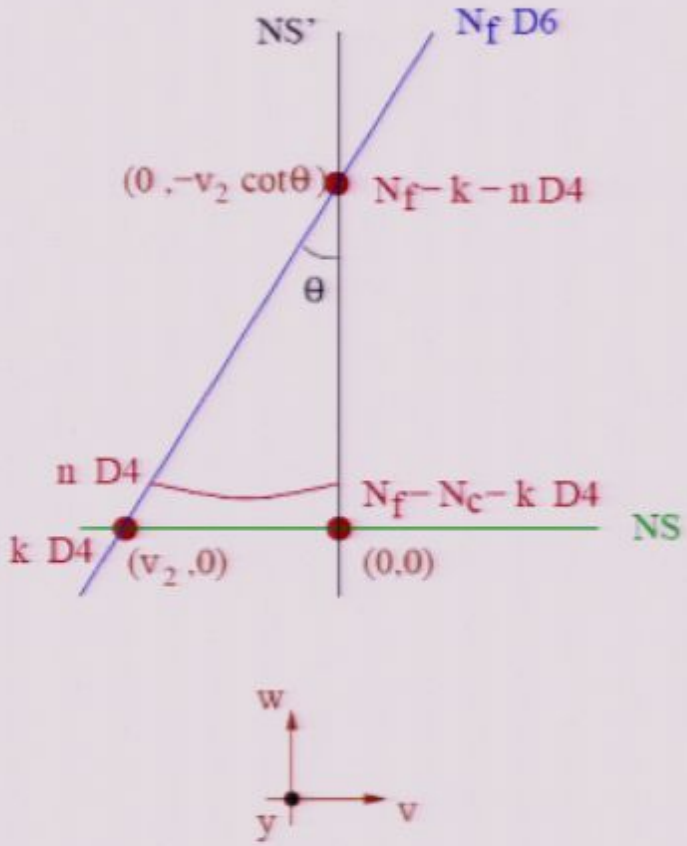

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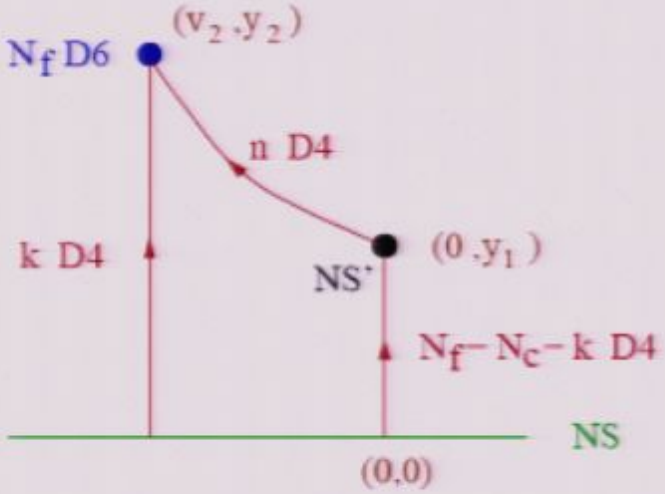

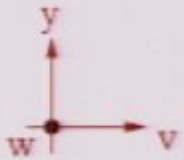

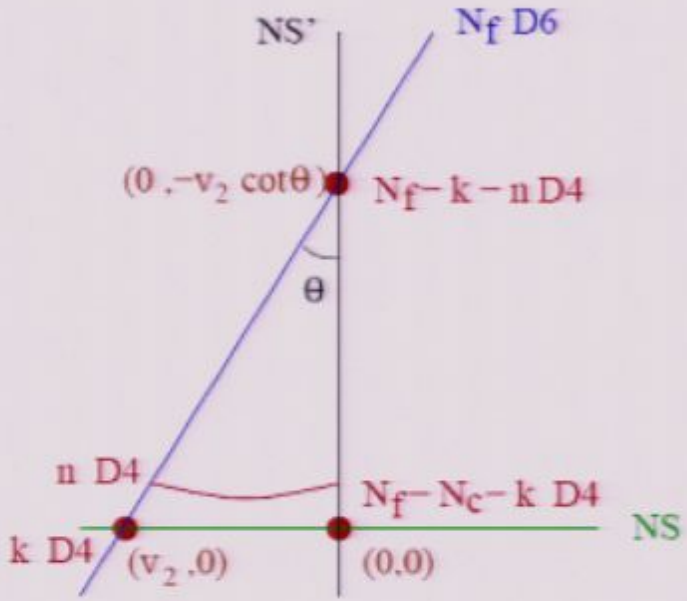

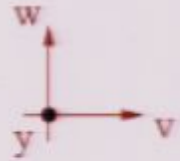

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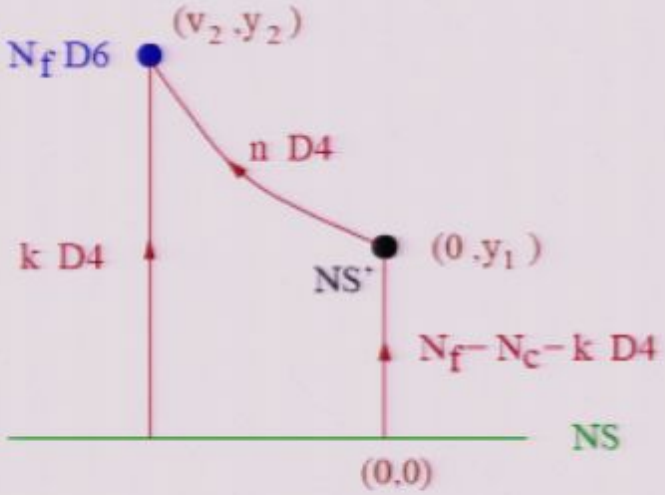

