Title: Beyond the Standard Model (Review) - Lecture 4

Date: Feb 16, 2012 09:00 AM

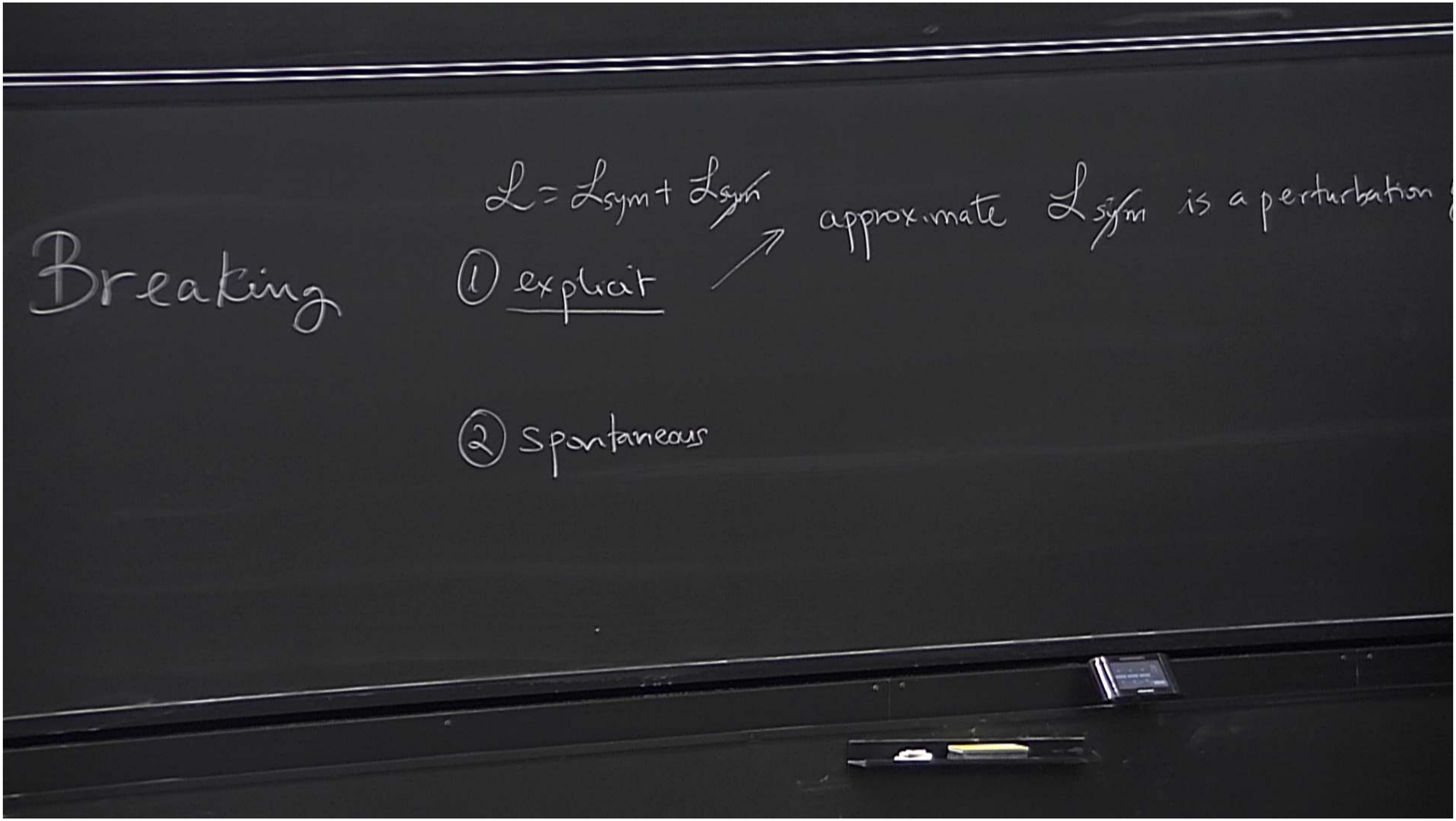
URL: http://pirsa.org/12020067

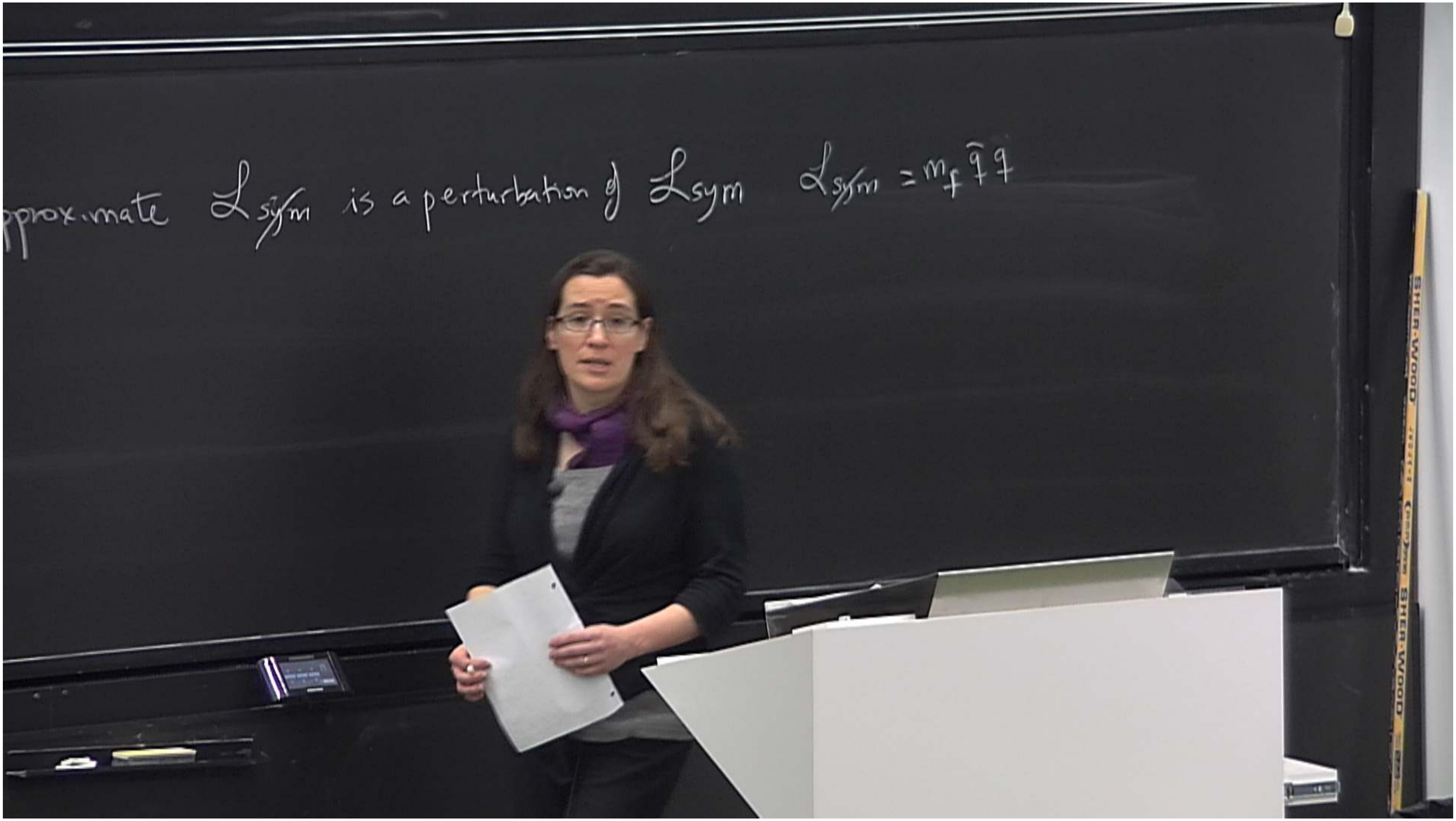
Abstract:

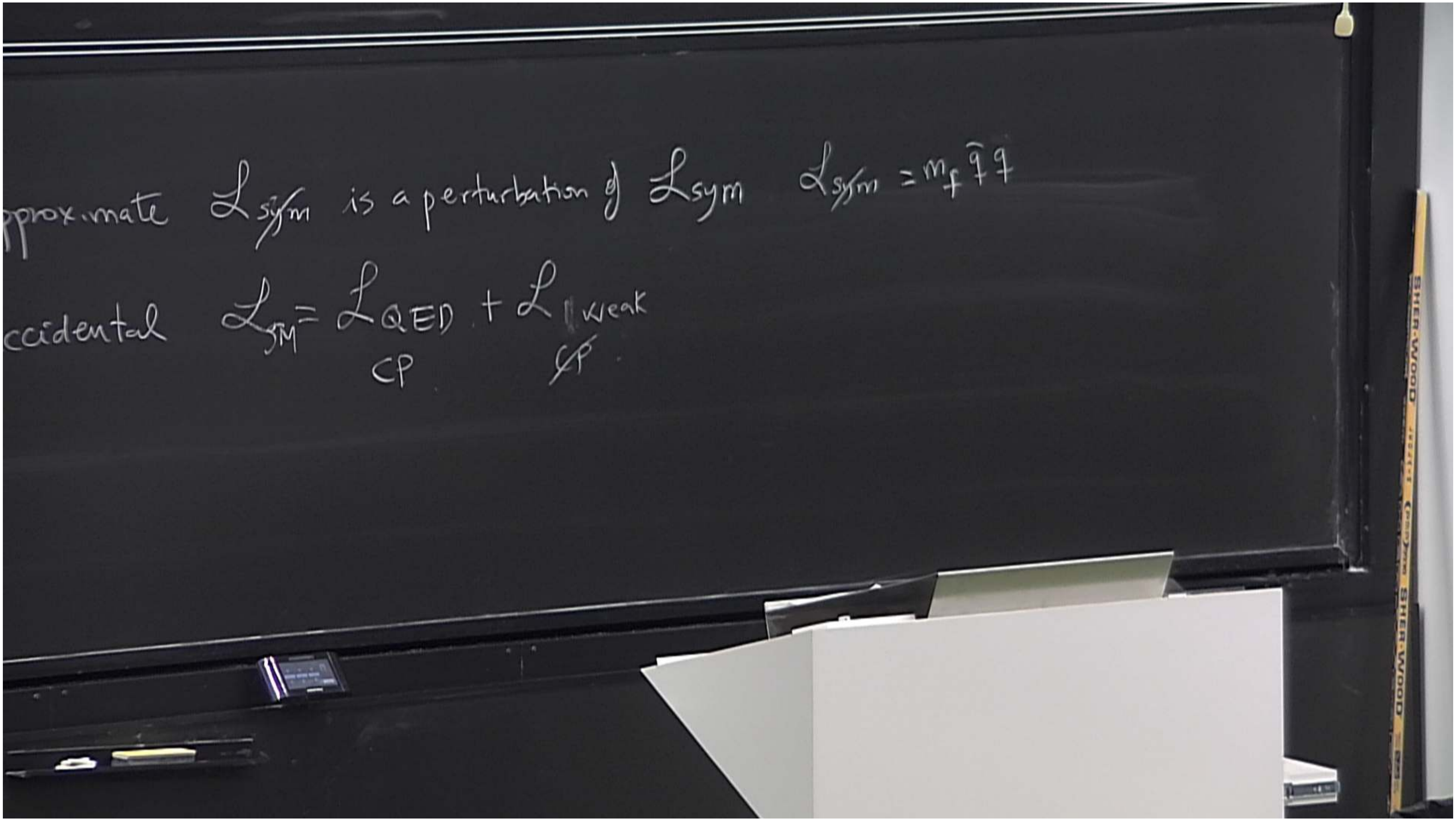
Breaking

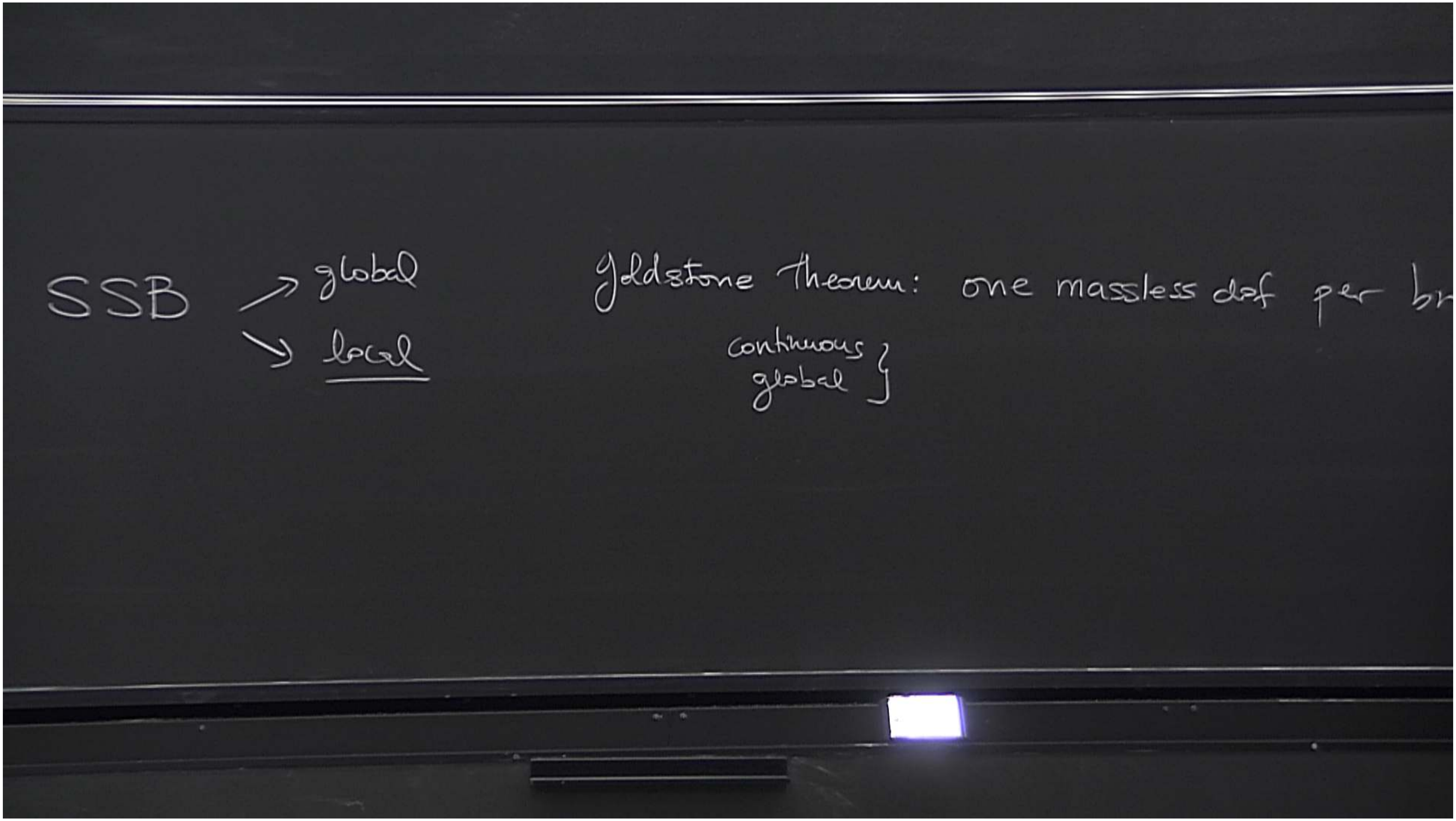
1. explicit

2. spontaneous


Breaking
$\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{\cancel{sym}}$
approximate $\mathcal{L}_{\cancel{sym}}$ is a perturbation
① explicit
② spontaneous

