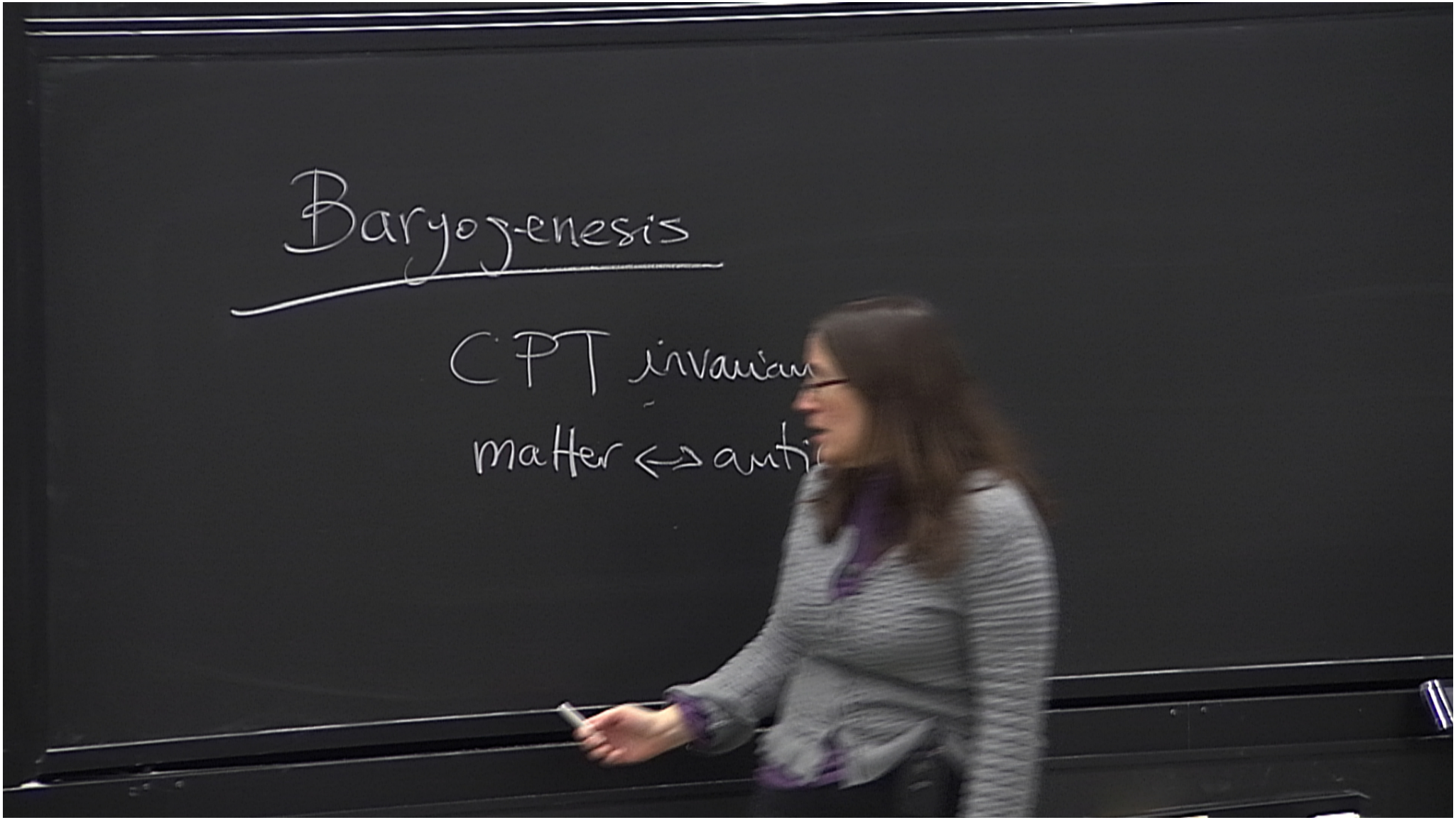
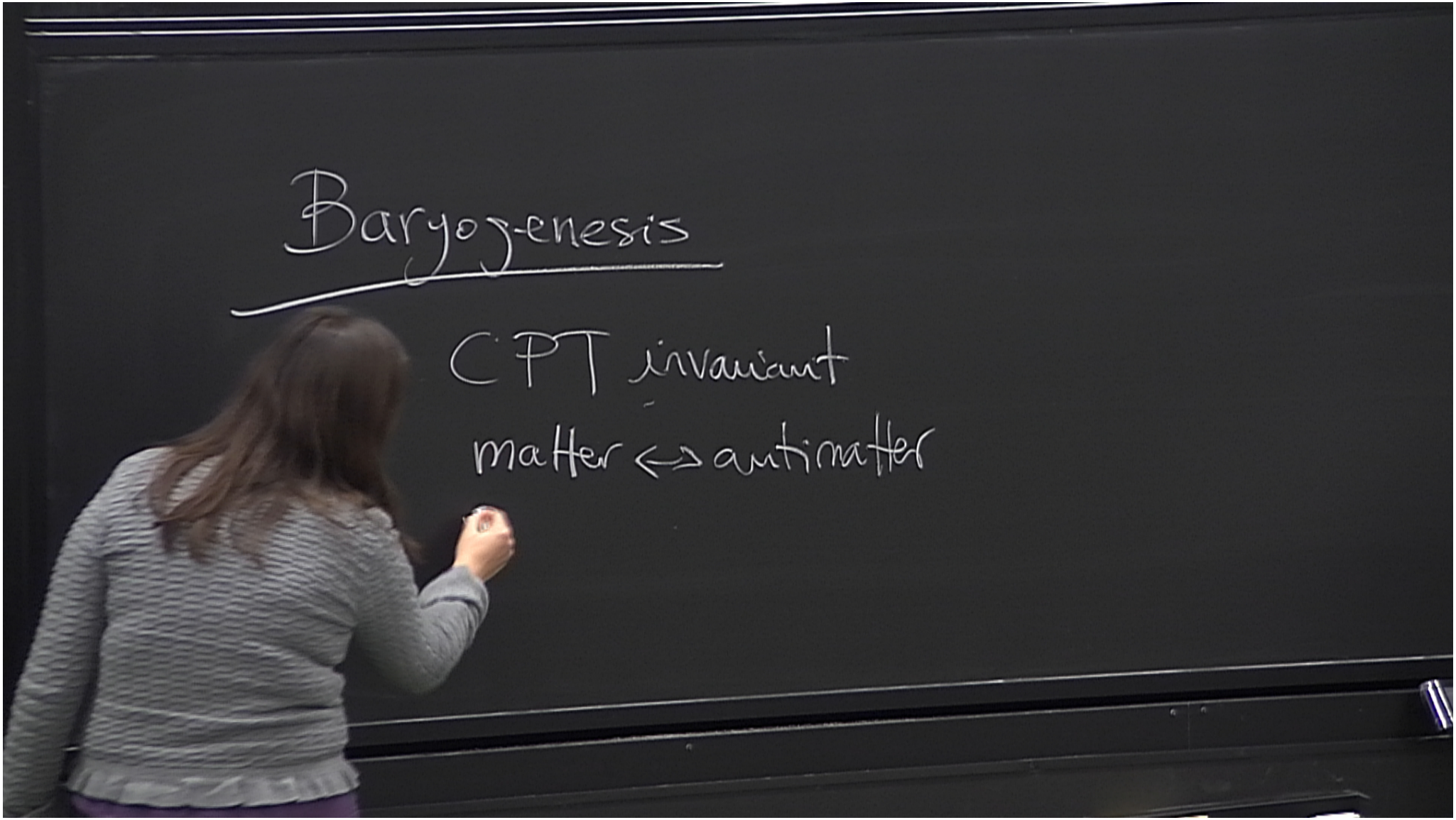
Title: Beyond the Standard Model (Review) - Lecture 2

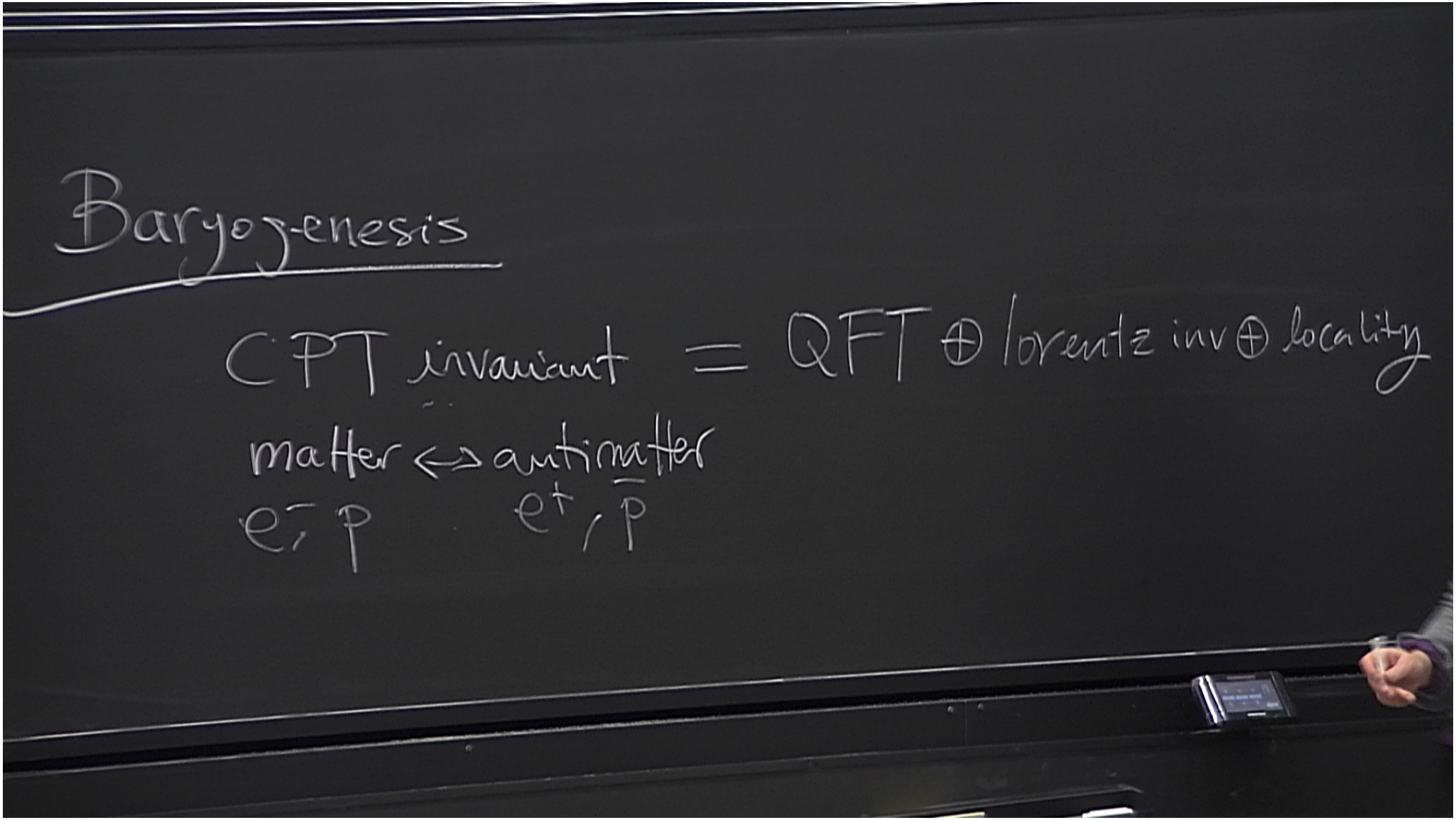
Date: Feb 14, 2012 09:00 AM

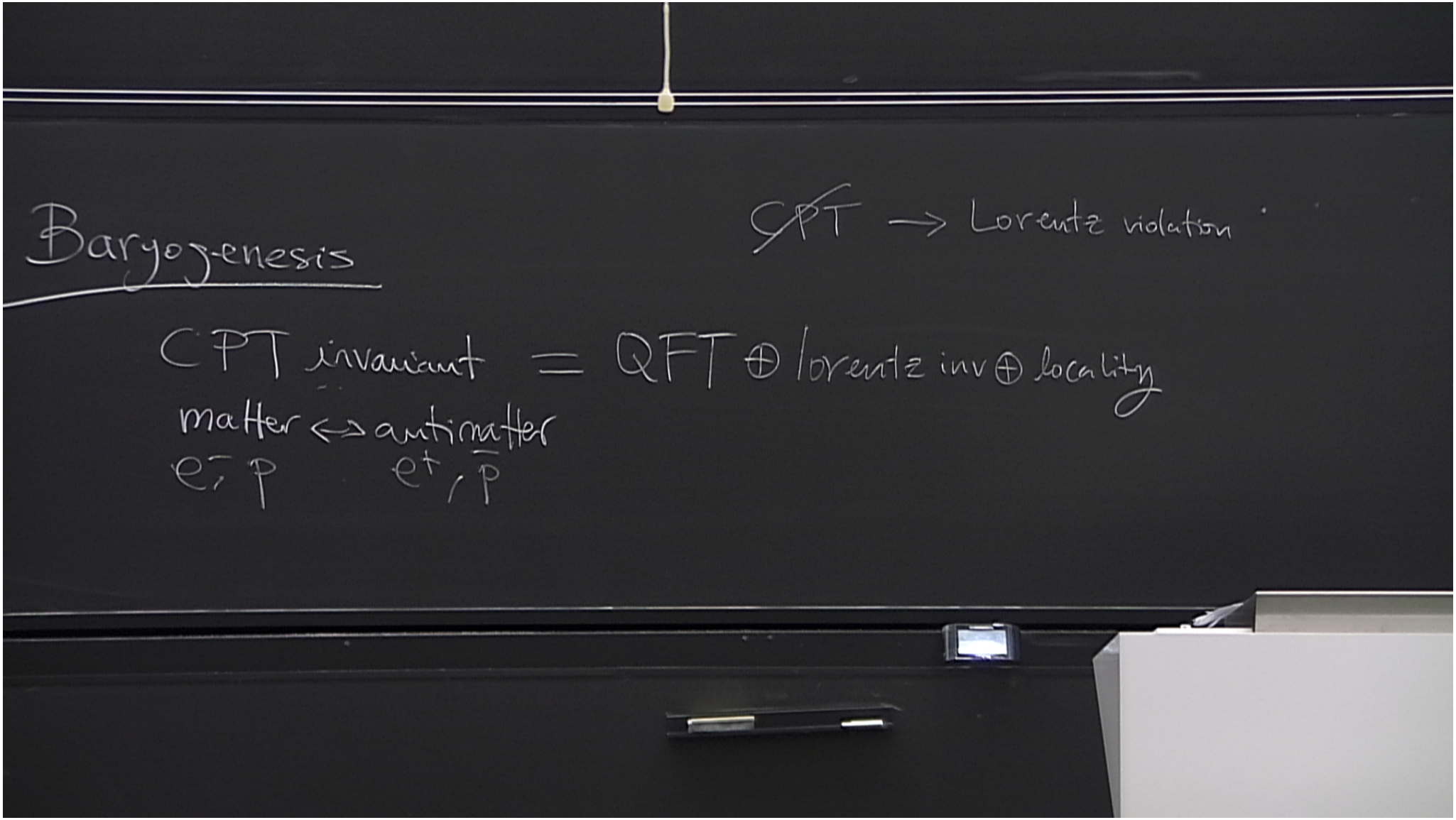
URL: http://pirsa.org/12020065

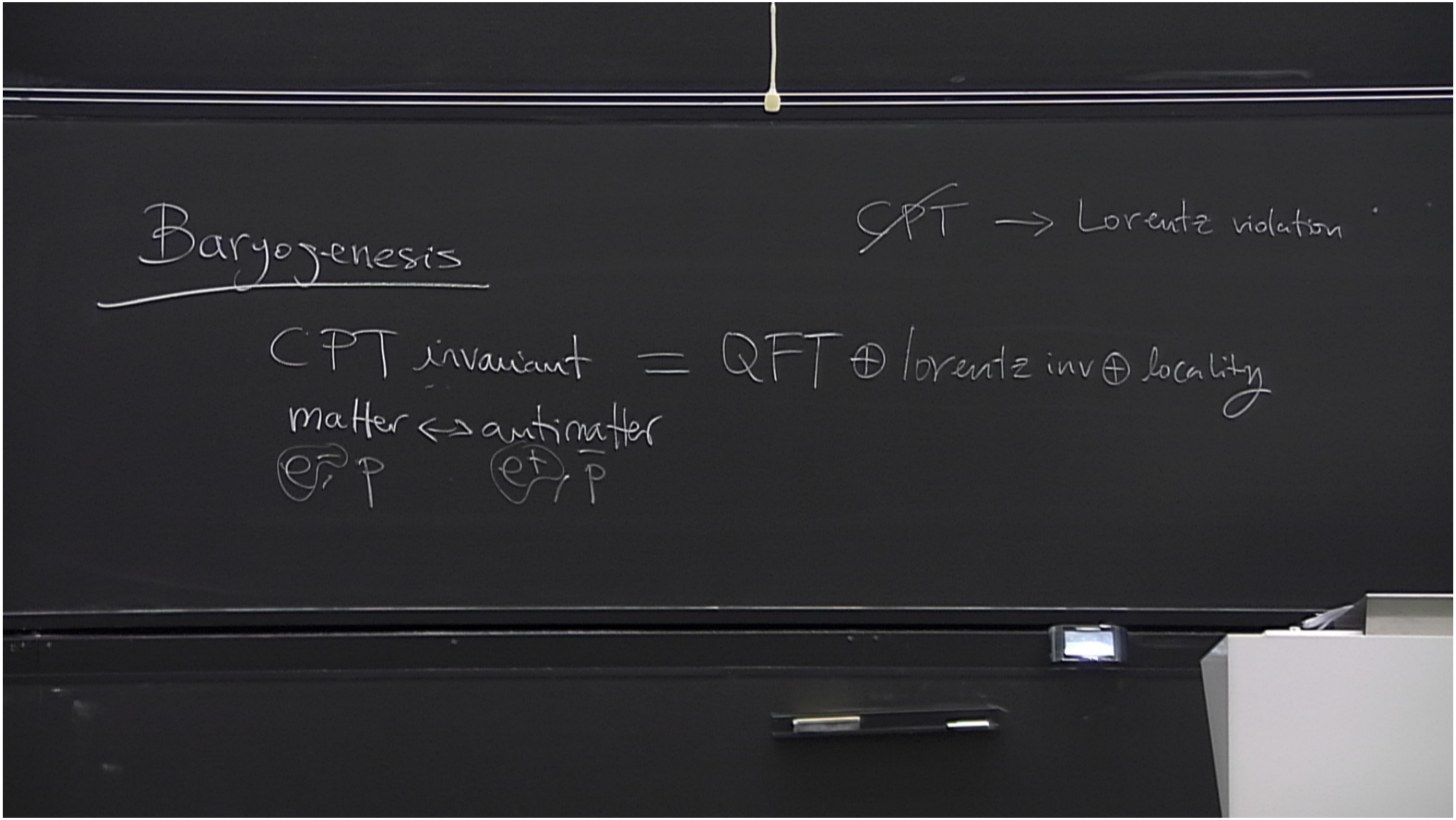
Abstract:


Baryogenesis
CPT invarian
matter ↔ anti


Baryogenesis
CPT invariant
matter ↔ antimatter


Baryogenesis
CPT invariant = QFT ⊕ Lorentz inv ⊕ locality
matter ⟷ antimatter
e⁻, p
e⁺, p̄


Baryogenesis
CPT → Lorentz violation
CPT invariant = QFT ⊕ lorentz inv ⊕ locality
matter ⇔ antimatter
e⁻, p e⁺, p̄


