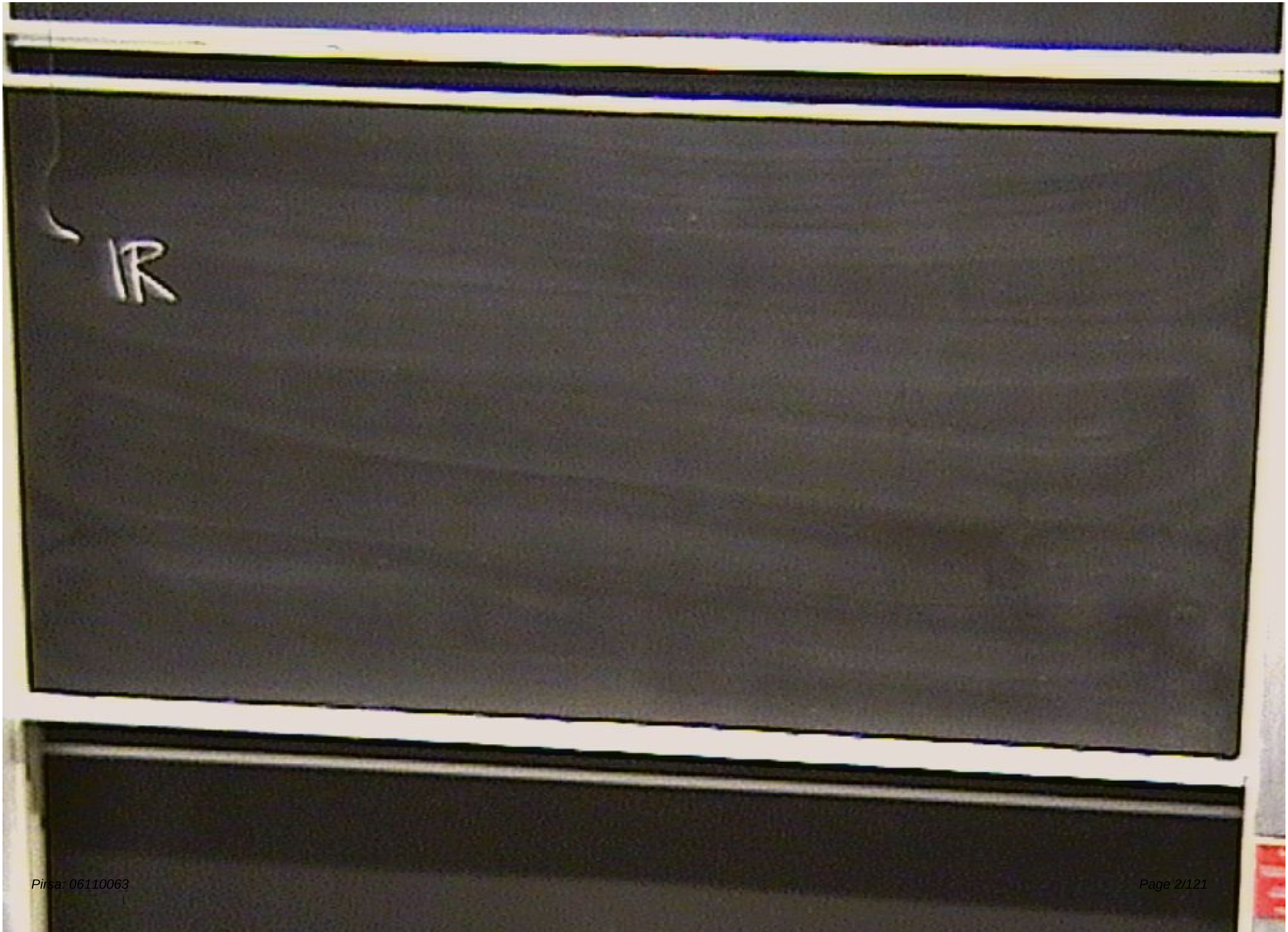
Title: IR Modifications of Gravity

Date: Nov 20, 2006 02:00 PM

URL: http://www.pirsa.org/06110063

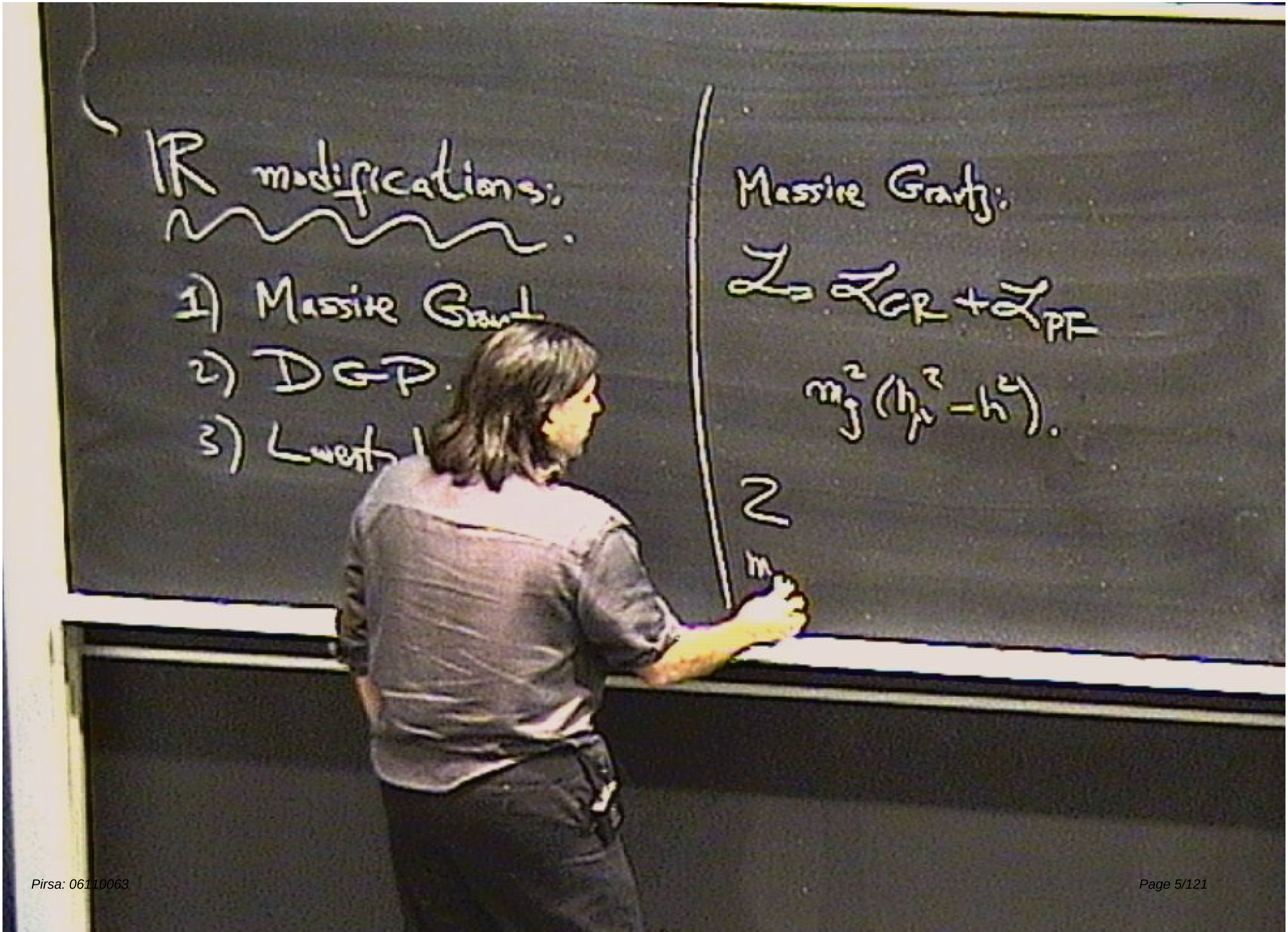
Abstract:

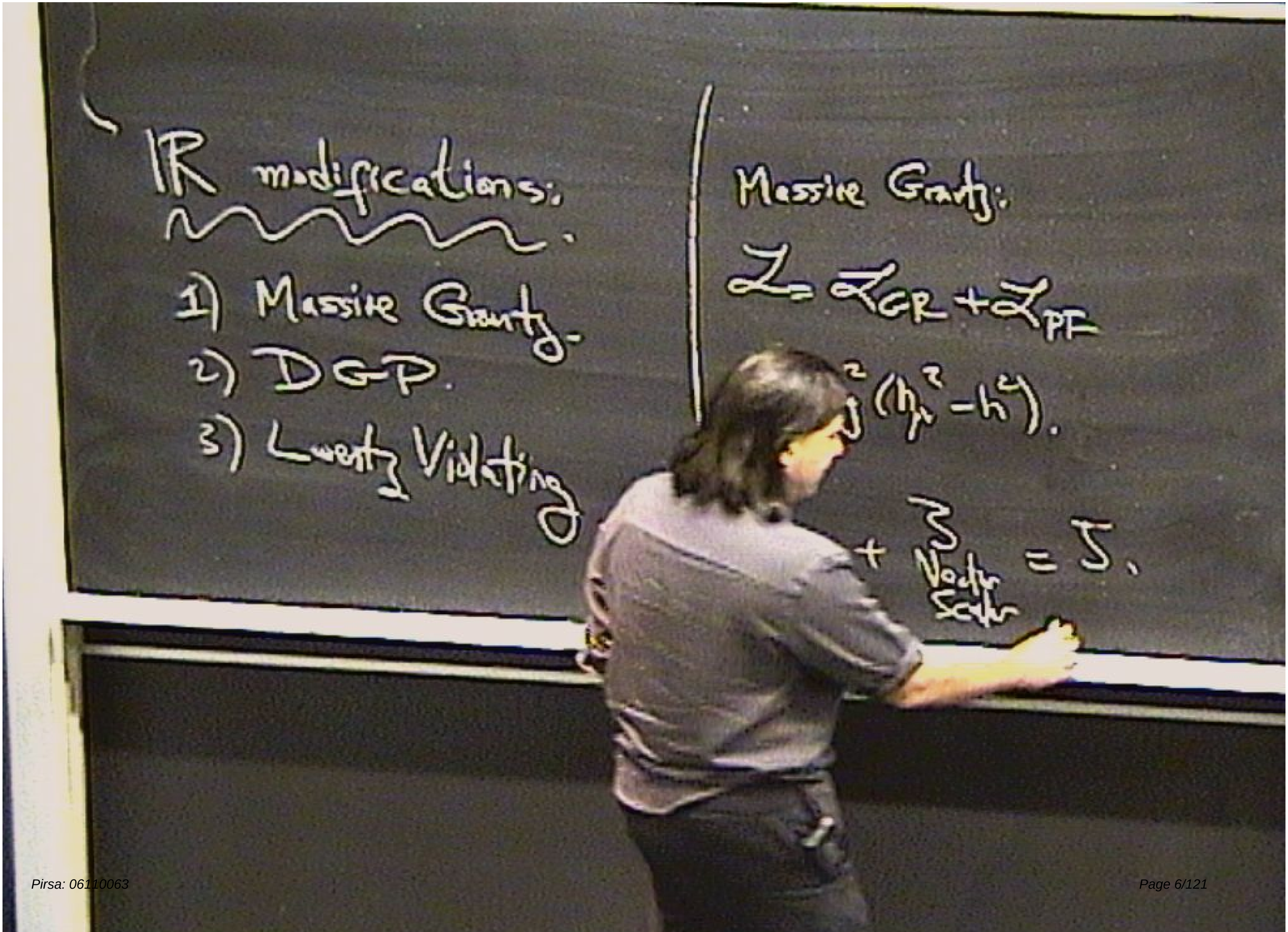

ℝ

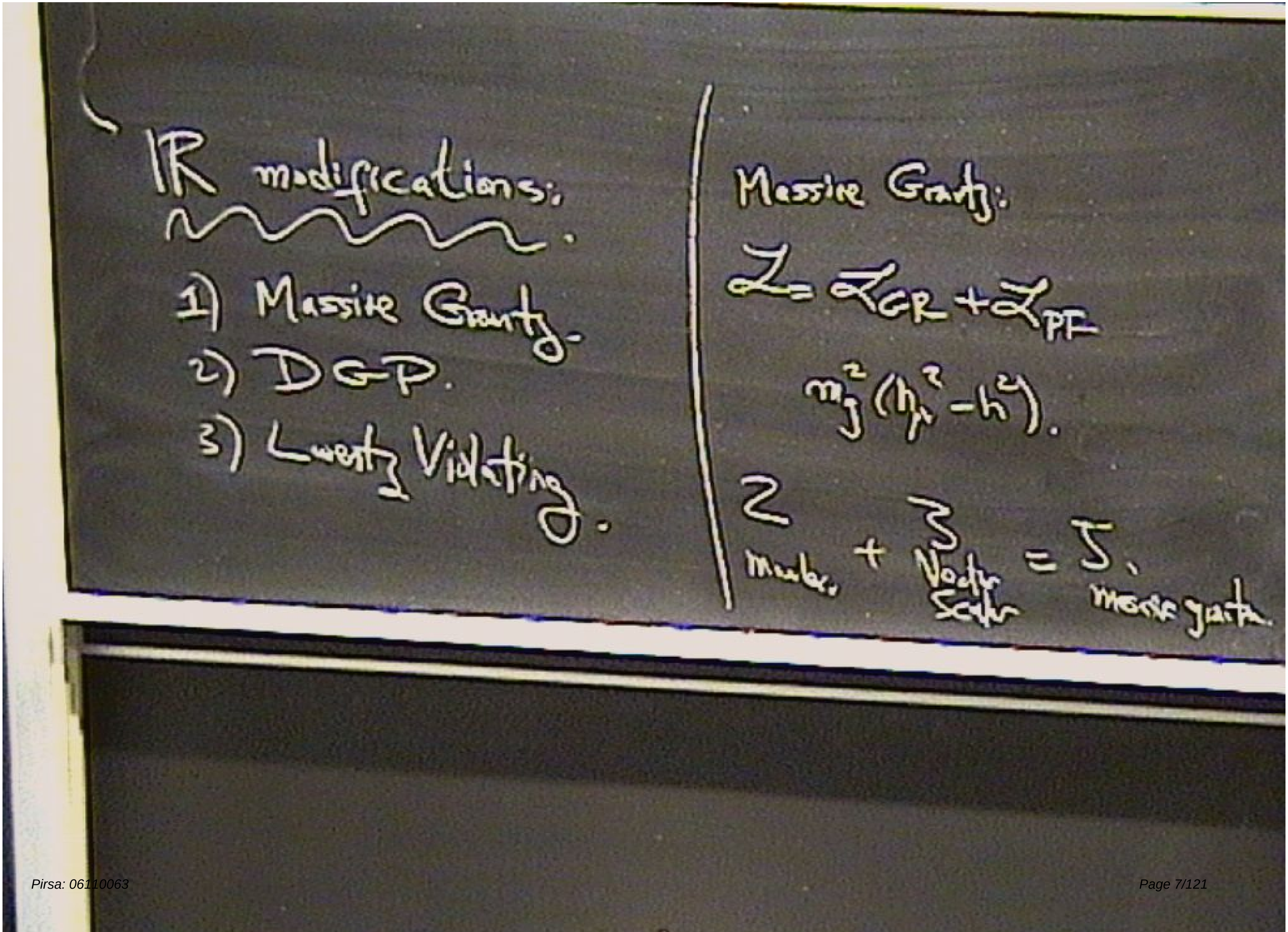
IR modifications:

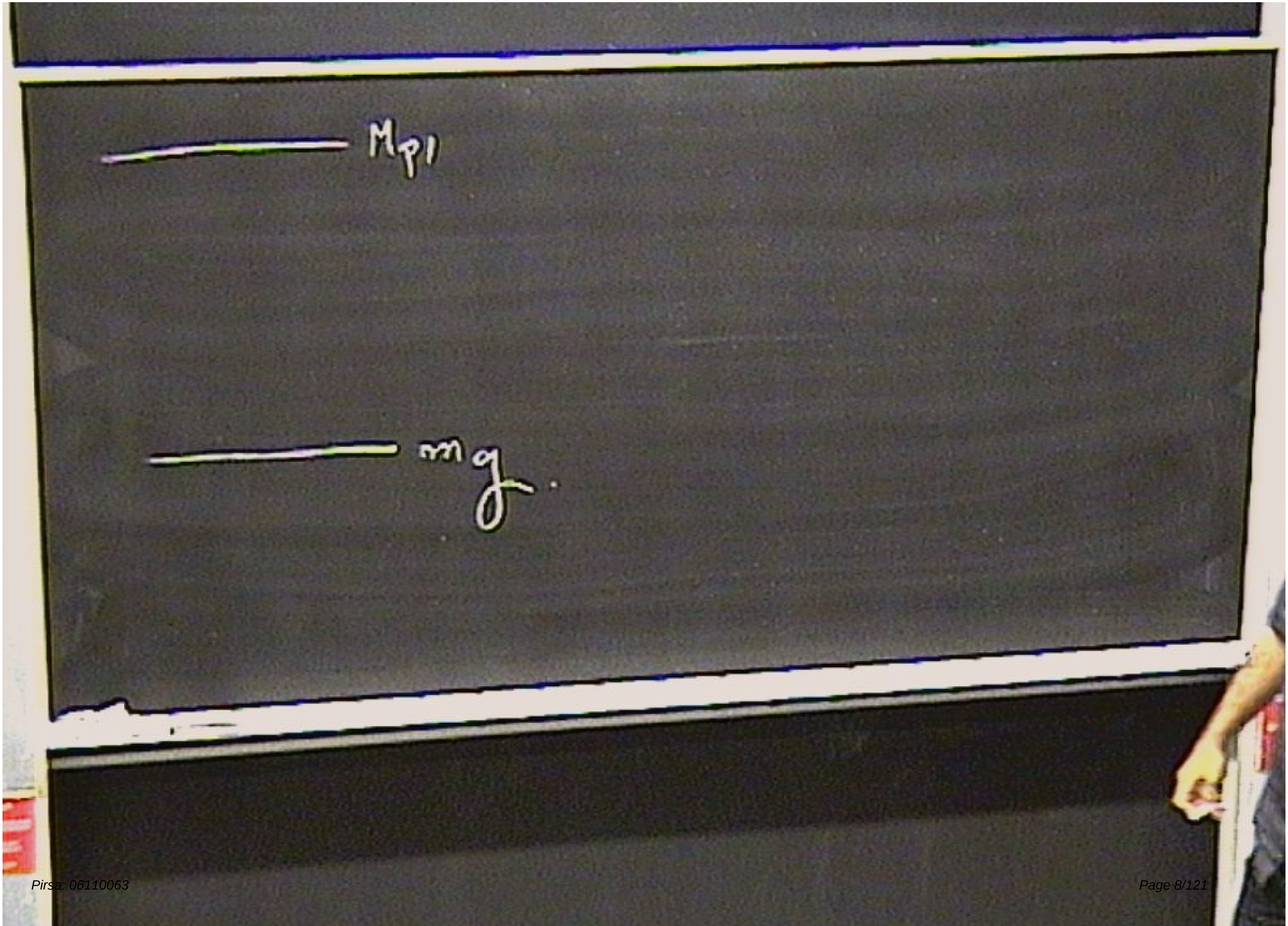
IR modifications:

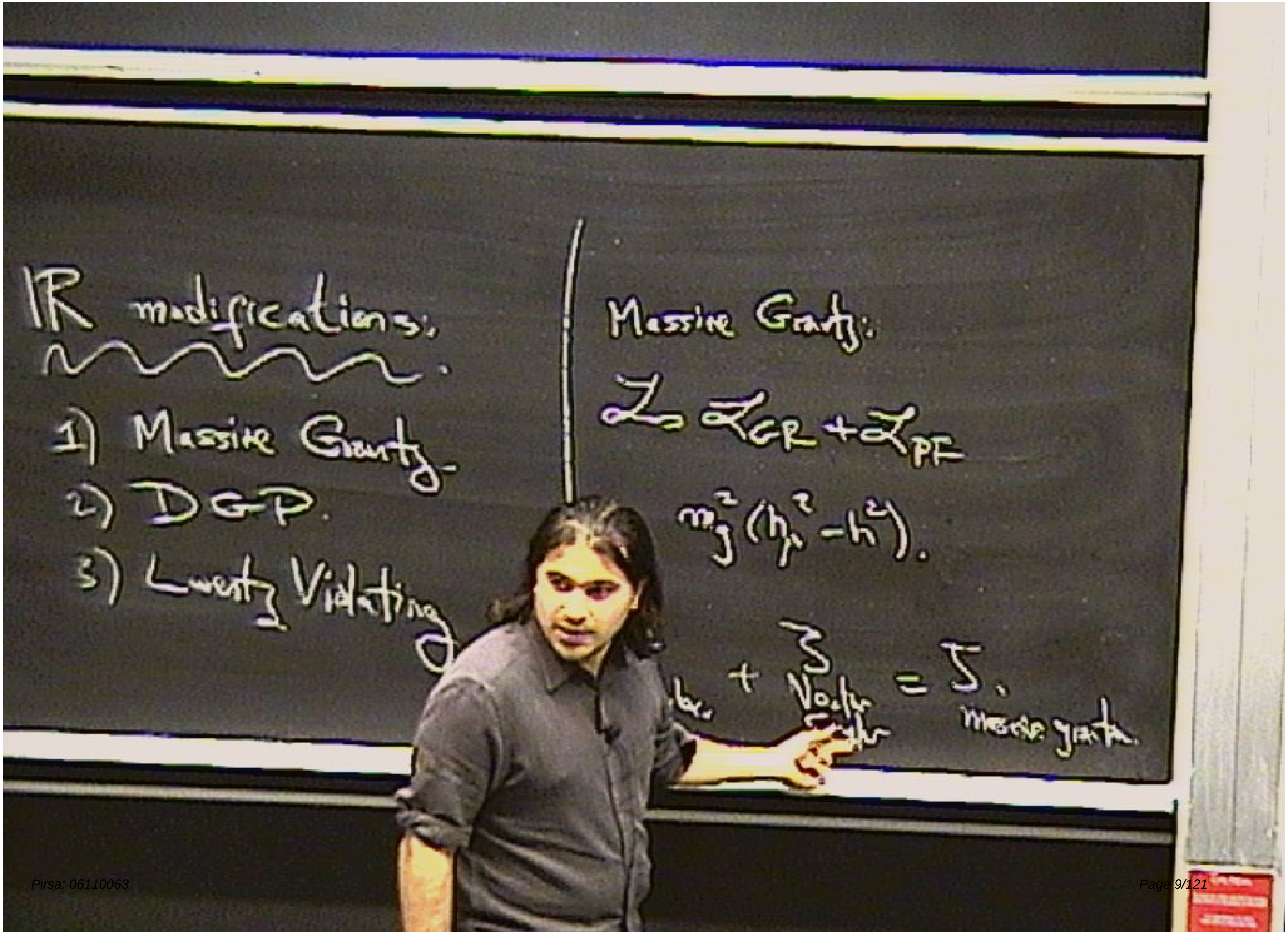
1) Massive Gravity.
2) DGP.
3) Lorentz Violating.

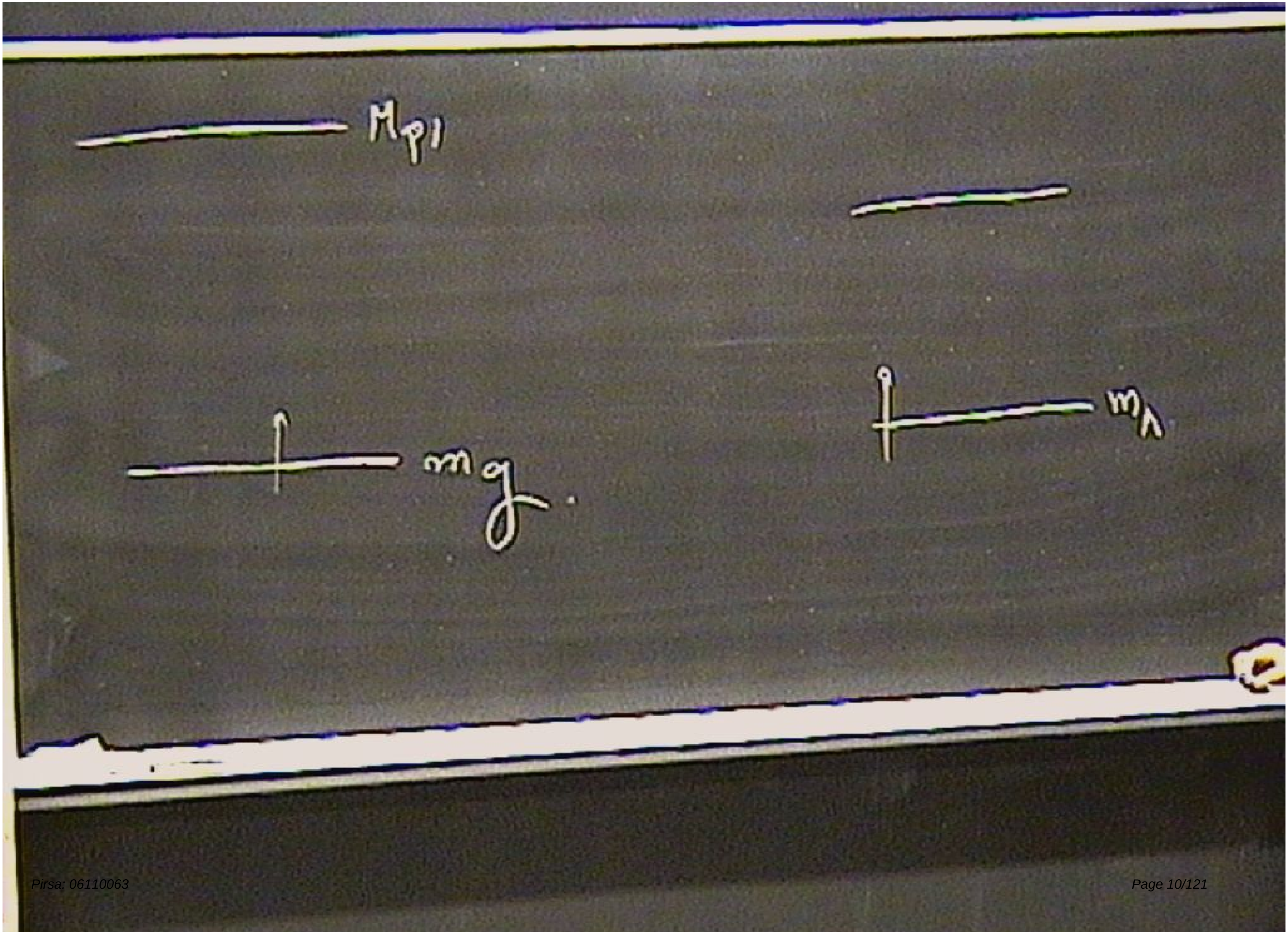

IR modifications:
1) Massive Grav
2) DGP.
3) Lorent
Massive Gravity:
$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{PF}$
$m_g^2 (h_{\mu\nu}^2 - h^2)$.

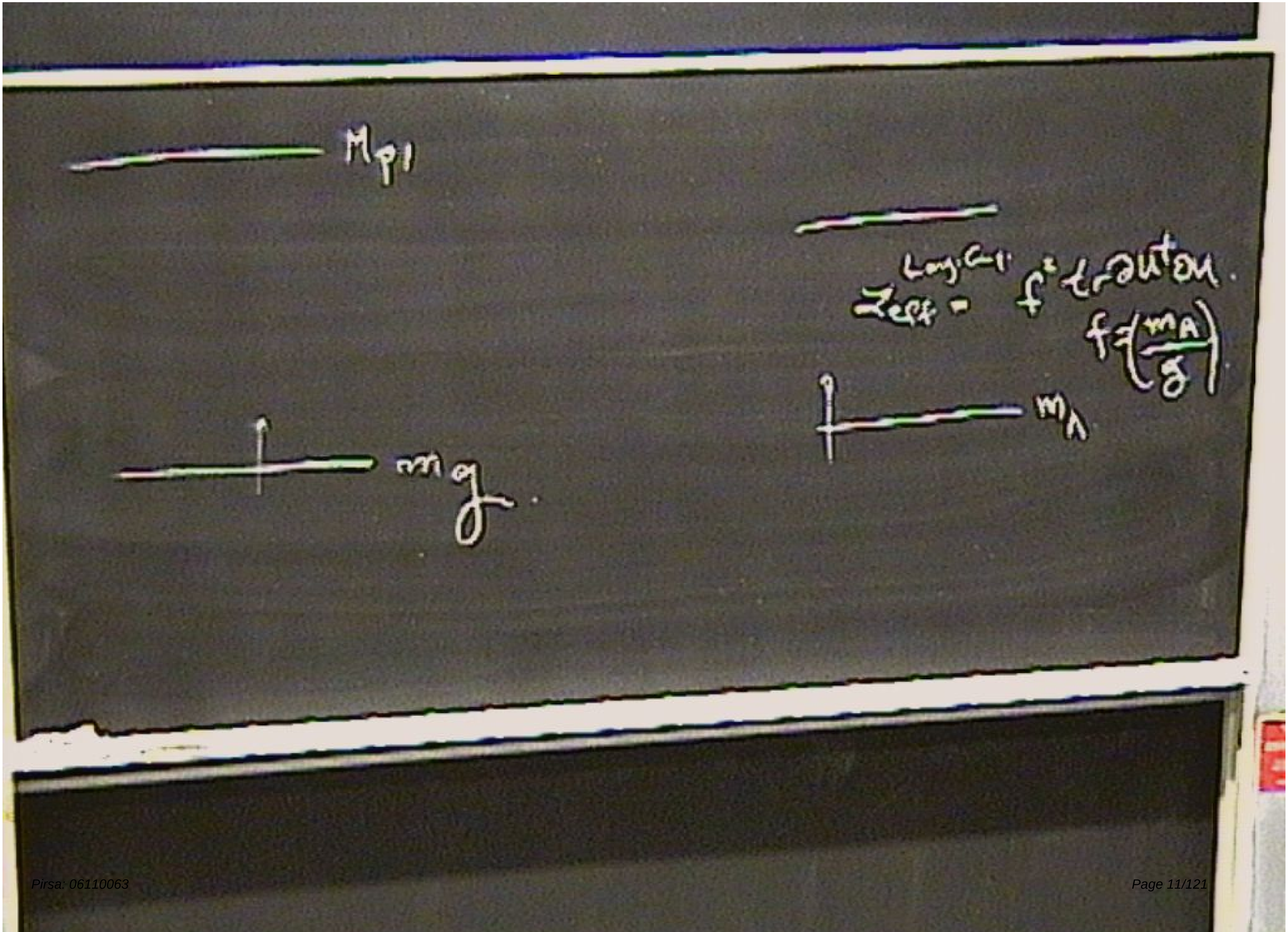

IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz Violating
Massive Gravity:
L = L_GR + L_PF
Vector
Scalar
= 5.

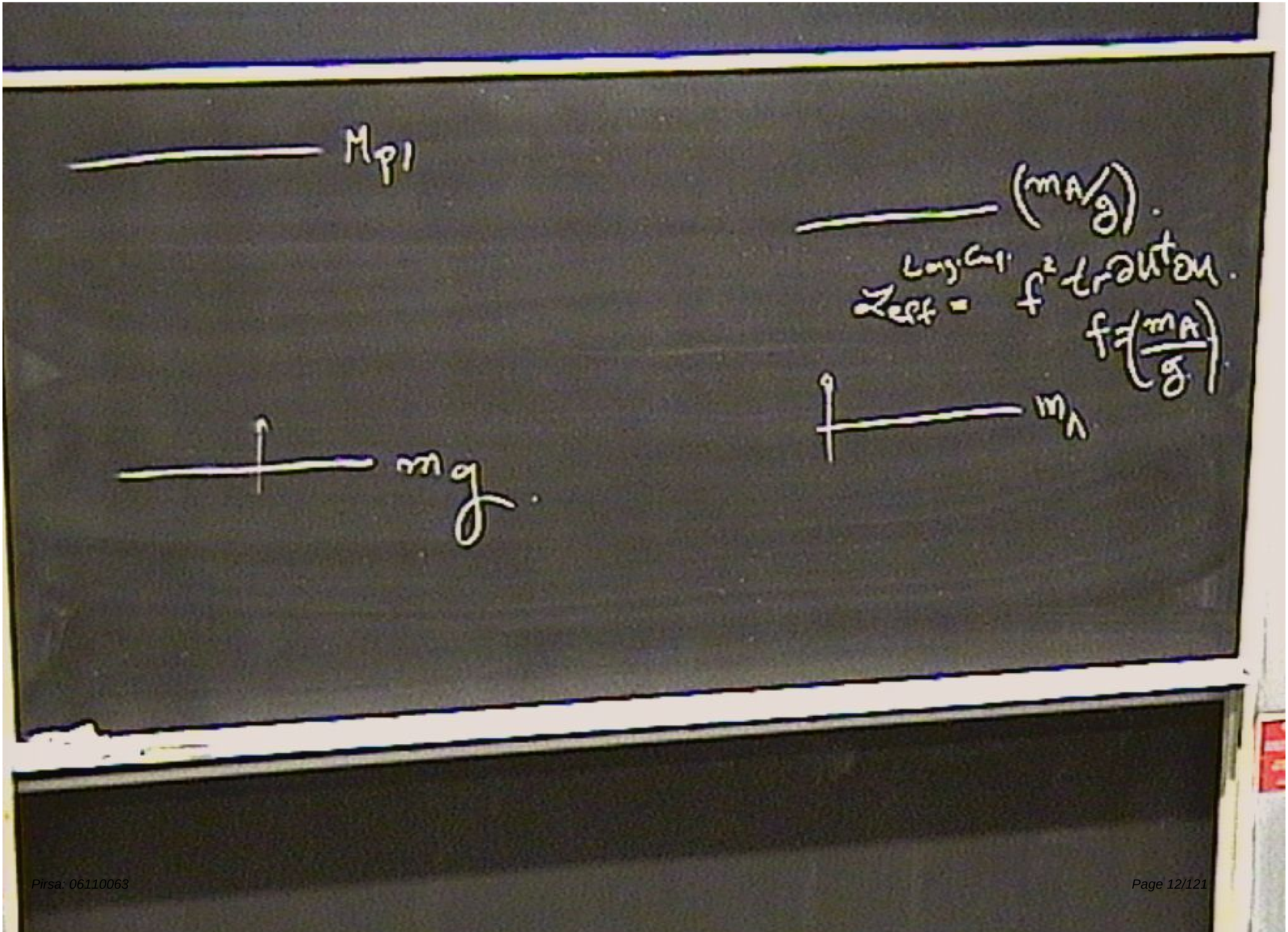

IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz Violating.
Massive Gravity:
$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{PF}$
$m_g^2(h_{\mu\nu}^2 - h^2)$.
2 massless + 3 Vector Scalar = 5. massive graviton

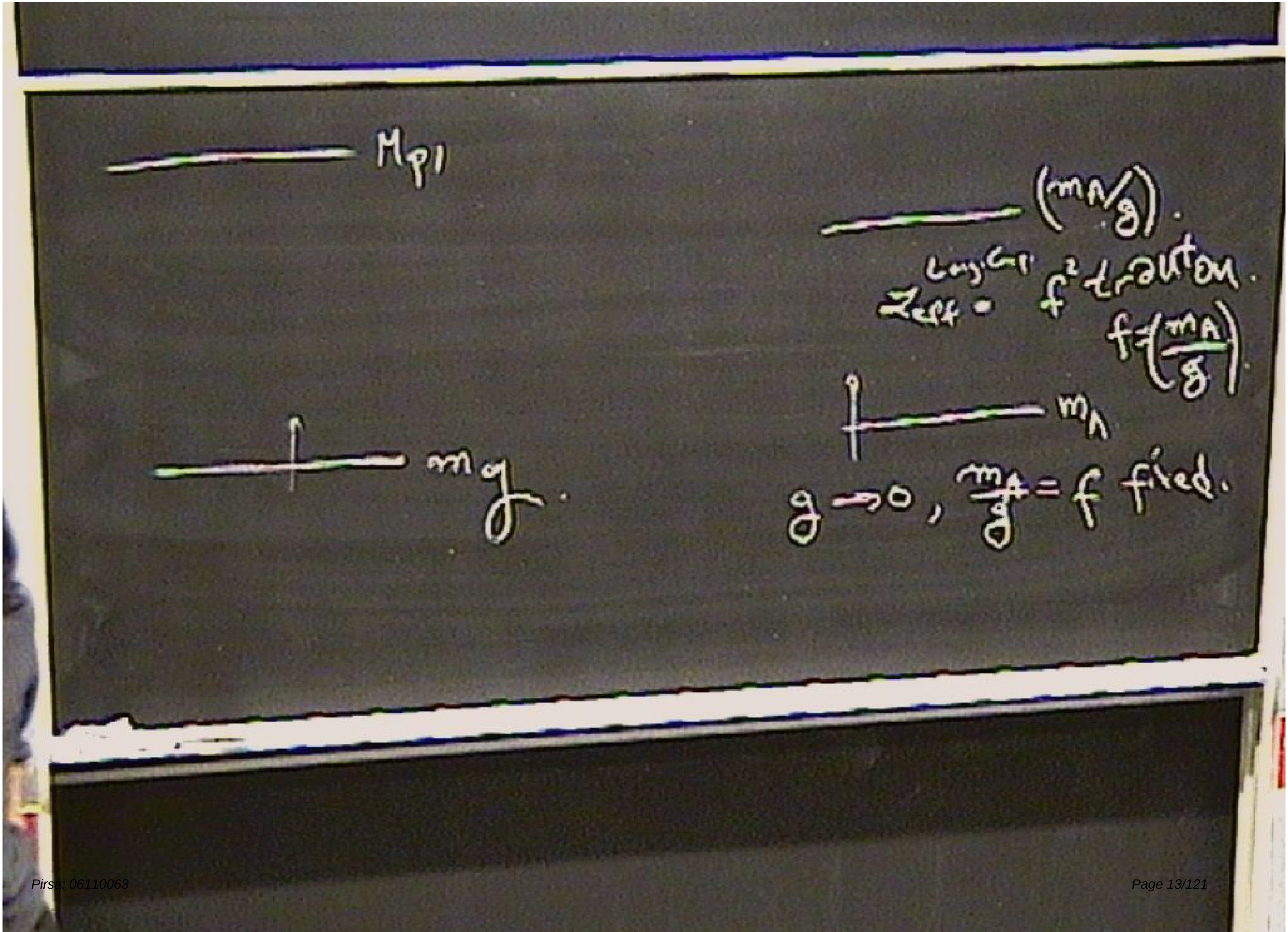

M_{pl}
m_g.


IR modifications:
1) Massive Gravity
2) DGP
3) Lorentz Violating
Massive Gravity:
$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{PF}$
$m_g^2(h_{\mu\nu}^2 - h^2)$.
+ 3 Vector = 5.
massive graviton

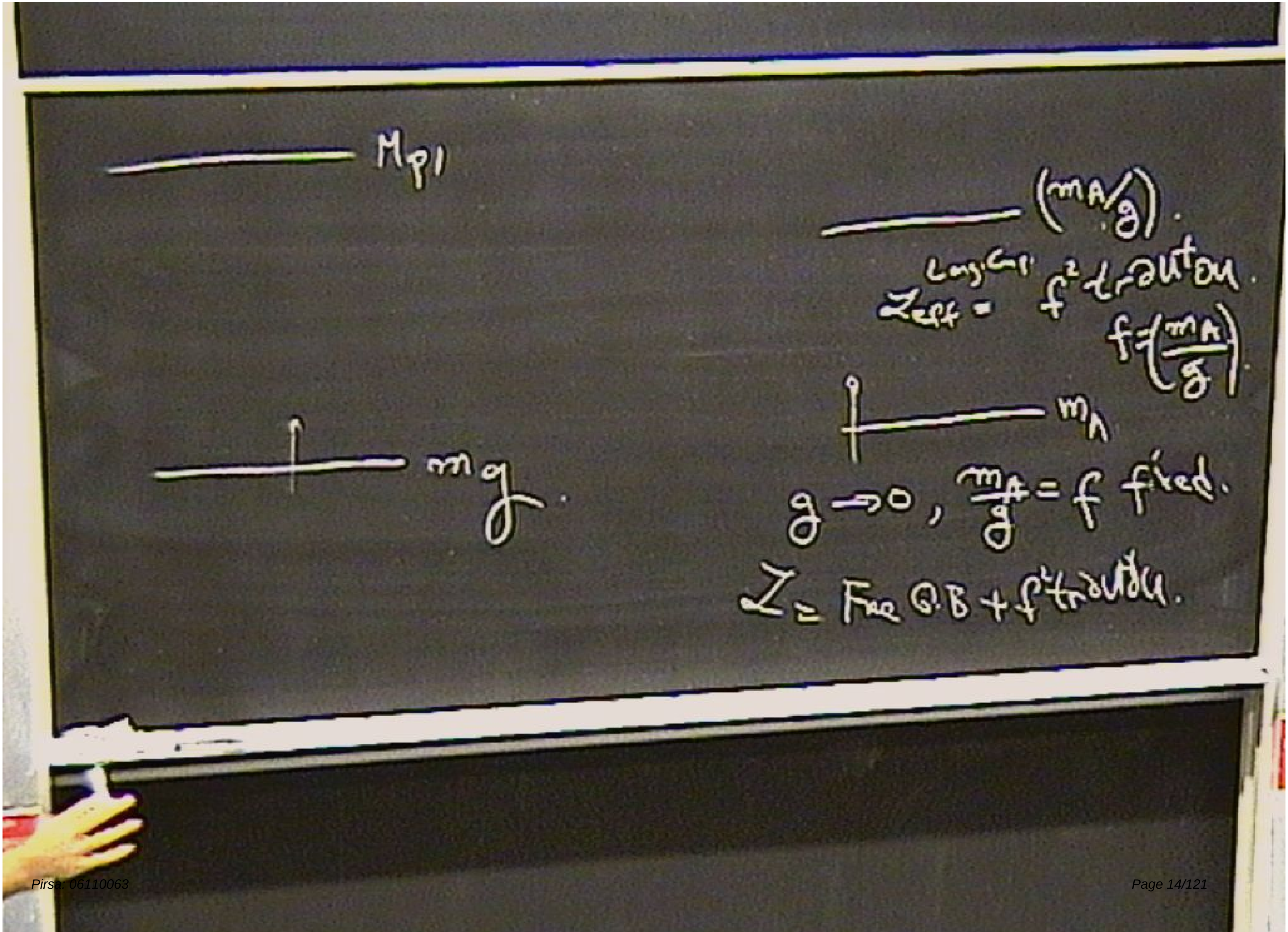

M_{pl}
m_g
m_Λ

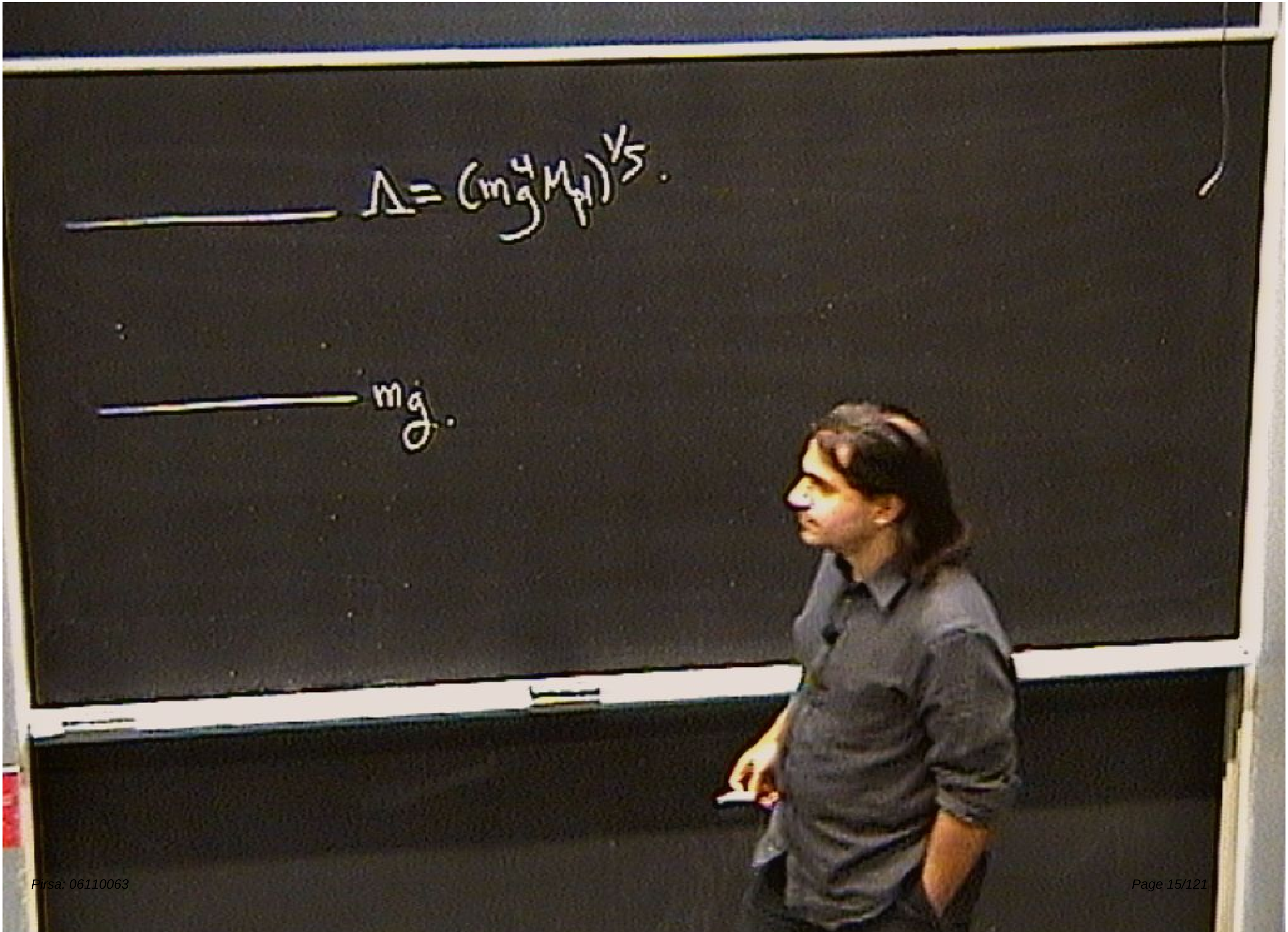

Mpl
mg
mΛ


M_pl
(m_A/g).
Long. Comp.
L_eff = f² tr ∂U ∂U.
f ~ (m_A/g).
m_Λ
m_g.



M_pl
(m_A/g)
m_A
m_g
g → 0, m_A/g = f fixed.


M_pl
(m_A/g)
f = (m_A/g)
m_A
m_g
g → 0, m_A/g = f fixed.
L = Free G.B


$\Lambda = (m_g^4 M_{pl})^{1/5}$.
m_g.

M_{Pl}

(m_A/g).

$\mathcal{L}_{eff}^{\text{Long. Comp.}} = f^2 \, tr \, \partial U^\dagger \partial U$.

