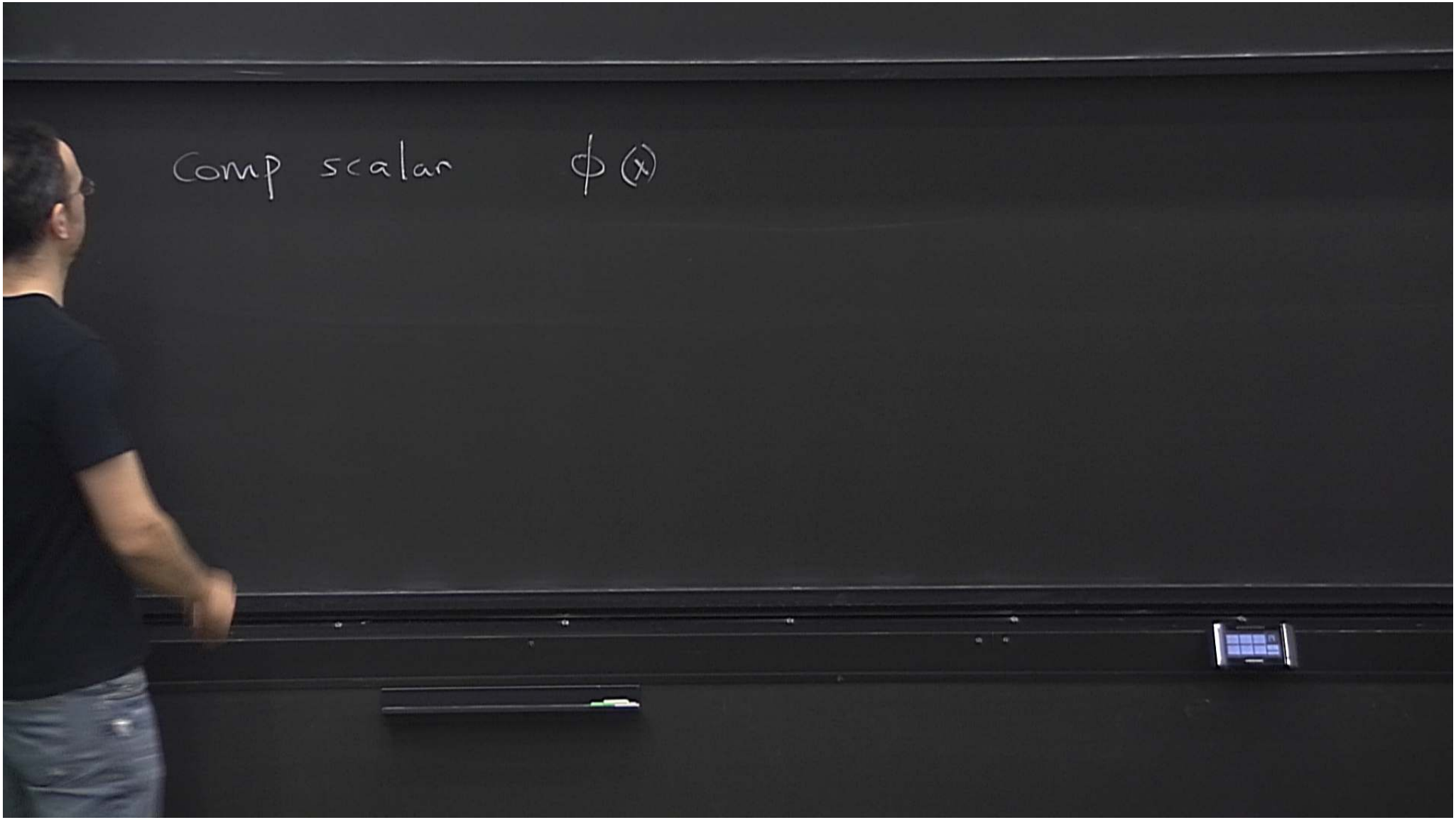
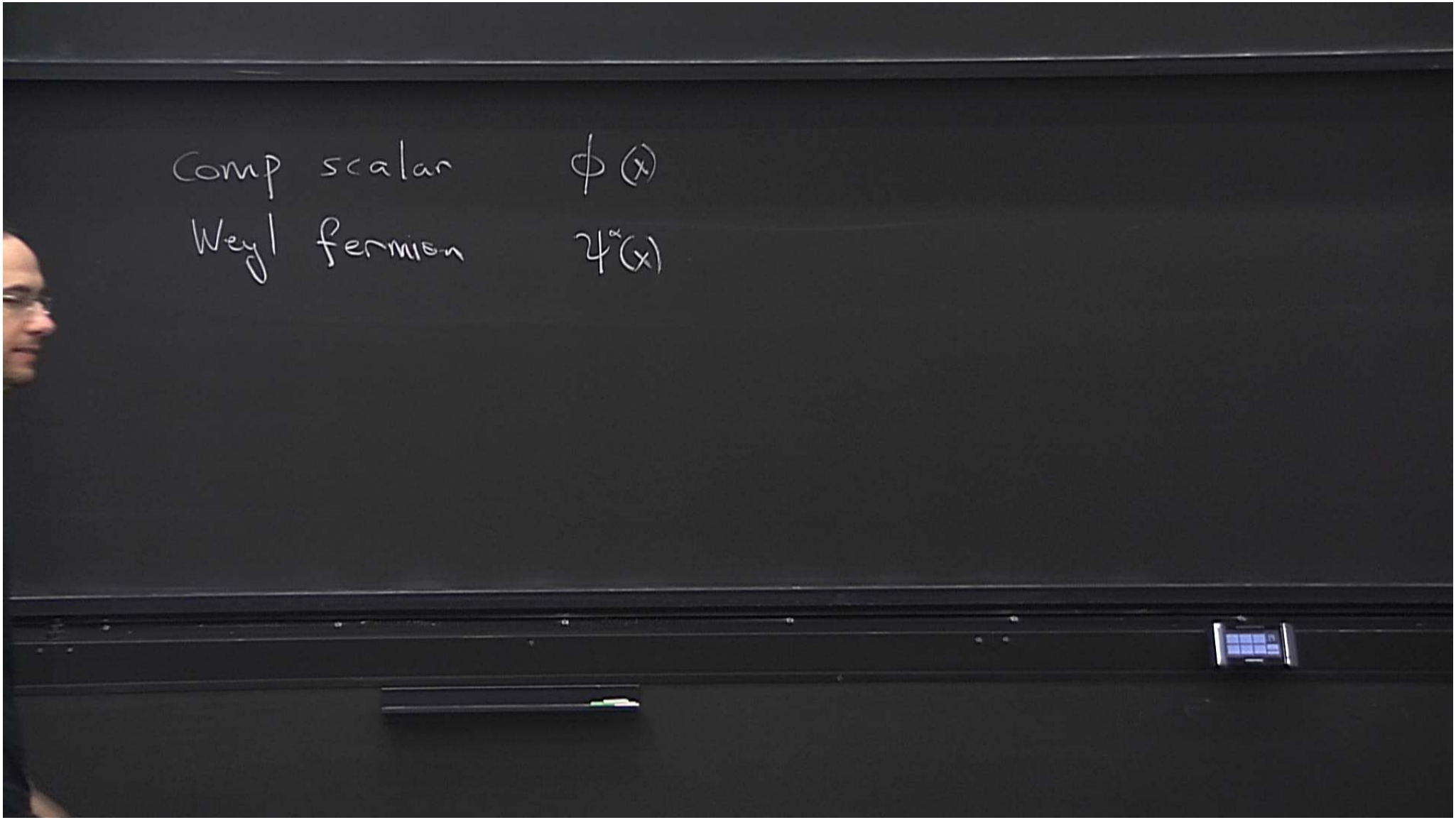
Title: 12/13 PSI - Beyond the Standard Model Lecture 1

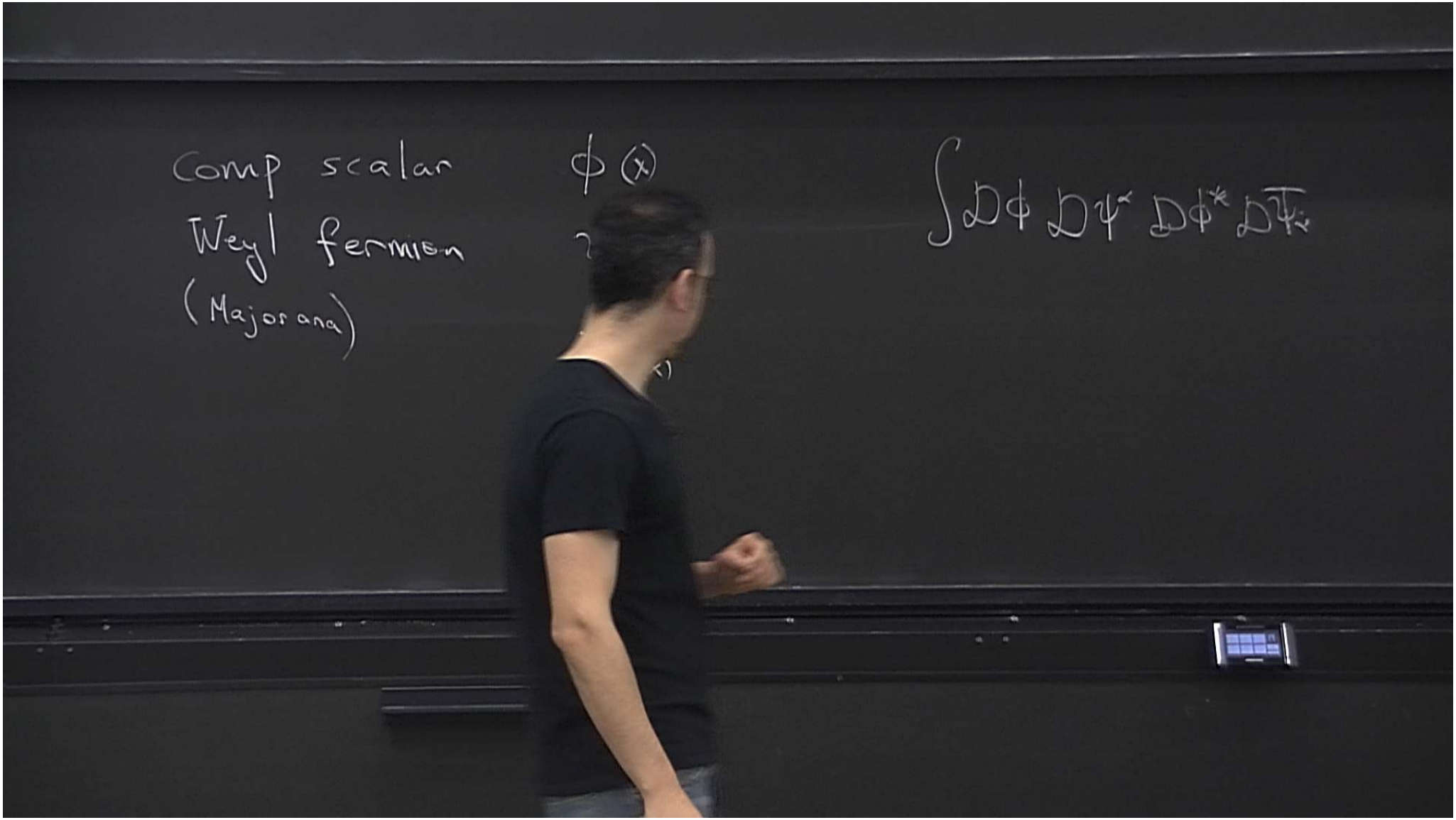
Date: Feb 19, 2013 09:00 AM

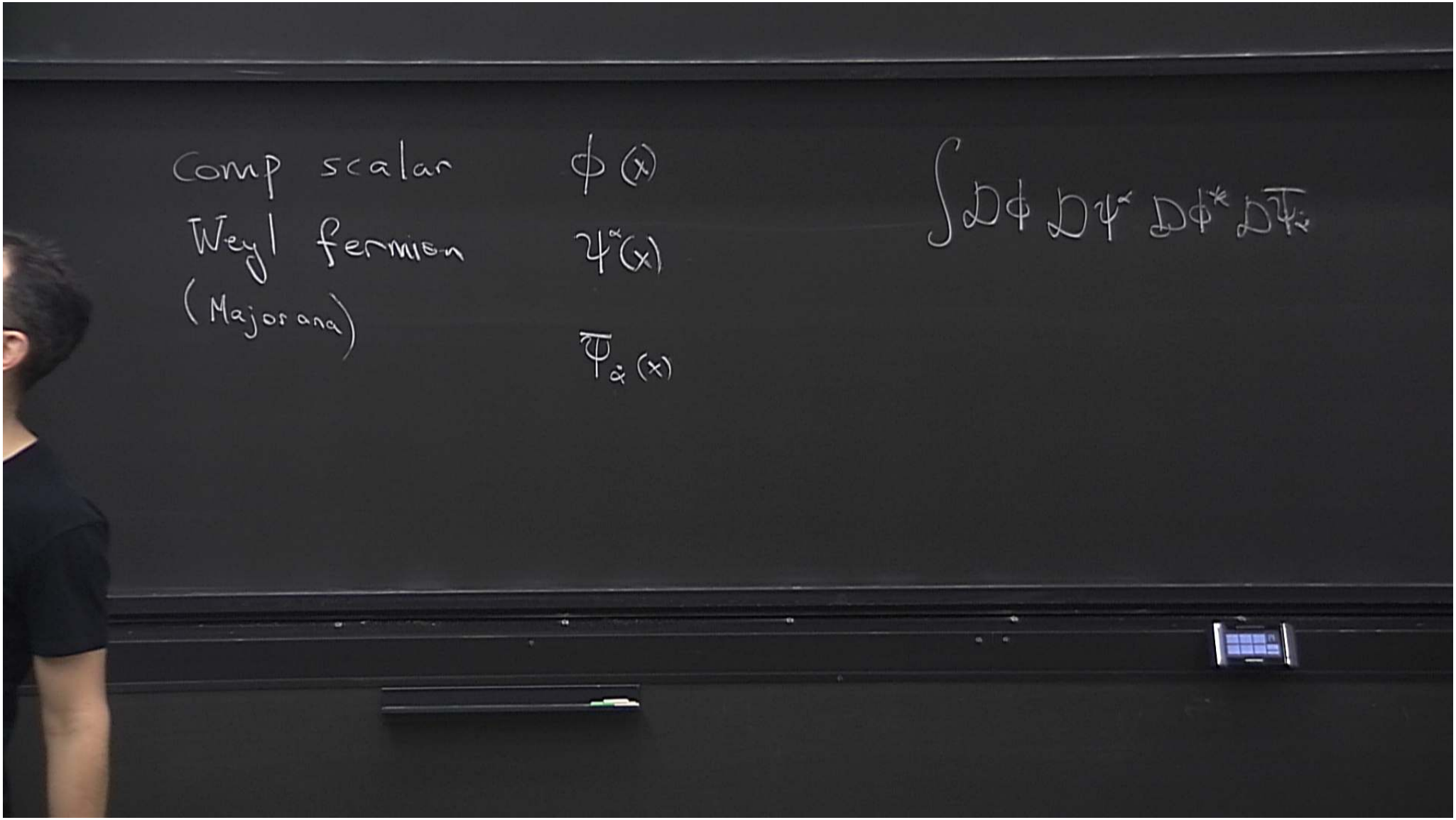
URL: http://www.pirsa.org/13020089

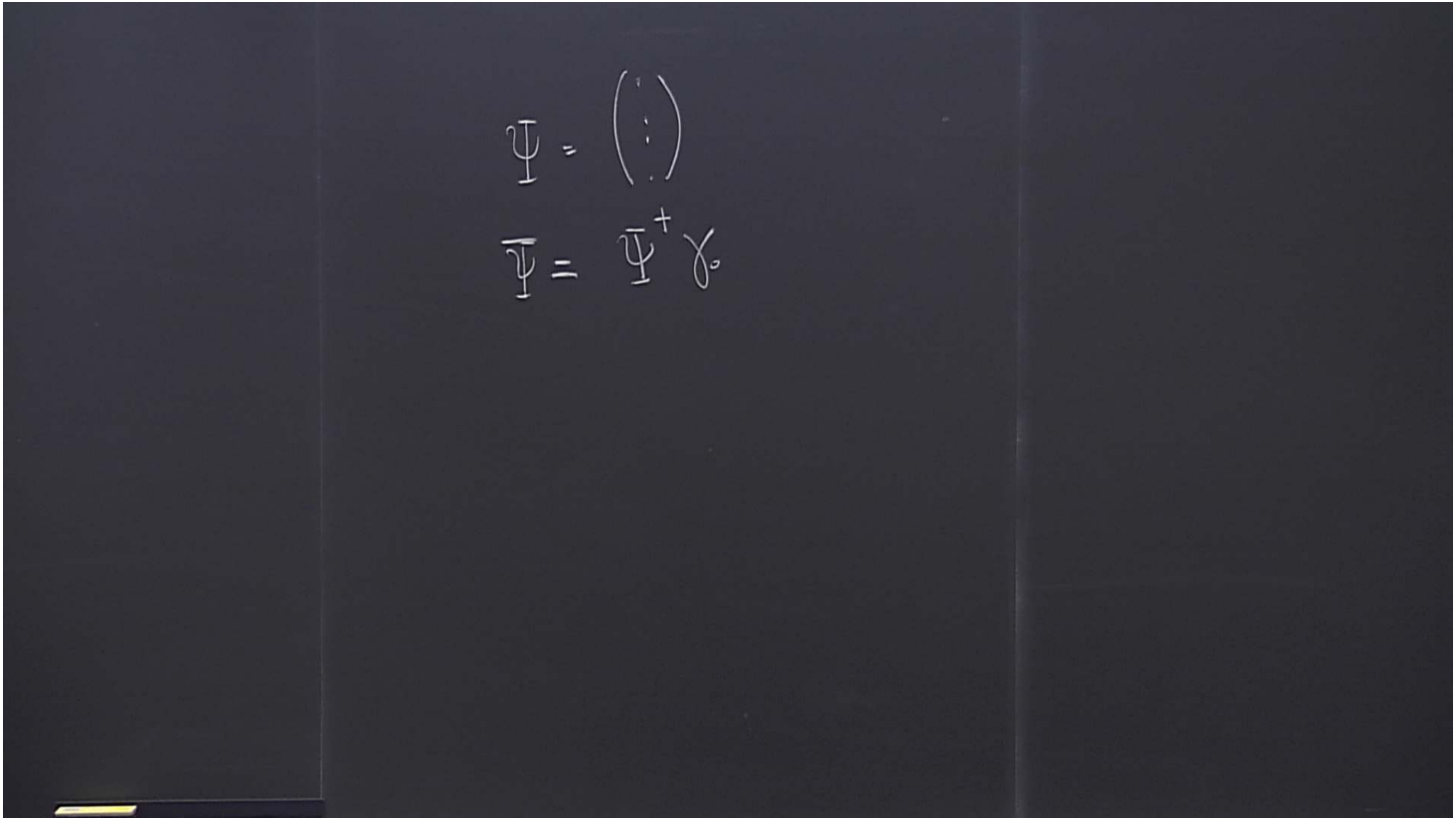
Abstract:

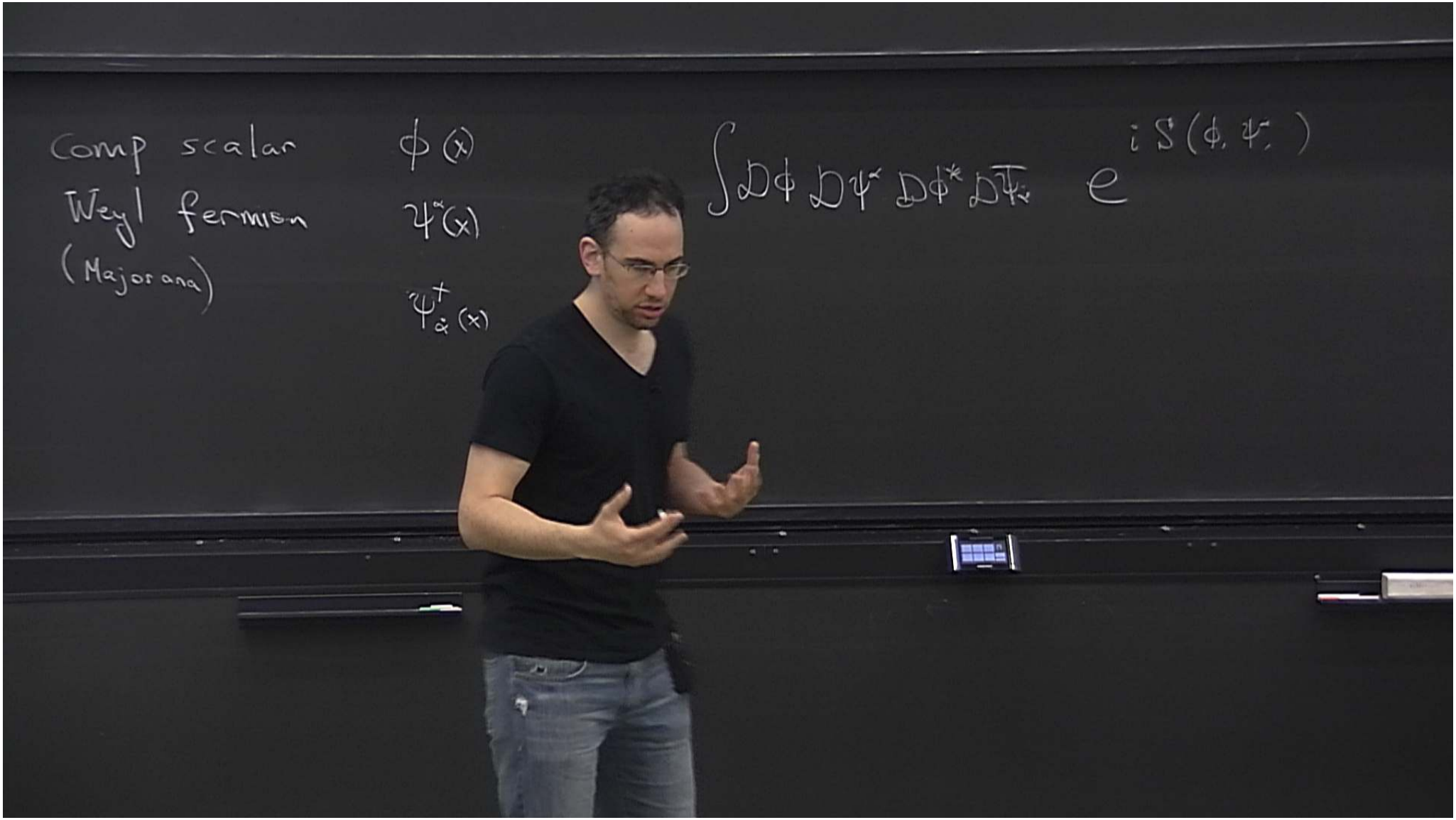

Comp scalar
$\phi(x)$

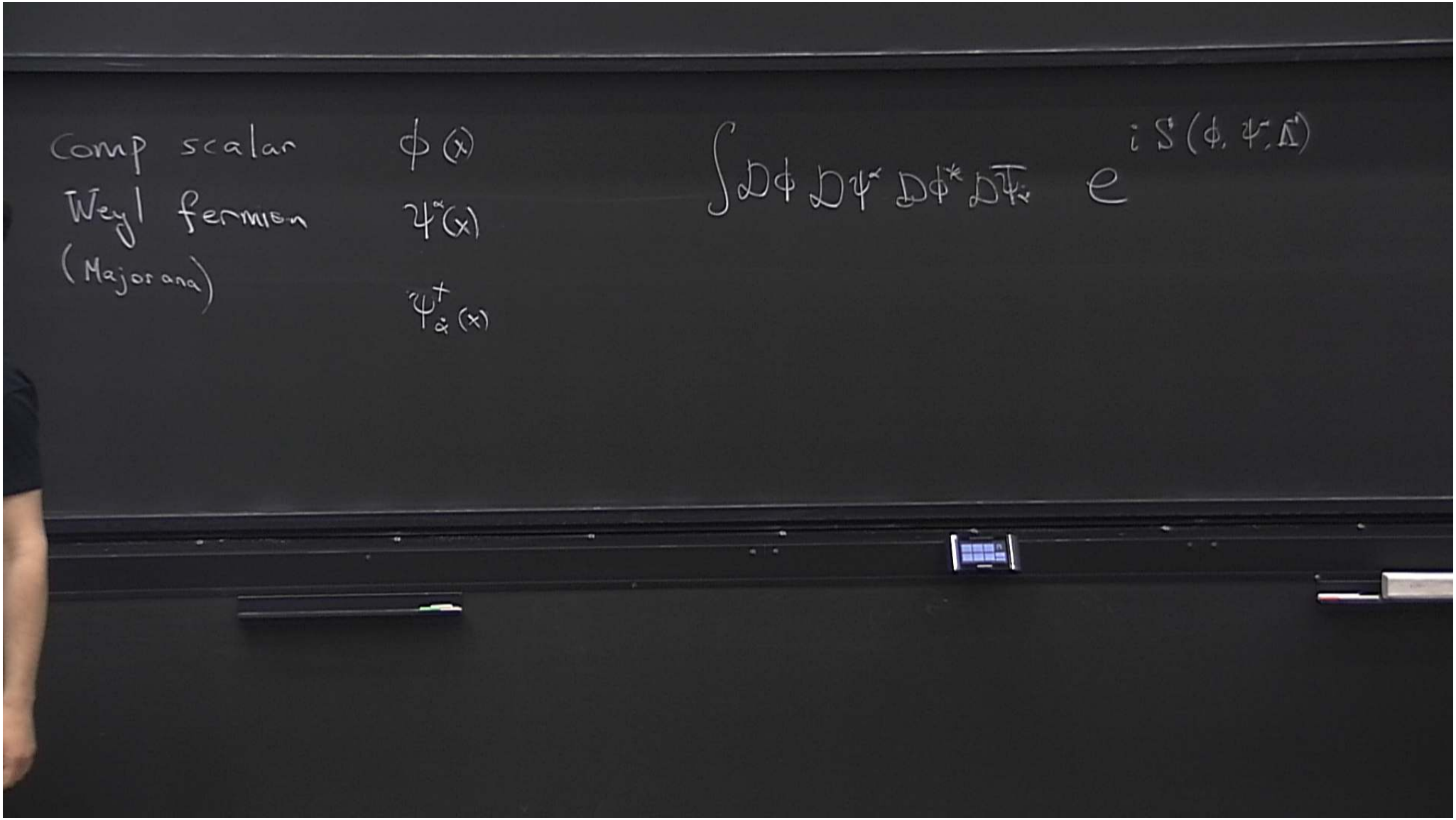

Comp scalar $\phi(x)$
Weyl fermion $\psi^{\alpha}(x)$

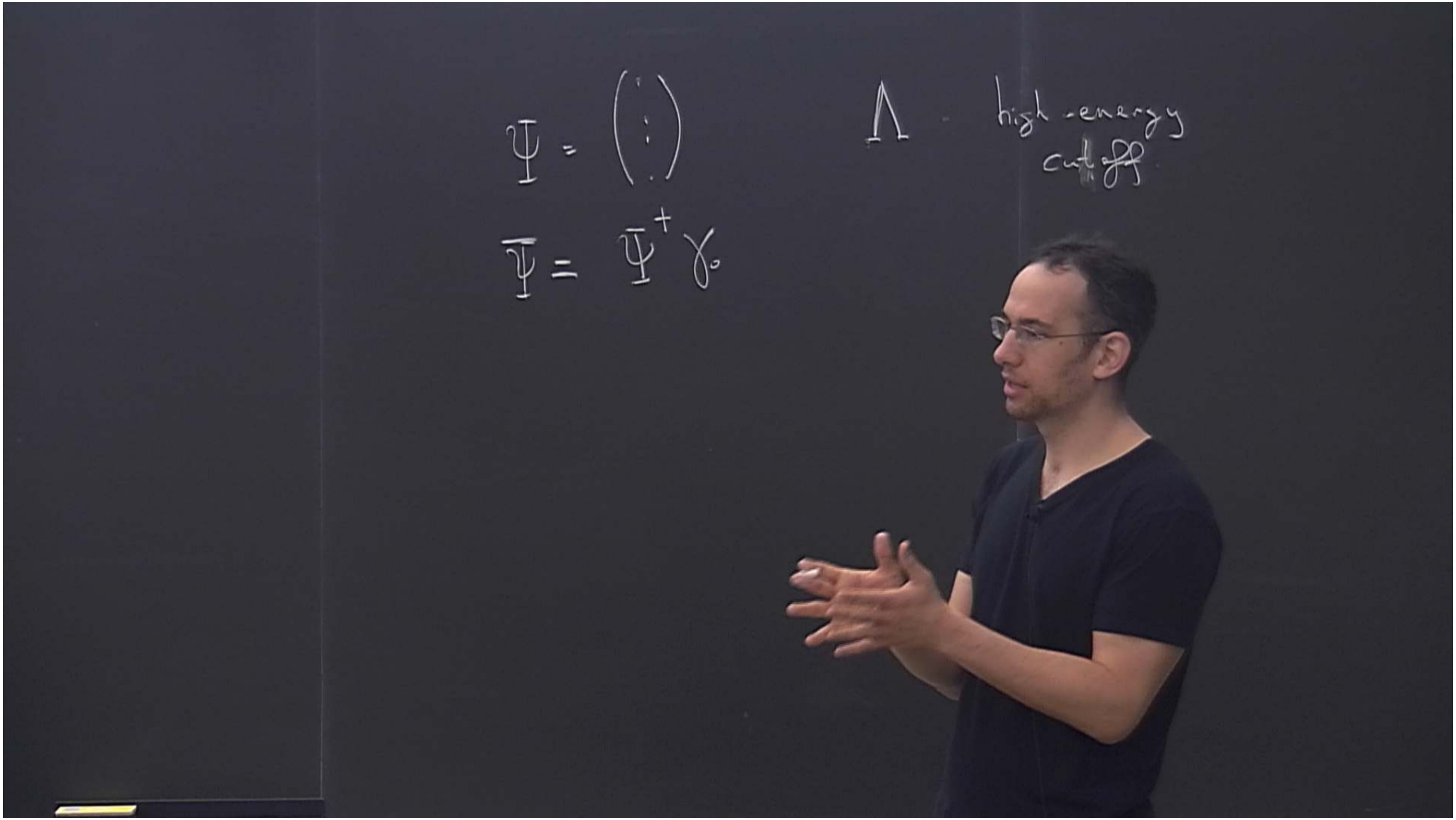

Comp scalar
Weyl fermion
(Majorana)
$\phi(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\bar{\psi}$

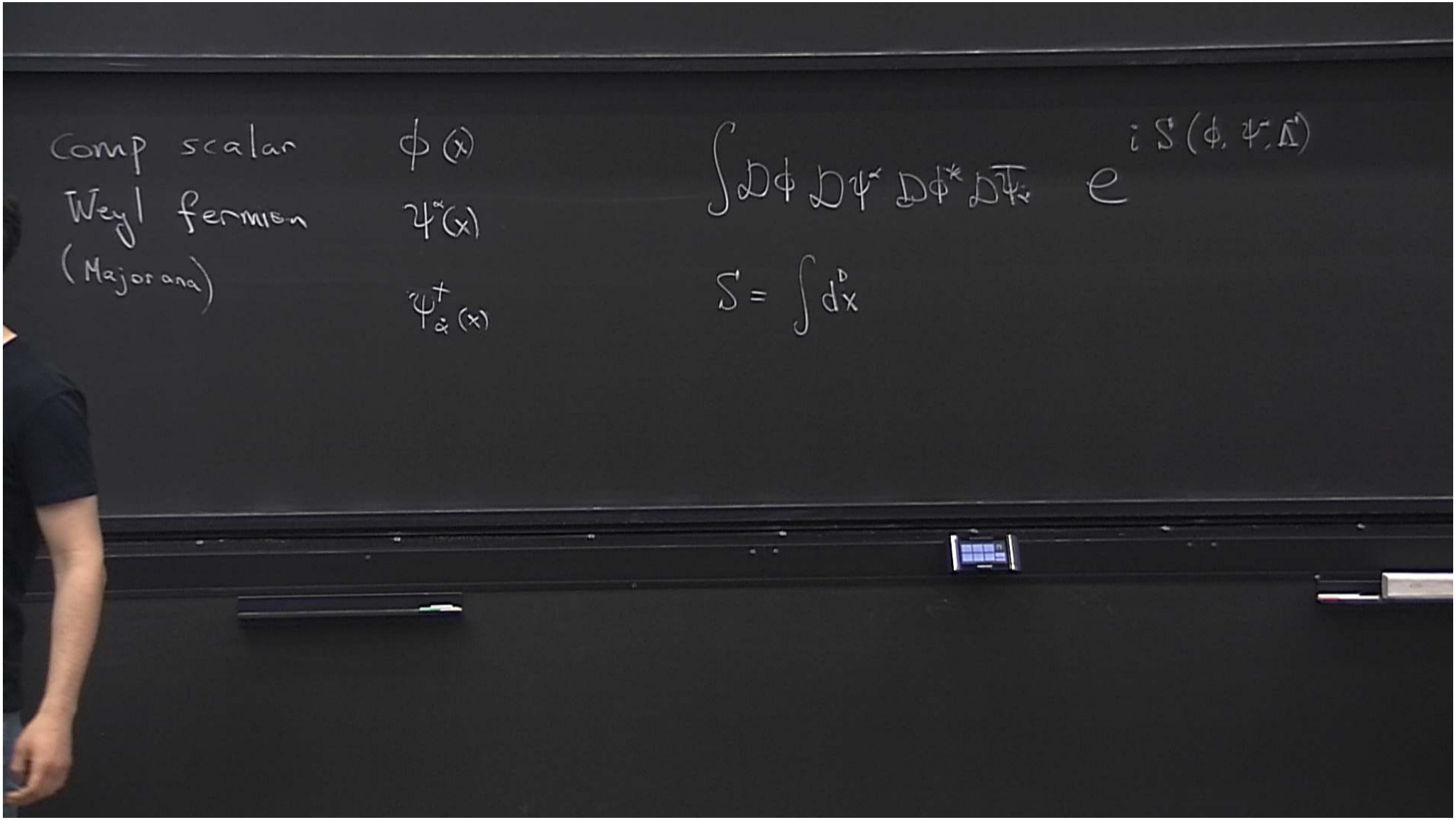

Comp scalar $\phi(x)$
Weyl fermion $\psi^\alpha(x)$
(Majorana)
$\bar{\psi}_{\dot{\alpha}}(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\bar{\psi}$


$\Psi = \begin{pmatrix} \vdots \\ \vdots \end{pmatrix}$
$\bar{\Psi} = \Psi^{+} \gamma_0$


Comp scalar
Weyl fermion
(Majorana)
$\phi(x)$
$\psi_\alpha(x)$
$\bar{\psi}^{\dot{\alpha}}(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi^\alpha\, \mathcal{D}\phi^*\, \mathcal{D}\bar{\psi}_{\dot{\alpha}}\; e^{iS(\phi,\psi,\ldots)}$


Comp scalar $\phi(x)$
Weyl fermion $\psi_\alpha(x)$
(Majorana)
$\bar{\psi}^{\dot{\alpha}}(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\bar{\psi}\; e^{iS(\phi,\psi,\bar{\psi})}$


$\Psi = \begin{pmatrix} \vdots \end{pmatrix}$
$\bar{\Psi} = \Psi^{+} \gamma_0$
Λ high-energy cutoff


Comp scalar $\phi(x)$
Weyl fermion $\psi_\alpha(x)$
(Majorana)
$\psi^\dagger_{\dot\alpha}(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\psi^\dagger\; e^{iS(\phi,\psi,\Lambda)}$
$S = \int d^D x$

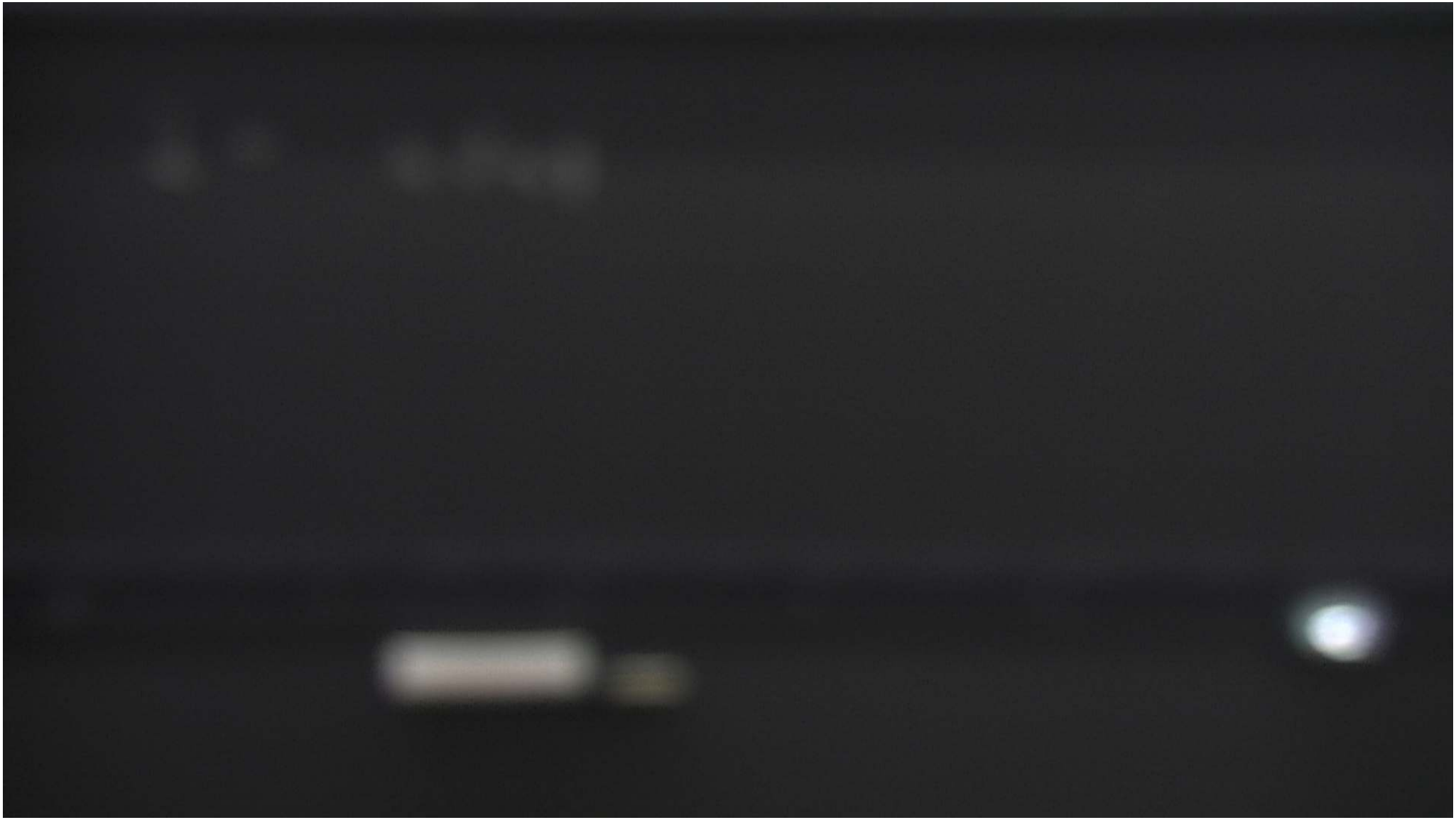
Comp scalar $\phi(x)$

Weyl fermion $\psi_\alpha(x)$

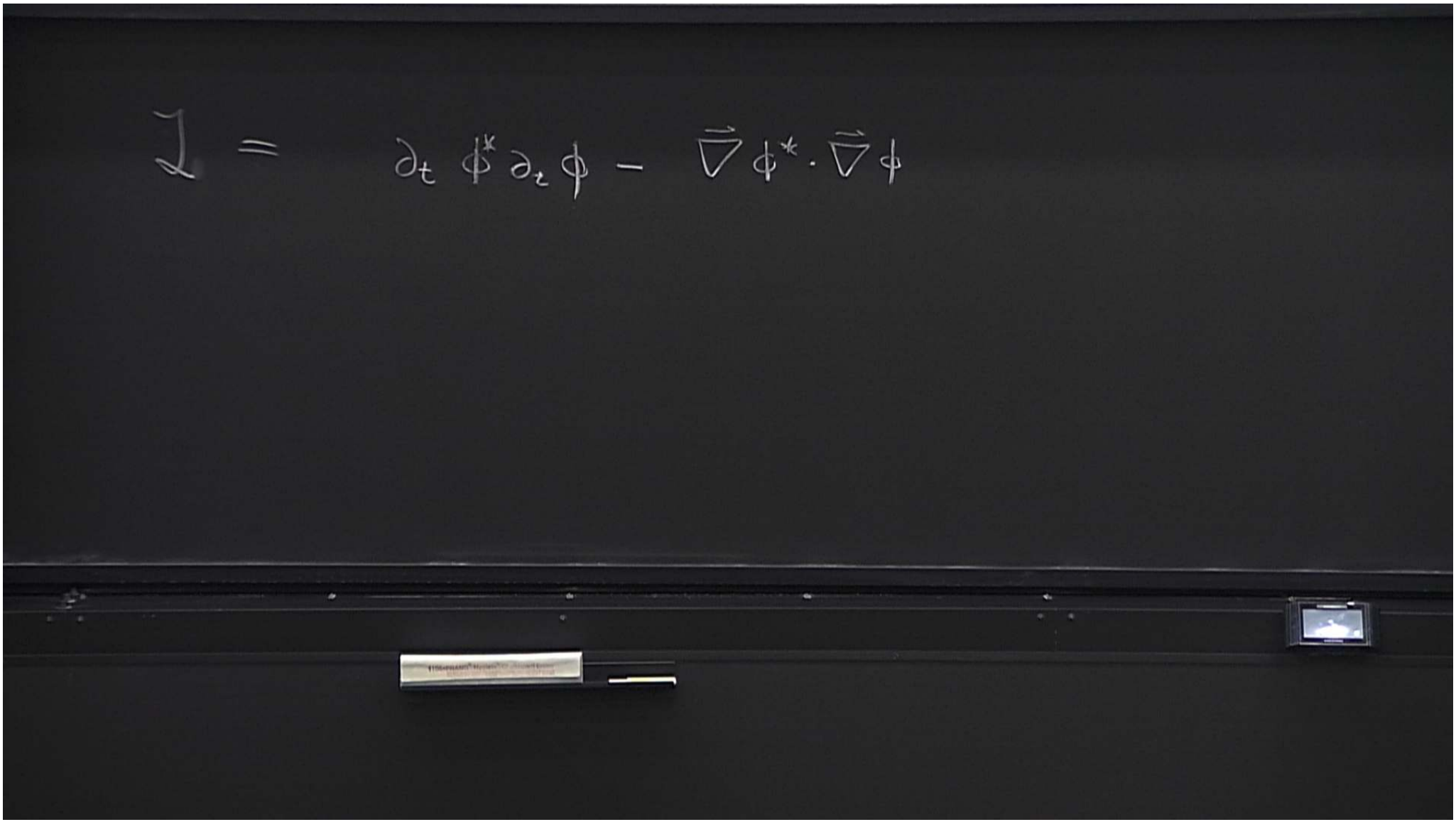
(Majorana) $\psi^\dagger_{\dot\alpha}(x)$

$$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\psi^\dagger\; e^{iS(\phi,\psi,\Lambda)}$$

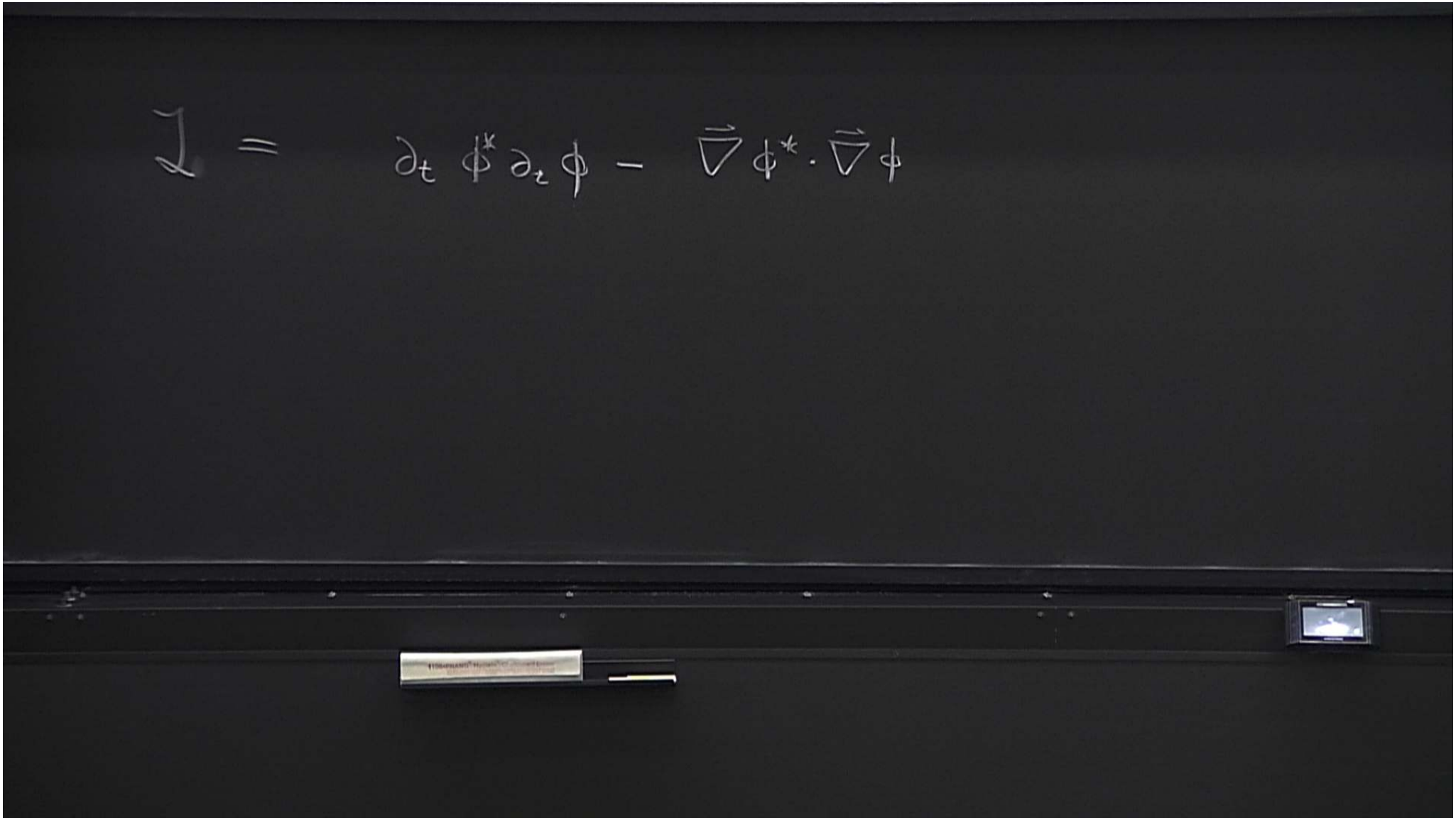
$$S = \int d^Dx\; \mathcal{L}(\phi,\psi,\Lambda)$$

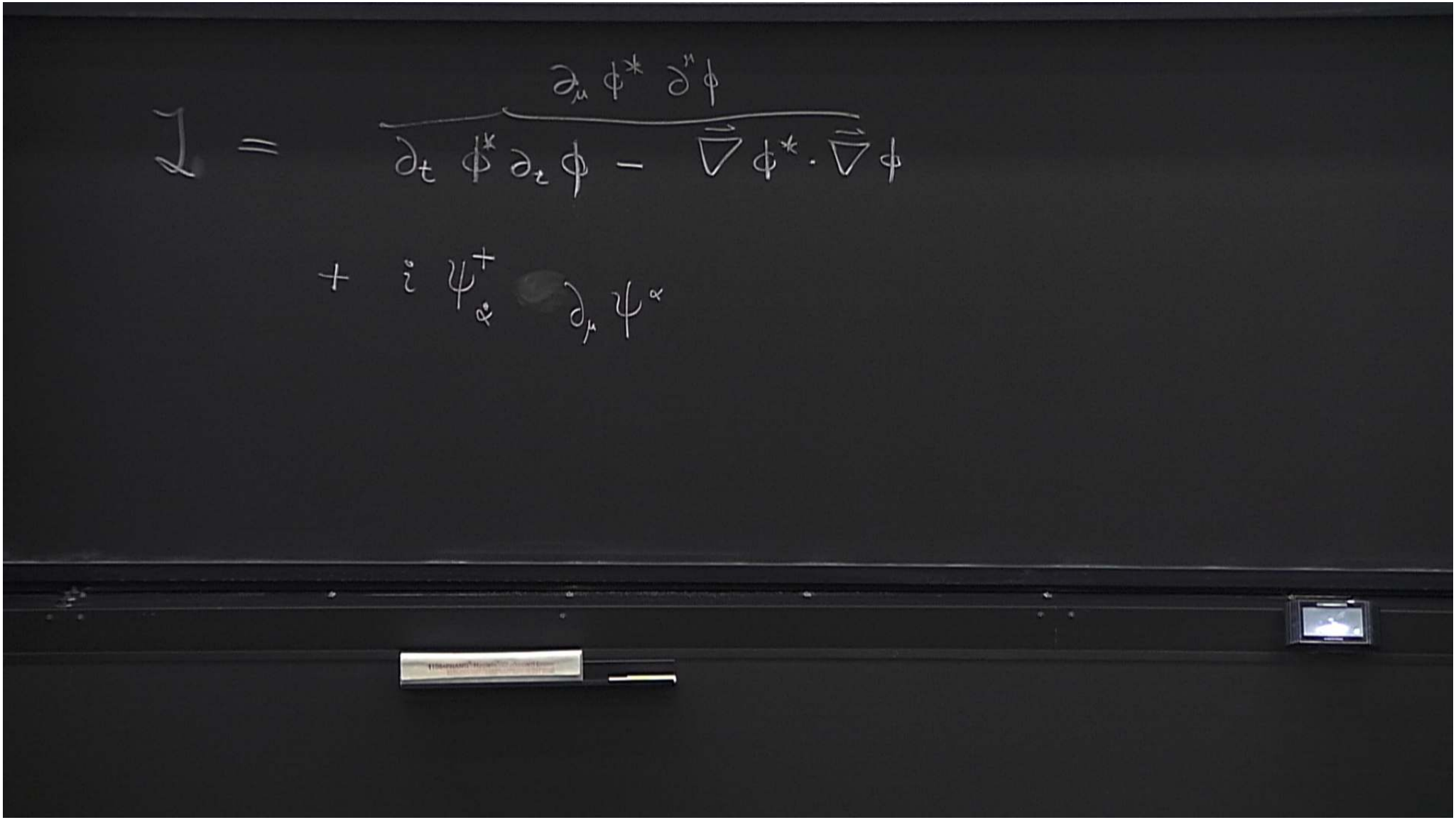


$$\mathcal{L} = \partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$



$$\mathcal{L} = \partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$




$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi$
$\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$
$+ i \psi^\dagger_\alpha \partial_\mu \psi^\alpha$