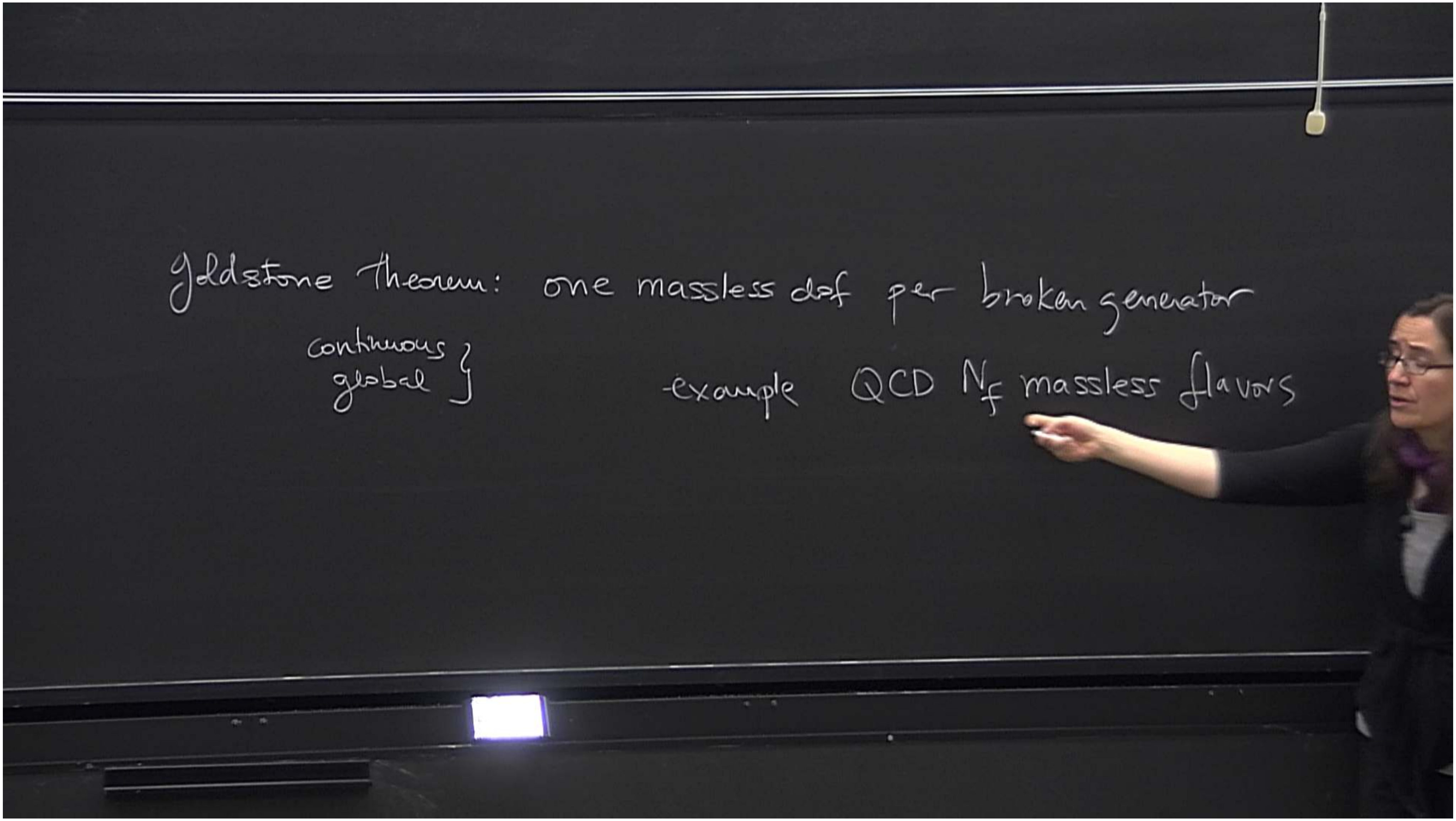

pproximate $\mathcal{L}_{\cancel{sym}}$ is a perturbation of $\mathcal{L}_{sym}$ $\mathcal{L}_{\cancel{sym}} = m_f \bar{q} q$
SHER-WOOD

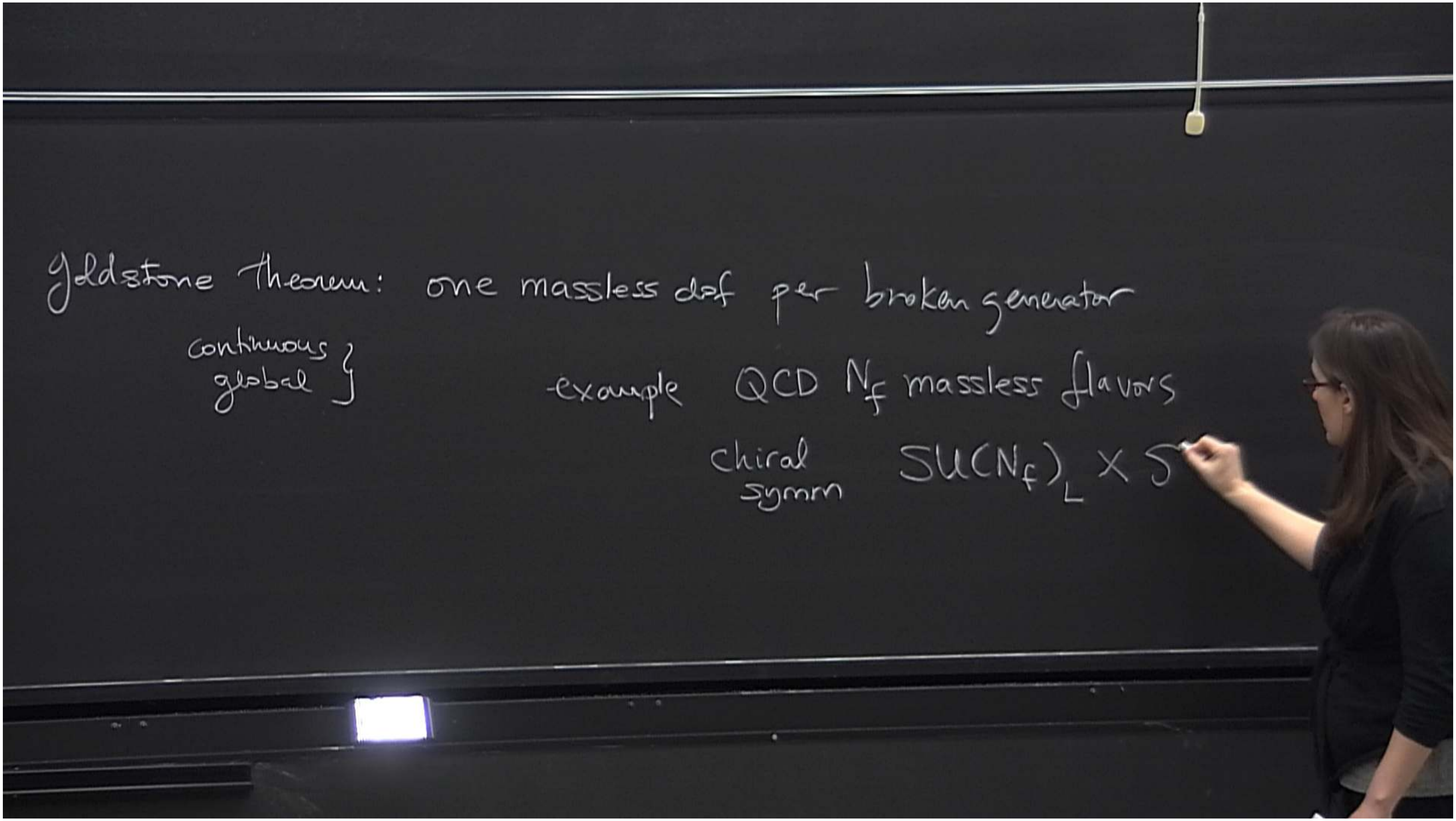

pprox.imate $\mathcal{L}_{\cancel{sym}}$ is a perturbation of $\mathcal{L}_{sym}$ $\mathcal{L}_{\cancel{sym}} = m_f \bar{q} q$
ccidental $\mathcal{L}_{SM} = \mathcal{L}_{QED} + \mathcal{L}_{weak}$
CP
$\cancel{CP}$
SHER-WOOD

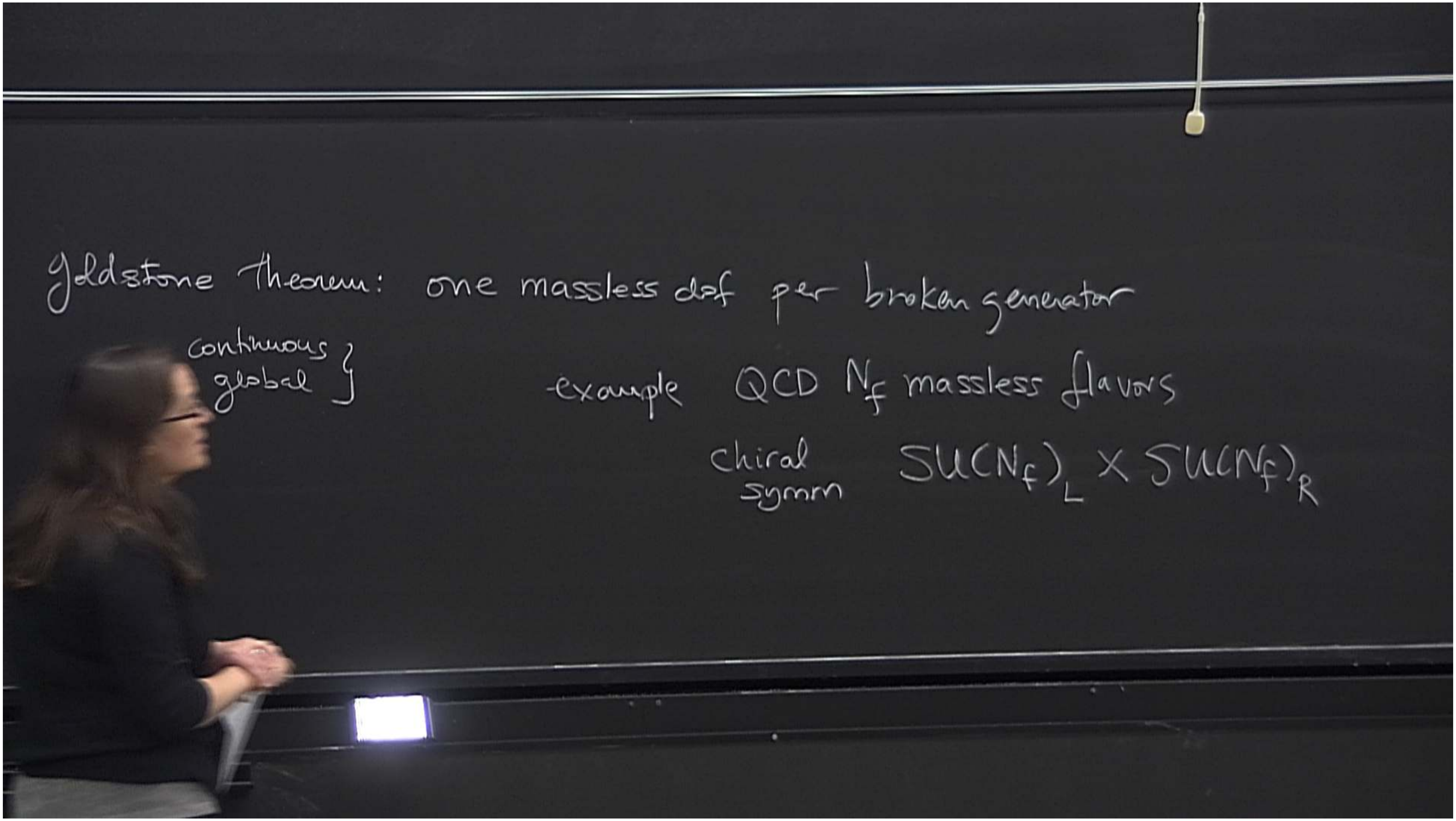

SSB
global
local
Goldstone theorem: one massless dof per br
continuous
global

Goldstone theorem: one massless dof per broken generator

continuous
global


Goldstone theorem: one massless dof per broken generator
continuous
global }
example QCD N_f massless flavors


Goldstone theorem: one massless dof per broken generator
continuous
global
example QCD N_f massless flavors
chiral
symm
SU(N_f)_L × S

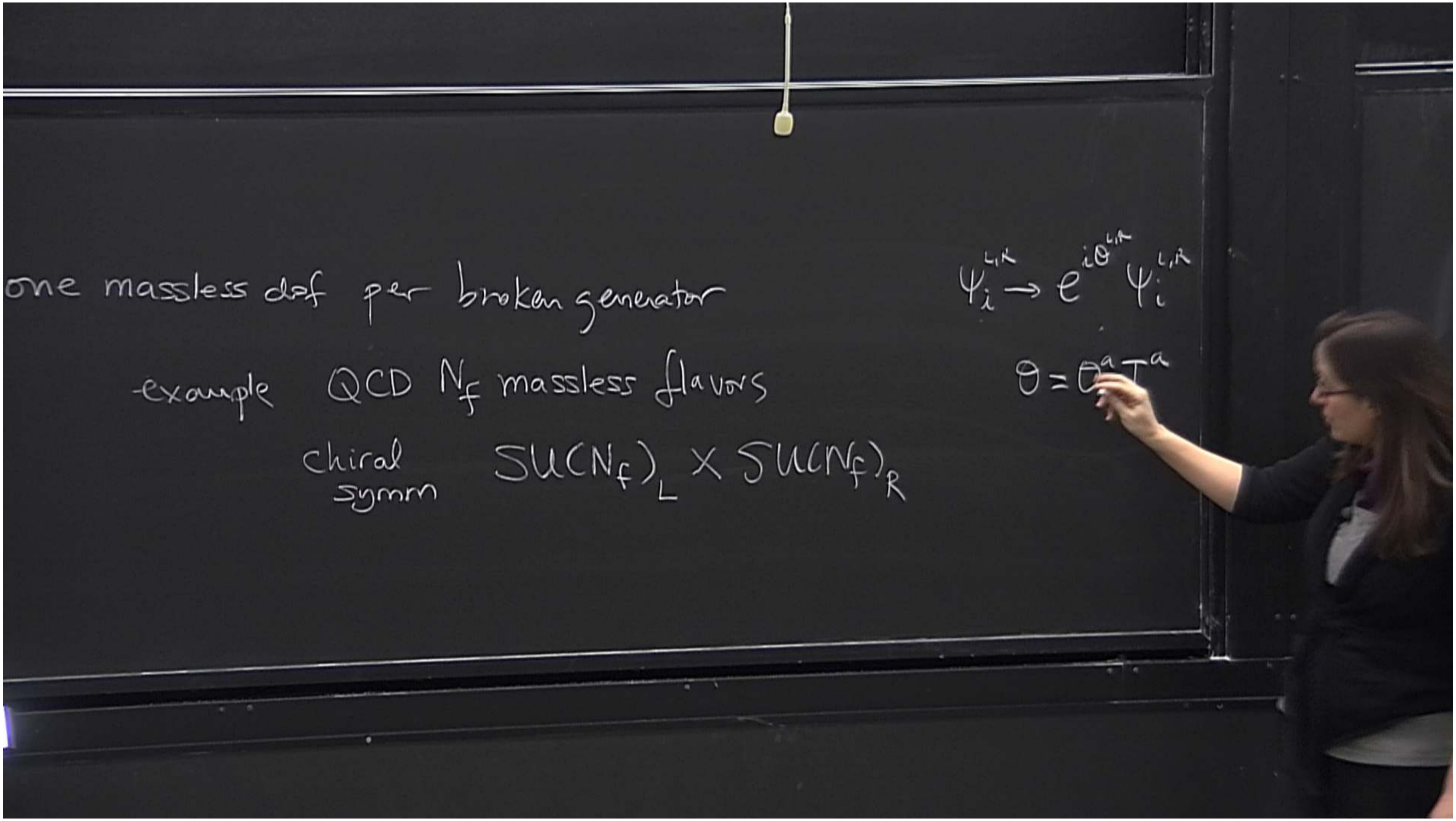

Goldstone theorem: one massless dof per broken generator
continuous
global
example QCD N_f massless flavors
chiral symm
SU(N_f)_L × SU(N_f)_R

