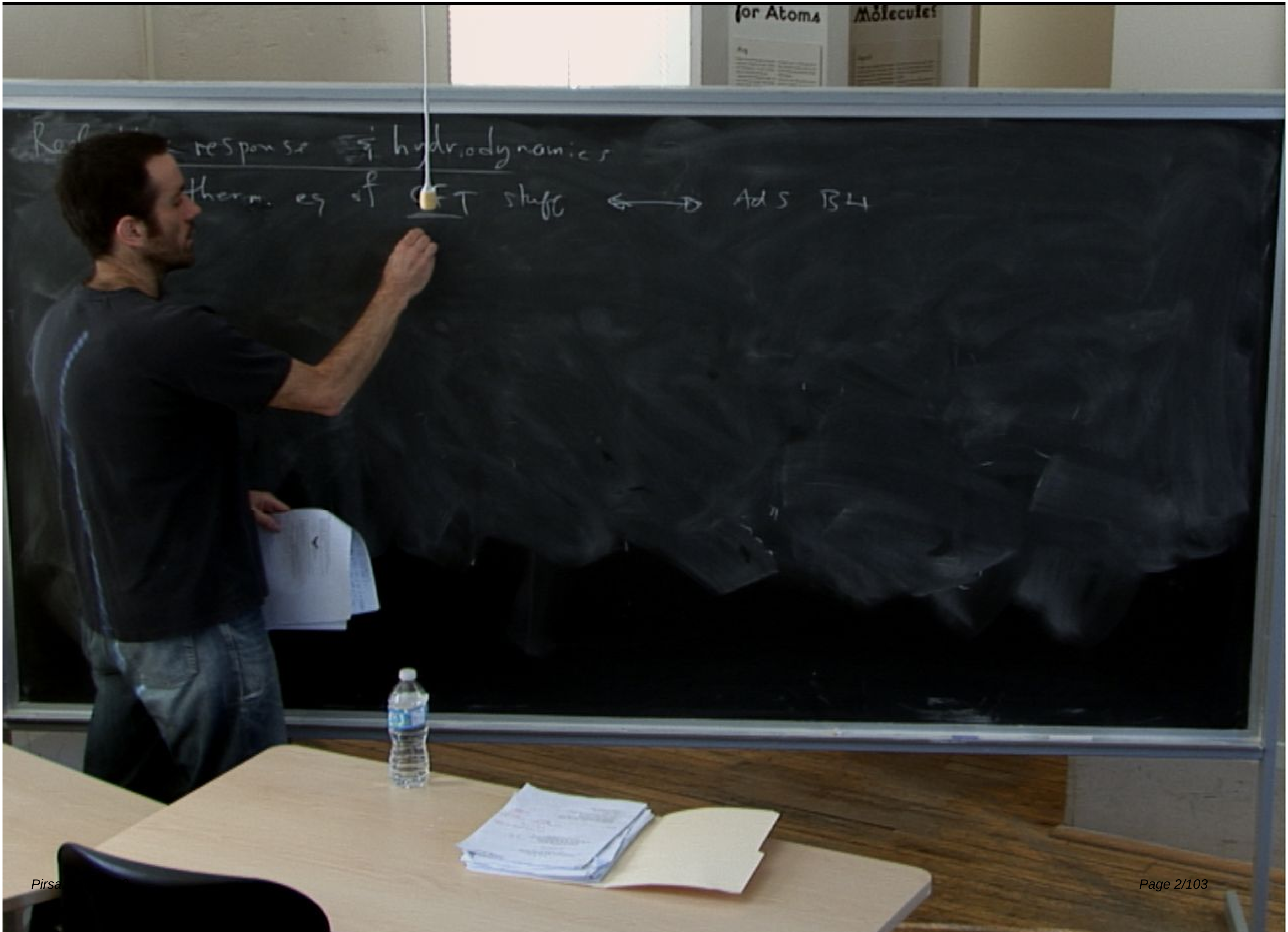
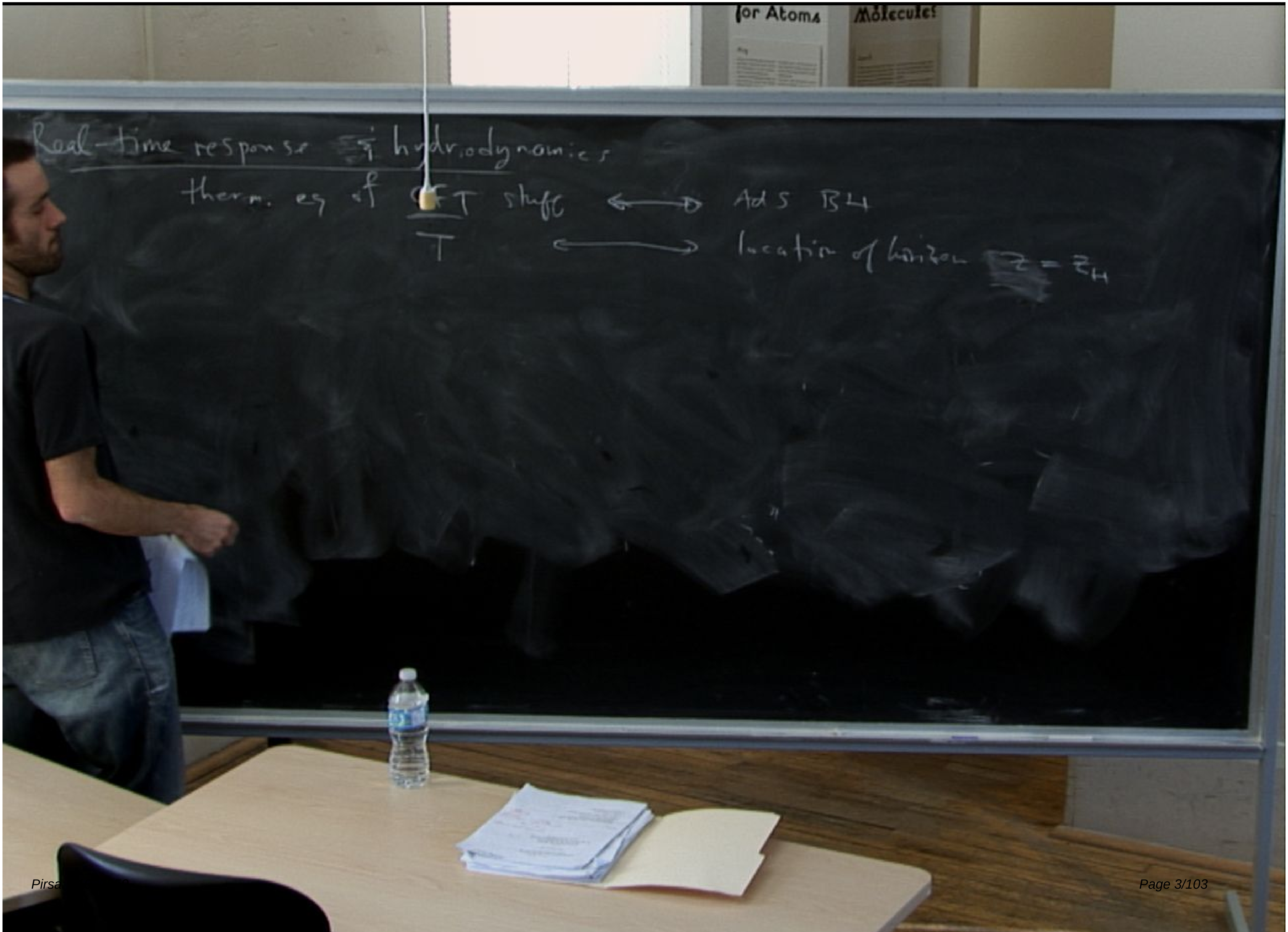
Title: Explorations in String Theory - Lecture 10

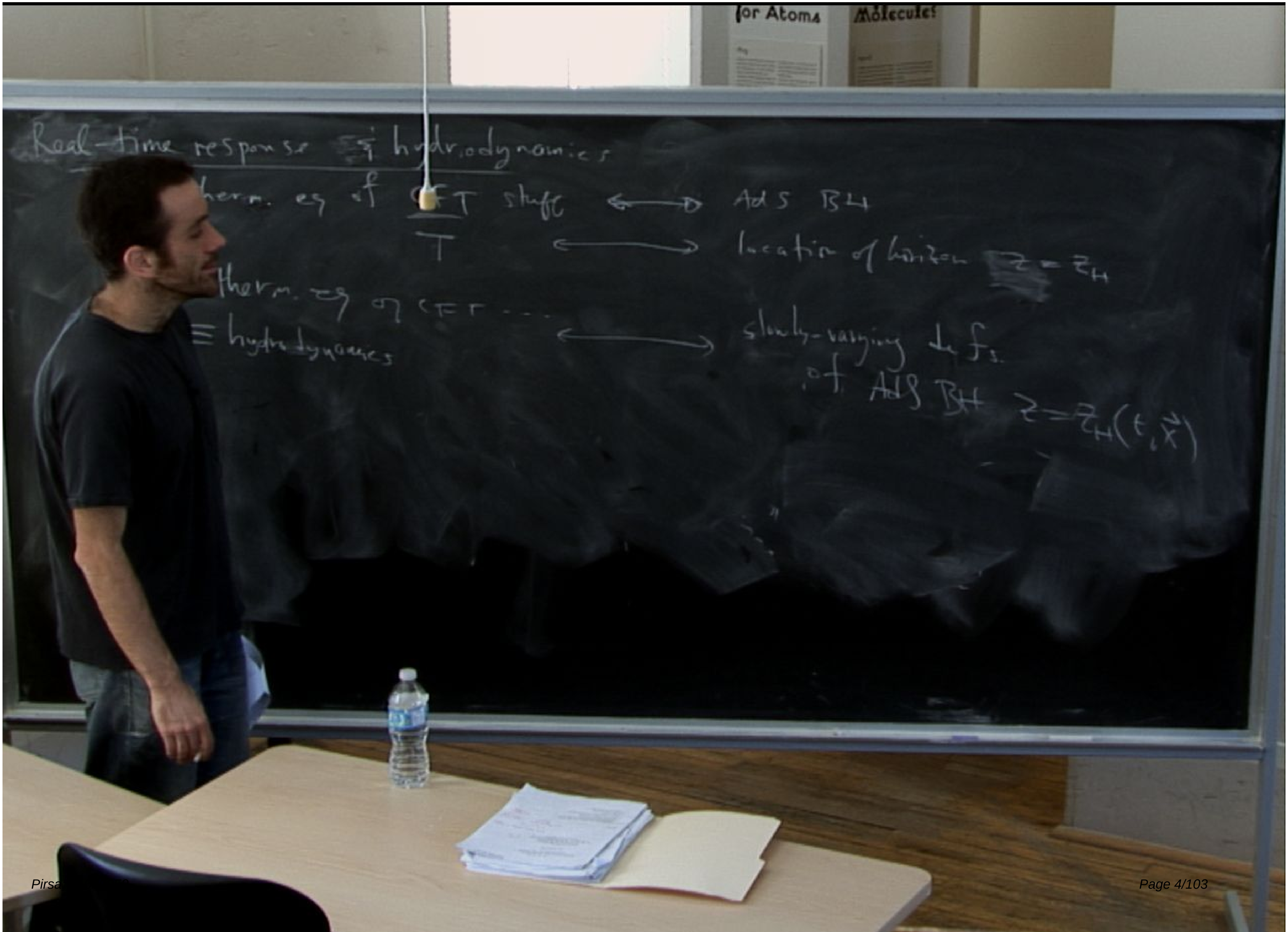
Date: Mar 25, 2011 11:30 AM

URL: http://pirsa.org/11030059

Abstract:


for Atoms
Molecules
response hydrodynamics
therm. eq of
stuff
AdS


for Atoms
Molecules
Real-time response & hydrodynamics
therm. eq of CFT stuff ⟷ AdS BH
T ⟷ location of horizon z = z_H


for Atoms
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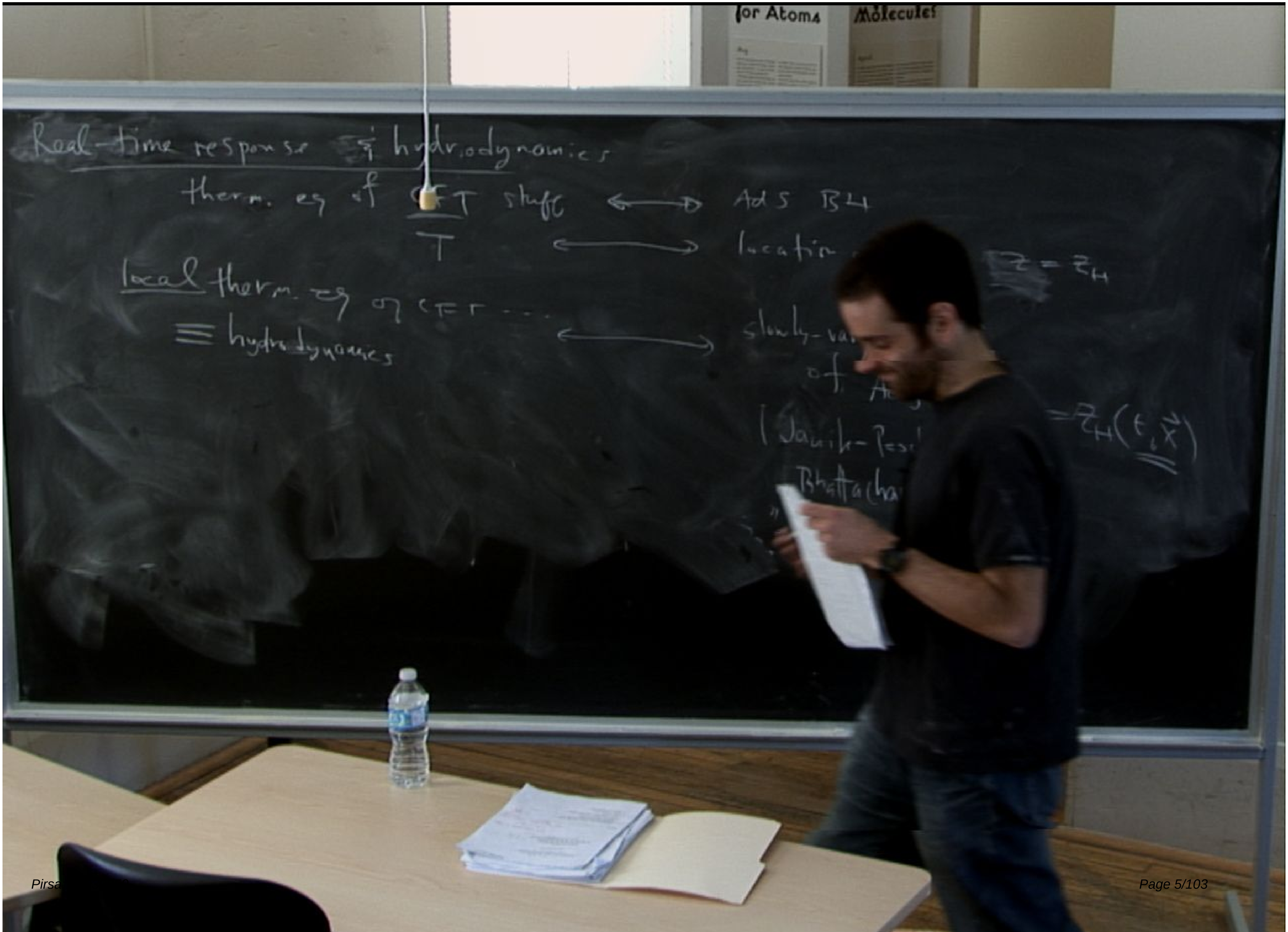
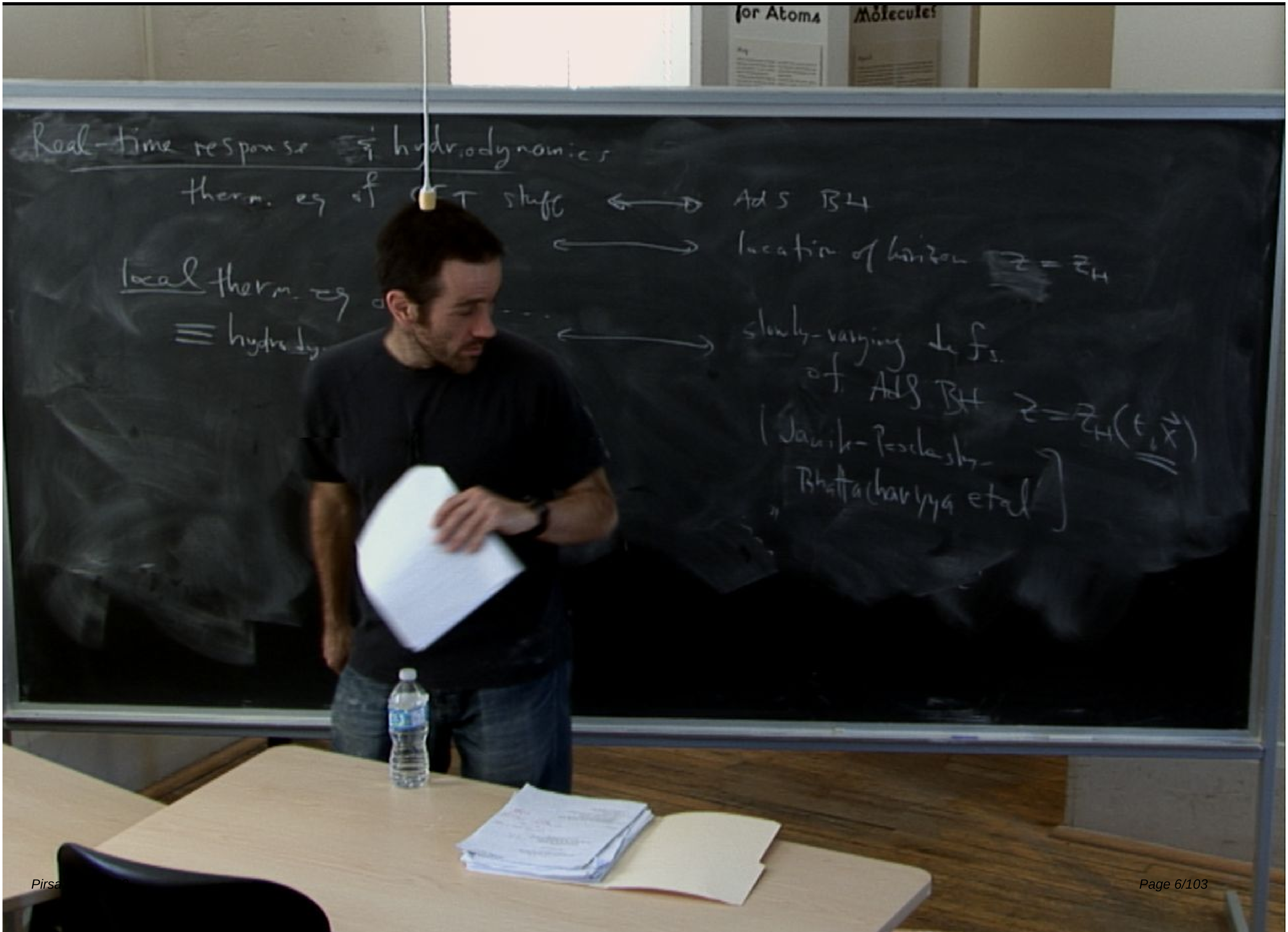
therm. eq of CFT stuff ⟷ AdS BH
T ⟷ location of horizon z = z_H
therm. eq of CFT ...
≡ hydrodynamics ⟷ slowly-varying dofs. of AdS BH z = z_H(t, x)


for Atoms
Molecules
Real-time response & hydrodynamics
therm. eq of CFT stuff ⟷ AdS BH
T ⟷ location
$z = z_H$
local therm. eq of CFT ...
≡ hydrodynamics ⟷
$z_H(t, \vec{x})$


for Atoms
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stuff ⟷ AdS BH
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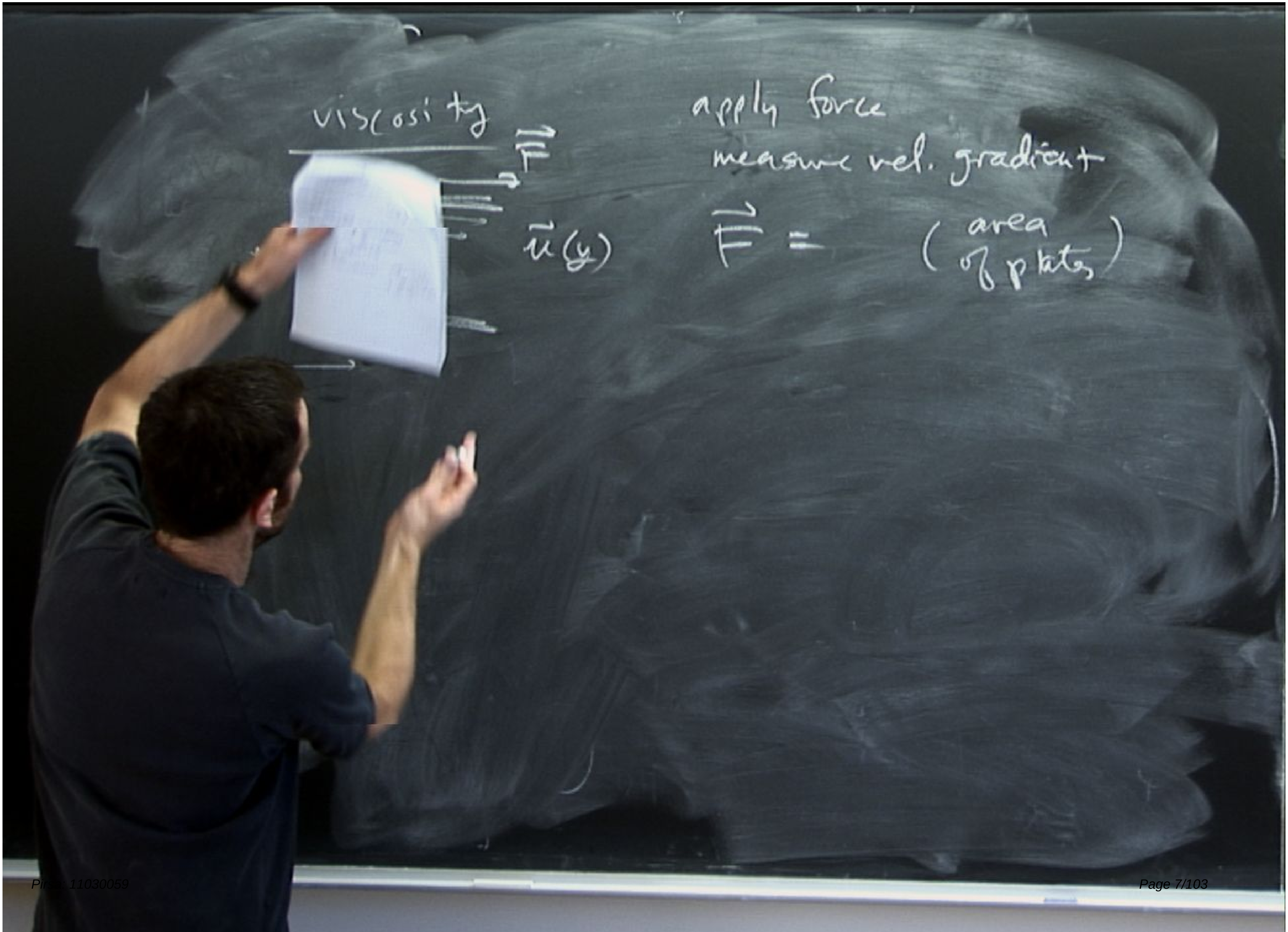
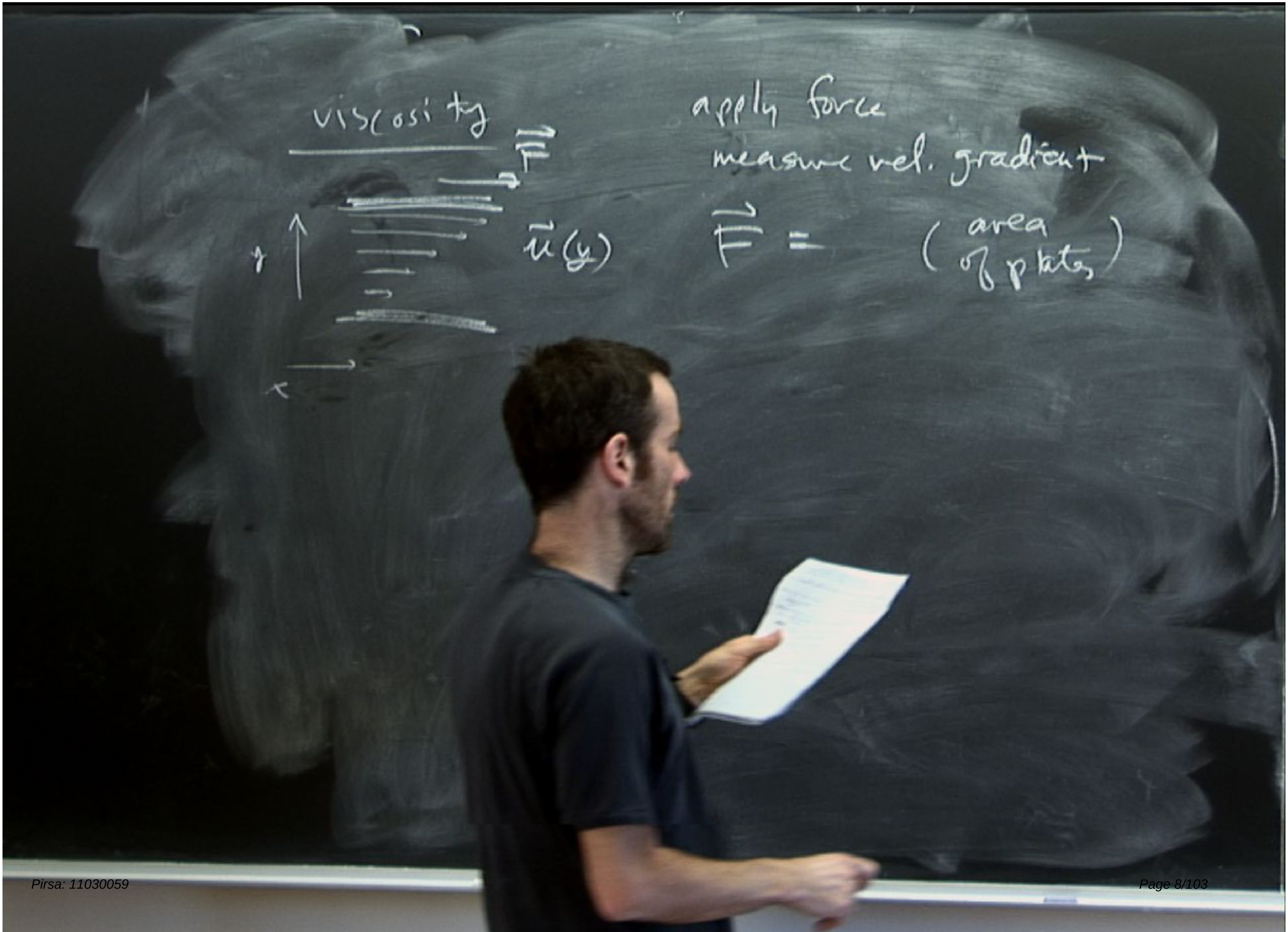
≡ hydrody
⟷ slowly-varying dofs.
of AdS BH z = z_H(t, x)
(Janik-Peschanski-
Bhattacharyya et al)