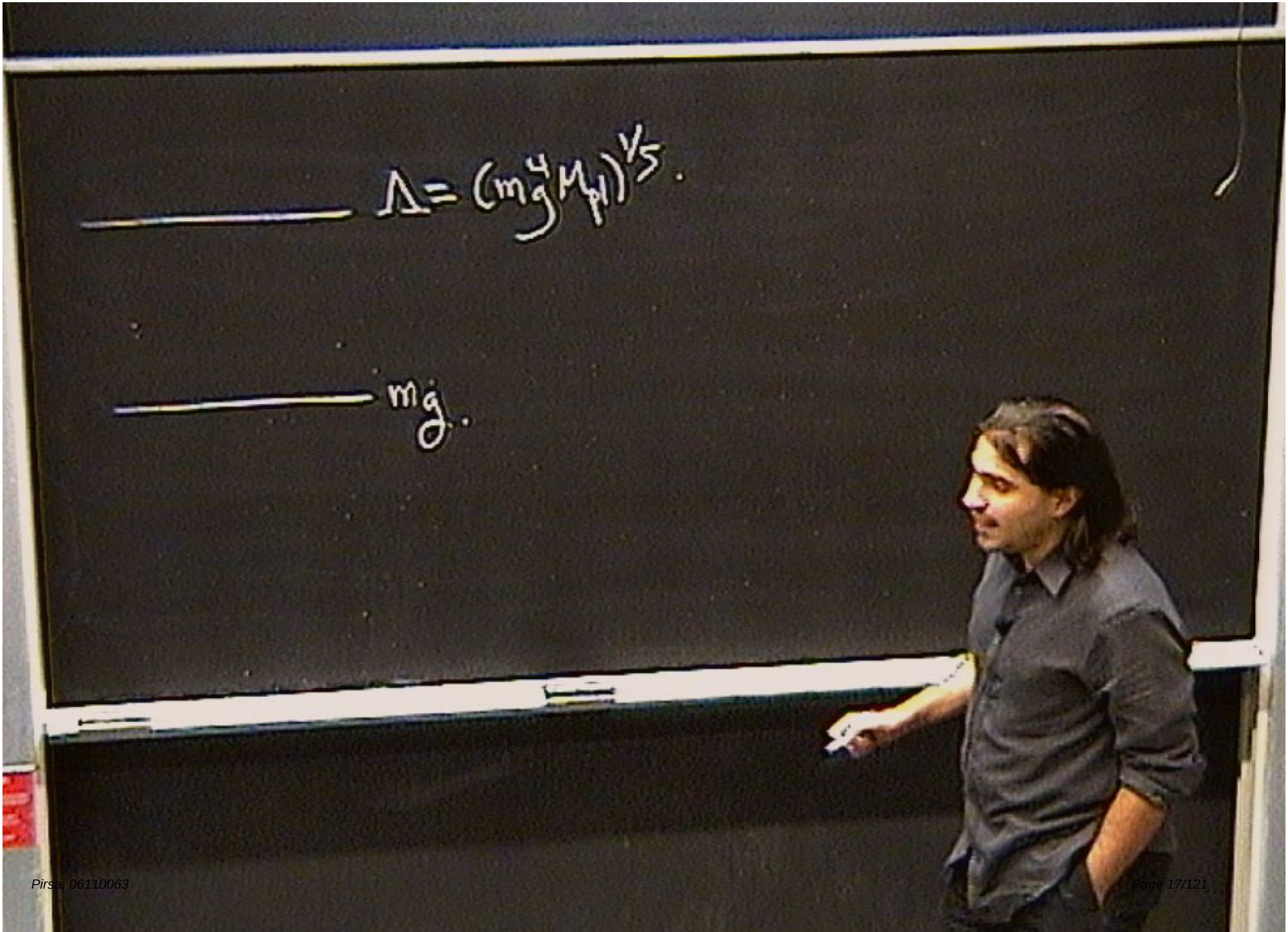
$f = \left(\frac{m_A}{g}\right)$.

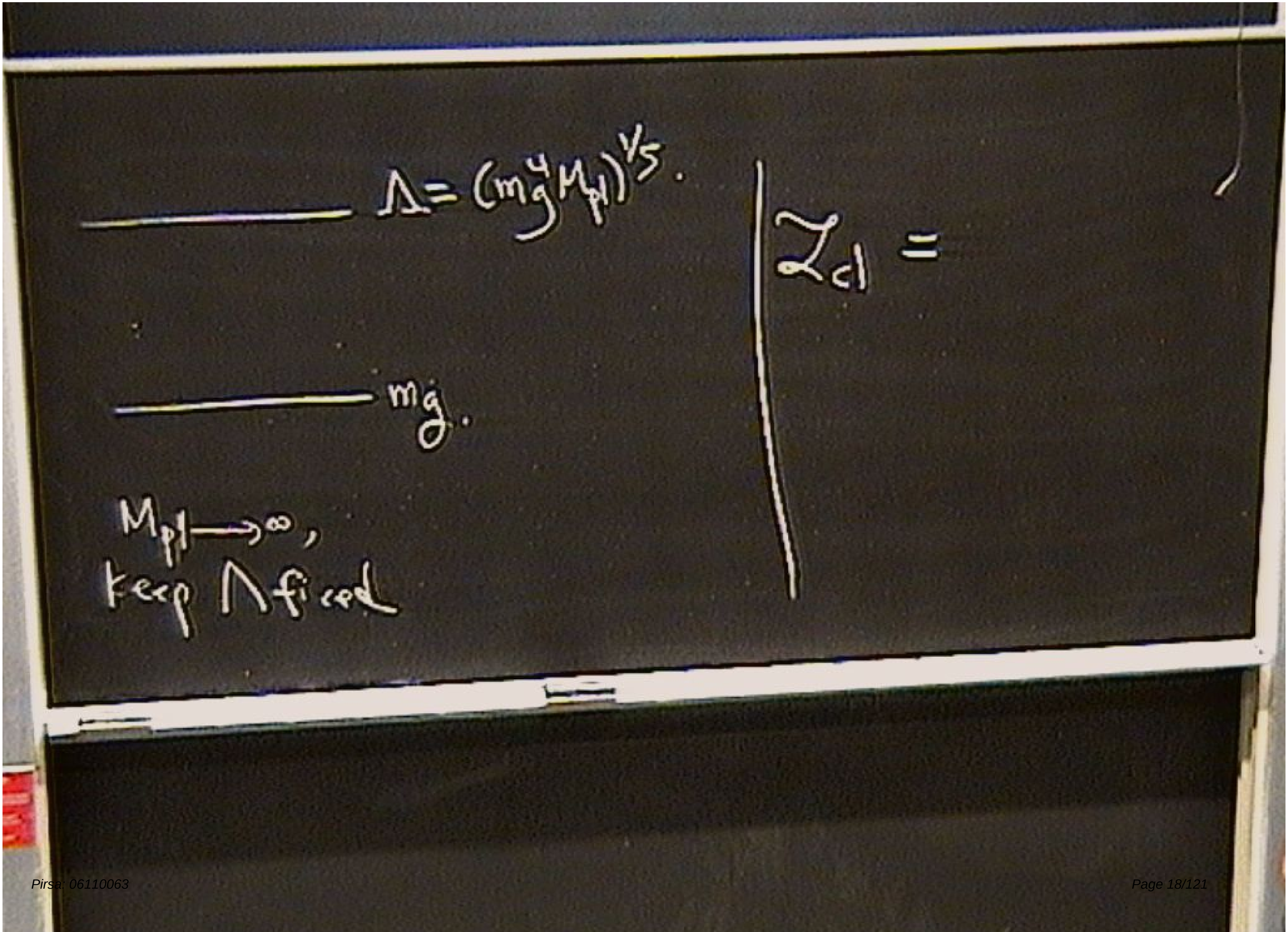
m_g.

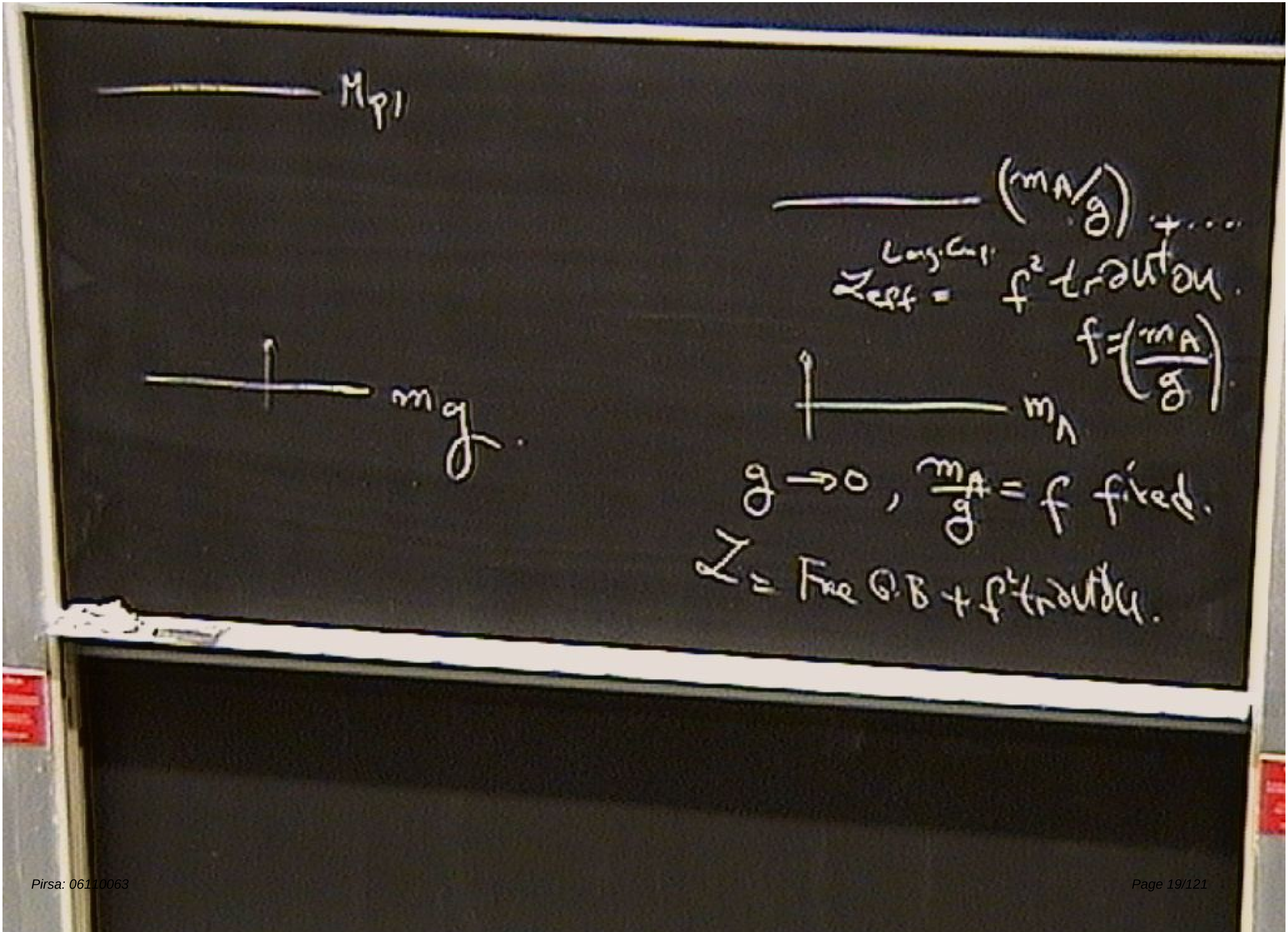
m_A

$g \to 0$, $\frac{m_A}{g} = f$ fixed.

$\mathcal{L} = \text{Free G.B} + f^2 \, tr \, \partial U^\dagger \partial U$.


Λ = (m_g^4 M_pl)^1/5 .
m_g .


$\Lambda = (m_g^4 M_{pl})^{1/5}$.
m_g.
$M_{pl} \longrightarrow \infty$,
keep Λ fixed
$\mathcal{L}_{cl} =$



M_Pl
(m_A/g) + . . .
Long. Comp.
L_eff = f² tr∂U†∂U.
f = (m_A/g)
m_g.
m_A
g → 0, m_A/g = f fixed.
L = Free G.B + f² tr∂U†∂U.

$$\Lambda = (m_g^4 M_{pl})^{1/5}.$$

m_g.

$M_{pl} \longrightarrow \infty$,
keep Λ fixed

$$\mathcal{L}_{cl}^{\text{scalar}} = (\partial\varphi)^2 + \frac{(\partial^2\varphi)^3}{\Lambda^5}$$

$$\Lambda = (m_g^4 M_{pl})^{1/5}.$$

m_g.

$M_{pl} \to \infty$,
keep Λ fixed

$$\mathcal{L}_{cl}^{\text{scalar lin}} = (\partial\varphi)^2 + \frac{(\partial^2\varphi)^3}{\Lambda^5} + \cdots$$

$$\Lambda = (m_g^4 M_{pl})^{1/5}.$$

$$m_g.$$

$M_{pl} \longrightarrow \infty$,
keep Λ fixed

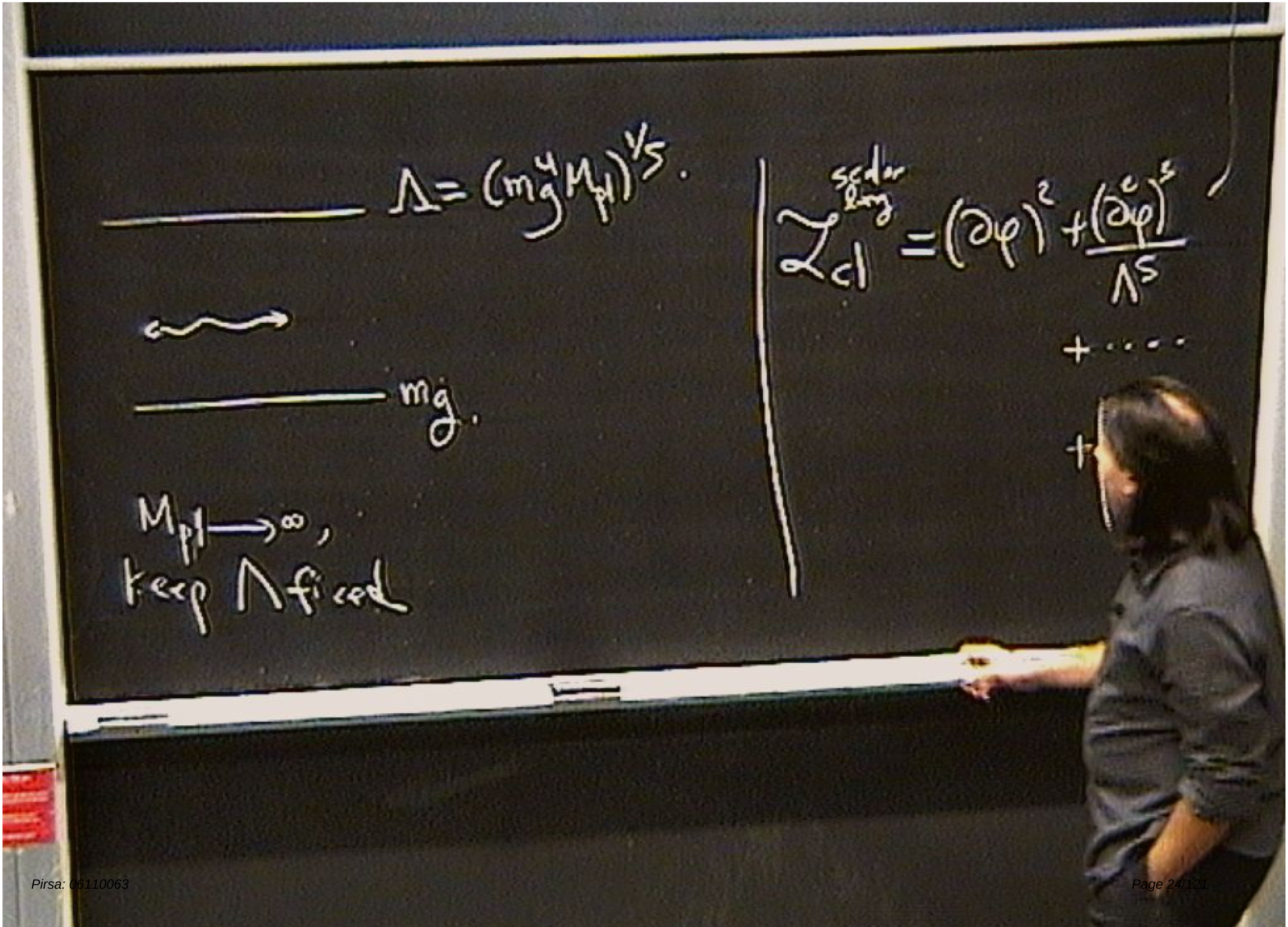
$$\mathcal{L}_{cl}^{\text{scalar, long}} = (\partial\varphi)^2 + \frac{(\partial^2\varphi)^3}{\Lambda^5} + \cdots + \frac{T}{M_{pl}}\varphi.$$

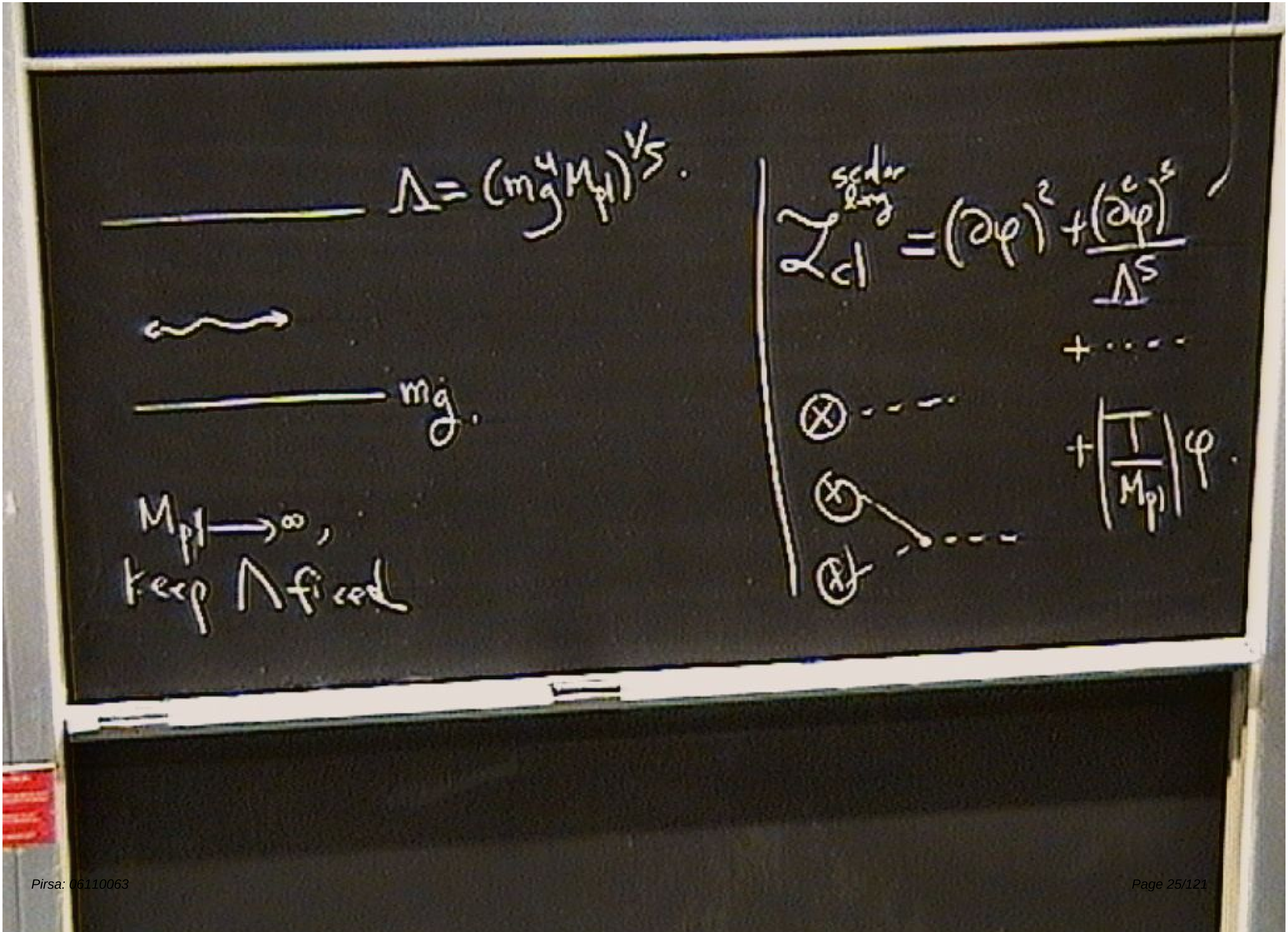
$$\Lambda = (m_g^4 M_{pl})^{1/5}.$$

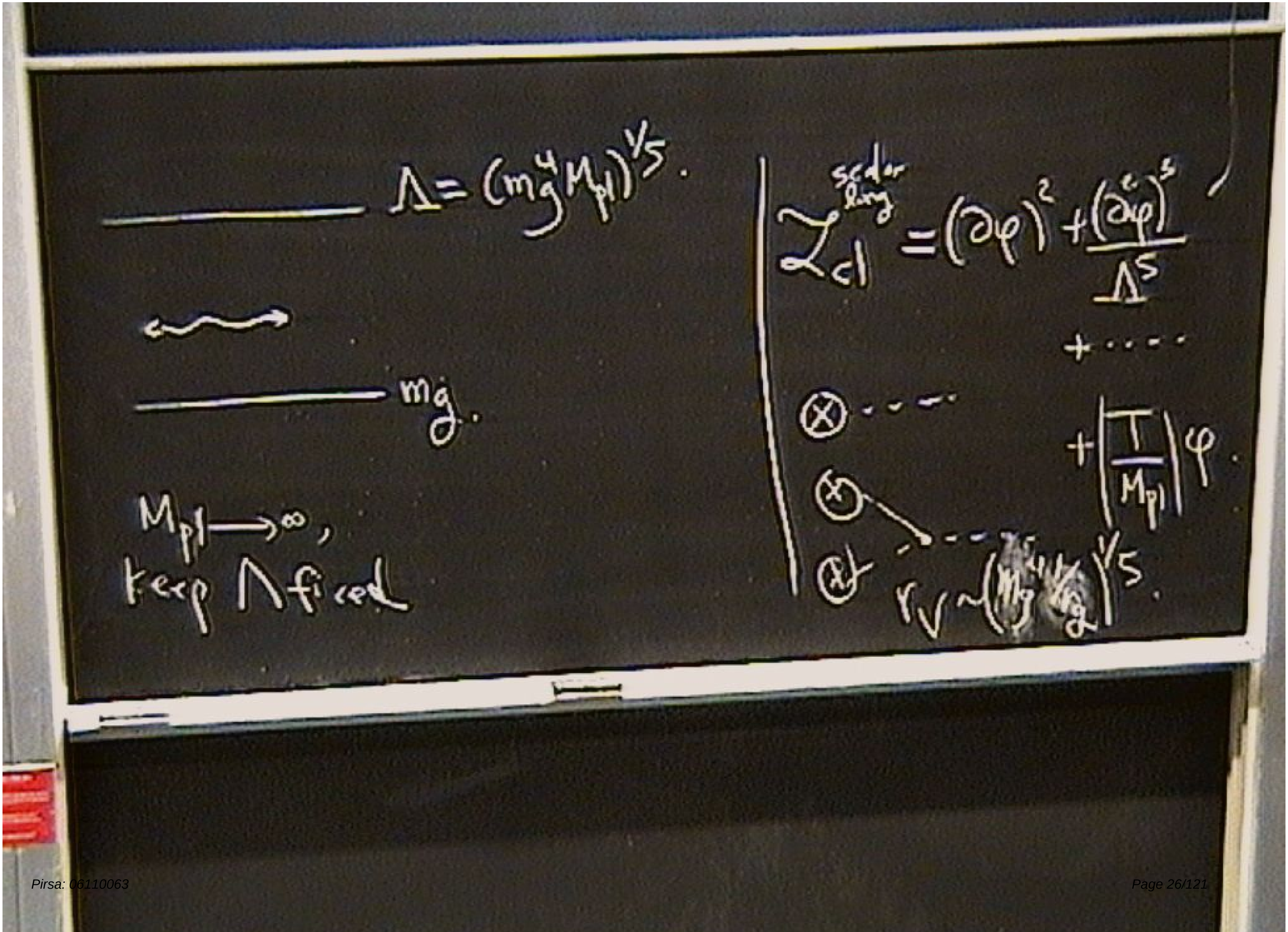
$$m_g.$$

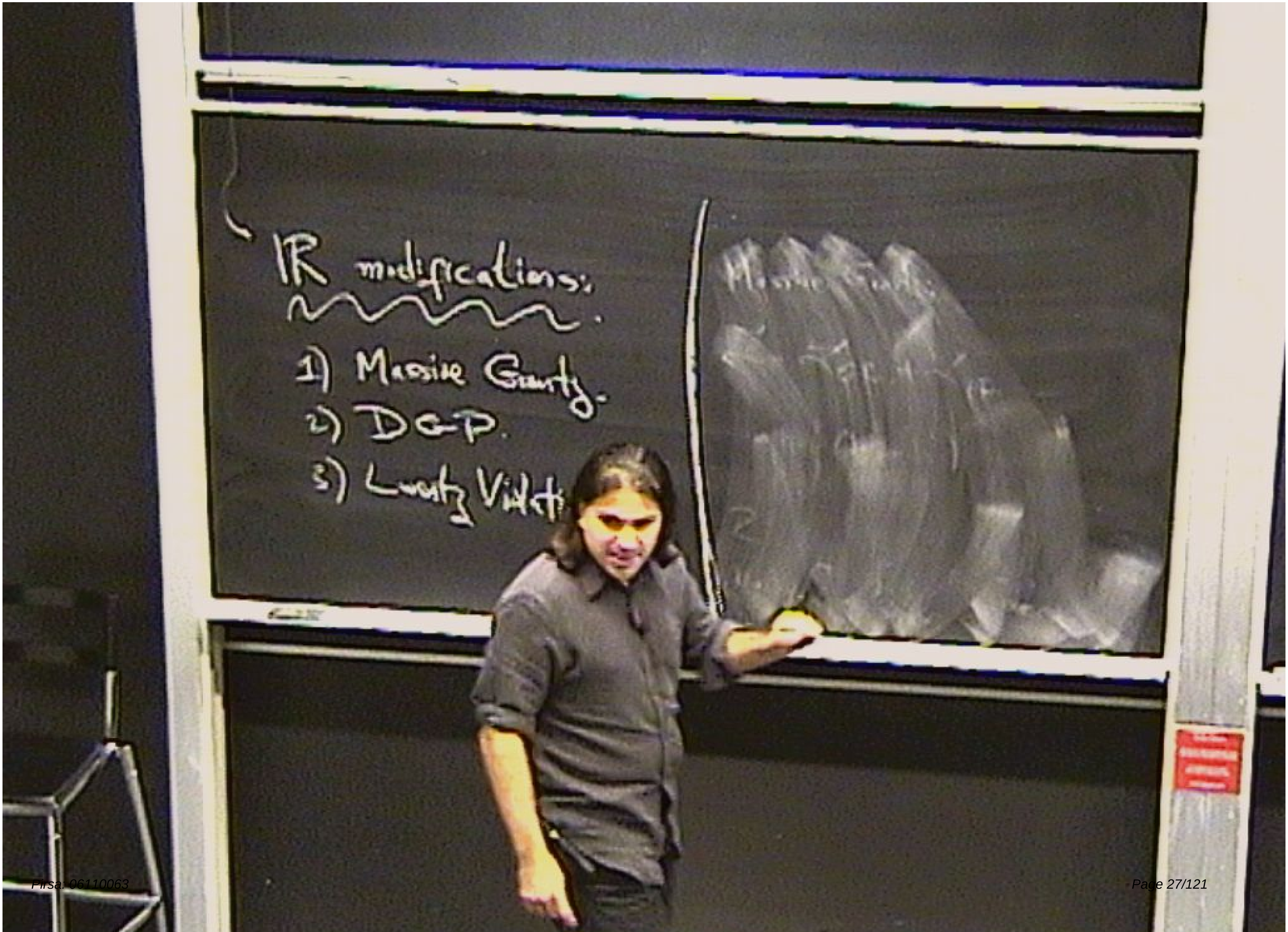
$M_{pl} \longrightarrow \infty$,
keep Λ fixed

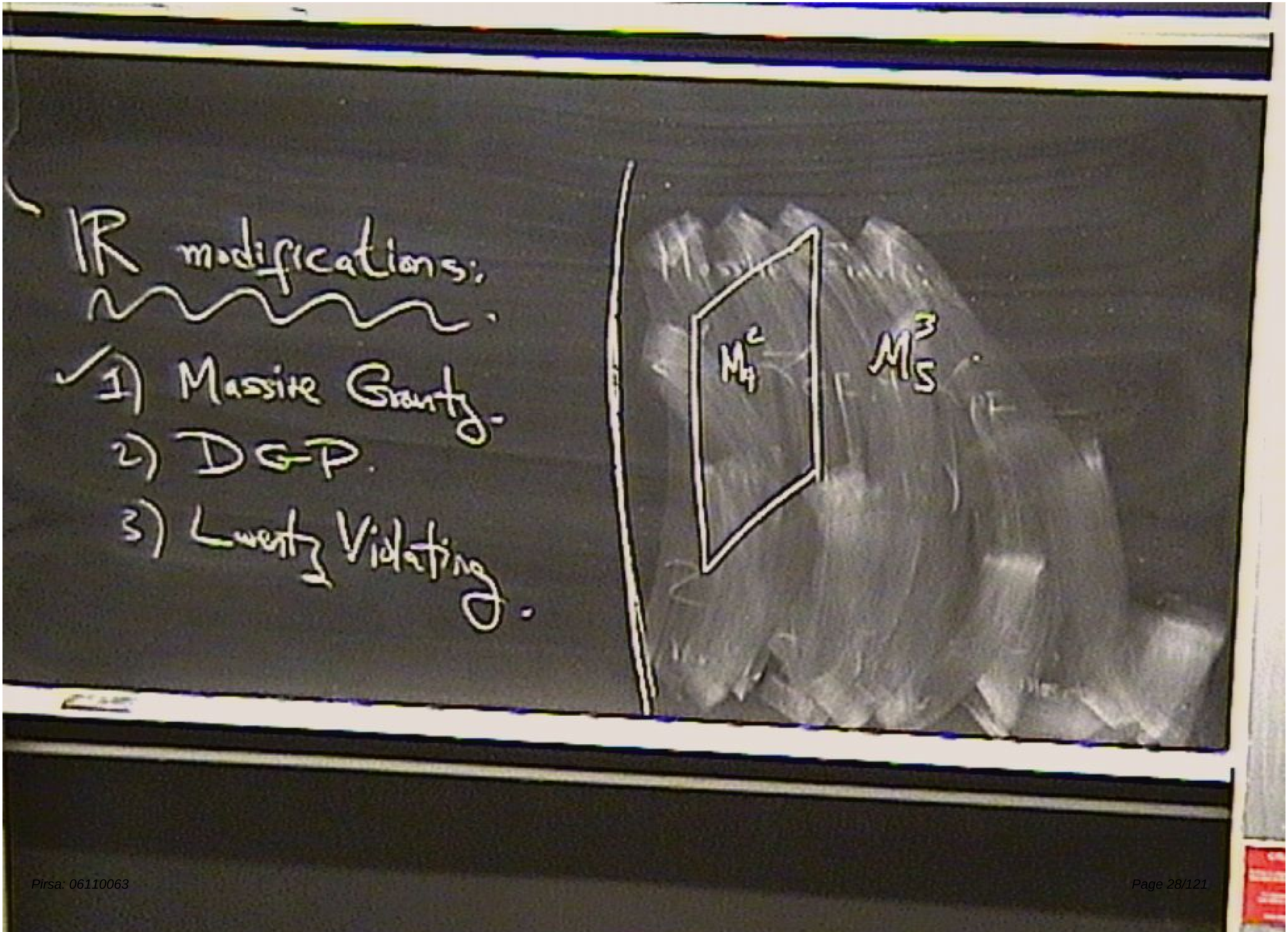
$$\mathcal{L}_{cl}^{\text{scalar lag}} = (\partial\varphi)^2 + \frac{(\partial^2\varphi)^3}{\Lambda^5} + \cdots + \frac{T}{M_{pl}}\varphi.$$

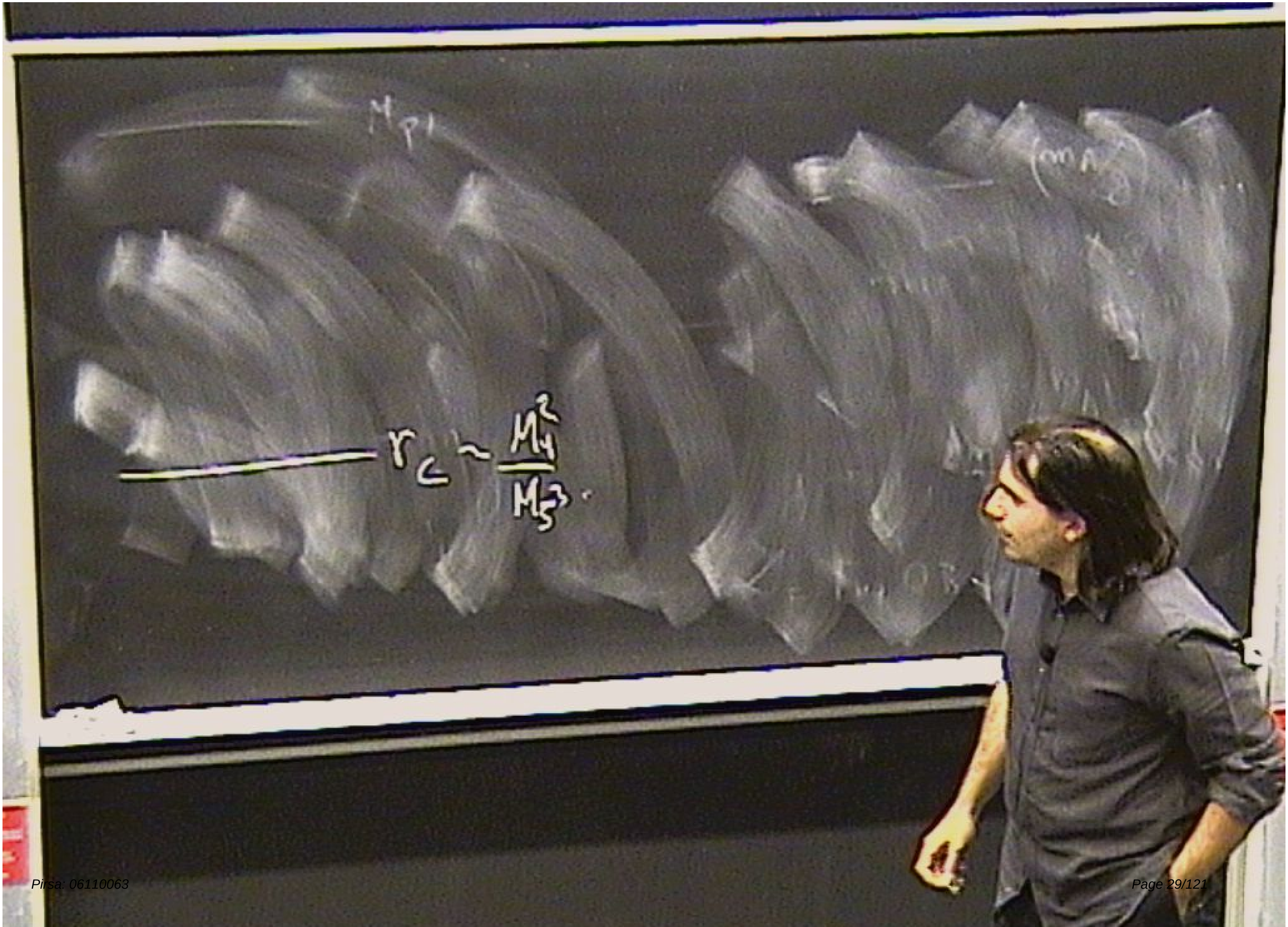

Λ = (m_g^4 M_pl)^{1/5}.
m_g.
M_pl → ∞,
keep Λ fixed
L_cl = (∂φ)^2 + (∂²φ)^3/Λ^5
+ ....

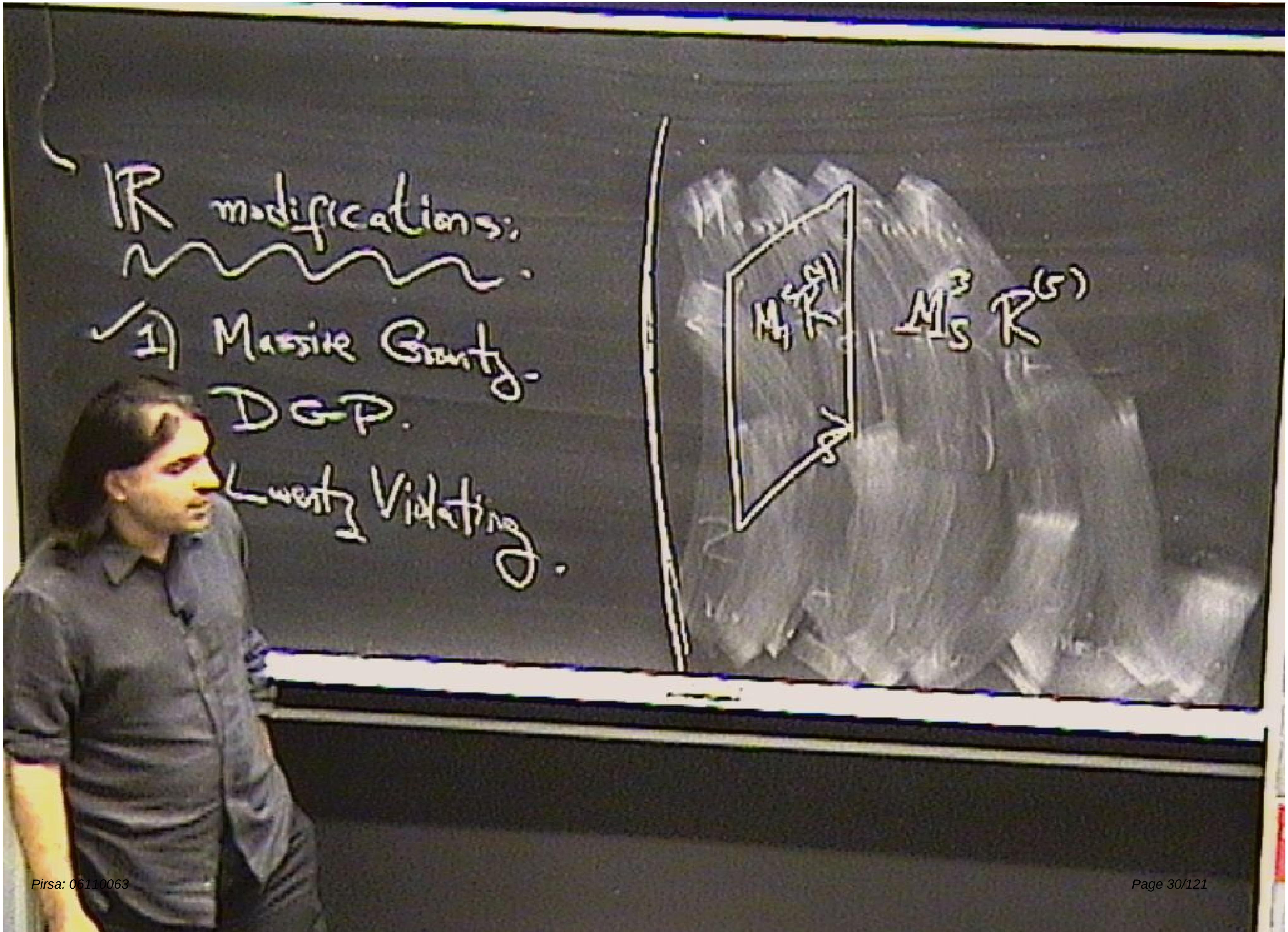

$\Lambda = (m_g^4 M_{pl})^{1/5}$.
m_g.
$M_{pl} \to \infty$,
keep Λ fixed
$\mathcal{L}_{cl}^{\text{scalar long}} = (\partial\varphi)^2 + \frac{(\partial^2\varphi)^3}{\Lambda^5} + \cdots + \left(\frac{T}{M_{pl}}\right)\varphi$.

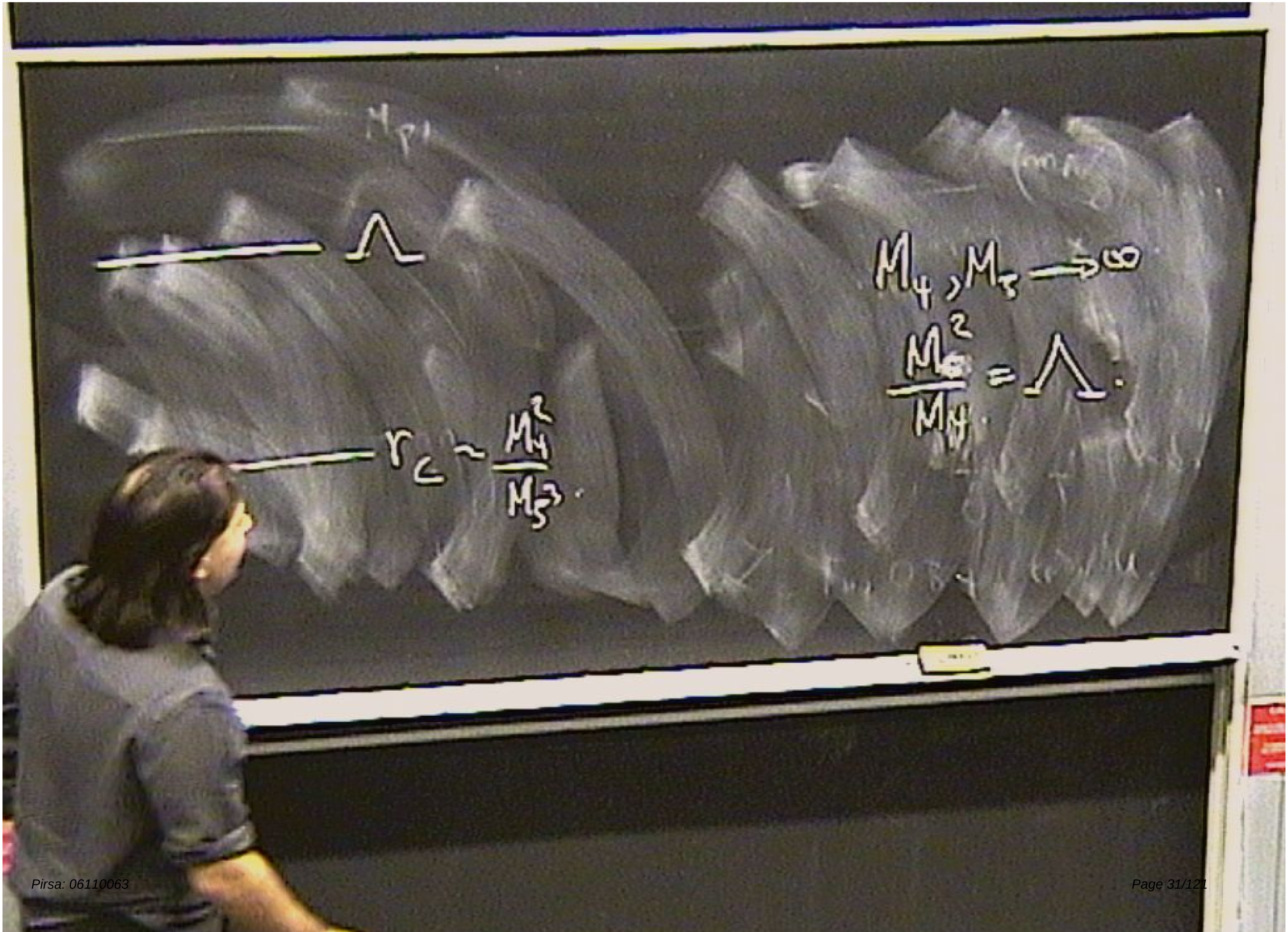

Λ = (m_g^4 M_pl)^{1/5}.
m_g.
M_pl → ∞,
keep Λ fixed
scalar
L_cl = (∂φ)^2 + (∂²φ)^3/Λ^5
+ ....
+ (T/M_pl) φ.
r_V ~

