Title: Fuzzballs to Firewalls: A Post-Firewall Review of the Fuzzball Proposal: Lecture 3

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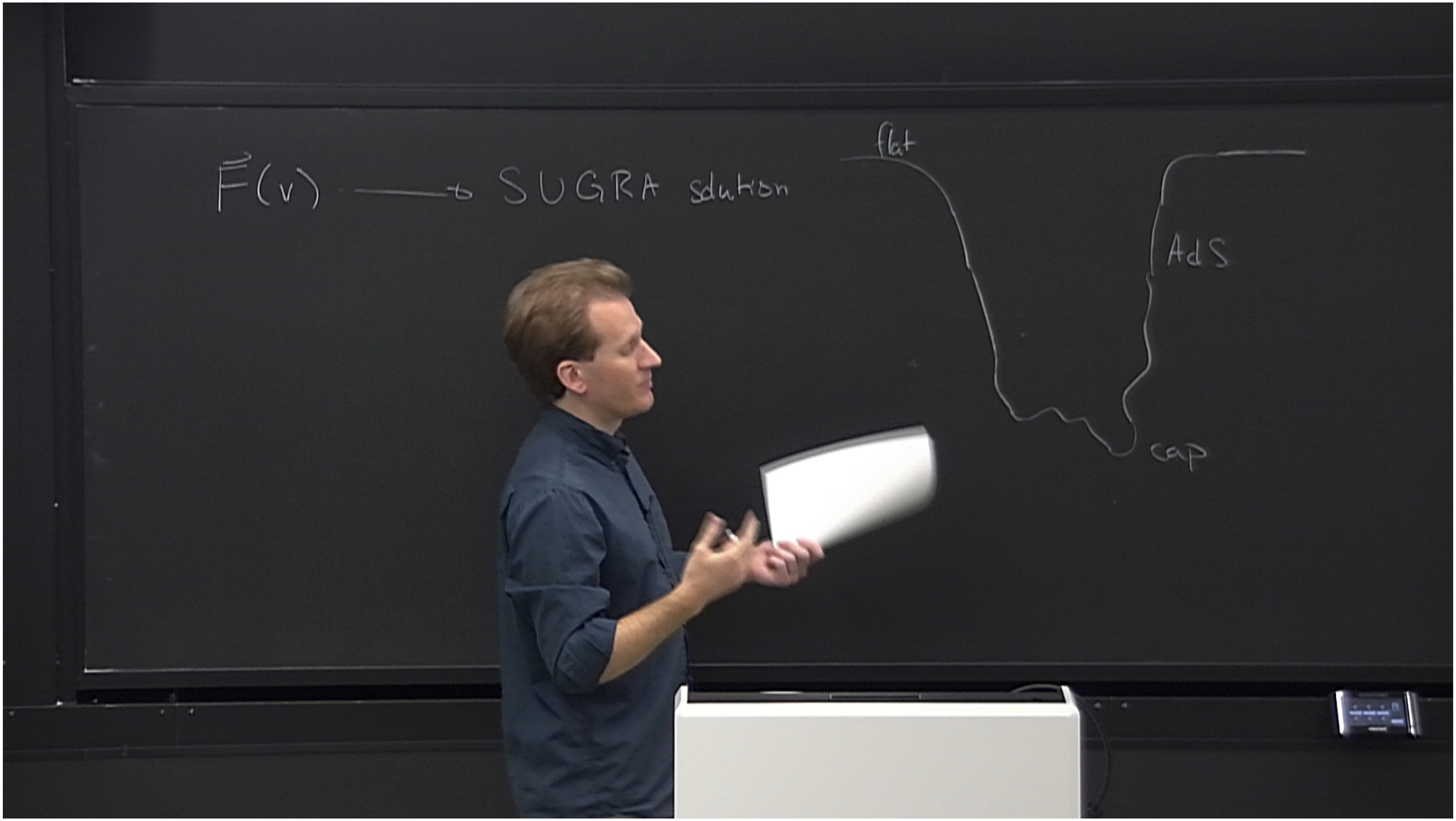
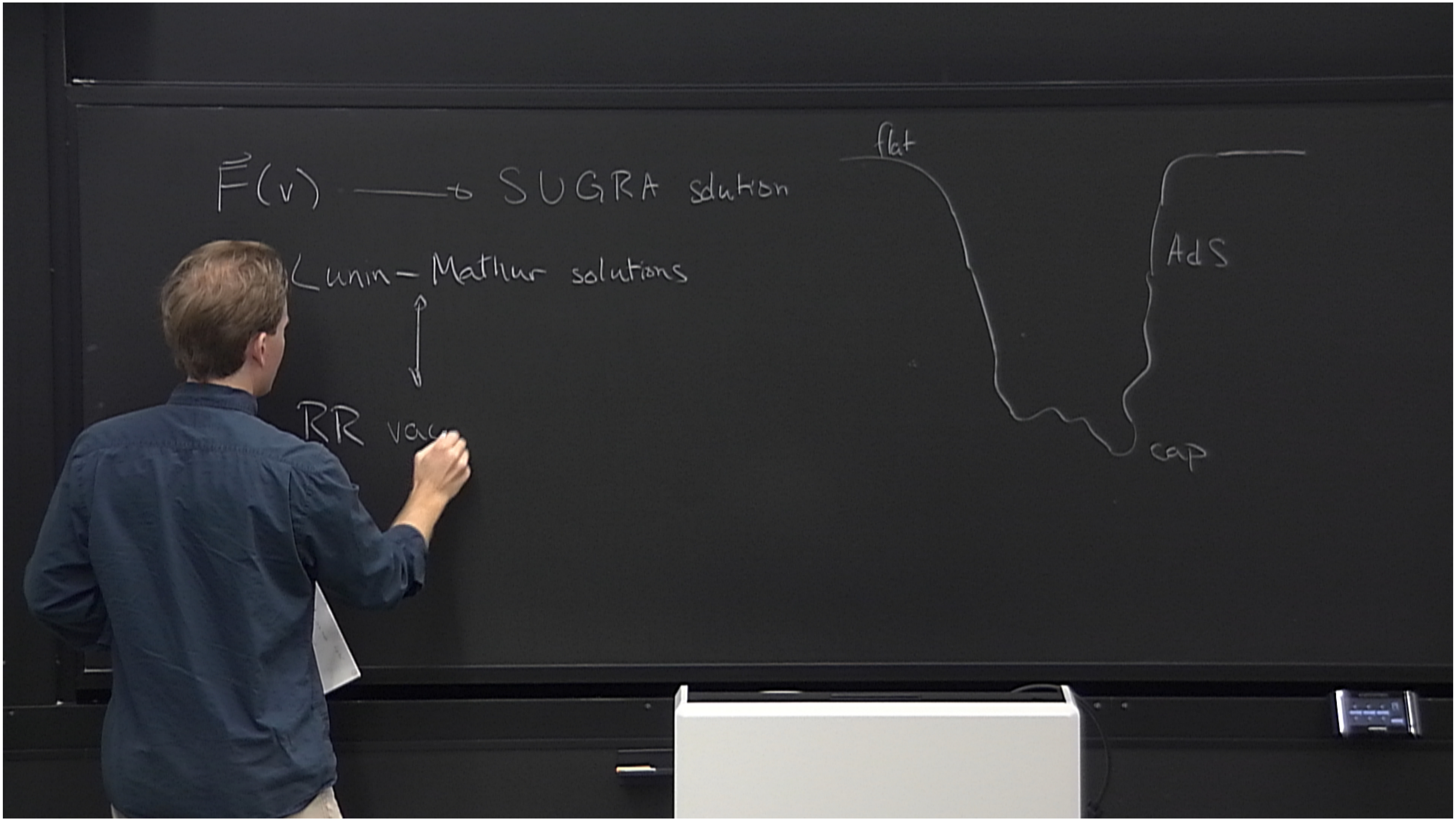
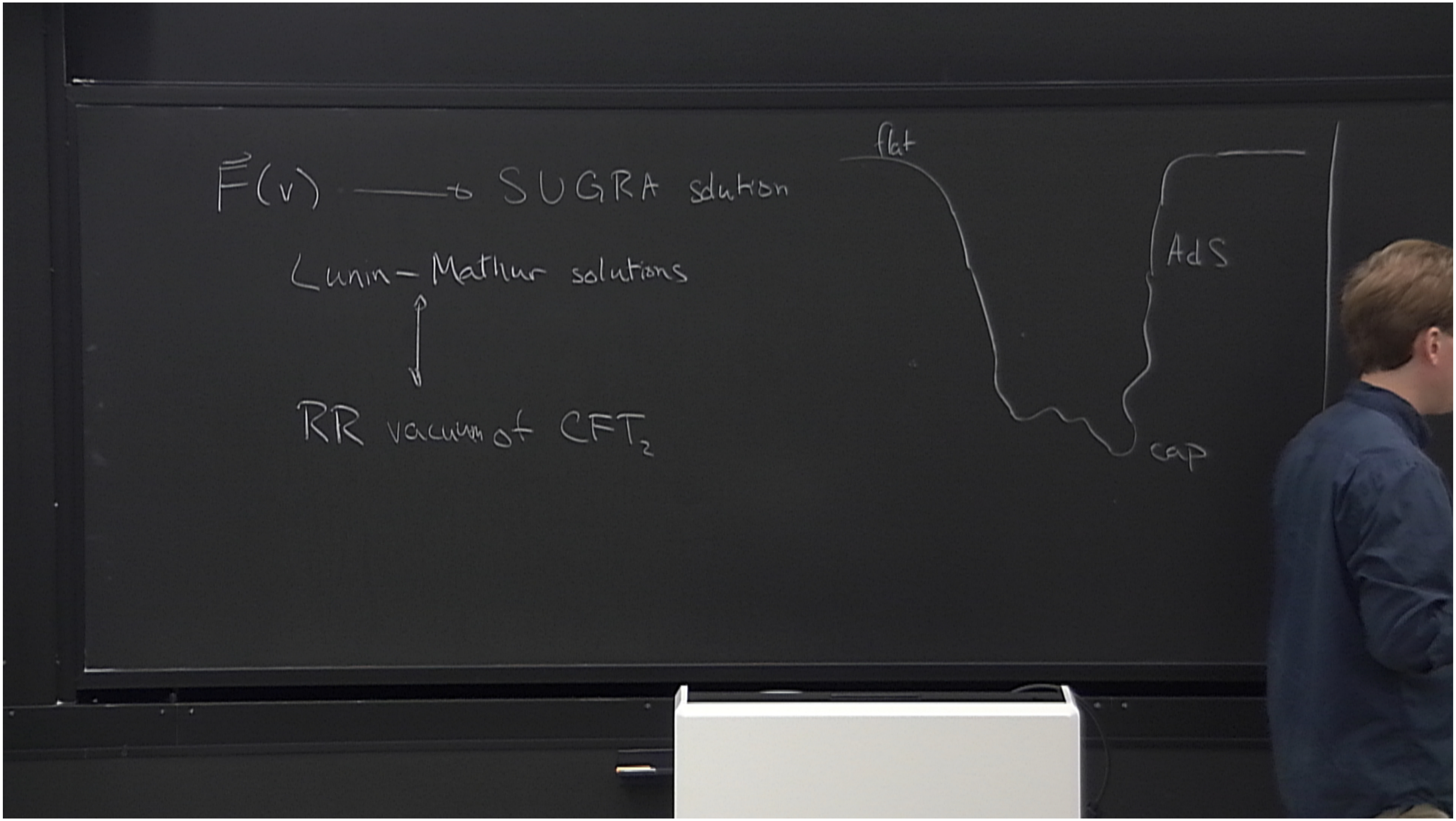
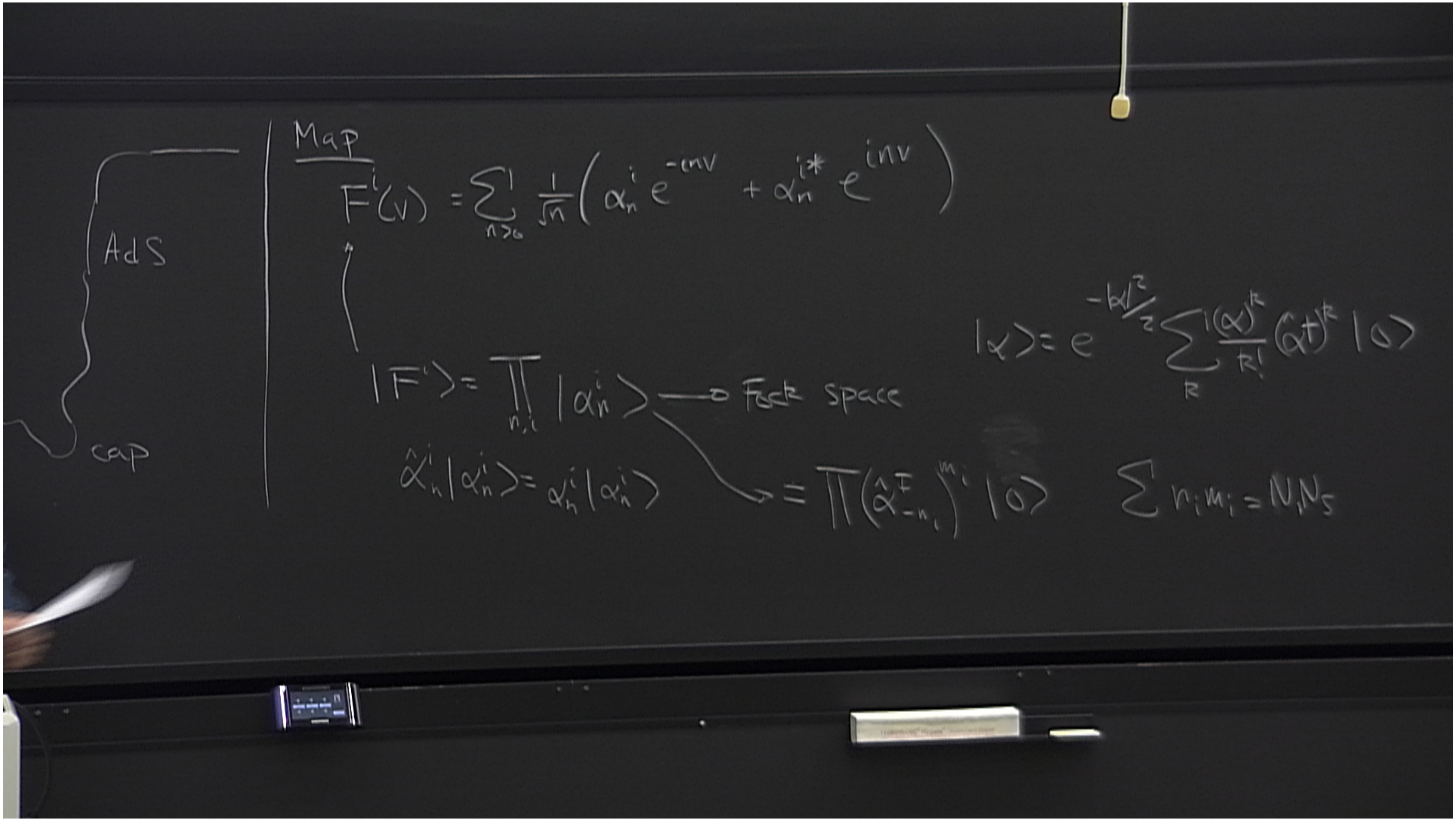
Abstract: The fuzzball proposal makes a conjecture about the nature of black hole
microstates. Now, more than a decade old and including several different
philosophies and perspectives, it is especially relevant after the recent
firewall argument and ensuing debate. Over three lectures, I plan to start
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.

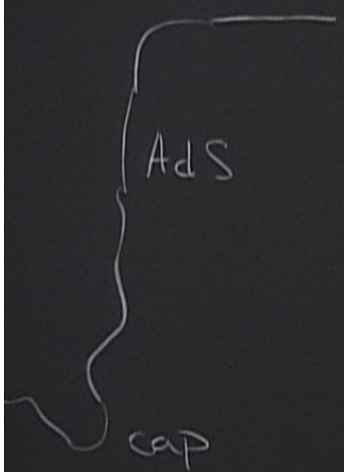

F(v) → SUGRA solution
flat
AdS
cap



$\vec{F}(v) \longrightarrow$ SUGRA solution
Lunin–Mathur solutions
RR vac
flat
AdS
cap


F(v) → SUGRA solution
Lunin – Mathur solutions
RR vacuum of CFT$_2$
flat
AdS
cap


AdS
cap
Map
$F^i(v) = \sum_{n>0} \frac{1}{\sqrt{n}}\left(\alpha_n^i e^{-inv} + \alpha_n^{i*} e^{inv}\right)$
$|F^i\rangle = \prod_{n,i} |\alpha_n^i\rangle$ → Fock space
$\hat{\alpha}_n^i |\alpha_n^i\rangle = \alpha_n^i |\alpha_n^i\rangle$
$= \prod (\hat{\alpha}^I_{-n_i})^{m_i} |0\rangle$
$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_k \frac{(\alpha)^k}{k!} (\hat{a}^\dagger)^k |0\rangle$
$\sum n_i m_i = N_1 N_5$