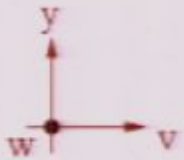

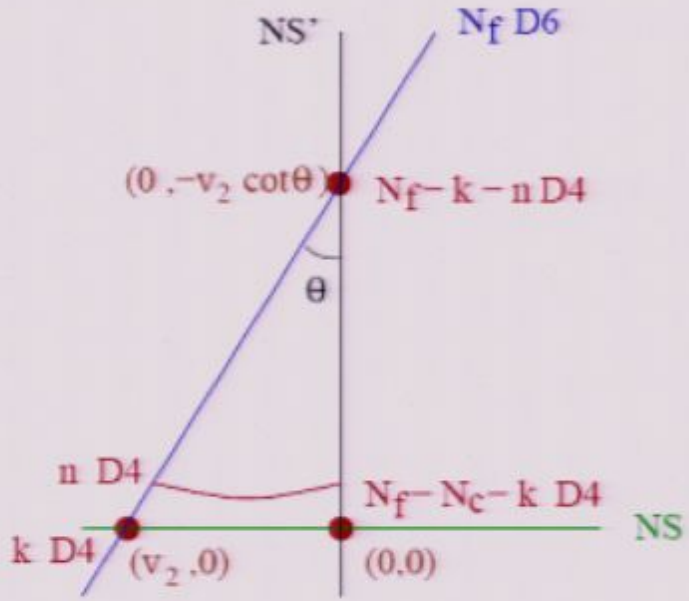

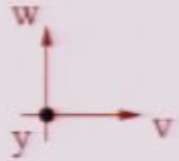

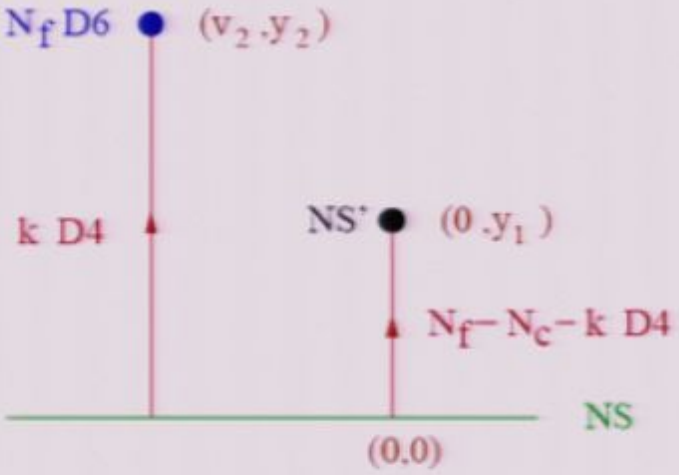

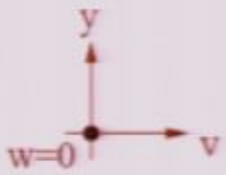

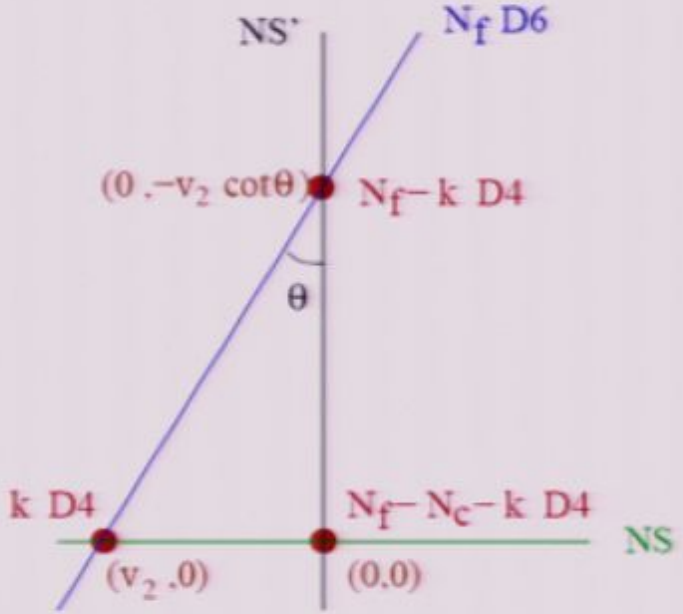

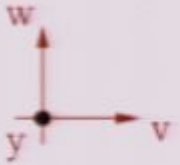

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Metastable vacua

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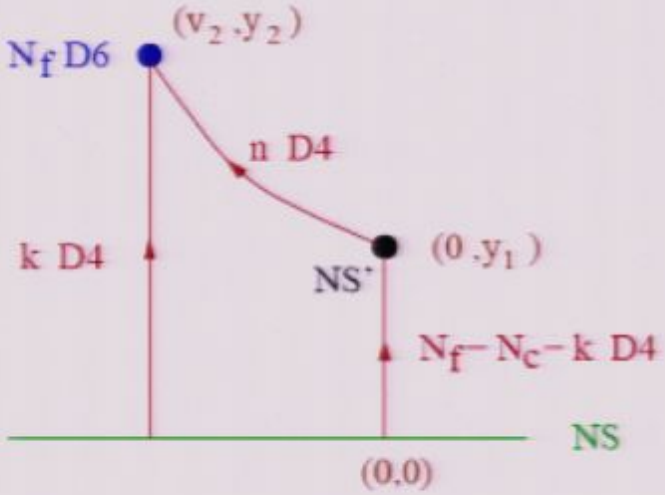

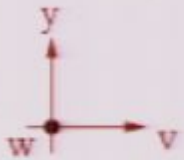

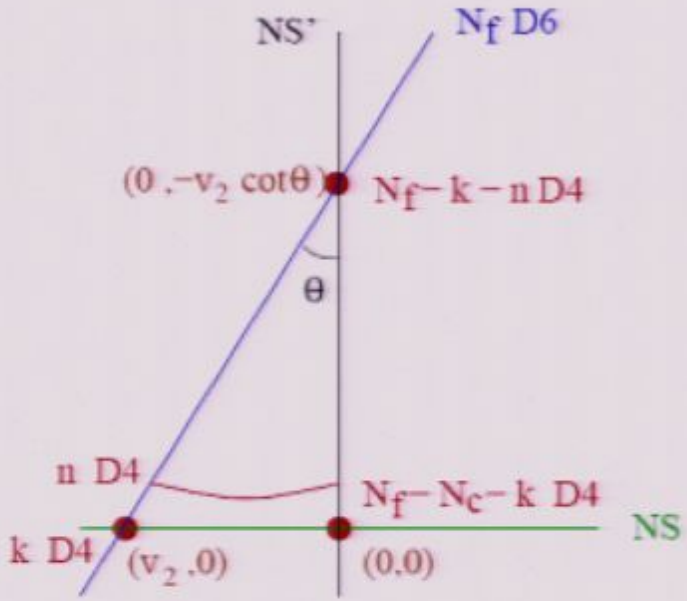

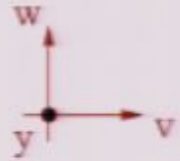

They are locally stable due to a competition between two effects:

1) The tension of the D4-branes attracts them to the D6-NS' intersection.

2) The gravitational attraction of the D4-branes towards the NS-brane pulls them in the opposite direction.

For small θ, one can show that there is a locally stable equilibrium in which the D4-branes remain close to the NS-brane.

For $N_f - N_c - k > 0$ there are two types of instabilities:

1) Reconnection of the endpoints of (some of) the D4-branes on the NS'-brane.

2) Motion of the n D4-branes to larger w back to the susy vacuum configuration described above.

Both are non-perturbative instabilities. For fixed values of the geometric parameters in the limit $g_s \to 0$, the lifetime goes like $\exp(C/g_s)$.

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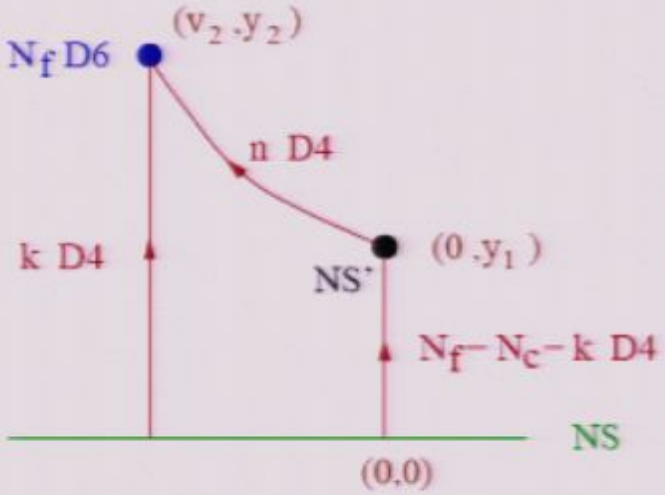

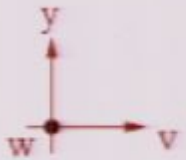

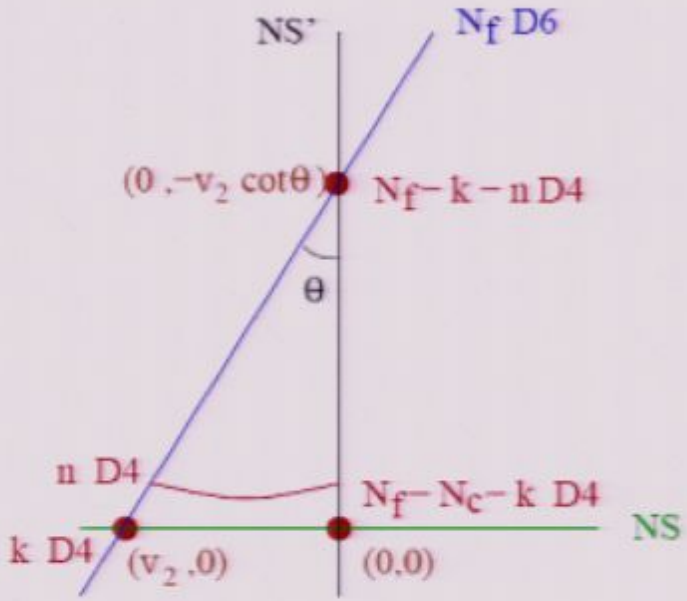

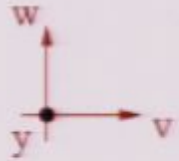

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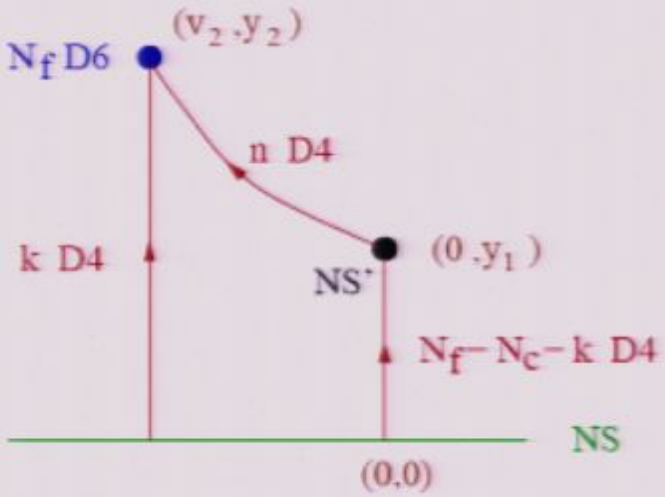