Baryogenesis
CPT → Lorentz violation
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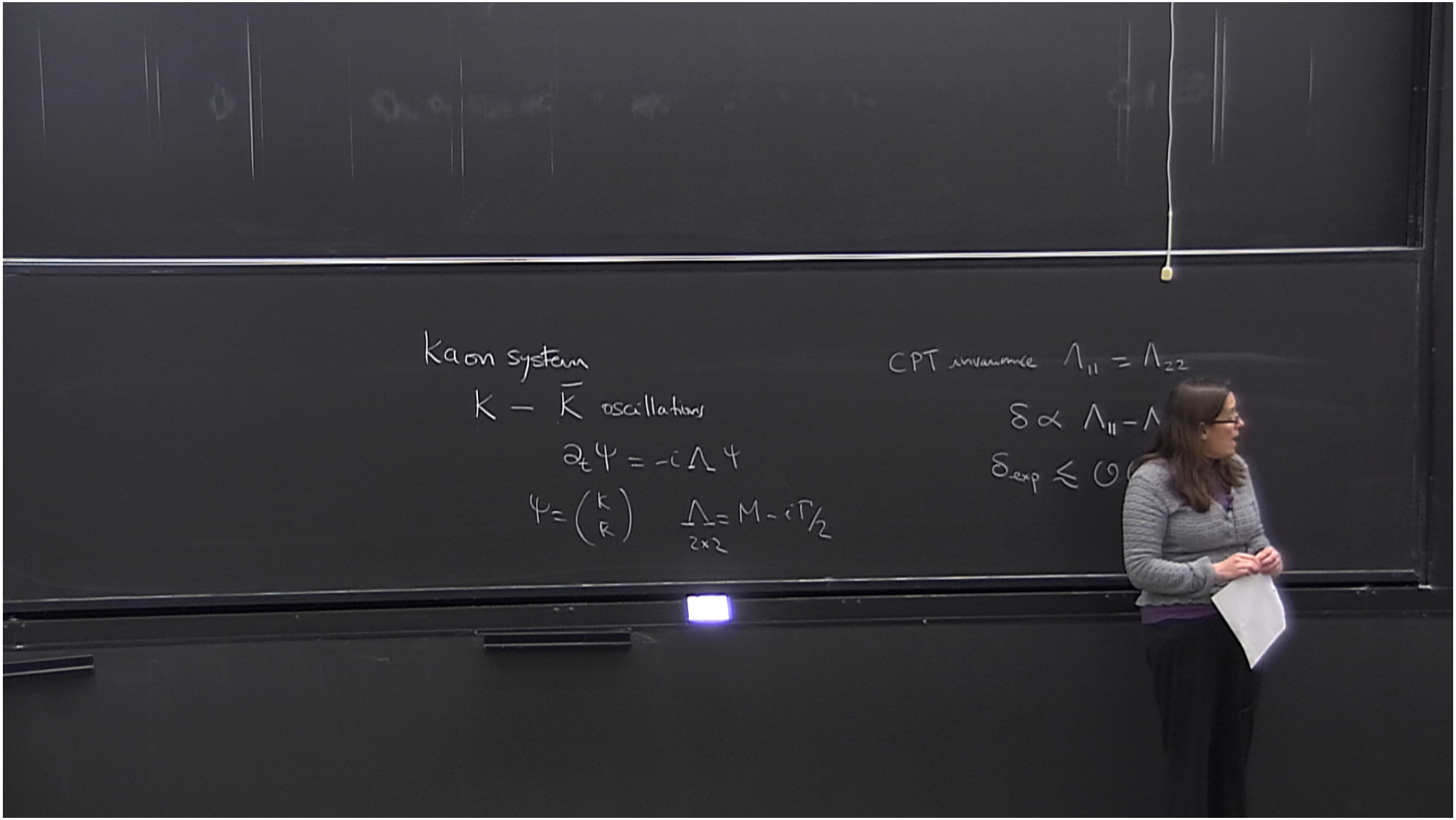
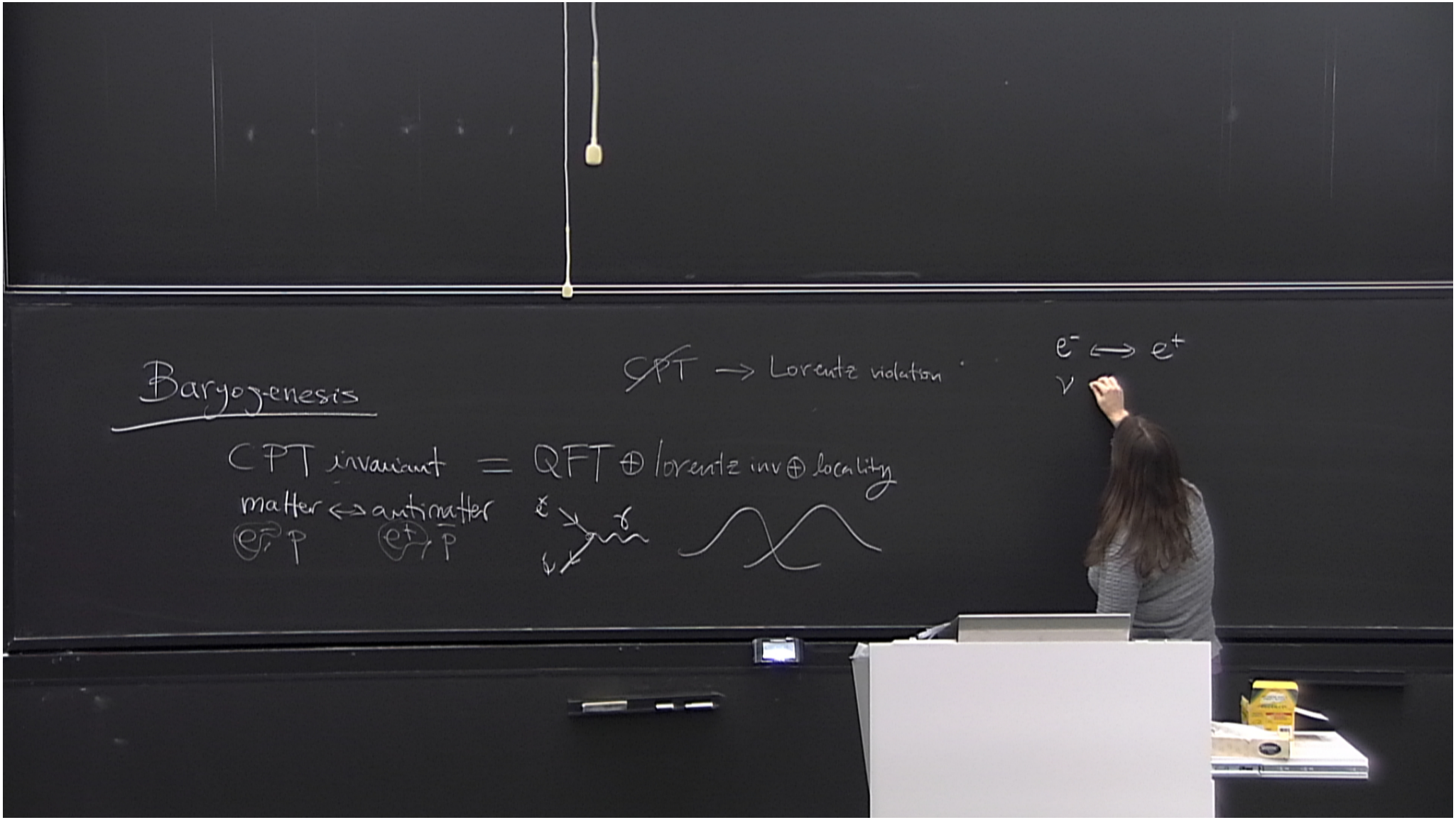
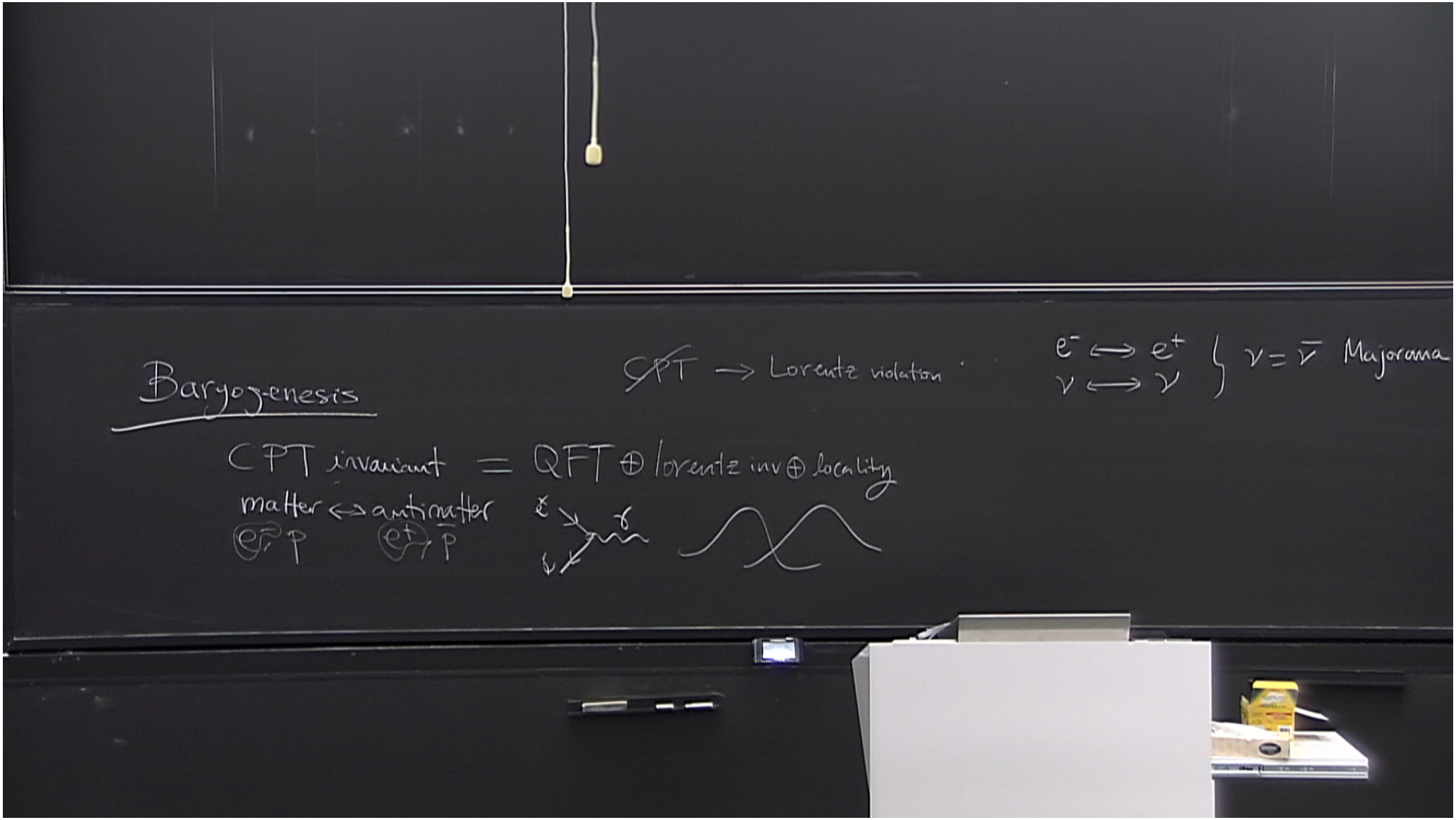
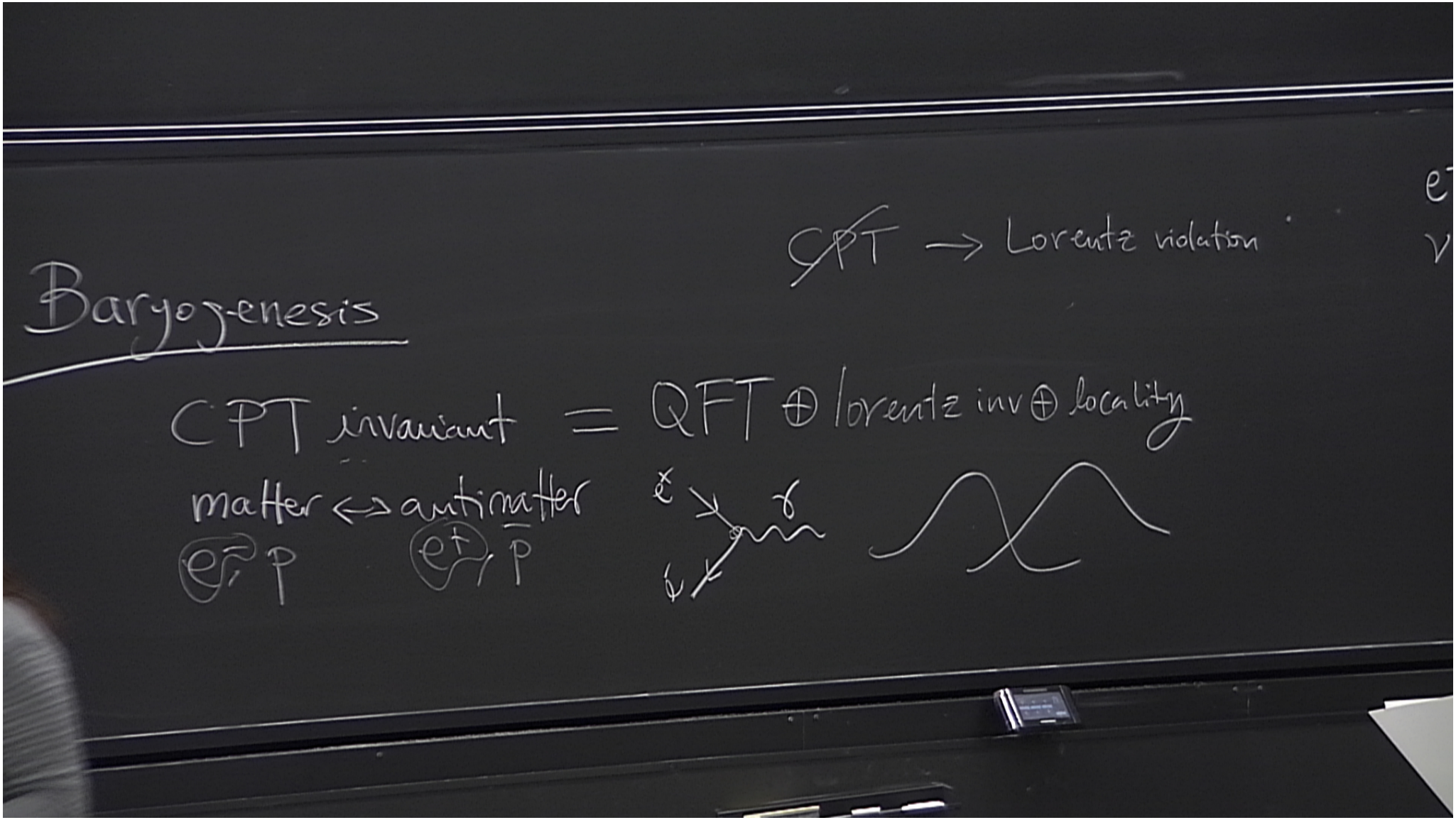
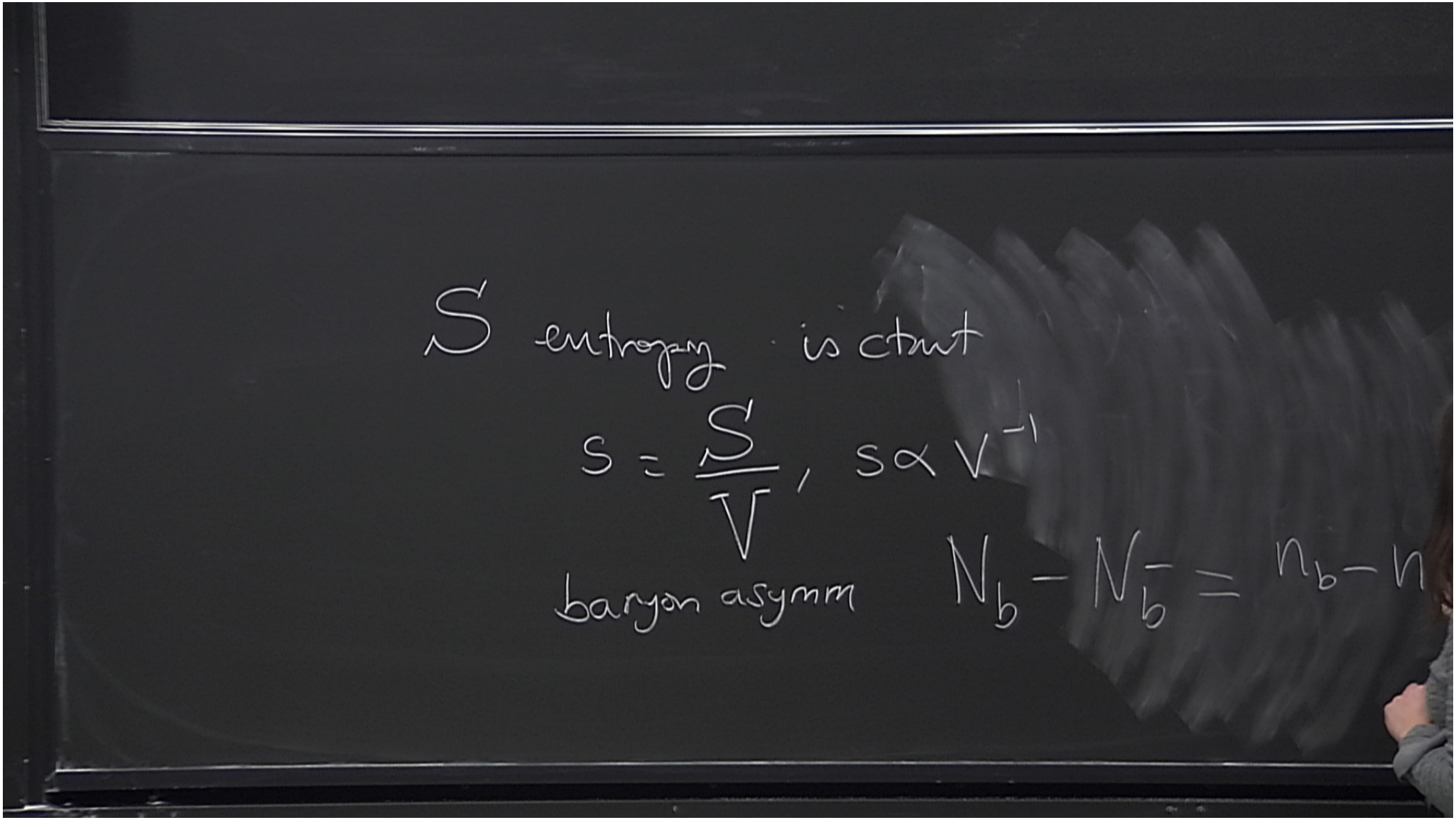
e⁻, p
e⁺, p̄

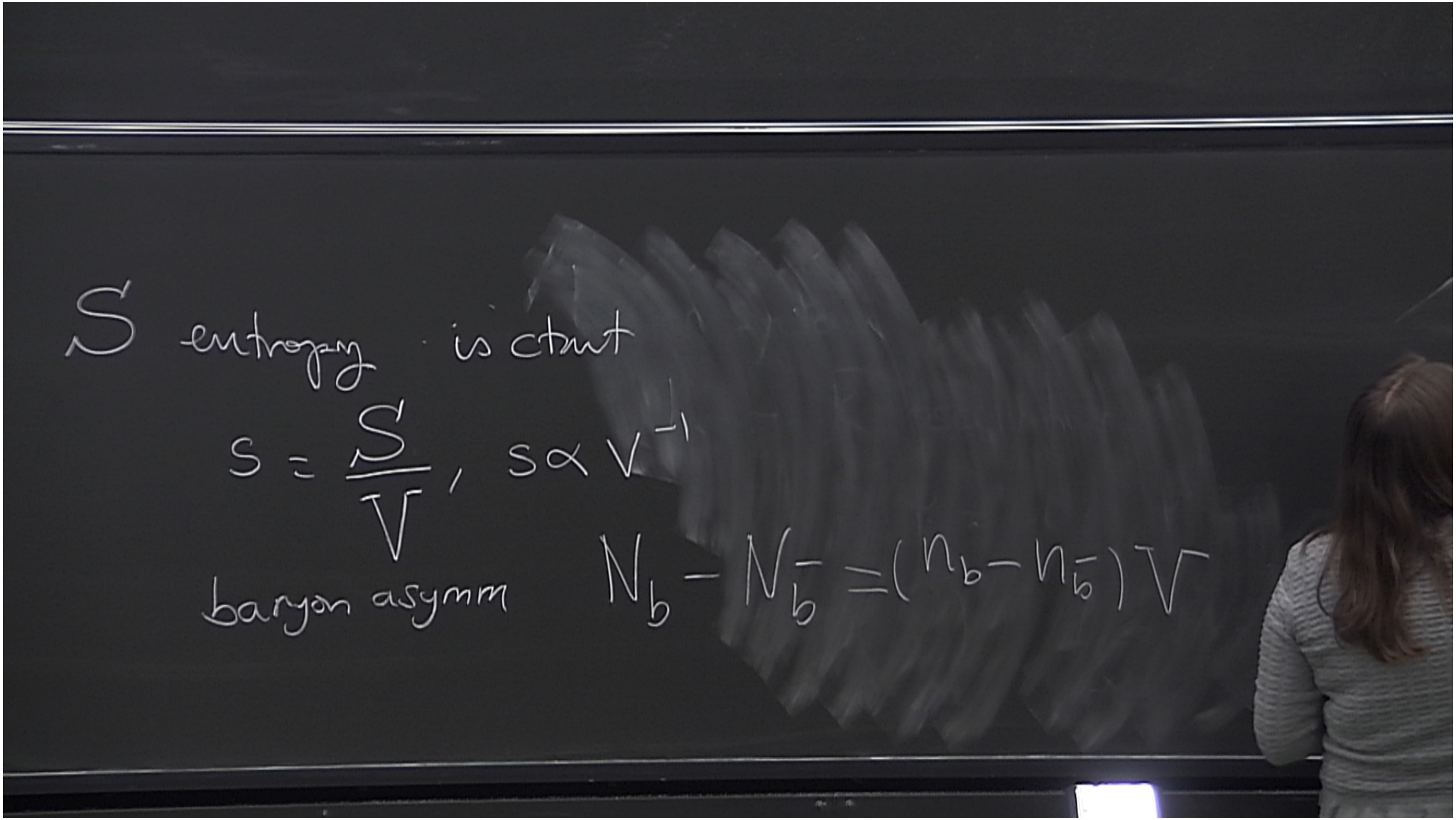

Kaon system
$K - \bar{K}$ oscillations
$\partial_t \psi = -i \Lambda \psi$
$\psi = \begin{pmatrix} K \\ \bar{K} \end{pmatrix}$ $\underset{2\times 2}{\Lambda} = M - i\Gamma/2$
CPT invariance $\Lambda_{11} = \Lambda_{22}$
$\delta \propto \Lambda_{11} - \Lambda$
$\delta_{exp} \lesssim$

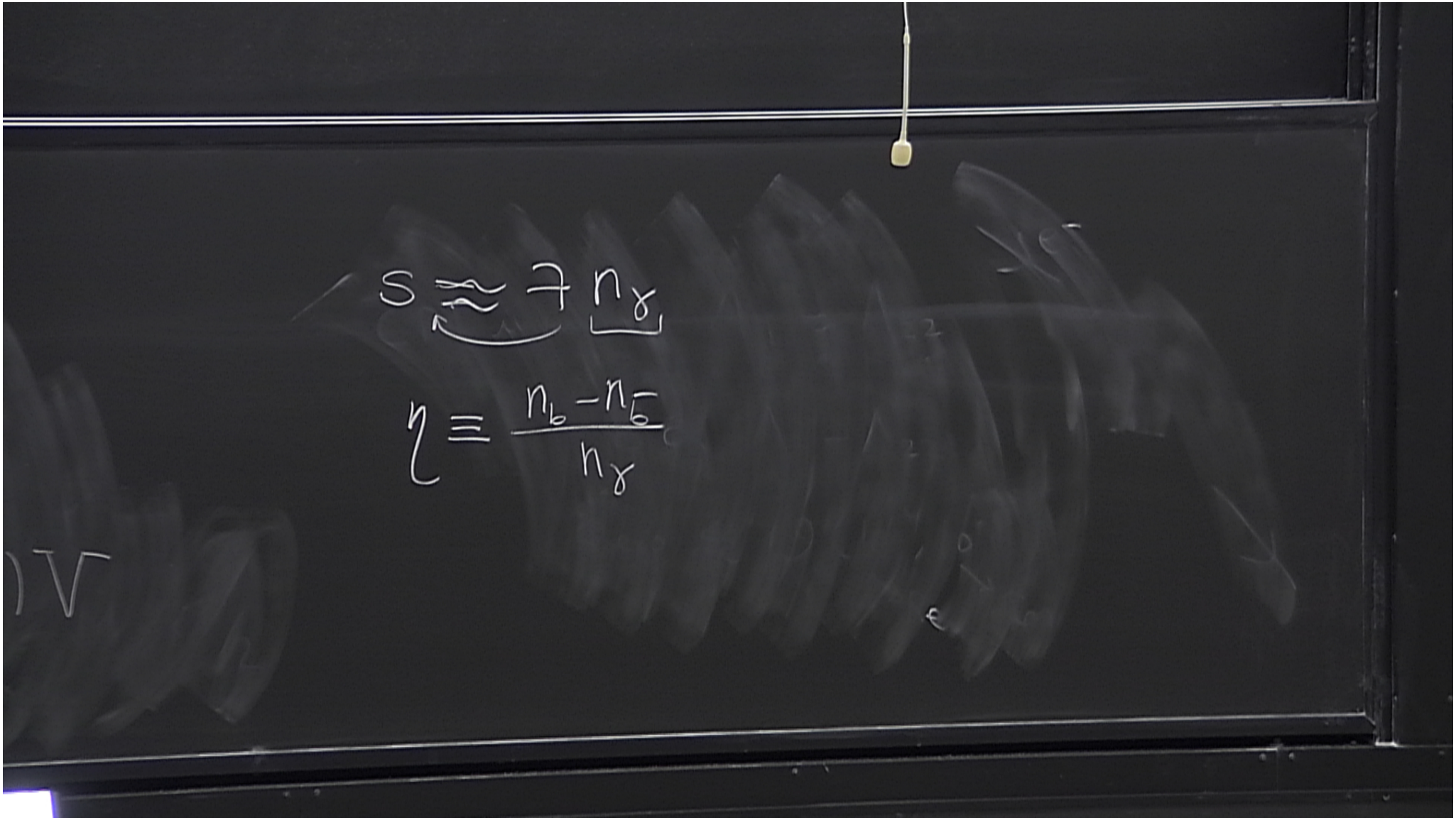

Baryogenesis
CPT → Lorentz violation
e⁻ ⟷ e⁺
CPT invariant = QFT ⊕ lorentz inv ⊕ locality
matter ⟷ antimatter
e⁻ p
e⁺ p̄

