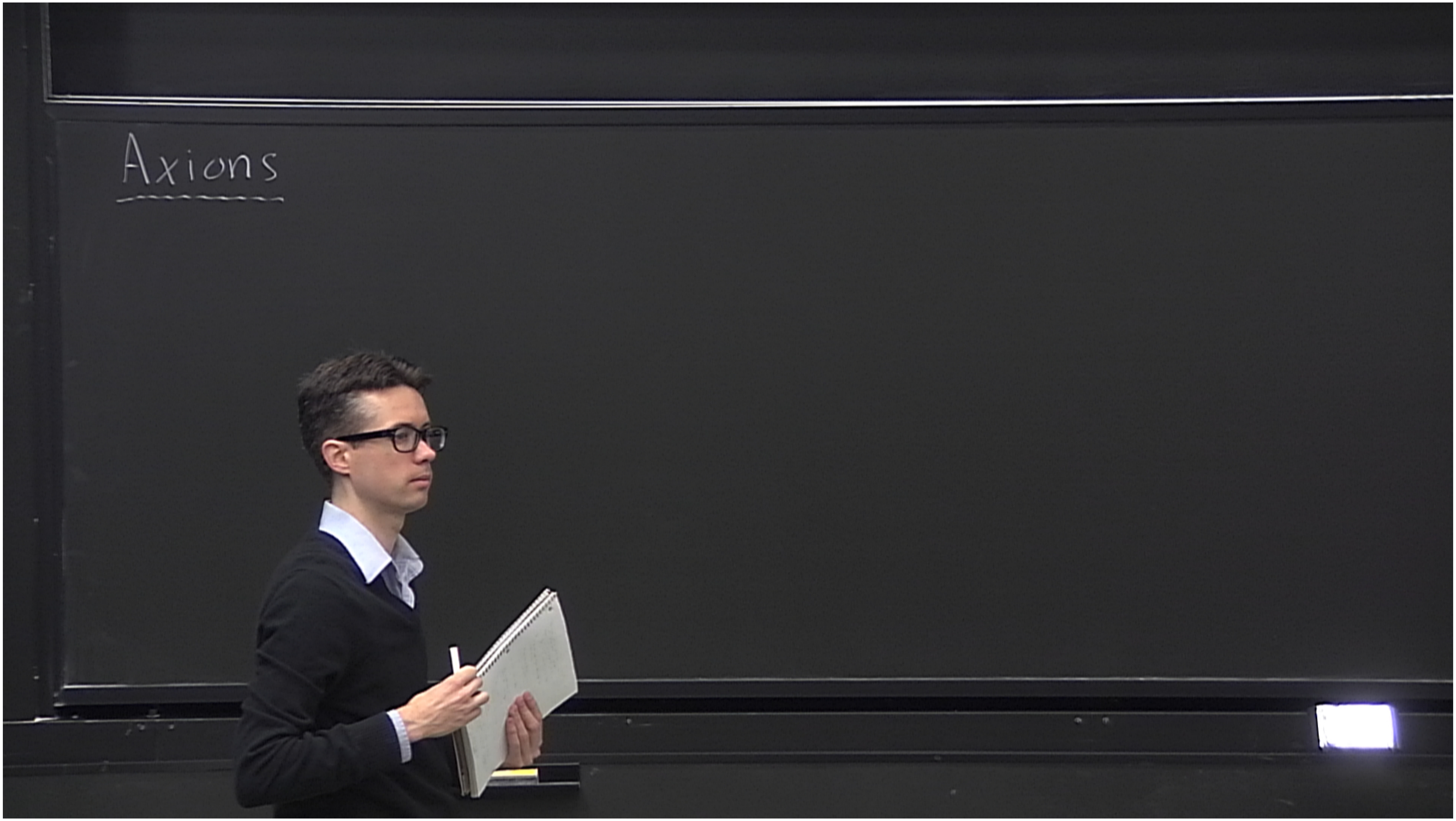
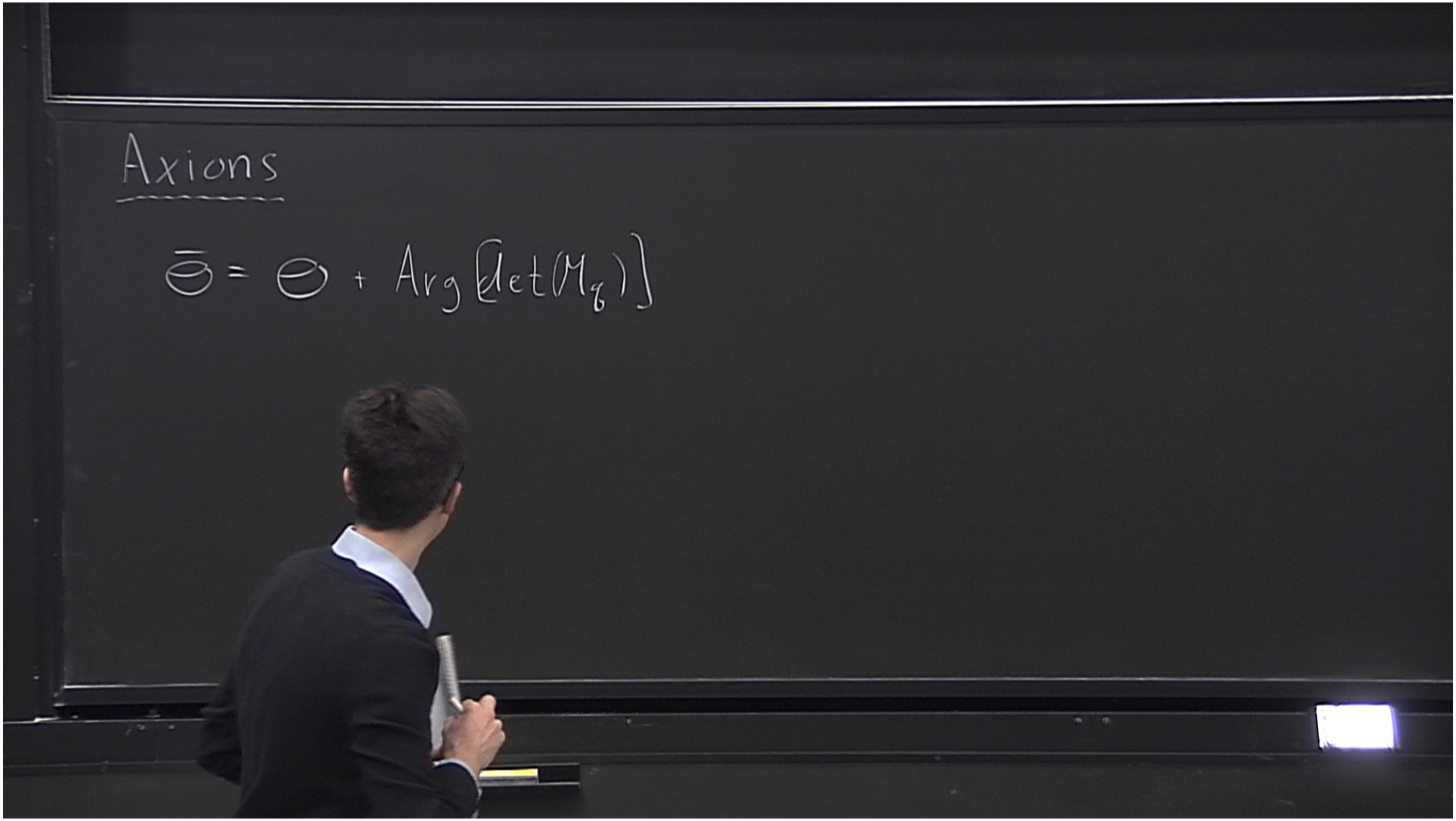
Title: Explorations in Particle Theory - Lecture 14

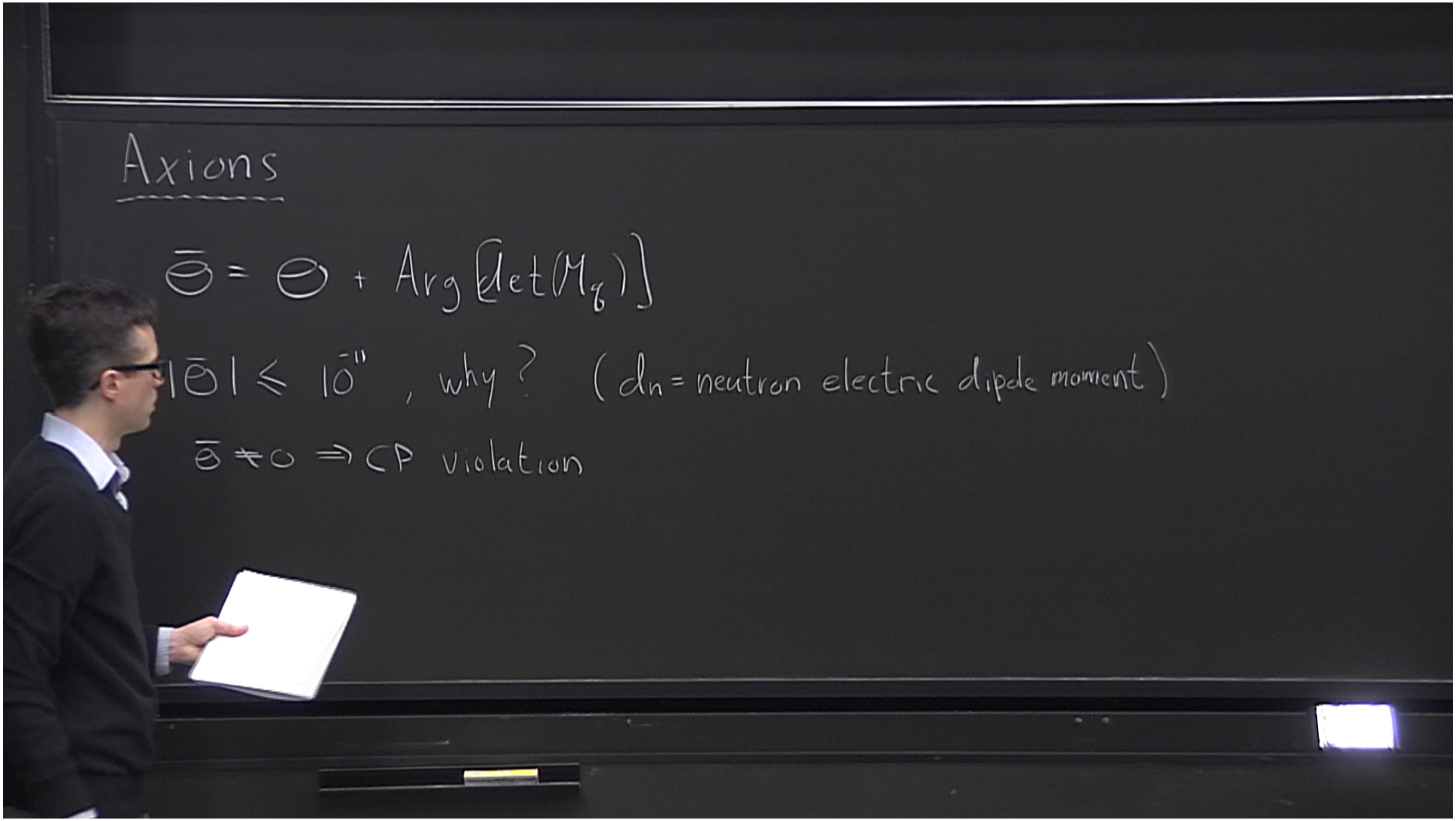
Date: Apr 20, 2012 09:00 AM

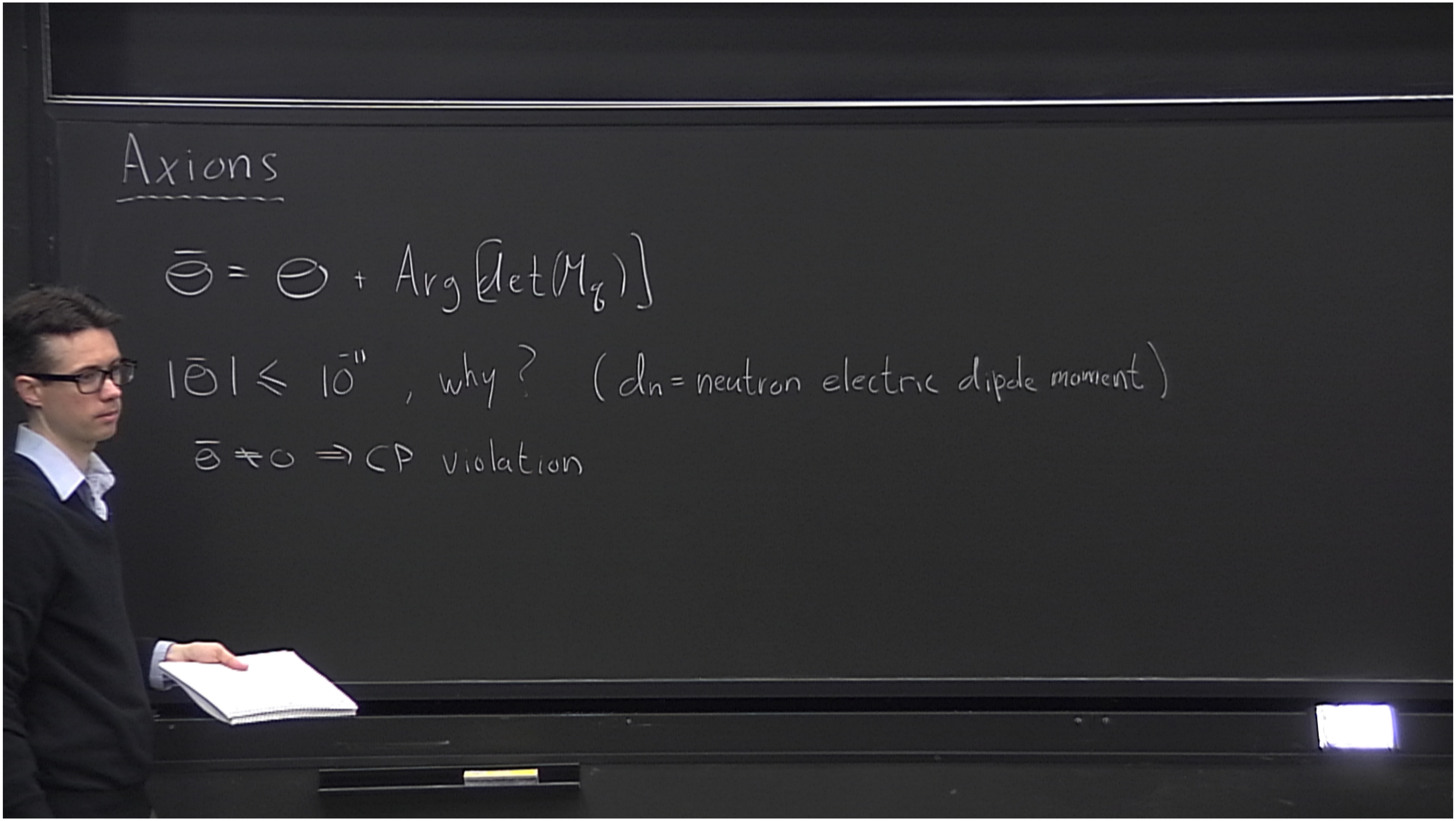
URL: http://pirsa.org/12040018

Abstract:


Axions


Axions
$\bar{\Theta} = \Theta + \mathrm{Arg}[\det(M_q)]$


Axions
$\bar{\Theta} = \Theta + \mathrm{Arg}[\det(M_q)]$
$|\bar{\Theta}| \leq 10^{-11}$, why ? (d_n = neutron electric dipole moment)
$\bar{\theta} \neq 0 \Rightarrow$ CP violation


Axions
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Axions

$$\bar{\Theta} = \Theta + \mathrm{Arg}\left[\det(M_q)\right]$$

$|\bar{\Theta}| \leq 10^{-11}$, why? (d_n = neutron electric dipole moment)

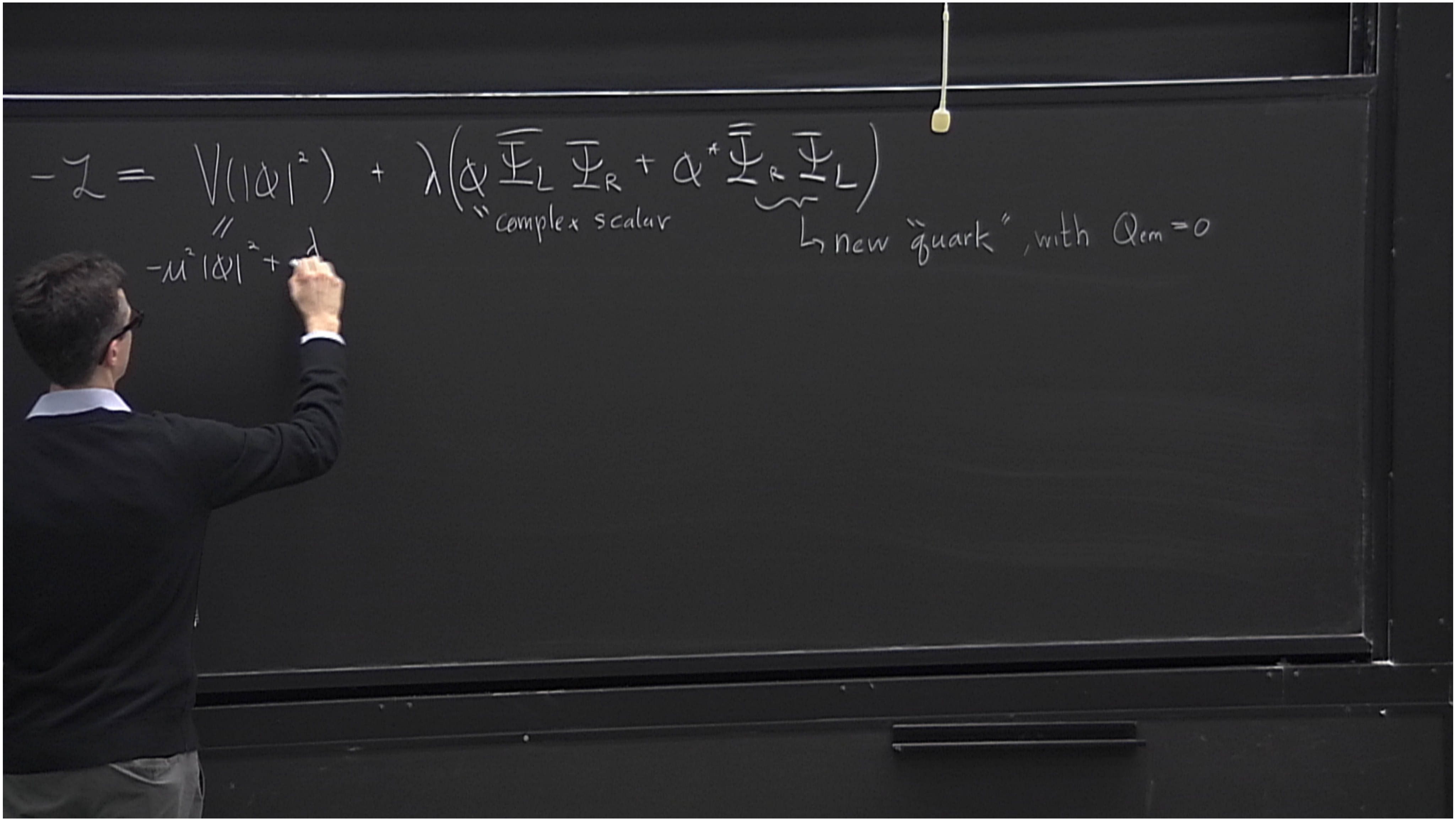
$\bar{\Theta} \neq 0 \Rightarrow$ CP violation

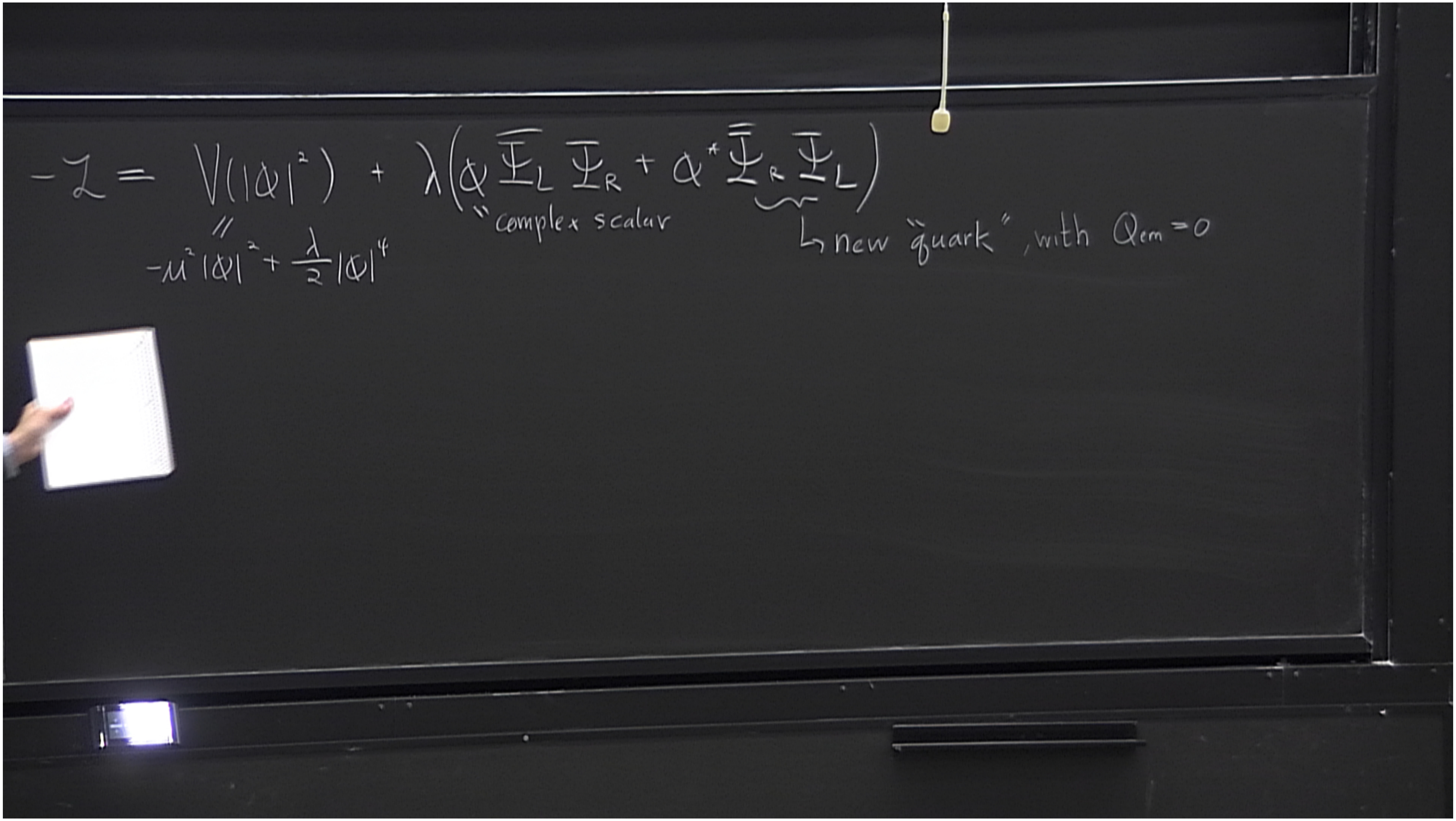
Axion $\Rightarrow$ "$\bar{\Theta} \to 0$" dynamically

$$-\mathcal{L} = V(|\phi|^2) + \lambda\left(\phi\,\bar{\Psi}_L \Psi_R + \phi^* \bar{\Psi}_R \Psi_L\right)$$

"complex scalar

↳ new "quark"


-ℒ = V(|φ|²) + λ(φ Ψ̄_L Ψ_R + φ* Ψ̄_R Ψ_L)
complex scalar
new "quark", with Q_em = 0
-μ²|φ|² + λ


$-\mathcal{L} = V(|\Phi|^2) + \lambda(\Phi \bar{\Psi}_L \Psi_R + \Phi^* \bar{\Psi}_R \Psi_L)$
$-\mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$
"complex scalar
new "quark", with $Q_{em} = 0$

$$-\mathcal{L} = V(|\Phi|^2) + \lambda\left(\Phi\, \bar{\Psi}_L \Psi_R + \Phi^* \bar{\Psi}_R \Psi_L\right)$$

$V(|\Phi|^2) = -\mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$

Φ = complex scalar

Ψ ↳ new "quark", with $Q_{em} = 0$

$$\Rightarrow \Phi(x) = \frac{1}{\sqrt{2}}\left[f + h(x)\right] e^{i a(x)/f}$$

f = VEV of Φ

$$-\mathcal{L} = V(|\Phi|^2) + \lambda\left(\Phi\,\bar{\Psi}_L \Psi_R + \Phi^* \bar{\Psi}_R \Psi_L\right)$$

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$$\Rightarrow \Phi(x) = \frac{1}{\sqrt{2}}\left[f + h(x)\right] e^{ia(x)/f}, \quad f \gg m_W$$