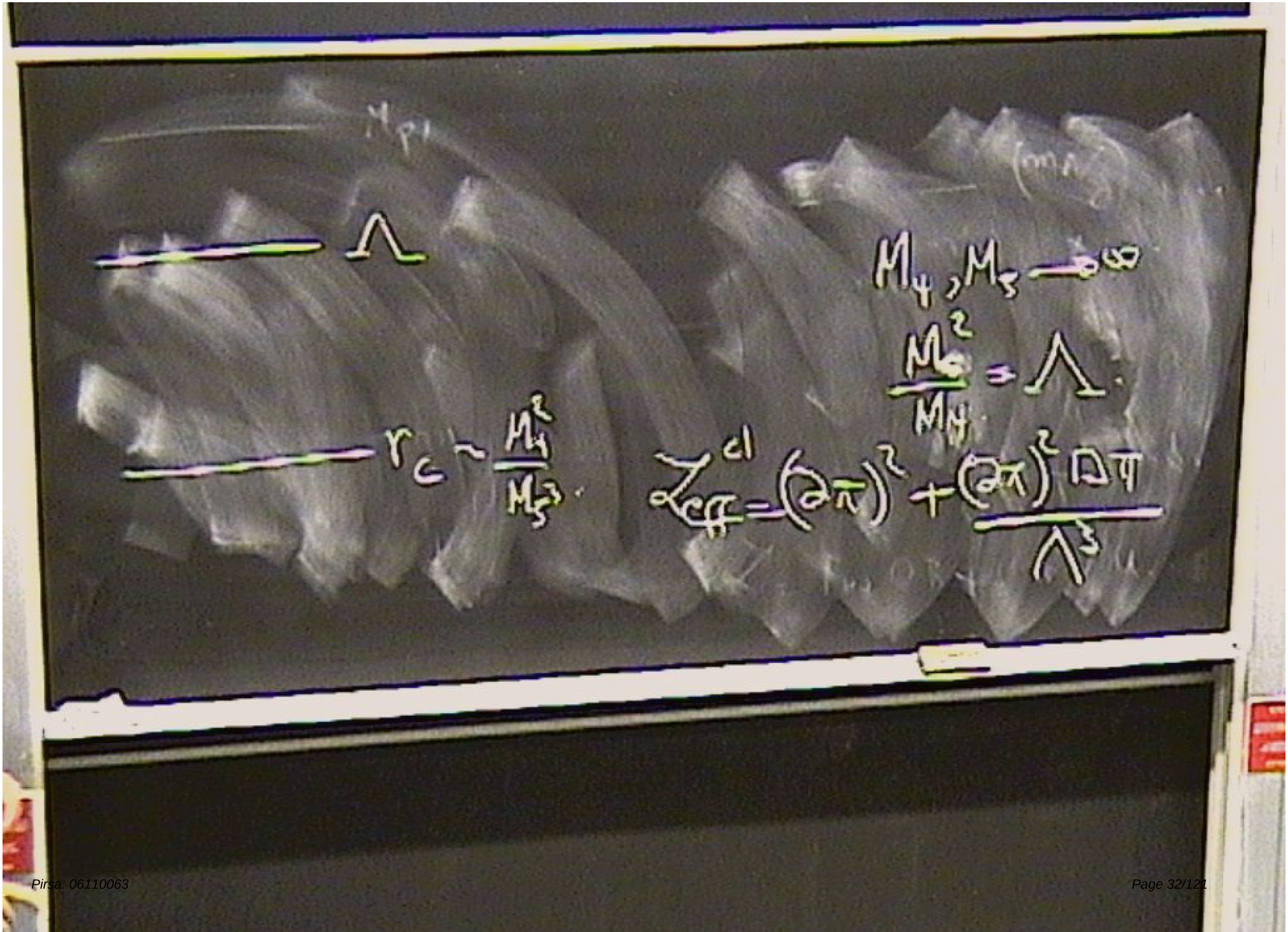

IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz

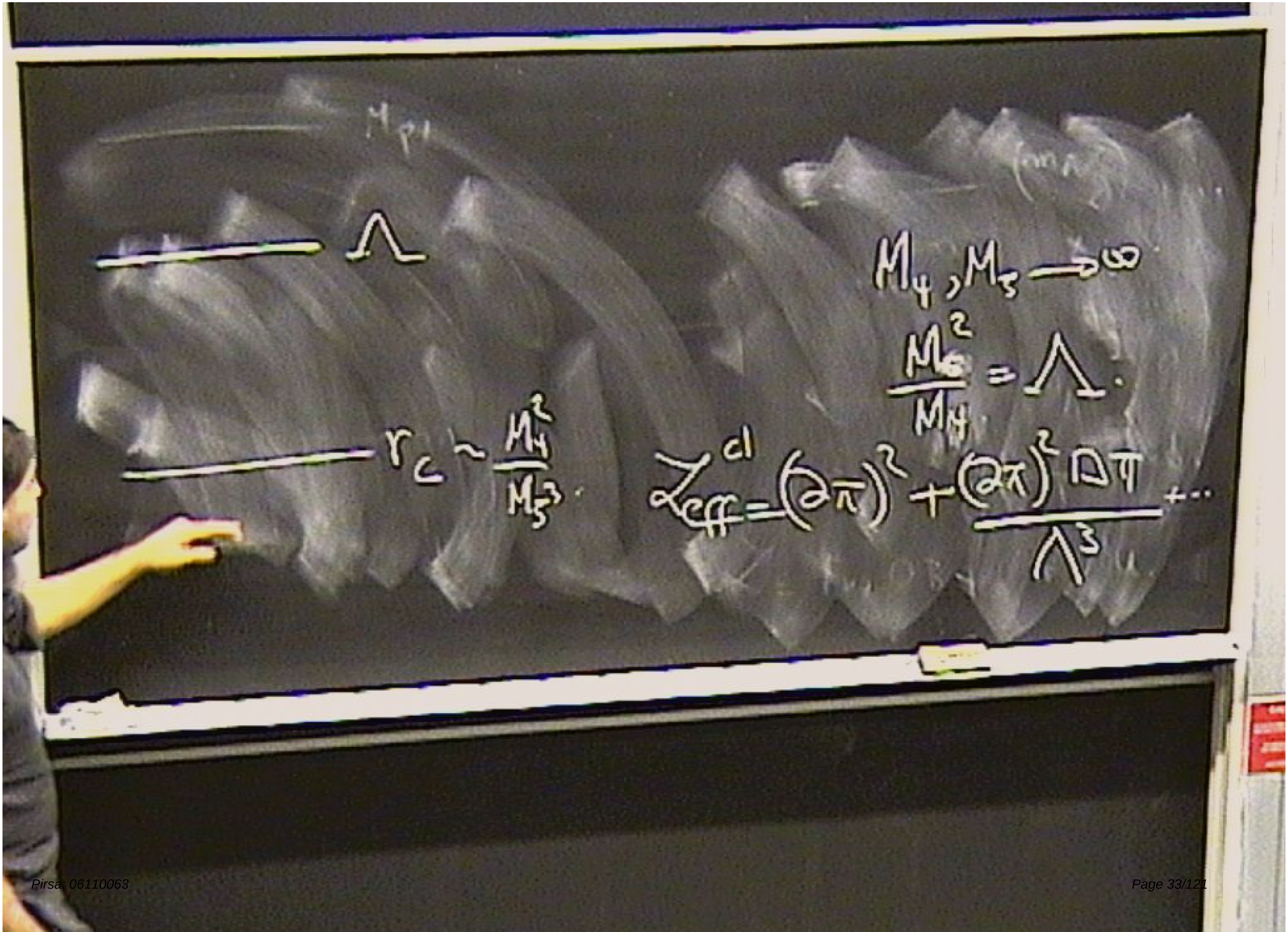

IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz Violating.
M_4^2
M_5^3

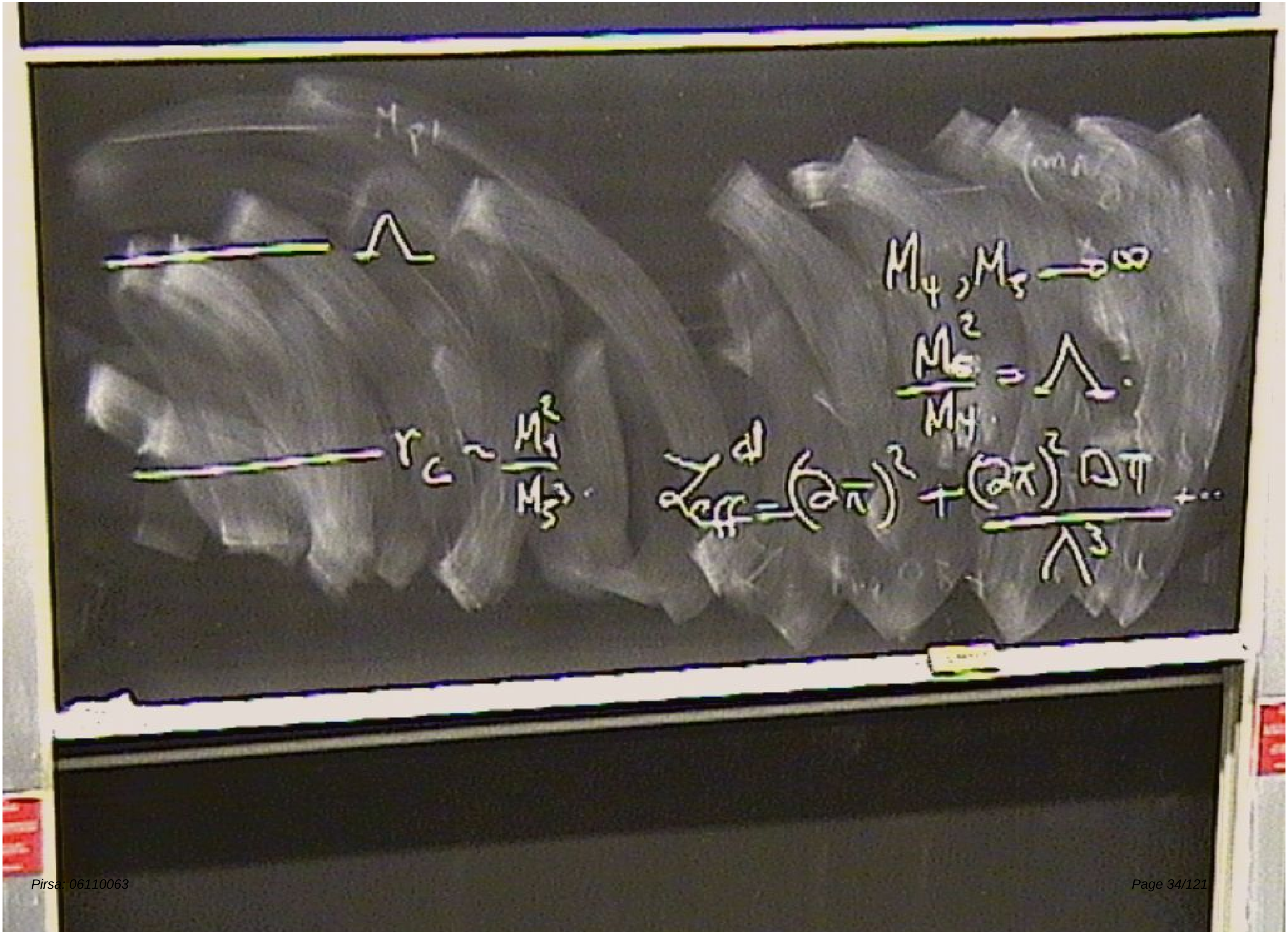

Mpl
rc ~ M4^2 / M5^3


IR modifications:
1) Massive Gravity.
DGP.
Lorentz Violating.
M_4^2 R^(4)
M_5^3 R^(5)

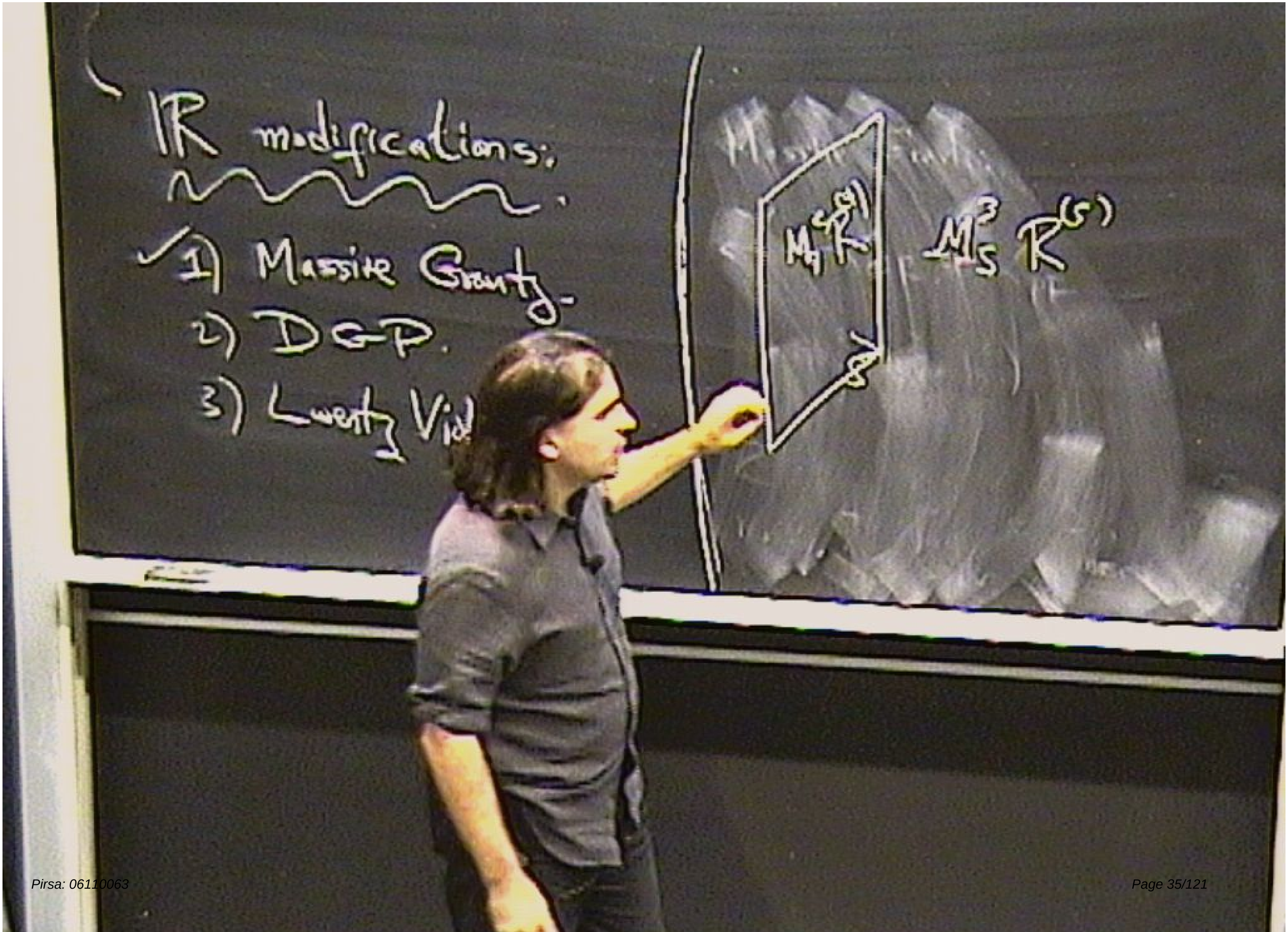

Λ
r_c ~ M_4^2 / M_5^3
M_4 , M_5 → ∞
M_5^2 / M_4 = Λ

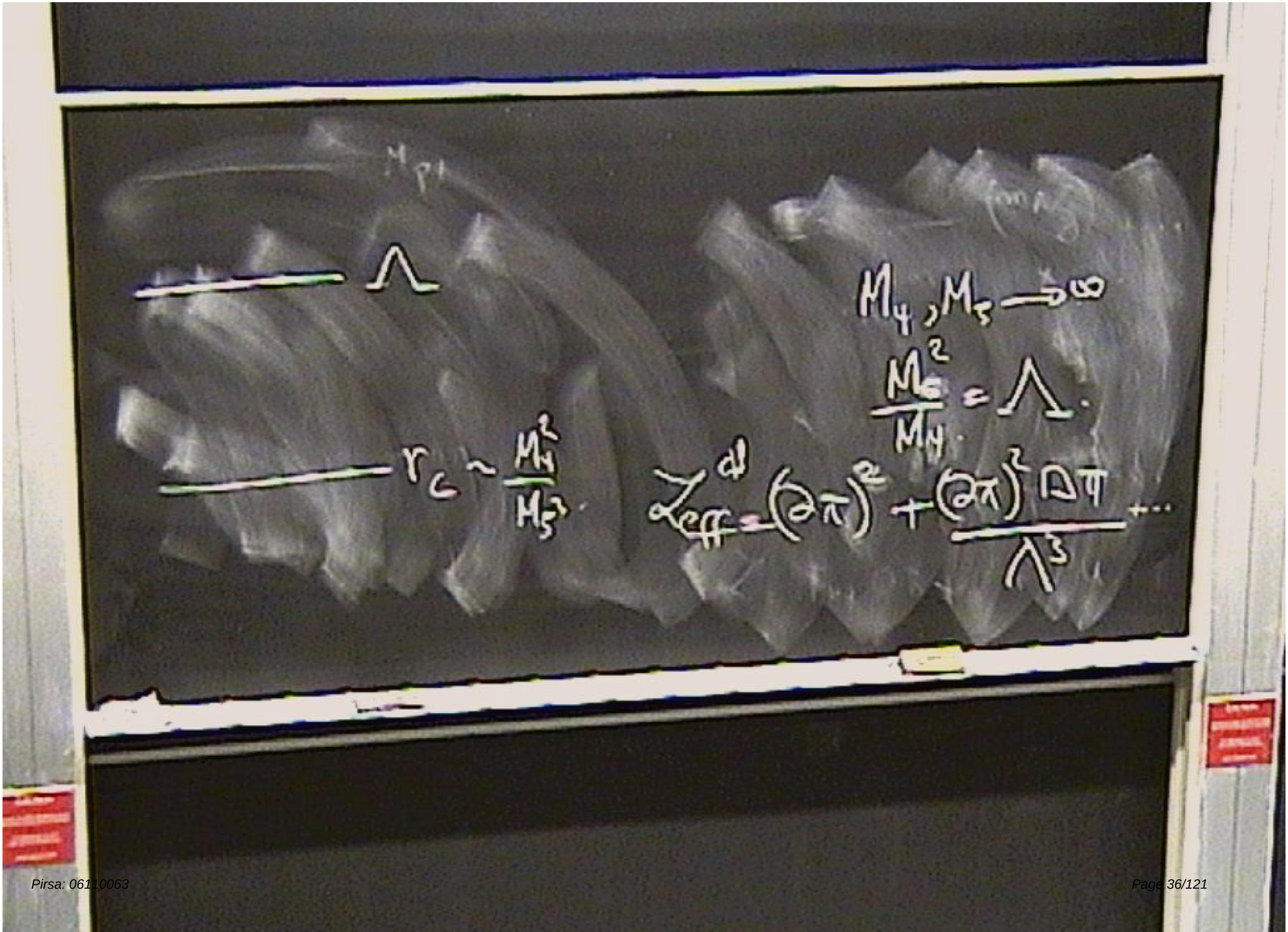

Λ
$M_4, M_5 \to \infty$
$\frac{M_5^2}{M_4} = \Lambda$
$r_c \sim \frac{M_4^2}{M_5^3}$
$\mathcal{L}_{eff}^{cl} = (\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3}$


M_pl
Λ
M_4, M_5 → ∞
M_5^2 / M_4 = Λ.
r_c ~ M_4^2 / M_5^3
L_eff^cl = (∂π)^2 + (∂π)^2 □π / Λ^3 + ...



Mpl
Λ
M4 , M5 → ∞
M5^2 / M4 = Λ.
rc ~ M4^2 / M5^3.
L_eff^4d = (∂π)^2 + (∂π)^2 □π / Λ^3 + ...


IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz
$M_4^2 R^{(4)}$
$M_5^3 R^{(5)}$


Λ
$M_4, M_5 \to \infty$
$\frac{M_5^2}{M_4} = \Lambda$
$r_c \sim \frac{M_4^2}{M_5^3}$
$\mathcal{L}_{eff}^{4d} = (\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \cdots$

M_{pl}

$(m\Lambda)$

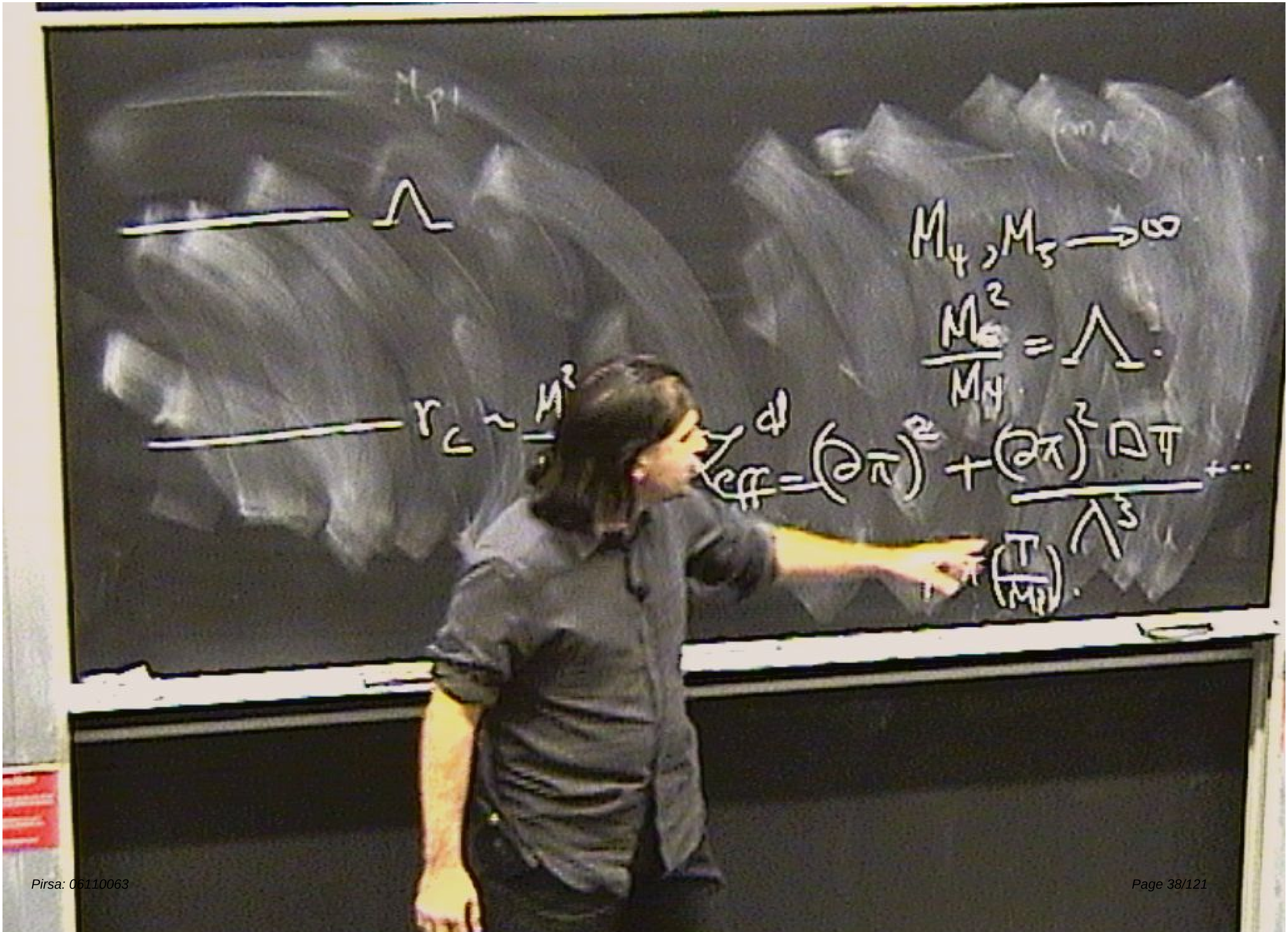
——— Λ

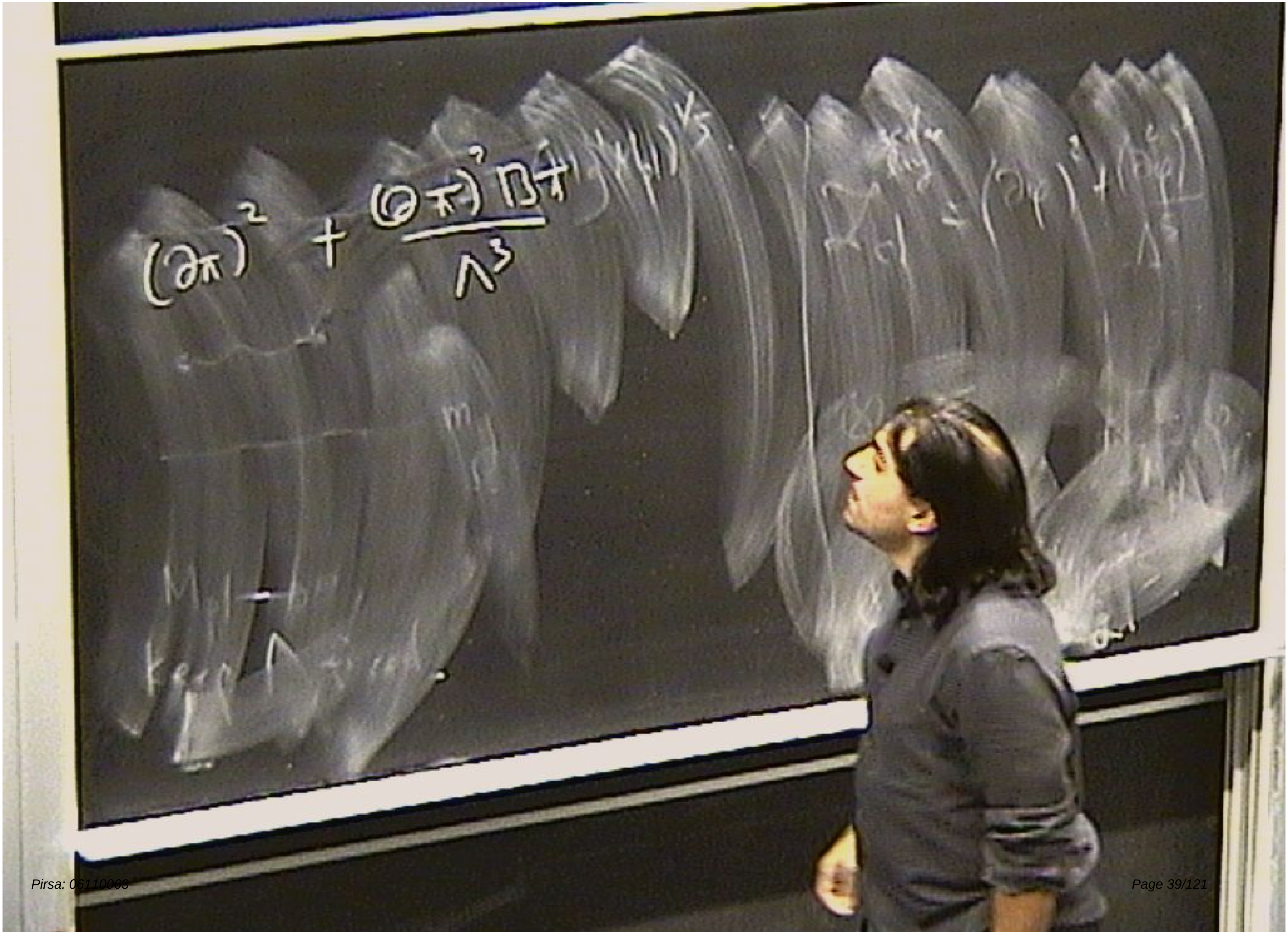
——— $r_c \sim \frac{M_4^2}{M_5^3}$.

$M_4, M_5 \longrightarrow \infty$

$\frac{M_5^2}{M_4} = \Lambda$.

$$\mathcal{L}_{eff}^{dl} = (\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \cdots + \pi\left(\frac{T}{M_4}\right).$$


M_pl
Λ
M_4, M_5 → ∞
M_5^2 / M_4 = Λ
r_c ~ M^2
L_eff = (∂π)^2 + (∂π)^2 □π / Λ^3 + ...


$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3}$

M_{pl}

Λ

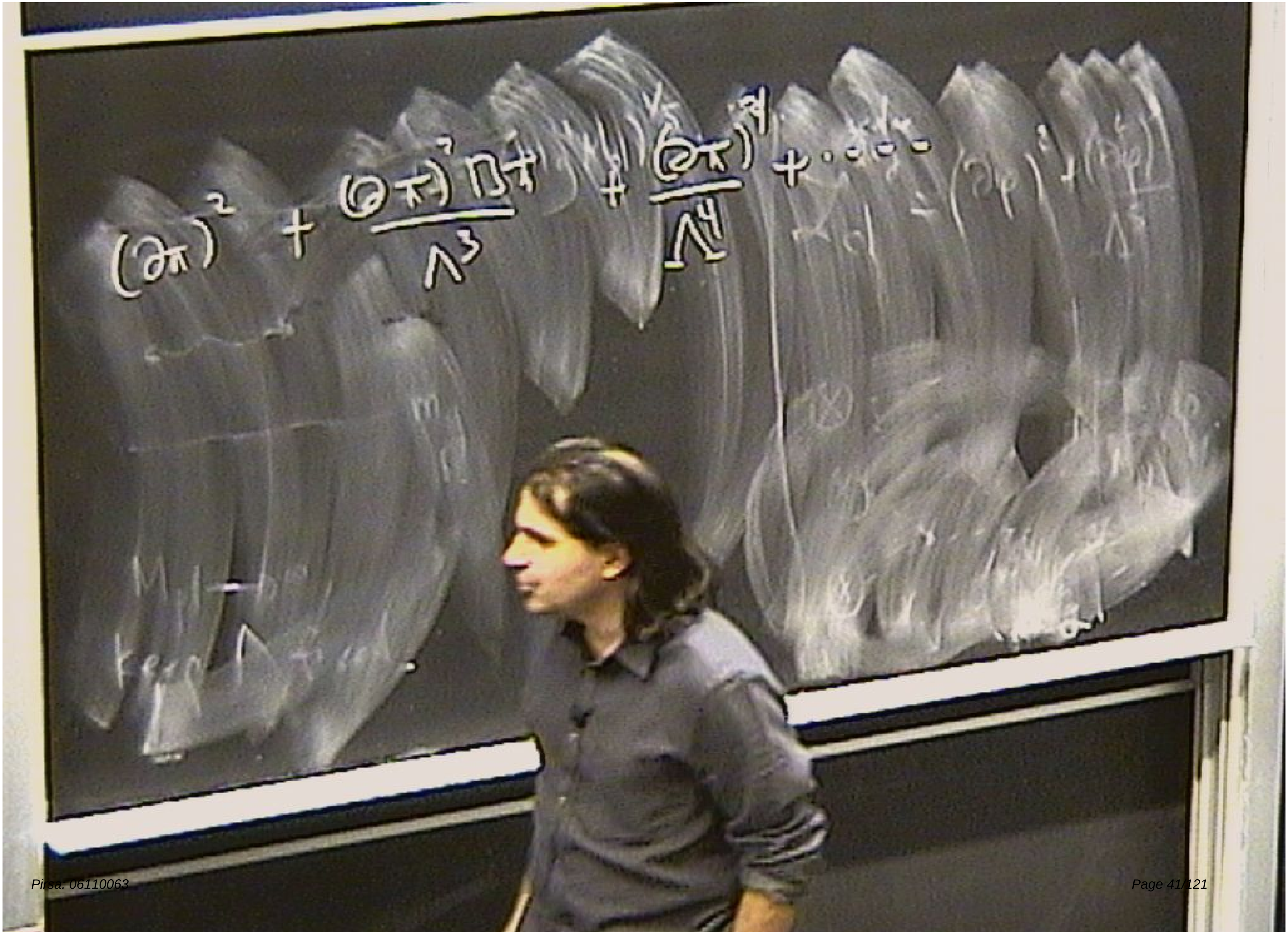
(m_A)

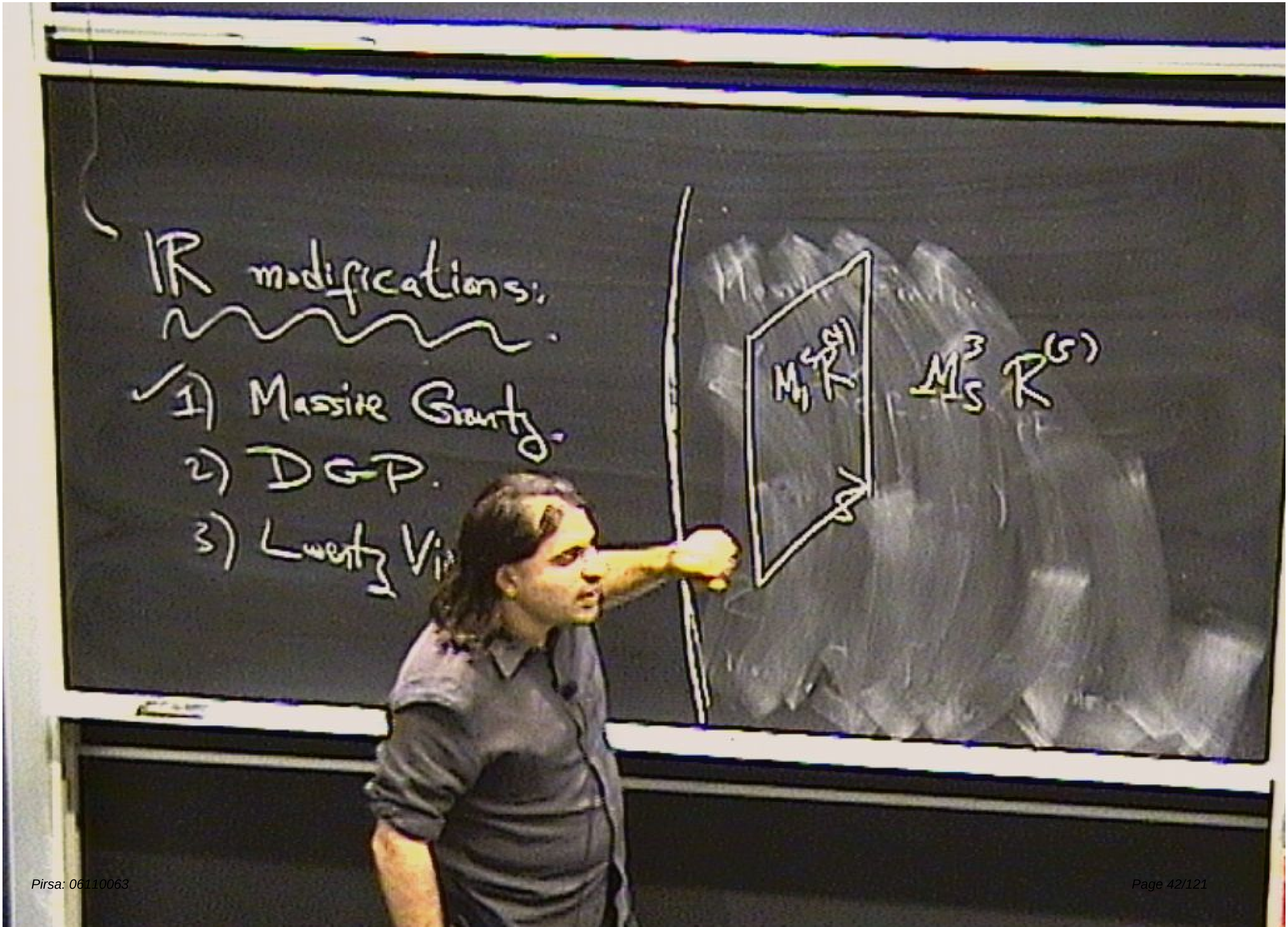
$M_4, M_5 \to \infty$

$$\frac{M_5^2}{M_4} = \Lambda .$$

$r_c \sim \frac{M_4^2}{M_5^3}$.

$$\mathcal{L}_{eff}^{4d} = (\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \cdots + \pi\left(\frac{T}{M_{pl}}\right).$$


$(\partial\pi)^2 + \frac{(\partial\pi)^2\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$


IR modifications:
1) Massive Gravity.
2) DGP.
3) Lorentz
$M_1^2 R^{(4)}$
$M_S^3 R^{(5)}$

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu\pi \longrightarrow \partial_\mu\pi + c_\mu\,.$$

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu\pi \longrightarrow \partial_\mu\pi + c_\mu$$

$$\partial^2\pi \longrightarrow \partial^2\pi$$

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu \pi \longrightarrow \partial_\mu \pi + c_\mu$$

$$\partial^2 \pi \longrightarrow \partial^2 \pi$$

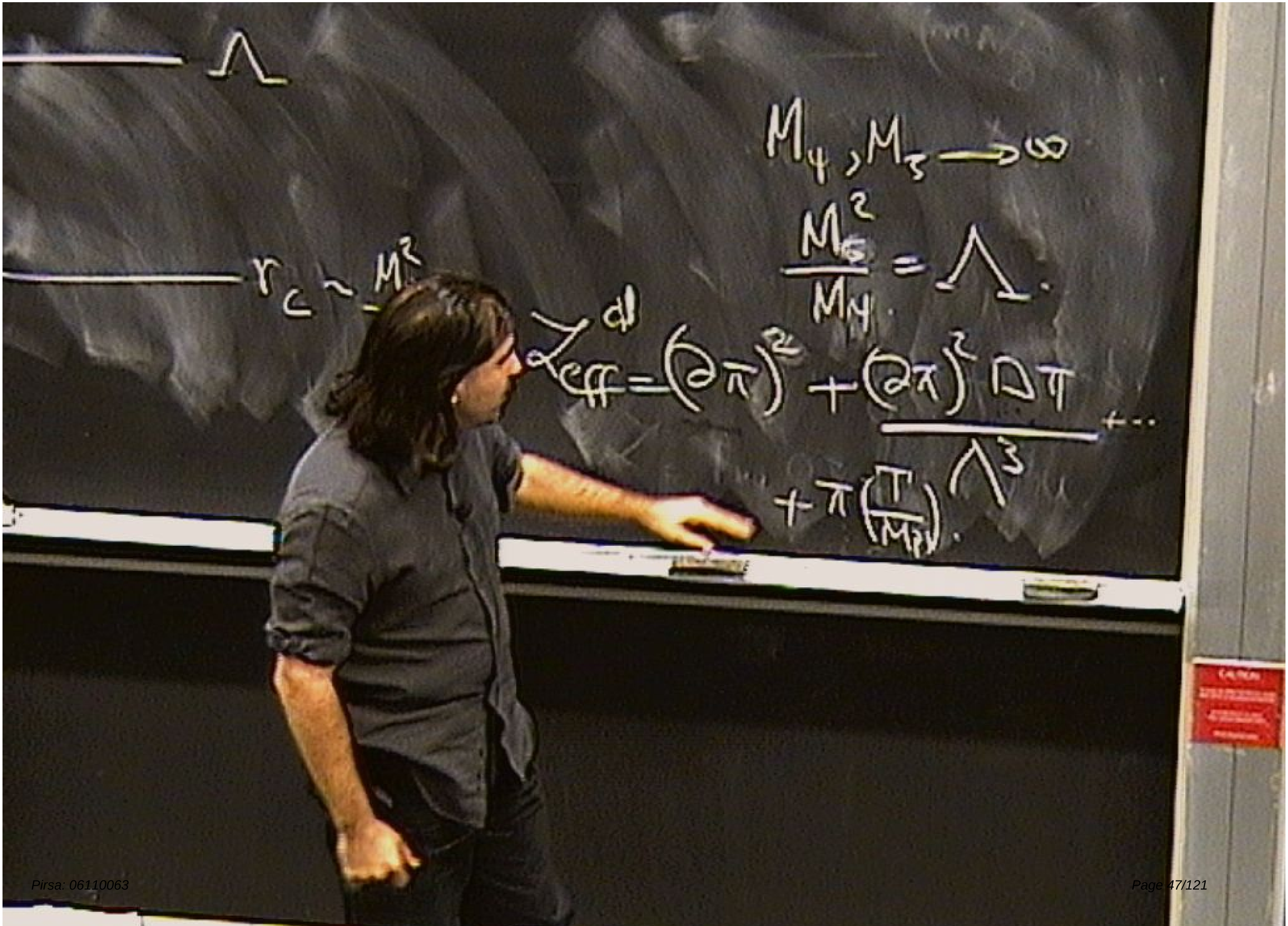
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3}$$

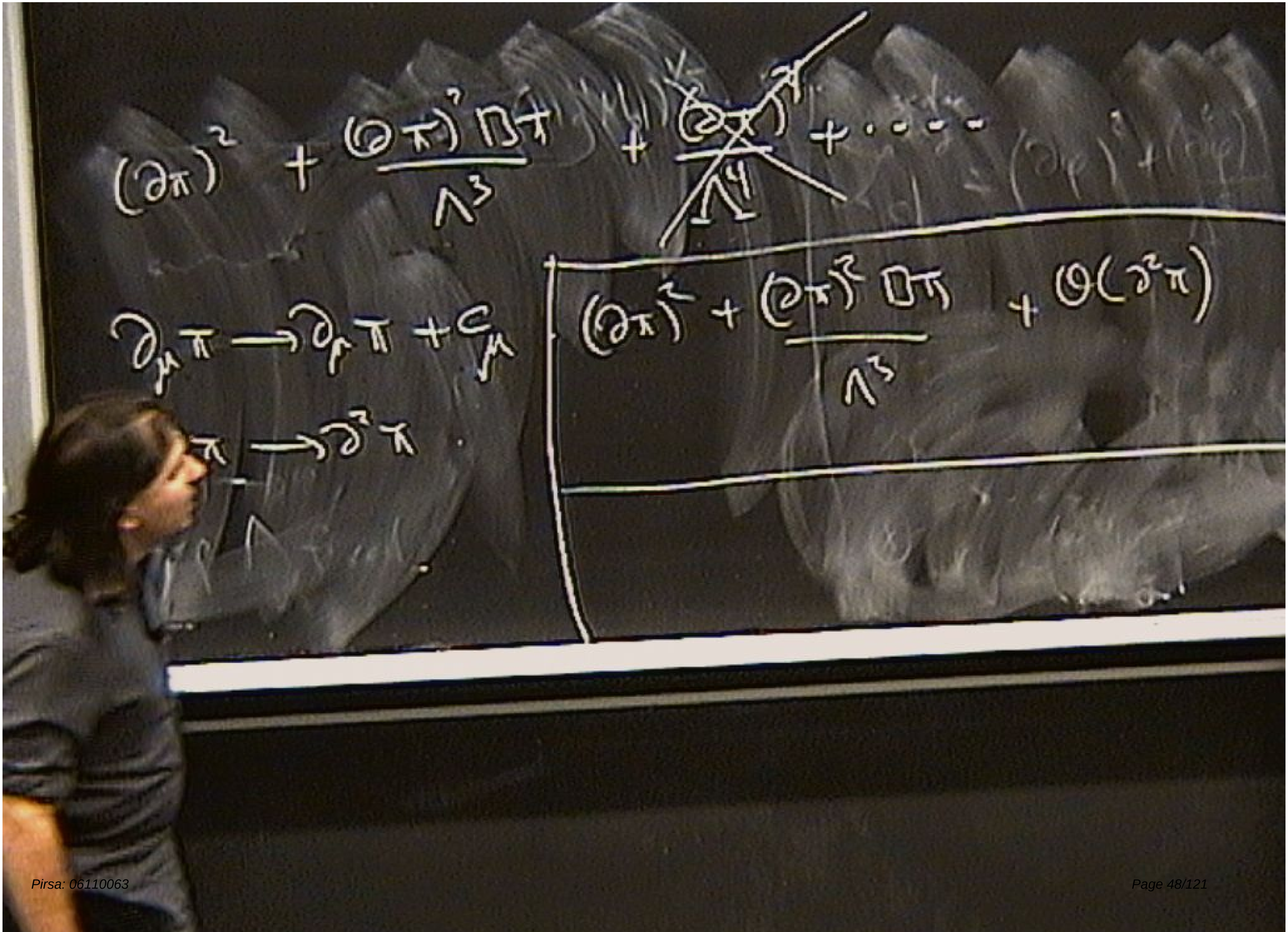
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + ~~\frac{(\partial\pi)^4}{\Lambda^4}~~ + \cdots$$

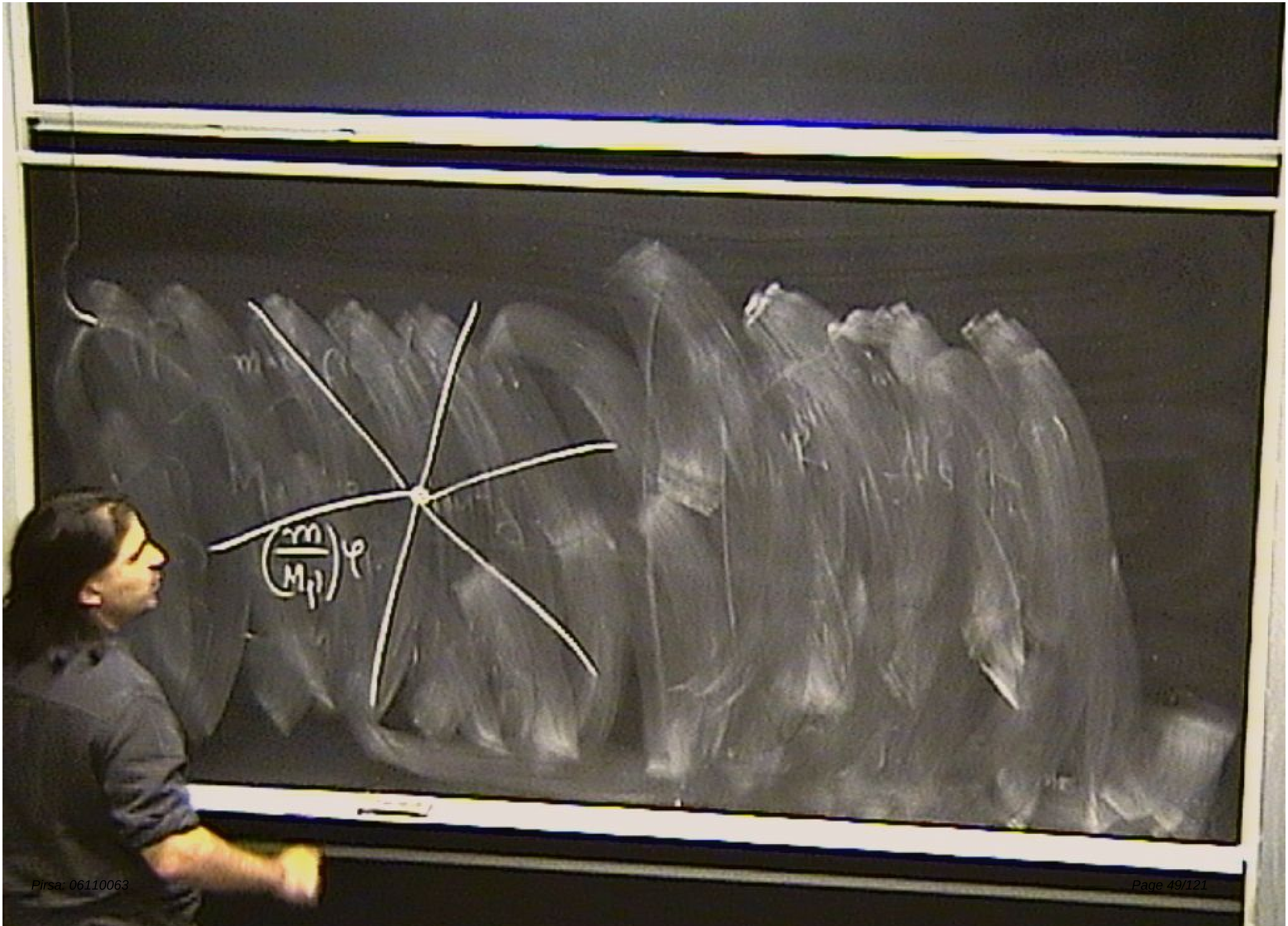
$$\partial_\mu\pi \longrightarrow \partial_\mu\pi + c_\mu$$

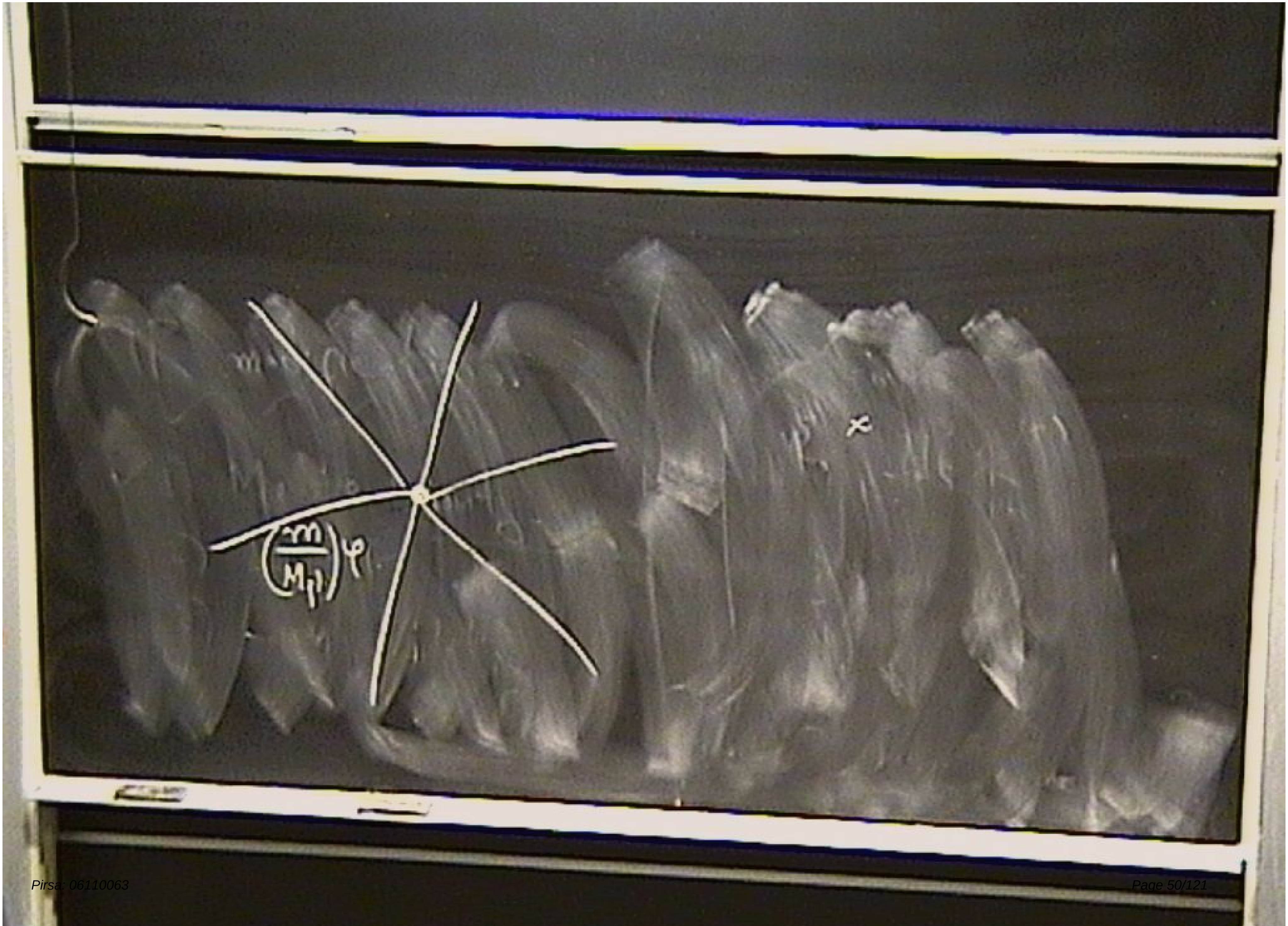
$$\partial^2\pi \longrightarrow \partial^2\pi$$

