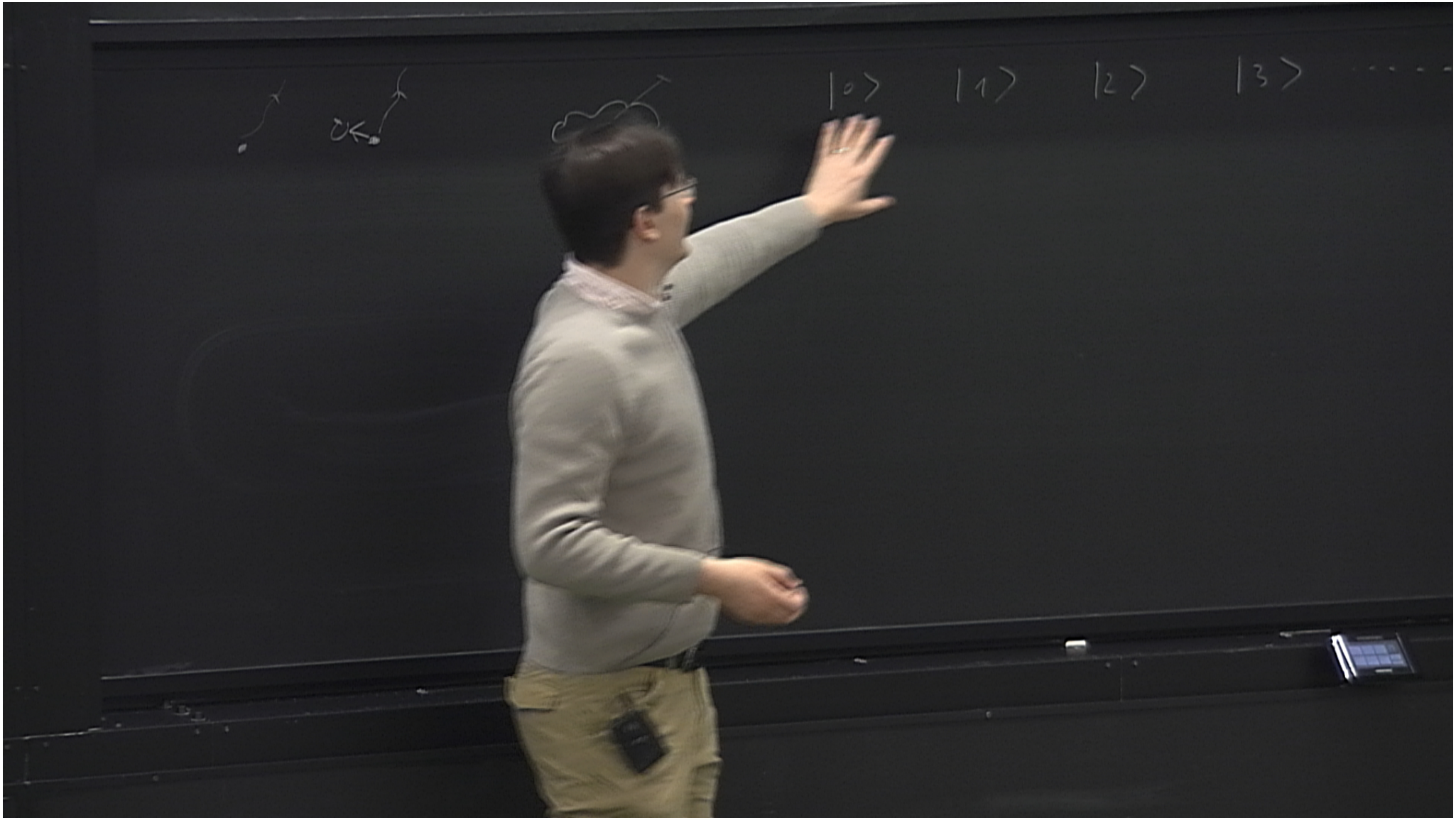
Title: 13/14 PSI - String Theory Review - Lecture 5

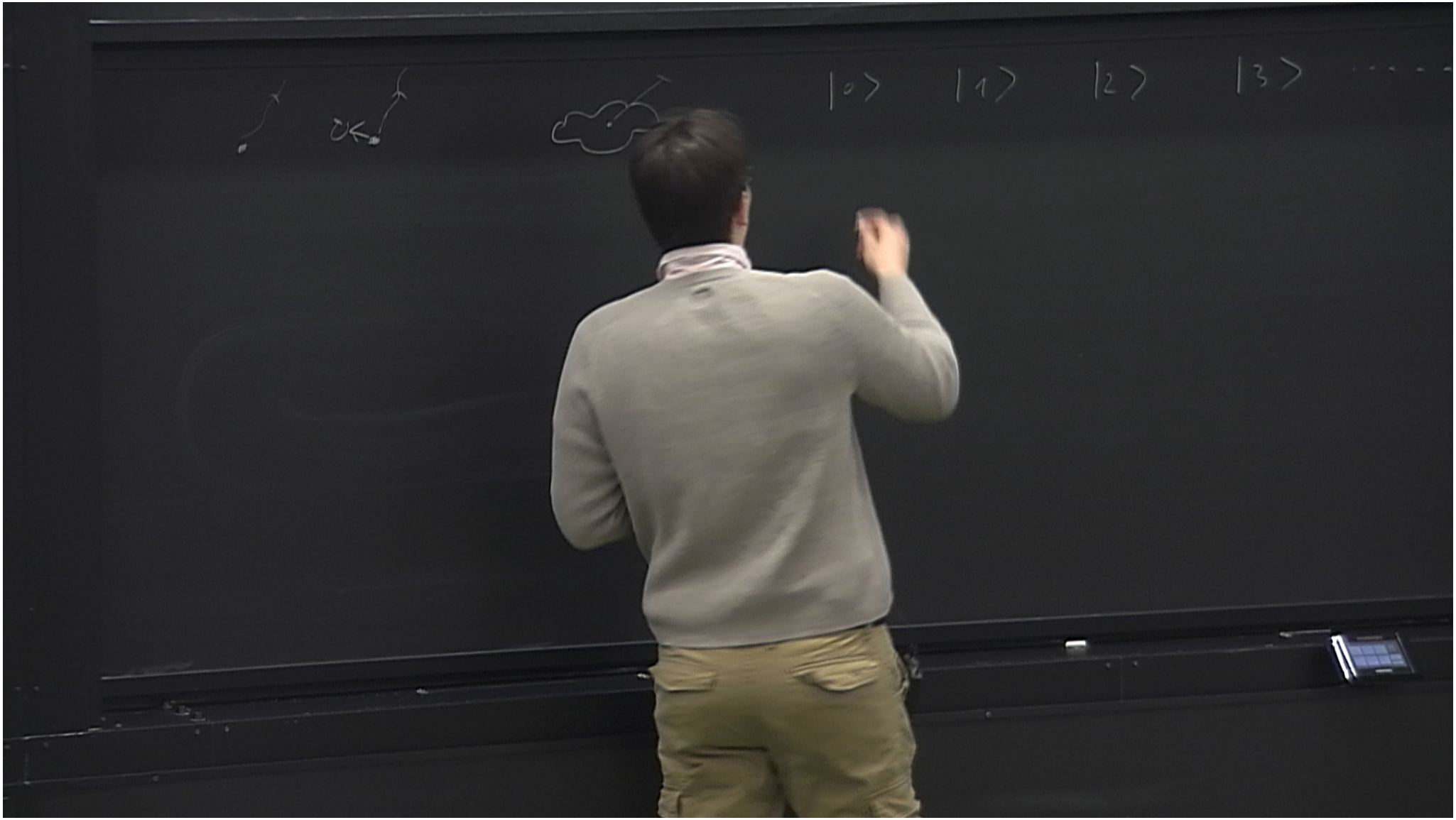
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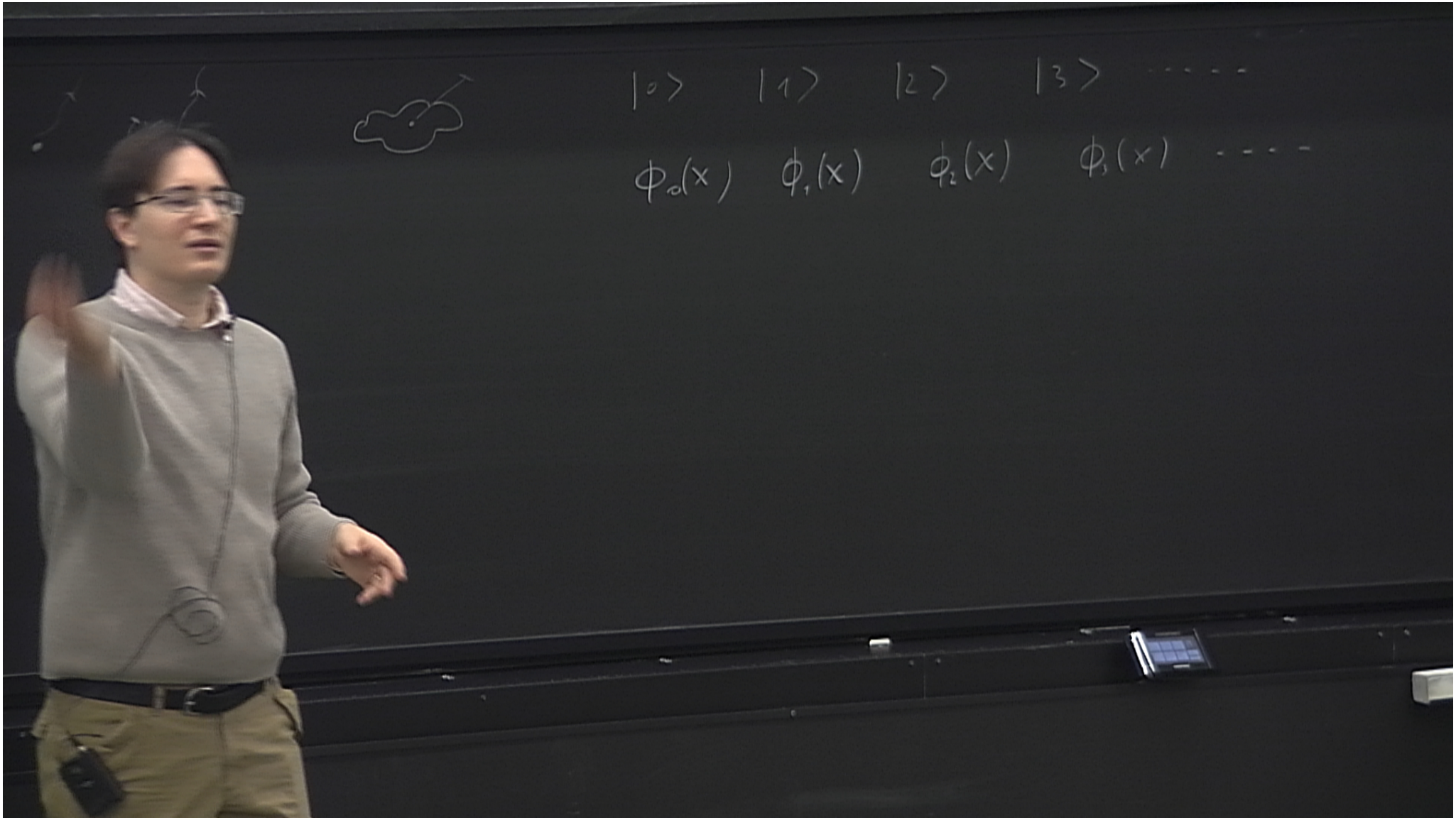
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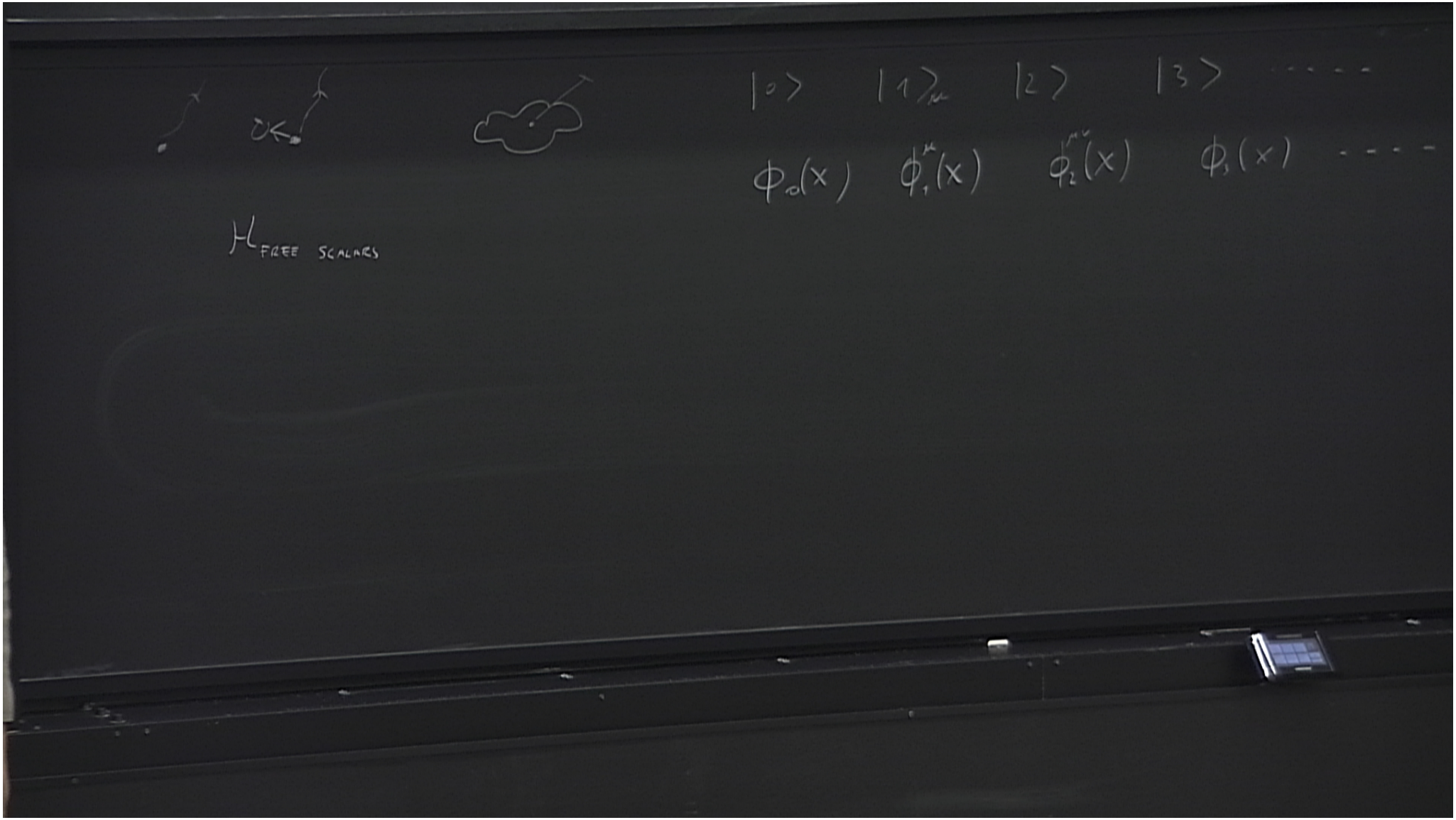
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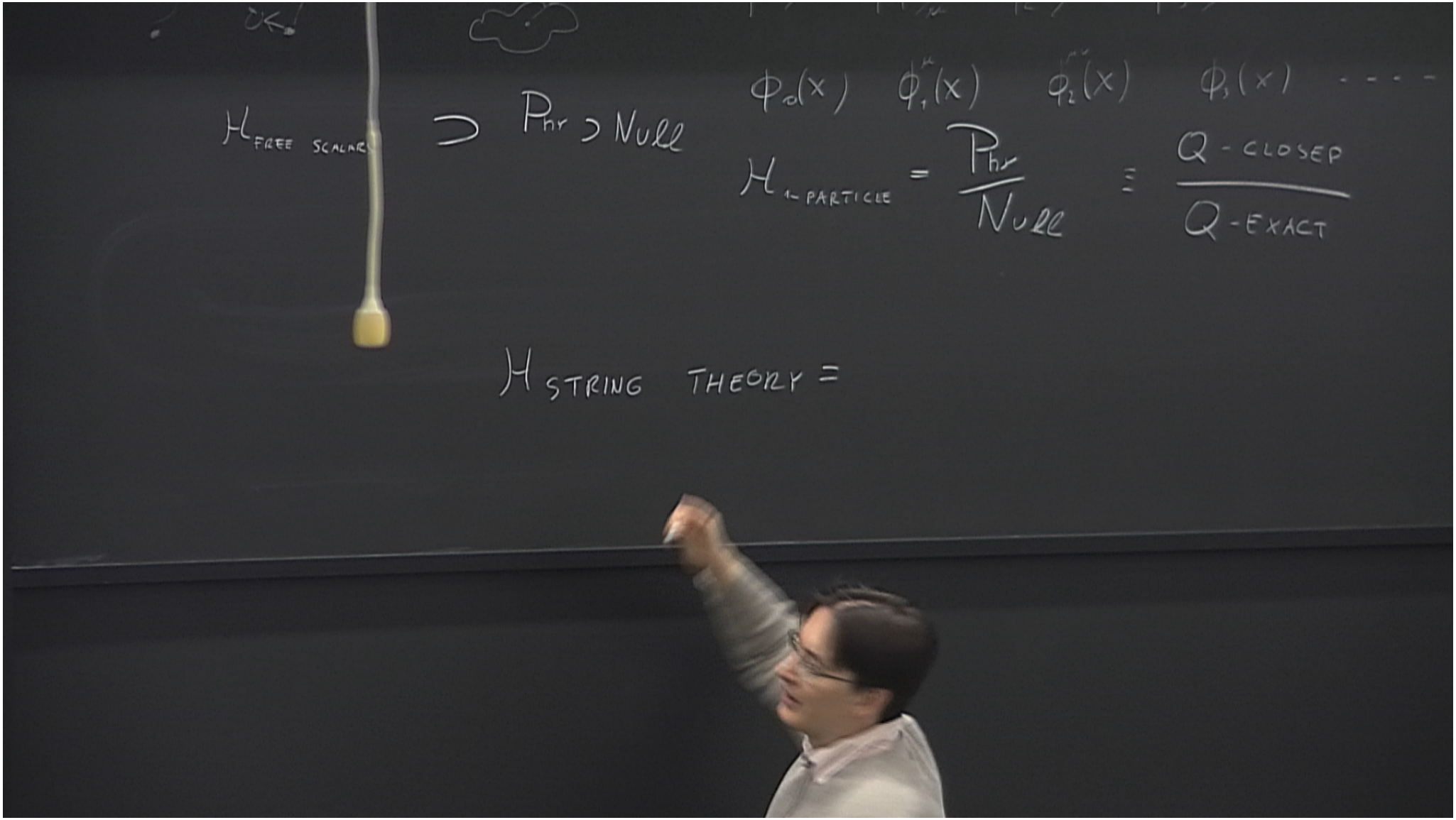


