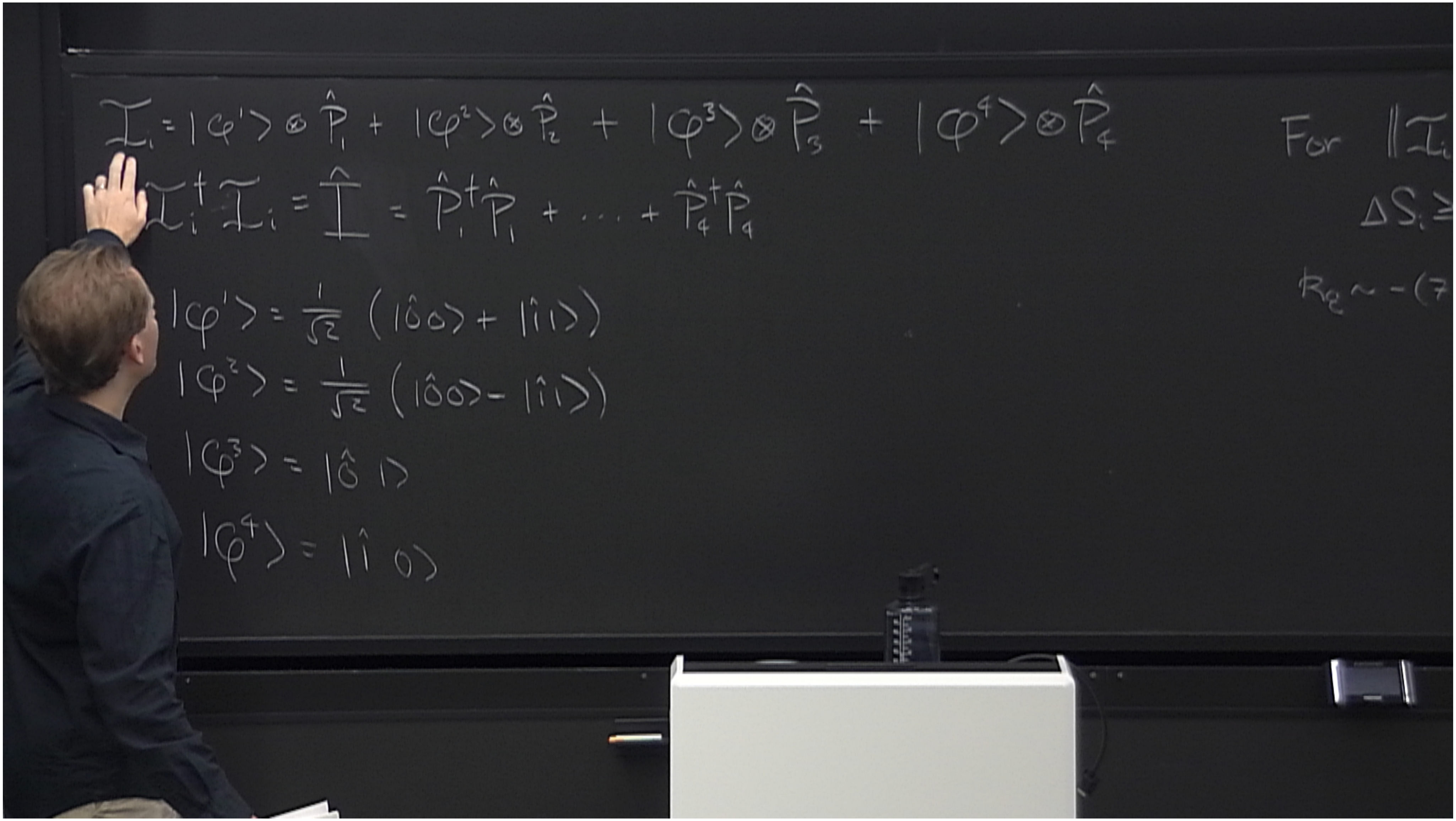
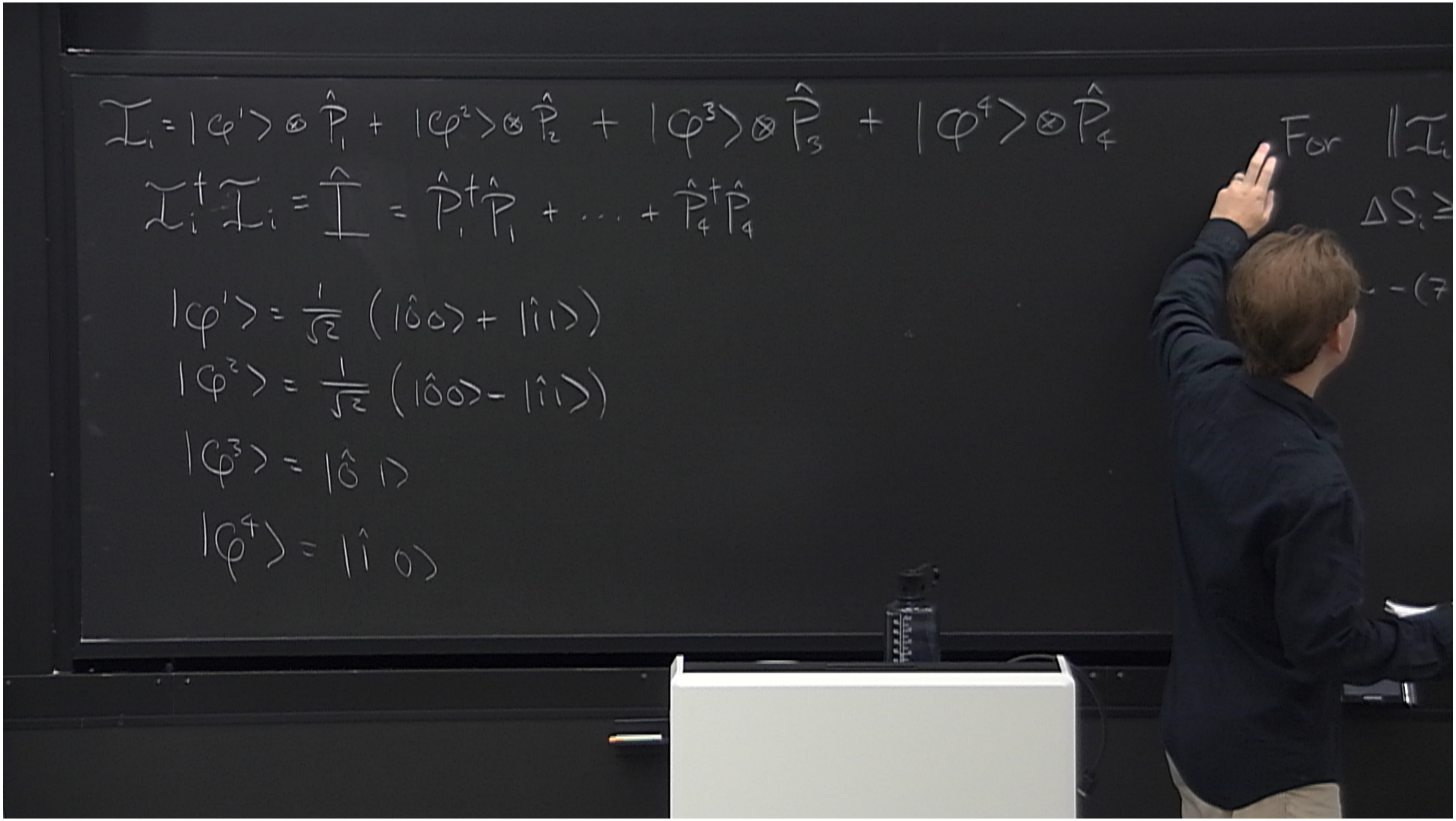
Title: Fuzzballs to Firewalls: A Post-Firewall Review of the Fuzzball Proposal: Lecture 2

