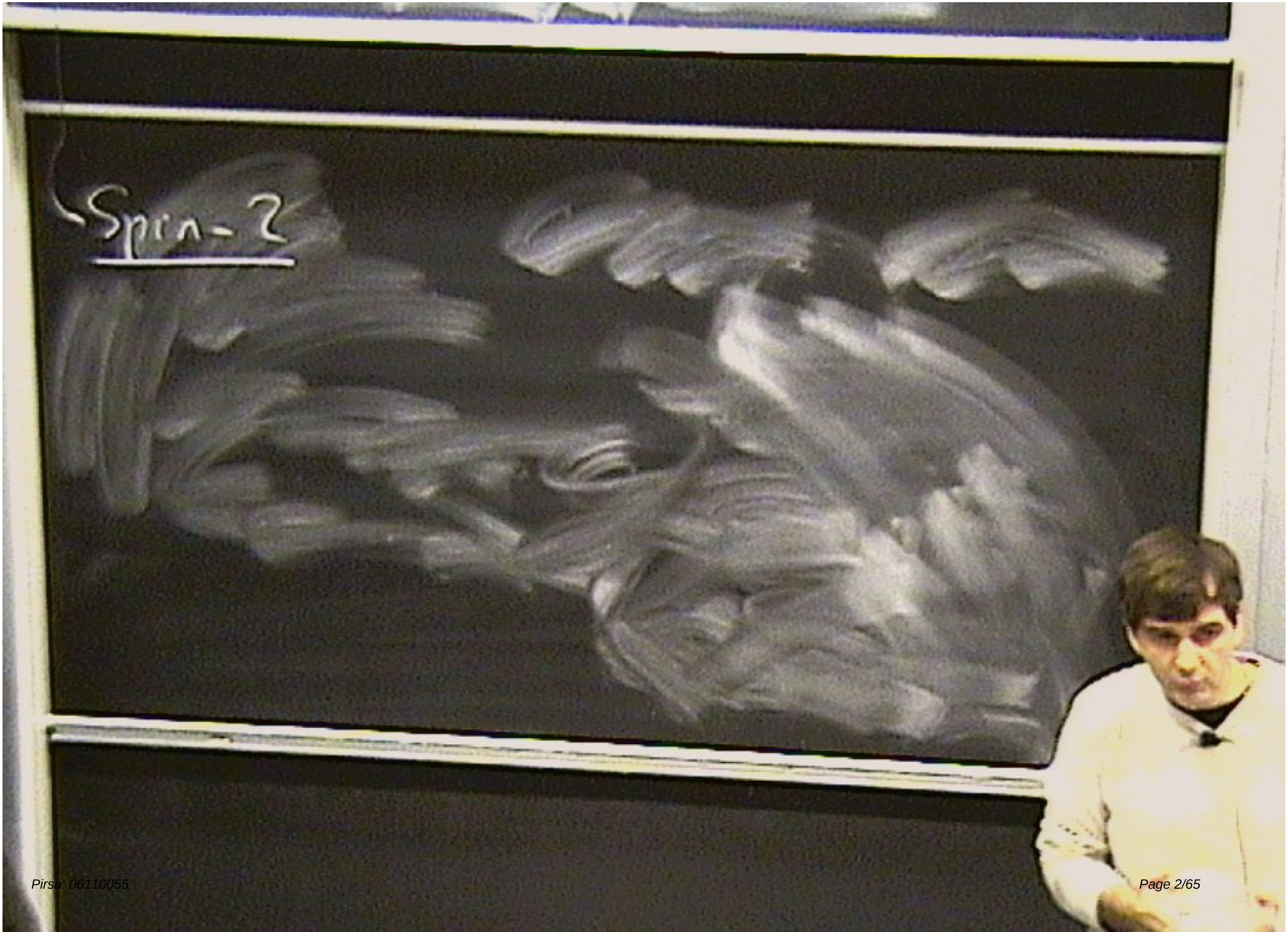
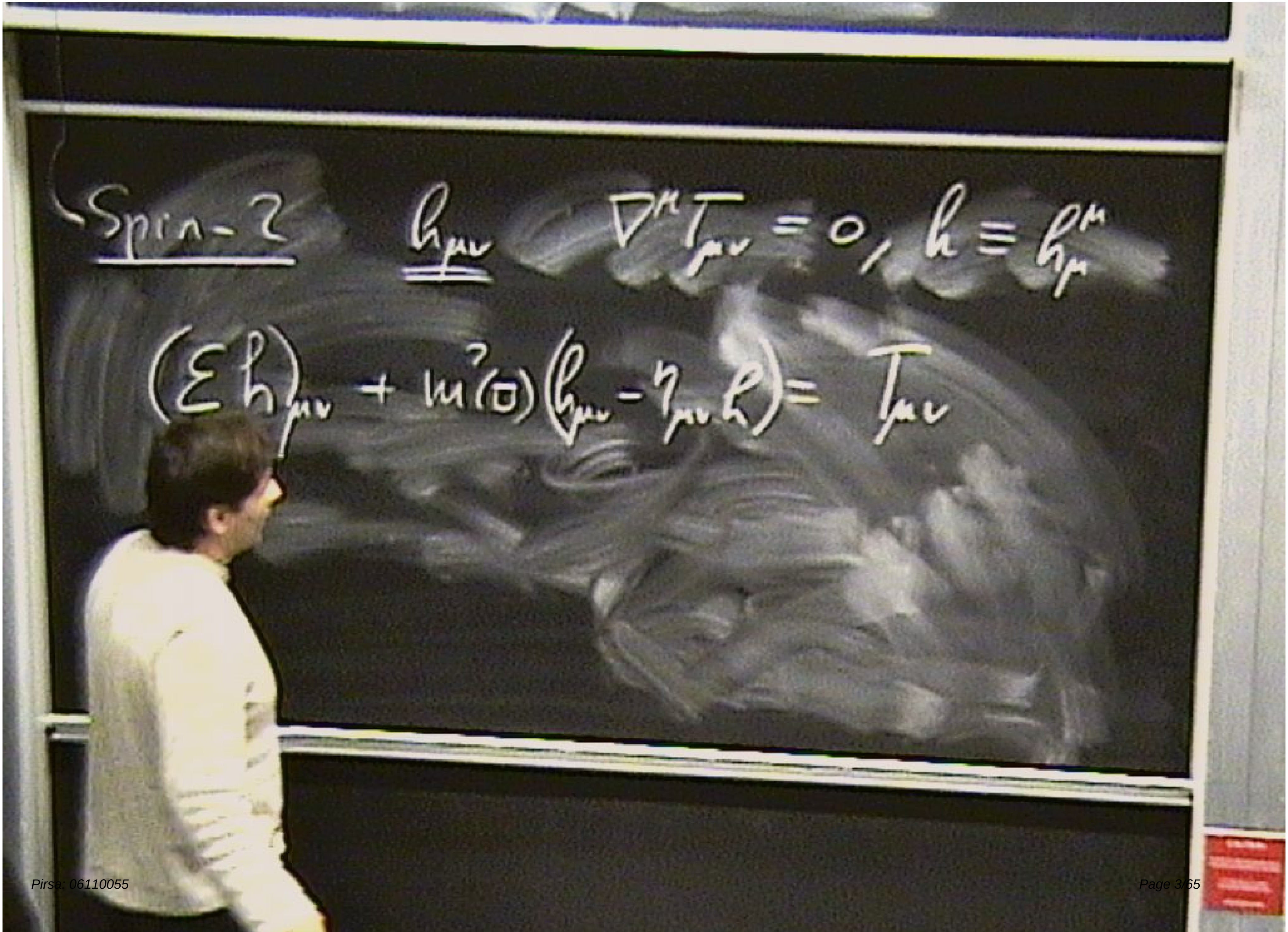
Title: Decoding the fundamental laws of gravity

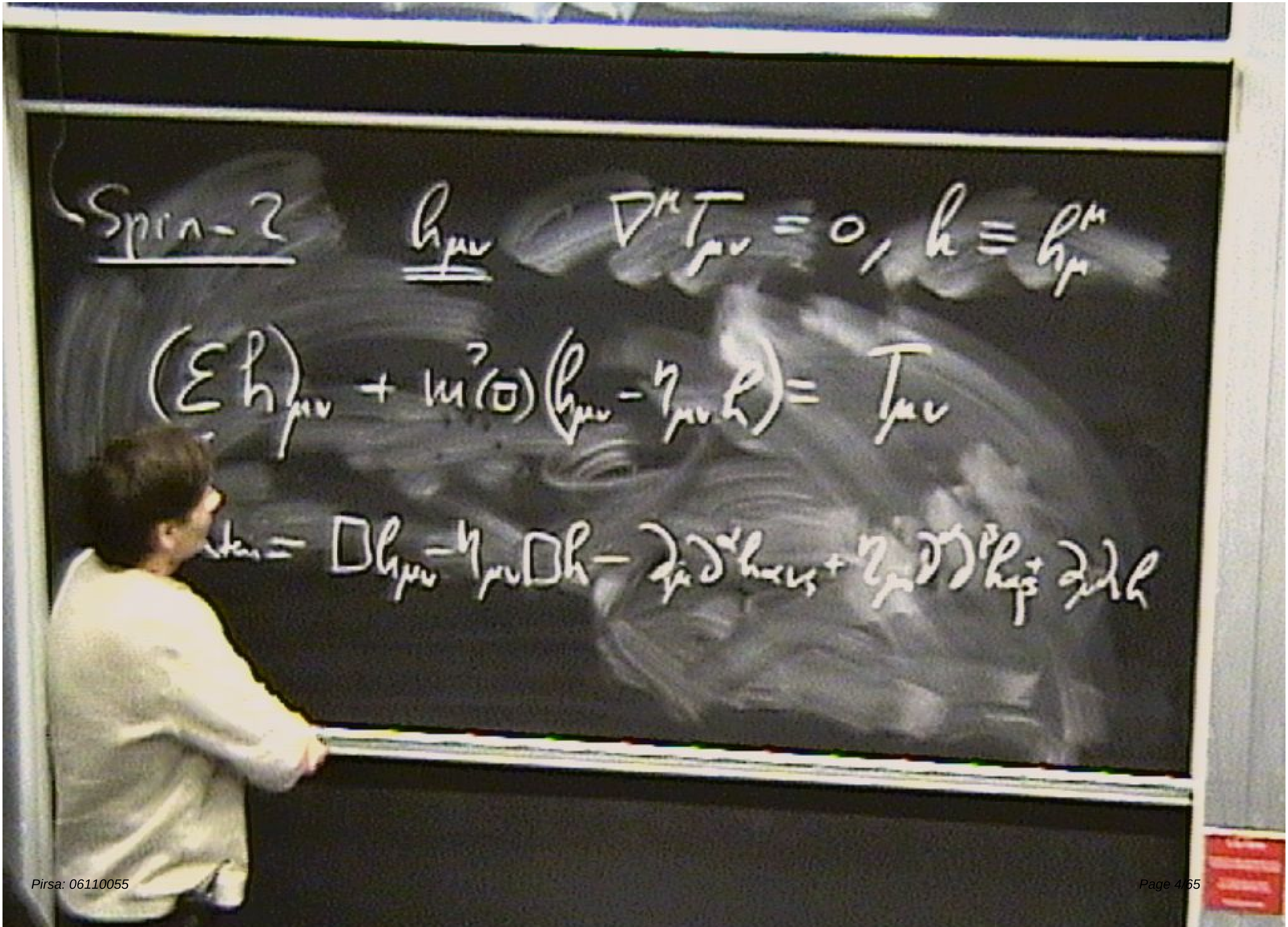
Date: Nov 11, 2006 03:00 PM

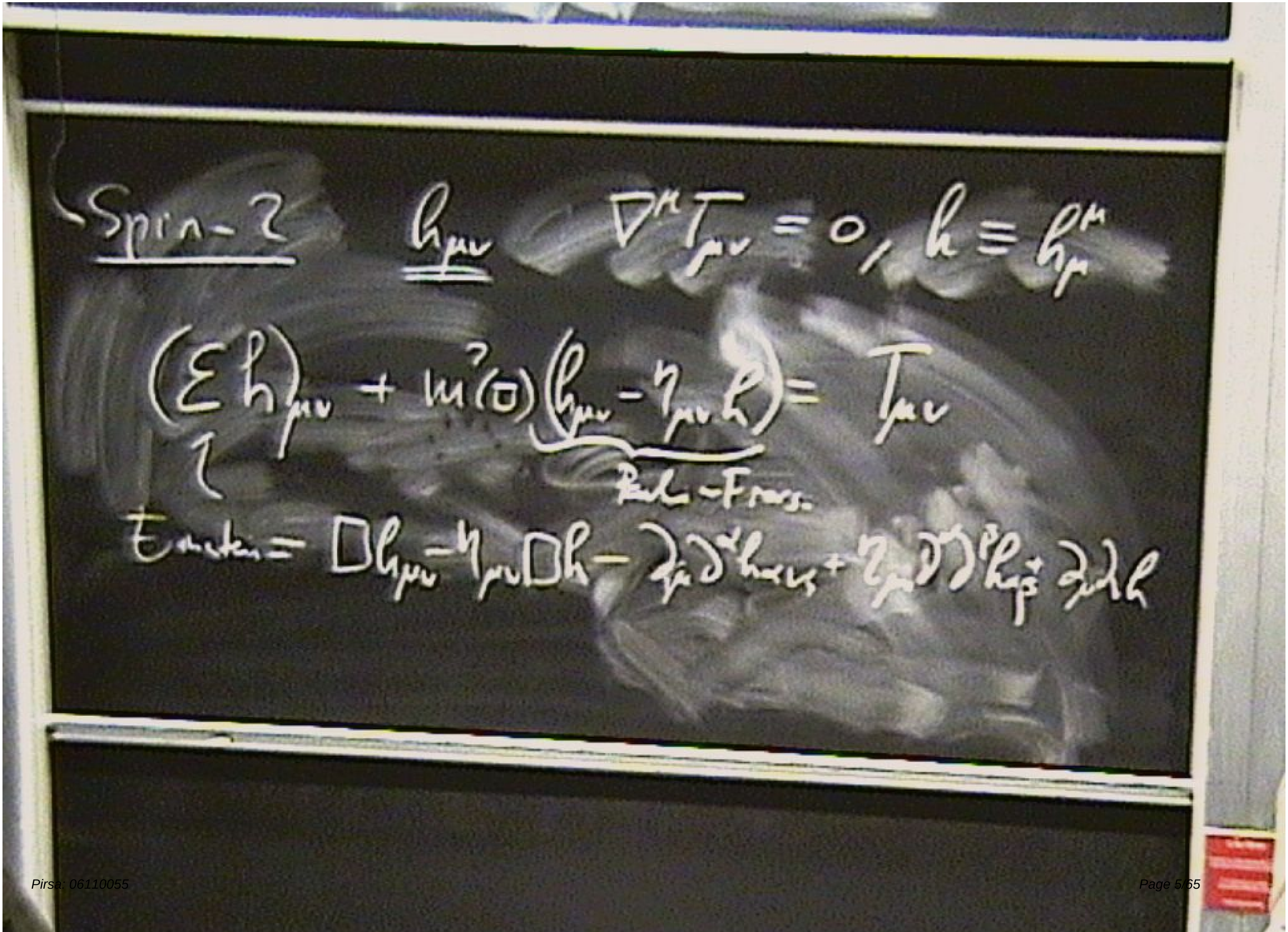
URL: http://pirsa.org/06110055

Abstract:


Spin-2


Spin-2
$h_{\mu\nu}$
$\nabla^\mu T_{\mu\nu} = 0, \; h \equiv h^\mu_\mu$
$(\mathcal{E} h)_{\mu\nu} + m^2(\Box)(h_{\mu\nu} - \eta_{\mu\nu} h) = T_{\mu\nu}$


Spin-2 $h_{\mu\nu}$ $\nabla^\mu T_{\mu\nu} = 0$, $h \equiv h^\mu_\mu$
$(\mathcal{E}h)_{\mu\nu} + m^2(\Box)(h_{\mu\nu} - \eta_{\mu\nu} h) = T_{\mu\nu}$
$= \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu\partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu\partial_\nu h$


Spin-2 $h_{\mu\nu}$ $\nabla^\mu T_{\mu\nu} = 0$, $h \equiv h_\mu^\mu$
$(\mathcal{E} h)_{\mu\nu} + m^2(\Box)(h_{\mu\nu} - \eta_{\mu\nu} h) = T_{\mu\nu}$
Pauli-Fierz
$\mathcal{E}_{\text{einstein}} = \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu \partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu\partial_\nu h$

Spin-2 $\quad h_{\mu\nu} \quad \nabla^\mu T_{\mu\nu} = 0, \; h \equiv h^\mu_\mu$

$r_c = H_0^{-1}$

$$(\mathcal{E} h)_{\mu\nu} + m^2(\Box)\underbrace{(h_{\mu\nu} - \eta_{\mu\nu} h)}_{\text{Pauli-Fierz}} = T_{\mu\nu}$$

$$\mathcal{E}_{\text{Einstein}} = \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu \partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu \partial_\nu h$$

Spin-2 $\quad h_{\mu\nu} \quad \nabla^\mu T_{\mu\nu} = 0, \; h \equiv h^\mu_\mu$

$r_c = H_0^{-1}$

$$(\mathcal{E} h)_{\mu\nu} + m^2(\Box)\underbrace{(h_{\mu\nu} - \eta_{\mu\nu} h)}_{\text{Pauli-Fierz}} = T_{\mu\nu}$$

$$\mathcal{E}_{\text{Einstein}} = \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu \partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu\partial_\nu h$$

$$m^2(\Box) = r_c^{2(\alpha-1)}\,\Box^\alpha$$

$\Box \to 0$

Spin-2 $\quad h_{\mu\nu} \quad \nabla^\mu T_{\mu\nu} = 0, \; h \equiv h^\mu_\mu$

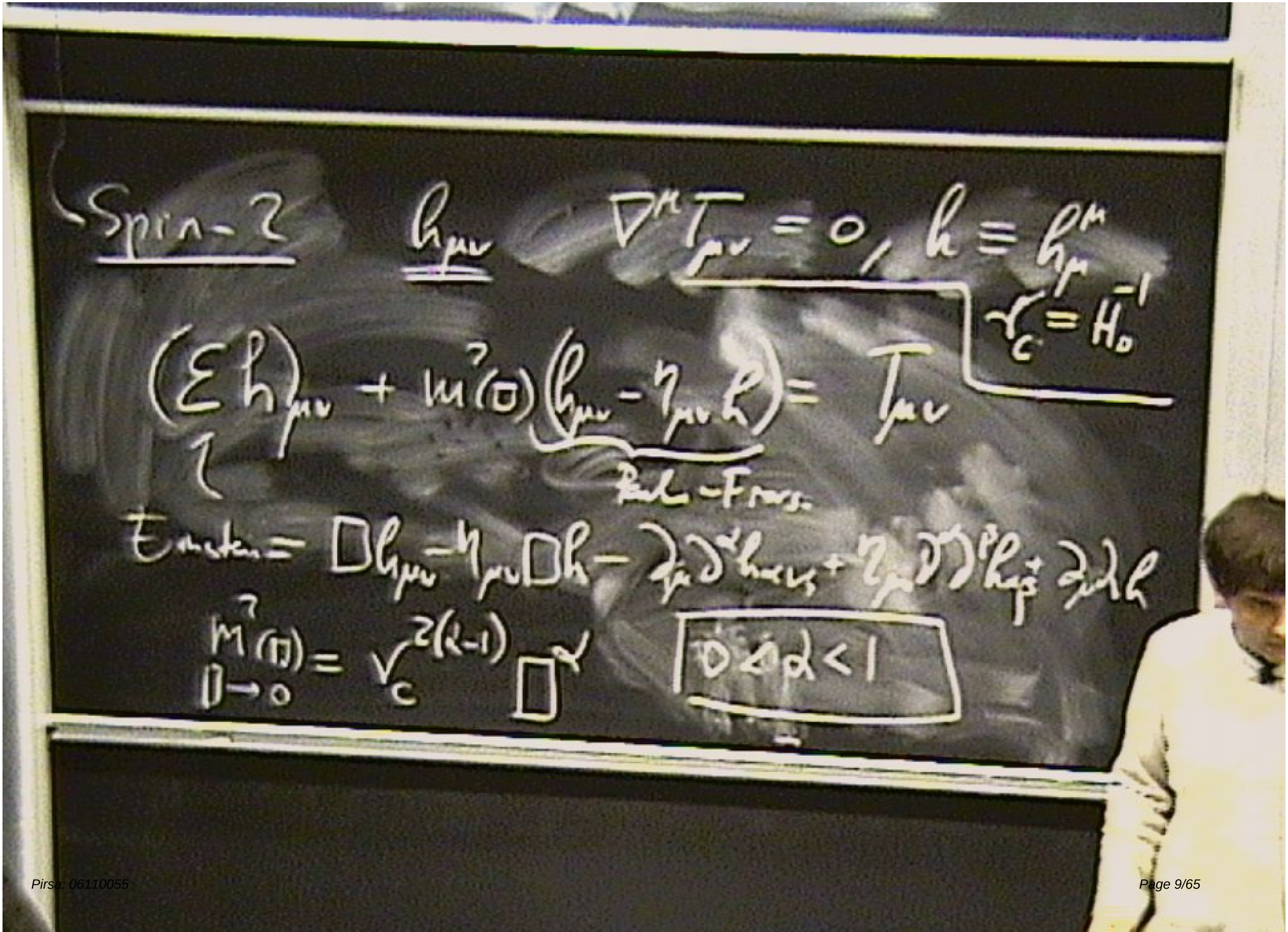
$$r_c = H_0^{-1}$$

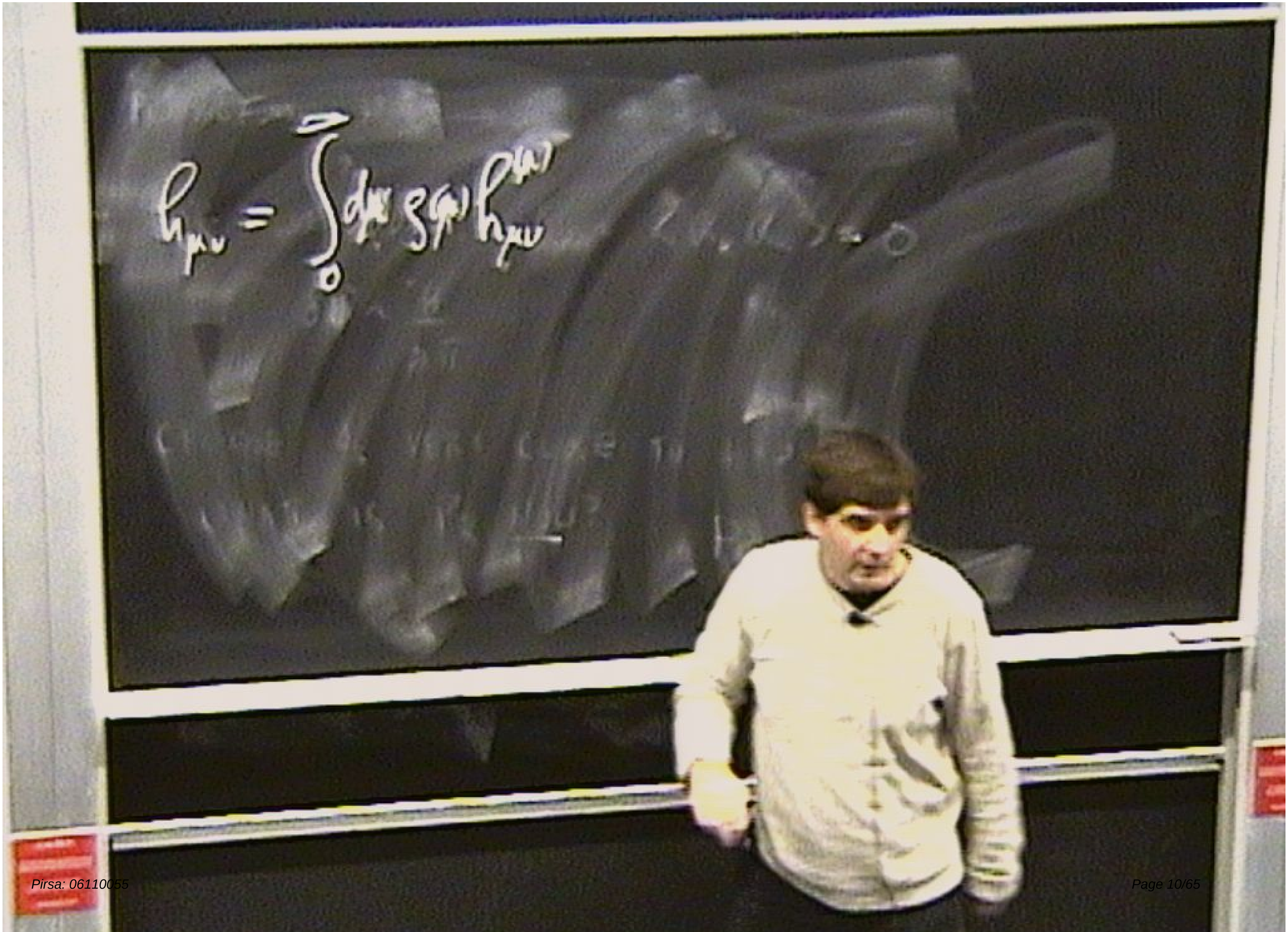
$$(\mathcal{E} h)_{\mu\nu} + m^2(\Box)\underbrace{(h_{\mu\nu} - \eta_{\mu\nu} h)}_{\text{Pauli-Fierz}} = T_{\mu\nu}$$

