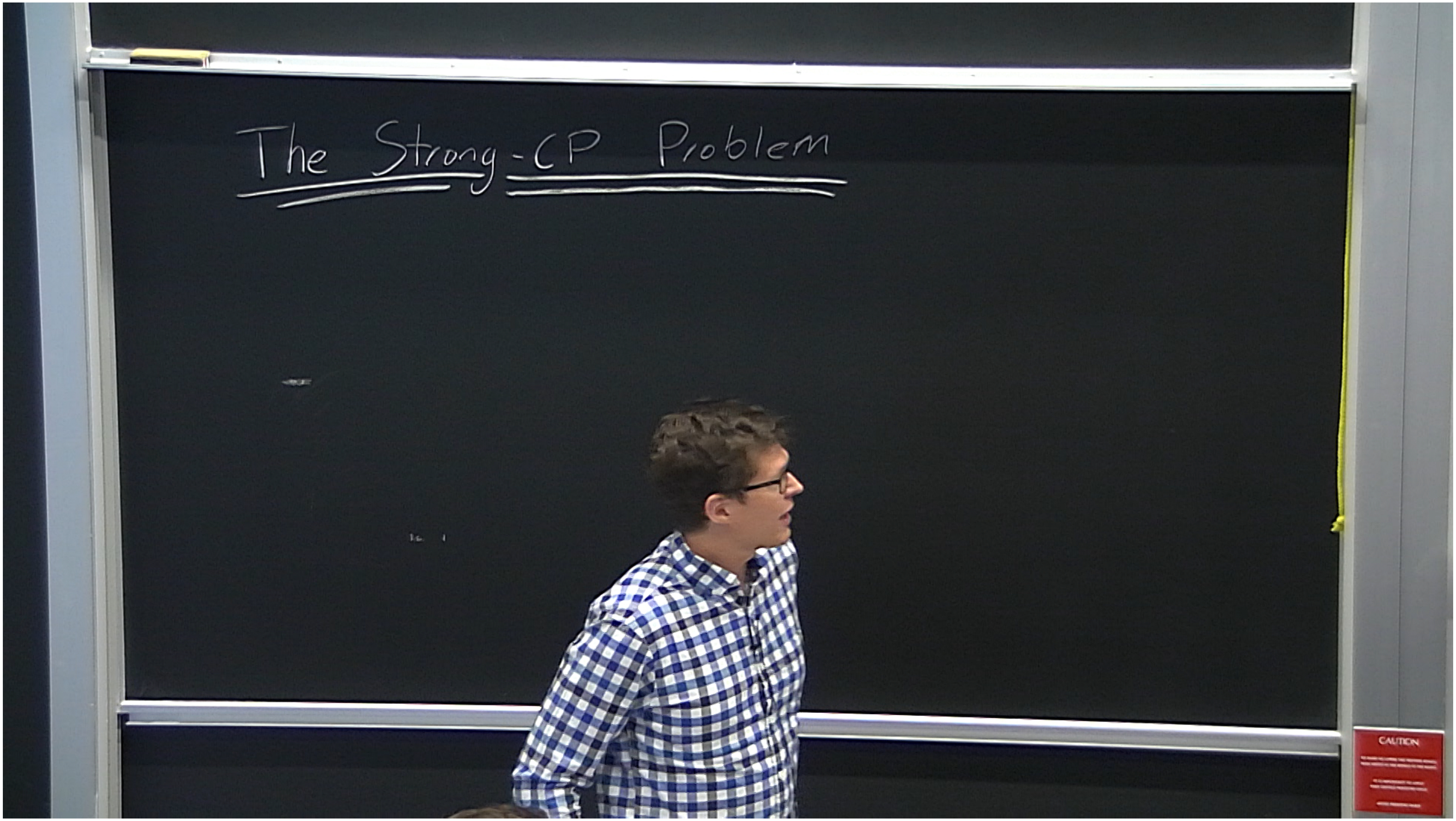
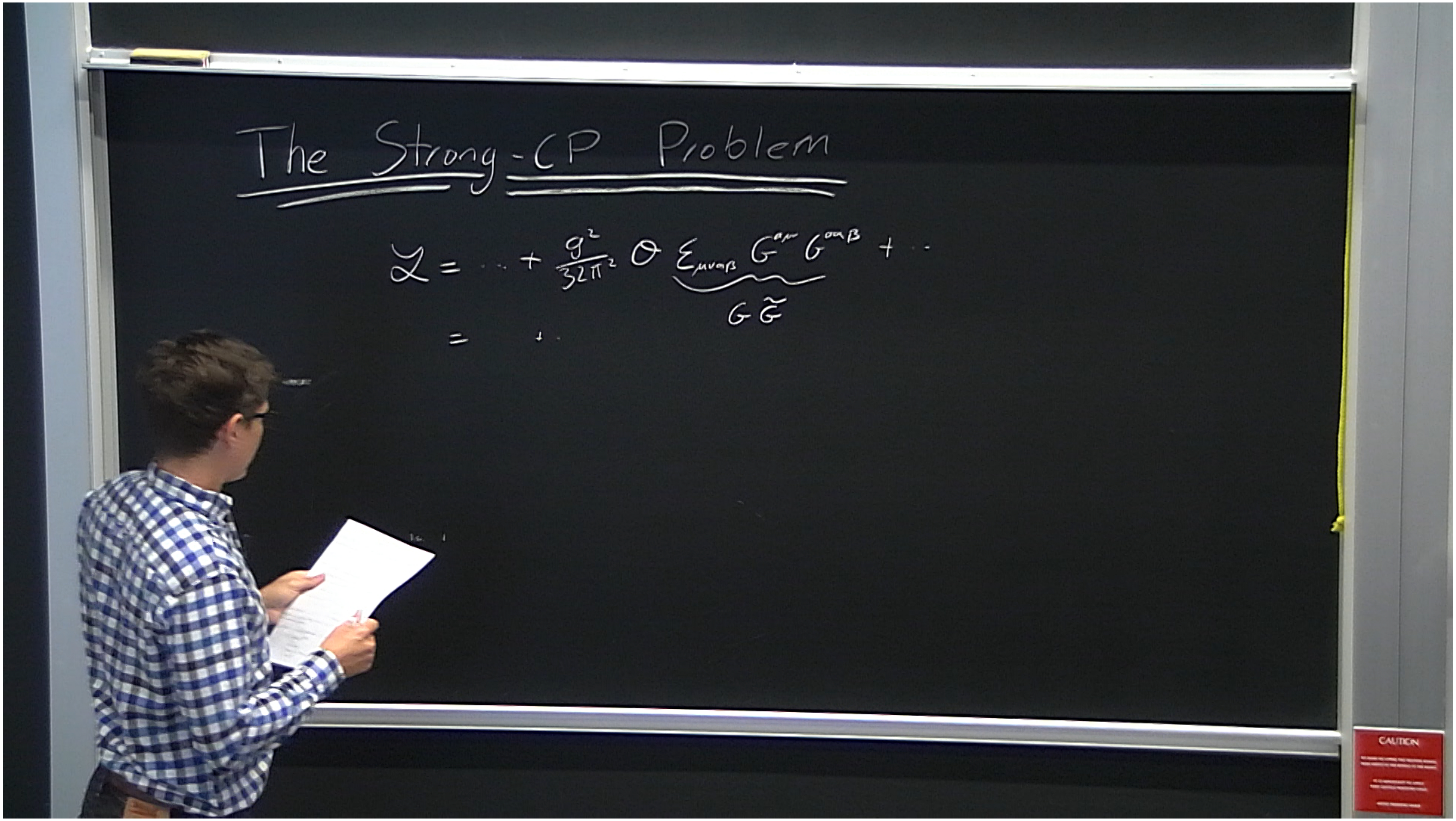
Title: BSM Theory 3

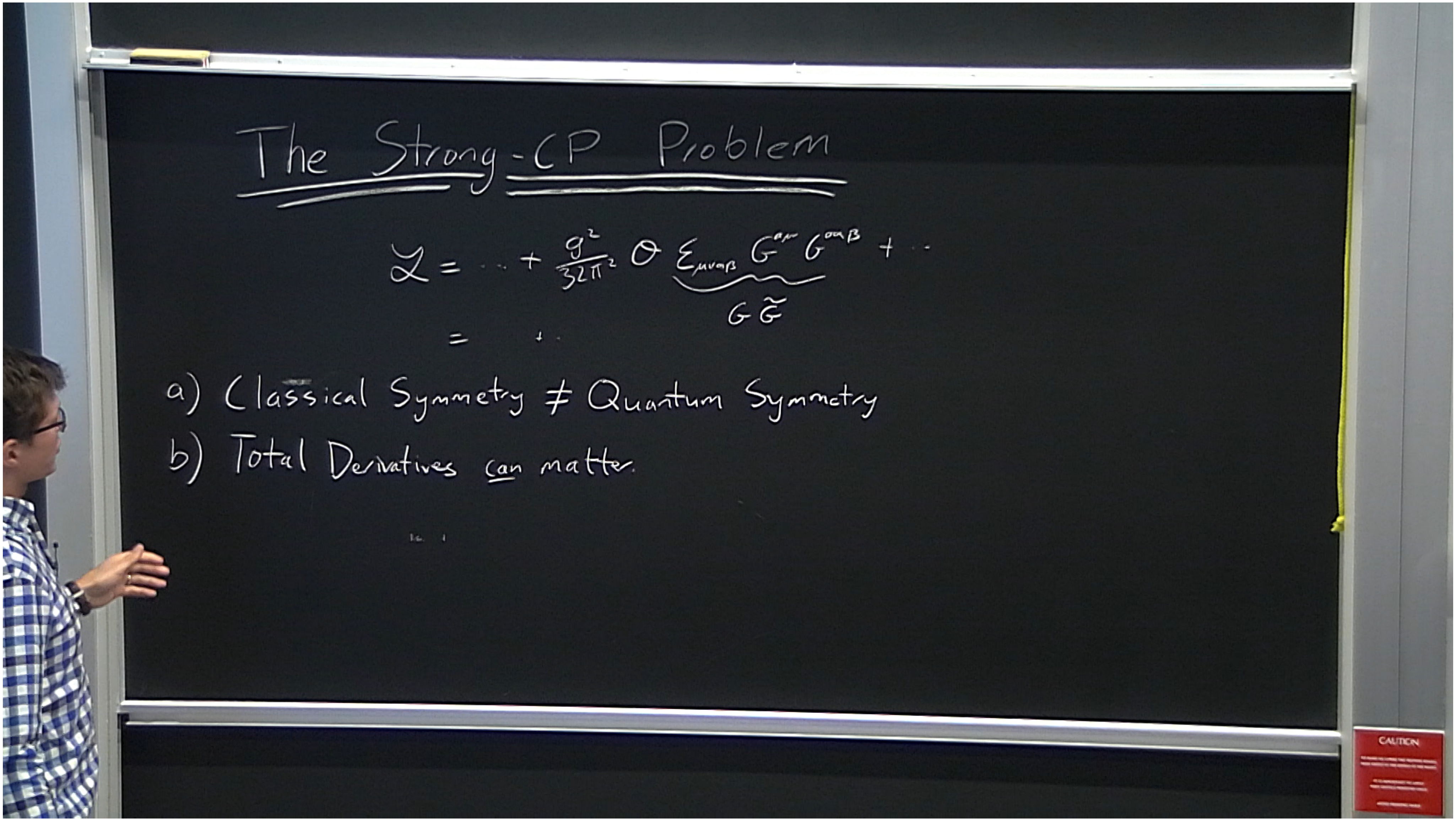
Date: Jul 13, 2018 11:00 AM

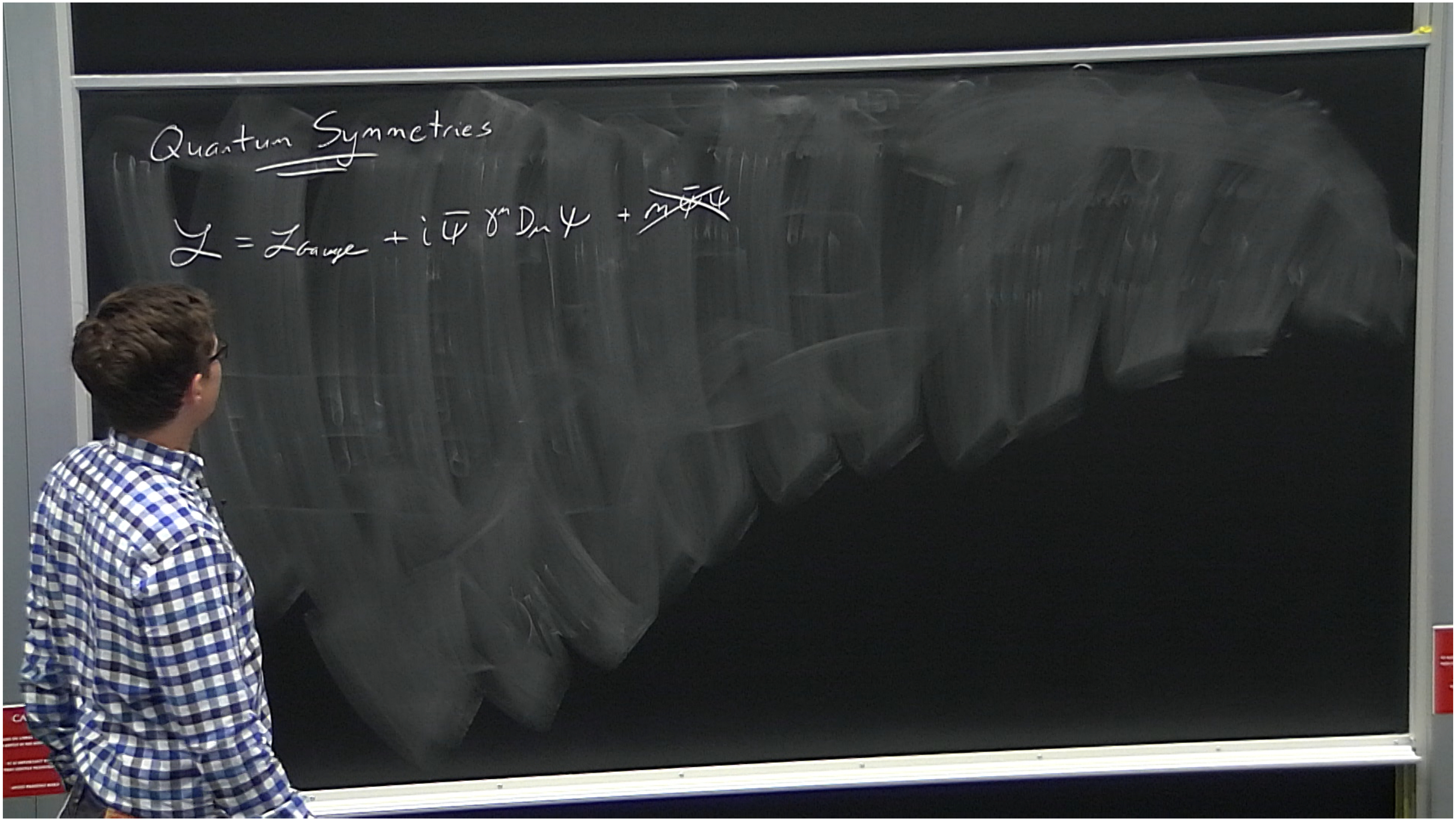
URL: http://pirsa.org/18070013

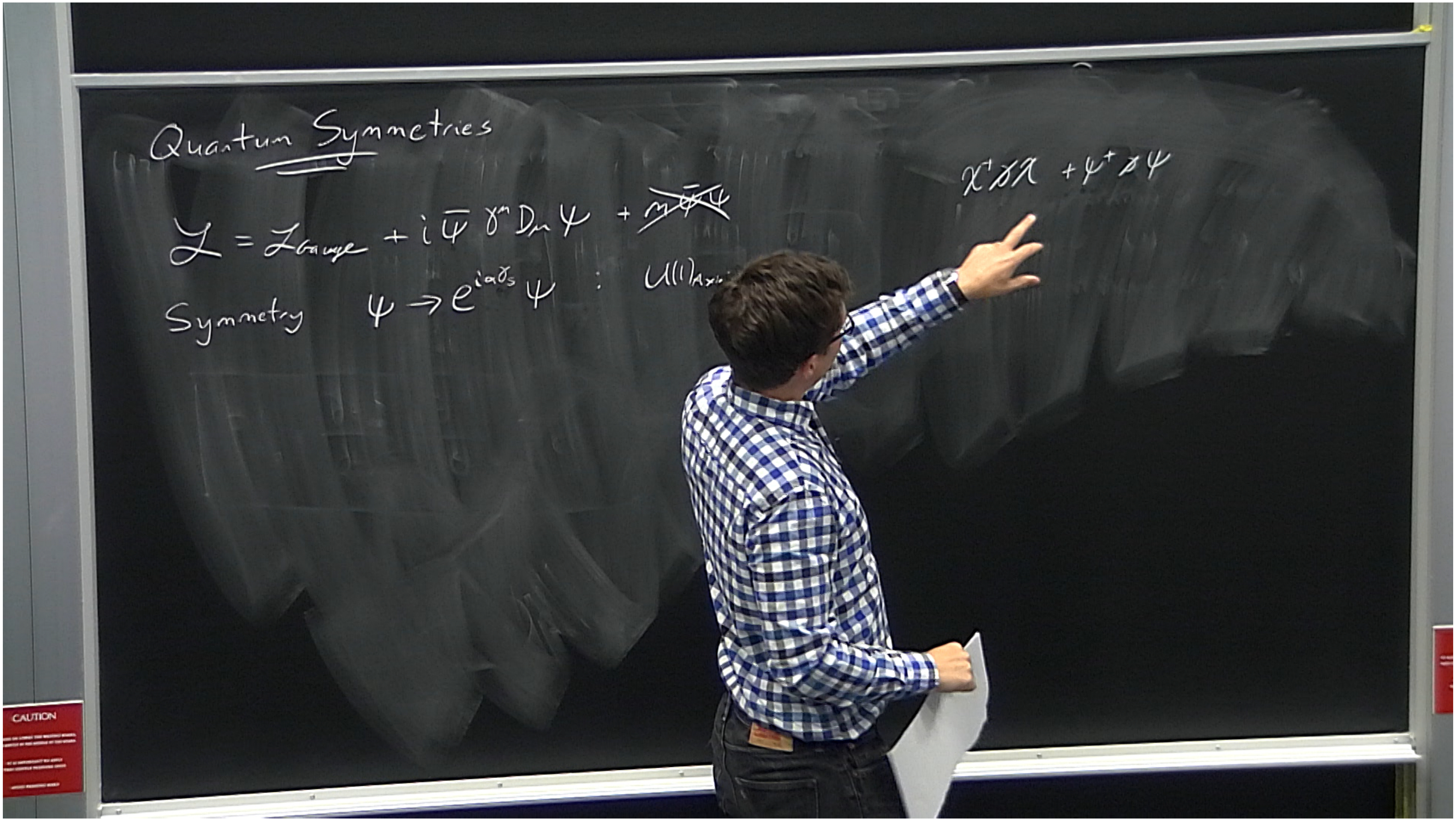
Abstract:


The Strong-CP Problem


The Strong-CP Problem
$\mathcal{L} = \cdots + \frac{g^2}{32\pi^2}\,\theta\,\underbrace{\epsilon_{\mu\nu\alpha\beta}\,G^{a\mu\nu}\,G^{a\alpha\beta}}_{G\tilde{G}} + \cdots$
$= \quad + \cdots$


The Strong-CP Problem
$\mathcal{L} = \dots + \frac{g^2}{32\pi^2}\,\theta\,\underbrace{\epsilon_{\mu\nu\alpha\beta}\,G^{a\mu\nu}\,G^{a\alpha\beta}}_{G\tilde{G}} + \dots$
a) Classical Symmetry ≠ Quantum Symmetry
b) Total Derivatives can matter.
CAUTION


Quantum Symmetries
$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar{\Psi}\gamma^\mu D_\mu \Psi + \cancel{m\bar{\Psi}\Psi}$


Quantum Symmetries
$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar{\Psi}\gamma^\mu D_\mu \Psi + \cancel{m\bar{\Psi}\Psi}$
Symmetry $\Psi \to e^{i\alpha\gamma_5}\Psi$: $U(1)_{Axi}$
$\chi^\dagger \not{\partial} \chi + \psi^\dagger \not{\partial} \psi$
CAUTION

Quantum Symmetries

$$\chi^\dagger \not{\partial} \chi + \psi^\dagger \not{\partial} \psi$$

$$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar{\Psi}\gamma^\mu D_\mu \Psi + \cancel{m\bar{\Psi}\Psi}$$

Symmetry $\Psi \to e^{i\alpha\gamma_5}\Psi$: $U(1)_{Axial}$

$$Z = \int \mathcal{D}\Psi \mathcal{D}\bar{\Psi}\, e^{i\int d^4x\, \mathcal{L}}$$