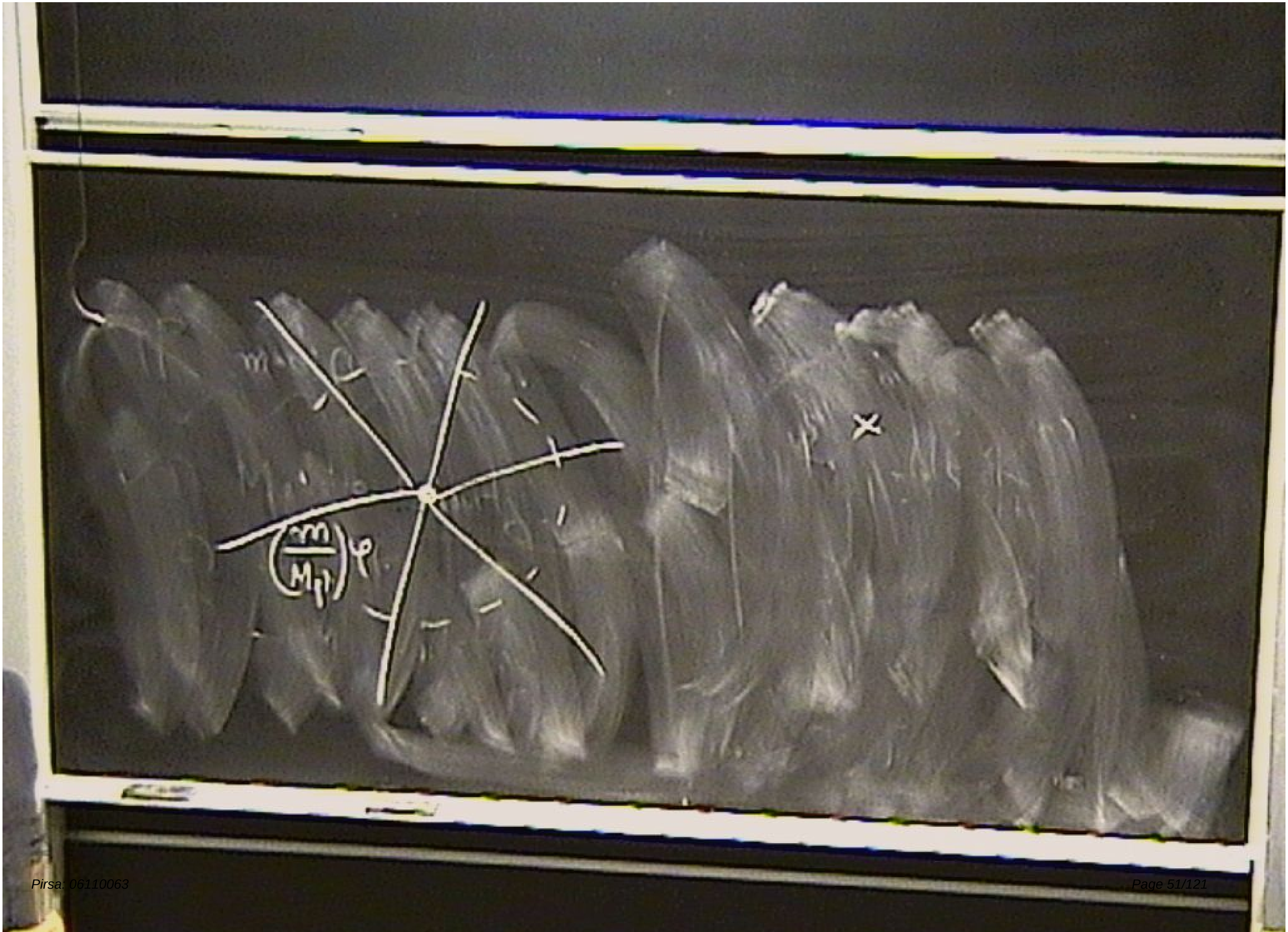
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \mathcal{O}(\partial^3\pi)$$

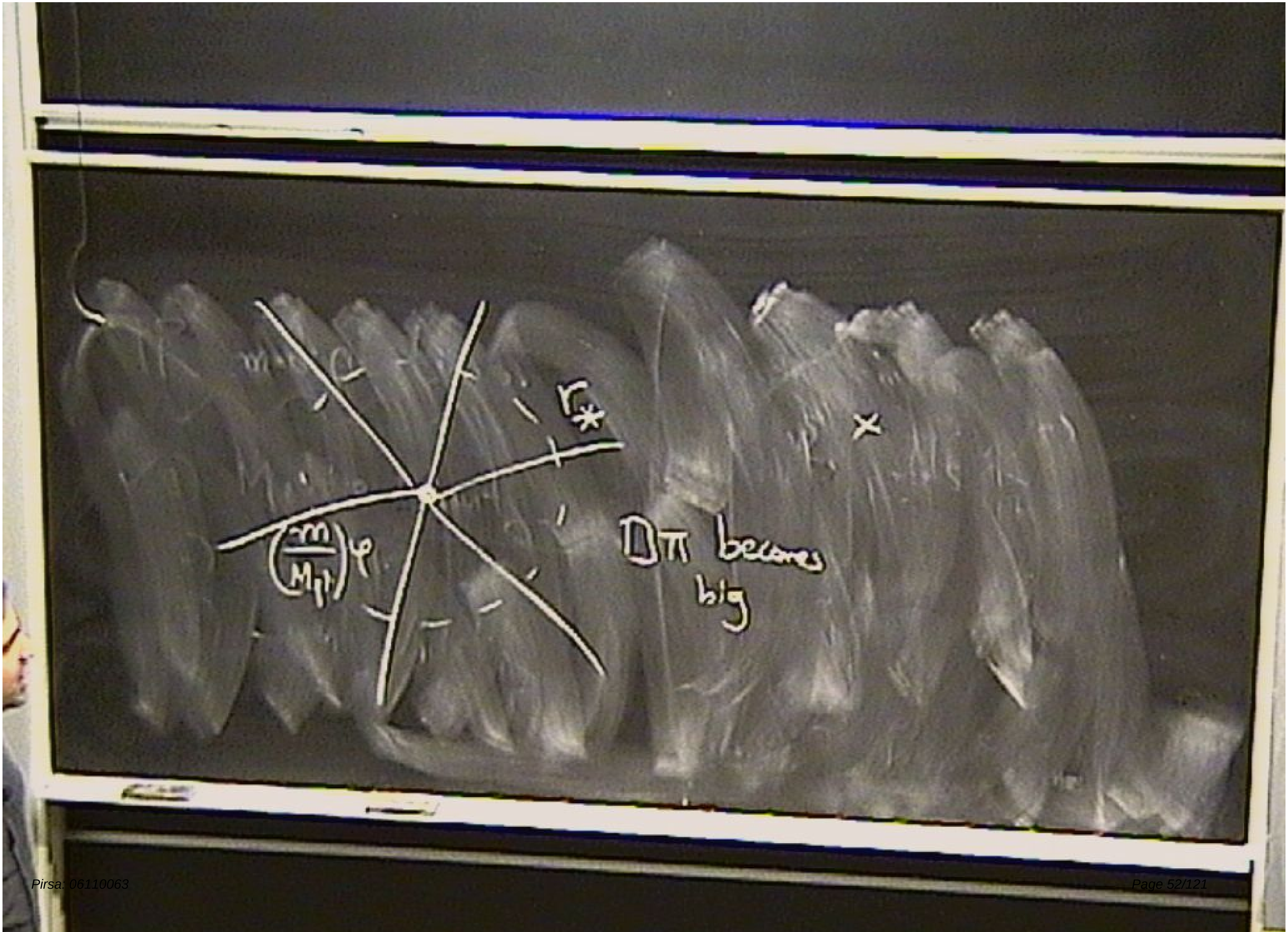

Λ
$M_4, M_5 \to \infty$
$\frac{M_5^2}{M_4} = \Lambda$
$r_c \sim M^2$
$\mathcal{L}_{eff} = (\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \cdots$
$+ \pi \left(\frac{T}{M_4}\right)$

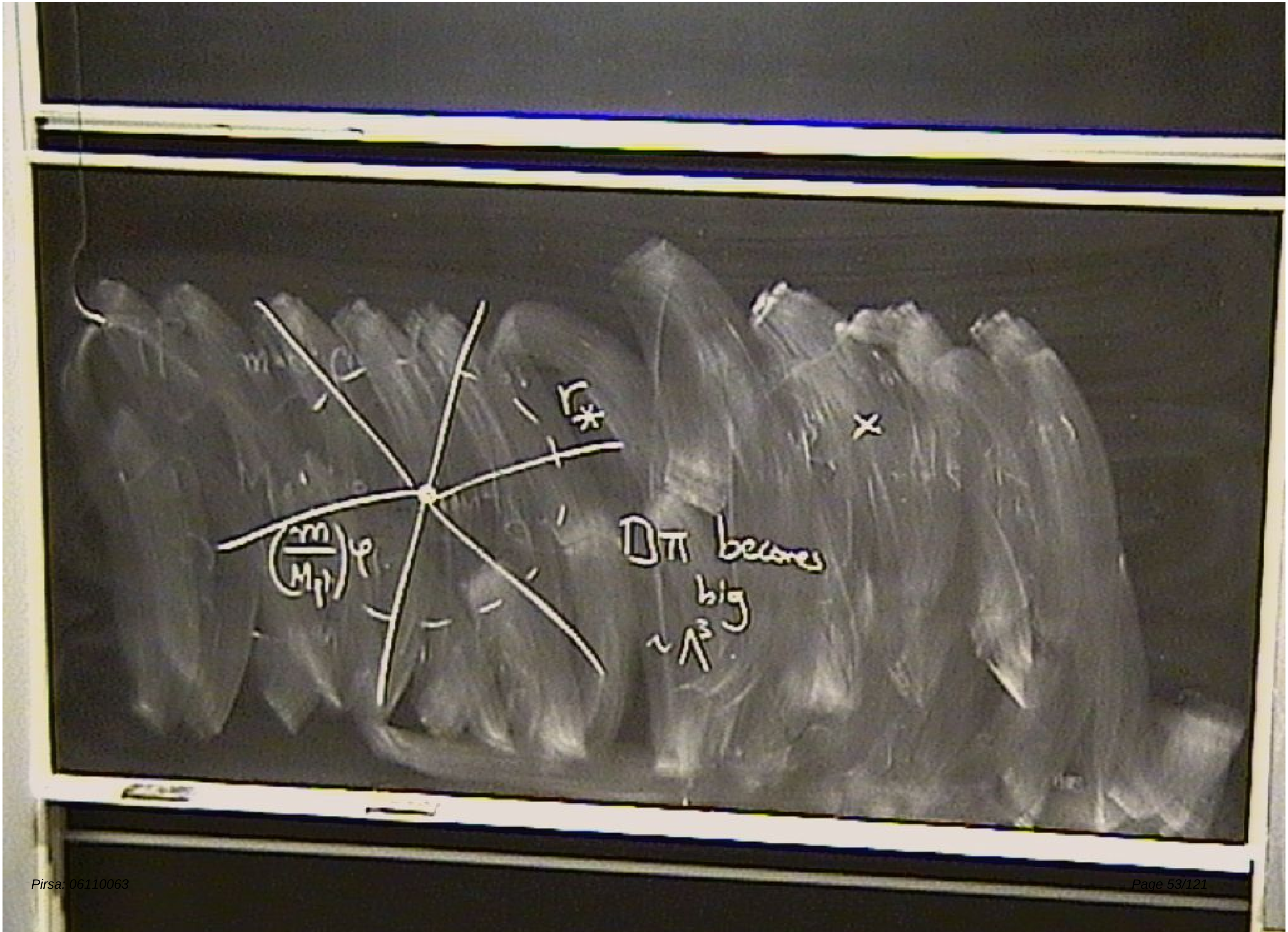

$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \ldots$
$\partial_\mu \pi \to \partial_\mu \pi + c_\mu$
$\pi \to \partial^2 \pi$
$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + O(\partial^2\pi)$




(m/M_Pl) φ


$\left(\frac{m}{M_p}\right)\varphi$


r*
×
$\left(\frac{m}{M_{pl}}\right)\varphi$
$\Box\pi$ becomes big


r*
(m/Mpl)φ
∂π becomes big
~Λ³

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu\pi \longrightarrow \partial_\mu\pi + c_\mu$$

$$\partial^2\pi \longrightarrow \partial^2\pi$$

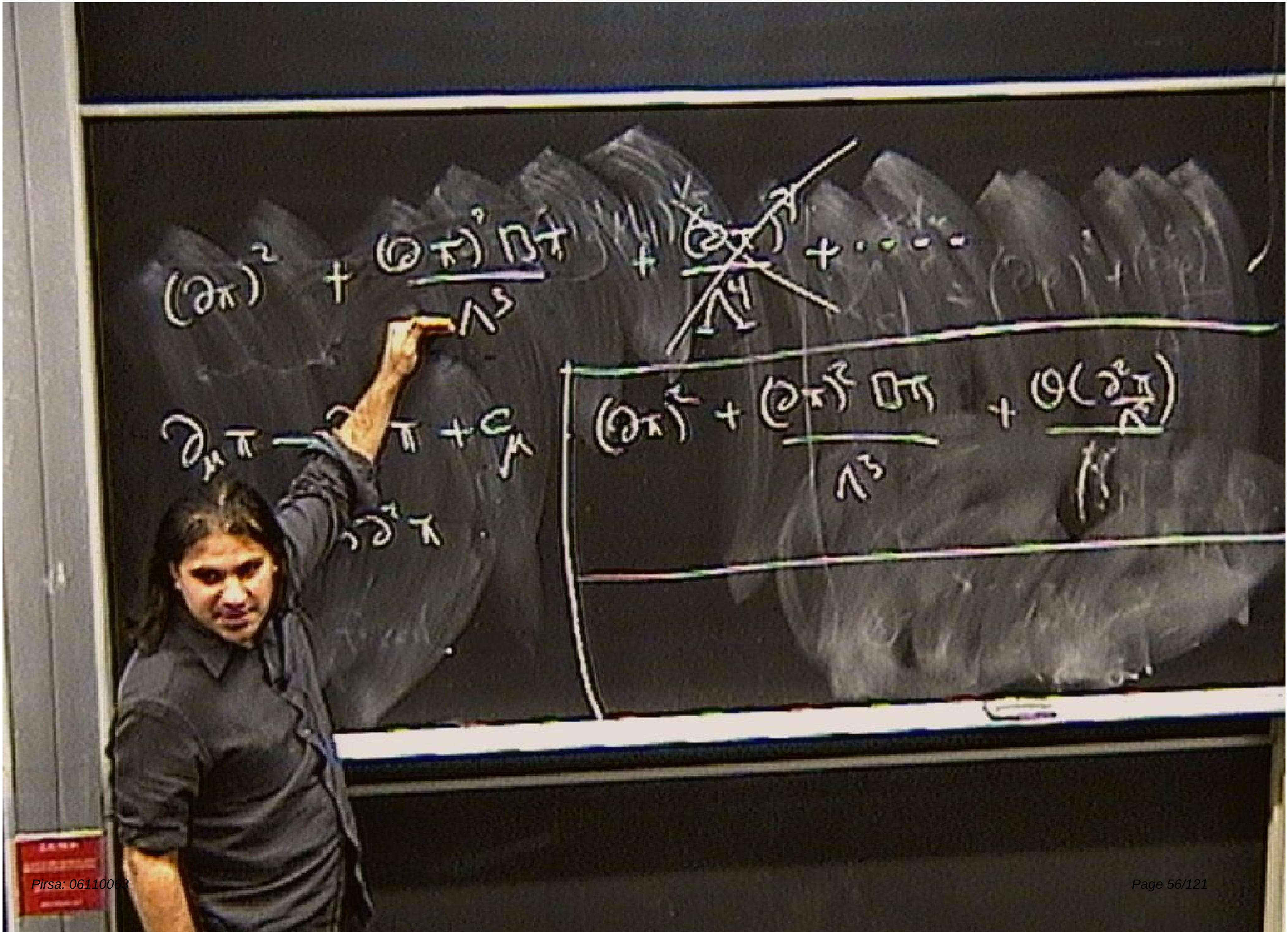
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\Box\pi}{\Lambda^3} + \mathcal{O}(\partial^2\pi)$$

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu\pi \longrightarrow \partial_\mu\pi + c_\mu$$

$$\partial^2\pi \longrightarrow \partial^2\pi$$

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \mathcal{O}\left(\frac{\partial^2\pi}{\Lambda^3}\right)$$

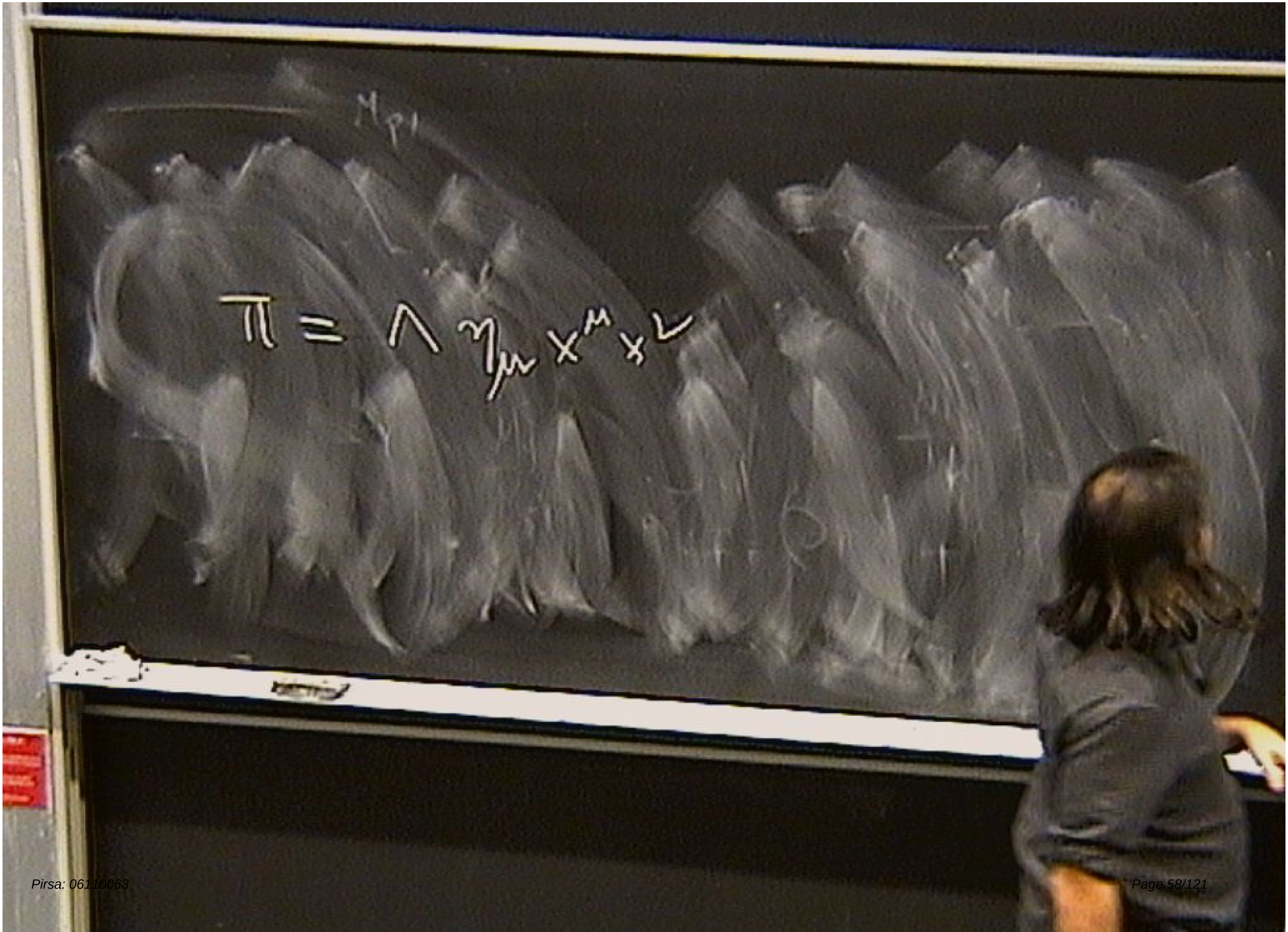

(∂π)² + (∂π)² □π / Λ³
(∂π)² + (∂π)² □π / Λ³ + O(∂²π / Λ)

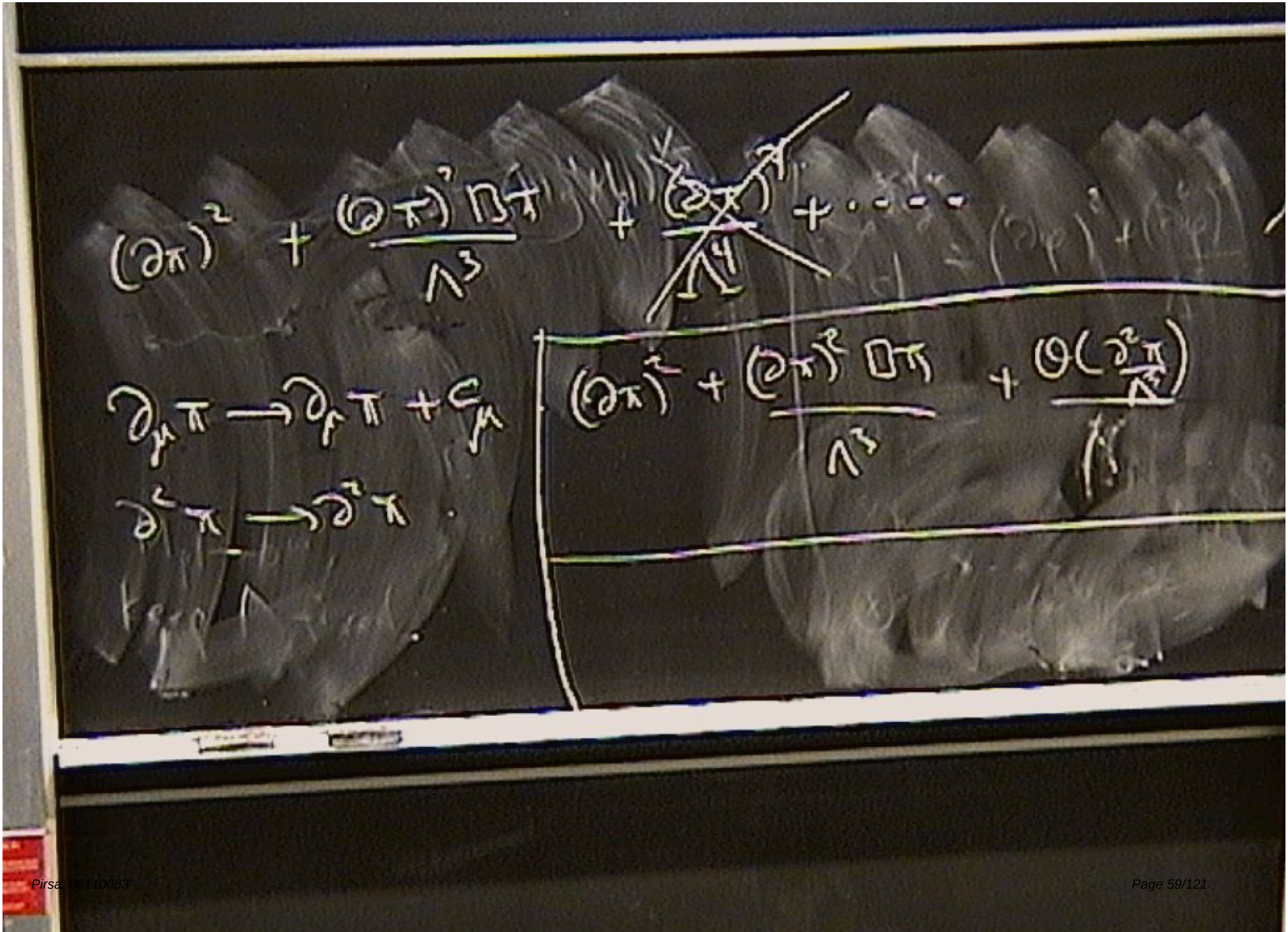
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$$

$$\partial_\mu\pi \to \partial_\mu\pi + c_\mu$$

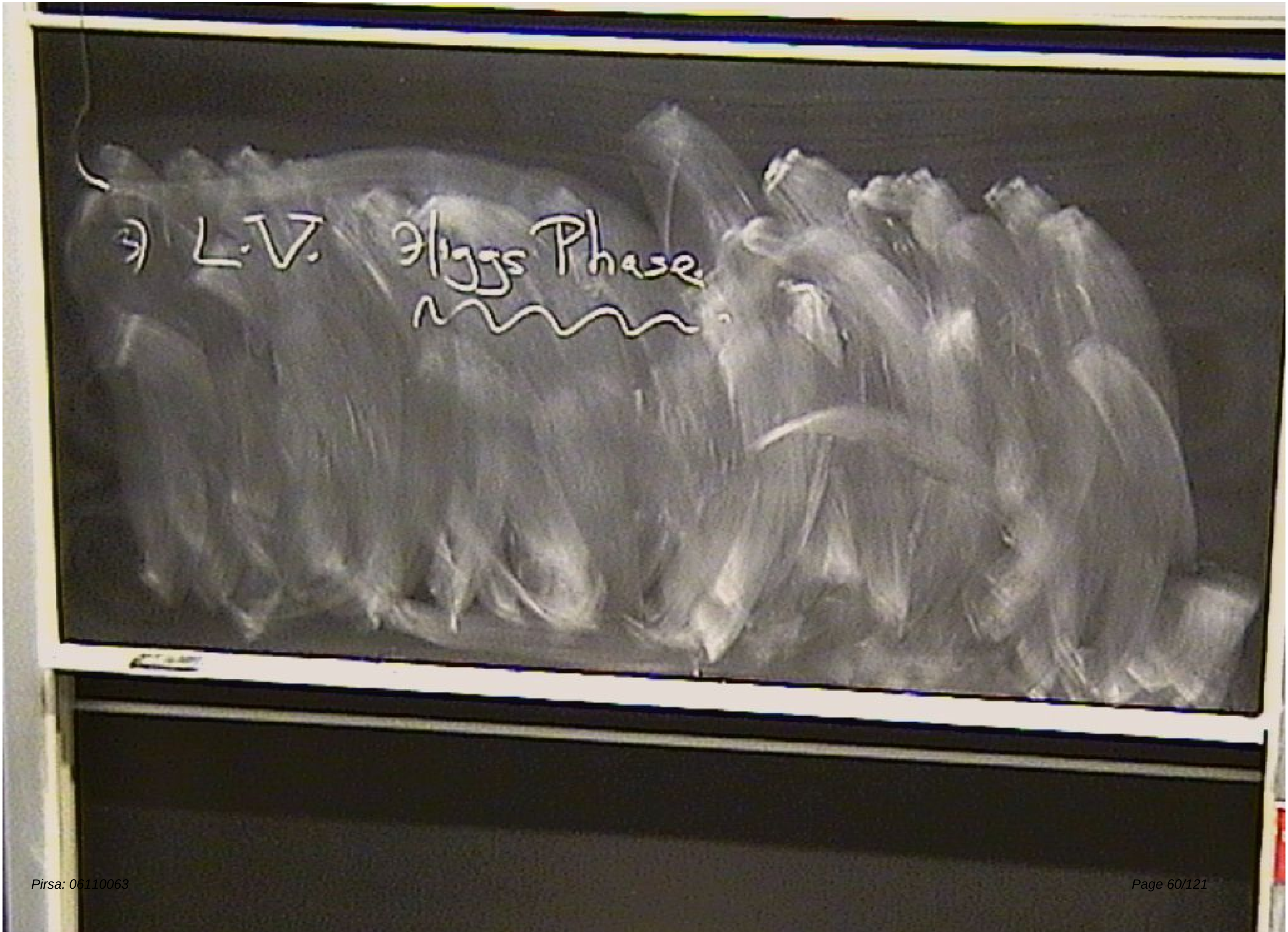
$$\partial^2\pi \to \partial^2\pi$$

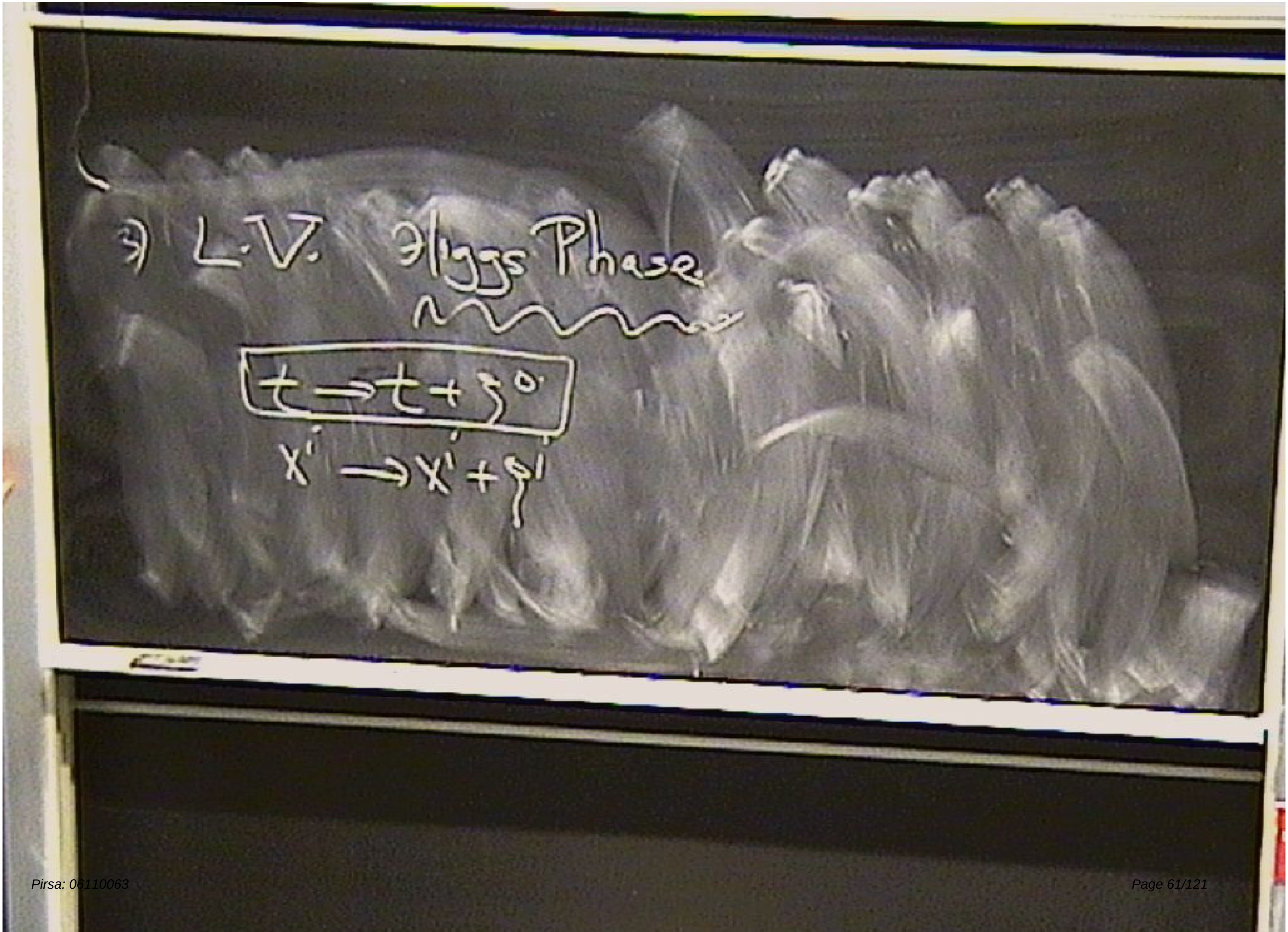
$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \mathcal{O}\left(\frac{\partial^2\pi}{\Lambda^3}\right)$$

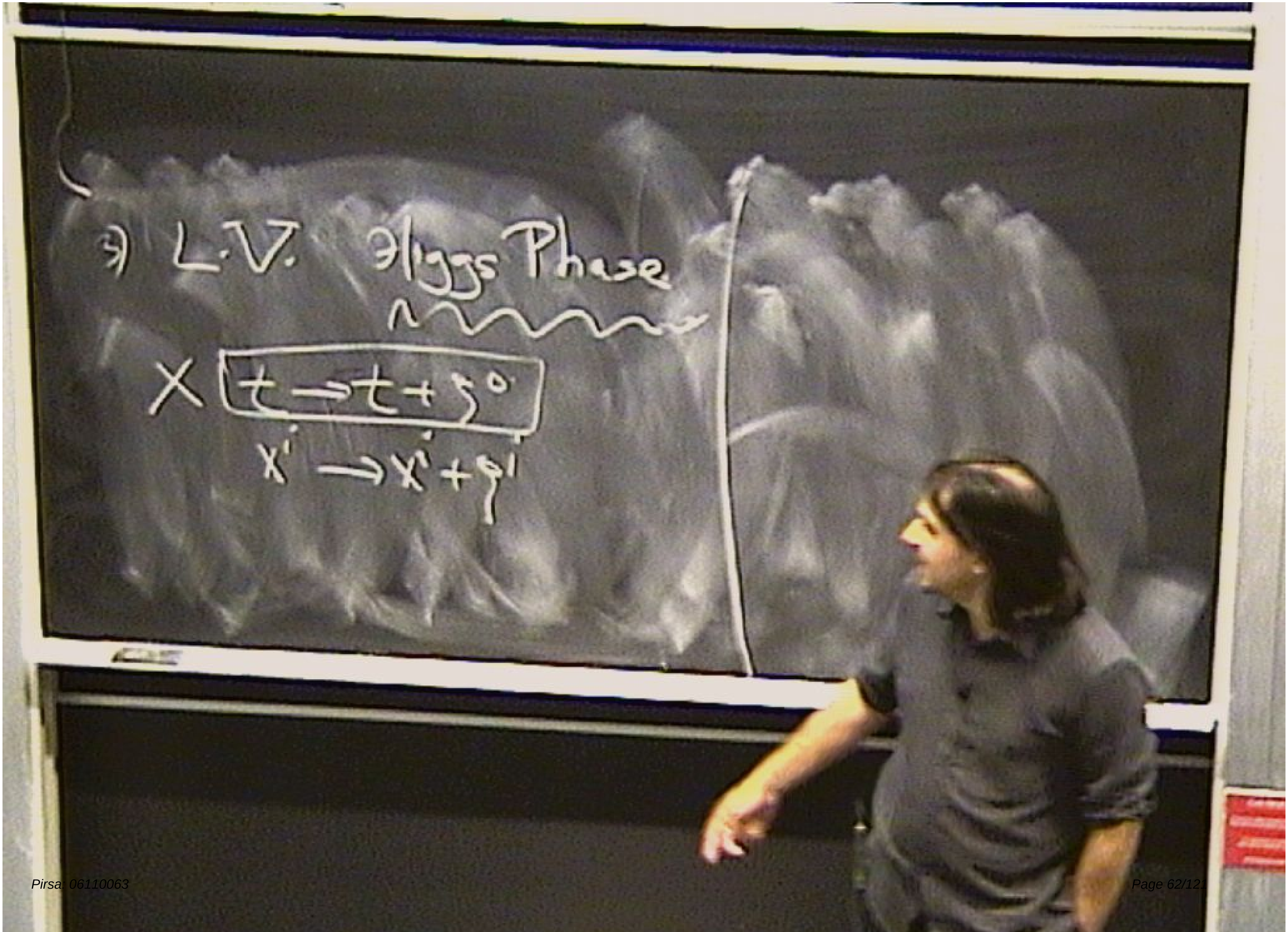

Mpl
π = Λ η_μν x^μ x^ν

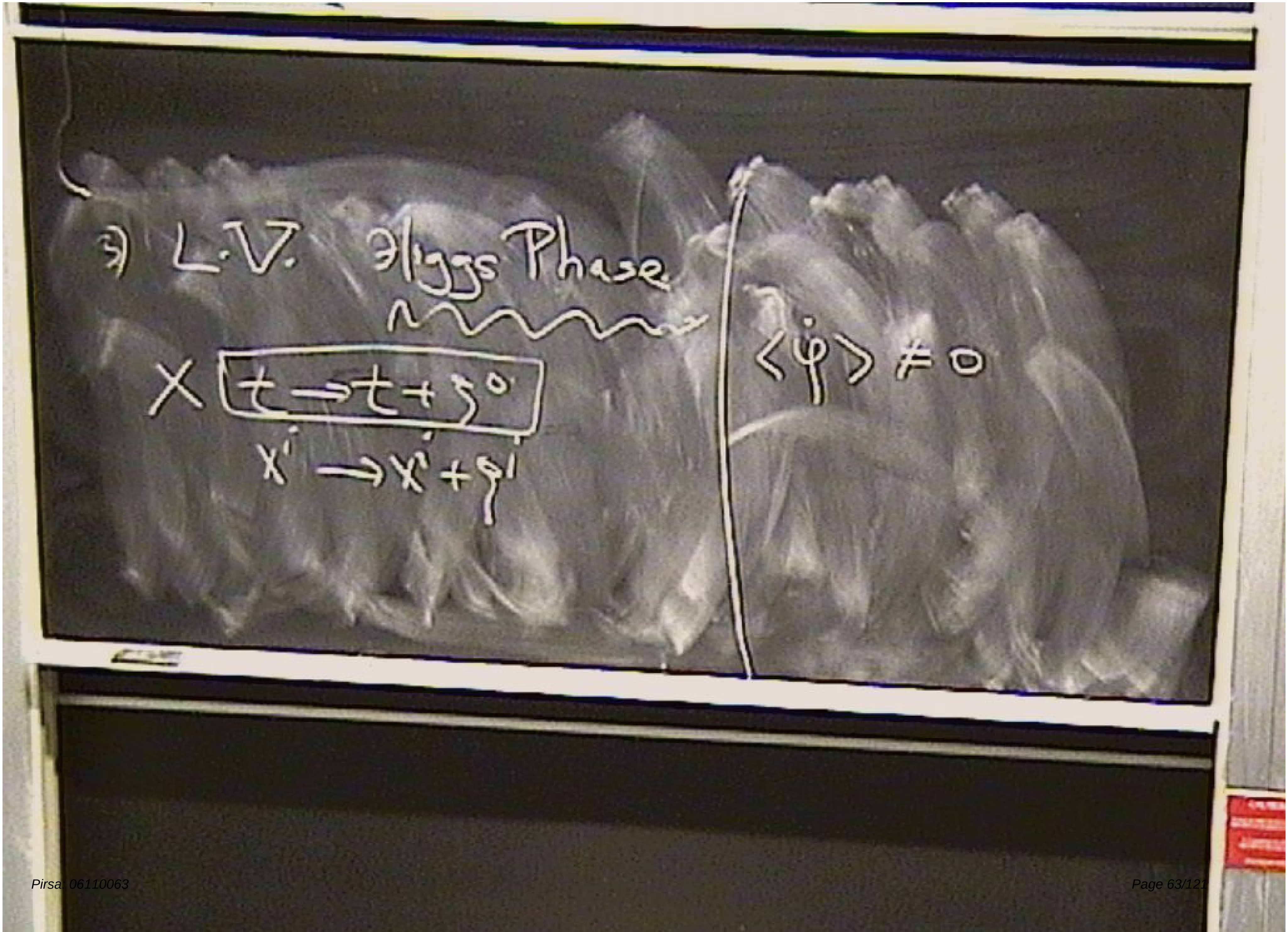


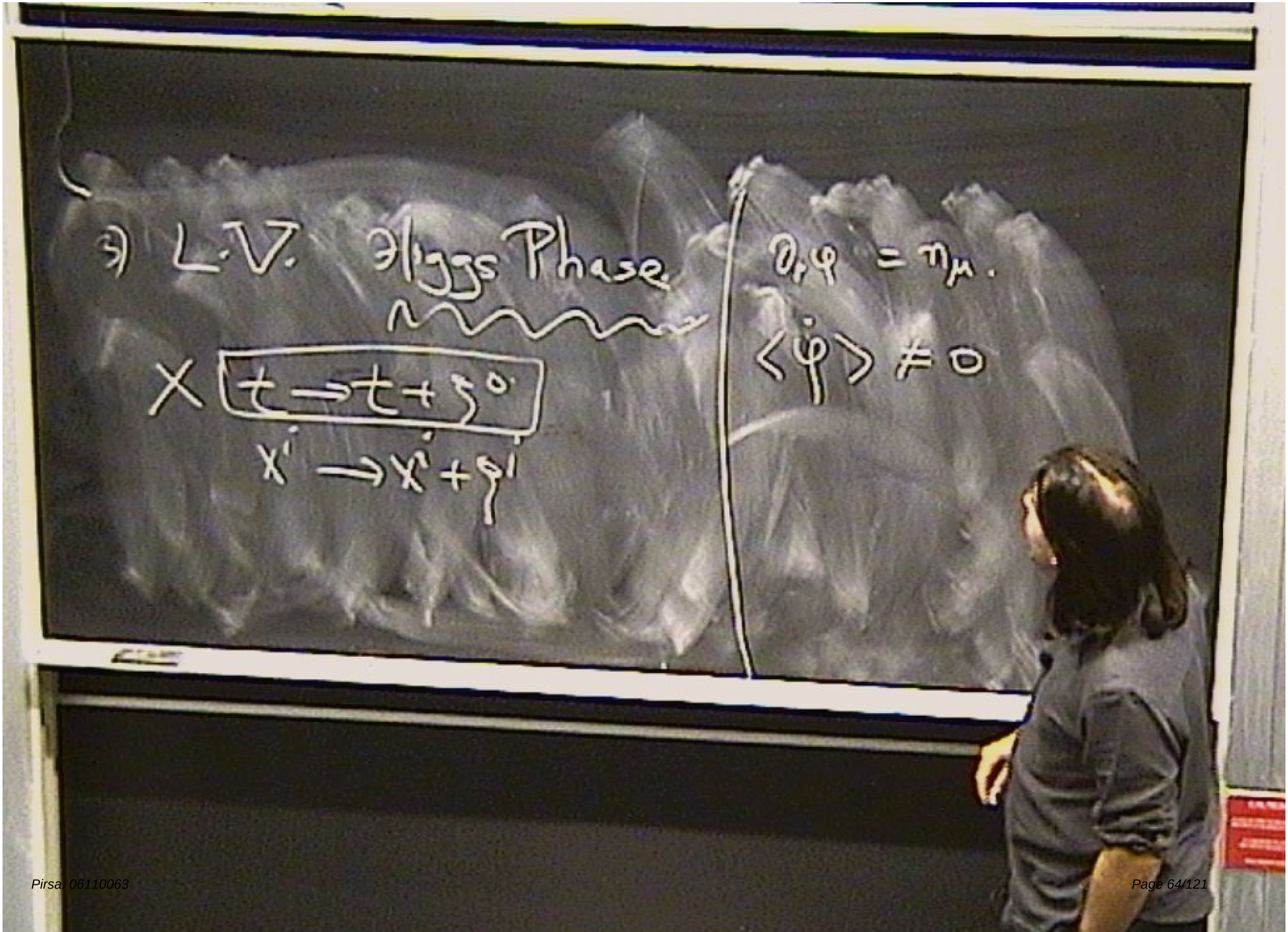
$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + \frac{(\partial\pi)^4}{\Lambda^4} + \cdots$
$\partial_\mu \pi \to \partial_\mu \pi + c_\mu$
$\partial^2 \pi \to \partial^2 \pi$
$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + O\left(\frac{\partial^2\pi}{\Lambda^3}\right)$

