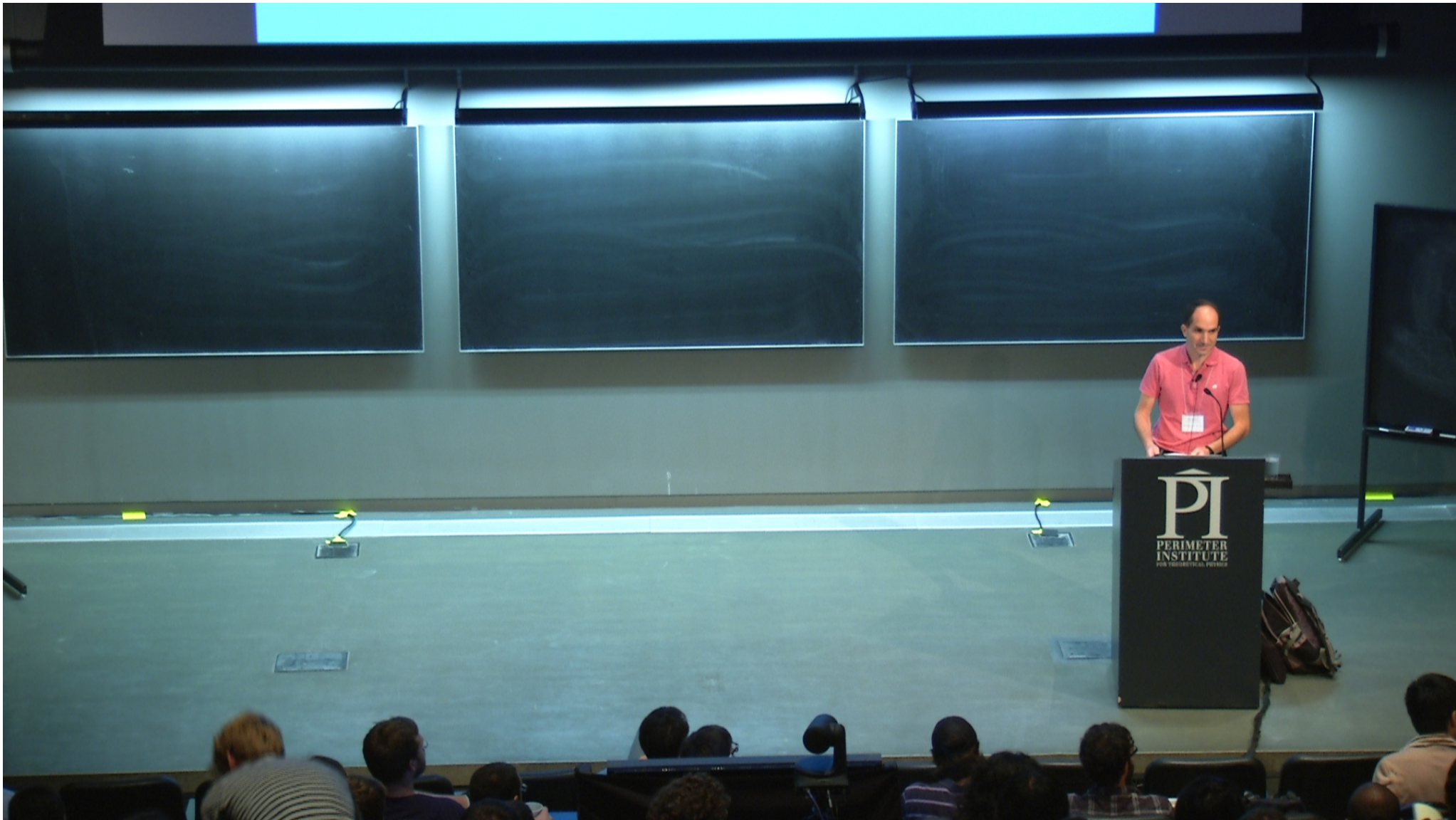


Title: Quantum mechanics in the early universe

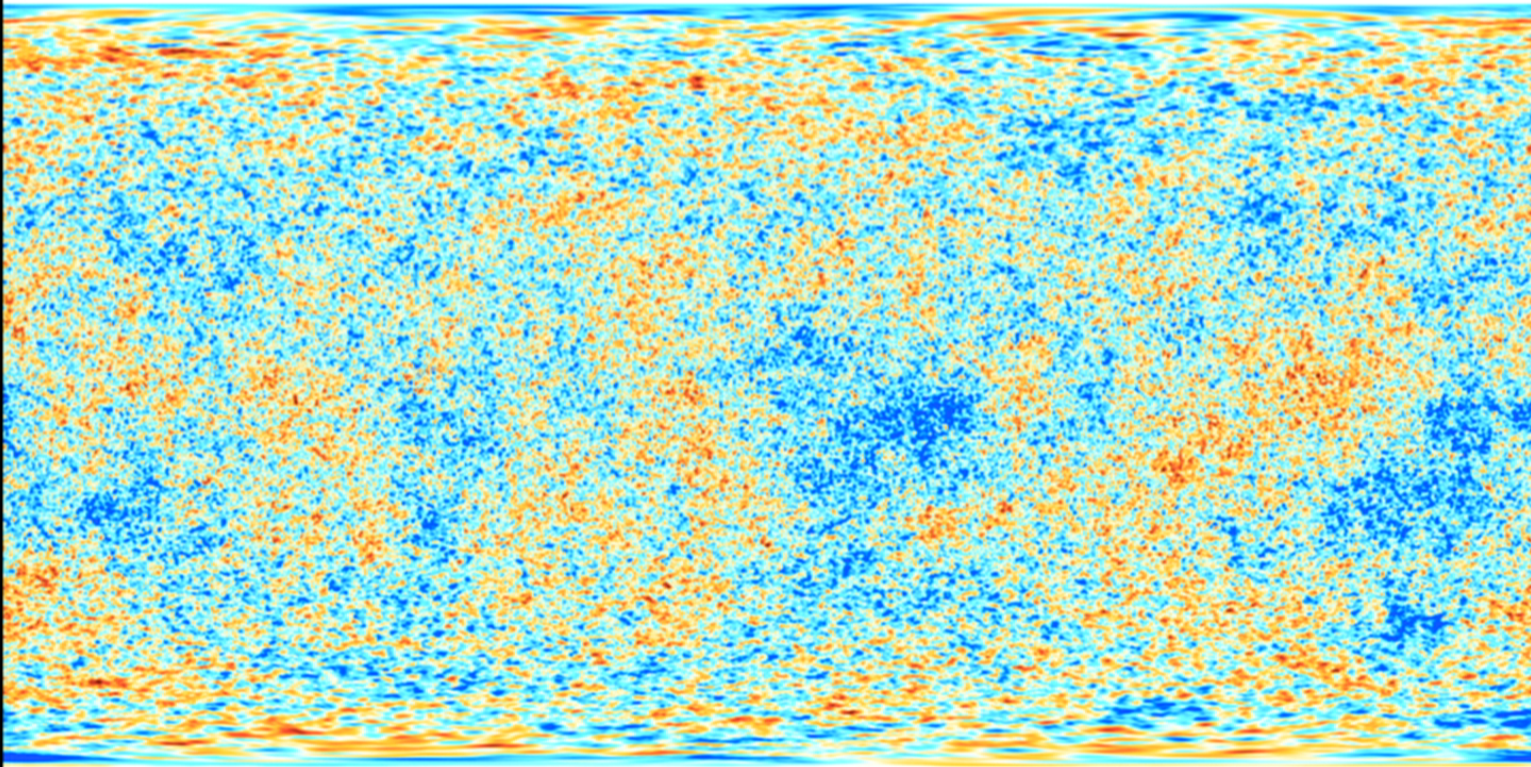
Date: Aug 24, 2015 11:00 AM

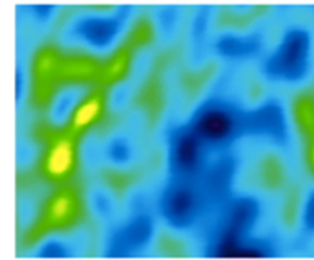
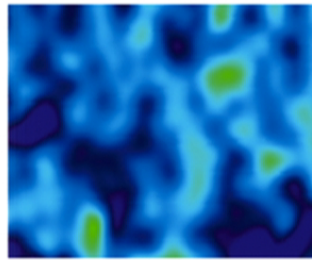
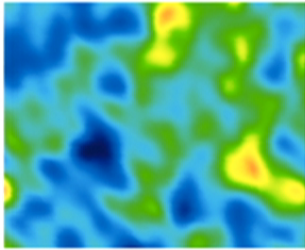
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Abstract: We will review the mechanism for the generation of primordial fluctuations. We will then discuss ways in which one can test their quantum mechanical nature.