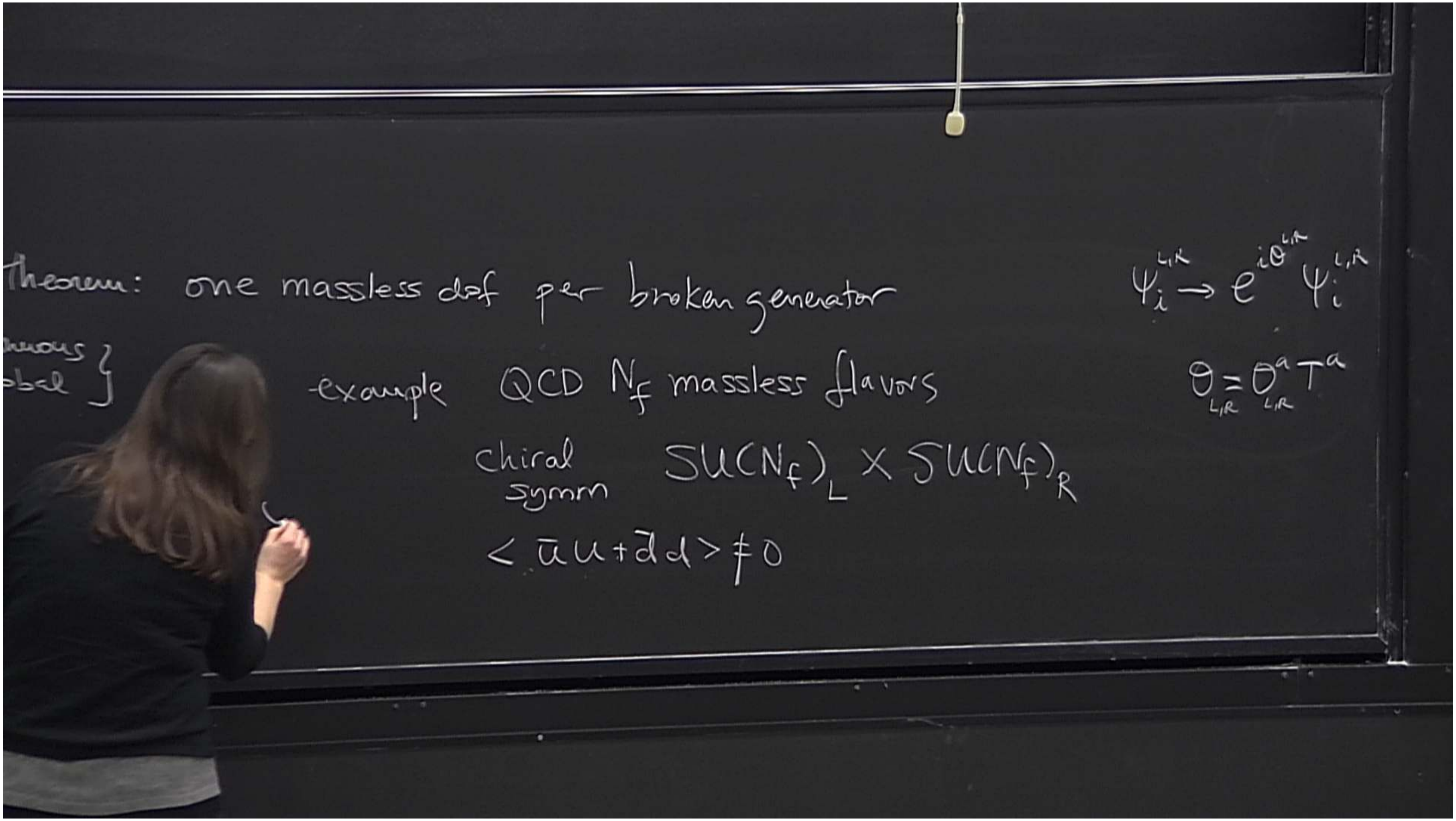
Goldstone theorem: one massless dof per broken generator ψ

continuous }
global }

- example QCD N_f massless flavors

chiral symm $SU(N_f)_L \times SU(N_f)_R$


one massless dof per broken generator
example QCD N_f massless flavors
chiral symm $SU(N_f)_L \times SU(N_f)_R$
$\psi_i^{L,R} \to e^{i\theta^{L,R}} \psi_i^{L,R}$
$\theta = \theta^a T^a$


Theorem: one massless dof per broken generator
...nuous
...obal
example QCD N_f massless flavors
chiral symm $SU(N_f)_L \times SU(N_f)_R$
$\langle \bar{u}u + \bar{d}d \rangle \neq 0$
$\psi_i^{L,R} \to e^{i\theta^{L,R}} \psi_i^{L,R}$
$\theta_{L,R} = \theta^a_{L,R} T^a$

Theorem: one massless dof per broken generator

$\Psi_i^{L,R} \to e^{i\theta^{L,R}} \Psi_i^{L,R}$

...nuous
...obal }

- example QCD N_f massless flavors

$\theta_{L,R} = \theta^a_{L,R} T^a$

chiral symm $SU(N_f)_L \times SU(N_f)_R$

$\bar{\psi}\psi$

$V \to$

$\langle \bar{u}u + \bar{d}d \rangle \neq 0$ $\quad \hookrightarrow SU(N_f)_V$

Theorem: one massless dof per broken generator

$\Psi_i^{L,R} \to e^{i\theta^{L,R}} \Psi_i^{L,R}$

tinuous
global }

example QCD N_f massless flavors

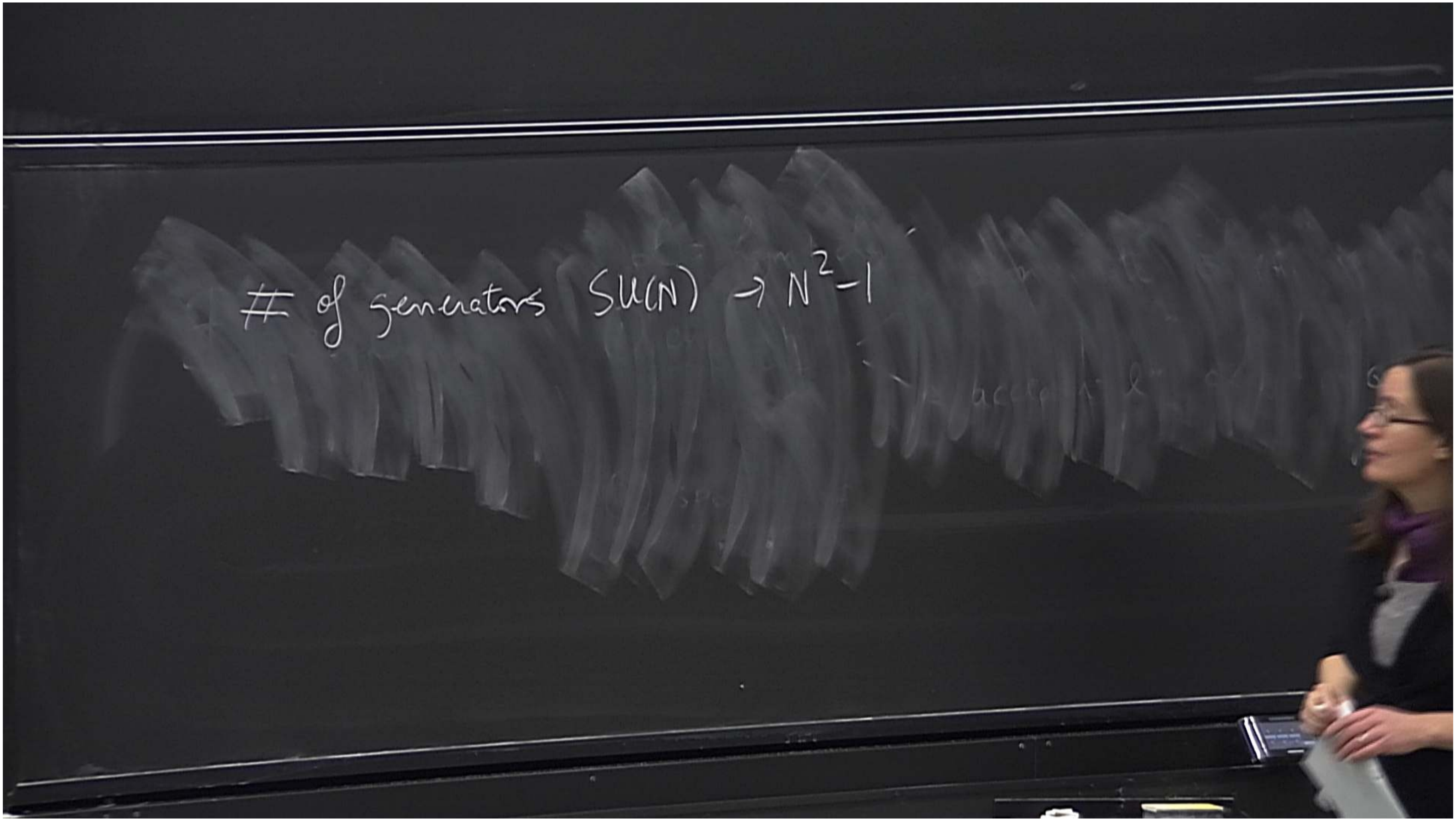
$\theta_{L,R} = \theta^a_{L,R} T^a$

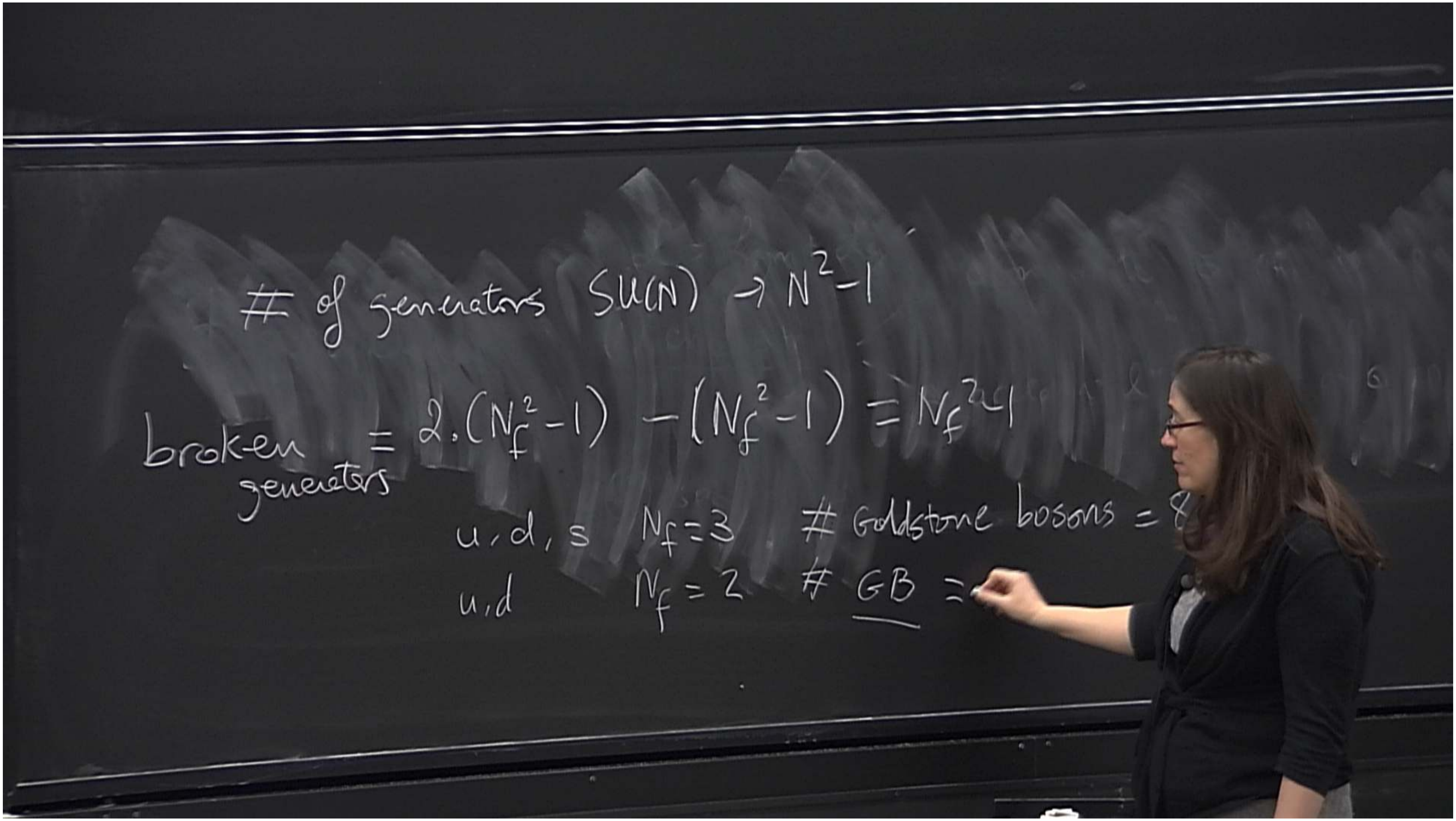
chiral symm $\boxed{SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V}$

$V = L + R$

$\bar{\Psi}\Psi$

$\langle \bar{u}u + \bar{d}d \rangle \neq 0$


# of generators SU(N) → N²-1

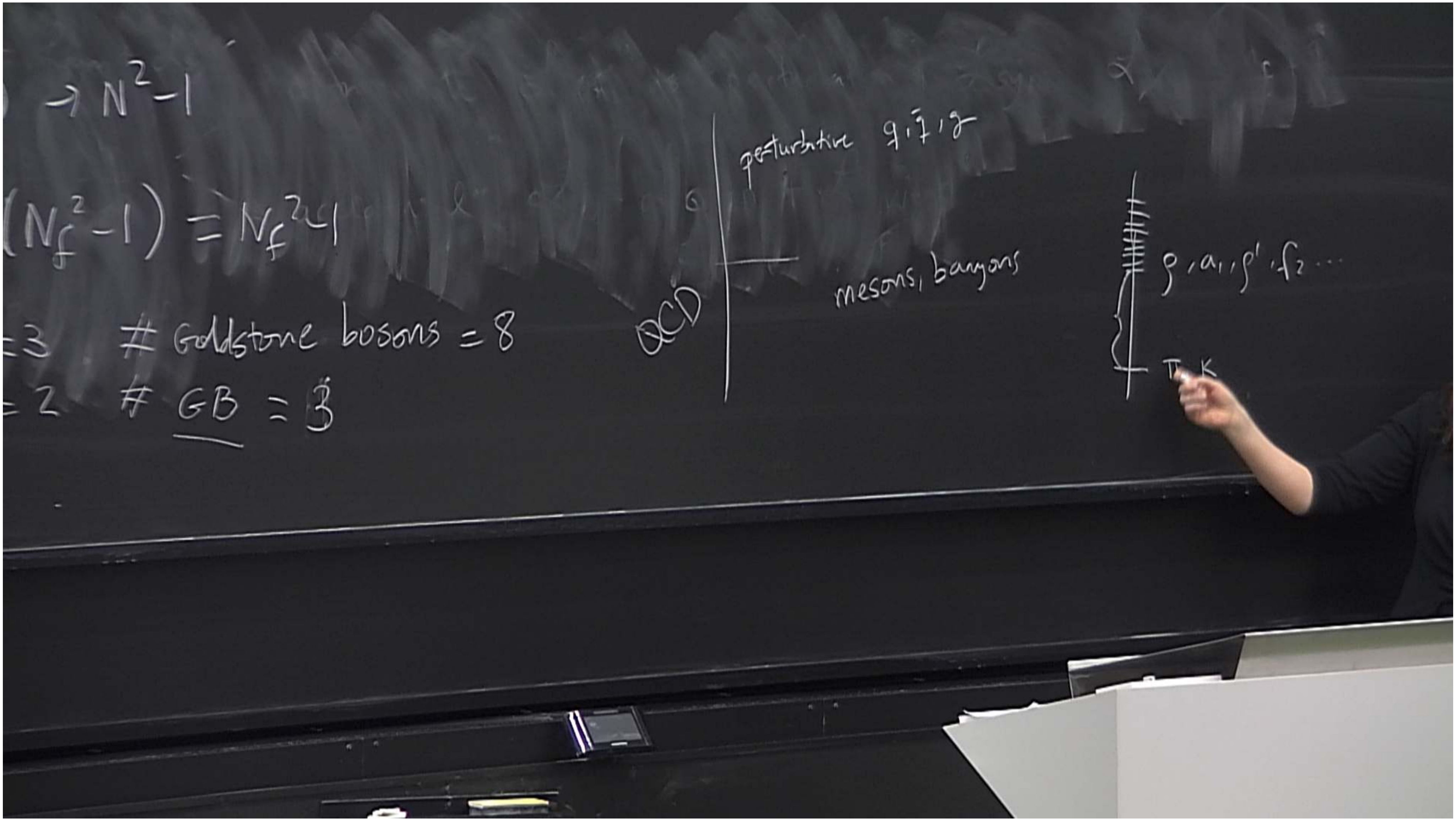

# of generators SU(N) → N^2-1
broken generators = $2.(N_f^2-1) - (N_f^2-1) = N_f^2-1$
u, d, s $N_f=3$ # Goldstone bosons = 8
u, d $N_f = 2$ # GB =