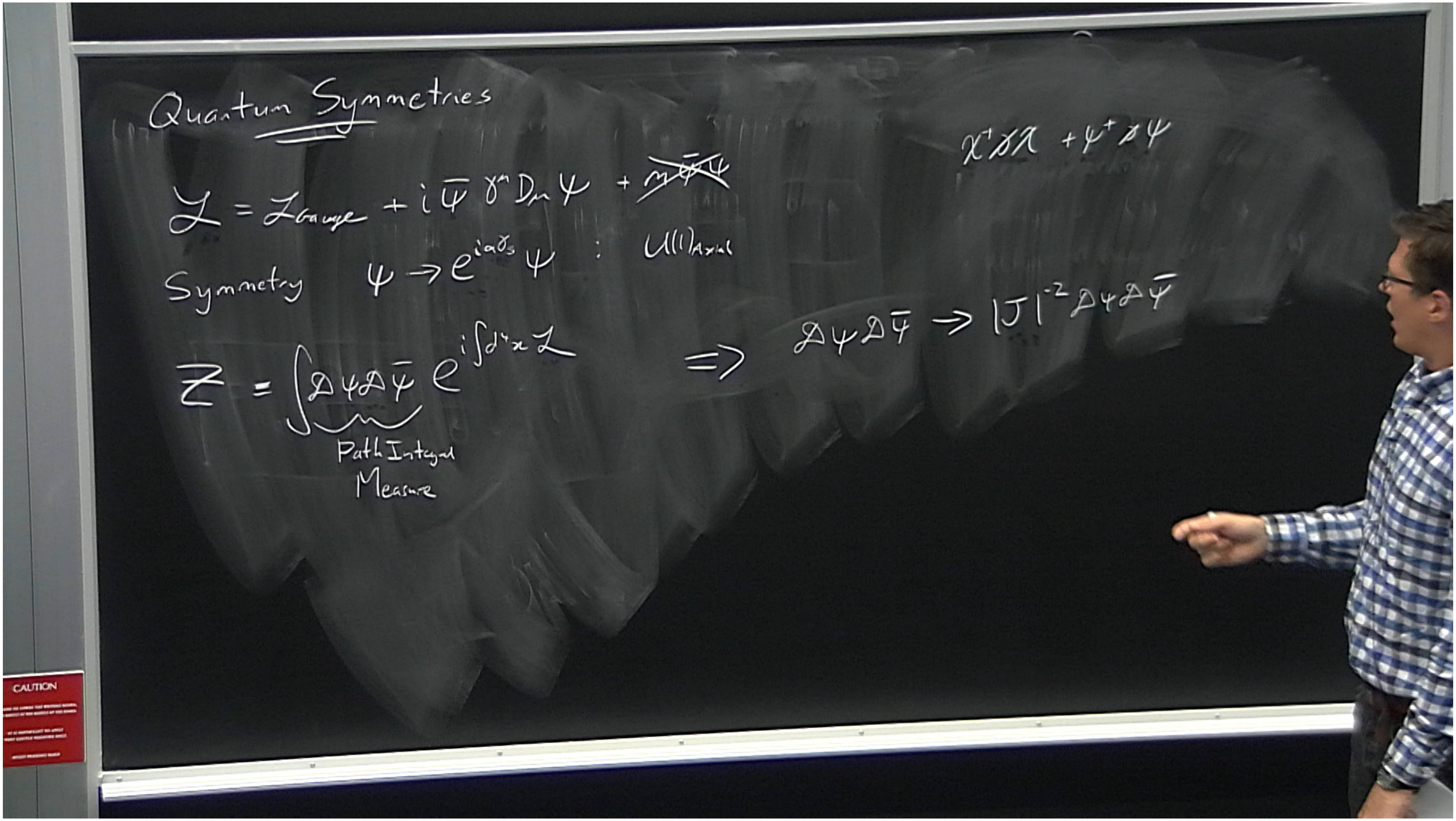
Quantum Symmetries

$$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + \cancel{m\bar{\psi}\psi}$$

Symmetry $\quad \psi \to e^{i\alpha\gamma_5}\psi \quad : \quad U(1)_{Axial}$

$$Z = \int \underbrace{\mathcal{D}\psi\,\mathcal{D}\bar{\psi}}_{\text{Path Integral Measure}} e^{i\int d^4x\,\mathcal{L}}$$

$$\chi^{\dagger}\not{\partial}\chi + \psi^{\dagger}\not{\partial}\psi$$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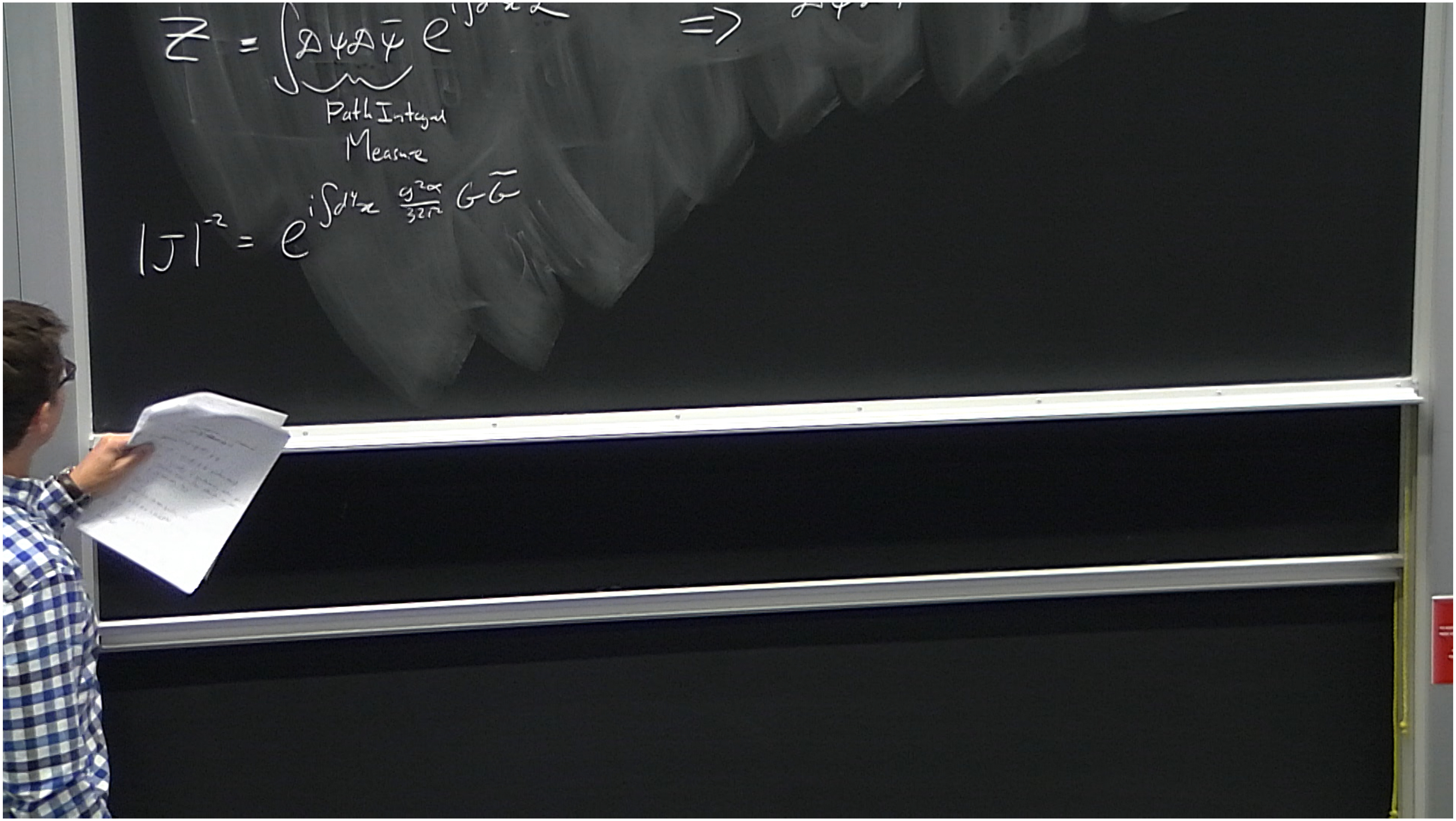
Symmetry $\Psi \to e^{i\alpha\gamma_5}\Psi$: $U(1)_{Axial}$
$Z = \int \underbrace{\mathcal{D}\Psi\mathcal{D}\bar{\Psi}}_{\text{Path Integral Measure}} e^{i\int d^4x\,\mathcal{L}}$
$\Rightarrow \mathcal{D}\Psi\mathcal{D}\bar{\Psi} \to |J|^{-2}\mathcal{D}\Psi\mathcal{D}\bar{\Psi}$
$\chi^{\dagger}\not{\partial}\chi + \psi^{\dagger}\not{\partial}\psi$
CAUTION


$Z = \int \underbrace{\mathcal{D}\psi \mathcal{D}\bar{\psi}}_{\text{Path Integral Measure}} e^{i\int d^4x \mathcal{L}}$
$\Rightarrow$
$|J|^{-2} = e^{i\int d^4x \frac{g^2\alpha}{32\pi^2} G\tilde{G}}$

Quantum Symmetries

$\partial_\mu + igA_\mu^a$

$$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar{\Psi}\gamma^\mu D_\mu \Psi + \cancel{m\bar{\Psi}\Psi}$$

$$\chi^\dagger \partial\!\!\!/ \chi + \psi^\dagger \partial\!\!\!/ \psi$$

Symmetry $\psi \to e^{i\alpha\gamma_5}\psi$: $U(1)_{Axial}$

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$$|J|^{-2} = e^{i\int d^4x \frac{g^2\alpha}{32\pi^2} G\tilde{G}}$$

$$Z' = \int \mathcal{D}\psi\mathcal{D}\bar{\psi}\, e^{i\int d^4x \left(\mathcal{L} + \frac{\alpha g^2}{32\pi^2} G\tilde{G}\right)}$$

Symmetry $\psi \to e$

$$Z = \int \underbrace{\mathcal{D}\psi\mathcal{D}\bar{\psi}}_{\text{Path Integral Measure}} e^{i\int d^4x\, \mathcal{L}} \Longrightarrow \mathcal{D}\psi\mathcal{D}\bar{\psi} \to |J|^{-2}\mathcal{D}\psi\mathcal{D}$$

$$|J|^{-2} = e^{i\int d^4x\, \frac{g^2\alpha}{32\pi^2} G\tilde{G}}$$

$$Z' = \int \mathcal{D}\psi\mathcal{D}\bar{\psi}\, e^{i\int d^4x \left(\mathcal{L} + \frac{\alpha g^2}{32\pi^2} G\tilde{G}\right)}$$

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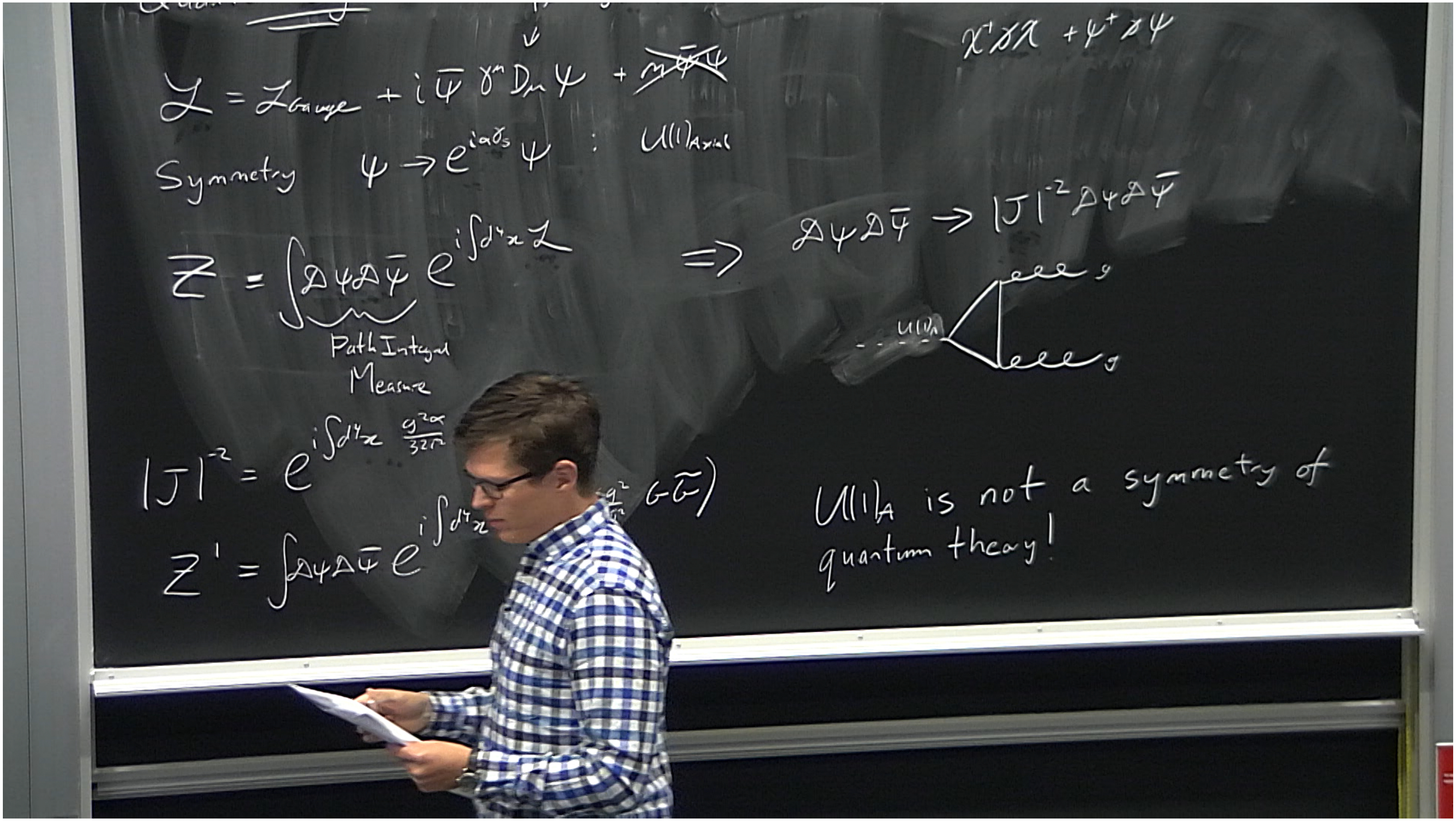
$U(1)_A$ is not a symmetry of quantum theory!


$\chi^\dagger \not{\partial} \chi + \psi^\dagger \not{\partial} \psi$
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$Z = \int \mathcal{D}\Psi\mathcal{D}\bar{\Psi}\, e^{i\int d^4x \mathcal{L}}$ $\Rightarrow$
Path Integral Measure
$U(1)_A$
g
g
$|J|^{-2} = e^{i\int d^4x \frac{g^2\alpha}{32\pi^2}}$
$G\tilde{G})$
$Z' = \int \mathcal{D}\Psi\mathcal{D}\bar{\Psi}\, e^{i\int d^4x}$
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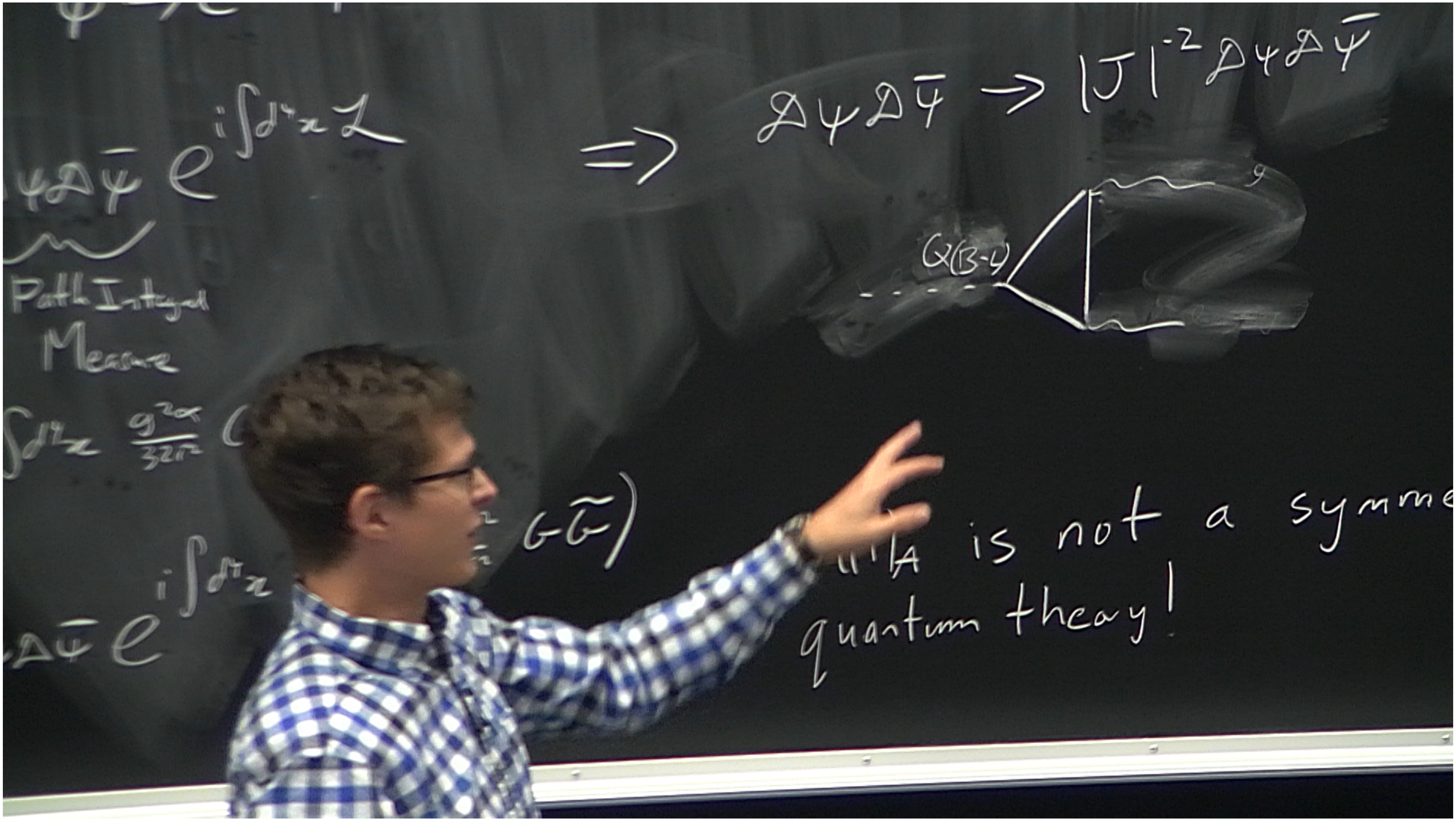
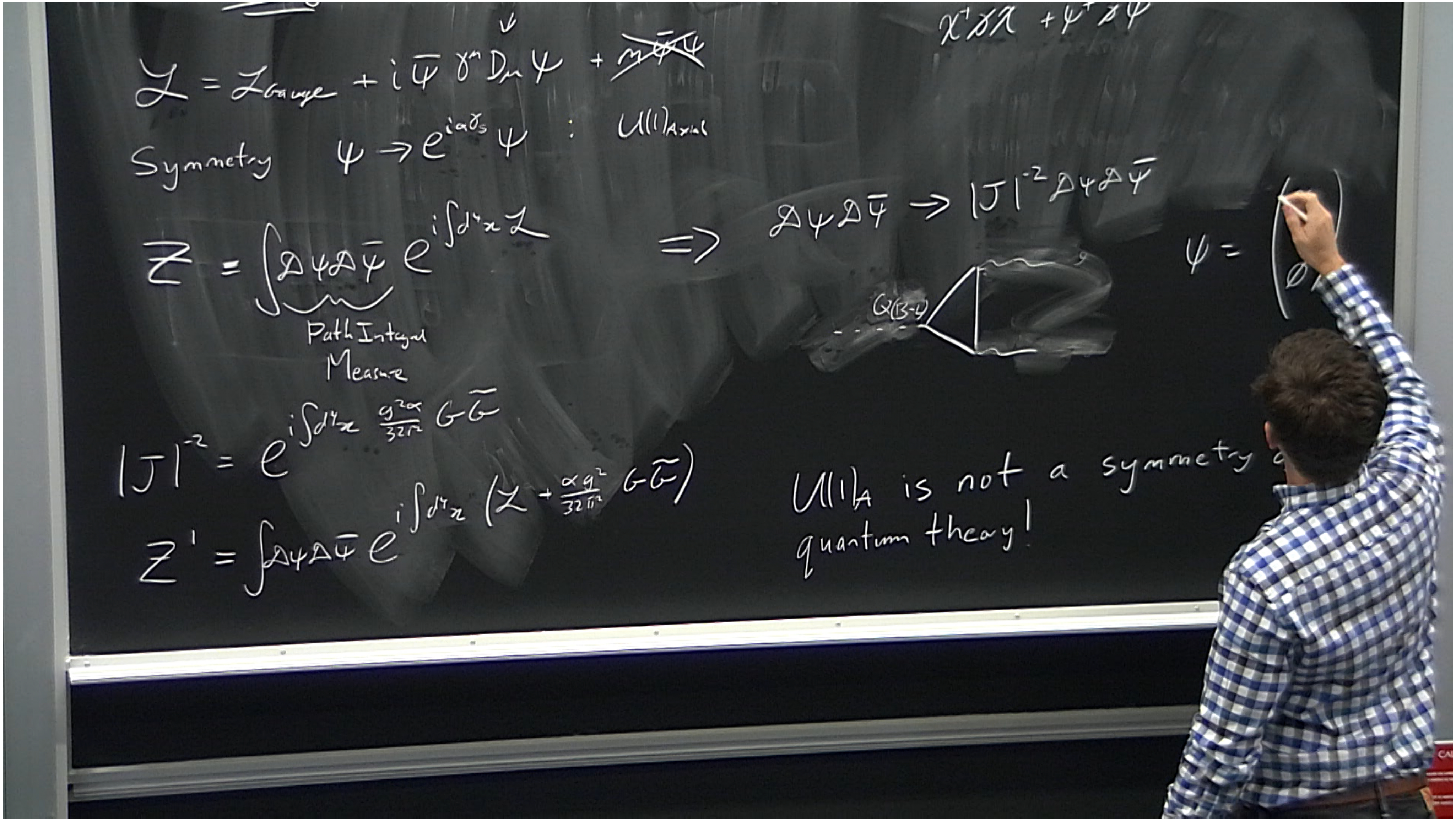

Path Integral Measure
Q(B-L)
is not a symme
quantum theory!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$U(1)_A$ is not a symmetry
quantum theory!