viscosity
$\vec{F}$
$\vec{u}(y)$
apply force
measure vel. gradient
$\vec{F} = \left(\text{area of plates} \right)$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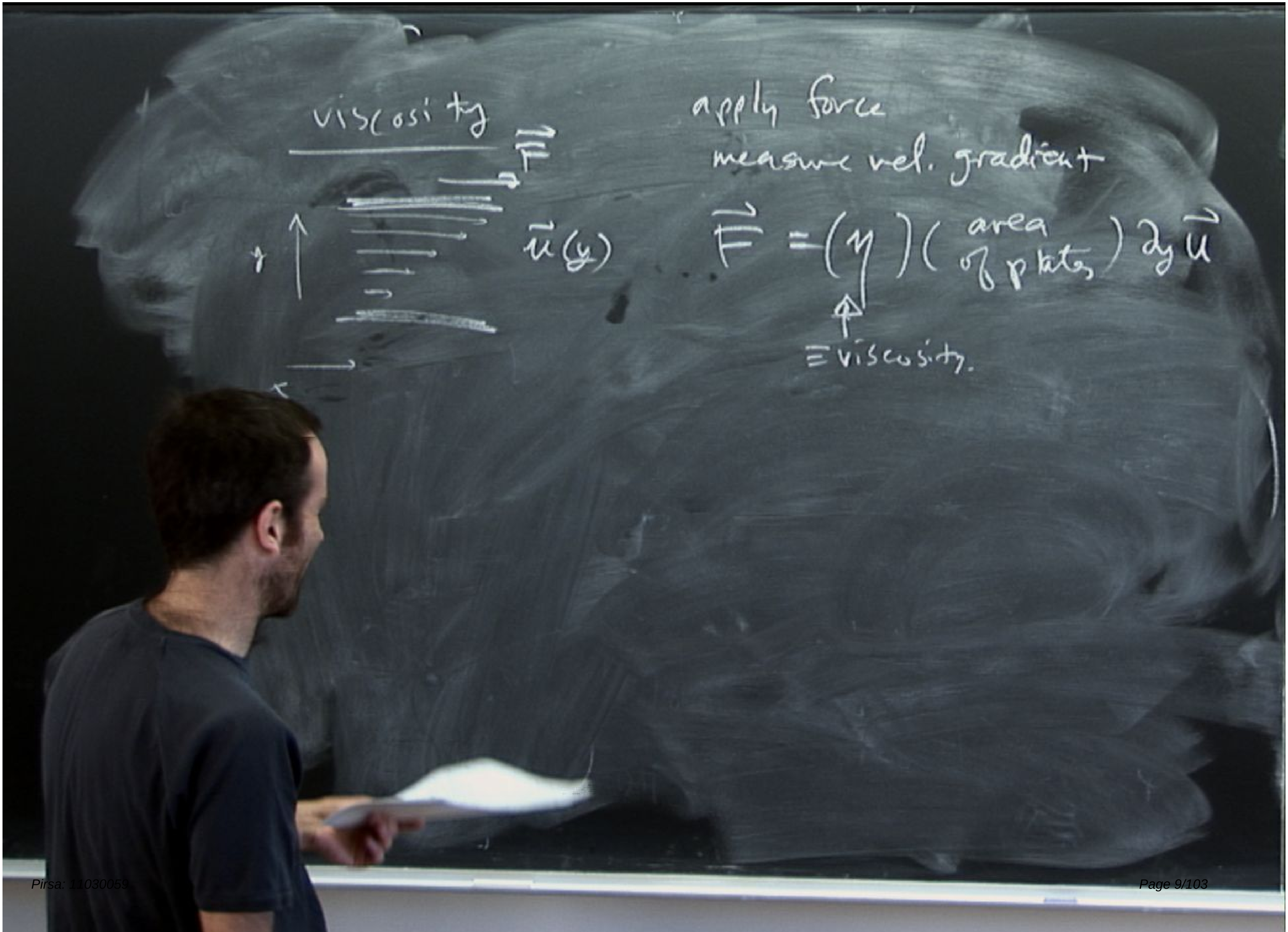
viscosity
$\vec{F}$
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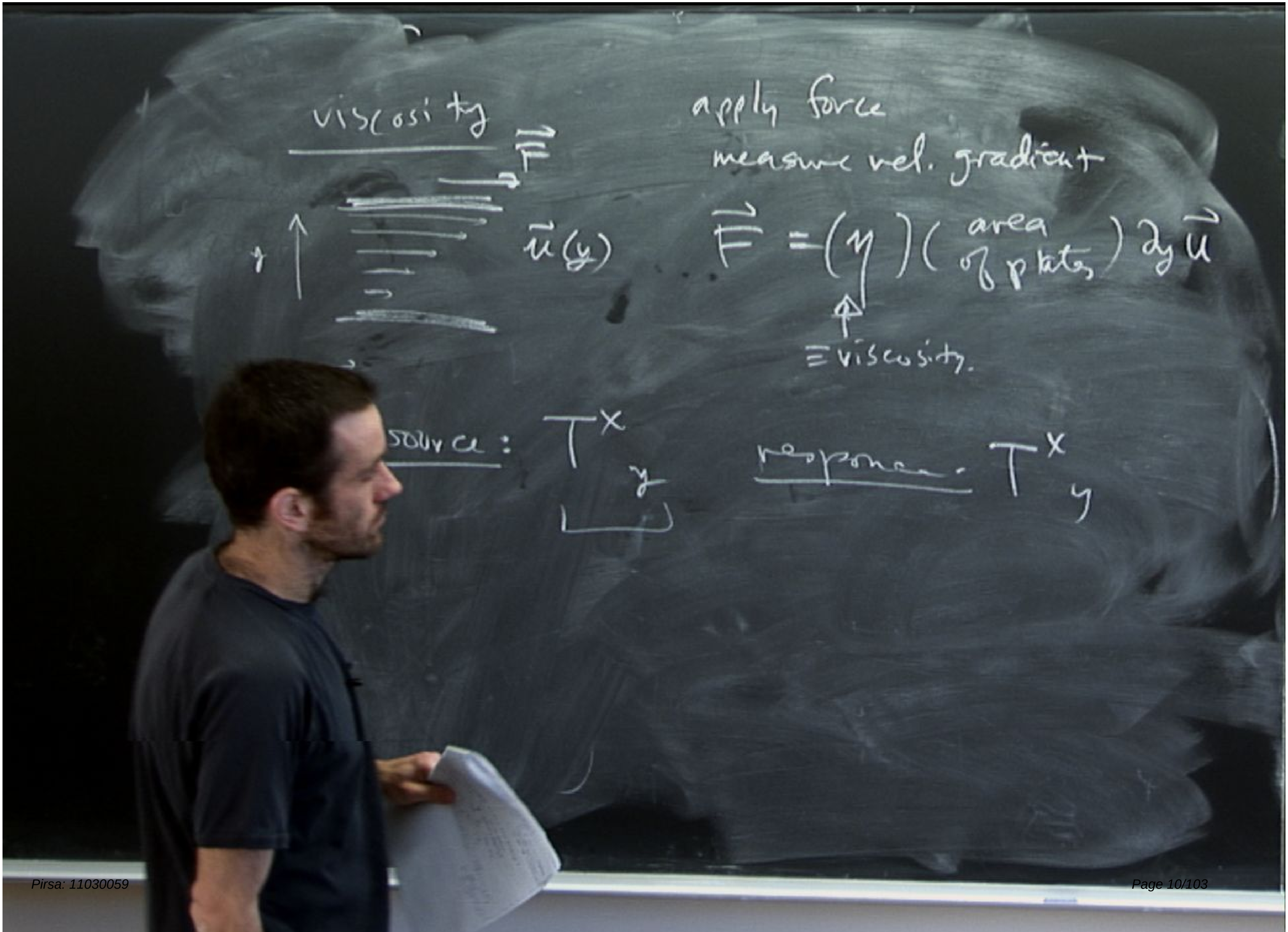
apply force
measure vel. gradient
$\vec{F} = (\eta)(\text{area of plates})\,\partial_y \vec{u}$
$\equiv$ viscosity.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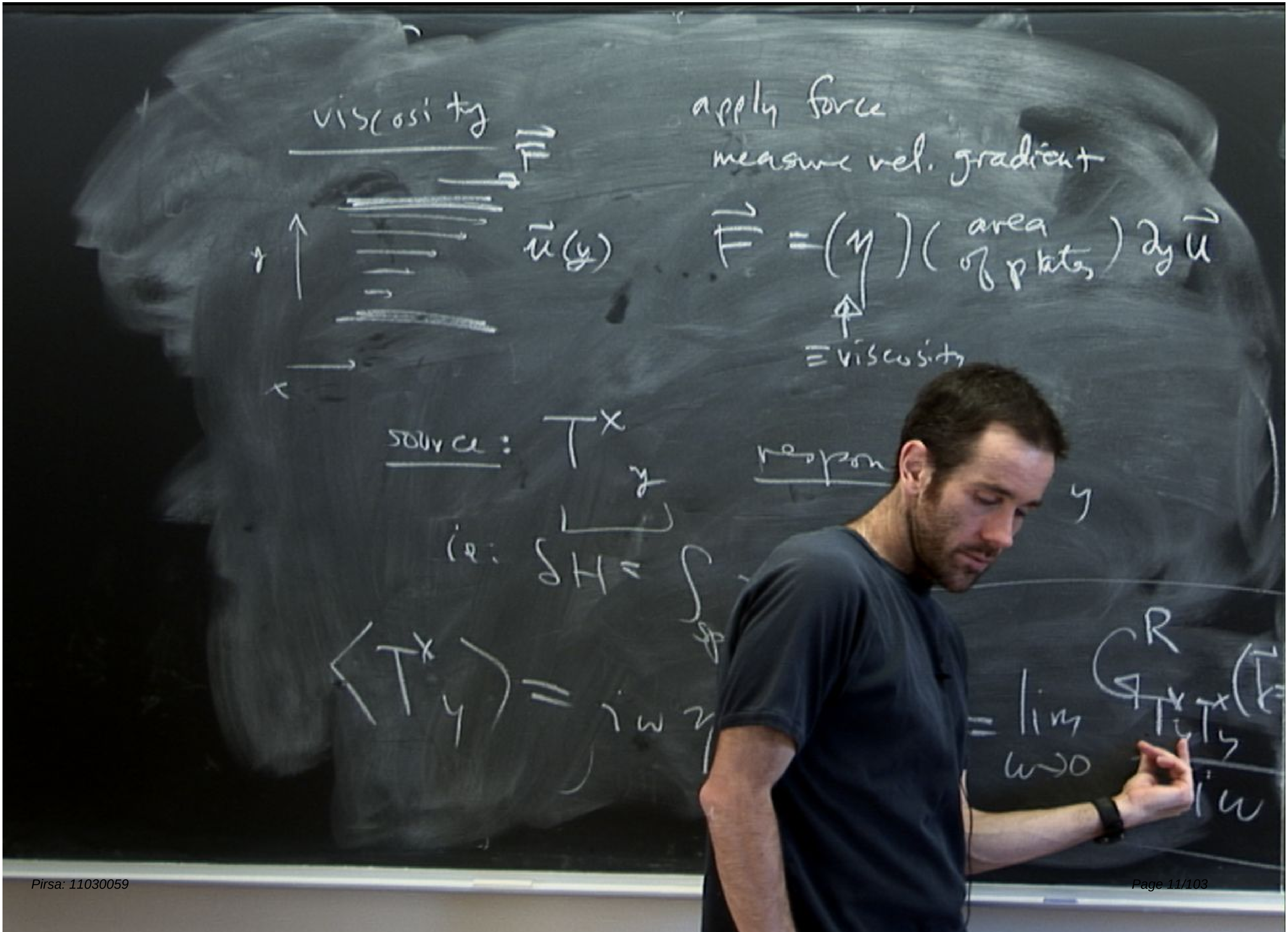
$\equiv$ viscosity.
source : $T^x{}_y$
response : $T^x{}_y$


viscosity
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$\vec{F} = (\eta)(\text{area of plates})\, \partial_y \vec{u}$
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source: $T^x{}_y$
respon
i.e. $\delta H = \int$
$\langle T^x{}_y \rangle = i\omega\,\eta$
$= \lim_{\omega \to 0} \dfrac{G^R_{T^x{}_y T^x{}_y}}{i\omega}$

viscosity

$\vec{F}$

$y \uparrow$ $\vec{u}(y)$

apply force

measure vel. gradient

$$\vec{F} = (\eta)\left(\begin{matrix}\text{area}\\ \text{of plates}\end{matrix}\right)\partial_y \vec{u}$$

$\equiv$ viscosity.

force : $T^x{}_y$ response : $T^x{}_y$

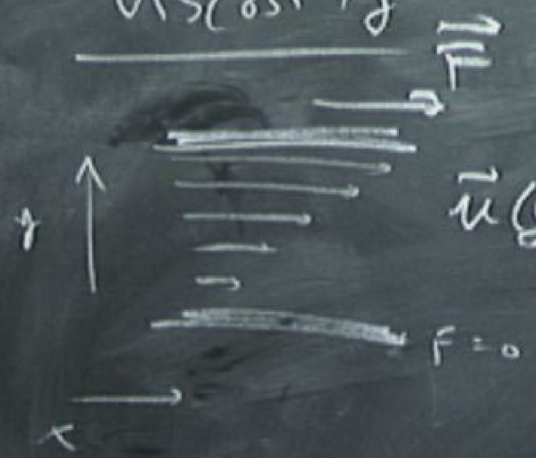
i.e.: $\delta H = \int_{\text{space}} \gamma^y{}_x T^x{}_y$

$\langle T^x{}_y \rangle = i\omega\,\eta\,\gamma^x{}_y \Longrightarrow$

Kubo:

$$\boxed{\eta = \lim_{\omega\to 0} \frac{G^R_{T^x_y T^x_y}(\vec{k}=}{i\omega}}$$

viscosity



apply force

measure vel. gradient

$$\vec{F} = (\eta)\left(\begin{matrix}\text{area}\\ \text{of plates}\end{matrix}\right)\partial_y \vec{u}$$

$\uparrow$

$\equiv$ viscosity.

source: $T^x_{\ y}$

response: $T^x_{\ y}$

i.e. $\delta H = \int_{\text{space}} \gamma^y_{\ x}\, T^x_{\ y}$

$$\langle T^x_{\ y}\rangle = i\omega\,\eta\,\gamma^x_{\ y} \Rightarrow$$

Kubo:

$$\boxed{\eta = \lim_{\omega\to 0} \frac{G^R_{T^x_y T^x_y}(\vec{k}}{i\omega}}$$

very general bulk metric:

$$ds^2 = g_{tt}\,dt^2 + g_{zz}\,dz^2 + g_{ij}\,dx^i dx^j$$

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<u>s.t.</u>: $g_{AB} = g_{AB}(z)$

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2) $\longrightarrow AdS_5$ near $z \to 0$.

($\exists$ holographic interpretation)

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s.t.: 1) $g_{AB} = g_{AB}(z)$

2) $\longrightarrow$ AdS5 near $z \to 0$.

3) $g_{tt} \xrightarrow{z \to z_H} -2K(z_H - z)$

$$g_{zz} \longrightarrow \frac{1}{2K(z_H - z)}$$

($\exists$ holographic interpretation)

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Rindler horizon

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Rindler horizon

($\exists$ holographic interpretation)

Consider $\dfrac{1}{2}\int d^{d+1}x \sqrt{g}\, (\partial\phi)^2 \dfrac{1}{g(z)}$

very general bulk metric:

$$ds^2 = g_{tt}\,dt^2 + g_{zz}\,dz^2 + g_{ij}\,dx^i dx^j$$

s.t.: 1) $g_{AB} = g_{AB}(z)$

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$g_{zz} \longrightarrow \dfrac{1}{2K(z_H - z)}$

Rindler horizon

(∃ holographic interpretation)

Consider: $S = -\frac{1}{2}\int d^{d+1}x \sqrt{g}\,(\partial\phi)^2 \frac{1}{q(z)}$

$\phi \leftrightarrow \mathcal{O}$

eg $\phi = h^x_y$

very general bulk metric:

$$ds^2 = g_{tt}\,dt^2 + g_{zz}\,dz^2 + g_{ij}\,dx^i dx^j$$

s.t.: 1) $g_{AB} = g_{AB}(z)$

2) $\longrightarrow AdS_5$ near $z \to 0$.

([$\exists$ holographic interpretation])

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Rindler horizon

Consider: $S = -\frac{1}{2}\int d^{d+1}x \sqrt{g}\left[(\partial\phi)^2 \frac{1}{g(z)}\right]$

$\phi \leftrightarrow \mathcal{O}$

eg. $\phi = h^x_{\ y}$

$\mathcal{O} = T^x_{\ y}$

very general bulk metric:

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Consider: $S = -\frac{1}{2}\int d^{d+1}x \sqrt{g}\left[(\partial\phi)^2 \frac{1}{q(z)}\right]$

$q = \frac{1}{16\pi G_N}$

eg. $\phi = h^x_y$

$O = T^x_y$

very general bulk metric:

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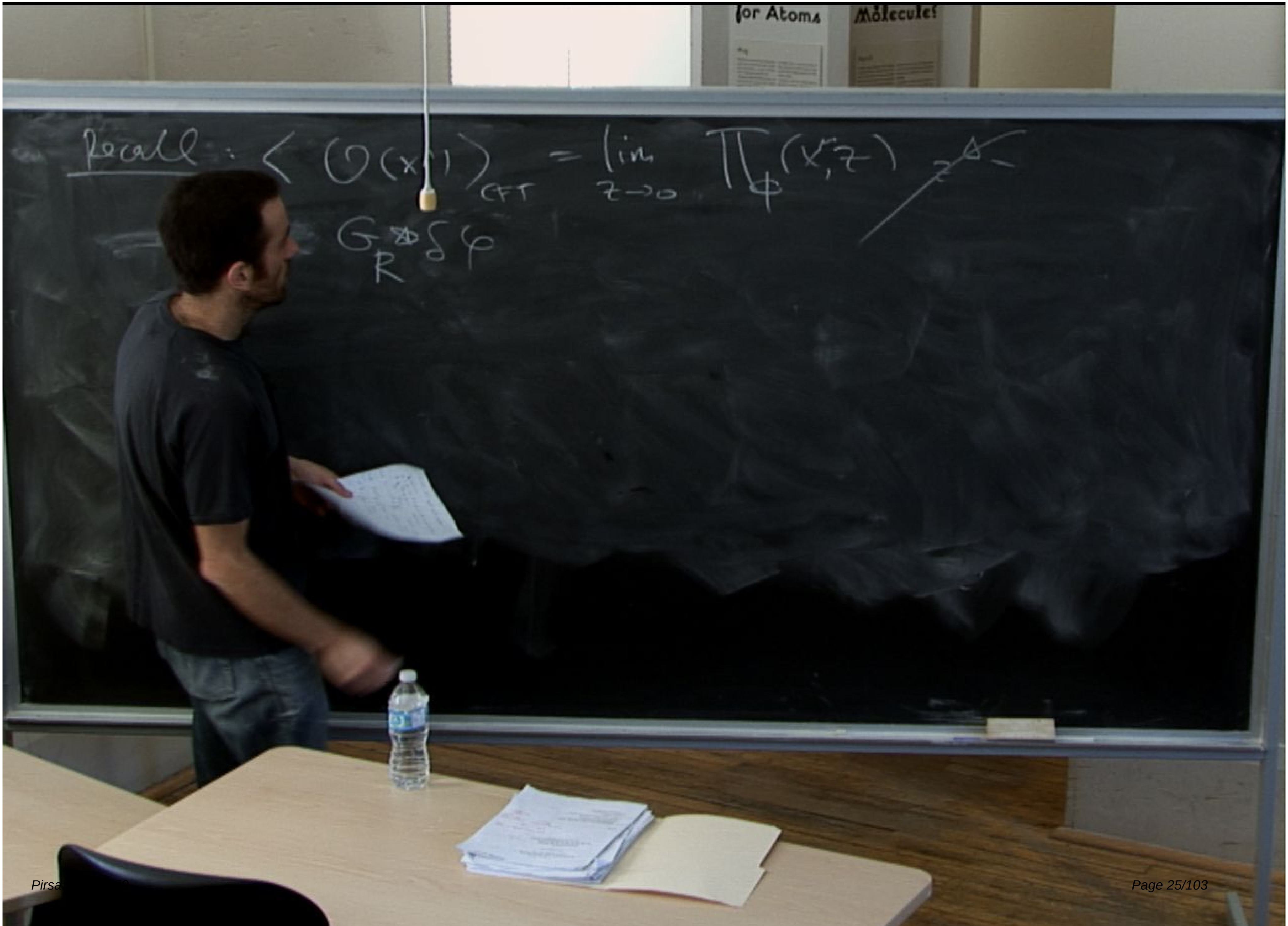
Consider: $S = -\frac{1}{2}\int d^{d+1}x \sqrt{g}\left[(\partial\phi)^2 \frac{1}{q(z)}\right]$

