Title: Quantum cosmology in Lorentz-violating gravity

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Abstract: Lorentz invariance is considered a fundamental symmetry of physical theories. However, while Lorentz violations are strongly constrained in the matter sector, constraints in the gravitational sector are weaker, allowing to contemplate the idea of Lorentz-violating gravity theories. In this talk I will discuss the effects of Lorentz violations in the quantum cosmology scenario by analyzing the properties of a simple anisotropic model in the framework of Horava-Lifshitz gravity and, if time permitting, some partial results on the viability of this class of theories.

Quantum Cosmology in Lorentz-Violating Gravity

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Universidad de Guanajuato, México

April 10, 2014

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- LV may give a better UV behaviour as in Horava-Lifshitz gravity (Power-counting Renormalizable)

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Motivation

- LV may give a better UV behaviour as in Horava-Lifshitz gravity (Power-counting Renormalizable)
- LV allows for MOND-like (Blanchet) or DE-like (Afshordi) phenomenology
- Strong constraints in the matter sector, but weaker ones in the gravity sector
- Examples: Hořava-Lifshitz gravity and Einstein-æther Theory (Jacobson)

The Theory

Inspired from Condensed Matter

- Anisotropic scaling

$$\mathbf{x} \to b\mathbf{x}, \qquad t \to b^z t.$$

- Gauge symmetries $\mathrm{Diff}_{\mathcal{F}}(\mathcal{M})$, generated by

$$\delta x^i = \zeta^i(t, \mathbf{x}), \qquad \delta t = f(t).$$

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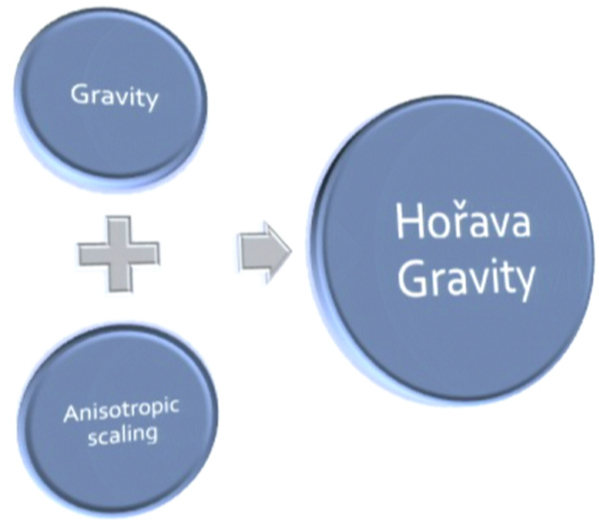

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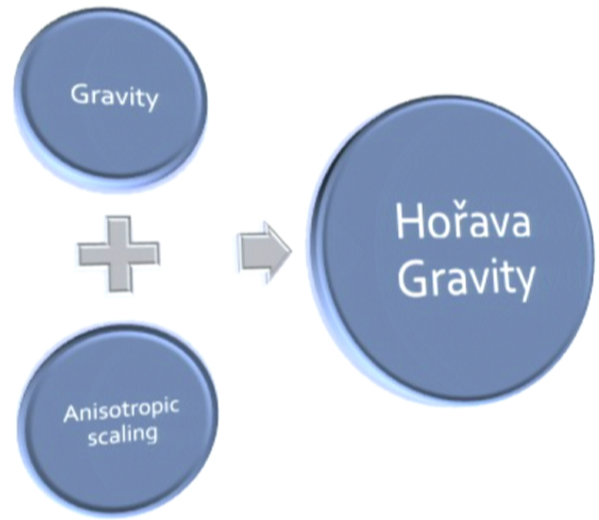

Action (ADM formulation)

$$S = \frac{2}{\kappa^2} \int dt d^D \mathbf{x} \sqrt{g} N \left(K_{ij} K^{ij} - \lambda K^2 - \mathcal{V} \right),$$

The Action

Conditions

- Projectability $N = N(t)$ (Otherwise $a_i = \partial_i \ln N \neq 0$)

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$$W = \frac{1}{w^2}\int_\Sigma \omega_3(\Gamma) + \mu \int d^3\mathbf{x}\sqrt{g}\,(R - 2\Lambda_W) + \beta \int d^3\mathbf{x}(a_i a^i)$$

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$$E^{ij} = \frac{2}{w^2}C^{ij} - \mu G^{ij} + \beta\left(\frac{1}{2}g^{ij}a_k a^k - a^i a^j\right)$$

where μ, w, and Λ_W are constant parameters and C_{ij} is the Cotton tensor

$$C^{ij} \equiv \varepsilon^{ikl}\nabla_k\left(R^j{}_l - \frac{1}{4}R\delta^j{}_l\right)$$

The Action

Action in $3+1$ dimensions

$$S = \int dt d^3\mathbf{x}\sqrt{g}N\left\{ \frac{2}{\kappa^2}(K_{ij}K^{ij} - \lambda K^2) - \frac{\kappa^2}{2w^4}C_{ij}C^{ij} + \frac{\kappa^2\mu}{2w^2}\varepsilon^{ijk}R_{il}\nabla_j R^l_k - \frac{\kappa^2\mu^2}{8}R_{ij}R^{ij} + \frac{\kappa^2\mu^2}{8(1-3\lambda)}\left[\frac{1-4\lambda}{4}R^2 + \Lambda_W(R - 3\Lambda_W)\right]\right\}$$

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Comparing with the Einstein-Hilbert action ($\lambda = 1$)

$$c = \frac{\kappa^2\mu}{4}\sqrt{\frac{\Lambda_W}{1-3\lambda}}, \qquad G_N = \frac{\kappa^2}{32\pi c}, \qquad \Lambda = \frac{3}{2}\Lambda_W.$$

Analytical continuation $\mu \to i\mu$ and $w^2 \to -iw^2$ implies $\mathcal{V} \to -\mathcal{V}$.