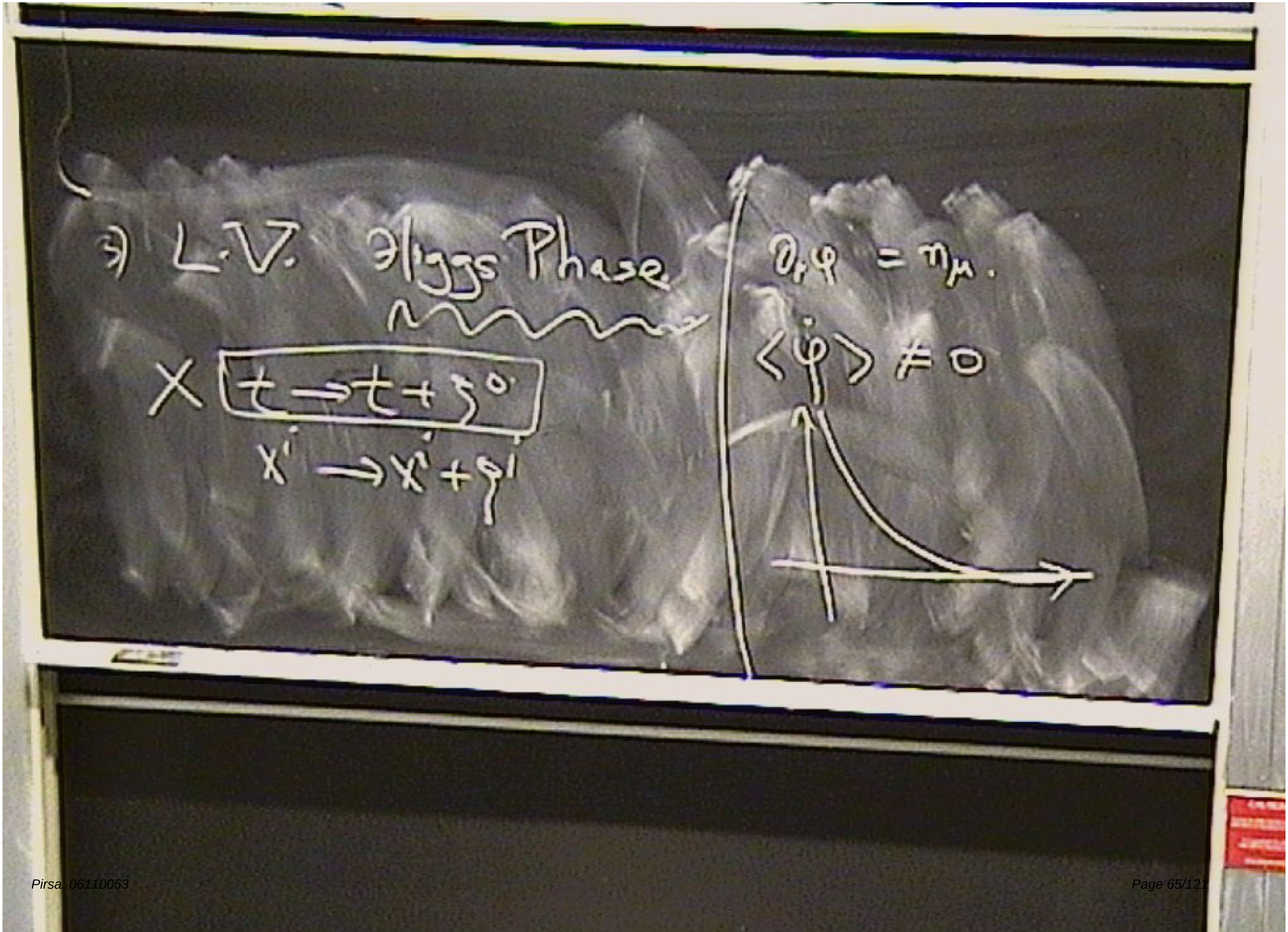

3) L.V. Higgs Phase

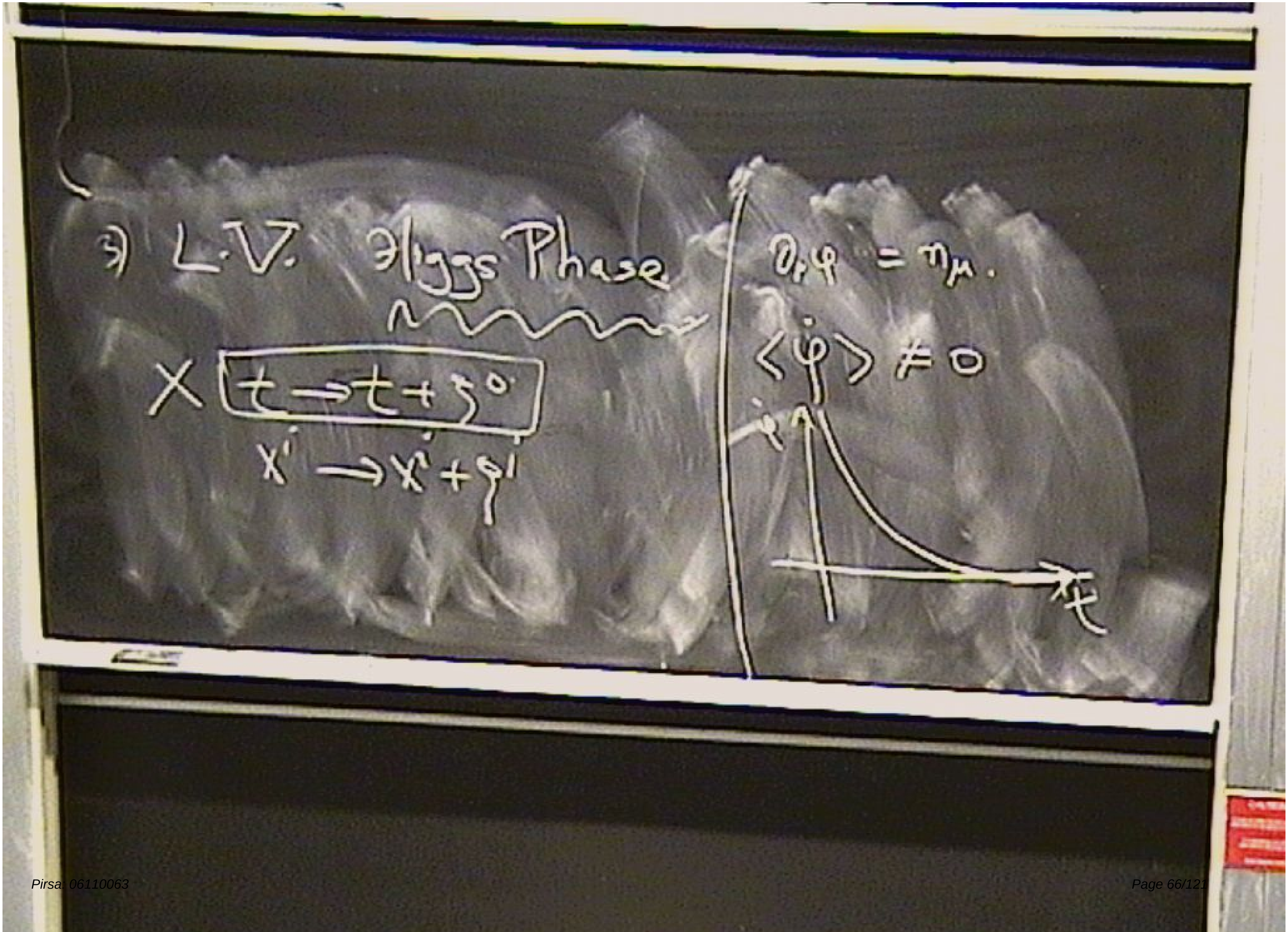

3) L.V. Higgs Phase
t → t + ξ⁰
xⁱ → xⁱ + ξⁱ

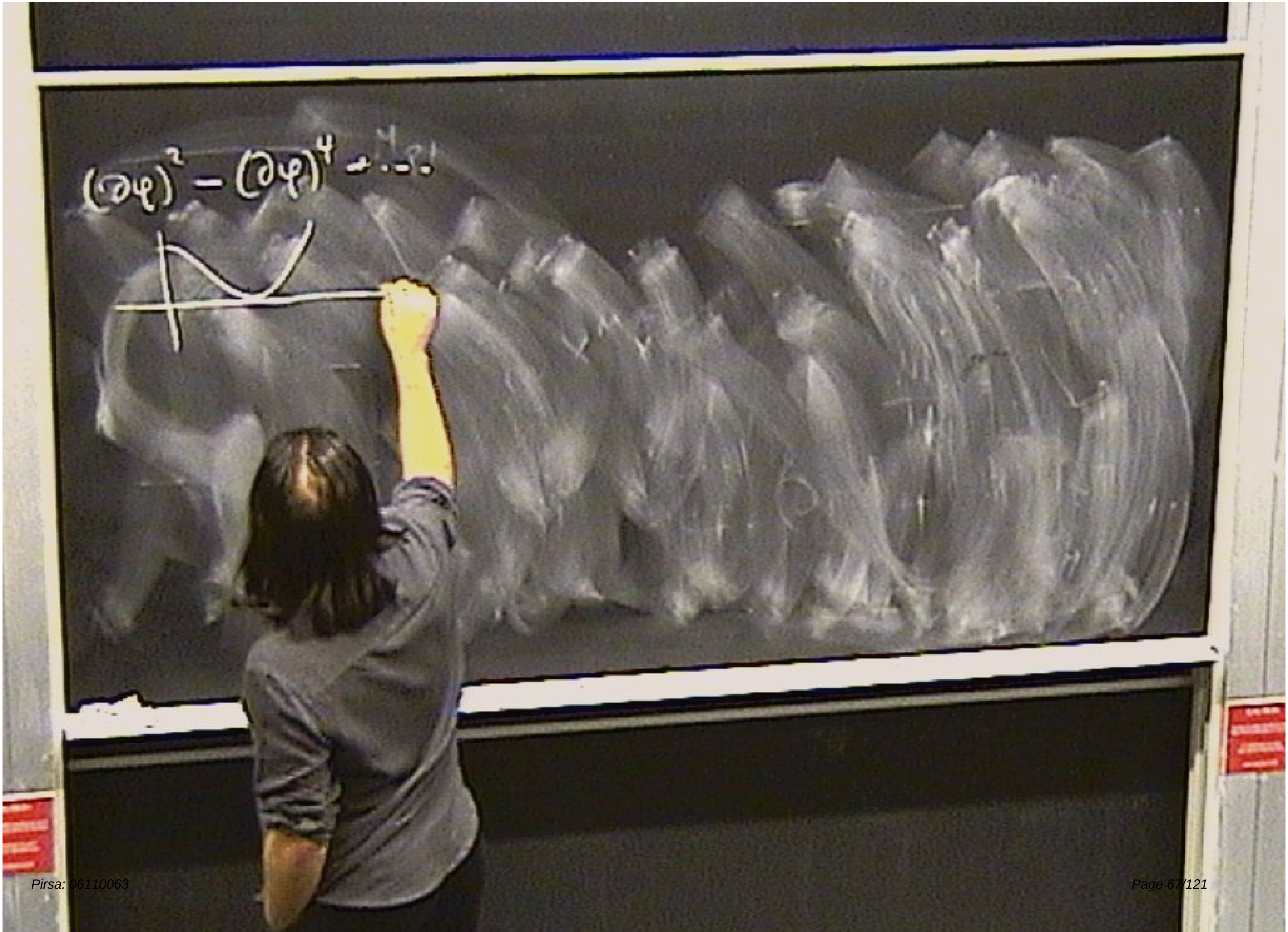

L.V. Higgs Phase

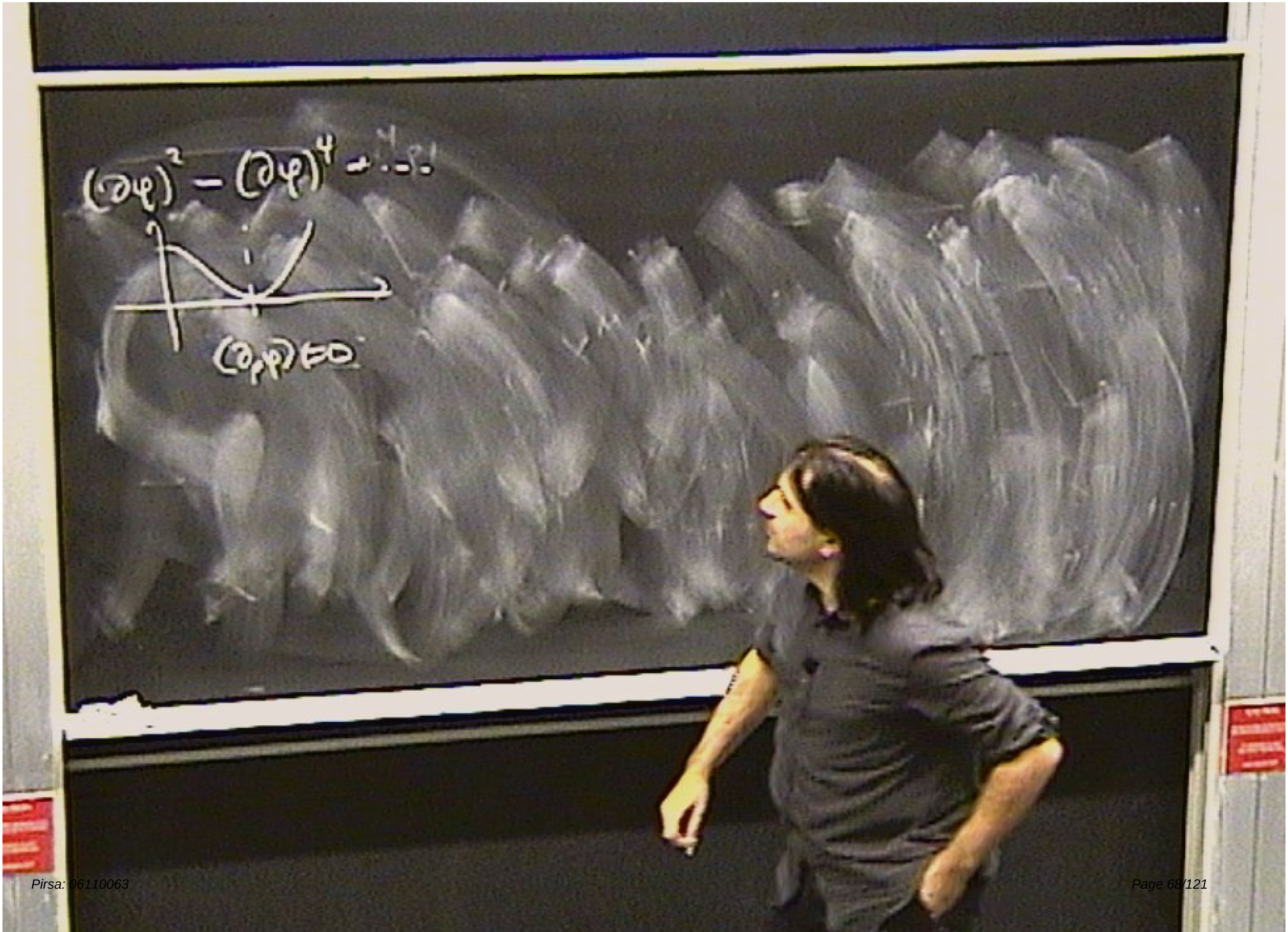

3) L.V. Higgs Phase
X t → t + ξ⁰
xⁱ → xⁱ + ξⁱ
⟨φ⟩ ≠ 0

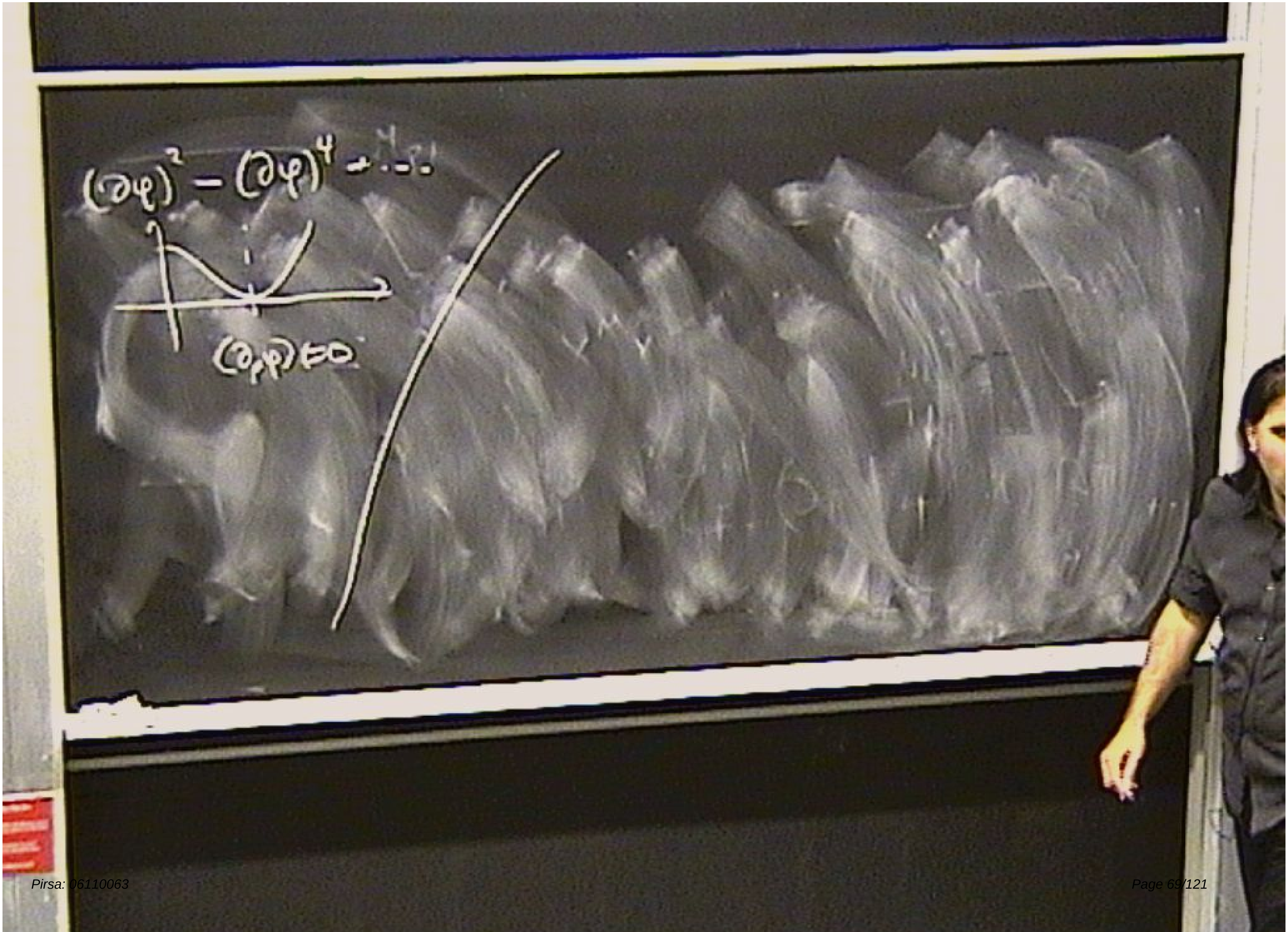

3) L.V. Higgs Phase
X t → t + ξ⁰
xⁱ → xⁱ + ξⁱ
∂_μ φ = n_μ.
⟨φ̇⟩ ≠ 0

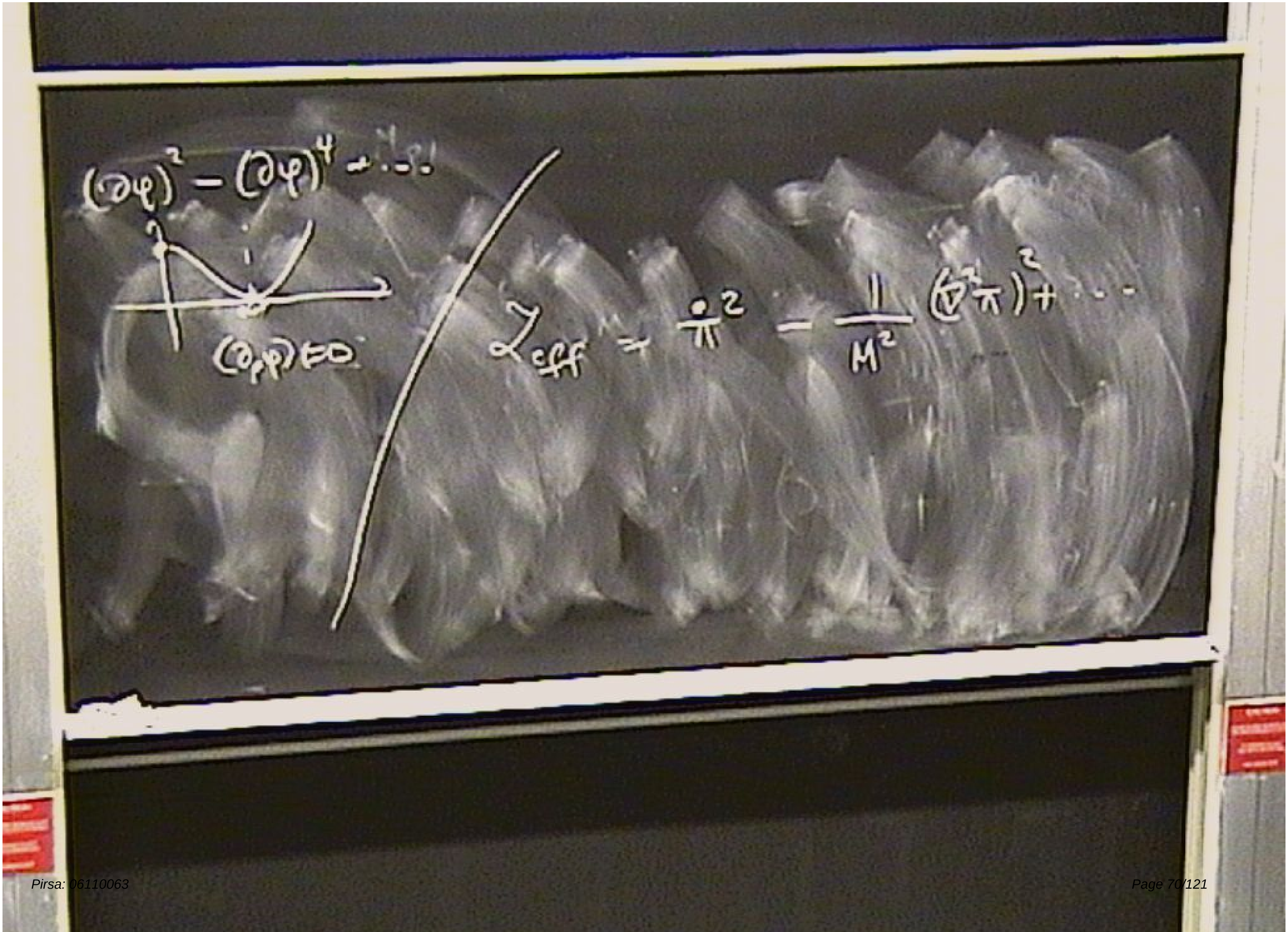

3) L.V. Higgs Phase
X t → t + ξ⁰
xⁱ → xⁱ + φⁱ
∂μφ = nμ
⟨φ⟩ ≠ 0


3) L.V. Higgs Phase
X t → t + ξ°
x^i → x^i + φ^i
∂_μ φ = n_μ
⟨φ̇⟩ ≠ 0
φ̇
t

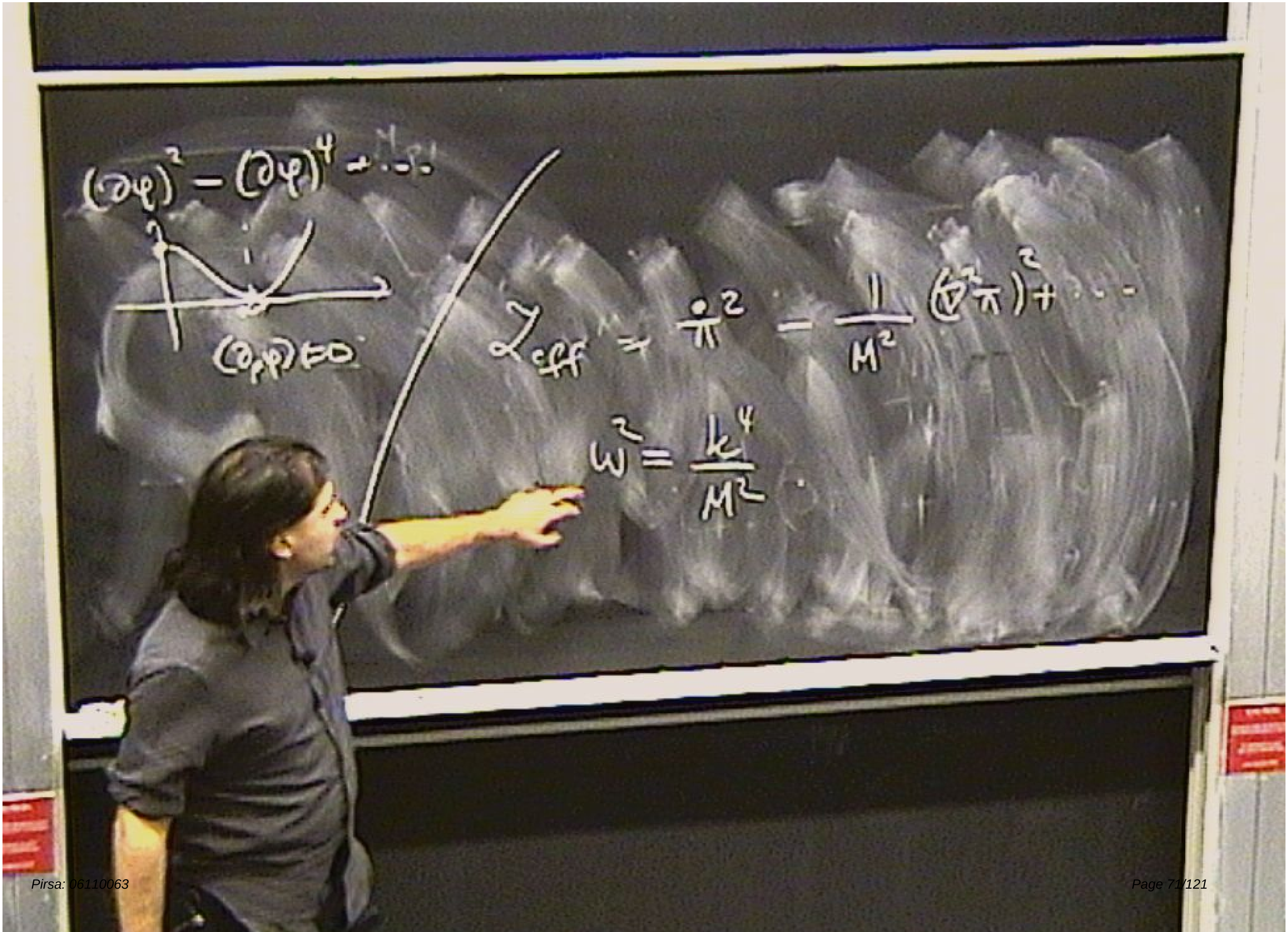

(∂φ)² − (∂φ)⁴ + ...

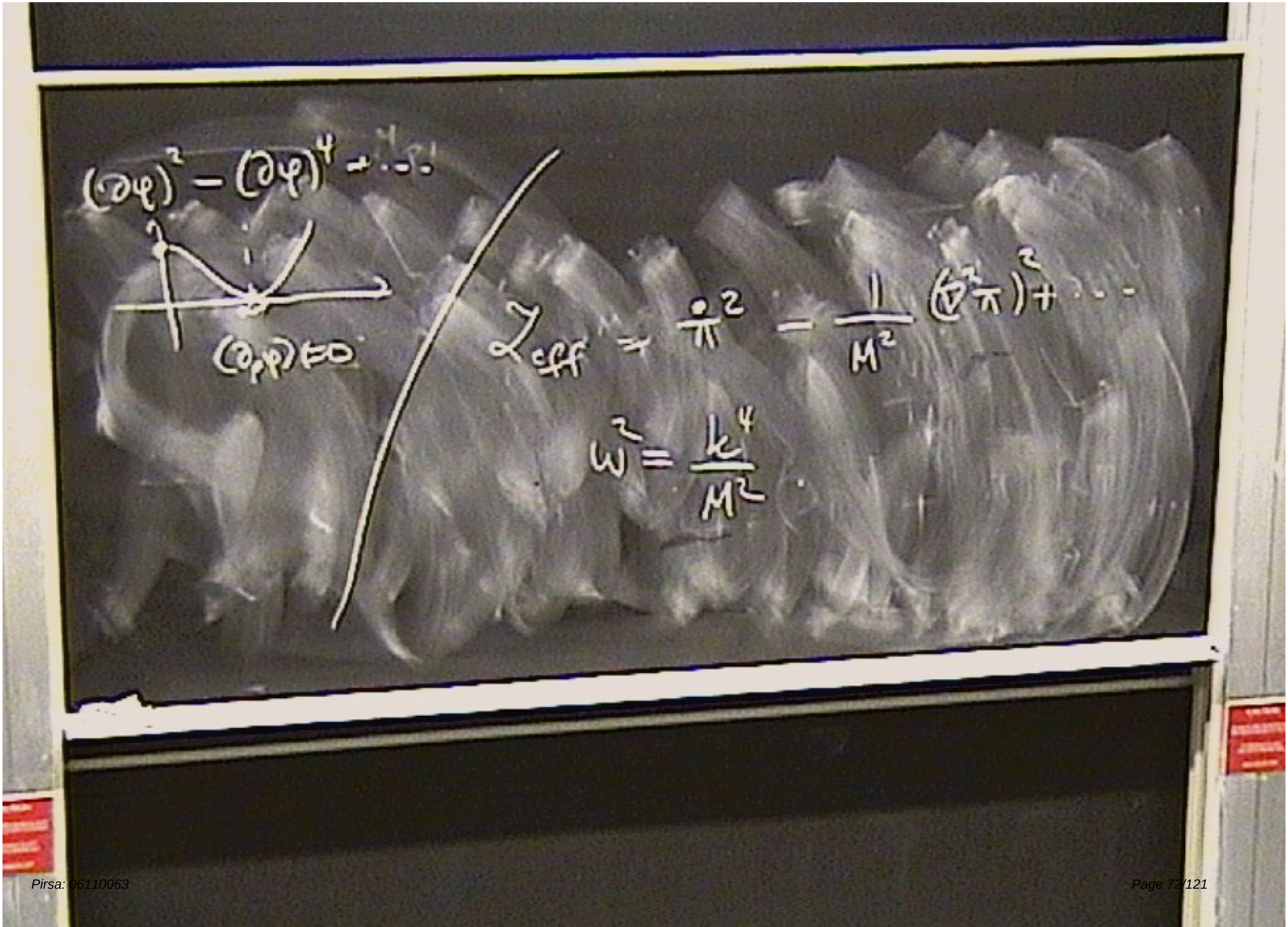

(∂φ)² − (∂φ)⁴ + ...

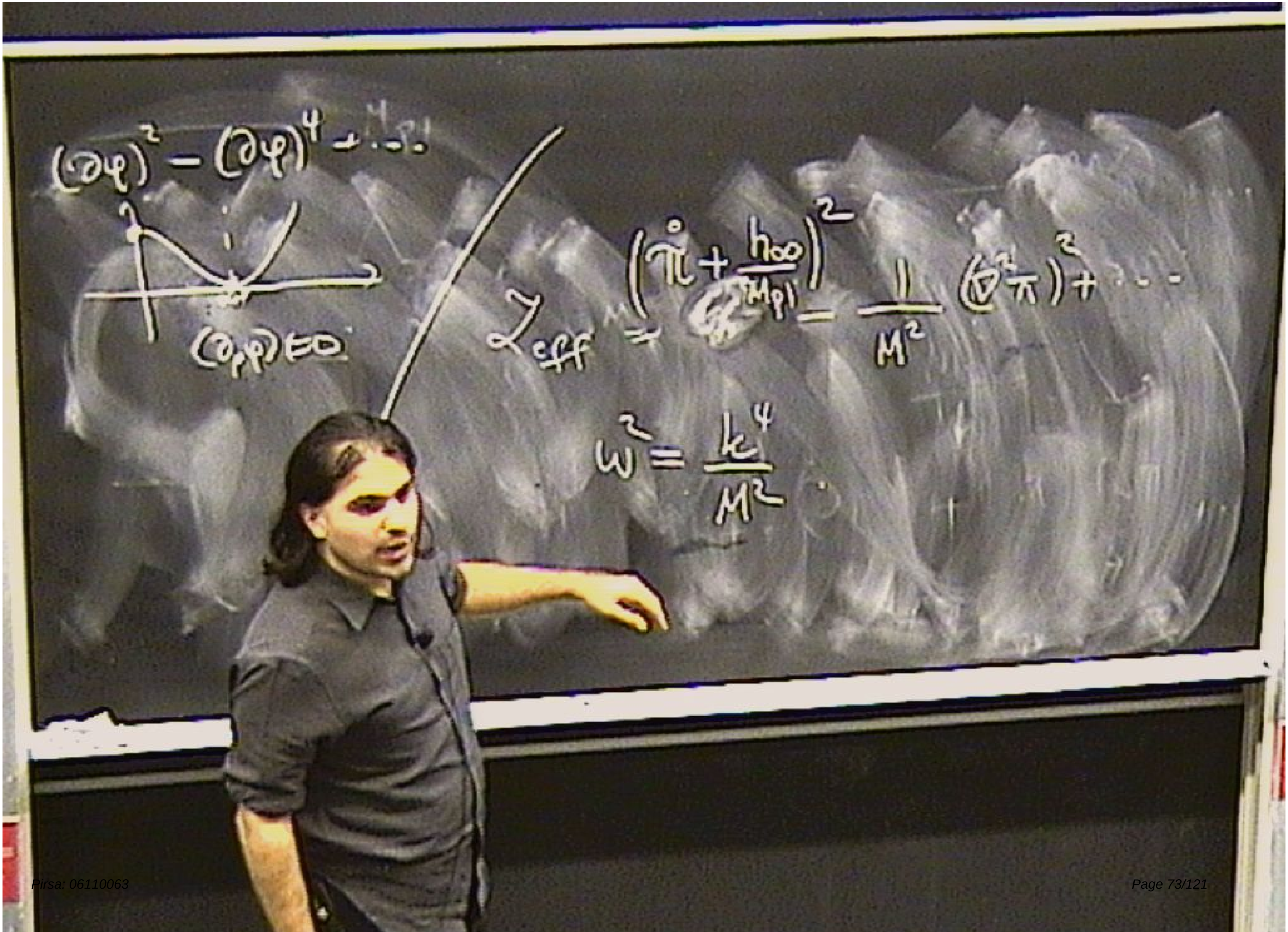

$(\partial\varphi)^2 - (\partial\varphi)^4 + \ldots$
$(\partial_t\varphi) \neq 0$



$(\partial\varphi)^2 - (\partial\varphi)^4 + \dots$
$(\partial_t\varphi) \neq 0$
$\mathcal{L}_{eff} = \dot{\pi}^2 - \frac{1}{M^2}(\nabla^2\pi)^2 + \dots$


(∂φ)² − (∂φ)⁴ + ...
L_eff = π̇² − 1/M² (∇²π)² + ...
ω² = k⁴/M²


$(\partial\varphi)^2 - (\partial\varphi)^4 + \ldots$
$\langle \partial_t \varphi \rangle \neq 0$
$\mathcal{L}_{eff} = \dot{\pi}^2 - \frac{1}{M^2}(\nabla^2\pi)^2 + \ldots$
$\omega^2 = \frac{k^4}{M^2}$


(∂φ)² − (∂φ)⁴ + ...
(∂ₜφ) = 0
L_eff = (π̇ + h₀₀/M_pl)² − 1/M² (∇²π)² + ...
ω² = k⁴/M²

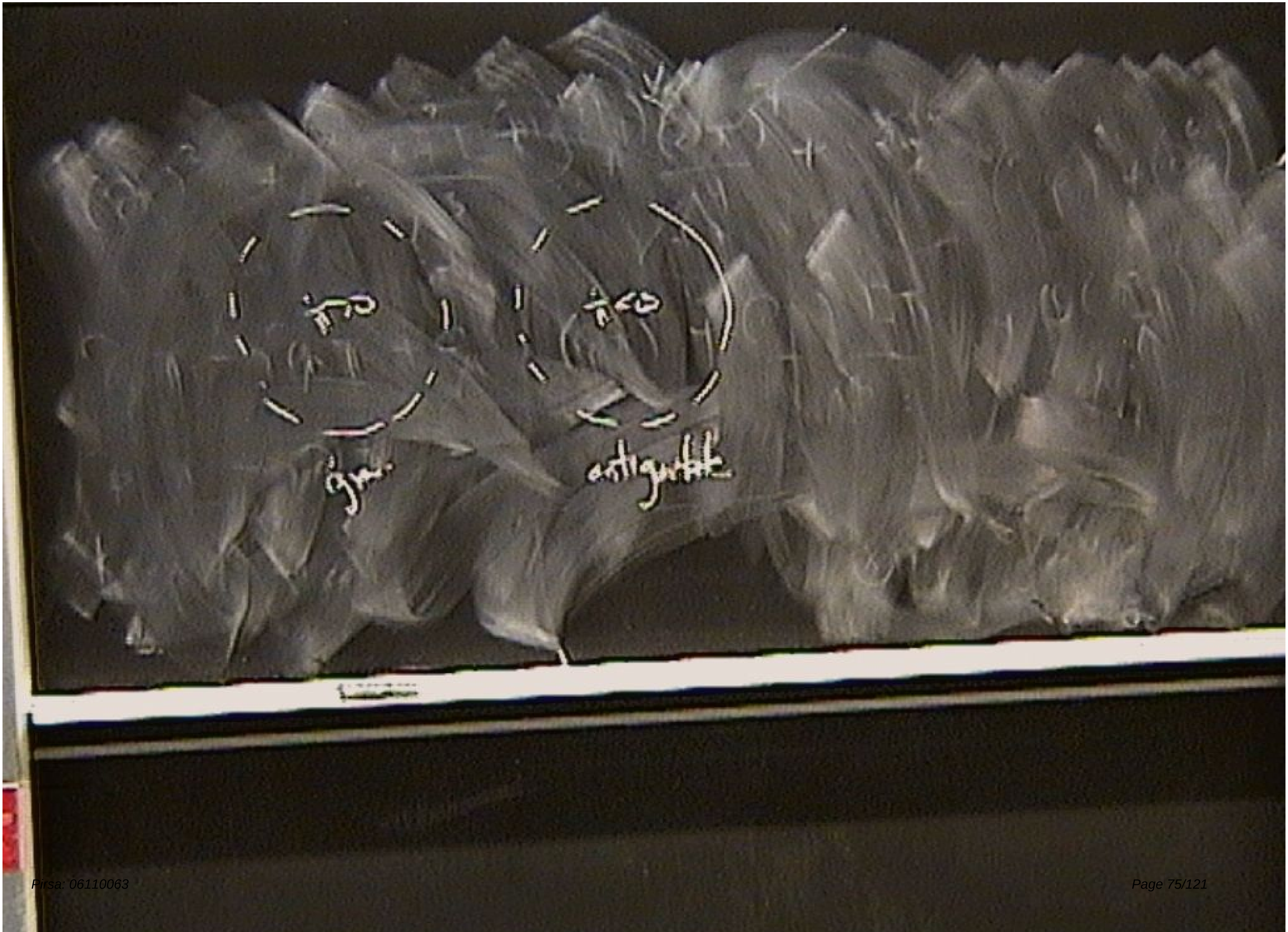
$(\partial\varphi)^2 - (\partial\varphi)^4 + \ldots$

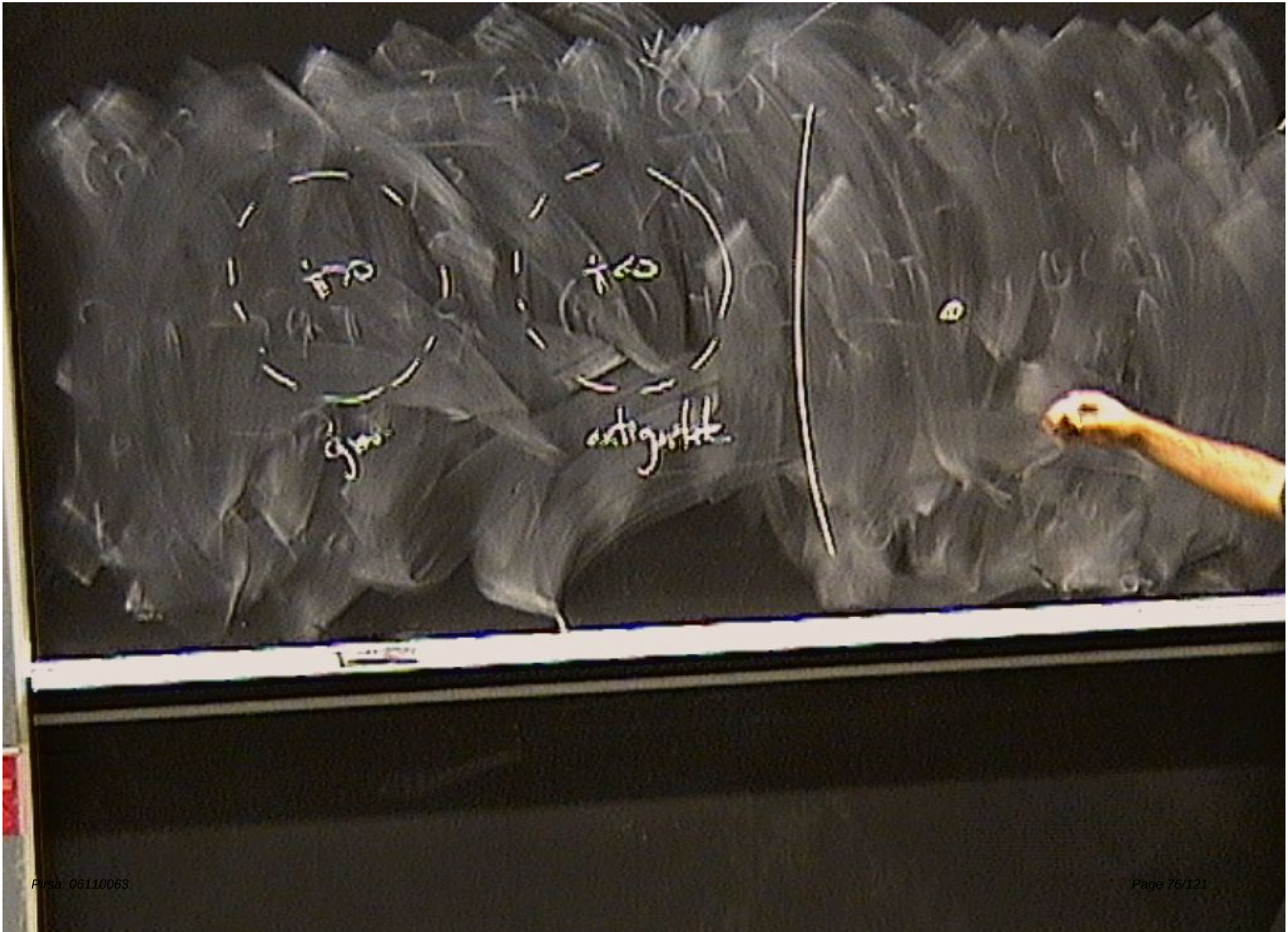
$\langle\partial_t\varphi\rangle \neq 0$

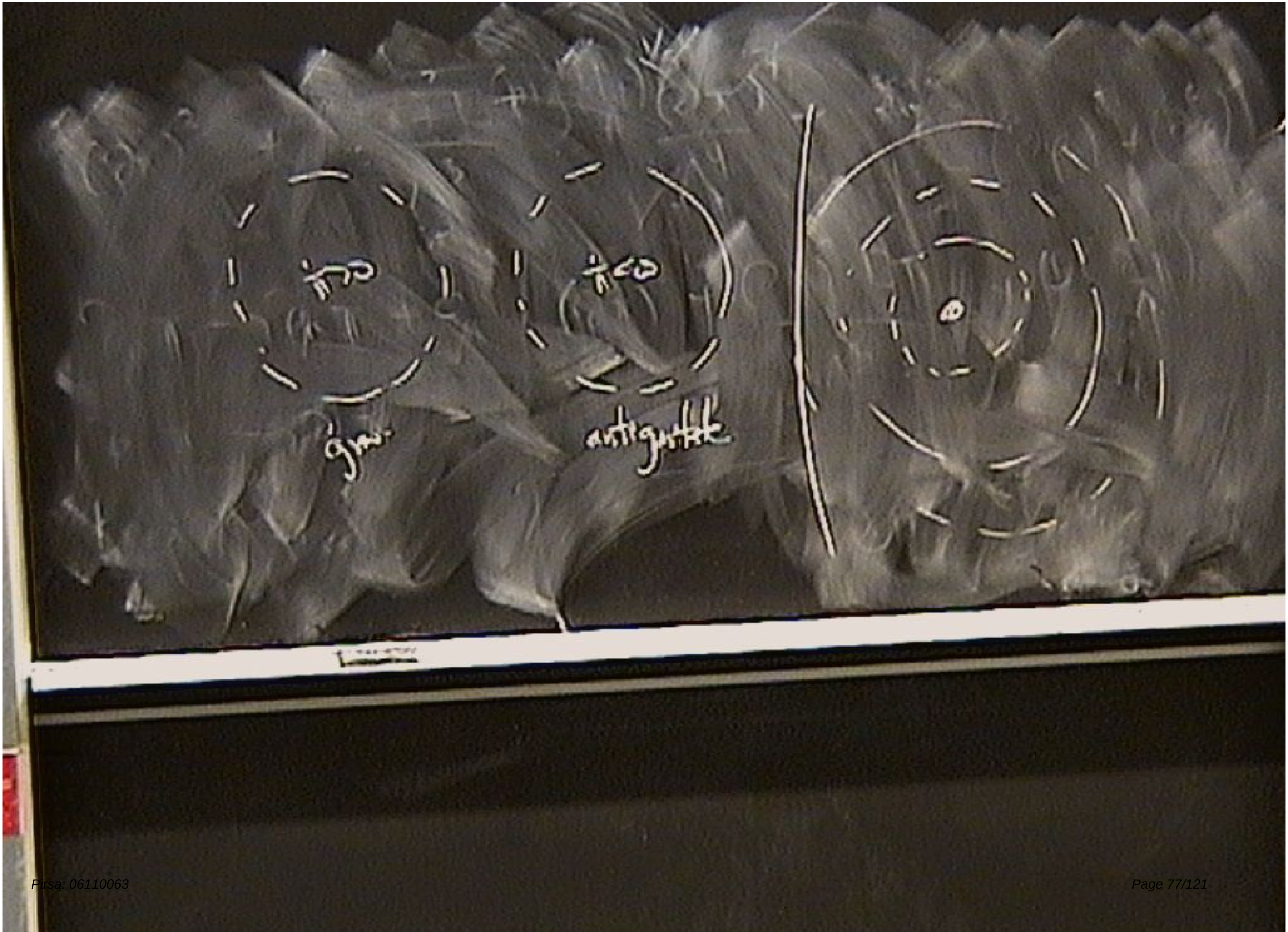
$(\dot{\pi}\, h_{00})$

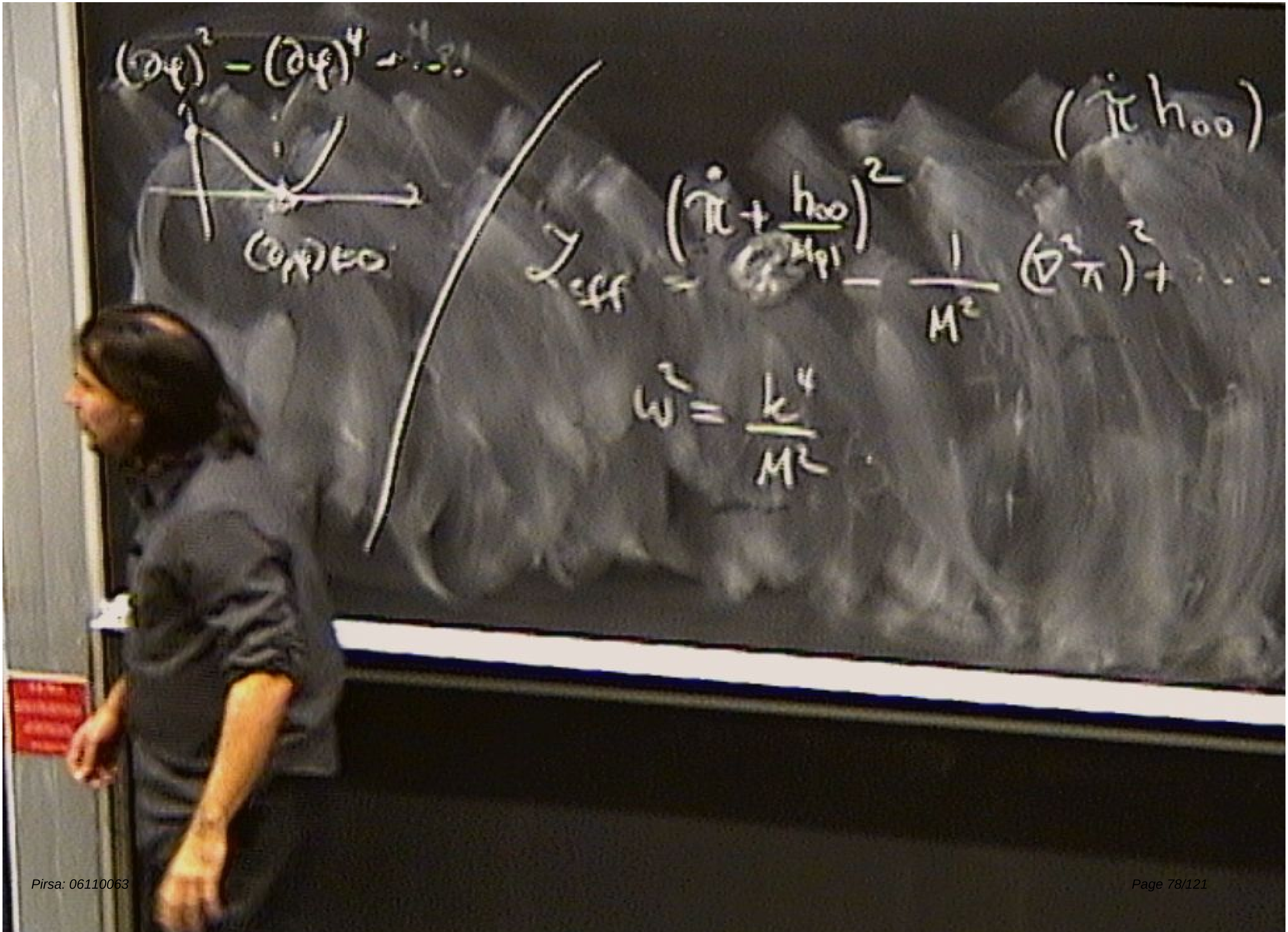
$$\mathcal{L}_{eff} = \left(\dot{\pi} + \frac{h_{00}}{M_{Pl}}\right)^2 - \frac{1}{M^2}(\nabla^2\pi)^2 + \ldots$$