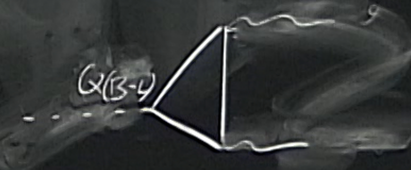
$\chi^\dagger \bar\sigma \chi + \psi^\dagger \sigma \psi$

$$\mathcal{L} = \mathcal{L}_{Gauge} + i\bar\Psi \gamma^\mu D_\mu \Psi + \cancel{m\bar\Psi\Psi}$$

Symmetry $\Psi \to e^{i\alpha\gamma_5}\Psi$: $U(1)_{Axial}$

$$Z = \int \underbrace{\mathcal{D}\Psi\mathcal{D}\bar\Psi}_{\text{Path Integral Measure}} e^{i\int d^4x\, \mathcal{L}} \implies \mathcal{D}\Psi\mathcal{D}\bar\Psi \to |J|^{-2}\mathcal{D}\Psi\mathcal{D}\bar\Psi$$

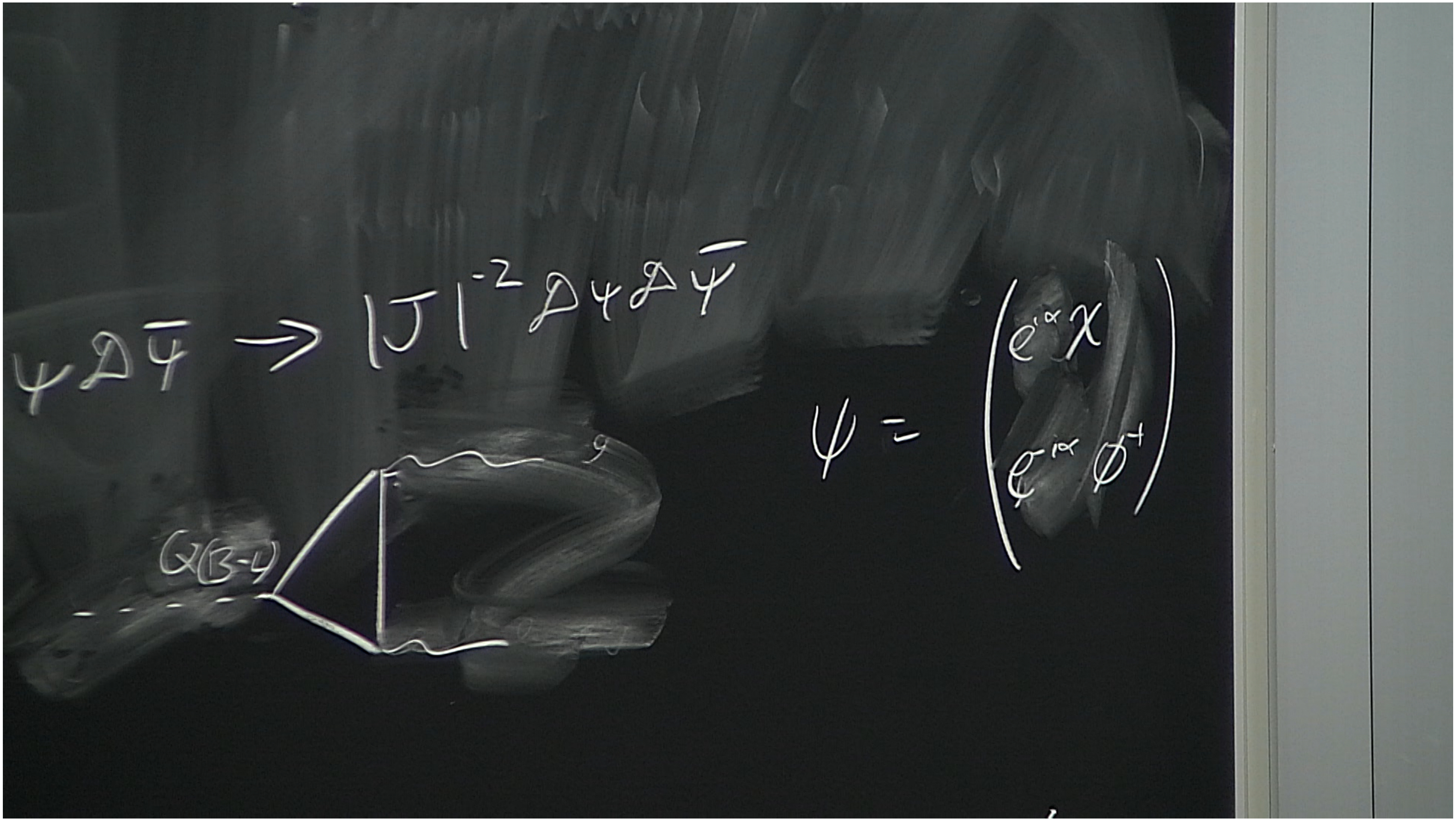
$$\psi = \begin{pmatrix} e^{i\alpha}\chi \\ e^{i\alpha}\phi^\dagger \end{pmatrix}$$

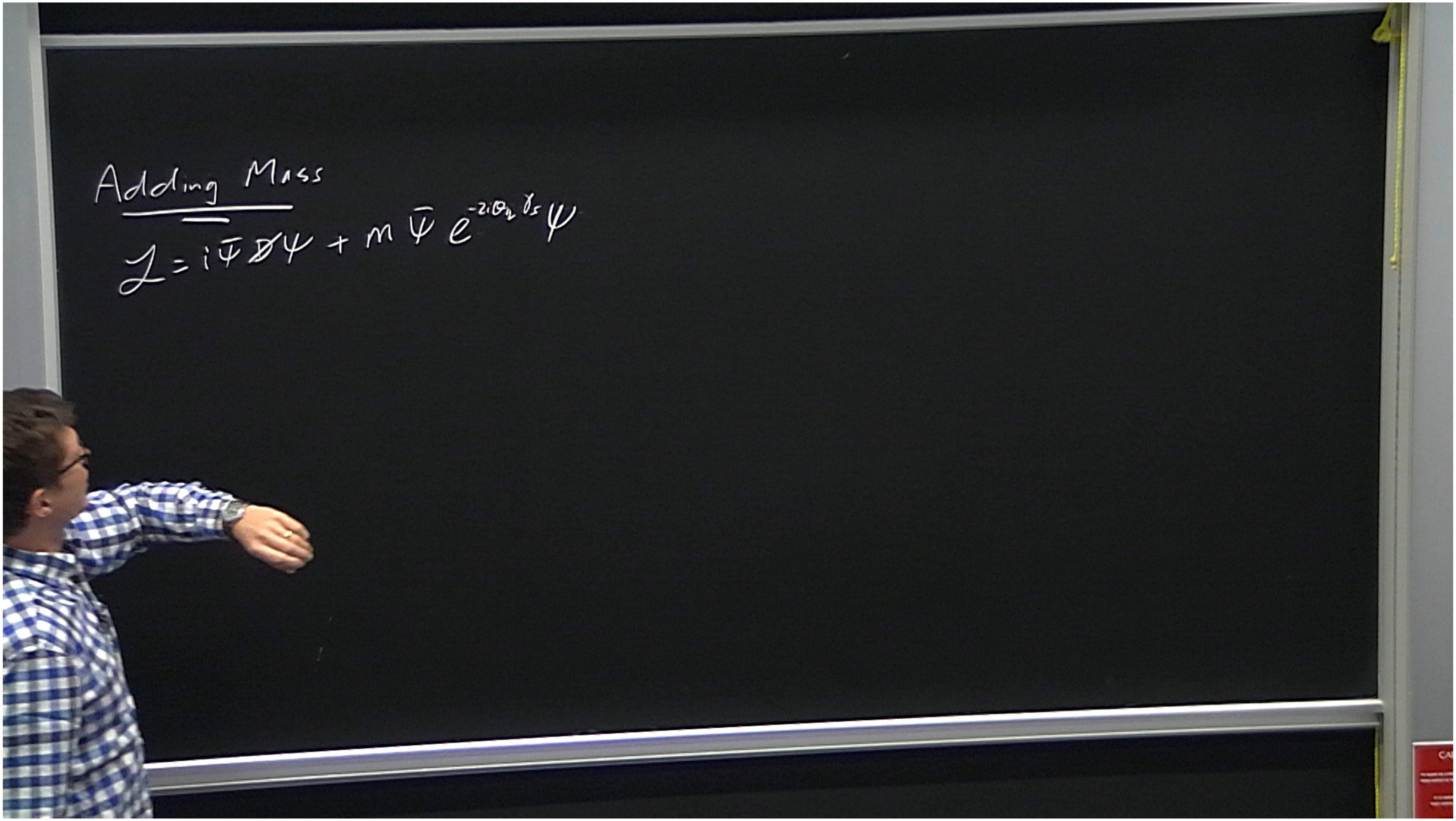


$$|J|^{-2} = e^{i\int d^4x\, \frac{g^2\alpha}{32\pi^2} G\tilde{G}}$$

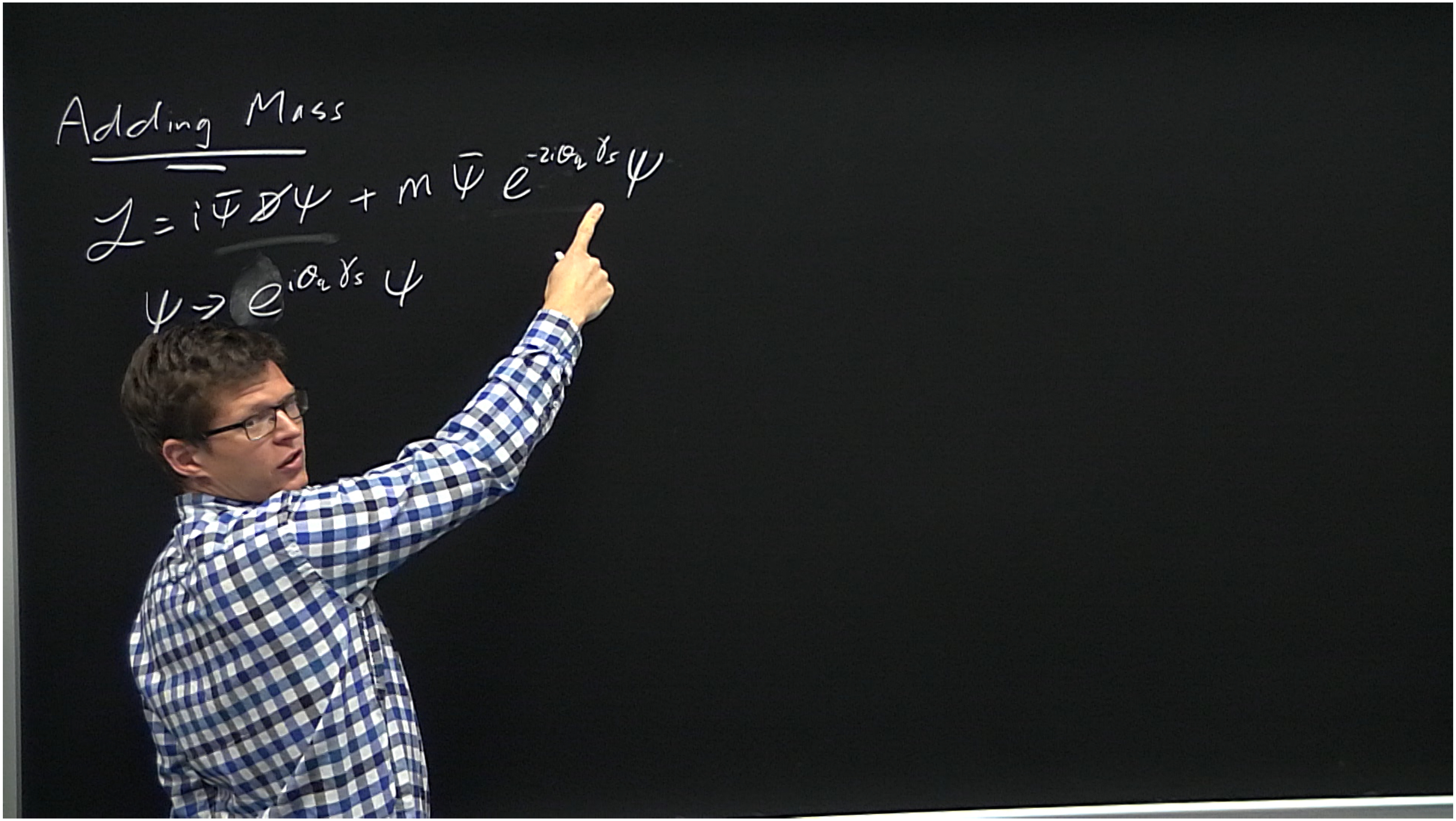
$$Z' = \int \mathcal{D}\Psi\mathcal{D}\bar\Psi\, e^{i\int d^4x \left(\mathcal{L} + \frac{\alpha g^2}{32\pi^2} G\tilde{G}\right)}$$

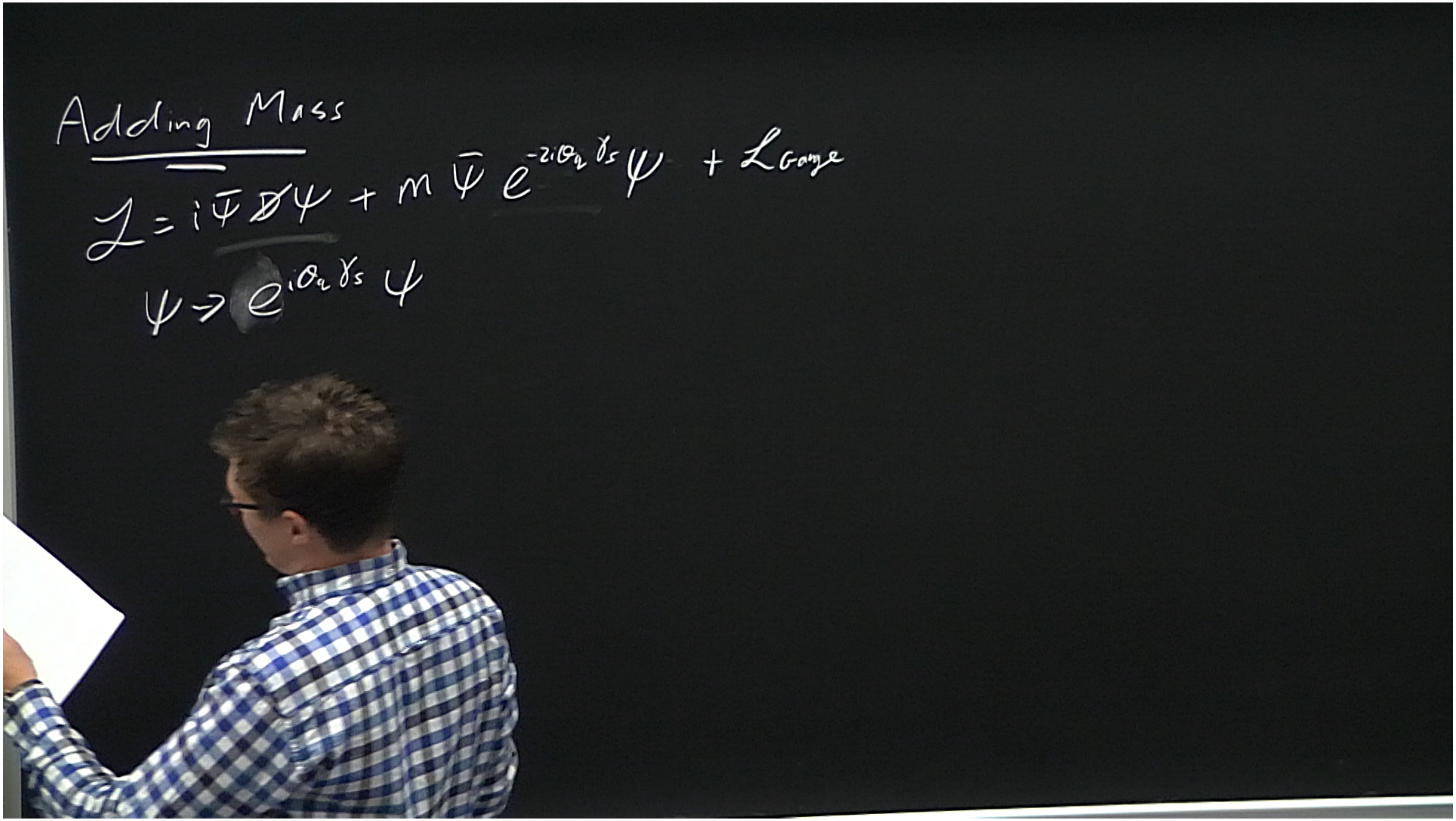
$U(1)_A$ is not a symmetry of quantum theory!