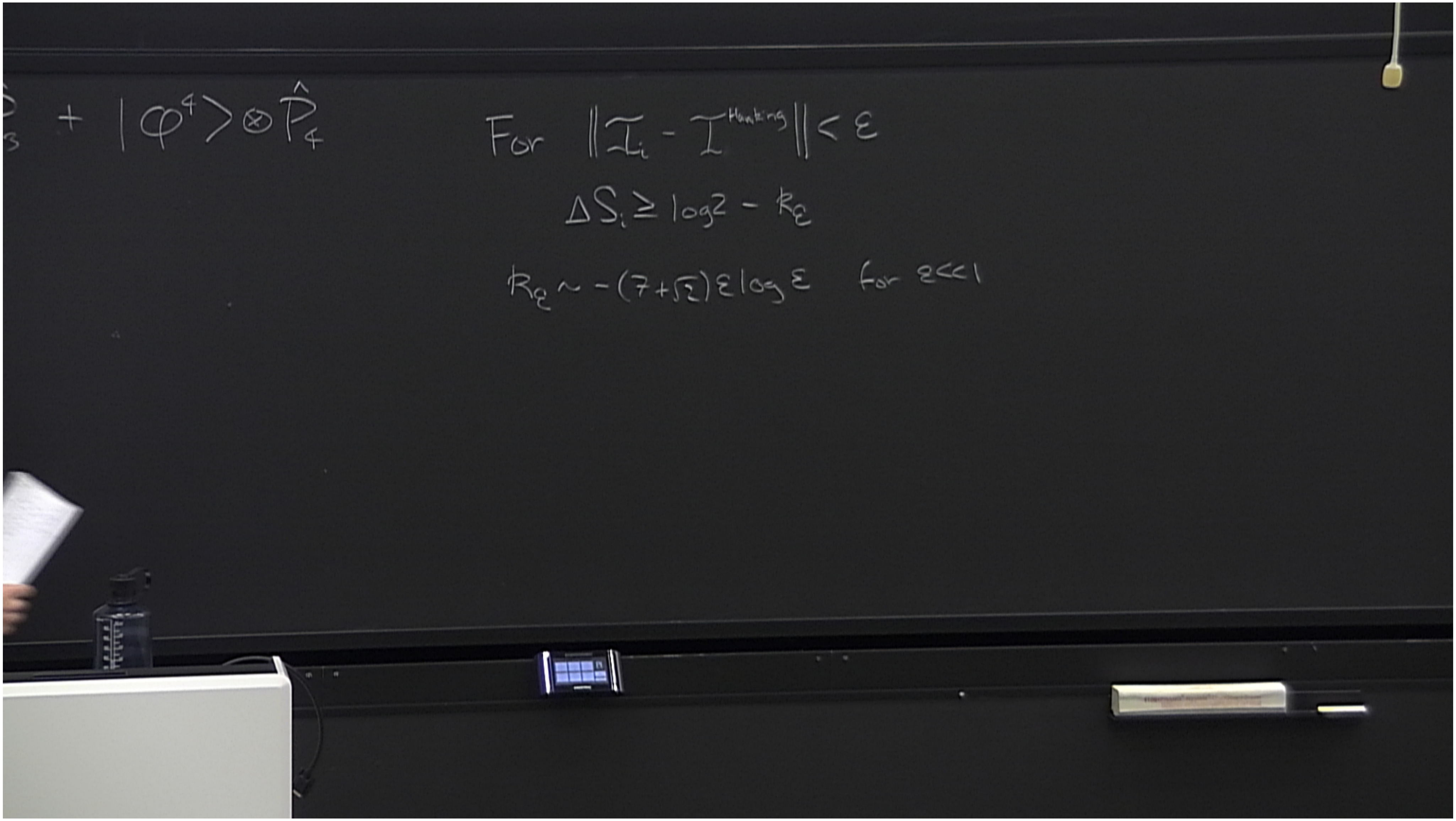
Date: Jun 03, 2013 11:00 AM

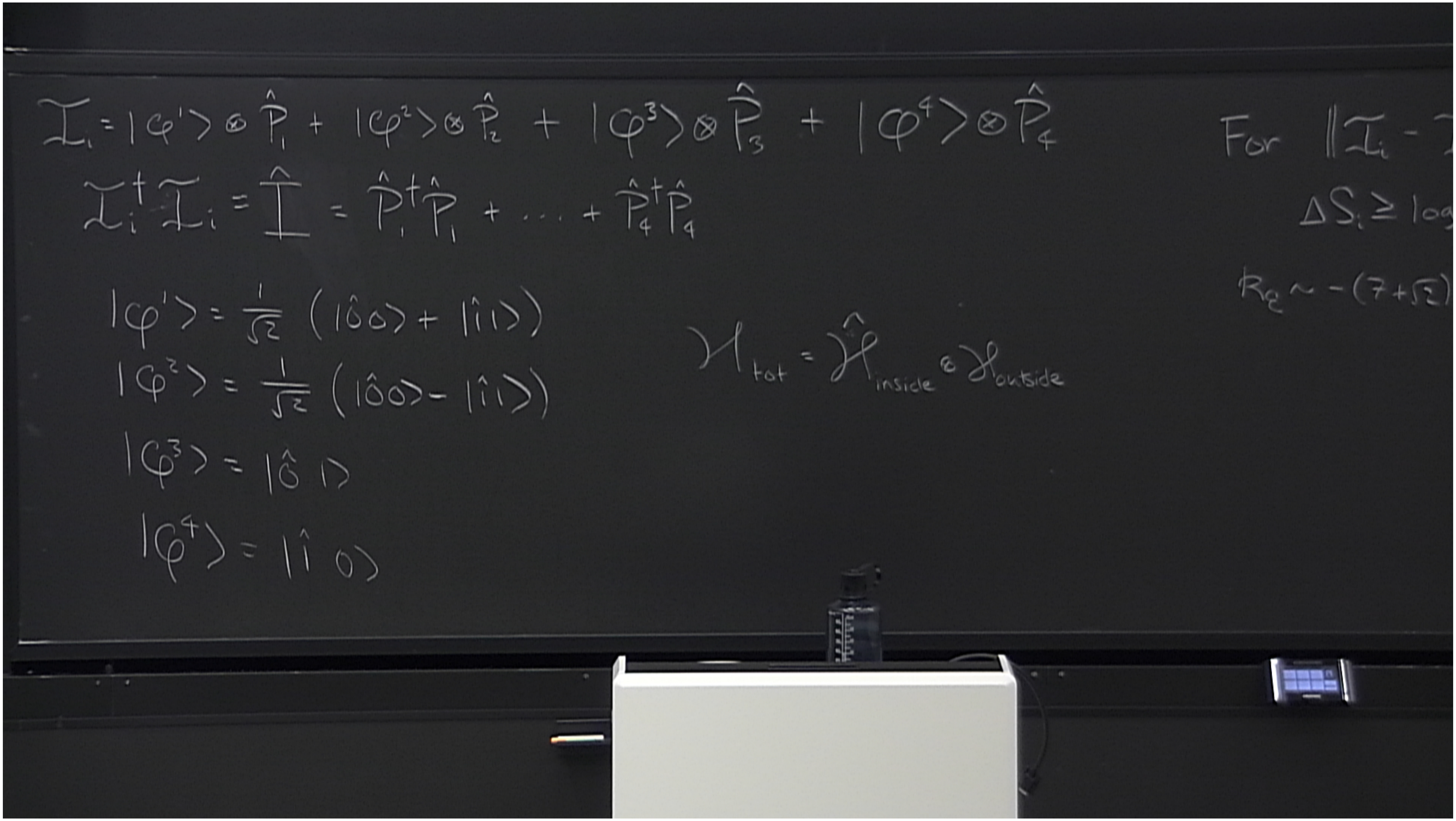
URL: http://pirsa.org/13050088

Abstract: The fuzzball proposal makes a conjecture about the nature of black hole
microstates. Now, more than a decade old and including several different
philosophies and perspectives, it is especially relevant after the recent
firewall argument and ensuing debate. Over three lectures, I plan to start
with a very general discussion of the general ideas and motivations, then
review the theoretical evidence from string theory, and finally close by
discussing open questions, including the fate of a freely falling observer
as he/she passes through the black hole horizon.


$I_i = |\varphi^1\rangle \otimes \hat{P}_1 + |\varphi^2\rangle \otimes \hat{P}_2 + |\varphi^3\rangle \otimes \hat{P}_3 + |\varphi^4\rangle \otimes \hat{P}_4$
$I_i^\dagger I_i = \hat{I} = \hat{P}_1^\dagger \hat{P}_1 + \dots + \hat{P}_4^\dagger \hat{P}_4$
$|\varphi^1\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle + |\hat{1}1\rangle)$
$|\varphi^2\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle - |\hat{1}1\rangle)$
$|\varphi^3\rangle = |\hat{0}\,1\rangle$
$|\varphi^4\rangle = |\hat{1}\,0\rangle$
For


$\mathcal{I}_i = |\varphi^1\rangle \otimes \hat{P}_1 + |\varphi^2\rangle \otimes \hat{P}_2 + |\varphi^3\rangle \otimes \hat{P}_3 + |\varphi^4\rangle \otimes \hat{P}_4$
$\mathcal{I}_i^\dagger \mathcal{I}_i = \hat{I} = \hat{P}_1^\dagger \hat{P}_1 + \dots + \hat{P}_4^\dagger \hat{P}_4$
$|\varphi^1\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle + |\hat{1}1\rangle)$
$|\varphi^2\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle - |\hat{1}1\rangle)$
$|\varphi^3\rangle = |\hat{0}\,1\rangle$
$|\varphi^4\rangle = |\hat{1}\,0\rangle$
For

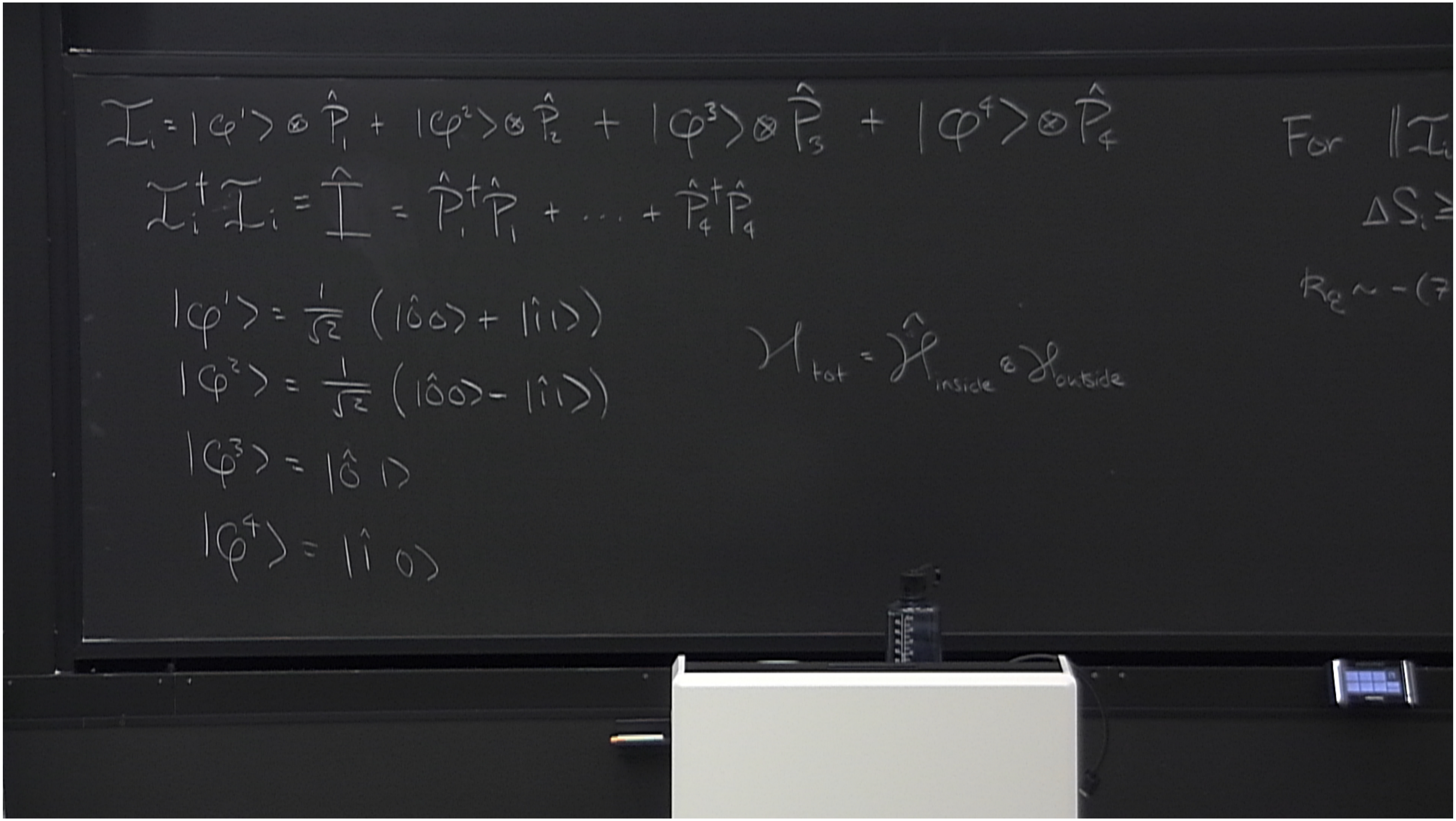

$+ |\varphi^4\rangle \otimes \hat{P}_4$
For $\|\mathcal{I}_i - \mathcal{I}^{\text{Hawking}}\| < \varepsilon$
$\Delta S_i \geq \log 2 - k_\varepsilon$
$k_\varepsilon \sim -(7+\sqrt{2})\,\varepsilon \log \varepsilon$ for $\varepsilon \ll 1$


$\mathcal{I}_i = |\varphi^1\rangle \otimes \hat{P}_1 + |\varphi^2\rangle \otimes \hat{P}_2 + |\varphi^3\rangle \otimes \hat{P}_3 + |\varphi^4\rangle \otimes \hat{P}_4$
$\mathcal{I}_i^\dagger \mathcal{I}_i = \hat{I} = \hat{P}_1^\dagger \hat{P}_1 + \dots + \hat{P}_4^\dagger \hat{P}_4$
$|\varphi^1\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle + |\hat{1}1\rangle)$
$|\varphi^2\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle - |\hat{1}1\rangle)$
$|\varphi^3\rangle = |\hat{0}\,1\rangle$
$|\varphi^4\rangle = |\hat{1}\,0\rangle$
$\mathcal{H}_{tot} = \hat{\mathcal{H}}_{inside} \otimes \mathcal{H}_{outside}$
For
$\Delta S_i \geq$
$R_\varepsilon \sim -(7+\sqrt{2})$

For $\|\mathcal{I}_i - \mathcal{I}^{\text{Hawking}}\| < \varepsilon$

$$\Delta S_i \geq \log 2 - k_\varepsilon$$

$k_\varepsilon \sim -(7+\sqrt{2})\,\varepsilon \log \varepsilon$ for $\varepsilon \ll 1$