Canonical Quantization

The Hamiltonian for the theory may be written, as in GR, is a sum of constraints

$$H = \int d^D\mathbf{x} \left(N\mathcal{H}_\perp + N^i\mathcal{H}_i \right),$$

$$\mathcal{H}_\perp = \frac{\kappa^2}{2\sqrt{g}}\Pi^{ij}\mathcal{G}_{ijkl}\Pi^{kl} + \frac{2\sqrt{g}}{\kappa^2}\mathcal{V}$$

$$\mathcal{H}^i = -2\nabla_j\Pi^{ij}$$

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$$\mathcal{H}^i = -2\nabla_j\Pi^{ij} \qquad \mathcal{G}^{ijkl} = \frac{1}{2}\left(g^{ik}g^{jl} + g^{il}g^{jk}\right) - \lambda g^{ij}g^{kl}$$

Wheeler-DeWitt equations

$$\hat{\mathcal{H}}_0\psi = 0, \qquad \text{(Hamiltonian Constraint)}$$

$$\hat{\mathcal{H}}_i\psi = 0, \qquad \text{(Momentum Constraints)}$$

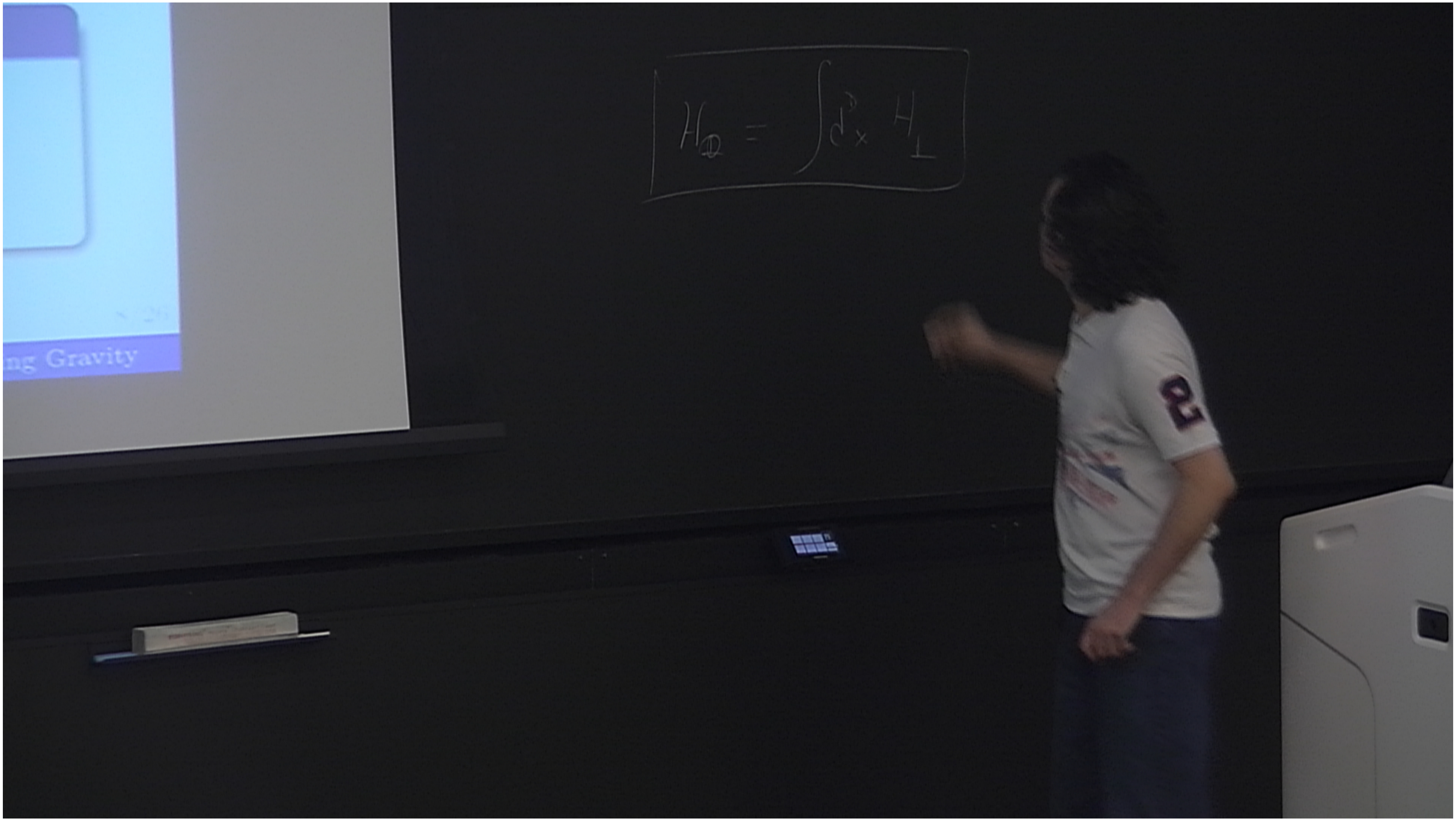
WKB Approximation

Take the ansatz

$$\psi[g_{ij}] = C[g_{ij}]\exp\left(\frac{i}{\hbar}S[g_{ij}]\right)$$

where $C[g_{ij}]$ is a slowly varying amplitude and $S[g_{ij}]$ is the phase. This corresponds to

$$\Pi^{ij} \to \frac{\delta S}{\delta g_{ij}}$$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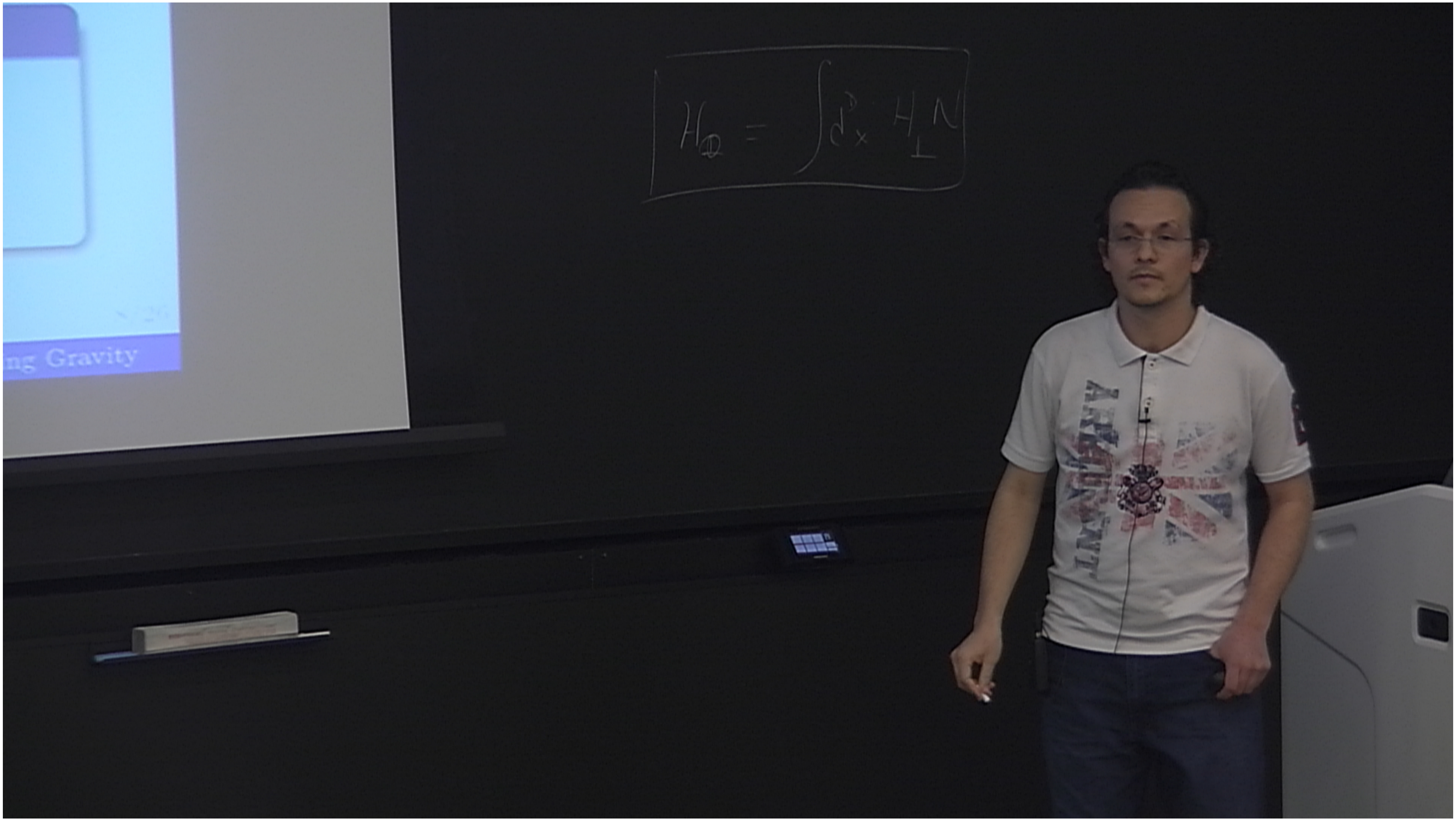
$H_{\Phi} = \int d^3x \, H_\perp$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And from the WDW equations one finds that