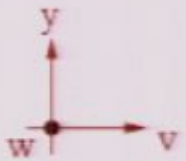

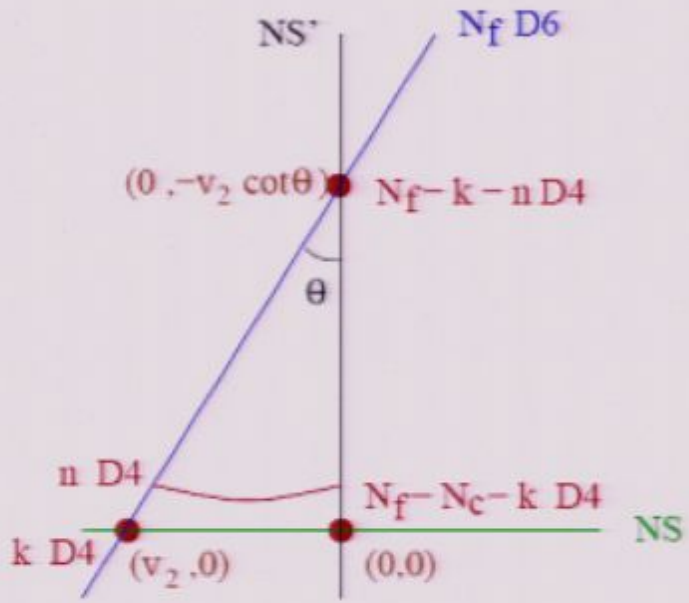

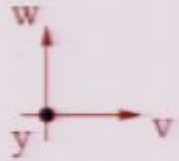

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All the elements of the gauge theory discussion have direct analogs in the brane construction. For example:

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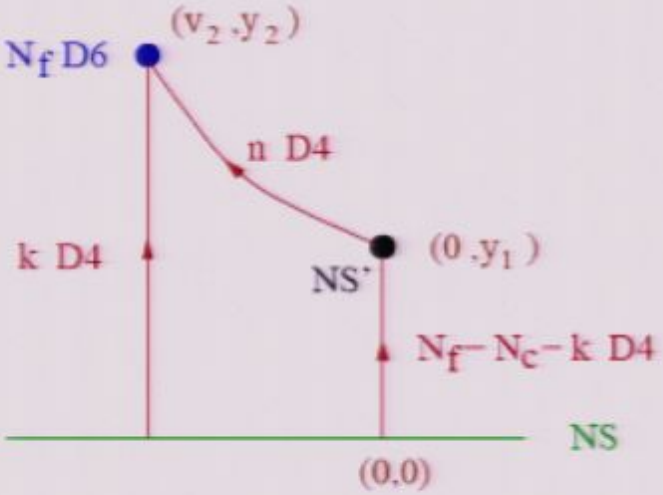

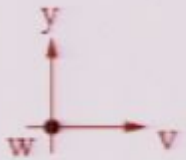

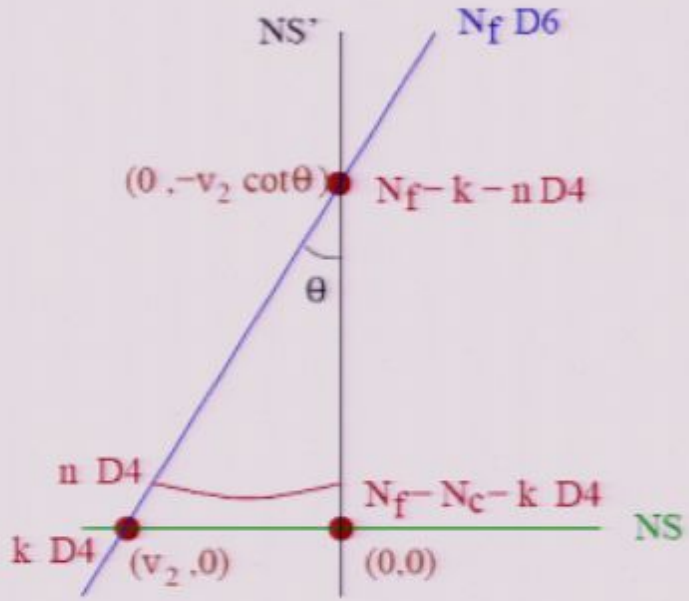

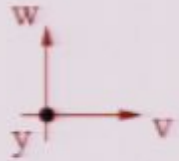

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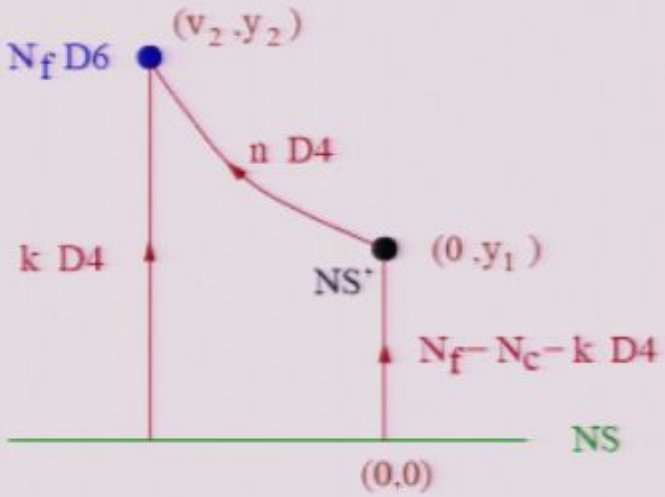