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f = VEV of Φ

$$\mathcal{L} \supset |\partial_\mu \Phi|^2$$

↳ $(\partial_\mu a)^2 \frac{1}{2} + \ldots$

$$-\mathcal{L} = V(|\Phi|^2) + \lambda\left(\Phi \bar{\Psi}_L \Psi_R + \Phi^* \bar{\Psi}_R \Psi_L\right)$$

$$V(|\Phi|^2) = -\mu^2 |\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$$

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Ψ ↳ new "quark", with $Q_{em} = 0$

$$\Rightarrow \Phi(x) = \frac{1}{\sqrt{2}}\left[f + h(x)\right] e^{i a(x)/f}$$

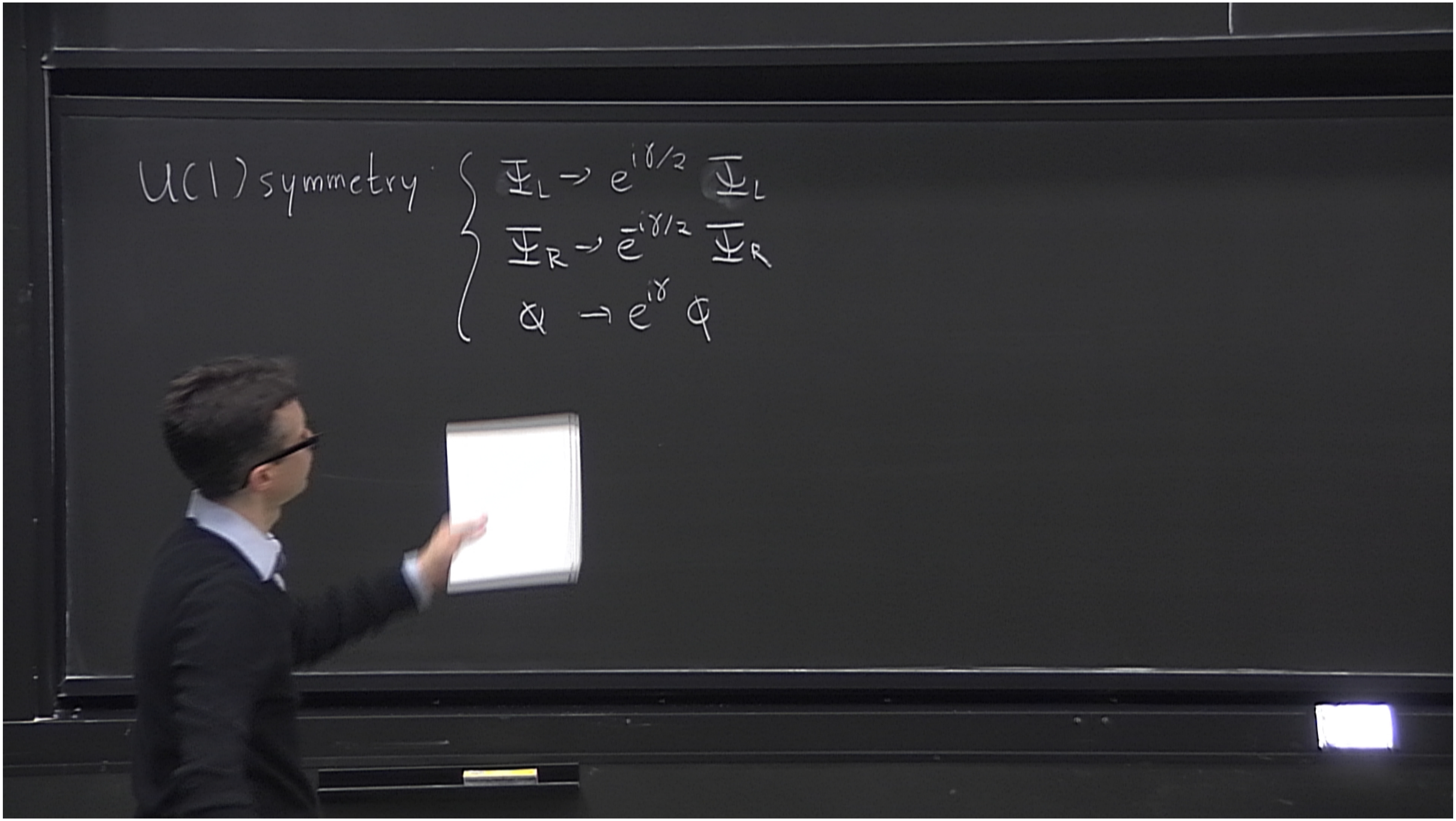
f = VEV of Φ

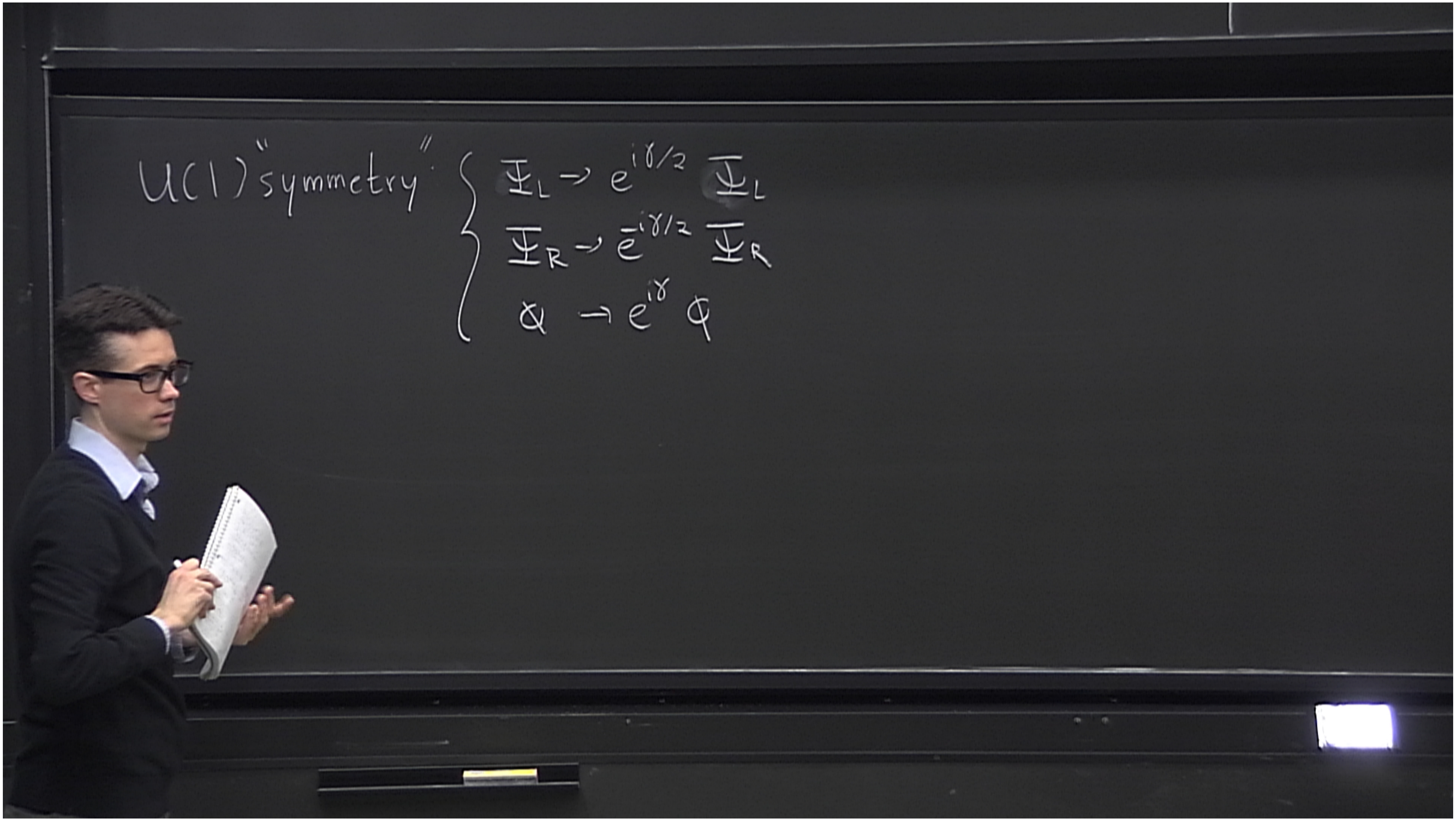
$f \gg m_W \Rightarrow h, \Psi_{L,R}$ get heavy

↳ get rid of heavy stuff

$$\mathcal{L} \supset |\partial_\mu \Phi|^2$$

↳ $(\partial_\mu a)^2 \frac{1}{2} + \dots$


U(1) symmetry
$\Psi_L \to e^{i\gamma/2}\,\Psi_L$
$\Psi_R \to e^{-i\gamma/2}\,\Psi_R$
$\phi \to e^{i\gamma}\,\phi$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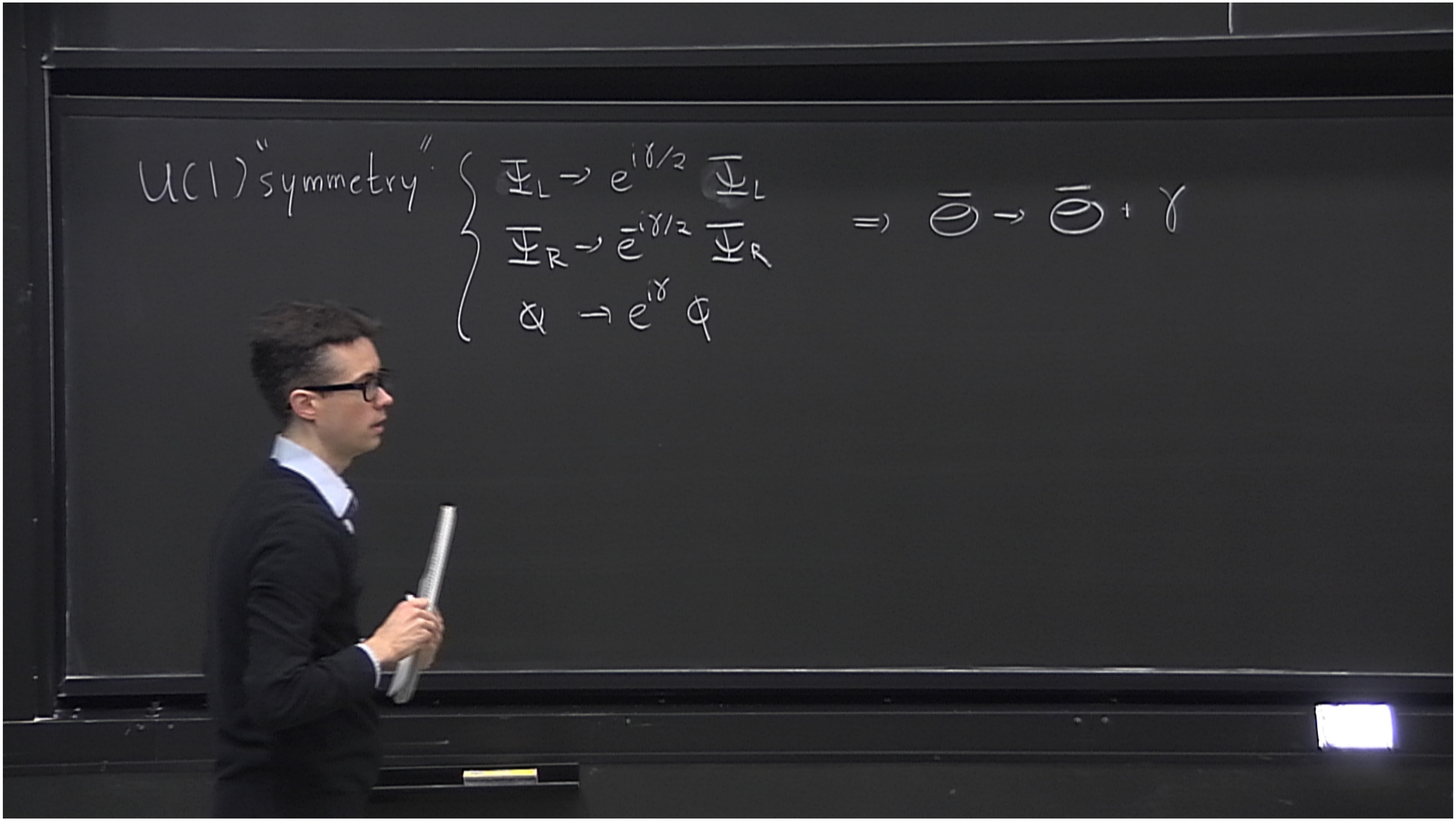
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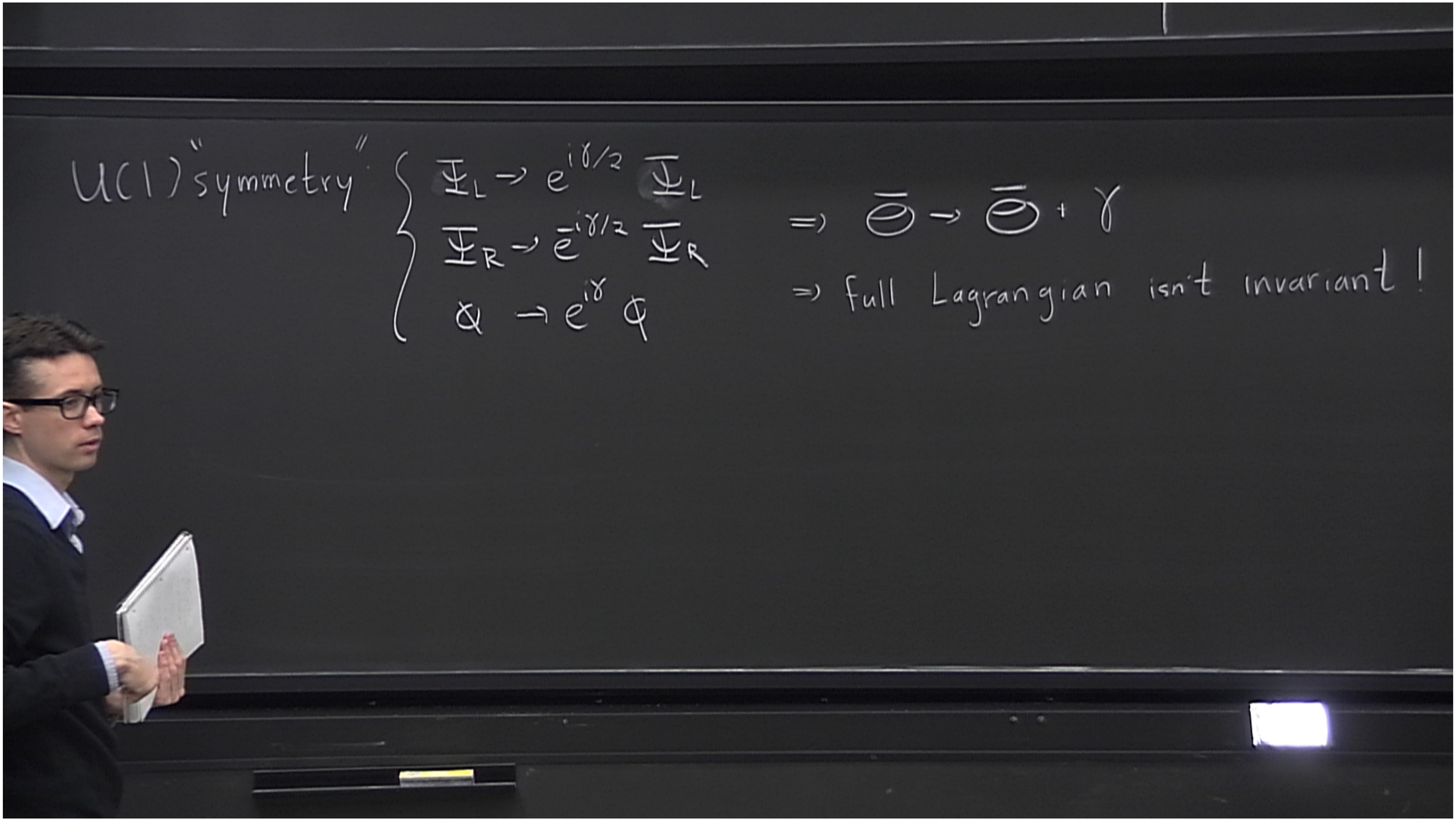
$\Rightarrow \bar{\Theta} \to \bar{\Theta} + \gamma$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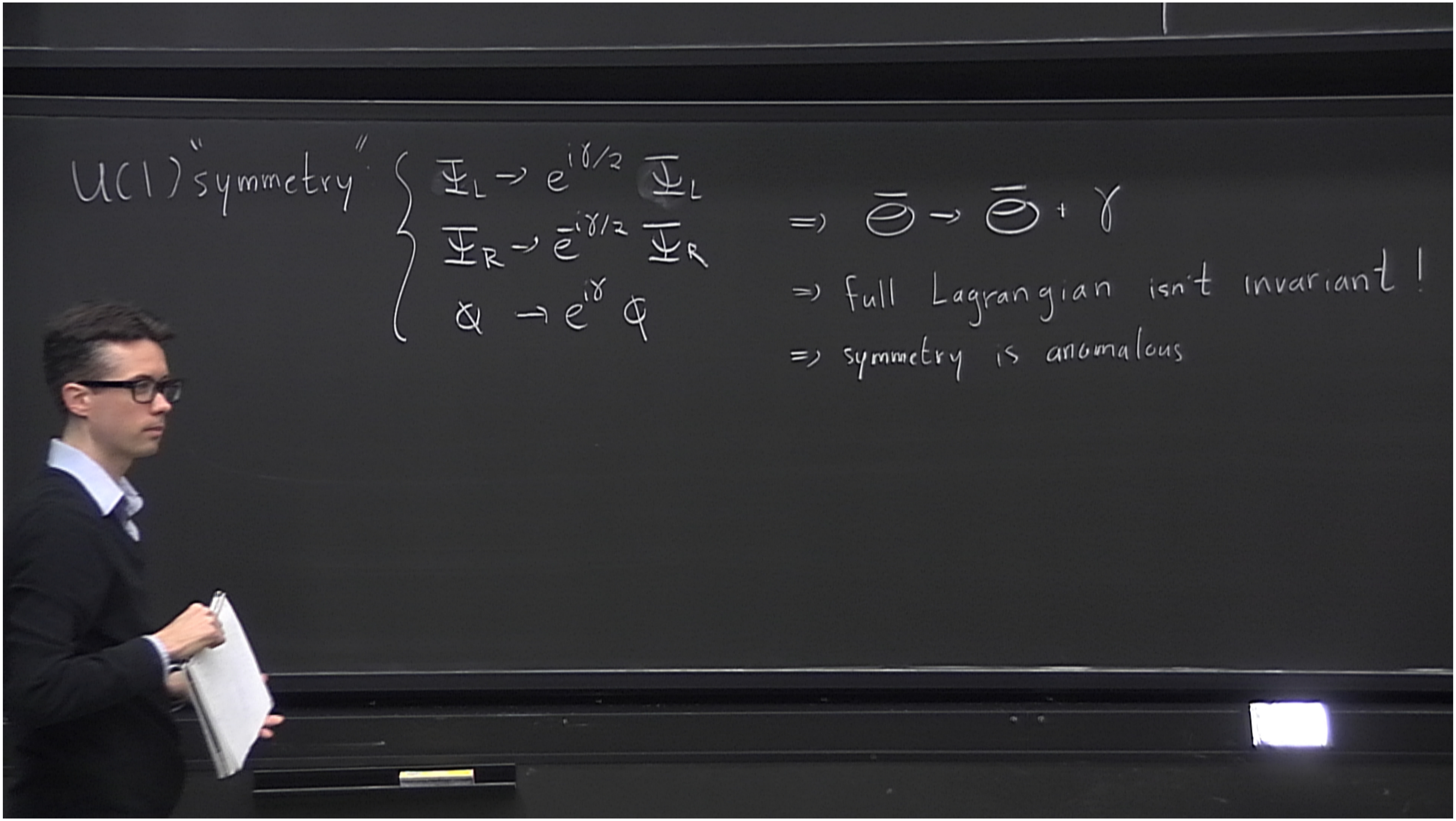
$\Rightarrow \bar{\Theta} \to \bar{\Theta} + \gamma$
$\Rightarrow$ full Lagrangian isn't invariant!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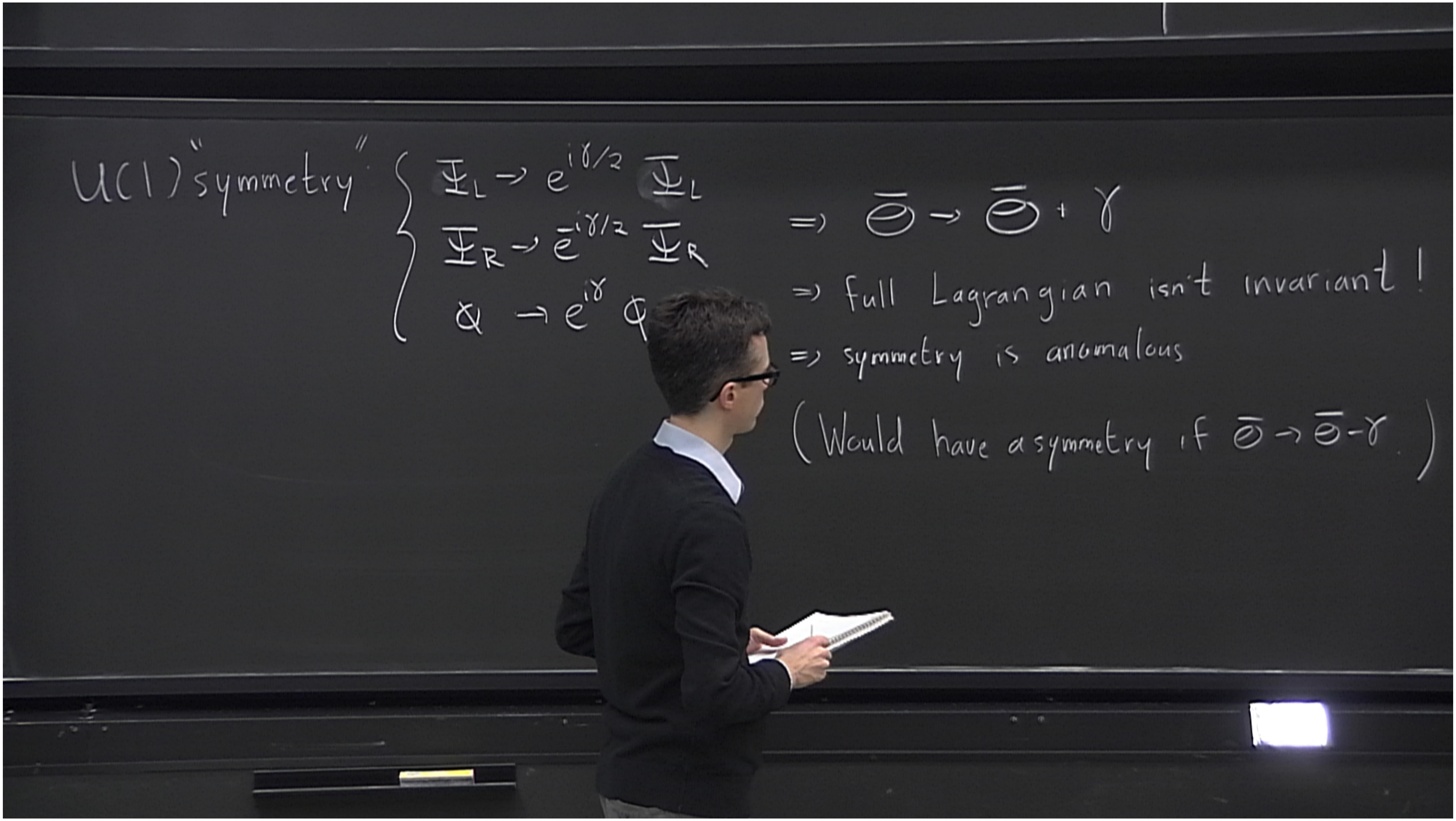
⇒ full Lagrangian isn't invariant!
⇒ symmetry is anomalous