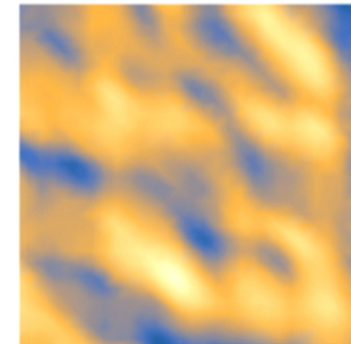
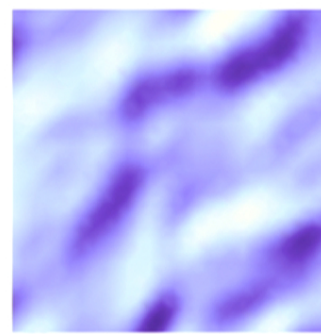
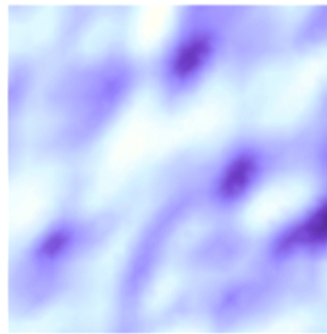
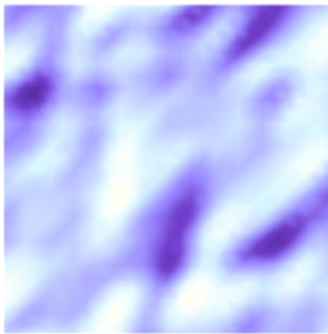


CMB map from Planck



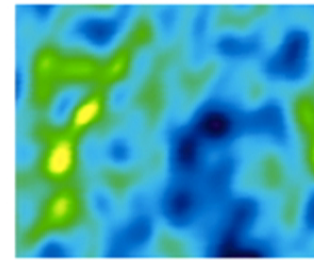
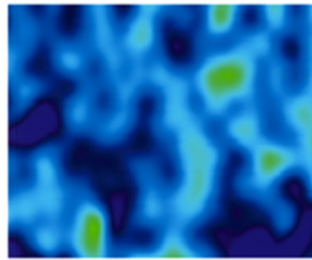
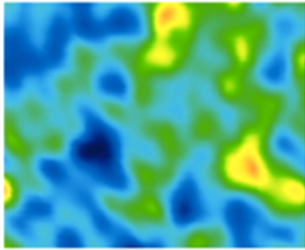


From the real CMB

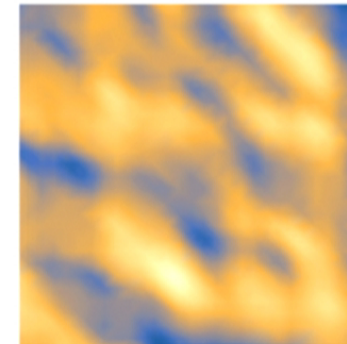
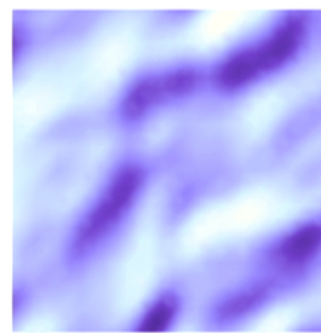
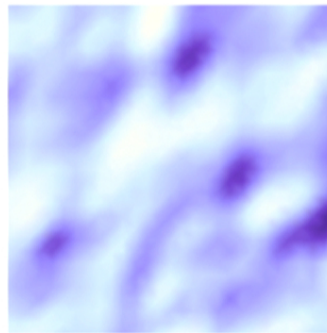
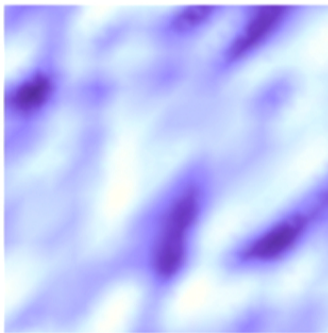


Simulated more correctly

Incorrect



From the real CMB



Simulated more correctly

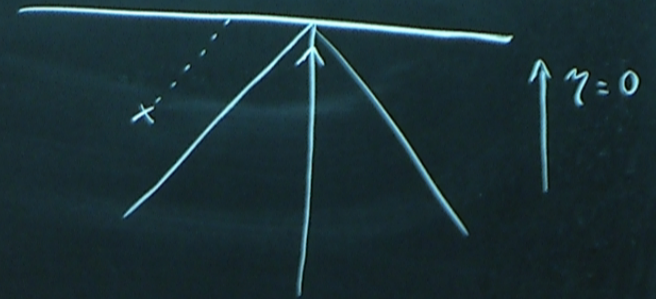
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DE SITTER.

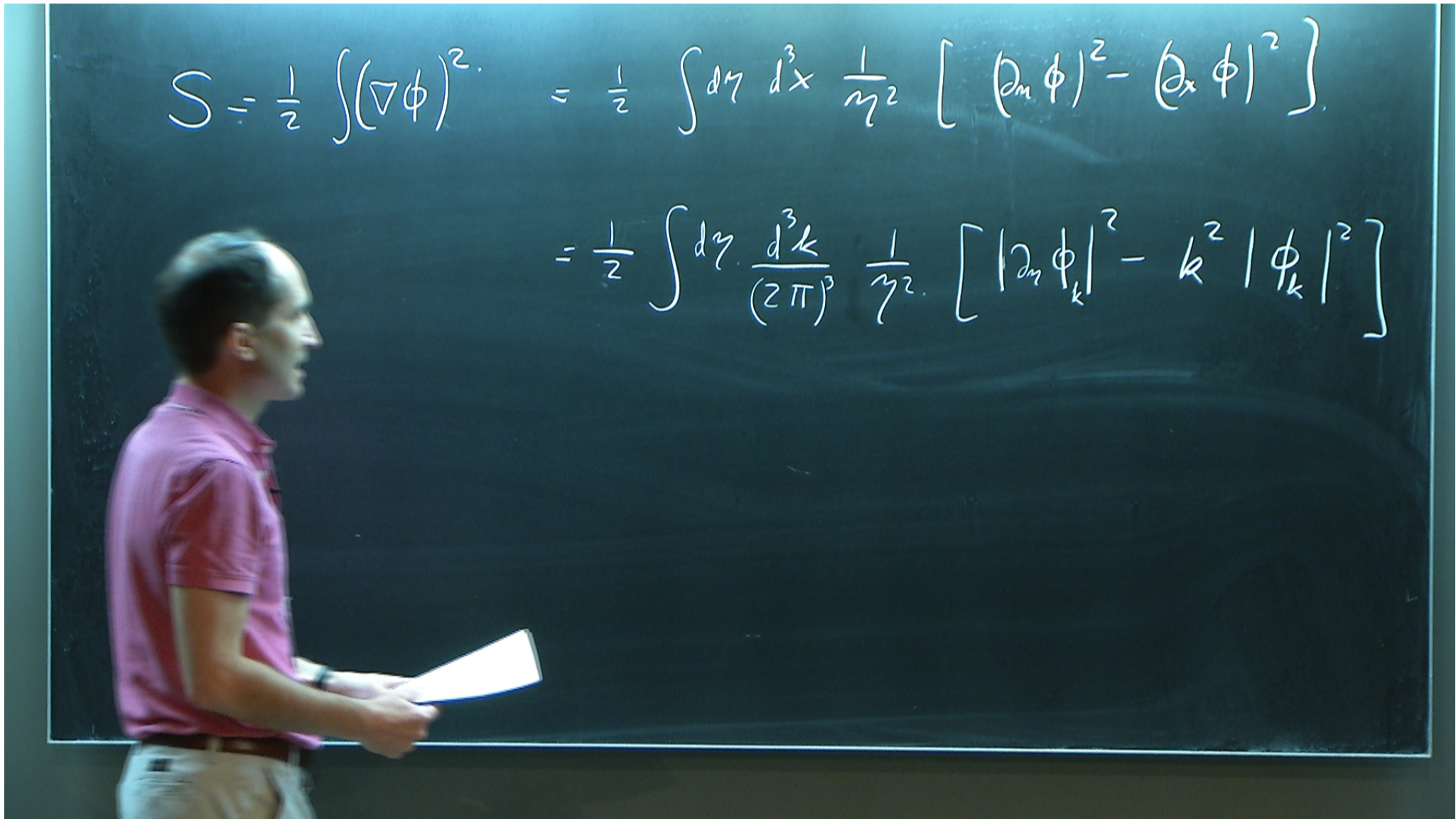
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{dr^2}{r^2} + d\vec{x}^2$$



$$S = \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d\eta \, d^3x \, \frac{1}{\eta^2} \left[\partial_m \phi \right]^2$$



A man in a pink polo shirt and light-colored trousers stands to the left of a large chalkboard. He is holding a white piece of paper and looking towards the board. The chalkboard is dark green and contains two lines of white chalk equations. The first line shows the action S as an integral over spacetime of the squared gradient of a scalar field ϕ . The second line shows the same action in momentum space, with the spatial gradient term replaced by k^2 and the volume element d^3x replaced by $\frac{d^3k}{(2\pi)^3}$.

$$S = \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d\eta \, d^3x \, \frac{1}{a^2} \left[(\partial_\eta \phi)^2 - (\partial_x \phi)^2 \right]$$
$$= \frac{1}{2} \int d\eta \, \frac{d^3k}{(2\pi)^3} \, \frac{1}{a^2} \left[|\partial_\eta \phi_k|^2 - k^2 |\phi_k|^2 \right]$$

$$\begin{aligned}
 S &= \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d\gamma \, d^3x \, \frac{1}{\gamma^2} \left[(\partial_m \phi)^2 - (\partial_x \phi)^2 \right] \\
 &= \frac{1}{2} \int d\gamma \, \frac{d^3k}{(2\pi)^3} \, \frac{1}{\gamma^2} \left[|\partial_m \phi_k|^2 - k^2 |\phi_k|^2 \right]
 \end{aligned}$$

$$\phi_k = (1 - ik\gamma) e^{ik\gamma}$$

$$\phi_k^* = (1 + ik\gamma) e^{-ik\gamma}$$

$$\phi_k(\gamma) = a^\dagger \phi_k^\alpha + b \phi_k^{\star\alpha}$$

$$\phi_k(\gamma) = a^\dagger \phi_k^\alpha + b \phi_k^{\star\alpha}$$

$[\pi, \phi$

$$\phi_k(\eta) = a^\dagger \phi_k^\mathcal{U} + b \phi_k^{*\mathcal{U}}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

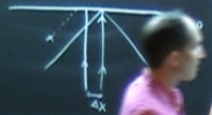
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\eta^2} + d\vec{x}^2$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}_3^2$$

$$ds^2 = (1-\kappa^2) dt^2 + \frac{dn^2}{1-\kappa^2} + n^2 d\Omega^2$$



$$S = \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d^4x \frac{1}{\eta^4} [(\partial_t \phi)^2 - (\partial_i \phi)^2]$$

$$= \frac{1}{2} \int d^4x \frac{1}{(\frac{2\pi}{\eta})^4} \frac{1}{\eta^4} [|\partial_t \phi|^2 - |\partial_i \phi|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2\pi}} (1 - i k \tau) e^{i k \tau}$$

$$\phi_k^{*u} = \frac{1}{\sqrt{2\pi}} (1 + i k \tau) e^{-i k \tau}$$

$$\phi_k(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$|0\rangle$$

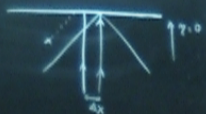


DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\tau^2} + \frac{d\vec{x}^2}{\tau^2}$$

$$ds^2 = -d\tilde{t}^2 + \cosh^2 \tilde{t} d\tilde{x}_3^2$$



$$ds^2 = -(n^2-1)dt^2 + \frac{dn^2}{1-n^2} + n^2 d\Omega^2$$

$$S = \frac{1}{2} \int (\dot{\phi})^2 + \int d\tau d\vec{x} \frac{1}{\tau^4} [|\vec{p}\phi|^2 - |\vec{q}\phi|^2]$$

$$= \frac{1}{2} \int d\tau \frac{d\vec{x}}{(2\pi)^3} \frac{1}{\tau^4} [|\vec{p}\phi|^2 - k^2 |\phi|^2]$$

$$\phi_k^{\vec{q}} = \frac{1}{\sqrt{2k}} (1 - i k \tau) e^{i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi_k^{\vec{q}} = \frac{1}{\sqrt{2k}} (1 + i k \tau) e^{-i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi(\tau) = a^\dagger \phi_k^{\vec{q}} + b \phi_k^{\vec{q}}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$|0\rangle$$