$\psi \Delta \bar{\psi} \to |J|^{-2} \Delta\psi \Delta\bar{\psi}$
$\psi = \begin{pmatrix} e^{i\alpha}\chi \\ e^{i\alpha}\phi^{+} \end{pmatrix}$
Q(B-L)



Adding Mass
$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_2\gamma_5}\psi$


Adding Mass
$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_2\gamma_5}\Psi$
$\Psi \to e^{i\theta_2\gamma_5}\Psi$


Adding Mass
$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_a\gamma_5}\psi + \mathcal{L}_{Gauge}$
$\psi \to e^{i\theta_a\gamma_5}\psi$

Adding Mass

$$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_q\gamma_5}\Psi + \mathcal{L}_{Gauge}$$

$$\Psi \to e^{i\theta_q\gamma_5}\Psi$$

$$\mathcal{L}' = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}\Psi + \mathcal{L}_{gauge} + \frac{\theta_q g^2}{32\pi^2}G\tilde{G}$$

Adding Mass

$$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_q\gamma_5}\Psi + \mathcal{L}_{Gauge} + \frac{\theta g^2}{32\pi^2}G\tilde{G}$$

$$\Psi \to e^{i\theta_q\gamma_5}\Psi$$

$$\mathcal{L}' = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}\Psi + \mathcal{L}_{Yang-Mills} + \frac{(\theta+\theta_q)g^2}{32\pi^2}G\tilde{G}$$

Adding Mass

$$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_q\gamma_5}\psi + \mathcal{L}_{Gauge} + \frac{\theta g^2}{32\pi^2}G\tilde{G}$$

$$\psi \to e^{i\theta_q\gamma_5}\psi$$

$$\mathcal{L}' = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}\Psi + \mathcal{L}_{gauge} + \frac{(\theta+\theta_q)g^2}{32\pi^2}G\tilde{G}$$

Totally Derivative

$$(\theta+\theta_q)G\tilde{G} = (\theta+\theta_q)\partial^\mu J_\mu \quad : \quad J_\mu = \epsilon_{\mu\nu\alpha\beta}\left(A^a_\nu G^a_{\alpha\beta} - \frac{2}{3}f^{abc}A^a_\nu A^b_\alpha A^c_\beta\right)$$

Adding Mass

$$\mathcal{L} = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}e^{-2i\theta_q\gamma_5}\psi + \mathcal{L}_{Gauge} + \frac{\theta g^2}{32\pi^2}G\tilde{G}$$

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$\mathcal{L} = i\bar{\Psi}\not{D}\Psi$

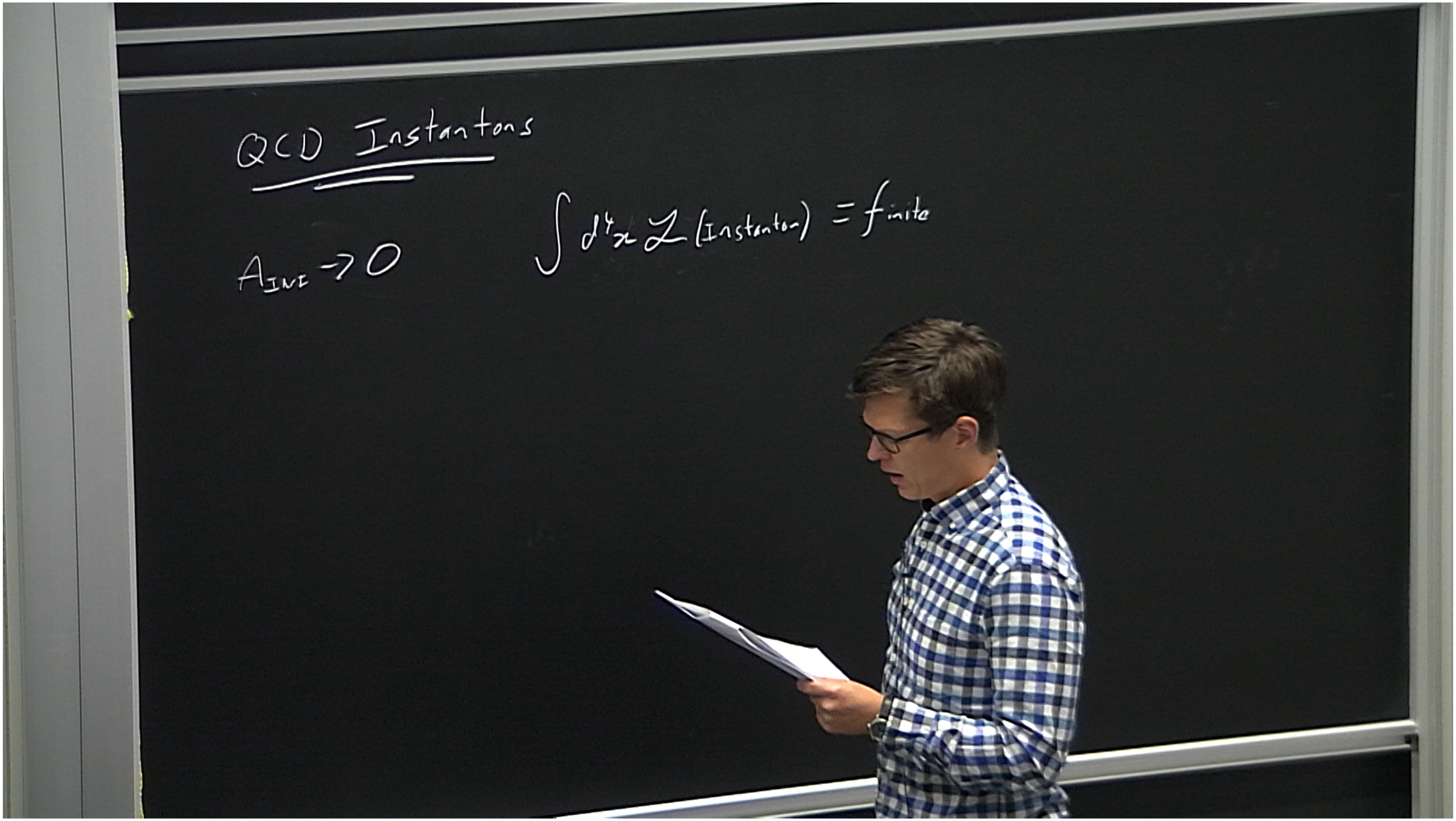
$\Psi \to e^{i\theta_a\gamma_5}\Psi$

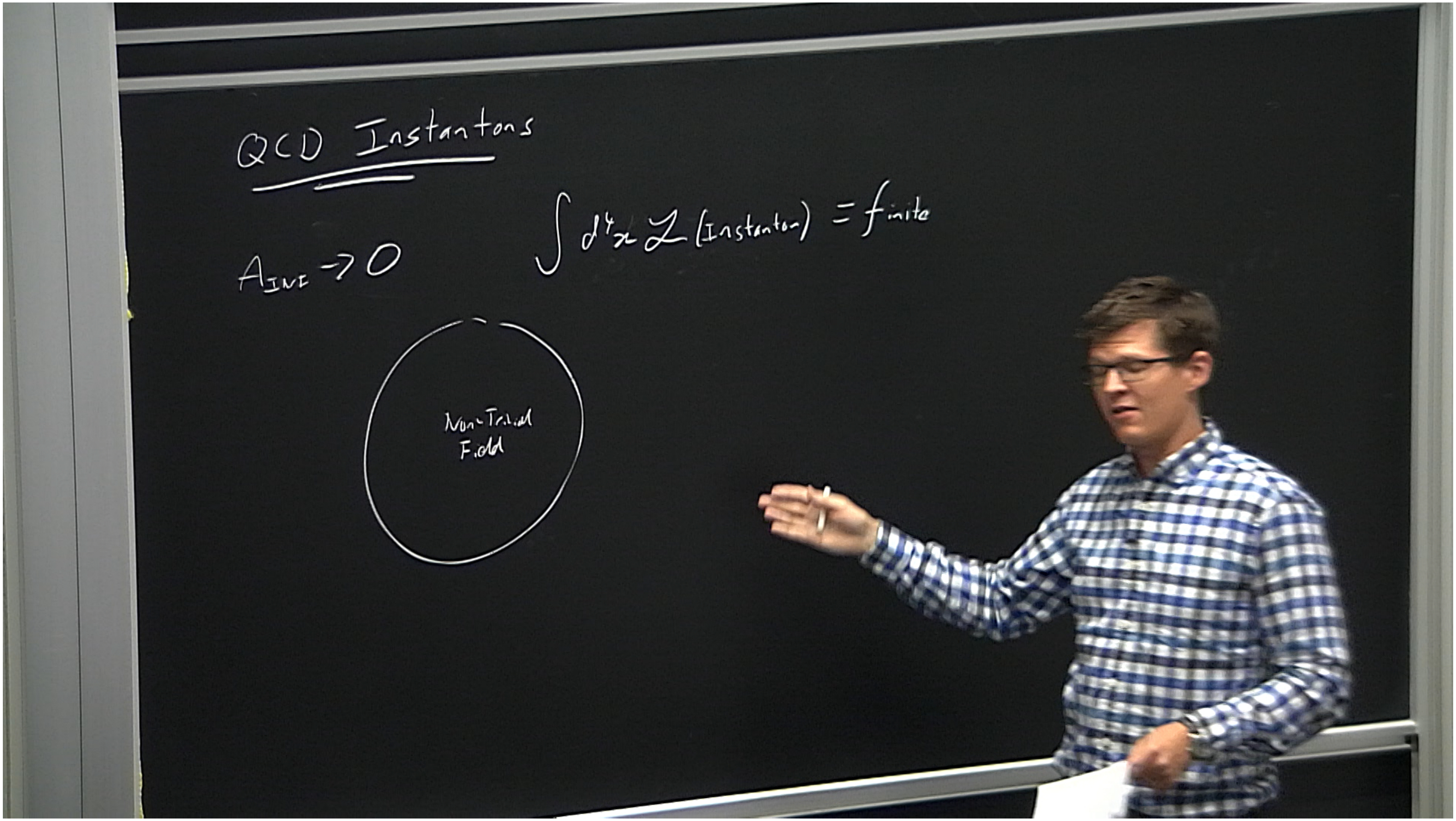
$\mathcal{L}' = i\bar{\Psi}\not{D}\Psi + m\bar{\Psi}\Psi + \mathcal{L}_{\text{yang-mills}} + \frac{(\theta+\theta_a)g^2}{32\pi^2} G\tilde{G}$

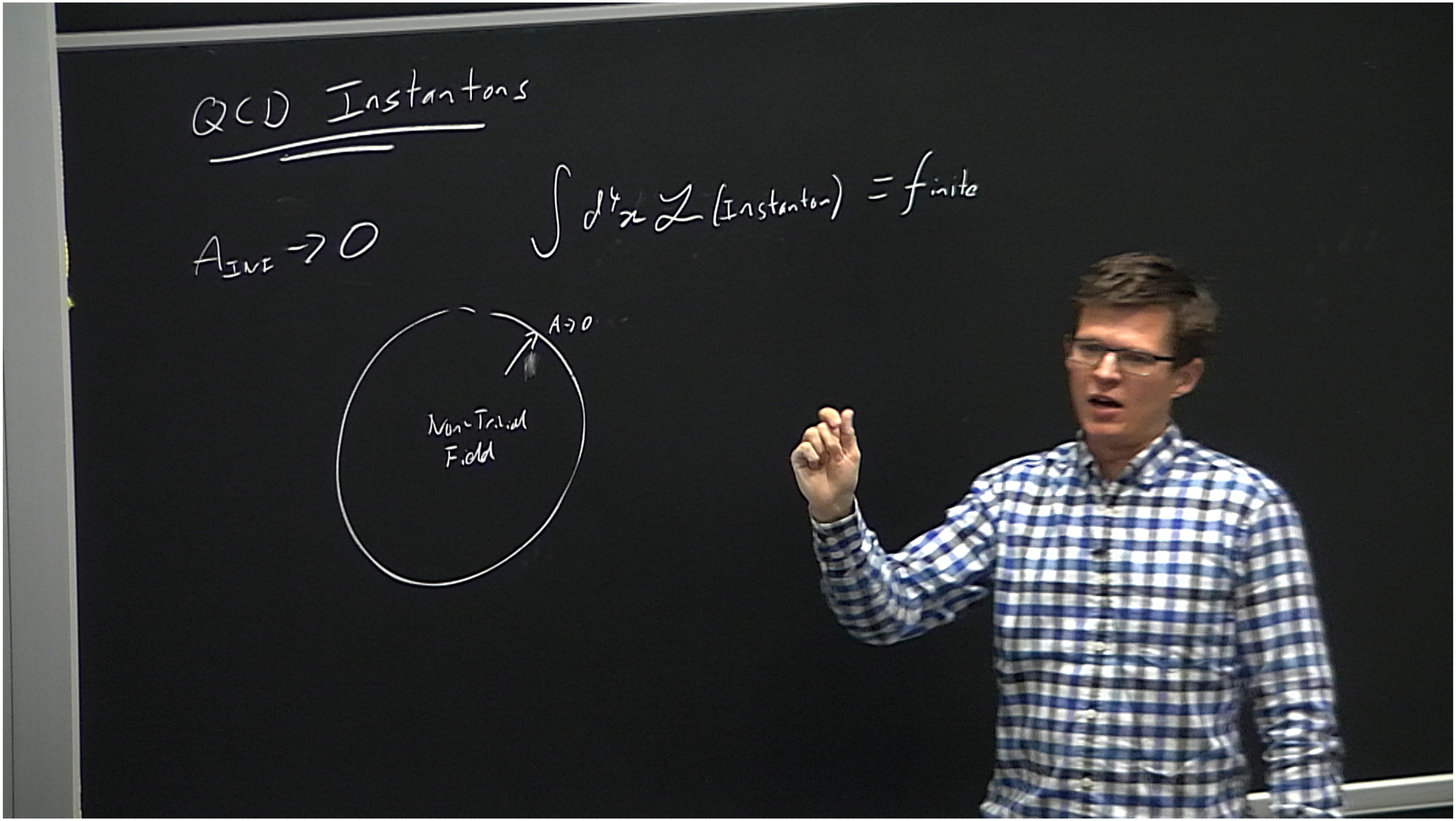
Totally Derivative

$(\theta+\theta_a)G\tilde{G} = (\theta+\theta_a)\partial^\mu J_\mu \quad : \quad J_\mu = \epsilon_{\mu\nu\alpha\beta}\left(A^a_\nu G^a_{\alpha\beta} - \frac{2}{3} f^{abc} A^a_\nu A^b_\alpha A^c_\beta\right)$

Aharanov-Bohm Effect:


QCD Instantons
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A_{\text{INF}} \to 0$


QCD Instantons
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A_{INF} \to 0$
Non-Trivial Field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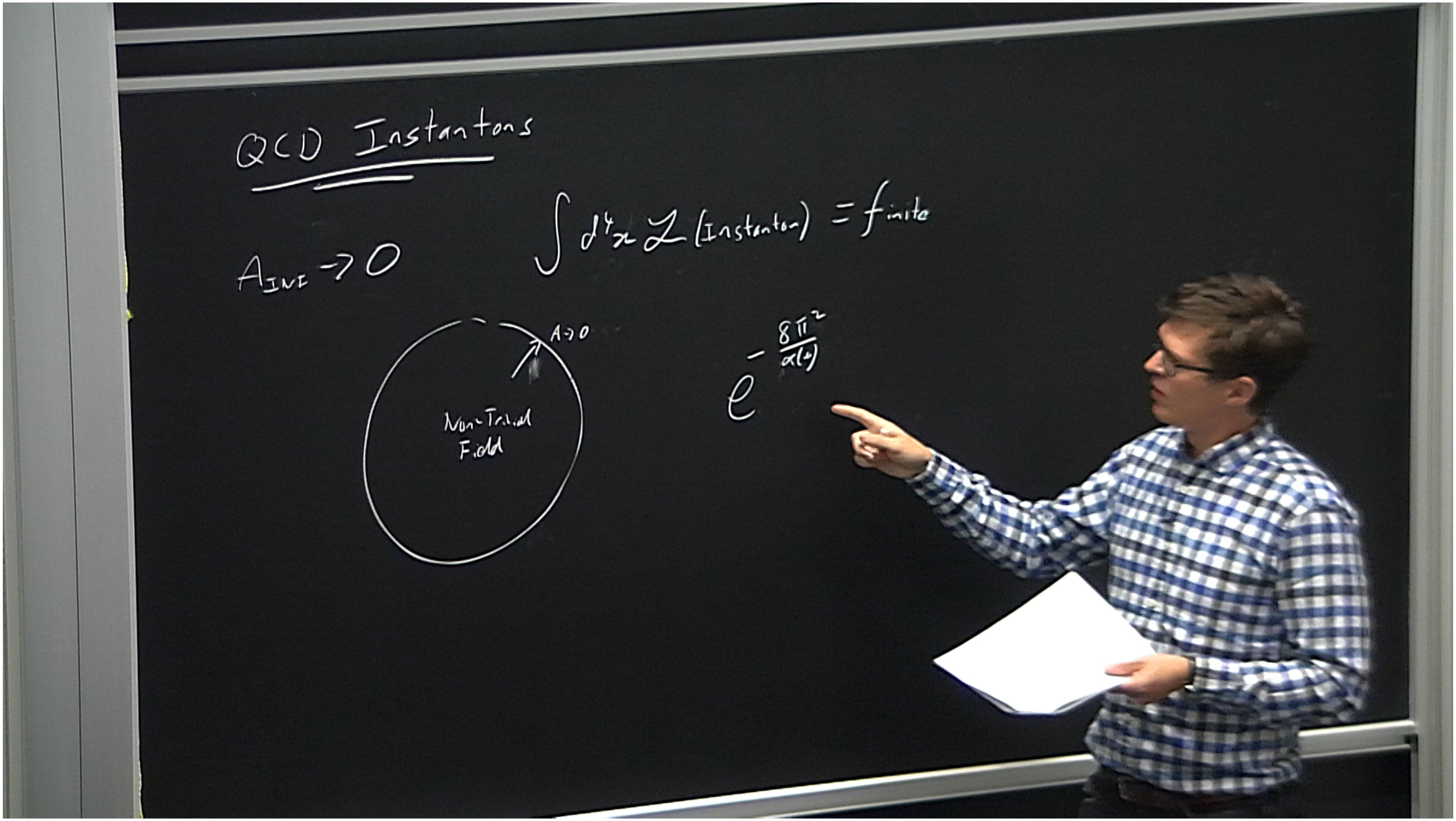
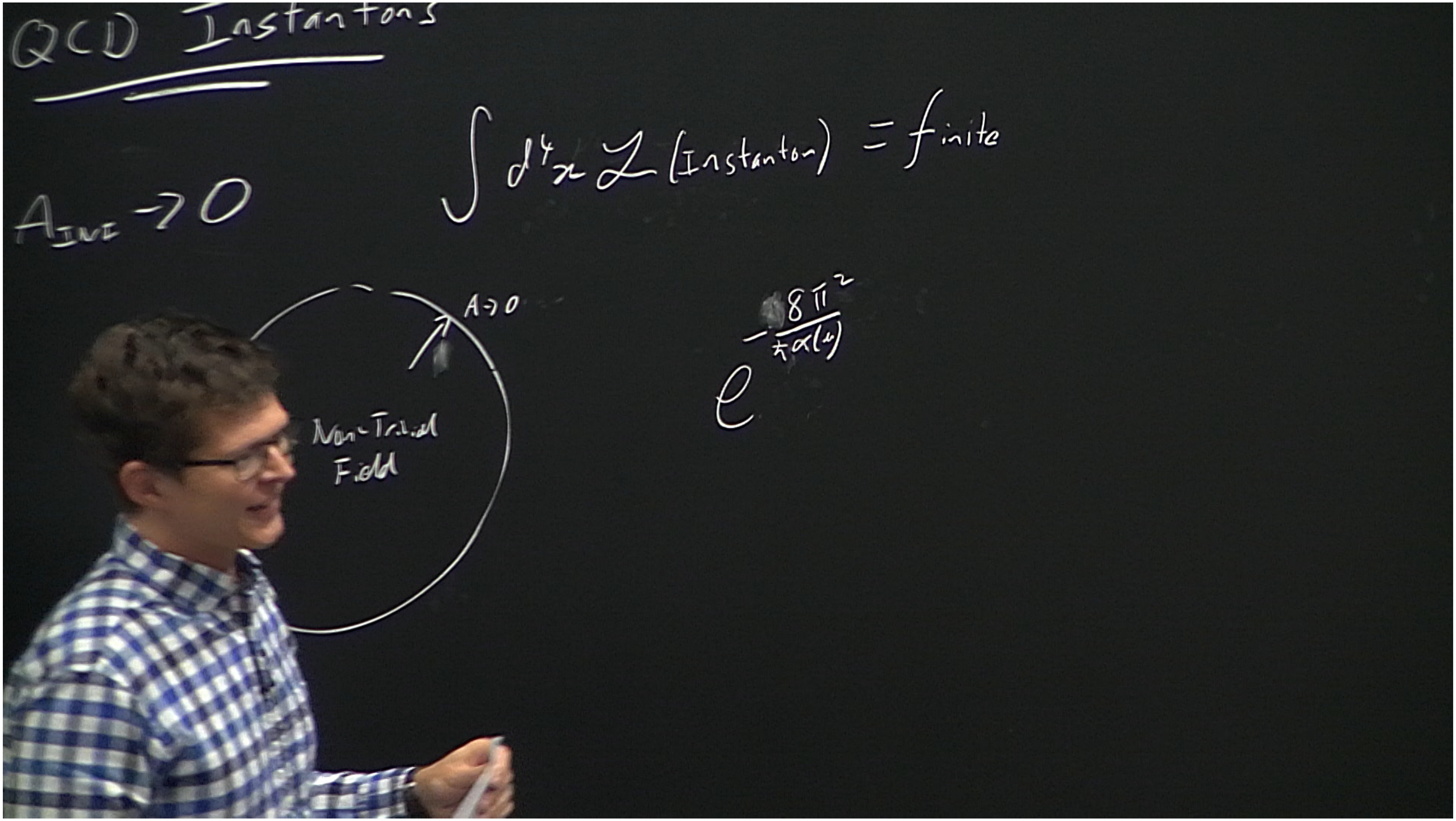
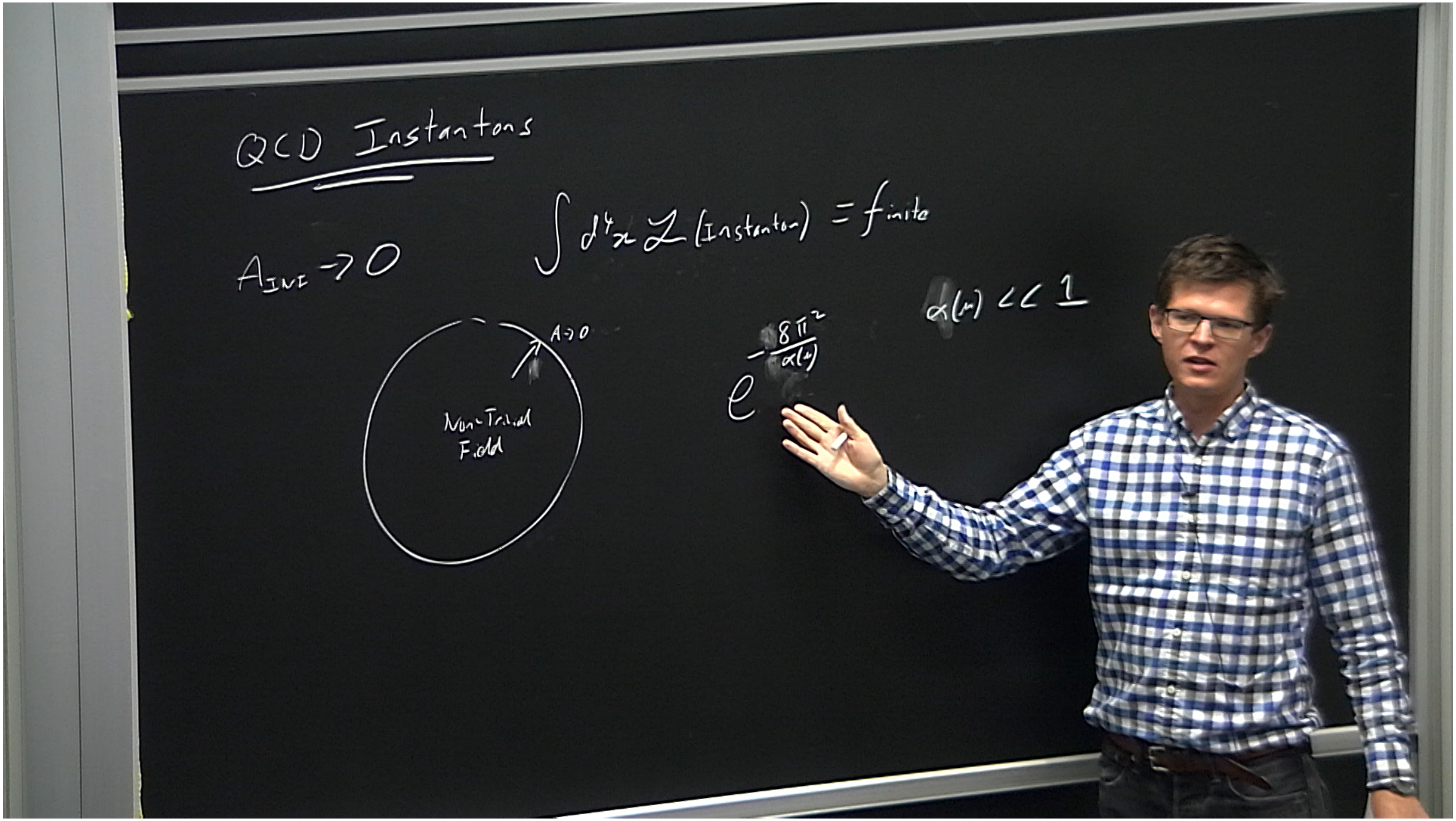
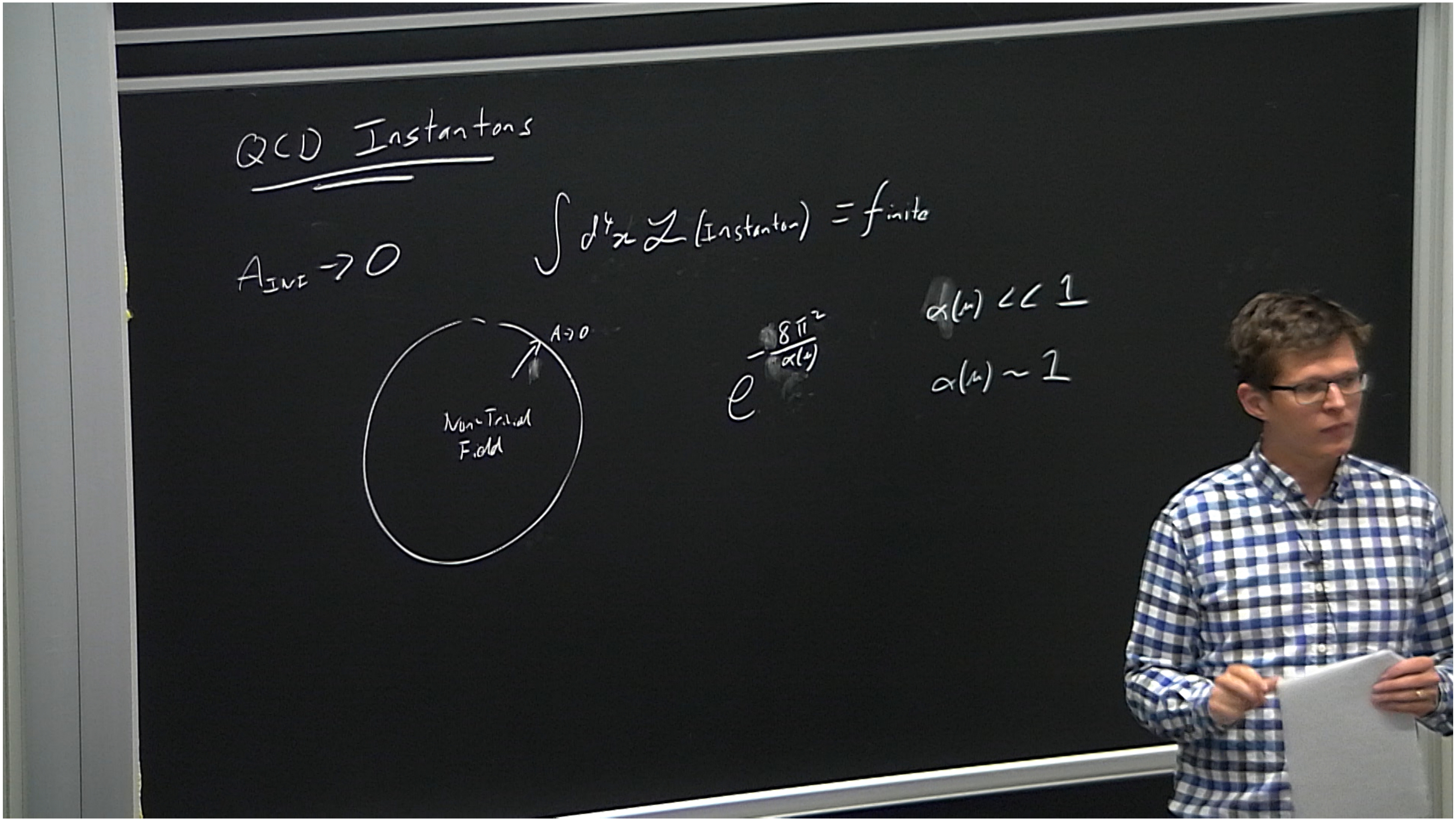
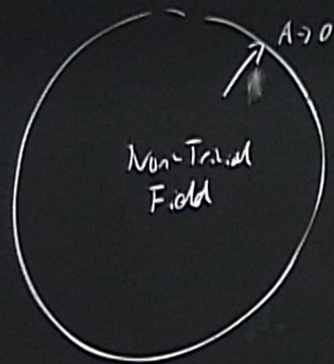
$A_{INF} \to 0$
$A \to 0$
Non-Trivial
Field