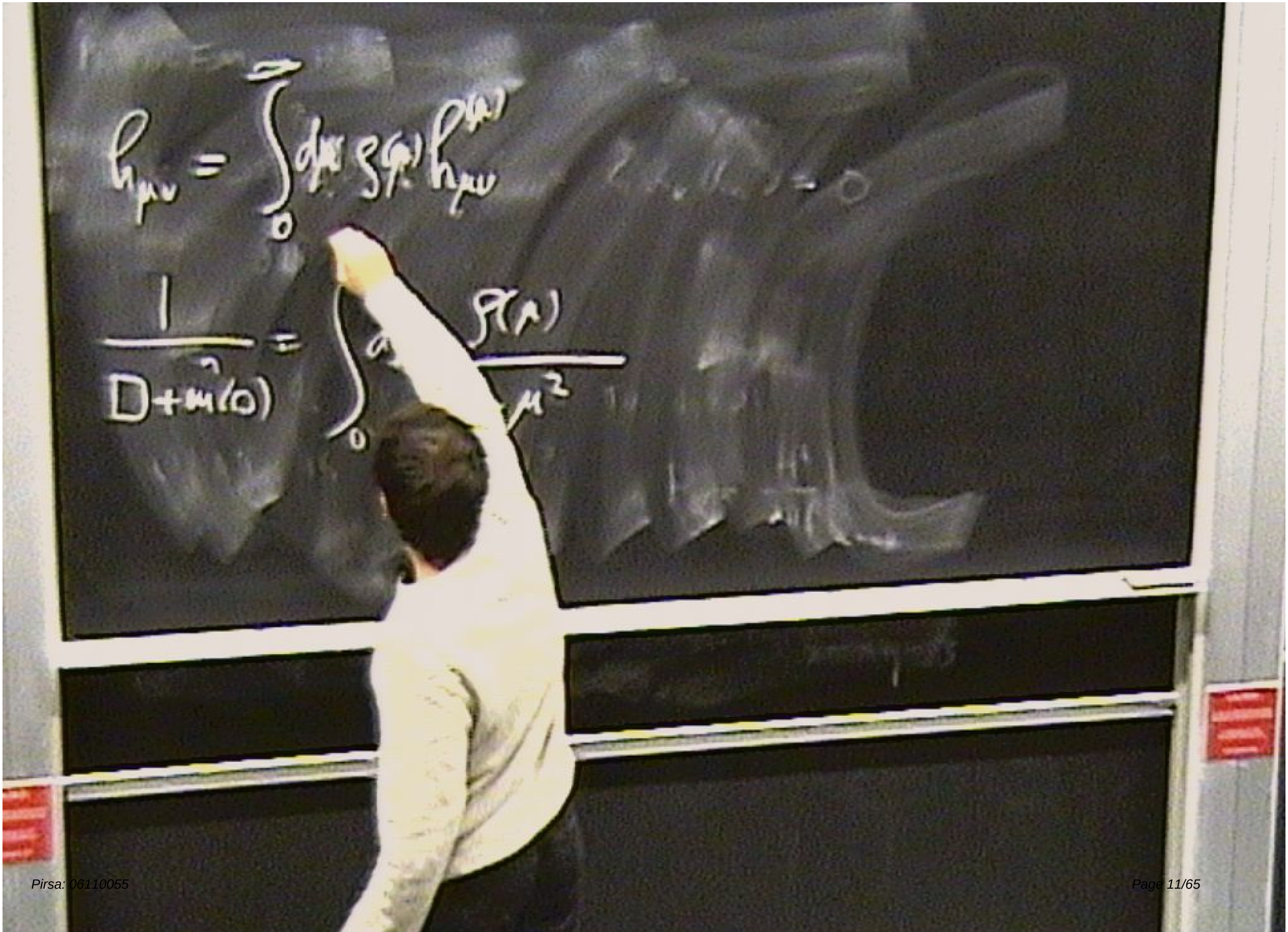
$$\mathcal{E}_{\text{Einstein}} = \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu \partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu\partial_\nu h$$

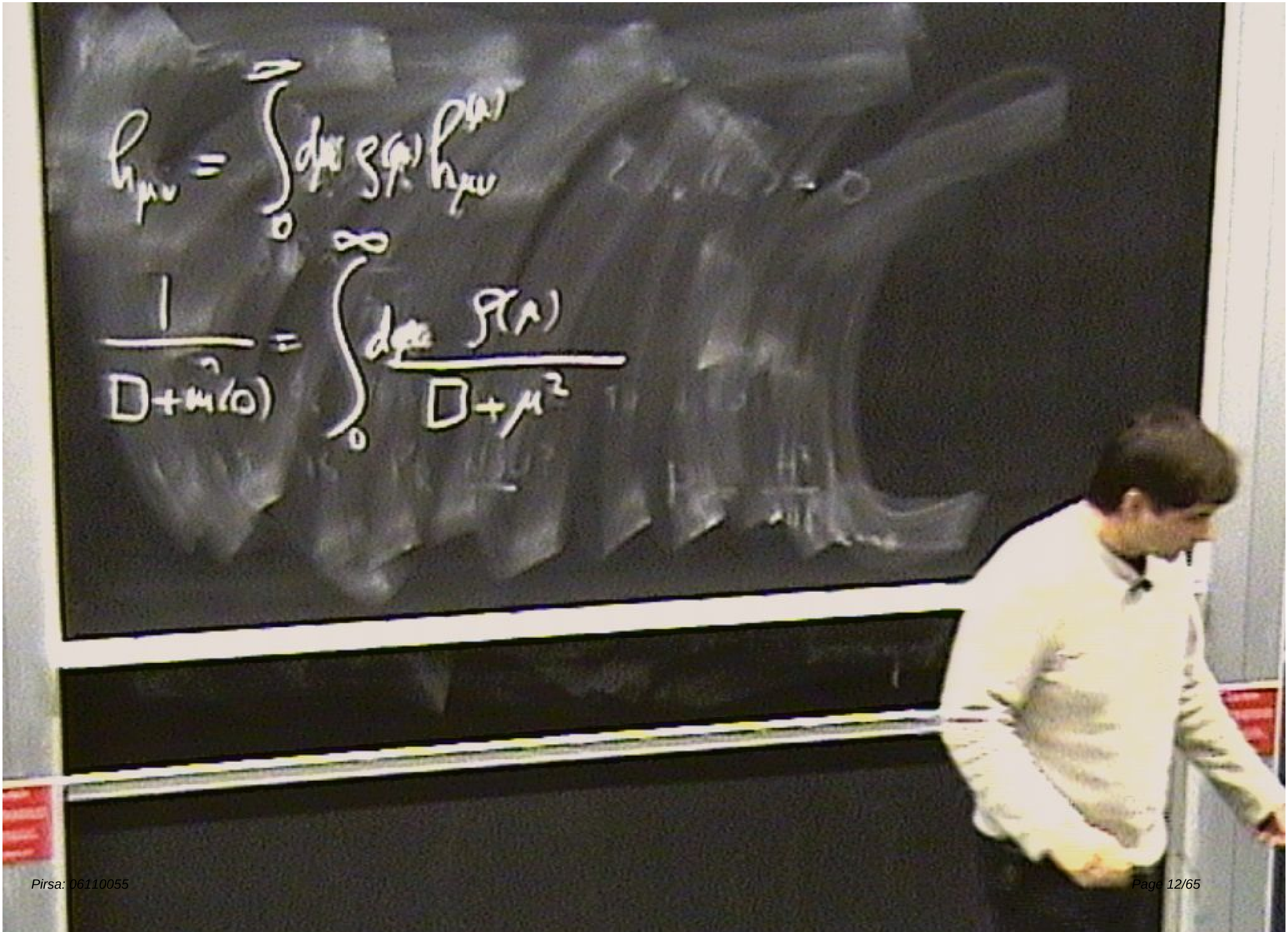
$$m^2(\Box) = r_c^{2(\alpha-1)} \Box^\alpha \qquad \alpha = 0$$

$$\Box \to 0 \qquad \alpha = \tfrac{1}{2}$$


Spin-2
$h_{\mu\nu}$
$\nabla^\mu T_{\mu\nu} = 0,\ h \equiv h^\mu_\mu$
$r_c = H_0^{-1}$
$(\mathcal{E}h)_{\mu\nu} + m^2(\Box)(h_{\mu\nu} - \eta_{\mu\nu} h) = T_{\mu\nu}$
Pauli-Fierz
$\text{Einstein} = \Box h_{\mu\nu} - \eta_{\mu\nu}\Box h - \partial_\mu \partial^\alpha h_{\alpha\nu} + \eta_{\mu\nu}\partial^\alpha\partial^\beta h_{\alpha\beta} + \partial_\mu\partial_\nu h$
$m^2(\Box) = r_c^{2(\alpha-1)}\Box^\alpha$
$\Box \to 0$
$0 < \alpha < 1$


$h_{\mu\nu} = \int_0^\infty d\mu^2 \, \rho(\mu^2) \, h_{\mu\nu}^{(\mu)}$


$h_{\mu\nu} = \int_0^\infty d\mu\, \rho(\mu)\, h_{\mu\nu}^{(\mu)}$

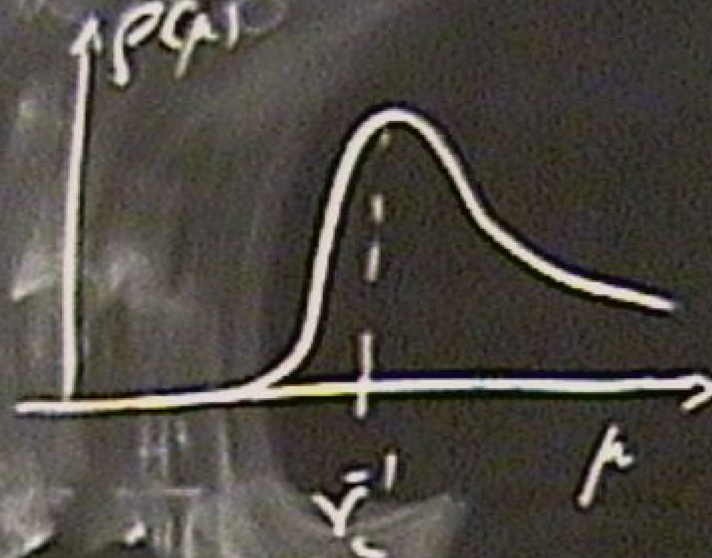

$h_{\mu\nu} = \int_0^\infty d\mu\, \rho(\mu)\, h_{\mu\nu}^{(\mu)}$
$\frac{1}{\Box + \hat{m}(\Box)} = \int_0^\infty d\mu\, \frac{\rho(\mu)}{\Box + \mu^2}$

$$h_{\mu\nu} = \int_0^\infty d\mu^2\, \rho(\mu^2)\, h_{\mu\nu}^{(\mu)}$$

$$\frac{1}{\Box + m^2(\Box)} = \int_0^\infty d\mu^2\, \frac{\rho(\mu^2)}{\Box + \mu^2}$$

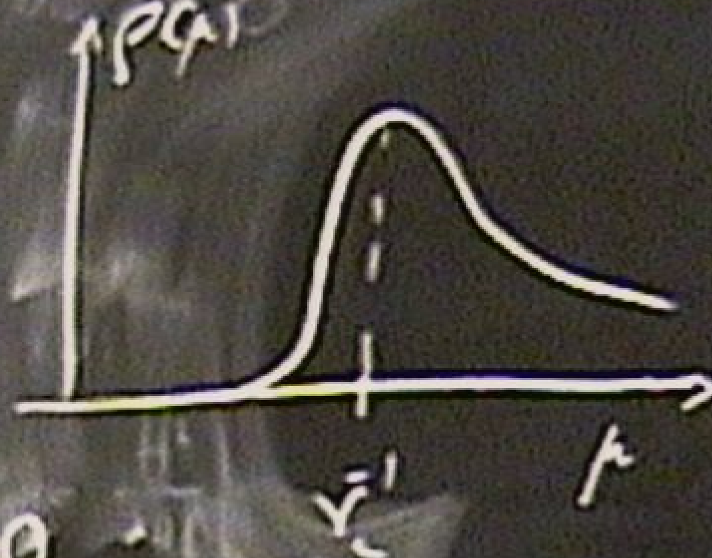
$$h_{\mu\nu} = \int_0^{\infty} d\mu \, \rho(\mu) \, h_{\mu\nu}^{(\mu)}$$

$$\frac{1}{\Box + m^2(\Box)} = \int_0^{\infty} d\mu \, \frac{\rho(\mu)}{\Box + \mu^2}$$



$$h_{\mu\nu} = \int_0^\infty d\mu\, \rho(\mu)\, h_{\mu\nu}^{(\mu)}$$

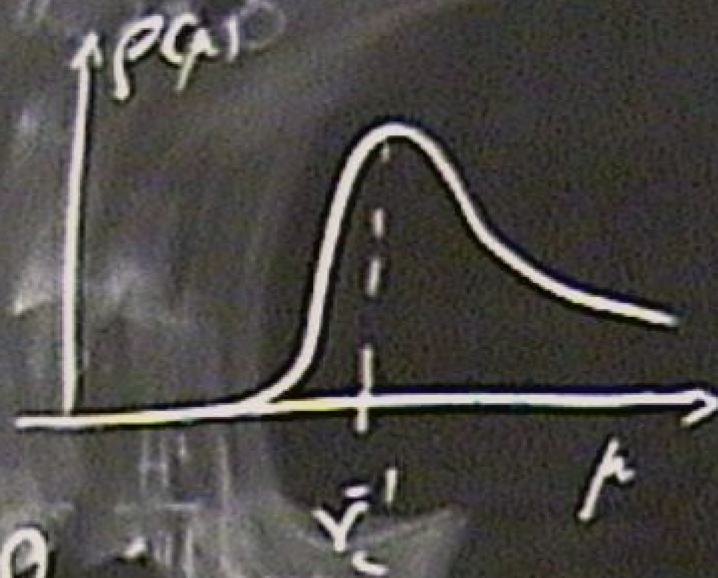
$$\frac{1}{\Box + m^2(0)} = \int_0^\infty d\mu\, \frac{\rho(\mu)}{\Box + \mu^2}$$



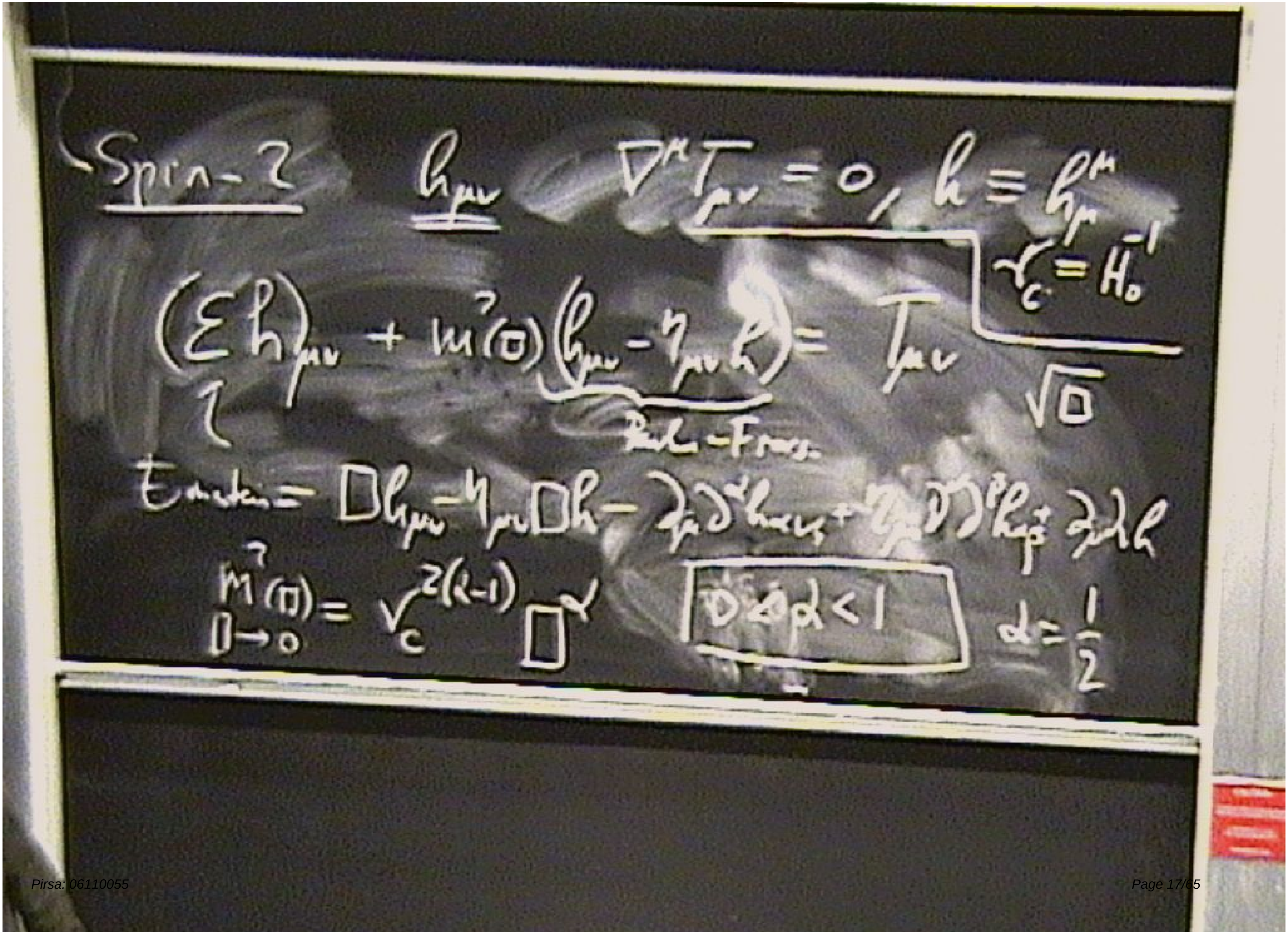
$$\rho(\mu) \geq 0 \Longleftrightarrow \alpha > 0$$

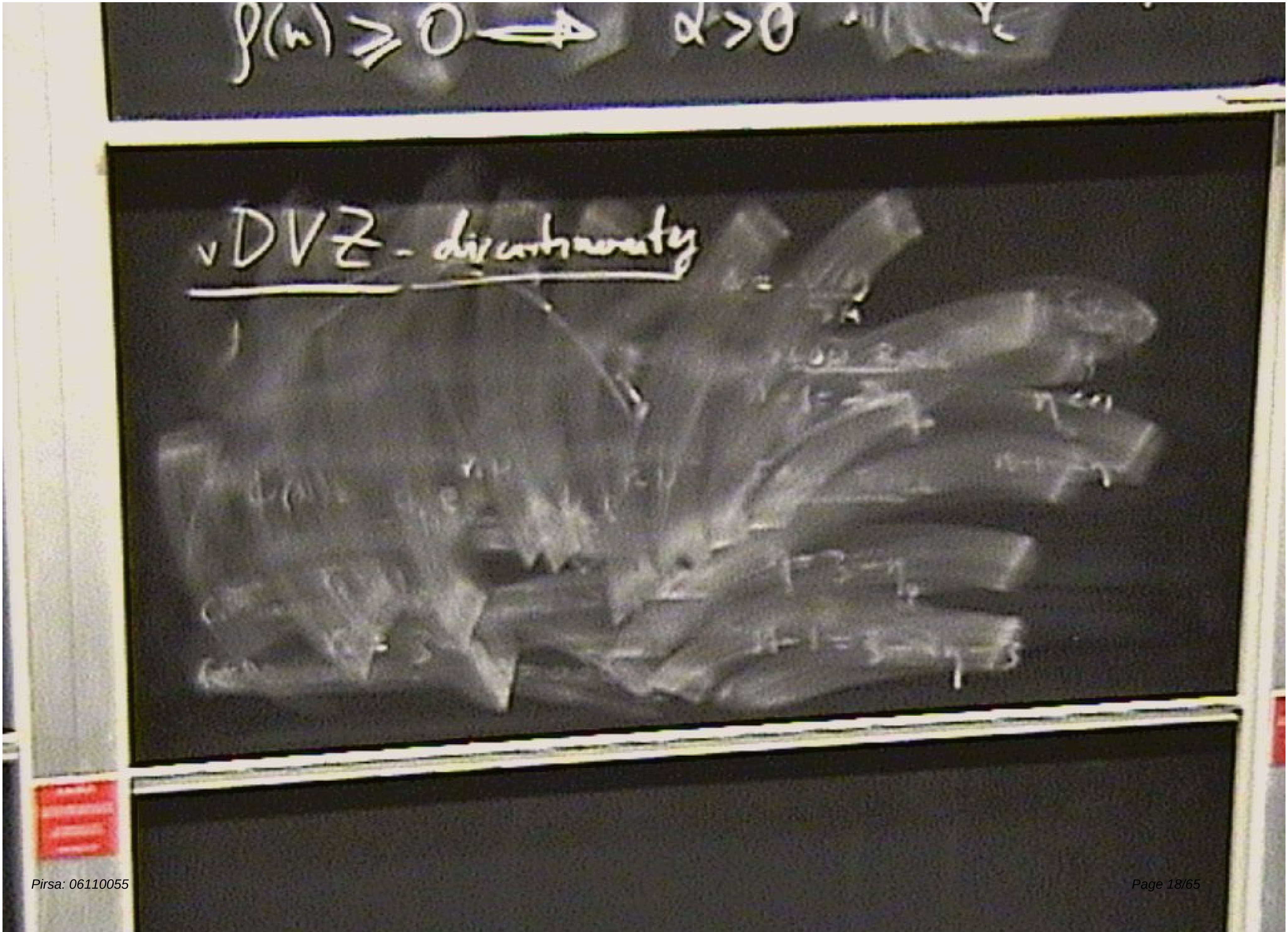
$$h_{\mu\nu} = \int_0^\infty d\mu\, \rho(\mu)\, h_{\mu\nu}^{(\mu)}$$

$$\frac{1}{\Box + m^2(\Box)} = \int_0^\infty d\mu\, \frac{\rho(\mu)}{\Box + \mu^2}$$



$$\rho(\mu) \geq 0 \Longleftrightarrow \alpha > 0$$


Spin-2   h_μν   ∇^μ T_μν = 0, h ≡ h^μ_μ
r_c = H_0^-1
(E h)_μν + m²(□)(h_μν − η_μν h) = T_μν
Pauli-Fierz
√□
Einstein = □h_μν − η_μν □h − ∂_μ∂^α h_αν + η_μν ∂^α∂^β h_αβ + ∂_μ∂_ν h
m²(□) = r_c^2(α−1) □^α
□ → 0
0 ≤ α < 1
α = 1/2

