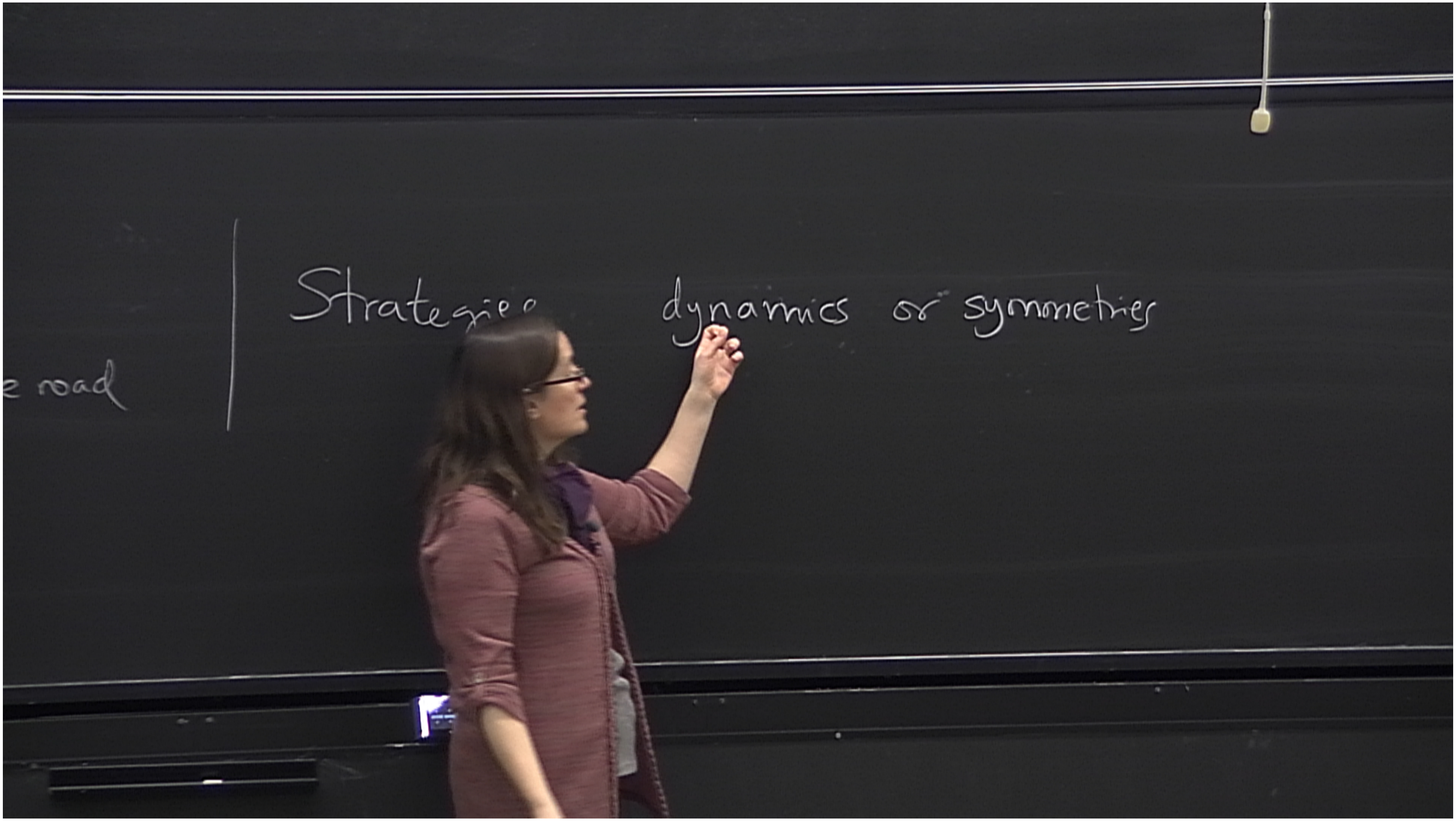
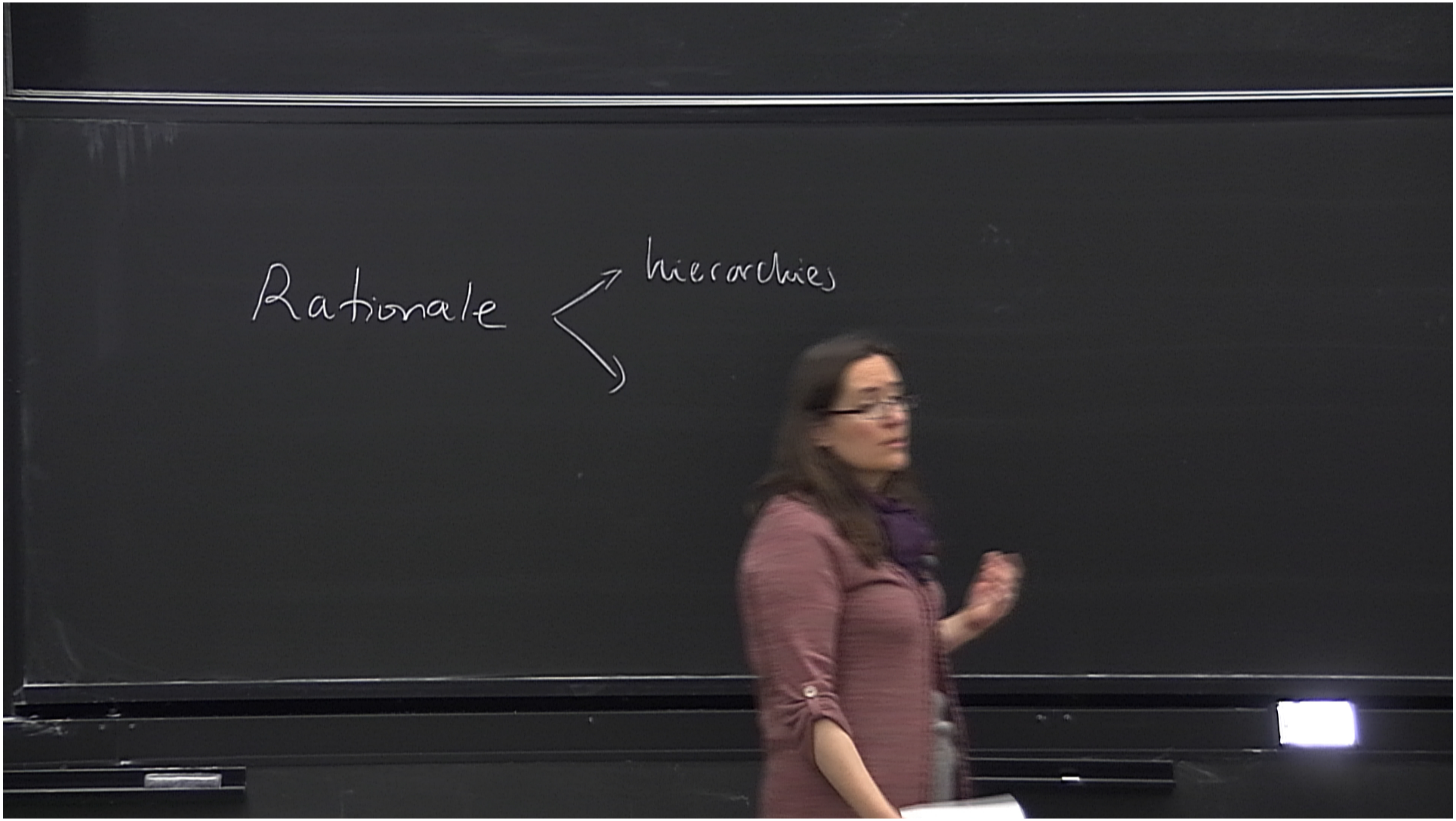
Title: Beyond the Standard Model (Review) - Lecture 3

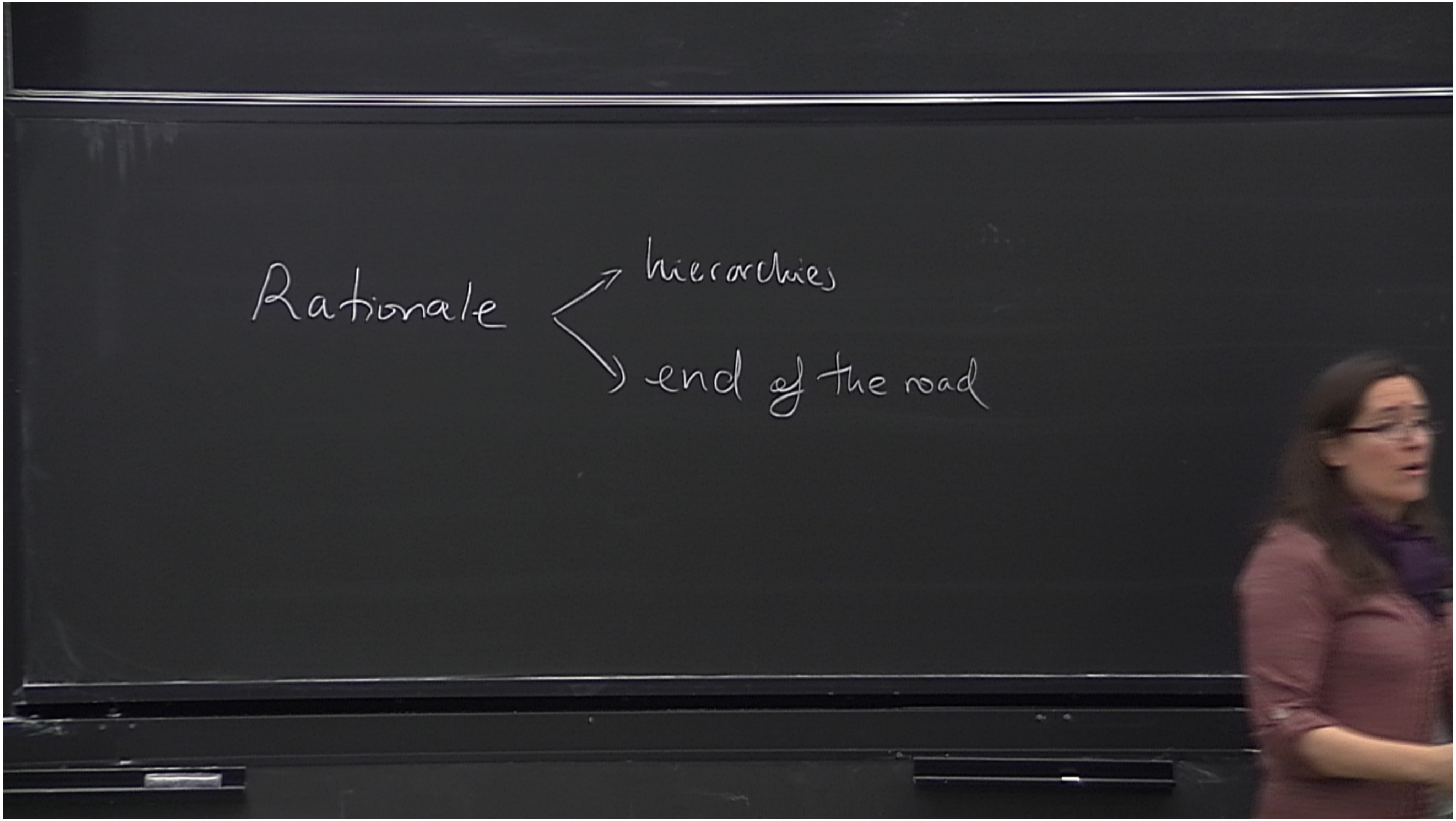
Date: Feb 15, 2012 09:00 AM

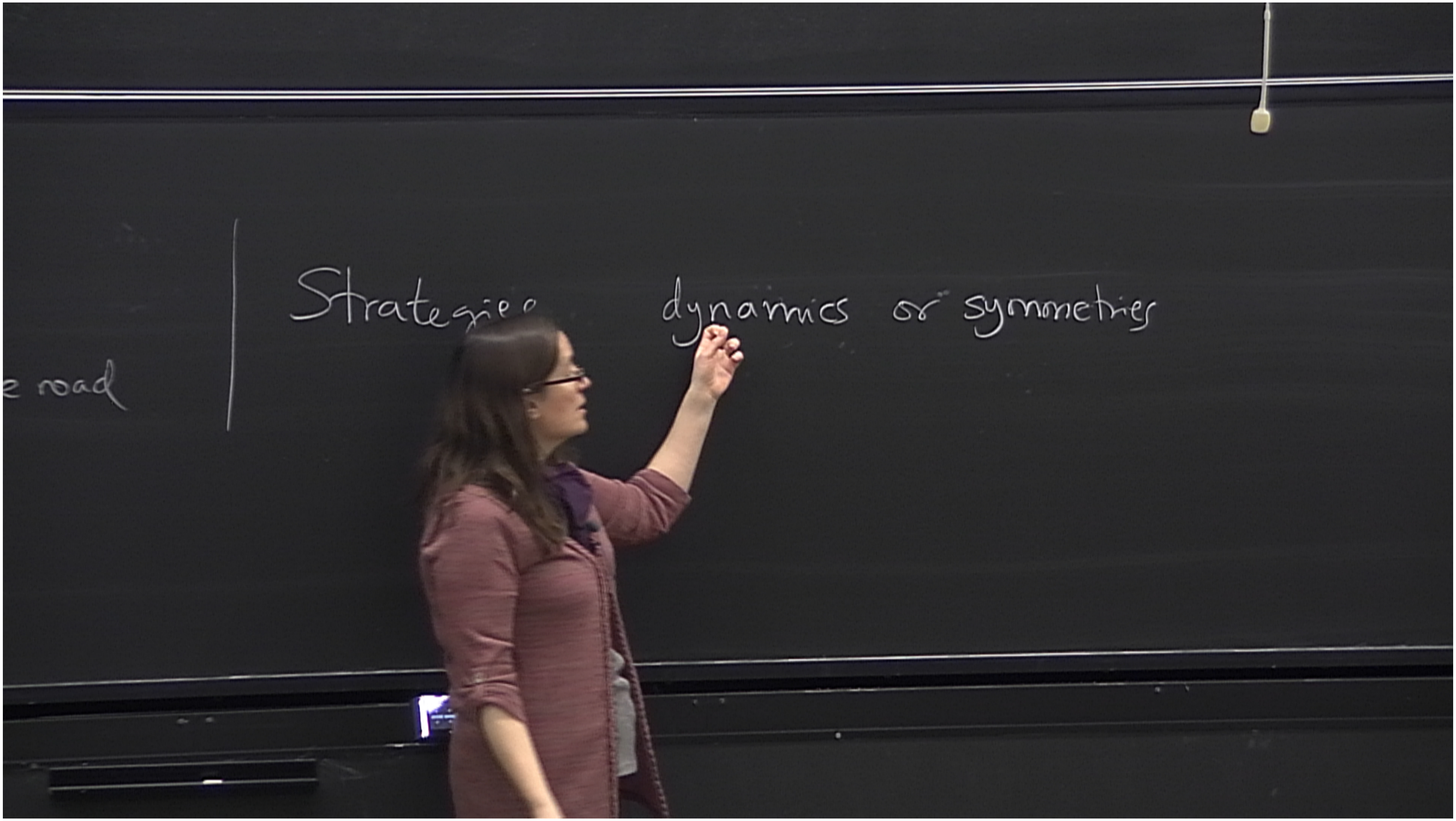
URL: http://pirsa.org/12020066

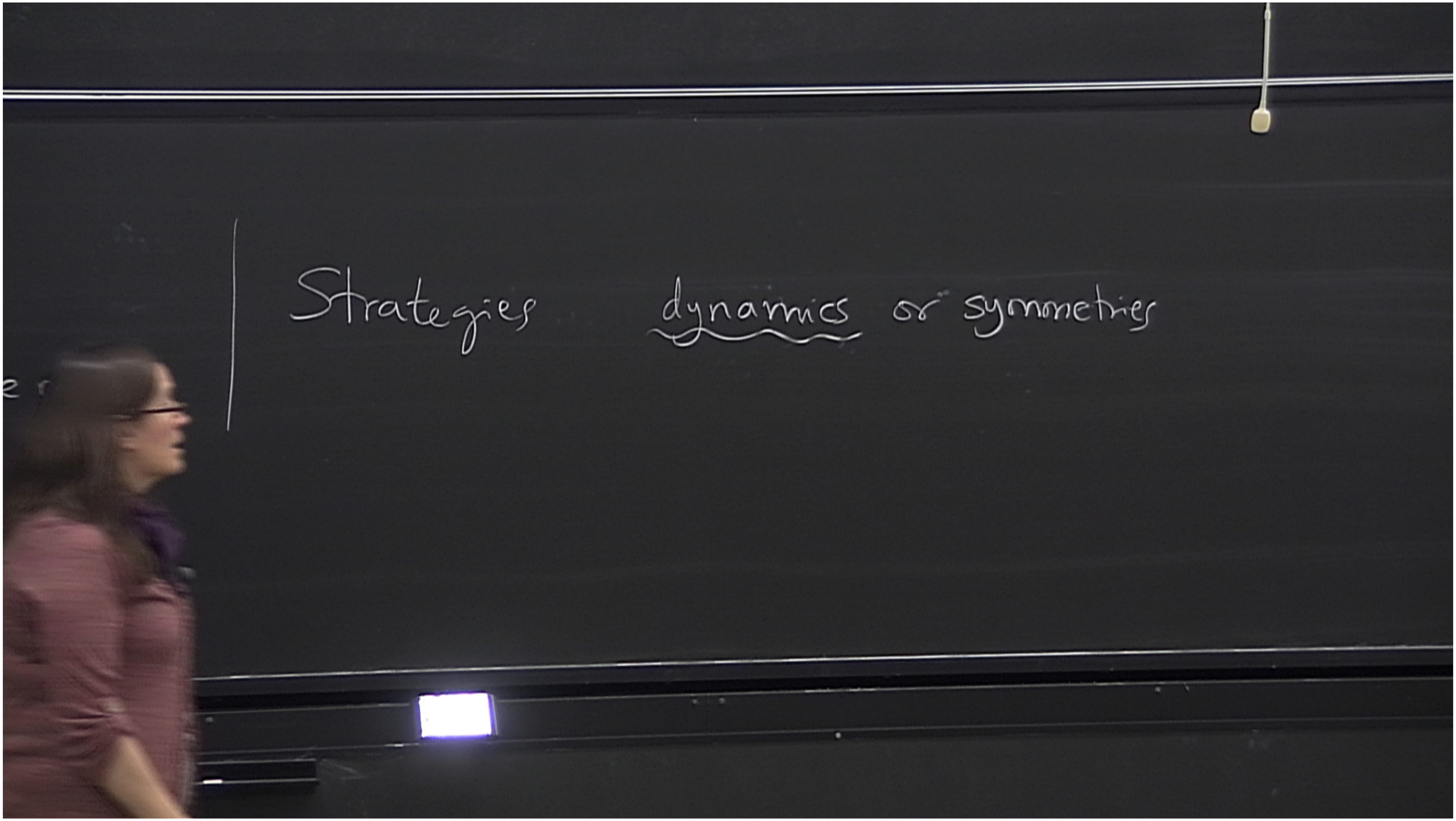
Abstract:

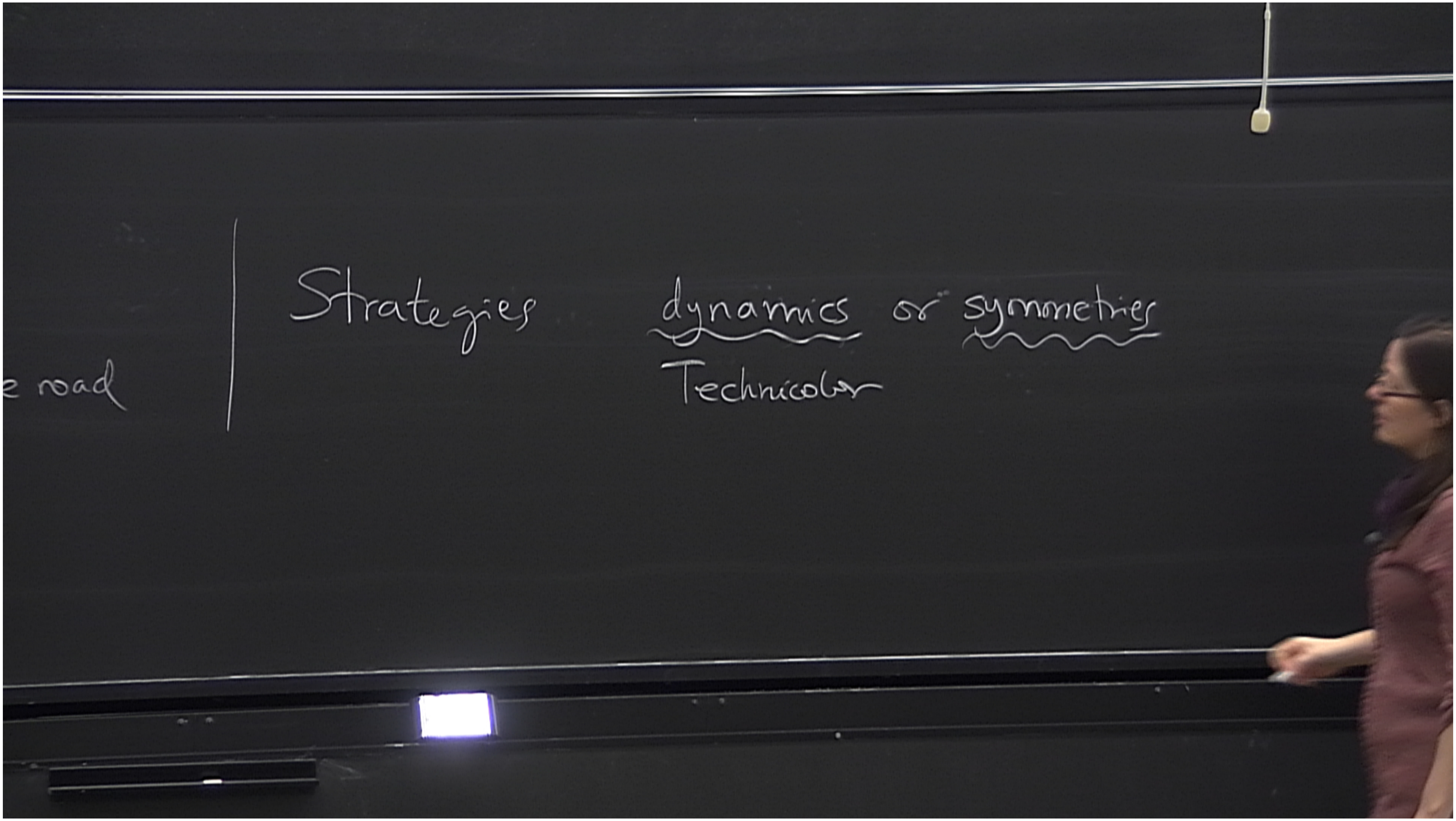

dynamics or symmetries

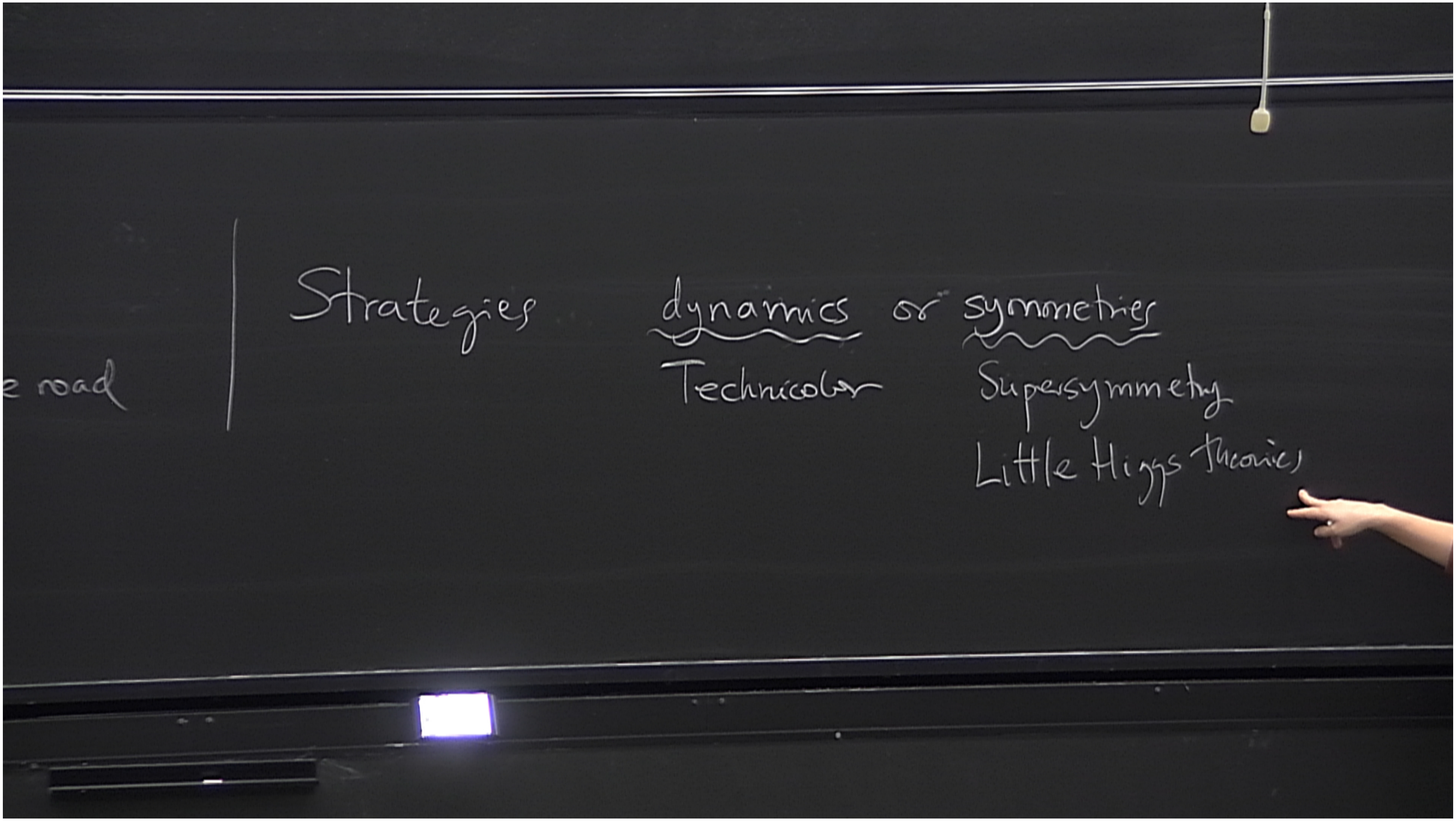

Rationale
hierarchies

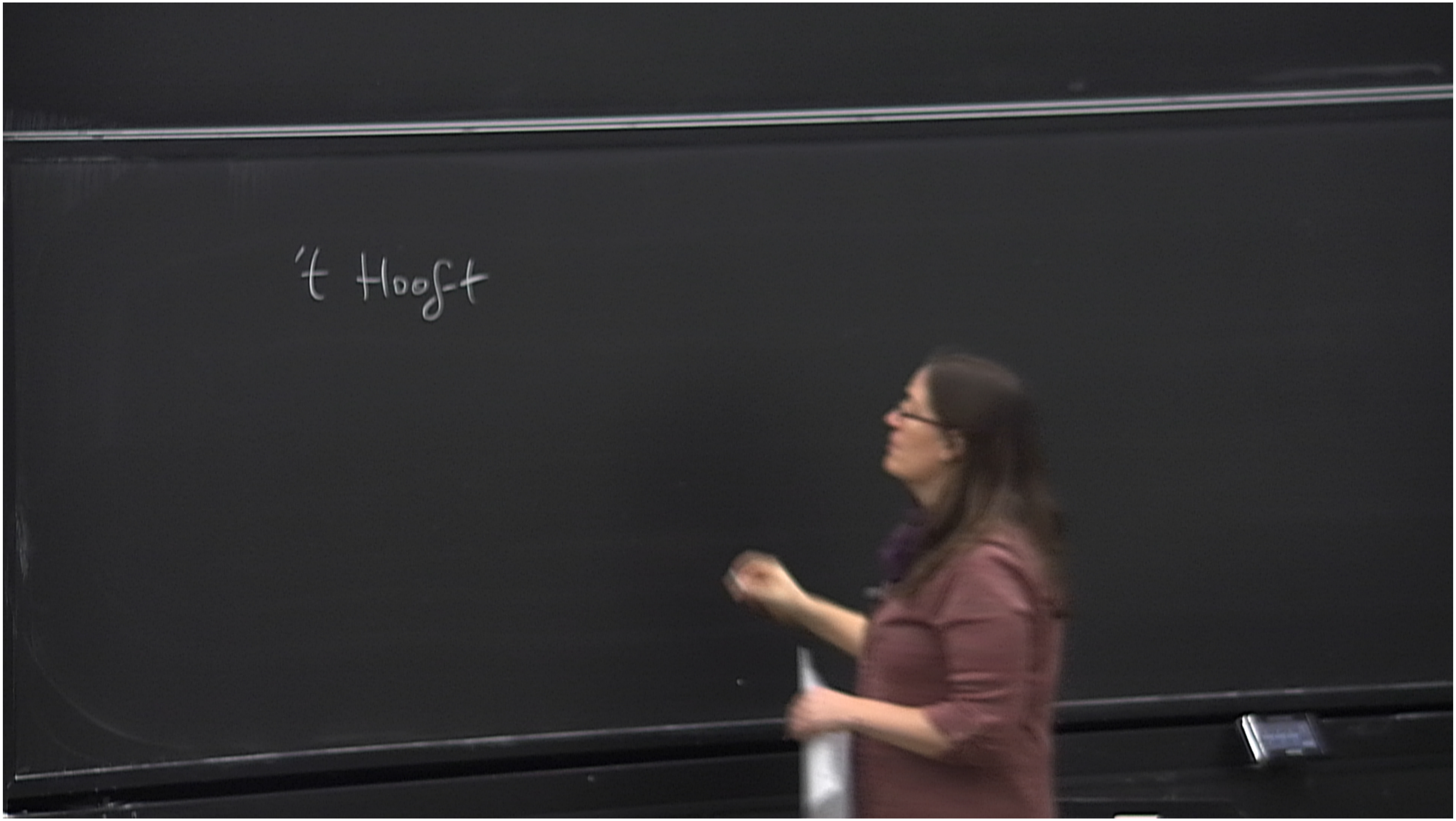

Rationale
hierarchies
end of the road

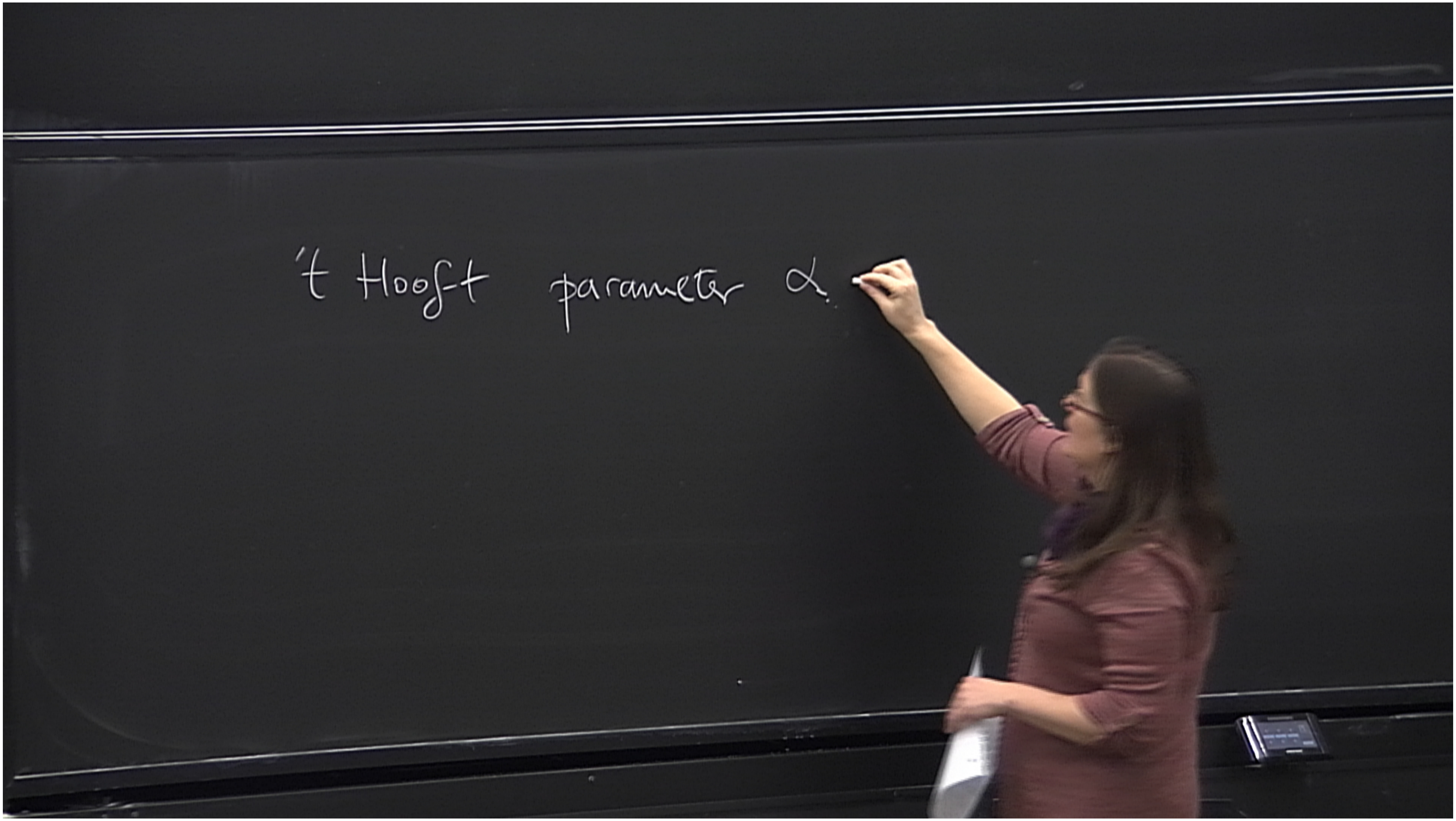

road
dynamics or symmetries

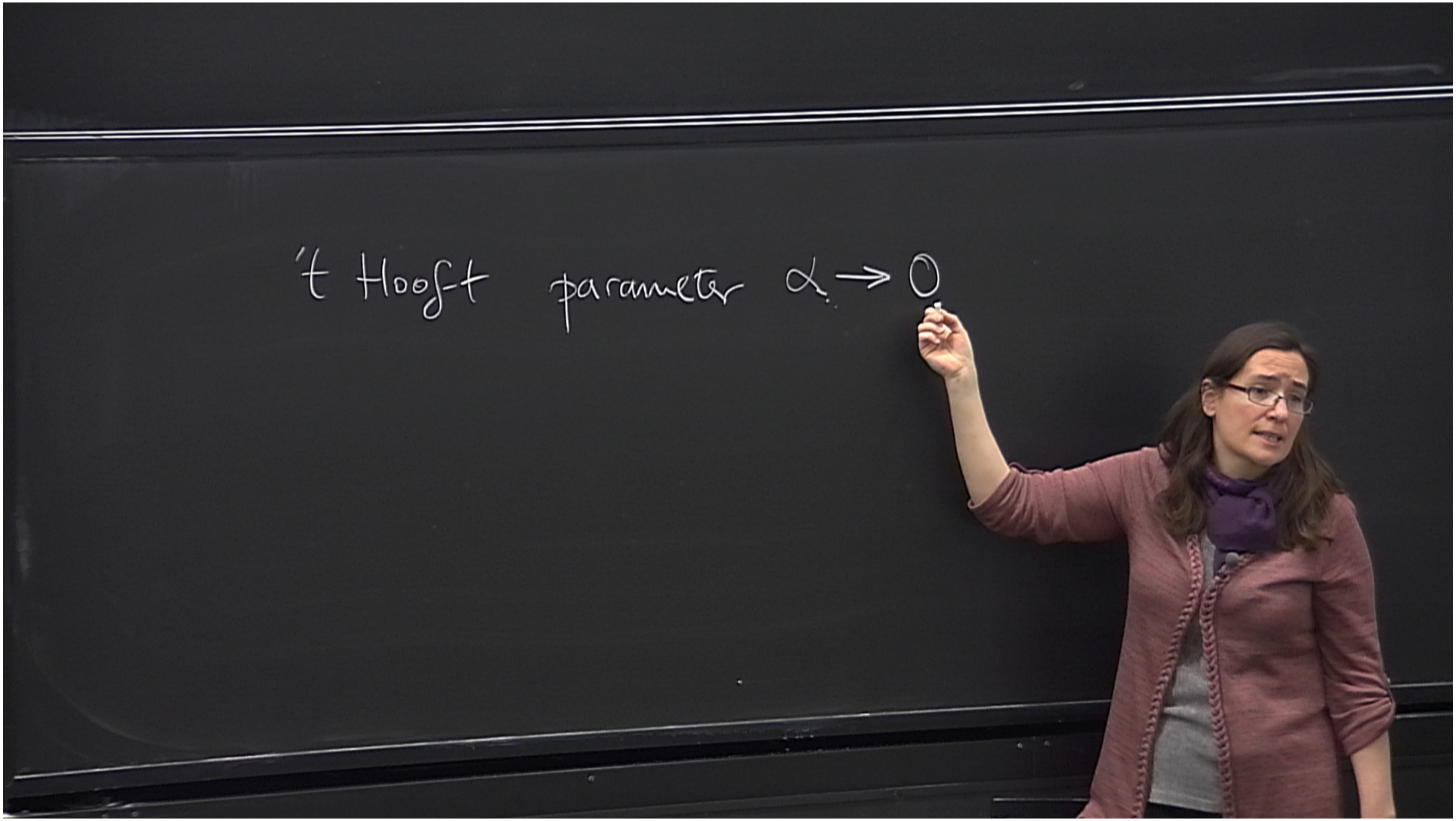

Strategies
dynamics or symmetries


e road
Strategies
dynamics or symmetries
Technicolor


e road
Strategies
dynamics or symmetries
Technicolor
Supersymmetry
Little Higgs theories

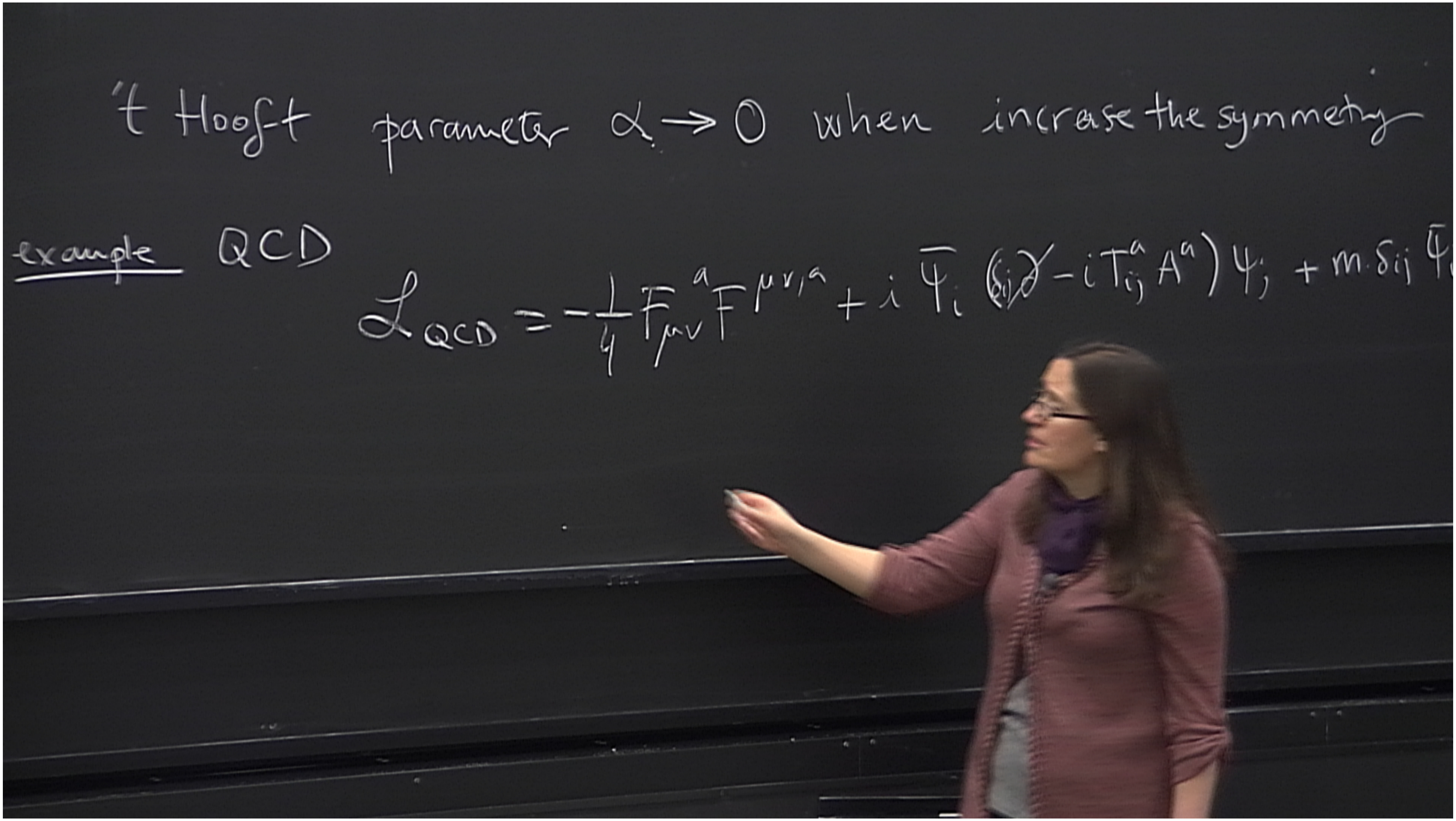

't Hooft


't Hooft parameter α


't Hooft parameter $\alpha \to 0$

't Hooft parameter $\alpha \to 0$ when incrase the symmetry

<u>example</u> QCD


't Hooft parameter $\alpha \to 0$ when increase the symmetry
example QCD
$\mathcal{L}_{QCD} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu,a} + i \bar{\psi}_i (\delta_{ij} \not\partial - i T^{a}_{ij} A^{a}) \psi_j + m \cdot \delta_{ij} \bar{\psi}$

't Hooft parameter $\alpha \to 0$ when increase the symmetry

QCD

$$\mathcal{L}_{QCD} = \underbrace{-\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu,a}}_{} + i \bar{\psi}_i \left(\delta_{ij} \not{\partial} - i T^{a}_{ij} \not{A}^{a} \right) \psi_j + m_i \delta_{ij} \bar{\psi}_i \psi_j$$

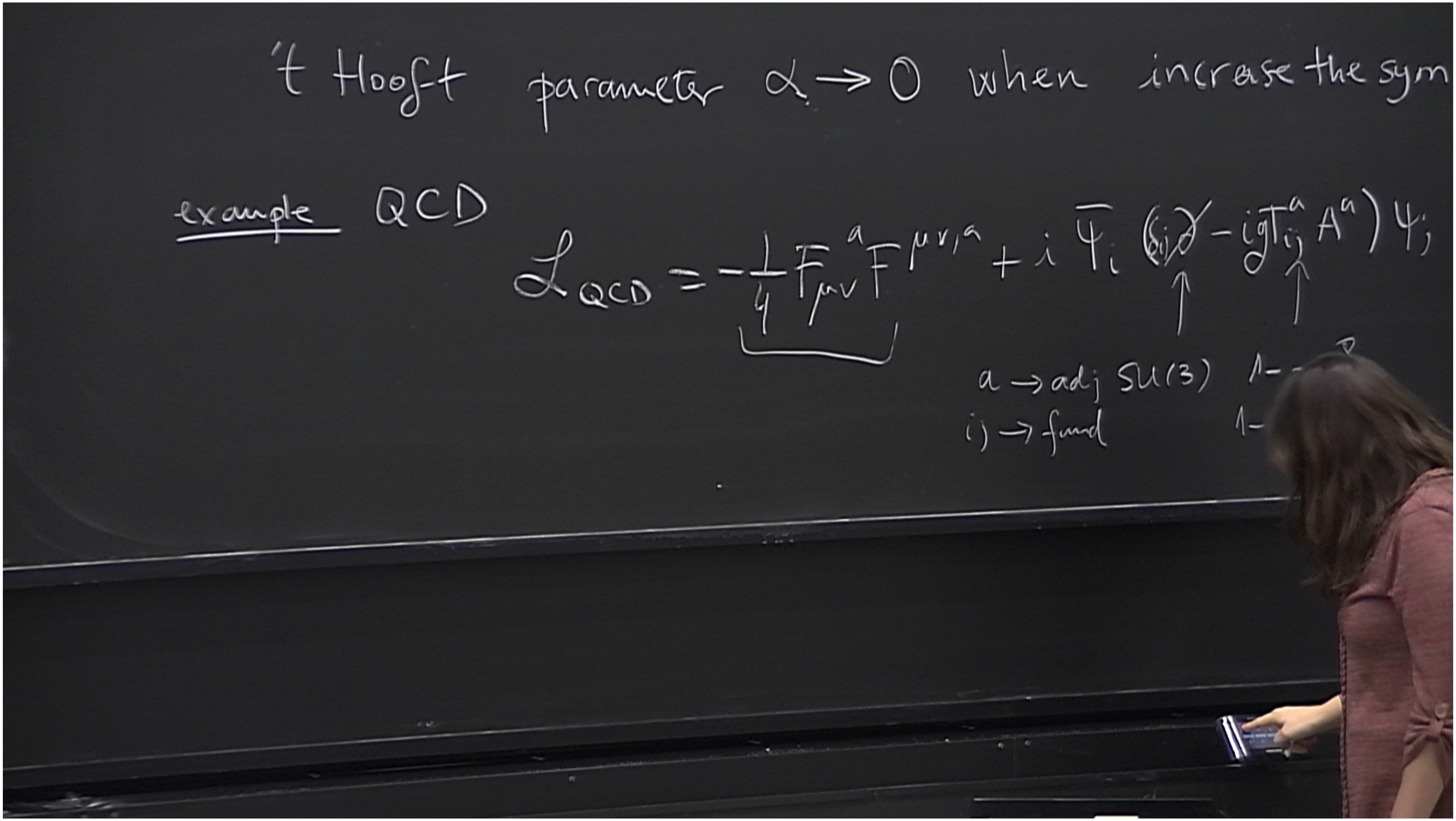
't Hooft parameter $\alpha \to 0$ when increase the symmetry