$c = 1$

$\hbar = 1$

$\eta_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix}$

$\Psi = \begin{pmatrix} \vdots \\ \vdots \end{pmatrix}$

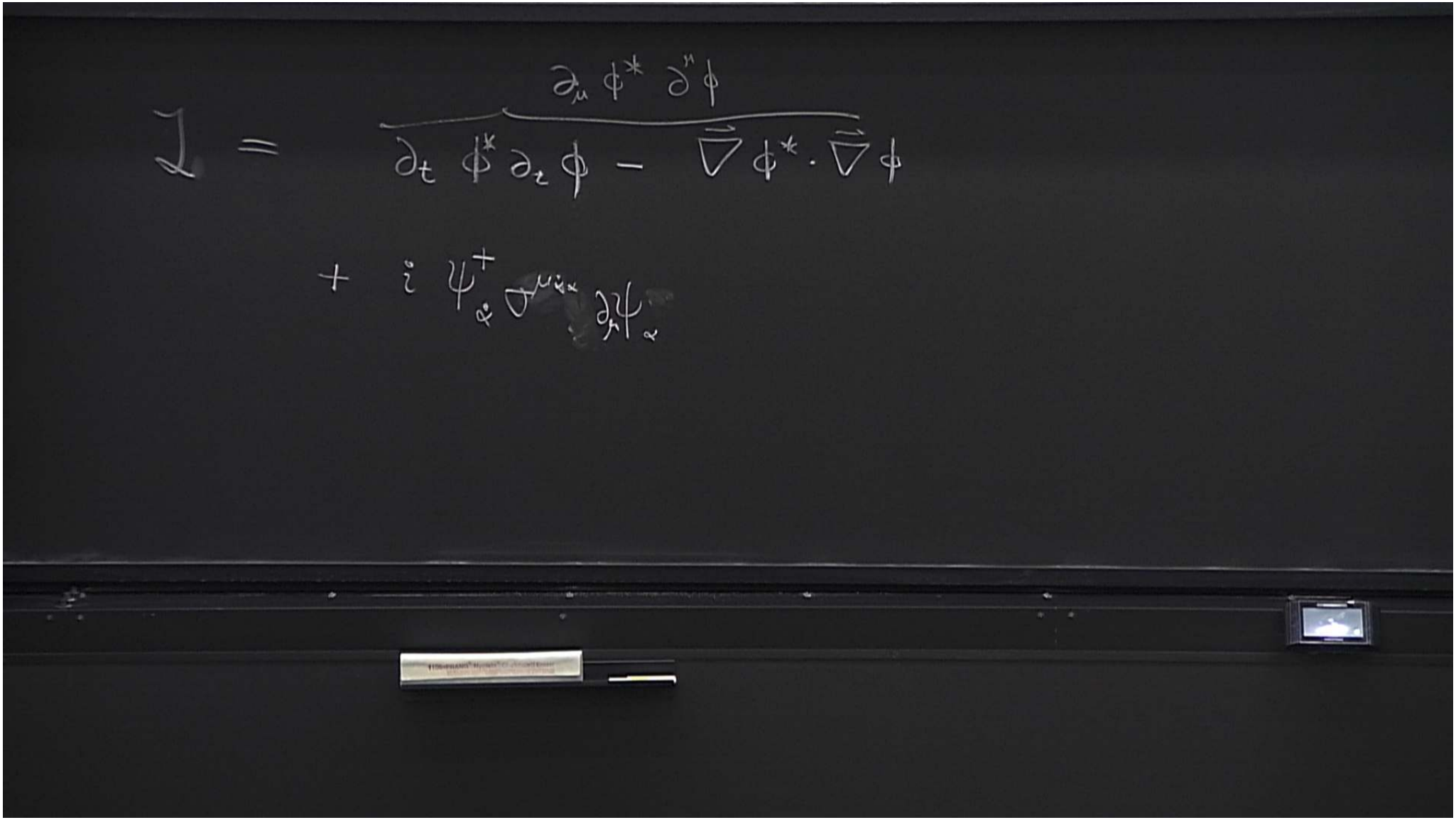
$\bar{\Psi} = \Psi^{+} \gamma_0$

Λ high-energy cutoff

$D = 4$

$$\mathcal{L} = \underbrace{\partial_\mu \phi^* \, \partial^\mu \phi}_{\partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi}$$

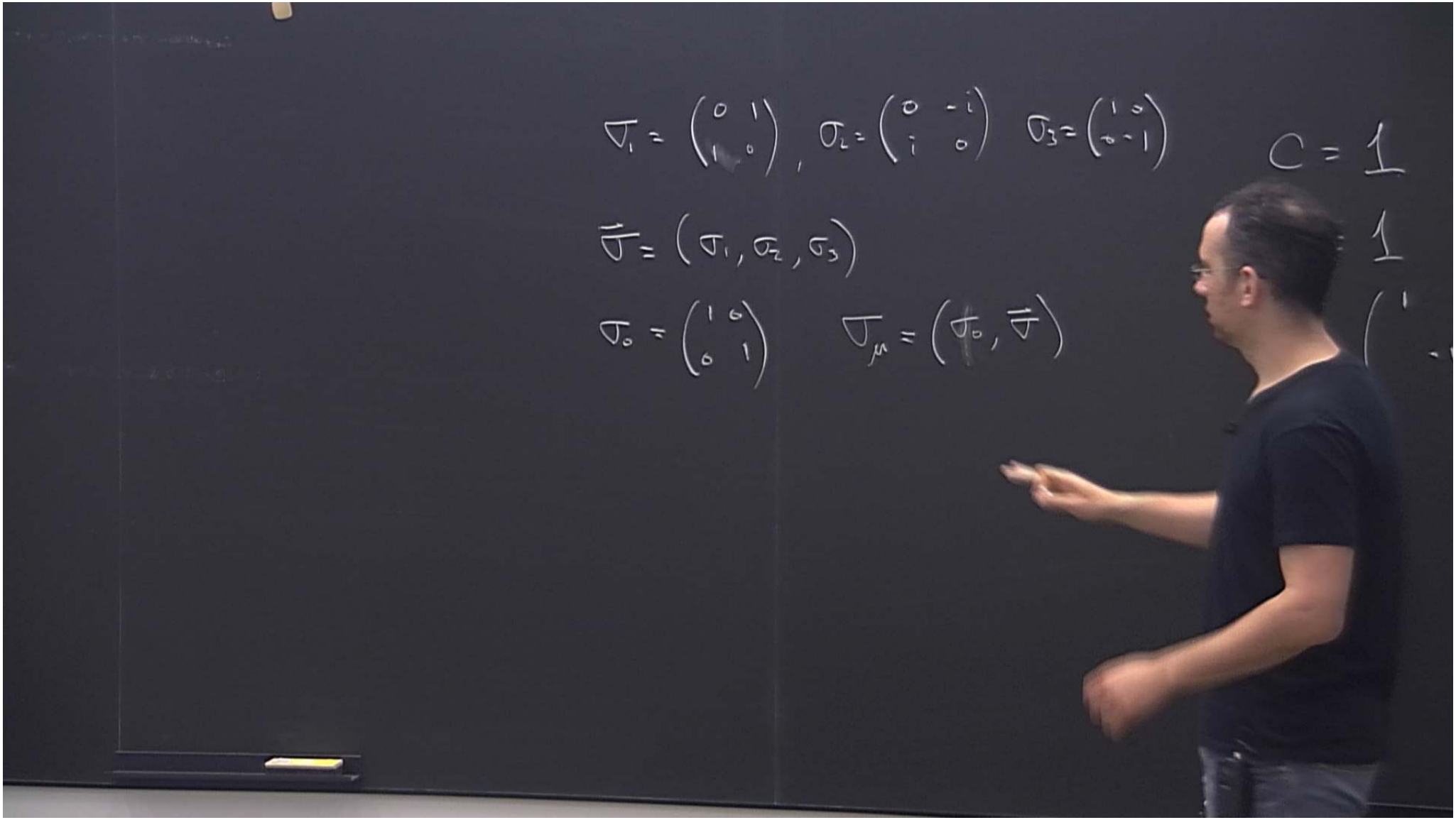
$$+ \; i \, \psi^\dagger_{\dot{\alpha}} \, \partial_\mu \psi^\alpha$$

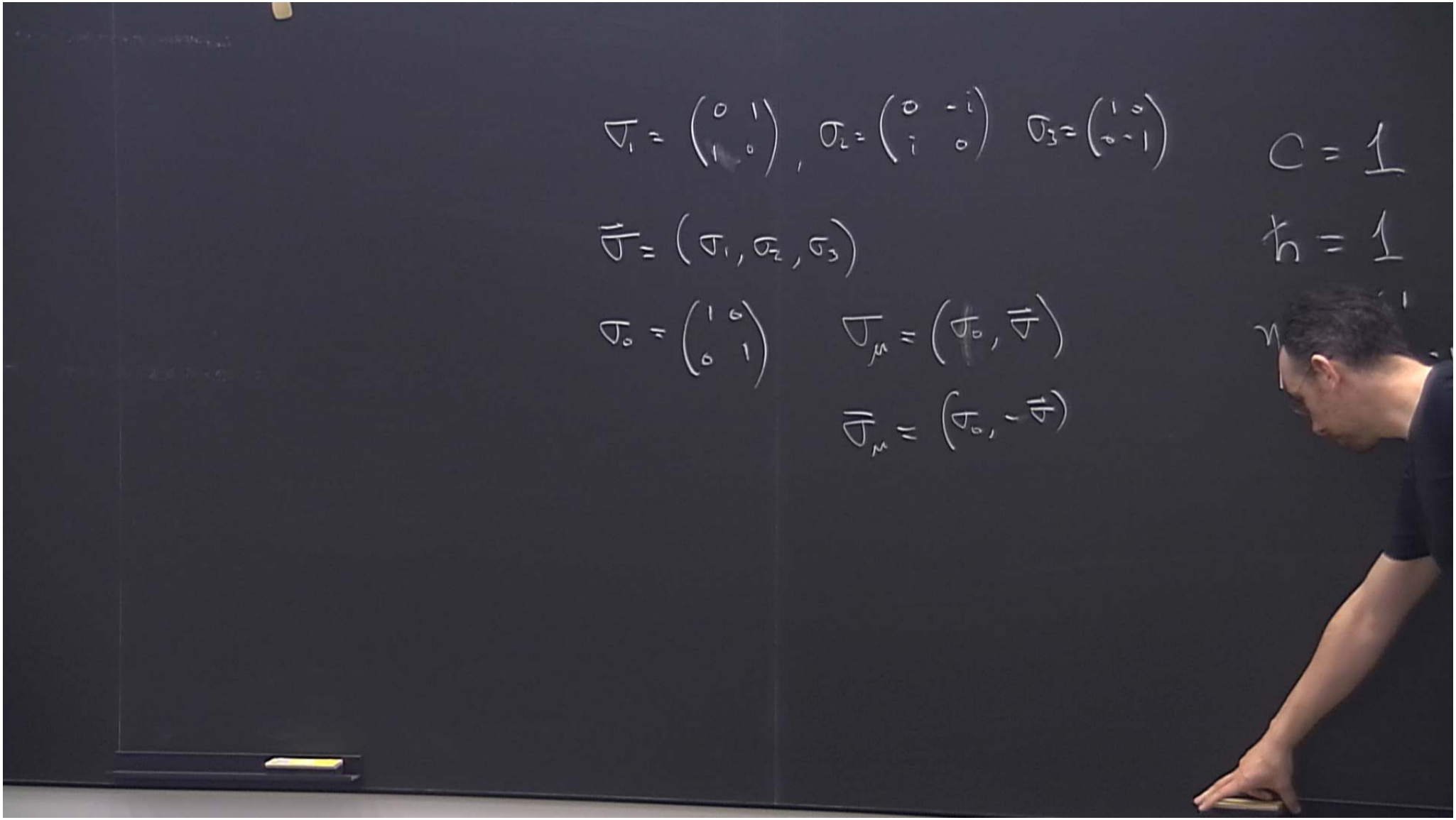

$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi$
$\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$
$+ i \psi^+_\alpha \bar{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \psi_\alpha$

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi$$

$$= \partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$

$$+ i \psi_\alpha^+ \bar{\sigma}^{\mu \dot{\alpha} \alpha} \partial_\mu \psi_\alpha$$


$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ $\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
$C = 1$
$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$
$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
$\sigma_\mu = (\sigma_0, \vec{\sigma})$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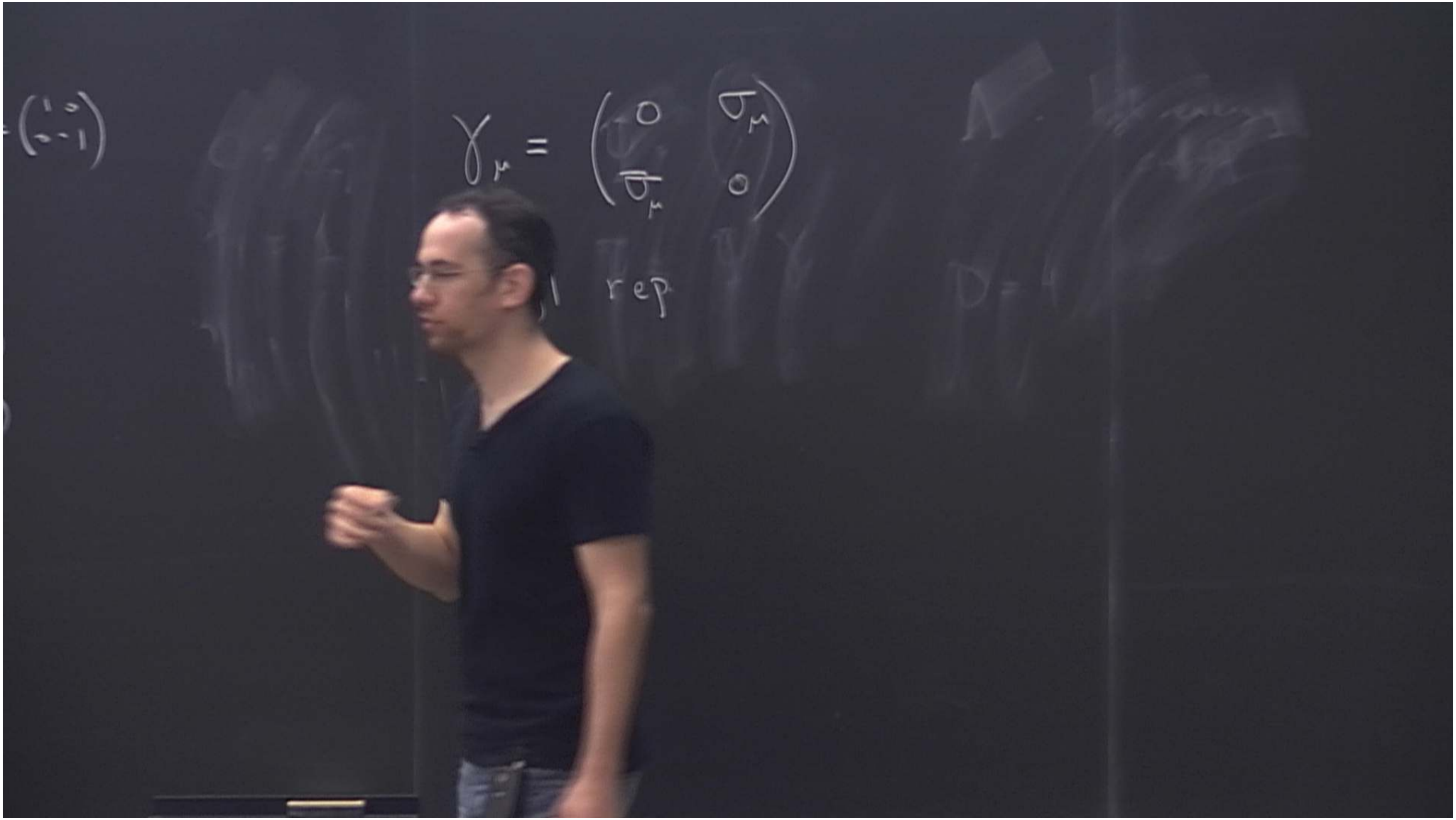
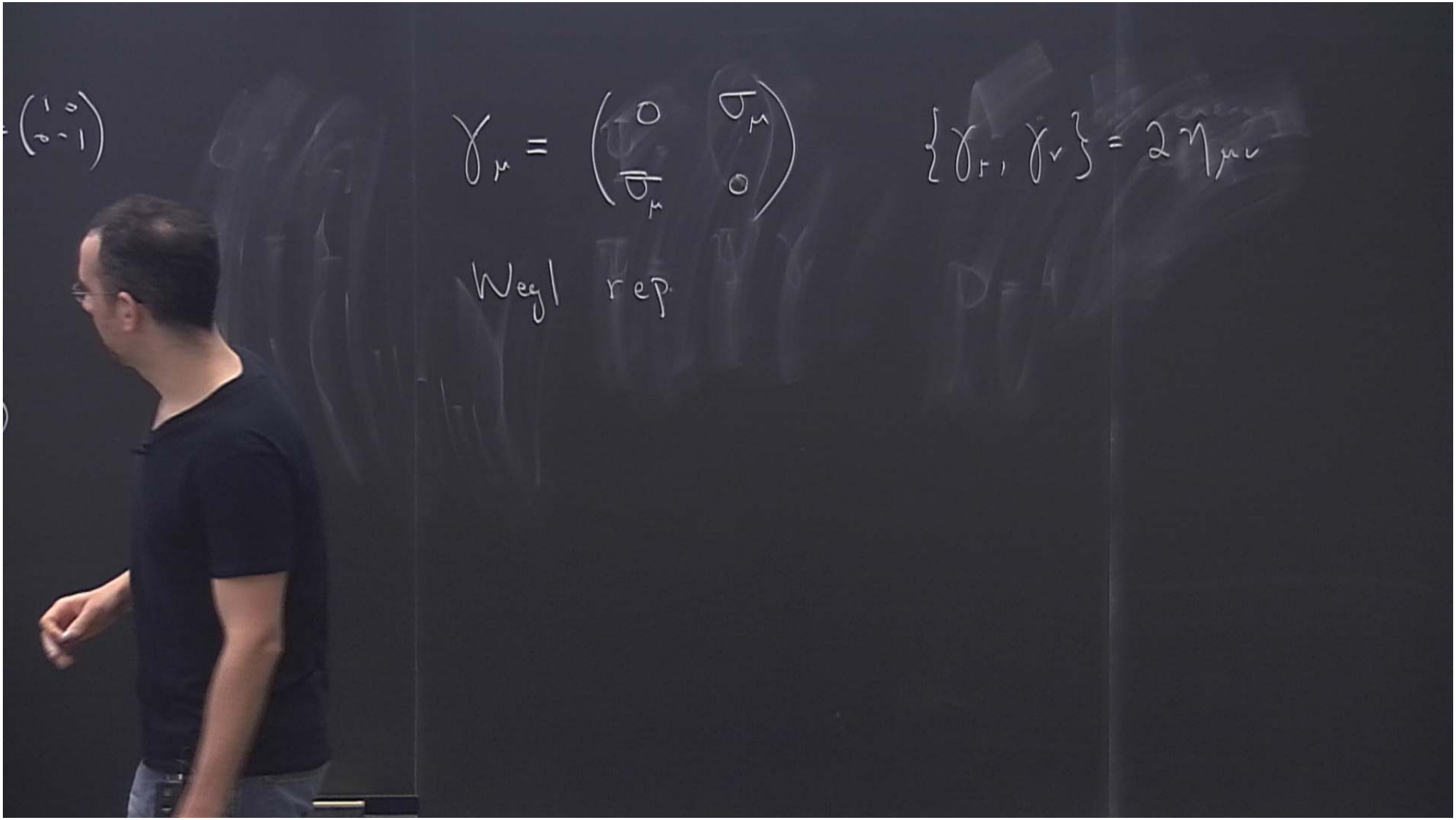
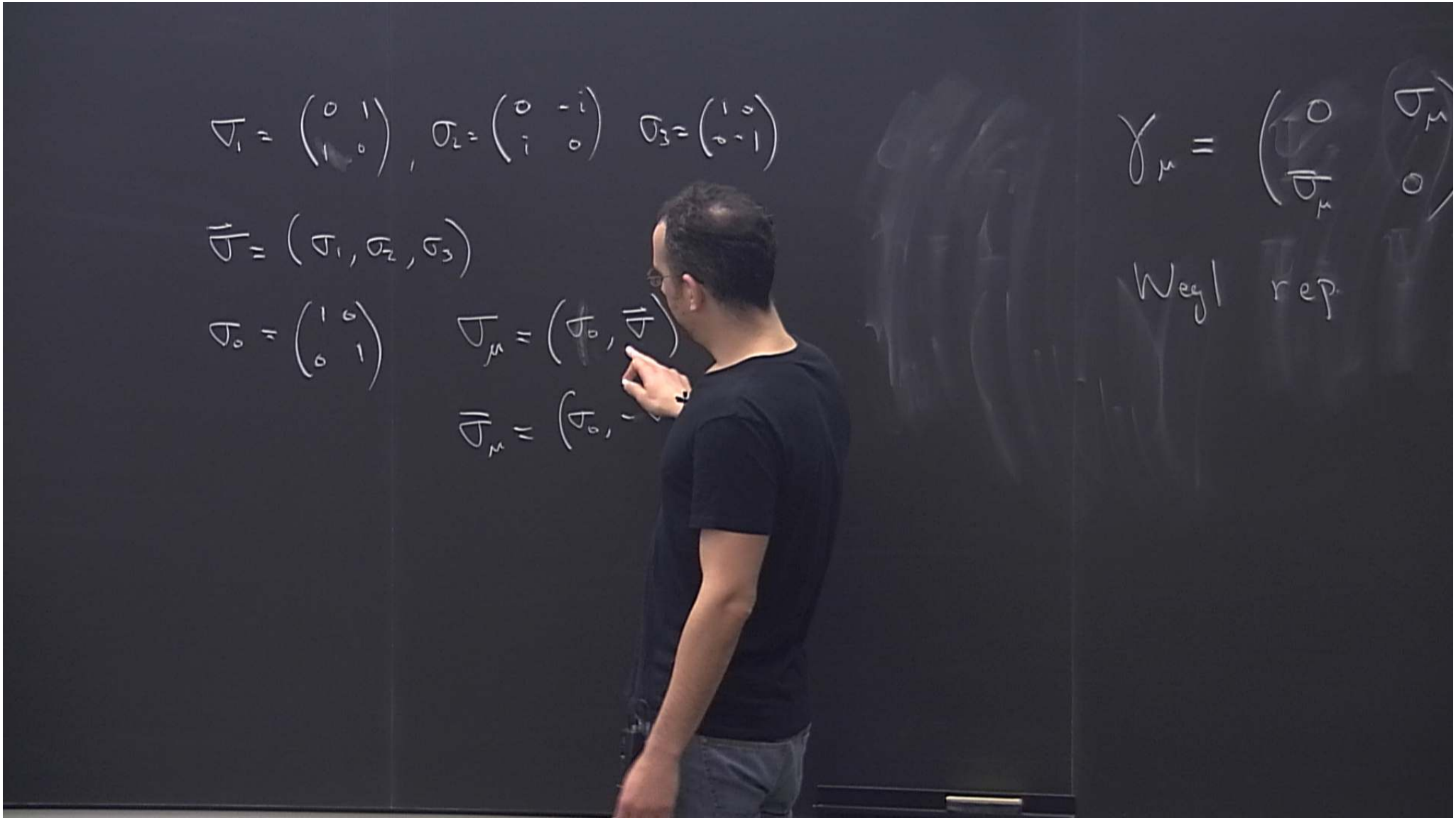
$\sigma_\mu = (\sigma_0, \vec{\sigma})$
$\bar{\sigma}_\mu = (\sigma_0, -\vec{\sigma})$
$c = 1$
$\hbar = 1$