QCD Instantons
$A_{INF} \to 0$
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A \to 0$
Non-Trivial Field
$e^{-\frac{8\pi^2}{\alpha(\mu)}}$


QCD Instantons
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A_{INF} \to 0$
$A \to 0$
Non-Trivial Field
$e^{-\frac{8\pi^2}{\hbar \alpha(\mu)}}$


QCD Instantons
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A_{INF} \to 0$
$\alpha(\mu) \ll 1$
$A \to 0$
Non-Trivial Field
$e^{-\frac{8\pi^2}{\alpha(\mu)}}$


QCD Instantons
$\int d^4x \, \mathcal{L}(\text{Instanton}) = \text{finite}$
$A_{INF} \to 0$
$A \to 0$
Non-Trivial Field
$e^{-\frac{8\pi^2}{\alpha(\mu)}}$
$\alpha(\mu) << 1$
$\alpha(\mu) \sim 1$



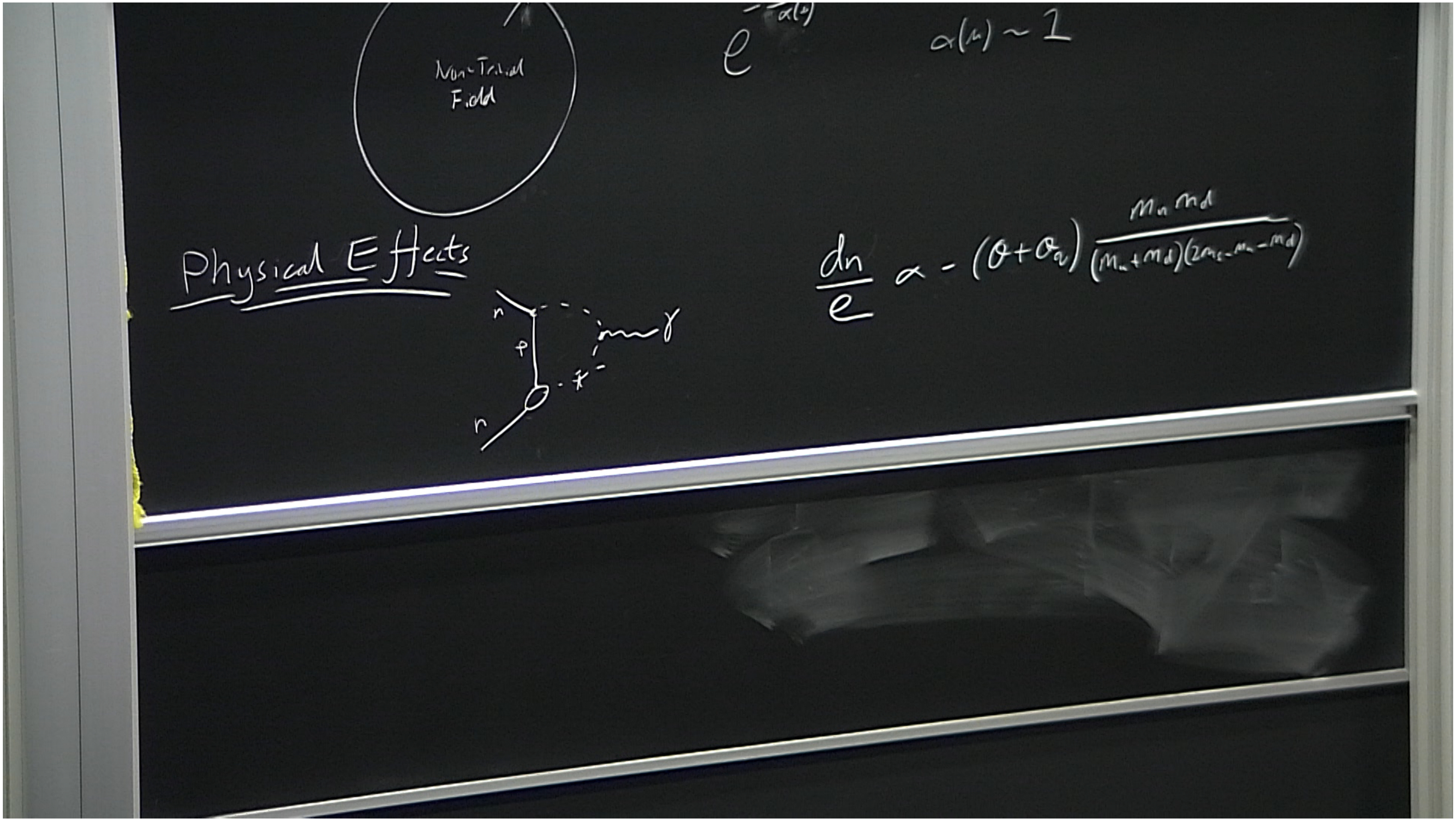
$$e^{-\frac{8\pi^2}{\alpha(\mu)}}$$

$\alpha(\mu) \ll 1$

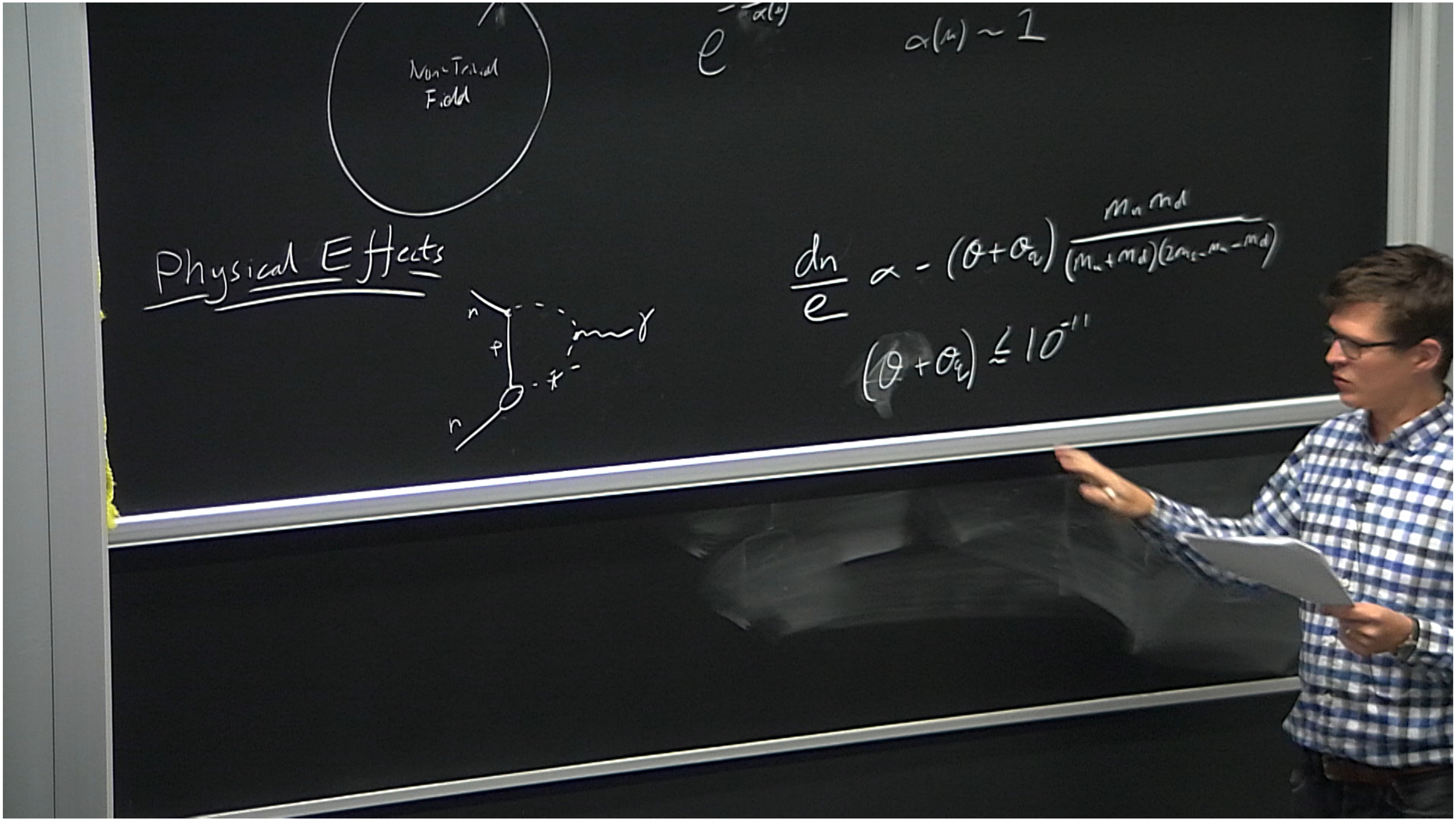
$\alpha(\mu) \sim 1$

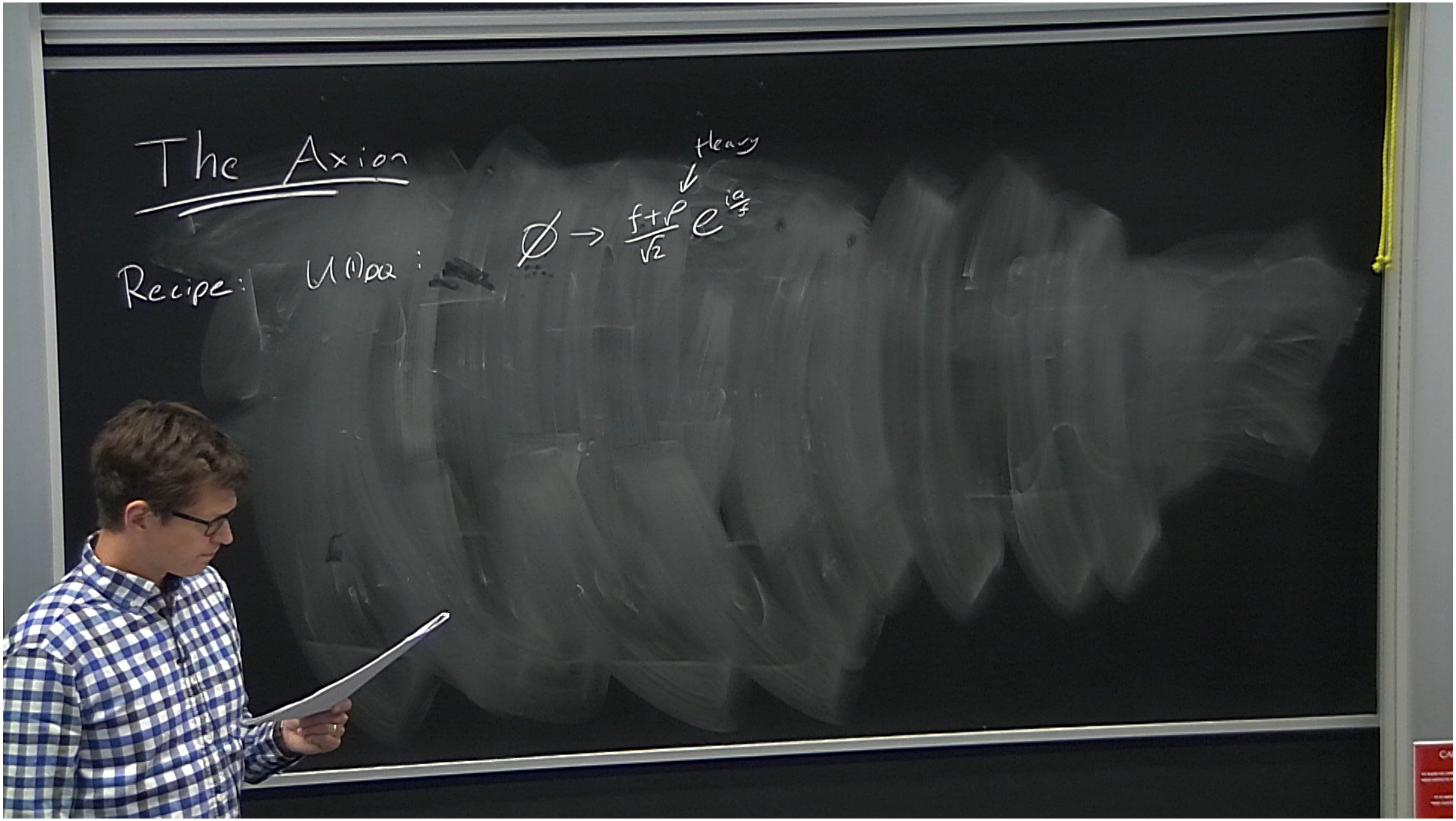
Physical Effects


Non-Trivial
Field
α(μ) ~ 1
Physical Effects


Non-Trivial Field
α(μ) ~ 1
Physical Effects
dn/e ∝ -(θ+θ_a) m_u m_d / ((m_u+m_d)(2m_s-m_u-m_d))


Field
ical Effects
n
γ
n
dn/e ∝ -(θ+θq) mu md / (mu+md)(2ms-mu-md)


Non-Trivial Field
α(μ) ~ 1
Physical Effects
dn/e ∝ -(θ+θ_q) m_u m_d / (m_u+m_d)(2m_s-m_u-m_d)
(θ+θ_q) ≲ 10^-11