QCD

$$\mathcal{L}_{QCD} = \underbrace{-\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a}}_{} + i \bar{\psi}_i (\delta_{ij} \not{\partial} - i T^a_{ij} A^a) \psi_j + m_i \delta_{ij} \bar{\psi}_i \psi_j$$

$a \to$ adj $SU(3)$ $1 \ldots 8$

$ij \to$ fund $1-3$


't Hooft parameter $\alpha \to 0$ when increase the sym
example QCD
$\mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + i \bar{\psi}_i (\delta_{ij} \partial\!\!\!/ - i g T^a_{ij} A^a) \psi_j$
$a \to$ adj $SU(3)$
$i \to$ fund

$a \to$ adj $SU(3)$ $1 \ldots 8$

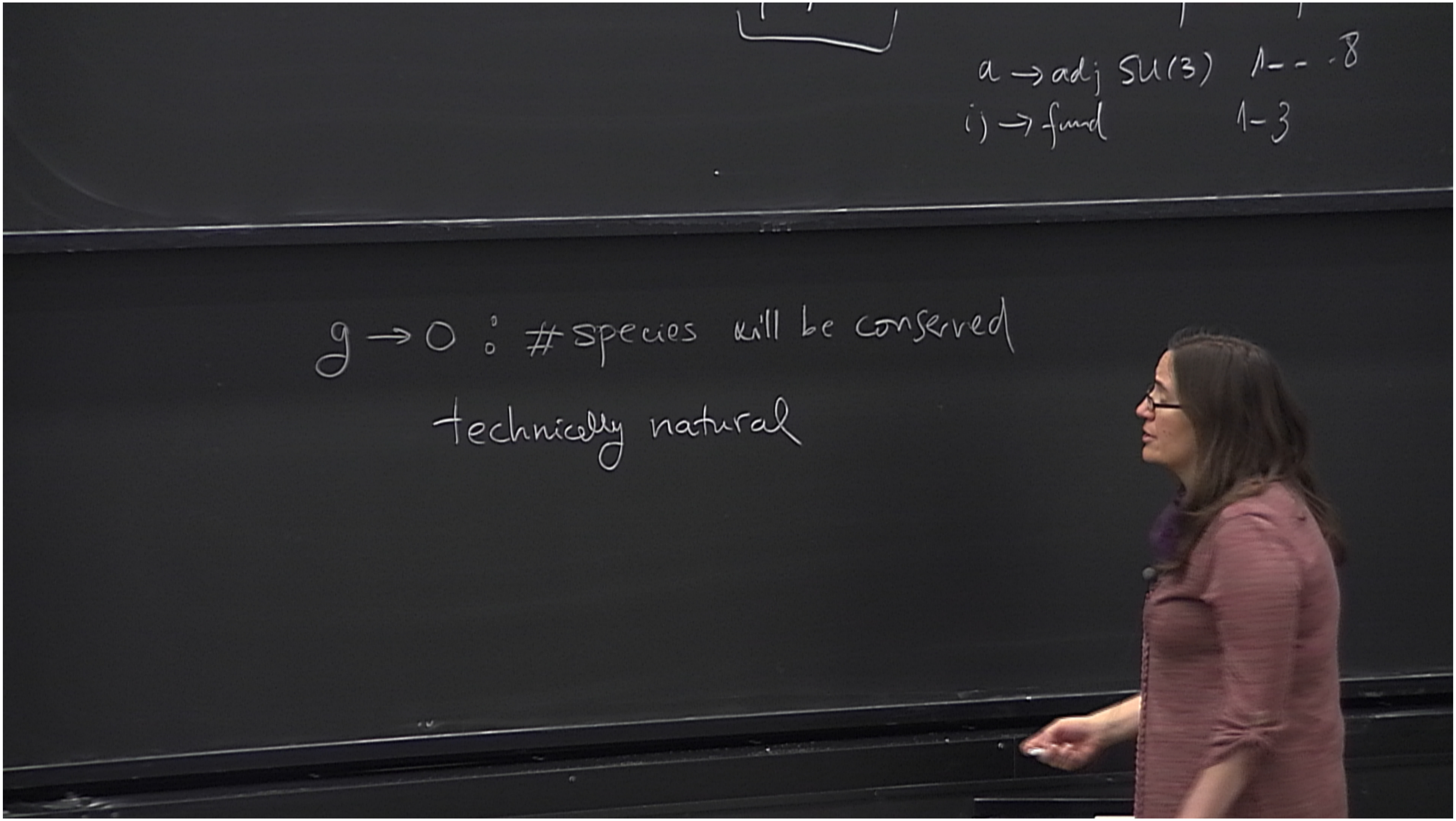
$i \to$ fund $1-3$

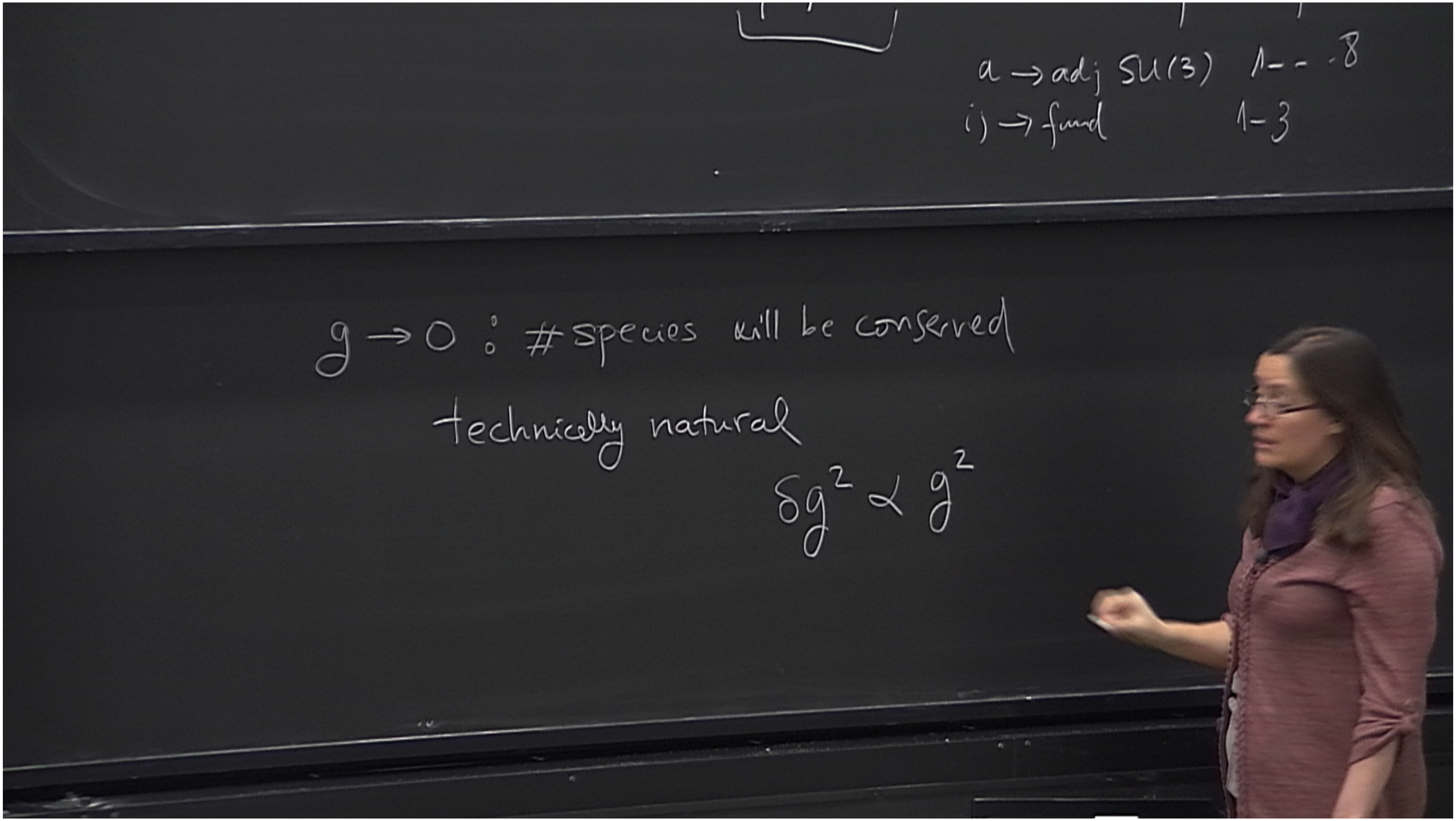
$g \to 0$

$a \to$ adj $SU(3)$ $1 - - 8$

$i \to$ fund $1 - 3$

$g \to 0$: # species will be conserved


a → adj SU(3) 1 - - - 8
i → fund 1 - 3
g → 0 : # species will be conserved
technically natural


a → adj SU(3) 1 - - 8
i → fund 1 - 3
g → 0 : # species will be conserved
technically natural
δg² ∝ g²

$a \to$ adj $SU(3)$ $1 \ldots 8$

$i \to$ fund $1-3$

$g \to 0$: # species will be conserved

technically natural

$\delta g^2 \propto g^2 \log$

$a \to$ adj $SU(3)$ $1 \ldots 8$

$i \to$ fund $1-3$

$g \to 0$: # species will be conserved

technically natural

$$\delta g^2 \propto g^2 \log \Lambda$$

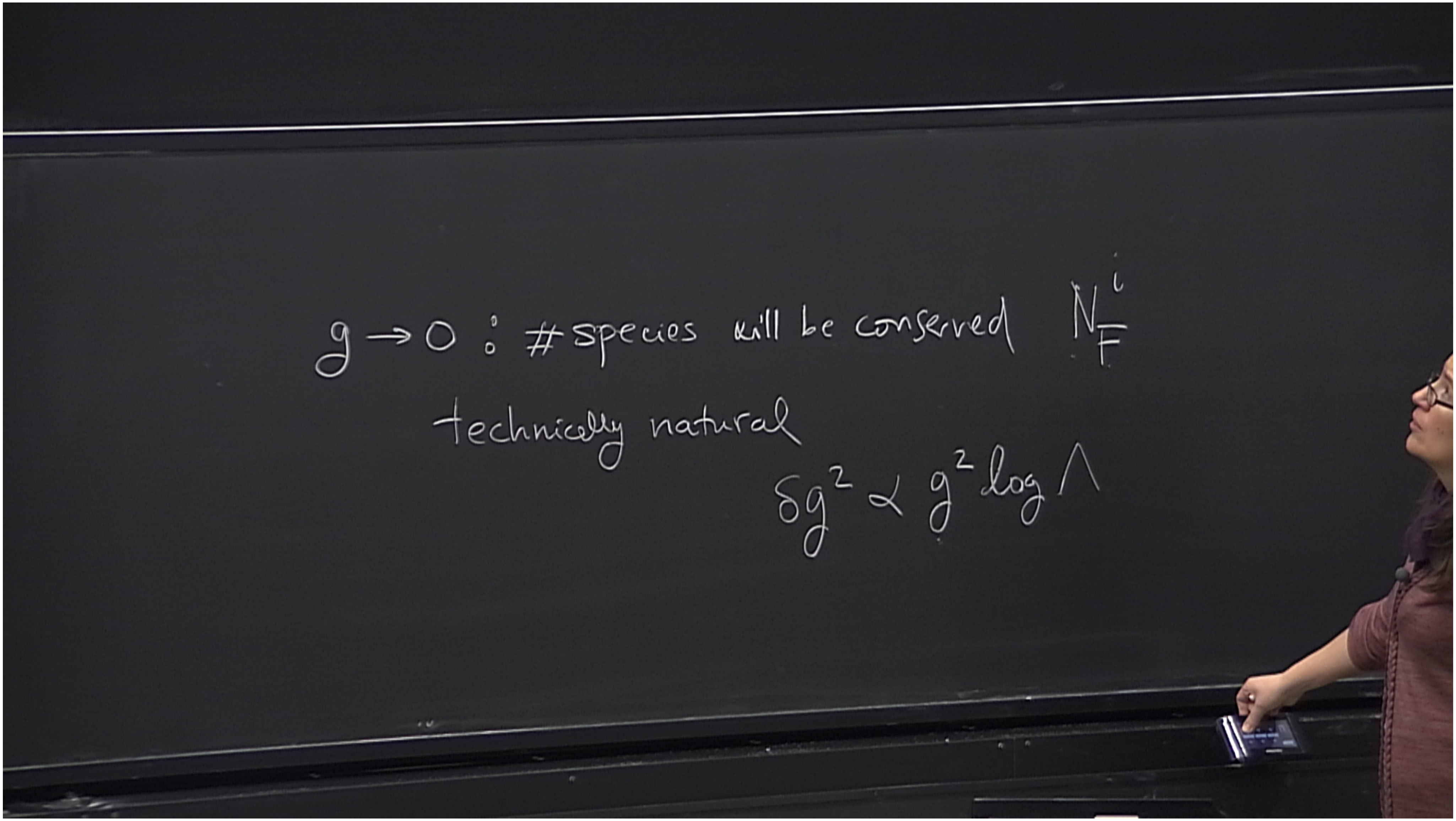
$a \to$ adj $SU(3)$ $1 \ldots 8$

$i \to$ fund $1-3$

$g \to 0$: # species will be conserved N_F^i

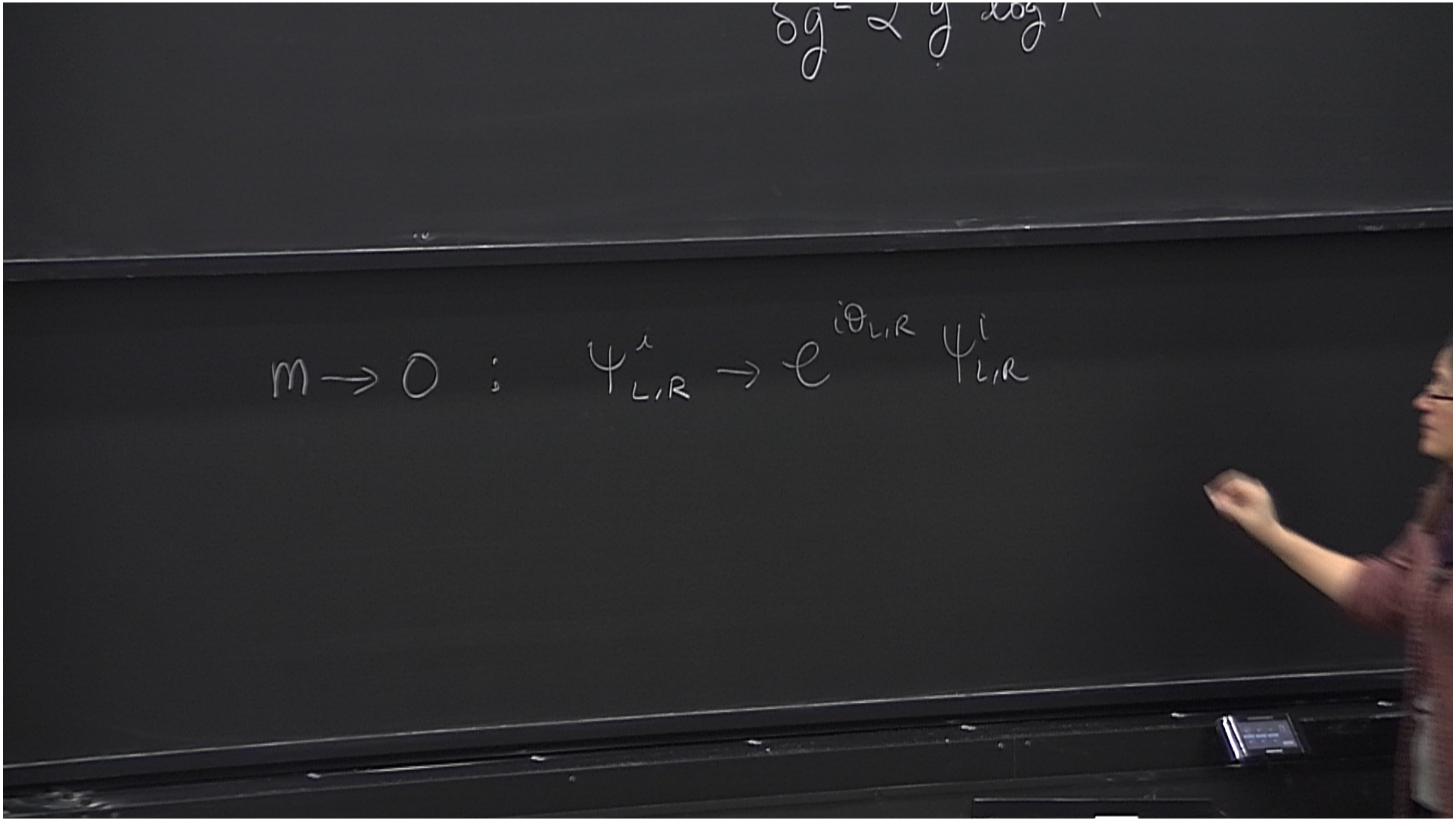
technically natural

$\delta g^2 \propto g^2 \log \Lambda$


$g \to 0$: # species will be conserved N_F^i
technically natural
$\delta g^2 \propto g^2 \log \Lambda$

$\delta g = 2 g \log \Lambda$

$m \to 0$


$\delta g = 2 g \log \Lambda$
$m \to 0 : \quad \psi^i_{L,R} \to e^{i\theta_{L,R}} \psi^i_{L,R}$

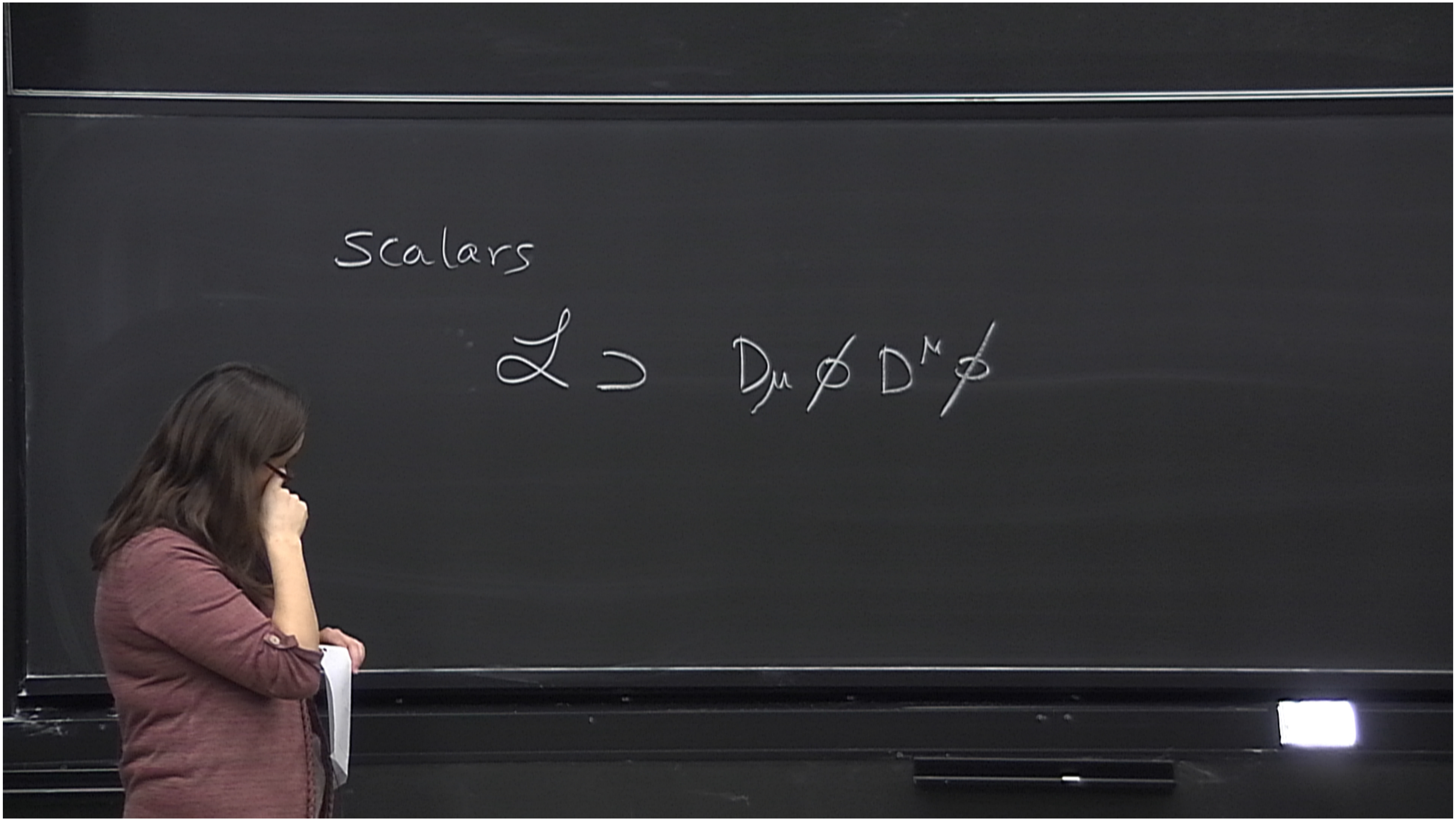
$$\delta g = \alpha\, g \log \Lambda$$

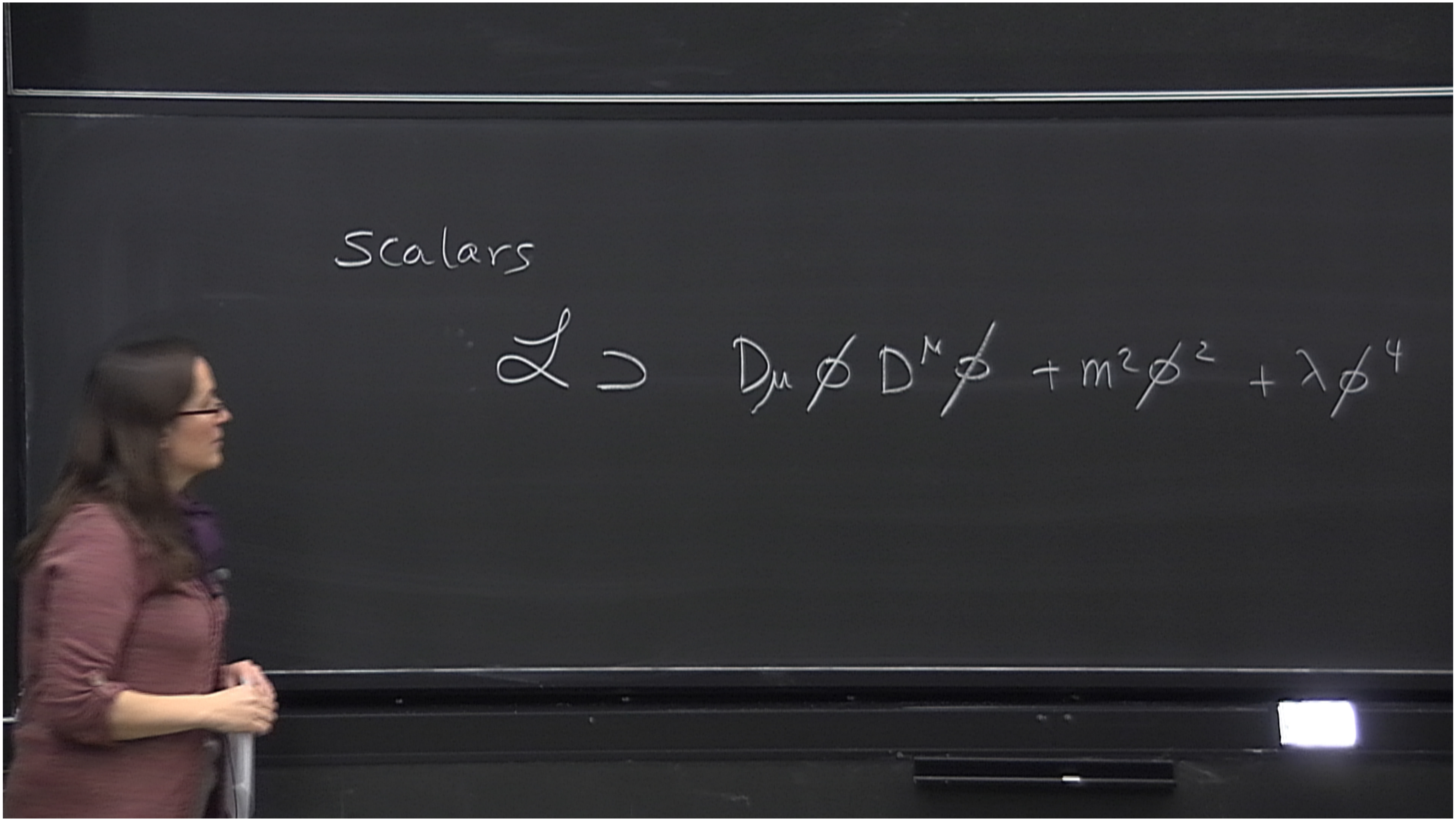
$$m \to 0 : \quad \psi^i_{L,R} \to e^{i\theta_{L,R}}\, \psi^i_{L,R} \quad \text{chiral symm}$$

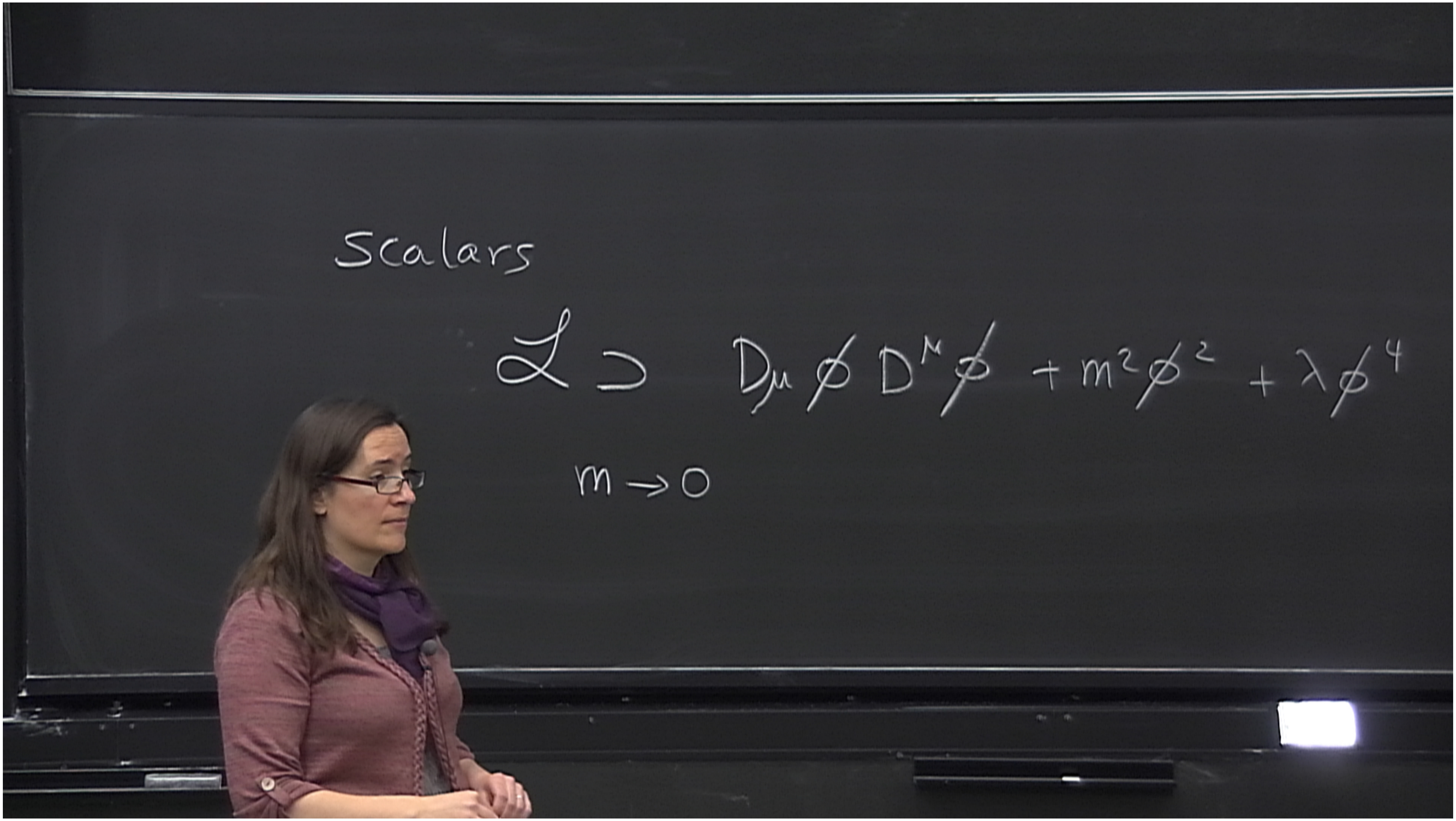
$$\delta g \propto g \log \Lambda$$

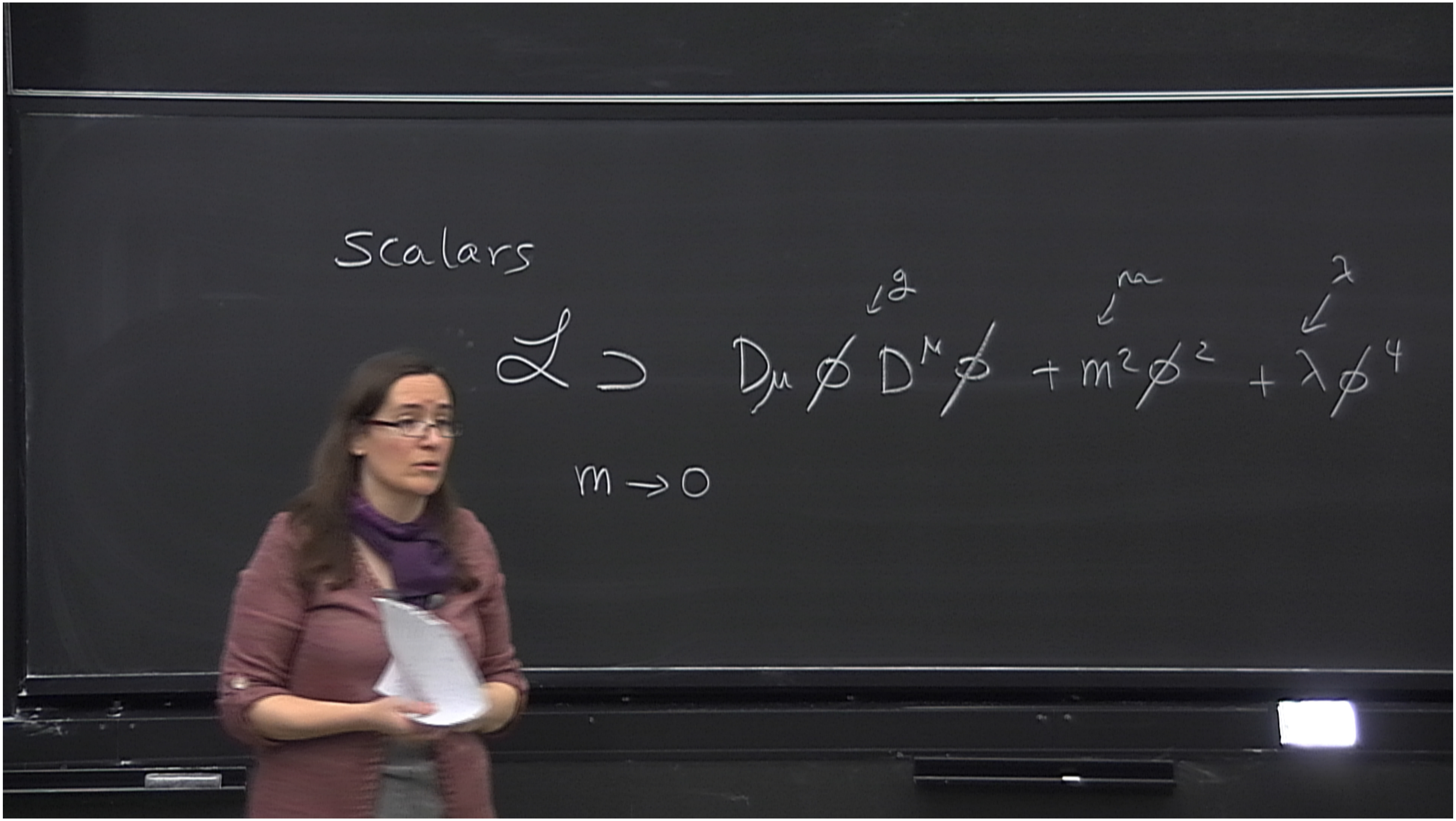
$$m \to 0 : \quad \psi^i_{L,R} \to e^{i\theta_{L,R}} \psi^i_{L,R} \quad \text{chiral symm}$$

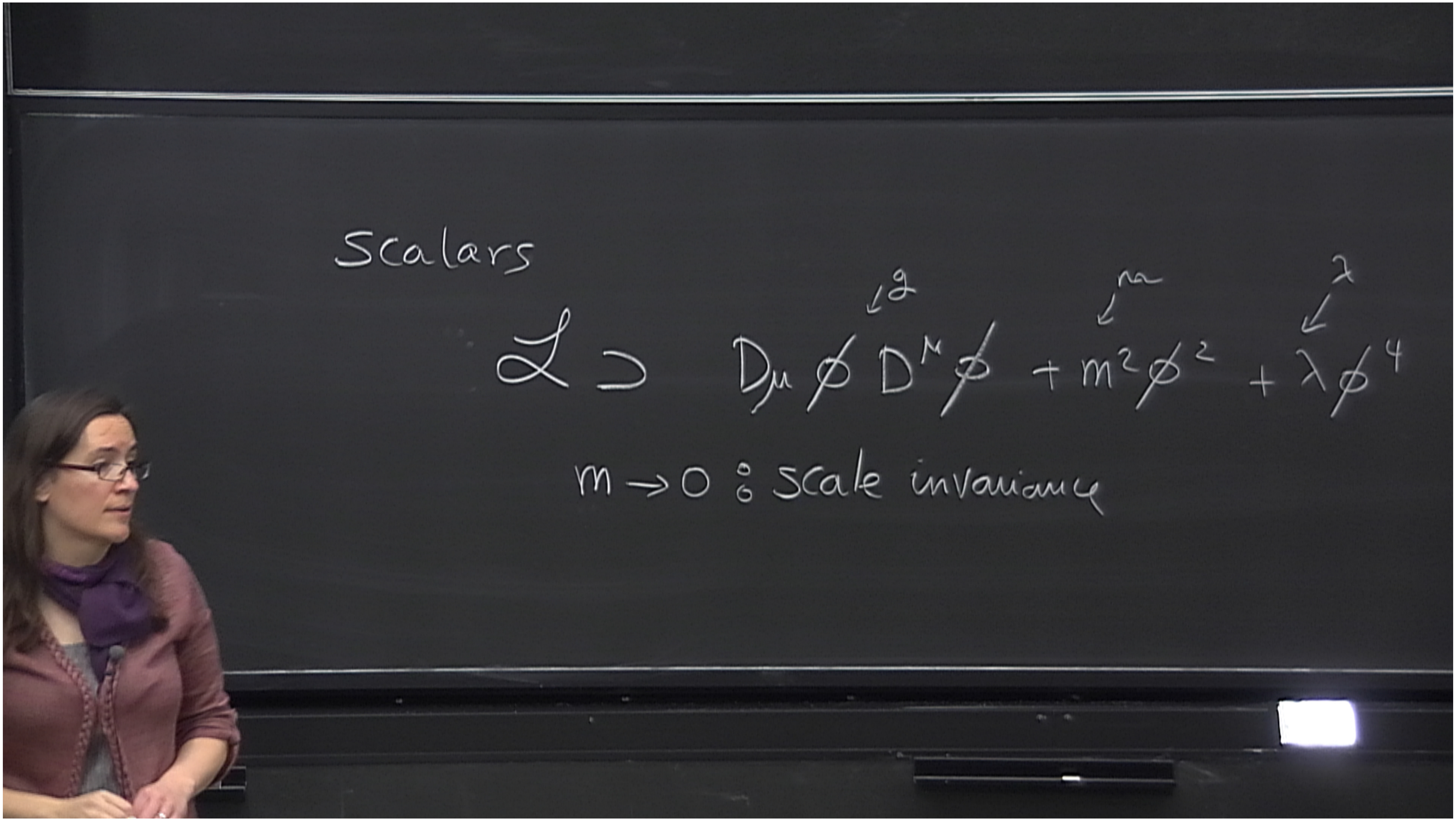
$$\delta m \propto m \log \Lambda$$


Scalars
$\mathcal{L} \supset D_\mu \phi D^\mu \phi$


Scalars
$\mathcal{L} \supset D_\mu \phi D^\mu \phi + m^2 \phi^2 + \lambda \phi^4$


Scalars
$\mathcal{L} \supset D_\mu \phi D^\mu \phi + m^2 \phi^2 + \lambda \phi^4$
$m \to 0$

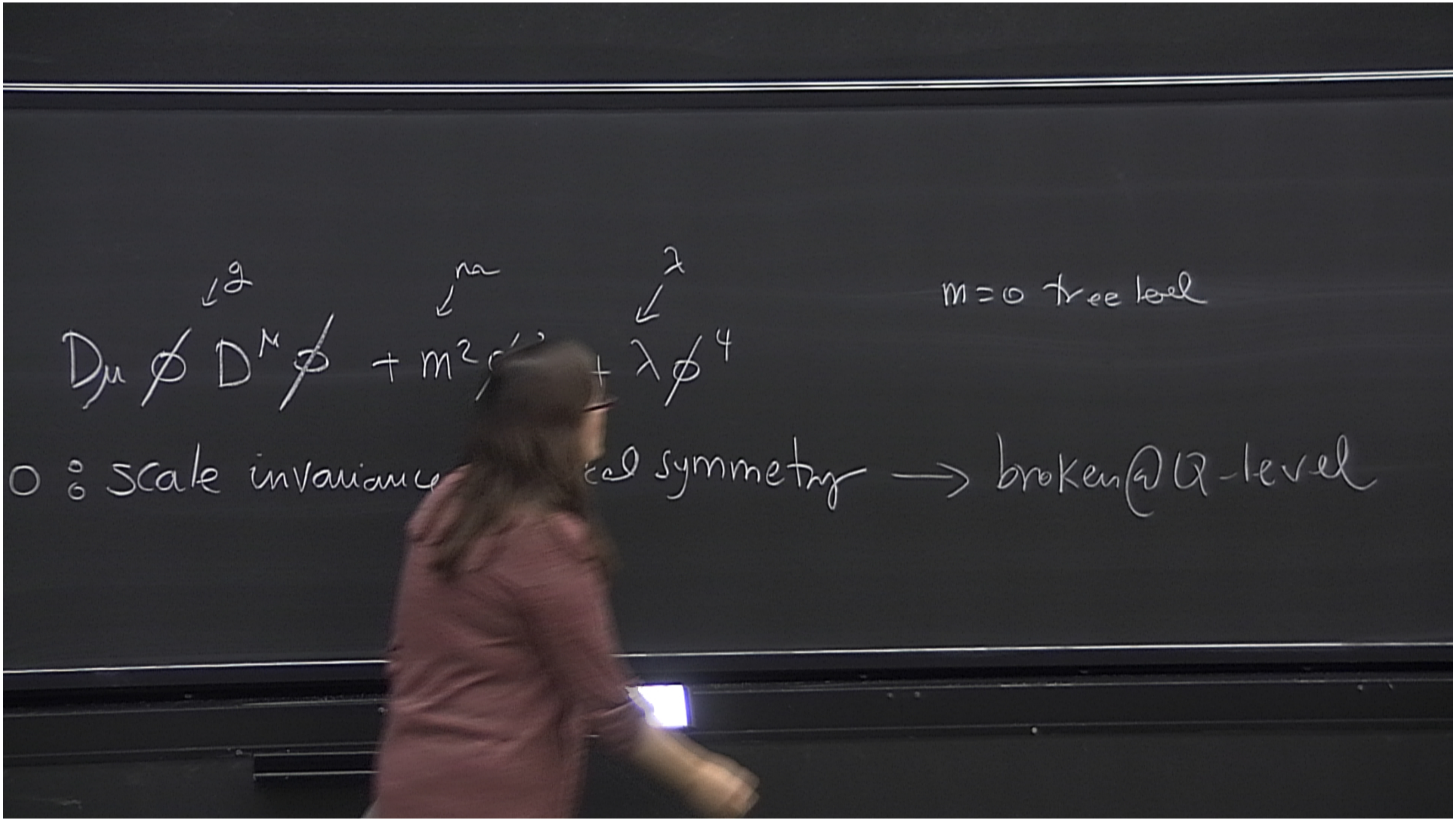

Scalars
g
m
λ
ℒ ⊃ D_μ φ D^μ φ + m² φ² + λ φ⁴
m → 0

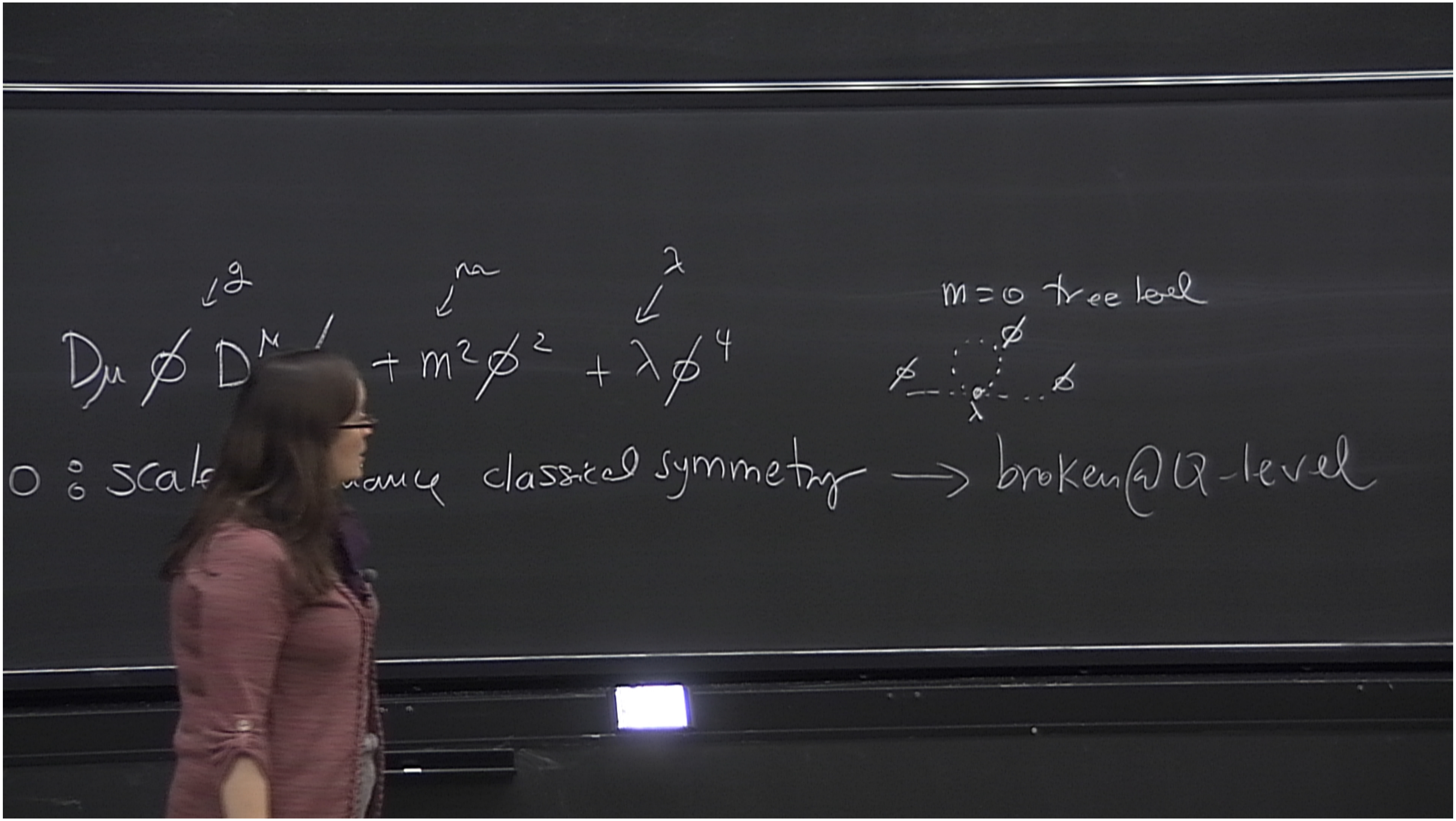

Scalars
g
m
λ
ℒ ⊃ D_μ ϕ D^μ ϕ + m² ϕ² + λ ϕ⁴
m → 0 : scale invariance

Scalars

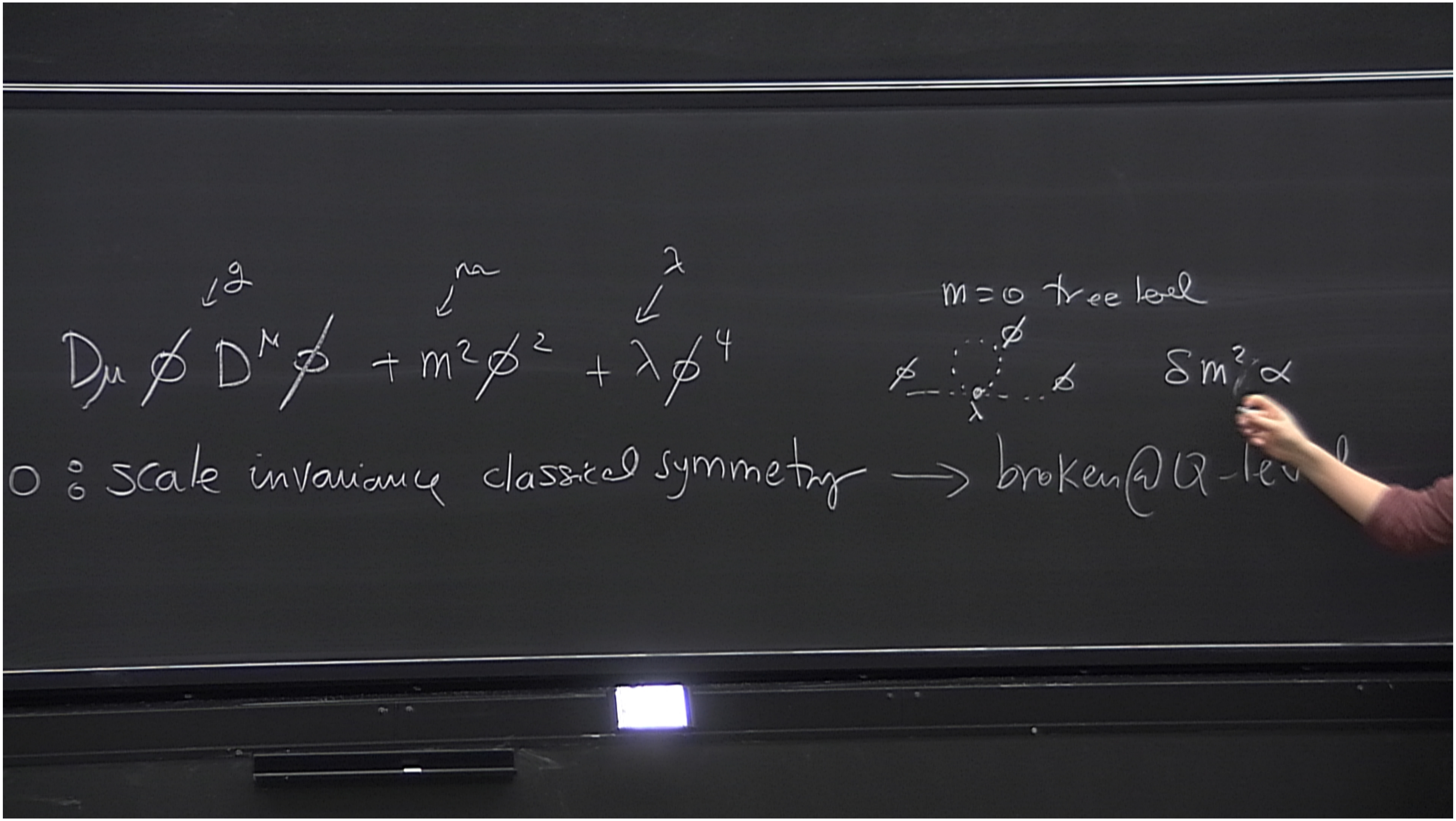
$$\mathcal{L} \supset \overset{g}{D_\mu \phi\, D^\mu \phi} + \overset{m}{m^2 \phi^2} + \overset{\lambda}{\lambda \phi^4}$$