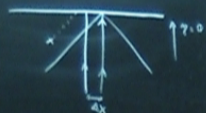
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\tau^2} + \frac{d\vec{x}^2}{\tau^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = (a^2 - 1) dt^2 + \frac{dn^2}{1-n^2} + dx_3^2$$



$$S = \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\tau^4} [(\partial_\tau \phi)^2 - (\partial_i \phi)^2]$$

$$= \frac{1}{2} \int d\tau \frac{V_k}{(2\pi)^3} \frac{1}{\tau^4} [|\partial_\tau \phi|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2k}} (1 - i k \tau) e^{i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

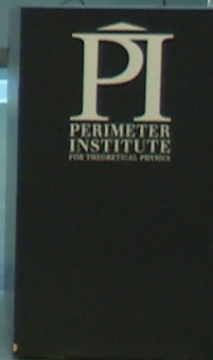
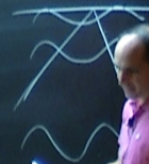
$$\phi_k^{*u} = \frac{1}{\sqrt{2k}} (1 + i k \tau) e^{-i k \tau} e^{-i \vec{k} \cdot \vec{x}}$$

$$\phi(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$|0\rangle$$



DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\tau^2} + \frac{d\vec{x}^2}{\tau^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = (a^2 - 1) dt^2 + \frac{da^2}{1-a^2} + dx^2$$



$$S = \frac{1}{2} \int (\partial\phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\tau^2} [(\partial_t\phi)^2 - (\partial_i\phi)^2]$$

$$= \frac{1}{2} \int d\tau \frac{V_k}{(2\pi)^3} \frac{1}{\tau^2} [|\partial_t\phi|^2 - k^2 |\phi|^2]$$

$$\phi_k^{\omega} = \frac{1}{\sqrt{V_k}} (1 - i k \tau) e^{-i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi_k^{\omega^*} = \frac{1}{\sqrt{V_k}} (1 + i k \tau) e^{-i k \tau} e^{-i \vec{k} \cdot \vec{x}}$$

$$\phi(\tau) = a^\dagger \phi_k^{\omega} + b \phi_k^{\omega^*}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$|0\rangle$$



$$\eta^2 \partial_\eta \frac{1}{\eta^2} \partial_\eta \phi + k^2 \phi = 0$$

$$\partial_\eta^2 \phi - \frac{2}{\eta} \partial_\eta \phi + k^2 \phi = 0$$

$$\eta^2 \partial_\eta \frac{1}{\eta^2} \partial_\eta \phi + k^2 \phi = 0$$

$$\partial_\eta^2 \phi - \frac{2}{\eta} \partial_\eta \phi + k^2 \phi = 0$$

$$\phi \sim e^{ik\eta}$$

DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\eta^2} + d\vec{x}^2$$

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$$ds^2 = -(n^2-1)dt^2 + \frac{dn^2}{1-n^2} + n^2 d\vec{x}^2$$



$$S = \frac{1}{2} \int (\partial\phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\eta^2} [(\partial_t\phi)^2 - (\partial_i\phi)^2]$$

$$= \frac{1}{2} \int d\tau \frac{d\vec{k}}{(2\pi)^3} \frac{1}{\eta^2} [|\partial_\tau\phi|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2k}} (1 - ik\tau) e^{ik\tau} e^{i\vec{k}\cdot\vec{x}}$$

$$\phi_k^{*u} = \frac{1}{\sqrt{2k}} (1 + ik\tau) e^{-ik\tau} e^{-i\vec{k}\cdot\vec{x}}$$

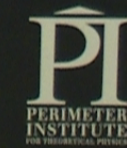
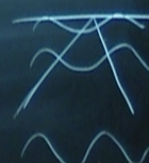
$$\phi(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

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$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$a|0\rangle = 0$$

$$b|0\rangle = 0$$



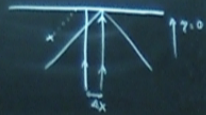
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\gamma^2}{\gamma^2} + \frac{d\vec{x}^2}{\gamma^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = -(n^2-1)dt^2 + \frac{dn^2}{1-n^2} + n^2 d\vec{x}^2$$



$$S = \frac{1}{2} \int (\partial\phi)^2 = \frac{1}{2} \int d\gamma d\vec{x} \frac{1}{\gamma^2} [(\partial_t\phi)^2 - (\partial_i\phi)^2]$$

$$= \frac{1}{2} \int d\gamma \frac{d\vec{k}}{(2\pi)^3} \frac{1}{\gamma^2} [|\dot{\phi}_k|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2k}} (1 - i k \gamma) e^{i k \gamma} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi_k^{*u} = \frac{1}{\sqrt{2k}} (1 + i k \gamma) e^{-i k \gamma} e^{-i \vec{k} \cdot \vec{x}}$$

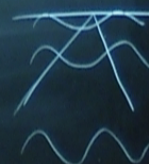
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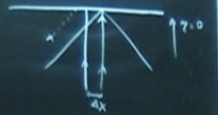
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\eta^2} + \frac{d\vec{x}^2}{\eta^2}$$

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$$= \frac{1}{2} \int d\tau \frac{d^3k}{(2\pi)^3} \frac{1}{\eta^4} [|\dot{\phi}_k|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2k}} (1 - i k \tau) e^{i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

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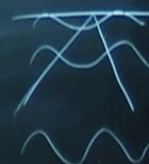
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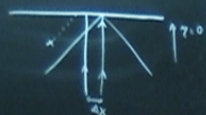
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

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$$S = \frac{1}{2} \int (\partial\phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\eta^2} [(\partial_t\phi)^2 - (\partial_i\phi)^2]$$

$$= \frac{1}{2} \int d\tau \frac{1}{(\cosh\tau)^2} \frac{1}{\eta^2} [|\partial_\tau\phi|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^{\alpha} = \frac{1}{\sqrt{2k}} (1 - i k \tau) e^{i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi_k^{\alpha\dagger} = \frac{1}{\sqrt{2k}} (1 + i k \tau) e^{-i k \tau} e^{-i \vec{k} \cdot \vec{x}}$$

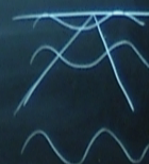
$$\phi(\tau) = a^\dagger \phi_k^{\alpha} + b \phi_k^{\alpha\dagger}$$

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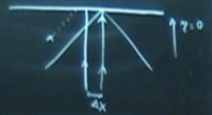
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\tau^2} + \frac{d\vec{x}^2}{\tau^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = -(n^2-1)dt^2 + \frac{dn^2}{1-n^2} + n^2 d\vec{x}^2$$



$$S = \frac{1}{2} \int (\partial\phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\tau^2} [|\partial_t \phi|^2 - |\partial_{\vec{x}} \phi|^2]$$

$$= \frac{1}{2} \int d\tau \frac{1}{(\frac{\tau}{2\pi})^2} \frac{1}{\tau^2} [|\partial_t \phi|^2 - |\partial_{\vec{x}} \phi|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2k}} (1 - i k \tau) e^{i k \tau} e^{i \vec{k} \cdot \vec{x}}$$

$$\phi_k^{*u} = \frac{1}{\sqrt{2k}} (1 + i k \tau) e^{-i k \tau} e^{-i \vec{k} \cdot \vec{x}}$$

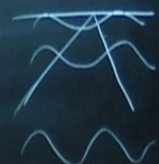
$$\phi(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