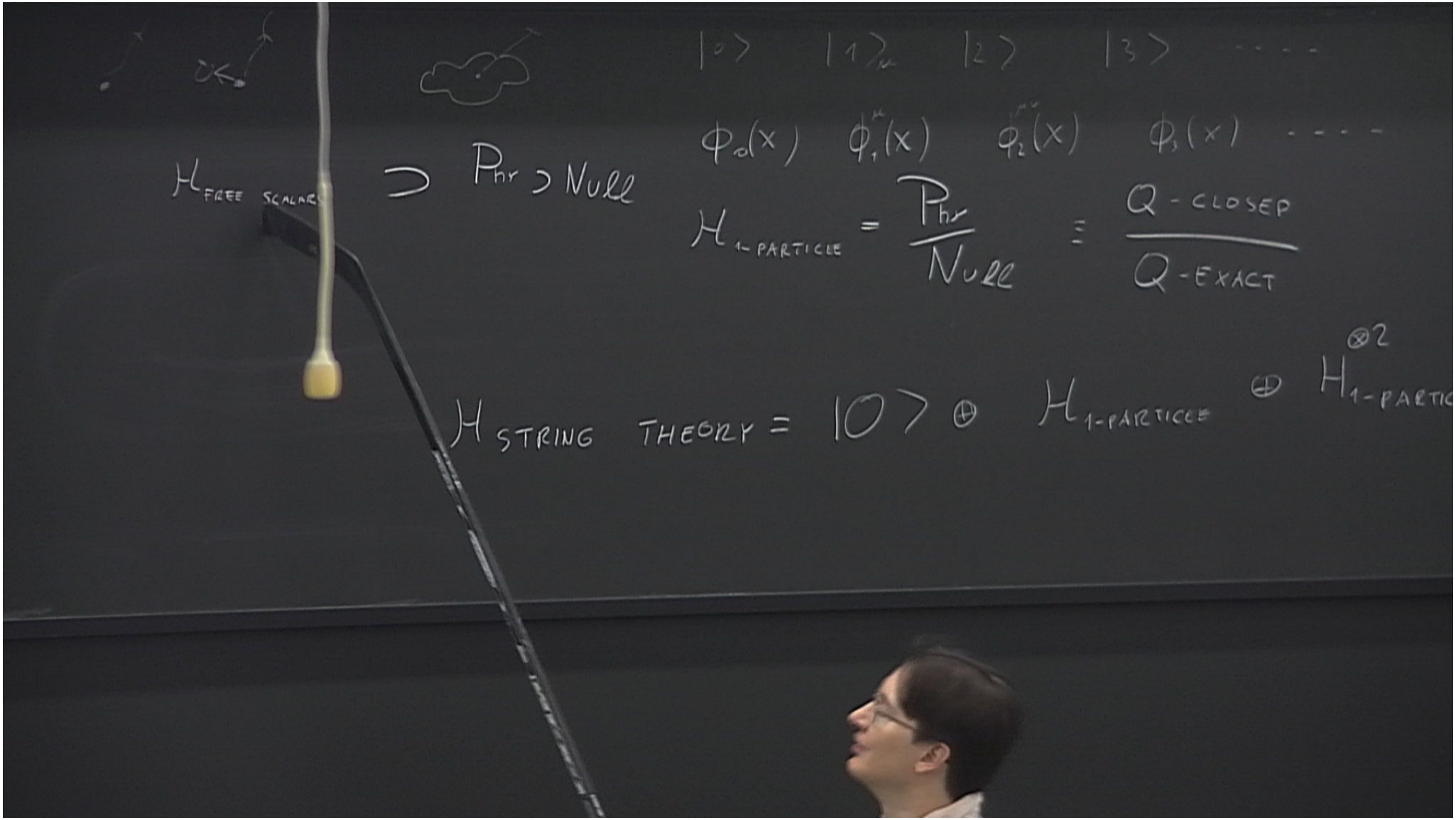

|0>
|1>
|2>
|3>

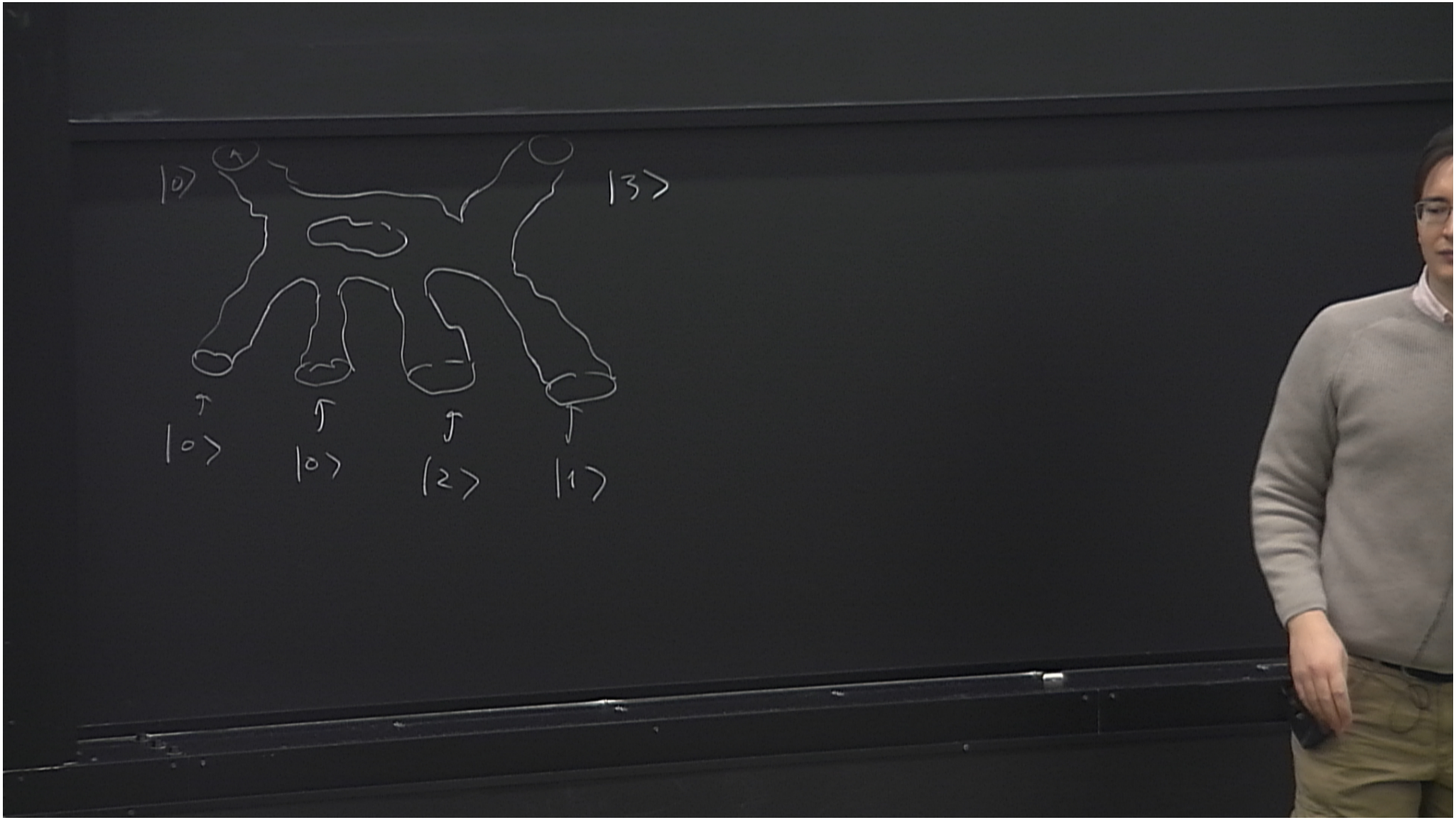

|0>
|1>
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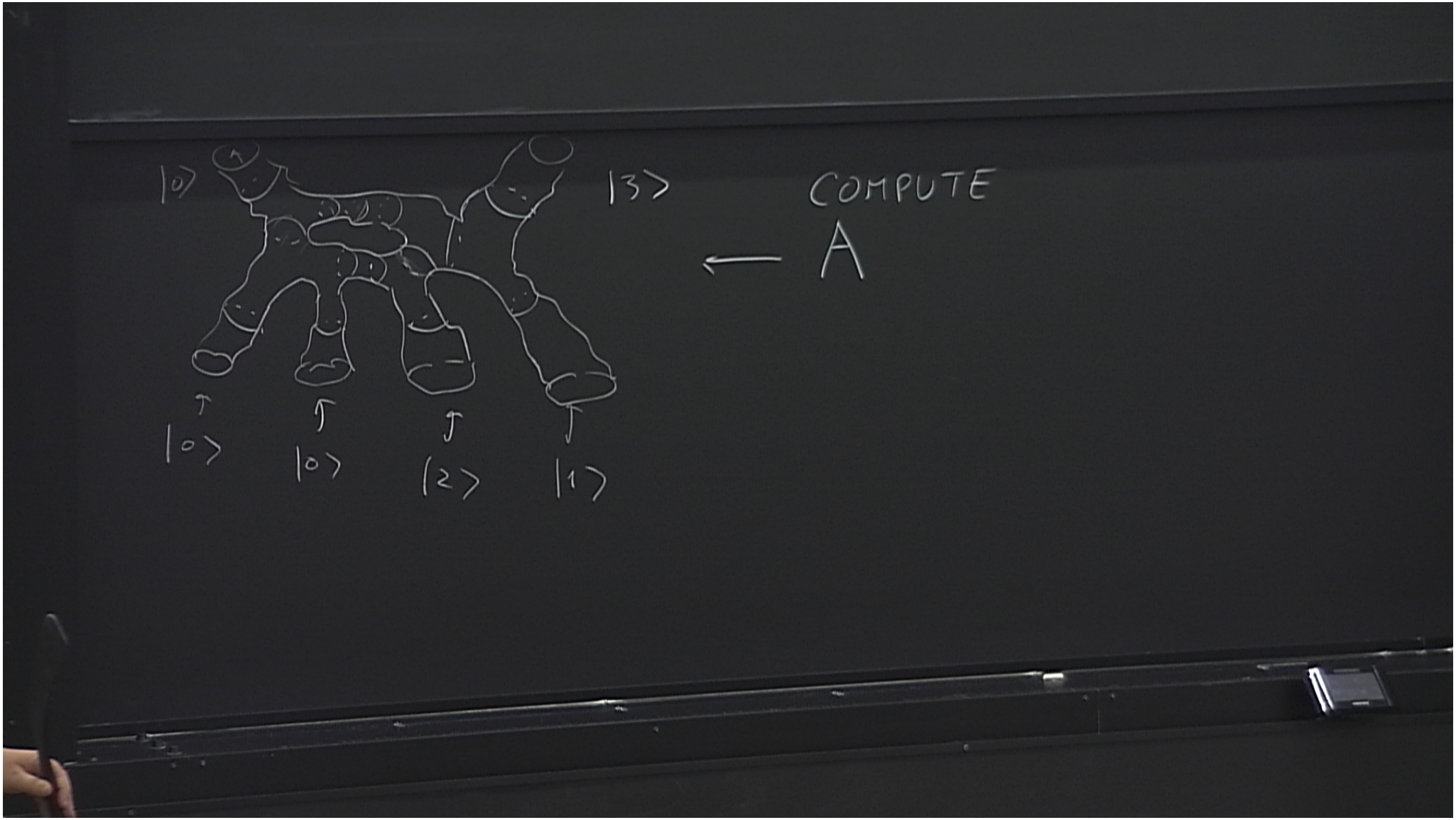

|0> |1> |2> |3> .....
$\phi_0(x)$ $\phi_1(x)$ $\phi_2(x)$ $\phi_3(x)$ ....