Map

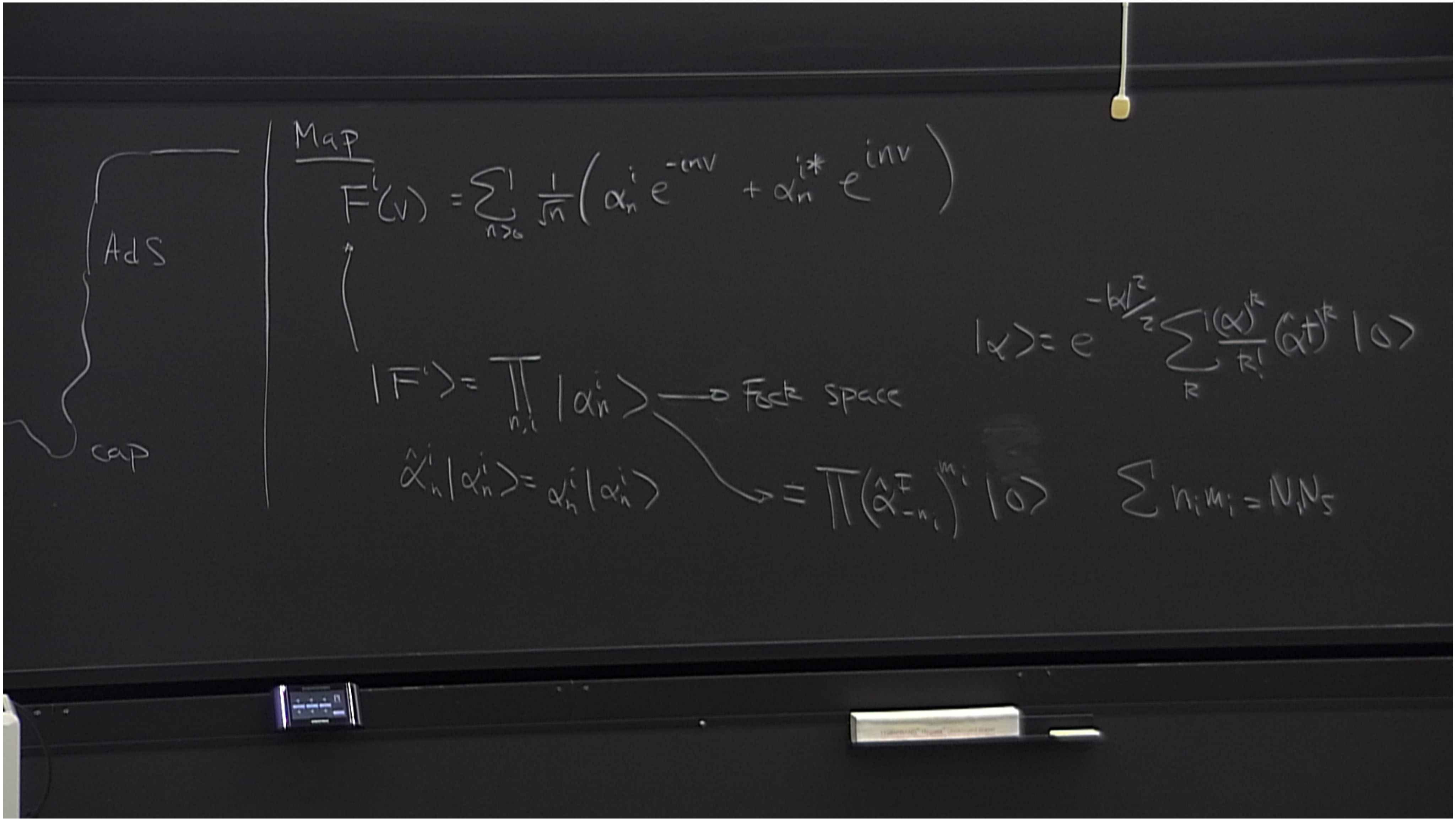
$$F^i(v) = \sum_{n>0}' \frac{1}{\sqrt{n}}\left(\alpha^i_n e^{-inv} + \alpha^{i*}_n e^{inv}\right)$$

$$|F^i\rangle = \prod_{n,i} |\alpha^i_n\rangle \longrightarrow \text{Fock space}$$

$$= \prod \left(\hat{\alpha}^I_{-n_i}\right)^{m_i} |0\rangle \qquad \sum n_i m_i = N_1 N_5$$

$$\hat{\alpha}^i_n |\alpha^i_n\rangle = \alpha^i_n |\alpha^i_n\rangle$$

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_k \frac{(\alpha)^k}{k!} (\hat{\alpha}^\dagger)^k |0\rangle$$


Map
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AdS
cap
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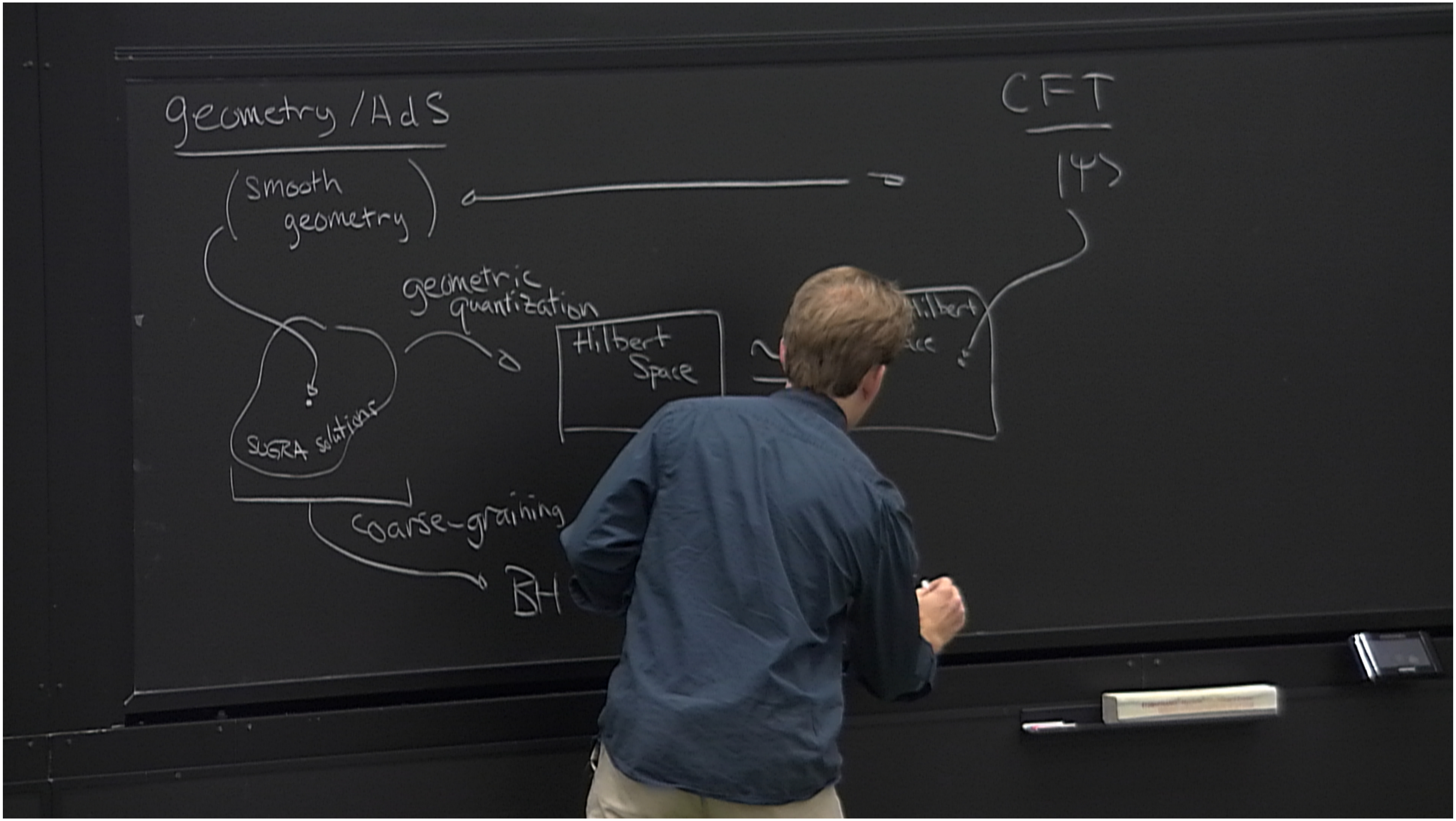
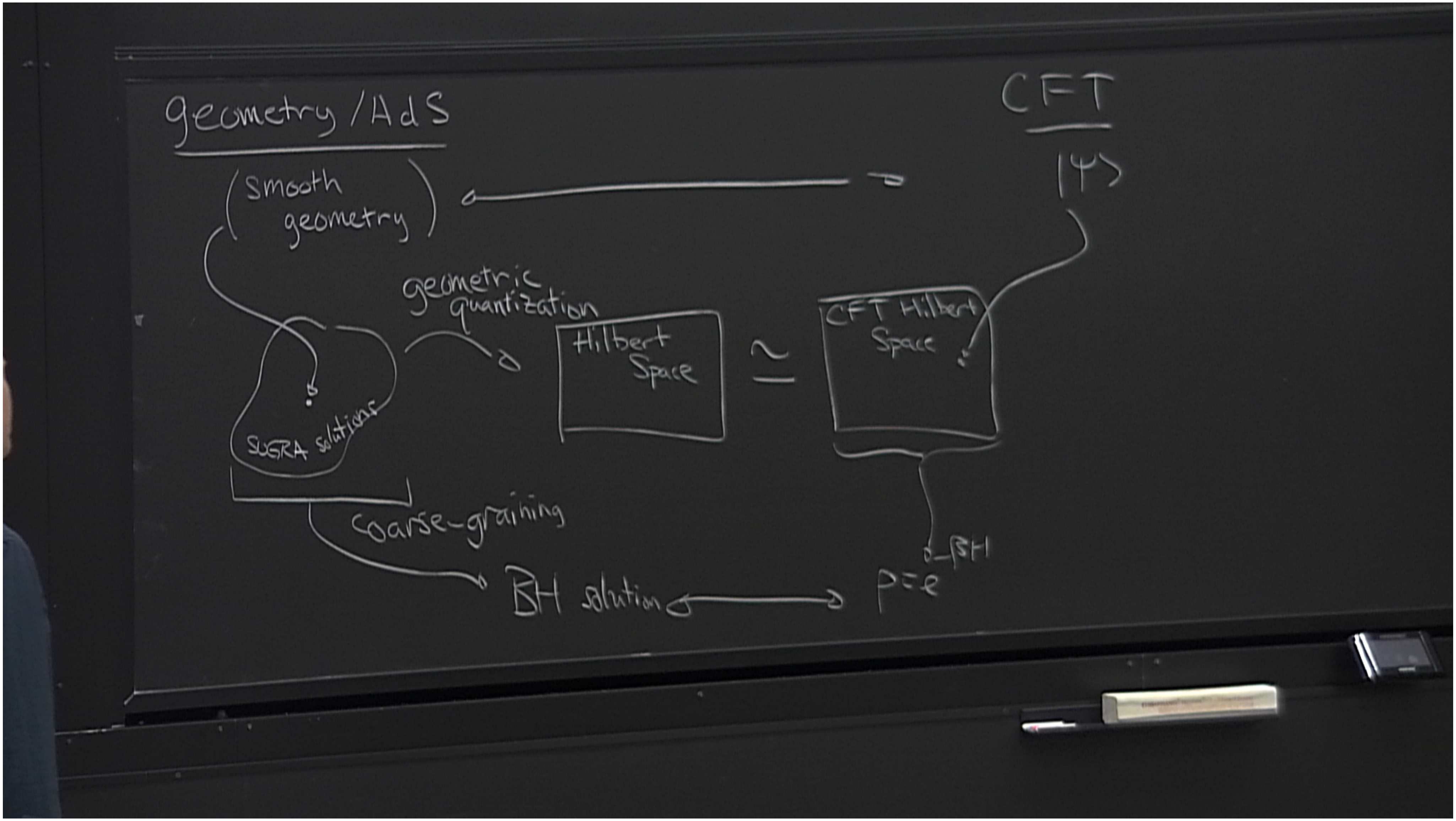
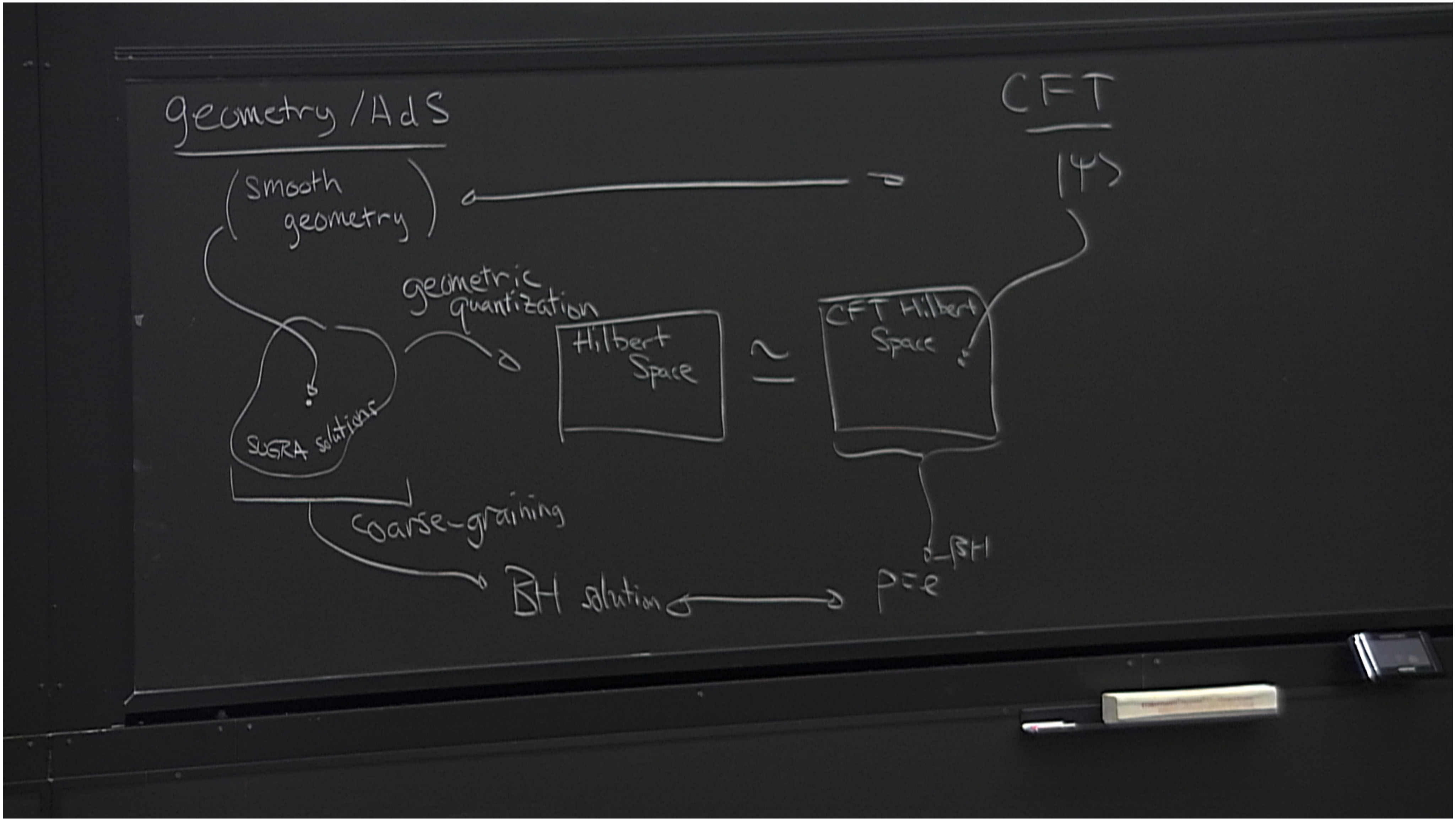
$= \prod (\hat{\alpha}^I_{-n_i})^{m_i} |0\rangle$
$\sum n_i m_i = N_1 N_5$


geometry / AdS
(smooth geometry)
CFT
|ψ⟩



geometry / AdS
CFT
smooth geometry
|ψ⟩
geometric quantization
Hilbert Space
SUGRA solutions
coarse-graining
BH


geometry / AdS
CFT
smooth geometry
|ψ⟩
geometric quantization
Hilbert Space
≃
CFT Hilbert Space
SUGRA solutions
coarse-graining
BH solution
ρ = e^{−βH}


