Title: Non-locality in Quantum Gravity

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Series: Quantum Gravity

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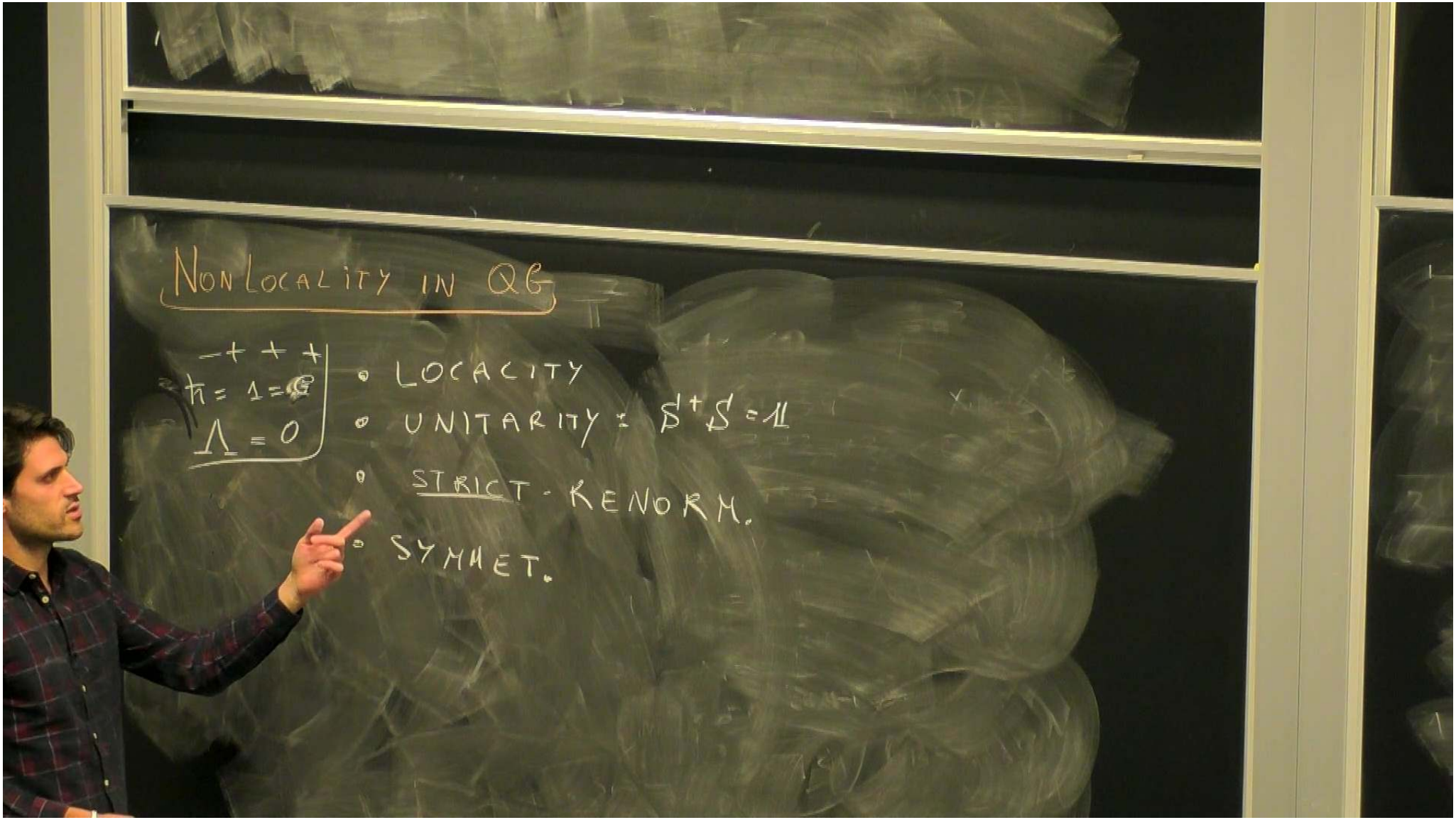
Abstract: A natural way to extend Einstein's General Relativity to the high-energy regime is to introduce quadratic curvature operators, which give rise to a renormalizable gravitational Lagrangian in four dimensions. However, this theory turns out to be pathological due to an additional massive spin-2 ghost that causes classical instabilities and breaks perturbative unitarity at the quantum level. In this talk, we investigate which principles of QFT are usually affected when higher-order derivative operators are present in a Lagrangian, and show that one possibility to avoid ghosts is giving up locality. In fact, the emergence of non-local physics at short distances and high energies is a common prediction for various quantum gravity approaches. We propose a model-independent approach to constrain the non-local Lagrangian in quantum gravity, thus providing a novel scenario in which different quantum gravity programs can be fruitfully contrasted in terms of foundational concepts and computational methods.

Zoom link: https://pitp.zoom.us/j/96167652193?pwd=OWFDV1JXVGxLdE1qMHo4N3ZKcDByQT09


