Title: Lecture - Standard Model (Elective), PHYS 622

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Collection/Series: Standard Model (Elective), PHYS 622, January 5 - February 6, 2026

Subject: Particle Physics

Date: January 09, 2026 - 4:30 PM

URL: https://pirsa.org/26010032

$$C: \quad \psi(t,x) \rightarrow -i\gamma^2 \psi^*(t,x)$$

$$a_p^s \leftrightarrow b_p^s$$

$$P: \quad \psi(t,x) \rightarrow \gamma^0 \psi(t,-x)$$

$$a_p^s \rightarrow a_{-p}^s \, ; \quad b_p^s \rightarrow b_{-p}^s$$

$$T : (t, x) \to (-t, x)$$

$$T e^{-iHt} T^{-1} = e^{iHt}$$

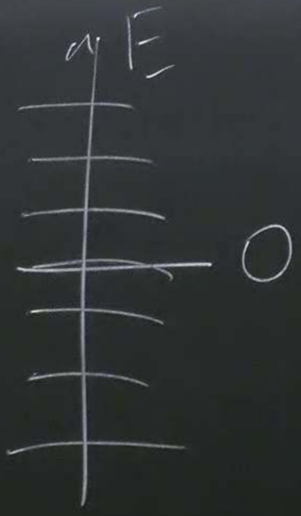
$$T|\Psi(t)\rangle = \eta|\Psi(-t)\rangle$$

$$T e^{-iHt}|\Psi_0\rangle = \eta e^{iHt}|\Psi_0\rangle = e^{iHt} T|\Psi_0\rangle$$

$$T|\Psi_0\rangle = \eta|\Psi_0\rangle$$

i) T - ~~linear,~~ unitary

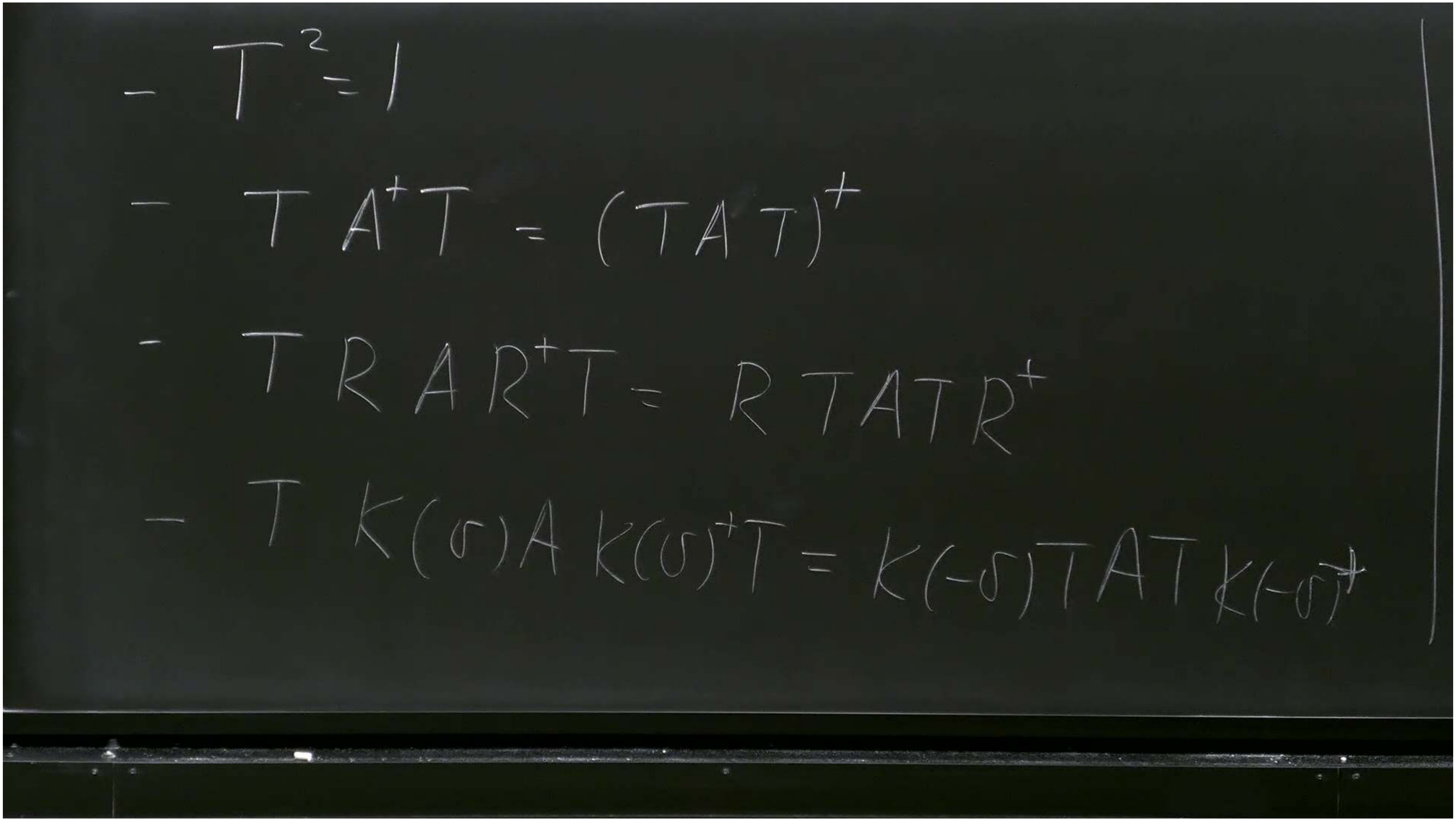
$$\underbrace{THT^{-1} = -H} \Rightarrow E \to -E$$



