Title: Schwinger-Keldysh effective field theory

Date: Mar 21, 2017 02:30 PM

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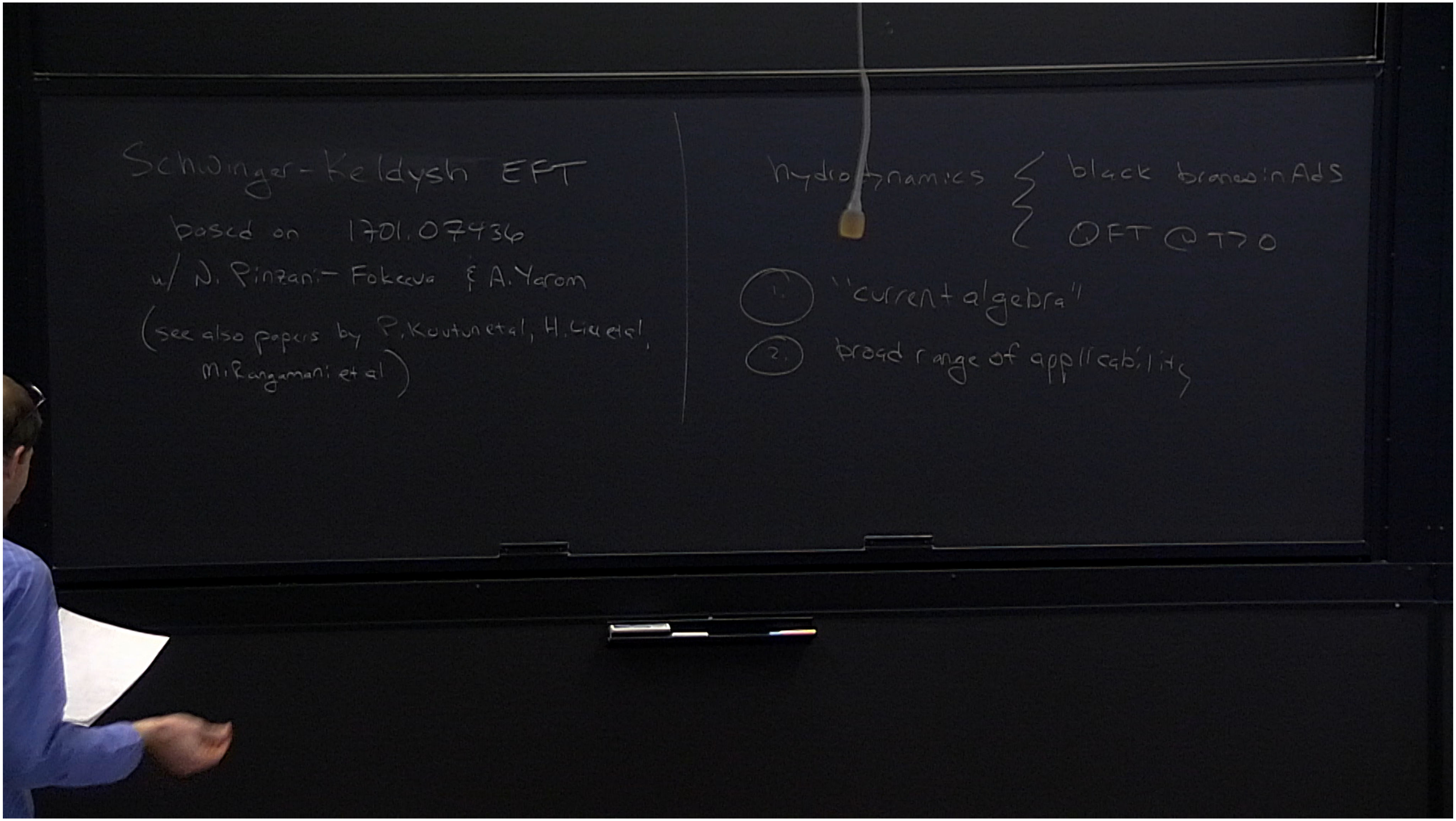
Abstract: <p>The subject of quantum field theory in mixed states of quantum matter is an old and rich one. The natural setting to discuss field theory in a mixed state is the Schwinger-Keldysh formalism. The subject of this talk is the set of peculiar symmetries that arise in Schwinger-Keldysh theories, and how they may be accounted for in effective field theory. In particular, when the mixed state is thermal, the effective description is constrained by two BRST-like supercharges which, at low energies, generate an algebra akin to minimal supersymmetric quantum mechanics. If time allows, I will also discuss a sort of Schwinger-Keldysh bootstrap for effective actions on more complicated closed-time-contours, which describe the out-of-time-ordered correlation functions that diagnose early-time chaotic growth in quantum systems.</p>

Schwinger-Keldysh EFT

based on 1701.07436

w/ N. Pinzani-Fokeeva & A. Yarom

(see also papers by P. Kovtun et al, H. Liu et al,
M. Rangamani et al)


Schwinger-Keldysh EFT
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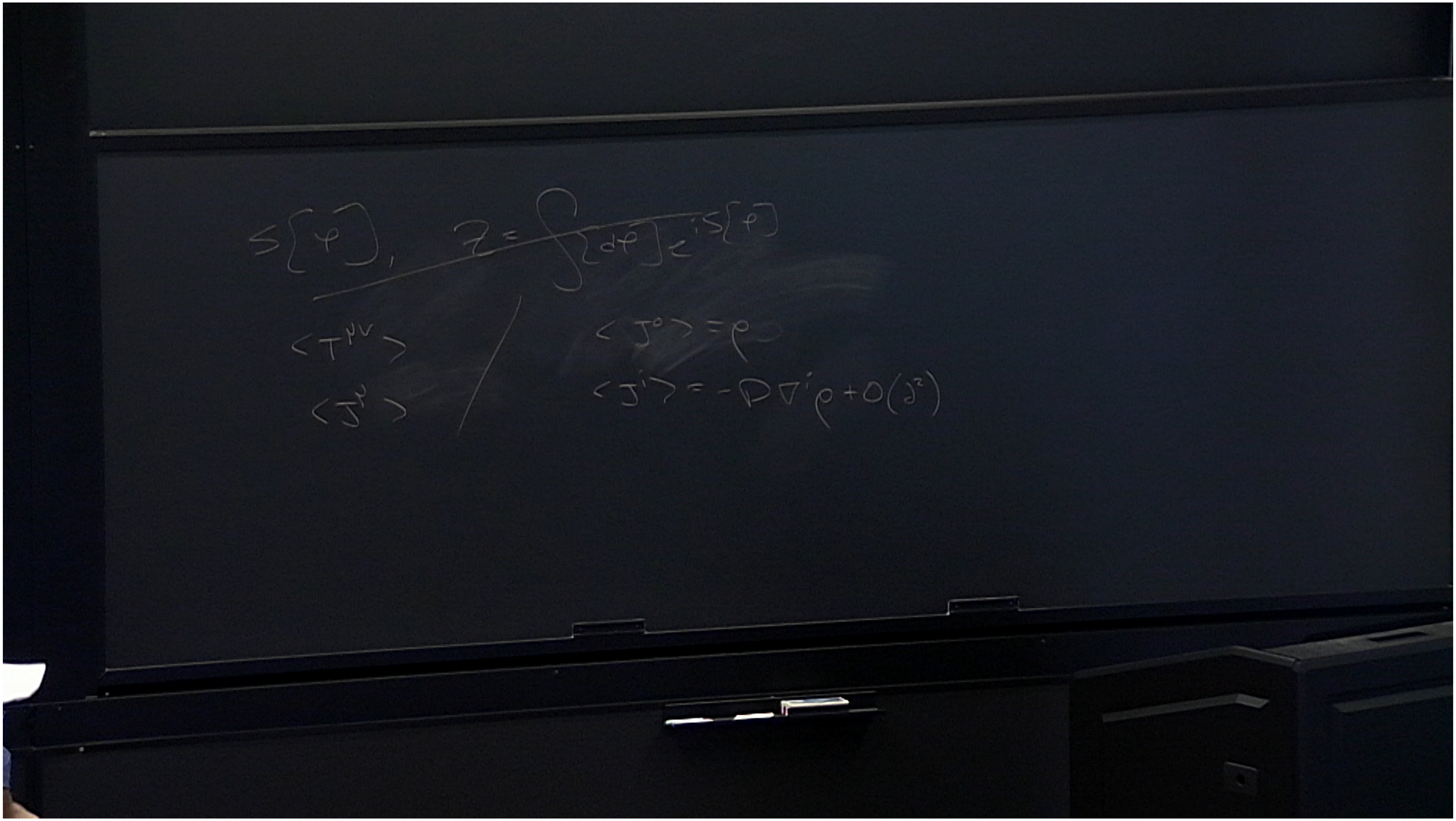
(see also papers by P. Kovtun et al, H. Liu et al, M. Rangamani et al)
hydrodynamics
black branes in AdS
QFT @ T>0
1. "current algebra"
2. broad range of applicability

$S[\varphi]$, $\quad Z = \int [d\varphi]\, e^{iS[\varphi]}$

$\langle T^{\mu\nu} \rangle$

$\langle J^{\mu} \rangle$


$S[\varphi]$, $Z = \int [d\varphi]\, e^{iS[\varphi]}$
$\langle T^{\mu\nu} \rangle$
$\langle J^{\mu} \rangle$
$\langle J^{0} \rangle = \rho$
$\langle J^{i} \rangle = -D\nabla^{i}\rho + O(\partial^{2})$

$S[\varphi]$, $Z = \int [d\varphi]\, e^{iS[\varphi]}$

$\langle T^{\mu\nu} \rangle$

$\langle J^{\mu} \rangle$

$\langle J^0 \rangle = \rho$

$\langle J^i \rangle = -D \nabla^i \rho + O(\partial^2)$

$\partial_\mu \langle J^\mu \rangle = 0$

$S[\varphi]$, $\cancel{Z = \int [d\varphi]\, e^{iS[\varphi]}}$

$\langle T^{\mu\nu} \rangle$

$\langle J^\mu \rangle$

$\langle J^0 \rangle = \rho$

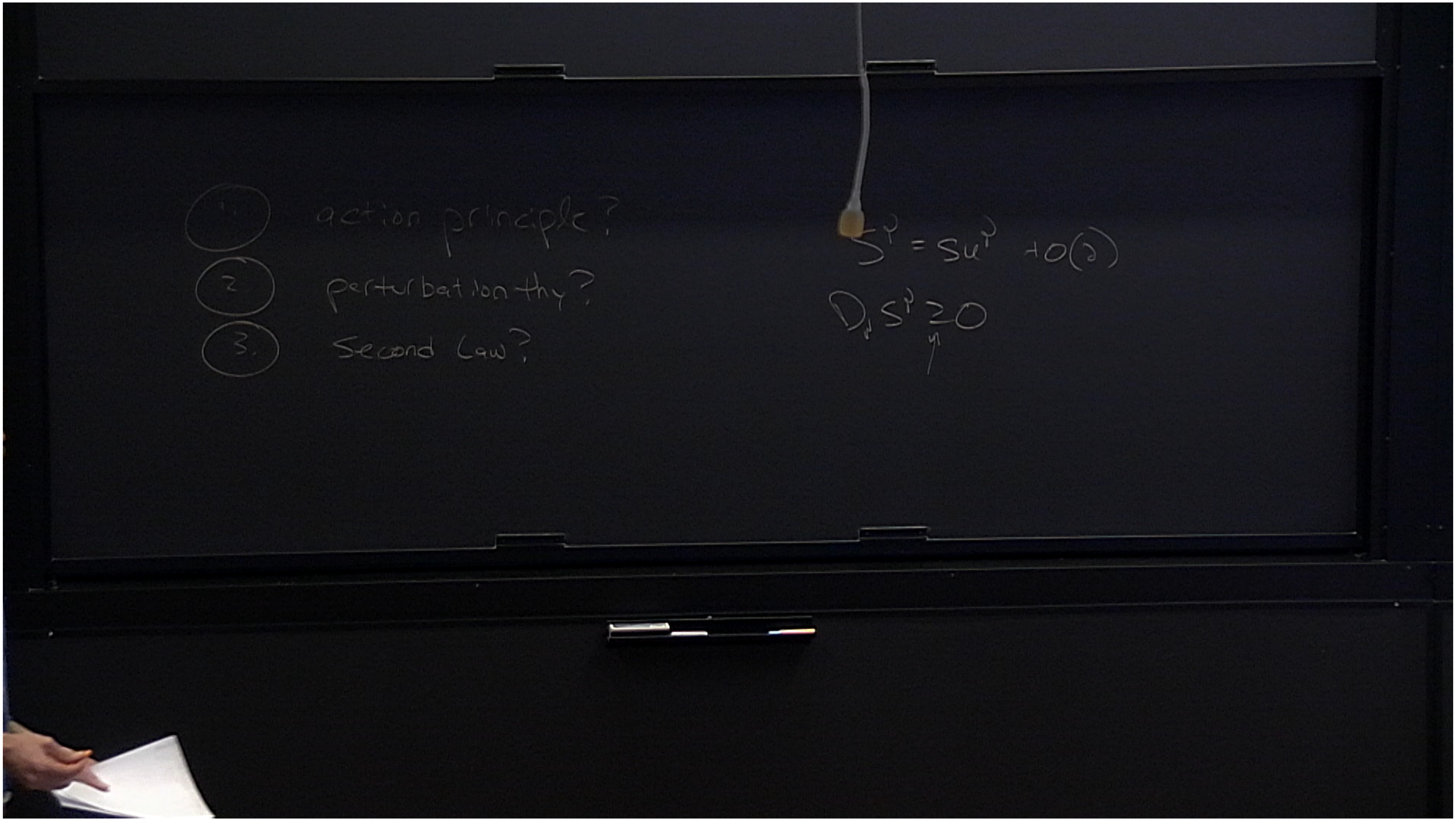
$\langle J^i \rangle = -D \nabla^i \rho + O(\partial^2)$

$\partial_\mu \langle J^\mu \rangle = 0$

slowly varying $(g_{\mu\nu}, A_\mu)$

$\langle J^\mu \rangle [A_\nu]$

$$\left. \frac{\delta \langle J^\mu(x) \rangle}{\delta A_\nu(y)} \right|_{A=0} = \langle J^\mu(x) J^\nu(y) \rangle$$


1. action principle?
2. perturbation thy?
3. Second law?
$S^\nu = s u^\nu + O(\partial)$
$D_\nu S^\nu \geq 0$

QFT in mixed states

1. action principle?

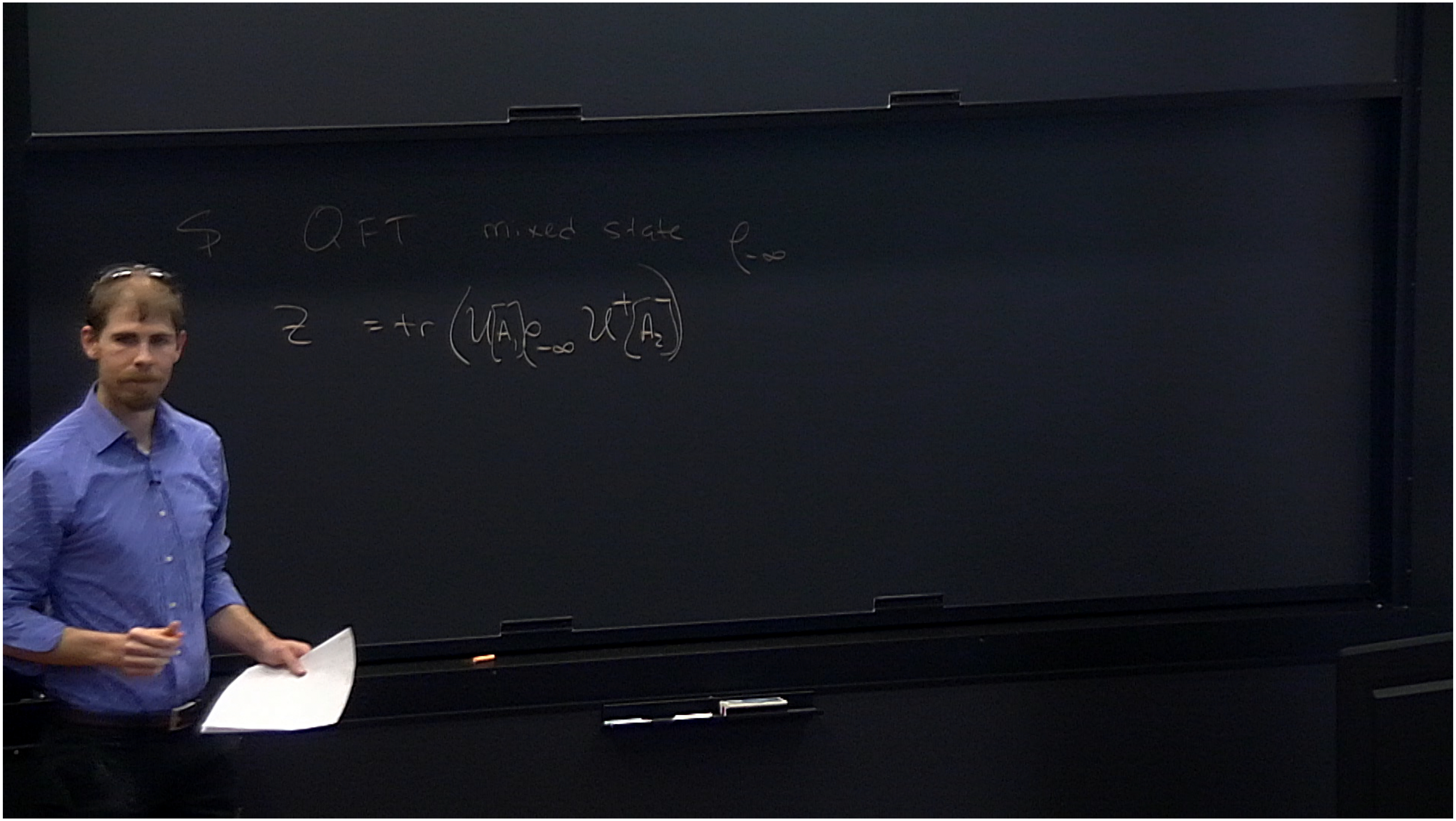
2. perturbation thy?