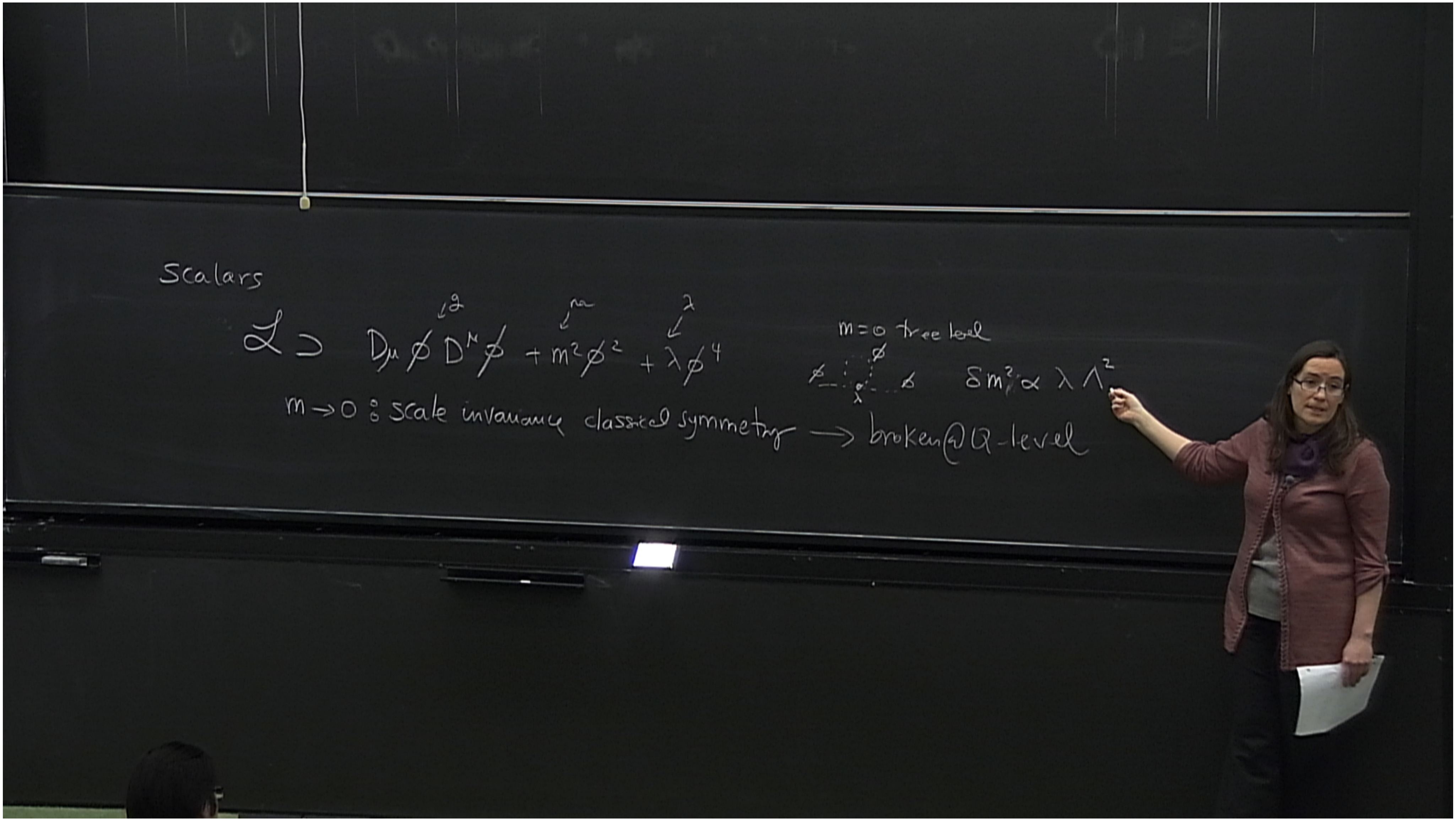
$m \to 0$: scale invariance classical symmetry


g
λ
m=0 tree level
$D_\mu \phi D^\mu \phi + m^2$
$+ \lambda \phi^4$
scale invariance
symmetry → broken@Q-level



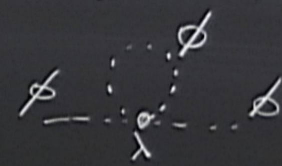
m = 0 tree level
classical symmetry → broken @ Q-level


g
m
λ
$D_\mu \phi D^\mu \phi + m^2 \phi^2 + \lambda \phi^4$
m = 0 tree level
$\delta m^2 \propto$
0 : scale invariance classical symmetry → broken @ Q-level


Scalars
$\mathcal{L} \supset D_\mu \phi D^\mu \phi + m^2 \phi^2 + \lambda \phi^4$
m=0 tree level
$\delta m^2 \propto \lambda \Lambda^2$
$m \to 0$: scale invariance classical symmetry → broken@Q-level

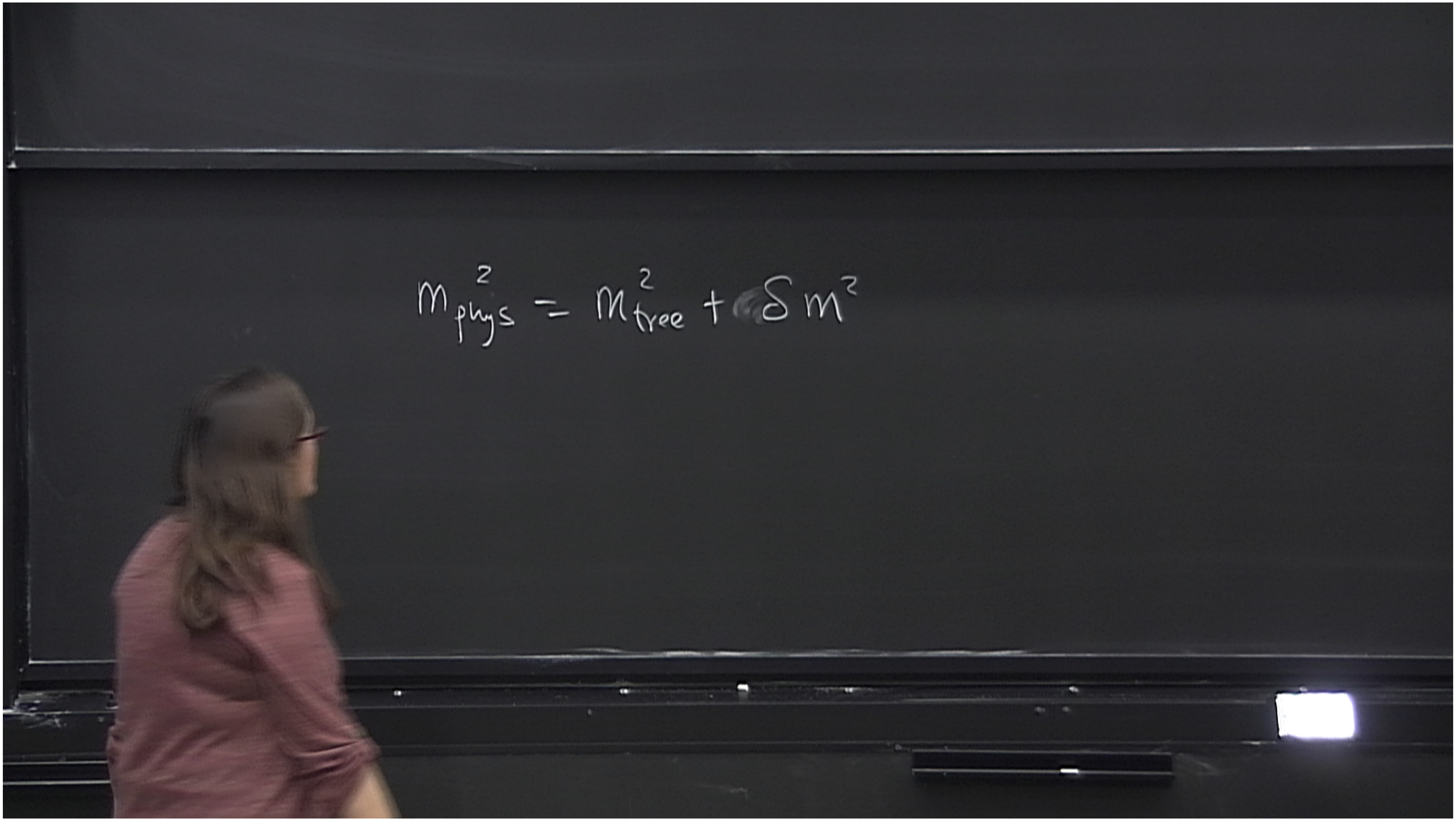
$$\overset{g}{D_\mu} \cancel{\phi}\, D^\mu \cancel{\phi} + \overset{m}{m^2} \cancel{\phi}^2 + \overset{\lambda}{\lambda} \cancel{\phi}^4$$

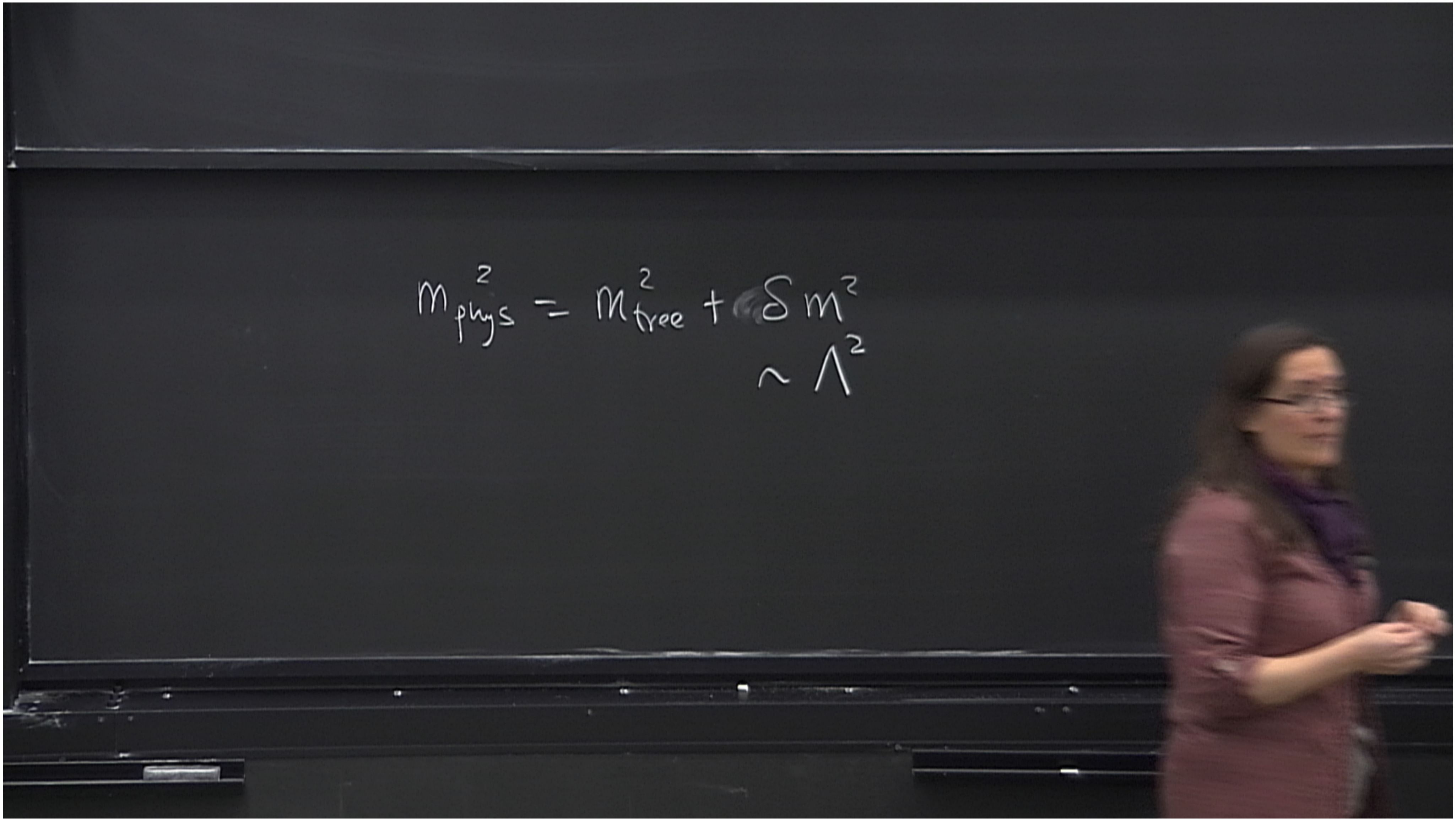
$m = 0$ tree level

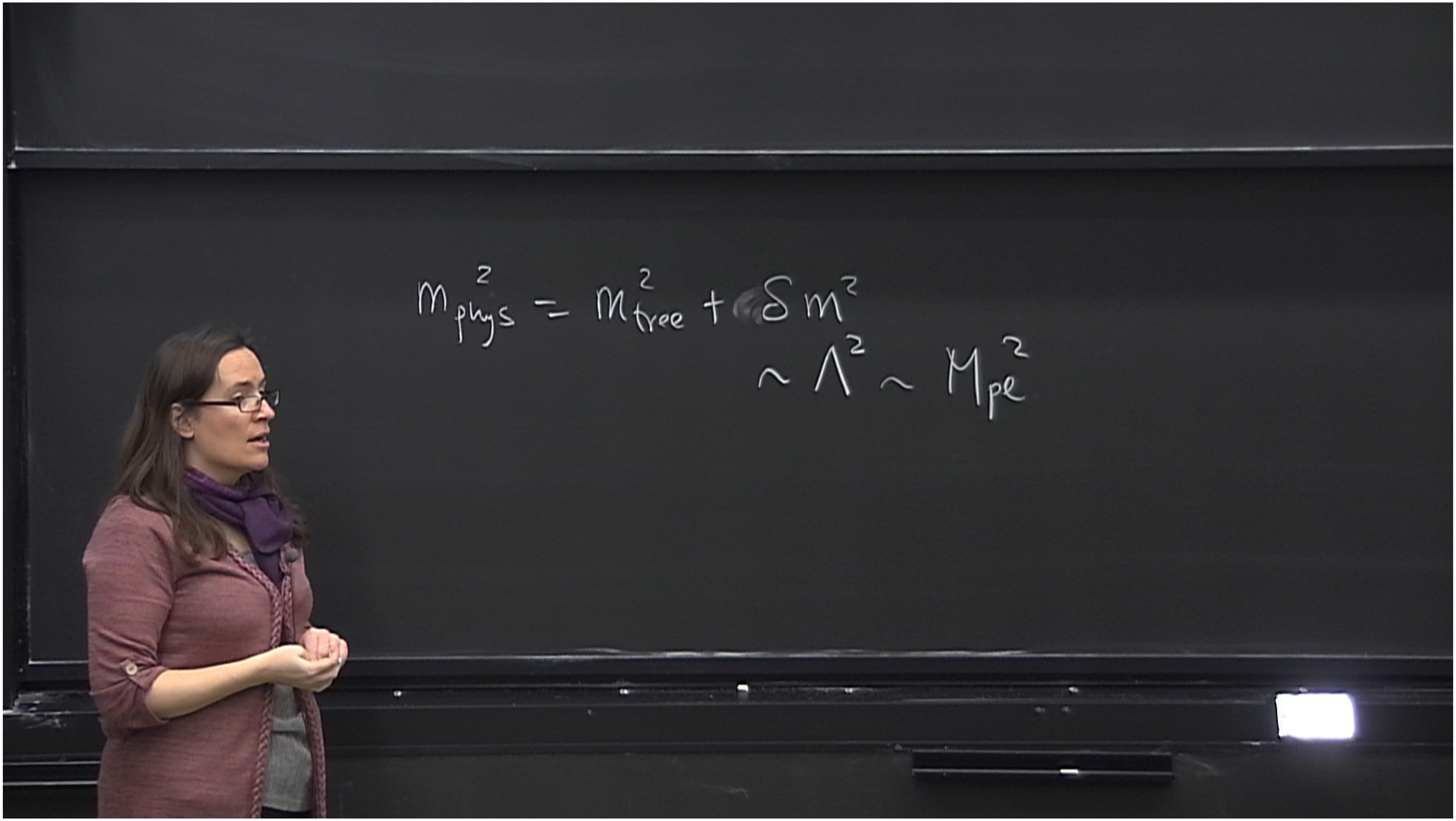


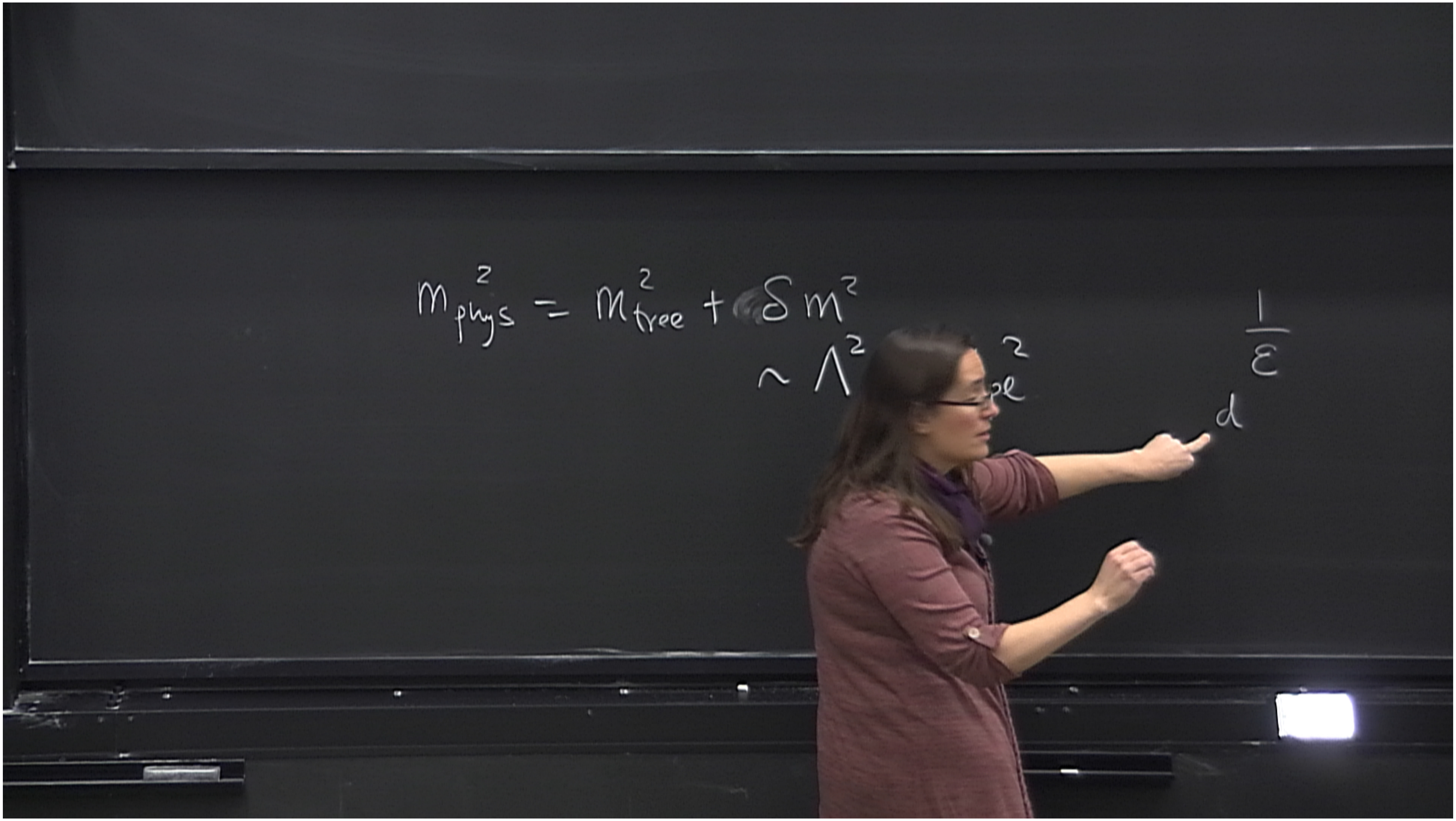
$$\delta m^2 \propto \lambda \Lambda^2$$

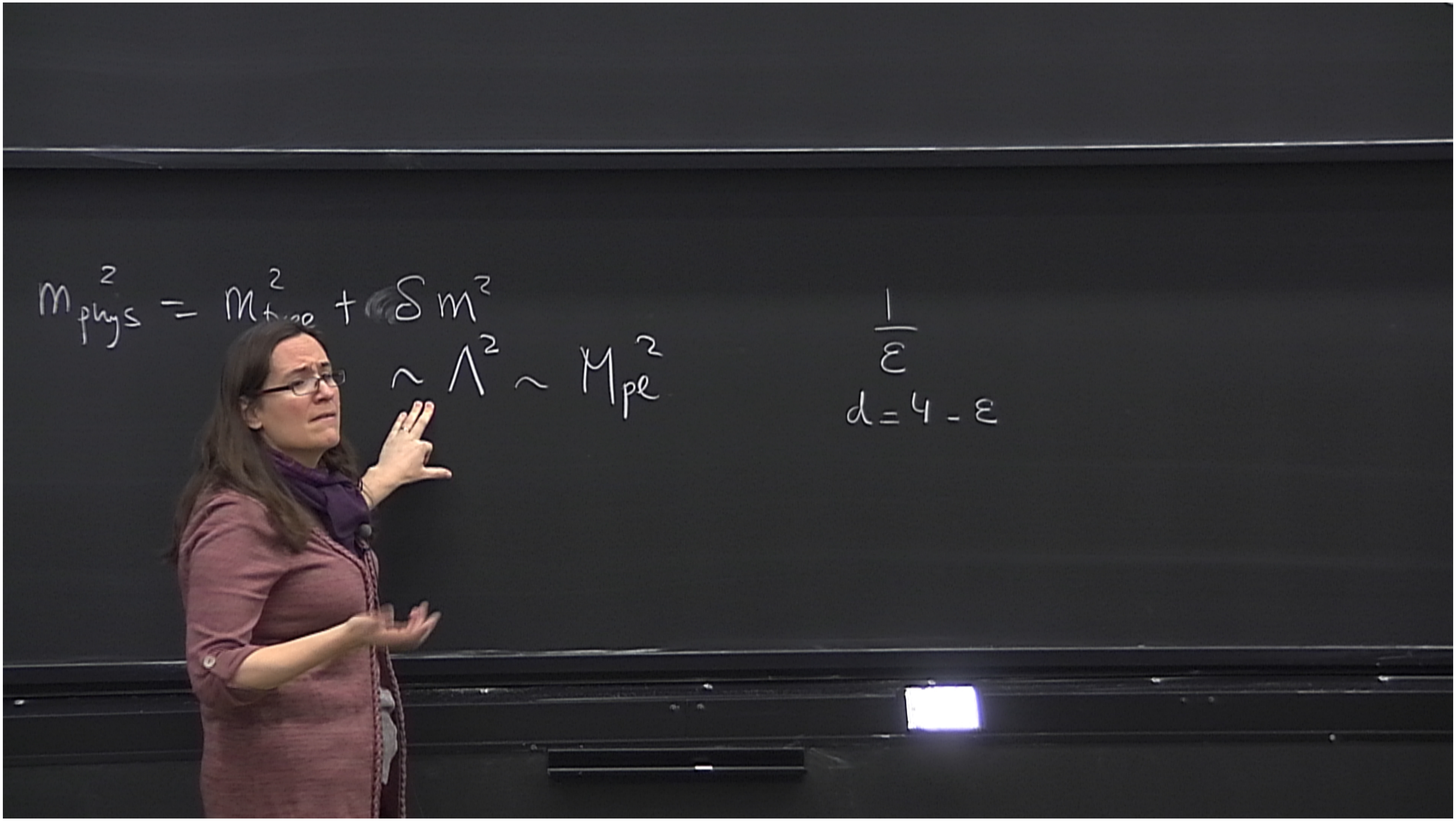
O : scale invariance classical symmetry $\longrightarrow$ broken @ Q-level

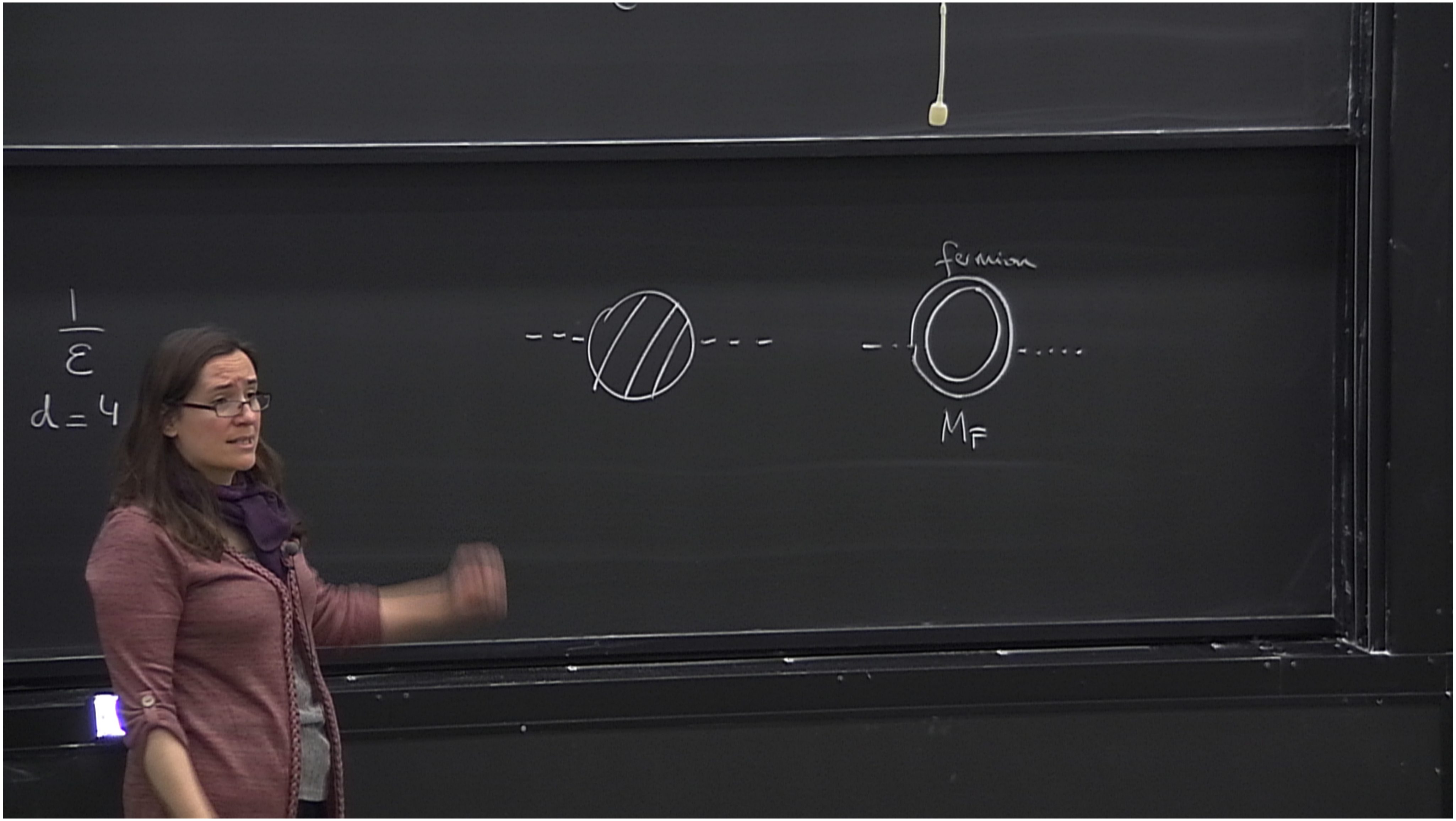

$m_{phys}^2 = m_{tree}^2 + \delta m^2$

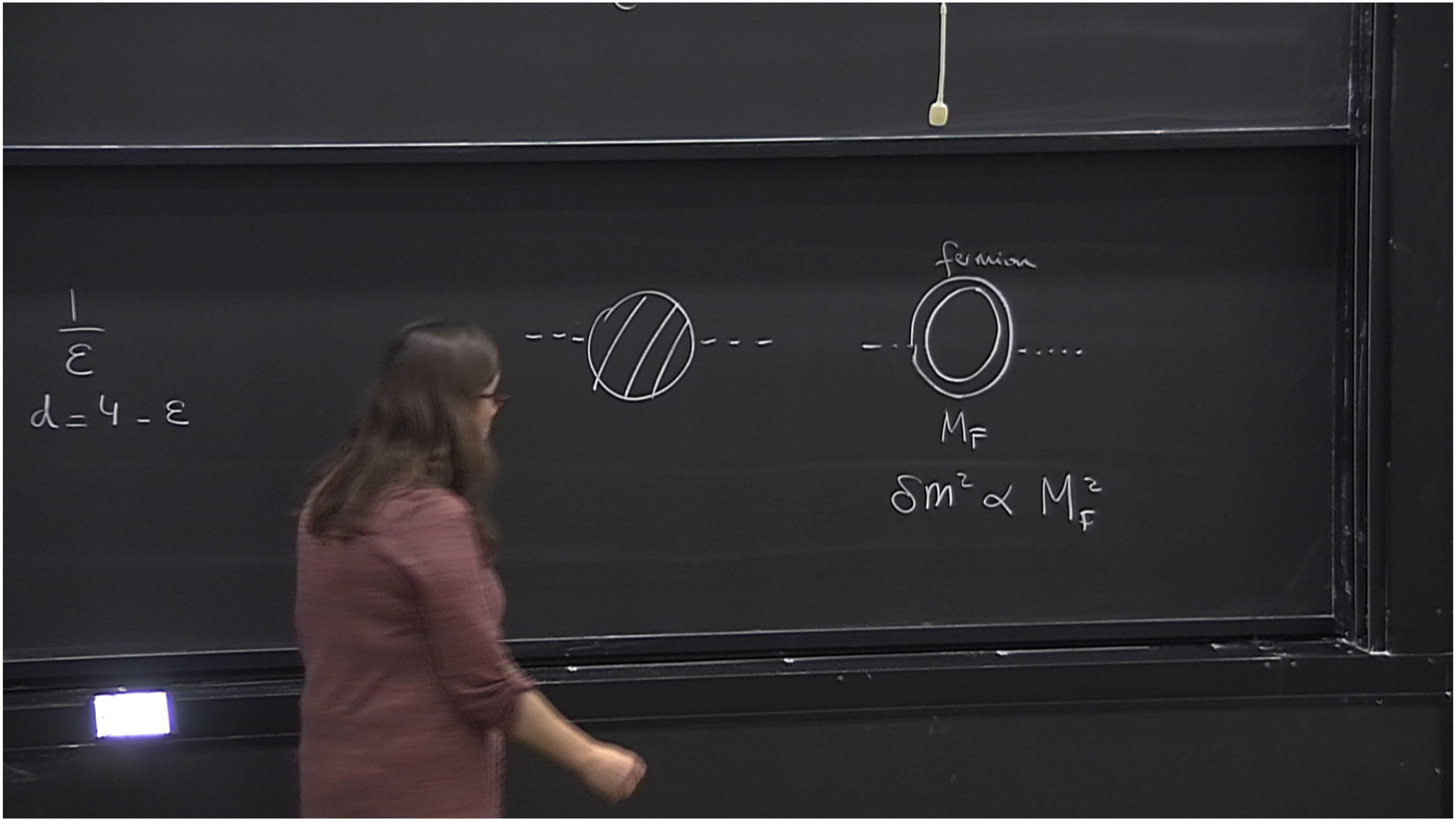

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
$\sim \Lambda^2$


$m_{phys}^2 = m_{tree}^2 + \delta m^2$
$\sim \Lambda^2 \sim M_{pl}^2$

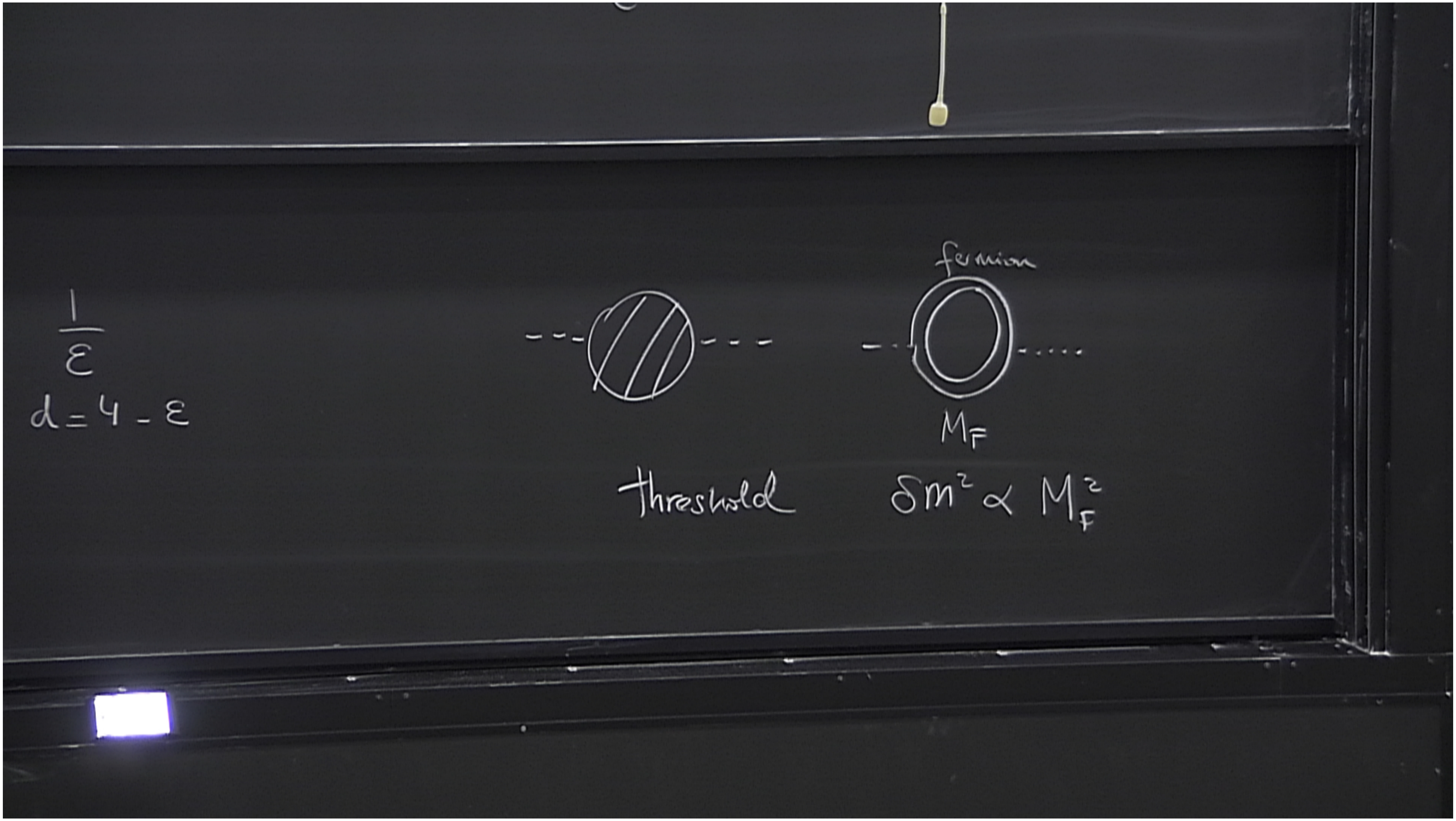

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
$\sim \Lambda^2$
$\frac{1}{\varepsilon}$
d

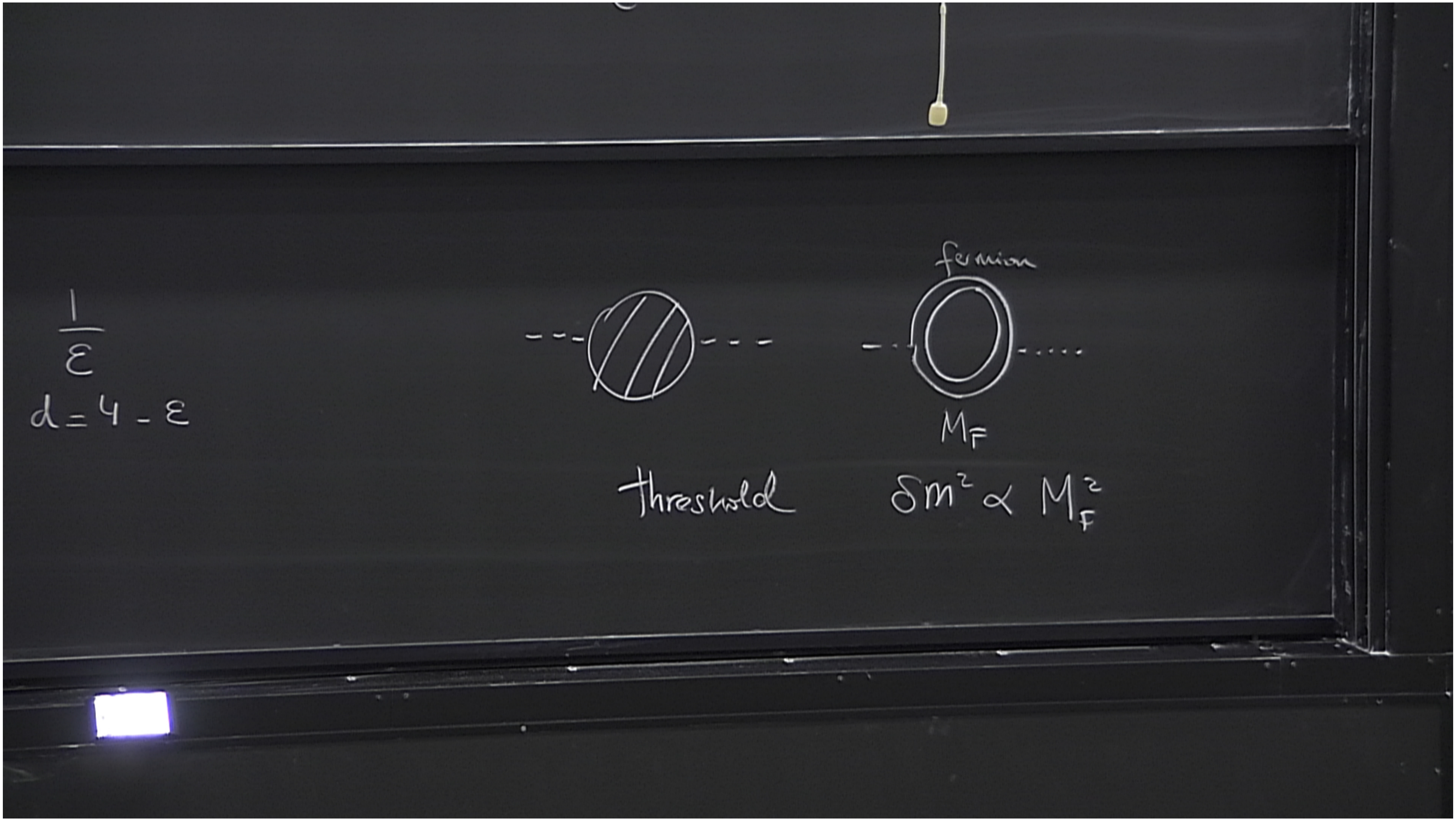

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
$\sim \Lambda^2 \sim M_{pl}^2$
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$