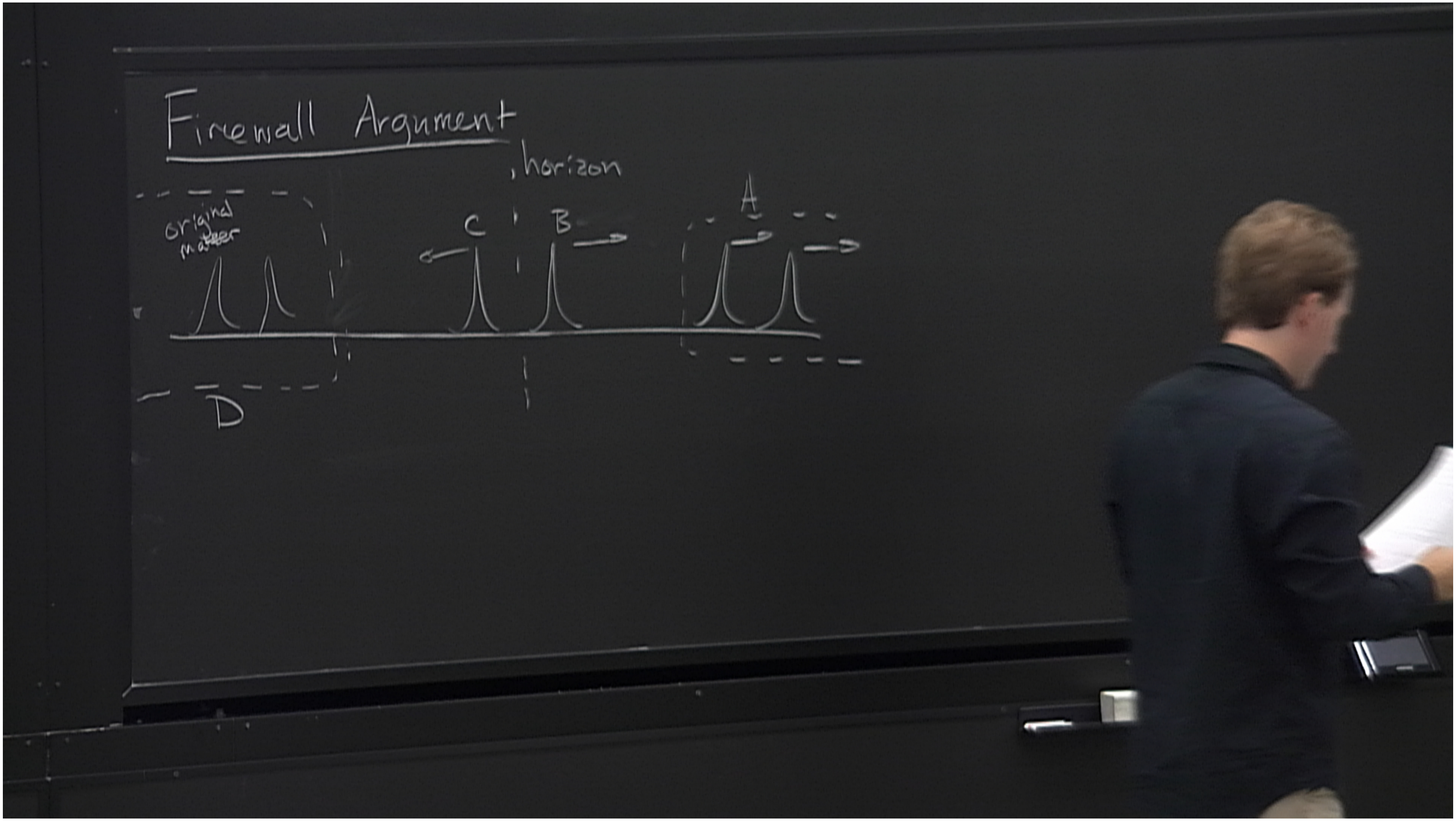


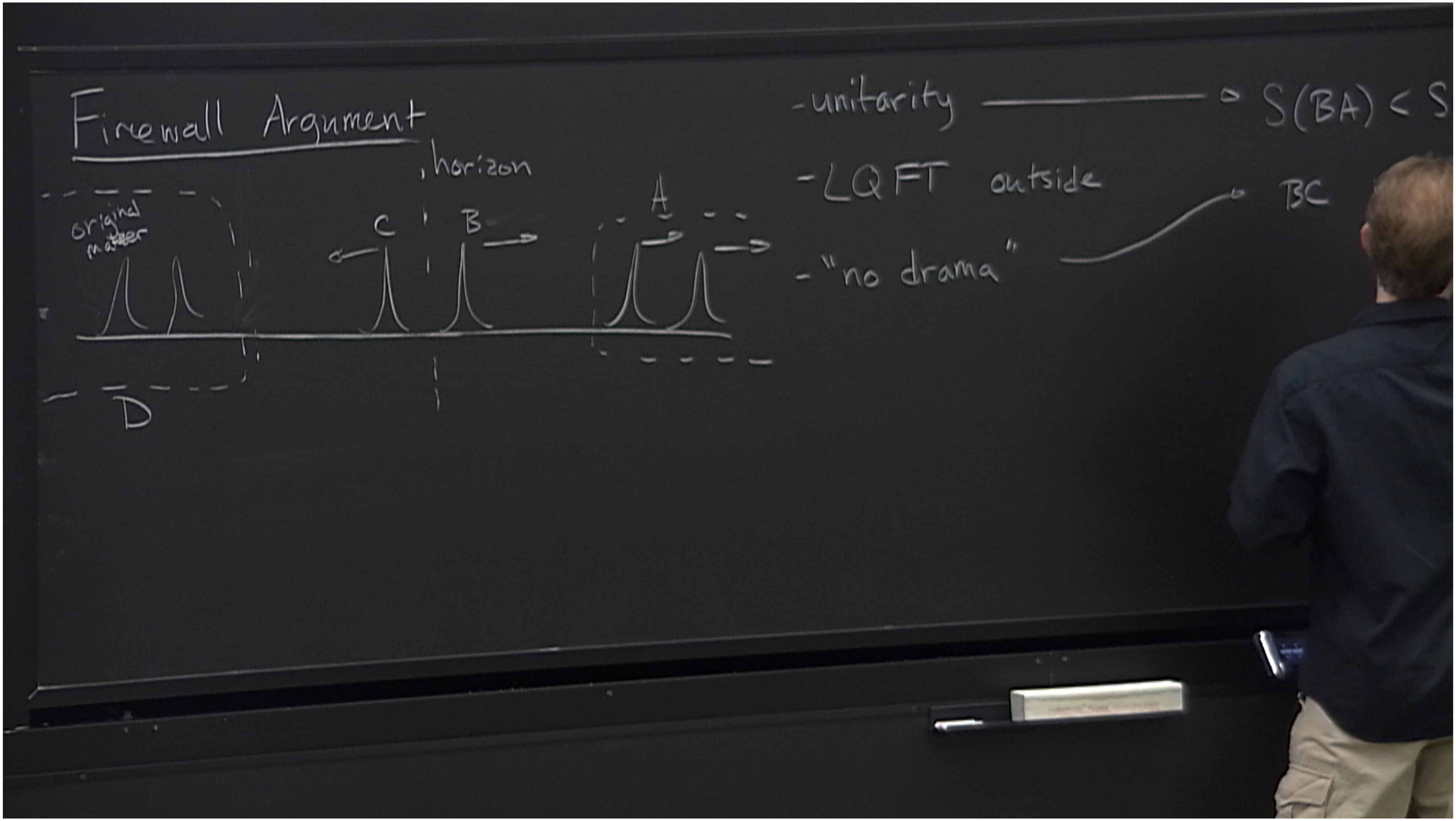
$\mathcal{I}_i = |\varphi^1\rangle \otimes \hat{P}_1 + |\varphi^2\rangle \otimes \hat{P}_2 + |\varphi^3\rangle \otimes \hat{P}_3 + |\varphi^4\rangle \otimes \hat{P}_4$
$\mathcal{I}_i^\dagger \mathcal{I}_i = \hat{I} = \hat{P}_1^\dagger \hat{P}_1 + \dots + \hat{P}_4^\dagger \hat{P}_4$
$|\varphi^1\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle + |\hat{1}1\rangle)$
$|\varphi^2\rangle = \frac{1}{\sqrt{2}}(|\hat{0}0\rangle - |\hat{1}1\rangle)$
$|\varphi^3\rangle = |\hat{0}1\rangle$
$|\varphi^4\rangle = |\hat{1}0\rangle$
$\mathcal{H}_{tot} = \mathcal{H}_{inside} \otimes \mathcal{H}_{outside}$
For

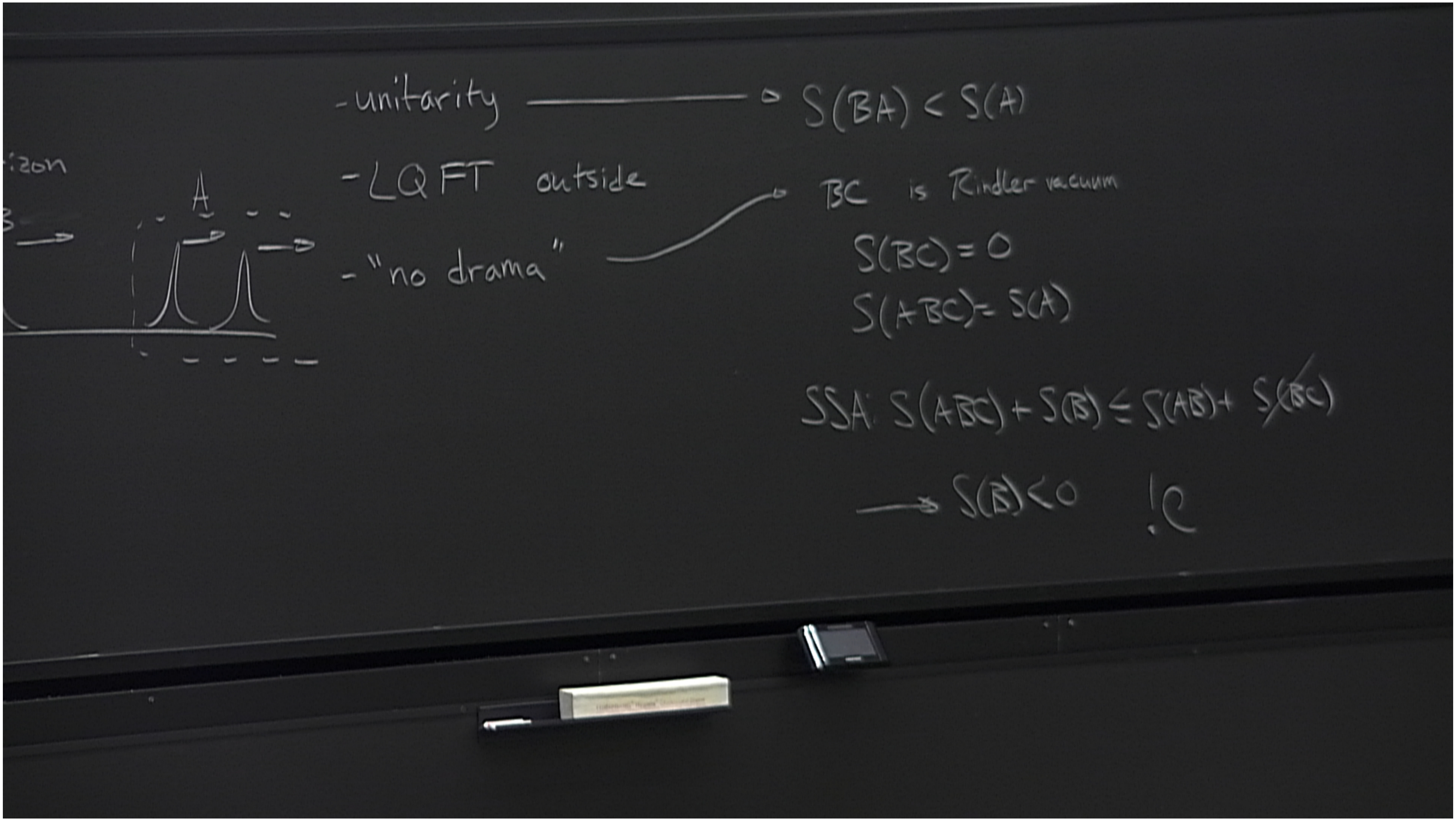
For $\| \mathcal{I}_i - \mathcal{I}^{\text{Hawking}} \| < \varepsilon$

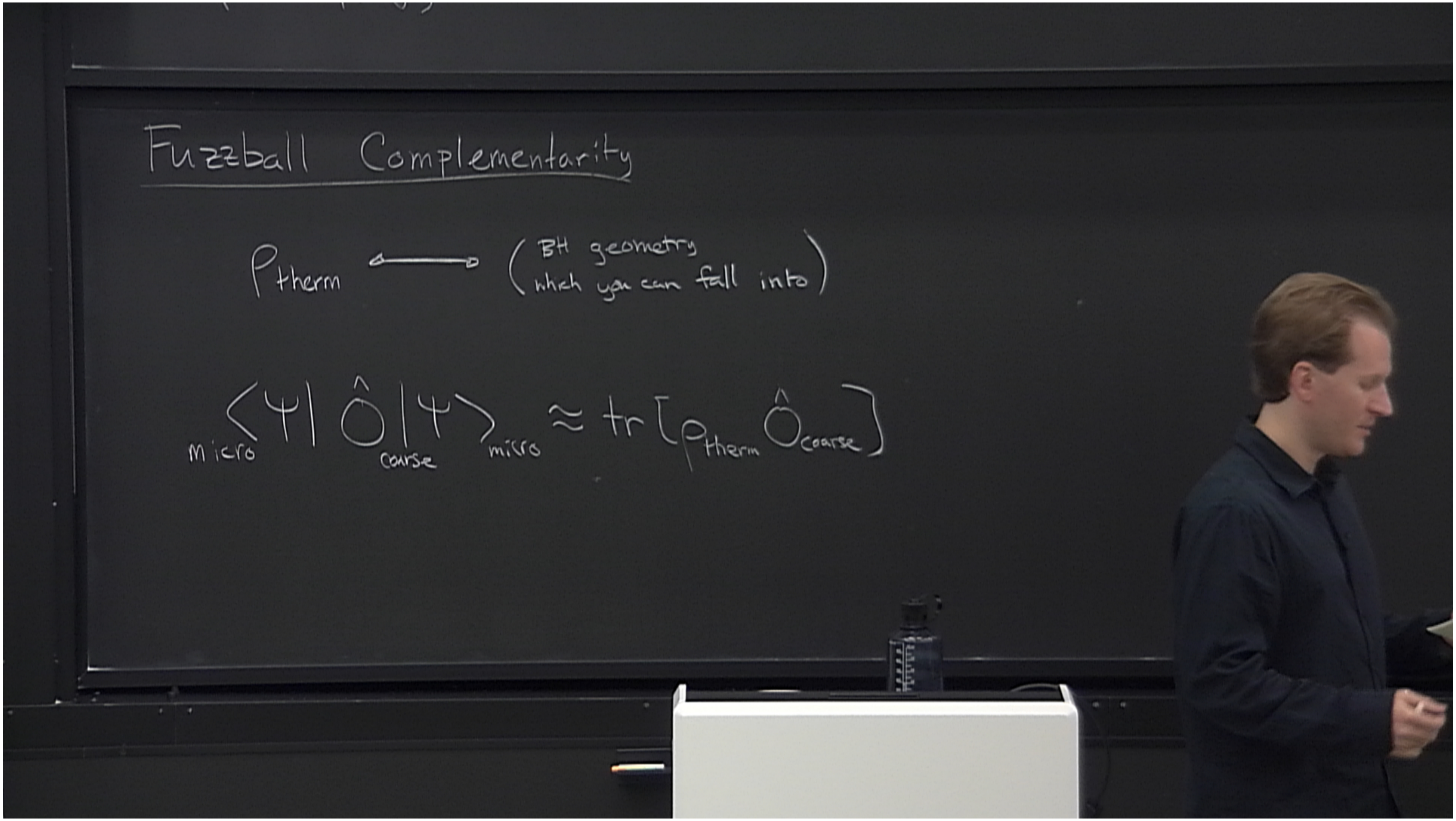
$$\Delta S_i \geq \log 2 - k_\varepsilon$$