U(1) "symmetry"
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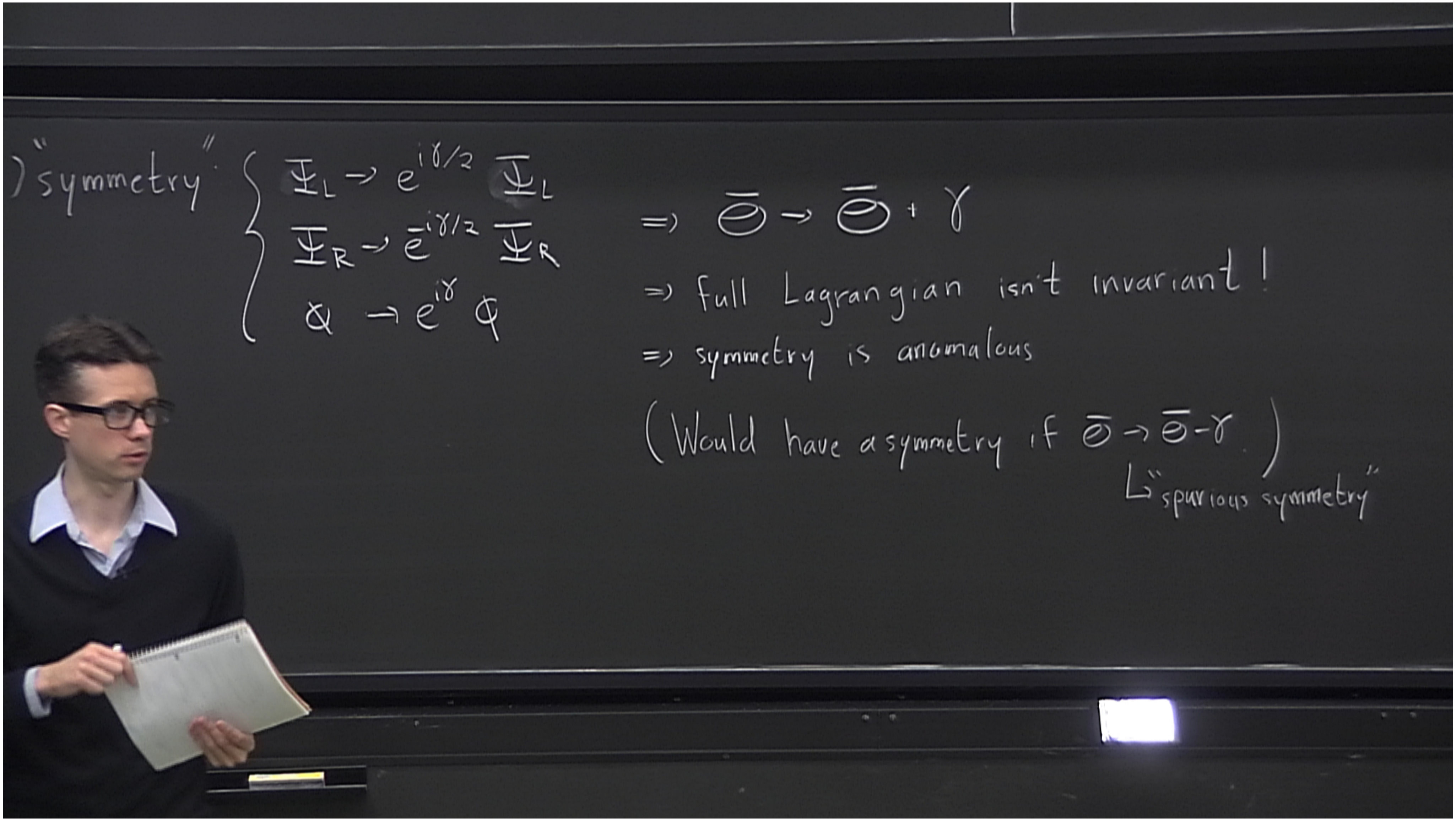
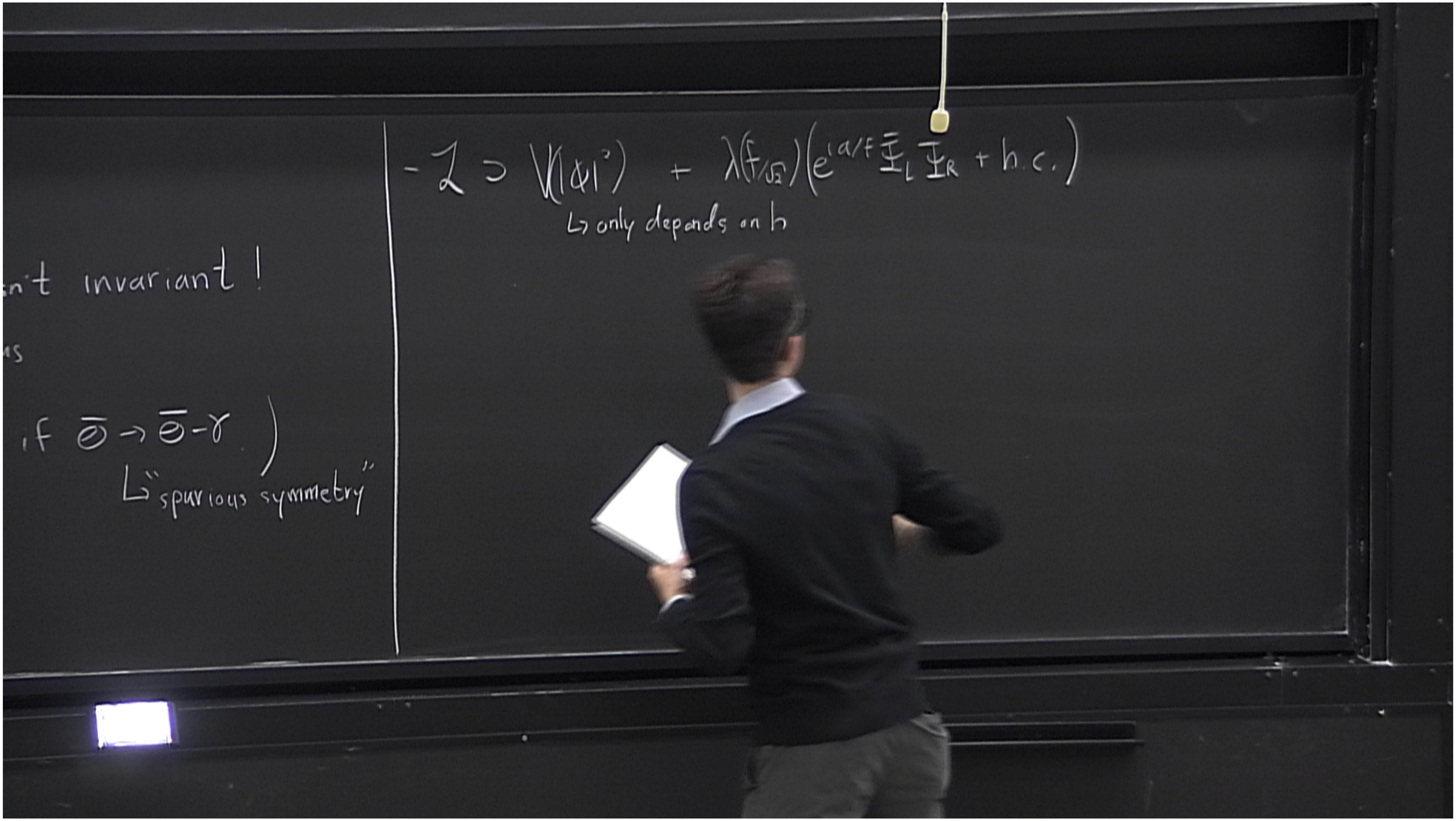
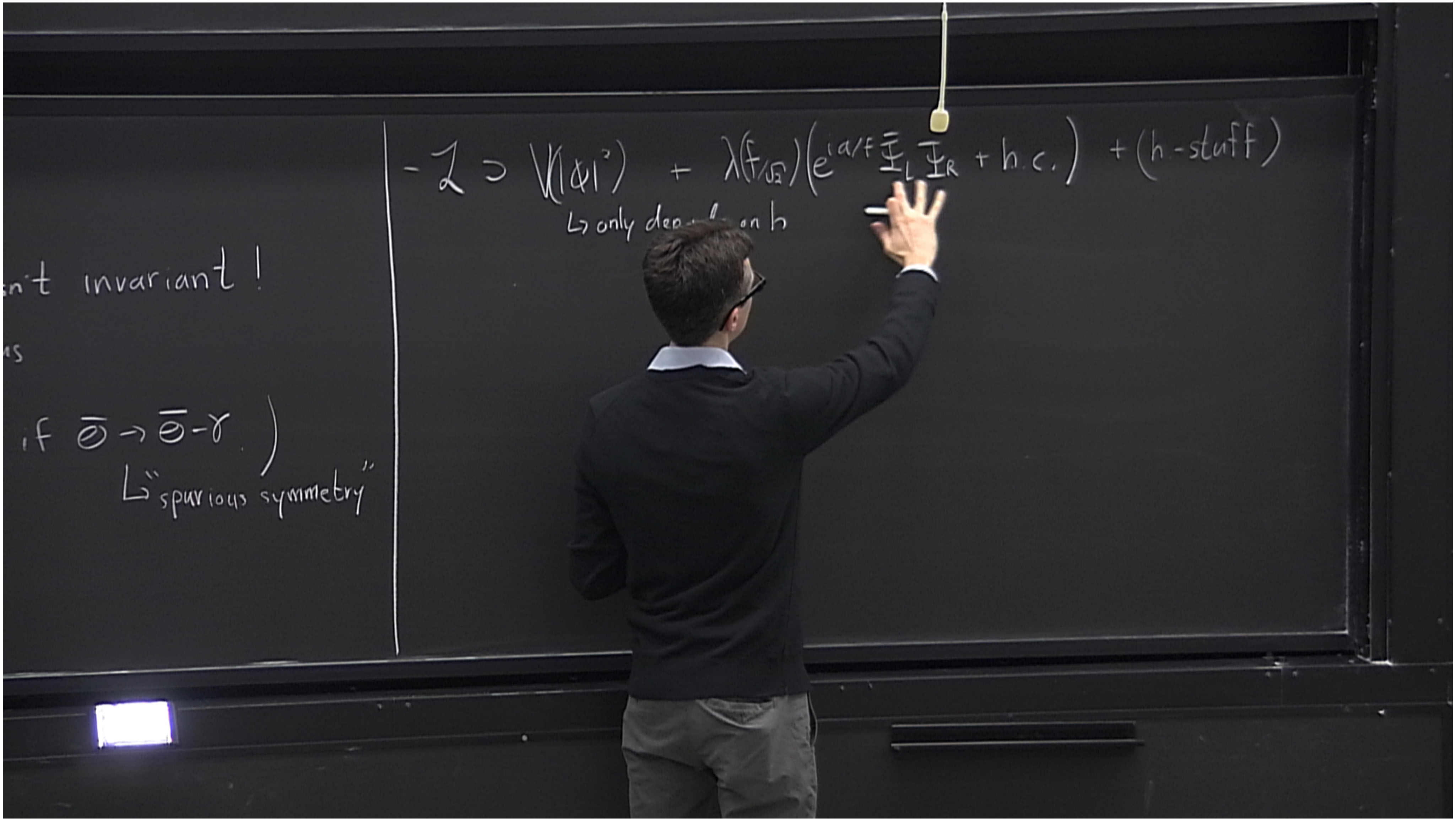
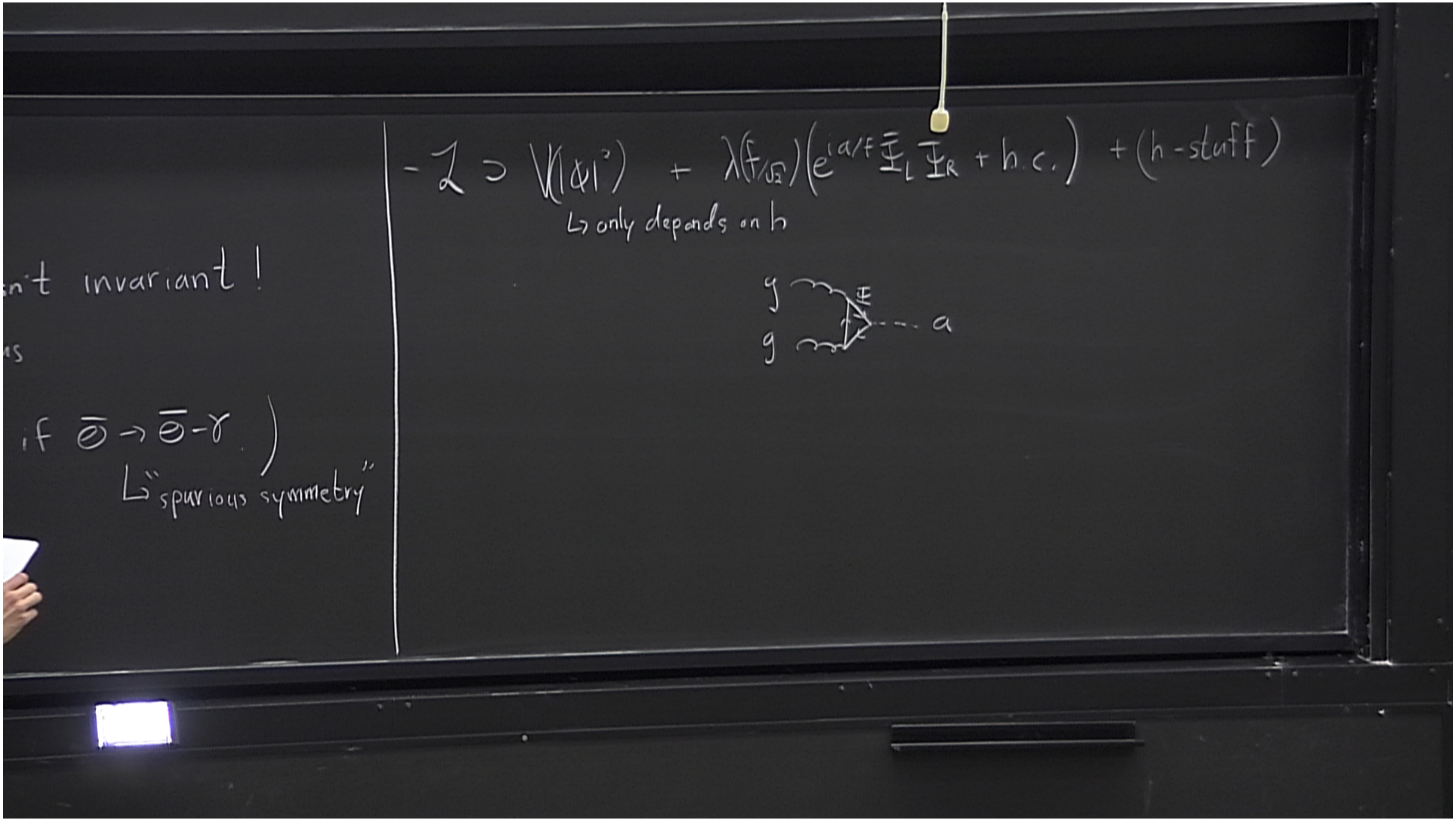
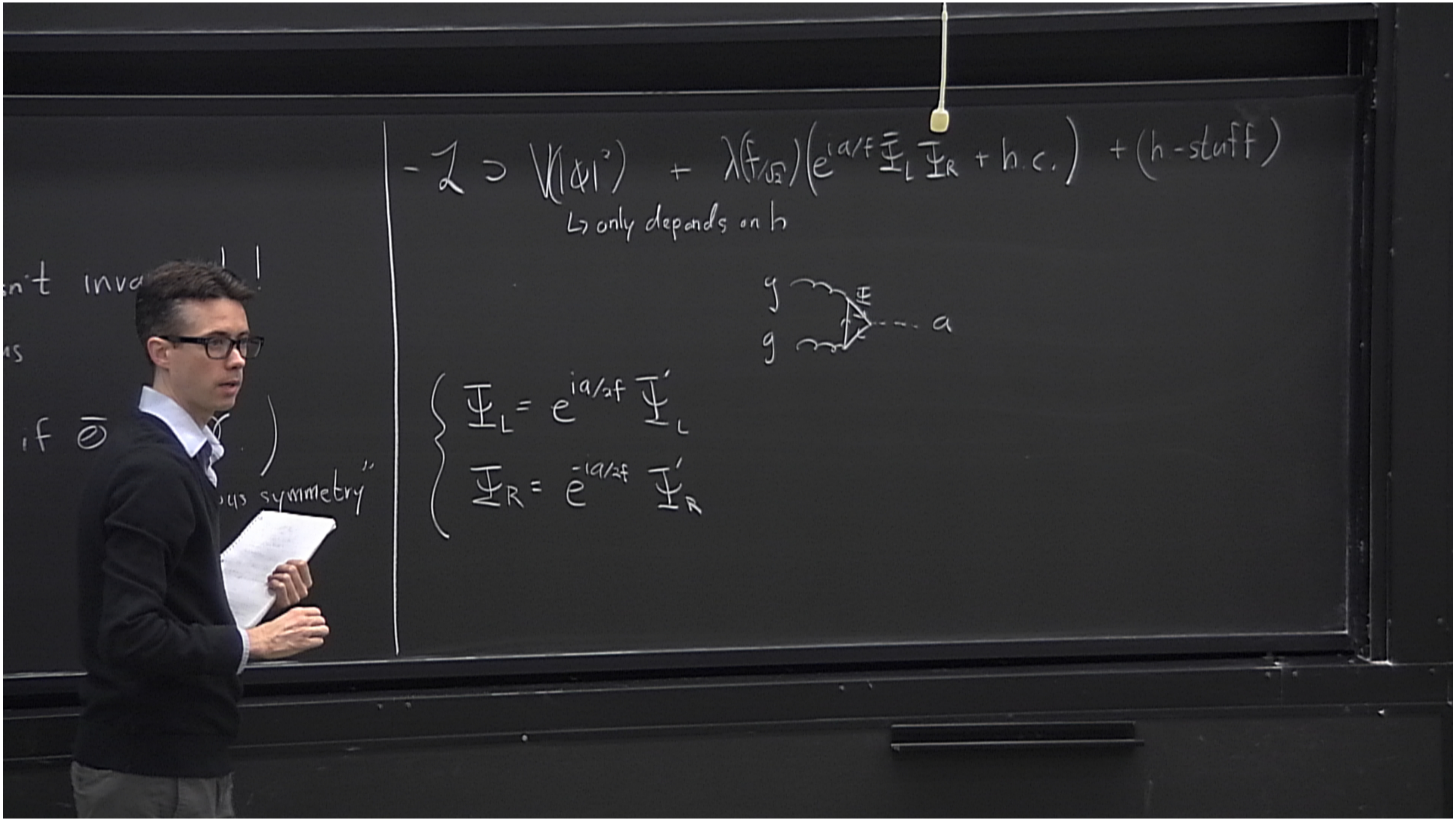
$\Phi_R \to e^{-i\gamma/2}\,\Phi_R$
$\phi \to e^{i\gamma}\,\phi$
$\Rightarrow \bar{\Theta} \to \bar{\Theta} + \gamma$
$\Rightarrow$ full Lagrangian isn't invariant!
$\Rightarrow$ symmetry is anomalous
(Would have a symmetry if $\bar{\Theta} \to \bar{\Theta} - \gamma$)

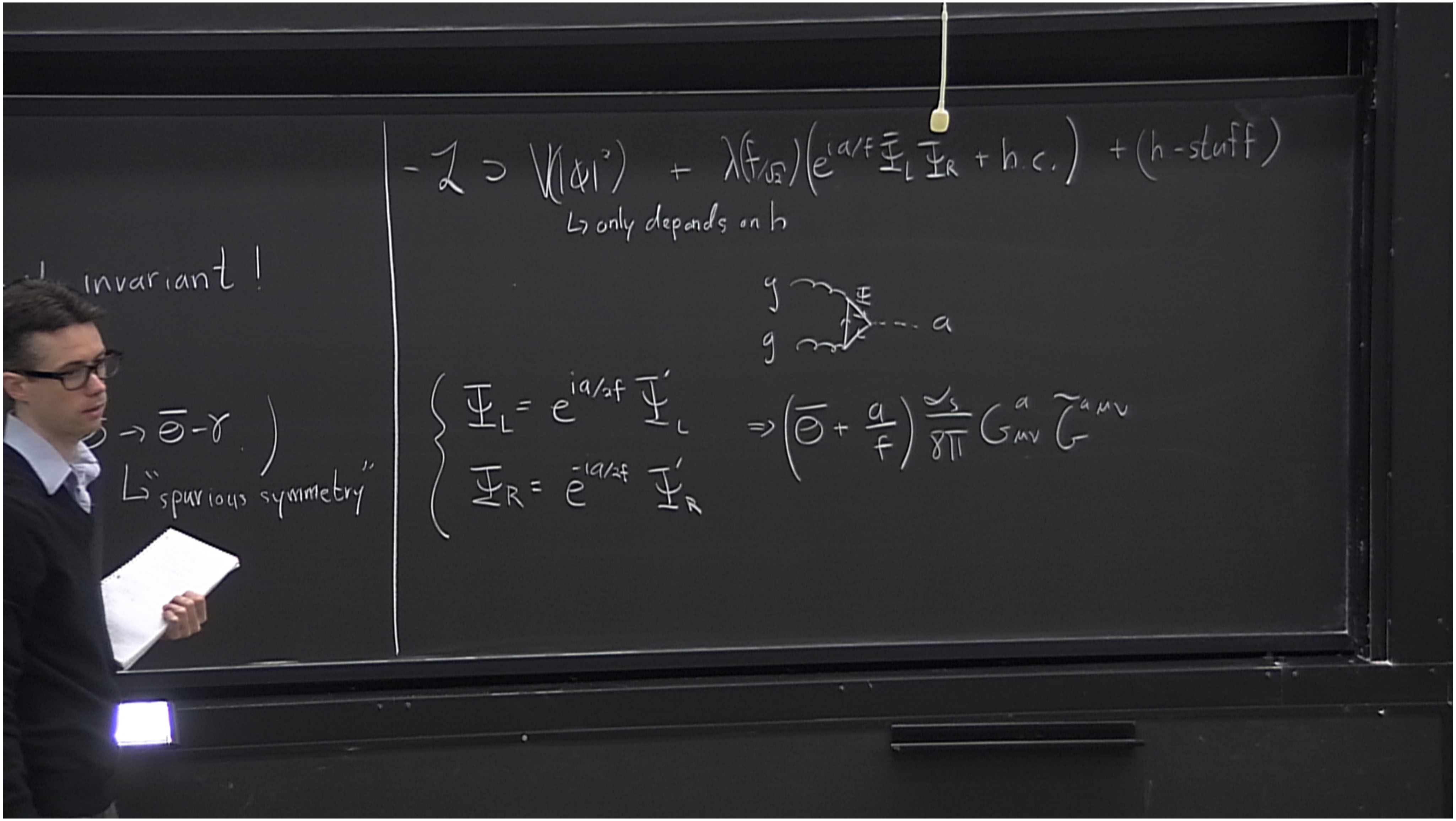

"symmetry"
Ψ_L → e^{iγ/2} Ψ_L
Ψ_R → e^{-iγ/2} Ψ_R
φ → e^{iγ} φ
⇒ θ̄ → θ̄ + γ
⇒ full Lagrangian isn't invariant!
⇒ symmetry is anomalous
(Would have a symmetry if θ̄ → θ̄ − γ)
↳ "spurious symmetry"


-L ⊃ V(|φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.)
↳ only depends on h
n't invariant !
if θ̄ → θ̄ - γ)
↳ "spurious symmetry"

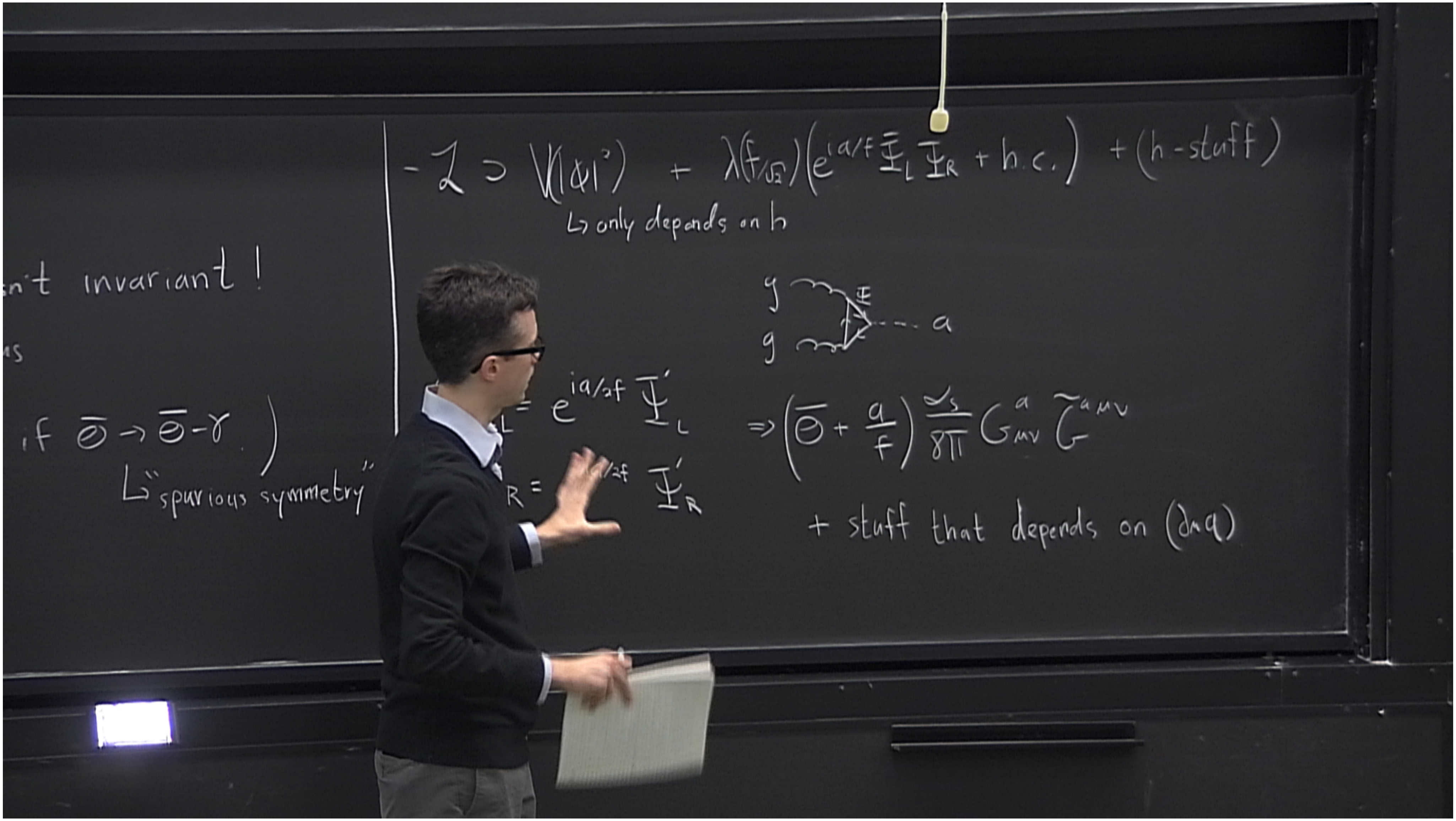

-L ⊃ V(|φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
invariant !
if θ̄ → θ̄ - γ
"spurious symmetry"


n't invariant !
if θ̄ → θ̄ − γ)
↳ "spurious symmetry"
−ℒ ⊃ V(|Φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
↳ only depends on h
g
g
Ψ
a


-L ⊃ V(|φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
↳ only depends on h
g
g
Ψ
a
Ψ_L = e^{ia/2f} Ψ'_L
Ψ_R = e^{-ia/2f} Ψ'_R
symmetry"



-ℒ ⊃ V(|Φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
↳ only depends on h
invariant !
→ θ̄ − γ)
↳ "spurious symmetry"
g g Ψ a
Ψ_L = e^{ia/2f} Ψ'_L
Ψ_R = e^{-ia/2f} Ψ'_R
⇒ (θ̄ + a/f) α_s/8π G^a_{μν} G̃^{aμν}


- L ⊃ V(|φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
↳ only depends on h
n't invariant!
if θ̄ → θ̄ - γ)
↳ "spurious symmetry"
g
g
Ψ
a
= e^{ia/2f} Ψ'_L
R =
Ψ'_R
⇒ (θ̄ + a/f) α_s/8π G^a_{μν} G̃^{aμν}
+ stuff that depends on (∂_μ a)

...n't invariant !

...s

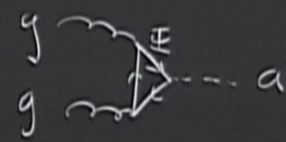
if $\bar{\theta} \to \bar{\theta} - \gamma$)

↳ "spurious symmetry"

$$-\mathcal{L} \supset V(|\phi|^2) + \lambda (f/\sqrt{2}) \left(e^{ia/f} \Psi_L \Psi_R + h.c. \right) + (h\text{-stuff})$$

↳ only depends on h

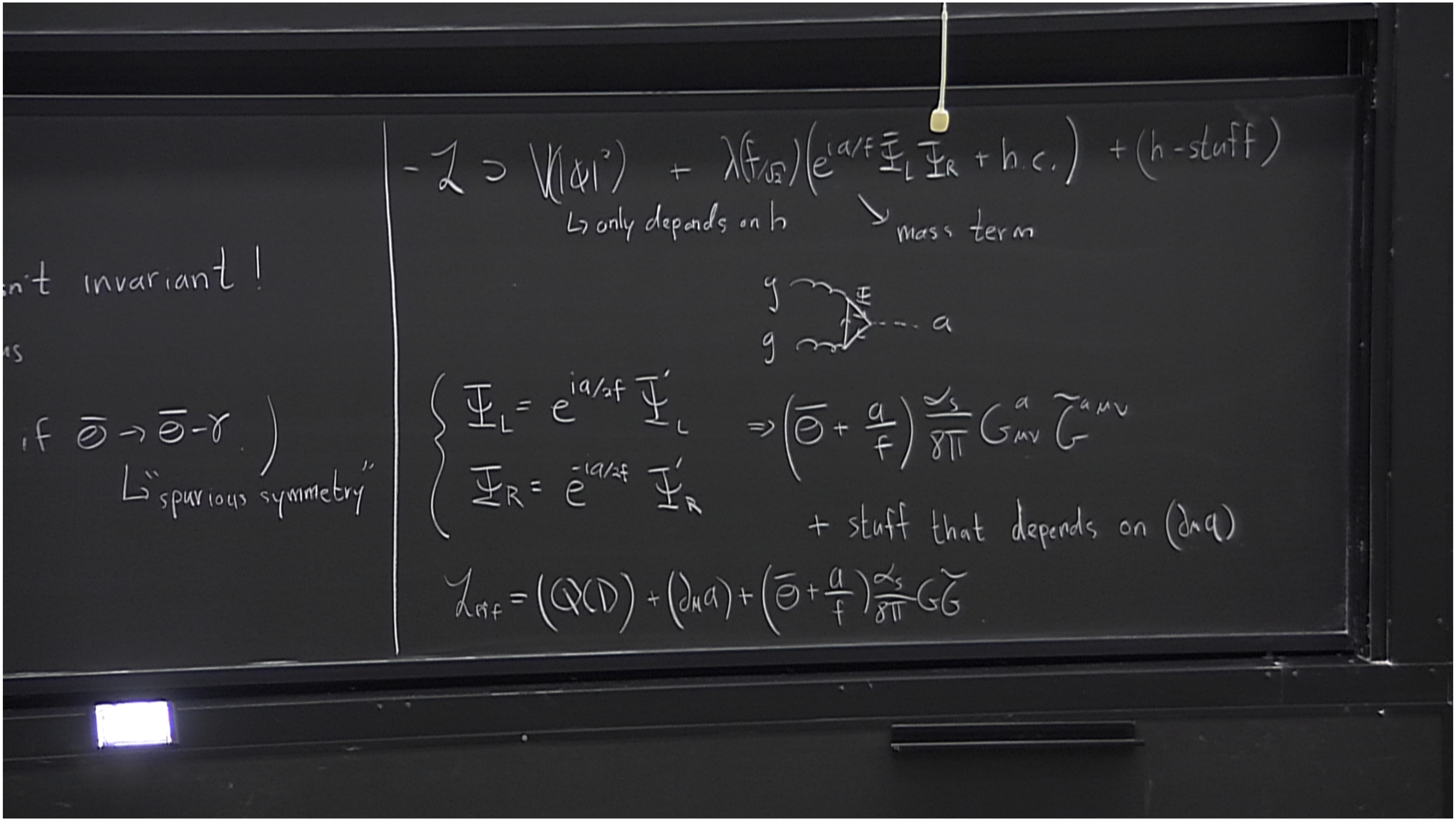
↘ mass term

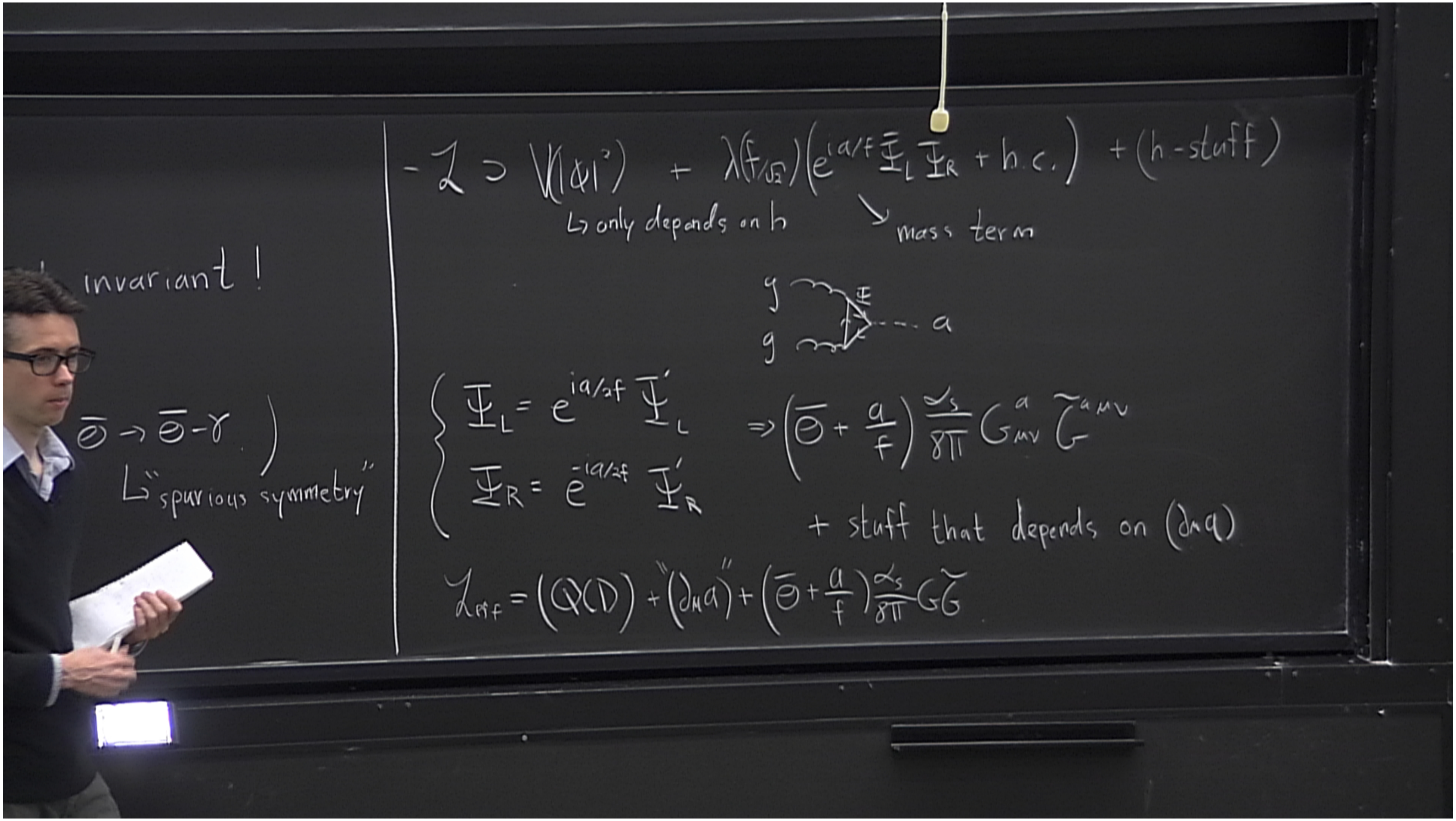


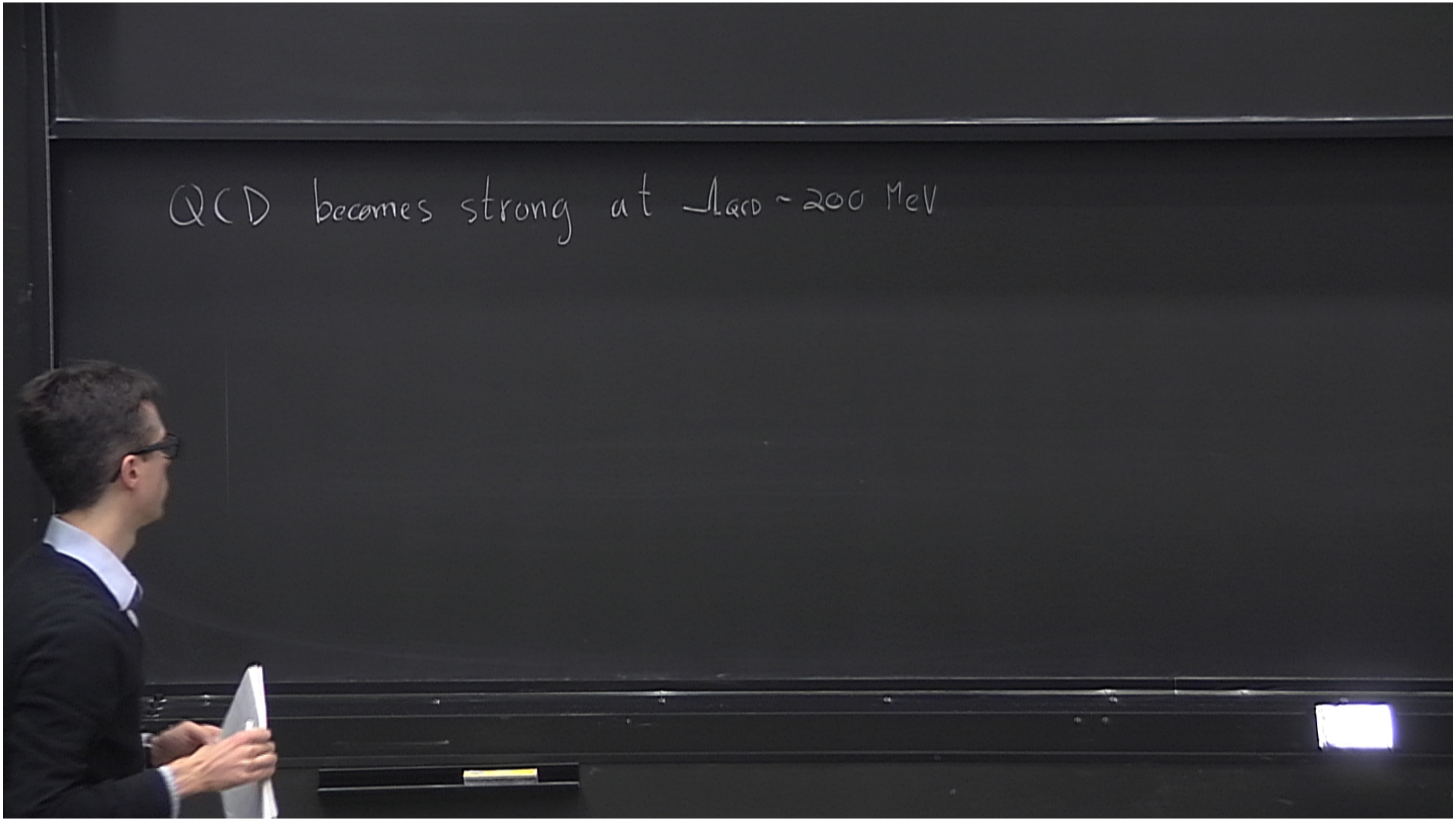
$$\begin{cases} \Psi_L = e^{ia/2f} \Psi'_L \\ \Psi_R = e^{-ia/2f} \Psi'_R \end{cases}$$

