Title: Old Friends, New Waves, and Unfinished Business

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Abstract:

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Patterns of Duality in N=1 SUSY Gauge Theories

or: *Seating Preferences of Theatre-Going Non-Abelian Dualities*

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We study the patterns in the duality of a wide class of N=1 supersymmetric gauge theories in four dimensions. We present many new generalizations of the classic duality models of Kutasov and Schwimmer, which have themselves been generalized numerous times in works of Intriligator, Leigh and the present authors. All of these models contain one or two fields in a two-index tensor representation, along with fields in the defining repre-

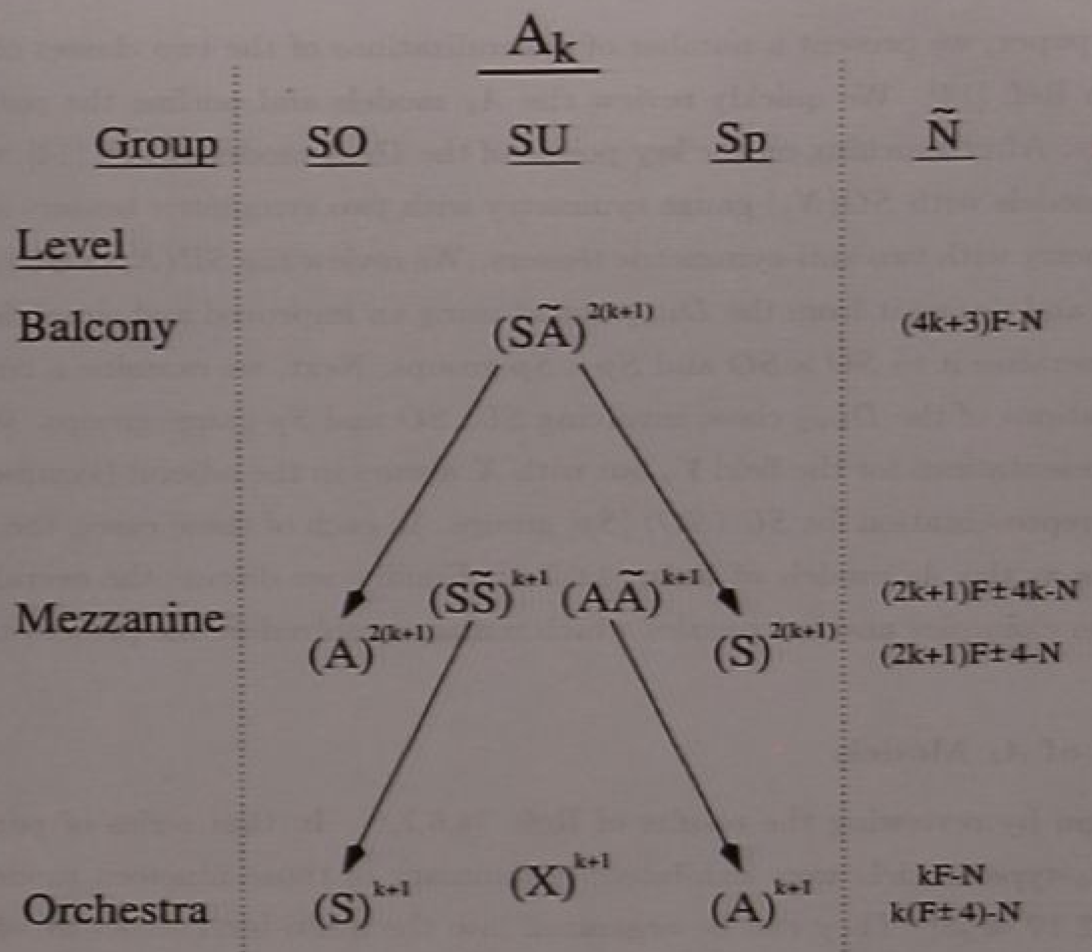

Fig. 1: The simplest A_k models of Refs. [4,6,7,8], organized as suggested by Sec. 2 of [8]. The notation in the figure is as follows: X represents a field in the adjoint representation of $SU(N)$, S and A represent symmetric and anti-symmetric tensor representations, and a tilde represents a conjugate representation of $SU(N)$. For SU [SO] (Sp) groups, $N = N_c$ [N_c] ($2N_c$) and $F = N_f$ [N_f] ($2N_f$). The superpotential for each model is given. Each model is dual to a model of similar type, with color group $SU(\tilde{N})$, $SO(\tilde{N})$ or $Sp(\frac{\tilde{N}}{2})$. The arrows indicate that there are flat directions along which the upper models flow to the lower ones.

$SU(N)$ w/ N_f $Q, \tilde{Q}$

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+ adj X and $W = \mathrm{tr}\, X^{k+1}$

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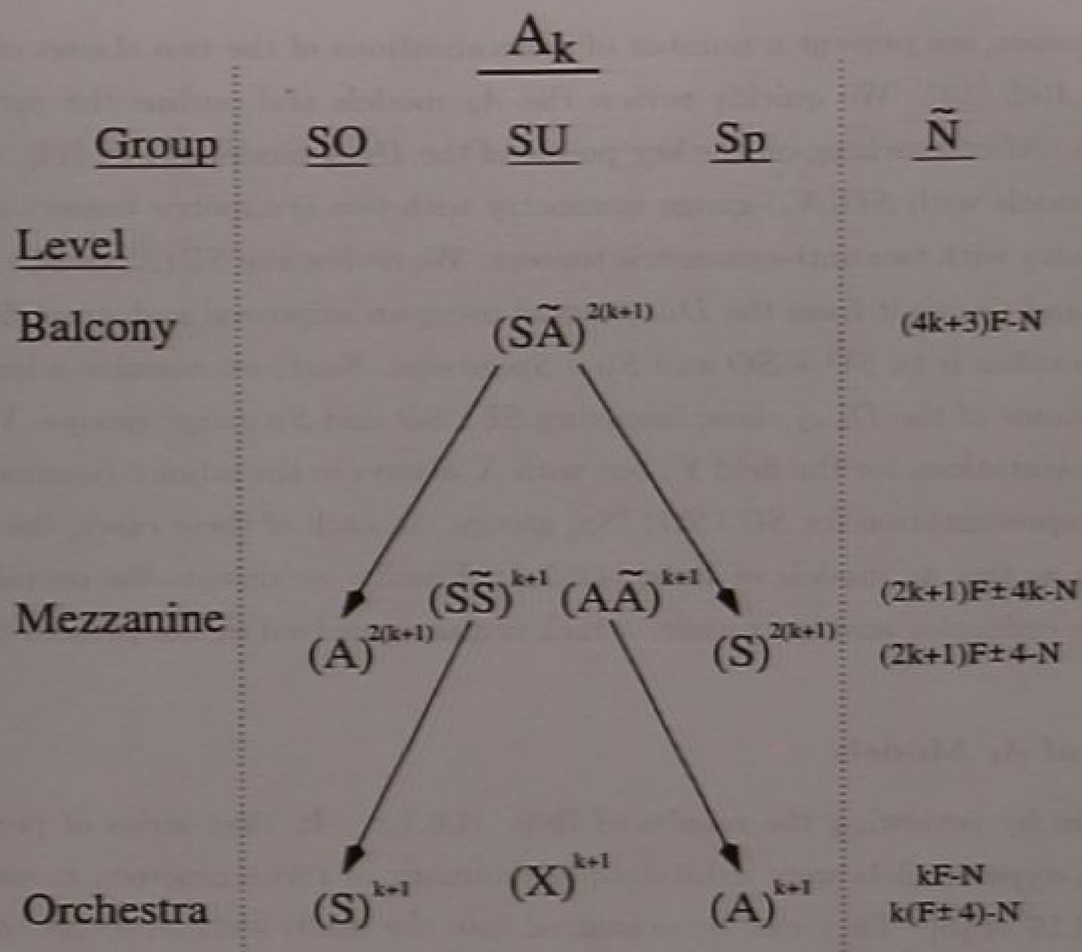
$+$ adj X and $W = \mathrm{tr}\, X^{k+1}$

$\tilde{N}_c = k N_c - N_f$



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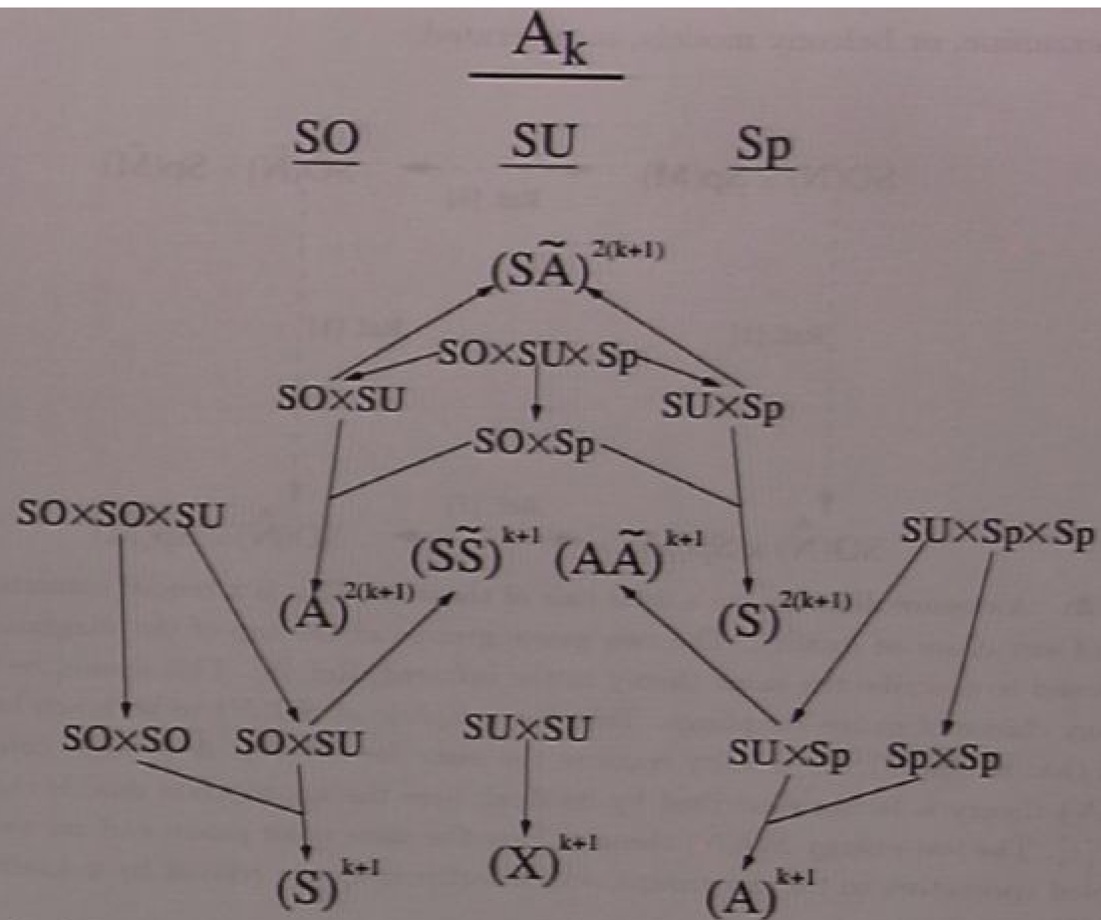


Fig. 2: The models of the previous figure along with the loge models of Ref. [8]. The loge models consist of a product of two or three gauge groups, which is displayed on the figure. Each is dual to a model of similar type, with the same groups. The process of confinement of one group factor causes the loge models to flow along the arrows in the diagram to models with one fewer group factor. More generally, duality of a single group factor relates the duality of each loge model to a duality of a model with one fewer group factor, along the same arrows.