3. Second Law?

SK

$$S^\mu = s u^\mu + O(\partial)$$

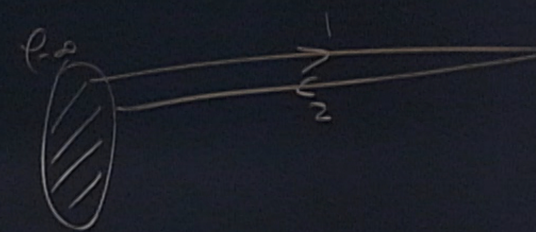
$$D_\mu S^\mu \geq 0$$


§ QFT mixed state ρ₋∞
Z = tr (U[A₁] ρ₋∞ U†[A₂])

§ QFT mixed state $\rho_{-\infty}$

$$Z[A_1, A_2] = \mathrm{tr}\left(\mathcal{U}_1 \rho_{-\infty} \mathcal{U}_2^\dagger\right)$$

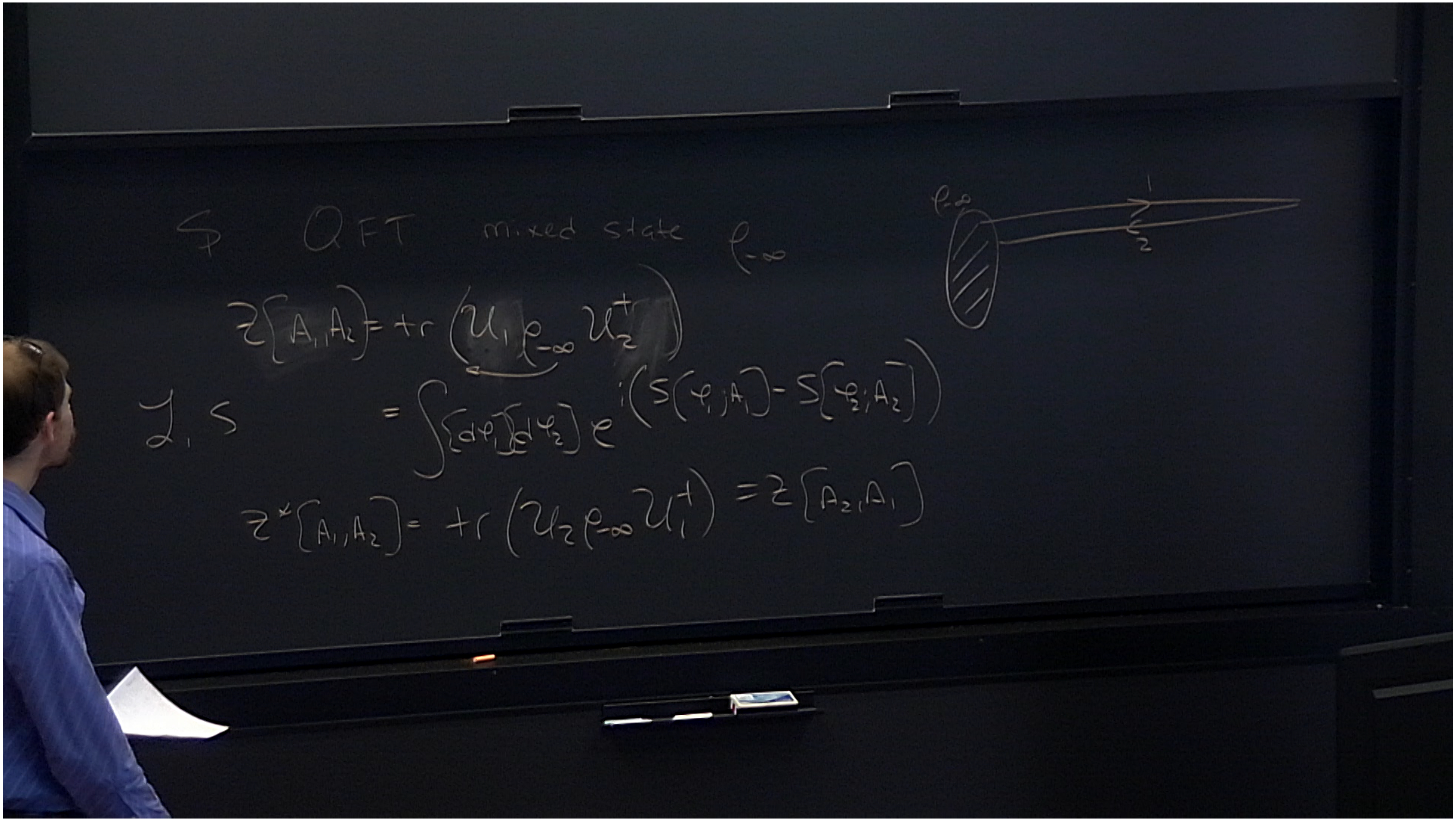
§ QFT mixed state $\rho_{-\infty}$

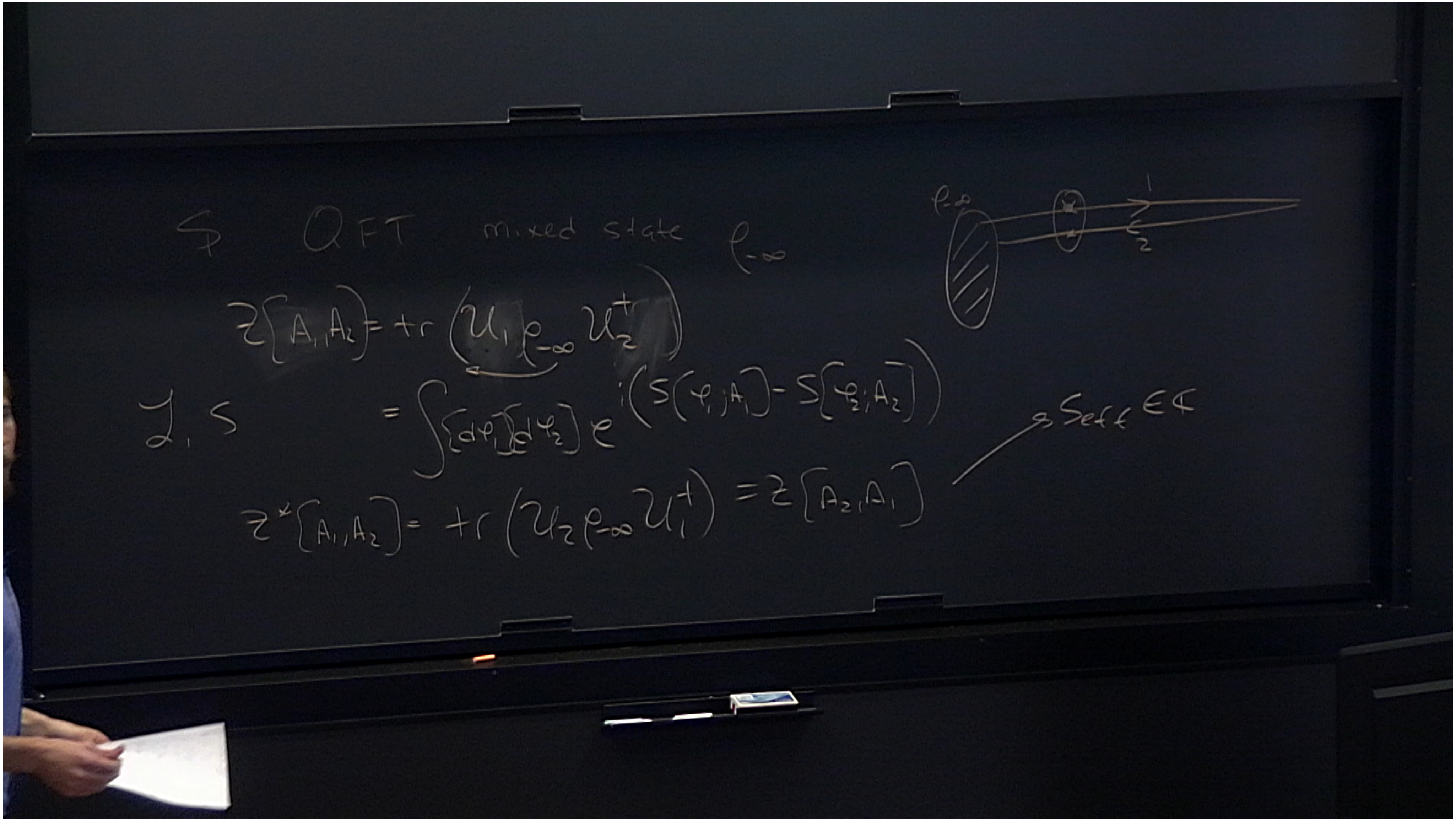


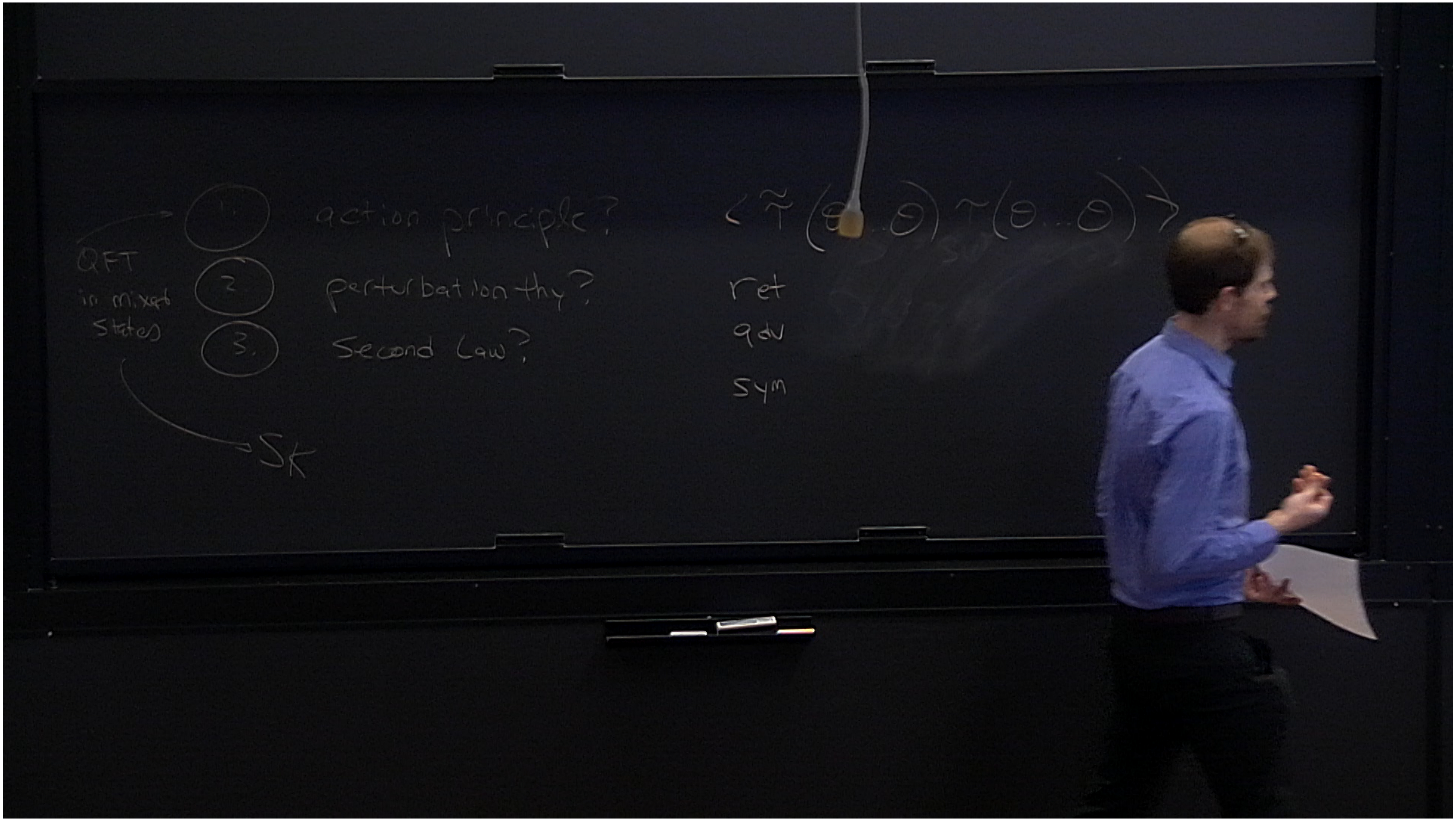
$$Z[A_1, A_2] = \mathrm{tr}\left(\mathcal{U}_1 \rho_{-\infty} \mathcal{U}_2^{\dagger}\right)$$

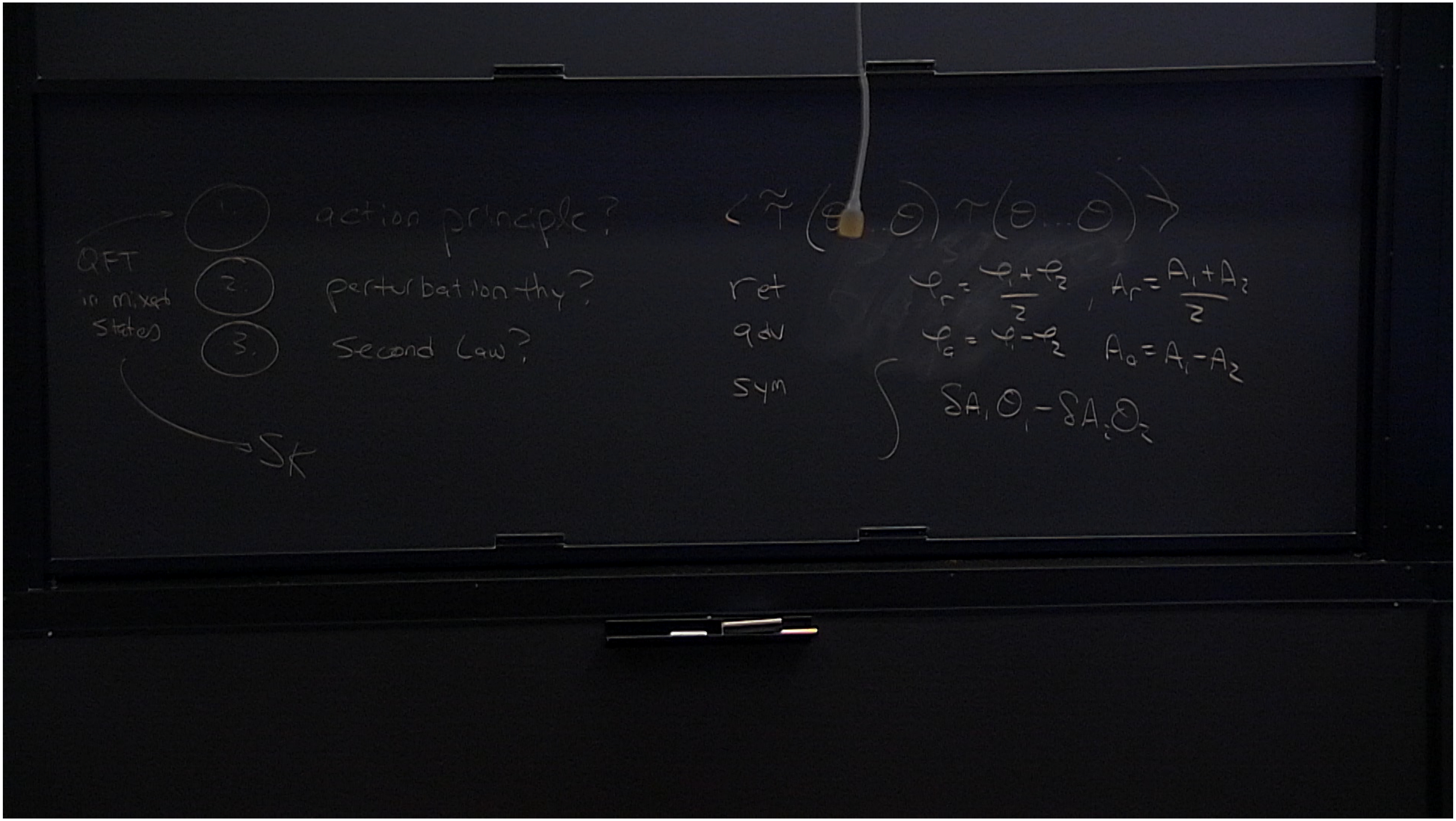
$\mathcal{L}, S$

$$= \int [d\varphi_1][d\varphi_2]\, e^{i\left(S[\varphi_1; A_1] - S[\varphi_2; A_2]\right)}$$

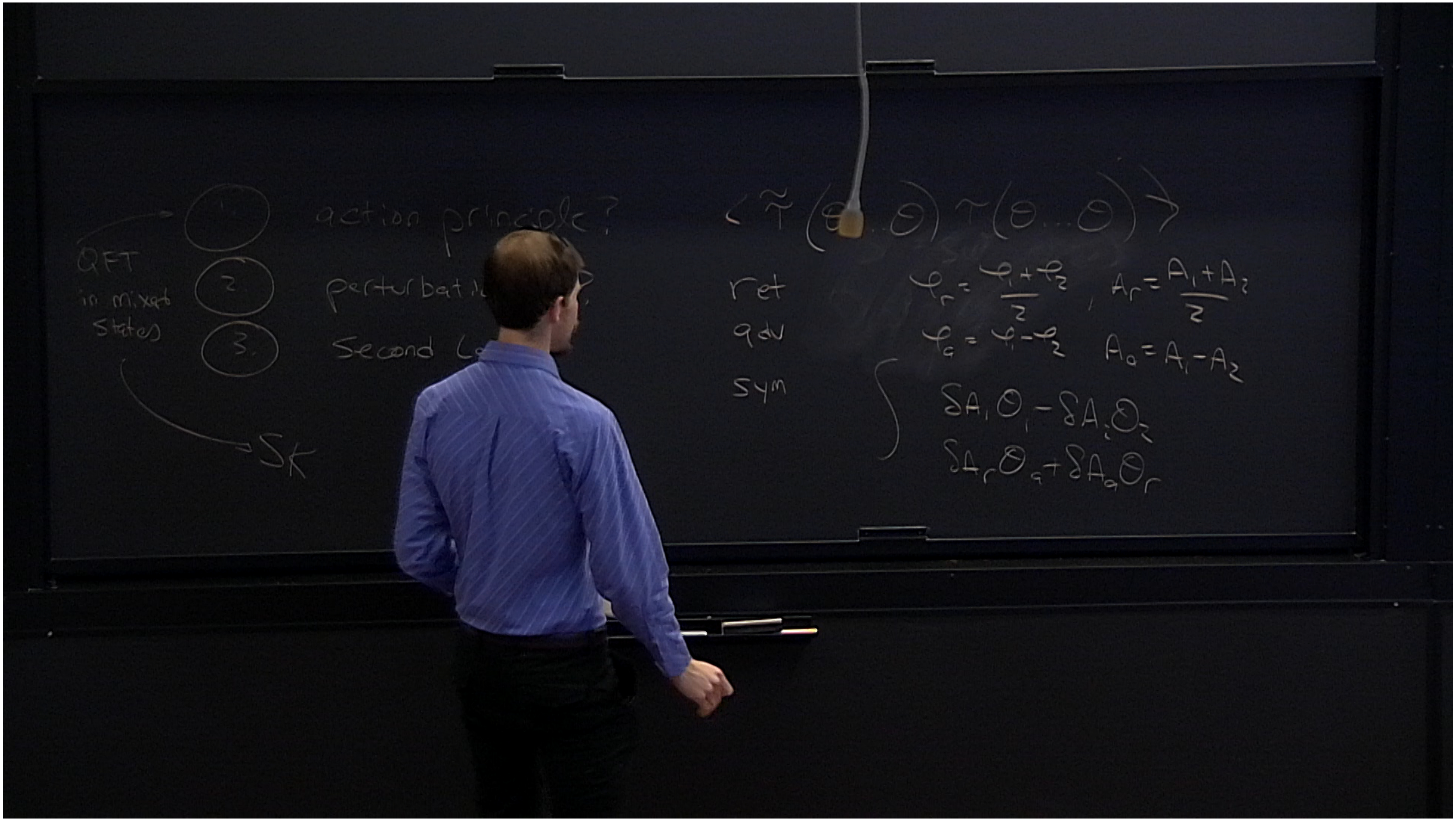

§ QFT mixed state $\rho_{-\infty}$
$Z[A_1, A_2] = \mathrm{tr}\left(\mathcal{U}_1 \rho_{-\infty} \mathcal{U}_2^{\dagger}\right)$
$\mathcal{L}, S$
$= \int [d\varphi_1][d\varphi_2]\, e^{i\left(S[\varphi_1; A_1] - S[\varphi_2; A_2]\right)}$
$Z^*[A_1, A_2] = \mathrm{tr}\left(\mathcal{U}_2 \rho_{-\infty} \mathcal{U}_1^{\dagger}\right) = Z[A_2, A_1]$
$\rho_{-\infty}$
1
2