geometry / AdS
CFT
smooth geometry
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Hilbert Space
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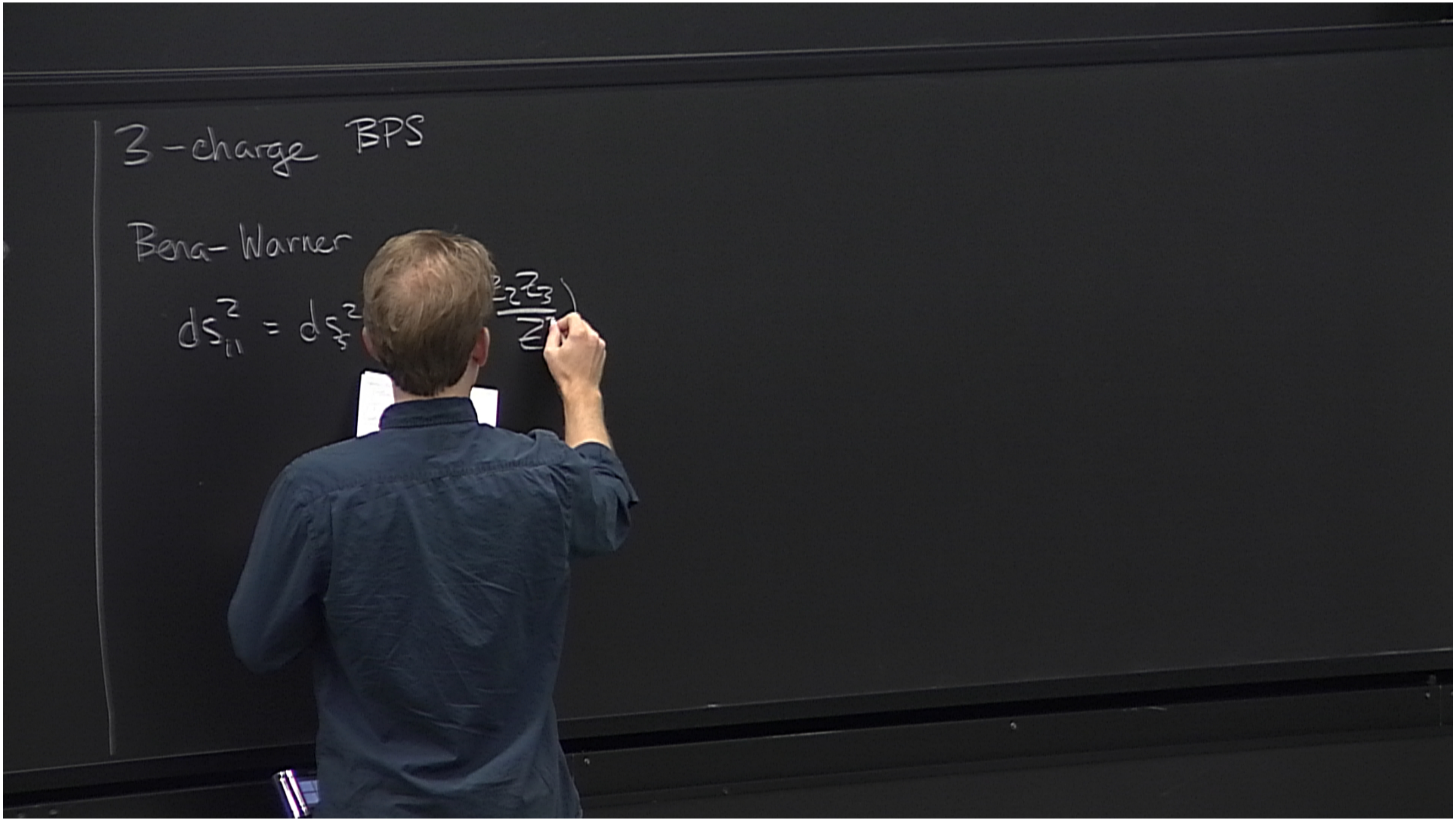
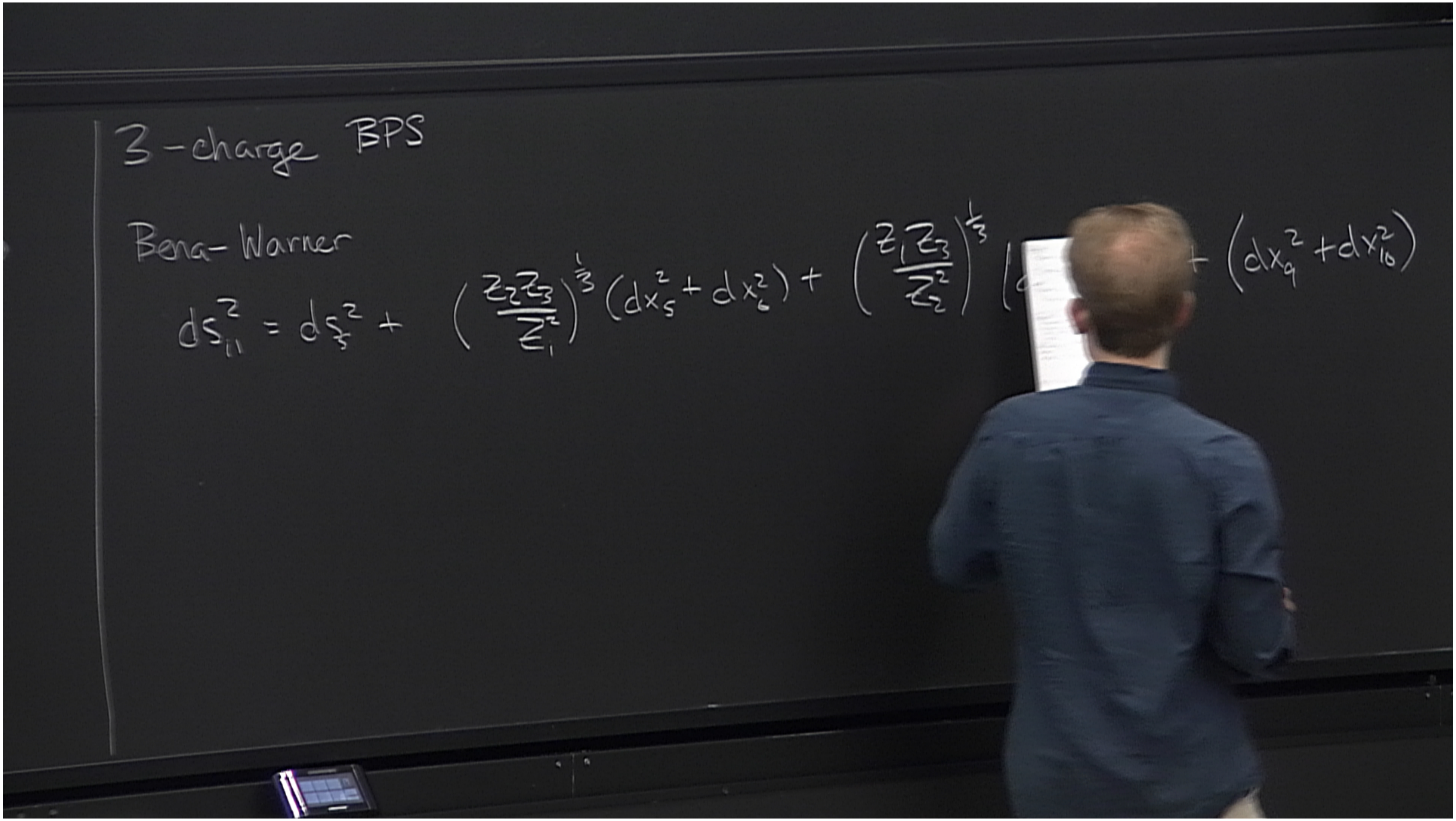
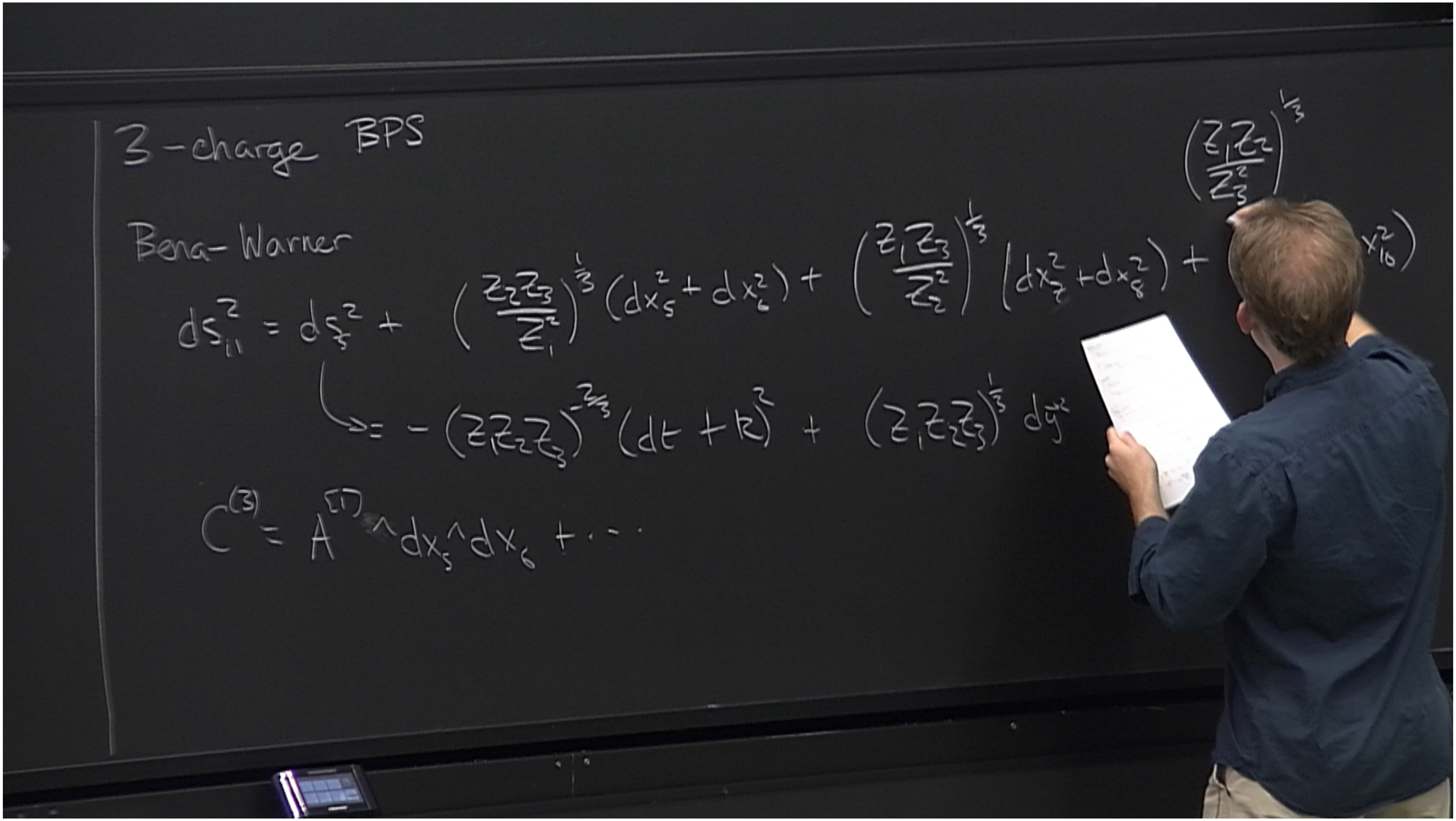
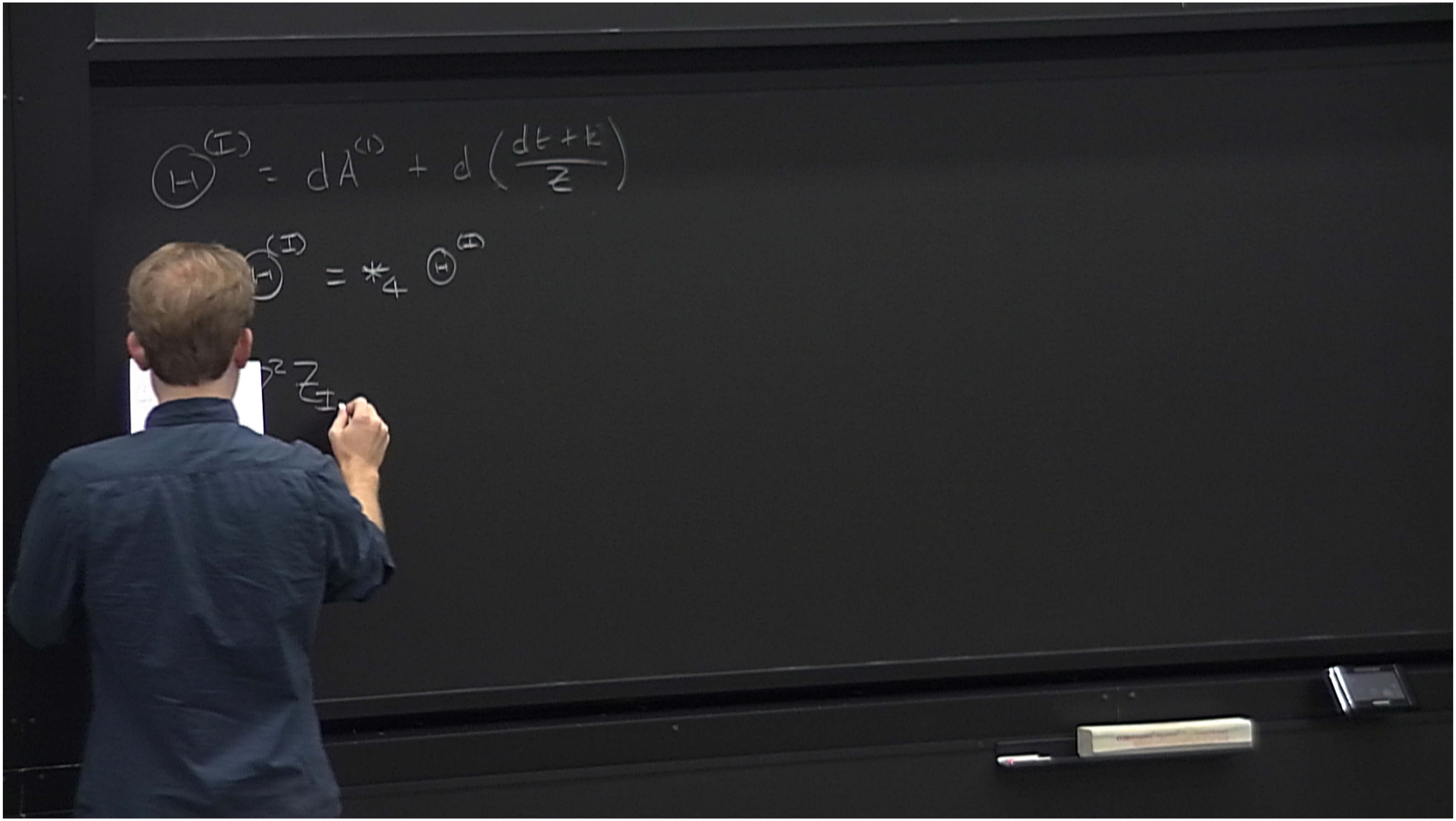
ρ = e^{-βH}


3-charge BPS
Bena-Warner


3-charge BPS
Bena-Warner
$ds_{11}^2 = ds_5^2 + \left(\frac{Z_2 Z_3}{Z_1^2}\right)^{\frac{1}{3}} (dx_5^2 + dx_6^2) + \left(\frac{Z_1 Z_3}{Z_2^2}\right)^{\frac{1}{3}}$
$+ (dx_9^2 + dx_{10}^2)$


3-charge BPS
Bena-Warner
$ds_{11}^2 = ds_5^2 + \left(\frac{Z_2 Z_3}{Z_1^2}\right)^{\frac{1}{3}}(dx_5^2 + dx_6^2) + \left(\frac{Z_1 Z_3}{Z_2^2}\right)^{\frac{1}{3}}(dx_7^2 + dx_8^2) + \left(\frac{Z_1 Z_2}{Z_3^2}\right)^{\frac{1}{3}}$ … $x_{10}^2)$
$= -(Z_1 Z_2 Z_3)^{-\frac{2}{3}}(dt + k)^2 + (Z_1 Z_2 Z_3)^{\frac{1}{3}} dy^2$
$C^{(3)} = A^{[1]} \wedge dx_5 \wedge dx_6 + \cdots$


Θ(I) = dA(I) + d((dt + k) / Z)
Θ(I) = *4 Θ(I)

$$\Theta^{(I)} = dA^{(I)} + d\left(\frac{dt + k}{Z}\right)$$

(1) $$\Theta^{(I)} = *_4 \Theta^{(I)}$$

(2) $$\nabla^2 Z_I = \frac{1}{2} C_{IJK} *_4 \left(\Theta^{(J)} \wedge \Theta^{(K)}\right)$$

(3) $$dk + *_4 dk = Z_I \Theta^{(I)}$$

$$\Theta^{(I)} = dA^{(I)} + d\left(\frac{dt+k}{Z}\right)$$

(1) $\Theta^{(I)} = *_4 \, \Theta^{(I)}$

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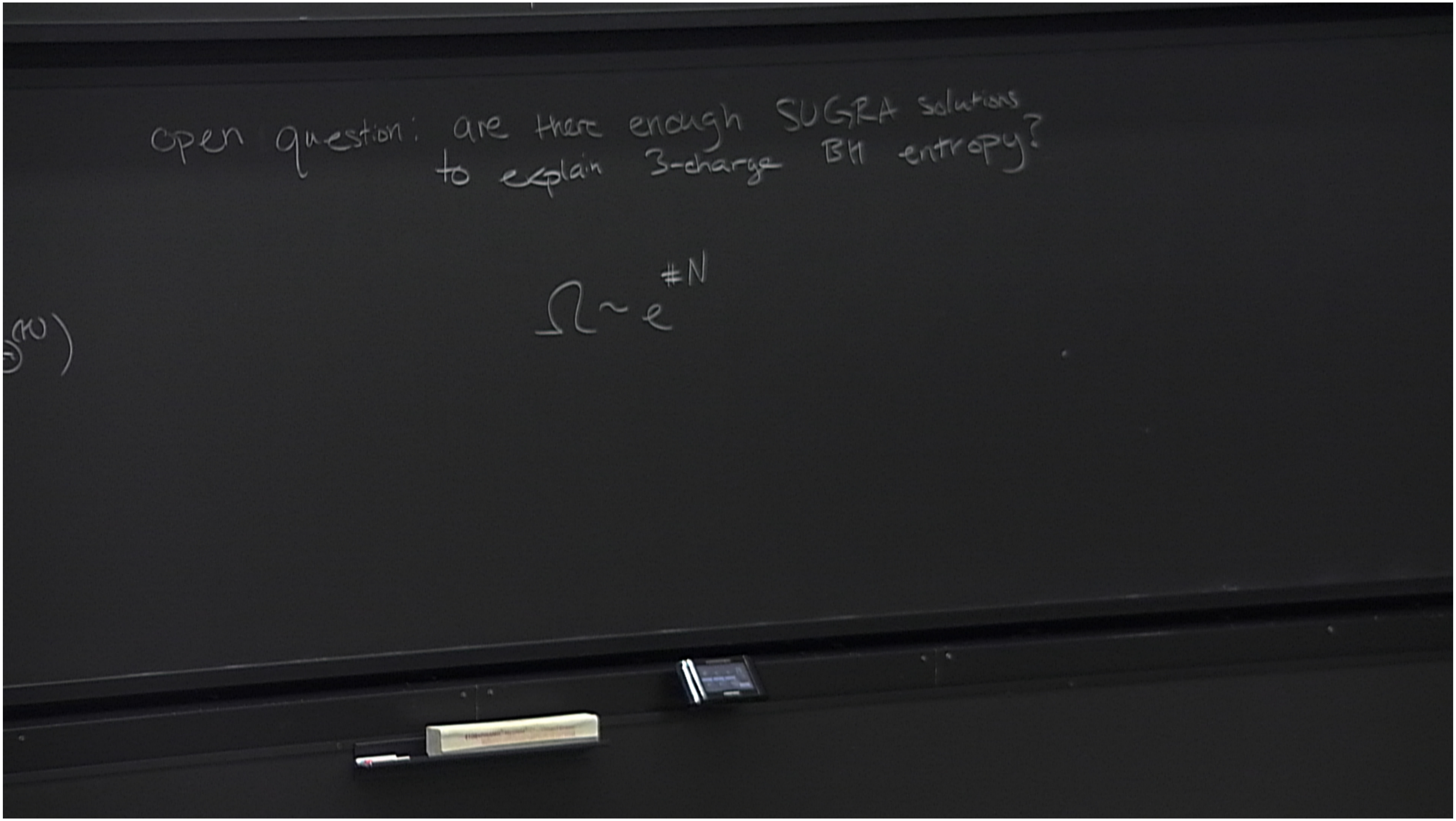
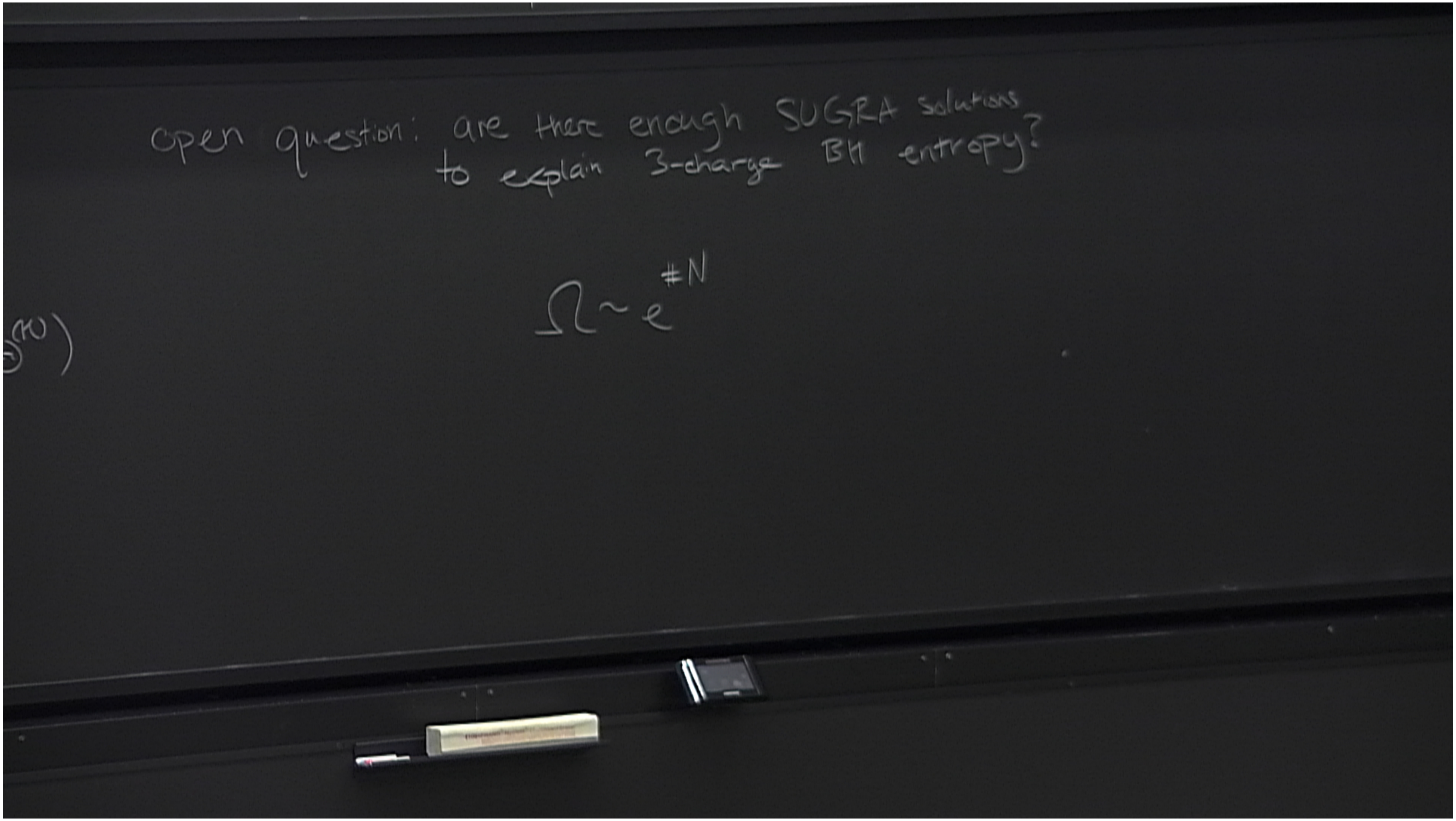
(3) $dk + *_4 dk = Z_I \, \Theta^{(I)}$