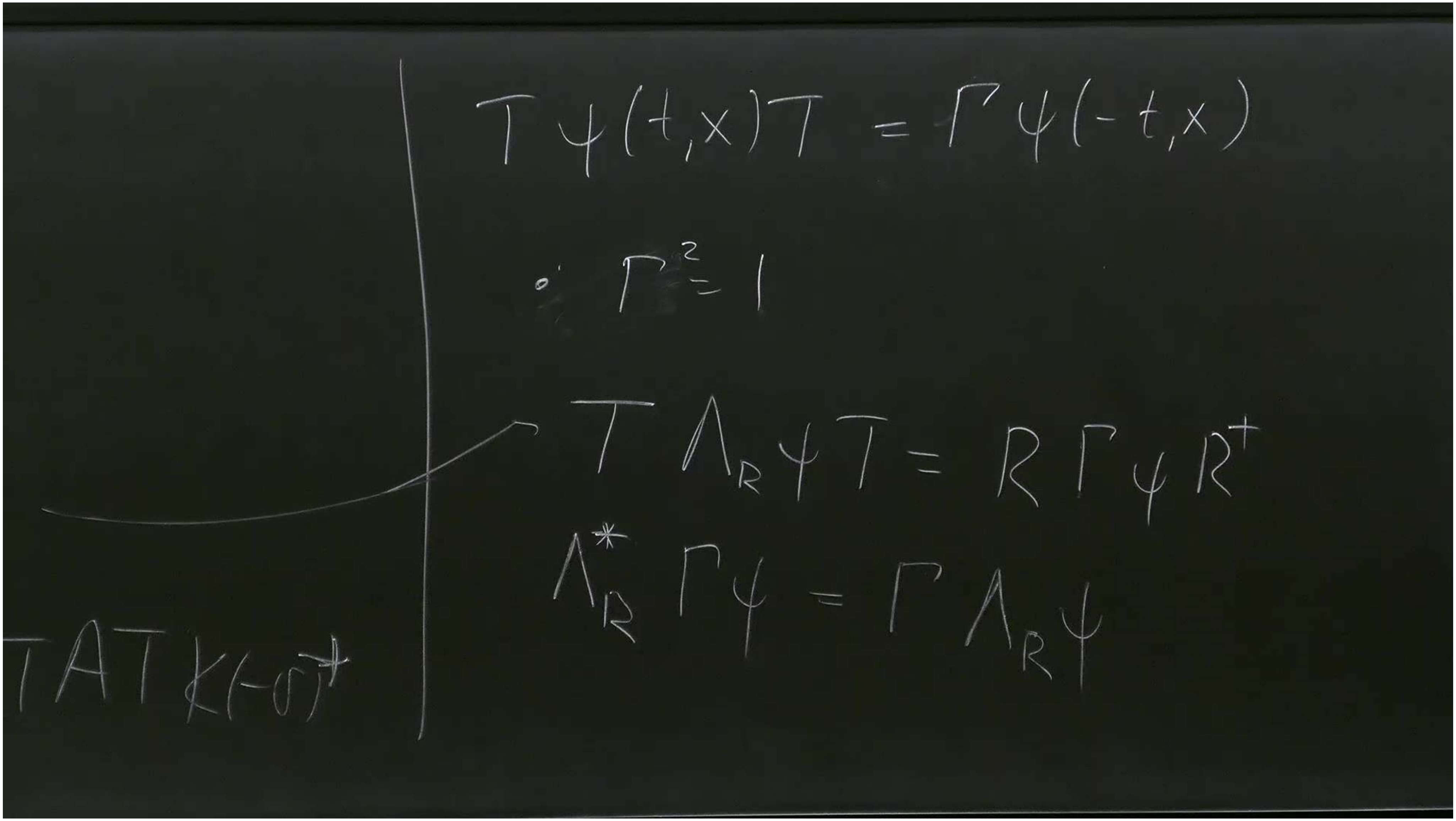
ii) T- anti-linear, anti-unitary

$$\hookrightarrow T(\alpha|\psi_1\rangle + \beta|\psi_2\rangle) = \alpha^* T|\psi_1\rangle + \beta^* T|\psi_2\rangle$$

$$THT^{-1} = H$$



- $T^2 = 1$
- $T A^\dagger T = (TAT)^\dagger$
- $T R A R^\dagger T = R T A T R^\dagger$
- $T K(\sigma) A K(\sigma)^\dagger T = K(-\sigma) T A T K(-\sigma)^\dagger$



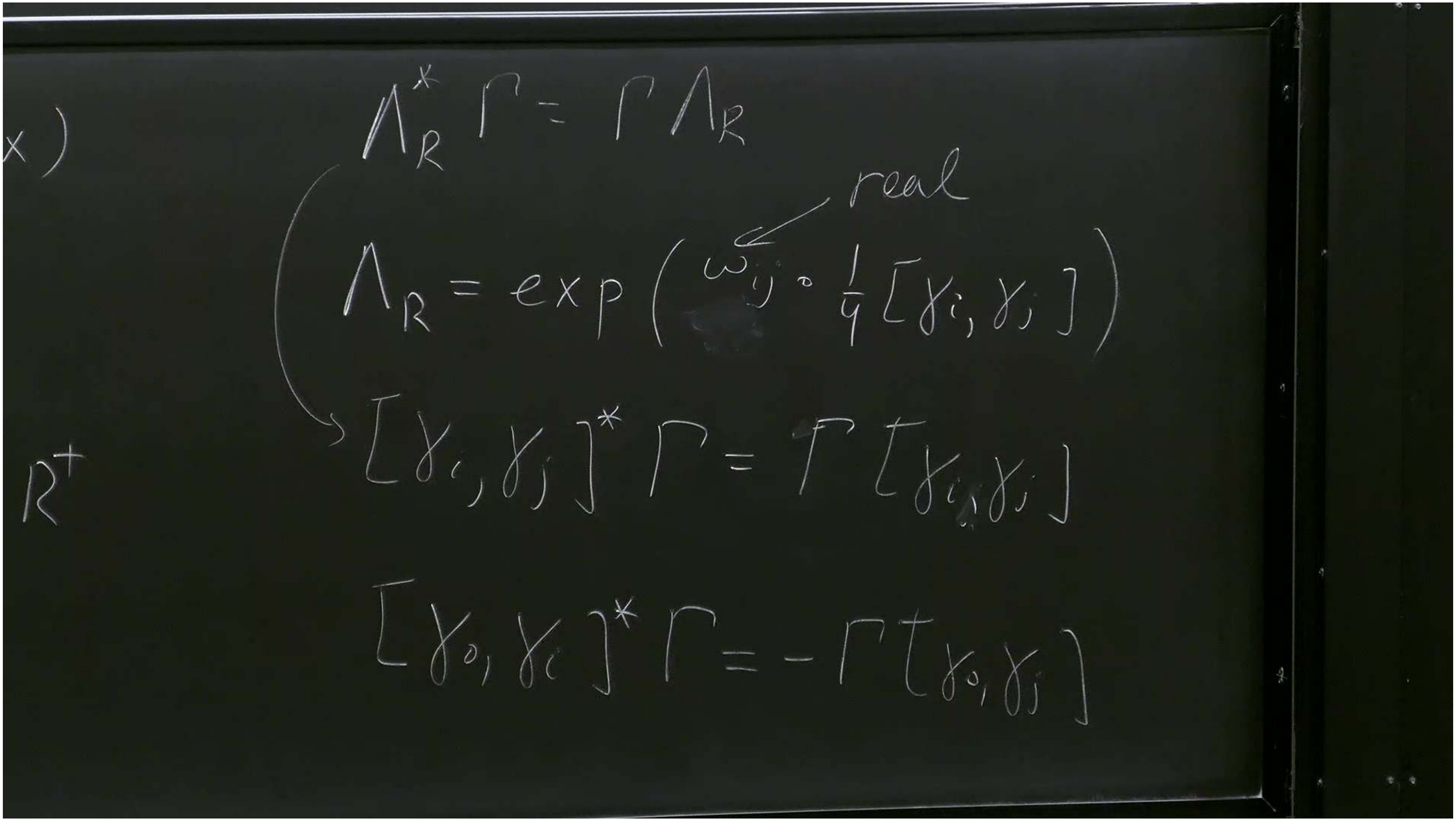
$$T\psi(t,x)T = \Gamma\psi(-t,x)$$

$$\Gamma^2 = 1$$

$$T\Lambda_R\psi T = R\Gamma\psi R^\dagger$$

$$\Lambda_R^*\Gamma\psi = \Gamma\Lambda_R\psi$$

$$TAT\,K(-\sigma)^\dagger$$



x)