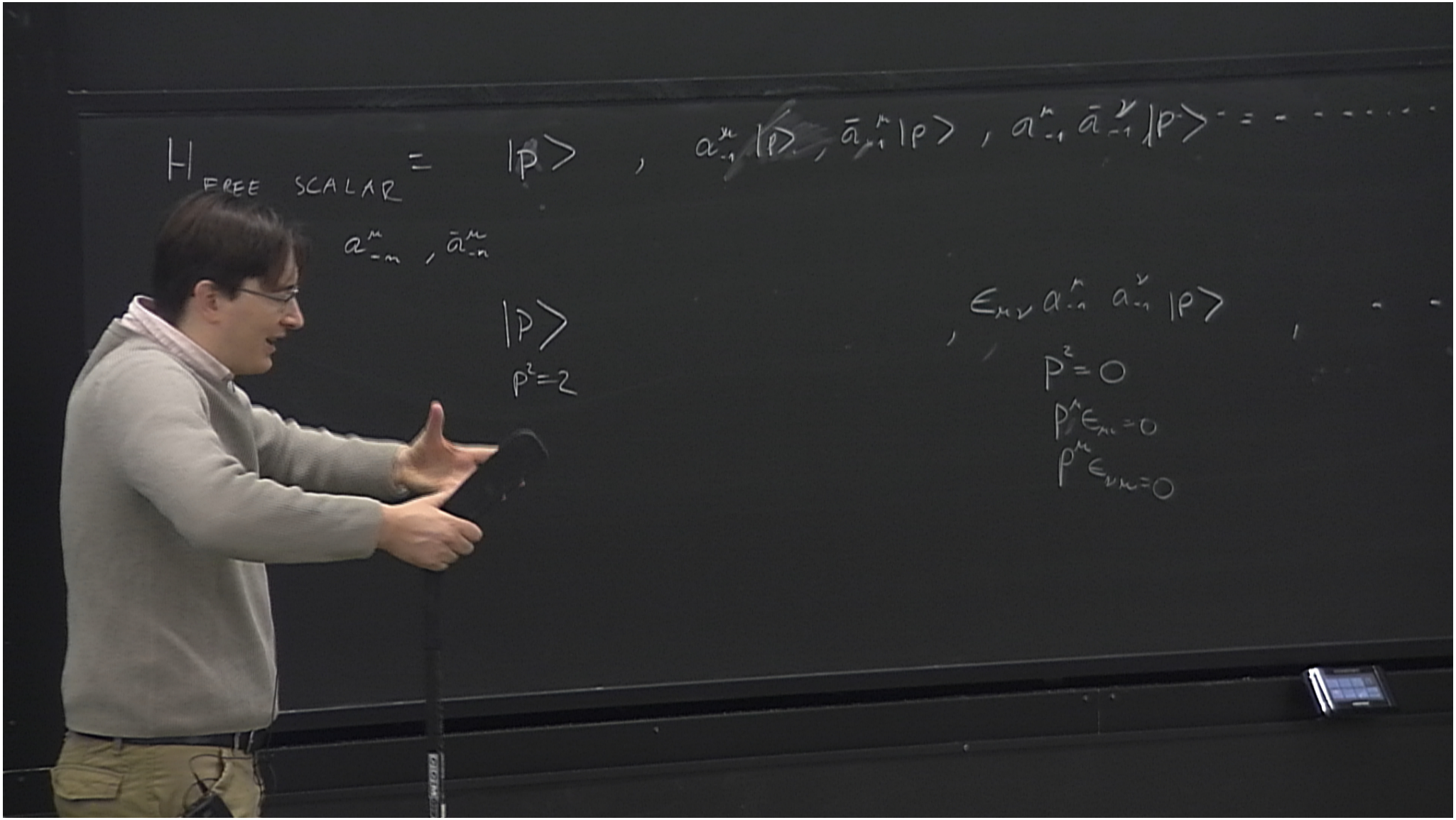

|0> |1>μ |2> |3> .....
φ0(x) φ1μ(x) φ2μν(x) φ3(x) ....
H FREE SCALARS

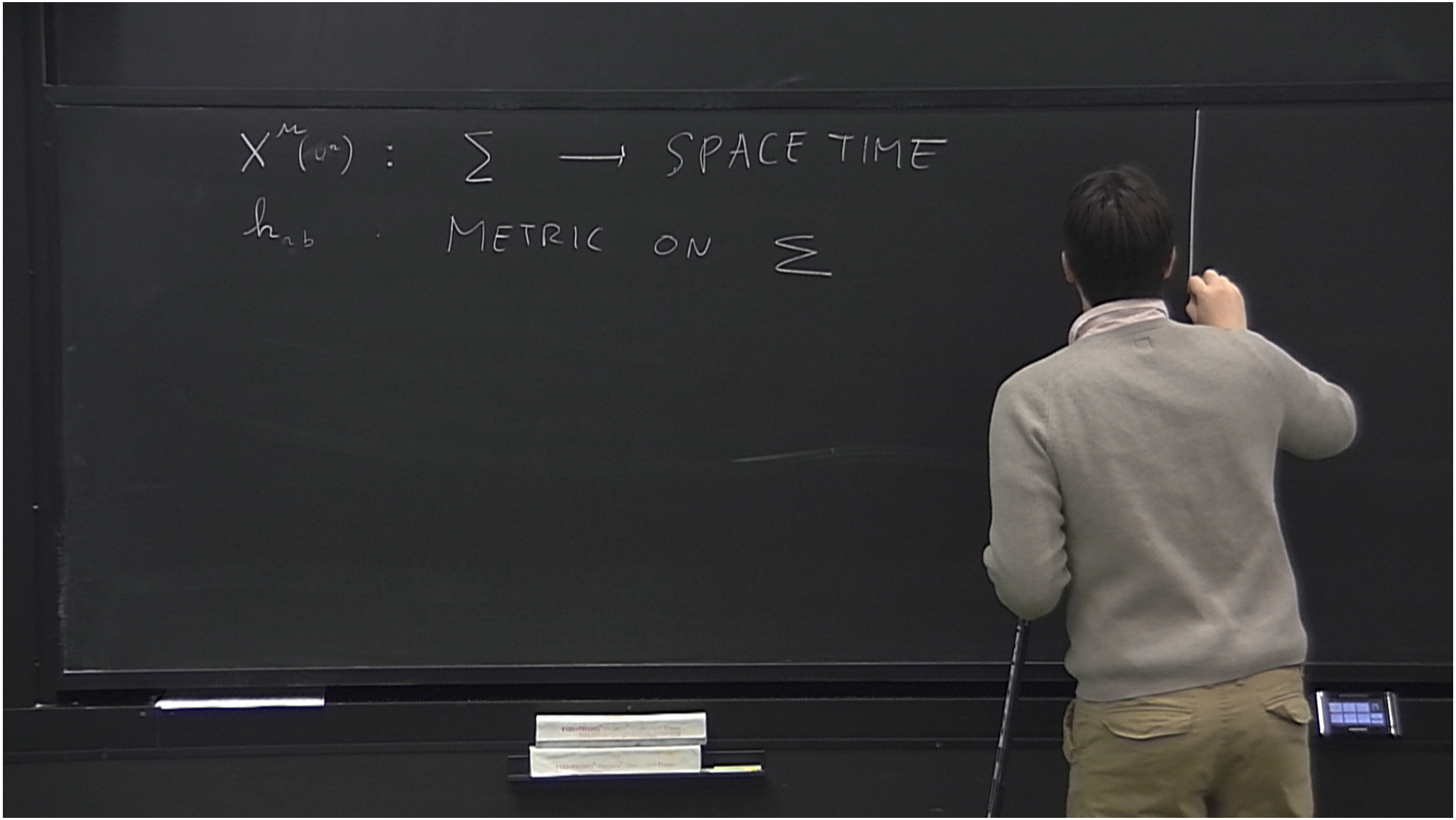

$\mathcal{H}_{\text{FREE SCALAR}} \supset P_{hr} \supset \text{Null}$
$\phi_0(x)$ $\phi_1^\mu(x)$ $\phi_2^{\mu\nu}(x)$ $\phi_3(x)$ ....
$\mathcal{H}_{1\text{-PARTICLE}} = \frac{P_{hr}}{\text{Null}} \equiv \frac{Q\text{-CLOSED}}{Q\text{-EXACT}}$
$\mathcal{H}_{\text{STRING THEORY}} =$

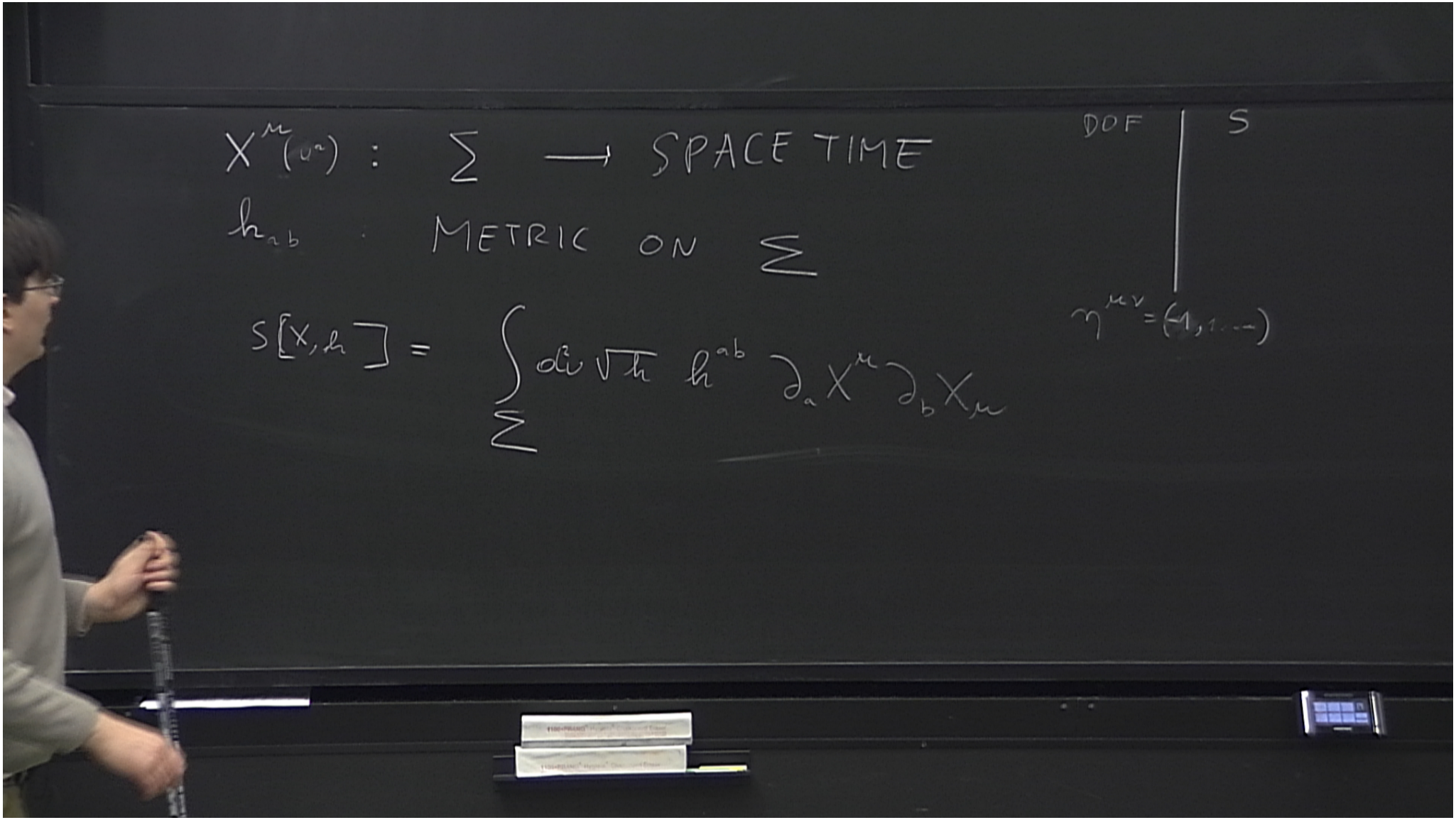

$|0\rangle$ $|1\rangle_\mu$ $|2\rangle$ $|3\rangle$ ....
$\phi_0(x)$ $\phi_1^\mu(x)$ $\phi_2^{\mu\nu}(x)$ $\phi_3(x)$ ....
$\mathcal{H}_{\text{FREE SCALARS}} \supset P_{hr} > \text{Null}$
$\mathcal{H}_{1\text{-PARTICLE}} = \frac{P_{hr}}{\text{Null}} \equiv \frac{Q\text{-CLOSED}}{Q\text{-EXACT}}$
$\mathcal{H}_{\text{STRING THEORY}} = |0\rangle \oplus \mathcal{H}_{1\text{-PARTICLE}} \oplus \mathcal{H}_{1\text{-PARTIC}}^{\otimes 2}$