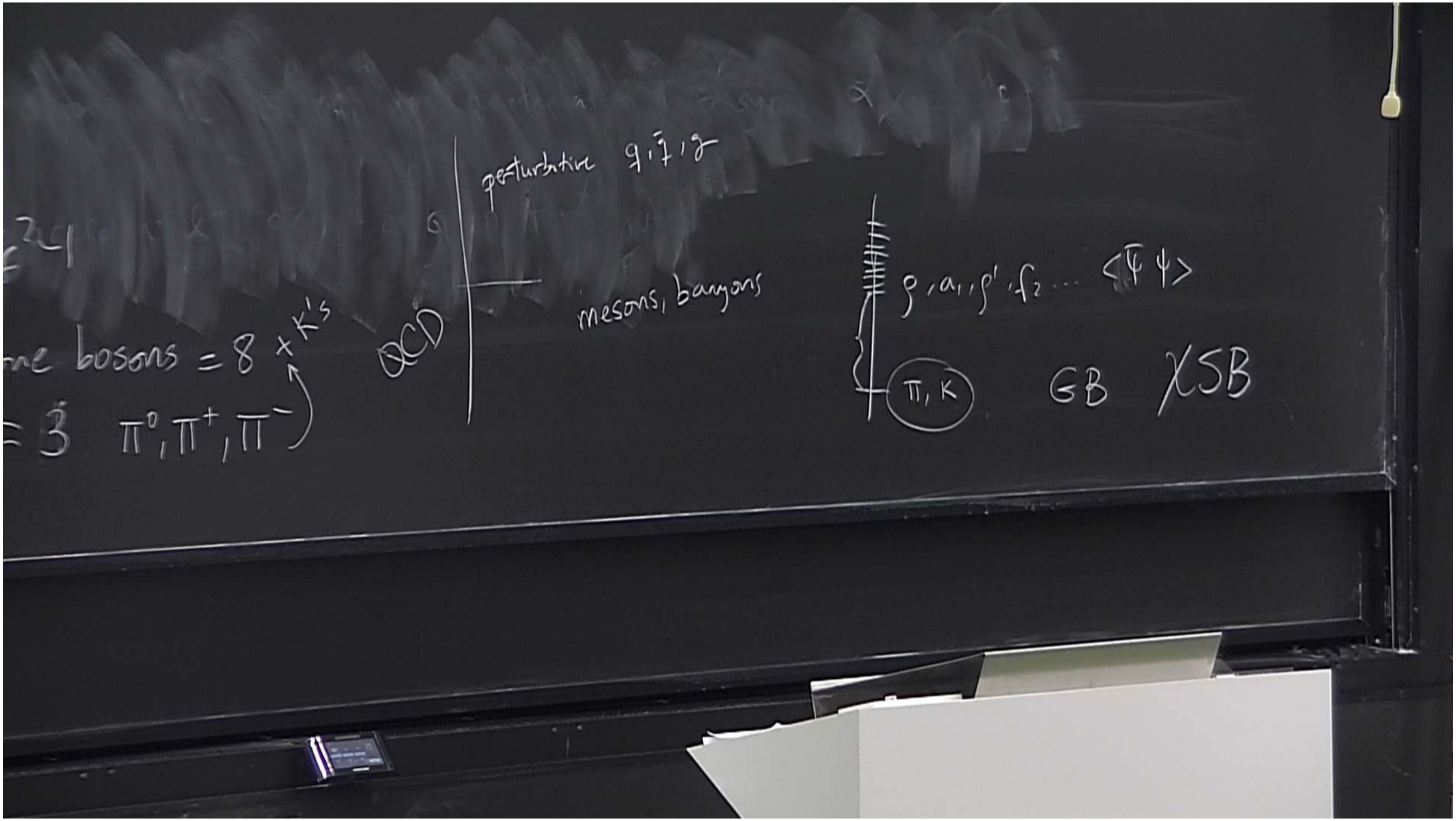
# of generators $SU(N) \to N^2 - 1$

broken generators $= 2 \cdot (N_f^2 - 1) - (N_f^2 - 1) = N_f^2 - 1$

u, d, s $\quad N_f = 3 \quad$ # Goldstone bosons $= 8$

u, d $\quad N_f = 2 \quad$ # $\underline{GB} = 3$


→ N²−1
(N_f²−1) = N_f²−1
=3 # Goldstone bosons = 8
=2 # GB = 3
QCD
perturbative q, q̄, g
mesons, baryons
ρ, a₁, ρ′, f₂ …
π, K


perturbative $q, \bar{q}, g$
QCD
mesons, baryons
ne bosons = 8 + K's
= 3 π^0, π^+, π^-
$\rho, a_1, \rho', f_2 \ldots \langle \bar{\psi}\psi \rangle$
π, K
GB χSB

SB $\nearrow$ global
$\searrow$ local

Goldstone theorem: one massless dof per broken ge

continuous }
global }

-example QCD N_f massles

$\bar{\psi}$

ψ

$\bar{\psi}\psi$

chiral symm $\boxed{SU(N}$

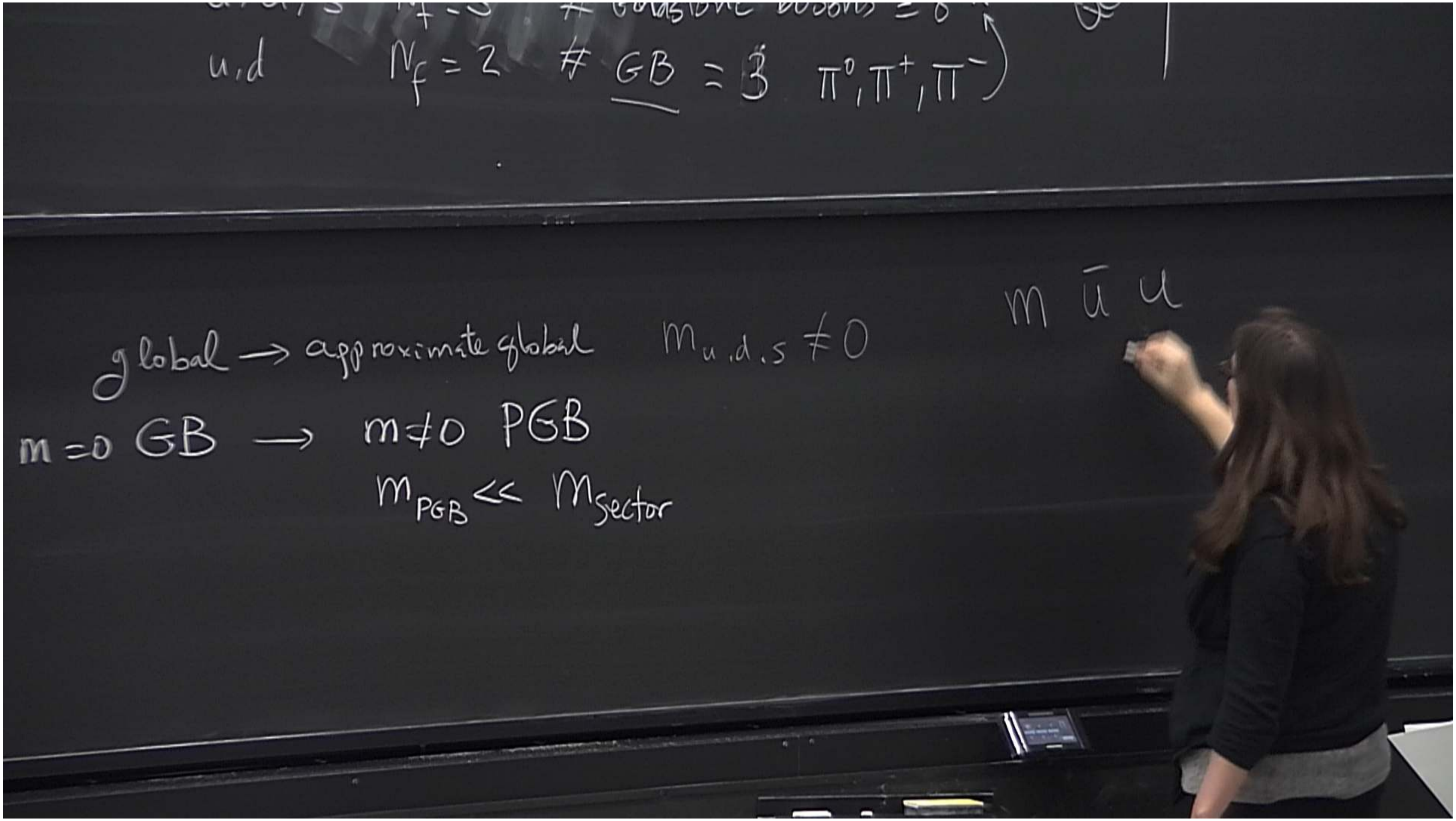
$< \bar{u}u + \bar{d}d > \neq 0$

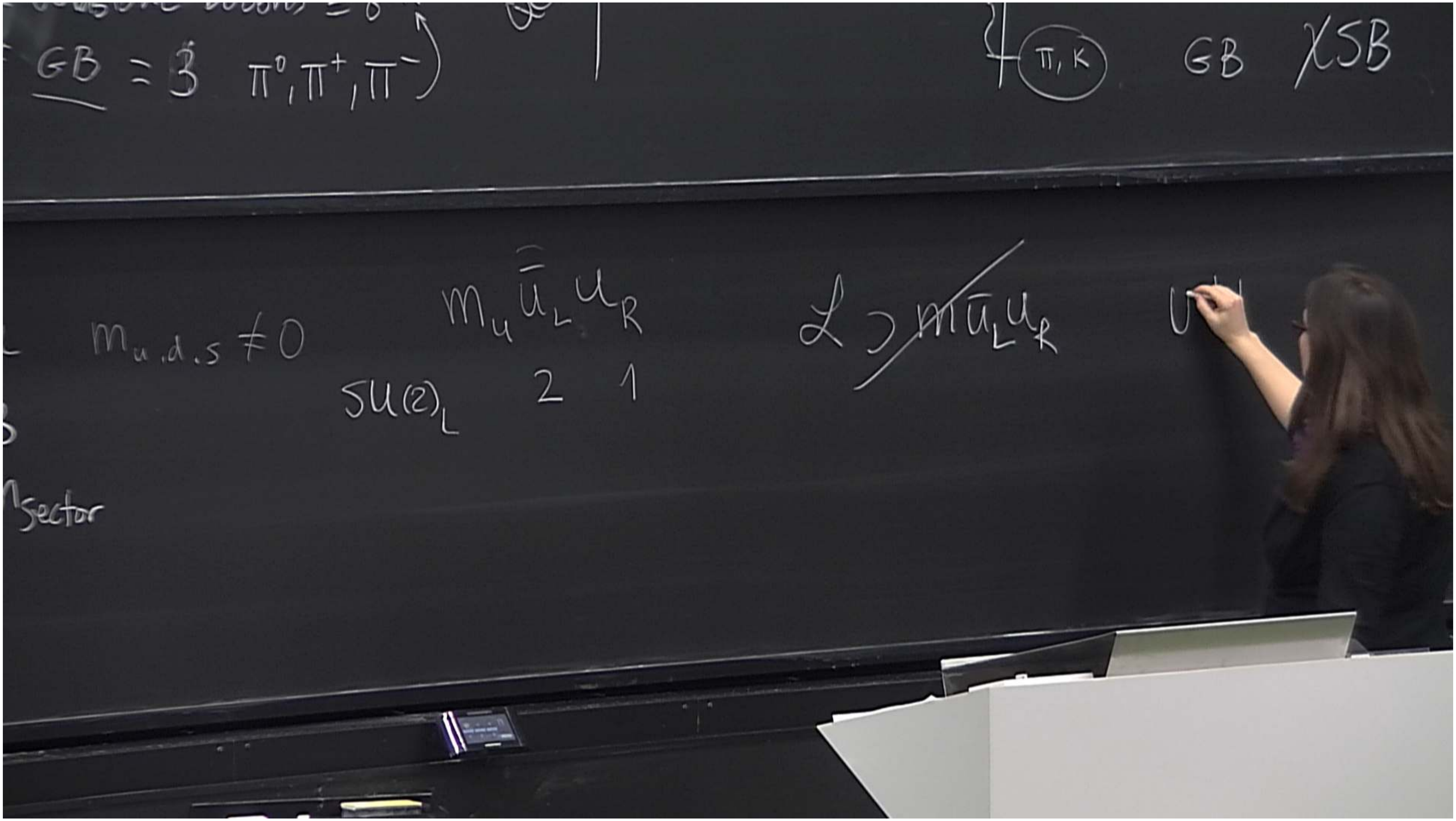
u,d $N_f = 2$ # $\underline{GB} = 3$ π^0, π^+, π^-

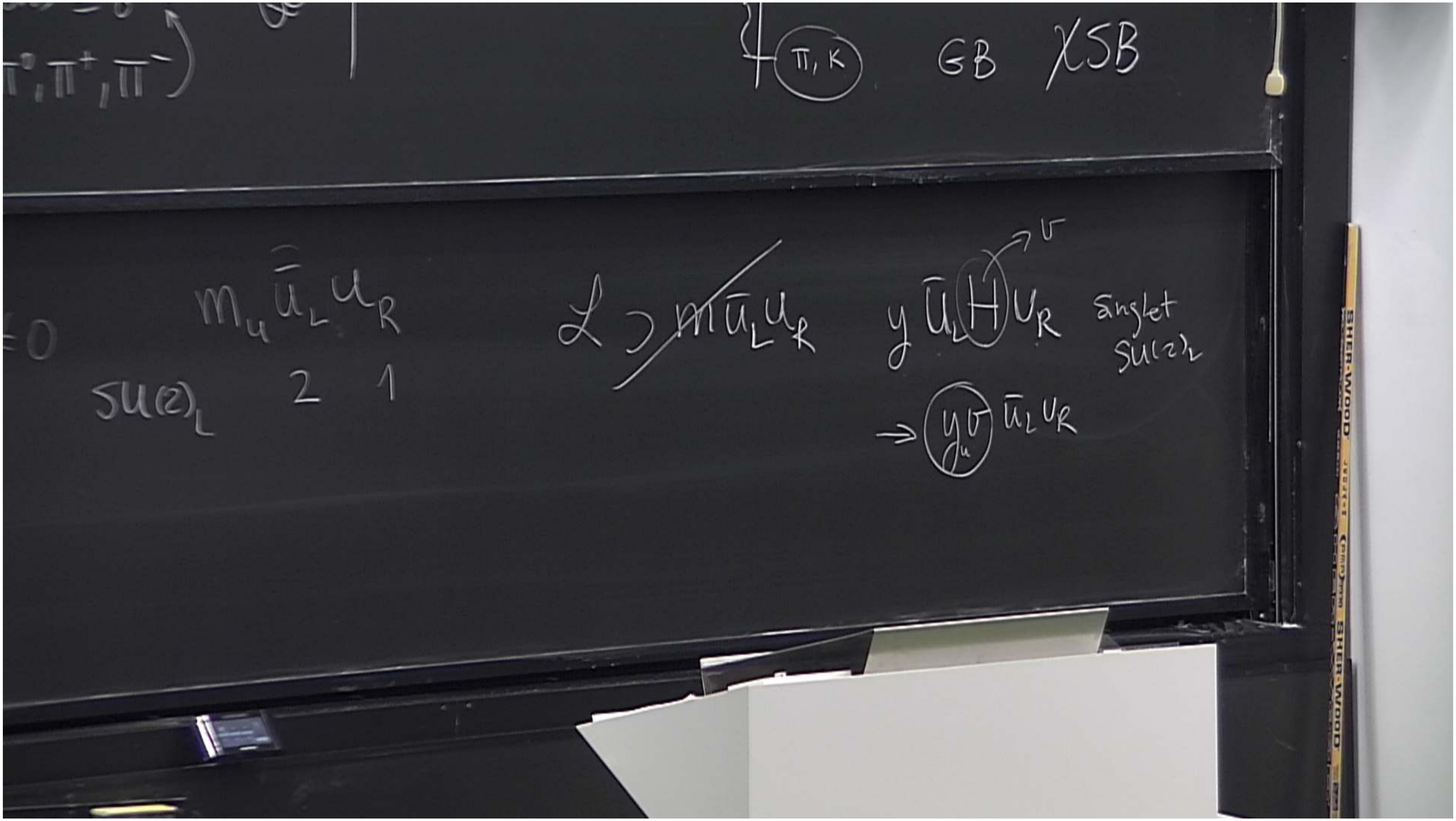
global $\longrightarrow$ approximate global

$m = 0$ GB $\longrightarrow$ $m \neq 0$ PGB

$m_{PGB} \ll m_{sector}$


u,d $N_f = 2$ # GB = 3 π^0, π^+, π^-
global → approximate global
$m_{u,d,s} \neq 0$
$m \bar{u} u$
m = 0 GB → m ≠ 0 PGB
$m_{PGB} \ll m_{sector}$


GB = 3 π⁰, π⁺, π⁻
π, K
GB χSB
m_u ū_L u_R
m_u,d,s ≠ 0
SU(2)_L 2 1
L ⊃ m ū_L u_R
sector



