Title: BSM Theory 4

Date: Jul 13, 2018 02:30 PM

URL: http://pirsa.org/18070014

Abstract:

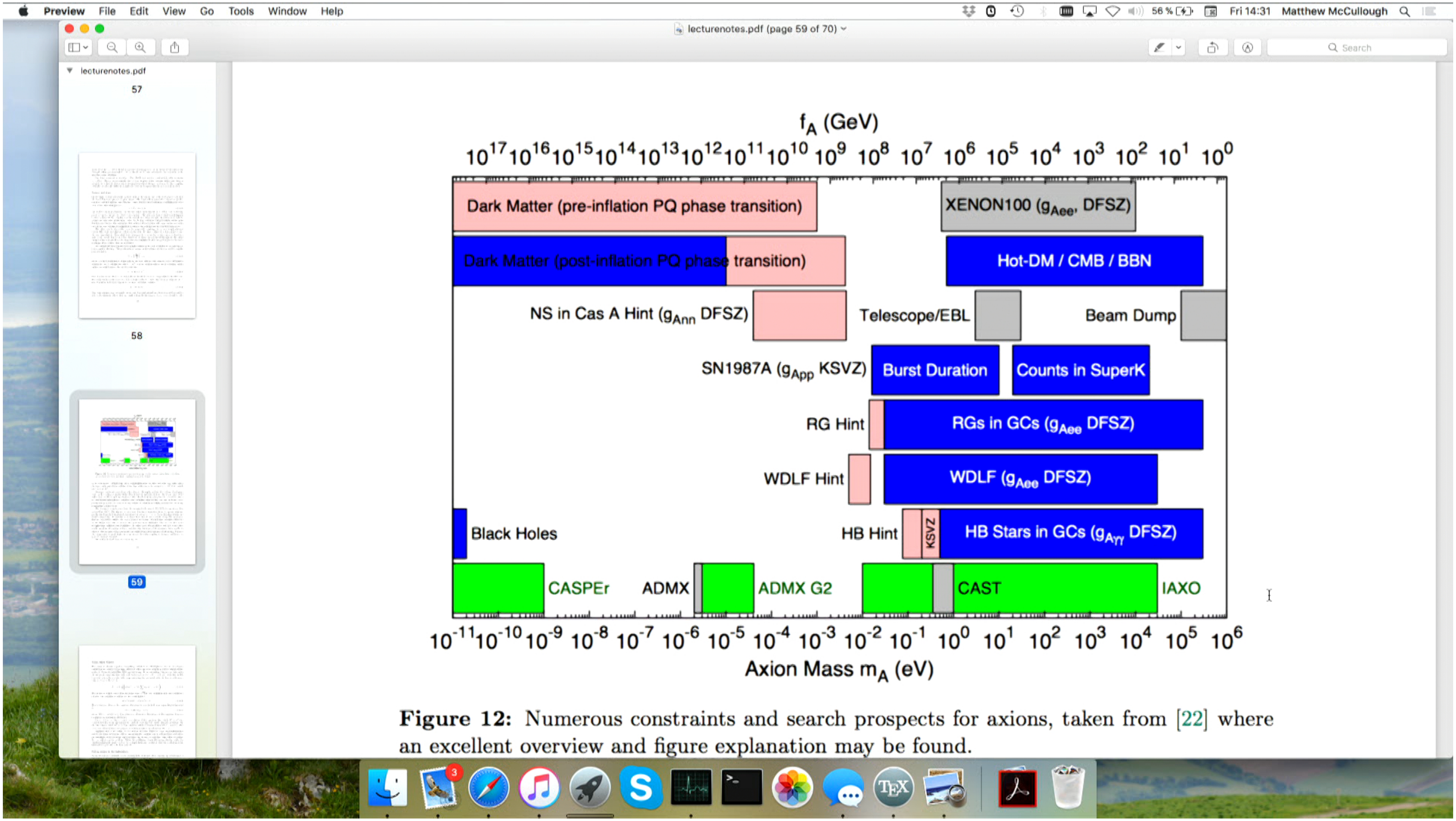
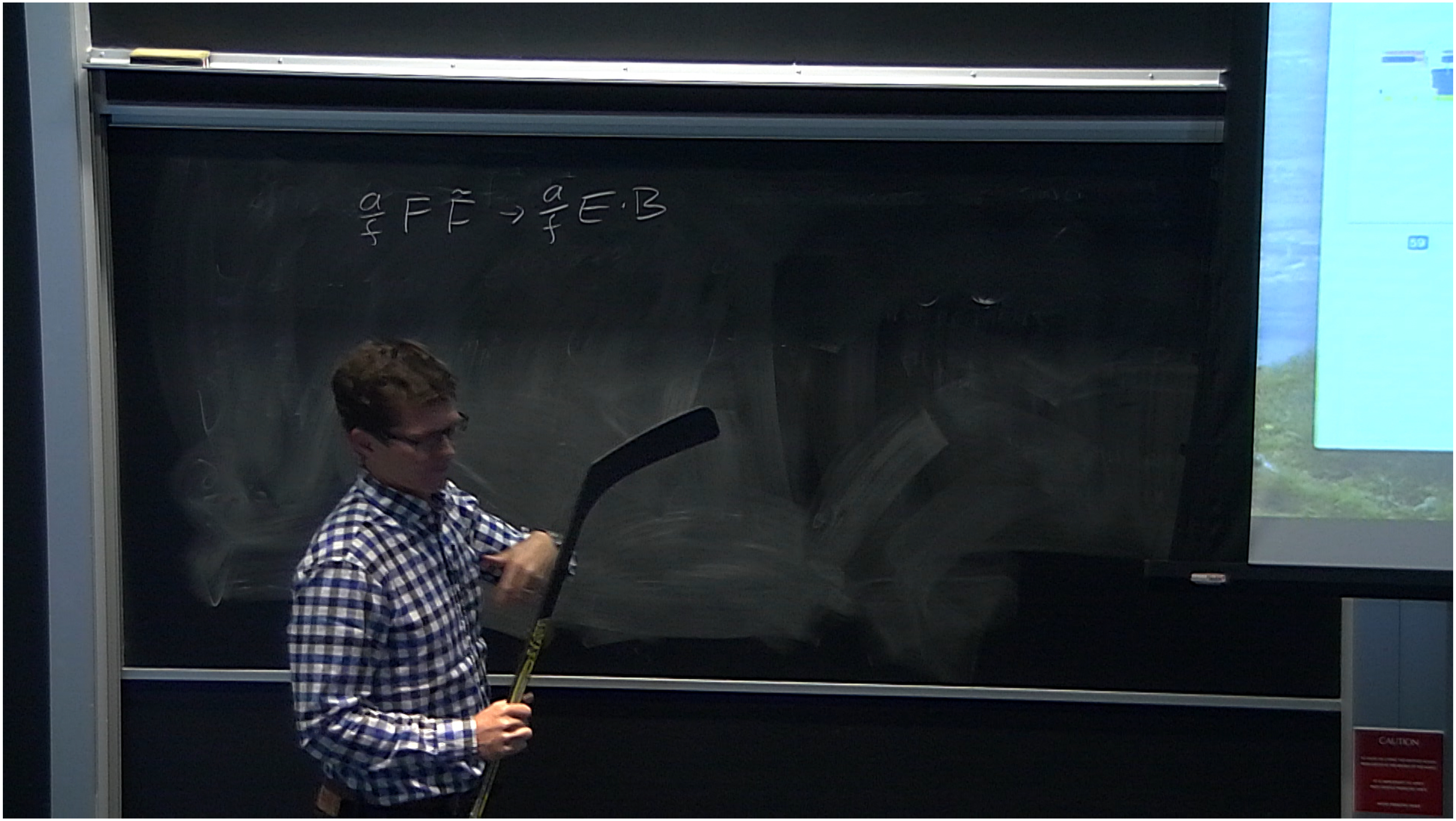
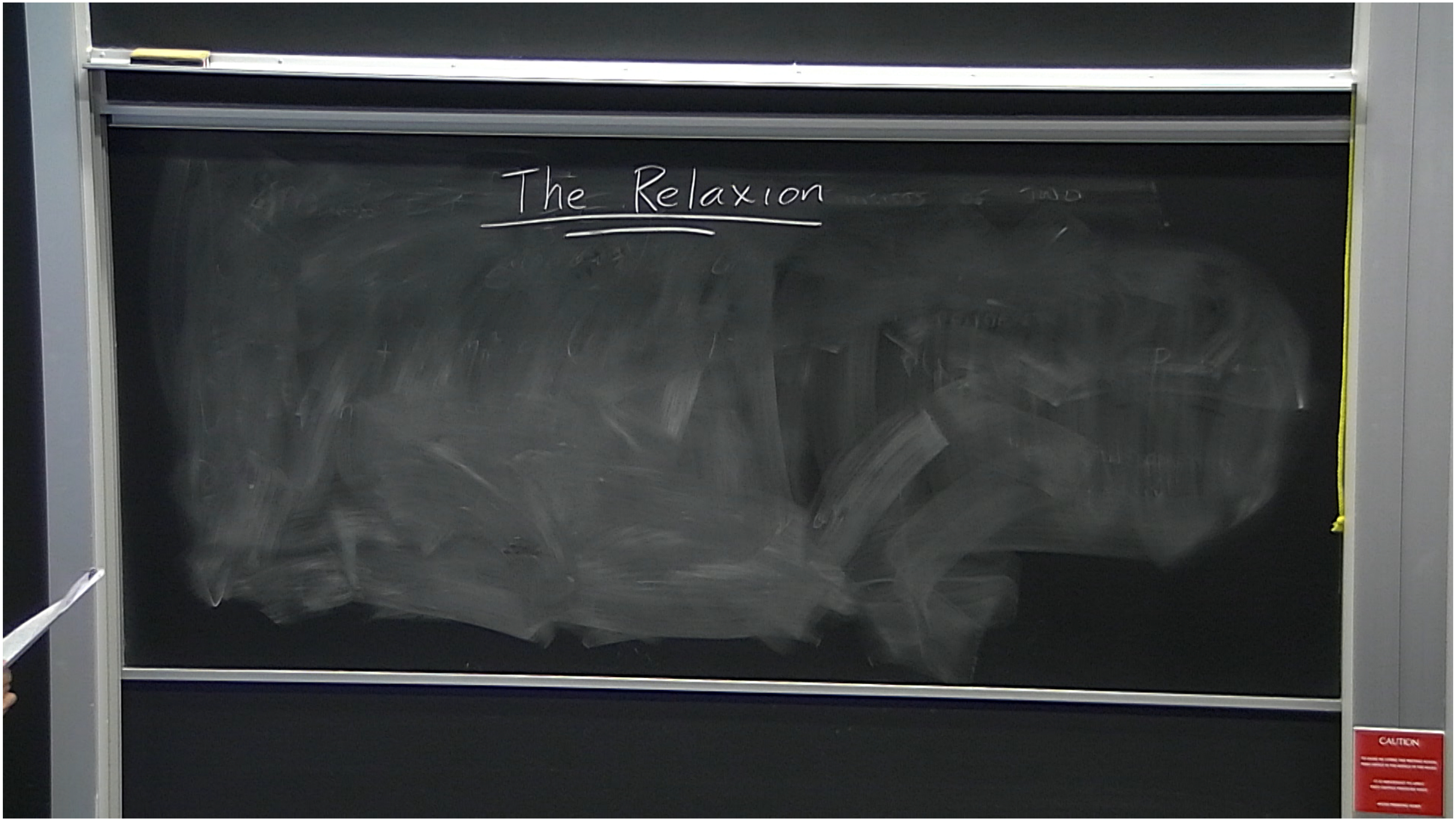
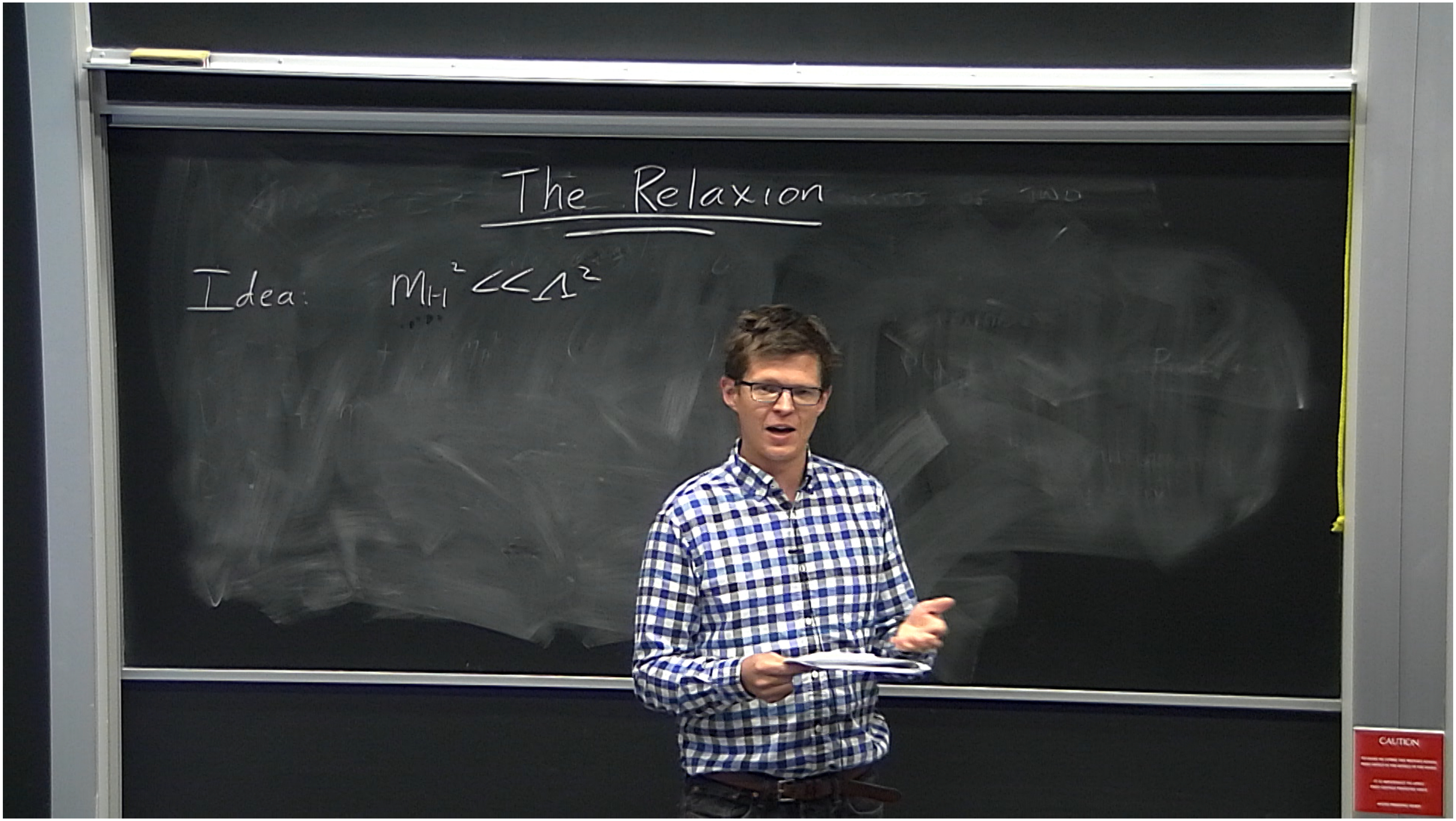
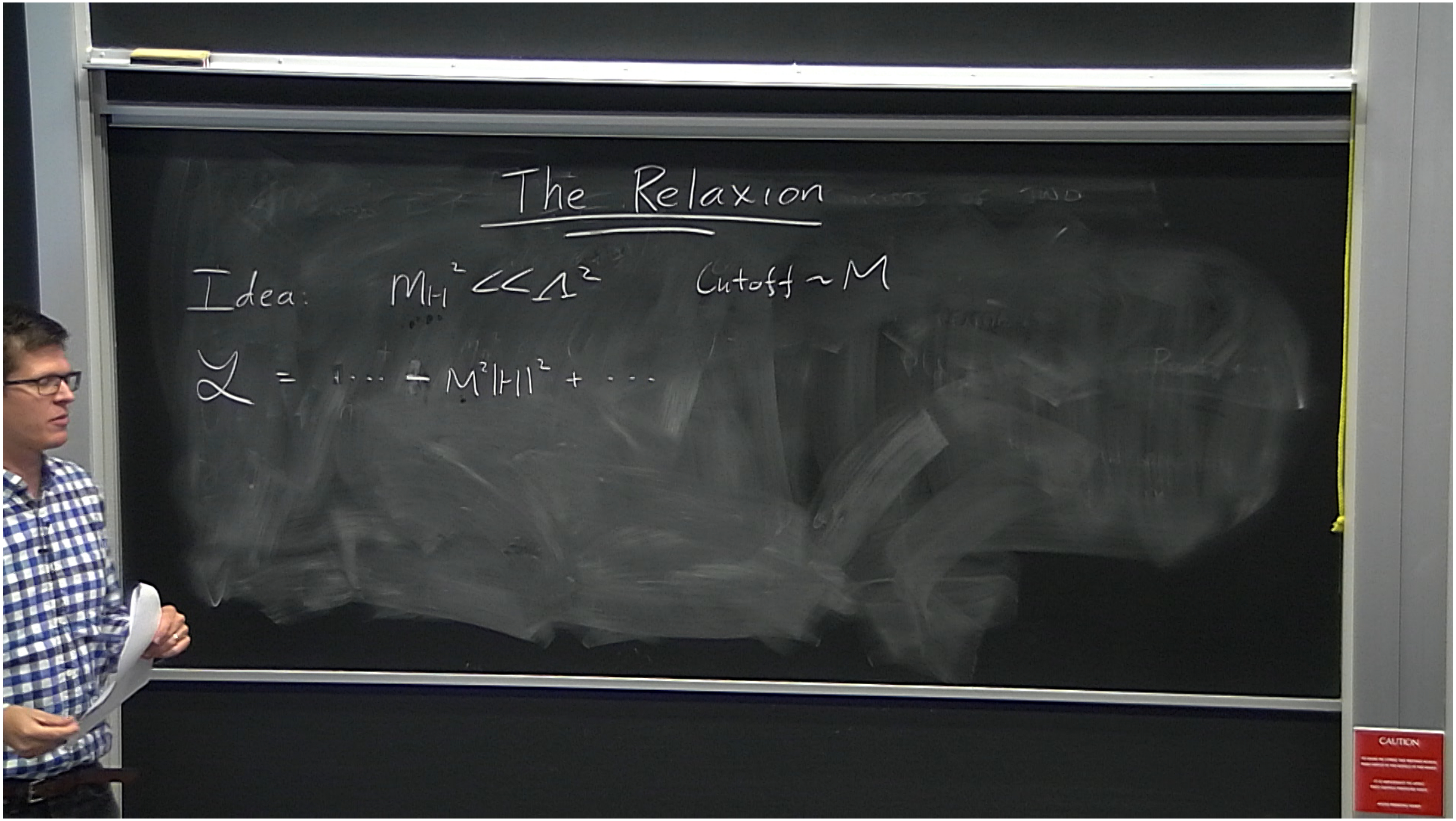


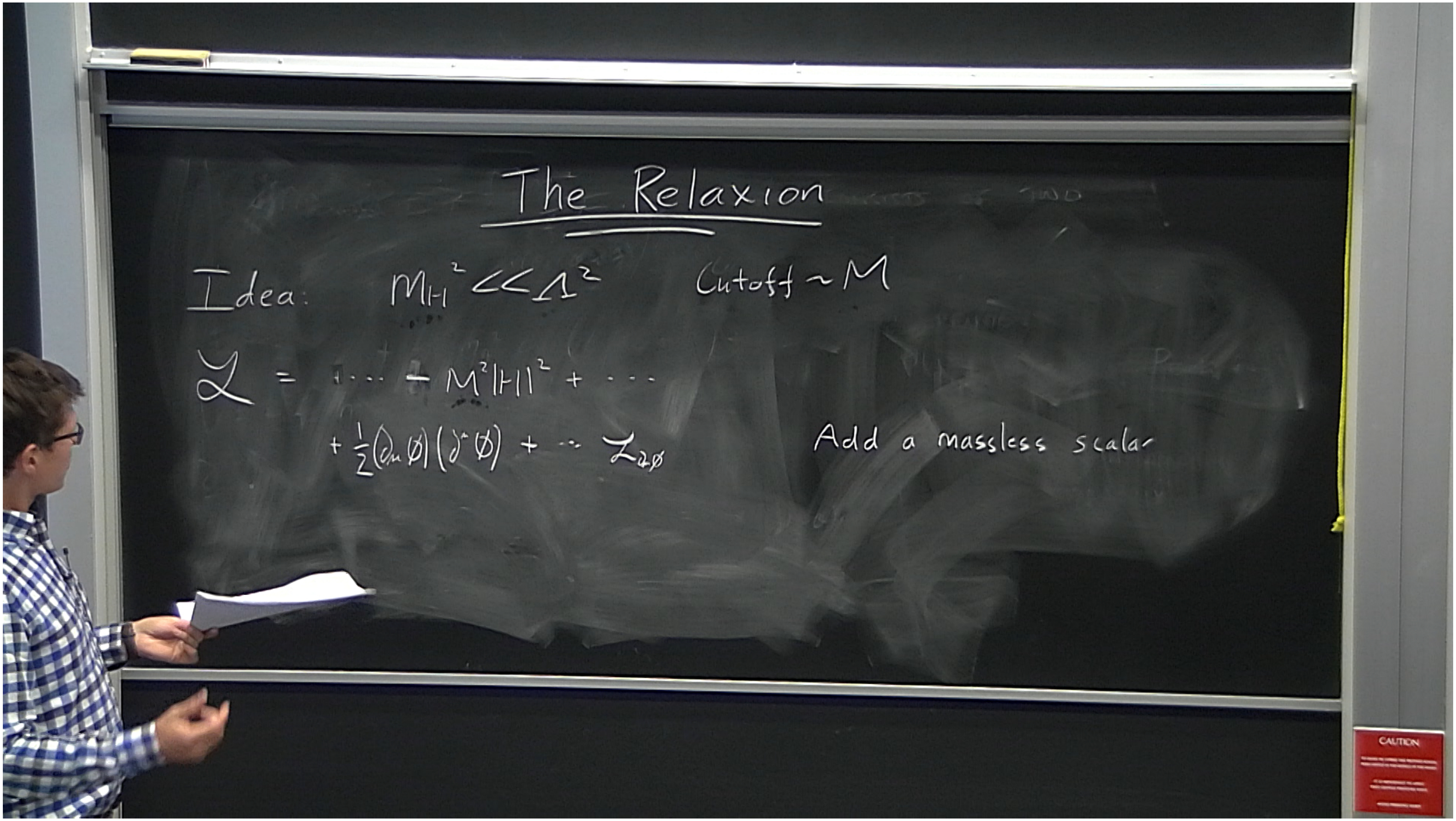
Figure 12: Numerous constraints and search prospects for axions, taken from [22] where an excellent overview and figure explanation may be found.