$R^\dagger$

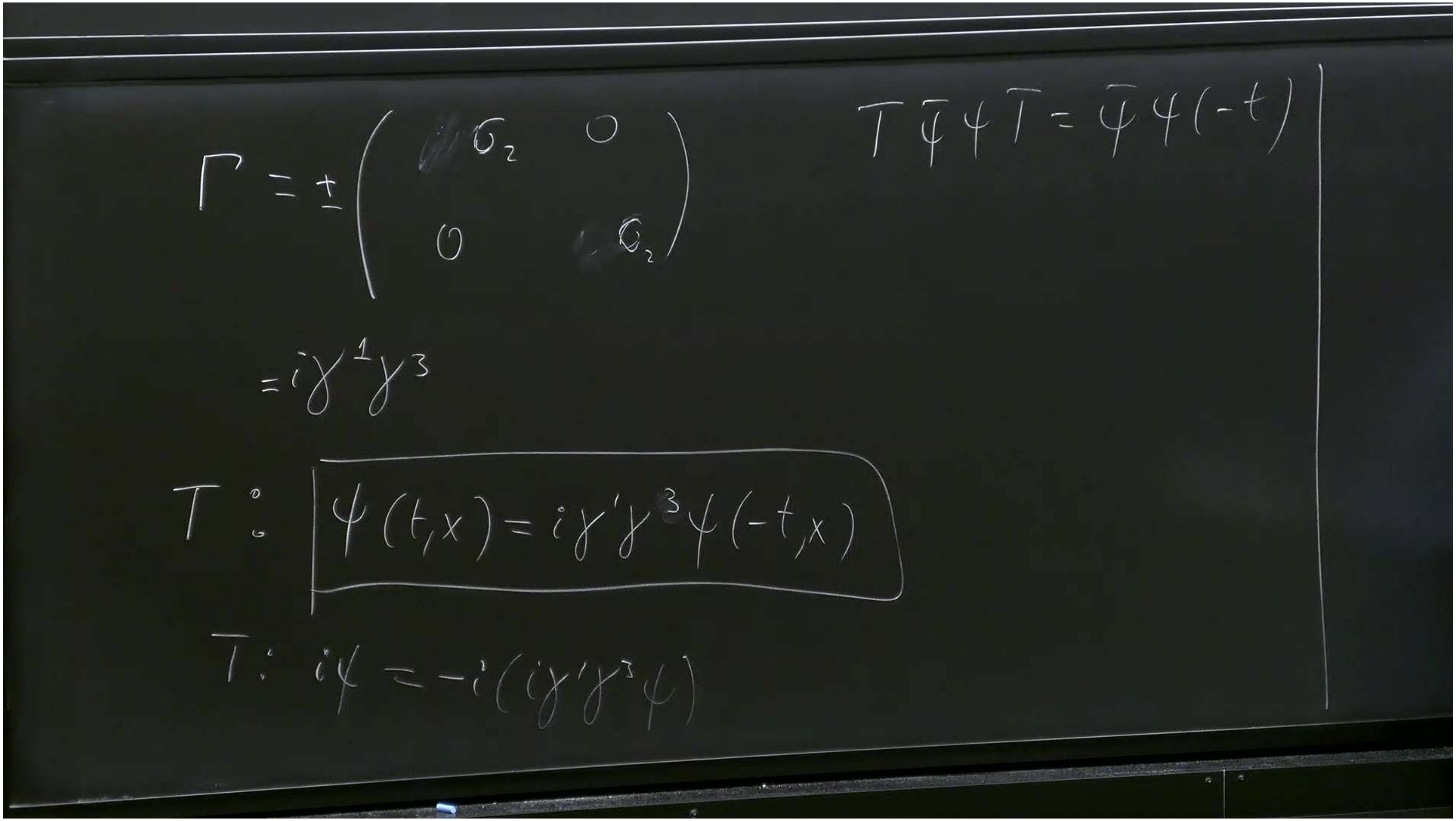
$$\Lambda_R^* \Gamma = \Gamma \Lambda_R$$

real

$$\Lambda_R = \exp\left(\omega_{ij} \cdot \frac{1}{4}[\gamma_i, \gamma_j]\right)$$