π, K
GB χSB
m_u ū_L u_R
SU(2)_L 2 1
L ⊃ m ū_L u_R
y ū_L H u_R
v
singlet
SU(2)_L
→ y_u v ū_L u_R

u, d, s $N_f = 3$ # Goldstone bosons = 8

u, d $N_f = 2$ # GB = 3 π^0, π^+, π^-

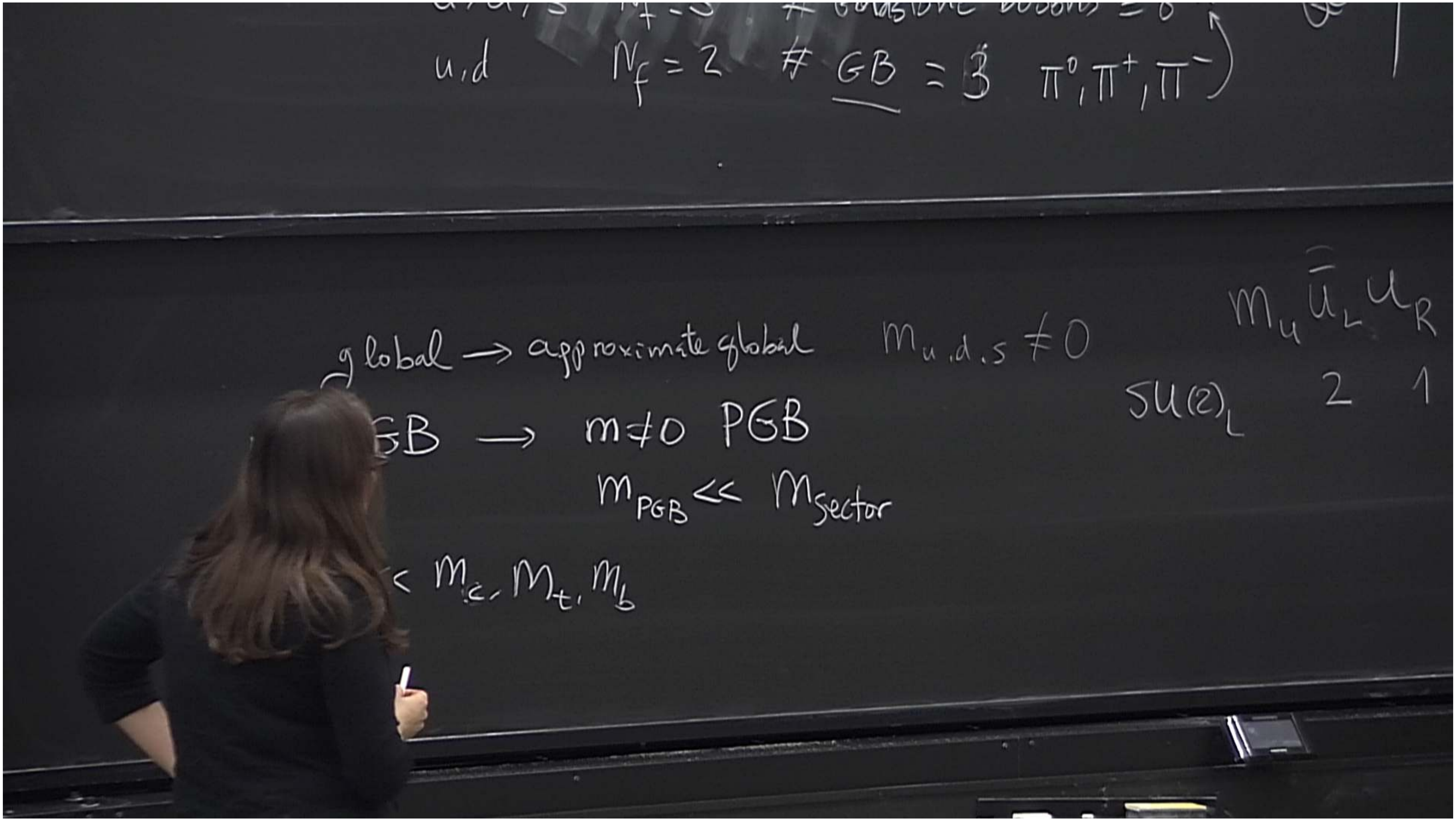
global $\longrightarrow$ approximate global $\quad m_{u,d,s} \neq 0 \quad m_u \bar{u}_L u_R$

$SU(2)_L \quad 2 \quad 1$

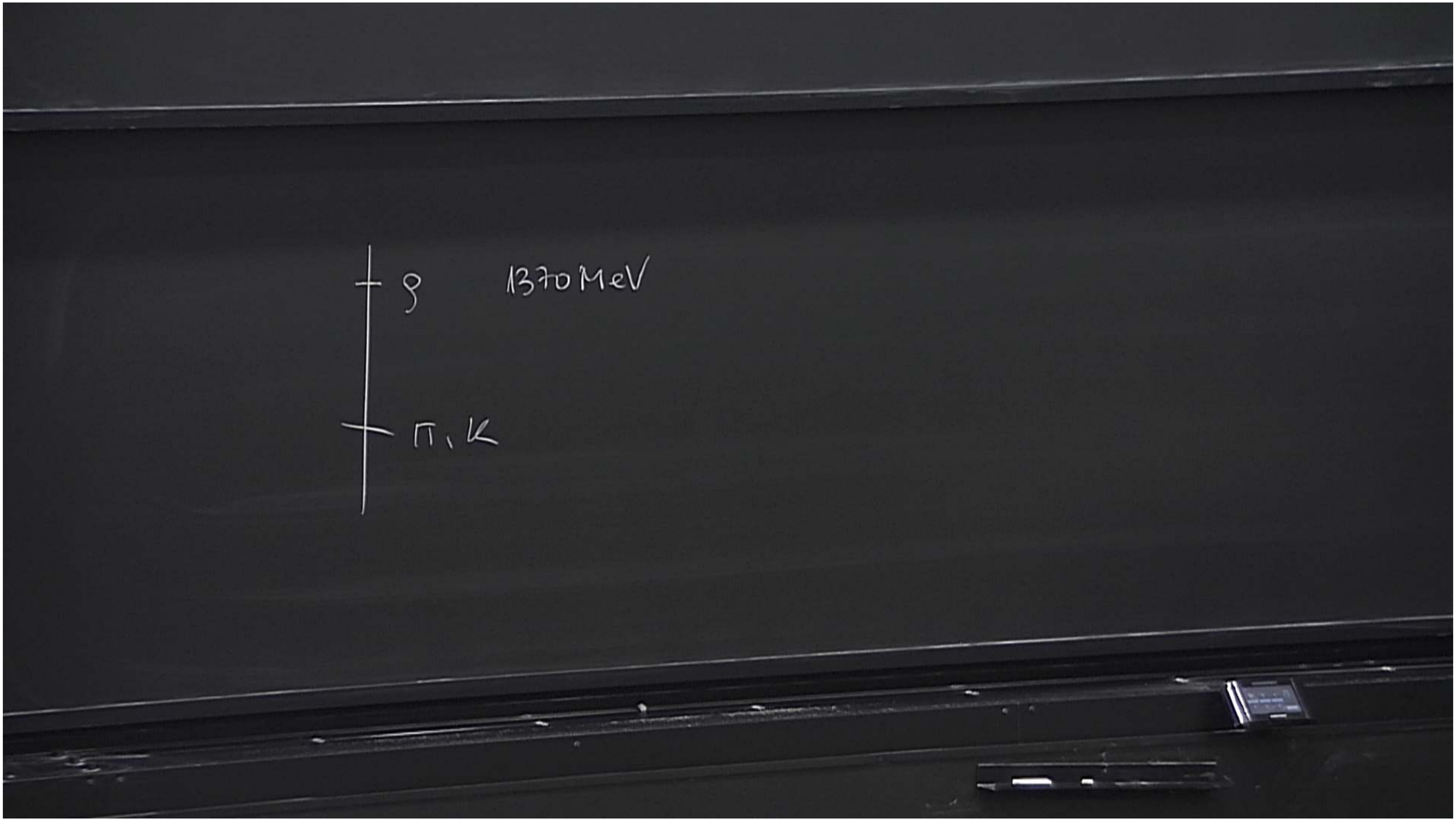
$m = 0$ GB $\longrightarrow$ $m \neq 0$ PGB

$$m_{PGB} \ll m_{sector}$$

$$m_{u,d,s} \ll m_c, m_t, m_b$$



u,d $N_f = 2$ # GB = 3 π^0, π^+, π^-
global → approximate global
$m_{u,d,s} \neq 0$
$m_u \bar{u}_L u_R$
$SU(2)_L$ 2 1
GB → $m \neq 0$ PGB
$m_{PGB} \ll m_{sector}$
$< m_c, m_t, m_b$


ρ
1370 MeV
π, K

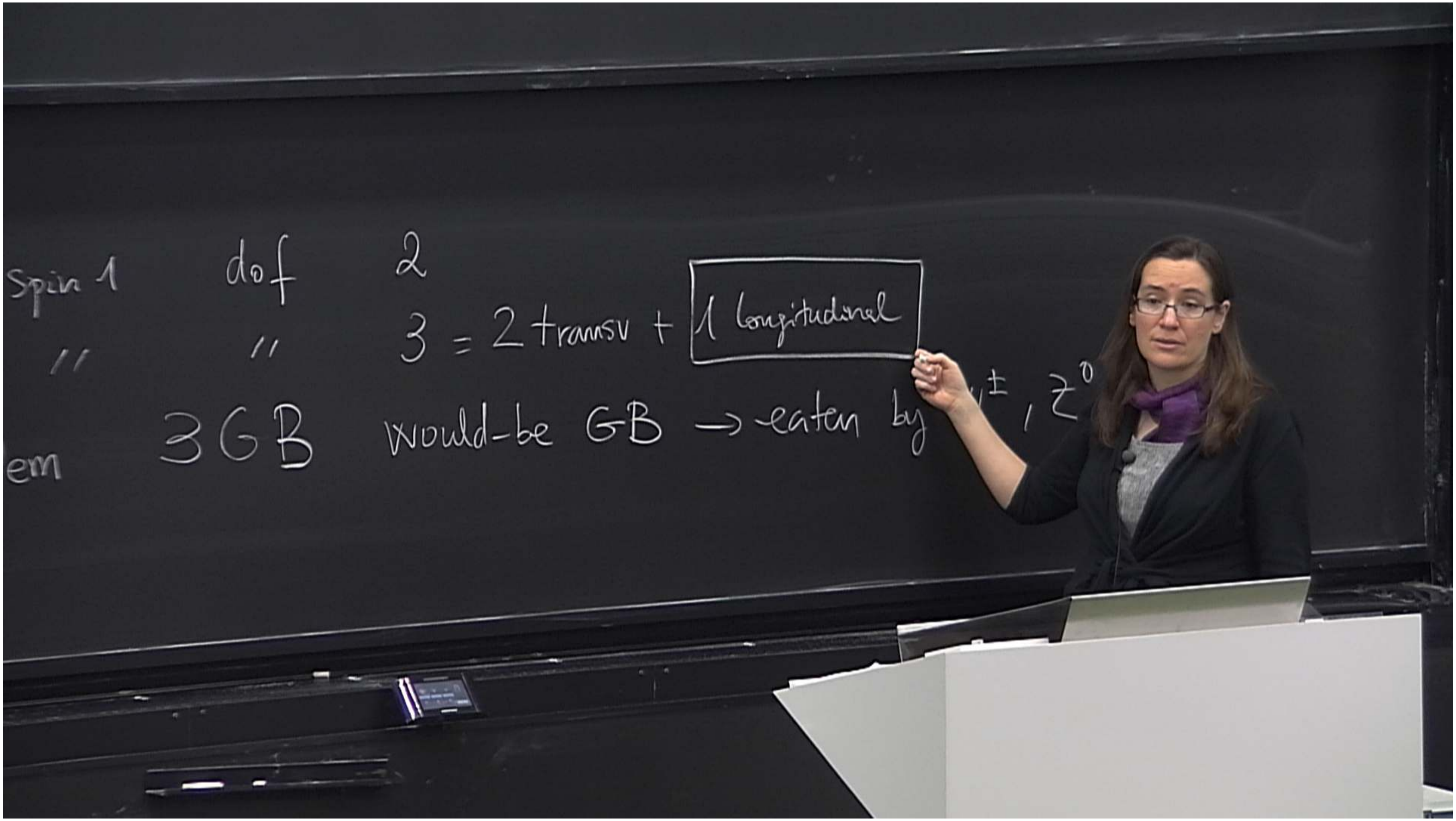
W, Z massless spin 1 dof

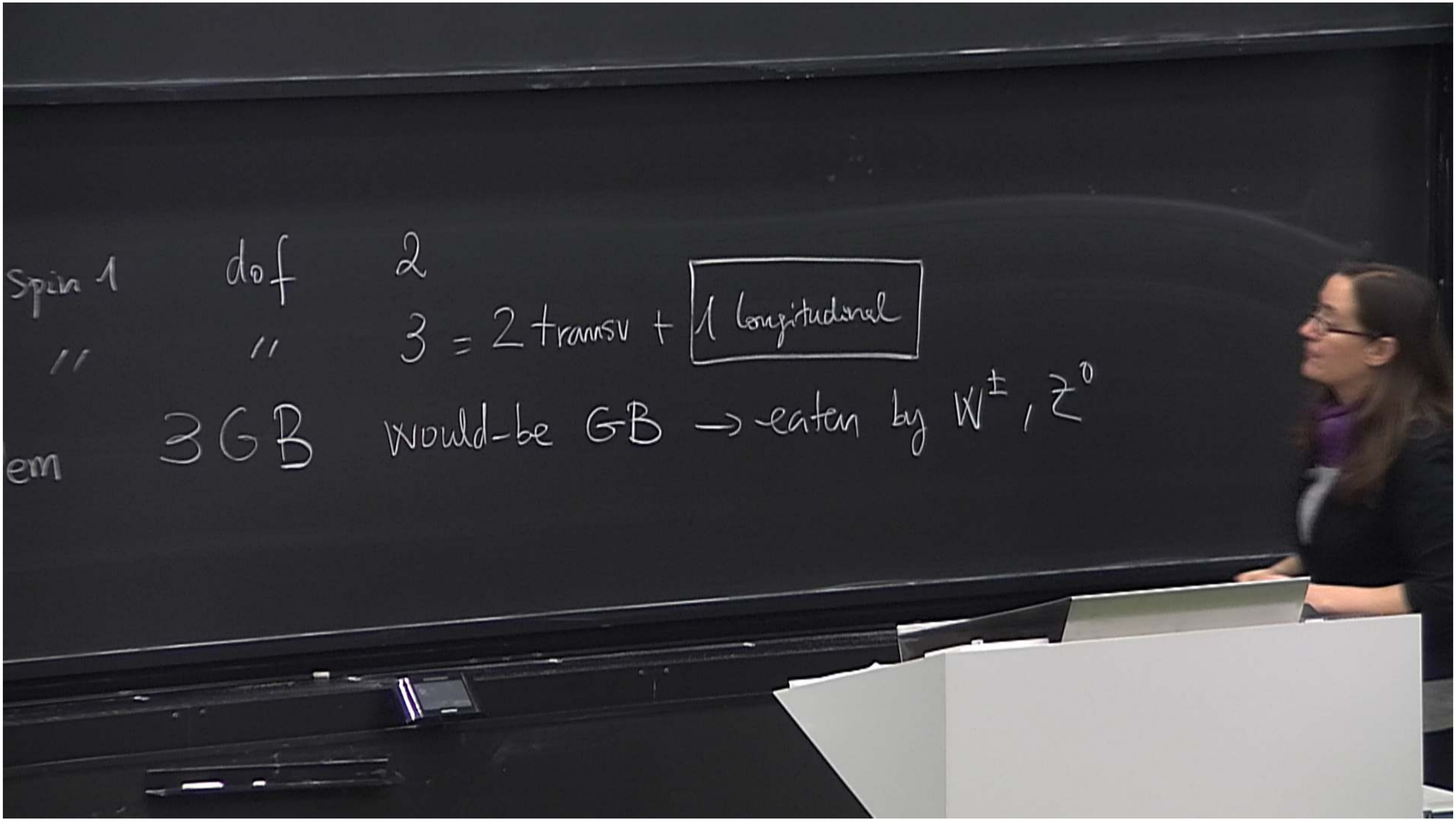
W, Z	massless spin 1	dof	2
	massive "	"	3 = 2 transv + 1 longit

