Title: Meta-stable Supersymmetry Breaking Vacua in Supersymmetric Gauge Theories

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Abstract: I will talk about meta-stable supersymmetry breaking vacua in SQCD and Seiberg-Witten Theories. Also I will mention their string theory embeddings

Meta-stable SUSY Breaking Vacua in Supersymmetric Gauge Theories

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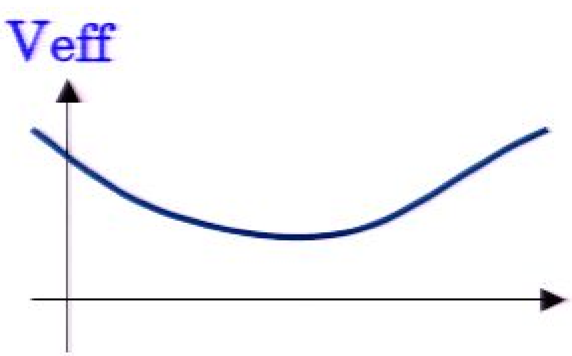
R. Kitano, H. Ooguri and Y. O. [arXiv hep-ph/0612139]
H. Ooguri, Y. O. and C-S. Park [arXiv 0704.3613 (hep-th)]
J. Marsano, H. Ooguri, Y. O. and C-S. Park
[arXiv 0712.XXXX (hep-th)]

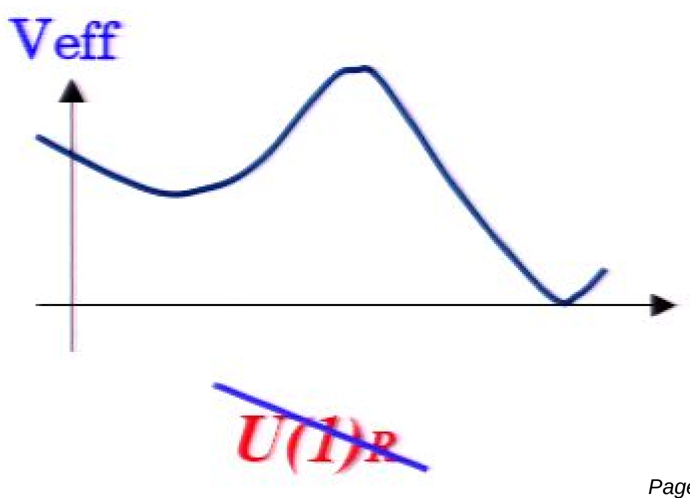
- 4D $\mathcal{N}=1$ Supersymmetry gauge theories are very nice
  - Controllability including non-perturbative effect
  - Rich physical phenomena
  - Phenomenologically attractive features
- Supersymmetry have to be broken in nature
- Dynamical SUSY Breaking is fascinating
  - Explain hierarchy problem: electroweak << plank

Until recently, it has been believed that dynamical SUSY breaking is special

- Witten index
- *U(1)R* symmetry



U(1)R



Dynamical supersymmetry breaking is not special but seems generic [Intriligator-Seiberg-Shih `06]

New points

- long-live meta-stable vacuum
- explicit breaking of $U(1)_R$
- vector-like model
- simple
- string embedding

It's time to revisit model building

$SU(N_C)$ SQCD in Free magnetic Range

$$N_C + 1 \leq N_F < \frac{3}{2} N_C$$

- Dual description is $SU(N_F\text{-}N_C)$ SQCD with singlet

$$W_{mag} = M\tilde{q}q$$

- Kahler potential is almost canonical

$$K_{IR} = \frac{1}{\alpha} Tr M^\dagger M + \frac{1}{\beta} Tr(q^\dagger q + \tilde{q}^\dagger q) + \cdots$$

- Small mass term makes vacuum structure rich

$$W_{mag} = M\tilde{q}q + \mu^2 M \qquad \mu^2 = m_Q \Lambda_e$$

- *F*-term condition for *M* can not be satisfied

$$q_c^i \tilde{q}_j^c + \mu^2 \delta_j^i = 0$$

Rank N_F-N_C Rank N_F

- Supersymmetry is broken at tree level
- Minimum of potential includes flat direction (θ, M_0), which is stabilized by one-loop effect

$$q = \begin{pmatrix} \mu e^{\theta} \\ 0 \end{pmatrix} \quad \tilde{q} = \Big(\underbrace{\mu e^{-\theta}}_{N_F - N_C} \; \underbrace{0}_{N_C} \Big) \Big\} N_F\text{-}N_C \quad M = \begin{pmatrix} 0 & 0 \\ 0 & M_0 \end{pmatrix}$$

- Long-lived when $\mu \ll \Lambda$

Plan of talk

First Part

Model of direct gauge mediation
(Realistic model building)