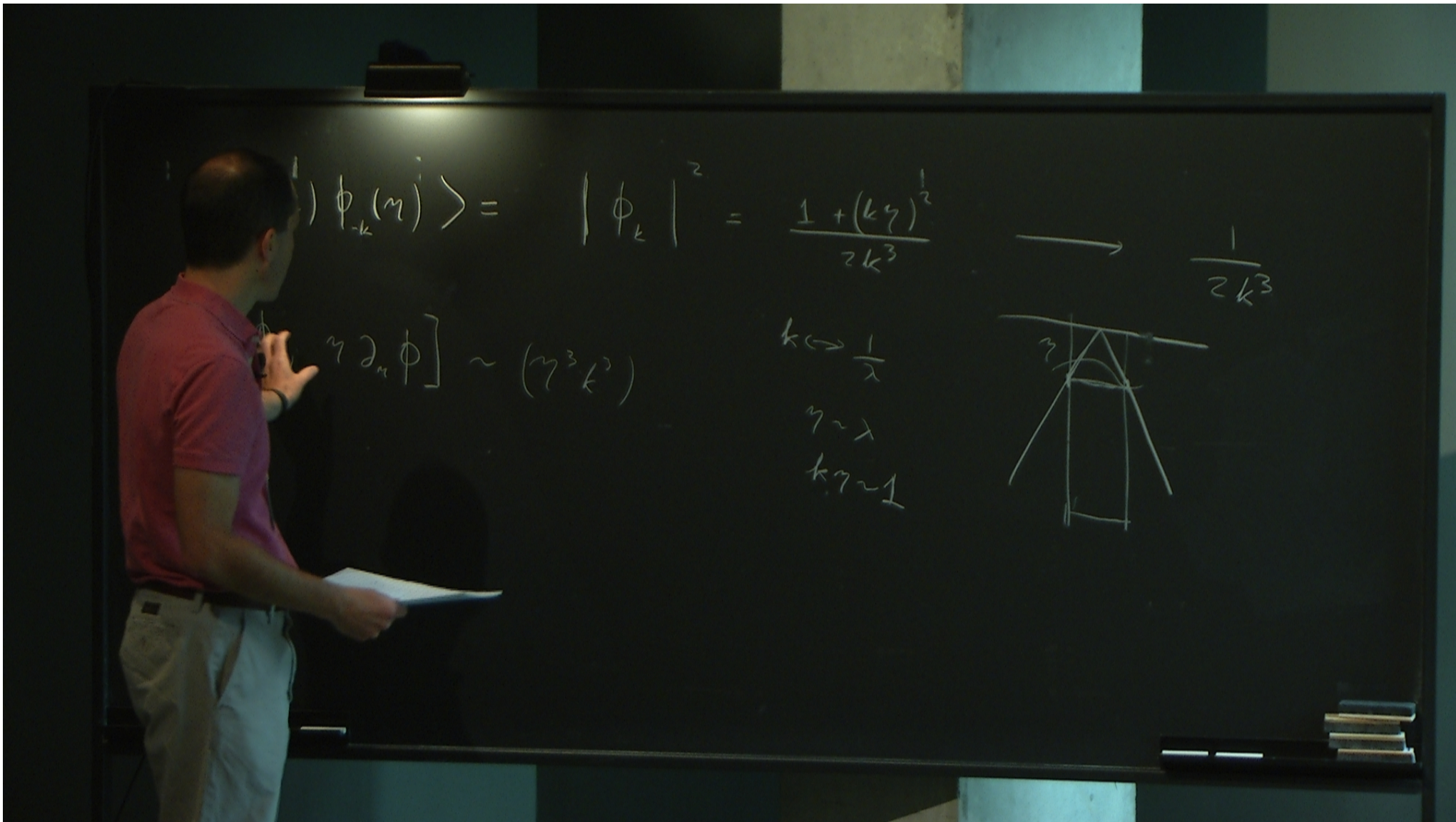
$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$a|0\rangle = 0$$

$$b|0\rangle = 0$$





$$\langle \phi_k(\eta) \phi_{-k}(\eta) \rangle = |\phi_k|^2 = \frac{1 + (k\gamma)^2}{2k^3}$$

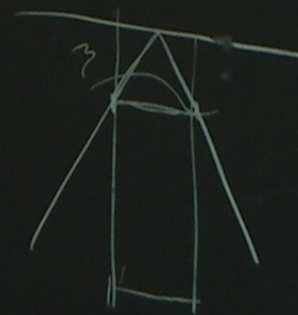
$$\longrightarrow \frac{1}{2k^3}$$

$$[\phi, \eta \partial_\eta \phi] \sim (\gamma^3 k^3)$$

$$k \leftrightarrow \frac{1}{\lambda}$$

$$\gamma \sim \lambda$$

$$k\gamma \sim 1$$



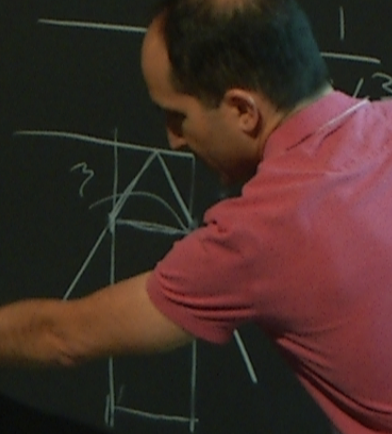
$$\langle \phi_k(\eta) \phi_{-k}(\eta) \rangle = |\phi_k|^2 = \frac{1 + (k\gamma)^2}{2k^3}$$

$$[\phi, \gamma \partial_\eta \phi] \sim (\gamma^3 k^3)$$

$$k \leftrightarrow \frac{1}{\lambda}$$

$$\gamma \sim \lambda$$

$$k\gamma \sim 1$$



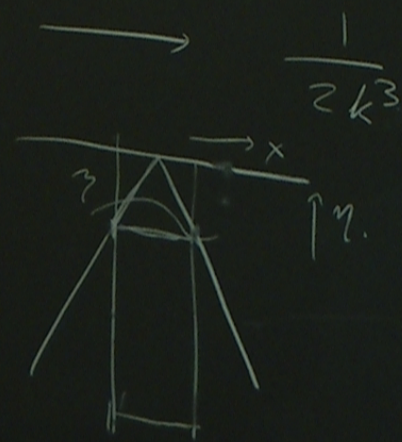
$$\langle \phi_k(\eta) \phi_{-k}(\eta) \rangle = |\phi_k|^2 = \frac{1 + (k\eta)^2}{2k^3}$$

$$[\phi, \eta \partial_\eta \phi] \sim (\eta^3 k^3)$$

$$k \leftrightarrow \frac{1}{\lambda}$$

$$\eta \sim \lambda$$

$$k\eta \sim 1$$



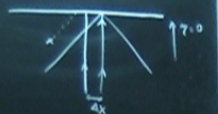
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\tau^2} + \frac{d\vec{x}^2}{\tau^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = -(n^2-1)dt^2 + \frac{dn^2}{1-n^2} + n^2 d\vec{x}^2$$



$$S = \frac{1}{2} \int (\nabla \phi)^2 = \frac{1}{2} \int d\tau d\vec{x} \frac{1}{\tau^2} [(\partial_\tau \phi)^2 - (\partial_i \phi)^2]$$

$$= \frac{1}{2} \int d\tau \frac{1}{(\frac{\tau}{2\pi})^2} \frac{1}{\tau^2} [|\partial_\tau \phi|^2 - k^2 |\phi_k|^2]$$

$$\phi_k^u = \frac{1}{\sqrt{2\pi}} (1 - ik\tau) e^{ik\tau} e^{i\vec{k} \cdot \vec{x}}$$

$$\phi_k^{*u} = \frac{1}{\sqrt{2\pi}} (1 + ik\tau) e^{-ik\tau}$$

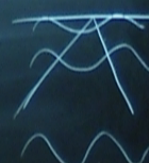
$$\phi(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

$$[\pi, \phi] = i$$

$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

$$a|0\rangle = 0$$

$$b|0\rangle = 0$$



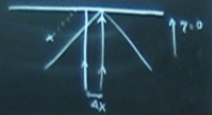
DE SITTER

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$$\phi_k^{*u} = \frac{1}{\sqrt{2k}} (1 + ik\tau) e^{ik\tau} e^{-i\vec{k}\cdot\vec{x}}$$

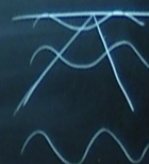
$$\phi(\tau) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