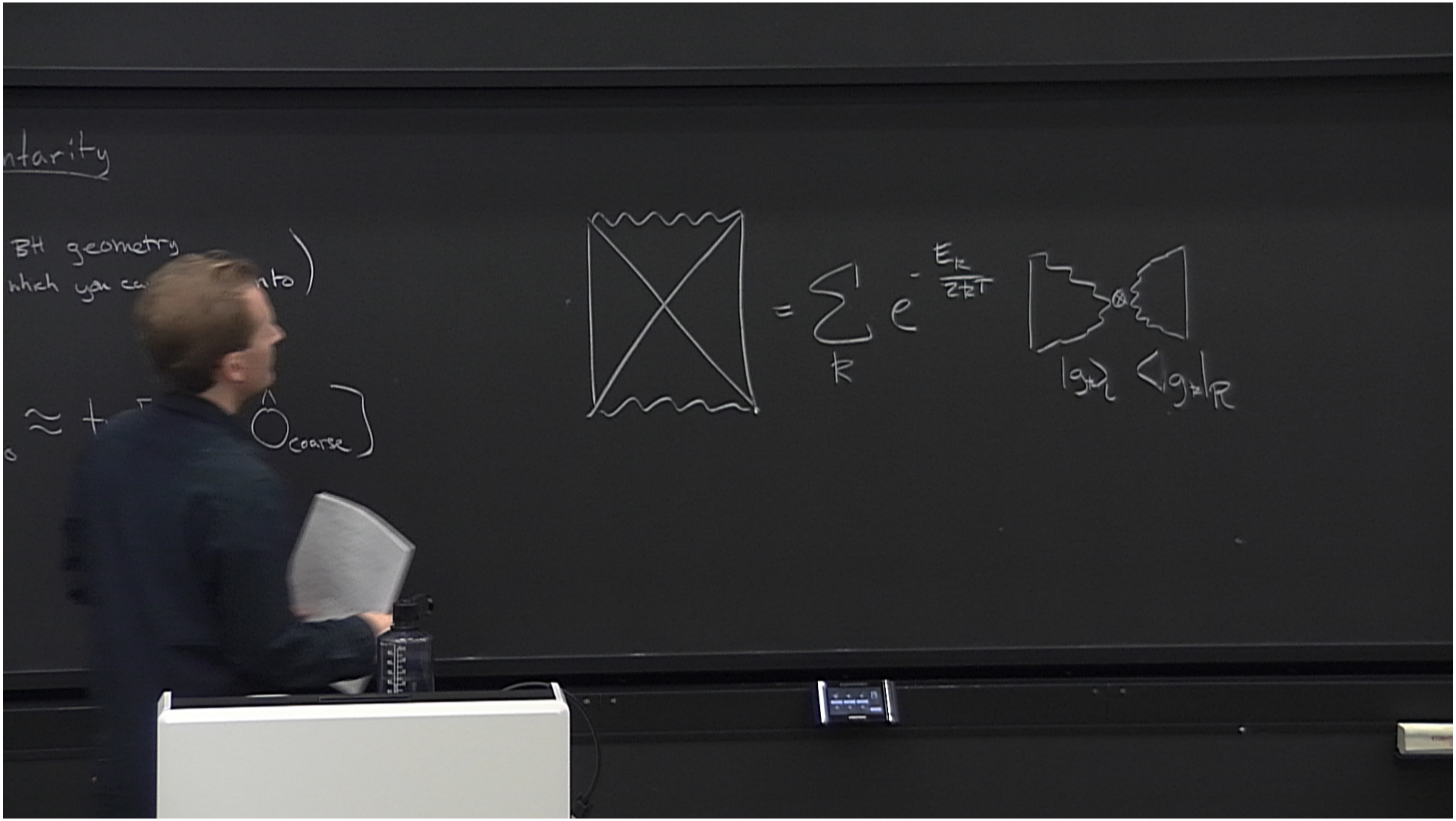
$k_\varepsilon \sim -(7+\sqrt{2})\,\varepsilon \log \varepsilon$ for $\varepsilon \ll 1$

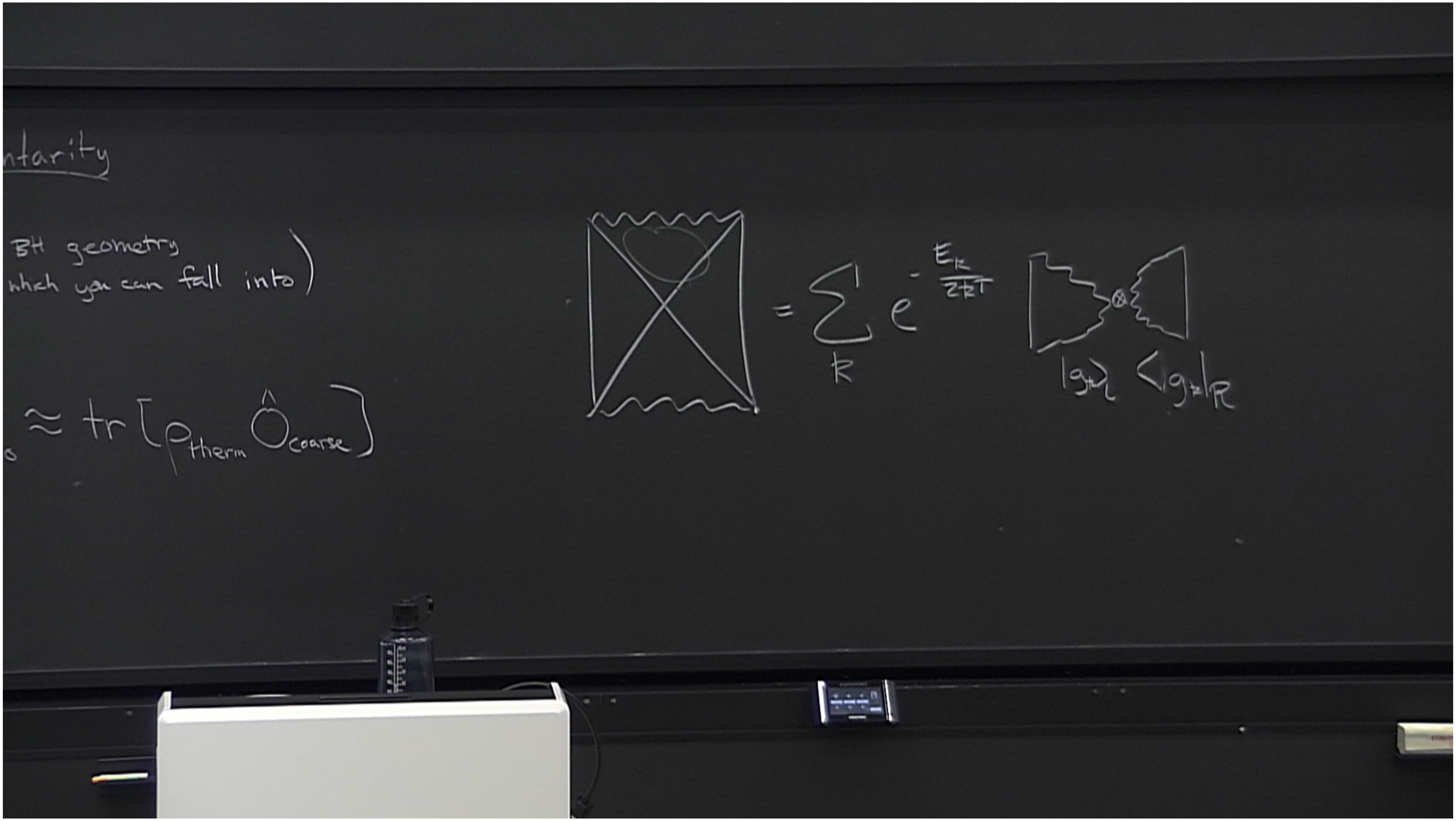

Firewall Argument
horizon
original matter
C
B
A
D

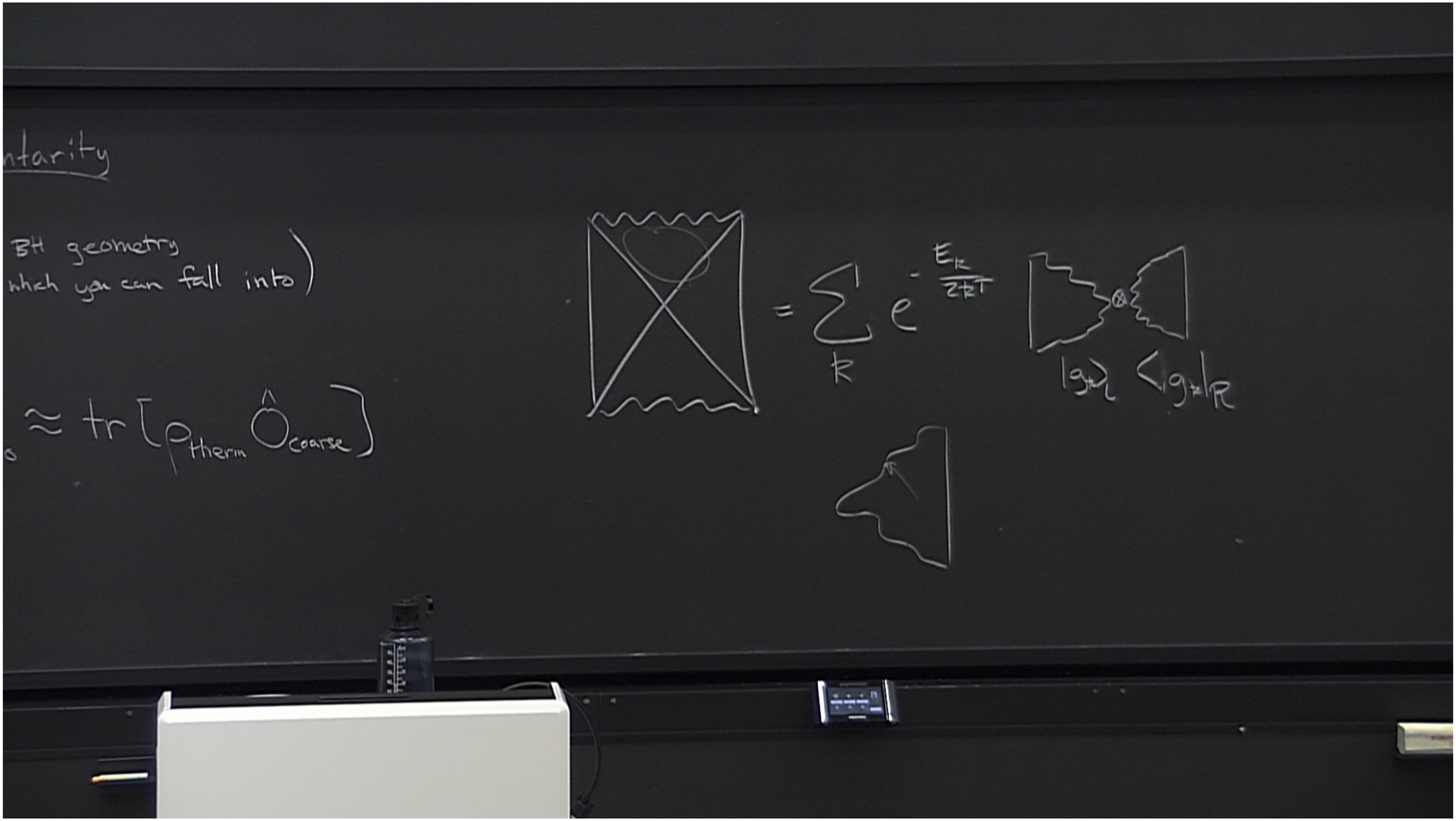

Firewall Argument
horizon
original matter
C
B
A
D
- unitarity
S(BA) < S
- LQFT outside
BC
- "no drama"

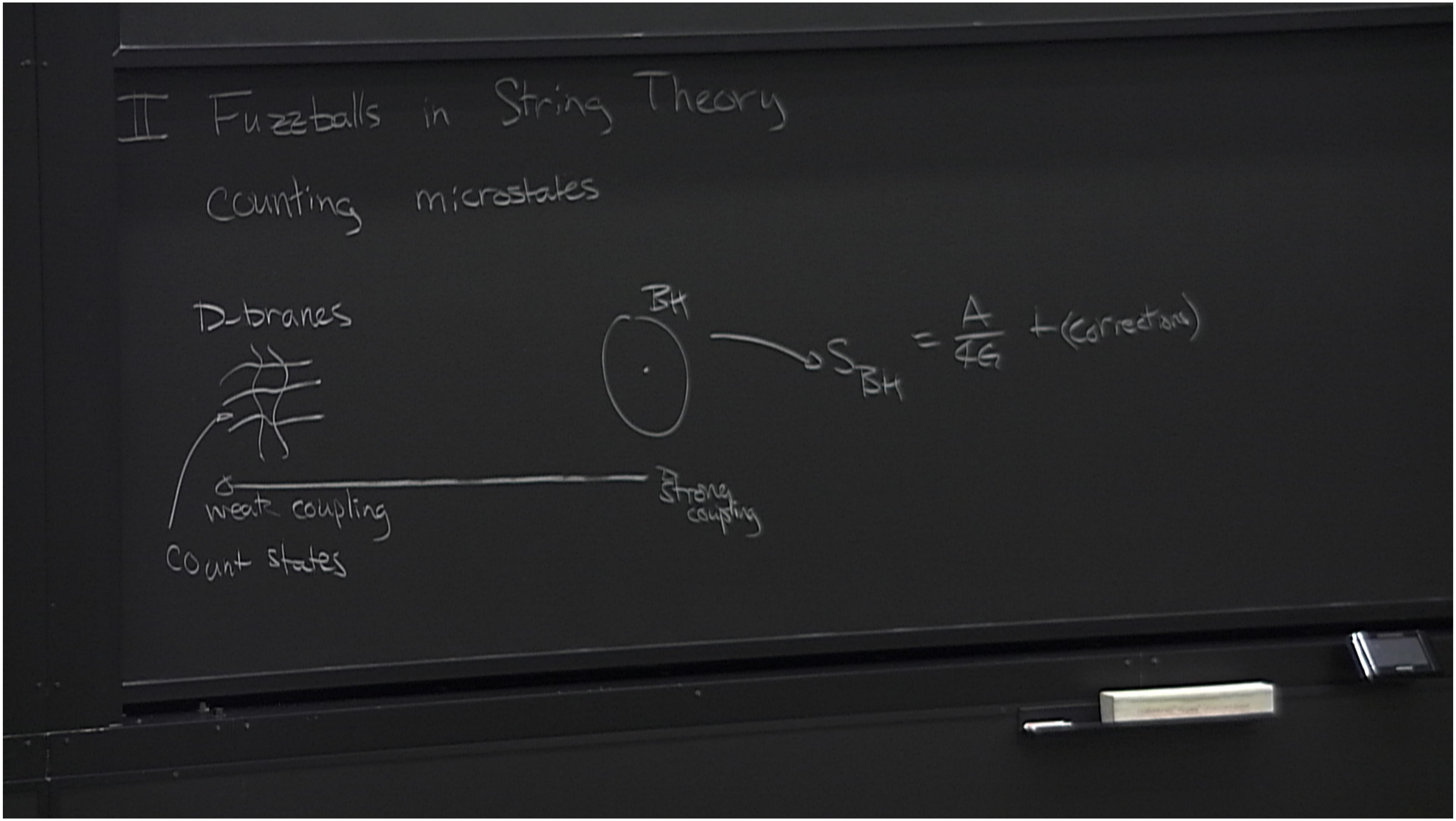

-unitarity → S(BA) < S(A)
izon
A
-LQFT outside
BC is Rindler vacuum
- "no drama"
S(BC) = 0
S(ABC) = S(A)
SSA: S(ABC) + S(B) ≤ S(AB) + S(BC)
→ S(B) < 0