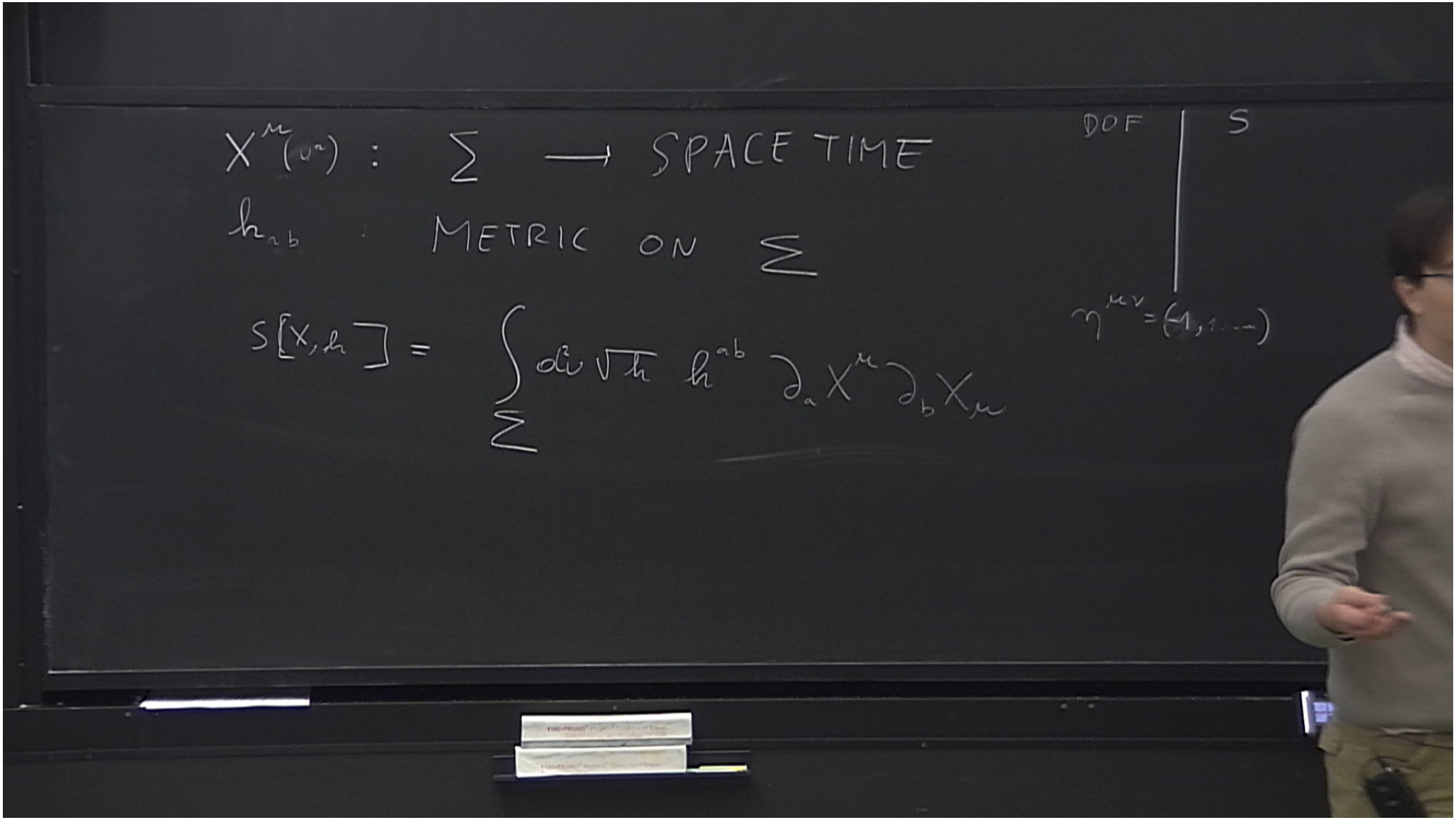

|0>
|3>
|0>
|0>
|2>
|1>

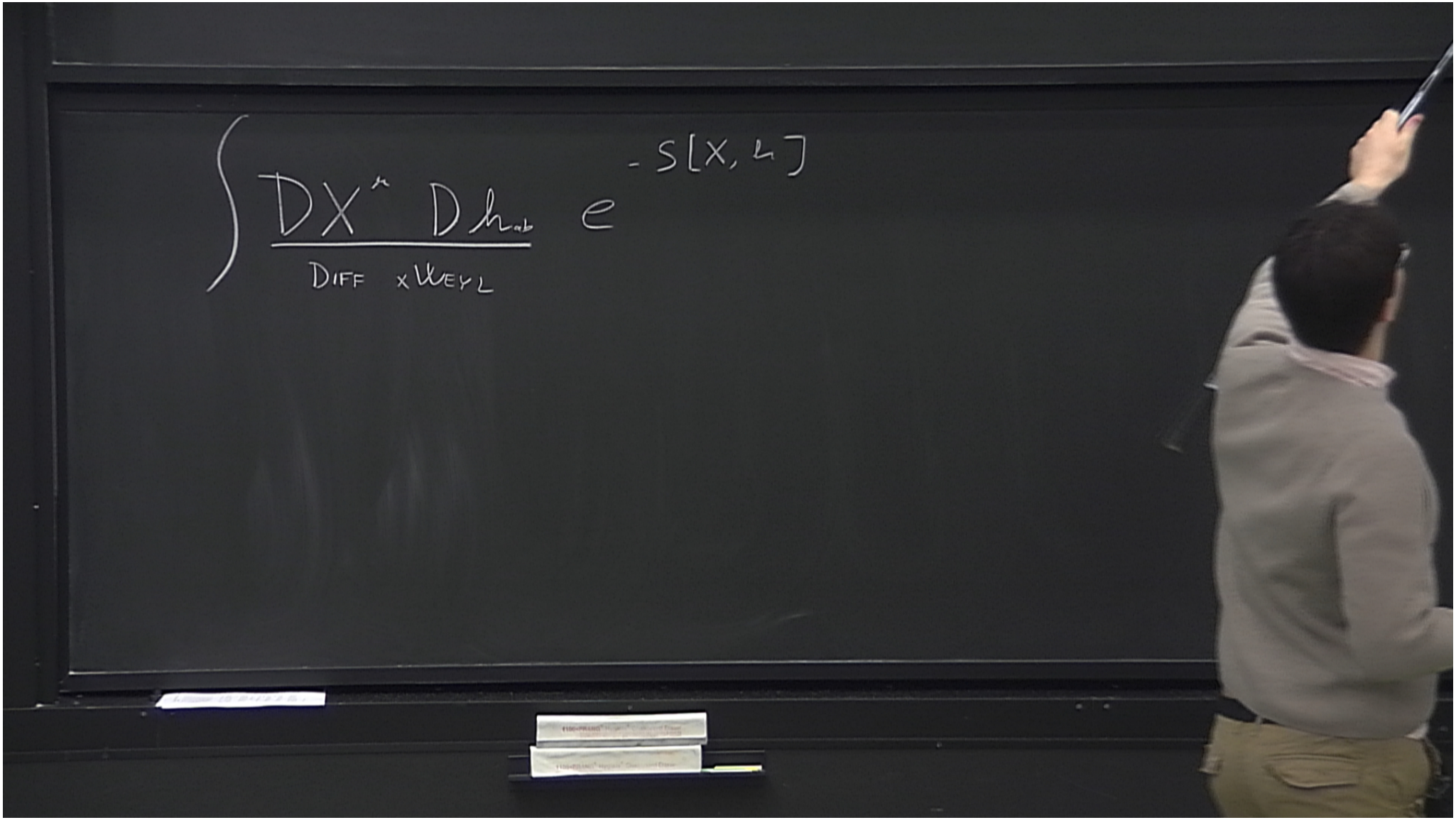

|0⟩
|3⟩
COMPUTE
A
|0⟩
|0⟩
|2⟩
|1⟩

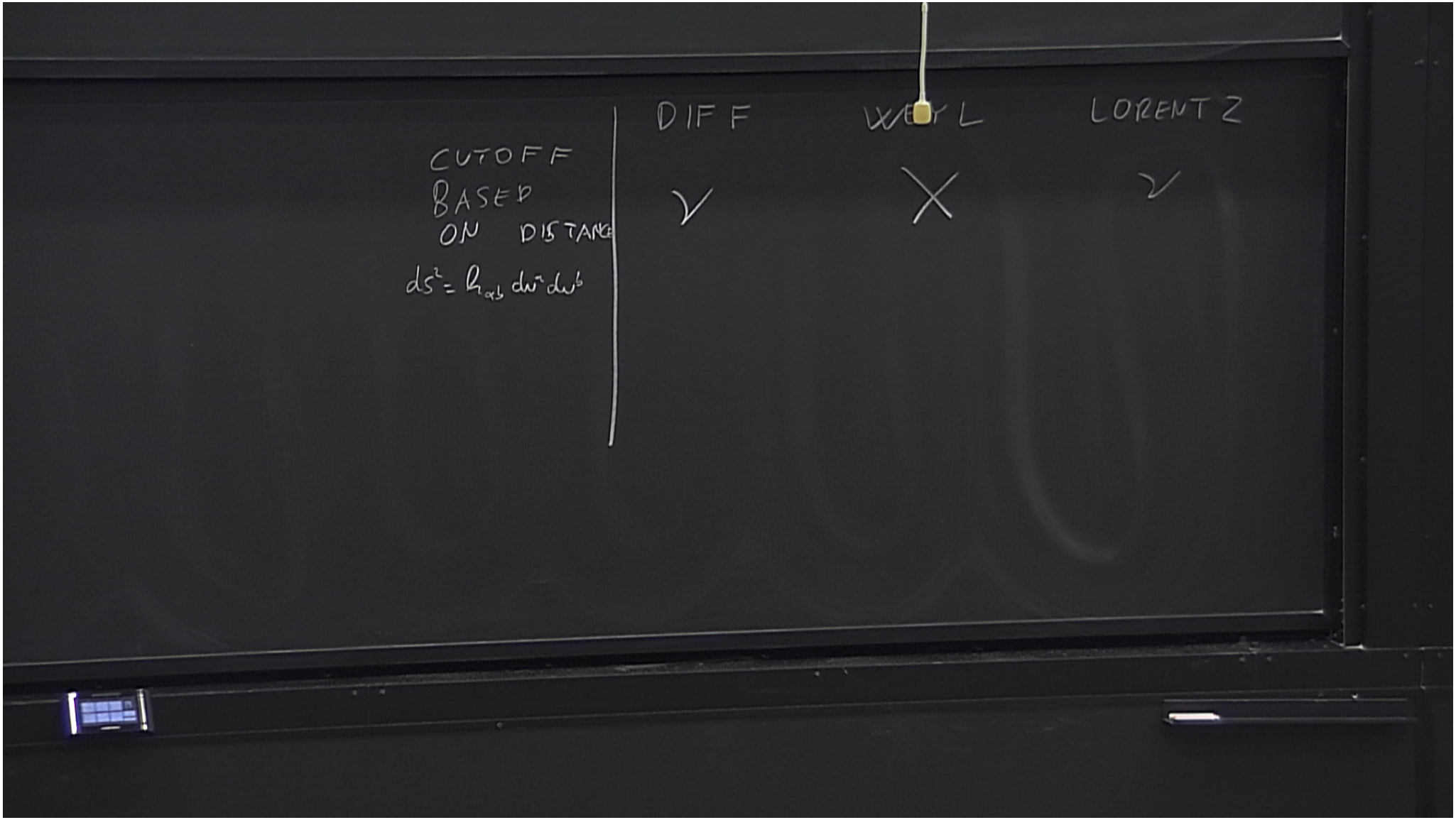

$H_{\text{FREE SCALAR}} = |p\rangle , \alpha_{-1}^{\mu}|p\rangle , \bar{\alpha}_{-1}^{\mu}|p\rangle , \alpha_{-1}^{\mu}\bar{\alpha}_{-1}^{\nu}|p\rangle , \ldots$
$\alpha_{-m}^{\mu} , \bar{\alpha}_{-n}^{\mu}$
$|p\rangle$
$p^2 = 2$
$\epsilon_{\mu\nu}\alpha_{-n}^{\mu}\alpha_{-1}^{\nu}|p\rangle$
$p^2 = 0$
$p^{\mu}\epsilon_{\mu\nu} = 0$
$p^{\mu}\epsilon_{\nu\mu} = 0$


$X^\mu(\sigma^a) : \Sigma \longrightarrow$ SPACE TIME
h_{ab} : METRIC ON Σ


$X^\mu(\sigma^a) : \Sigma \longrightarrow$ SPACE TIME
h_{ab} : METRIC ON Σ
$S[X,h] = \int_\Sigma d\sigma \sqrt{h}\, h^{ab}\, \partial_a X^\mu \partial_b X_\mu$
DOF
S
$\eta^{\mu\nu} = (-1,1\ldots-)$


$X^\mu(u^a) : \Sigma \longrightarrow$ SPACE TIME
h_{ab} : METRIC ON Σ
$S[X,h] = \int_\Sigma d^2u \sqrt{h}\, h^{ab}\, \partial_a X^\mu \partial_b X_\mu$
DOF | S
$\eta^{\mu\nu} = (-1,1\ldots1)$