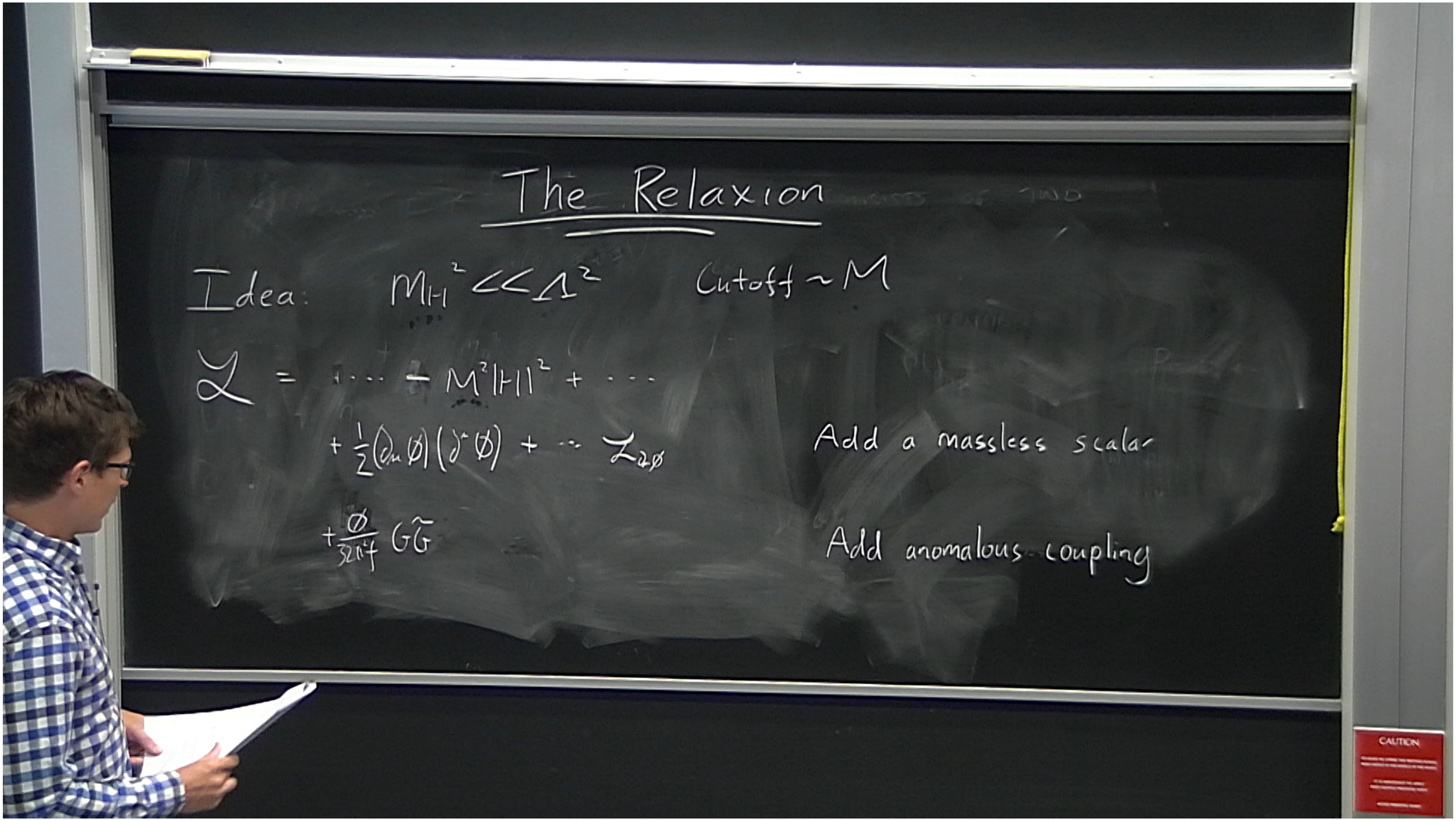

$\frac{a}{f} F\tilde{F} \to \frac{a}{f} E \cdot B$

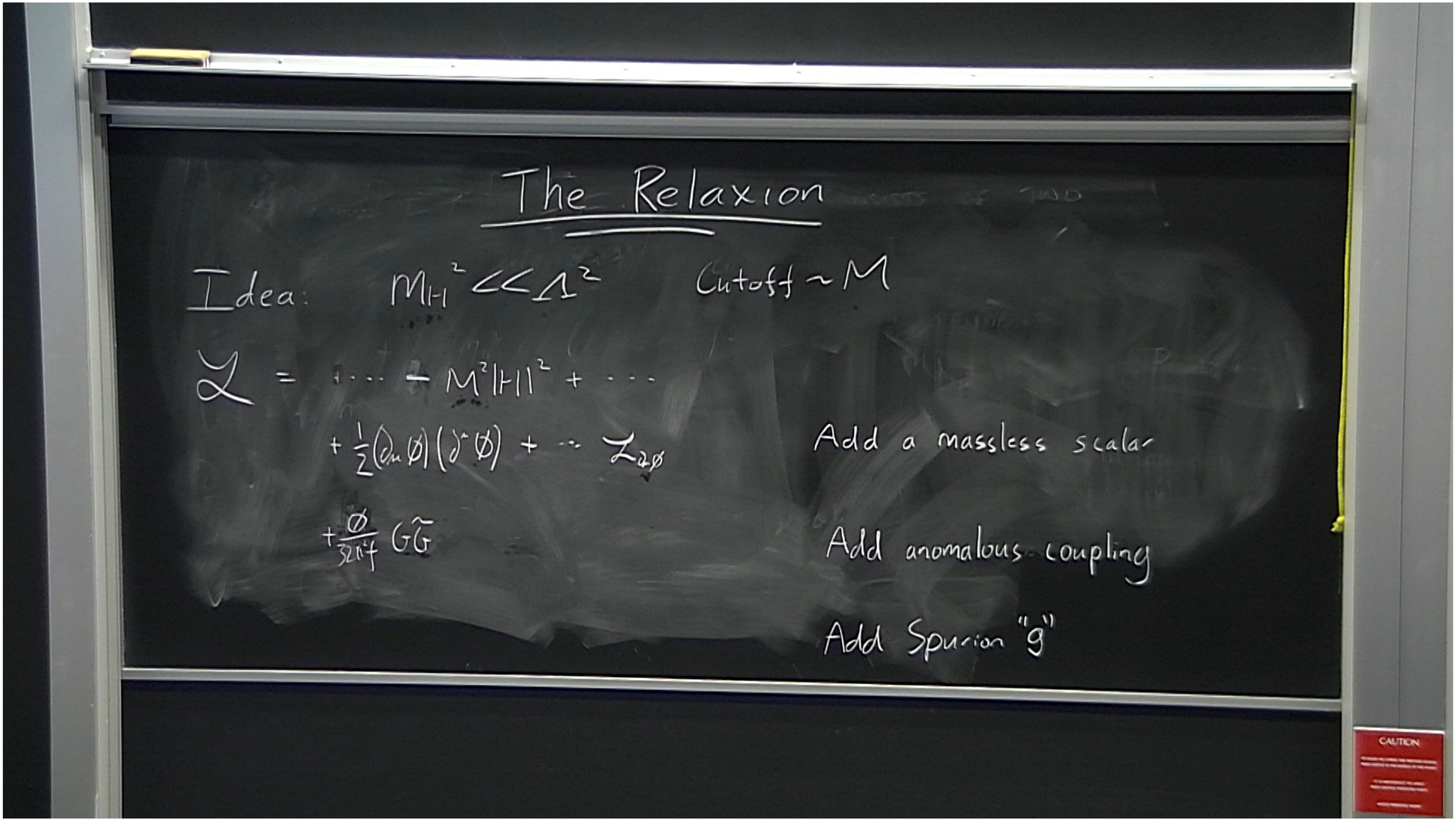

The Relaxion

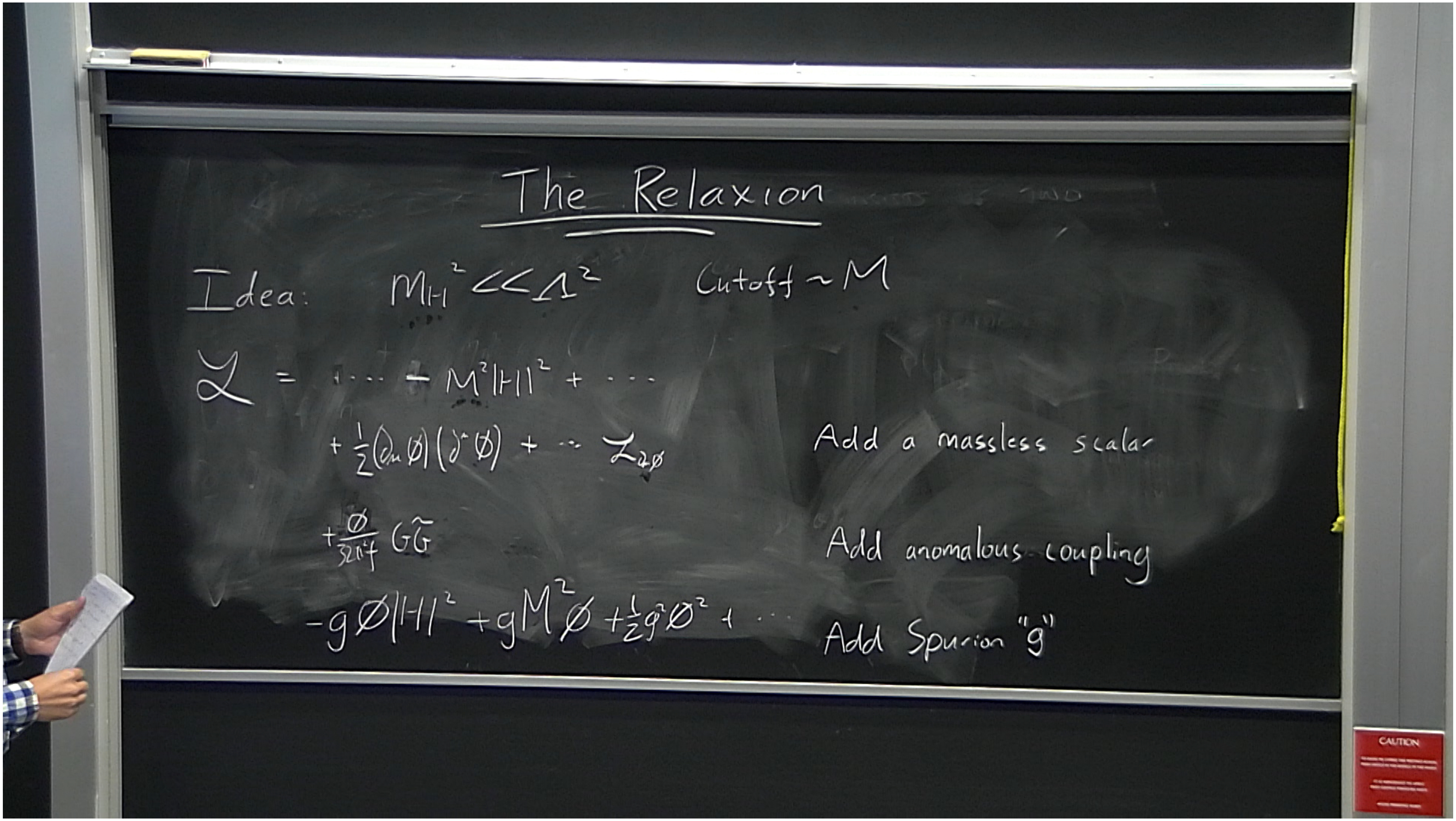

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$

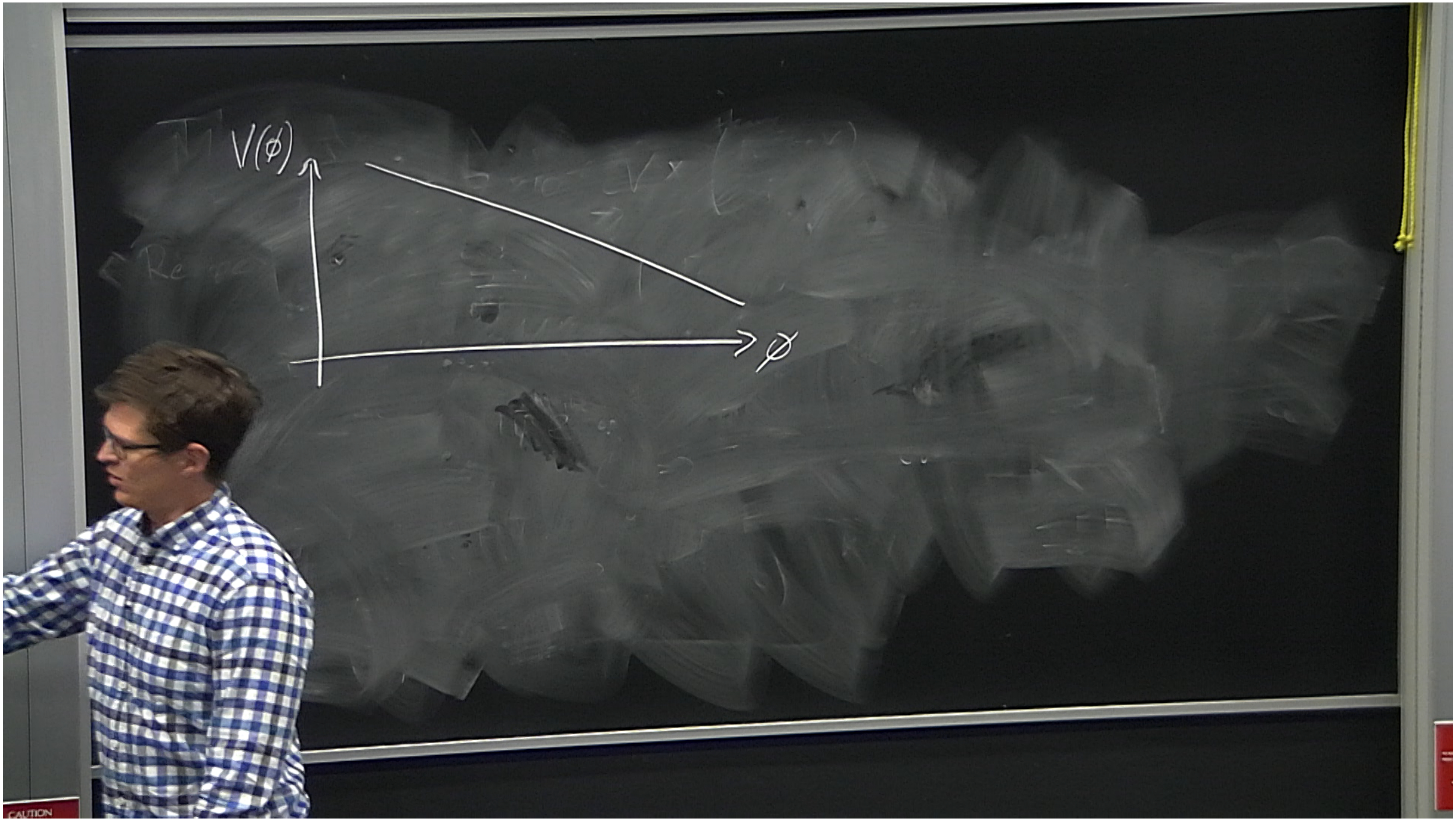

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$
Cutoff ~ M
$\mathcal{L} = \cdots - M^2|H|^2 + \cdots$
CAUTION

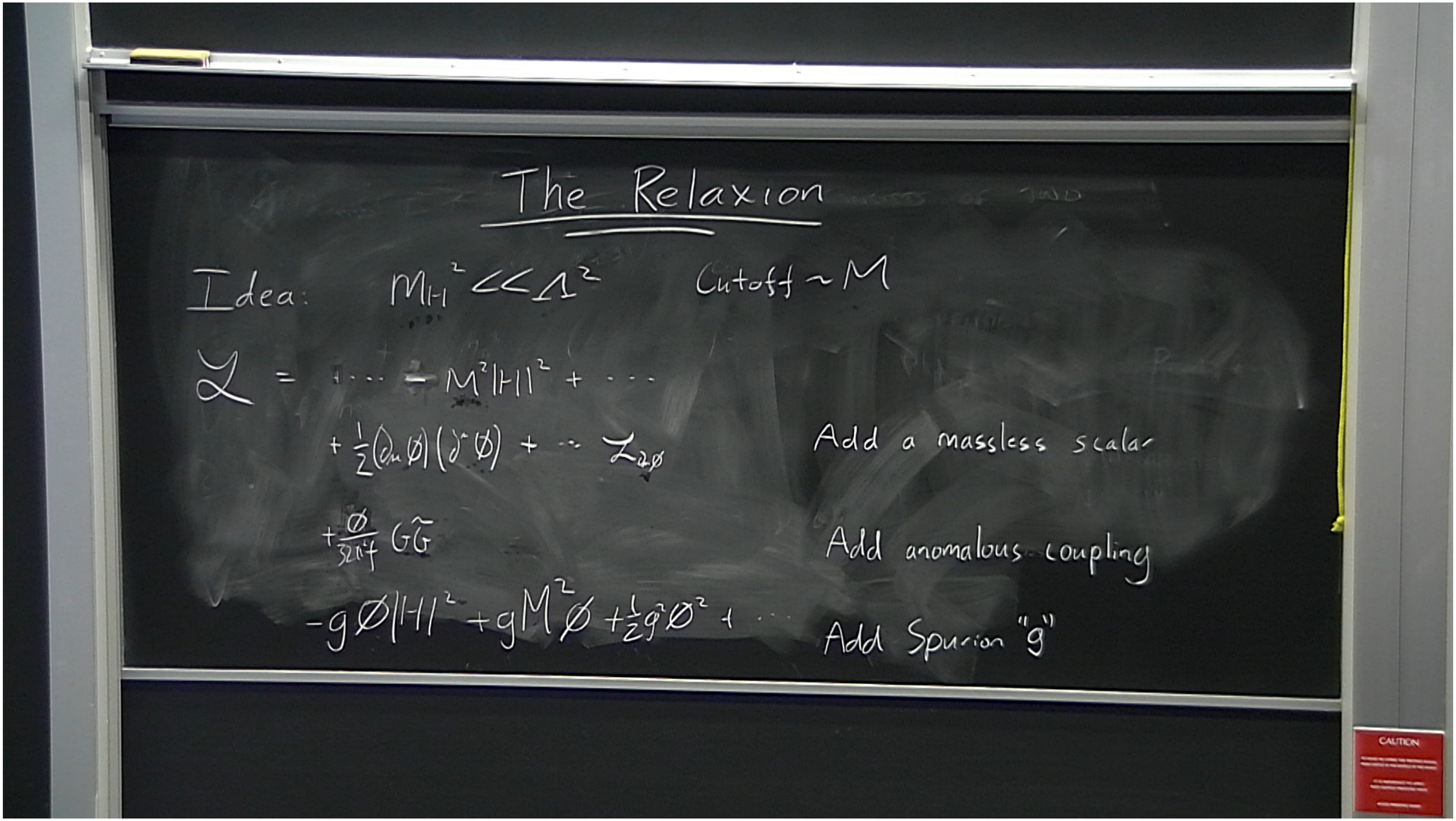

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$ Cutoff ~ M
$\mathcal{L} = \dots - M^2|H|^2 + \dots$
$+ \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \dots \mathcal{L}_{H\phi}$
Add a massless scalar

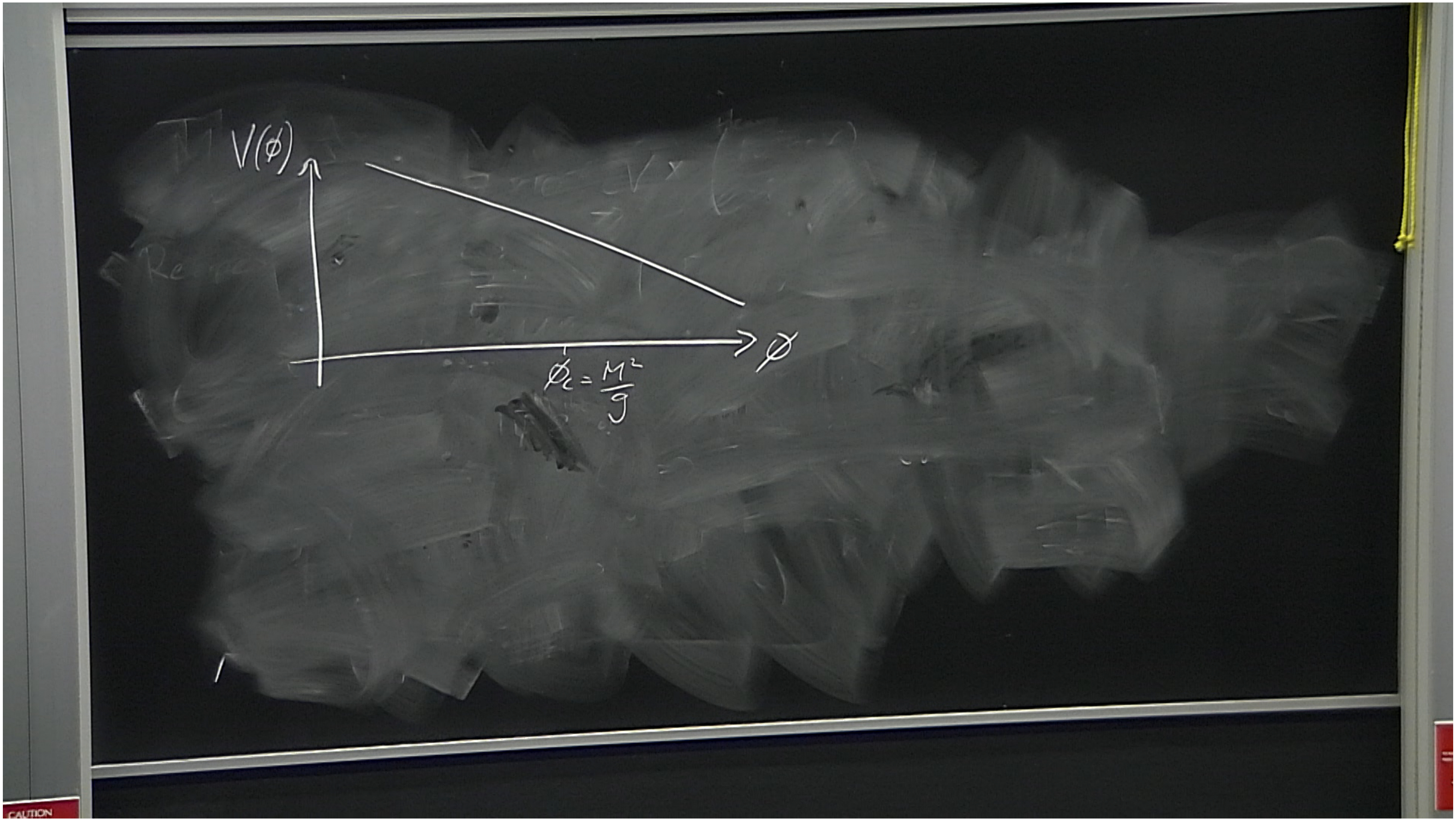

The Relaxion
Idea: M_H^2 << Λ^2
Cutoff ~ M
L = ... − M^2|H|^2 + ...
+ 1/2 (∂_μ φ)(∂^μ φ) + ... L_Hφ
Add a massless scalar
+ φ/(32π^2 f) G G̃
Add anomalous coupling
CAUTION


The Relaxion
Idea: $m_H^2 \ll \Lambda^2$
Cutoff ~ M
$\mathcal{L} = + \cdots - M^2|H|^2 + \cdots$
$+ \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \cdots \mathcal{L}_{H\phi}$
$+ \frac{\phi}{32\pi^2 f} G\tilde{G}$
Add a massless scalar
Add anomalous coupling
Add Spurion "g"

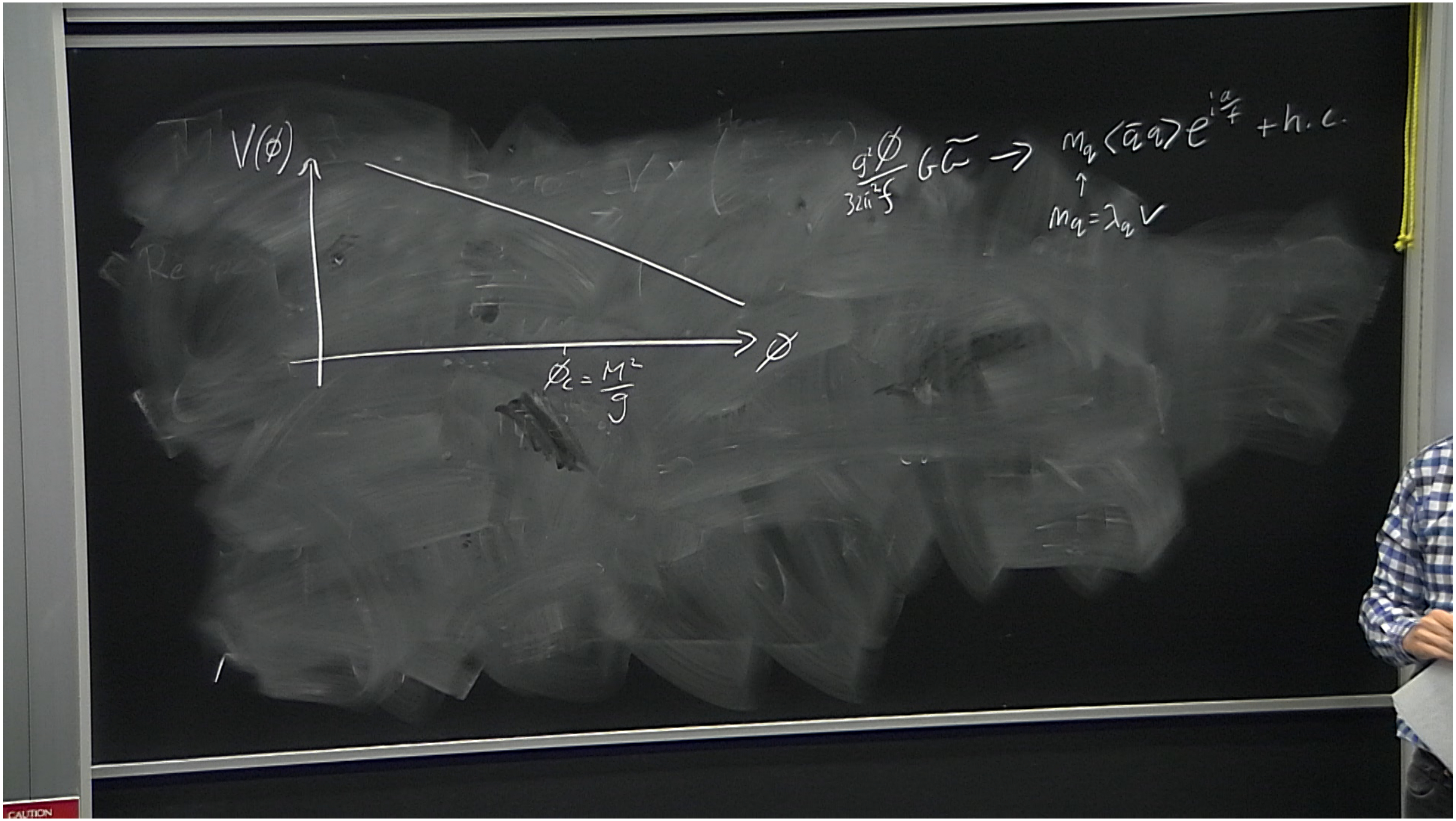

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$
Cutoff ~ M
$\mathcal{L} = + \cdots - M^2|H|^2 + \cdots$
$+ \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \cdots \mathcal{L}_{2\phi}$
Add a massless scalar
$+ \frac{\phi}{32\pi^2 f} G\tilde{G}$
Add anomalous coupling
$- g\phi|H|^2 + gM^2\phi + \frac{1}{2}g^2\phi^2 + \cdots$
Add Spurion "g"