open question: are there enough SUGRA solutions
to explain 3-charge BH entropy?
Ω ~ e^#N


open question: are there enough SUGRA solutions to explain 3-charge BH entropy?
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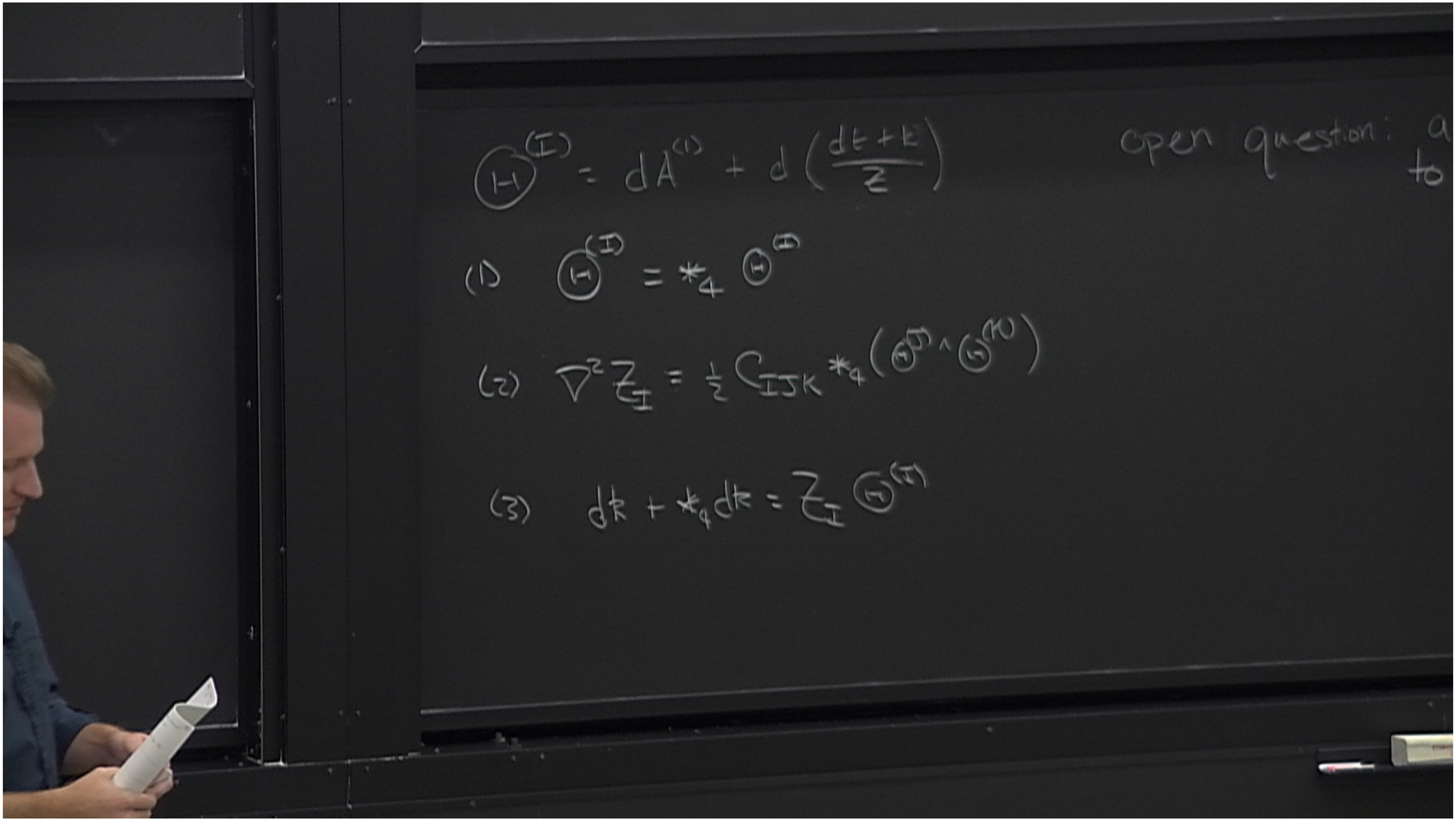
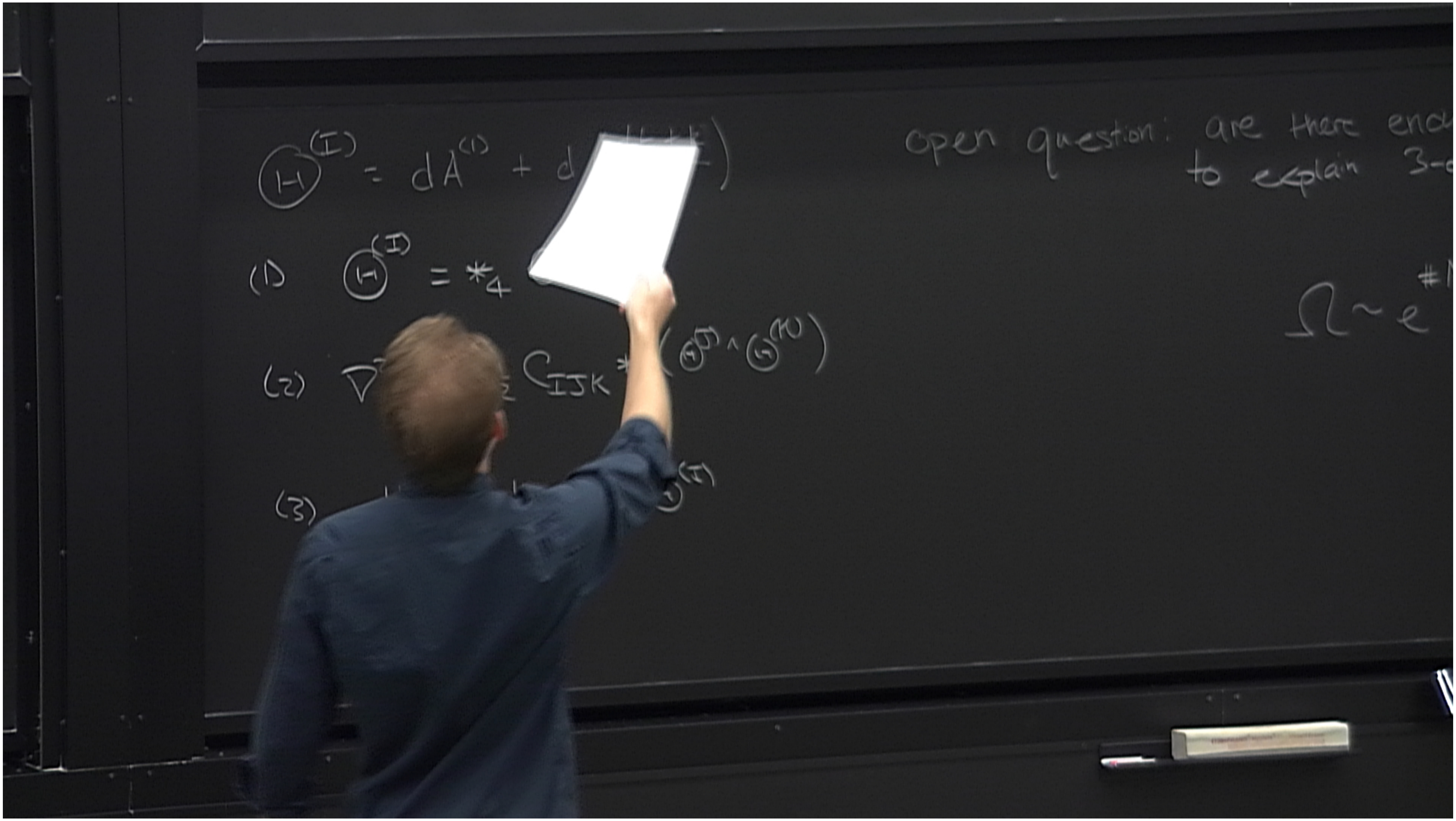
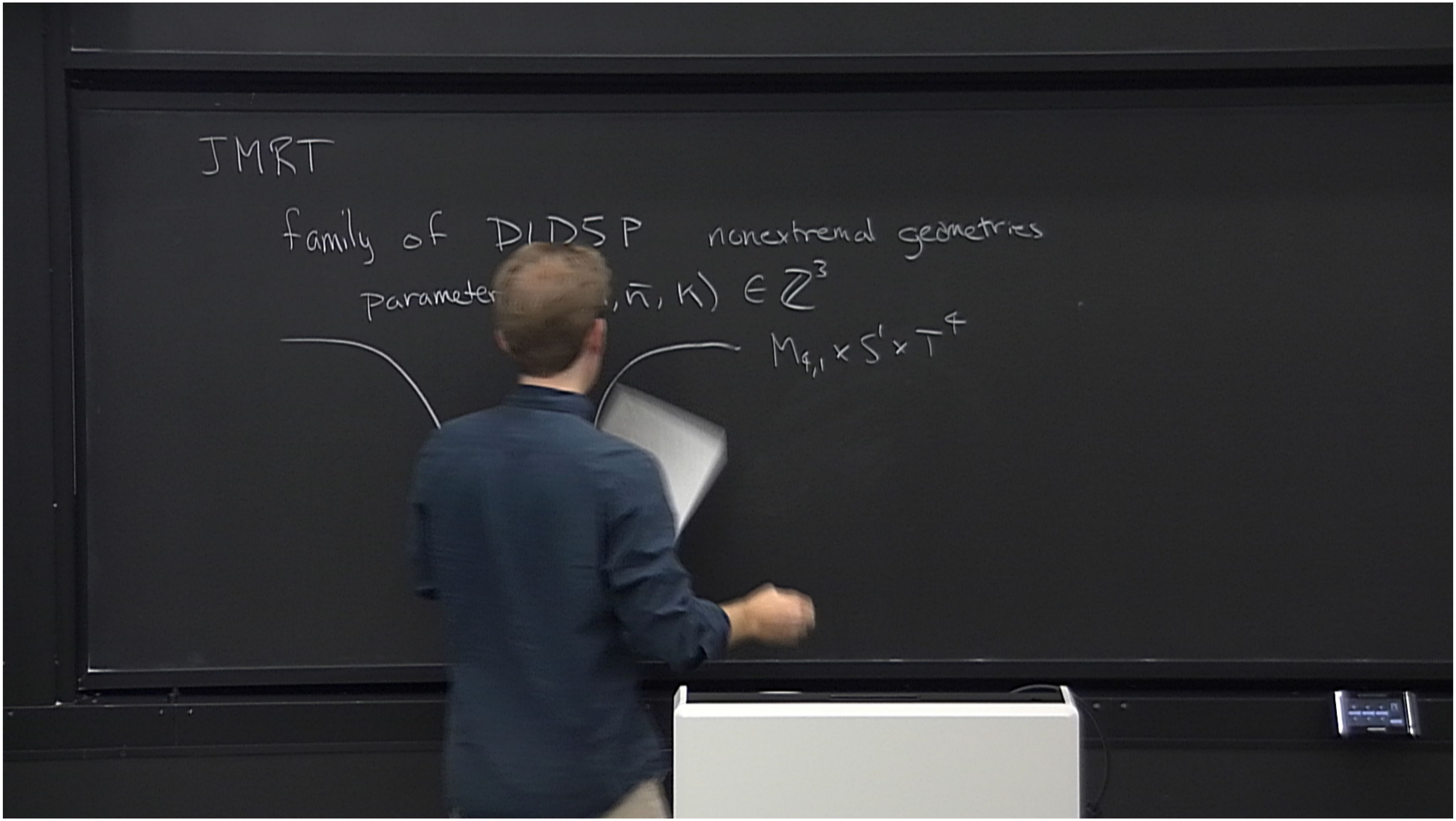
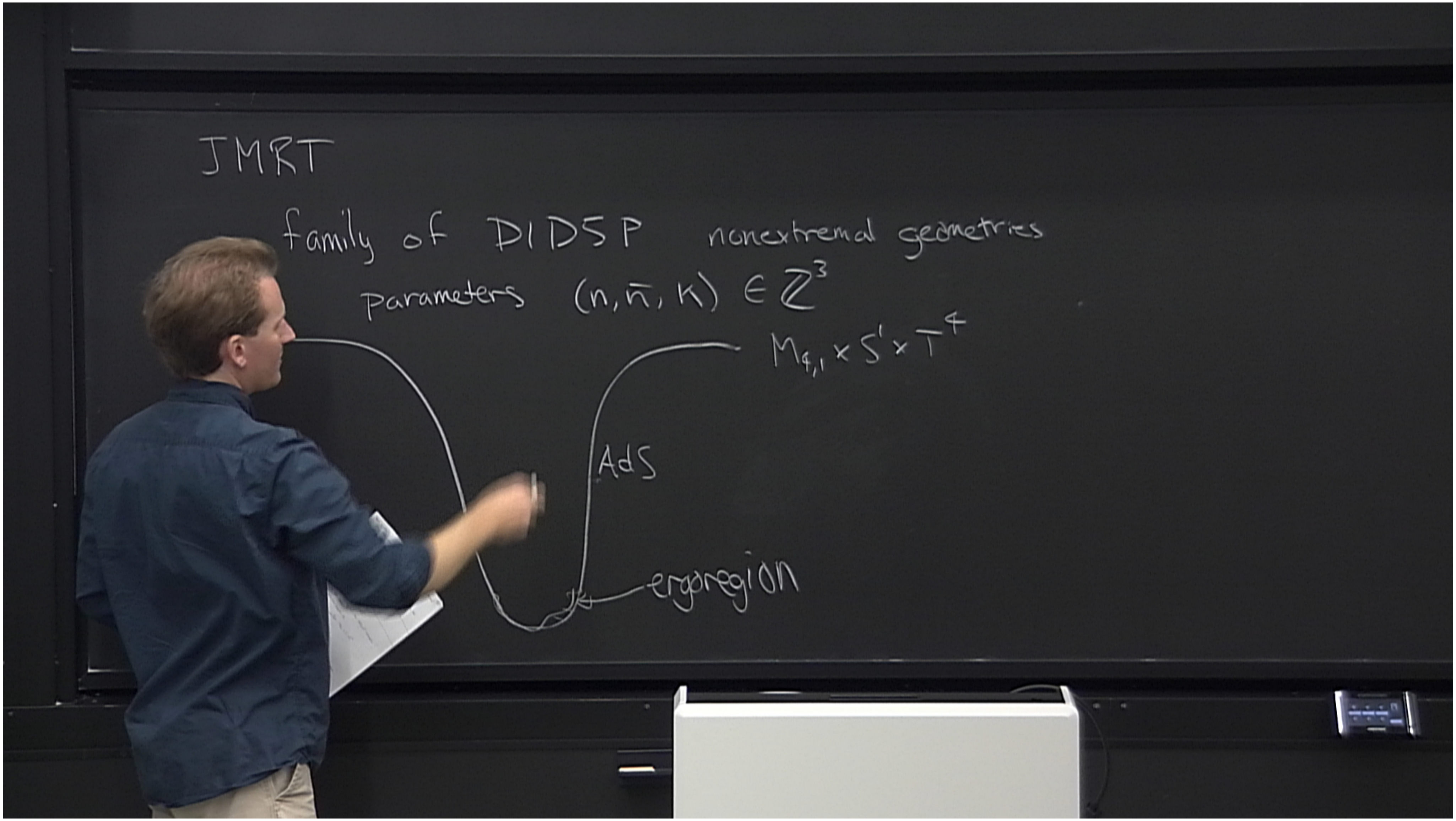
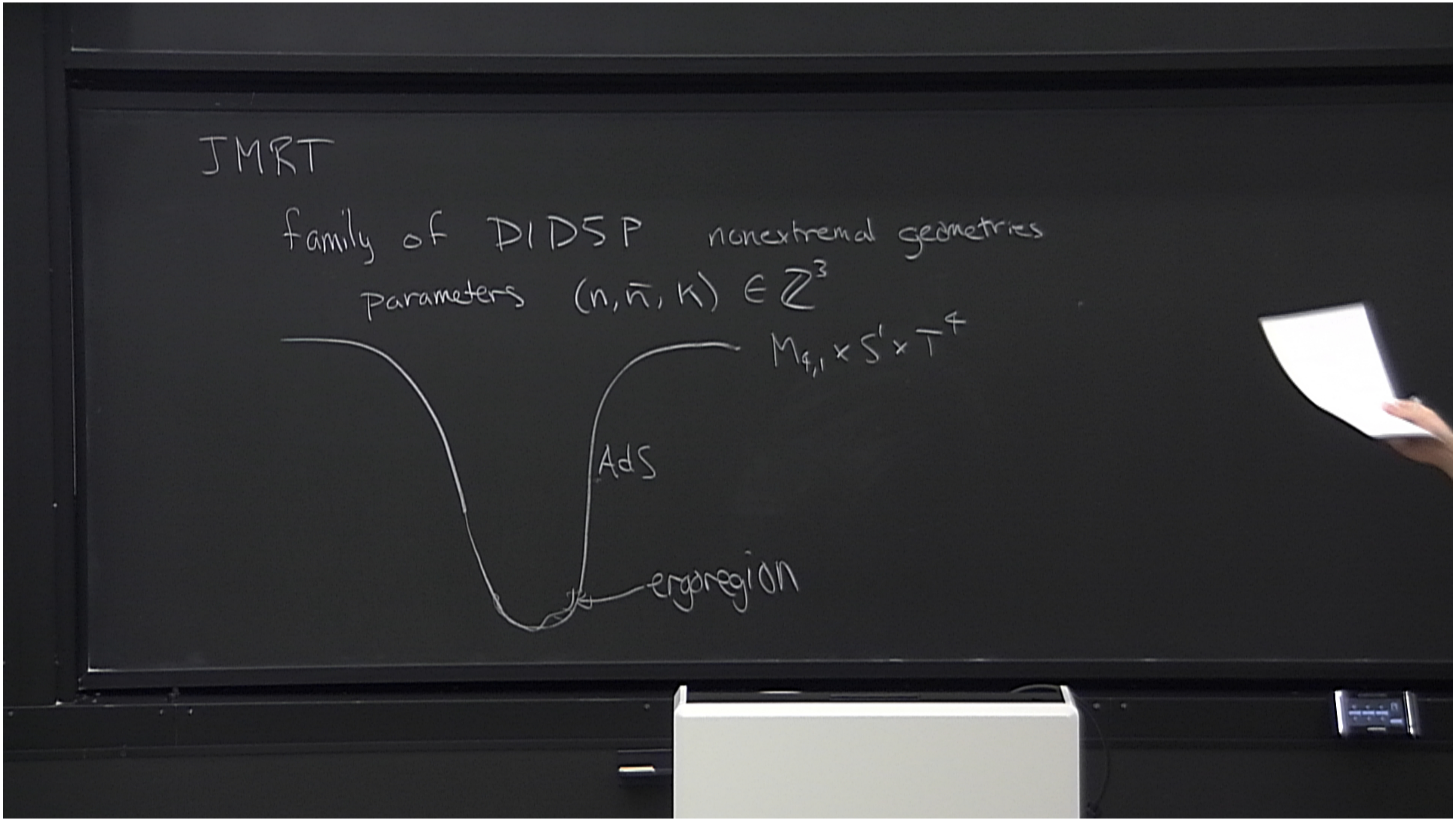
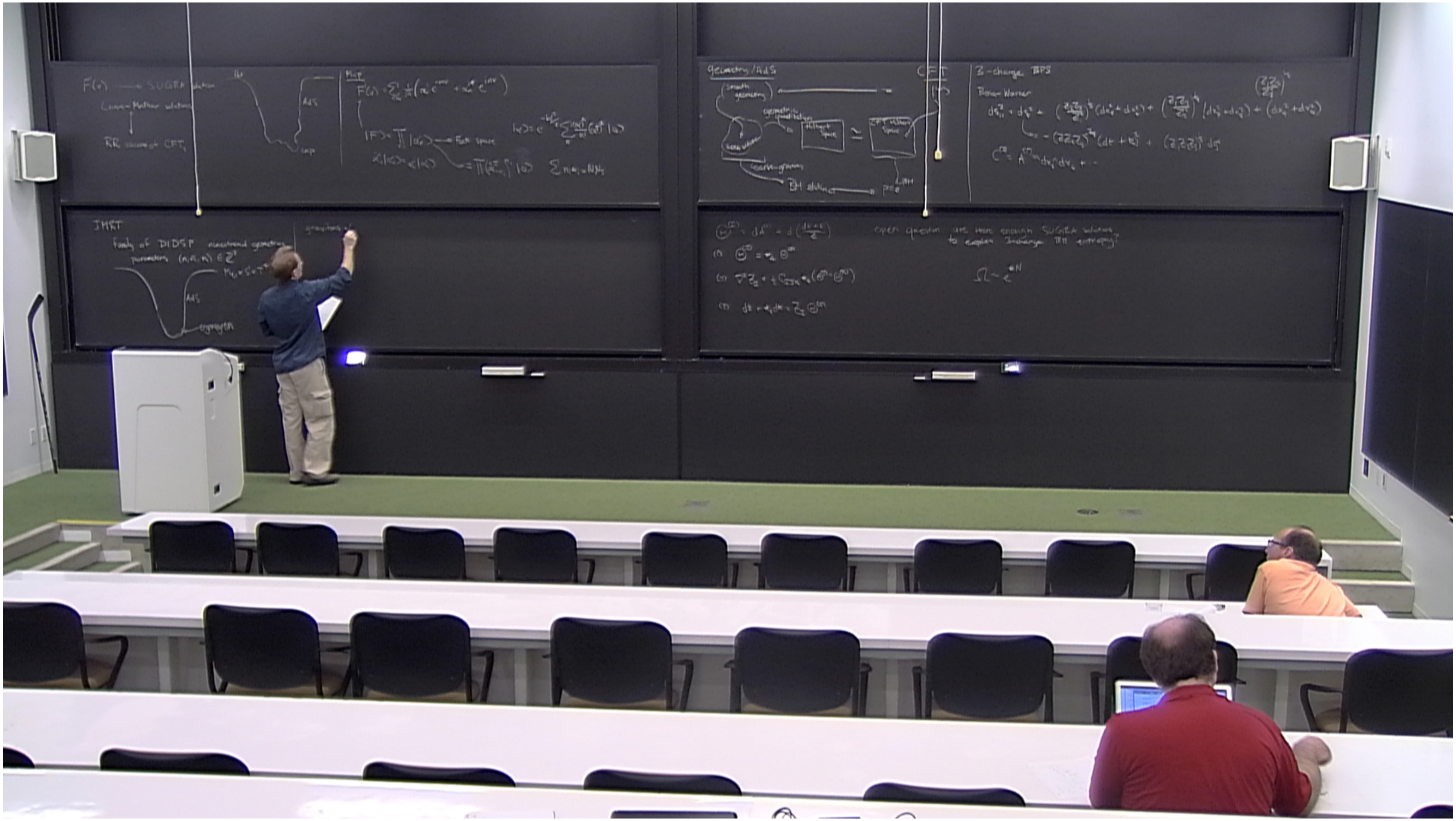