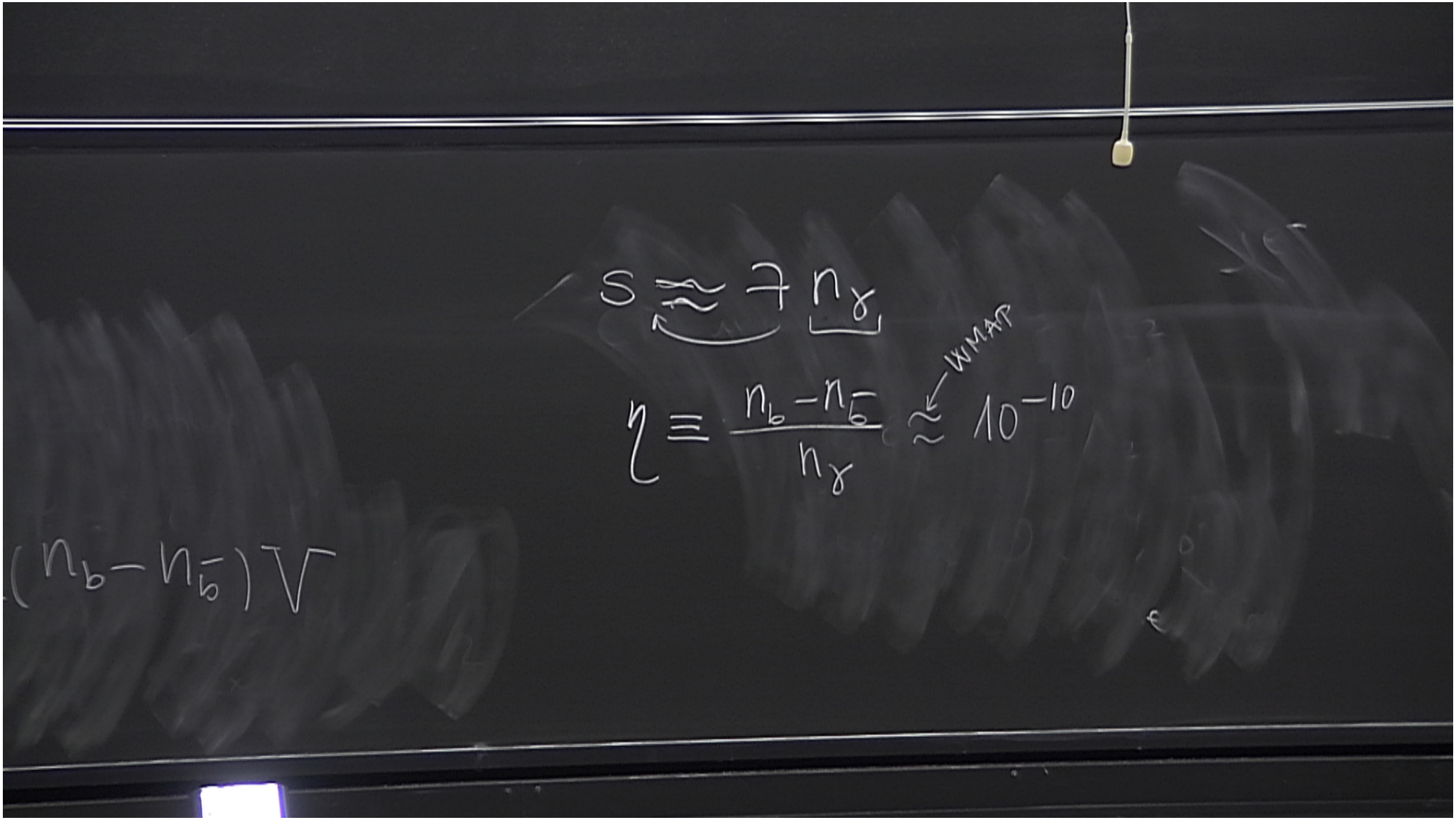

Baryogenesis
CPT → Lorentz violation
$e^- \leftrightarrow e^+$
$\nu \leftrightarrow \bar{\nu}$
$\nu = \bar{\nu}$ Majorana
CPT invariant = QFT ⊕ lorentz inv ⊕ locality
matter ↔ antimatter
e^-, p
$e^+, \bar{p}$
γ
ν

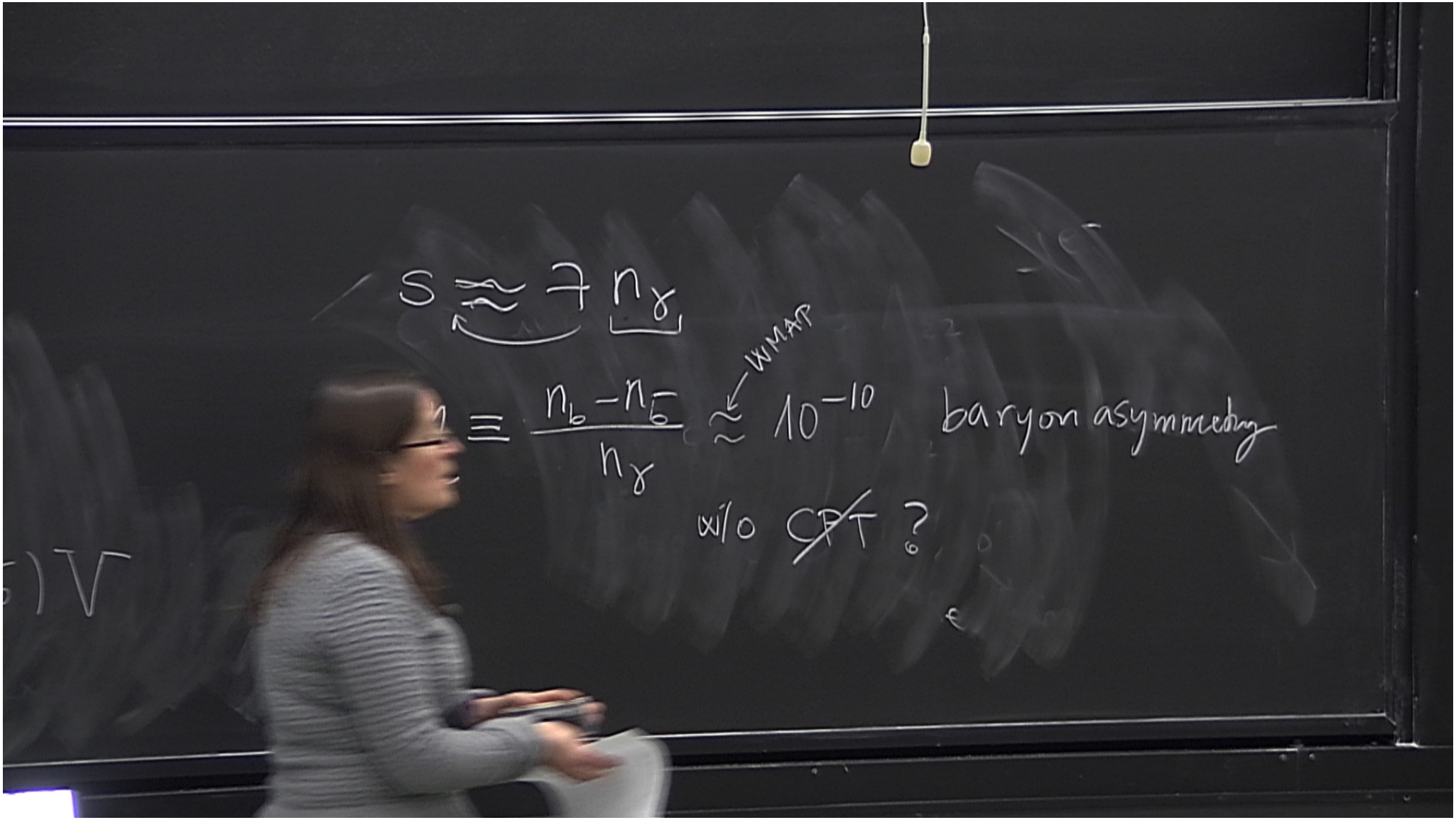

CPT → Lorentz violation
Baryogenesis
CPT invariant = QFT ⊕ lorentz inv ⊕ locality
matter ↔ antimatter
e⁻ p
e⁺ p̄
e⁻
γ
γ

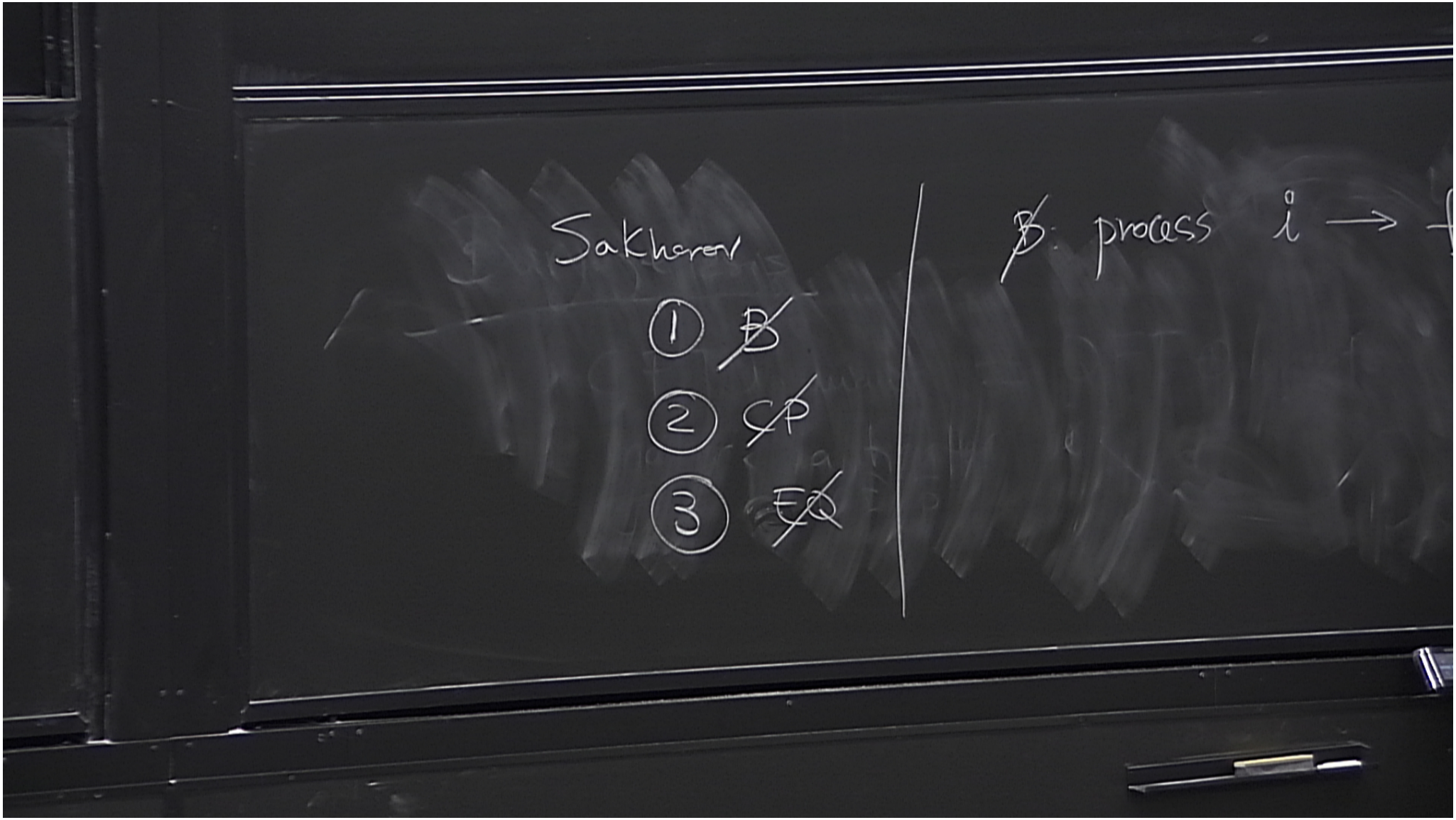

S entropy is const
$s = \frac{S}{V}$, $s \propto V^{-1}$
baryon asymm $N_b - N_{\bar{b}} = n_b - n$

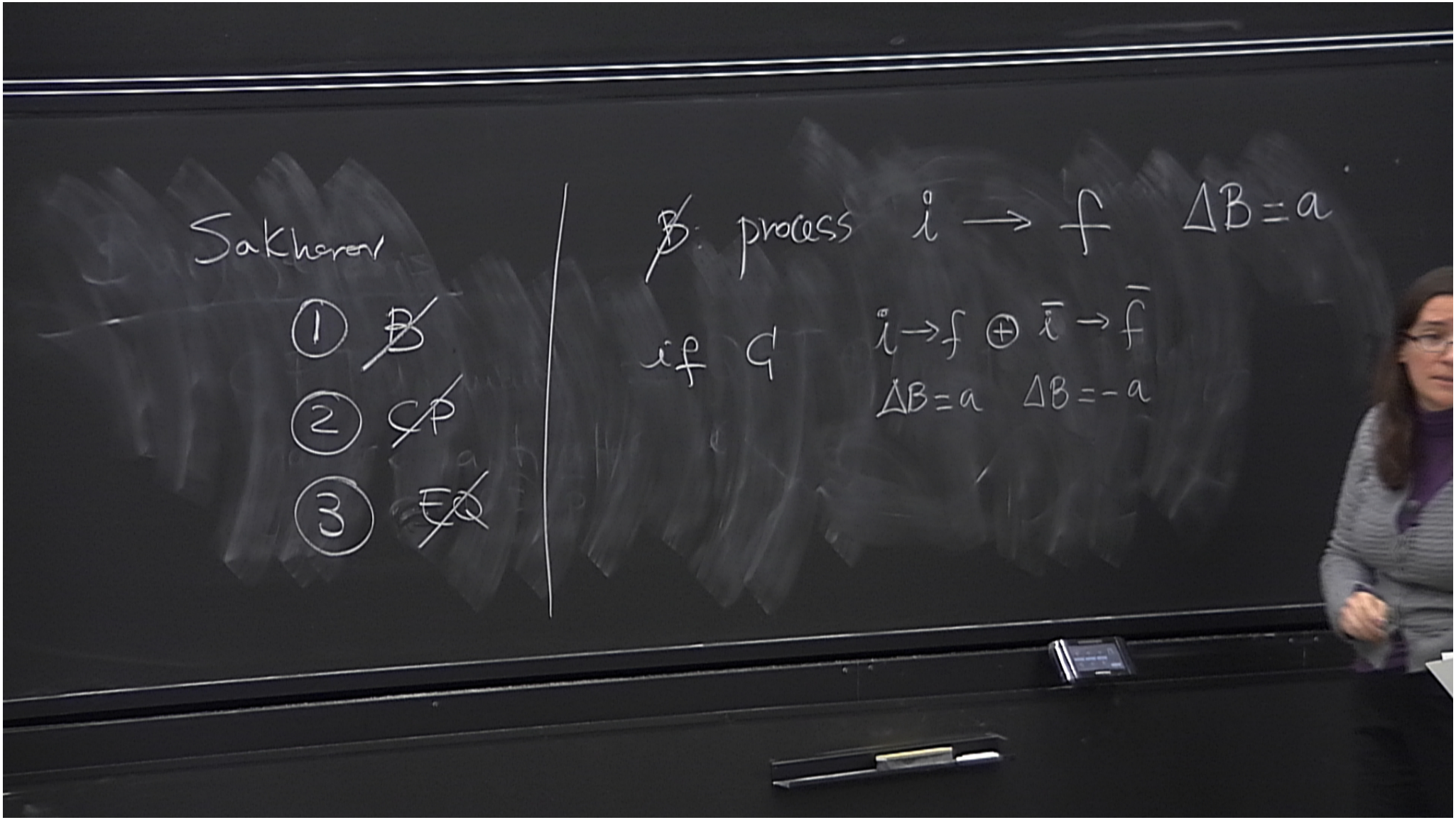

S entropy is const
$s = \frac{S}{V}$, $s \propto V^{-1}$
baryon asymm $N_b - N_{\bar{b}} = (n_b - n_{\bar{b}})V$

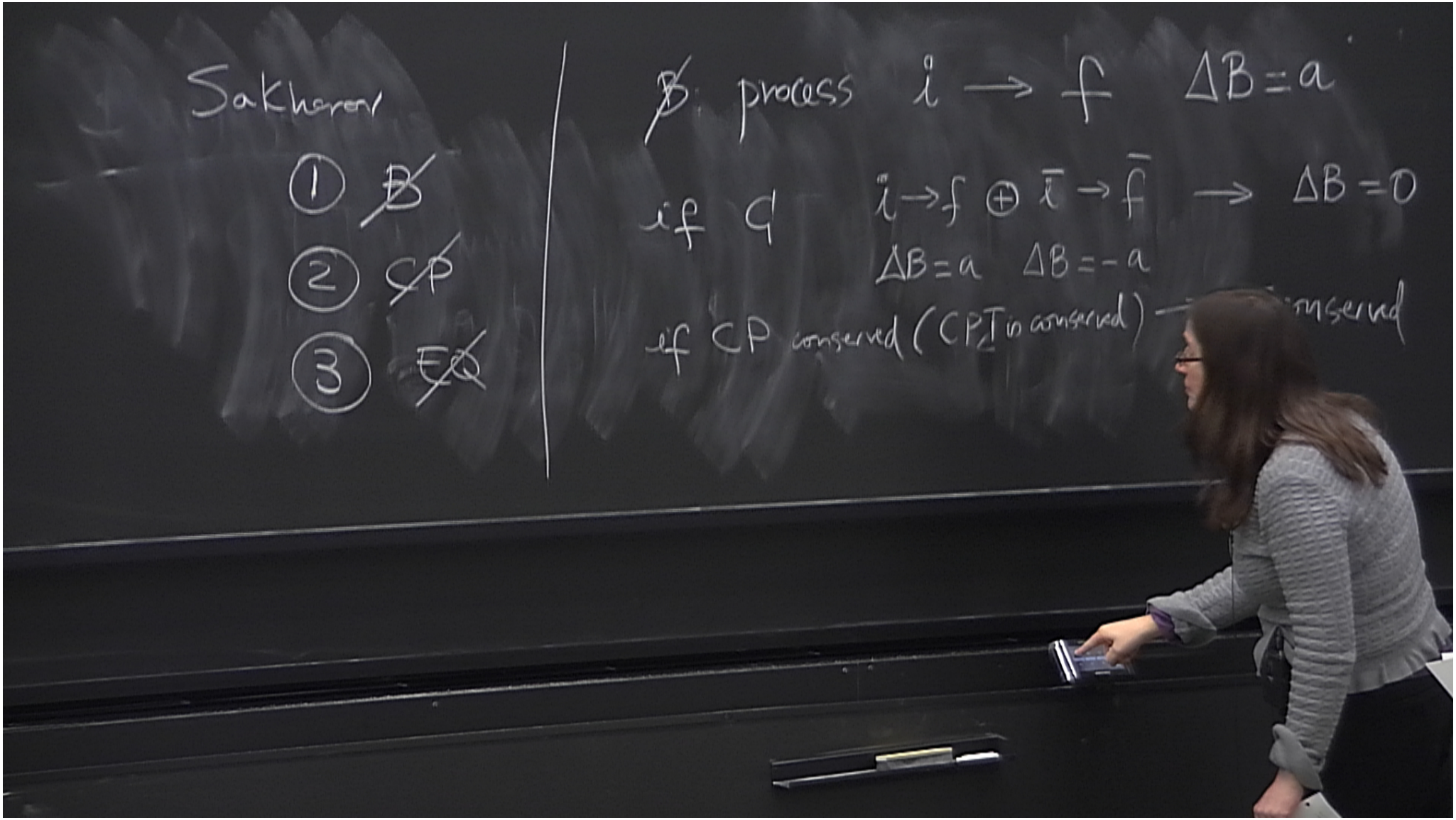

$s \approx 7 n_\gamma$
$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma}$