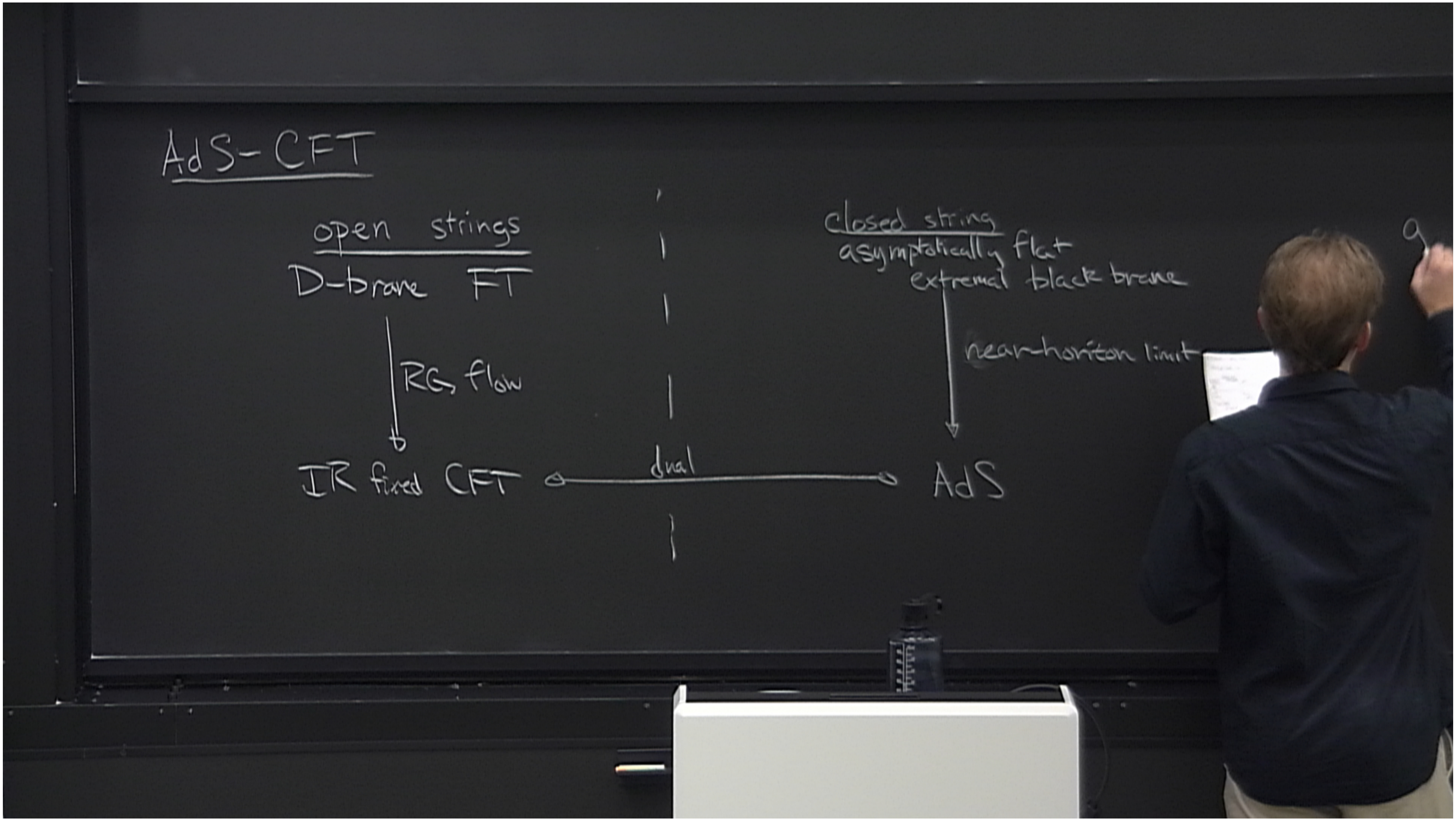

Fuzzball Complementarity
$\rho_{therm} \longleftrightarrow$ (BH geometry which you can fall into)
$_{micro}\langle\Psi|\hat{O}_{coarse}|\Psi\rangle_{micro} \approx \mathrm{tr}[\rho_{therm}\hat{O}_{coarse}]$


ntarity
BH geometry
which you ca
nto
coarse
$= \sum_k e^{-\frac{E_k}{2kT}}$
$|g_k\rangle_L \langle g_k|_R$


ntarity
BH geometry
which you can fall into)
$\approx \mathrm{tr}[\rho_{therm} \hat{O}_{coarse}]$
$= \sum_k e^{-\frac{E_k}{2kT}}$
$|g_k\rangle_L \langle g_k|_R$


ntarity
BH geometry
which you can fall into)
≈ tr[ρ_therm Ô_coarse]
= Σ_k e^(-E_k/2kT)
|g_k⟩_L ⟨g_k|_R


II Fuzzballs in String Theory
Counting microstates
D-branes
BH
$S_{BH} = \frac{A}{4G}$ + (corrections)
weak coupling
Strong coupling
Count states

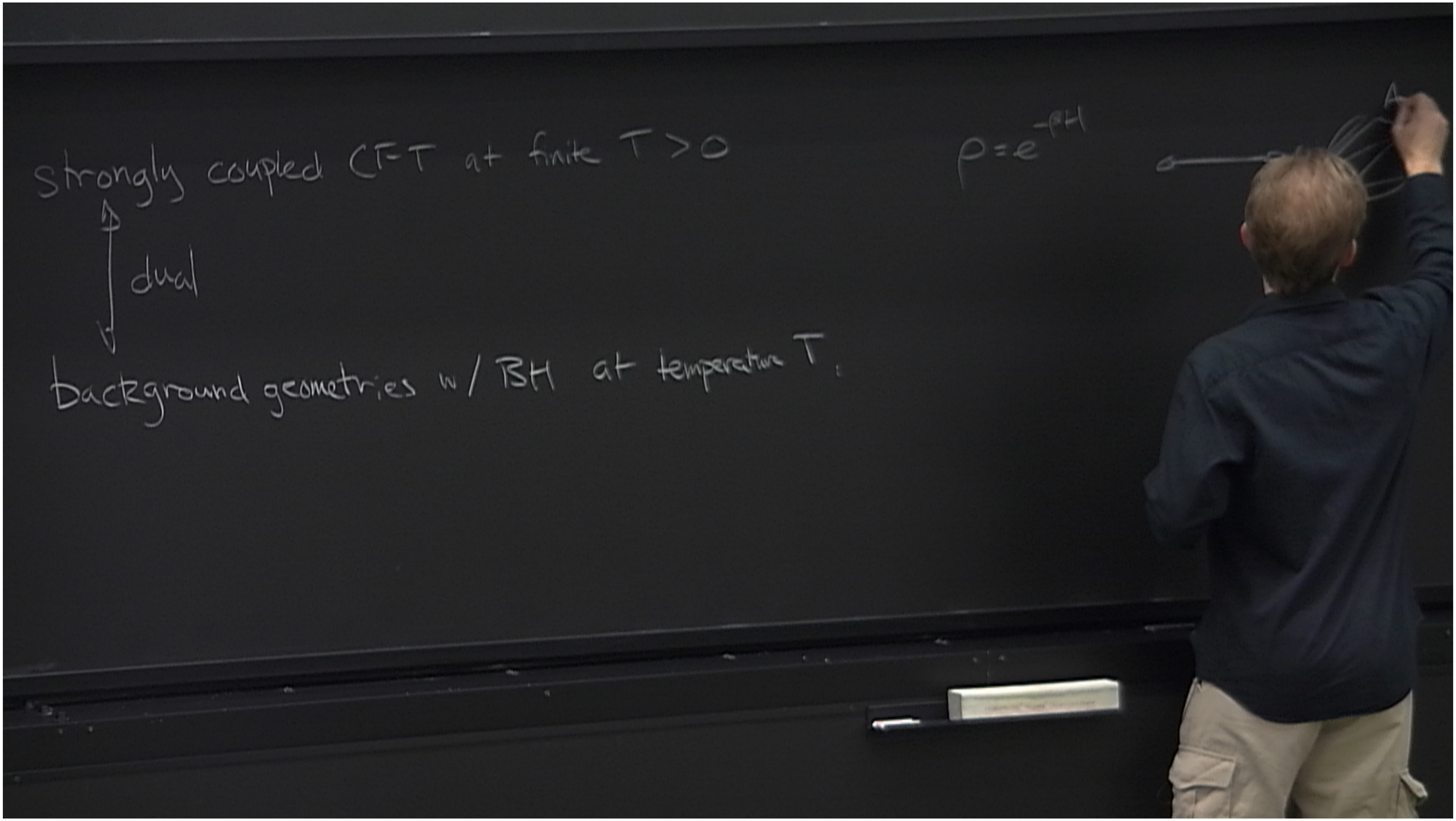

AdS-CFT
open strings
D-brane FT
RG flow
IR fixed CFT
dual
closed string
asymptotically flat
extremal black brane
near-horizon limit
AdS

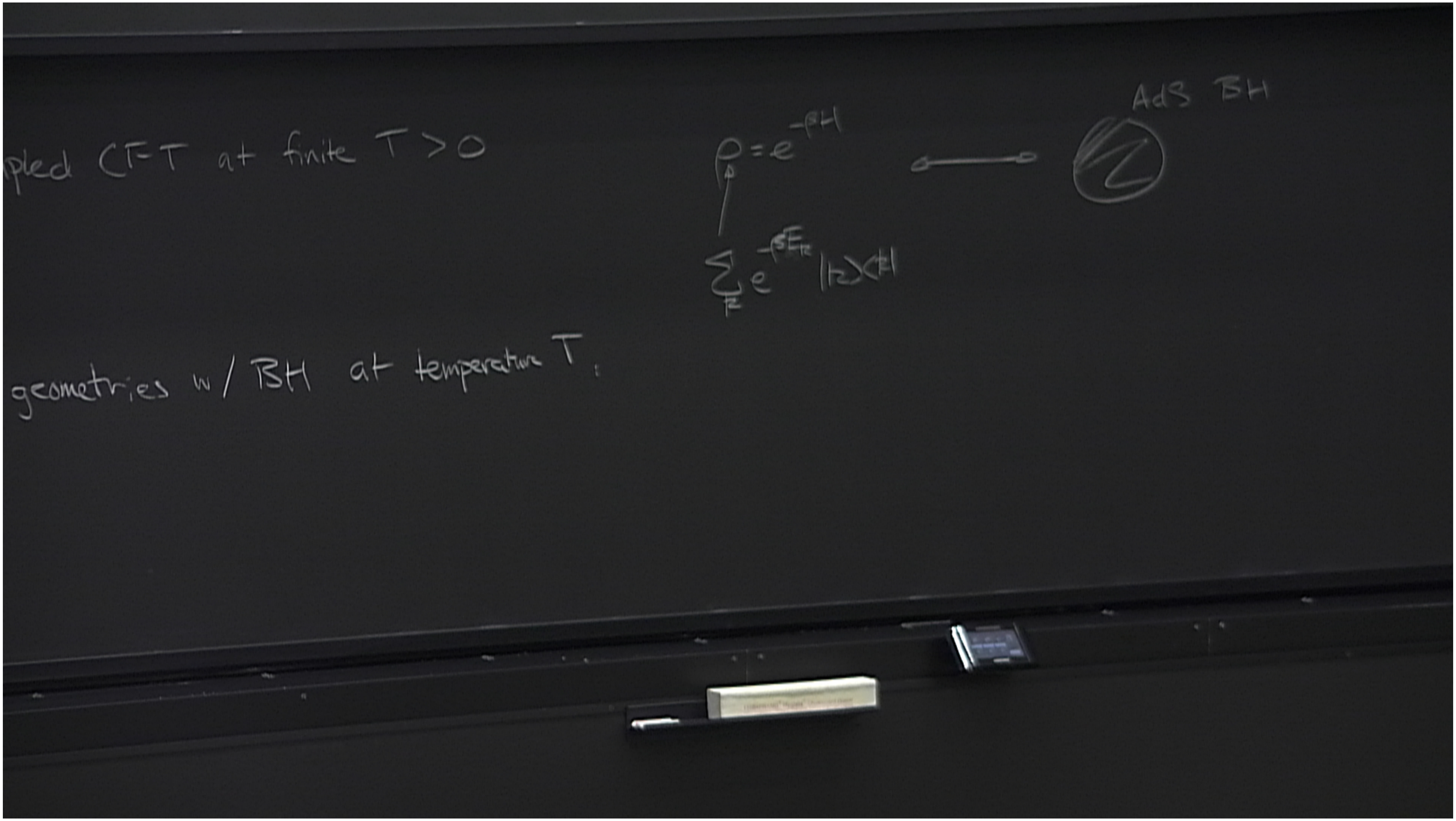
geometry: (large α' corrections) (SUGRA)