$$[\gamma_i, \gamma_j]^* \Gamma = \Gamma [\gamma_i, \gamma_j]$$

$$[\gamma_0, \gamma_i]^* \Gamma = -\Gamma [\gamma_0, \gamma_j]$$



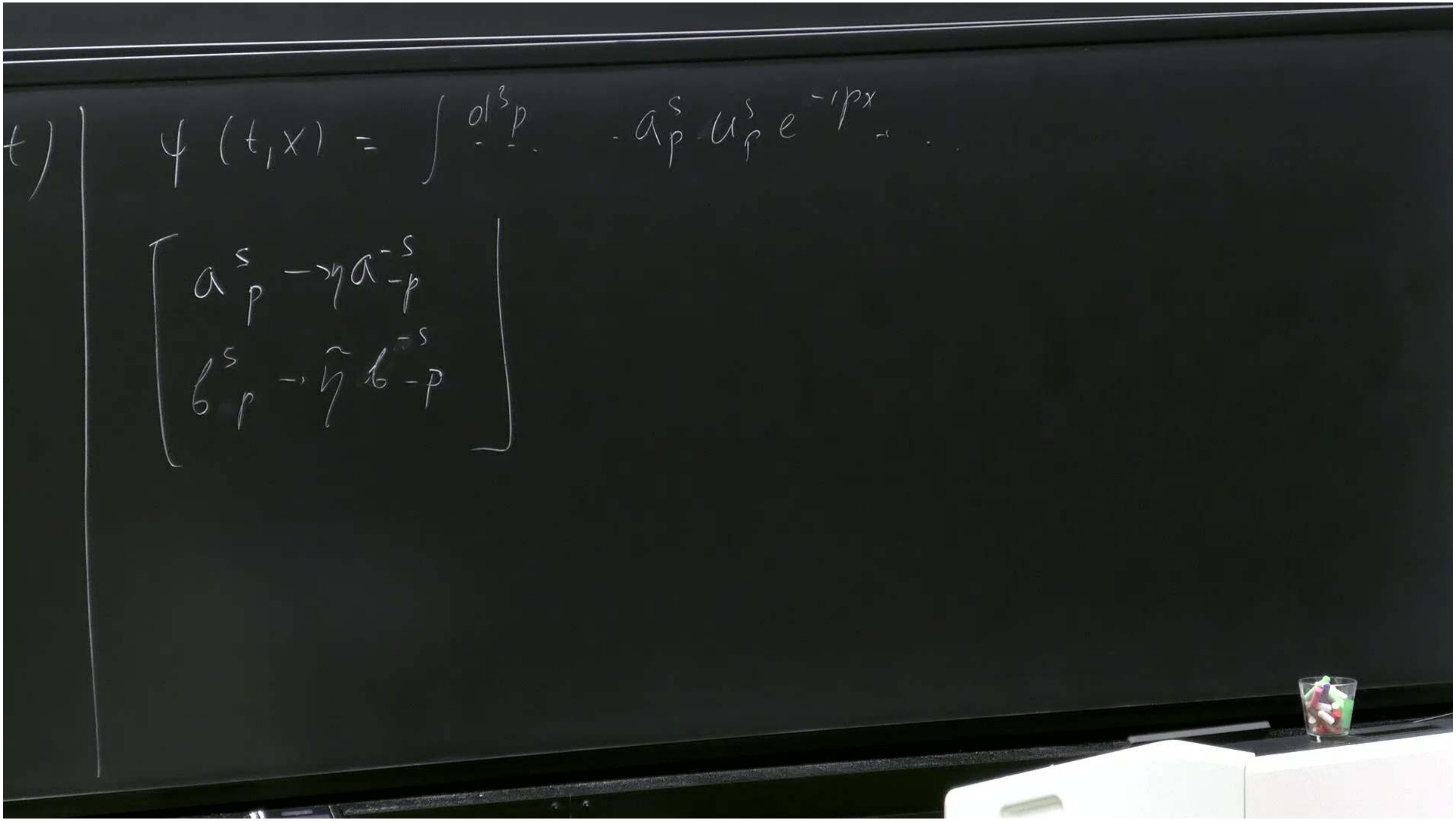
$$\Gamma = \pm\begin{pmatrix} \sigma_2 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$

$$= i\gamma^1\gamma^3$$

$$T: \boxed{\psi(t,x) = i\gamma^1\gamma^3\psi(-t,x)}$$

$$T: i\psi = -i(i\gamma^1\gamma^3\psi)$$

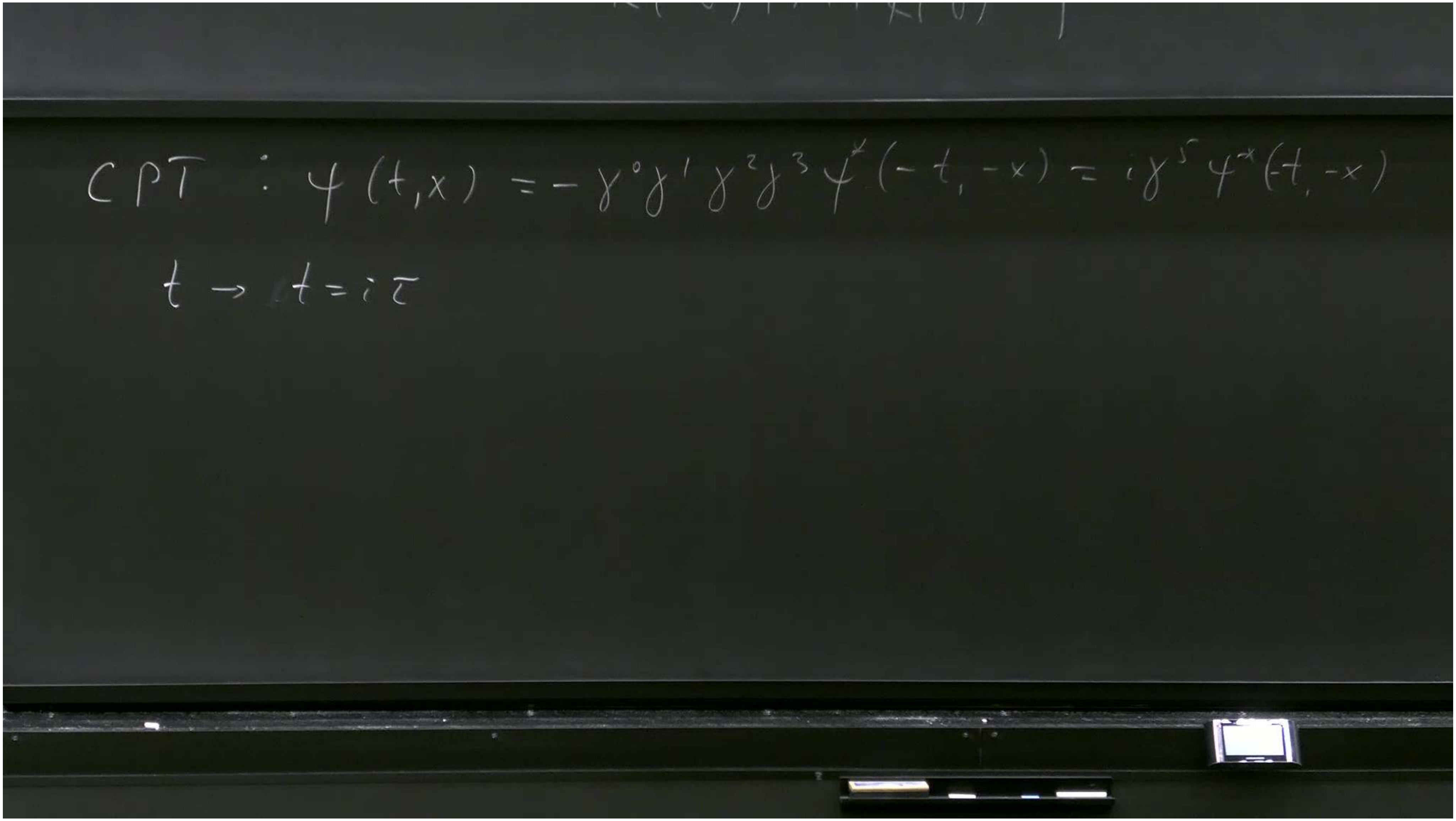
$$T\bar{\psi}\psi T = \bar{\psi}\psi(-t)$$