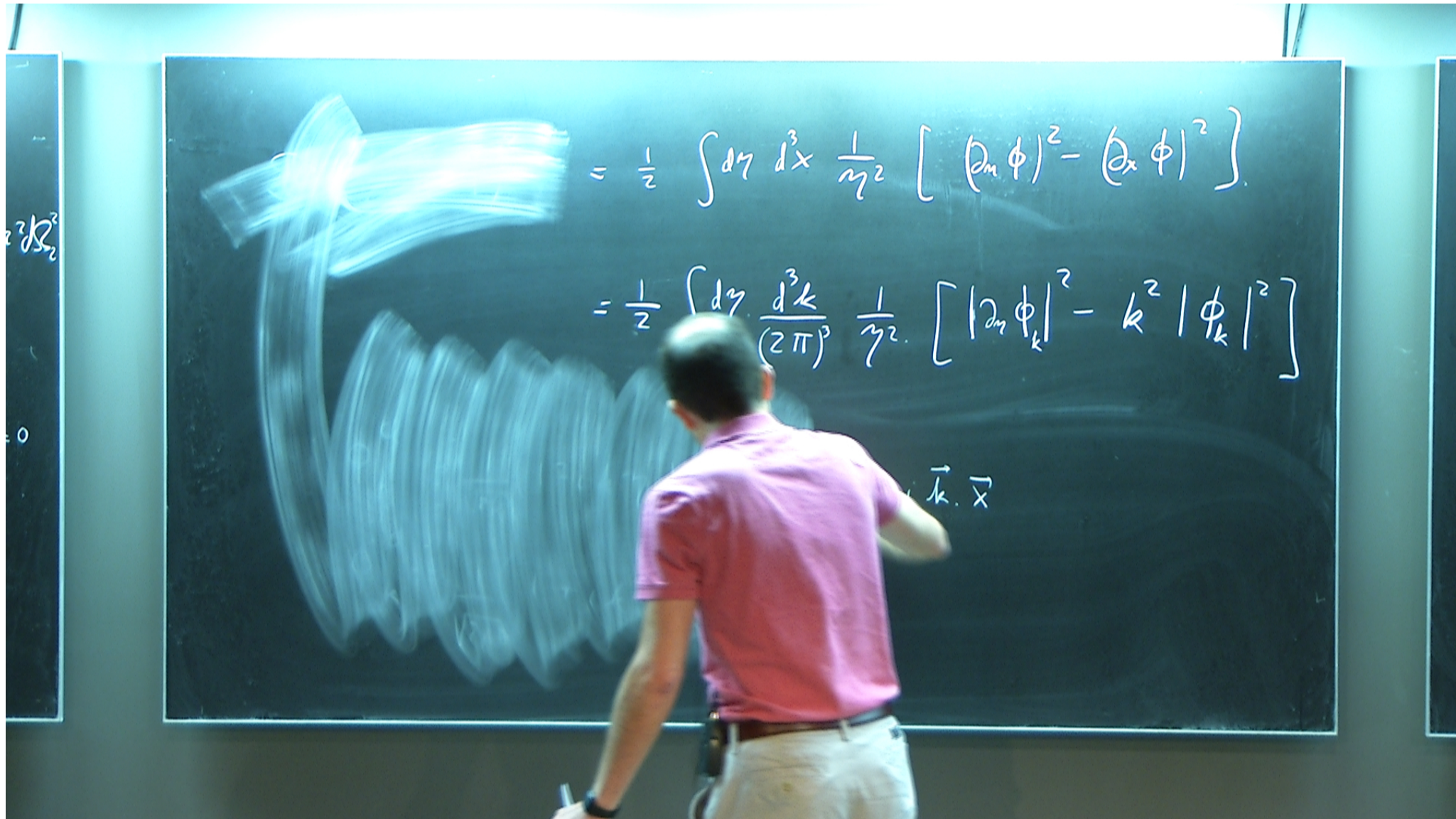
$$[\pi, \phi] = i$$

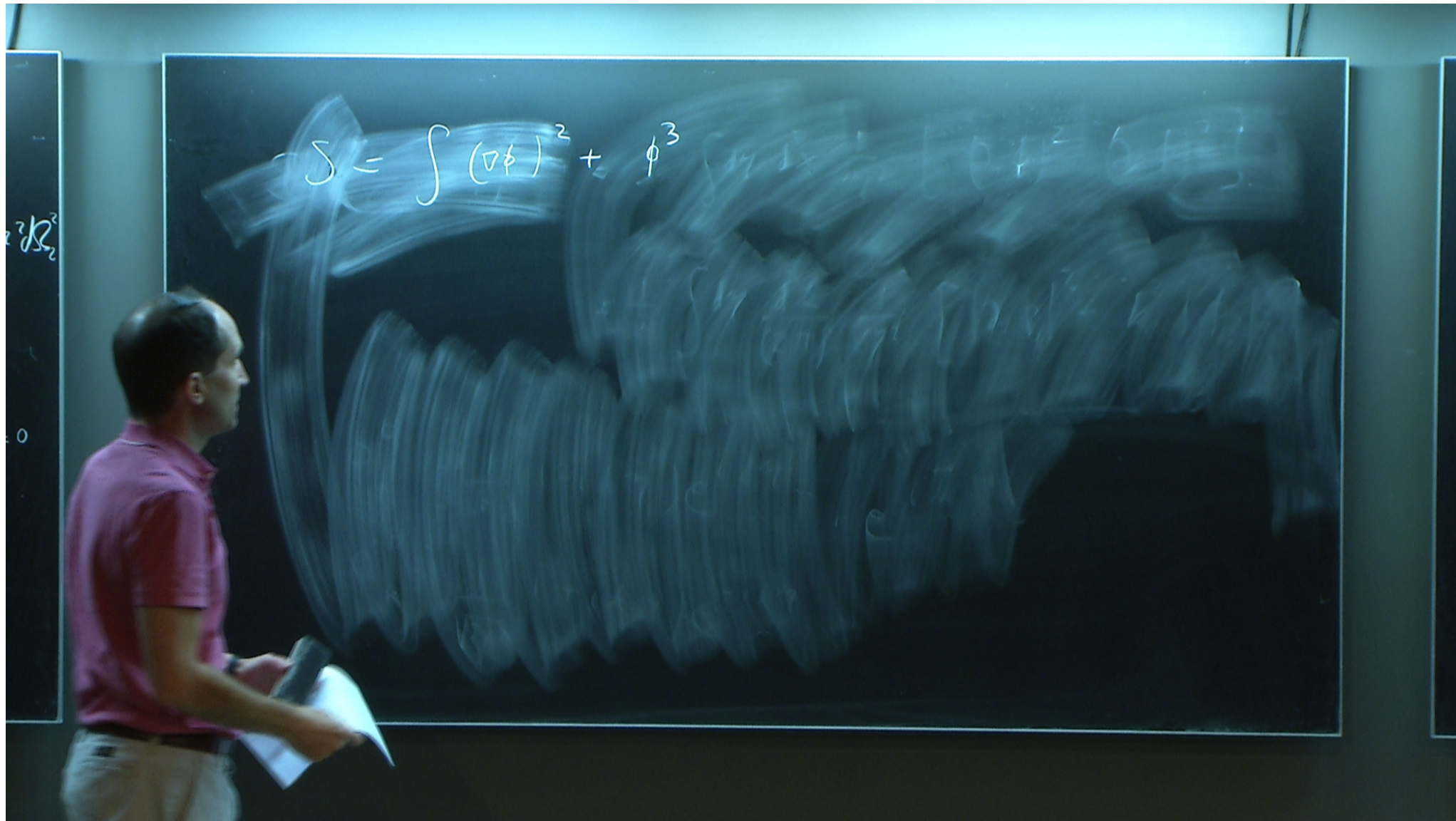
$$[a, a^\dagger] = 1 = [b, b^\dagger]$$

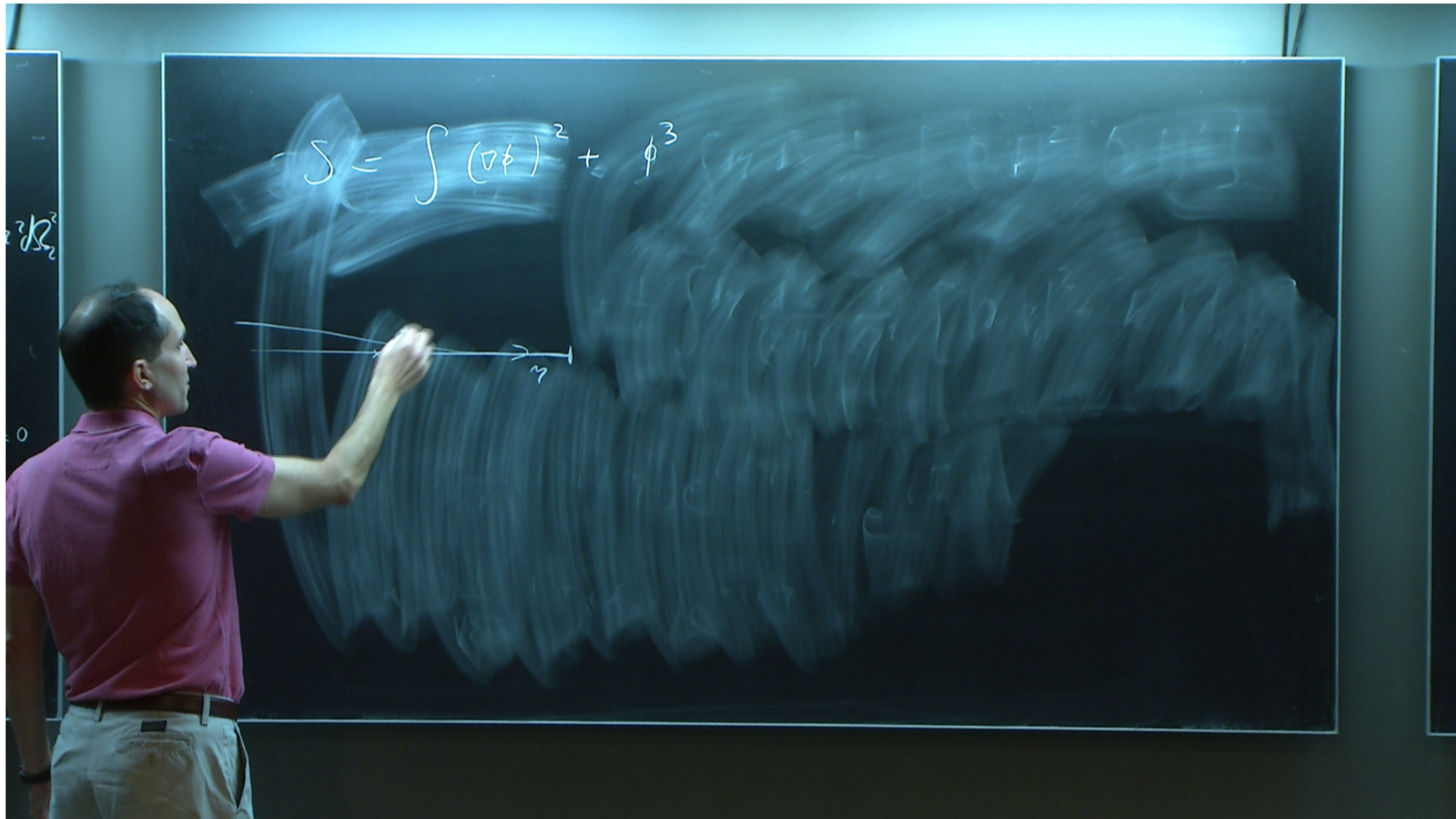
$$a|0\rangle = 0$$

$$b|0\rangle = 0$$





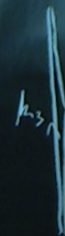
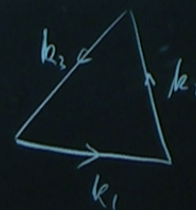




$$S = \int (\nabla \phi)^2 + \phi^3$$



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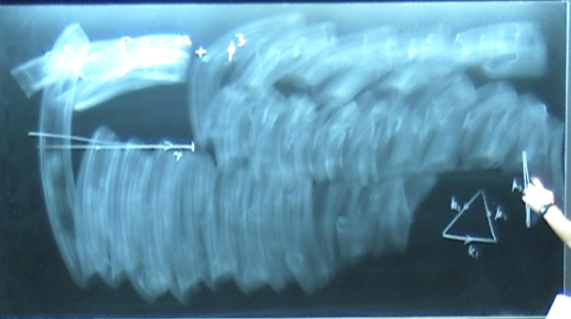
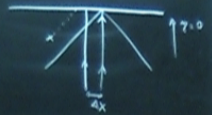
DE SITTER