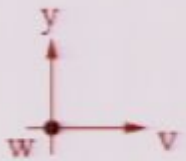

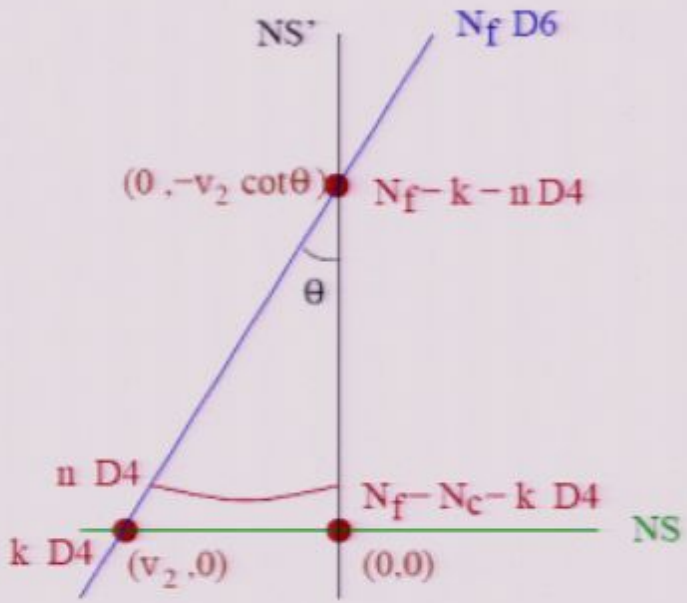

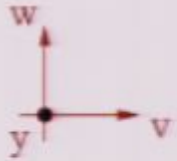

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Comments

- Deforming N=1 SQCD leads to a large number of non-supersymmetric vacua, which may be made long-lived by tuning parameters in the superpotential. In other regions of parameter space, many of these states become unstable and disappear.
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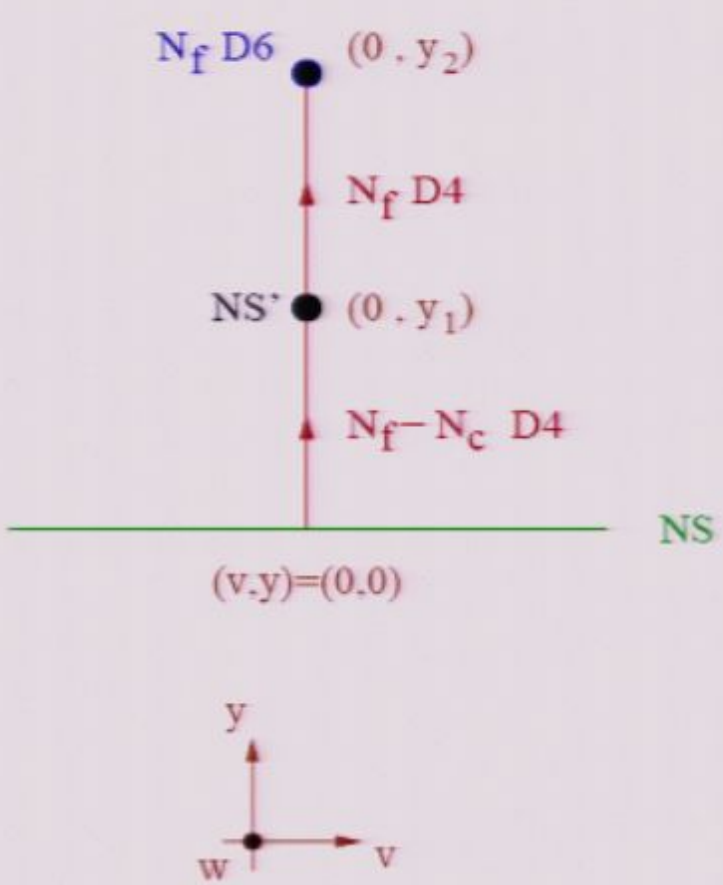
The deformation

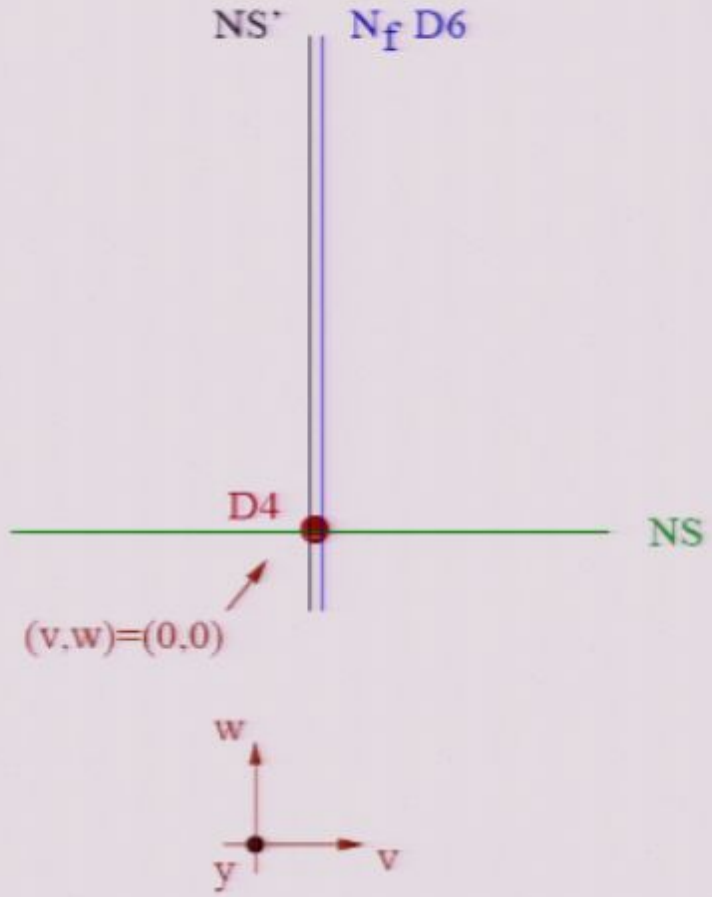
Deforming the superpotential to

$$W_{\rm mag} = \frac{1}{\Lambda}\tilde{q}_i M^i_j q^j + \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

corresponds geometrically to a translation (m) and rotation (α) of the D6-branes:

Seiberg dual (magnetic) brane configuration





All the branes are stretched in the 3+1 directions (0123). The NS-branes are also stretched in the directions (45), the NS'-branes in (89), the D4-branes in 6 and the D6-branes in (789). One can check that any configuration containing all these branes preserves N=1 supersymmetry in the 3+1 common dimensions (0123).

The branes are arranged in the extra dimensions as follows:

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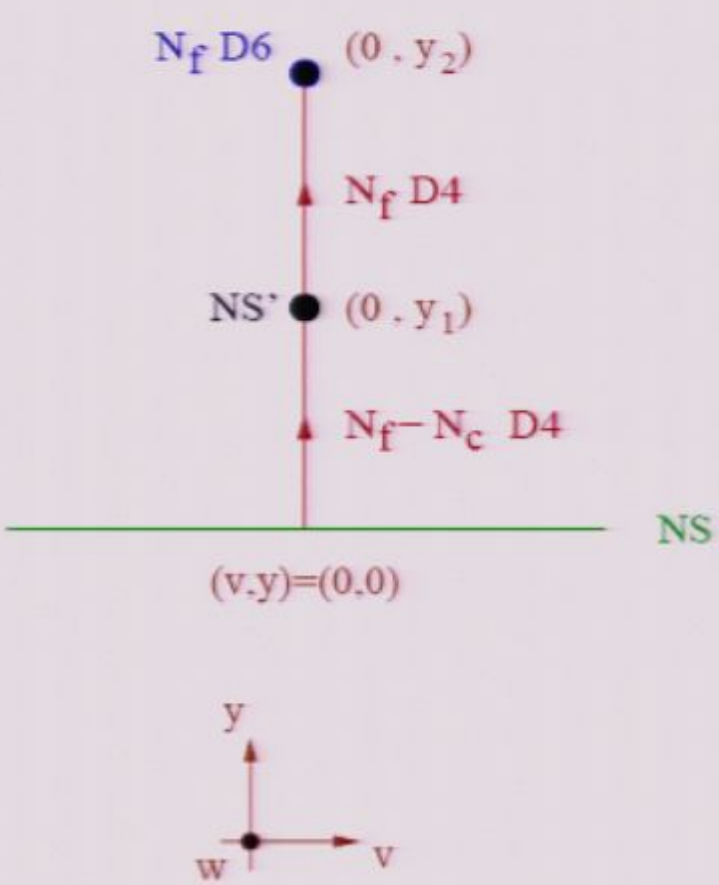