$t)$

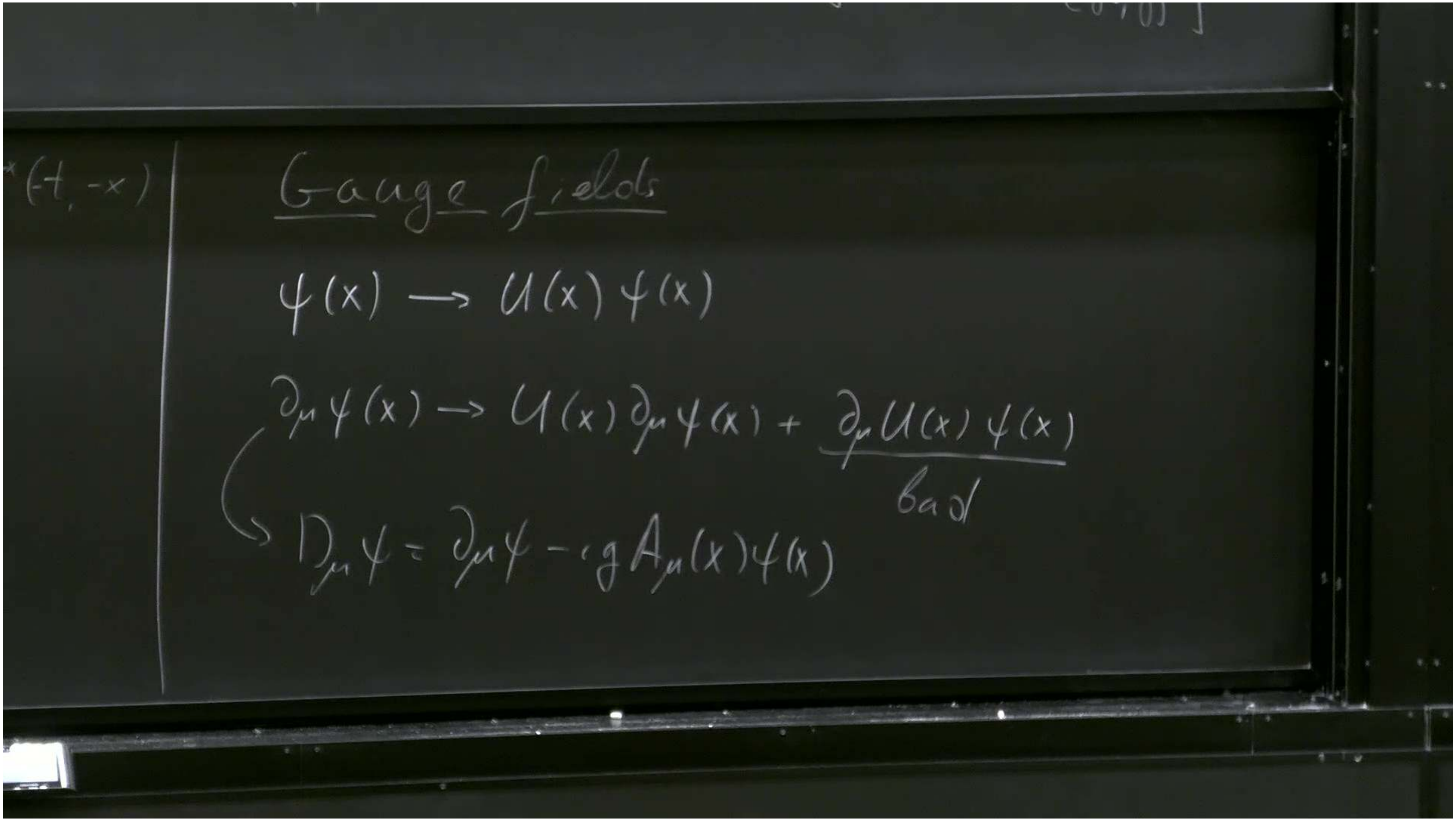
$$\psi(t,x) = \int d^3p \; a_p^s \, u_p^s \, e^{-ipx}$$

$$\begin{bmatrix} a_p^s \to \eta \, a_{-p}^{-s} \\ b_p^s \to \tilde{\eta} \, b_{-p}^{-s} \end{bmatrix}$$



$$\text{CPT}: \psi(t,x) = -\gamma^0\gamma^1\gamma^2\gamma^3\psi^*(-t,-x) = i\gamma^5\psi^*(-t,-x)$$