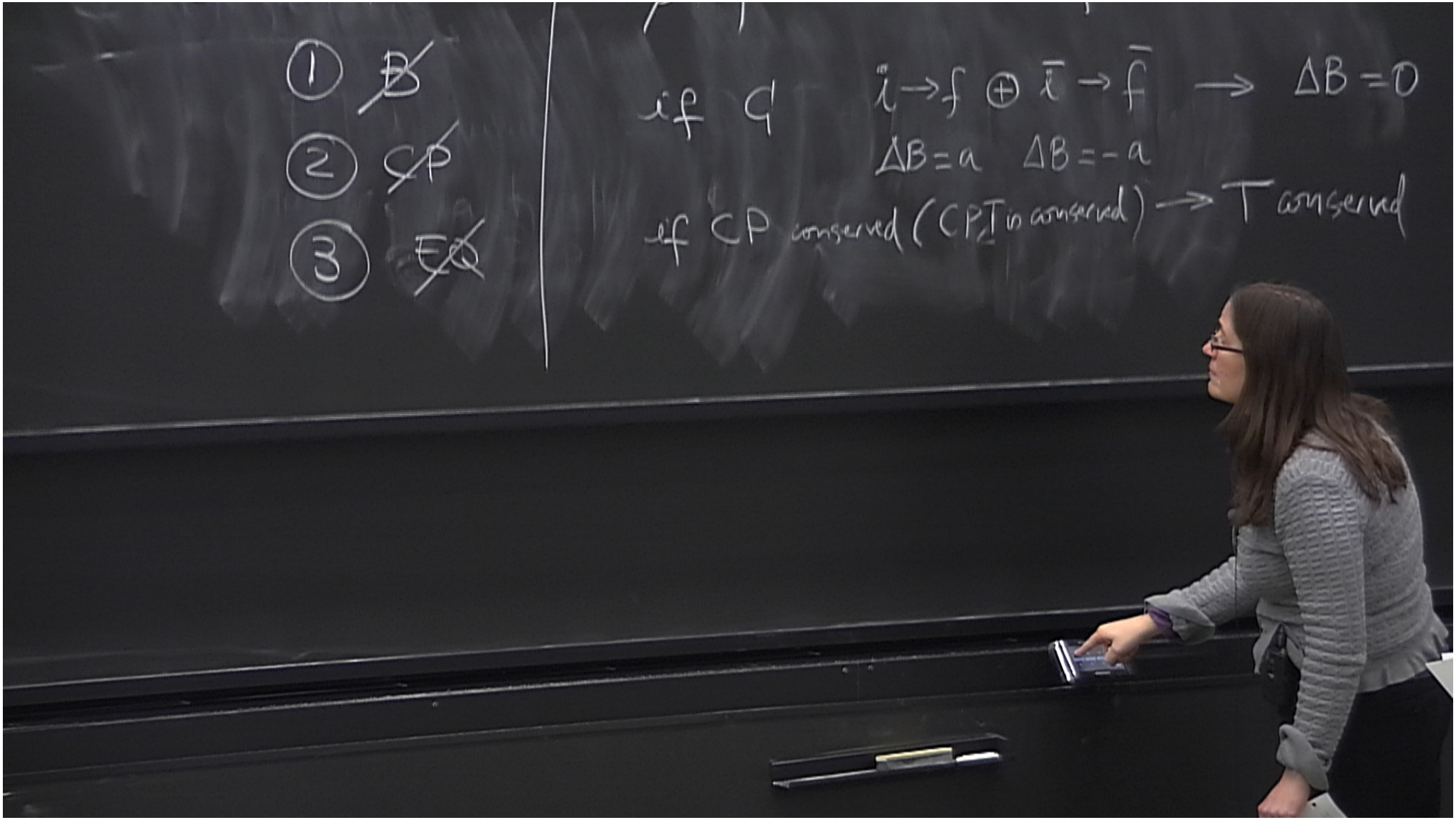

$s \approx 7 n_\gamma$
$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 10^{-10}$
WMAP
$(n_b - n_{\bar{b}})V$

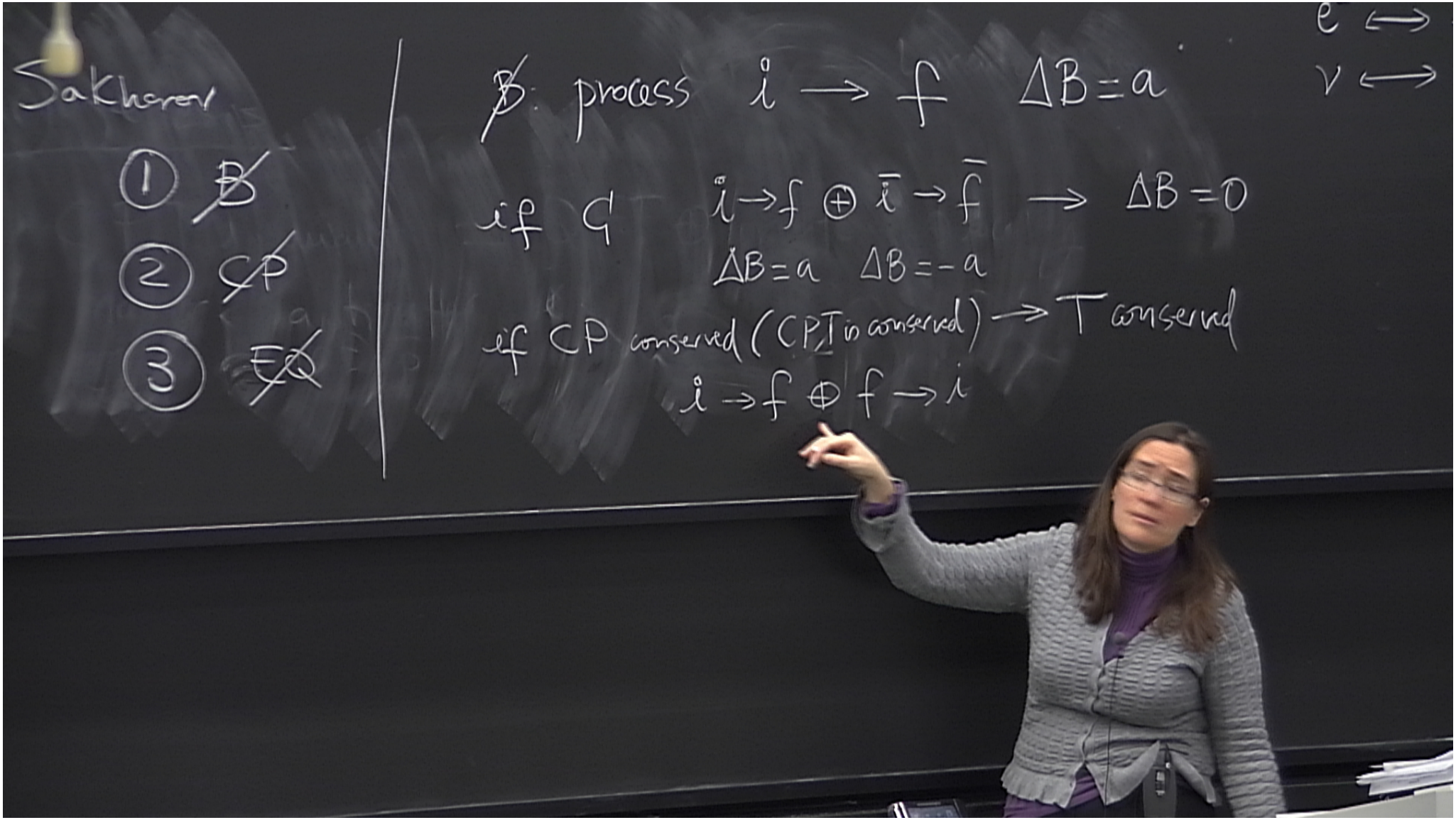

$s \approx 7 n_\gamma$
$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 10^{-10}$
WMAP
baryon asymmetry
w/o CPT ?

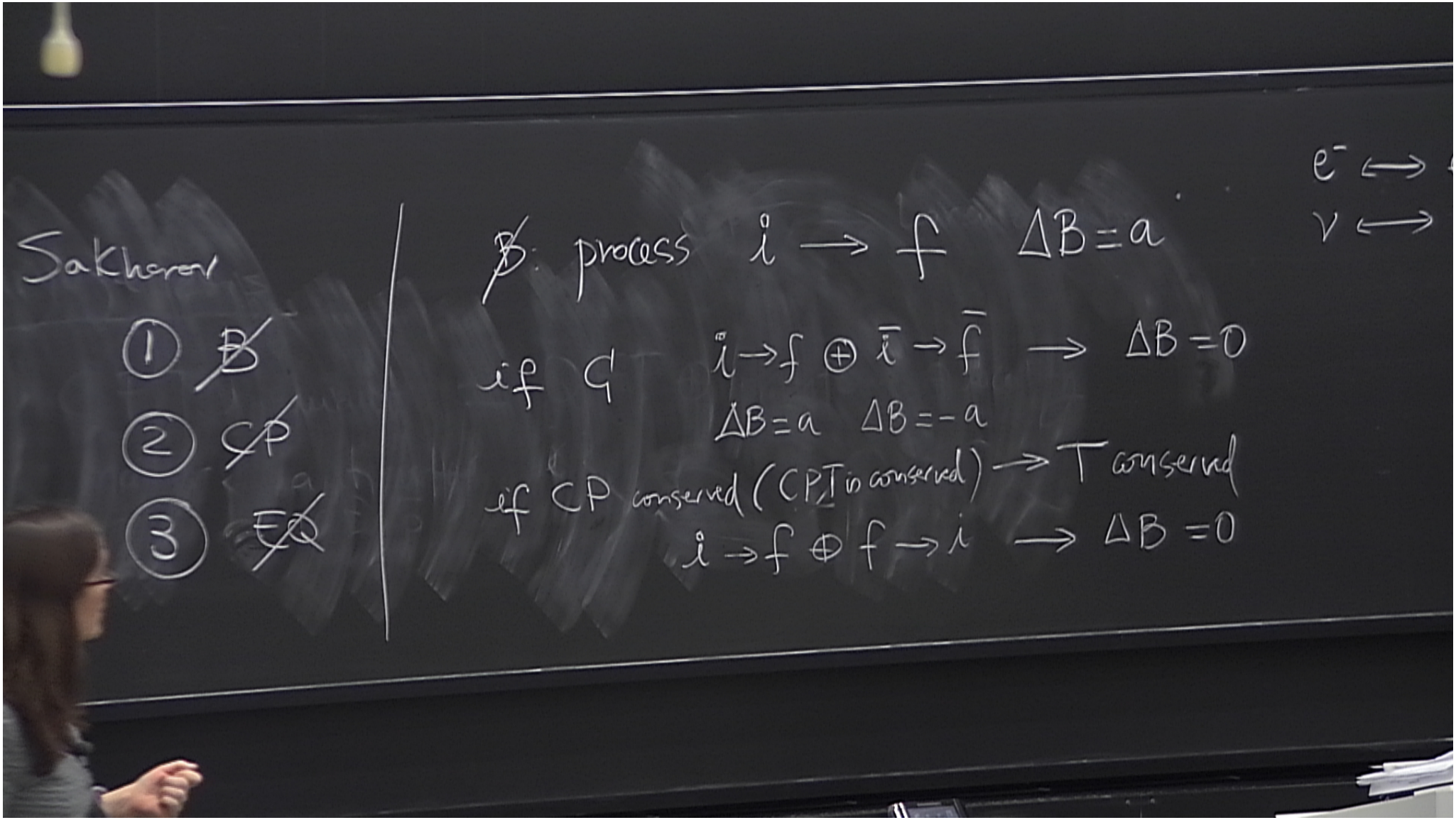

Sakharov
1 B
2 CP
3 EQ
B: process i →

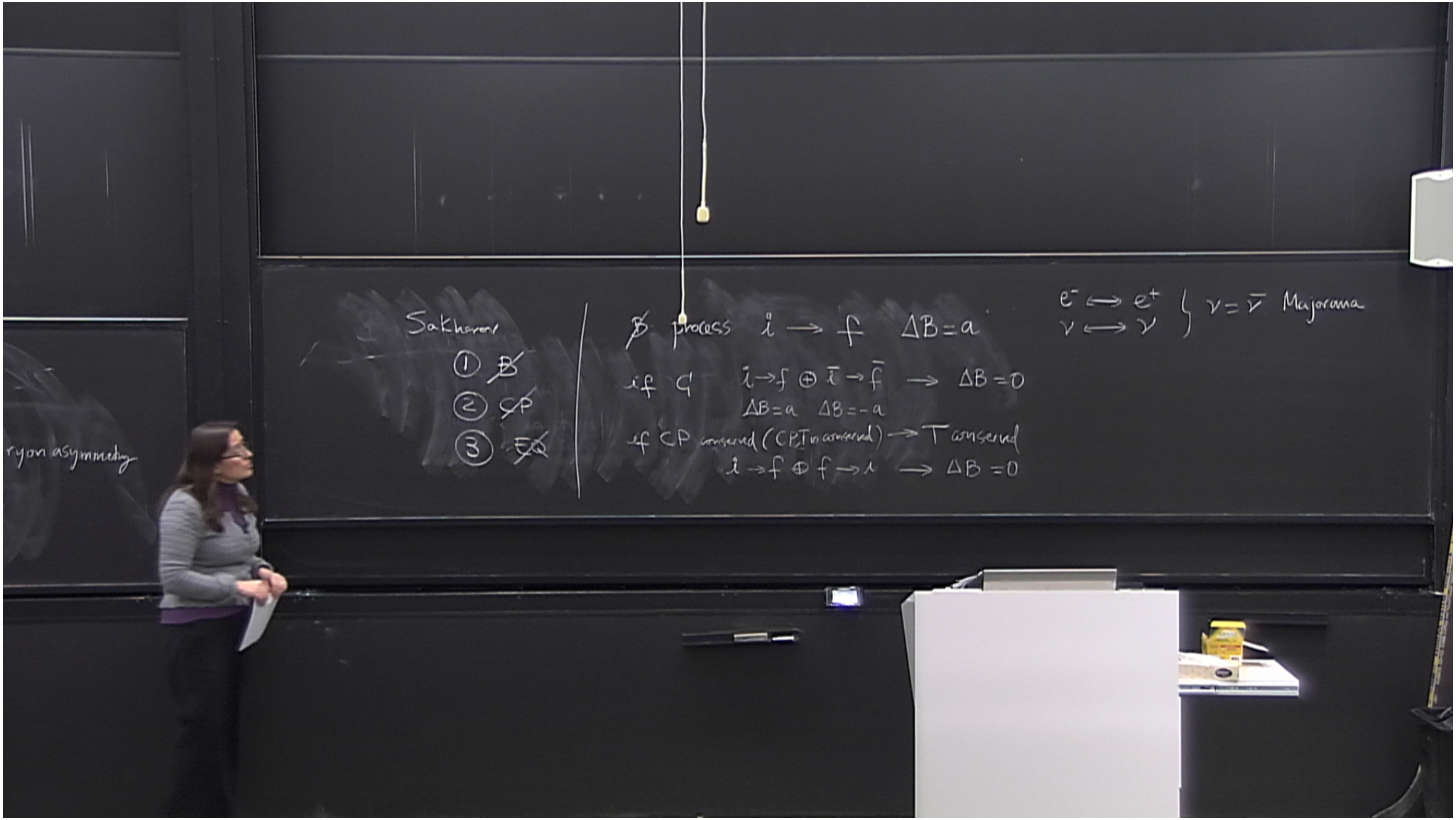

Sakharov
1 B
2 CP
3 EQ
B process i → f ΔB = a
if q i → f ⊕ ī → f̄
ΔB = a ΔB = -a

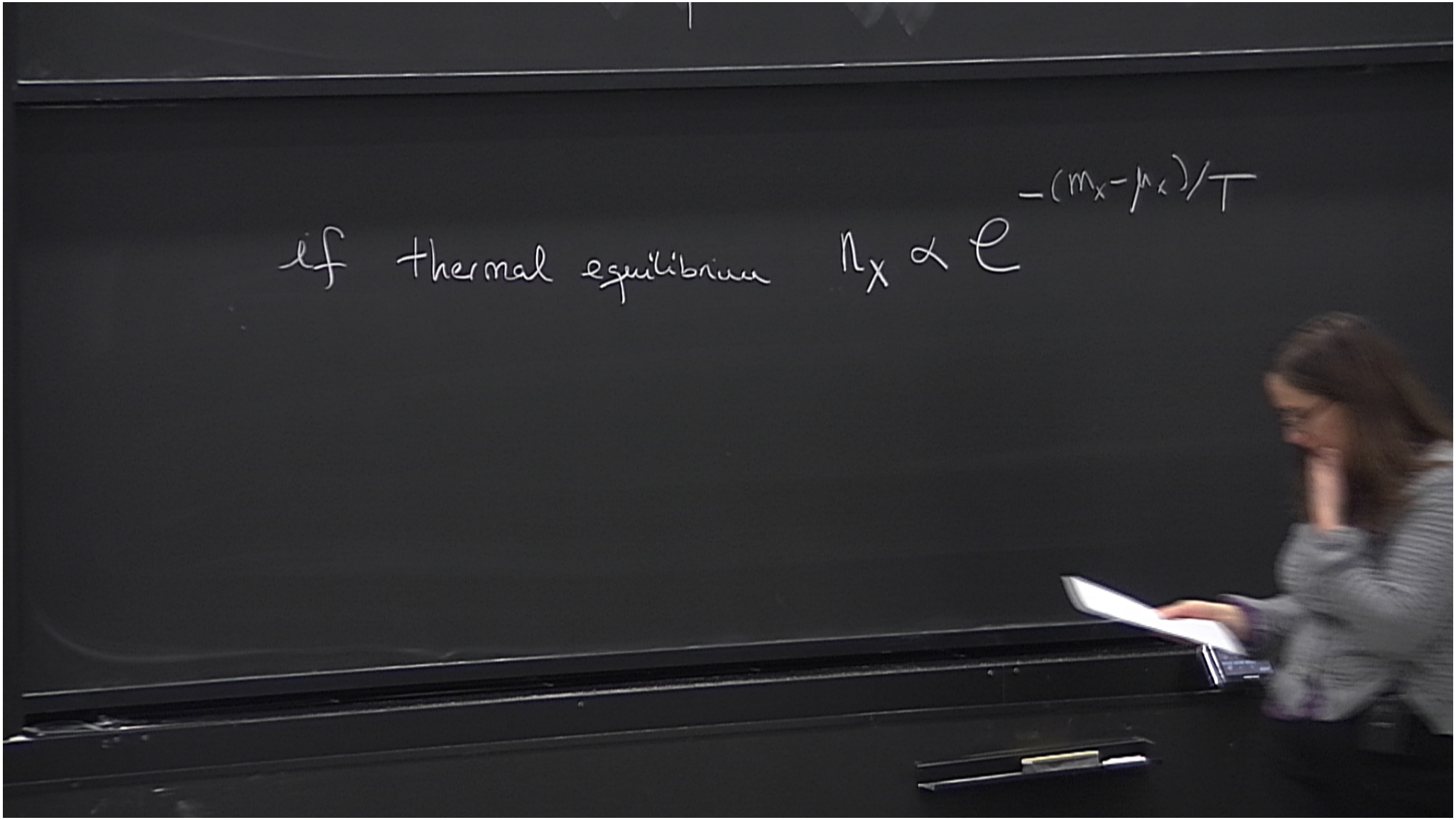

Sakharov
1 B
2 CP
3 Eq
B process i → f ΔB = a
if C i → f ⊕ ī → f̄ → ΔB = 0
ΔB = a ΔB = -a
if CP conserved (CPT is conserved)

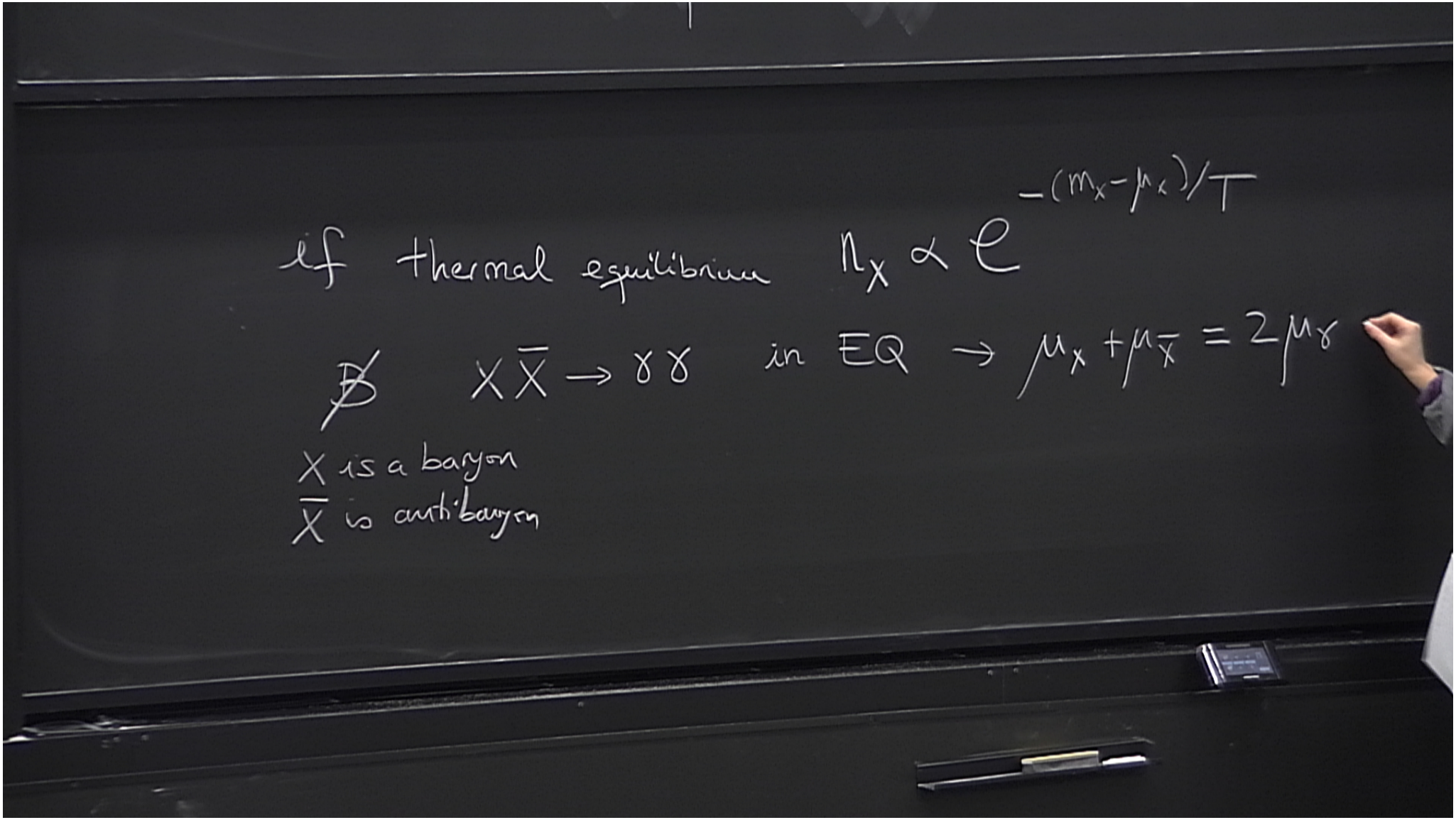

1 B
2 CP
3 EQ
if Q
$i \to f \oplus \bar{i} \to \bar{f} \to \Delta B = 0$
$\Delta B = a \quad \Delta B = -a$
if CP conserved (CPT is conserved) → T conserved

