Title: Introduction to Massive Gravity

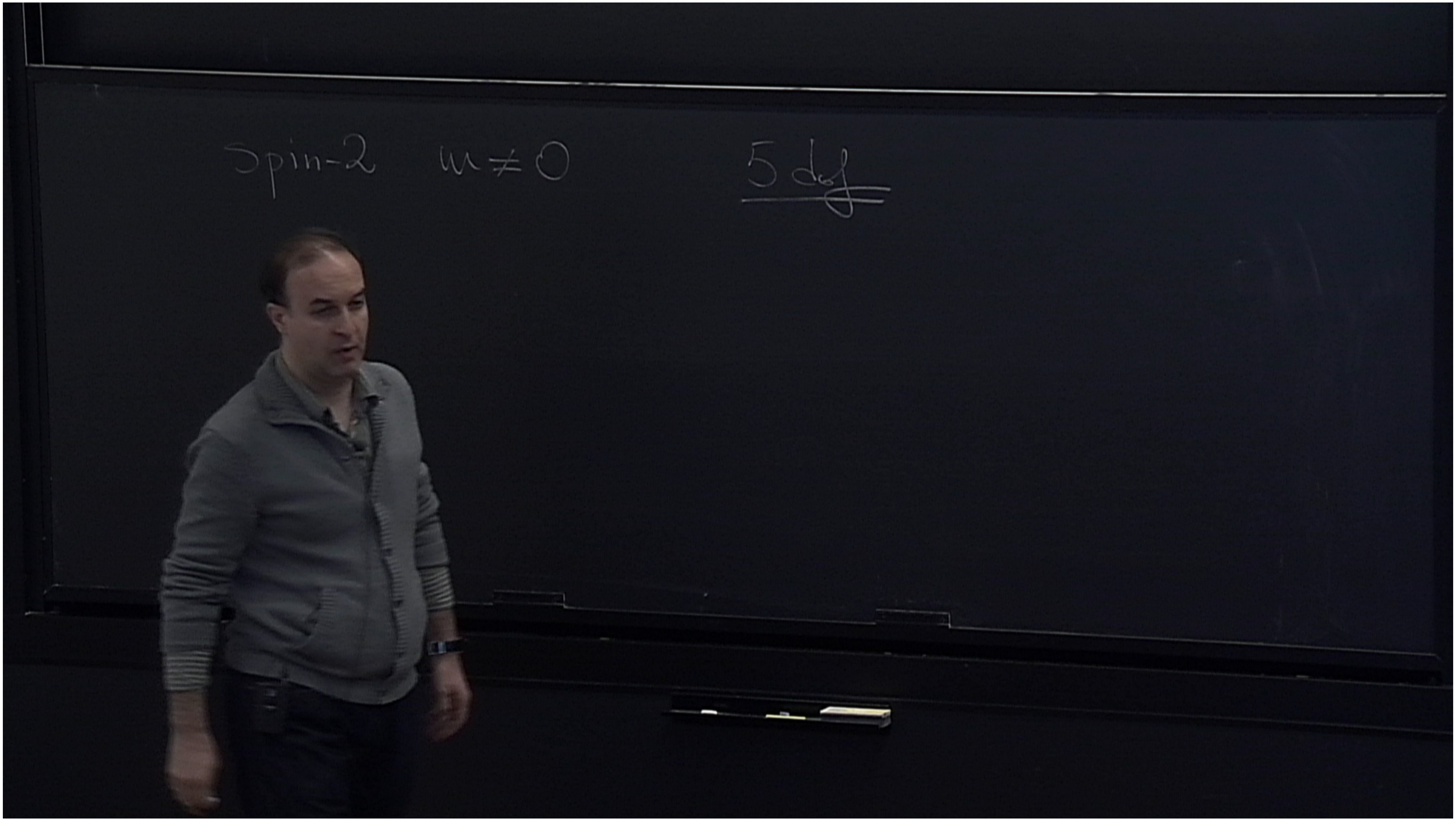
Date: Jan 31, 2012 01:00 PM

URL: http://pirsa.org/12010123

Abstract: For a long time it was believed that a classical nonlinear theory of a single massive spin-2 state does not exist.


Spin-2 m ≠ 0
5 dof
Pauli (39)
Theory
„Observ"
linear. theory
VDVZ
Vainshtein


Spin-2 m ≠ 0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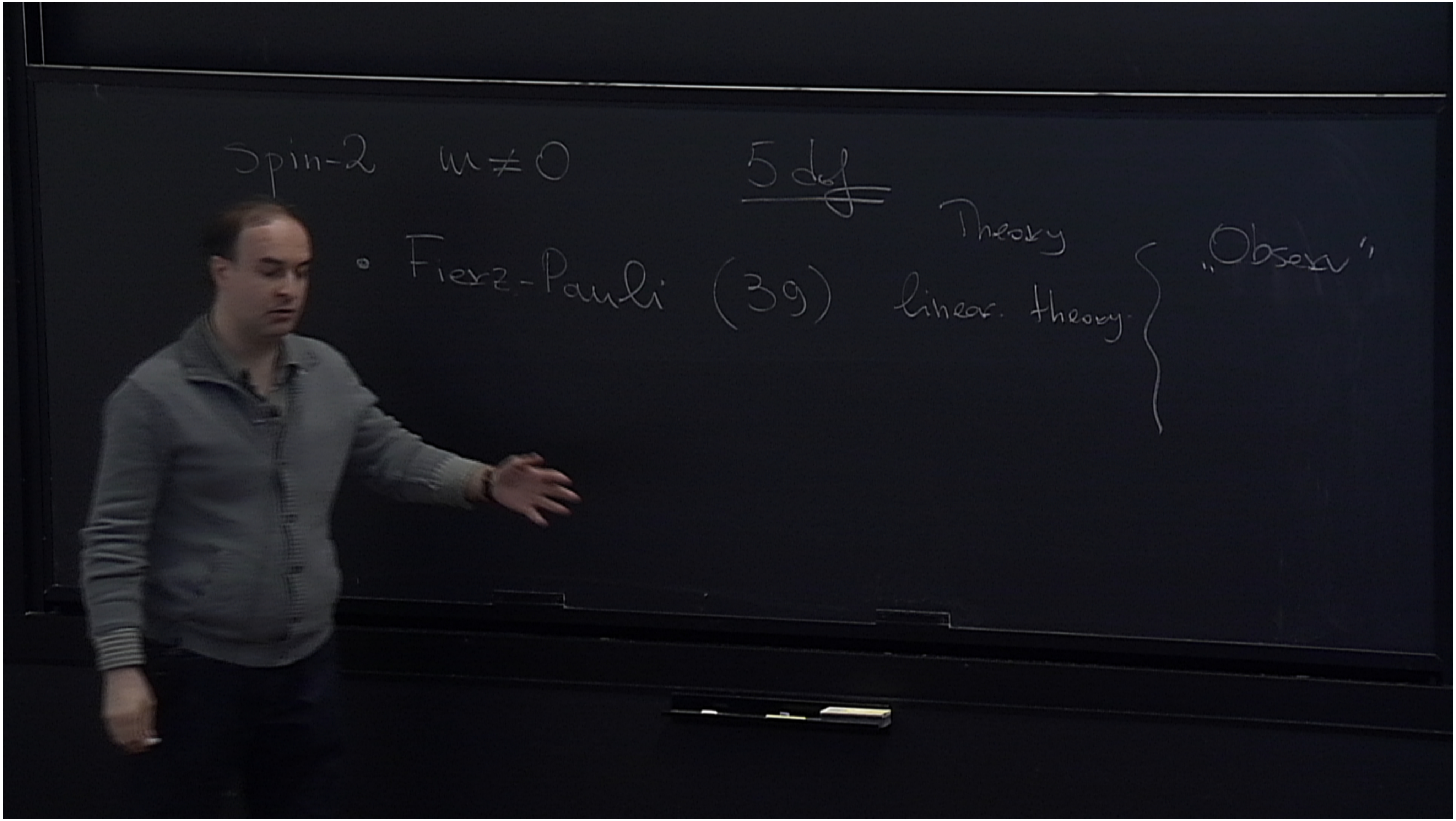
Spin-2 m ≠ 0
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linear theory
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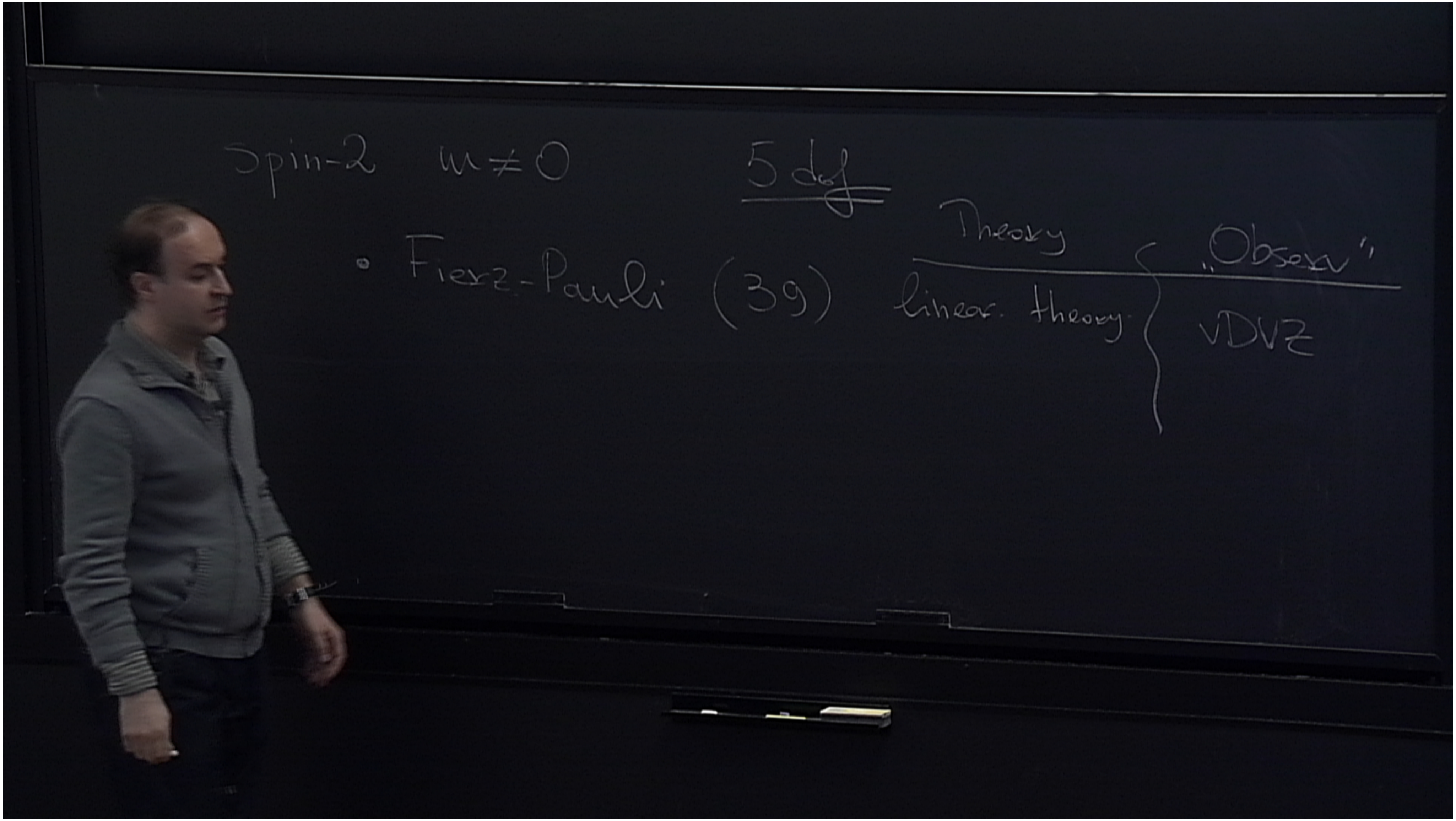
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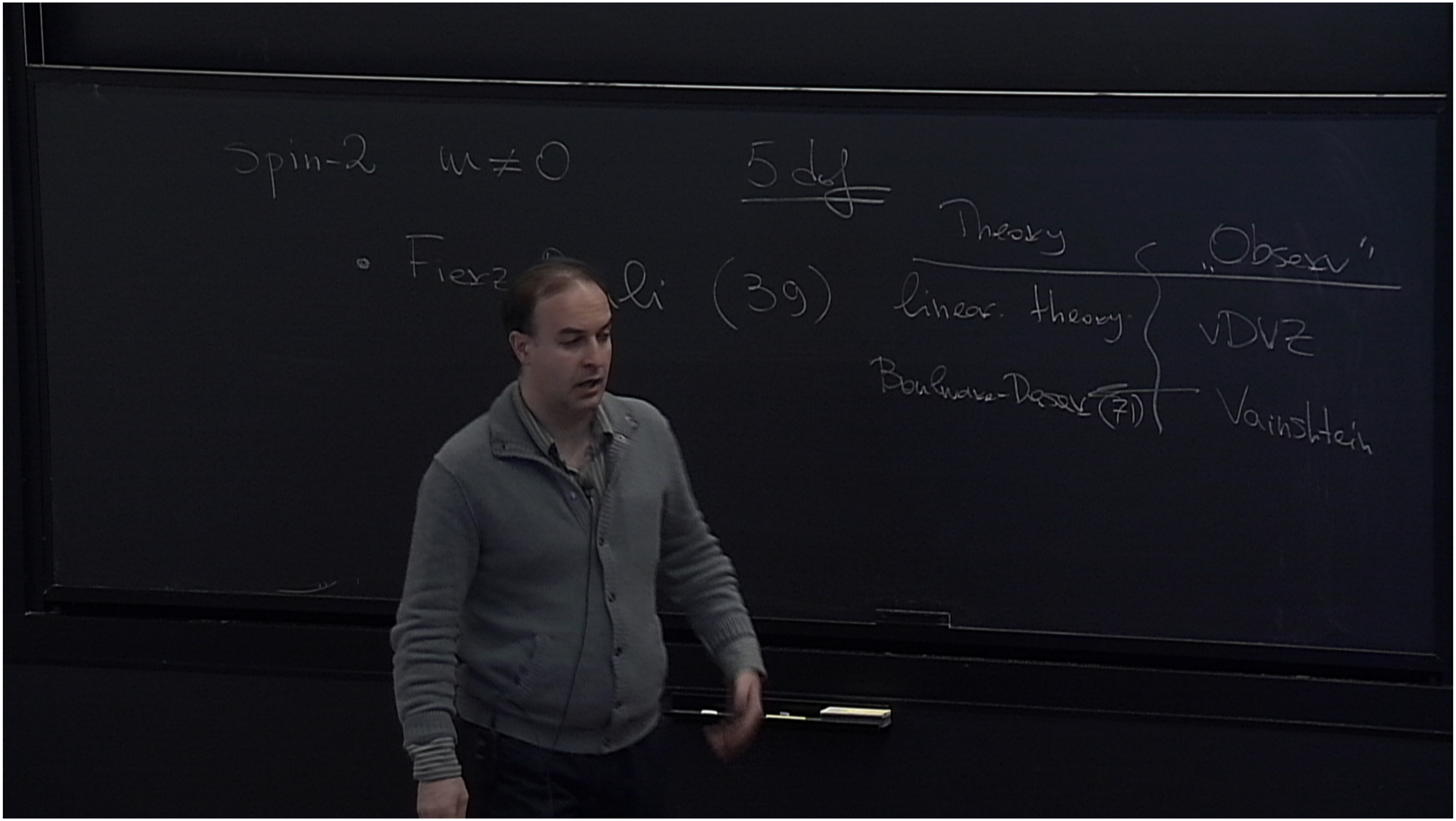
Spin-2 m ≠ 0
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vDVZ
Boulware-Deser (71)
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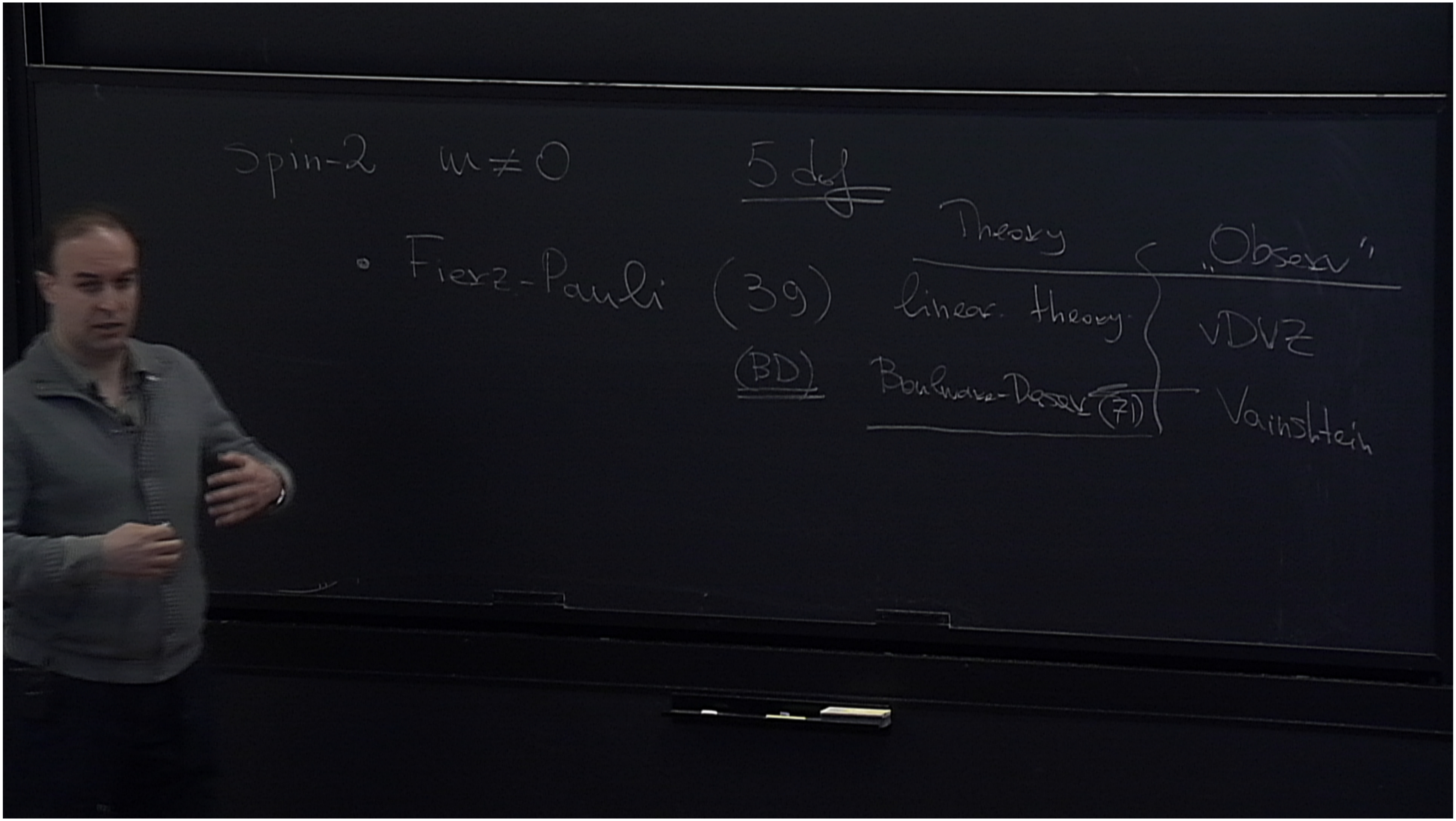
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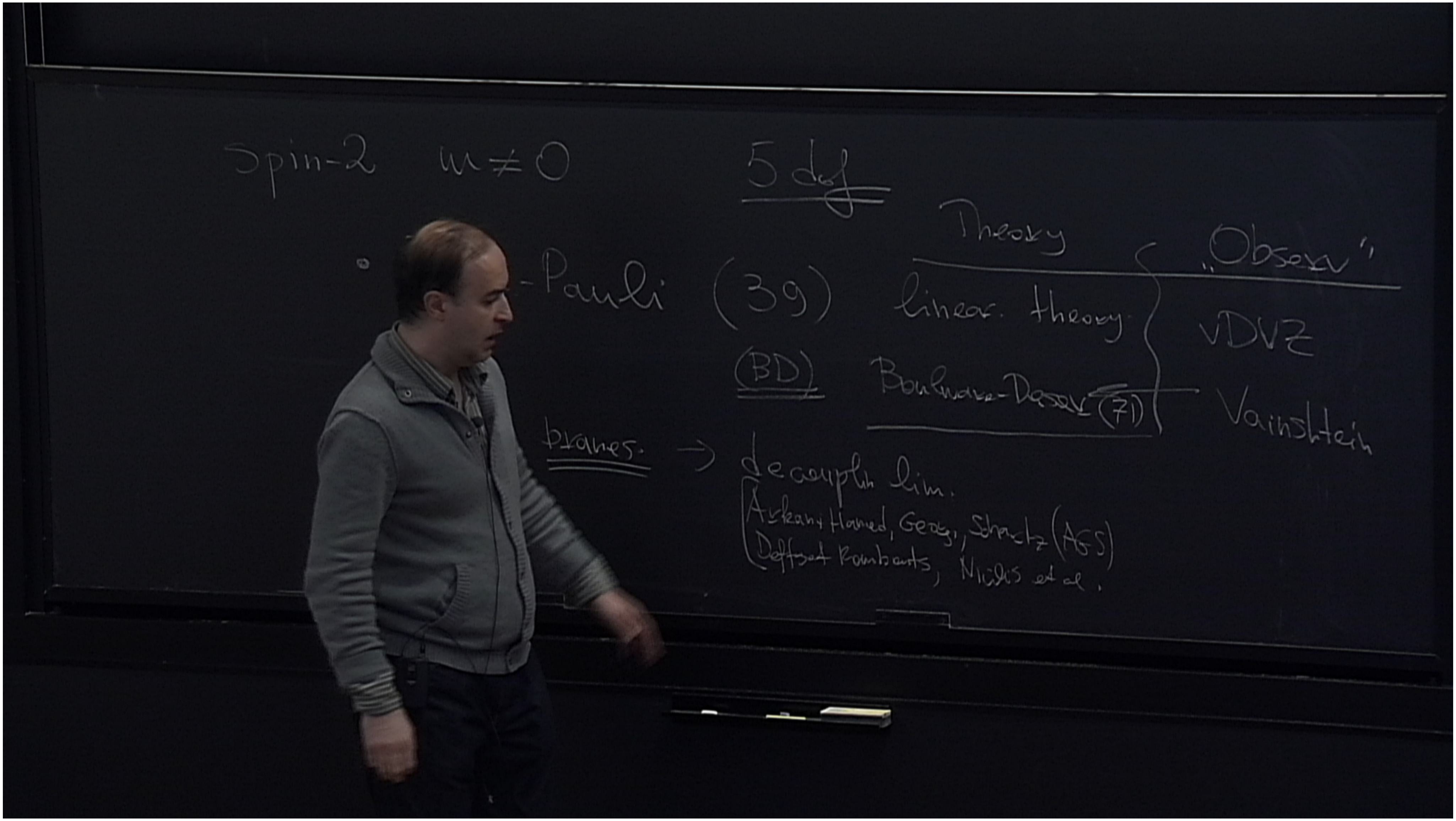
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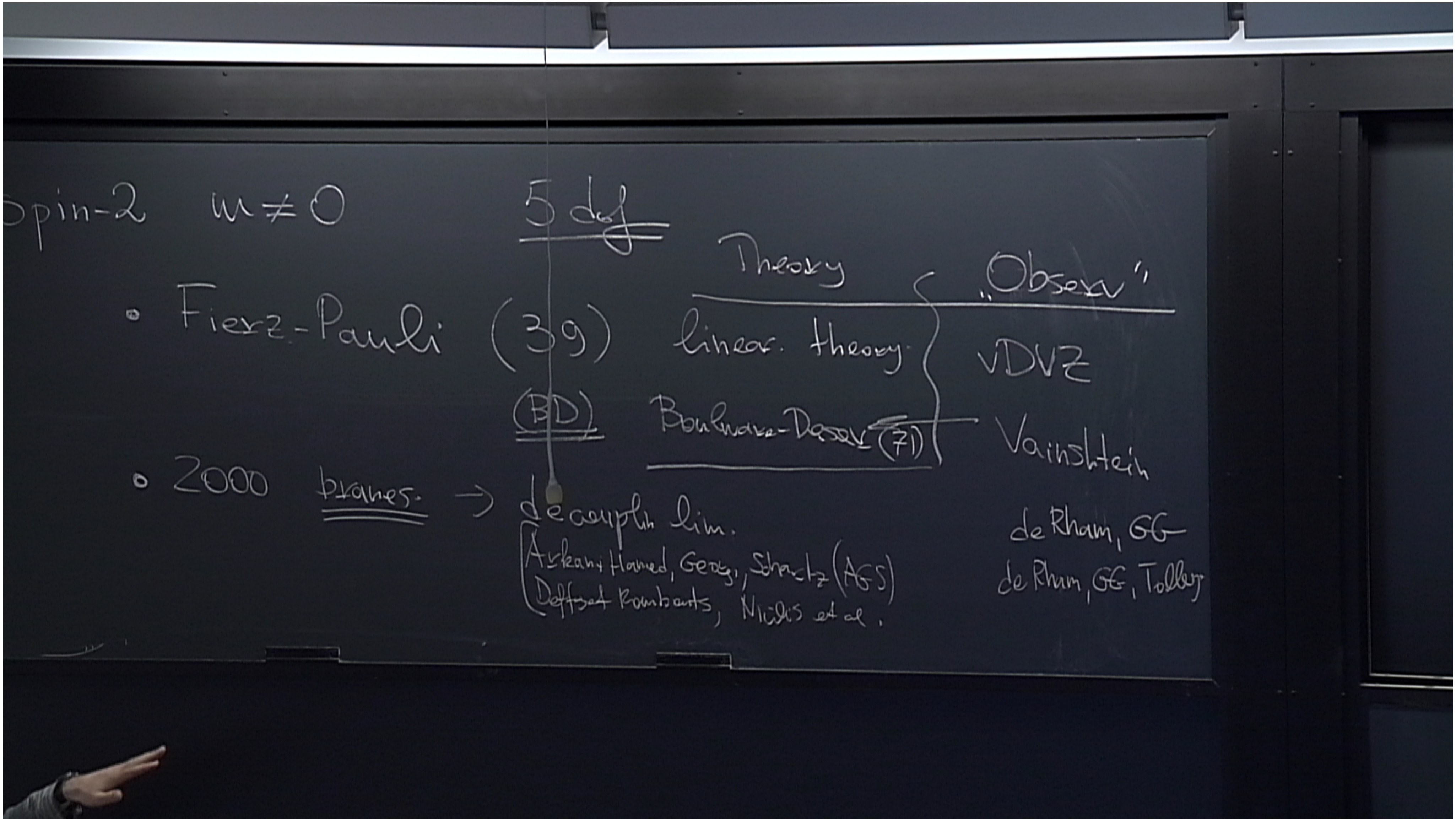
Vainshtein
branes
decoupl lim.
Arkani Hamed, Georgi, Schwartz (AGS)
Deffayet Rombouts, Nicolis et al.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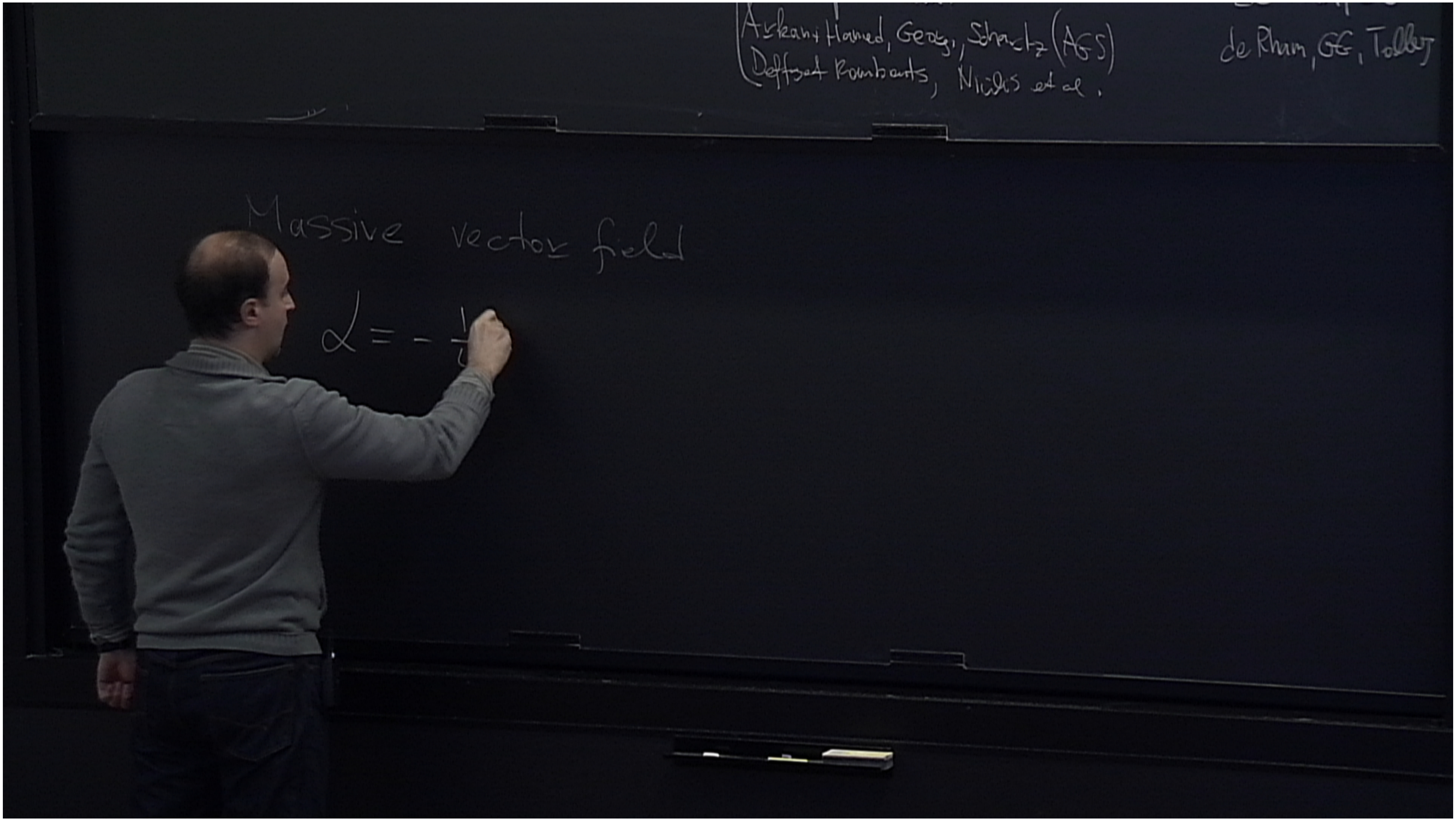
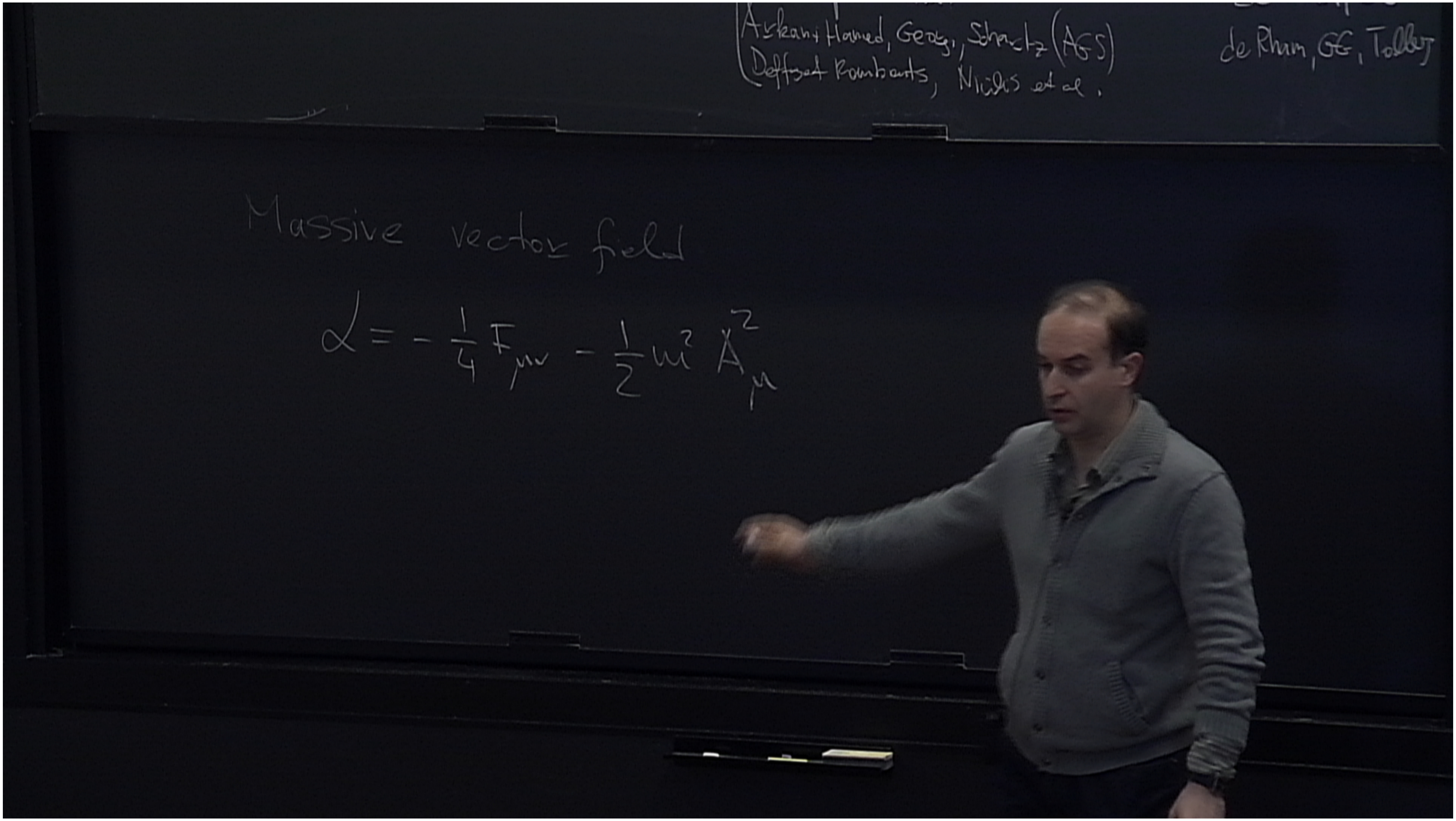
• 2000 branes → decoupl. lim.
de Rham, GG
de Rham, GG, Tolley