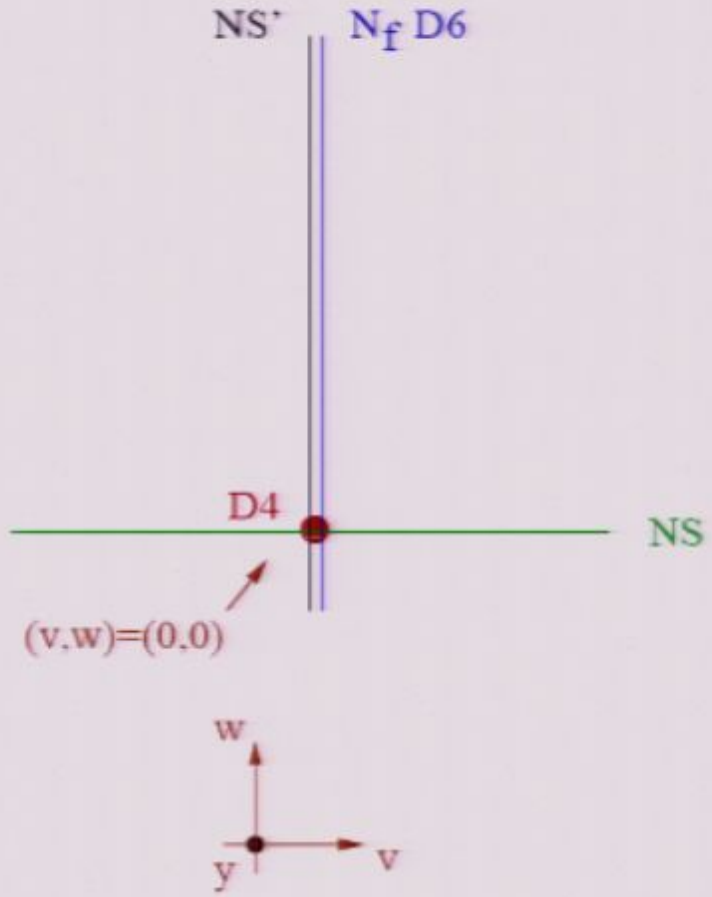

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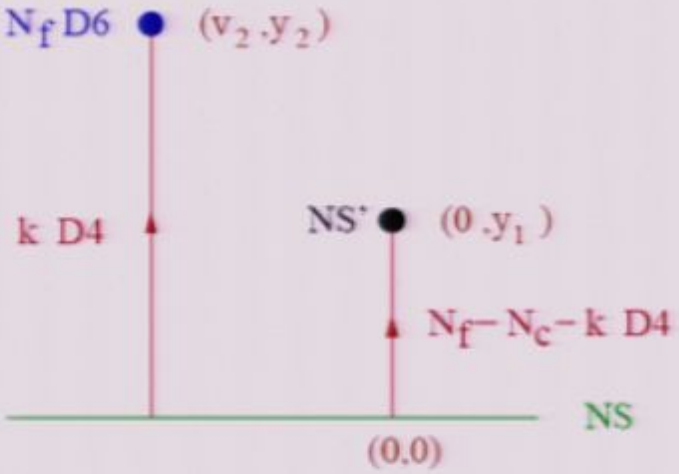

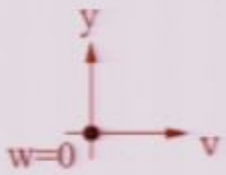

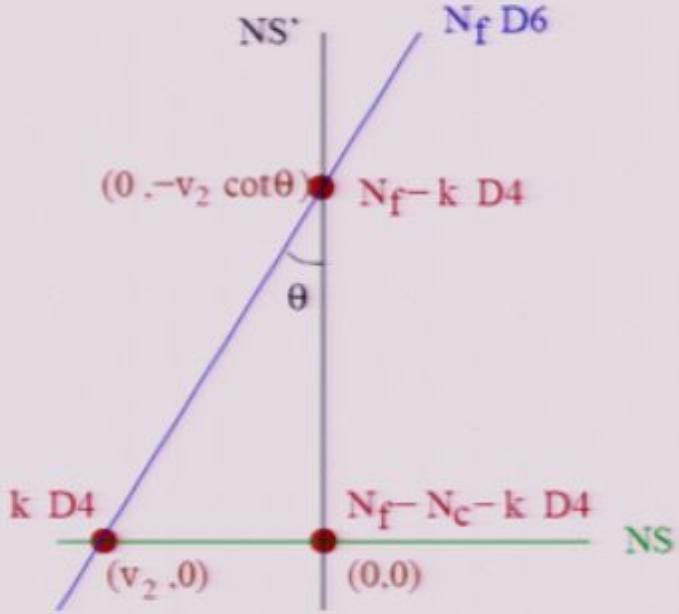

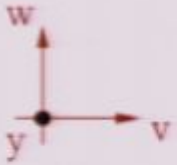

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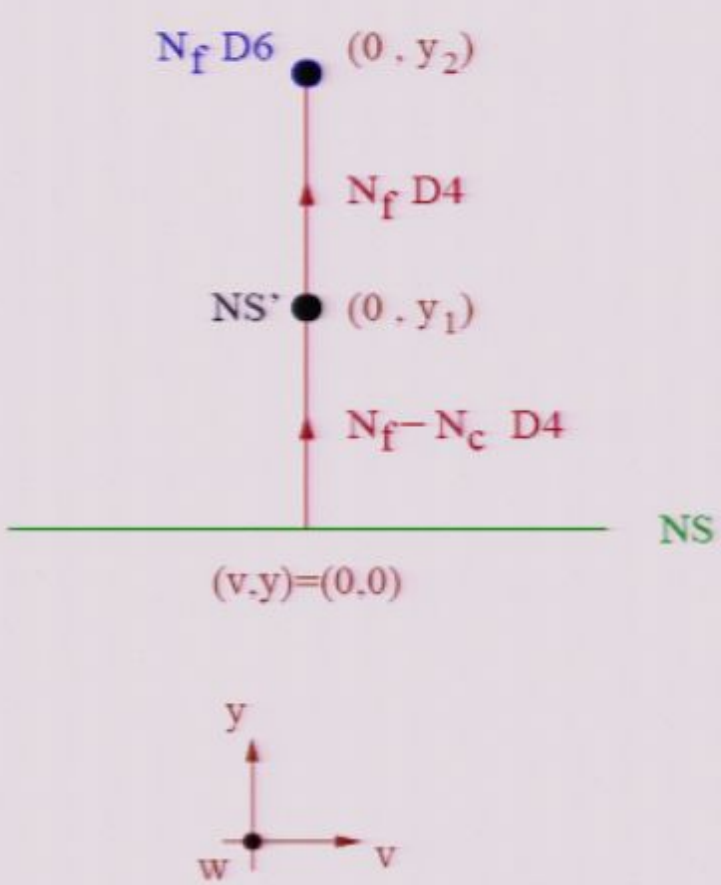
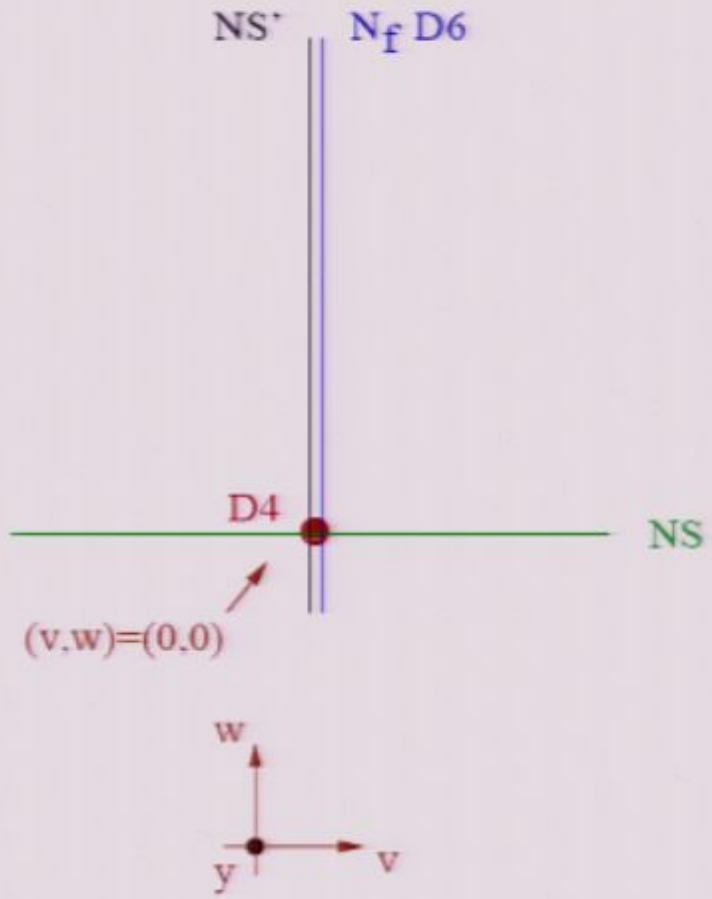
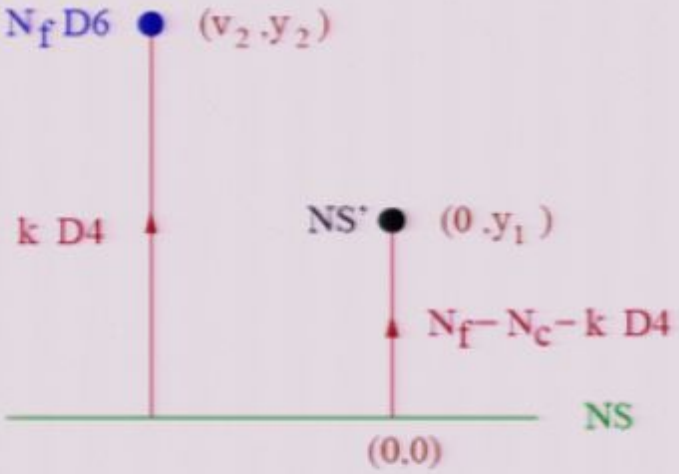
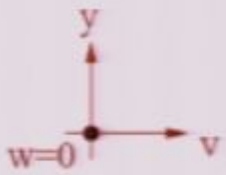
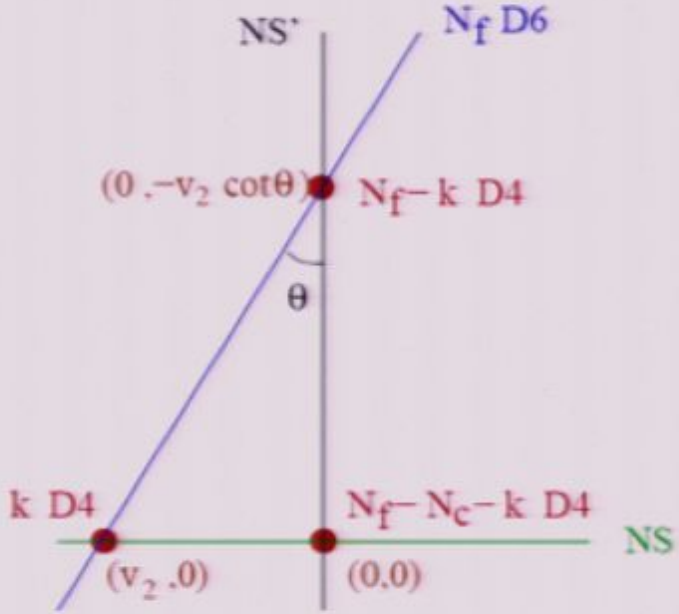
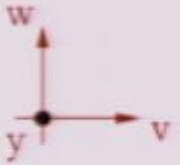