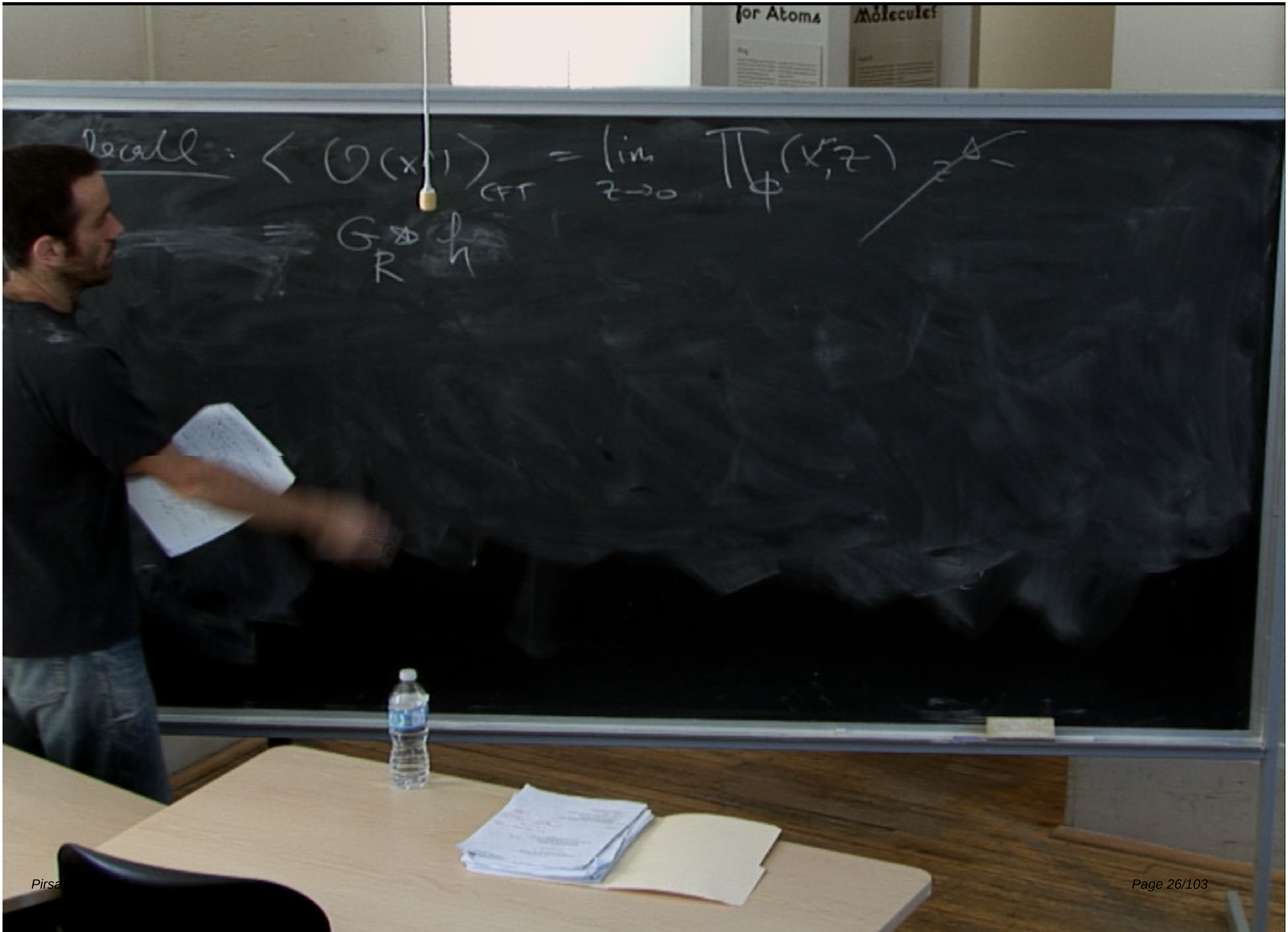
$$\boxed{q = 16\pi G_N}$$

$\underline{eg}$: $\phi = h^x_y$

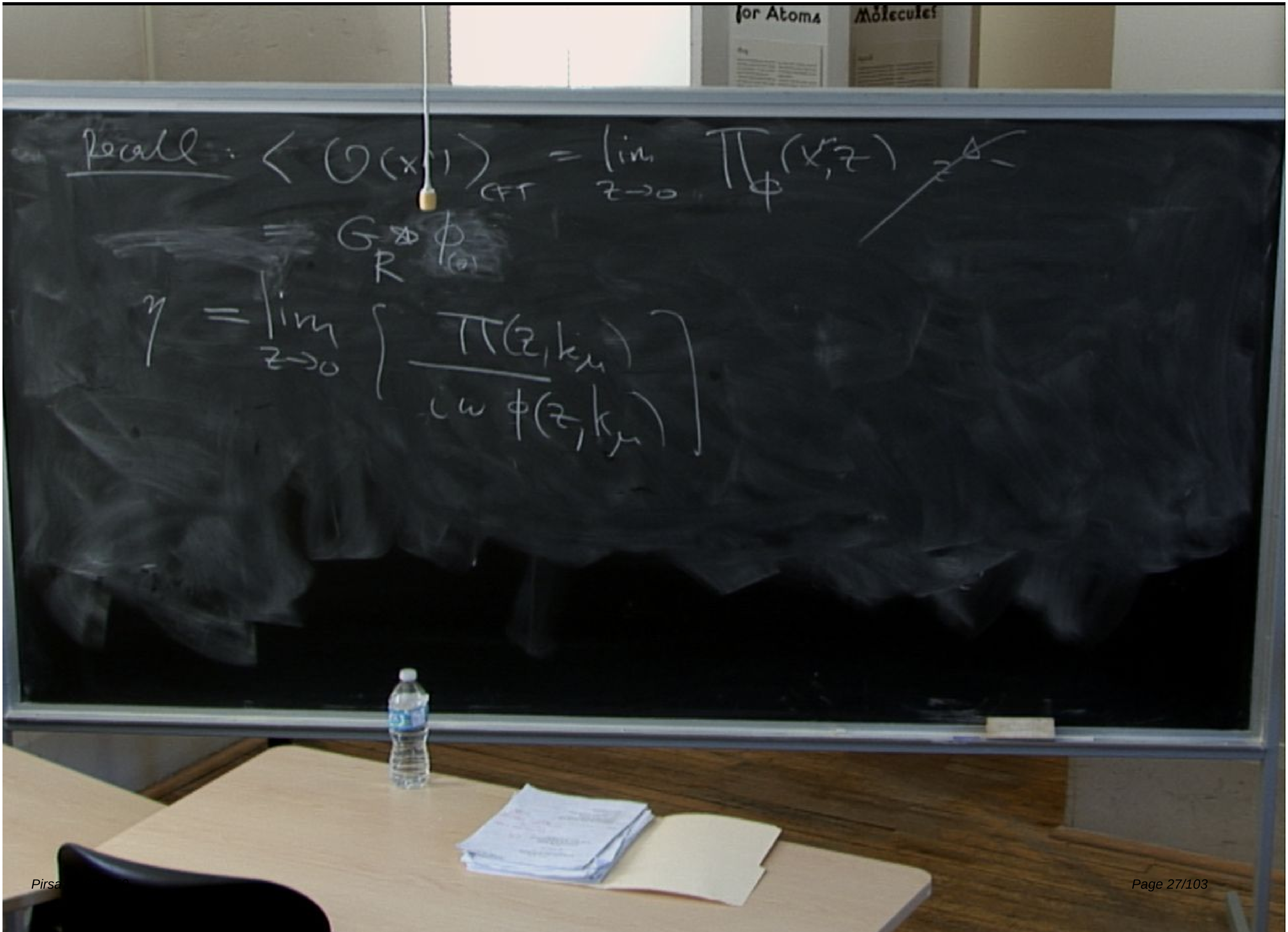
$\quad\; \mathcal{O} = T^x_y$

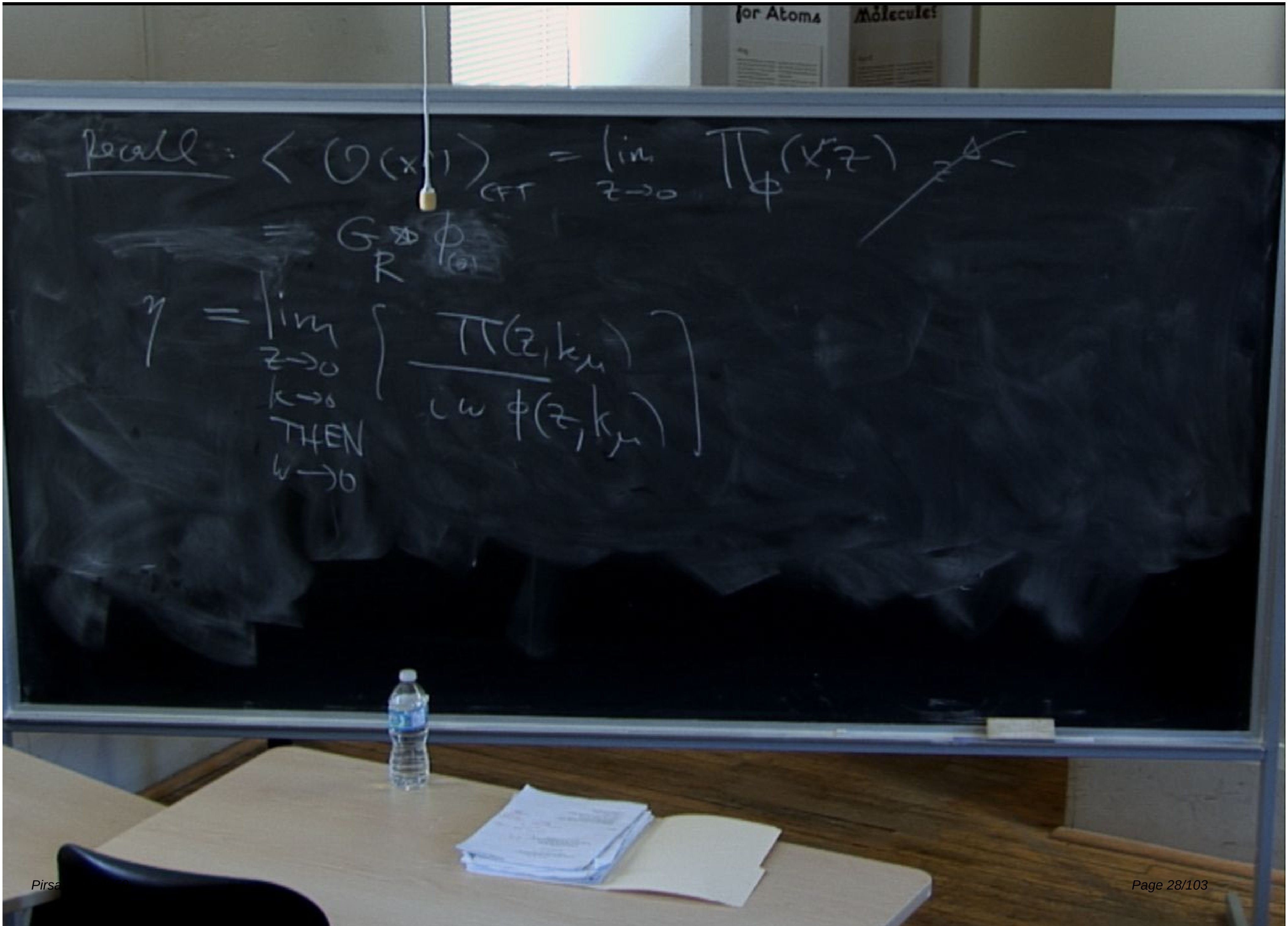
$$\boxed{m = 0}$$


for Atoms
Molecules
Recall



for Atoms
Molecules
Recall :


for Atoms
Molecules
Recall: $\langle \mathcal{O}(x,1) \rangle_{CFT} = \lim_{z \to 0} \Pi_\phi(x,z)$
$= G_R \, \phi_{(0)}$
$\eta = \lim_{z \to 0} \left[\frac{\Pi(z, k_\mu)}{i\omega \, \phi(z, k_\mu)} \right]$


for Atoms
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Recall: $\langle \mathcal{O}(x^\mu) \rangle_{CFT} = \lim_{z \to 0} \Pi_\phi(x^\mu, z)$
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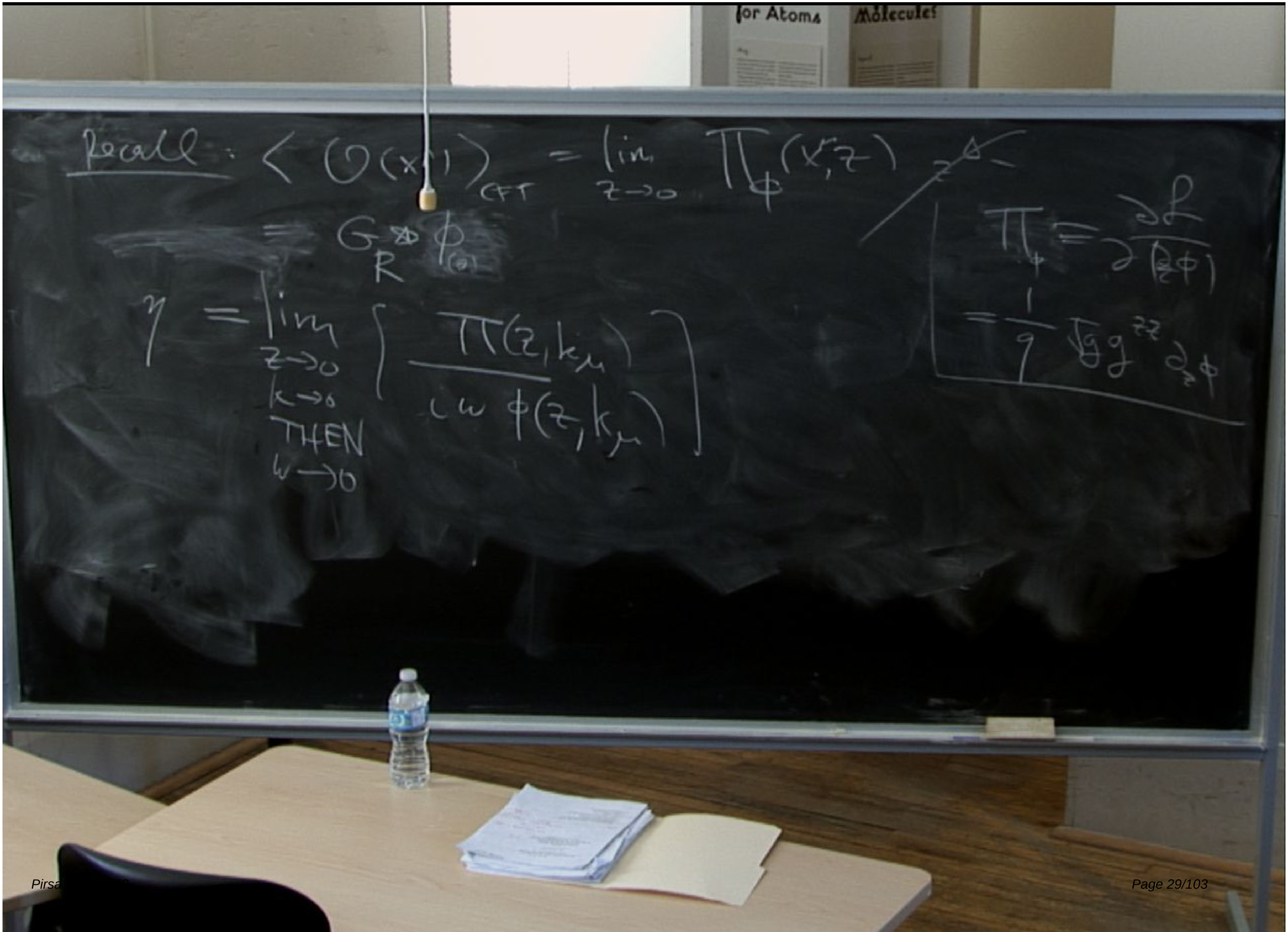
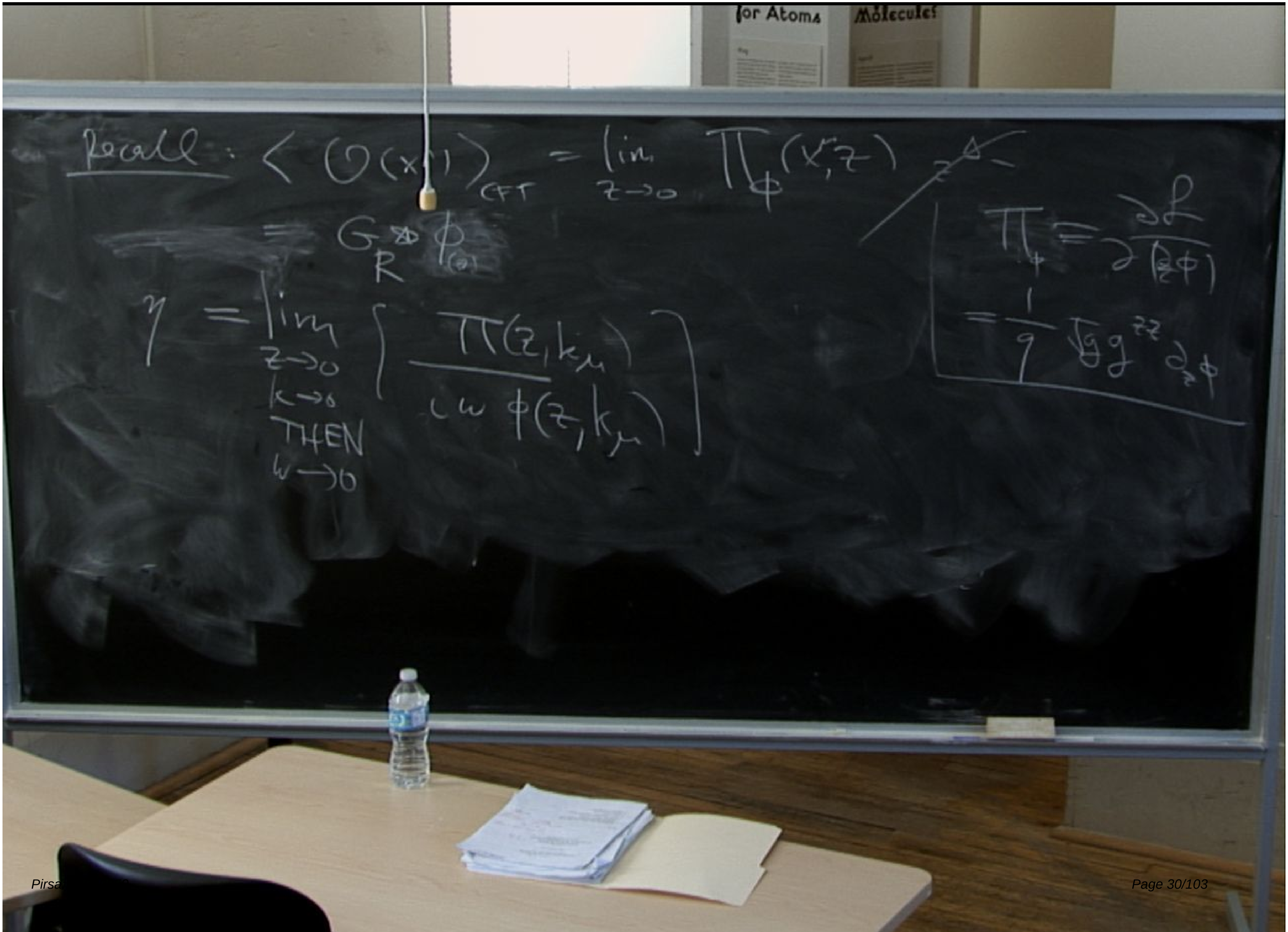

for Atoms
Molecules
Recall: $\langle \mathcal{O}(x,t)\rangle_{CFT} = \lim_{z\to 0} \Pi_\phi(x,z)$
$= G_R\, \phi_{(0)}$
$\eta = \lim_{\substack{z\to 0\\ k\to 0\\ \text{THEN}\\ \omega\to 0}} \left[\frac{\Pi(z,k_\mu)}{i\omega\, \phi(z,k_\mu)}\right]$
$\Pi_\phi = \frac{\partial \mathcal{L}}{\partial(\partial_z \phi)}$
$= -\frac{1}{q}\sqrt{-g}\, g^{zz}\, \partial_z \phi$


for Atoms
Molecules
Recall: $\langle \mathcal{O}(x^\mu) \rangle_{CFT} = \lim_{z \to 0} \Pi_\phi(x^\mu, z)$
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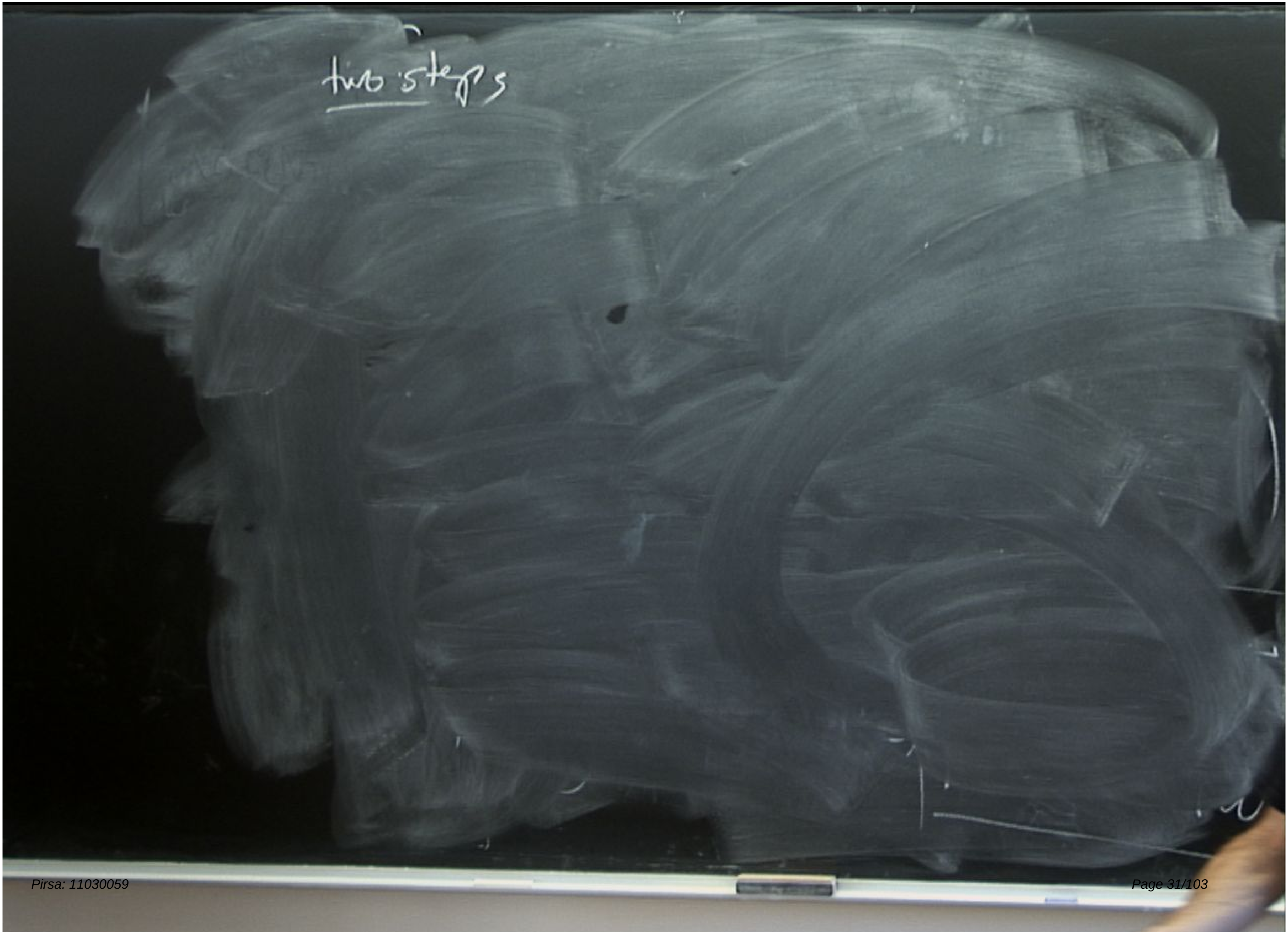
$= \frac{1}{q} \sqrt{g} \, g^{zz} \, \partial_z \phi$