Arkani Hamed, Georgi, Schwartz (AGS)
Deffayet Rombouts, Nicolis et al.
de Rham, GG, Tolley
Massive vector field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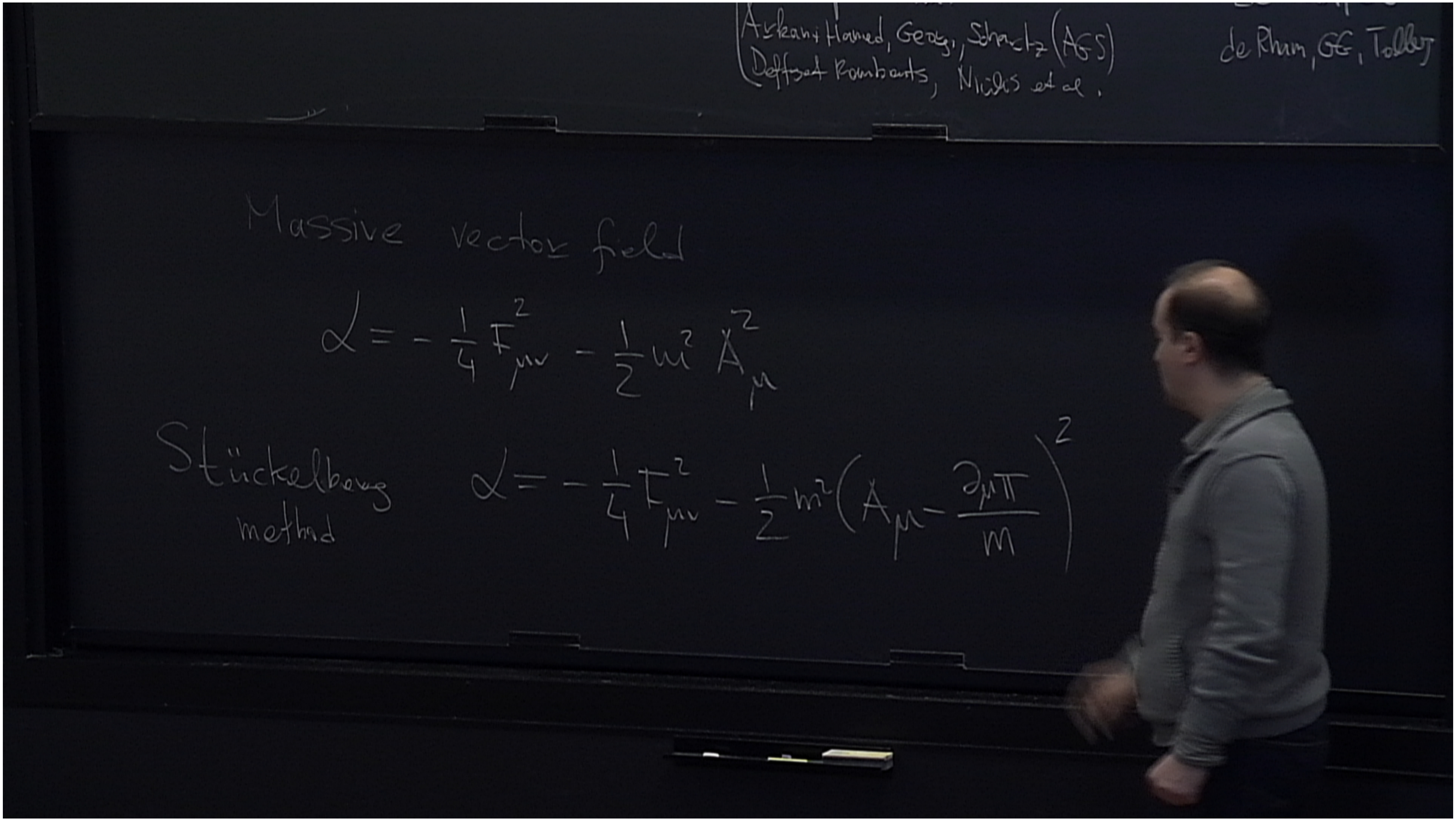
Massive vector field
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} - \frac{1}{2} m^2 A_\mu^2$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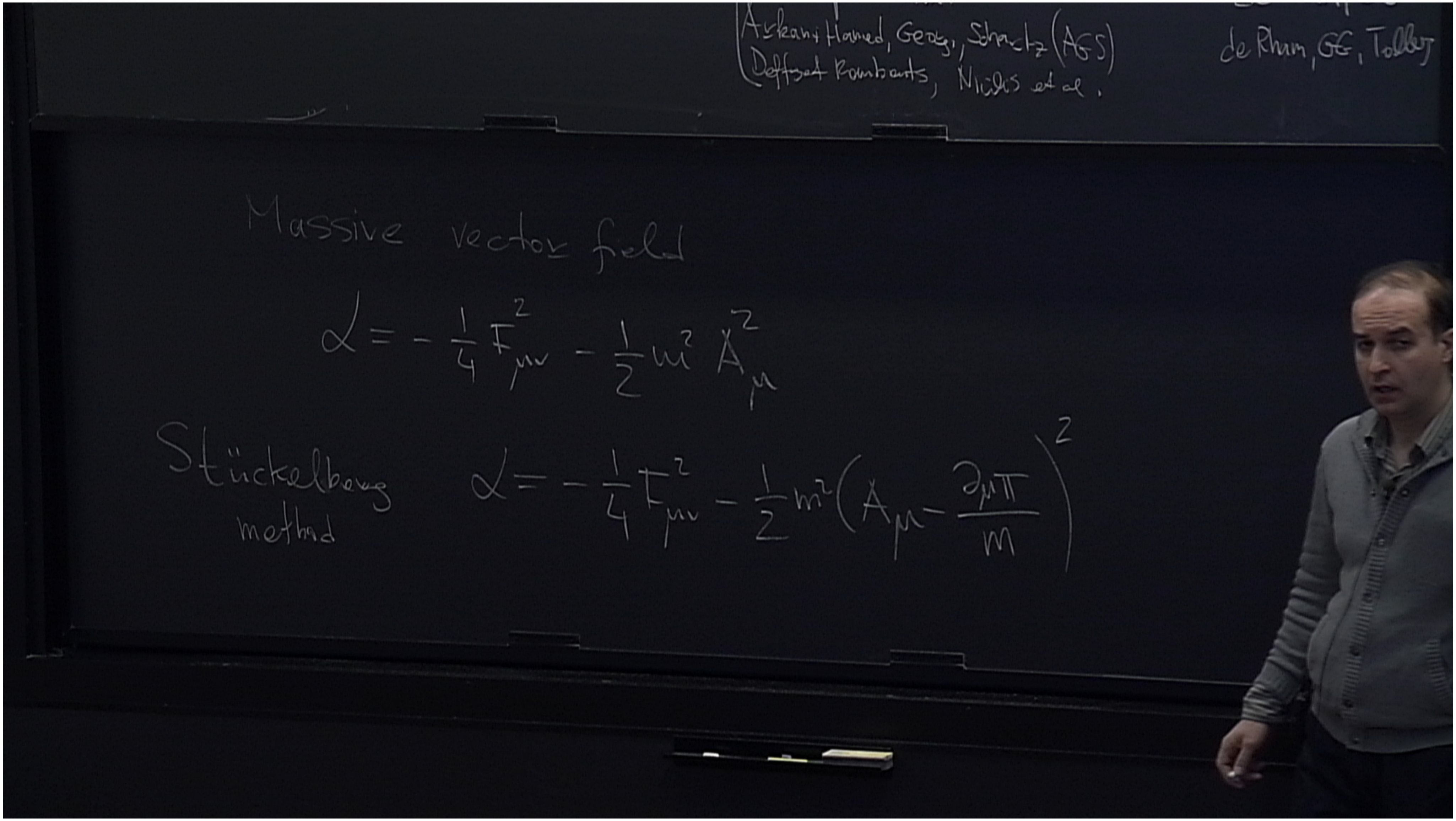
Massive vector field
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2 A_\mu^2$
Stückelberg method
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2\left(A_\mu - \frac{\partial_\mu \pi}{m}\right)^2$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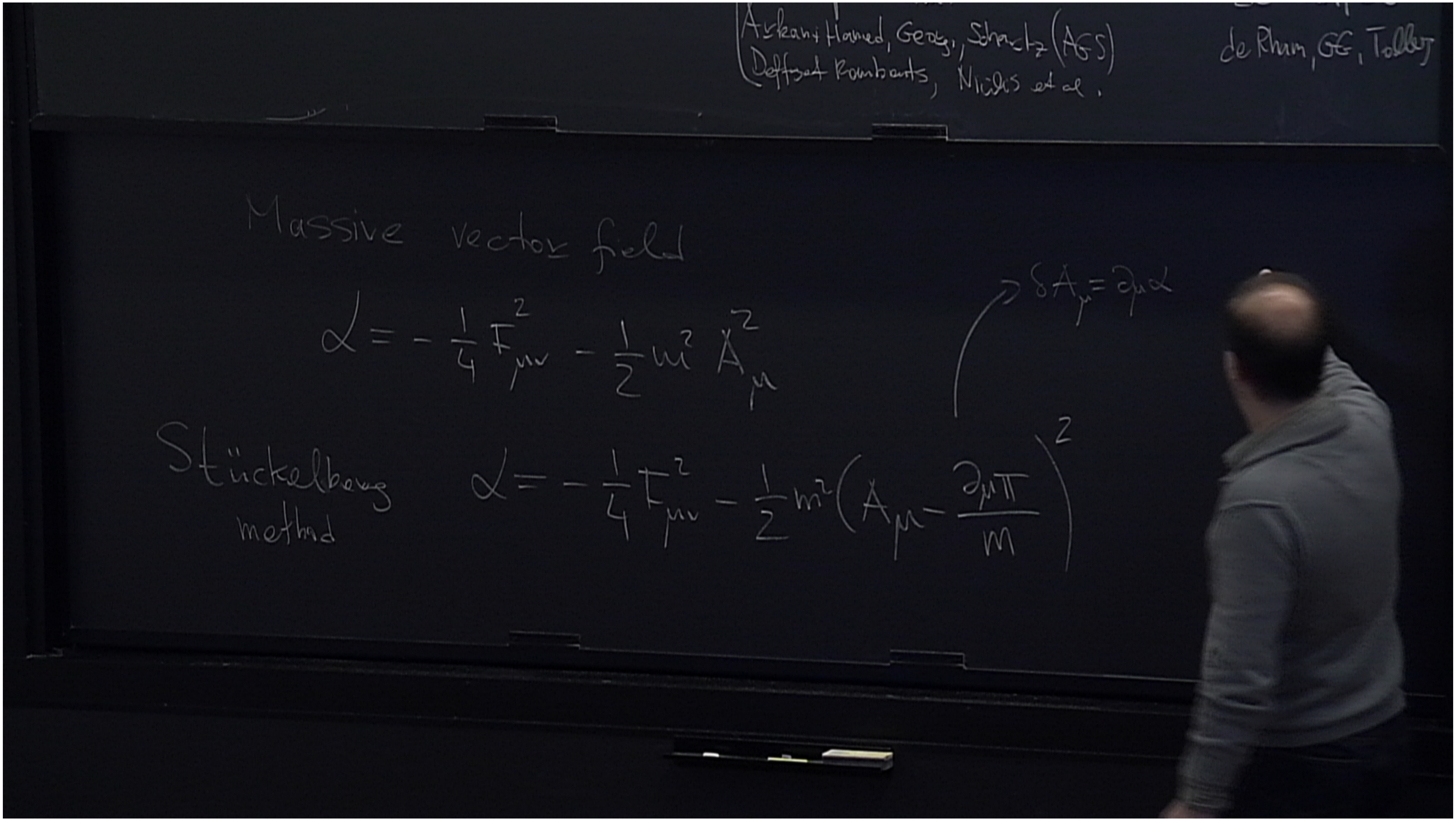
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Massive vector field
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2 A_\mu^2$
$\delta A_\mu = \partial_\mu \alpha$
Stückelberg method
$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}m^2\left(A_\mu - \frac{\partial_\mu \pi}{m}\right)^2$

(Arkani-Hamed, Georgi, Schwartz (AGS)
Deffayet Rombouts, Nicolis et al.

de Rham, GG, Tolley

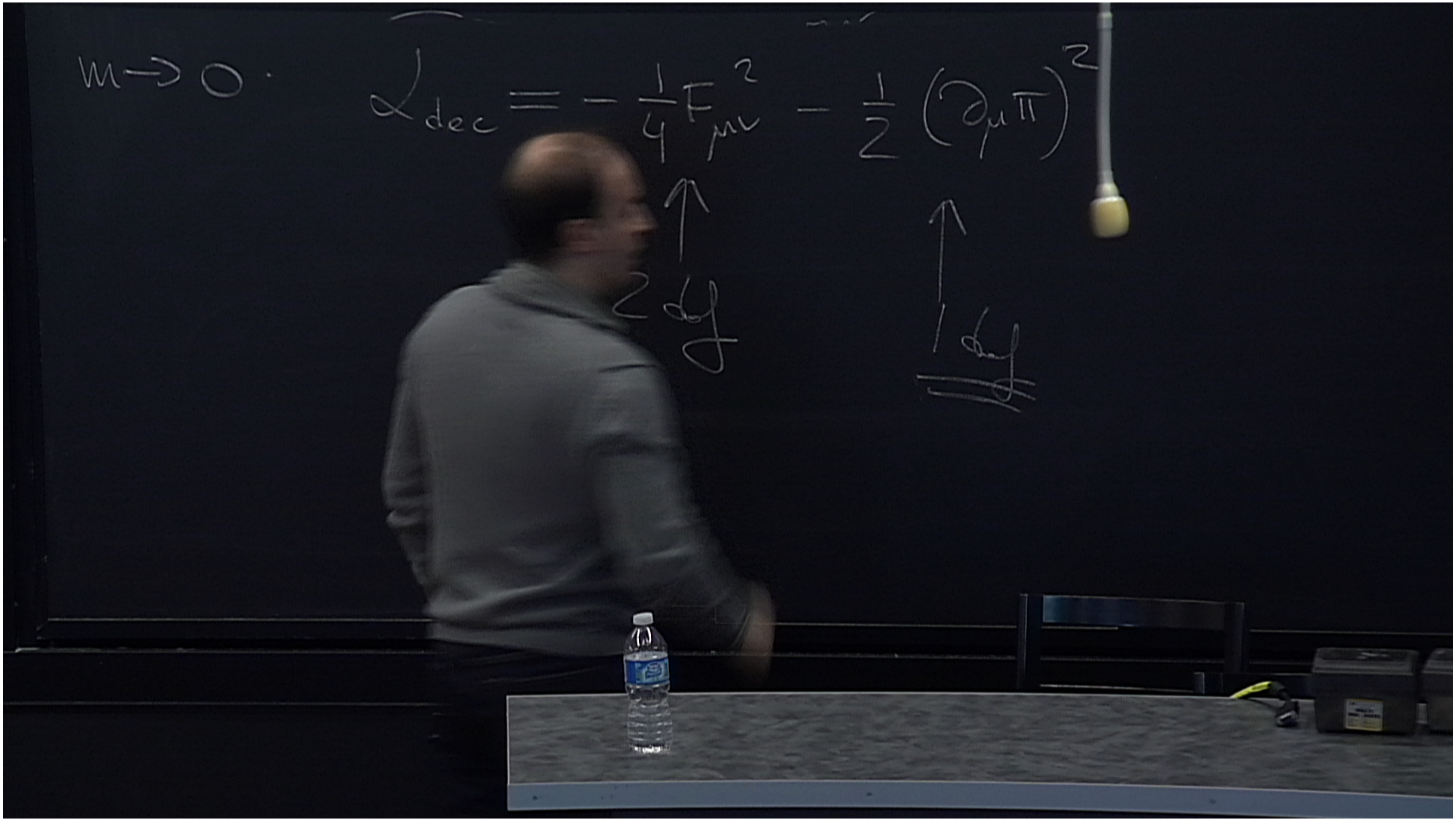
Massive vector field

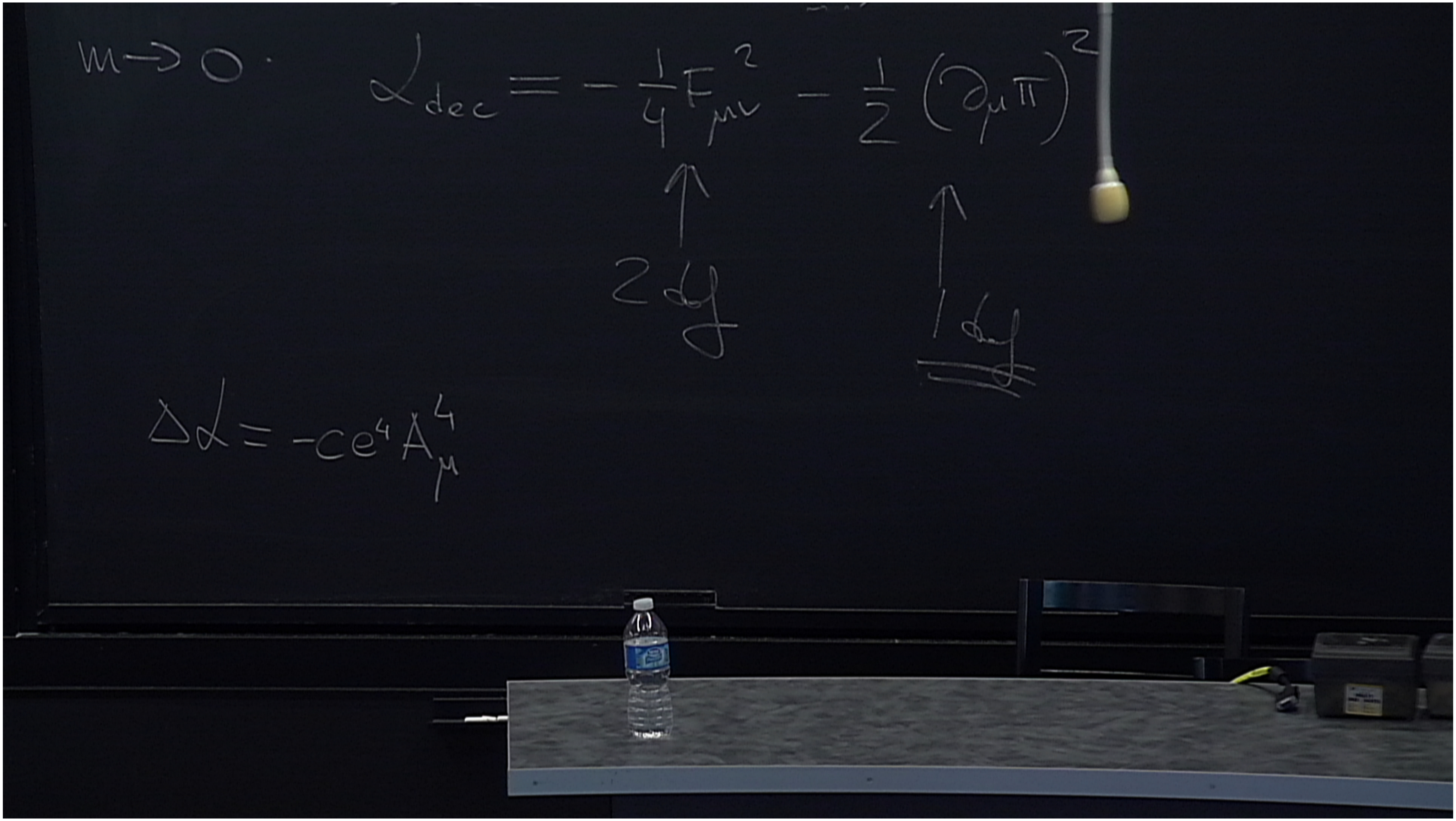
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - \frac{1}{2} m^2 A_\mu^2$$

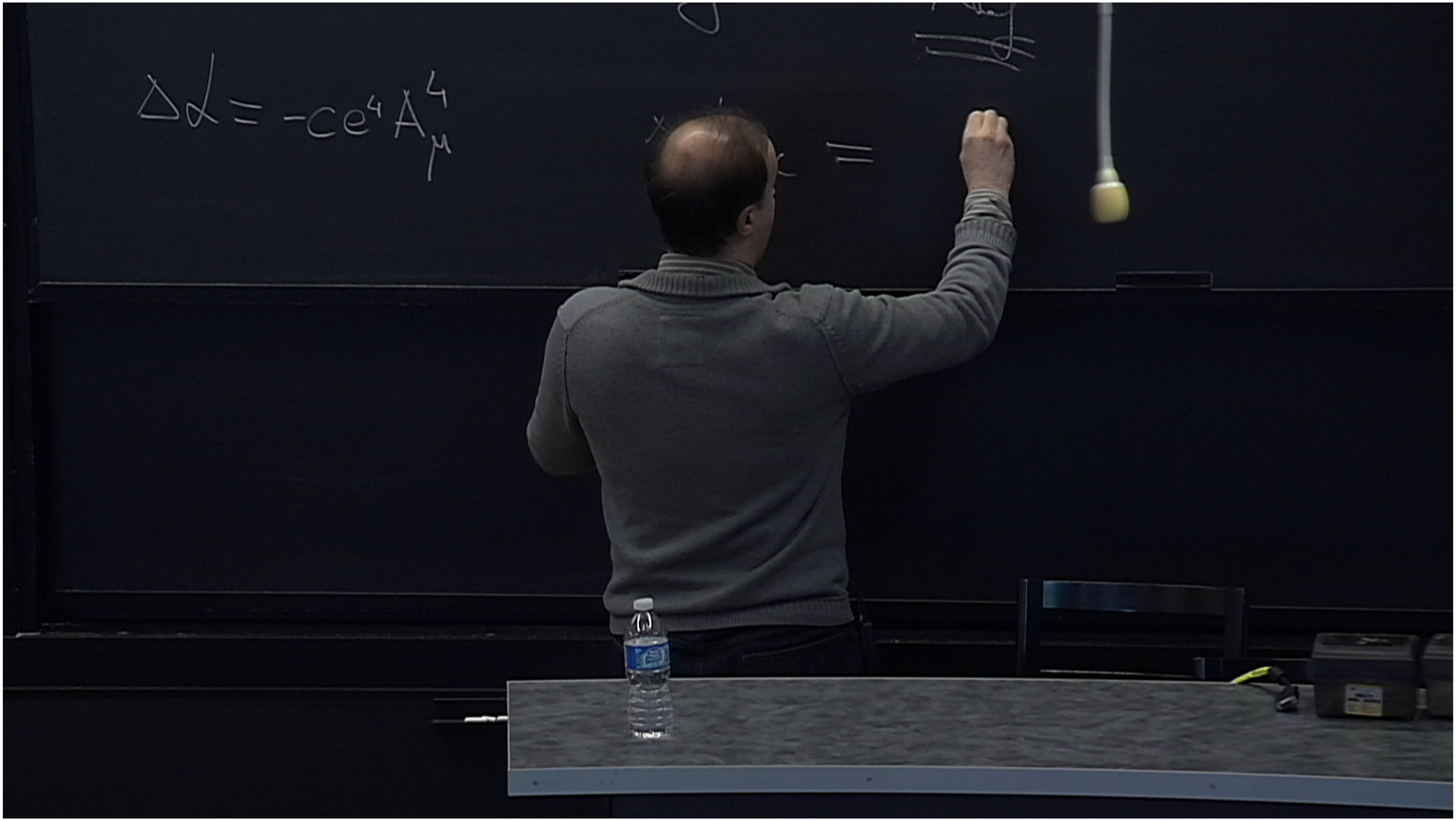
$\delta A_\mu = \partial_\mu \alpha \qquad \delta \pi = m \alpha$