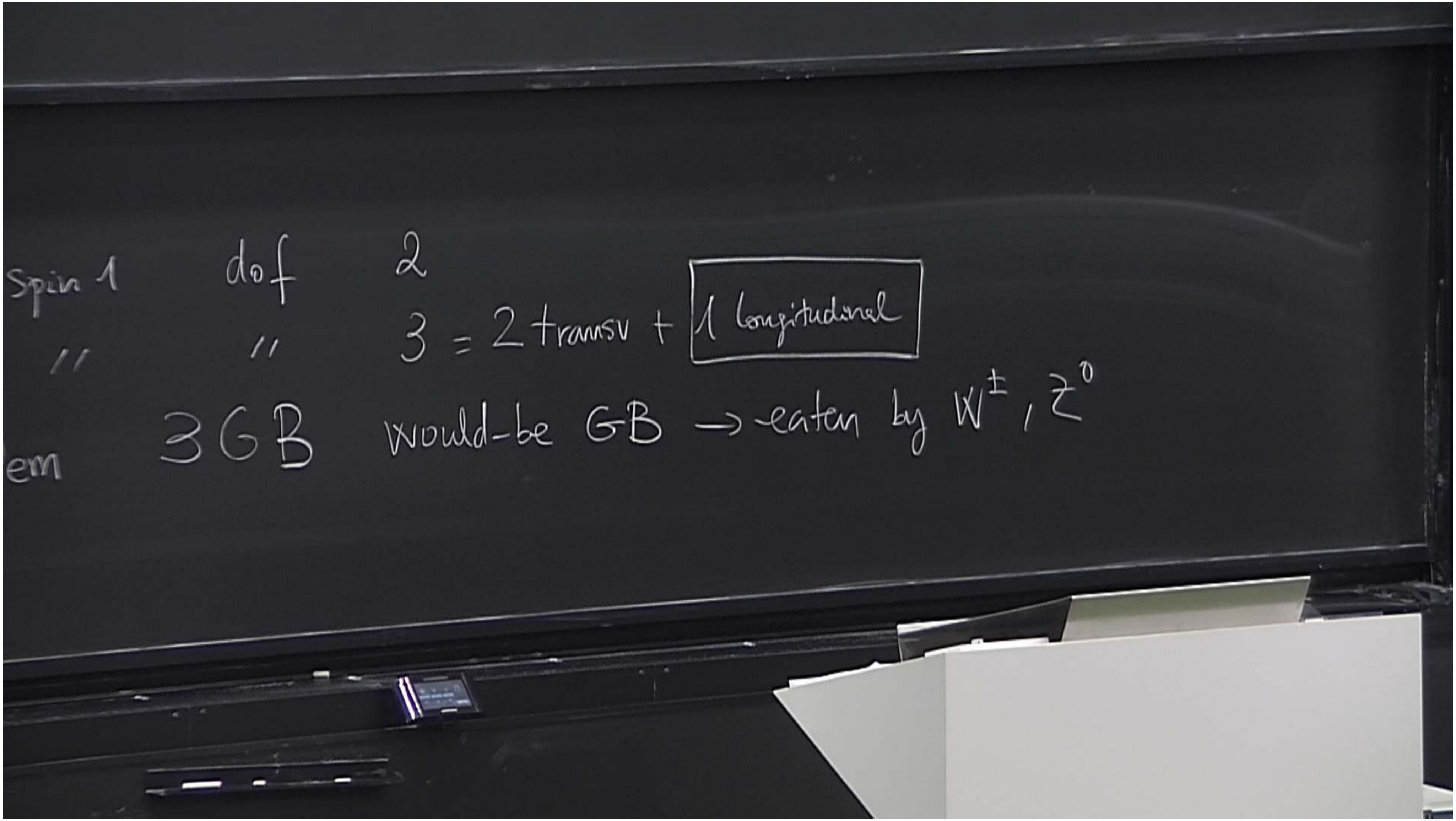
W, Z massless spin 1 dof 2

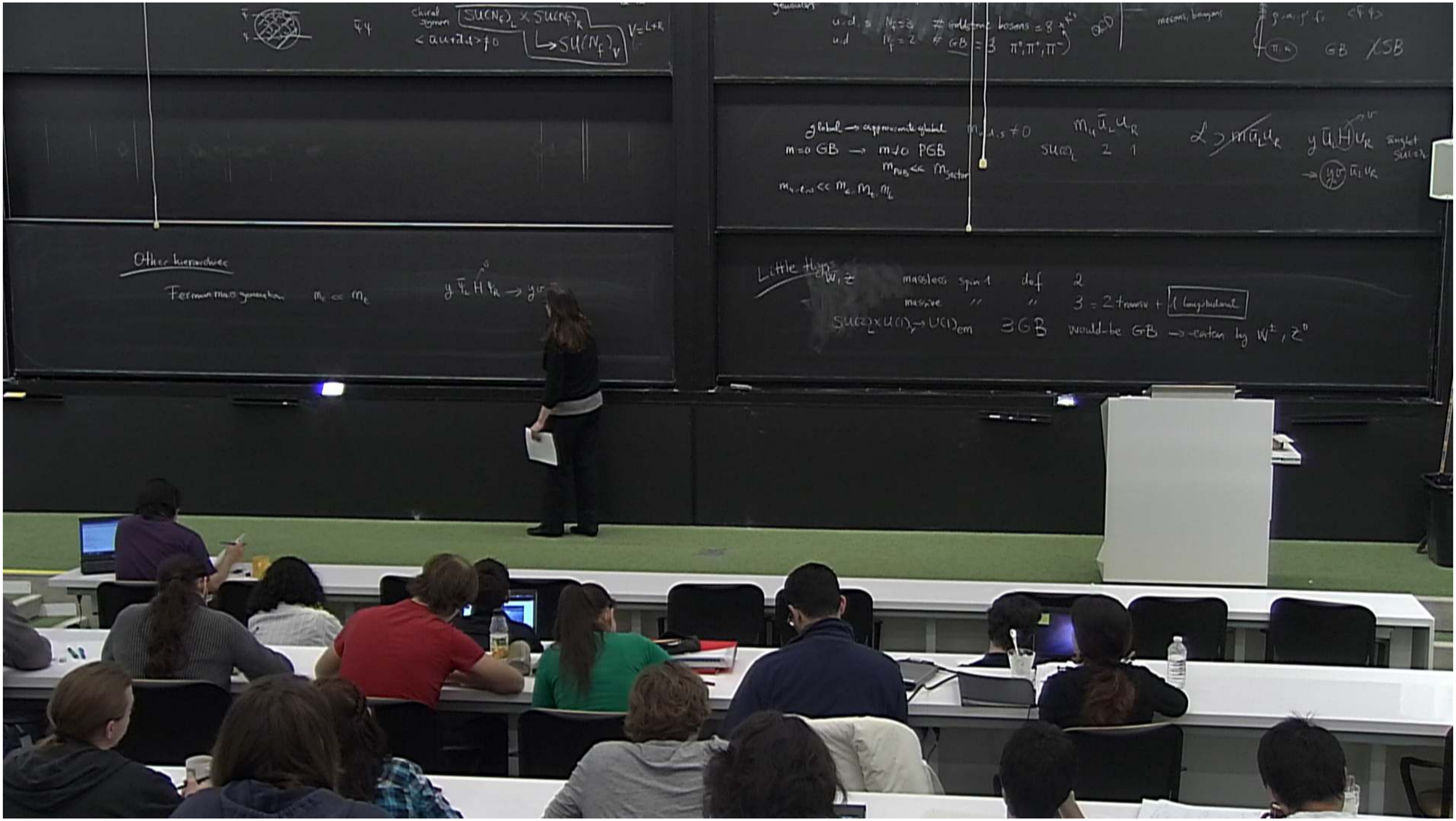
massive // // $3 = 2$ transv + $\boxed{1 \text{ longit}}$

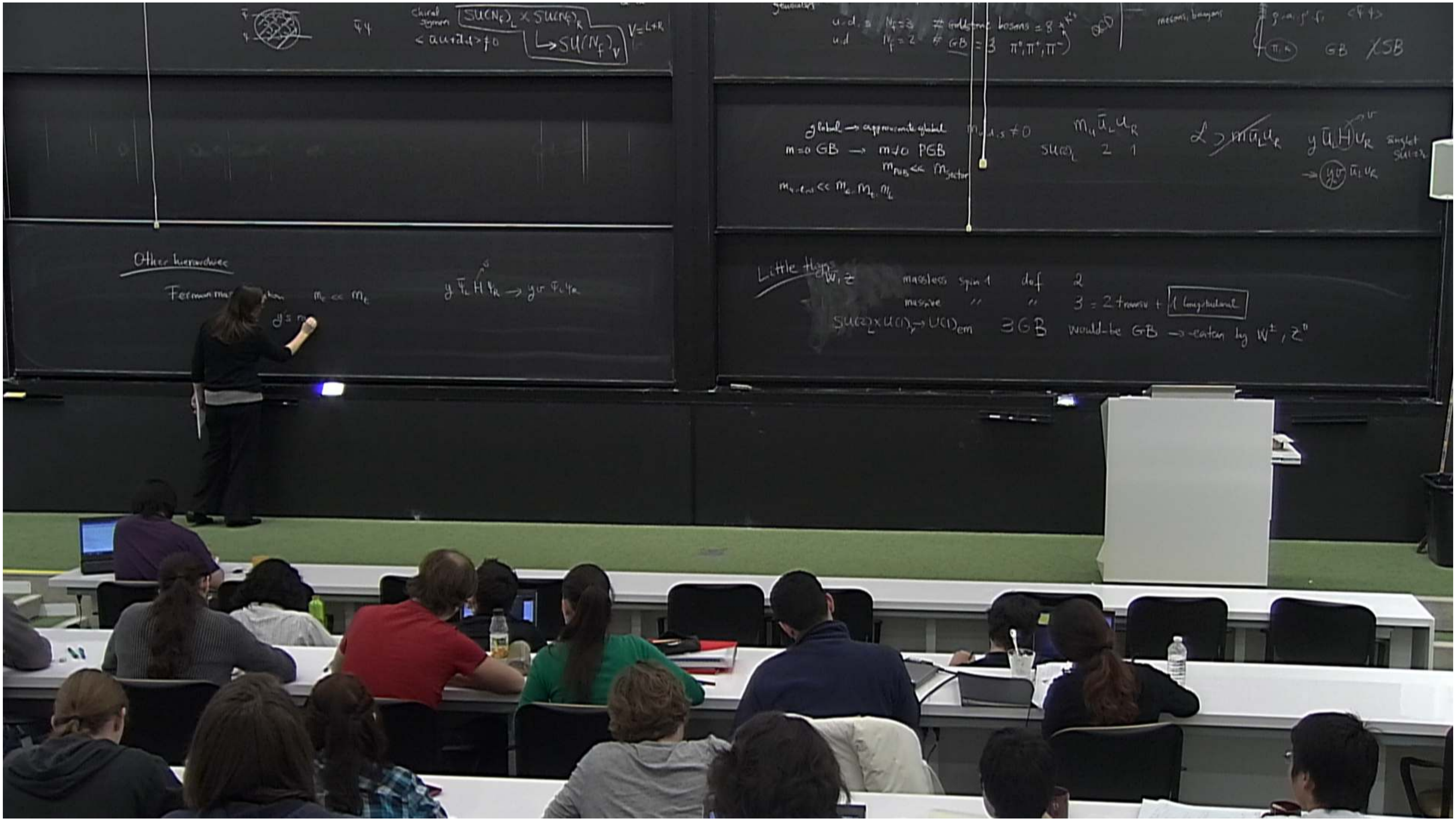
$SU(2)_L \times U(1)_Y \to U(1)_{em}$ 3 GB would-be GB → ea


spin 1
dof
2
3 = 2 transv + 1 longitudinal
em
3 GB
would-be GB → eaten by


spin 1 dof 2
" " 3 = 2 transv + 1 longitudinal
em 3 GB would-be GB → eaten by W±, Z0


spin 1 dof 2
" " 3 = 2 transv + 1 longitudinal
em 3 GB would-be GB → eaten by W±, Z0


Chiral symm
global → approximate global
m=0 GB → m≠0 PGB
Other hierarchies
Fermion mass generation
Little Higgs
massless spin 1 dof 2
massive 3 = 2 transv + 1 longitudinal
would-be GB → eaten by W±, Z0
GB XSB
singlet


Other hierarchies
Little Higgs
massless spin 1
massive
would-be GB
meson, baryons
global → approximate global
singlet

$$y\,\bar{\Psi}_L \overset{v}{H} \Psi_R \rightarrow y v\, \bar{\Psi}_L \Psi_R$$

$m_e \ll m_t$

range many orders of magnitude

tural? $\mathcal{L}_{tree} \supset y_e \;\; y_t$ stable under rad. corrections?

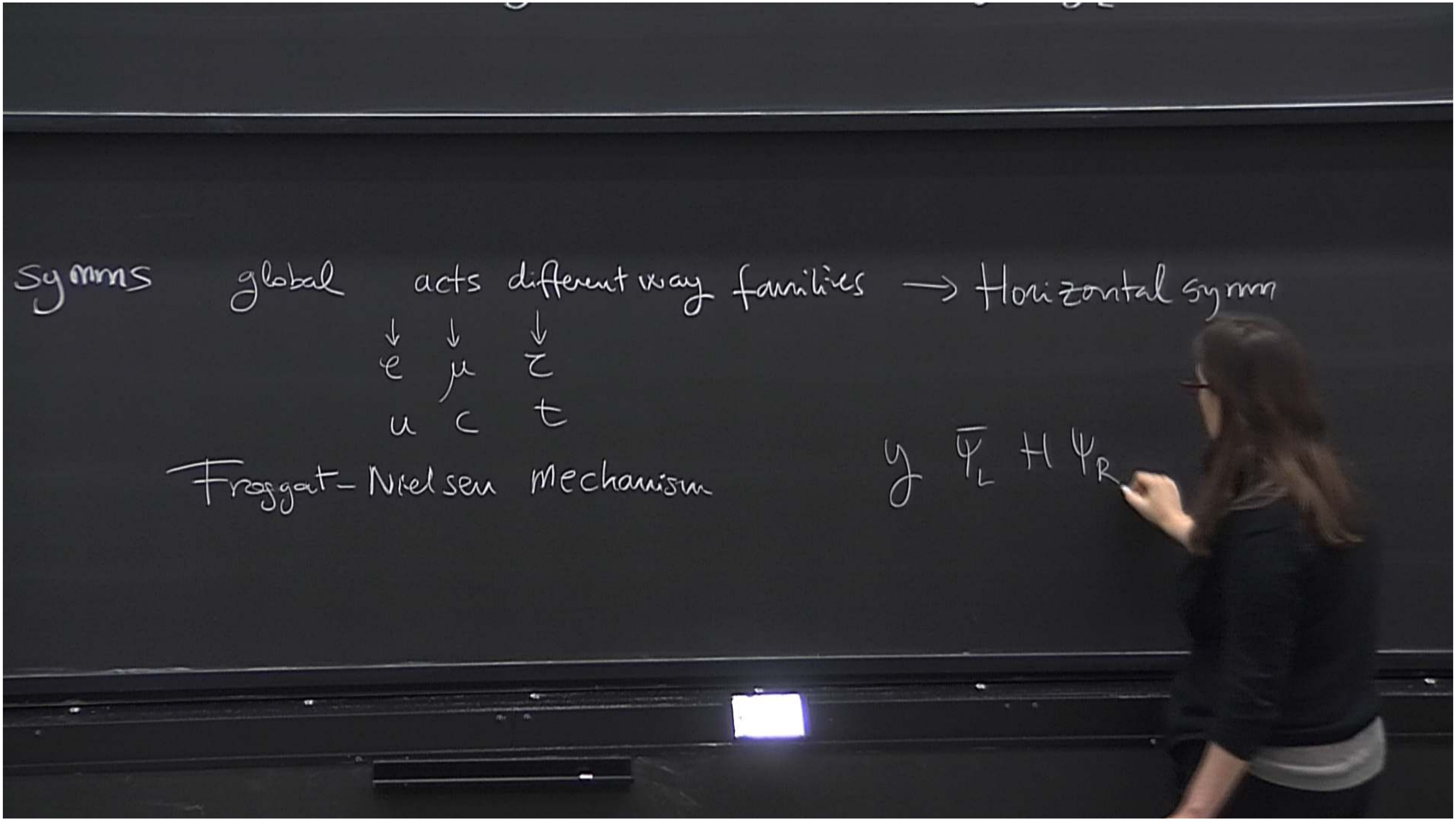
$$y\,\bar{\Psi}_L \overset{v}{H}\, \Psi_R \to y v\, \bar{\Psi}_L \Psi_R$$

$$m_e \ll m_t$$

$$\delta m_f \propto m_f$$

ange many orders of magnitude

ral? $\mathcal{L}_{tree} \supset y_e \; y_t$ stable under rad. corrections?


symms global acts different way families → Horizontal symm
e μ τ
u c t
Froggat-Nielsen mechanism
$y \bar{\Psi}_L H \Psi_R$

symms global acts different way families $\longrightarrow$ Horizontal symm

$$\begin{array}{ccc} \downarrow & \downarrow & \downarrow \\ e & \mu & \tau \\ u & c & t \end{array}$$