Second Part

Perturbed Seiberg-Witten Theories

First Part

Model of Direct Gauge Mediation

R. Kitano, H. Ooguri and Y. O.
[arXiv hep-ph/0612139]

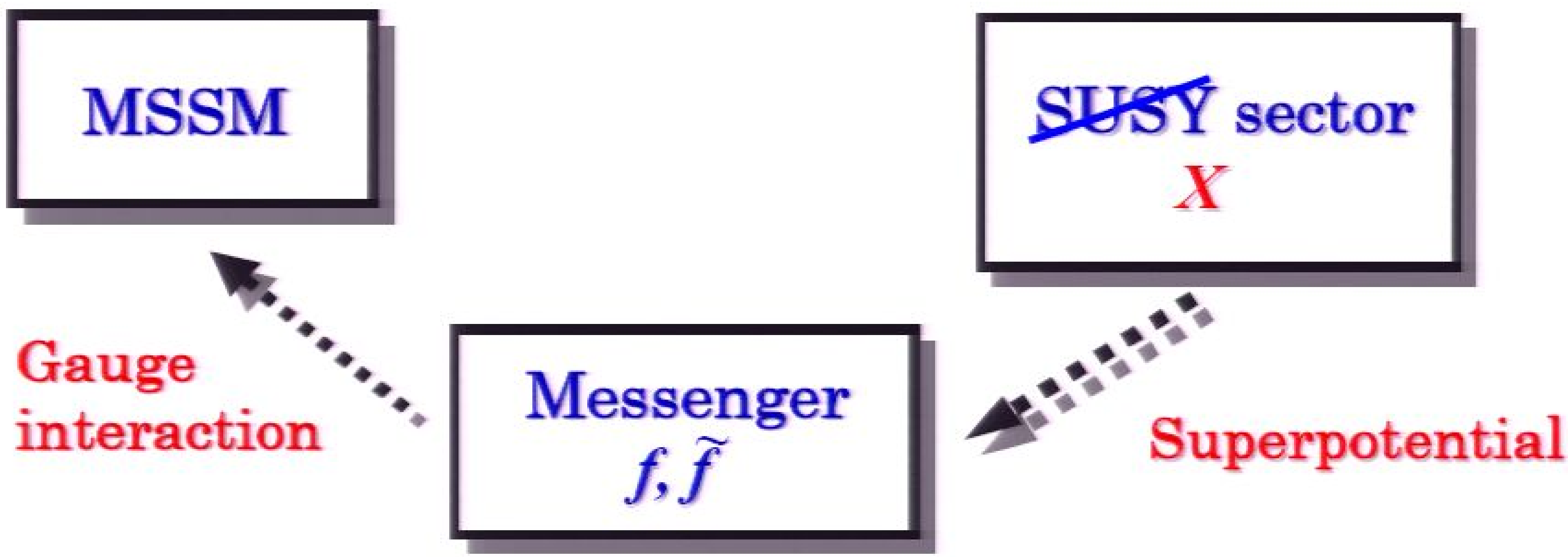
Related works

[M. Dine and J. Mason `06]
[C. Caki, Y. Shirman and J. Terning '06]
[H. Murayama, Y. Nomura '06]

Gauge Mediation

Among several possibilities for mediation of SUSY breaking effect, gauge mediation seems better

- Low energy SUSY breaking
- Dynamics was well studied in 90s
- Flavor blind mediation (suppress FCNC)

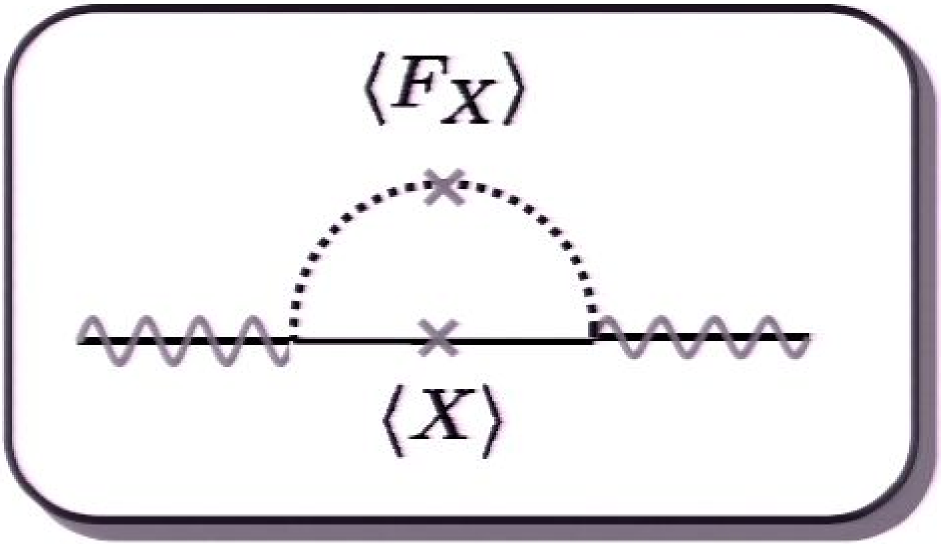


- Messengers carry SM charge and interact with SUSY breaking sector by Yukawa interaction

$$W = X f \tilde{f} \qquad \langle X \rangle = \langle X \rangle + \theta^2 \langle F_X \rangle$$

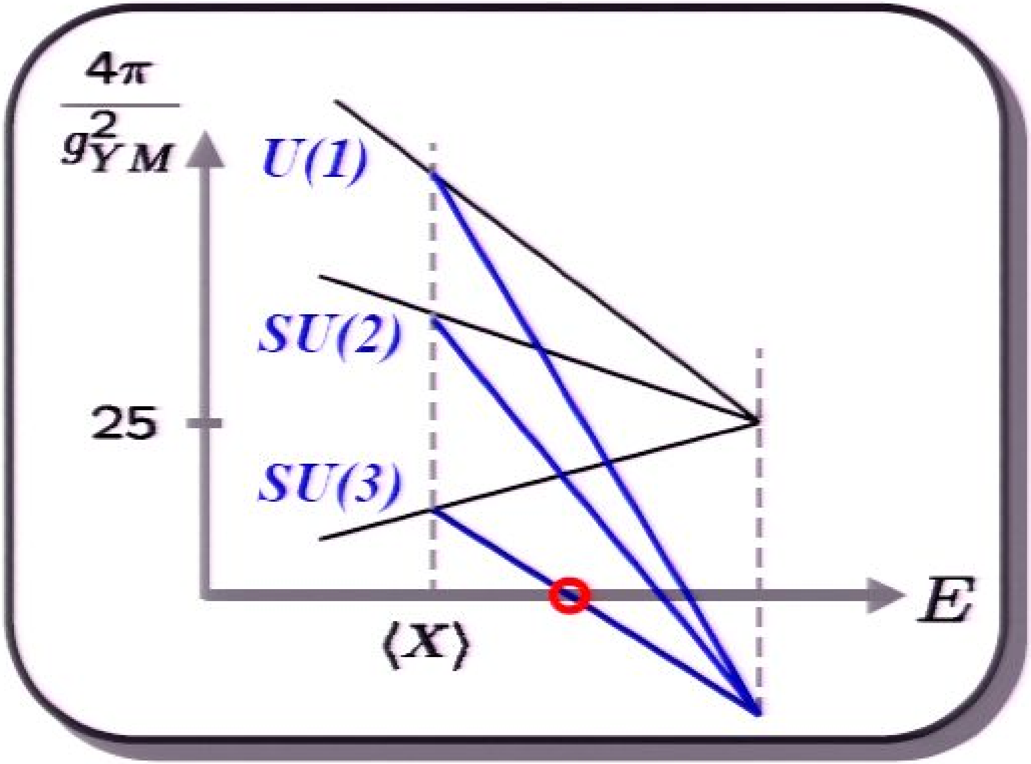
- Radiative corrections generate soft SUSY breaking terms including gaugino and scalar masses

- Gaugino can get mass from one-loop correction if $U(1)_R$ symmetry does not exist
- Scalar mass is generated at two loop level