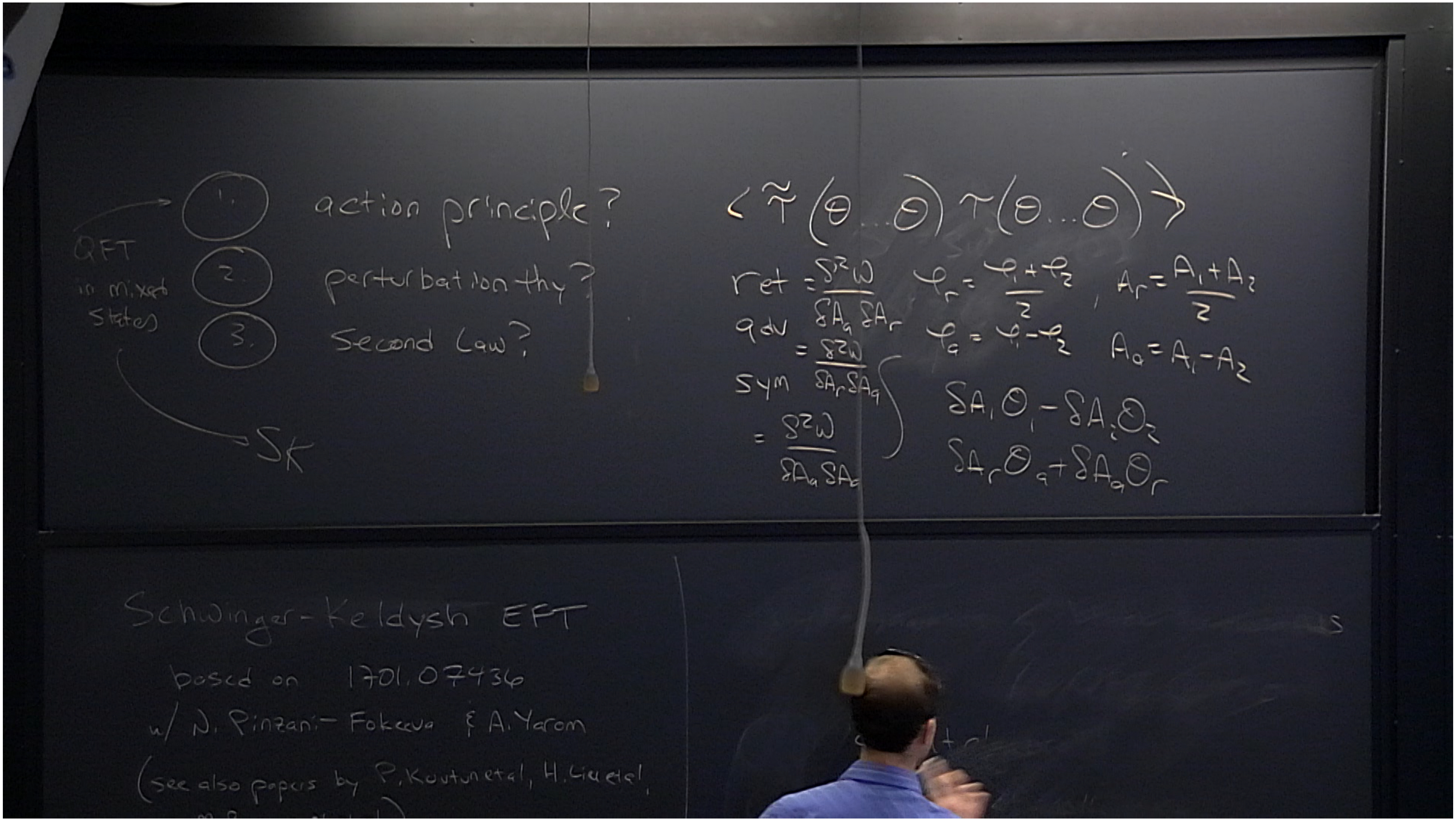

QFT mixed state ρ-∞
Z[A1,A2] = tr(U1 ρ-∞ U2†)
L, S
= ∫[dφ1][dφ2] e^i(S[φ1;A1] - S[φ2;A2])
Z*[A1,A2] = tr(U2 ρ-∞ U1†) = Z[A2,A1]
Seff ∈ ℂ
ρ-∞
1
2


QFT
in mixed
states
1.
action principle?
2
perturbation thy?
3.
Second Law?
SK
ret
adv
sym



QFT
in mixed
states
1. action principle?
2. perturbation thy?
3. Second Law?
SK
$\langle \tilde{T}(O \ldots O)\, T(O \ldots O) \rangle$
ret $\varphi_r = \frac{\varphi_1 + \varphi_2}{2}$, $A_r = \frac{A_1 + A_2}{2}$
adv $\varphi_a = \varphi_1 - \varphi_2$ $A_a = A_1 - A_2$
sym $\int \delta A_1 O_1 - \delta A_2 O_2$


QFT in mixed states
action principle?
perturbati
Second L
SK
ret
adv
sym
$\varphi_r = \frac{\varphi_1+\varphi_2}{2}$, $A_r = \frac{A_1+A_2}{2}$
$\varphi_a = \varphi_1-\varphi_2$ $A_a = A_1 - A_2$
$\delta A_1 O_1 - \delta A_2 O_2$
$\delta A_r O_a + \delta A_a O_r$


1. action principle?
2. perturbation thy?
3. Second Law?
QFT in mixed states
SK
$\langle \tilde{T}(\mathcal{O} \dots \mathcal{O})\, T(\mathcal{O} \dots \mathcal{O}) \rangle$
ret $= \frac{\delta^2 W}{\delta A_a \delta A_r}$
adv $= \frac{\delta^2 W}{\delta A_r \delta A_a}$
sym $= \frac{\delta^2 W}{\delta A_a \delta A_a}$
$\varphi_r = \frac{\varphi_1 + \varphi_2}{2}$, $A_r = \frac{A_1 + A_2}{2}$
$\varphi_a = \varphi_1 - \varphi_2$ $A_a = A_1 - A_2$
$\delta A_1 \mathcal{O}_1 - \delta A_2 \mathcal{O}_2$
$\delta A_r \mathcal{O}_a + \delta A_a \mathcal{O}_r$
Schwinger-Keldysh EFT
based on 1701.07436
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$\delta A_a \, \delta A_a \qquad \partial A_r O_a + \partial A_a O_r$

Schwinger-Keldysh EFT

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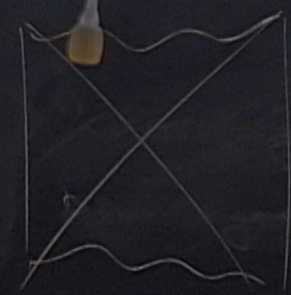
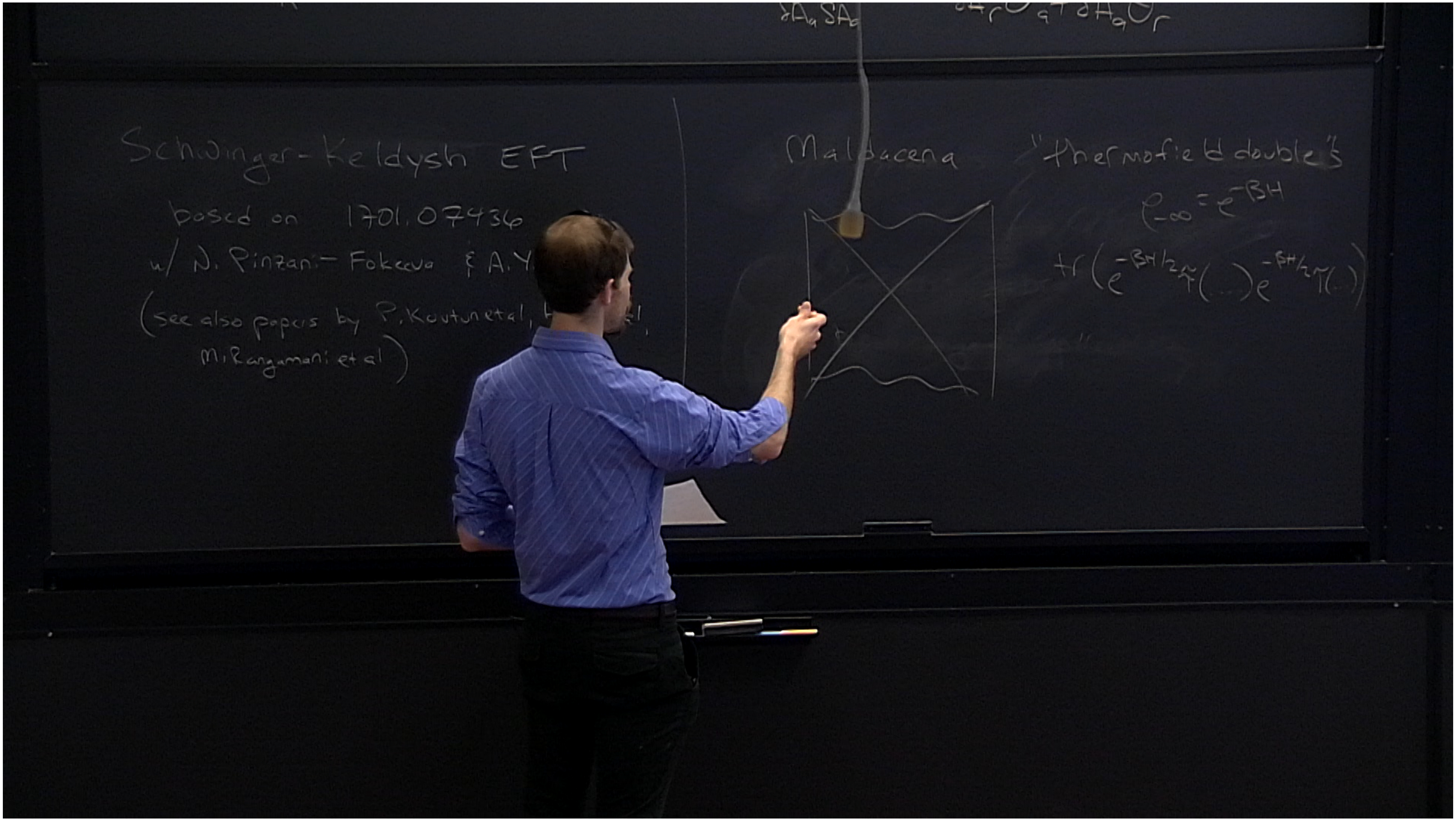
(see also papers by P. Kovtun et al, H. Liu et al, M. Rangamani et al)

Maldacena "thermofield double"s



$\rho_{-\infty} = e^{-\beta H}$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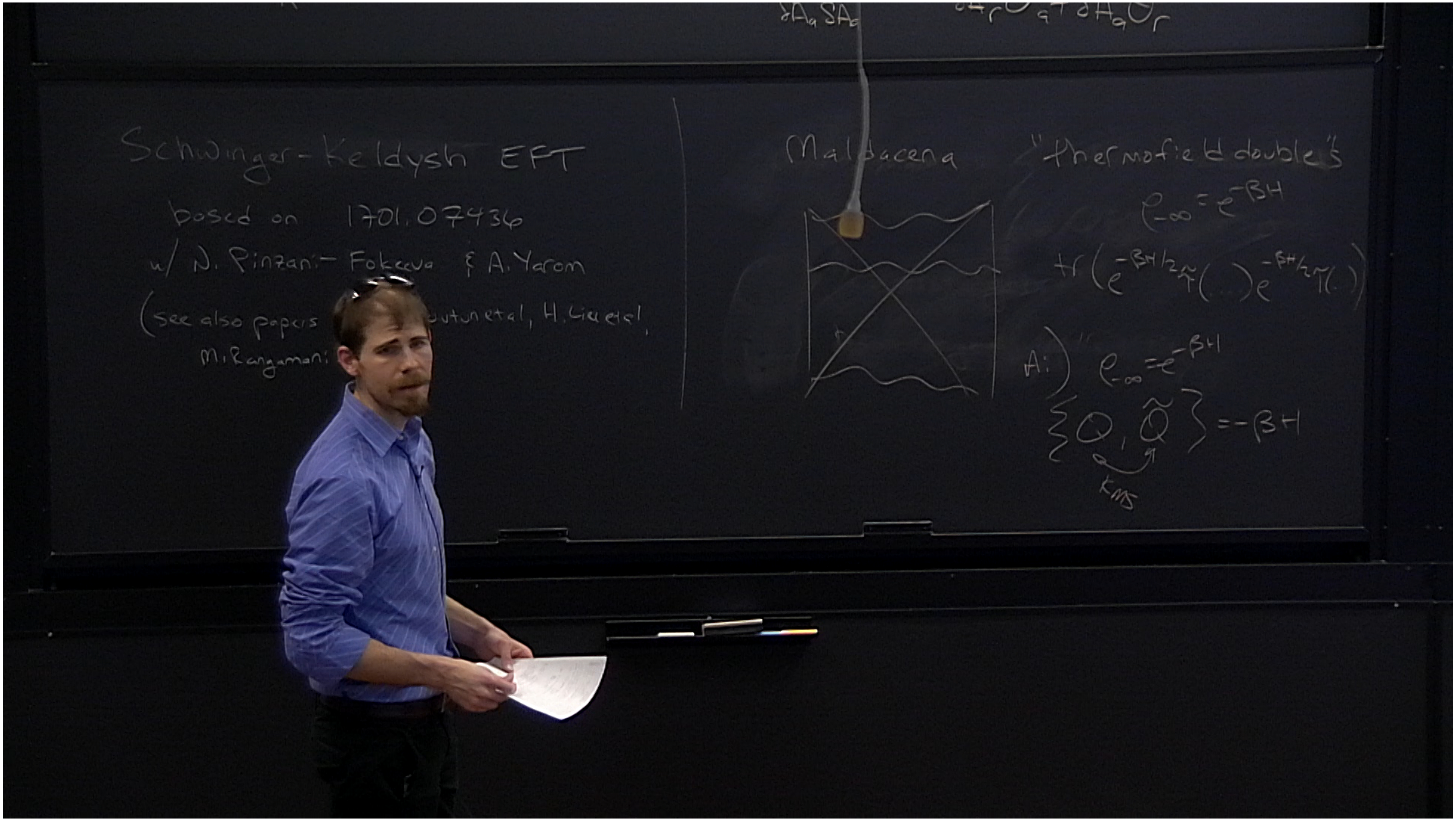
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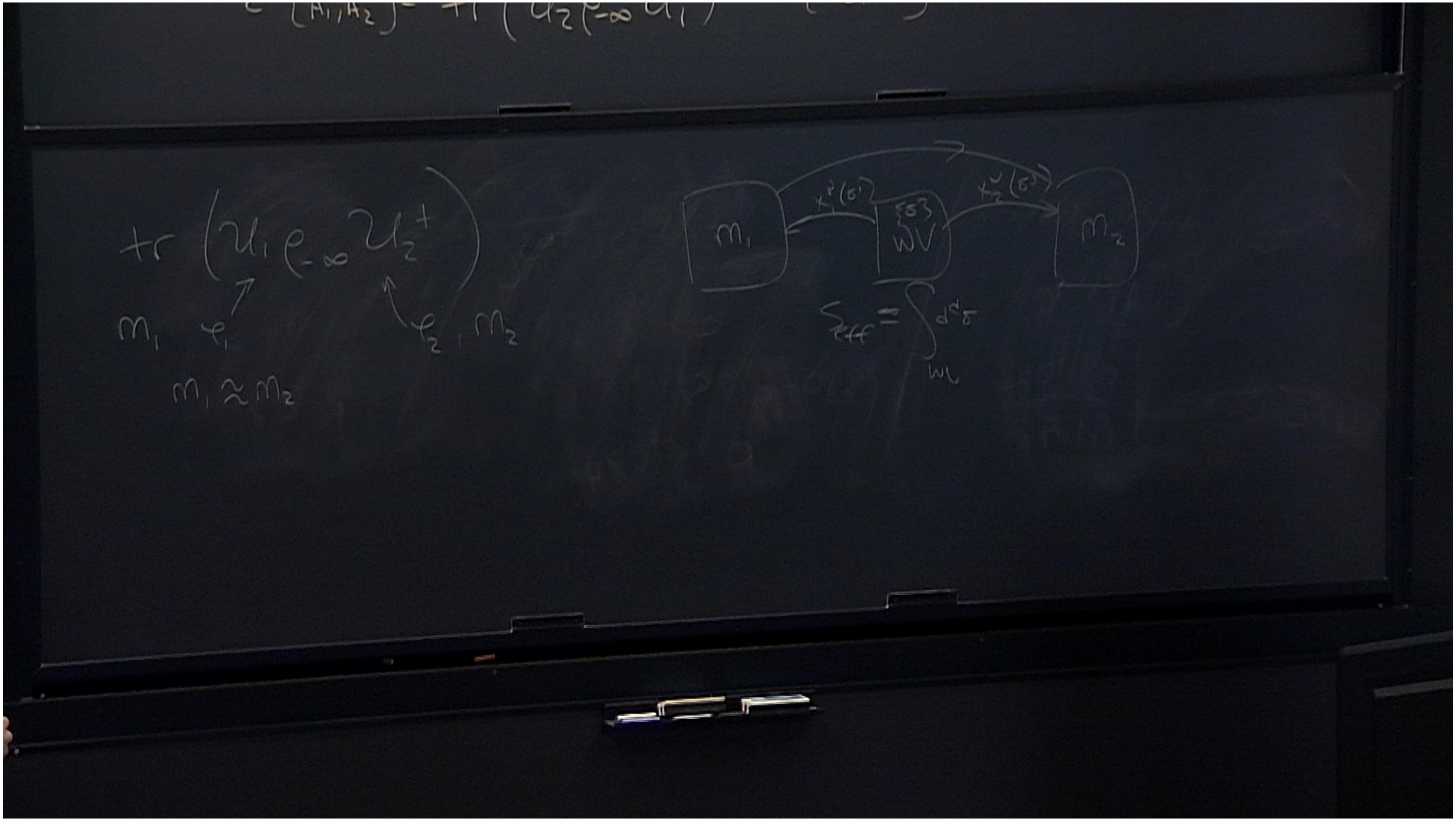
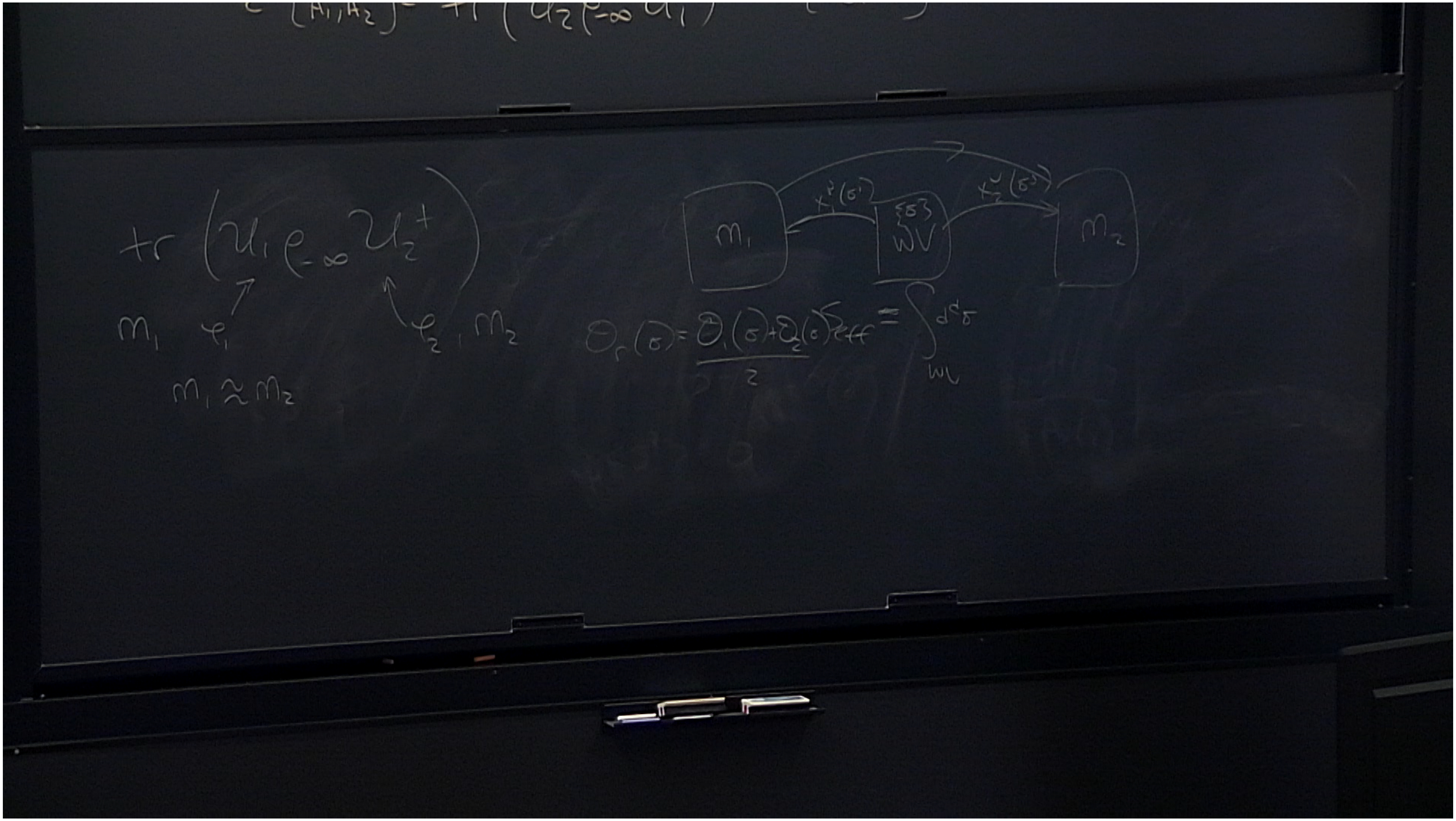
(see also papers
M. Rangamani
Maldacena
"thermofield doubles"
KMS