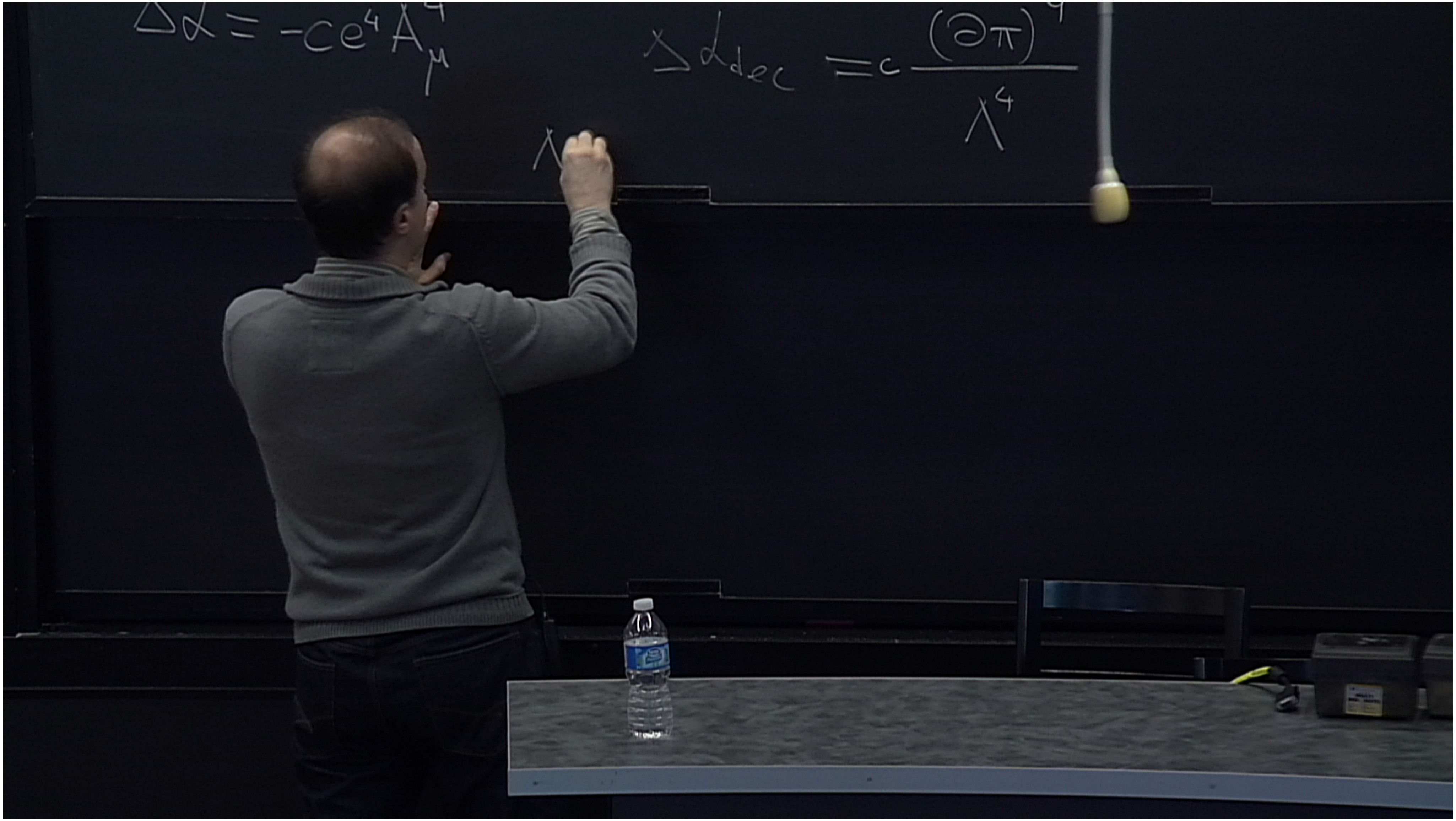
Stückelberg method

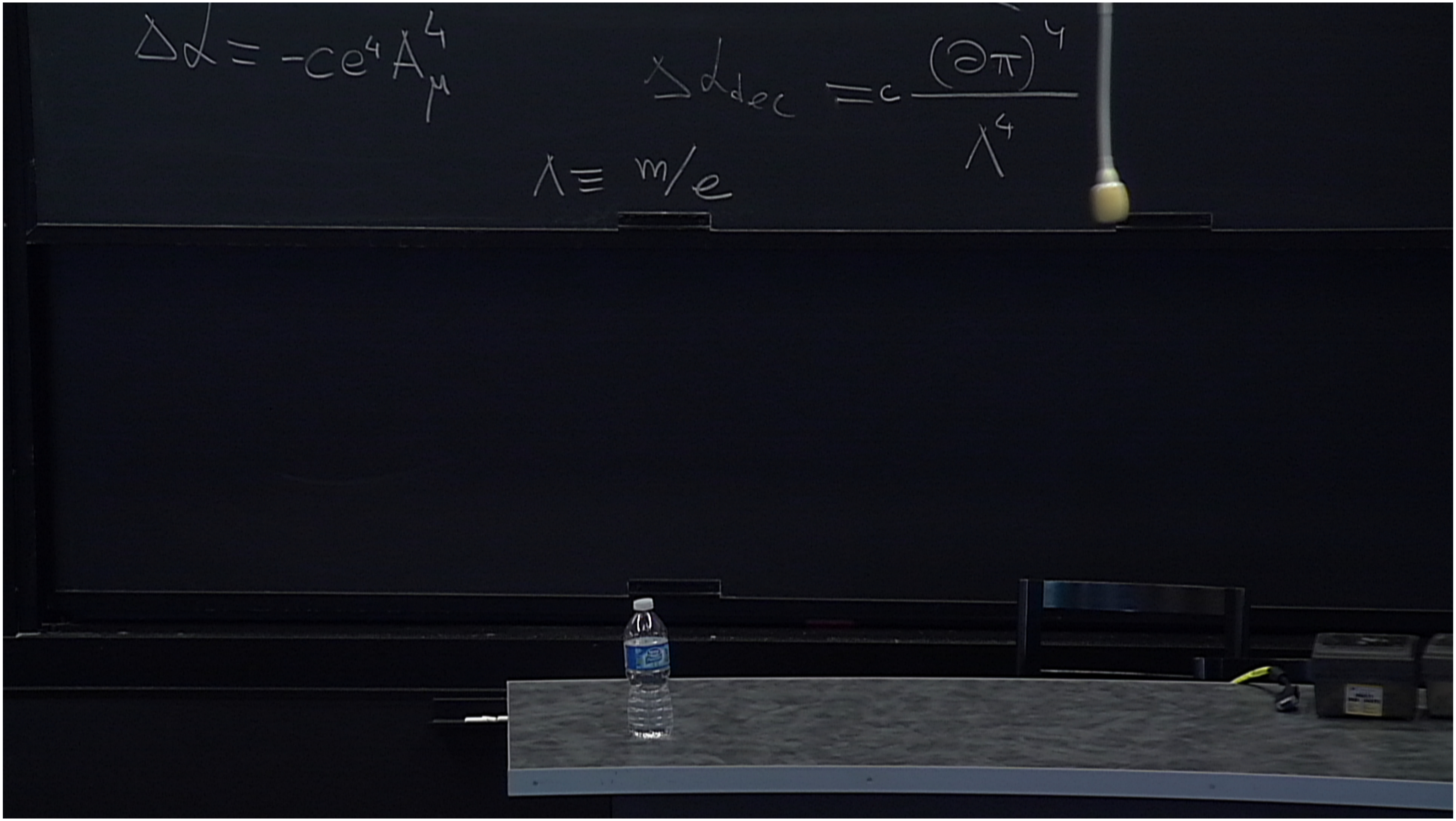
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - \frac{1}{2} m^2 \left(A_\mu - \frac{\partial_\mu \pi}{m} \right)^2$$

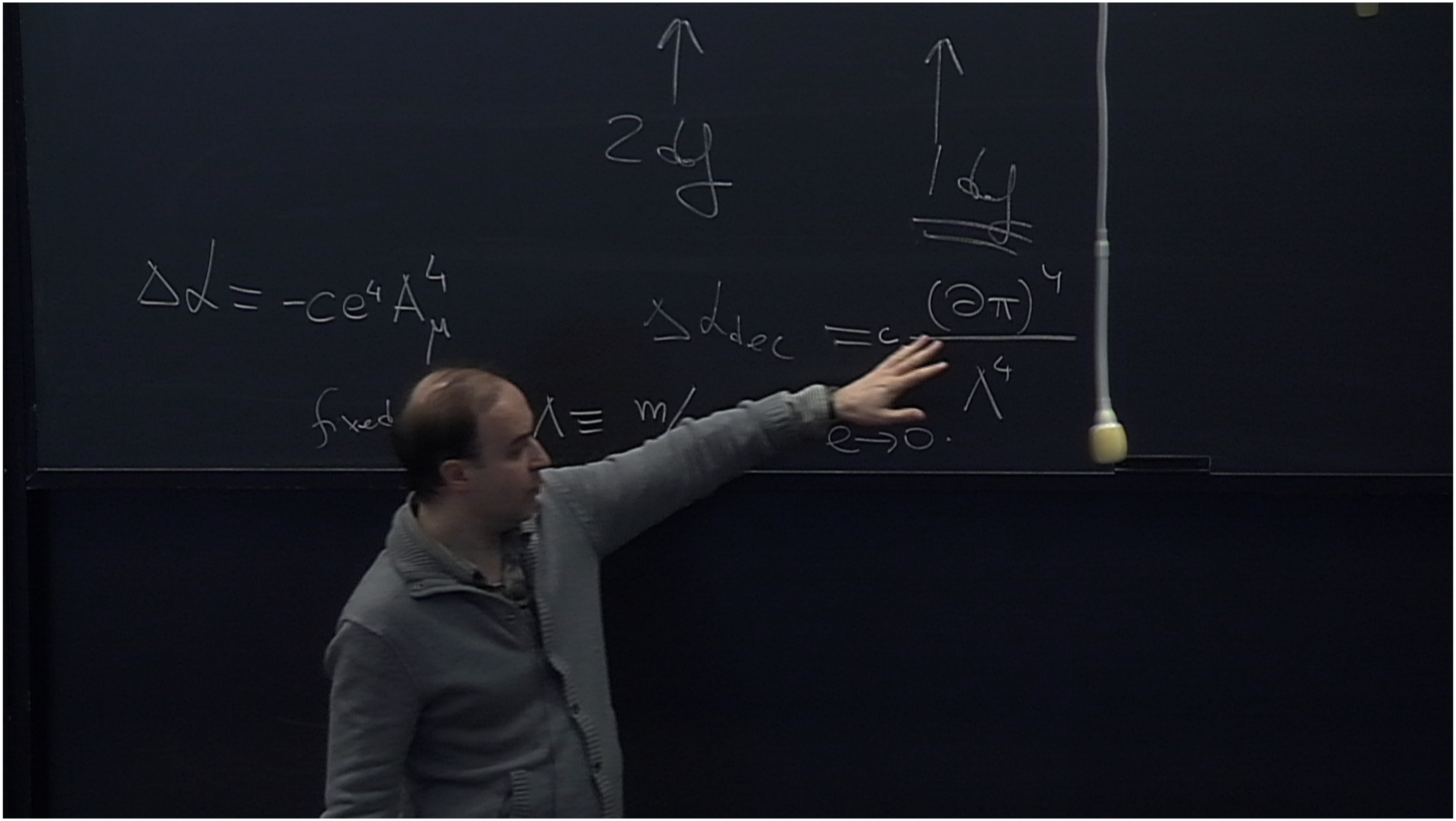

m → 0.
L_dec = − 1/4 F_μν^2 − 1/2 (∂_μ π)^2
2 dof
1 dof

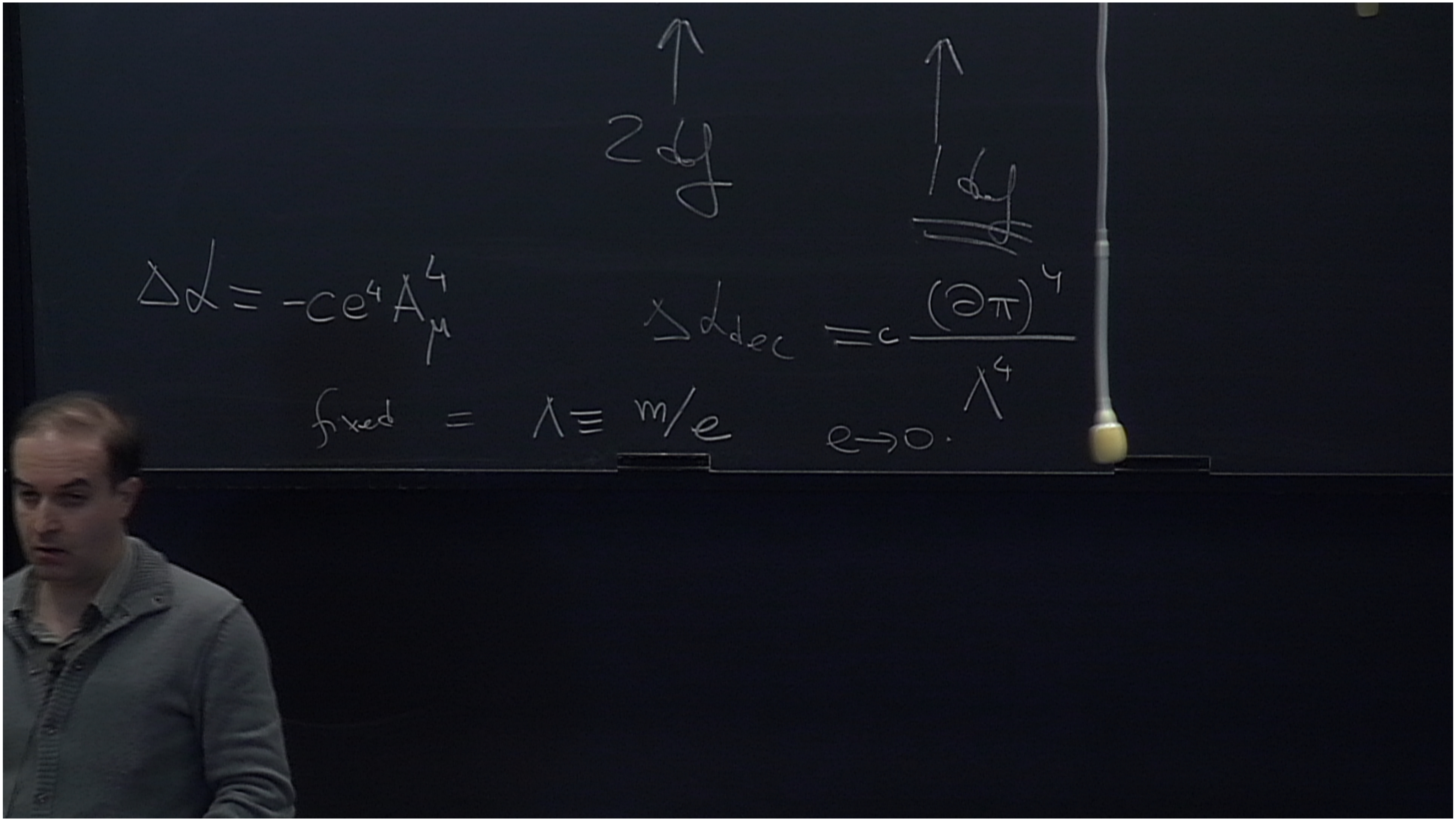

$m \to 0.$
$\mathcal{L}_{dec} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2}(\partial_\mu \pi)^2$
2 dof
1 dof
$\Delta\mathcal{L} = -ce^4 A_\mu^4$

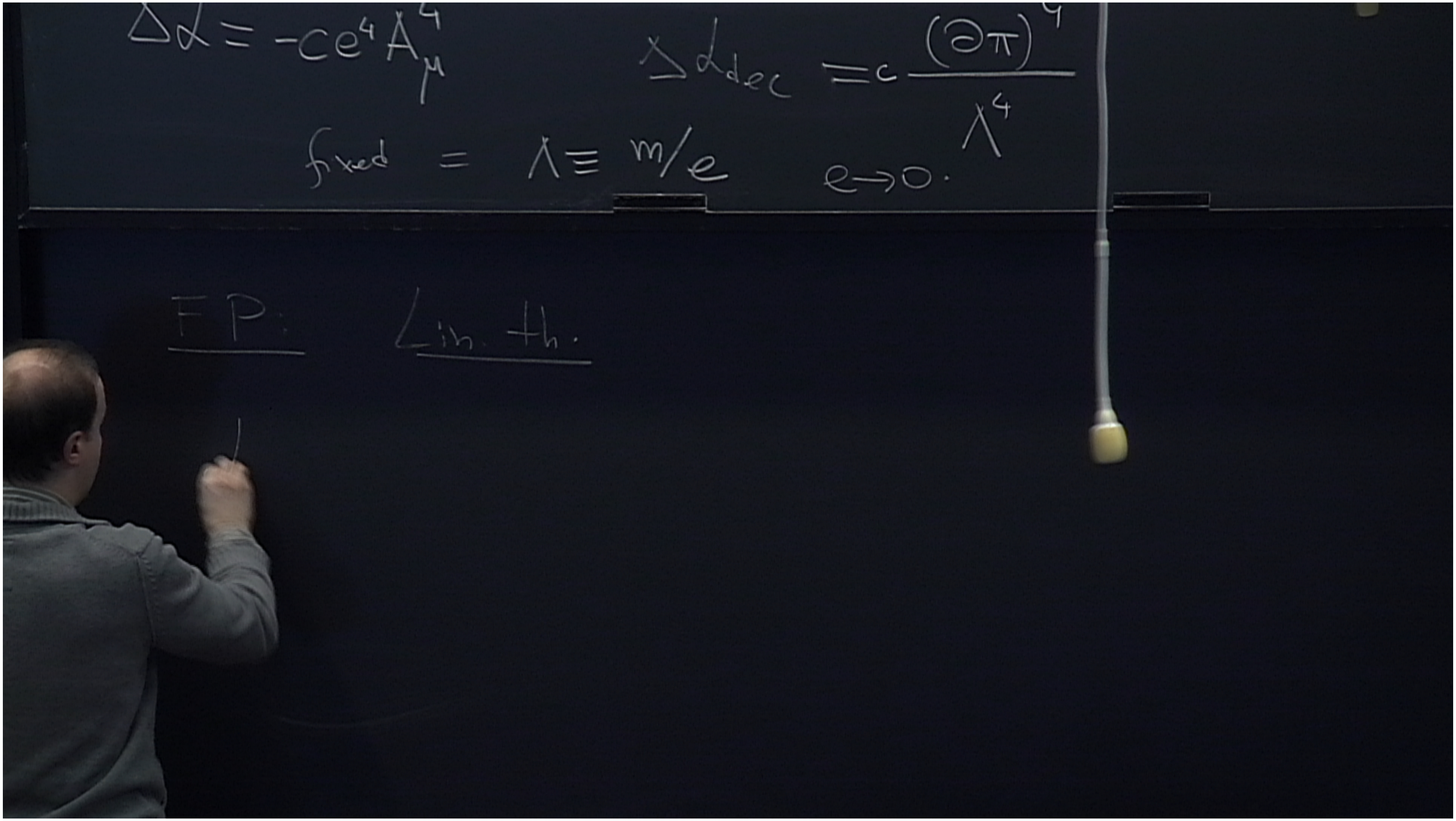

$\Delta\mathcal{L} = -ce^4 A_\mu^4$


ΔL = -ce⁴A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
Λ


$\Delta \mathcal{L} = -c e^4 A_\mu^4$
$\Delta \mathcal{L}_{dec} = c \frac{(\partial \pi)^4}{\Lambda^4}$
$\Lambda \equiv m/e$


2 dy
1 dy
ΔL = -ce⁴ A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed
Λ ≡ m/
e→0.


ΔL = -ce⁴ A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e → 0.


ΔL = -ce^4 A_μ^4
ΔL_dec = c (∂π)^4 / Λ^4
fixed = Λ ≡ m/e
e→0.
FP:
L_in. th.

$$\Delta \mathcal{L} = -c e^4 A_\mu^4 \qquad \Delta \mathcal{L}_{dec} = c \frac{(\partial \pi)^4}{\Lambda^4}$$

fixed $= \Lambda \equiv m/e \quad e \to 0.$

FP: $\mathcal{L}$ in. th. $h_{\mu\nu}$

$$\mathcal{L} = -\frac{M_p^2}{2} h_{\mu\nu} \mathcal{E}^{\mu\nu}_{\alpha\beta} h^{\alpha\beta} - \frac{M_p^2 m^2}{4} \left(h_{\mu\nu}^2 - h^2 \right)$$

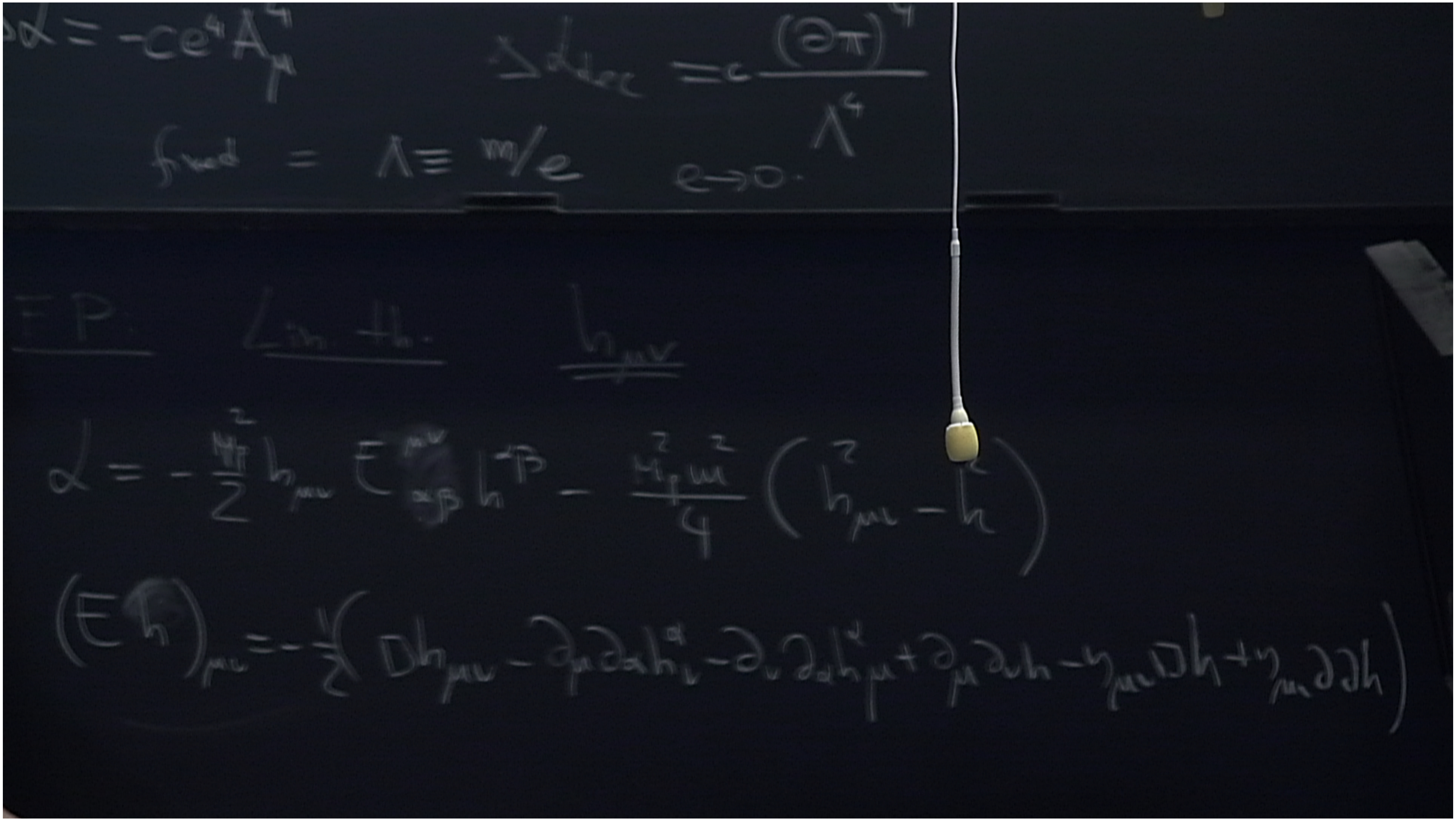
$$\Delta\mathcal{L} = -c e^4 A_\mu^4 \qquad \Delta\mathcal{L}_{dec} = c\,\frac{(\partial\pi)^4}{\Lambda^4}$$

fixed $= \Lambda \equiv m/e \quad e \to 0.$

FP: Lin. th. $h_{\mu\nu}$

$$\mathcal{L} = -\frac{M_p^2}{2} h_{\mu\nu} \mathcal{E}^{\mu\nu}_{\alpha\beta} h^{\alpha\beta} - \frac{M_p^2 m^2}{4}\left(h_{\mu\nu}^2 - h^2\right)$$

$$(\mathcal{E} h)_{\mu\nu} = -\frac{1}{2}\left(\Box h_{\mu\nu} - \partial_\mu\partial_\alpha h^\alpha_\nu - \partial_\nu\partial_\alpha h^\alpha_\mu + \partial_\mu\partial_\nu h - \eta_{\mu\nu}\Box h + \eta_{\mu\nu} \ldots\right.$$


$\Delta\mathcal{L} = -ce^4 A_\mu^4$
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fixed $= \Lambda \equiv m/e$
$e \to 0$.
FP. Lin. th. $h_{\mu\nu}$
$\mathcal{L} = -\frac{M_P^2}{2} h_{\mu\nu} \mathcal{E}^{\mu\nu}{}_{\alpha\beta} h^{\alpha\beta} - \frac{M_P^2 m^2}{4}\left(h_{\mu\nu}^2 - h^2\right)$
$(\mathcal{E}h)_{\mu\nu} = -\frac{1}{2}\left(\Box h_{\mu\nu} - \partial_\mu\partial_\alpha h^\alpha_\nu - \partial_\nu\partial_\alpha h^\alpha_\mu + \partial_\mu\partial_\nu h - \eta_{\mu\nu}\Box h + \eta_{\mu\nu}\partial\partial h\right)$

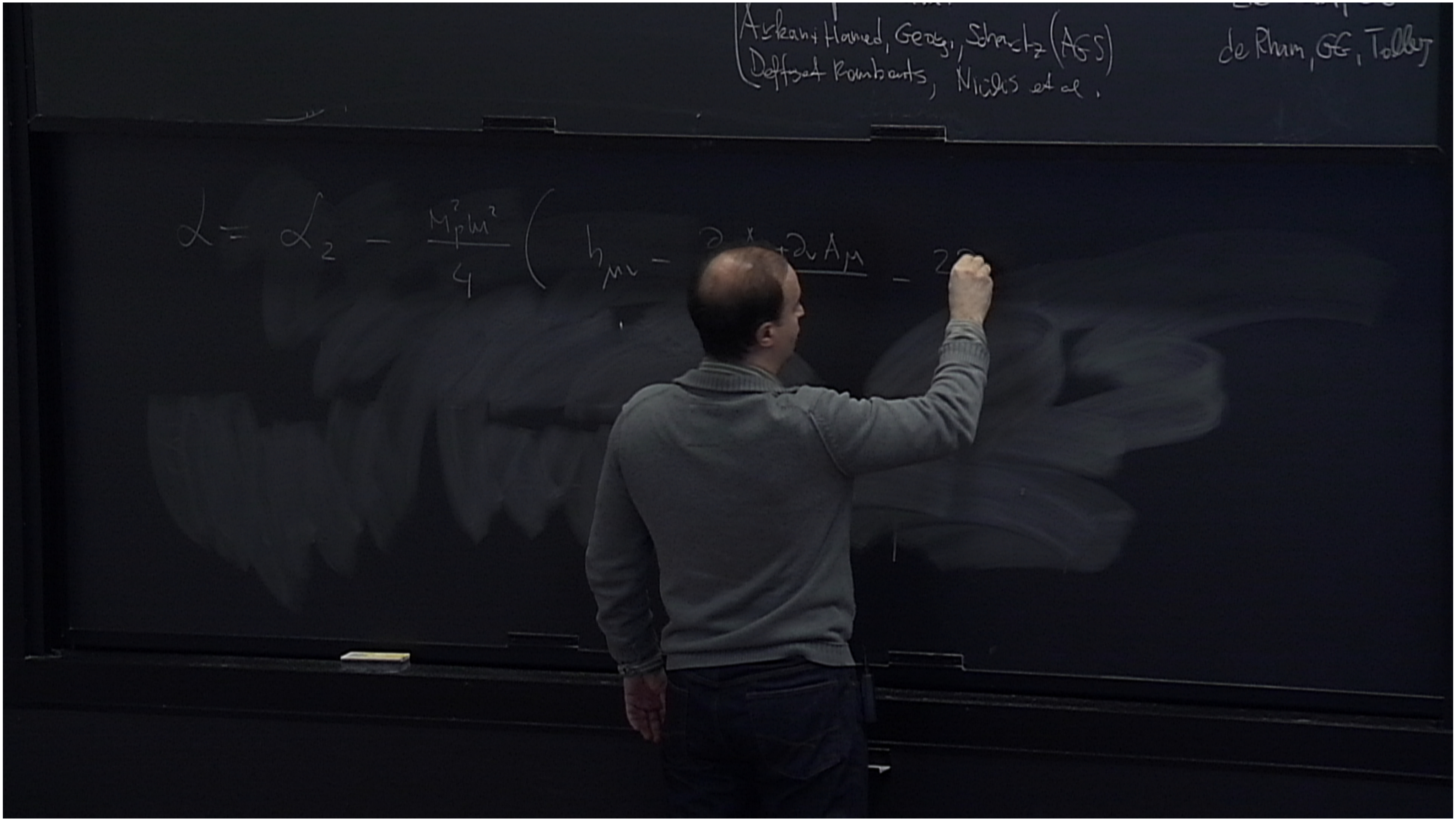
$$\Delta \mathcal{L} = -c e^4 A_\mu^4 \qquad \Delta \mathcal{L}_{dec} = c \, \frac{(\partial \pi)^4}{\Lambda^4}$$

fixed $= \Lambda \equiv m/e \qquad e \to 0.$

FP: Lin. th. $h_{\mu\nu}$

$$\mathcal{L} = \underbrace{-\frac{M_p^2}{2} h_{\mu\nu} \mathcal{E}^{\mu\nu}_{\alpha\beta} h^{\alpha\beta}}_{\mathcal{L}_2} - \frac{M_p^2 m^2}{4}\left(h_{\mu\nu}^2 - h^2\right)$$