- Messengers contribute to running of coupling

$$b = -3C_2(G) + quark + T(R)(\# \text{ of } f)$$



- Including many messenger develops Landau-Pole below *GUT* scale (serious issue for direct-type model)

Set up of Our Model

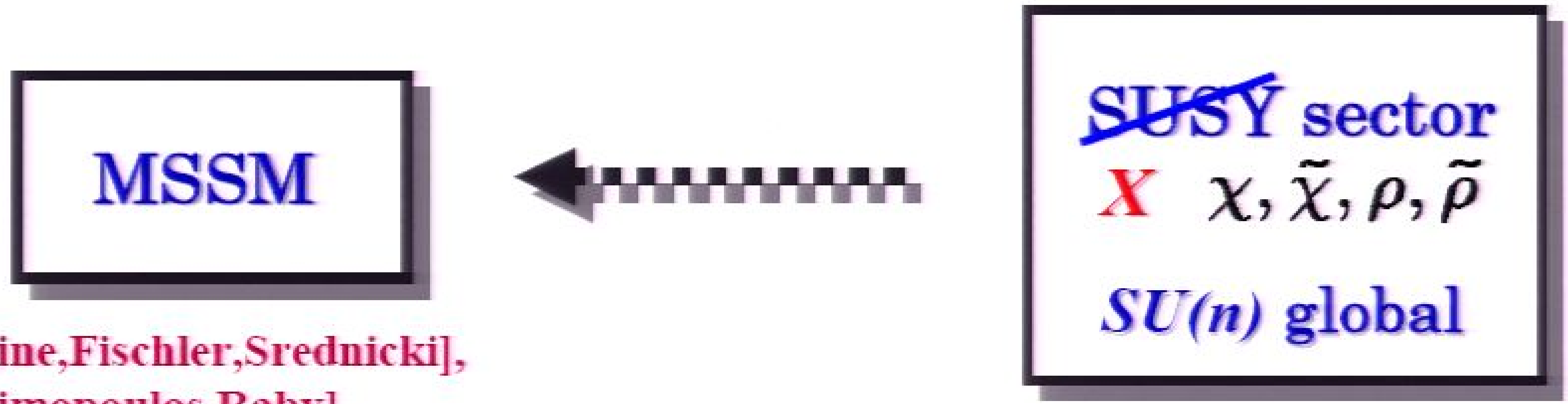
- Free magnetic range
- Modification of ISS by adding R-breaking term
- Global symmetries are $SU(N_F - N_C) \times SU(N_C) \times U(1)$

$$W_{ele} = \mu_e Q_2 \tilde{Q}_2 + m_e Q_1 \tilde{Q}_1 + \frac{1}{m_X} Q_1 \tilde{Q}_2 Q_2 \tilde{Q}_1$$

$$\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} \cdot (\tilde{Q}_1, \tilde{Q}_2) \to \quad M = \Lambda_e \begin{pmatrix} Y & Z \\ \tilde{Z} & \widehat{\Phi} \end{pmatrix}$$

$$W_{mag} = \mu^2 \widehat{\Phi} + m^2 Y + m_z Z \tilde{Z} + \frac{M}{\Lambda_e} q \tilde{q}$$

$$\mu^2 \equiv \mu_e \Lambda_e, \ m^2 \equiv m_e \Lambda_e, \ m_z \equiv \Lambda_e^2 / m_X$$



[Dine,Fischler,Srednicki],
[Dimopoulos,Raby]

- By gauging subgroup of unbroken global symmetry *SU(n)* and identify with SM gauge group, SUSY breaking sector can directly couple to MSSM

$$SU(n) \supset SU(3) \times SU(2) \times U(1)$$

- Fields that carry charge of *SU(n)* are regarded as messenger and contribute to running of coupling (They might cause Landau pole problem)

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$$\mu^2 \equiv \mu_e \Lambda_e, \ m^2 \equiv m_e \Lambda_e, \ m_z \equiv \Lambda_e^2 / m_X$$

ISS supersymmetry breaking vacua

$$q = \begin{pmatrix} me^{\theta} \\ 0 \end{pmatrix} \quad \tilde{q} = \begin{pmatrix} me^{-\theta} & 0 \end{pmatrix}$$

$$M = \begin{pmatrix} 0 & 0 \\ 0 & M_0 \end{pmatrix}$$

Non-compact flat directions

- Coleman-Weinberg potential lift all flat directions when

$$m_z < m$$

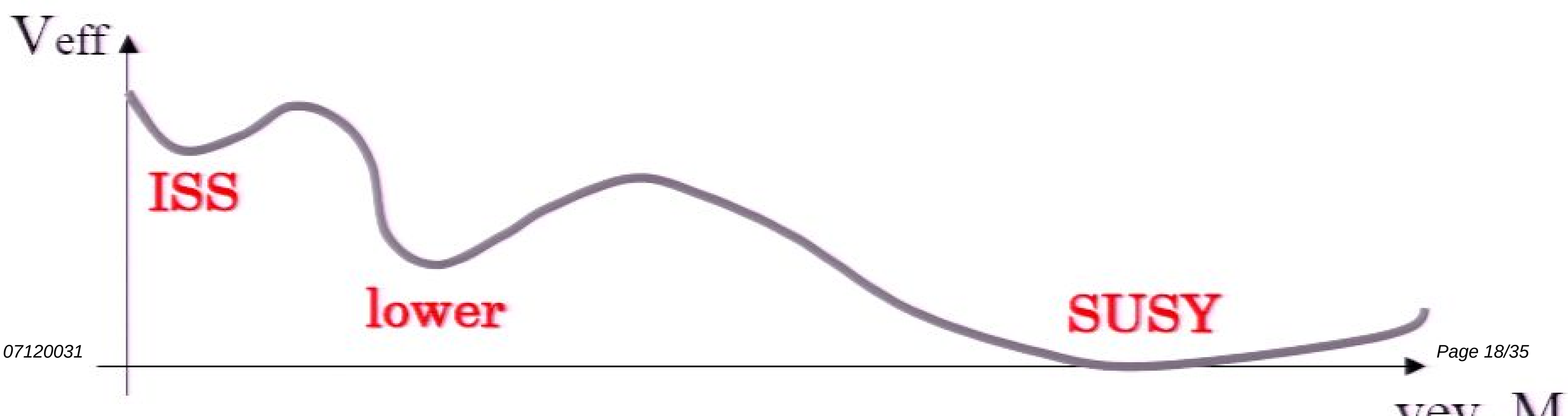
- Unbroken global symmetry $SU(N_F - N_C) \times SU(N_C)$