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$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$

$$ds^2 = -(1-n^2)dt^2 + \frac{dn^2}{1-n^2} + dx^2$$



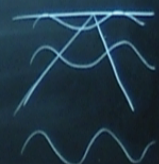
$$\phi(\gamma) = a^+ \phi_k^+ + b \phi_k^-$$

$$[\pi, \phi] = i$$

$$[a, a^+] = 1 = [b, b^+]$$

$$|0\rangle = 0$$

$$|0\rangle = 0$$



$$\langle \phi_k^\dagger \phi_{k'}^\dagger \rangle = |\phi_k|^2 = \frac{1 + (k\gamma)^2}{2k^3} \quad \phi_{k'}^\dagger \rightarrow \frac{\delta^3(k+k')}{k^3}$$

$$[\phi, \gamma \partial_\mu \phi] \sim (\gamma^3 k')$$

$$k \leftrightarrow \frac{1}{\lambda}$$

$$\gamma \sim \lambda$$

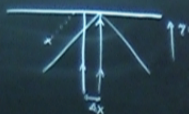
$$k\gamma \sim 1$$

DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\eta^2} + \frac{d\vec{x}^2}{\eta^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}^2$$



$$ds^2 = -(1-r^2)dt^2 + \frac{dr^2}{1-r^2} + r^2 d\Omega^2$$

RELATIONS

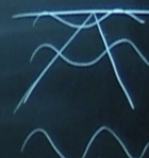
$$\phi(\gamma) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

$$[\pi, \phi] = i$$

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$$a|0\rangle = 0$$

$$b|0\rangle = 0$$



PI
PERIMETER
INSTITUTE
FOR THEORETICAL PHYSICS

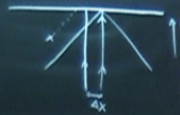
DE SITTER

$$ds^2 = -dt^2 + e^{2Ht} d\vec{x}^2$$

$$= -\frac{d\tau^2}{\eta^2} + \frac{d\vec{x}^2}{\eta^2}$$

$$ds^2 = -dz^2 + \cosh^2 z d\vec{x}_3^2$$

$$ds^2 = -(1-\frac{r^2}{4})dt^2 + \frac{dr^2}{1-\frac{r^2}{4}} + r^2 d\Omega^2$$



INTEGRATION

$$S = \int \sqrt{g} R + (\nabla \phi)^2 - V(\phi)$$

$$\dot{\phi}(t) = -\dot{\tau} + e^{\frac{1}{2}\tau} \dot{\phi}(\tau)$$

$$3\dot{\phi}^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

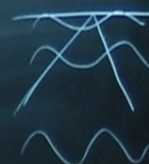
$$\phi(\gamma) = a^\dagger \phi_k^u + b \phi_k^{*u}$$

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INFLATION

$$S = \int \sqrt{g} R + (\nabla \phi)^2 - V(\phi)$$

$$\phi(t) \quad -dt^2 + e^{2\rho(t)} d\vec{x}^2$$

$$3\dot{\rho}^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$\epsilon \sim M_{pl}^2 \left(\frac{V'}{V} \right)^2 \ll 1$$

$$\eta \sim M_{pl}^2 \frac{V''}{V} \ll 1$$

INFLATION

$$S = \int \sqrt{g} R + (\nabla \phi)^2 - V(\phi)$$

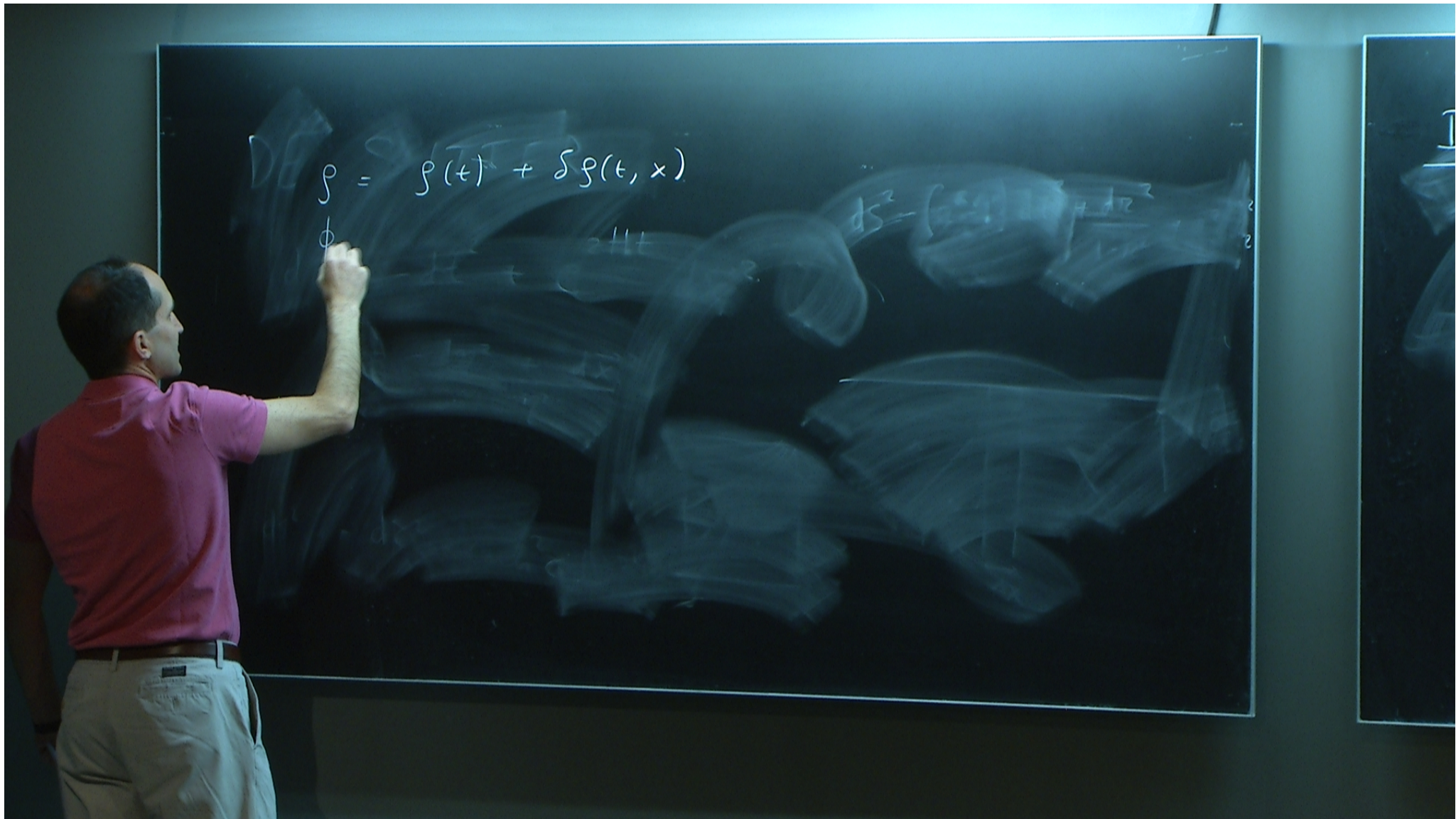
$$\phi(t) \quad -dt^2 + e^{2\rho(t)} d\vec{x}^2$$

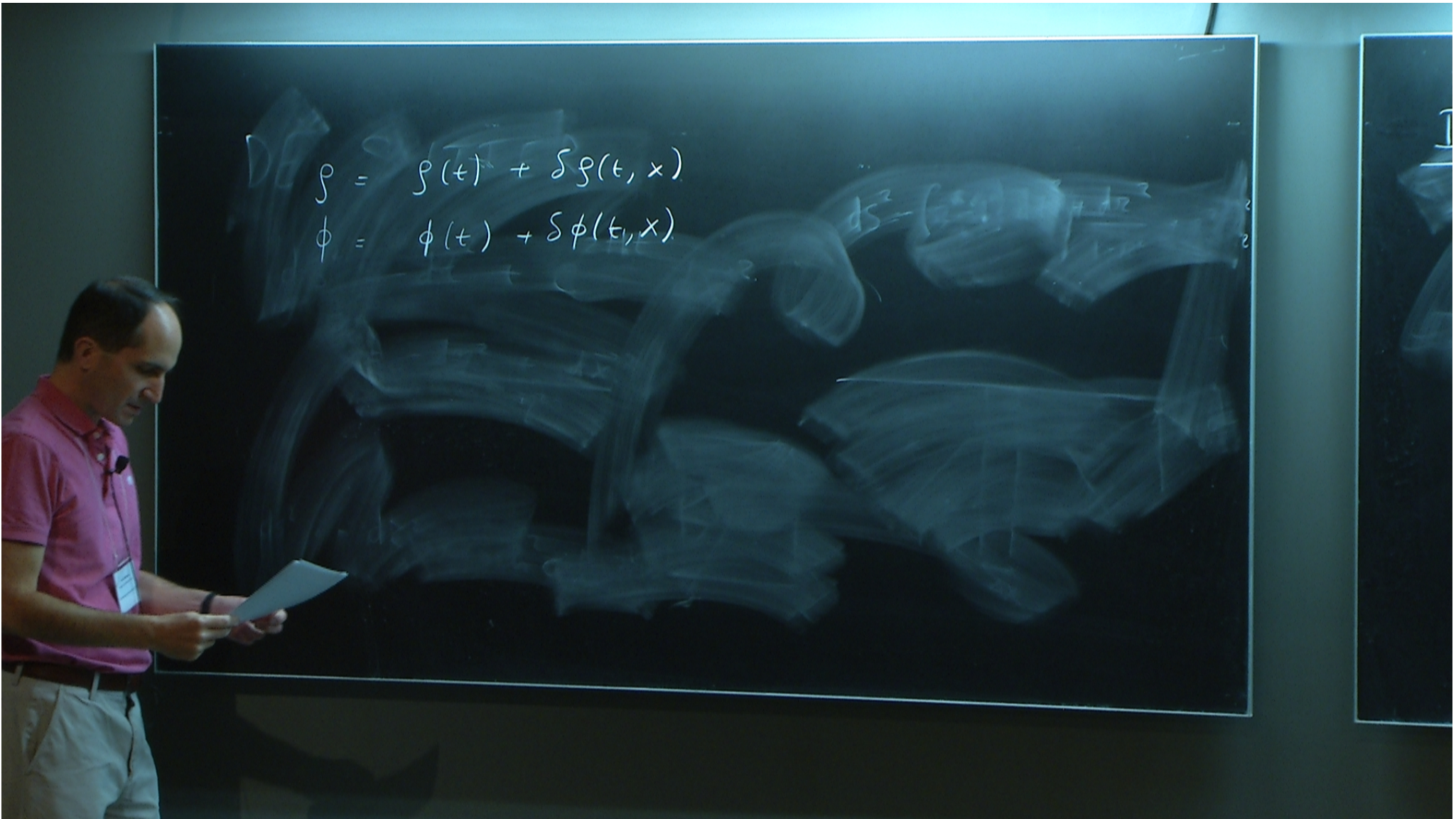
$$3\dot{\rho}^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$\epsilon \sim M_{pl}^2 \left(\frac{V'}{V} \right)^2 \ll 1$$