$$(\mathcal{E} h)_{\mu\nu} = -\frac{1}{2}\left(\Box h_{\mu\nu} - \partial_\mu \partial_\alpha h^\alpha_\nu - \partial_\nu \partial_\alpha h^\alpha_\mu + \partial_\mu \partial_\nu h - \eta_{\mu\nu} \Box h + \eta_{\mu\ldots}\right.$$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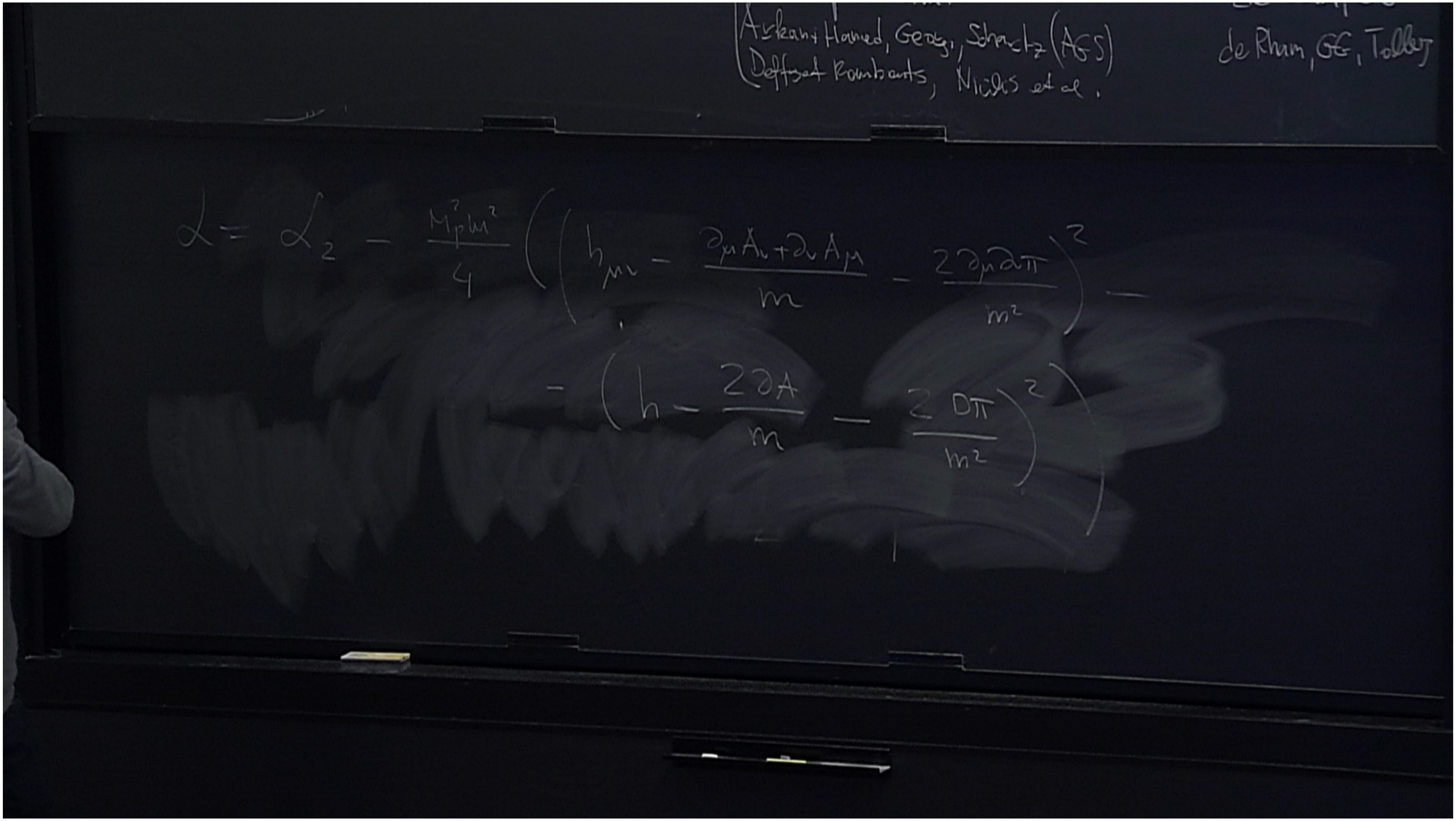
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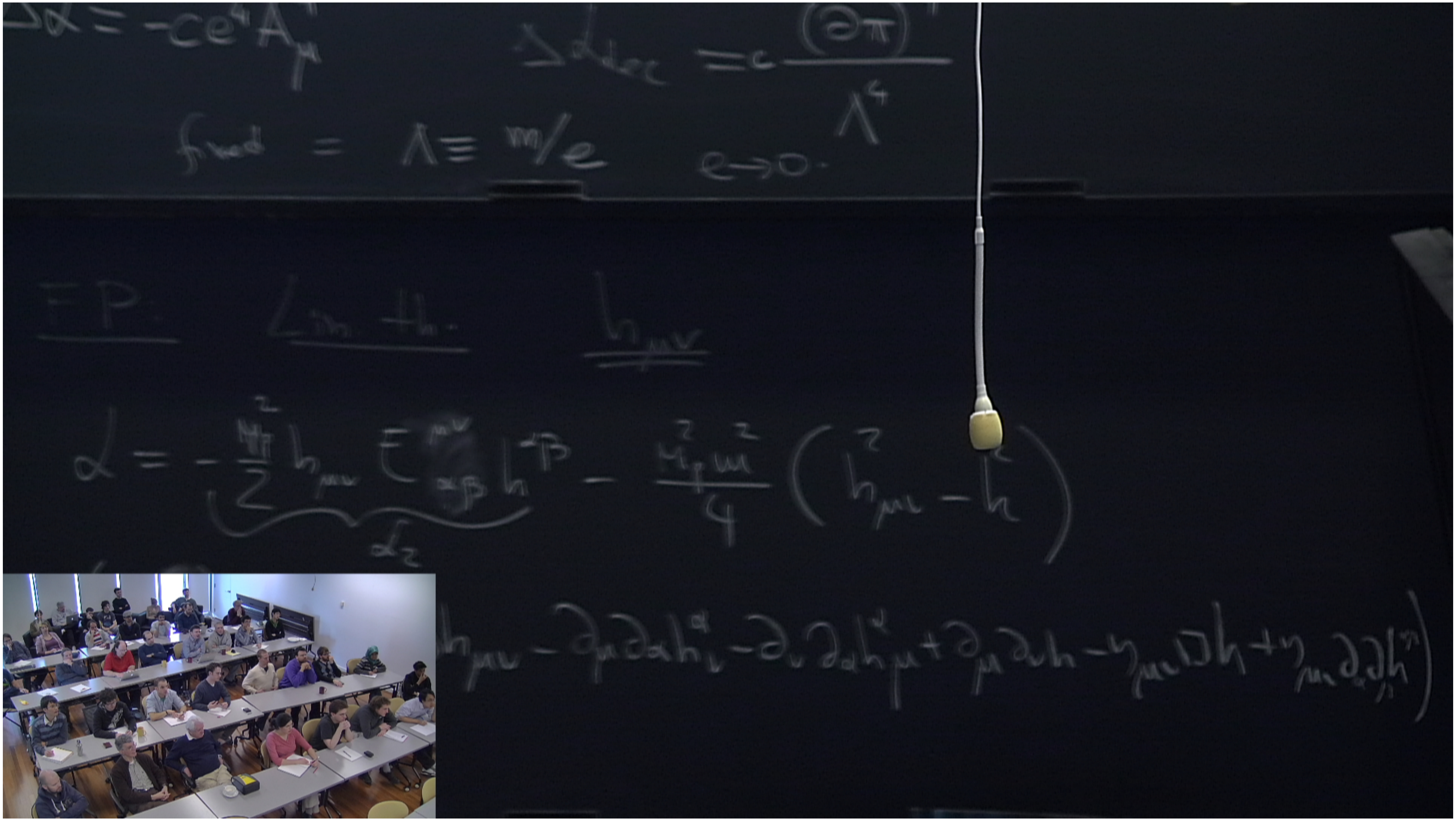
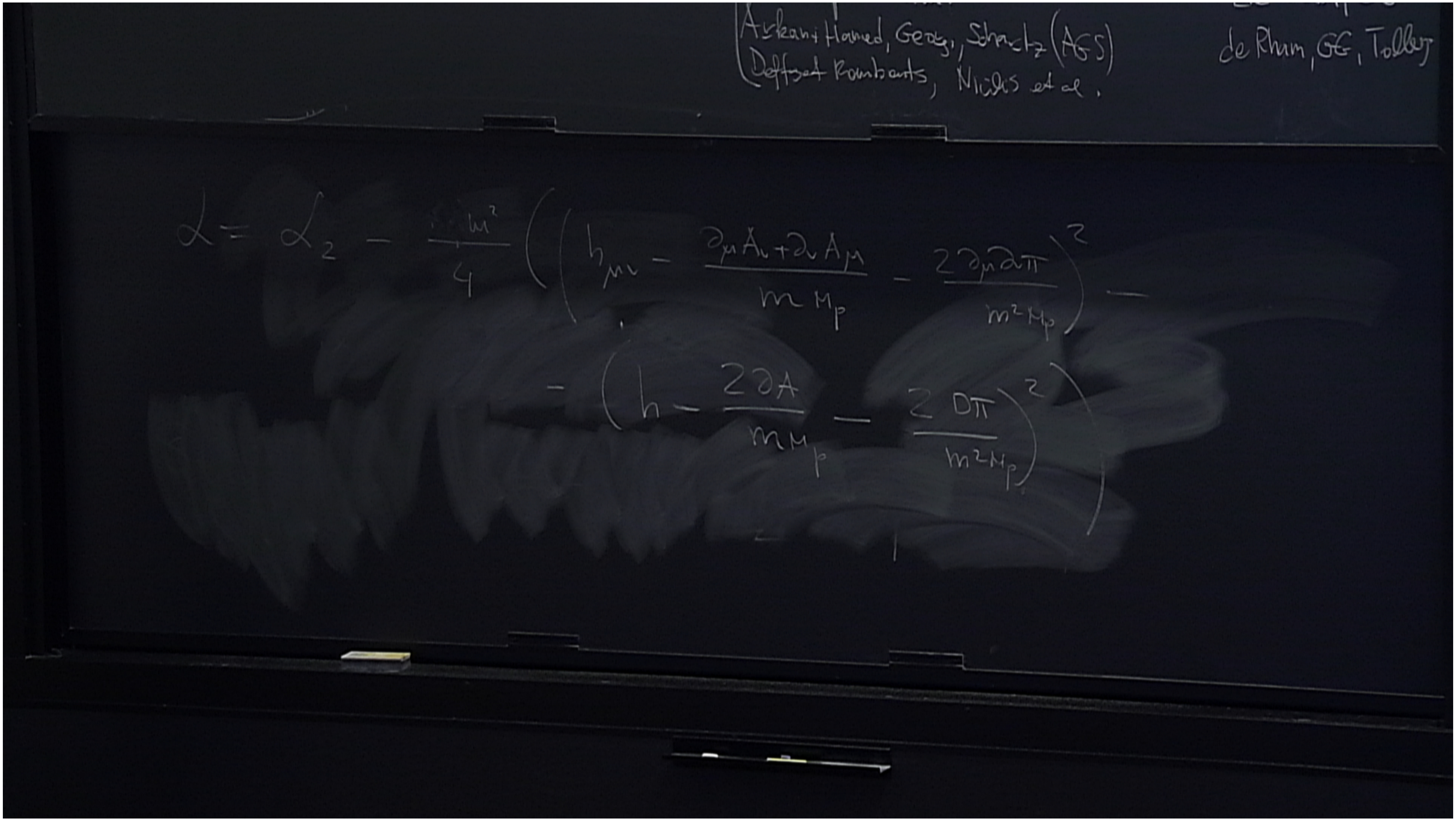
$\mathcal{L} = \mathcal{L}_2 - \frac{M_p^2 m^2}{4}\left(\left(h_{\mu\nu} - \frac{\partial_\mu A_\nu + \partial_\nu A_\mu}{m} - \frac{2\partial_\mu\partial_\nu\pi}{m^2}\right)^2 - \left(h - \frac{2\partial A}{m} - \frac{2\Box\pi}{m^2}\right)^2\right)$


FP:
Lin. th.
fixed
e→0.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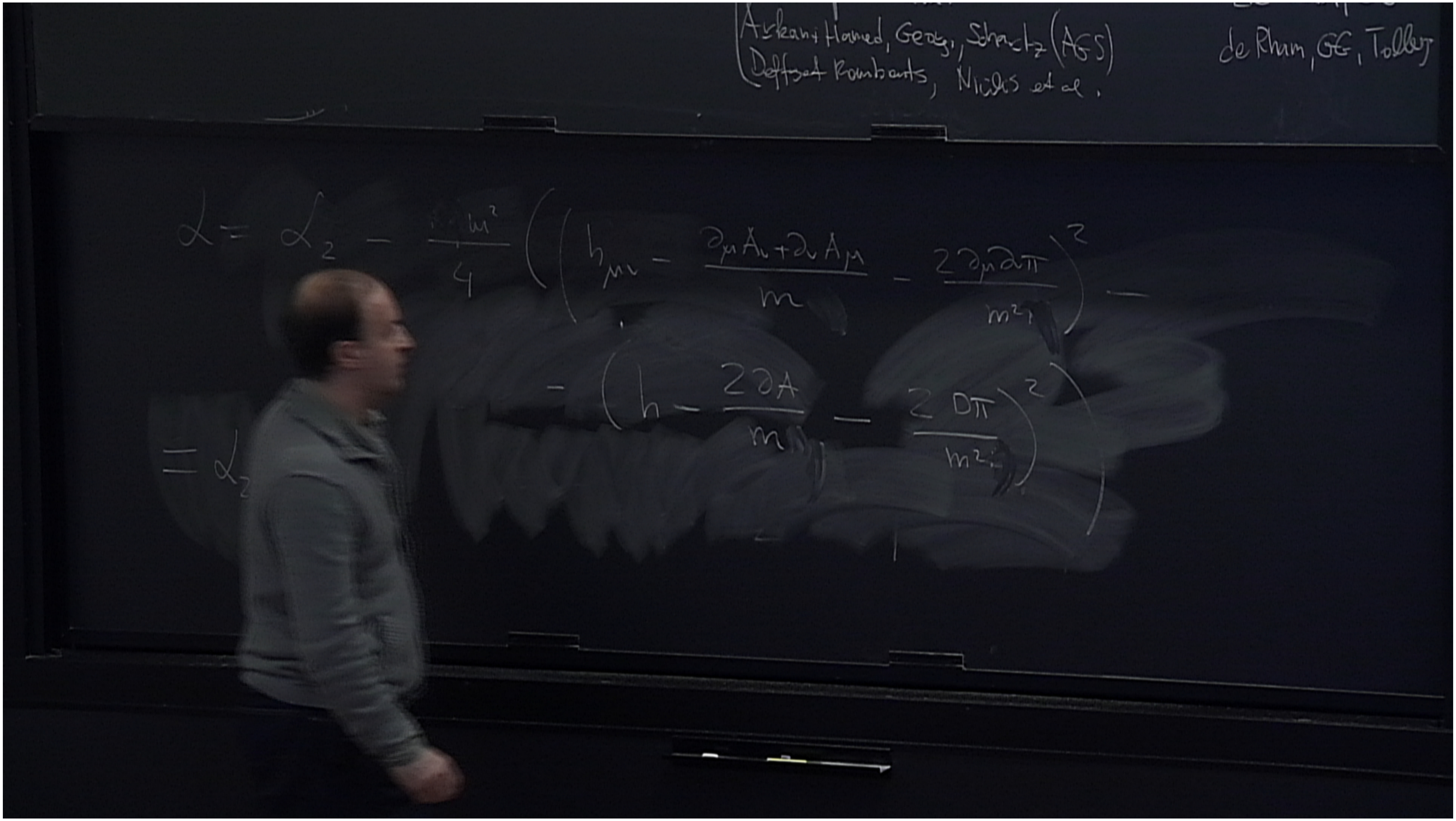
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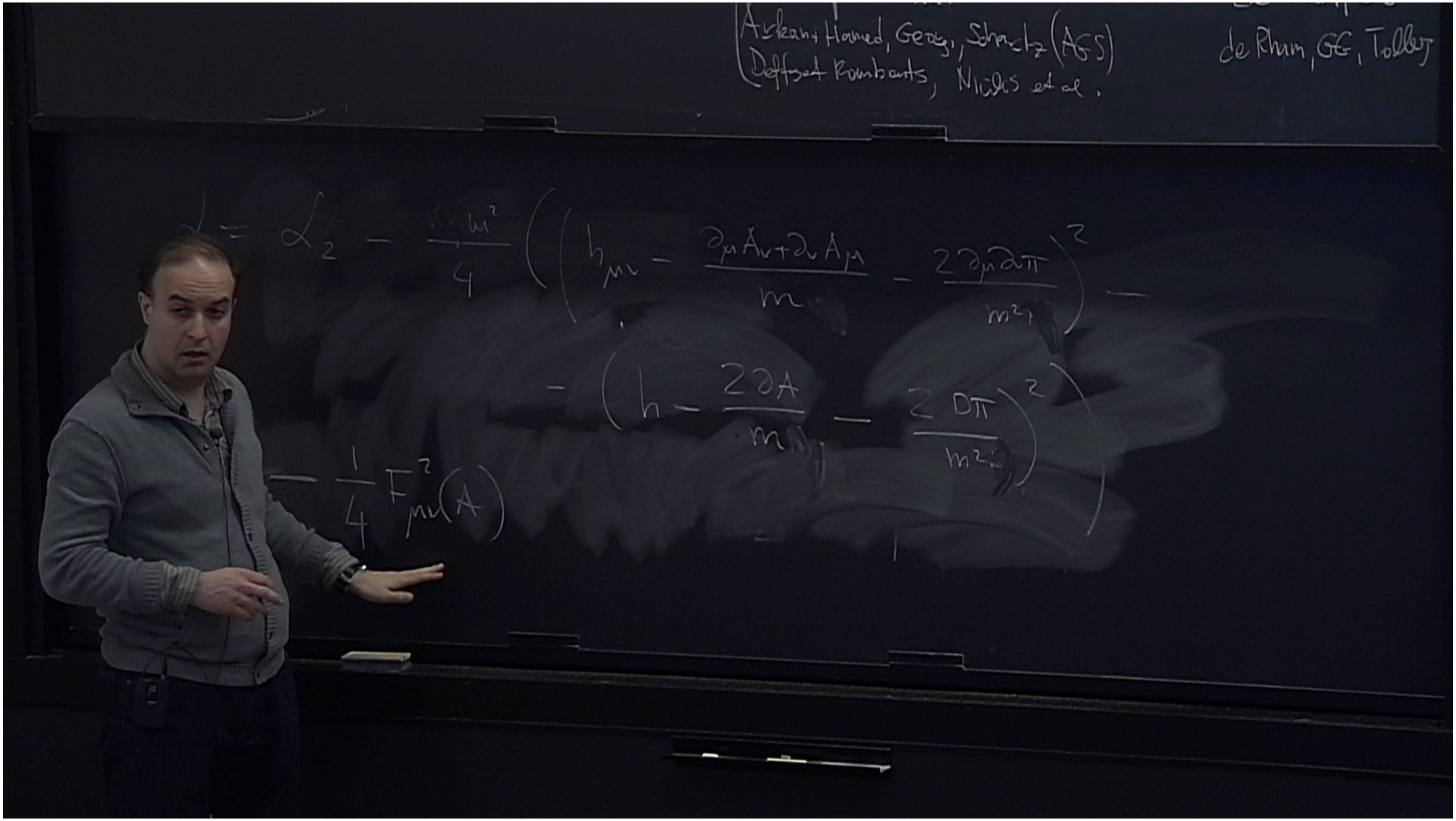
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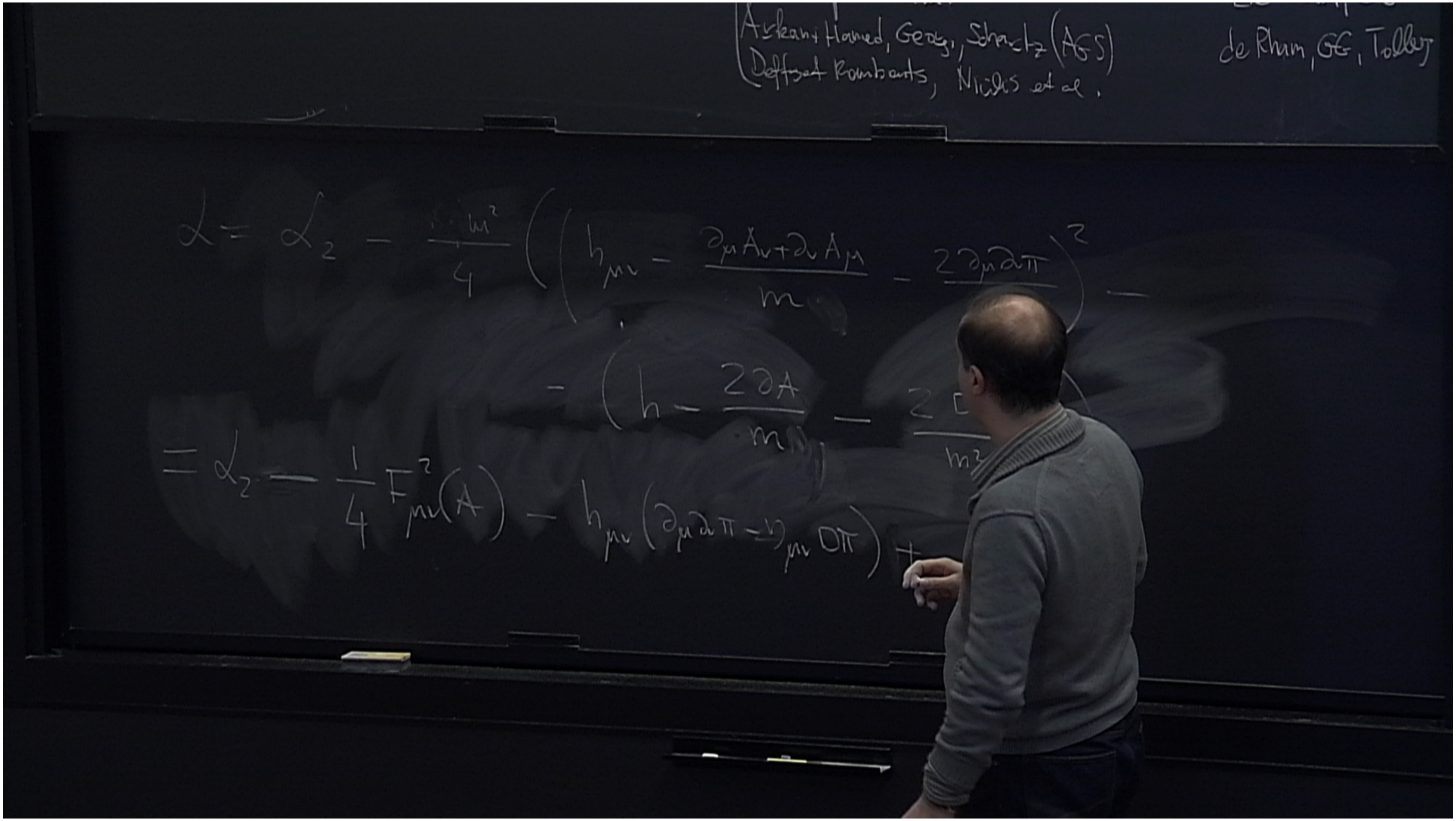
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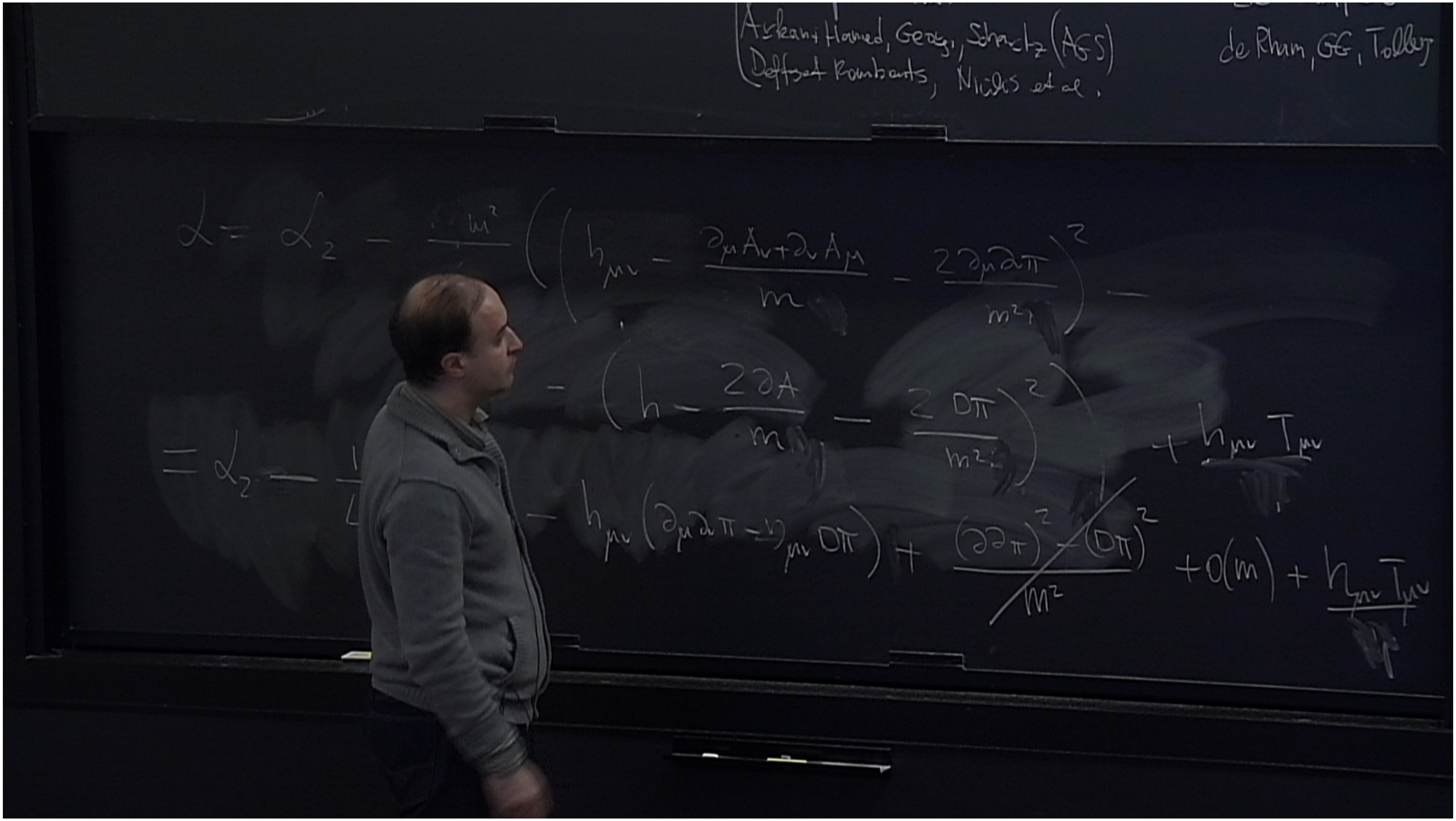
$$\mathcal{L} = \mathcal{L}_2 - \frac{m^2}{4}\left(\left(h_{\mu\nu} - \frac{\partial_\mu A_\nu + \partial_\nu A_\mu}{m} - \frac{2\partial_\mu\partial_\nu\pi}{m^2}\right)^2 - \left(h - \frac{2\partial A}{m} - \frac{2\Box\pi}{m^2}\right)^2\right) + h_{\mu\nu}T_{\mu\nu}$$