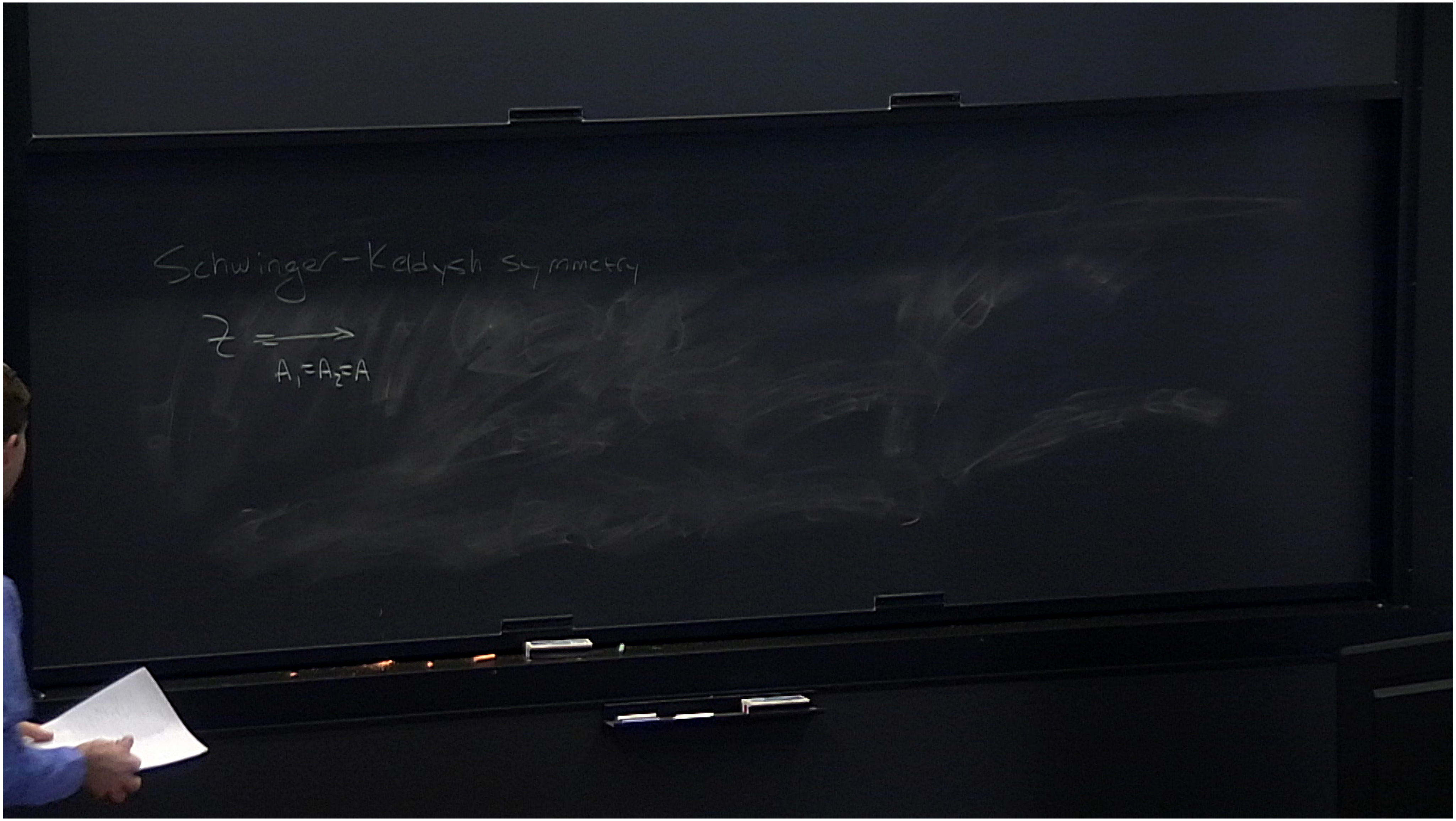
$$(A_1, A_2) = \mathrm{tr}\,(U_2\, \rho_{-\infty}\, U_1)$$

$$\mathrm{tr}\,(U_1\, \rho_{-\infty}\, U_2^{\dagger})$$

φ_1 φ_2


tr (U₁ ρ₋∞ U₂†)
m₁ φ₁
φ₂ , m₂
m₁ ≈ m₂
m₁
WV
m₂
S_eff = ∫ d^d σ
WV


tr (U1 ρ-∞ U2†)
m1 φ1
φ2 , m2
m1 ≈ m2
m1
{σ}
WV
m2


Schwinger-Keldysh symmetry
Z ⟹
A1=A2=A

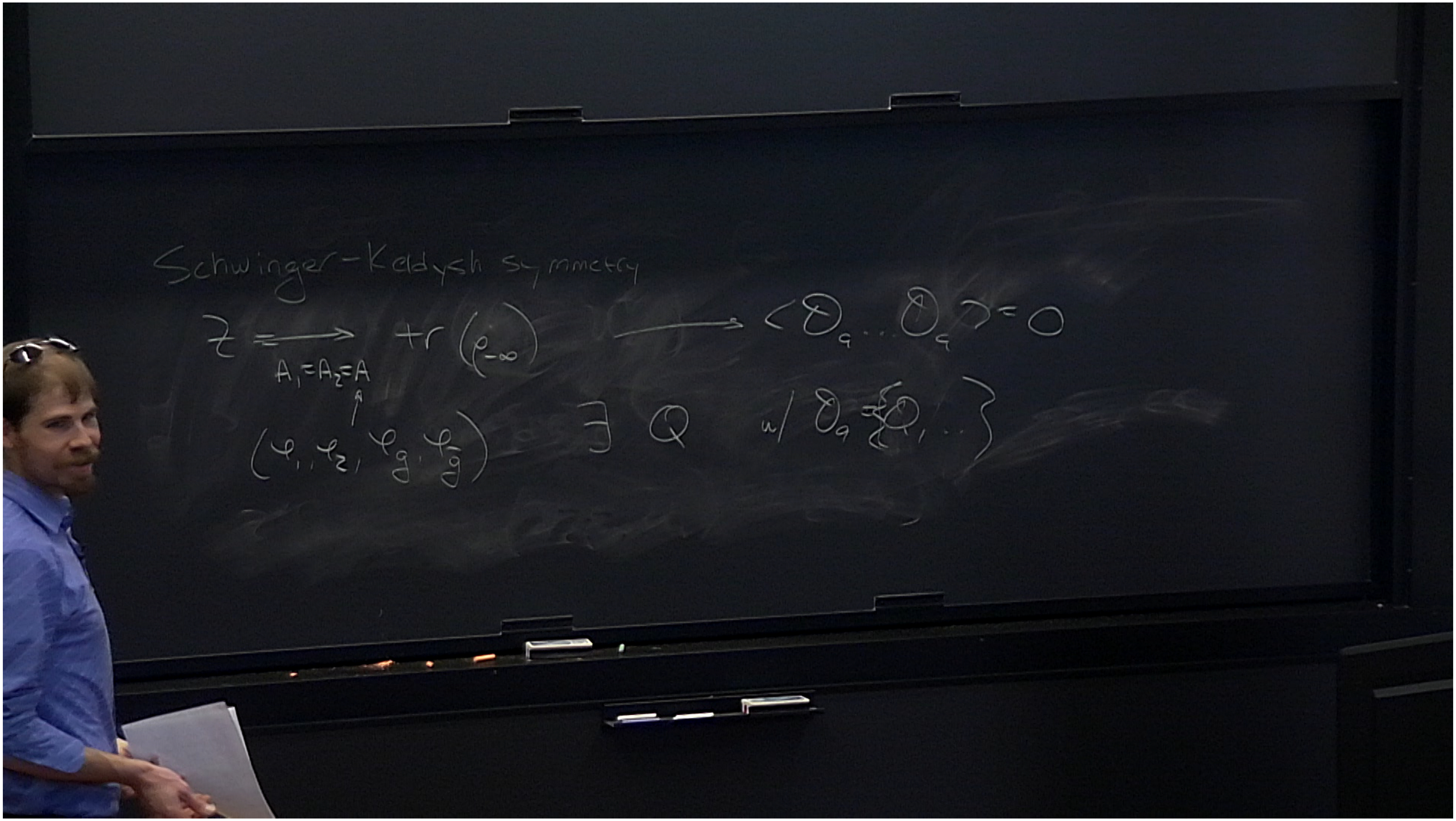
Schwinger-Keldysh symmetry

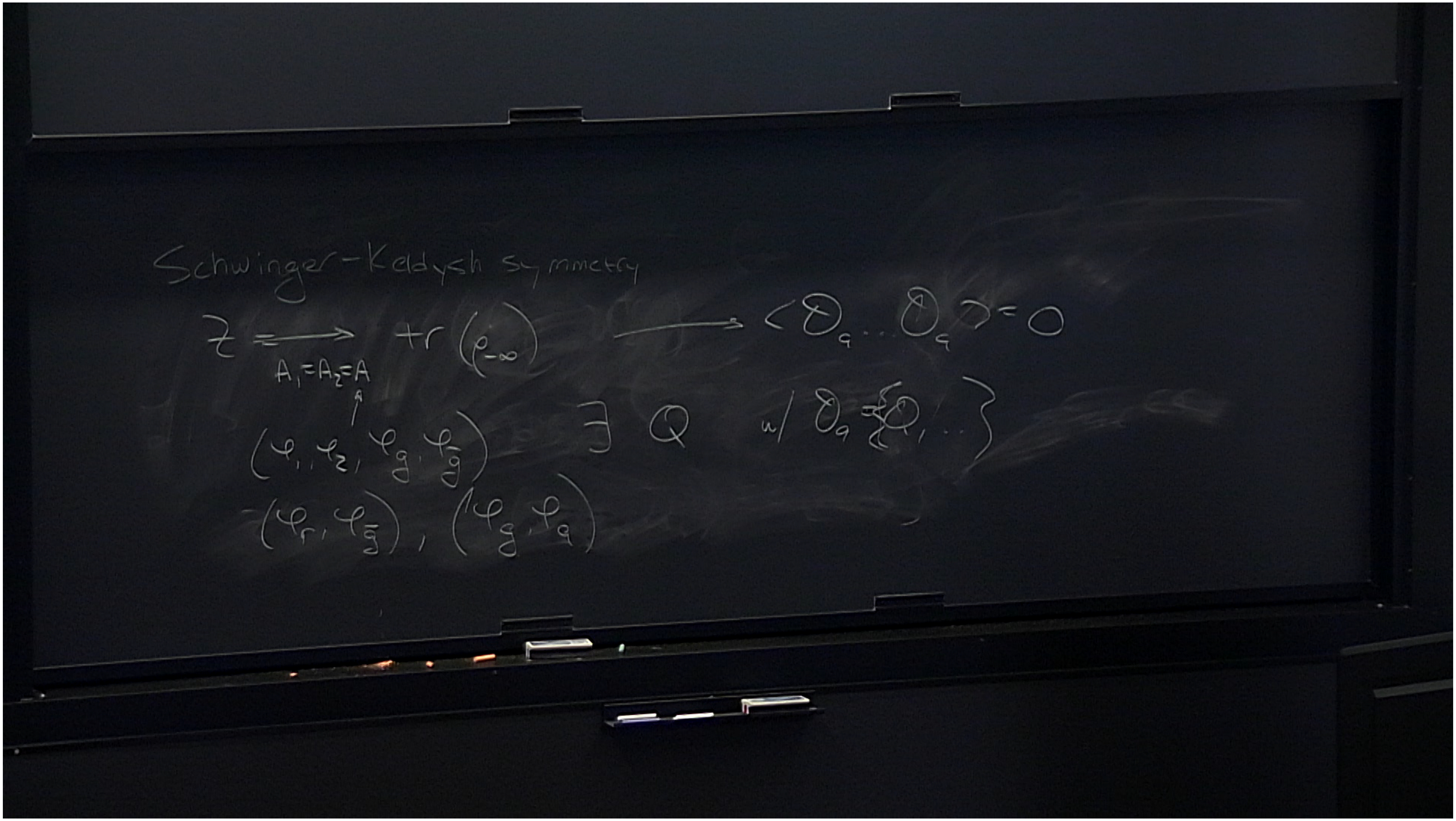
$$Z \xrightarrow[A_1=A_2=A]{} \mathrm{tr}\left(\rho_{-\infty}\right) \longrightarrow \langle \mathcal{O}_a \cdots \mathcal{O}_a \rangle = 0$$

Schwinger-Keldysh symmetry

$$Z \xrightarrow[A_1=A_2=A_a]{} \operatorname{tr}(\rho_{-\infty}) \longrightarrow \langle \mathcal{O}_a \cdots \mathcal{O}_a \rangle = 0$$

$$(\varphi_1, \varphi_2, \varphi_g, \varphi_{\bar{g}})$$


Schwinger-Keldysh symmetry
Z
A1=A2=A
tr(ρ-∞)
<Oq ... Oq> = 0
(φ1, φ2, φg, φḡ)
∃ Q
w/ Oq = {Q, ...}

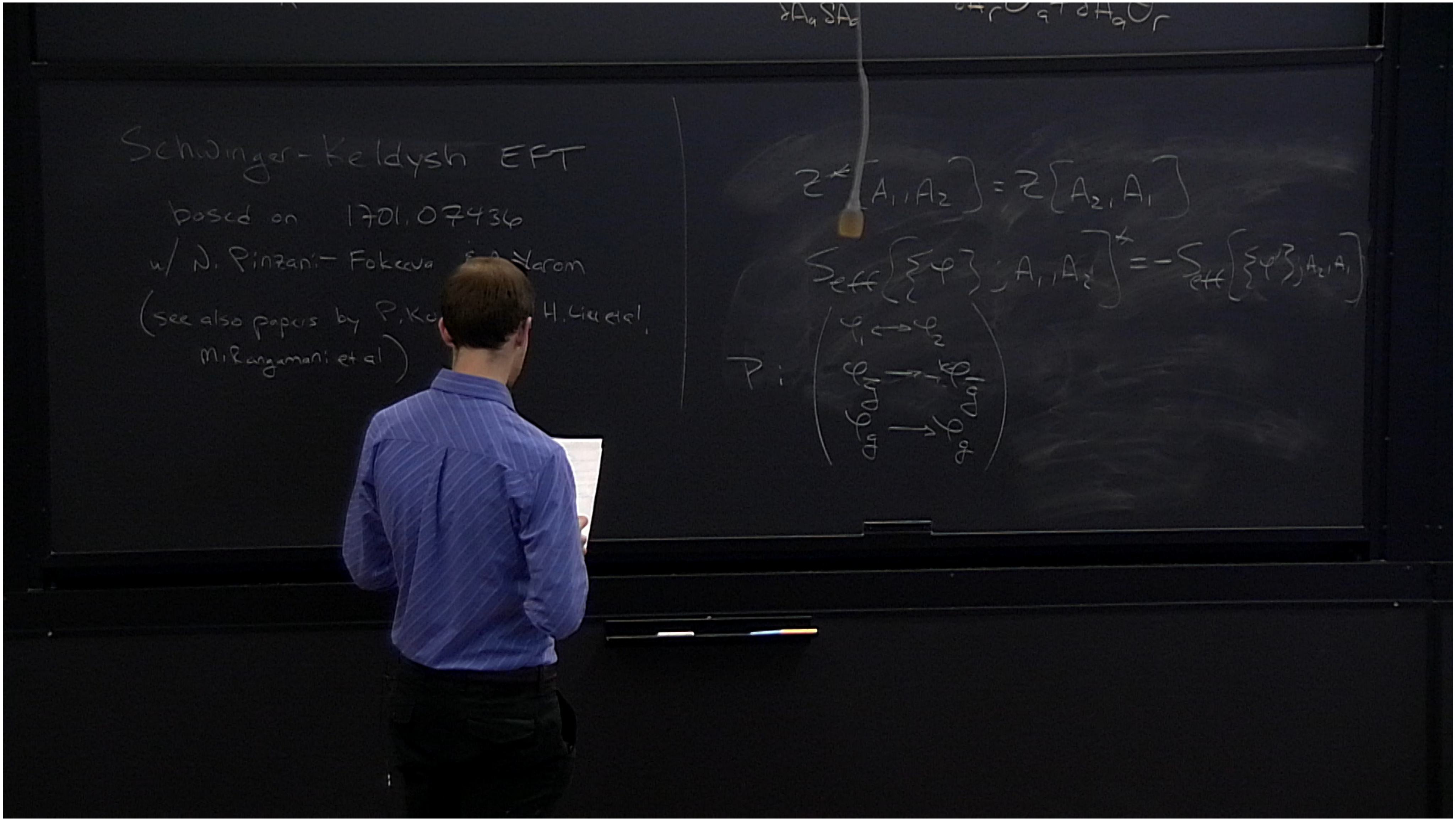

Schwinger-Keldysh symmetry
Z = tr(ρ_{-∞}) → ⟨O_a … O_a⟩ = 0
A_1=A_2=A
(φ_1, φ_2, φ_g, φ_ḡ)
∃ Q w/ O_a = {Q, …}
= (φ_r, φ_ḡ), (φ_g, φ_a)