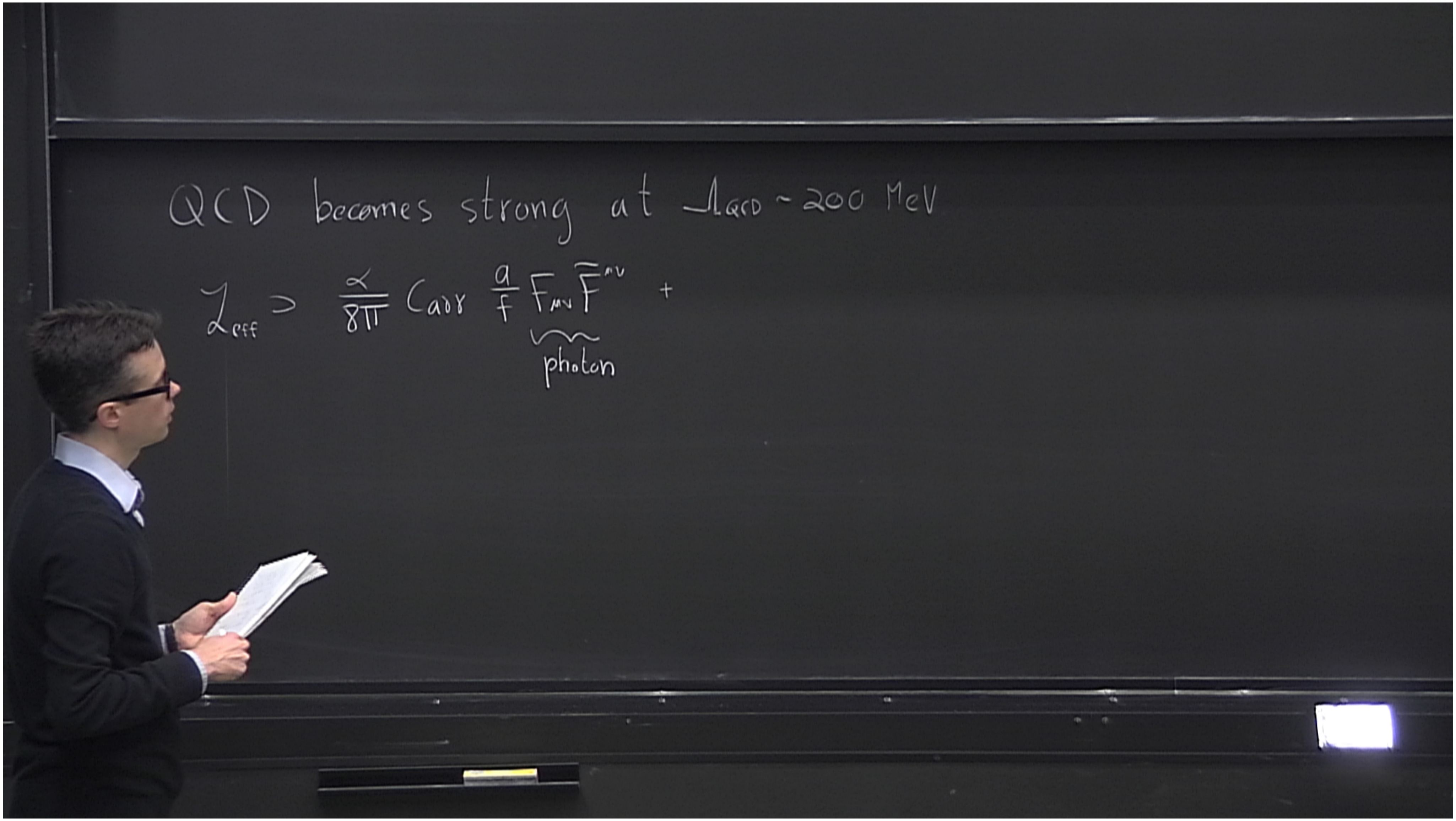
$$\Rightarrow \left(\bar{\theta} + \frac{a}{f} \right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

+ stuff that depends on $(\partial_\mu a)$


$-\mathcal{L} \supset V(|\Phi|^2) + \lambda(f/\sqrt{2})(e^{ia/f}\Psi_L \Psi_R + h.c.) + (h\text{-stuff})$
↳ only depends on h
mass term
n't invariant !
ns
if $\bar{\theta} \to \bar{\theta} - \gamma$)
↳ "spurious symmetry"
g
g
Ψ
a
$\Psi_L = e^{ia/2f}\,\Psi'_L$
$\Psi_R = e^{-ia/2f}\,\Psi'_R$
$\Rightarrow \left(\bar{\theta} + \frac{a}{f}\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$
+ stuff that depends on $(\partial_\mu a)$
$\mathcal{L}_{eff} = (QCD) + (\partial_\mu a) + \left(\bar{\theta} + \frac{a}{f}\right)\frac{\alpha_s}{8\pi} G\tilde{G}$

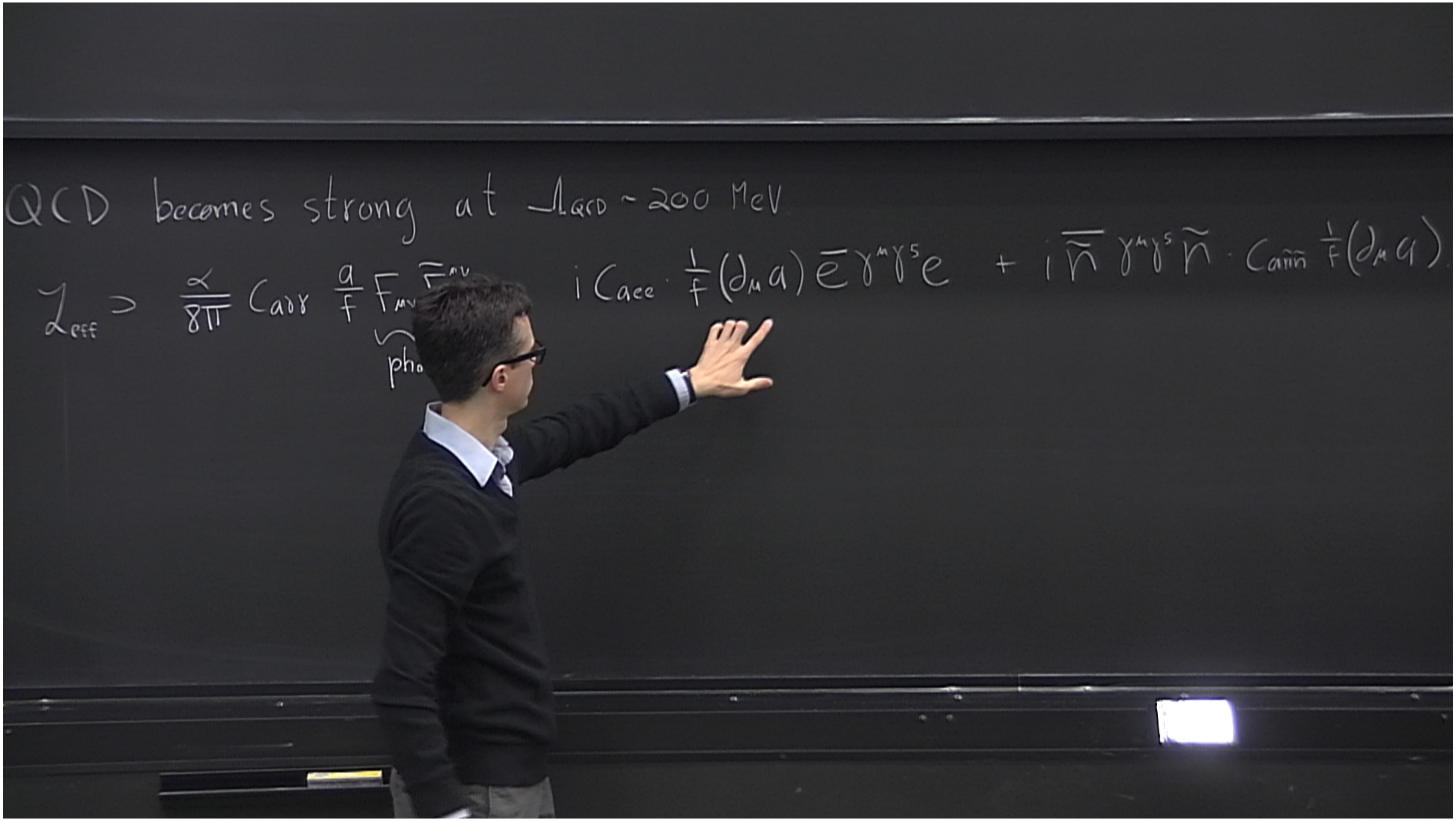

invariant !
θ̄ → θ̄ − γ
"spurious symmetry"
− L ⊃ V(|Φ|²) + λ(f/√2)(e^{ia/f} Ψ_L Ψ_R + h.c.) + (h-stuff)
only depends on h
mass term
g
g
a
Ψ_L = e^{ia/2f} Ψ'_L
Ψ_R = e^{−ia/2f} Ψ'_R
⇒ (θ̄ + a/f) α_s/8π G^a_{μν} G̃^{aμν}
+ stuff that depends on (∂_μ a)
L_eff = (QCD) + "(∂_μ a)" + (θ̄ + a/f) α_s/8π G G̃

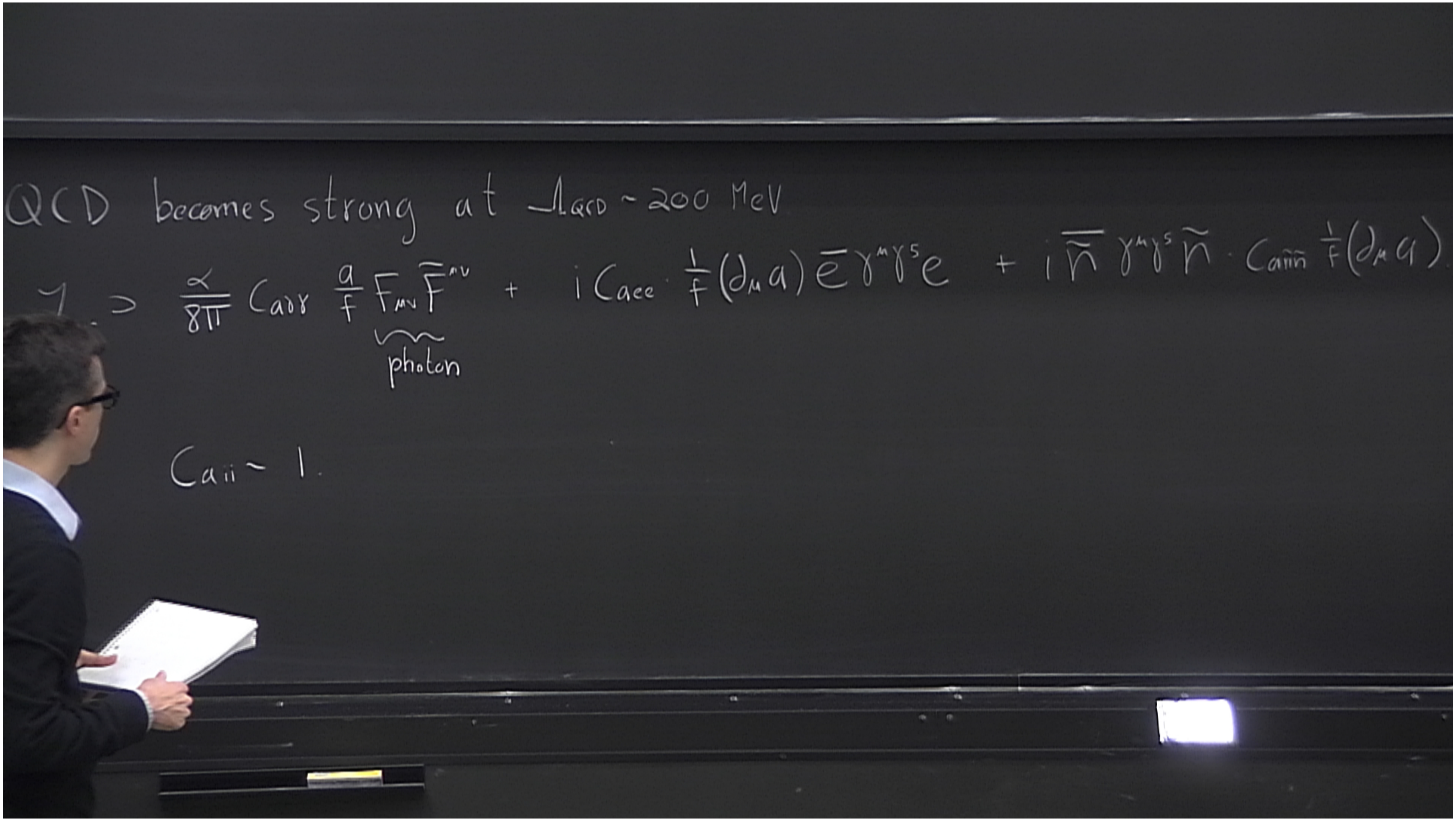

QCD becomes strong at $\Lambda_{QCD} \sim 200$ MeV


QCD becomes strong at $\Lambda_{QCD} \sim 200$ MeV
$\mathcal{L}_{eff} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} +$
photon

QCD becomes strong at $\Lambda_{QCD} \sim 200$ MeV

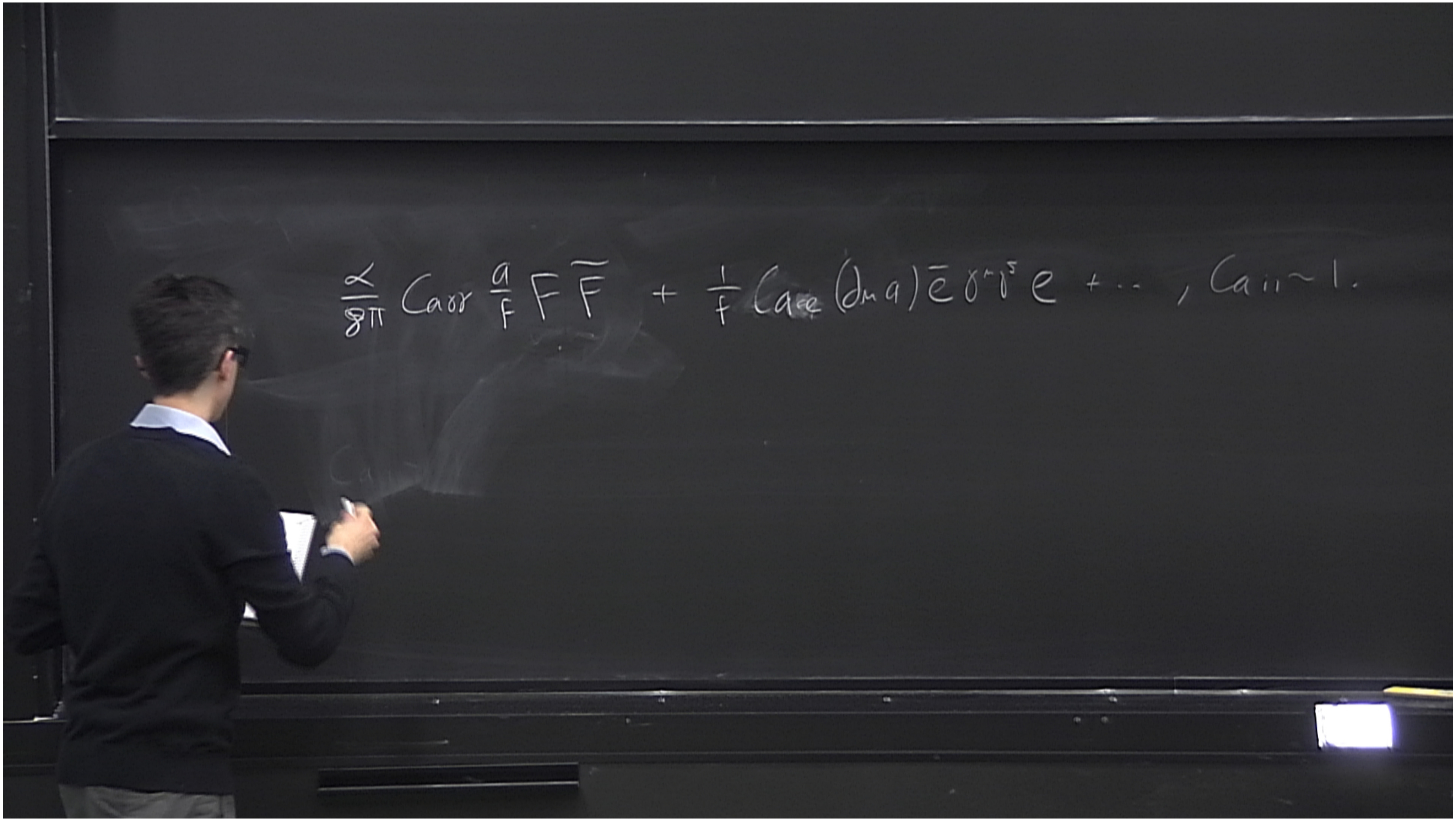
$$\mathcal{L}_{eff} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} \underbrace{F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{photon}} + i C_{aee} \frac{1}{f}(\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e + i\bar{\tilde{n}}\gamma^\mu\gamma^5\tilde{n} \cdot C_{a\tilde{n}\tilde{n}} \frac{1}{f}(\partial_\mu a)$$

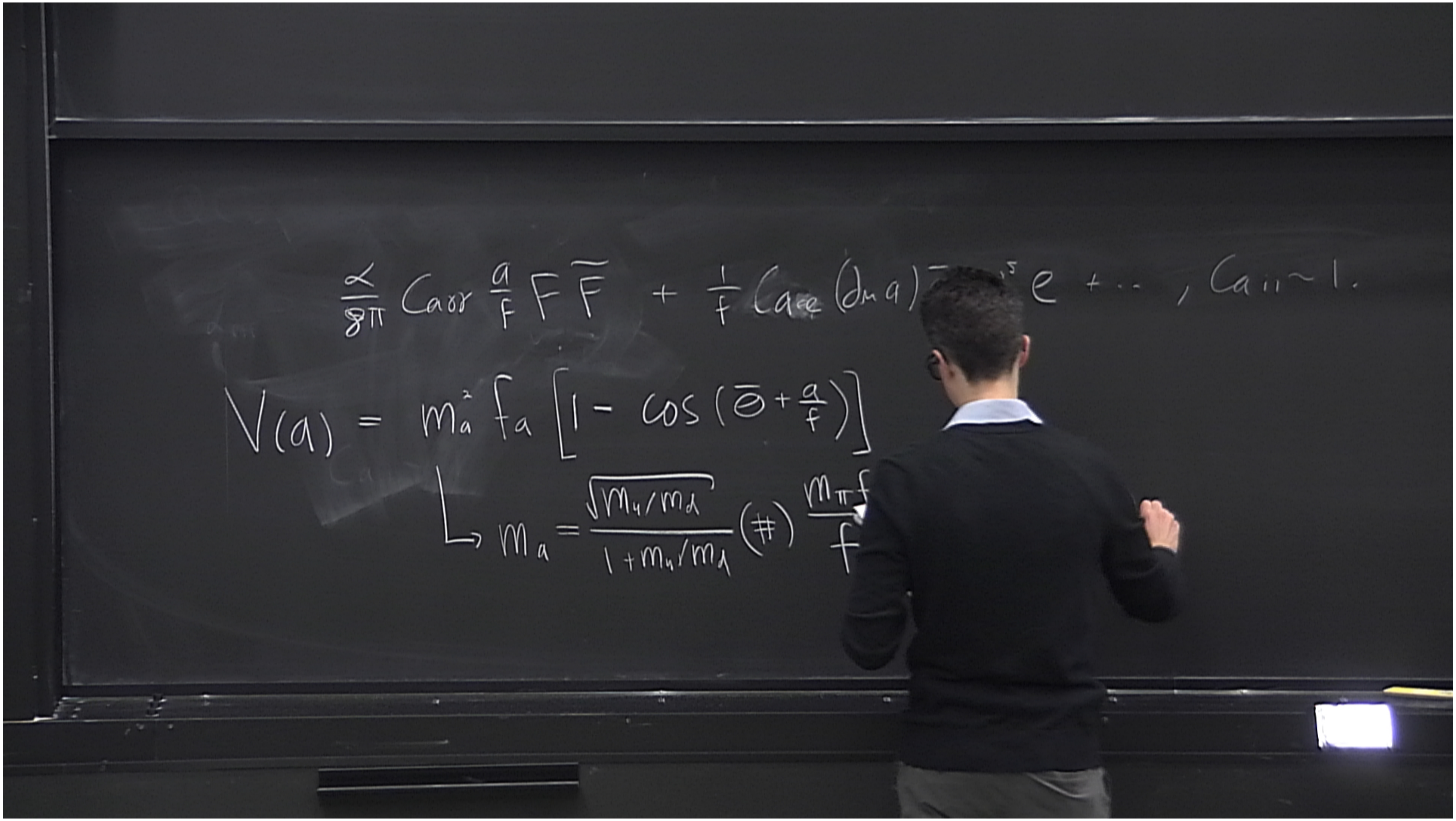

QCD becomes strong at $\Lambda_{QCD} \sim 200$ MeV
$\mathcal{L}_{eff} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F_{\mu\nu}$
$i C_{aee} \cdot \frac{1}{f} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e + i \bar{\tilde{n}} \gamma^\mu \gamma^5 \tilde{n} \cdot C_{a\tilde{n}\tilde{n}} \frac{1}{f} (\partial_\mu a)$

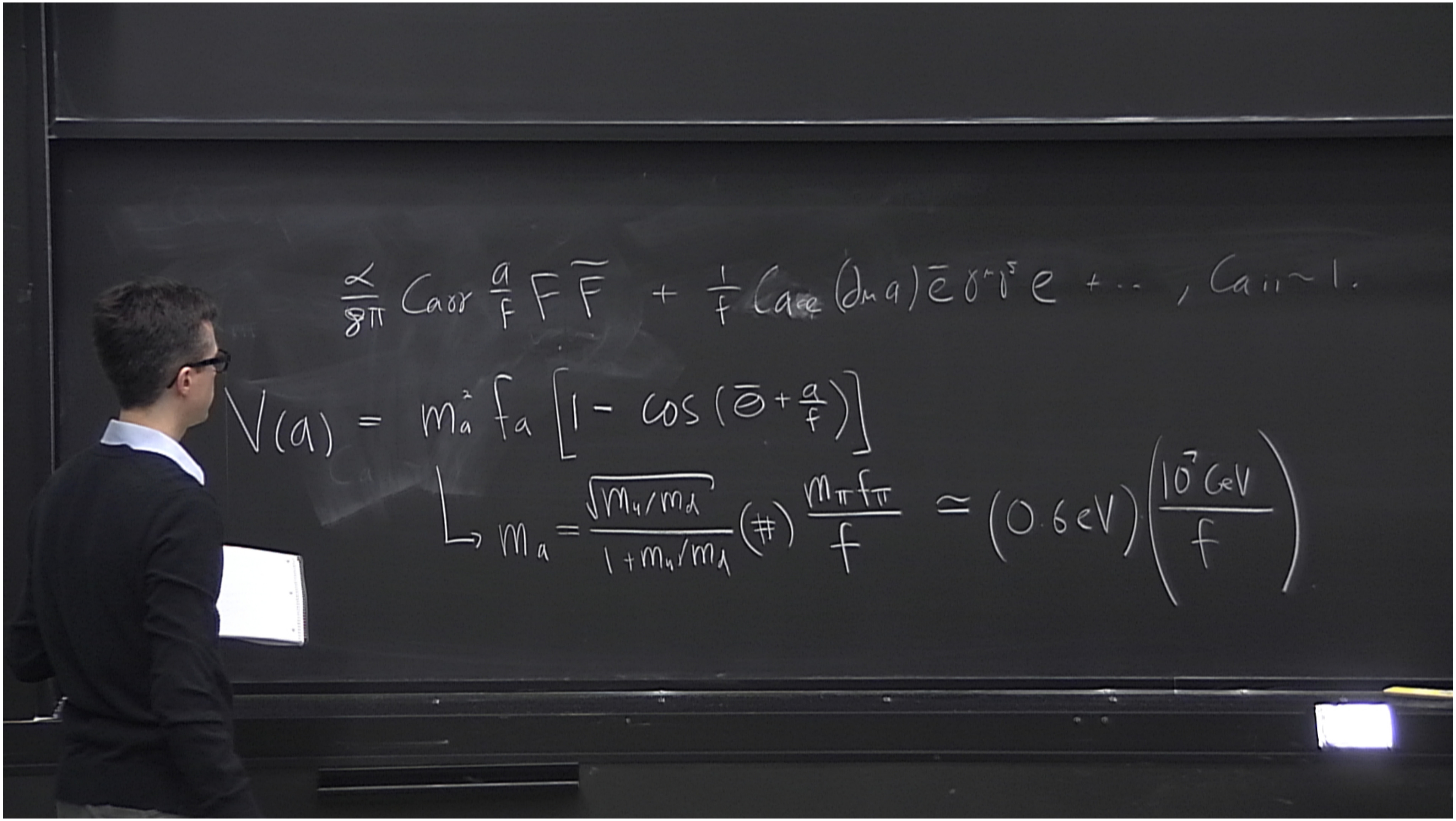

QCD becomes strong at $\Lambda_{QCD} \sim 200$ MeV
$\mathcal{L} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu} + i C_{aee} \frac{1}{f}(\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e + i\bar{\tilde{n}}\gamma^\mu\gamma^5\tilde{n} \cdot C_{a\tilde{n}\tilde{n}} \frac{1}{f}(\partial_\mu a)$
photon
$C_{aii} \sim 1.$