embedding into

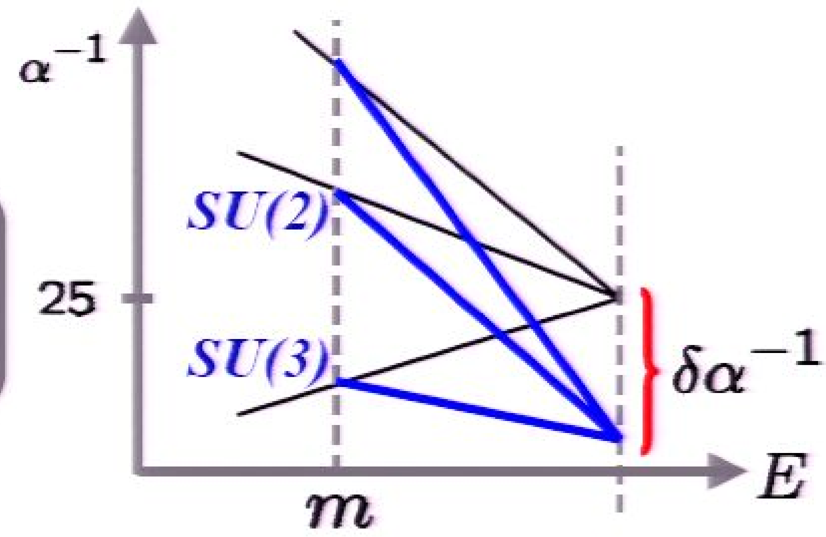
Radiative corrections generate gaugino and scalar masses

$$m_\lambda = \# \frac{\mu^2}{m}\frac{m_z}{m} + \mathcal{O}(\frac{m_z^2}{m^2}), \quad m_s^2 = \#^2 \left(\frac{\mu^2}{m}\right)^2 + \mathcal{O}(\frac{m_z^4}{m^4})$$

- To be same order $m \sim m_z$
- Longevity $\mu \ll m \quad , \mu \ll \Lambda$



$$\delta\alpha^{-1} = \frac{2N_F - N_C}{2\pi} \ln \frac{M_{GUT}}{m} \leq 25$$



Any solution for all conditions?

$$N_C + 1 \leq N_F \leq \frac{3N_C}{2}$$

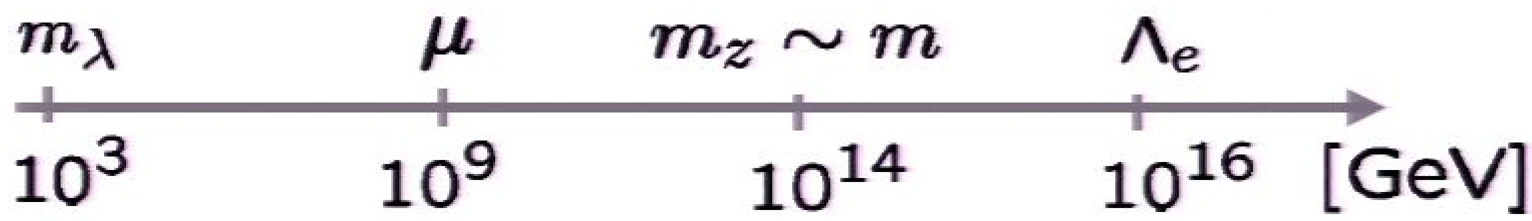
$$N_F - N_C \geq 5$$

$$\mu \ll m_z \sim m \ll \Lambda_e \ll m_X$$

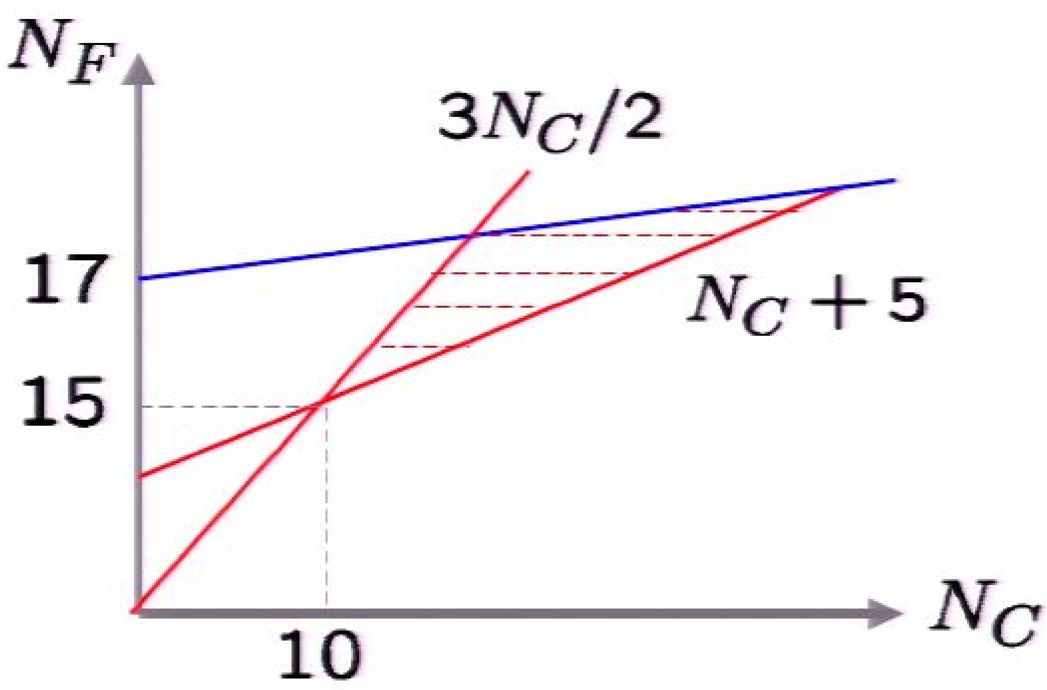
$$m_\lambda \sim \mathcal{O}(100)\text{GeV}$$

$$\mu \leq 10^{9.5} \text{ GeV}$$

One example



m_λ
μ
$m_z \sim m$
Λ_e
10^3
10^9
10^{14}
10^{16}
[GeV]