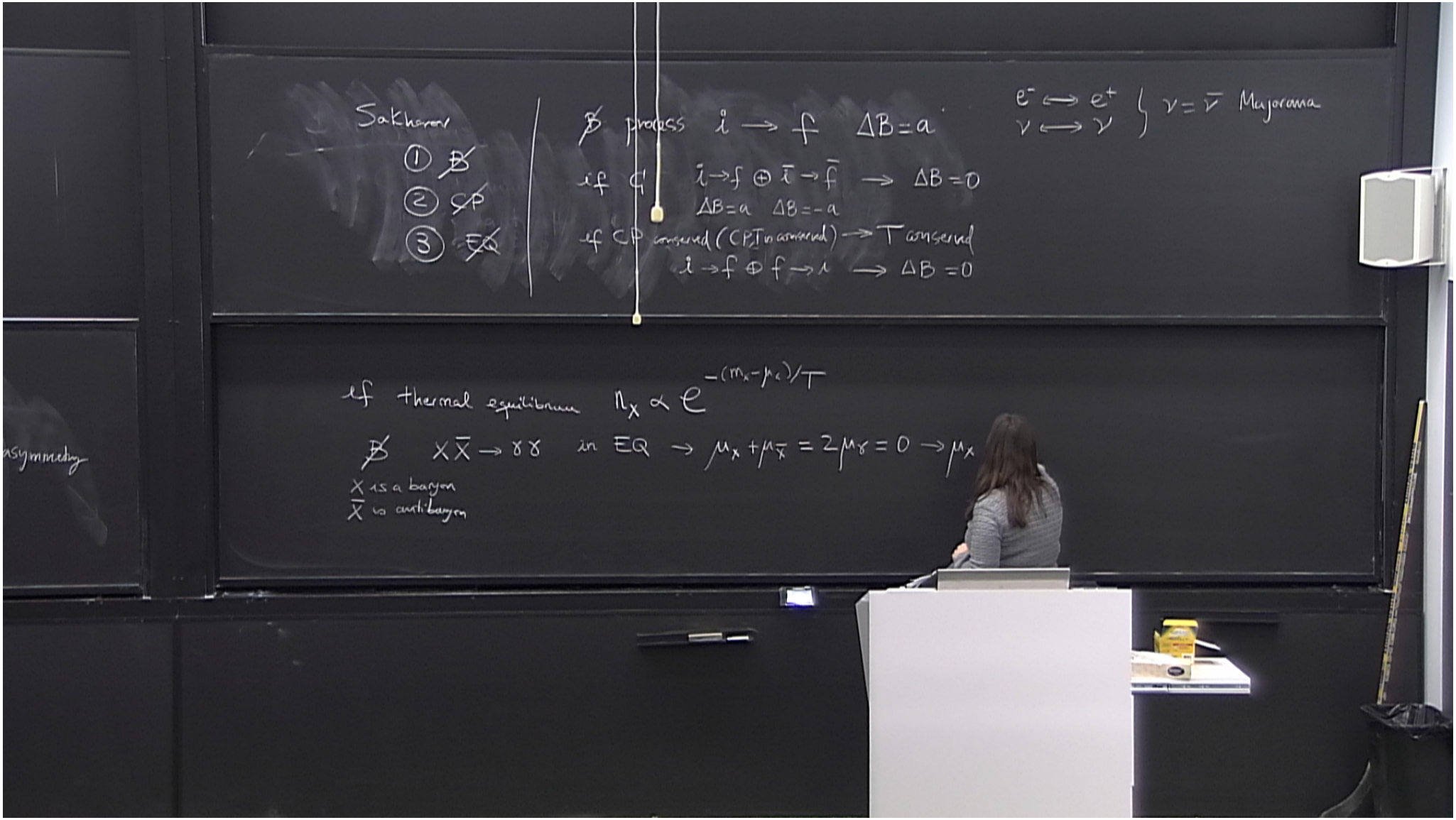

Sakharov
1 B
2 CP
3 EQ
B: process i → f ΔB = a
if C i → f ⊕ ī → f̄ → ΔB = 0
ΔB = a ΔB = -a
if CP conserved (CPT is conserved) → T conserved
i → f ⊕ f → i
e ⟷
ν ⟷

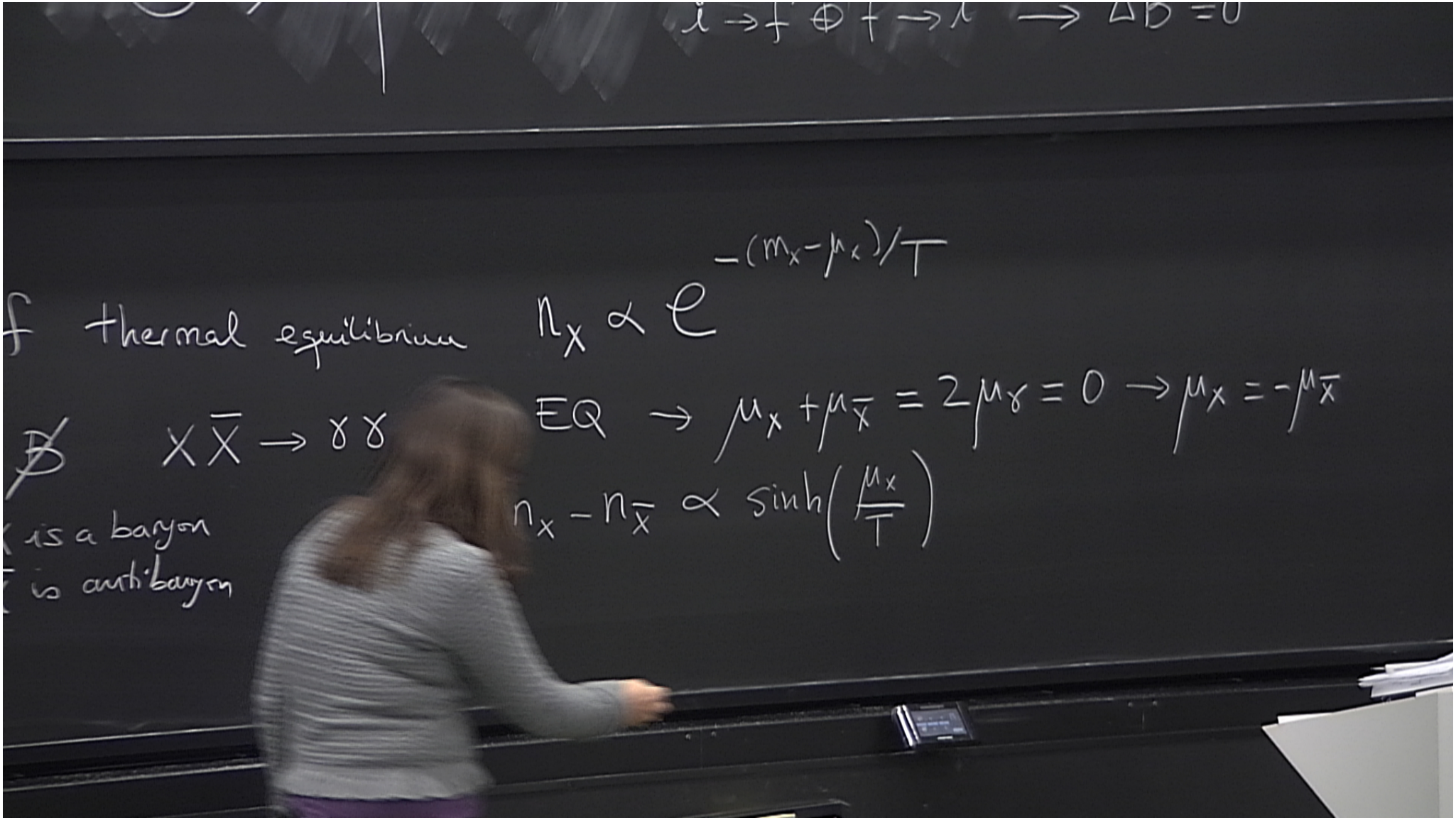

Sakharov
① B
② CP
③ Eq
B: process i → f ΔB = a
if C i → f ⊕ ī → f̄ → ΔB = 0
ΔB = a ΔB = -a
if CP conserved (CPT is conserved) → T conserved
i → f ⊕ f → i → ΔB = 0
e⁻ ⟷
ν ⟷

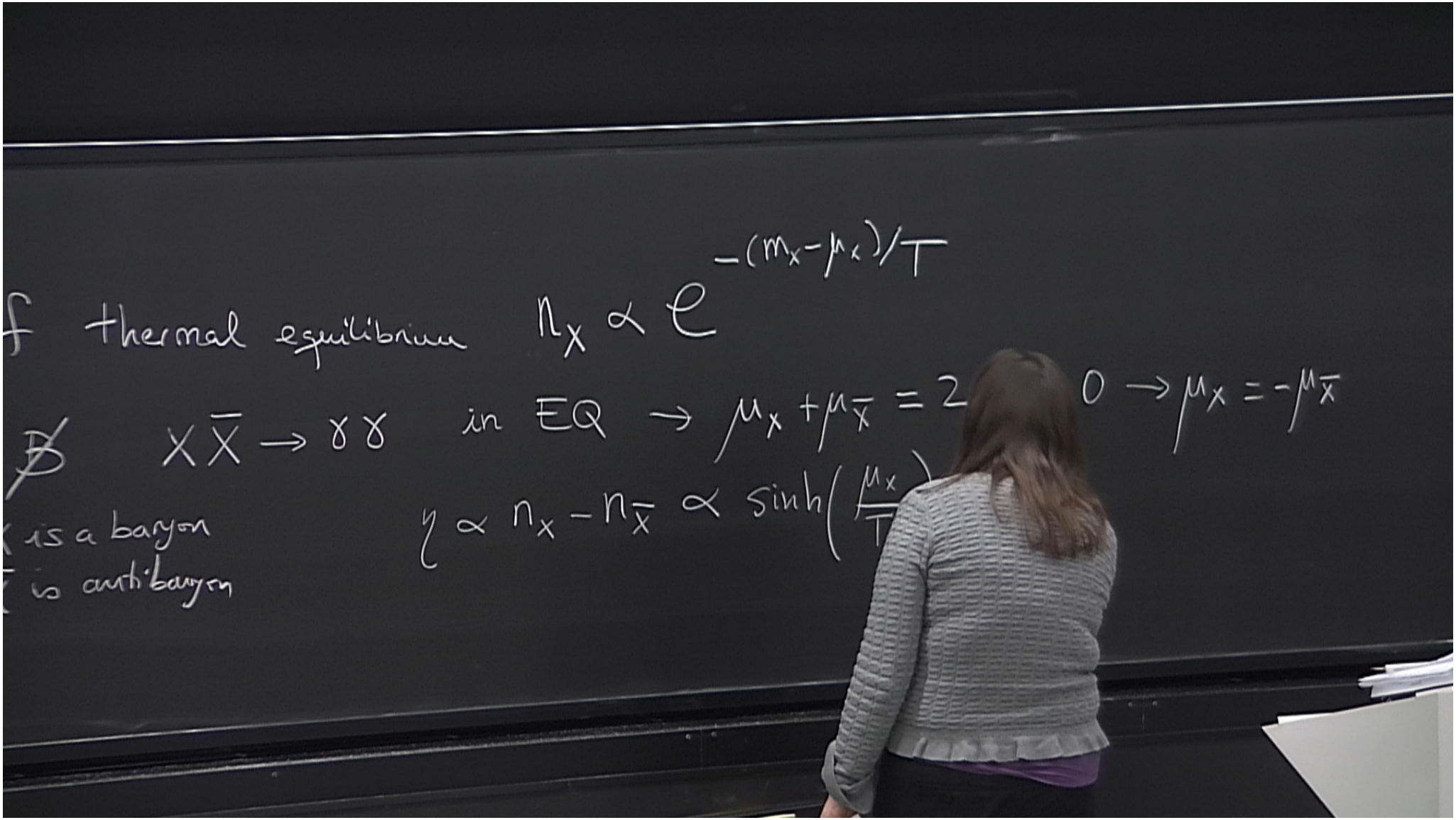

Sakharov
① B̸
② C̸P
③ T̸
B̸ process i → f ΔB=a
if C i→f ⊕ ī→f̄ → ΔB=0
ΔB=a ΔB=-a
if CP conserved (CP,T violated) → T conserved
i→f ⊕ f→i → ΔB=0
e⁻ ⟷ e⁺
ν ⟷ ν̄
ν=ν̄ Majorana
ryon asymmetry

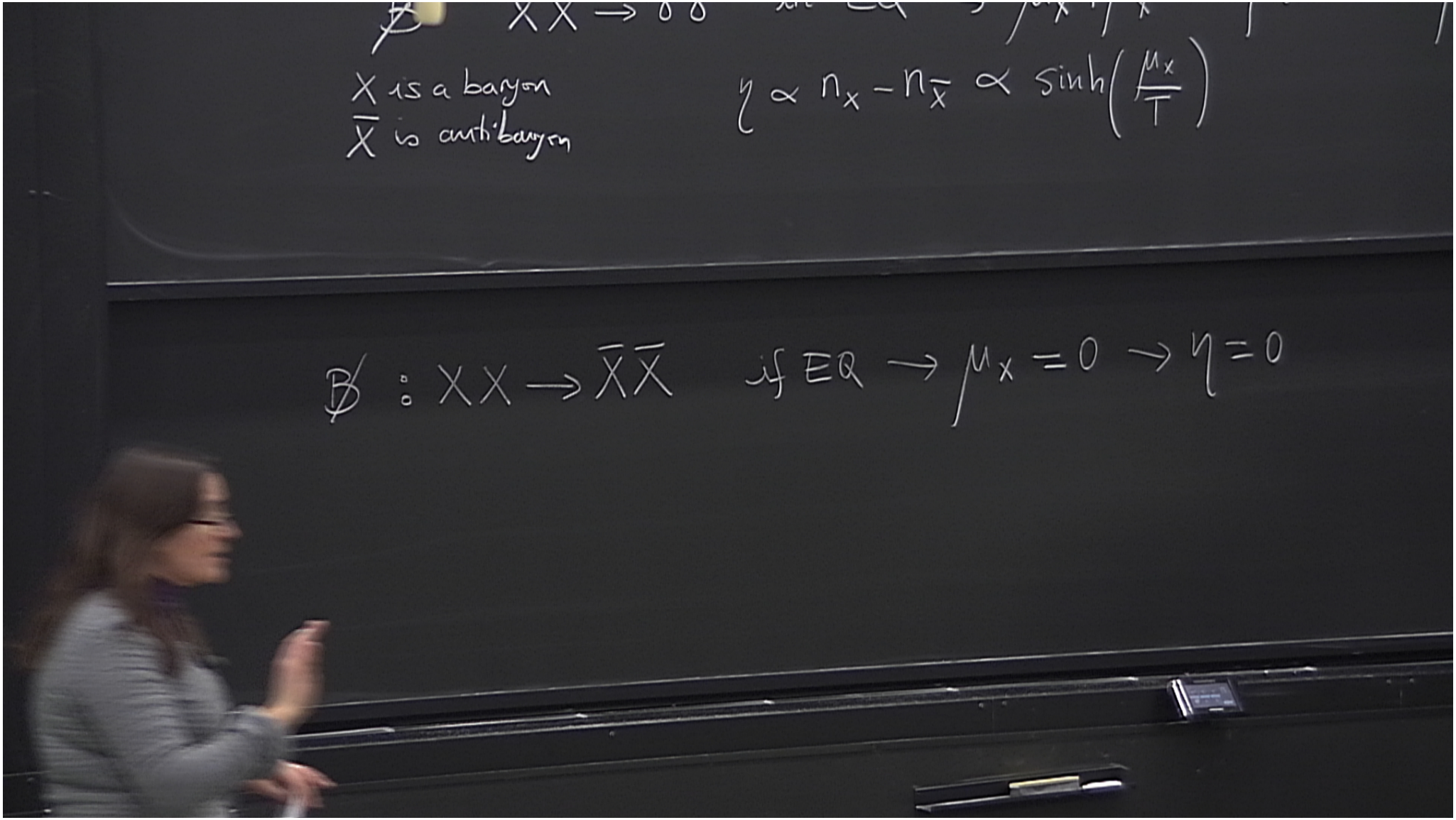

if thermal equilibrium $n_X \propto e^{-(m_X - \mu_X)/T}$

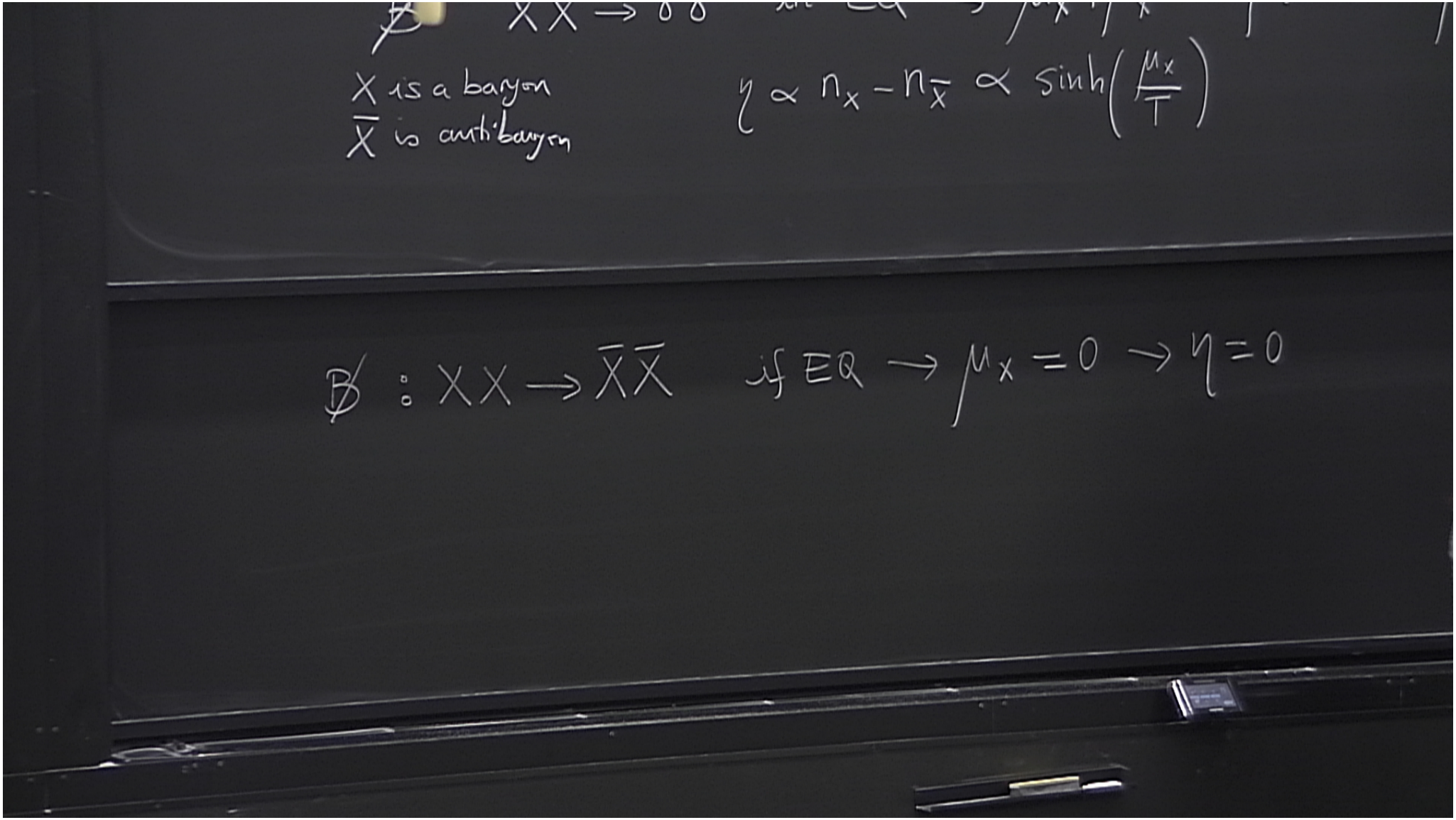

if thermal equilibrium $n_X \propto e^{-(m_X-\mu_X)/T}$
$\not{B}$ $X\bar{X} \to \gamma\gamma$ in EQ $\to \mu_X + \mu_{\bar{X}} = 2\mu_\gamma$
X is a baryon
$\bar{X}$ is antibaryon