two steps

two steps

1) near horizon: $\phi(z) \simeq (z - z_H)^{\pm i\omega/4\pi T}$

two steps

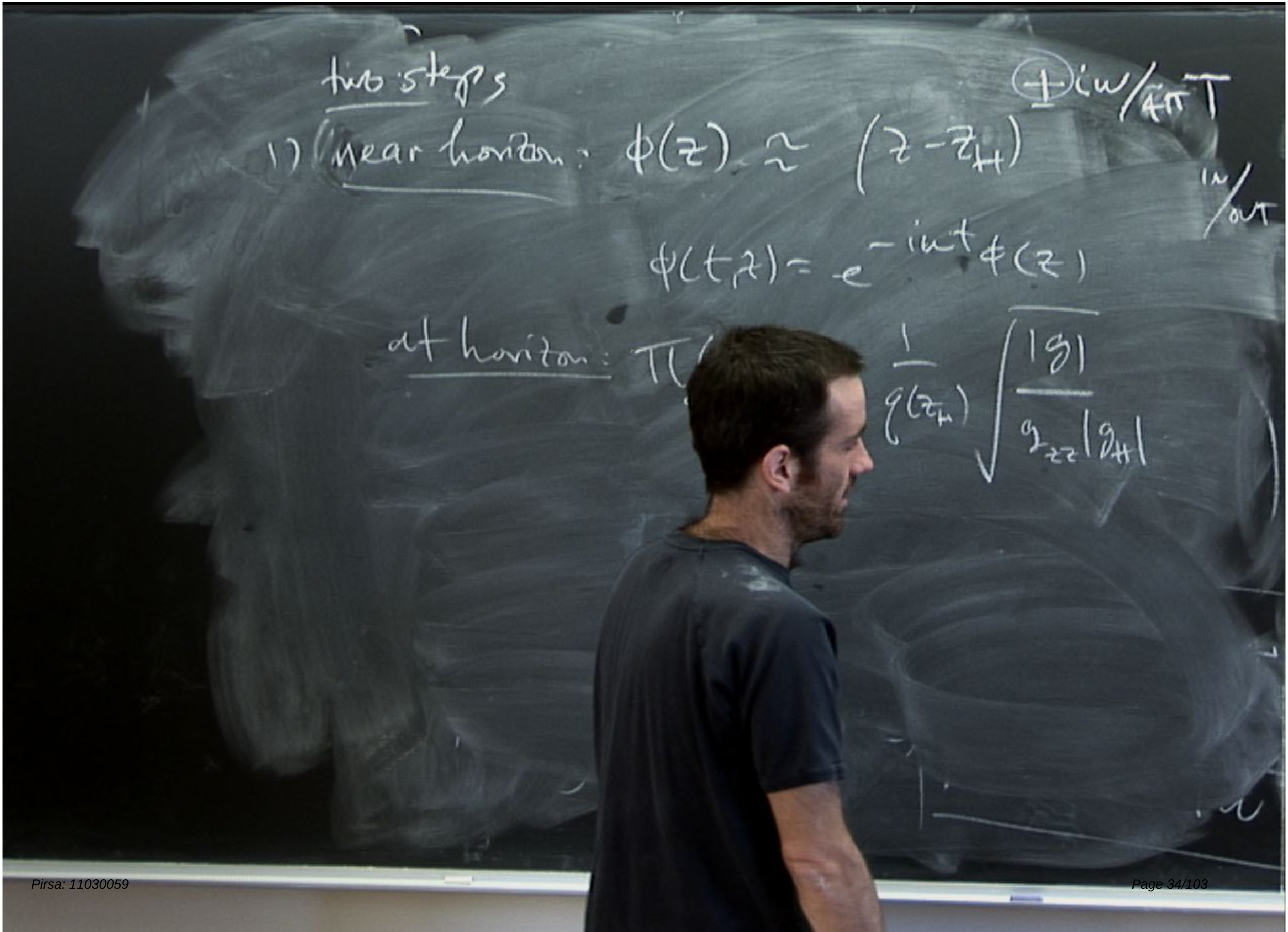
$\pm i\omega / 4\pi T$

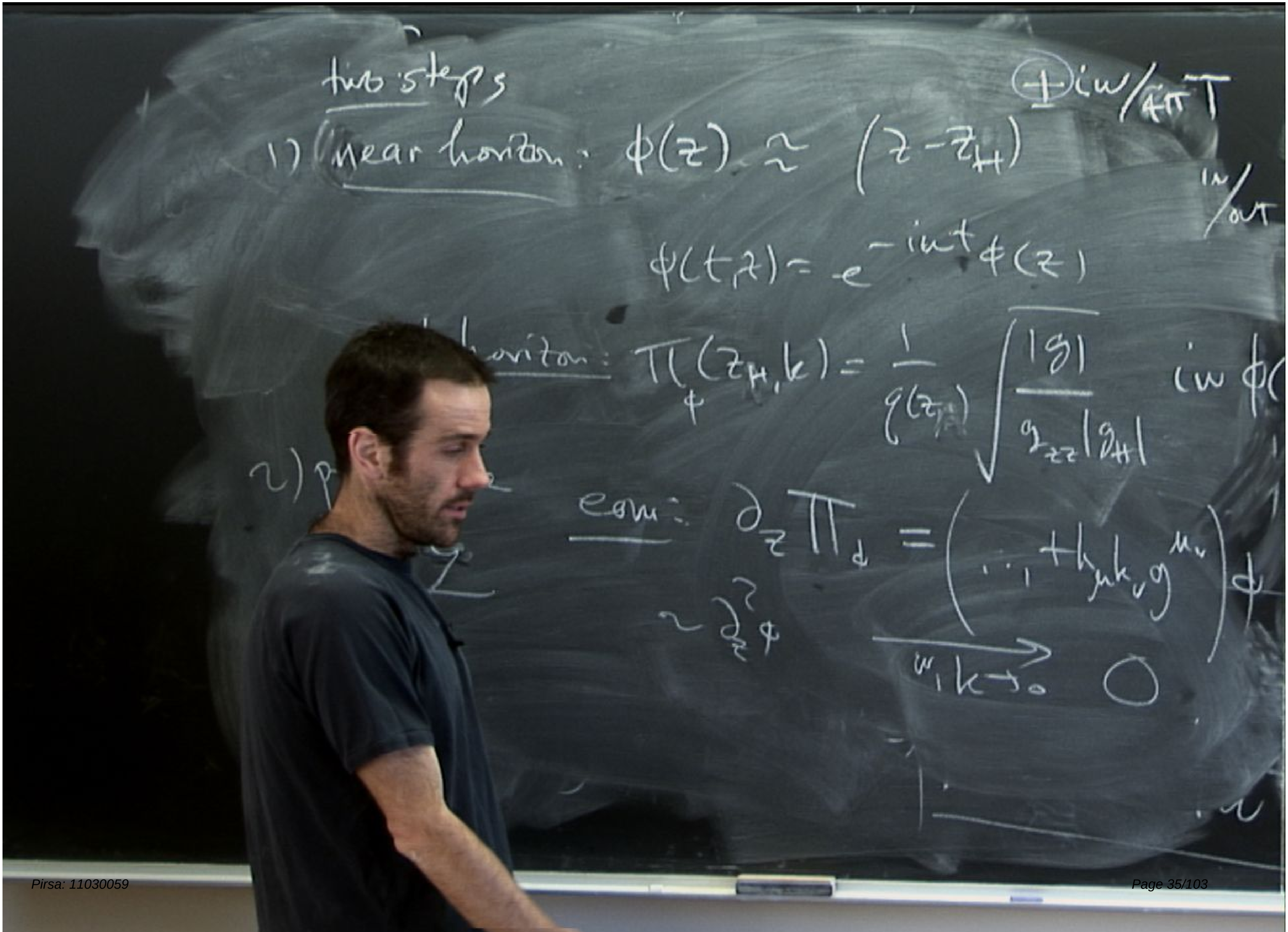
1) near horizon: $\phi(z) \sim (z - z_H)^{\pm i\omega/4\pi T}$

in/out

$\phi(t,z) = e^{-i\omega t} \phi(z)$

at horizon: $\Pi_\phi(z_H, k) = \frac{1}{q(z_H)} \sqrt{\frac{|g|}{g_{zz}|g_H|}}$


two steps
± iω/4πT
1) near horizon: φ(z) ≈ (z − z_H)
in/out
φ(t,z) = e^{−iωt} φ(z)
at horizon: Π(


two steps
$\pm i\omega/4\pi T$
1) near horizon: $\phi(z) \simeq (z-z_H)$
in/out
$\phi(t,z) = e^{-i\omega t}\phi(z)$
horizon: $\Pi_\phi(z_H,k) = \frac{1}{q(z_H)}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}\, i\omega\phi$
2)
eom: $\partial_z \Pi_\phi = (\ldots, + k_\mu k_\nu g^{\mu\nu})\phi$
$\sim \partial_z^2 \phi$
$\omega, k \to 0$
0

two steps

1) near horizon: $\phi(z) \approx (z - z_H)^{\pm i\omega/4\pi T}$ in/out

$$\phi(t,z) = e^{-i\omega t}\phi(z)$$

at horizon: $\Pi_\phi(z_H, k) = \frac{1}{q(z_H)}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}\; i\omega\,\phi($

2) propagate to bdy.

eom: $\partial_z \Pi_\phi = \left(\dots, + k_\mu k_\nu g^{\mu\nu}\right)\phi \xrightarrow{\omega, k \to 0} 0$

$$\sim \partial_z^2 \phi$$

$$\partial_z(\phi\omega) = \frac{q}{\sqrt{g}\,g^{zz}}\,\omega\,\Pi_\phi$$

two steps $\pm i\omega/4\pi T$

1) near horizon: $\phi(z) \simeq (z - z_H)$ in/out

$\phi(t,z) = e^{-i\omega t}\phi(z)$

at horizon: $\Pi_\phi(z_H,k) = \frac{1}{q(z_H)}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}\; i\omega\,\phi($

2) propagate to bdy

eom: $\partial_z \Pi_\phi = \left(\ldots, + k_\mu k_\nu g^{\mu\nu} \right)\phi$ $\xrightarrow{\omega, k \to 0} 0$

$\sim \partial_z^2 \phi$

$\partial_z \left(\frac{\phi}{\omega} \right) = \frac{q}{\sqrt{g}\, g^{zz}\, \omega}\, \Pi_\phi \xrightarrow{\omega \to 0} 0$

$\omega\phi$ fixed

$$\left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=0} = \left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=z_H}$$

$\Big|_{z=z_H}$

$$\left.\frac{\Pi_\phi}{w\,\phi}\right|_{z=0} = \left.\frac{\Pi_\phi}{w\,\phi}\right|_{z=z_H}$$

$z=z_{H}$

$$\frac{\Pi_\phi}{w\phi}\Big|_{z=0} = \frac{\Pi_\phi}{w\phi}\Big|_{z=z_H}$$

"membrane paradigm"

$z=z_H$

$$\left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=0} = \left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=z_H}$$

"membrane paradigm"

$$\Rightarrow \eta = \frac{1}{q(z_H)} \sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}.$$

entropy density: $s = \frac{a}{4G_N} = \frac{1}{4G_N}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}$

$$\left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=0} = \left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=z_H}$$

"membrane paradigm"

$$\Longrightarrow \eta = \frac{1}{16\pi G_N}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}.$$

$z=z_H$

<u>entropy density</u>: $s = \frac{a}{4G_N} = \frac{1}{4G_N}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}$

$\eta =$

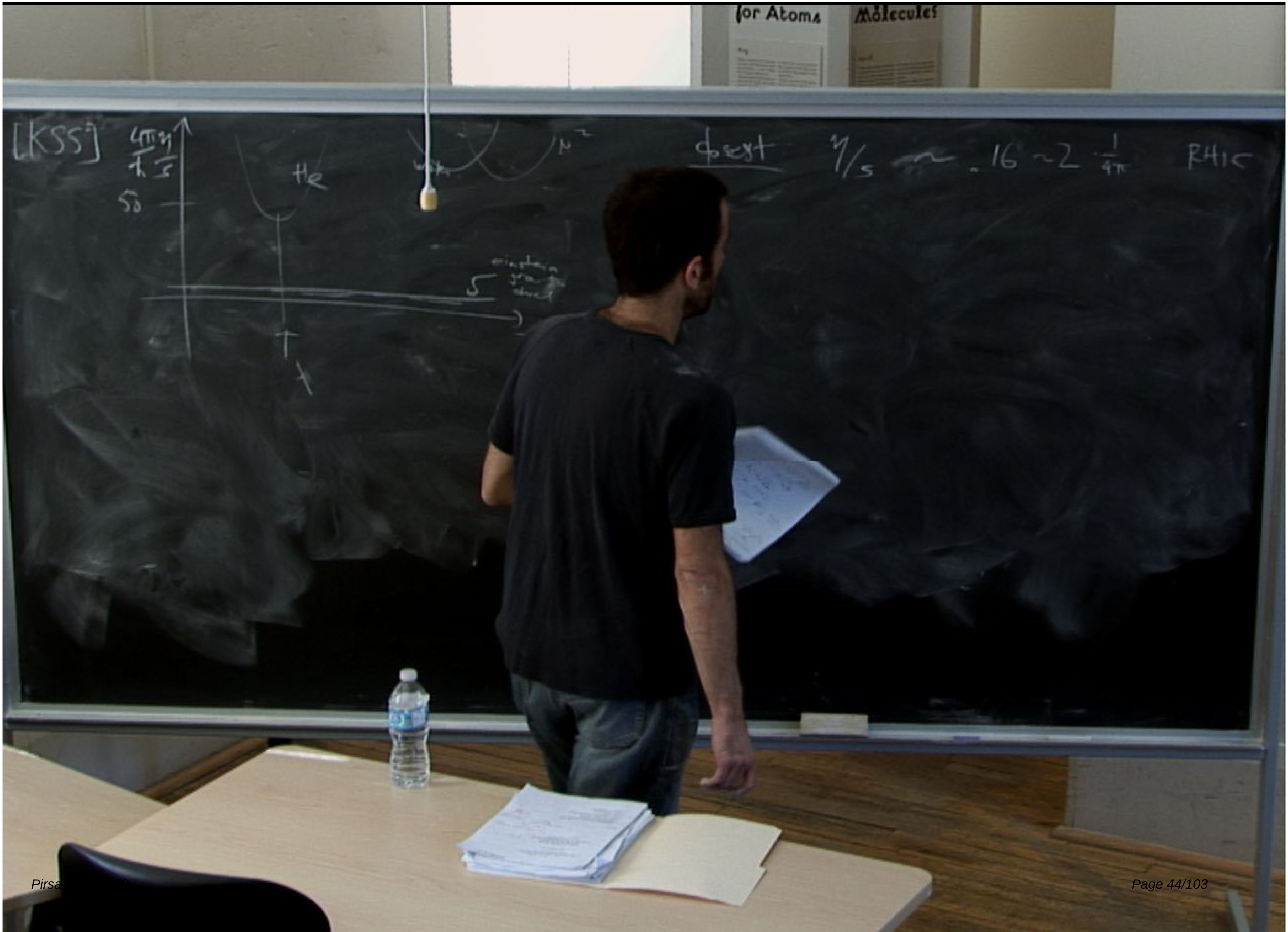
$$\left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=0} = \left.\frac{\Pi_\phi}{\omega\phi}\right|_{z=z_H}$$

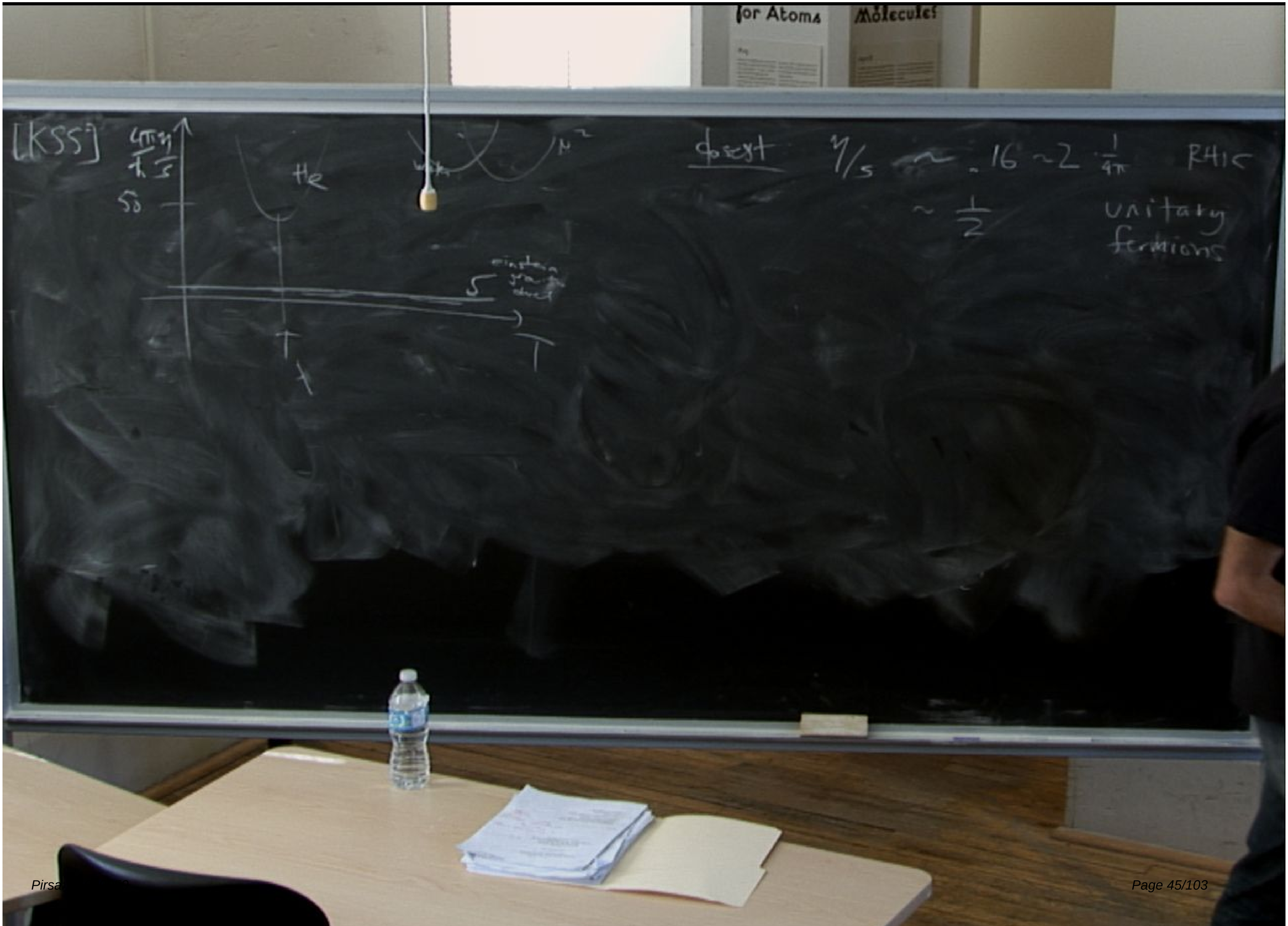
"membrane paradigm"

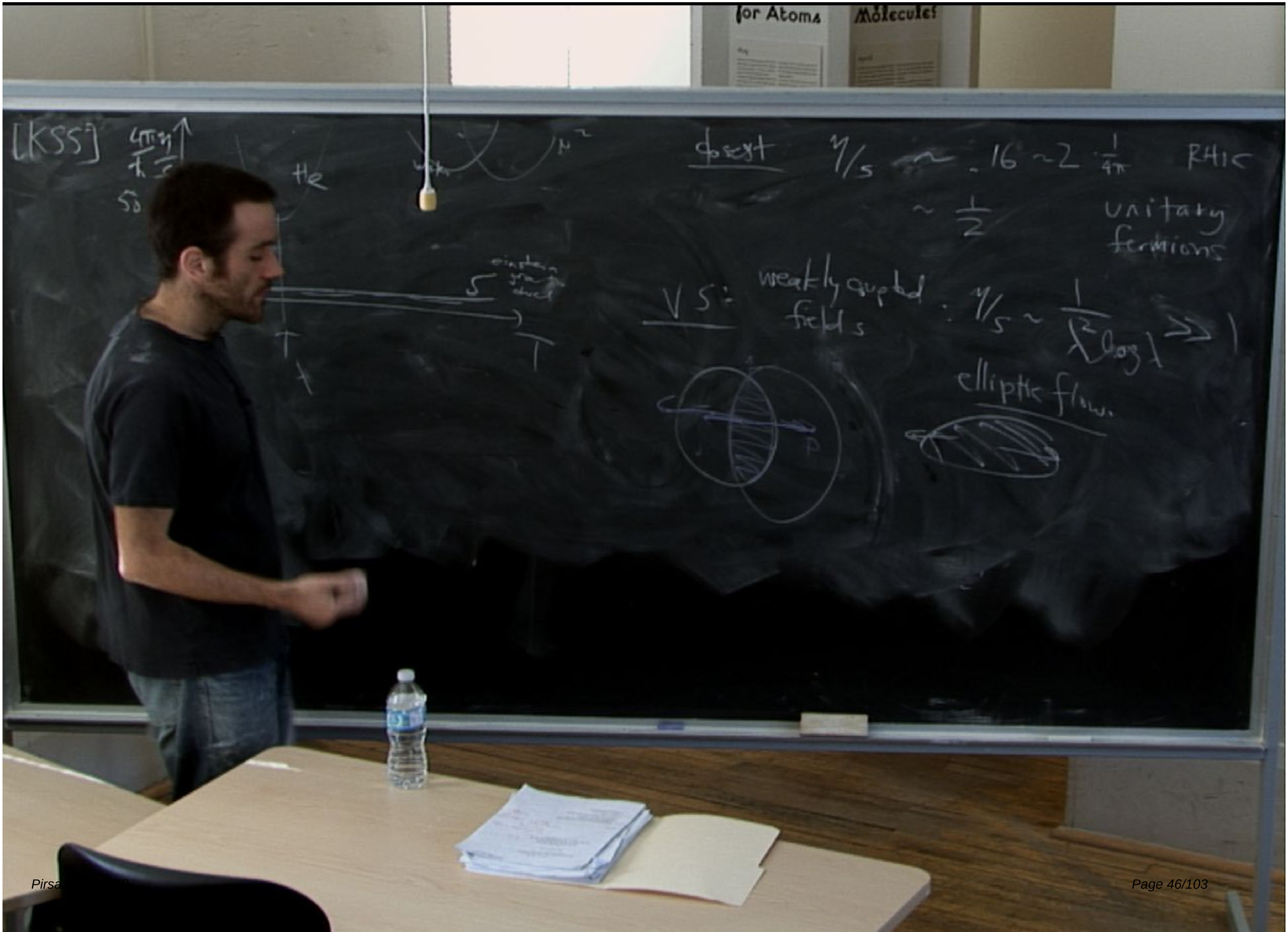
$$\Longrightarrow \eta = \frac{1}{16\pi G_N}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}\Bigg|_{z=z_H}.$$