1/ε
d = 4
fermion
M_F

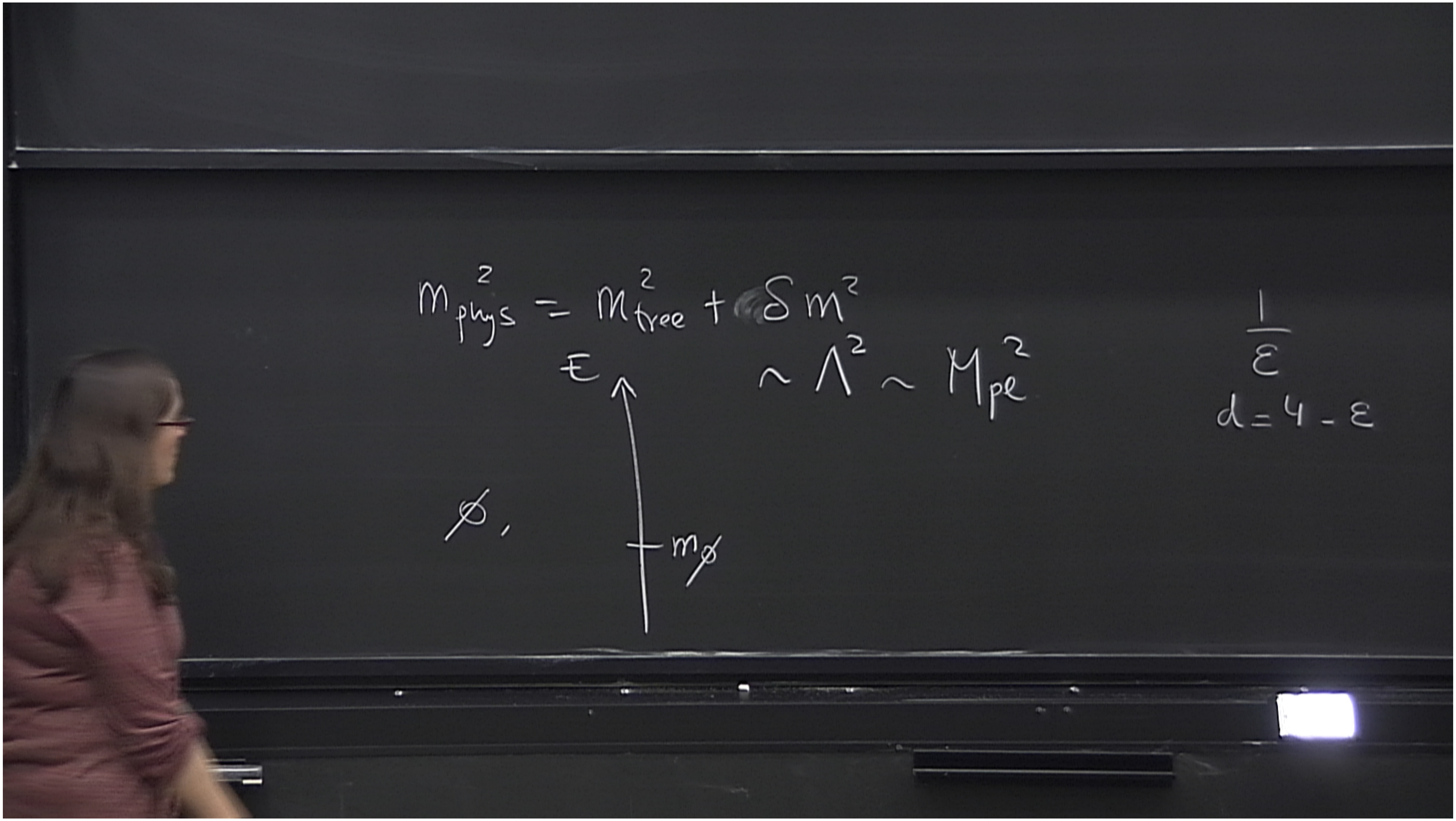


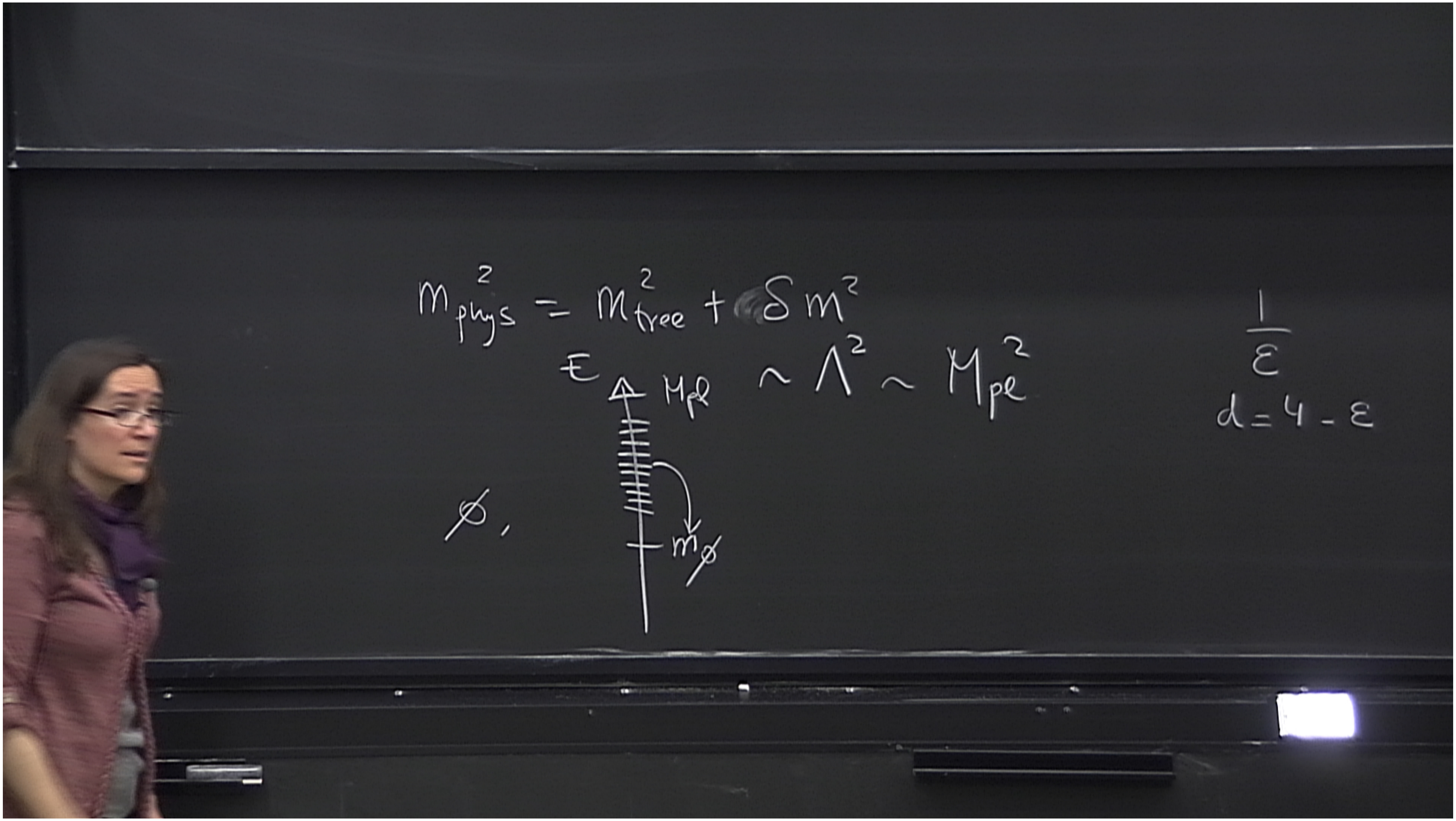
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$
fermion
M_F
$\delta m^2 \propto M_F^2$

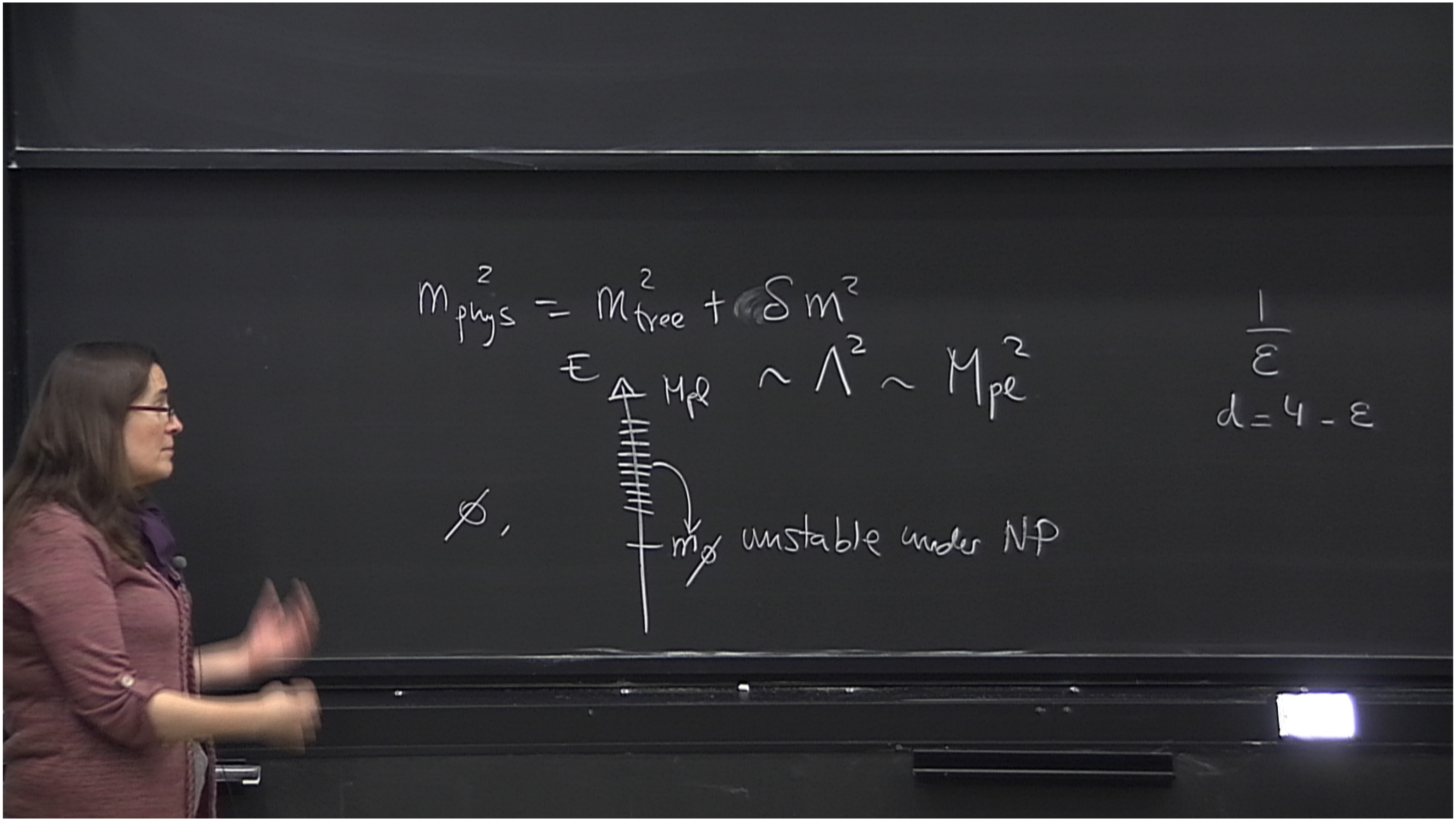

$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$
fermion
M_F
threshold
$\delta m^2 \propto M_F^2$



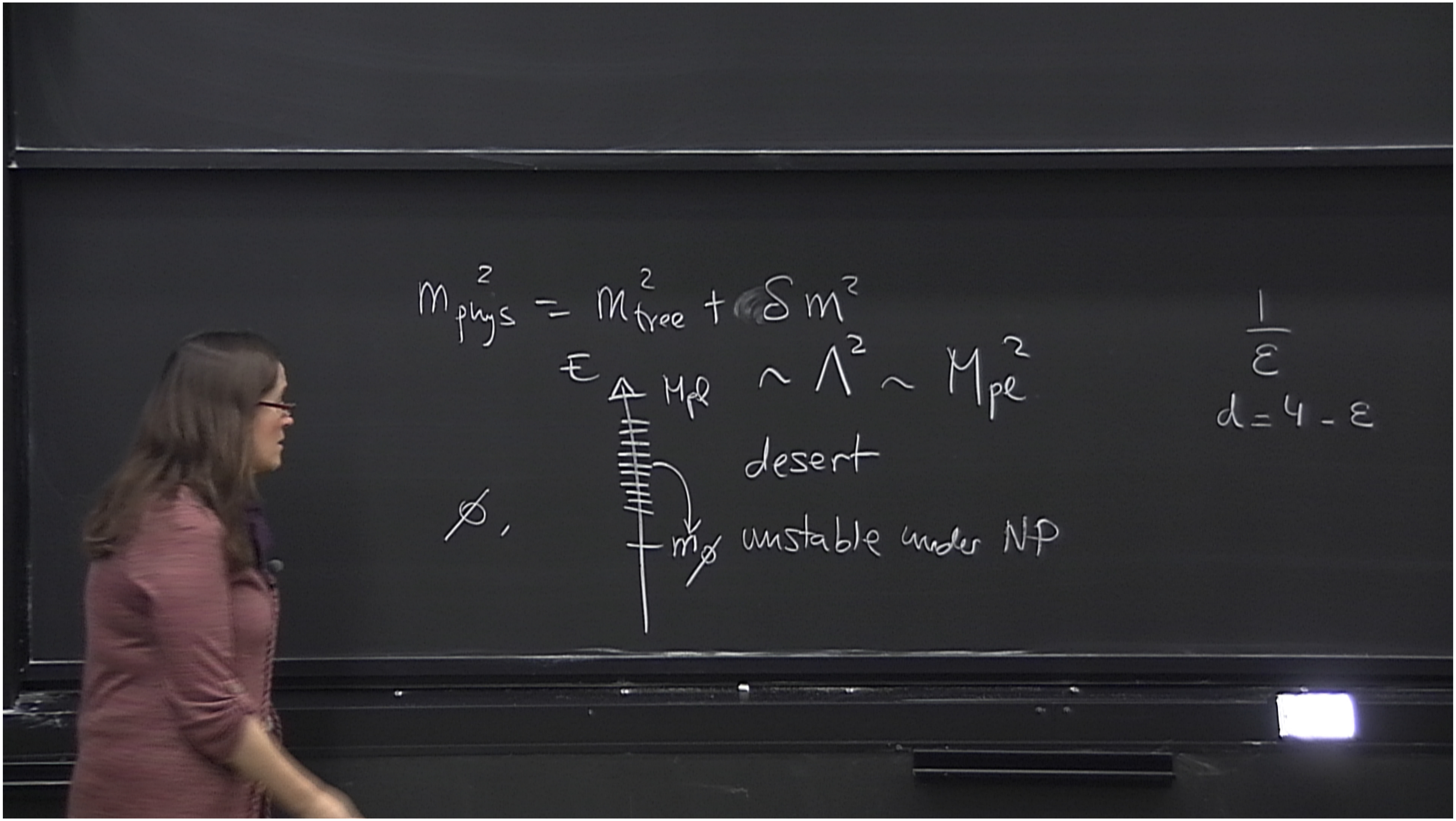
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$
fermion
M_F
threshold
$\delta m^2 \propto M_F^2$

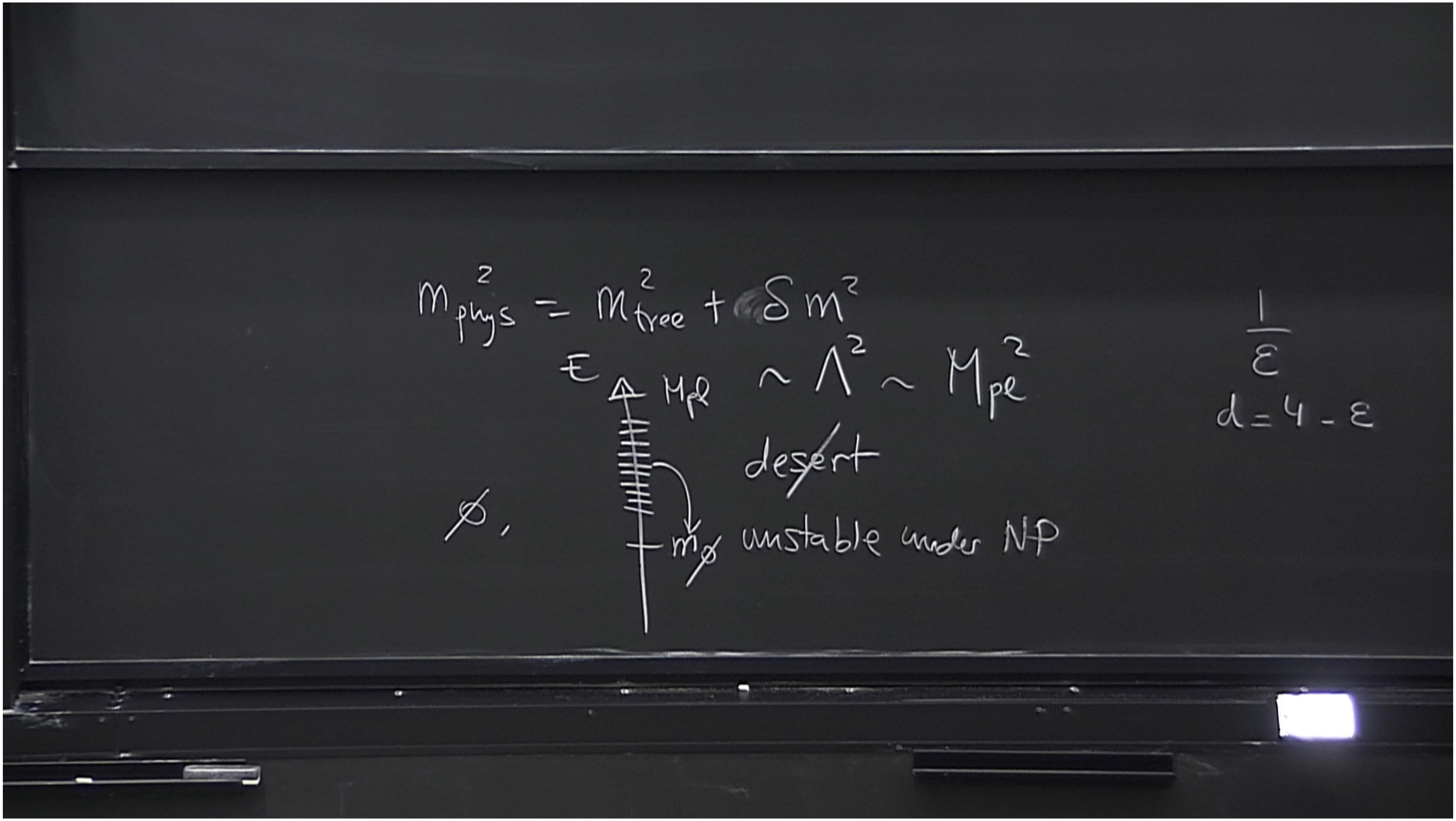

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
ε
$\sim \Lambda^2 \sim M_{pl}^2$
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$
$\phi,$
m_ϕ

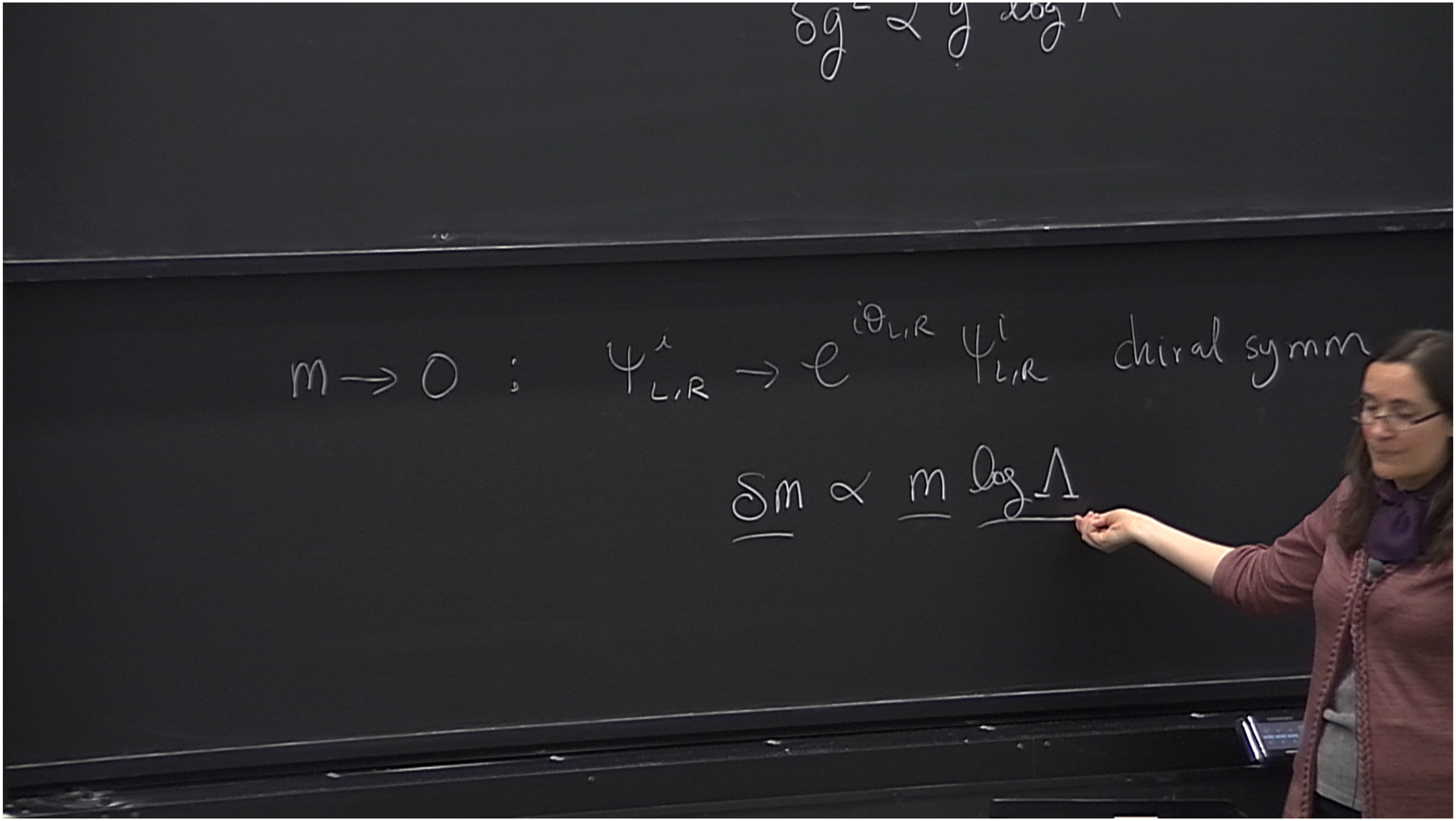

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
E
$M_{pl} \sim \Lambda^2 \sim M_{pl}^2$
$\phi ,$
m_ϕ
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$

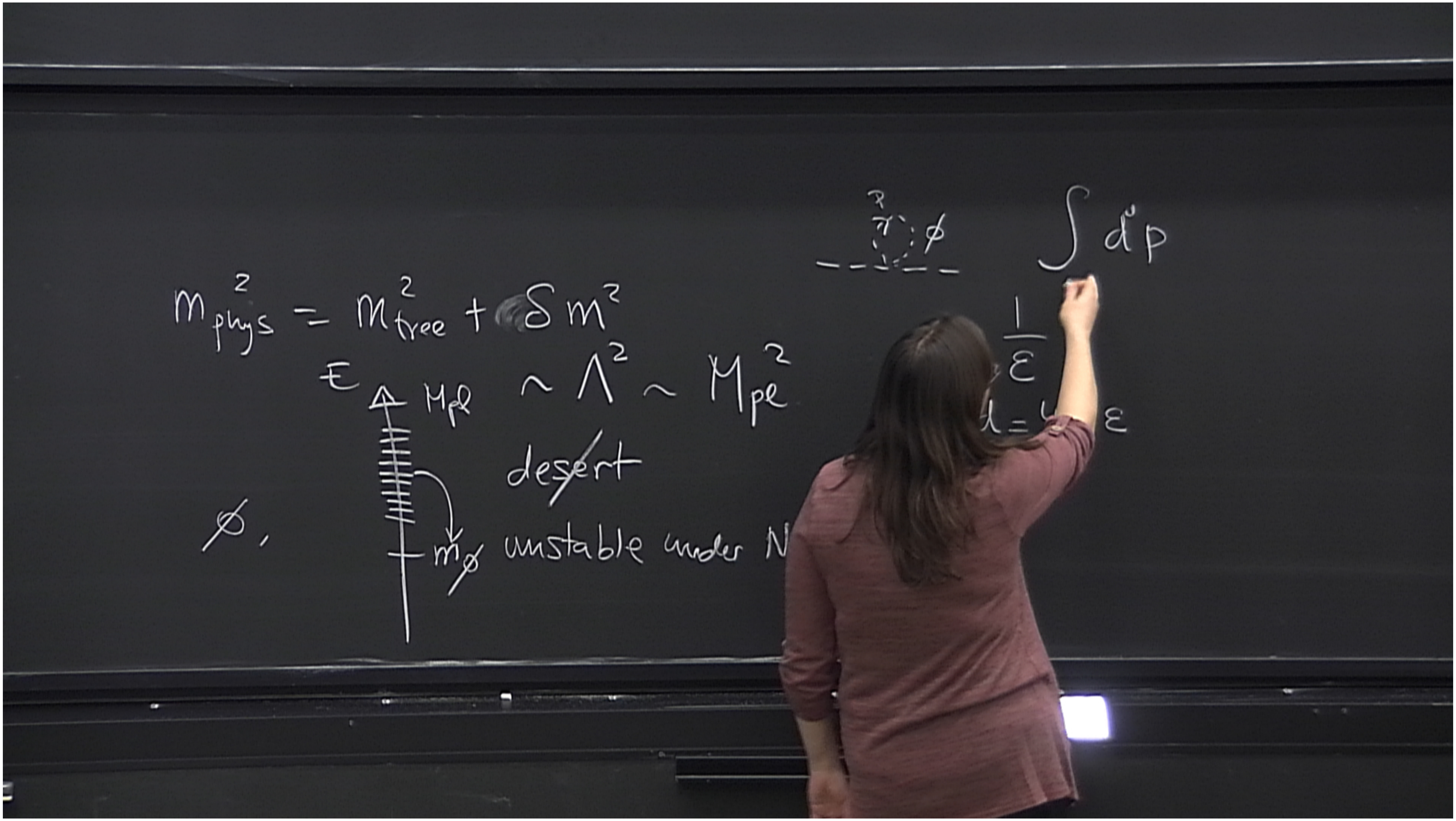


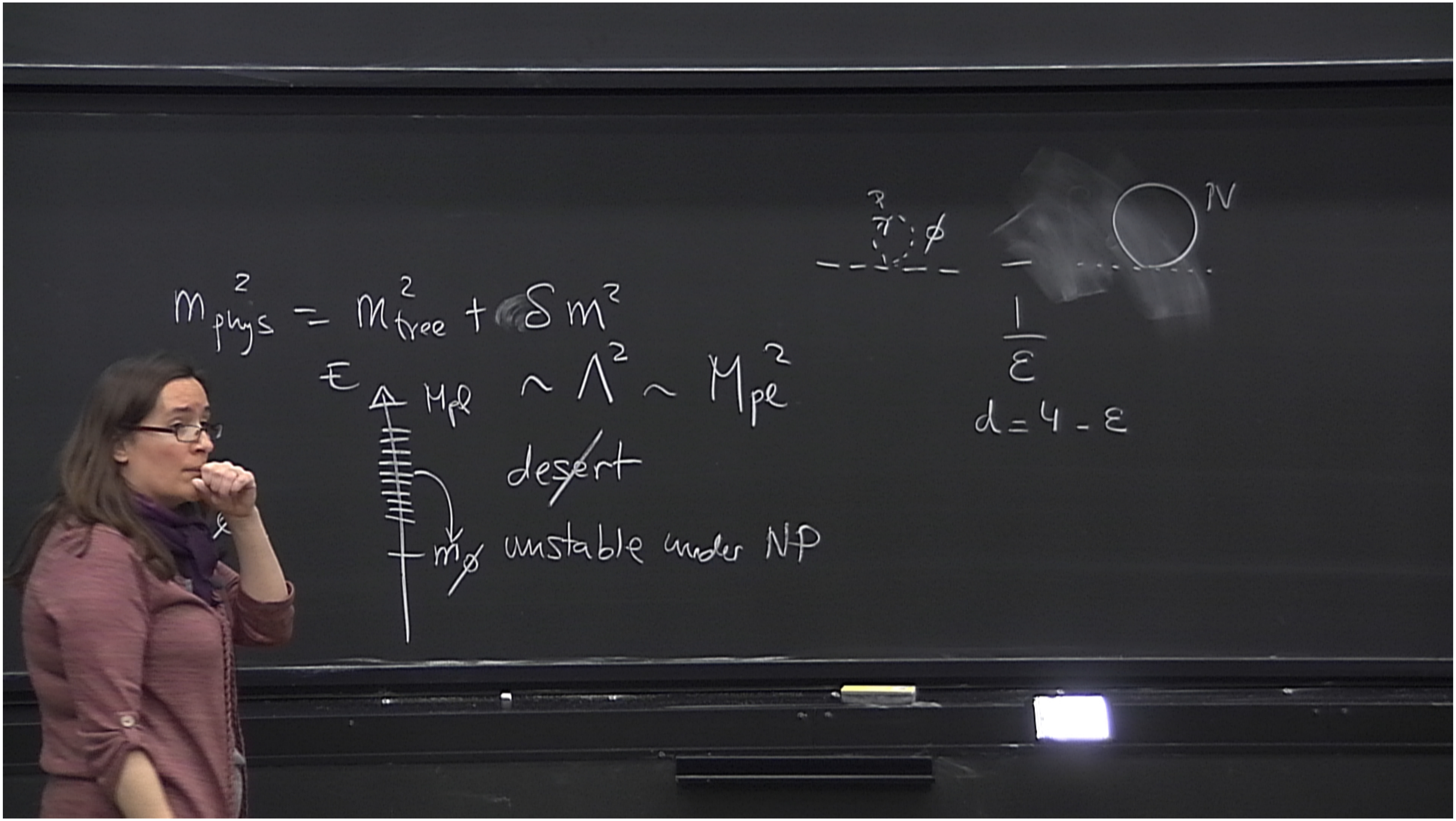
$m_{phys}^2 = m_{tree}^2 + \delta m^2$
$\epsilon \quad \Lambda \quad M_{pl} \sim \Lambda^2 \sim M_{pl}^2$
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$
$\phi,$
m_ϕ unstable under NP

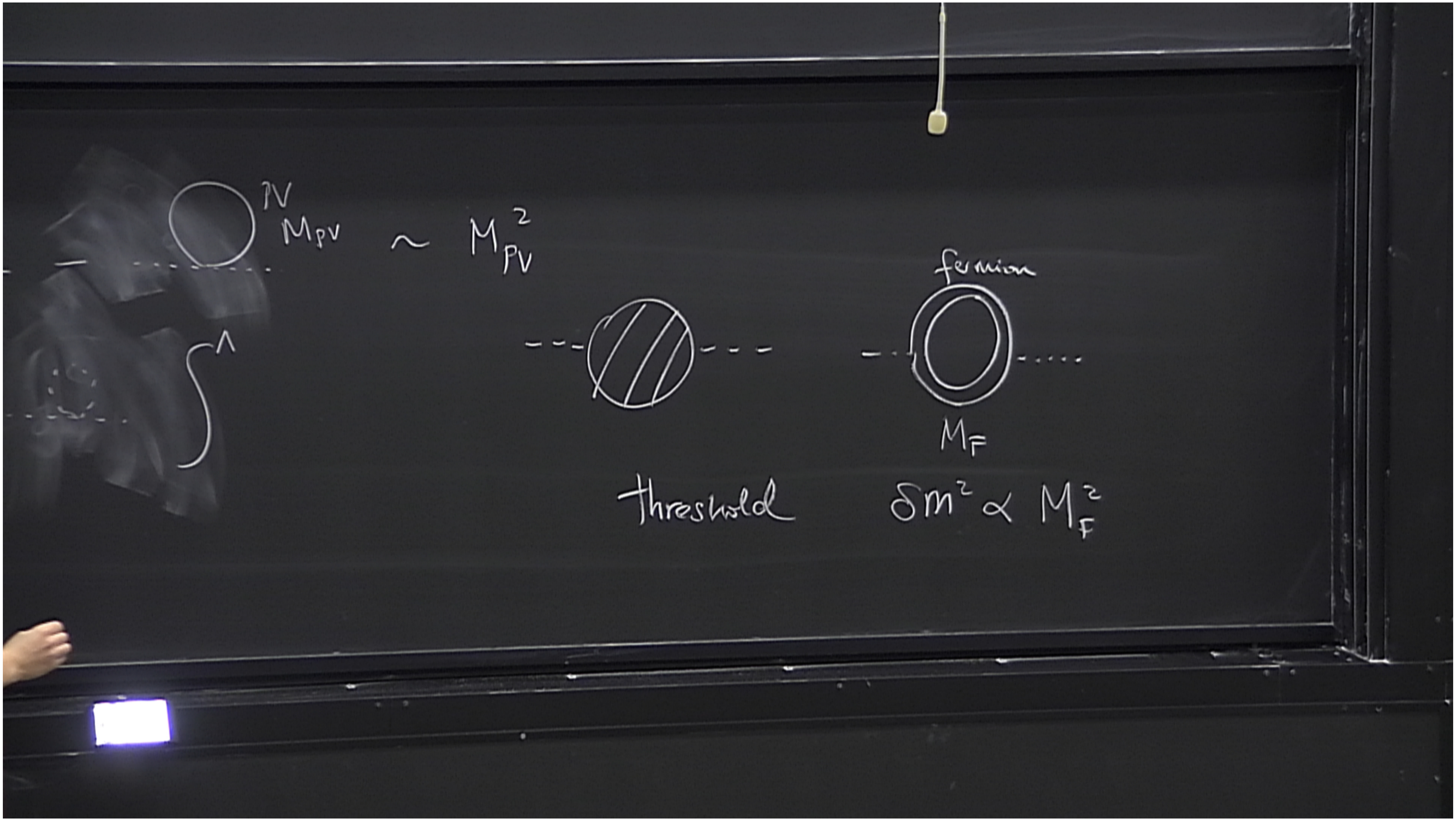

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
E
M_{pl} $\sim \Lambda^2 \sim M_{pl}^2$
desert
ϕ,
m_ϕ unstable under NP
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$

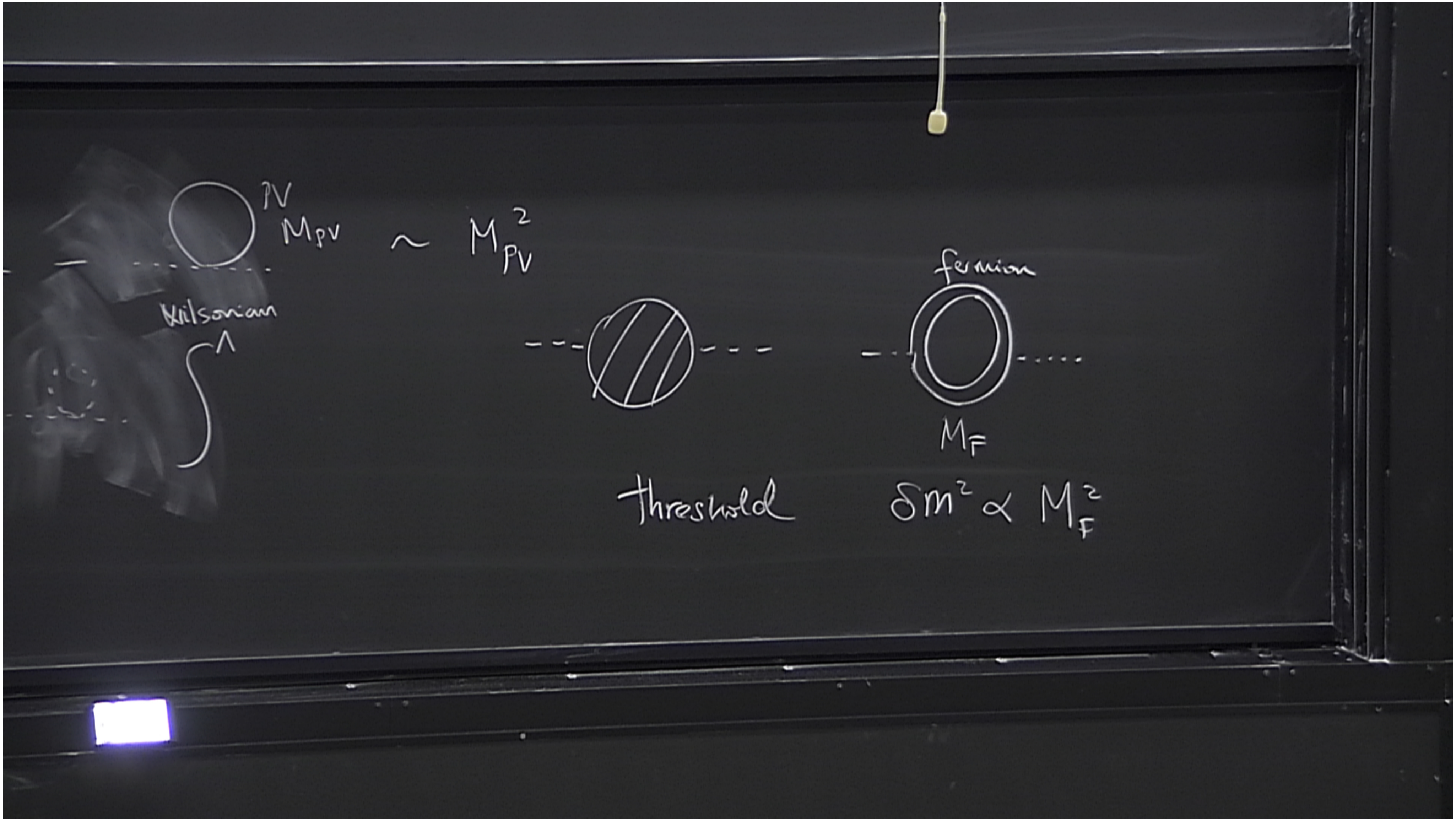

$m_{phys}^2 = m_{tree}^2 + \delta m^2$
E
M_{pl}
$\sim \Lambda^2 \sim M_{pl}^2$
desert
ϕ,
m_ϕ unstable under NP
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$

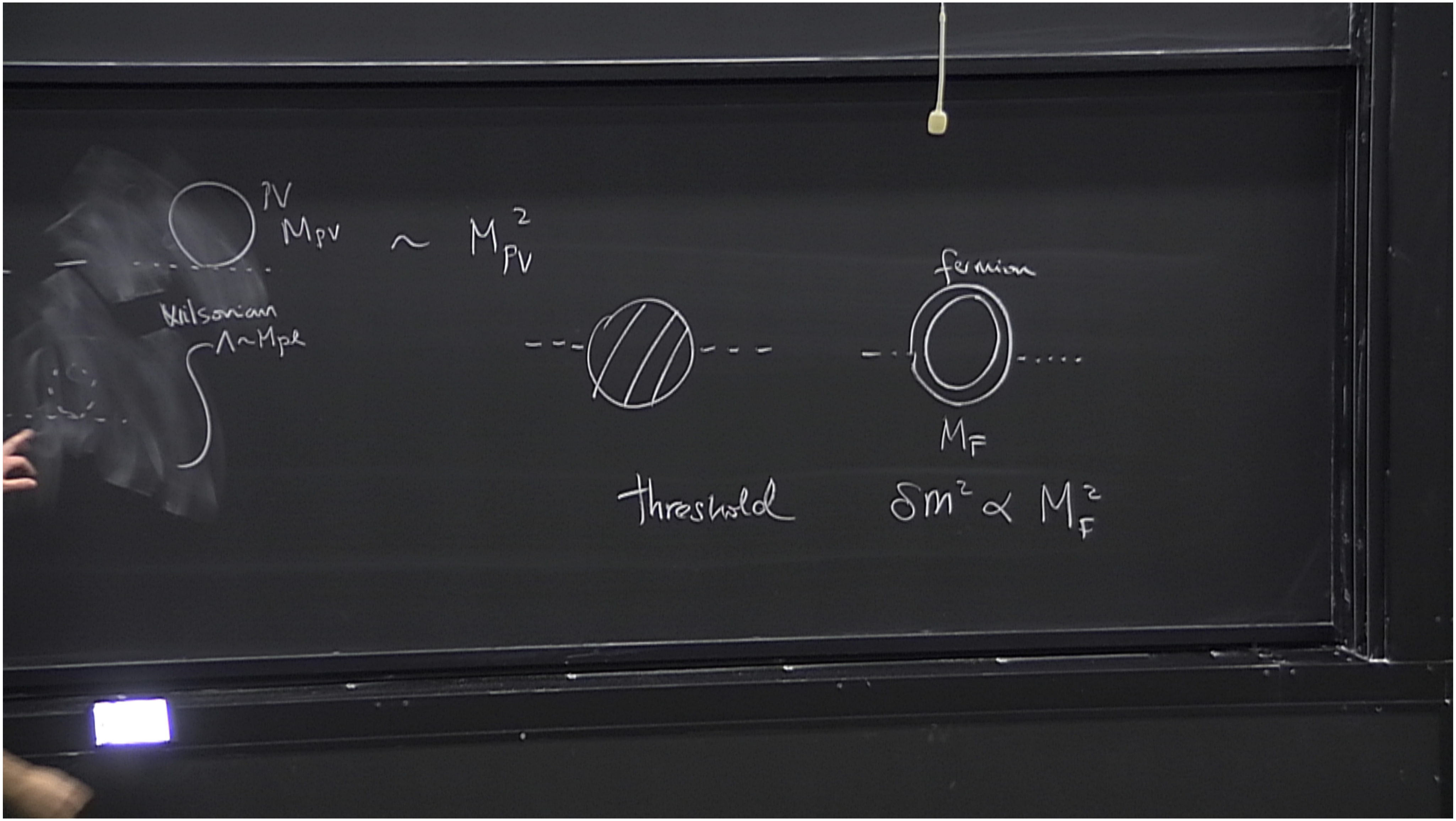

$m \to 0 : \quad \psi^i_{L,R} \to e^{i\theta_{L,R}} \psi^i_{L,R}$ chiral symm
$\delta m \propto m \log \Lambda$

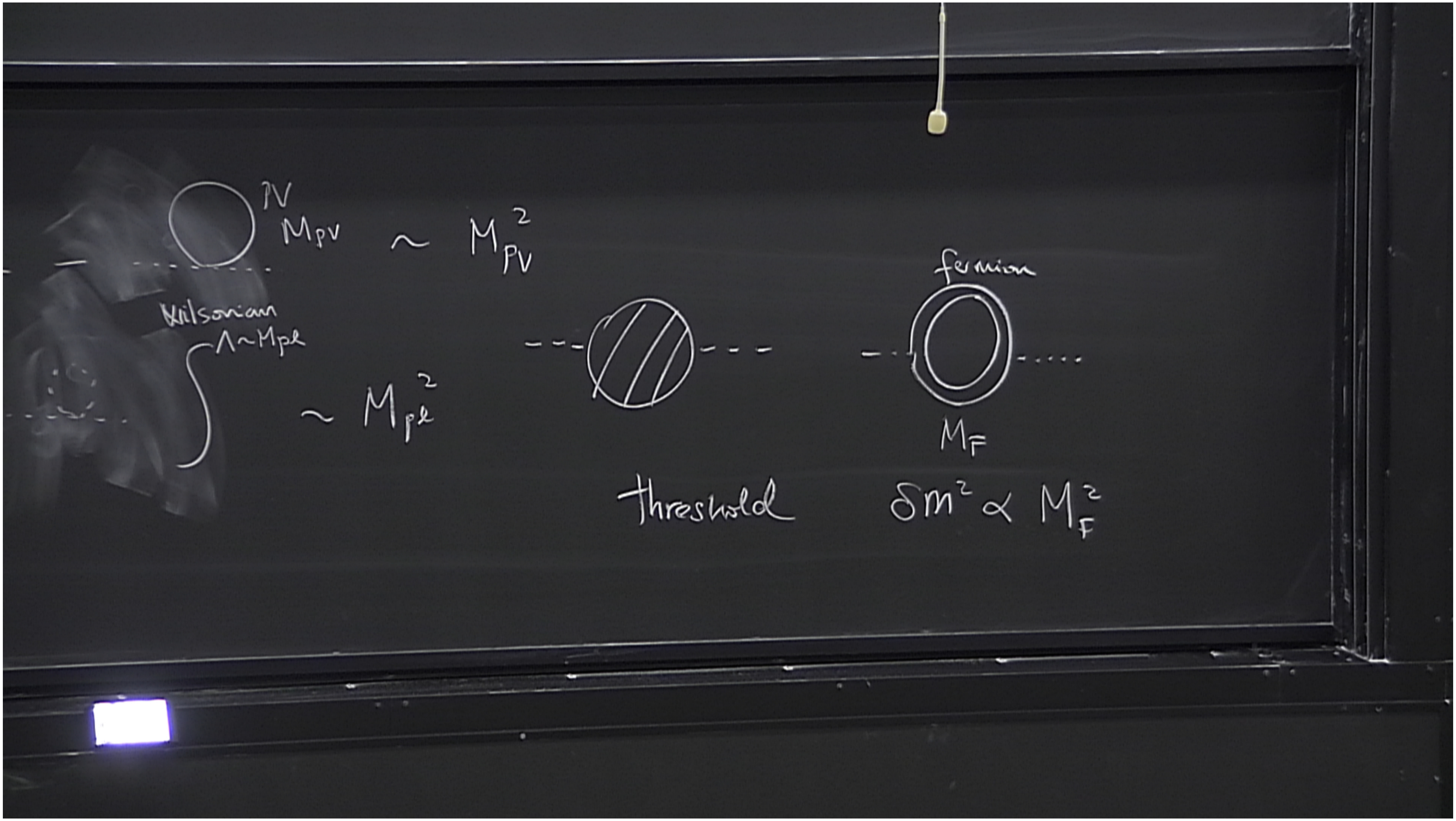

m phys 2 = m tree 2 + δm 2
E
Mpl ~ Λ2 ~ Mpl 2
desert
φ,
mφ unstable under N
φ
∫ d4p
1/ε
d = 4 − ε