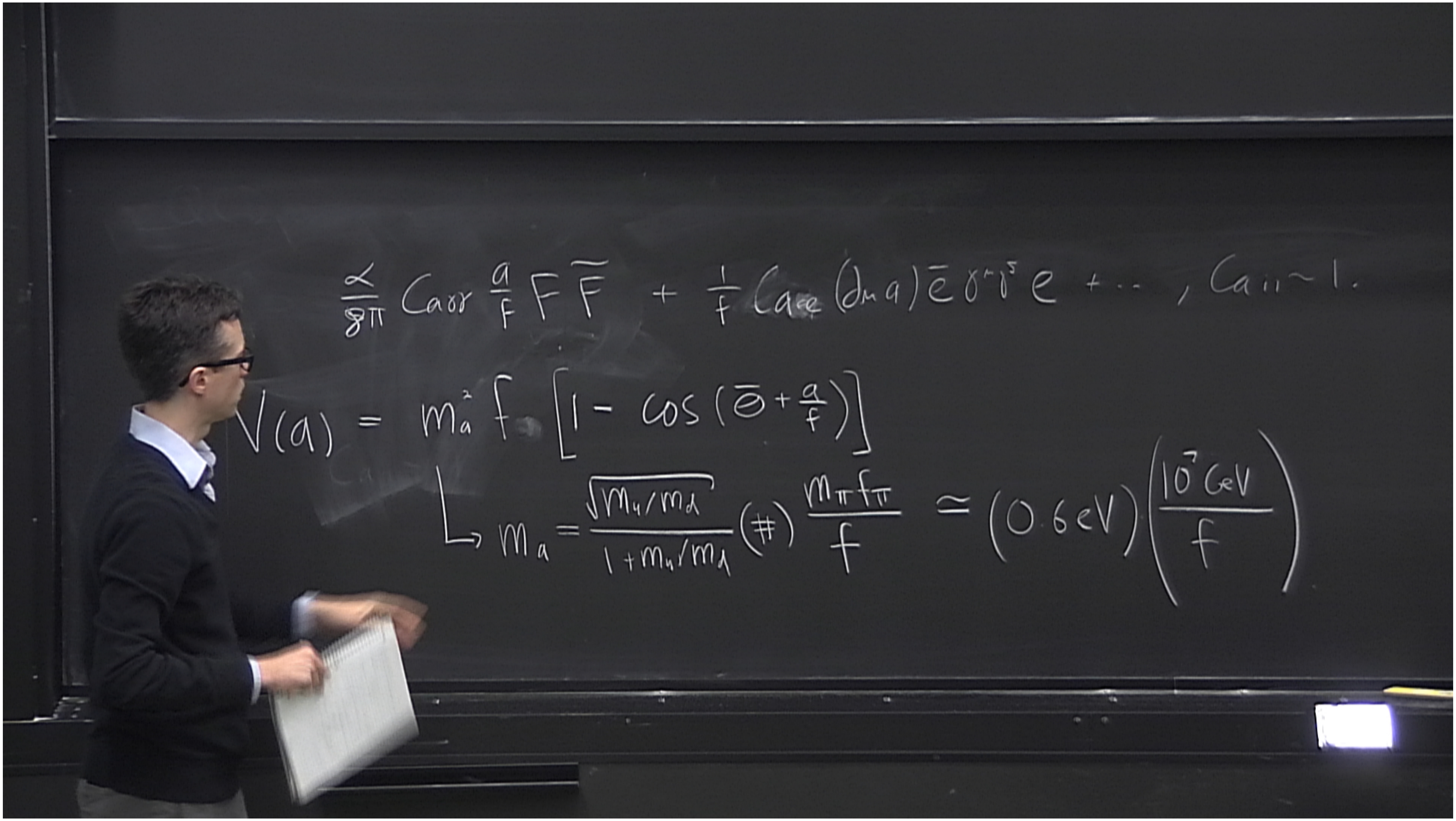
$$\mathcal{L}_{eff} = \text{"}(QCD)\text{"} + \text{"}(\partial_\mu a)\text{"} + \left(\bar{\Theta} + \frac{a}{f}\right)\frac{\alpha_s}{8\pi} G\tilde{G}$$

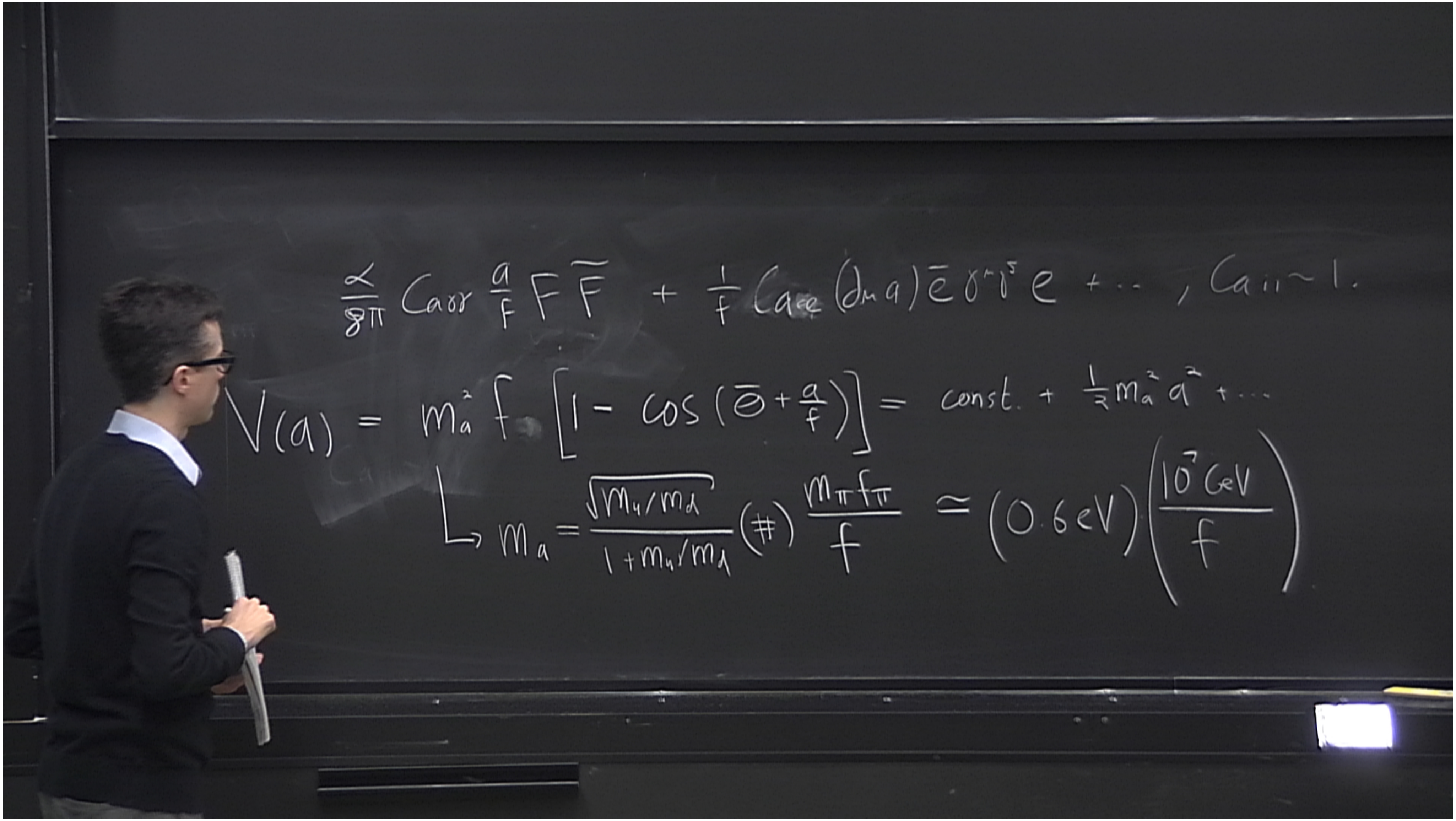
$$\bar{\tilde{n}}\, \gamma^\mu \gamma^5 \tilde{n} \cdot C_{a\tilde{n}\tilde{n}} \frac{1}{f}(\partial_\mu a) \quad , \quad C_{a..} \sim 1$$


$\frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e + \ldots, \quad C_{aii} \sim 1.$


α/8π Caγγ a/f F F̃ + 1/f Caee (∂μ a)
e + … , Ca.. ~ 1.
V(a) = ma² fa [1 − cos(θ̄ + a/f)]
ma = √(mu/md) / (1 + mu/md) (#) mπ f / f


$\frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e + \ldots , \quad C_{a ii} \sim 1.$
$V(a) = m_a^2 f_a \left[1 - \cos(\bar{\theta} + \frac{a}{f})\right]$
$\hookrightarrow m_a = \frac{\sqrt{m_u/m_d}}{1 + m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,eV) \left(\frac{10^7\,GeV}{f}\right)$


$\frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e + \dots , \quad C_{a ii} \sim 1.$
$V(a) = m_a^2 f^2 \left[1 - \cos\left(\bar{\theta} + \frac{a}{f}\right)\right]$
$m_a = \frac{\sqrt{m_u/m_d}}{1 + m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,\text{eV}) \left(\frac{10^7\,\text{GeV}}{f}\right)$


$\frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e + \dots , C_{aii} \sim 1.$
$V(a) = m_a^2 f \left[1 - \cos(\bar{\theta} + \frac{a}{f})\right] = \text{const.} + \frac{1}{2} m_a^2 a^2 + \dots$
$\hookrightarrow m_a = \frac{\sqrt{m_u/m_d}}{1+m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,\text{eV}) \left(\frac{10^7\,\text{GeV}}{f}\right)$

$$\mathcal{L}_{eff} = \left(Q(D)\right) + "(\partial_\mu a)" + \left(\bar{\Theta} + \frac{a}{f}\right)\frac{\alpha_s}{8\pi} G\tilde{G}$$

$a_{ii} \sim 1.$

...

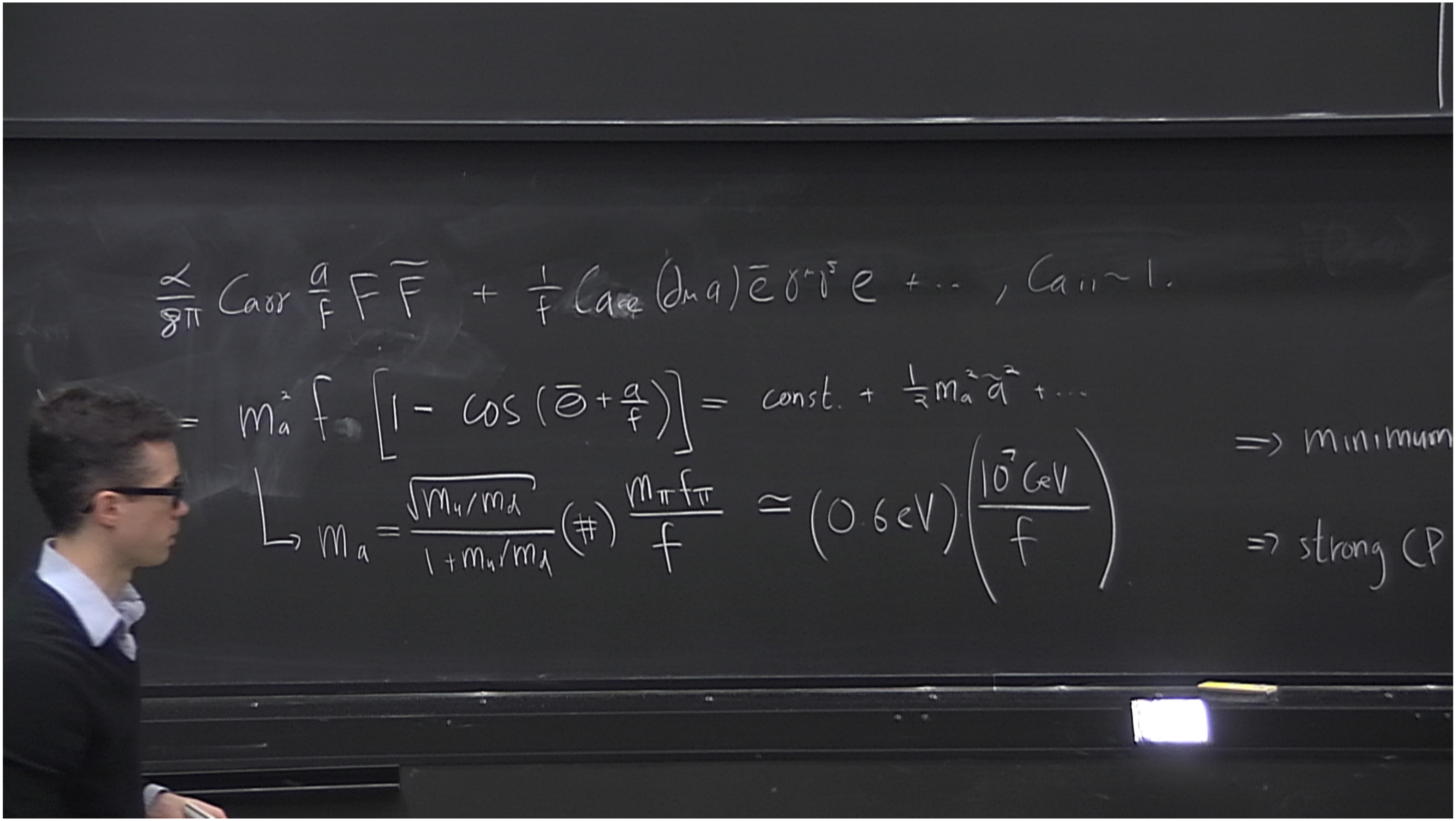
eV

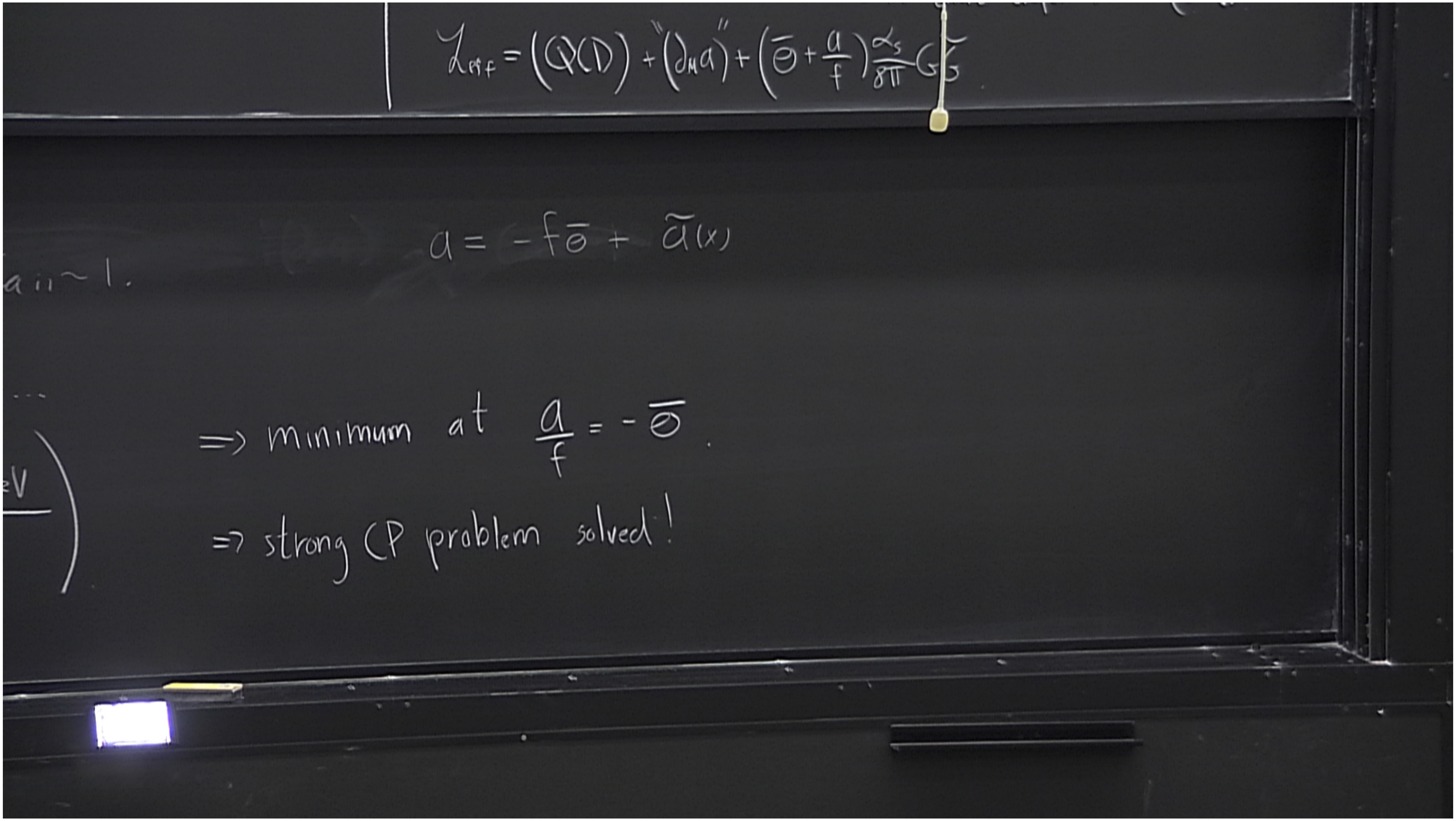
$\Rightarrow$ minimum at $\frac{a}{f} = -\bar{\Theta}$.

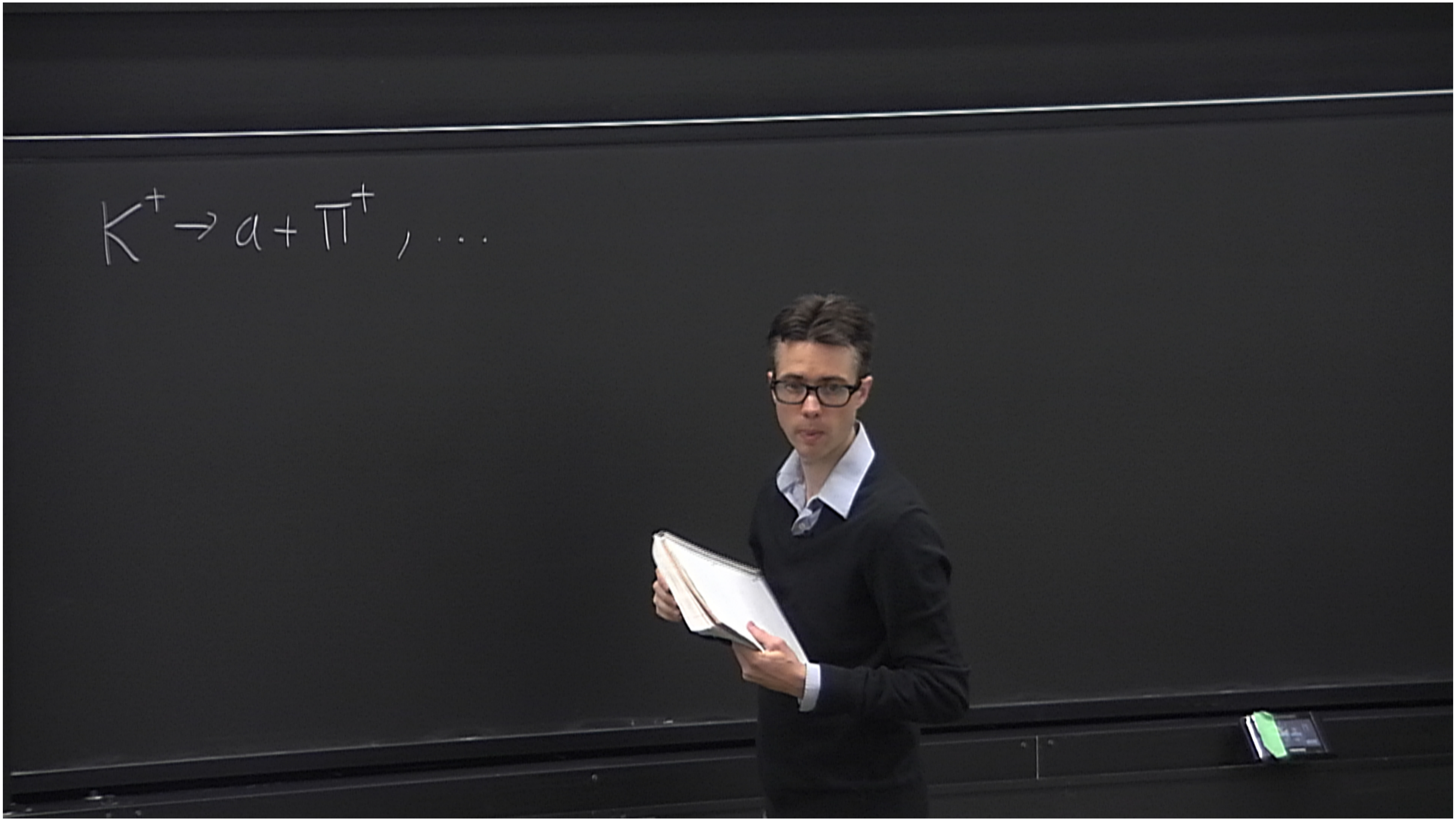
$$\mathcal{L}_{eff} = (QCD) + \text{"}(\partial_\mu a)\text{"} + \left(\bar{\theta} + \frac{a}{f}\right)\frac{\alpha_s}{8\pi} G\tilde{G}$$

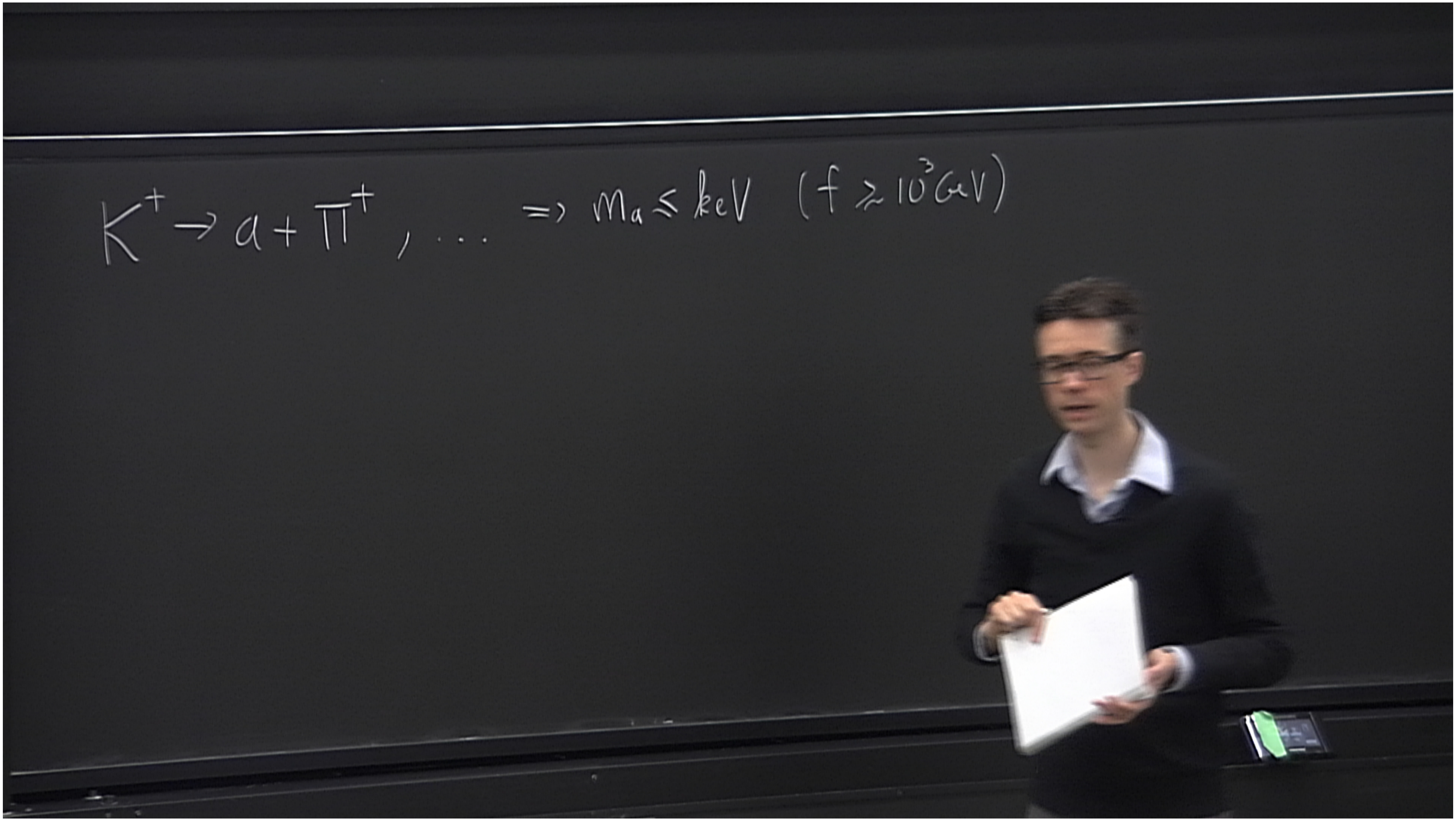
$$a = -f\bar{\theta} + \tilde{a}(x)$$

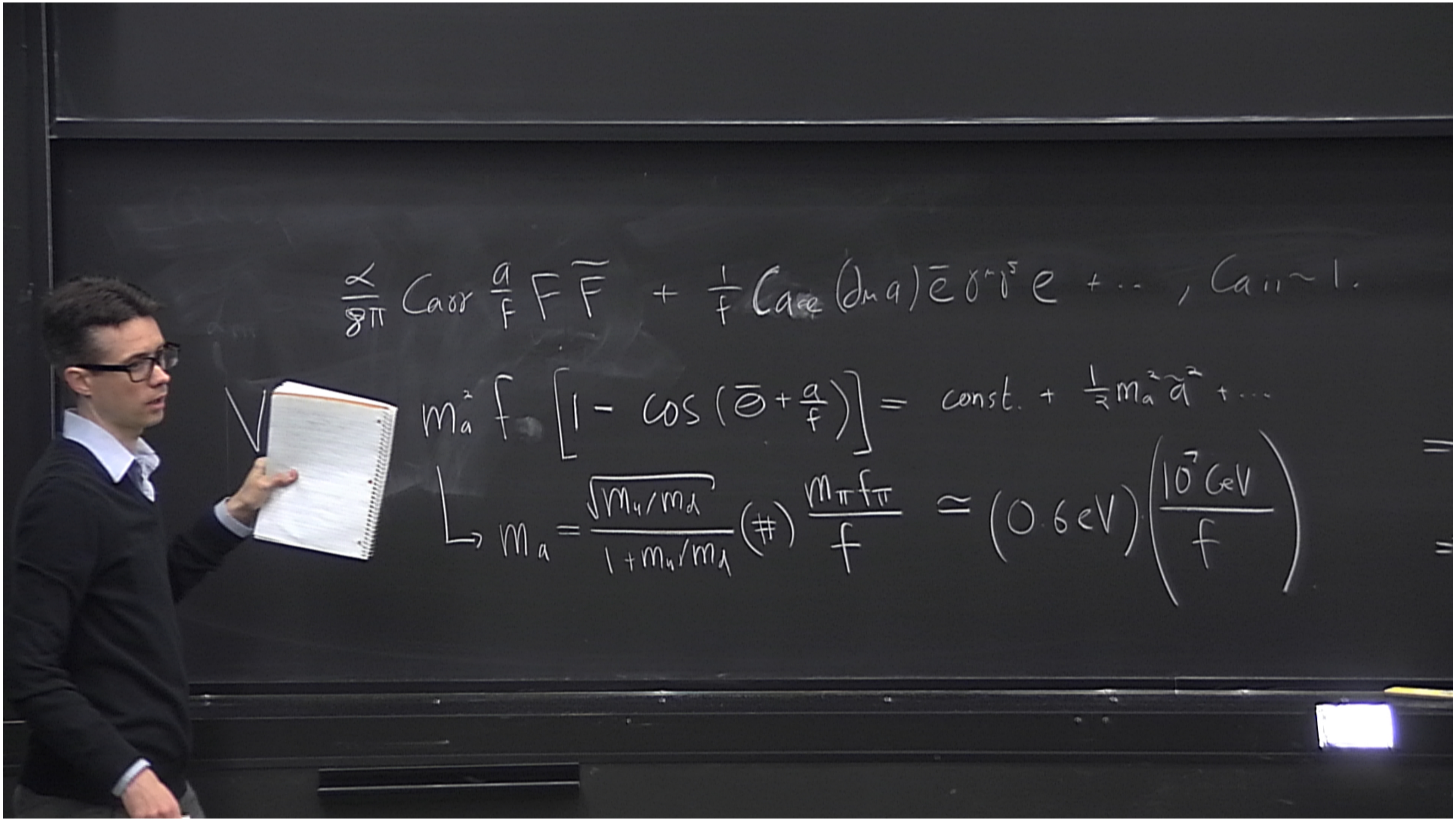
$\Rightarrow$ minimum at $\frac{a}{f} = -\bar{\theta}$.