NONLOCALITY IN QG
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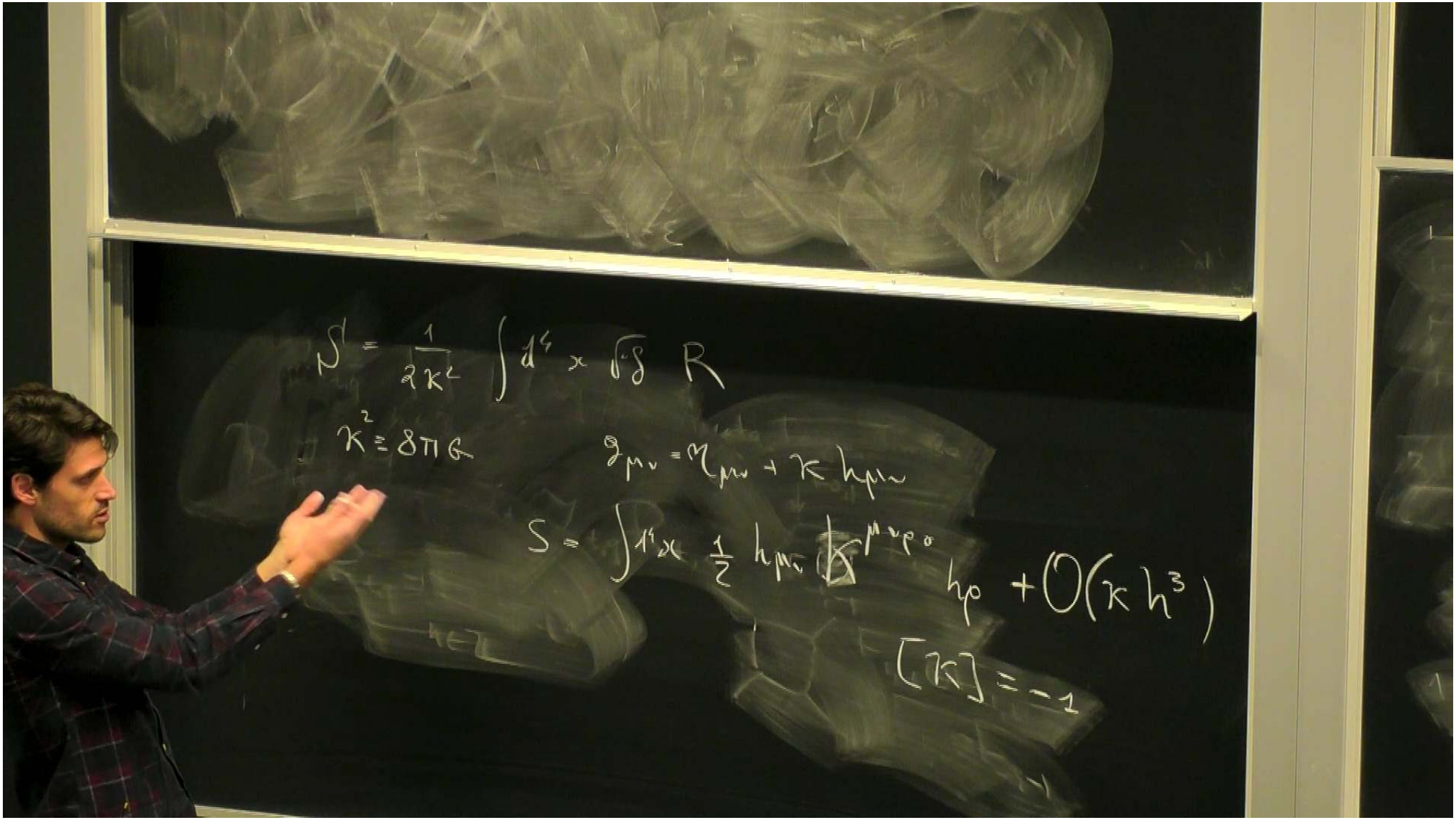
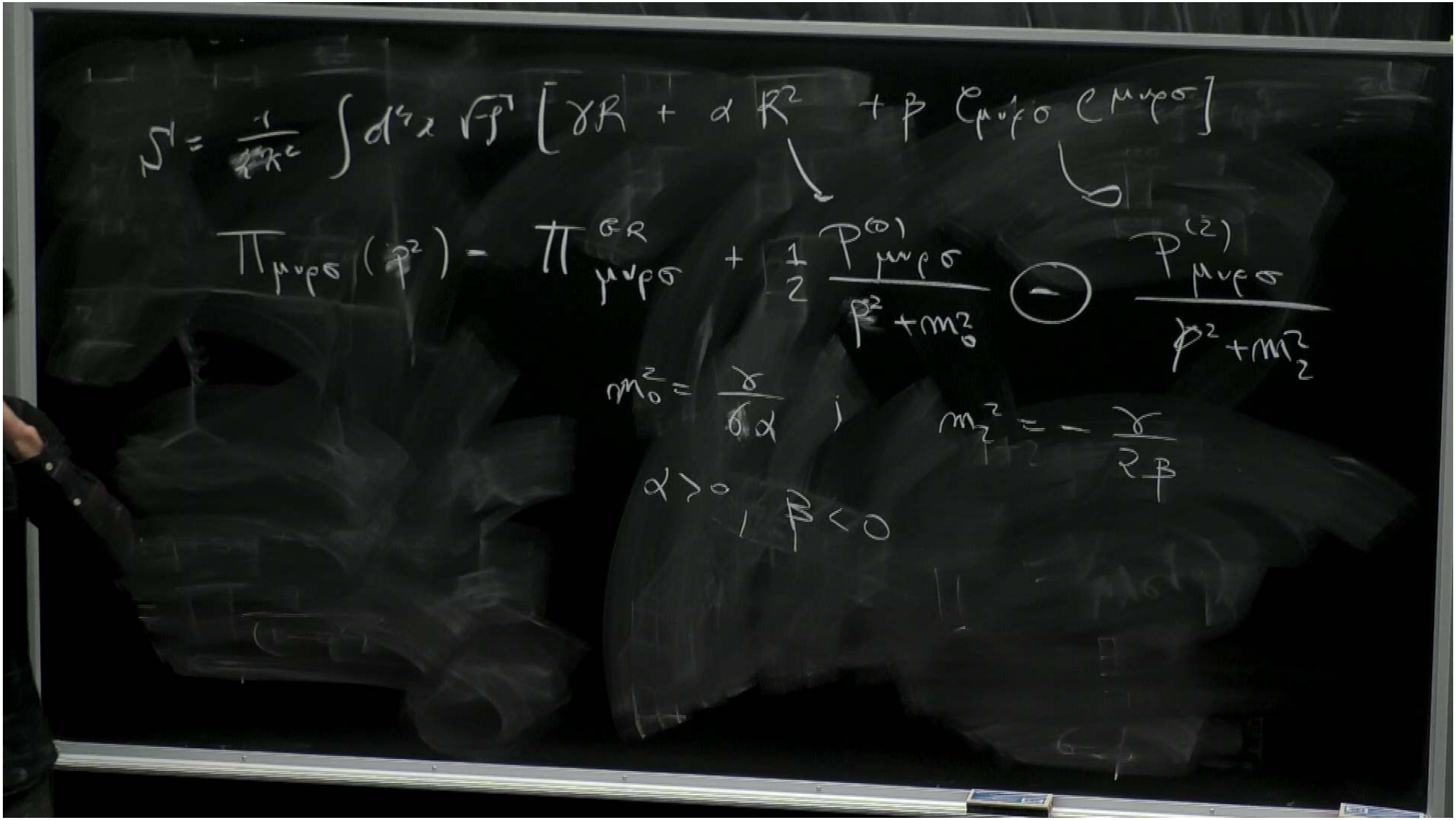
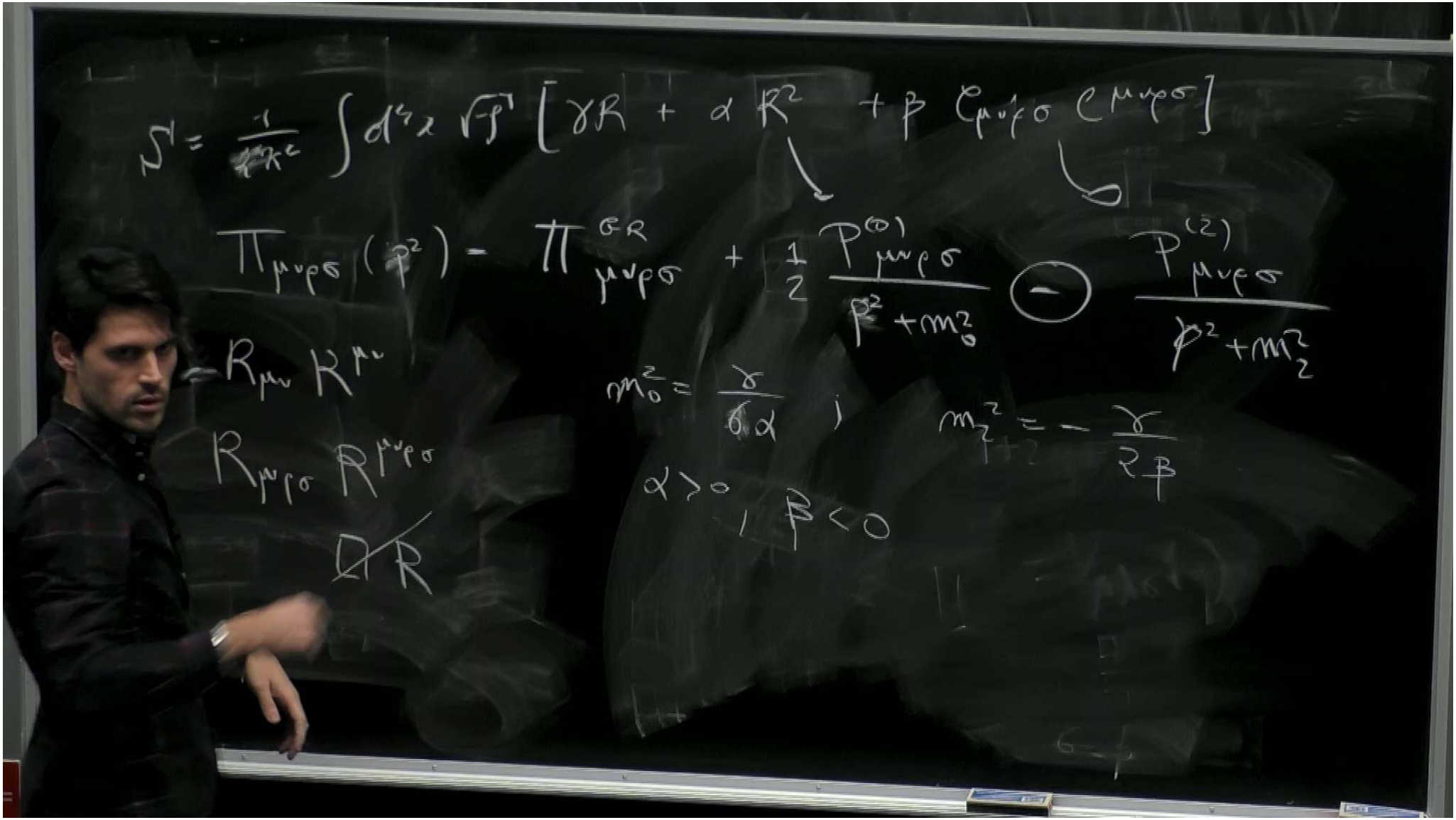
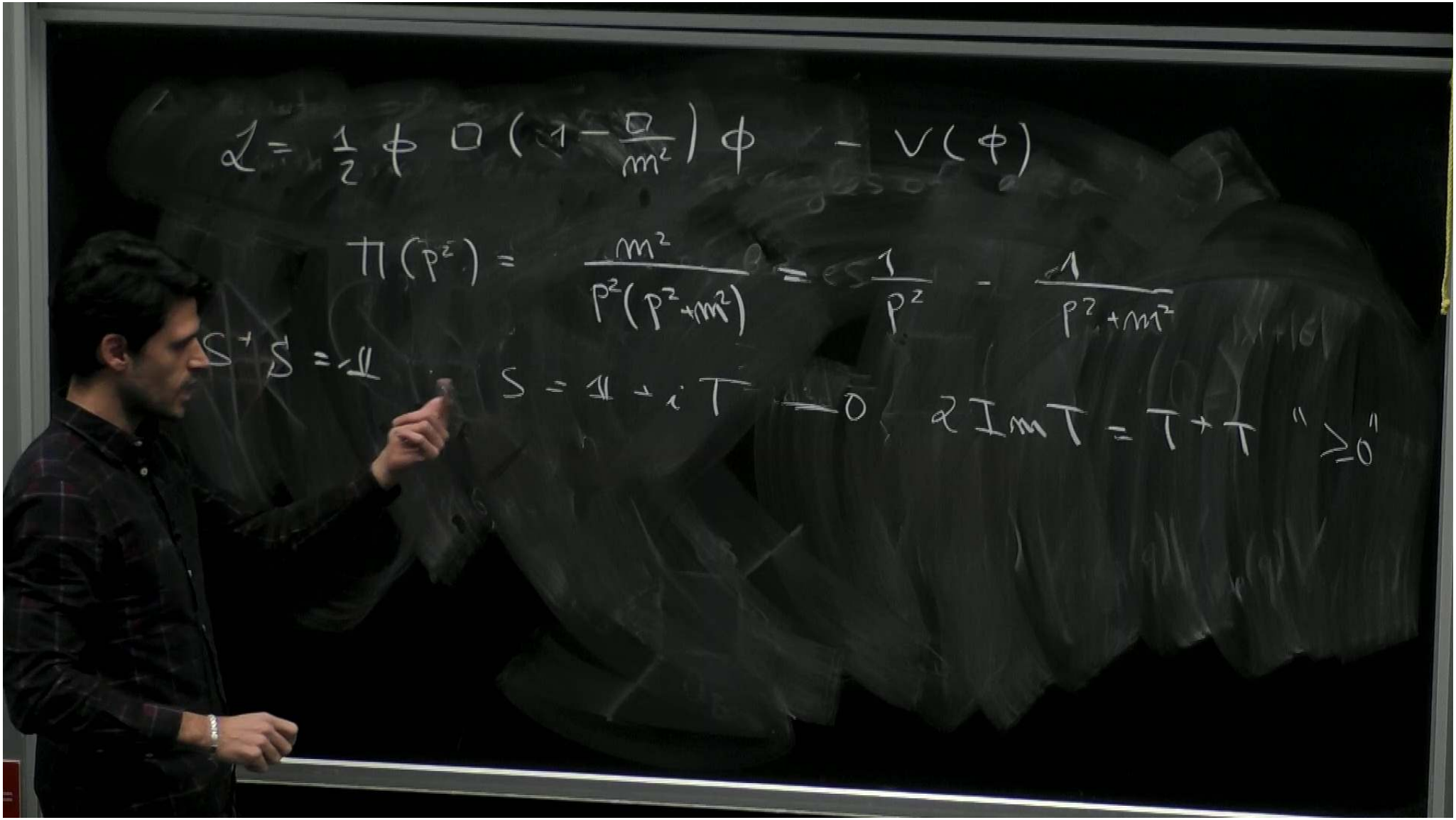
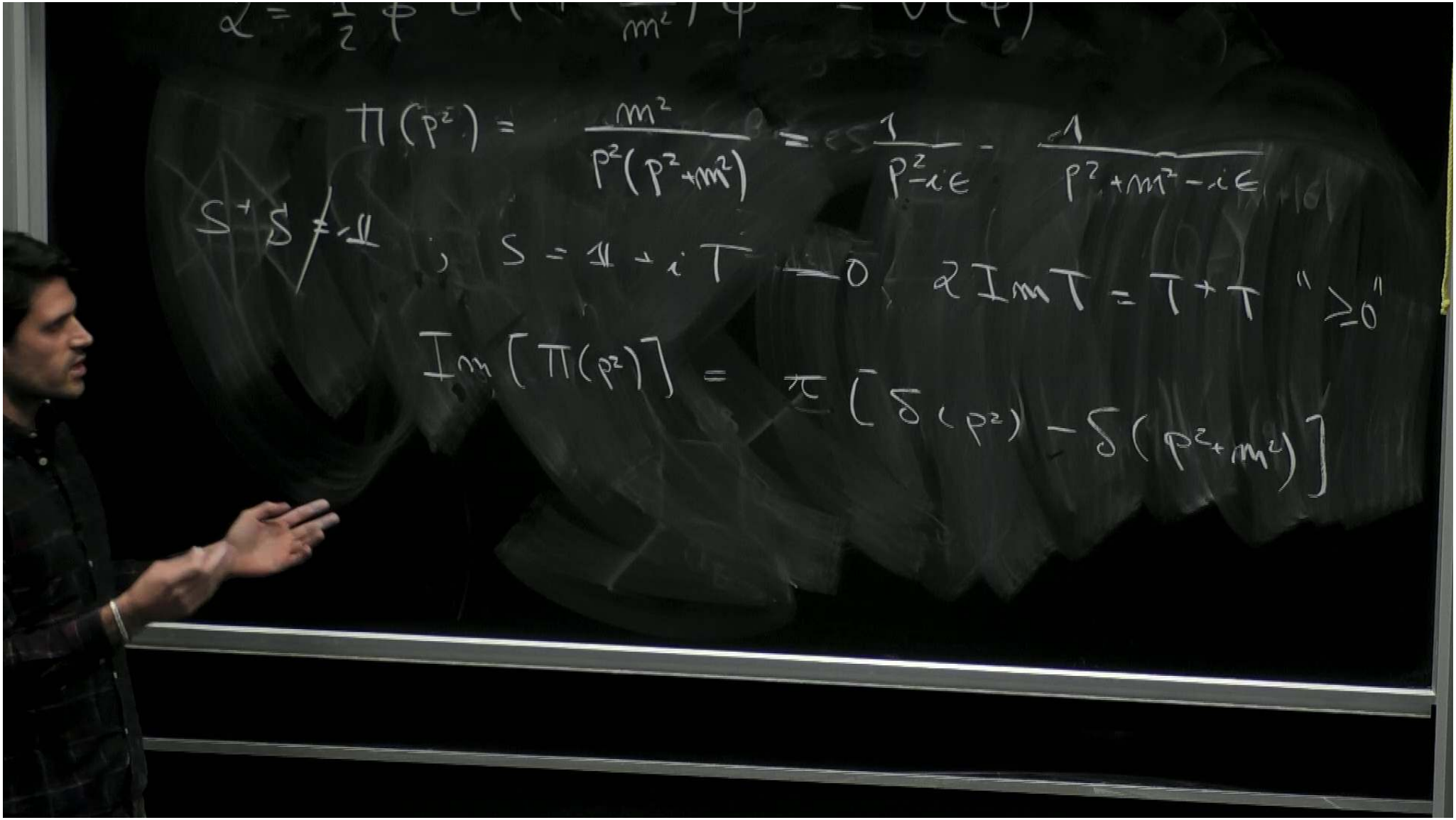
ħ = 1 = G
Λ = 0
• LOCACITY
• UNITARITY : S†S = 1
• STRICT - RENORM.
• SYMMET.