$\int \frac{DX\hat{}\, Dh_{ab}}{\text{DIFF} \times \text{WEYL}}\, e^{-S[X,h]}$


CUTOFF
BASED
ON DISTANCE
$ds^2 = h_{ab} dw^a dw^b$
DIFF
WEYL
LORENTZ
✓
✗
✓

$a_{-1}^{\mu} \tilde{a}_{-1}^{\nu} |p\rangle \phi$

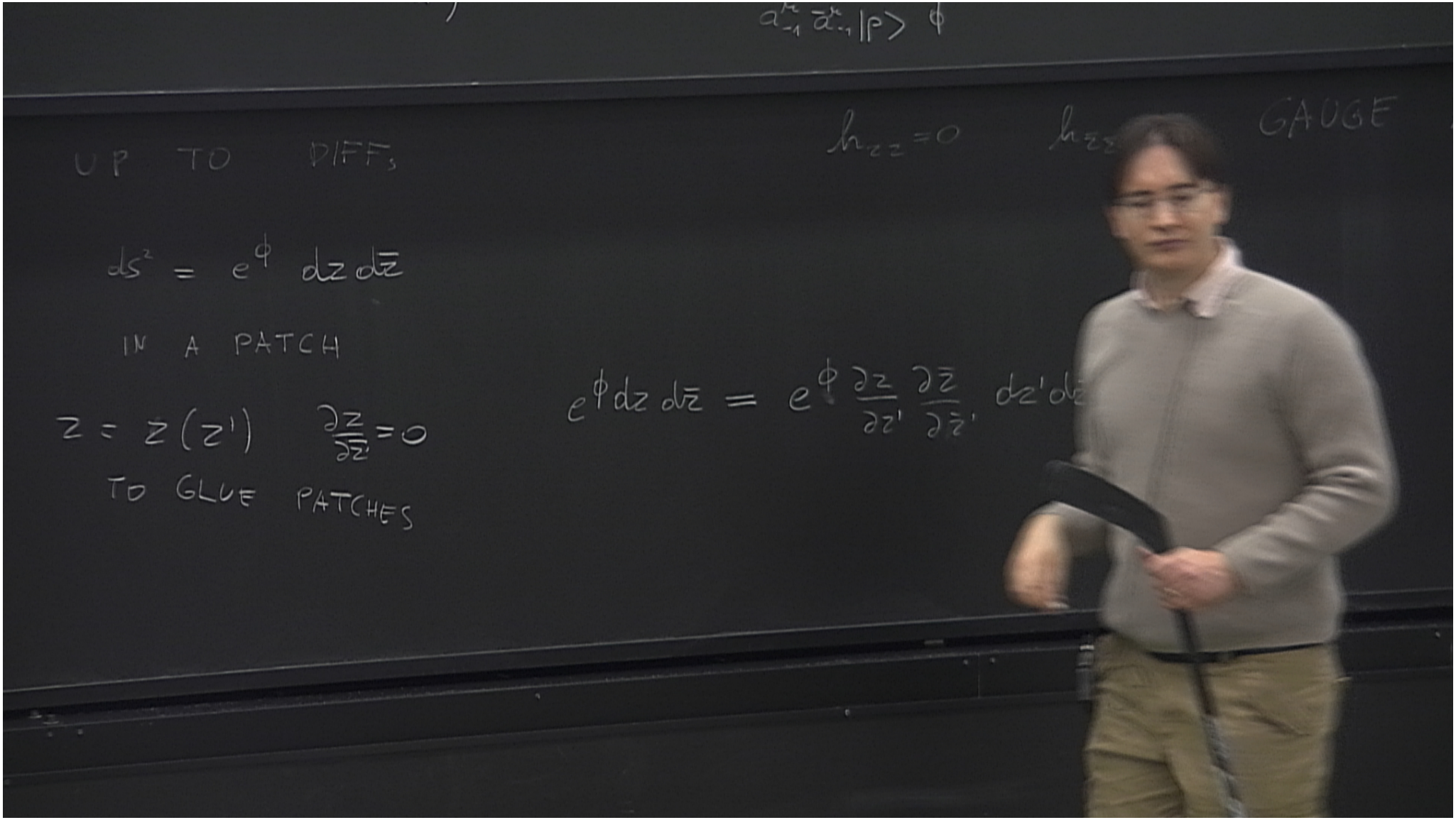
UP TO DIFFS

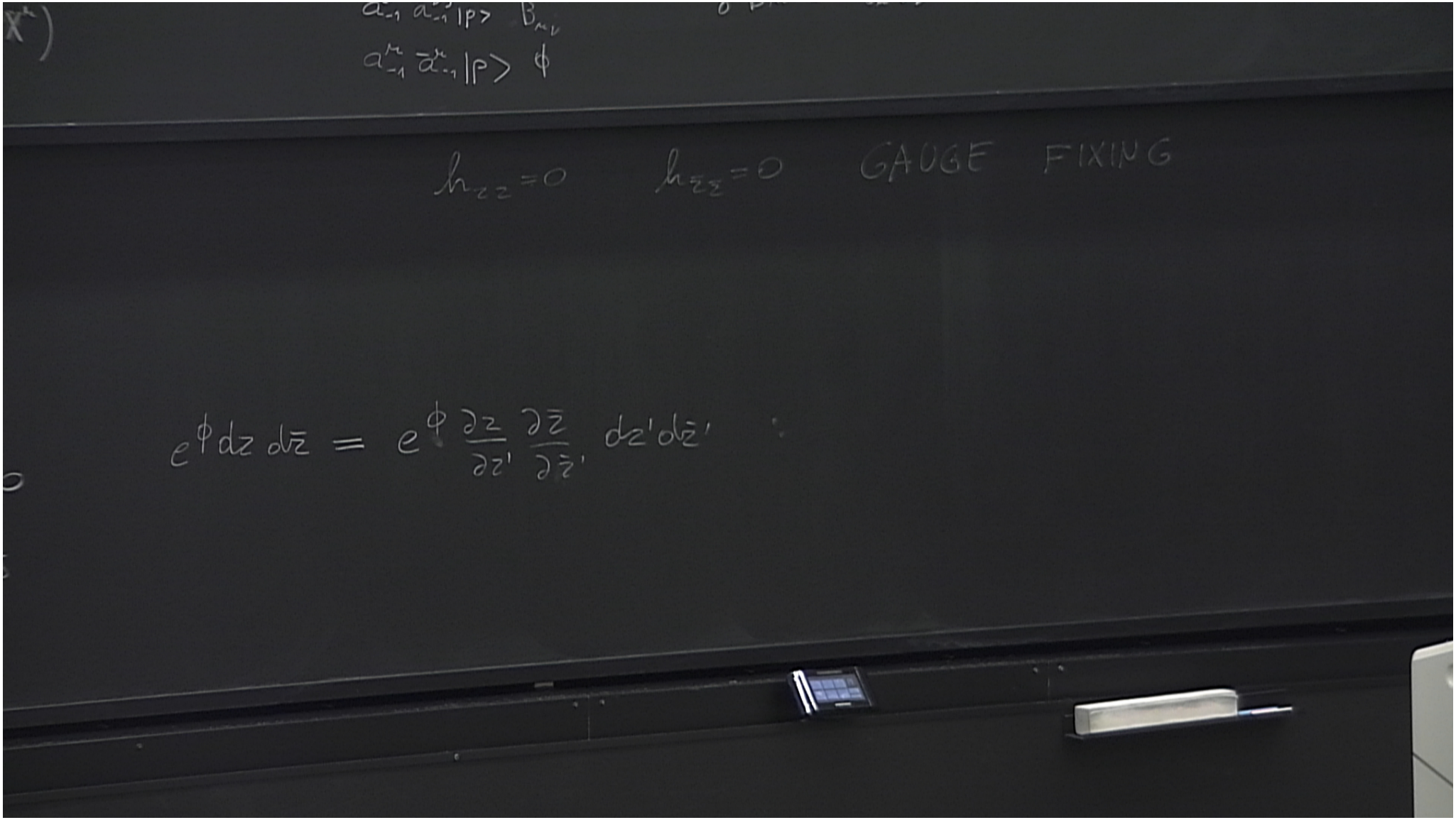
$$ds^2 = e^{\phi} dz d\bar{z}$$

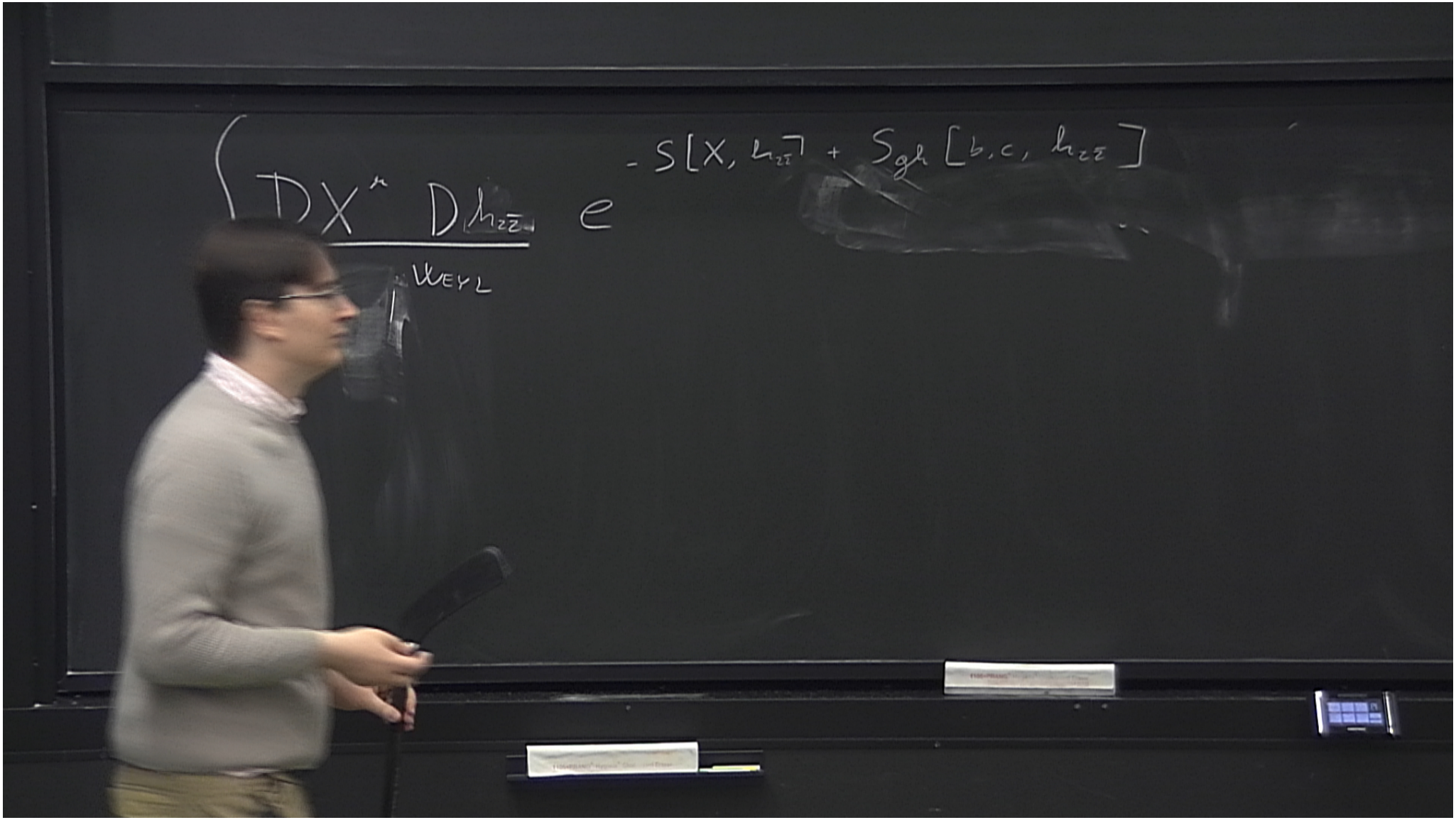
IN A PATCH

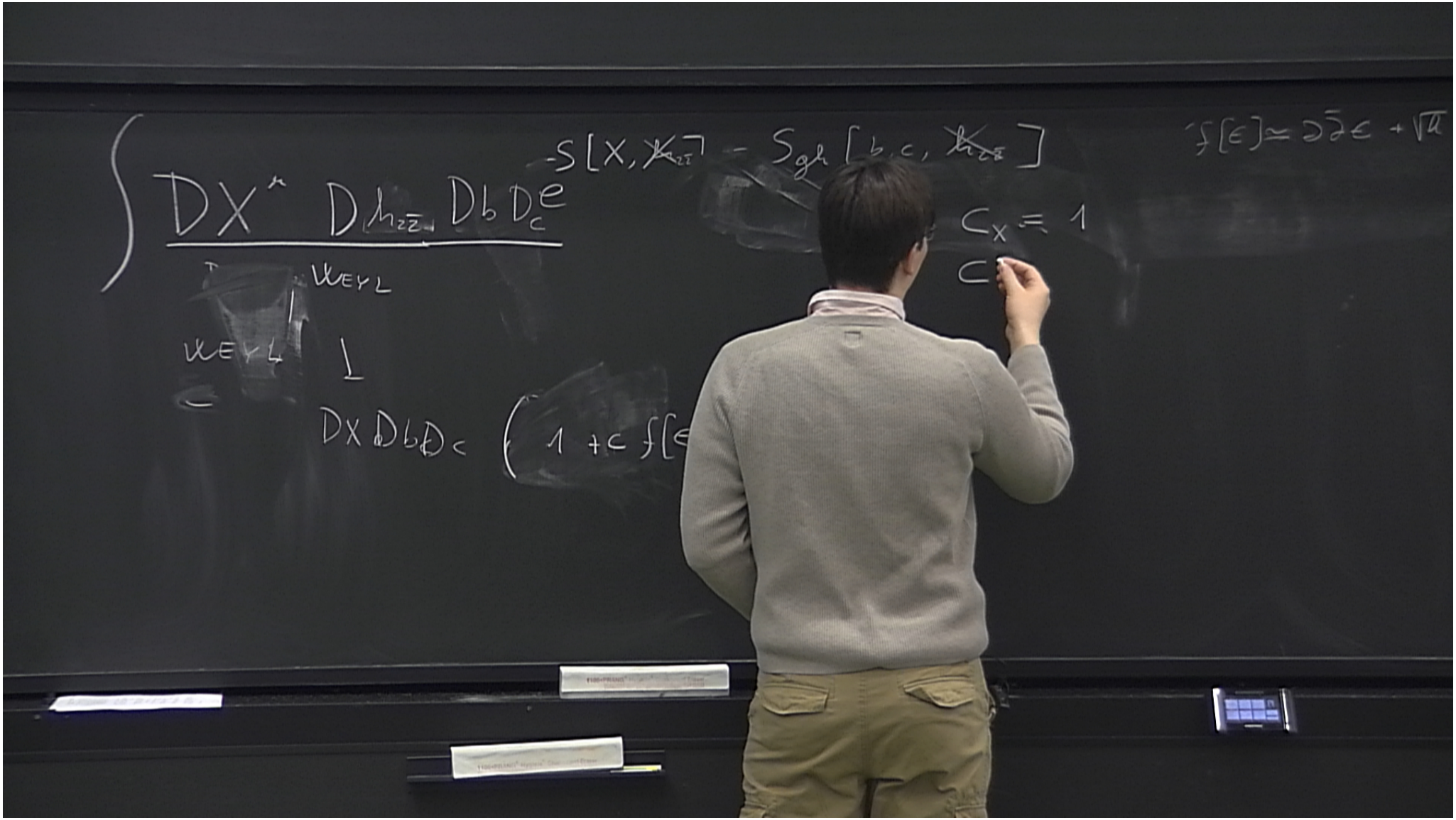
$$z = z(z') \qquad \frac{\partial z}{\partial \bar{z}'} = 0$$

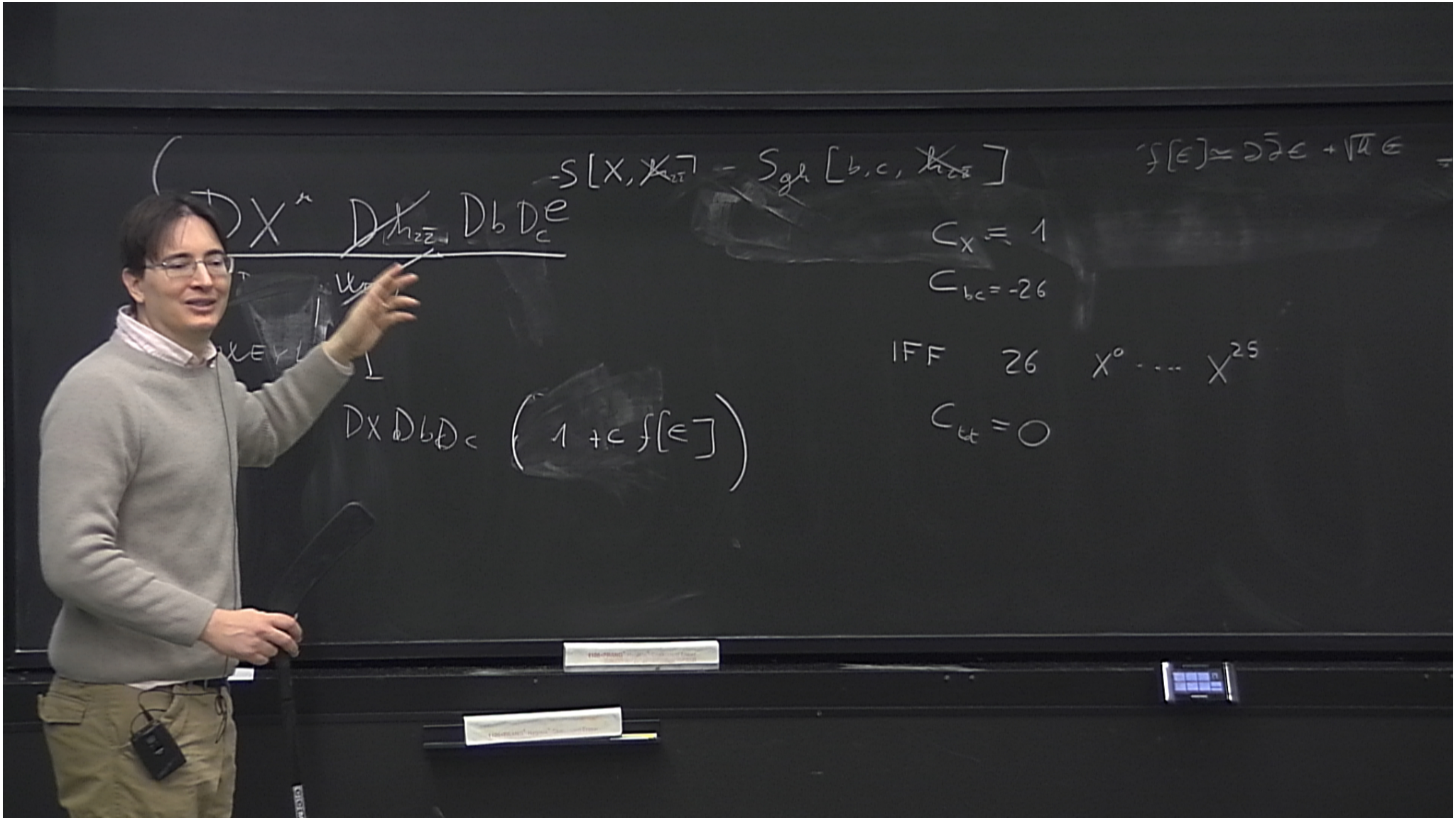
TO GLUE PATCHES

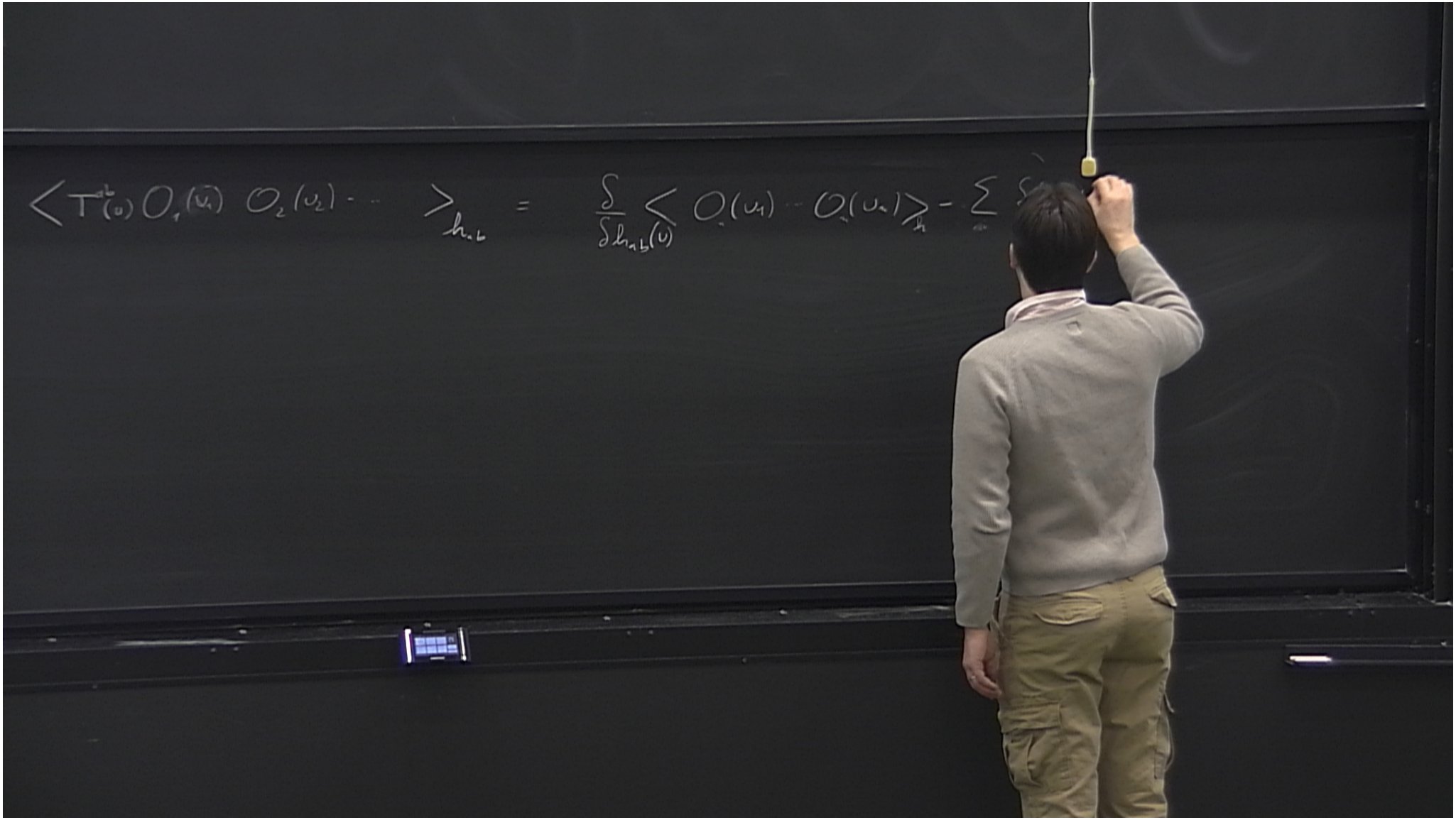

$a^{\mu}_{-1}\,\tilde{a}^{\nu}_{-1}|p\rangle\ \phi$
UP TO DIFFS
$h_{zz}=0$
$h_{z\bar{z}}$
GAUGE
$ds^2 = e^{\phi}\,dz\,d\bar{z}$
IN A PATCH
$z = z(z')$ $\frac{\partial z}{\partial \bar{z}'}=0$
TO GLUE PATCHES
$e^{\phi}dz\,d\bar{z} = e^{\phi}\frac{\partial z}{\partial z'}\frac{\partial \bar{z}}{\partial \bar{z}'}\,dz'd$