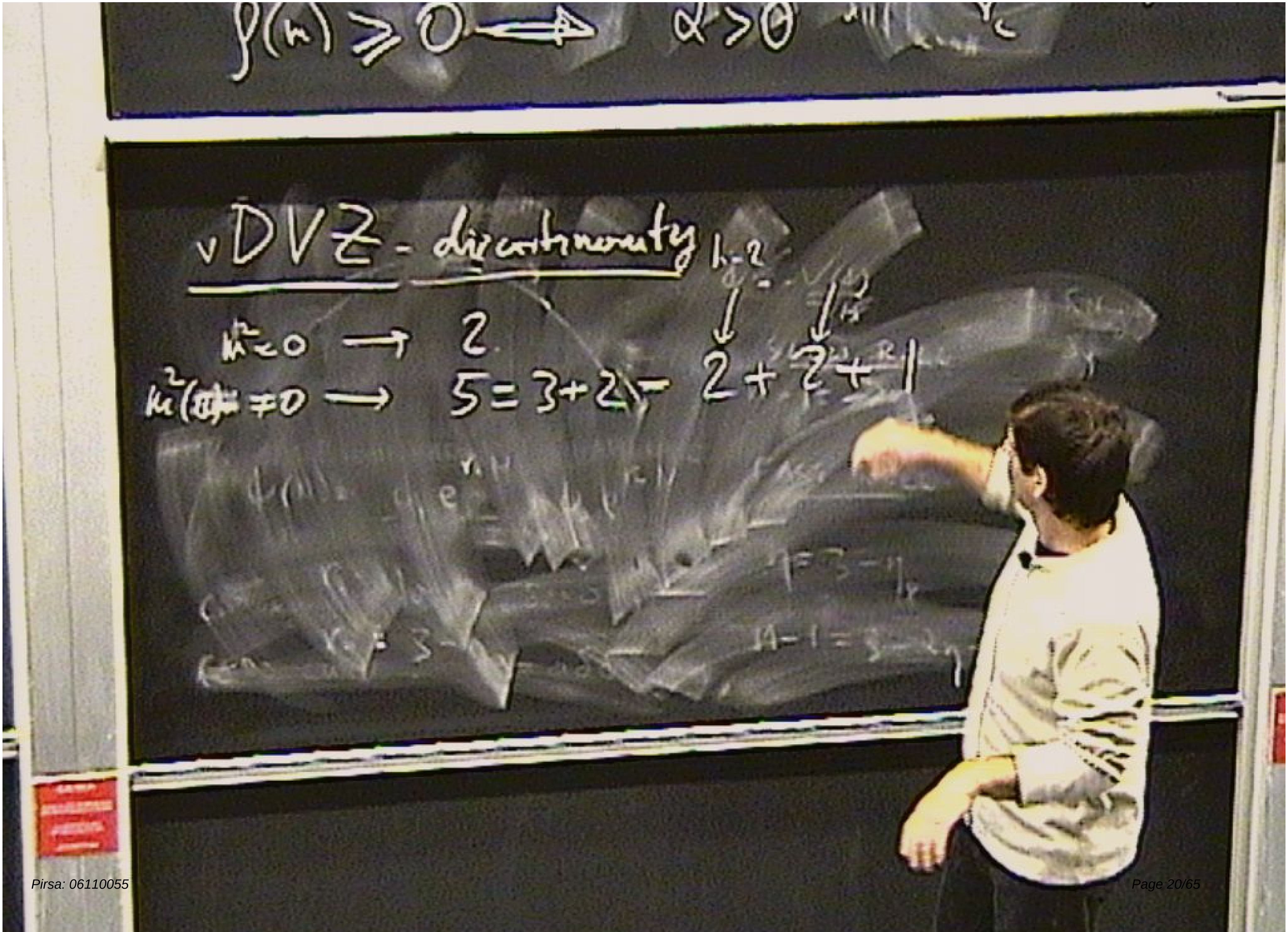

ρ(r) ≥ 0 ⟺ α > 0
vDVZ - discontinuity

$\rho(n) \geq 0 \Longrightarrow \alpha > 0$

vDVZ - discontinuity

$m^2 = 0 \longrightarrow 2$

$m^2 \neq 0 \longrightarrow 5 = 3 + 2$


ρ(r) ≥ 0 ⟶ α > 0
vDVZ - discontinuity
m² = 0 ⟶ 2
m² ≠ 0 ⟶ 5 = 3 + 2 → 2 + 2 + 1

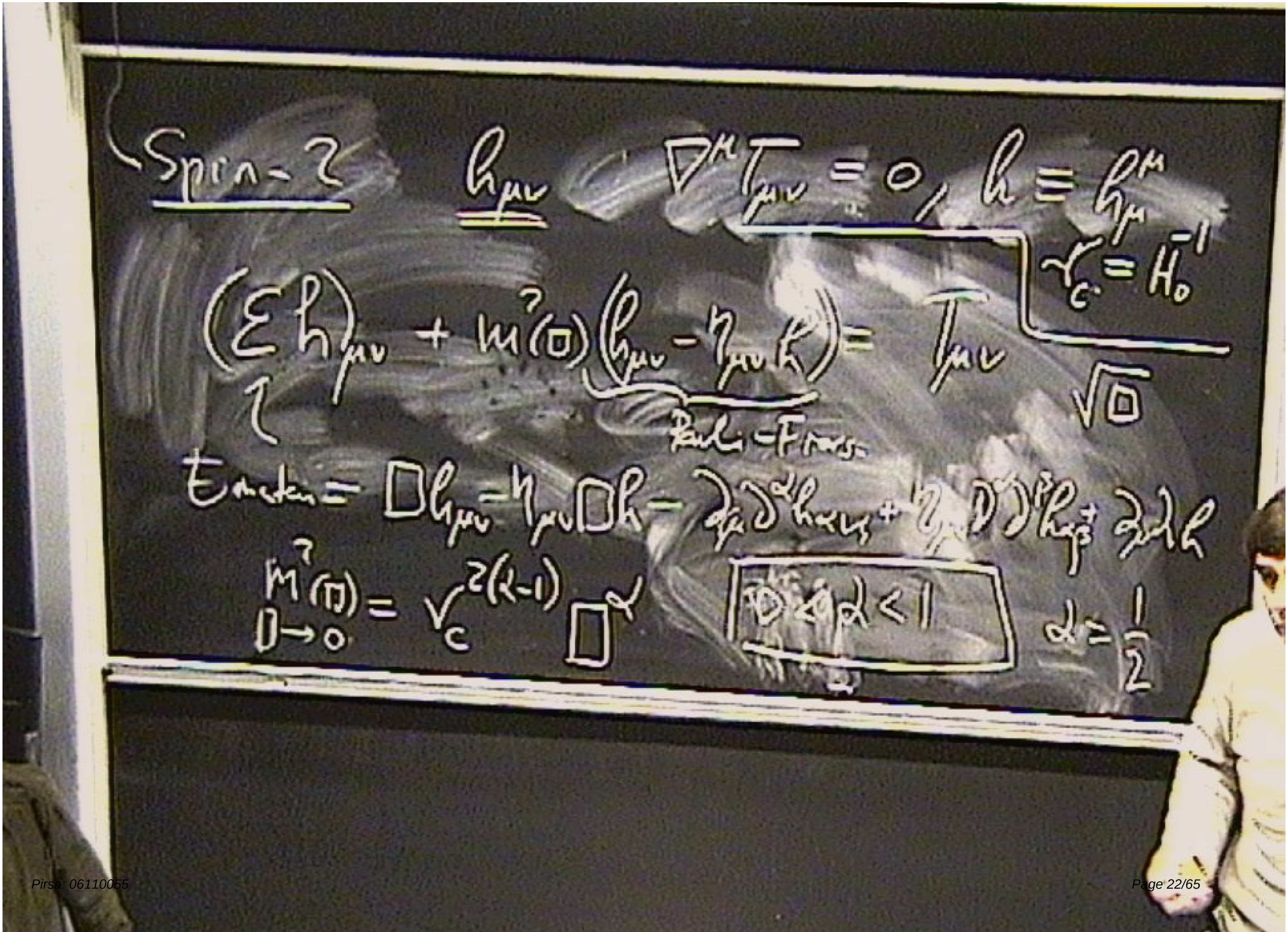
$\rho(n) \geq 0 \Longrightarrow \alpha > \theta$

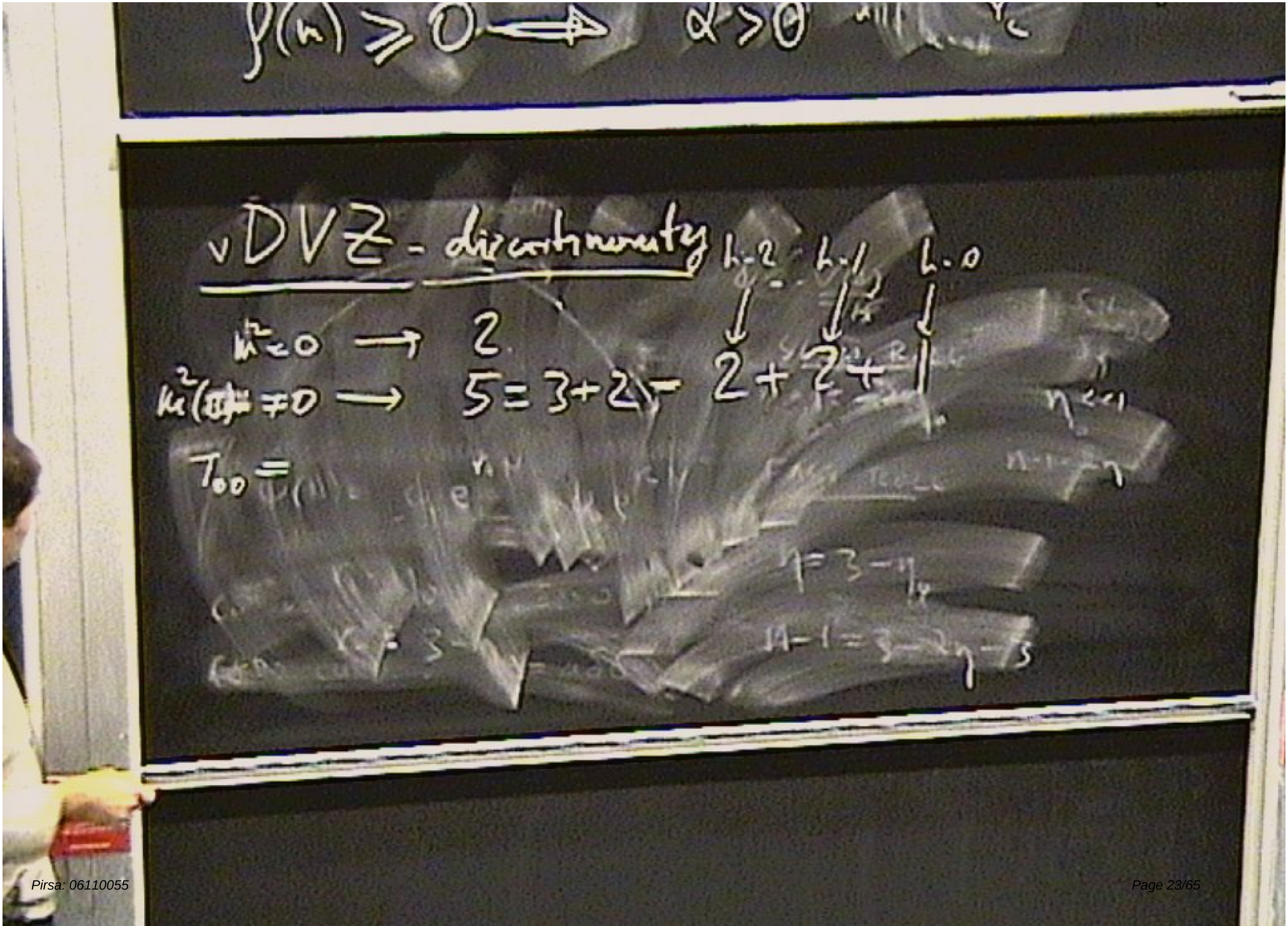
vDVZ - discontinuity

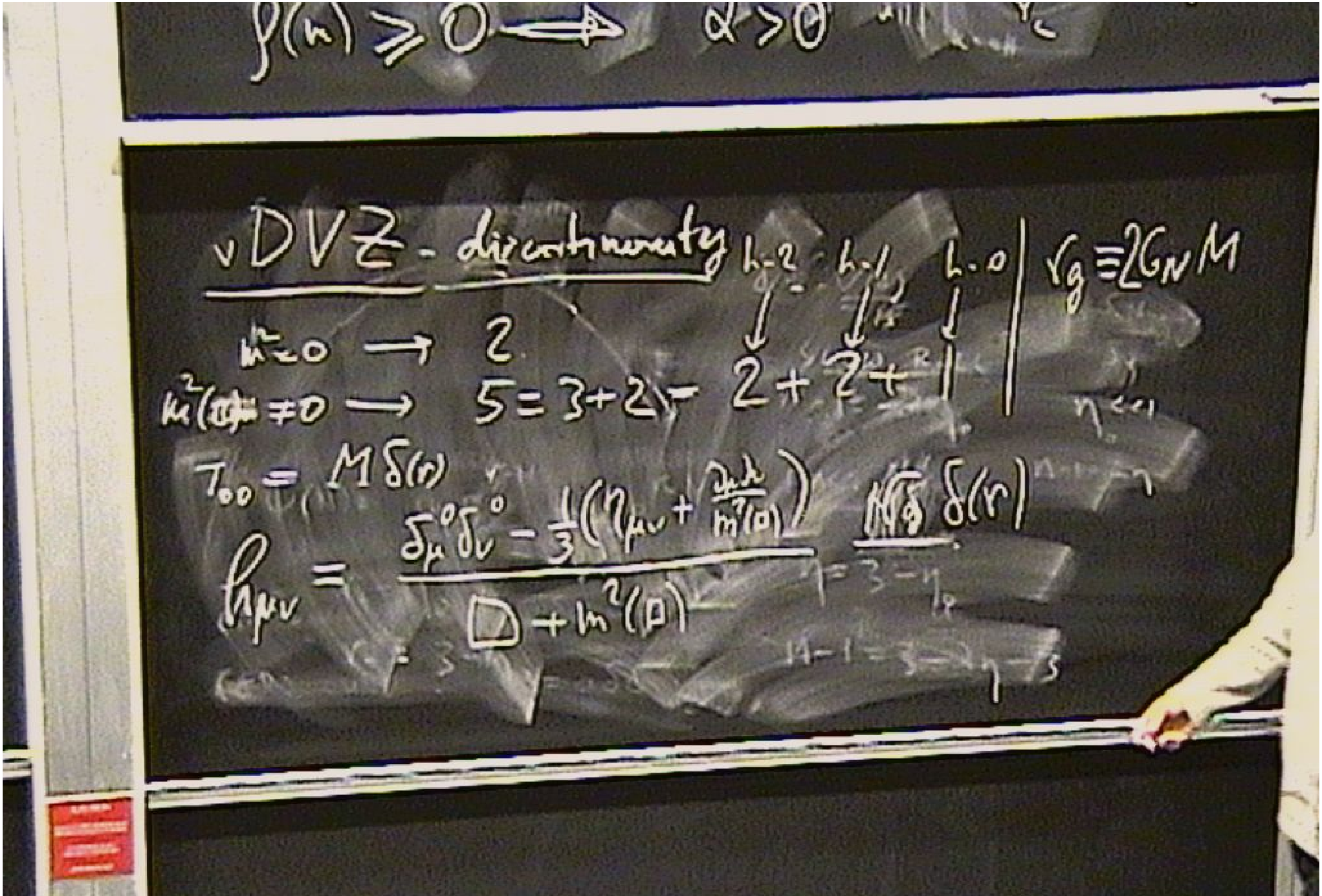
$h=2 \quad h=1 \quad h=0$

$m^2 = 0 \longrightarrow 2$

$m^2 \neq 0 \longrightarrow 5 = 3 + 2 \rightarrow 2 + 2 + 1$


Spin-2
$h_{\mu\nu}$
$\nabla^\mu T_{\mu\nu} = 0$, $h \equiv h^\mu_\mu$
$r_c = H_0^{-1}$
$(\mathcal{E}h)_{\mu\nu} + m^2(\Box)(h_{\mu\nu} - \eta_{\mu\nu}h) = T_{\mu\nu}$
Pauli-Fierz
$\sqrt{\Box}$
$m^2(\Box) = r_c^{2(\alpha-1)}\Box^\alpha$
$\Box \to 0$
$0 < \alpha < 1$
$\alpha = \frac{1}{2}$


vDVZ - discontinuity
h=2 h=1 h=0
m²=0 → 2
m² ≠ 0 → 5 = 3+2 → 2+2+1
T00 =


vDVZ - discontinuity
h=2 h=1 h=0
r_g = 2G_N M
m² = 0 → 2
m²(□) ≠ 0 → 5 = 3 + 2 = 2 + 2 + 1
T₀₀ = M δ(r)
h_μν = (δ_μ⁰ δ_ν⁰ − 1/3 (η_μν + ∂_μ∂_ν / m²(□))) / (□ + m²(□)) · M G δ(r)

