

Title: One-loop corrections in slow-roll and in more general theories of inflation

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Abstract: I will present our work on loop corrections to the power spectrum of curvature fluctuations in single-field inflationary models. We consider both standard slow-roll (where the interactions between gravitons and the scalar are included for the first time) and non-canonical Lagrangians. We show that the tensor modes cannot be neglected since, in some models, they produce one loop contributions with an amplitude that is comparable to the one coming from the scalar sector. Our study of loop corrections in non-canonical theories characterized by a small speed of sound (c_s) provides quantitative bounds on c_s , to be compared with similar constraints derived from CMB observations.

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ONE LOOP CORRECTIONS IN SLOW-ROLL AND
IN MORE GENERAL THEORIES OF INFLATION



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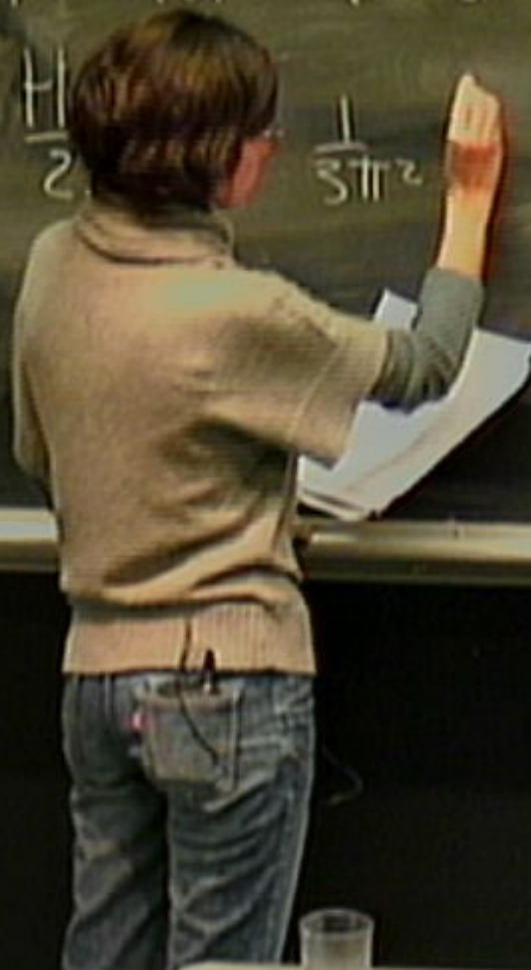
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ONE LOOP CORRECTIONS IN SLOW-ROLL AND IN MORE GENERAL THEORIES OF INFLATION



$$\frac{H^2}{2}$$

$$\frac{1}{32\pi^2}$$



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$$\frac{H^2}{2k^3} \left(1 + \frac{1}{3\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_{xx}}{H_x} \right) + \dots \right)$$

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ONE LOOP CORRECTIONS IN SLOW-ROLL AND
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$$\frac{H_x}{2k^3} \left(1 + \frac{1}{3\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{M_{UV}}{H_x} \right) + \dots \right)$$



$$S = \frac{1}{2} \int dt d^3x \sqrt{h} \left[NR^{(3)} + 2NP + N^{-1}(\vec{E}_j^2 - E^2) \right]$$

$$S = \frac{1}{2} \int dt d^3x \sqrt{h} \left[NR^{(3)} + 2NP + N^{-1}(\epsilon_{ij} \dot{\phi}^i \dot{\phi}^j) \right]$$

$$P = X - V$$

$$X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

$$S = \frac{1}{2} \int dt d^3x \sqrt{h} \left[NR^{(3)} + 2NP + N^{-1}(\epsilon_{ij}e^i - e^j) \right]$$

$$P = X - V$$

$$V = \int g^{ij} \partial_i \phi \partial_j \phi$$

flat gauge

$$ds^2 = -N^2 dt^2 + h_{ij} (dx^i + N^i dt) (dx^j + N^j dt)$$

$$\langle \Omega | \underline{\underline{0}}(\hat{H}) | \Omega \rangle = \langle 0 | \left(\int e^{iS[\phi]} \right)$$

$$\langle \Omega | \underline{\underline{\theta(H)}} | \Omega \rangle = \langle 0 | \left(T \left(e^{i \int_{t_0}^t H dt'} \right) \theta(H) T \left(e^{-i \int_{t_0}^t H dt'} \right) \right) | 0 \rangle$$

$$\langle \Omega | \underline{\underline{\theta(H)}} | \Omega \rangle = \langle 0 | \left(\overline{T} \left(e^{i \int_0^t H dt'} \right) \theta(H) \left(T \left(e^{-i \int_0^t H dt'} \right) | 0 \rangle \right) \right)$$