$$\frac{\kappa^2}{2}\mathcal{G}^{ijkl}\frac{\delta S}{\delta g_{ij}}\frac{\delta S}{\delta g_{kl}} + \frac{2\sqrt{g}}{\kappa^2}\mathcal{V} = 0$$

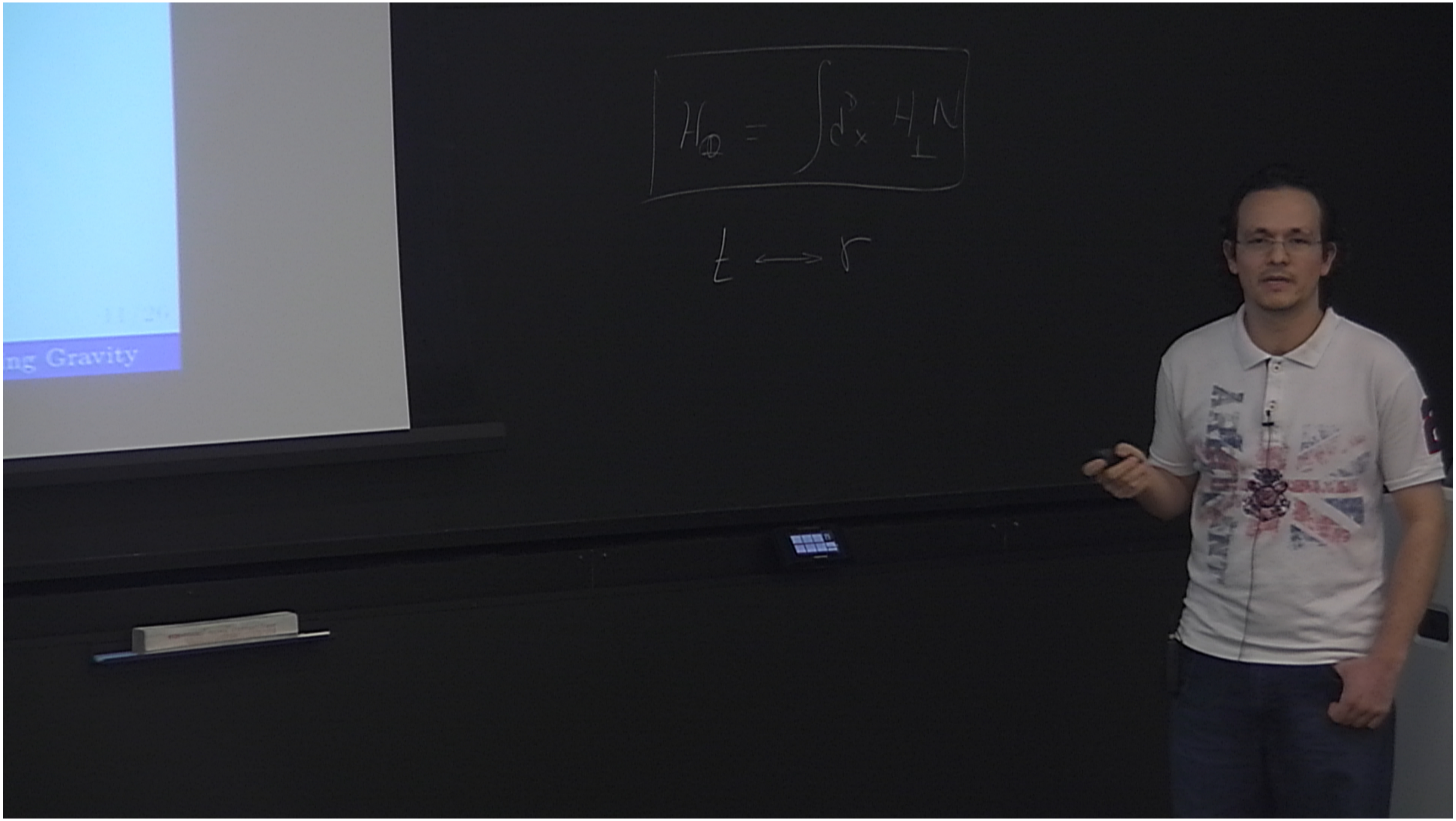
$$\nabla_j \frac{\delta S}{\delta g_{ij}} = 0$$

It can be shown that this equations are equivalent to the classical HL field equations.