$\rho(n) \geq 0 \Longrightarrow \alpha > 0$

vDVZ - discontinuity

$h=2 \quad h=1 \quad h=0$

$r_g \equiv 2 G_N M$

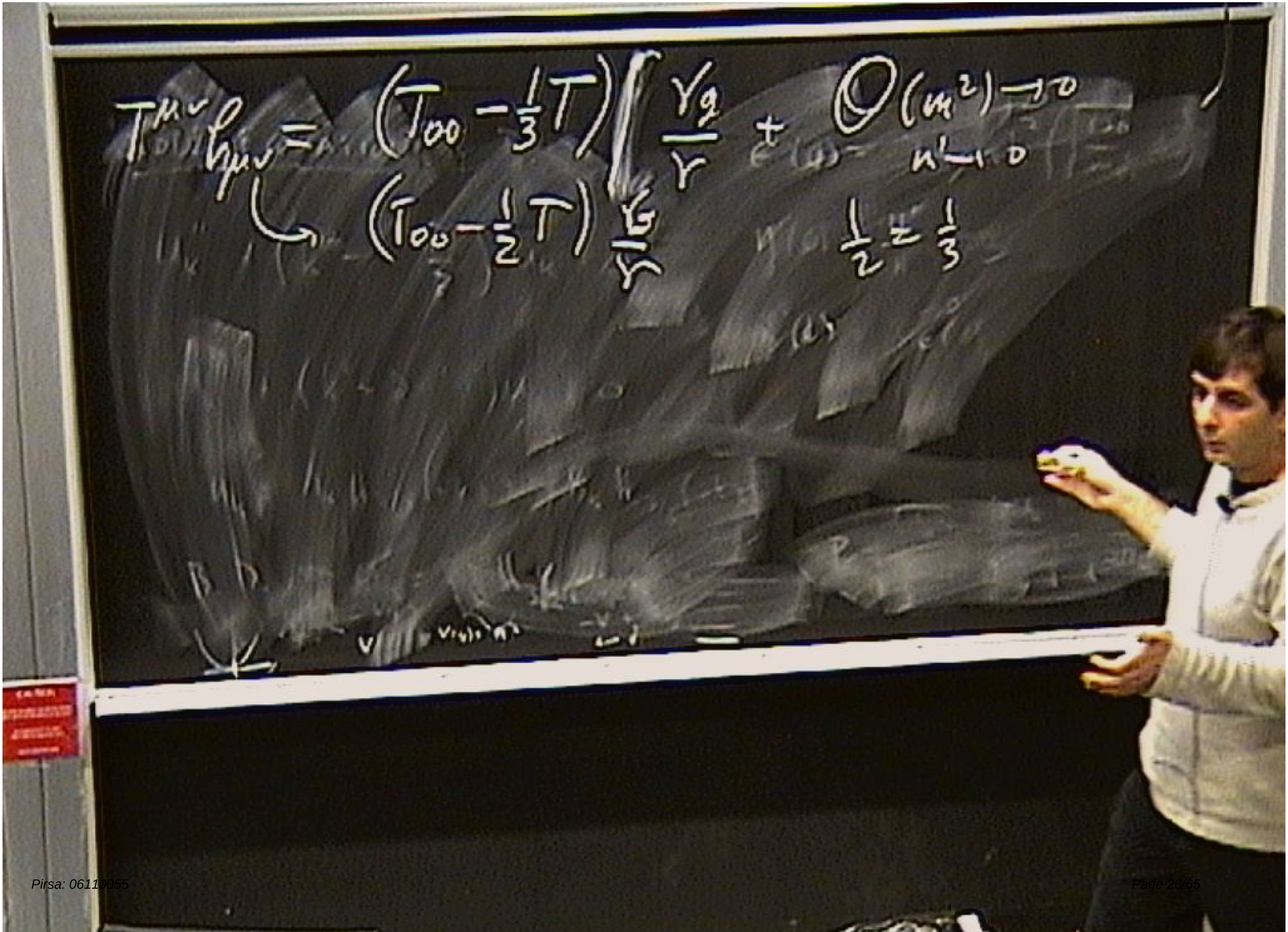
$m^2 = 0 \longrightarrow 2$

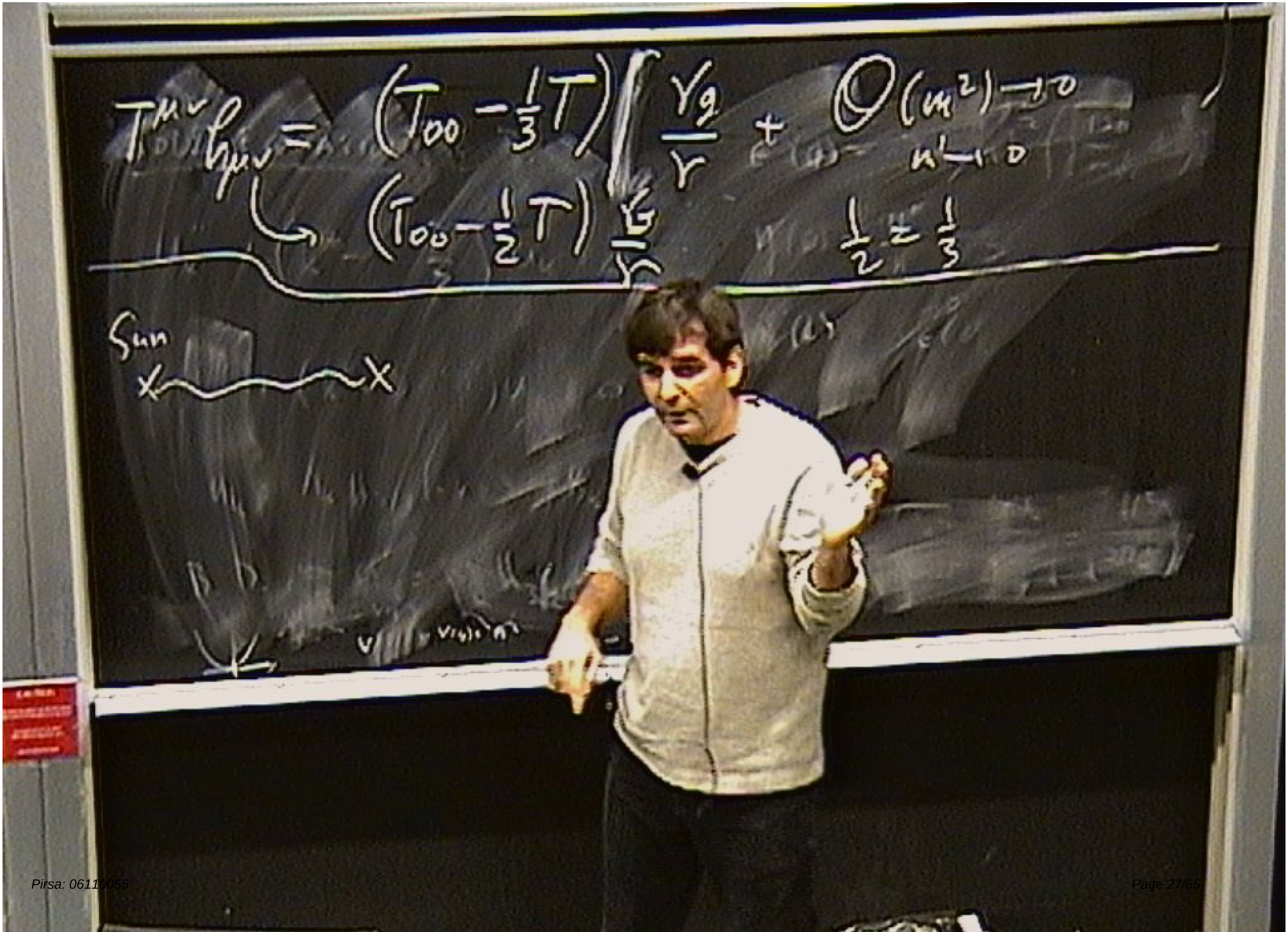
$m^2(\Box) \neq 0 \longrightarrow 5 = 3 + 2 = 2 + 2 + 1$

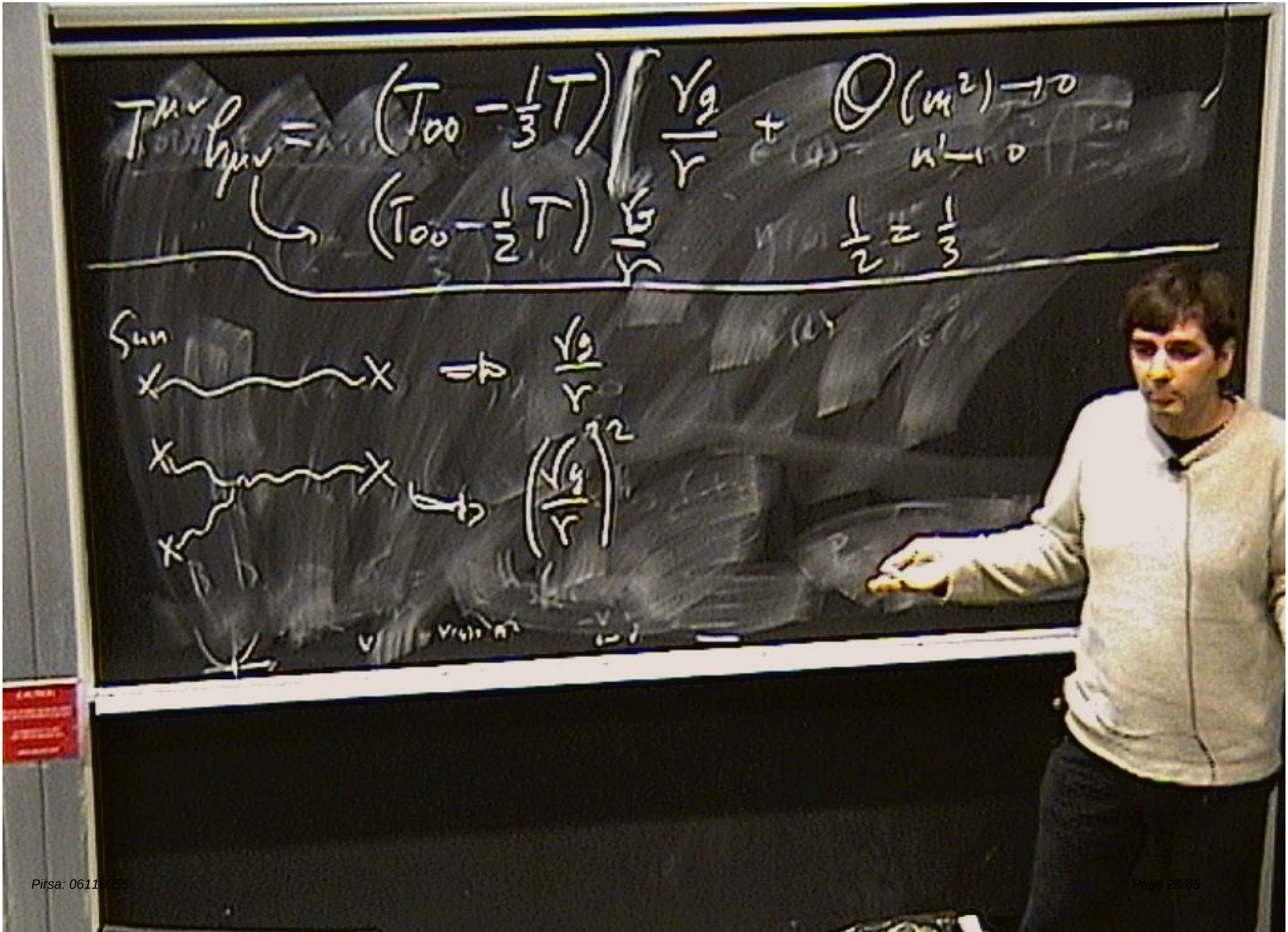
$\partial^\mu T_{\mu\nu} = 0$

$T_{00} = M\,\delta(r)$

$$h_{\mu\nu} = \frac{\delta_\mu^0 \delta_\nu^0 - \frac{1}{3}\left(\eta_{\mu\nu} + \frac{\partial_\mu \partial_\nu}{m^2(\Box)}\right)}{\Box + m^2(\Box)}\, r_g\, \delta(r)$$


T^μν h_μν = (T_00 − 1/3 T) [γG/r ± O(m²) → 0
m² → 0
(T_00 − 1/2 T) G/r
1/2 ≠ 1/3


$T^{\mu\nu} h_{\mu\nu} = (T_{00} - \frac{1}{3} T) \frac{r_g}{r} + O(m^2) \to 0$
$m^2 \to 0$
$(T_{00} - \frac{1}{2} T) \frac{G}{r}$
$\frac{1}{2} \neq \frac{1}{3}$
Sun


Sun

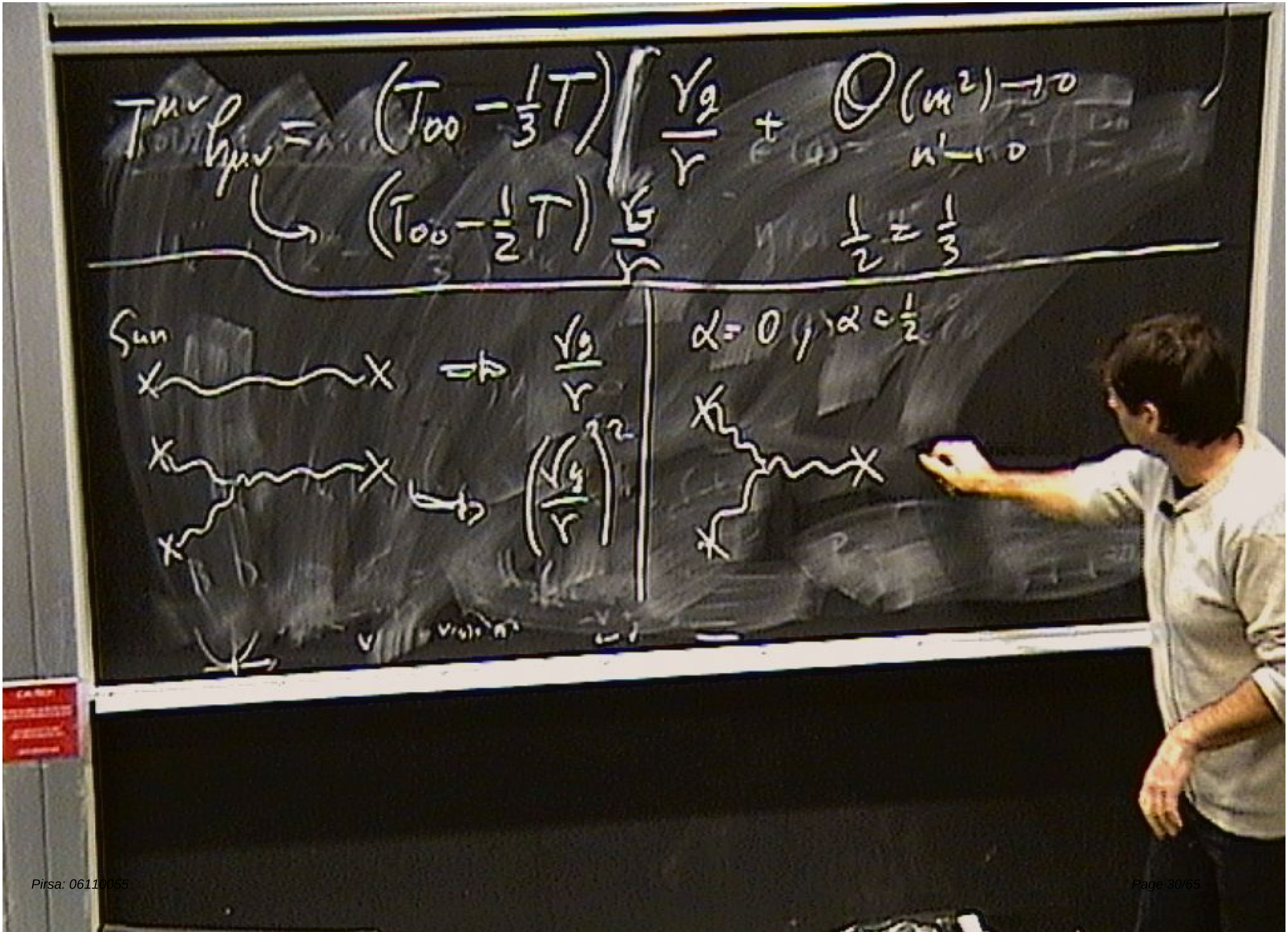
$$T^{\mu\nu} h_{\mu\nu} = \left(T_{00} - \tfrac{1}{3}T\right)\left[\frac{V_g}{r} + \mathcal{O}(m^2) \underset{m^2 \to 0}{\longrightarrow} 0\right.$$

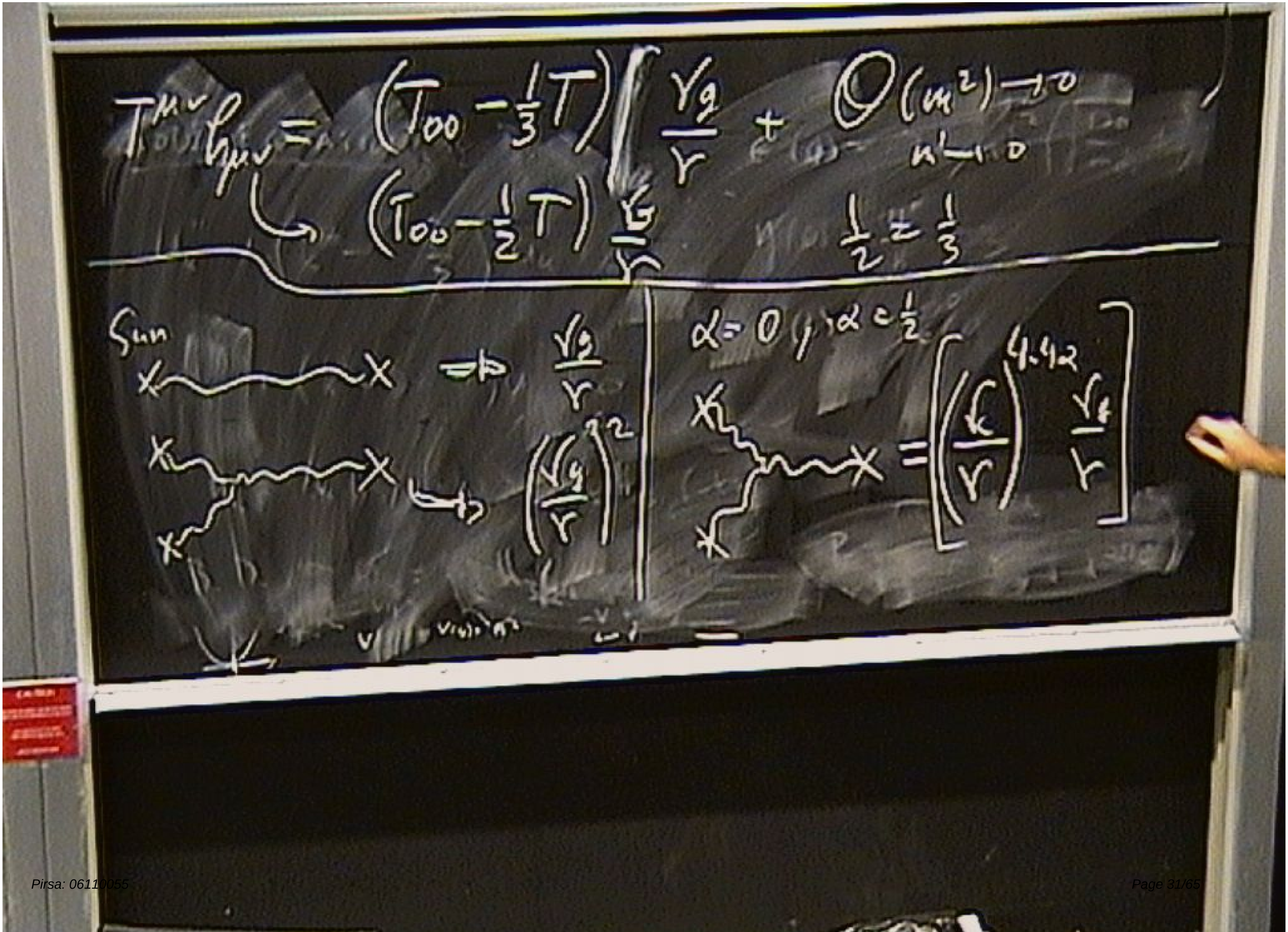
$$\hookrightarrow \left(T_{00} - \tfrac{1}{2}T\right)\frac{V_g}{r} \qquad \tfrac{1}{2} \neq \tfrac{1}{3}$$