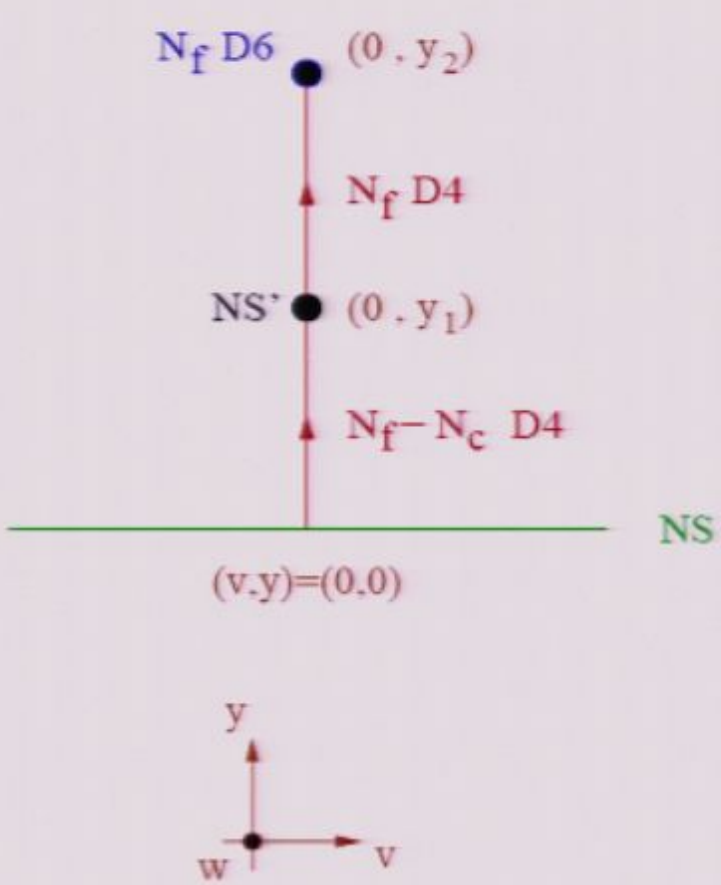


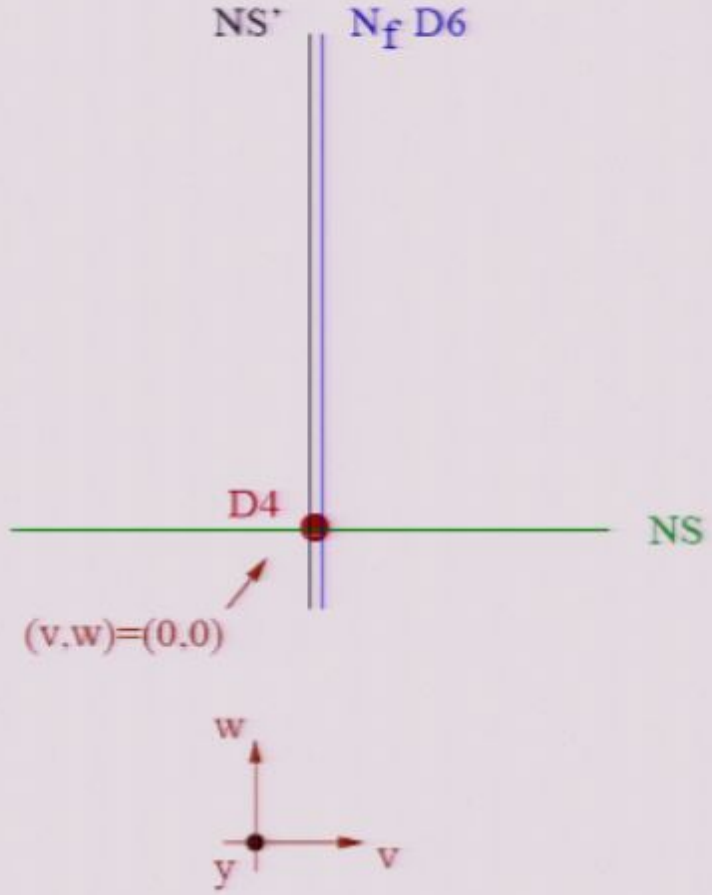


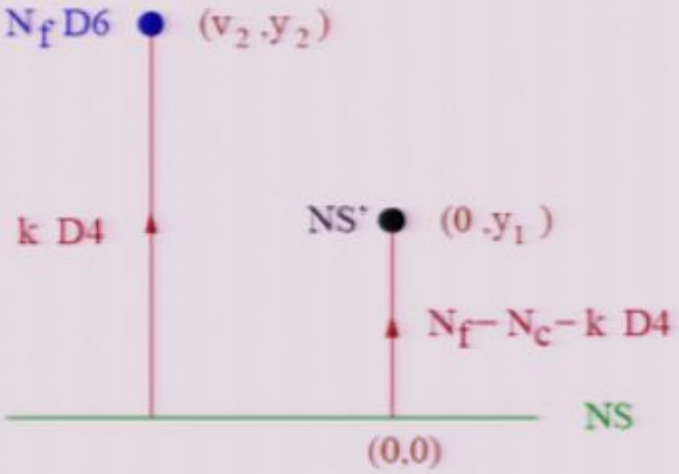
where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

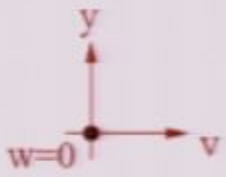
k labels supersymmetric vacua (as before).