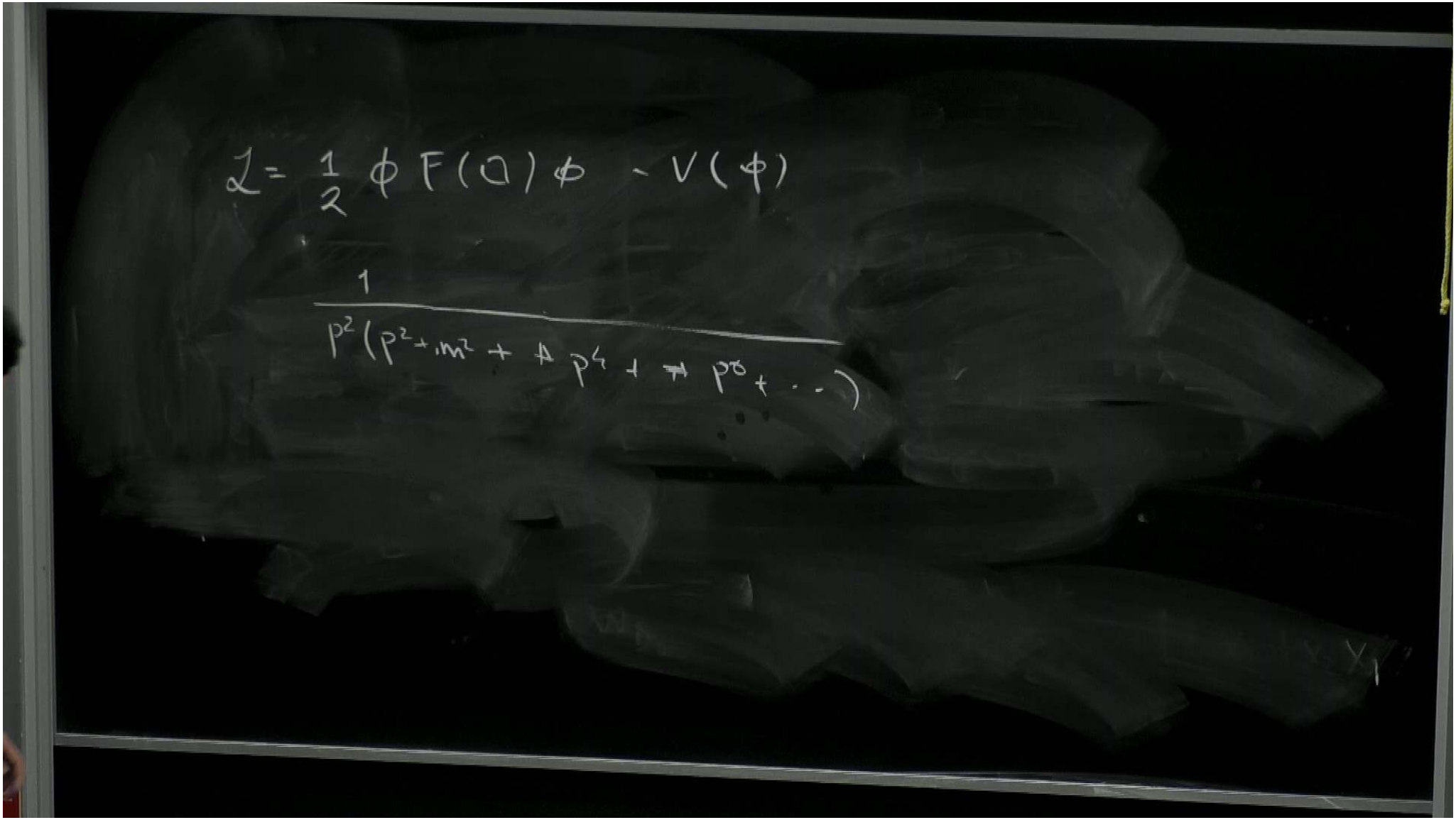

$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{g}\, R$
$\kappa^2 = 8\pi G$
$g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$
$S = \int d^4x \, \frac{1}{2} h_{\mu\nu} \Box^{\mu\nu\rho\sigma} h_{\rho\sigma} + O(\kappa h^3)$
$[\kappa] = -1$