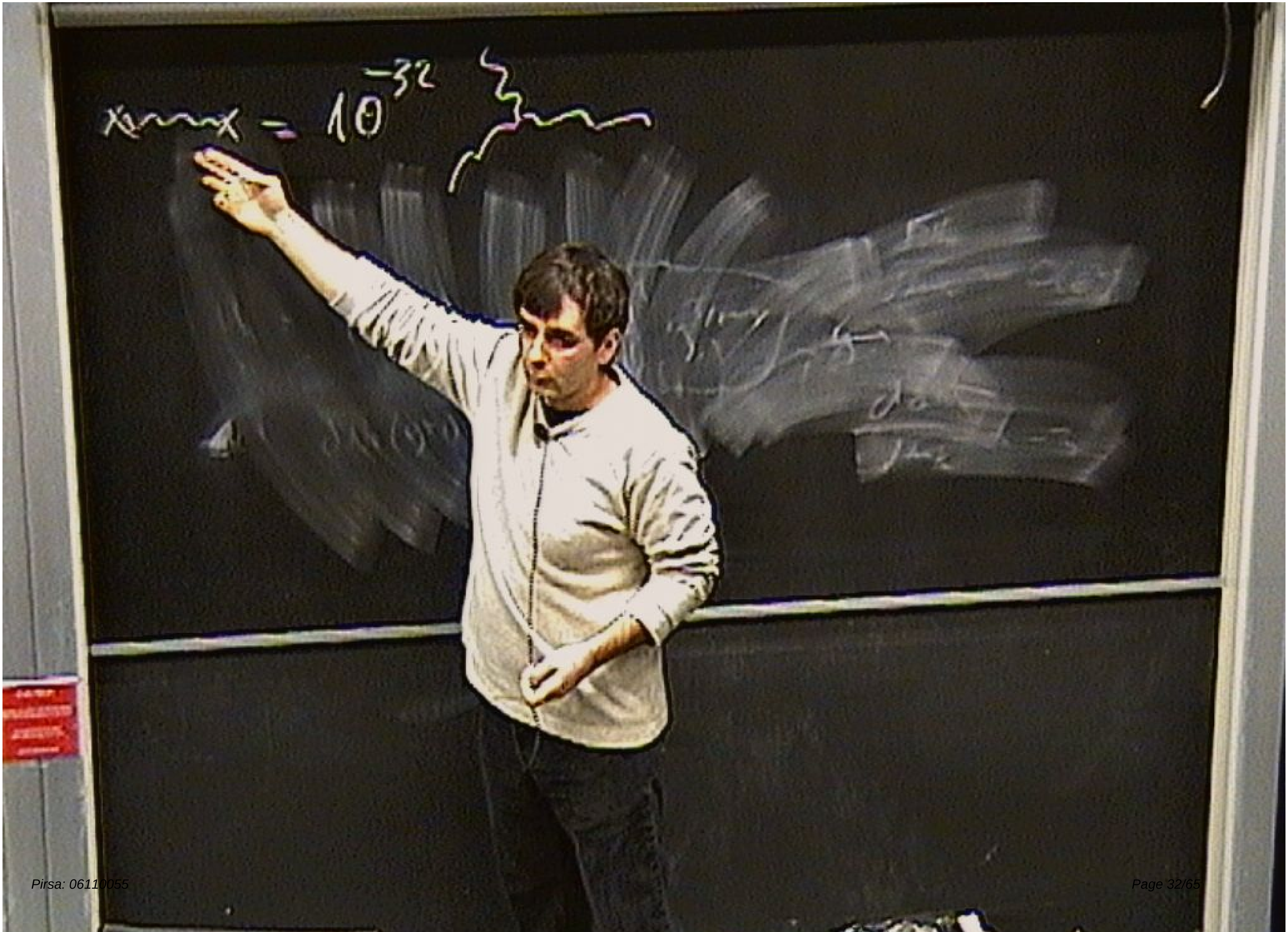
Sun

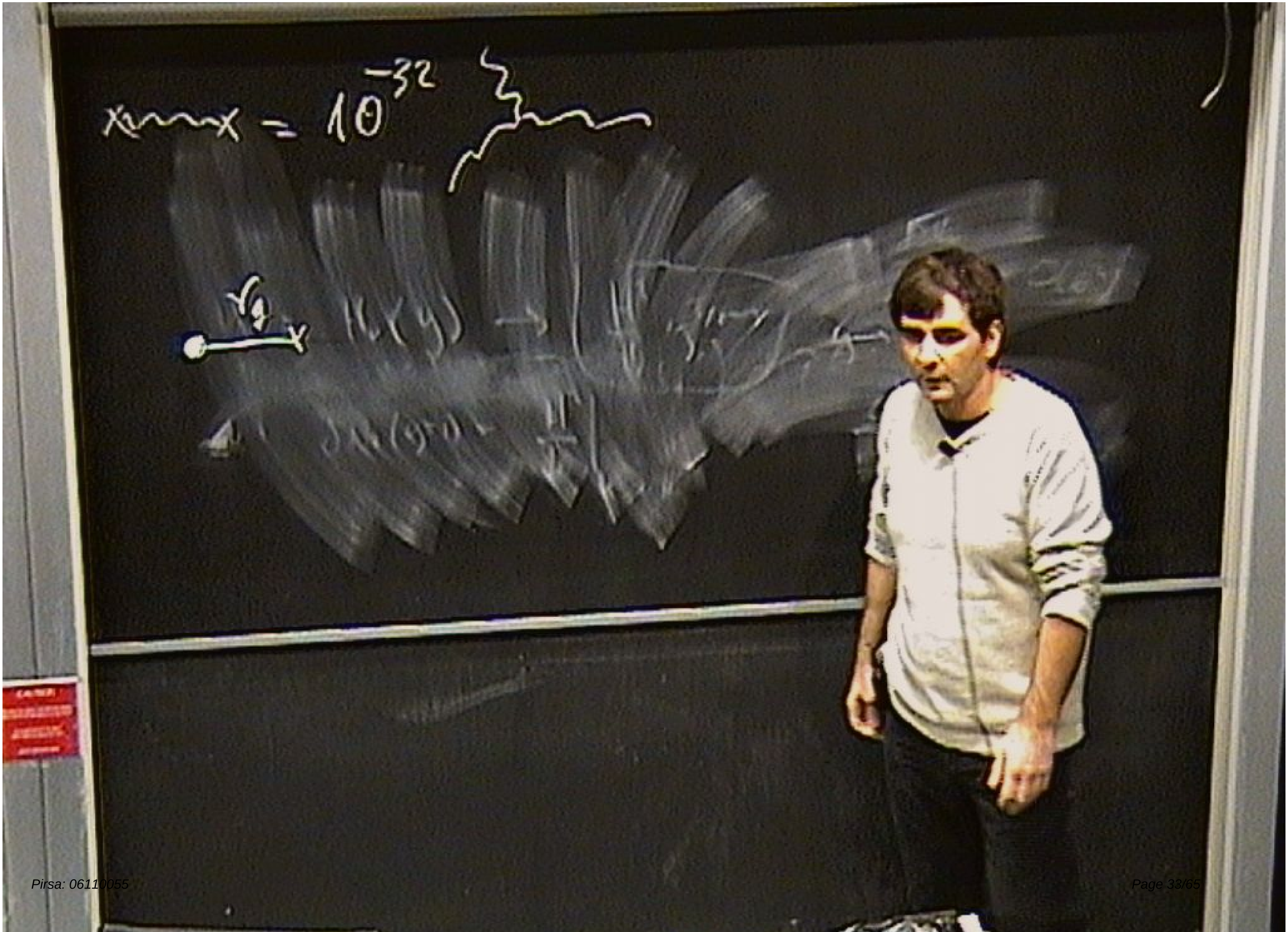
$$\Rightarrow \frac{V_g}{r}$$

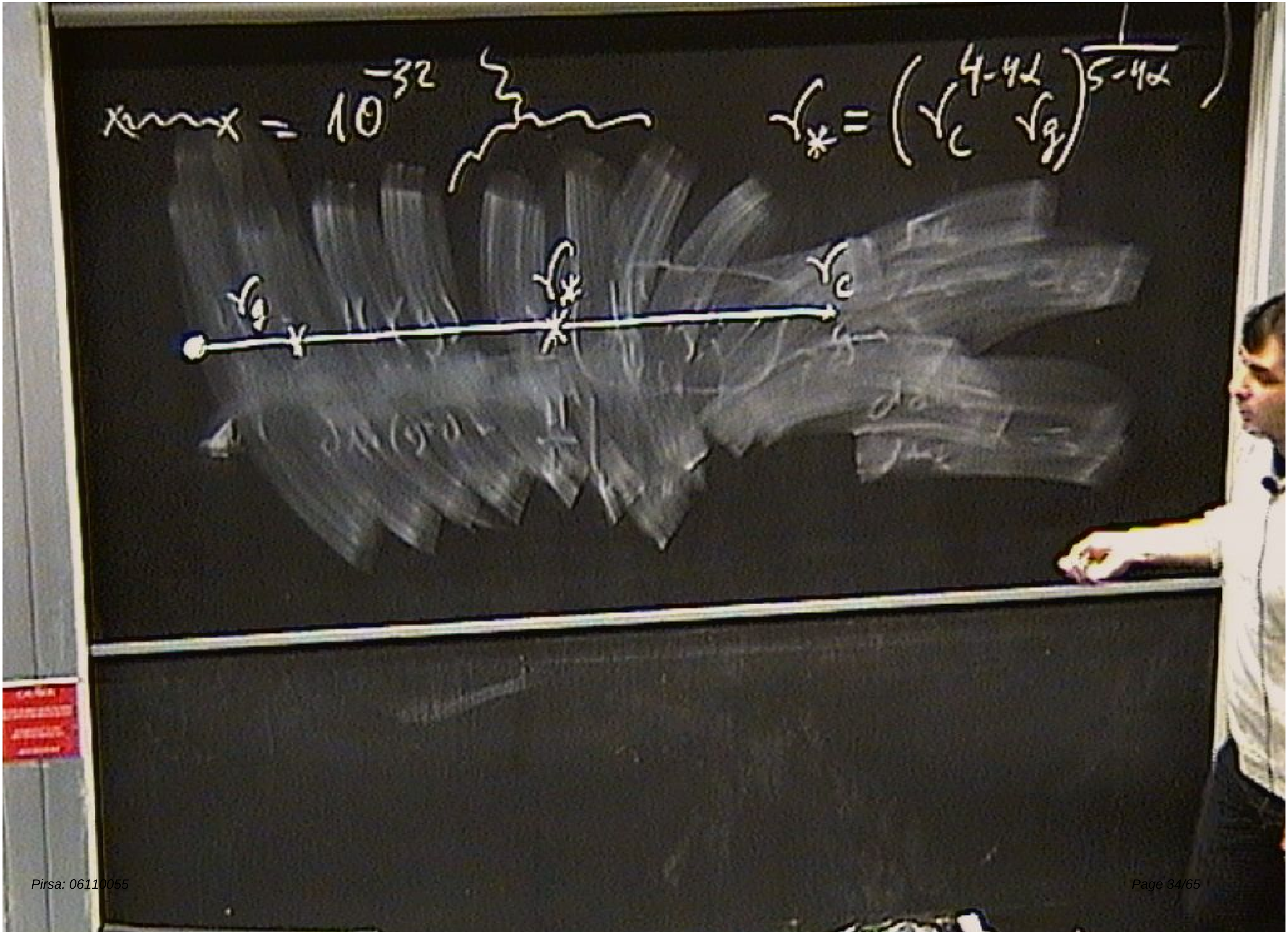
$$\Rightarrow \left(\frac{V_g}{r}\right)^2$$

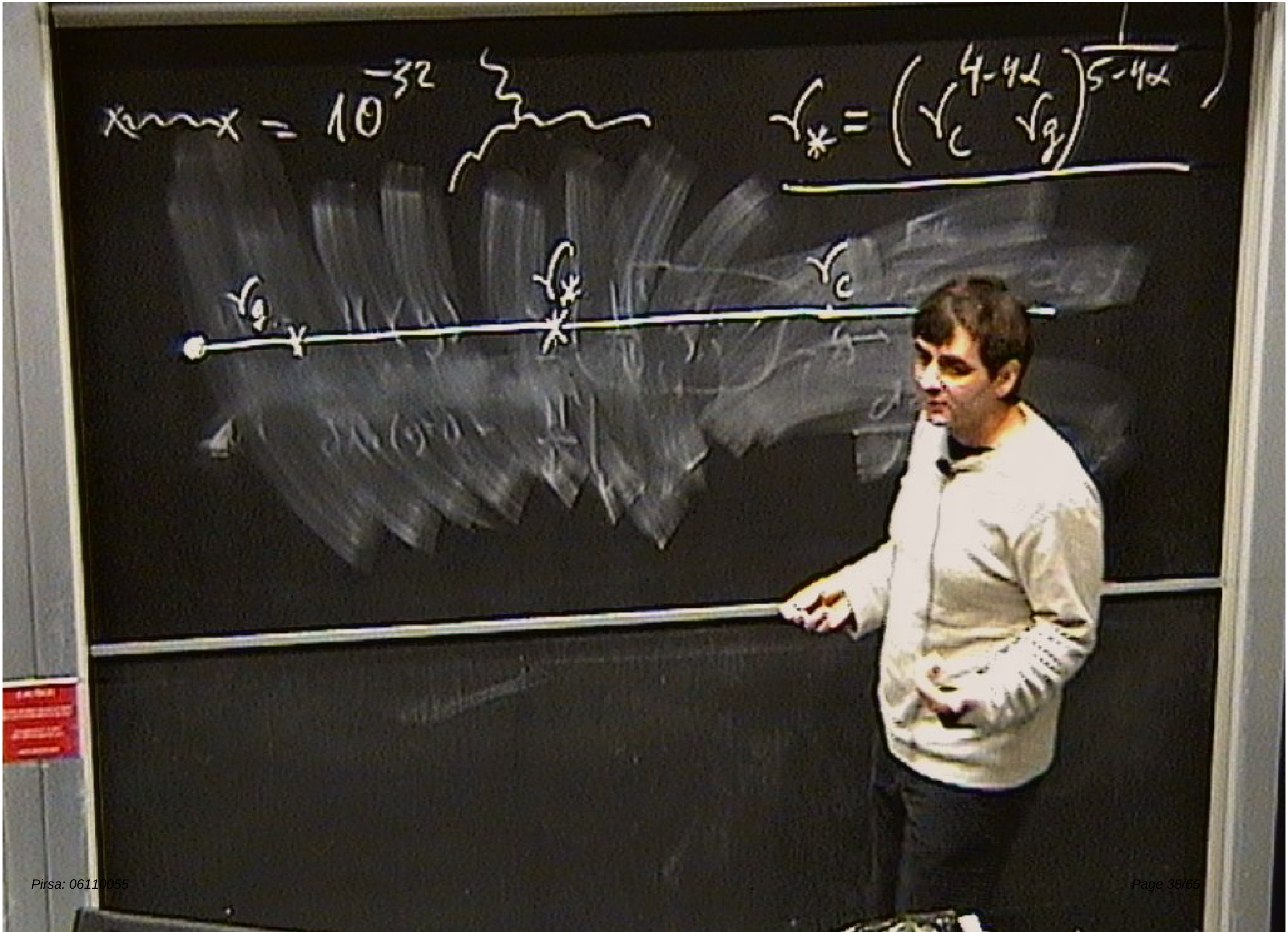

T^{μν} h_{μν} = (T_00 − 1/3 T) [Y_g/r + O(m²) → 0
m² → 0
(T_00 − 1/2 T) G/r
1/2 ≠ 1/3
Sun
X ~~~ X ⟹ Y_g/r
(Y_g/r)²
α = 0 , α < 1/2

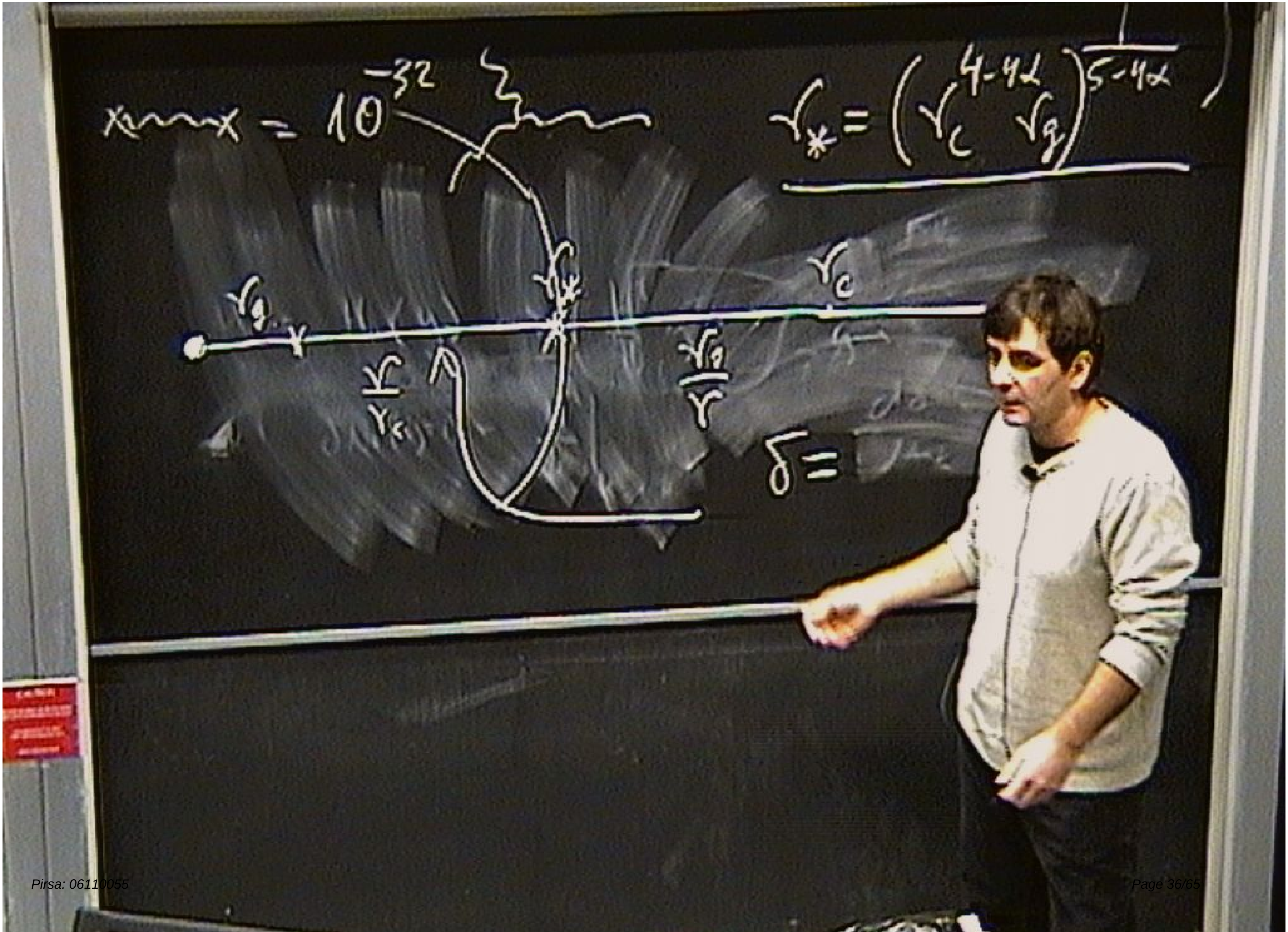

$T^{\mu\nu} h_{\mu\nu} = (T_{00} - \frac{1}{3}T)\left[\frac{r_g}{r} + O(m^2) \to 0\right]$
$(T_{00} - \frac{1}{2}T)\frac{G}{r}$
$\frac{1}{2} \neq \frac{1}{3}$
Sun
$\frac{r_g}{r}$
$\left(\frac{r_g}{r}\right)^2$
$\alpha = 0,\ \alpha < \frac{1}{2}$