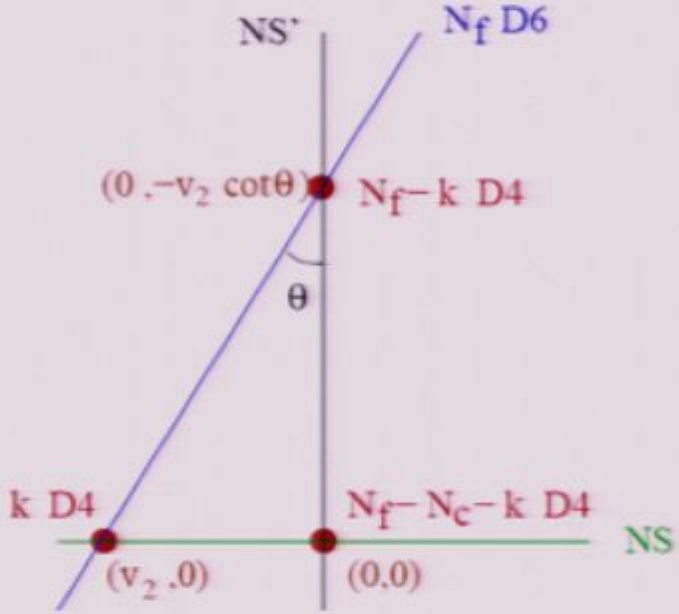
Seiberg dual (magnetic) brane configuration

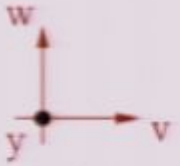










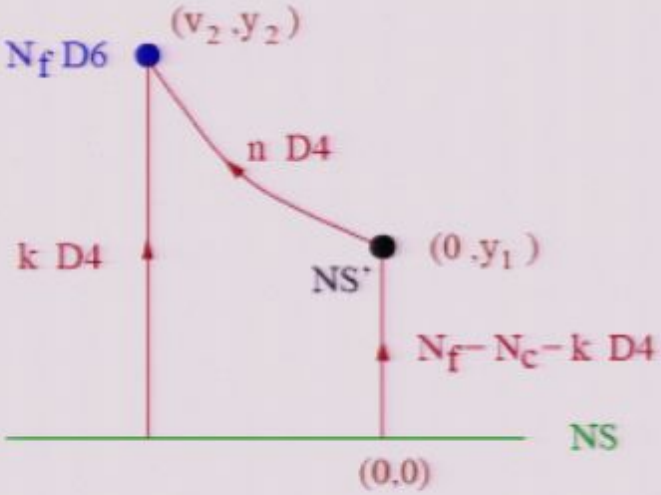


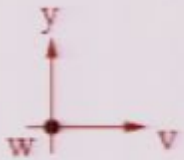
where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

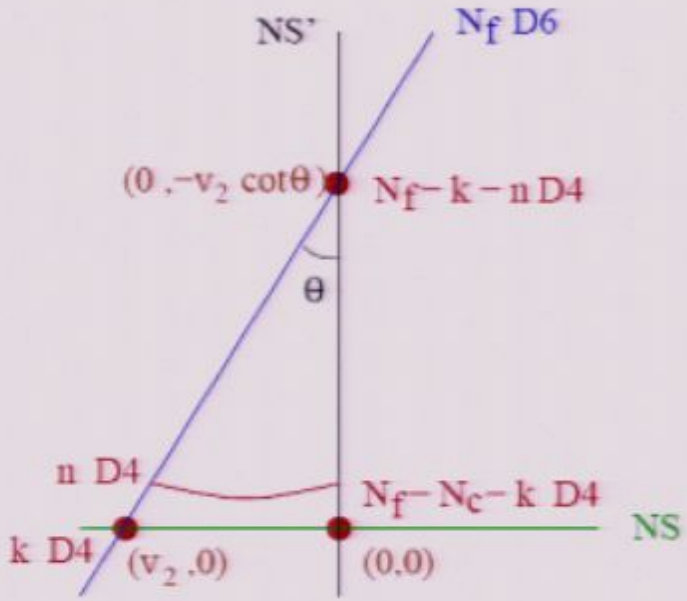
k labels supersymmetric vacua (as before).

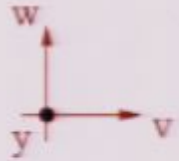
Metastable vacua

correspond to the following brane configurations:









For $N_f - N_c - k > 0$ there are two types of instabilities:

1) Reconnection of the endpoints of (some of) the D4-branes on the NS'-brane.

2) Motion of the n D4-branes to larger w back to the susy vacuum configuration described above.

Both are non-perturbative instabilities. For fixed values of the geometric parameters in the limit $g_s \to 0$, the lifetime goes like $\exp(C/g_s)$.

For $N_f - N_c - k = 0$ the first type of instability is absent.

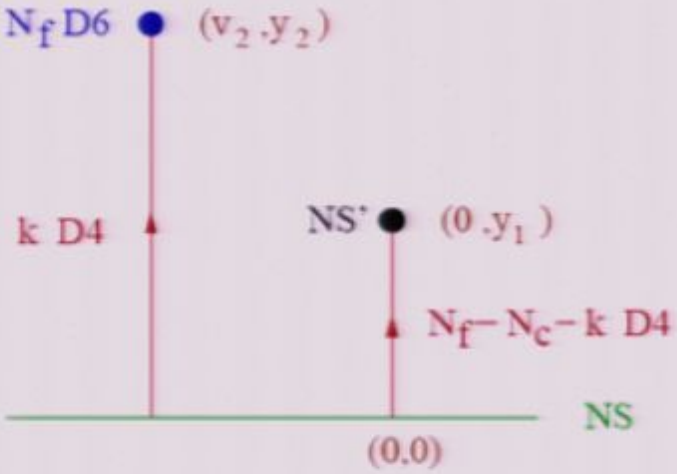
All the elements of the gauge theory discussion have direct analogs in the brane construction. For example:

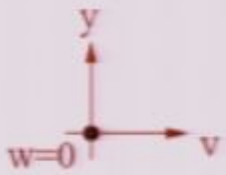
- The n light fundamentals of $SU(N_f - N_c - k)$, $\varphi, \tilde{\varphi}$, correspond to fundamental strings stretched between the n flavor D4-branes and the $N_f - N_c - k$ color ones.
- The one loop effects that are necessary for stabilizing the metastable states in gauge theory are replaced by the gravitational attraction of the D4-branes to the NS-brane.

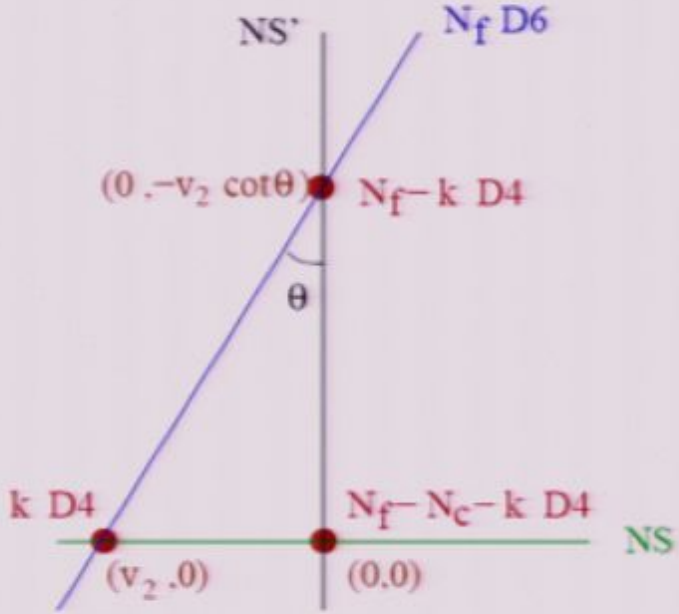
Comments

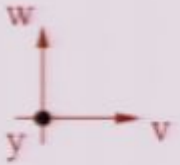
- Deforming N=1 SQCD leads to a large number of non-supersymmetric vacua, which may be made long-lived by tuning parameters in the superpotential. In other regions of parameter space, many of these states become unstable and disappear.
- Can generalize to higher order superpotentials; the number of metastable states grows rapidly with the order.

- Intersecting NS and D-brane systems provide a useful qualitative guide for the study of supersymmetric and non-supersymmetric ground states.
- One can use the brane picture to perform a quantitative analysis of the metastable vacua in a regime of parameter space where the gauge theory picture is not valid.
- Phenomenological applications?









where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

k labels supersymmetric vacua (as before).

We will use the NS5-brane picture, which was found to be more useful than the CY one in studying supersymmetric vacua. It turns out to be more useful for studying metastable vacua as well.

In particular, this description provides a nice geometric picture of the vacua that we found in the gauge theory before.

There are two ways of realizing it as a low energy theory on D-branes:

- Near conical singularities of Calabi-Yau manifolds.
- In the vicinity of Neveu-Schwartz fivebranes.

The two descriptions are related by a version of T-duality.