N_F
$3N_C/2$
17
$N_C + 5$
15
N_C
10

String Embedding I : TypeIIB on ADE fibered geometry

$$U(N_1) \times U(N_2) \times U(N_3) \qquad \Lambda_1, \Lambda_3 \ll \Lambda_2$$

$$W = Q_{21}X_1Q_{12} - Q_{12}X_2Q_{21} + Q_{32}X_2Q_{23} - Q_{23}X_3Q_{32} + W_1 + W_2 + W_3$$

$$W_1 = \frac{m_X}{2}(X_1 - \mu)^2 \quad W_2 = -\frac{m_X}{2}X_2^2 \quad W_3 = \frac{m_X}{2}(X_3 - m)^2$$

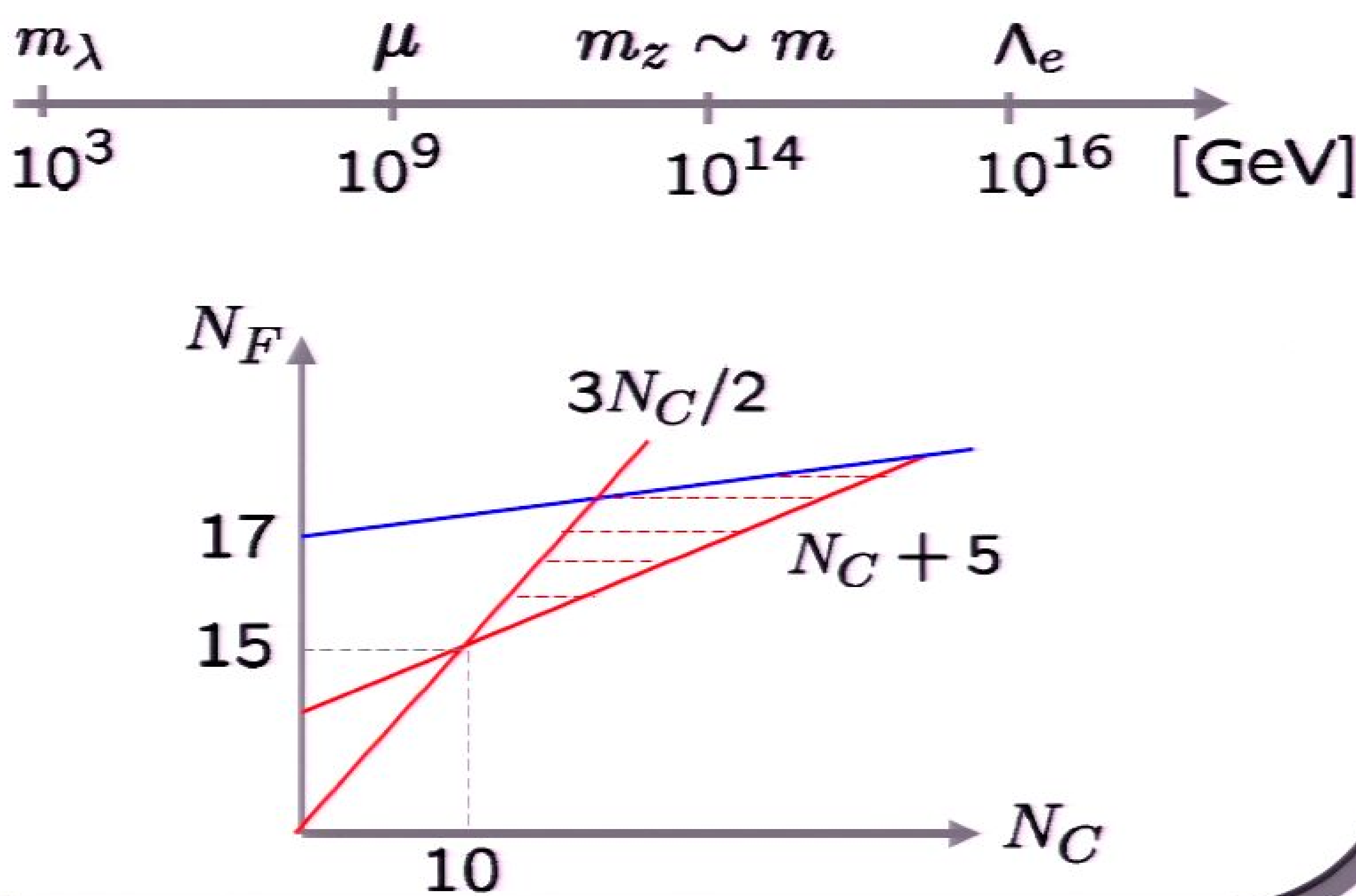
Low energy theory on D5 branes partially wrapping S^2 in the geometry

[Cachazo-Katz-Vafa , Cachazo-Fiol-Intriligator-Katz-Vafa

String Embedding II : TypeIIB on Conifold / Z_N

[Argurio-Bertolini-Franco-Kachru]

One example


m_λ
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Λ_e
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$$W_1 = \frac{m_X}{2}(X_1-\mu)^2 \quad W_2 = -\frac{m_X}{2}X_2^2 \quad W_3 = \frac{m_X}{2}(X_3-m)^2$$

Low energy theory on D5 branes partially wrapping S^2 in the geometry

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Second Part

Perturbed Seiberg-Witten Theories

H. Ooguri, Y. O. and C-S. Park
[arXiv 0704.3613 (hep-th)]

J. Marsano, H. Ooguri, Y. O. and C-S. Park
[arXiv 0712.XXXX (hep-th)]

Related works

[G. Pastras `06]

Motivation

- Formal interest rather than phenomenology
- Different phase from ISS (free magnetic)
- Toward geometric construction of
  metastable vacua in terms of CY+flux

Perturbed Seiberg-Witten Theories

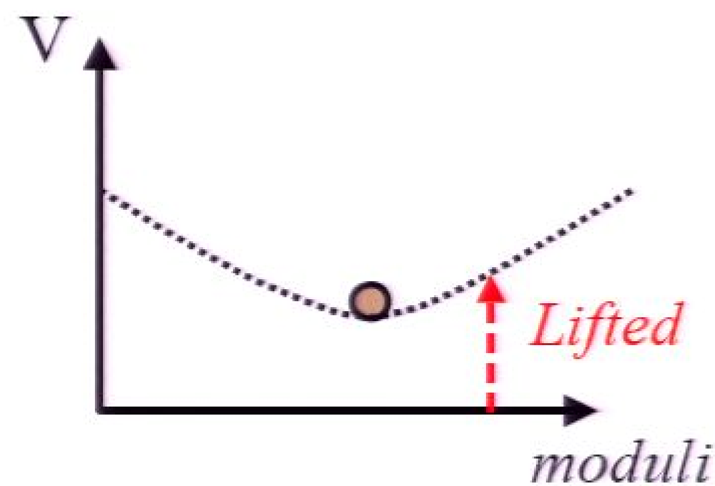
$$\mathcal{L}_{SW} = Im\left[\int d^4\theta \partial_i F(A)\bar{A}^i + \int d^2\theta \frac{\partial^2 F}{\partial A^i \partial A^j} W_\alpha^i W_\alpha^j\right]$$

$$g_{ij} = Im\frac{\partial^2 F}{\partial a^i \partial a^j} \qquad i = 1, \cdots rankG$$