$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
rep


$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$
Weyl rep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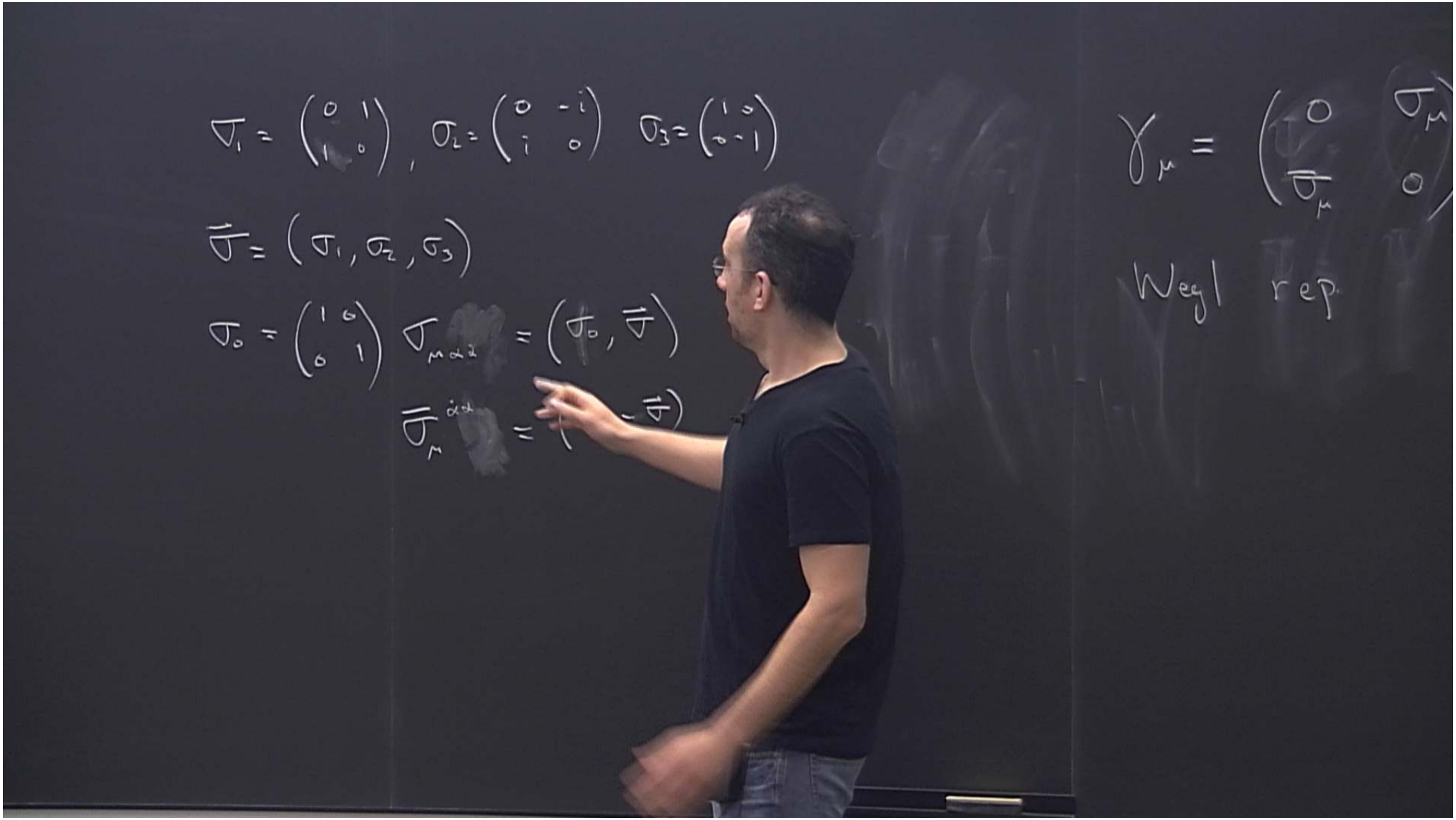
$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$
$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $\sigma_\mu = (\sigma_0, \vec{\sigma})$
$\bar{\sigma}_\mu = (\sigma_0, -$
$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
Weyl rep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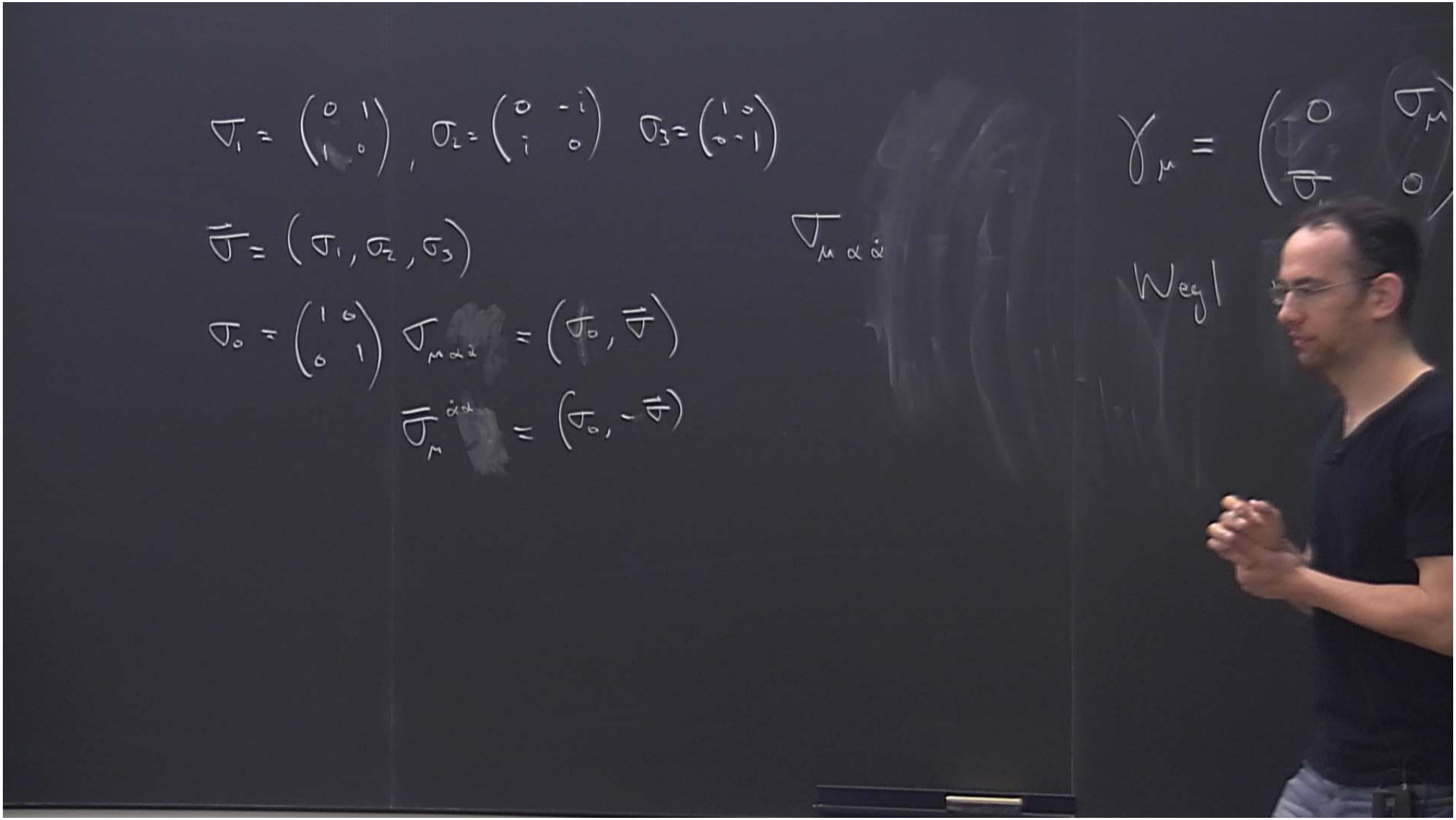
$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$
$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
Weyl rep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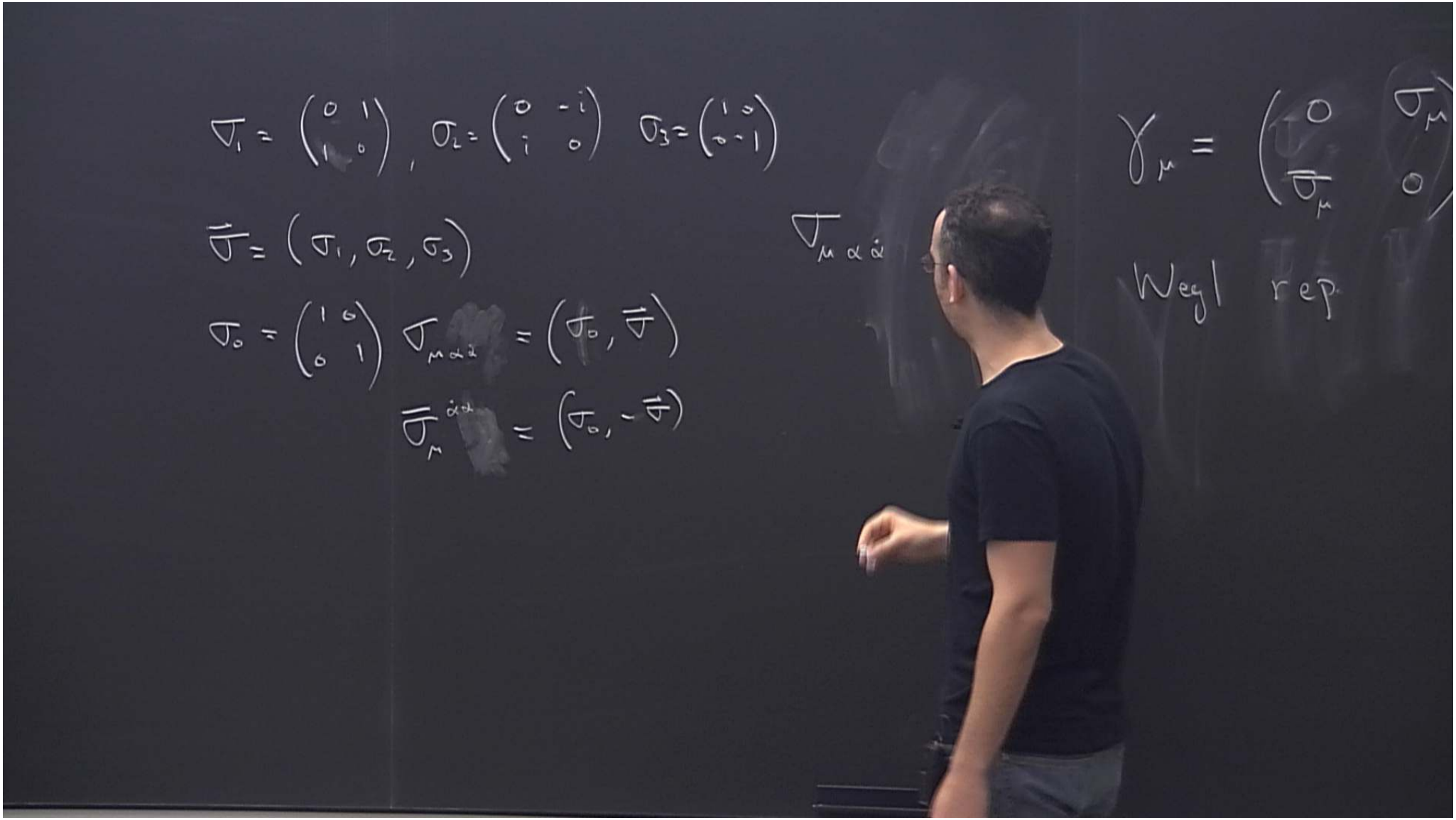
$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$
$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $\sigma_{\mu\alpha\dot{\alpha}} = (\sigma_0, \vec{\sigma})$
$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$
$\sigma_{\mu\alpha\dot{\alpha}}$
$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
Weyl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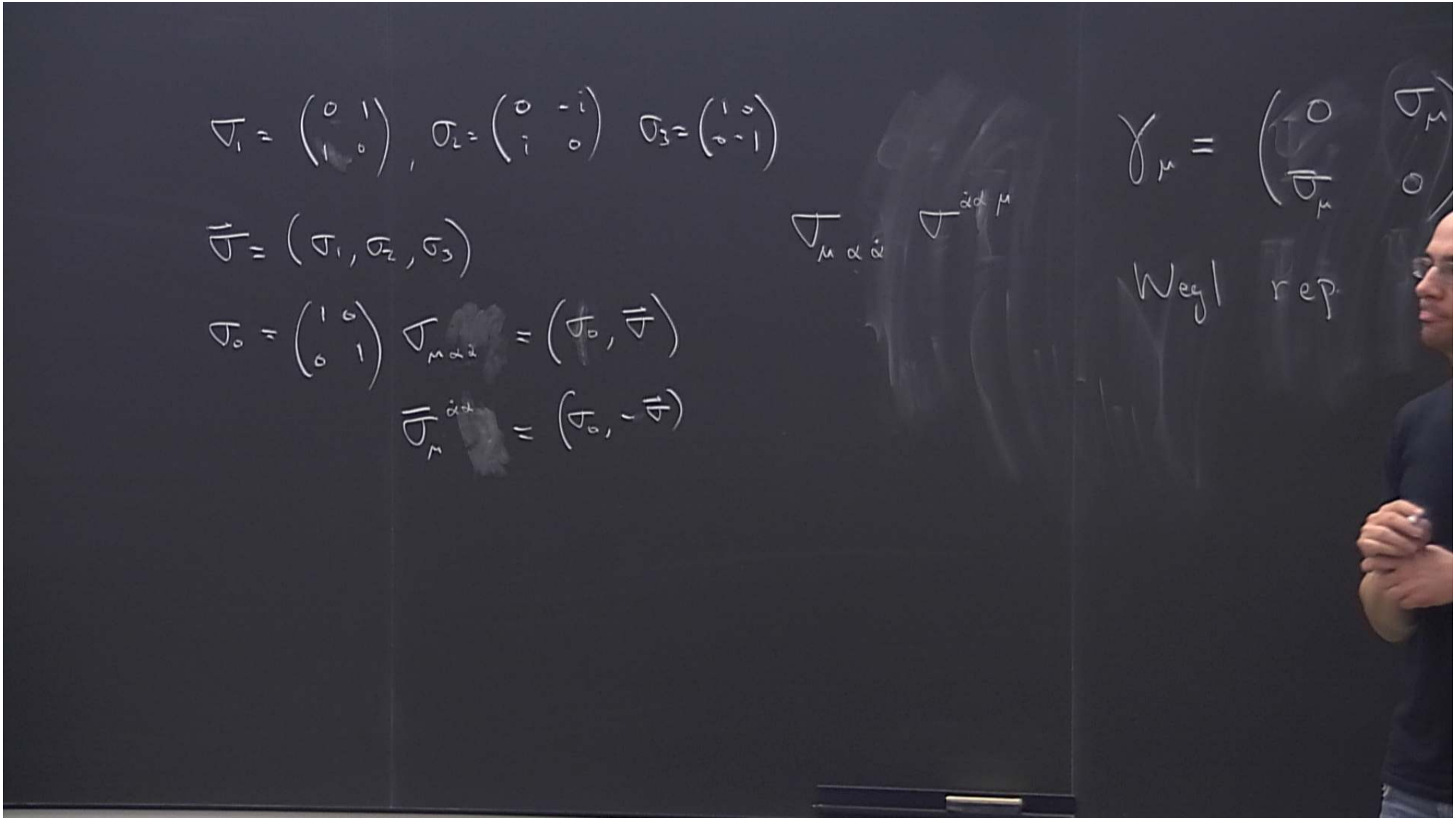
$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
Weyl rep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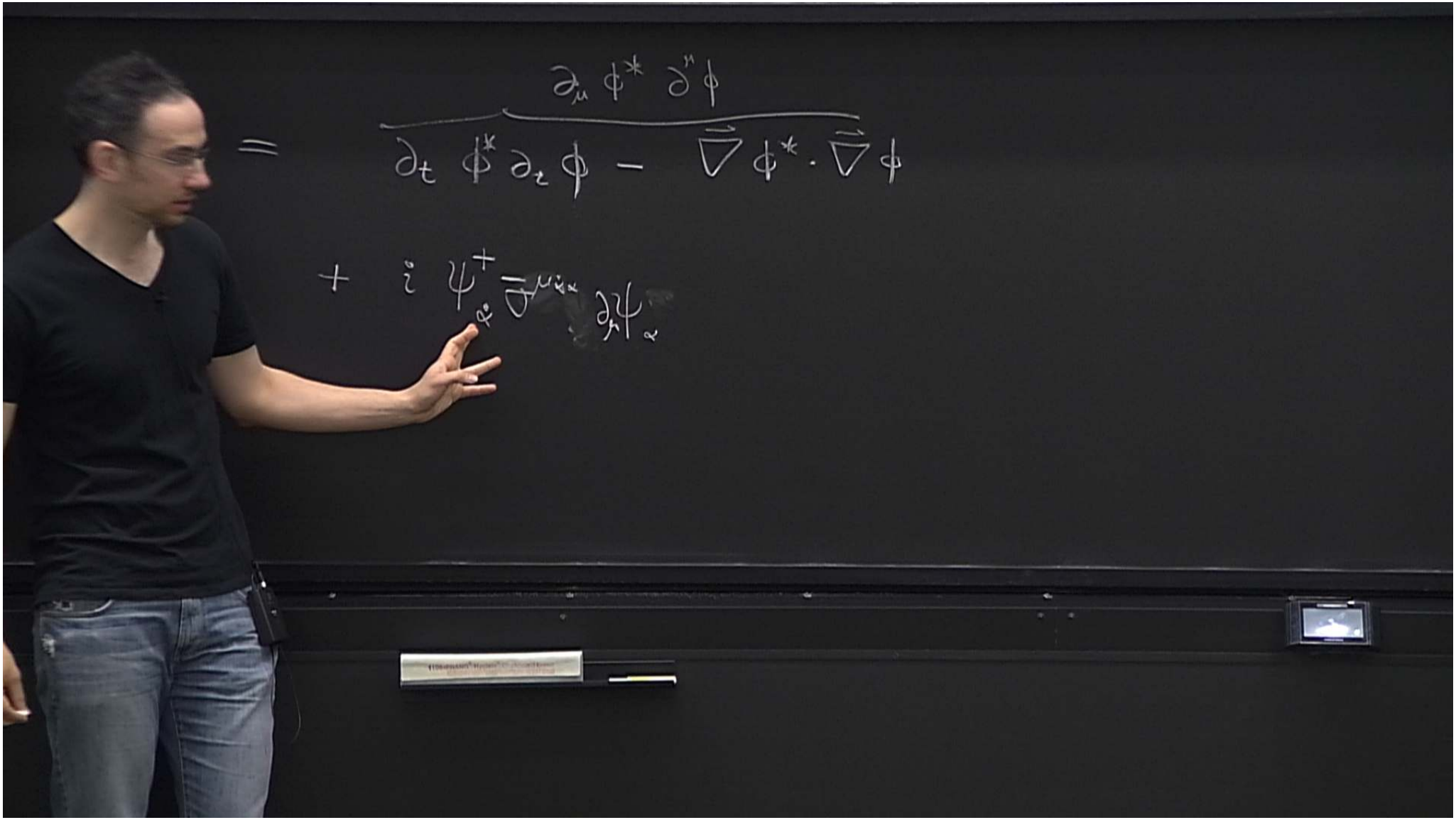
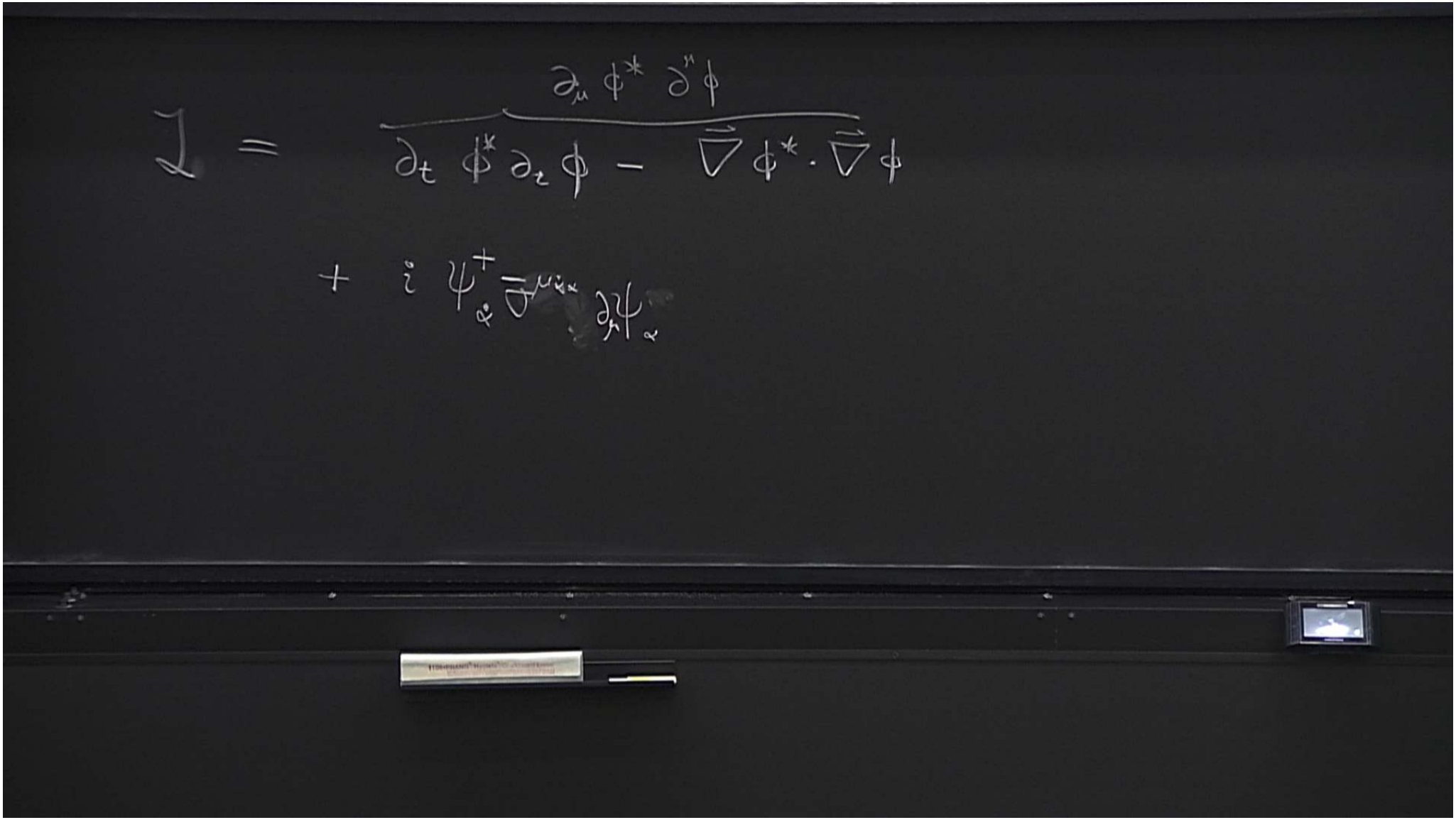
$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $\sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$
$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$
$\sigma_{\mu \alpha \dot{\alpha}}$ $\sigma^{\dot{\alpha}\alpha \mu}$
$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
Weyl rep


$= \partial_\mu \phi^* \partial^\mu \phi$
$\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$
$+ i \psi^+ \bar{\sigma}^\mu \partial_\mu \psi$

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi$$

$$\partial_t \phi^* \partial_t \phi - \vec{\nabla} \phi^* \cdot \vec{\nabla} \phi$$

$$+ \; i \psi_\alpha^+ \bar{\sigma}^{\mu\alpha\dot{\alpha}} \partial_\mu \psi_{\dot{\alpha}}$$



$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$$\sigma_{\mu \alpha \dot{\alpha}} \bar{\sigma}^{\dot{\alpha}\alpha}_\nu = \eta_{\mu\nu}$$

Weyl rep

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

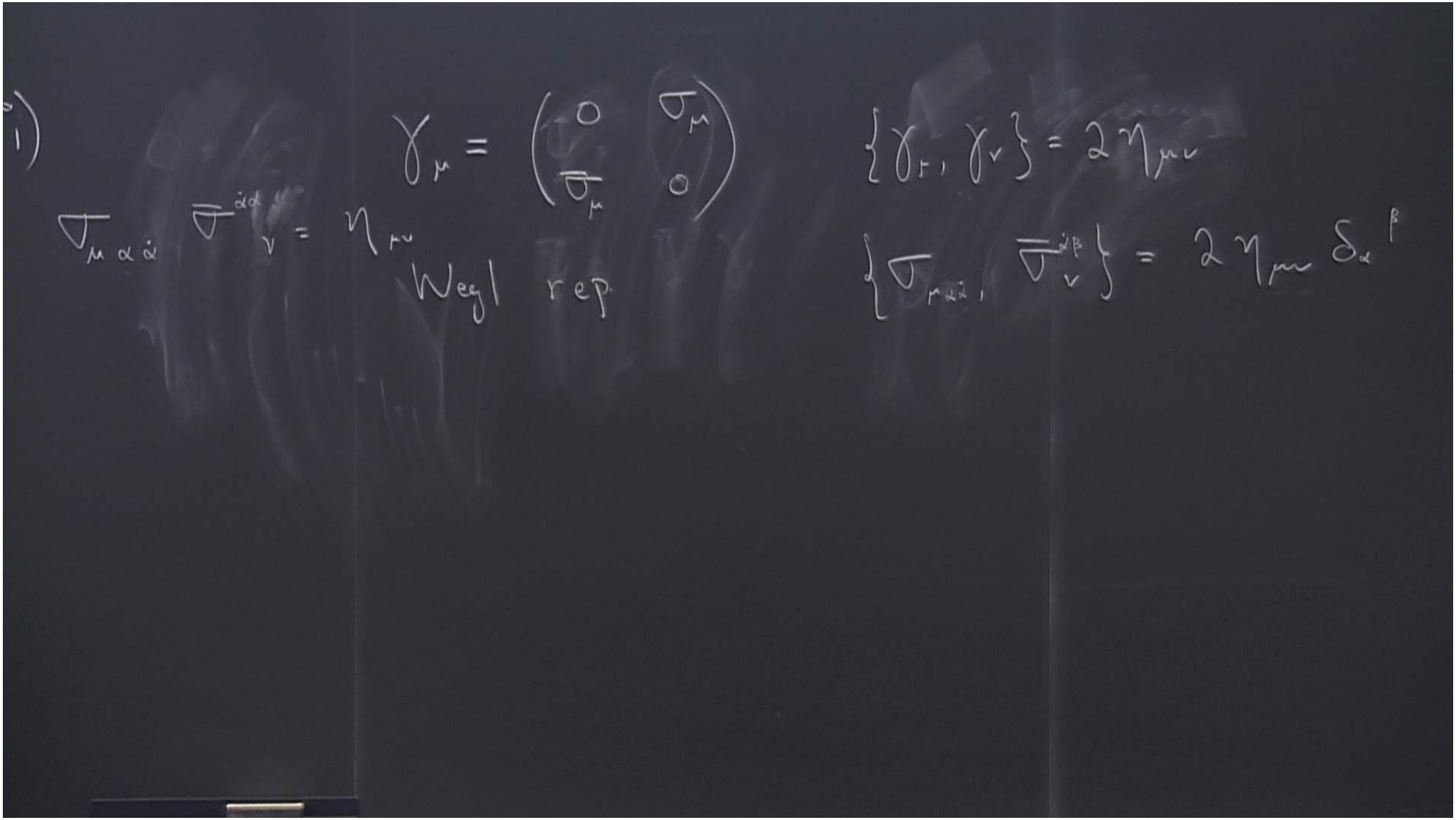
$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$$\sigma_{\mu \alpha \dot{\alpha}} \bar{\sigma}^{\dot{\alpha}\alpha}_\nu = \eta_{\mu\nu}$$

Weyl rep


$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$
$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$
$\sigma_{\mu\,\alpha\dot{\alpha}}\,\bar{\sigma}^{\dot{\alpha}\alpha}{}_{\nu} = \eta_{\mu\nu}$
Weyl rep
$\{\sigma_{\mu\,\alpha\dot{\alpha}}, \bar{\sigma}^{\dot{\alpha}\beta}_{\nu}\} = 2\eta_{\mu\nu}\,\delta_\alpha{}^\beta$

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix} \qquad \{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

$\sigma_{\mu\,\alpha\dot{\alpha}}\,\bar{\sigma}^{\dot{\alpha}\alpha}{}_{\nu} = \eta_{\mu\nu}$

Weyl rep

$\{\sigma_{\mu\alpha\dot{\alpha}}, \bar{\sigma}^{\dot{\alpha}\beta}_{\nu}\} = 2\eta_{\mu\nu}\,\delta_\alpha{}^\beta$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