Froggat-Nielsen mechanism

$$y \, \bar{\Psi}_L H \Psi_R \left(\frac{\Phi}{\Lambda}\right)$$

cts different way families $\longrightarrow$ Horizontal symm

$\downarrow$ $\downarrow$

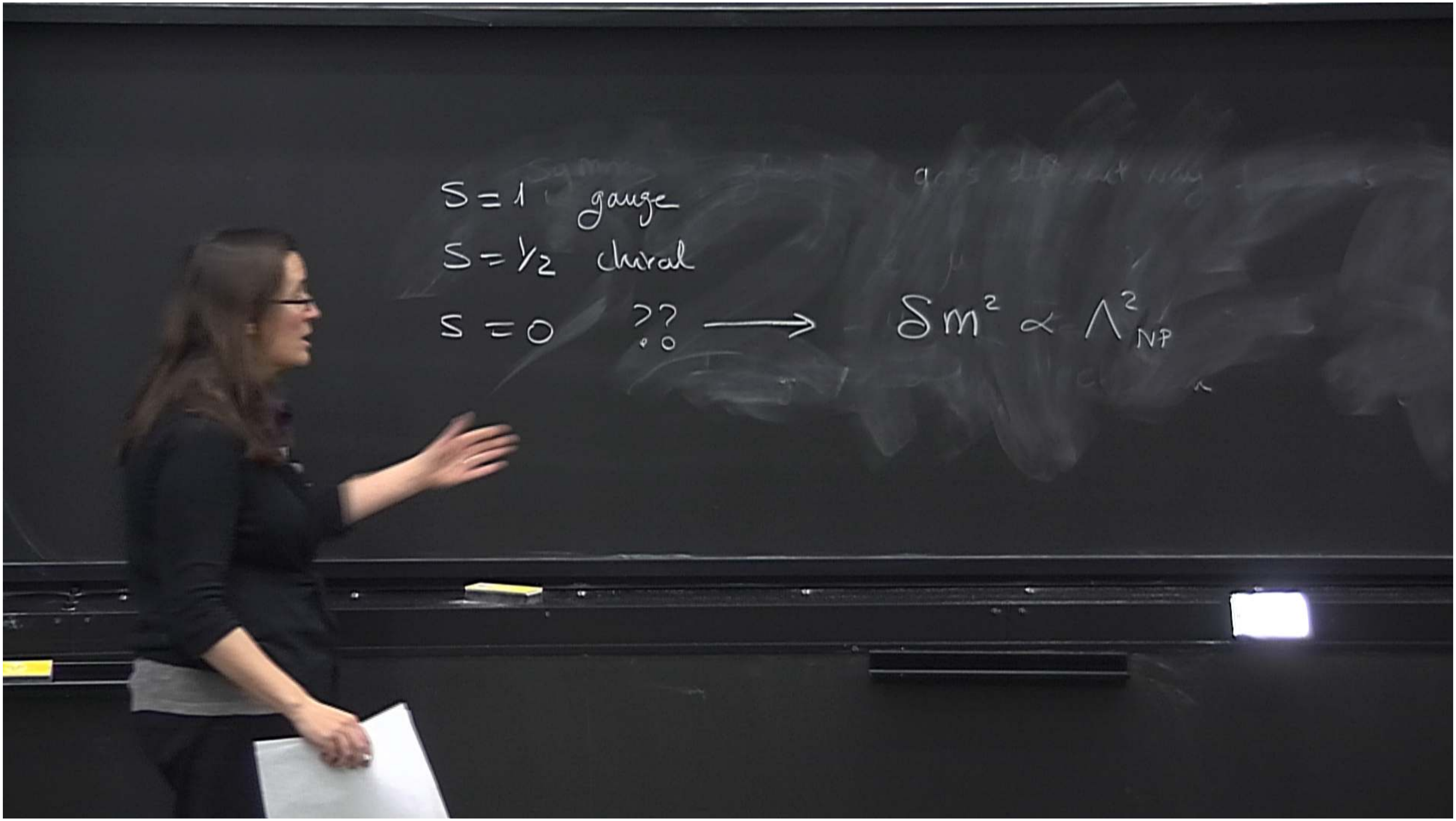
μ τ

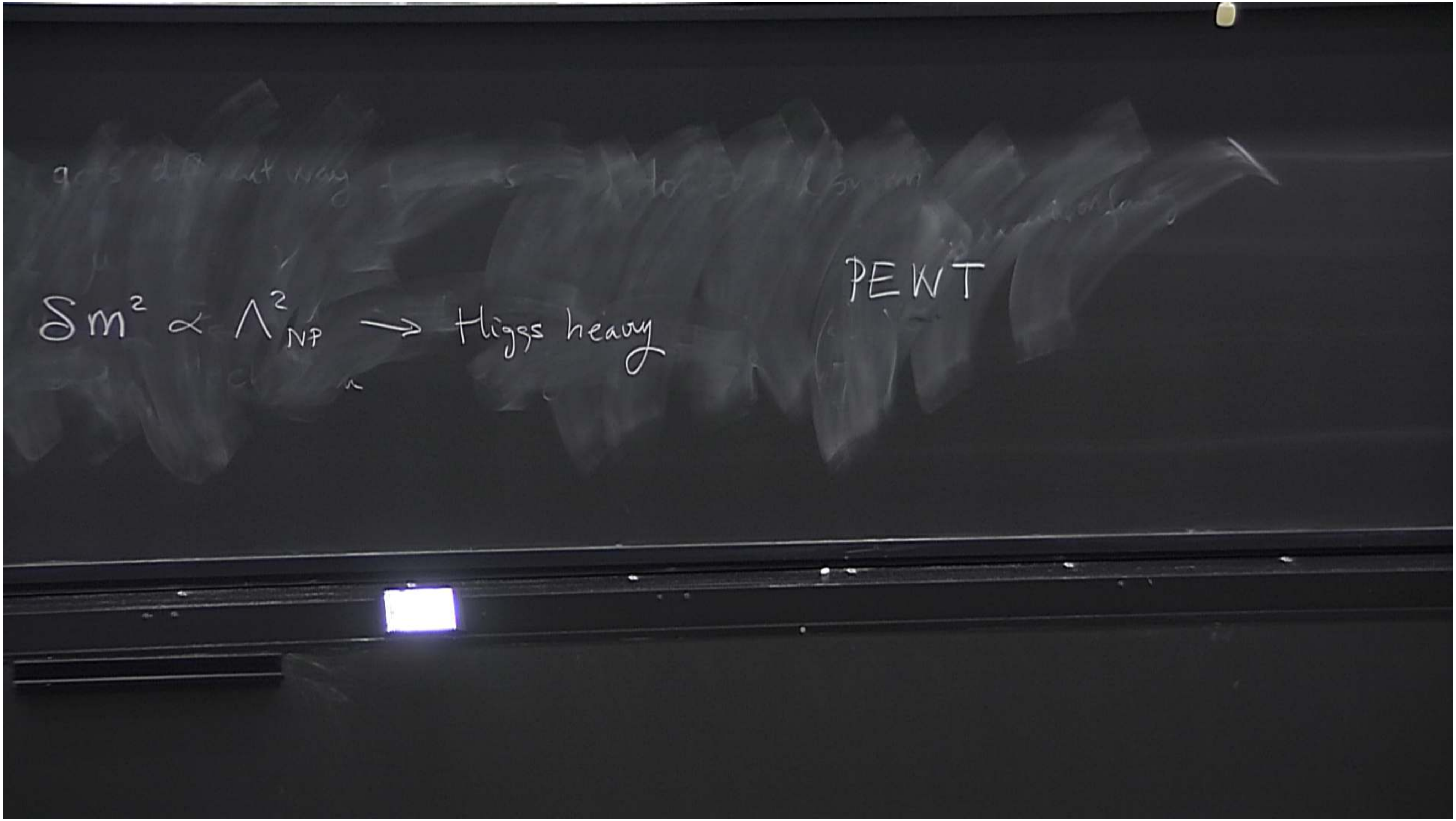
c t

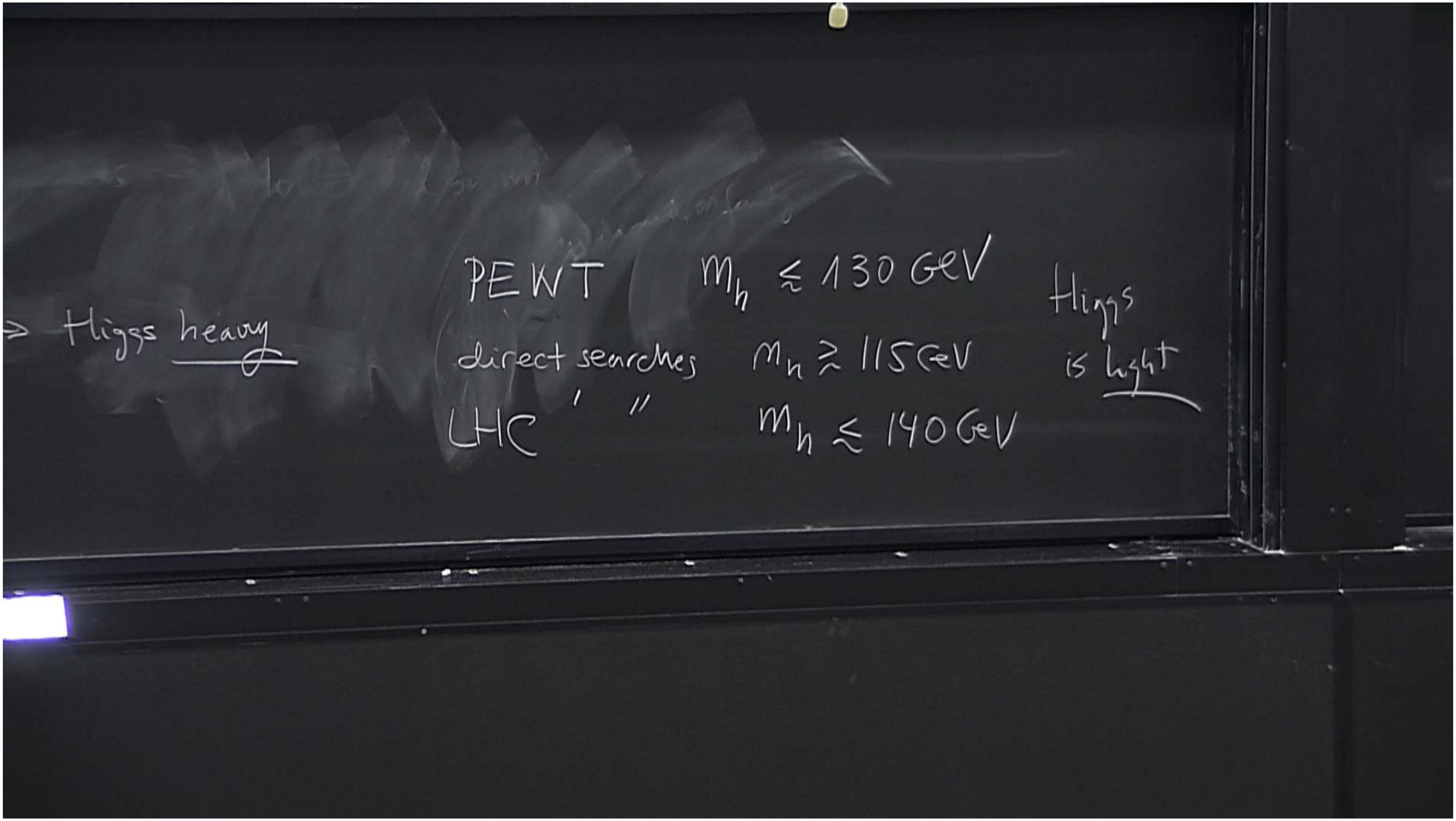
lsen mechanism

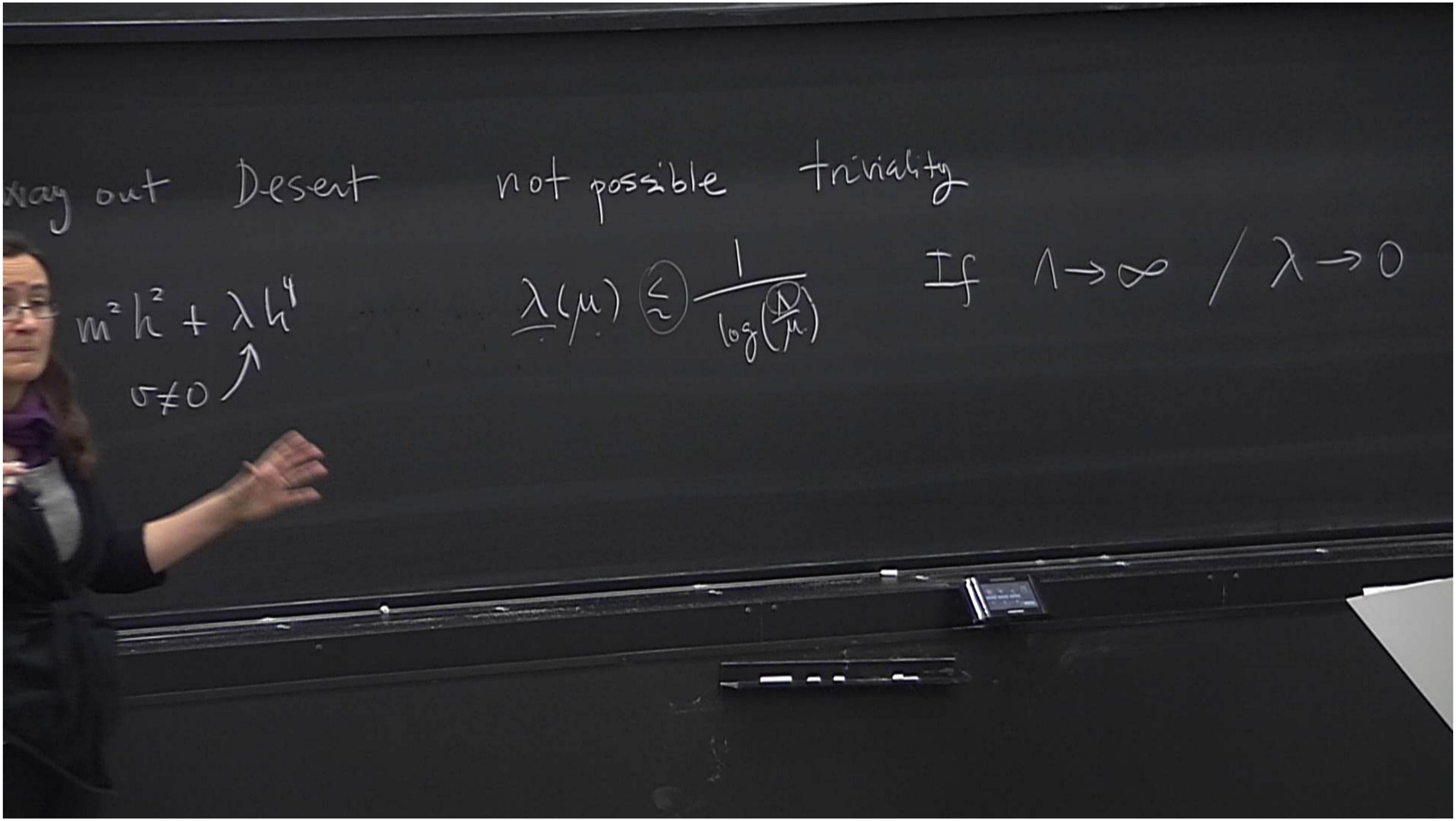
$$y \, \bar{\Psi}_L H \Psi_R \left(\frac{\langle \Phi \rangle}{\Lambda}\right)^{c}$$

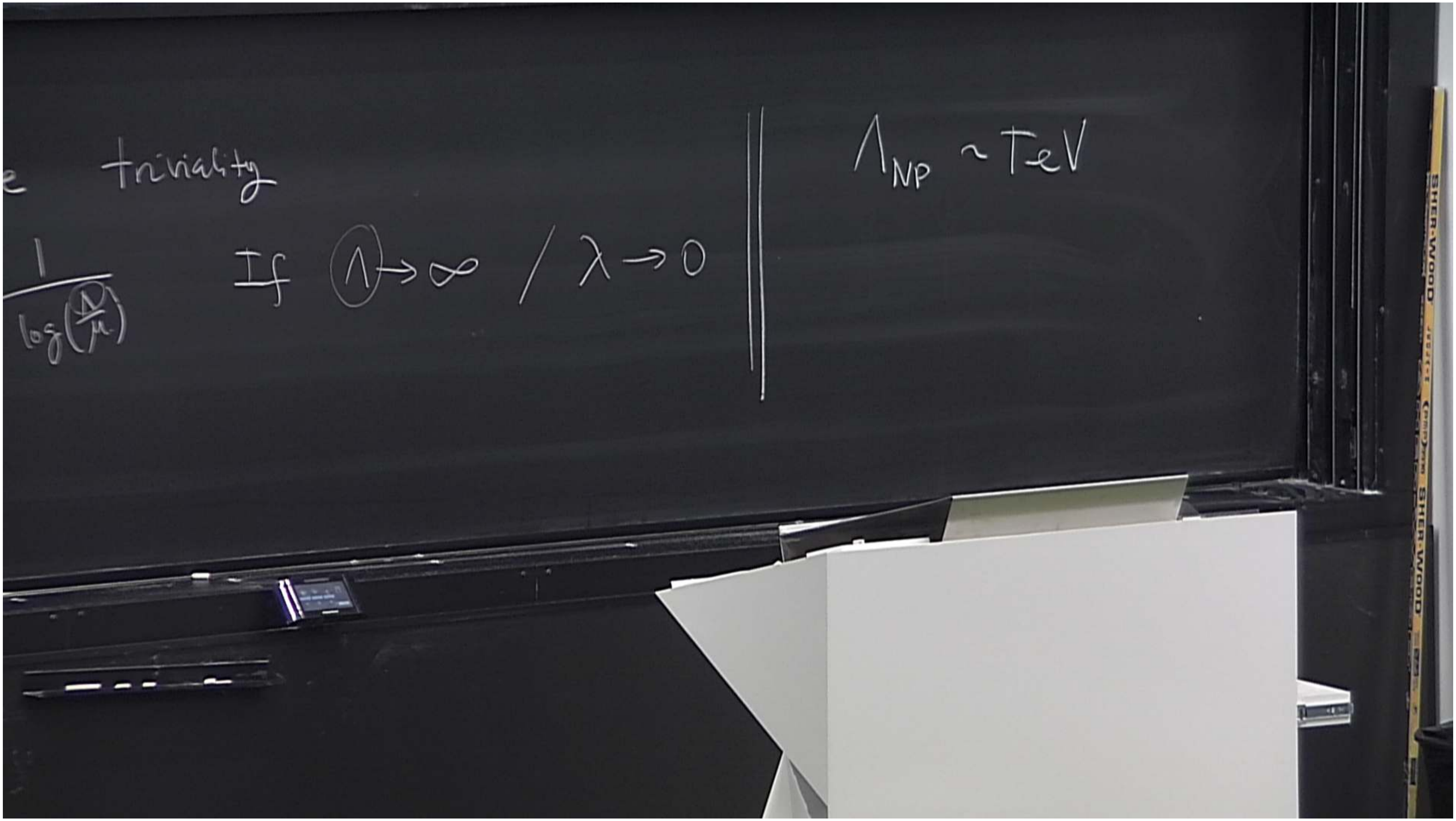
depends on family


S = 1 gauge
S = 1/2 chiral
S = 0 ?? → δm² ∝ Λ²_NP


PEWT
$\delta m^2 \propto \Lambda^2_{NP} \rightarrow$ Higgs heavy


⇒ Higgs heavy
PEWT $m_h \lesssim 130$ GeV
direct searches $m_h \gtrsim 115$ GeV
LHC " " $m_h \lesssim 140$ GeV
Higgs is light