Here Φ_n is an $n \times n$ matrix, while $\varphi, \tilde{\varphi}$ are matrices of size $n \times (N_f - N_c - k)$. The classical supersymmetric vacua discussed before correspond to

$$h\Phi_n = \frac{\mu^2}{\mu_\phi} I_n; \quad \varphi = \tilde{\varphi} = 0$$

In these vacua, Φ_n has a large vev, $h\Phi_n \gg \mu$. Classically, there are no additional vacua. However, after including the one loop correction to the potential, new vacua appear near the origin of field space.

where h is a free dimensionless parameter and μ, μ_ϕ are mass scales. We will work in the regime

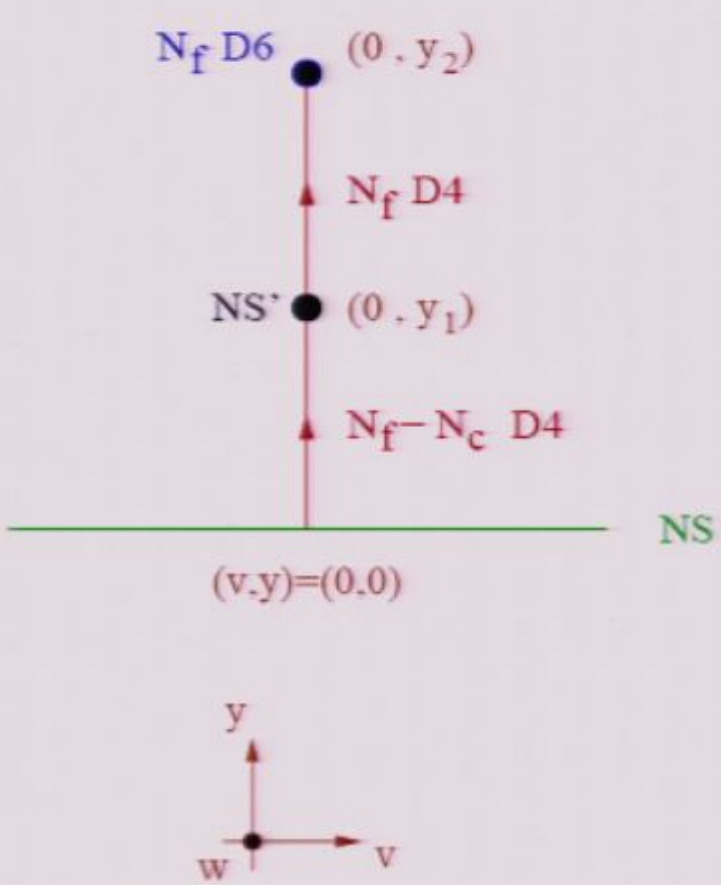
$$h, \frac{\mu_\phi}{\mu} \ll 1$$

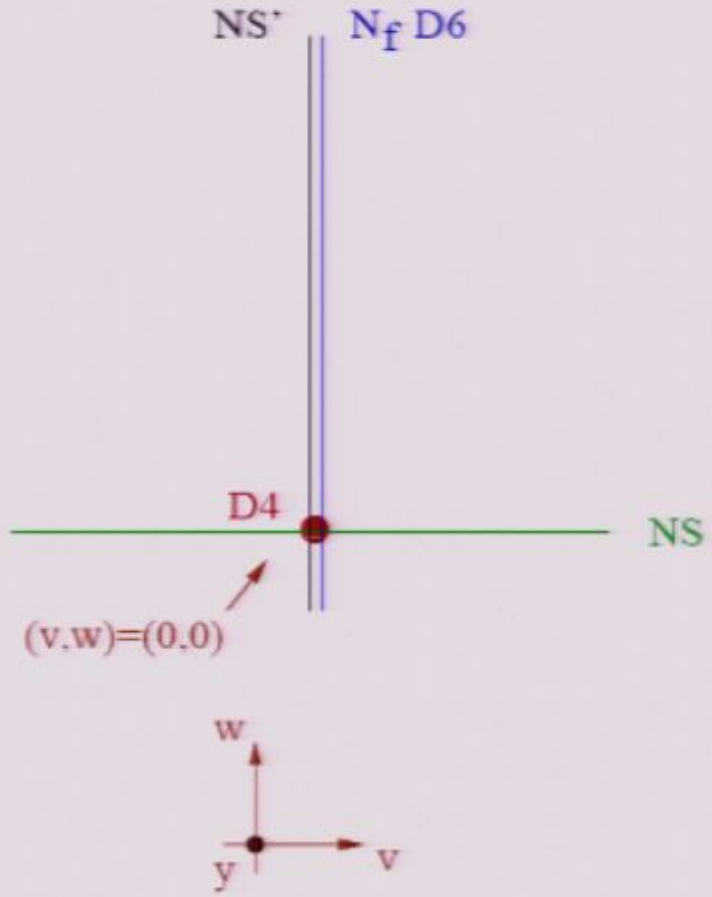
in which we can study the O'Raifeartaigh model for $q, \tilde{q}, \Phi$, as in ISS. The small parameters above will be responsible for the long lifetime of the metastable vacua that we will find.

Brane realization of SQCD

The electric SQCD described above can be realized in string theory as the low energy theory corresponding to a brane configuration containing two kinds of NS5-branes, which we will denote by NS and NS', as well as D4 and D6-branes.

Seiberg dual (magnetic) brane configuration



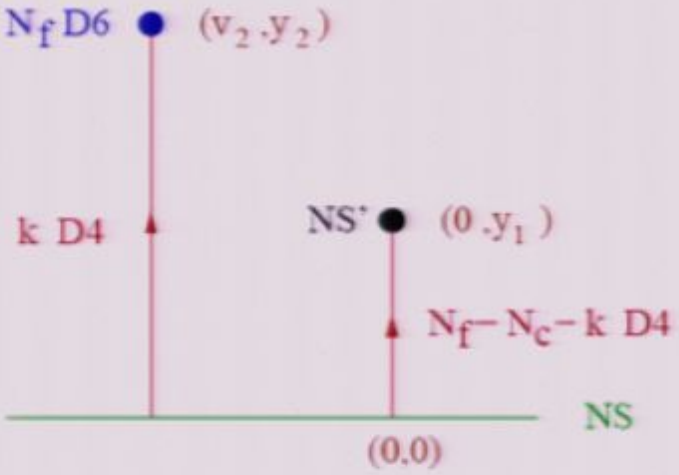


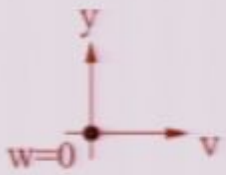
The deformation

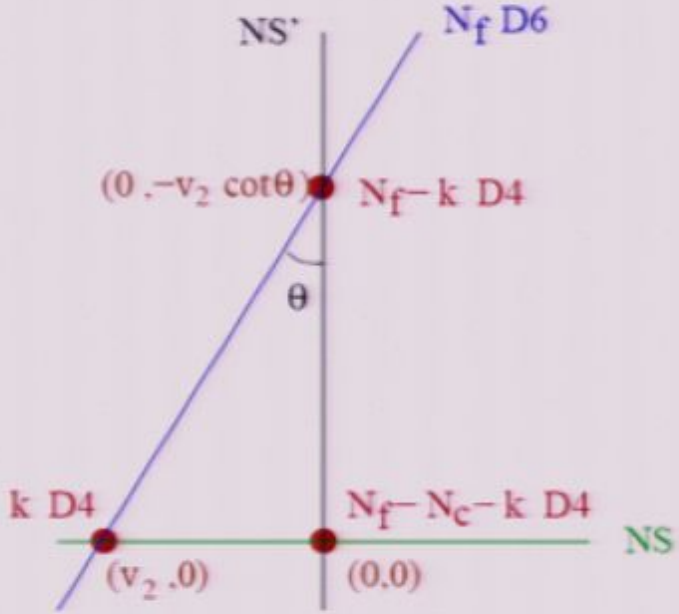
Deforming the superpotential to

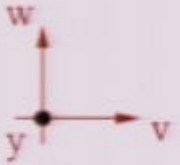
$$W_{\rm mag} = \frac{1}{\Lambda}\tilde{q}_i M^i_j q^j + \frac{\alpha}{2}{\rm Tr}M^2 - m{\rm Tr}M$$

corresponds geometrically to a translation (m) and rotation (α) of the D6-branes:









where $m = -Tv_2, \quad \alpha\Lambda = \tan\theta;$

k labels supersymmetric vacua (as before).

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