Θ^(I) = dA^(I) + d((dt+k)/Z)
(1) Θ^(I) = *4 Θ^(I)
(2) ∇² Z_I = ½ C_IJK *4 (Θ^(J) ∧ Θ^(K))
(3) dk + *4 dk = Z_I Θ^(I)
open question: a
to

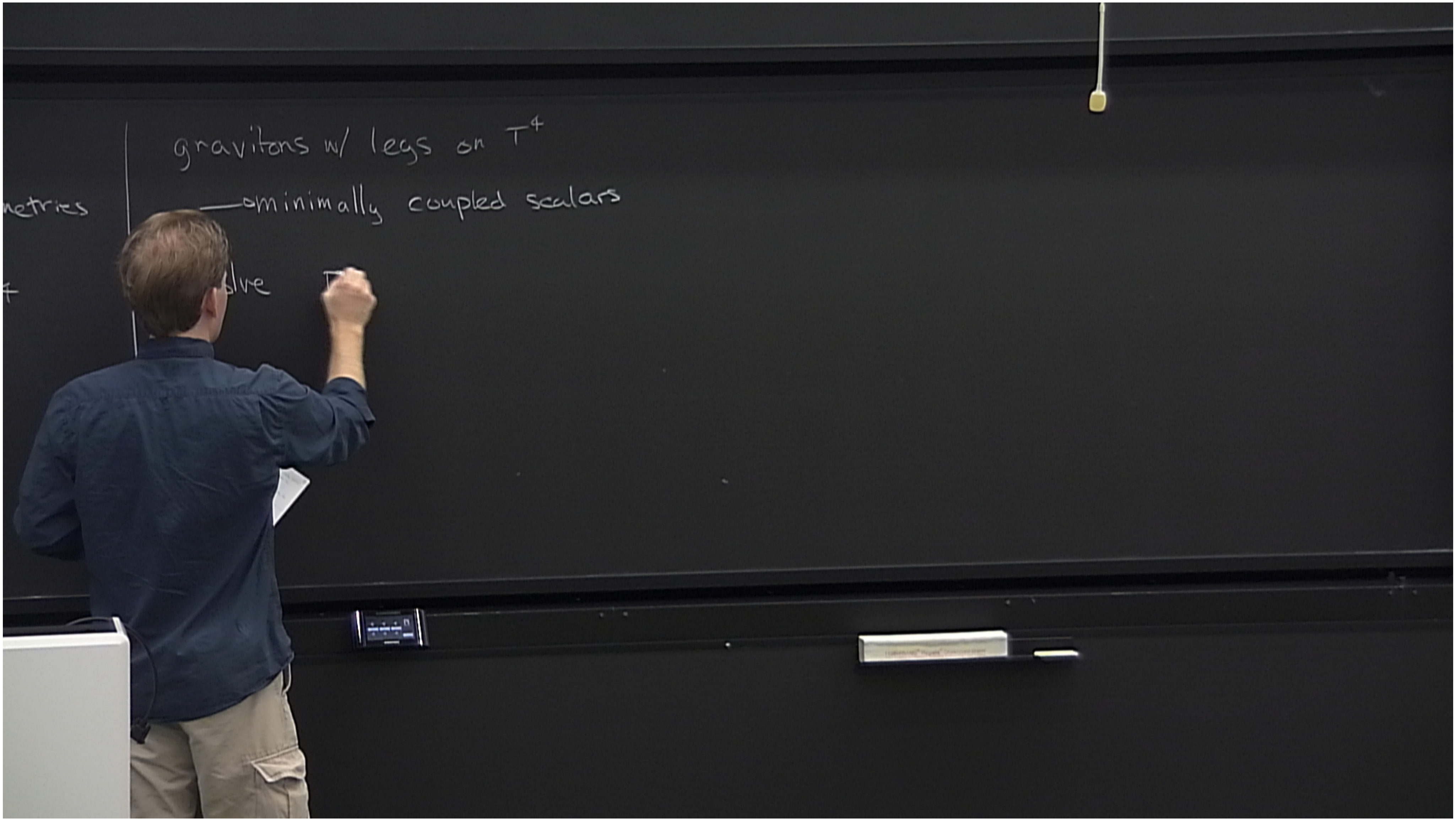

open question: are there
to explain

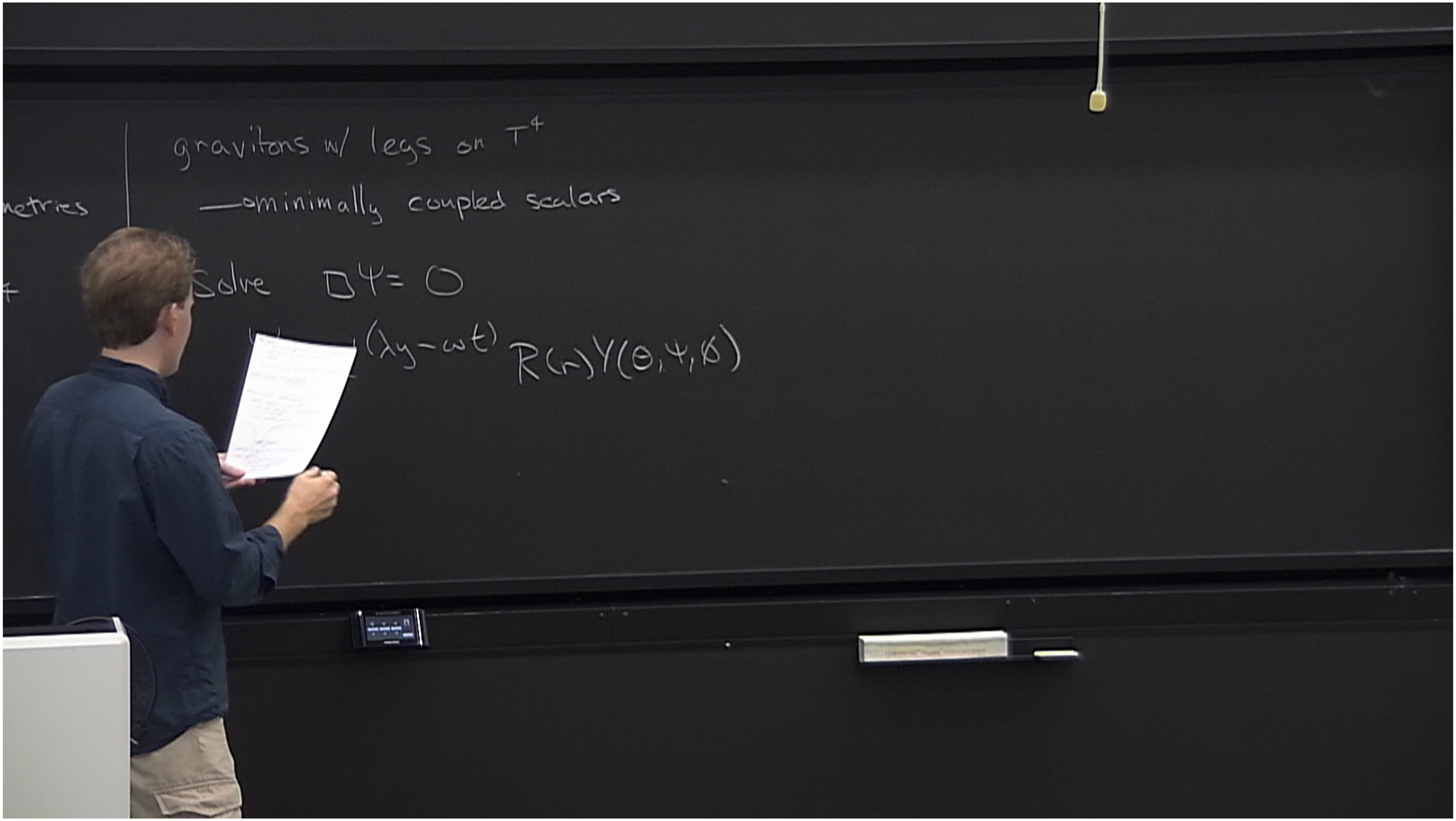

JMRT
family of D1D5P nonextremal geometries
parameter
, n̄, k) ∈ Z³
M₄,₁ × S¹ × T⁴

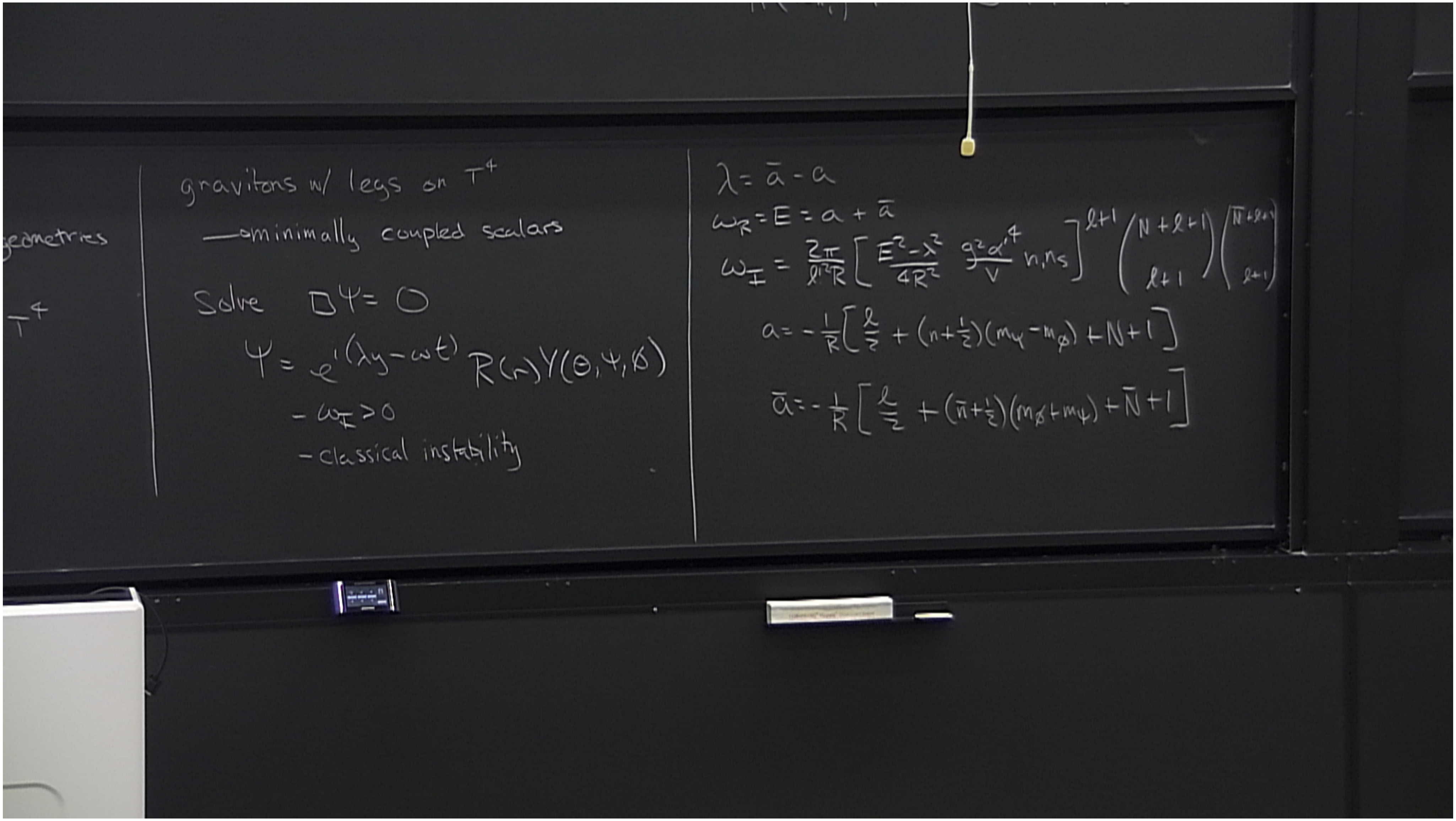

JMRT
family of D1D5P nonextremal geometries
parameters $(n, \bar{n}, k) \in \mathbb{Z}^3$
$M_{4,1} \times S^1 \times T^4$
AdS
ergoregion