$$t \rightarrow t = i\tau$$



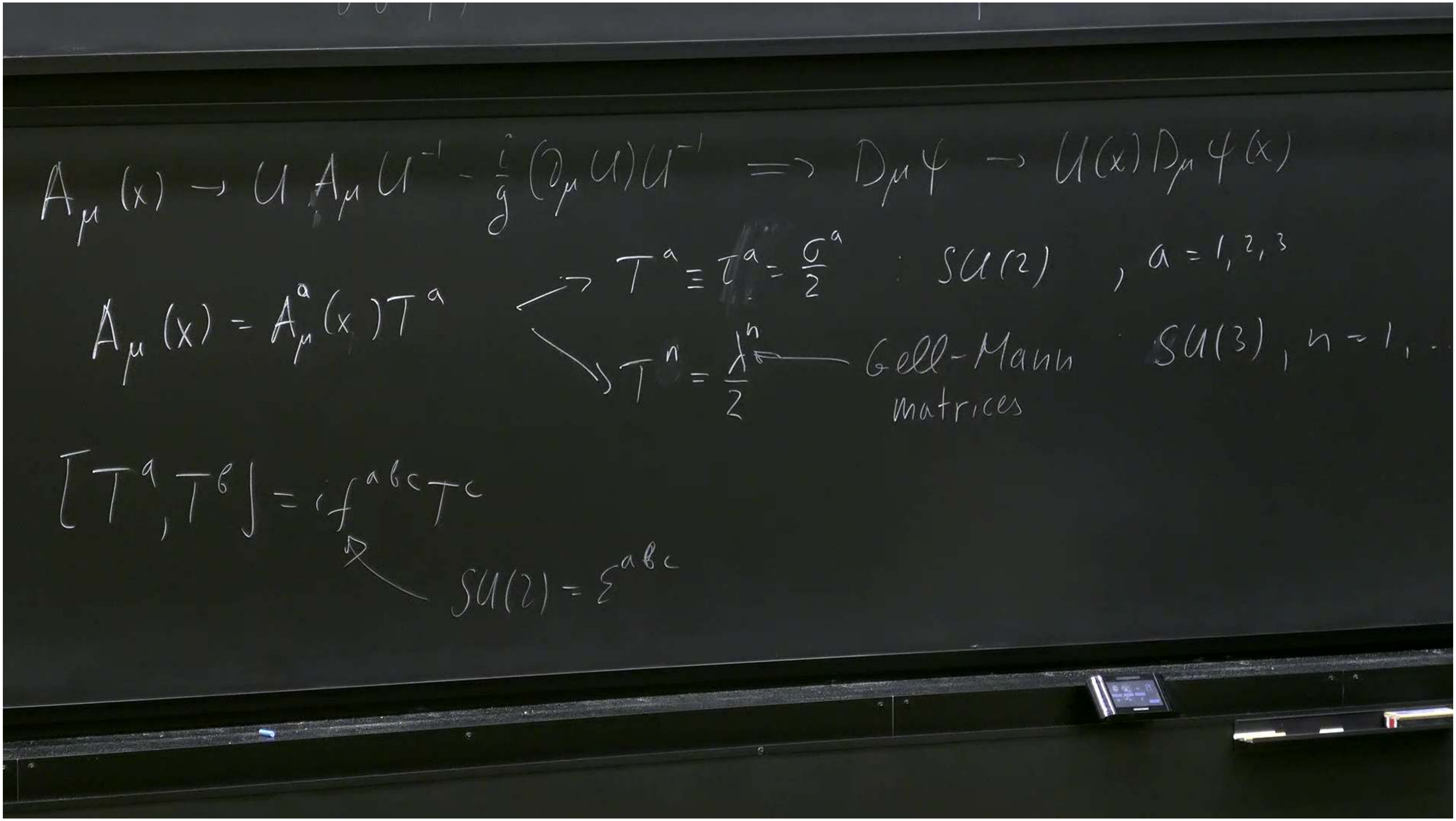
$^*(-t,-x)$

Gauge fields

$$\psi(x) \longrightarrow U(x)\,\psi(x)$$

$$\partial_\mu \psi(x) \longrightarrow U(x)\,\partial_\mu \psi(x) + \underbrace{\partial_\mu U(x)\,\psi(x)}_{\text{bad}}$$

$$D_\mu \psi = \partial_\mu \psi - i g A_\mu(x)\,\psi(x)$$



$$A_\mu(x) \to U A_\mu U^{-1} - \frac{i}{g}(\partial_\mu U)U^{-1} \Longrightarrow D_\mu\psi \to U(x) D_\mu \psi(x)$$

$$A_\mu(x) = A_\mu^a(x) T^a$$

$\nearrow$ $T^a \equiv \tau^a = \frac{\sigma^a}{2}$: SU(2) , $a = 1, 2, 3$

$\searrow$ $T^n = \frac{\lambda^n}{2}$ ← Gell-Mann matrices : SU(3) , $n = 1, \ldots$

$$[T^a, T^b] = i f^{abc} T^c$$

↖ SU(2) = ε^{abc}

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig\left[A_\mu, A_\nu\right]$$

$$F_{\mu\nu} \rightarrow U F_{\mu\nu} U^{-1}$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$\mathcal{L}_{YM} = -\frac{1}{2} \operatorname{tr}\left(F_{\mu\nu} F_{\mu\nu}\right) = -\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu}$$

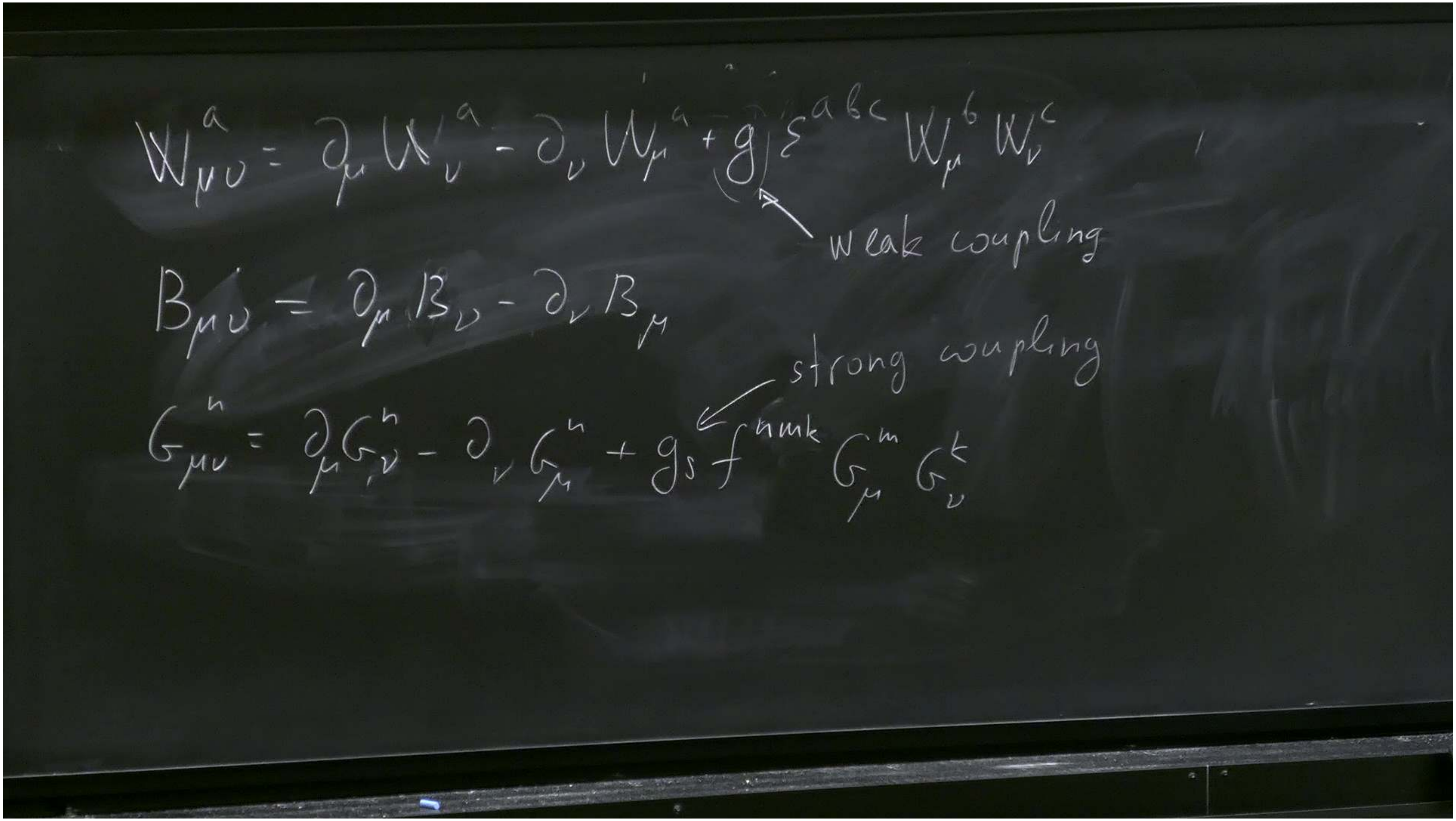
Interactions of gauge bosons and matter fermions

$$\mathcal{L}_{g+f} = -\frac{1}{4}\left(W^{a}_{\mu\nu}\right)^2 - \frac{1}{4} B^2_{\mu\nu} - \frac{1}{4}\left(G^{n}_{\mu\nu}\right)^2$$

$$+ i \bar{L}_i \not{D} L_i + i \bar{e}_{R_i} \not{D} e_{R_i}$$

$$+ i \bar{Q}_i \not{D} Q_i + i \bar{u}_{R_i} \not{D} u_{R_i} + i \bar{d}_{R_i} \not{D} d_{R_i}$$