The Axion
Recipe:
U(1)PQ :
Heavy
$\phi \to \frac{f+\rho}{\sqrt{2}} e^{ia/f}$

The Axion

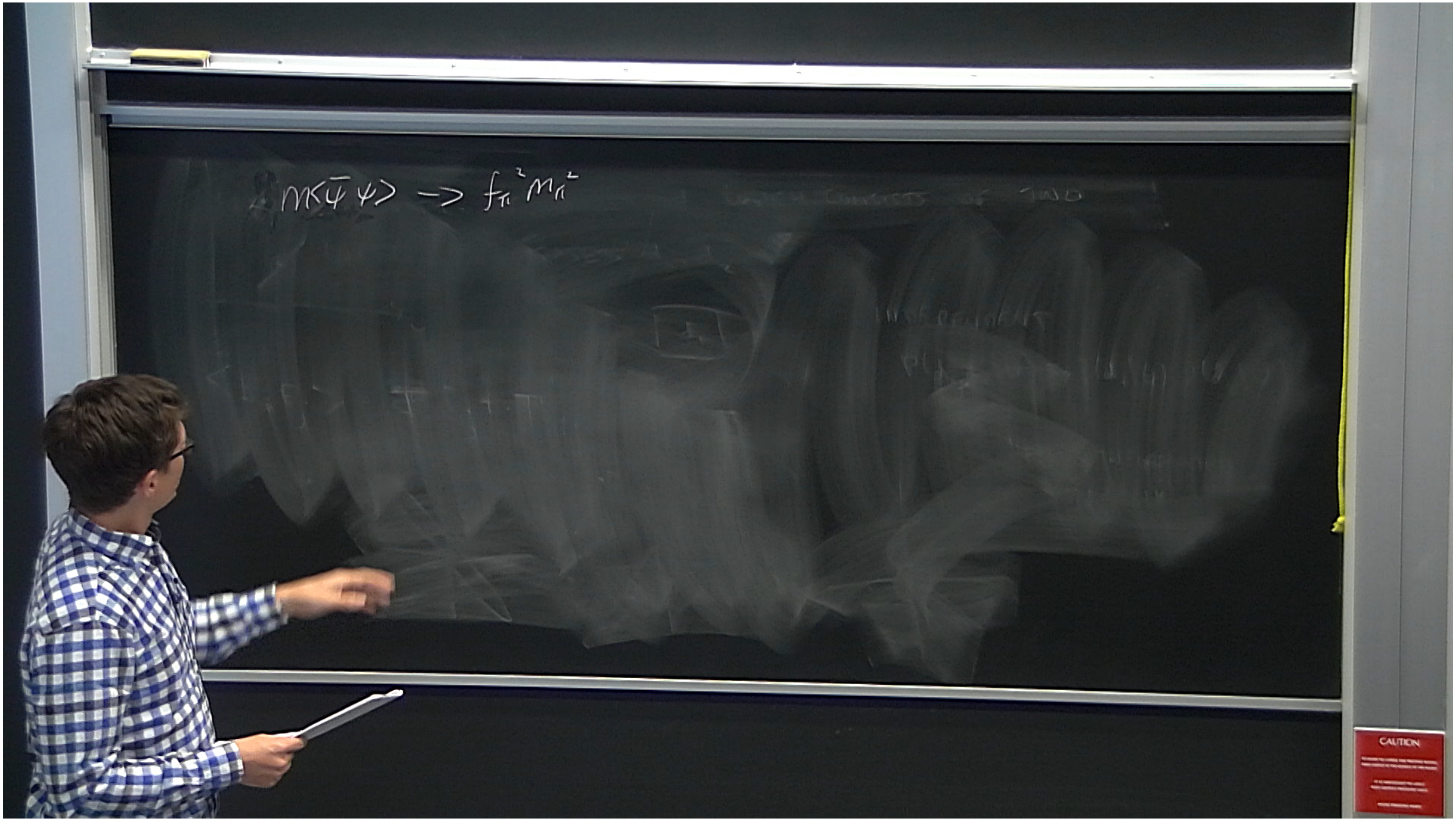
$$\phi \to \frac{f+\overset{\text{Heavy}}{\rho}}{\sqrt{2}}\, e^{\frac{ia}{f}}$$

Recipe: $U(1)_{PQ}$:

$$\mathcal{L} = \cdots + \lambda \frac{\phi}{\Lambda} H \bar{\Psi} \psi + h.c + \cdots + \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

$$= + \tilde{\lambda} H \bar{\Psi} e^{i\gamma_5(\theta_a + \frac{a}{f})} \psi +$$

$$\mathcal{L}' = + \tilde{\lambda} H \bar{\Psi} e^{i\gamma_5(\theta_a + \theta + \frac{a}{f})} \psi + \cdots$$


$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$

$$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$$

$$\mathcal{L} = \cdots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$$

$$= \quad + f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right) + \cdots$$

$$V = -f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$$

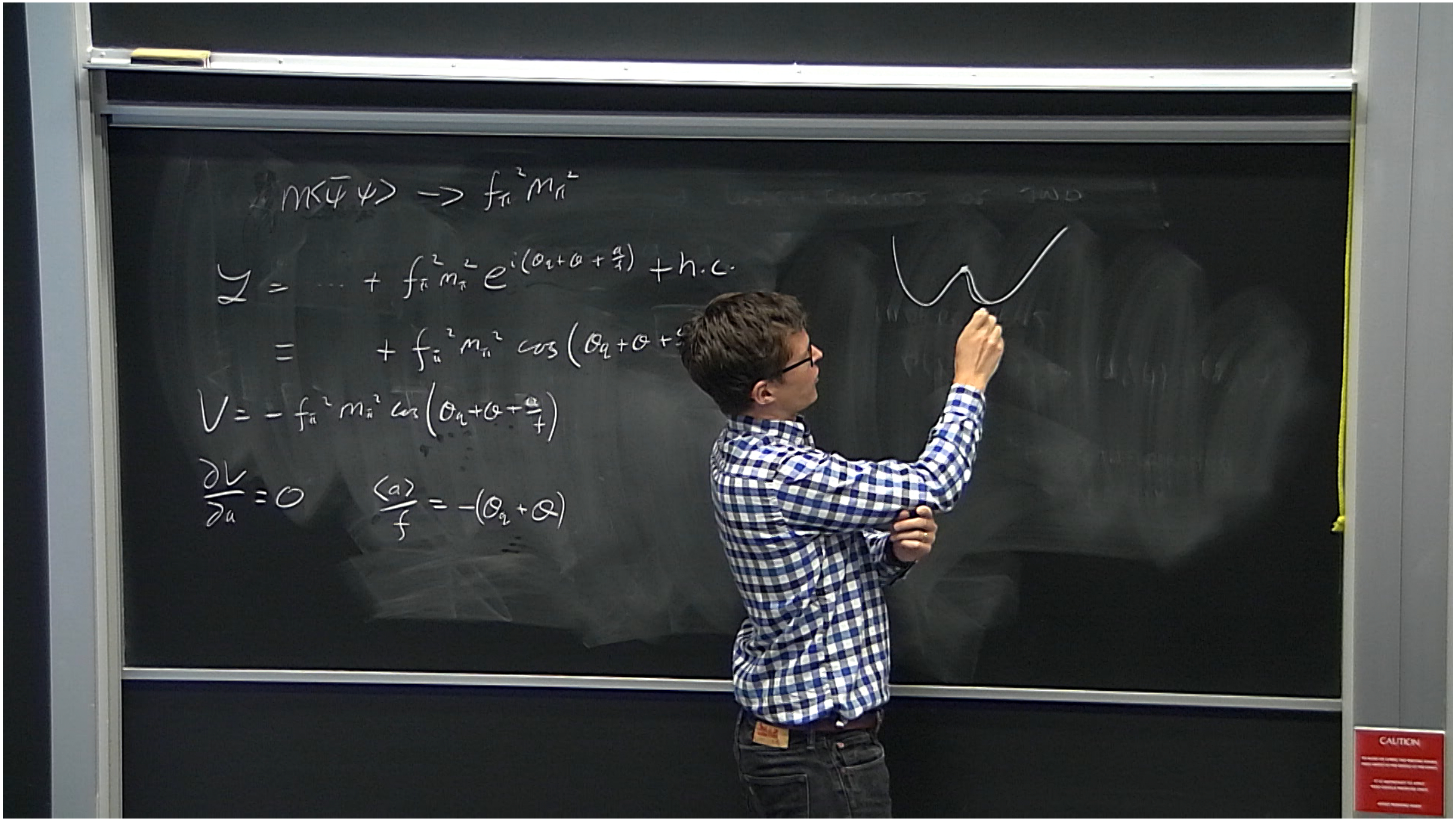
$$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$$

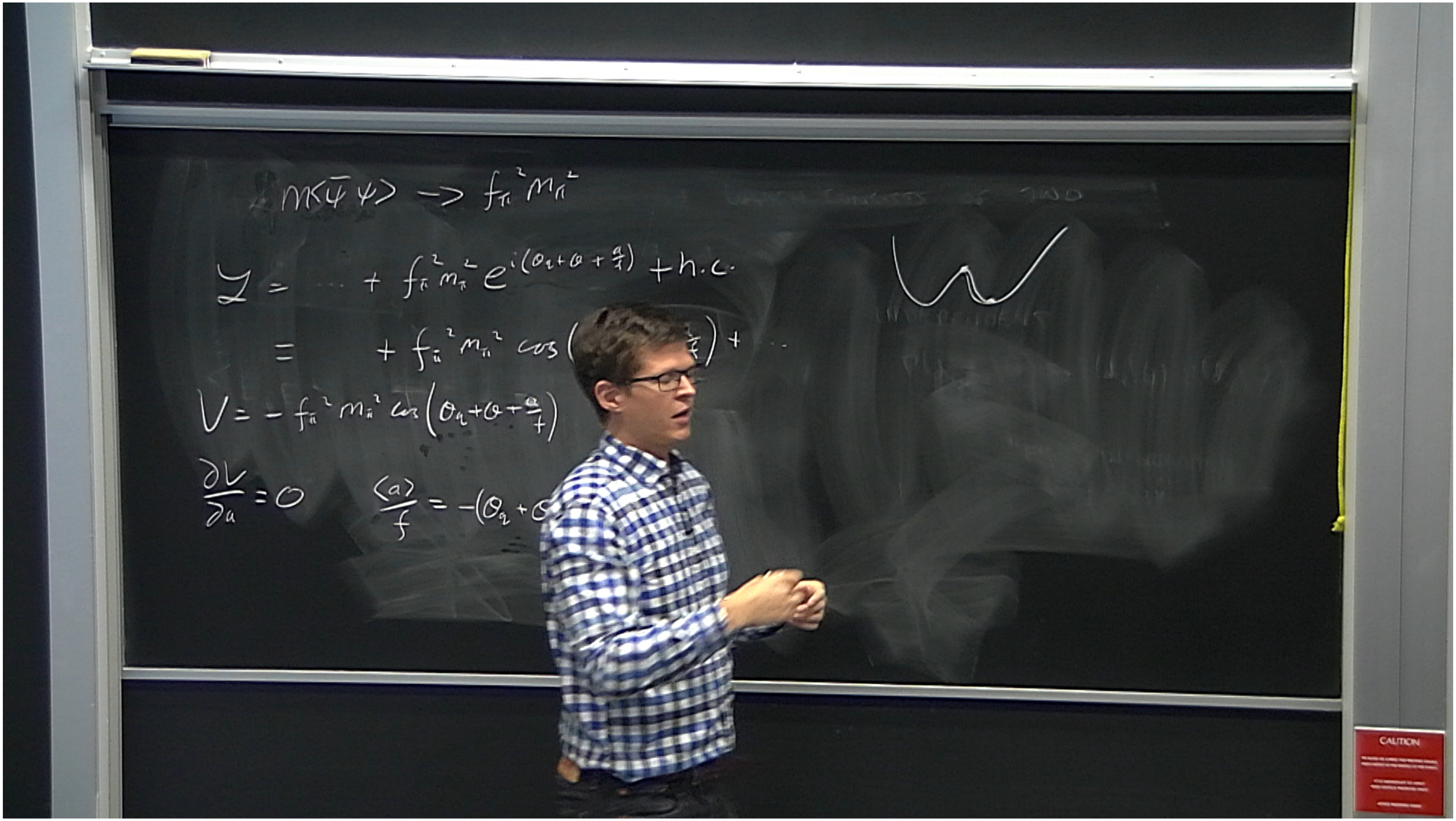
$$\mathcal{L} = \dots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$$

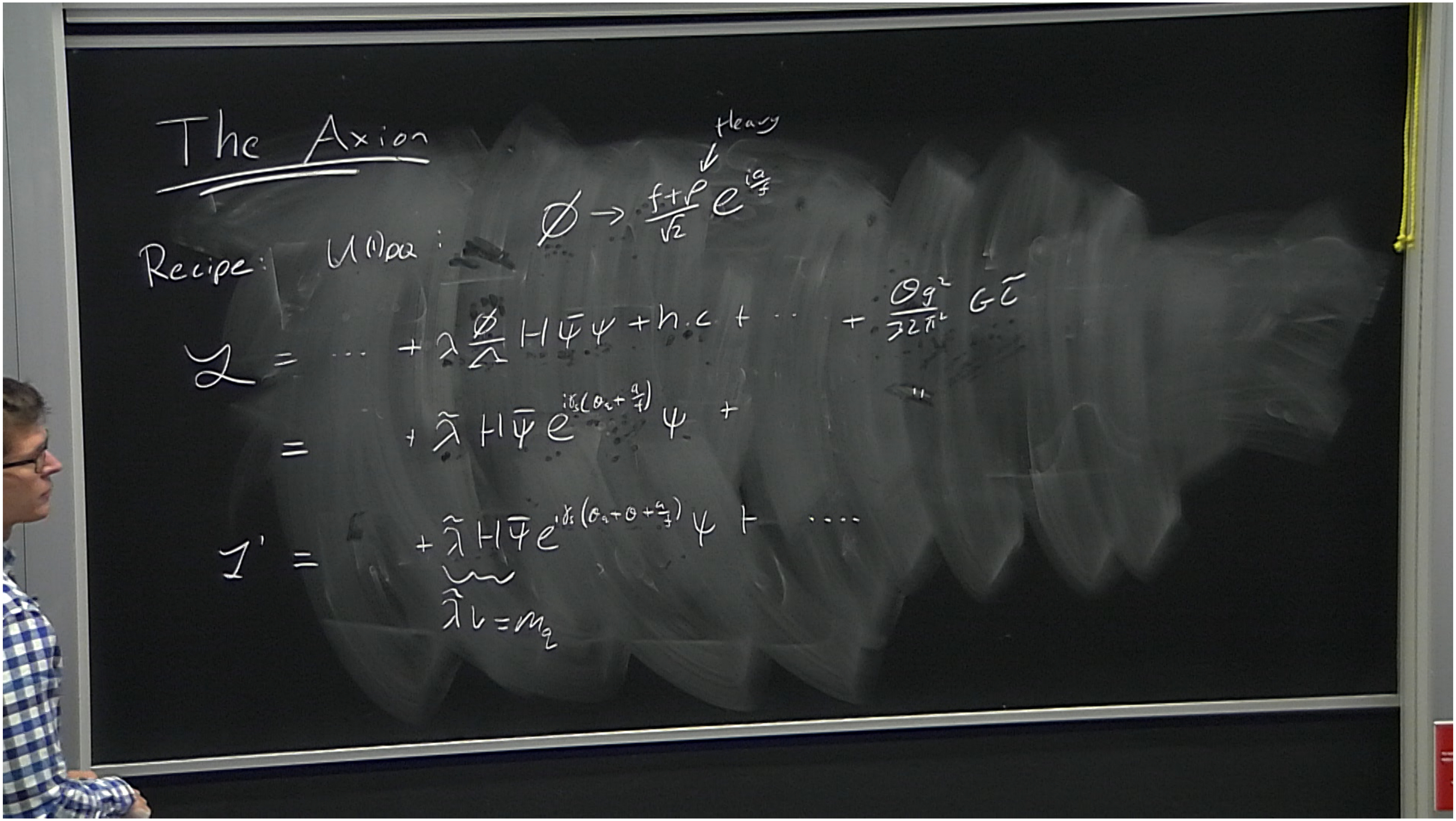
$$= \quad + f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right) + \dots$$

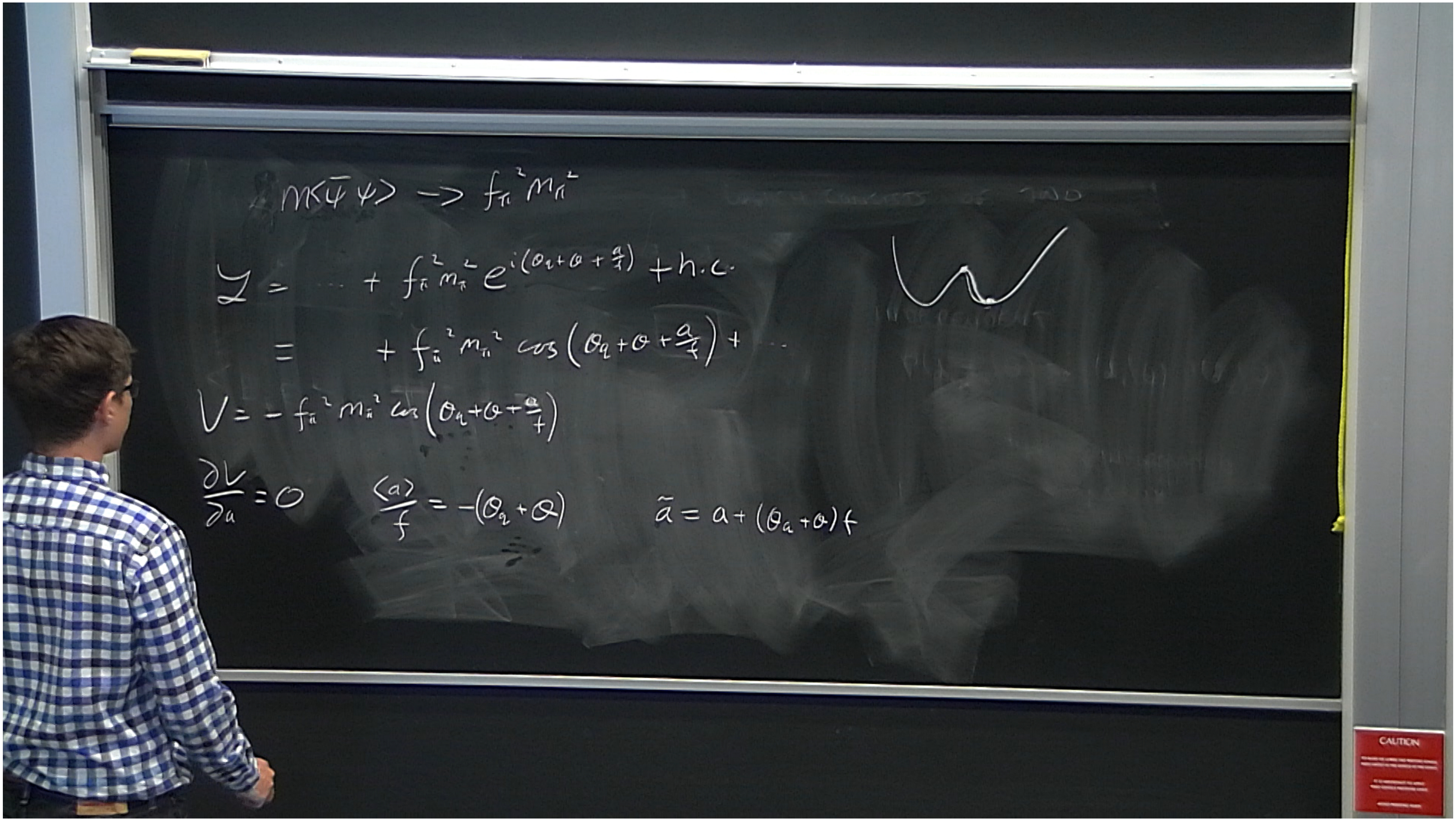
$$V = -f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$$

$$\frac{\partial V}{\partial a} = 0 \qquad \frac{\langle a\rangle}{f} = -(\theta_q+\theta)$$


$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$
$\mathcal{L} = \cdots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$
$= + f_\pi^2 m_\pi^2 \cos(\theta_q + \theta +$
$V = - f_\pi^2 m_\pi^2 \cos(\theta_q+\theta+\frac{a}{f})$
$\frac{\partial V}{\partial a} = 0$
$\frac{\langle a\rangle}{f} = -(\theta_q+\theta)$


$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$
$\mathcal{L} = \cdots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$
$= + f_\pi^2 m_\pi^2 \cos($
$) + \cdots$
$V = - f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$
$\frac{\partial V}{\partial a} = 0$
$\frac{\langle a\rangle}{f} = -(\theta_q + \theta$


The Axion
Recipe: $U(1)_{PQ}$:
Heavy
$\phi \to \frac{f+\rho}{\sqrt{2}} e^{\frac{ia}{f}}$
$\mathcal{L} = \cdots + \lambda \frac{\phi}{\Lambda} H \bar{\Psi} \Psi + h.c + \cdots + \frac{\theta g^2}{32\pi^2} G\tilde{G}$
$= \quad + \tilde{\lambda} H \bar{\Psi} e^{i\gamma_5(\theta_q + \frac{a}{f})} \Psi +$
$\mathcal{L}' = \quad + \tilde{\lambda} H \bar{\Psi} e^{i\gamma_5(\theta_q + \theta + \frac{a}{f})} \Psi + \cdots$
$\tilde{\lambda} v = m_q$