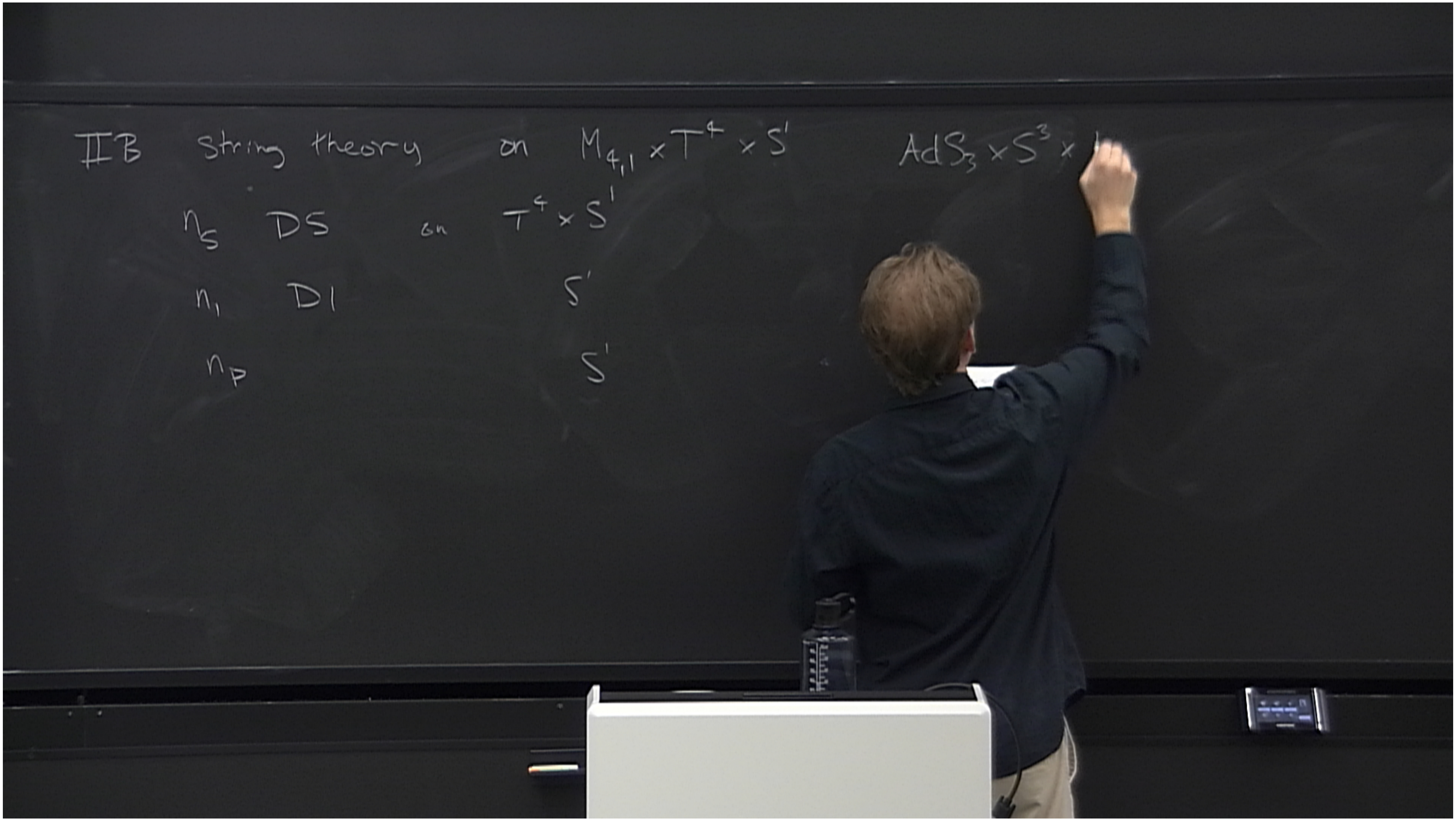
ane

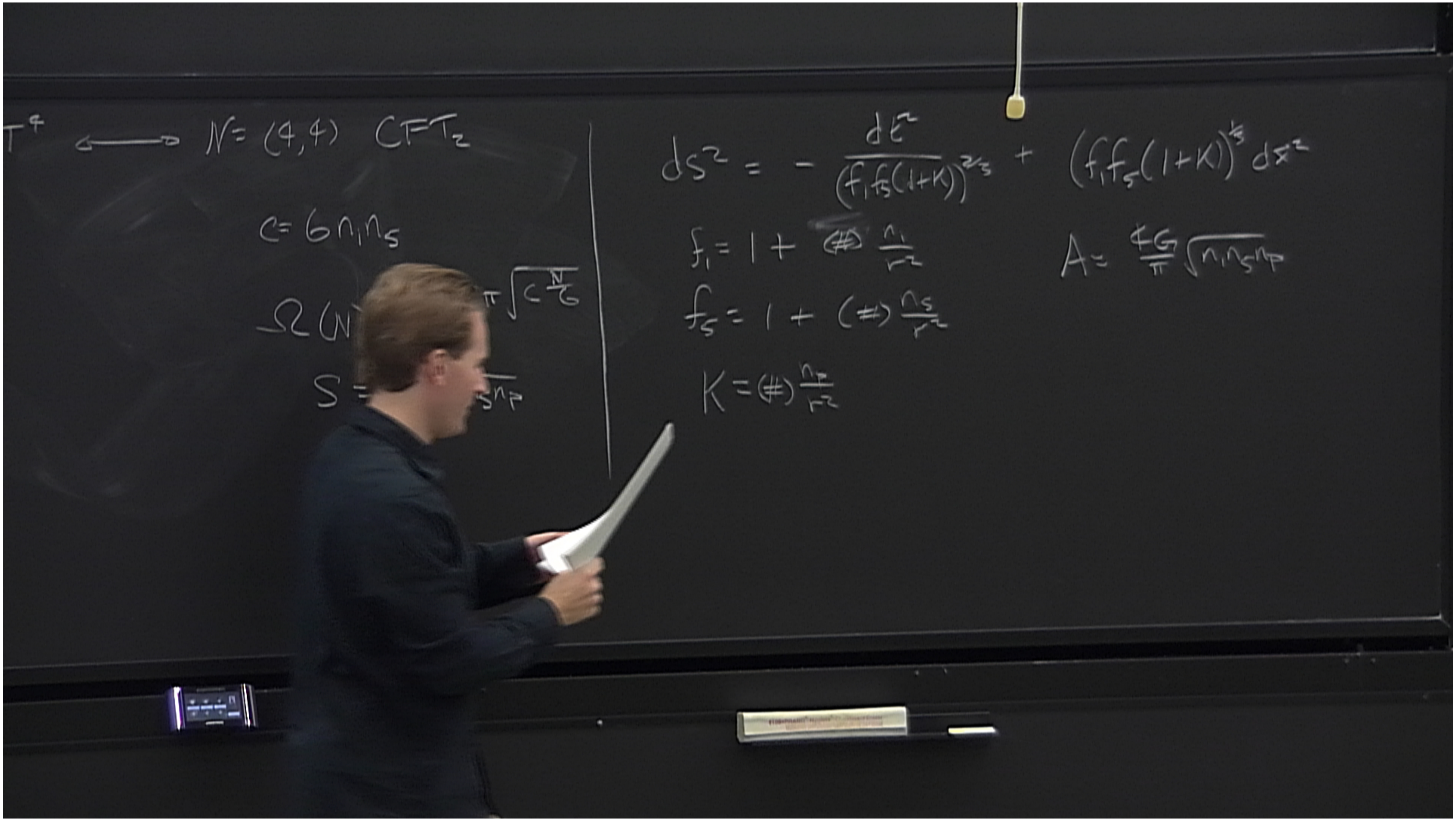
limit

FT: (weakly coupled) (strongly coupled)


strongly coupled CFT at finite T > 0
dual
background geometries w/ BH at temperature T.
ρ = e^{-βH}


pled CFT at finite T > 0
ρ = e^{-βH}
AdS BH
Σ e^{-βE} |E⟩⟨E|
geometries w/ BH at temperature T :


IIB string theory on $M_{4,1} \times T^4 \times S^1$
$AdS_3 \times S^3 \times$
n_5 D5 on $T^4 \times S^1$
n_1 D1 S^1
n_p S^1



$T^4 \longleftrightarrow \mathcal{N}=(4,4)\ CFT_2$
$c = 6 n_1 n_5$
$ds^2 = -\frac{dt^2}{(f_1 f_5 (1+K))^{2/3}} + (f_1 f_5 (1+K))^{1/3} dx^2$
$f_1 = 1 + (\#)\frac{n_1}{r^2}$
$f_5 = 1 + (\#)\frac{n_5}{r^2}$
$K = (\#)\frac{n_p}{r^2}$
$A = \frac{4G}{\pi}\sqrt{n_1 n_5 n_p}$