$\frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e + \dots , \quad C_{aii} \sim 1.$
$= m_a^2 f^2 \left[1 - \cos(\bar{\theta} + \frac{a}{f})\right] = \text{const.} + \frac{1}{2} m_a^2 a^2 + \dots$
$\hookrightarrow m_a = \frac{\sqrt{m_u/m_d}}{1 + m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,\text{eV}) \left(\frac{10^7\,\text{GeV}}{f}\right)$
⇒ minimum
⇒ strong CP


$\mathcal{L}_{eff} = (QCD) + "(\partial_\mu a)" + (\bar{\theta} + \frac{a}{f})\frac{\alpha_s}{8\pi} G\tilde{G}$
$a = -f\bar{\theta} + \tilde{a}(x)$
$a_{ii} \sim 1.$
$\Rightarrow$ minimum at $\frac{a}{f} = -\bar{\theta}$.
$\Rightarrow$ strong CP problem solved!


K+ → a + π+ , . . .


K+ → a + π+ , . . . ⇒ ma ≲ keV (f ≳ 10³ GeV)


α/8π C_aγγ a/f F F̃ + 1/f C_aee (∂_μ a) ē γ^μ γ^5 e + . . . , C_a.. ~ 1.
V m_a^2 f [1 - cos(θ̄ + a/f)] = const. + 1/2 m_a^2 a^2 + . . .
m_a = √(m_u/m_d) / (1 + m_u/m_d) (#) m_π f_π / f ≃ (0.6 eV) (10^7 GeV / f)

$$\mathcal{L}_{eff} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} \overbrace{F\tilde{F}}^{\partial_\mu K^\mu} + \frac{1}{f} C_{aee} (\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e + \dots, \quad C_{aii} \sim 1.$$

$$V(a) = m_a^2 f \left[1 - \cos\left(\bar{\theta} + \frac{a}{f}\right)\right] = \text{const.} + \frac{1}{2} m_a^2 \tilde{a}^2 + \dots$$

$$\hookrightarrow m_a = \frac{\sqrt{m_u/m_d}}{1 + m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,\text{eV}) \left(\frac{10^7\,\text{GeV}}{f}\right)$$

$K^+ \to a + \pi^+, \ldots \Rightarrow m_a \lesssim \text{keV} \quad (f \gtrsim 10^3\,\text{GeV})$

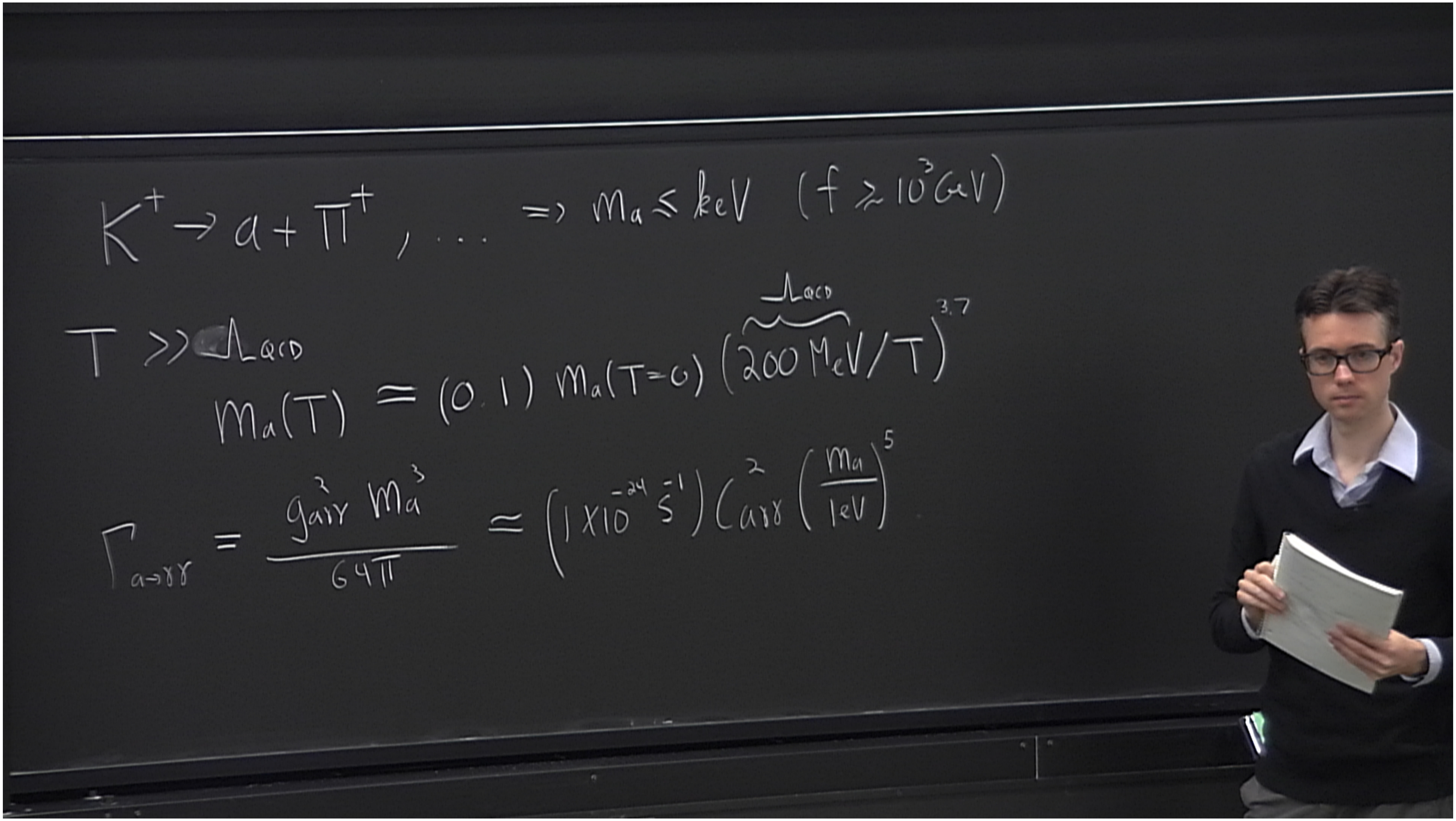
$T \gg \Lambda_{QCD}$

$$m_a(T) \simeq (0.1)\, m_a(T=0) \Big(\underbrace{200\,\text{MeV}}_{\Lambda_{QCD}}/T\Big)^{3.7}$$

$$\mathcal{L}_{eff} \supset \overbrace{\frac{\alpha}{8\pi} C_{a\gamma\gamma}}^{g_{a\gamma\gamma}} \frac{a}{f} \overbrace{F\tilde{F}}^{\partial_\mu K^\mu} + \frac{1}{f} C_{aee} (\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e + \dots, \quad C_{aii} \sim 1.$$

$$V(a) = m_a^2 f \left[1 - \cos\left(\bar{\theta} + \frac{a}{f}\right)\right] = \text{const.} + \frac{1}{2} m_a^2 a^2 + \dots =$$

$$\hookrightarrow m_a = \frac{\sqrt{m_u/m_d}}{1+m_u/m_d} (\#) \frac{m_\pi f_\pi}{f} \simeq (0.6\,\text{eV})\left(\frac{10^7\,\text{GeV}}{f}\right)$$


$K^+ \to a + \pi^+ , \ldots \Rightarrow m_a \lesssim \text{keV} \quad (f \gtrsim 10^3 \text{GeV})$
$T \gg \Lambda_{QCD}$
$m_a(T) \simeq (0.1)\, m_a(T=0) \left(\overbrace{200\,\text{MeV}}^{\Lambda_{QCD}}/T\right)^{3.7}$
$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} \simeq (1\times10^{-24}\,\text{s}^{-1})\, C_{a\gamma\gamma}^2 \left(\frac{m_a}{1\text{eV}}\right)^5$

$$g_{a\gamma\gamma} \qquad \partial_\mu K^\mu = a F\tilde{F}\, g_{a\gamma\gamma}$$

$$\mathcal{L}_{\rm eff} \supset \frac{\alpha}{8\pi} C_{a\gamma\gamma} \frac{a}{f} F\tilde{F} + \frac{1}{f} C_{aee} (\partial_\mu a)\, \bar{e}\gamma^\mu\gamma^5 e + \dots, \quad C_{aii} \sim 1.$$

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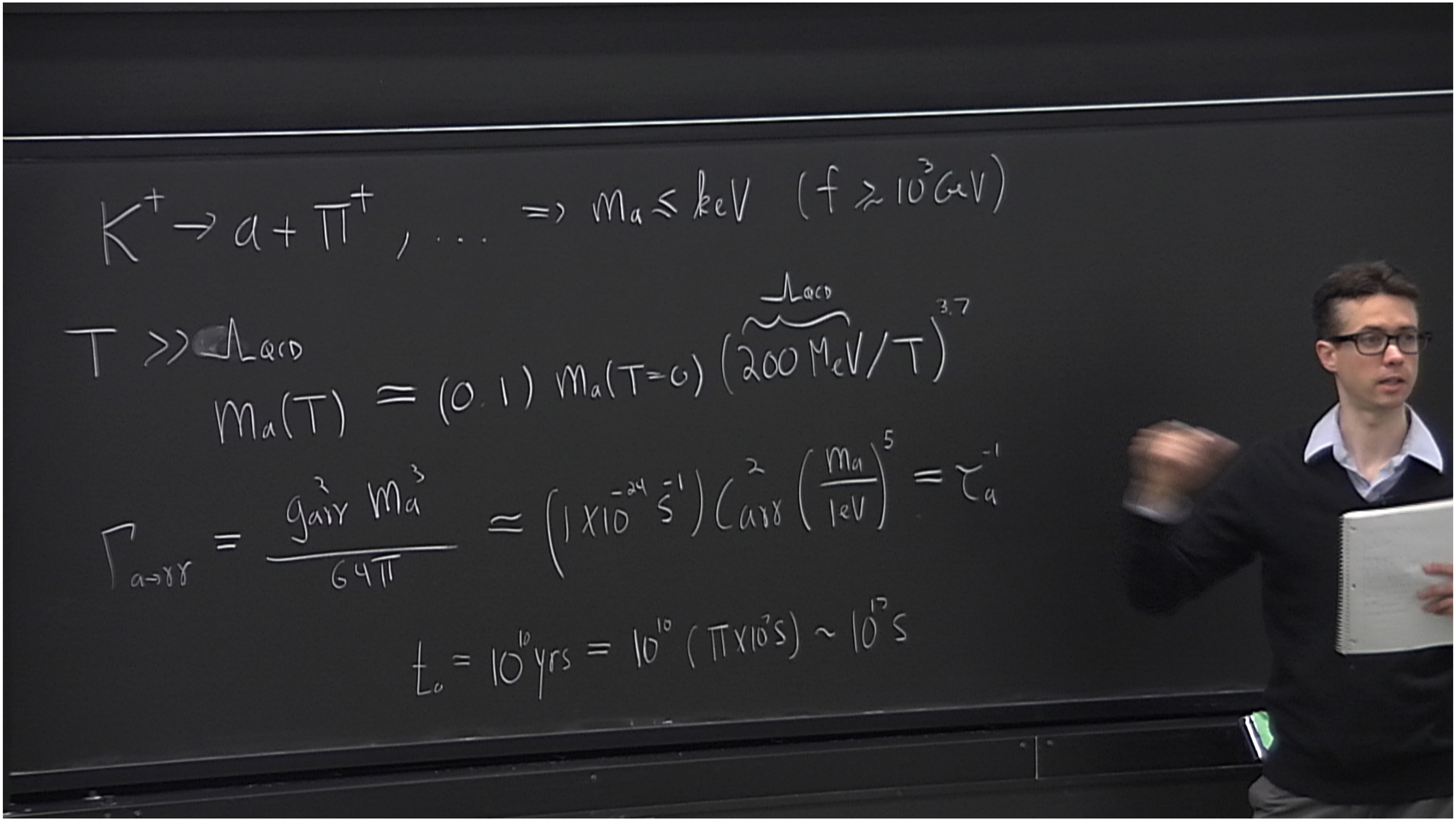
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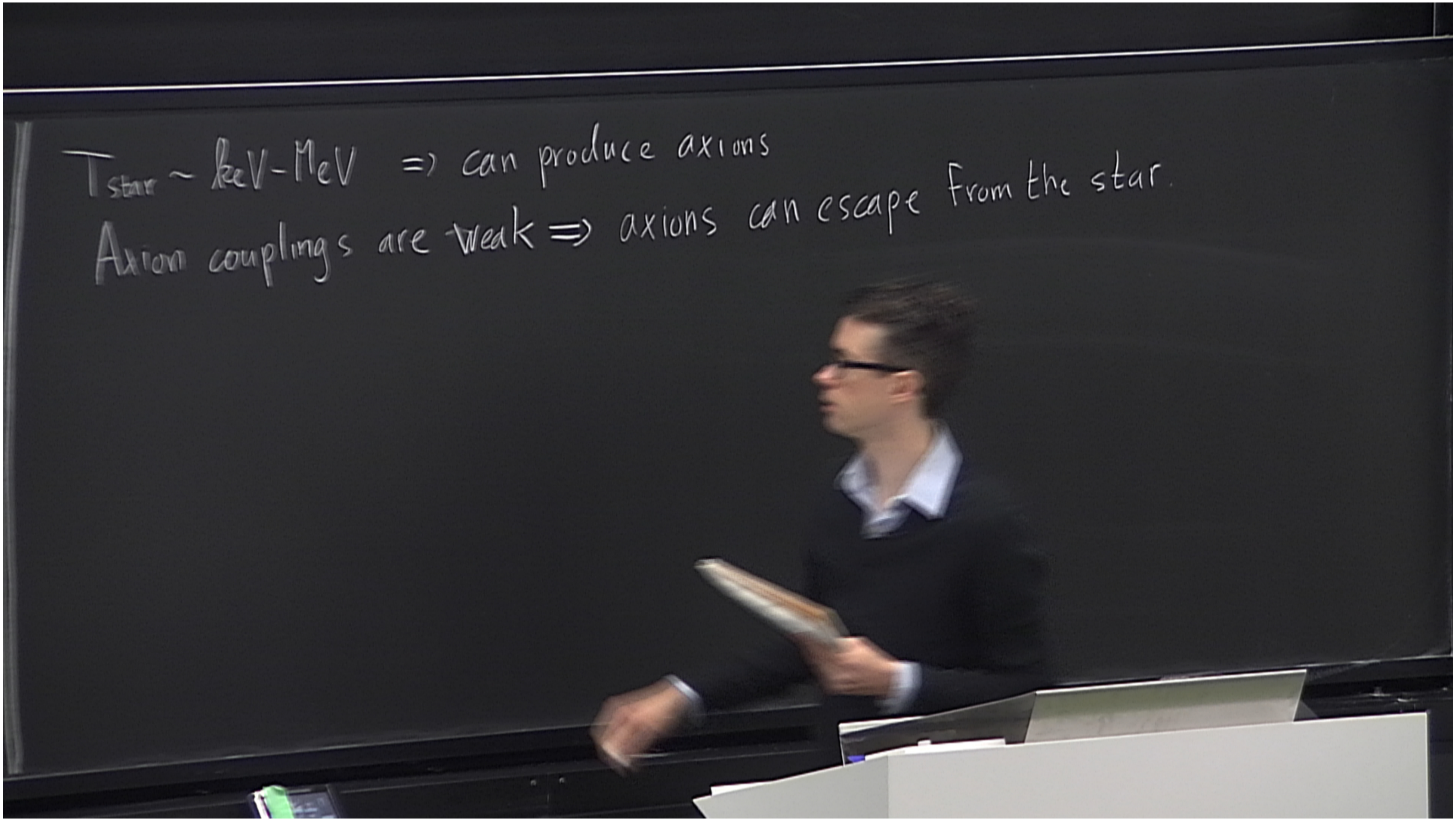
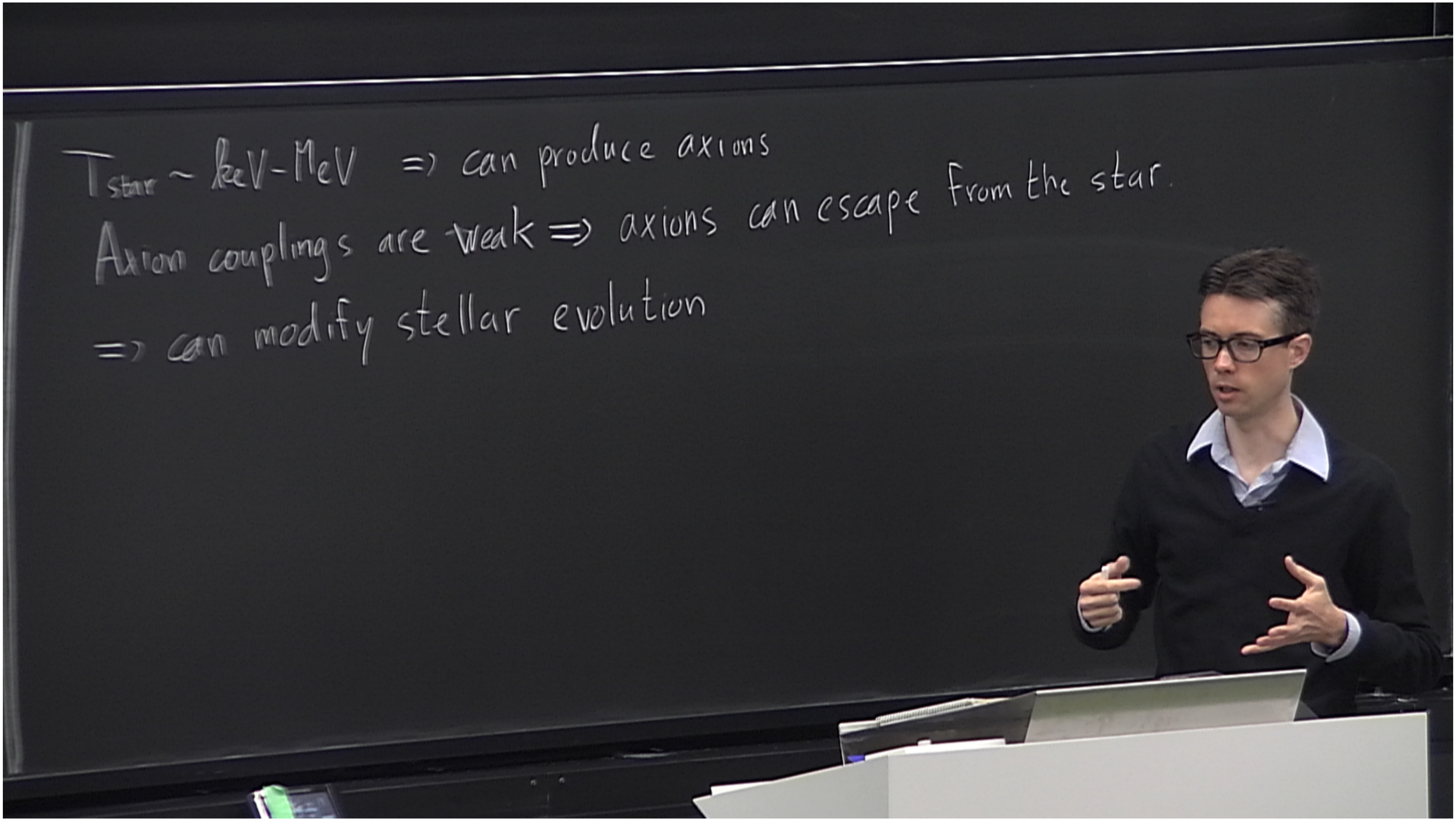
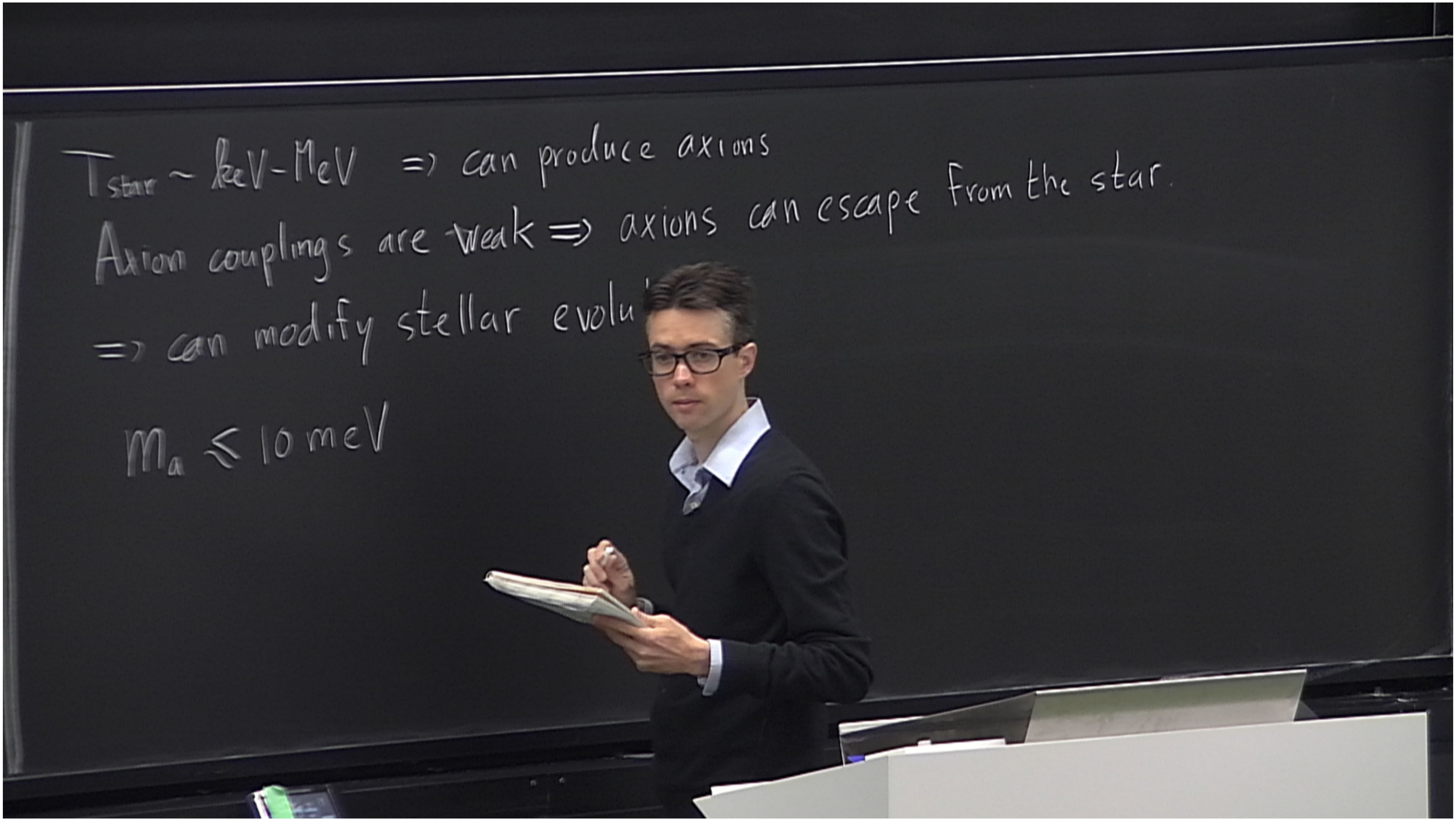
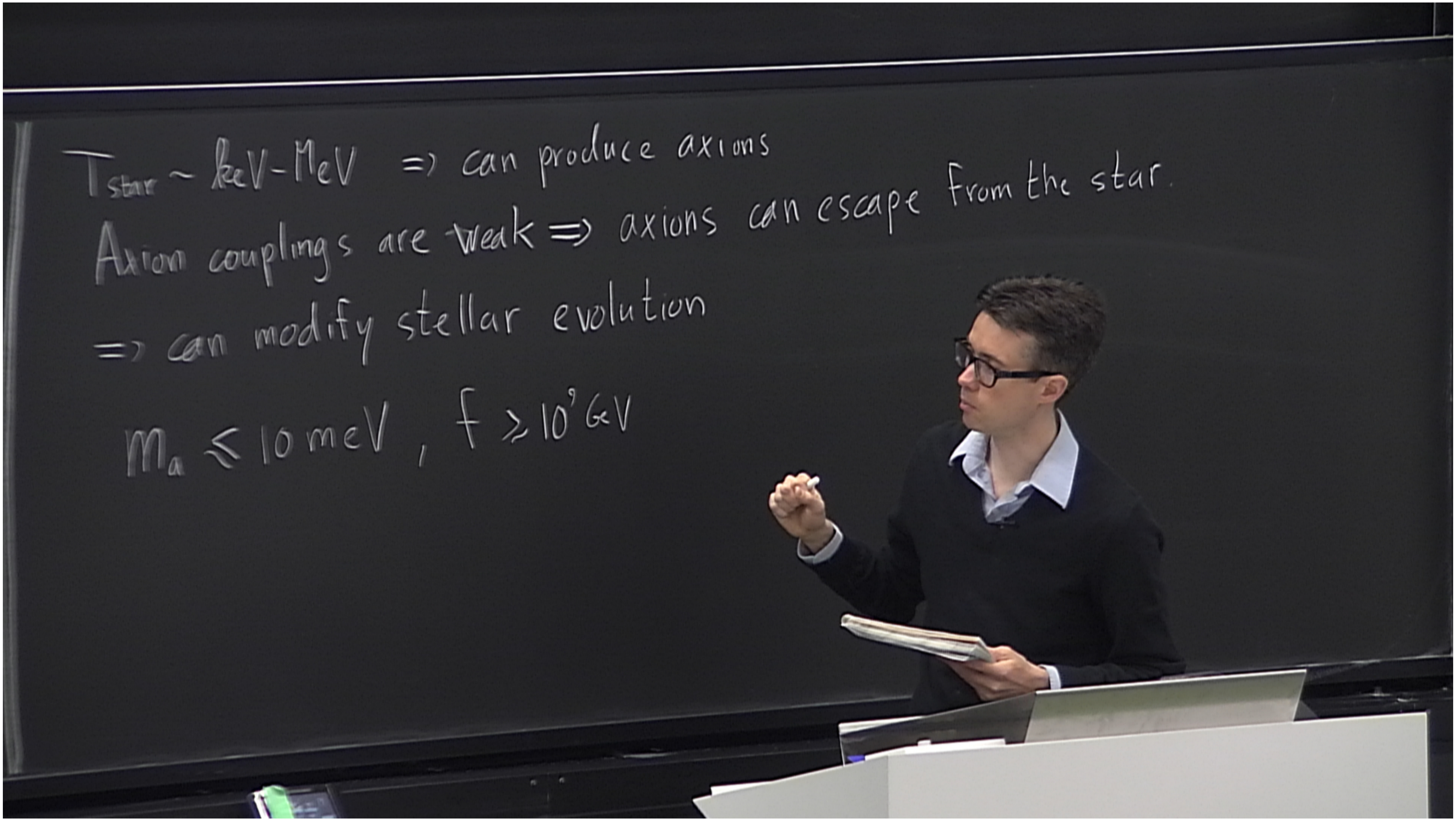
$t_0 = 10^{10} \text{yrs} = 10^{10} (\pi \times 10^7 s) \sim 10^{17} s$


Tstar ~ keV - MeV

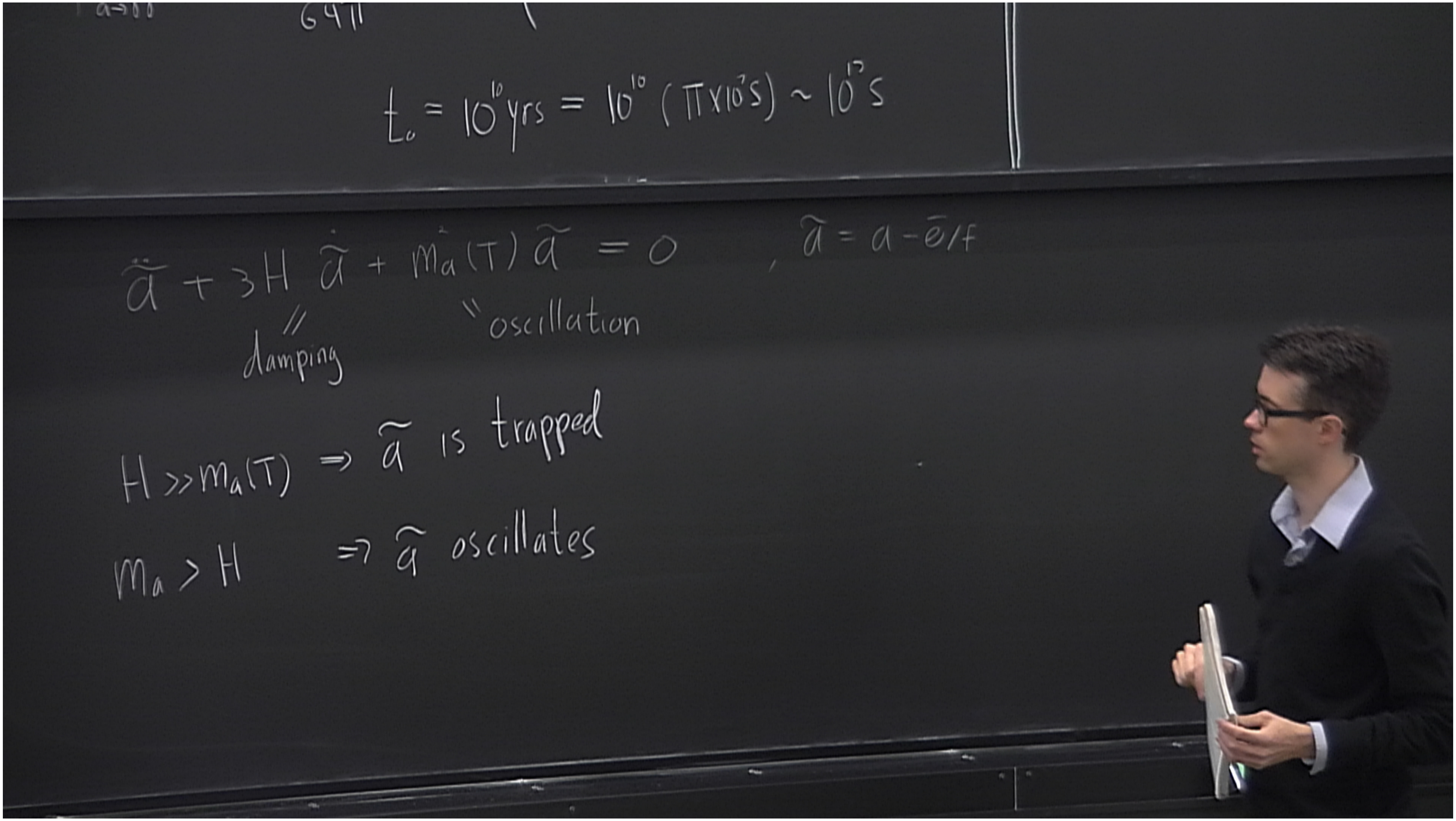

Tstar ~ keV-MeV => can produce axions
Axion couplings are weak => axions can escape from the star.