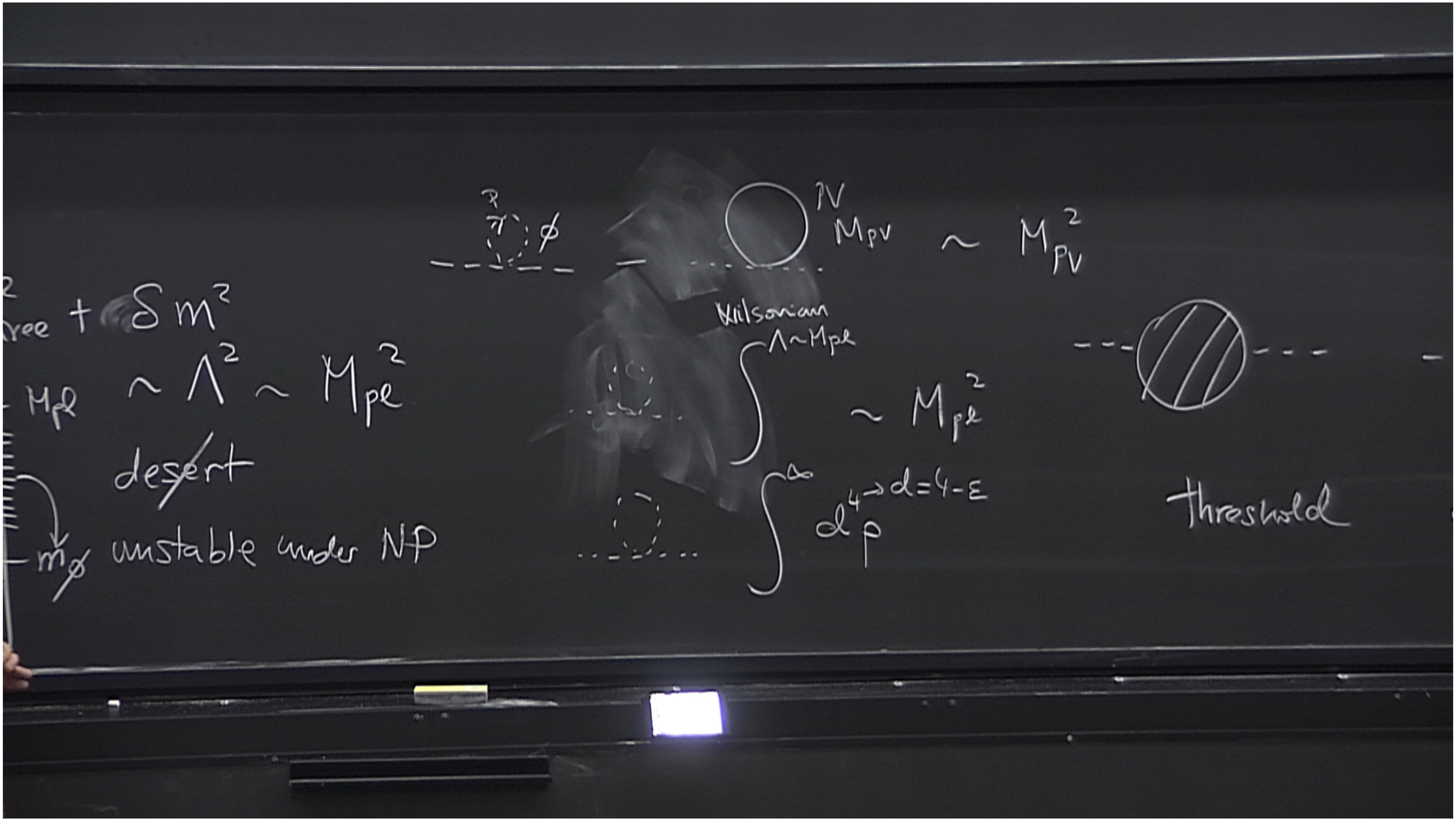

$m^2_{phys} = m^2_{tree} + \delta m^2$
E
$M_{pl} \sim \Lambda^2 \sim M_{pl}^2$
desert
m_ϕ unstable under NP
ϕ
$\frac{1}{\varepsilon}$
$d = 4 - \varepsilon$


PV
M_{PV}
$\sim M_{PV}^2$
Λ
fermion
M_F
threshold
$\delta m^2 \propto M_F^2$

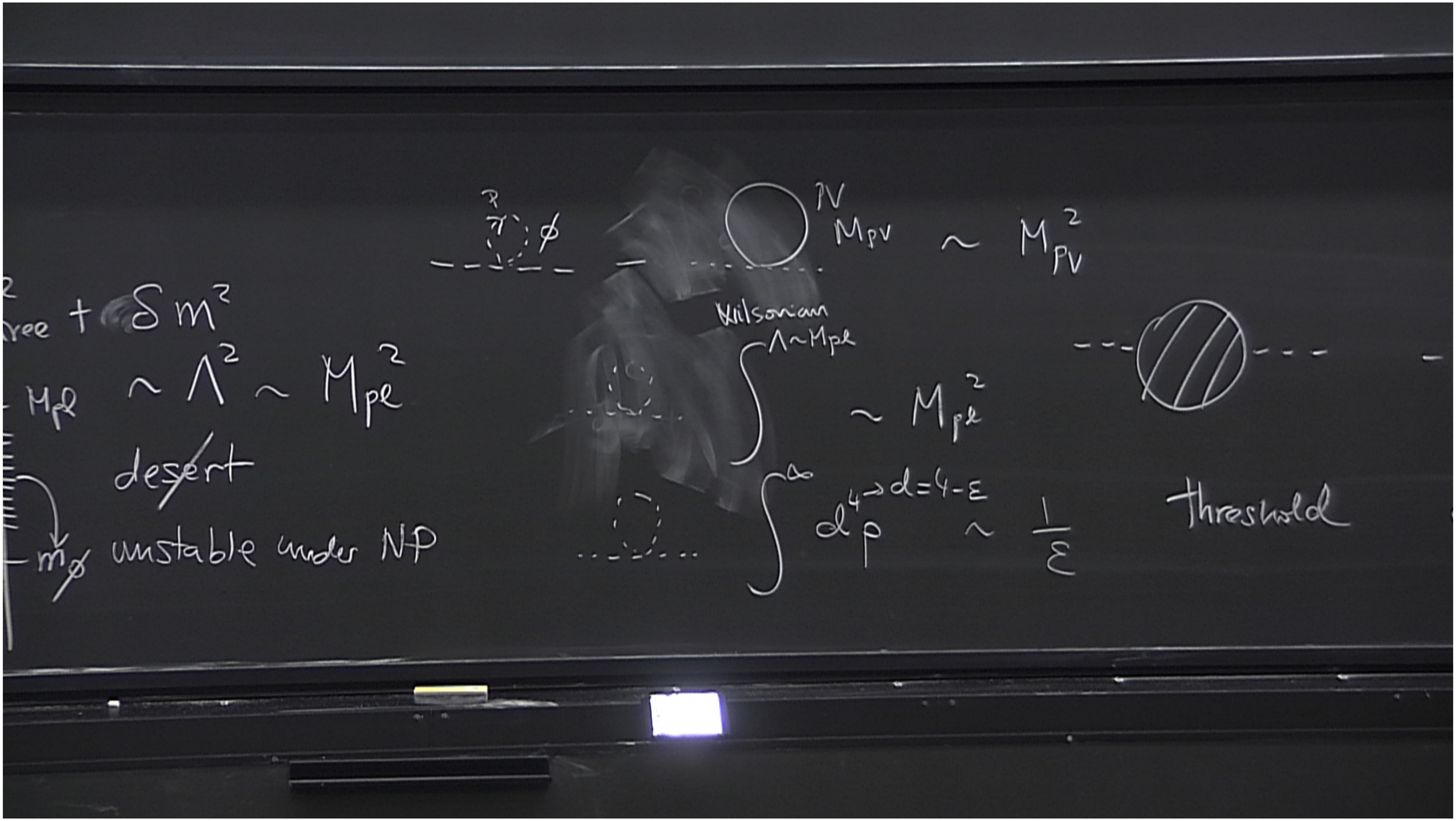

PV
M_{PV}
$\sim M_{PV}^2$
Wilsonian
Λ
fermion
M_F
threshold
$\delta m^2 \propto M_F^2$


PV
M_{PV}
$\sim M_{PV}^2$
Wilsonian
$\Lambda \sim M_{pl}$
fermion
M_F
threshold
$\delta m^2 \propto M_F^2$

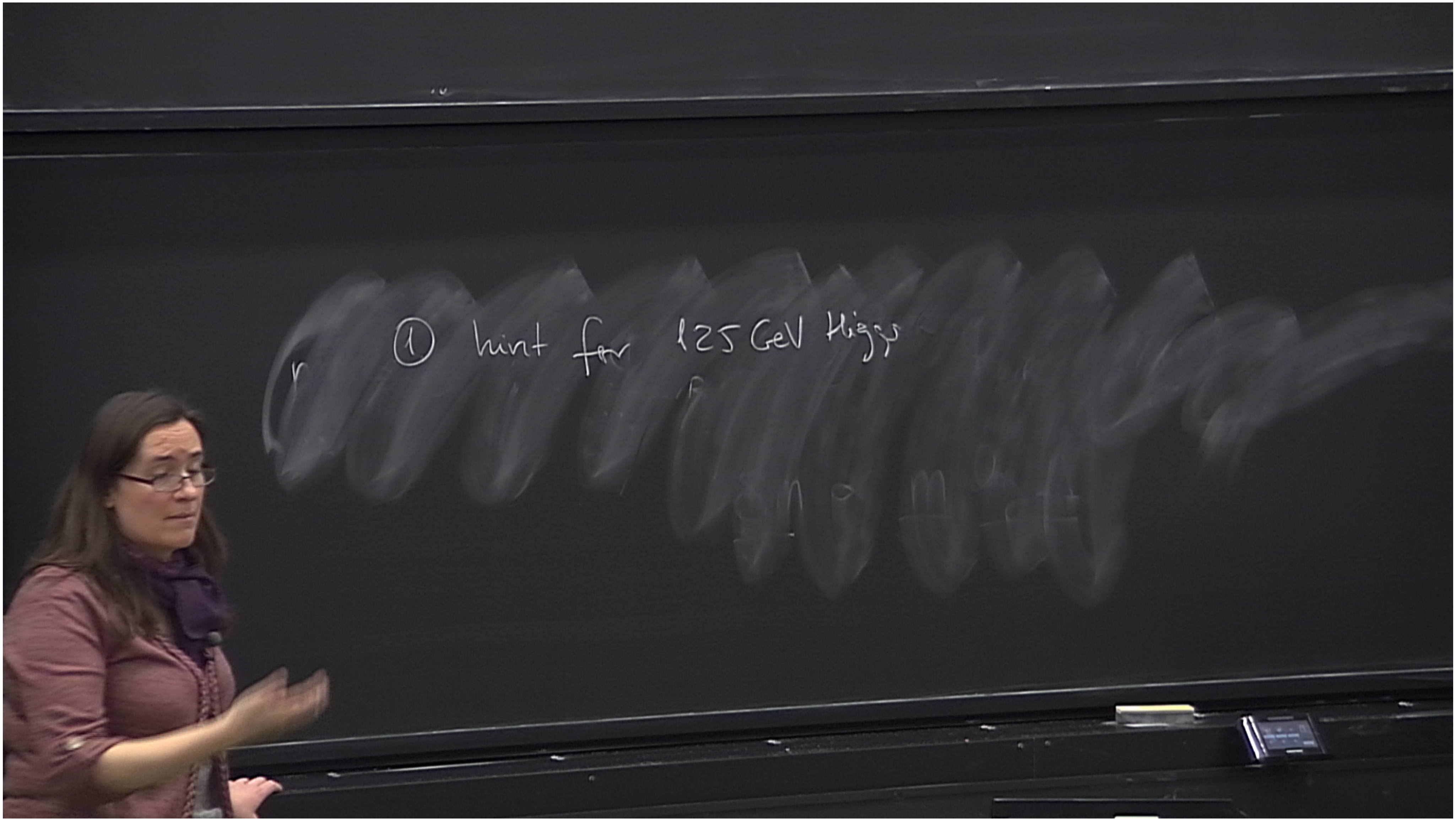

PV
Mpv
~ M²PV
fermion
Wilsonian
Λ~Mpl
~ Mpl²
MF
threshold
δm² ∝ MF²

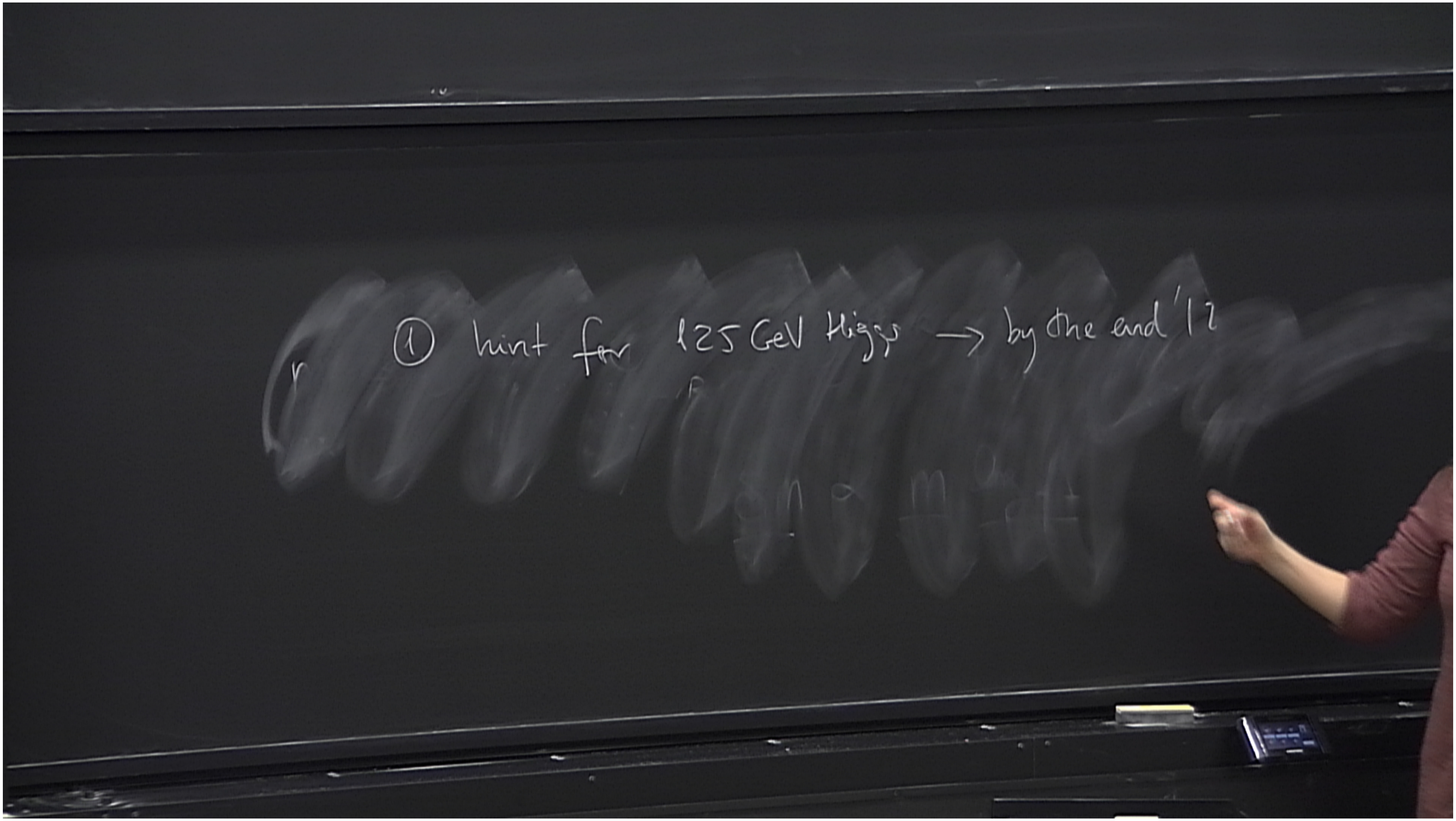


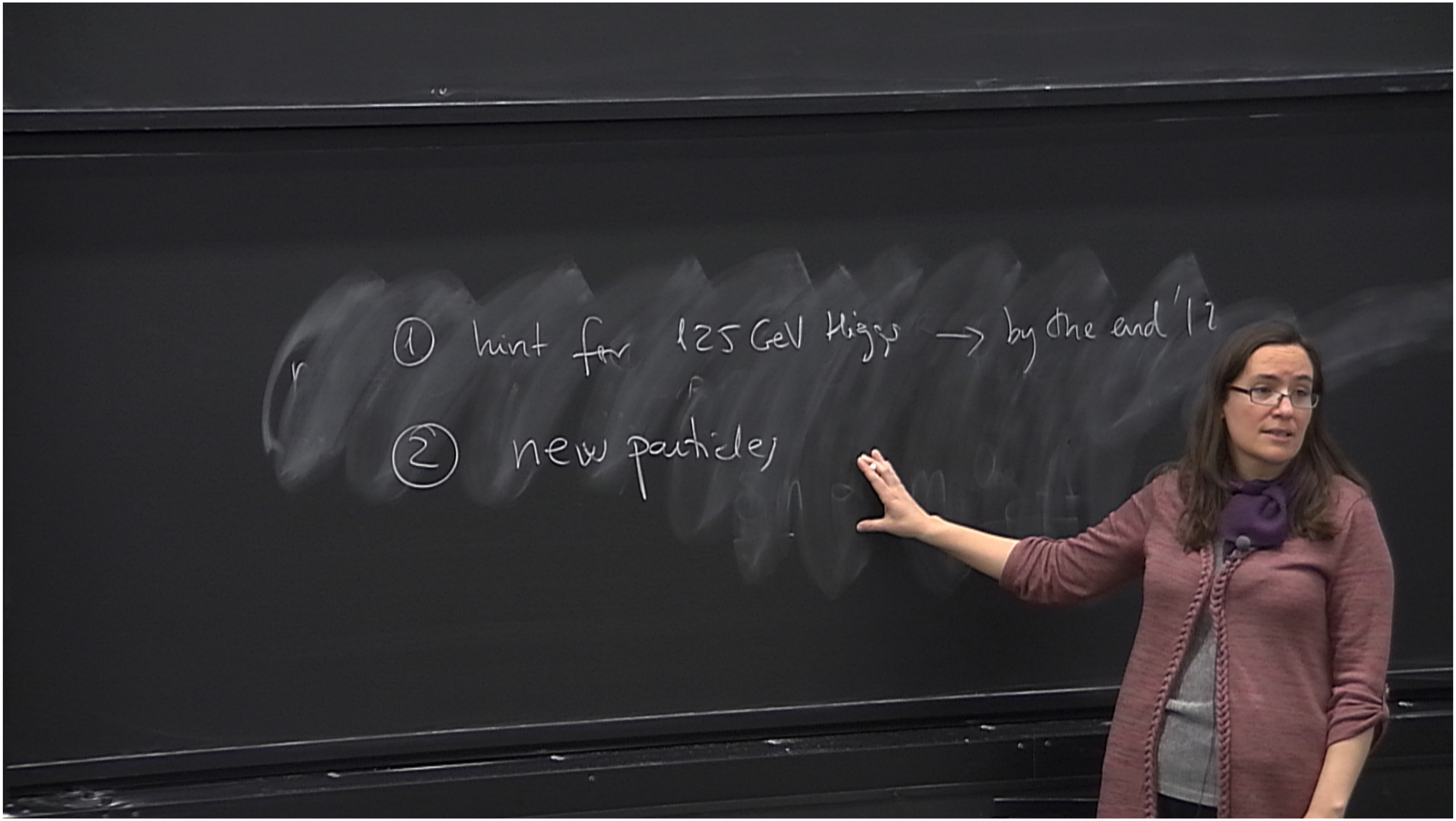
ϕ
M_{PV}
$\sim M_{PV}^2$
ree + δm^2
M_{pl} $\sim \Lambda^2 \sim M_{pl}^2$
Wilsonian
$\Lambda \sim M_{pl}$
$\sim M_{pl}^2$
~~desert~~
$\int^\infty d^{4\to d=4-\epsilon}p$
threshold
m_ϕ unstable under NP



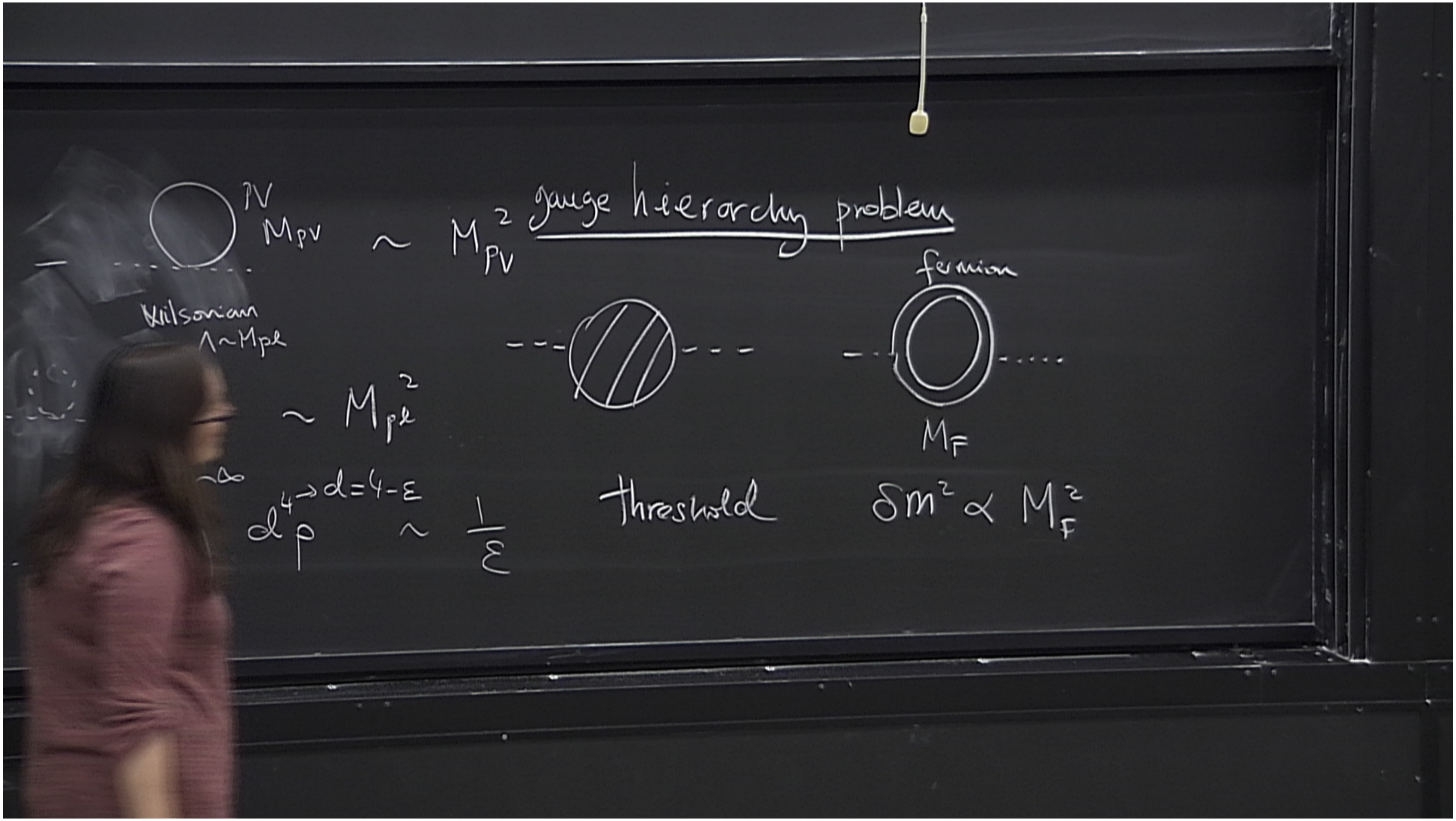
φ
PV
M_{PV} ~ M_{PV}^2
ree + δm²
Wilsonian
Λ~Mpl
Mpl ~ Λ² ~ Mpl²
~ Mpl²
desert
threshold
∞
d⁴→d=4-ε
d⁴p ~ 1/ε
mφ unstable under NP

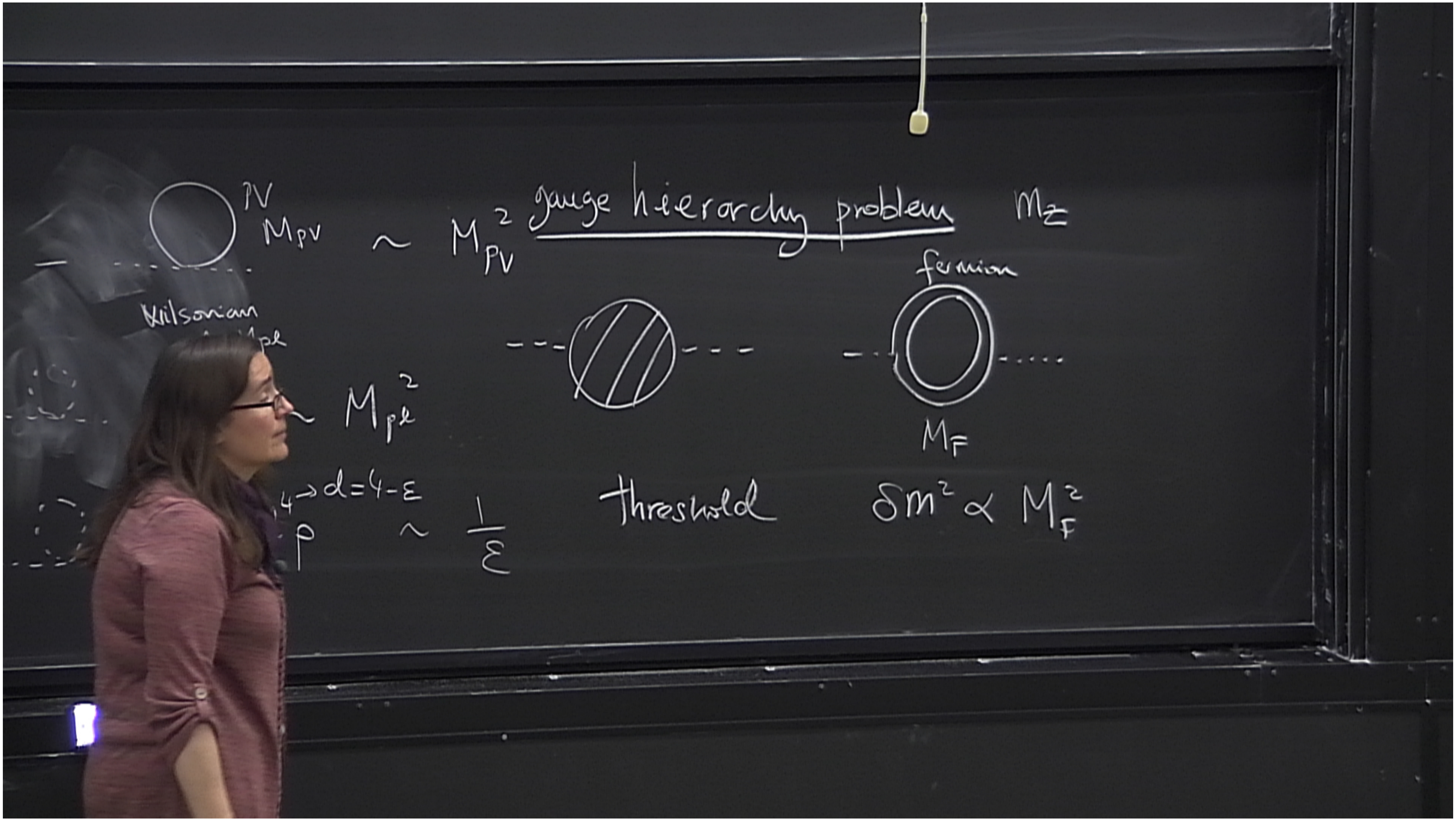

① hint for 125 GeV Higgs

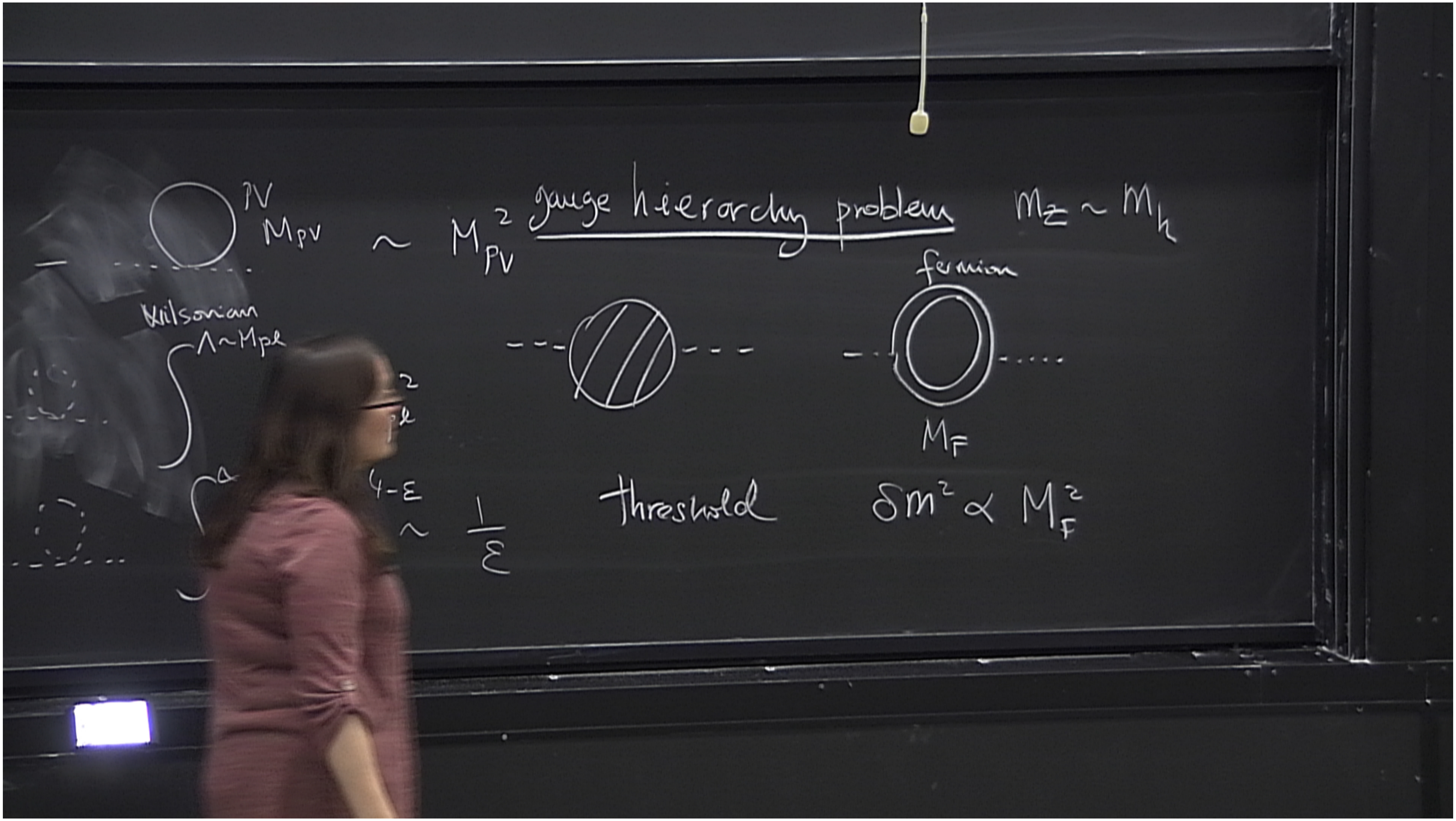

① hint for 125 GeV Higgs → by the end '12

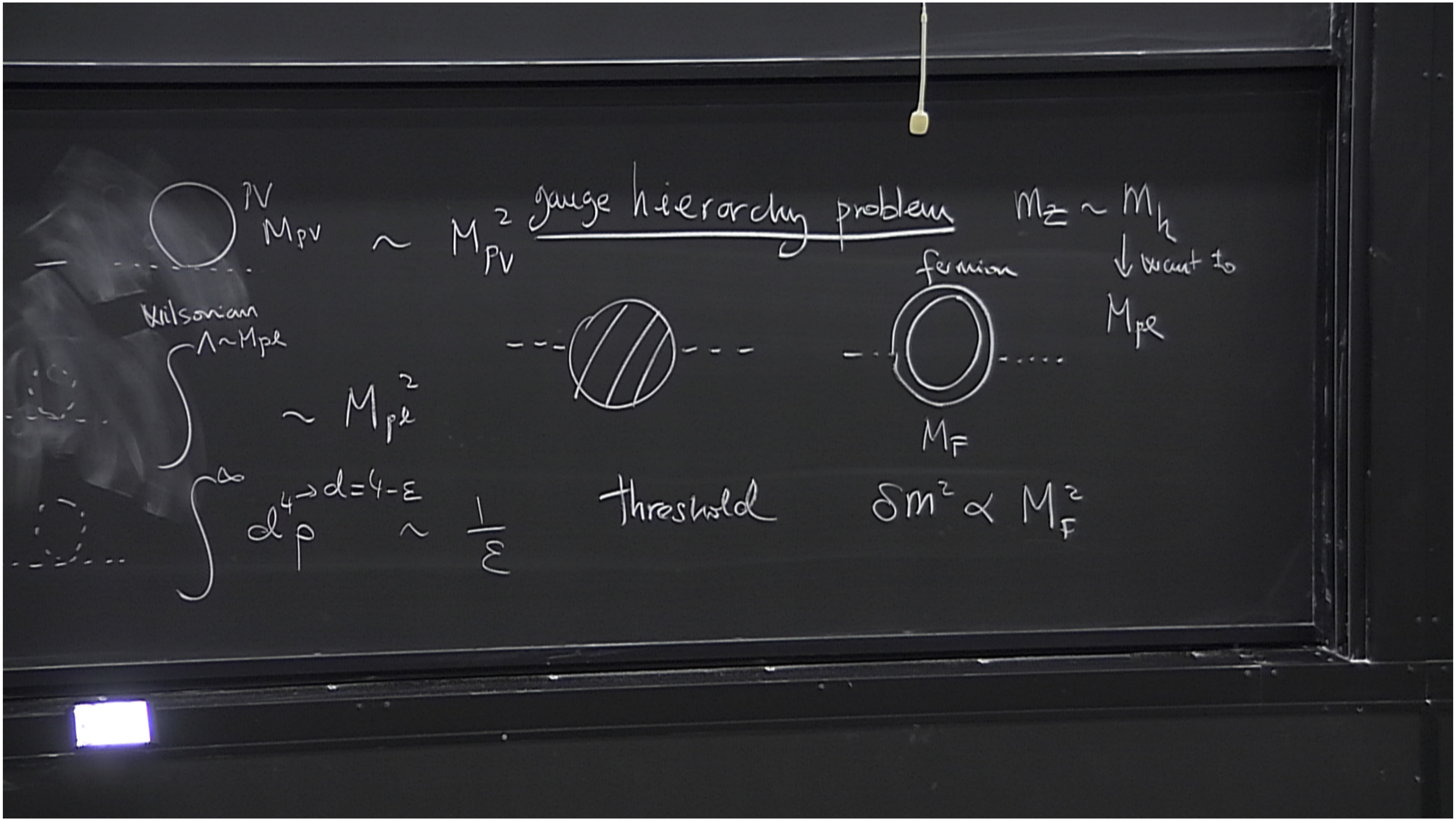


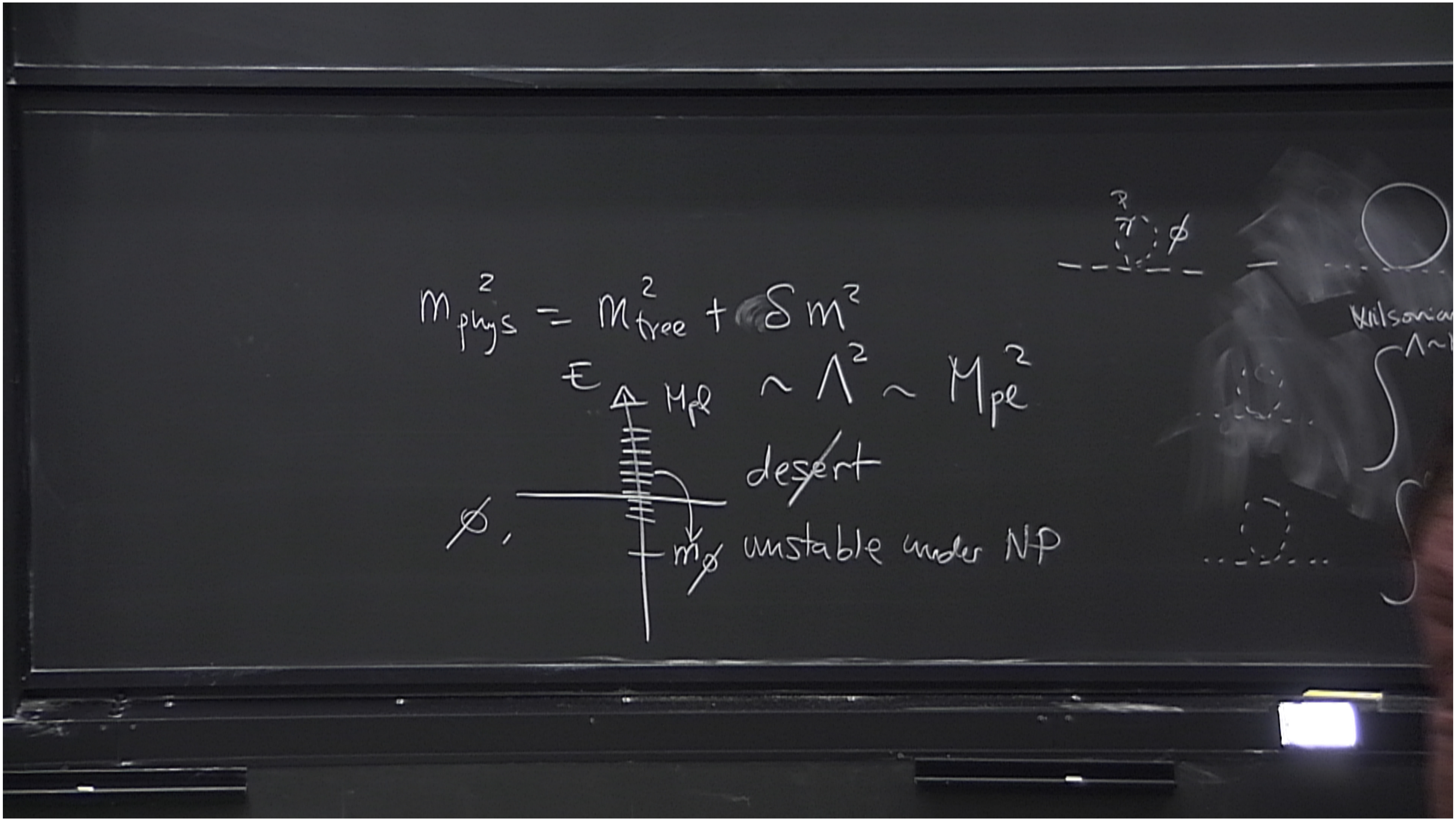
1 hint for 125 GeV Higgs → by the end '12
2 new particles


PV
M_{PV}
$\sim M_{PV}^2$
gauge hierarchy problem
fermion
Wilsonian
$\Lambda \sim M_{pl}$
$\sim M_{pl}^2$
M_F
$d^4p \to d=4-\varepsilon$
$\sim \frac{1}{\varepsilon}$
threshold
$\delta m^2 \propto M_F^2$

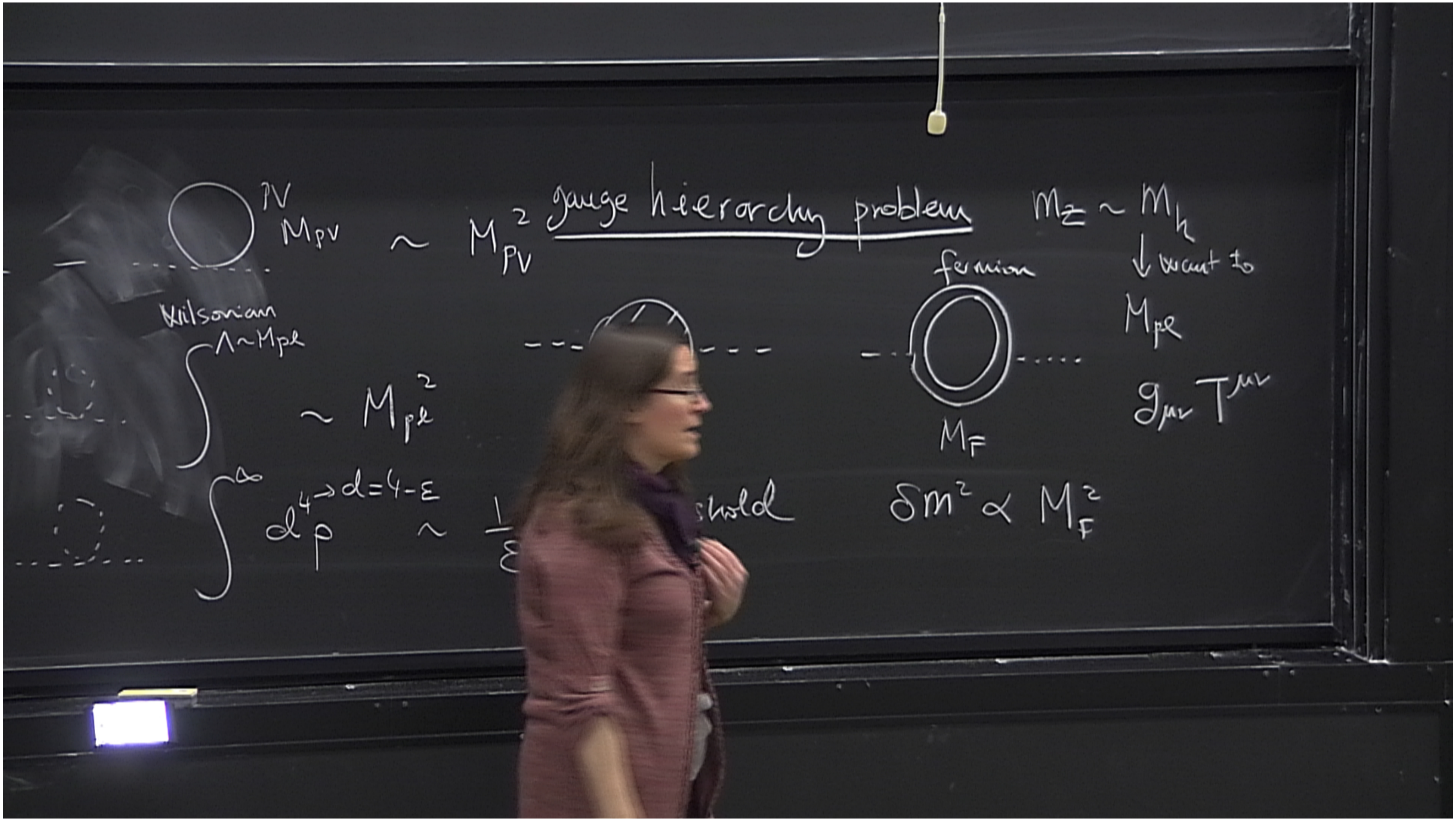

PV
Mpv
~ Mpv^2
gauge hierarchy problem
Mz
Wilsonian
~ Mpl^2
d=4-ε
~ 1/ε
fermion
MF
threshold
δm² ∝ MF²

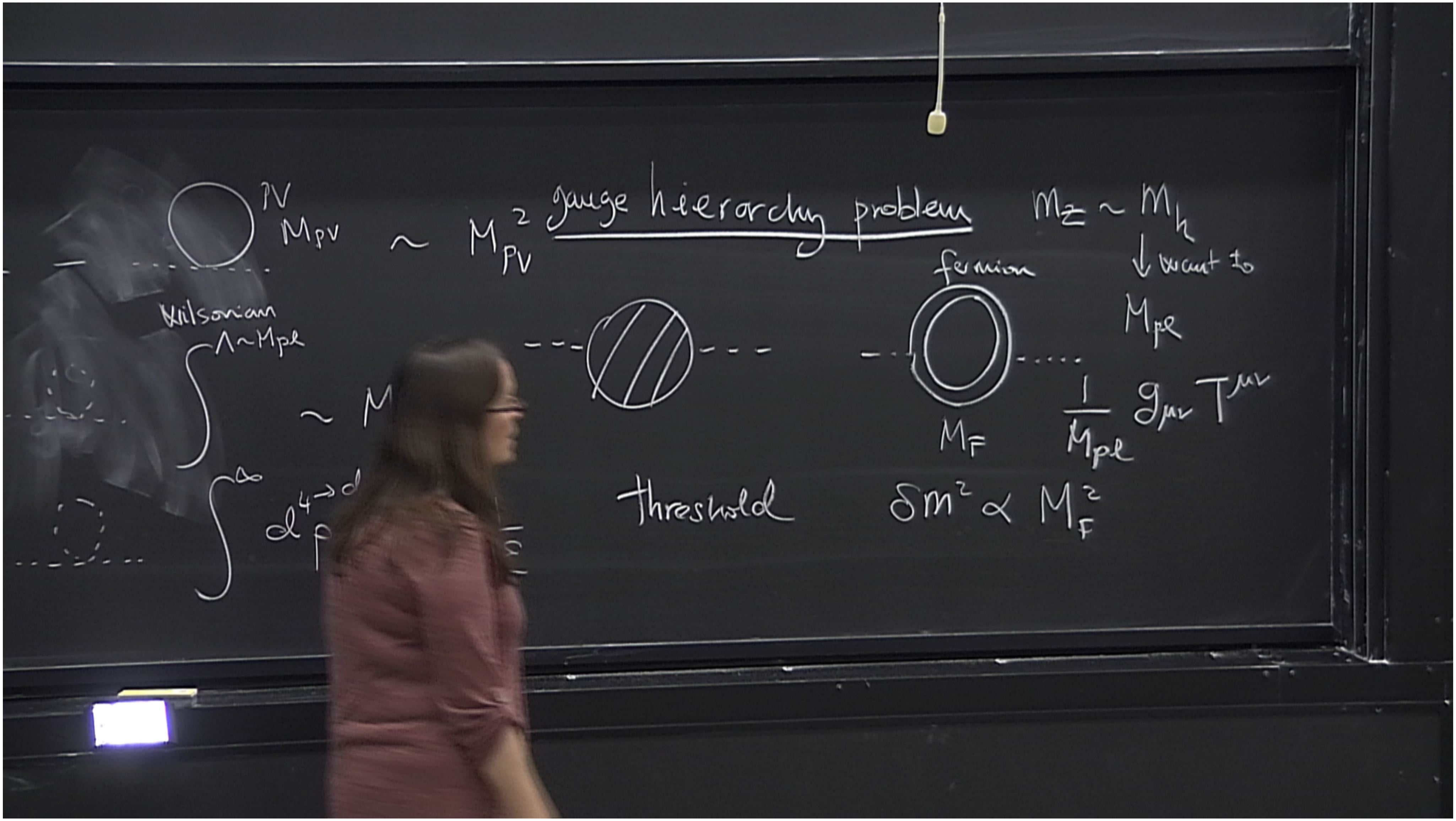

PV
M_{PV}
$\sim M_{PV}^2$
gauge hierarchy problem
$M_Z \sim M_h$
fermion
Wilsonian
$\Lambda \sim M_{pl}$
M_F
$4-\varepsilon$
$\sim \frac{1}{\varepsilon}$
threshold
$\delta m^2 \propto M_F^2$


gauge hierarchy problem
PV
M_{PV}
$\sim M_{PV}^2$
$M_Z \sim M_h$
want to
M_{pl}
fermion
Wilsonian
$\Lambda \sim M_{pl}$
$\sim M_{pl}^2$
M_F
$\int^{\infty} d^{4 \to d = 4-\epsilon} p \sim \frac{1}{\epsilon}$
threshold
$\delta m^2 \propto M_F^2$