Schwinger-Keldysh symmetry

$$Z \xrightarrow[A_1 = A_2 = A]{} \mathrm{tr}(\rho_{-\infty}) \longleftrightarrow \langle \mathcal{O}_a \ldots \mathcal{O}_a \rangle = 0$$

$$(\varphi_1, \varphi_2, \varphi_g, \varphi_{\bar{g}}) \quad \exists\, Q \quad \text{w/ } \mathcal{O}_a = \{Q, \ldots\}$$

$$(\varphi_r, \varphi_{\bar{g}}), \ (\varphi_g, \varphi_a)$$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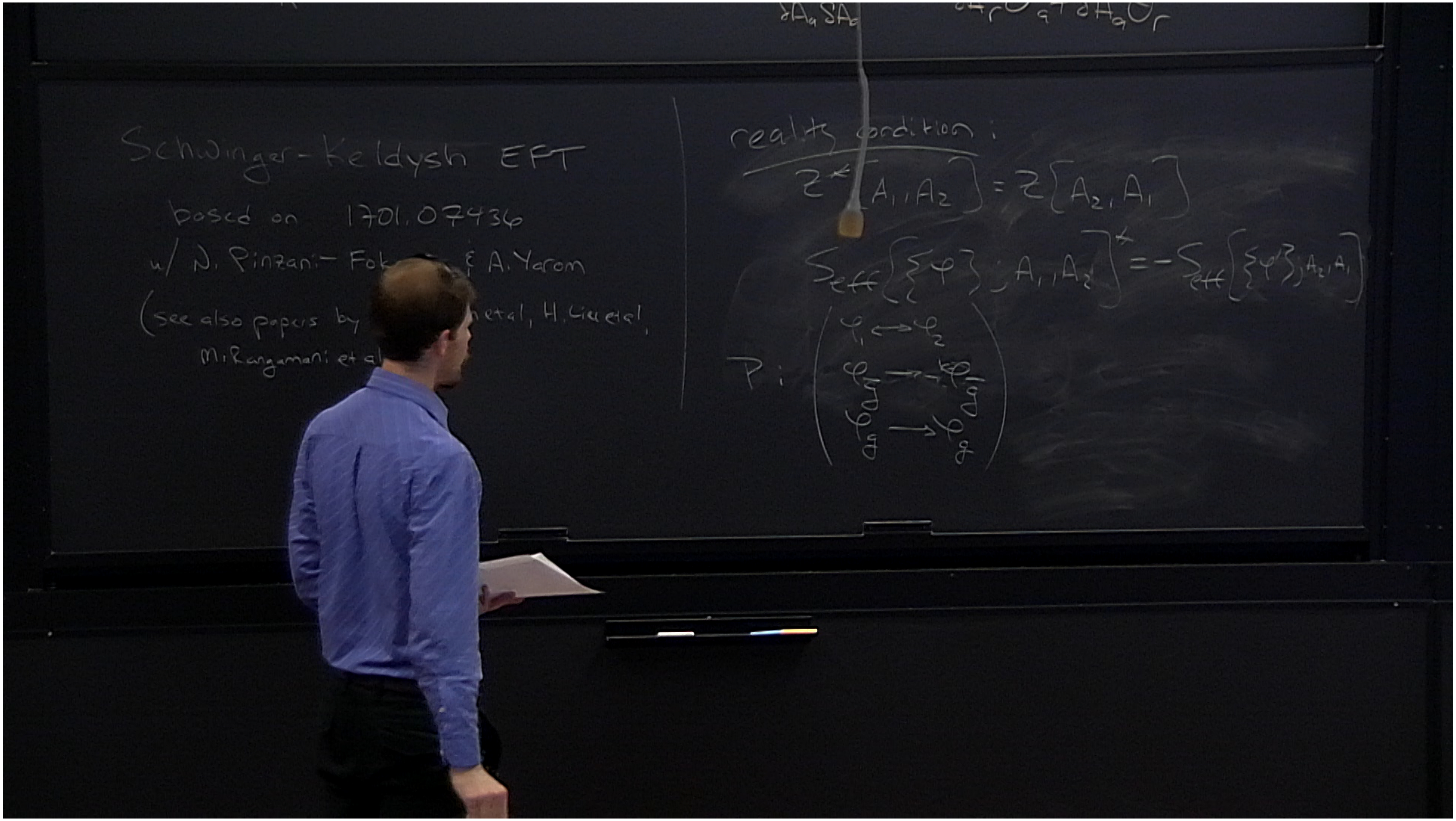
Z*[A1, A2] = Z[A2, A1]
Seff[{φ}; A1, A2]* = −Seff[{φ'}; A2, A1]
P :
φ1 ⟷ φ2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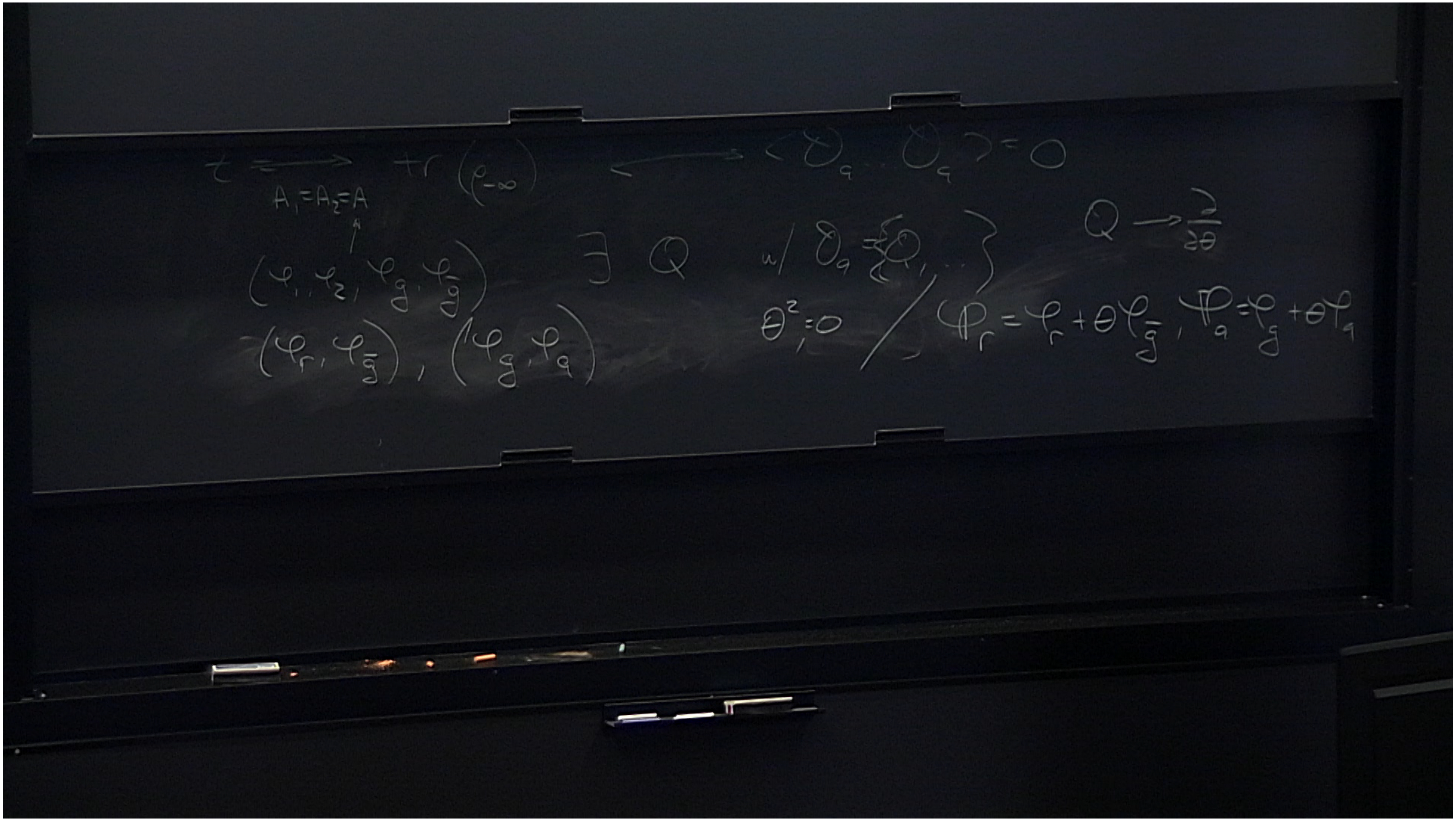
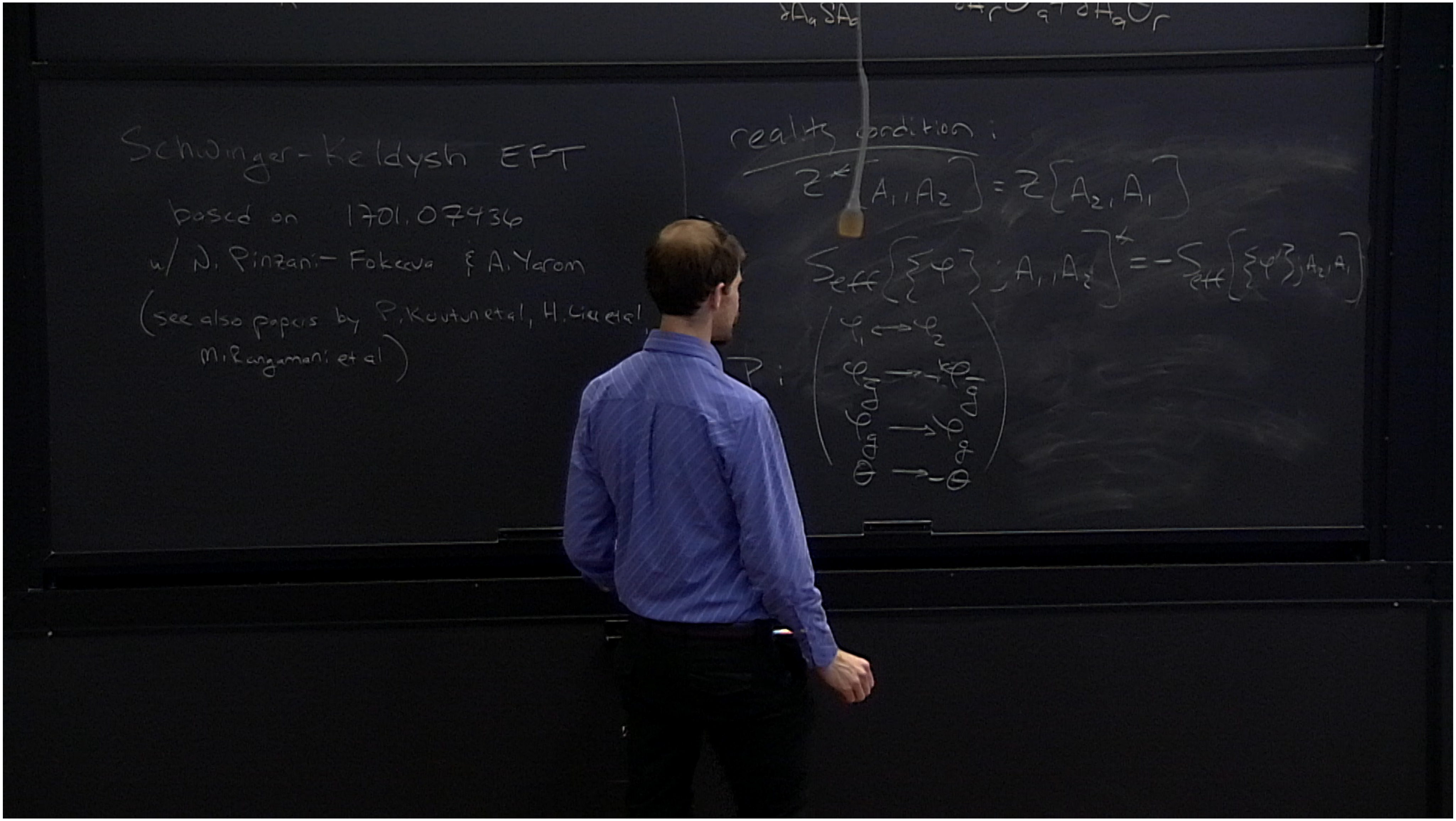
reality condition:
$Z^*[A_1, A_2] = Z[A_2, A_1]$
$S_{eff}[\{\varphi\}; A_1, A_2]^* = -S_{eff}[\{\varphi'\}; A_2, A_1]$
P:



$t = \longrightarrow \mathrm{tr}(\rho_{-\infty}) \longleftrightarrow \langle O_a \dots O_a \rangle = 0$
$A_1 = A_2 = A$
$(\varphi_1, \varphi_2, \varphi_g, \varphi_{\bar{g}})$
$(\varphi_r, \varphi_{\bar{g}}), (\varphi_g, \varphi_a)$
$\exists\ Q$ w/ $O_a = \{Q, \dots\}$
$Q \longrightarrow \frac{\partial}{\partial\theta}$
$\theta^2 = 0$
$\Phi_r = \varphi_r + \theta\varphi_{\bar{g}}, \Phi_a = \varphi_g + \theta\varphi_a$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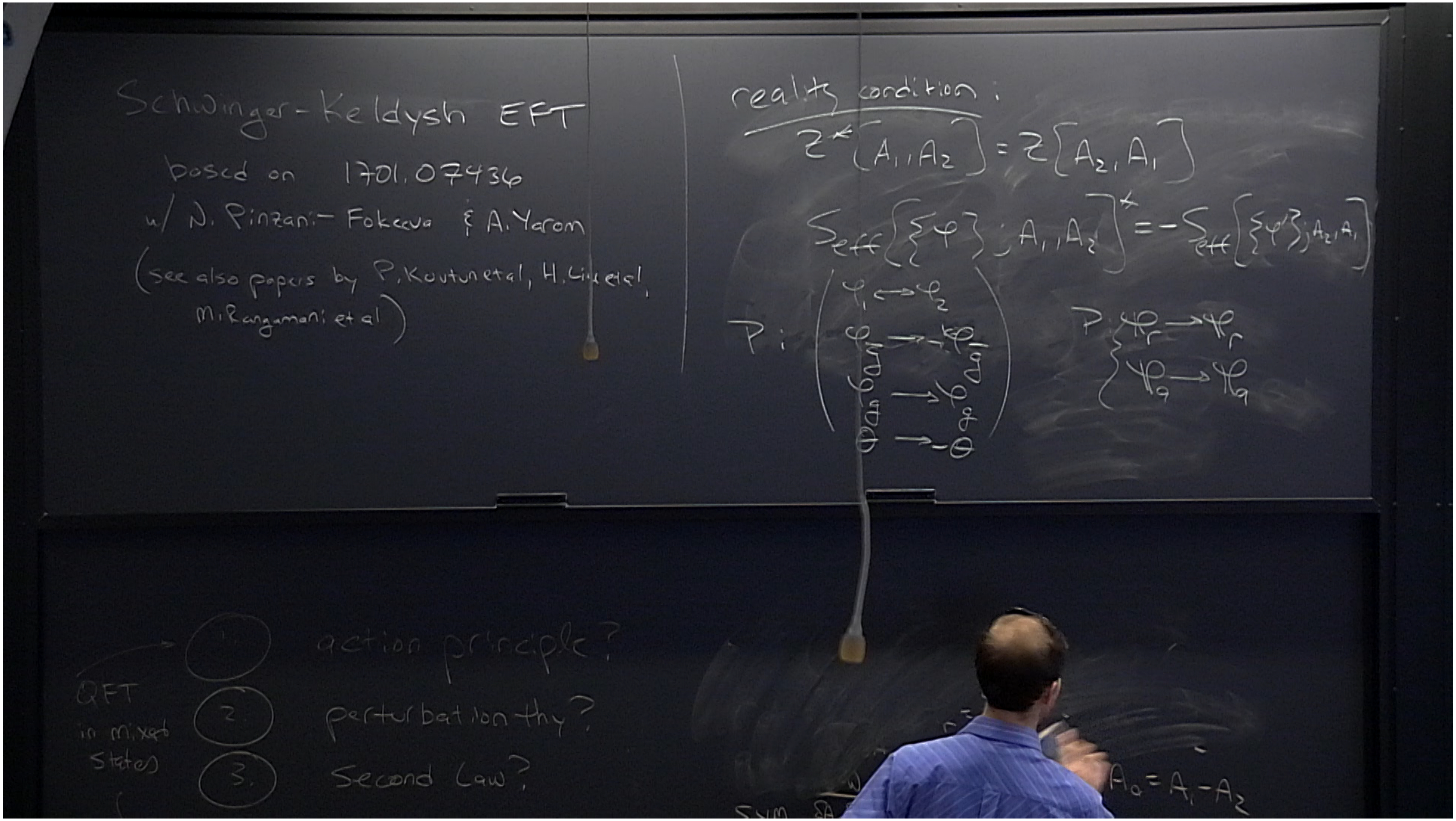
reality condition:
$Z^*[A_1, A_2] = Z[A_2, A_1]$
$S_{eff}[\{\varphi\}; A_1, A_2]^* = -S_{eff}[\{\varphi'\}; A_2, A_1]$
$\varphi_1 \leftrightarrow \varphi_2$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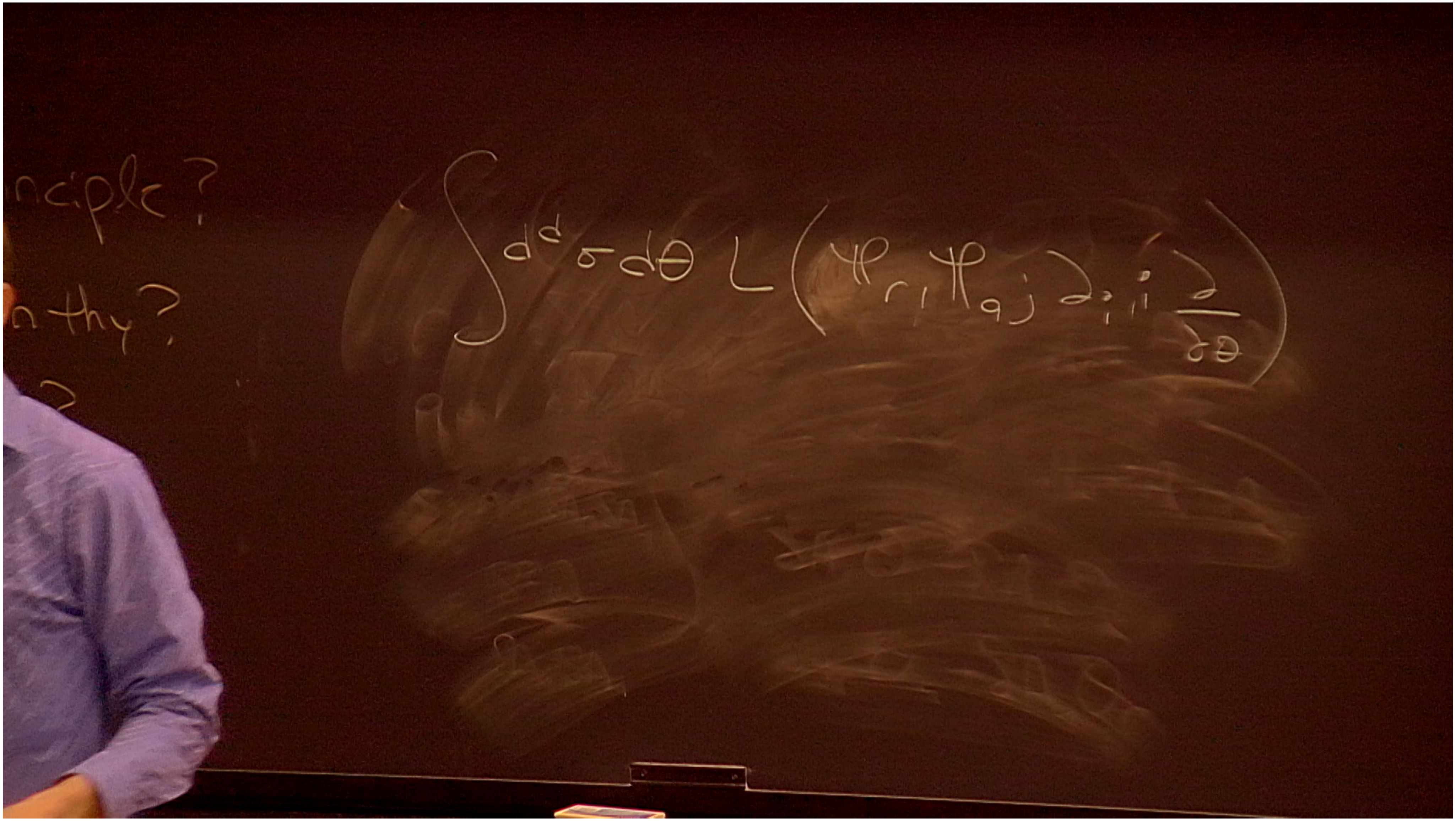
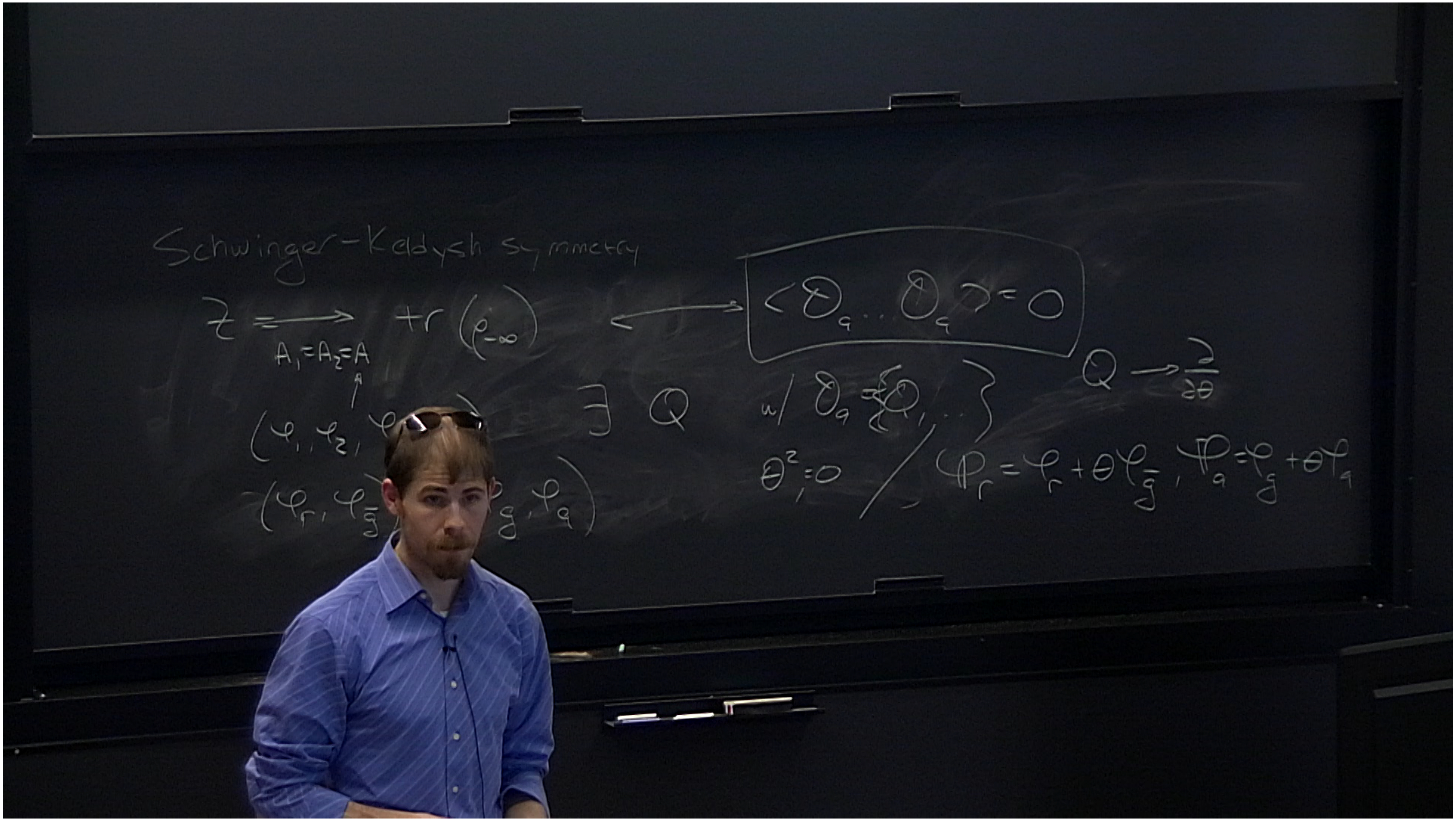
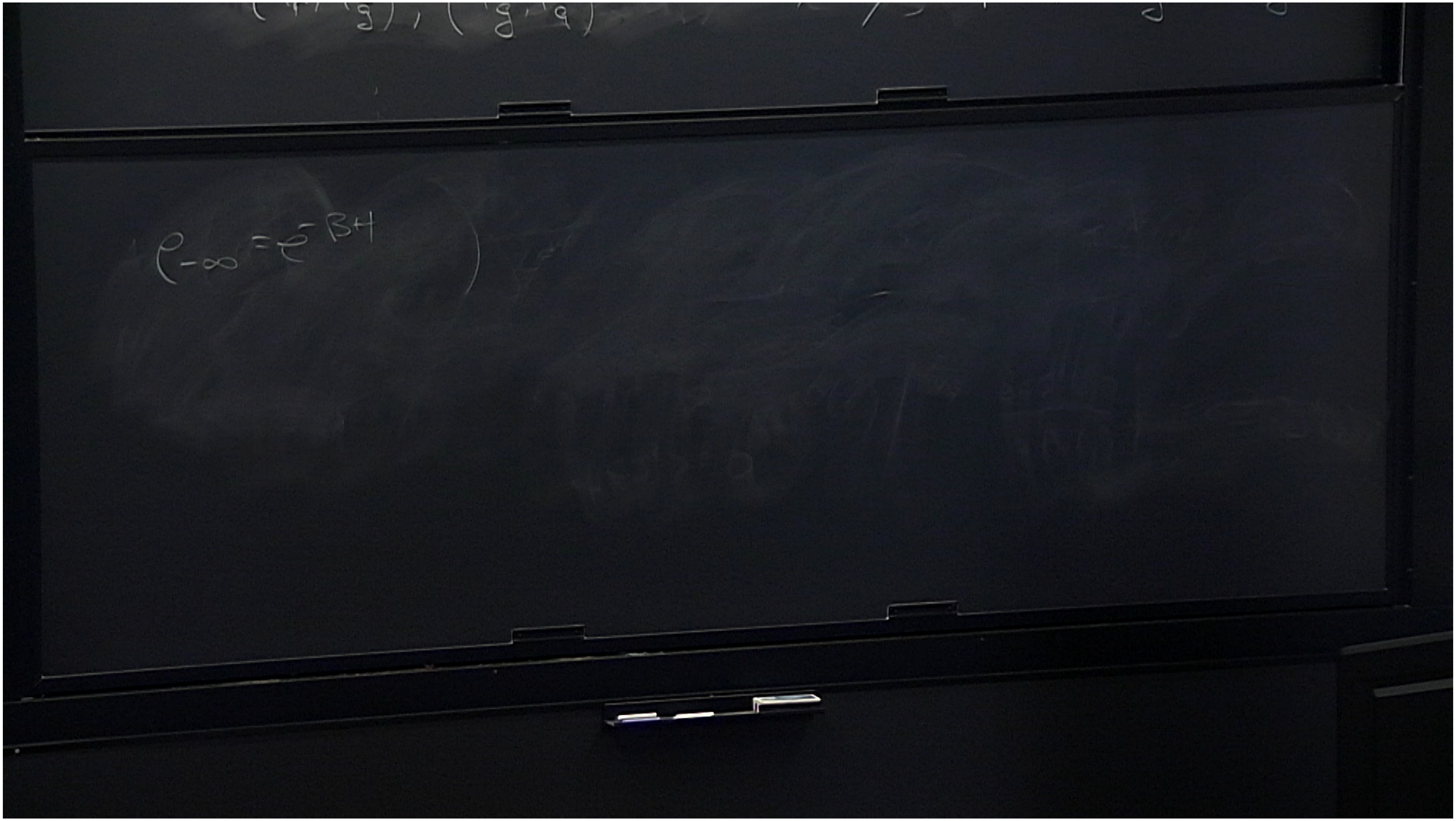
reality condition:
$Z^*[A_1, A_2] = Z[A_2, A_1]$
$S_{eff}[\{\varphi\}; A_1, A_2]^* = -S_{eff}[\{\varphi'\}; A_2, A_1]$
$\varphi_1 \leftrightarrow \varphi_2$
$\varphi_r \to \varphi_r$
$\varphi_a \to \varphi_a$
$A_a = A_1 - A_2$
action principle?
QFT in mixed states
perturbation thy?
Second Law?


ncìple ?
n thy ?
?
$\int d^d\sigma\, d\theta\, L\left(\Psi_r, \Psi_a; \partial_i, \frac{\partial}{\partial\theta}\right)$


Schwinger-Keldysh symmetry
Z = tr(ρ−∞)
A1=A2=A
∃ Q
<Oa ... Oa> = 0
w/ Oa ∈ {O1, ...}
Q → ∂/∂θ
θ²=0
Φr = φr + θφḡ , Φa = φg + θφa


$\rho_{-\infty} = e^{-\beta H}$

$$\rho_{-\infty} = e^{-\beta H}$$

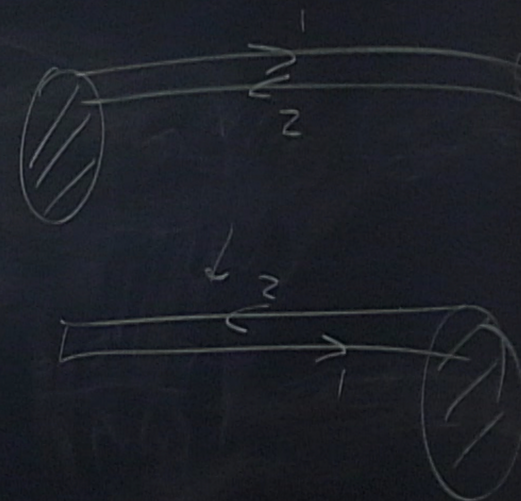
$$e^{-\beta H}\, \mathcal{U}_2^{\dagger}\left[A_2(t)\right] = \mathcal{U}_2^{\dagger}\left[A_2(t-i\beta)\right] e^{-\beta H}$$

$$\mathrm{tr}\left(\mathcal{U}_1 e^{-\beta H} \mathcal{U}_2^{\dagger}\right) = \mathrm{tr}\left(\mathcal{U}_2^{\dagger}\left[A_2(t-i\beta)\right] e^{-\beta H} \mathcal{U}_1\right)$$

$$\rho_{-\infty} = e^{-\beta H}$$

$$e^{-\beta H}\, \mathcal{U}_2^{\dagger}\left[A_2(t)\right] = \mathcal{U}_2^{\dagger}\left[A_2(t-i\beta)\right] e^{-\beta H}$$

$$\mathrm{tr}\left(\mathcal{U}_1 e^{-\beta H} \mathcal{U}_2^{\dagger}\right) = \mathrm{tr}\left(\mathcal{U}_2^{\dagger}\left[A_2(t-i\beta)\right] e^{-\beta H} \mathcal{U}_1\right)$$

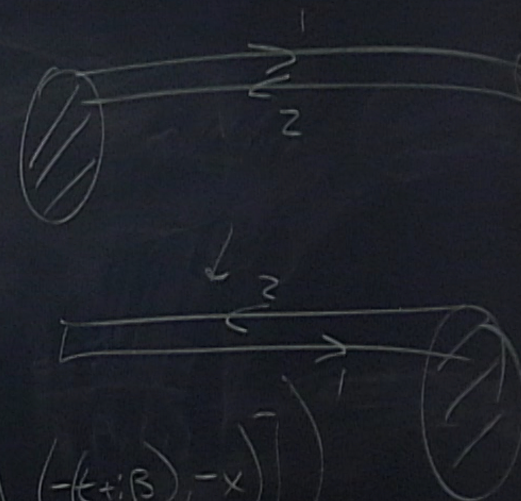


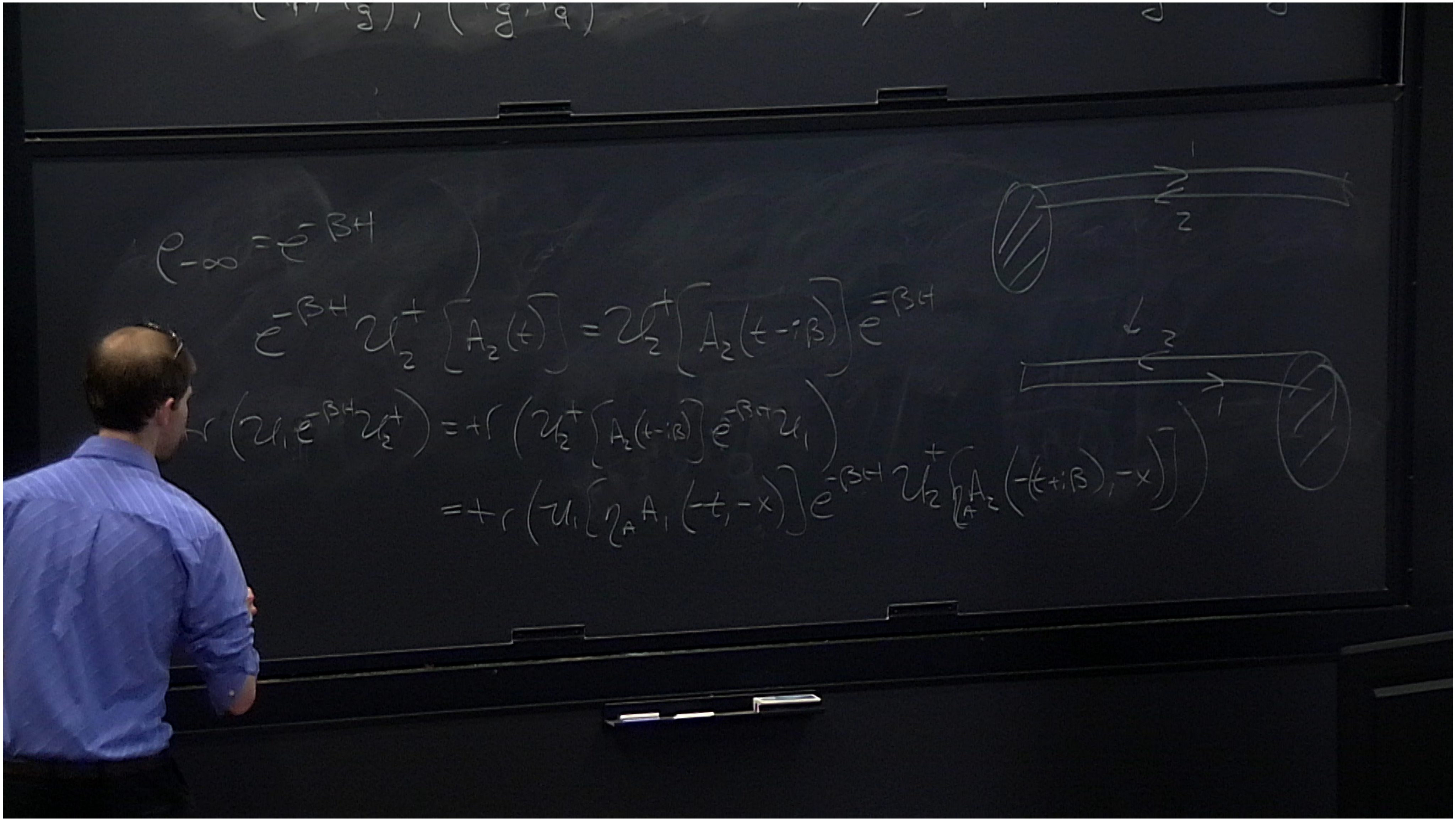
$$\rho_{-\infty} = e^{-\beta H}$$

$$e^{-\beta H}\, \mathcal{U}_2^{\dagger}\left[A_2(t)\right] = \mathcal{U}_2^{\dagger}\left[A_2(t - i\beta)\right] e^{-\beta H}$$

$$\mathrm{tr}\left(\mathcal{U}_1 e^{-\beta H} \mathcal{U}_2^{\dagger}\right) = \mathrm{tr}\left(\mathcal{U}_2^{\dagger}\left[A_2(t-i\beta)\right] e^{-\beta H} \mathcal{U}_1\right)$$

$$= \mathrm{tr}\left(\mathcal{U}_1\left[\eta_A A_1(-t,-x)\right] e^{-\beta H} \mathcal{U}_2\left[\eta_A A_2(-(t+i\beta),-x)\right]\right)$$





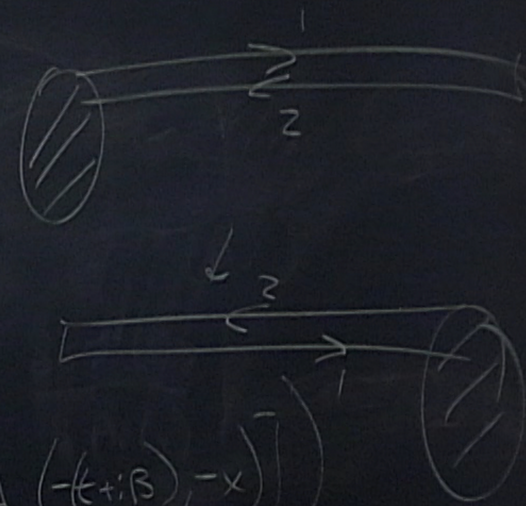
$\rho_{-\infty} = e^{-\beta H}$
$e^{-\beta H} U_2^\dagger [A_2(t)] = U_2^\dagger [A_2(t - i\beta)] e^{-\beta H}$
$tr(U_1 e^{-\beta H} U_2^\dagger) = tr(U_2^\dagger [A_2(t-i\beta)] e^{-\beta H} U_1)$
$= tr(U_1 [\eta_A A_1(-t,-x)] e^{-\beta H} U_2^\dagger [\eta_A A_2(-(t+i\beta),-x)])$
1
2
2
1