The Quantum Model

KS universe

$$ds^2 = -\left(\frac{\Lambda t^2}{3} + \frac{2m}{t} - 1\right)^{-1} dt^2 + \left(\frac{\Lambda t^2}{3} + \frac{2m}{t} - 1\right) dr^2 + t^2 d\bar{\Omega}^2.$$


Gravity
$H_D = \int d^D x \, H_\perp N$
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Misner parametrization

$$ds^2 = -N^2 dt^2 + e^{2\sqrt{3}\beta} dr^2 + e^{-2\sqrt{3}(\beta+\Omega)} d\bar{\Omega}^2$$

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$$e^{-2\sqrt{3}(\beta+\Omega)} = t^2$$

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WDW equation

$$\left\{-\frac{\partial^2}{\partial\Omega^2} + \frac{\partial^2}{\partial\beta^2} + 48e^{-2\sqrt{3}\Omega}\left[1 - \Lambda e^{-2\sqrt{3}(\beta+\Omega)}\right]\right\}\psi(\Omega,\beta) = 0.$$

Solution for $\Lambda = 0$

$$\psi_\nu^\pm(\Omega,\beta) = e^{\pm i\nu\sqrt{3}\beta} K_{i\nu}(4e^{-\sqrt{3}\Omega}),$$

The WKB model

The WKB approximation leads to the Hamilton-Jacobi equation

$$-\left(\frac{\partial S}{\partial \Omega}\right)^2+\left(\frac{\partial S}{\partial \beta}\right)^2-48e^{-2\sqrt{3}\Omega}\left[1-\Lambda e^{-2\sqrt{3}(\beta+\Omega)}\right]=0.$$

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Identifying

$$\frac{\partial S}{\partial \Omega} \to \pi_\Omega = -\frac{12}{N} e^{-\sqrt{3}(\beta+2\Omega)} \dot{\Omega}$$

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leads us to the classical equation

$$\frac{3}{N^2}(\dot{\Omega}^2 - \dot{\beta}^2) + e^{2\sqrt{3}(\beta+\Omega)}\left[1 - \Lambda e^{-2\sqrt{3}(\beta+\Omega)}\right] = 0.$$

The Misner Map!!!

$$e^{-2\sqrt{3}\Omega}(1 + 2\sqrt{3}t\dot{\Omega}) - t^2\left(1 - \Lambda t^2\right) = 0,$$

Classical Solution

$$e^{-2\sqrt{3}\Omega} = t^2\left(\frac{\Lambda t^2}{3} + \frac{2m}{t} - 1\right)$$

The WKB method applied to the WDW eq. gives the same solution as the one obtained through the classical Einstein's field equations.

The Quantum Model

Hamiltonian Constraint

$$\mathcal{H}_0 = \frac{\kappa^2 e^{\sqrt{3}(\beta+\Omega)}}{24(1-3\lambda)}\Big\{ -\frac{1}{2}(\lambda-3)\Pi_\Omega^2 + 2(\lambda-1)\Pi_\Omega\Pi_\beta - (2\lambda-1)\Pi_\beta^2 \mp 3\mu^2\Lambda_W e^{-2\sqrt{3}\Omega}\Big[2 - 3\Lambda_W e^{-2\sqrt{3}(\beta+\Omega)} + \frac{(2\lambda-1)}{\Lambda_W} e^{2\sqrt{3}(\beta+\Omega)}\Big]\Big\}$$

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WDW equation in the UV limit

$$\Big[\frac{1}{2}(\lambda-3)\partial_\Omega^2 - 2(\lambda-1)\partial_\Omega\partial_\Omega + (2\lambda-1)\partial_\beta^2 \mp 3\mu^2(2\lambda-1)e^{2\sqrt{3}\beta}\Big] * \psi_{1,2}(\Omega,\beta) = 0$$

$$\begin{bmatrix}\psi_{1\nu}\\ \psi_{2\nu}\end{bmatrix} = e^{\pm i\nu\sqrt{3}\Omega}\left(\mu e^{\sqrt{3}\beta}\right)^{\pm\frac{\lambda-1}{2\lambda-1}i\nu}\begin{bmatrix}K_{\frac{\sqrt{3\lambda-1}}{\sqrt{2}(2\lambda-1)}i\nu}\left(\mu e^{\sqrt{3}\beta}\right)\\ J_{\frac{\sqrt{3\lambda-1}}{\sqrt{2}(2\lambda-1)}i\nu}\left(\mu e^{\sqrt{3}\beta}\right)\end{bmatrix},$$

Particularly for $\lambda = 1$

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Noncommutative QC

Proposed by Compeán Obregón & Ramírez (Phys. Rev. Lett. 88 161301).

$$\left[\hat{\Omega}, \hat{\beta}\right] = i\theta, \qquad \left[\hat{\Pi}_\Omega, \hat{\Pi}_\beta\right] = 0$$

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Seiberg-Witten Map.

$$\Omega = \Omega_c - \frac{\theta}{2}\Pi_\beta, \qquad \beta = \beta_c + \frac{\theta}{2}\Pi_\Omega$$

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WDW equation in the UV limit

$$\left[\frac{1}{2}(\lambda-3)\partial_\Omega^2 - 2(\lambda-1)\partial_\Omega\partial_\Omega + (2\lambda-1)\partial_\beta^2 \mp 3\mu^2(2\lambda-1)e^{2\sqrt{3}\beta}\right] * \psi_{1,2}(\Omega,\beta) = 0$$

$$\begin{bmatrix}\psi_{1\nu}\\ \psi_{2\nu}\end{bmatrix} = e^{\pm i\nu\sqrt{3}\Omega}\left(\mu e^{\sqrt{3}\beta}\right)^{\pm\frac{\lambda-1}{2\lambda-1}i\nu}\begin{bmatrix}K_{\frac{\sqrt{3\lambda-1}}{\sqrt{2}(2\lambda-1)}i\nu}\left(\mu e^{\sqrt{3}\beta}\right)\\ J_{\frac{\sqrt{3\lambda-1}}{\sqrt{2}(2\lambda-1)}i\nu}\left(\mu e^{\sqrt{3}\beta}\right)\end{bmatrix},$$

Particularly for $\lambda = 1$

$$\psi_{1\nu}(\Omega,\beta) = e^{\pm i\nu\sqrt{3}\Omega}K_{i\nu}\left(\mu e^{\sqrt{3}\beta}\right)$$

Noncommutative QC

Proposed by Compeán Obregón & Ramírez (Phys. Rev. Lett. 88 161301).

$$\left[\hat{\Omega},\hat{\beta}\right]=i\theta, \qquad \left[\hat{\Pi}_\Omega,\hat{\Pi}_\beta\right]=0$$

Moyal product

$$f(\Omega,\beta)*g(\Omega,\beta)=f(\Omega,\beta)e^{i\frac{\theta}{2}(\overleftarrow{\partial}_\Omega\overrightarrow{\partial}_\beta-\overleftarrow{\partial}_\beta\overrightarrow{\partial}_\Omega)}g(\Omega,\beta)$$

Seiberg-Witten Map.

$$\Omega=\Omega_c-\frac{\theta}{2}\Pi_\beta, \qquad \beta=\beta_c+\frac{\theta}{2}\Pi_\Omega$$

$$\left[\hat{\Omega}_c,\hat{\beta}_c\right]=0, \qquad \left[\hat{\Pi}_\Omega,\hat{\Pi}_\beta\right]=0$$