Related to each of these models are the loge models [8] shown in fig. 2 in which the fields X or $\tilde{X}$ are deconfined. An adjoint representation of $SU(N)$ can always be deconfined [1,10,8,11] using an $SU(N) \times SU(N-1)$ group with a field F in the $(\mathbf{N}, \mathbf{N-1})$ and a field $\tilde{F}$ in its conjugate. Symmetric [anti-symmetric] representations ...

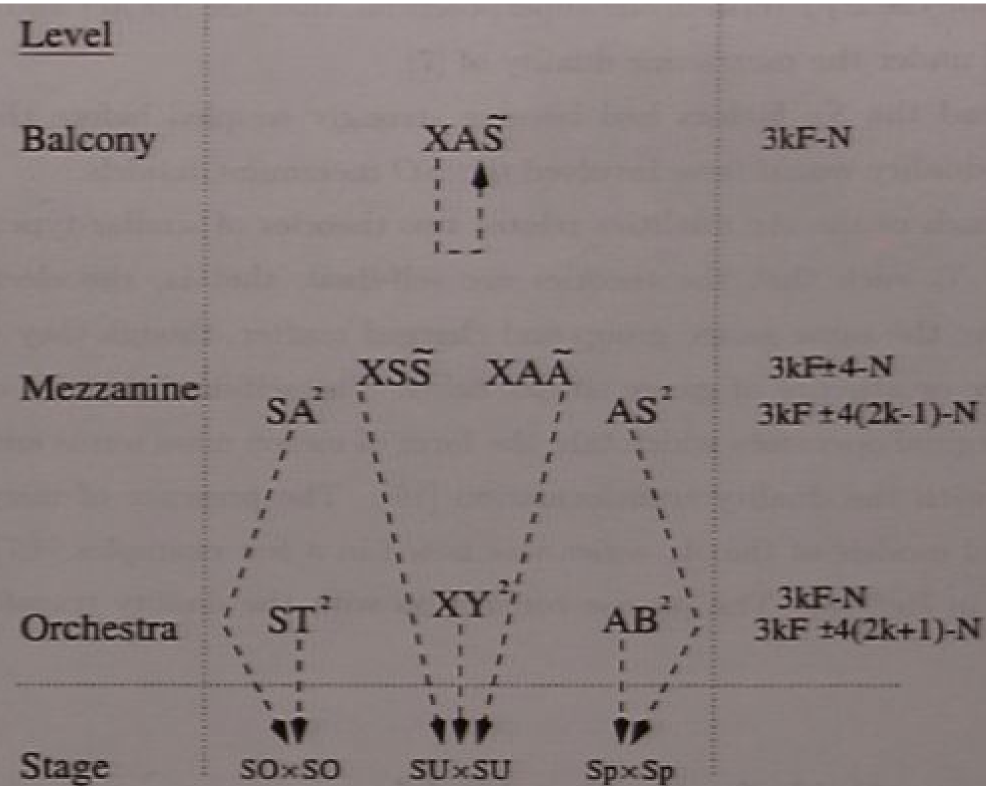


Fig. 4: The ensemble of D_{k+2} models described in this paper, along with the product models to which they are related. Notation is similar to fig. 1, with X, Y adjoint fields of $SU(N)$, S, T symmetric tensors and A, B anti-symmetric tensors, and a tilde representing a conjugate representation of $SU(N)$. For SU $[SO]$ (Sp) groups, $N = N_c$ $[N_c]$ $(2N_c)$ and $F = N_f$ $[N_f]$ $(2N_f)$. The superpotential for each model is given, with the first term listed at the top and the second at the position of the model in the diagram; thus the superpotential for the Mezzanine $SO(N)$ model is $S^{k+1} + SA^2$, *etc.* Each model is dual to a model of similar type, with color group $SU(\tilde{N})$, $SO(\tilde{N})$ or $Sp(\frac{\tilde{N}}{2})$. The dashed arrows indicate that under certain perturbations the D_{k+2} models flow to stage models, except for the balcony model which flows to copies of itself with lower k.

anti-symmetric or symmetric representation and $\tilde{Y}$ is in its conjugate. In the latter case the superpotential is $W = \mathrm{Tr}X^{k+1} + \mathrm{Tr}XY\tilde{Y}$.

The balcony model, which is chiral, has gauge group SU with fields Y in the anti-

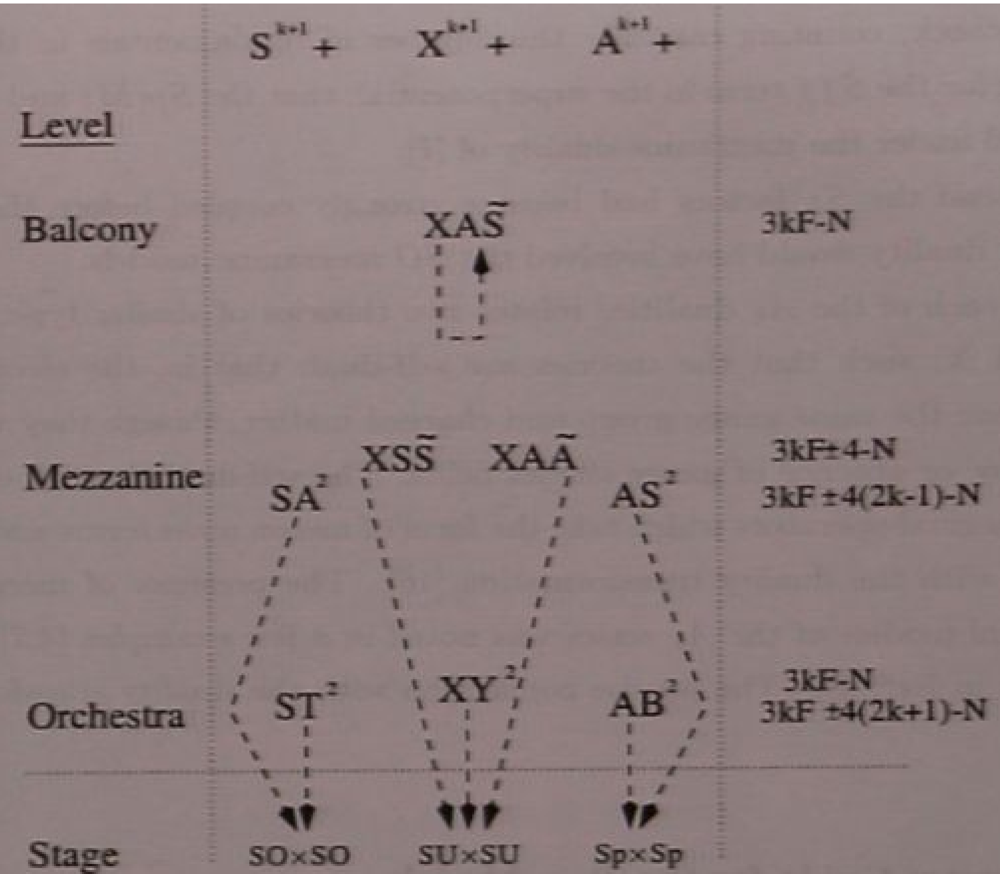
$SU(N)$ w/ N_f $Q, \tilde{Q}$

$+$ adj X and $W = \mathrm{tr}\, X^{k+1}$

$\tilde{N}_c = k N_c - N_f$ A_k

2 adj X, Y

$\mathrm{tr}\, X^{k+1} + XY^2$ D_k



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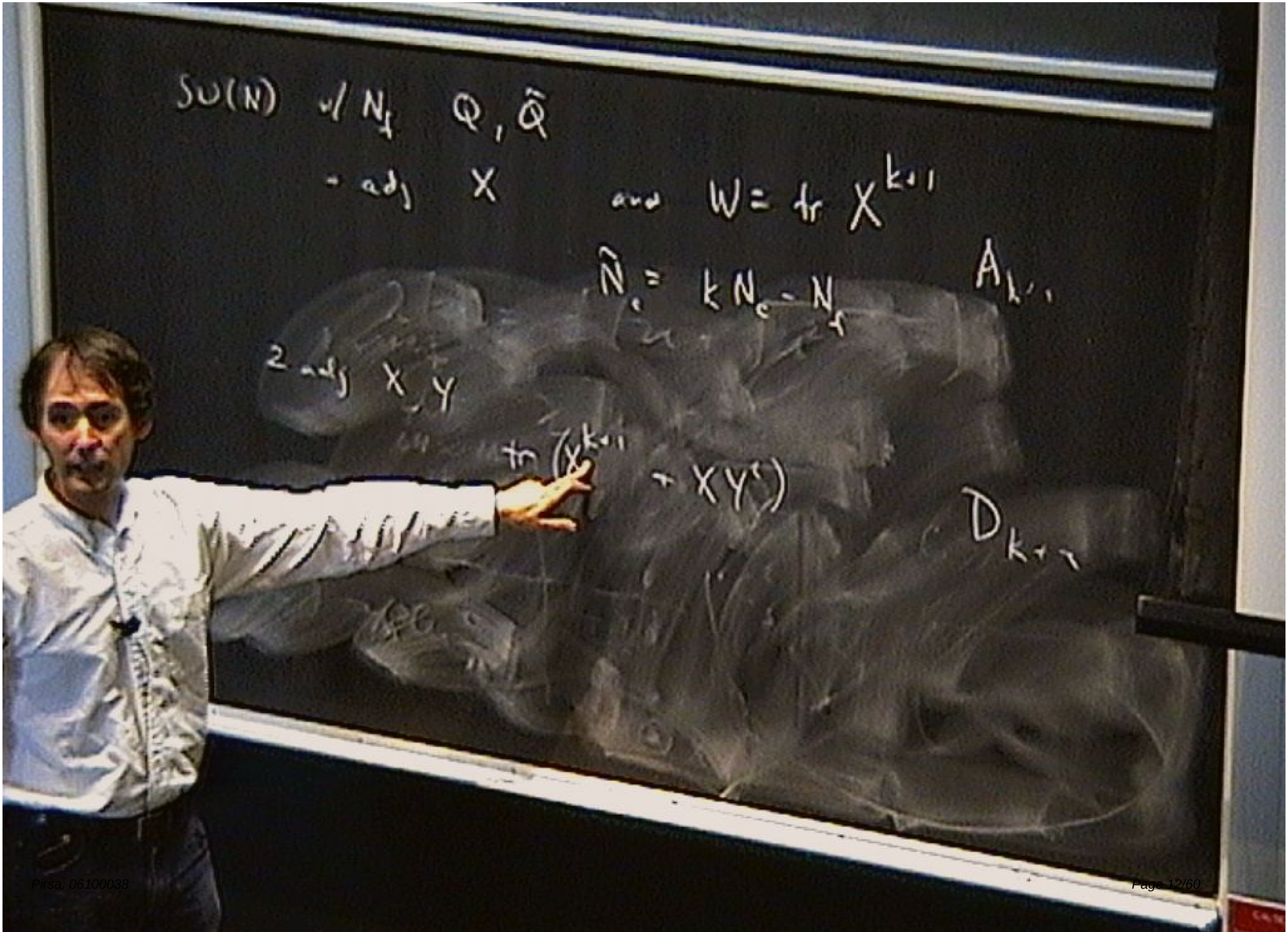
SU(N) w/ N_f Q, Q̃
+ adj X and W = tr X^{k+1}
Ñ_c = kN_c − N_f
A_{k+1}
2 adj X, Y
tr (X^{k+1} + XY^2)
D_{k+2}