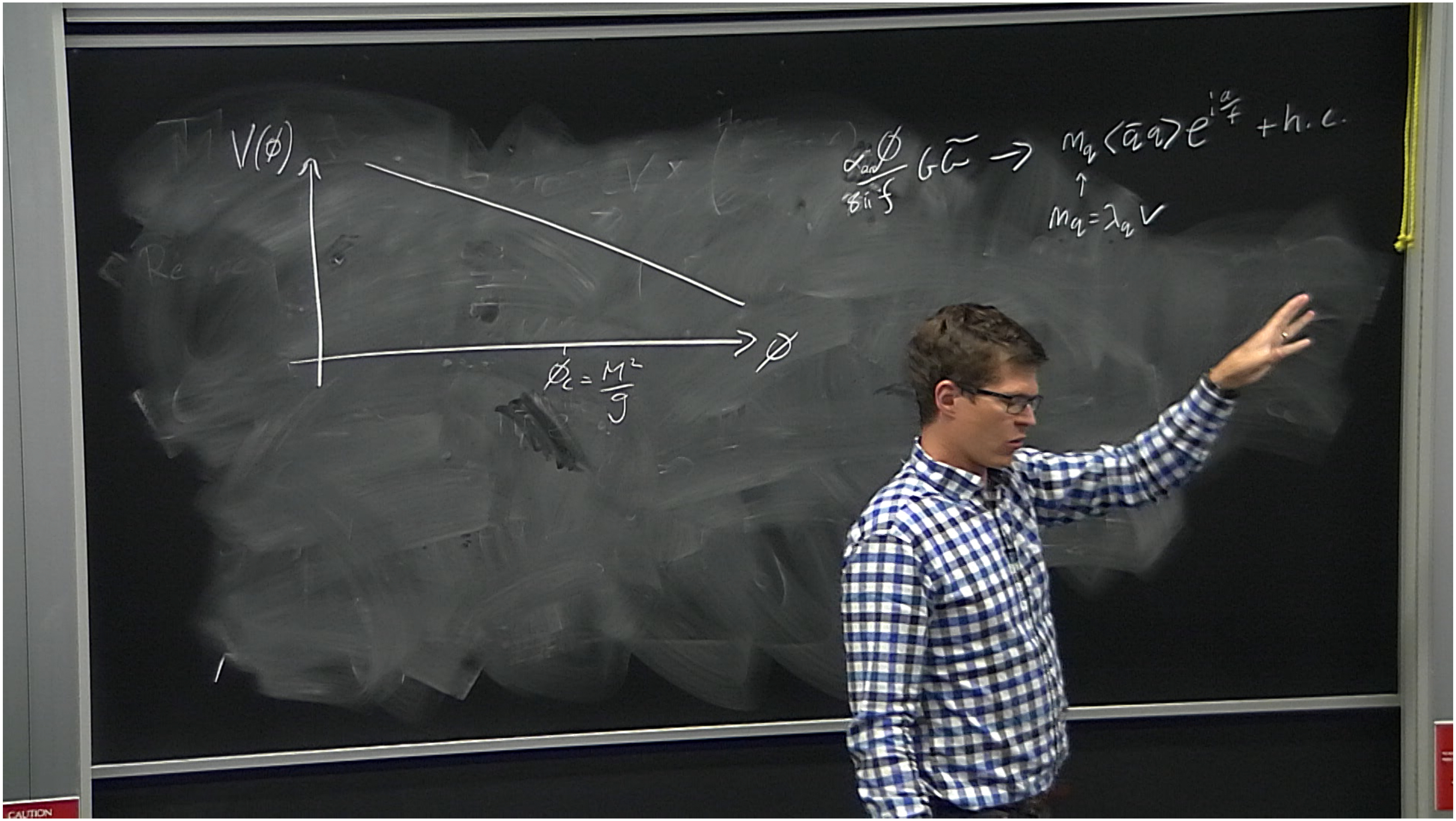

V(ϕ)
ϕ

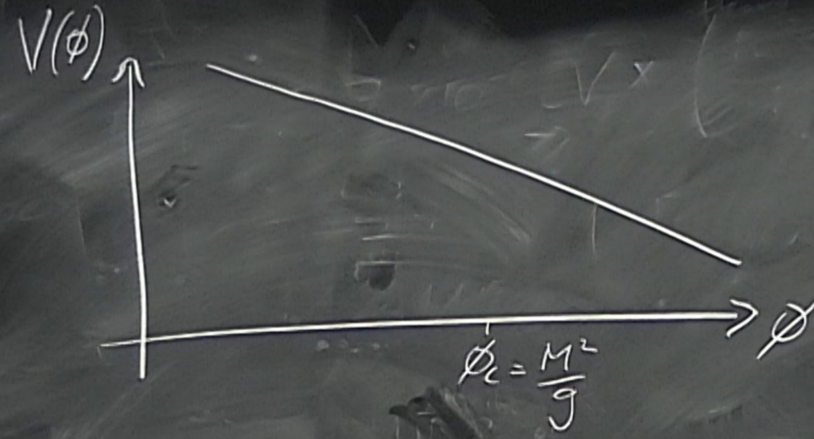

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$
Cutoff ~ M
$\mathcal{L} = + \cdots - M^2|H|^2 + \cdots$
$+ \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \cdots \mathcal{L}$
Add a massless scalar
$+ \frac{\phi}{32\pi^2 f} G\tilde{G}$
Add anomalous coupling
$-g\phi|H|^2 + gM^2\phi + \frac{1}{2}g^2\phi^2 + \cdots$
Add Spurion "g"



$V(\phi)$
ϕ
$\phi_c = \frac{M^2}{g}$


$V(\phi)$
ϕ
$\phi_c = \frac{M^2}{g}$
$\frac{g^2 \phi}{32\pi^2 f} G\tilde{G} \rightarrow m_q \langle \bar{q} q \rangle e^{i\frac{a}{f}} + h.c.$
$m_q = \lambda_q v$


V(φ)
φ
φc = M²/g
αs φ / 8π f G G̃ → mq ⟨q̄q⟩ e^{i a/f} + h.c.
mq = λq v

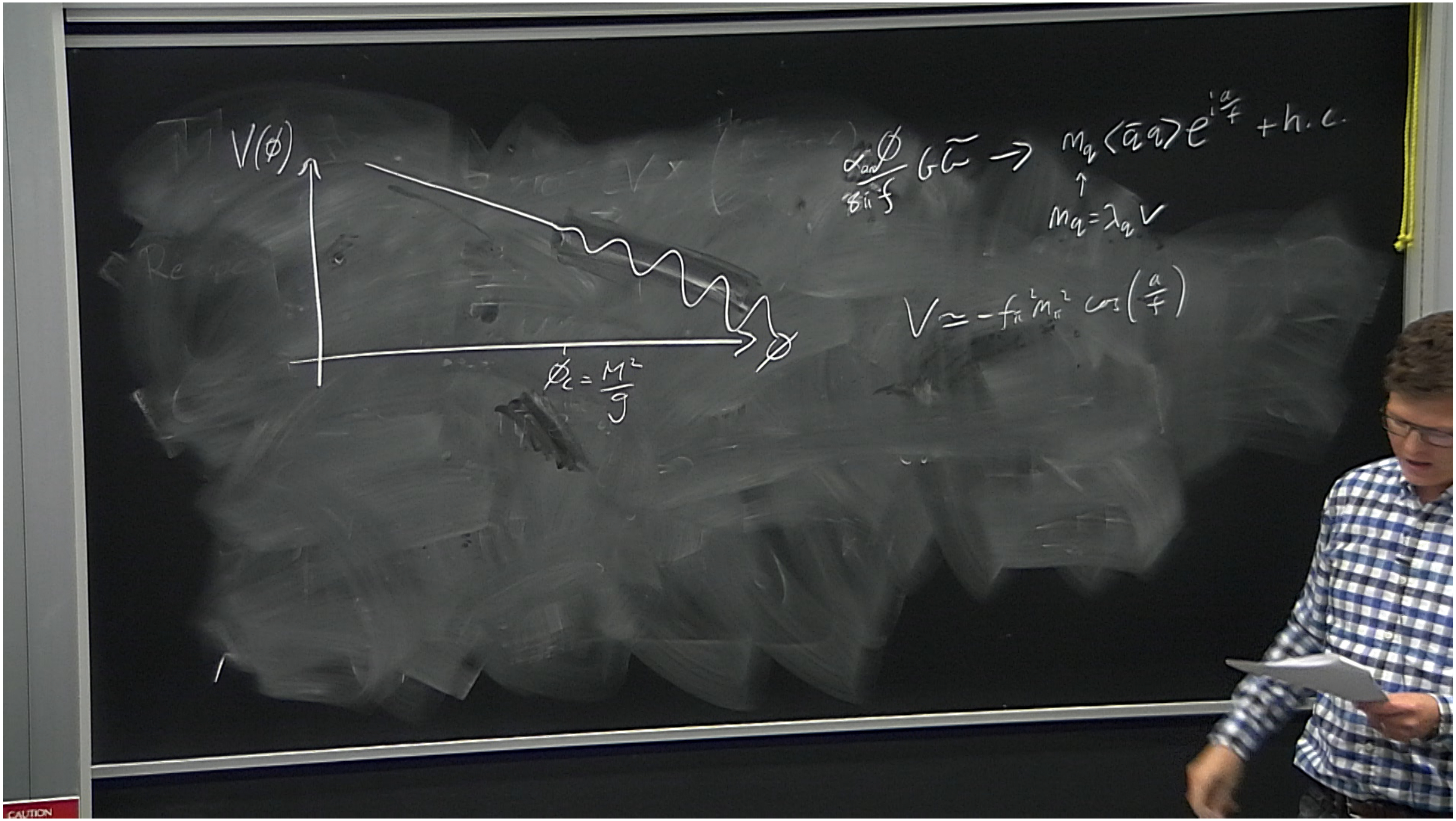


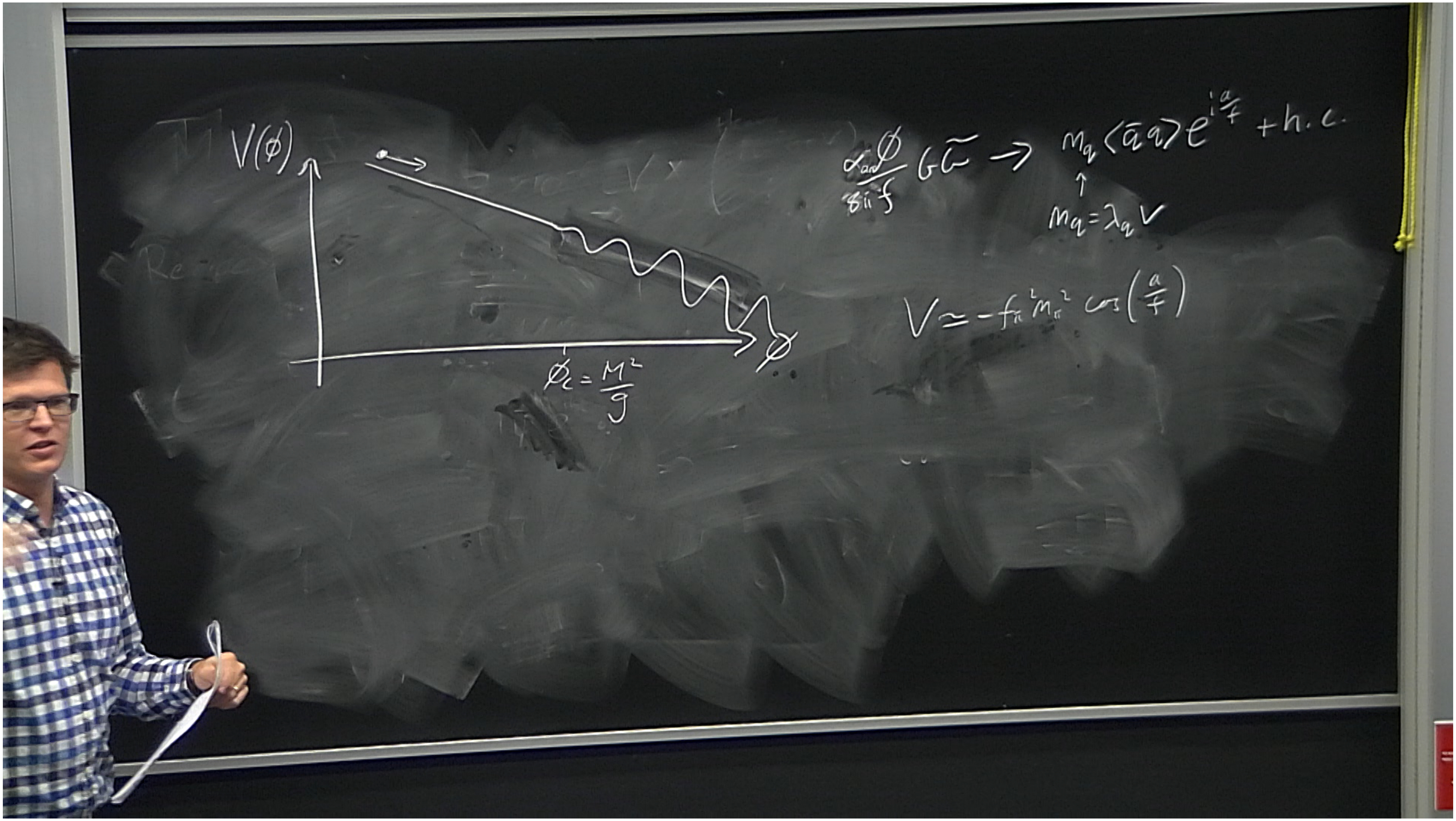
$$\frac{\alpha_{an}\,\phi}{8\pi f}\, G\tilde{G} \rightarrow m_q \langle \bar{q} q \rangle e^{i\frac{a}{f}} + h.c.$$

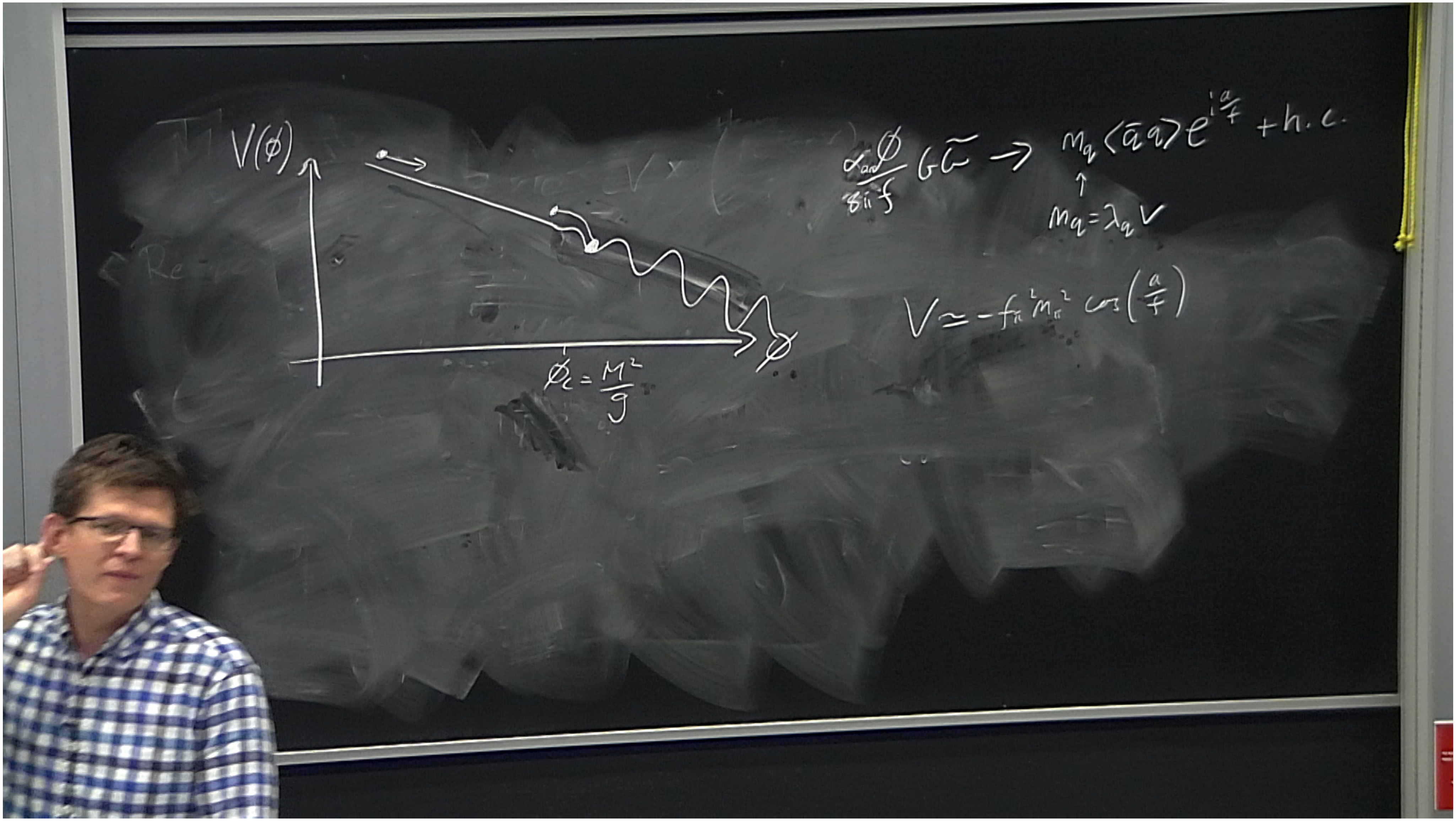
$$\uparrow$$

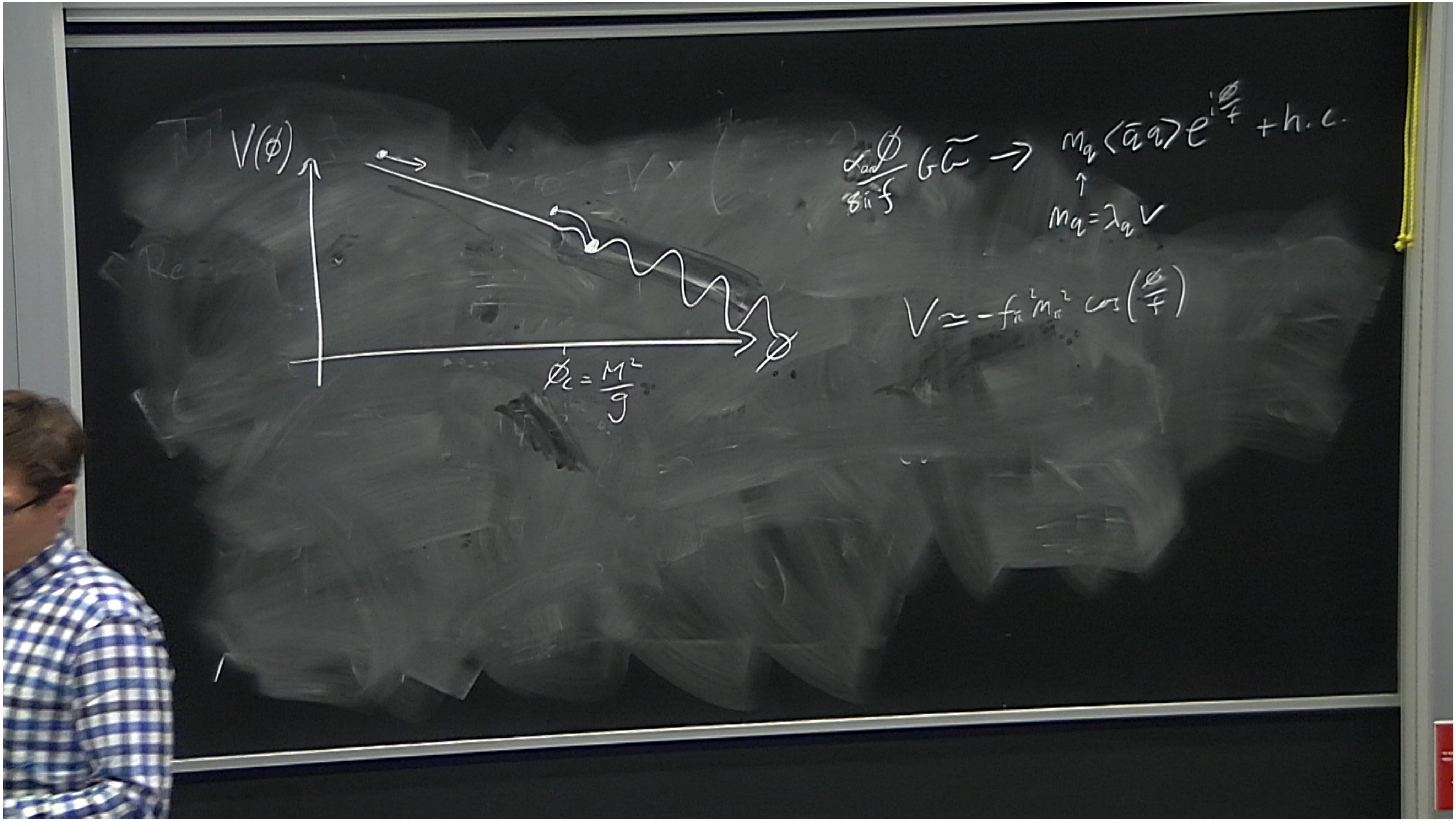
$$m_q = \lambda_q v$$

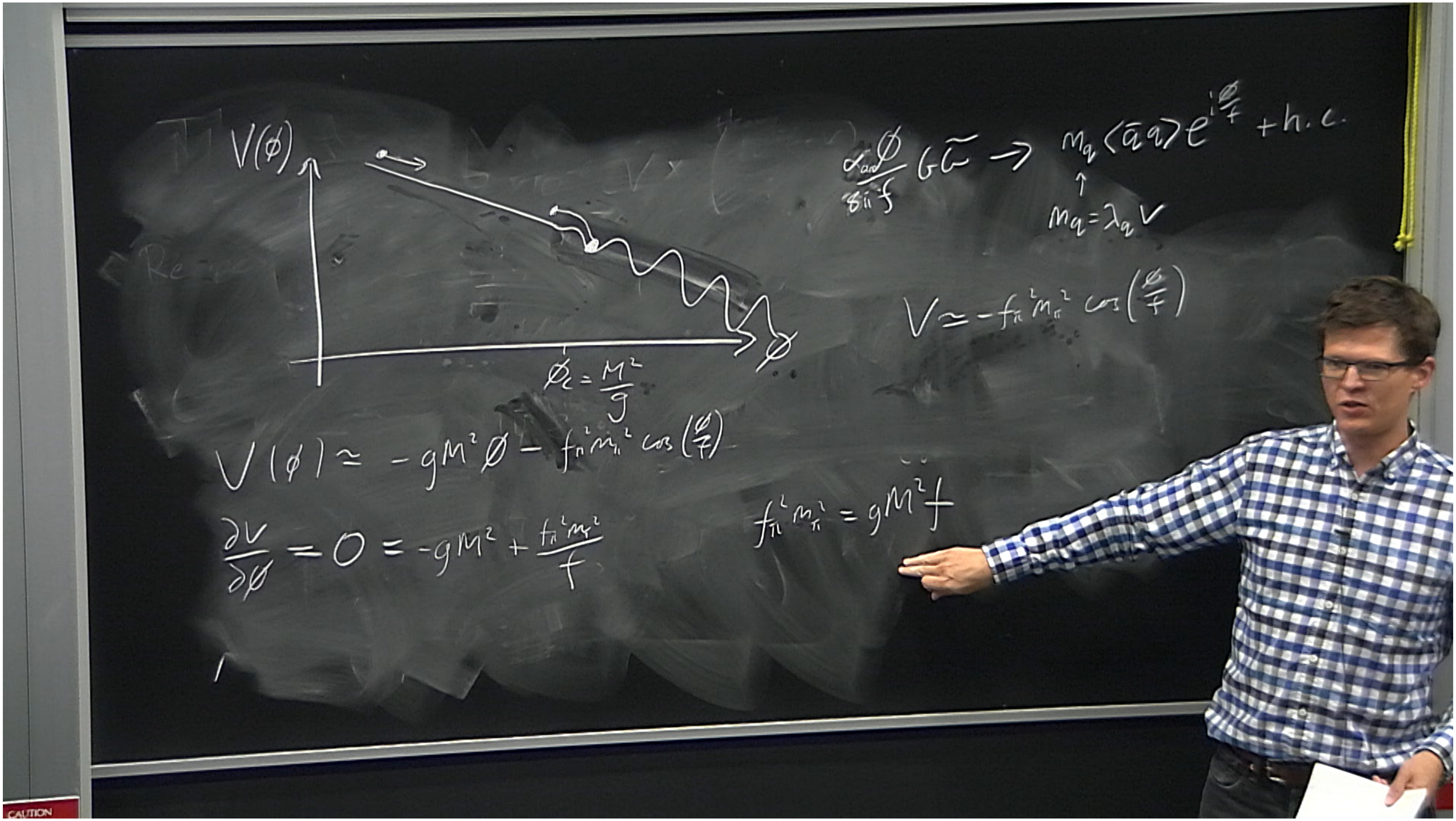
$$V \simeq -f_\pi^2 m_\pi^2 \cos\left(\frac{a}{f}\right)$$