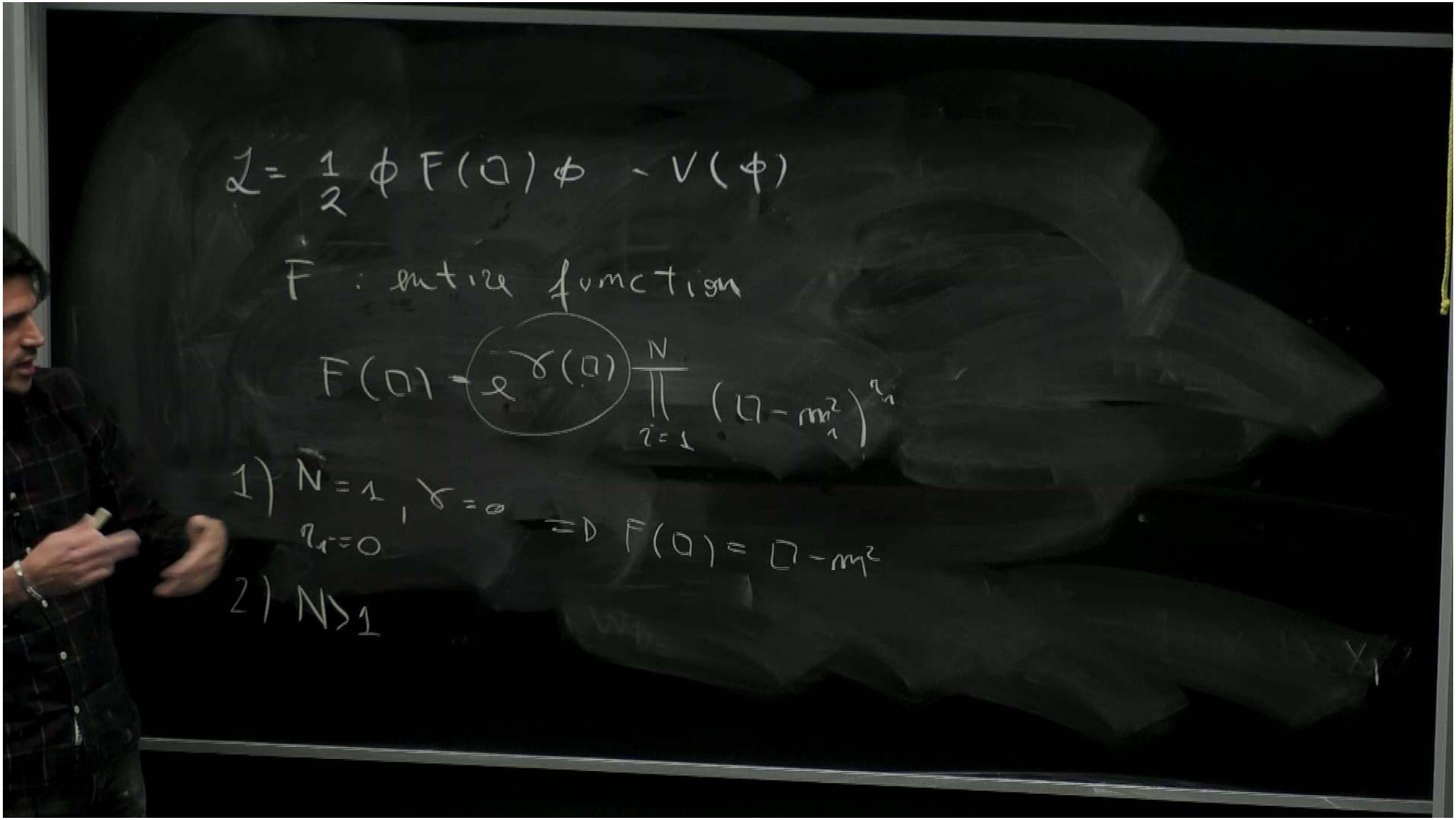

$S^{(1)} = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left[\gamma R + \alpha R^2 + \beta C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} \right]$
$\Pi_{\mu\nu\rho\sigma}(p^2) = \Pi^{GR}_{\mu\nu\rho\sigma} + \frac{1}{2} \frac{P^{(0)}_{\mu\nu\rho\sigma}}{p^2 + m_0^2} - \frac{P^{(2)}_{\mu\nu\rho\sigma}}{p^2 + m_2^2}$
$m_0^2 = \frac{\gamma}{6\alpha}$;
$m_2^2 = -\frac{\gamma}{2\beta}$
$\alpha > 0$, $\beta < 0$


$\Gamma = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left[\gamma R + \alpha R^2 + \beta C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} \right]$
$\Pi_{\mu\nu\rho\sigma}(p^2) = \Pi^{GR}_{\mu\nu\rho\sigma} + \frac{1}{2} \frac{P^{(0)}_{\mu\nu\rho\sigma}}{p^2 + m_0^2} - \frac{P^{(2)}_{\mu\nu\rho\sigma}}{p^2 + m_2^2}$
$R_{\mu\nu} R^{\mu\nu}$
$R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$
R^2
$m_0^2 = \frac{\gamma}{6\alpha}$
$m_2^2 = -\frac{\gamma}{2\beta}$
$\alpha > 0$, $\beta < 0$


$\mathcal{L} = \frac{1}{2}\phi\,\Box\left(1 - \frac{\Box}{m^2}\right)\phi - V(\phi)$
$\Pi(p^2) = \frac{m^2}{p^2(p^2+m^2)} = \frac{1}{p^2} - \frac{1}{p^2+m^2}$
$S^\dagger S = \mathbb{1}$
$S = \mathbb{1} + iT = 0$
$2\,\mathrm{Im}\,T = T + T^\dagger \geq 0$


$\mathcal{L} = \frac{1}{2}\phi$
$m^2)\phi = V(\phi)$
$\Pi(p^2) = \frac{m^2}{p^2(p^2+m^2)} = \frac{1}{p^2-i\epsilon} - \frac{1}{p^2+m^2-i\epsilon}$
$S^+S \neq \mathbb{1}$; $S = \mathbb{1} + iT = 0$ $2\,\mathrm{Im}\,T = T + T^+$ "≥ 0"
$\mathrm{Im}\,[\Pi(p^2)] = \pi[\delta(p^2) - \delta(p^2+m^2)]$


$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$
$\frac{1}{p^2(p^2 + m^2 + A p^4 + \ldots)}$


$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$
F : entire function
$F(\Box) = e^{\gamma(\Box)} \prod_{i=1}^{N} (\Box - m_i^2)^{n_i}$
1) $N = 1$, $\gamma = 0$ $\Rightarrow$ $F(\Box) = \Box - m^2$
$n_i = 0$
2) $N > 1$

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$$

F : entire function

$$e^{\gamma(\Box)} = \sum_{n=0}^{\infty} \gamma_n \Box^n$$

$$F(\Box) = e^{\gamma(\Box)} \prod_{i=1}^{N} (\Box - m_i^2)^{\eta_i}$$

1) $N = 1$, $\gamma = 0$, $\eta_1 = 0$ $\Rightarrow F(\Box) = \Box - m^2$

2) $N > 1$

$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$

F : entire function

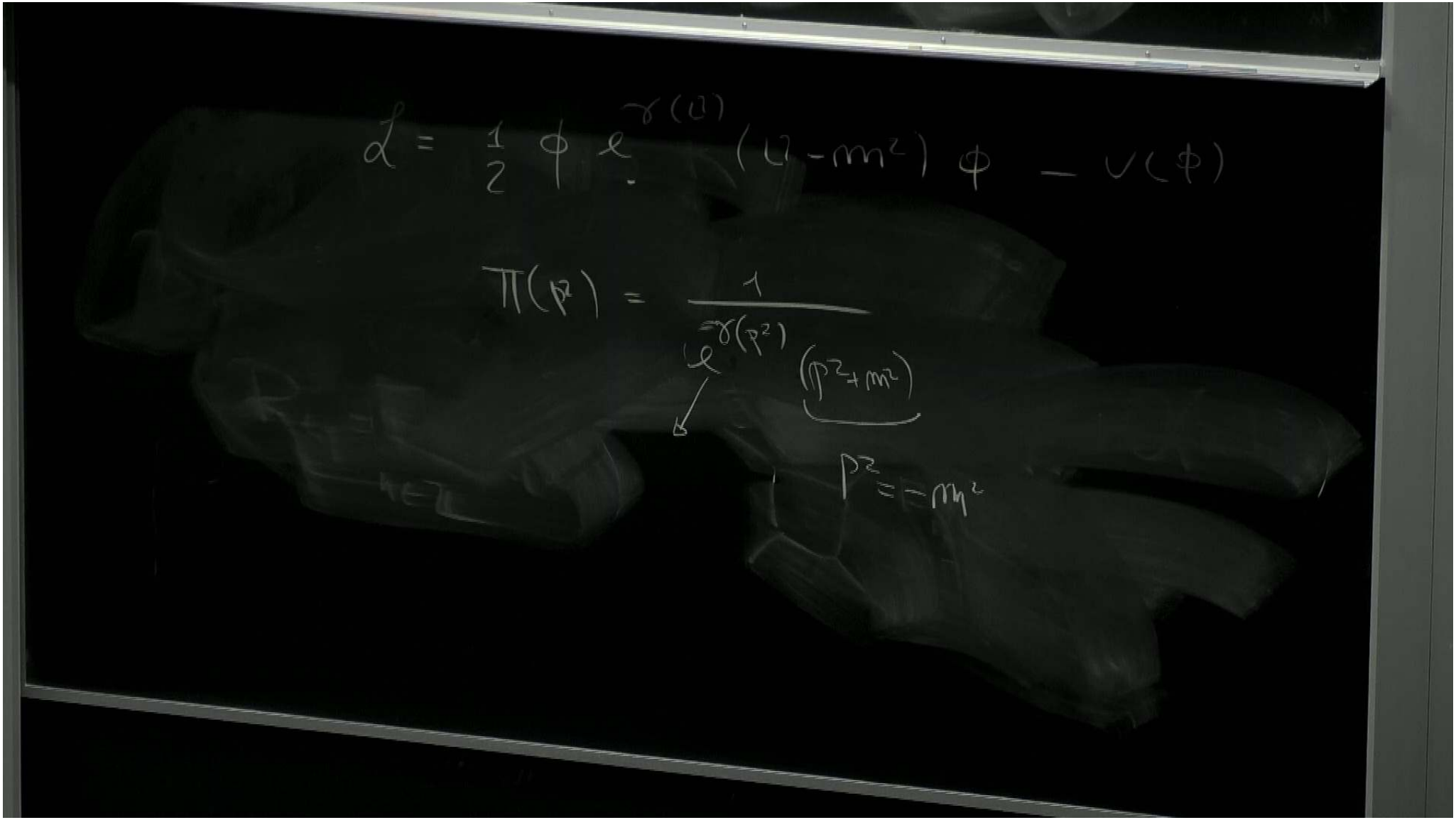
$F(\Box) = e^{\gamma(\Box)} \prod_{i=1}^{N} (\Box - m_i^2)^{n_i}$