$SU(N)$ w/ N_f $\quad Q, \tilde{Q}$

$+$ adj X $\quad$ and $\quad W = \mathrm{tr}\, X^{k+1}$

$\tilde{N}_c = k N_c - N_f \qquad A_{k+1}$

2 adj X, Y

$\mathrm{tr}\left(X^{k+1} + XY^2\right) \qquad D_{k+2}$

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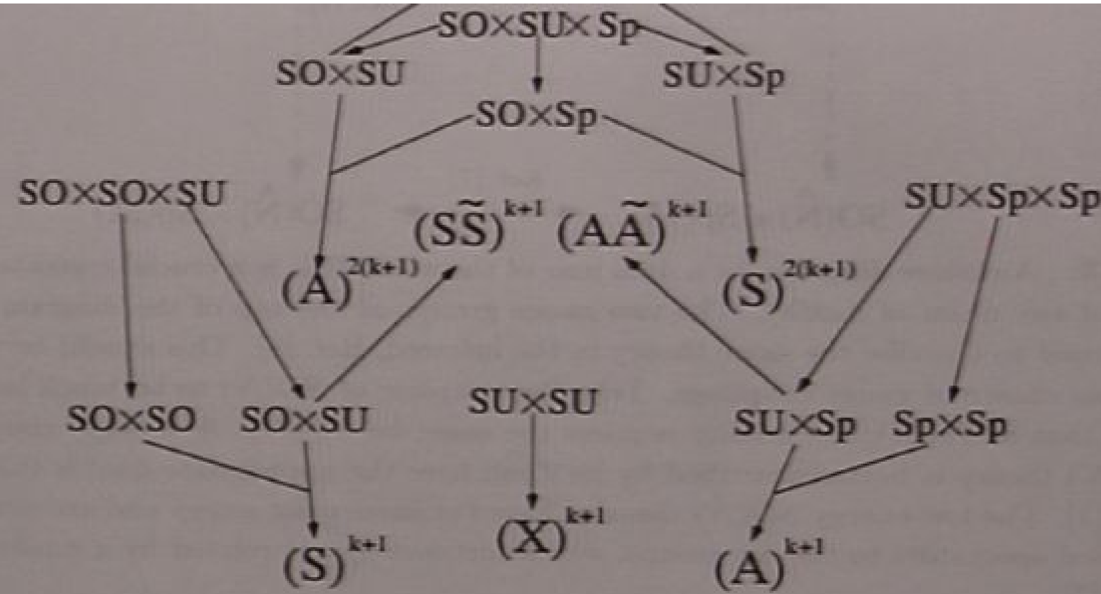
2 adj X, Y

$\mathrm{tr}\left(X^{k+1} + XY^2\right)$ $\quad D_{k+2}$

$+ (X^4 + XY^2) + \mathrm{tr}\, X^3$



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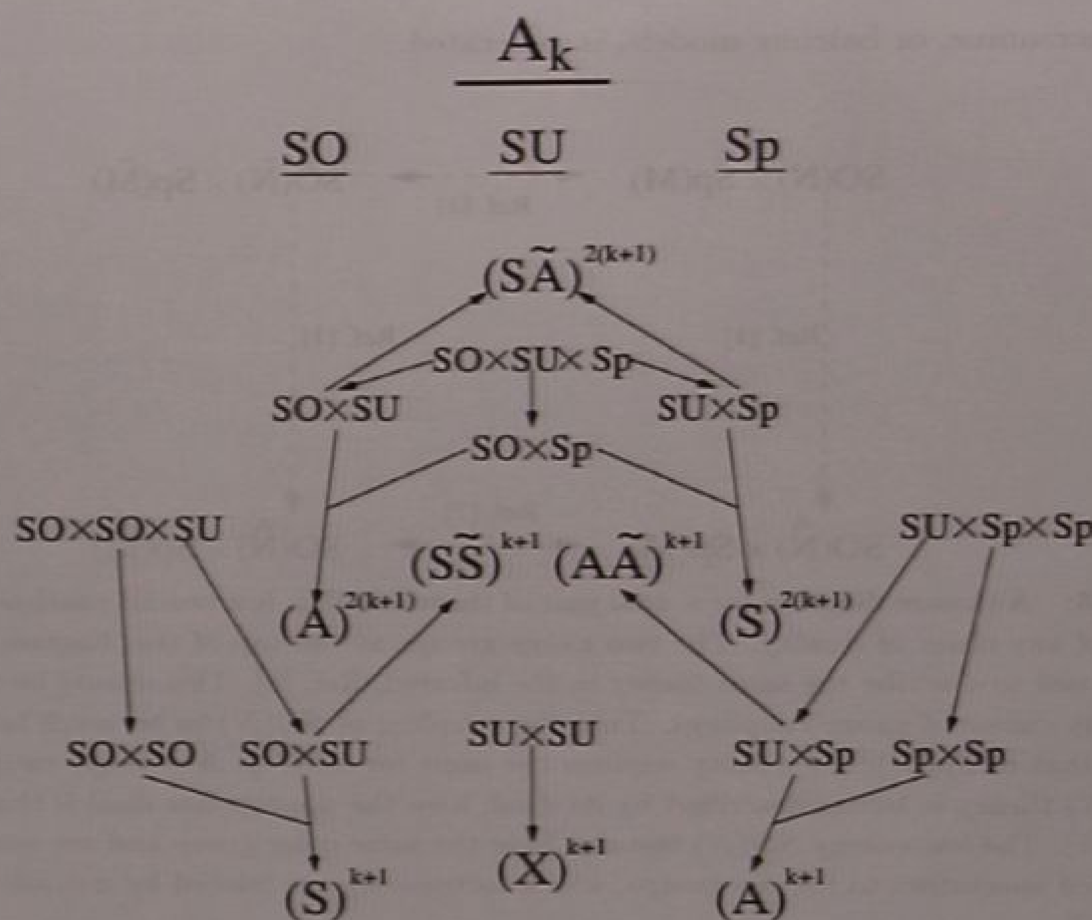

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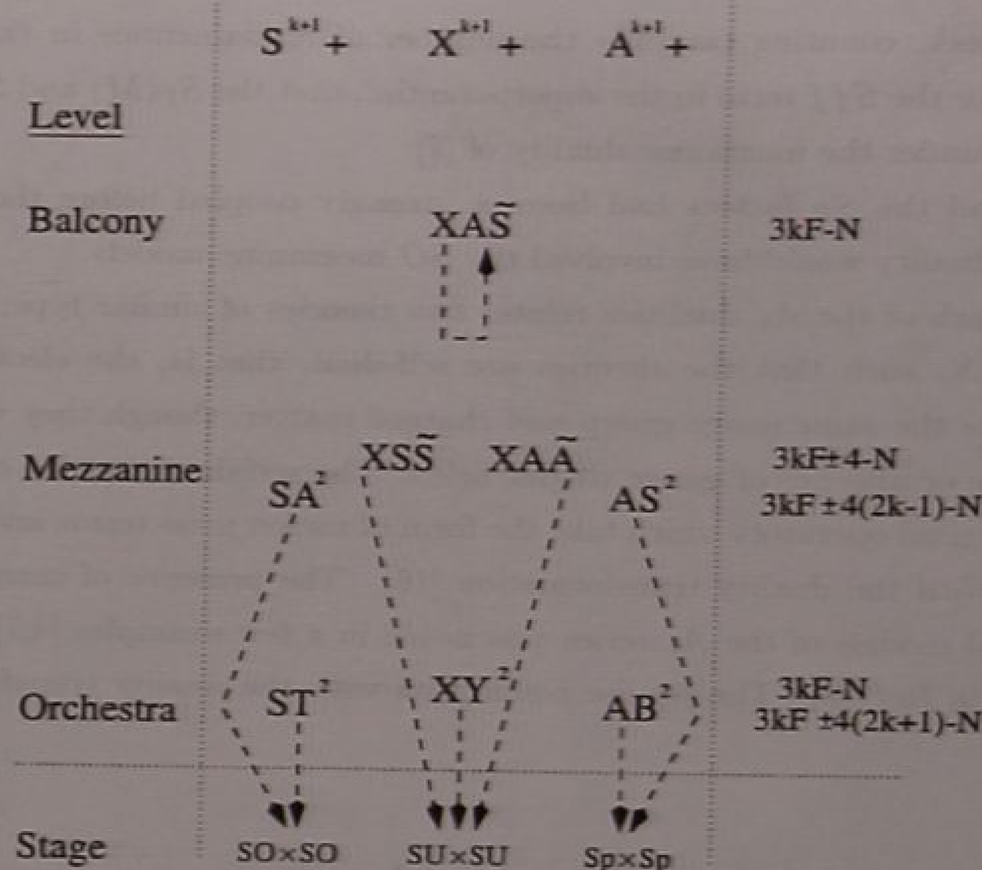

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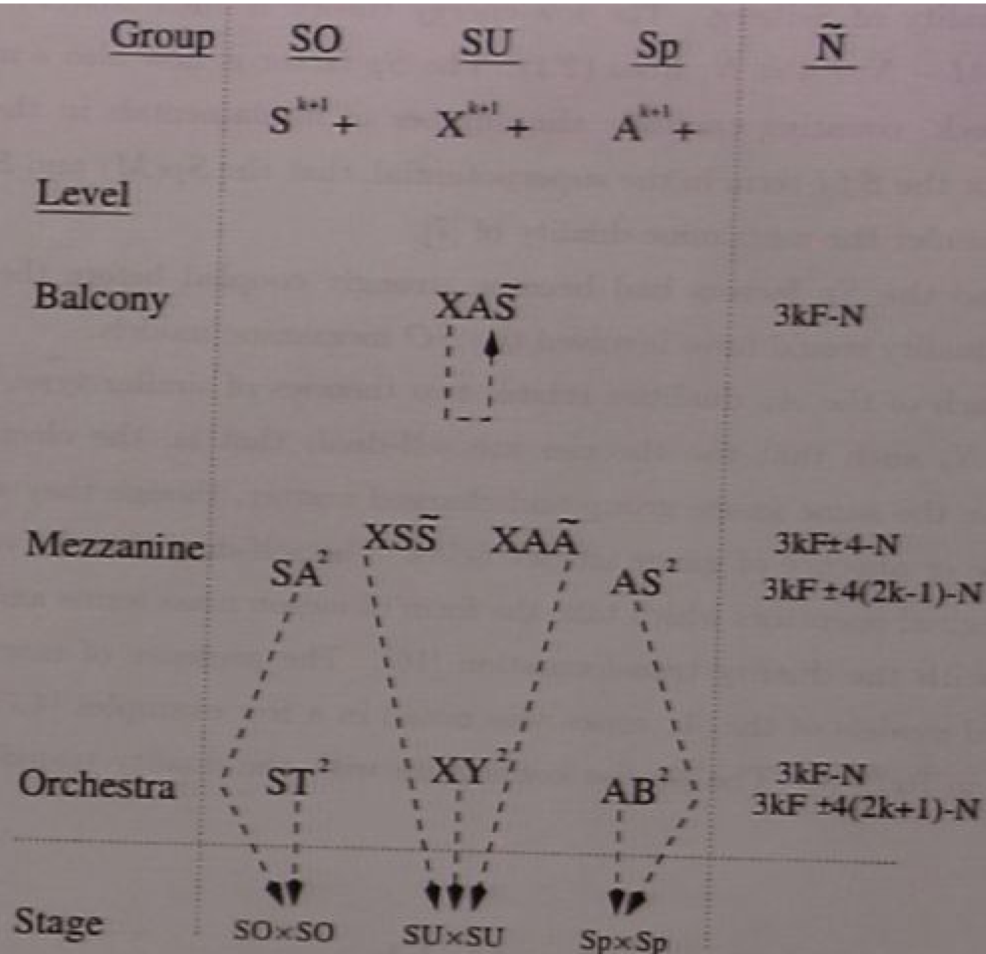
2 adj X, Y X AS

$\mathrm{tr}\,(X^{k+1} + XY^2)$

$(X^4 + XY^2) + \mathrm{tr}\, X^3$ D_{k+2}



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Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

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Pouliot:

G_2

$SO(7)$

$SO(8)$

Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

Pouliot:

G_2

$SO(7)$

$SO(8)$

$SO(9)$

$SO(10)$

Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

Pouliot:

G_2

$SO(7)$

$SO(8)$

$SO(9)$

$SO(10) \rightarrow N_v\ \underset{\sim}{10},\ N_q\ \underset{\sim}{16}$

Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

Pouliot:

G_2

$SO(7)$

$SO(8)$

$SO(9)$

$SO(10)$ $\to$ N_v $\underline{10}$, N_q $\underline{16}$ [not $\overline{\underline{16}}$!] [

Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

Pouliot:

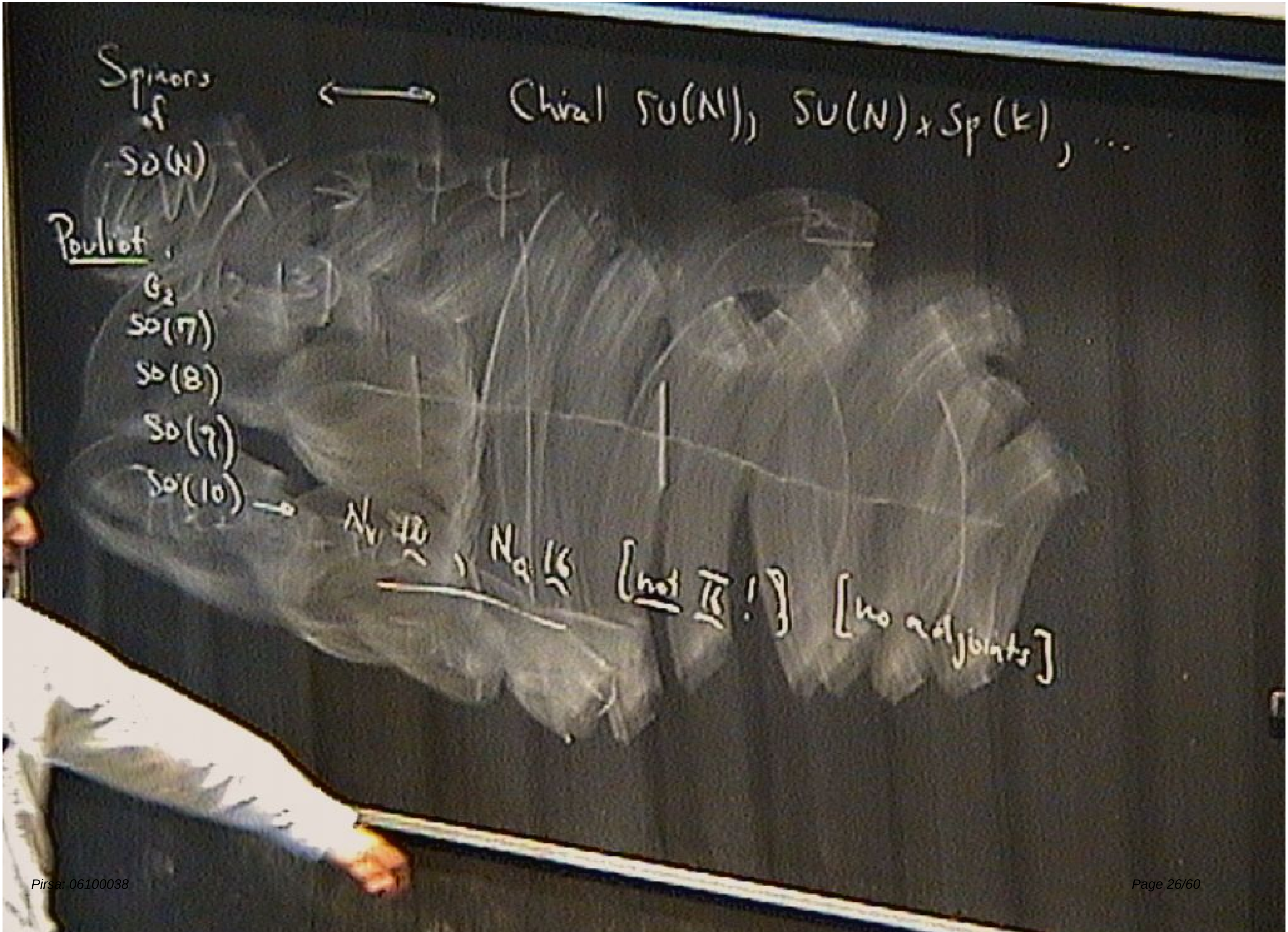
G_2

$SO(7)$

$SO(8)$

$SO(9)$

$SO(10)$ $\to$ $N_v\ \underset{\sim}{10}$, $N_q\ \underset{\sim}{16}$ [not $\overline{16}$!] [no adjoints]


Spinors of SO(N) ⟷ Chiral SU(N), SU(N) × Sp(k), ...
Pouliot:
G2
SO(7)
SO(8)
SO(9)
SO(10) → Nv 10, Nq 16 [not 16 !] [no adjoints]

Spinors of $SO(N)$ $\longleftrightarrow$ Chiral $SU(N)$, $SU(N) \times Sp(k)$, ...

Pouliot:

G_2

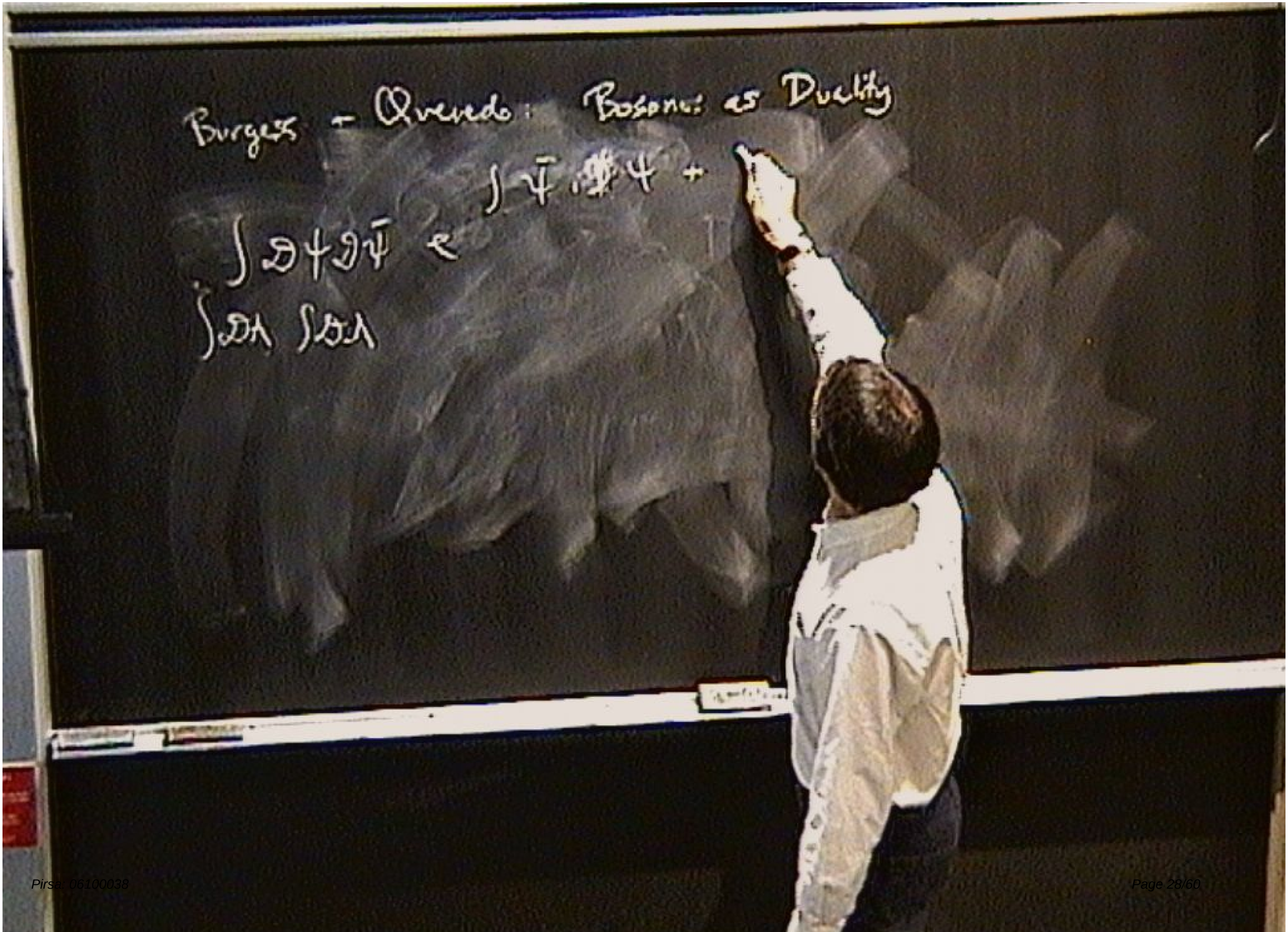
$SO(7)$

$SO(8)$

$SO(9)$

$SO(10)$ $\leftarrow$ DSB

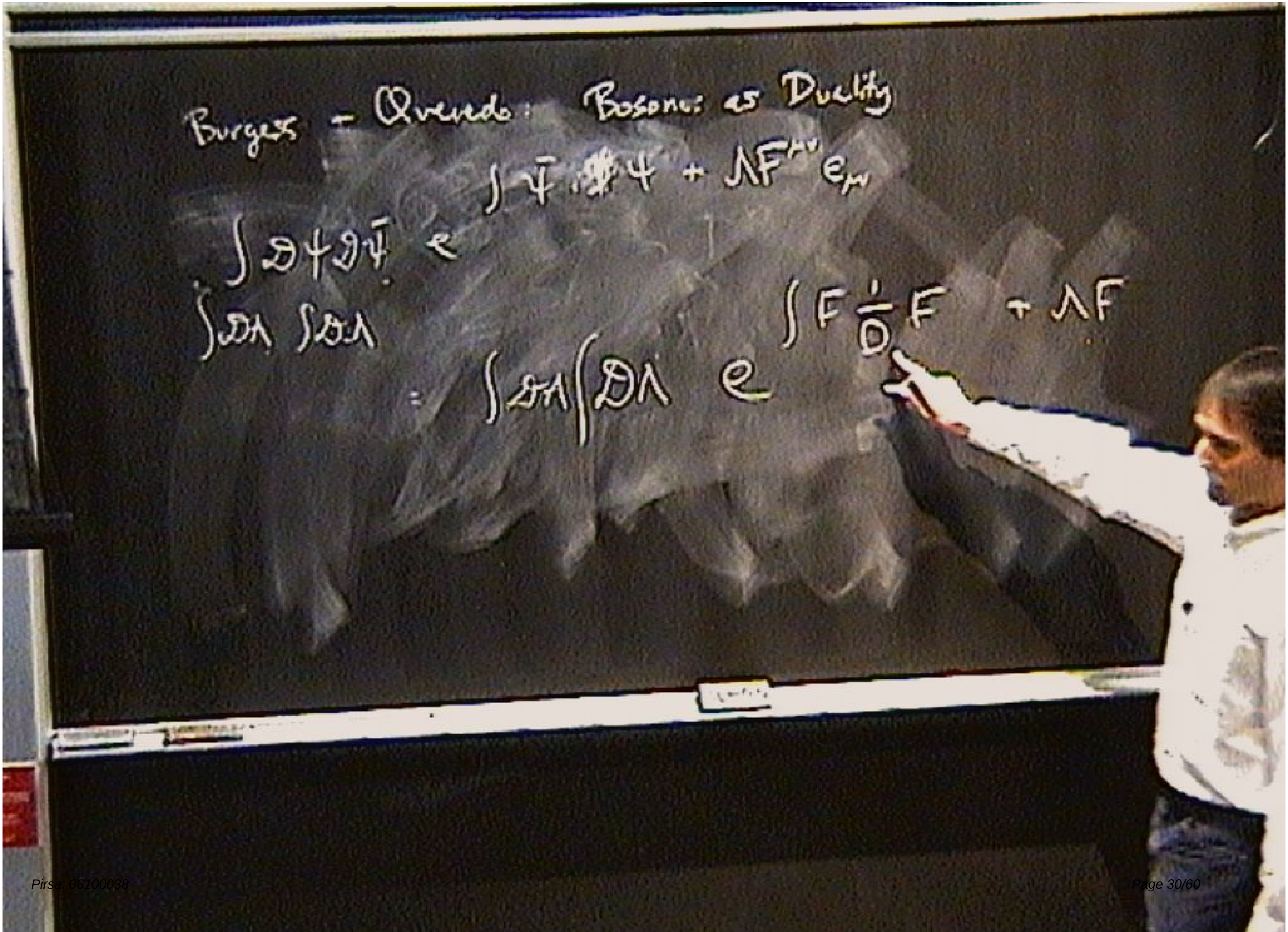
$SO(10) \rightarrow$ $N_f\ \underset{\sim}{10}$, $N_a\ \underset{\sim}{16}$ [not $\overline{\underset{\sim}{16}}$!] [no adjoints]