The potential is modified

$$V(\Omega_c,\beta_c)*\psi(\Omega_c,\beta_c)=V(\Omega,\beta)\,\psi(\Omega_c,\beta_c)$$

WDW equation in the UV limit

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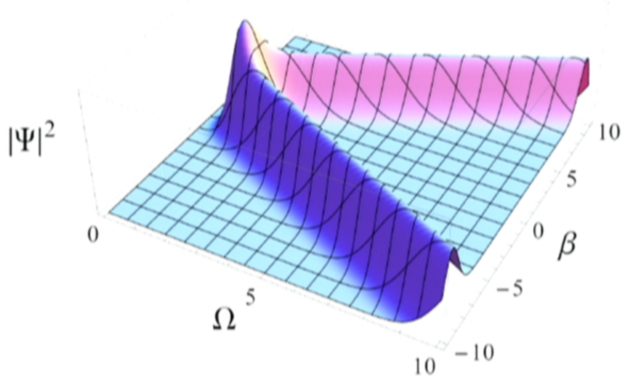
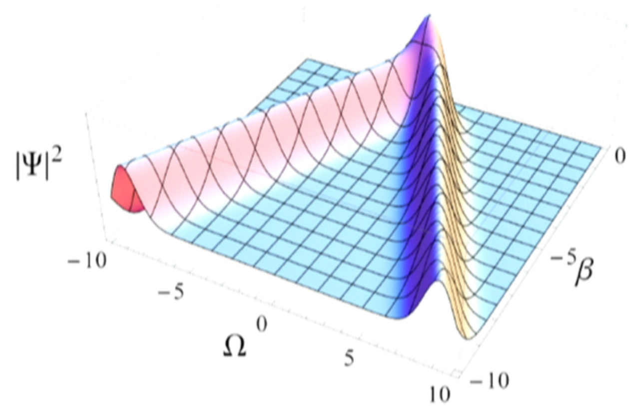
Wave Packets

Consider a wave packet weighted by a Gaussian for $\psi_{1\nu}$

$$\Psi(\Omega,\beta) = \mathcal{N}\int_{-\infty}^{\infty} e^{-\frac{1}{2\sigma^2}(\nu-\bar{\nu})^2}\psi_{1\nu}(\Omega,\beta)d\nu.$$



The GR Case



UV limit $\lambda = 1$

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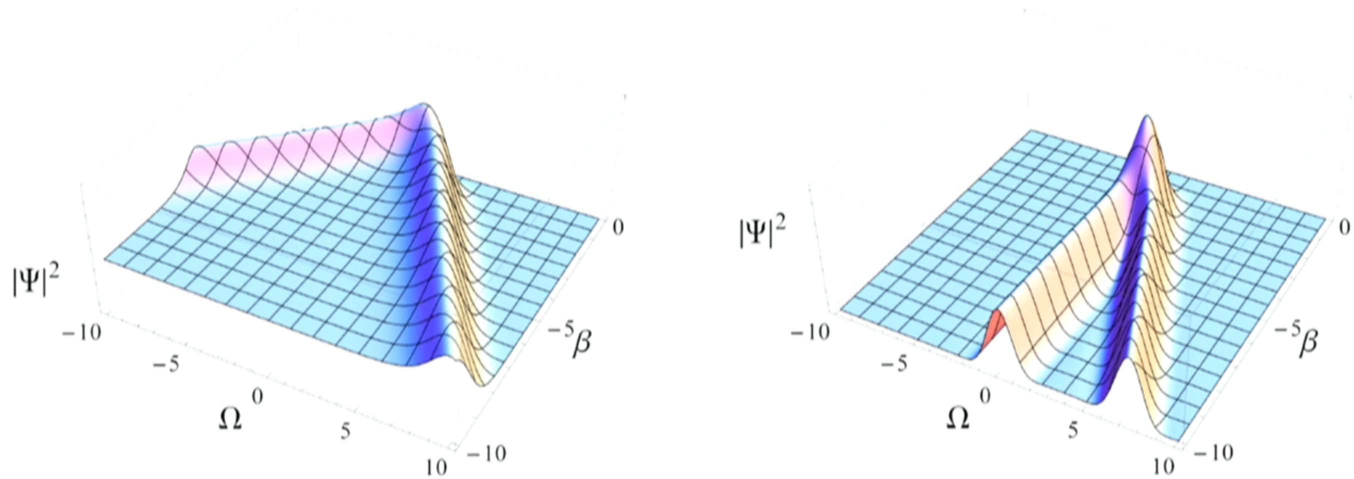

UV limit $\lambda = 0.75$ UV limit $\lambda = 3$

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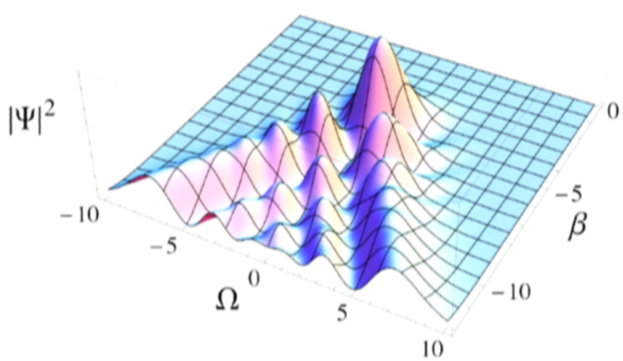
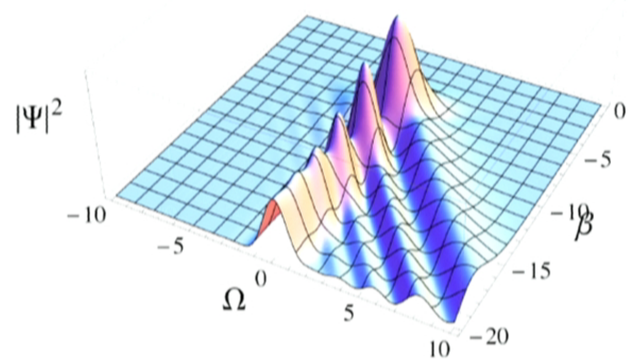


NC UV limit $\lambda = 1$



NC UV limit $\lambda = 3$

The WKB model

For the general WDW equation the WKB procedure results in:

$$\frac{3e^{-2\sqrt{3}(\beta+\Omega)}}{N^2}\left[(3-\lambda)\dot{\beta}^2+4(1-\lambda)\dot{\beta}\dot{\Omega}-2(2\lambda-1)\dot{\Omega}^2\right]$$
$$\mp\frac{\kappa^4\mu^2\Lambda_W}{16(1-3\lambda)}\left[2-3\Lambda_W e^{-2\sqrt{3}(\beta+\Omega)}+\frac{(2\lambda-1)}{\Lambda_W}e^{2\sqrt{3}(\beta+\Omega)}\right]=0.$$