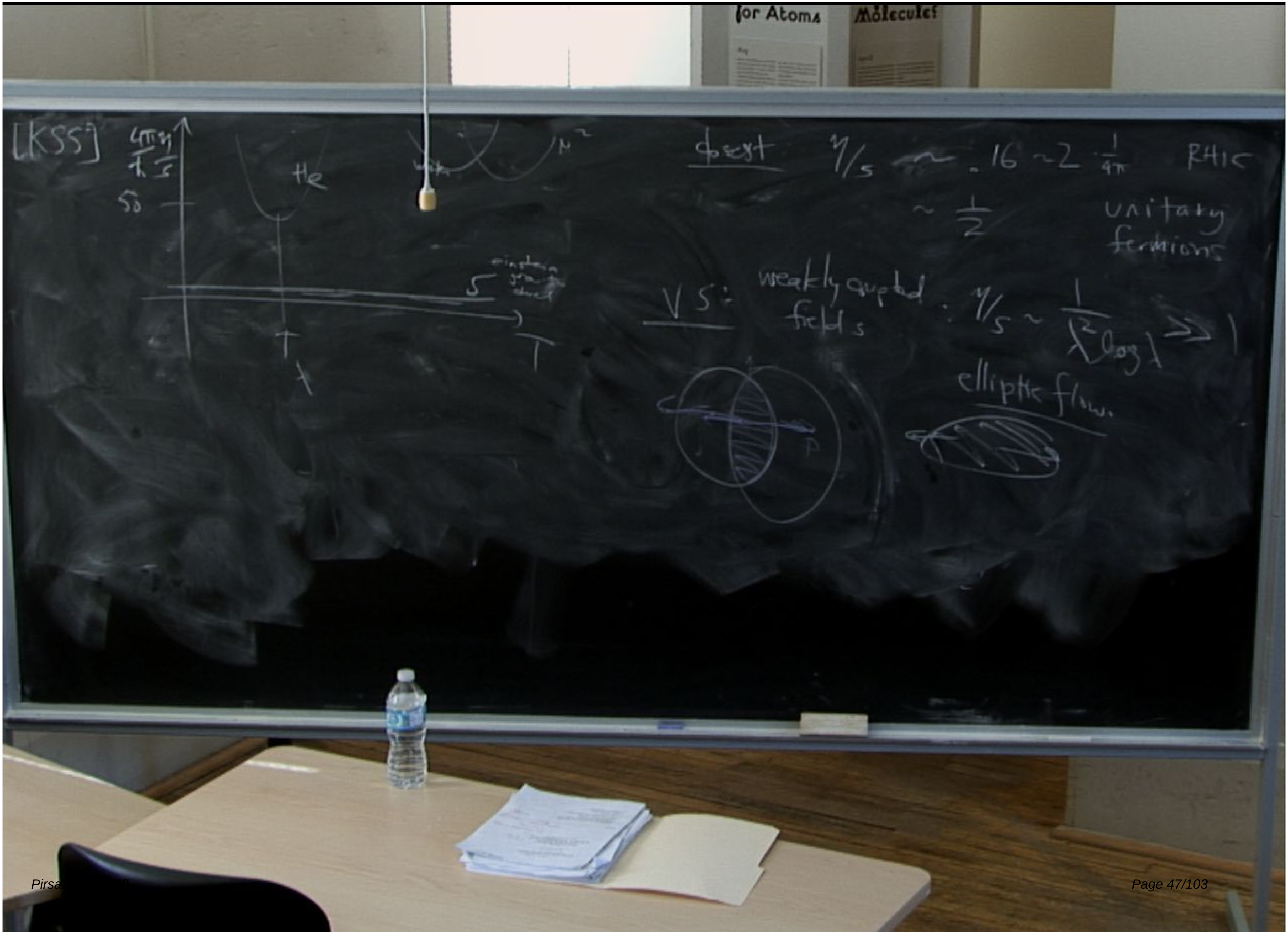
entropy density : $s = \frac{a}{4G_N} = \frac{1}{4G_N}\sqrt{\frac{|g|}{g_{zz}|g_{tt}|}}$

$$\eta = \frac{1}{4\pi} s \sim .08\, s$$


for Atoms
Molecules
[KSS]
He
RHIC


for Atoms
Molecules
[KSS]
He
T
η/s ~ .16 ~ 2 · 1/4π
RHIC
~ 1/2
unitary fermions


for Atoms
Molecules
[KSS]
He
concept
$\eta/s \sim .16 \sim 2 \cdot \frac{1}{4\pi}$ RHIC
$\sim \frac{1}{2}$ unitary fermions
vs: weakly coupled fields : $\eta/s \sim \frac{1}{\lambda^2 \log \lambda} >> 1$
elliptic flow



for Atoms
Molecules
[KSS]
He
RHIC
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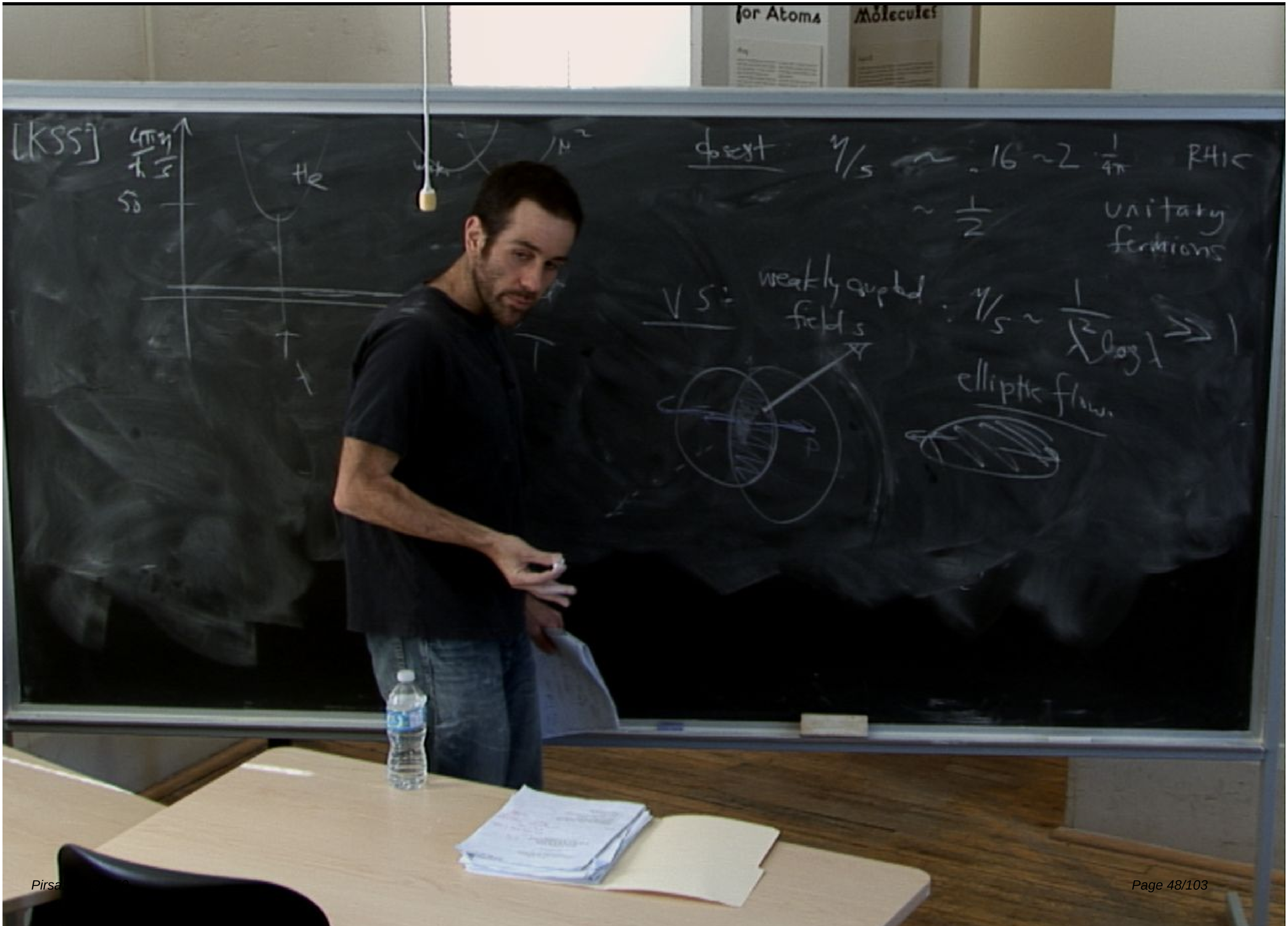
for Atoms
Molecules
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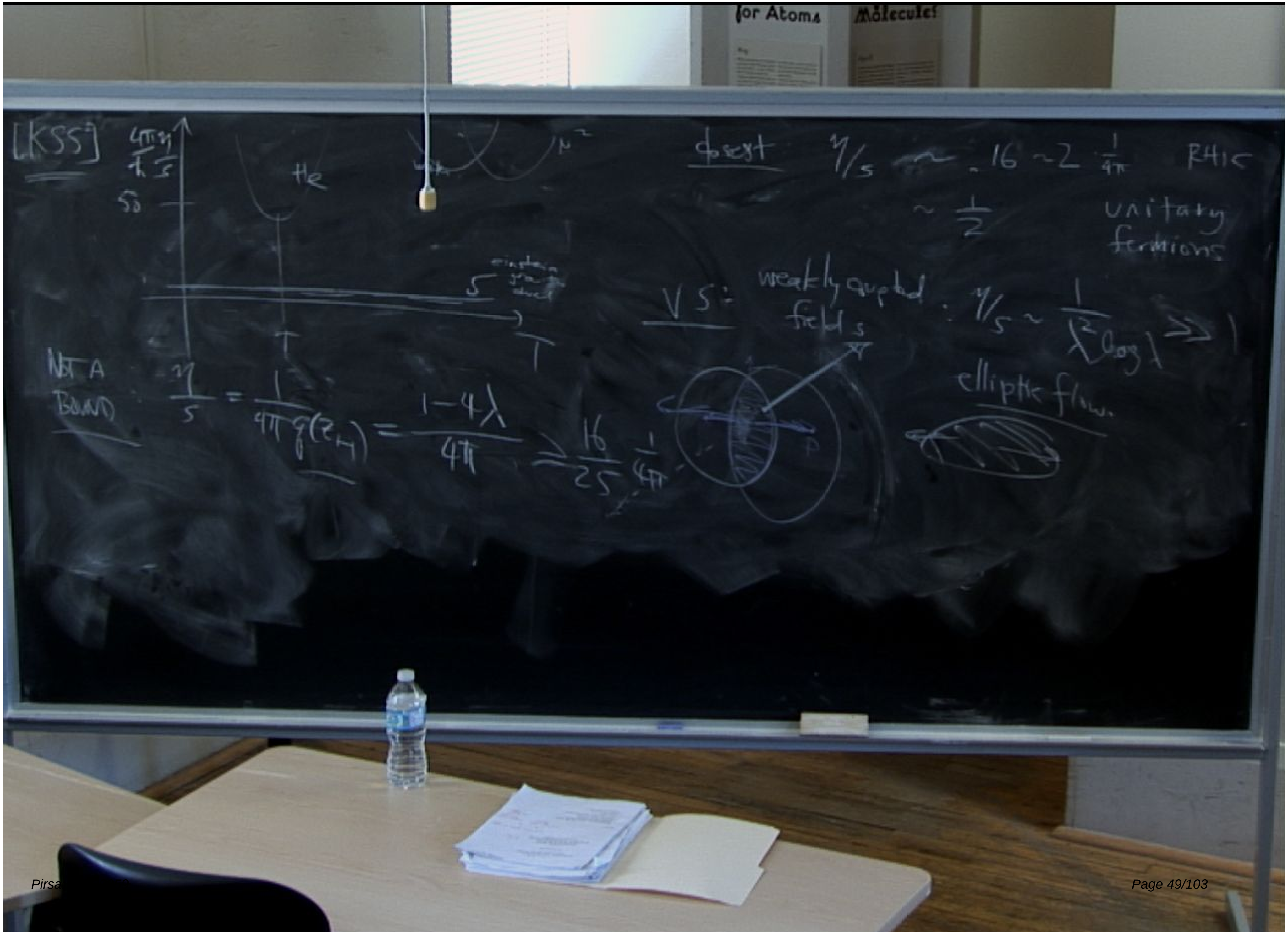
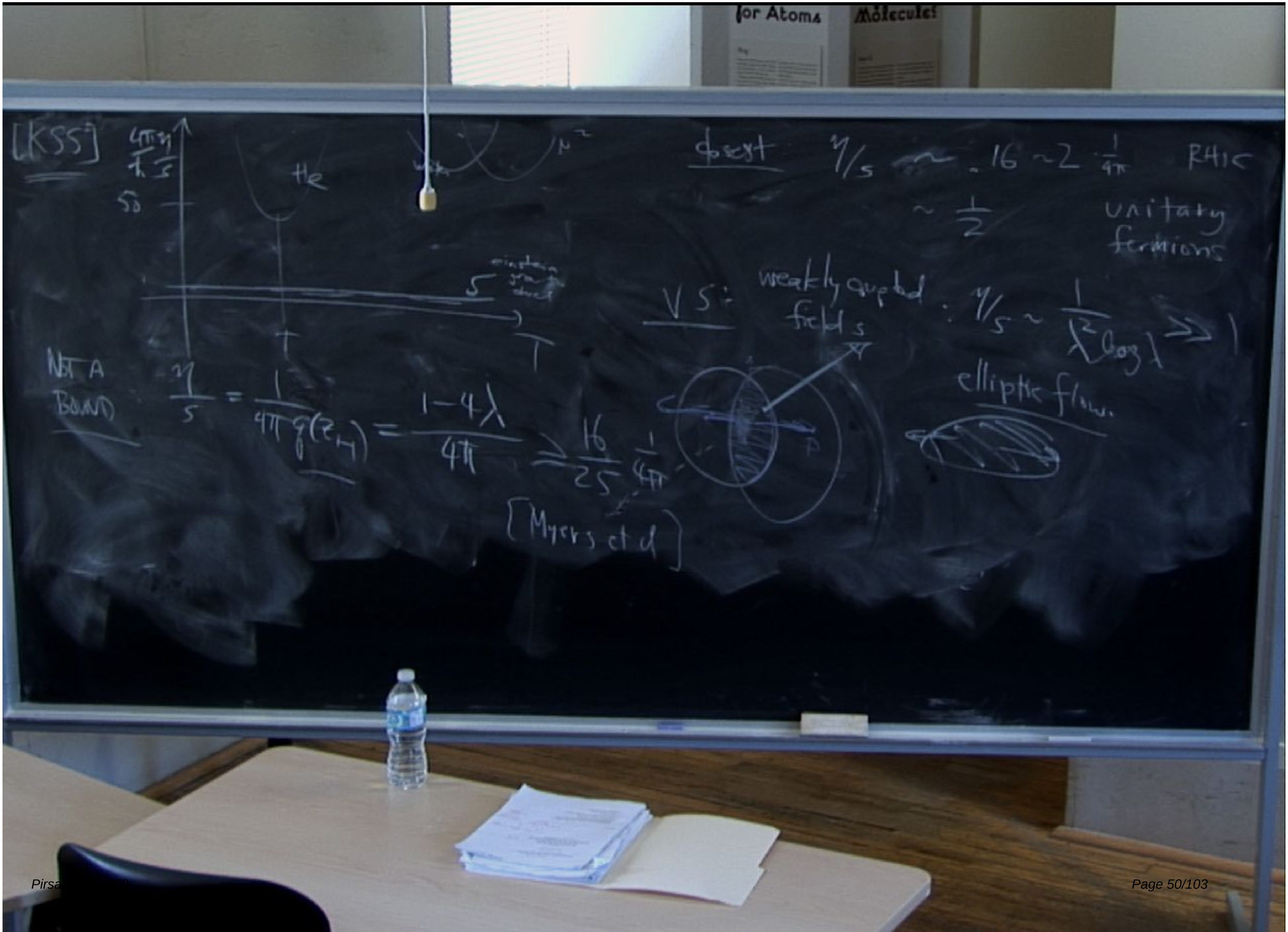
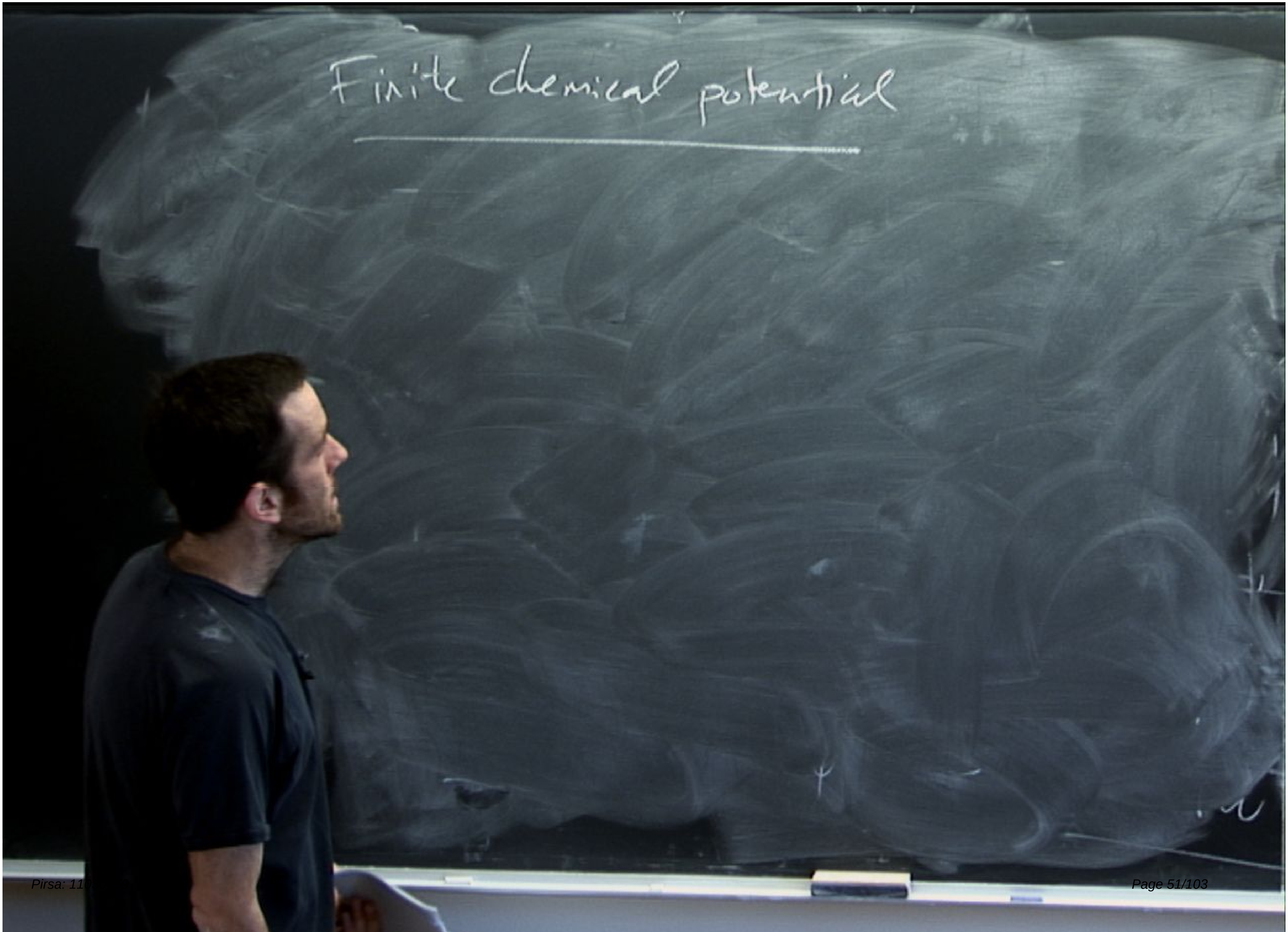

for Atoms
Molecules
[KSS]
He
RHIC
unitary fermions
VS: weakly coupled fields
elliptic flow
NOT A BOUND


for Atoms
Molecules
[KSS]
NOT A BOUND
weakly coupled fields
elliptic flow
unitary fermions
RHIC
[Myers et al]


Finite chemical potential

Finite chemical potential

suppose ∃ $U(1)$ current J_μ

$\longrightarrow$ massless gauge field A_μ in bulk

$$\Delta S_{bulk} = -\frac{1}{4g^2}\int d^{d+1}x\,\sqrt{g}\,F_{AB}F^{AB} +$$

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max eq

$0 = \frac{\delta S}{\delta \ldots}$

$A \underset{z\to 0}{\sim} A^{(0)}(x) + \left(\frac{z}{L}\right)^{d-2} A^{(1)}(x)$

$F_{AB} = \partial_A A_B - \partial_B A_A$

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$$\boxed{\delta S = \int J_t\,\mu}$$

Finite chemical potential

$T_{AB} = \partial_A A_B - \partial_B A_A$

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Wilson:

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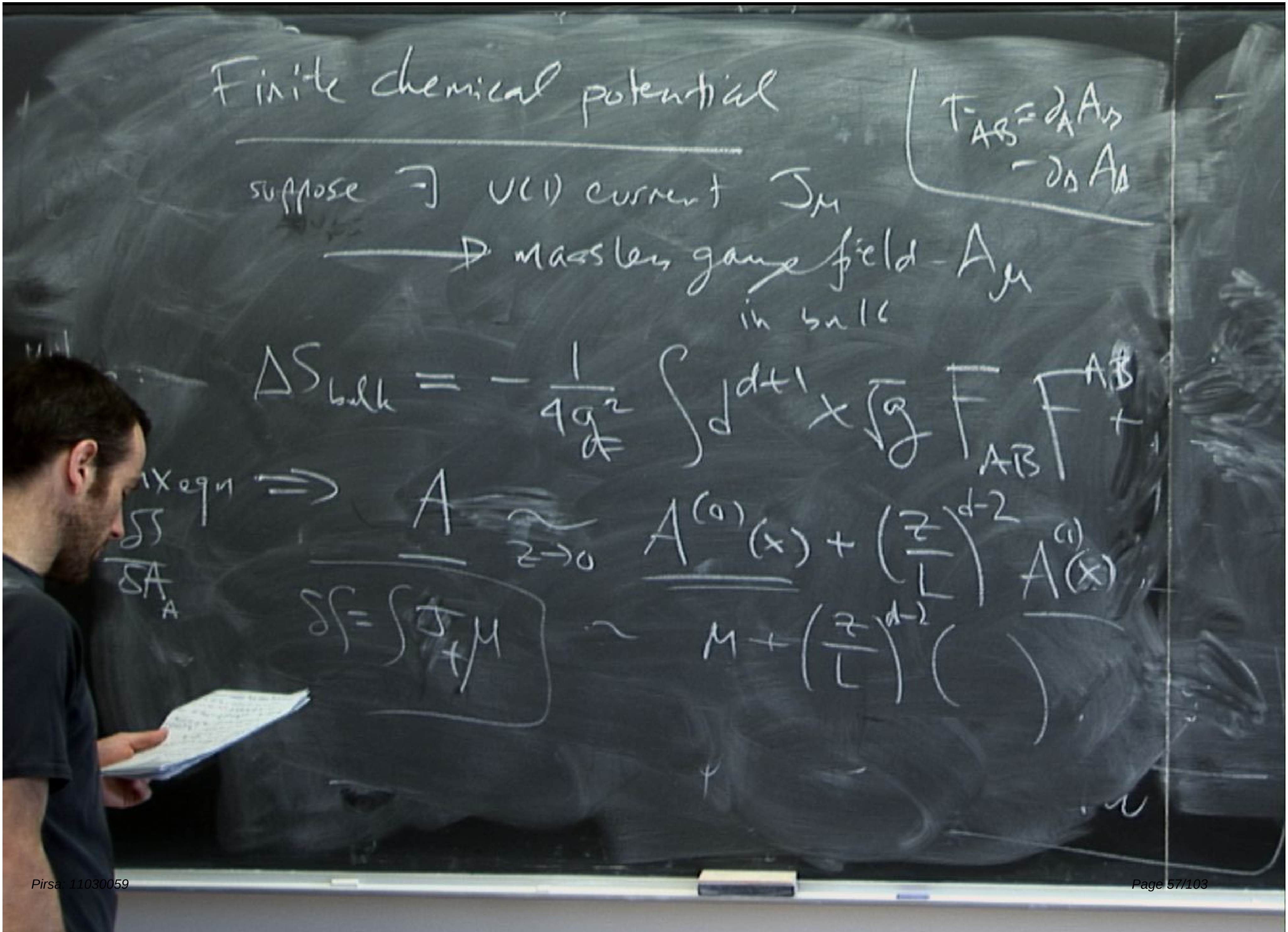
Finite chemical potential
suppose ∃ U(1) current J_μ
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F_AB = ∂_A A_B − ∂_B A_A
ΔS_bulk = − 1/(4g_d²) ∫ d^{d+1}x √g F_AB F^AB +
x eqn ⟹ A ~_{z→0} A^(0)(x) + (z/L)^{d-2} A^(1)(x)
δS/δA_A
δS = ∫ J_t μ
~ μ + (z/L)^{d-2} ( )

Finite chemical potential

$$F_{AB} = \partial_A A_B - \partial_B A_A$$

suppose $\exists$ U(1) current J_μ

$\Longrightarrow$ massless gauge field A_μ in bulk

Wilson:

$$\Delta S_{bulk} = -\frac{1}{4g_d^2}\int d^{d+1}x\sqrt{g}\,F_{AB}F^{AB} + \ldots$$

max eqn $\Longrightarrow$

$$0 = \frac{\delta S}{\delta A_A}$$

$$A \underset{z\to 0}{\sim} A^{(0)}(x) + \left(\frac{z}{L}\right)^{d-2} A^{(1)}(x)$$

$$\boxed{\delta S = \int J_t \mu} \qquad \sim \qquad \mu + \left(\frac{z}{L}\right)^{d-2}(\rho)$$

$$\frac{\partial F}{\partial \mu} = \rho$$

Finite chemical potential

suppose $\exists$ U(1) current J_μ

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saddle pt w/ these BC :

saddle pt w/ these BC : charged BH (AdS-RN)

$f(z)$

saddle pt w/ these BC: charged BH (AdS-RN)

$$f(z) = 1 - Mz^{d} + Qz^{2d-2}$$

$$A = dt\, A_t = dt\, \mu\left(1 - \left(\frac{z}{z_0}\right)^{d-2}\right)$$

saddle pt w/ these BC: charged BH (AdS-RN)