Perturbation

$$\mathcal{L} = \mathcal{L}_{SW} + \epsilon W$$

$$V = \epsilon^2 \underline{g}^{ij}\partial_i W \bar{\partial}_j \bar{W} + \cdots$$



Can we engineer W to make metastable vacuum?

Claim

For a generic choice of a point on Coulomb branch, it is possible to find a perturbation which generates a metastable vacuum at the point

Take first three terms of Kahler Normal coordinate at the point as a superpotential

$$W = k^i z^i$$

$$z^i = x^i + \frac{1}{2}\Gamma^i_{jk}|_0 x^j x^k + \frac{1}{6} g^{im}\partial(g_{nm}\Gamma^n_{jk})|_0 x^j x^k x^l$$

Kahler Normal Coordinate

$$\partial_{i_1} \cdots \partial_{i_N} \Gamma^i_{jk}| = 0$$

[Alvarez-Gaume et al.]

$$z_{All} = x^i + \sum_{N=2}^{\infty} \frac{1}{N!} g^{ij} K_{,i_1,\cdots i_N,j}| x^{i_1} \cdots x^{i_N}$$

[Higashijima et al.]

$$g_{ij} = g_{ij}| + R_{ijkl}| z^k \bar{z}^l + \mathcal{O}(z^3)$$

$$V = g^{ij}| k_i \bar{k}_j + \underline{k_i \bar{k}_j R^{ij}_{kl}| z^k \bar{z}^l} + \mathcal{O}(z^3)$$

Positive in SW

Truncation of higher order terms of the Coordinate is very important to get SUSY breaking

It changes global structure of potential

$$z_{All} = x^i + \sum_{N=2}^{\infty} \frac{1}{N!} g^{ij} K_{,i_1,\cdots i_N,j}| x^{i_1} \cdots x^{i_N}$$

Deformation by all order of KNC $W = k_i z^i_{All}$
preserve hidden Supersymmetry on the vacua!

Equivalence between Kahler Normal Coordinate and electric/magnetic FI-terms

$$W_{ele/mag} = e_i a^i + m_i a_D^i$$
$$= e_i \left(a^i + \frac{m_i}{e^i} a_D^i \right)$$

This can be equivalent to Kahler normal coordinate to all order when

$$e_i + m_j \bar{\tau}_{ji} = 0$$

Direct relation to

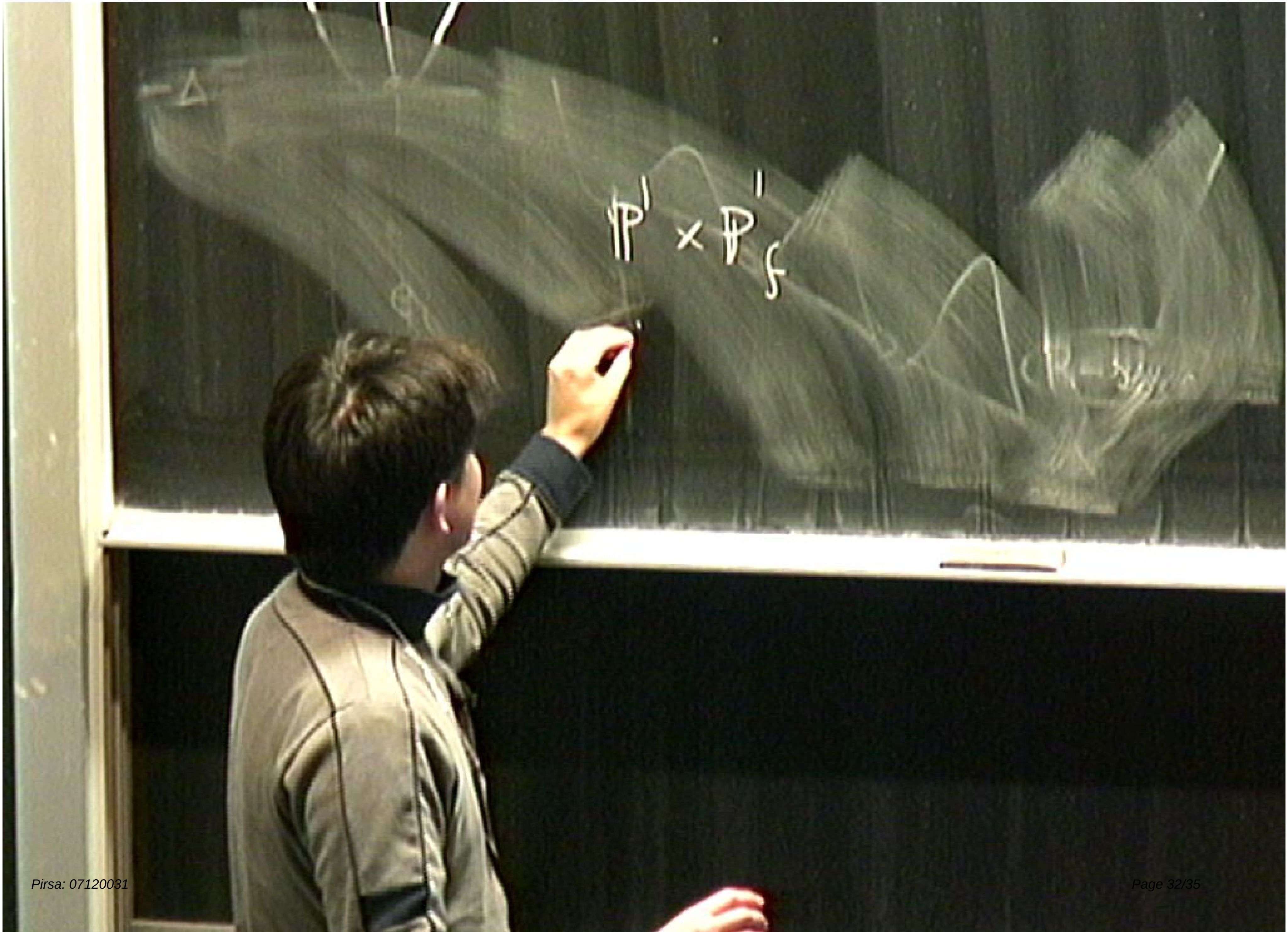
[Antoniadis-Partouche-Taylor]