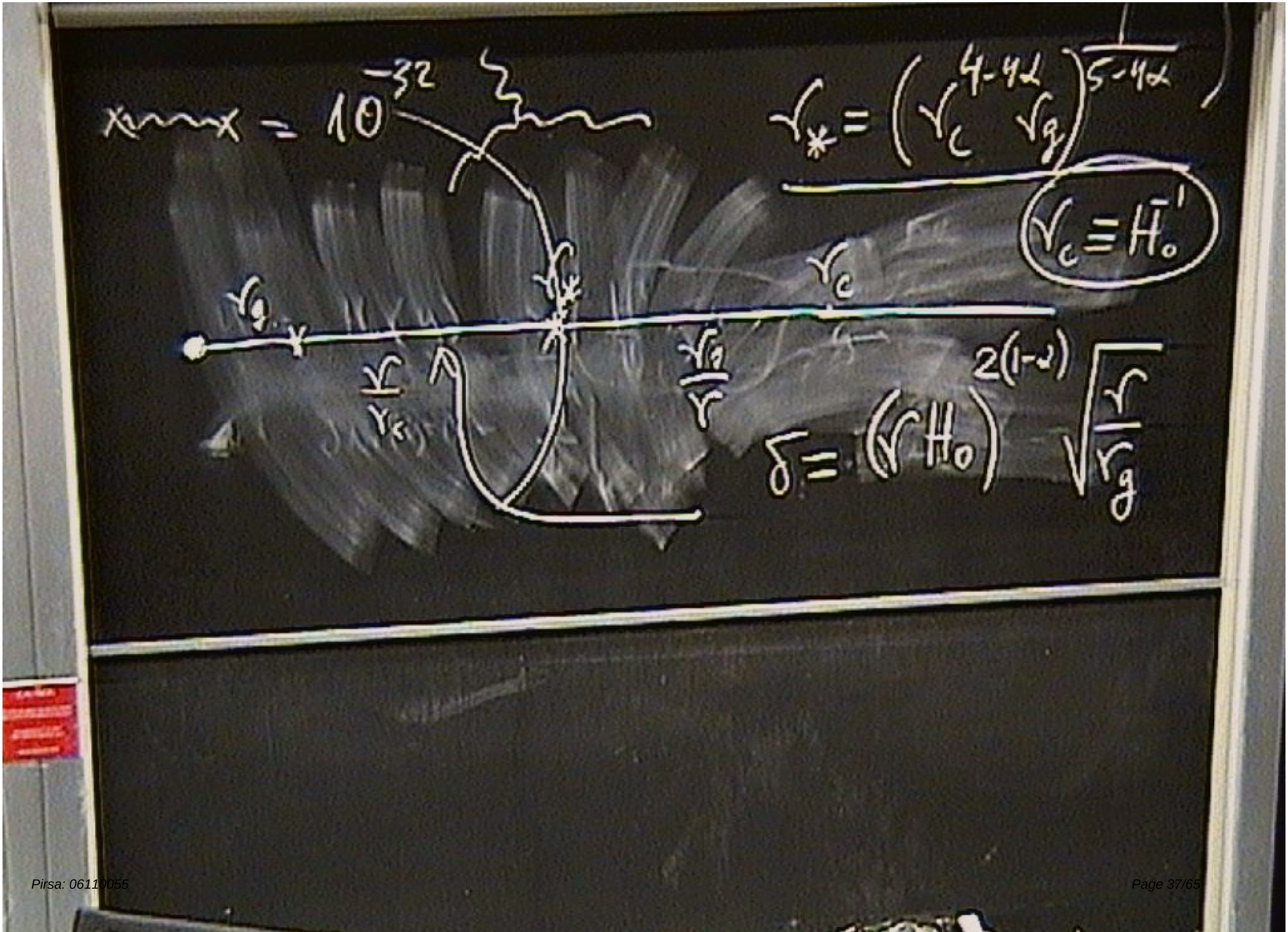

$x_{max} = 10^{-32}$

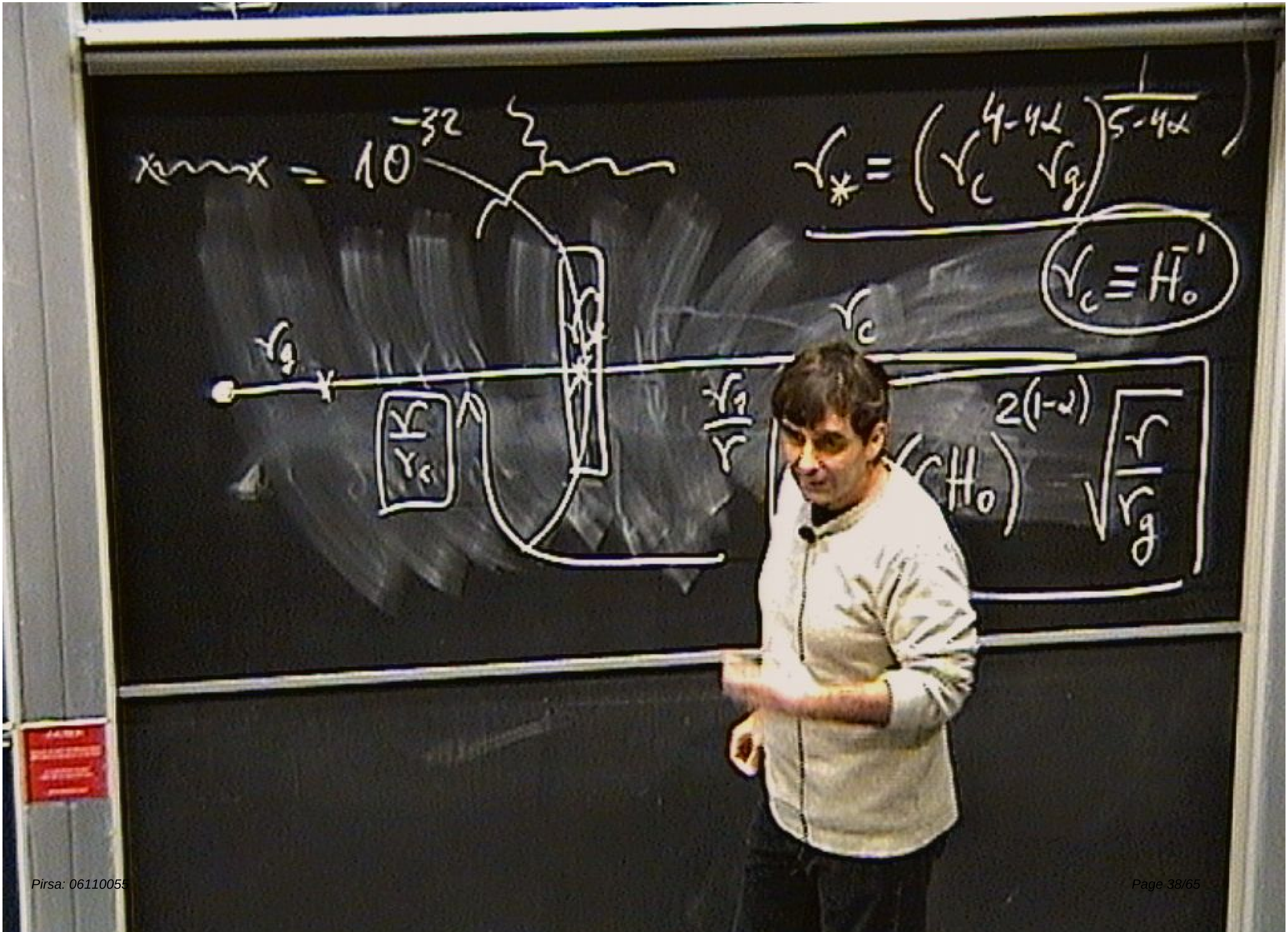


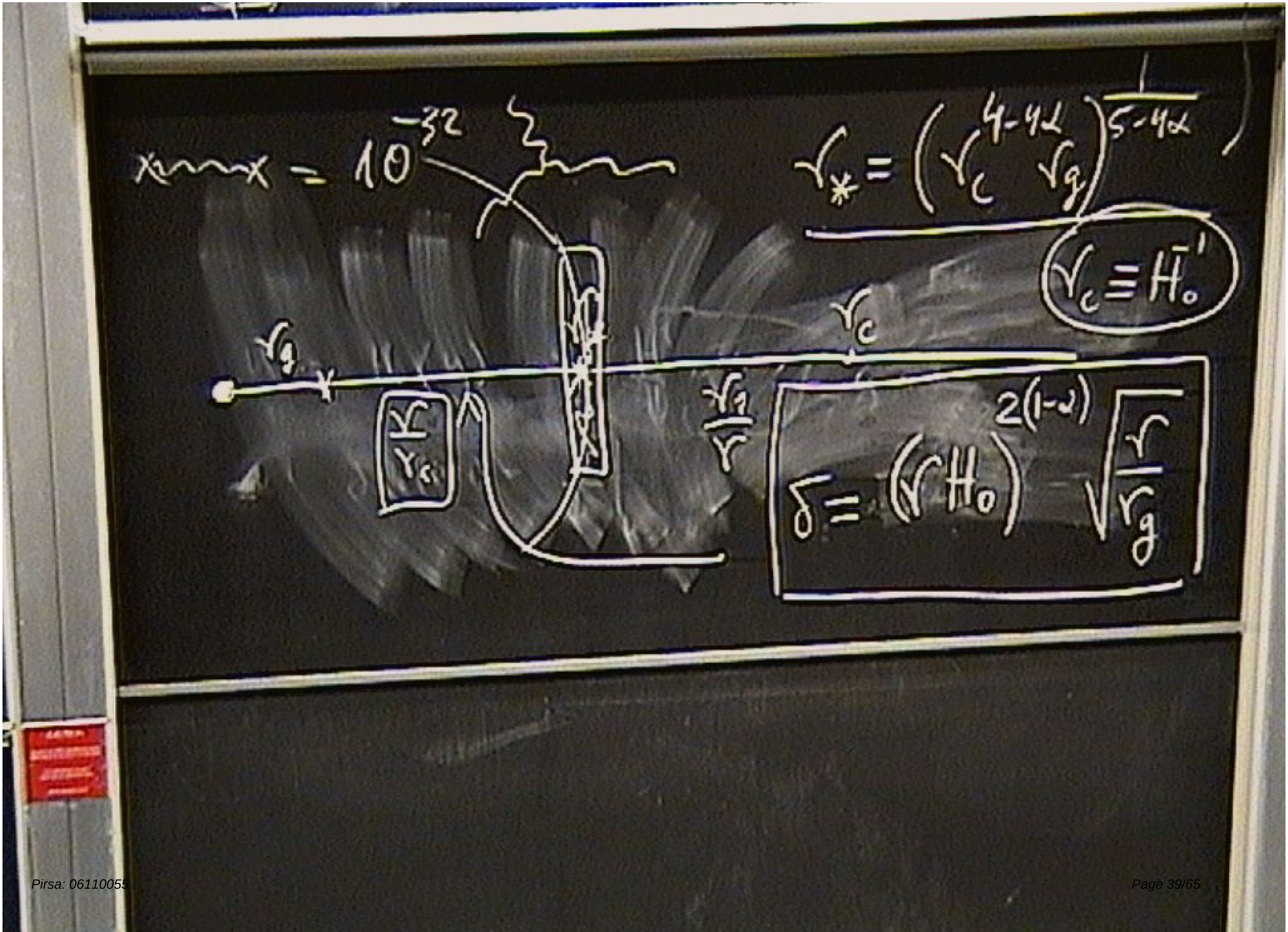

x~~~x = 10^-32
r_* = (r_c^(4-4α) r_g)^(1/(5-4α))
r_g
r_*
r_c

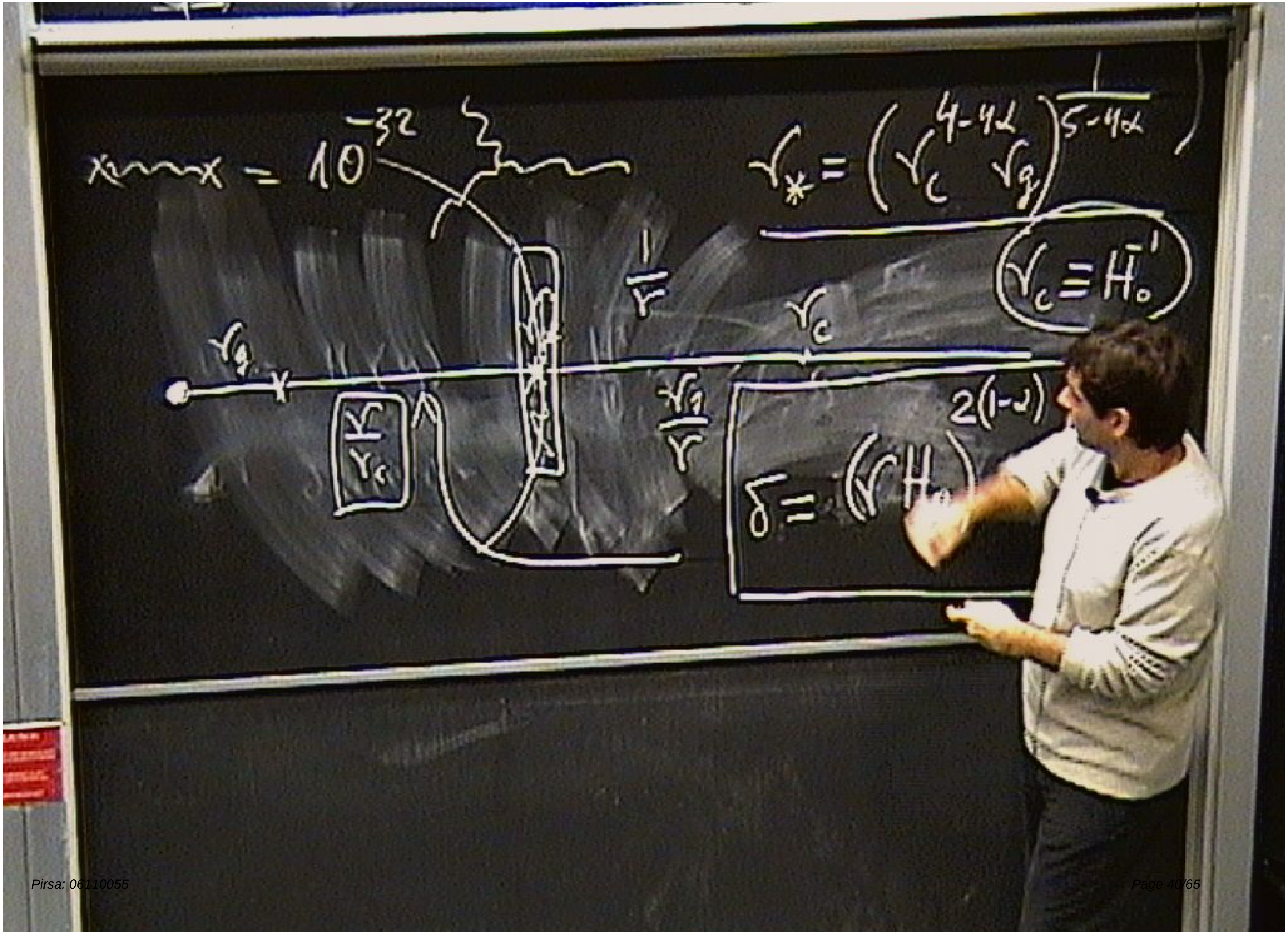

$= 10^{-32}$
$r_* = \left(r_c^{4-4\alpha} \, r_g \right)^{\frac{1}{5-4\alpha}}$
r_g
r_*
r_c

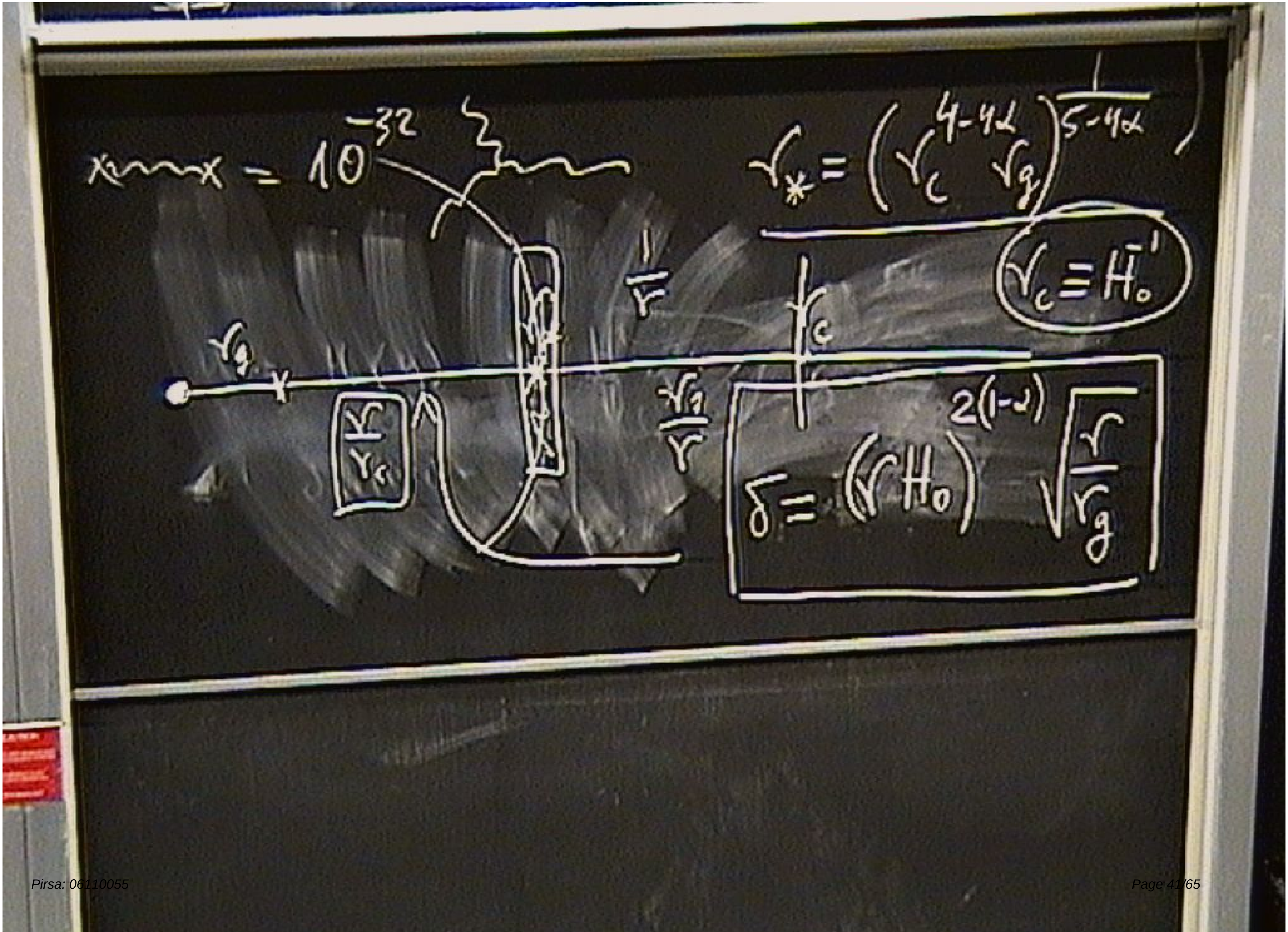

= 10^-32
r* = (rc^(4-4α) rg)^(1/(5-4α))
rg
rc
r*
δ =

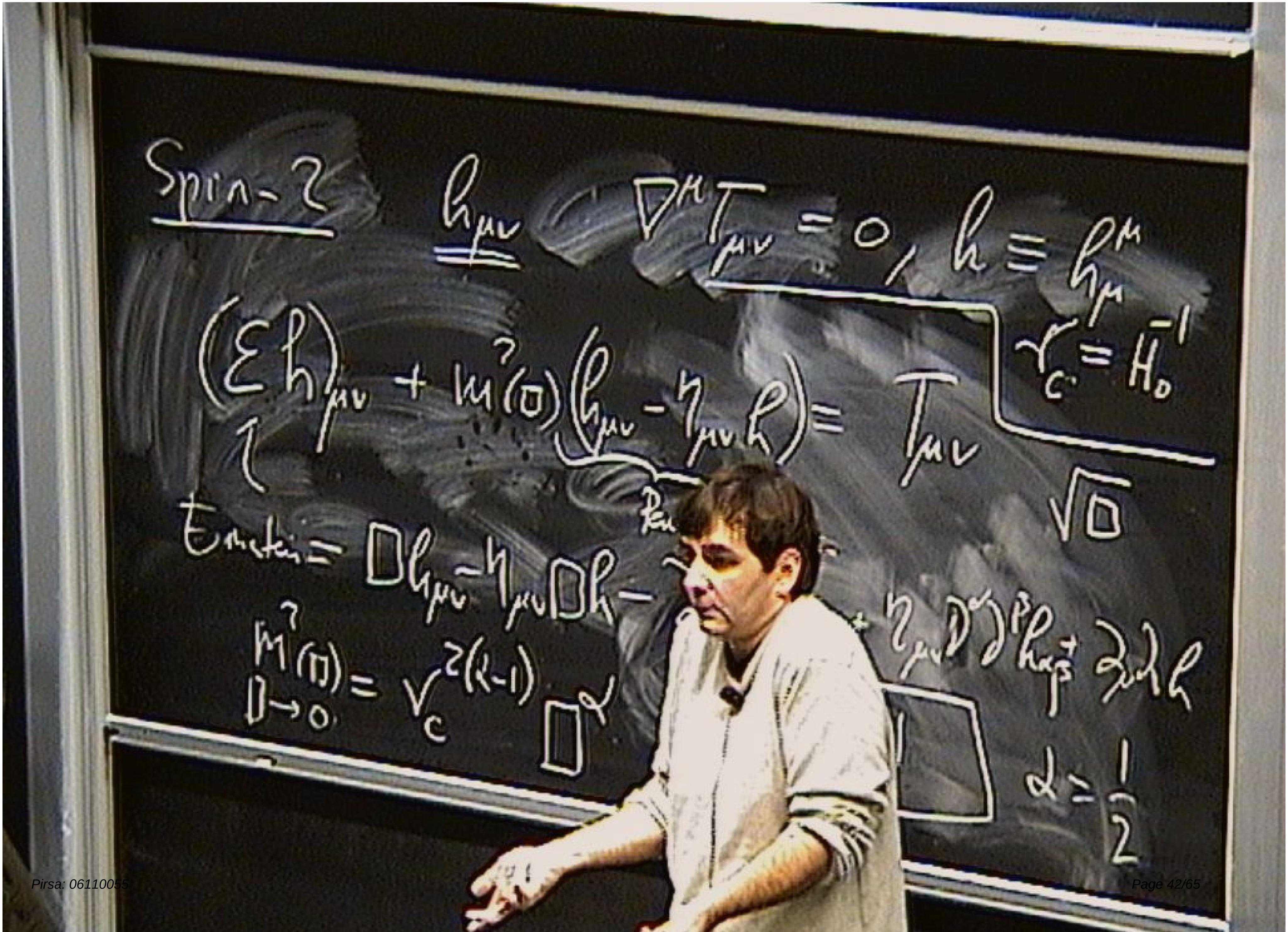

x~~~x = 10^-32
r_* = (r_c^{4-4α} r_g)^{1/(5-4α)}
r_c ≡ H_0^{-1}
r_g
r_*
r_c
δ = (r H_0)^{2(1-α)} √(r/r_g)

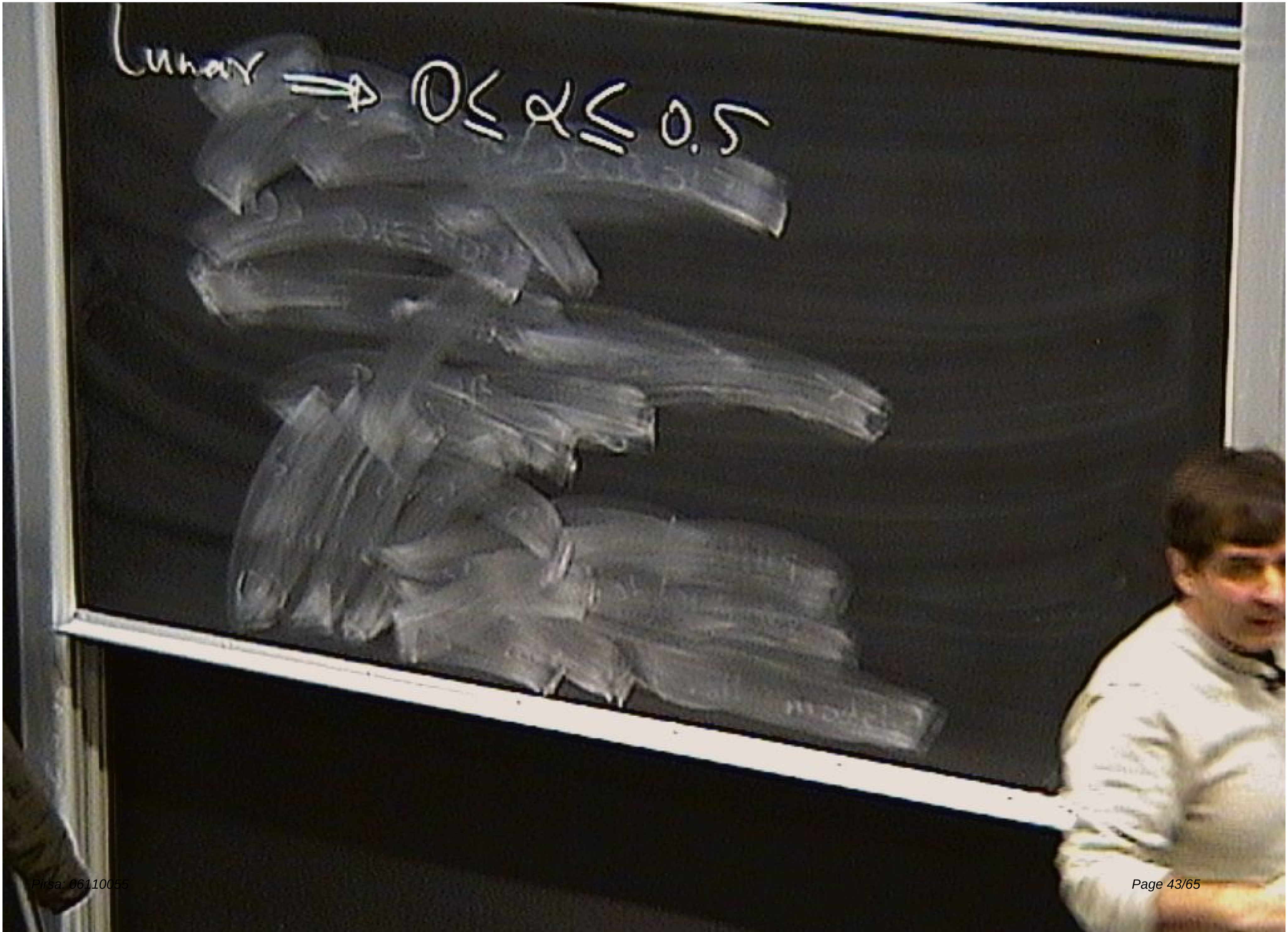


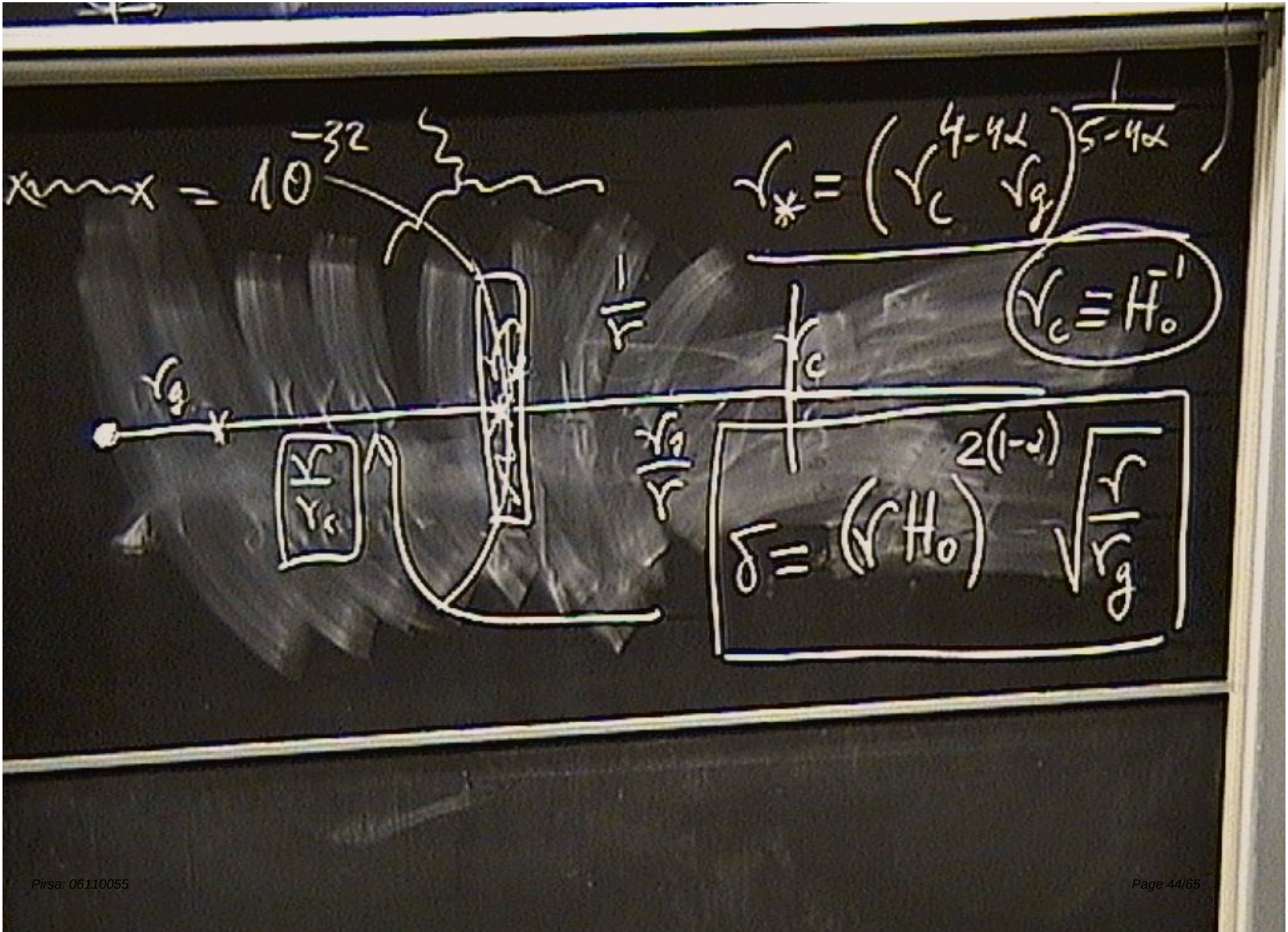

10^-32
r_* = (r_c^{4-4α} r_g)^{1/(5-4α)}
r_c ≡ H_0^{-1}
r_g
r_c
r/r_c
δ = (r H_0)^{2(1-α)} √(r/r_g)