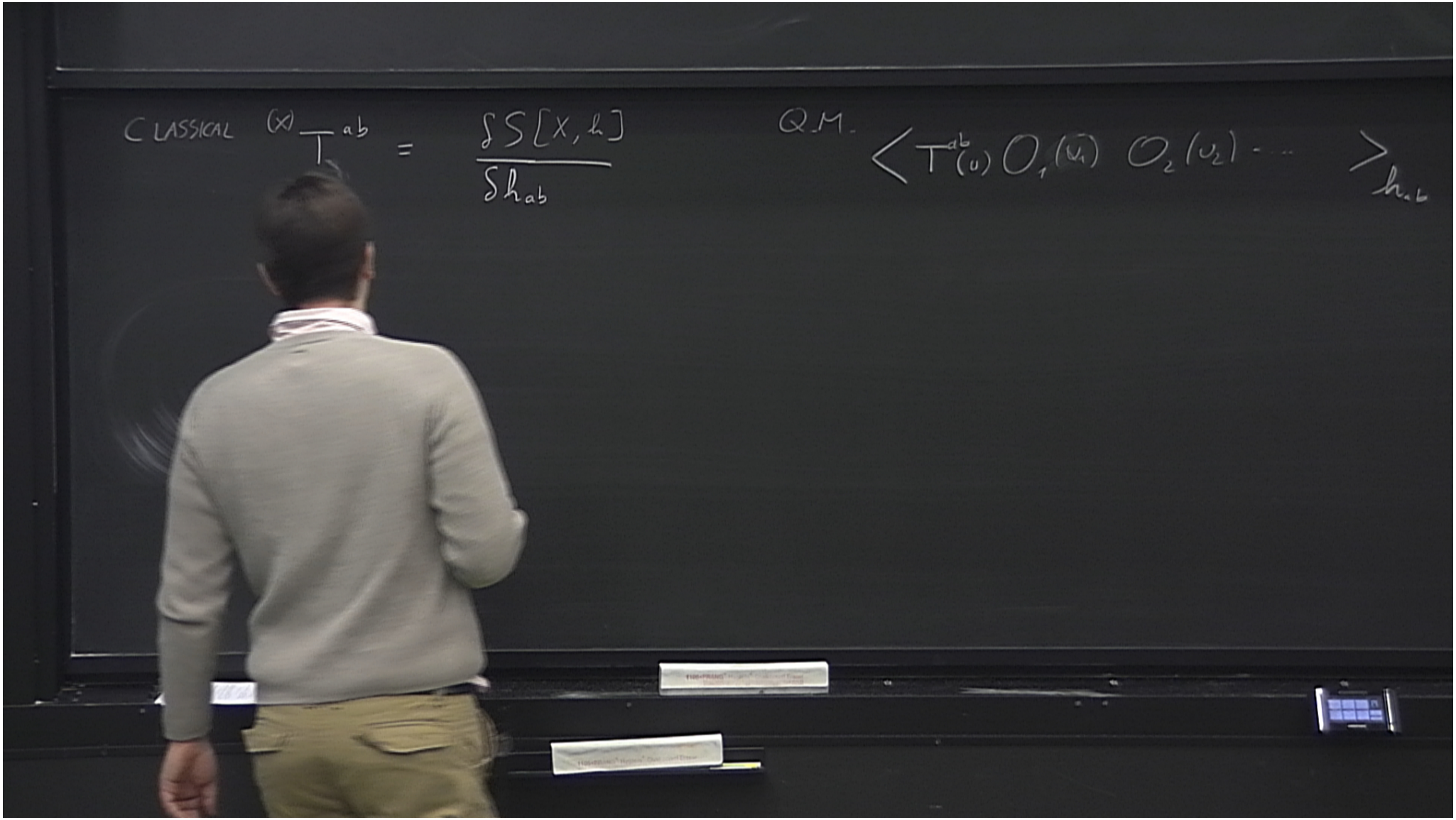

$h_{zz} = 0$ $h_{\bar{z}\bar{z}} = 0$ GAUGE FIXING
$e^{\phi} dz\, d\bar{z} = e^{\phi} \frac{\partial z}{\partial z'} \frac{\partial \bar{z}}{\partial \bar{z}'} dz' d\bar{z}'$

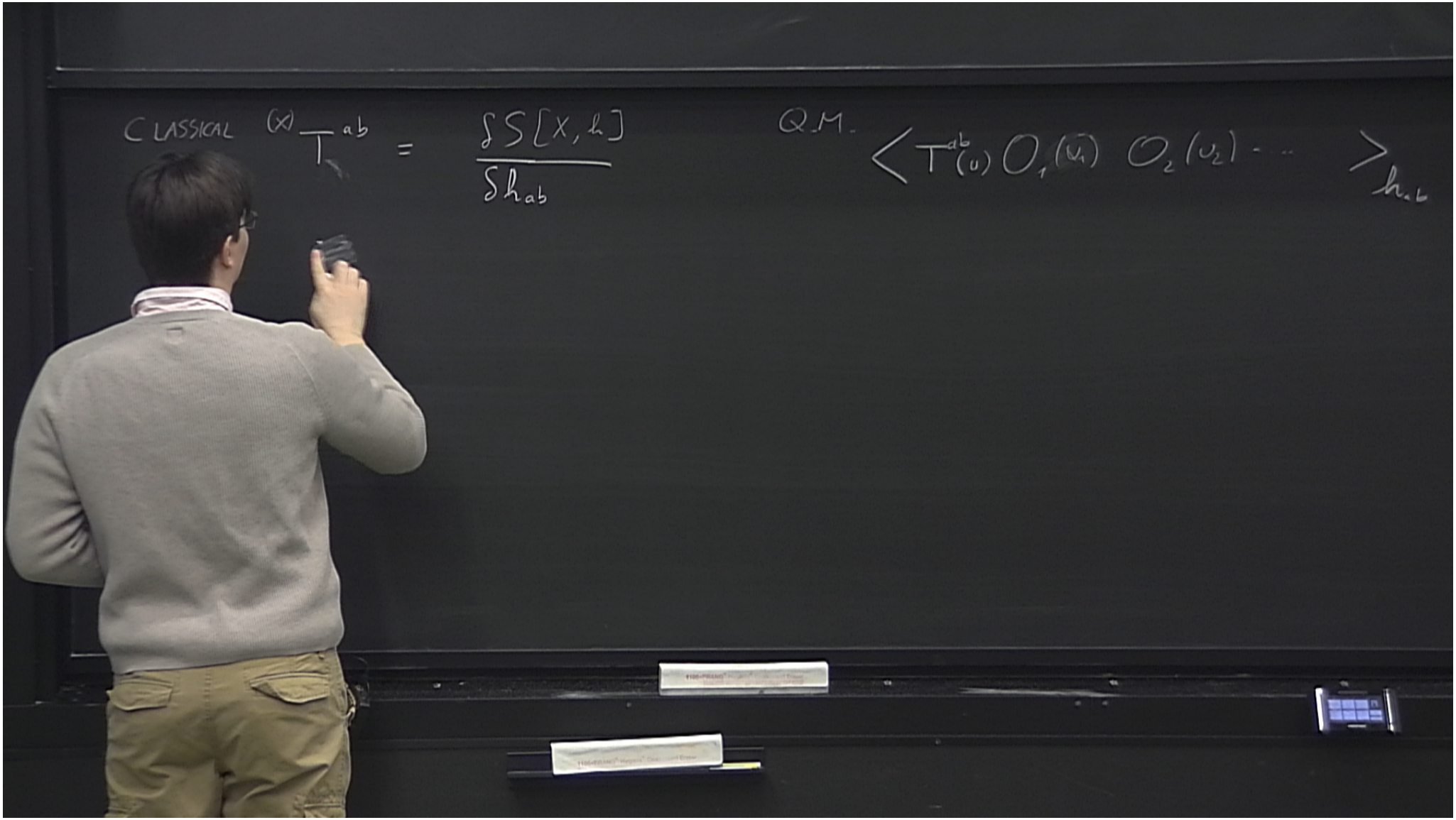

$\int \frac{DX\, Dh_{z\bar{z}}}{\text{Weyl}}\, e^{-S[X, h_{z\bar{z}}] + S_{gh}[b, c, h_{z\bar{z}}]}$

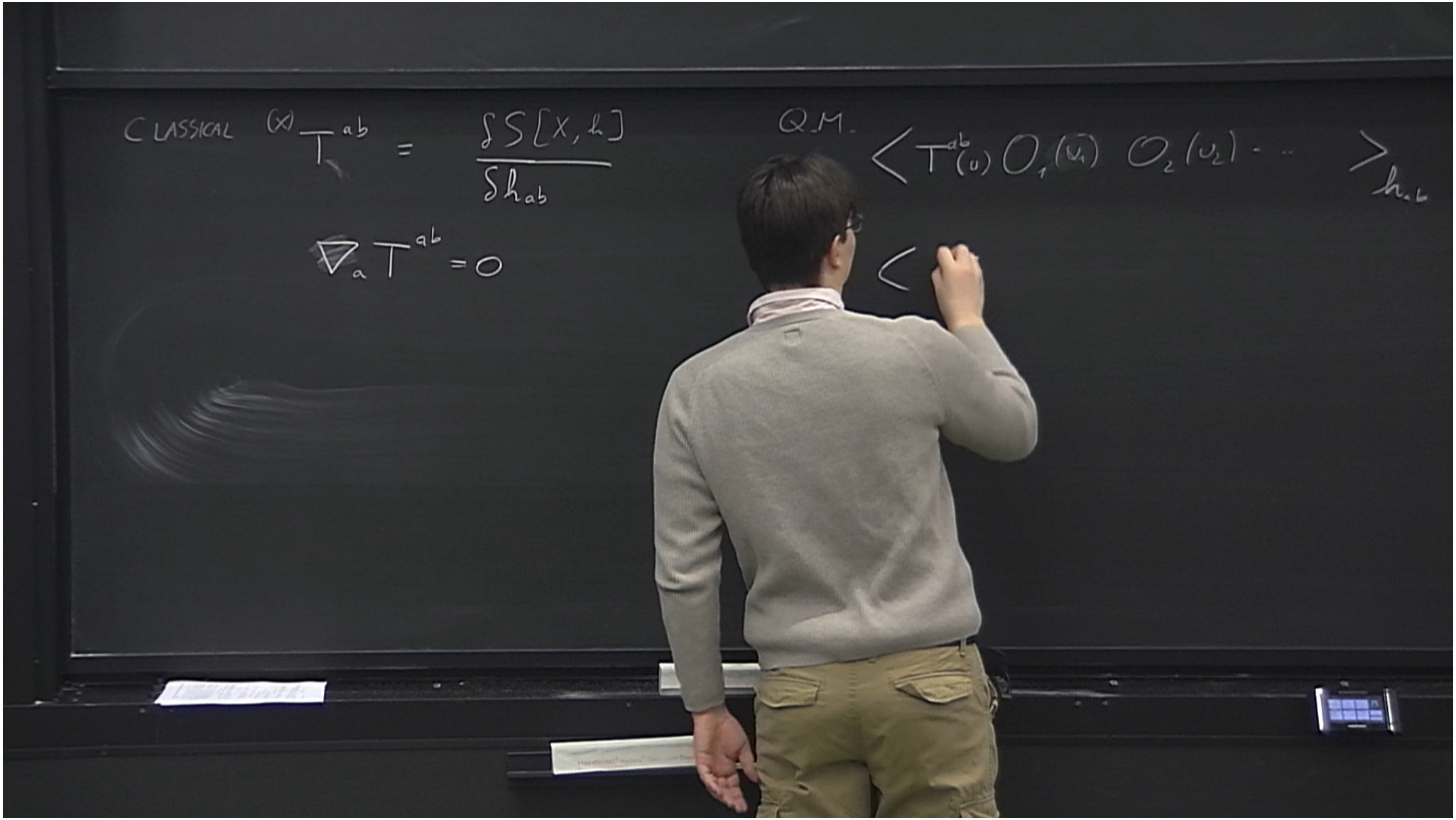

$\int \mathcal{D}X\, \mathcal{D}h_{z\bar{z}}\, \mathcal{D}b\, \mathcal{D}c\, e^{-S[X,h_{z\bar{z}}] - S_{gh}[b,c,h_{z\bar{z}}]}$
Weyl
Weyl
$\mathcal{D}X\, \mathcal{D}b\, \mathcal{D}c\, (1 + c f[$
$f[\epsilon] \simeq \partial\bar{\partial}\epsilon + \sqrt{h}$
$c_X = 1$
c

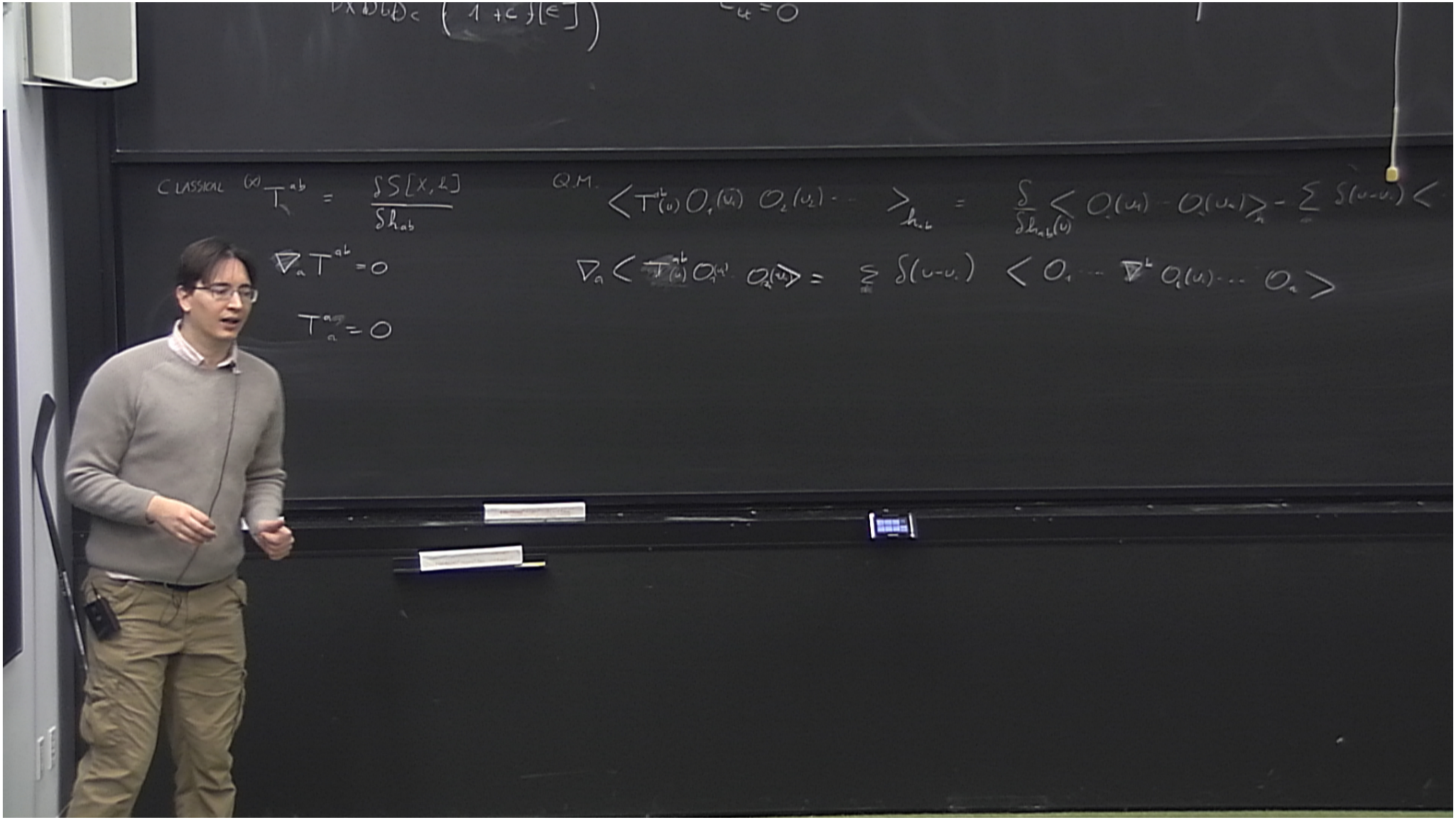

$\int DX^\mu \, Dh_{zz} \, Db \, Dc \, e^{-S[X,h_{zz}] - S_{gh}[b,c,h_{zz}]}$
$f[\epsilon] \simeq \partial\bar{\partial}\epsilon + \sqrt{\mu}\,\epsilon$
$C_X = 1$
$C_{bc} = -26$
IFF 26 $X^0 \cdots X^{25}$
$C_{tt} = 0$
$DX\,Db\,Dc\,(1 + c\,f[\epsilon])$