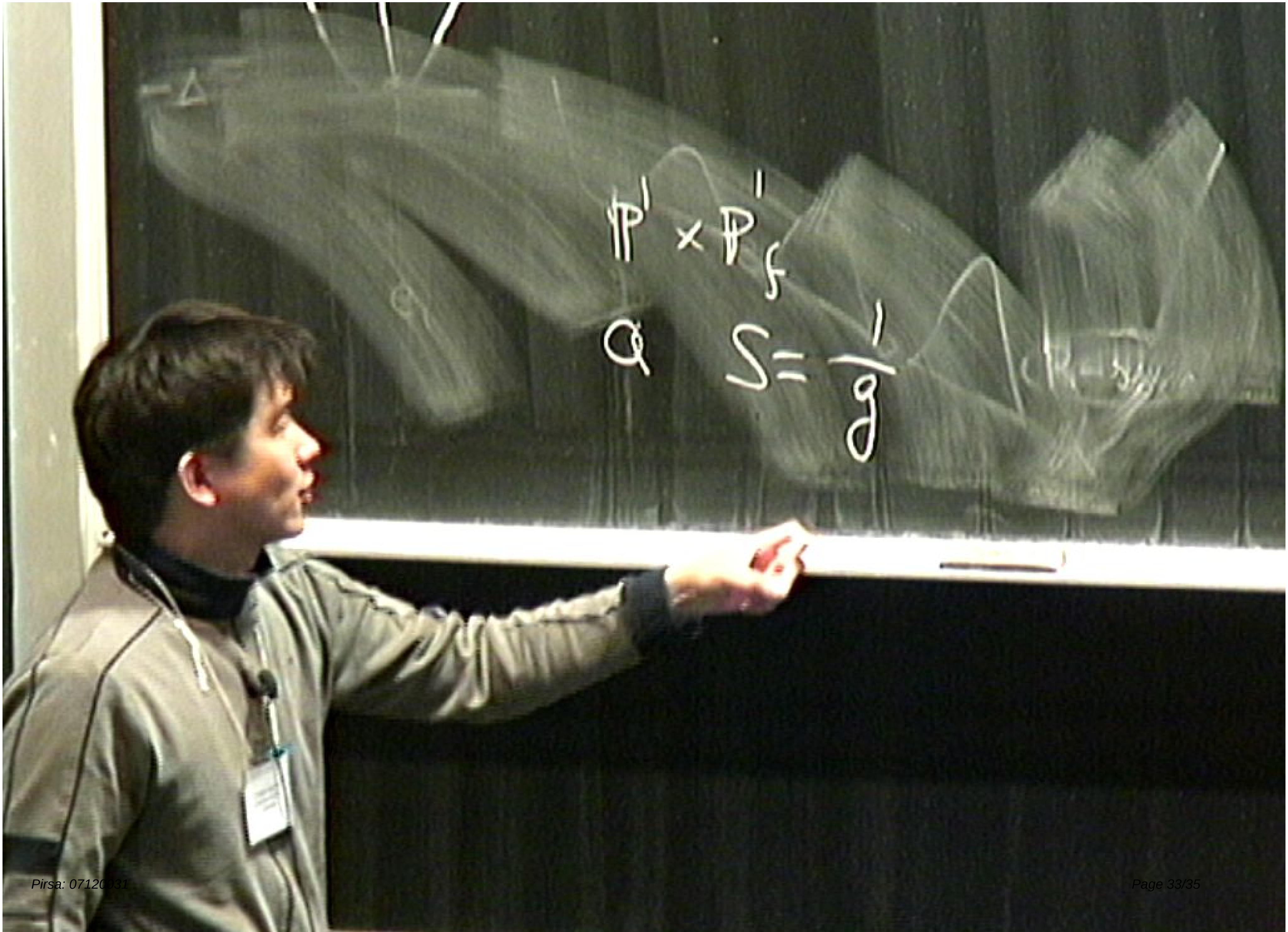
[Aganagic-Beem-Seo-Vafa]

In Part I, we demonstrated phenomenologically viable model which can be embedded into string theories