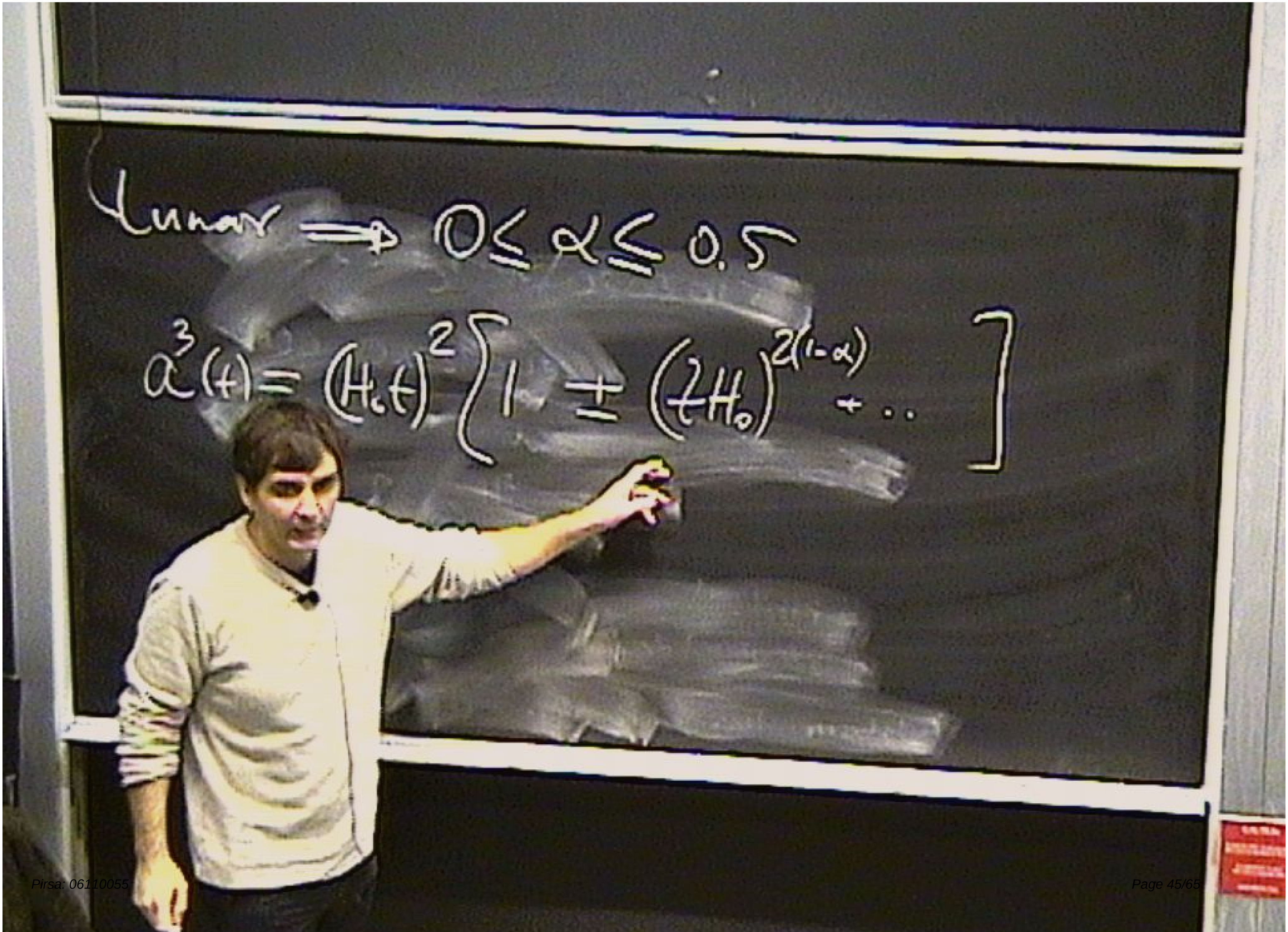

x~~~x = 10^-32
r* = (rc^4-4α rg)^1/(5-4α)
rc ≡ H0^-1
rg
rc
δ = (r H0)^2(1-α)

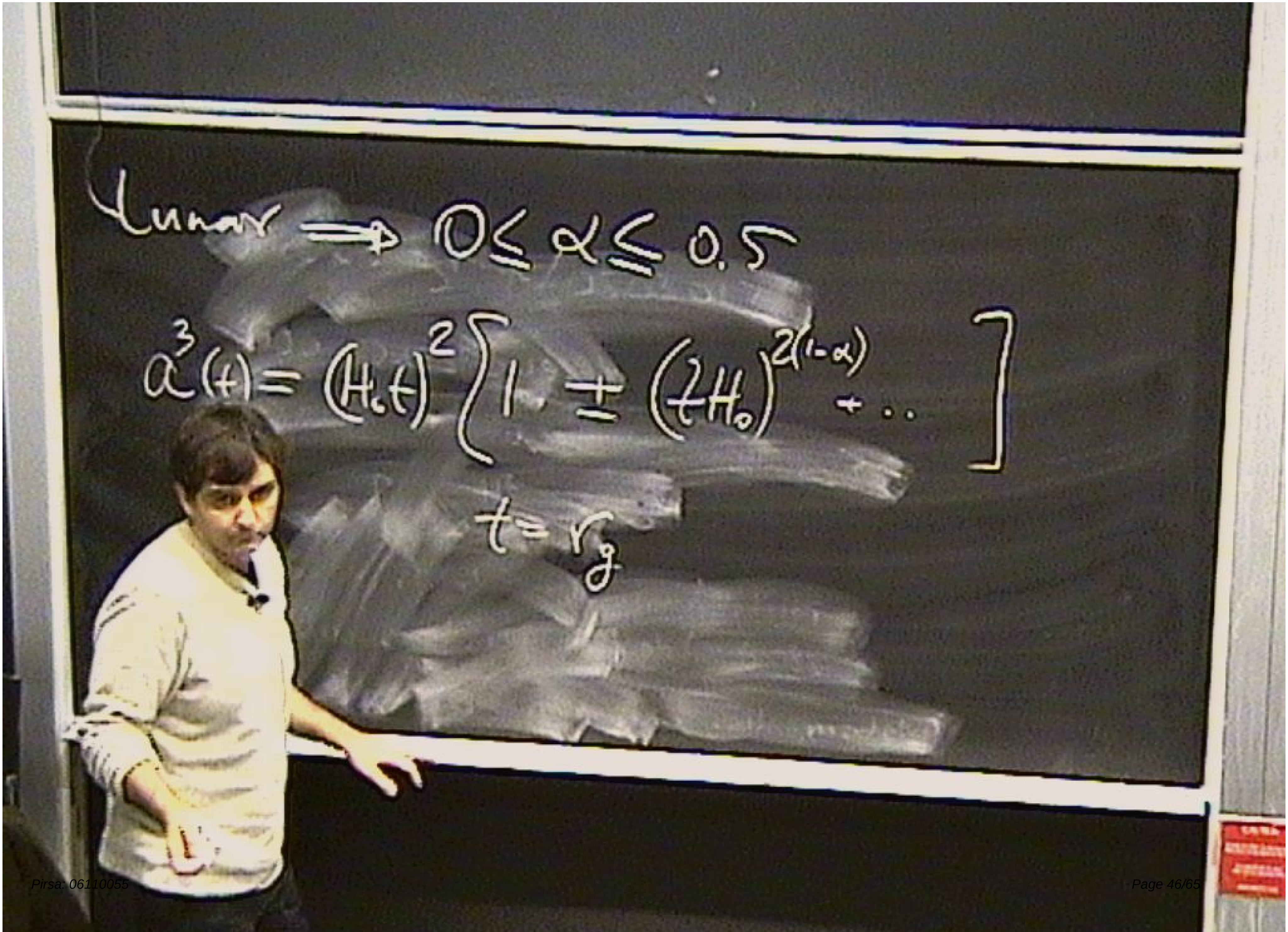

$x \sim\sim x = 10^{-32}$
$r_* = \left(r_c^{4-4\alpha}\, r_g\right)^{\frac{1}{5-4\alpha}}$
$r_c \equiv H_0^{-1}$
r_g
r_c
$\frac{1}{r}$
$\frac{r_g}{r}$
$\frac{r}{r_c}$
$\delta = (r H_0)^{2(1-\alpha)} \sqrt{\frac{r}{r_g}}$

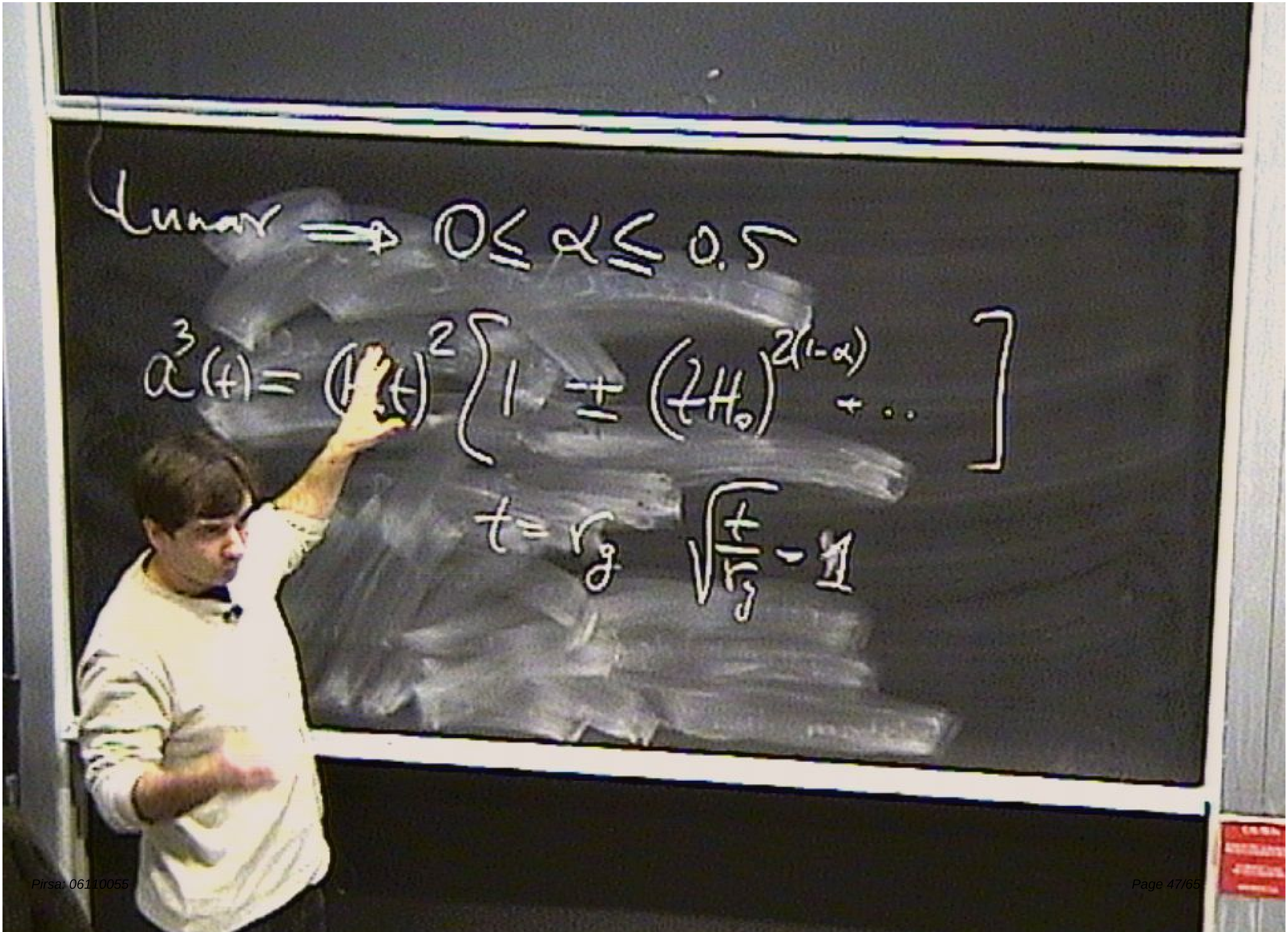

Spin-2
hμν
∇μ Tμν = 0, h ≡ hμμ
(Eh)μν + m²(□)(hμν − ημν h) = Tμν
rc = H0⁻¹
√□
m²(□) = rc^2(α−1) □^α
□→0
α = 1/2

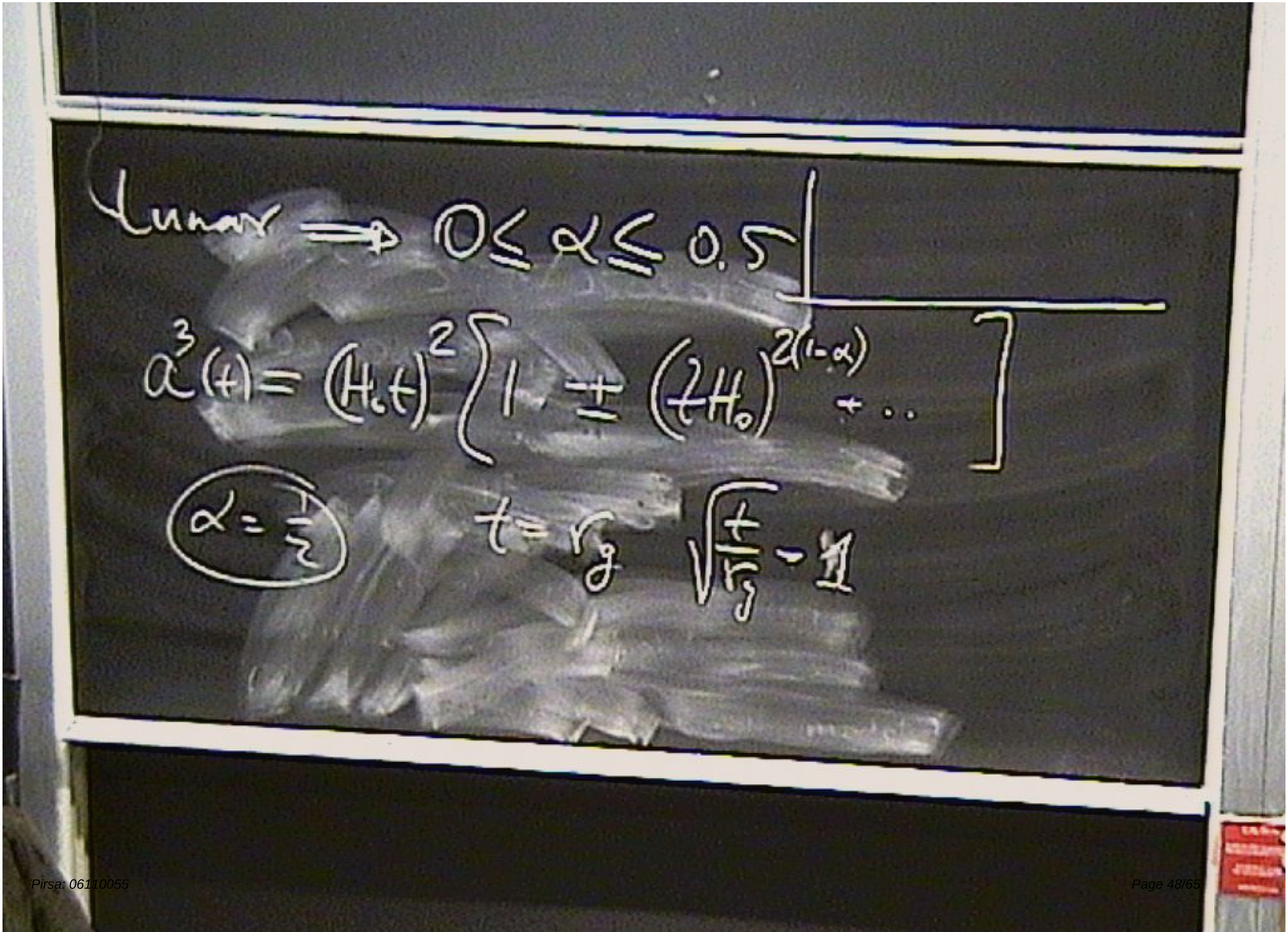

Lunar ⟹ 0 ≤ α ≤ 0.5

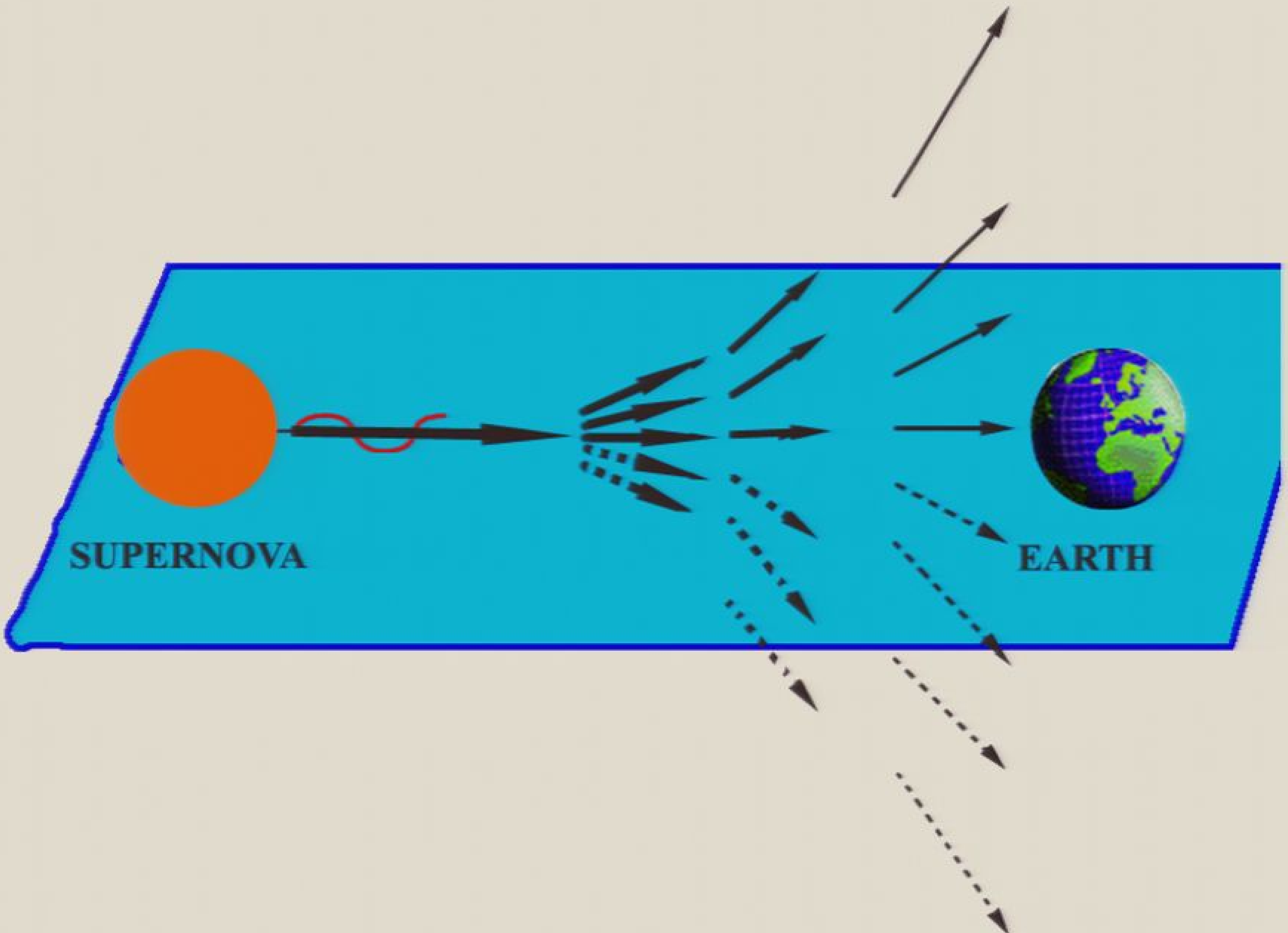

10^{-32}
$r_* = \left(r_c^{4-4\alpha}\, r_g\right)^{\frac{1}{5-4\alpha}}$
$r_c \equiv H_0^{-1}$
r_g
r_c
$\frac{1}{r}$
$\frac{r_g}{r}$
$\frac{r}{r_c}$
$\delta = (r H_0)^{2(1-\alpha)} \sqrt{\frac{r}{r_g}}$

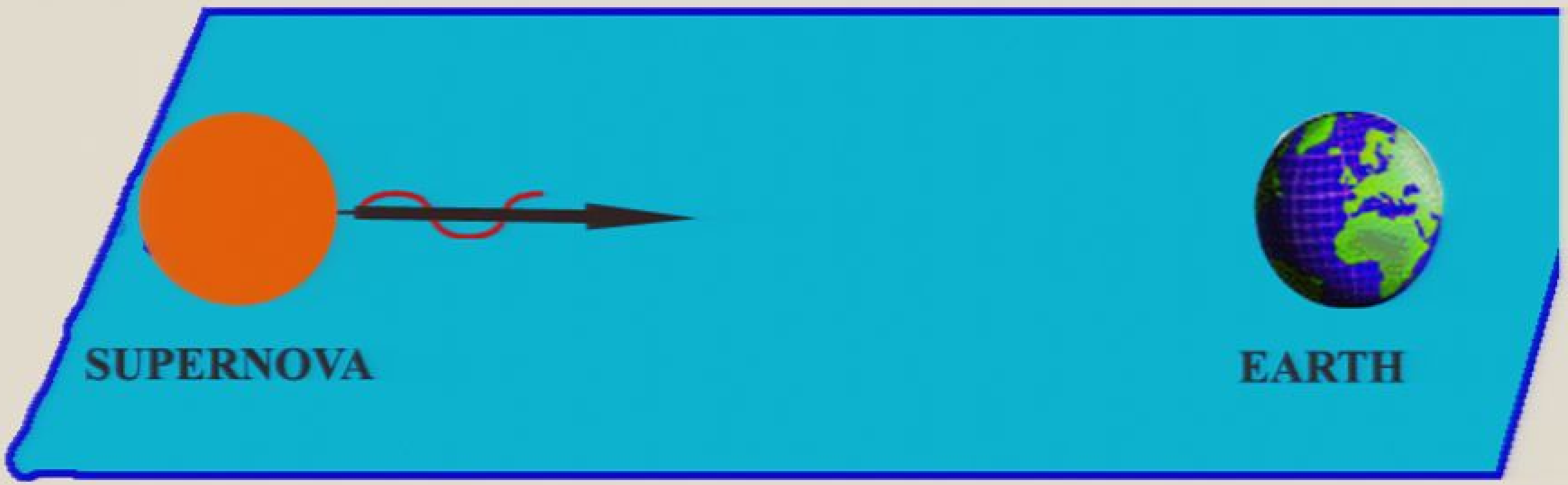

Lunar ⟹ 0 ≤ α ≤ 0.5
a³(t) = (H₀t)² [1 ± (tH₀)^2(1-α) + ..]


linear ⟹ 0 ≤ α ≤ 0.5
a³(t) = (H₀t)² [1 ± (tH₀)^{2(1-α)} + ...]
t = r_g


lunar ⇒ 0 ≤ α ≤ 0.5
t = r_g √(t/r_g − 1)