$$= \mathcal{L}_2 - \frac{1}{4}F^2_{\mu\nu}(A) - h_{\mu\nu}\left(\partial_\mu\partial_\nu\pi - \eta_{\mu\nu}\Box\pi\right) + \frac{(\partial\partial\pi)^2 - (\Box\pi)^2}{m^2} + O(m) + h_{\mu\nu}T_{\mu\nu}$$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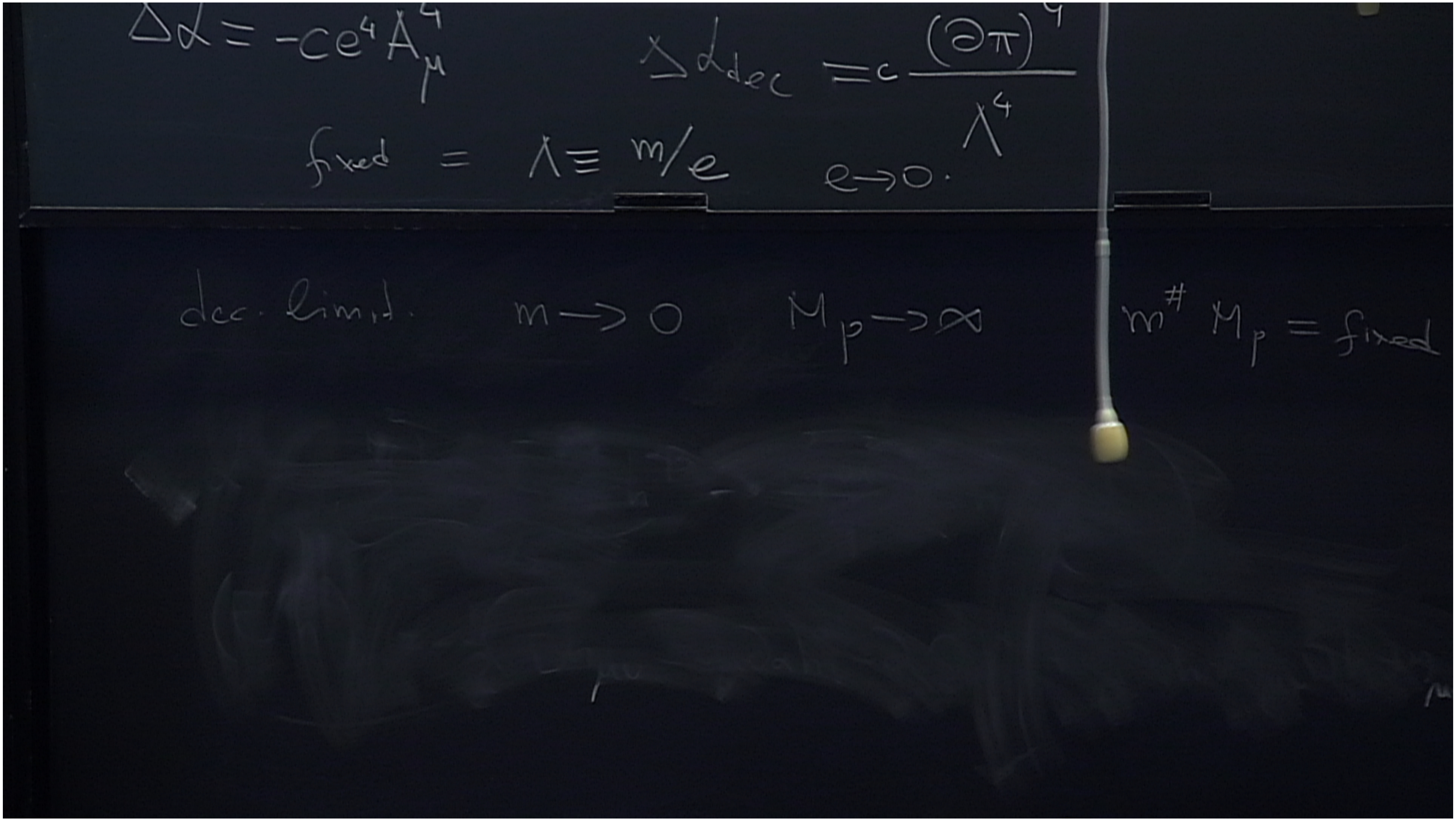
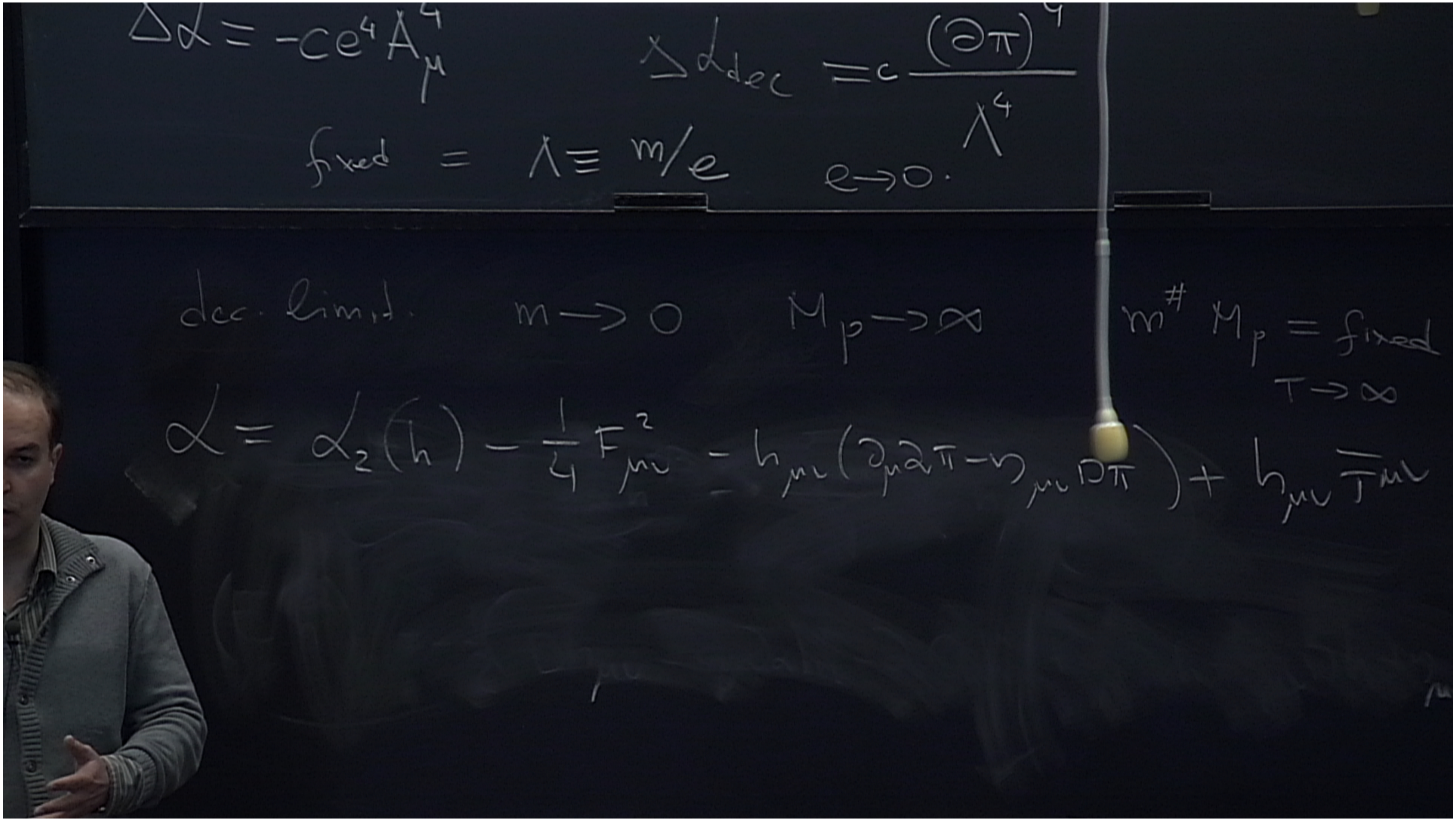
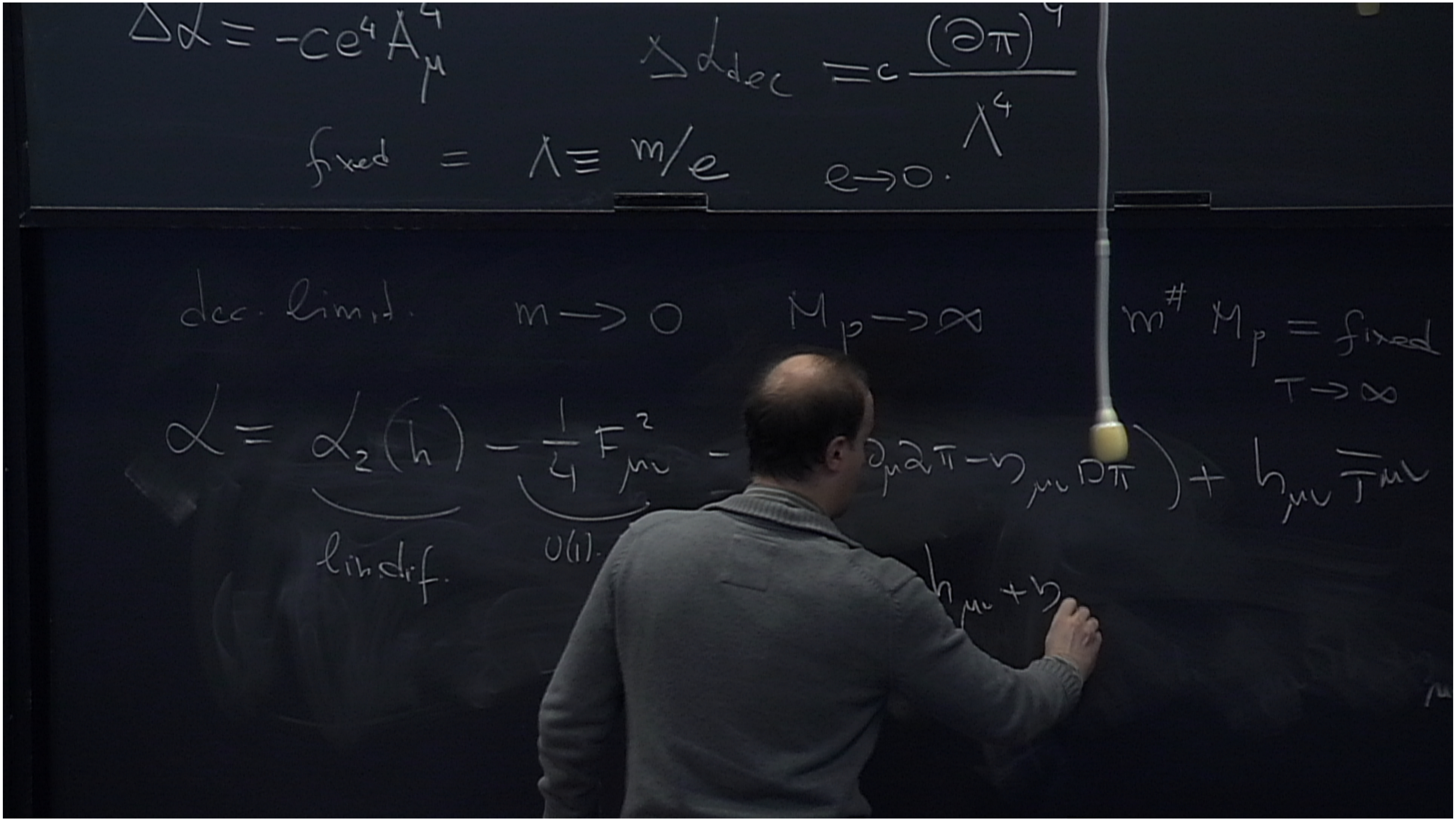
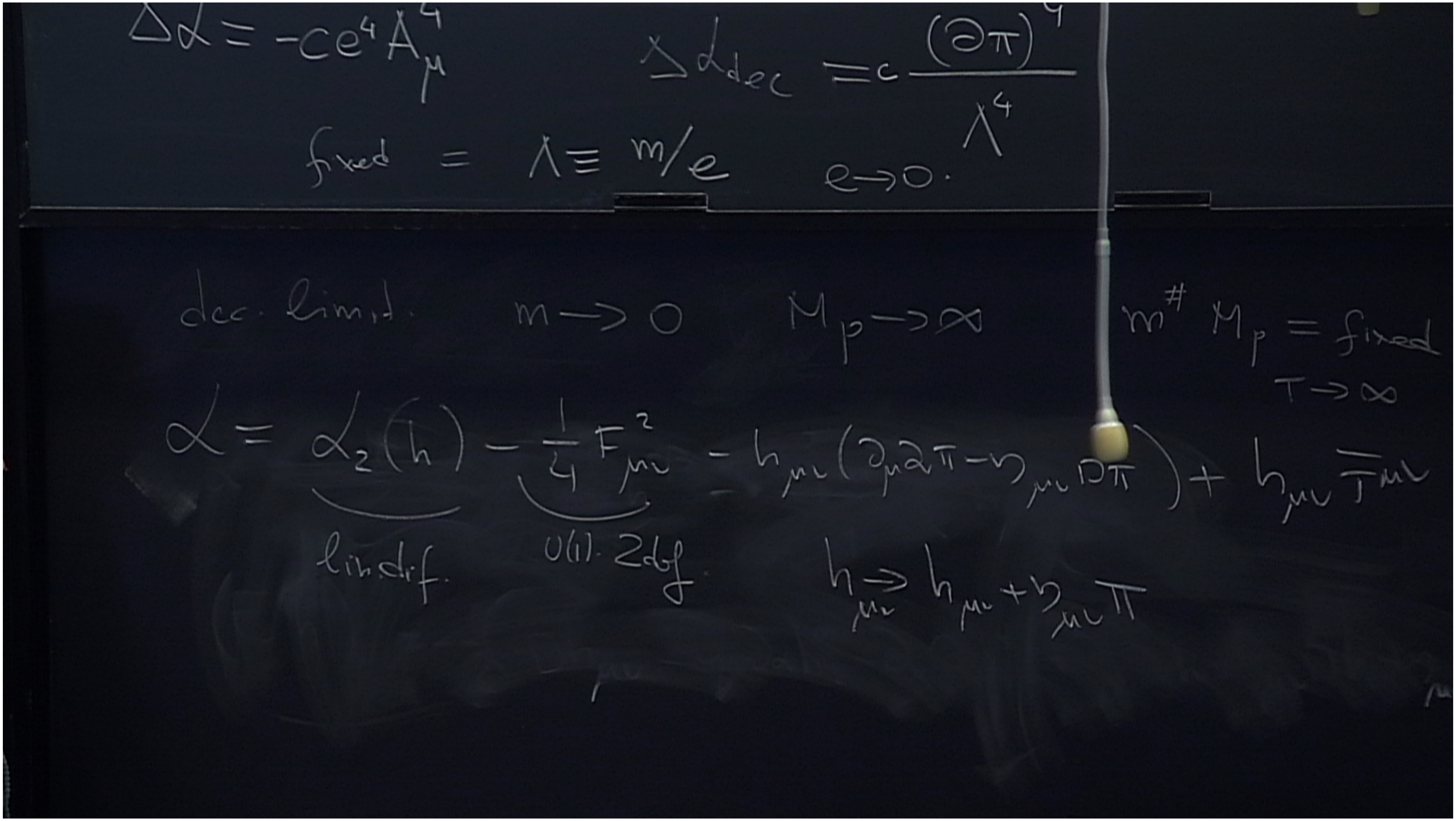
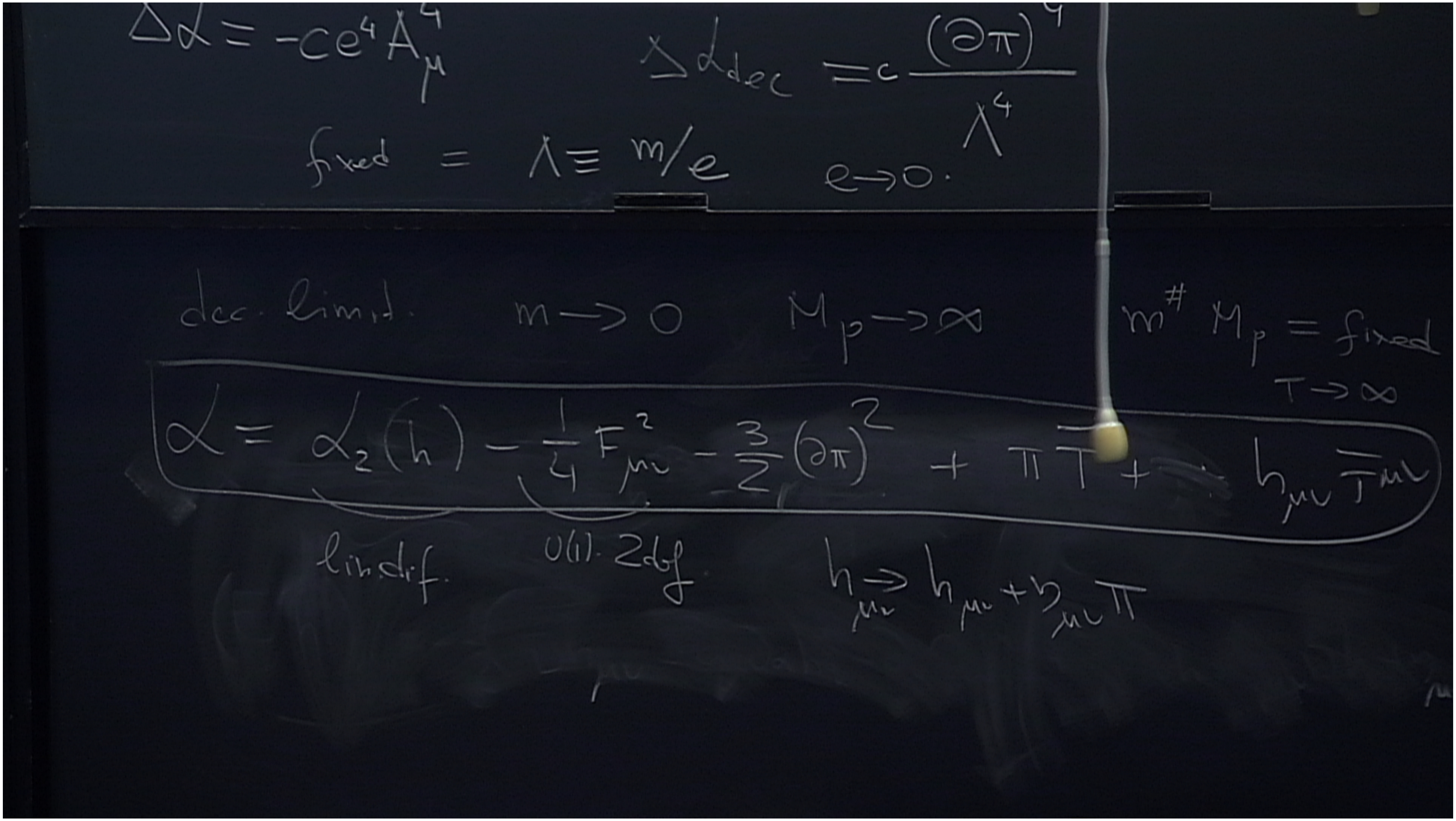
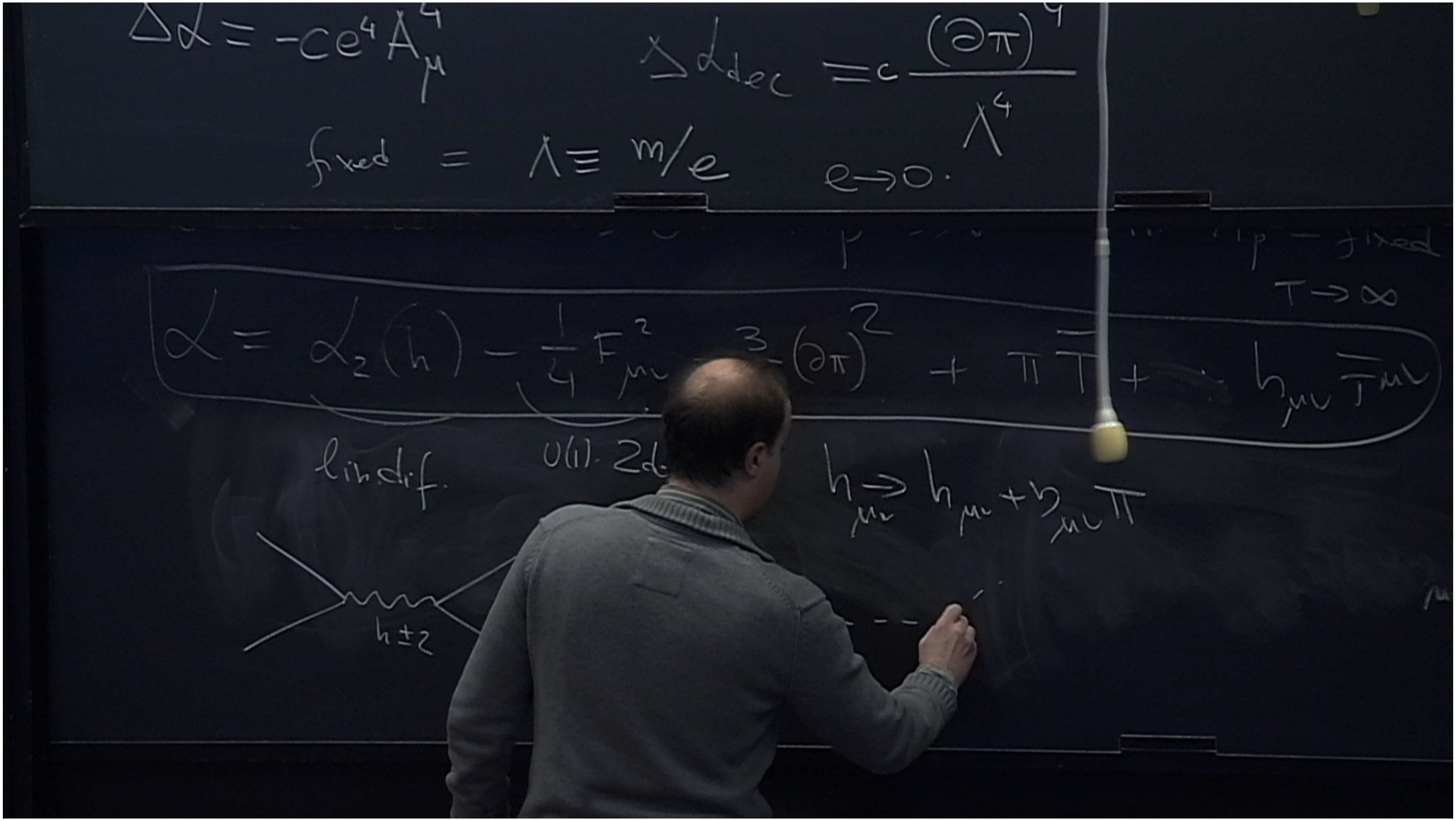

$\Delta\mathcal{L} \equiv -c e^4 A_\mu^4$
$\Delta\mathcal{L}_{dec} \equiv c \frac{(\partial\pi)^4}{\Lambda^4}$
fixed = $\Lambda \equiv m/e$
$e \to 0.$
dec. limit. $m \to 0$ $M_p \to \infty$ $m^{\#} M_p$ = fixed


ΔL = -ce⁴ A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e → 0.
dec. limit. m → 0 M_p → ∞
m⁴ M_p = fixed
T → ∞
L = L_2(h) − 1/4 F_μν² − h_μν(∂_μ∂_ν π − η_μν □π) + h_μν T^μν


ΔL = -ce⁴A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e→0.
dec. limit. m→0 M_p→∞
m^# M_p = fixed
T→∞
lin.dif.
U(1).


ΔL = -ce⁴ A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e → 0.
dec. limit. m → 0 M_p → ∞ m# M_p = fixed
T → ∞
L = L₂(h) − 1/4 F_μν² − h_μν(∂_μ∂_ν π − η_μν □π) + h_μν T^μν
lin. dif.
U(1). 2dof.
h_μν → h_μν + η_μν π


fixed
Λ ≡ m/e
e→0.
dec. limit.
m → 0
M_p → ∞
m^# M_p = fixed
T → ∞
lin.dif.
U(1). 2dof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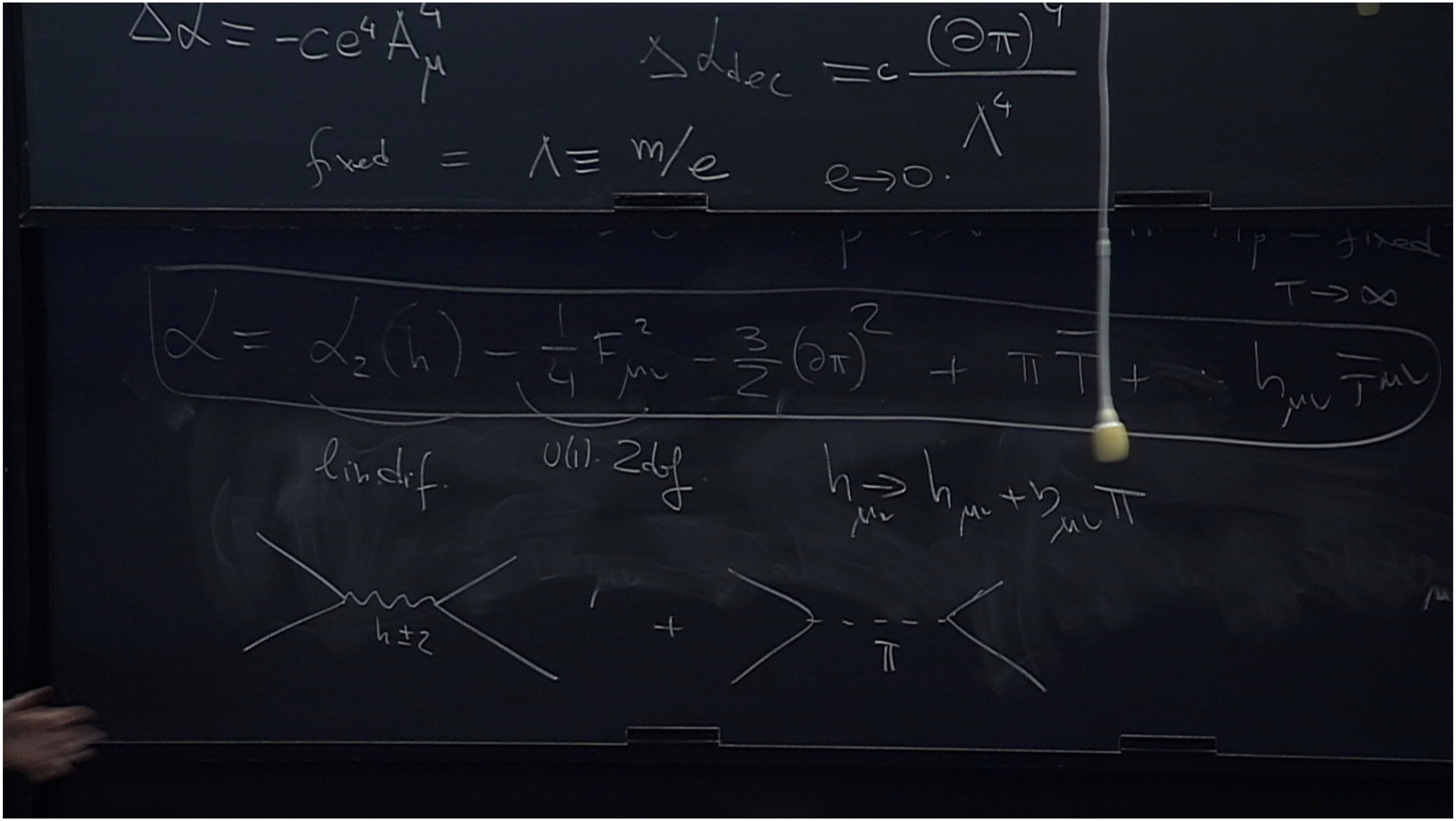
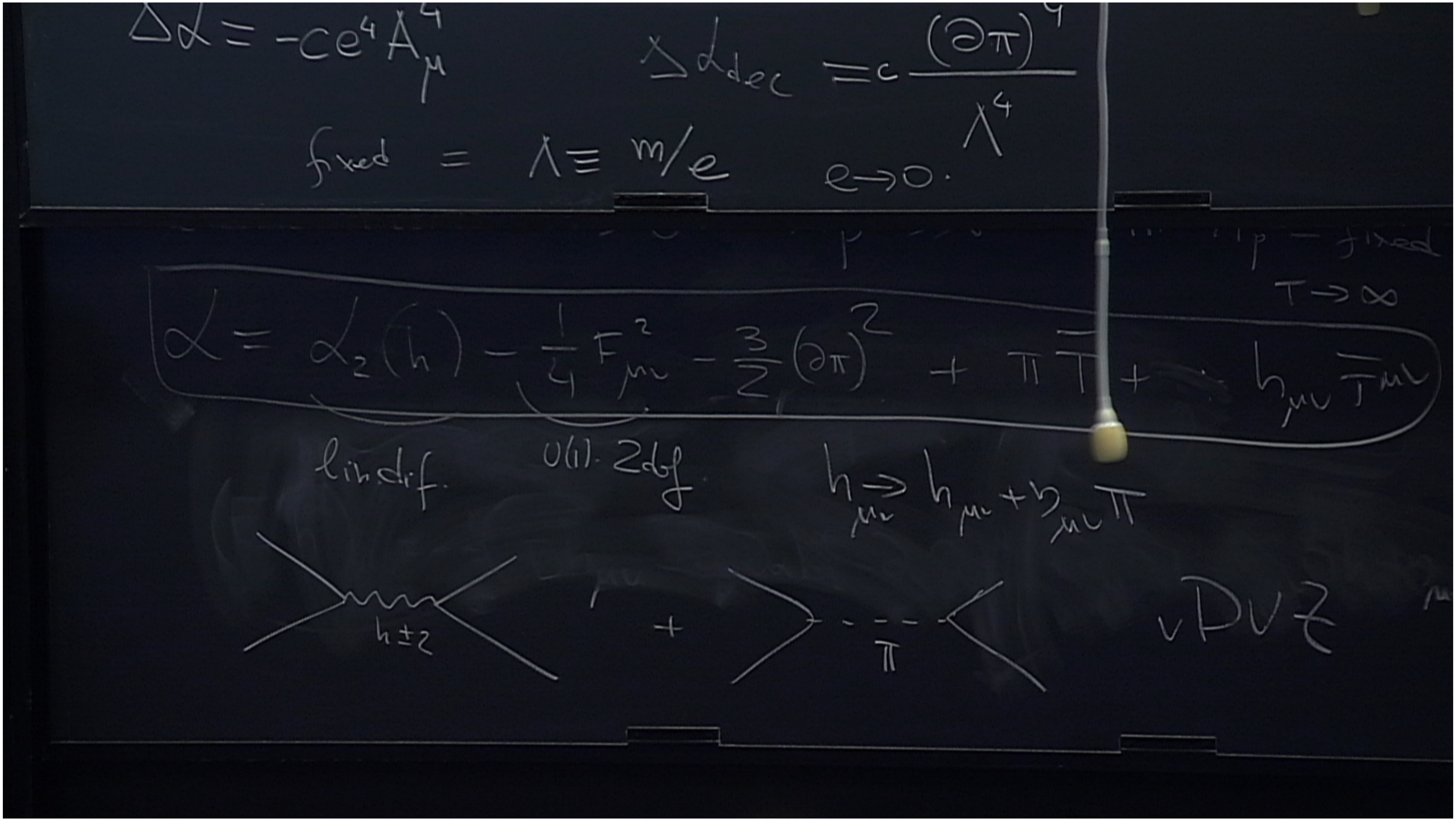
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e→0.
T→∞
L = L₂(h) - 1/4 F²_μν
(∂π)²
+ π T + h_μν T^μν
lin.dif.
U(1). 2d
h_μν → h_μν + η_μν π
h±2


ΔL = -ce⁴A_μ⁴
ΔL_dec = c (∂π)⁴ / Λ⁴
fixed = Λ ≡ m/e
e→0.
T→∞
L = L₂(h) - 1/4 F_μν² - 3/2 (∂π)² + π T + h_μν T^μν
lin.dif.
U(1). 2dof
h_μν → h_μν + η_μν π
h±2
+
π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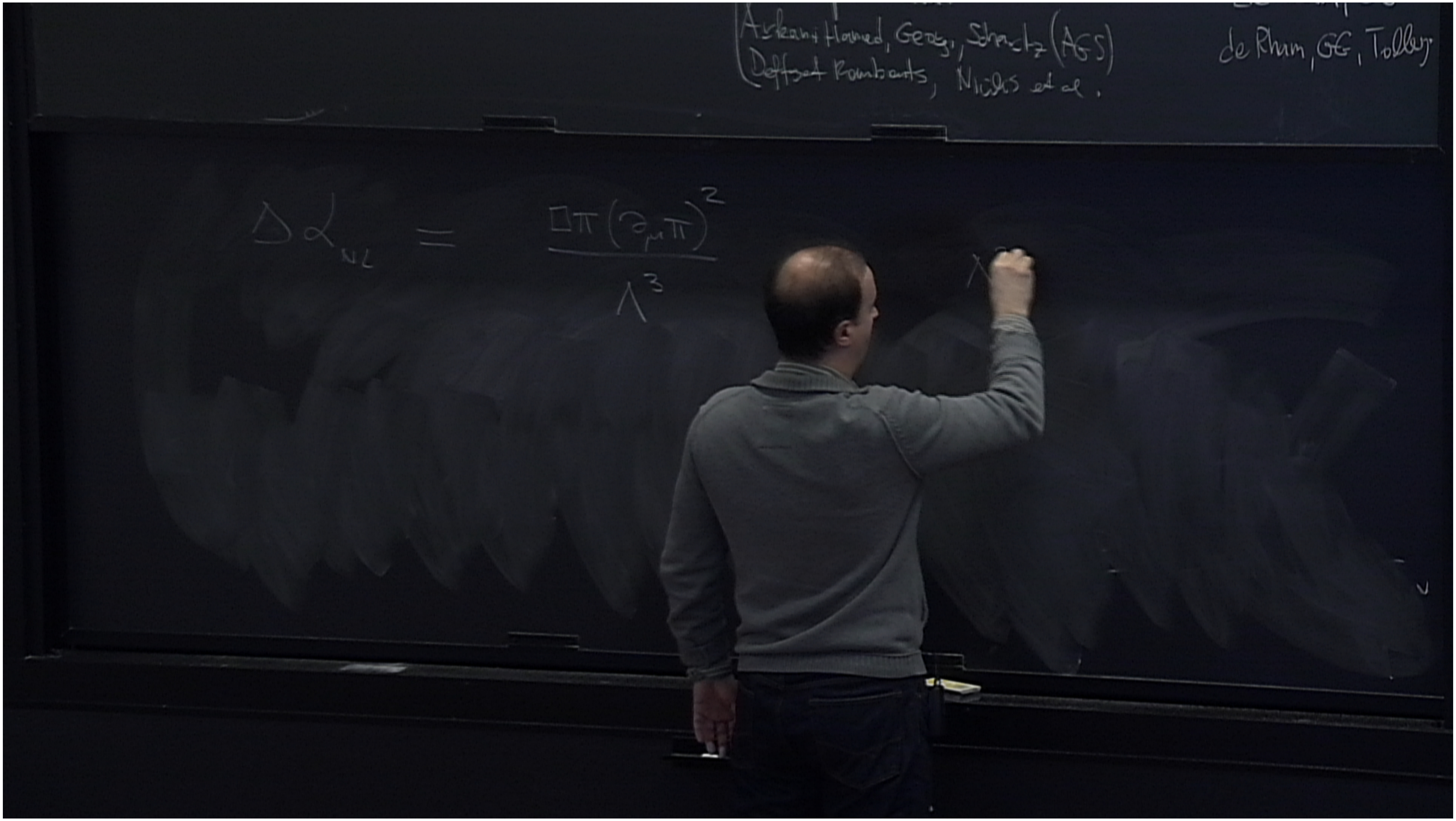
fixed = $\Lambda \equiv m/e$ $e \to 0$.
$T \to \infty$
$\mathcal{L} = \mathcal{L}_2(h) - \frac{1}{4} F_{\mu\nu}^2 - \frac{3}{2}(\partial\pi)^2 + \pi T + h_{\mu\nu} T^{\mu\nu}$
lin. dif.
U(1). 2dof
$h_{\mu\nu} \to h_{\mu\nu} + \eta_{\mu\nu}\pi$
$h \pm 2$
+
π
vDVZ