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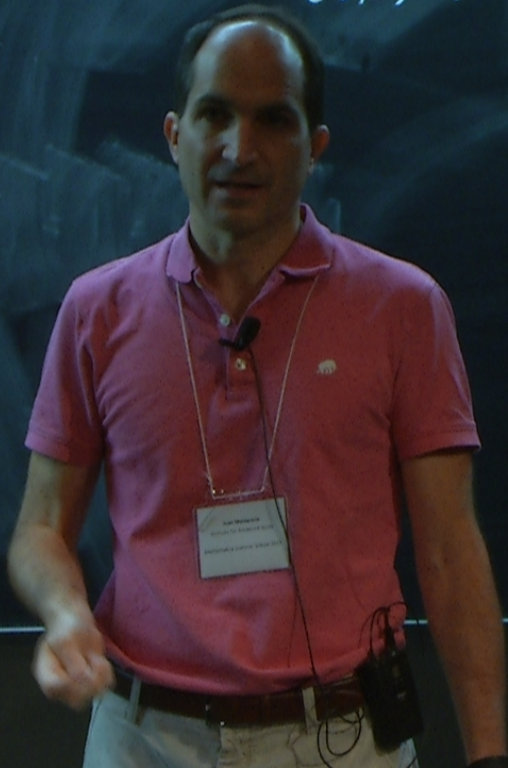
$$\rho = \rho(t) + \delta \rho(t, x)$$

$$\phi = \phi(t) + \delta \phi(t, x)$$

$$t \rightarrow t + \tau(x, t) = t'$$

10 + 1.

4 rep. + 4 CONSTR.



$$10 + 1.$$

4 rep. + 4 CONSTR.

3 dof

2 SPIN 2

1 SPIN 0

$$10 + 1.$$

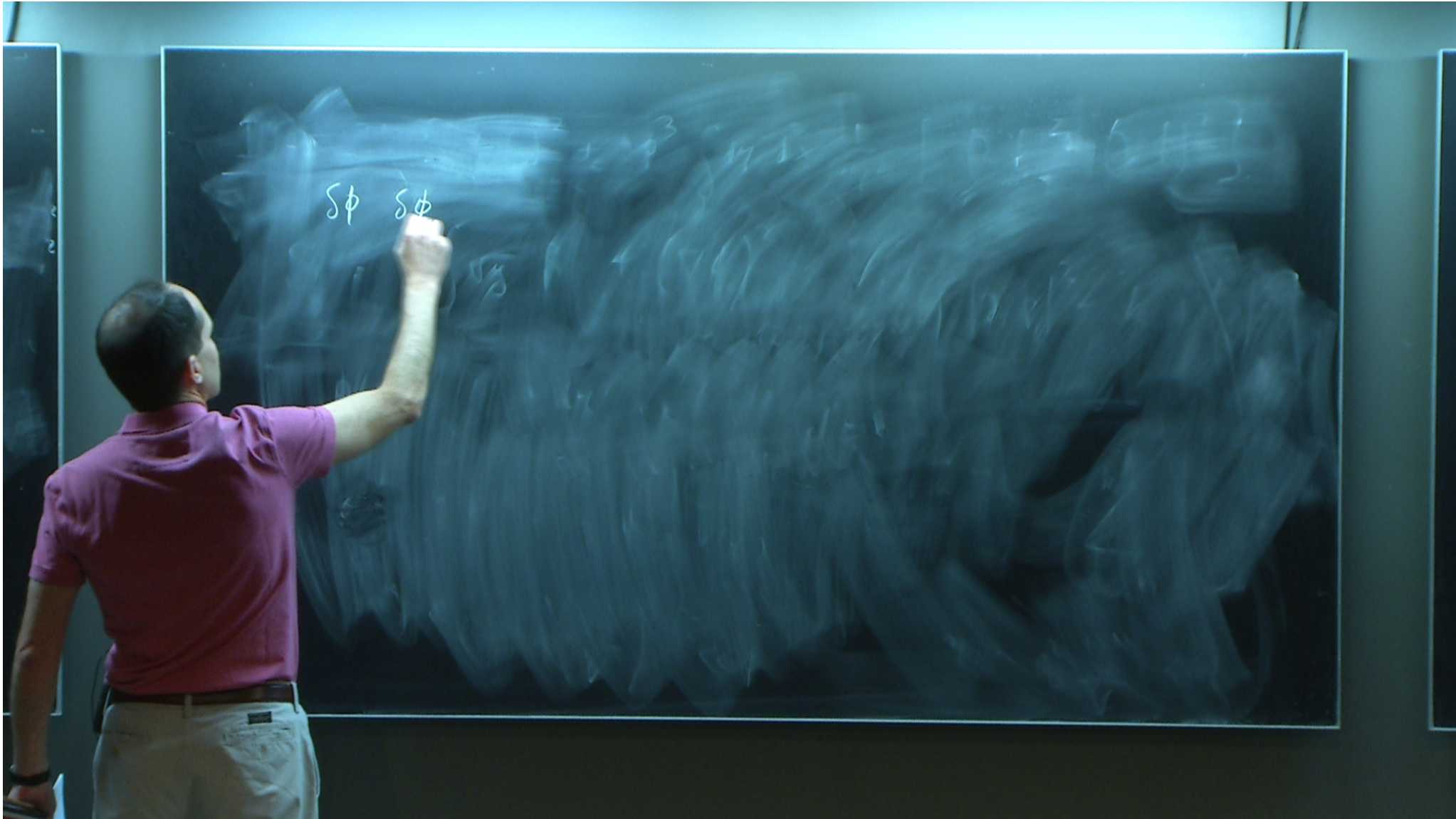
4 rep. + 4 CONSTR.

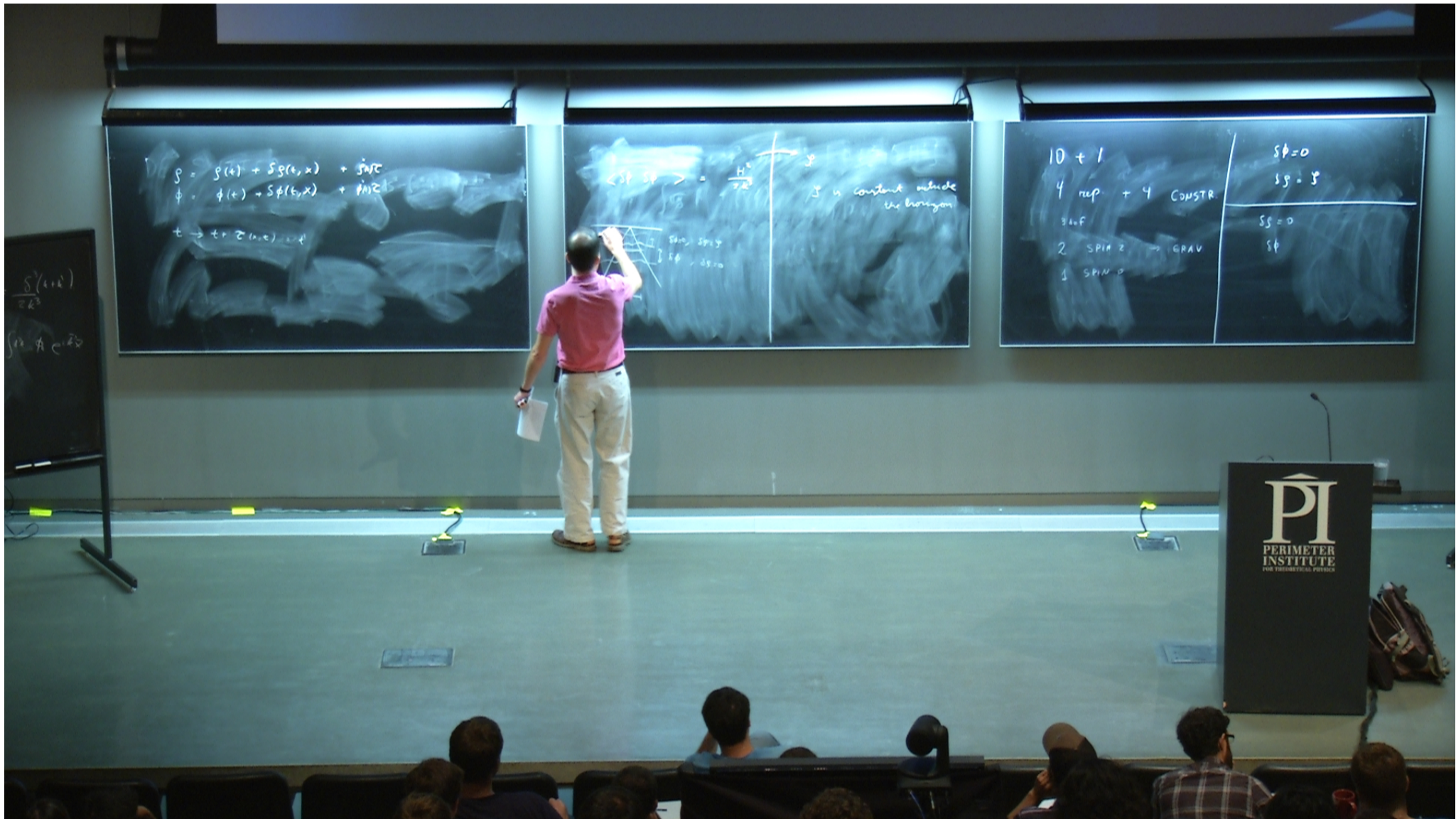
3 dof

2 SPIN 2. $\rightarrow$ GRAV.

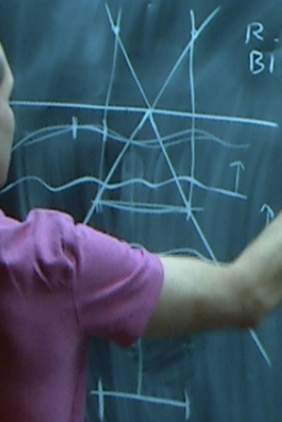
1 SPIN 0

$$\delta\phi = 0$$





$$\langle \delta\phi \delta\phi \rangle = \frac{H^2}{2k^3}$$

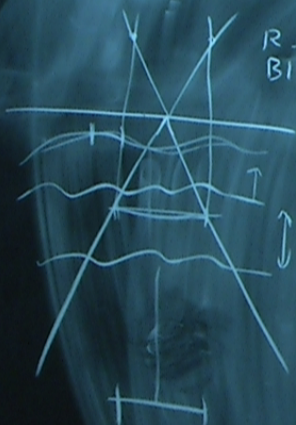


$\delta\phi = \phi$
 $\delta\phi = 0$

ϕ

ϕ is constant outside the horizon.