$T^4 \longleftrightarrow \mathcal{N}=(4,4)\ CFT_2$

$c = 6 n_1 n_5$

$\Omega(N) \sim e^{2\pi\sqrt{c\frac{N}{6}}}$

$S = 2\pi\sqrt{n_1 n_5 n_p}$

$$ds^2 = -\frac{dt^2}{(f_1 f_5(1+K))^{2/3}} + (f_1 f_5(1+K))^{1/3} dx^2$$

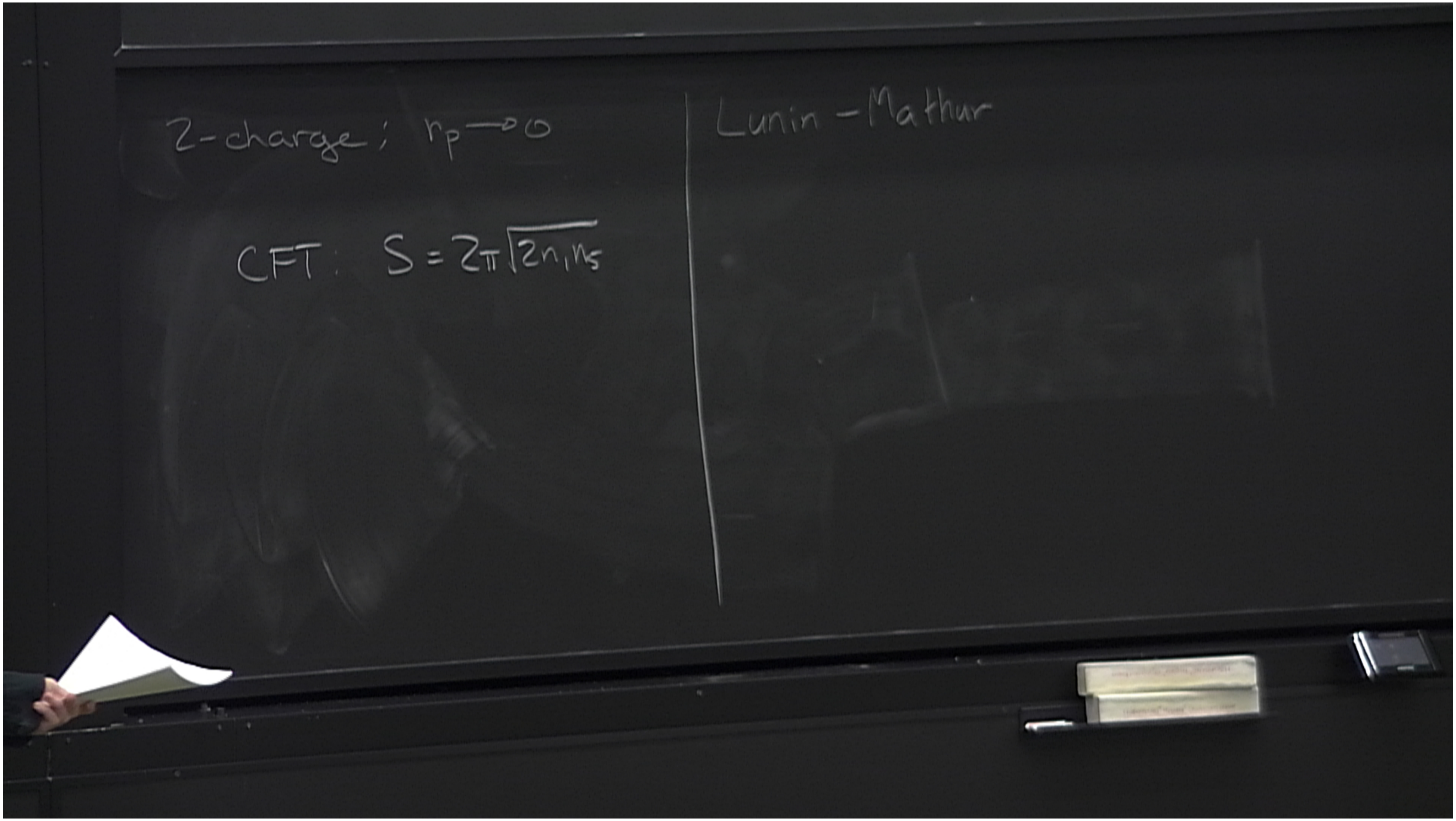
$f_1 = 1 + (\#)\frac{n_1}{r^2}$

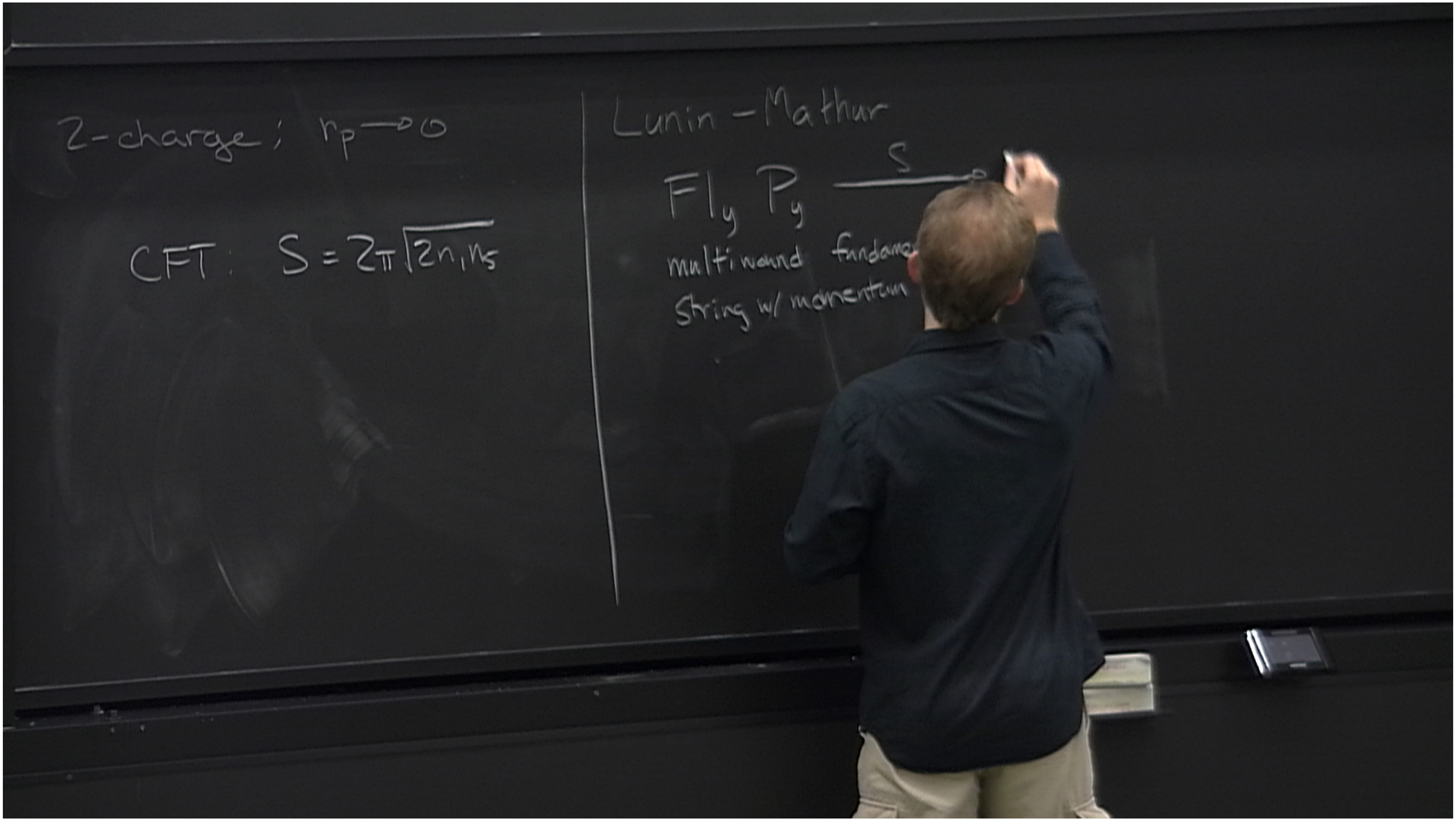
$f_5 = 1 + (\#)\frac{n_5}{r^2}$

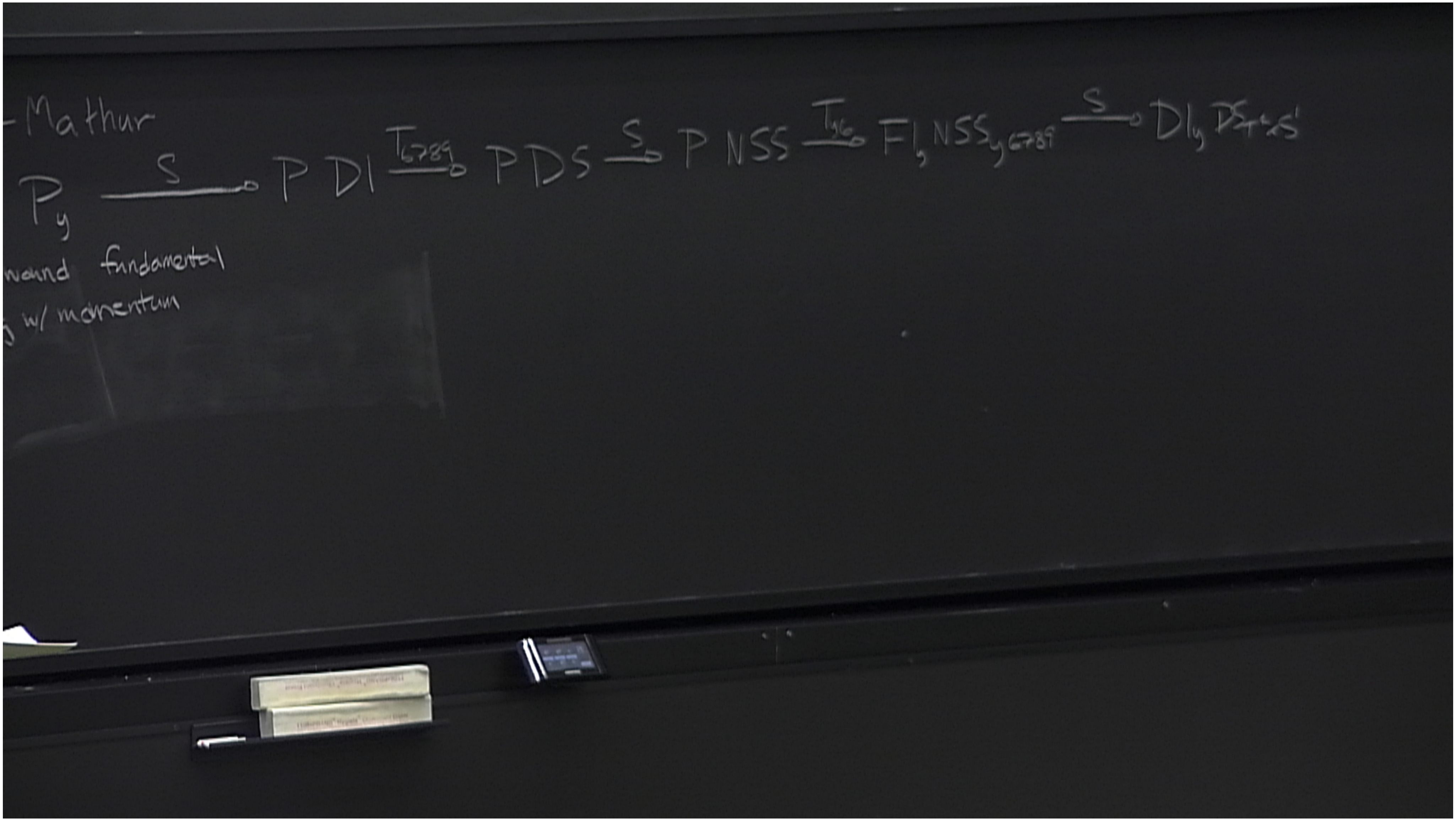
$K = (\#)\frac{n_p}{r^2}$

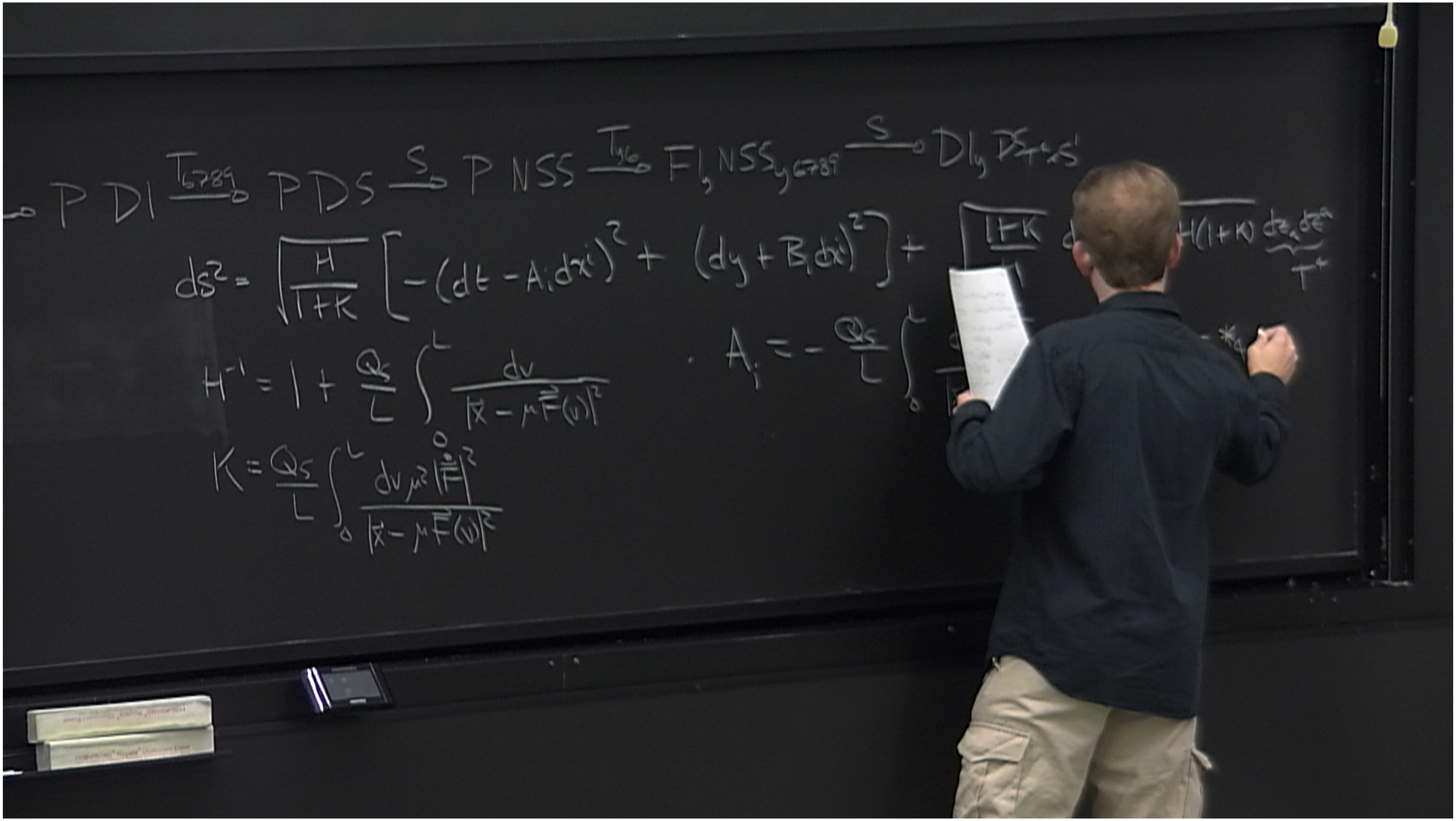
$A = \frac{4G}{\pi}\sqrt{n_1 n_5 n_p}$

near horizon. $BTZ \times S^3$


2-charge ; $r_p \to 0$
CFT : $S = 2\pi\sqrt{2n_1n_5}$
Lunin - Mathur


2-charge ; $r_p \to 0$
CFT: $S = 2\pi\sqrt{2n_1n_5}$
Lunin - Mathur
$F1_y\ P_y \xrightarrow{S}$
multiwound
String w/ momentum


Mathur
P D1
P DS
P NSS
NSS
fundamental
w/ momentum


P DI → PDS → P NSS → F1 NSS → DI
ds² = √(H/(1+K)) [−(dt − Aᵢdxⁱ)² + (dy + Bᵢdxⁱ)²] +
H⁻¹ = 1 + Qs/L ∫₀ᴸ dv / |x − μF(v)|²
K = Qs/L ∫₀ᴸ dv μ² |Ḟ|² / |x − μF(v)|²
Aᵢ = − Qs/L ∫

$$\to \mathrm{P\,D1} \xrightarrow{T_{6789}} \mathrm{PDS} \xrightarrow{S} \mathrm{P\,NSS} \xrightarrow{T_{y6}} \mathrm{F1}_y\,\mathrm{NSS}_{y6789} \xrightarrow{S} \mathrm{D1}_y\,\mathrm{DS}_{T^4\times S^1}$$

$$ds^2 = \sqrt{\frac{H}{1+K}}\left[-(dt - A_i dx^i)^2 + (dy + B_i dx^i)^2\right] + \sqrt{\frac{1+K}{H}}\, d\vec{x}^2 + \sqrt{H(1+K)}\, \underbrace{dz_a dz^a}_{T^4}$$

$$H^{-1} = 1 + \frac{Q_5}{L}\int_0^L \frac{dv}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad A_i = -\frac{Q_5}{L}\int_0^L \frac{dv\, \mu\, \dot{F}_i}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad dB = -*_4 dA$$