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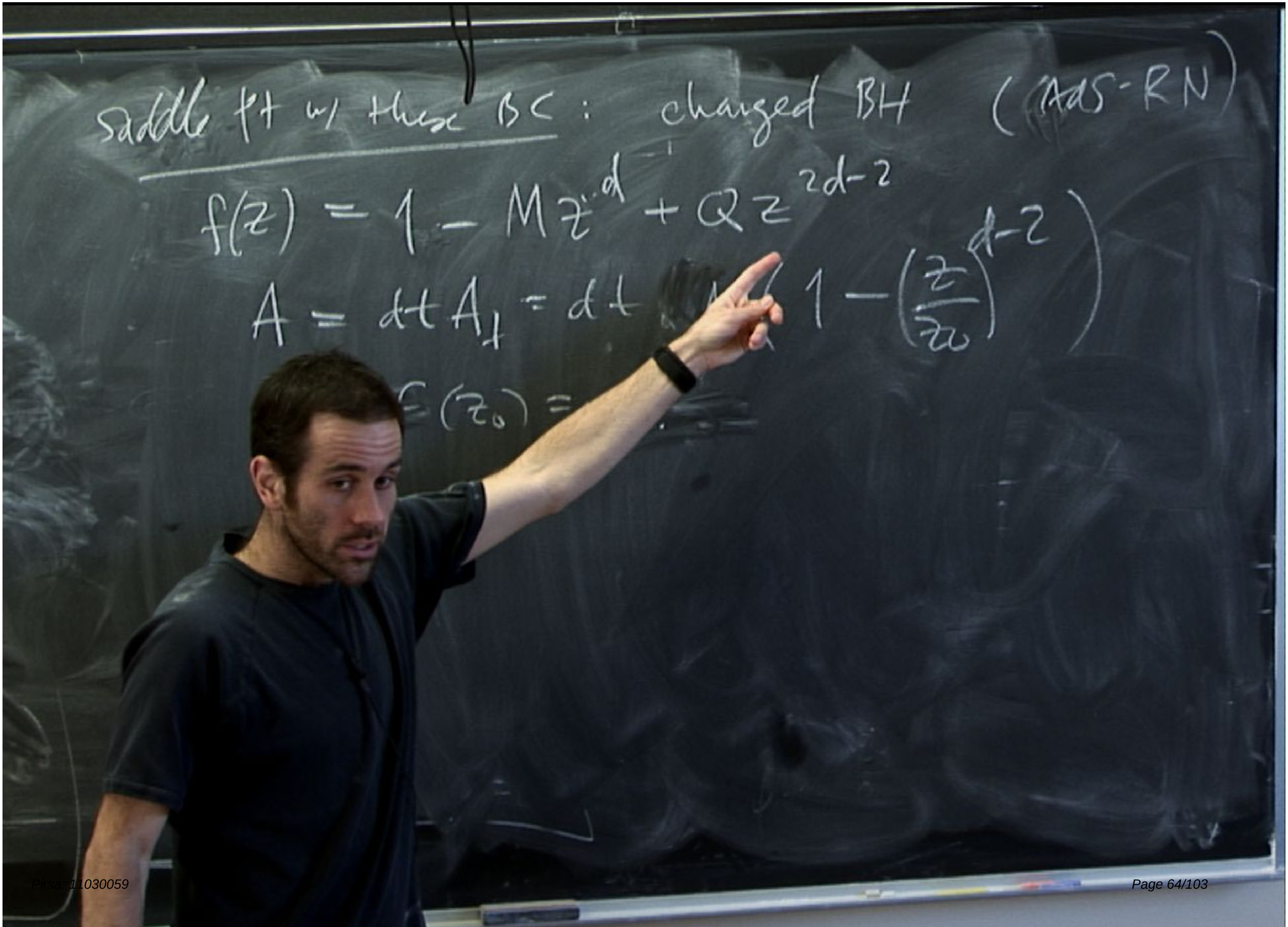
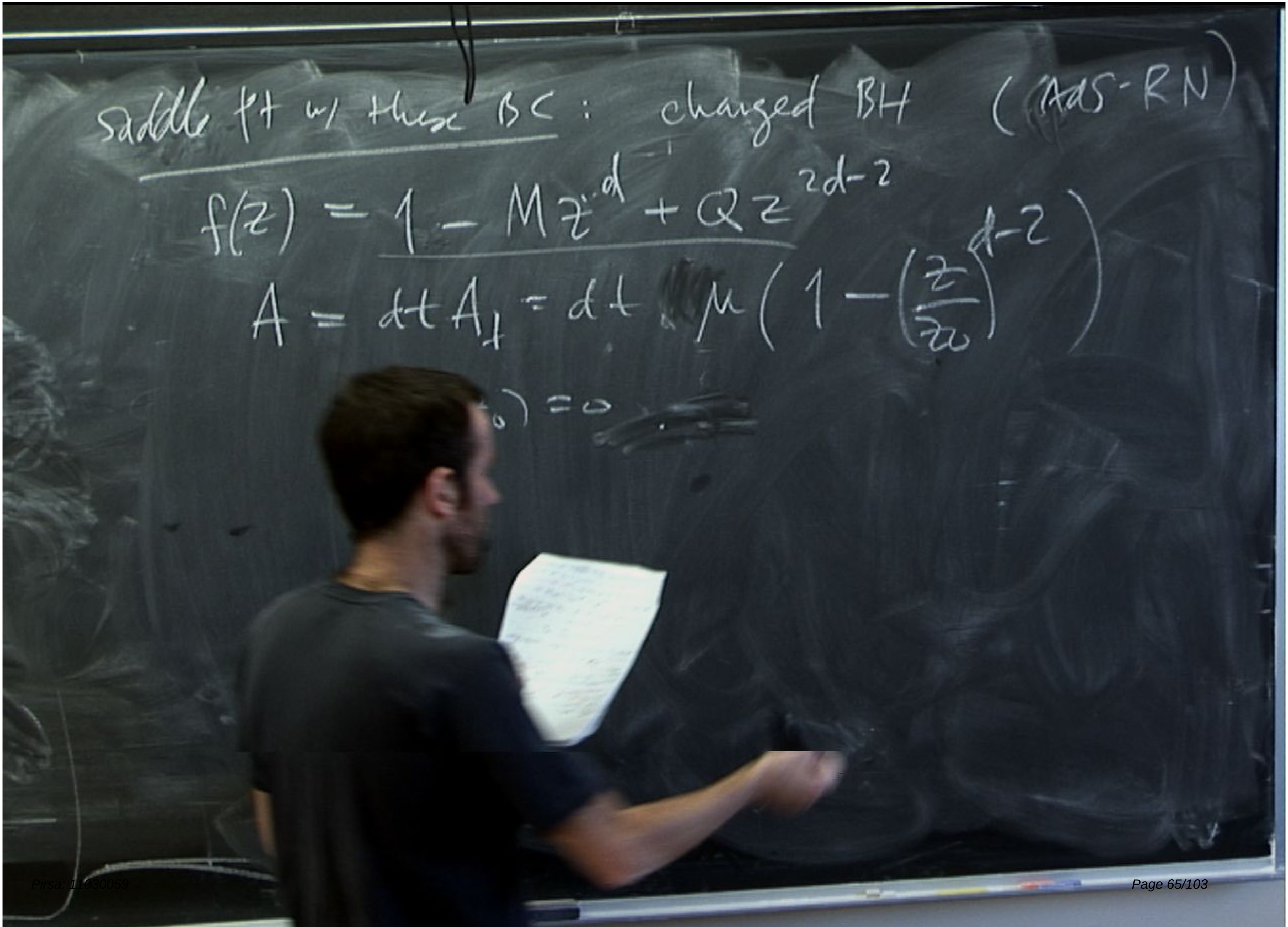

saddle pt w/ these BC: charged BH (AdS-RN)
f(z) = 1 − Mz^d + Qz^{2d−2}
A = dt A_t = dt
1 − (z/z_0)^{d−2}
f(z_0) =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$$f(z_0) = 0 \qquad Q = \frac{\mu L^2}{z_0^{d-1} g_F}$$

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2}\right) \end{cases}$$

$f(z_0) = 0$

$$Q = \frac{\mu L^2}{z_0^{d-1} g_F}$$

$z = z_0$

$\frac{z}{L} \sim \frac{\mu}{T}$

$z = 0$

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2} \right) \end{cases}$$

$f(z_0) = 0$

$Q = \frac{\mu L^2}{z_0^{d-1} g_F}$

AdS_{d+1} UV

$z = 0$

$z = z_0$

$\sim \frac{\mu}{T}$

$T \ll \mu$

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2} \right) \end{cases}$$

$$f(z_0) = 0 \qquad Q = \frac{\mu L^2}{z_0^{d-1} g_F}$$

IR

AdS_{d+1} UV

$z = z_0$ $\qquad \frac{z}{L} \sim \frac{\mu}{T} \qquad$ $z = 0$

$T \ll \mu$:

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2}\right) \end{cases}$$

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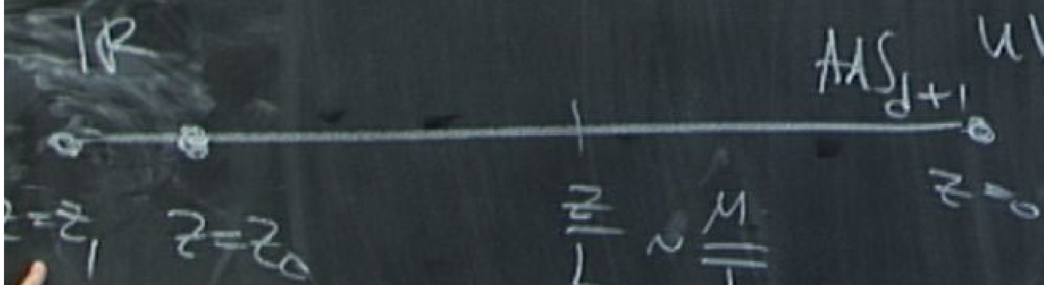
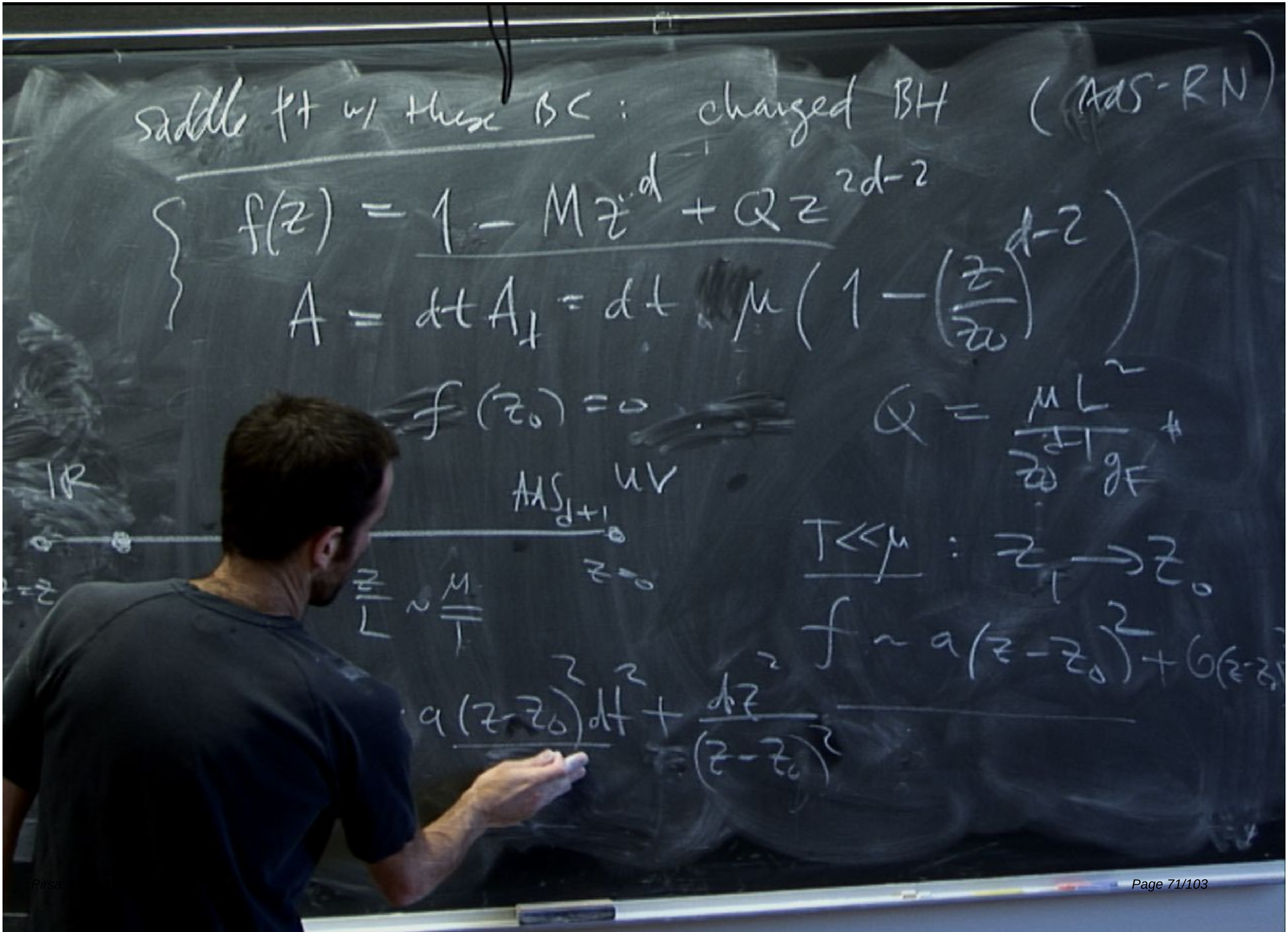


$\frac{z}{L} \sim \frac{\mu}{T}$

$T \ll \mu$:


saddle pt w/ these BC : charged BH (AdS-RN)
f(z) = 1 - M z^d + Q z^(2d-2)
A = dt A_t = dt μ (1 - (z/z_0)^(d-2))
f(z_0) = 0
Q = μ L^2 / (z_0^(d-1) g_F)
IR
AdS_(d+1) UV
z=0
T<<μ : z_T → z_0
f ~ a(z - z_0)^2 + b(z-z_0)
z/L ~ μ/T
a(z - z_0)^2 dt^2 + dz^2/(z - z_0)^2

saddle pt w/ these BC : charged BH (AdS-RN)

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$$f(z_0) = 0 \qquad Q = \frac{\mu L^2}{z_0^{d-1} g_F} \#$$

AdS_{d+1} UV

$z = z_0$ $\qquad z = 0$

$$\frac{z}{L} \sim \frac{\mu}{T}$$

$T \ll \mu$: $z_T \to z_0$

$$f \sim a(z - z_0)^2 + b(z - z_0)$$

$$ds^2 = -a(z - z_0)^2 dt^2 + \frac{dz^2}{(z - z_0)^2}$$

saddle pt w/ these BC : charged BH ((AdS-RN))

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2} \right) \end{cases}$$

$f(z_0) = 0$ $\quad Q = \frac{\mu}{z_0^{d}}$

IR

AdS_{d+1} UV

$z = z_1$ $\quad z = z_0$ $\quad z = 0$

$\frac{z}{L} \sim \frac{\mu}{T}$

$\underline{T \ll \mu}$: z_T

$f \sim a (z - z_0)^2$

$$ds^2 = -a (z - z_0)^2 dt^2 + \frac{dz^2}{(z - z_0)^2} + d\vec{x}^2$$

saddle pt w/ these BC: charged BH (AdS-RN)

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AdS_{d+1} UV

$z = z_1$ $z = z_0$ $z = 0$

$\frac{z}{L} \sim \frac{\mu}{T}$

$\underline{T \ll \mu}$: $z_1 \to z_0$

$f \sim a(z - z_0)^2 + O(z - z_0)$

$$ds^2_{z \to z_0} \sim -a(z-z_0)^2 dt^2 + \frac{dz^2}{(z-z_0)^2} + \frac{d\vec{x}^2}{z_0^2}$$

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$\underline{T \ll \mu}$: $z_1 \to z_0$

$f \sim a(z - z_0)^2 + O(z-z_0)^3$

$$ds^2_{z \to z_0} \approx -a(z-z_0)^2 dt^2 + \frac{dz^2}{(z-z_0)^2} + \frac{d\vec{x}^2}{z_0^2} = -u^2 dt^2 + \frac{du^2}{u^2} + d\vec{x}^2$$

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2}\right) \end{cases}$$

$f(z_0) = 0$ $\qquad Q = \frac{\mu L^2}{z_0^{d-1} g_F}$

IR $\qquad AdS_{d+1}$ UV

$z_1 \quad z = z_0 \qquad \frac{z}{L} \sim \frac{\mu}{T} \qquad z = 0$

$\underline{T \ll \mu}$: $z_1 \to z_0$

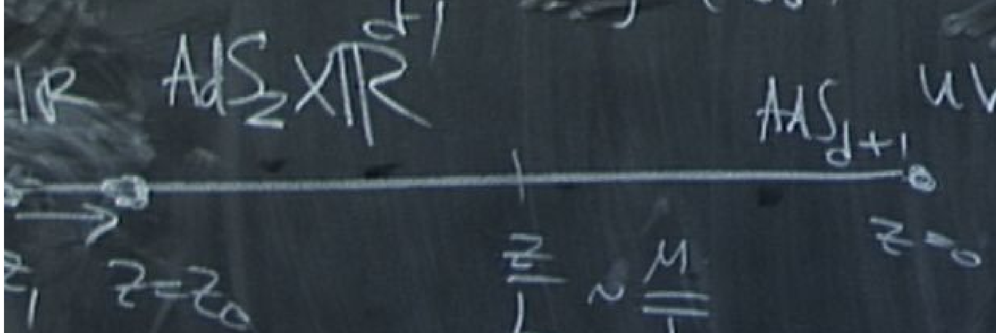
$f \sim a(z - z_0)^2 + O(z-z_0)^3$

$$ds^2_{z \to z_0} \sim -a(z-z_0)^2 dt^2 + \frac{dz^2}{(z-z_0)^2} + \frac{d\vec{x}^2}{z_0^2} = -\eta^2 dt^2 + \frac{d\eta^2}{\eta^2} + d\vec{x}^2$$

saddle pt w/ these BC: charged BH (AdS-RN)

$$\begin{cases} f(z) = 1 - M z^{d} + Q z^{2d-2} \\ A = dt\, A_t = dt\, \mu \left(1 - \left(\frac{z}{z_0}\right)^{d-2}\right) \end{cases}$$

$$f(z_0) = 0 \qquad Q = \frac{\mu L^2}{z_0^{d-1} g_F}$$



$$\frac{z}{L} \sim \frac{\mu}{T}$$

$T \ll \mu$: $z_1 \to z_0$

$$f \sim a(z-z_0)^2 + b(z-z_0)^3$$

$$ds^2_{z\to z_0} \sim -a(z-z_0)^2 dt^2 + \frac{dz^2}{(z-z_0)^2} + \frac{d\vec{x}^2}{z_0^2} = \underbrace{\frac{-dt^2 + dy^2}{y^2}}_{} + \underbrace{d\vec{x}^2}_{\mathbb{R}^{d-1}}$$

saddle pt w/ these BC: charged BH (AdS-RN)

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$f(z_0) = 0$

$$Q = \frac{\mu L^2}{z_0^{d-1} g_F}$$

IR $AdS_2 \times \mathbb{R}^{d-1}$ $\quad AdS_{d+1}$ UV

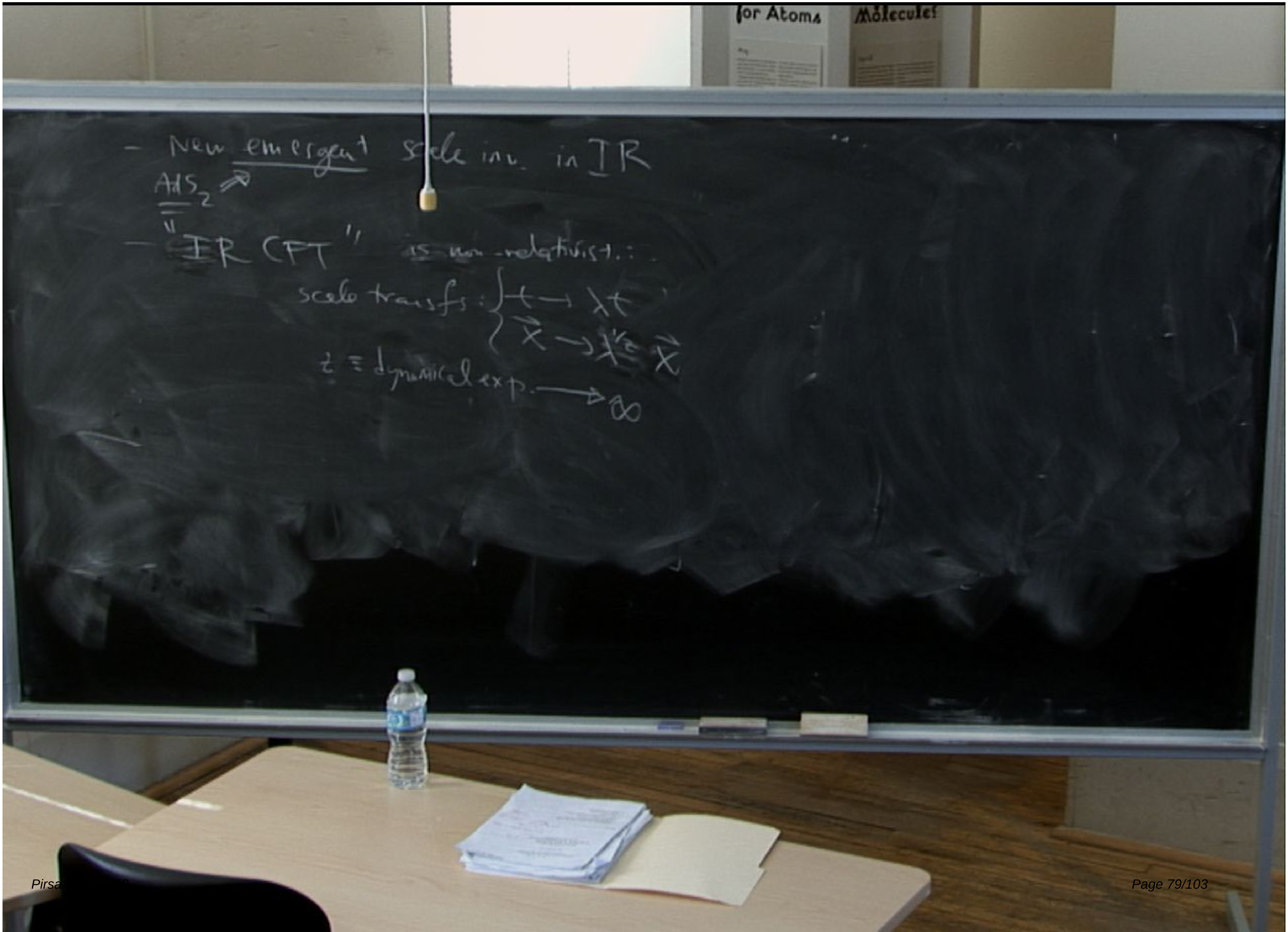
$z_1 \quad z = z_0 \qquad z = 0$

$$\frac{z}{L} \sim \frac{\mu}{T}$$

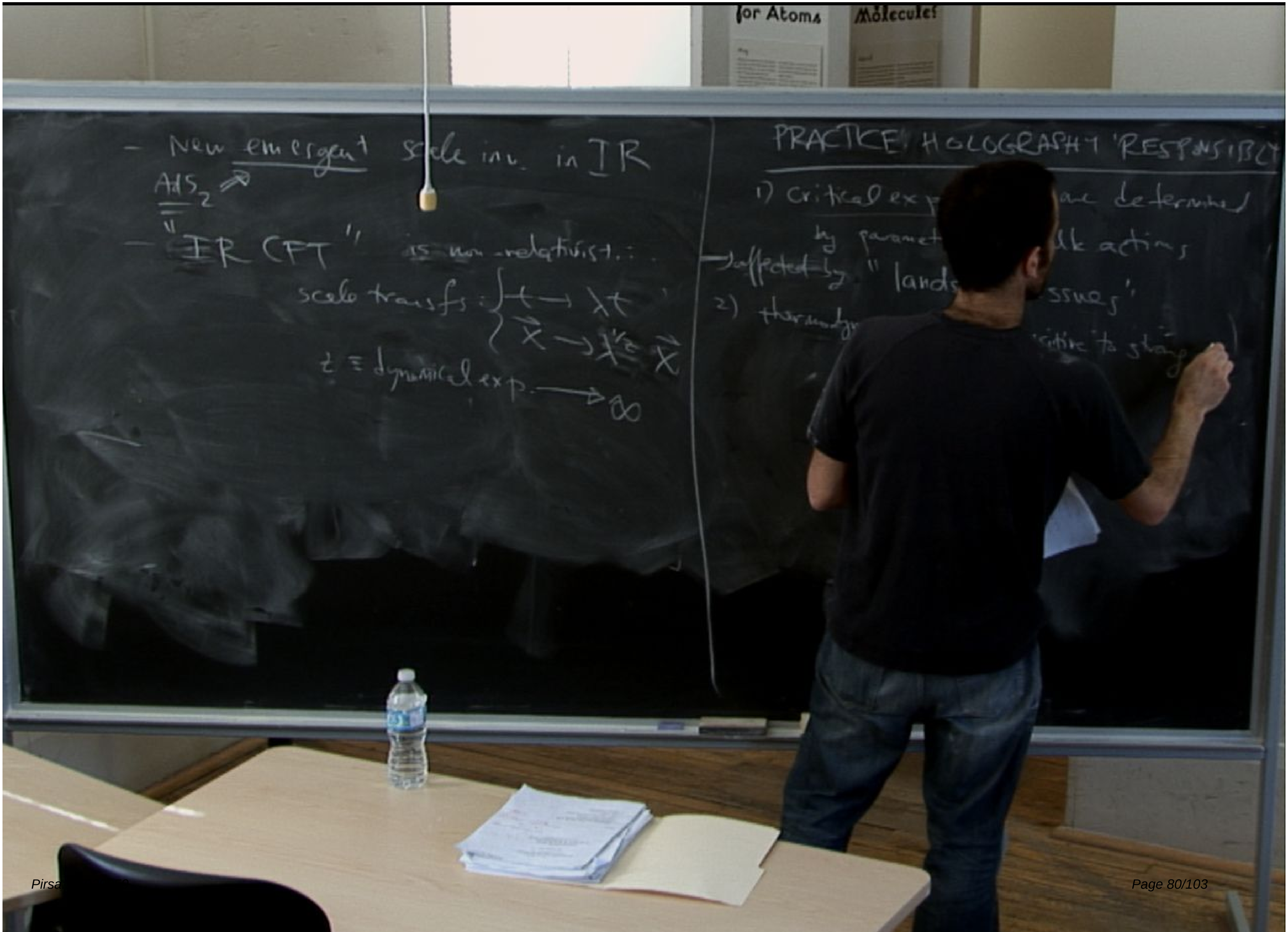
$\underline{T \ll \mu}$: $z_1 \to z_0$

$$f \sim a(z - z_0)^2 + \mathcal{O}(z - z_0)^3$$

$$ds^2_{z \to z_0} \sim -a(z - z_0)^2 dt^2 + \frac{dz^2}{(z - z_0)^2} + \frac{d\vec{x}^2}{z_0^2} = \underbrace{\frac{-dt^2 + dy^2}{y^2}}_{} + \underbrace{d\vec{x}^2}_{\mathbb{R}^{d-1}}$$