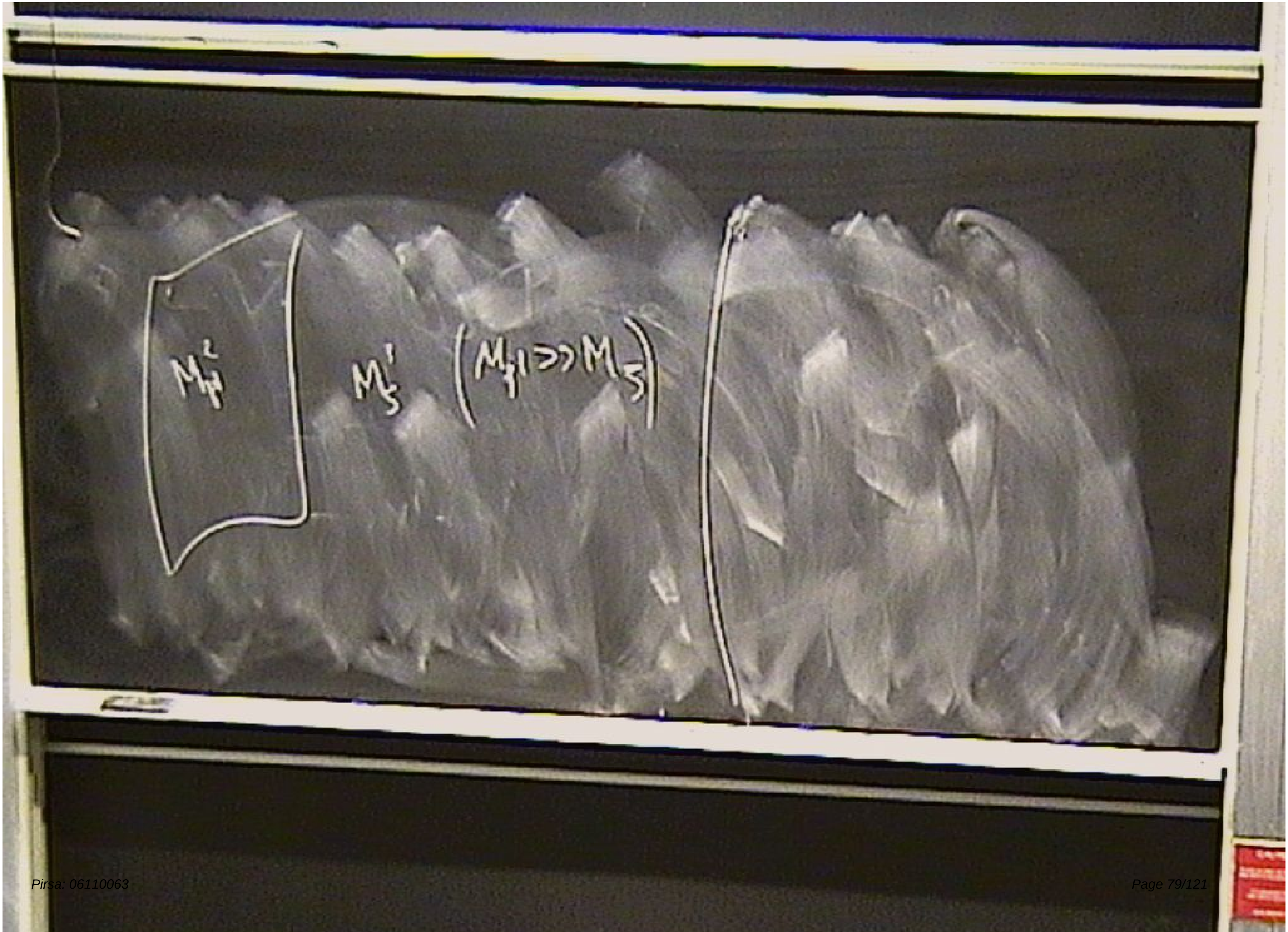
$$\omega^2 = \frac{k^4}{M^2}$$

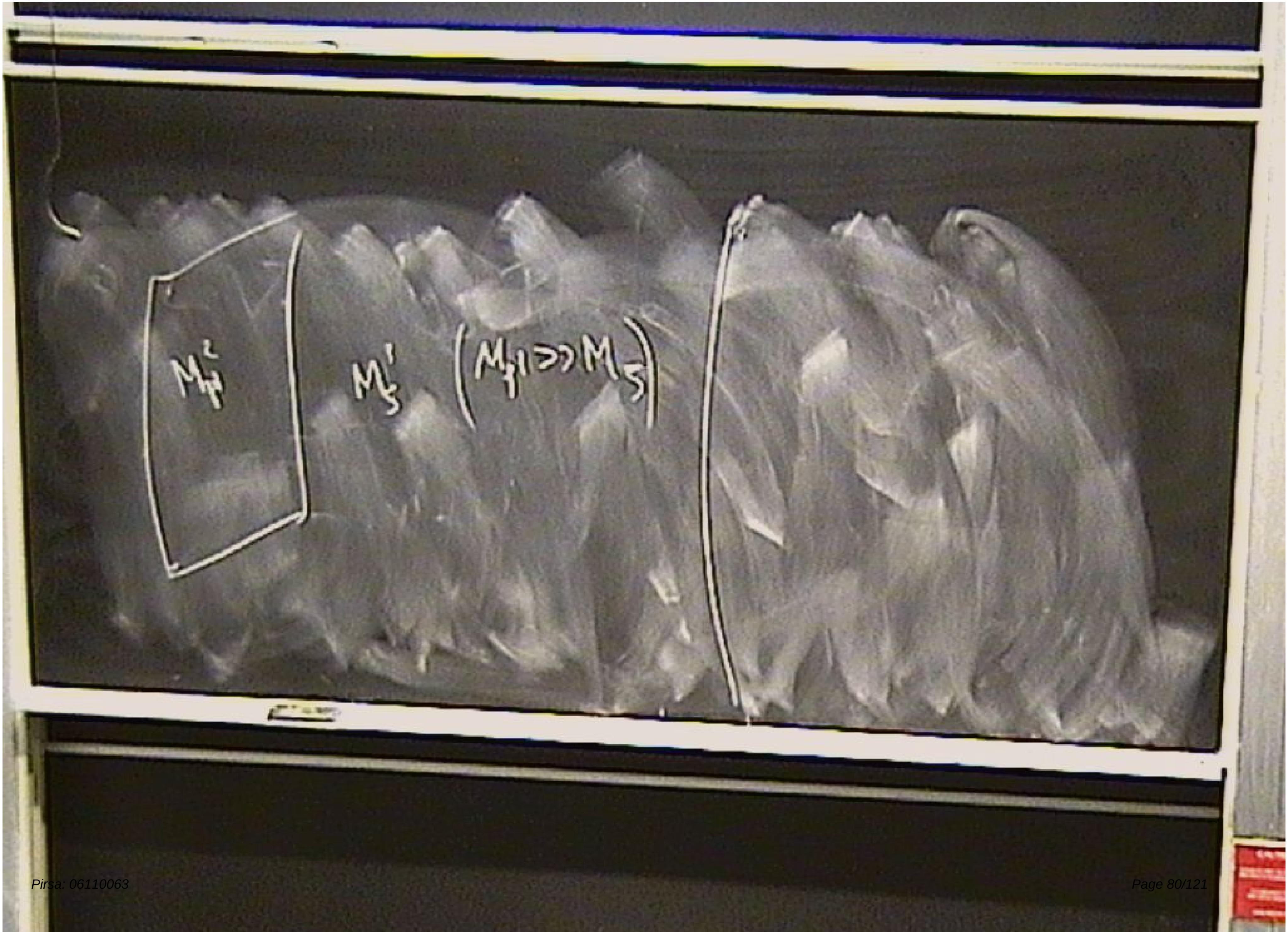


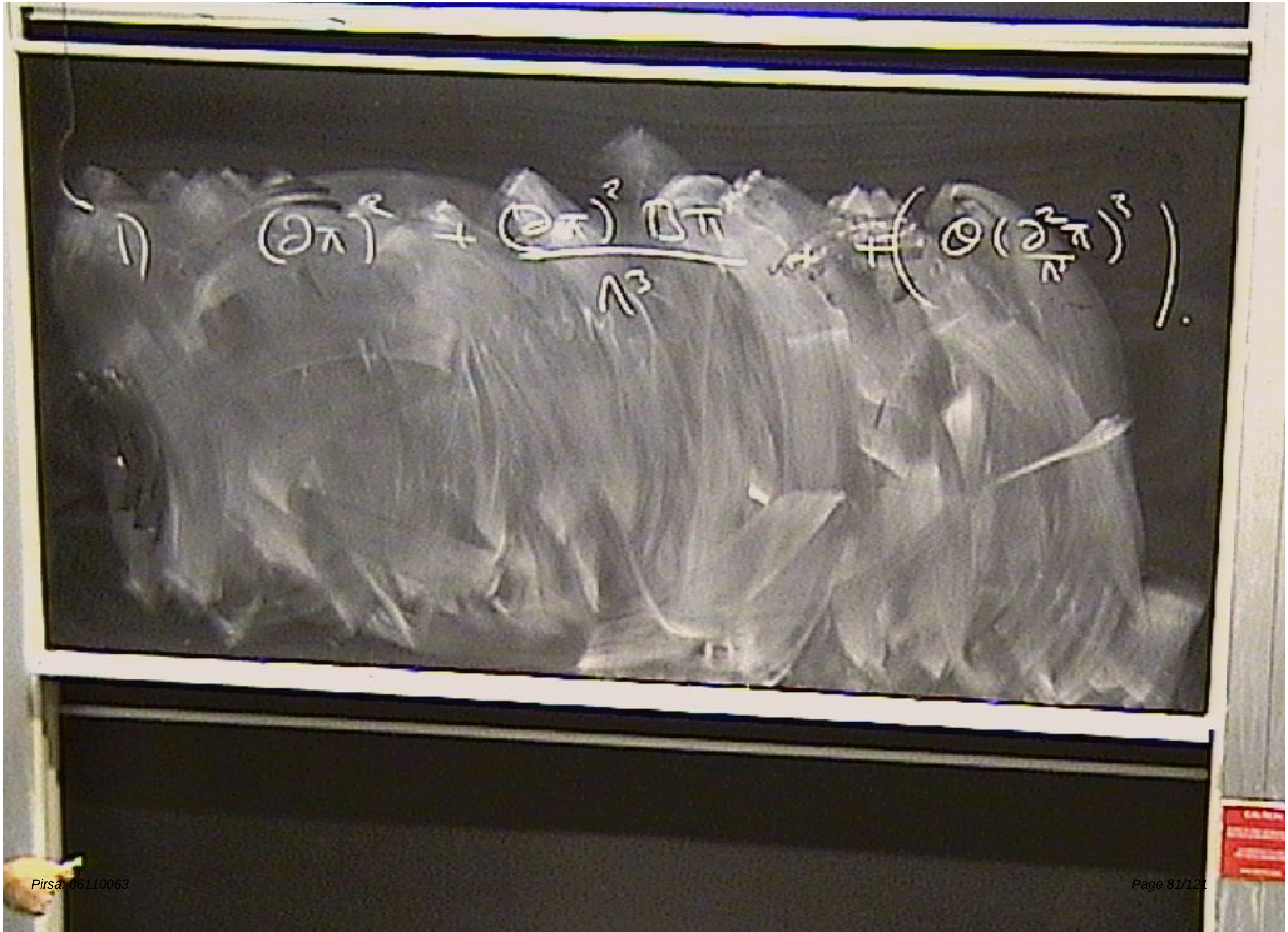


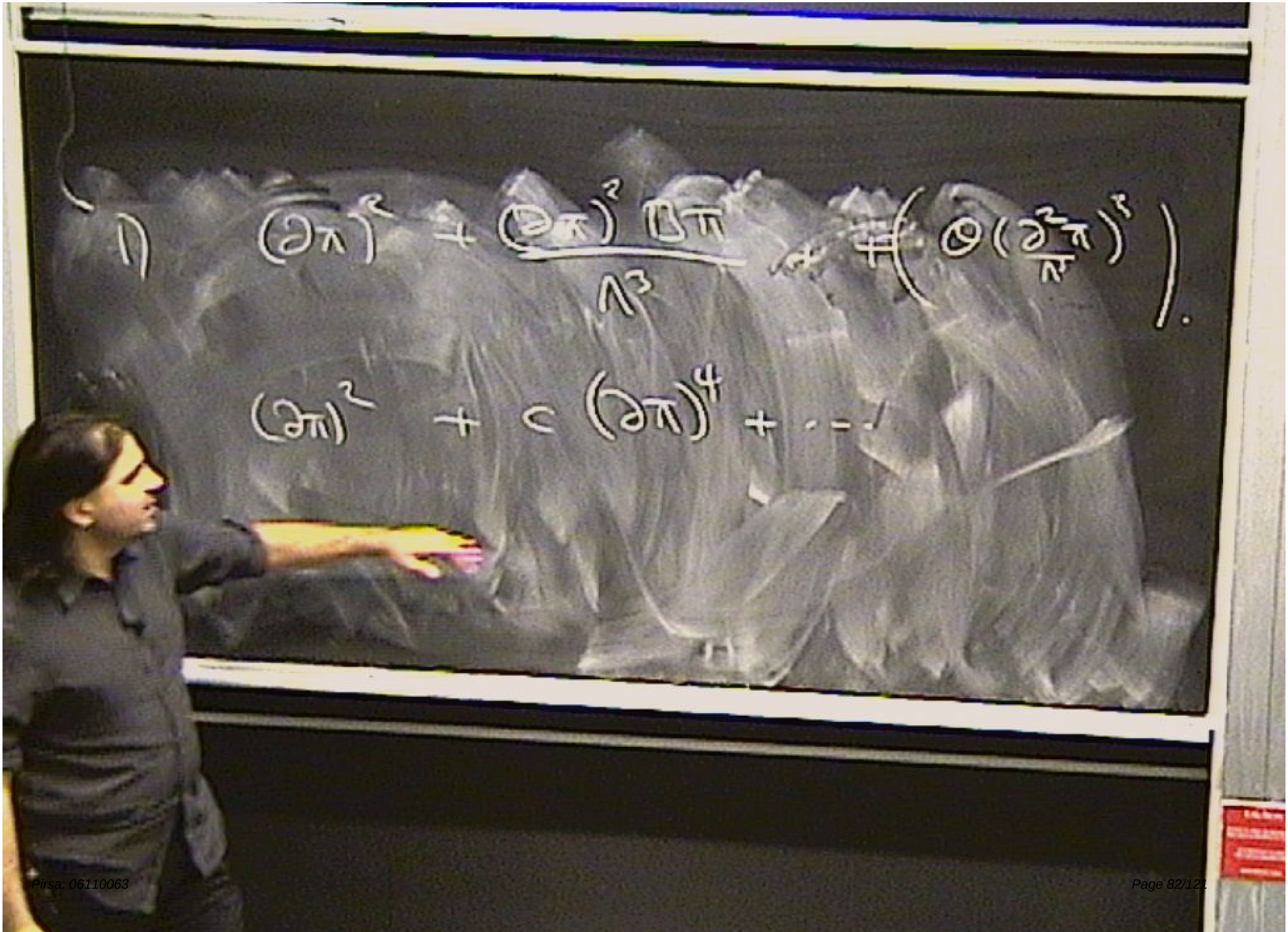


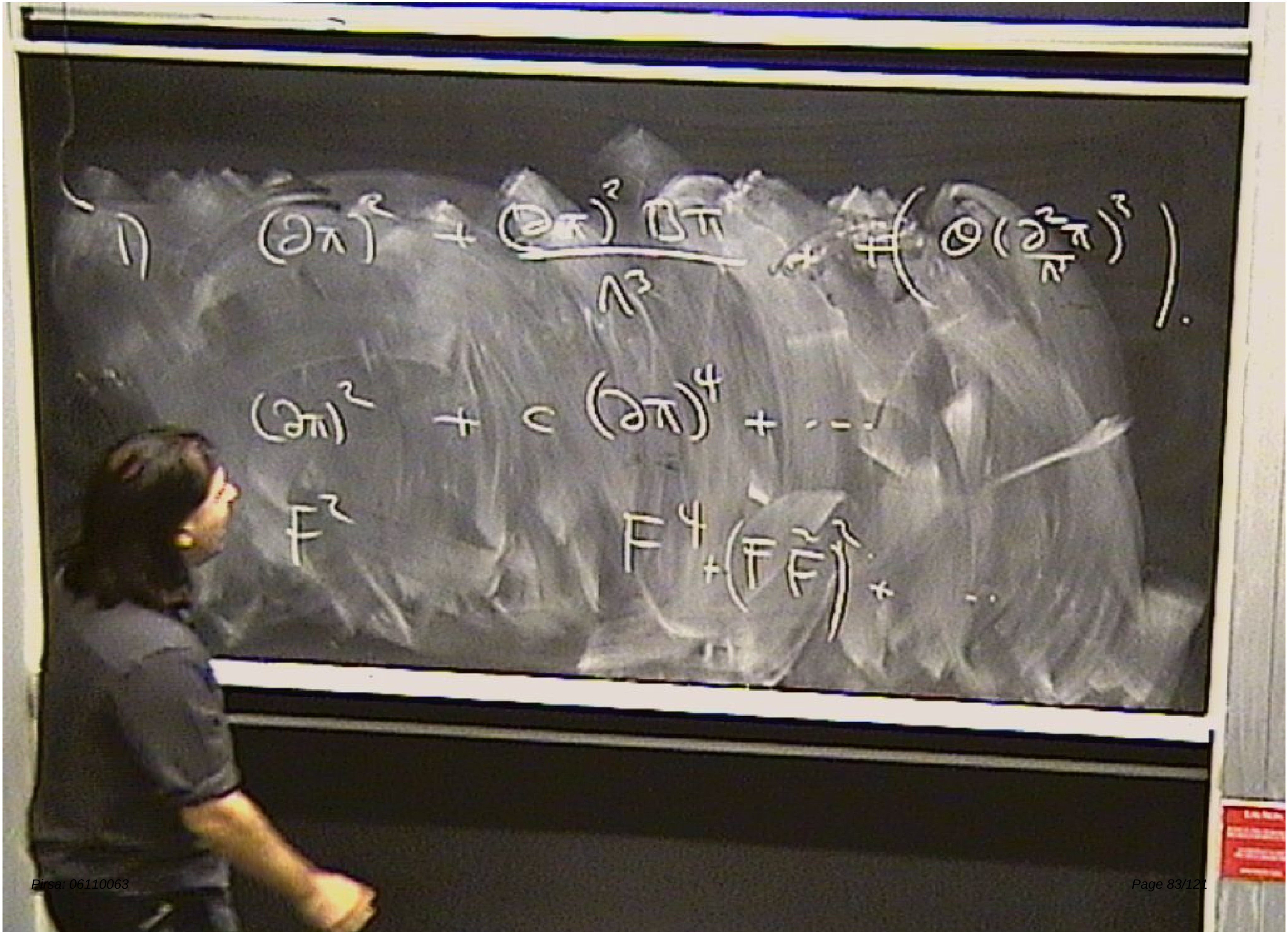

$(\partial\varphi)^2 - (\partial\varphi)^4 + \ldots$
$(\dot{\pi}\, h_{00})$
$\mathcal{L}_{eff} = \left(\dot{\pi} + \frac{h_{00}}{M_{pl}}\right)^2 - \frac{1}{M^2}(\nabla^2\pi)^2 + \ldots$
$\omega^2 = \frac{k^4}{M^2}$

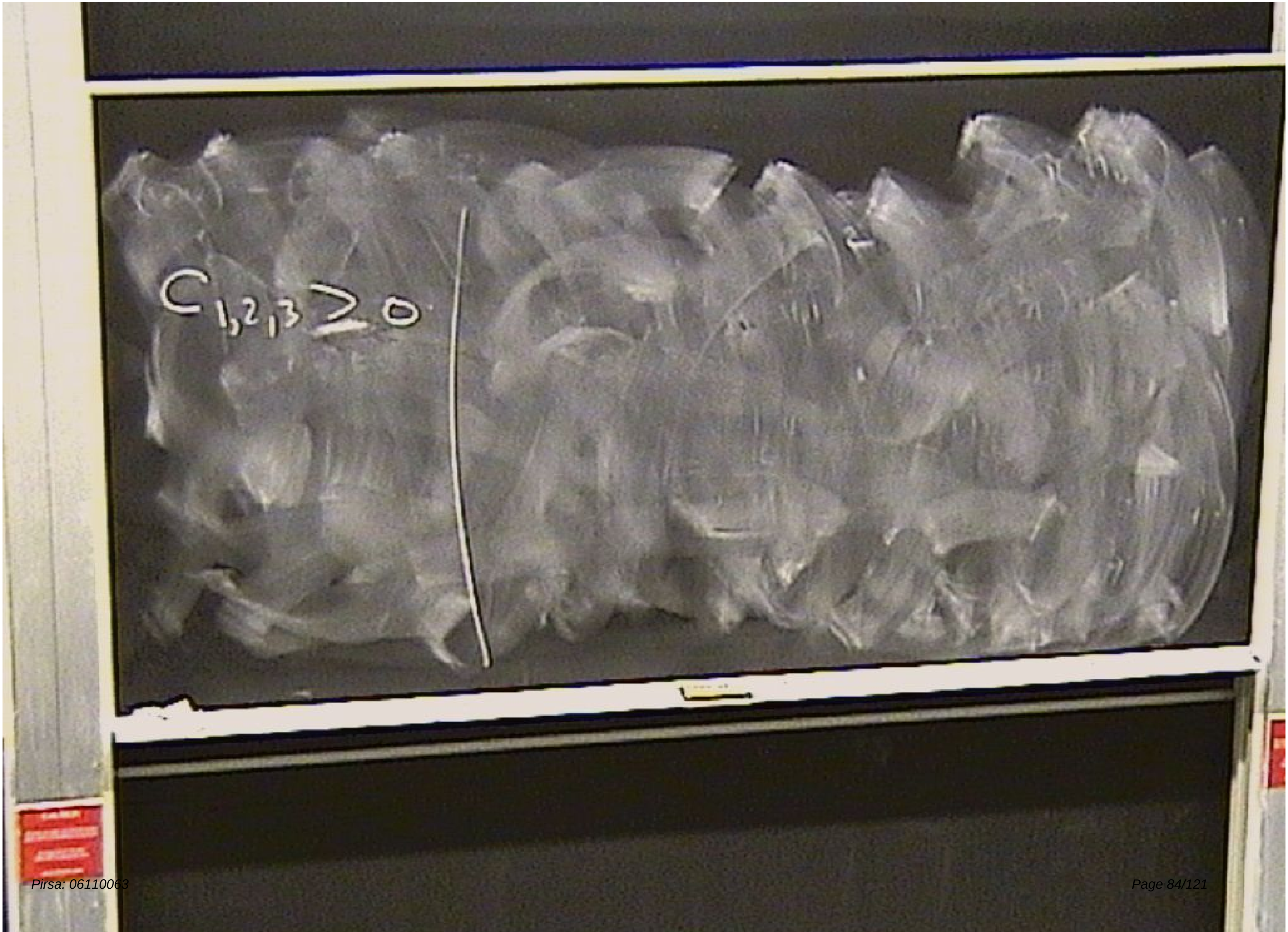

M_{pl}^2
M_5^1
$(M_{pl} >> M_5)$


(M_Pl >> M_5)




1) (∂π)² + (∂π)² □π / Λ³ + O((∂²π/π)⁵).
(∂π)² + c (∂π)⁴ + ...

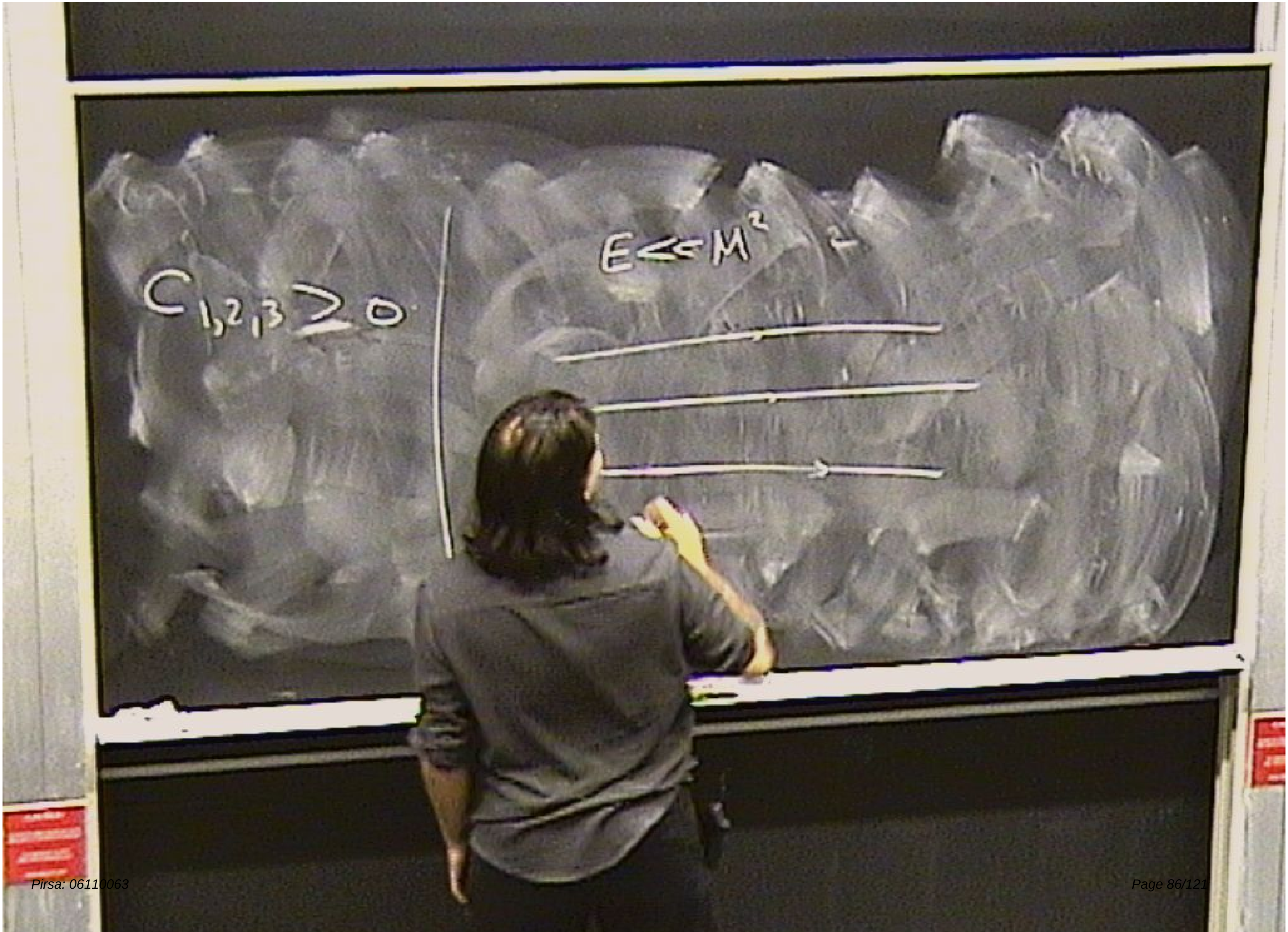

$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3} + O\left(\left(\frac{\partial^2\pi}{\pi}\right)^2\right)$.
$(\partial\pi)^2 + c\,(\partial\pi)^4 + \ldots$
F^2
$F^4 + (F\tilde{F})^2 + \ldots$

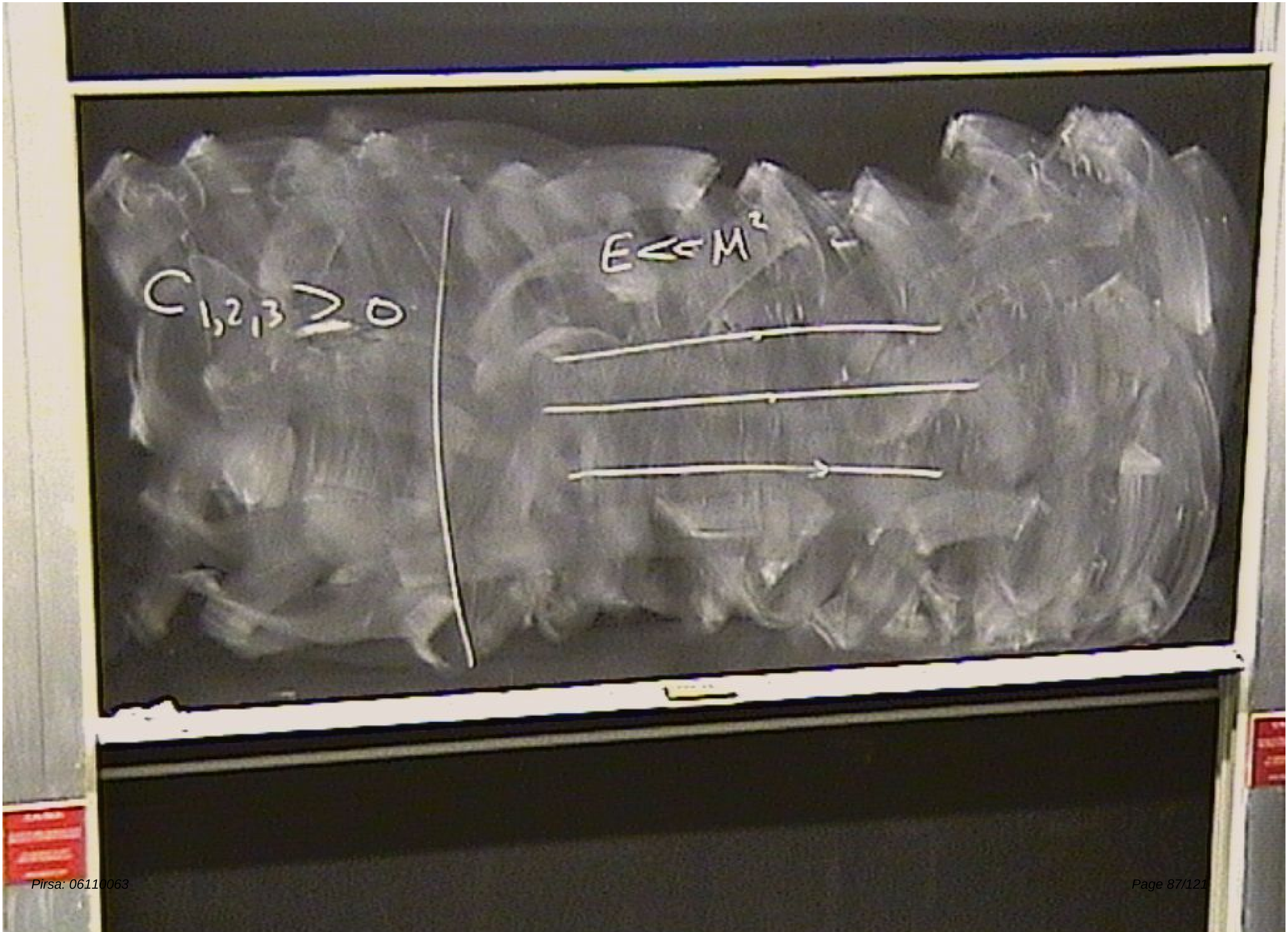

$C_{1,2,3} \geq 0$

$$\mathcal{L} = (\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \left(\mathcal{O}\left(\frac{\partial^2\pi}{\Lambda^3}\right)^2\right).$$

$$(\partial\pi)^2 + c_1(\partial\pi)^4 + \ldots$$

$$F^2 + c_2\frac{F^4}{M^4} + c_3\frac{(F\tilde{F})^2}{M^4} + \ldots$$

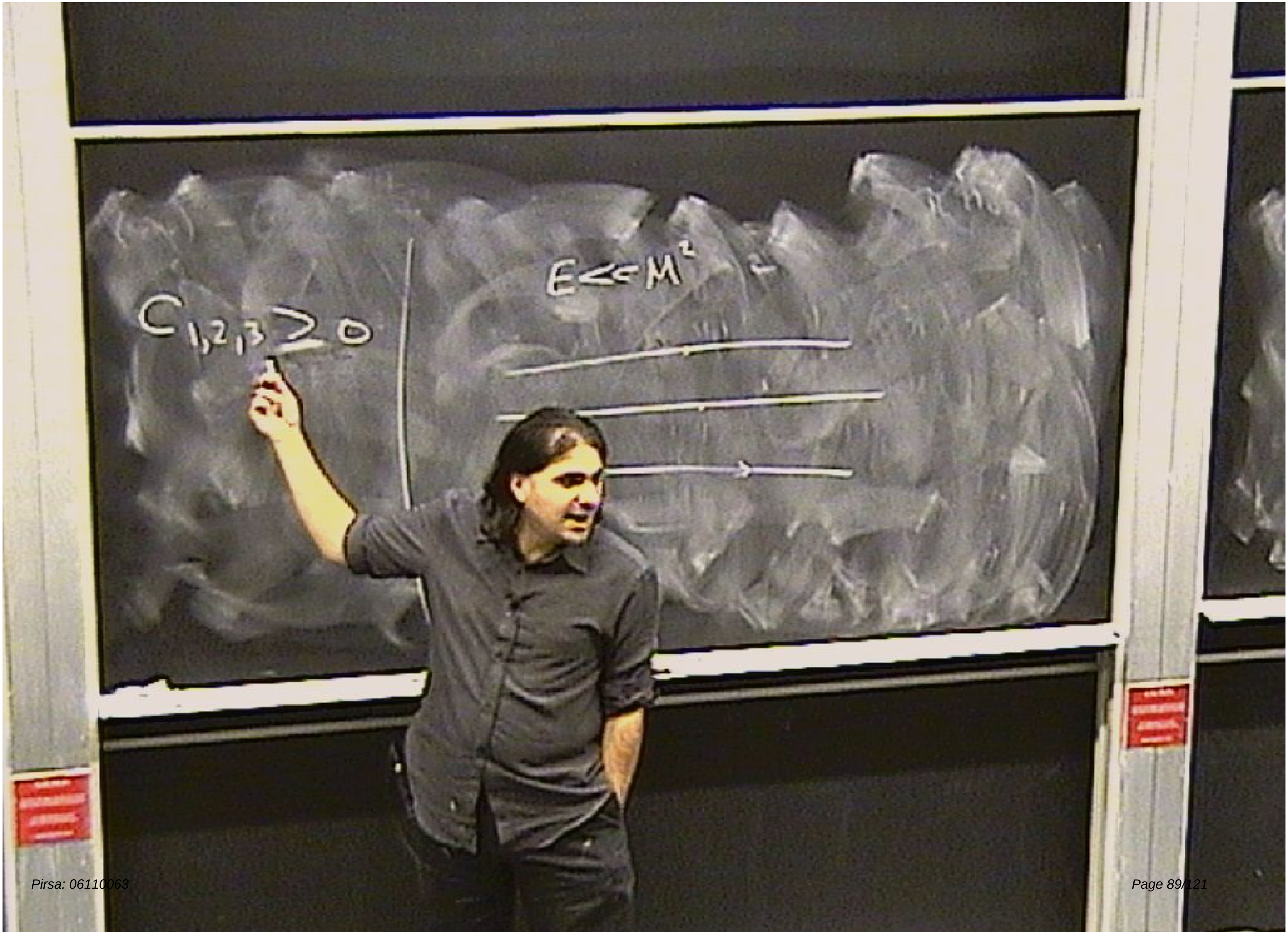

C1,2,3 ≥ 0
E << M2


C1,2,3 ≥ 0
E << M2

$$(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \mathcal{O}\left(\frac{(\partial^2\pi)^3}{\Lambda}\right)$$

$$(\partial\pi)^2 + c_1\frac{(\partial\pi)^4}{M^4} + \cdots$$

$$F^2 + c_2\frac{F^4}{M^4} + c_3\frac{(F\tilde{F})^2}{M^4} + \cdots$$

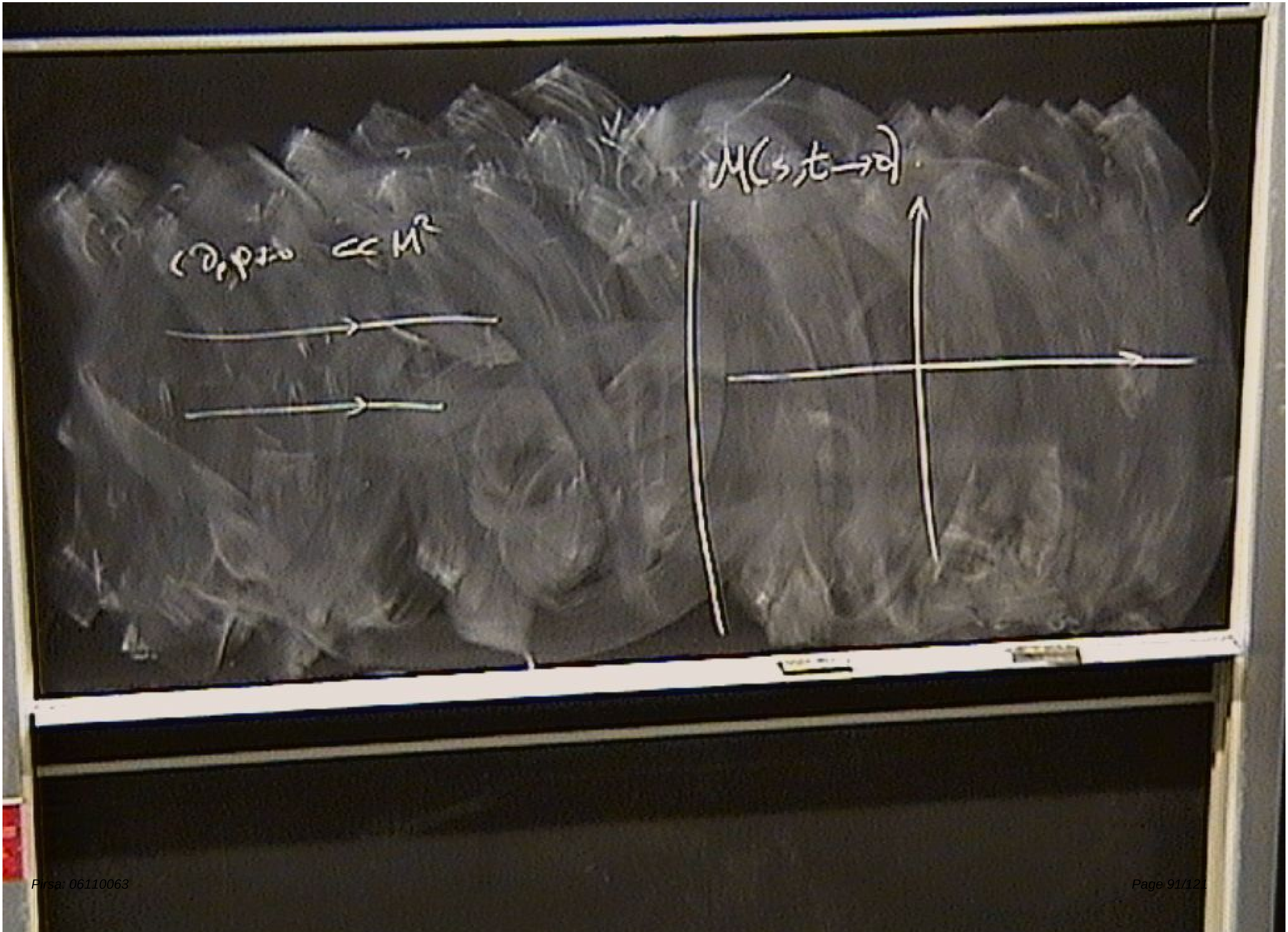


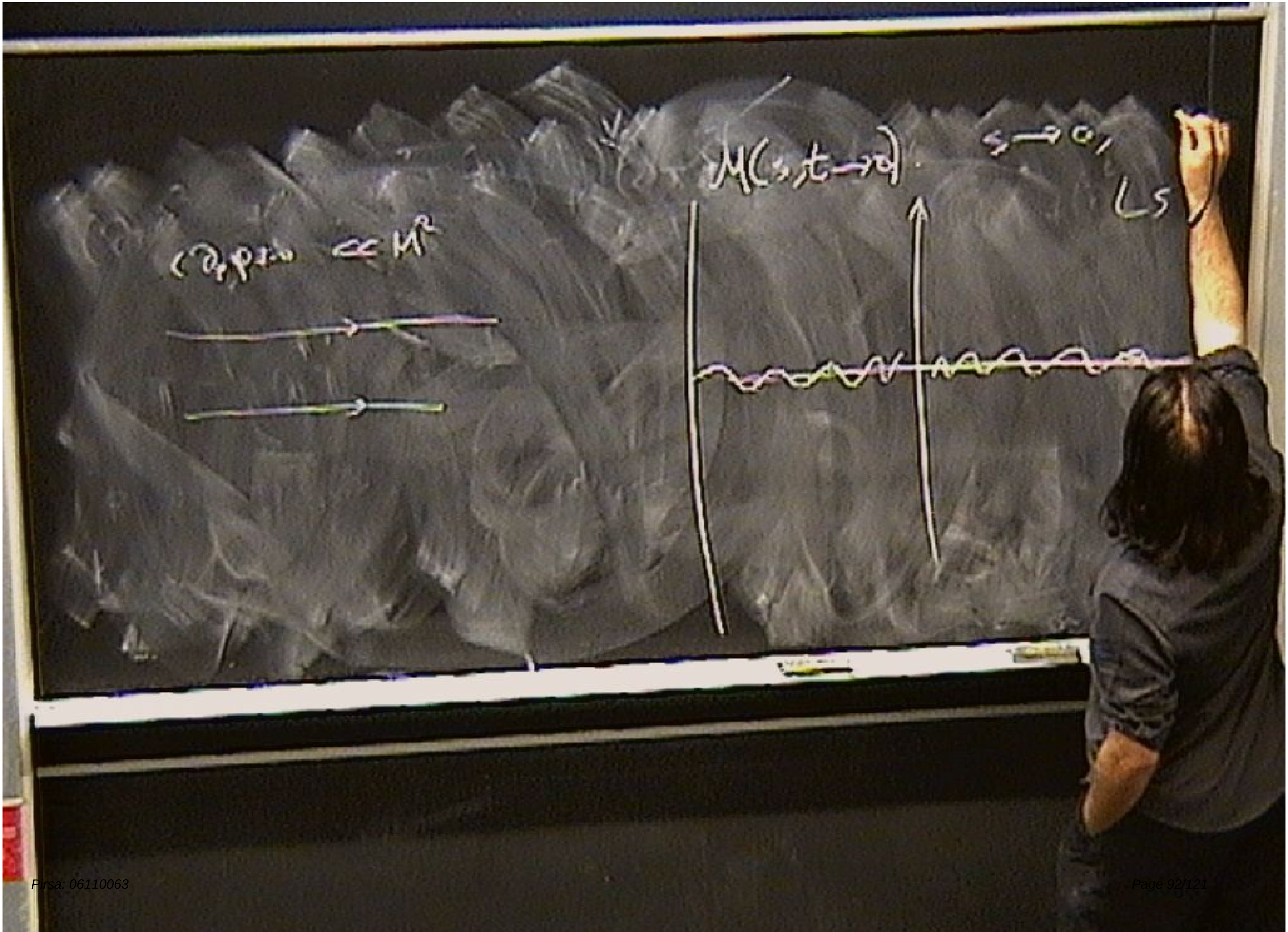
$E << M^2$
$C_{1,2,3} \geq 0$

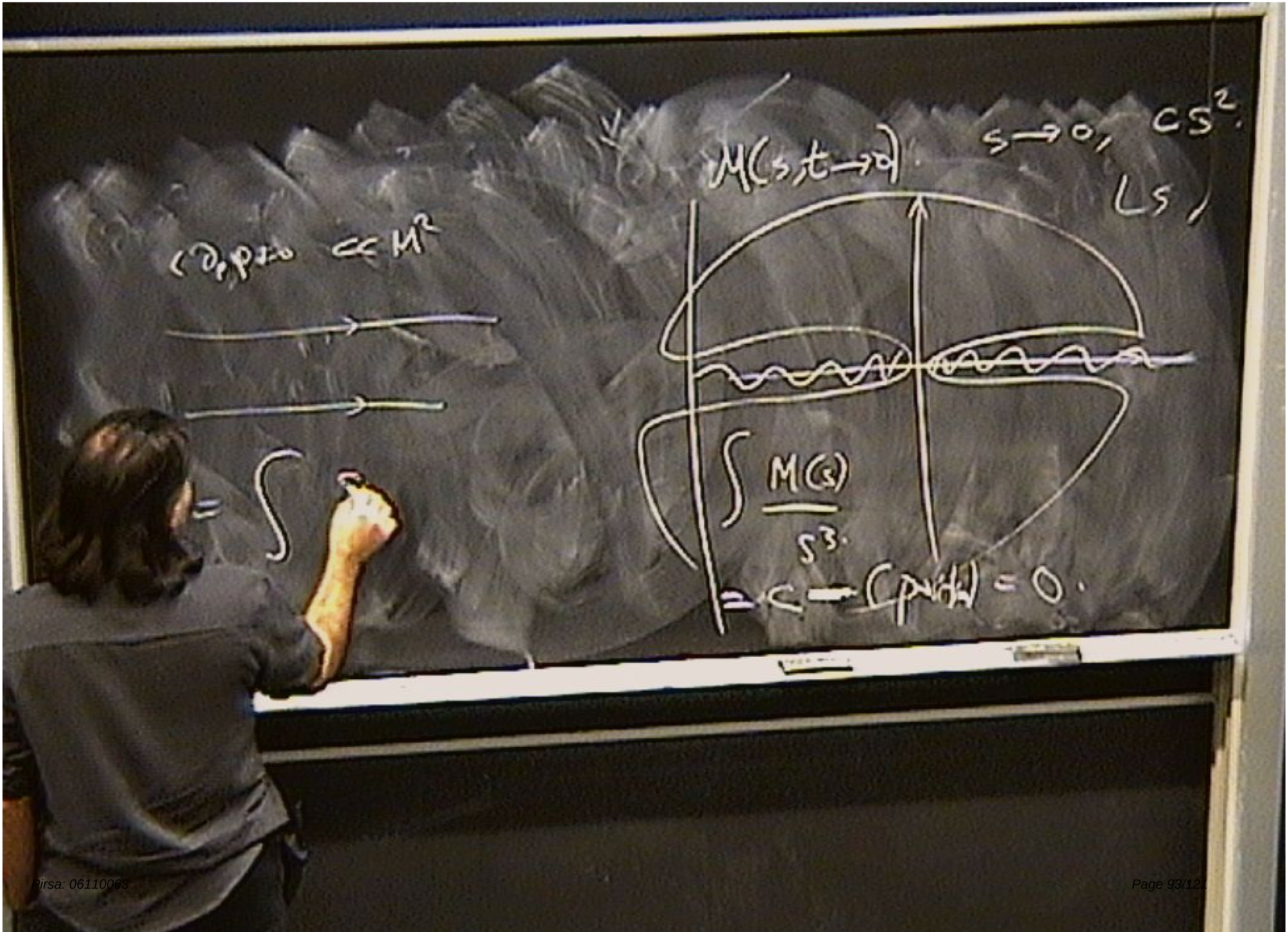
1) $(\partial\pi)^2 + \frac{(\partial\pi)^2\,\Box\pi}{\Lambda^3} + \mathcal{O}\left(\left(\frac{\partial^2\pi}{\Lambda^3}\right)^3\right).$

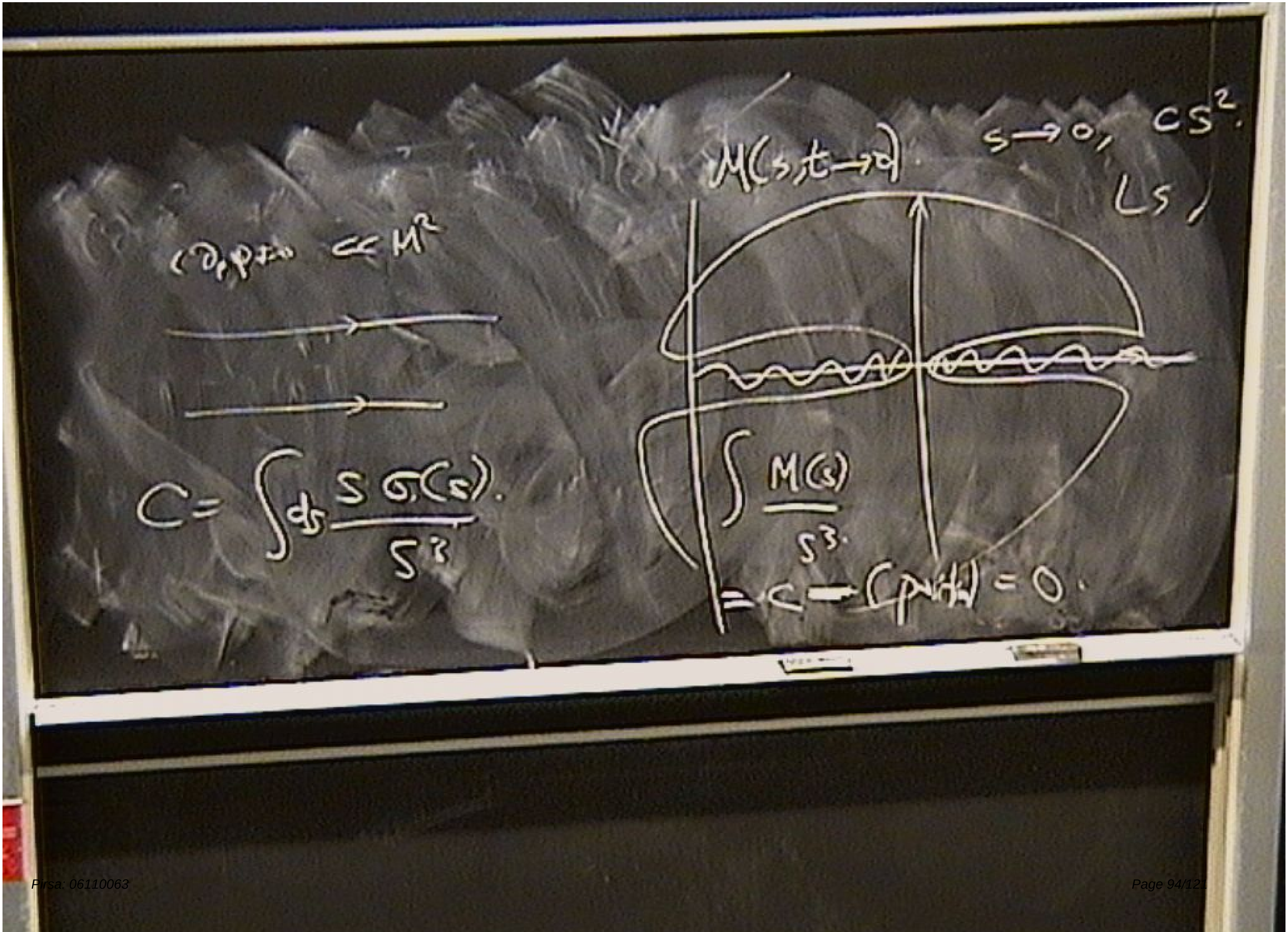
$$(\partial\pi)^2 + c_1\frac{(\partial\pi)^4}{M^4} + \cdots$$