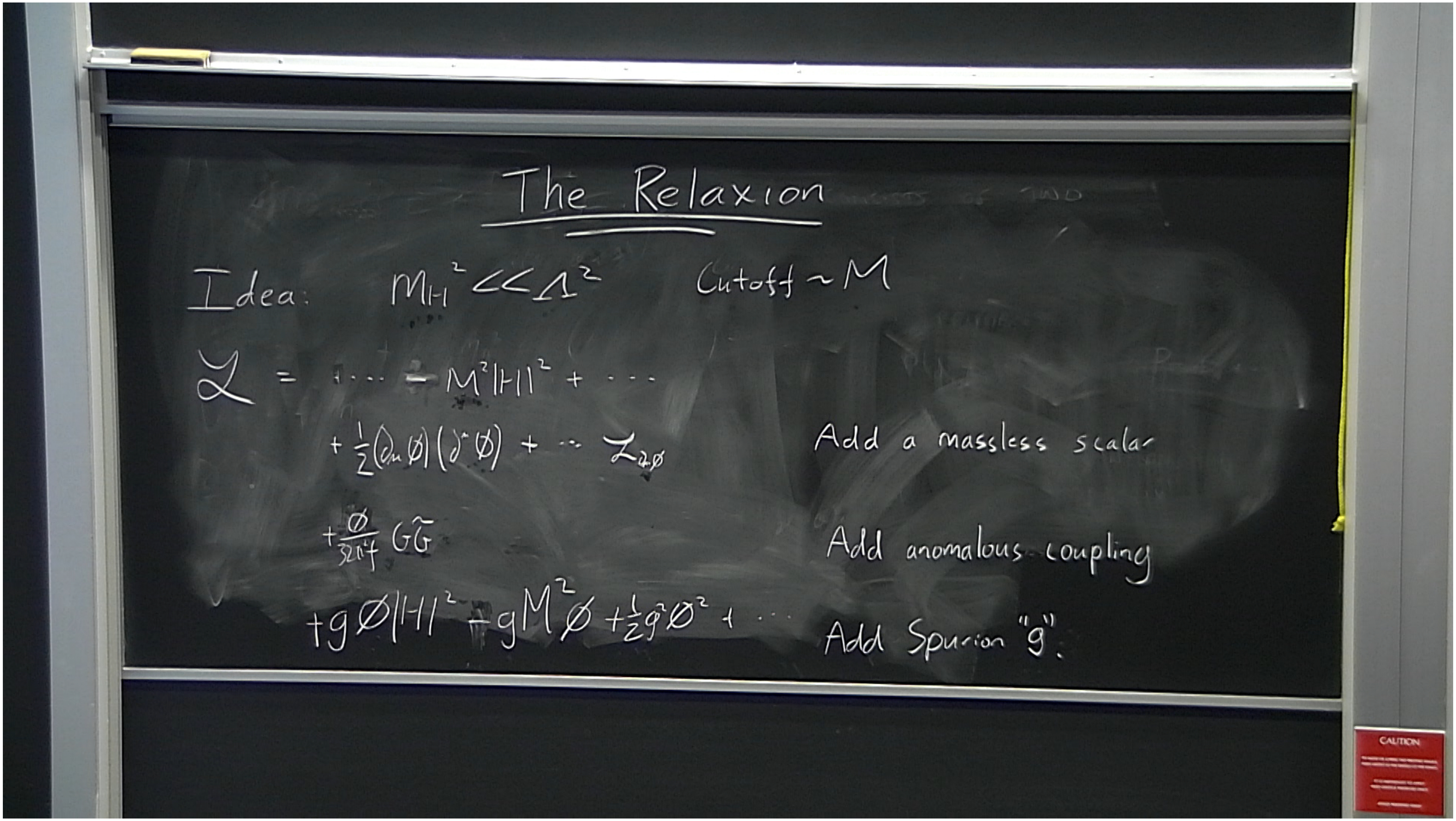

$V(\phi)$
$\phi_c = \frac{M^2}{g}$
ϕ
$\frac{\alpha_{em}\phi}{8\pi f} G\tilde{G} \rightarrow m_q \langle \bar{q} q \rangle e^{i\frac{a}{f}} + h.c.$
$m_q = \lambda_q v$
$V \simeq -f_\pi^2 m_\pi^2 \cos\left(\frac{a}{f}\right)$
CAUTION

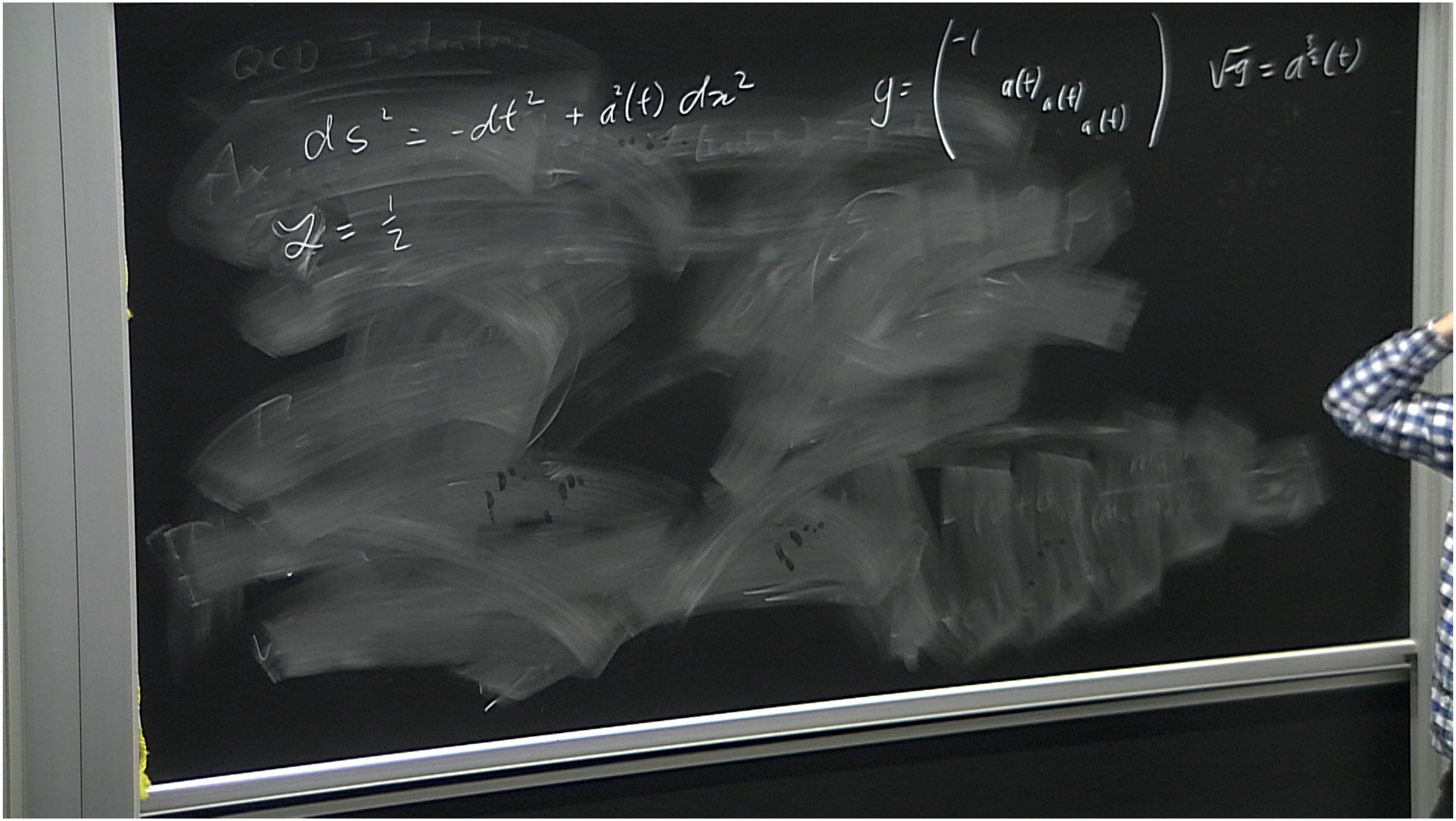

V(ϕ)
ϕ
ϕ_c = M²/g
α_em ϕ / 8π f G G̃ → m_q ⟨q̄q⟩ e^{i a/f} + h.c.
m_q = λ_q v
V ≃ −f_π² m_π² cos(a/f)


V(φ)
φ
φc = M²/g
αem φ / 8π f GG̃ → mq ⟨q̄q⟩ e^(i a/f) + h.c.
mq = λq V
V ≃ -fπ² mπ² cos(a/f)

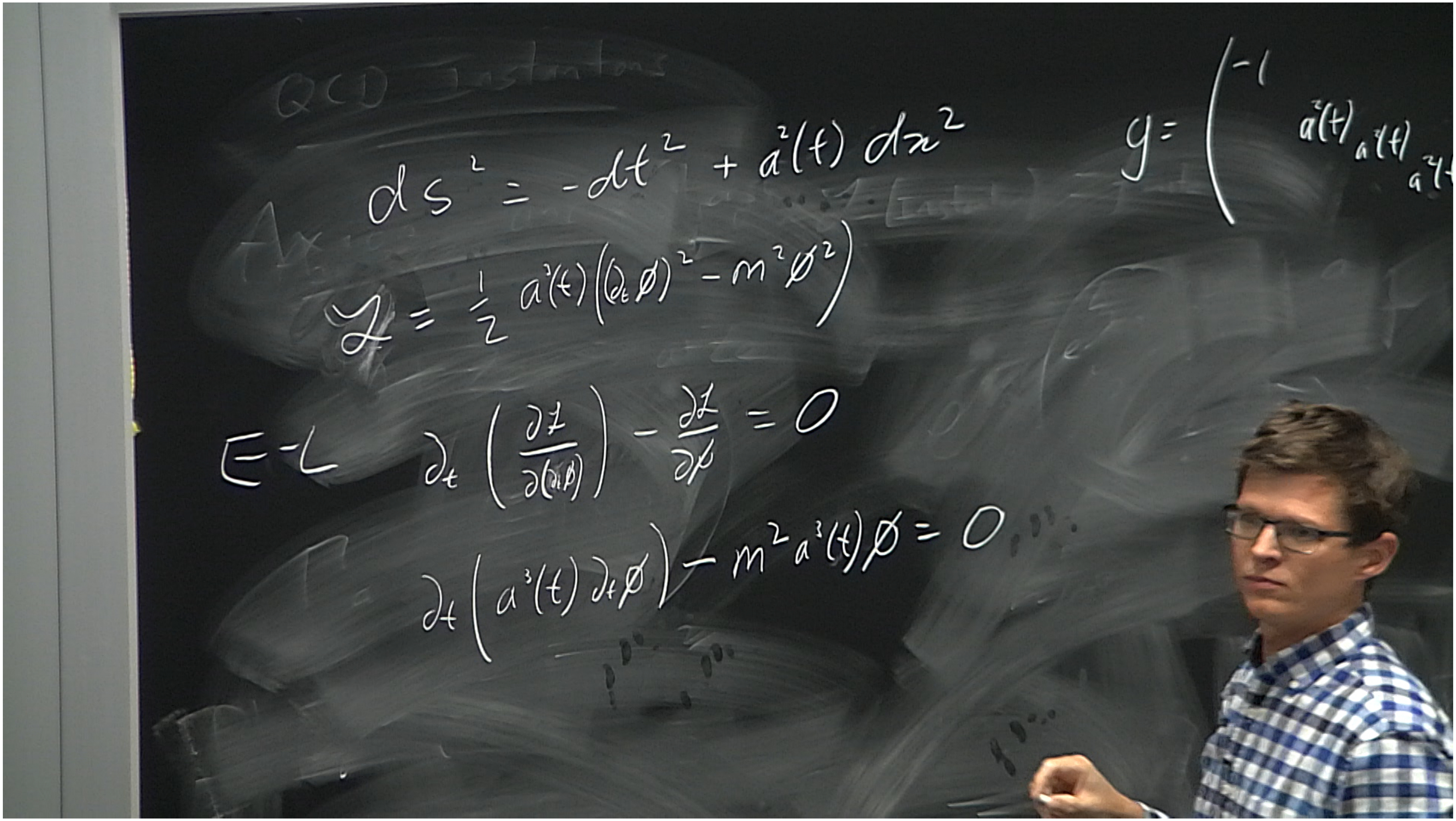

V(ϕ)
ϕ
ϕ_c = M²/g
α_em ϕ/(8π f) G G̃ → m_q ⟨q̄q⟩ e^{iϕ/f} + h.c.
m_q = λ_q v
V ≃ − f_π² m_π² cos(ϕ/f)

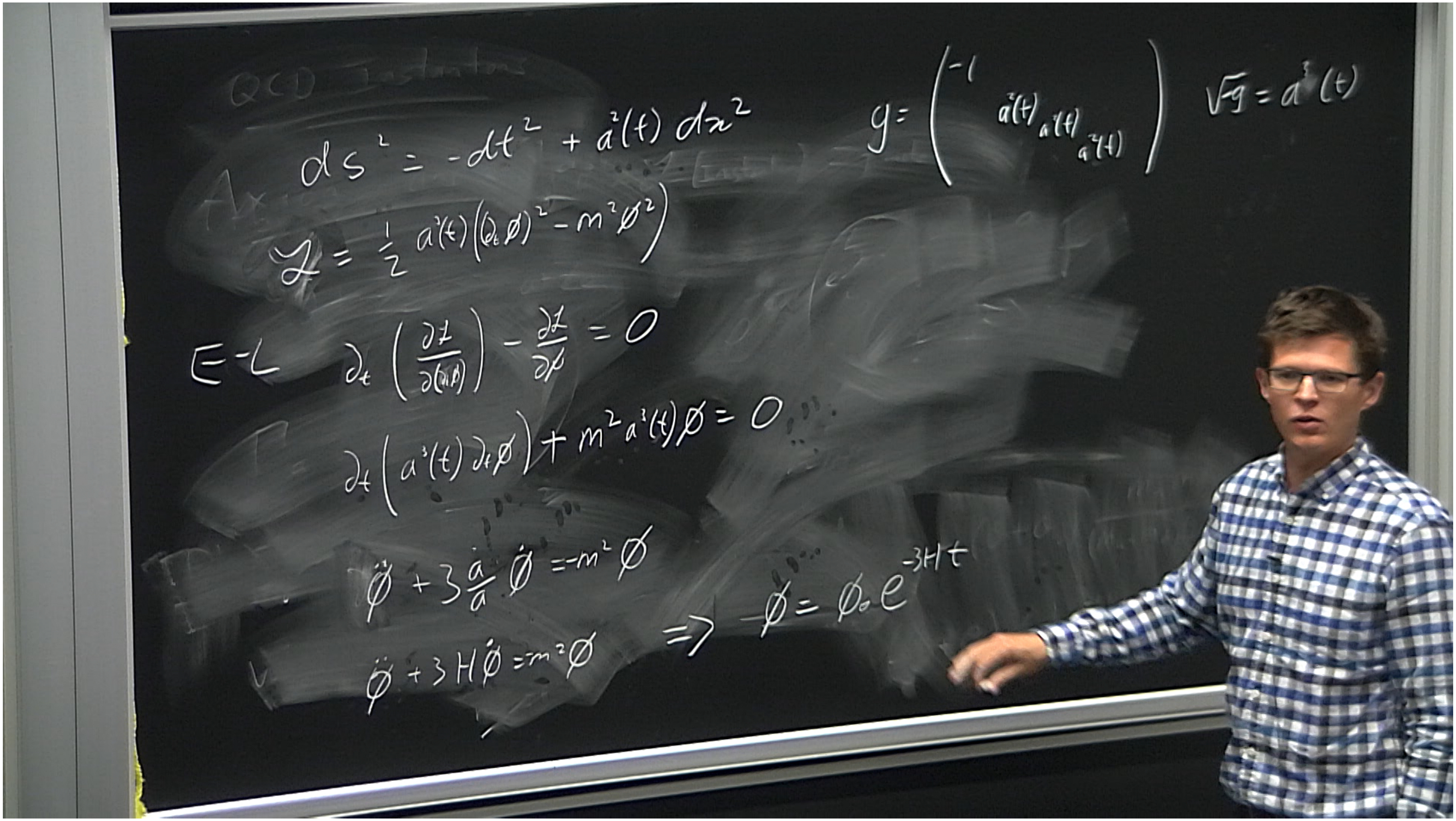

V(ϕ)
ϕ_c = M²/g
ϕ
V(ϕ) ≃ −gM²ϕ − f_π² m_π² cos(ϕ/f)
∂V/∂ϕ = 0 = −gM² + f_π² m_π²/f
f_π² m_π² = gM² f
α_s ϕ/(8π f) G G̃ → m_q ⟨q̄q⟩ e^{iϕ/f} + h.c.
m_q = λ_q V
V ≃ −f_π² m_π² cos(ϕ/f)

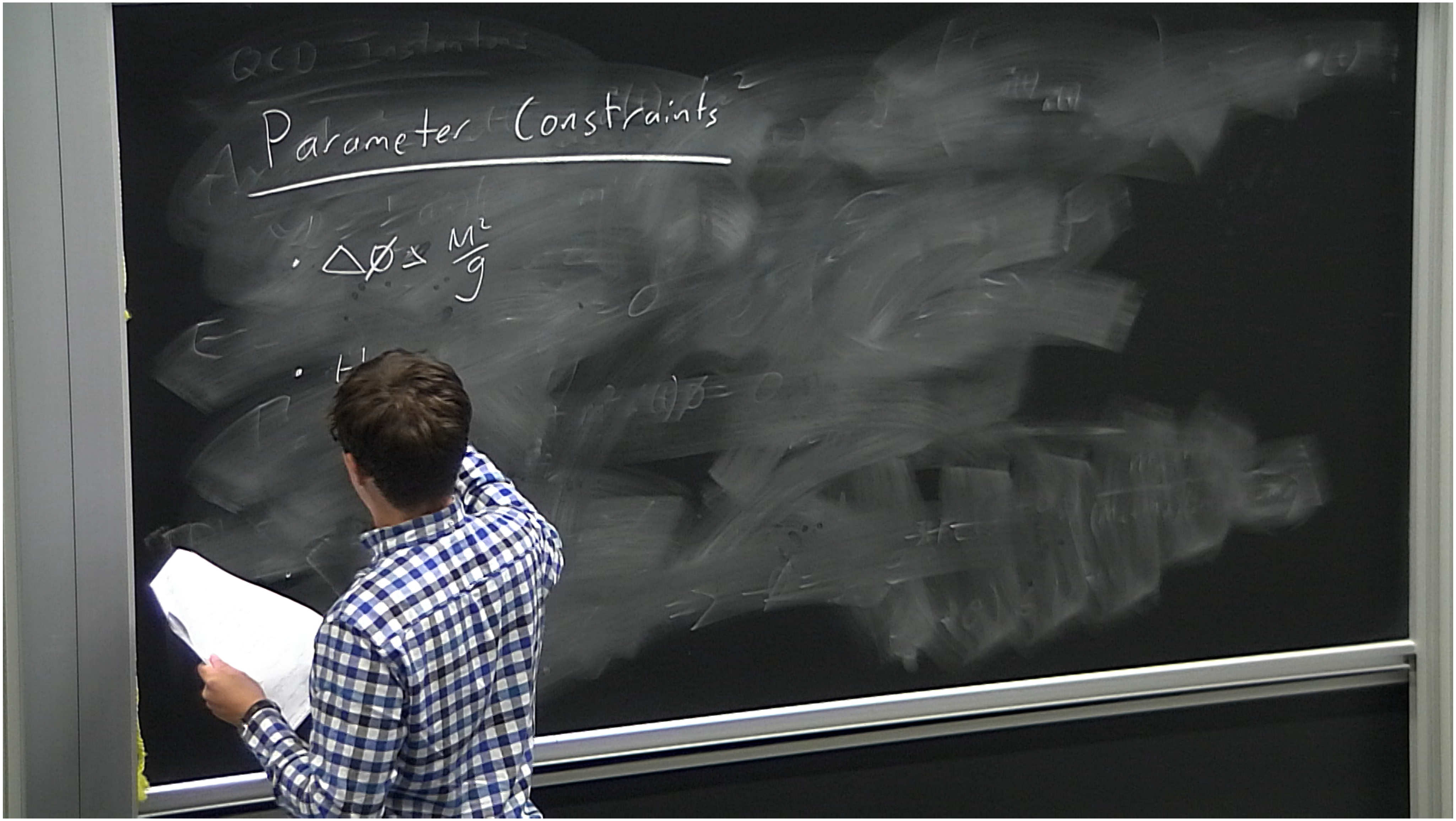

The Relaxion
Idea: $m_H^2 \ll \Lambda^2$ Cutoff $\sim M$
$\mathcal{L} = \cdots - M^2|H|^2 + \cdots$
$+ \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) + \cdots \mathcal{L}_{H\phi}$
Add a massless scalar
$+ \frac{\phi}{32\pi^2} G\tilde{G}$
Add anomalous coupling
$+ g\phi|H|^2 - gM^2\phi + \frac{1}{2}g^2\phi^2 + \cdots$
Add Spurion "g".

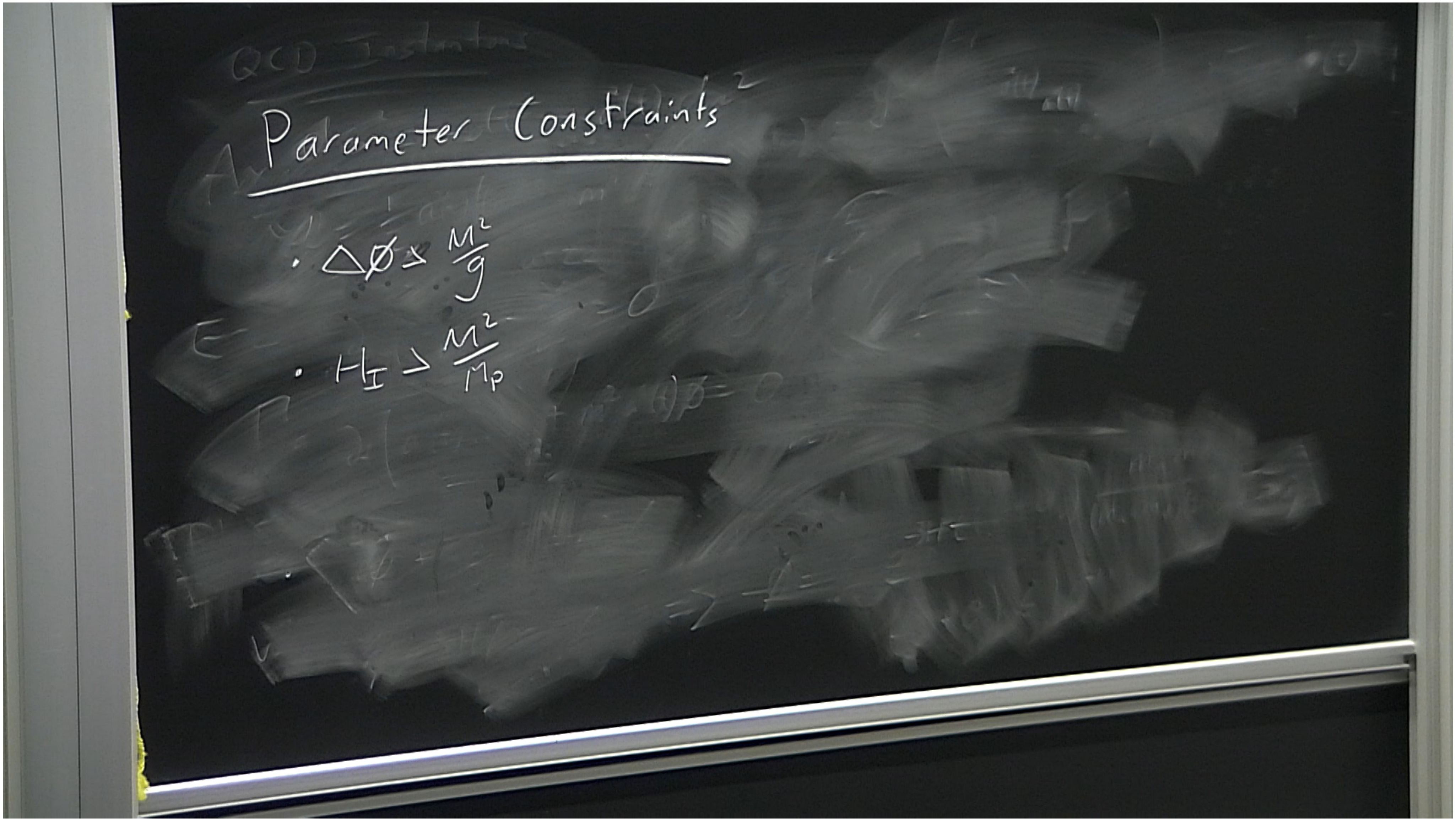

$ds^2 = -dt^2 + a^2(t)\, dx^2$
$g = \begin{pmatrix} -1 & & & \\ & a(t) & & \\ & & a(t) & \\ & & & a(t) \end{pmatrix}$
$\sqrt{-g} = a^{3/2}(t)$
$\gamma = \frac{1}{2}$

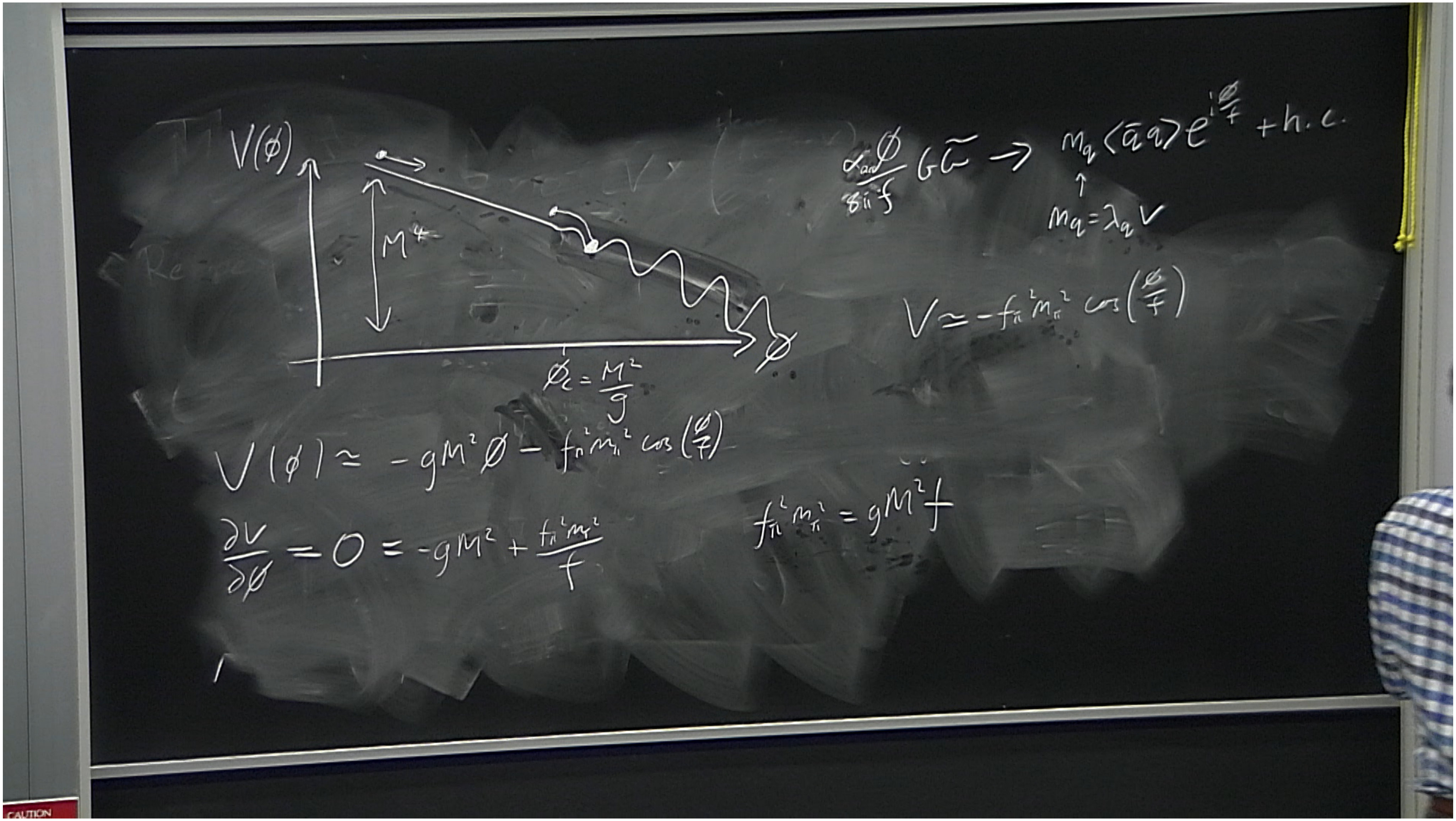
$$g = \begin{pmatrix} -1 & & & \\ & a^2(t) & & \\ & & a^2(t) & \\ & & & a^2(t) \end{pmatrix} \qquad \sqrt{-g} = a^3(t)$$