1) $N = 1$, $\gamma = 0$, $n_1 = 0$ $\Rightarrow F(\Box) = \Box - m^2$

2) $N > 1$

$\gamma(\Box) = \alpha\Box$

$e^{\alpha\Box} = e^{\gamma(\Box)} = \sum_{n=0}^{\infty} \gamma_n \Box^n$

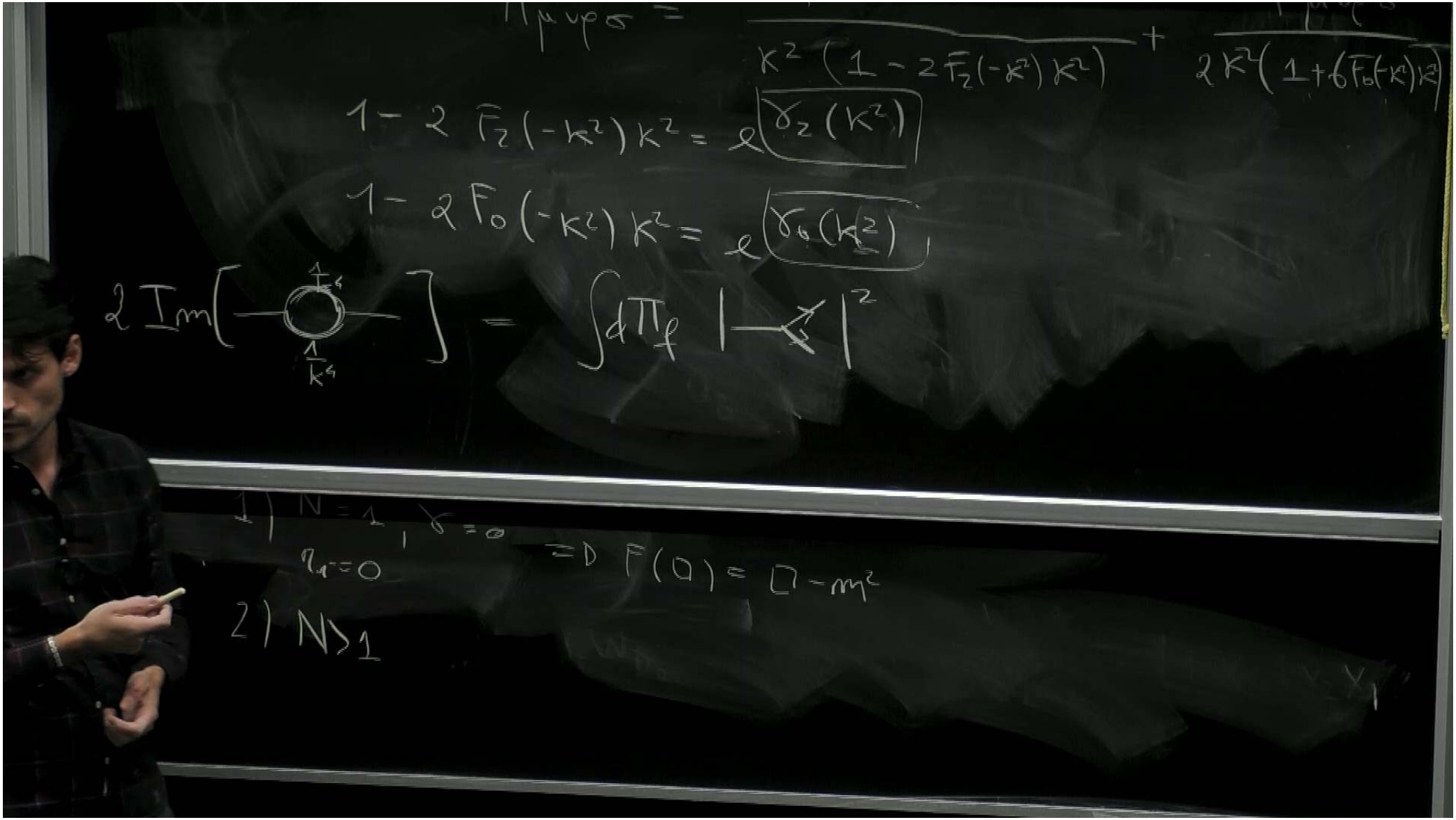

$\mathcal{L} = \frac{1}{2}\phi\, e^{\gamma(\Box)}\,(\Box - m^2)\,\phi - V(\phi)$
$\Pi(p^2) = \frac{1}{e^{\gamma(p^2)}\,(p^2+m^2)}$
$p^2 = -m^2$

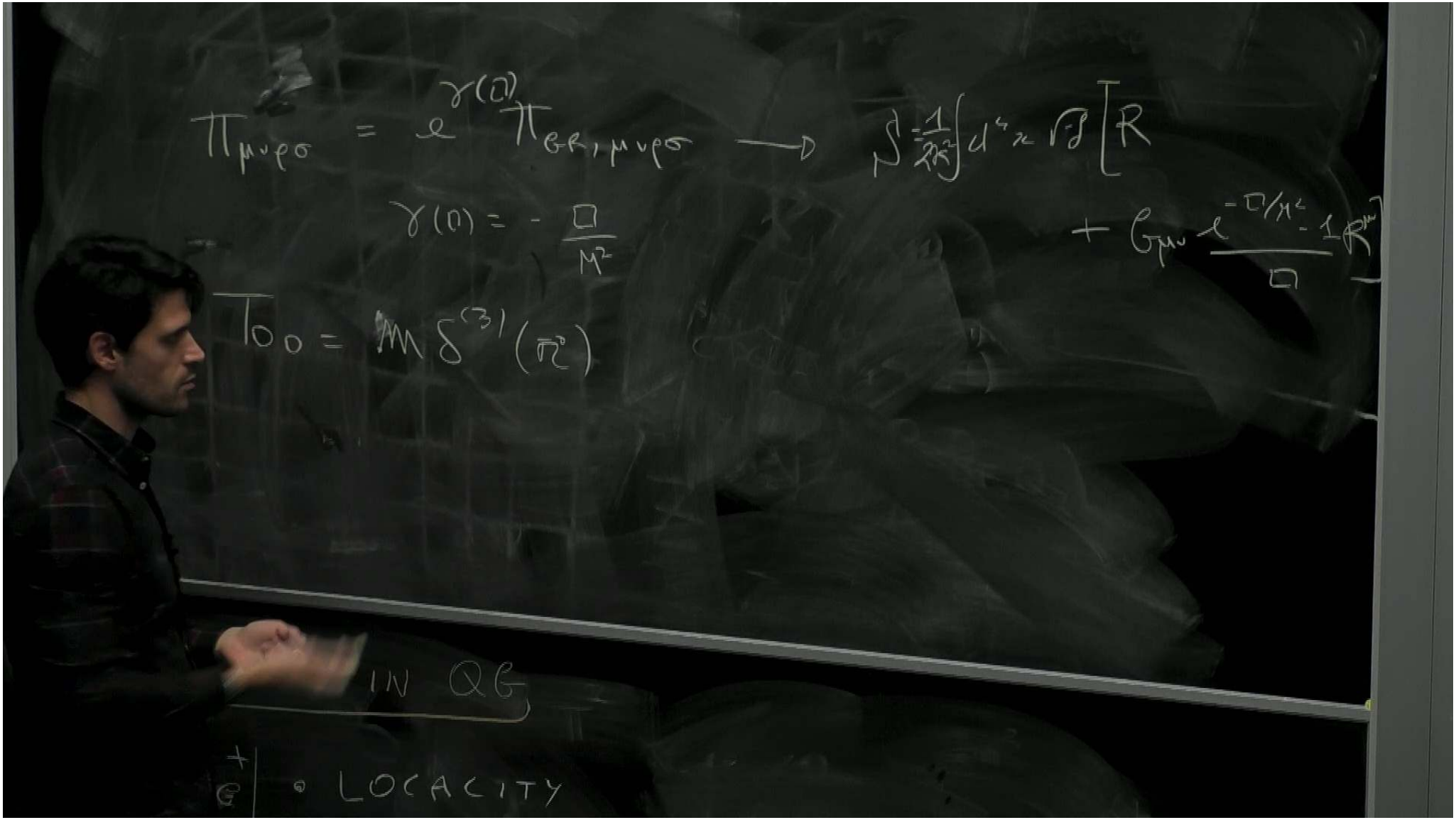
$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\left[R + R F_0(\Box) R + C_{\mu\nu\rho\sigma} F_2(\Box) C^{\mu\nu\rho\sigma}\right]$$

$$\Pi_{\mu\nu\rho\sigma} = \frac{P^{(2)}}{k^2\left(1 - 2\tilde{F}_2(-k^2)k^2\right)} + \frac{P^{(0)}_{\mu\nu\rho\sigma}}{2k^2\left(1 + 6\tilde{F}_0(-k^2)k^2\right)}$$

$$1 - 2\tilde{F}_2(-k^2)k^2 = e^{\gamma_2(k^2)}$$

$$1 - 2\tilde{F}_0(-k^2)k^2 = e^{\gamma_0(k^2)}$$

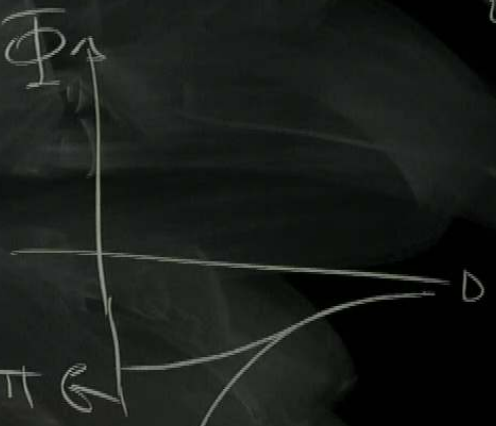

$\Pi_{\mu\nu\rho\sigma} =$
$k^2 (1 - 2\bar{F}_2(-k^2)k^2)$
$+ \; 2k^2(1 + 6\bar{F}_0(-k^2)k^2)$
$1 - 2\bar{F}_2(-k^2)k^2 = e^{\gamma_2(k^2)}$
$1 - 2F_0(-k^2)k^2 = e^{\gamma_0(k^2)}$
$2\,\mathrm{Im}[$
k^2
$] = \int d\Pi_f \,|$
$|^2$
1) $N = 1$, $\gamma = 0$ $\Rightarrow$ $F(0) = 0 - m^2$
$\eta_1 = 0$
2) $N > 1$


$\Pi_{\mu\nu\rho} = e^{\gamma(\Box)} \Pi_{GR,\mu\nu\rho} \longrightarrow S = \frac{1}{2\kappa^2} \int d^4x \sqrt{g} \left[R \right.$
$\gamma(\Box) = -\frac{\Box}{M^2}$
$+ G_{\mu\nu} \frac{e^{-\Box/M^2} - 1}{\Box} R^{\mu\nu}$
$T_{00} = M \delta^{(3)}(\vec{r})$
IN QG
+
• LOCALITY