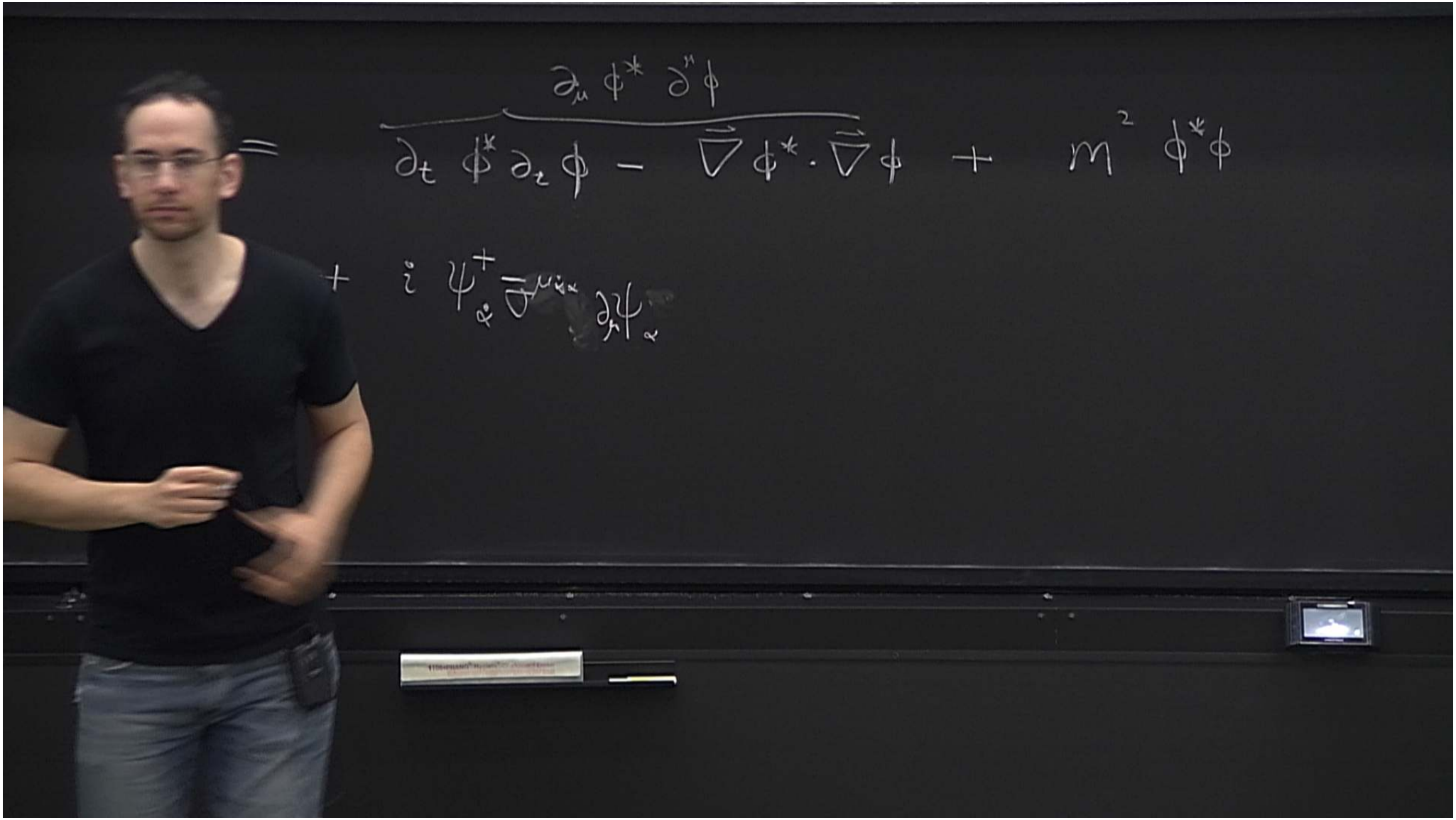
$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$$\sigma_{\mu \alpha \dot{\alpha}} \bar{\sigma}^{\dot{\alpha}\alpha}_\nu = \eta_{\mu\nu}$$

Weyl rep

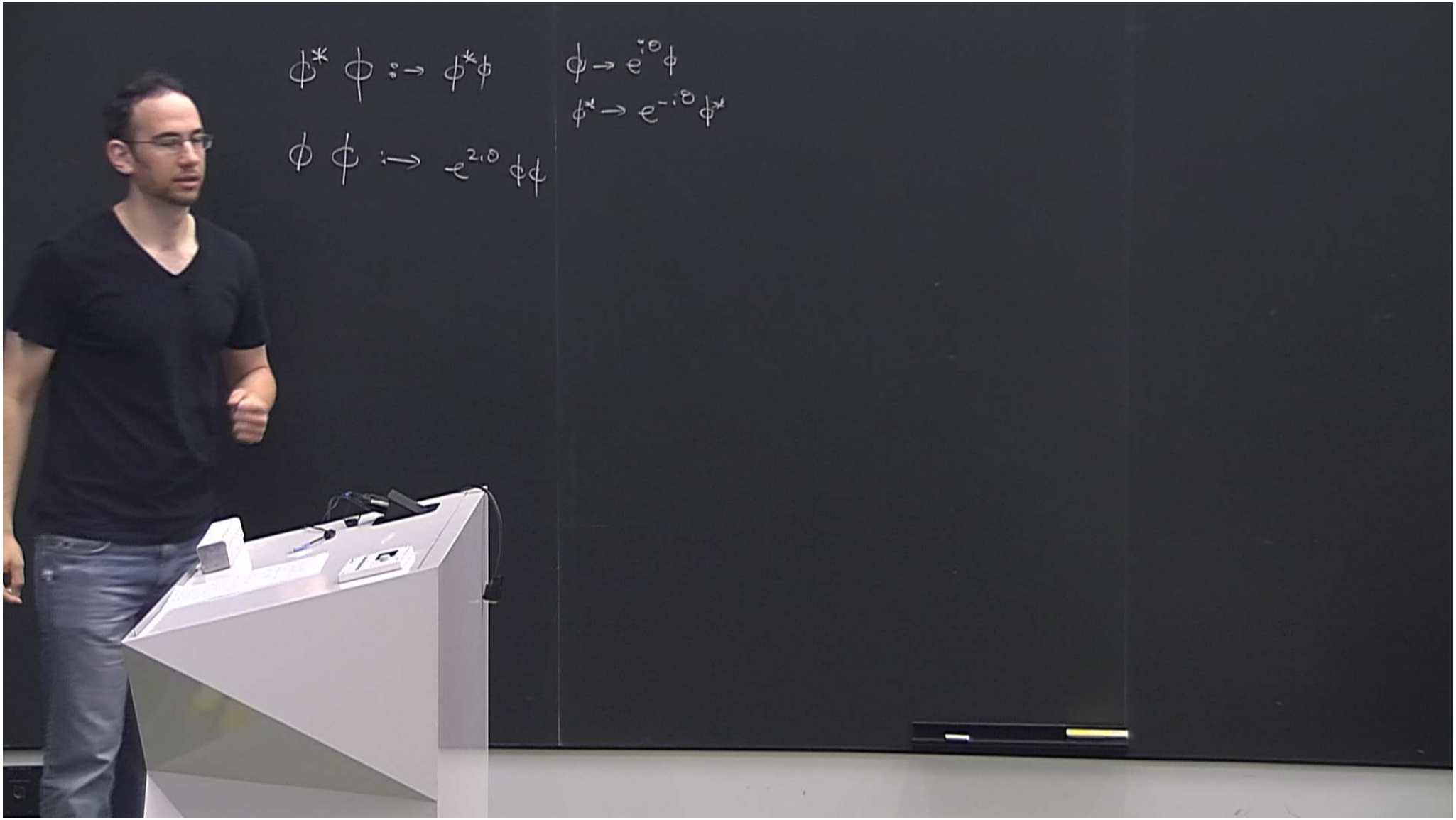
$$\epsilon_{\alpha\dot{\alpha}} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\epsilon^{\dot{\alpha}\alpha} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$


$\partial_\mu \phi^* \partial^\mu \phi$
$= \partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi + m^2 \phi^* \phi$
$+ i \psi_\alpha^+ \bar{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \psi_{\dot{\alpha}}$

$$\mathcal{L} = \overbrace{\partial_\mu \phi^* \partial^\mu \phi}^{\partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi} + m^2 \phi^*(x)\phi(x)$$

$$+ i \psi^\dagger_\alpha \bar{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \psi_\alpha$$


$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

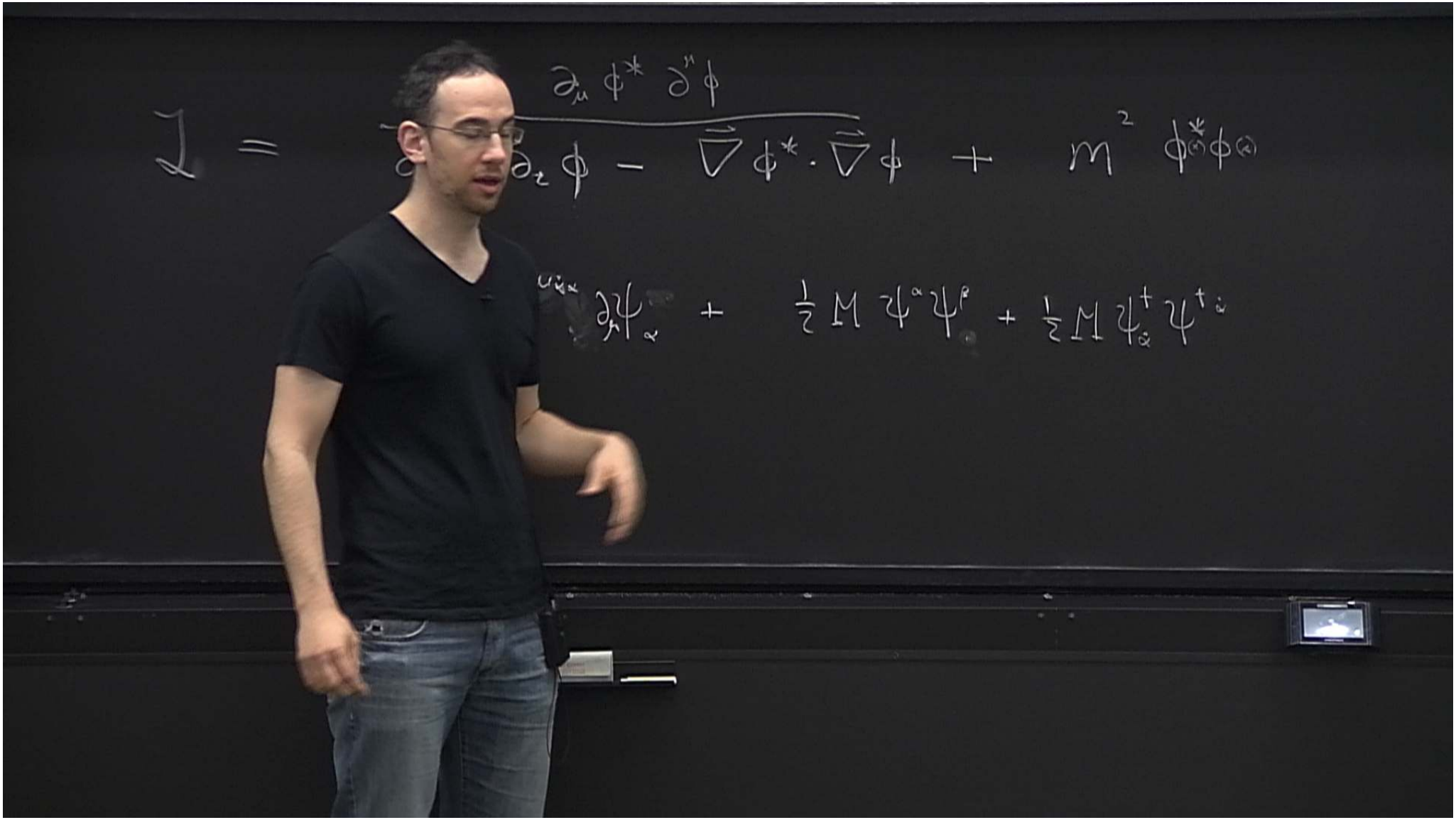
$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$$\sigma_{\mu \alpha \dot{\alpha}} \bar{\sigma}^{\dot{\alpha}\alpha}_\nu = \eta_{\mu\nu}$$

Weyl rep

$$\epsilon_{\alpha\dot{\alpha}} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\epsilon^{\dot{\alpha}\alpha} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$


$\partial_\mu \phi^* \partial^\mu \phi$
$\mathcal{L} = \partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi + m^2 \phi^*\phi$
$\partial_\mu \psi_\alpha + \frac{1}{2} M \psi^\alpha \psi^\beta + \frac{1}{2} M \psi^\dagger_{\dot\alpha} \psi^{\dagger \dot\alpha}$

$$\mathcal{L} = \overbrace{\partial_\mu \phi^* \partial^\mu \phi}^{\partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi} + m^2 \phi^*(x)\phi(x)$$

$$+ i \psi^\dagger_{\dot{\alpha}} \bar{\sigma}^{\mu \dot{\alpha}\alpha} \partial_\mu \psi_\alpha + \frac{1}{2} M \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} M \psi^\dagger_{\dot{\alpha}} \psi^{\dagger \dot{\alpha}}$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\vec{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma_{\mu \alpha \dot{\alpha}} = (\sigma_0, \vec{\sigma})$$

$$\bar{\sigma}_\mu^{\dot{\alpha}\alpha} = (\sigma_0, -\vec{\sigma})$$

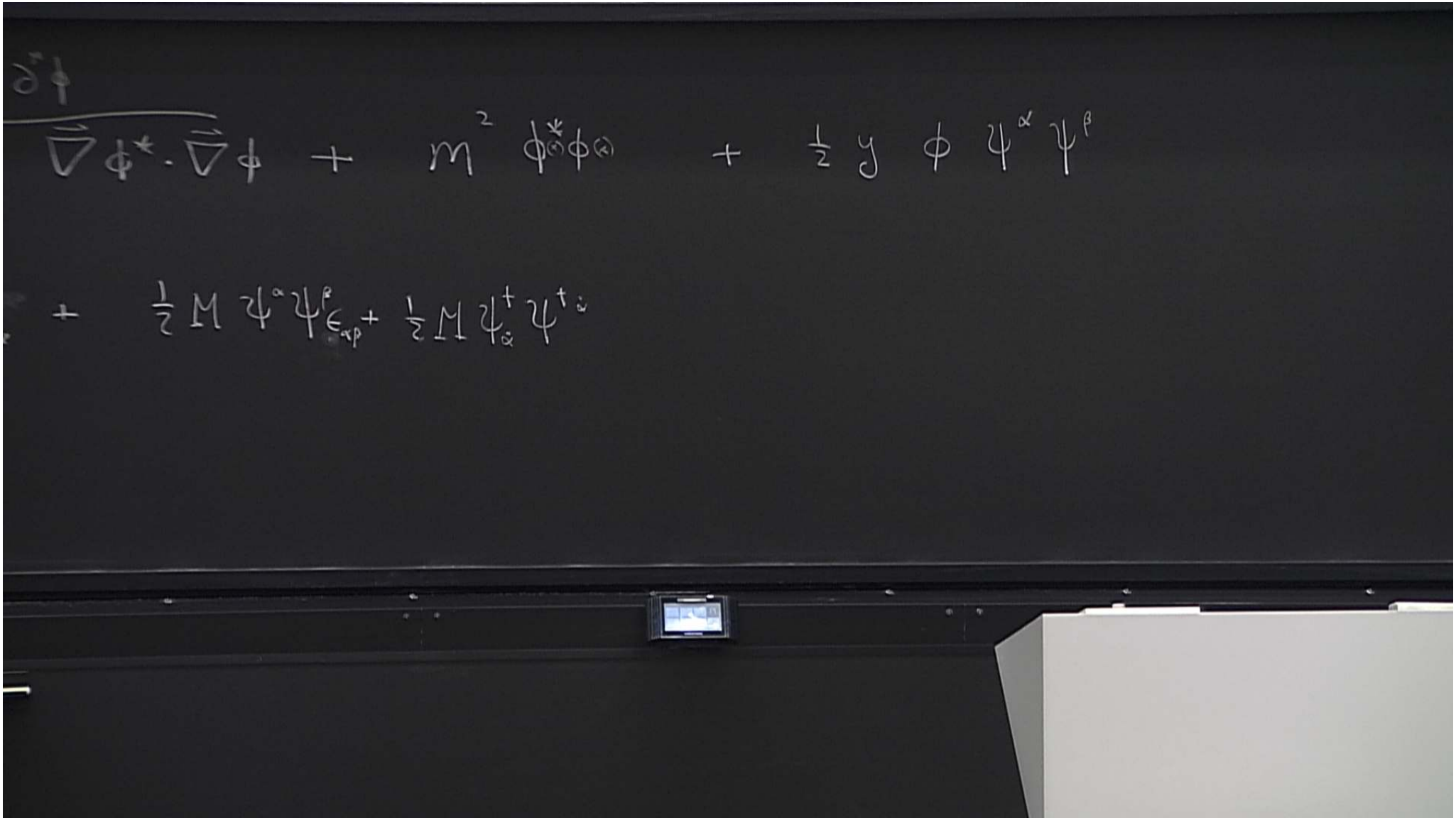
$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

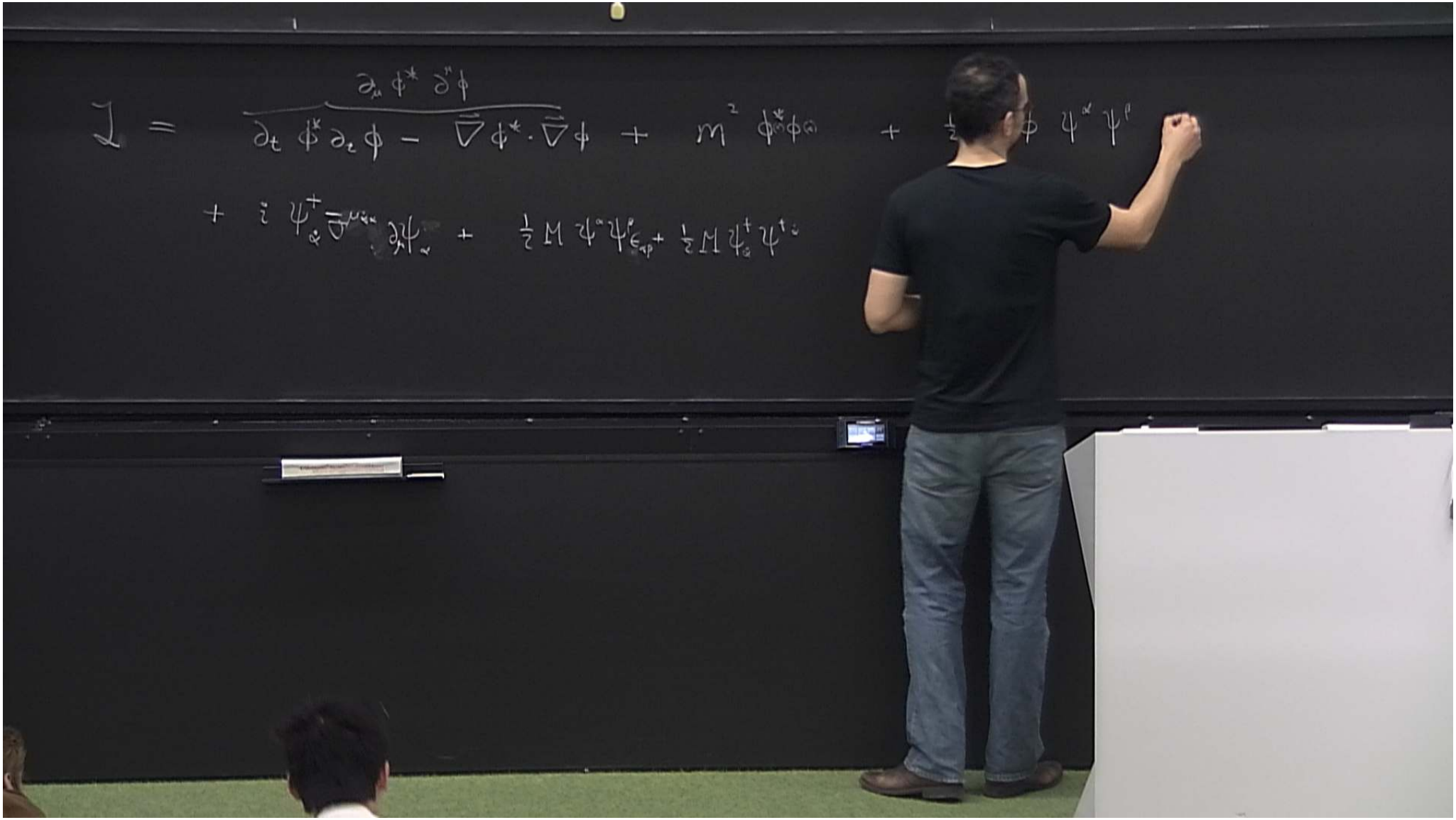
$$\sigma_{\mu \alpha \dot{\alpha}} \bar{\sigma}^{\dot{\alpha}\alpha}_\nu = \eta_{\mu\nu}$$

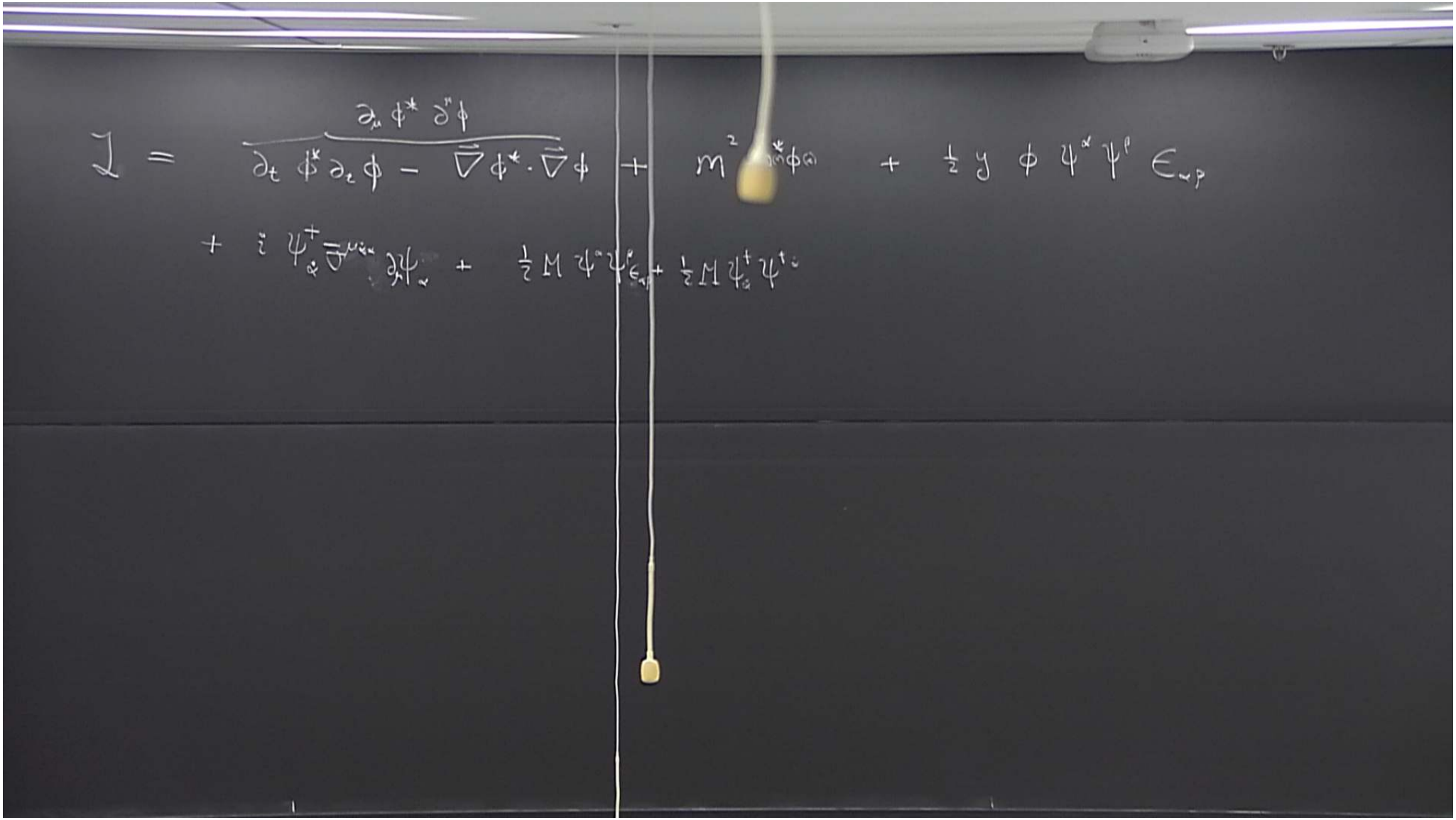
Weyl rep

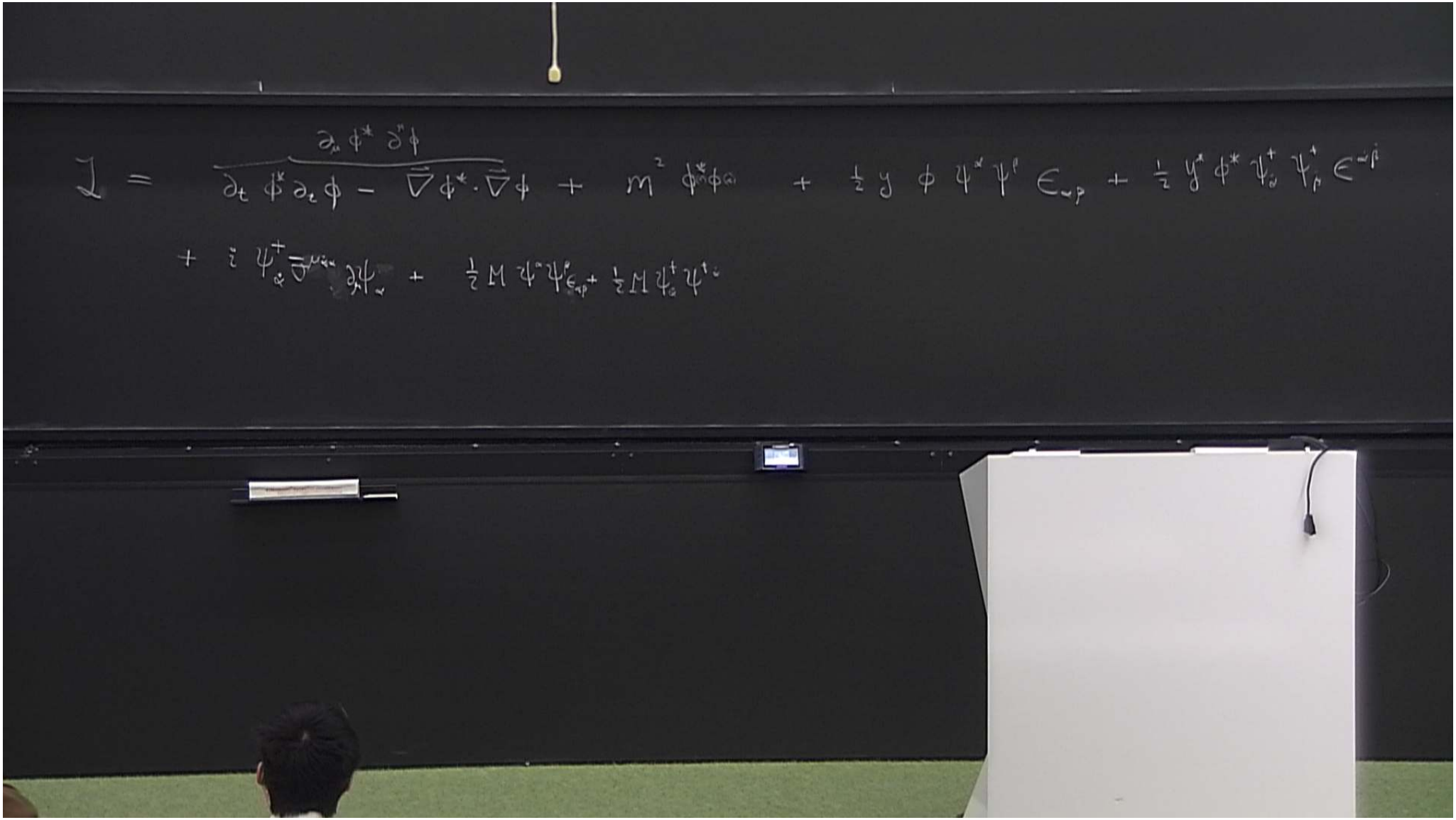
$$\epsilon_{\alpha\beta} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