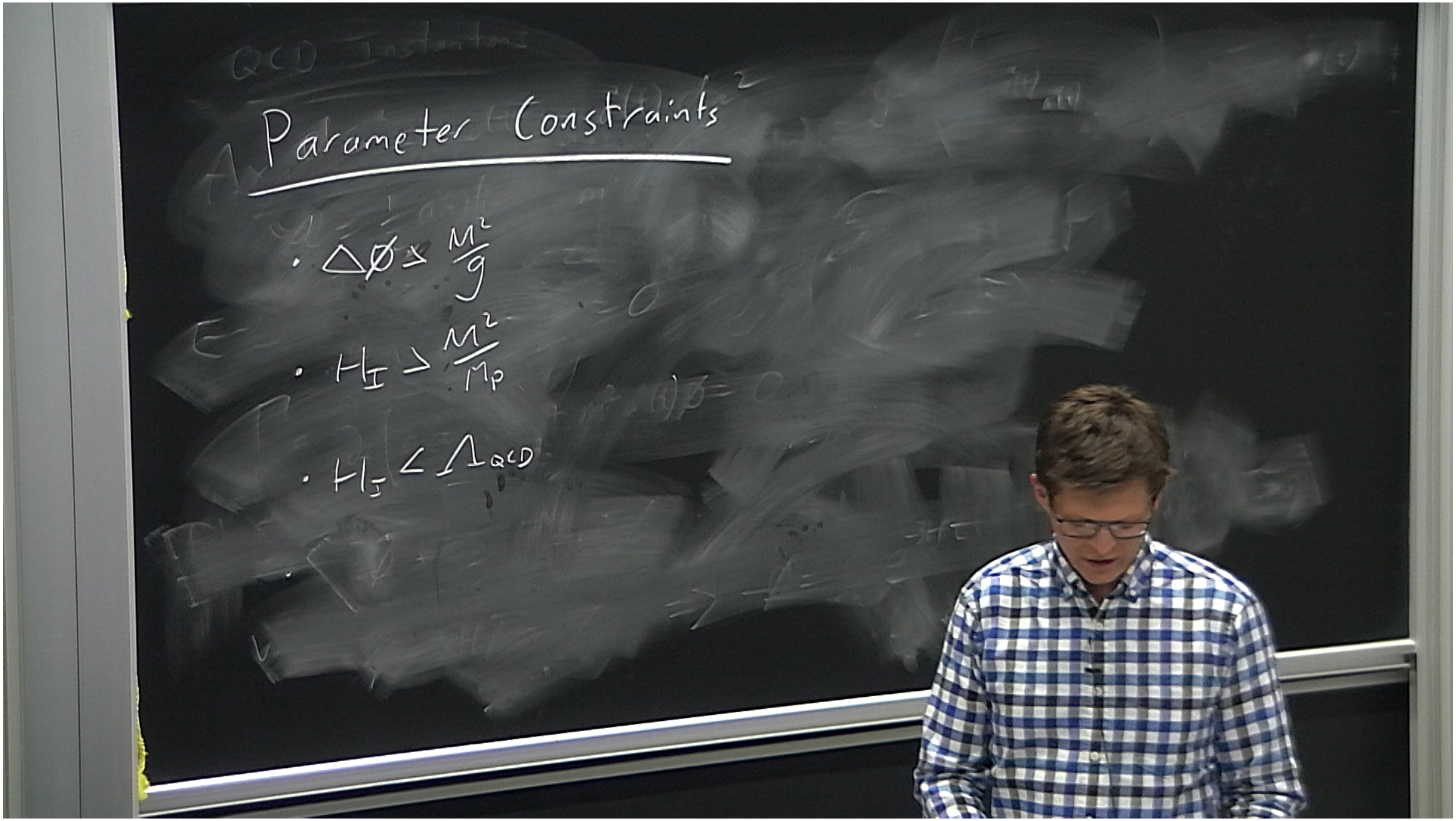

ds² = -dt² + a²(t) dx²
g = (-1 a²(t) a²(t) a²(t)
L = ½ a²(t)((∂ₜφ)² - m²φ²)
E-L ∂ₜ(∂L / ∂(∂ₜφ)) - ∂L/∂φ = 0
∂ₜ(a³(t) ∂ₜφ) - m² a³(t) φ = 0

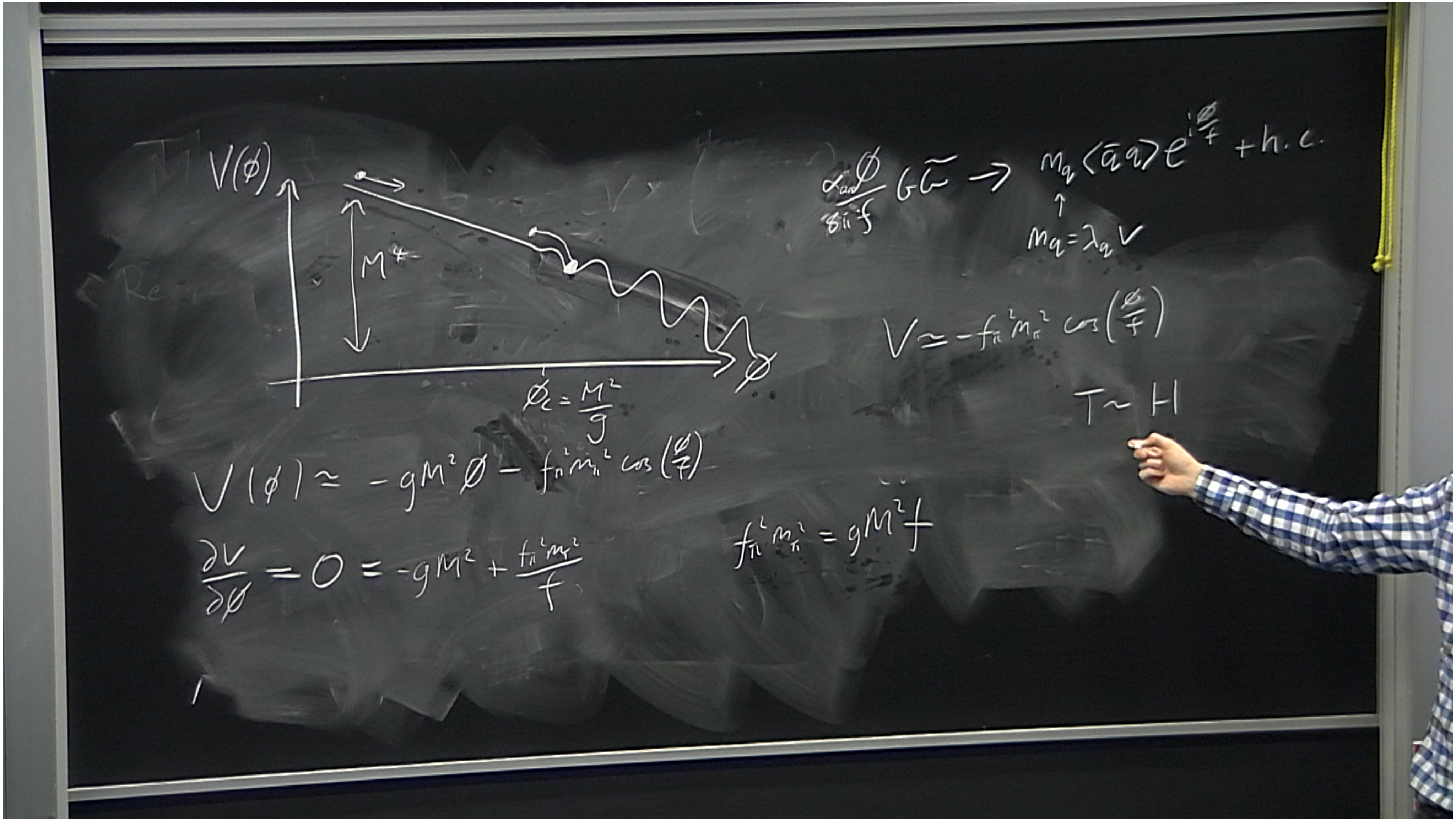

ds² = -dt² + a²(t) dx²
g = (-1 a²(t) a²(t) a²(t))
√-g = a³(t)
𝓛 = ½ a³(t) ((∂ₜφ)² - m²φ²)
E-L ∂ₜ (∂𝓛 / ∂(∂ₜφ)) - ∂𝓛/∂φ = 0
∂ₜ (a³(t) ∂ₜφ) + m² a³(t) φ = 0
φ̈ + 3 (ȧ/a) φ̇ = -m² φ
φ̈ + 3Hφ̇ = -m²φ
=> φ = φ₀ e^{-3Ht}

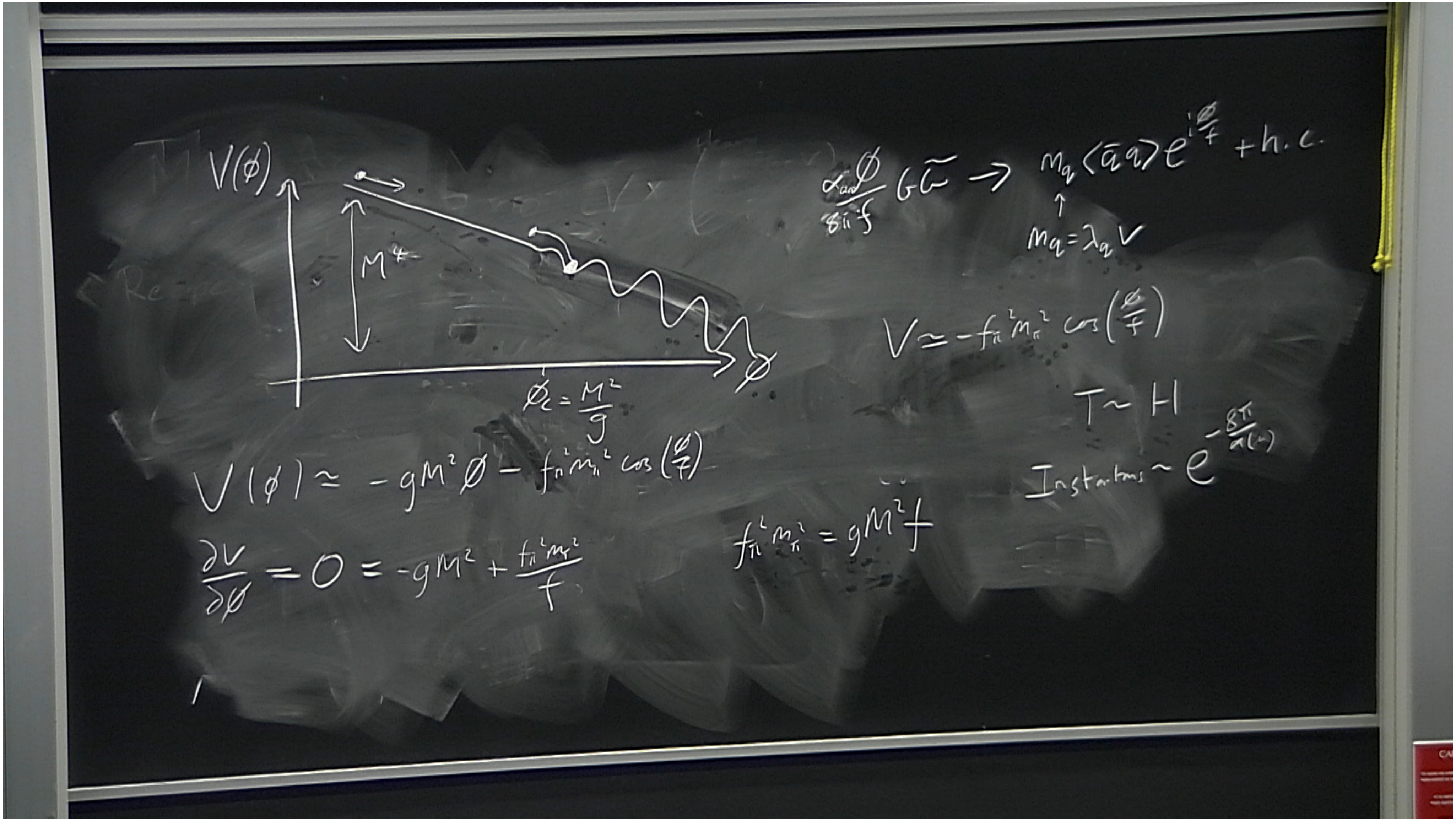

Parameter Constraints
· ΔØ ≳ M²/g
· H

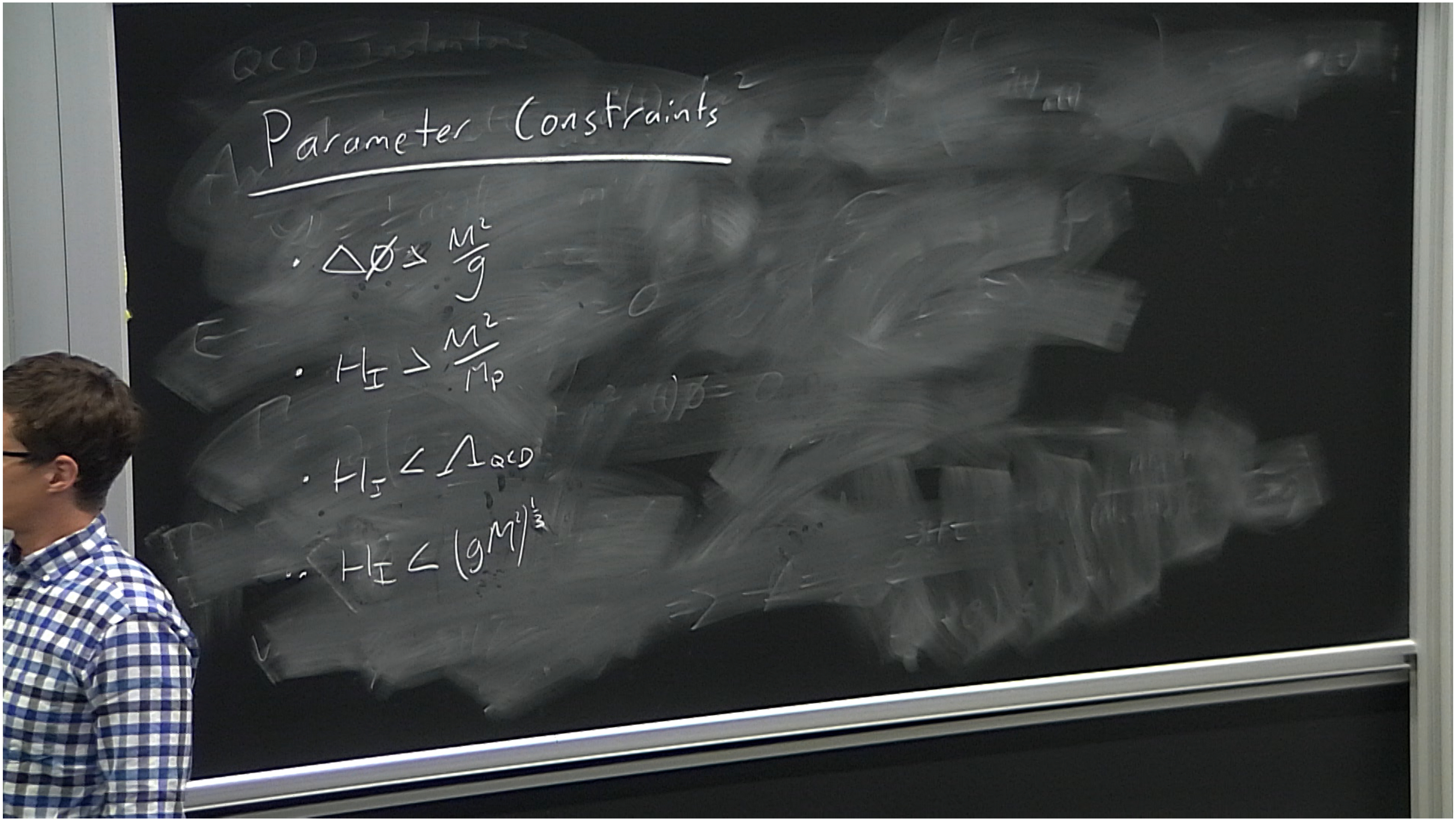

Parameter Constraints
• ΔΦ ≳ M²/g
• H_I ≳ M²/M_p

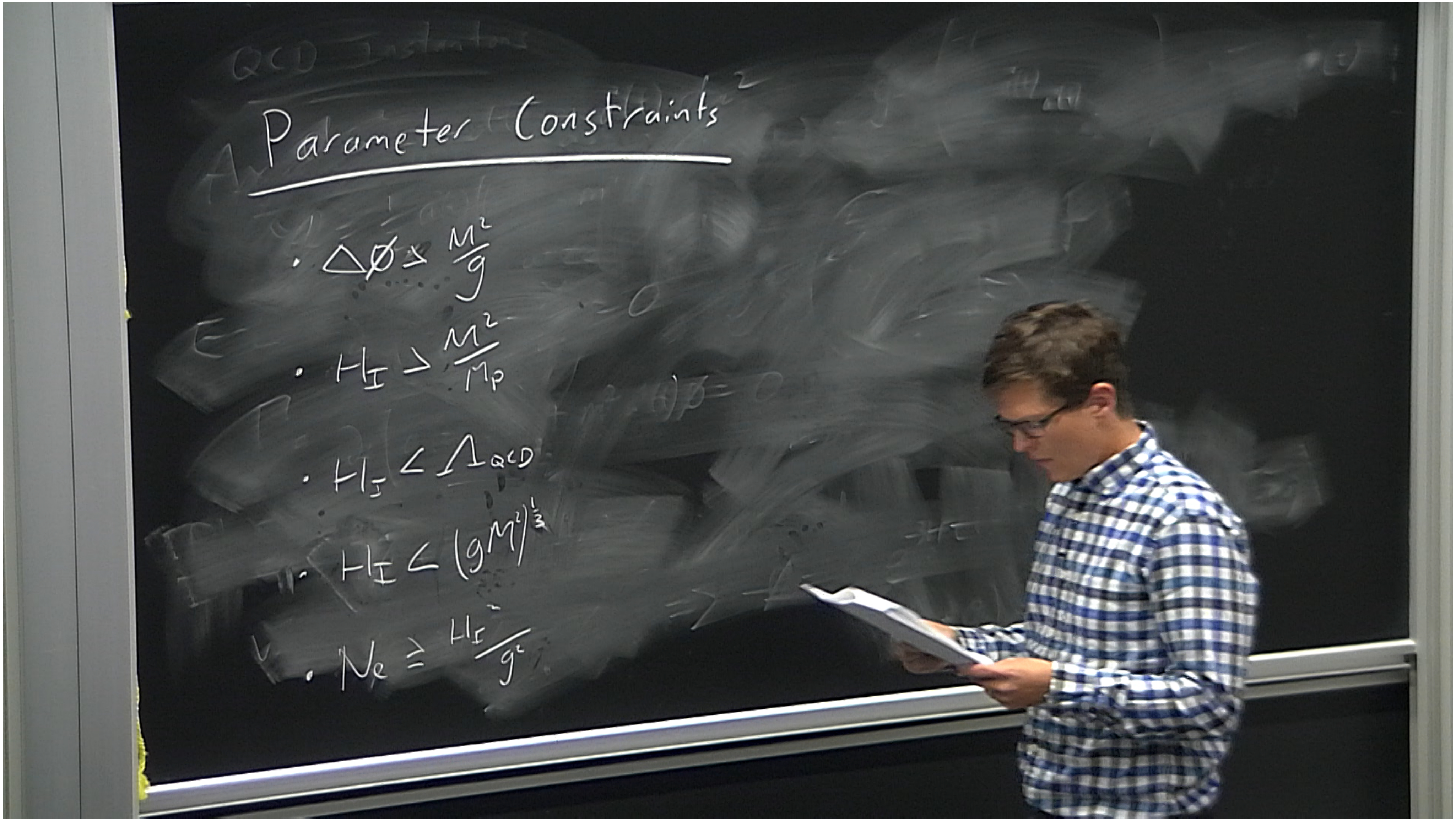

V(ϕ)
M⁴
ϕ_c = M²/g
ϕ
α_s ϕ / 8π f G G̃ → m_q ⟨q̄q⟩ e^{iϕ/f} + h.c.
m_q = λ_q v
V ≃ − f_π² m_π² cos(ϕ/f)
V(ϕ) ≃ − gM² ϕ − f_π² m_π² cos(ϕ/f)
∂V/∂ϕ = 0 = − gM² + f_π² m_π² / f
f_π² m_π² = gM² f

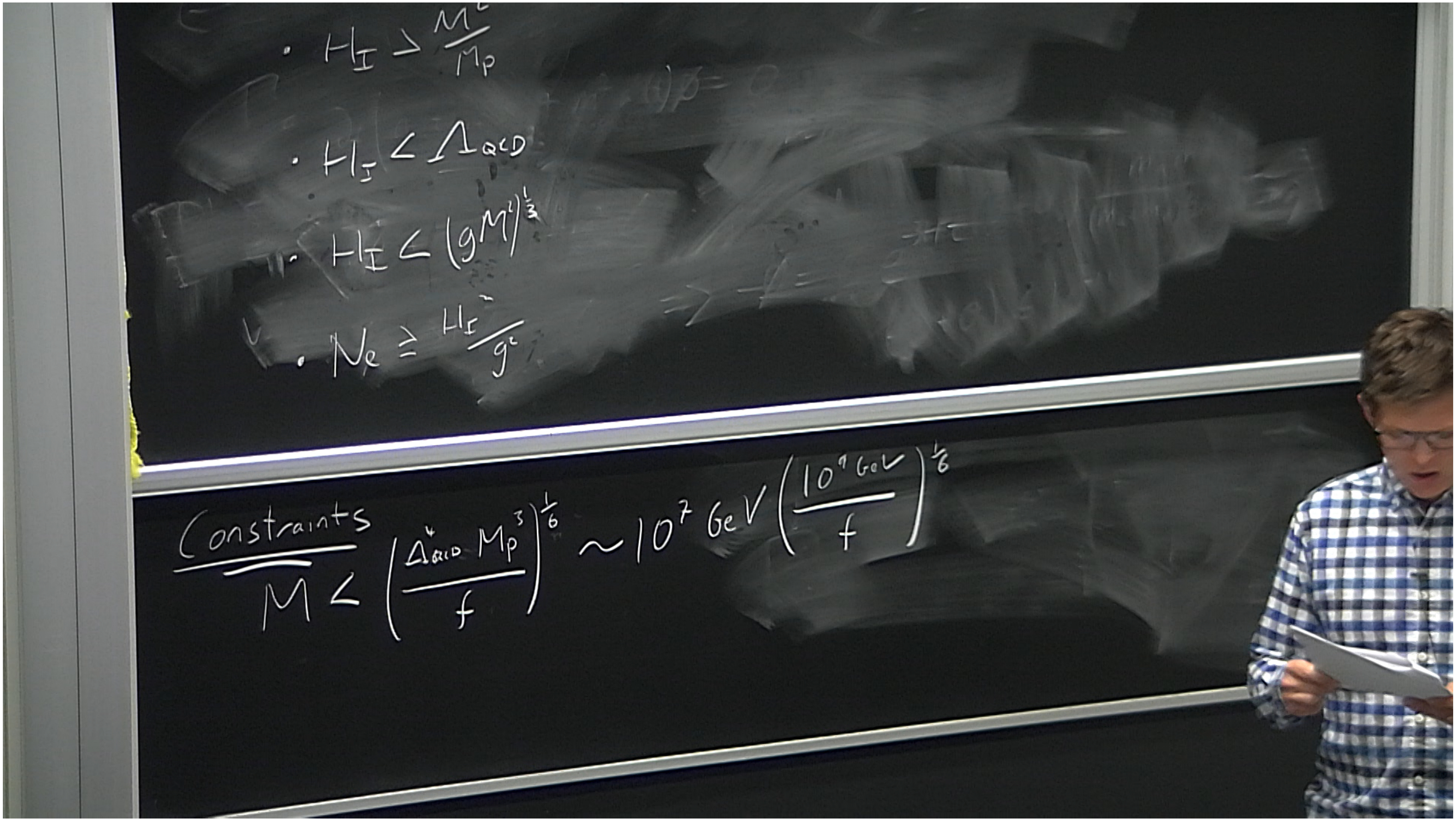

Parameter Constraints
• $\Delta\phi > \frac{M^2}{g}$
• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$