$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$
$\mathcal{L} = \cdots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$
$= + f_\pi^2 m_\pi^2 \cos(\theta_q+\theta+\frac{a}{f}) + \cdots$
$V = -f_\pi^2 m_\pi^2 \cos(\theta_q+\theta+\frac{a}{f})$
$\frac{\partial V}{\partial a} = 0$
$\frac{\langle a\rangle}{f} = -(\theta_q+\theta)$
$\tilde{a} = a + (\theta_a+\theta) f$

$$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$$

$$\mathcal{L} = \dots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$$

$$= \quad + f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right) + \dots$$

$$V = -f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$$

$$\frac{\partial V}{\partial a} = 0 \qquad \frac{\langle a\rangle}{f} = -(\theta_q+\theta) \qquad \tilde{a} = a + (\theta_q+\theta) f$$

$$V = -f_\pi^2 m_\pi^2 \cos\left(\frac{\tilde{a}}{f}\right)$$

$$m\langle\bar{\psi}\psi\rangle \to f_\pi^2 m_\pi^2$$

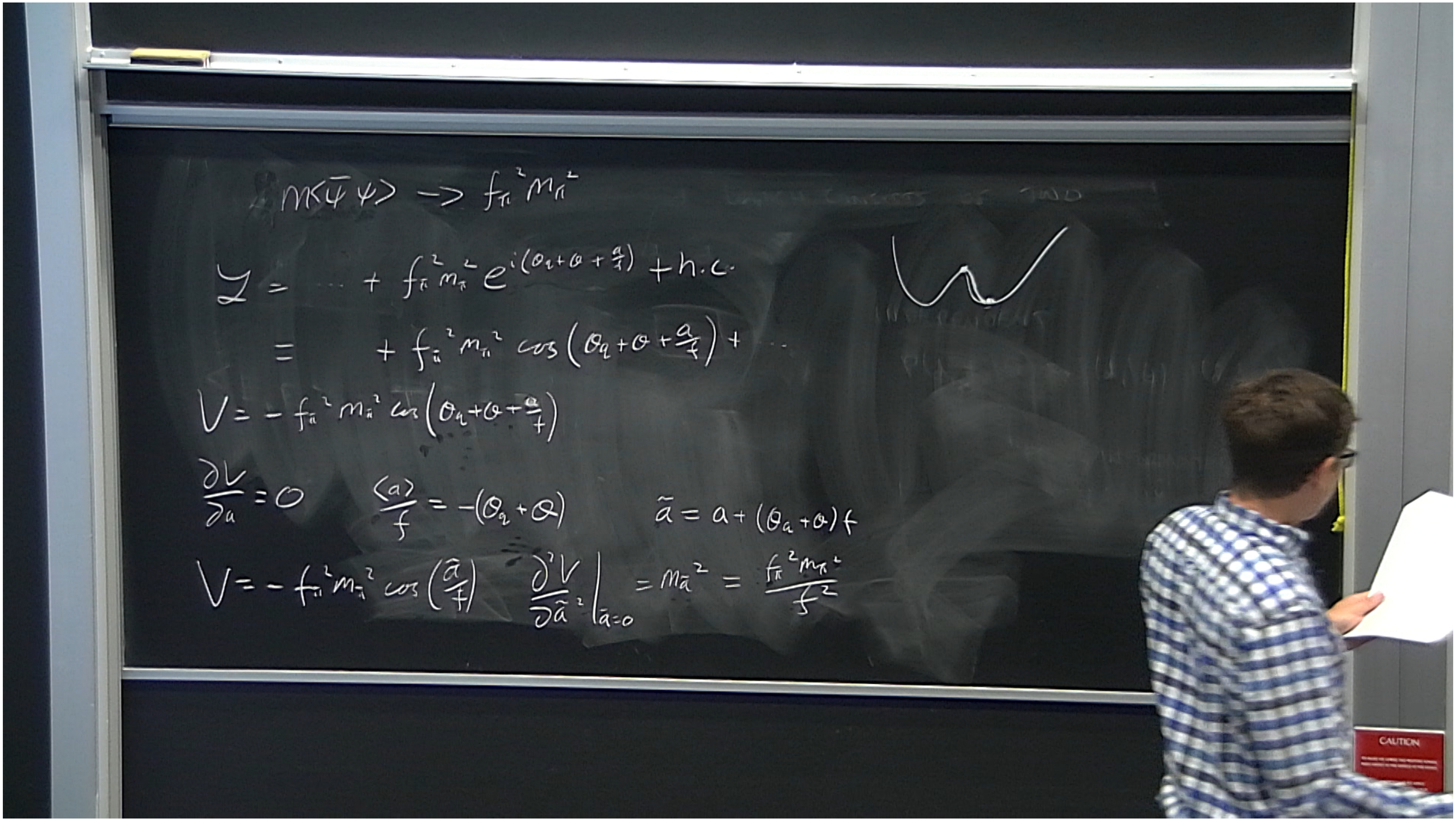
$$\mathcal{L} = \cdots + f_\pi^2 m_\pi^2 e^{i(\theta_q+\theta+\frac{a}{f})} + h.c.$$

$$= \quad + f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right) + \cdots$$

$$V = -f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$$

$$\frac{\partial V}{\partial a} = 0 \qquad \frac{\langle a\rangle}{f} = -(\theta_q+\theta) \qquad \tilde{a} = a + (\theta_a+\theta) f$$

$$V = -f_\pi^2 m_\pi^2 \cos\left(\frac{\tilde{a}}{f}\right) \qquad \left.\frac{\partial^2 V}{\partial \tilde{a}^2}\right|_{\tilde{a}=0} = m_{\tilde{a}}^2 = \frac{f_\pi^2 m_\pi^2}{f^2}$$


$m\langle\bar\psi\psi\rangle \to f_\pi^2 m_\pi^2$
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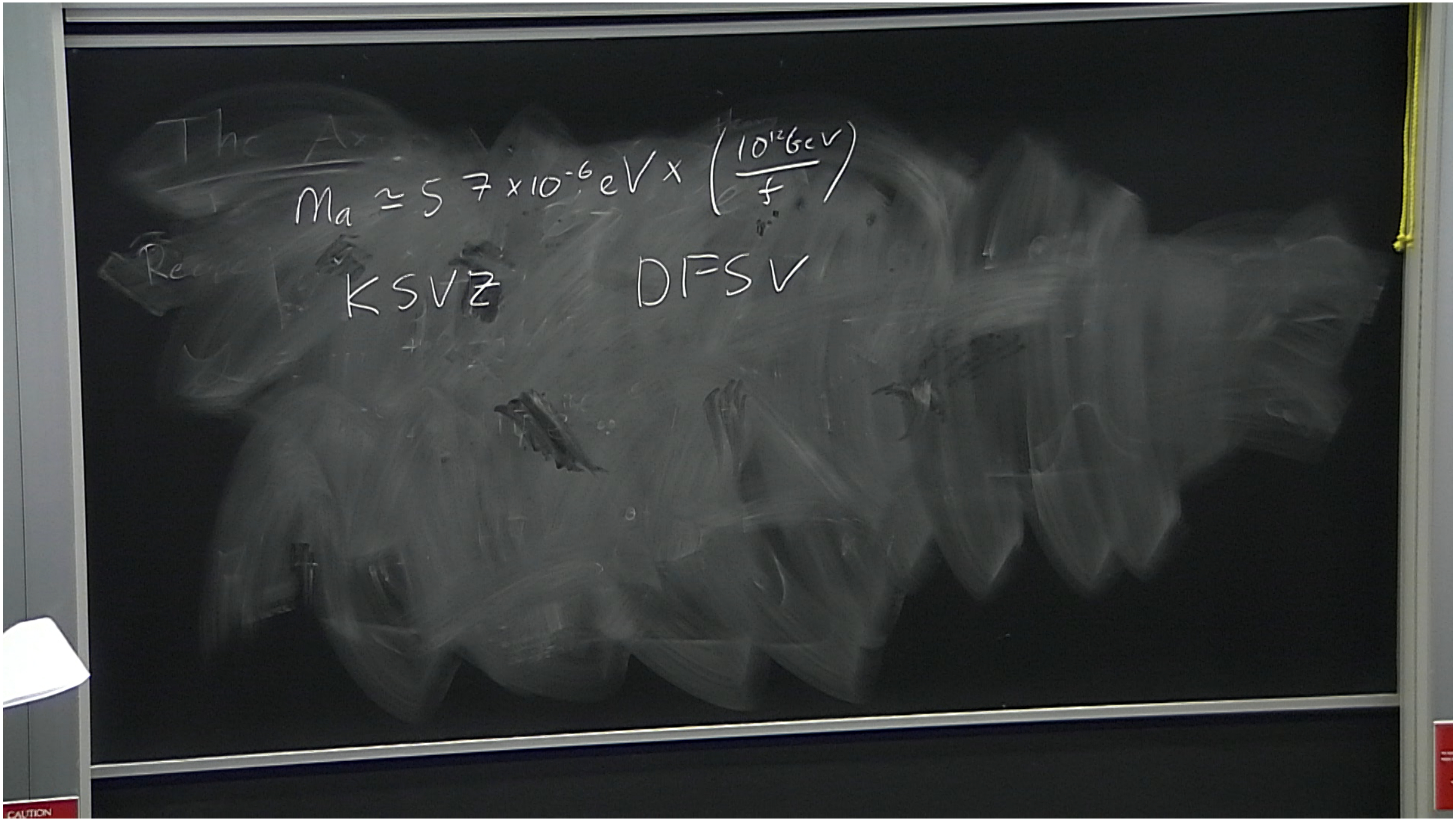
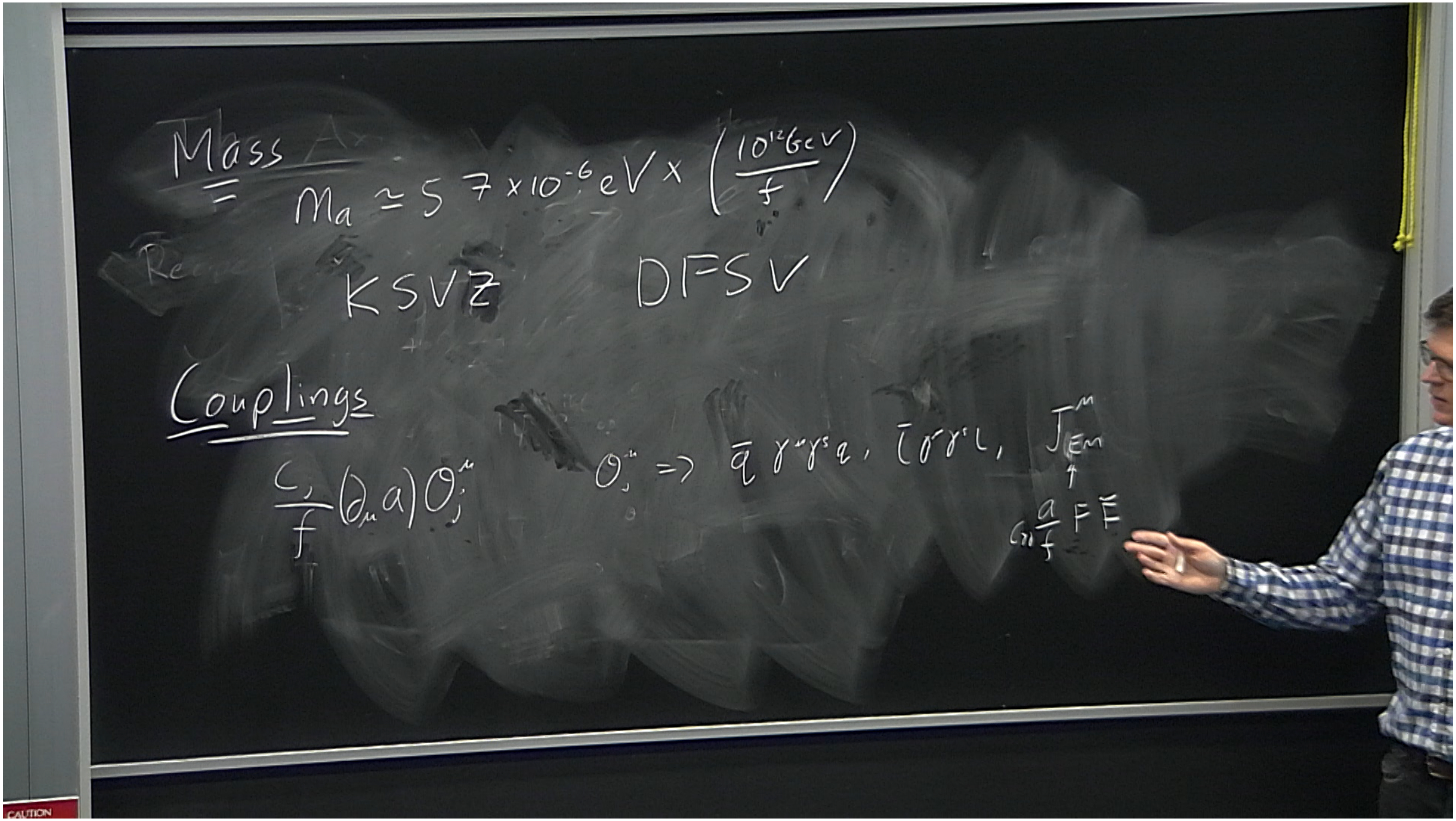
$V = -f_\pi^2 m_\pi^2 \cos\left(\theta_q+\theta+\frac{a}{f}\right)$
$\frac{\partial V}{\partial a} = 0 \qquad \frac{\langle a\rangle}{f} = -(\theta_q+\theta) \qquad \tilde a = a + (\theta_a+\theta) f$
$V = -f_\pi^2 m_\pi^2 \cos\left(\frac{\tilde a}{f}\right) \qquad \left.\frac{\partial^2 V}{\partial \tilde a^2}\right|_{\tilde a=0} = m_{\tilde a}^2 = \frac{f_\pi^2 m_\pi^2}{f^2}$

$$m_a \simeq 5.7 \times 10^{-6}\,\mathrm{eV} \times \left(\frac{10^{12}\,\mathrm{GeV}}{f}\right)$$


$m_a \simeq 5.7 \times 10^{-6}\,eV \times \left(\frac{10^{12}\,GeV}{f}\right)$
KSVZ
DFSV


Mass
$m_a \simeq 5.7 \times 10^{-6}\,\mathrm{eV} \times \left(\frac{10^{12}\,\mathrm{GeV}}{f}\right)$
KSVZ
DFSV
Couplings
$\frac{c_j}{f}(\partial_\mu a)\mathcal{O}_j^\mu$
$\mathcal{O}_j^\mu \Rightarrow \bar{q}\gamma^\mu\gamma^5 q,\ \bar{l}\gamma^\mu\gamma^5 l,\ J^\mu_{EM}$
$C_{\gamma}\frac{a}{f}F\tilde{F}$

Mass

$$m_a \simeq 5.7\times 10^{-6}\,\text{eV}\times\left(\frac{10^{12}\,\text{GeV}}{f}\right)$$

KSVZ DFSV

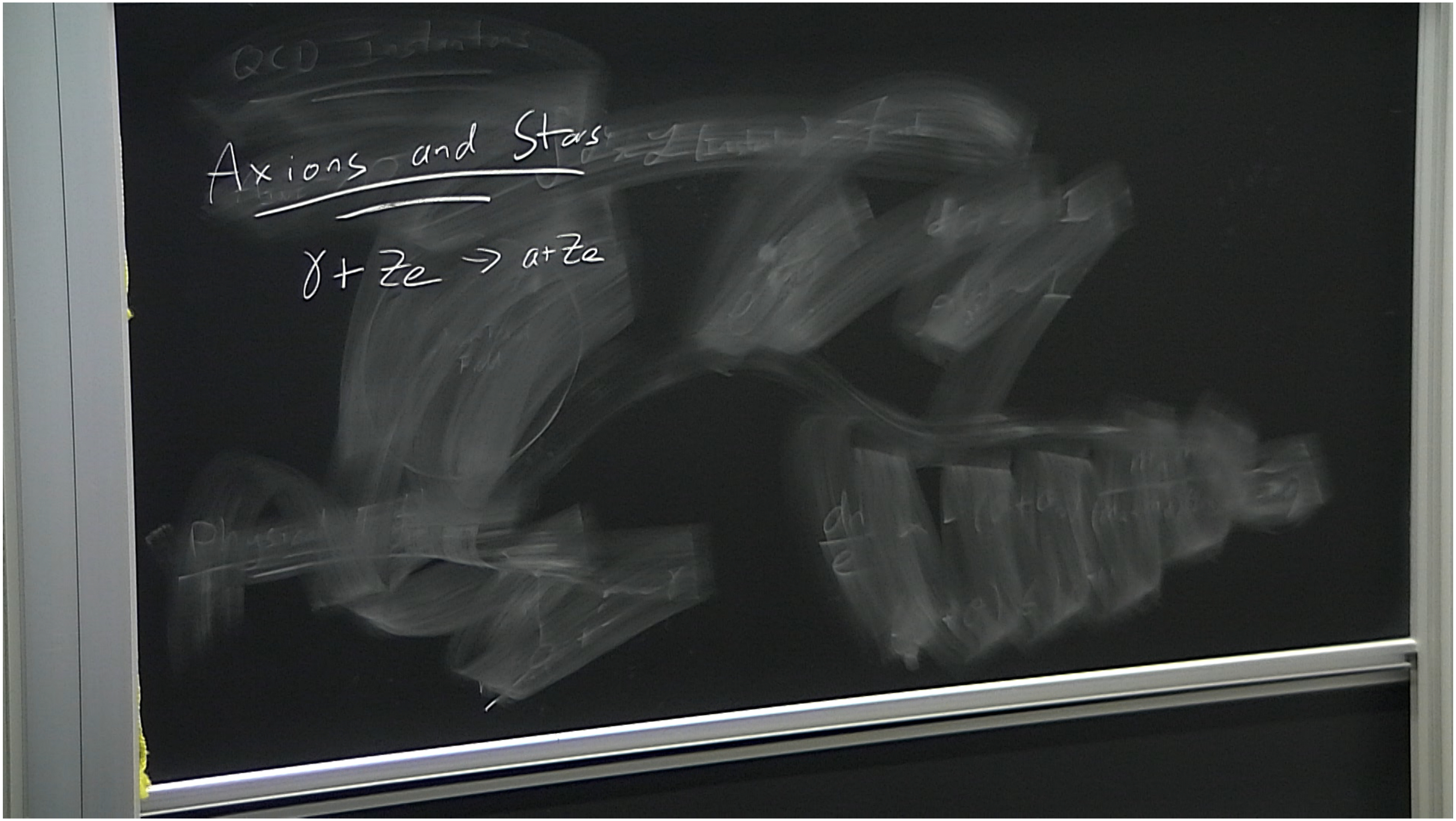
Couplings

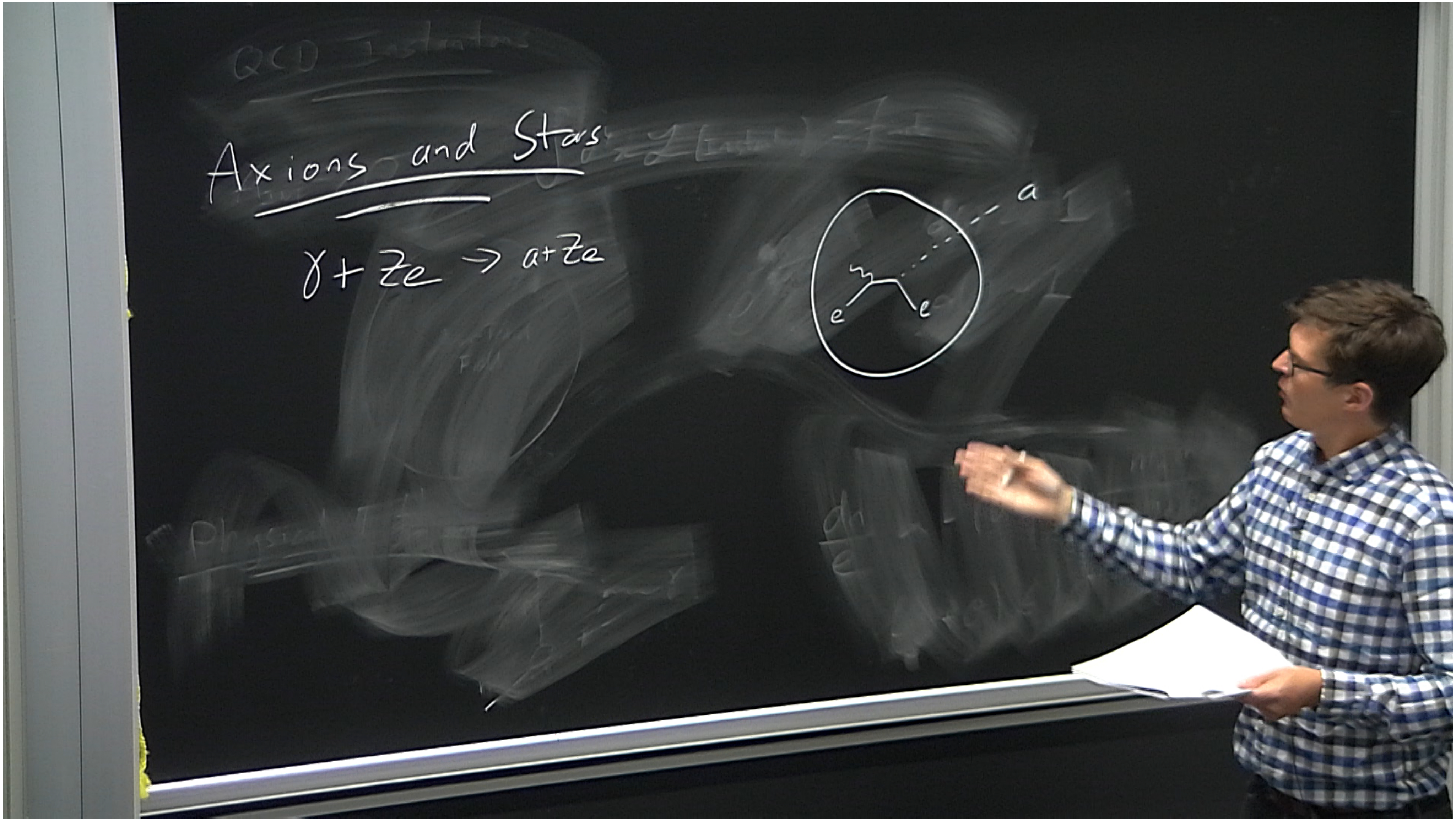
$$\frac{c_i}{f}(\partial_\mu a)\mathcal{O}_i^\mu$$