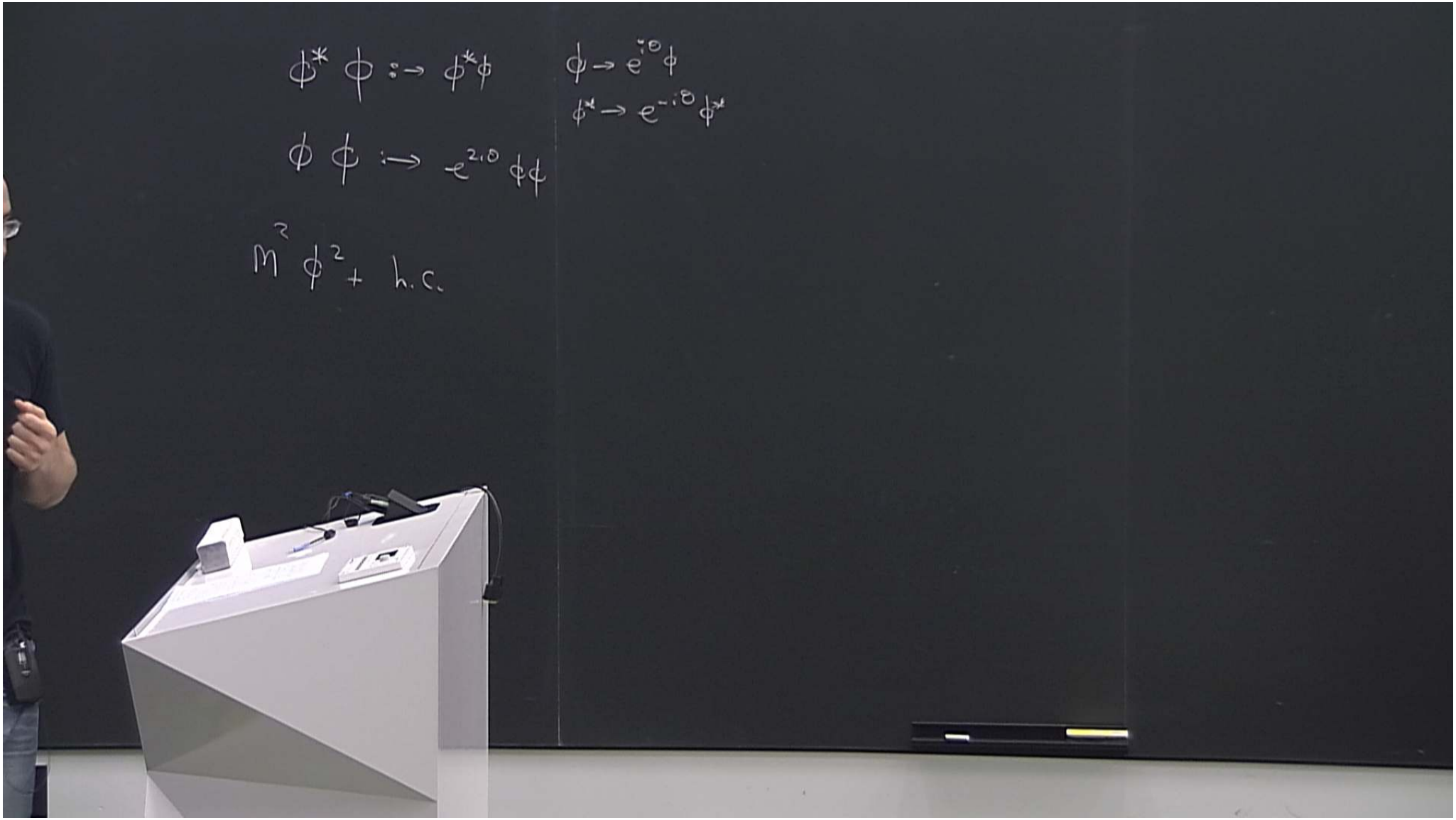
$$\epsilon^{\dot{\alpha}\dot{\beta}} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

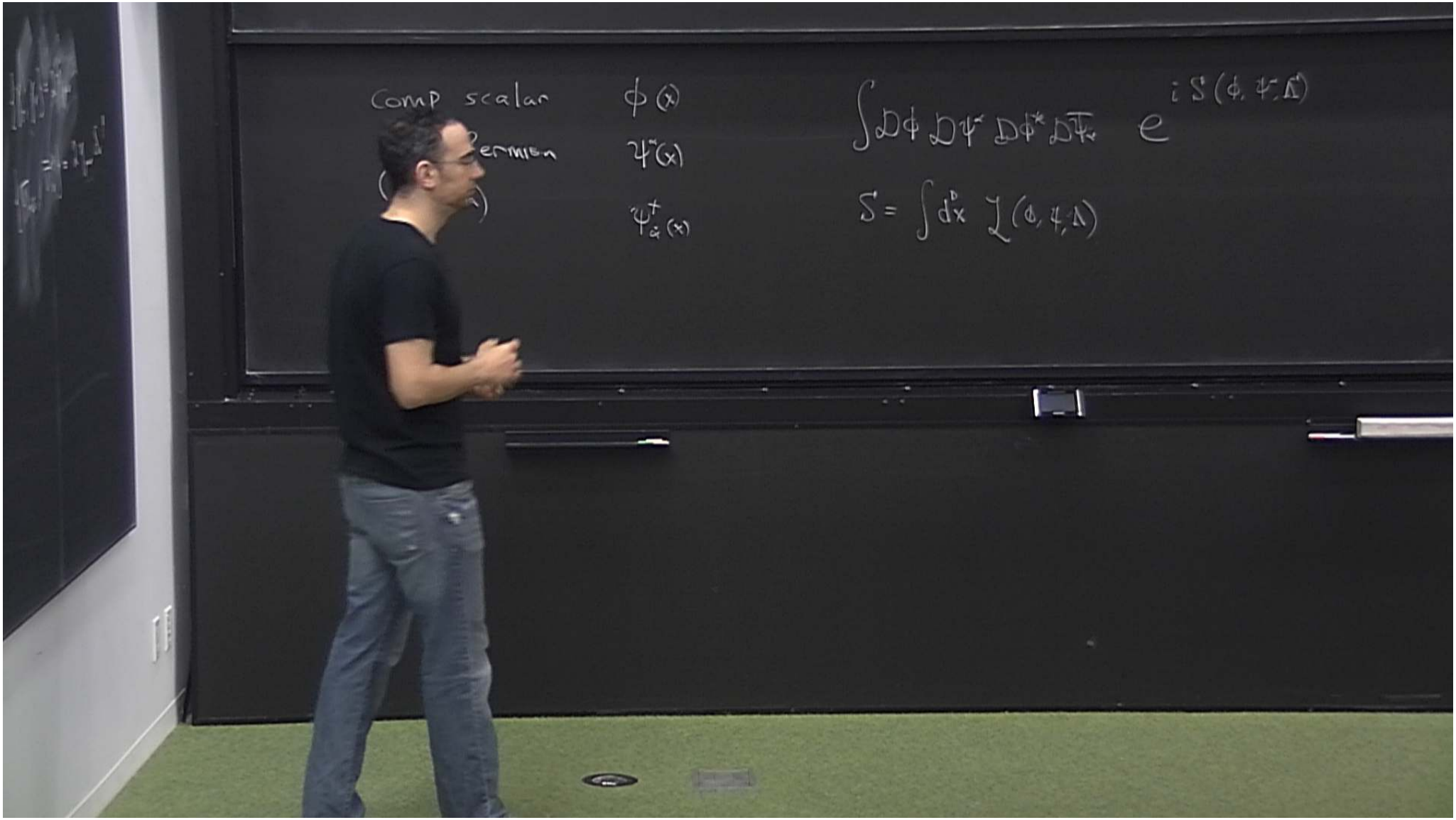

$\partial^\mu \phi$
$\vec{\nabla}\phi^* \cdot \vec{\nabla}\phi + m^2 \phi^*_{(x)}\phi_{(x)} + \frac{1}{2} y \phi \psi^\alpha \psi^\beta$
$+ \frac{1}{2} M \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} M \psi^\dagger_{\dot{\alpha}} \psi^{\dagger \dot{\alpha}}$

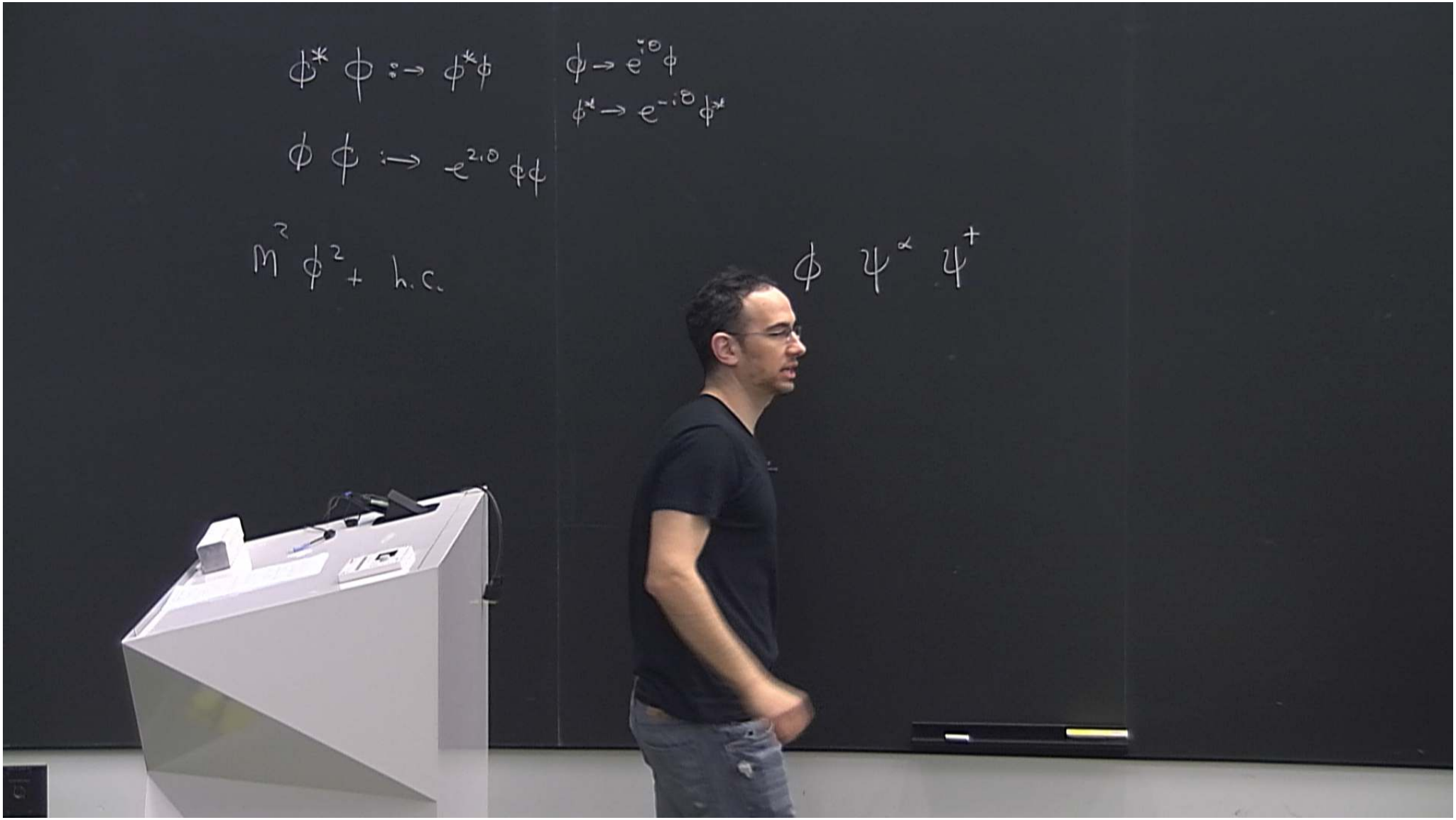


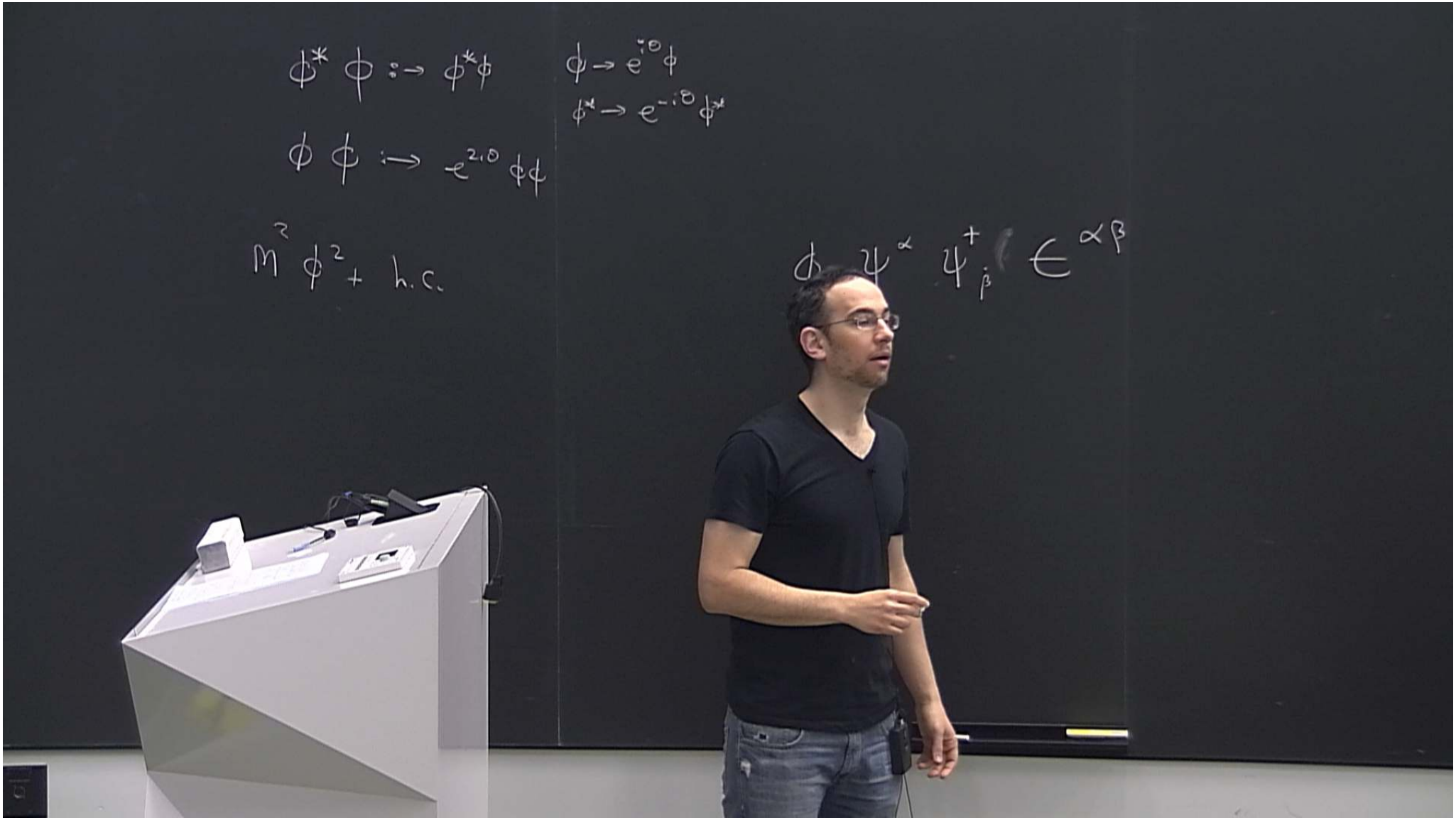


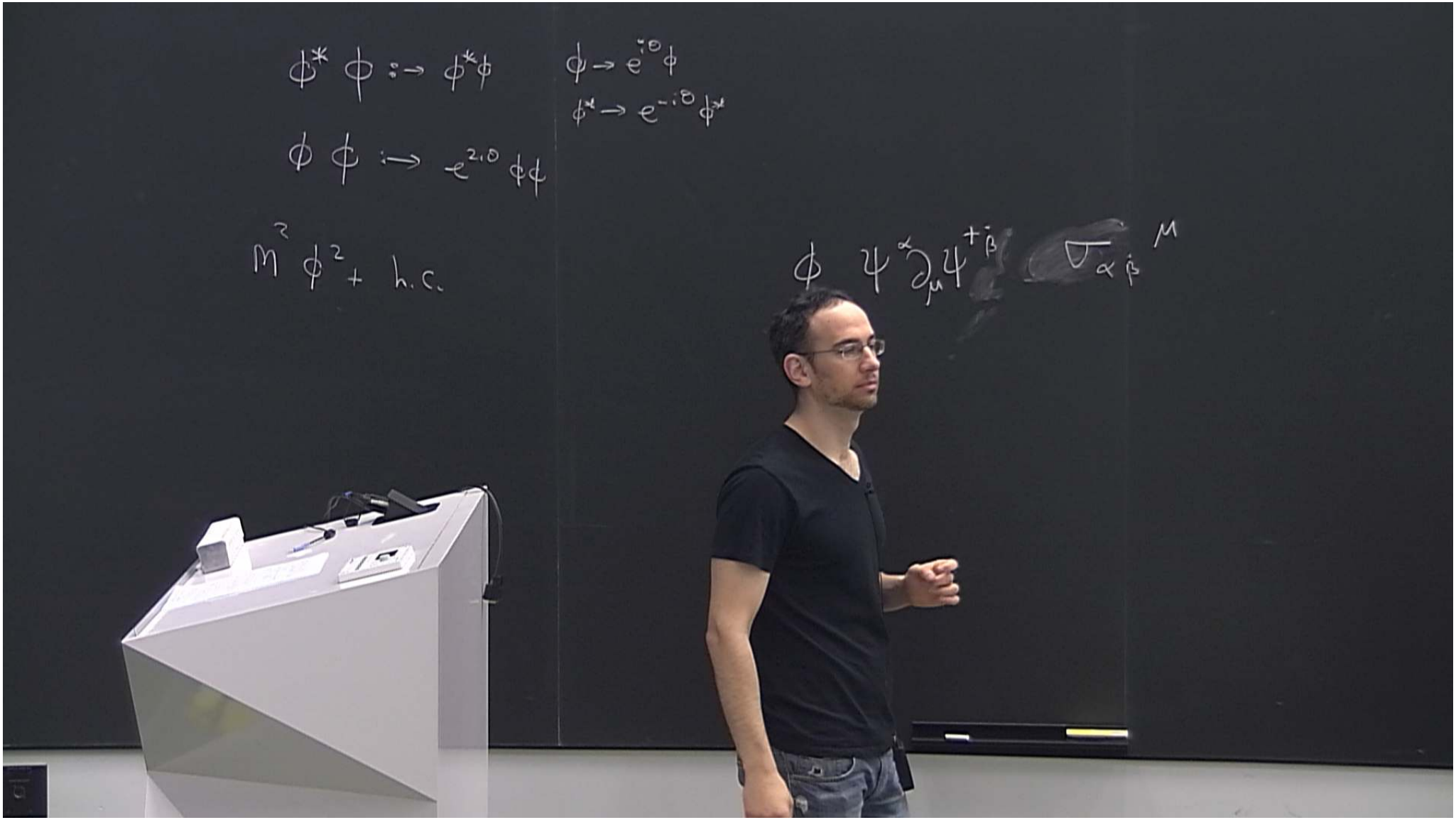

$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - \partial_t \phi^* \partial_t \phi - \vec{\nabla}\phi^* \cdot \vec{\nabla}\phi + m^2 \phi^* \phi + \frac{1}{2} y \phi \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} y^* \phi^* \psi^\dagger_{\dot\alpha} \psi^\dagger_{\dot\beta} \epsilon^{\dot\alpha\dot\beta}$
$+ i \psi^\dagger_{\dot\alpha} \bar\sigma^{\mu\dot\alpha\beta} \partial_\mu \psi_\beta + \frac{1}{2} M \psi^\alpha \psi^\beta \epsilon_{\alpha\beta} + \frac{1}{2} M \psi^\dagger_{\dot\alpha} \psi^{\dagger\dot\beta}$