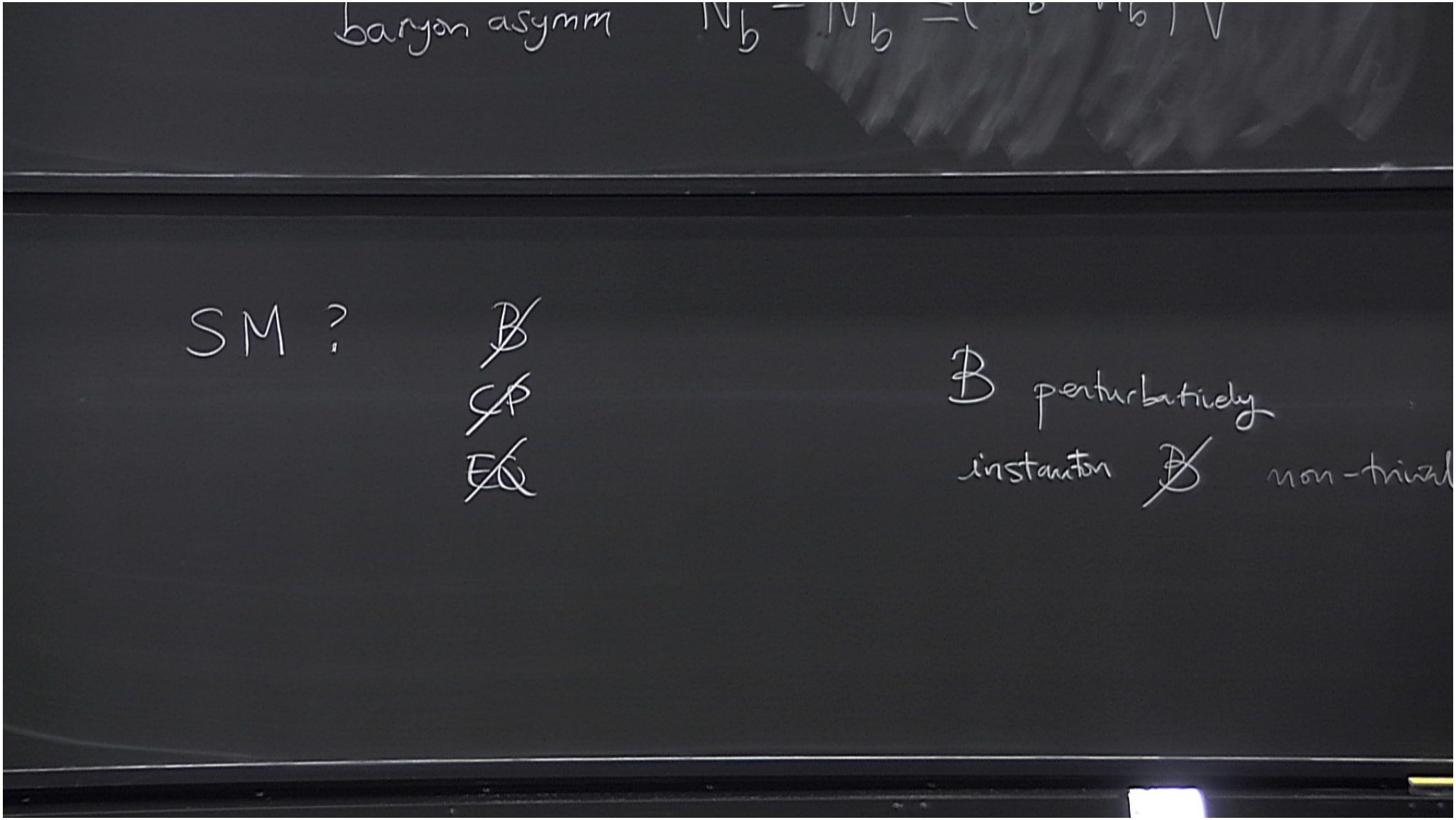

Sakharov
① B̸
② C̸P̸
③ E̸Q̸
B̸ process i → f ΔB = a
if C̸ i → f ⊕ ī → f̄ → ΔB = 0
ΔB = a ΔB = −a
if CP conserved (CPT is conserved) → T conserved
i → f ⊕ f → i → ΔB = 0
e⁻ ⟷ e⁺
ν ⟷ ν̄
ν = ν̄ Majorana
if thermal equilibrium n_X ∝ e^{−(m_X − μ_X)/T}
B̸ X X̄ → γγ in EQ → μ_X + μ_X̄ = 2μ_γ = 0 → μ_X
X is a baryon
X̄ is antibaryon
asymmetry

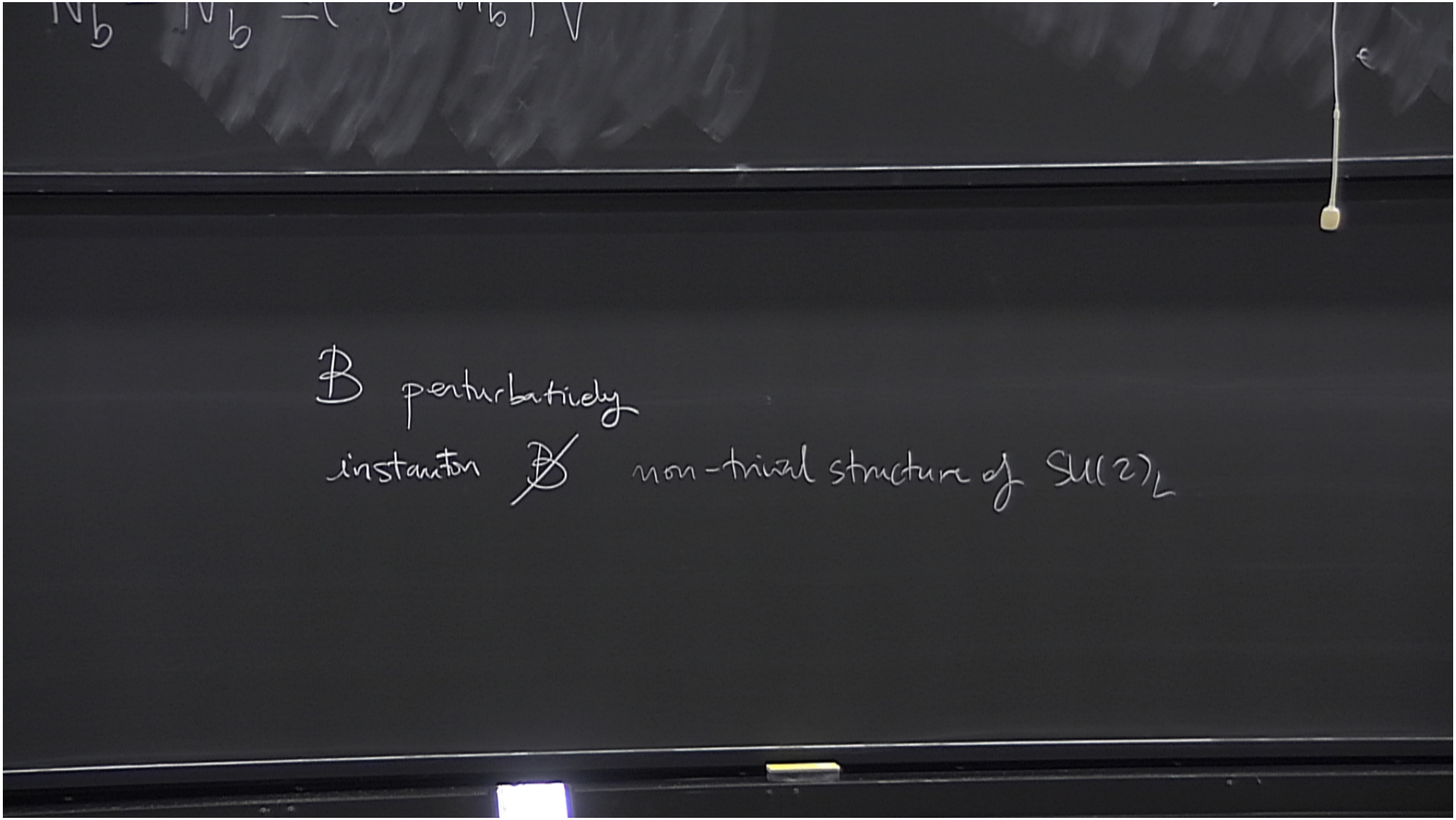

$i \to f \oplus f \to \lambda \to \Delta B = 0$
$n_X \propto e^{-(m_X - \mu_X)/T}$
f thermal equilibrium
$X\bar{X} \to \gamma\gamma$
EQ $\to \mu_X + \mu_{\bar{X}} = 2\mu_\gamma = 0 \to \mu_X = -\mu_{\bar{X}}$
$n_X - n_{\bar{X}} \propto \sinh\left(\frac{\mu_X}{T}\right)$
is a baryon
is antibaryon

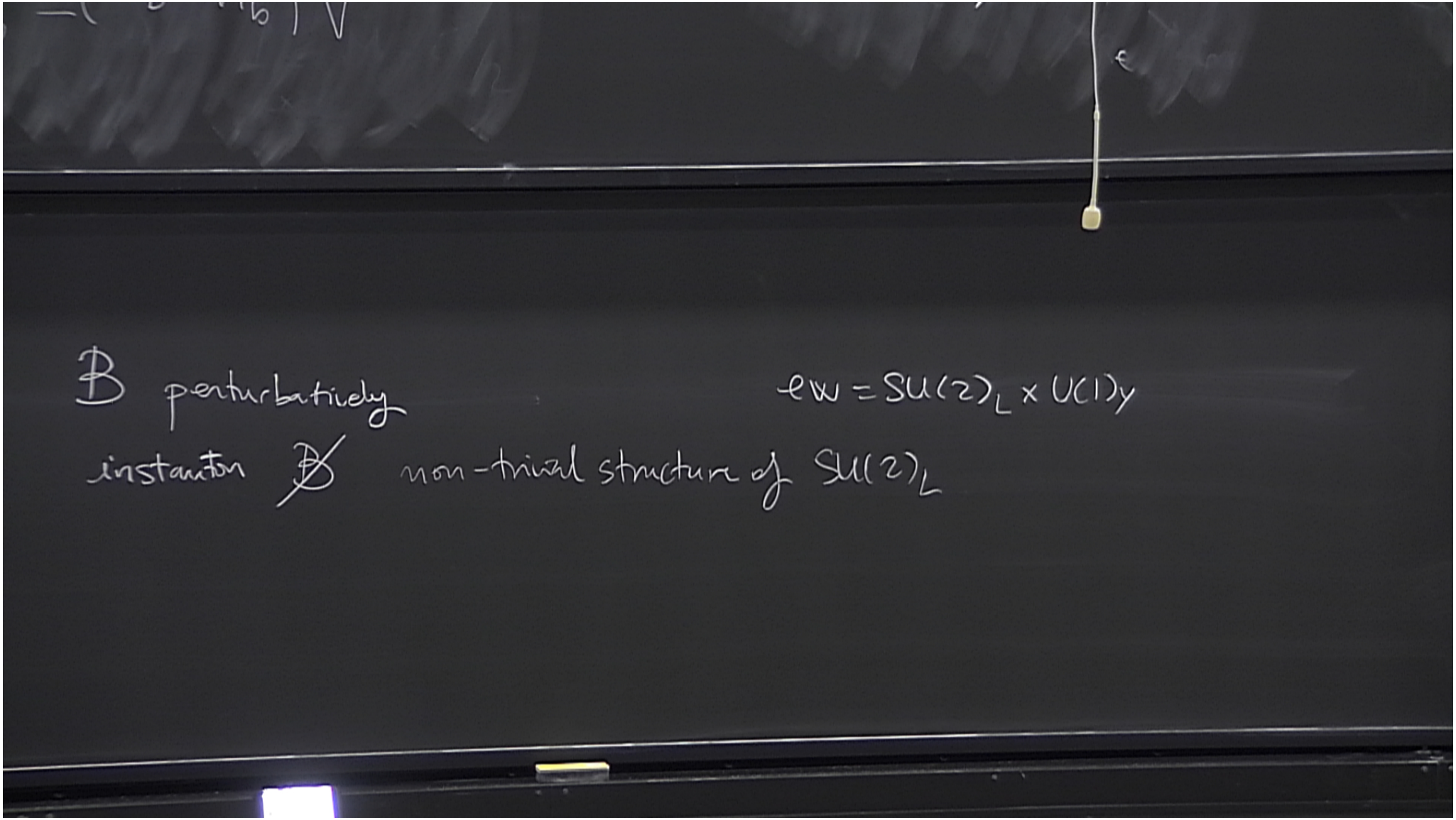

f thermal equilibrium $n_X \propto e^{-(m_X-\mu_X)/T}$
$X\bar{X} \to \gamma\gamma$ in EQ $\to \mu_X + \mu_{\bar{X}} = 2 \quad 0 \to \mu_X = -\mu_{\bar{X}}$
is a baryon
is antibaryon
$\eta \propto n_X - n_{\bar{X}} \propto \sinh\left(\frac{\mu_X}{T}\right)$


X is a baryon
$\bar{X}$ is antibaryon
$\eta \propto n_X - n_{\bar{X}} \propto \sinh\left(\frac{\mu_X}{T}\right)$
$\not{B}: XX \to \bar{X}\bar{X}$ if EQ $\to \mu_X = 0 \to \eta = 0$


$\not{B}$ $XX \to \bar{X}\bar{X}$ ... $\eta_X \eta_{\bar{X}}$
X is a baryon
$\bar{X}$ is antibaryon
$\eta \propto n_X - n_{\bar{X}} \propto \sinh\left(\frac{\mu_X}{T}\right)$
$\not{B}$: $XX \to \bar{X}\bar{X}$ if EQ $\to \mu_X = 0 \to \eta = 0$


baryon asymm
SM ?
B
CP
EQ
B perturbatively
instanton B non-trivial

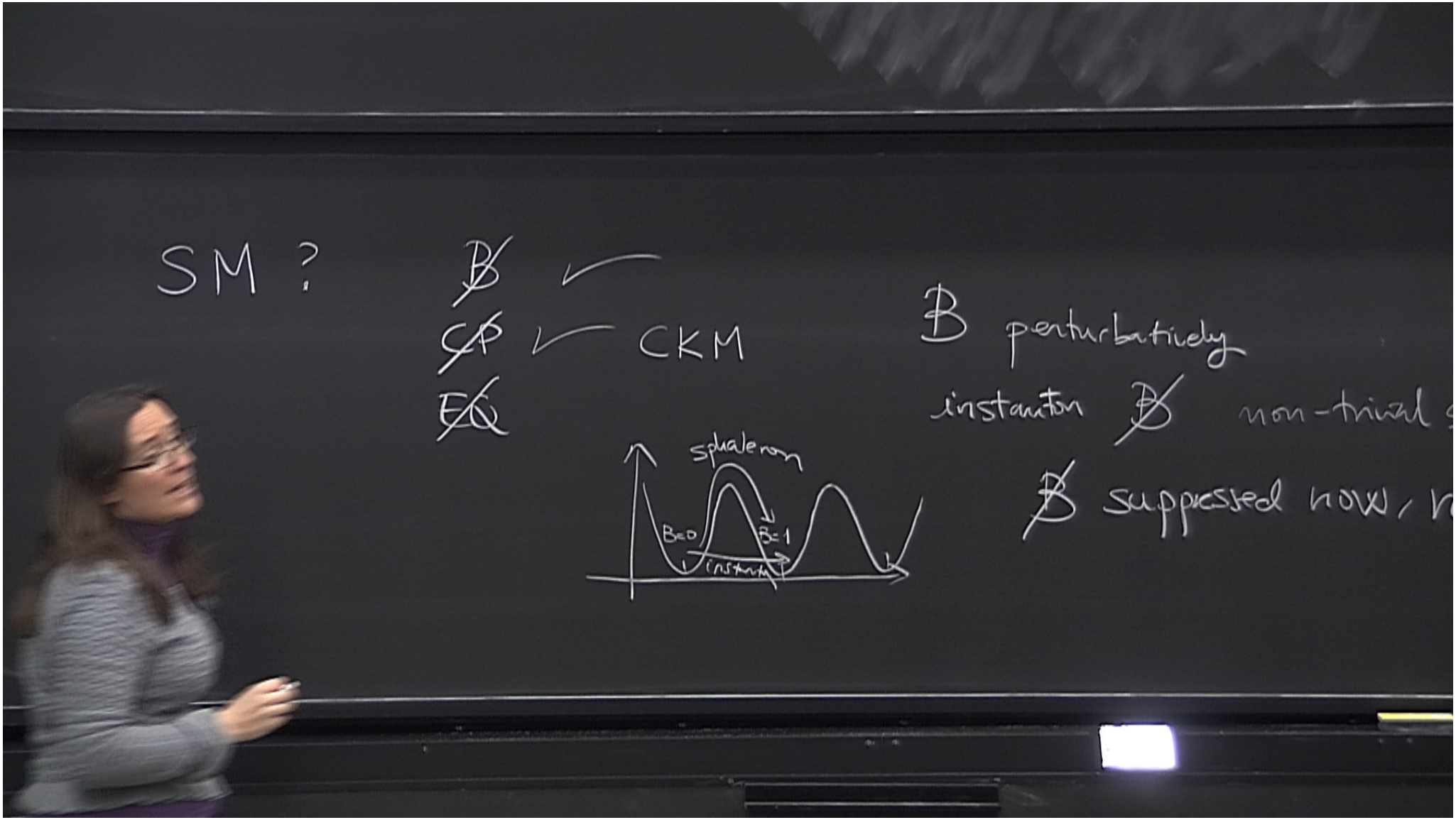

$N_b \quad N_b - (\quad N_b) V$
$\not{B}$ perturbatively
instanton $\not{B}$ non-trivial structure of $SU(2)_L$

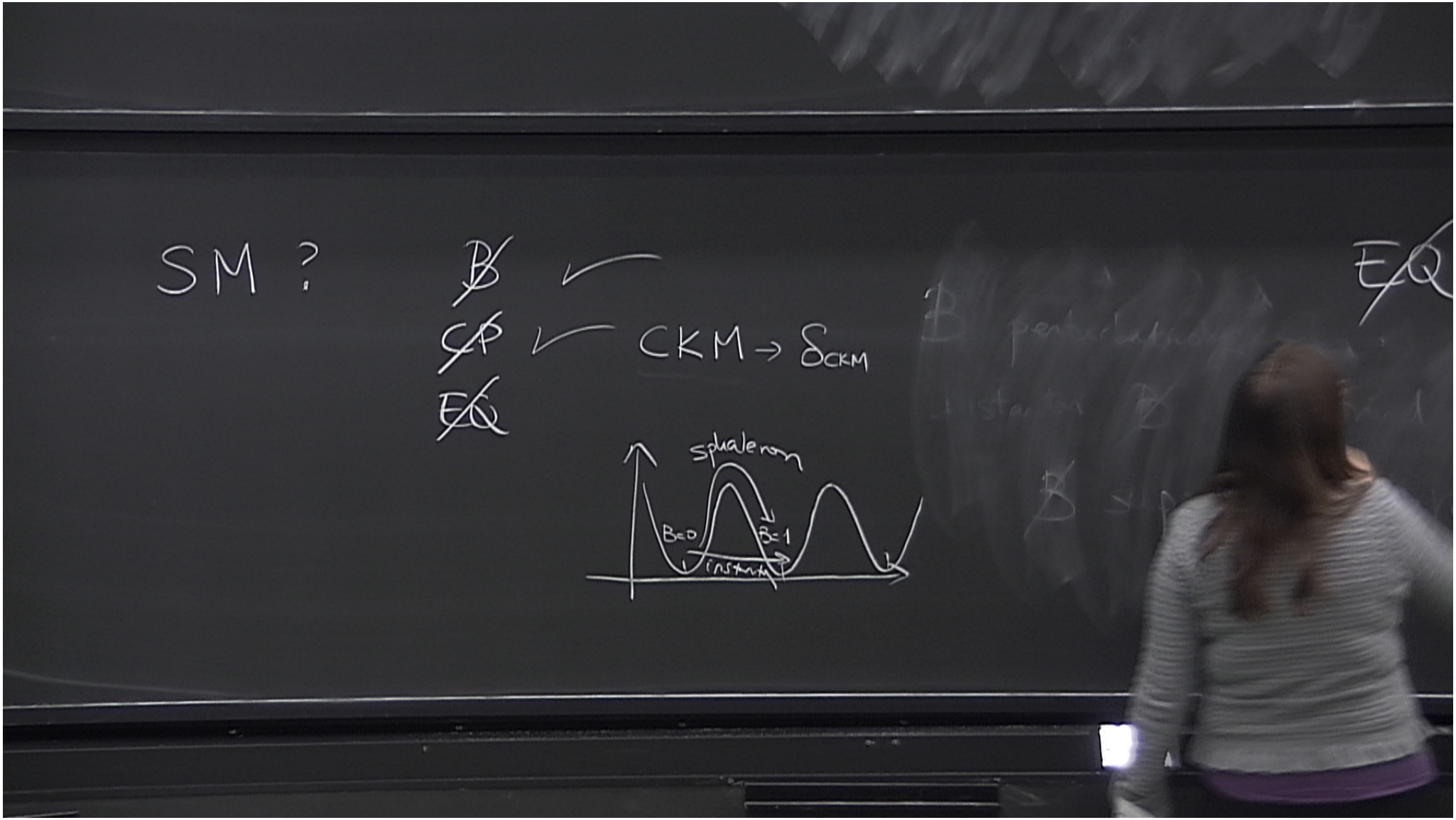

B perturbatively
ew = SU(2)L x U(1)Y
instanton ⇏ non-trivial structure of SU(2)L

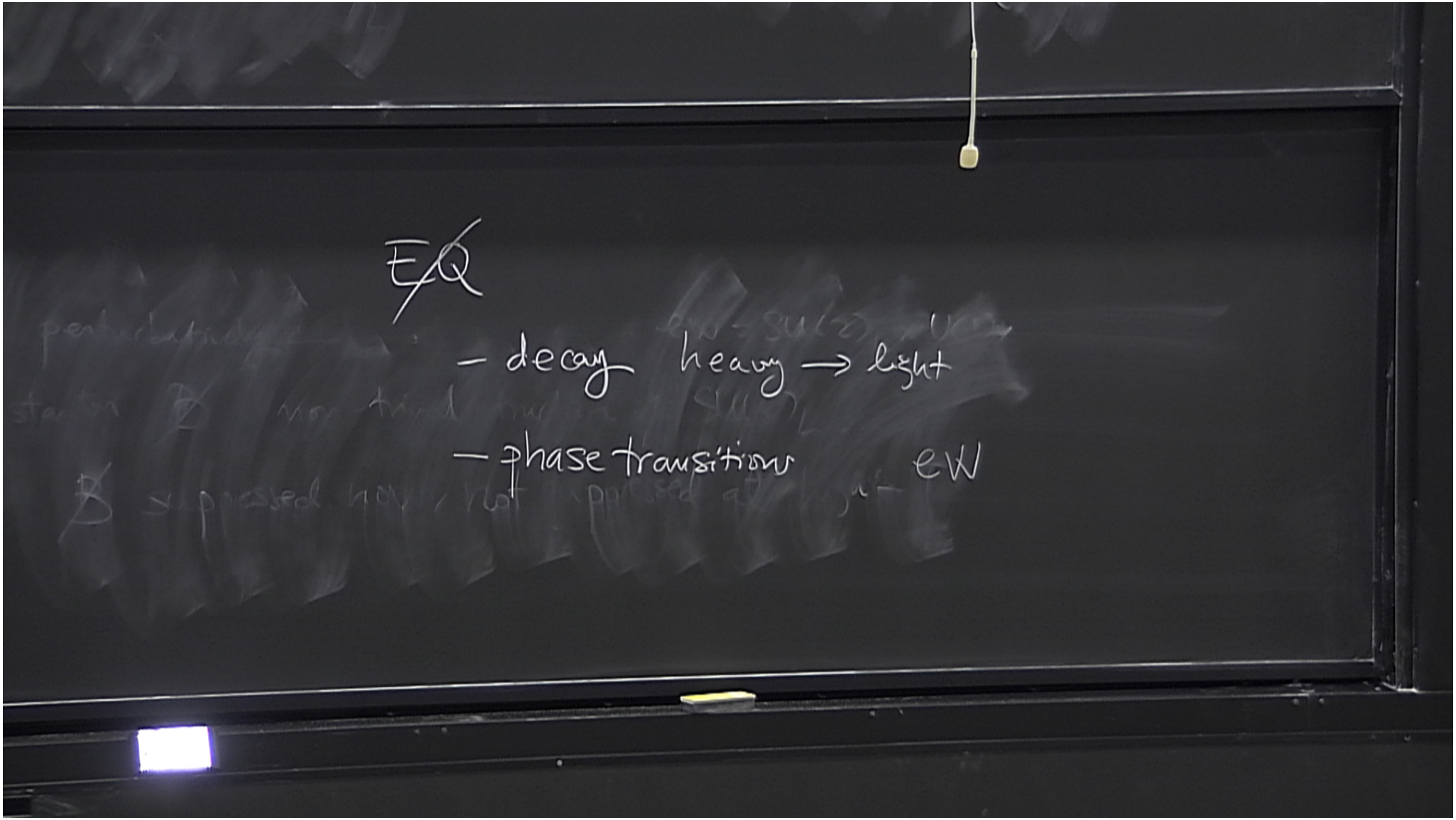
$\not{B}$ perturbatively $\qquad$ $ew = SU(2)_L \times U(1)_Y$