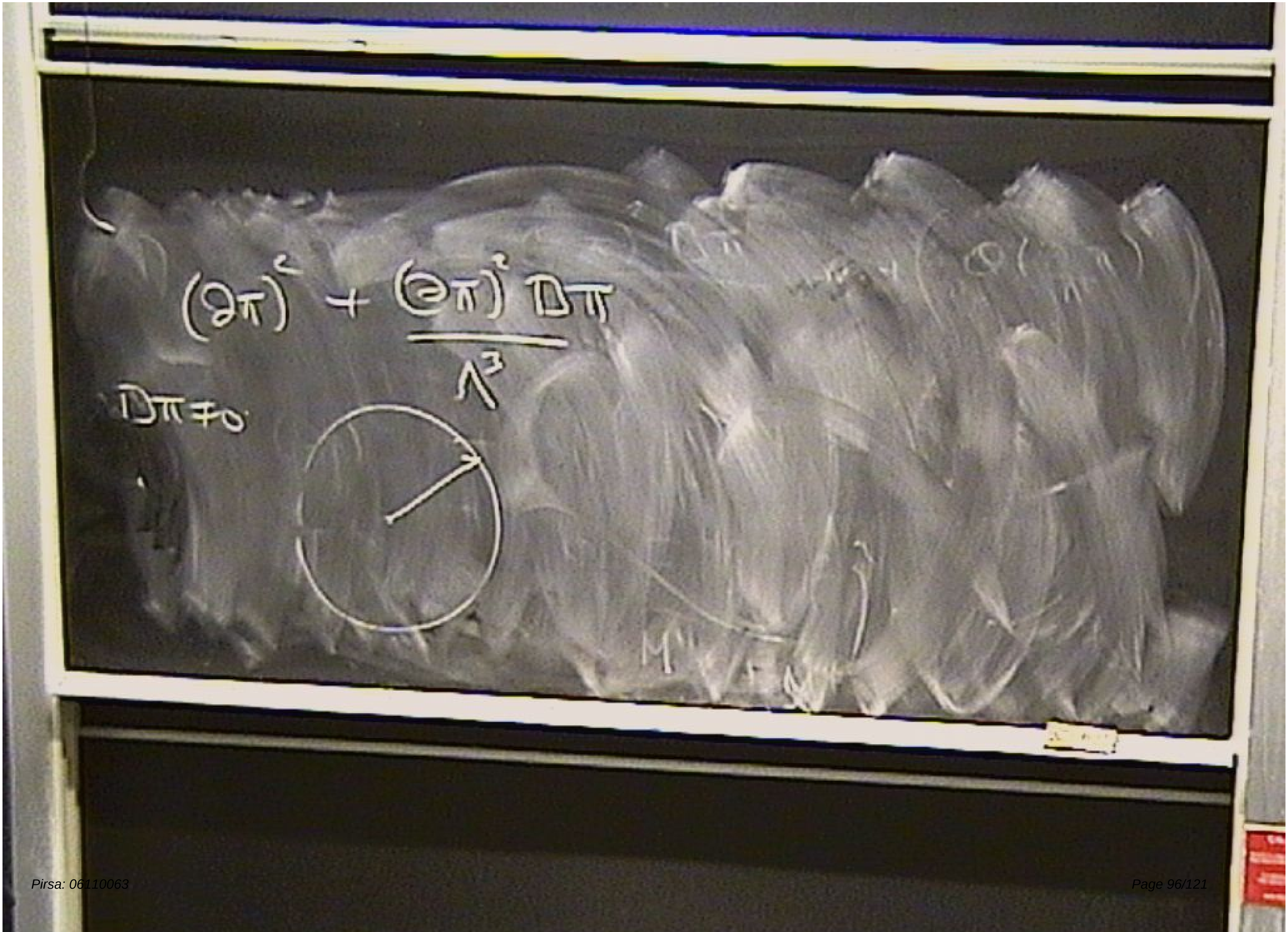
$$F^2 + c_2\frac{F^4}{M^4} + c_3\frac{(F\tilde{F})^2}{M^4} + \cdots$$

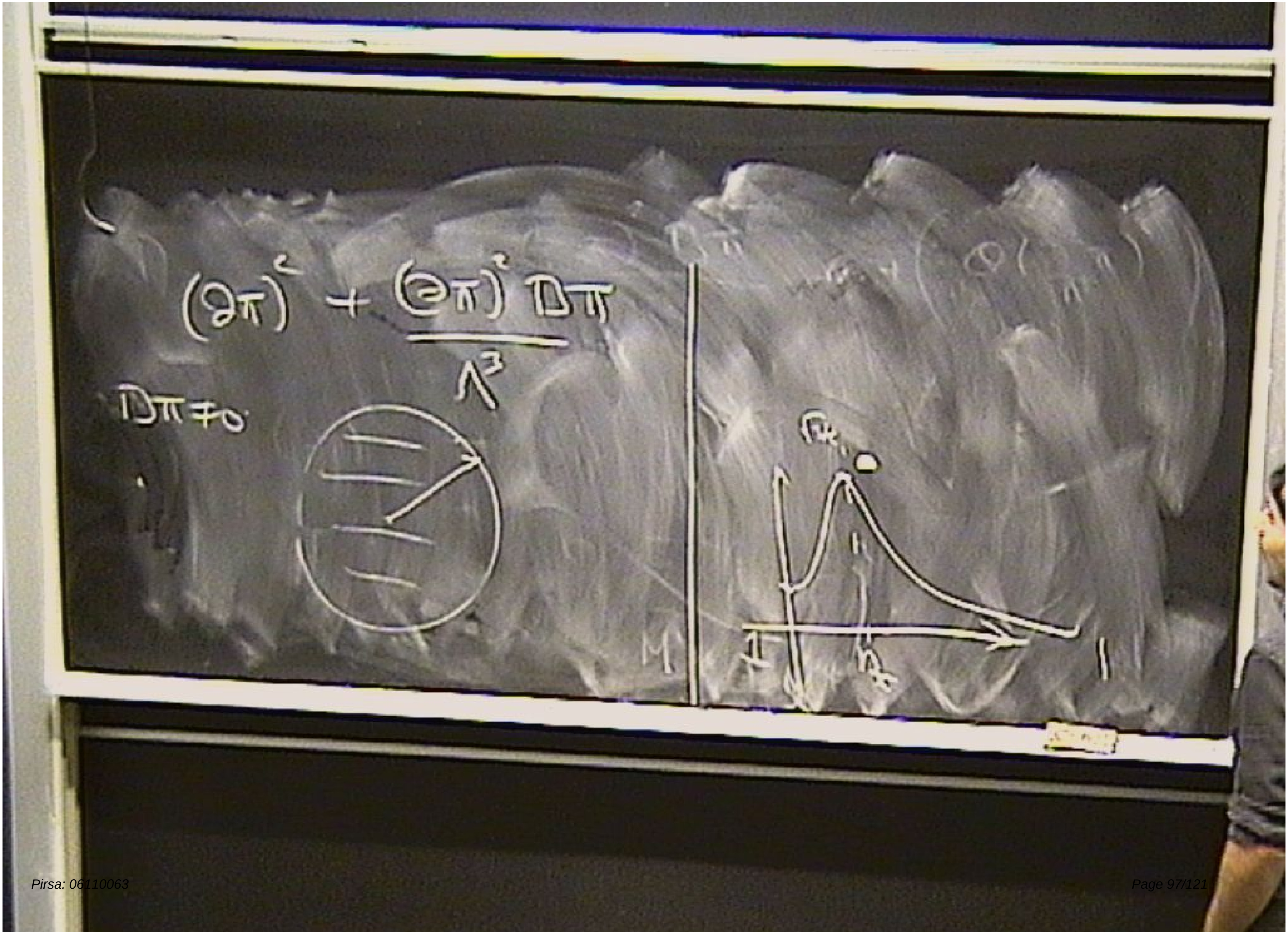

M(s,t→∞)

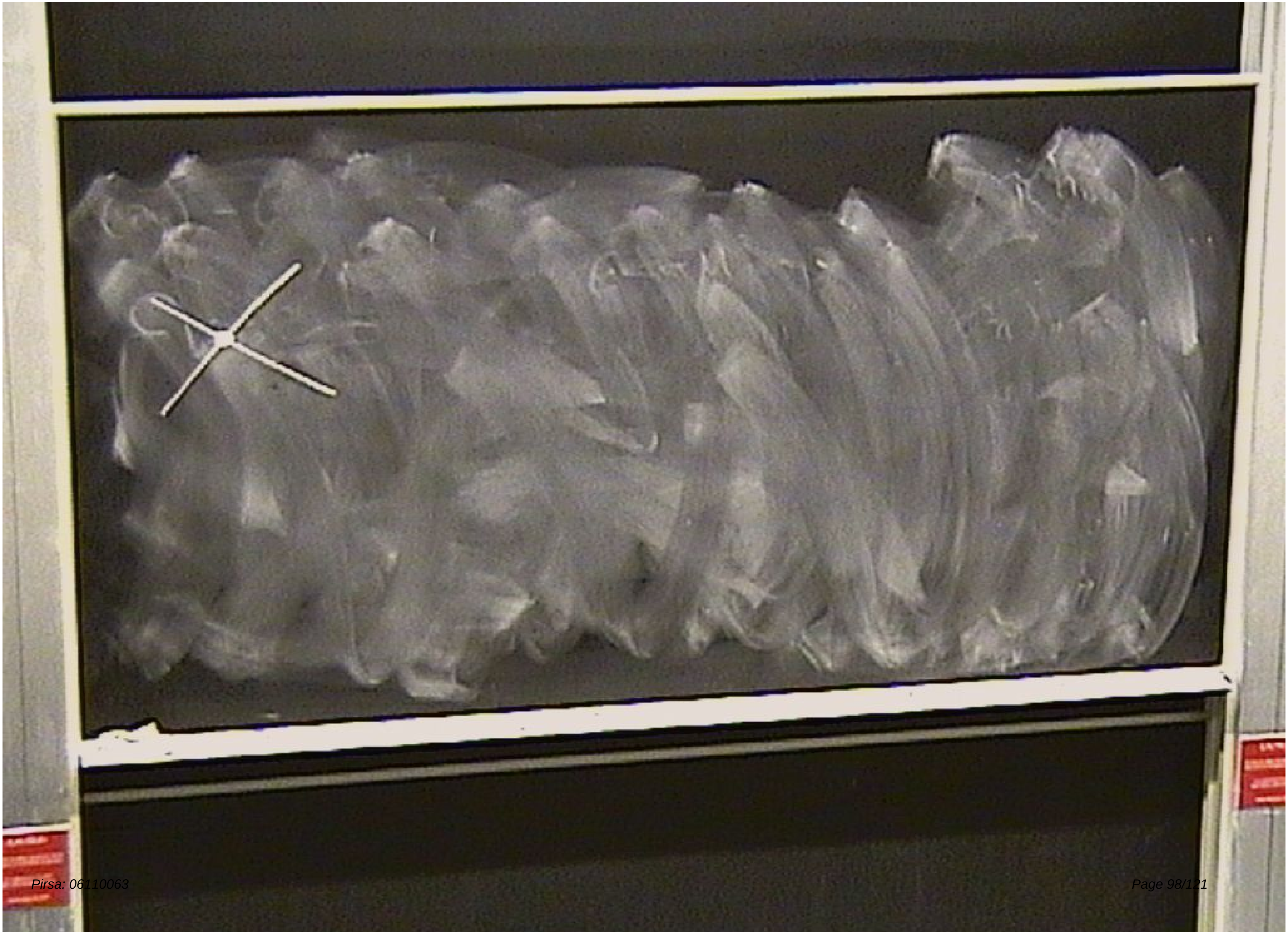

M(s,t→∞)
Ls

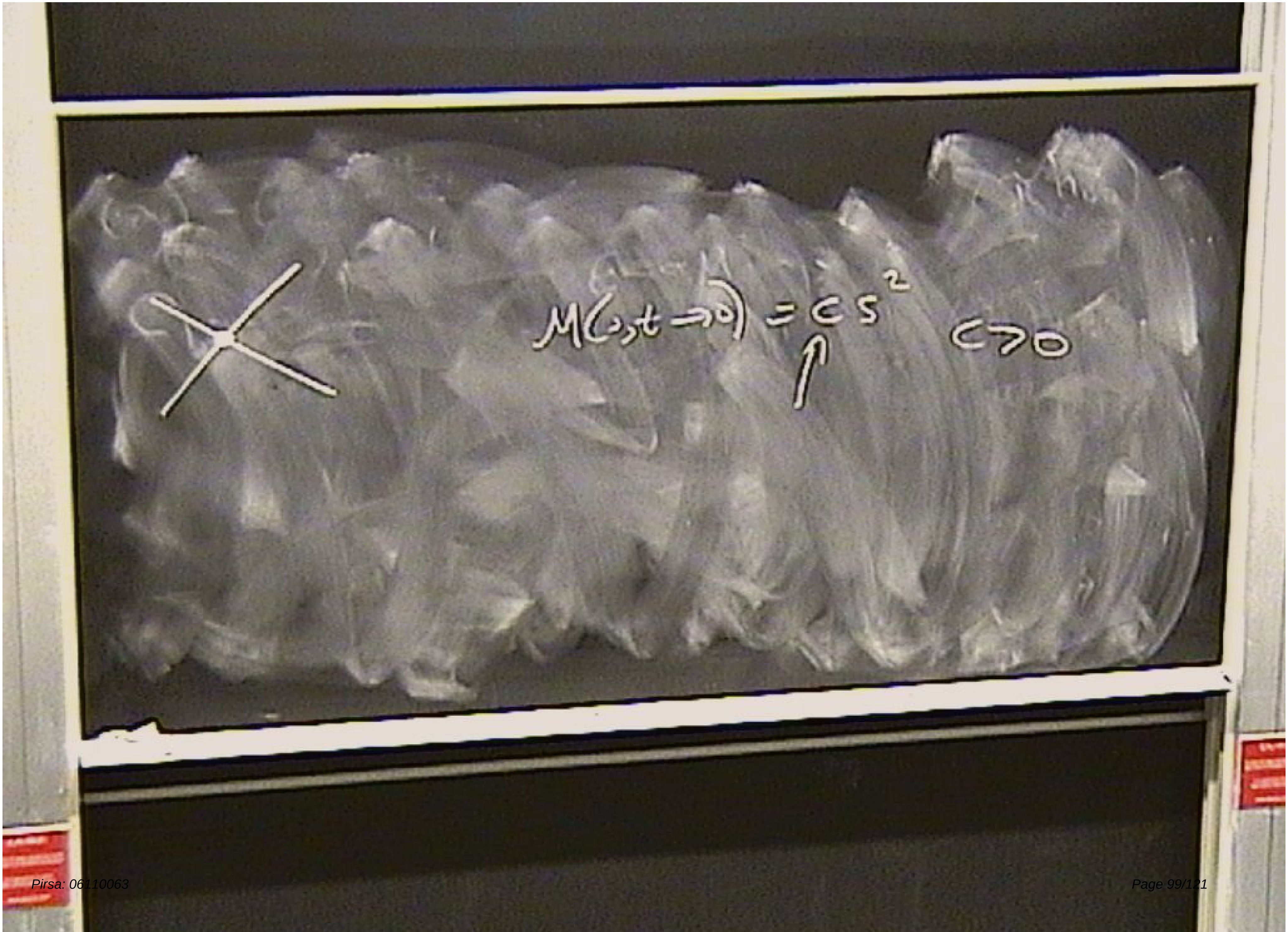


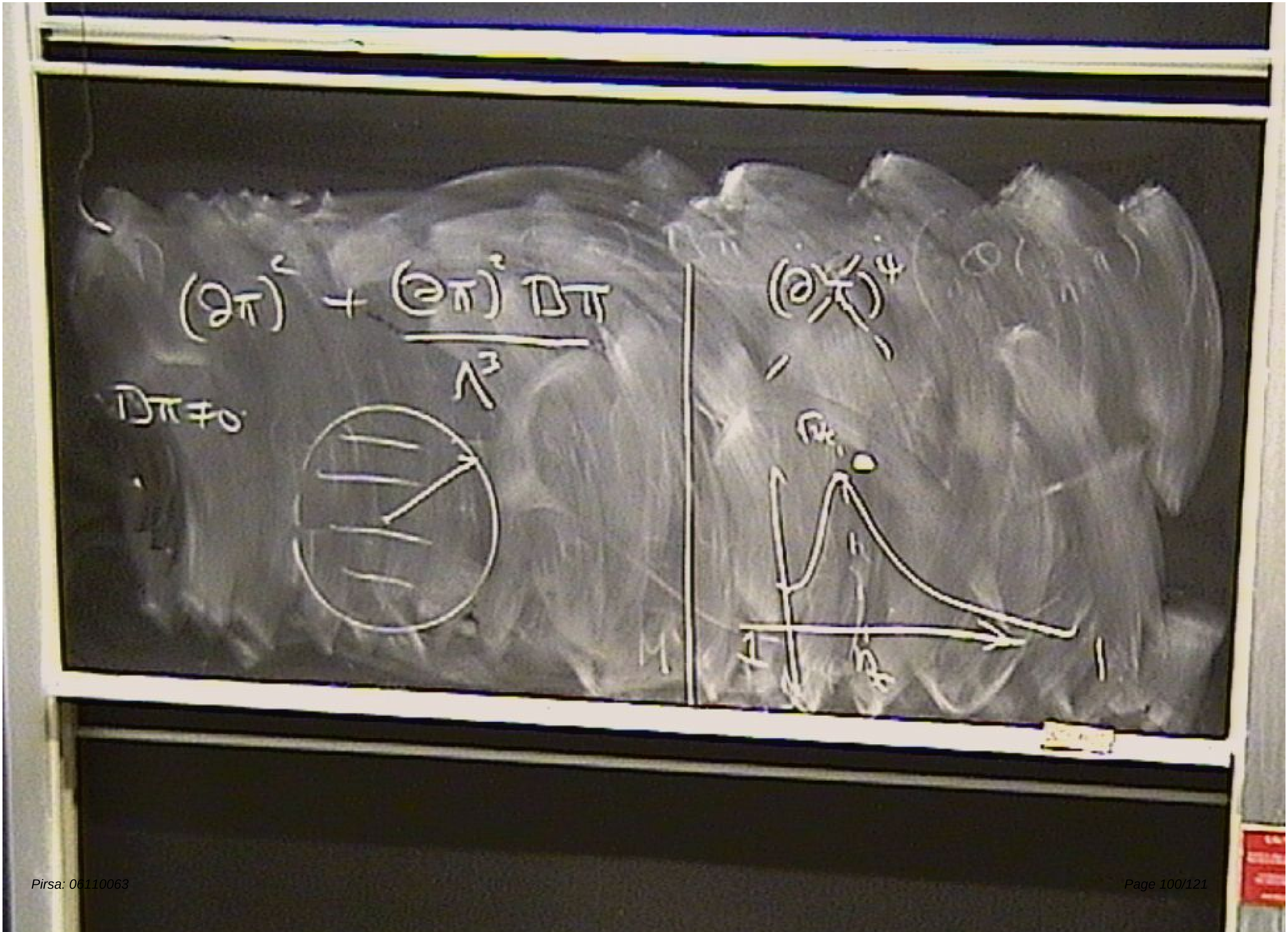

M(s, t→0)
s → 0, cs²
≪ M²
C = ∫ ds s σ(s) / s³
∫ M(s) / s³
= 0

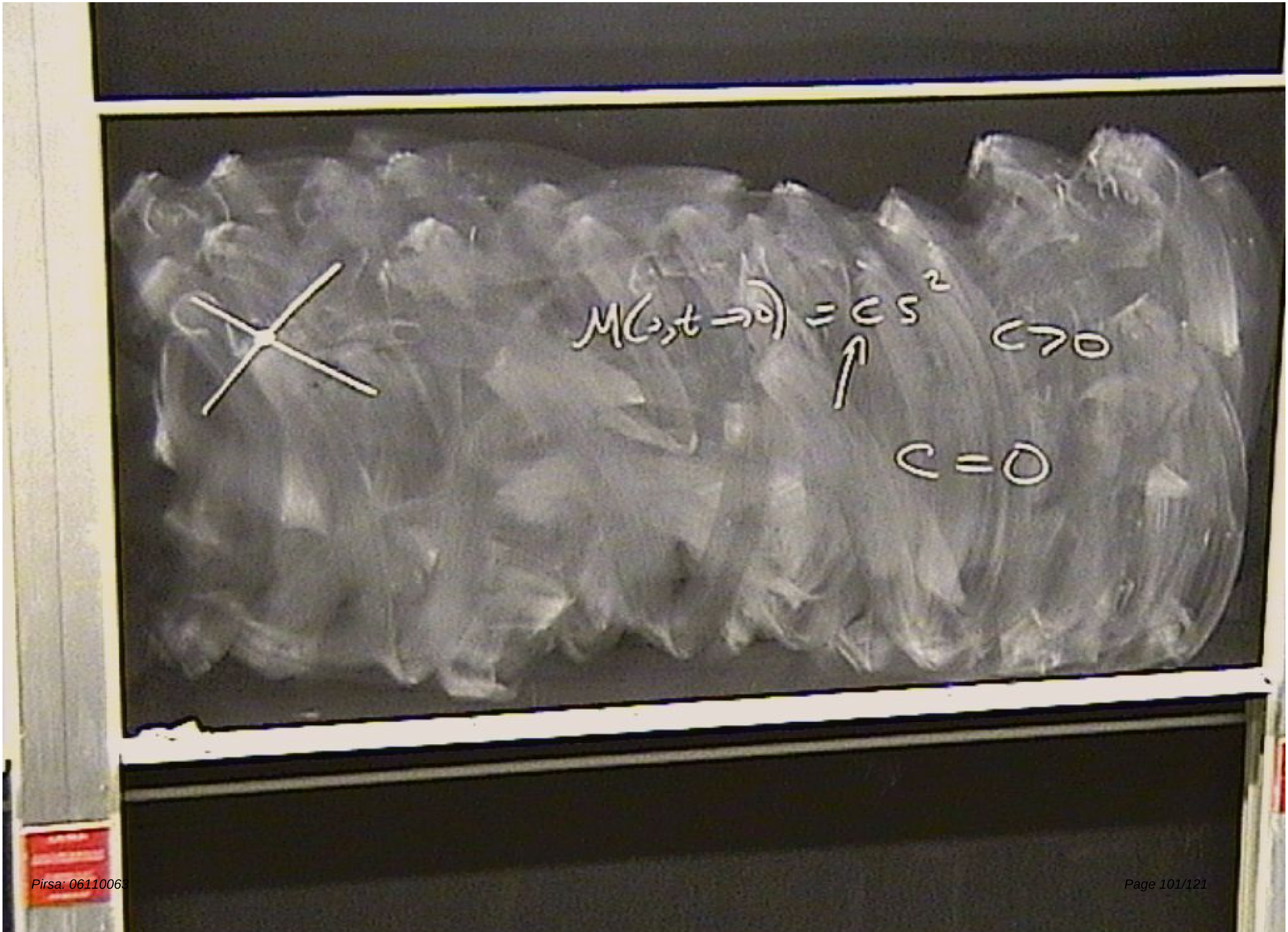

$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3}$
$\Box\pi \neq 0$

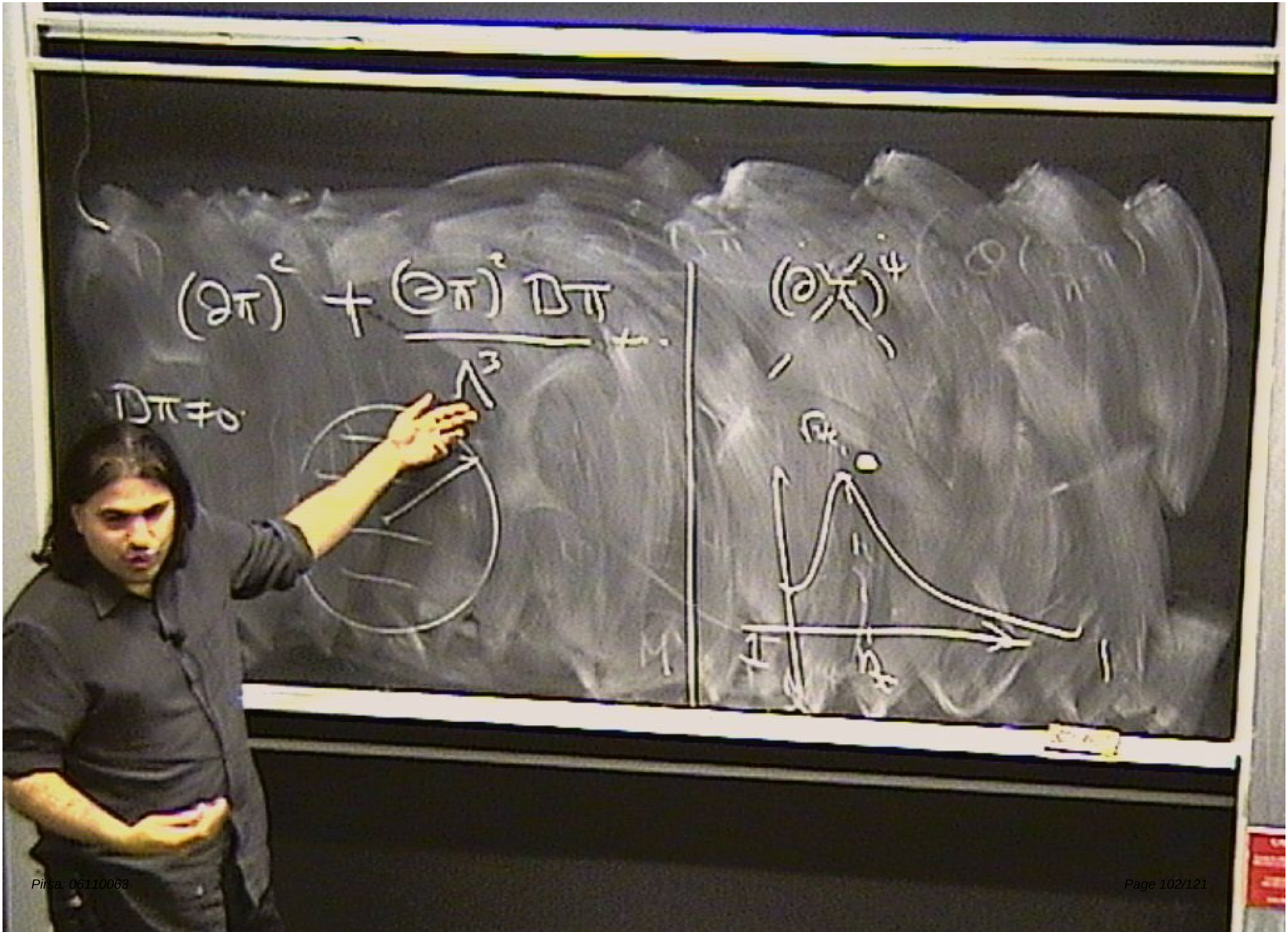

(∂π)² + (∂π)² □π / Λ³
□π ≠ 0



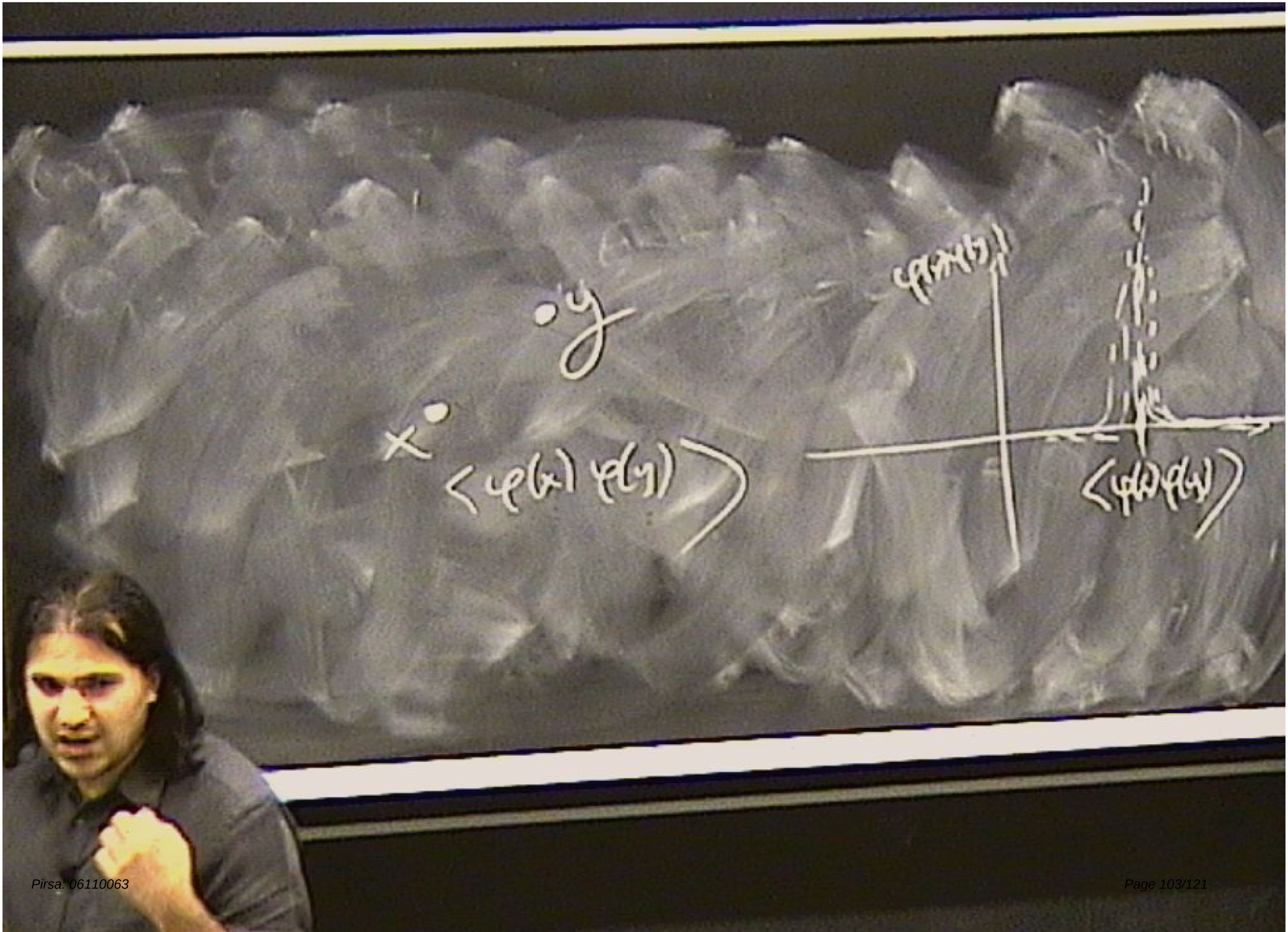

M(s,t→0) = c s²
c>0

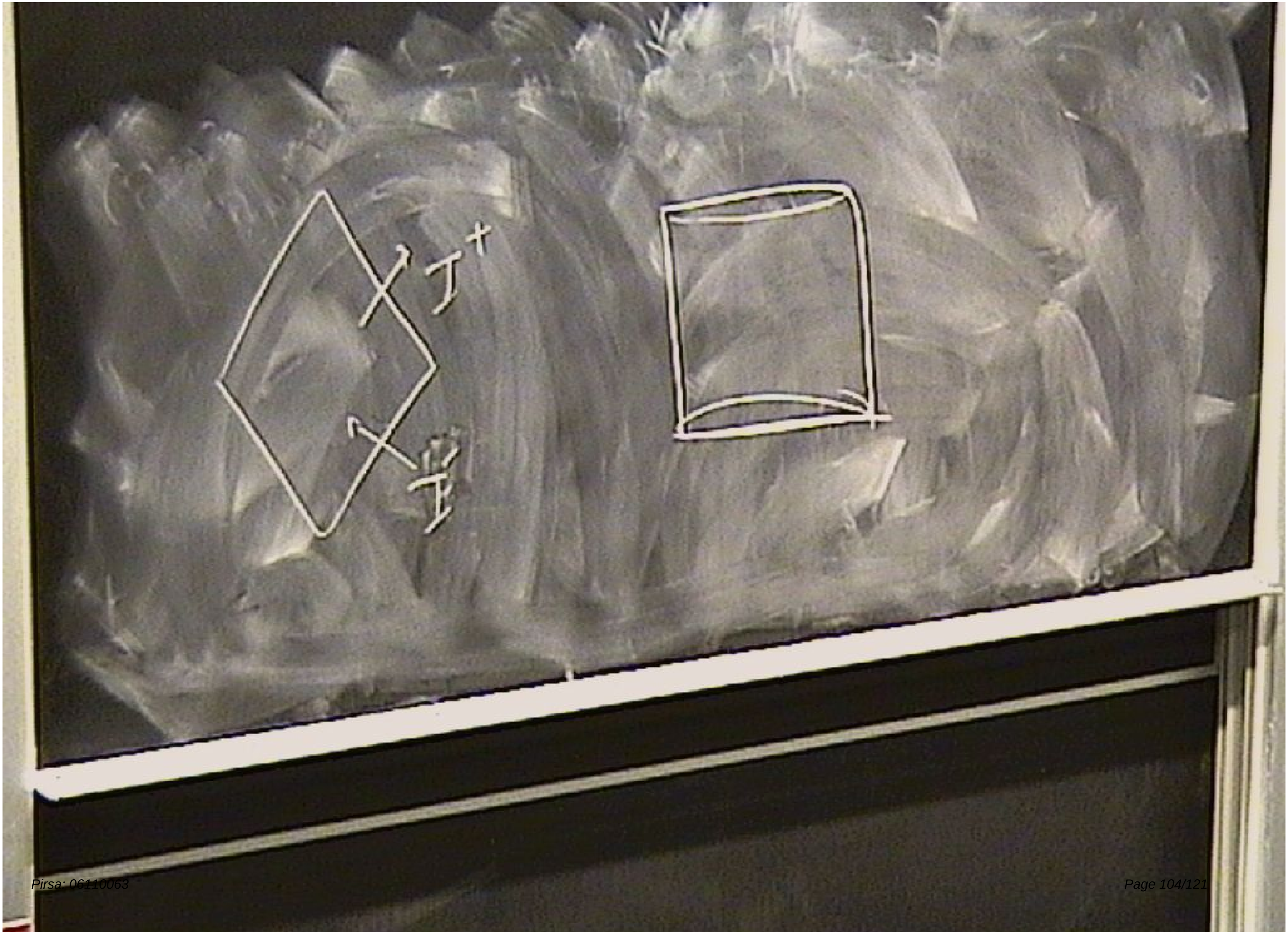

$(\partial\pi)^2 + \frac{(\partial\pi)^2 \Box\pi}{\Lambda^3}$
$\Box\pi \neq 0$
$(\partial\pi)^4$

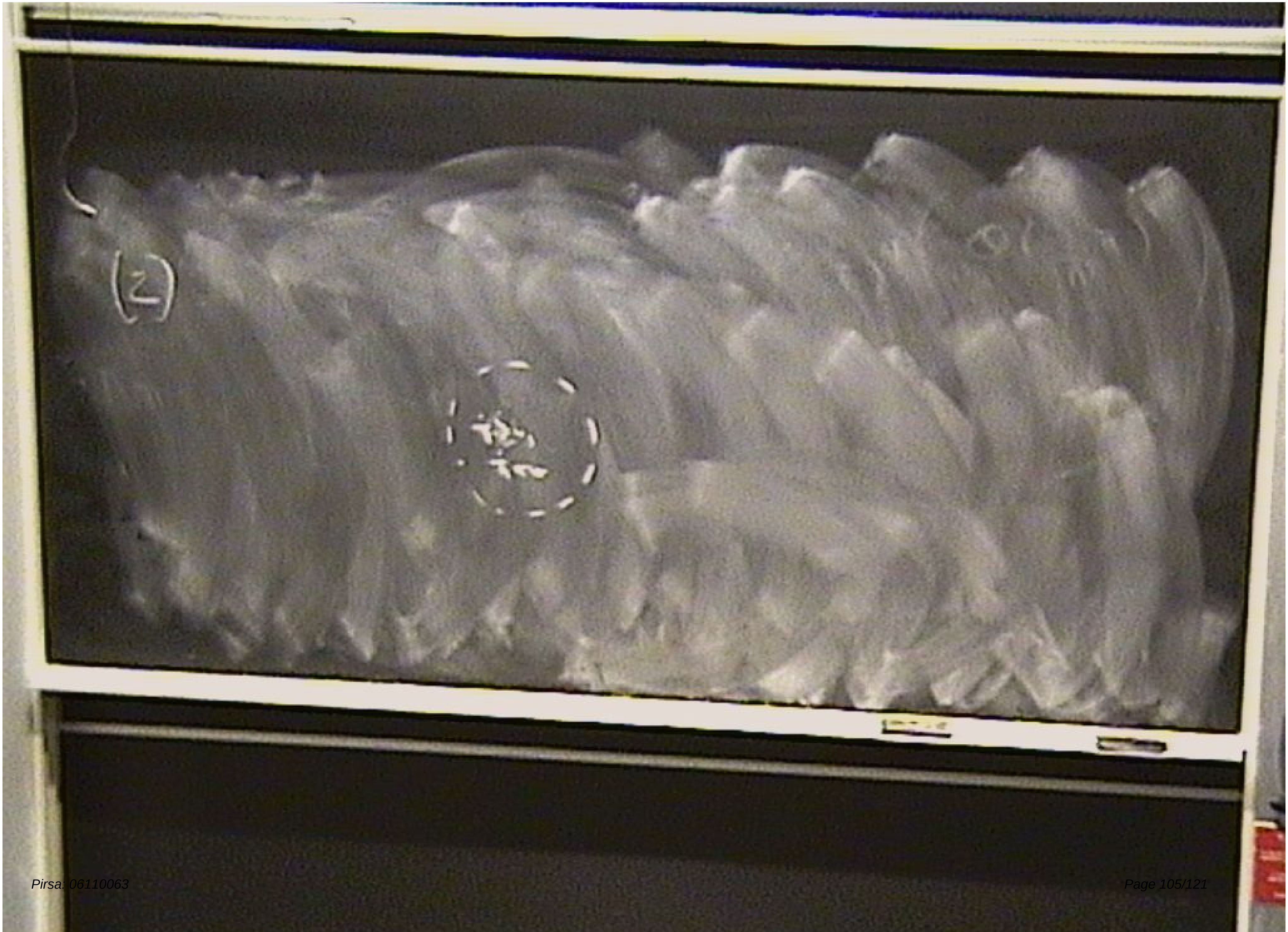

M(s,t→0) = c s²
c>0
c=0

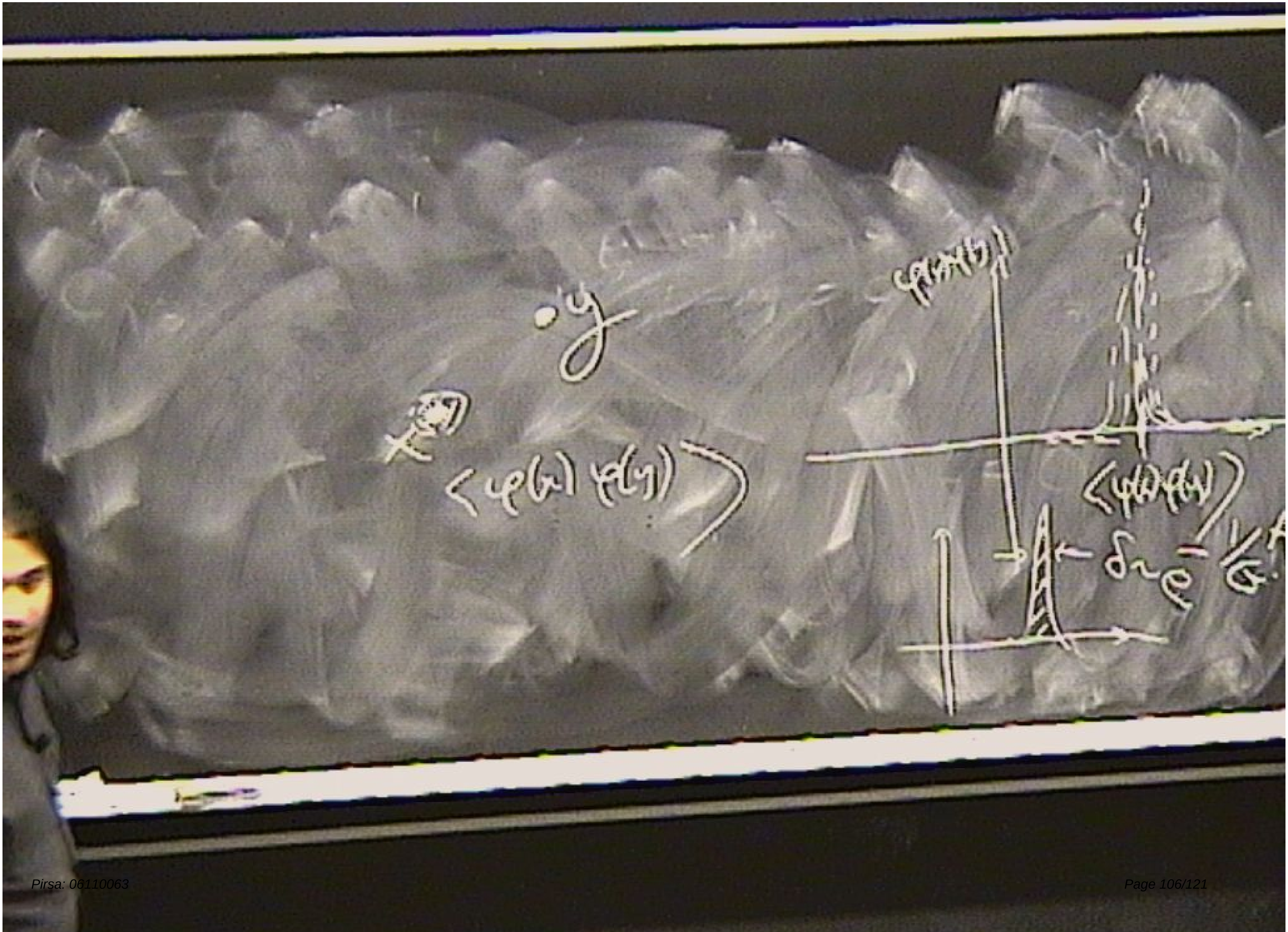


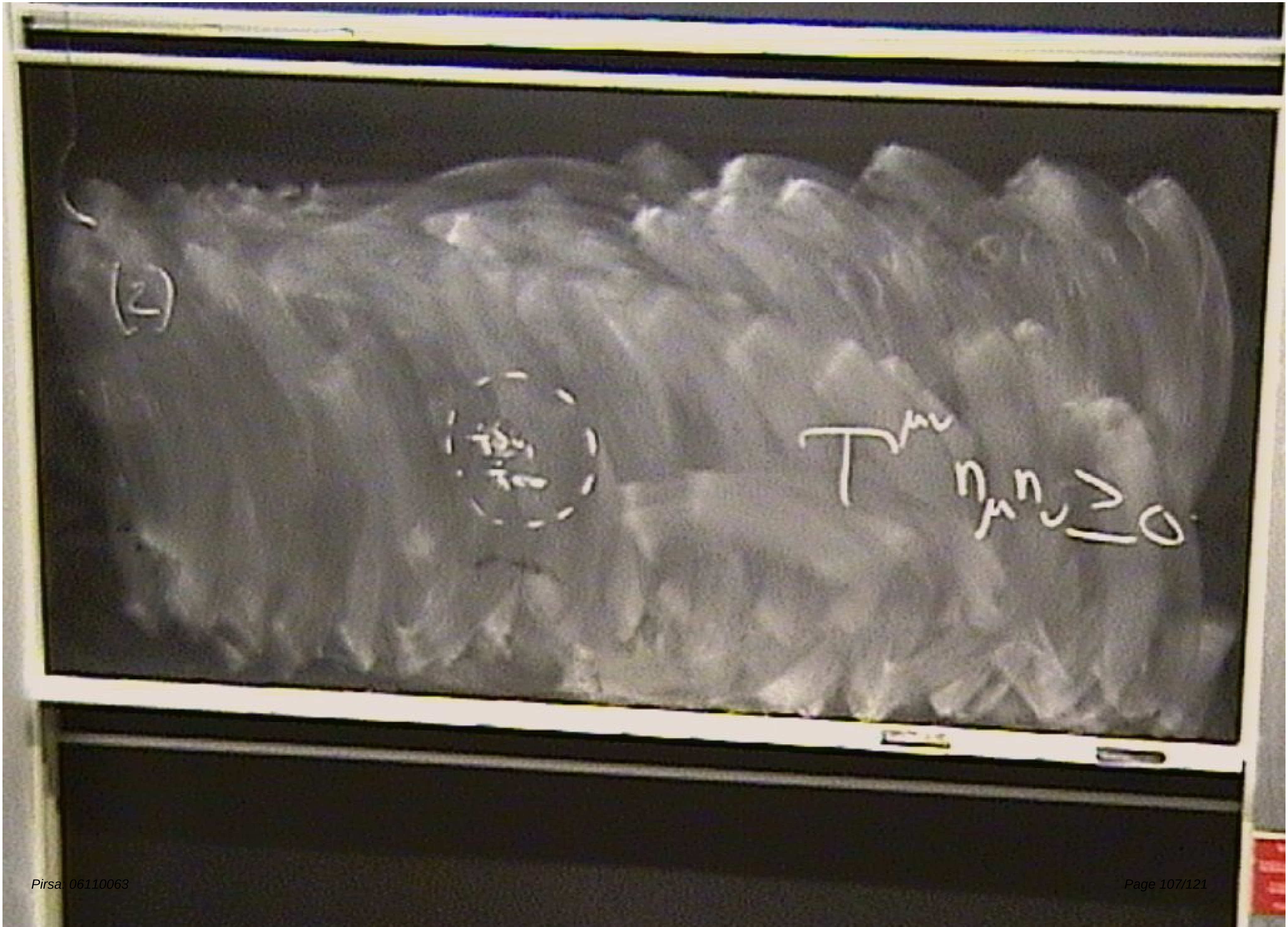
(∂π)² + (∂π)² □π / Λ³ + …
□π ≠ 0
(∂X)⁴

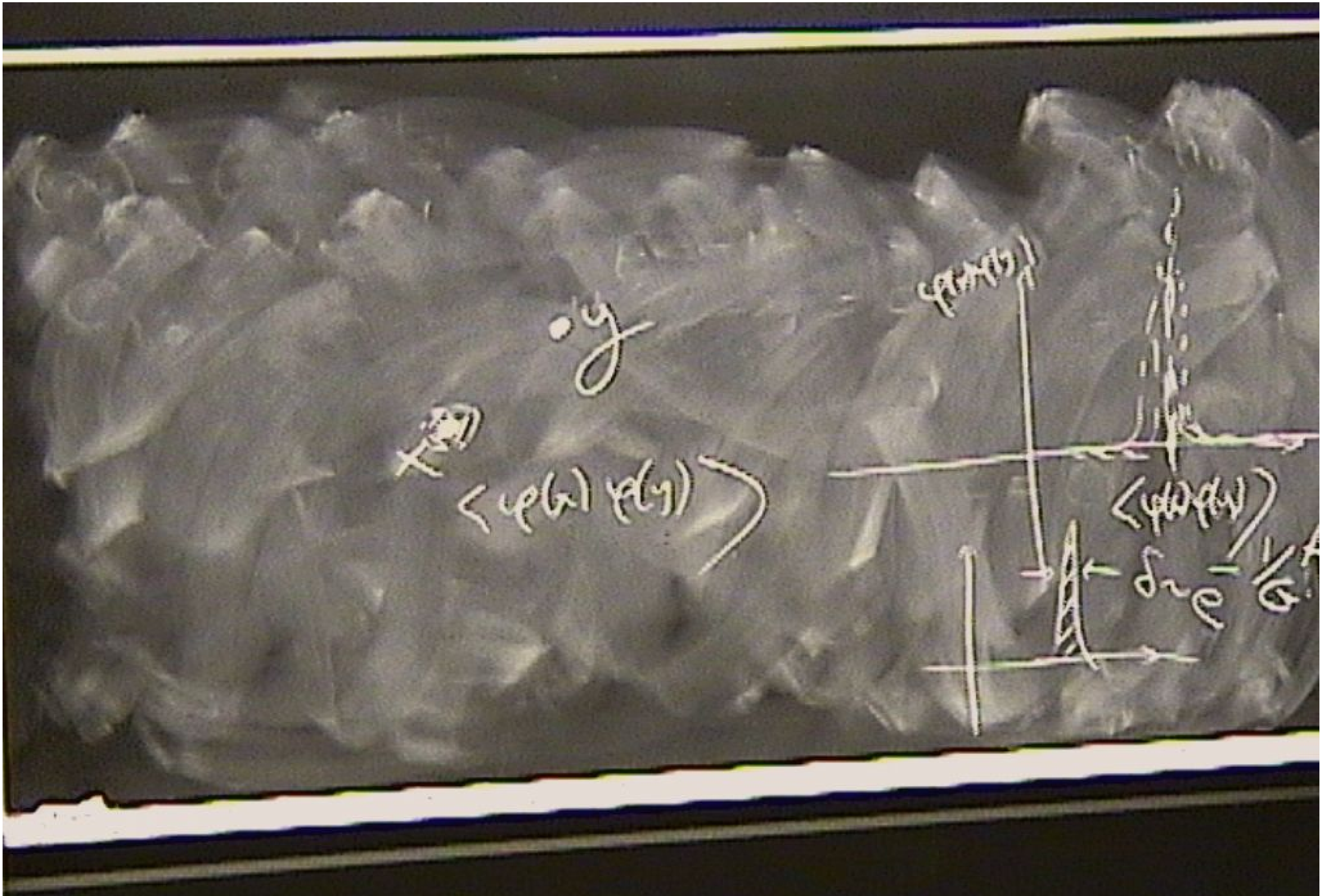

y
x
< φ(x) φ(y) >


$\mathcal{I}^+$

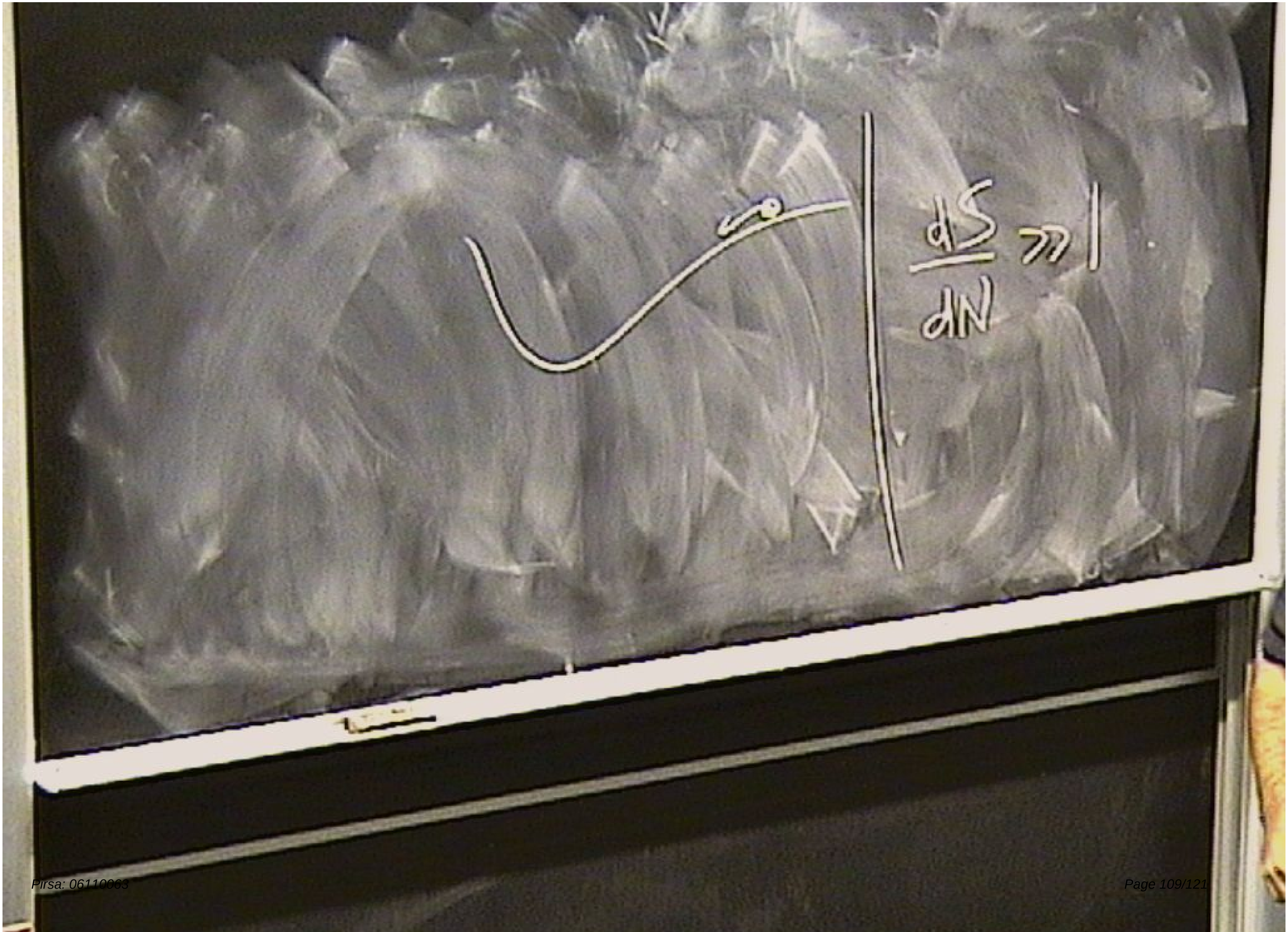

(2)