way out Desert
not possible
triviality
$m^2 h^2 + \lambda h^4$
$v \neq 0$
$\lambda(\mu) \lesssim \frac{1}{\log(\Lambda/\mu)}$
If $\Lambda \to \infty$ / $\lambda \to 0$


e triviality
1 / log(Λ/μ)
If Λ → ∞ / λ → 0
Λ_NP ~ TeV
SHER-WOOD

$S = 1$ gauge

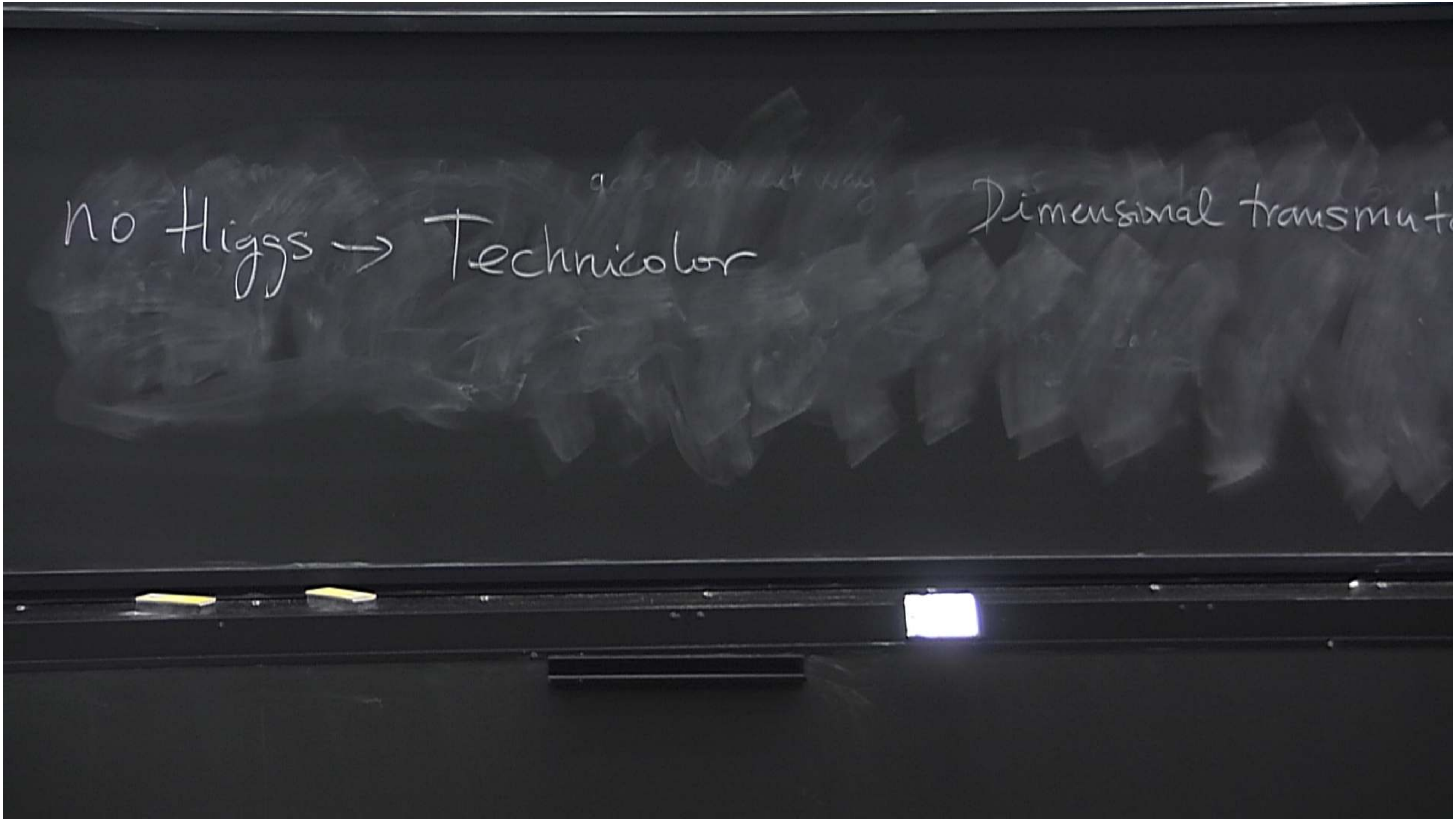
$S = 1/2$ chiral

$S = 0$?? $\longrightarrow$ $\delta m^2 \propto \Lambda^2_{NP}$ $\rightarrow$ Higgs <u>heavy</u>

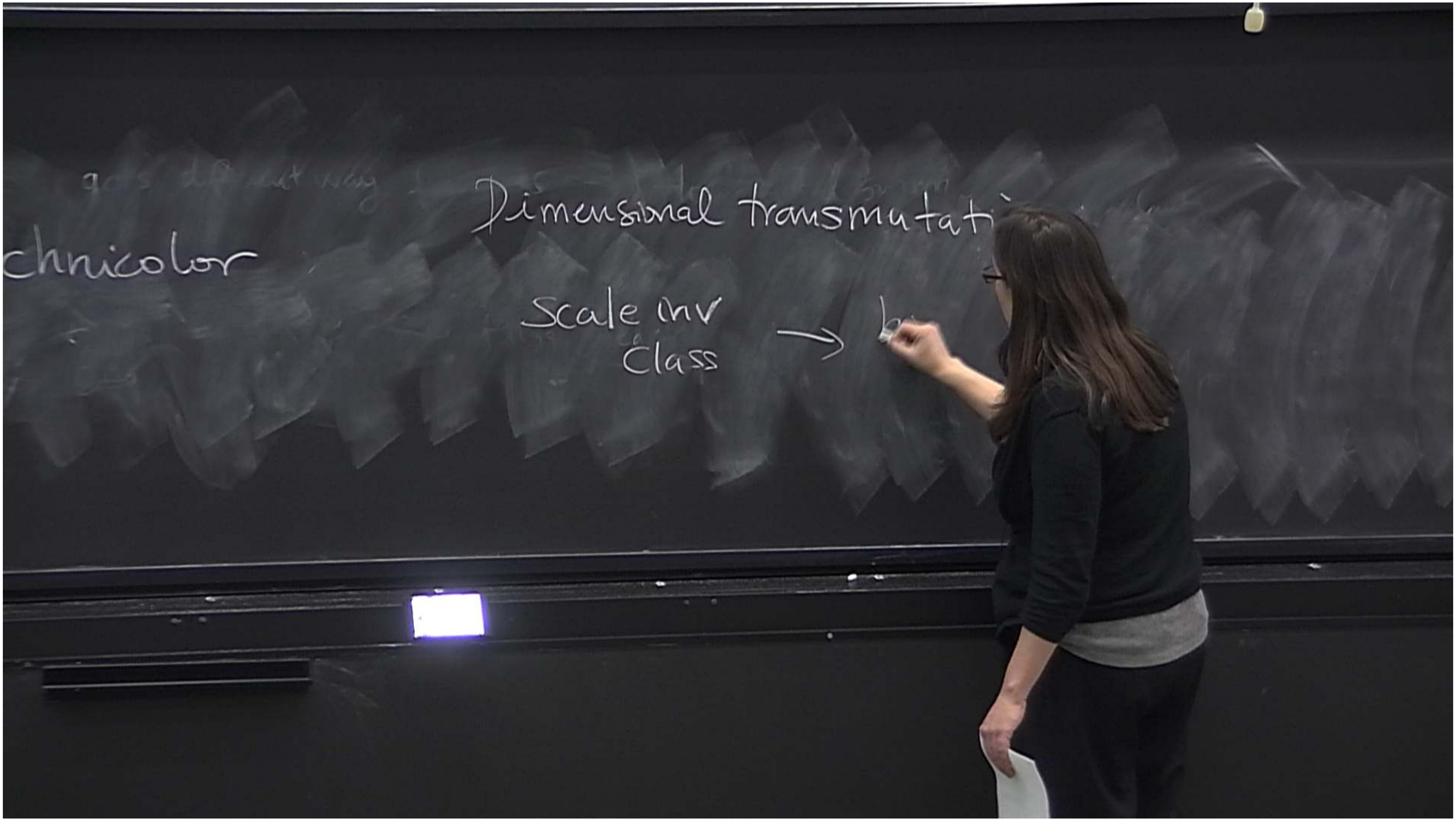
PE

dire

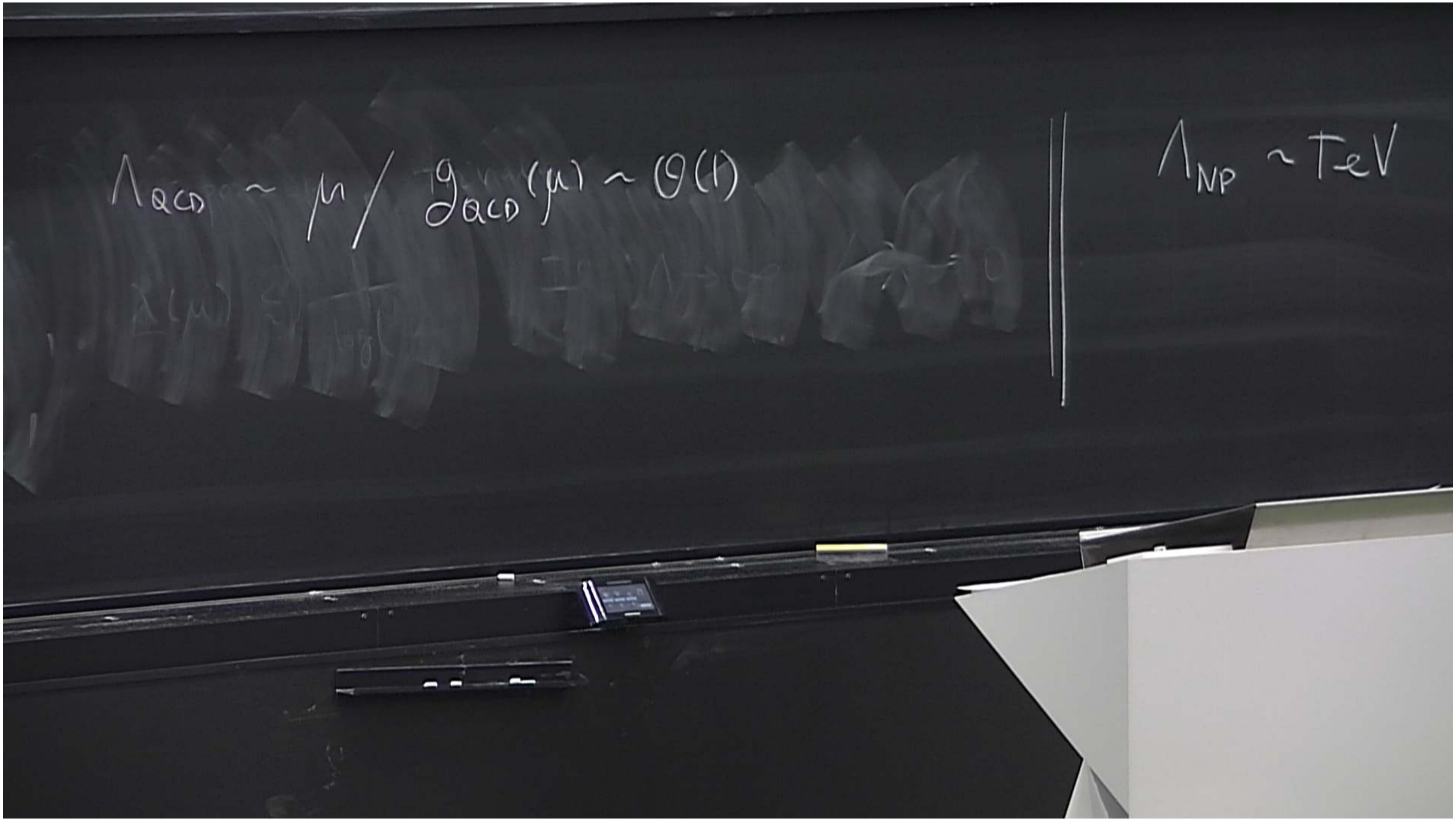
LHC

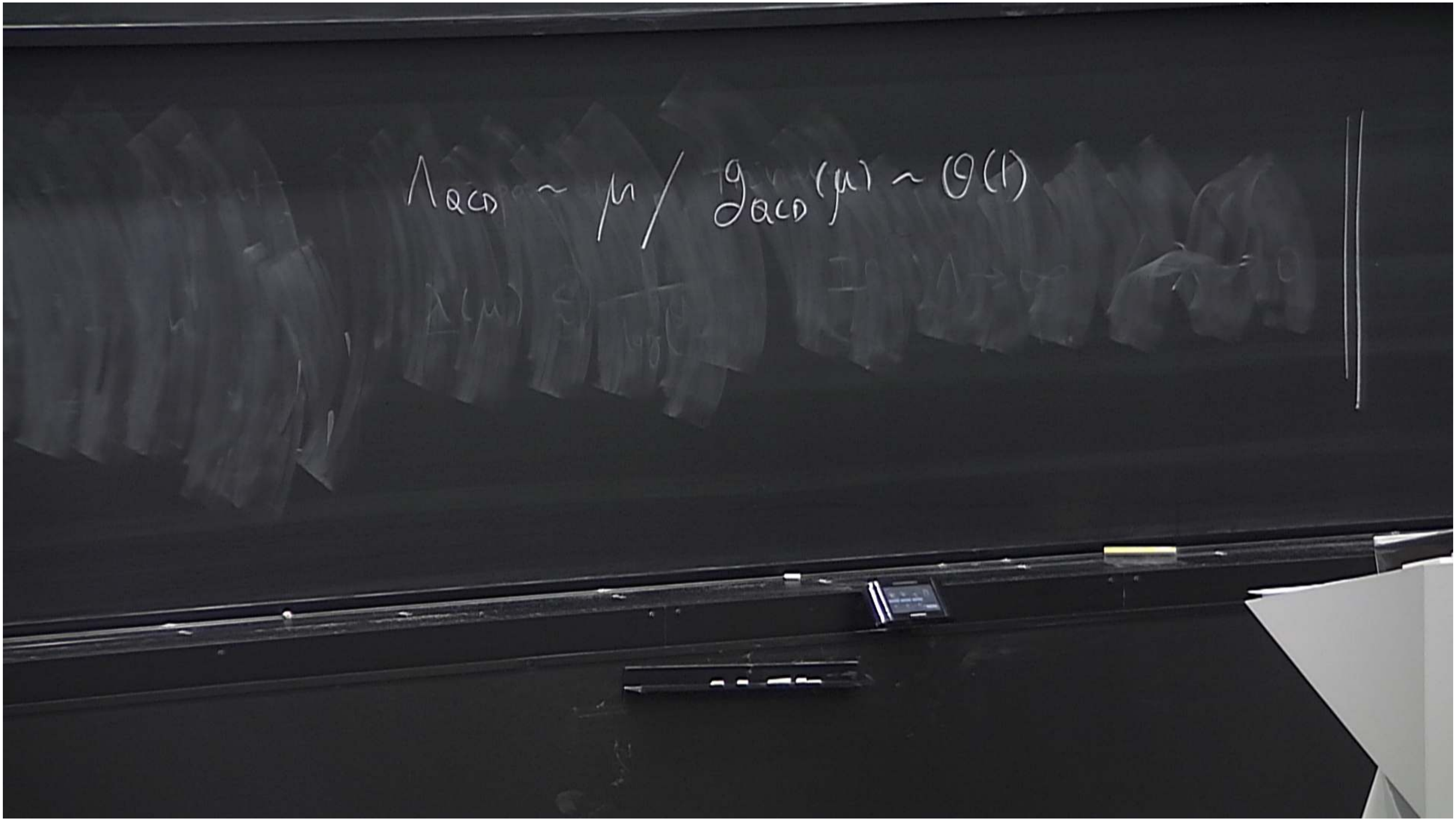


no Higgs → Technicolor
Dimensional transmut



Dimensional transmutati
chnicolor
Scale inv
Class


$\Lambda_{QCD} \sim \mu / \; g_{QCD}(\mu) \sim \mathcal{O}(1)$
$\Lambda_{NP} \sim \mathrm{TeV}$


$\Lambda_{QCD} \sim \mu / g_{QCD}(\mu) \sim \mathcal{O}(1)$