Burgess - Quevedo

Burgess + Quevedo: Bosoniz. as Duality

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi}\, e^{\int \bar{\psi}\, i\not{\partial}\psi + \Lambda F^{\mu\nu} \epsilon_{\mu\nu}}$$

$$\int \mathcal{D}A \int \mathcal{D}\Lambda$$


Burgess – Quevedo
Duality

Burgess – Quevedo: Bosoni as Duality

$$\int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\; e^{\int \bar{\psi}\, i \not{\partial} \psi + \Lambda F^{\mu\nu} \epsilon_{\mu\nu}}$$

$$\int \mathcal{D}\Lambda \int \mathcal{D}A$$

$$= \int \mathcal{D}A \int \mathcal{D}\Lambda\; e^{\int F \frac{1}{\square} F + \Lambda F}$$

$$= \int \mathcal{D}\Lambda\; e^{\int \Lambda \square \Lambda}$$

Burgess - Quevedo: Bosonization as Duality

$$Z(a) = \int \mathcal{D}\psi \mathcal{D}\bar\psi \; e^{\int \bar\psi \not{D} \psi + \Lambda F^{\mu\nu} \epsilon_{\mu\nu} - \bar\psi \gamma^\mu \gamma_5 \psi a_\mu}$$

$$\int \mathcal{D}A \int \mathcal{D}\Lambda$$

$$= \int \mathcal{D}A \int \mathcal{D}\Lambda \; e^{\int F \frac{1}{\Box} F + \Lambda F}$$

$$= \int \mathcal{D}\Lambda \; e^{\int \Lambda \Box \Lambda}$$

Burgess - Quevedo: Bosoniz as Duality

$$Z[a] = \int \mathcal{D}\psi \mathcal{D}\bar\psi \; e^{\int \bar\psi \not{D} \psi + \Lambda F^{\mu\nu} \epsilon_{\mu\nu} - \bar\psi \gamma^\mu \gamma_5 \psi \, a^\mu}$$

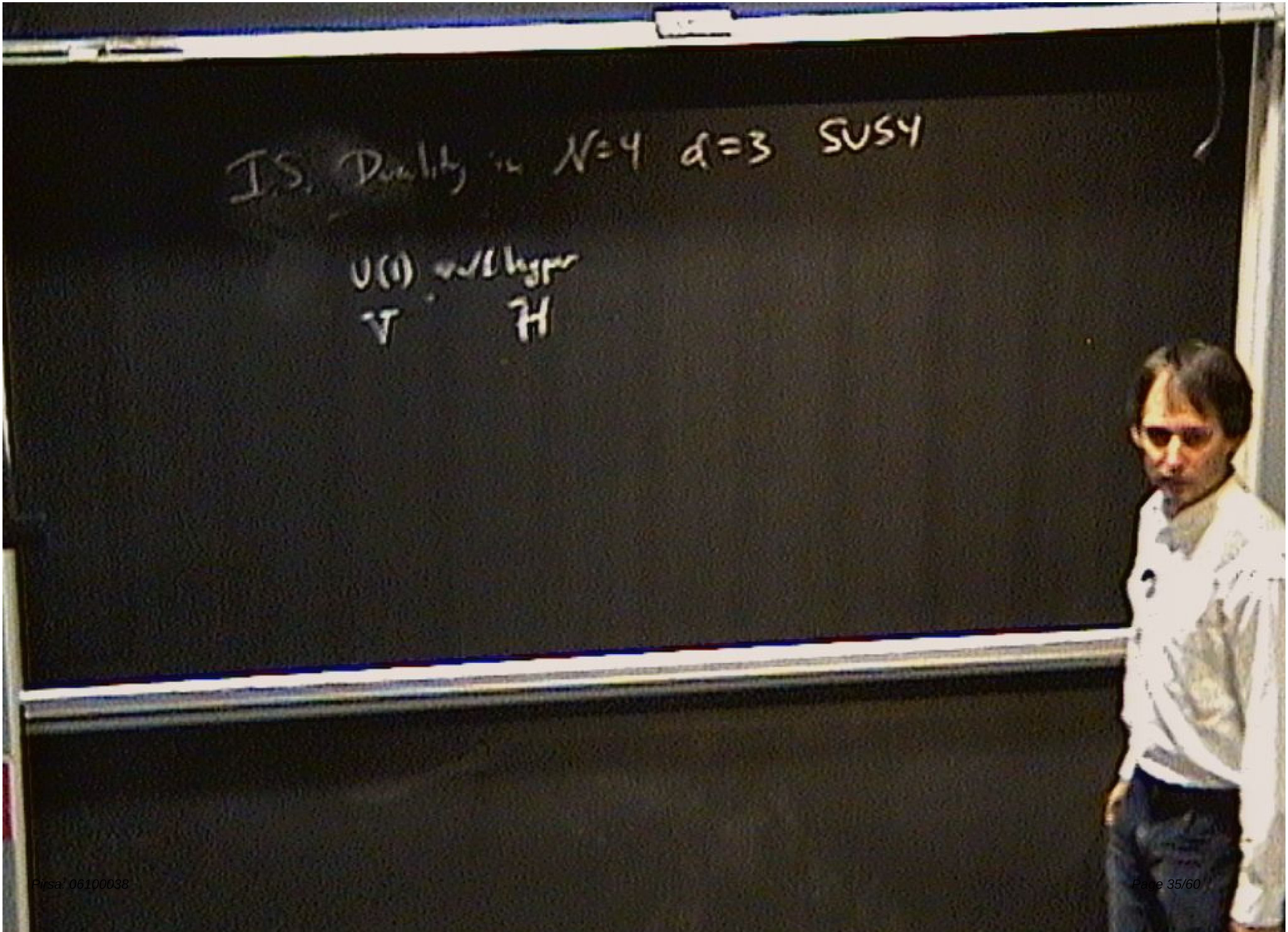
$$\int \mathcal{D}\Lambda \int \mathcal{D}\Lambda$$

$$\int F \frac{1}{\Box} F + \Lambda F + \cdots$$

$$= \int \mathcal{D}a \int \mathcal{D}\Lambda \; e$$

$$= \int \mathcal{D}\Lambda \; e^{\int \Lambda \Box \Lambda + a^\mu \partial_\mu \Lambda + a_\mu a^\mu}$$

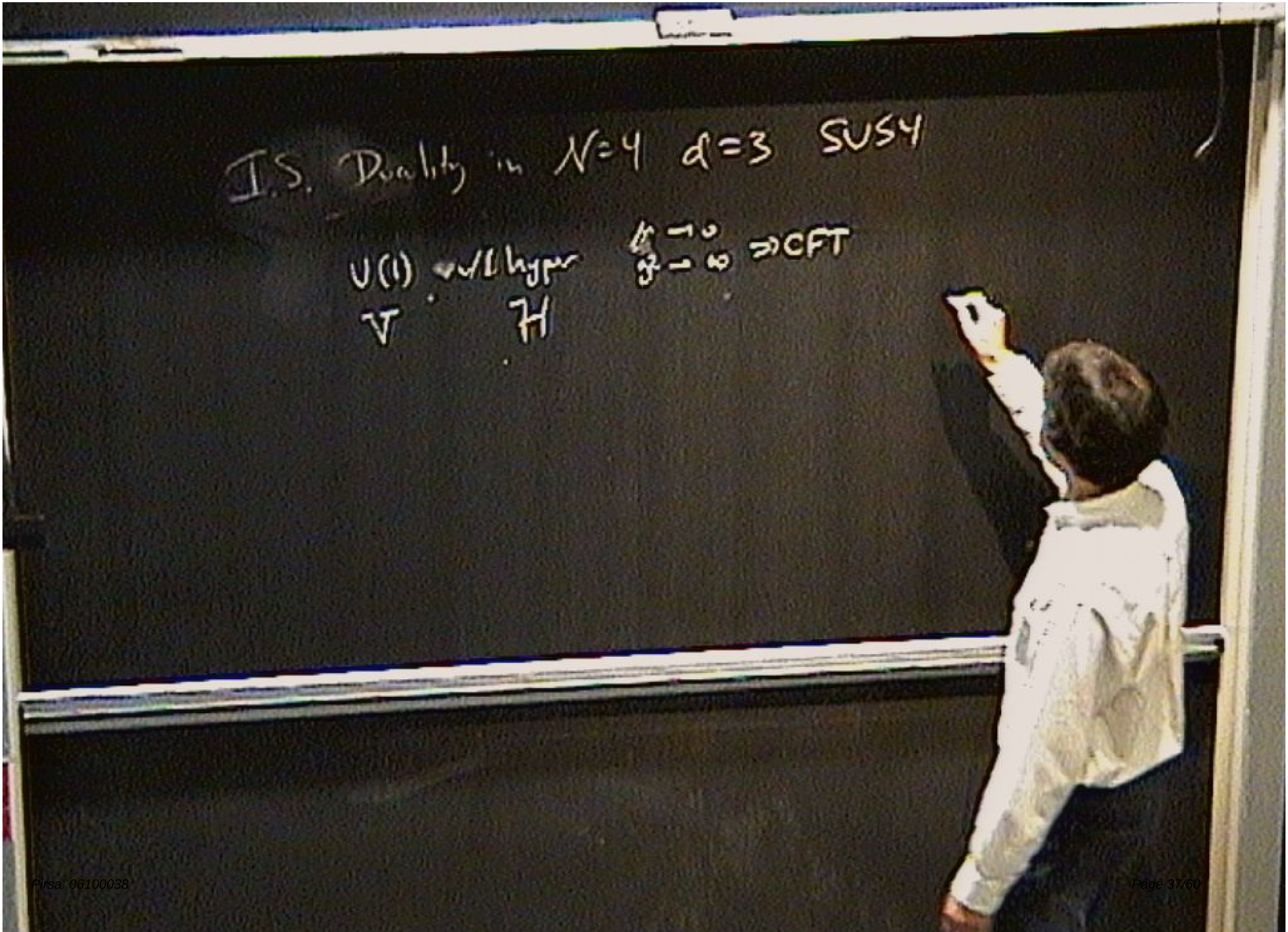
I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