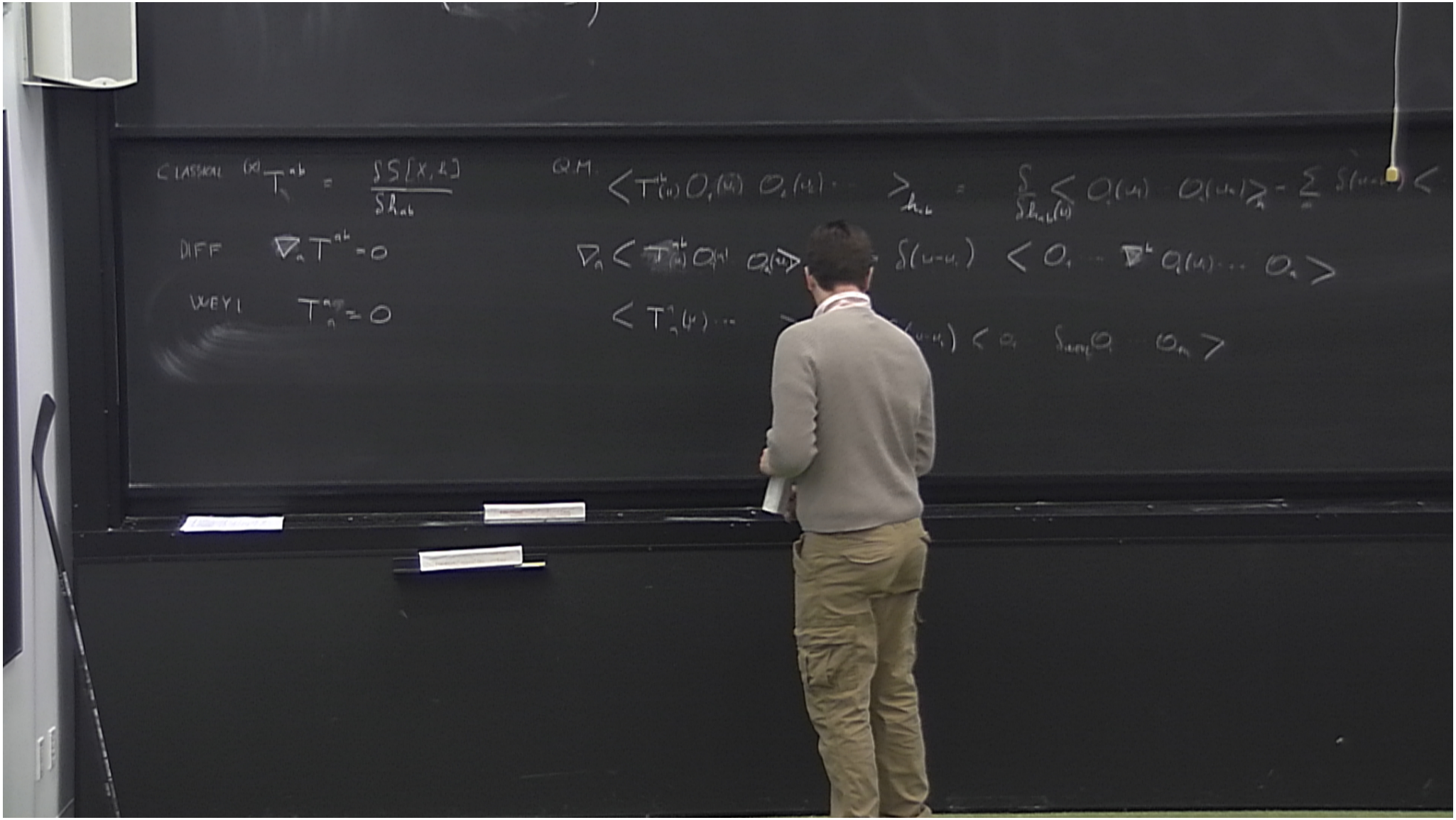

$\langle T^{ab}(x) O_1(x_1) O_2(x_2) \cdots \rangle_{h_{ab}} = \frac{\delta}{\delta h_{ab}(x)} \langle O_1(x_1) \cdots O_n(x_n) \rangle_{h} - \sum$

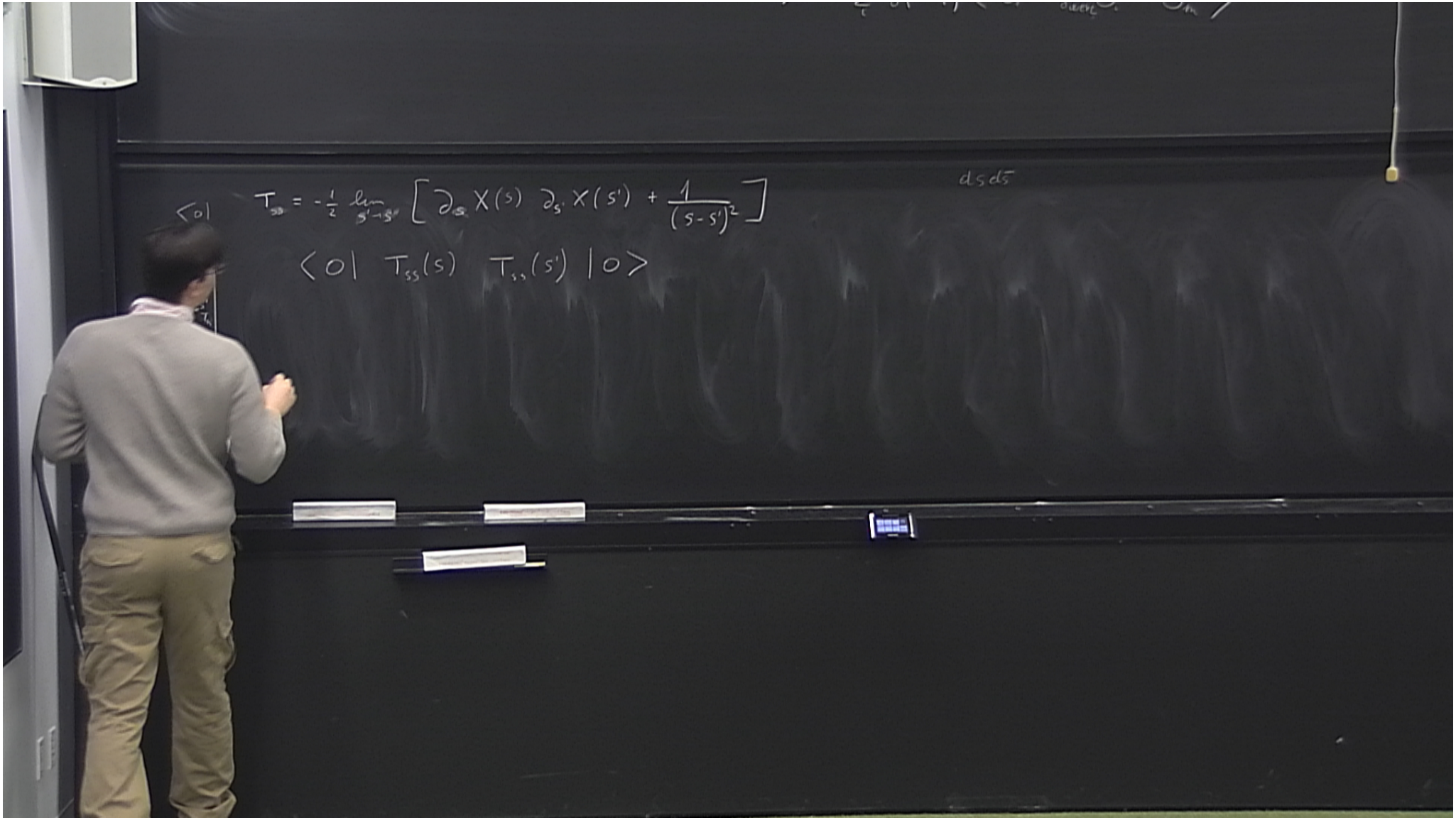

CLASSICAL
$\langle T^{ab}(x) \rangle = \frac{\delta S[X,h]}{\delta h_{ab}}$
Q.M.
$\langle T^{ab}(x) O_1(x_1) O_2(x_2) \cdots \rangle_{h_{ab}}$

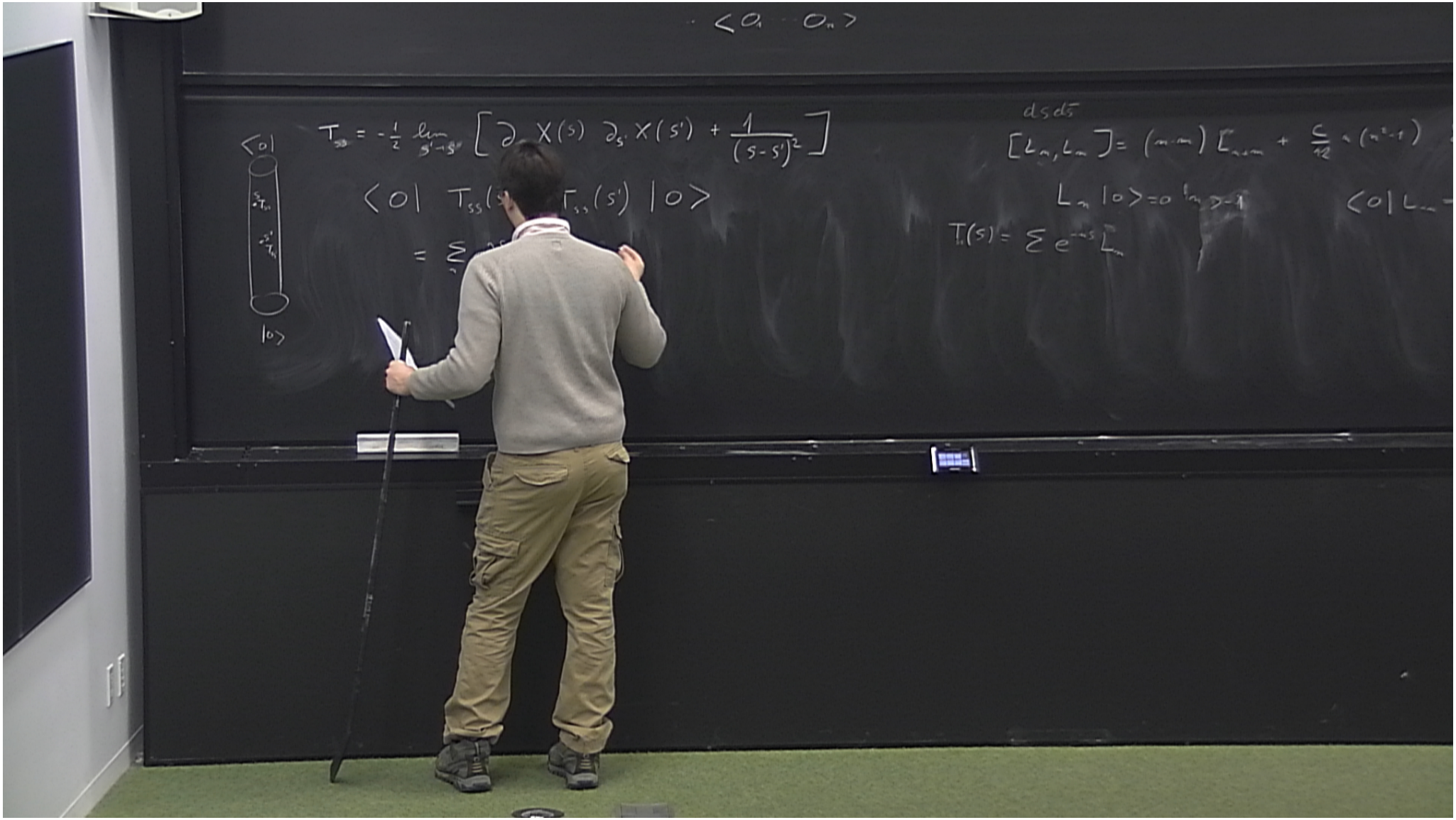

CLASSICAL
$\langle T^{ab}(x) \rangle = \frac{\delta S[X,h]}{\delta h_{ab}}$
Q.M.
$\langle T^{ab}(x) O_1(x_1) O_2(x_2) \cdots \rangle_{h,b}$

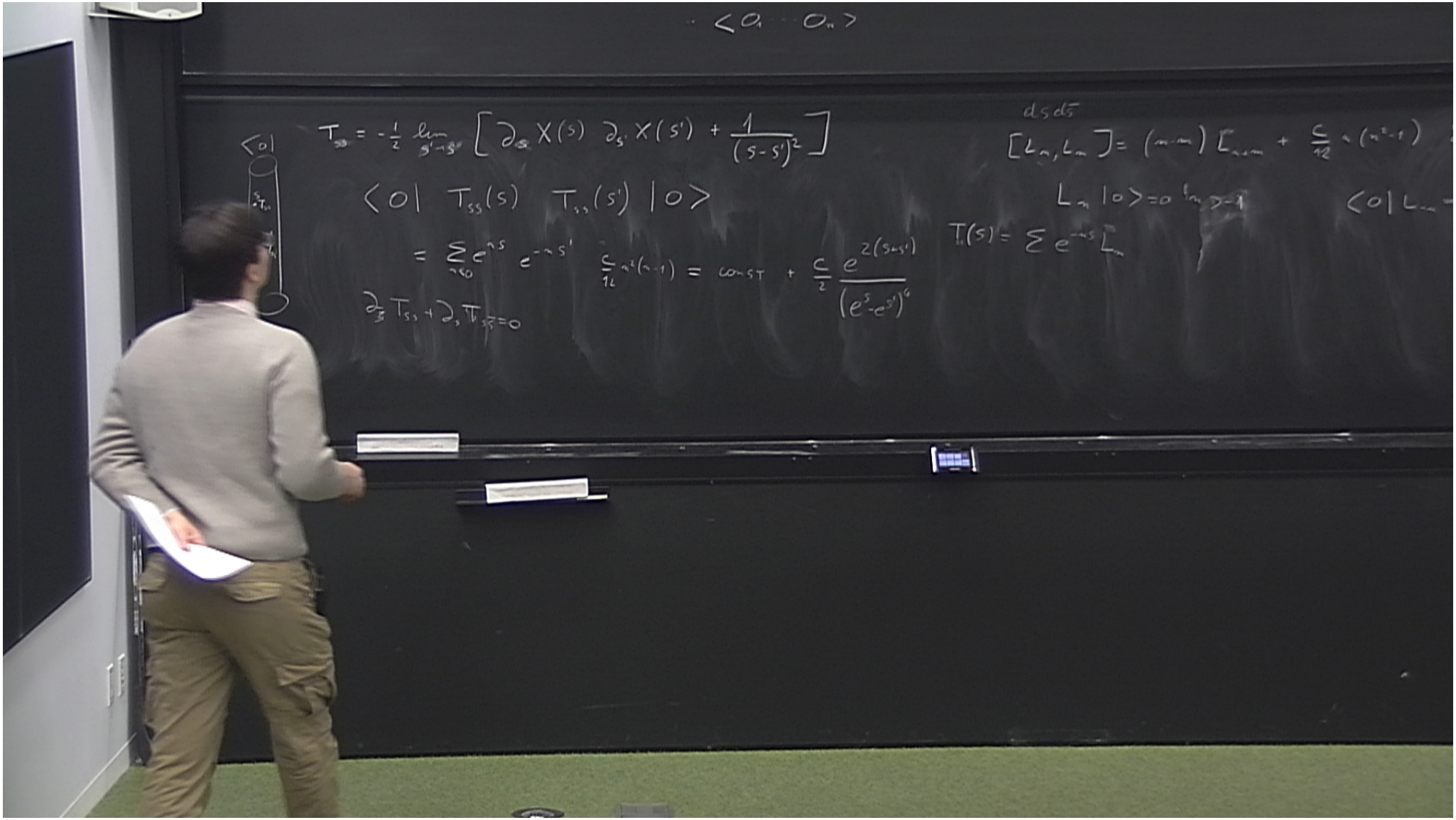

CLASSICAL
$\langle T^{ab} \rangle = \frac{\delta S[X,h]}{\delta h_{ab}}$
Q.M.
$\langle T^{ab}(x) O_1(x_1) O_2(x_2) \cdots \rangle_{h_{ab}}$
$\nabla_a T^{ab} = 0$