Using the Misner map and solving for $\lambda=1$ and $c=1$

$$e^{-2\sqrt{3}\Omega}=\frac{\Lambda t^4}{3}+2\xi t+\frac{3}{4\Lambda}-t^2$$

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$$e^{-2\sqrt{3}\Omega} = \frac{\Lambda t^4}{3} + 2\xi t + \frac{3}{4\Lambda} - t^2$$

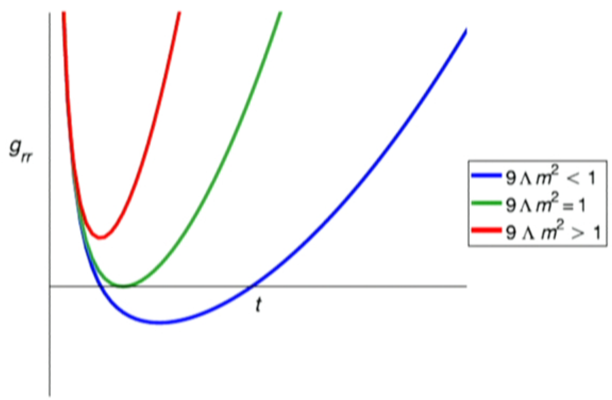
Classical Solution

$$ds^2 = -\left(\frac{\Lambda t^2}{3} + \frac{2\xi}{t} + \frac{3}{4\Lambda t^2} - 1\right)^{-1} dt^2 + \left(\frac{\Lambda t^2}{3} + \frac{2\xi}{t} + \frac{3}{4\Lambda t^2} - 1\right) dr^2 + t^2 d\Omega^2,$$

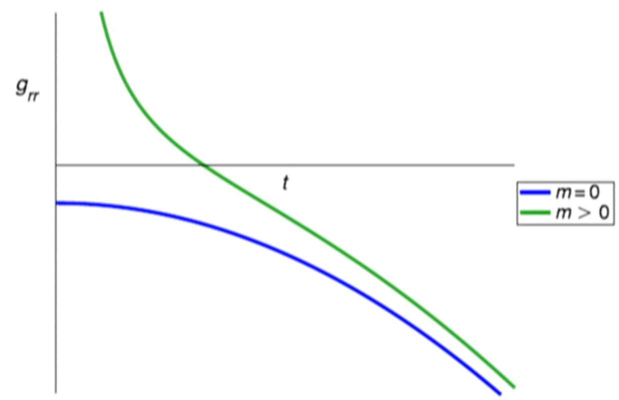
where ξ is an integration constant. This is a solution of the original action with $\Lambda < 0$ and of its analytical continuation with $\Lambda > 0$.

S(A)dS in GR

Case	Condition	Horizons or Singularities
$\Lambda > 0$	$9\Lambda m^2 < 1$	$t = t_\bullet$ and $t = t_\star$
	$9\Lambda m^2 = 1$	$t_\bullet = t_\star = 3m$
	$9\Lambda m^2 > 1$	Dynamical at all $t > 0$
$\Lambda < 0$	$m > 0$	$t = t_-$
	$m = 0$	No horizon
	$m < 0$	Unphysical



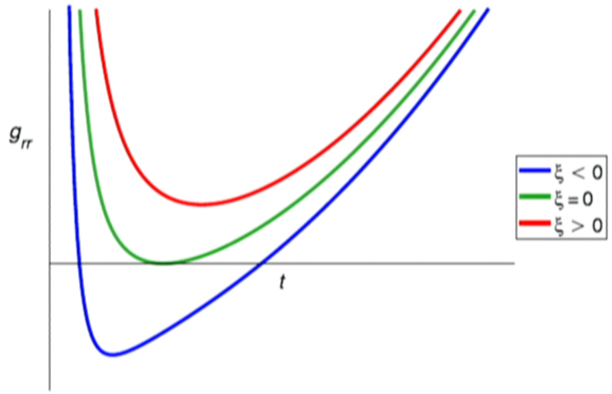
Case $\Lambda > 0$



Case $\Lambda < 0$

S(A)dS in HL

Case	Condition	Horizons or Singularities
$\Lambda > 0$	$\xi > 0$	Dynamical at all $t > 0$
	$\xi = 0$	$t = \sqrt{\frac{3}{2\Lambda}}$
	$\xi < 0$	Unphysical?? $t = t_+$ and $t = t_{++}$
$\Lambda < 0$	$9\Lambda\xi^2 < -8$	$t = t_\star$ and $t = t_\bullet$
	$9\Lambda\xi^2 = -8$	$t_\star = t_\bullet = \frac{3m}{4}$
	$9\Lambda\xi^2 > -8$	Unphysical



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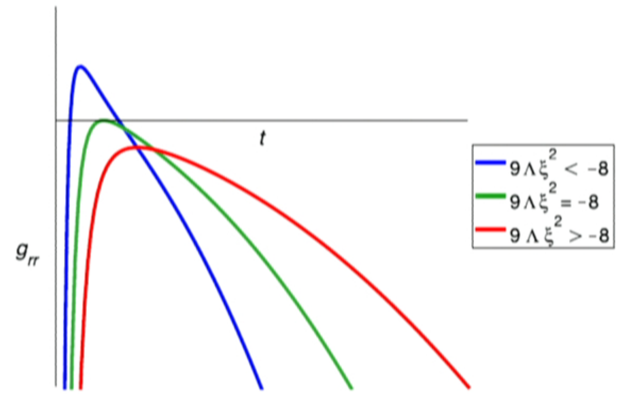

Case $\Lambda < 0$

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$$H = \frac{1}{2}\{Q, \bar{Q}\} = H_0 + \frac{\hbar}{2} \frac{\partial^2 \phi}{\partial q^\mu \partial q^\nu} [\bar{\theta}^\mu, \theta^\nu],$$

with the non-Hermitian supercharges

$$Q = \theta^\mu \left(\Pi_\nu + i \frac{\partial \phi}{\partial q^\mu} \right), \quad \bar{Q} = \bar{\theta}^\mu \left(\Pi_\nu - i \frac{\partial \phi}{\partial q^\mu} \right),$$

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$$ds^2 = -N^2 dt^2 + a^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

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For this model

$$U = -qc^2 \left(ka - \frac{1}{2} \Lambda_W a^3 - \frac{k^2}{2\Lambda_W a} \right) = -\frac{q\Lambda_W}{2a} \left(a^2 - \frac{k}{\Lambda_W} \right)^2$$