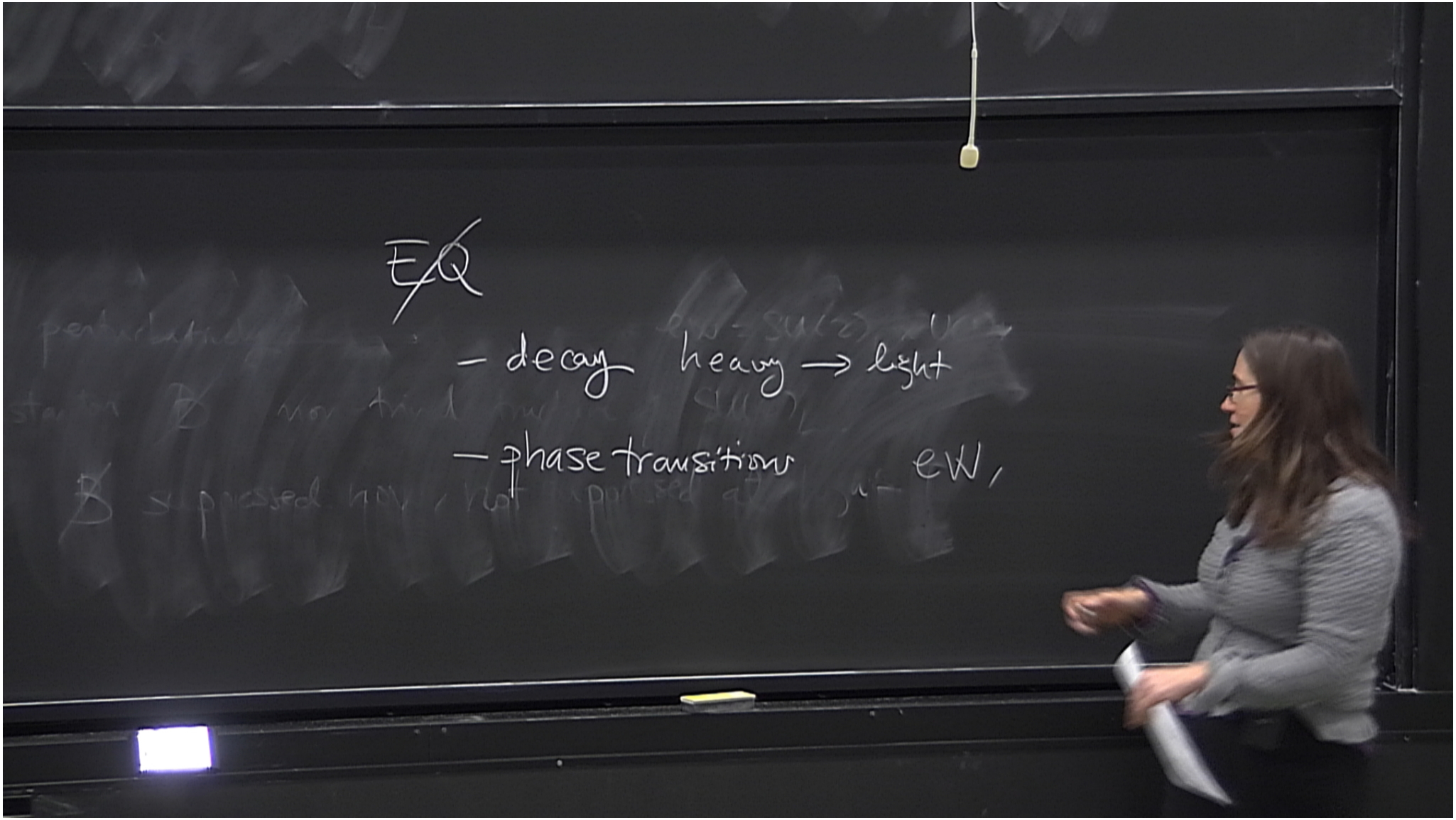
instanton $\not{B}$ non-trivial structure of $SU(2)_L$

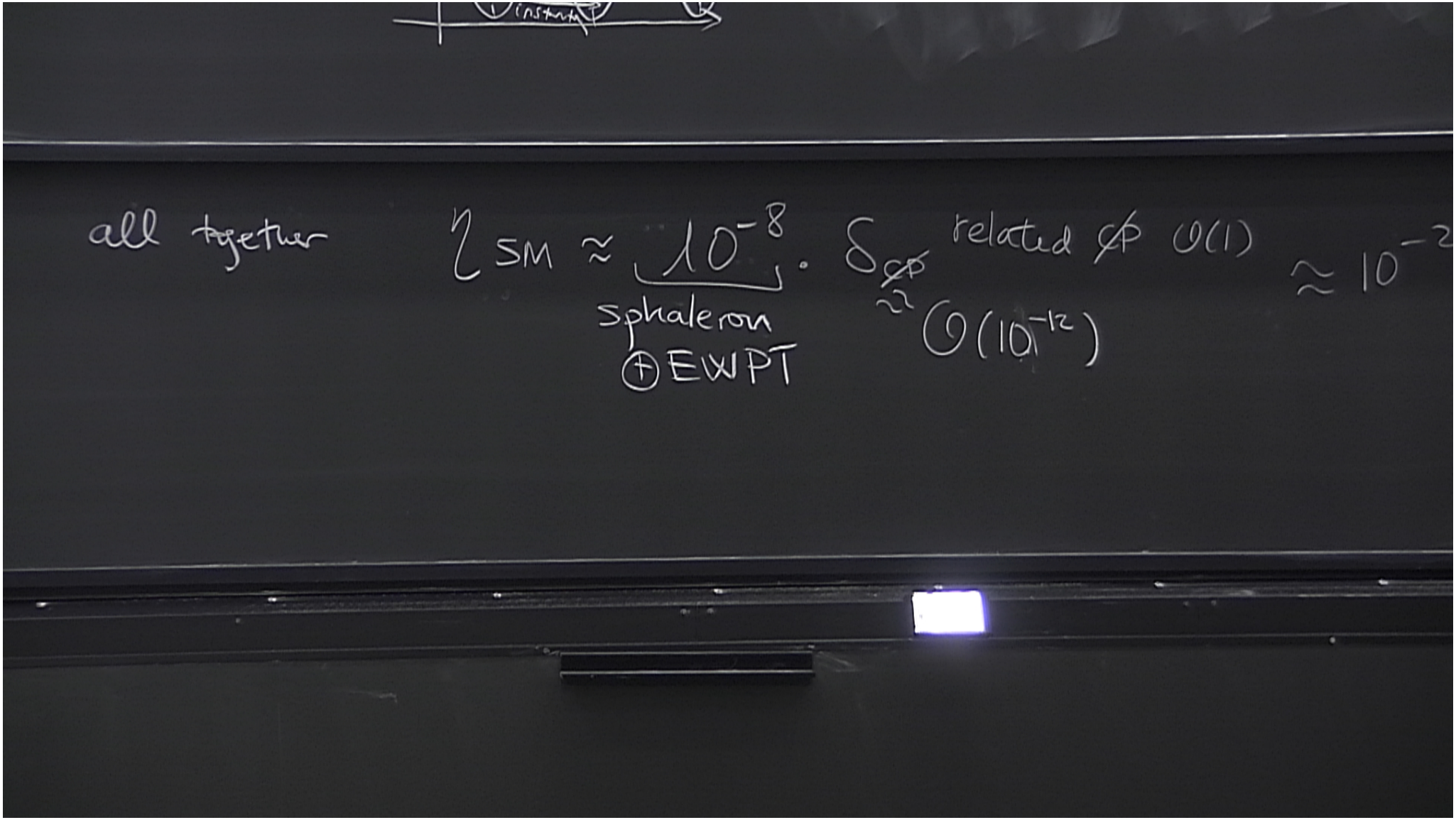
$\not{B}$ suppressed now, not suppressed at high-T

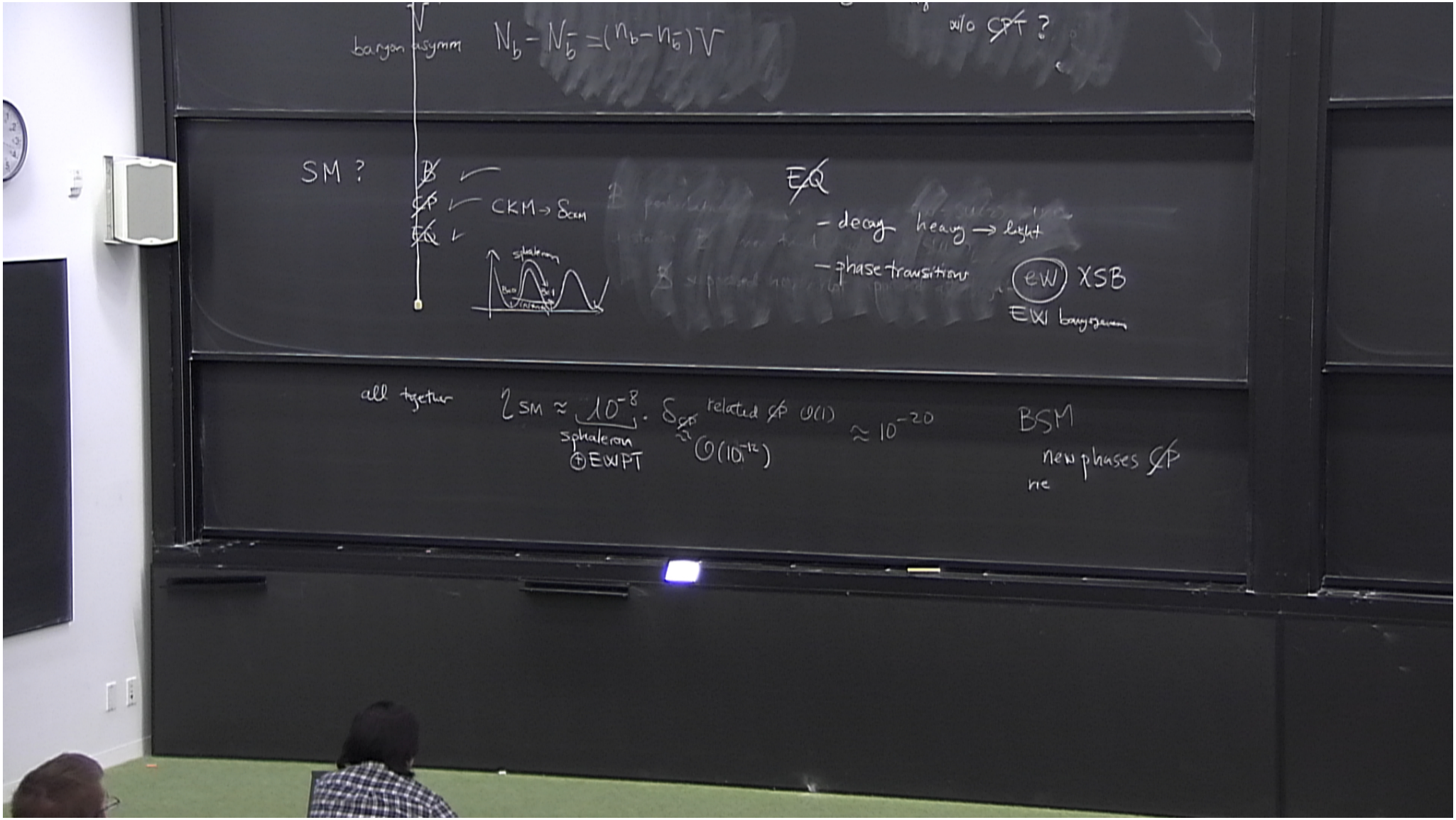

SM ?
B
CP
EW
CKM
B perturbatively
instanton
sphaleron
B=0
B=1
instanton

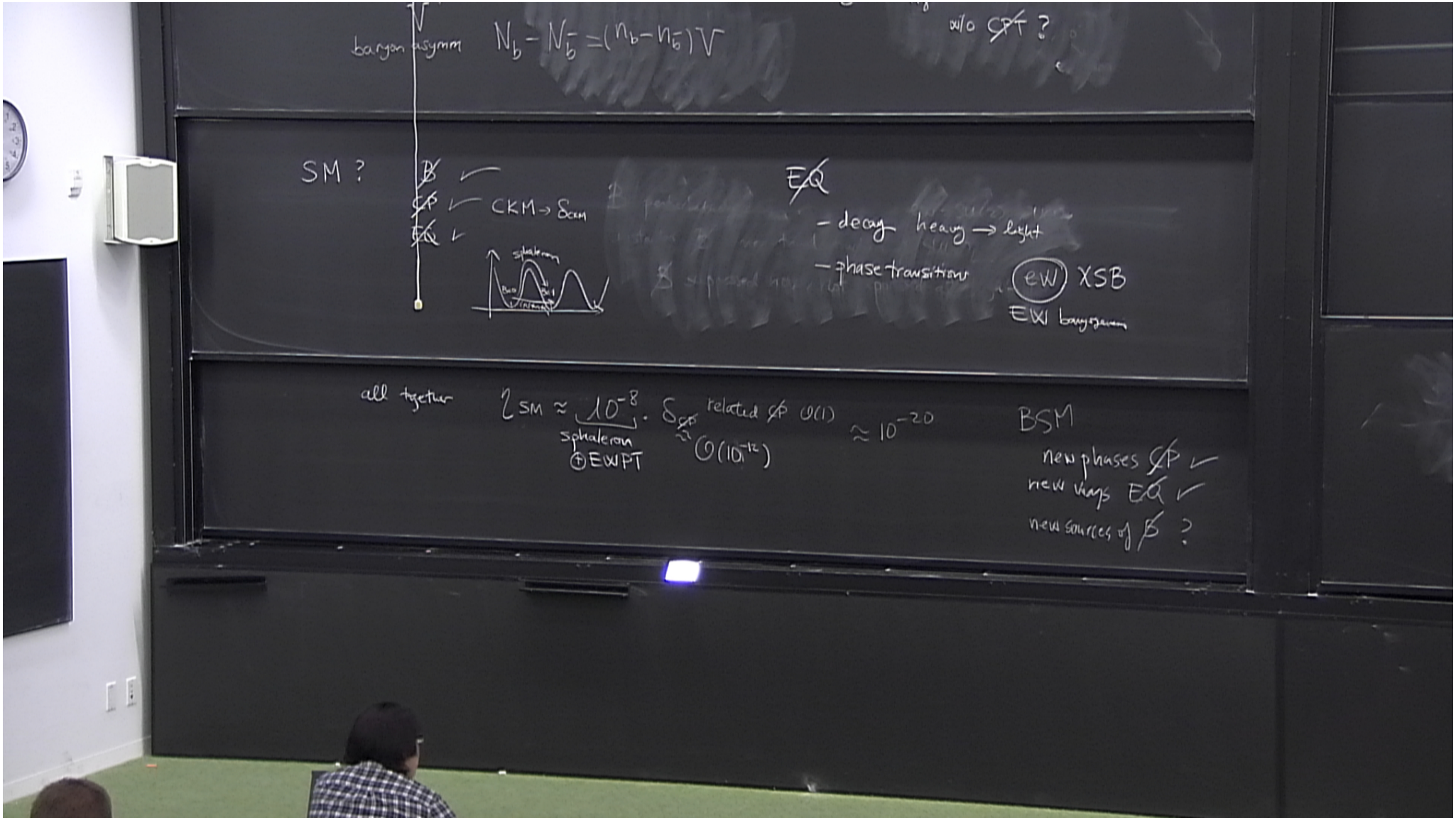

SM ?
B
CP
EQ
CKM → δ_{CKM}
sphaleron
B=0
B=1
instanton


EQ
- decay heavy → light
- phase transitions EW


EW
- decay heavy → light
- phase transitions - EW,


all together
$\eta_{SM} \approx \underbrace{10^{-8}}_{\text{sphaleron} \oplus \text{EWPT}} \cdot \delta_{\not CP}$
related $\not CP$ $\mathcal{O}(1)$
$\approx \mathcal{O}(10^{-12})$
$\approx 10^{-2}$


baryon asymm
$N_b - N_{\bar{b}} = (n_b - n_{\bar{b}})V$
w/o CPT ?
SM ?
B
CP
EQ
CKM → δ_{CKM}
sphaleron
- decay heavy → light
- phase transitions
EW XSB
EW baryogenesis
all together
$\zeta_{SM} \approx \underbrace{10^{-8}}_{\text{sphaleron}} \cdot \underbrace{\delta_{CP}}_{\text{related CP } \mathcal{O}(1)} \approx \mathcal{O}(10^{-12}) \approx 10^{-20}$
⊕EWPT
BSM
new phases CP
ne

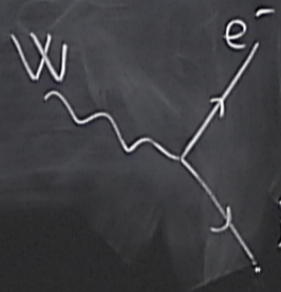

baryon asymm
$N_b - N_{\bar{b}} = (n_b - n_{\bar{b}})V$
w/o CPT ?
SM ?
B
CP
EQ
CKM → δ_{CKM}
sphaleron
- decay heavy → light
- phase transitions
EW XSB
EW baryogenesis
all together
$\zeta_{SM} \approx \underbrace{10^{-8}}_{\text{sphaleron} \oplus \text{EWPT}} \cdot \delta_{CP}$ related CP $\mathcal{O}(1)$ $\approx \mathcal{O}(10^{-12}) \approx 10^{-20}$
BSM
new phases CP
new ways EQ
new sources of B ?