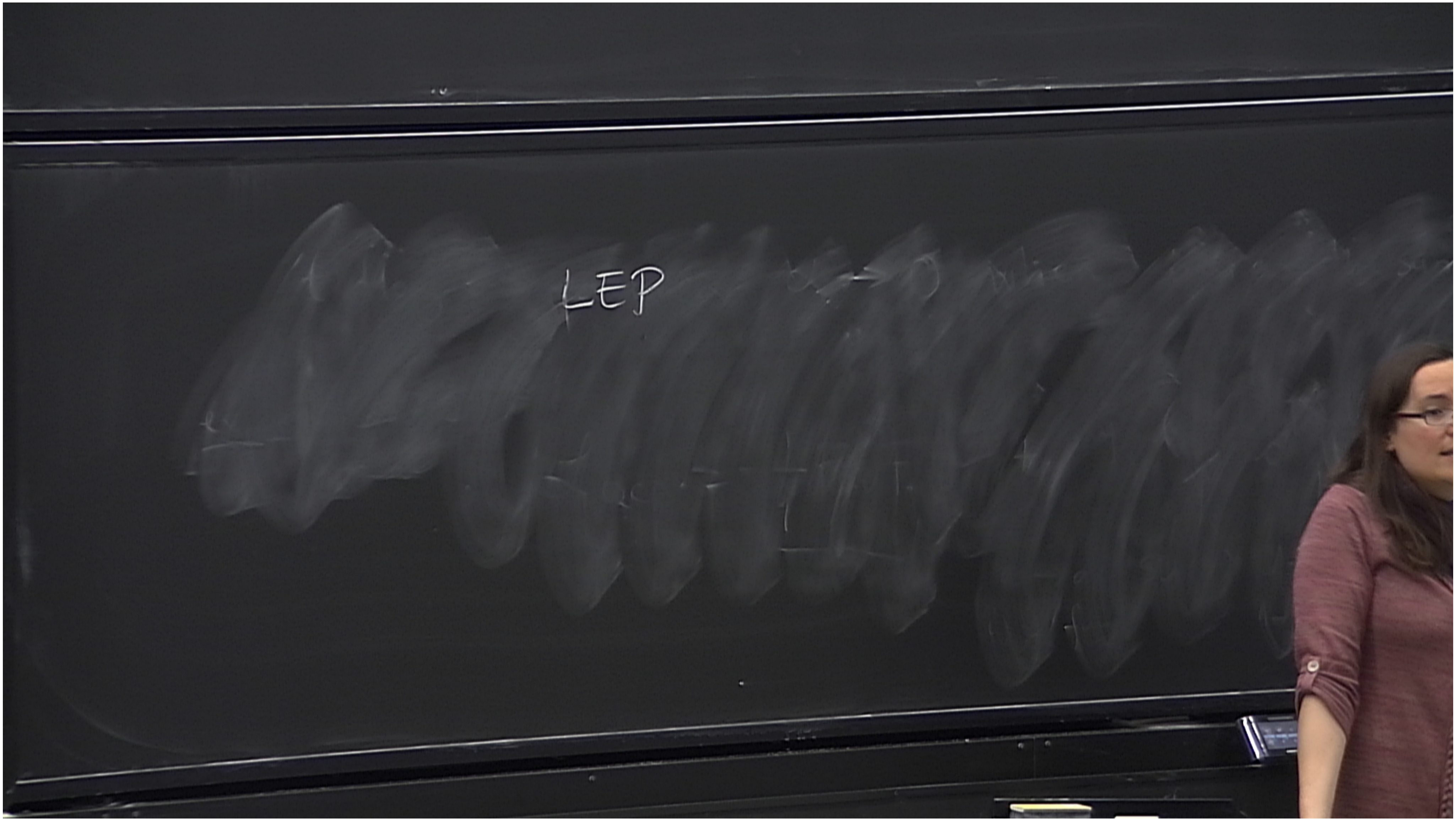


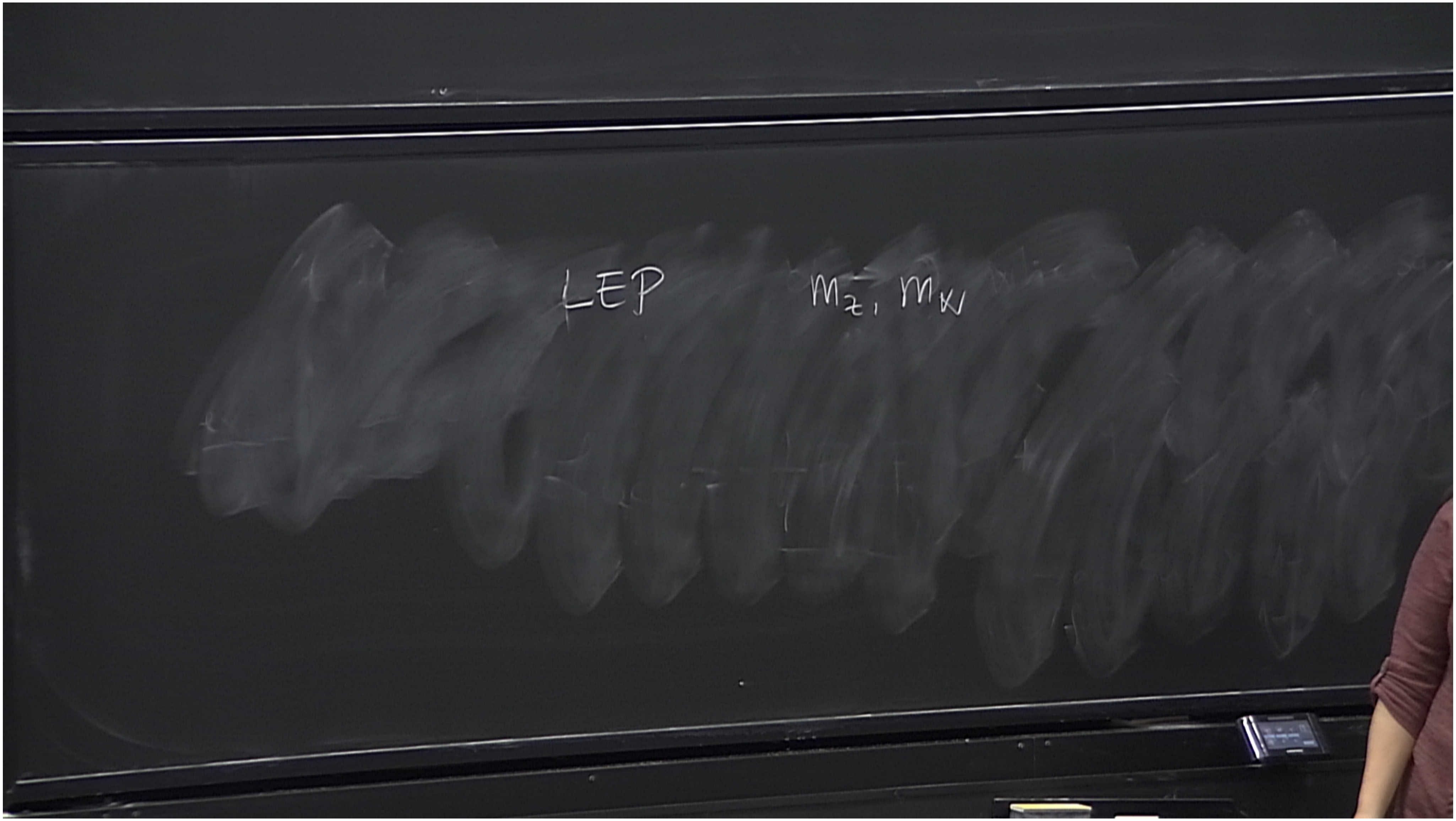
m_phys^2 = m_tree^2 + δm^2
~ Λ^2 ~ M_pl^2
E
M_pl
desert
φ,
m_φ unstable under NP

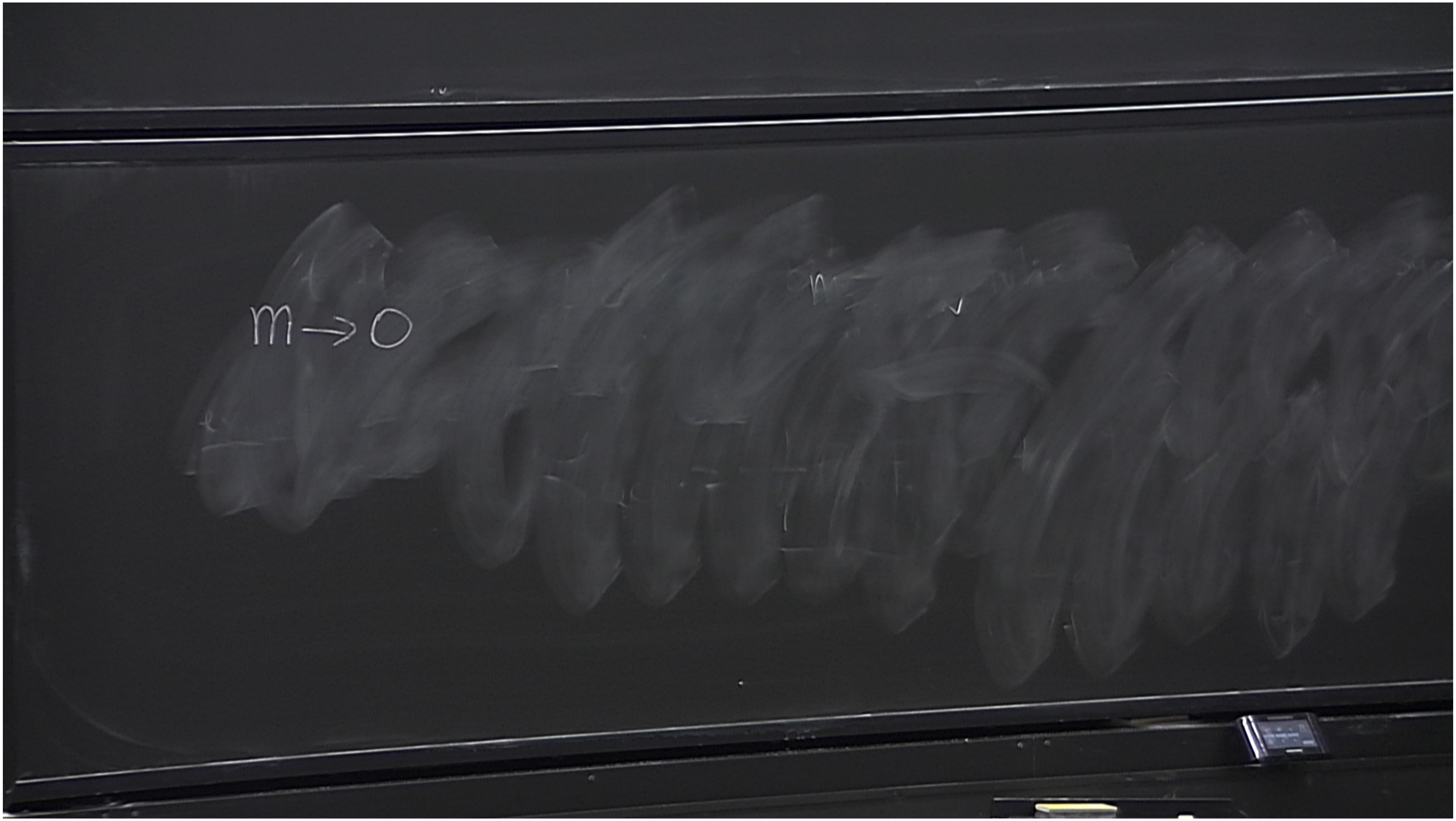

PV
M_PV
~ M_PV^2
gauge hierarchy problem
M_Z ~ M_h
want to
M_pl
fermion
Wilsonian
Λ~M_pl
~ M_pl^2
g_μν T^μν
M_F
d^4 → d=4-ε
d^4 p
~ 1/ε
δm^2 ∝ M_F^2

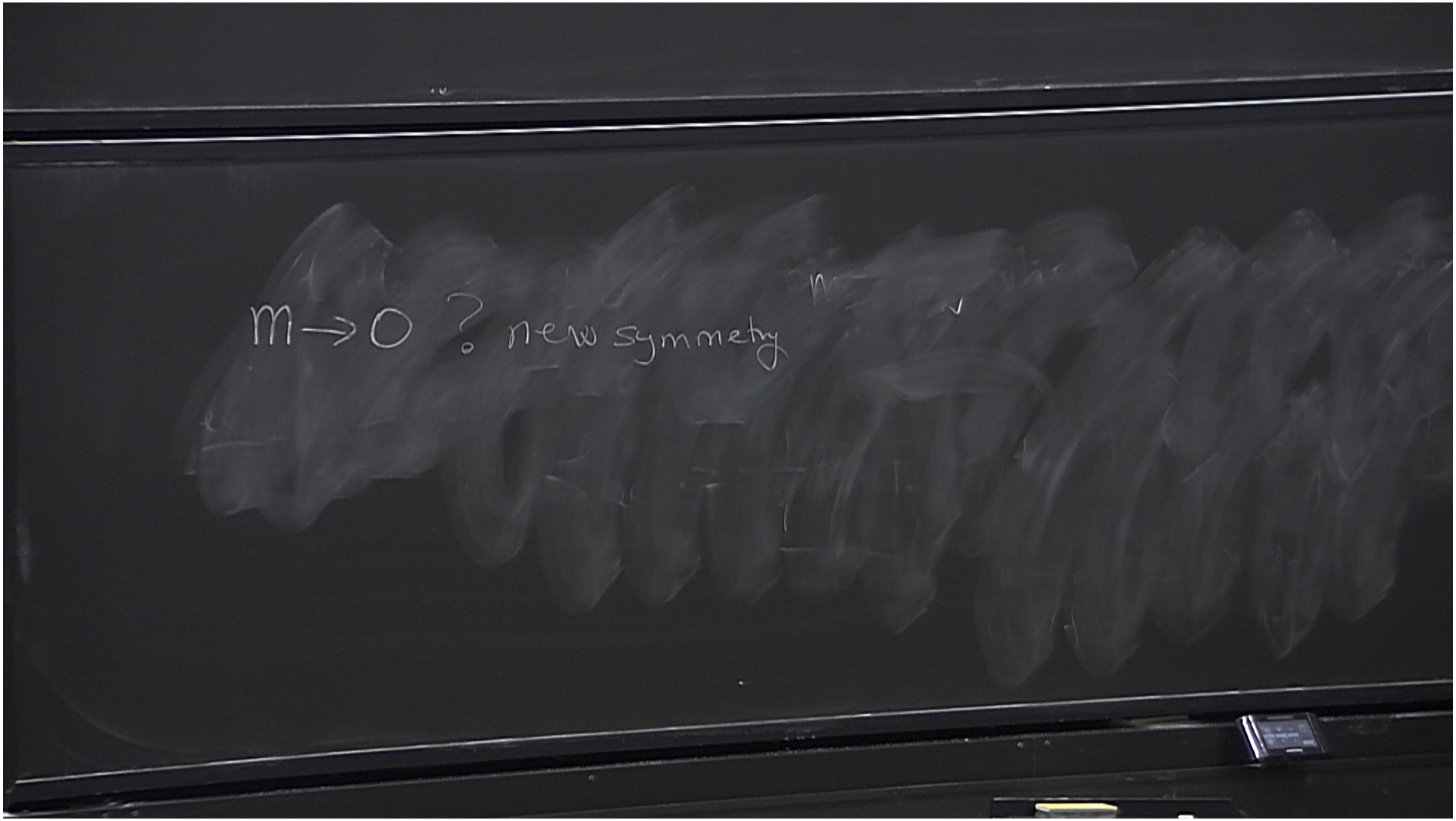


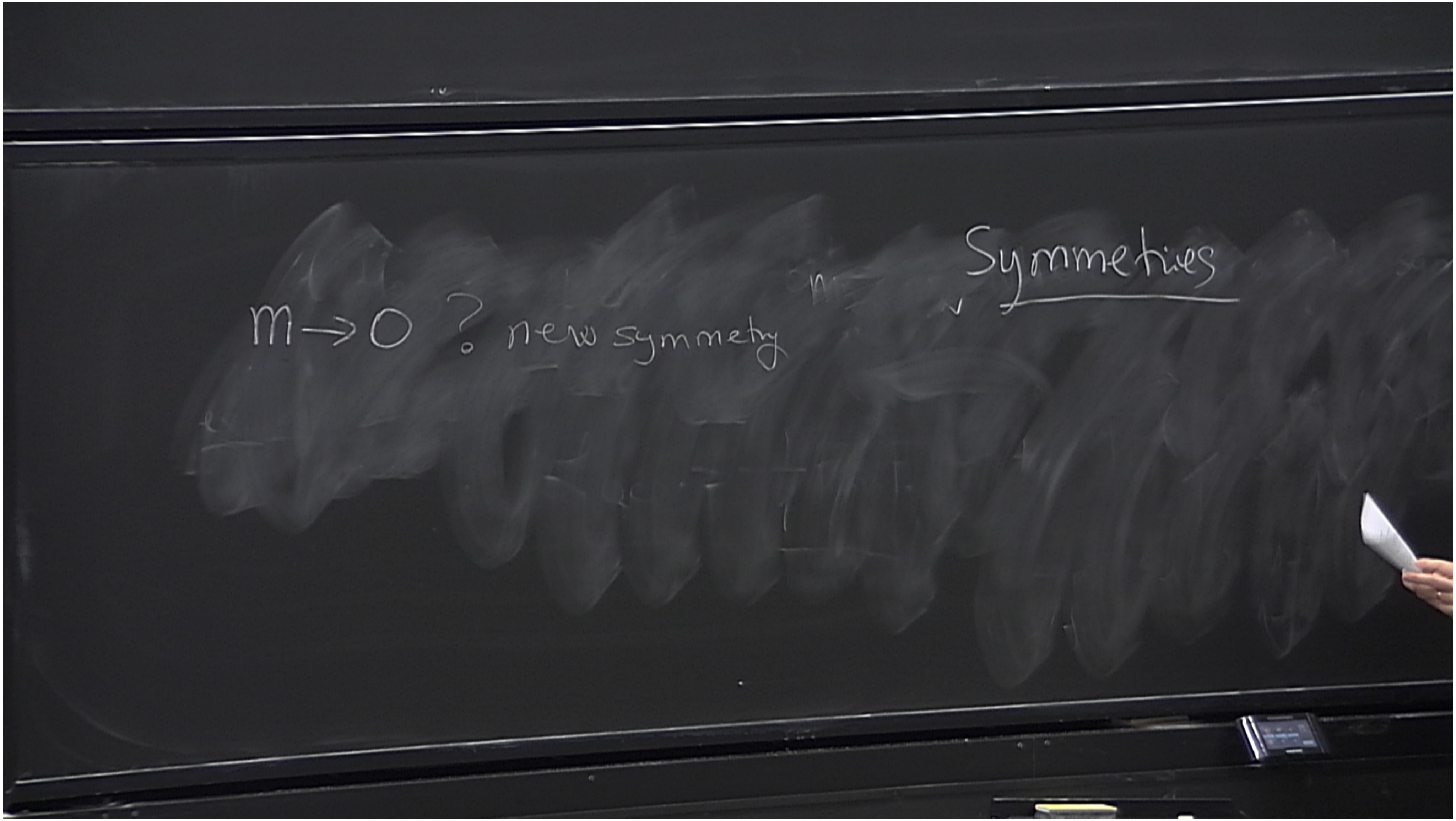
gauge hierarchy problem
$M_Z \sim M_h$
want to
M_{pl}
PV
M_{PV}
$\sim M_{PV}^2$
Wilsonian
$\Lambda \sim M_{pl}$
fermion
M_F
$\frac{1}{M_{pl}} g_{\mu\nu} T^{\mu\nu}$
threshold
$\delta m^2 \propto M_F^2$

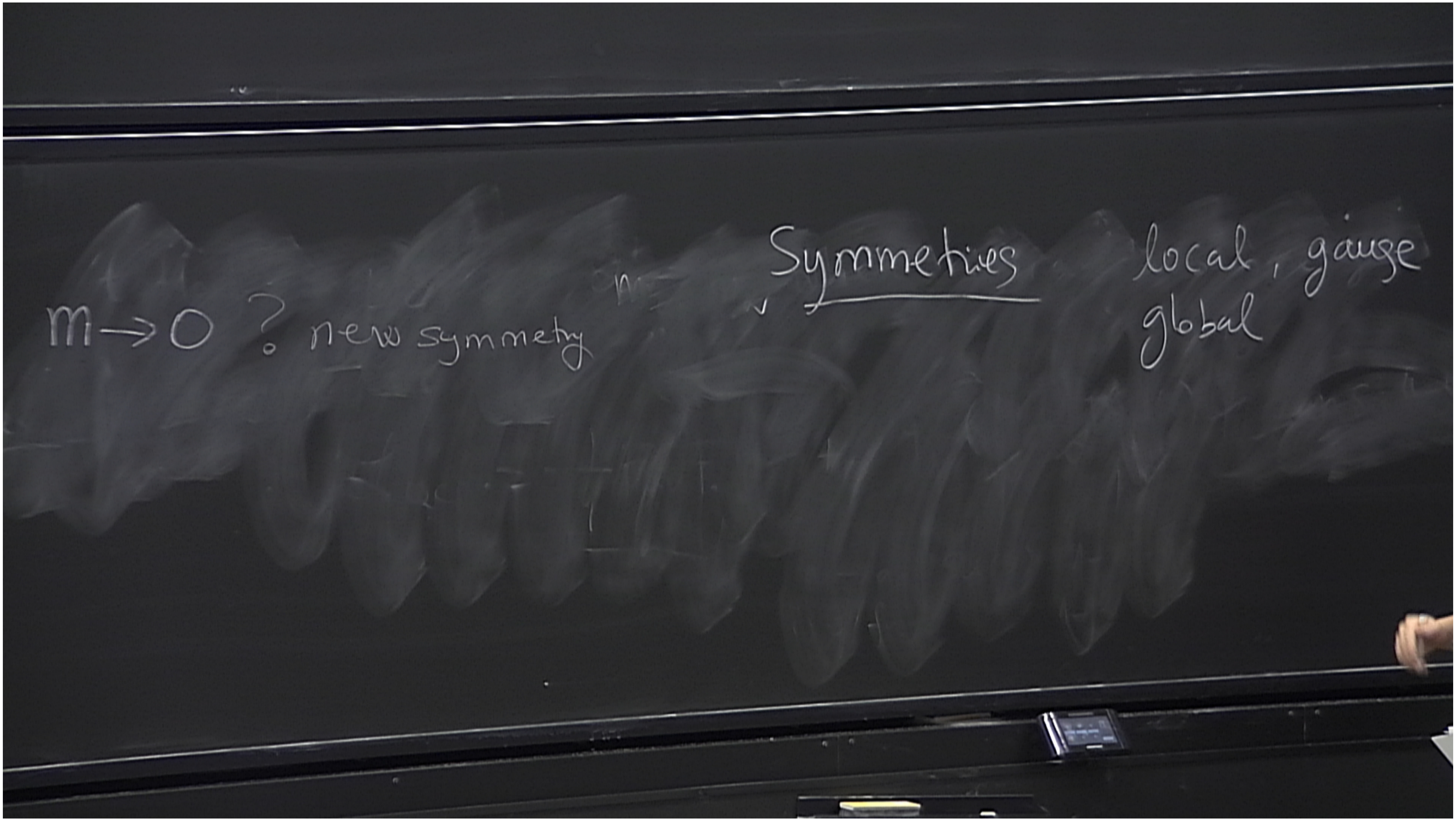

LEP

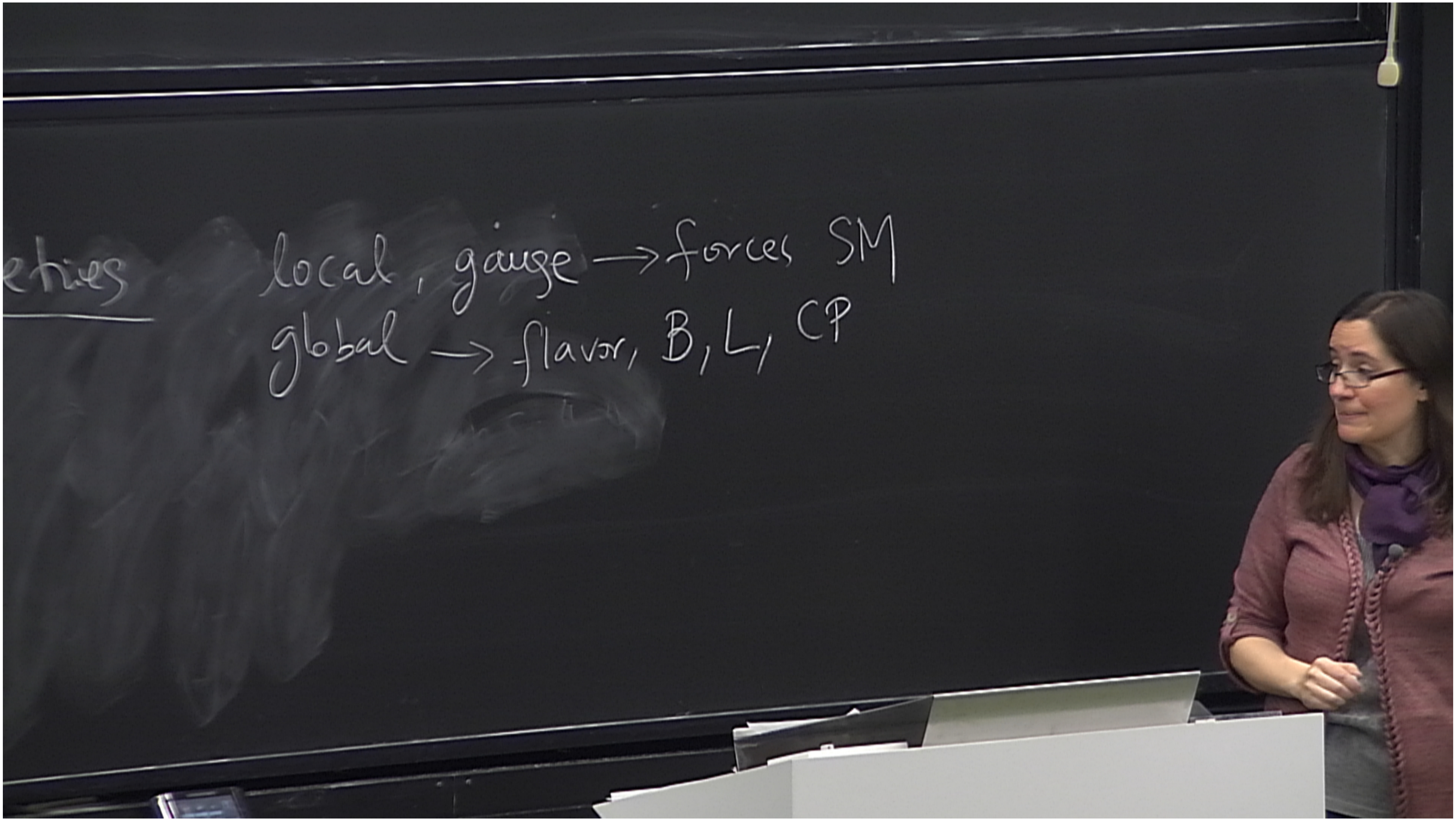

LEP
m_Z, m_W


$m \to 0$


m → 0 ? new symmetry


Symmetries
m → 0 ? new symmetry


m → 0 ? new symmetry
Symmetries
local, gauge
global



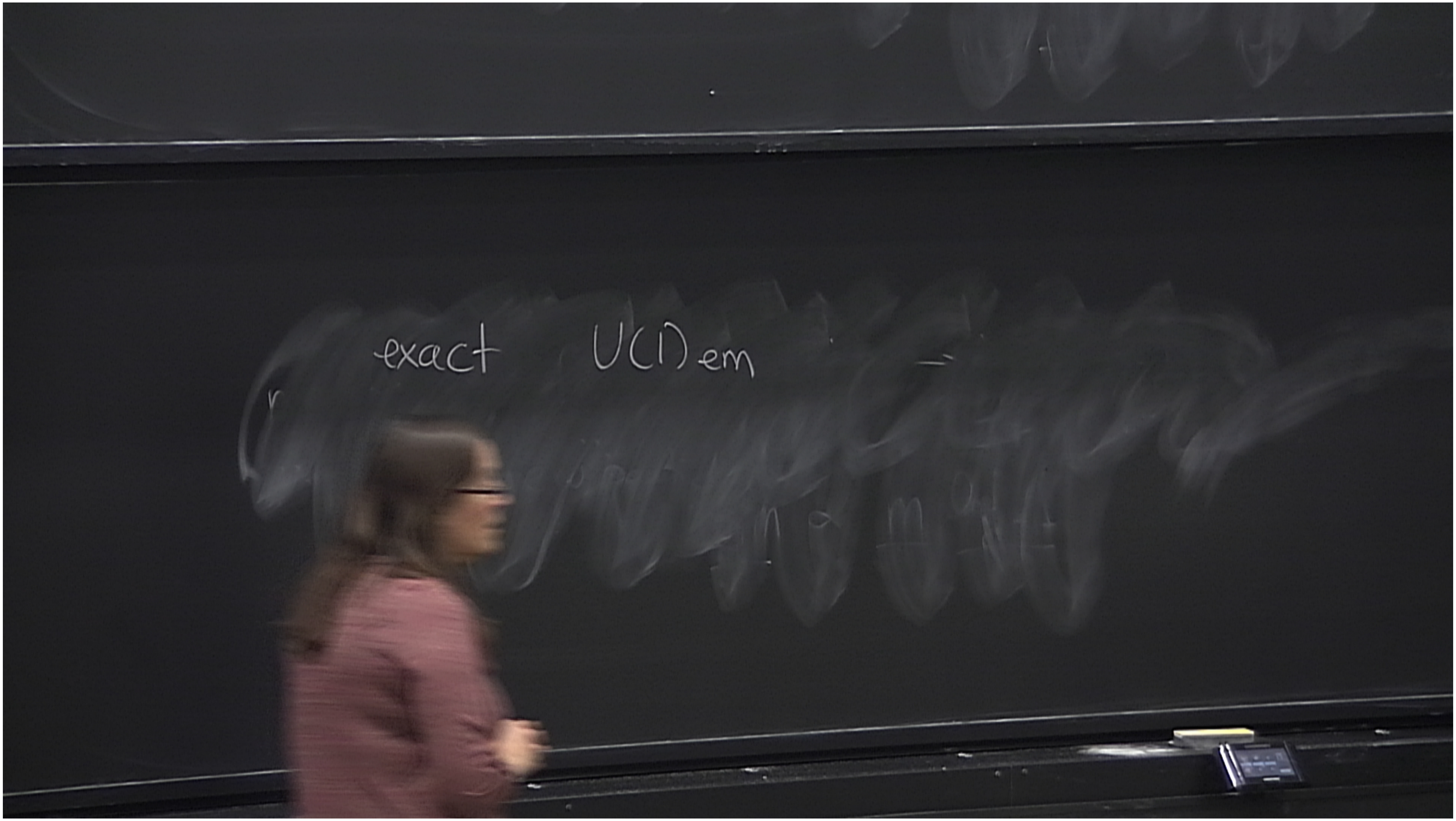
...etries
local, gauge → forces SM
global → flavor, B, L, CP

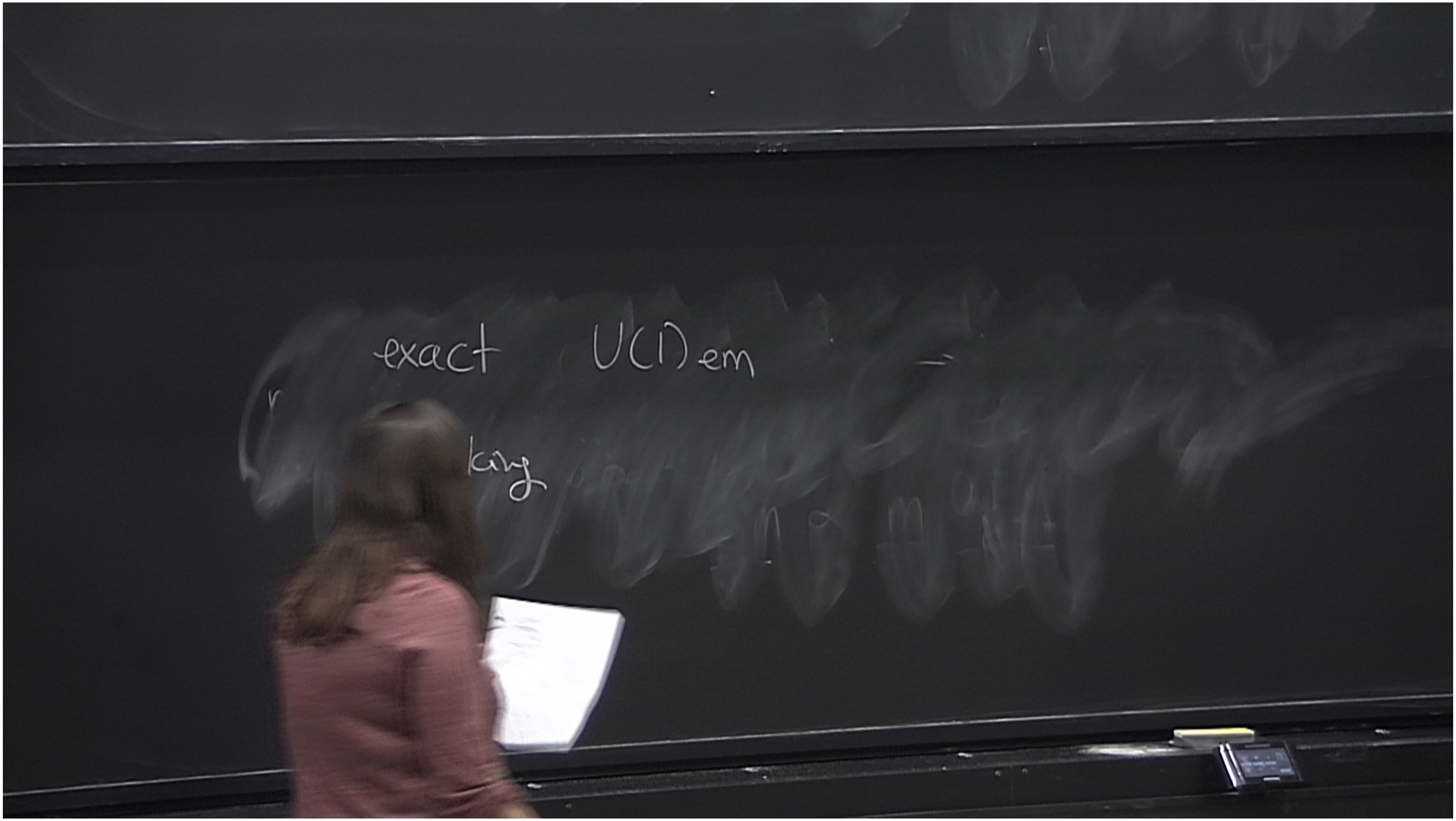
...ties

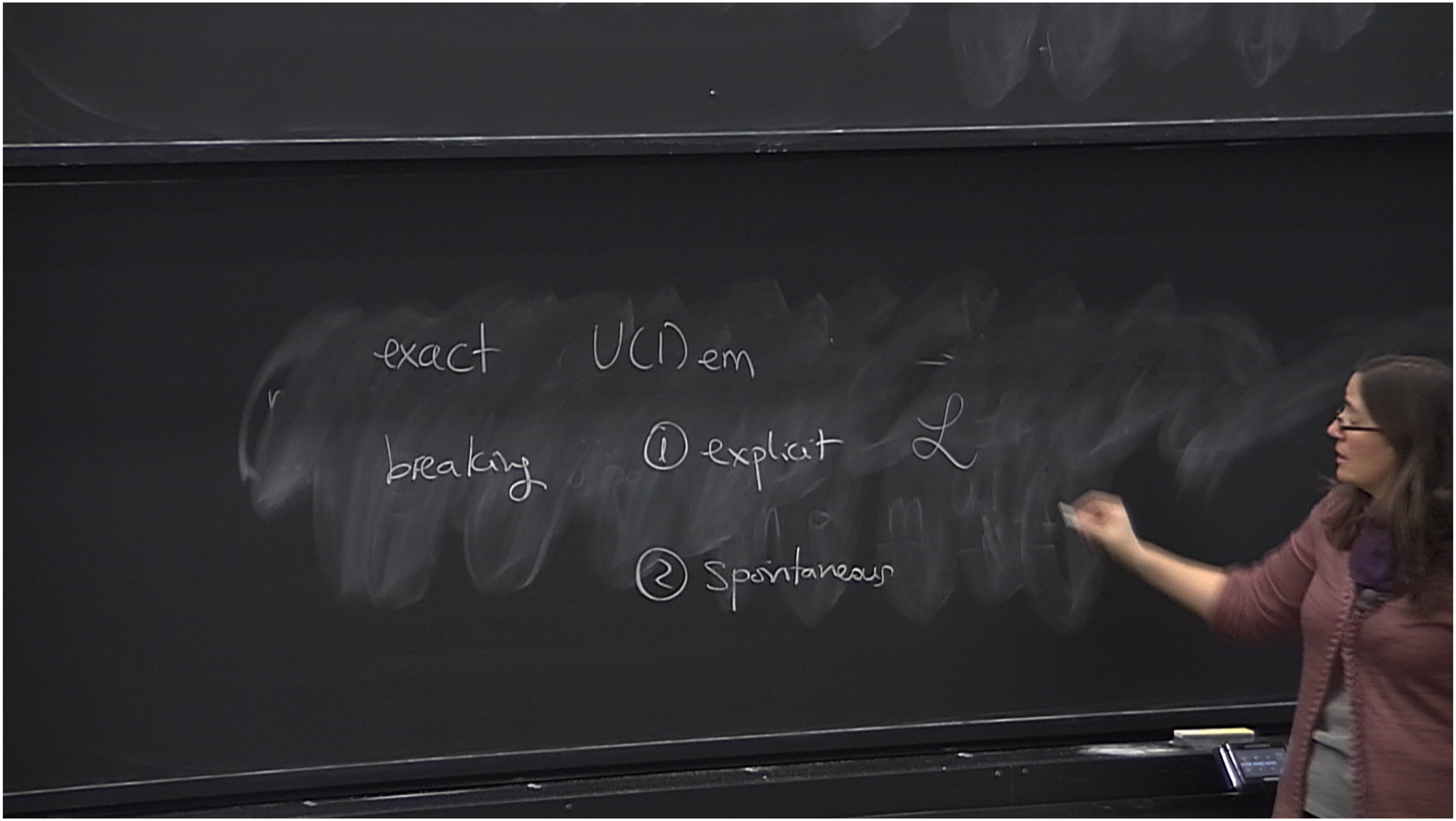
local, gauge $\longrightarrow$ forces SM

global $\longrightarrow$ flavor, B, L, CP

$\psi \longrightarrow -\psi$


exact U(1) em

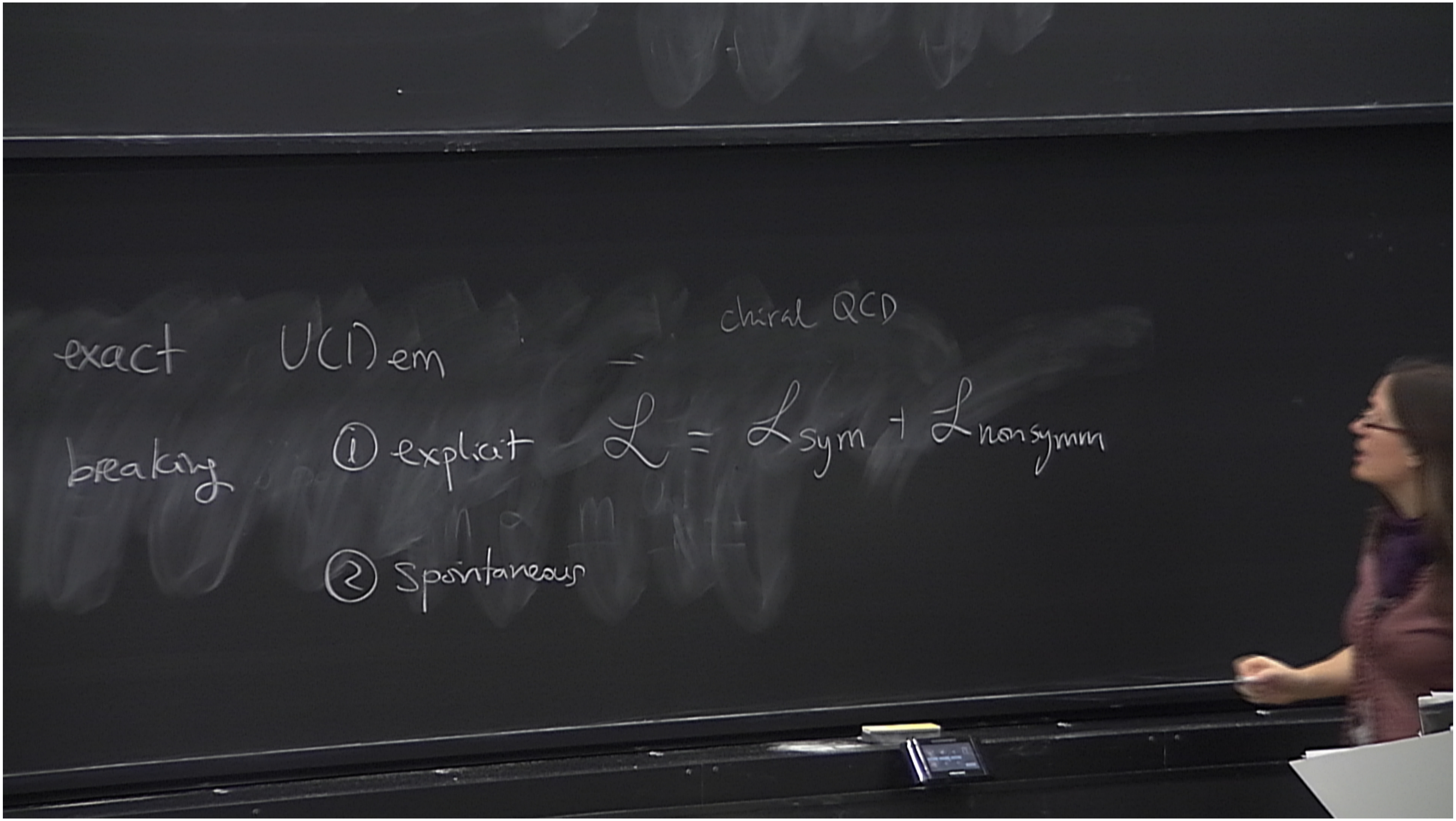

exact U(1) em


exact U(1) em
breaking
1 explicit $\mathcal{L}$
2 spontaneous

exact $U(1)_{em}$

breaking ① explicit $\mathcal{L} = \mathcal{L}_{sym}$

② spontaneous


chiral QCD
exact U(1) em
breaking
1 explicit $\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$
2 spontaneous