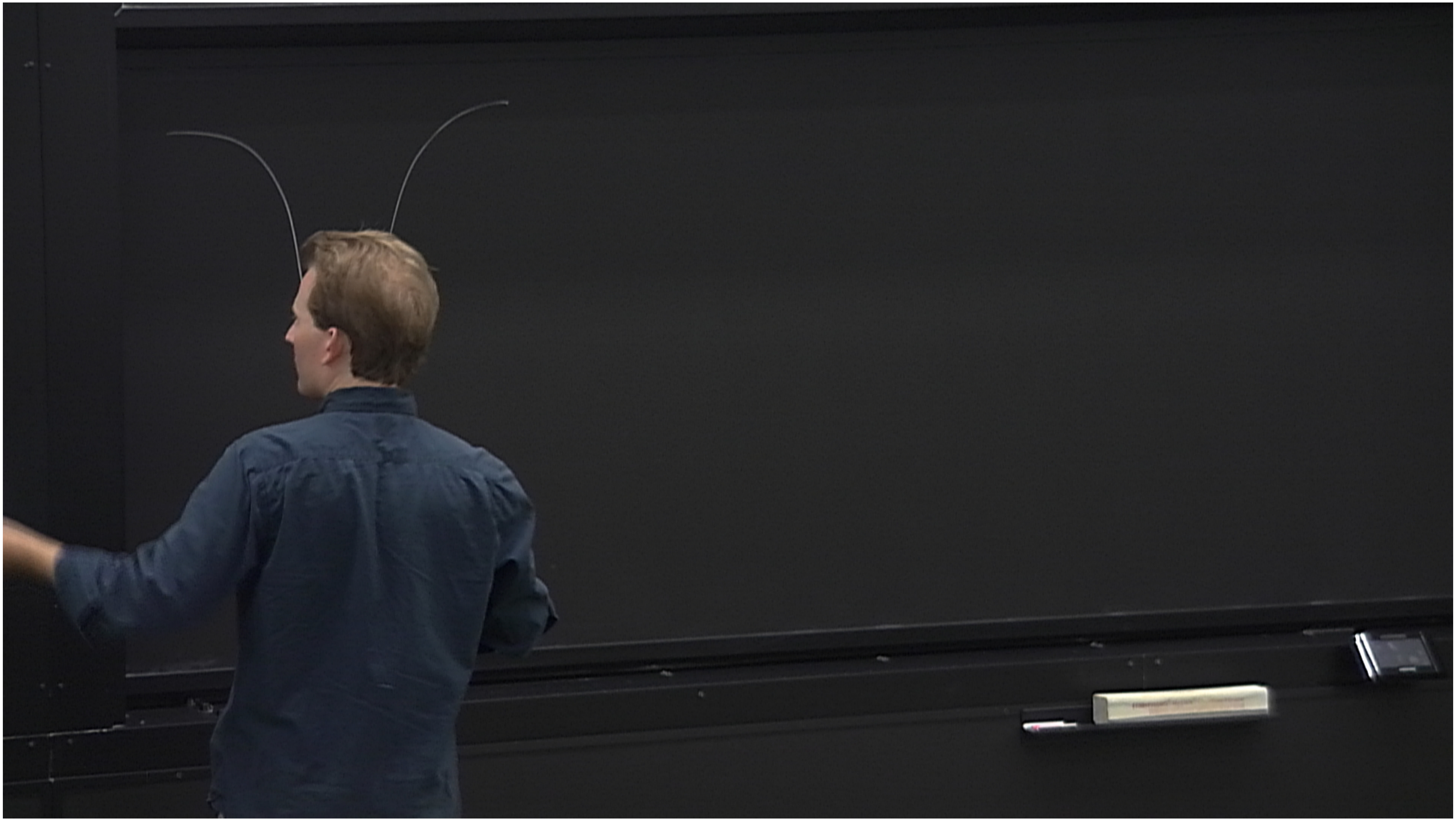

JMRT
family of D1D5P nonextremal geometries
parameters $(n, \bar{n}, k) \in \mathbb{Z}^3$
$M_{4,1} \times S^1 \times T^4$
AdS
ergoregion

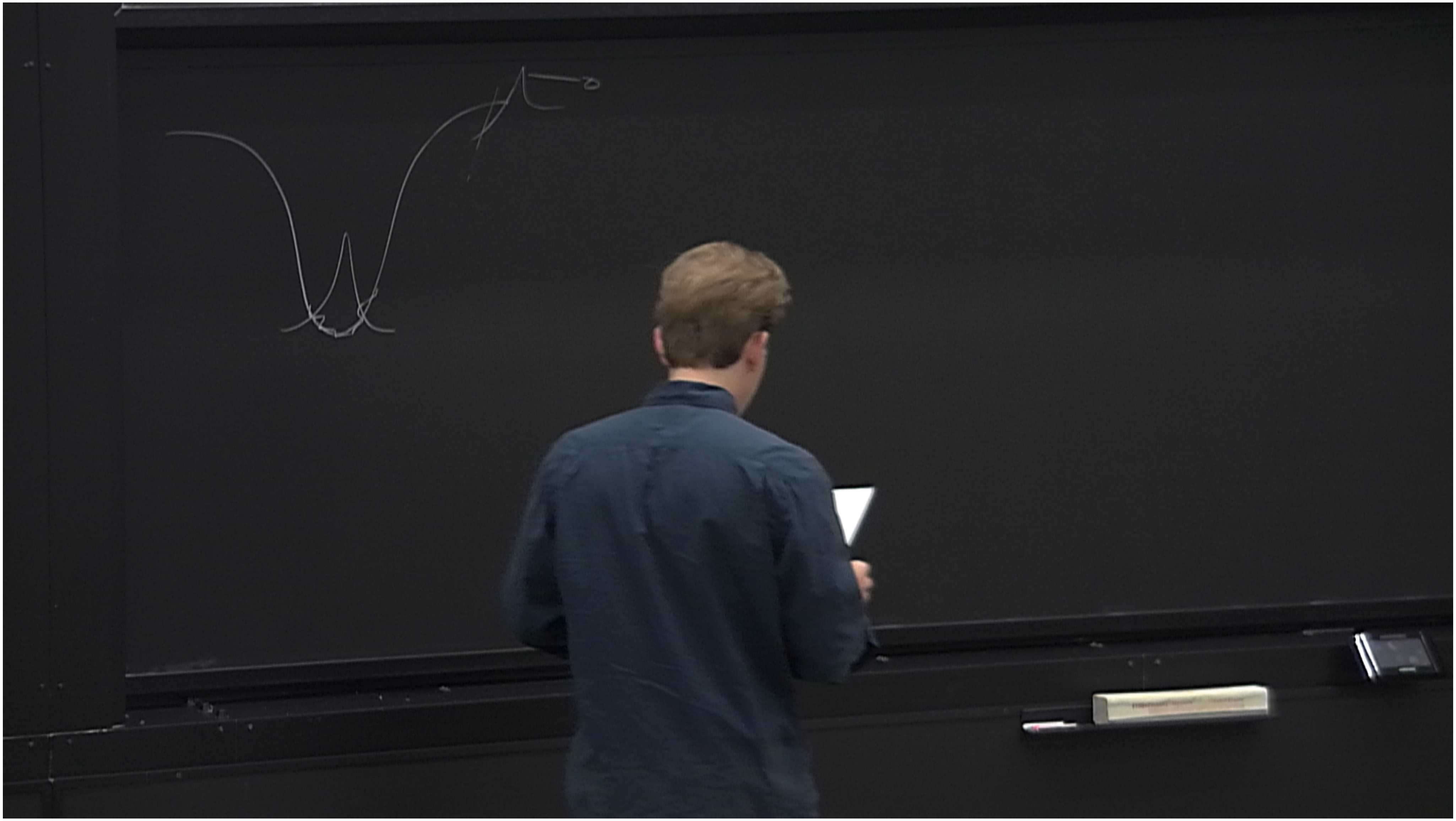

SUGRA
AdS
CFT
3-charge BPS
Fock space
BH
JMRT

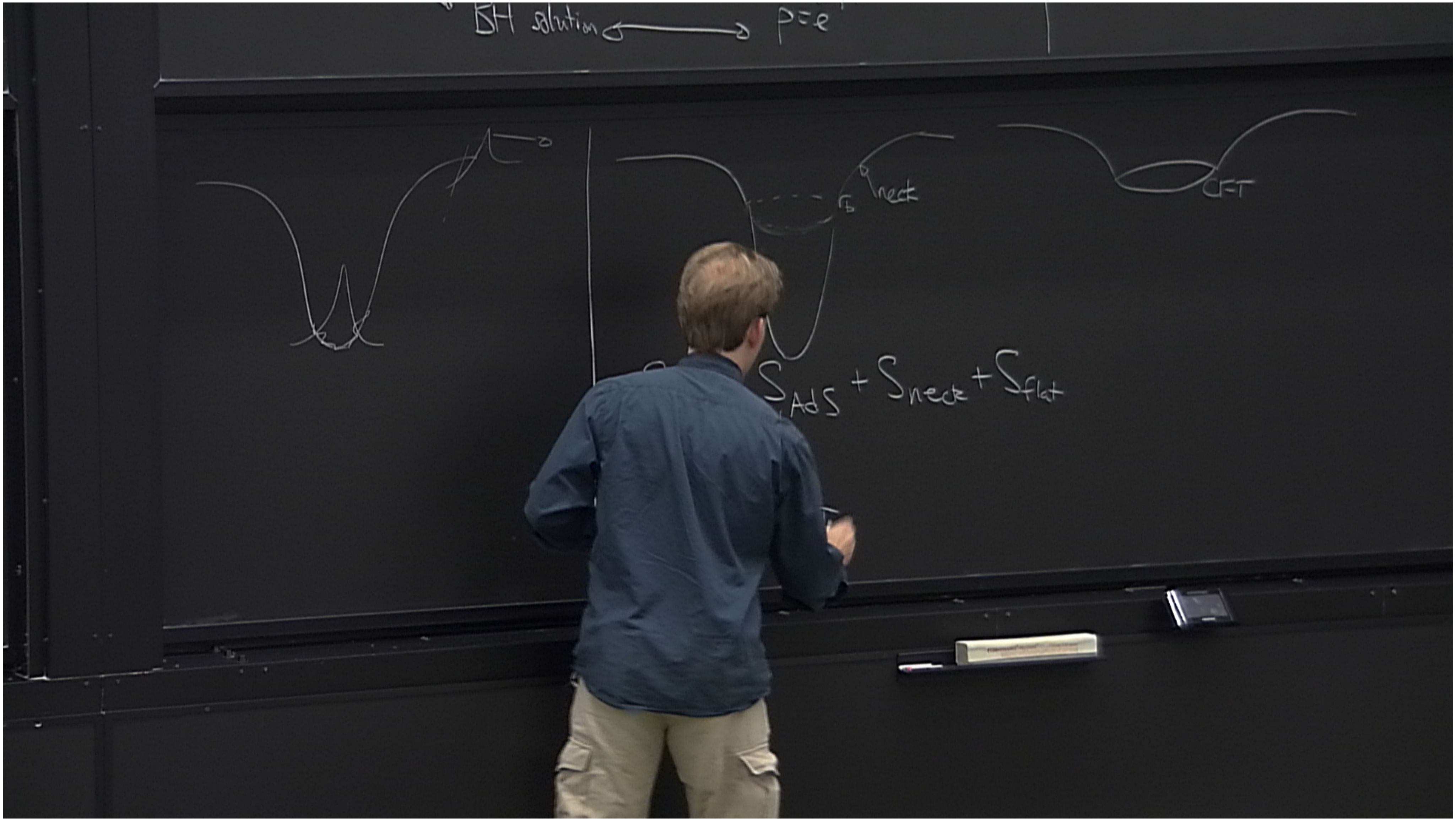

gravitons w/ legs on T4
minimally coupled scalars

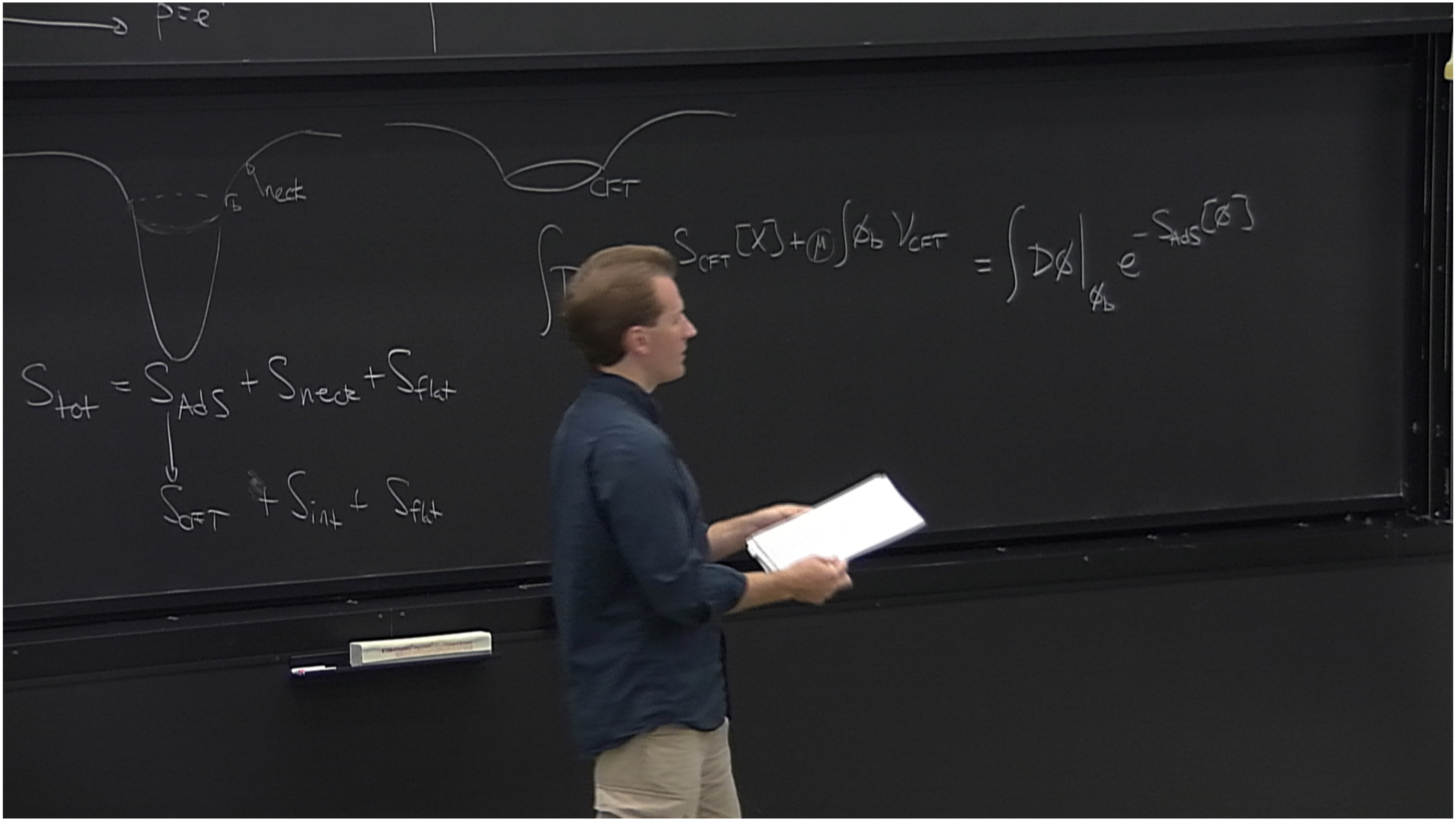

gravitons w/ legs on T^4
— minimally coupled scalars
Solve □Ψ = 0
(λy − ωt) R(r) Y(θ, ψ, φ)