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$$\left(\frac{d\phi}{da} \right)^2 = -\frac{1}{2} q\Lambda_W \left(a^2 - \frac{k}{\Lambda_W} \right)^2 .$$

A solution of this equation is

$$\phi = \sqrt{-\frac{q}{2\Lambda_W}} \left(ka - \frac{1}{3}\Lambda_W a^3 \right)$$

FRW SUSY Model

The supercharges are given by

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Representation for the bosonic variables and the fermionic ones θ^a and $\bar{\theta}^a$. The momentum will be as usual $\Pi_a \to -i\frac{\partial}{\partial a}$ and to realize the fermionic variables algebra we will represent them as matrices

$$\hat{\theta}^a = \frac{1}{\sqrt{a}} \sigma_+, \qquad \hat{\bar{\theta}}^a = \frac{1}{\sqrt{a}} \sigma_-,$$

where $\sigma_\pm = \frac{1}{2}(\sigma_1 \pm i\sigma_2)$ are the Pauli matrices. We define then

$$\hat{\theta}^a = \frac{1}{\sqrt{a}} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \qquad \hat{\bar{\theta}}^a = \frac{1}{\sqrt{a}} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}.$$

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Making use of these operators representation, the $\hat{Q}$ and $\hat{\bar{Q}}$ operators can be constructed from and with them, a diagonal Hamiltonian operator $\hat{H}$ is obtained.

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The WKB Approximation will give us a modified Friedmann equation

$$\frac{3\lambda-1}{2}\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} - \frac{k}{a^2} + \frac{3k^2}{\Lambda a^4} \mp \frac{1}{a^3}\sqrt{-\frac{q\Lambda}{3}}$$

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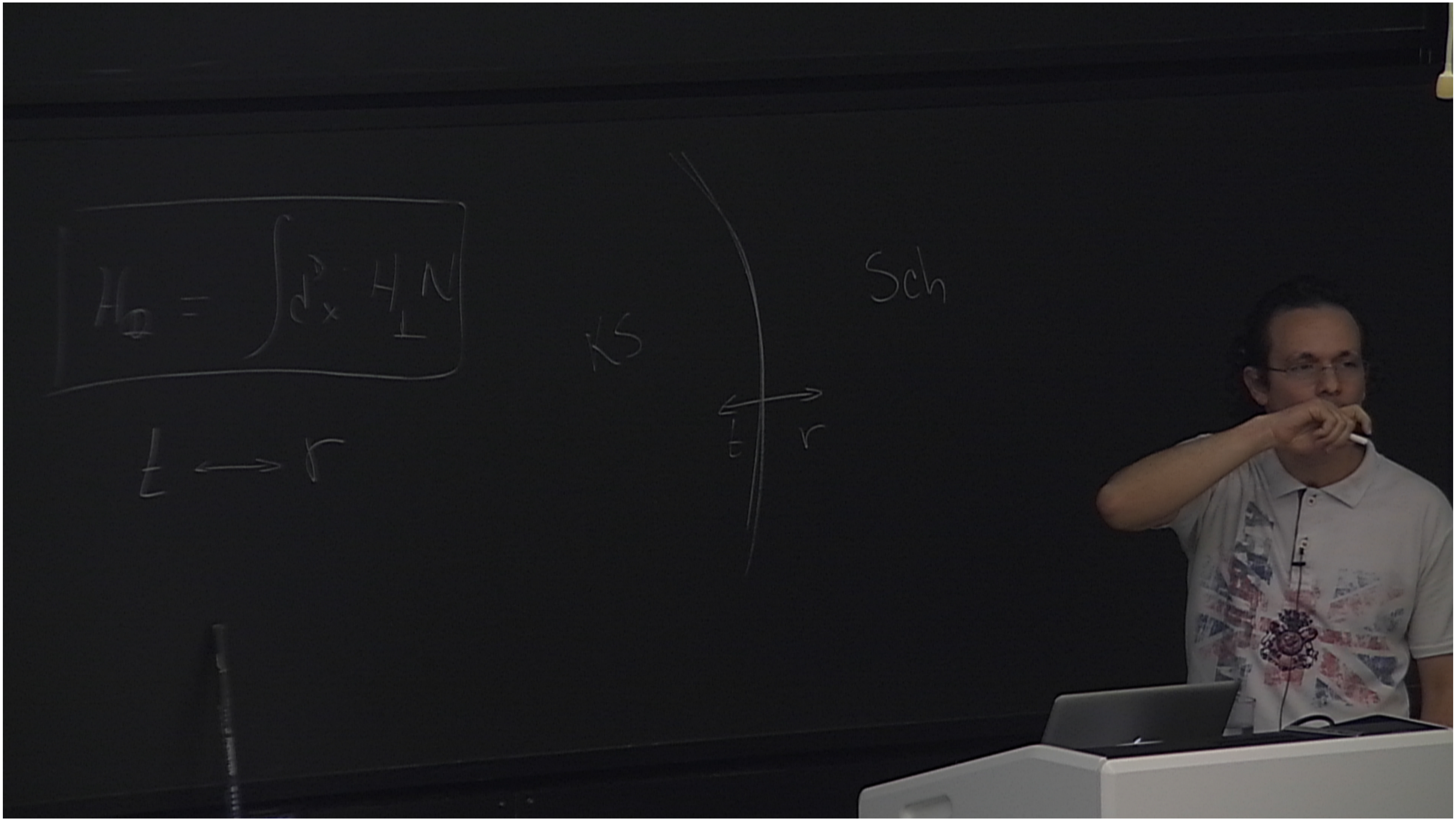