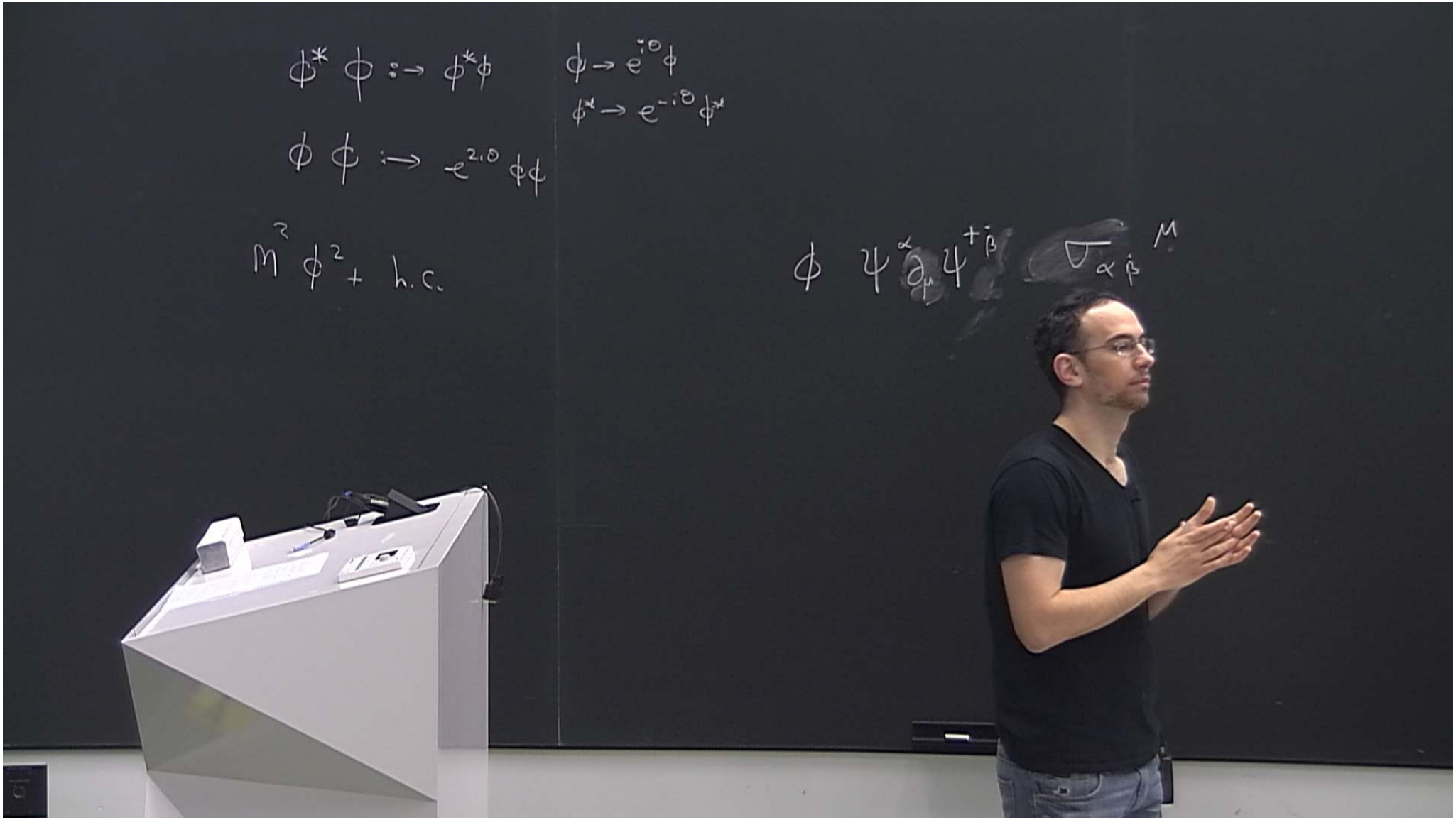

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$

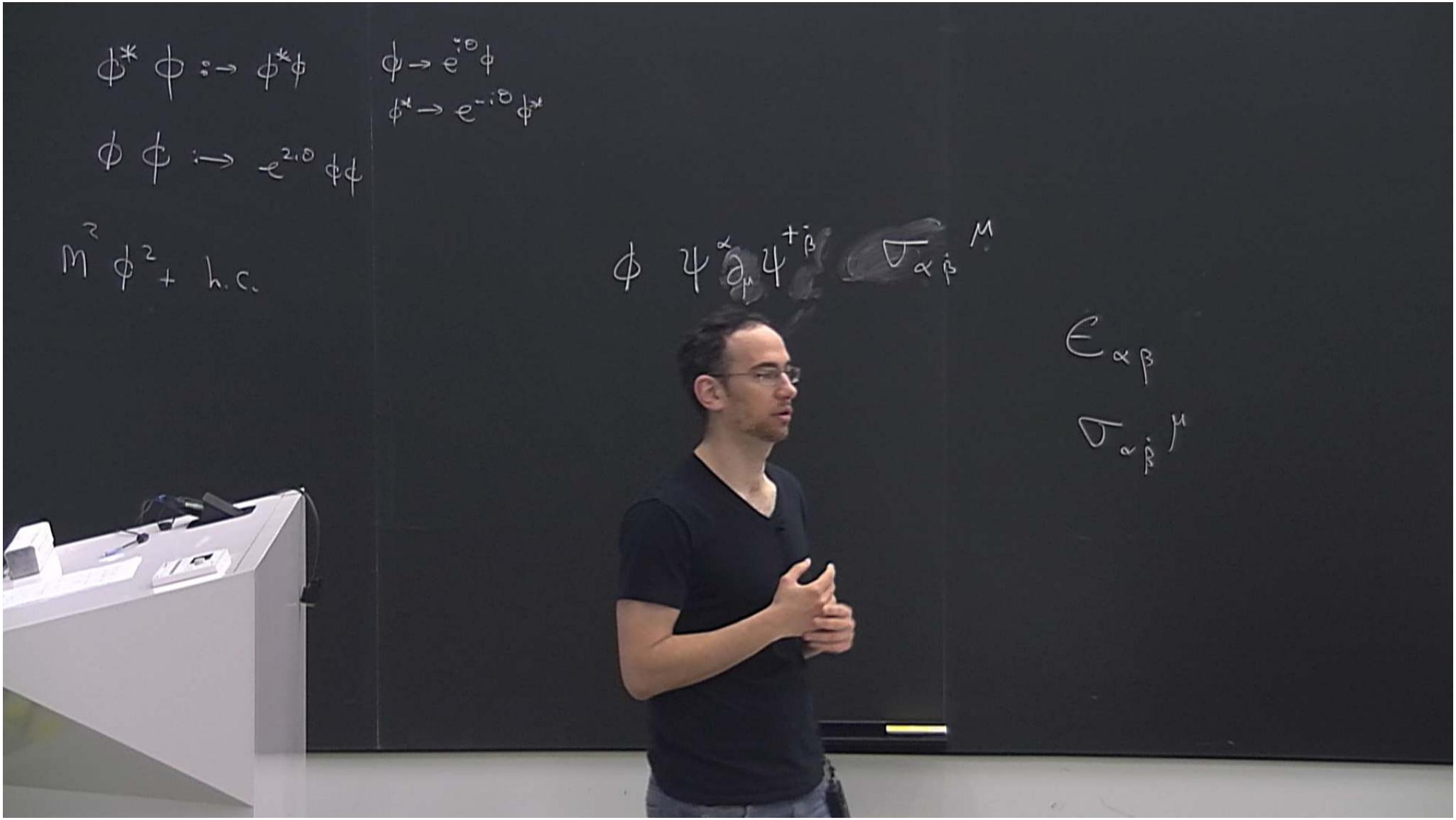

Comp scalar
$\phi(x)$
$\psi_a^*(x)$
$\int \mathcal{D}\phi\, \mathcal{D}\psi\, \mathcal{D}\phi^*\, \mathcal{D}\psi^*\, e^{iS(\phi,\psi,A)}$
$S = \int d^4x\, \mathcal{L}(\phi,\psi,A)$

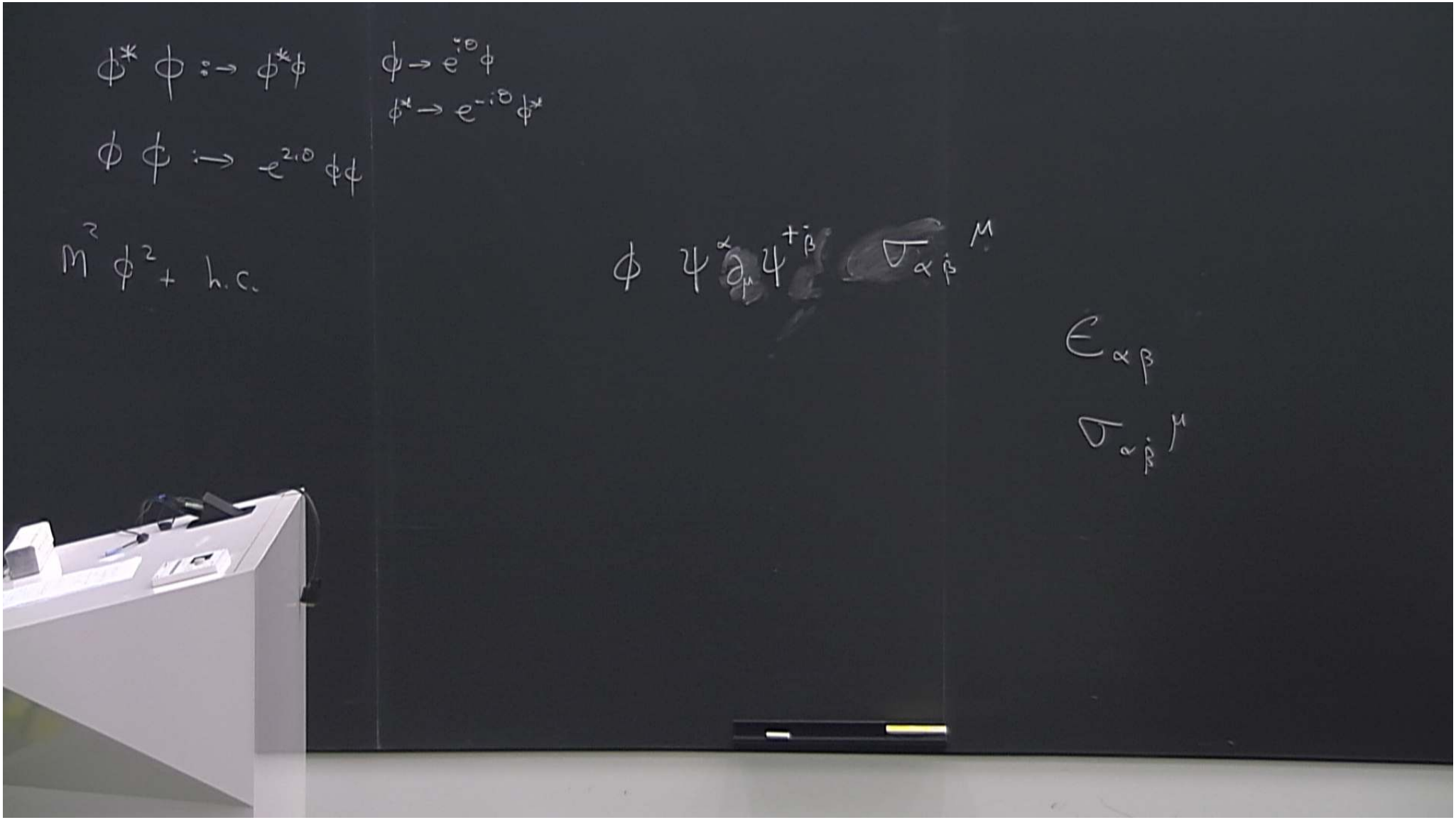

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \psi^+$

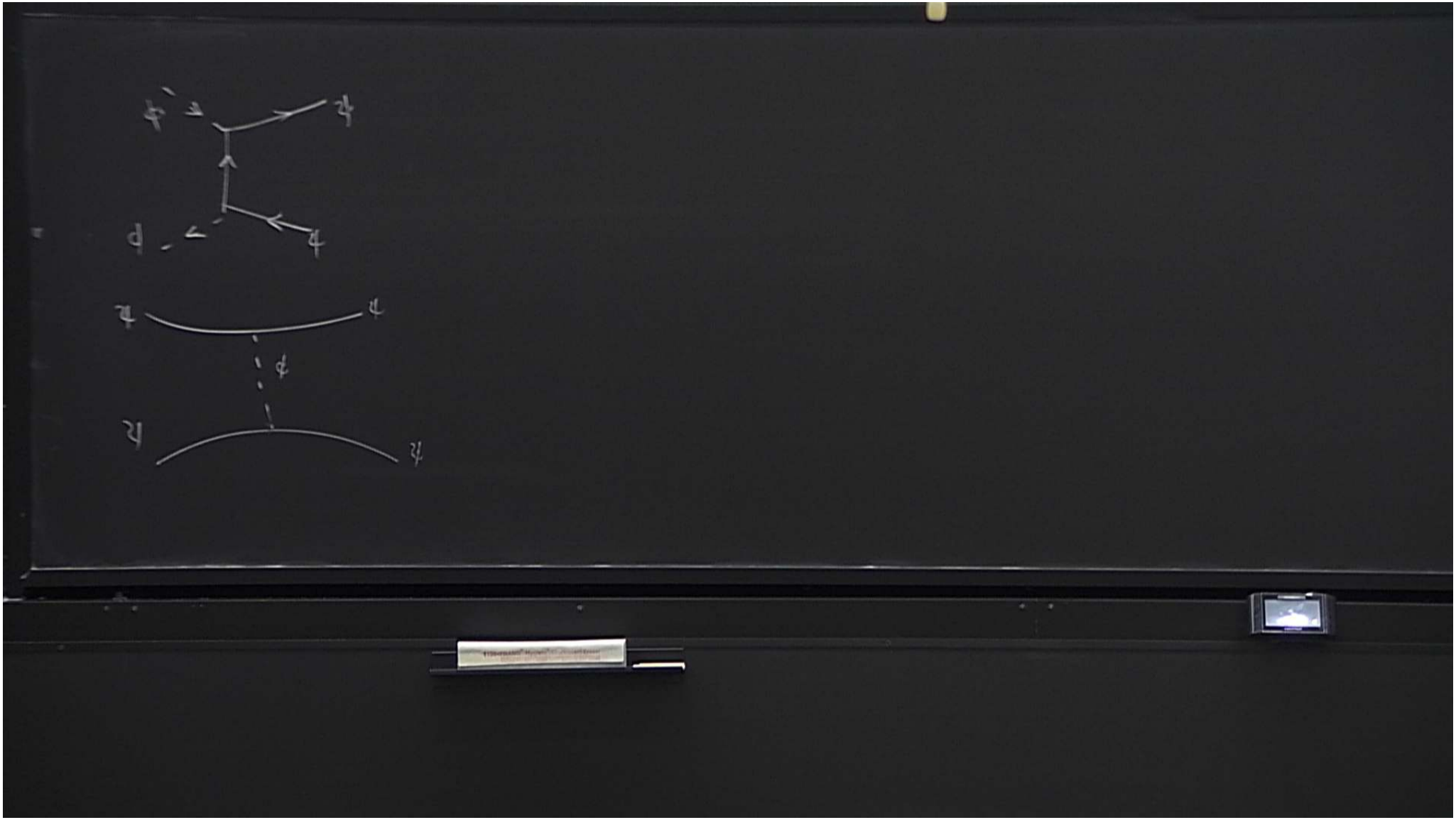

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \psi^+_\beta \epsilon^{\alpha\beta}$

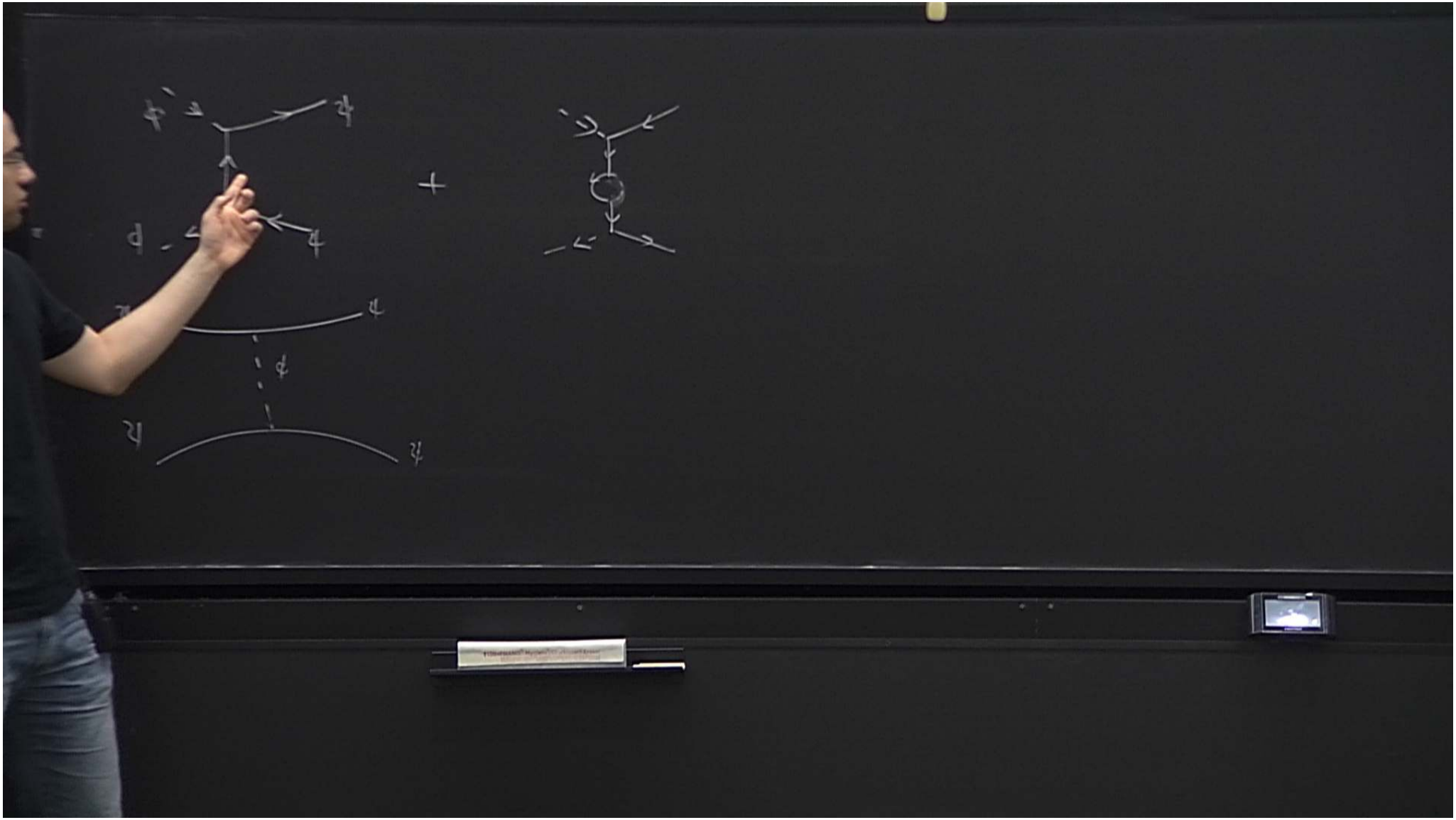

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \partial_\mu \psi^{+\dot{\beta}} \sigma^\mu_{\alpha\dot{\beta}}$

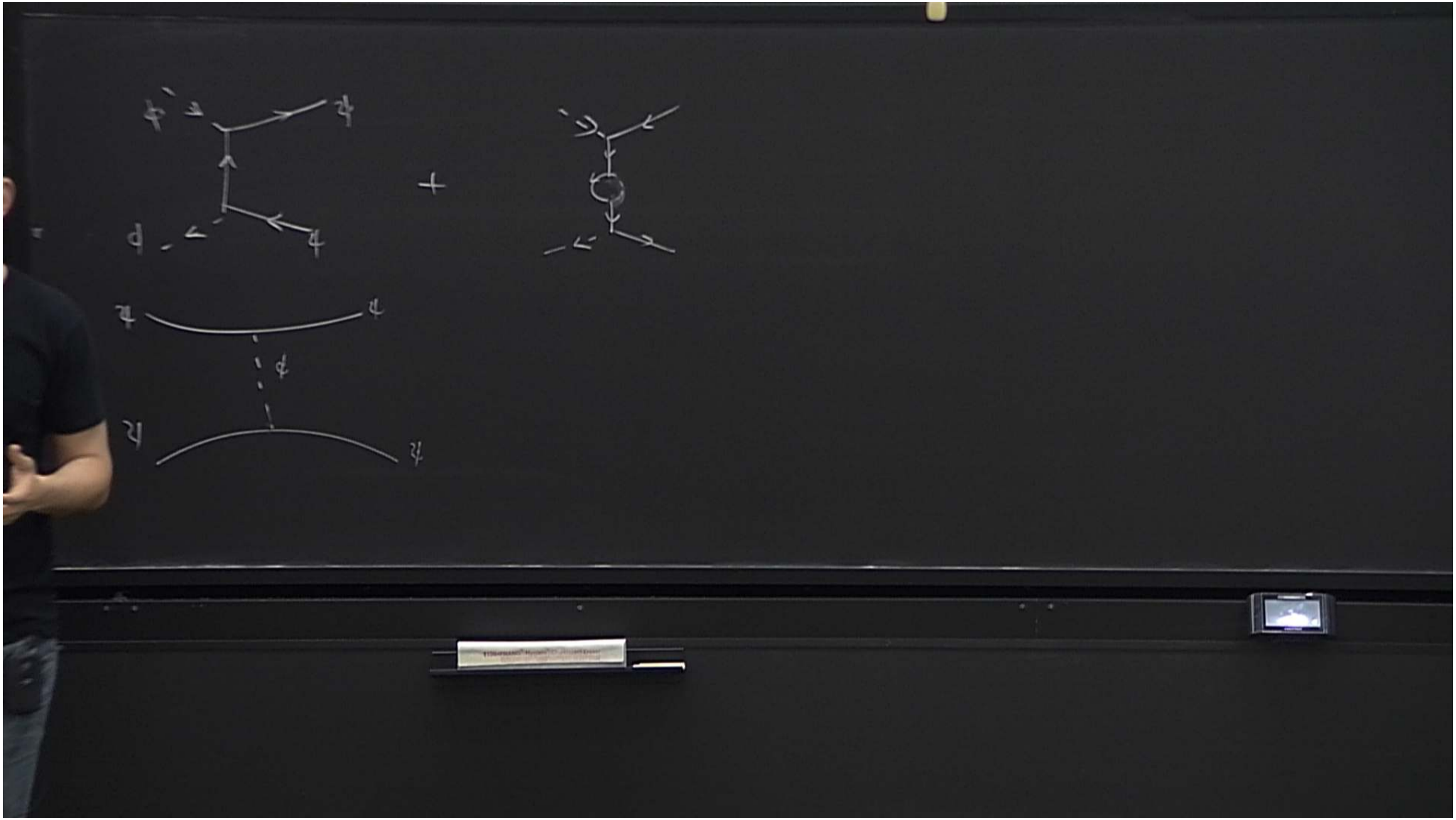

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \partial_\mu \psi^{+\dot{\beta}} \sigma^\mu_{\alpha\dot{\beta}}$

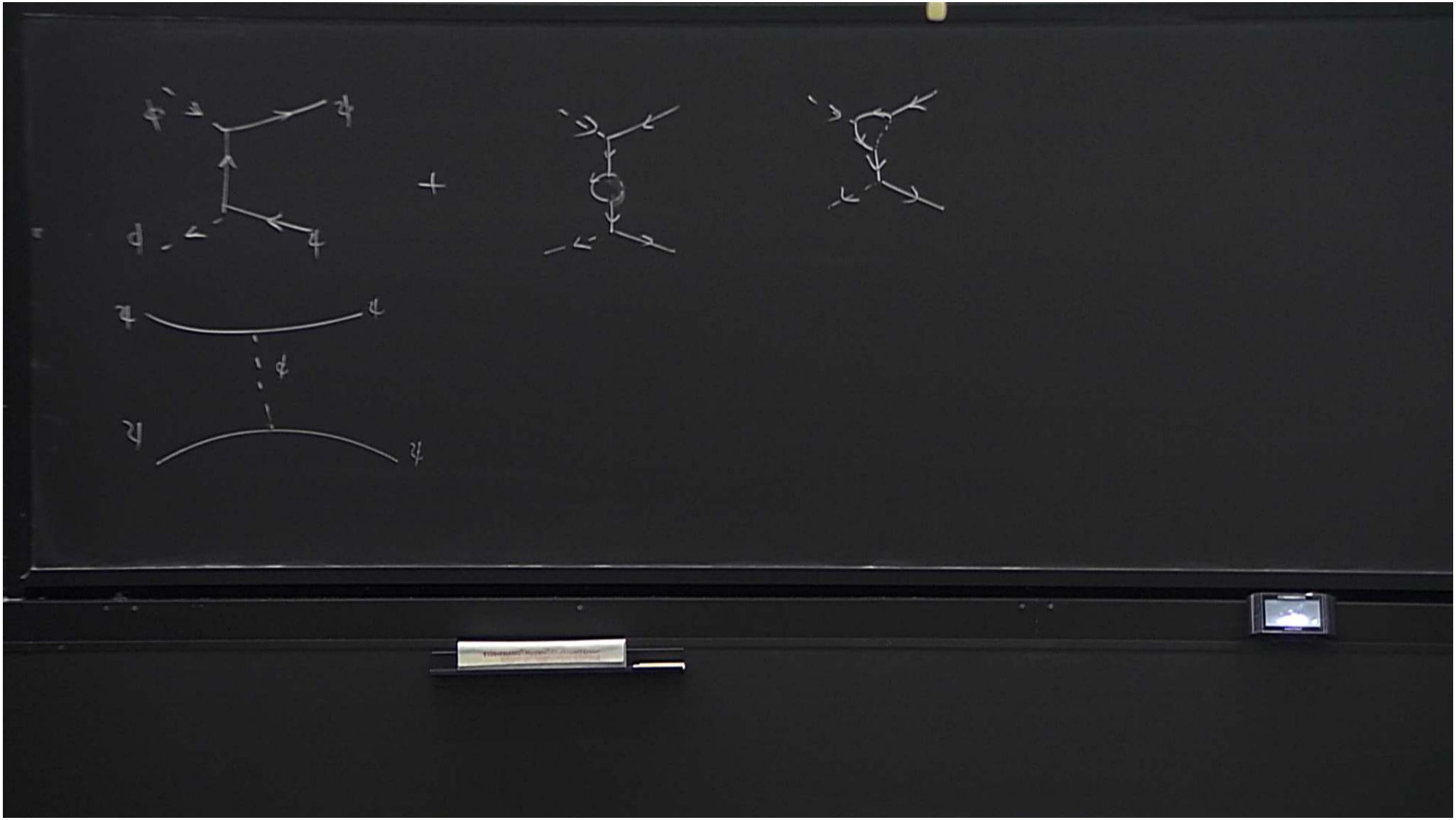

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi \phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \partial_\mu \psi^{+\dot\beta} \sigma^\mu_{\alpha\dot\beta} M$
$\epsilon_{\alpha\beta}$
$\sigma^\mu_{\alpha\dot\beta}$