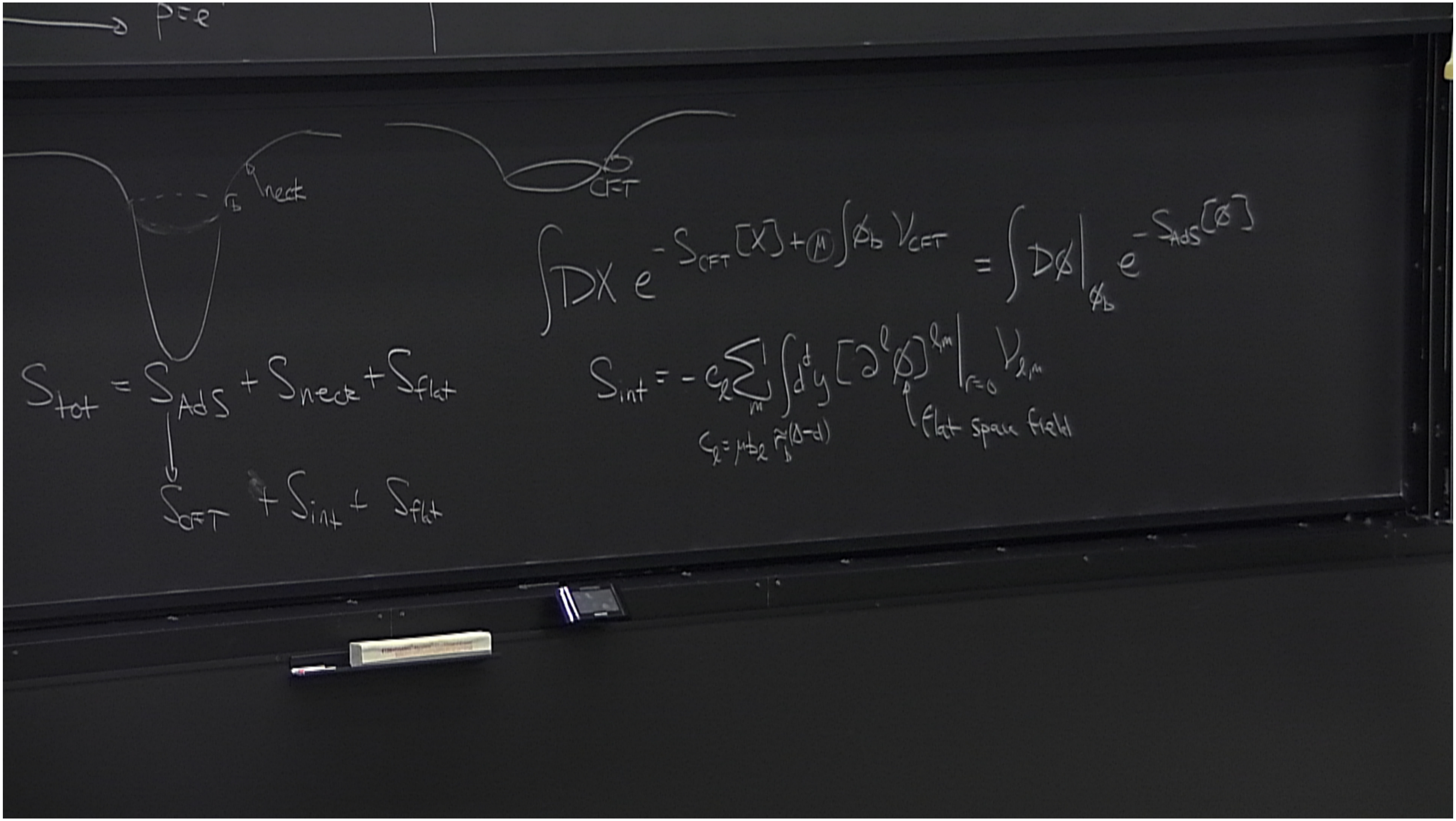

geometries
T^4
gravitons w/ legs on T^4
— minimally coupled scalars
Solve □Ψ = 0
Ψ = e^{i(λy−ωt)} R(r) Y(θ,ψ,φ)
− ω_I > 0
− classical instability
λ = ā − a
ω_R = E = a + ā
ω_I = 2π/(ℓ!²R) [(E²−λ²)/(4R²) g²α'⁴/V n₁n₅]^{ℓ+1} (N+ℓ+1 choose ℓ+1) (N̄+ℓ+1 choose ℓ+1)
a = −1/R [ℓ/2 + (n+½)(m_ψ − m_φ) + N + 1]
ā = −1/R [ℓ/2 + (n̄+½)(m_φ + m_ψ) + N̄ + 1]

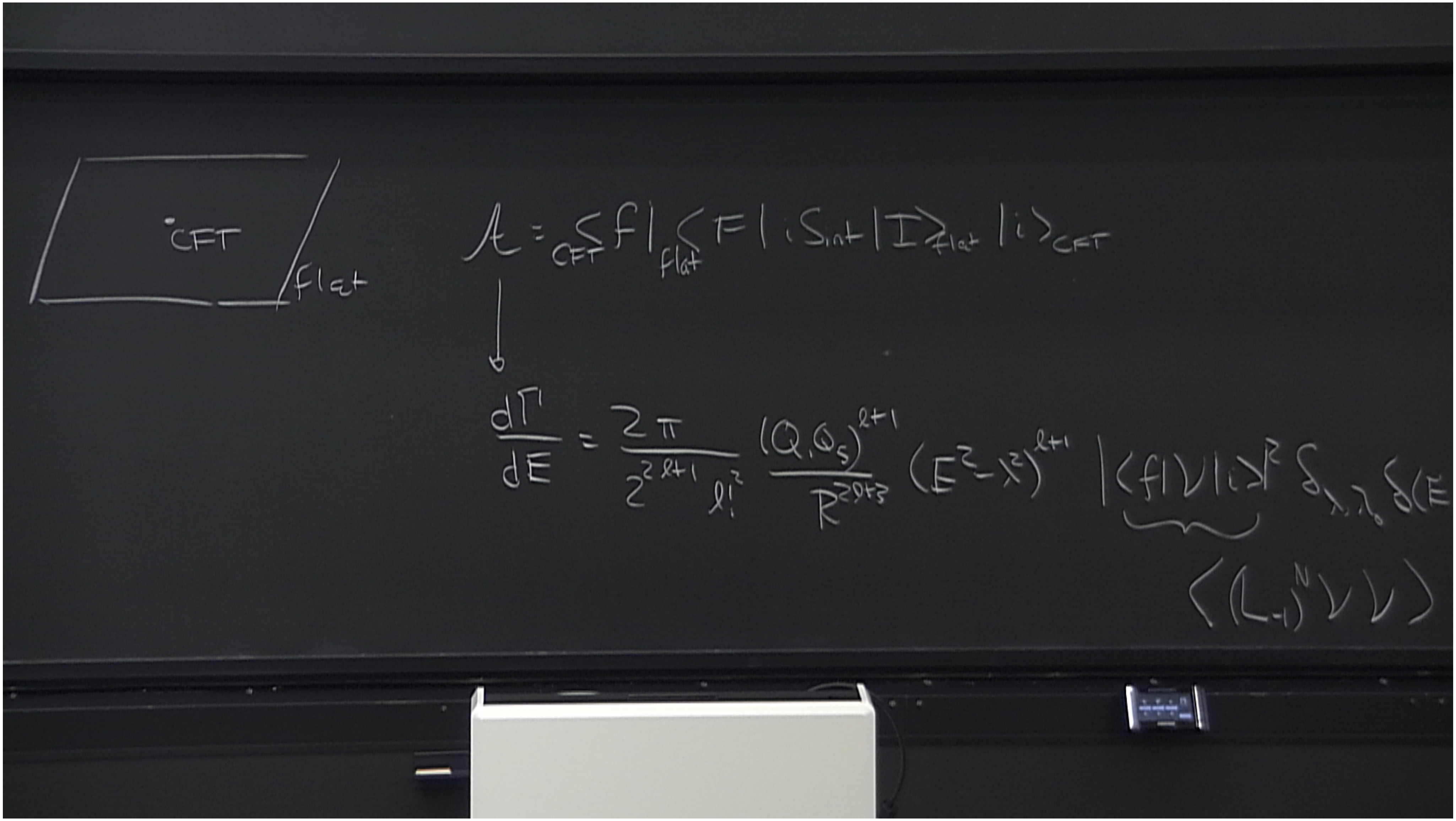


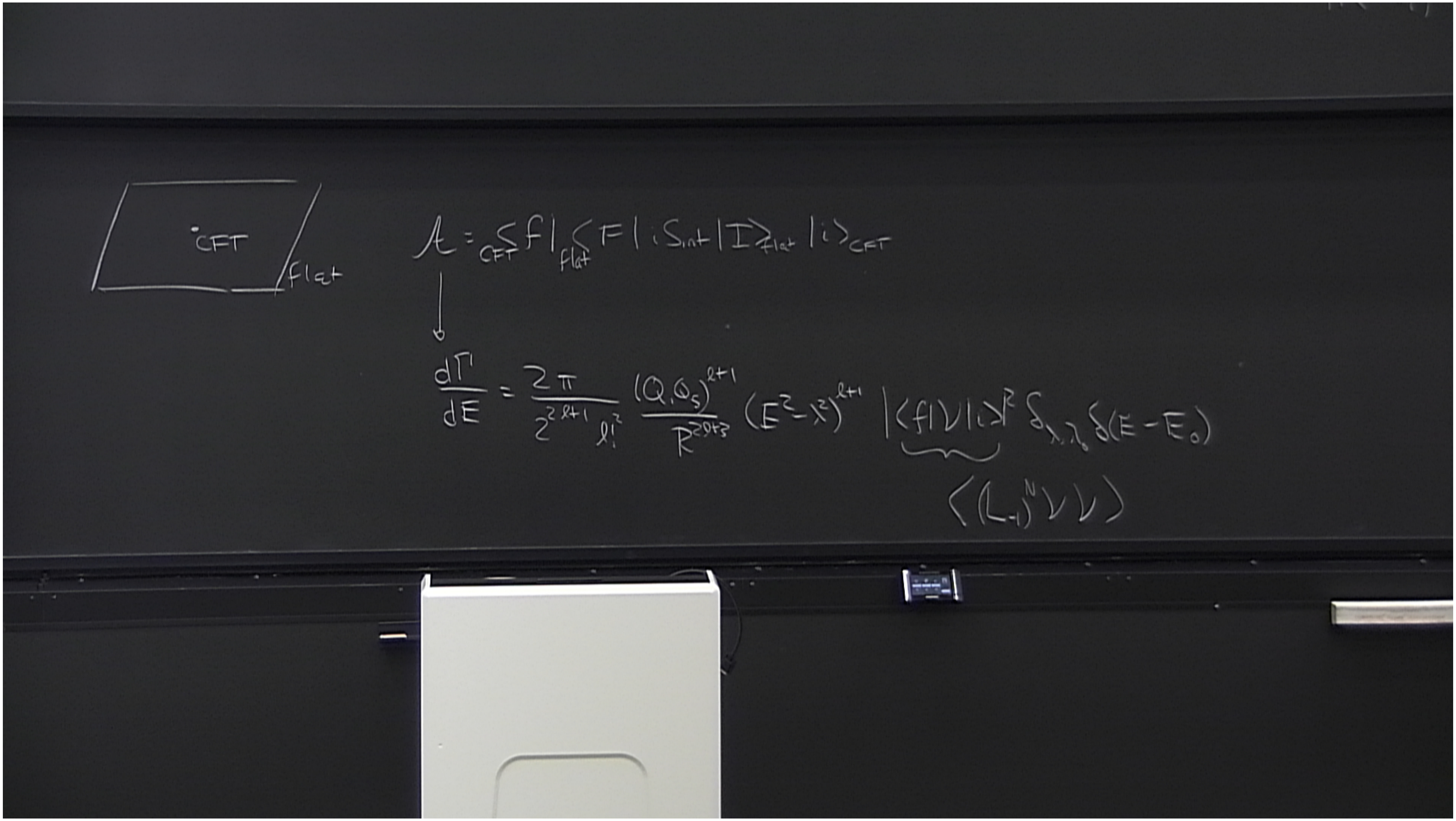


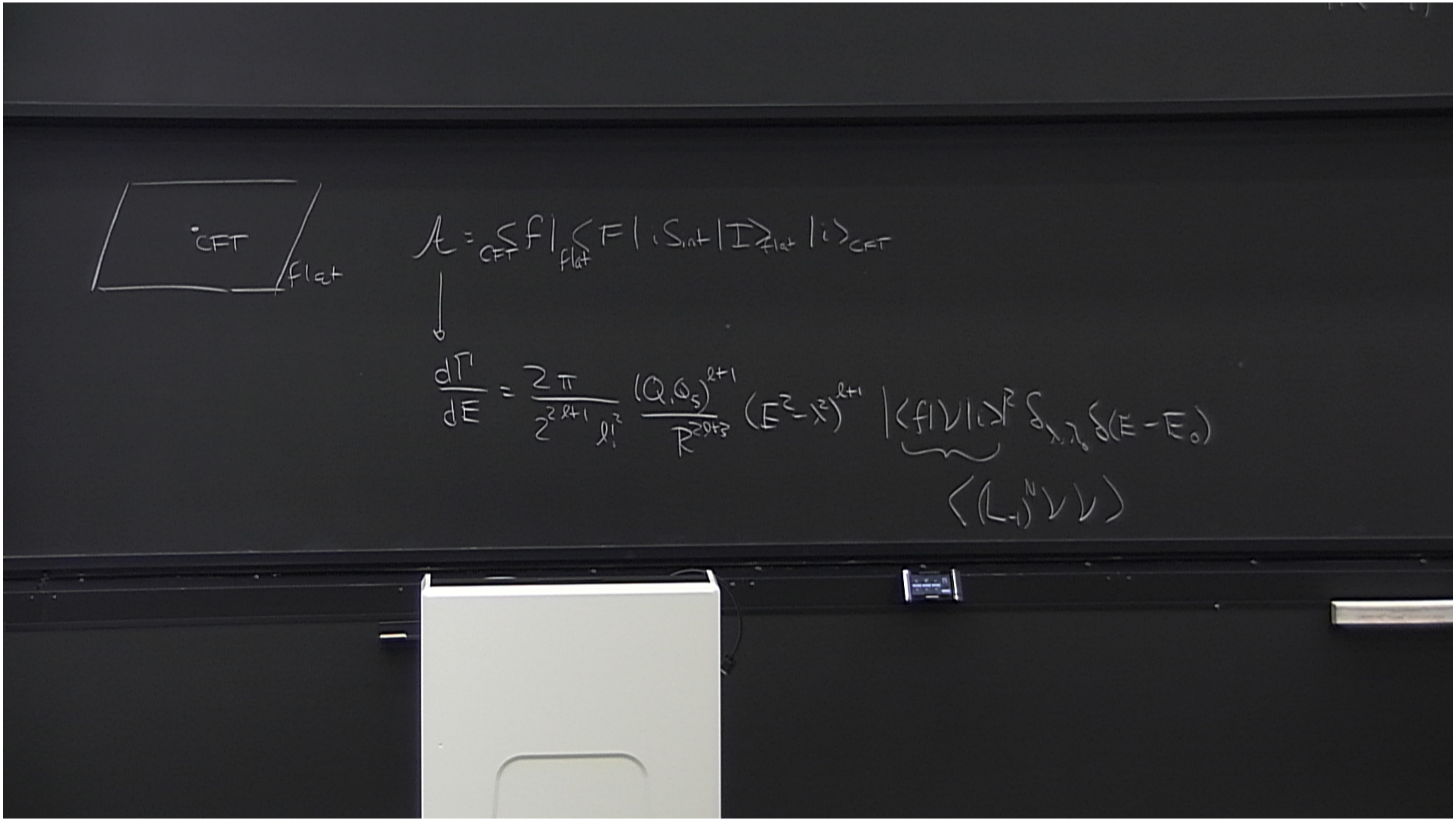

BH solution
neck
CFT
S_AdS + S_neck + S_flat

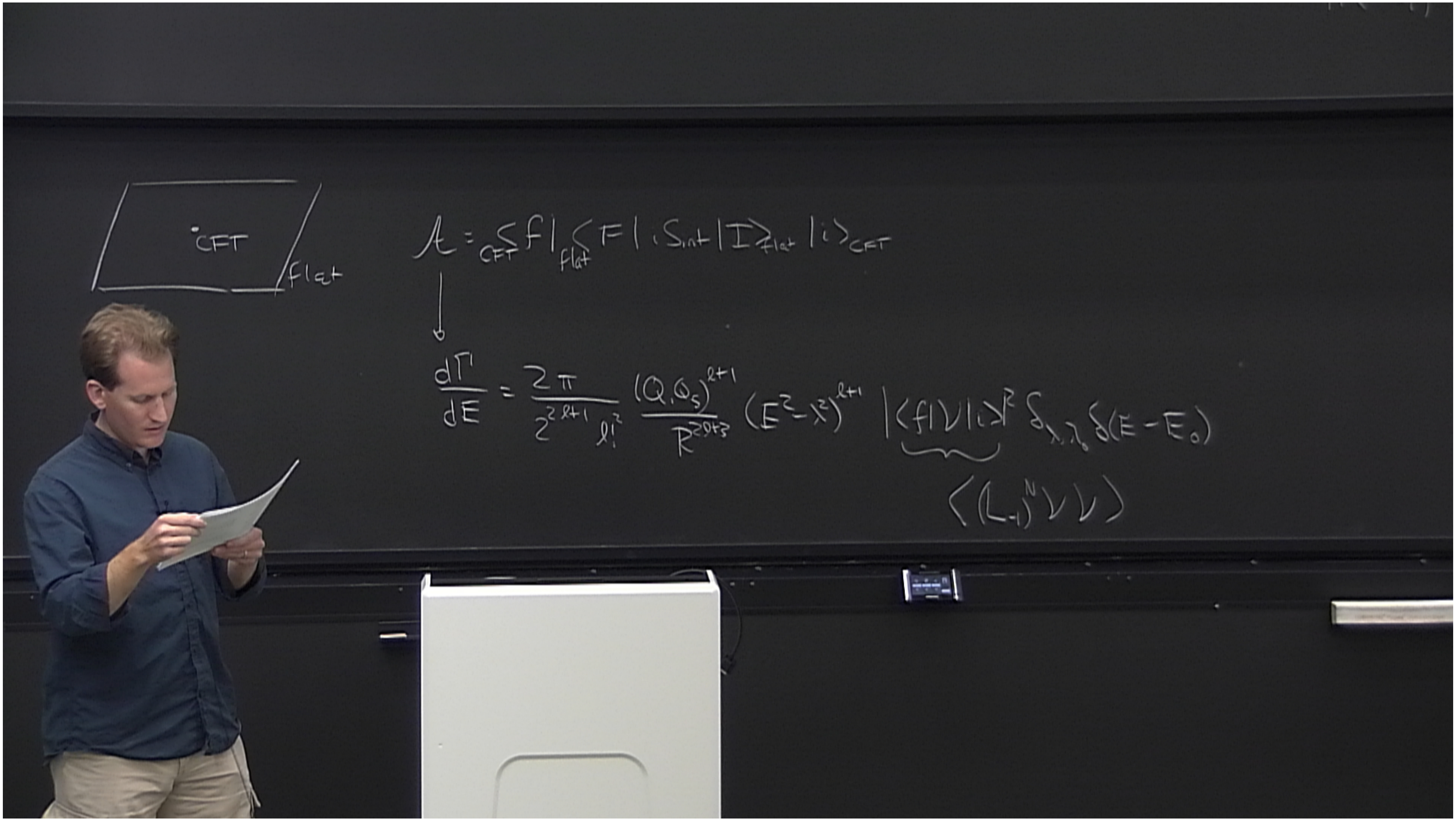

neck
CFT
$S_{CFT}[X] + \mu \int \phi_b V_{CFT} = \int D\phi \big|_{\phi_b} e^{-S_{AdS}[\phi]}$
$S_{tot} = S_{AdS} + S_{neck} + S_{flat}$
$S_{CFT} + S_{int} + S_{flat}$