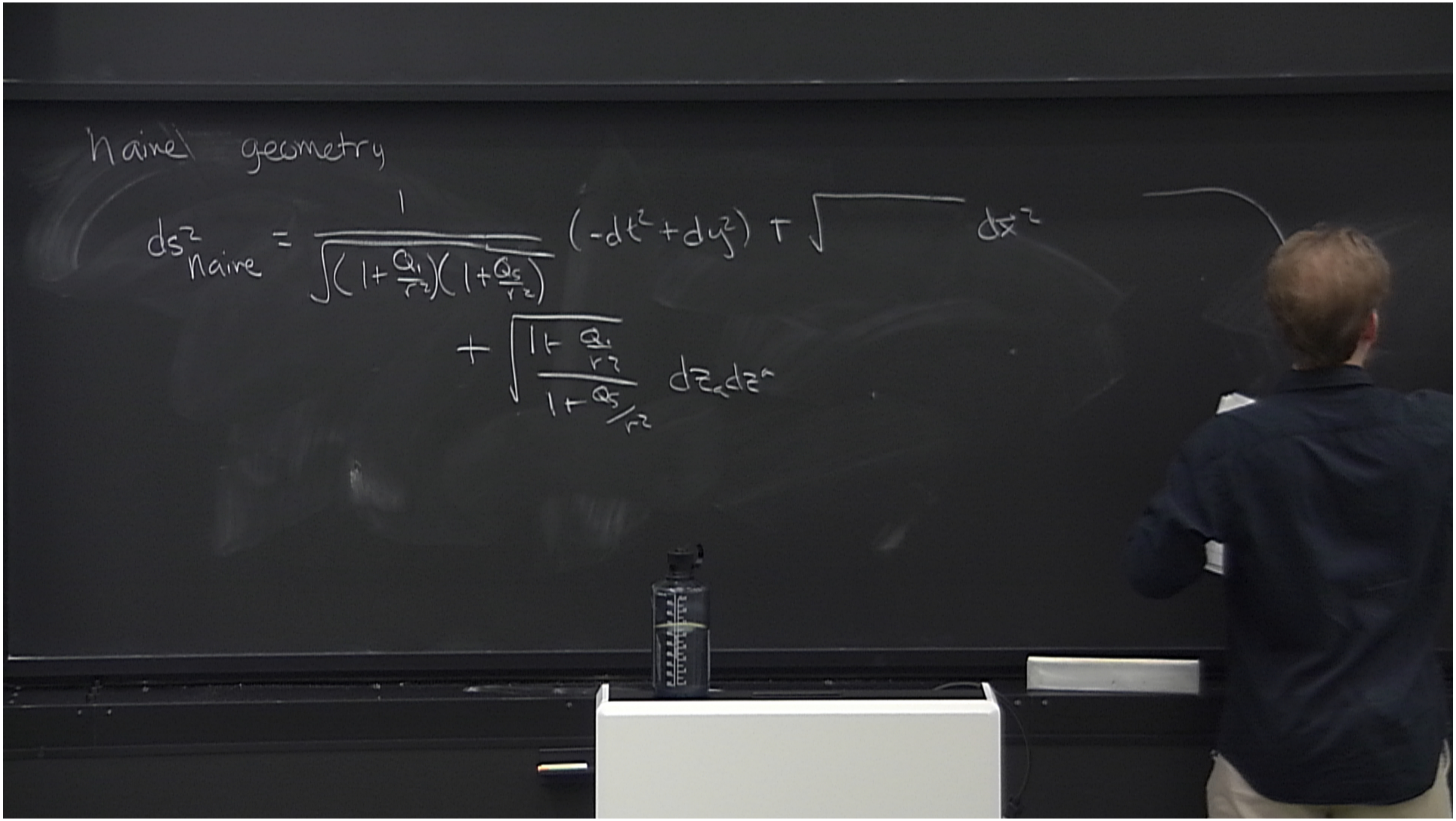
$$K = \frac{Q_5}{L}\int_0^L \frac{dv\, \mu^2 |\dot{\vec{F}}|^2}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad n_1 = \frac{V}{(\alpha')^3}\frac{\alpha' n_5}{L}\int_0^L dv\, |\dot{F}(v)|^2$$

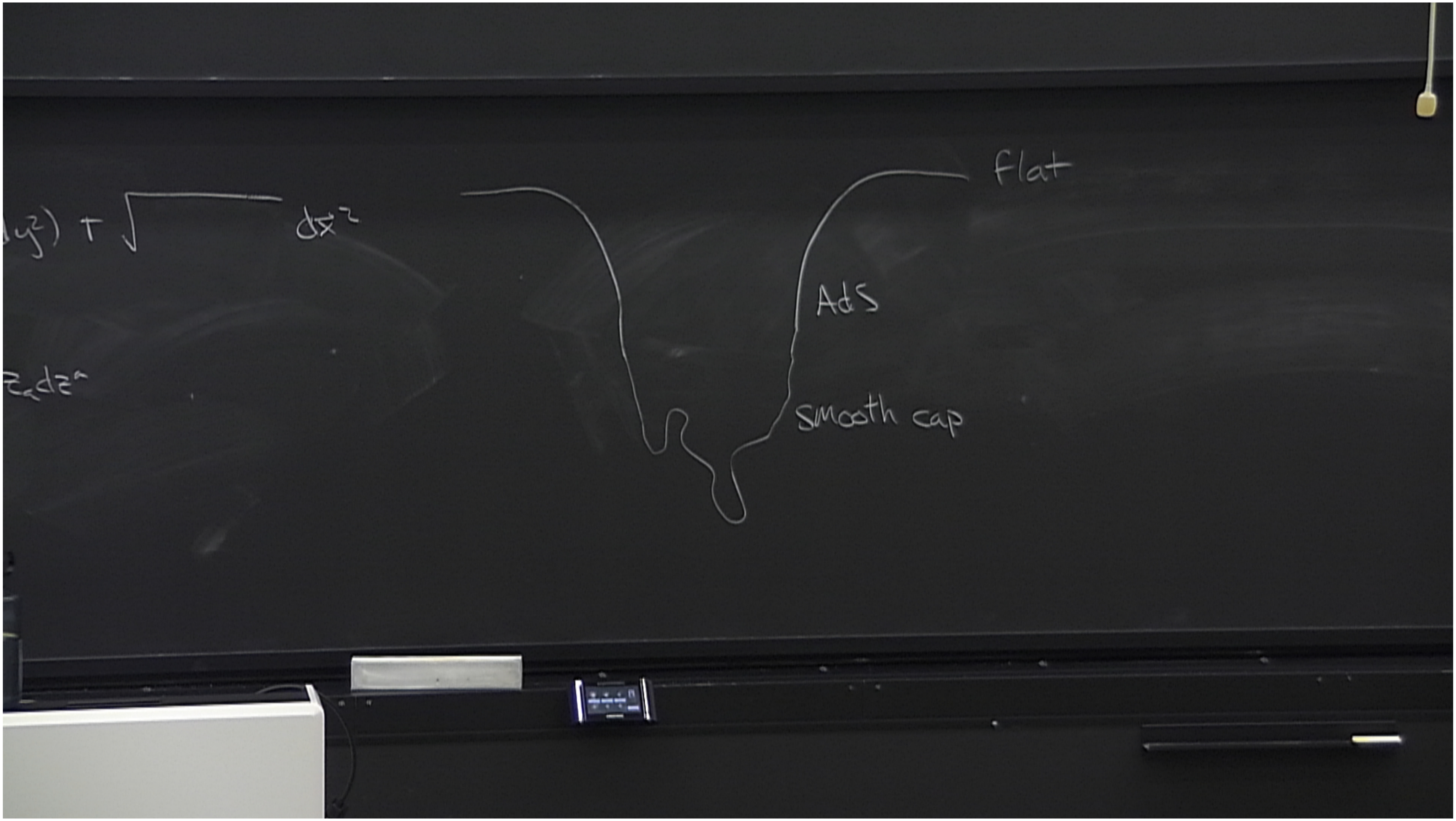
$$\xrightarrow{T_{6789}} PDS \xrightarrow{S} P\,NSS \xrightarrow{T_{y6}} F1_y\, NSS_{y6789} \xrightarrow{S} D1_y\, DS_{T^4\times S^1}$$

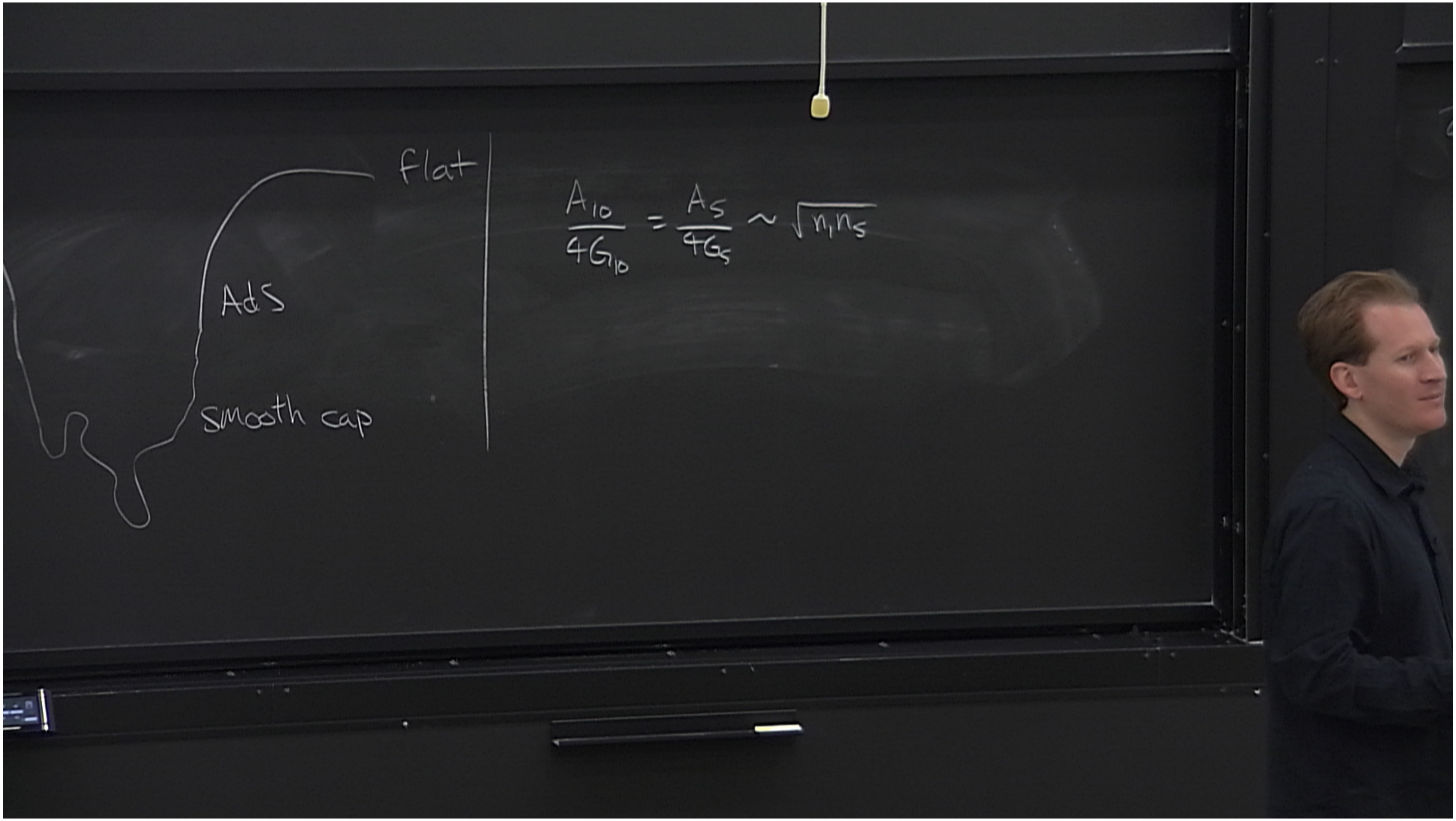
$$ds^2 = \sqrt{\frac{H}{1+K}}\left[-(dt - A_i dx^i)^2 + (dy + B_i dx^i)^2\right] + \sqrt{\frac{1+K}{H}}\, d\vec{x}_1^{\,2} + \sqrt{H(1+K)}\, \underbrace{dz_a dz^a}_{T^4}$$

$$H^{-1} = 1 + \frac{Q_5}{L}\int_0^L \frac{dv}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad A_i = -\frac{Q_5}{L}\int_0^L \frac{dv\, \mu\, \dot{F}_i}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad dB = -*_4 dA$$

$$K = \frac{Q_5}{L}\int_0^L \frac{dv\, \mu^2 |\dot{\vec{F}}|^2}{|\vec{x} - \mu \vec{F}(v)|^2} \qquad n_1 = \frac{V}{(\alpha')^3}\frac{\alpha' n_5}{L}\int_0^L dv\, |\dot{F}(v)|^2$$


naive geometry
$ds^2_{naive} = \frac{1}{\sqrt{(1+\frac{Q_1}{r^2})(1+\frac{Q_5}{r^2})}}(-dt^2+dy^2) + \sqrt{}\, dx^2$
$+ \sqrt{\frac{1+\frac{Q_1}{r^2}}{1+Q_5/r^2}}\, dz_a dz^a$


flat
AdS
smooth cap


flat
AdS
smooth cap
$\frac{A_{10}}{4G_{10}} = \frac{A_5}{4G_5} \sim \sqrt{n_1 n_5}$