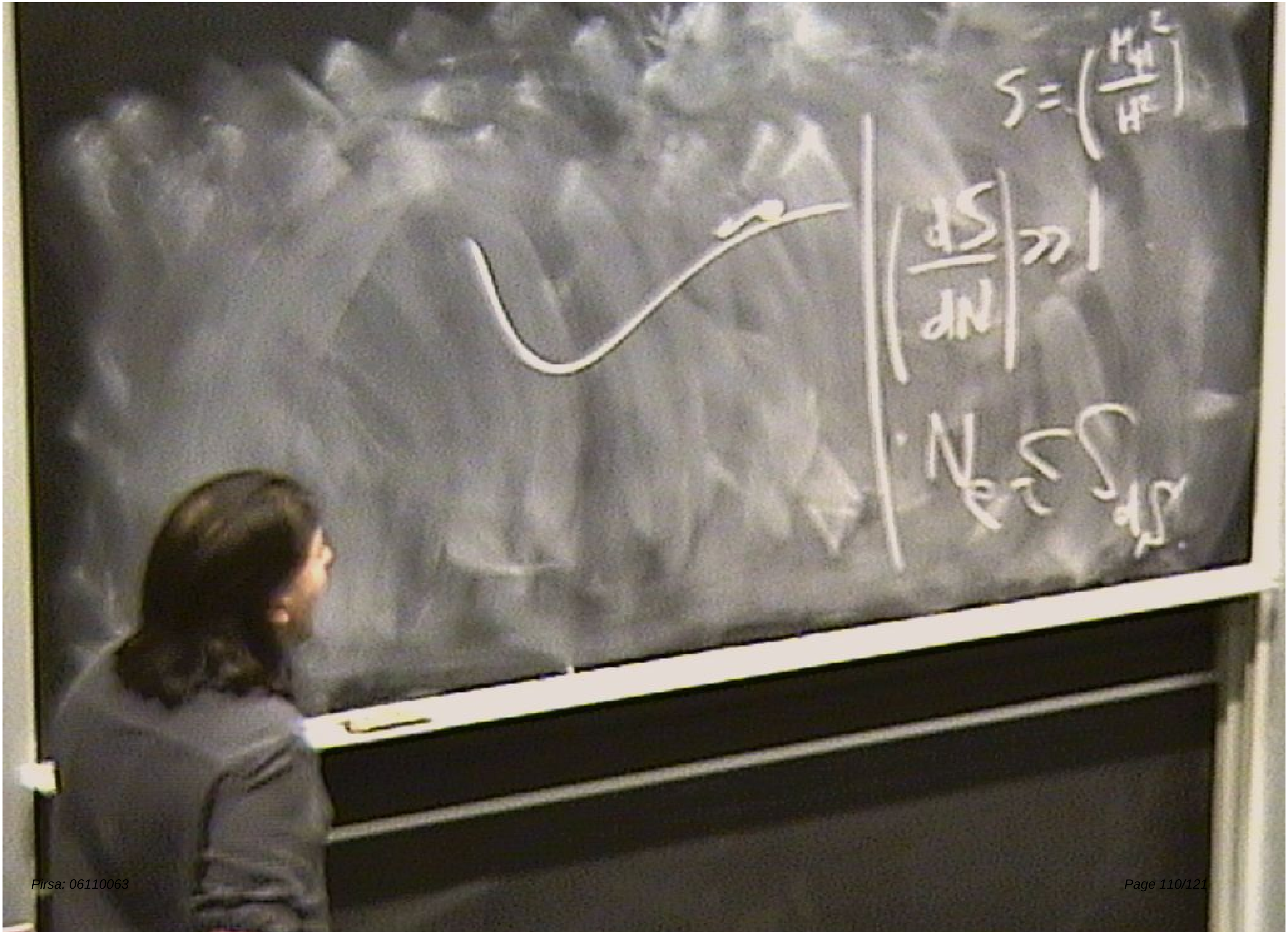


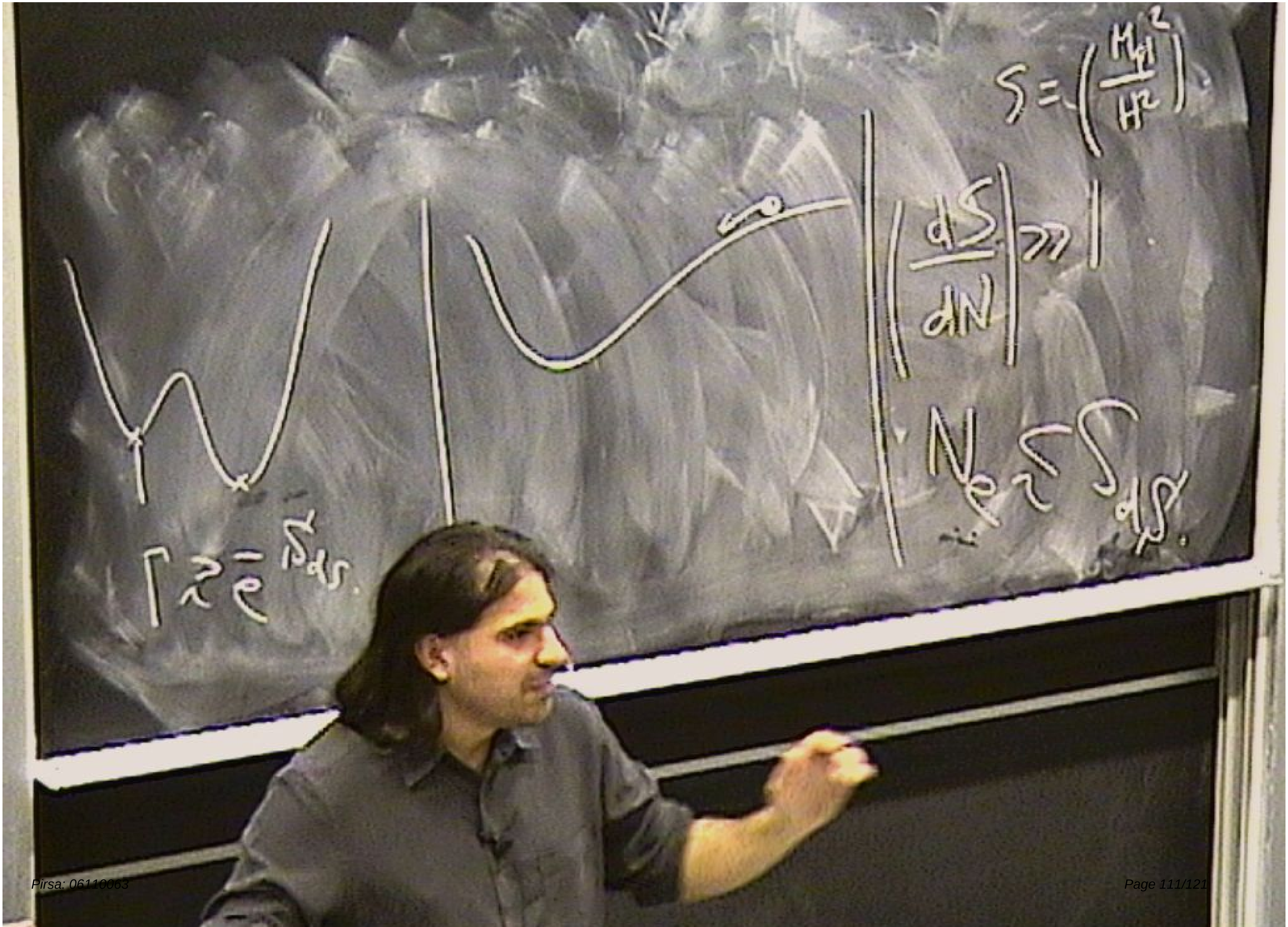

(2)
$T^{\mu\nu} n_\mu n_\nu \geq 0$

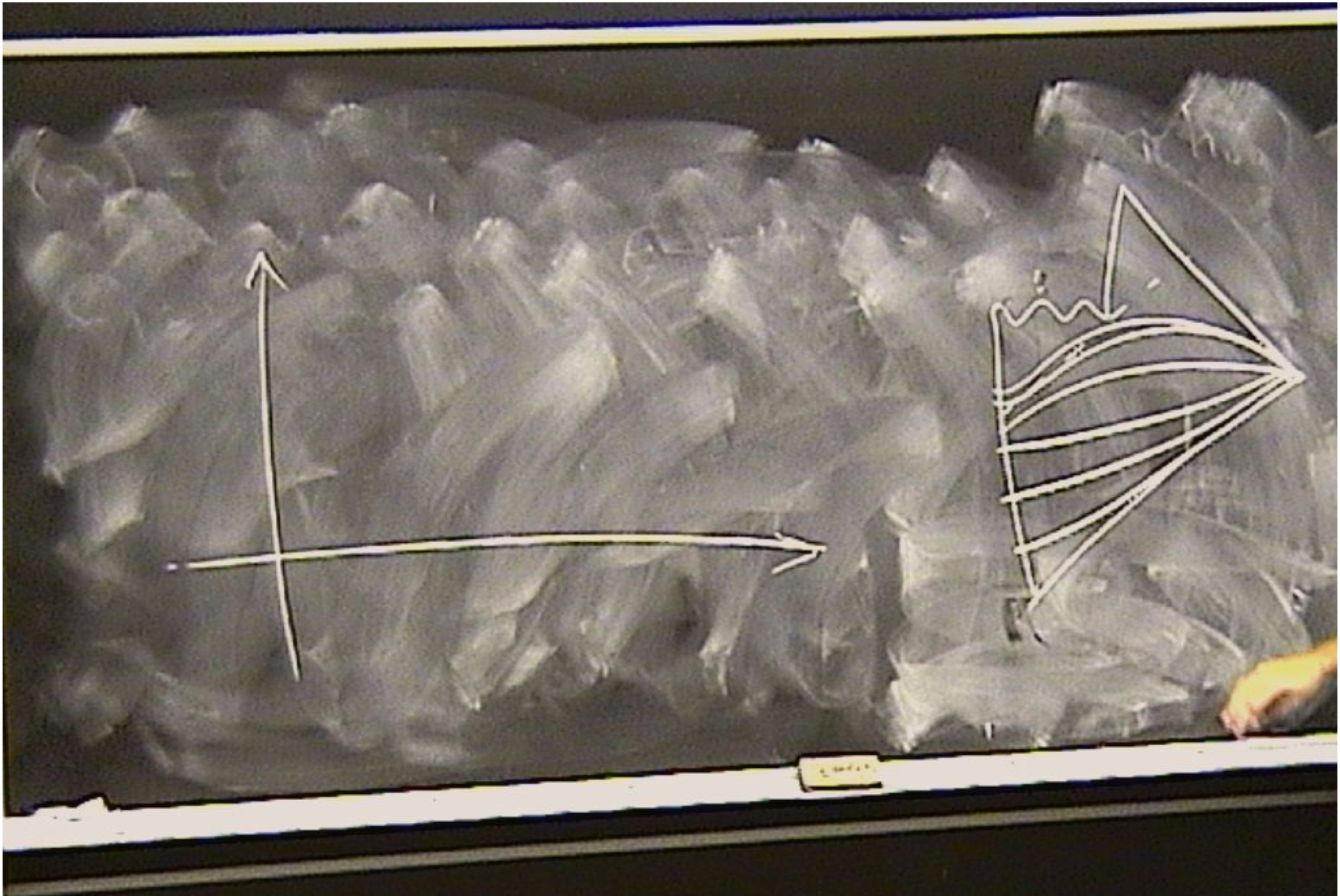


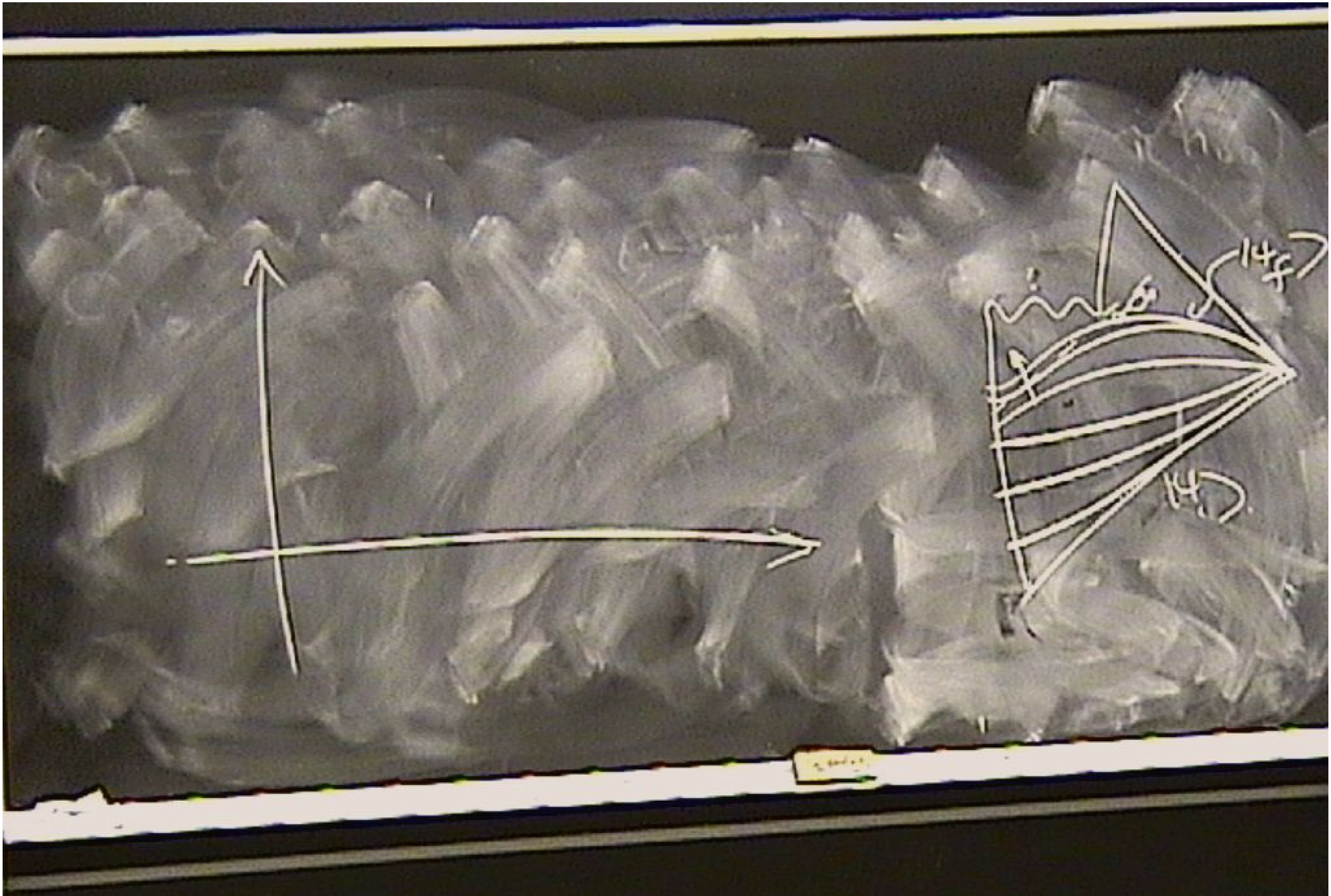
y
x
⟨φ(x) φ(y)⟩
⟨φ(x)φ(y)⟩
δ ~ e

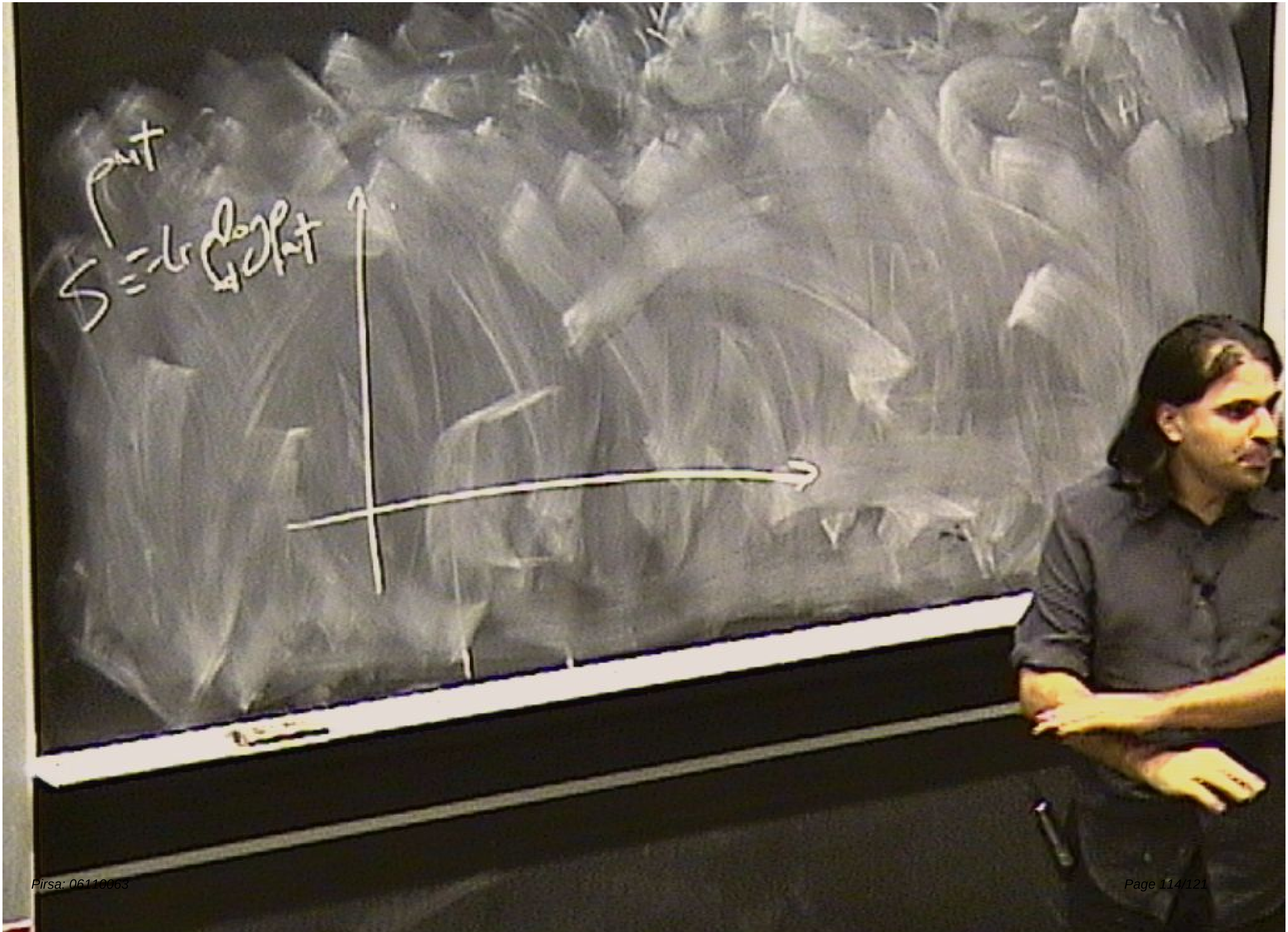

$\frac{dS}{dN} \gg 1$

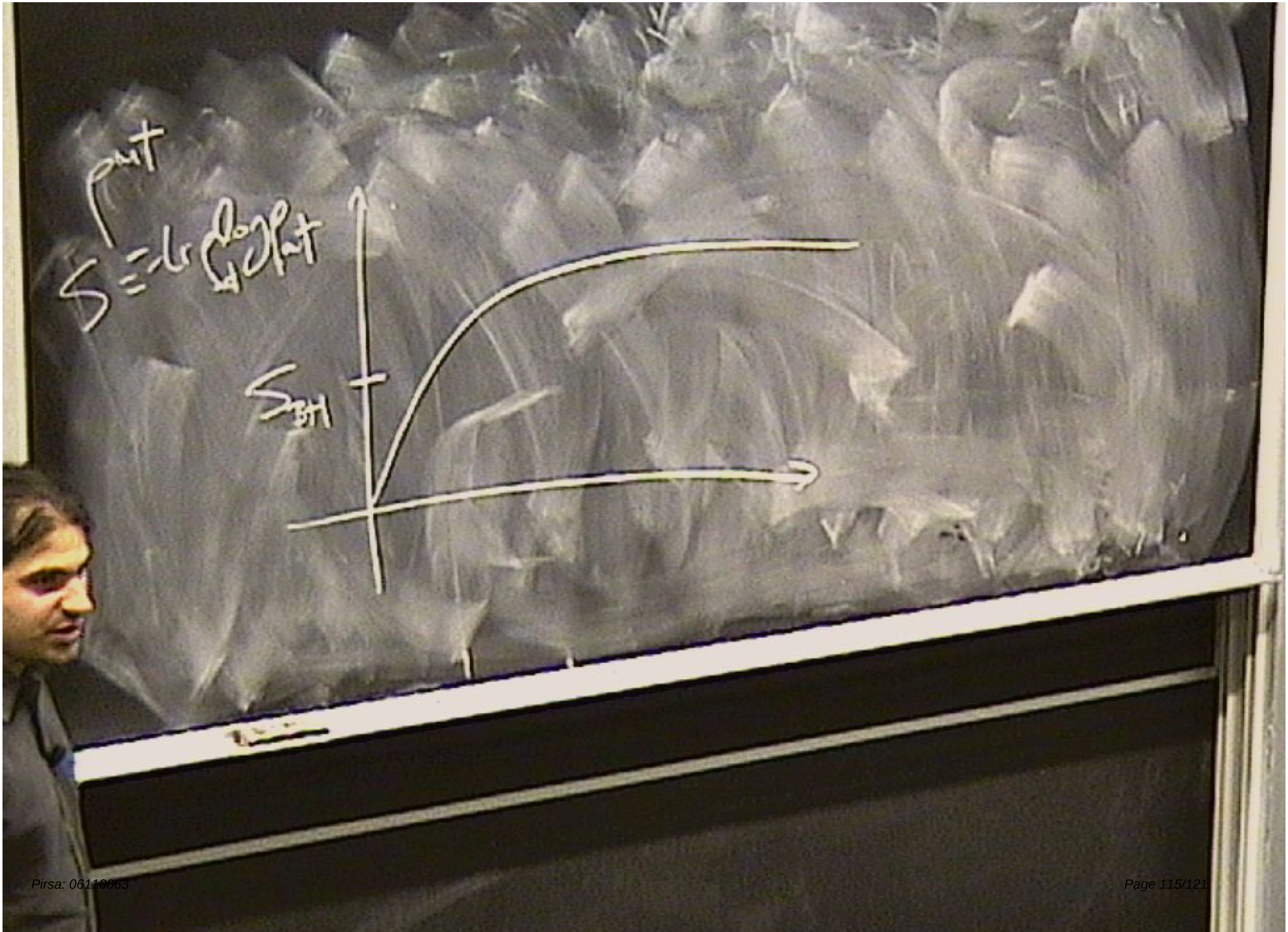

S = (Mpl^2 / H^2)
|dS/dN| >> 1
N_e ≲ S_dS

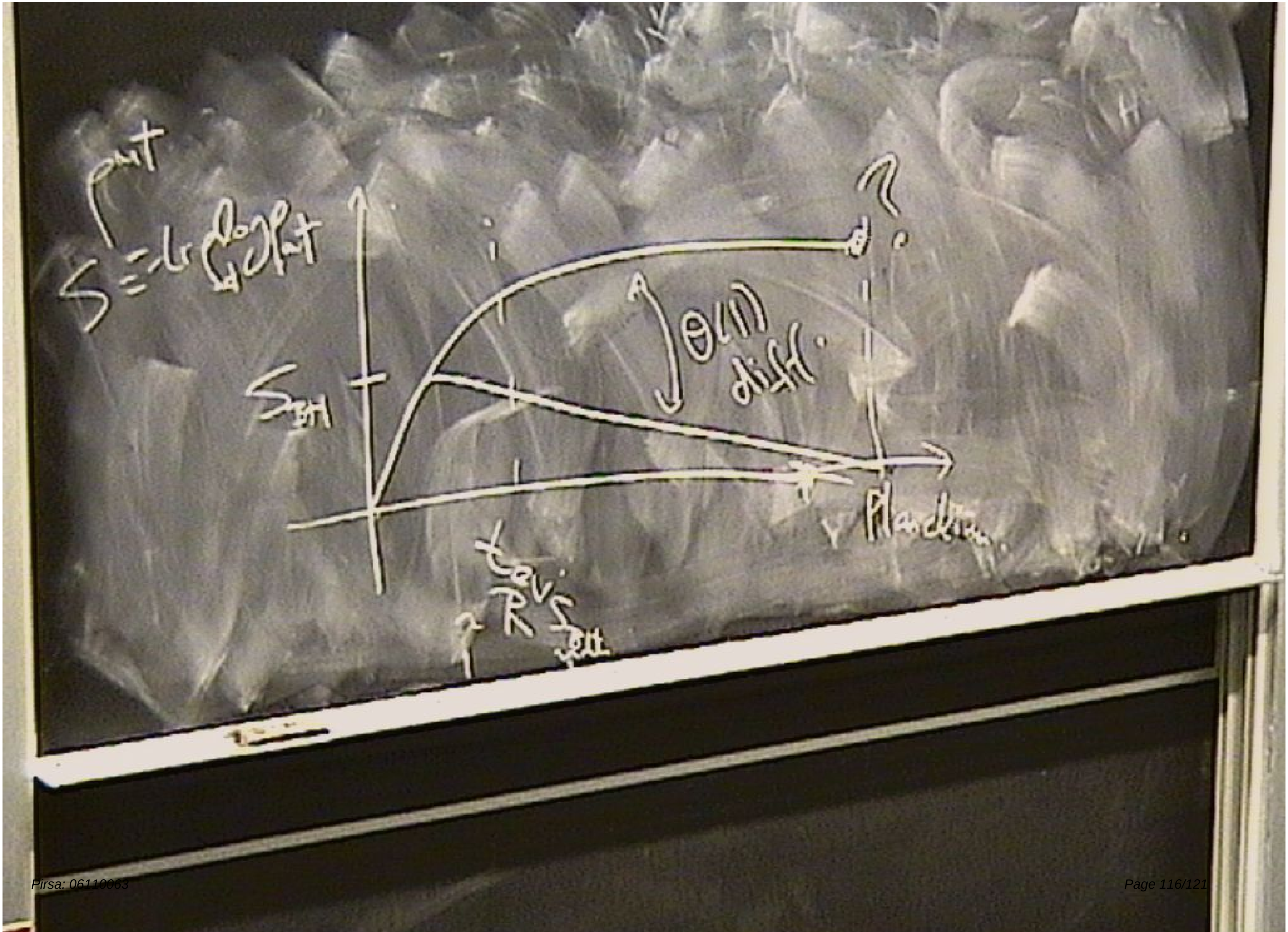

S = (M_pl^2 / H^2)
|dS/dN| >> 1
N_e ≲ S_dS
Γ ~ e^{-S_dS}

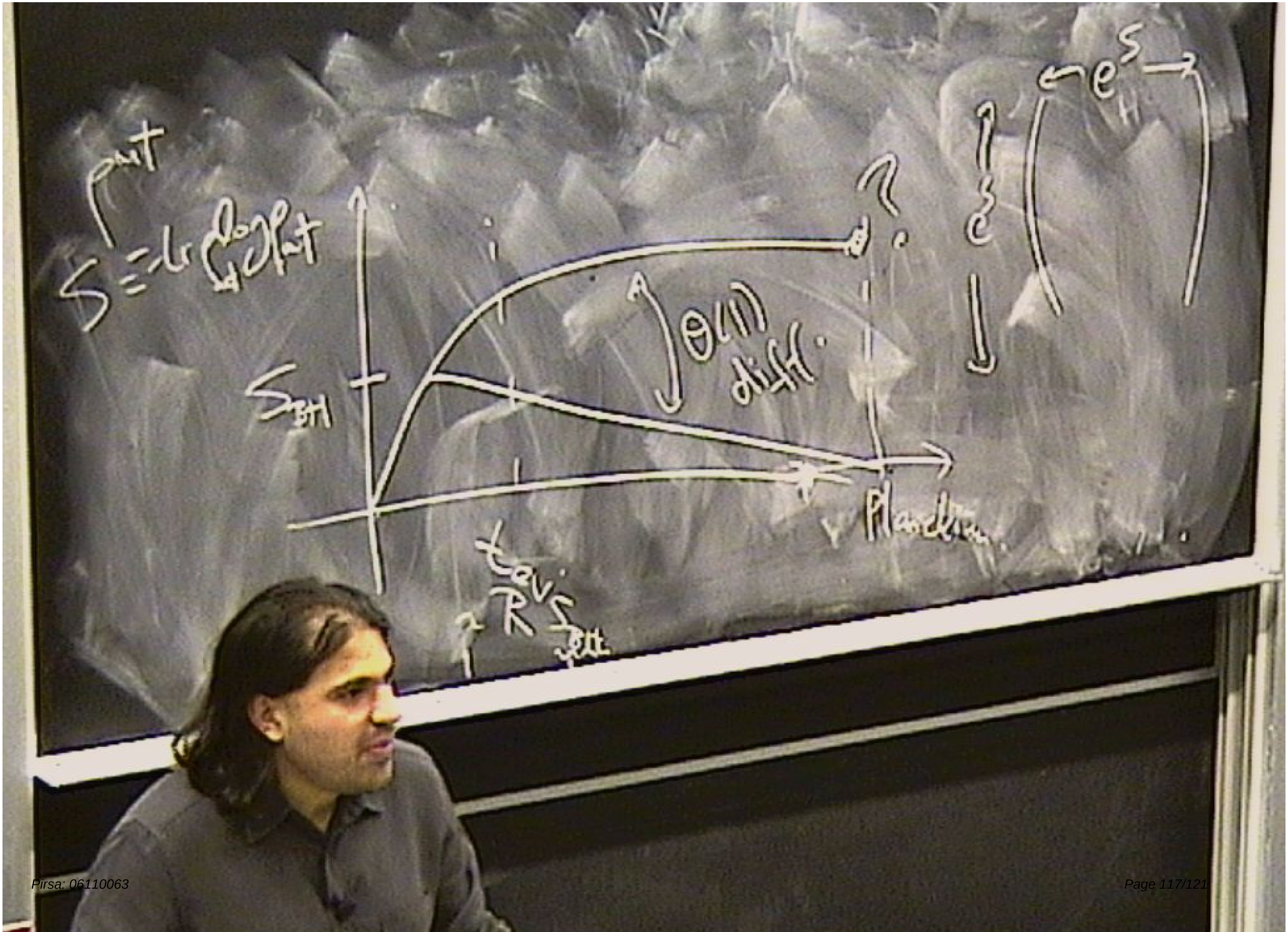




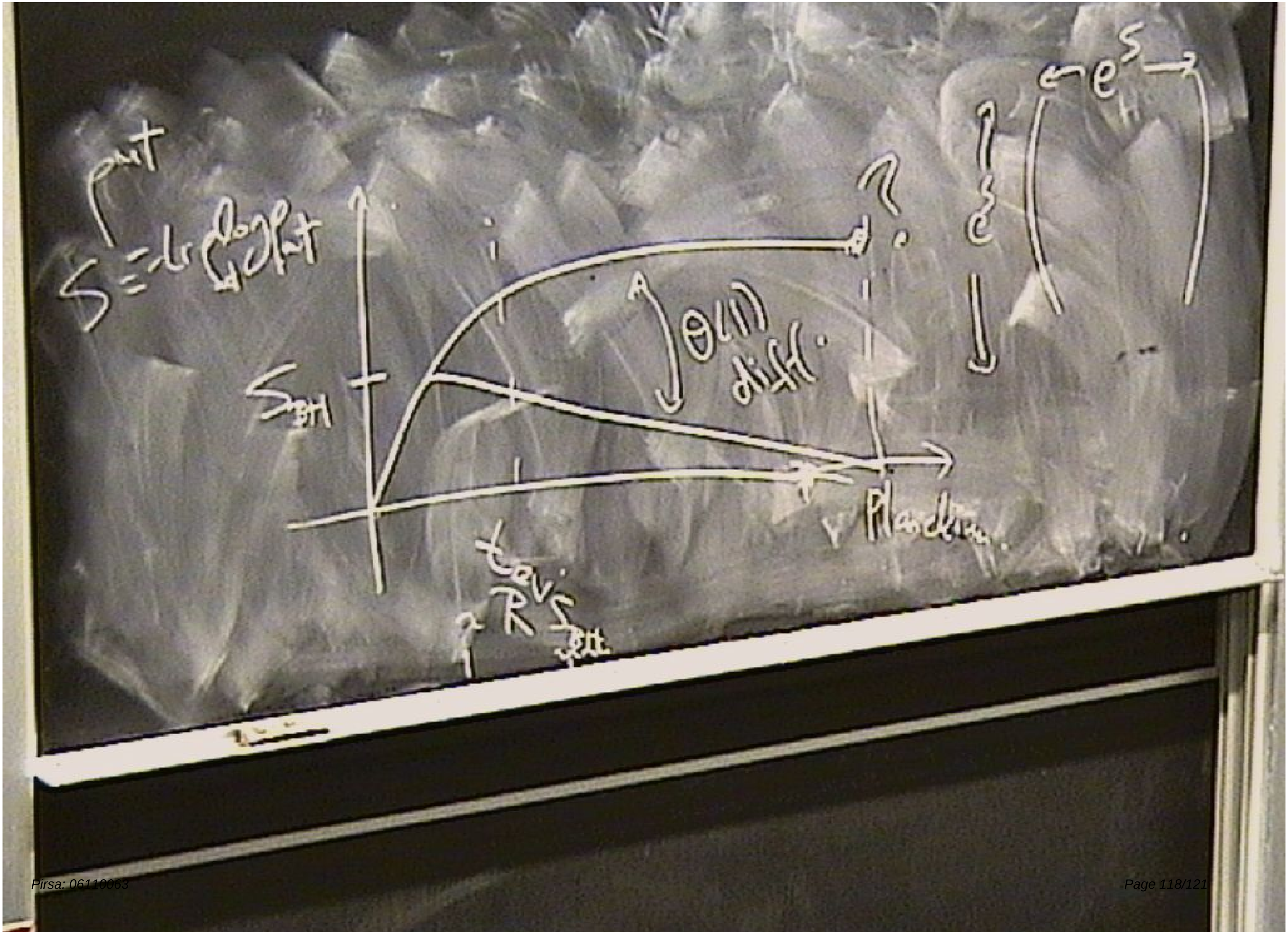



S_BH

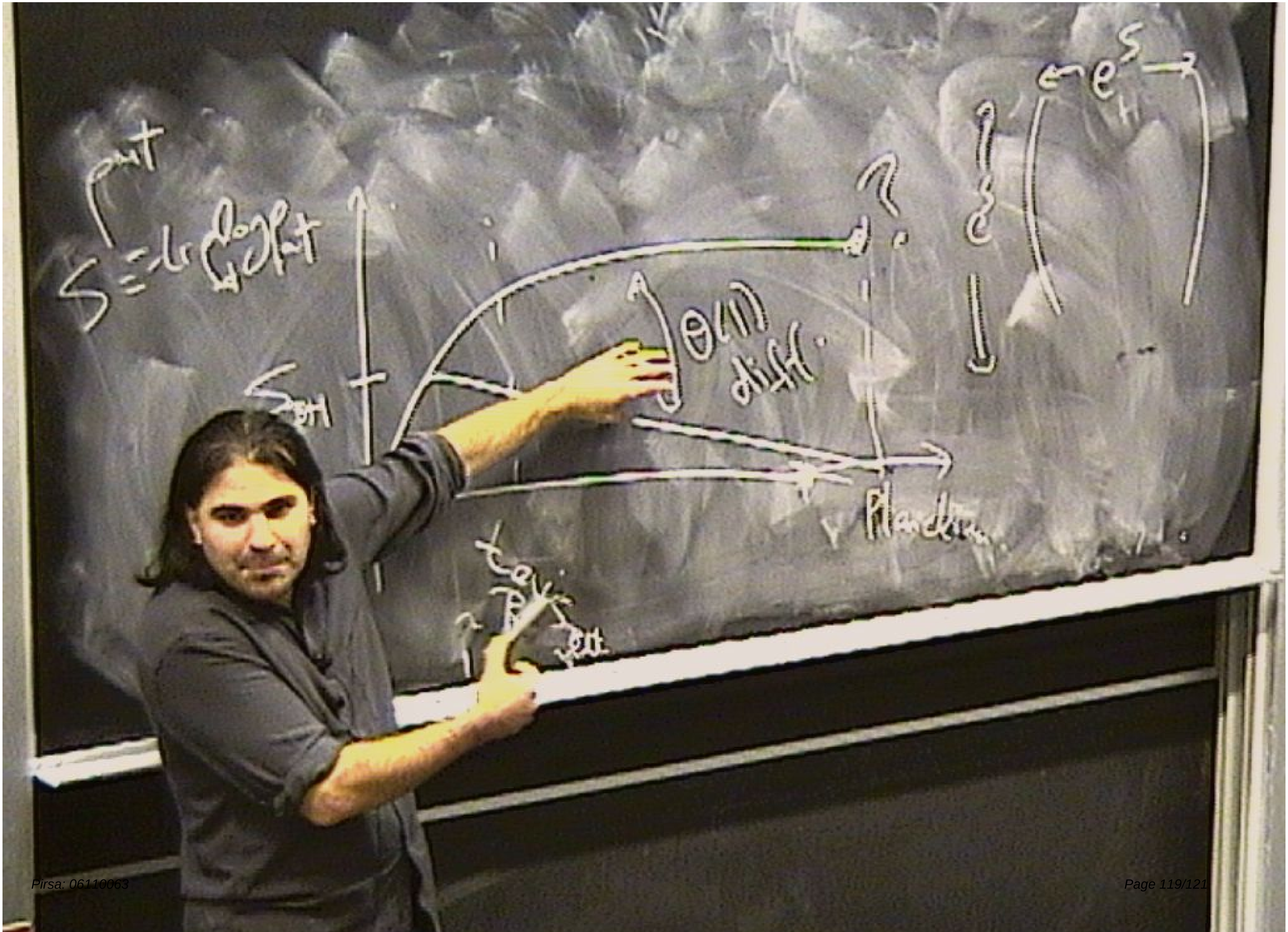

S_BH
O(1) diff.
t_evap
Planck

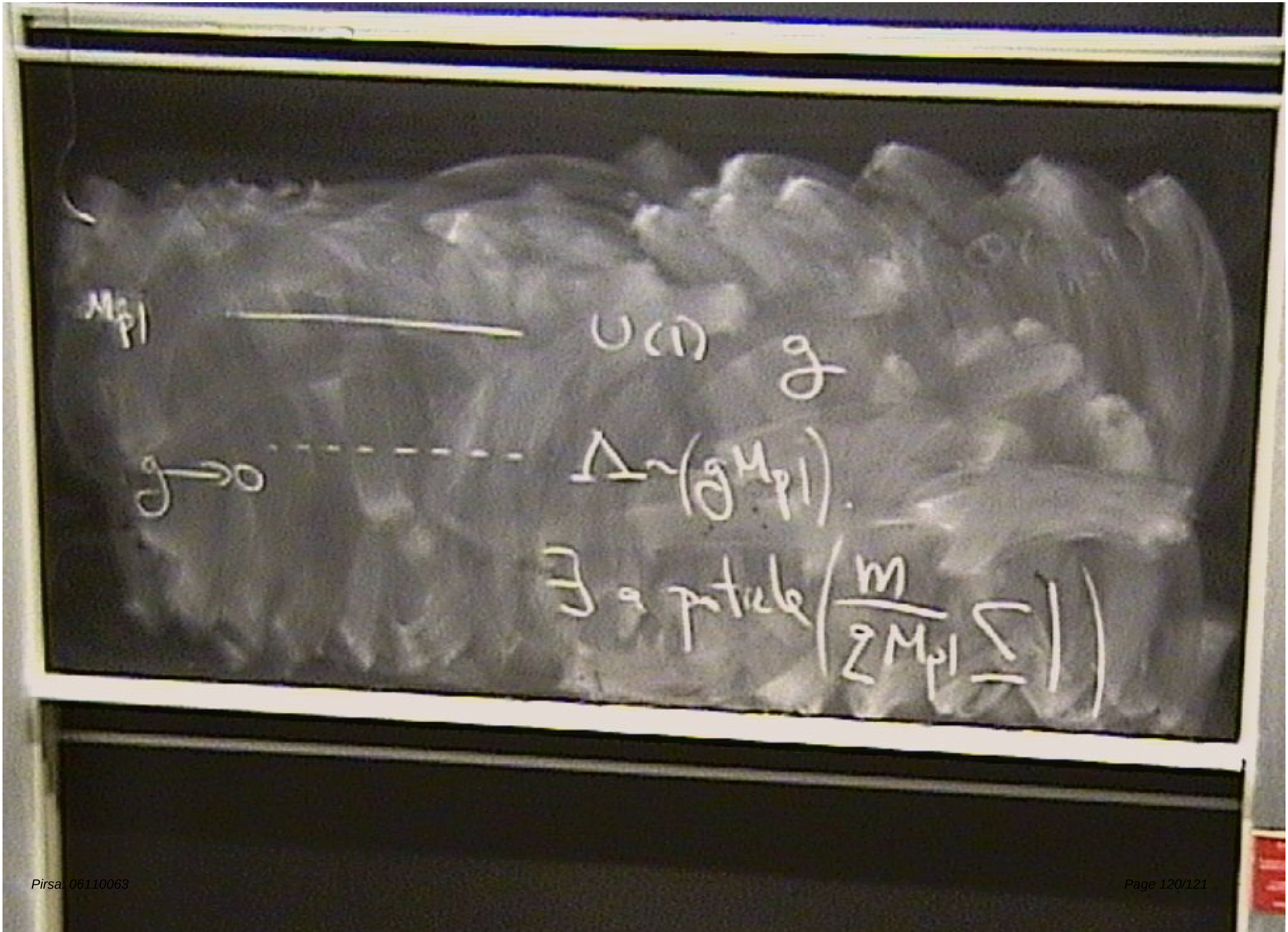


diff.
Planck



$S = -\mathrm{tr}\, \rho \log \rho$
S_{BH}
$O(1)$ diff.
Planck
e^{S_H}




M_pl
U(1)
g
g → 0
Λ ~ (g M_pl).
∃ a particle (m / (g M_pl) ≤ 1)