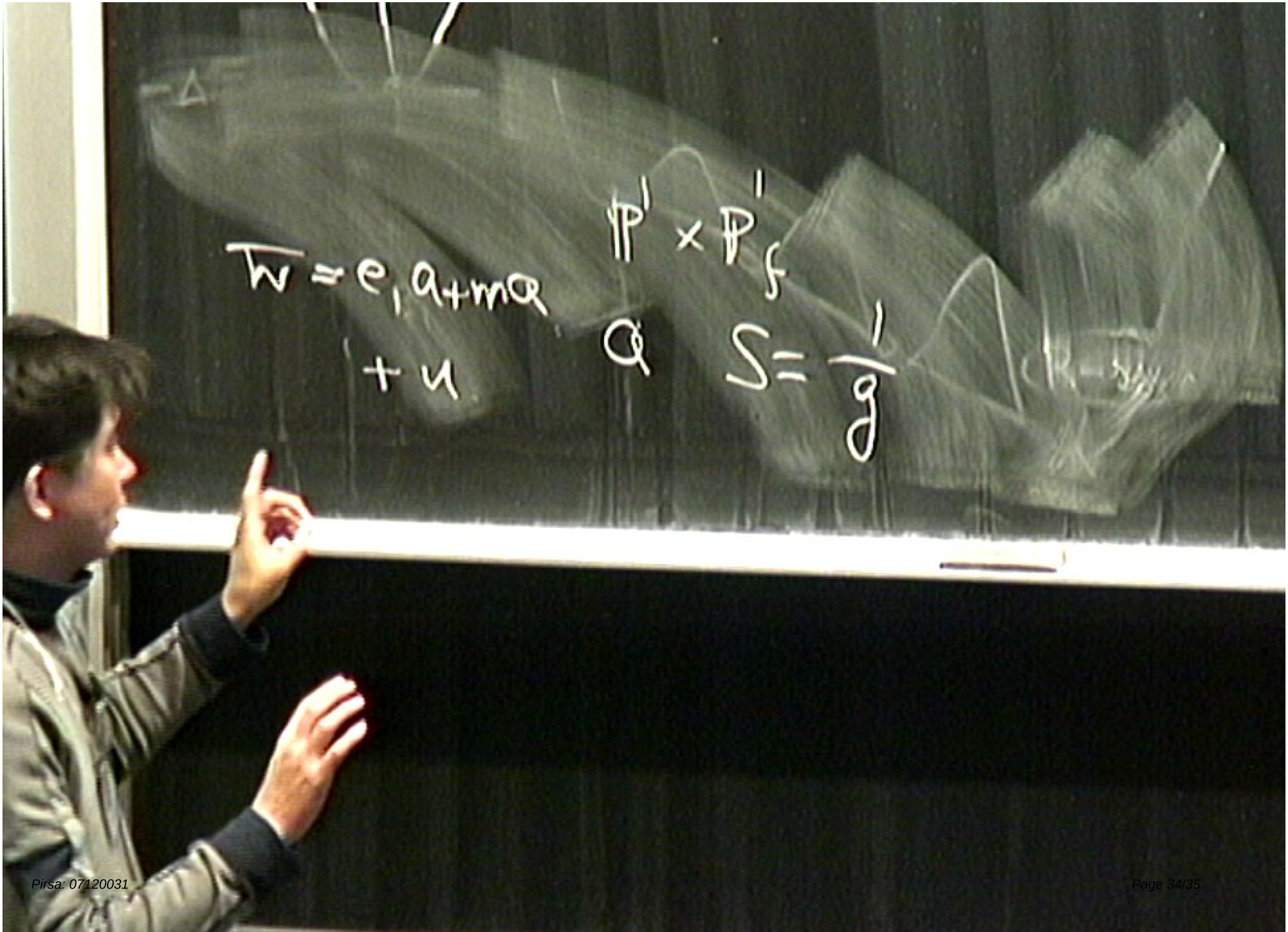
In Part II, we showed general recipe for constructing meta-stable vacua in any Seiberg-Witten theories

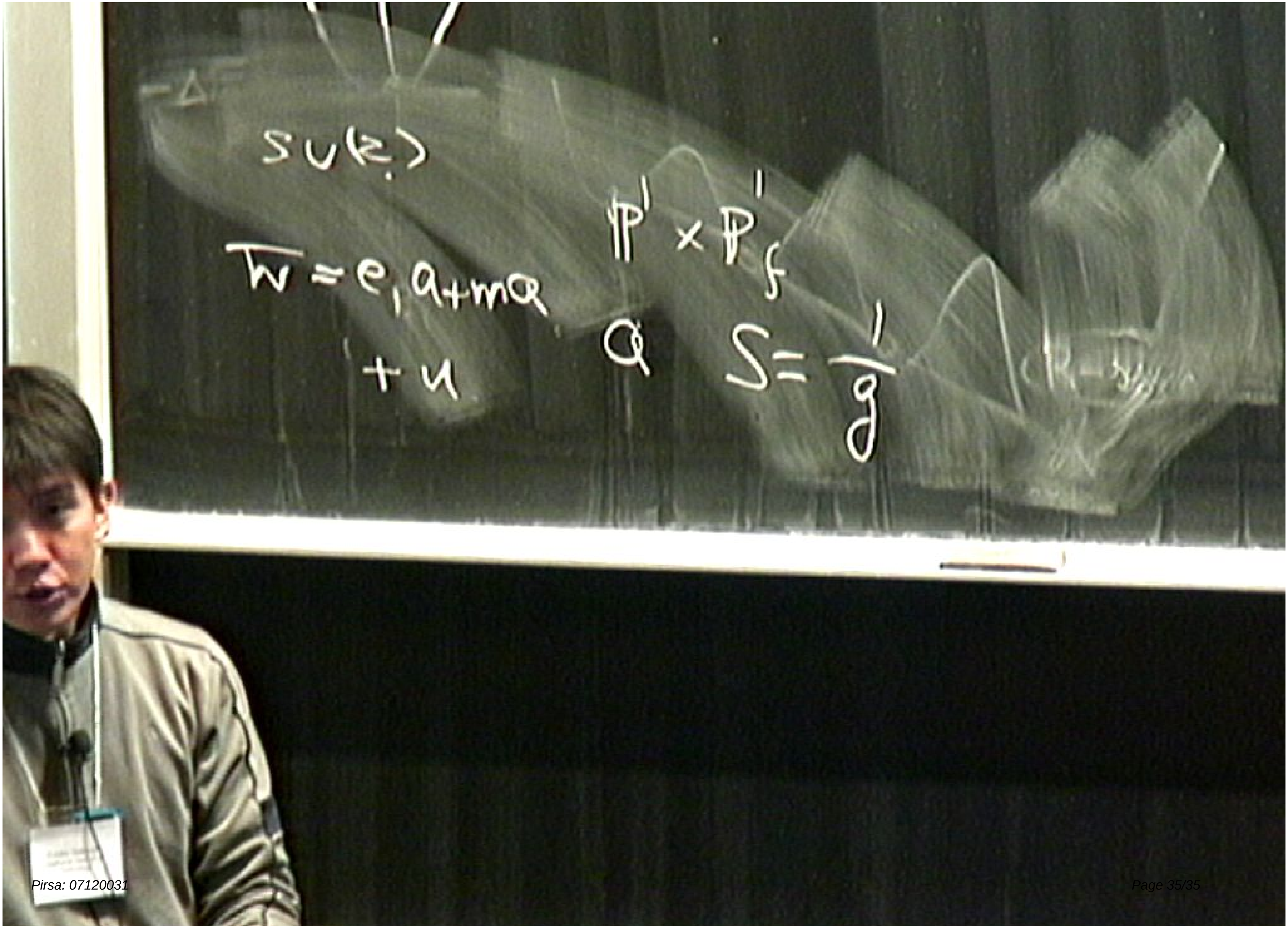
Genericity suggests that we are in a meta-stable state!


$\mathbb{P}^1 \times \mathbb{P}^1_f$



$\mathbb{P}^1 \times \mathbb{P}^1_f$
Q $S = \frac{1}{g}$


W = e, a + m a
+ u
P' × P'f
Q
S = 1/g


SU(2)
W = e, a+mQ
+ u
P' × P'f
Q
S = 1/g