Arkani Hamed, Georgi, Schwartz (AGS)
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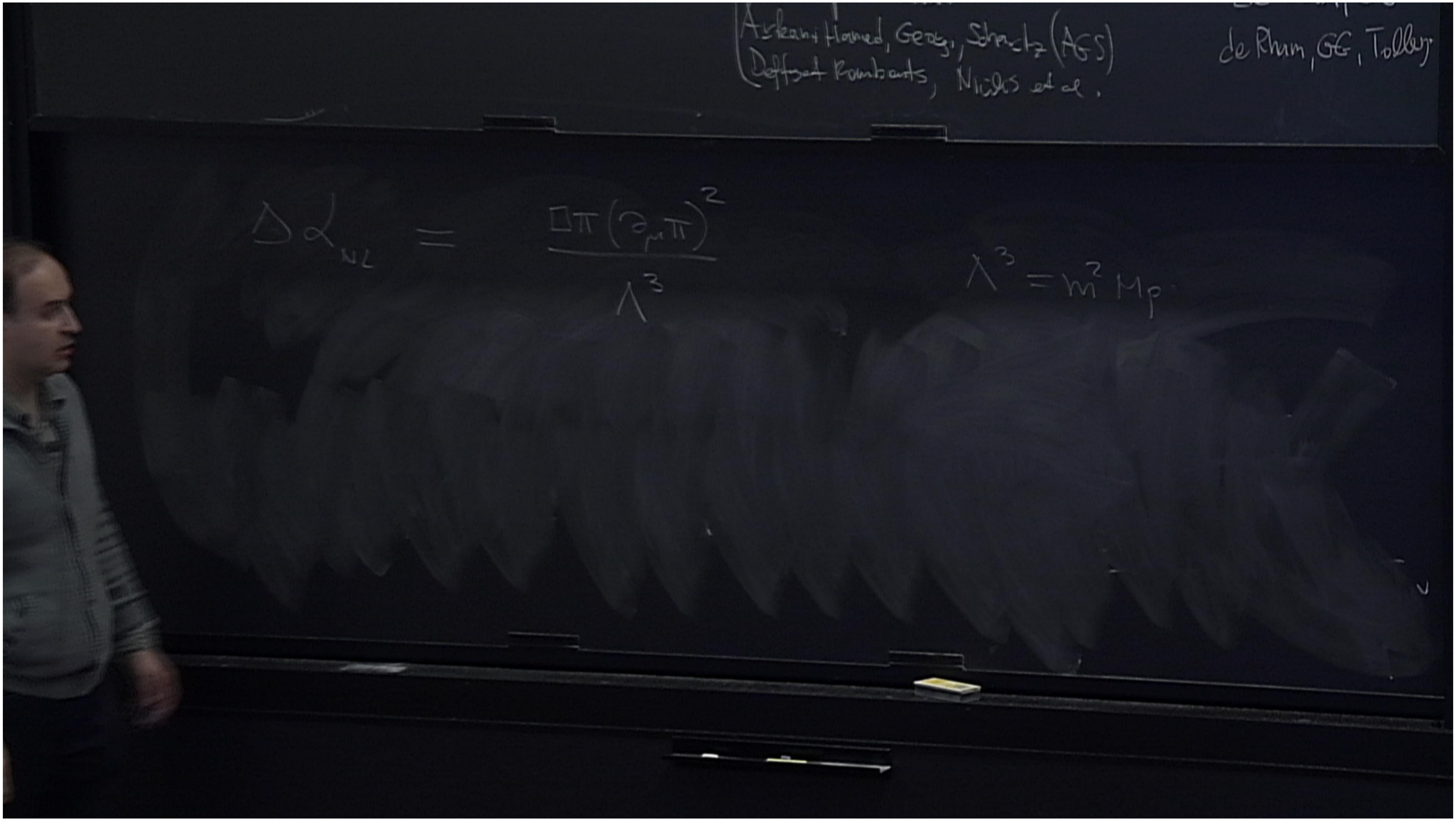
de Rham, GG, Tolley
$\Delta \mathcal{L}_{NL} = \frac{\Box\pi(\partial_\mu\pi)^2}{\Lambda^3}$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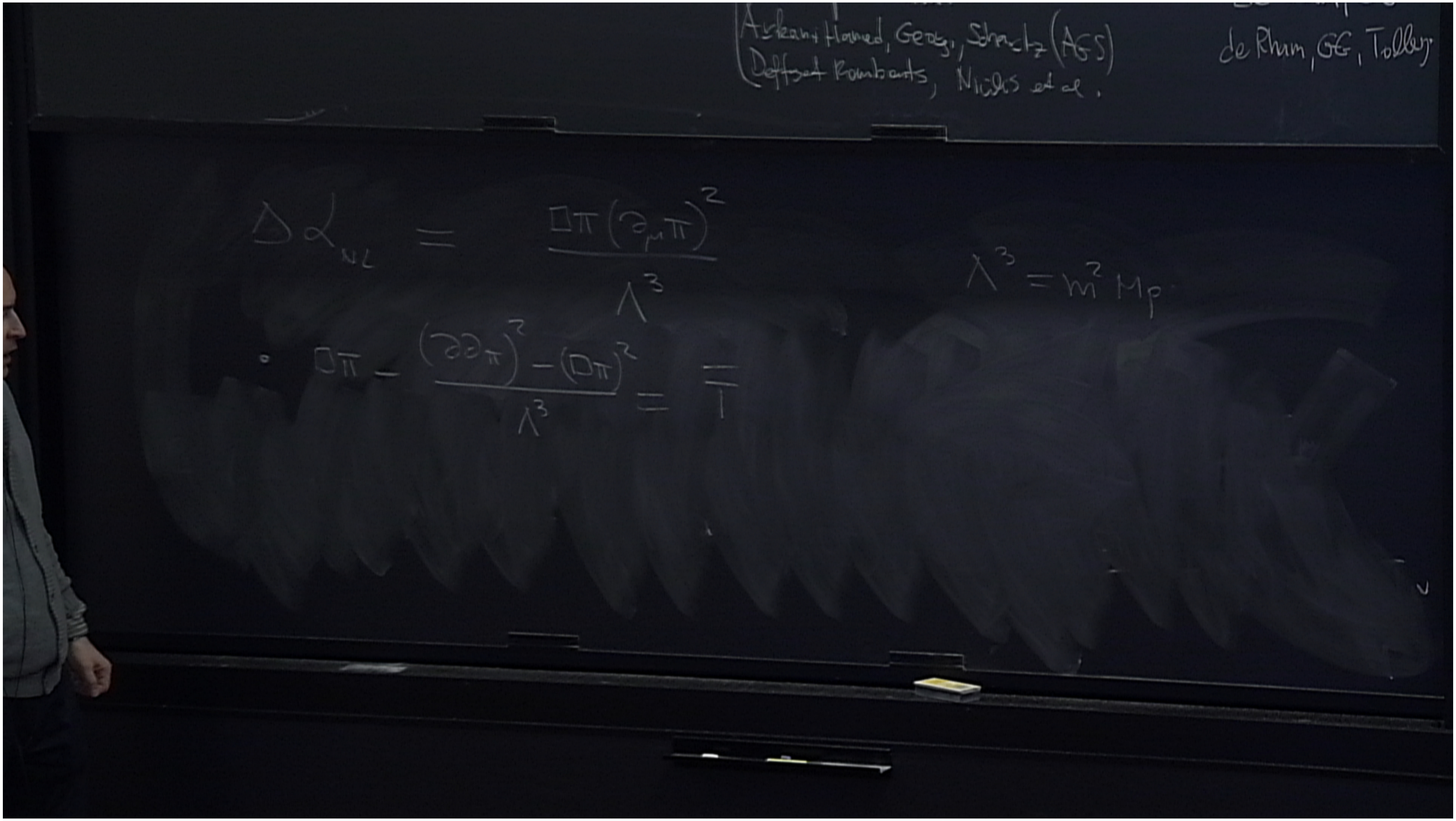
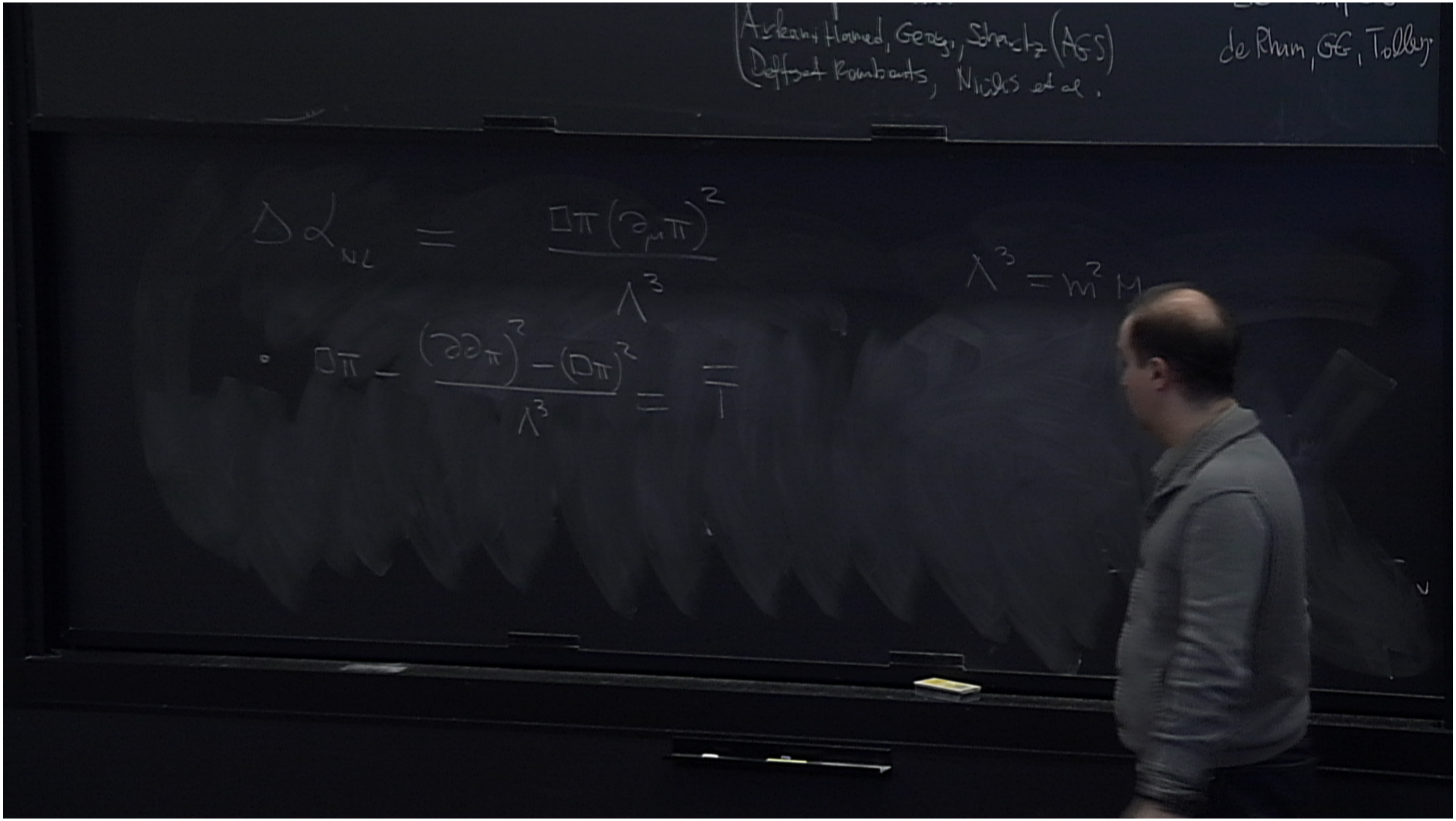

(Arkani Hamed, Georgi, Schwartz (AGS)
Deffayet Rombouts, Nicolis et al.
de Rham, GG, Tolley
ΔL_NL = □π(∂_μπ)^2 / Λ^3
Λ^3 = m^2 M_p
□π − ((∂∂π)^2 − (□π)^2) / Λ^3 = T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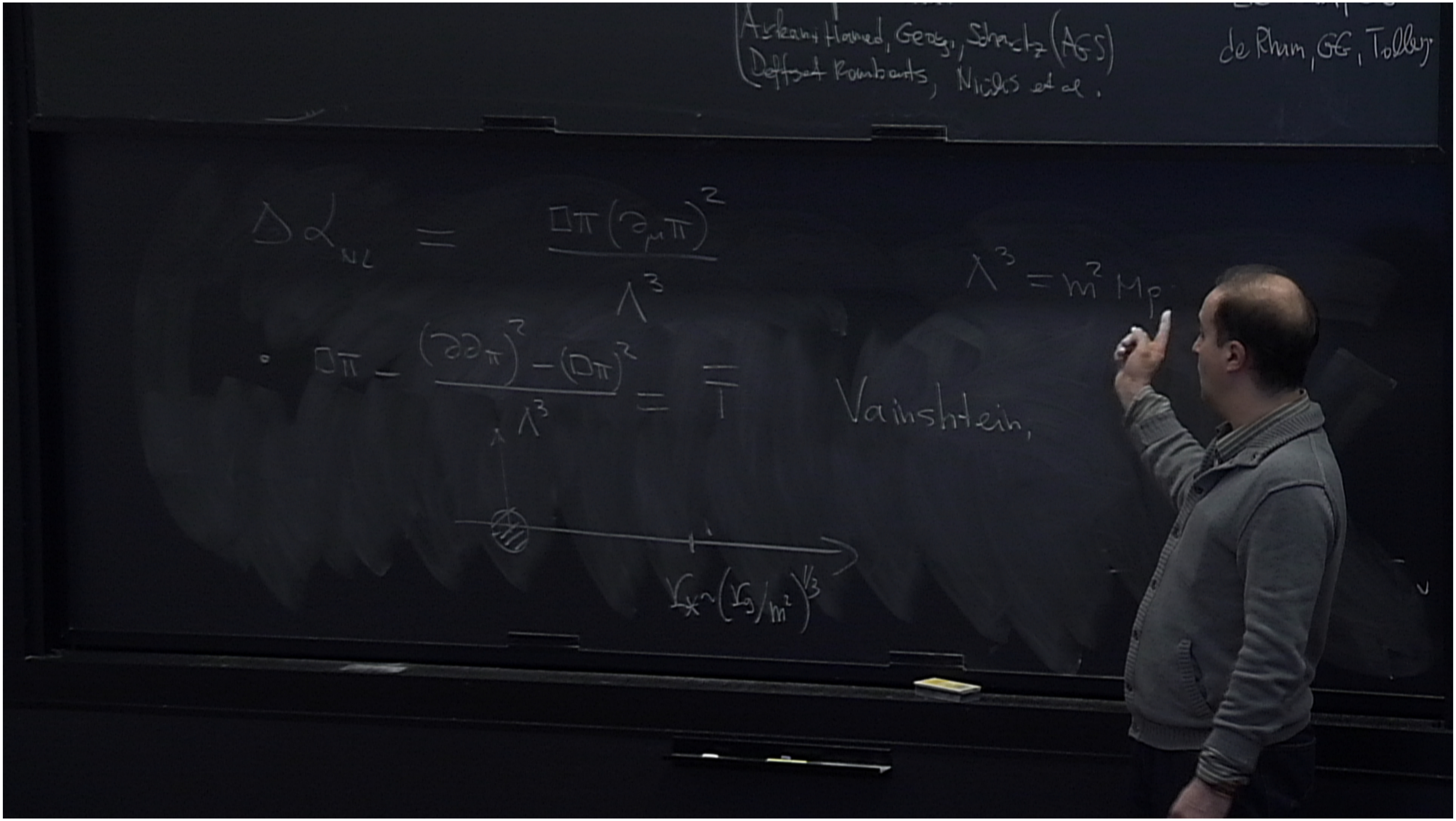
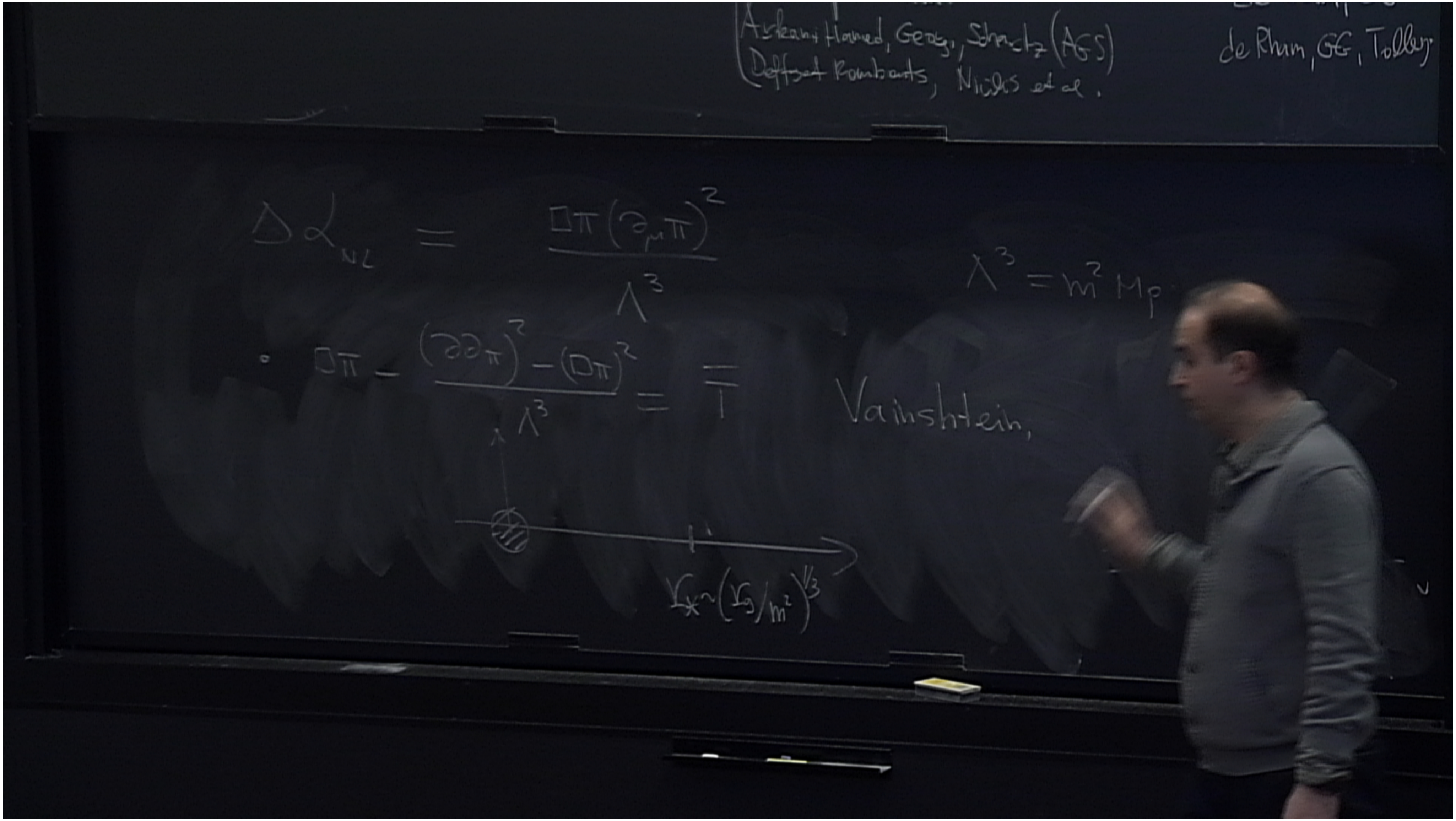
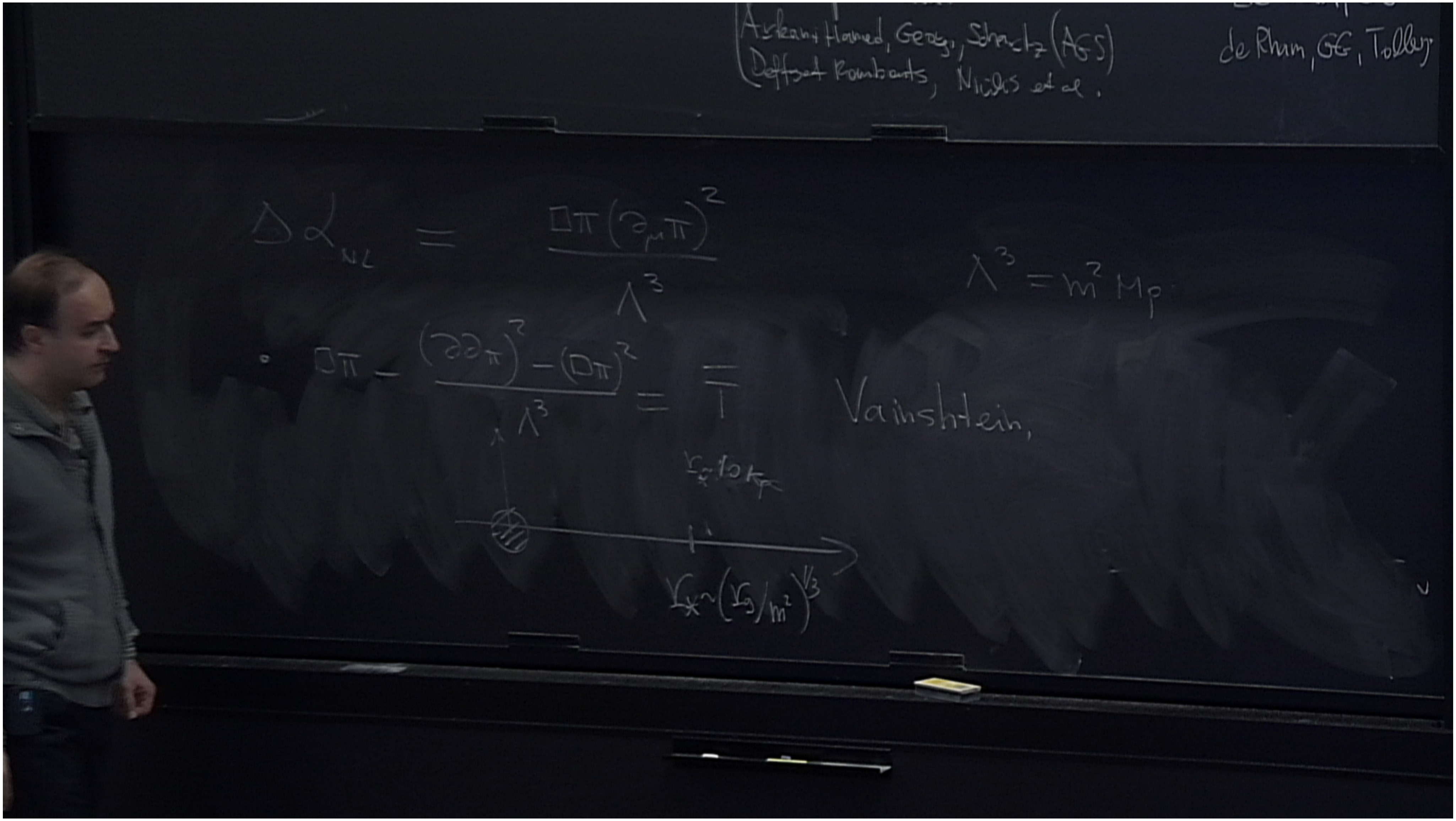
$\Box\pi - \frac{(\partial\partial\pi)^2 - (\Box\pi)^2}{\Lambda^3} = T$