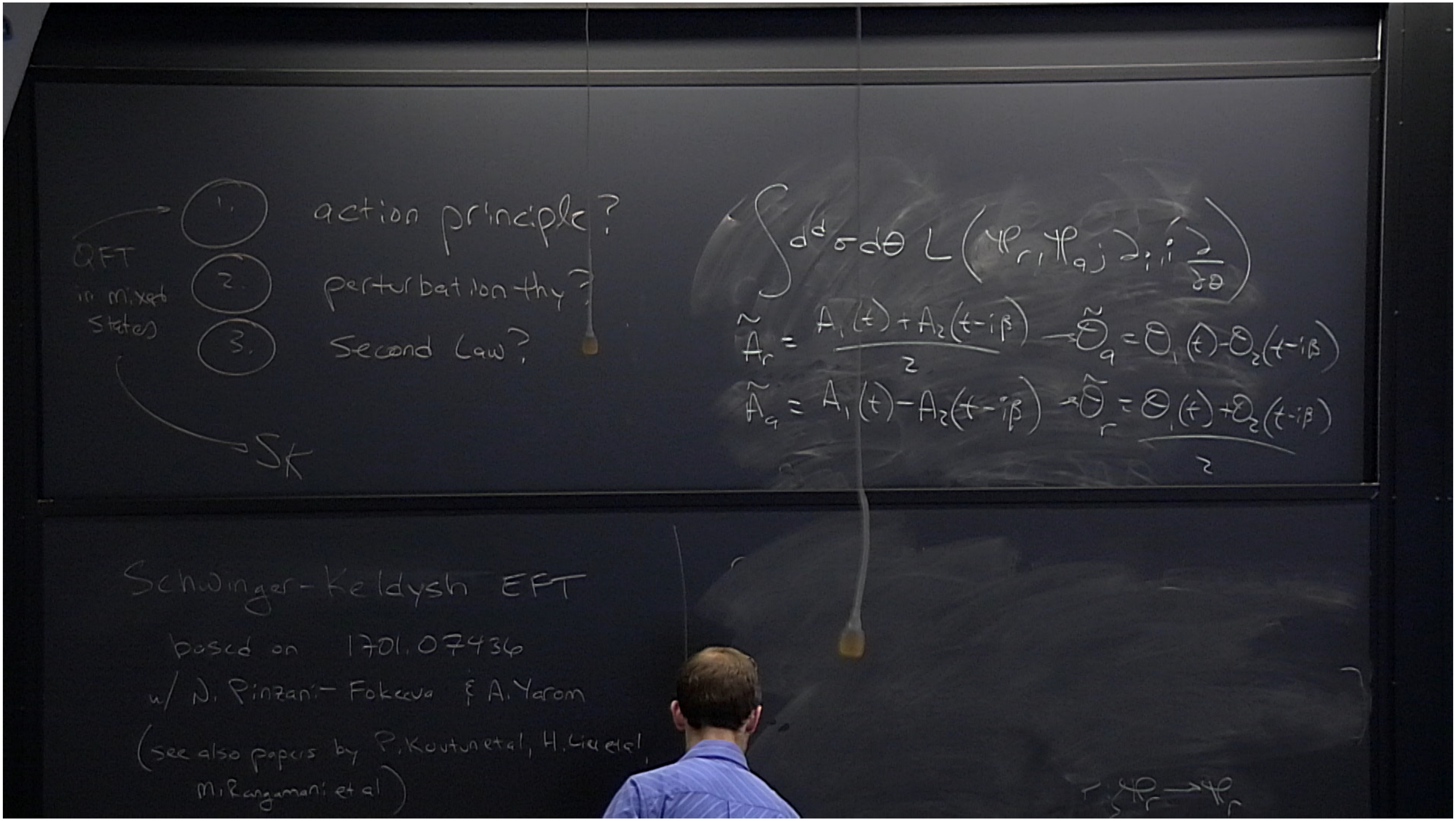
$$\rho_{-\infty} = e^{-\beta H}$$

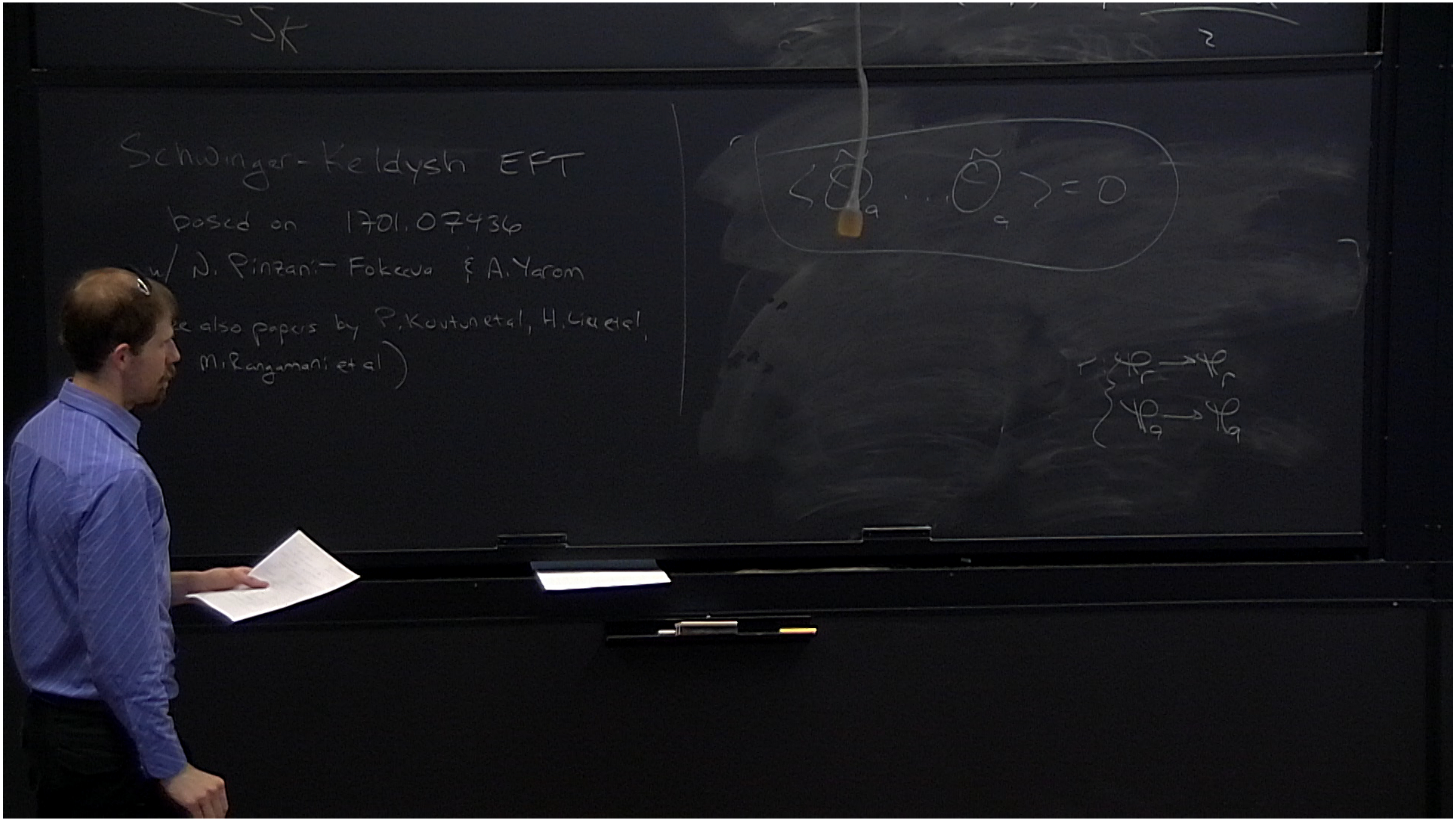
$$e^{-\beta H}\, \mathcal{U}_2^{+}\left[A_2(t)\right] = \mathcal{U}_2^{+}\left[A_2(t-i\beta)\right] e^{-\beta H}$$

$$\mathrm{tr}\left(\mathcal{U}_1 e^{-\beta H} \mathcal{U}_2^{+}\right) = \mathrm{tr}\left(\mathcal{U}_2^{+}\left[A_2(t-i\beta)\right] e^{-\beta H} \mathcal{U}_1\right)$$

$$A_2(t) = A_1(t+i\beta) \qquad = \mathrm{tr}\left(\mathcal{U}_1\left[\eta_A A_1(-t,-x)\right] e^{-\beta H}\, \mathcal{U}_2^{+}\left[\eta_A A_2(-(t+i\beta),-x)\right]\right)$$




QFT in mixed states
1. action principle?
2. perturbation thy?
3. Second Law?
SK
$\int d^d\sigma\, d\theta\, L\left(\Psi_r, \Psi_a; \partial_i, i\frac{\partial}{\partial\theta}\right)$
$\tilde{A}_r = \frac{A_1(t) + A_2(t-i\beta)}{2} \rightarrow \tilde{\Theta}_a = \Theta_1(t) - \Theta_2(t-i\beta)$
$\tilde{A}_a = A_1(t) - A_2(t-i\beta) \rightarrow \tilde{\Theta}_r = \frac{\Theta_1(t) + \Theta_2(t-i\beta)}{2}$
Schwinger-Keldysh EFT
based on 1701.07436
w/ N. Pinzani-Fokeeva & A. Yarom
(see also papers by P. Kovtun et al, H. Liu et al, M. Rangamani et al)
$\Psi_r \rightarrow \Psi_r$


Schwinger-Keldysh EFT
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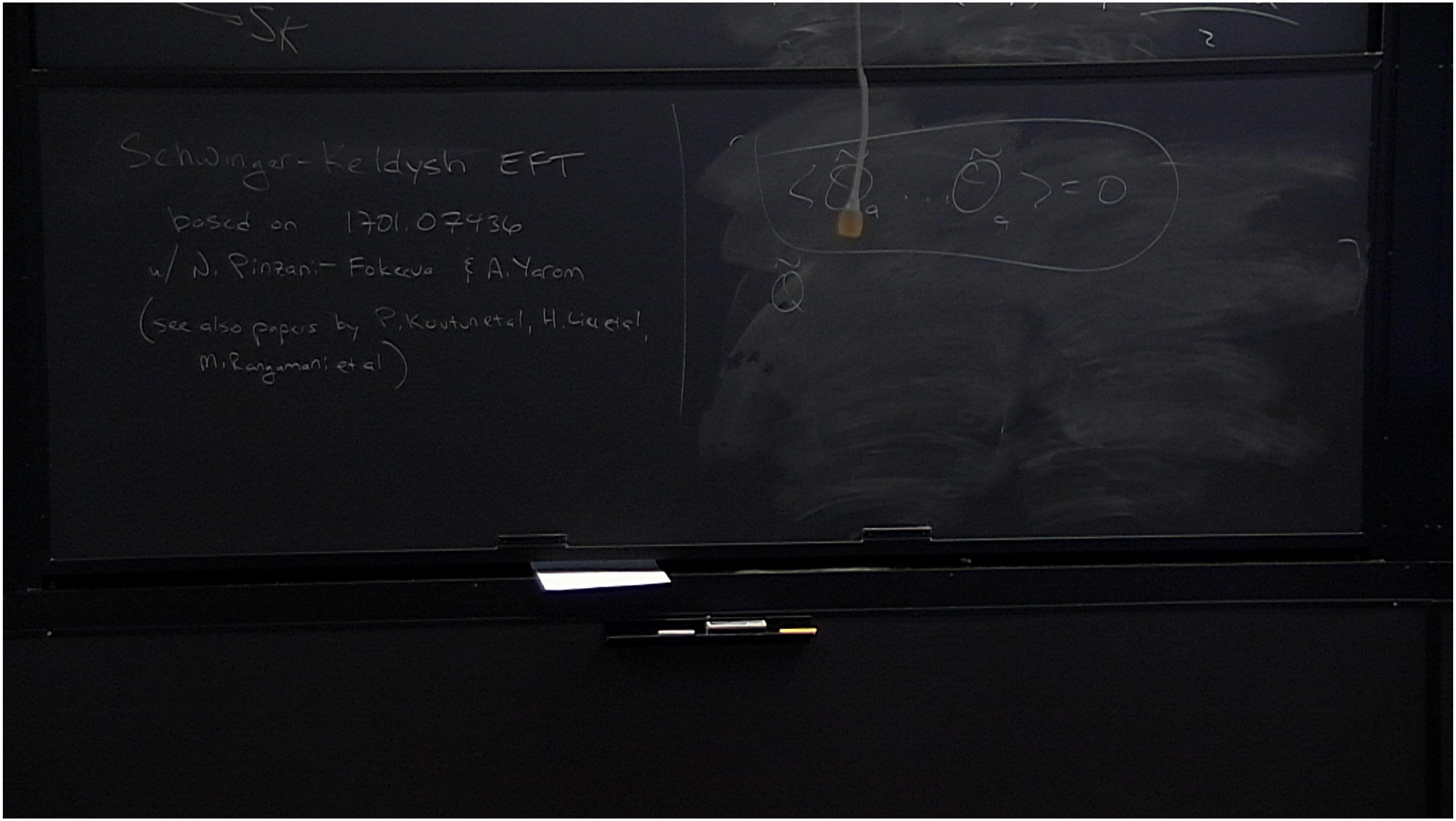
see also papers by P. Kovtun et al, H. Liu et al,
M. Rangamani et al)
SK
$\langle \tilde{O}_a \ldots \tilde{O}_a \rangle = 0$


SK
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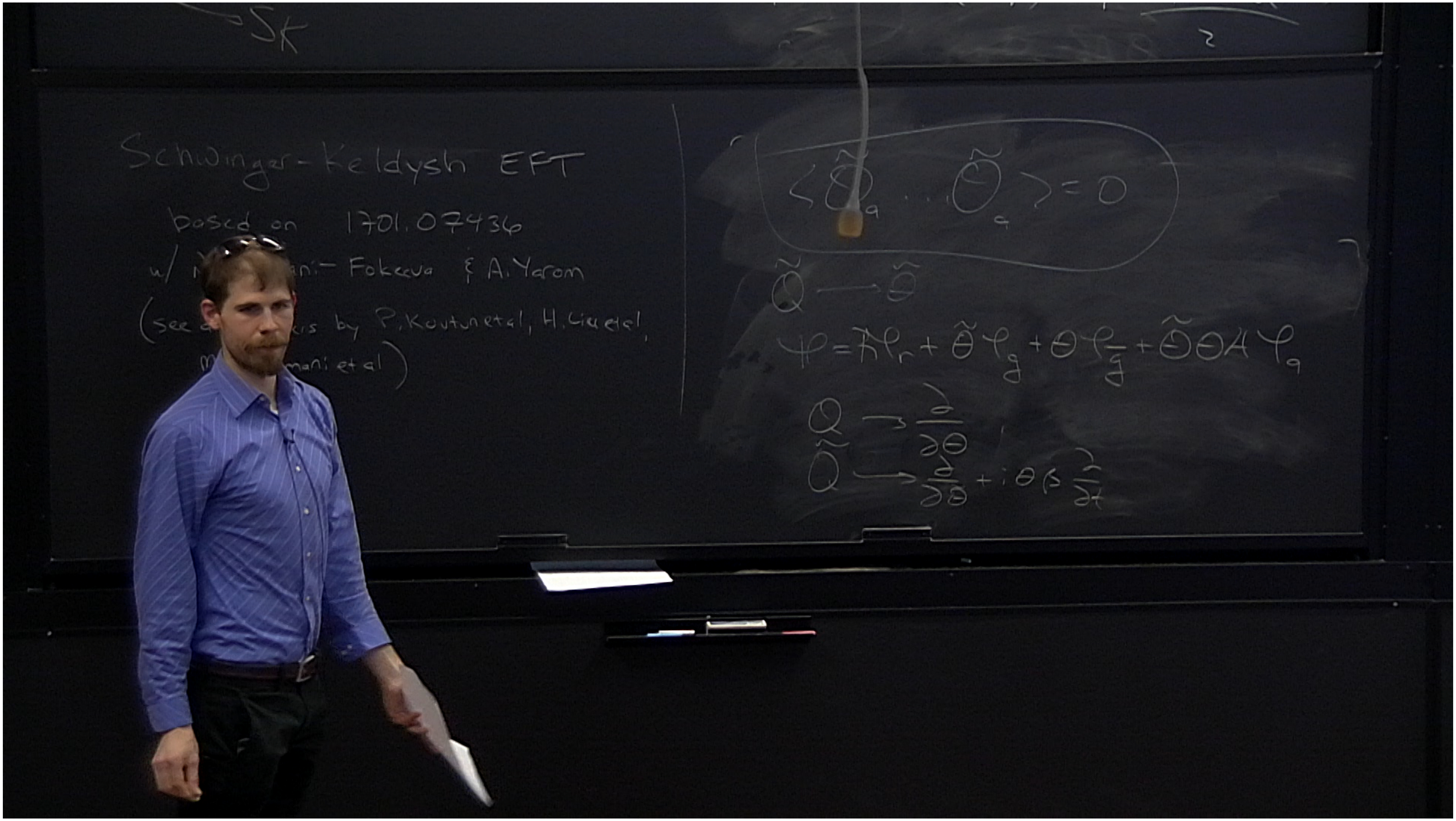
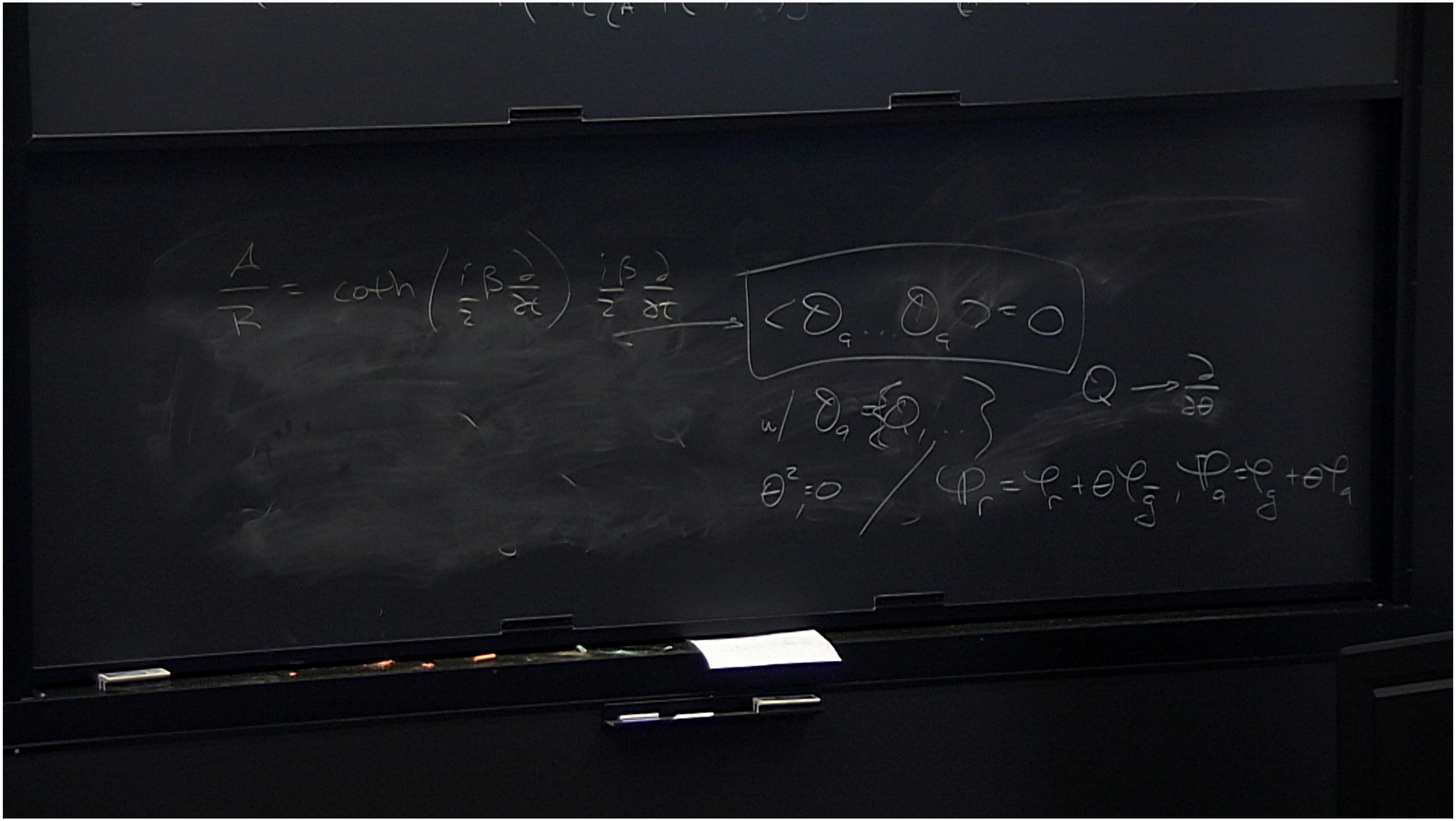
M. Rangamani et al)
⟨Õa … Õa⟩ = 0
Õ