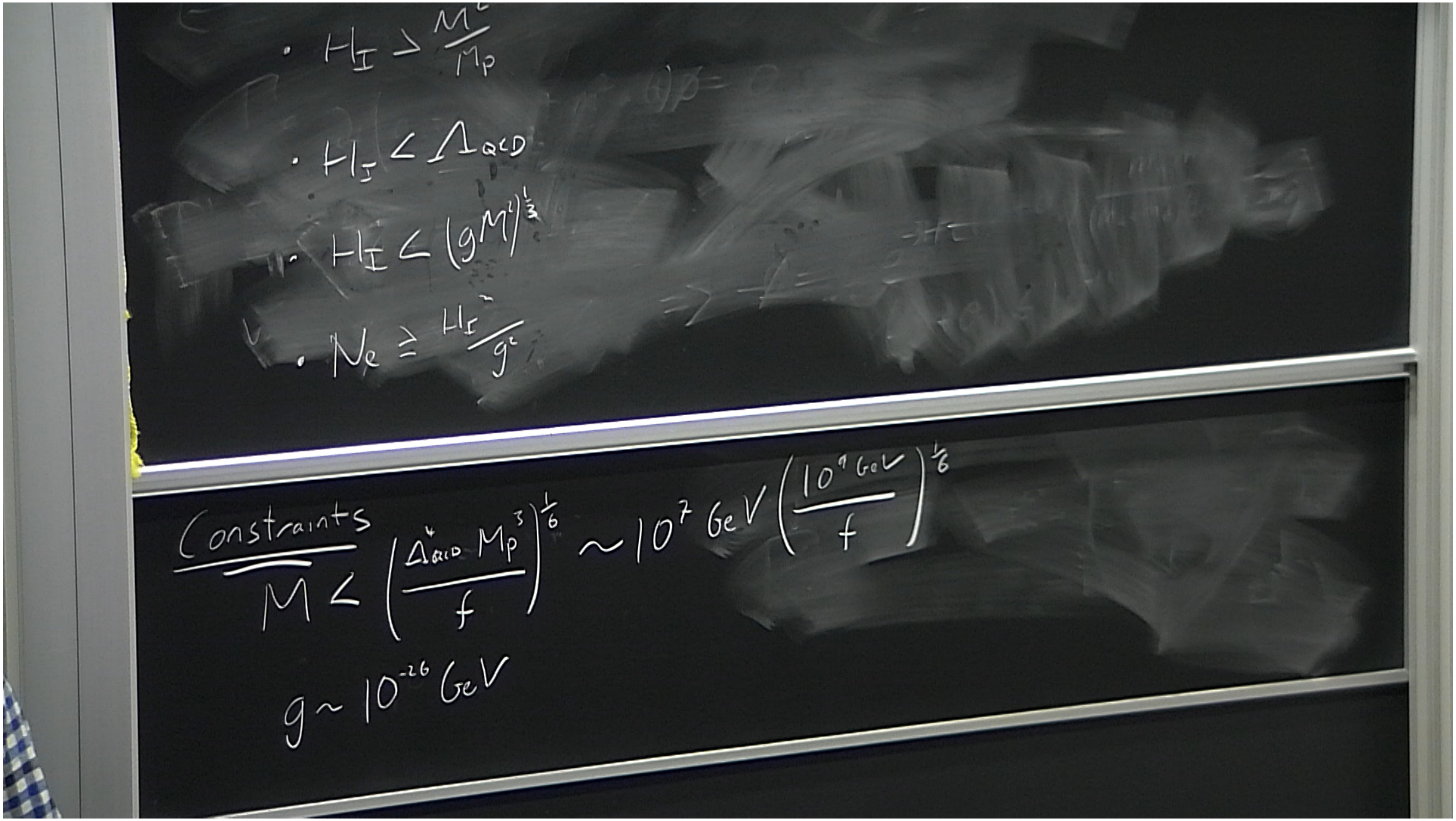

V(ϕ)
M⁴
ϕc = M²/g
ϕ
αem ϕ / 8π f G G̃ → mq ⟨q̄q⟩ e^(iϕ/f) + h.c.
mq = λq V
V ≃ − fπ² mπ² cos(ϕ/f)
T ~ H
V(ϕ) ≃ − gM² ϕ − fπ² mπ² cos(ϕ/f)
∂V/∂ϕ = 0 = −gM² + fπ² mπ² / f
fπ² mπ² = gM² f

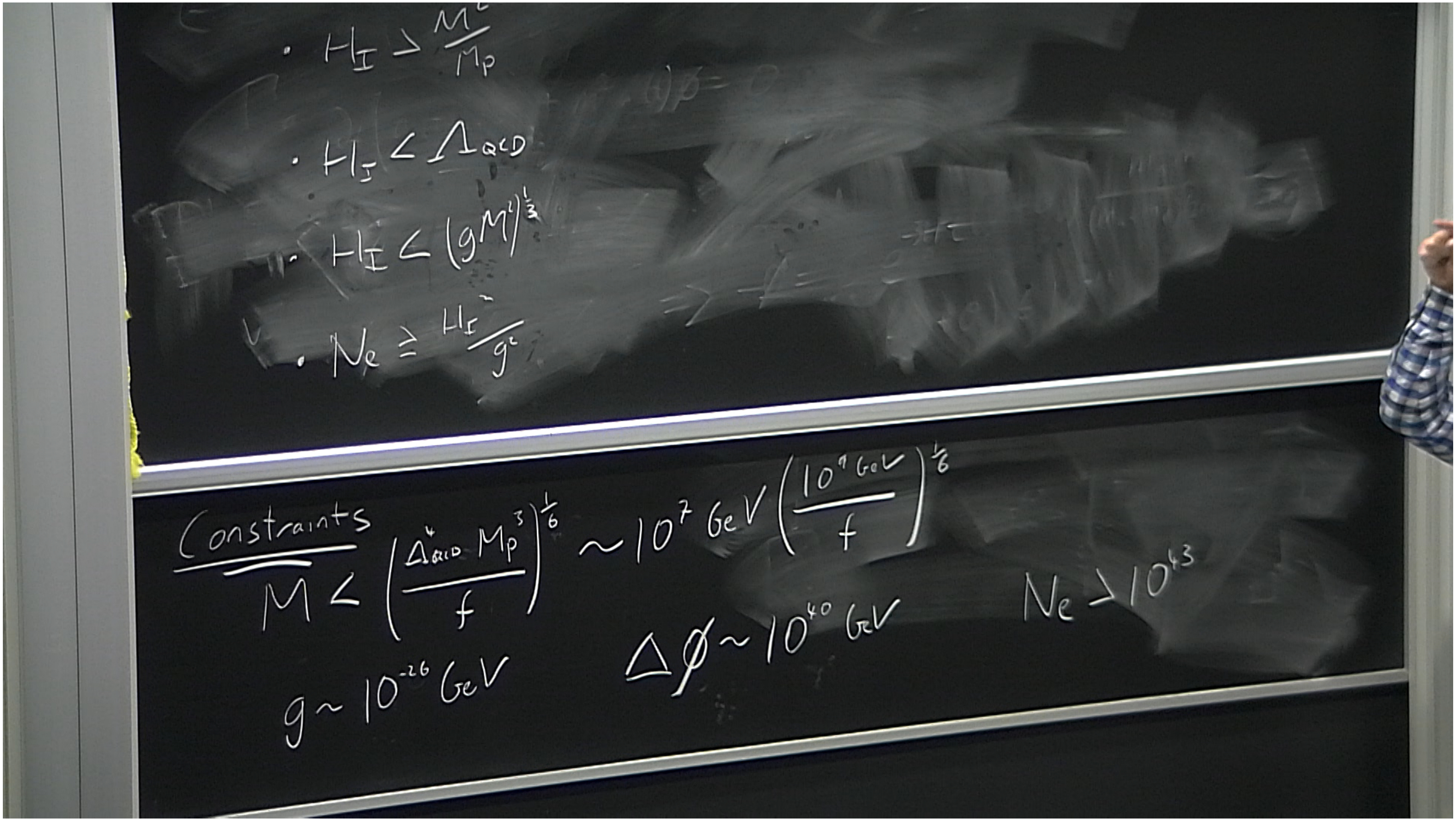

V(ϕ)
M^4
ϕ_c = M^2/g
V(ϕ) ≃ −gM^2 ϕ − f_π^2 m_π^2 cos(ϕ/f)
∂V/∂ϕ = 0 = −gM^2 + f_π^2 m_π^2 / f
f_π^2 m_π^2 = gM^2 f
α_an ϕ / 8π f GG̃ → m_q ⟨q̄q⟩ e^{iϕ/f} + h.c.
m_q = λ_q V
V ≃ −f_π^2 m_π^2 cos(ϕ/f)
T ~ H
Instantons ~ e^{−8π/α(μ)}

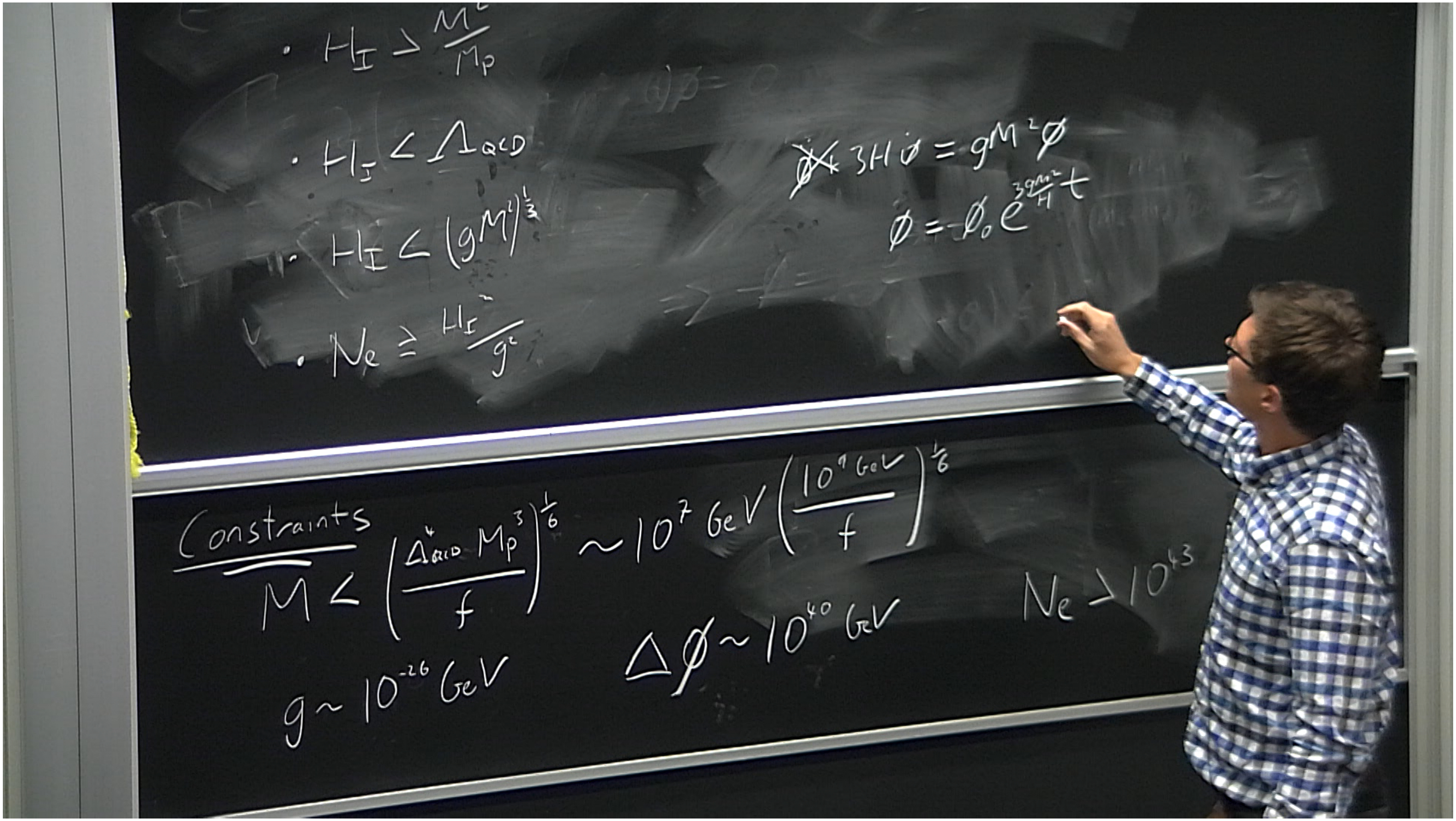

Parameter Constraints
• $\Delta\phi > \frac{M^2}{g}$
• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$
• $H_I < (gM^2)^{\frac{1}{3}}$

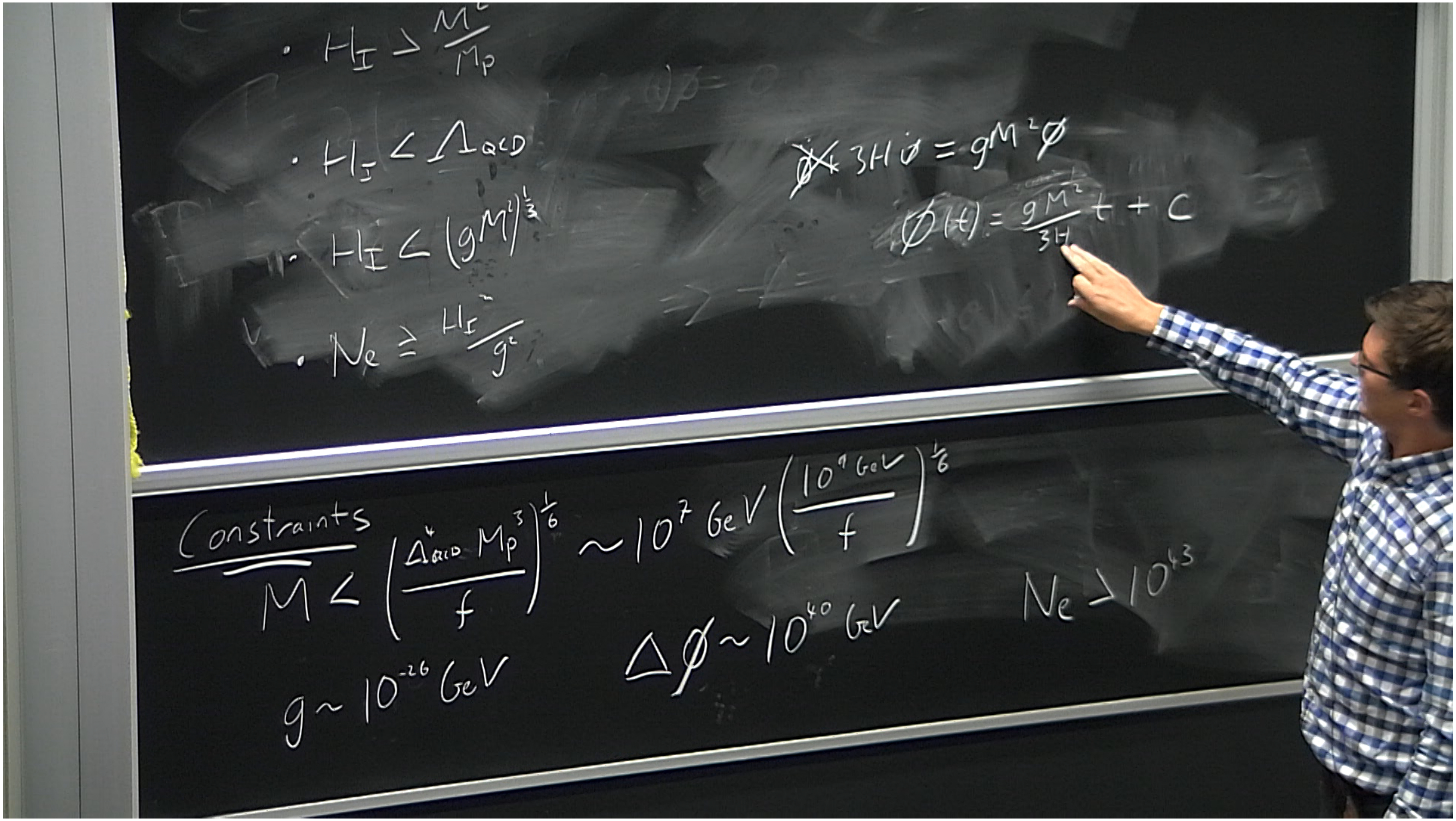

Parameter Constraints
• ΔØ ≳ M²/g
• H_I > M²/M_p
• H_I < Λ_QCD
• H_I < (gM²)^(1/3)
• N_e ≳ H_I²/g²

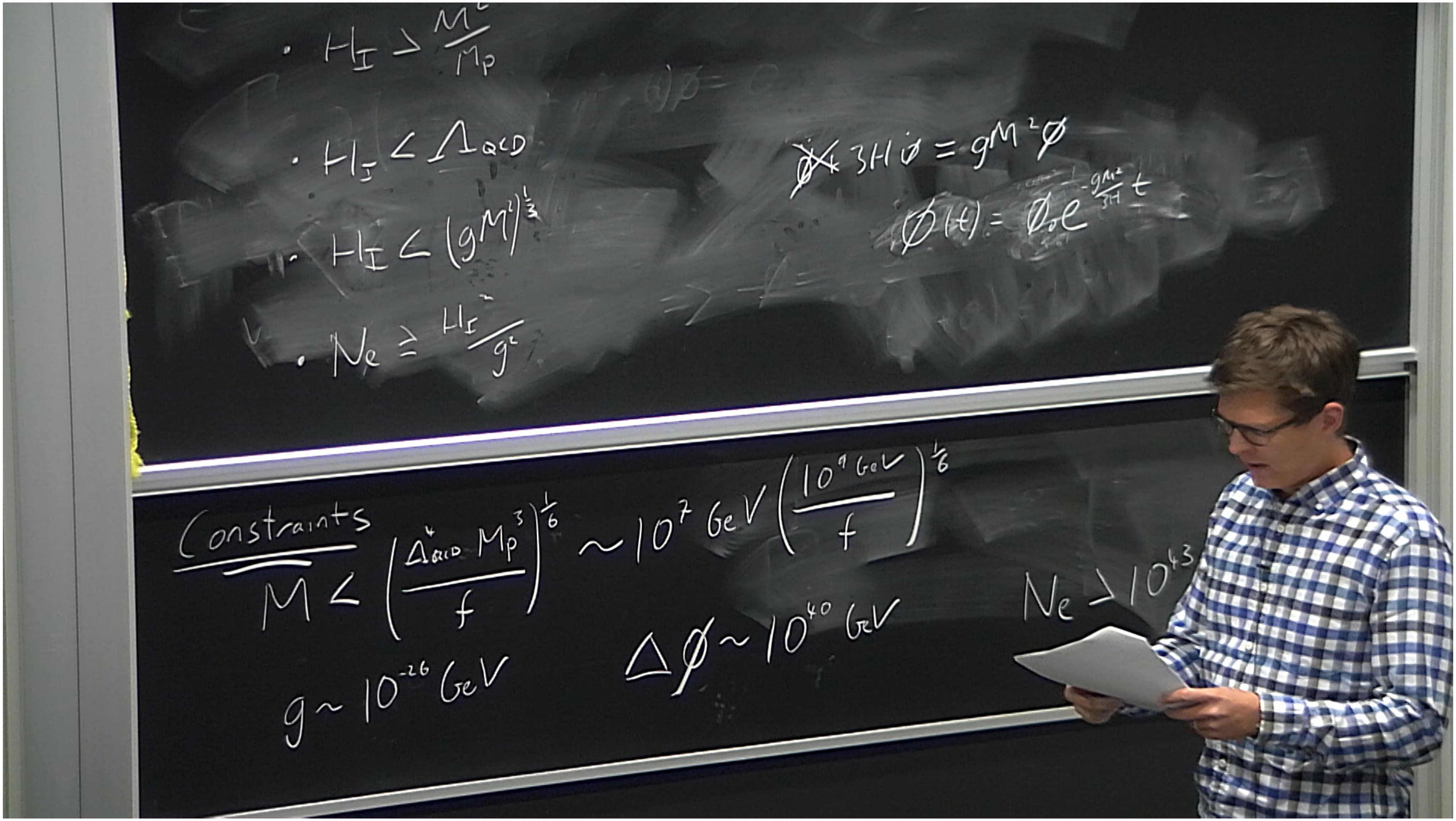

• H_I > M^2 / M_p
• H_I < Λ_QCD
• H_I < (gM^2)^(1/3)
• N_e ≳ H_I^2 / g^2
Constraints
M < (Λ_QCD^4 M_p^3 / f)^(1/6) ~ 10^7 GeV (10^9 GeV / f)^(1/6)

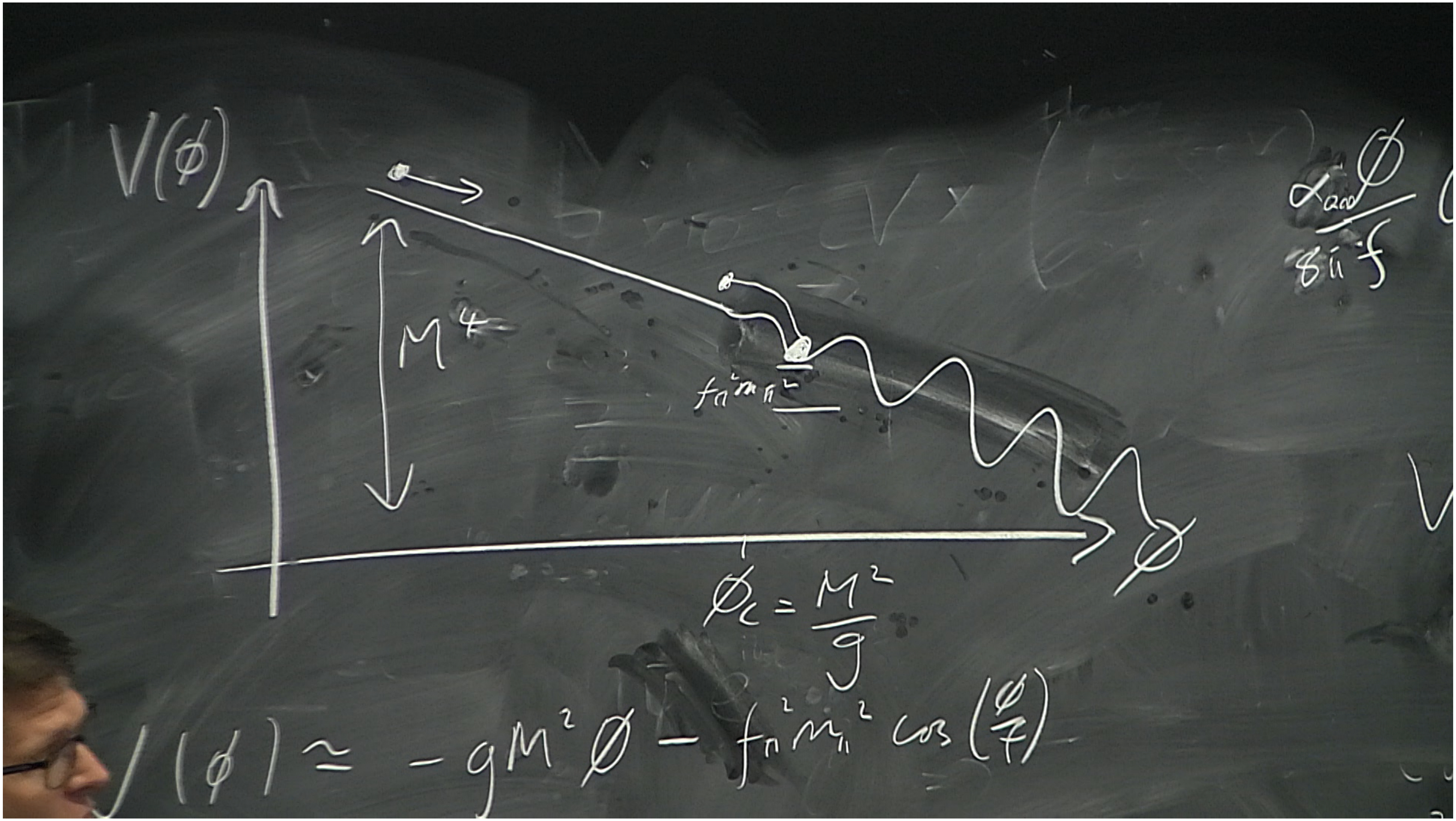

• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$
• $H_I < (gM^2)^{\frac{1}{3}}$
• $N_e \gtrsim \frac{H_I^2}{g^2}$
Constraints
$M < \left(\frac{\Lambda_{QCD}^4 M_p^3}{f}\right)^{\frac{1}{6}} \sim 10^7 \, GeV \left(\frac{10^9 \, GeV}{f}\right)^{\frac{1}{6}}$
$g \sim 10^{-26} \, GeV$


• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$
• $H_I < (gM^2)^{\frac{1}{3}}$
• $N_e \gtrsim \frac{H_I^2}{g^2}$
Constraints
$M < \left(\frac{\Lambda_{QCD}^4 M_p^3}{f}\right)^{\frac{1}{6}} \sim 10^7\, GeV \left(\frac{10^9\, GeV}{f}\right)^{\frac{1}{6}}$
$g \sim 10^{-26}\, GeV$
$\Delta\phi \sim 10^{40}\, GeV$
$N_e > 10^{43}$