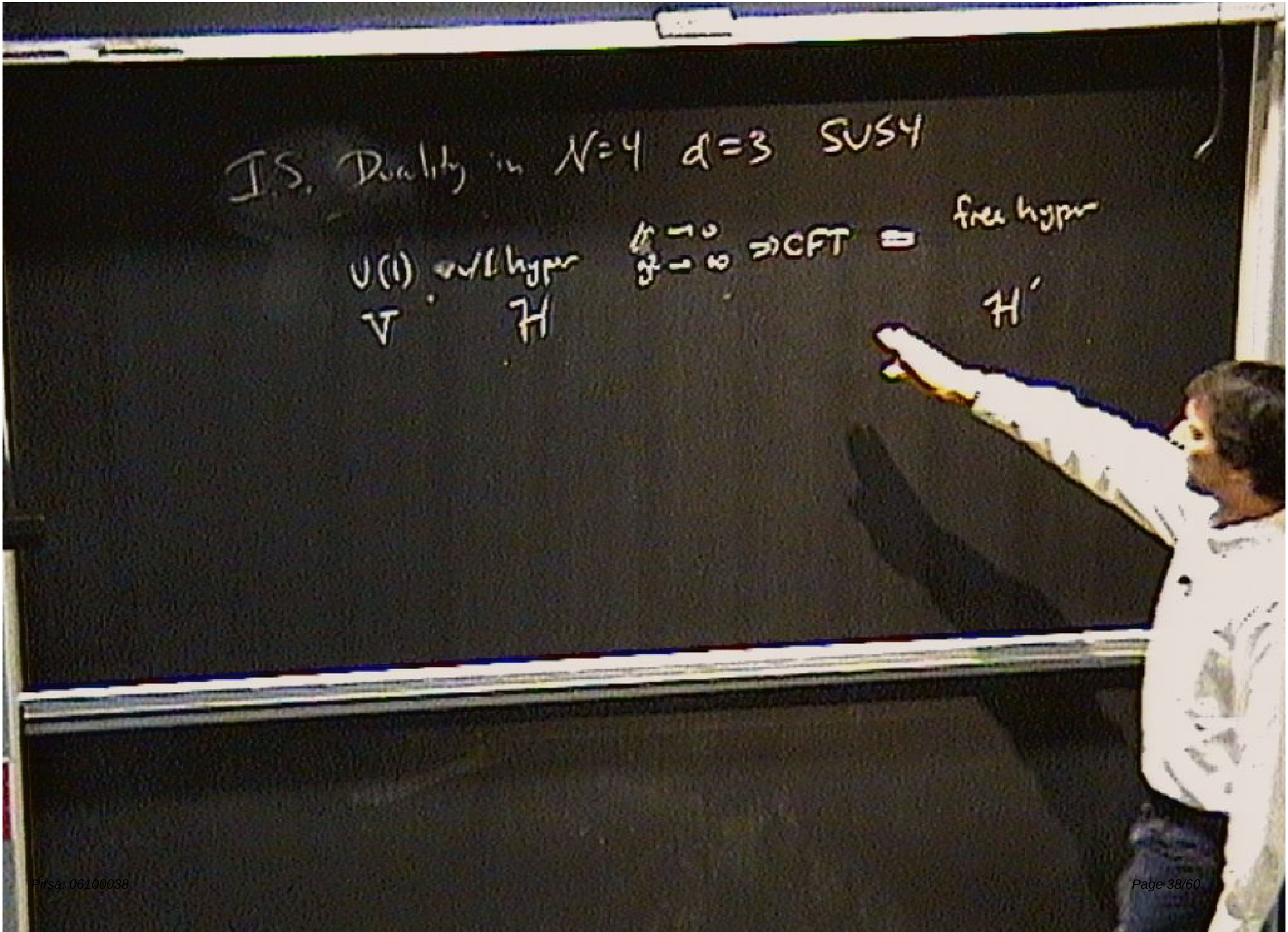

I.S. Duality in N=4 d=3 SUSY
U(1) w/1 hyper
V H

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

$U(1)$ w/ 1 hyper $g \to$

$\mathcal{V}$ $\mathcal{H}$


I.S. Duality in N=4 d=3 SUSY
U(1) w/1 hyper
⇒CFT
V
H


I.S. Duality in N=4 d=3 SUSY
U(1) w/1 hyper
⇒CFT = free hyper
V H H'

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

$U(1)$ w/ 1 hyper $\quad \begin{matrix} g \to 0 \\ g \to \infty \end{matrix} \Rightarrow$ CFT $=$ free hyper

$V \qquad \mathcal{H} \qquad\qquad\qquad \mathcal{H}'$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/ 1 hyper $\quad$ $g \to 0$, $g \to \infty$ $\Rightarrow$ $\boxed{\text{CFT} = \text{free hyper } \mathcal{H}'}$

$V \qquad \mathcal{H}$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/1 hyper $\quad e \to 0,\ g \to \infty \Rightarrow$ CFT = free hyper

V $\quad$ H $\quad\quad\quad\quad\quad\quad\quad\quad$ H'

flavor current J

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

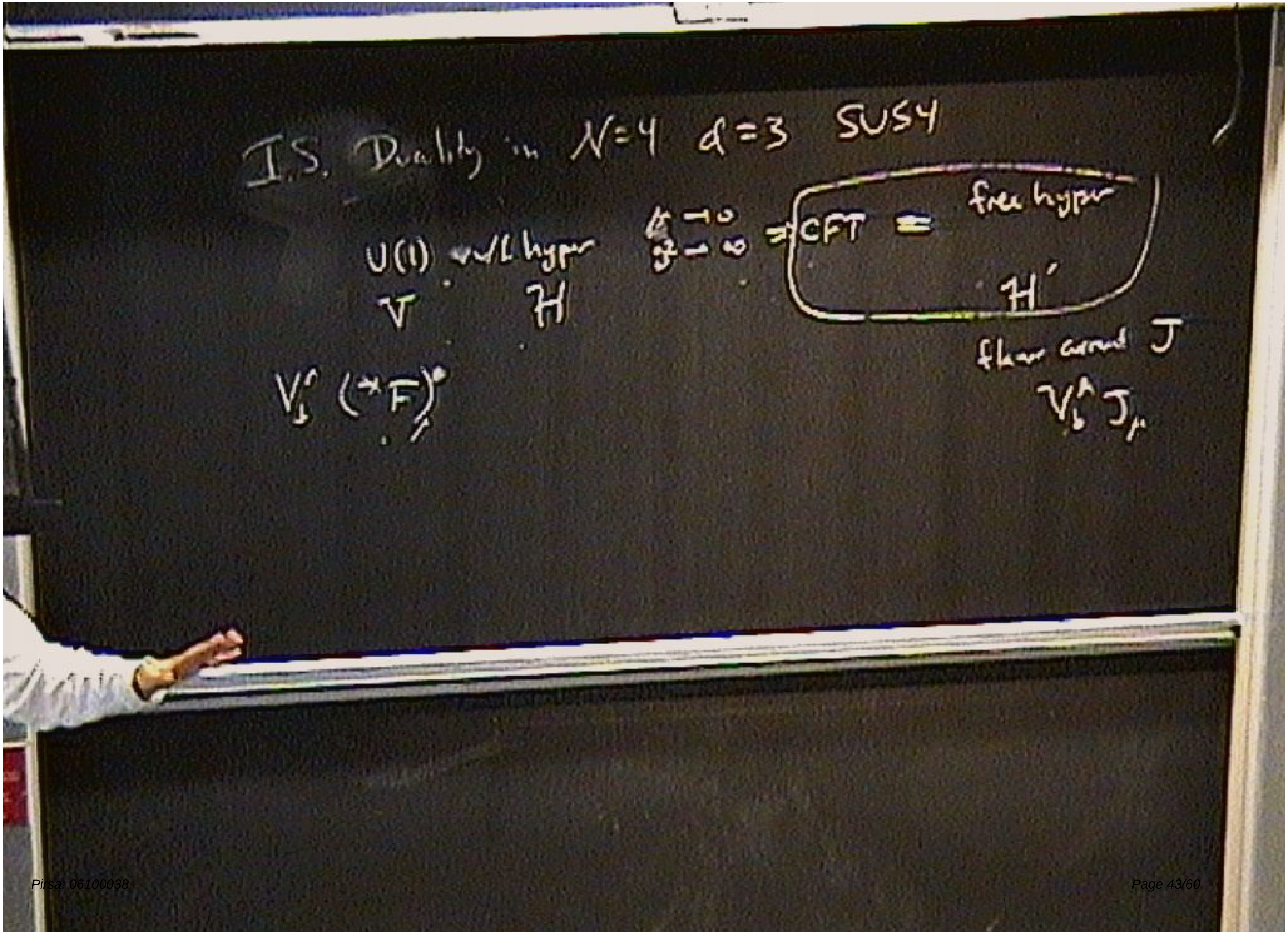
$U(1)$ w/1 hyper $\quad g \to 0, \; g \to \infty \Rightarrow \boxed{\text{CFT} = \text{free hyper} \;\; \mathcal{H}'}$

$V \qquad \mathcal{H}$

$({}^*F)^2$

flavor current J

V_b


I.S. Duality in N=4 d=3 SUSY
U(1) w/1 hyper
V H
CFT = free hyper
H'
flux around J

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/1 hyper $\quad \begin{matrix} g \to 0 \\ g \to \infty \end{matrix} \Rightarrow$ CFT $=$ free hyper

$\mathcal{V} \qquad \mathcal{H} \qquad\qquad\qquad\qquad \mathcal{H}'$

flavor current J

$V_b^\mu ({}^*F)_\mu \cdot V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \qquad\qquad V_b^\mu J_\mu$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/ 1 hyper $\quad g \to \infty \Rightarrow$ CFT = free hyper

$V \qquad \mathcal{H} \qquad\qquad\qquad \mathcal{H}'$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \qquad\qquad V_b^\mu J_\mu$

$Z(V_b)$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

$U(1)$ w/1 hyper $\quad g \to \infty \Rightarrow$ CFT $=$ free hyper

$V \qquad H \qquad\qquad\qquad H'$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \qquad V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V \mathcal{D}H \, e^{\int \mathcal{L}(V,H)}$$

III.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

$U(1)$ w/1 hyper $\quad g \to \infty \Rightarrow \boxed{\text{CFT} = \text{free hyper } \mathcal{H}'}$

$V \quad \mathcal{H}$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \qquad V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V \, \mathcal{D}\mathcal{H} \, e^{-\int \mathcal{L}(V,\mathcal{H}) + \frac{1}{g^2}(F_{\mu\nu}^2 \cdots)}$$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/1 hyper $\quad g \to 0$, $g \to \infty$ $\Rightarrow$ $\boxed{\text{CFT} = \text{free hyper} \; \mathcal{H}'}$

$V \quad \mathcal{H}$

flavor current J

$V_b^{\mu} ({}^*F)^{\mu} = V_b^{\mu} F^{\nu\rho} \epsilon_{\mu\nu\rho}$ $\qquad V_b^{\mu} J_{\mu}$

$$Z(V_b) = \int \mathcal{D}V \, \mathcal{D}\mathcal{H} \, e^{-\int \mathcal{L}(V,\mathcal{H}) + \frac{1}{g^2}(F_{\mu\nu}^2 + \cdots) + V_b {}^*F}$$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/1 hyper $\quad g \to 0$, $g \to \infty$ $\Rightarrow$ CFT $=$ free hyper

$V \quad \mathcal{H} \quad\quad\quad\quad\quad\quad \mathcal{H}'$

flavor current J

$V_b' F^{\nu\rho} \epsilon_{\mu\nu\rho} \quad\quad V_b^\mu J_\mu$

$Z[\ldots] = \int \mathcal{D}V \mathcal{D}\mathcal{H}\, e^{\int \mathcal{L}(V,\mathcal{H}) + \frac{1}{g^2}(F_{\mu\nu}^2 \cdots) + V_b F}$

$V]$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/1 hyper $\quad g \to 0, \; g \to \infty \Rightarrow$ $\boxed{\text{CFT} = \text{free hyper} \quad \mathcal{H}'}$