$T:\ \psi(t,x) = i\gamma^1\gamma^3\psi(-t$



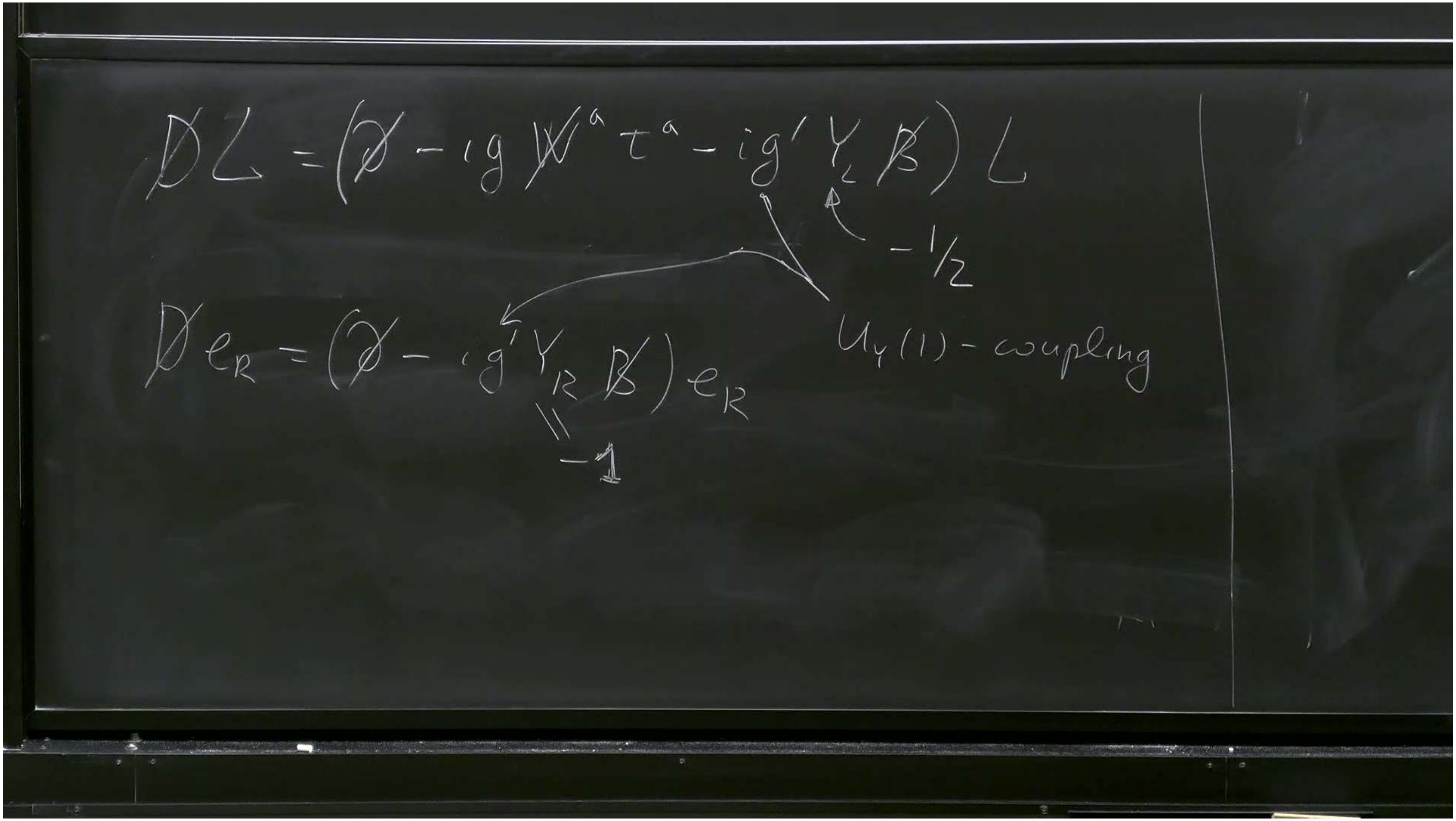
$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\,\varepsilon^{abc} W^b_\mu W^c_\nu$$

weak coupling

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

strong coupling

$$G^n_{\mu\nu} = \partial_\mu G^n_\nu - \partial_\nu G^n_\mu + g_s f^{nmk} G^m_\mu G^k_\nu$$



$$\not{D} L = \left(\not{\partial} - i g \not{W}^a \tau^a - i g' \underbrace{Y_L}_{-1/2} \not{B}\right) L$$

$U_Y(1)$ - coupling

$$\not{D} e_R = \left(\not{\partial} - i g' \underbrace{Y_R}_{= -1} \not{B}\right) e_R$$

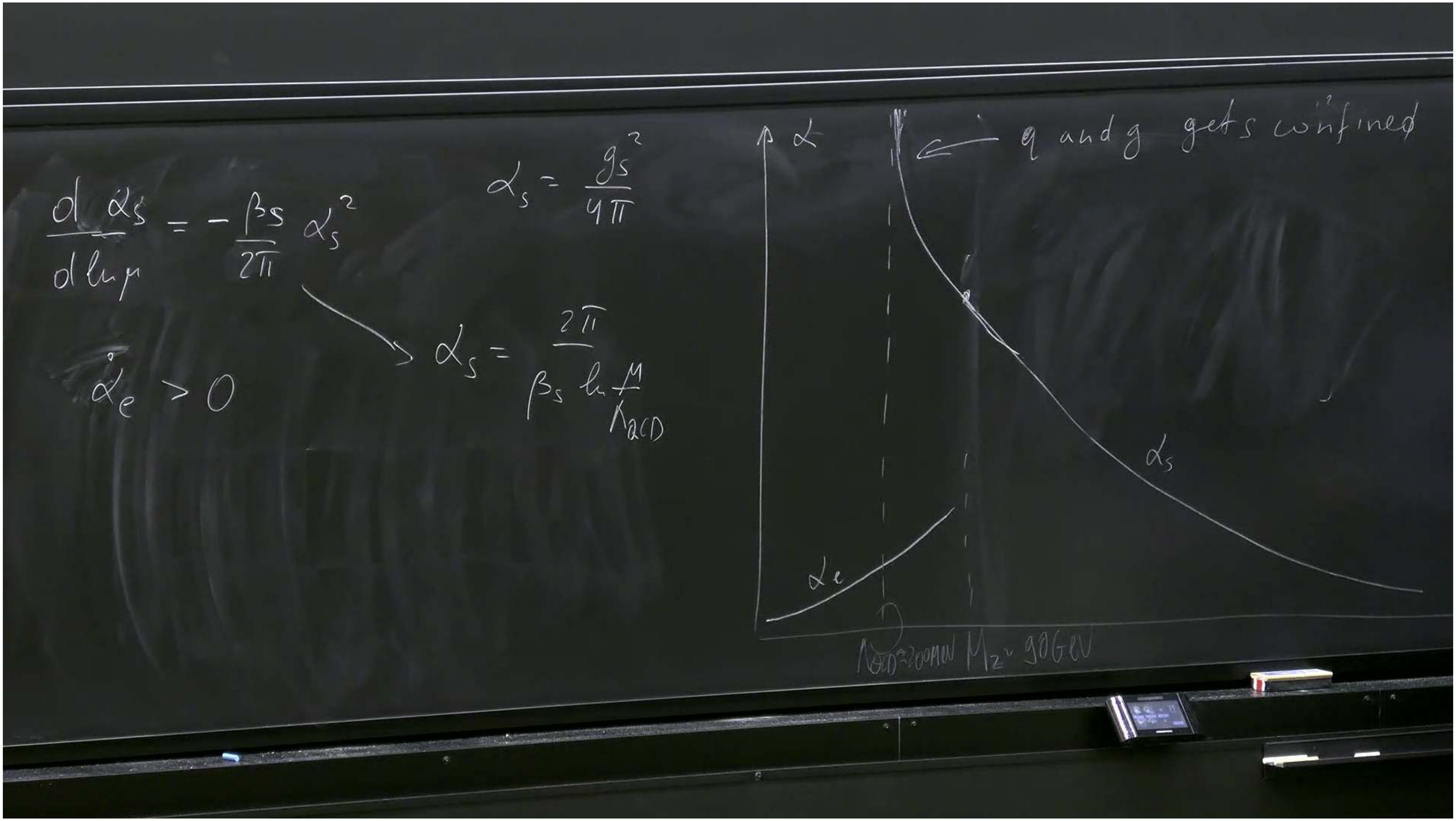
$$\not{D} Q^\alpha = \left(\left(\not{\partial} - i g \not{W}^a \tau^a - i g' \underset{\uparrow \atop \frac{1}{6}}{Y_Q} \not{B} \right) \delta^{\alpha\beta} - i g_s \not{G}^n \left(\frac{\hat{\lambda}^n}{2} \right)^{\alpha\beta} \right) Q^\beta$$