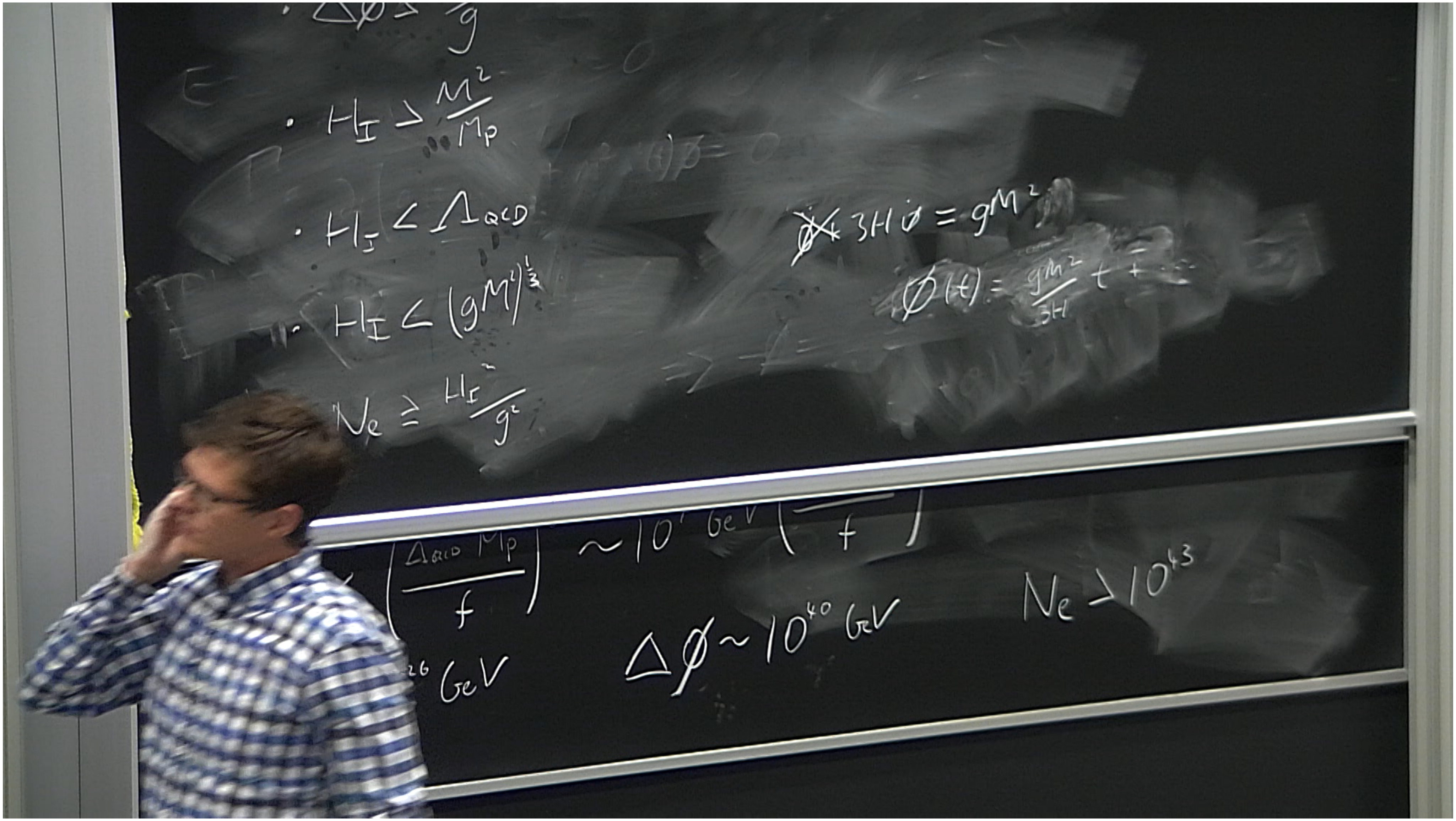

• H_I < Λ_QCD
• H_I < (gM²)^{1/3}
• N_e ≥ H_I²/g²
3Hφ̇ = gM²φ
φ = φ₀ e^{3gM²t/H}
Constraints
M < (Λ_QCD⁴ M_p³ / f)^{1/6} ~ 10⁷ GeV (10⁹ GeV / f)^{1/6}
N_e > 10⁴³
g ~ 10⁻²⁶ GeV
Δφ ~ 10⁴⁰ GeV

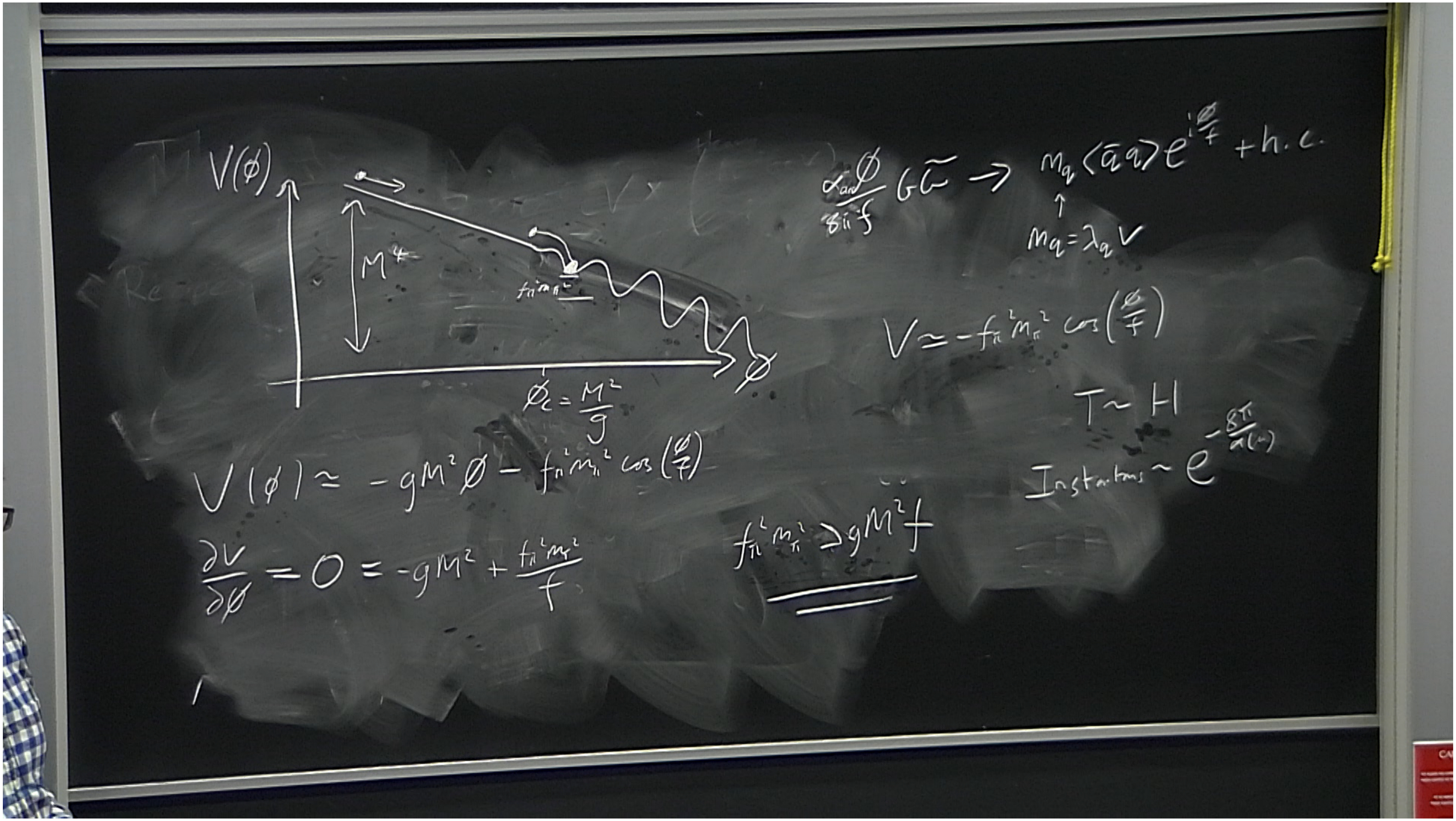

• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$
• $H_I < (gM^2)^{\frac{1}{3}}$
• $N_e \gtrsim \frac{H_I^2}{g^2}$
$3H\dot{\phi} = gM^2\phi$
$\phi(t) = \frac{gM^2}{3H} t + C$
Constraints
$M < \left(\frac{\Lambda_{QCD}^4 M_p^3}{f}\right)^{\frac{1}{6}} \sim 10^7 \text{ GeV} \left(\frac{10^9 \text{ GeV}}{f}\right)^{\frac{1}{6}}$
$g \sim 10^{-26}$ GeV
$\Delta\phi \sim 10^{40}$ GeV
$N_e > 10^{43}$

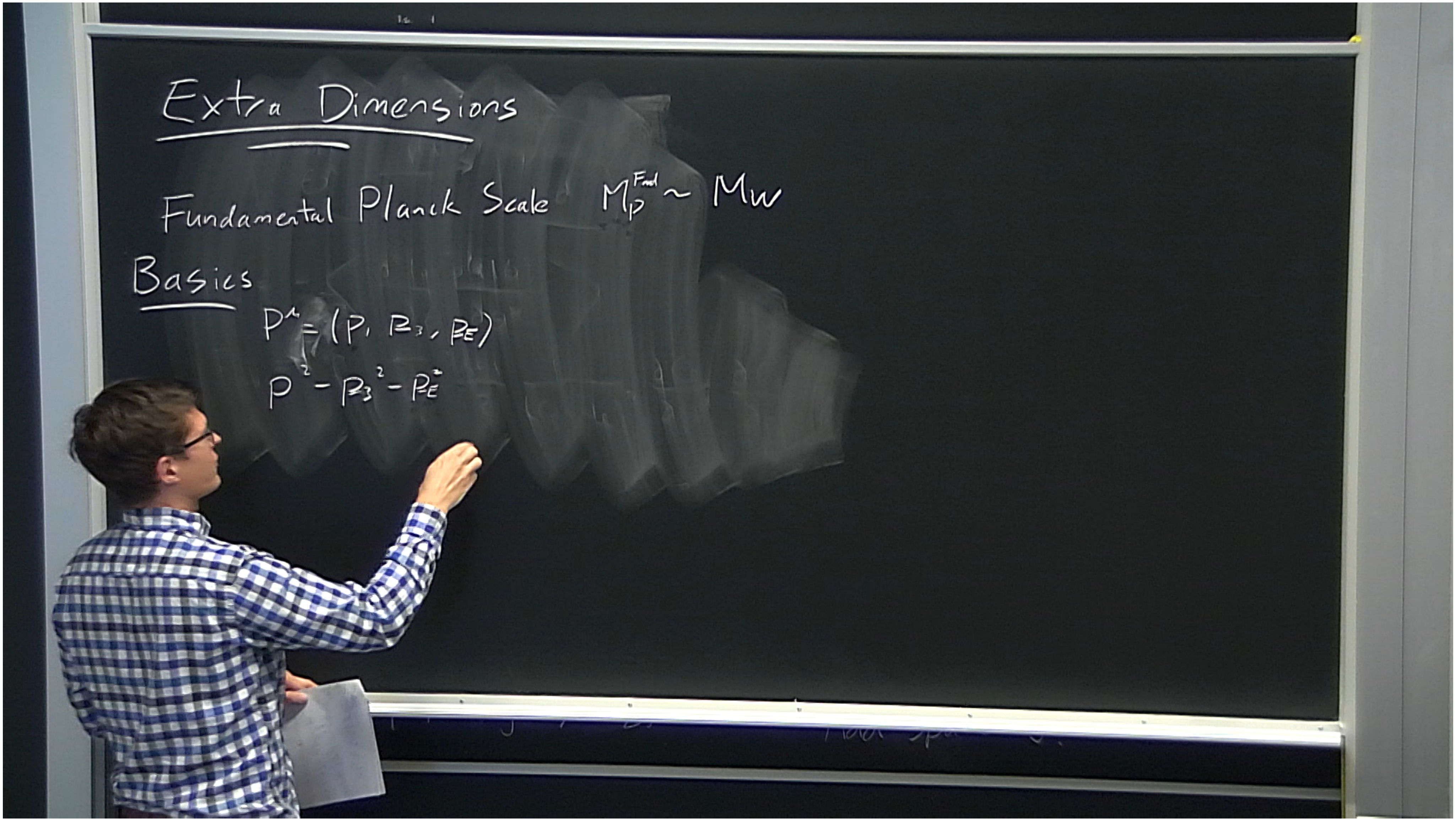

• H_I > M^2/M_p
• H_I < Λ_QCD
• H_I < (gM^2)^(1/3)
• N_e ≥ H_I^2/g^2
3Hφ̇ = gM^2 φ
φ(t) = φ_0 e^(-(gM^2/3H) t)
Constraints
M < (Λ_QCD^4 M_p^3 / f)^(1/6) ~ 10^7 GeV (10^9 GeV / f)^(1/6)
g ~ 10^-26 GeV
Δφ ~ 10^40 GeV
N_e > 10^43

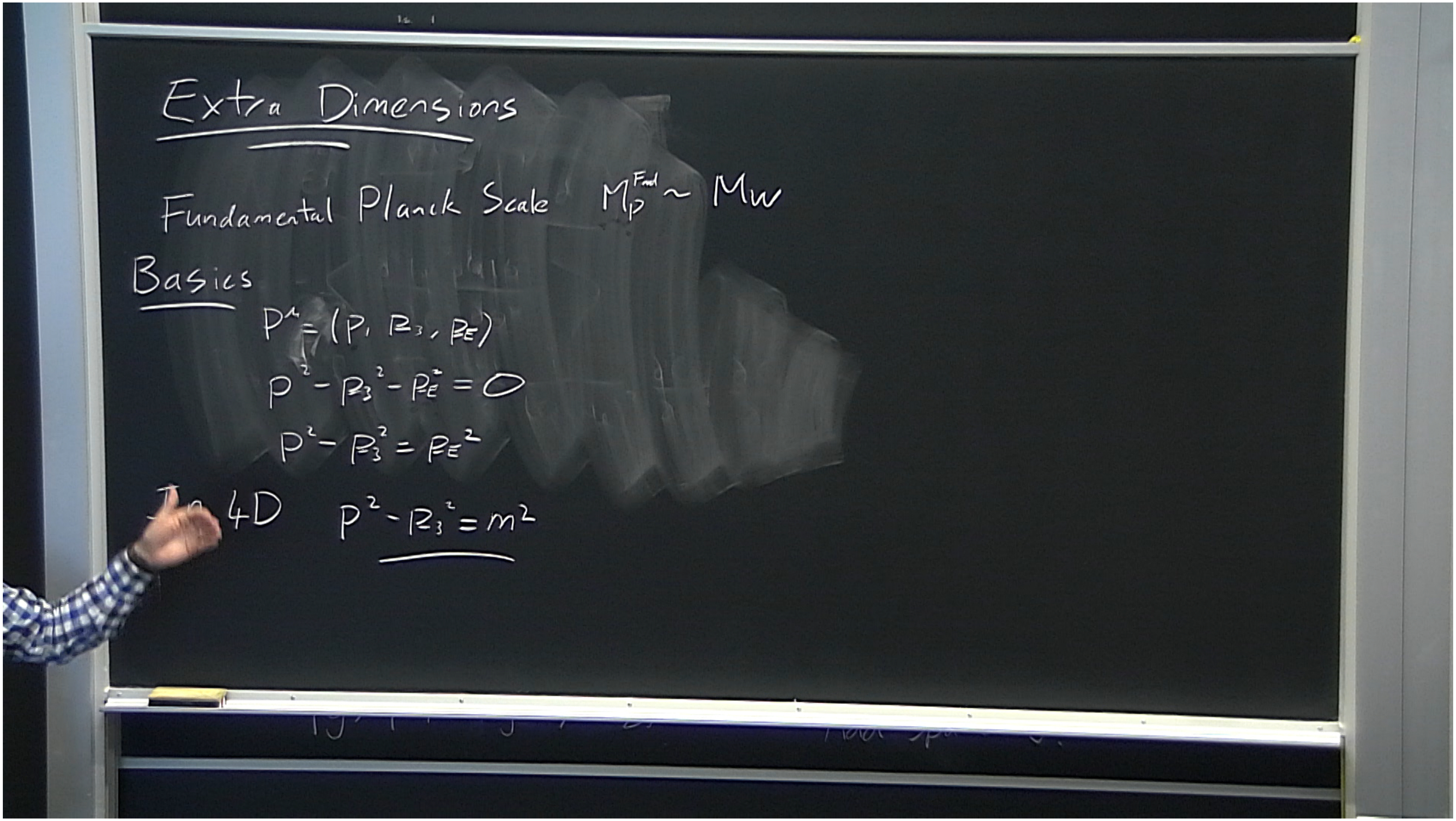


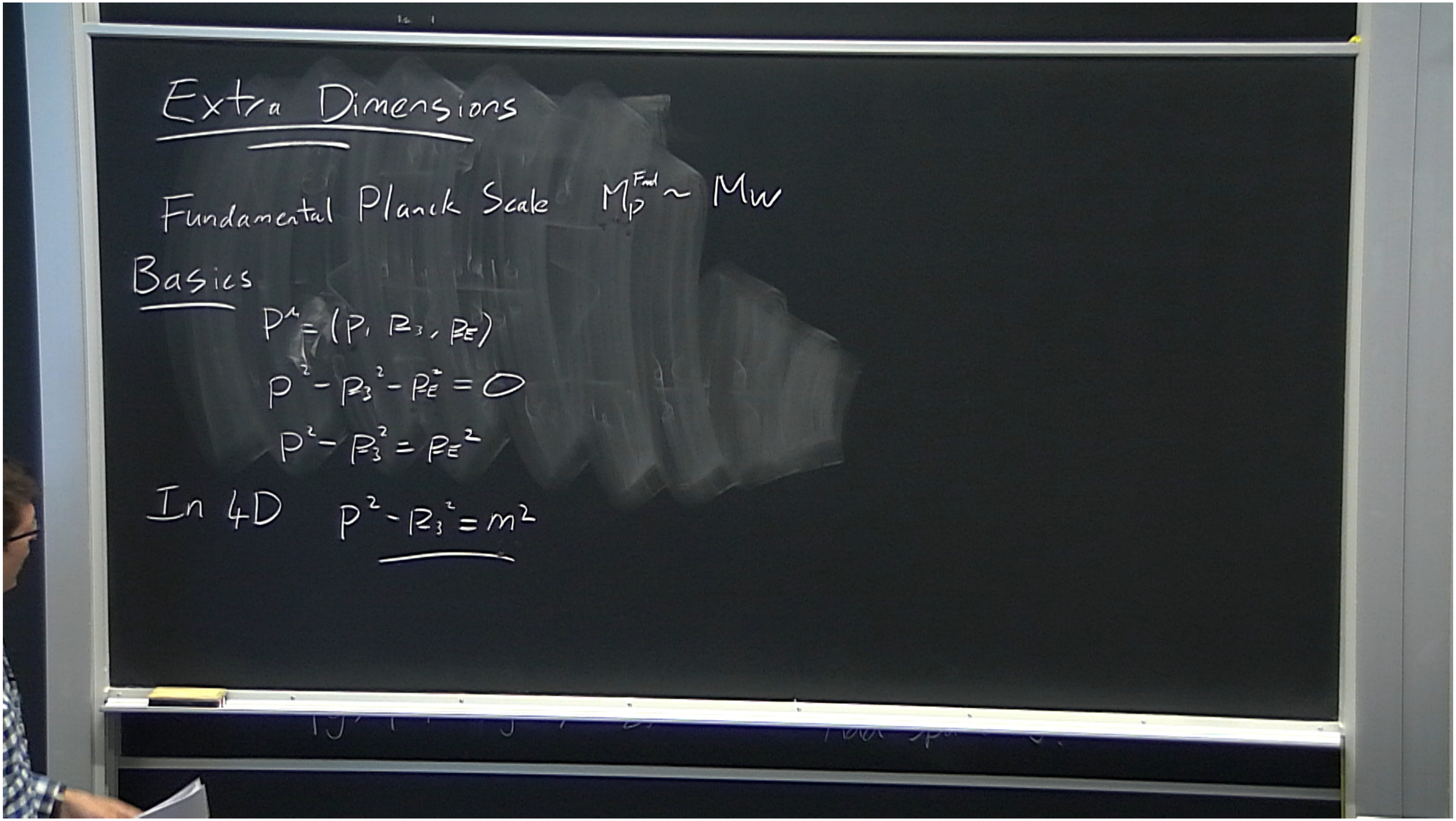
V(ϕ)
M⁴
$f_\pi^2 m_\pi^2$
ϕ
$\phi_c = \frac{M^2}{g}$
$\frac{\alpha_{QCD}\,\phi}{8\pi f}$
$V(\phi) \simeq -gM^2\phi - f_\pi^2 m_\pi^2 \cos(\frac{\phi}{f})$

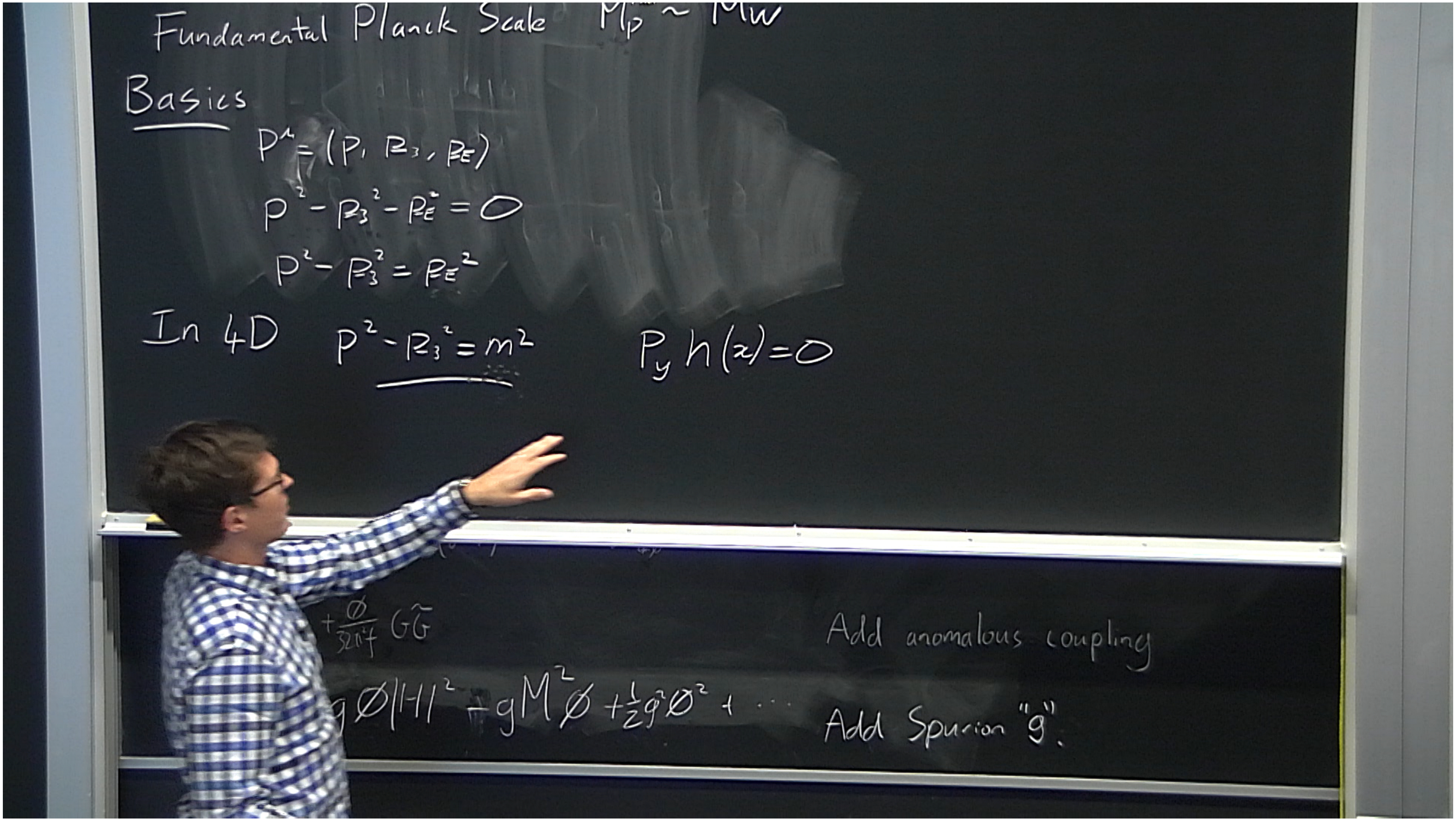

• $H_I > \frac{M^2}{M_p}$
• $H_I < \Lambda_{QCD}$
• $H_I < (gM^2)^{\frac{1}{3}}$
$N_e \geq \frac{H_I^2}{g^2}$
$3H\dot{\phi} = gM^2$
$\phi(t) = \frac{gM^2}{3H} t + \ldots$
$\Delta\phi \sim 10^{40}$ GeV
$N_e > 10^{43}$