$\gamma(\Box) = -\frac{\Box}{M^2}$

$+ G_{\mu\nu} \frac{e^{-\Box/M^2} - 1}{\Box} R^{\mu\nu}$

$T_{00} = m\delta^{(3)}(\vec{r})$



$e^{-\nabla^2/M^2} \nabla\Phi = m\delta^{(3)}(\vec{r})\, 4\pi G$

$\Rightarrow \Phi(r) = -\frac{Gm}{r} Erf\left(\frac{Mr}{2}\right)$

NONLOCALITY IN QG

$-+++$

$\hbar = 1 = G$ | • LOCACITY

$\gamma(0) = -\frac{\Box}{M^2}$

$+ G_{\mu\nu} \frac{e^{-\Box/M^2} - 1}{\Box} R^{\mu\nu}$

$T_{00} = m\,\delta^{(3)}(\vec{r})$

$GMm \ll 1$

$e^{-\nabla^2/M^2} \nabla\Phi = m\delta^{(3)}(\vec{r})\, 4\pi G$

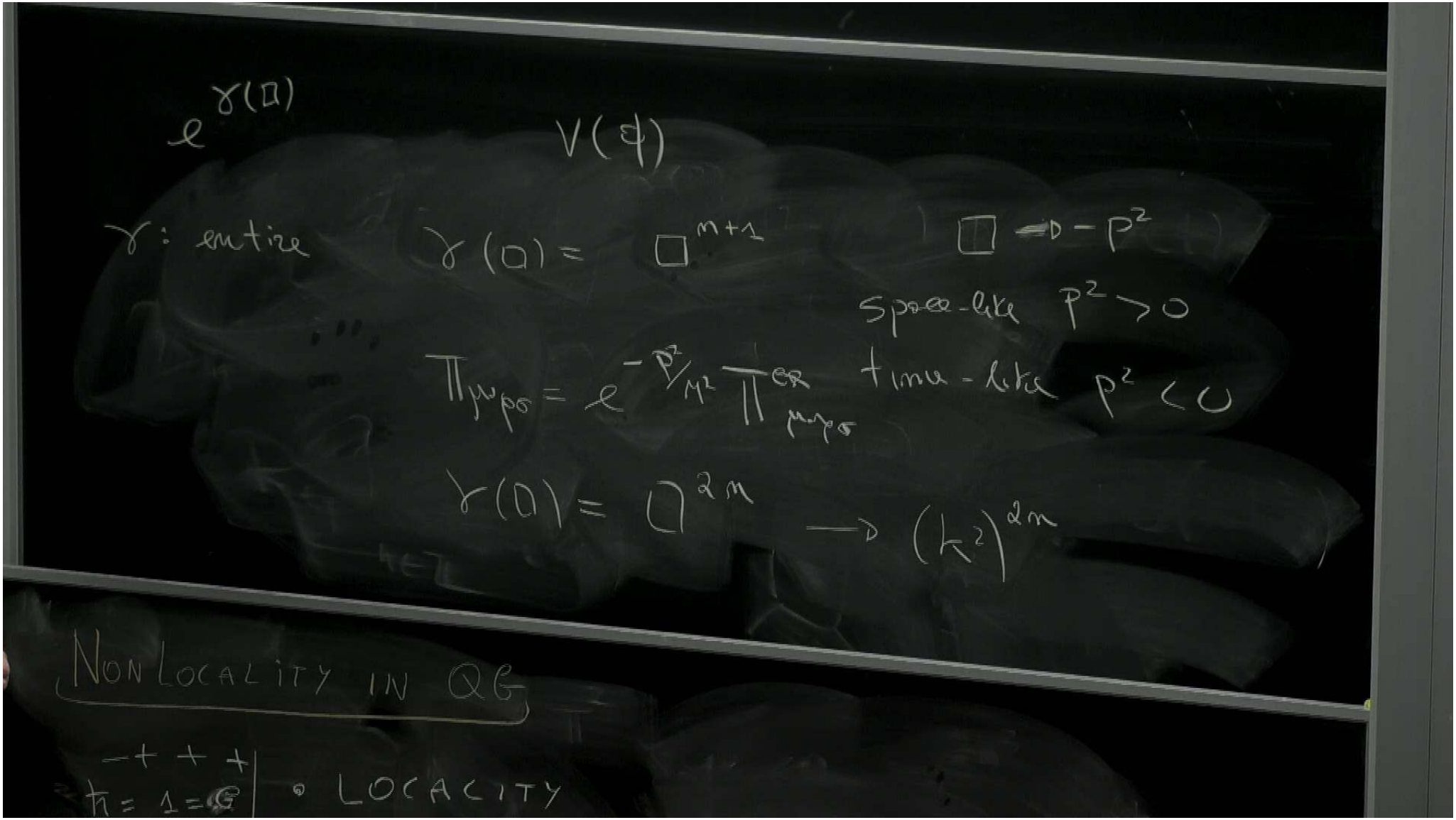
$\Rightarrow \Phi(r) = -\frac{Gm}{r} E_4\left(\frac{Mr}{2}\right)$

Φ $\quad$ $= -m^2$

NONLOCALITY IN QG

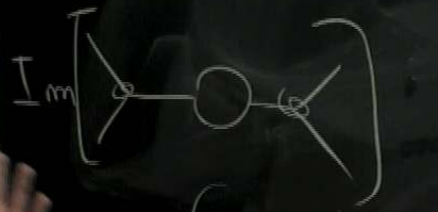
$-+++$

$\hbar = 1 = G$ | • LOCACITY


$e^{\gamma(\Box)}$
$V(\phi)$
γ: entire
$\gamma(\Box) = \Box^{m+1}$
$\Box \to -p^2$
space-like $p^2 > 0$
time-like $p^2 < 0$
$\Pi_{\mu\nu\rho\sigma} = e^{-p^2/M^2} \Pi^{GR}_{\mu\nu\rho\sigma}$
$\gamma(\Box) = \Box^{2m} \to (k^2)^{2m}$
NONLOCALITY IN QG
$-+++$
$\hbar = 1 = G$
• LOCACITY

$e^{\gamma(\Box)}$ $V(\phi)$

γ : entire $\gamma(\Box) = \Box^{n+1}$ $\Box \to -p^2$



$= \int d\Pi_f \left| \right|^2$ $\gamma(0) = 0^{2n} \to (k^2)^{2n}$

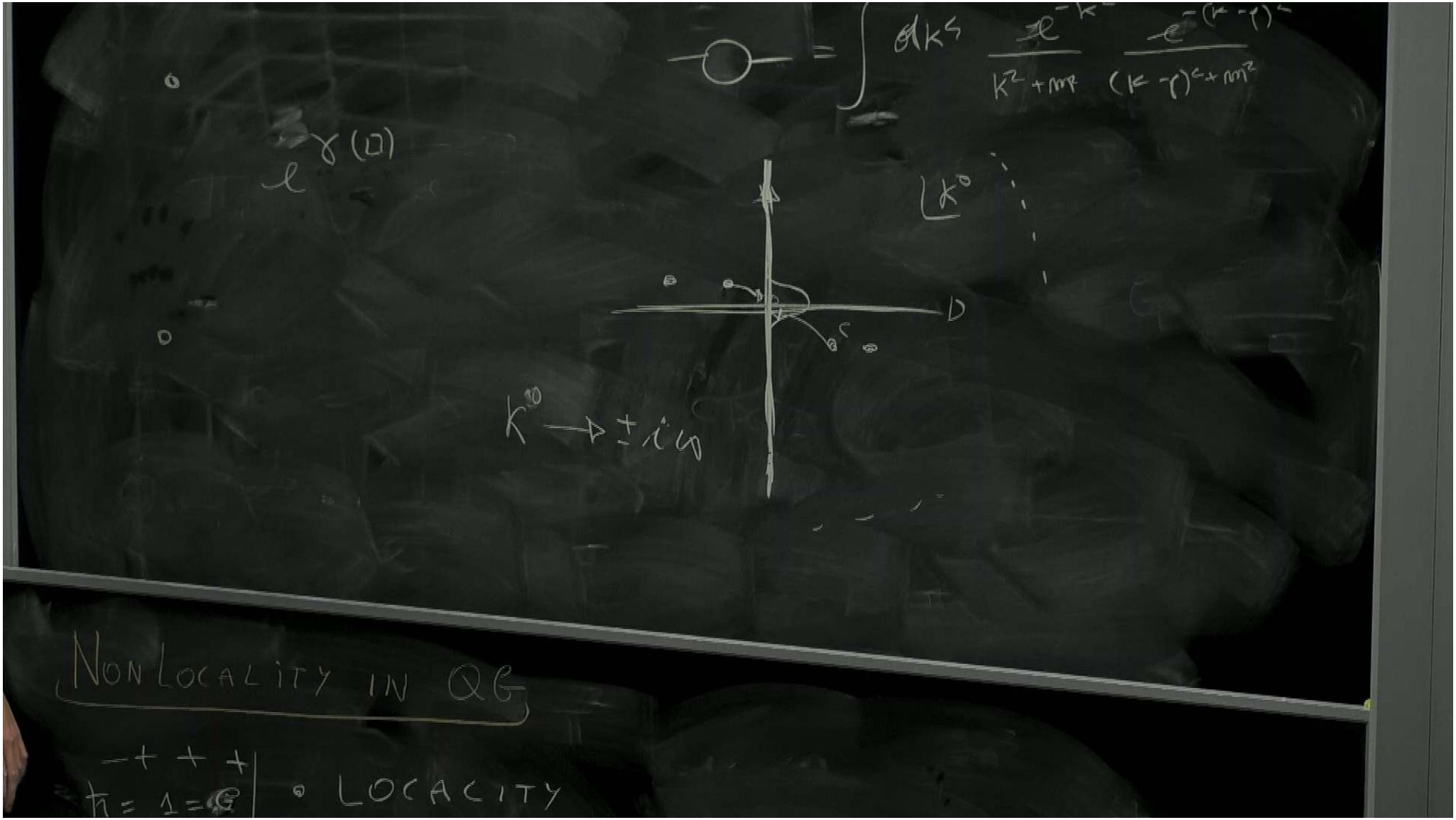
$\Pi_{\mu\nu\rho\sigma} = e^{-p^2/M^2} \Pi^{GR}_{\mu\nu\rho\sigma}$