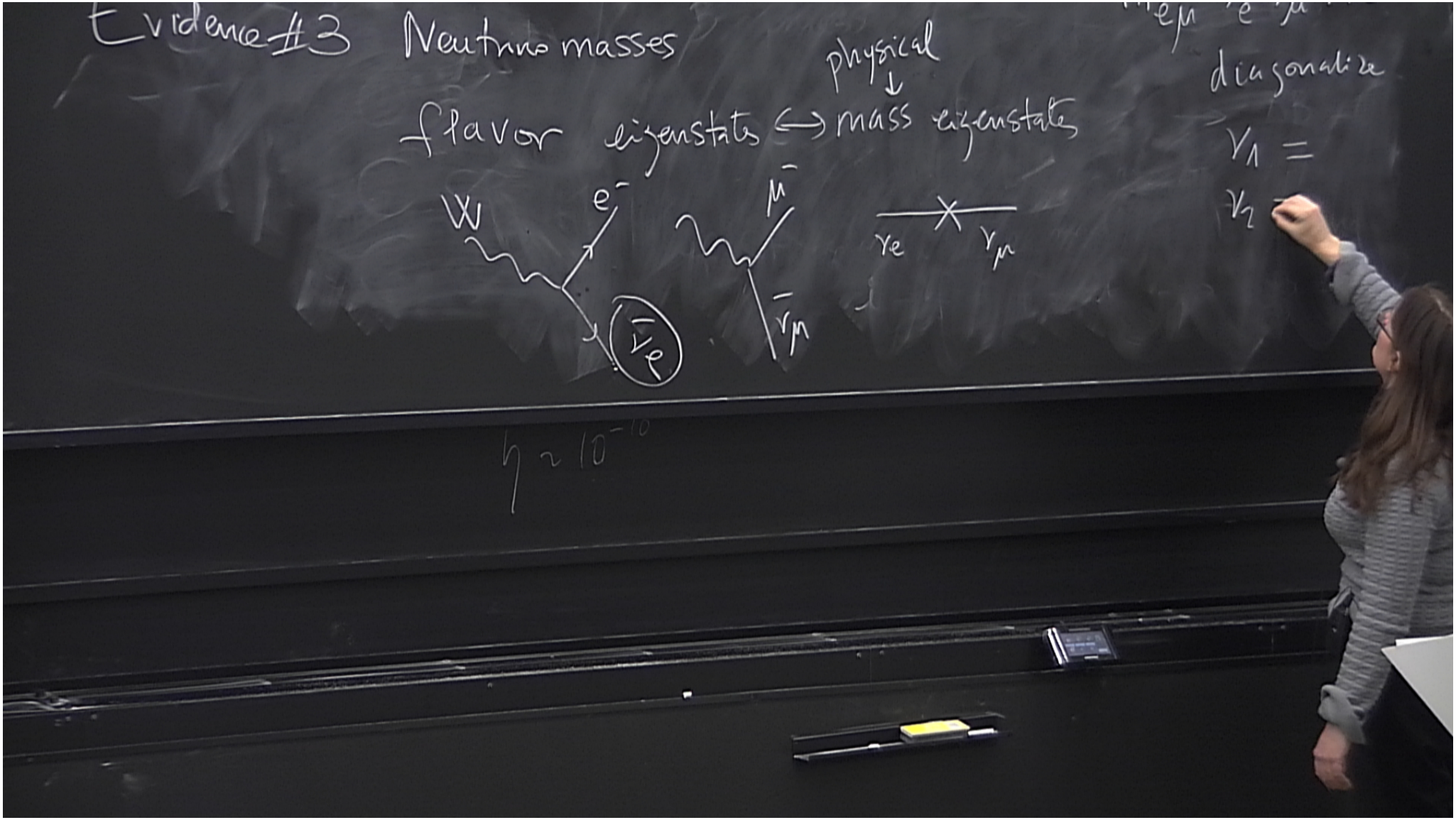
X is a baryon
$\bar{X}$ is antibaryon

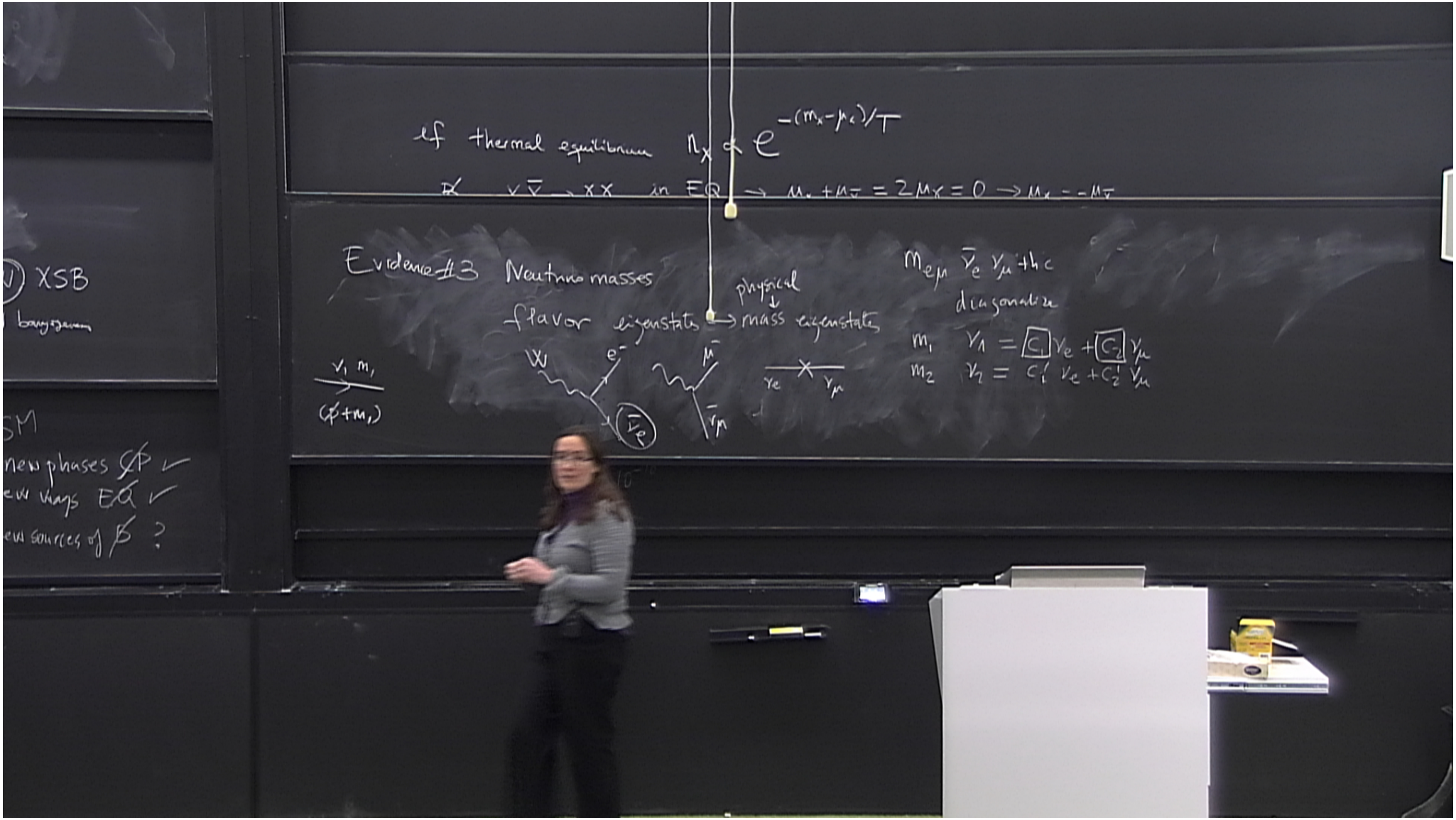
$\eta \propto n_X - n_{\bar{X}} \propto \sinh\left(\frac{\mu_X}{T}\right)$

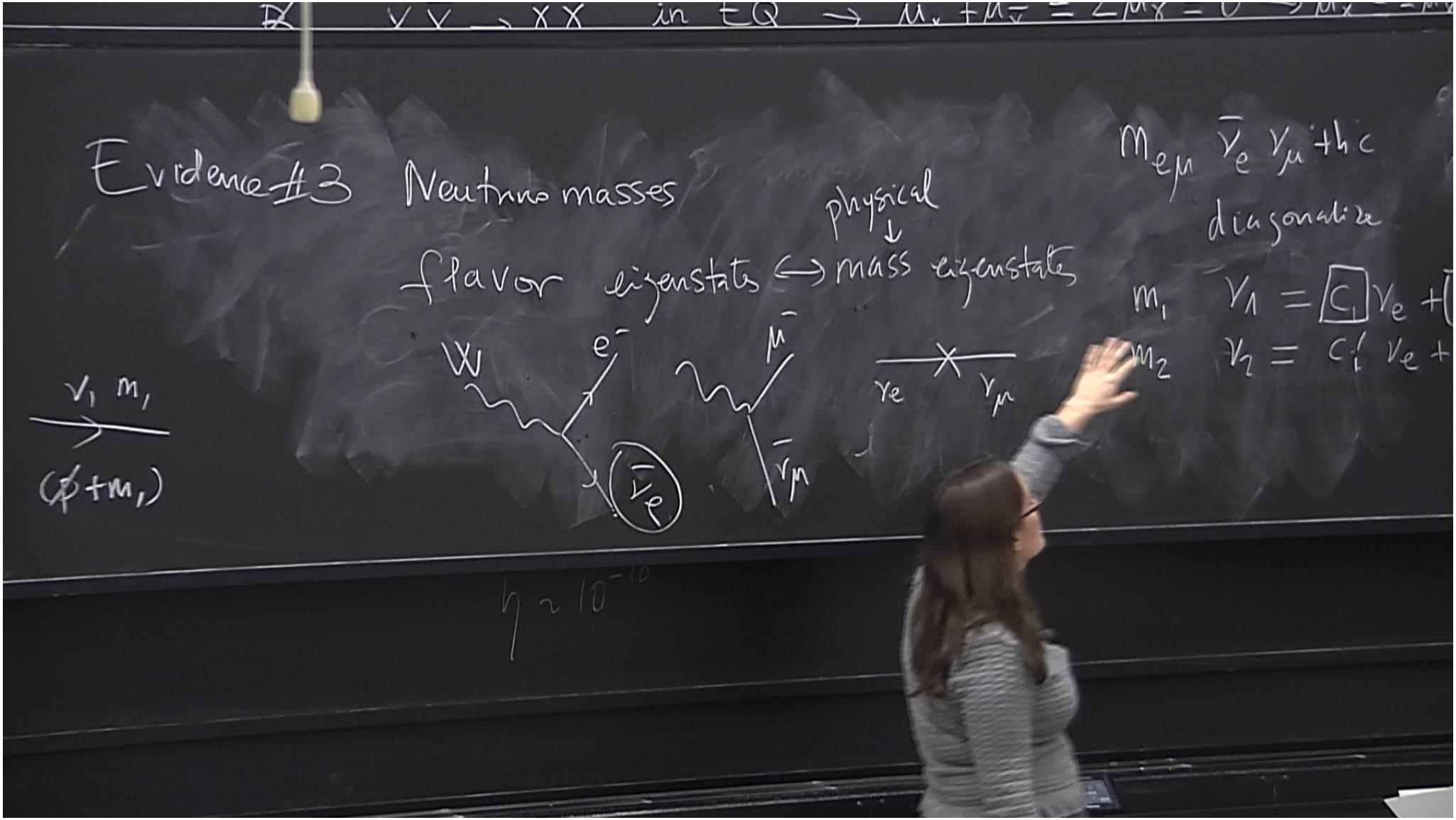
Evidence #3 Neutrino masses

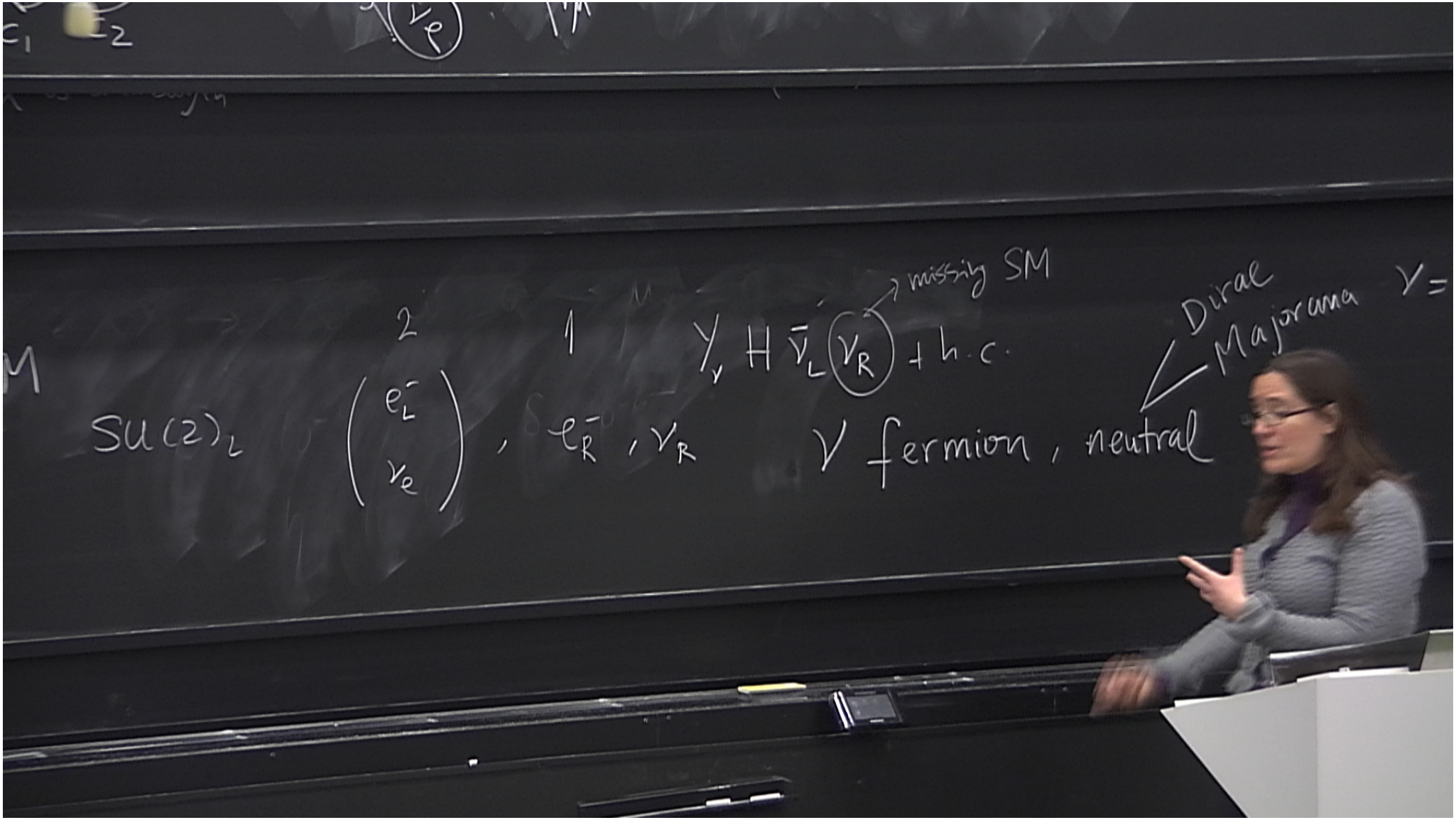
flavor eigenstates $\leftrightarrow$ mass eigenstates

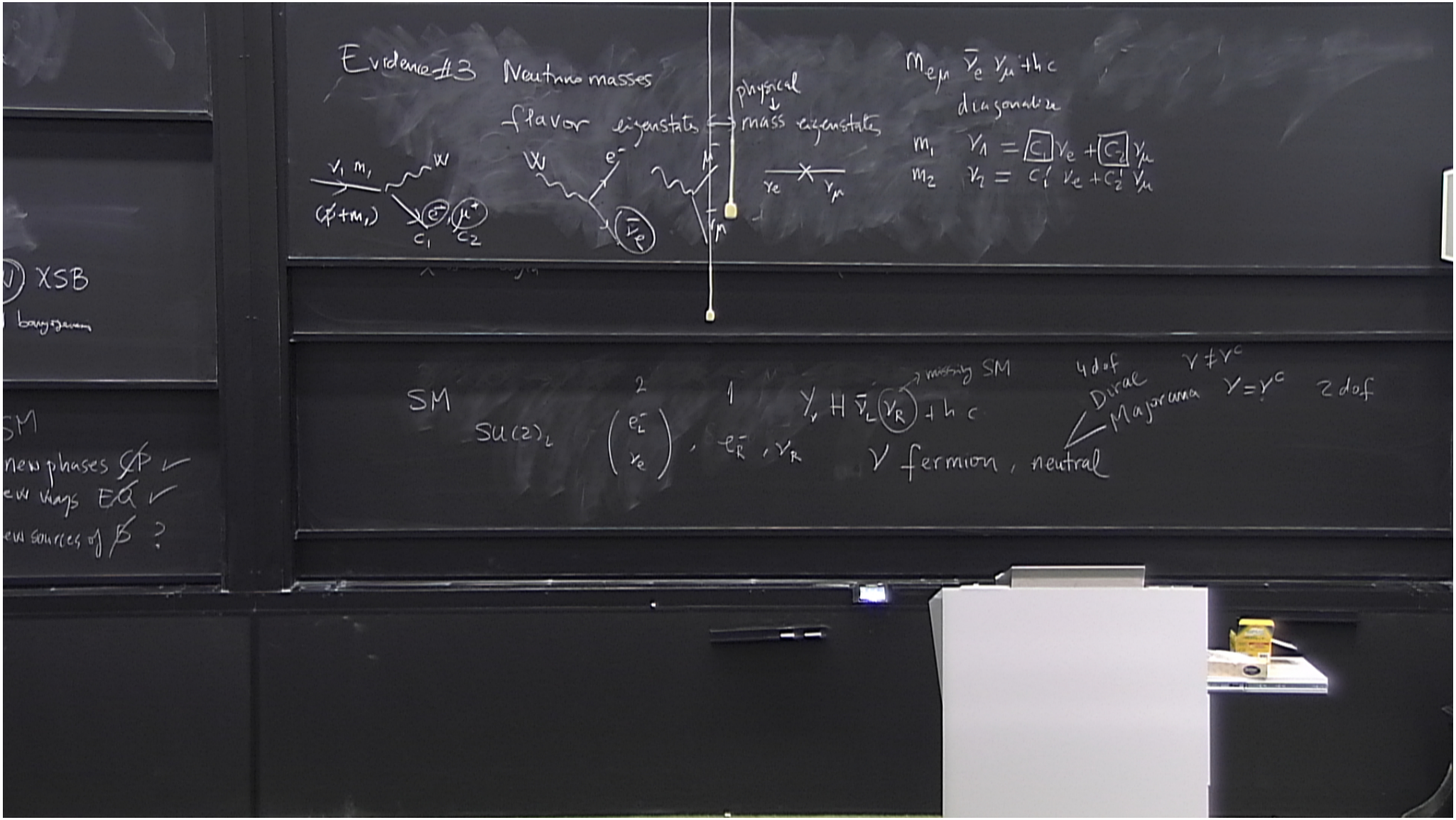


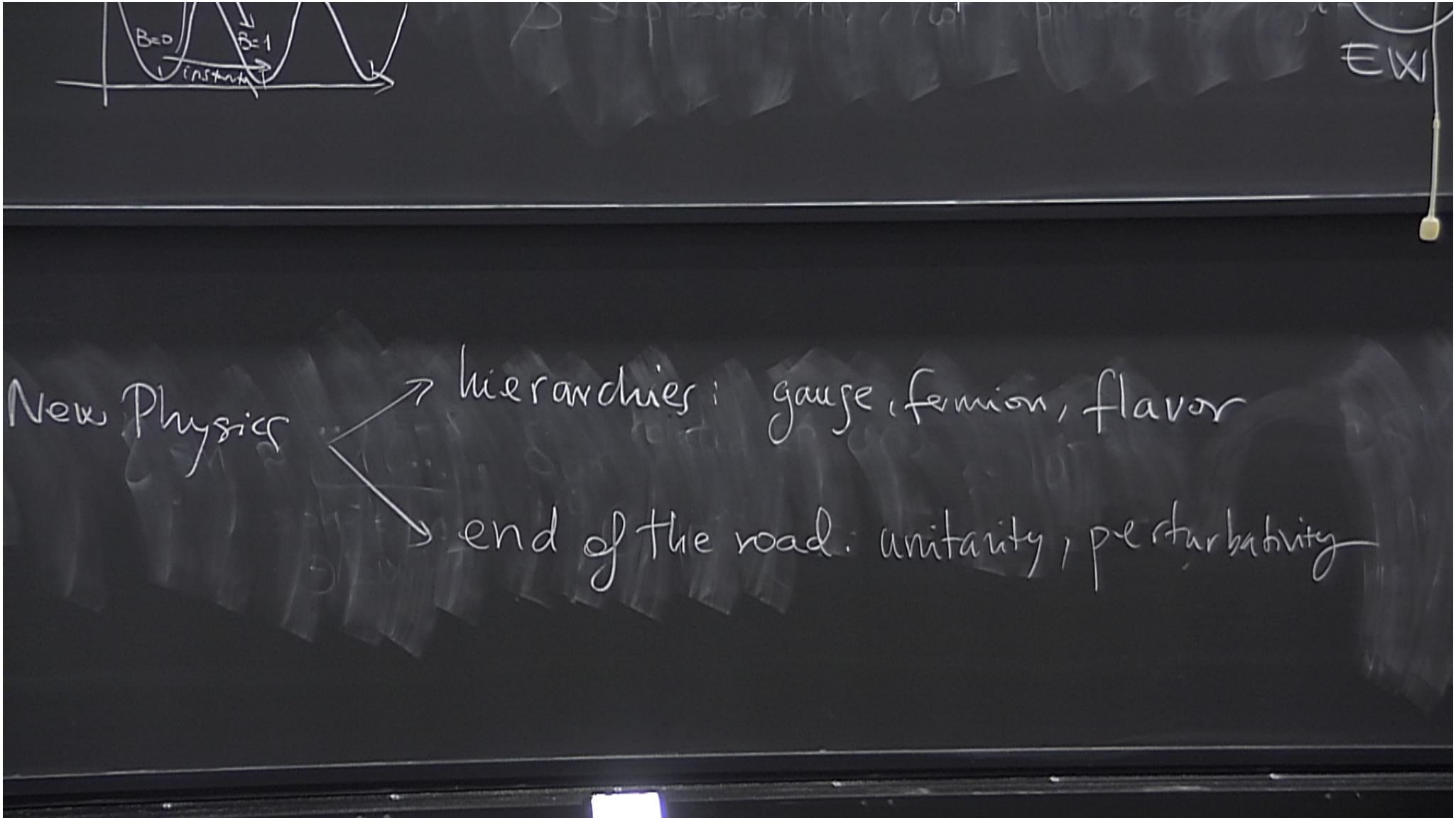

Evidence #3 Neutrino masses
physical
flavor eigenstates ⟷ mass eigenstates
diagonalize
W
e⁻
μ⁻
ν̄e
ν̄μ
νe
νμ
ν1 =
ν2 =
η ≈ 10⁻¹⁰


if thermal equilibrium $n_X \propto e^{-(m_X-\mu_X)/T}$
$X\bar{X} \to \nu\bar{\nu}, \bar{\nu}\nu, XX$ in EQ $\to \mu_\nu + \mu_{\bar{\nu}} = 2\mu_X = 0 \to \mu_X = -\mu_{\bar{X}}$
Evidence #3 Neutrino masses
flavor eigenstates → physical → mass eigenstates
$m_{e\mu}\ \bar{\nu}_e \nu_\mu + h.c.$
diagonalize
m_1 $\nu_1 = C_1 \nu_e + C_2 \nu_\mu$
m_2 $\nu_2 = C_1' \nu_e + C_2' \nu_\mu$
W
e^-
μ^-
$\bar{\nu}_e$
$\bar{\nu}_\mu$
ν_e ν_μ
ν_i, m_i
$(p+m_i)$
XSB
baryogenesis
SM
new phases CP ✓
new things EQ ✓
new sources of B ?


Evidence #3 Neutrino masses
flavor eigenstates ↔ mass eigenstates
physical
$m_{e\mu}\ \bar{\nu}_e \nu_\mu$ + h.c
diagonalize
m_1 $\nu_1 = c_1 \nu_e$ +
m_2 $\nu_2 = c_i \nu_e$ +
ν_1, m_1
$(\not{p} + m_1)$
W
e^-
μ^-
$\bar{\nu}_e$
$\bar{\nu}_\mu$
ν_e
ν_μ
$\eta \sim 10^{-10}$


missig SM
Dirac
Majorana
$SU(2)_L$
$\begin{pmatrix} e_L^- \\ \nu_e \end{pmatrix}$, e_R^-, ν_R
ν fermion, neutral
$Y_\nu H \bar{\nu}_L \nu_R + h.c.$


Evidence #3 Neutrino masses
flavor eigenstates ⟷ physical ↓ mass eigenstates
$m_{e\mu}\ \bar{\nu}_e \nu_\mu + h.c$
diagonalize
$m_1\ \ \nu_1 = c_1 \nu_e + c_2 \nu_\mu$
$m_2\ \ \nu_2 = c_1' \nu_e + c_2' \nu_\mu$
ν_1, m_1
W
$(\not{p} + m_1)$
c_1 c_2
ν_e ν_μ
XSB
SM
new phases CP ✓
new things EQ ✓
new sources of B ?
SM
$SU(2)_L$
$\begin{pmatrix} e_L^- \\ \nu_e \end{pmatrix}$ 2 , e_R^- 1 , ν_R
$Y_\nu H \bar{\nu}_L \nu_R + h.c$
missing SM
4 d.o.f
Dirac $\nu \neq \nu^c$
Majorana $\nu = \nu^c$ 2 d.o.f
ν fermion, neutral


B=0
B=1
instanton
EW
New Physics
hierarchies: gauge, fermion, flavor
end of the road: unitarity, perturbativity