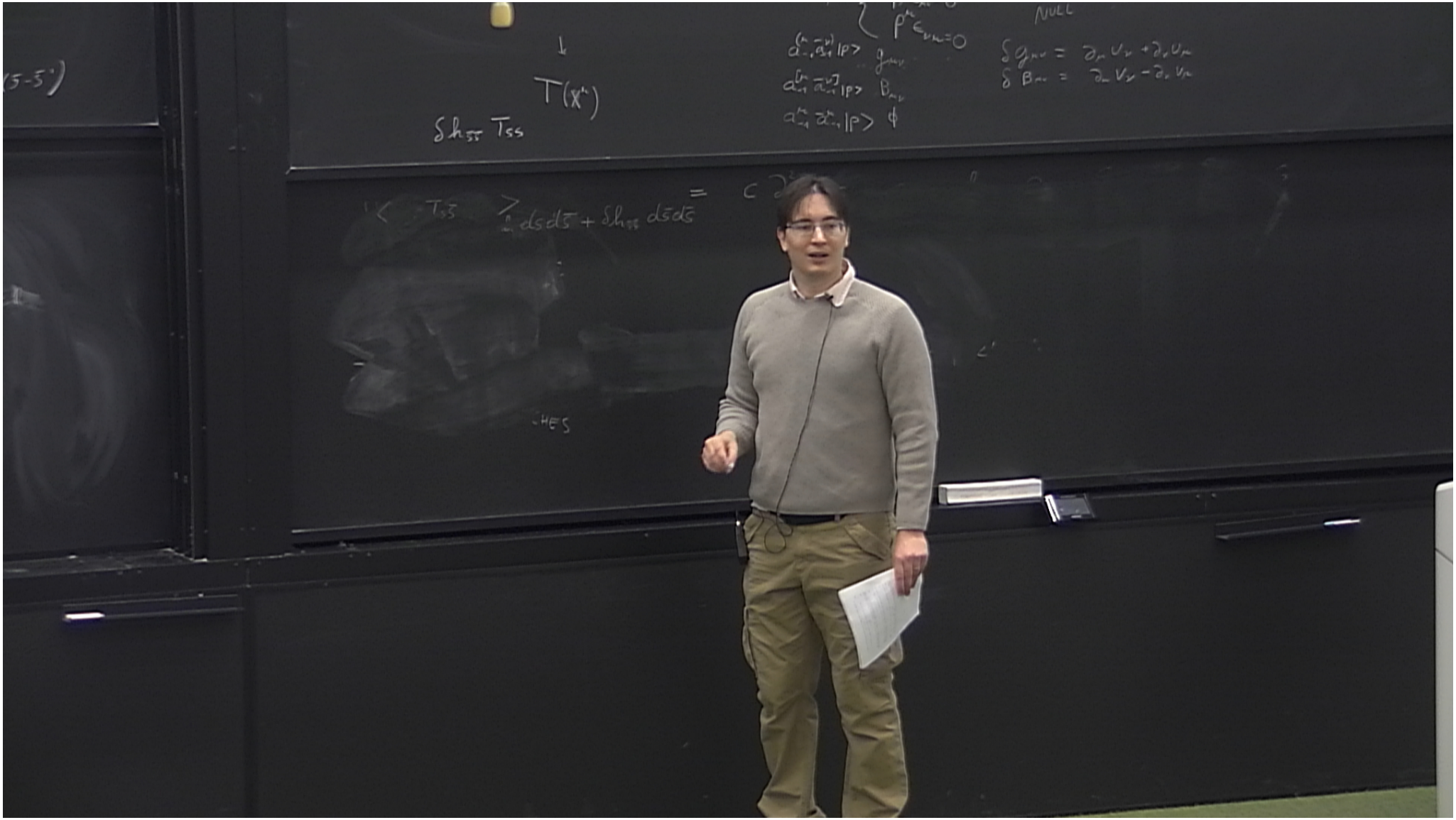

CLASSICAL
$T^{ab} = \frac{\delta S[X,L]}{\delta h_{ab}}$
$\nabla_a T^{ab} = 0$
$T^a_a = 0$
Q.M.
$\langle T^{ab}(u) O_1(u_1) O_2(u_2) \cdots \rangle_{h_{ab}} = \frac{\delta}{\delta h_{ab}(u)} \langle O_1(u_1) \cdots O_n(u_n) \rangle - \sum \delta(u-u_i) \langle$
$\nabla_a \langle T^{ab}(u) O_1(u_1) O_2(u_2) \rangle = \sum \delta(u-u_i) \langle O_1 \cdots \nabla^b O_i(u_i) \cdots O_n \rangle$

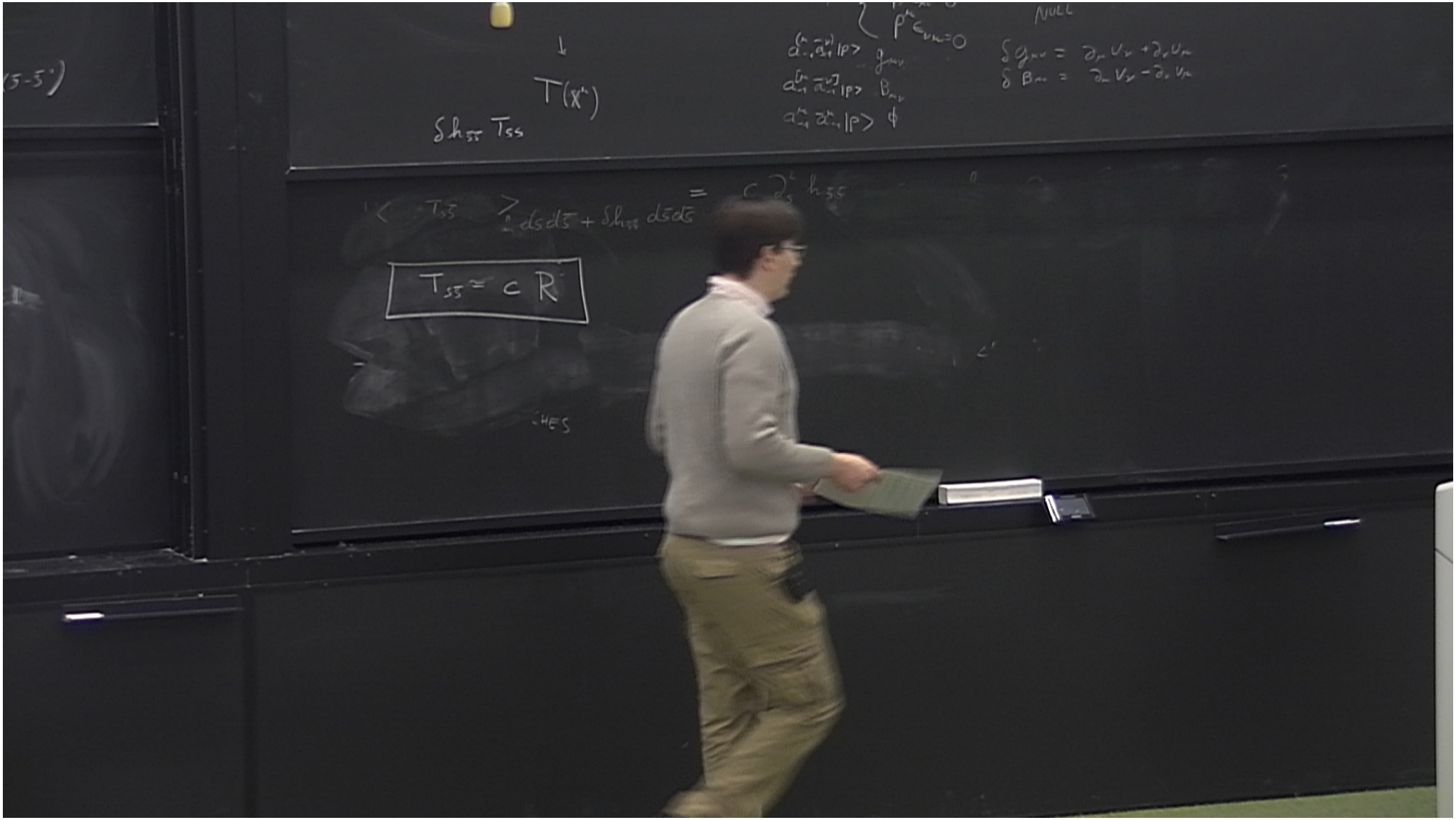

CLASSICAL
DIFF
WEYL
QM

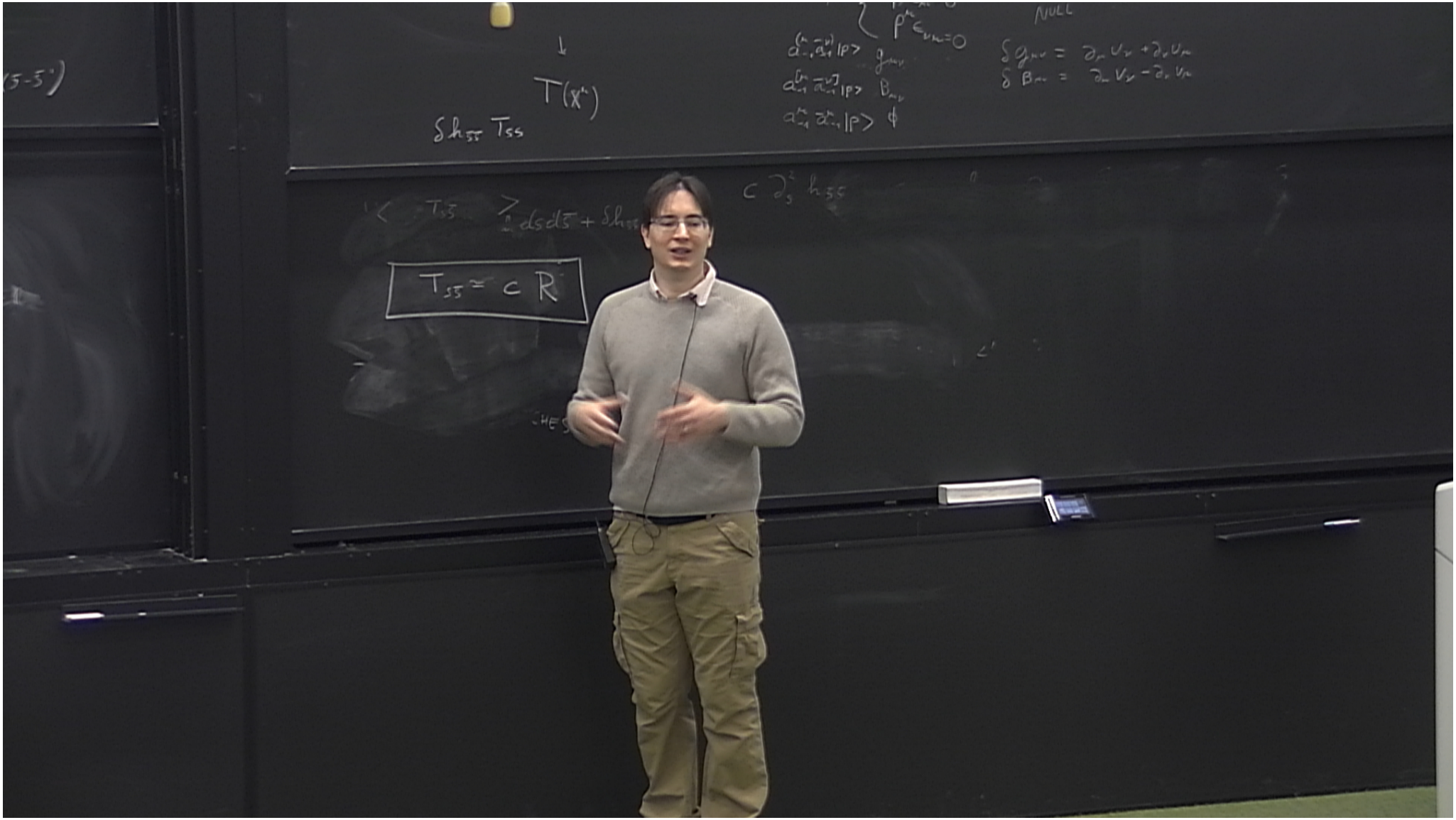

$\langle 0| \quad T_{ss} = -\frac{1}{2} \lim_{s' \to s} \left[\partial_s X(s) \, \partial_{s'} X(s') + \frac{1}{(s-s')^2} \right]$
$ds \, d\bar{s}$
$\langle 0 | \, T_{ss}(s) \quad T_{ss}(s') \, | 0 \rangle$

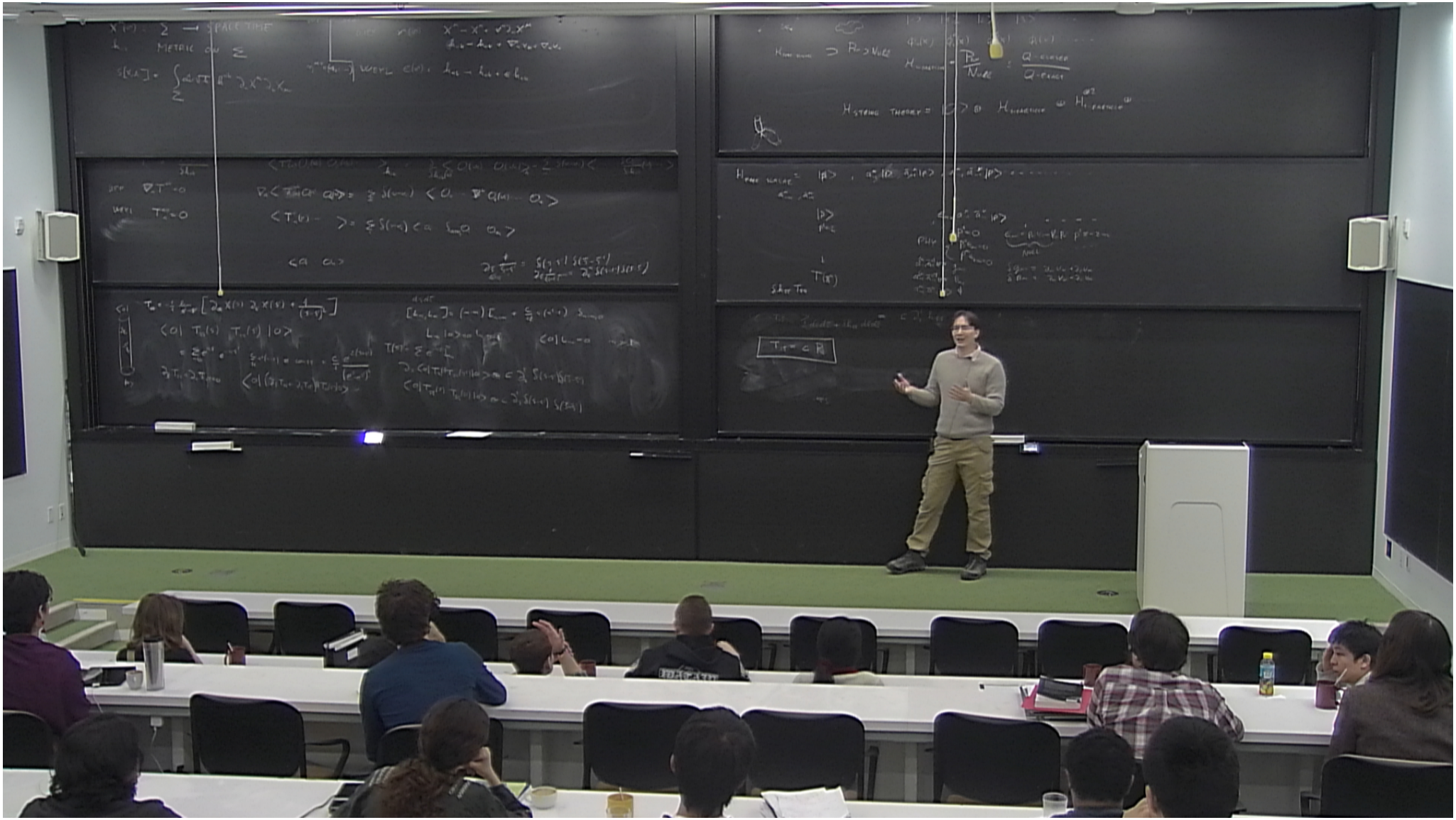

$\langle O_1 \cdots O_n \rangle$
$T_{ss} = -\frac{1}{2} \lim_{s' \to s} \left[\partial_s X(s)\, \partial_{s'} X(s') + \frac{1}{(s-s')^2} \right]$
$\langle 0 | T_{ss}(s) \cdots T_{ss}(s') | 0 \rangle$
$= \sum$
$\langle 0 |$
$| 0 \rangle$
$ds\,ds'$
$[L_n, L_m] = (n-m) L_{n+m} + \frac{c}{12} n(n^2-1)$
$L_n | 0 \rangle = 0 \quad n \geq -1$
$\langle 0 | L_{-n}$
$T(s) = \sum e^{-ns} L_n$


$\langle O_1 \cdots O_n \rangle$
$T_{ss} = -\frac{1}{2} \lim_{s' \to s} \left[\partial_s X(s)\, \partial_{s'} X(s') + \frac{1}{(s-s')^2} \right]$
$\langle 0 | \; T_{ss}(s) \; T_{ss}(s') \; | 0 \rangle$
$= \sum_{n \geq 0} e^{-ns} \; e^{-ns'}$
$\sum_{n} n^2 (n-1) = \text{const} + \frac{c}{2} \frac{e^{2(s+s')}}{(e^s - e^{s'})^6}$
$\partial_s T_{ss} + \partial_s T_{s\bar{s}} = 0$
$ds\, d\bar{s}$
$[L_n, L_m] = (n-m) L_{n+m} + \frac{c}{12} n (n^2-1)$
$L_n |0\rangle = 0 \quad n \geq -1$
$\langle 0 | L_{-n}$
$T(s) = \sum e^{-ns} L_n$


T(X^μ)
δh_ss T_ss
NULL
δ g_μν = ∂_μ V_ν + ∂_ν V_μ
δ B_μν = ∂_μ V_ν − ∂_ν V_μ


T(x^μ)
δh_ss T_ss
T_ss = c R
NULL


T(x^μ)
δh_ss T_ss
T_ss = c R
NULL




T(X^μ)
δh_ss T_ss
NULL
T_ss̄ = c R