T_star ~ keV-MeV => can produce axions
Axion couplings are weak => axions can escape from the star.
=> can modify stellar evolution

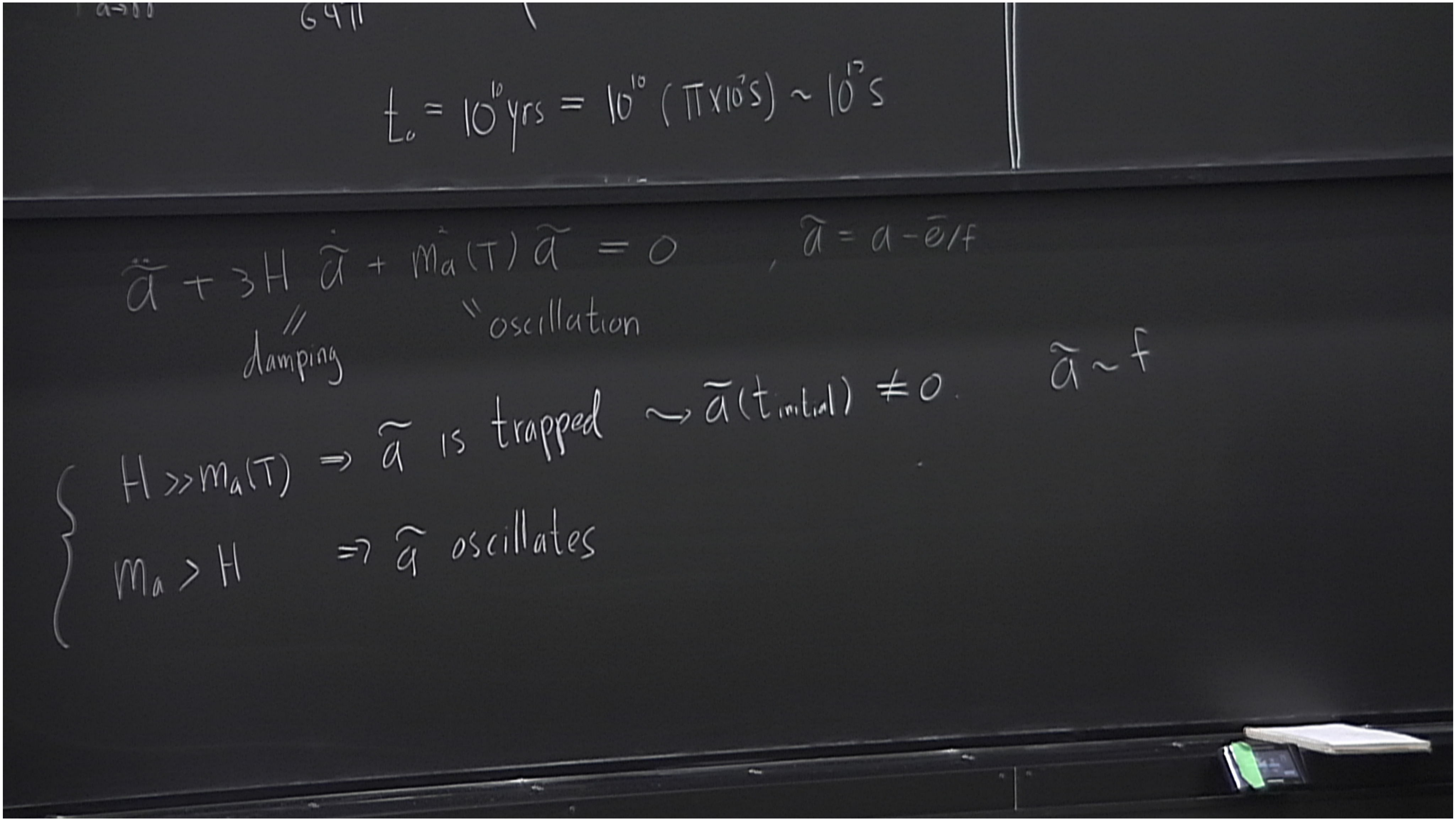

T_star ~ keV-MeV => can produce axions
Axion couplings are weak => axions can escape from the star.
=> can modify stellar evolu
m_a ≲ 10 meV

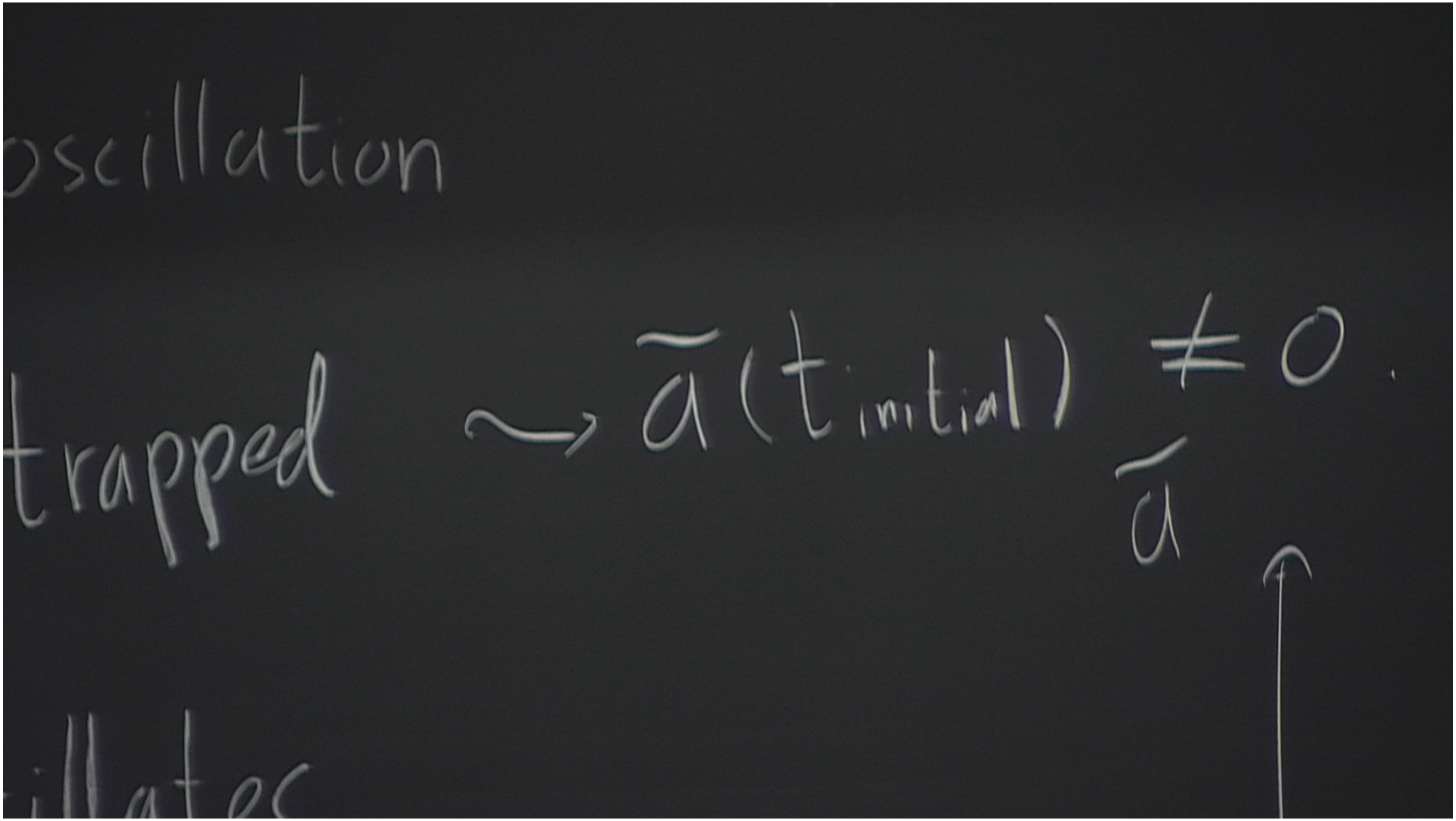

T_star ~ keV-MeV => can produce axions
Axion couplings are weak => axions can escape from the star.
=> can modify stellar evolution
m_a ≲ 10 meV , f ≳ 10^9 GeV

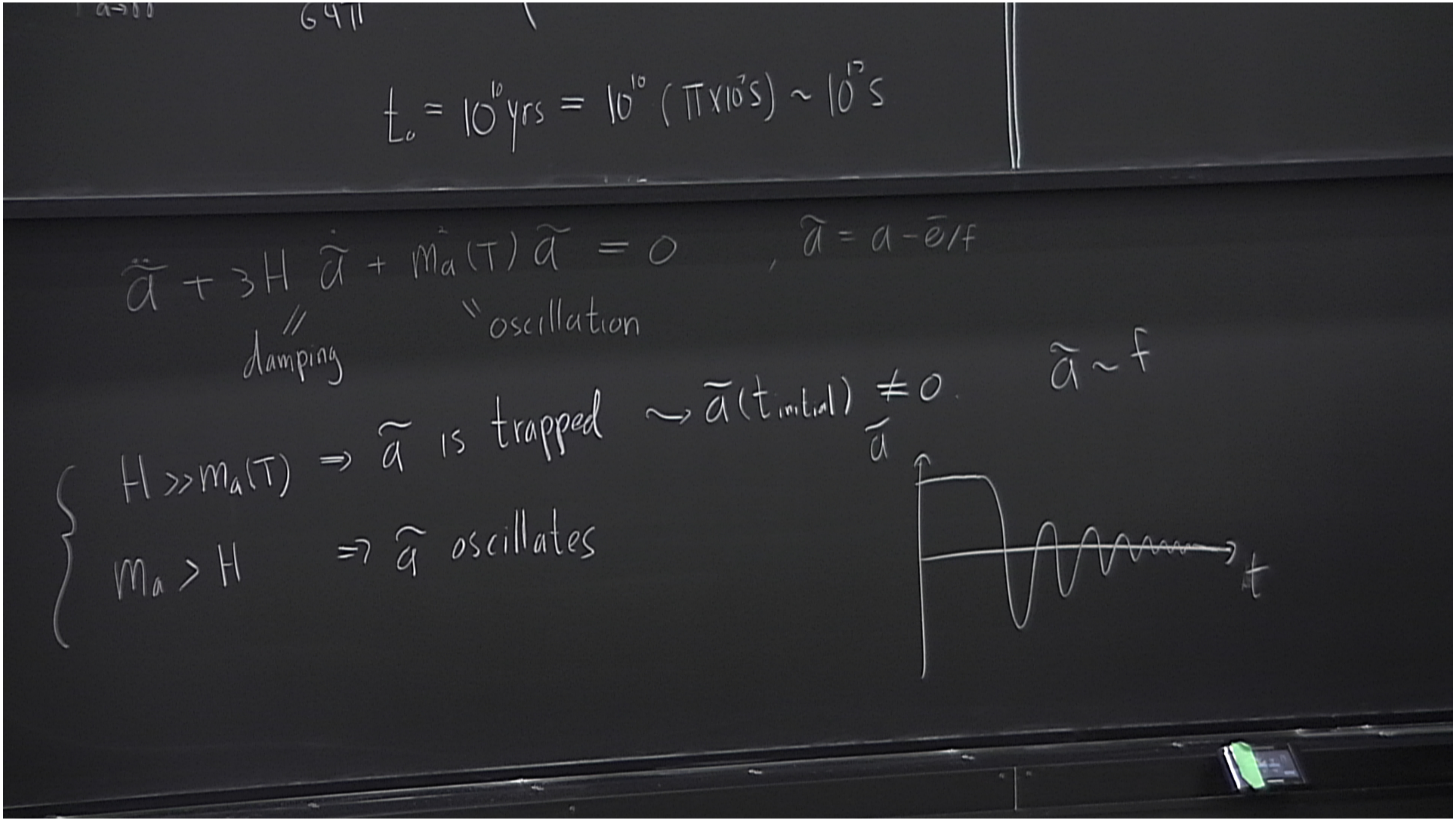

$t_0 = 10^{10}$ yrs $= 10^{10}(\pi \times 10^7 s) \sim 10^{17}$ s
$\ddot{\tilde{a}} + 3H\dot{\tilde{a}} + m_a^2(T)\tilde{a} = 0$, $\tilde{a} = a - \bar{\theta}/f$
damping
oscillation
$H \gg m_a(T) \Rightarrow \tilde{a}$ is trapped

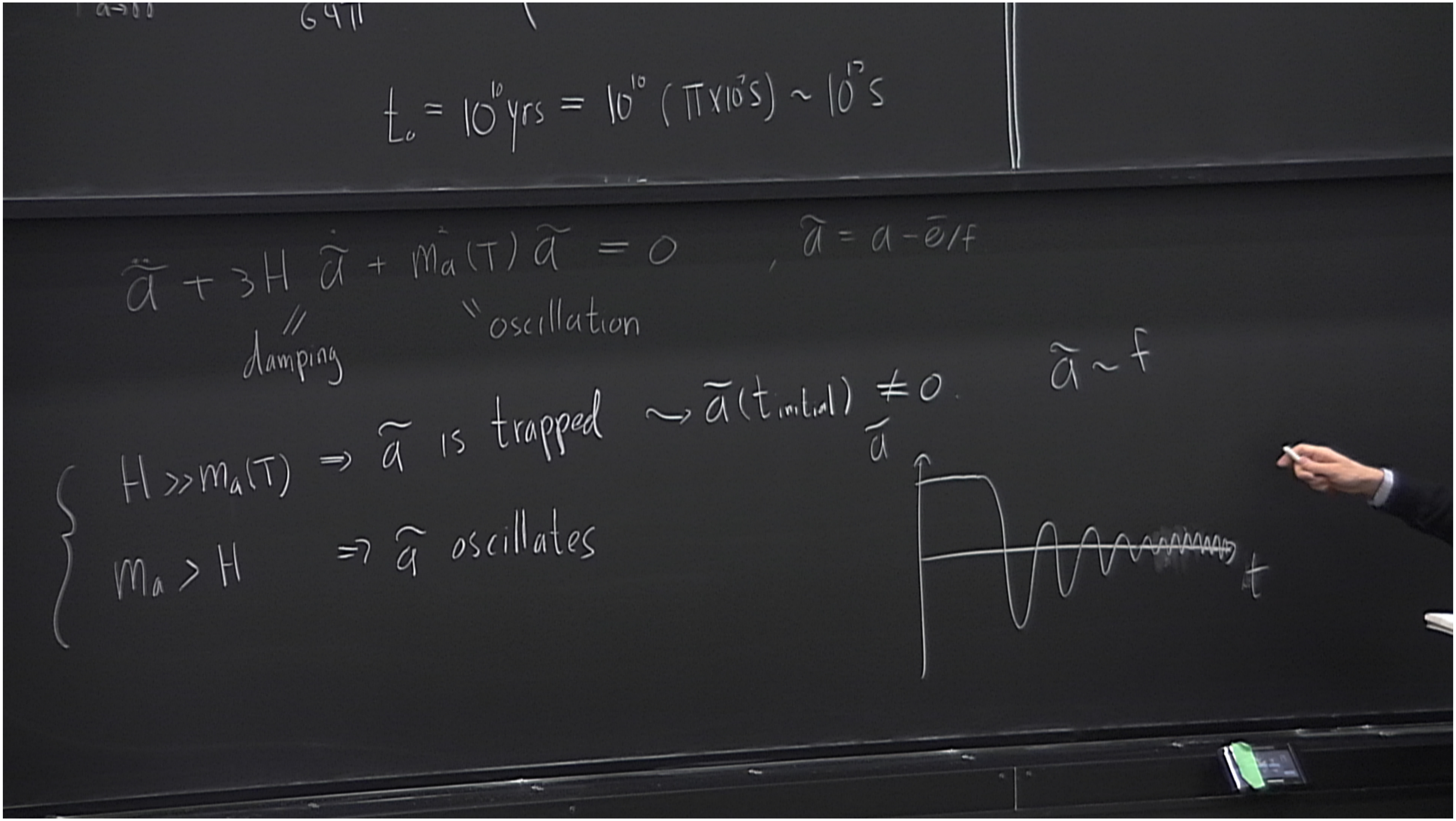


$t_0 = 10^{10}$ yrs $= 10^{10}(\pi \times 10^7 s) \sim 10^{17} s$
$\ddot{\tilde{a}} + 3H\dot{\tilde{a}} + m_a^2(T)\tilde{a} = 0$, $\tilde{a} = a - \bar{\theta}/f$
damping
oscillation
$H \gg m_a(T) \Rightarrow \tilde{a}$ is trapped
$m_a > H \Rightarrow \tilde{a}$ oscillates


t₀ = 10^10 yrs = 10^10 (π×10^7 s) ~ 10^17 s
ä + 3H ȧ + m_a^2(T) ã = 0 , ã = a − θ̄/f
damping
oscillation
ã ~ f
H >> m_a(T) ⇒ ã is trapped ~ ã(t_initial) ≠ 0.
m_a > H ⇒ ã oscillates


oscillation
trapped ⇝ $\bar{a}(t_{initial}) \neq 0$.
$\bar{a}$
illates


$t_0 = 10^{10}$ yrs $= 10^{10} (\pi \times 10^7 s) \sim 10^{17} s$
$\ddot{\tilde{a}} + 3H \dot{\tilde{a}} + m_a^2(T) \tilde{a} = 0$, $\tilde{a} = a - \bar{\theta}/f$
damping
oscillation
$\tilde{a} \sim f$
$H \gg m_a(T) \Rightarrow \tilde{a}$ is trapped $\rightsquigarrow \tilde{a}(t_{initial}) \neq 0$.
$m_a > H \Rightarrow \tilde{a}$ oscillates
$\tilde{a}$
t