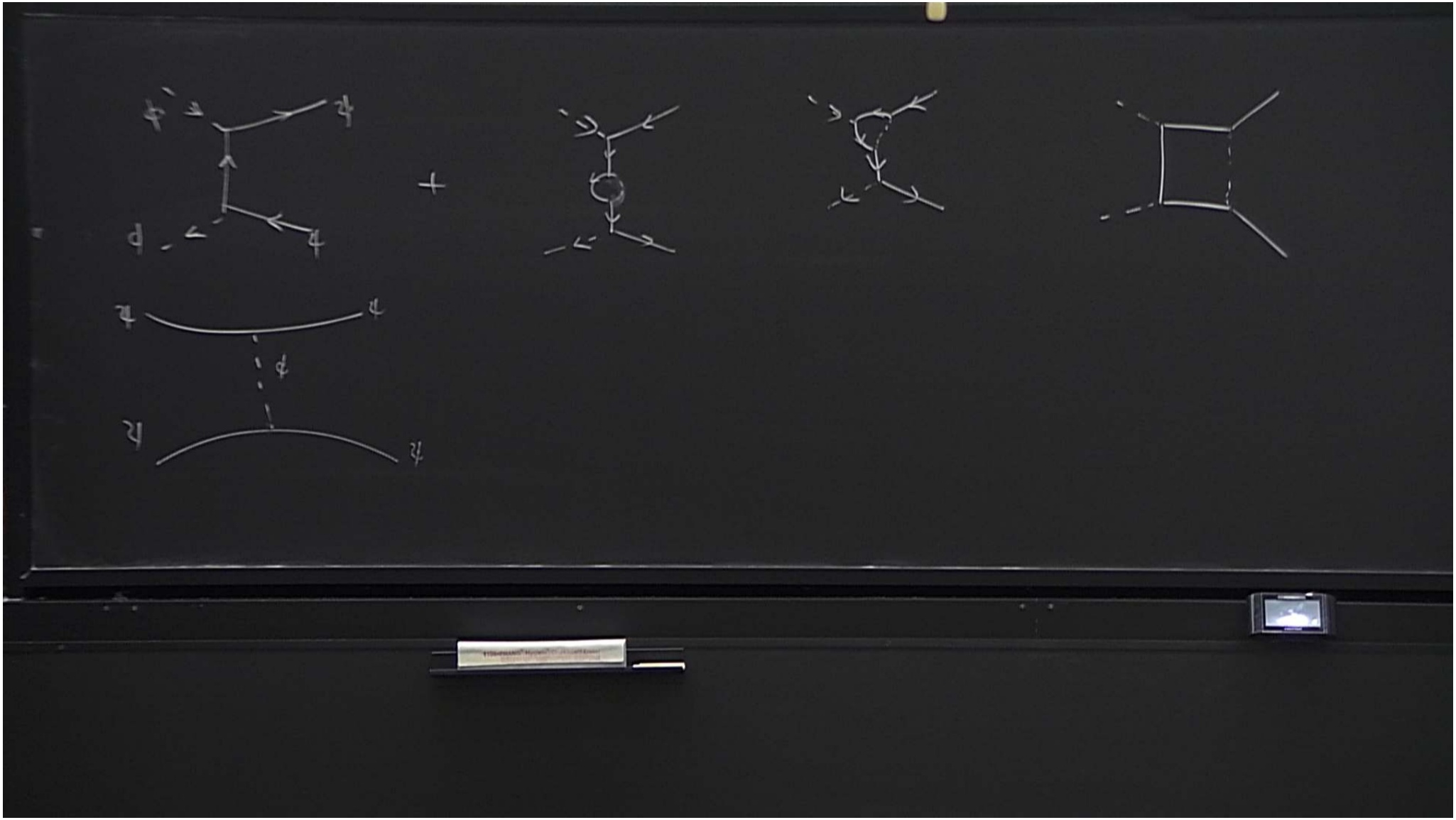

$\phi^* \phi :\to \phi^* \phi$
$\phi \to e^{i\theta} \phi$
$\phi^* \to e^{-i\theta} \phi^*$
$\phi\phi :\to e^{2i\theta} \phi\phi$
$m^2 \phi^2 + h.c.$
$\phi \psi^\alpha \partial_\mu \psi^{+\dot\beta} \sigma^\mu_{\alpha\dot\beta}$
$\epsilon_{\alpha\beta}$
$\sigma^\mu_{\alpha\dot\beta}$

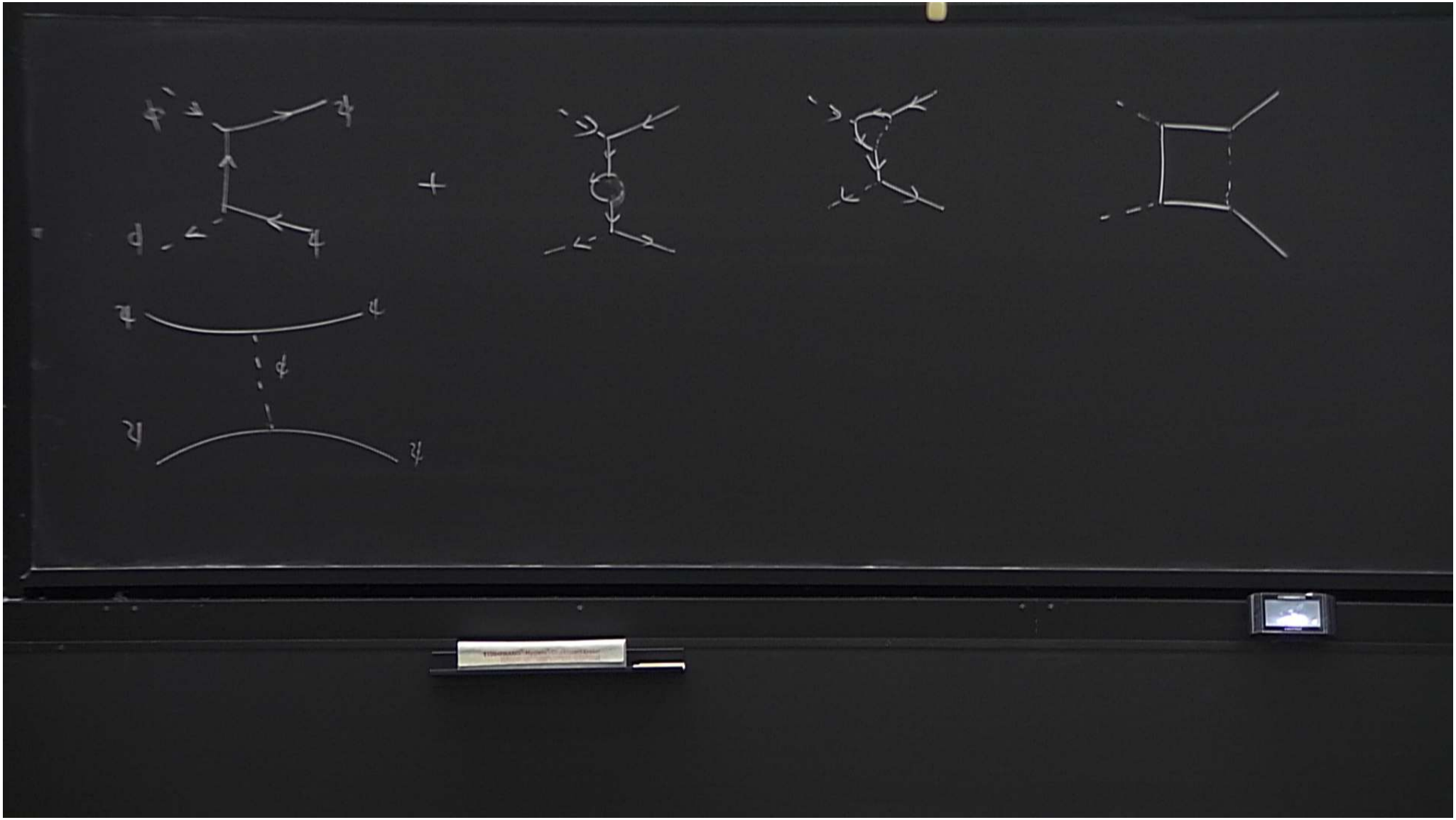


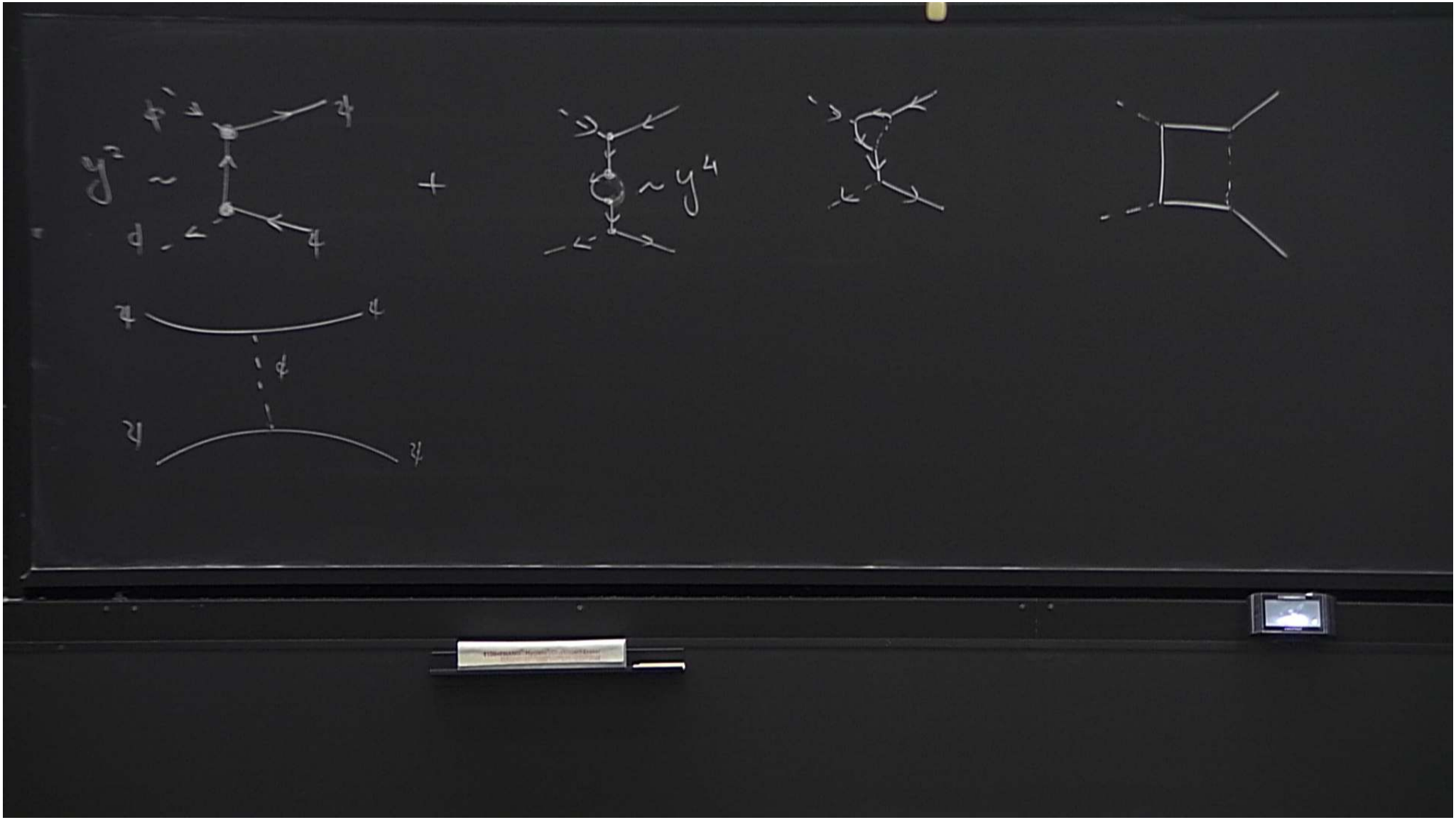


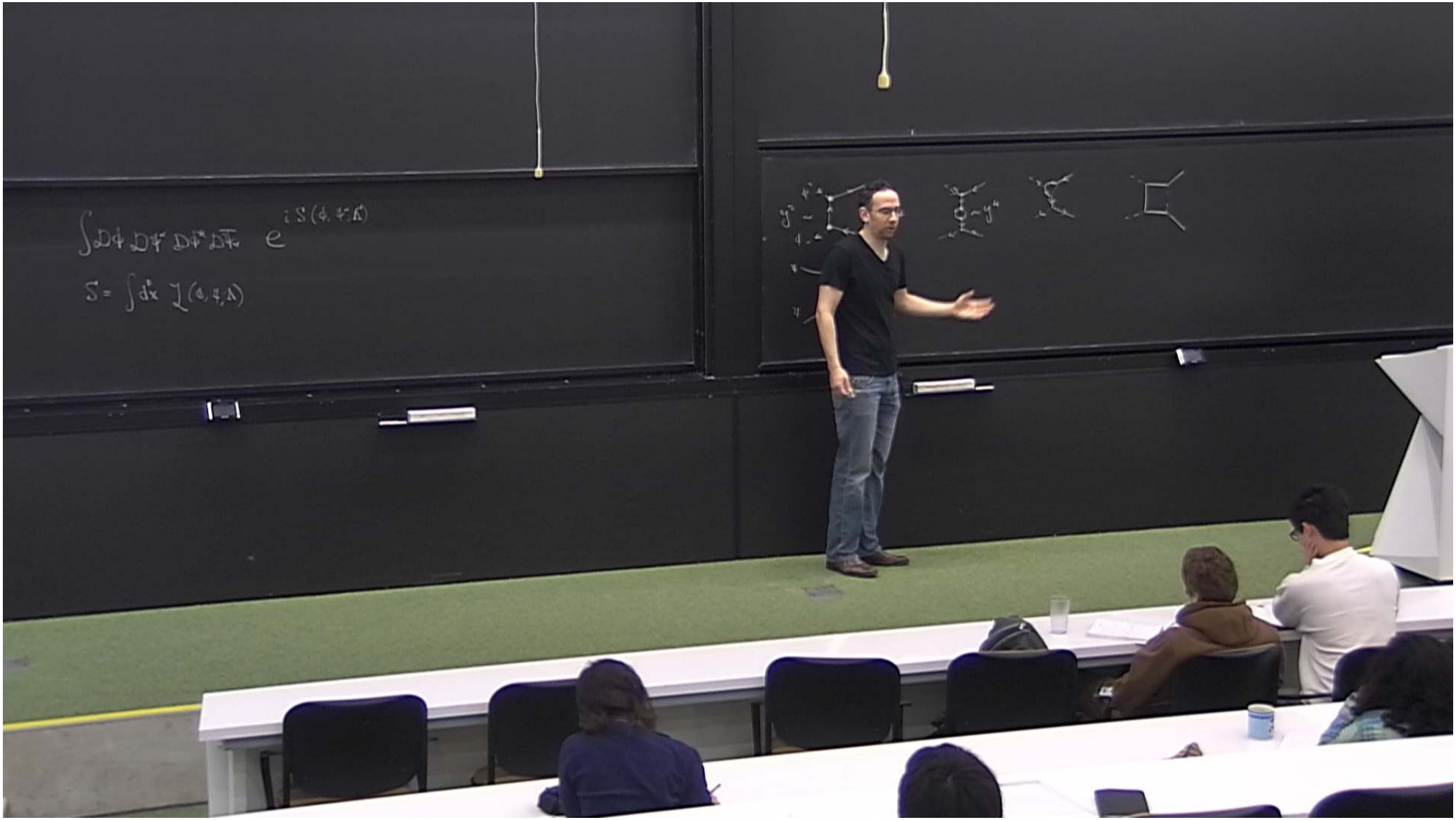


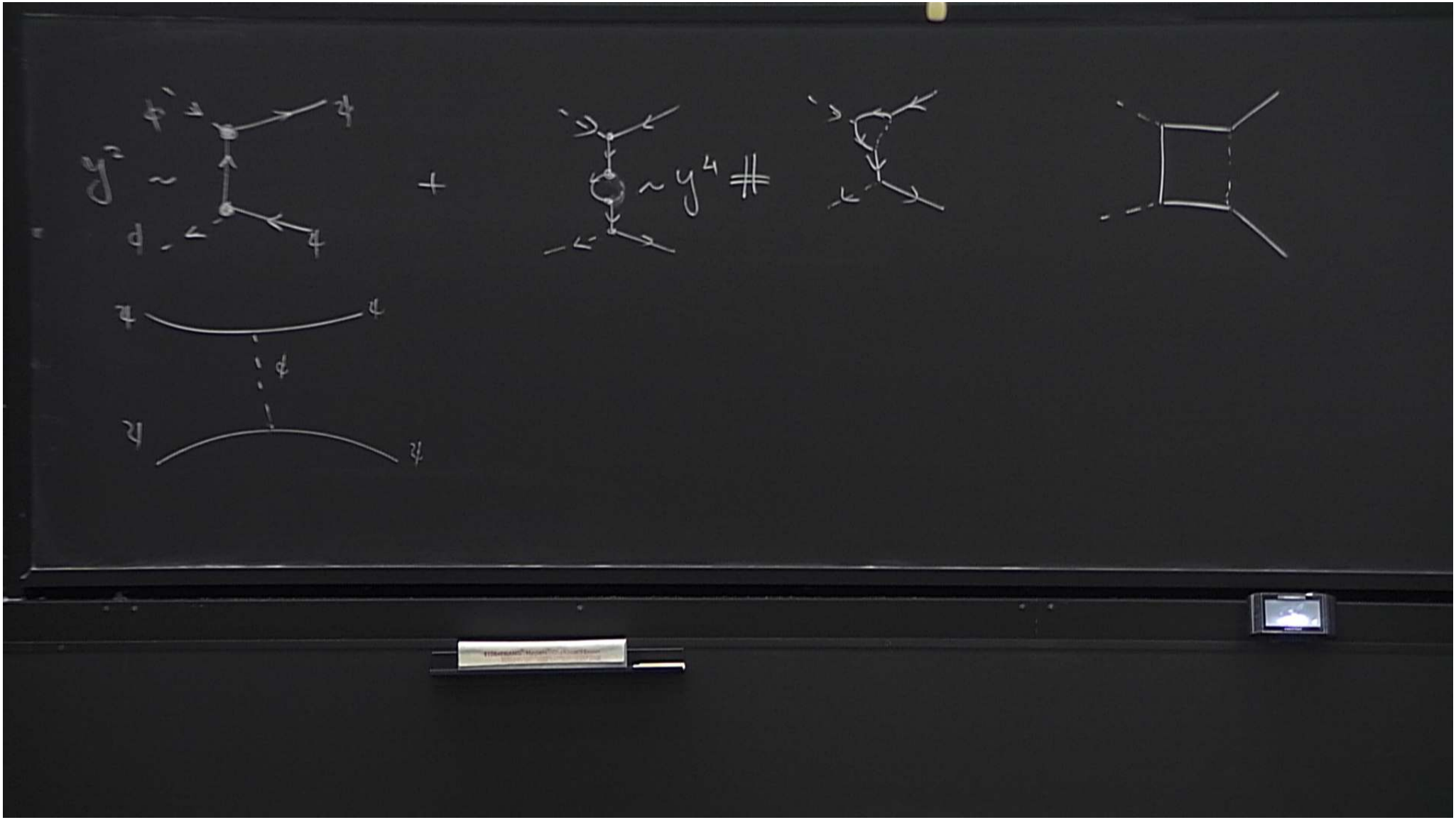


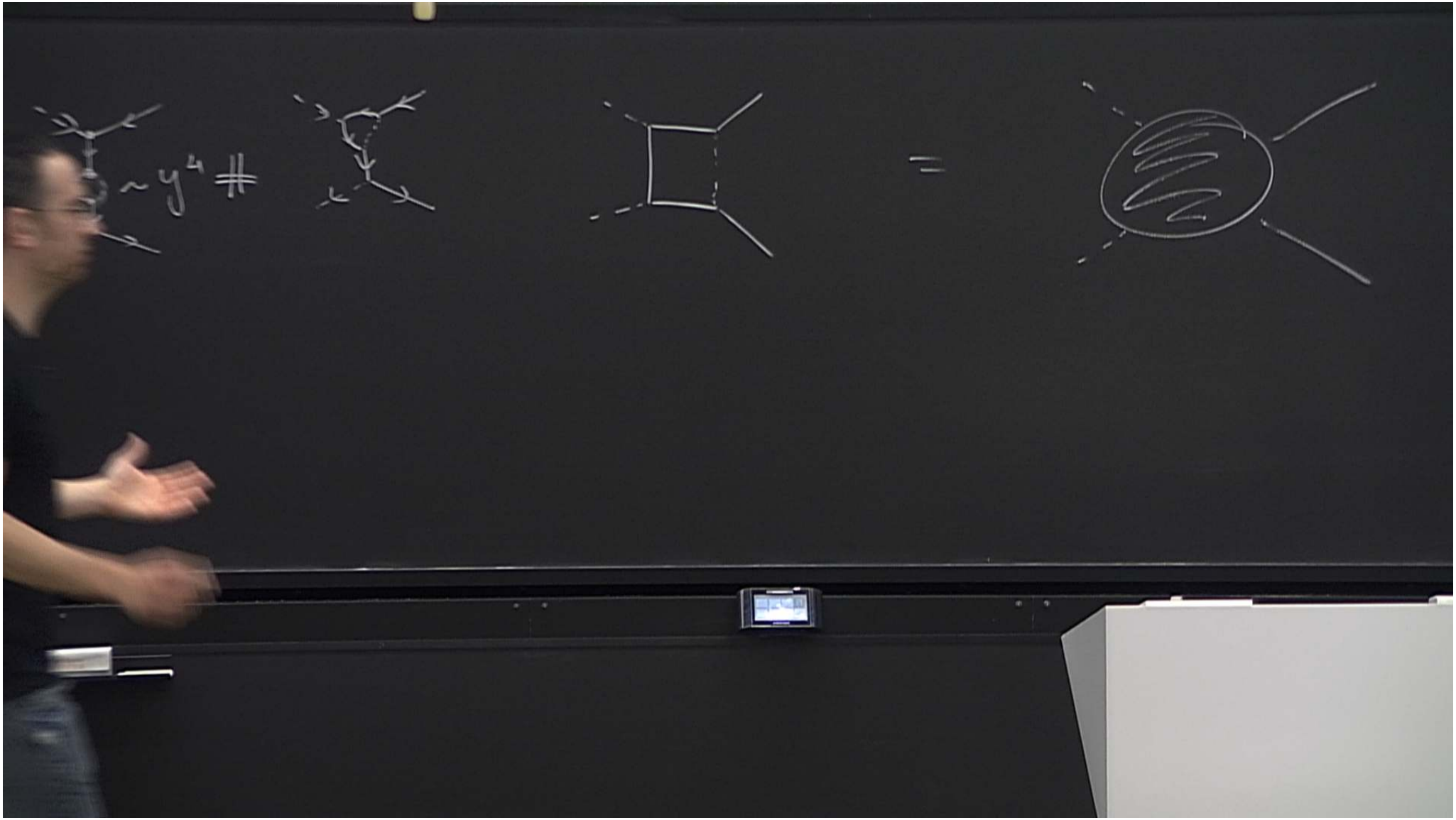


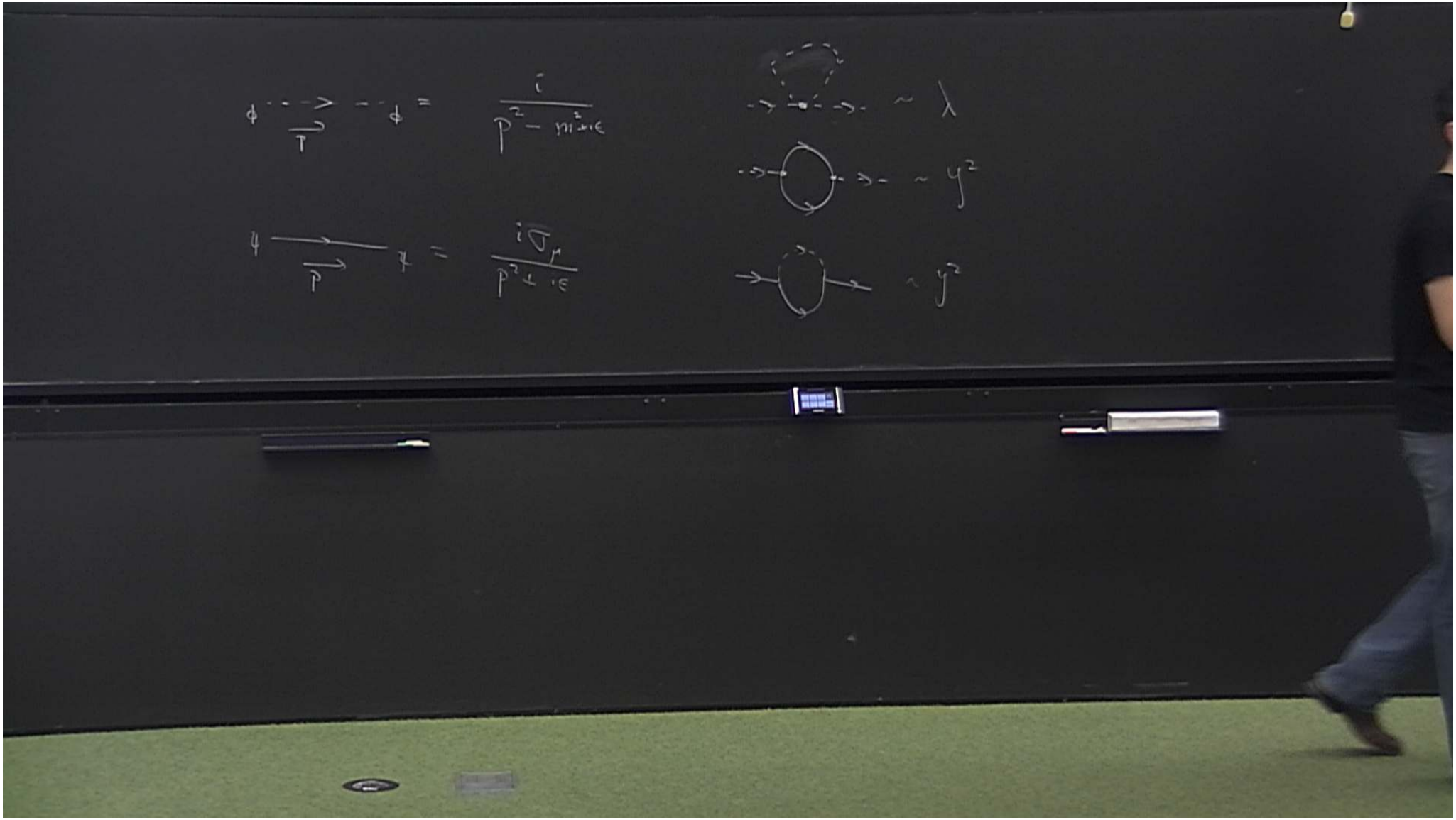



y^2
$\sim$
+
$\sim y^4$


$\int \mathcal{D}\phi\,\mathcal{D}\psi\,\mathcal{D}\psi^*\mathcal{D}\bar{\psi}\; e^{iS(\phi,\psi,\bar{\psi})}$
$S = \int d^4x\, \mathcal{L}(\phi,\psi,\bar{\psi})$


$y^2 \sim$
$+$
$\sim y^4 \#$


~ y⁴ #


$\phi \xrightarrow{p} \phi = \frac{i}{p^2 - m^2 + i\epsilon}$
$\sim \lambda$
$\sim y^2$
$\psi \xrightarrow{p} \chi = \frac{i \not{p}}{p^2 + i\epsilon}$
$\sim y^2$