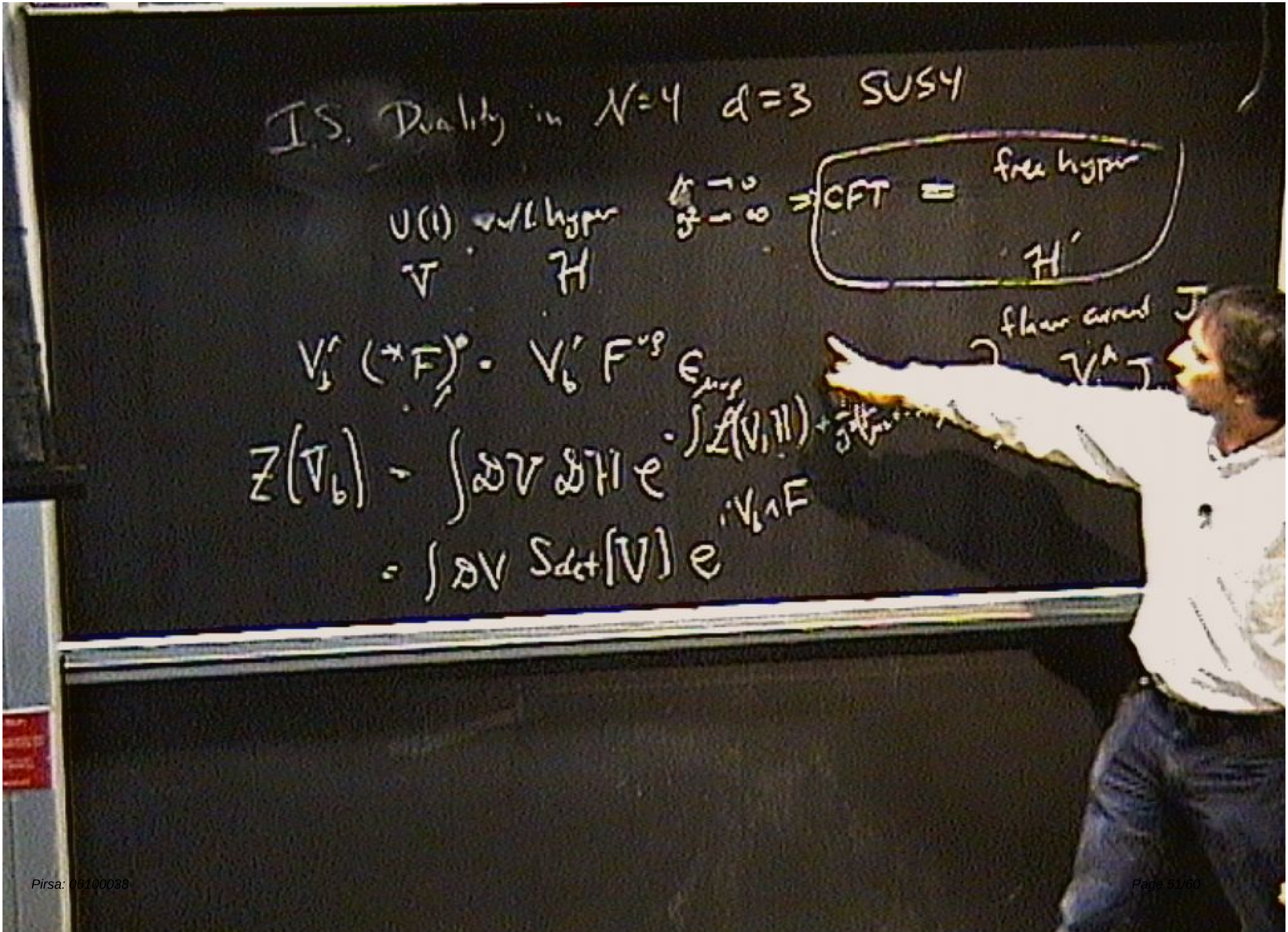
$V \qquad \mathcal{H}$

flavor current J

$V_b^\mu ({}^*F)^\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho}$ $\qquad V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V \mathcal{D}\mathcal{H} \, e^{-\int \mathcal{L}(V,\mathcal{H}) + \frac{1}{g^2}(F) \ldots + V_b F}$$

$$= \int \mathcal{D}V \, \mathrm{Sdet}[V]$$


I.S. Duality in N=4 d=3 SUSY
U(1) w/1 hyper
CFT = free hyper
flavor current J

II.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/ 1 hyper $\quad g \to 0$, $g \to \infty$ $\Rightarrow$ CFT = free hyper

$V \quad \mathcal{H} \qquad\qquad\qquad\qquad \mathcal{H}'$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho}\epsilon_{\mu\nu\rho} \qquad V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V\,\mathcal{D}\mathcal{H}\, e^{i\int \mathcal{L}(V,\mathcal{H}) + \frac{1}{g^2}(F_{\mu\nu}^2 + \cdots) + iV_b \wedge F}$$

$$= \int \mathcal{D}V\, \mathrm{Sdet}[V]\, e^{iV_b \wedge F}$$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/ 1 hyper $\;\; g \to \infty \Rightarrow$ $\boxed{\text{CFT} = \text{free hyper} \;\; \mathcal{H}'}$

$V \qquad \mathcal{H}$

flavor current J

$$V_b^\mu \, ({}^*F)_\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \qquad \underbrace{V_b^\mu J_\mu}$$

$$Z(V_b) = \int \mathcal{D}V \, \mathcal{D}\mathcal{H} \, e^{i\int \mathcal{L}(V,\mathcal{H}) + \cancel{\frac{1}{g^2}(F^2 + \cdots)} + i V_b \wedge F}$$

$$= \int \mathcal{D}V \, \mathrm{Sdet}[V] \, e^{i V_b \wedge F}$$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

$U(1)$ w/1 hyper $\quad g \to 0,\ g \to \infty \Rightarrow \boxed{\text{CFT} = \text{free hyper } \mathcal{H}'}$

$V \qquad \mathcal{H}$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho} \epsilon_{\mu\nu\rho} \quad V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V \, \mathcal{D}\mathcal{H} \, e^{i\int \mathcal{L}(V,\mathcal{H}) + \cancel{\frac{1}{g^2}(F^2 \ldots)} + i V_b \wedge F}$$

$$= \int \mathcal{D}V \, \mathrm{Sdet}[V] \, e^{i V_b \wedge F} =$$

I.S. Duality in $\mathcal{N}=4$ $d=3$ SUSY

U(1) w/ 1 hyper $\quad g\to 0$, $g\to\infty$ $\Rightarrow$ $\boxed{\text{CFT} = \text{free hyper } H'}$

$V \quad H$

flavor current J

$V_b^\mu ({}^*F)_\mu = V_b^\mu F^{\nu\rho}\epsilon_{\mu\nu\rho} \to V_b^\mu J_\mu$

$$Z(V_b) = \int \mathcal{D}V\,\mathcal{D}H\, e^{-\int \mathcal{L}(V,H) + \cancel{\frac{1}{g^2}(F^2+\cdots)} + iV_b F} = \int \mathcal{D}H'\, e^{-\int \mathcal{L}(V_b,H')}$$

$$= \boxed{\int \mathcal{D}V\, S_{det}[V]\, e^{iV_b\wedge F} = S_{det}[V_b]}$$

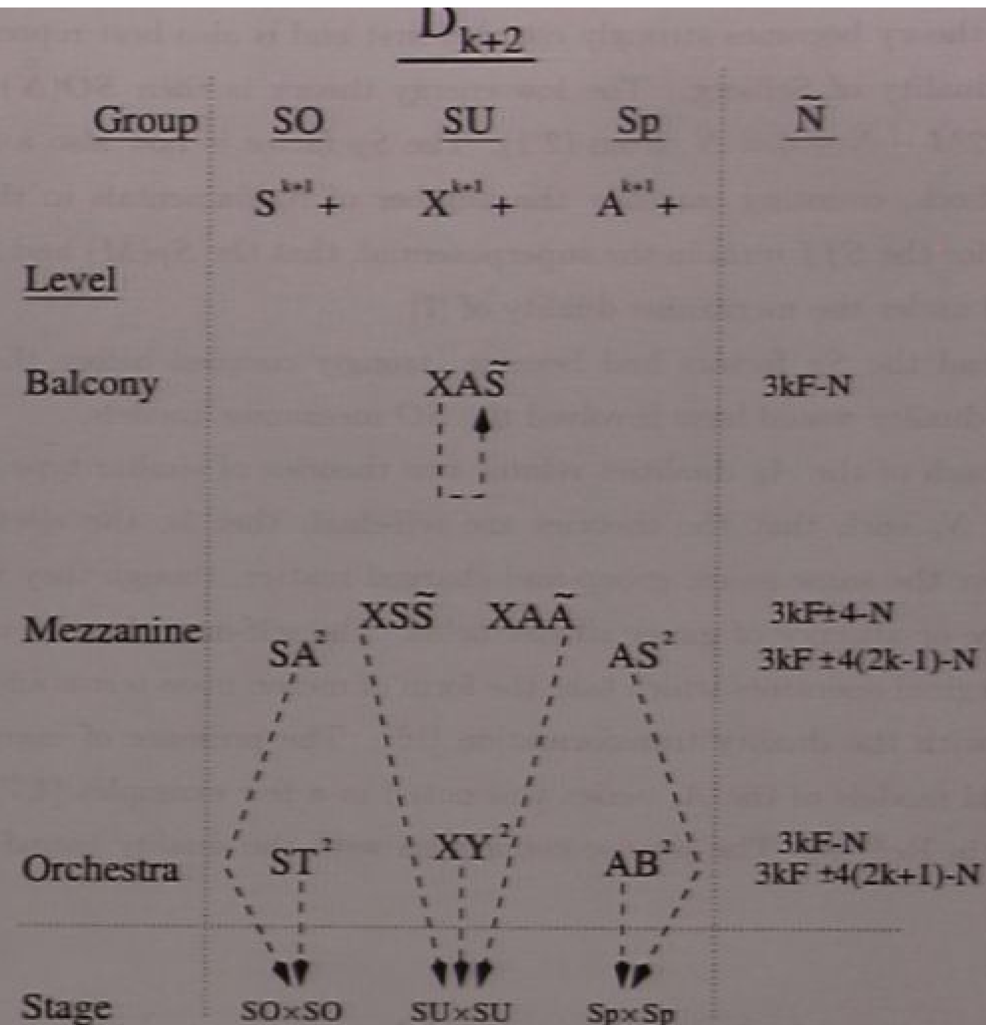


Fig. 4: The ensemble of D_{k+2} models described in this paper, along with the product models to which they are related. Notation is similar to fig. 1, with X, Y adjoint fields of $SU(N)$, S, T symmetric tensors and A, B anti-symmetric tensors, and a tilde representing a conjugate representation of $SU(N)$. For SU $[SO]$ (Sp) groups, $N = N_c$ $[N_c]$ $(2N_c)$ and $F = N_f$ $[N_f]$ $(2N_f)$. The superpotential for each model is given, with the first term listed at the top and the second at the position of the model in the diagram; thus the superpotential for the Mezzanine $SO(N)$ model is $S^{k+1} + SA^2$, *etc.* Each model is dual to a model of similar type, with color group $SU(\tilde{N})$, $SO(\tilde{N})$ or $Sp(\frac{\tilde{N}}{2})$. The dashed arrows indicate that under certain perturbations the D_{k+2} models flow to stage models, except for the balcony model which flows to copies of itself with lower k.