$$\langle \phi \phi \rangle = \frac{H^2}{2k^3}$$

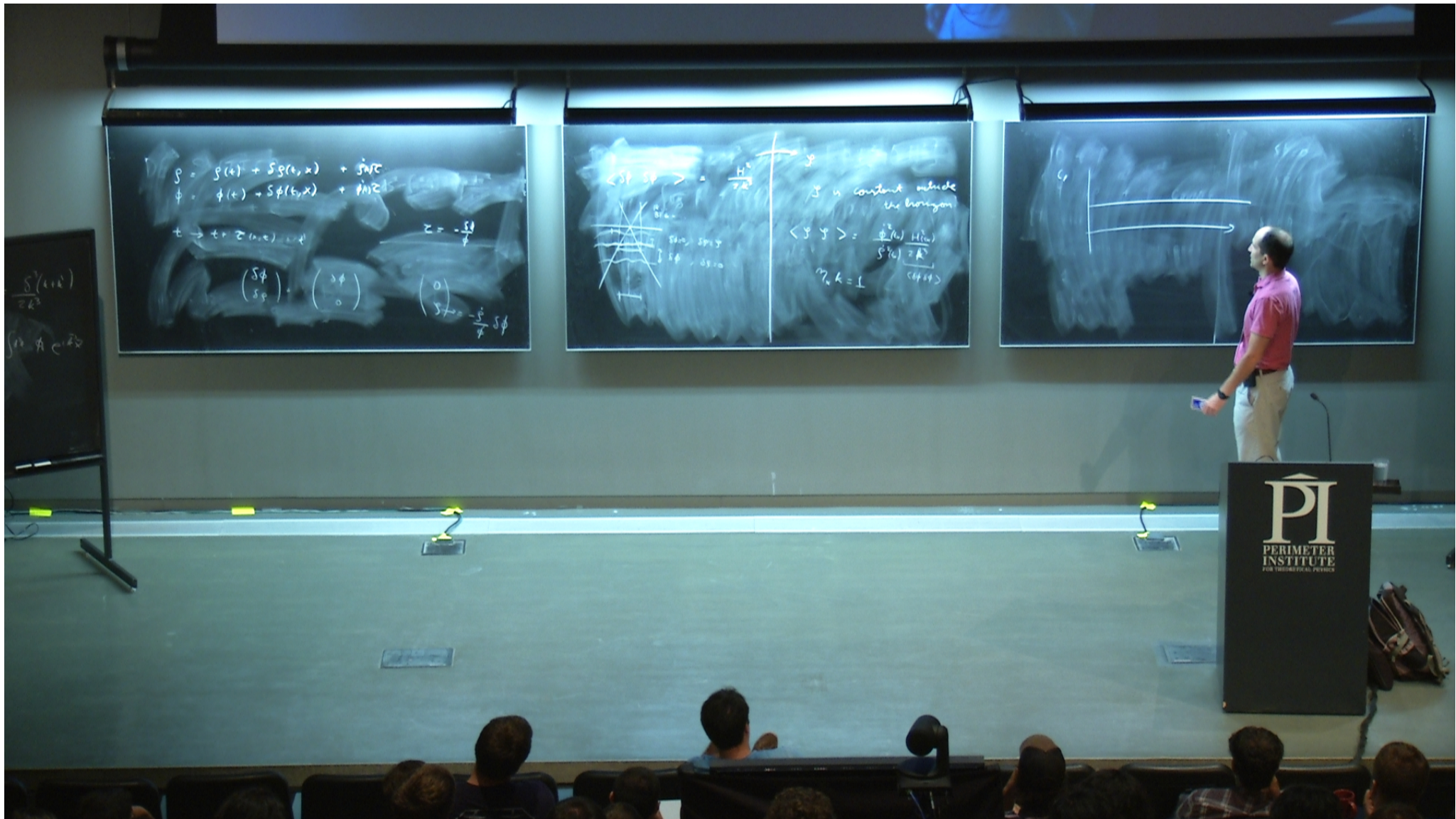


$$\delta\phi=0, \quad \delta\rho=\varphi$$

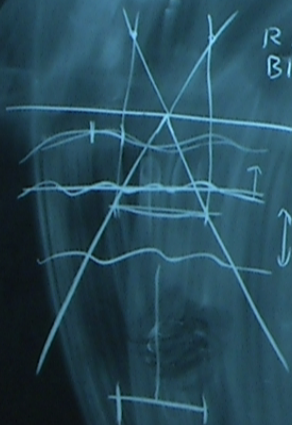
3

ϕ is constant outside the horizon.

$$\langle \mathcal{Y} = \frac{\phi^2}{\mathcal{F}^2}$$



$$\langle \delta\phi \delta\phi \rangle = \frac{H^2}{2k^3}$$



$$\delta\phi=0, \delta\rho=\phi$$

$$\delta\phi, \delta\rho=0$$

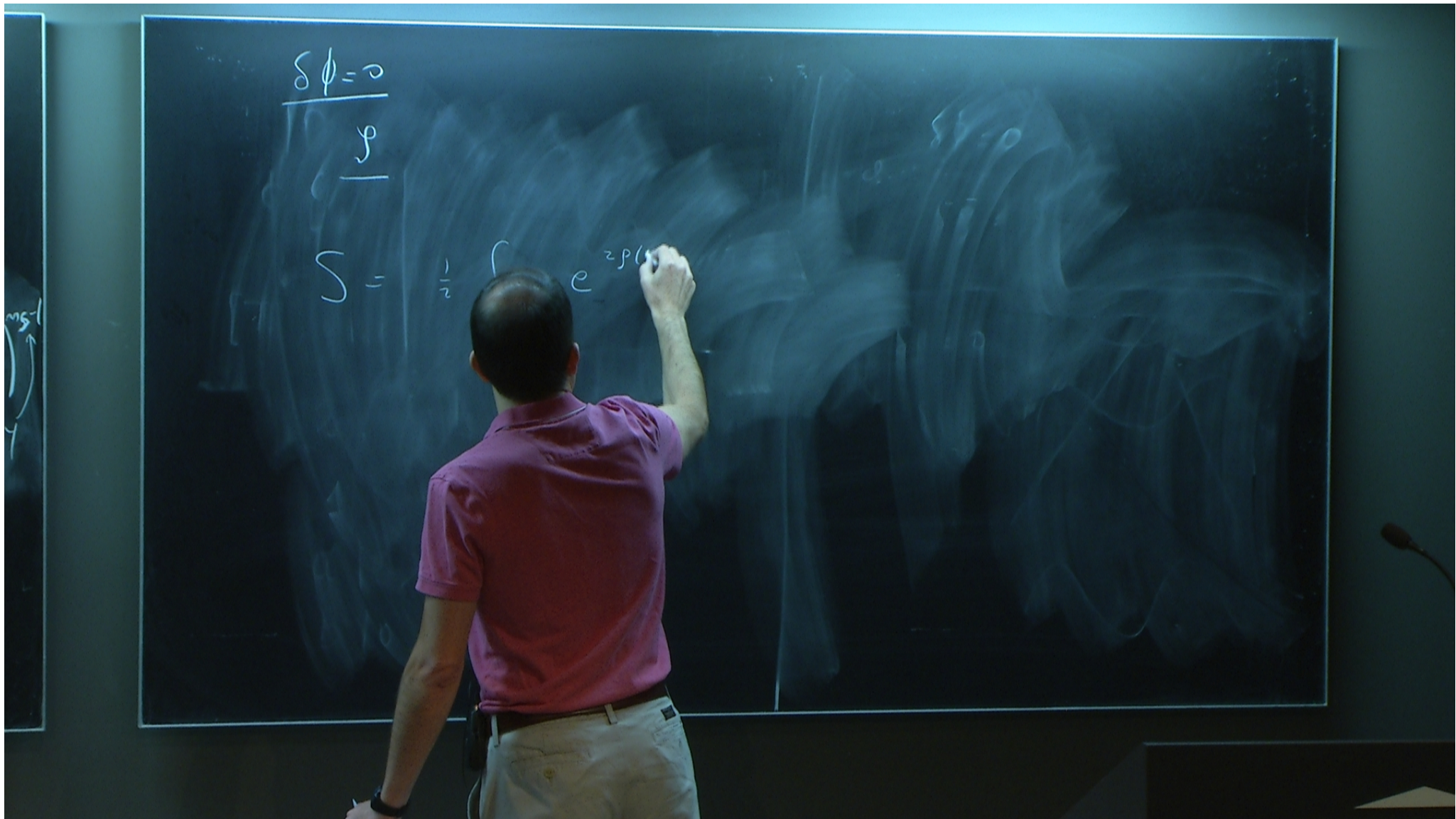
ϕ

ϕ is constant outside the horizon.

$$\langle \phi \phi \rangle = \frac{\dot{\phi}^2(t_*)}{\dot{\phi}^2(t_*)} \frac{H^2(t_*)}{2k^3} \left(\frac{k}{k_0} \right)^{n_s-1}$$

$n_s k = 1$

$\langle \delta\phi \delta\phi \rangle$



$$\frac{\delta \phi = 0}{\gamma}$$

$$S = \frac{1}{2} \int d\tau e^{2p(\tau)} \frac{\dot{\phi}^2}{\dot{\gamma}^2} \left[(\partial_t \gamma)^2 - (\vec{\partial}_x \gamma)^2 \right] + \sigma$$

$$\frac{\delta \phi = 0}{\gamma}$$

$$S = \frac{1}{2} \int d\tau e^{2\phi(\tau)} \frac{\dot{\phi}^2}{\dot{\gamma}^2} \left[(\partial_t \gamma)^2 - (\vec{\partial}_x \gamma)^2 \right] + \sigma(\gamma^3)$$