Schwinger-Keldysh EFT
based on 1701.07436
Fokeeva & A. Yarom
P. Kovtun et al, H. Liu et al,
SK



$\frac{A}{R} = \coth\left(\frac{i\beta}{2}\frac{\partial}{\partial t}\right) \frac{i\beta}{2}\frac{\partial}{\partial t}$
$\boxed{\langle \mathcal{O}_a \ldots \mathcal{O}_a \rangle = 0}$
$Q \longrightarrow \frac{\partial}{\partial \theta}$
w/ $\mathcal{O}_a \in \{\mathcal{O}_1, \ldots\}$
$\theta^2 = 0$
$\Phi_r = \varphi_r + \theta \varphi_{\bar{g}}, \ \Phi_a = \varphi_g + \theta \varphi_a$

$$\frac{A}{R} = \coth\left(\frac{i\beta}{2}\frac{\partial}{\partial t}\right) \frac{i\beta}{2}\frac{\partial}{\partial t}$$

$$\boxed{\langle \mathcal{O}_a \cdots \mathcal{O}_a \rangle = 0}$$

$$A = 1 + O(\partial)$$

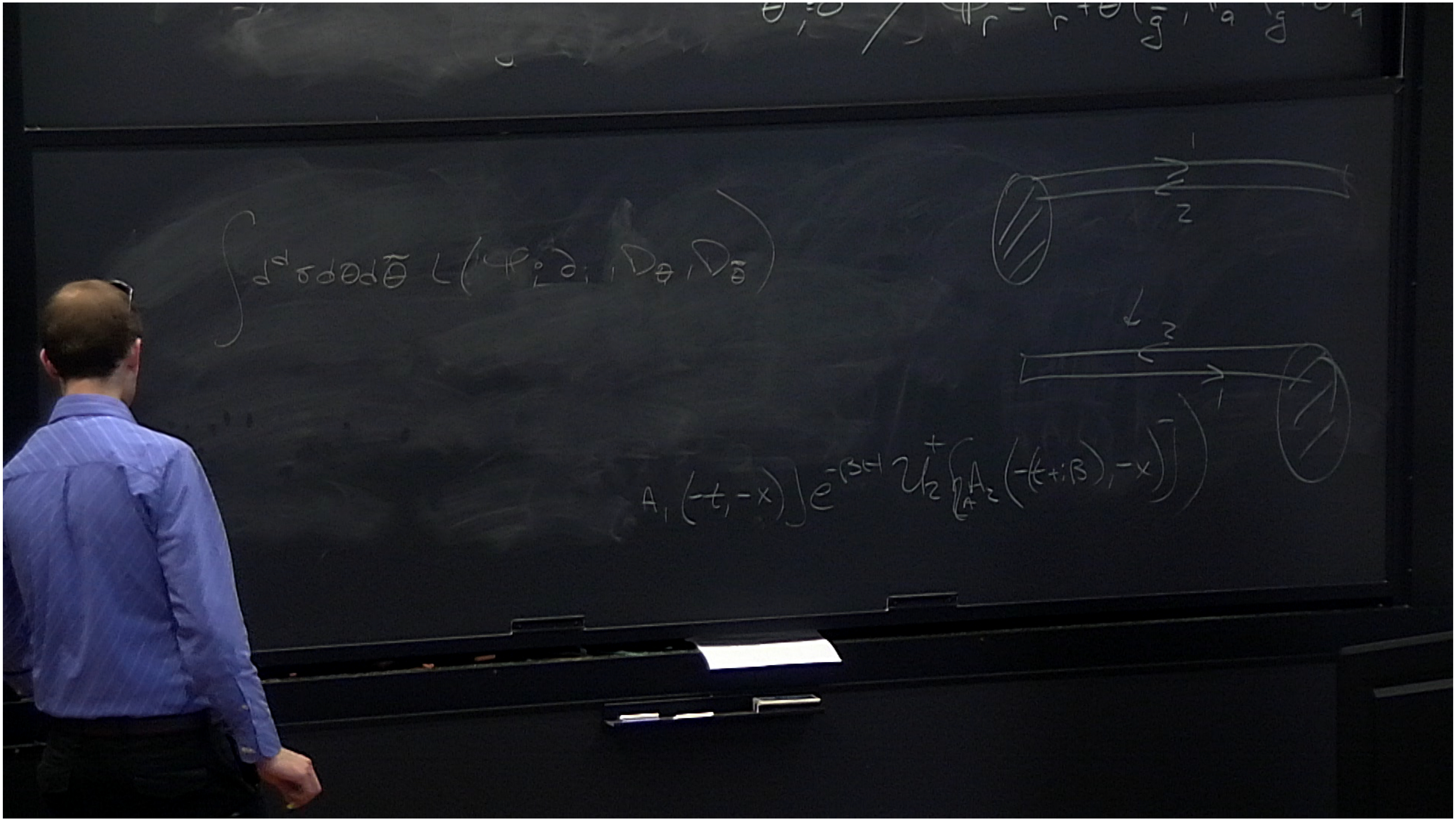
$$R = 1 + O(\partial)$$

w/ $\mathcal{O}_a = \{\mathcal{O}_1, \ldots\}$

$$Q \longrightarrow \frac{\partial}{\partial\theta}$$

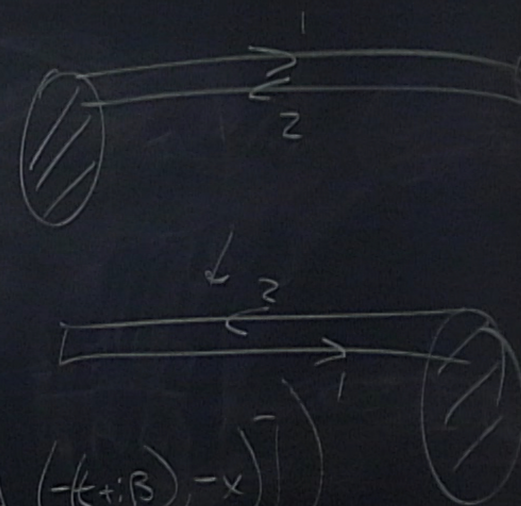
$$\theta^2 = 0$$

$$\Phi_r = \varphi_r + \theta \varphi_g, \quad \Phi_a = \varphi_g + \theta \varphi_a$$



$$\int d^d\sigma\, d\theta\, d\tilde{\theta}\; L(\varphi_i, \partial_i, D_\theta, D_{\tilde{\theta}})$$

$$\tilde{\varphi} = R\tilde{\varphi}_r + \tilde{\theta}\tilde{\varphi}_g + \theta\tilde{\varphi}_{\bar{g}} + \tilde{\theta}\theta A\tilde{\varphi}_a$$



$$A_1(-t,-x)]\, e^{-\beta H}\, U_2^\dagger \{ A_2(-(t+i\beta),-x)^\dagger]\}$$

$$\int d^d\sigma\, d\theta\, d\tilde{\theta} \left(L(\varphi; \partial_i, D_\theta, D_{\tilde{\theta}}) + L(\tilde{\varphi}; \partial_i \ldots) \right)$$

$$\tilde{\varphi} = R\tilde{\varphi}_r + \tilde{\theta}\tilde{\varphi}_g + \theta\tilde{\varphi}_{\bar{g}} + \tilde{\theta}\theta A\tilde{\varphi}_a$$

$$K : \varphi \longleftrightarrow \tilde{\varphi}$$

$$A_1(-t,-x)]\, e^{-\beta H}\, U_2^{\dagger}[A_2(-(t+i\beta),-x)]]$$

$$\int d^d\sigma\, d\theta\, d\tilde{\theta} \left(L(\varphi;\partial_i, D_\theta, D_{\tilde\theta}) + L(\tilde{\varphi};\partial_i, \ldots) \right)$$

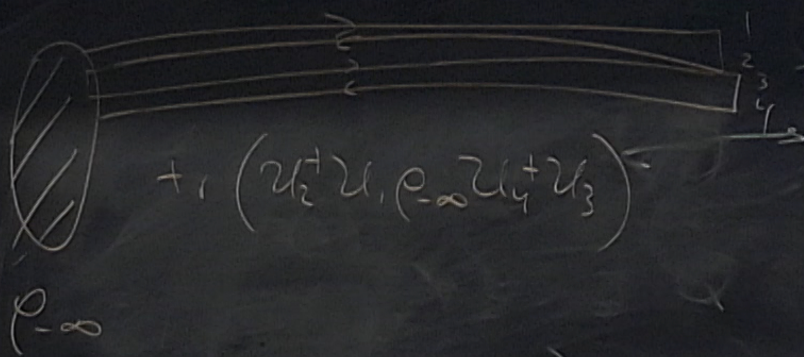
$$\tilde{\varphi} = R\tilde{\varphi}_r + \tilde{\theta}\tilde{\varphi}_g + \theta\tilde{\varphi}_{\bar{g}} + \tilde{\theta}\theta A\tilde{\varphi}_a$$

$$\{\underbrace{Q, \tilde{Q}}_{K}\} = -\beta H$$

$$K : \varphi \longleftrightarrow \tilde{\varphi}$$

$$K : \begin{array}{l} Q \longrightarrow -\tilde{Q} \\ \tilde{Q} \longrightarrow Q \end{array}$$

$$K : Q \to -\tilde{Q}$$
$$\tilde{Q} \to Q$$



$$\mathrm{tr}\left(U_2^\dagger U_1 \rho_{-\infty} U_4^\dagger U_3\right)$$

$\rho_{-\infty}$

$$\boxed{\langle O_a \dots O_a \rangle = 0}$$

w/ $O_a \in \{O_1, \dots\}$

$$Q \to \frac{\partial}{\partial \theta}$$

$$\theta^2 = 0 \quad \Phi_r = \varphi_r + \theta \varphi_{\bar{g}}, \quad \Phi_a = \varphi_g + \theta \varphi_a$$

$K: Q \to -\tilde{Q}$

$\tilde{Q} \to Q$

$\mathrm{tr}\left(U_2^\dagger U_1 \rho_{-\infty} U_4^\dagger U_3\right)$

$\boxed{\langle O_a \ldots O_a \rangle = 0}$

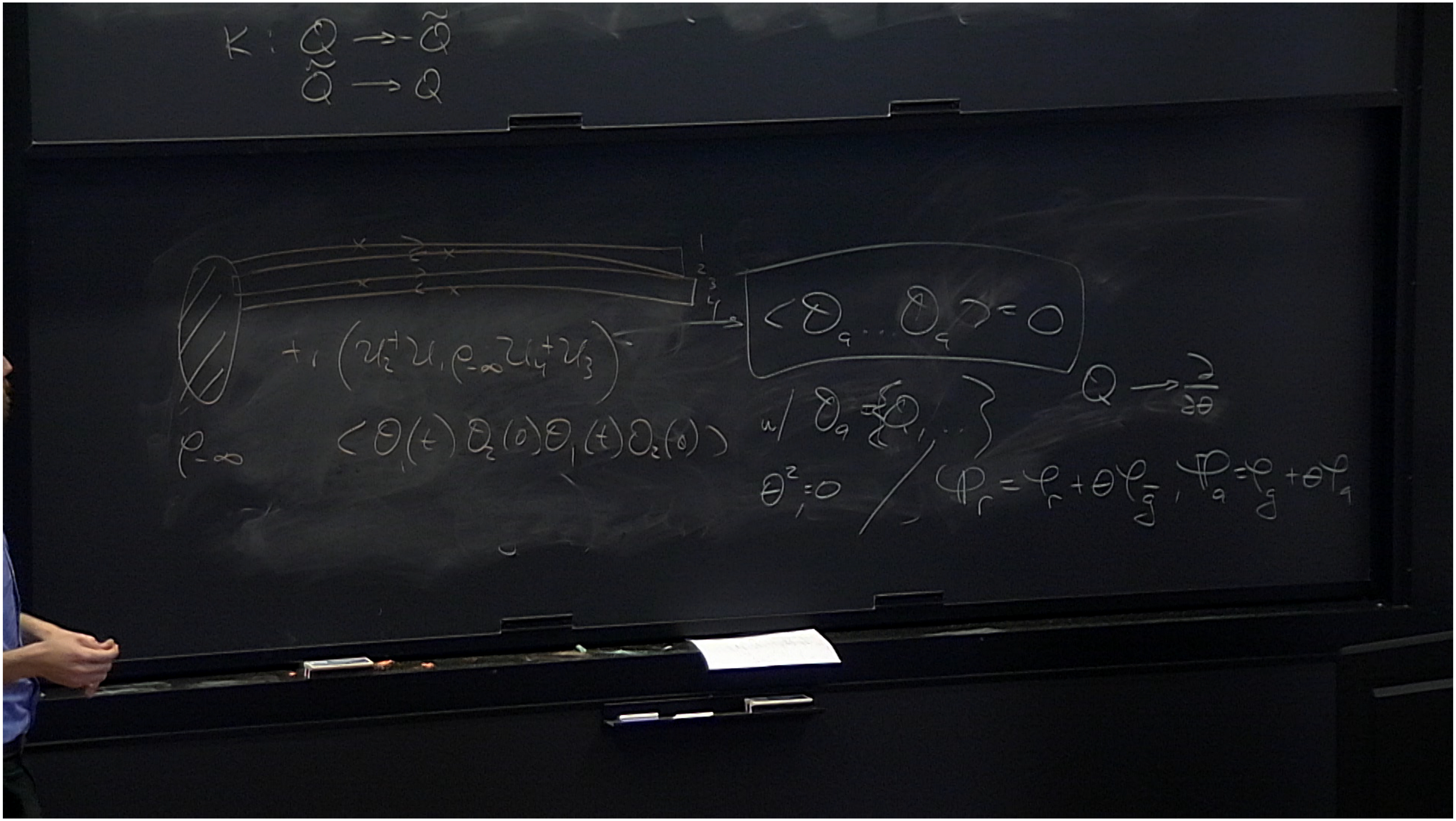
$Q \to \frac{\partial}{\partial\theta}$

w/ $O_a = \{O_1, \ldots\}$

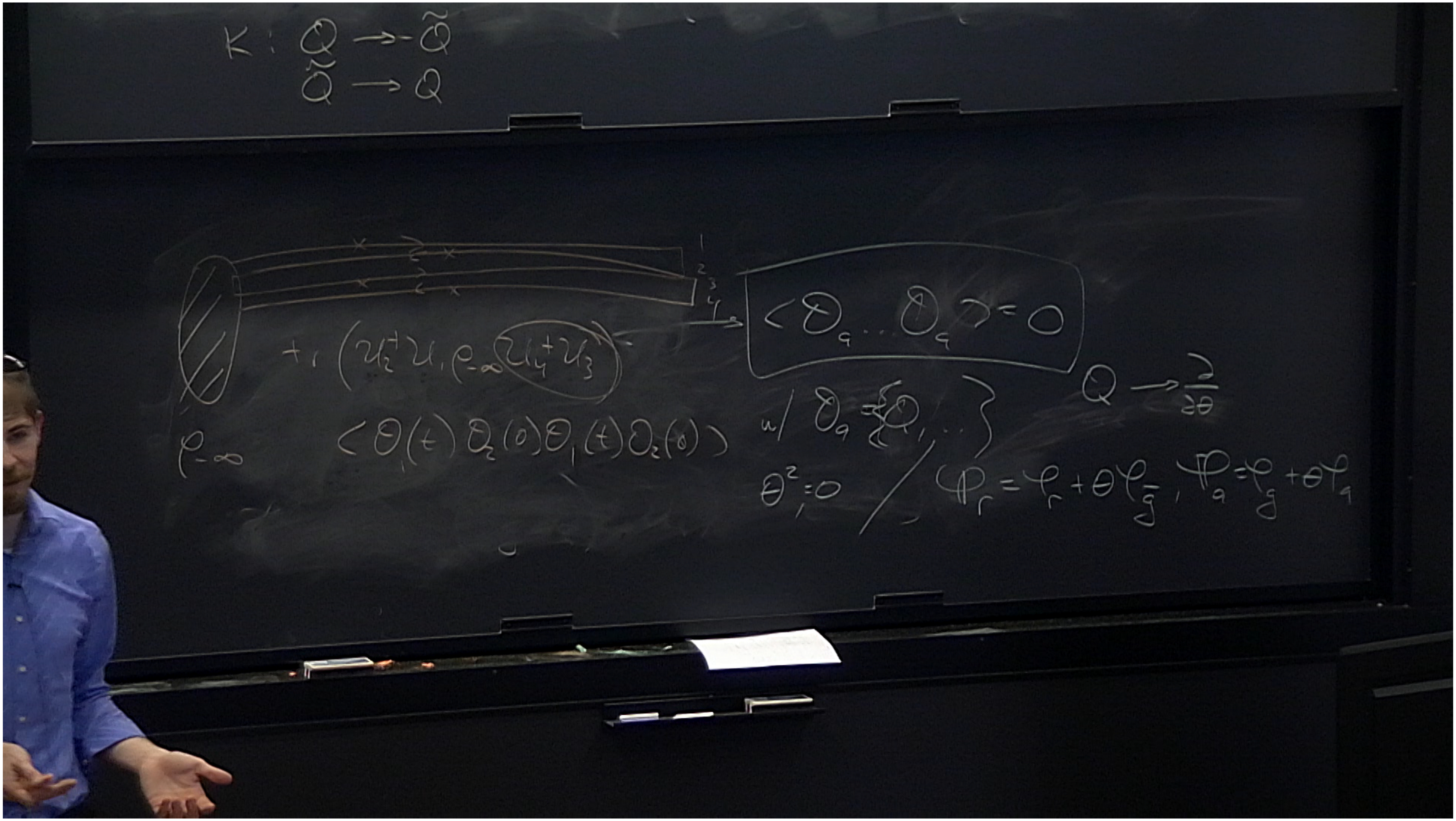
$\rho_{-\infty}$ $\quad \langle O_1(t)\, O_2(0)\, O_1(t)\, O_2(0) \rangle$

$\theta_1^2 = 0$

$\Phi_r = \varphi_r + \theta \varphi_{\bar{g}}, \quad \Phi_a = \varphi_g + \theta \varphi_a$



K : Q → -Q̃
Q̃ → Q
1
2
3
4
< O_a ... O_a > = 0
Q → ∂/∂θ
+ (U_2^† U_1 ρ_{-∞} U_4^† U_3)
w/ O_a = {O_1, ...}
ρ_{-∞}
< O_1(t) O_2(0) O_1(t) O_2(0) >
θ_1^2 = 0
Φ_r = φ_r + θ φ_g , Φ_a = φ_g + θ φ_a


K : Q → -Q̃
Q̃ → Q
⟨O_a ... O_a⟩ = 0
w/ O_a = {O_1, ...}
Q → ∂/∂θ
⟨O_1(t) O_2(0) O_1(t) O_2(0)⟩
θ_1^2 = 0
Φ_r = φ_r + θ φ_g̃ , Φ_a = φ_g + θ φ_a