Vainshtein,
Λ³ = m² Mp


Vainshtein,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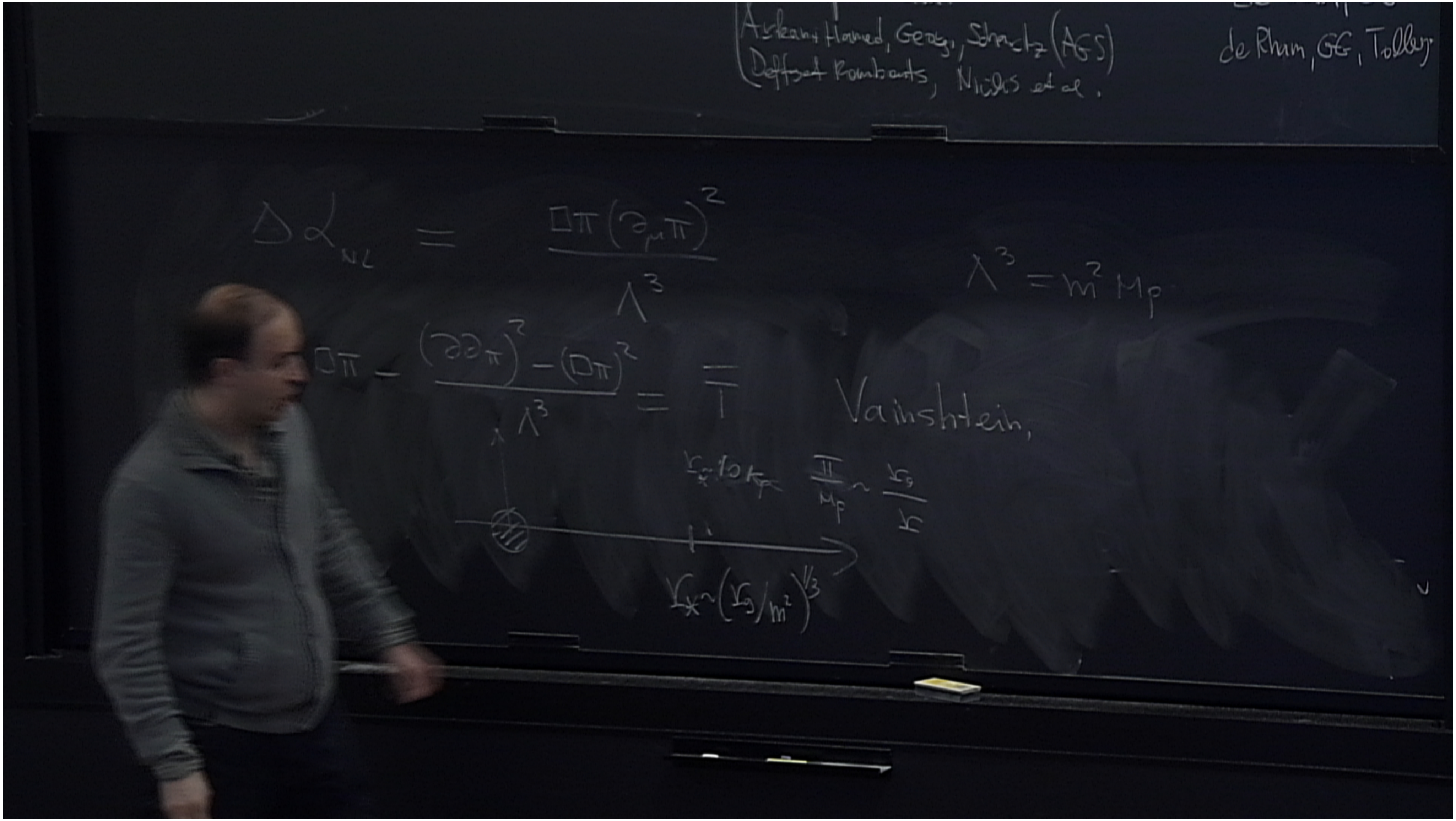
Vainshtein,
$r_* \sim (r_g/m^2)^{1/3}$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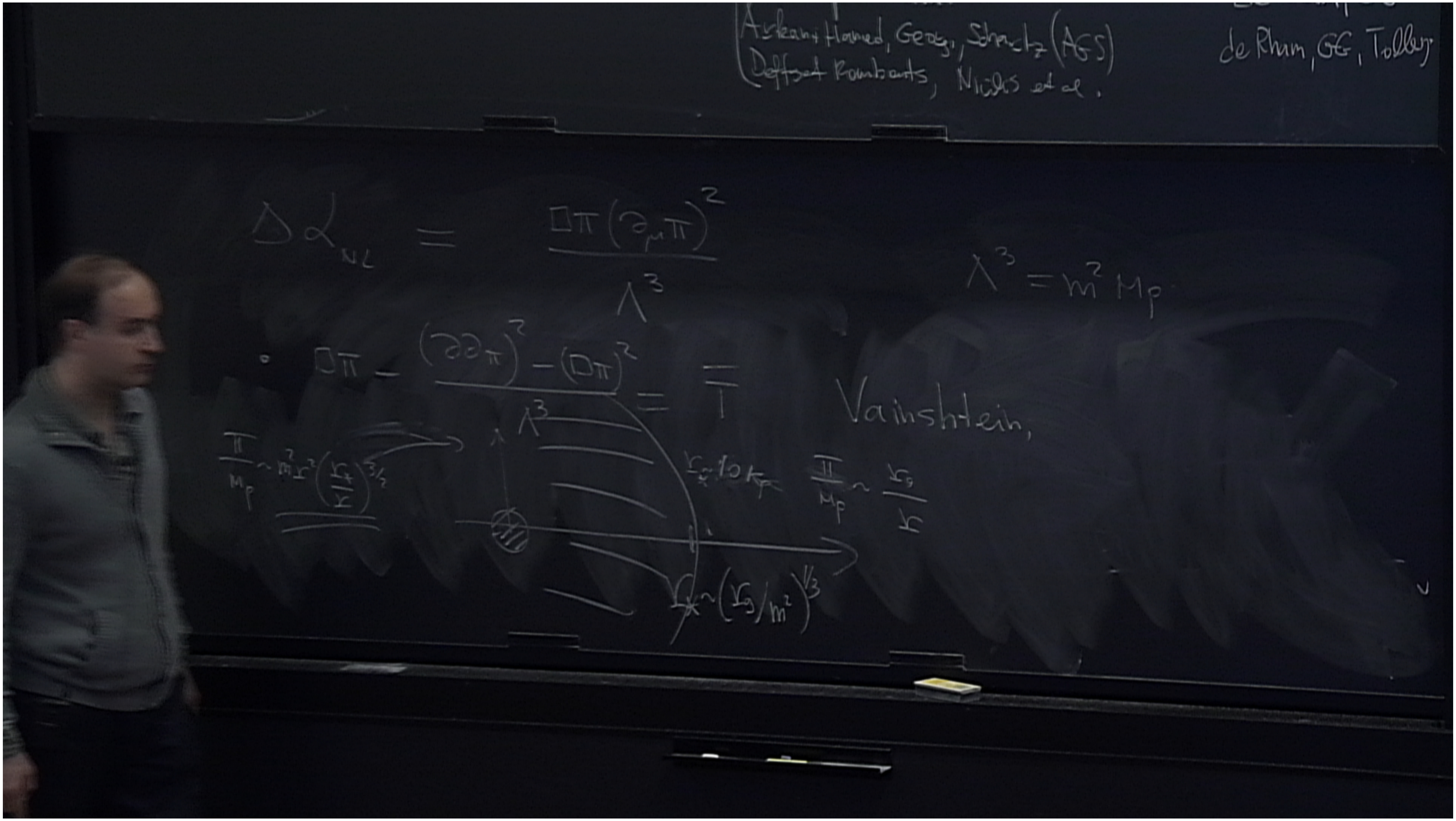
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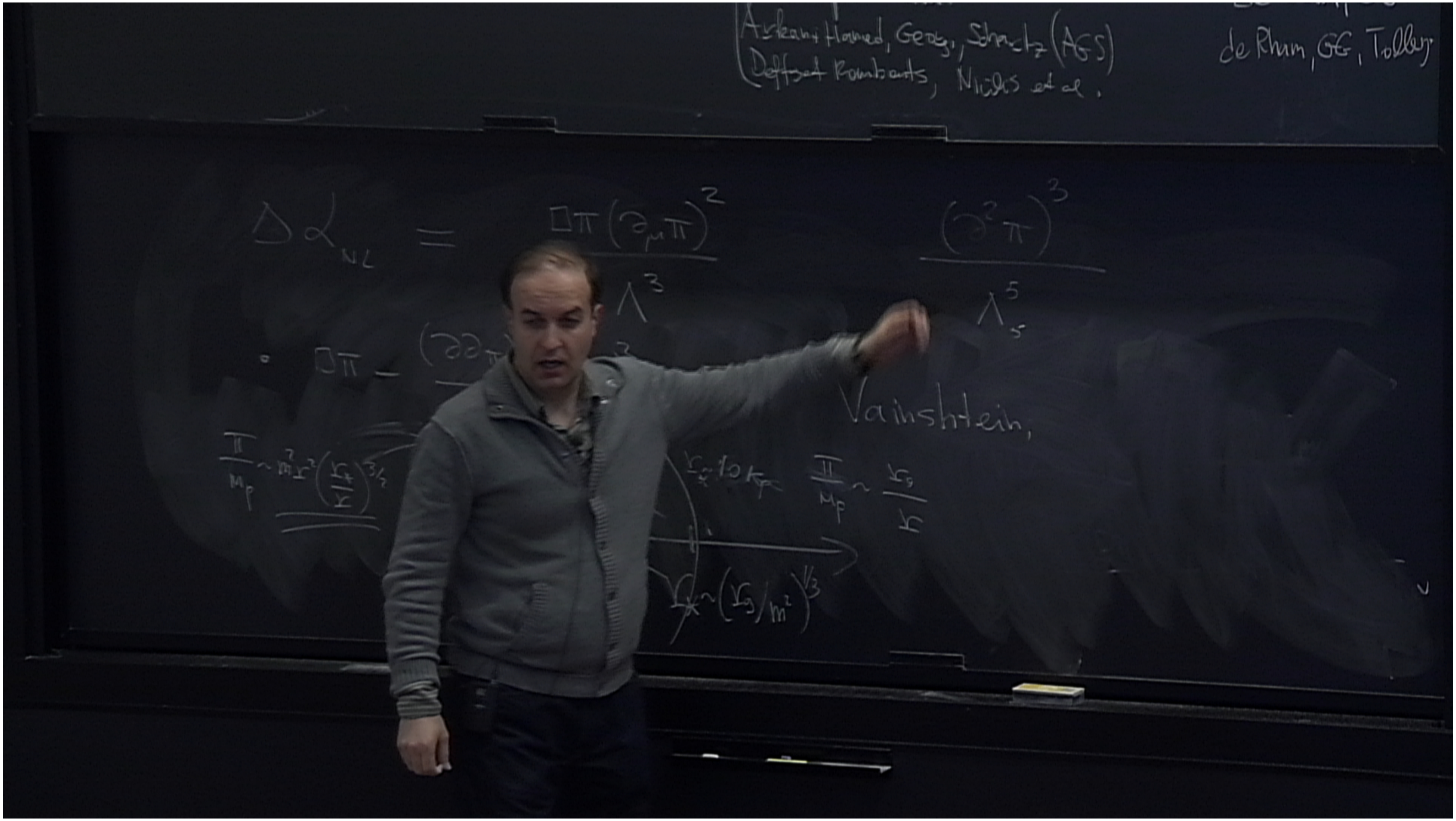
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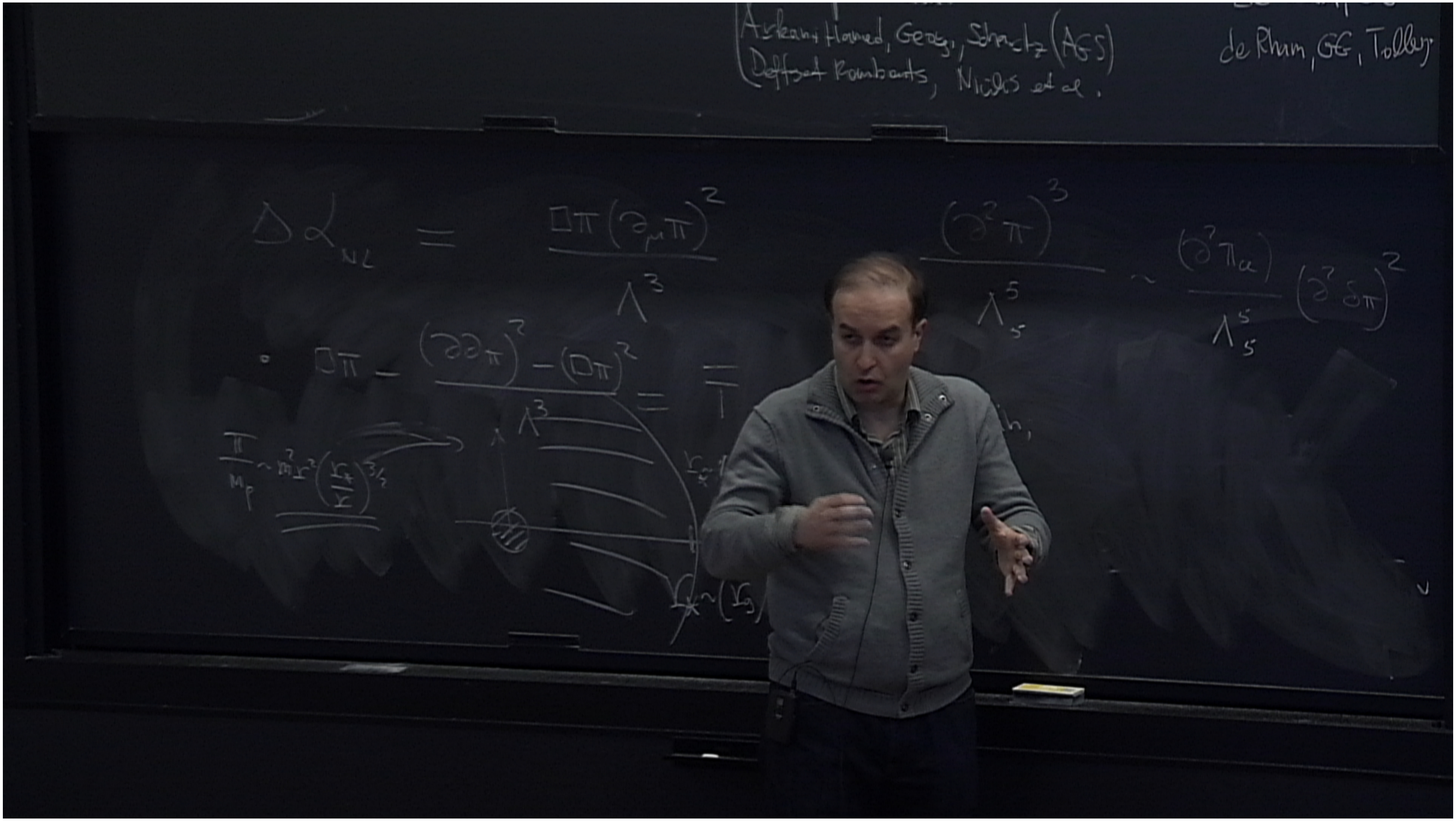
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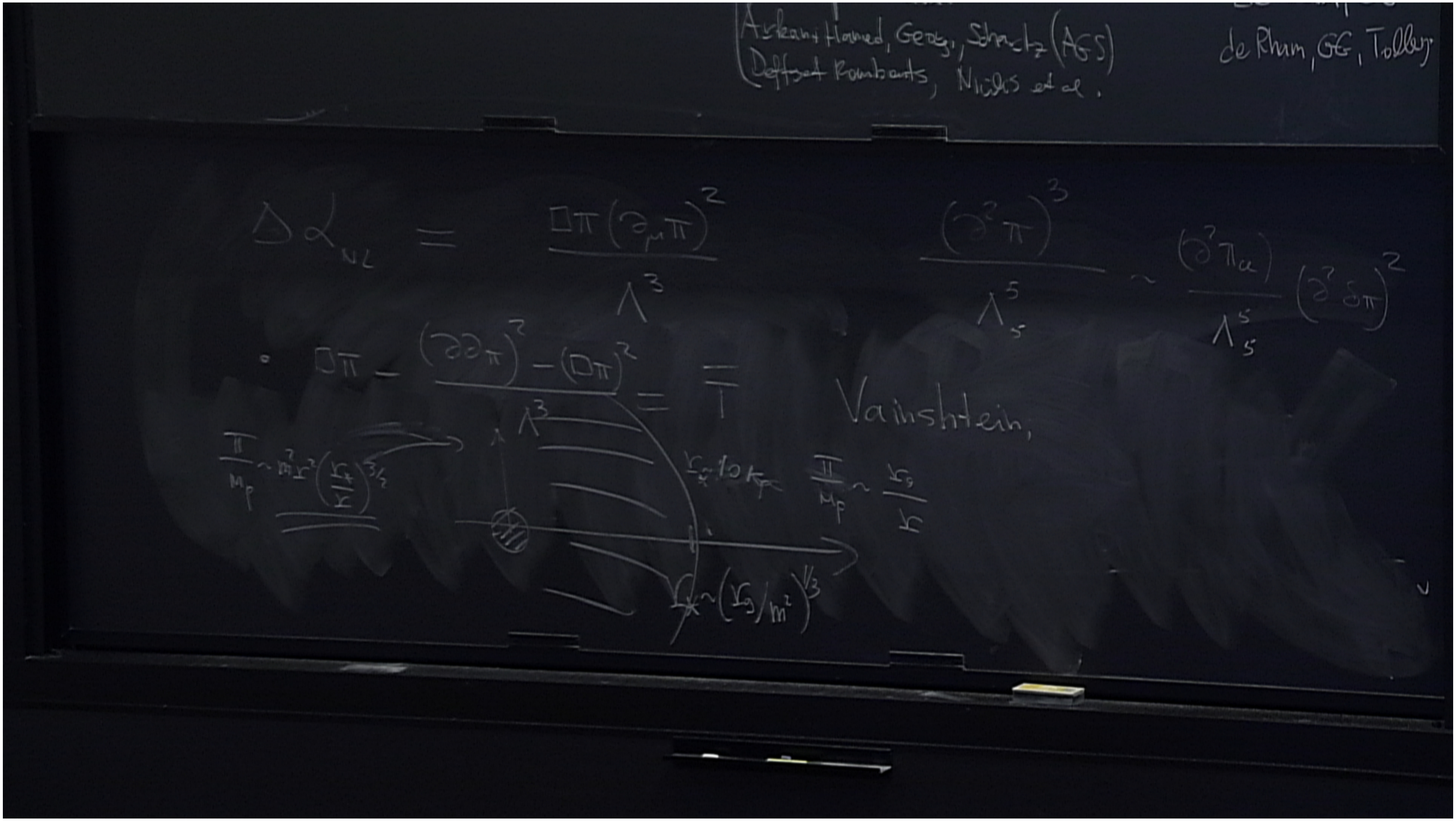
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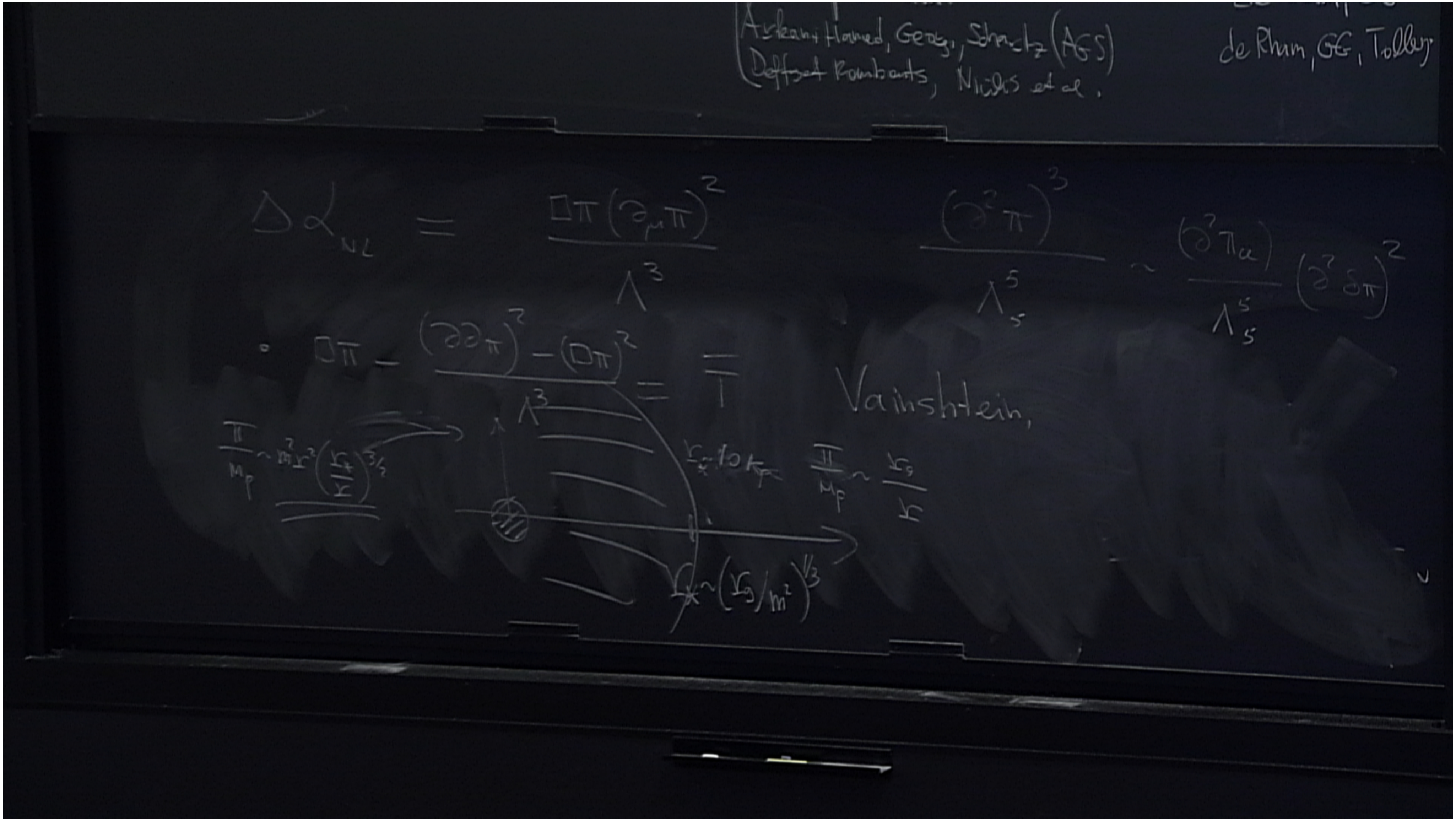
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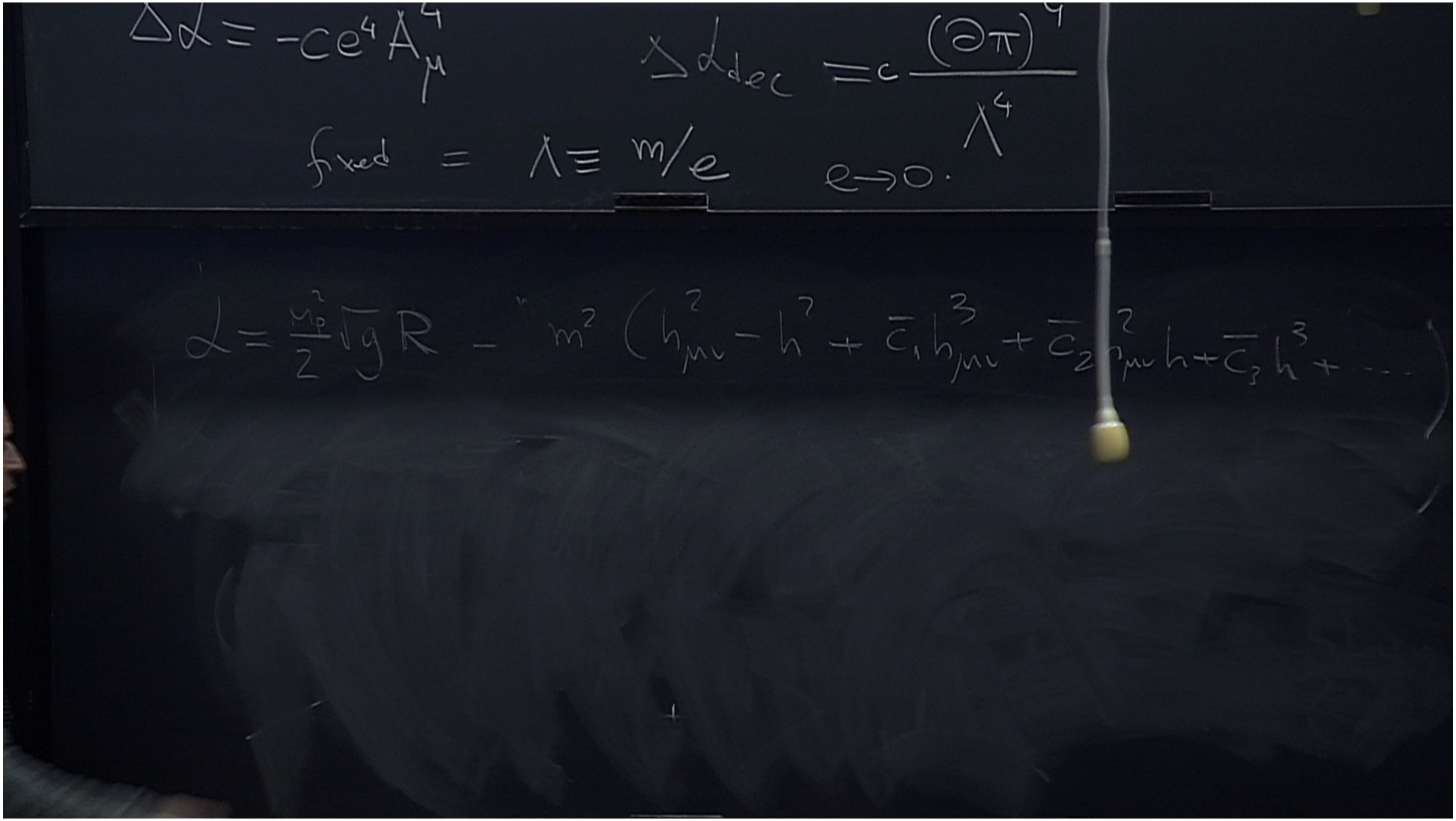
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fixed $= \Lambda \equiv m/e$ $e \to 0$.
$\mathcal{L} = \frac{M_P^2}{2}\sqrt{g}R - m^2 \left(h_{\mu\nu}^2 - h^2 + \bar{c}_1 h_{\mu\nu}^3 + \bar{c}_2 h_{\mu\nu}^2 h + \bar{c}_3 h^3 + \dots \right)$

$$\Delta \mathcal{L} = -c e^4 A_\mu^4 \qquad \Delta \mathcal{L}_{dec} = c \frac{(\partial \pi)^4}{\Lambda^4}$$

$$\text{fixed} = \Lambda \equiv m/e \qquad e \to 0.$$

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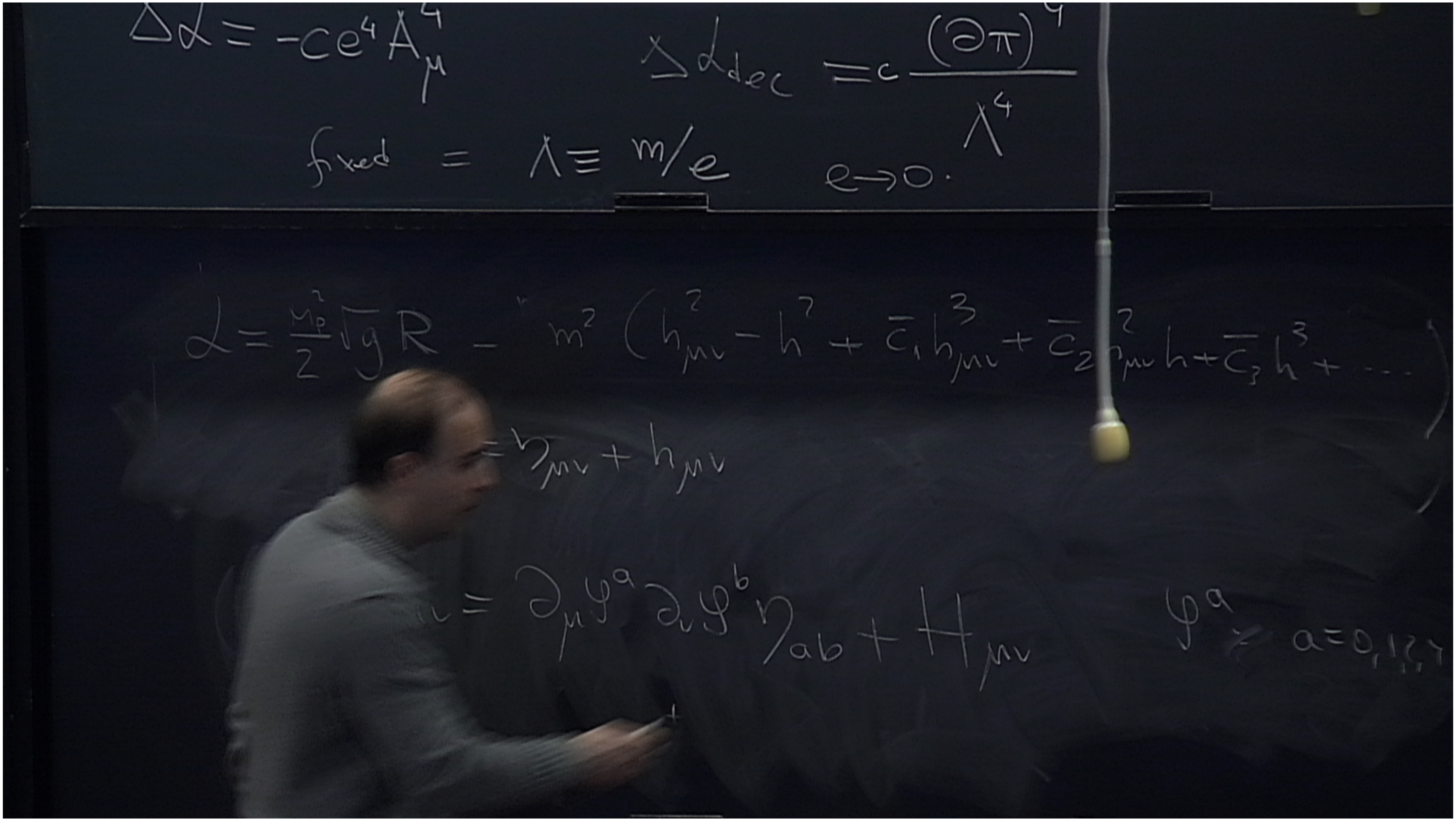
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$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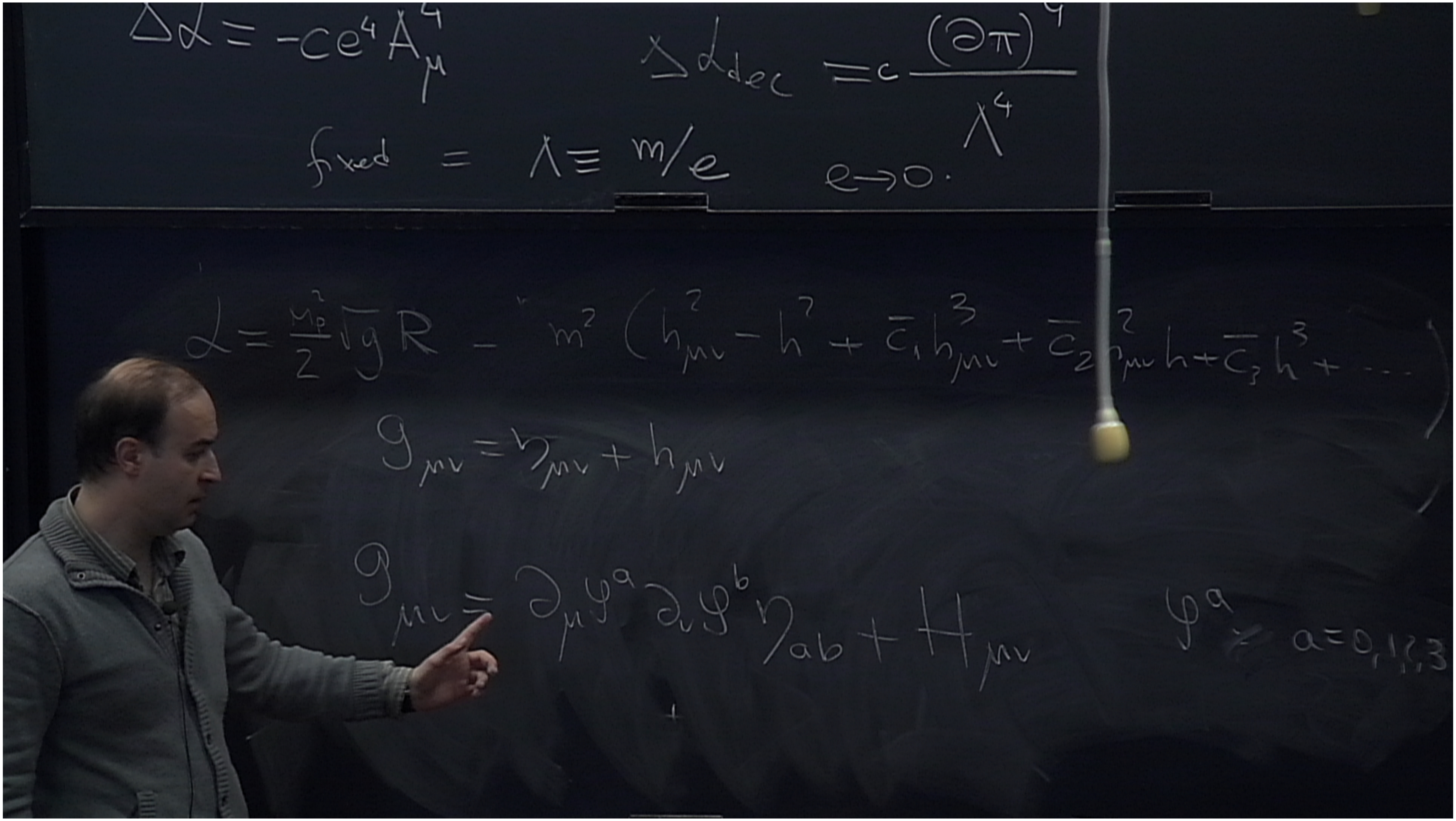
$= \eta_{\mu\nu} + h_{\mu\nu}$
$= \partial_\mu \varphi^a \partial_\nu \varphi^b \eta_{ab} + H_{\mu\nu}$
φ^a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$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
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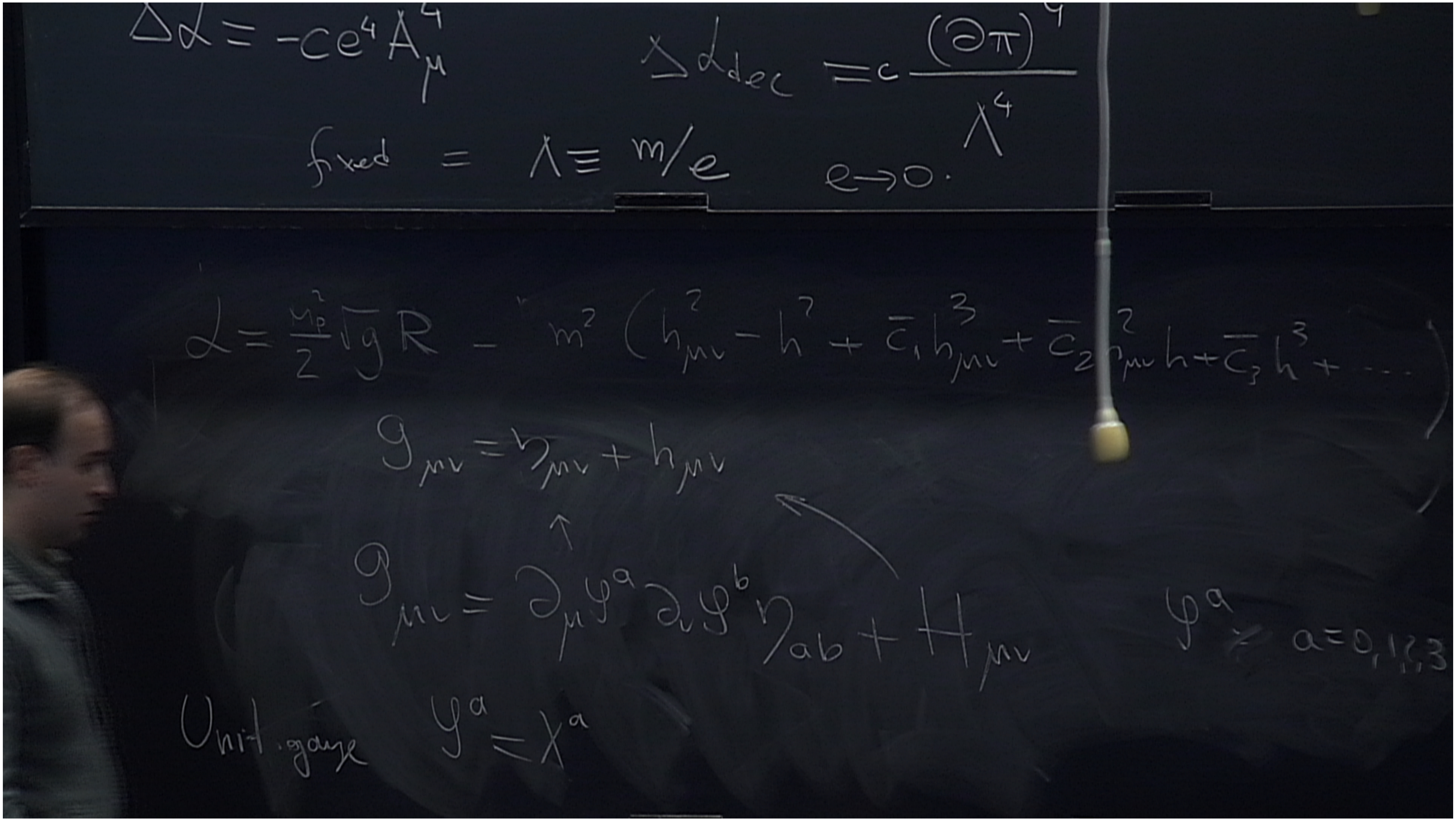
φ^a $a = 0,1,2,3$