On Mediating Supersymmetry Breaking in D-brane Models

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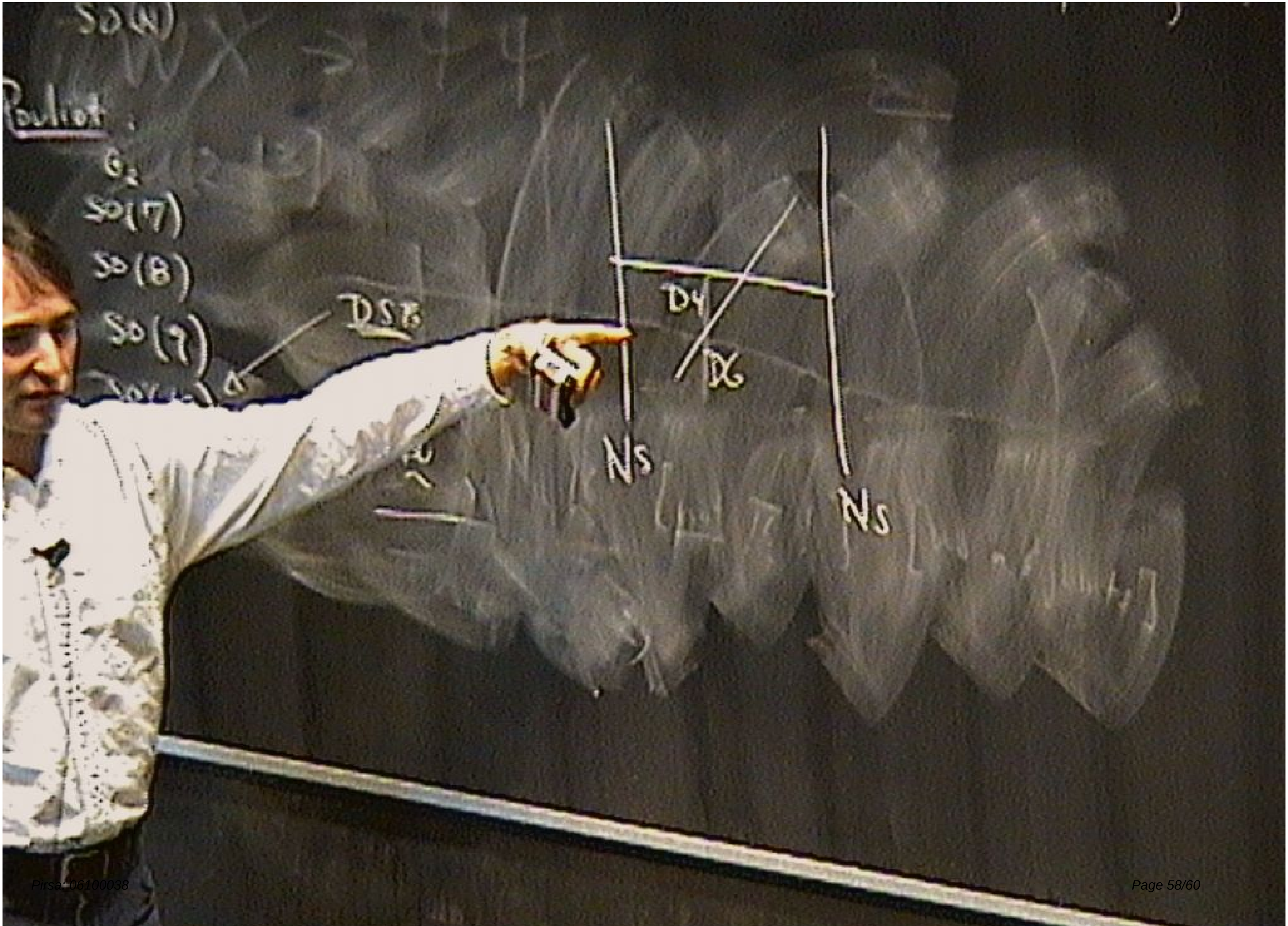
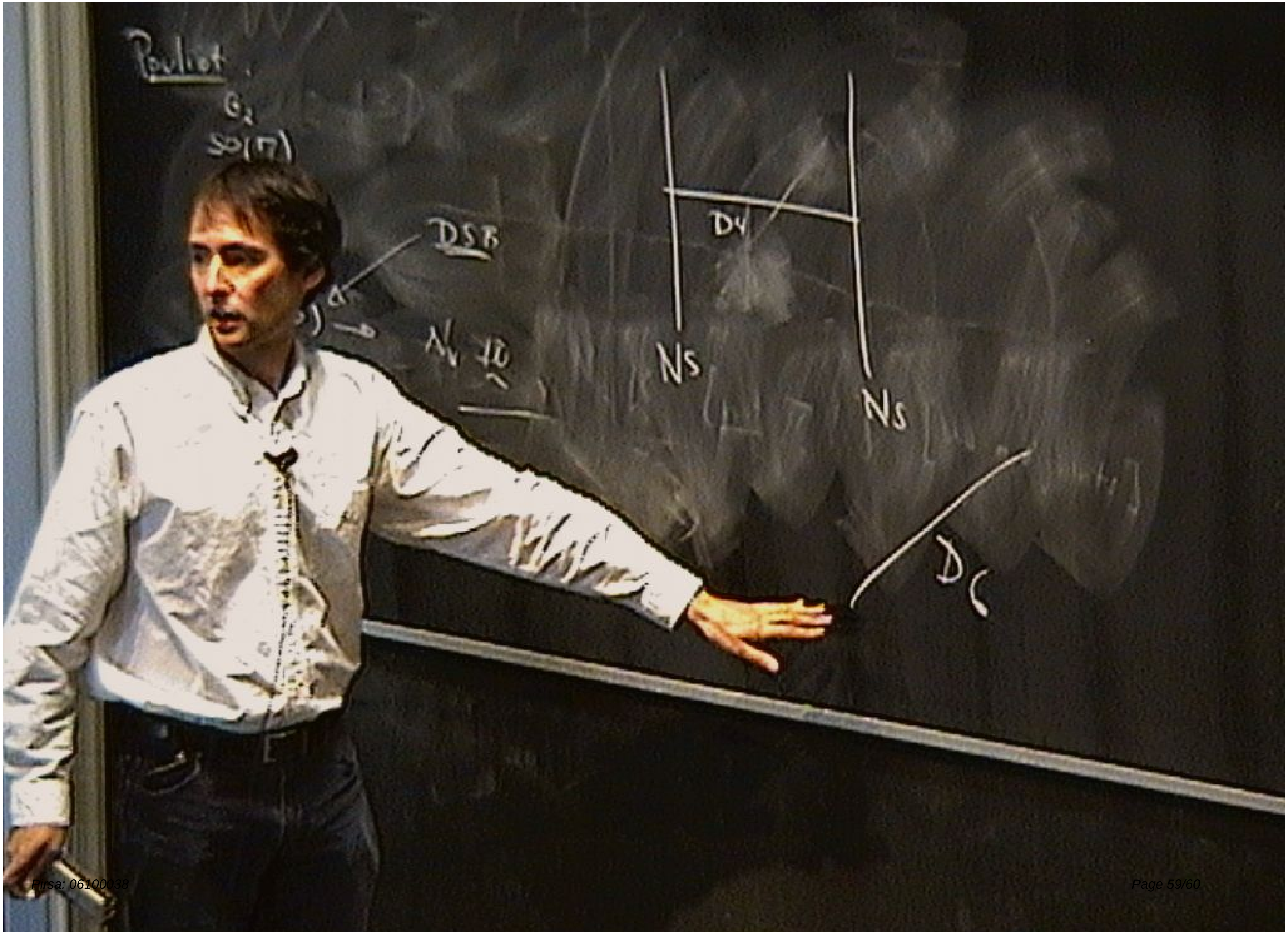
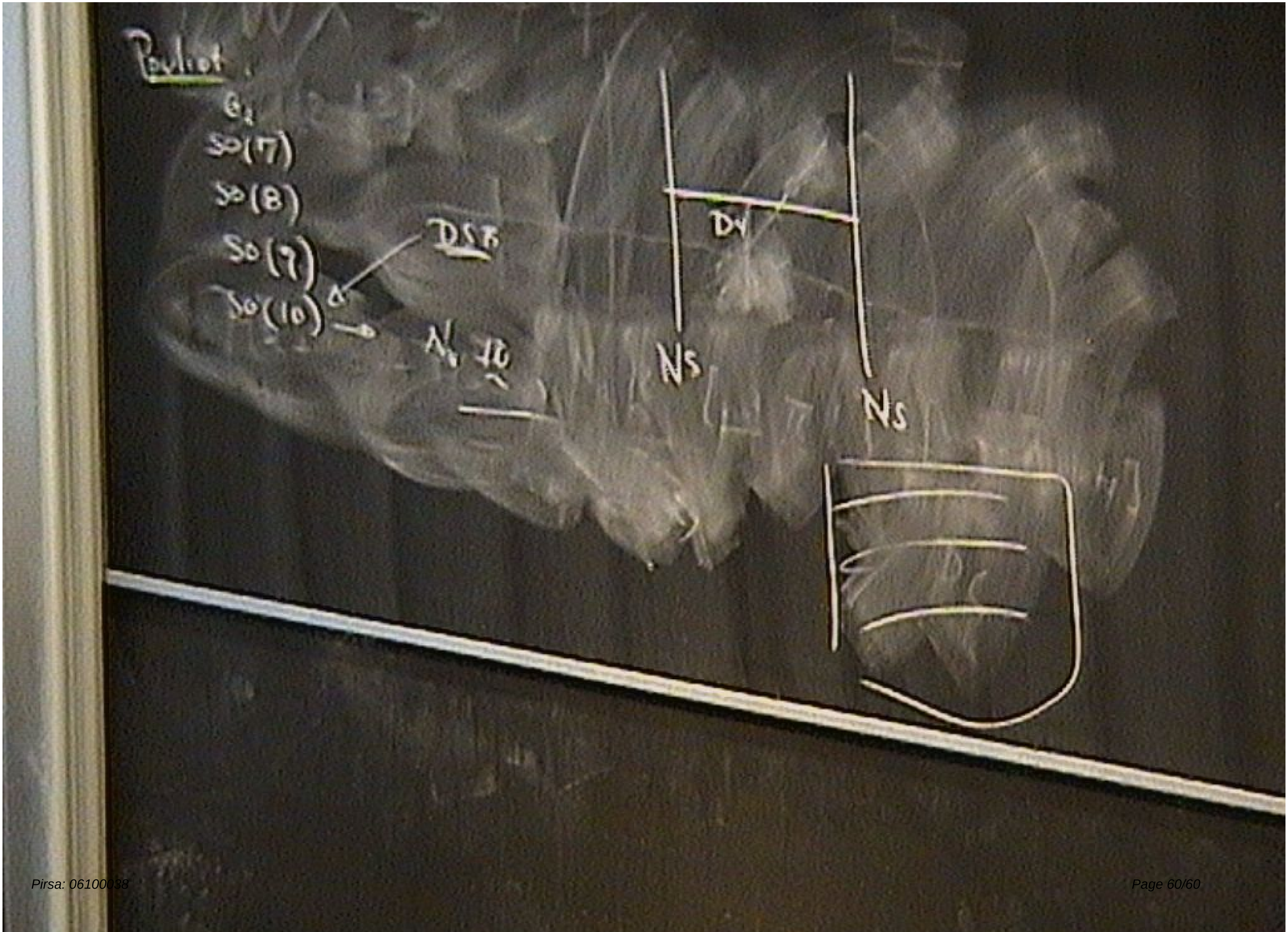
Abstract

We consider the 3+1 visible sector to live on a Hanany-Witten D-brane construction in type IIA string theory. The messenger sector consists of stretched strings from the visible brane to a hidden D6-brane in the extra spatial dimensions. In the open string channel supersymmetry is broken by gauge mediation while in the closed string channel supersymmetry is broken by gravity mediation. Hence, we call this kind of mediation "string mediation". We propose an extension of the Dimopoulos-Georgi theorem to brane models: only detached probe branes can break supersymmetry without generating a tachyon. Fermion masses are generated at one loop if the branes break a sufficient amount of the ten dimensional Lorentz group while scalar potentials are generated if there is a force between the visible brane and the hidden brane. Scalars can be lifted at two loops through a combination of brane bending and brane forces. We find a large class of stable non-supersymmetric brane configurations of ten dimensinoal string theory.


SO(17)
SO(8)
SO(9)
DSB
D4
D6
NS
NS


Poulist
G_2
SO(17)
DSB
NS
D4
NS
D6


SO(7)
SO(8)
SO(9)
SO(10)
DSB
Ns
Ns