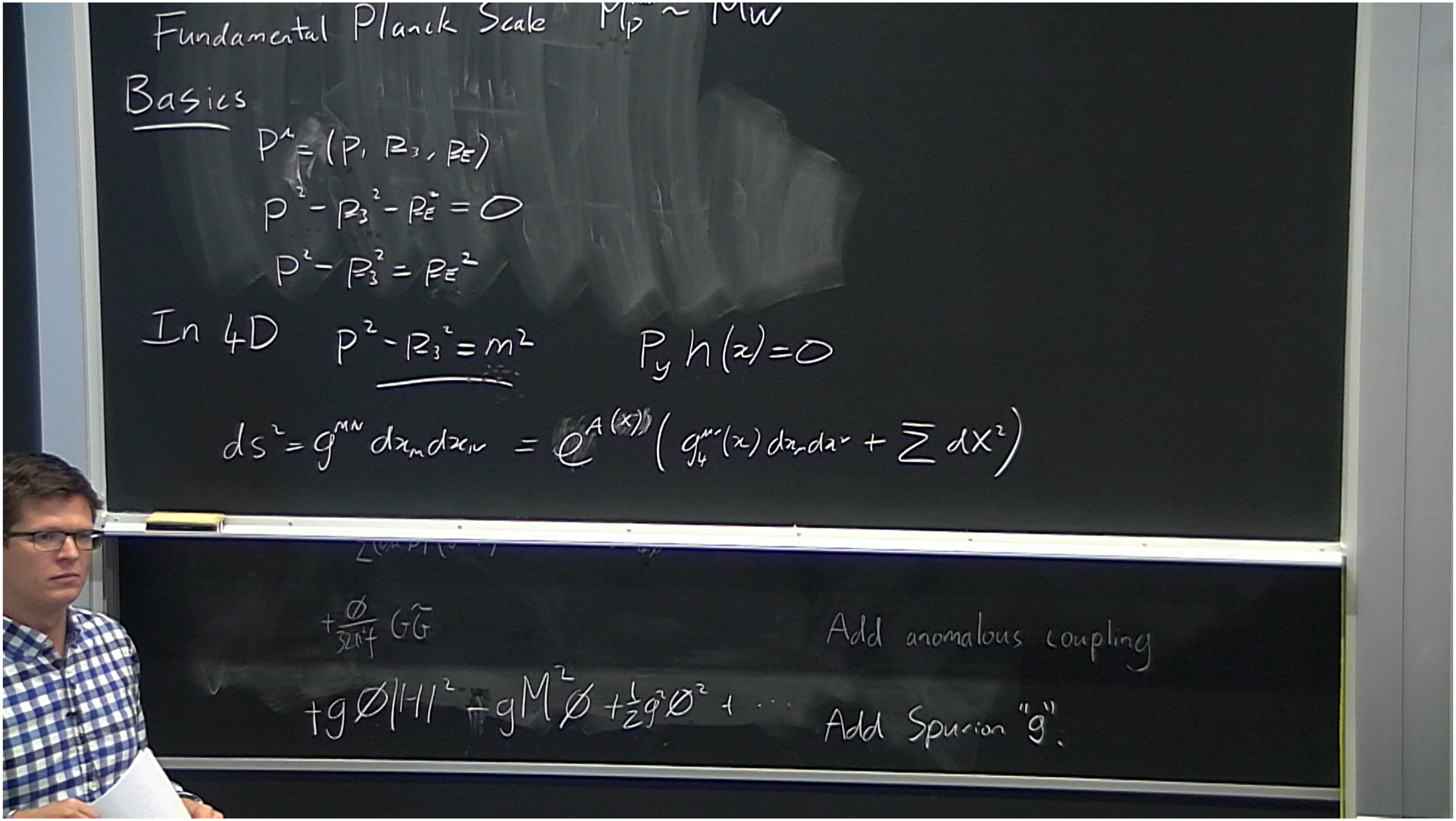

V(ϕ)
M^4
ϕ_c = M²/g
V(ϕ) ≃ −gM²ϕ − f_π² m_π² cos(ϕ/f)
∂V/∂ϕ = 0 = −gM² + f_π² m_π²/f
f_π² m_π² ≥ gM² f
α_{QCD} ϕ/(8π f) G G̃ → m_q ⟨q̄q⟩ e^{iϕ/f} + h.c.
m_q = λ_q V
V ≃ −f_π² m_π² cos(ϕ/f)
T ~ H
Instantons ~ e^{−8π/α(μ)}


Extra Dimensions
Fundamental Planck Scale $M_P^{Fund} \sim M_W$
Basics
$p^\mu = (p_1, p_3, p_E)$
$p^2 - p_3^2 - p_E^2$

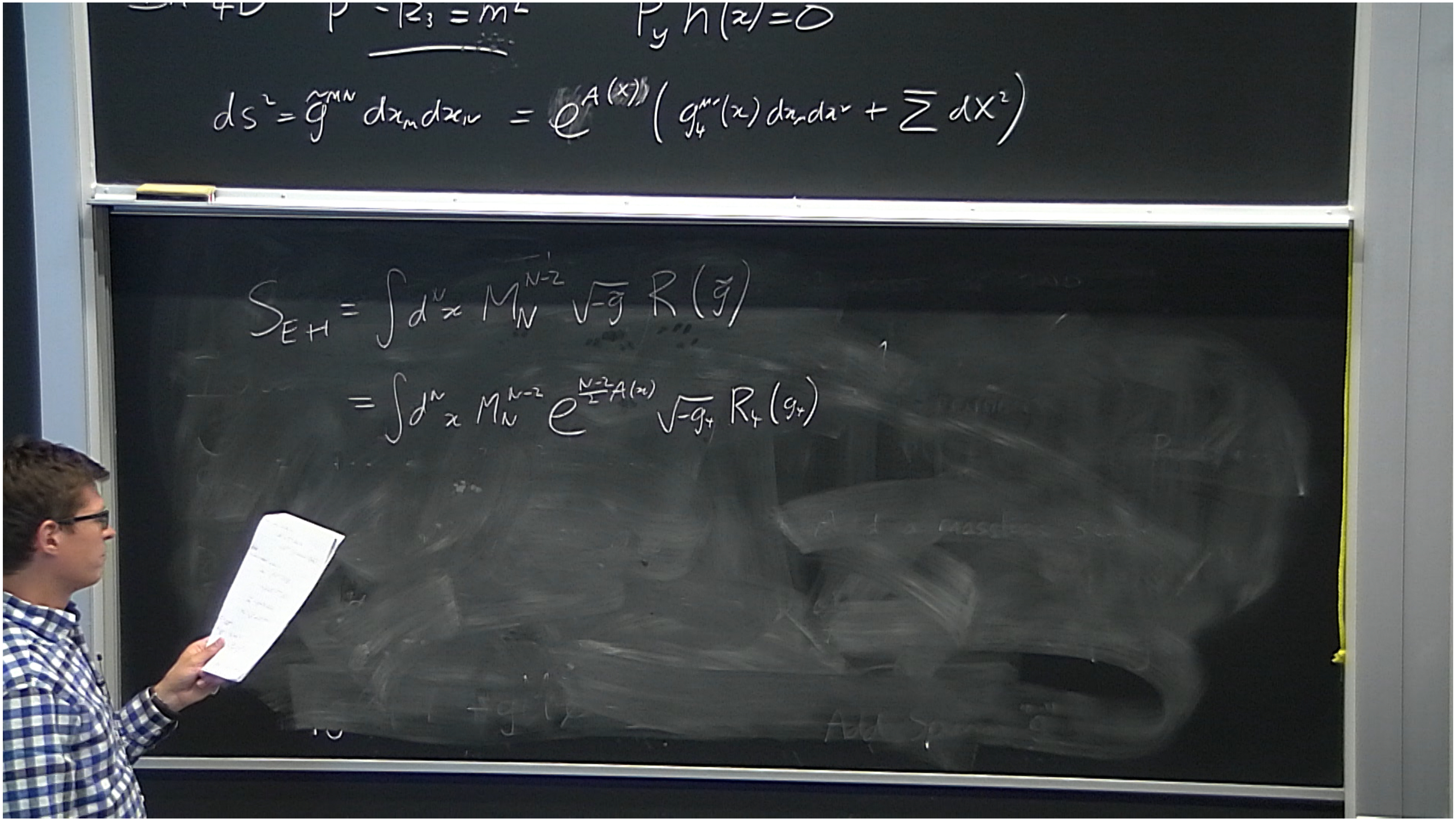

Extra Dimensions
Fundamental Planck Scale $M_p^{Fund} \sim M_W$
Basics
$p^\mu = (p, p_3, p_E)$
$p^2 - p_3^2 - p_E^2 = 0$
$p^2 - p_3^2 = p_E^2$
In 4D $p^2 - p_3^2 = m^2$


Extra Dimensions
Fundamental Planck Scale $M_p^{Fund} \sim M_W$
Basics
$P^\mu = (p, p_3, p_E)$
$p^2 - p_3^2 - p_E^2 = 0$
$p^2 - p_3^2 = p_E^2$
In 4D $p^2 - p_3^2 = m^2$


Fundamental Planck Scale
Basics
In 4D
Add anomalous coupling
Add Spurion "g".



Fundamental Planck Scale $M_p \sim M_W$
Basics
$P^\mu = (p, p_3, p_E)$
$p^2 - p_3^2 - p_E^2 = 0$
$p^2 - p_3^2 = p_E^2$
In 4D $p^2 - p_3^2 = m^2$
$P_y h(x) = 0$
$ds^2 = g^{MN} dx_M dx_N = e^{A(x)} (g_4^{\mu\nu}(x) dx_\mu dx_\nu + \sum dX^2)$
$+ \frac{\phi}{32\pi^2 f} G\tilde{G}$
Add anomalous coupling
$+ g\phi|H|^2 - gM^2\phi + \frac{1}{2}g^2\phi^2 + \cdots$
Add Spurion "g".


$P_y h(x) = 0$
$ds^2 = \tilde{g}^{MN} dx_M dx_N = e^{A(x)} \left(g_4^{\mu\nu}(x) dx_\mu dx_\nu + \sum dX^2 \right)$
$S_{EH} = \int d^N x \, M_N^{N-2} \sqrt{-\tilde{g}} \, R(\tilde{g})$
$= \int d^N x \, M_N^{N-2} e^{\frac{N-2}{2}A(x)} \sqrt{-g_4} \, R_4(g_4)$

$\ldots 4D \quad p^2 - k_3 = m^2 \qquad P_y h(x) = 0$

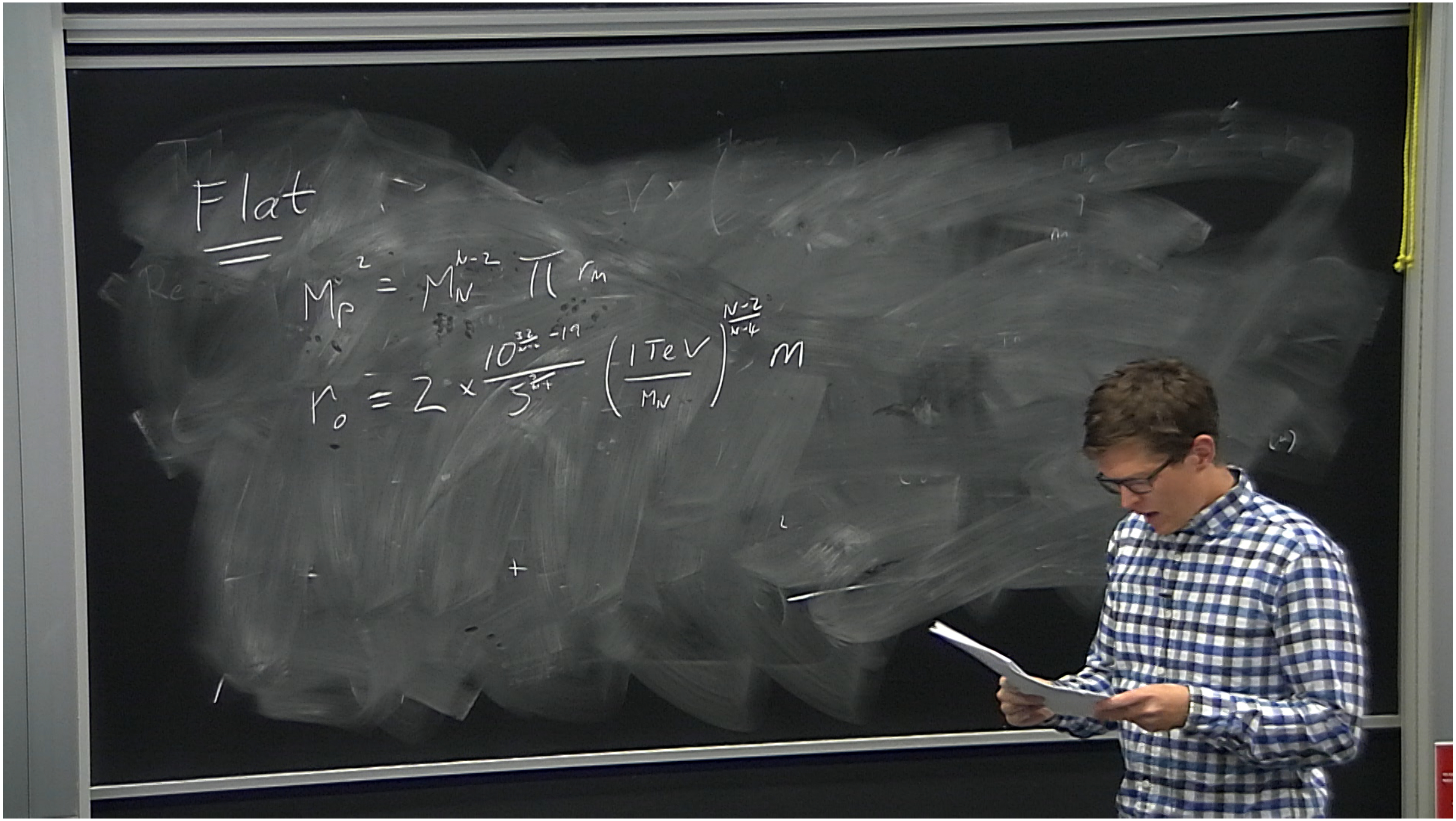
$$ds^2 = \tilde{g}^{MN} dx_M dx_N = e^{A(x)}\left(g_4^{\mu\nu}(x)\, dx_\mu dx_\nu + \sum dX^2 \right)$$

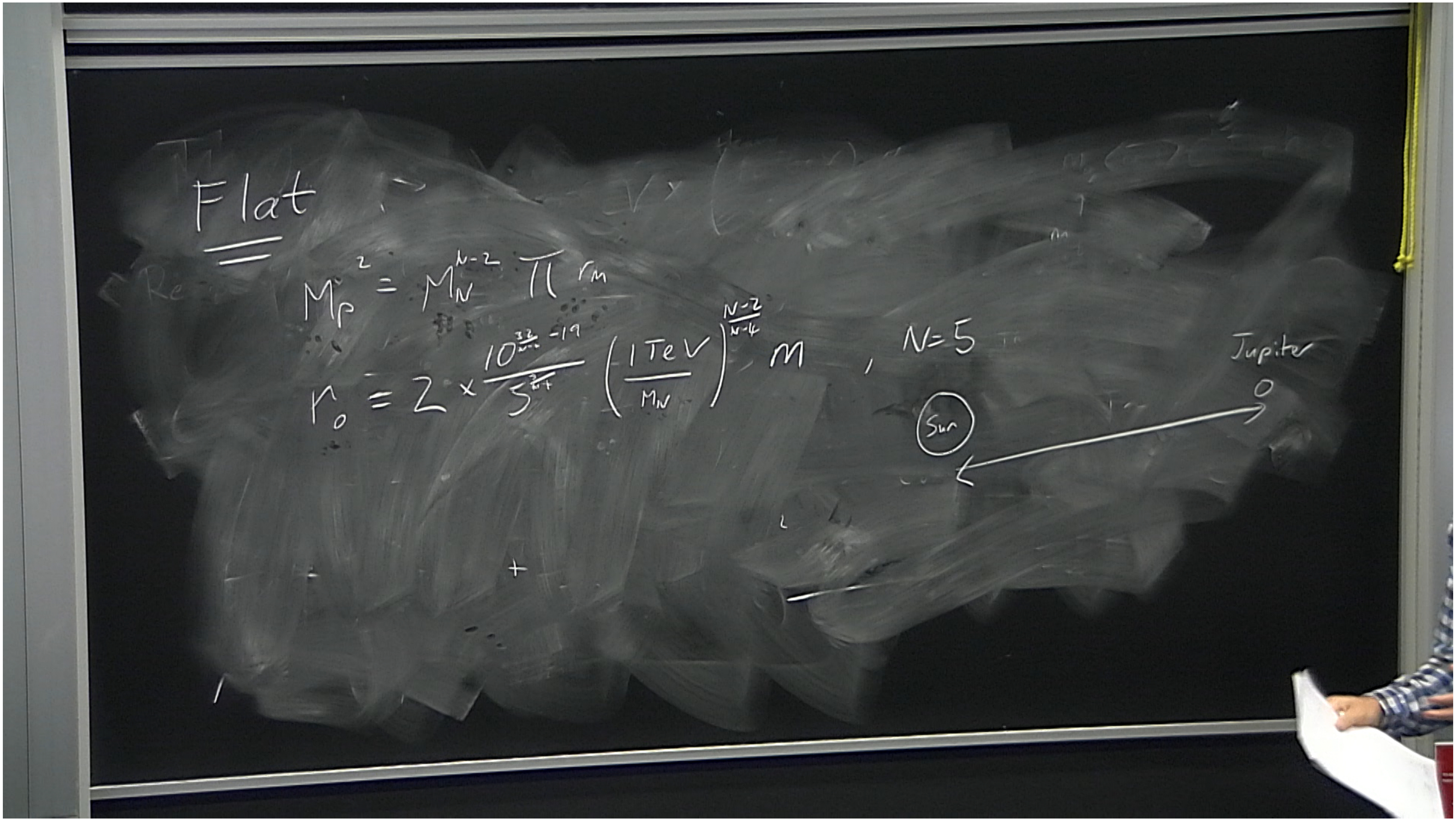
$$S_{EH} = \int d^N x\, M_N^{N-2} \sqrt{-\tilde{g}}\, R(\tilde{g})$$

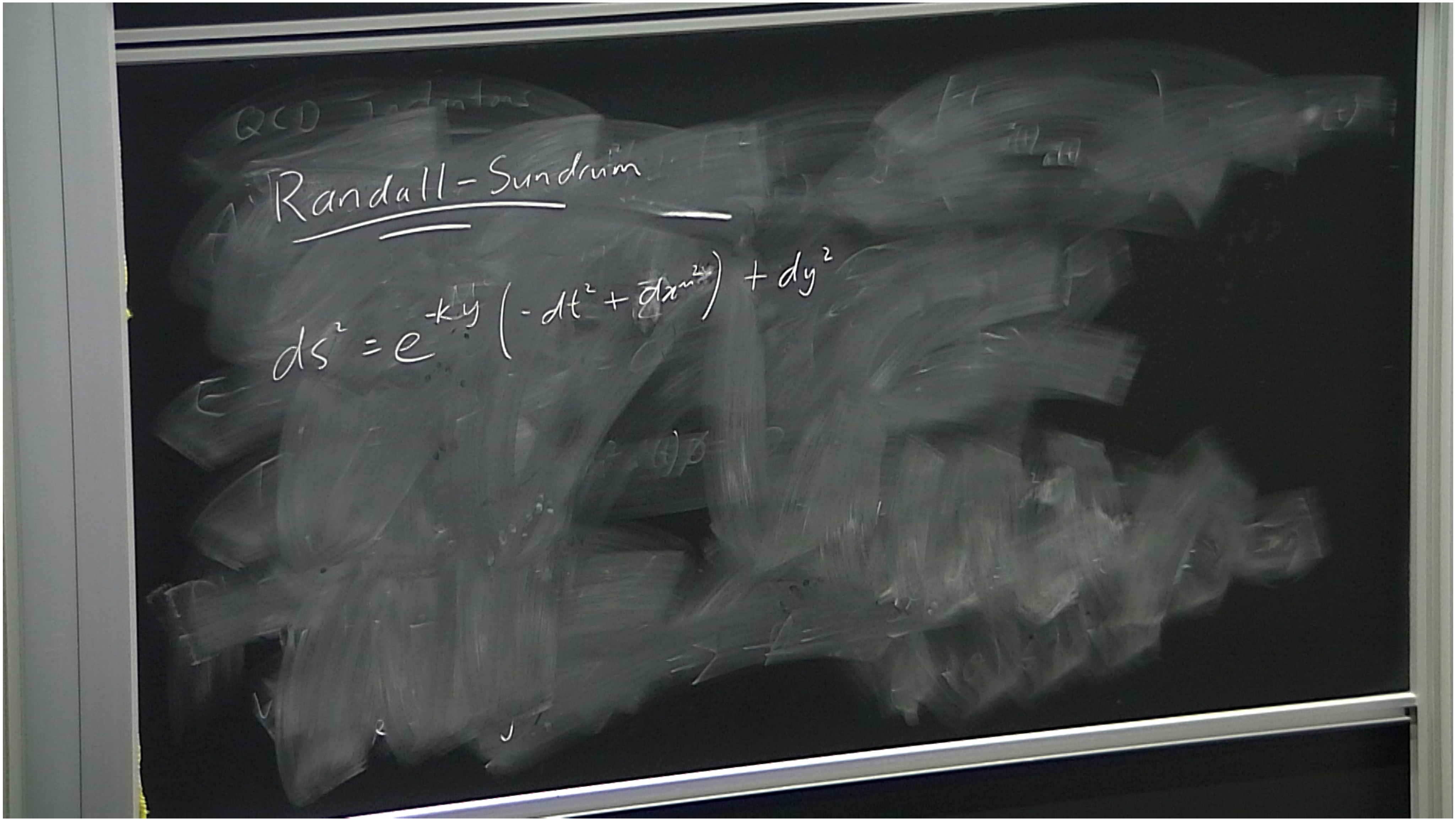
$$= \int d^N x\, M_N^{N-2}\, e^{\frac{N-2}{2}A(x)} \sqrt{-g_4}\, R_4(g_4)$$

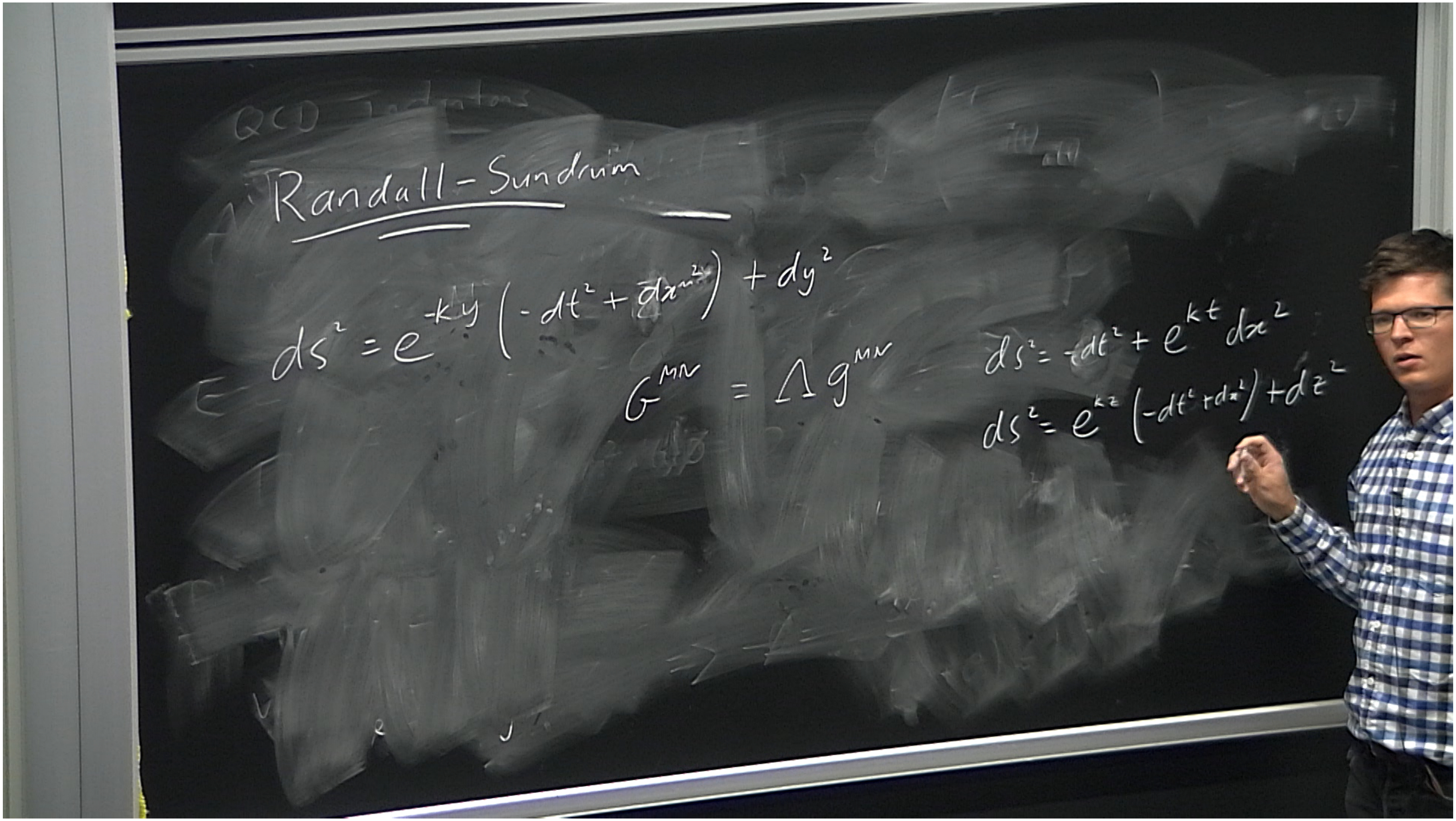
Compare to $S^{4D} = \int d^4 x\, M_P^2 \sqrt{-g_4}\, R_4(g_4)$

$$M_P^2 = \int d^{N-4} X\, M_N^{N-2}\, e^{\frac{N-2}{2}A(X)}$$


Flat
M_p^2 = M_N^{N-2} Π r_m
r_0 = 2 × 10^{32/(N-4) - 19} / 5^{2/(N-4)} (1 TeV / M_N)^{(N-2)/(N-4)} m


Flat
N=5
Sun
Jupiter


Randall-Sundrum
$ds^2 = e^{-ky}(-dt^2 + dx^2) + dy^2$


Randall-Sundrum
$ds^2 = e^{-ky}(-dt^2 + dx^2) + dy^2$
$G^{MN} = \Lambda g^{MN}$
$ds^2 = -dt^2 + e^{kt} dx^2$
$ds^2 = e^{kz}(-dt^2 + dx^2) + dz^2$