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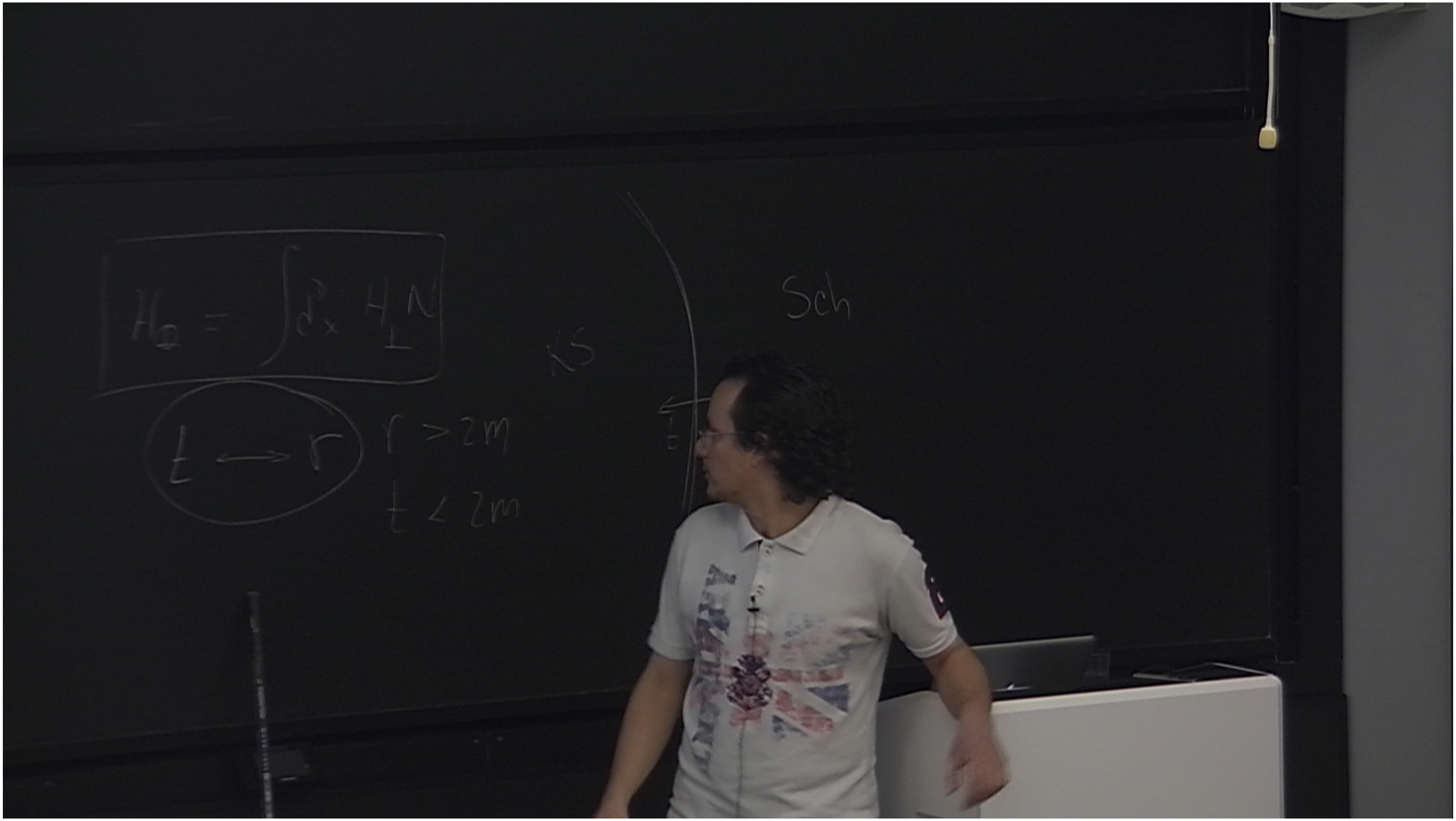
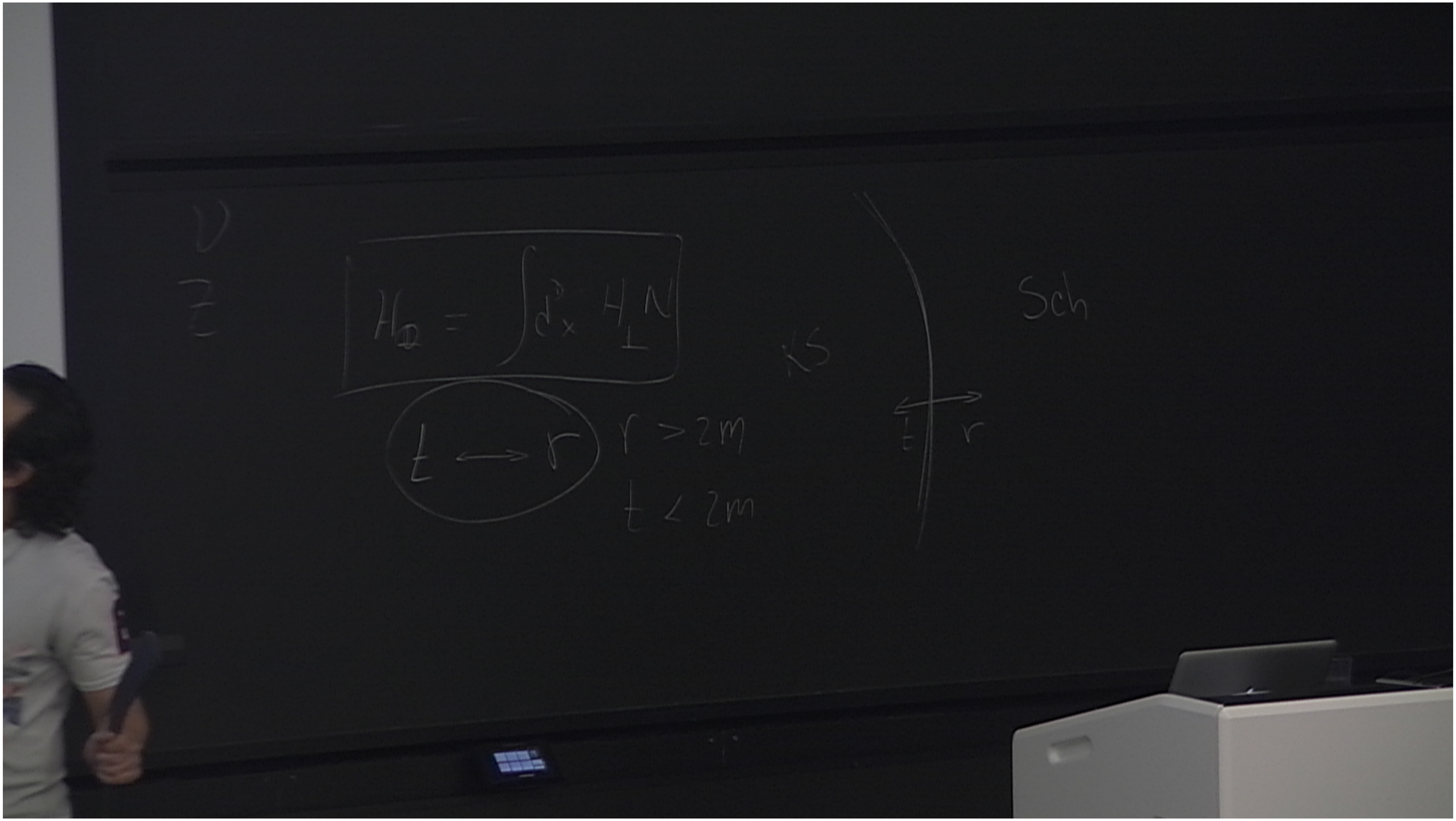


H_Ω = ∫d³x H_⊥ N
t ⟷ r
r > 2m
t < 2m
KS
Sch
t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