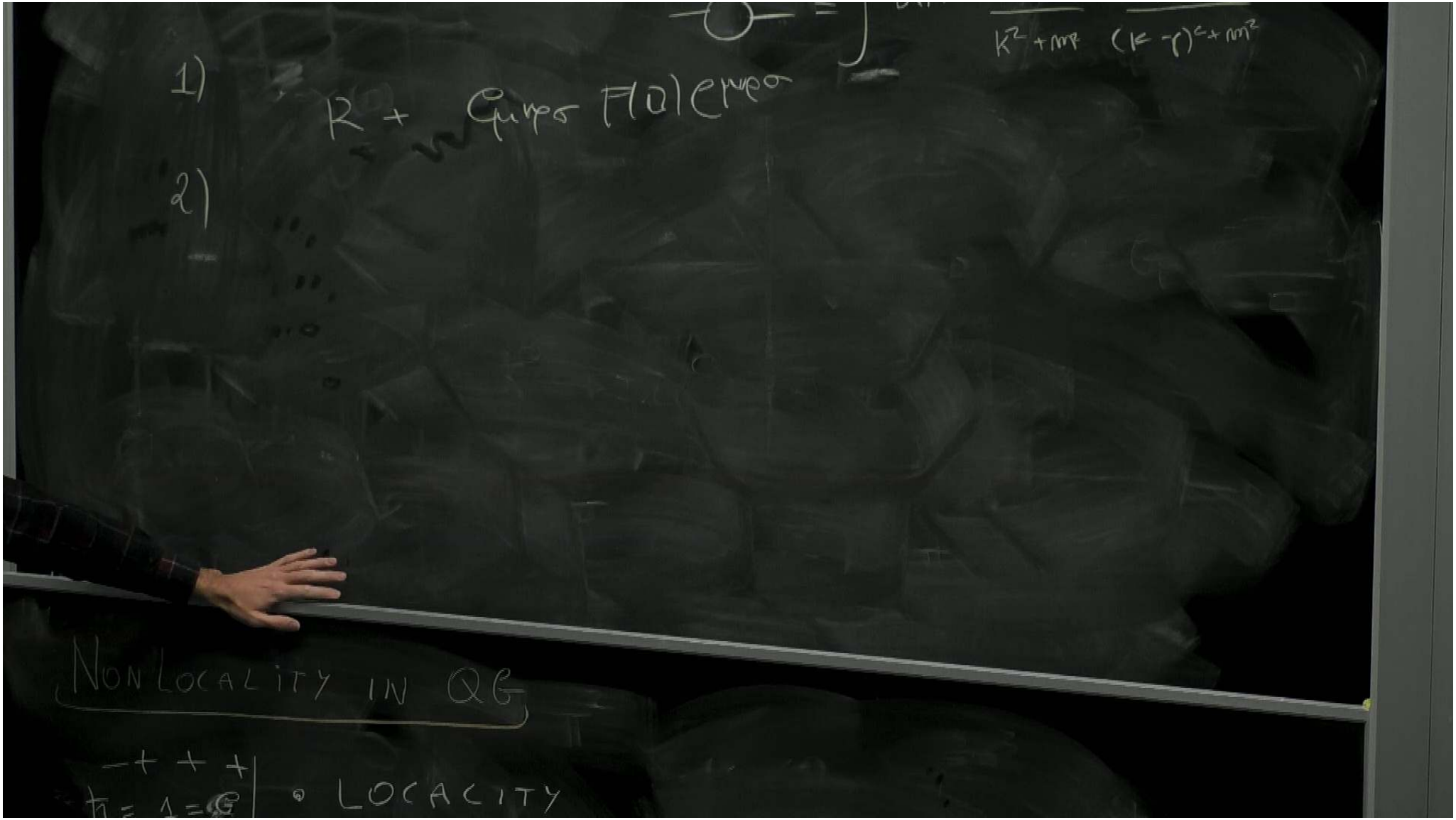
space-like $p^2 > 0$

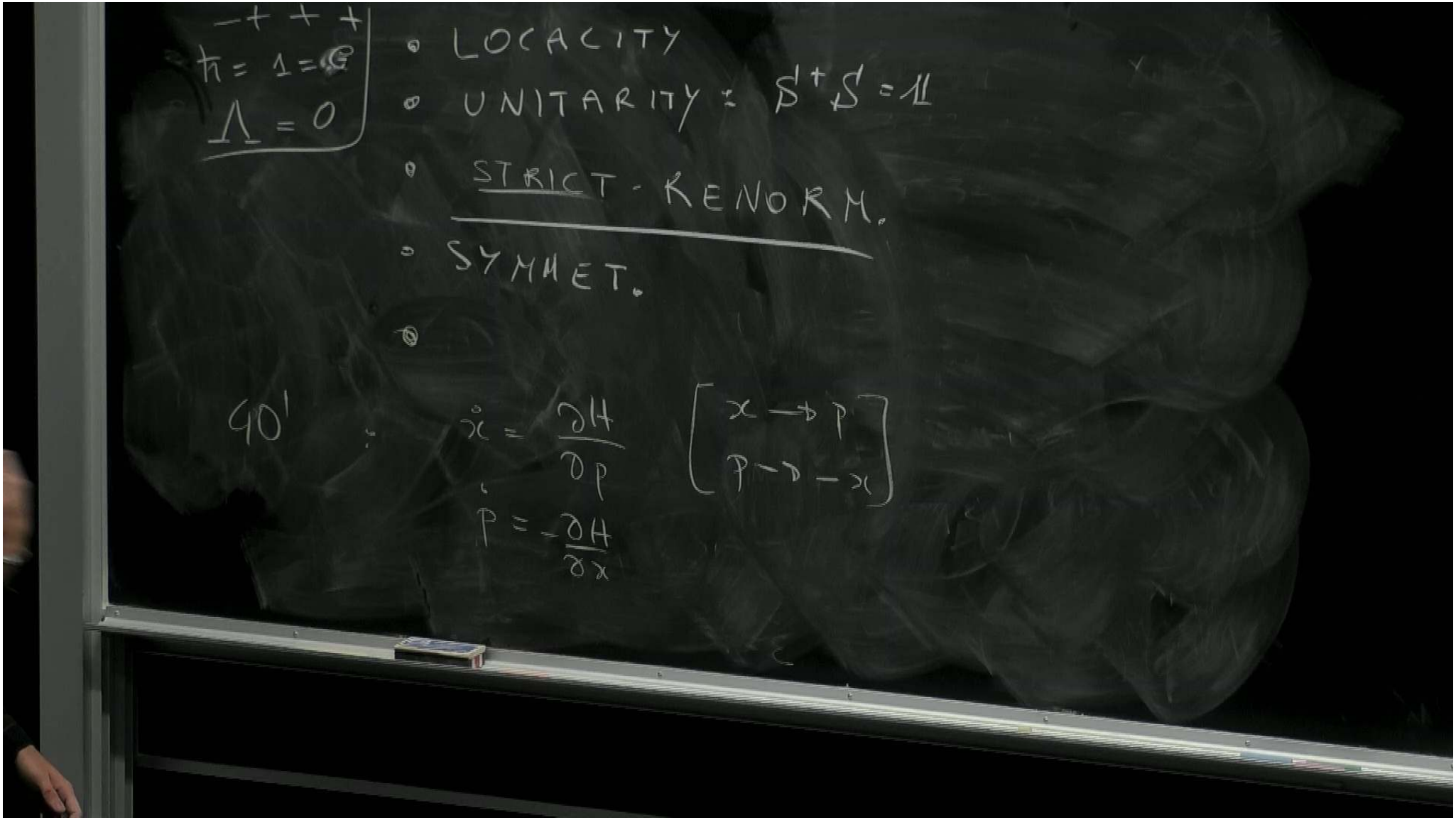
time-like $p^2 < 0$

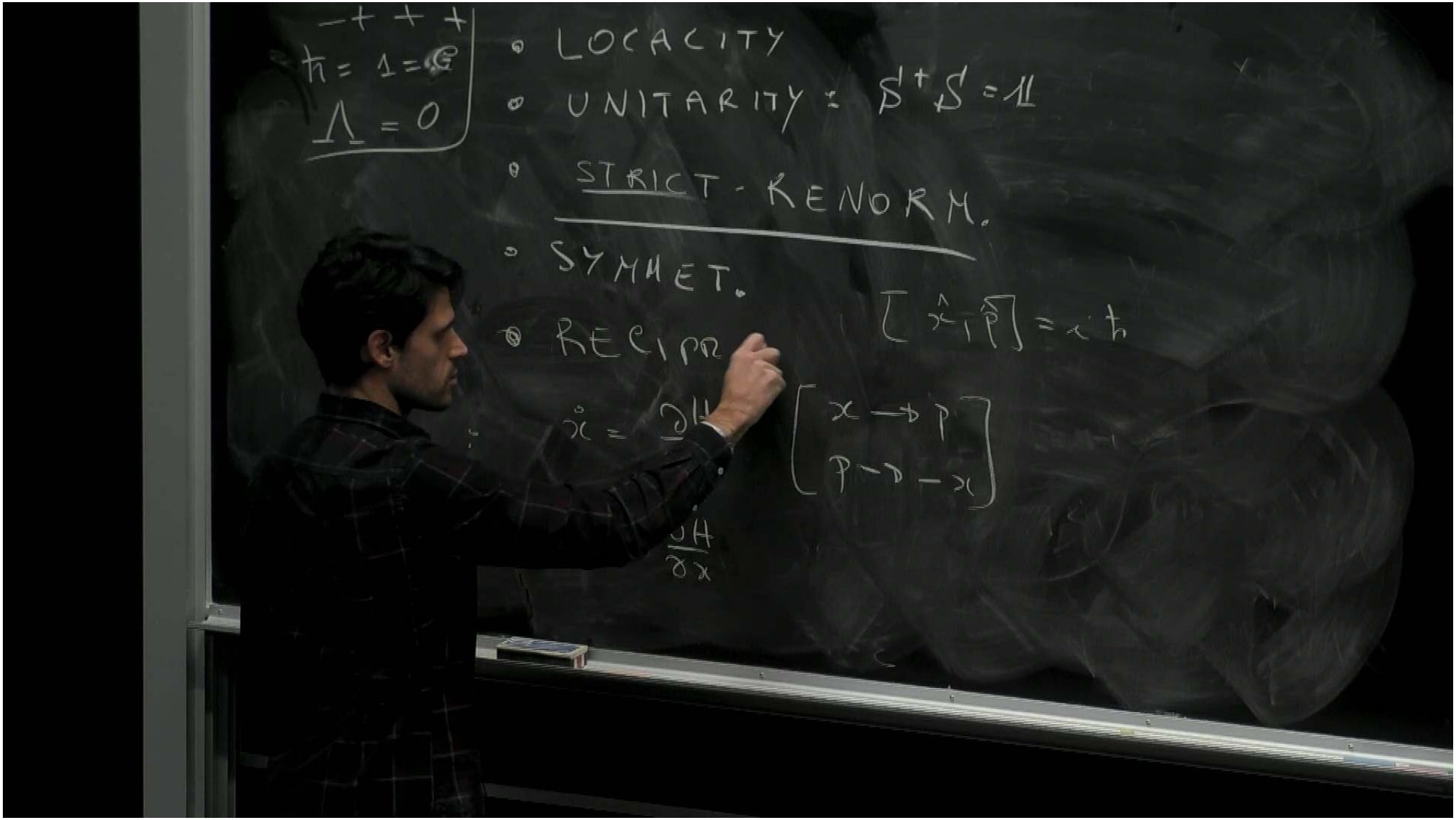
NONLOCALITY IN QG

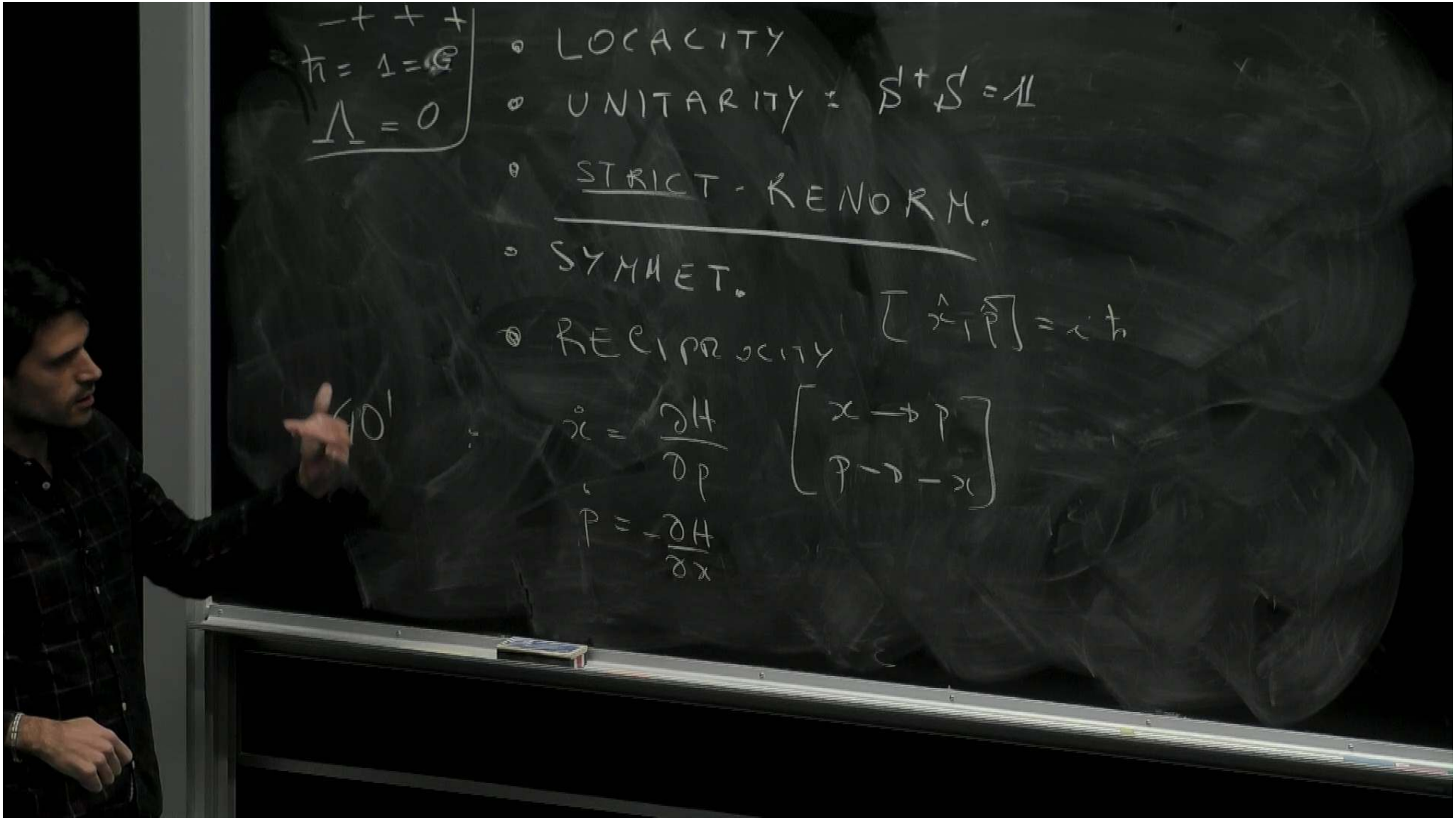
$\hbar = 1 = G$ | $-+++$ | • LOCACITY

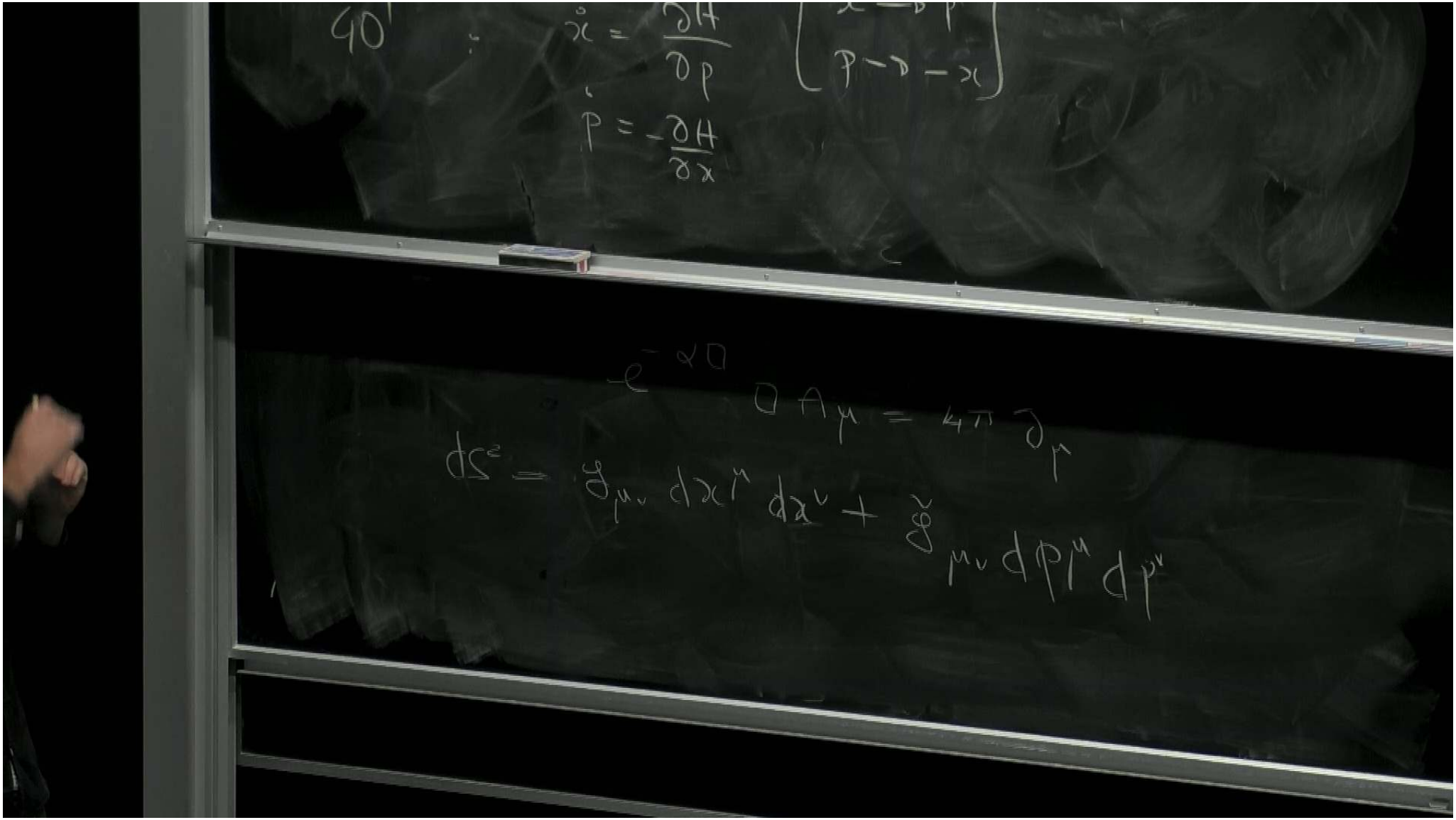

$\int d^4k$
$k^2 + m^2$
$(k-p)^2 + m^2$
$\gamma(0)$
k^0
$k^0 \to \pm i\omega$
NONLOCALITY IN QG
$\hbar = 1 = G$
LOCACITY


1)
2)
NONLOCALITY IN QG
LOCACITY


- + + +
ħ = 1 = G
Λ = 0
• LOCACITY
• UNITARITY : S†S = 𝟙
• STRICT - RENORM.
• SYMMET.
40'
ẋ = ∂H/∂p
ṗ = -∂H/∂x
[x → p
p → -x]


LOCACITY
UNITARITY : $S^\dagger S = \mathbb{1}$
STRICT - RENORM.
SYMMET.
RECIPR
$\hbar = 1 = G$
$\Lambda = 0$
$[\hat{x}, \hat{p}] = i\hbar$
$x \rightarrow p$
$p \rightarrow -x$


- + + +
ħ = 1 = G
Λ = 0
• LOCACITY
• UNITARITY : S†S = 𝟙
• STRICT - KENORM.
• SYMMET.
• RECIPROCITY
[x̂, p̂] = i ħ
ẋ = ∂H/∂p
ṗ = -∂H/∂x
x → p
p → -x


$\dot{x} = \frac{\partial H}{\partial p}$
$\dot{p} = -\frac{\partial H}{\partial x}$
$p \to -x$
$\partial A_\mu = 4\pi j_\mu$
$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + g^{\mu\nu} dp_\mu dp_\nu$