for Atoms
Molecules
- New emergent scale inv. in IR
AdS2
- "IR CFT" is non-relativist.:
scale transfs: t → λt
x → λ^{1/z} x
z = dynamical exp. → ∞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- "IR CFT" is non-relativist.
scale transfs:
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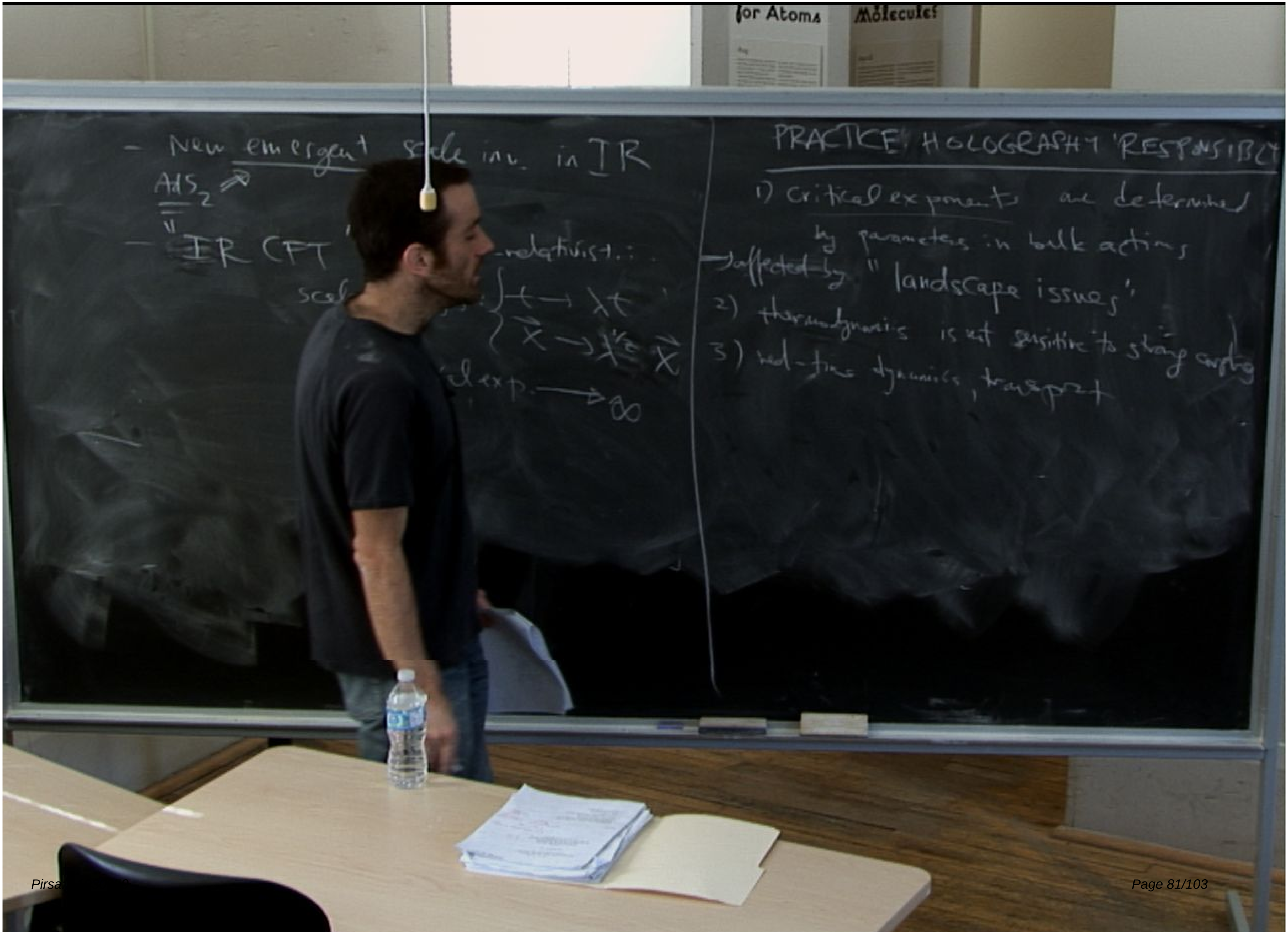
PRACTICE HOLOGRAPHY RESPONSIBLY
1) critical exp
are determined
2)


for Atoms
Molecules
- New emergent scale inv. in IR
AdS2
- "IR CFT"
relativist.
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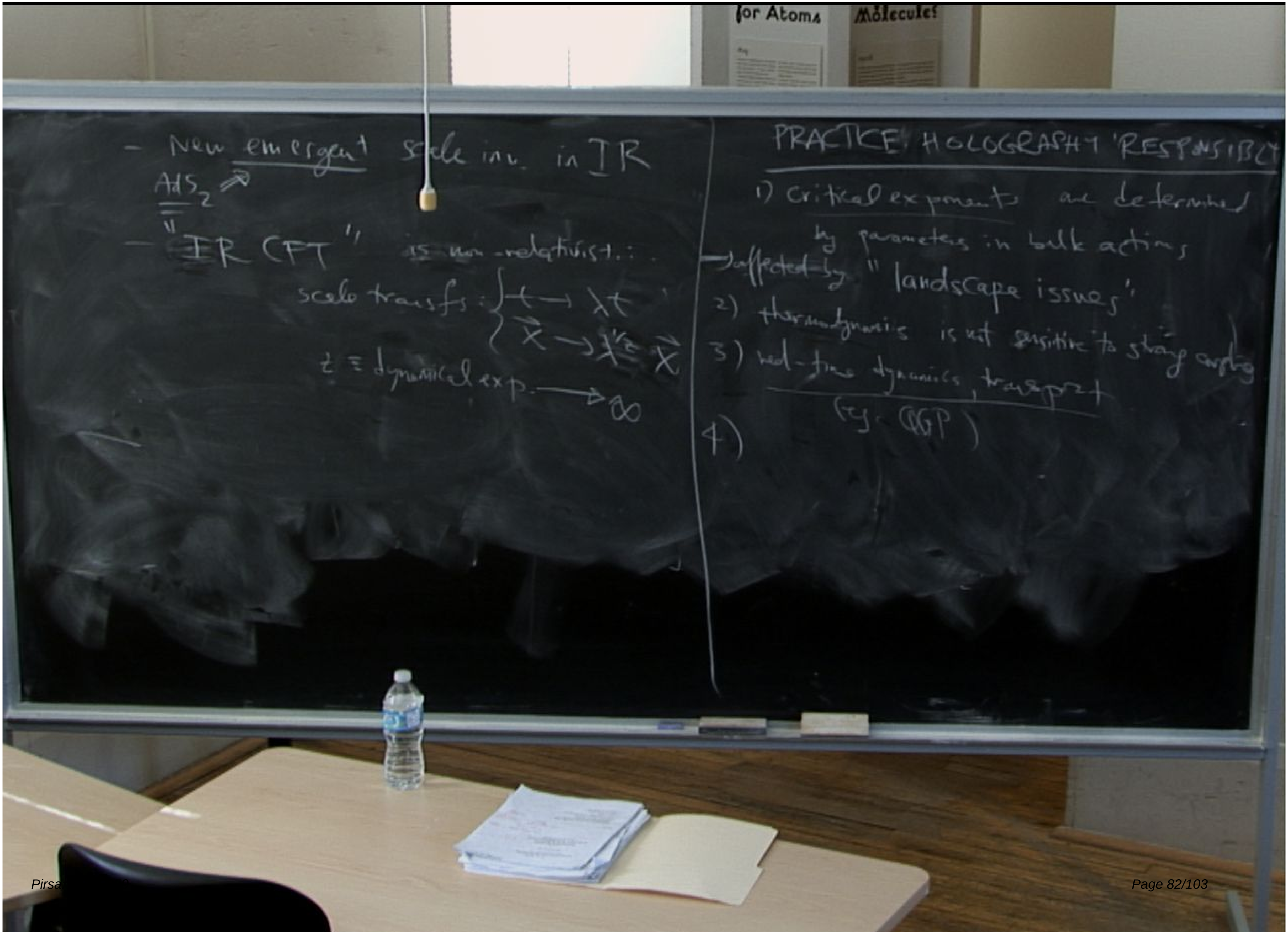
PRACTICE HOLOGRAPHY RESPONSIBLY
1) critical exponents are determined
by parameters in bulk action,
affected by "landscape issues"
2) thermodynamics is not sensitive to strong coupling
3) real-time dynamics, transport



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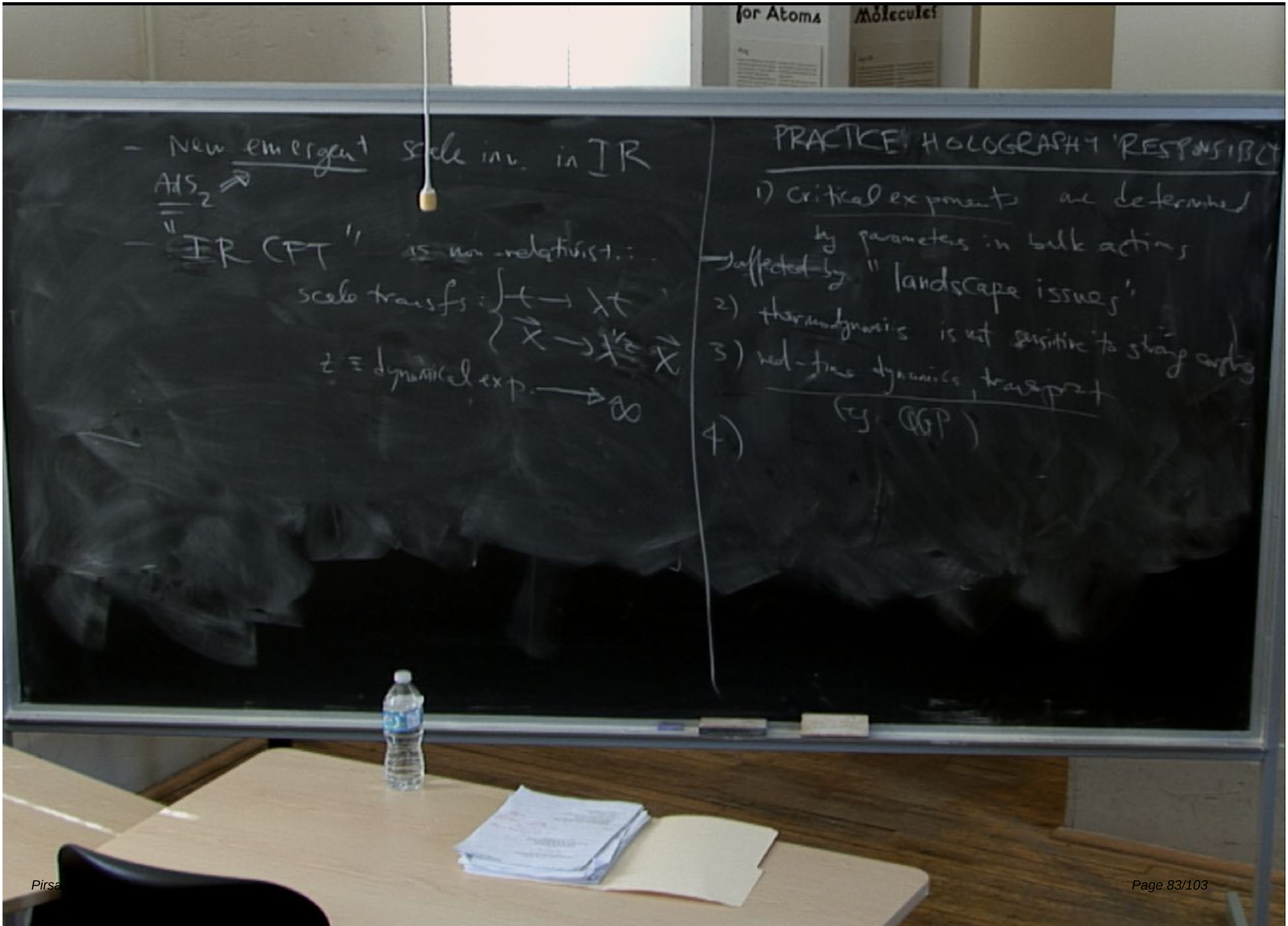
- "IR CFT" is non-relativist.:
scale transfs: t → λt, x → λ^{1/z} x
z ≡ dynamical exp. → ∞
PRACTICE HOLOGRAPHY RESPONSIBLY
1) critical exponents are determined by parameters in bulk action;
affected by "landscape issues"
2) thermodynamics is not sensitive to strong coupling
3) real-time dynamics, transport (e.g. QGP)
4)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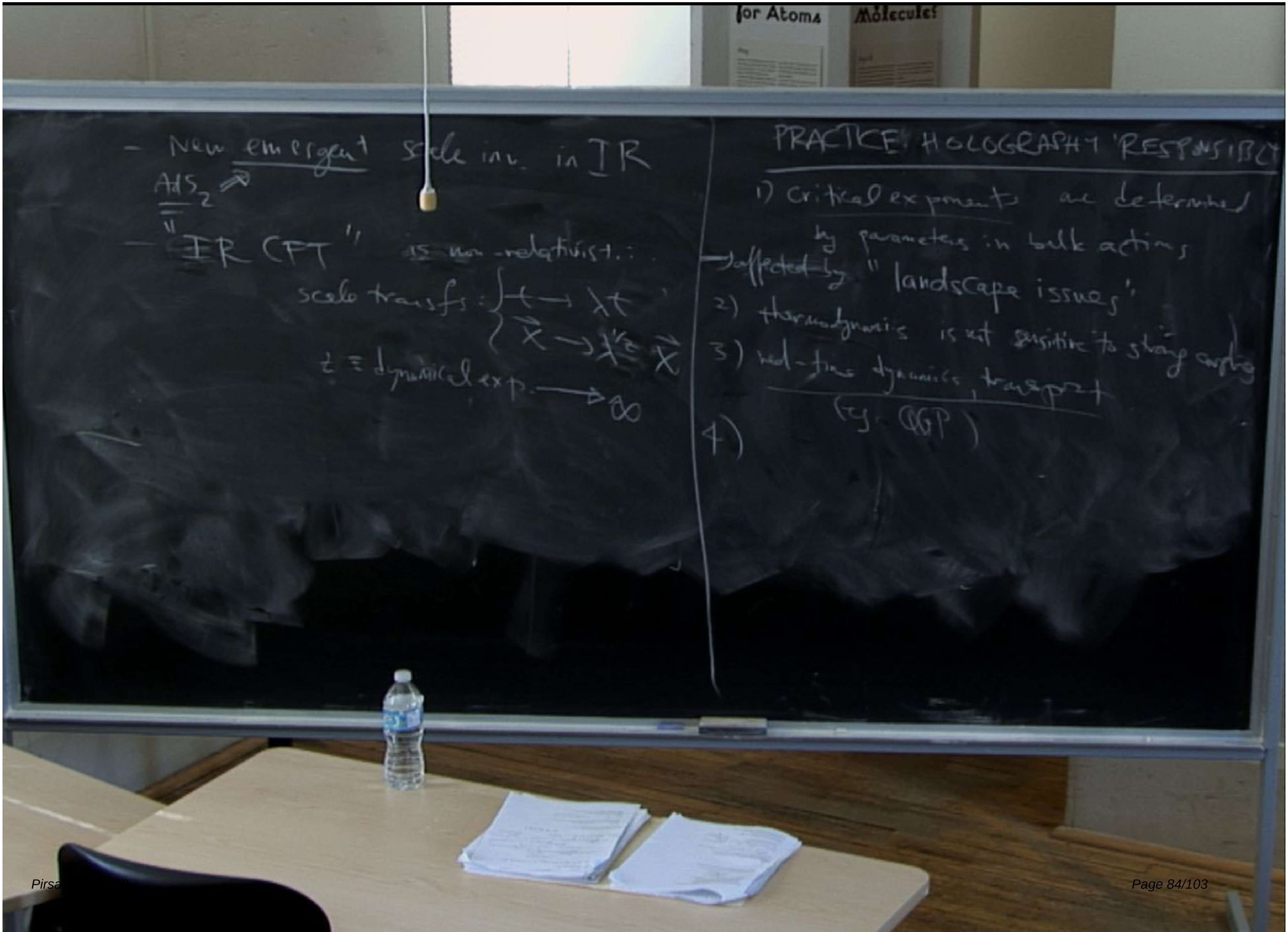