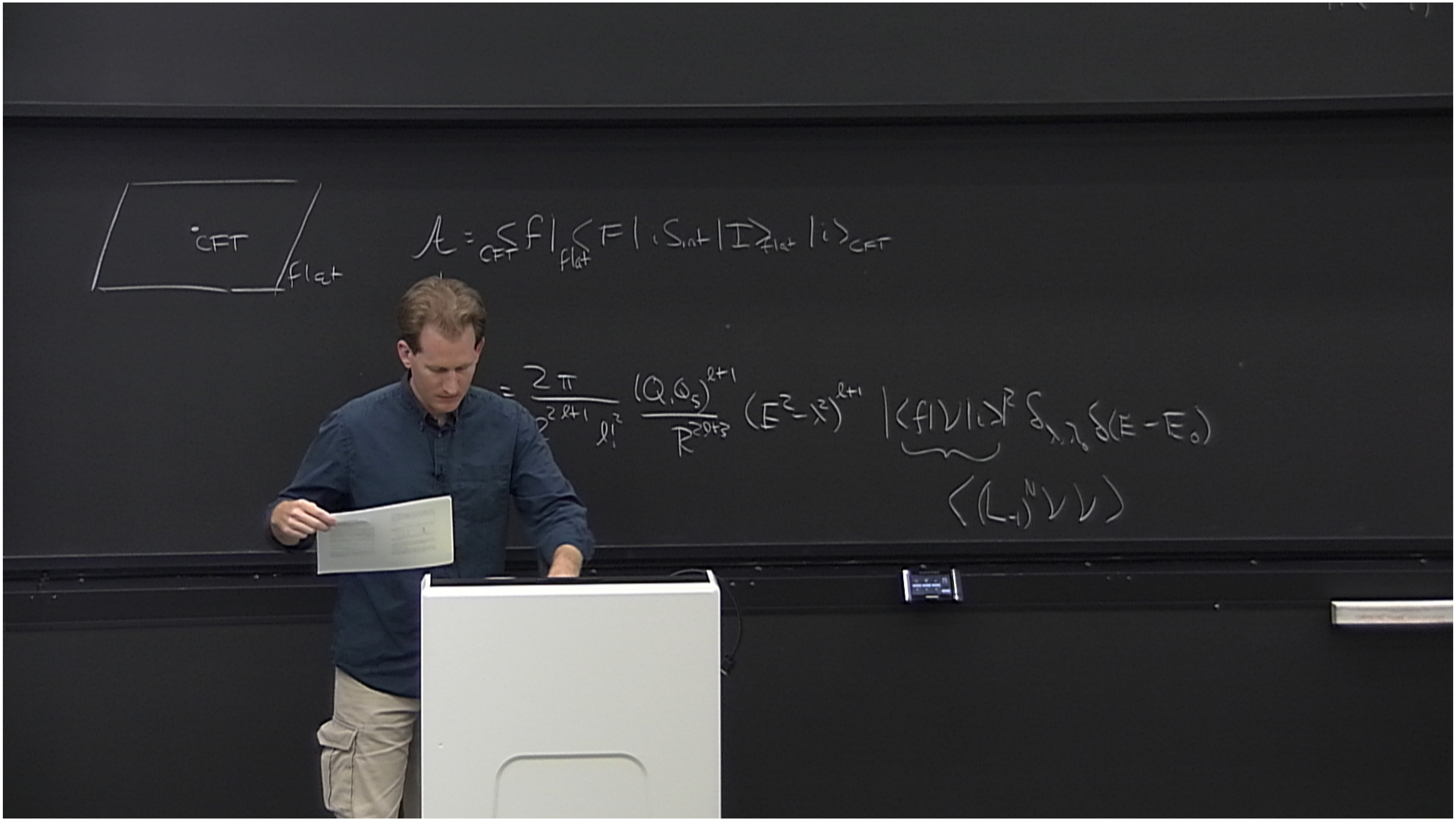

neck
CFT
$\int DX\, e^{-S_{CFT}[X] + \mu \int \phi_b V_{CFT}} = \int D\phi \big|_{\phi_b} e^{-S_{AdS}[\phi]}$
$S_{tot} = S_{AdS} + S_{neck} + S_{flat}$
$S_{CFT} + S_{int} + S_{flat}$
$S_{int} = -c_\ell \sum_m \int d^d y\, [\partial^\ell \phi]^{\ell m} \big|_{r=0} V_{\ell, m}$
flat space field


CFT
flat
$\mathcal{A} = {}_{CFT}\langle f|\, {}_{flat}\langle F|\, iS_{int}\, |I\rangle_{flat}\, |i\rangle_{CFT}$
$\frac{d\Gamma}{dE} = \frac{2\pi}{2^{2\ell+1}\,\ell!^2}\,\frac{(Q_1 Q_s)^{\ell+1}}{R^{2\ell+3}}\,(E^2-\lambda^2)^{\ell+1}\,|\langle f|\mathcal{V}|i\rangle|^2\,\delta_{\lambda,\lambda_0}\,\delta(E$
$\langle (L_{-1})^N \mathcal{V} \mathcal{V} \rangle$

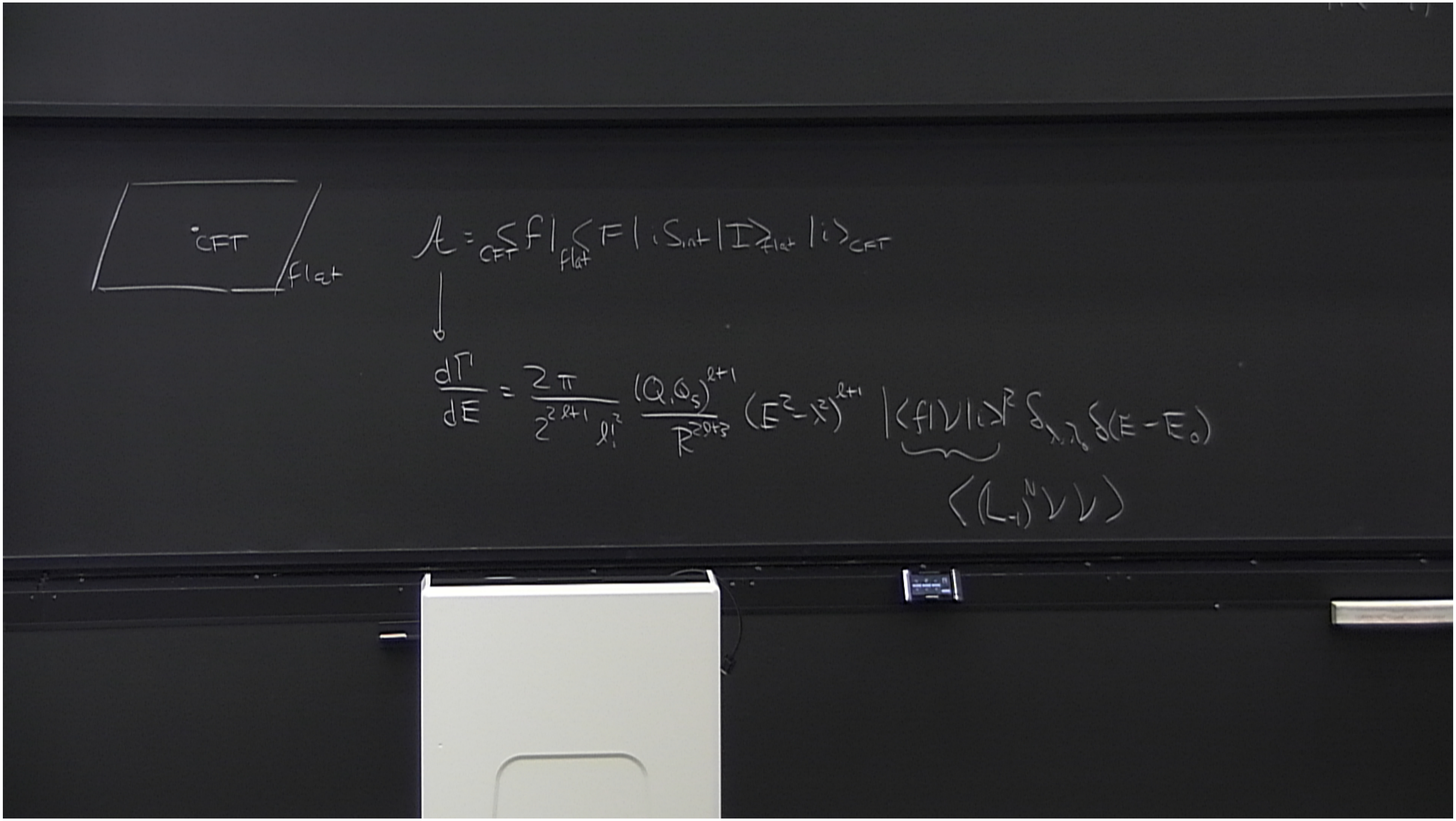

CFT
flat
A = CFT⟨f| flat⟨F| i S_int |I⟩flat |i⟩CFT
dΓ/dE = 2π/(2^(2ℓ+1) ℓ!²) (Q Q_s)^(ℓ+1)/R^(2ℓ+3) (E² − λ²)^(ℓ+1) |⟨f|V|i⟩|² δ_(λ,λ0) δ(E − E0)
⟨(L_-1)^N V V⟩

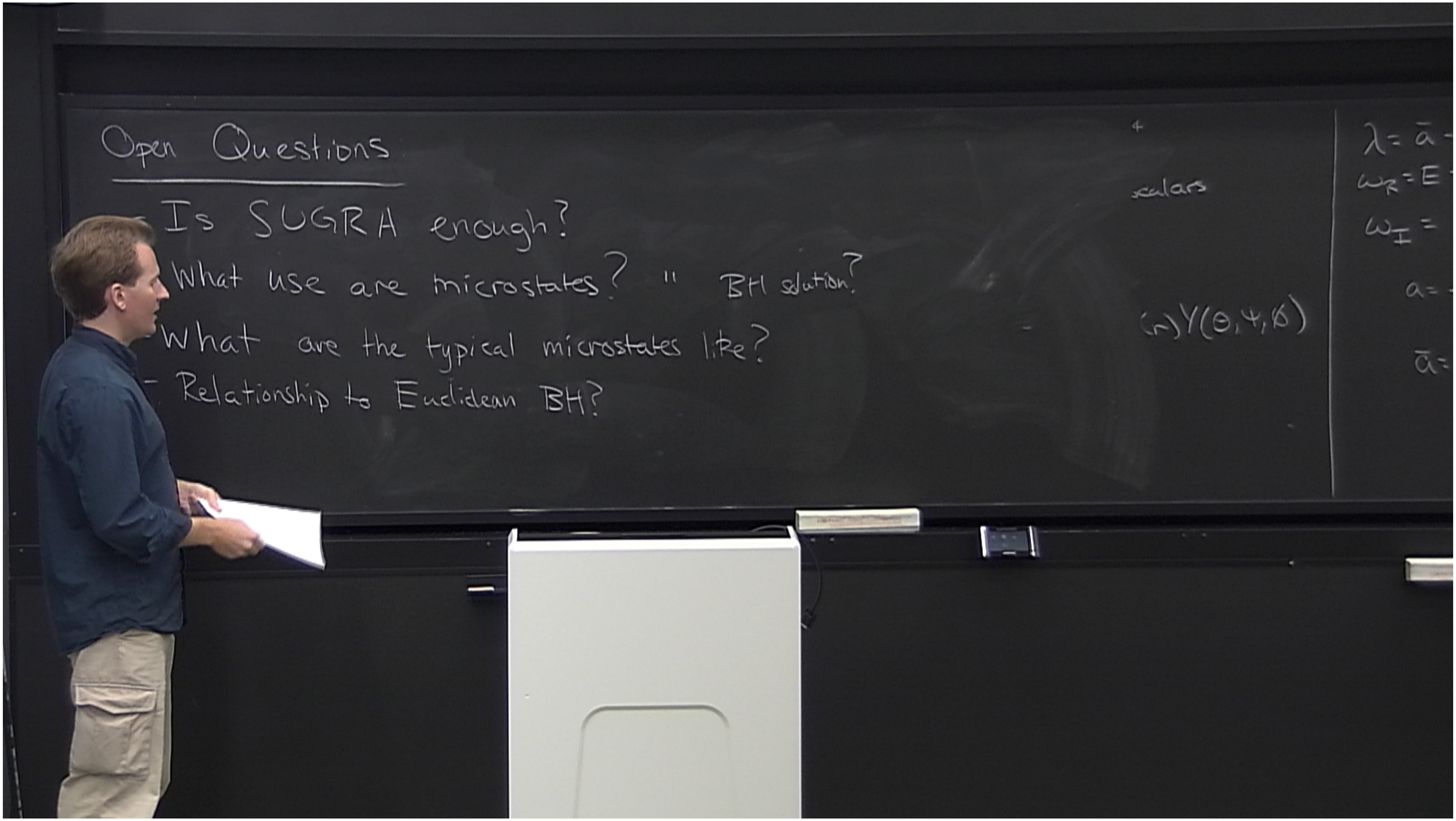

CFT
flat
A = CFT⟨f| flat⟨F| i S_int |I⟩flat |i⟩CFT
dΓ/dE = 2π / (2^{2l+1} l!^2) (Q_1 Q_5)^{l+1} / R^{2l+3} (E^2 − λ^2)^{l+1} |⟨f|V|i⟩|^2 δ_{λ,λ_0} δ(E − E_0)
⟨(L_{-1})^N V V⟩

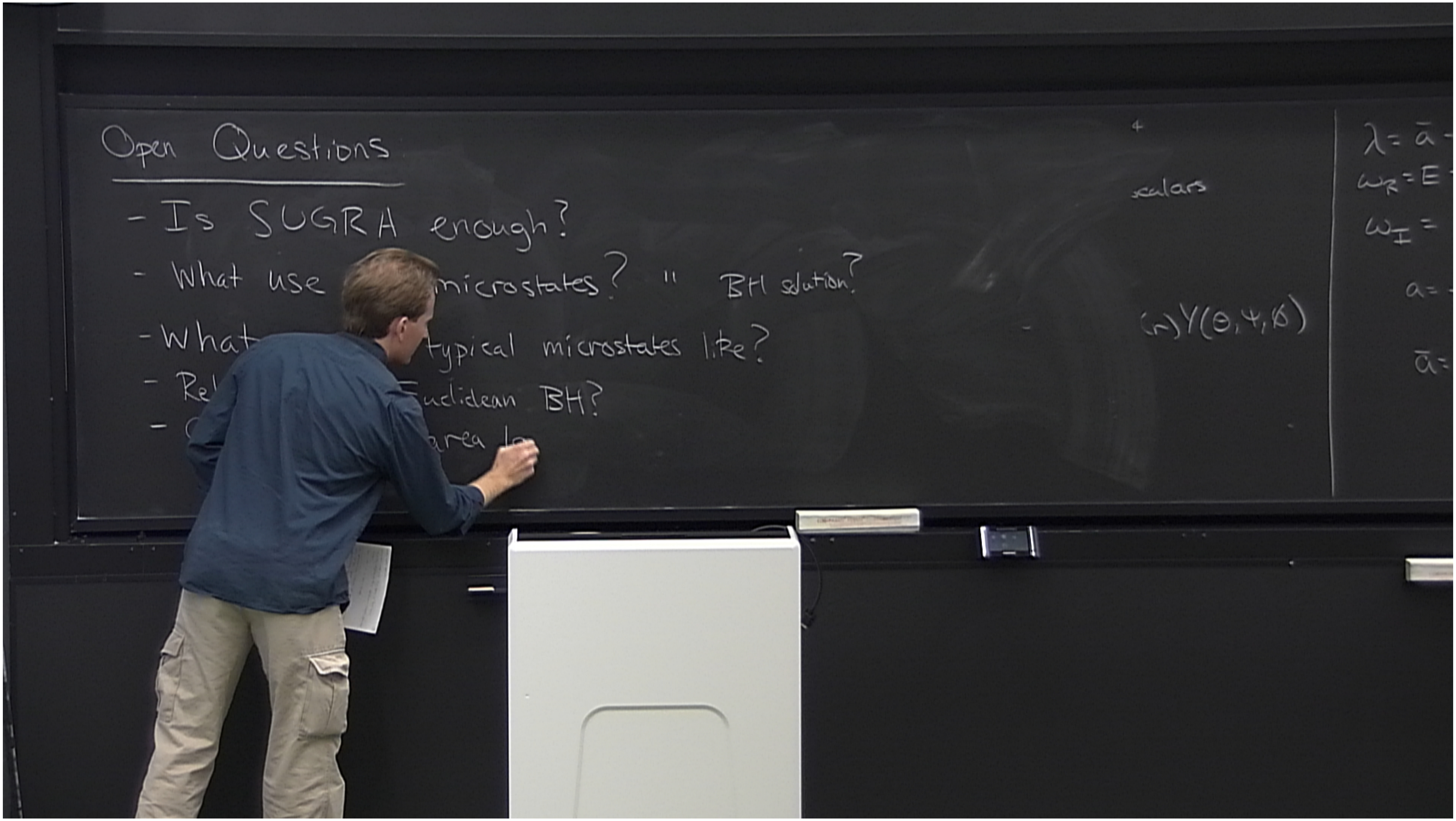

CFT
flat
$A = {}_{CFT}\langle f|\,{}_{flat}\langle F|\, i S_{int}\, |I\rangle_{flat}\, |i\rangle_{CFT}$
$\frac{d\Gamma}{dE} = \frac{2\pi}{2^{2\ell+1}\,\ell!^2}\,\frac{(Q_1 Q_S)^{\ell+1}}{R^{2\ell+3}}\,(E^2-\lambda^2)^{\ell+1}\,|\langle f|V|i\rangle|^2\,\delta_{\lambda,\lambda_0}\,\delta(E-E_0)$
$\langle (L_{-1})^N V\, V\rangle$



CFT
flat


CFT
flat
$A = {}_{CFT}\langle f| {}_{flat}\langle F| i S_{int} |I\rangle_{flat} |i\rangle_{CFT}$
$\frac{d\Gamma}{dE} = \frac{2\pi}{2^{2l+1} l!^2} \frac{(Q_1 Q_s)^{l+1}}{R^{2l+3}} (E^2 - \lambda^2)^{l+1} |\langle f|V|i\rangle|^2 \delta_{\lambda,\lambda_0} \delta(E - E_0)$
$\langle (L_{-1})^N V V \rangle$


Open Questions
Is SUGRA enough?
What use are microstates? " BH solution?
What are the typical microstates like?
Relationship to Euclidean BH?
scalars


Open Questions
- Is SUGRA enough?
- What use microstates? " BH solution?
- What typical microstates like?
- Euclidean BH?
- area
scalars
$\lambda = \bar{a}$
$\omega_R = E$
$\omega_I =$
$a =$
$\bar{a} =$