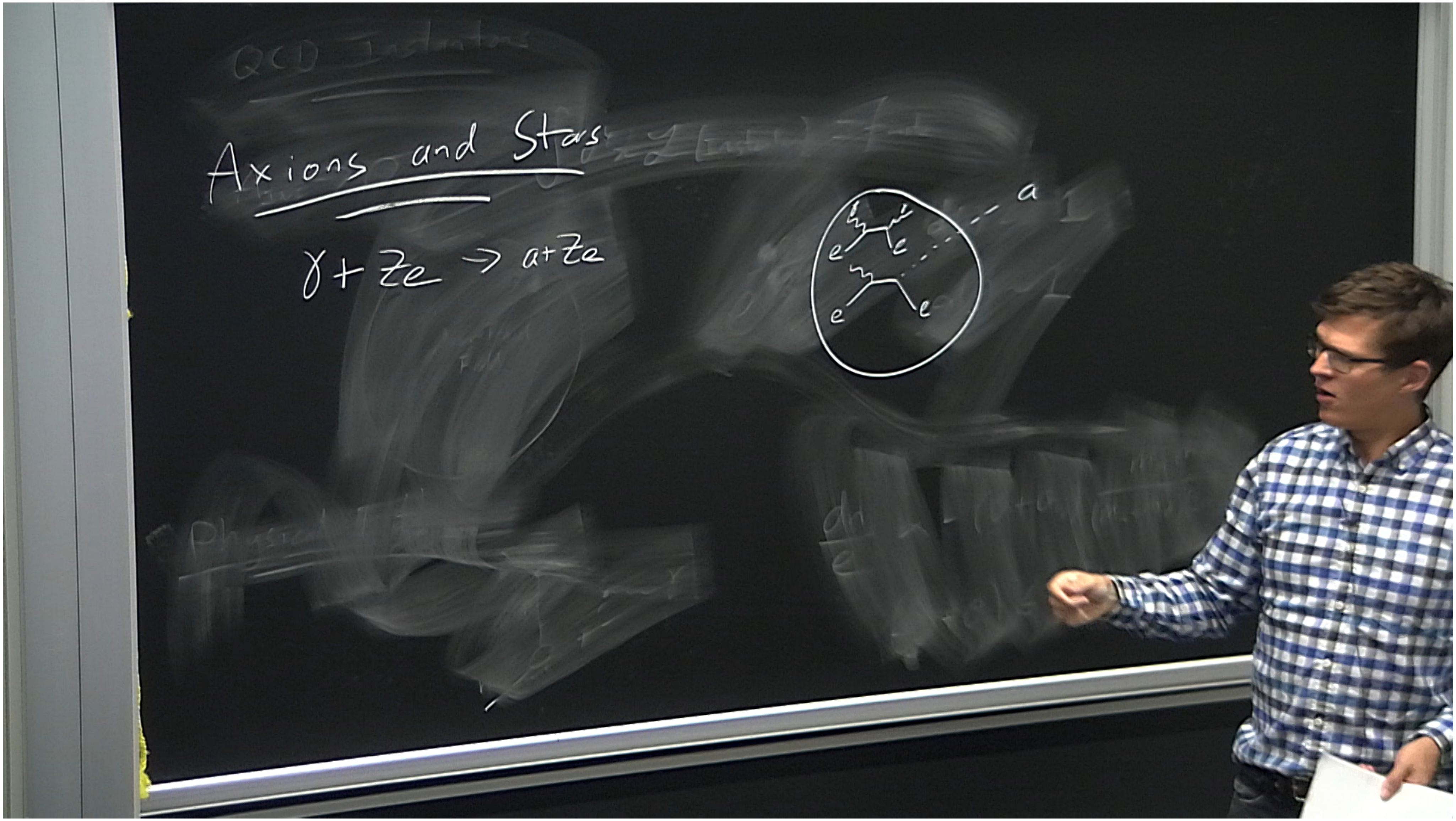
$$\mathcal{O}_i^\mu \Rightarrow \bar{q}\gamma^\mu\gamma^5 q,\ \bar{\ell}\gamma^\mu\gamma^5\ell,\ J^\mu_{EM}$$

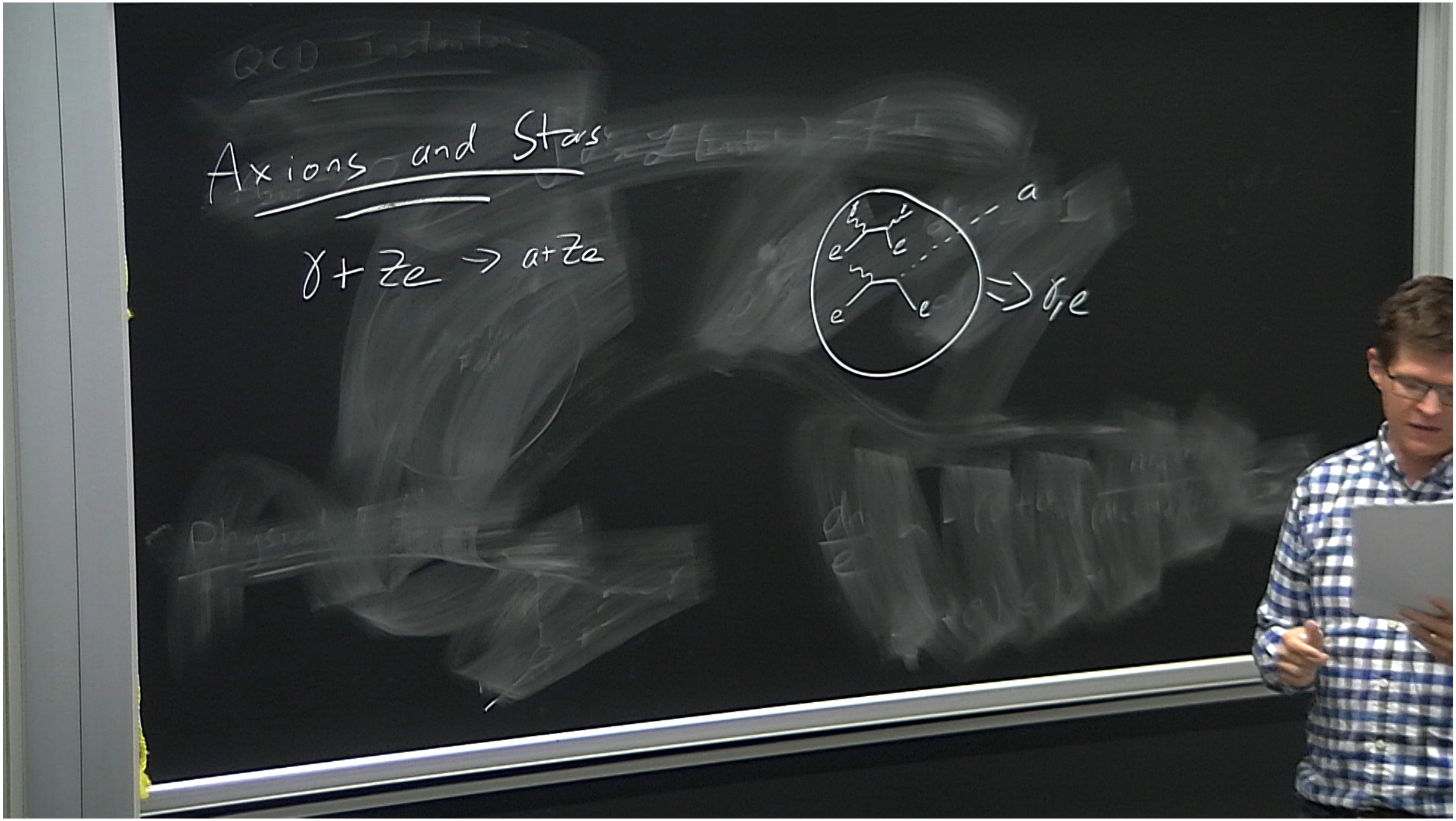
$$G_{\gamma}\frac{a}{f}F\tilde{F}$$

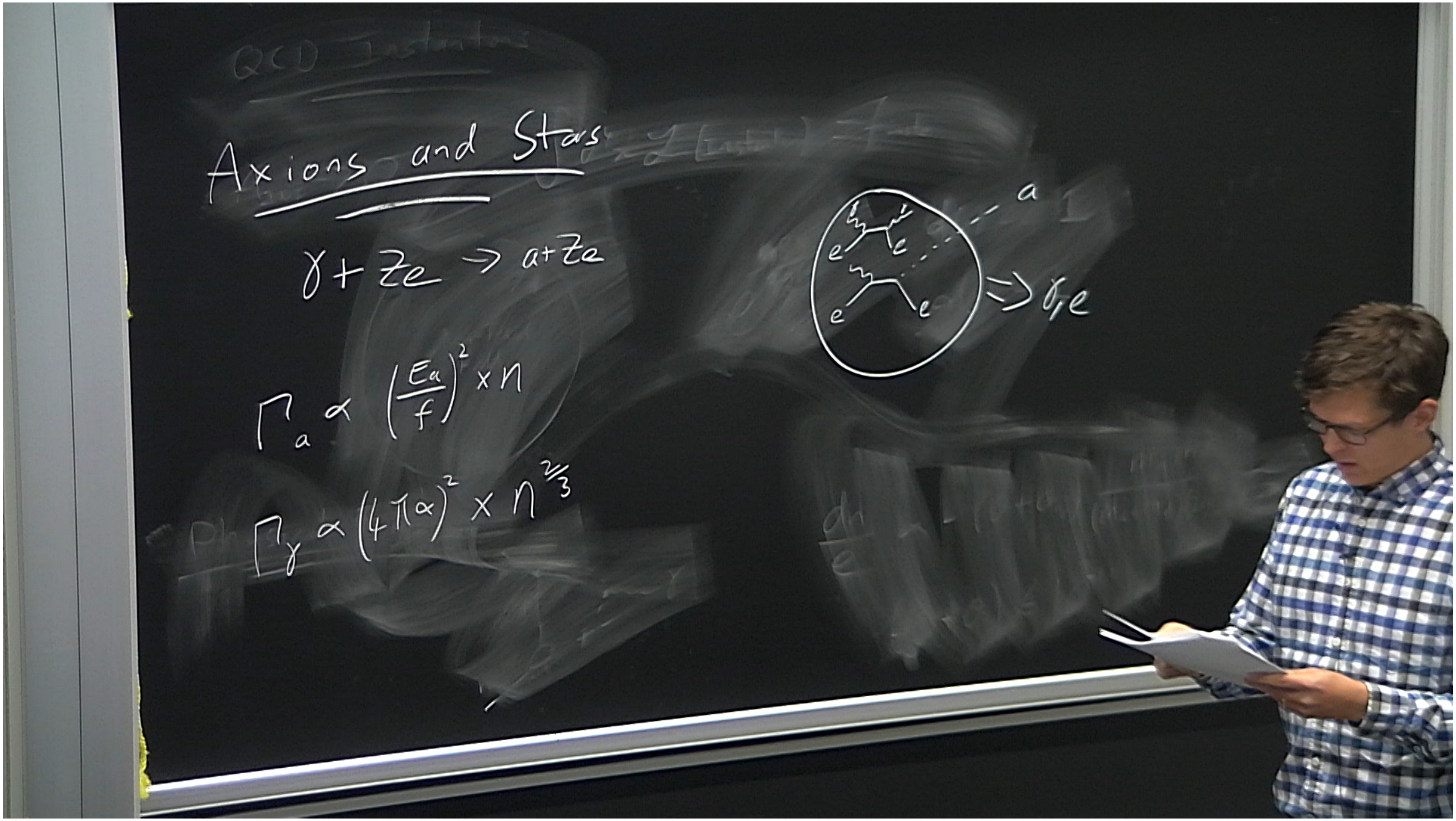
$$A \propto \left(\frac{E}{f}\right)^n$$


Axions and Stars
$\gamma + Ze \to a + Ze$

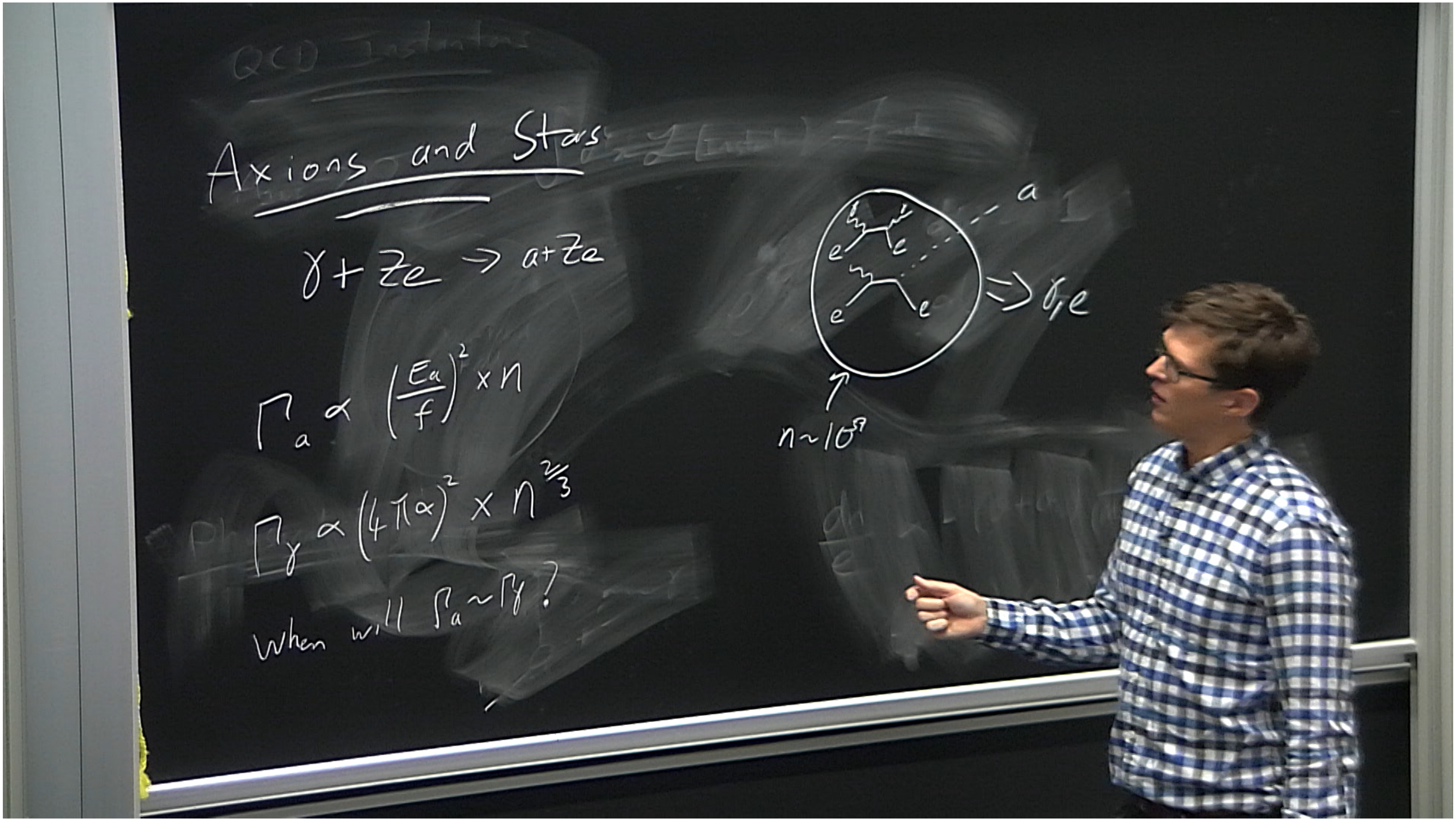

Axions and Stars
γ + Ze → a + Ze
a
e
e

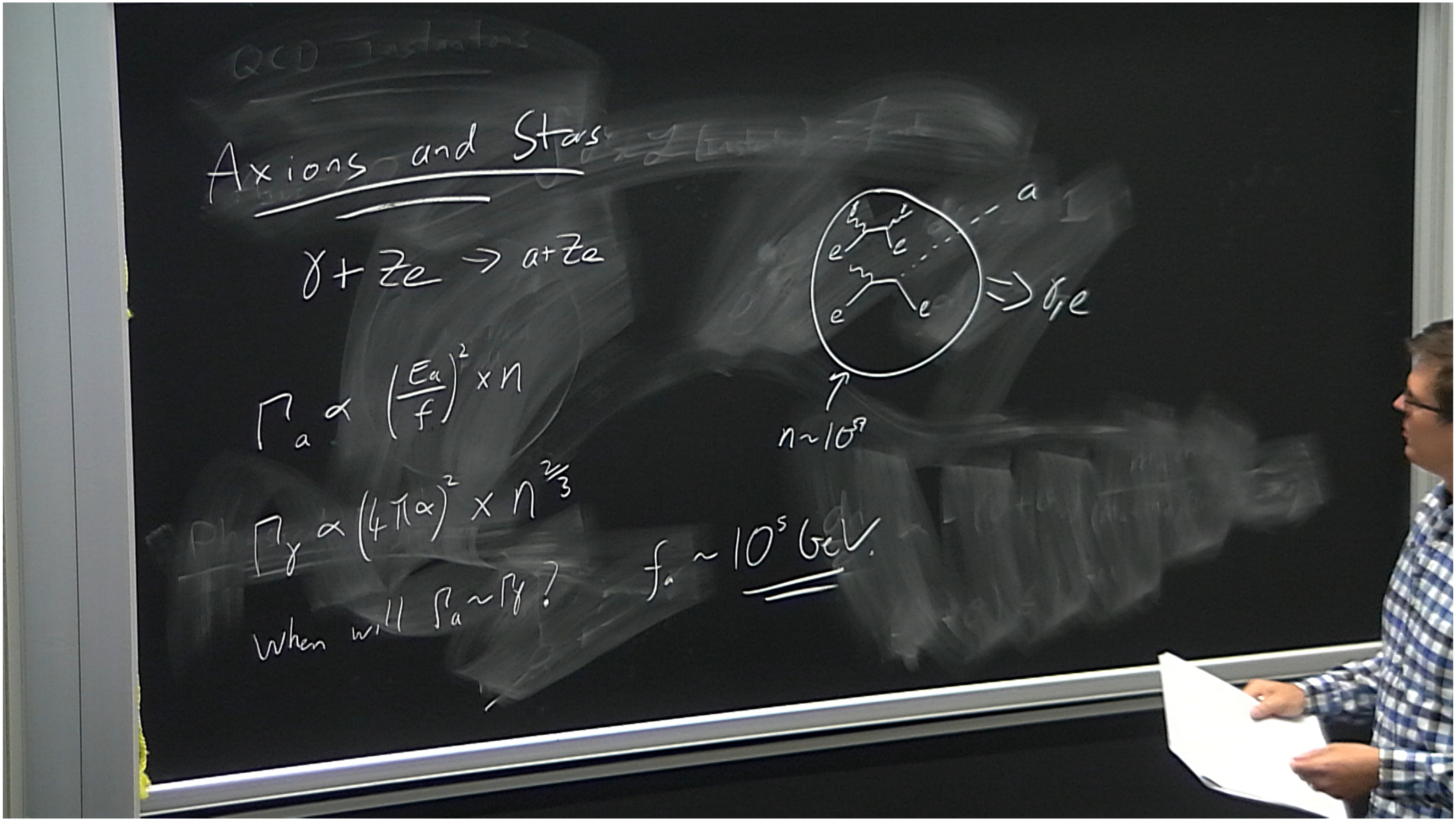

Axions and Stars
γ + Ze → a + Ze
e
e
a
e
e


Axions and Stars
γ + Ze → a+Ze
a
e
e
e
e
⇒ γ,e



Axions and Stars
$\gamma + Ze \to a + Ze$
$\Gamma_a \propto \left(\frac{E_a}{f}\right)^2 \times n$
$\Gamma_\gamma \propto (4\pi\alpha)^2 \times n^{2/3}$
a
e
e
e
e
$\Rightarrow \gamma, e$


Axions and Stars
$\gamma + Ze \to a + Ze$
$\Gamma_a \propto \left(\frac{E_a}{f}\right)^2 \times n$
$\Gamma_\gamma \propto (4\pi\alpha)^2 \times n^{2/3}$
When will $\Gamma_a \sim \Gamma_\gamma$?
a
e
$\Rightarrow \gamma, e$


Axions and Stars
$\gamma + Ze \to a + Ze$
$\Gamma_a \propto \left(\frac{E_a}{f}\right)^2 \times n$
$\Gamma_\gamma \propto (4\pi\alpha)^2 \times n^{2/3}$
When will $\Gamma_a \sim \Gamma_\gamma$?
$f_a \sim 10^5$ GeV
$n \sim 10^{?}$
a
e
$\Rightarrow \gamma, e$