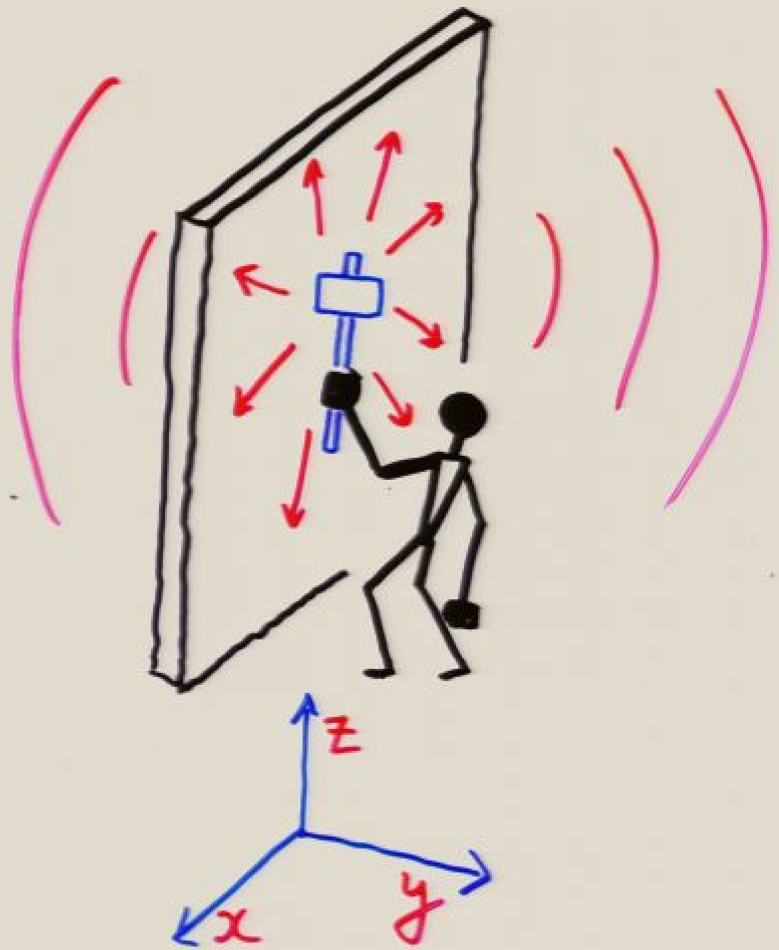

Linear ⇒ $0 \leq \alpha \leq 0.5$
$a^3(t) = (H_0 t)^2 \left[1 \pm (t H_0)^{2(1-\alpha)} + \dots \right]$
$\alpha = \frac{1}{2}$
$t = r_g \sqrt{\frac{t}{r_g} - 1}$


SUPERNOVA
EARTH

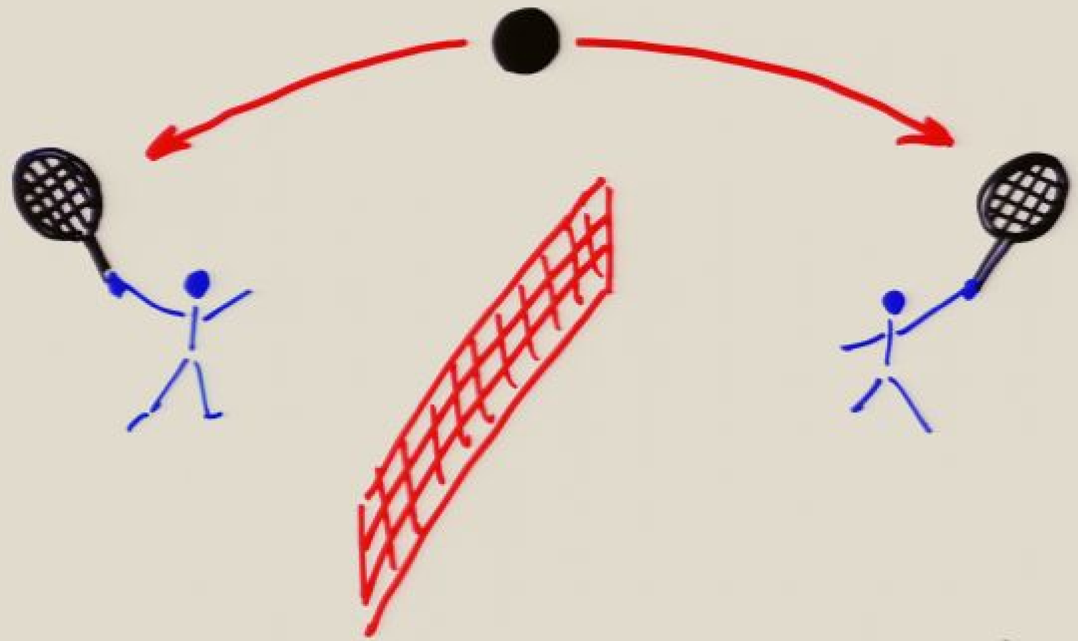

SUPERNOVA
EARTH

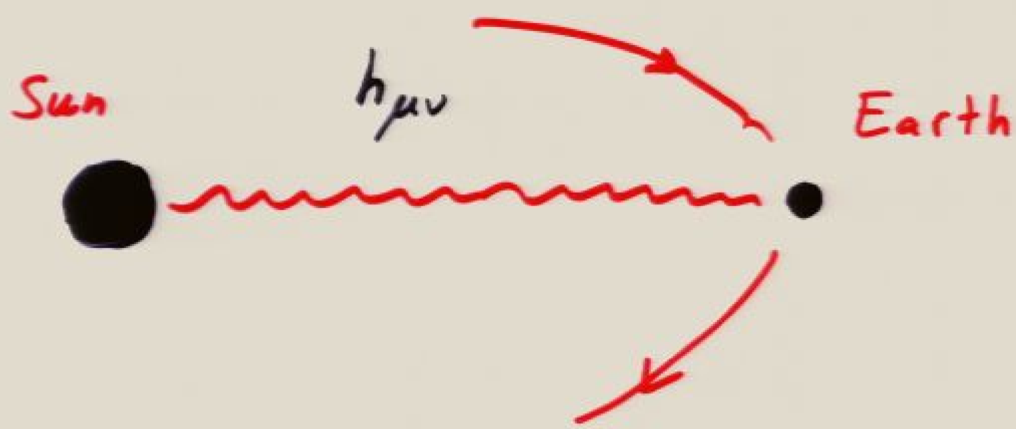
SOUND WAVE

DGP '00



$$\left\{ \delta(y)\,\Box_{2+1} + \frac{1}{r_c}\,\Box_{3+1} \right\} \phi = S^{4}(x)$$




Sun
$h_{\mu\nu}$
Earth

FRW Equation is modified

$$H^2 - H/r_c = \frac{8\pi}{3} G_N \rho$$

Early cosmology in normal $H >> r_c^{-1}$

Late cosmology $H \rightarrow H = r_c^{-1}$

At late times Universe is self-accelerating!

NO NEED IN DARK ENERGY.

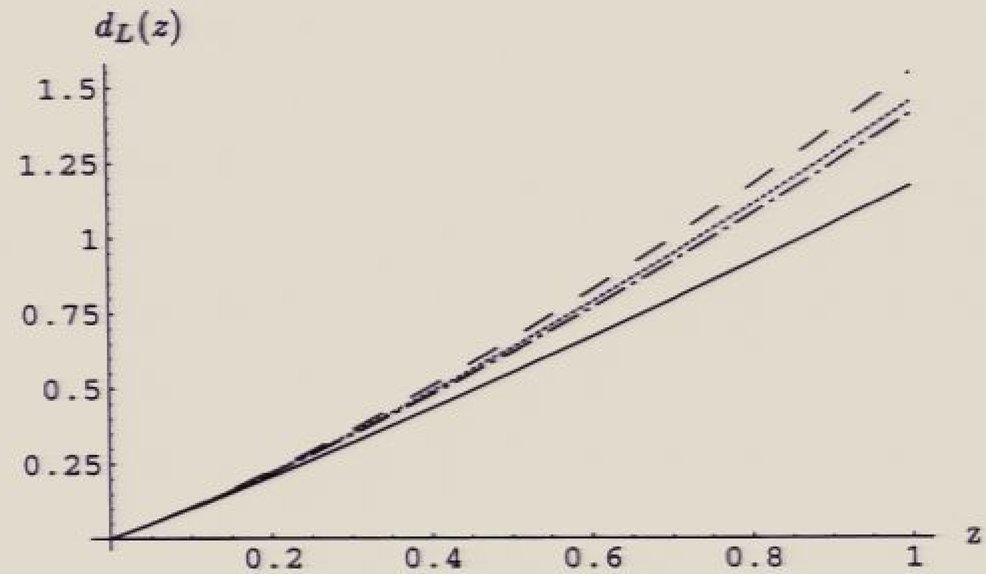
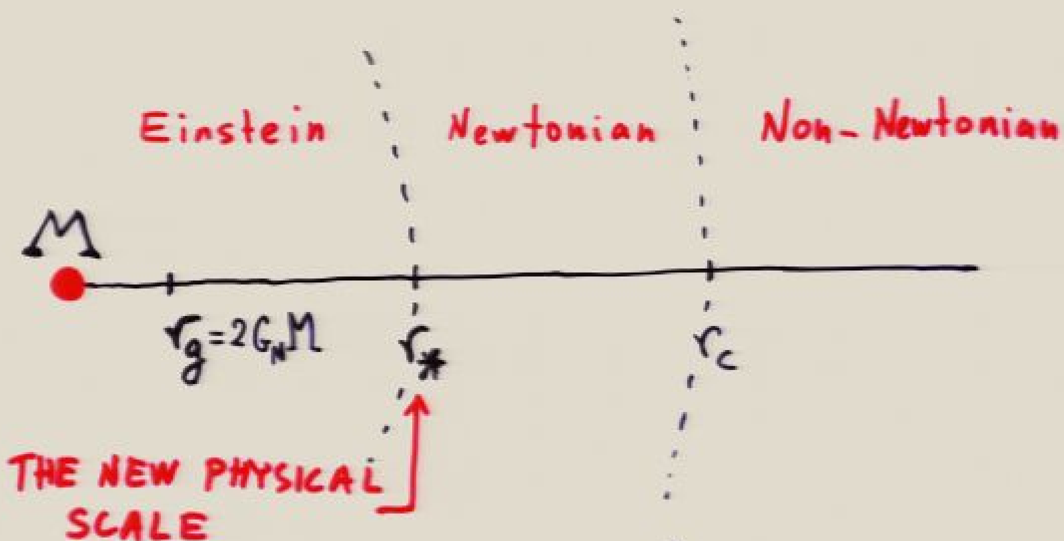


Figure 2: Luminosity distance as a function of red-shift for ordinary cosmology with $\Omega_\Lambda = 0.7, \Omega_M = 0.3, k = 0$ (dashed line), $\Omega_\Lambda = 0, \Omega_M = 1, k = 0$ (solid line), and dark energy with $\Omega_X = 0.7, w_X = -0.6, \Omega_M = 0.3, k = 0$ (dotted-dashed line) and in our model (dotted line) with $\Omega_M = 0.3$ and a flat universe (for which one gets from equation (28) $\Omega_{r_c} = 0.12$ and $r_c = 1.4H_0^{-1}$).

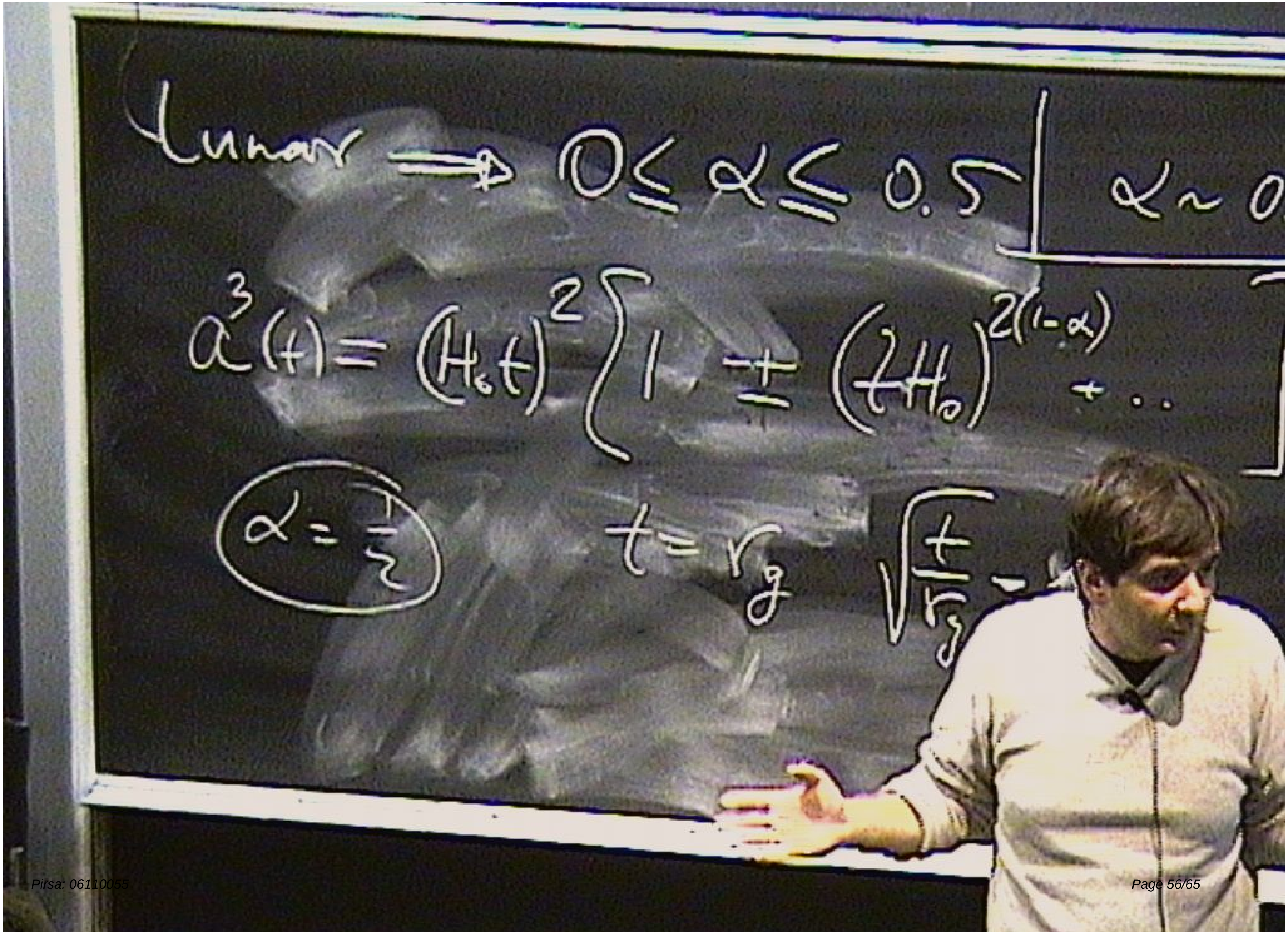
Corrections to Einstein are Source-dependent

Corrections to Einstein

$$\begin{cases} \neq \dfrac{r}{r_c} \\[2ex] = \left(\dfrac{r}{r_*}\right)^{3/2} \end{cases} \qquad r_* \ll r_c$$

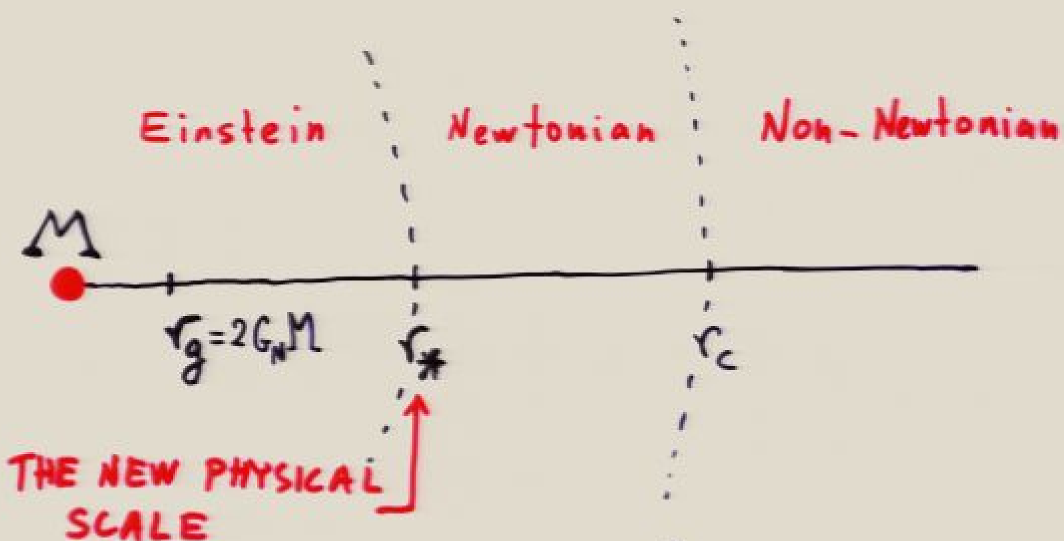


$$r_* = \left(r_c^2 r_g\right)^{\frac{1}{3}}$$

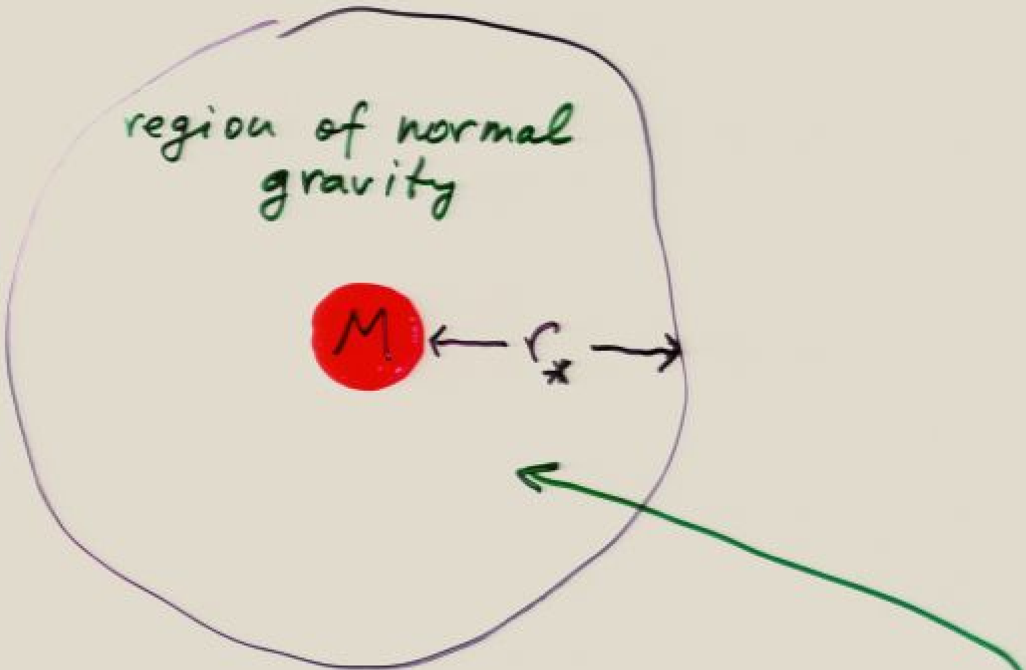

Lunar ⟹ 0 ≤ α ≤ 0.5
α ~ 0
a^3(t) = (H_0 t)^2 [1 ± (t H_0)^2(1-α) + ...
α = 1/2
t = r_g √(t/r_g

Corrections to Einstein are Source-dependent

Corrections to Einstein
$$\begin{cases} \neq \dfrac{r}{r_c} \\ = \left(\dfrac{r}{r_*}\right)^{3/2} \end{cases} \qquad r_* \ll r_c$$



$$r_* = \left(r_c^2 r_g\right)^{\frac{1}{3}}$$



Extra polarizations are "shielded" here

$$r_* \sim \left(r_c^2 r_g\right)^{\frac{1}{3}} \ll r_c \;!$$

$$r_g \equiv 2 G_N M$$

LUNAR RANGING TEST OF MODIFIED GRAVITY

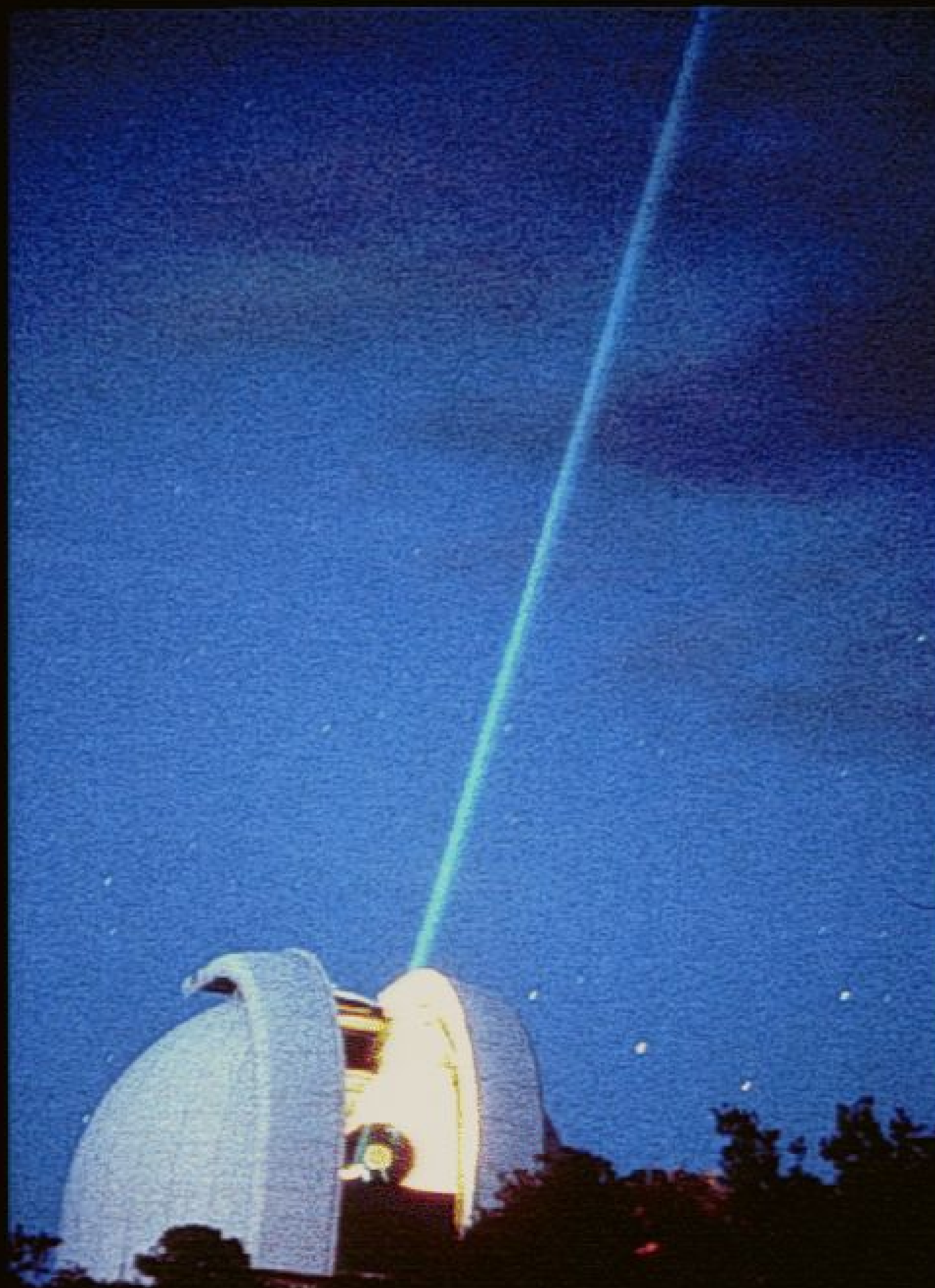
Predicted anomalous perihelion precession of the lunar orbit

$$\delta\phi = 1.4 \times 10^{-12}$$

Todays accuracy:

$$\sigma_\phi = 2.4 \times 10^{-11}$$

10-fold improvement is expected



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