$$* \quad \Delta\mathcal{L} = \theta_1 \frac{g'^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} B_{\mu\nu} B_{\alpha\beta} + \theta_2 \frac{g^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^a_{\mu\nu} +$$

$$+ \theta_{QCD} \frac{g_s^2}{32\pi^2} G^n_{\mu\nu} \tilde{G}^n_{\mu\nu}$$

$$\to \partial_\mu \left(\varepsilon^{\mu\nu\alpha\beta} B_\nu B_{\alpha\beta} \right)$$

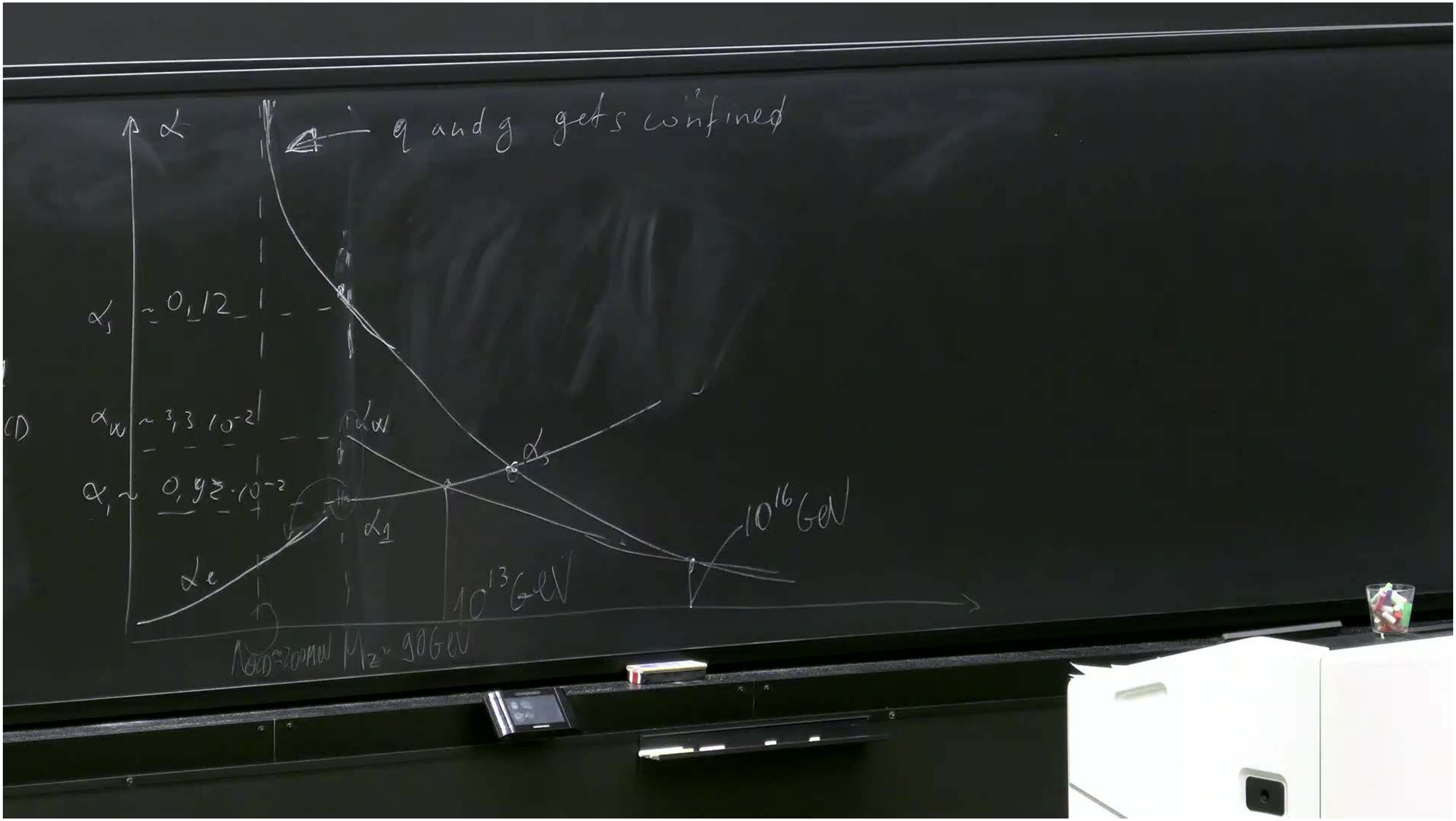
$$\to \partial_\mu \left(\varepsilon^{\mu\nu\alpha\beta} \dots \right)$$



$$\frac{d\alpha_s}{d\ln\mu} = -\frac{\beta_s}{2\pi}\alpha_s^2 \xrightarrow{\quad} \alpha_s = \frac{2\pi}{\beta_s \ln\frac{\mu}{\Lambda_{QCD}}}$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$\dot{\alpha}_e > 0$$


α
q and g gets confined
α_s ≈ 0,12
α_W ~ 3,3 10^-2
α_1 ~ 0,93·10^-2
α_W
α_s
α_1
α_e
10^13 GeV
10^16 GeV
Λ_QCD ≈ 200 MeV
M_Z ≈ 90 GeV