$t_0 = 10^{10}$ yrs $= 10^{10}(\pi \times 10^7 s) \sim 10^{17} s$
$\ddot{\tilde{a}} + 3H\dot{\tilde{a}} + m_a^2(T)\tilde{a} = 0$, $\tilde{a} = a - \bar{\theta}/f$
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oscillation
$\tilde{a} \sim f$
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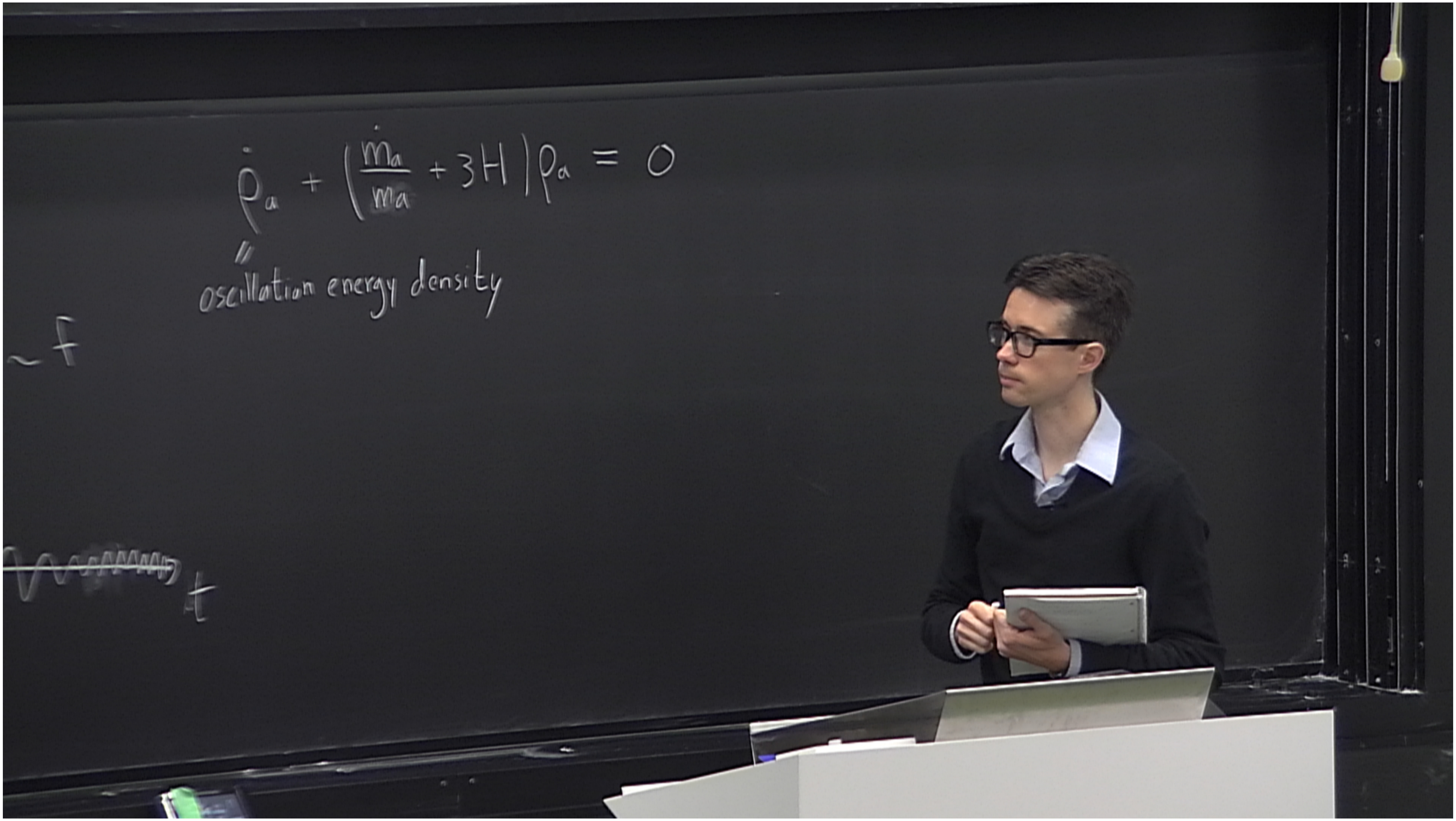
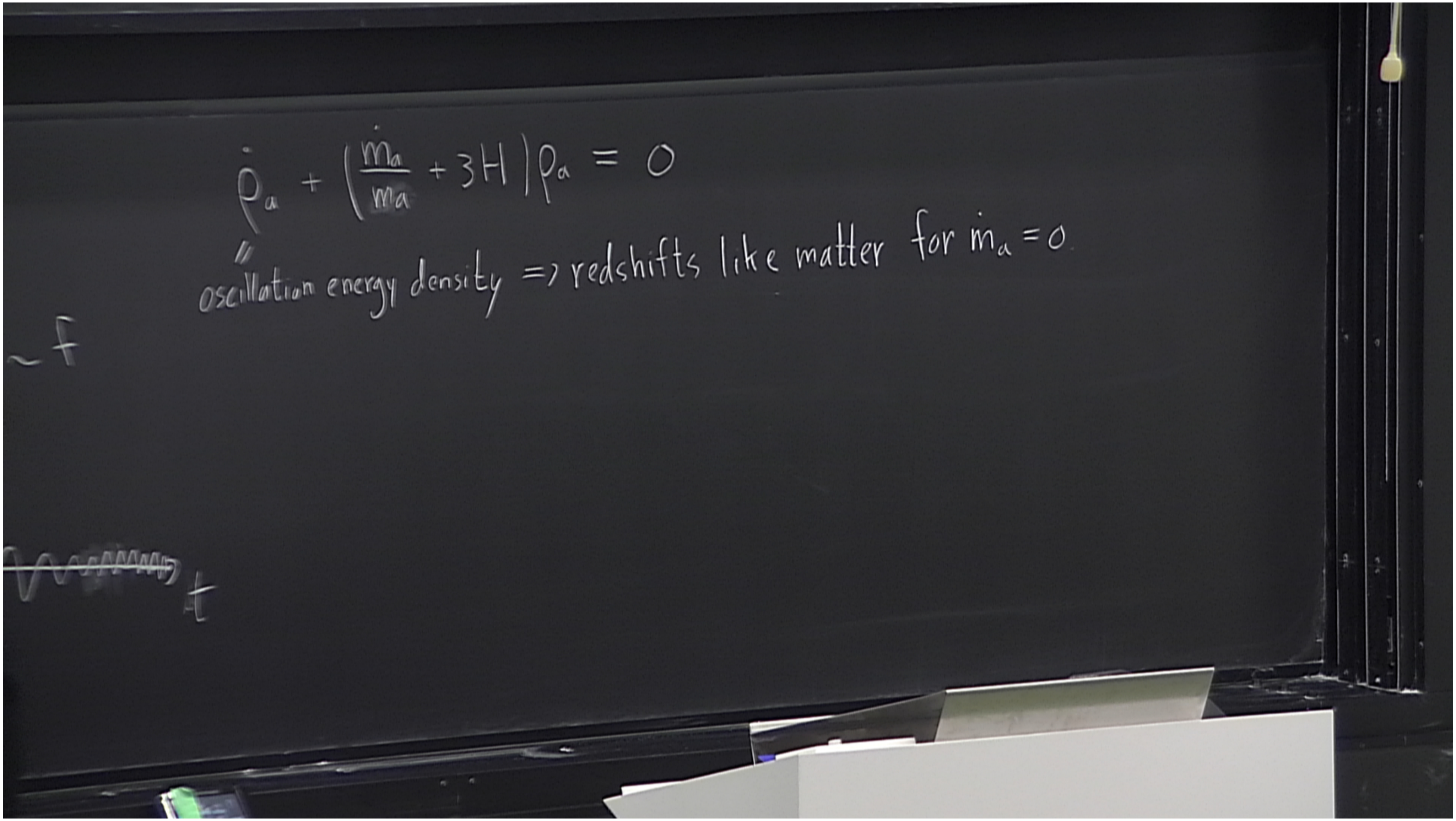
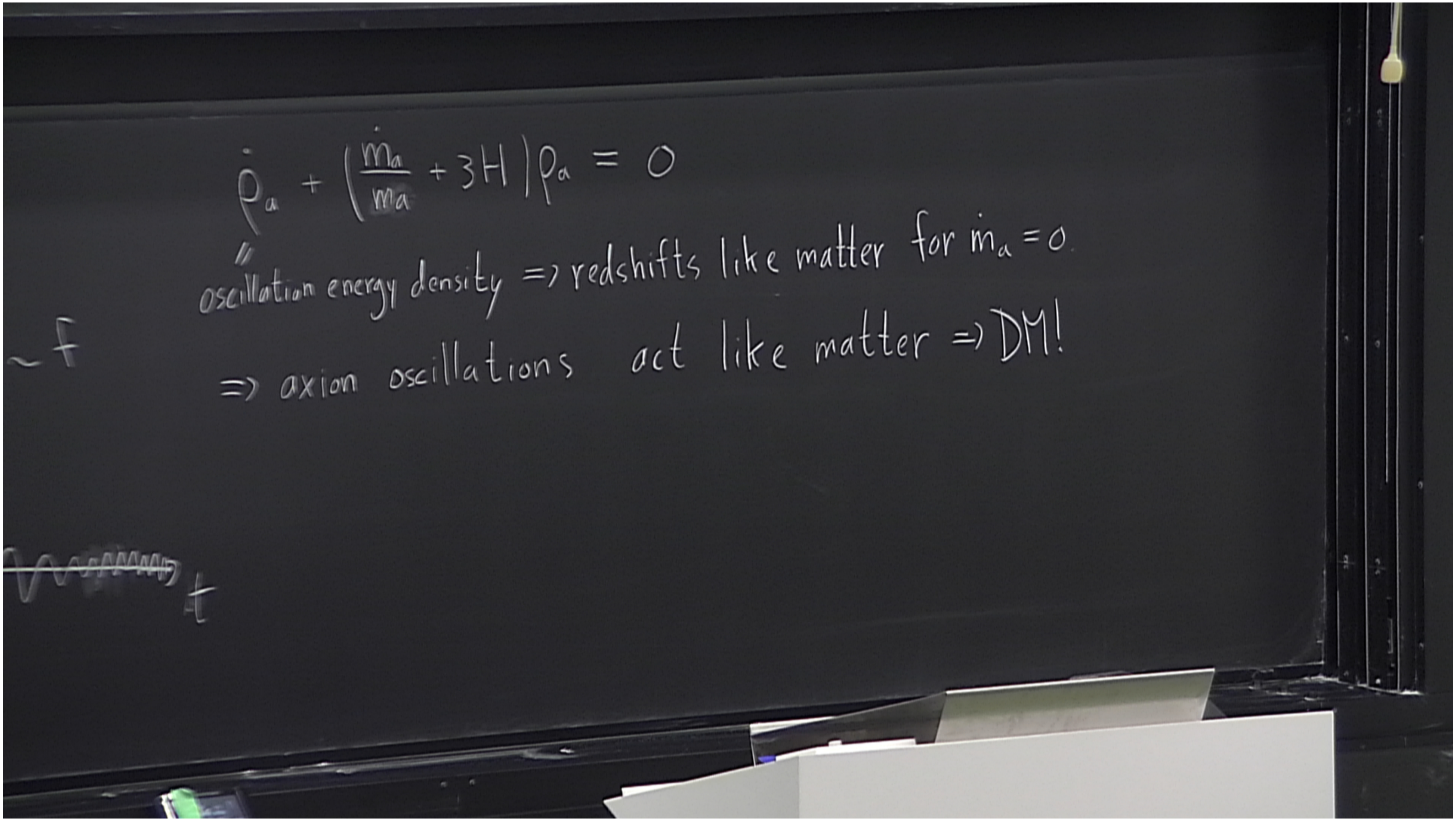
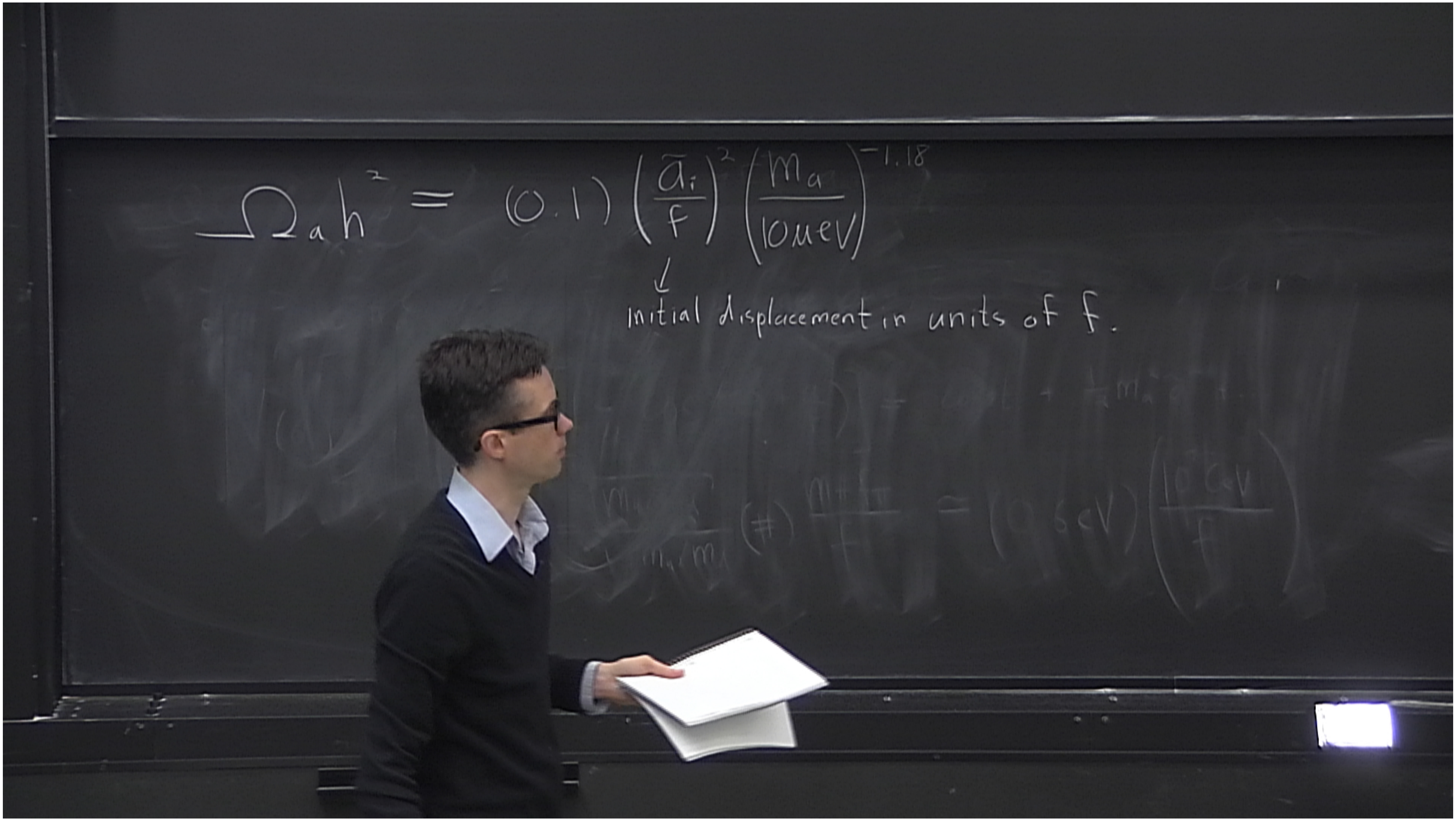
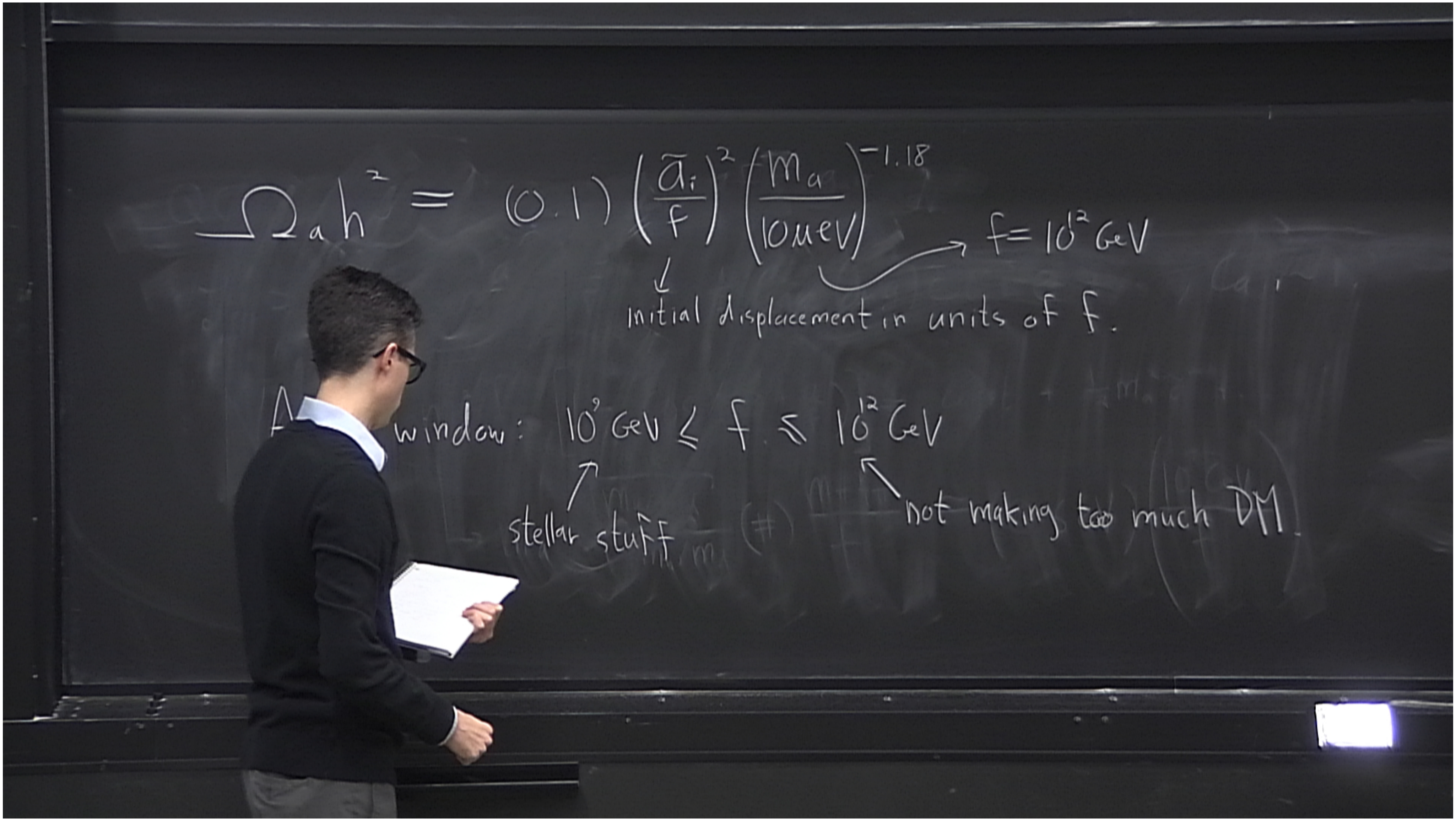
$m_a > H \Rightarrow \tilde{a}$ oscillates
$\tilde{a}$
t

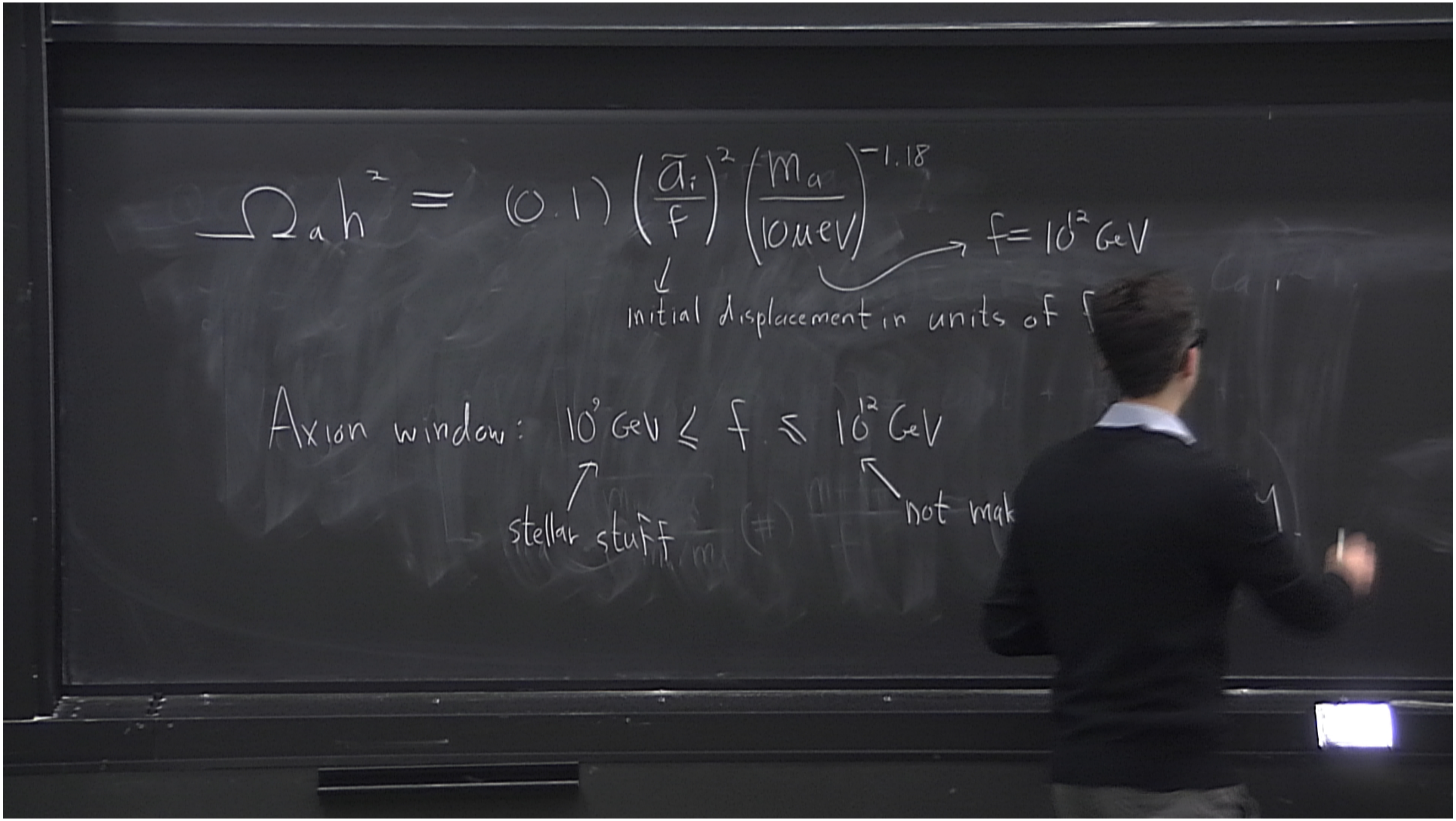

ρ̇a + (ṁa/ma + 3H) ρa = 0
oscillation energy density
~f
t


$\dot{\rho}_a + \left(\frac{\dot{m}_a}{m_a} + 3H\right)\rho_a = 0$
oscillation energy density => redshifts like matter for $\dot{m}_a = 0$
~f
t

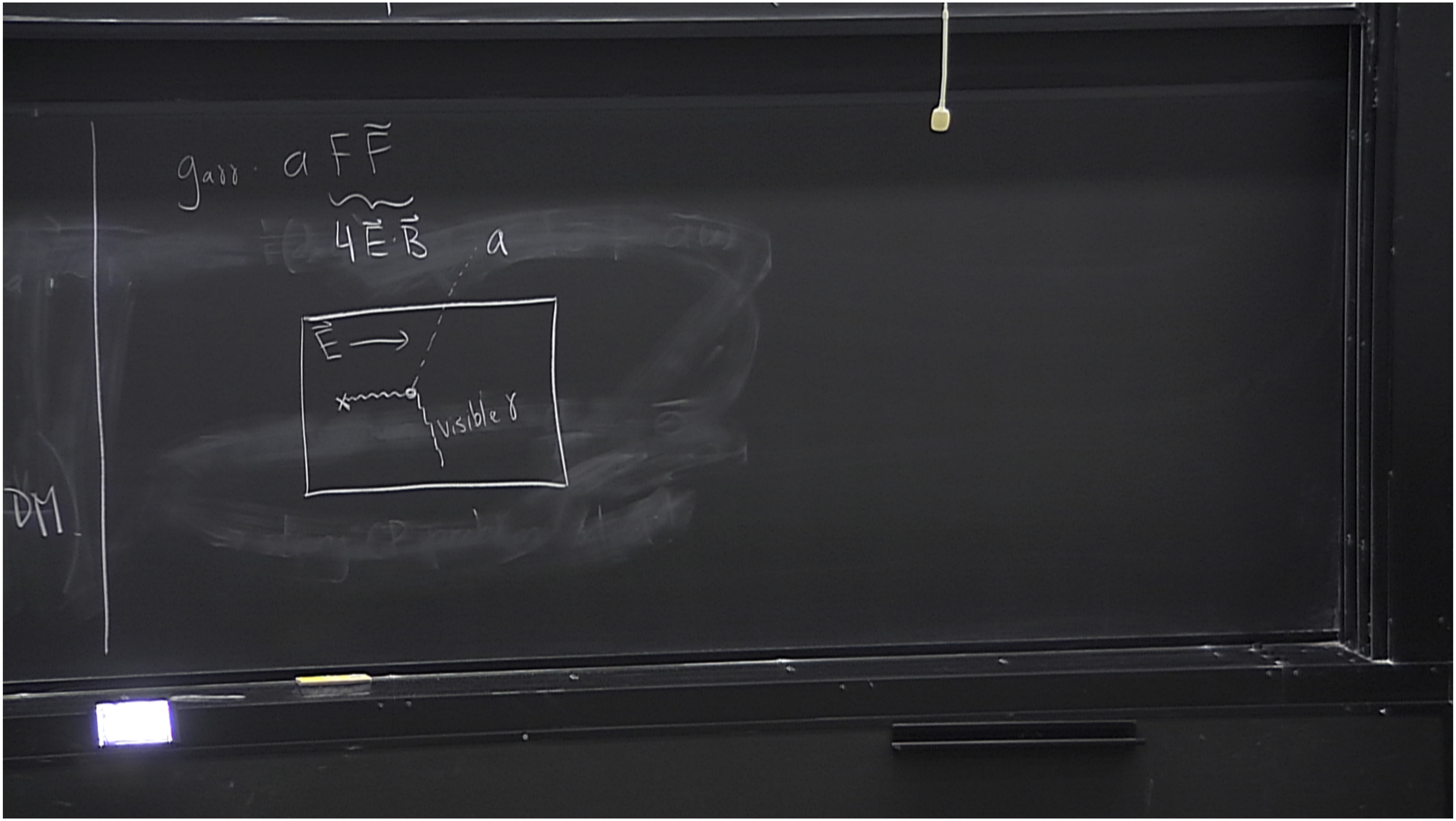

$\dot{\rho}_a + \left(\frac{\dot{m}_a}{m_a} + 3H\right)\rho_a = 0$
oscillation energy density => redshifts like matter for $\dot{m}_a = 0$
=> axion oscillations act like matter => DM!
~f
t

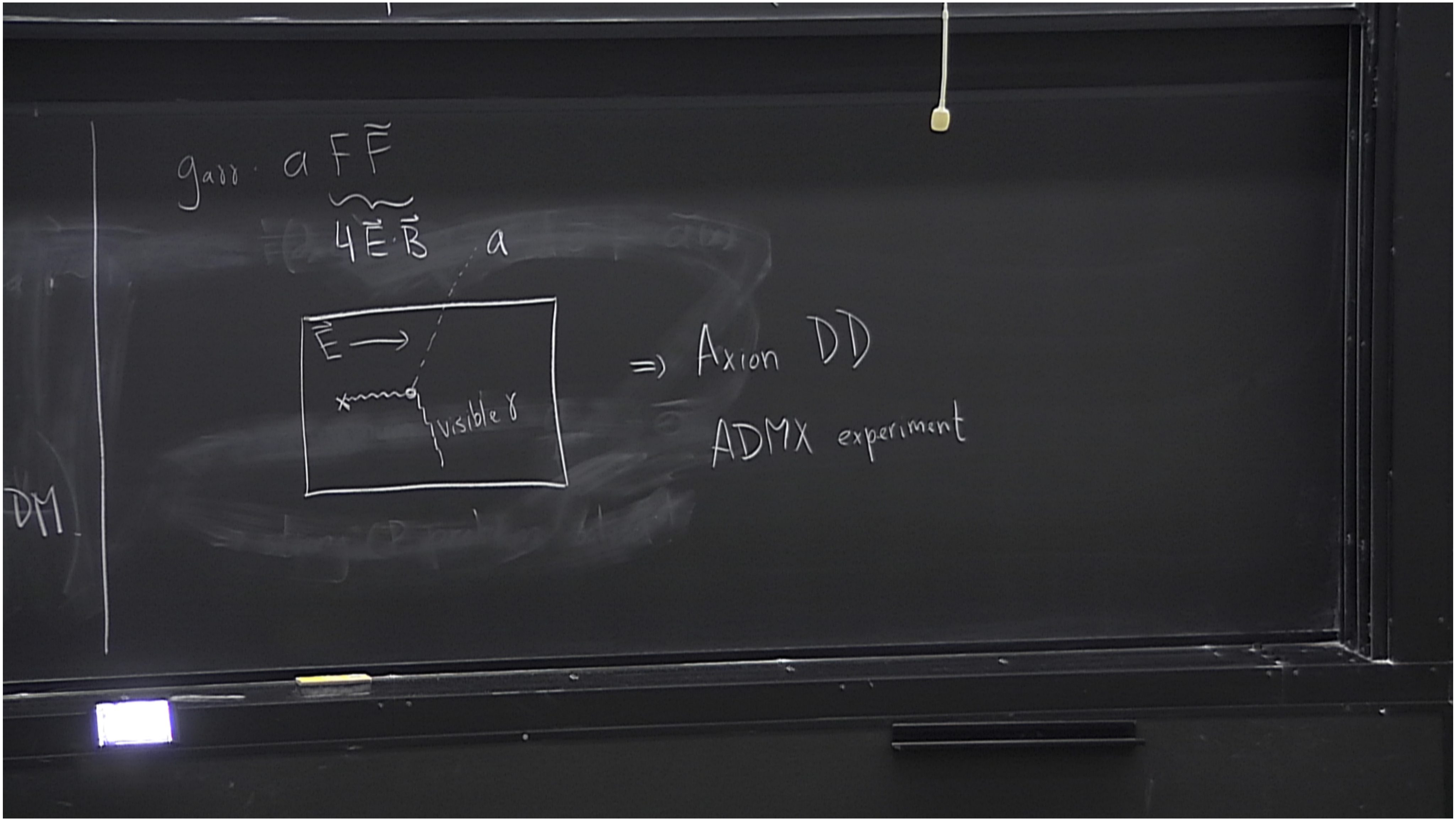

$\Omega_a h^2 = (0.1)\left(\frac{\bar{a}_i}{f}\right)^2\left(\frac{m_a}{10\mu eV}\right)^{-1.18}$
initial displacement in units of f.

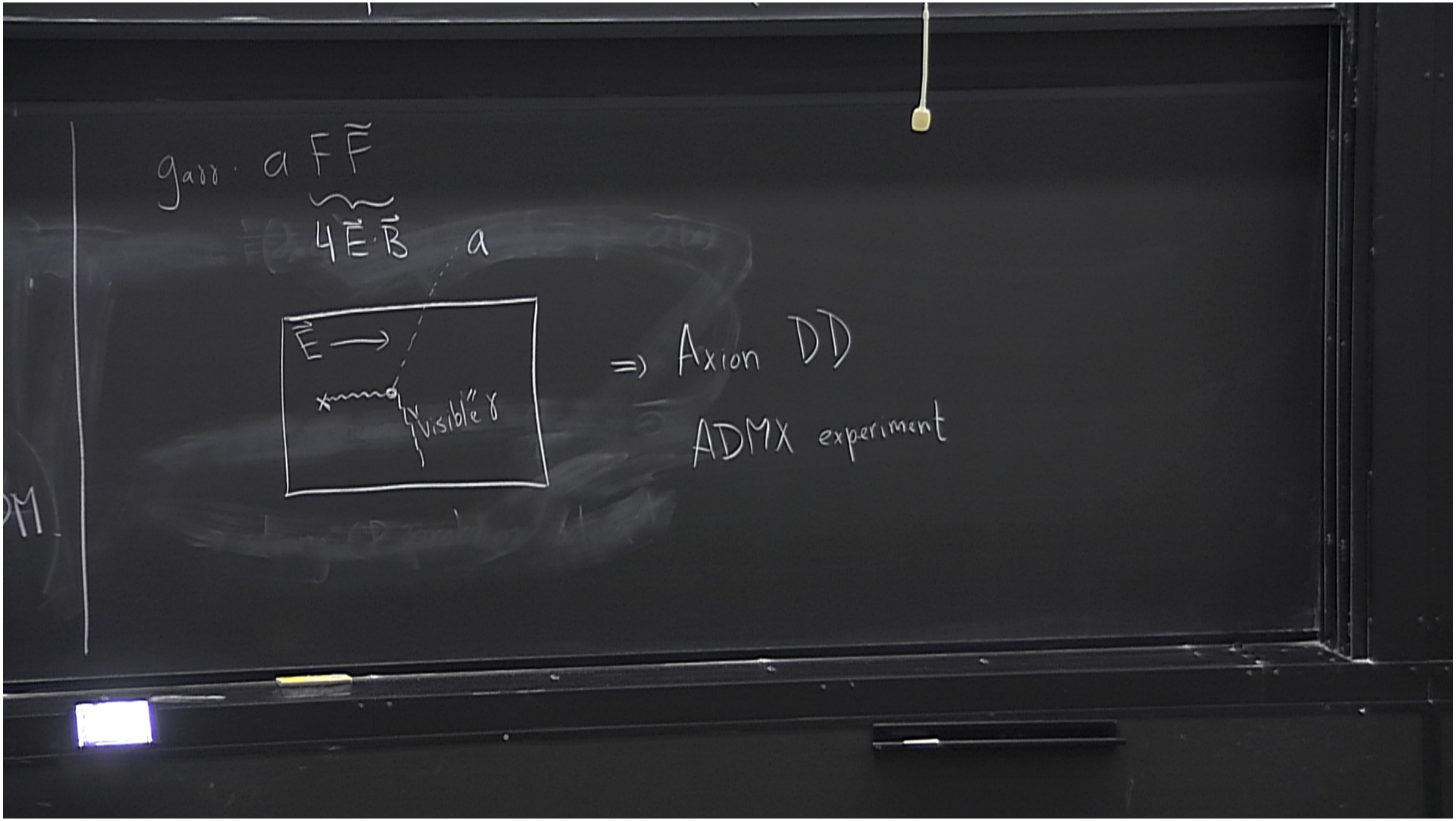

$\Omega_a h^2 = (0.1)\left(\frac{\bar{a}_i}{f}\right)^2\left(\frac{m_a}{10\,\mu eV}\right)^{-1.18}$
$f = 10^{12}$ GeV
initial displacement in units of f.
window: 10^9 GeV $\lesssim f \lesssim 10^{12}$ GeV
stellar stuff
not making too much DM


Ωa h² = (0.1) (ã_i / f)² (m_a / 10 μeV)^-1.18
f = 10¹² GeV
initial displacement in units of f
Axion window: 10⁹ GeV ≲ f ≲ 10¹² GeV
stellar stuff
not mak


gaγγ · a F F̃
4E·B
DM


gaγγ · a F F̃
4 E·B
a
E
visible γ
DM


gaγγ · a F F̃
4 E·B
a
E
visible γ
⇒ Axion DD
ADMX experiment
DM


g_aγγ · a F F̃
4 E⃗·B⃗
a
E⃗ ⟶
"visible" γ
⇒ Axion DD
ADMX experiment