chiral QCD $\quad \gamma \quad A^a \quad m\bar{\psi}\psi$

exact $\quad U(1)_{em}$

breaking

1. explicit $\quad \mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$

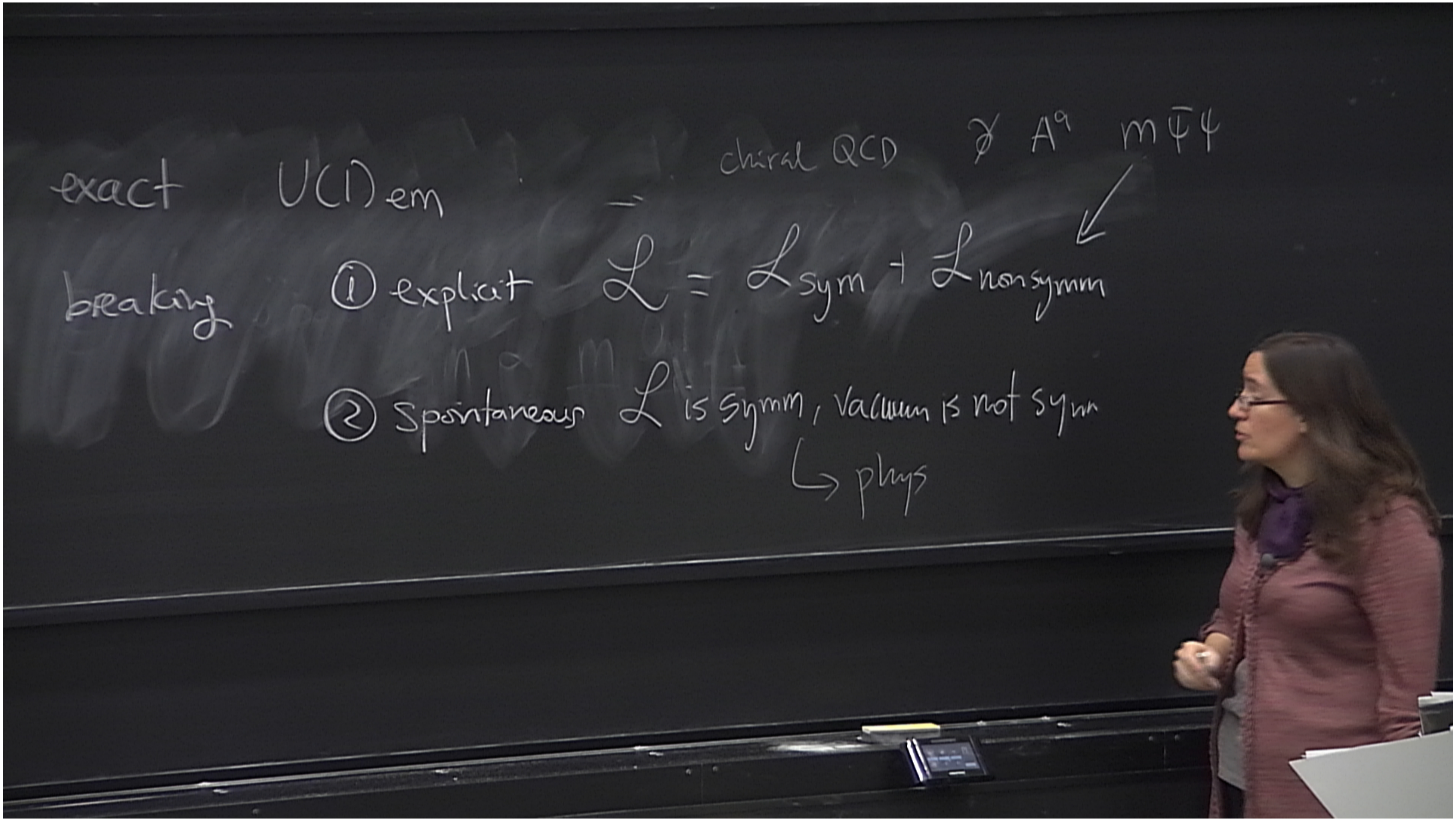
2. spontaneous

chiral QCD $\quad \gamma \quad A^a \quad m\bar{\psi}\psi$

exact $\quad U(1)_{em}$

breaking ① explicit $\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$

② spontaneous $\mathcal{L}$ is symm, vacuum is not symm


exact
U(1) em
chiral QCD
γ A^a m ψ̄ψ
breaking
① explicit
ℒ = ℒ_sym + ℒ_nonsymm
② spontaneous
ℒ is symm, vacuum is not symm
phys

chiral QCD γ A^a $m\bar{\psi}\psi$

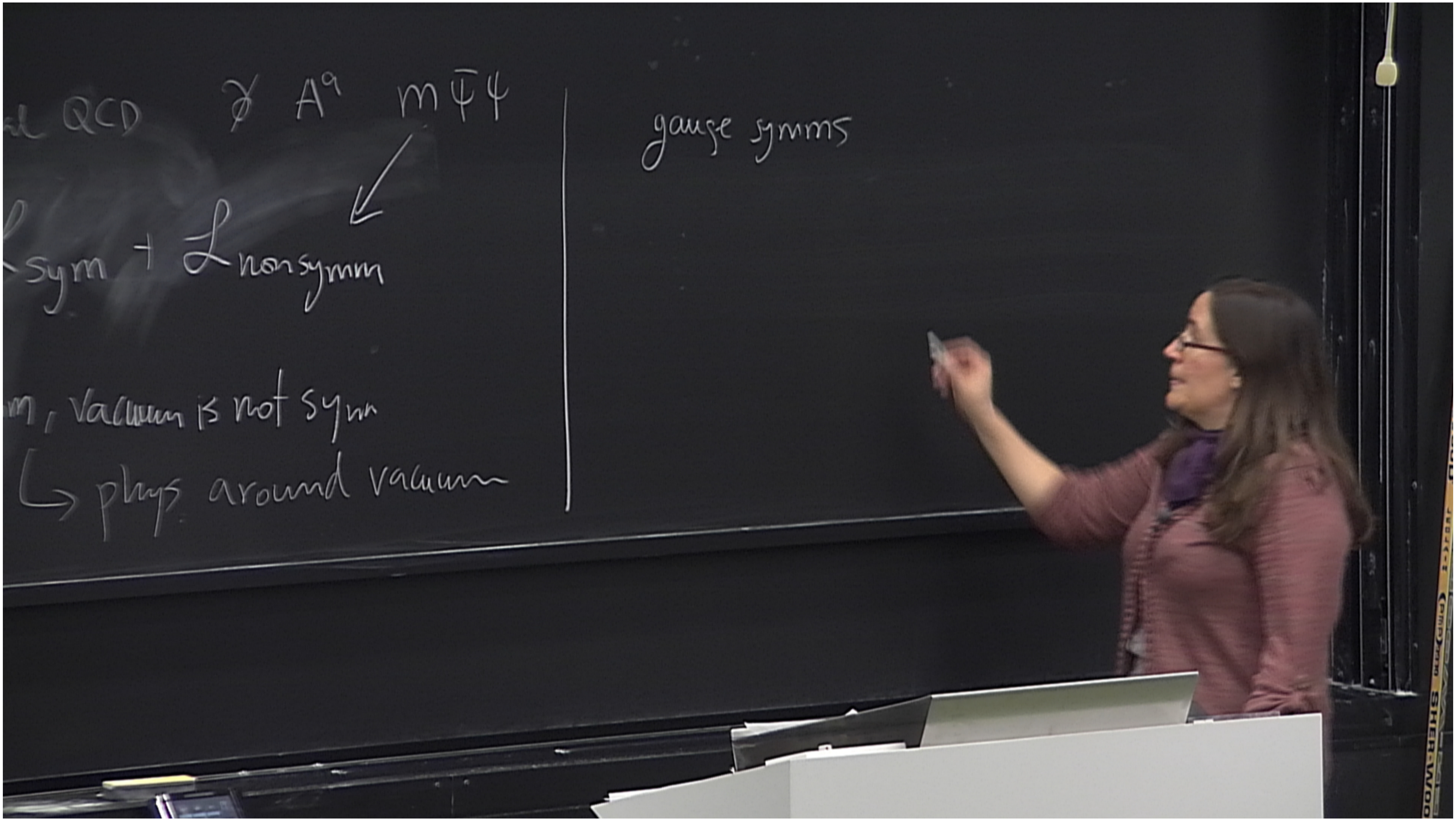
exact $U(1)_{em}$

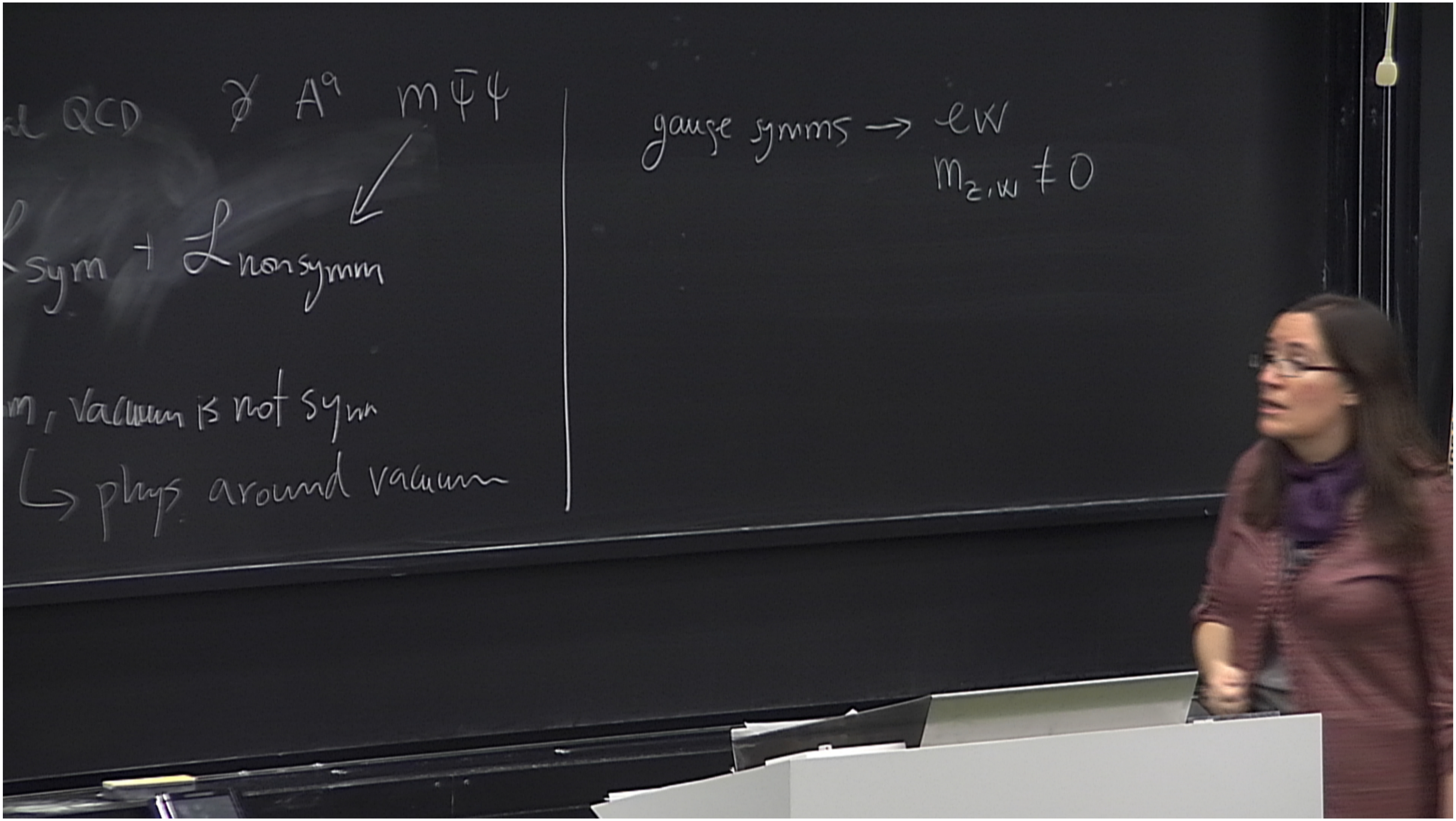
breaking

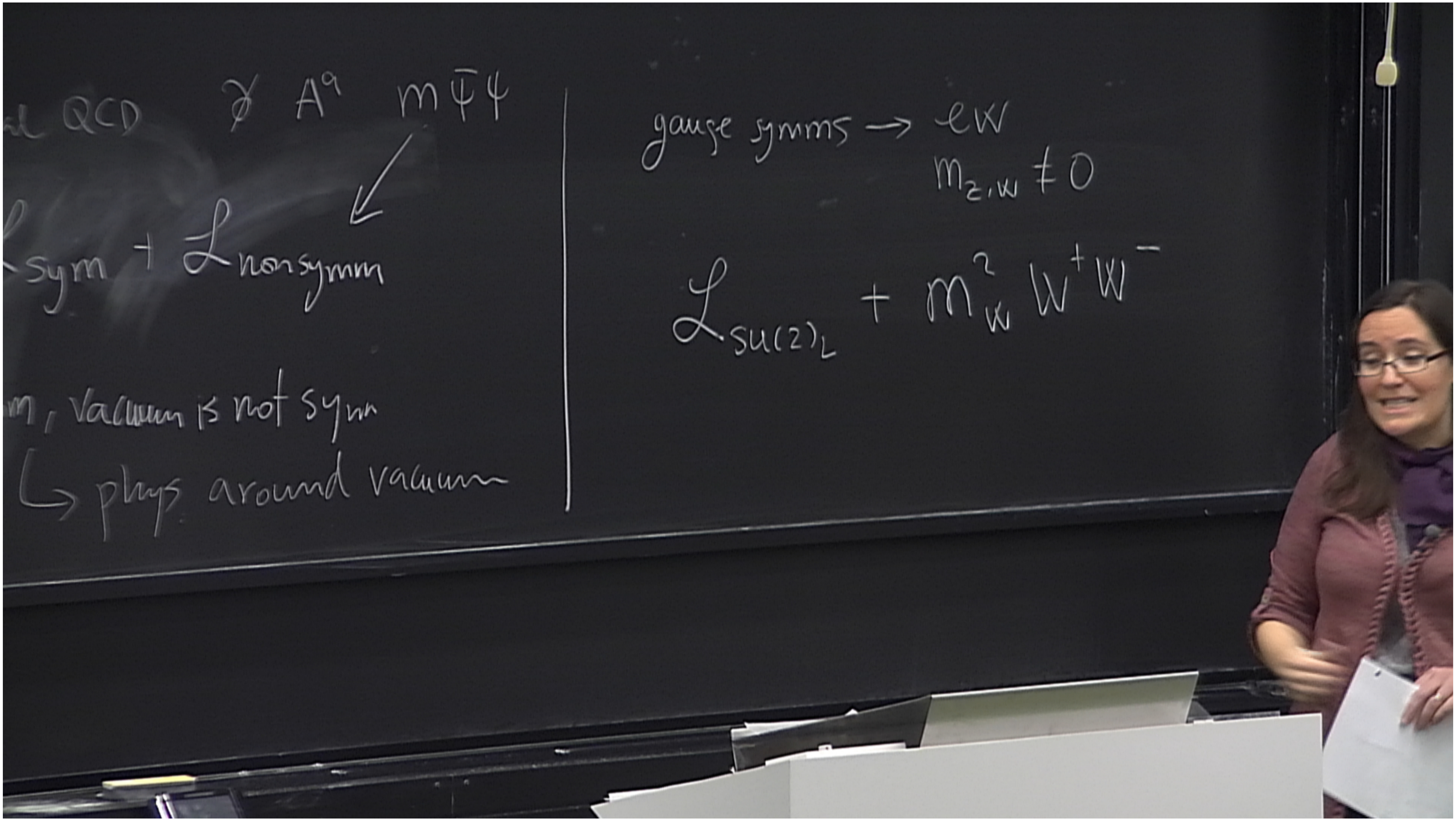
① explicit $\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$

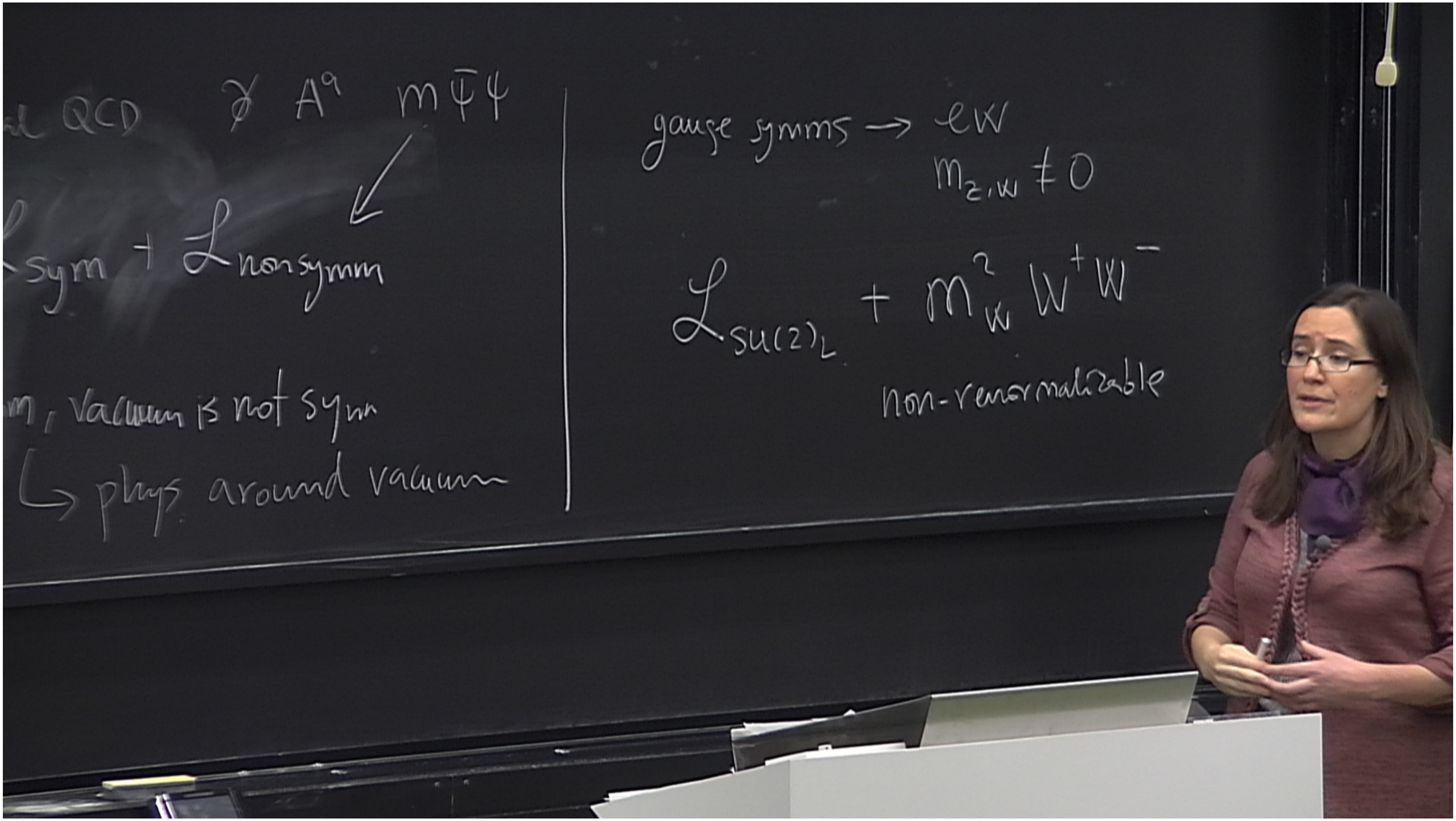
② spontaneous $\mathcal{L}$ is symm, vacuum is not symm

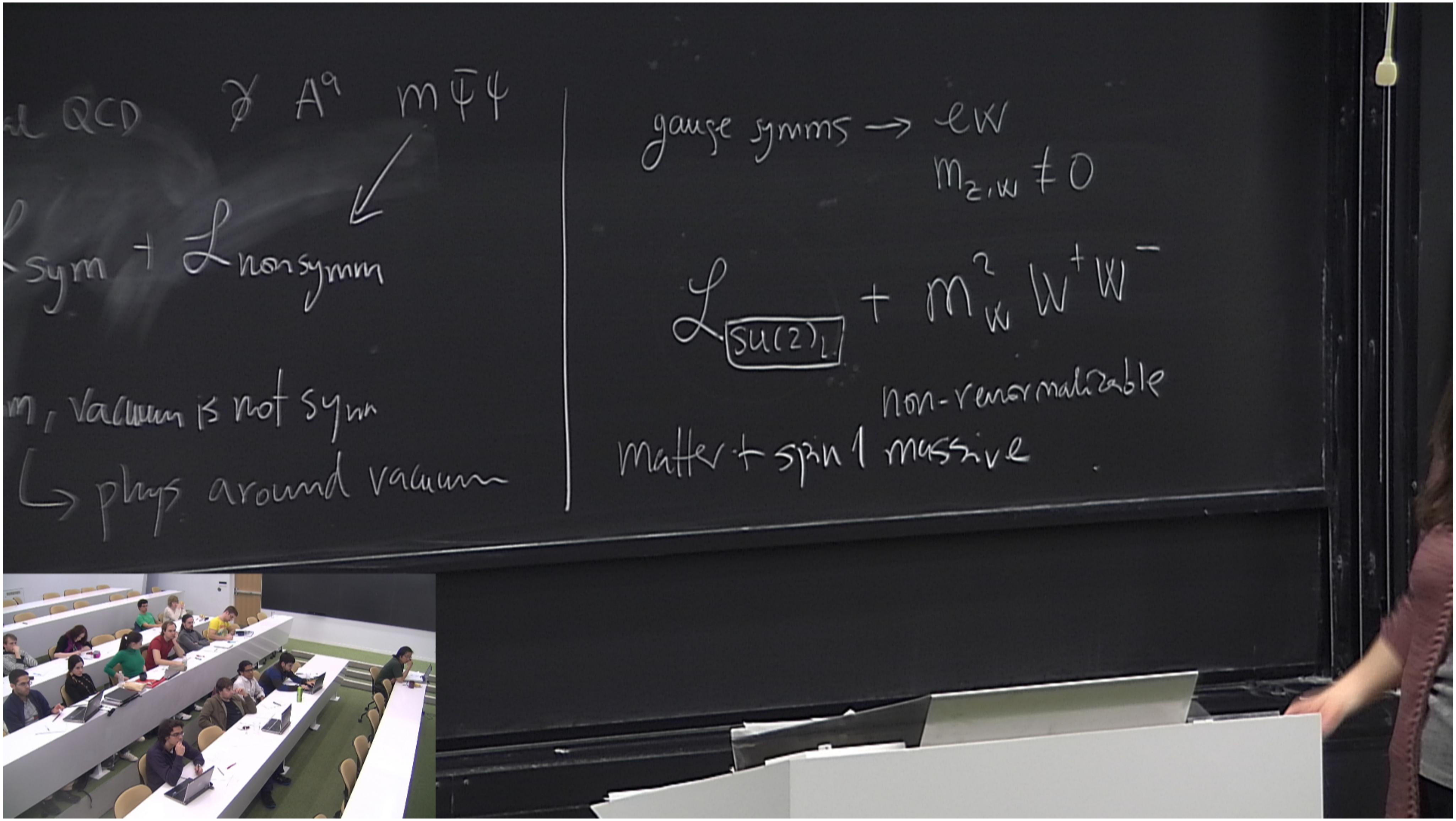
$\hookrightarrow$ phys around vacuum

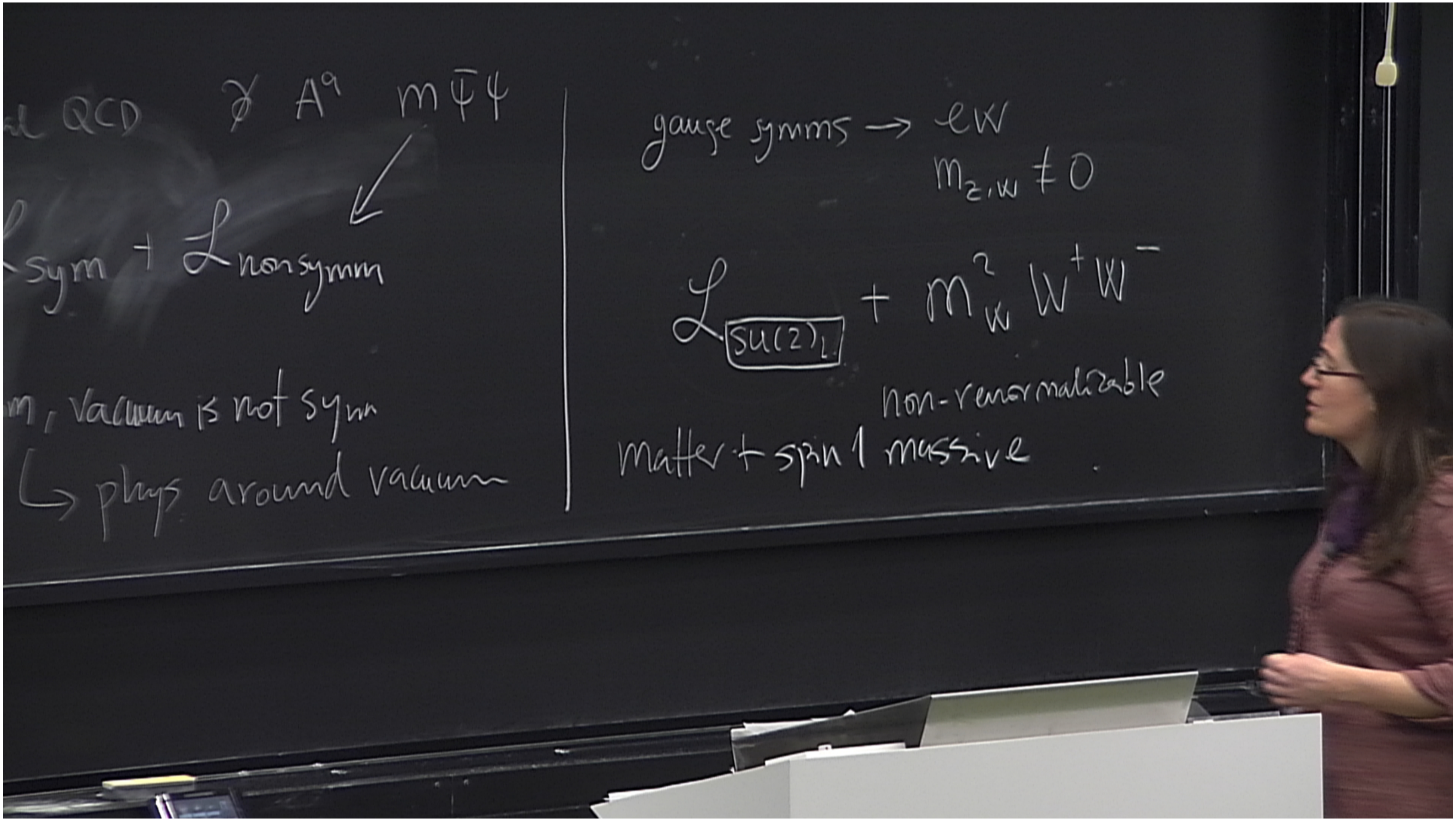

QCD
A^a m ψ̄ψ
sym + L nonsymm
vacuum is not symm
phys around vacuum
gauge symms

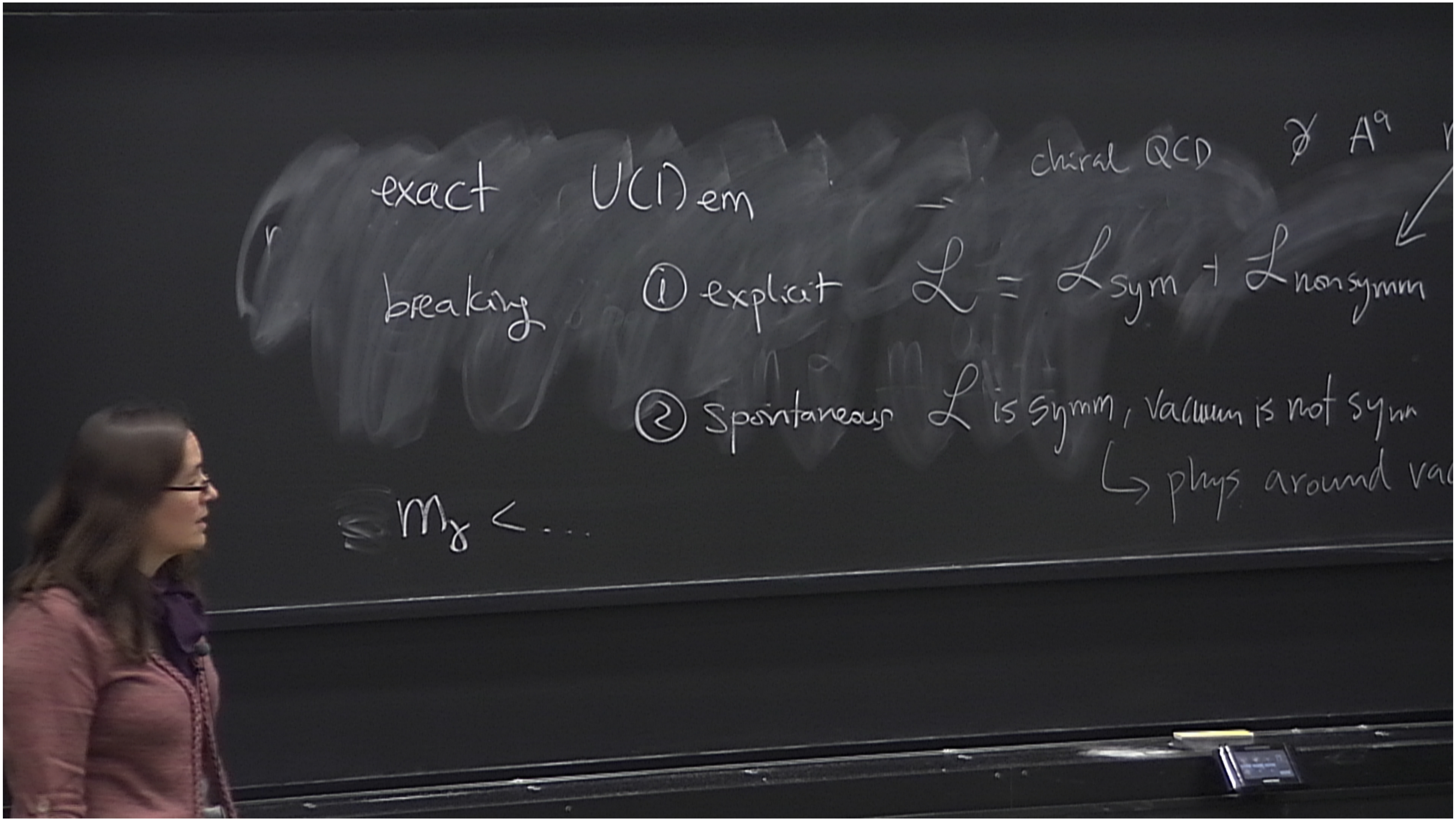

QCD
mΨ̄Ψ
sym + L nonsymm
vacuum is not symm
↳ phys around vacuum
gauge symms → eW
m z,W ≠ 0

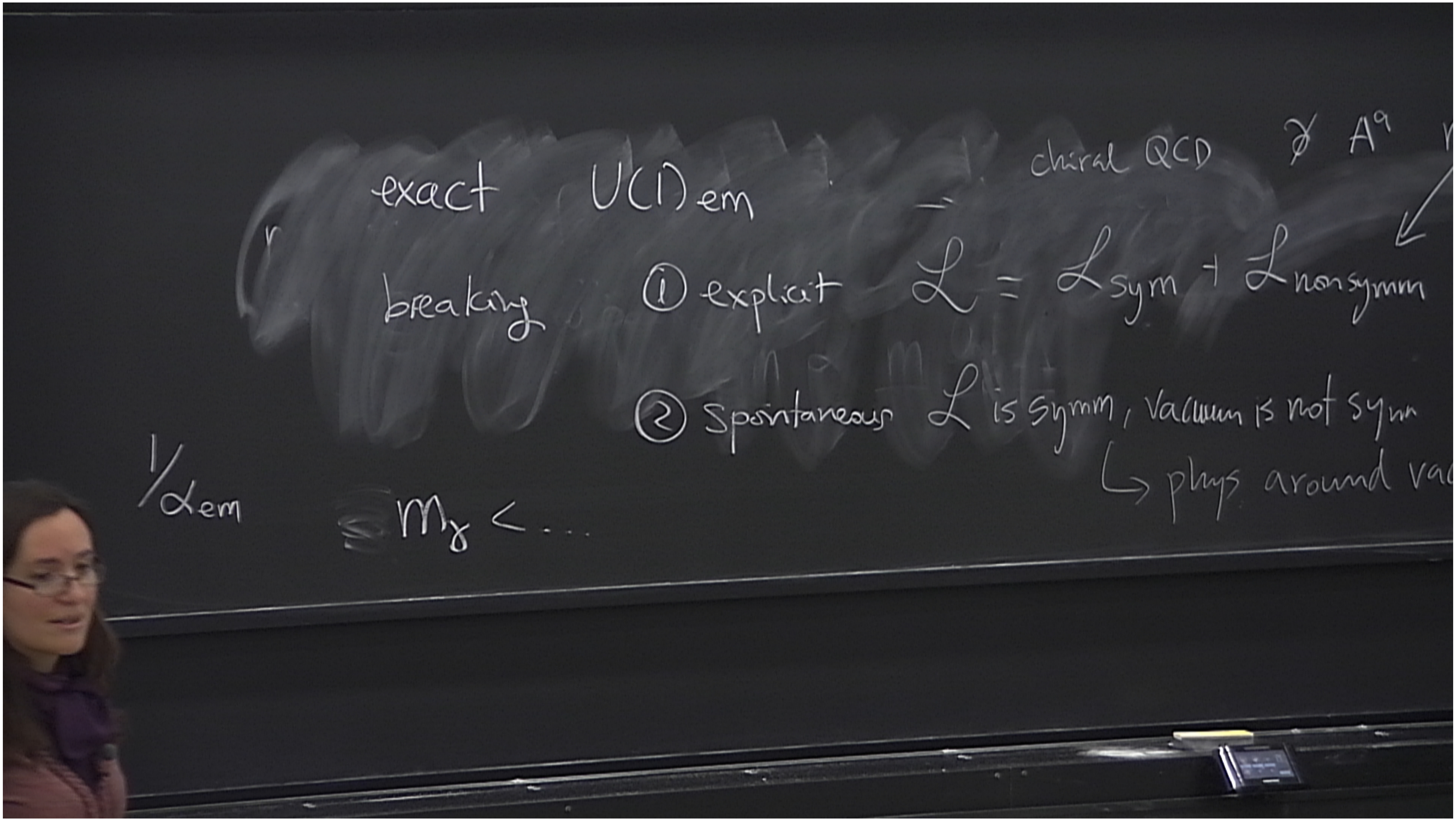

QCD   γ   A^a   m ψ̄ψ
L_sym + L_nonsymm
vacuum is not symm
↳ phys around vacuum
gauge symms → EW
m_{Z,W} ≠ 0
L_{SU(2)_L} + m_W^2 W^+ W^-

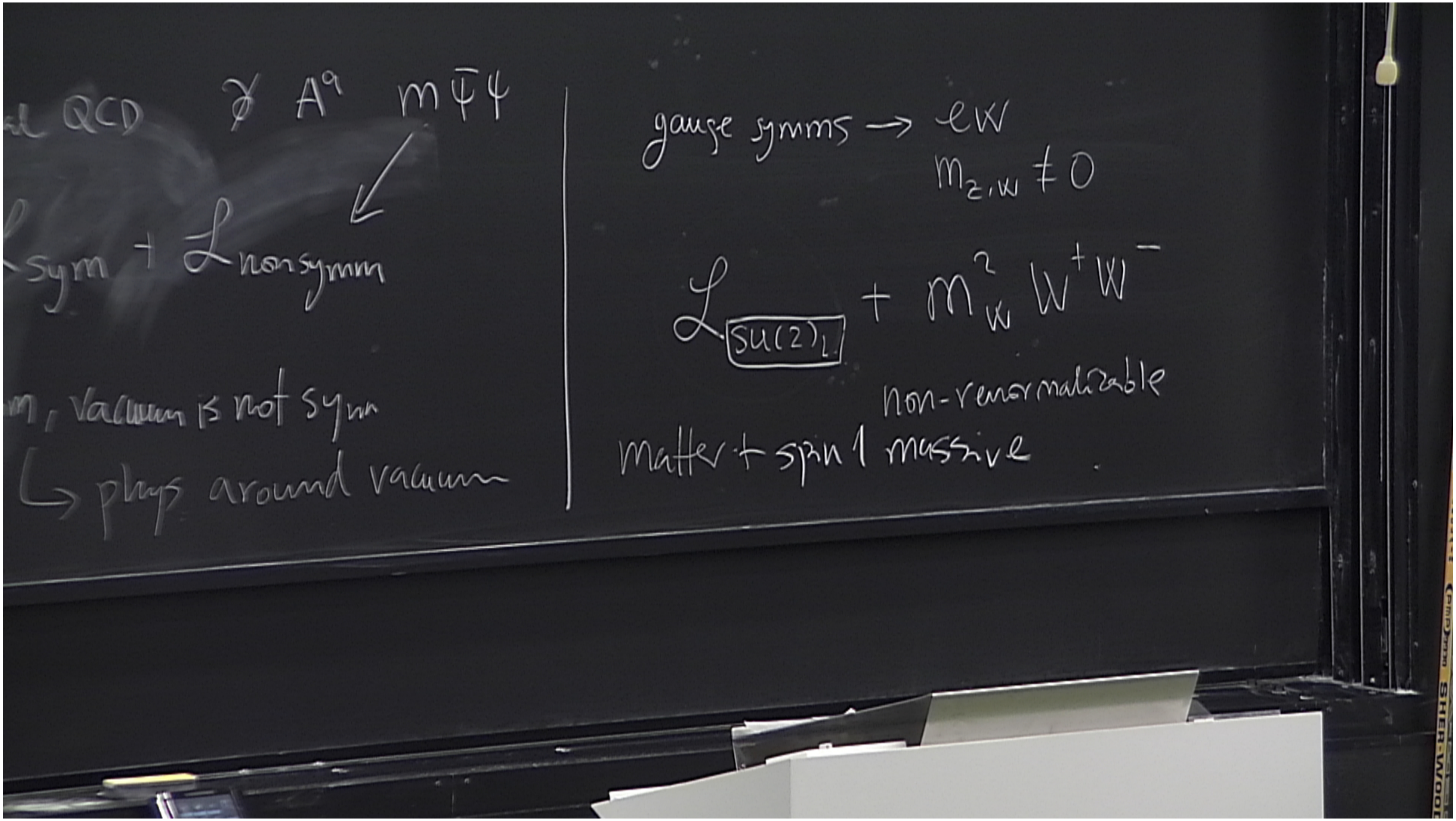

QCD
A^a $m\bar{\psi}\psi$
$\mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$
vacuum is not symm
phys around vacuum
gauge symms → EW
$m_{Z,W} \neq 0$
$\mathcal{L}_{SU(2)_L} + m_W^2 W^+ W^-$
non-renormalizable

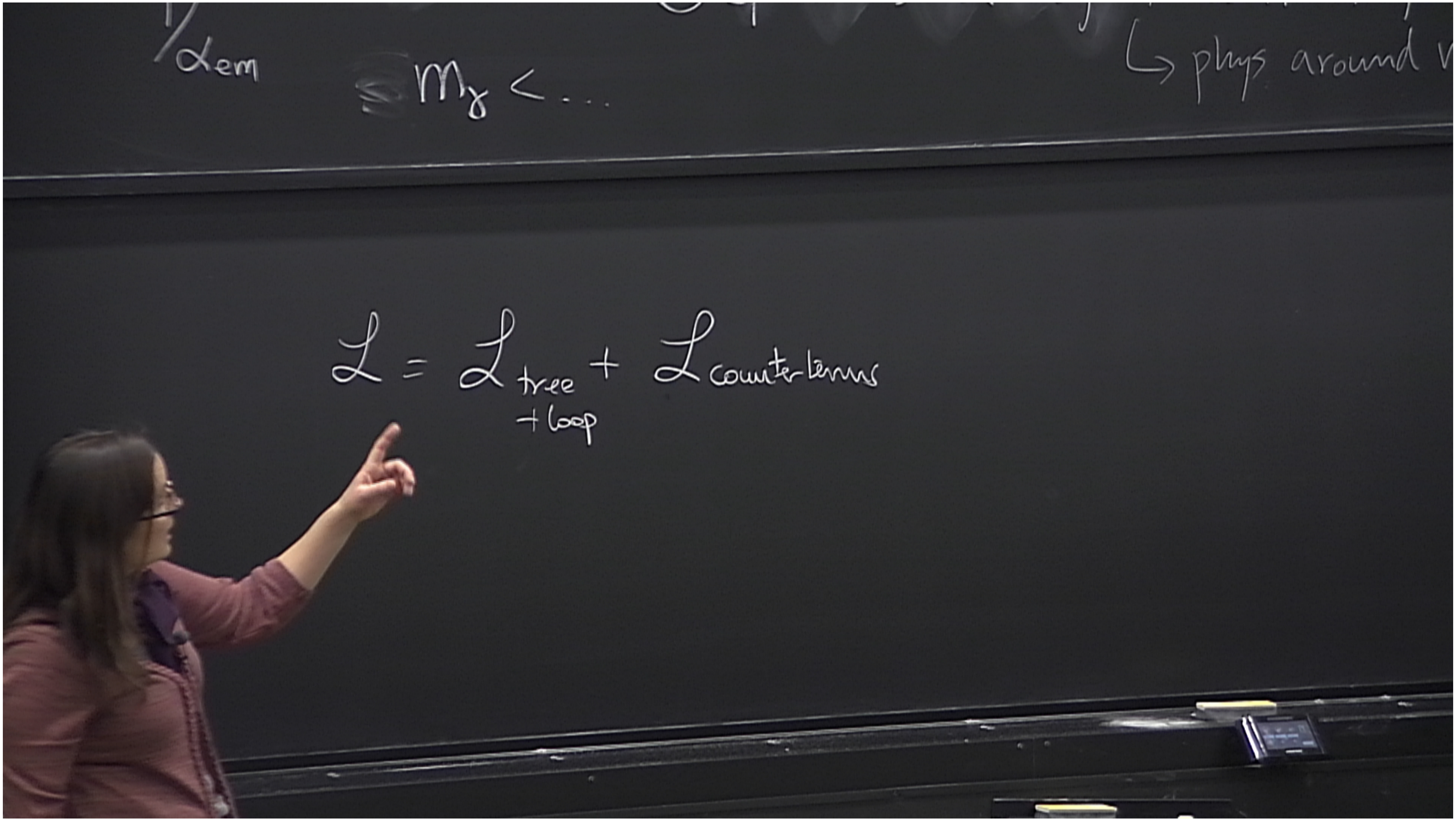

QCD
γ A^a mψ̄ψ
L_sym + L_nonsymm
vacuum is not symm
↳ phys around vacuum
gauge symms → EW
m_{Z,W} ≠ 0
L_{SU(2)_L} + m_W^2 W^+ W^-
non-renormalizable
matter + spin 1 massive

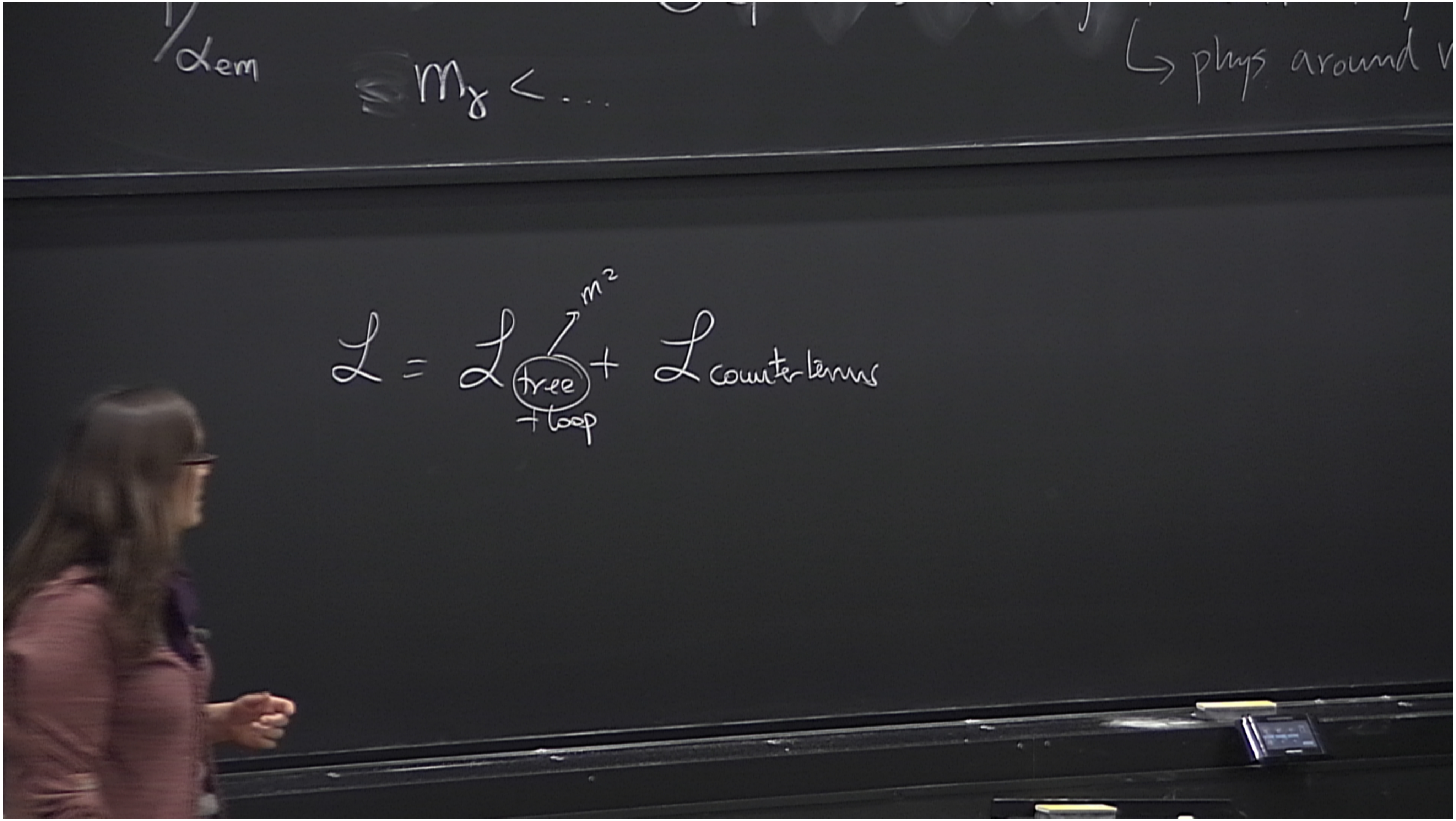

QCD
γ A^a m ψ̄ψ
L_sym + L_nonsymm
vacuum is not symm
↳ phys around vacuum
gauge symms → EW
m_{Z,W} ≠ 0
L_{SU(2)_L} + m_W^2 W^+ W^-
non-renormalizable
matter + spin 1 massive


exact U(1) em
chiral QCD
γ A^a
breaking
① explicit L = L sym + L nonsymm
② spontaneous L is symm, vacuum is not symm
↳ phys around vac
m_γ < ...