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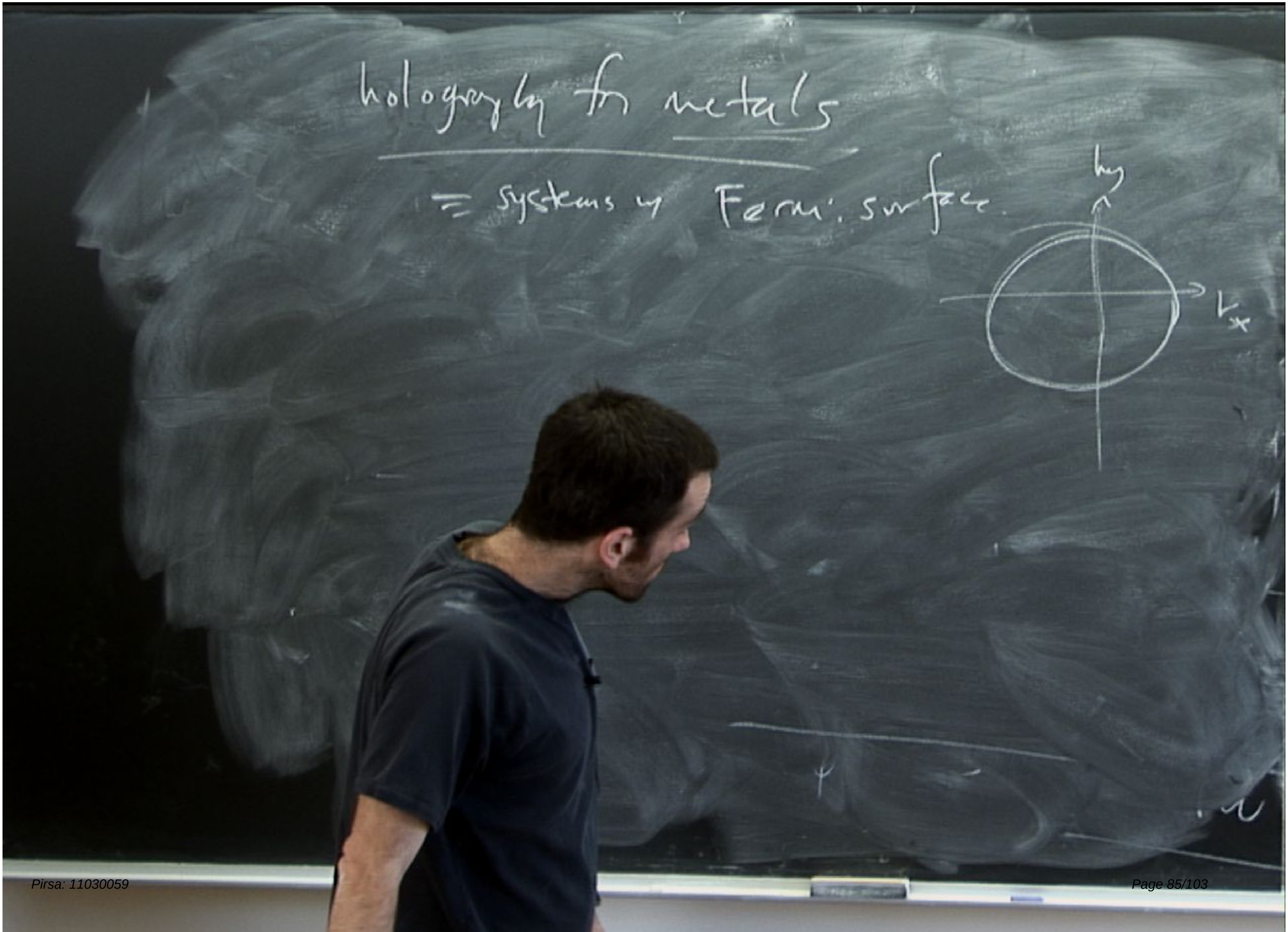
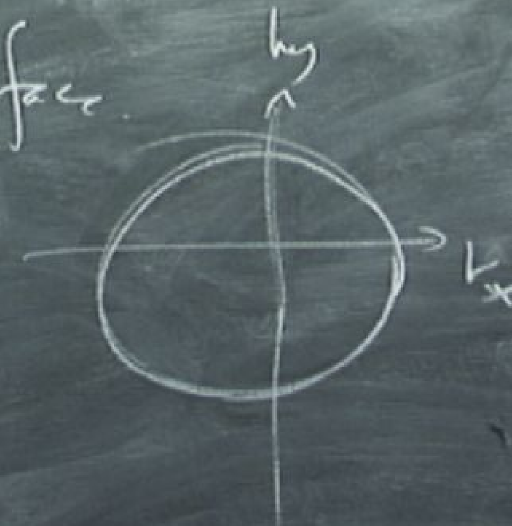
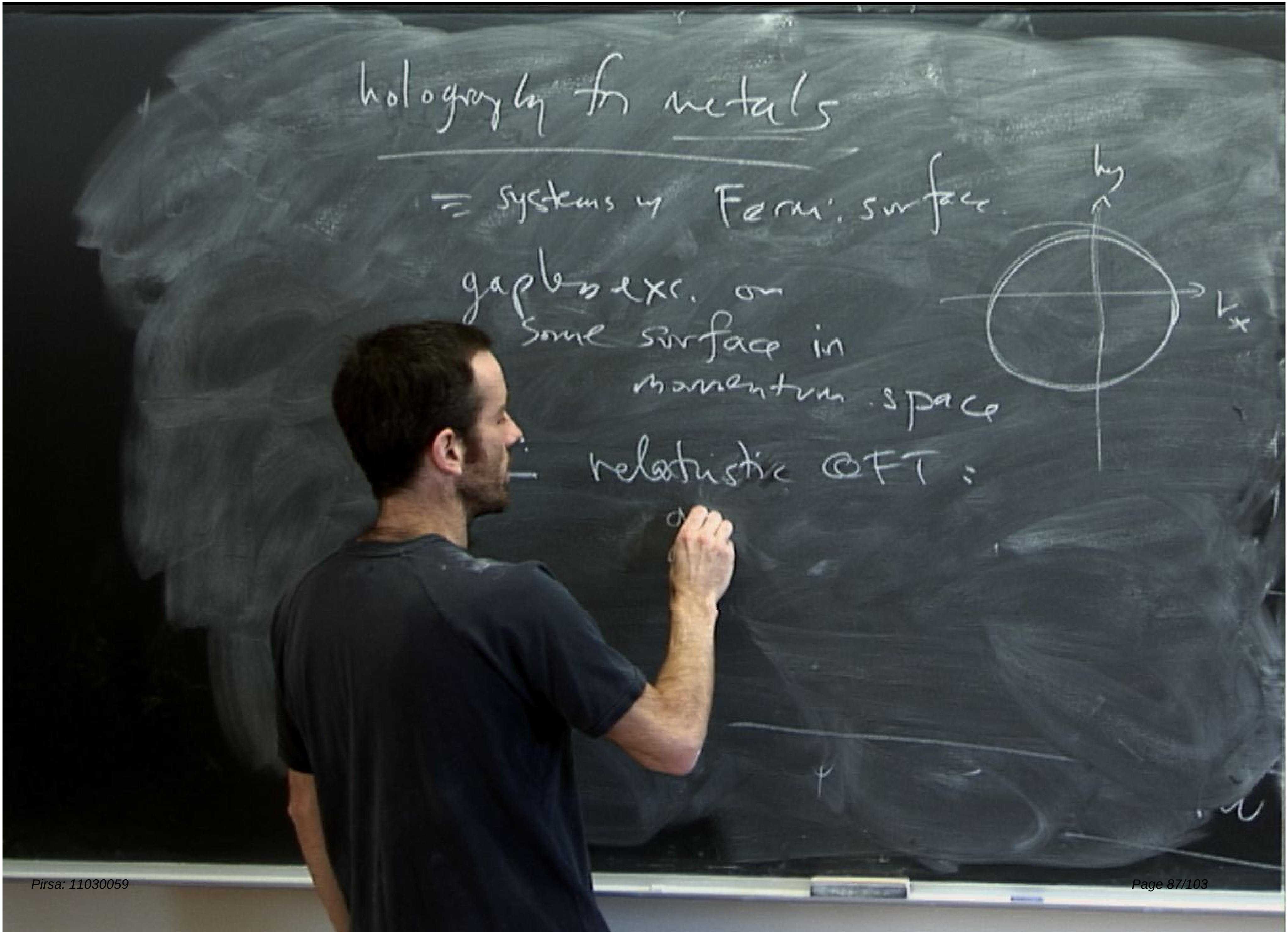
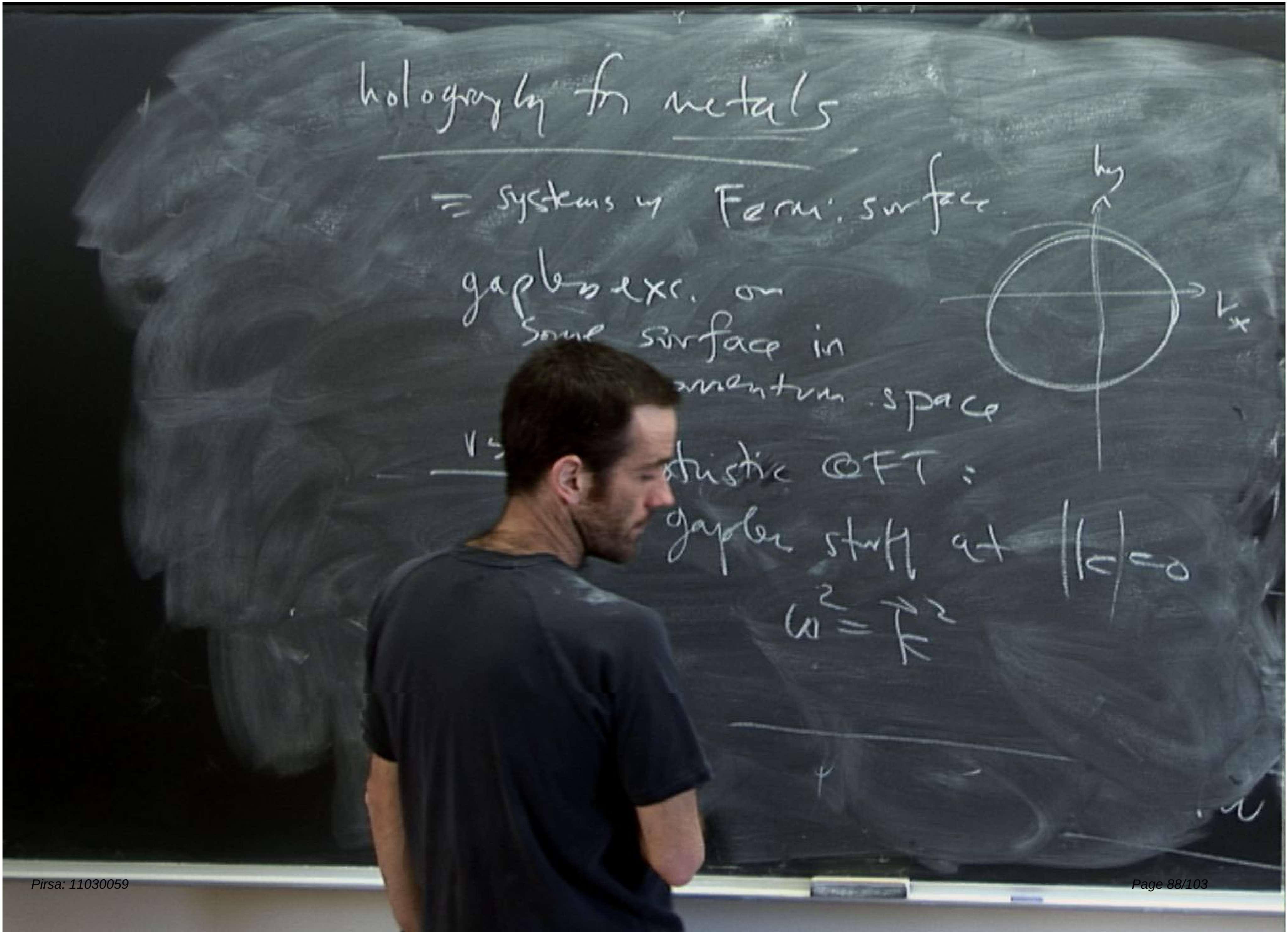

holography for metals
= systems w/ Fermi surface
k_y
k_x

holography for metals

= systems w/ Fermi surface




holography for metals
= systems w/ Fermi surface
gapless exc. on
some surface in
momentum space
relativistic QFT :
k_y
k_x


holography for metals
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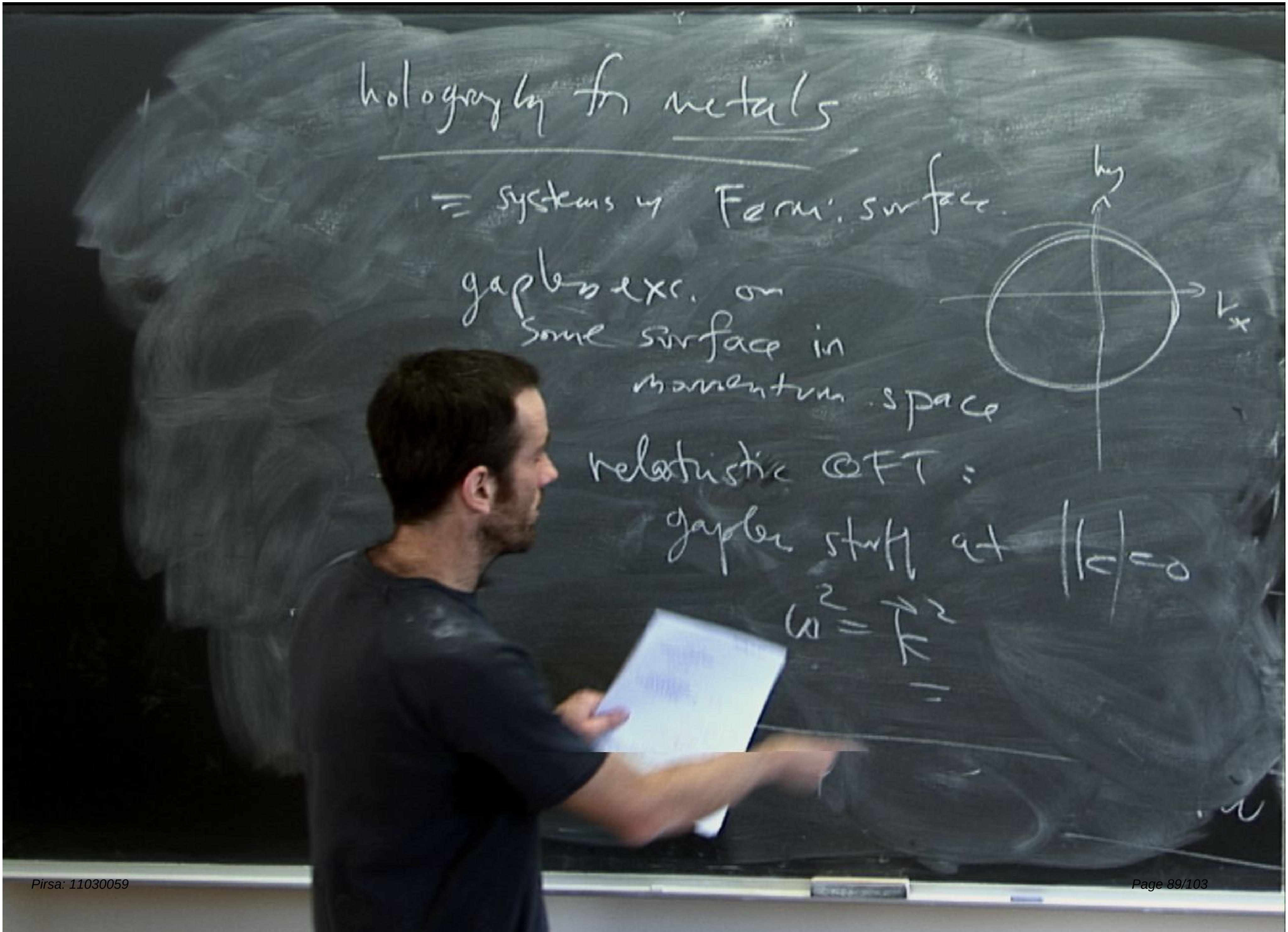
gapless exc. on
Some surface in
mentum space
gapless stuff at |k|=0
ω² = k²
k_y
k_x


holography for metals
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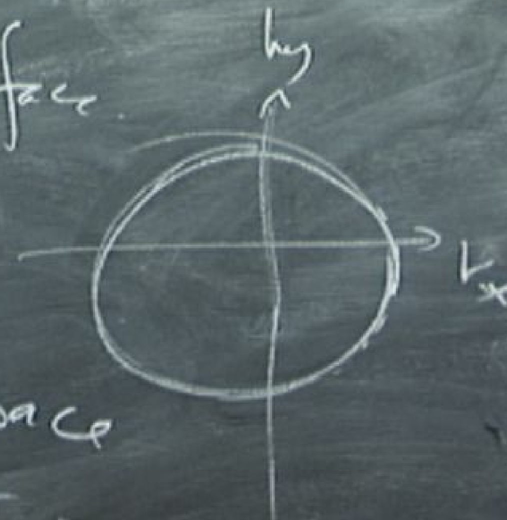
gapless exc. on some surface in momentum space
k_y
k_x
relativistic QFT:
gapless stuff at $|k| = 0$
$\omega^2 = \vec{k}^2$

holography for metals

= systems w/ Fermi surface

gapless exc. on some surface in momentum space



vs: relativistic QFT: gapless stuff at $|k| = 0$

$$\omega^2 = \vec{k}^2$$

Suppose: $T^{\mu\nu}$, J^{μ}, Ψ

suppose: $T^{\mu\nu}$, J^{μ}, Ψ_{Δ}

$\longrightarrow$ $g_{\mu\nu}$ A_{μ}, ψ charge q
mass m

Suppose: $T^{\mu\nu}$, J^{μ}, Ψ_{Δ}

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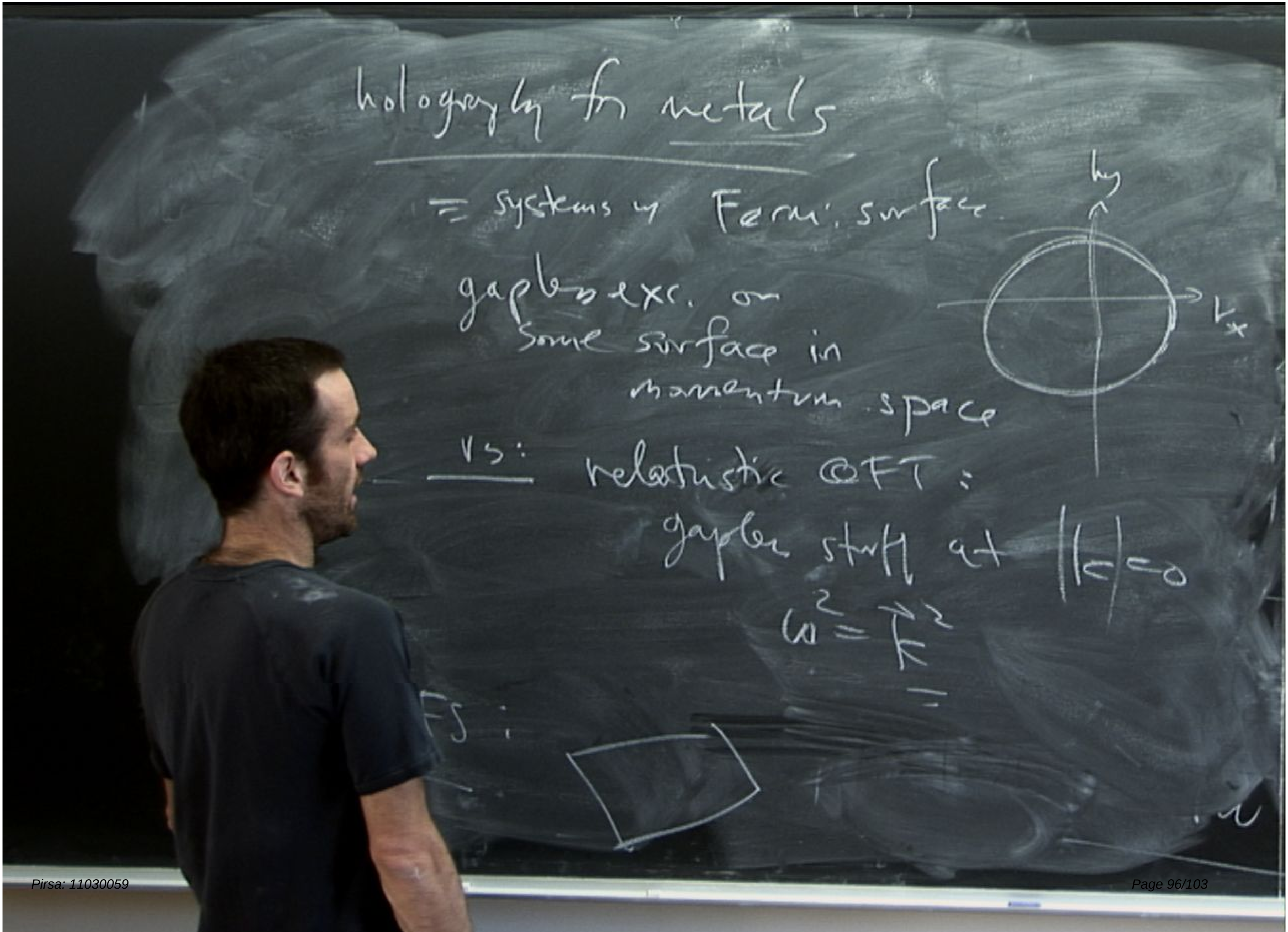
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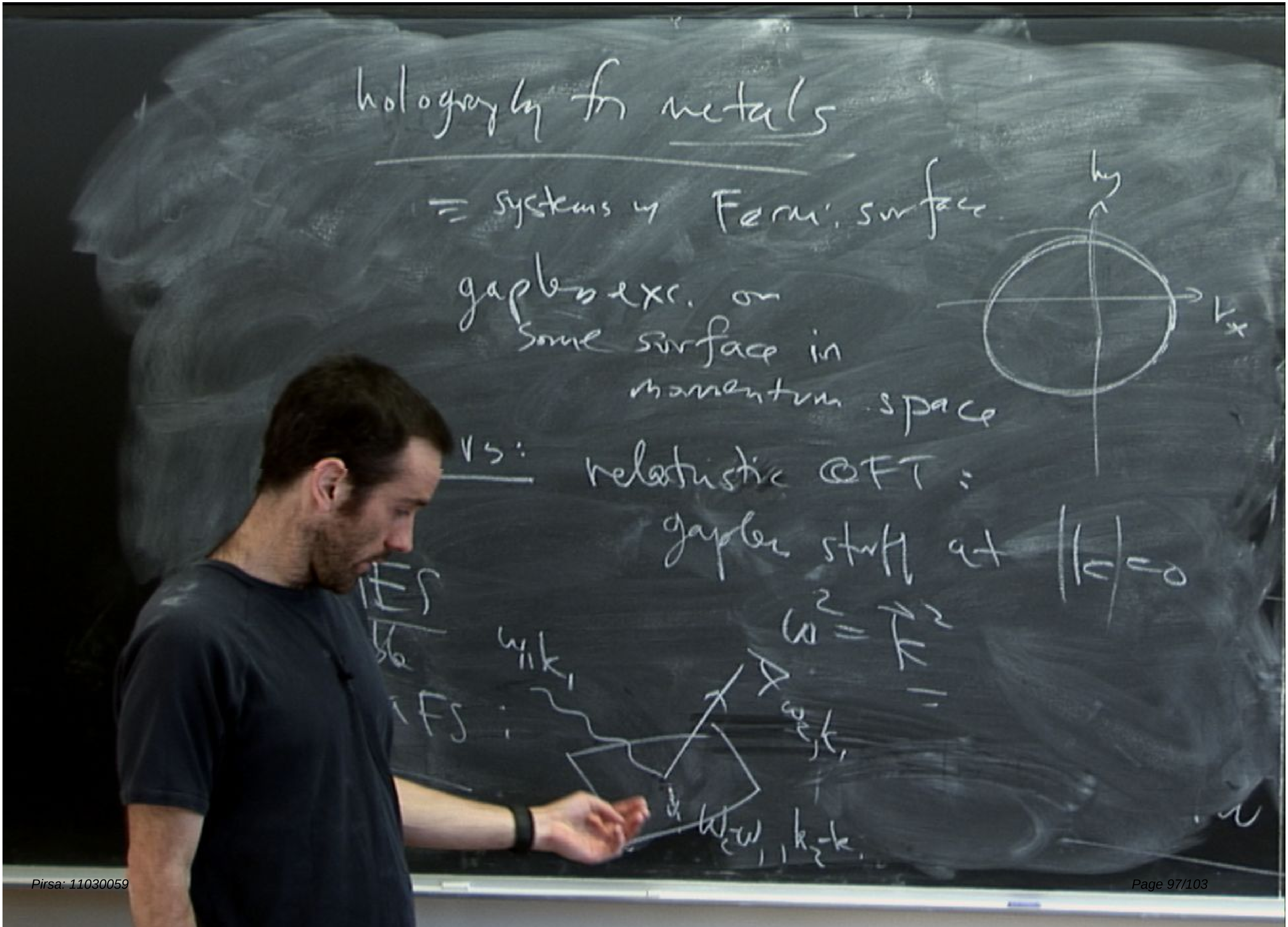
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holography for metals

= systems w/ Fermi surface

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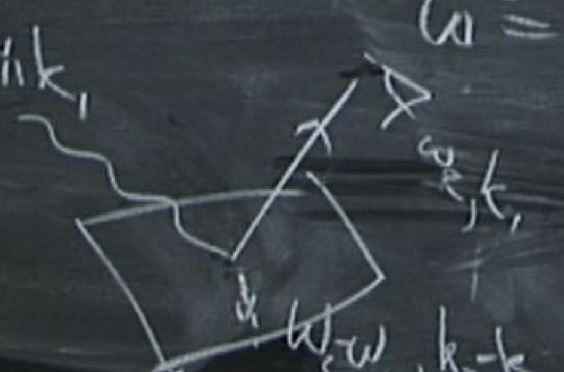
$\omega^2 = \vec{k}^2$

ARPES

observable to see a FS:



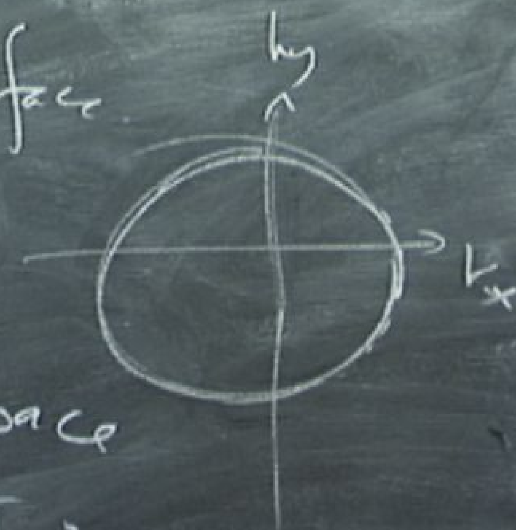
$I \propto$

$\omega_e = \omega_1, k_e - k$

holography for metals

= systems w/ Fermi surface

gapless exc. on some surface in momentum space



vs: relativistic QFT: gapless stuff at $|k|=0$

$$\omega^2 = \vec{k}^2$$

ARPES

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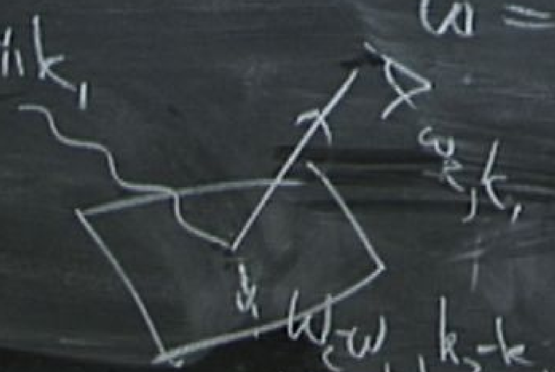

$$I \propto \mathrm{Im}\, G_R(\omega_2 - \omega_1, \ldots$$

- suppose: $T^{\mu\nu}$, J^{μ}, Ψ_{Δ}

$\longrightarrow$ $g_{\mu\nu}$ A_{μ}, ψ charge q
mass m

$$G(p) = \int dm^2 \frac{\rho(m)}{p^2+m^2}$$

$$G^R = G^R_{\Psi\Psi}$$

$$\rho = \mathrm{Im}\, G$$

$w_2 - w_1, \vec{k}_2 - \vec{k}_1)$

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$$G(p) = \int dm^2 \frac{\rho(m)}{p^2+m^2}$$

$$\rho = \mathrm{Im}\, G$$

$$G^R = G^R_{\Psi\bar{\Psi}}$$

$$S_{bulk} = \dots + \int d^{d+1}x \sqrt{g}\, \bar{\psi}(\not{D} \dots$$

$$(\not{D} - m)\psi = 0$$

$N_2 - N_1, \vec{k}_2 - \vec{k}_1)$

suppose: $T^{\mu\nu}$, J^{μ}, Ψ_{Δ}

$\longrightarrow$ $g_{\mu\nu}$, A_{μ}, ψ charge q, mass m

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