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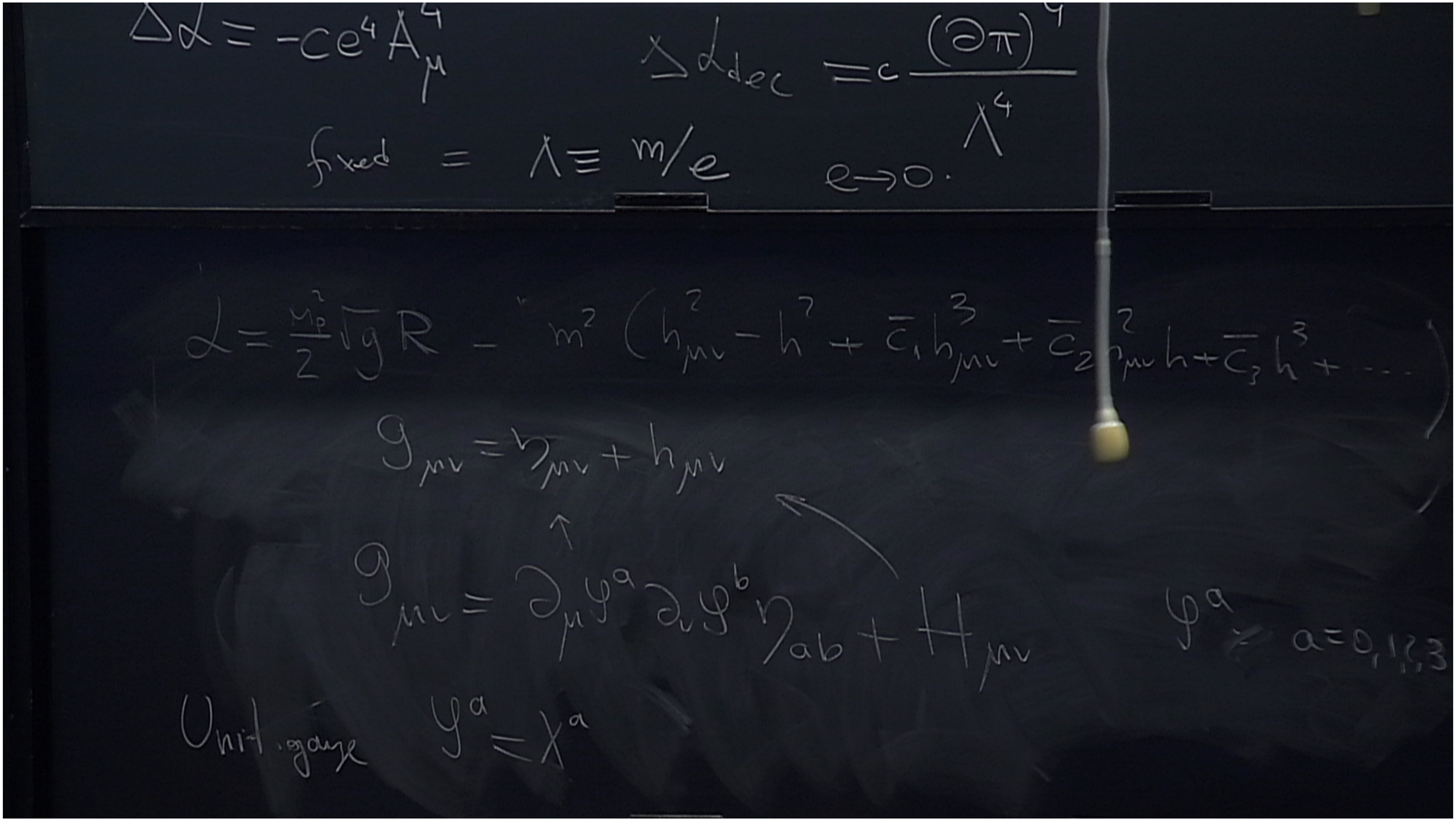
Unit. gauge $\varphi^a = x^a$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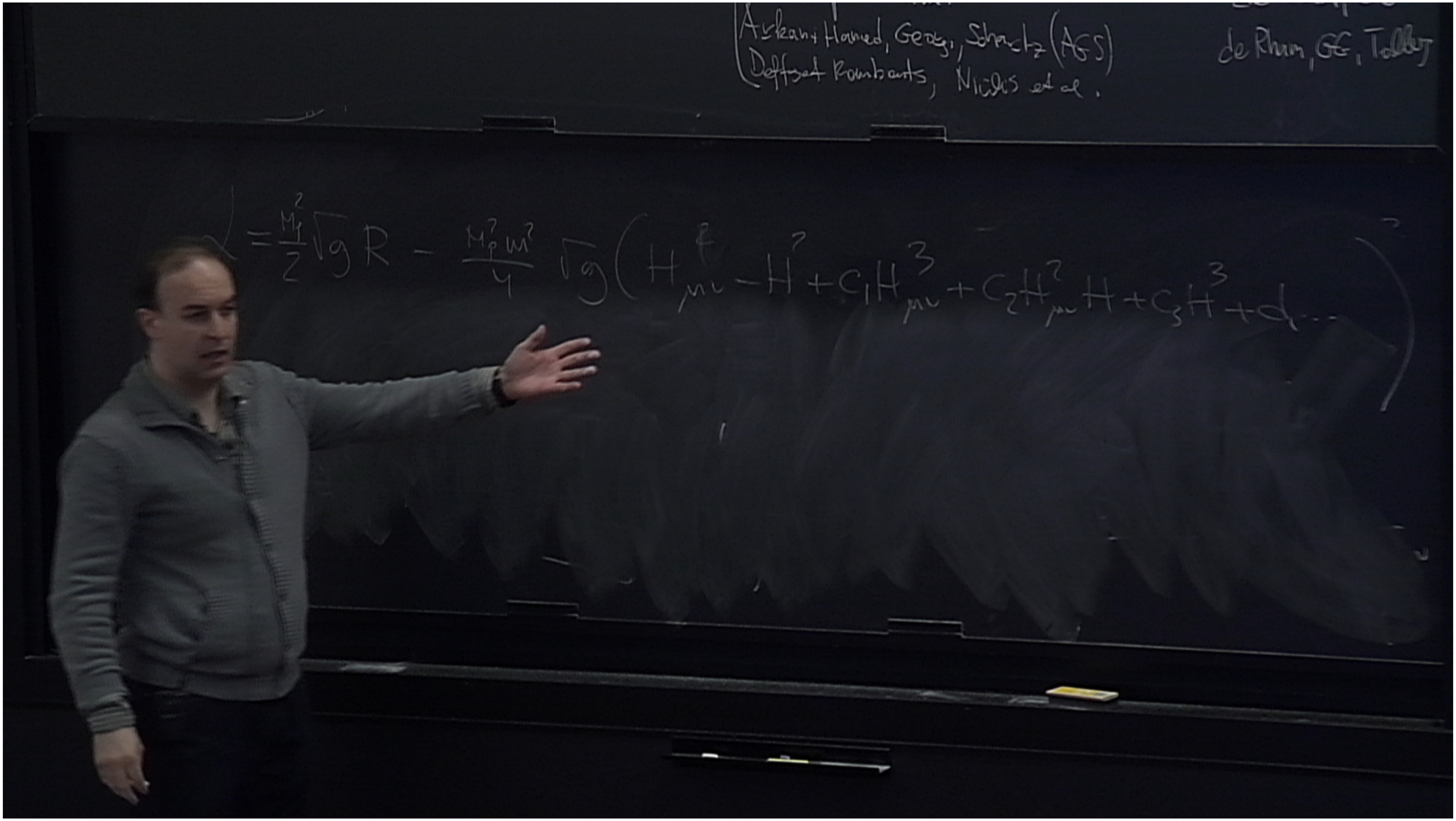
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$g_{\mu\nu} = \partial_\mu \varphi^a \partial_\nu \varphi^b \eta_{ab} + H_{\mu\nu}$$

φ^a, $a = 0,1,2,3$

Unit. gauge $\varphi^a = x^a$

$$\varphi^a = x^a - \frac{m A^a_\mu}{m^2 M_p} - \frac{\partial^a \pi}{m^2 M_p}$$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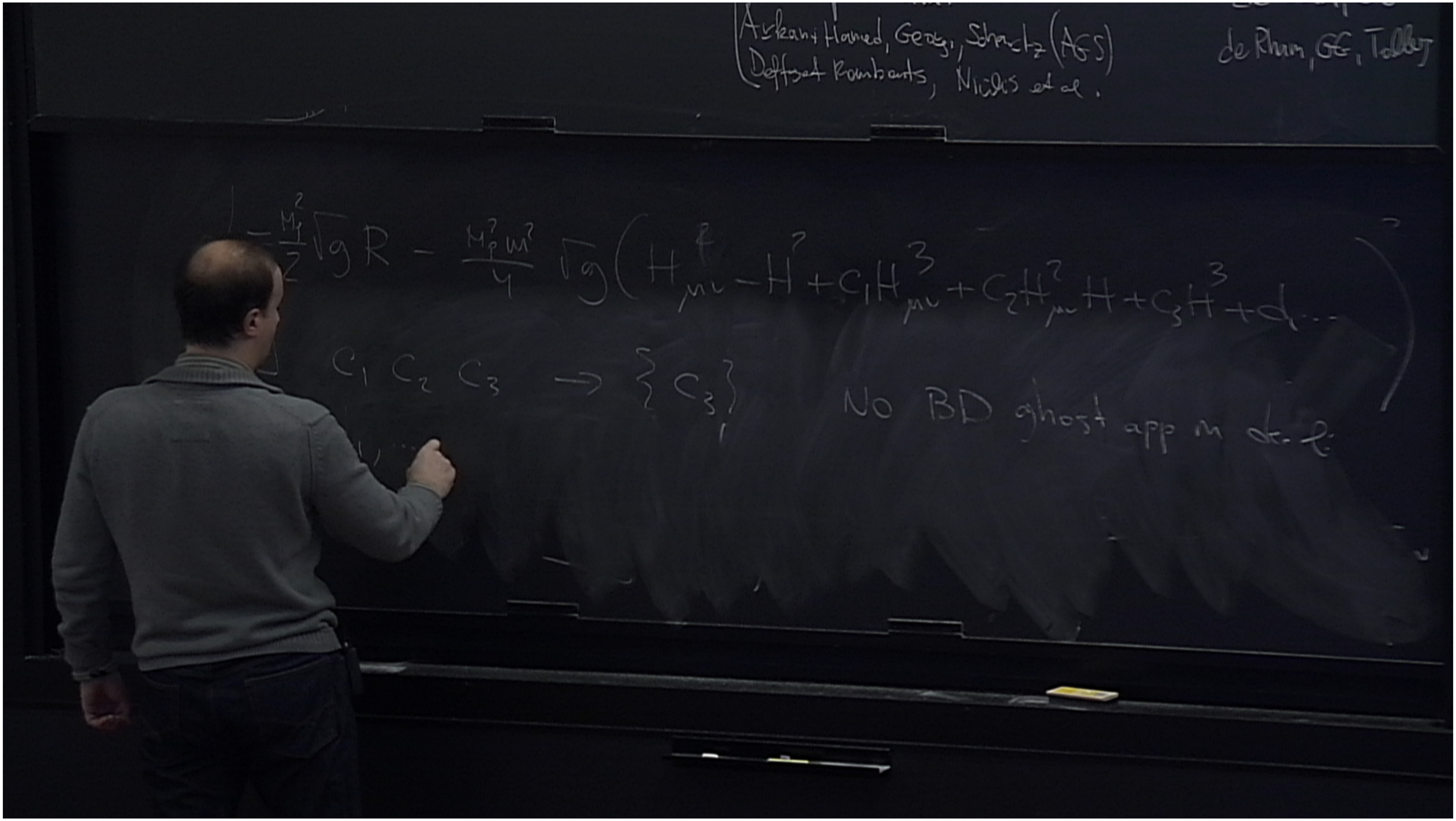
(Arkani Hamed, Georgi, Schwartz (AGS)
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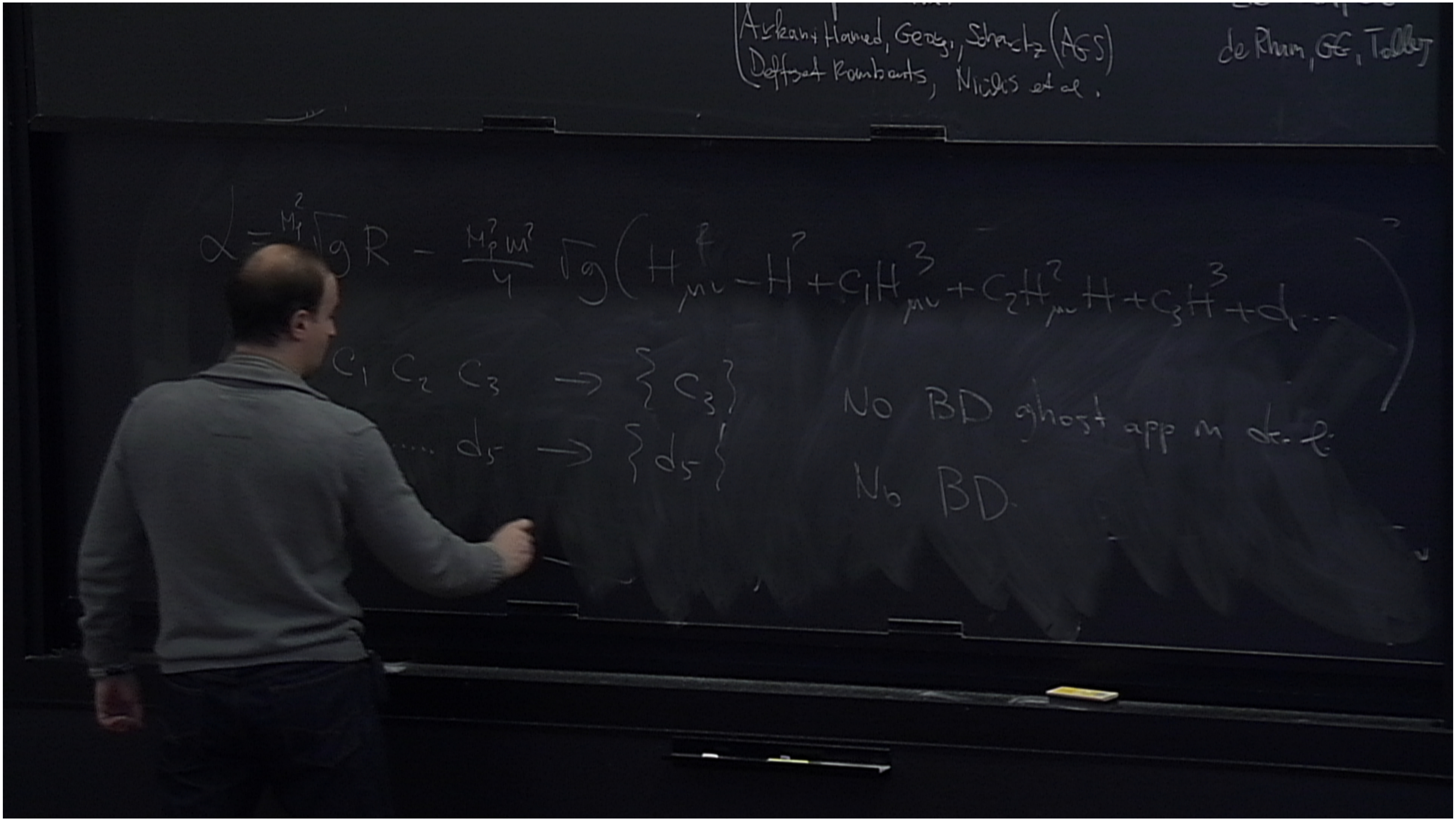
No BD ghost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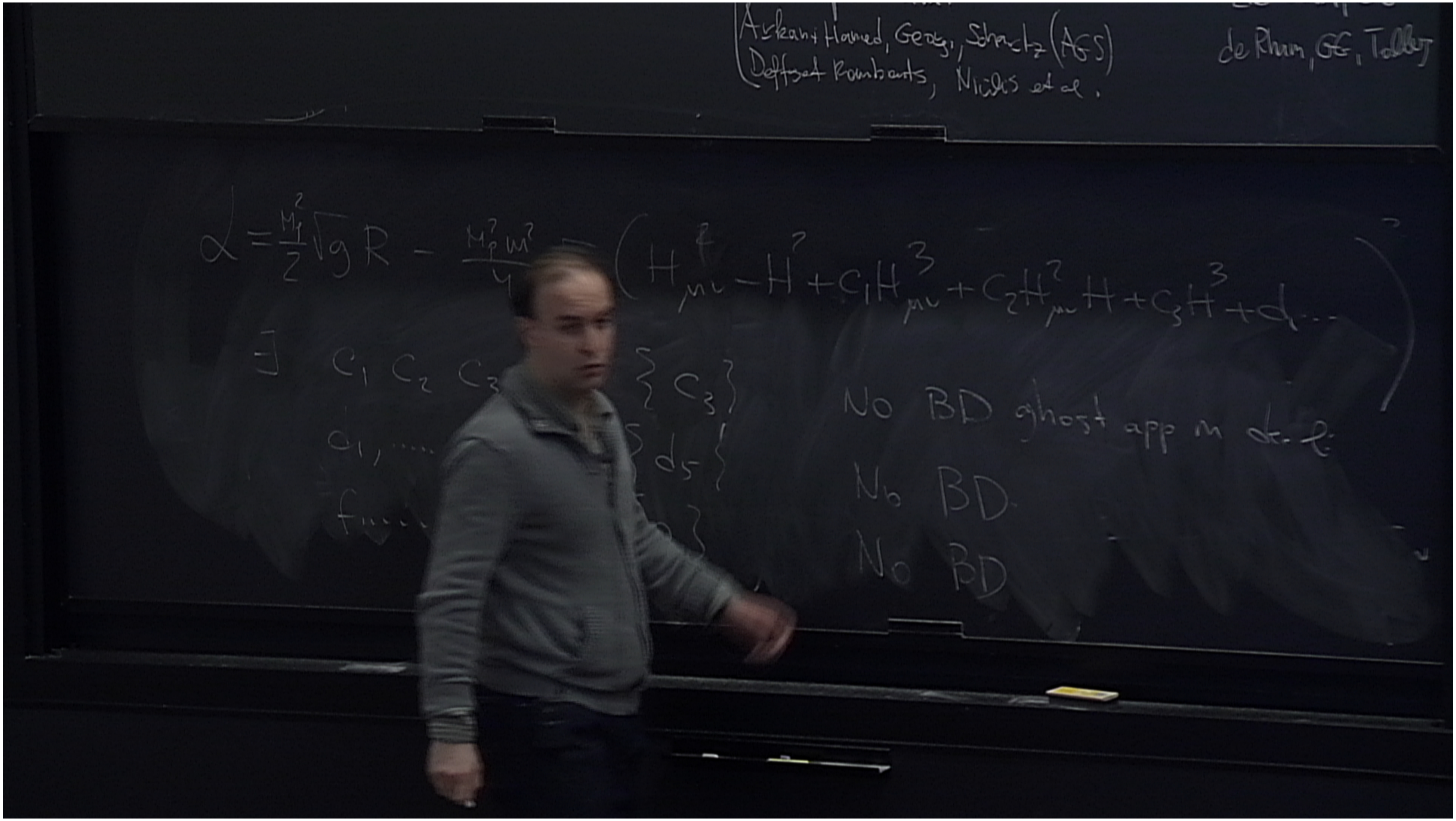
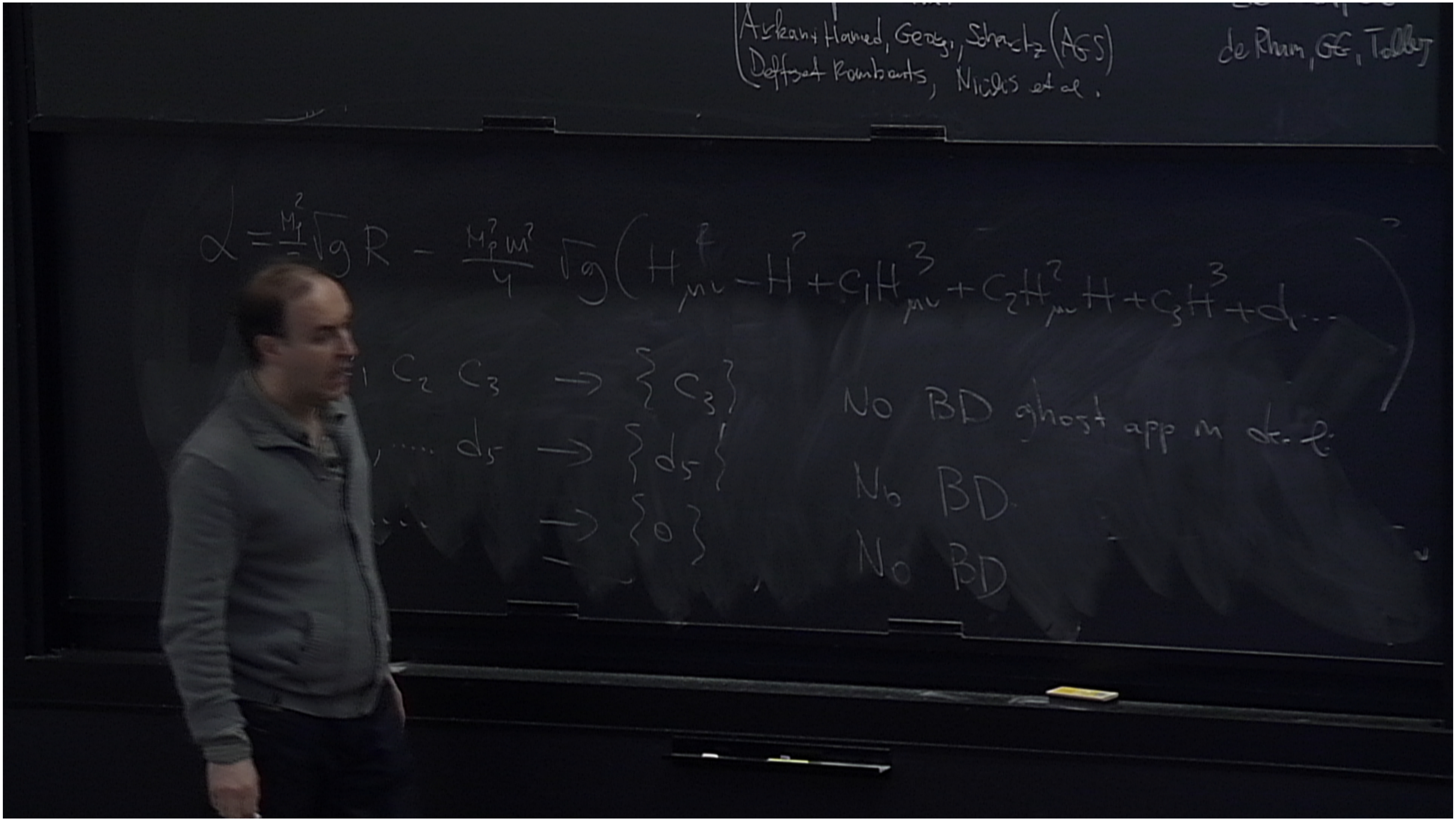
de Rham, GG, Tolley
No BD ghost app in dec. l.
No BD


de Rham, GG, Tolley
No BD
No BD


(AGS)
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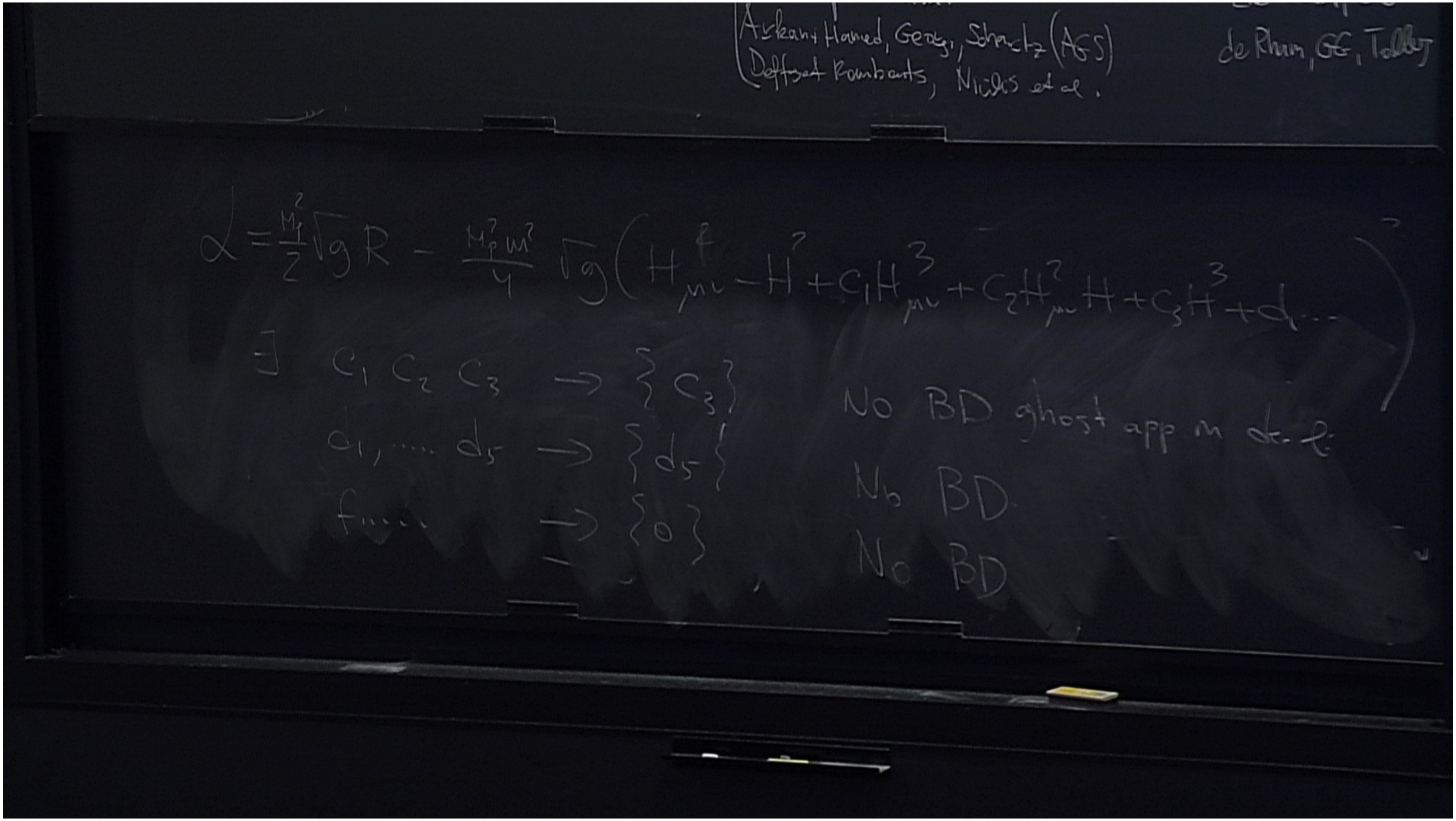
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