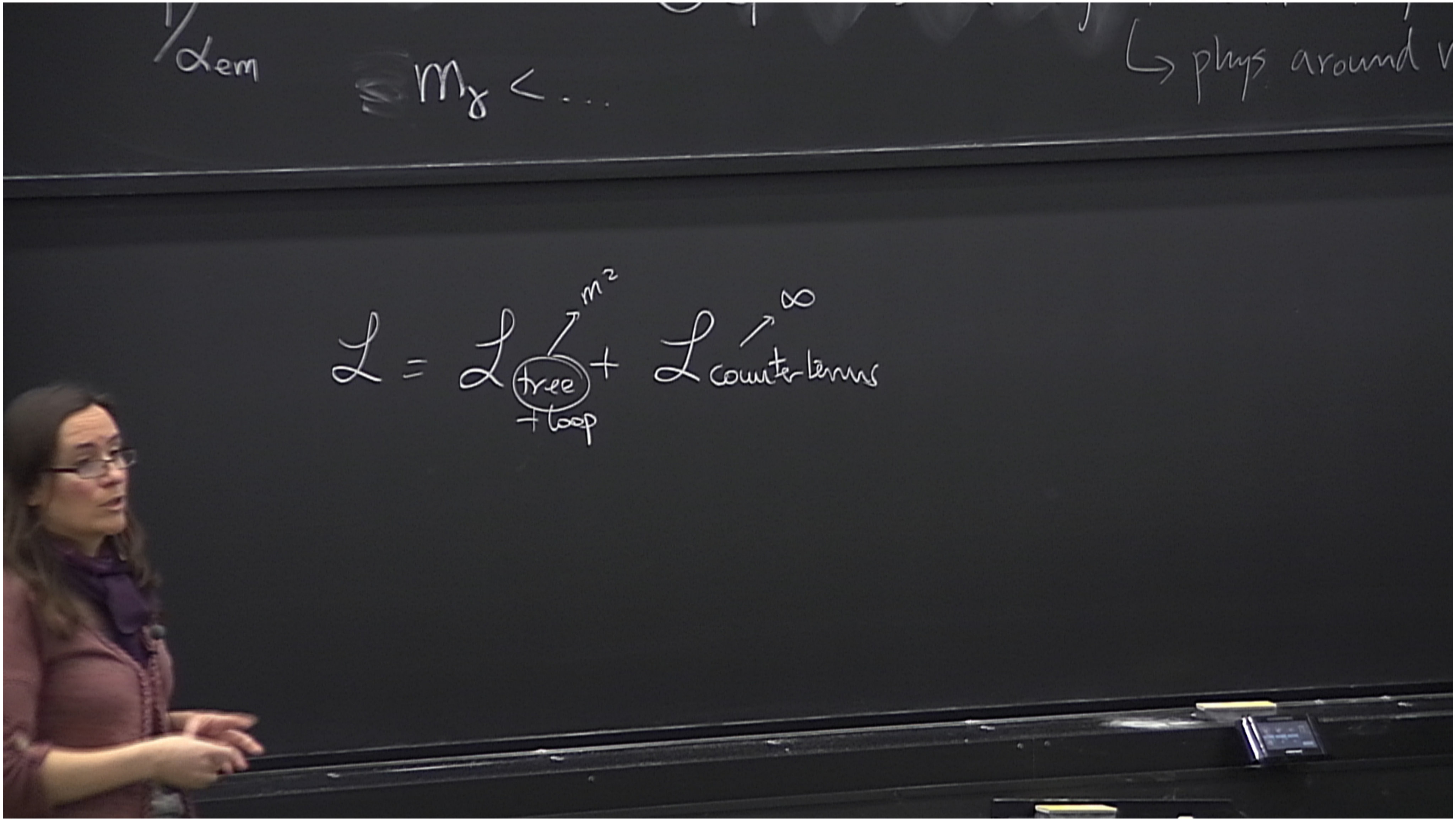

exact U(1) em
chiral QCD γ A^a
breaking
① explicit L = L_sym + L_nonsymm
② spontaneous L is symm, vacuum is not symm
↳ phys around vac
1/α_em
m_γ < ...

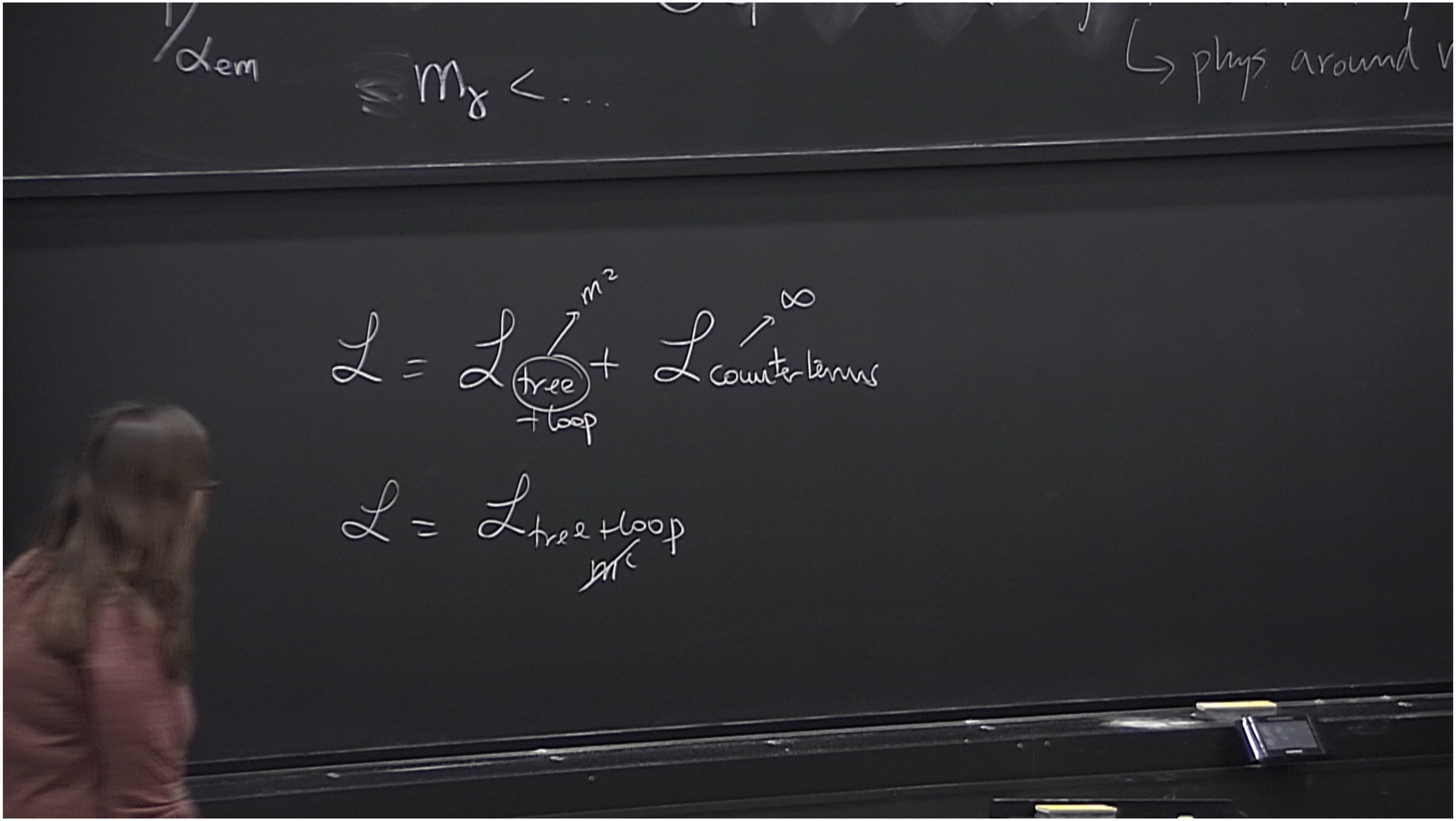

QCD γ A^a $m\bar{\psi}\psi$
$\mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$
m, vacuum is not sym
↳ phys around vacuum
gauge symms → EW
$m_{Z,W} \neq 0$
$\mathcal{L}_{\boxed{SU(2)_L}} + m_W^2 W^+ W^-$
non-renormalizable
matter + spin 1 massive

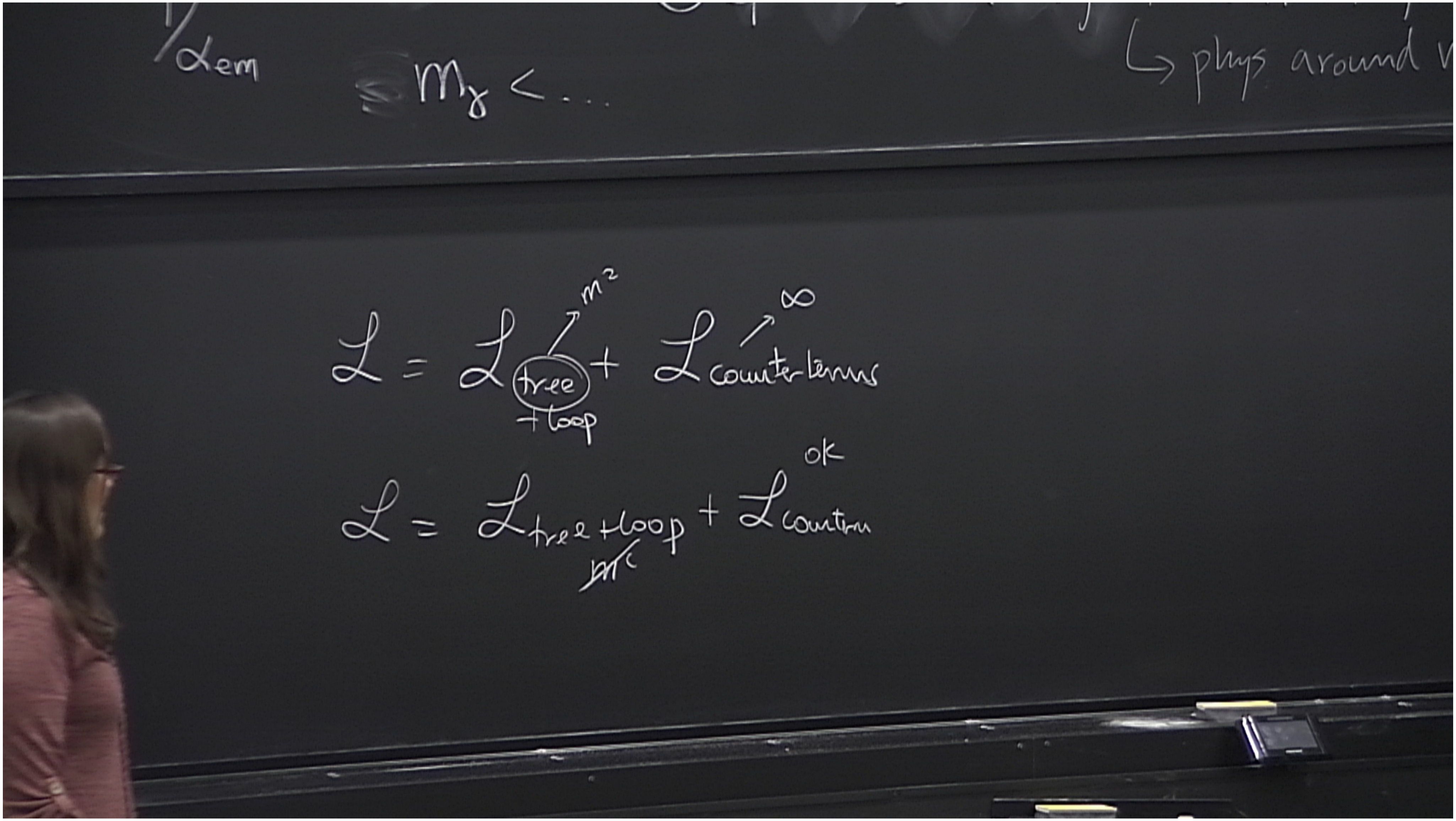

$1/\alpha_{em}$
$m_\gamma < \ldots$
↳ phys around
$\mathcal{L} = \mathcal{L}_{\text{tree + loop}} + \mathcal{L}_{\text{counterterms}}$



$1/\alpha_{em}$
$m_\gamma < \ldots$
phys around
$\mathcal{L} = \mathcal{L}_{tree} + \mathcal{L}_{counterterms}$
m^2
+ loop


1/αem
mγ < ...
↳ phys around
m²
∞
L = L tree + loop + L counterterms


$1/\alpha_{em}$
$m_\gamma < \ldots$
↳ phys around
$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}} + \mathcal{L}_{\text{counterterms}}$
m^2
∞
$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}}$
$\cancel{m^2}$

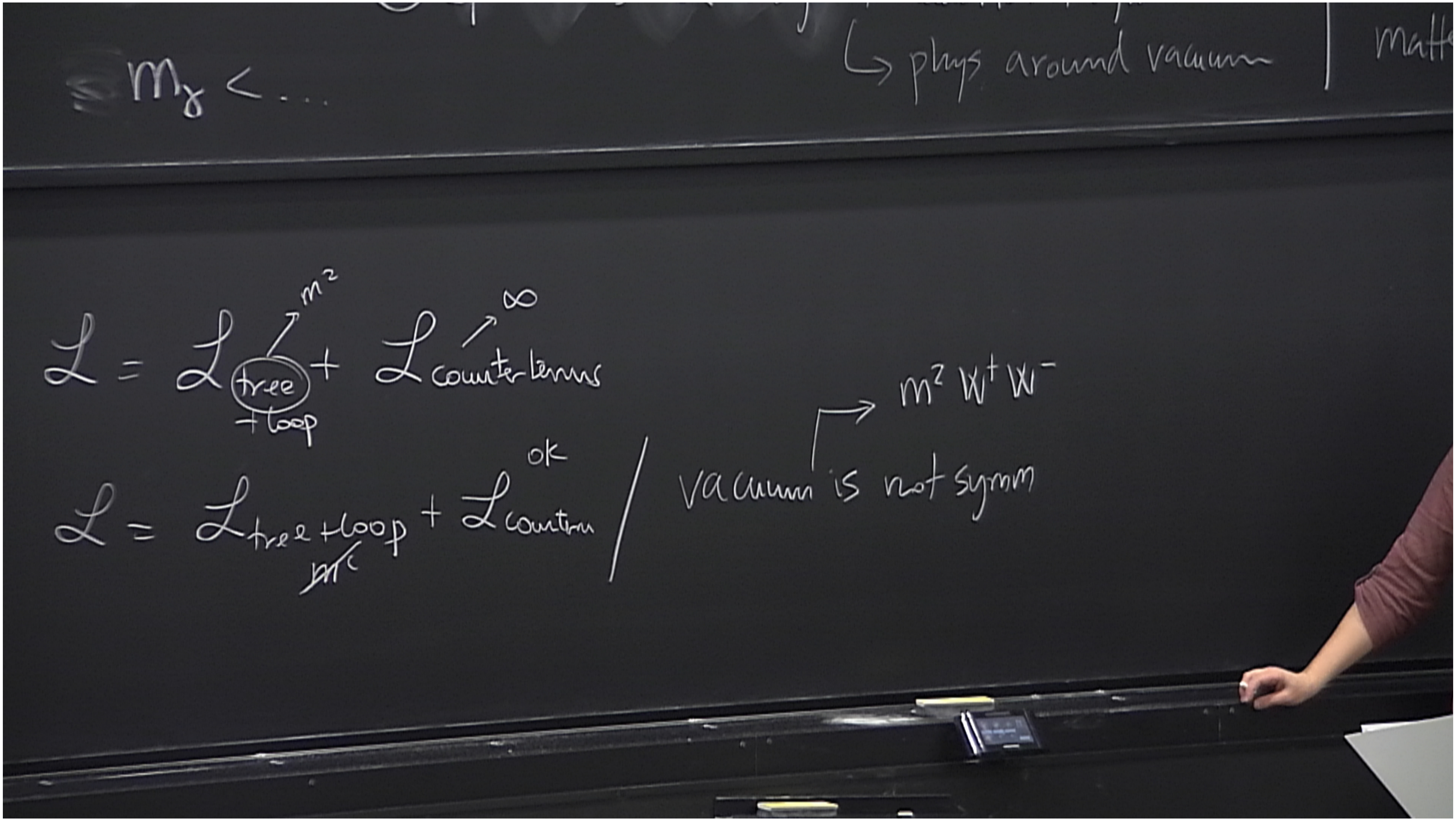


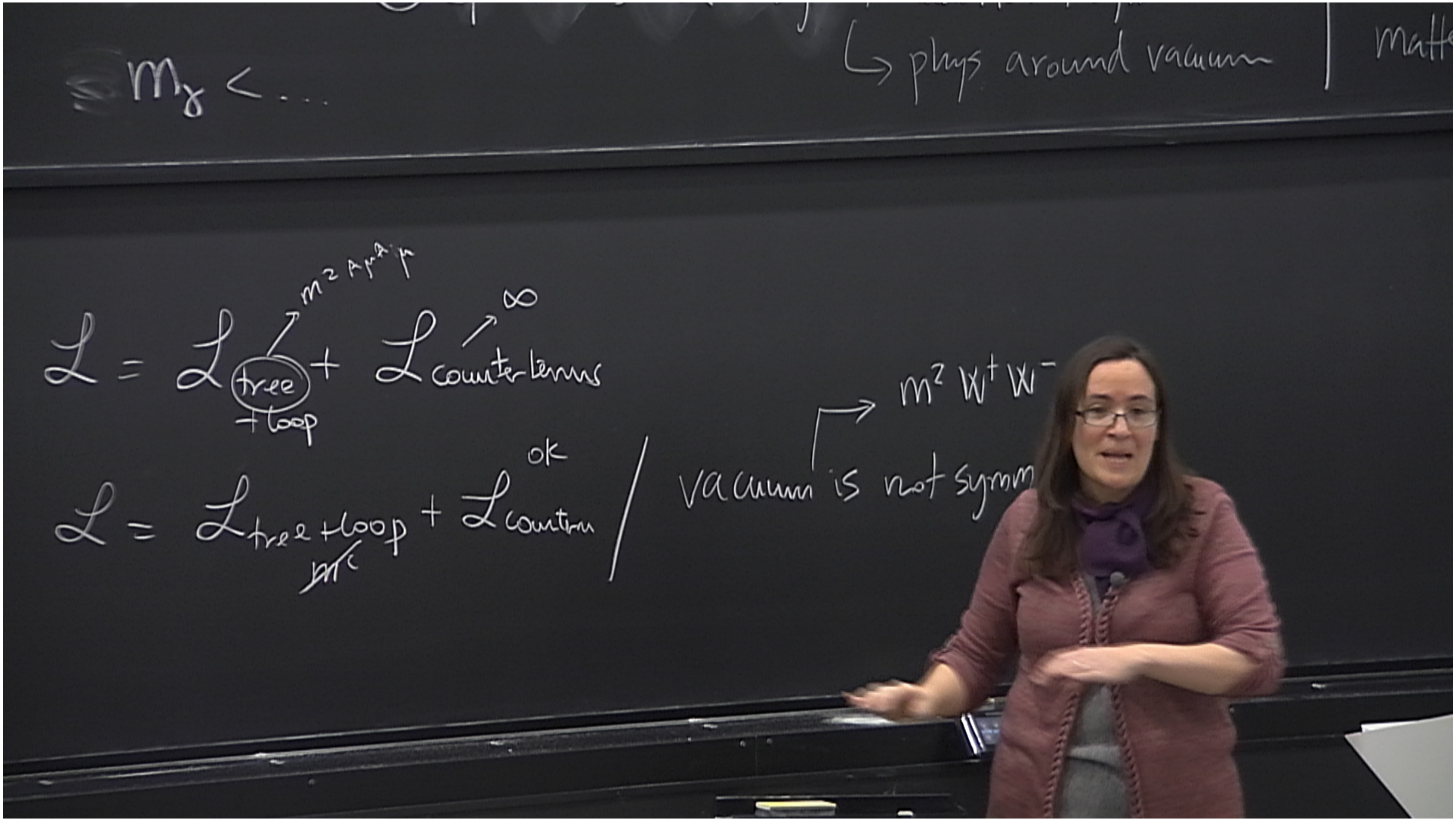
$1/\alpha_{em}$
$m_\gamma < \ldots$
↳ phys around
$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}} + \mathcal{L}_{\text{counterterms}}$
m^2
∞
$\mathcal{L} = \mathcal{L}_{\text{tree+loop}} + \mathcal{L}_{\text{counterm}}$
ok

$1/\alpha_{em}$ $\quad m_\gamma < \ldots$ $\quad$ ↳ phys around v

$$\mathcal{L} = \mathcal{L}_{\overset{\nearrow m^2}{\text{tree}}\,+\,\text{loop}} + \mathcal{L}_{\overset{\nearrow \infty}{\text{counterterms}}}$$

$$\mathcal{L} = \mathcal{L}_{\underset{\cancel{m^2}}{\text{tree}+\text{loop}}} + \overset{\text{ok}}{\mathcal{L}_{\text{countrm}}}$$ / vacuum is not symm


$m_\gamma < \ldots$
↳ phys around vacuum
matte
$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}} + \mathcal{L}_{\text{counterterms}}$
m^2
∞
$m^2 W^+ W^-$
ok
$\mathcal{L} = \mathcal{L}_{\text{tree}+\text{loop}} + \mathcal{L}_{\text{counterm}}$
$\cancel{m^2}$
vacuum is not symm


m_γ < ...
↳ phys around vacuum
L = L_tree + loop + L_counterterms
m² A_μ A^μ
∞
L = L_tree + loop + L_counterterm
ok
vacuum is not symm
m² W⁺ W⁻

$m_\gamma < \ldots$

$\hookrightarrow$ phys around vacuum | matte

$$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}} + \mathcal{L}_{\text{counterterms}}$$

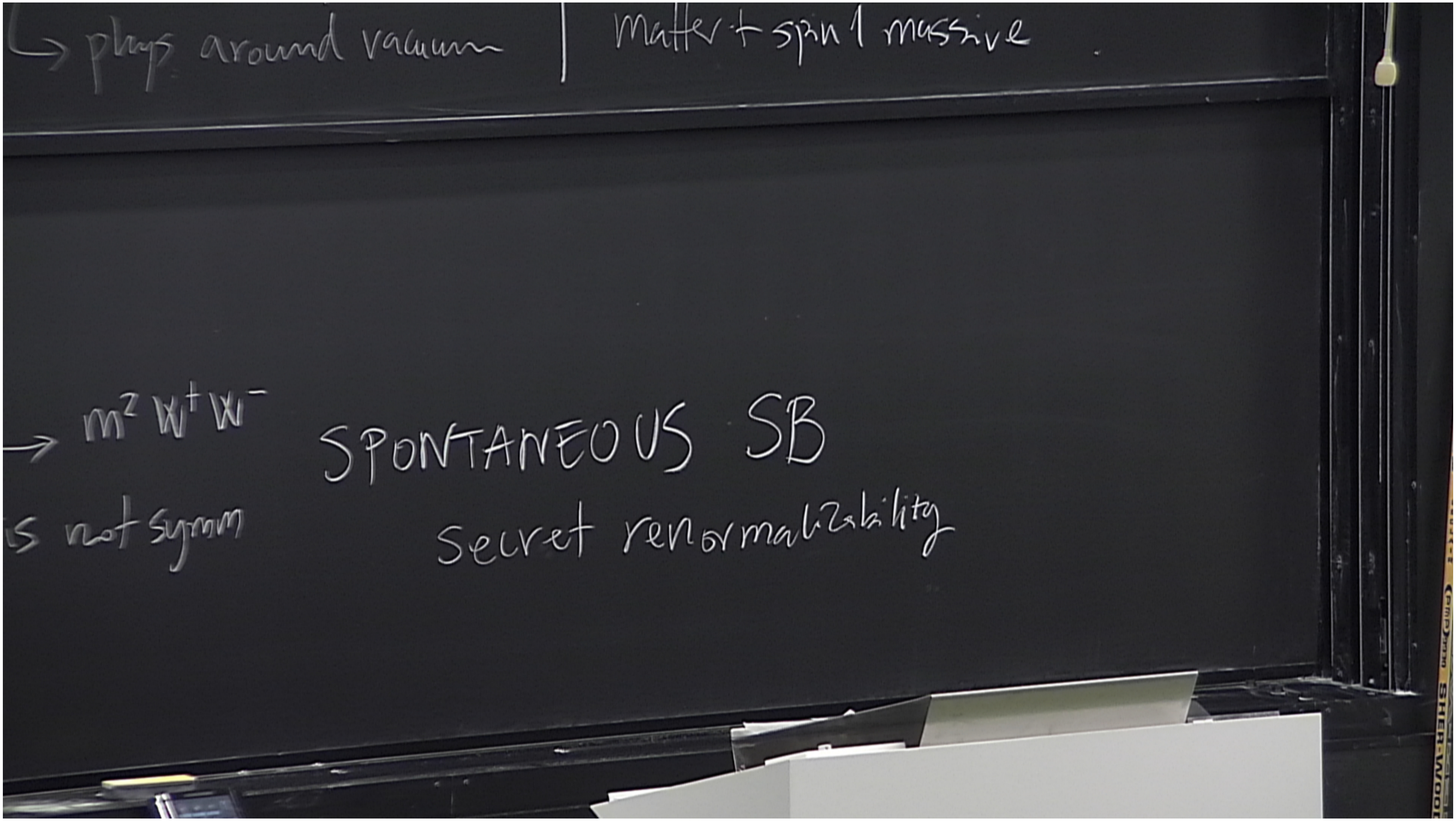
$\text{tree} \to m^2 A_\mu A^\mu \qquad \text{counterterms} \to \infty$

$$\mathcal{L} = \mathcal{L}_{\text{tree+loop}} + \mathcal{L}^{\text{ok}}_{\text{counterm}}$$

$\cancel{m^2}$

vacuum is not symm $\to m^2 W^+ W^-$

SPONTANEOUS


↳ phys around vacuum
matter + spin 1 massive
→ m² W⁺ W⁻
is not symm
SPONTANEOUS SB
secret renormalizability

$1/\alpha_{em}$

$m_\gamma < \ldots$

(2) Spontaneous $\mathcal{L}$ is symm, vacuum is not symm

↳ phys around va

$\langle \phi \rangle$

$m^2 A_\mu A^\mu$ $\qquad \infty$

$$\mathcal{L} = \mathcal{L}_{\text{tree} + \text{loop}} + \mathcal{L}_{\text{counterterms}}$$

$m^2 W^+ W^-$

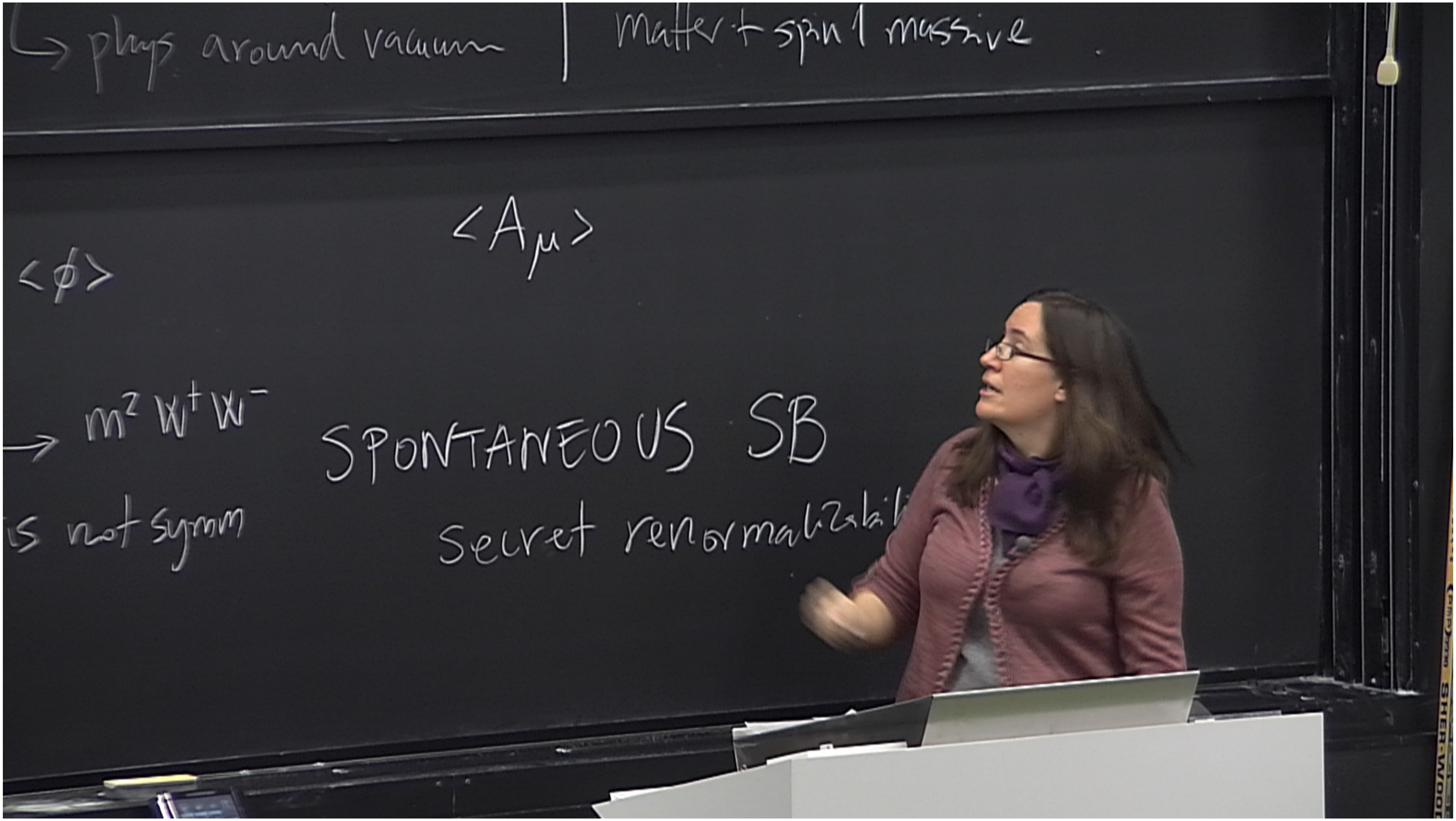
SPO

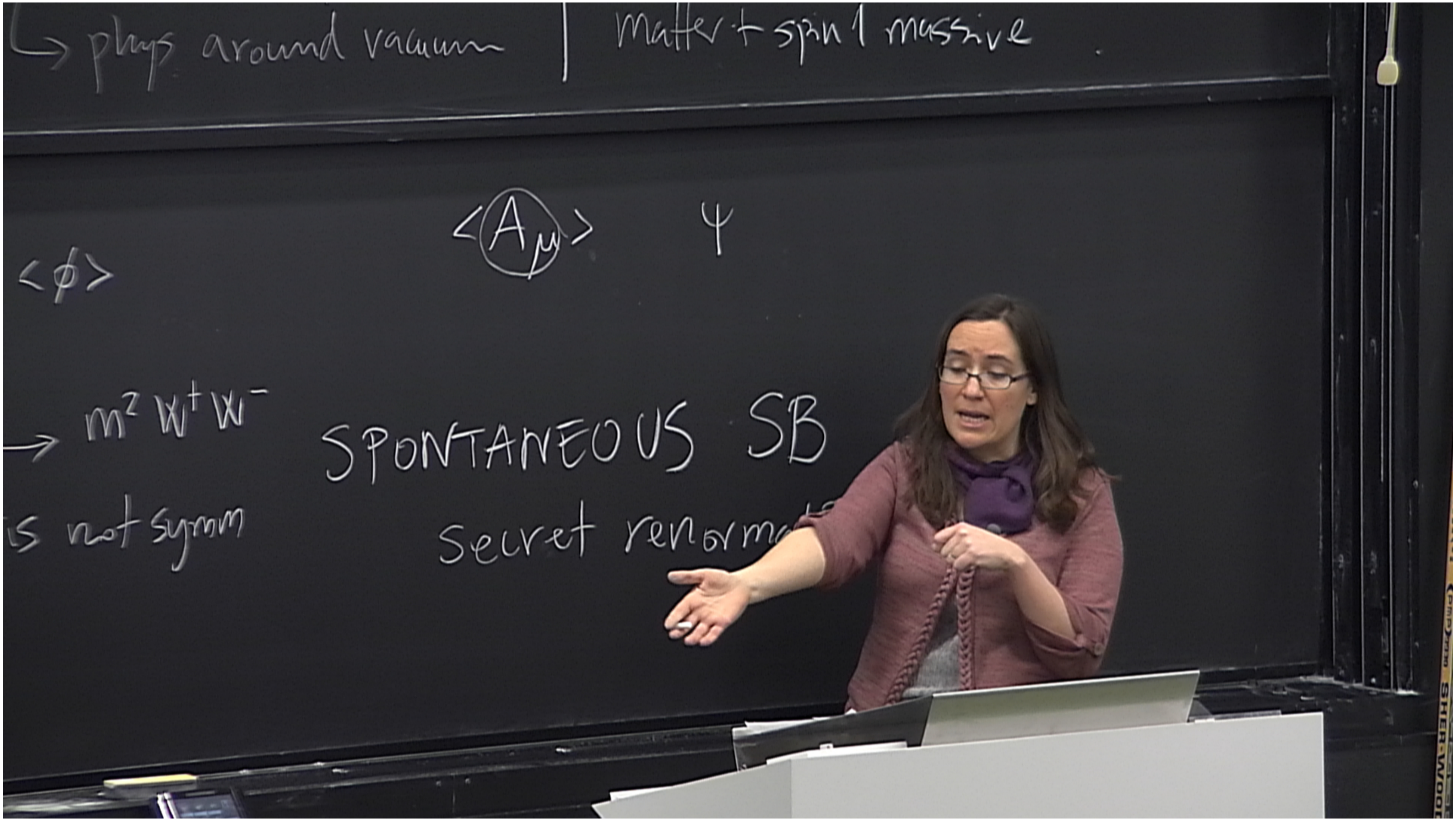
ok

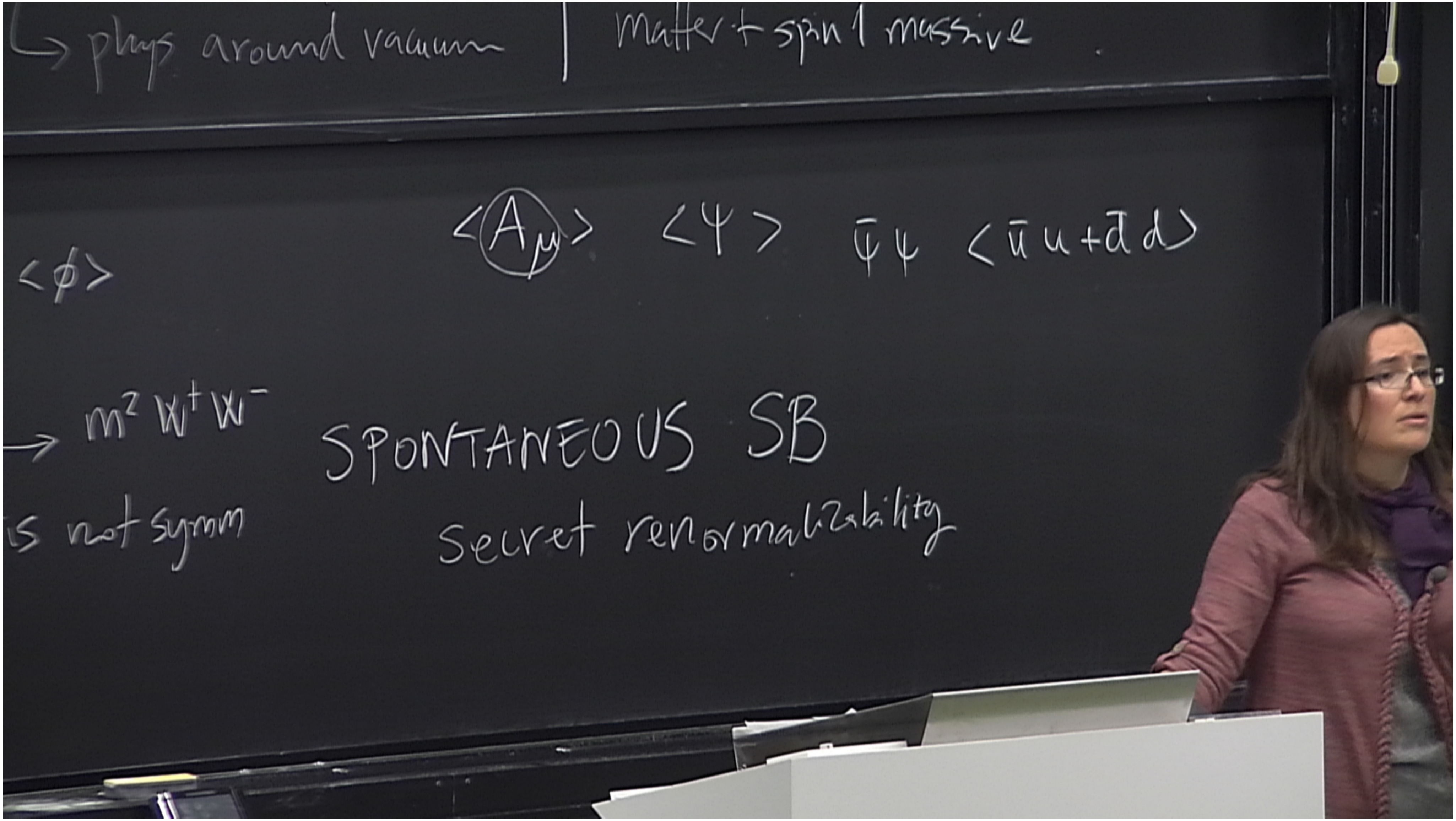
$$\mathcal{L} = \mathcal{L}_{\text{tree}+\text{loop}} + \mathcal{L}_{\text{countm}}$$

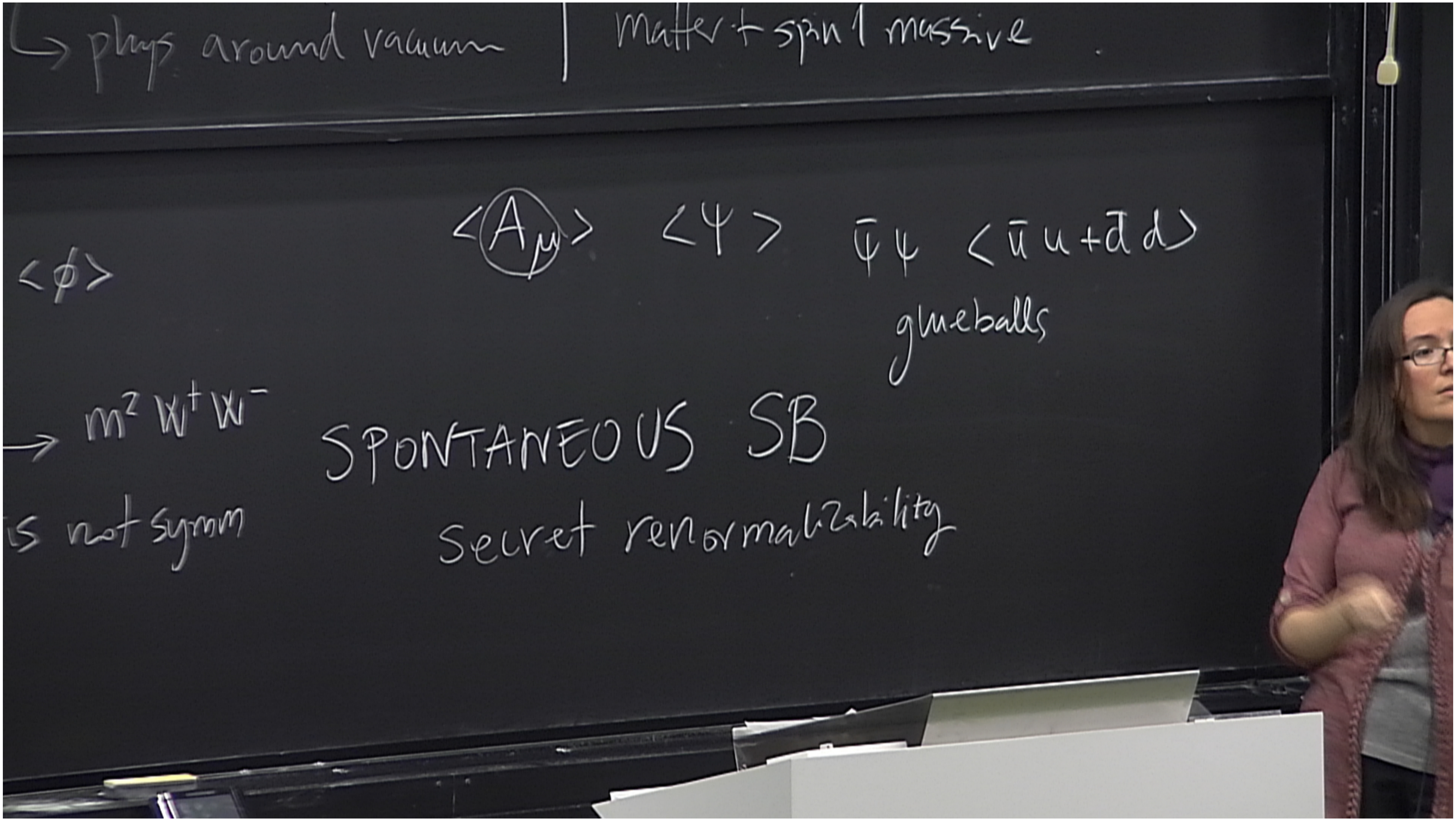
$\cancel{m^2}$

vacuum is not symm


↳ phys around vacuum
matter + spin 1 massive
$\langle A_\mu \rangle$
$\langle \phi \rangle$
$\rightarrow m^2 W^+ W^-$
SPONTANEOUS SB
is not symm
secret renormalizabil


↳ phys around vacuum
matter + spin 1 massive
$\langle A_\mu \rangle$ ψ
$\langle \phi \rangle$
$\rightarrow m^2 W^+ W^-$
SPONTANEOUS SB
is not symm
secret renormal


↳ phys around vacuum
matter + spin 1 massive
$\langle A_\mu \rangle$ $\langle \psi \rangle$ $\bar{\psi}\psi$ $\langle \bar{u}u + \bar{d}d \rangle$
$\langle \phi \rangle$
$\to m^2 W^+ W^-$
SPONTANEOUS SB
is not symm
secret renormalizability


↳ phys around vacuum
matter + spin 1 massive
⟨φ⟩
⟨A_μ⟩ ⟨ψ⟩ ψ̄ψ ⟨ūu + d̄d⟩
glueballs
→ m² W⁺ W⁻
SPONTANEOUS SB
is not symm
secret renormalizability

exact $U(1)_{em}$

breaking ① explicit $\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{nonsymm}$

② spontaneous $\mathcal{L}$ is symm, vacuum is not symm

↳ phys around vacuum

$1/\alpha_{em}$

$m_\gamma <$ ...

chiral QCD γ A^a $m\bar{\psi}\psi$

gauge symms → EW

$m_{Z,W} \neq 0$

$\mathcal{L}_{\boxed{SU(2)_L}} + m_W^2 W^+ W^-$

non-renormalizable

matter + spin 1 massive

$\langle \phi \rangle$ $\langle A_\mu \rangle$ $\langle \psi \rangle$ $\bar{\psi}\psi$ $\langle \bar{u}u + \bar{d}d \rangle$

glueballs

$\mathcal{L} = \mathcal{L}_{tree + loop} + \mathcal{L}_{counterterms}$ ($m^2 A_\mu^2$; ∞)

$\mathcal{L} = \mathcal{L}_{tree+loop} + \mathcal{L}_{counterm}$ (ok) / vacuum is not symm → $m^2 W^+ W^-$

SPONTANEOUS SB

secret renormalizability