CAUTION

$$\langle \Omega | \underline{\underline{\theta(t)H}} | \Omega \rangle = \langle 0 | \left(T \left(e^{i \int_0^t H(t') dt'} \right) \theta(t) T \left(e^{-i \int_0^t H(t') dt'} \right) \right) | 0 \rangle$$

$$H^{(3)} = \int \frac{a^2}{2} \delta_y \delta$$

$$S = \frac{1}{2} \int dt d^3x \sqrt{h} \left[NR^{(3)} + 2NP + N^{-1}(\mathcal{E}_j \mathcal{E}^j - \mathcal{E}^2) \right]$$

$$P = X - V$$

$$X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

flat gauge

$$ds^2 = -N^2 dt^2 + h_{ij} (dx^i + N^i dt) (dx^j + N^j dt)$$

$$a^2(t) (e^{\delta})_{ij}$$

$$\langle \Omega | \underline{\underline{O}}(t) | \Omega \rangle = \langle 0 | \left(T \left(e^{i \int_{t_0}^t \mathcal{H}_I dt'} \right) O(t) T \left(e^{-i \int_{-t_0}^t \mathcal{H}_I dt'} \right) | 0 \right) \rangle$$

$$H_I^{(3)} = \int \frac{d^3q}{2} \delta_{ij} a_i \delta\phi a_j \delta\phi \xrightarrow{4^0} \text{Diagram 1}$$

$$H_I^{(5)} = \int \frac{d^3q}{2} \delta_{ik} \delta_{jl} a_i \delta\phi a_j \delta\phi \xrightarrow{\int \frac{d^3q}{q^3} \rightarrow}$$



$\langle \Omega | \underline{\underline{O}}(t) | \Omega \rangle = \langle 0 | \left(T \left(e^{\int_0^t H(t') dt'} \right) O(t) T \left(e^{-\int_0^t H(t') dt'} \right) | 0 \right) \rangle$

$H_2^{(S)} = \int \frac{d^3x}{2} \gamma_{ij} \partial_i \phi \partial_j \phi$

$H_5^{(S)} = \int \frac{d^3x}{2} \gamma_{ij} \partial_i \phi \partial_j \phi$

$\int \frac{d^3q}{q^3} \rightarrow \int \frac{dq}{q}$

$\sim \ln\left(\frac{UV}{\mu R}\right)$



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$$\langle \Omega | \mathcal{O}(t) | \Omega \rangle = \langle 0 | \left(\overleftarrow{T} \left(e^{i \int_{t_0}^t \mathcal{H}(t') dt'} \right) \right) \mathcal{O}(t) \left(T \left(e^{-i \int_{t_0}^t \mathcal{H}(t') dt'} \right) \right) | 0 \rangle$$

$$H_{\text{int}}^{(3)} = \int \frac{g^2}{2} \delta_{ij} \psi_i \psi_j \phi$$

$$H_{\text{int}}^{(4)} = \int \frac{g^2}{2} \delta_{ik} \delta_{jl} \psi_i \psi_j \psi_k \psi_l$$

$$\int \frac{d^3q}{(2\pi)^3 q^3} \left[\int \frac{dq}{q} \right]_{k=0}^k$$

$$\int \frac{d^3q}{q^3} \rightarrow \int \frac{dq}{q} \sim \ln\left(\frac{\Lambda}{\mu}\right)$$



$$S = \frac{1}{2} \int dt d^3x \sqrt{h} \left[N R^{(3)} + 2NP + N^{-1} (\vec{e}_j e^j - E^2) \right]$$

$$P = X - V$$

$$X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

flat gauge


$$ds^2 = -N^2 dt^2 + h_{ij} (dx^i + N^i dt) (dx^j + N^j dt)$$

$$a^2(t) (e^{\delta})_{ij}$$

$$\Psi = 0$$

$$\frac{H_0^2}{2k^3} \left(1 - \frac{1}{2f^2} \left(\frac{H_0}{H_4} \right)^2 \ln \left(\frac{f_{100}}{f_{10}} \right) + \dots \right)$$





$$\frac{H_v^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_v}{H_v} \right)^2 \ln \left(\frac{\mu_{UV}}{\mu_{IR}} \right) + \dots \right)$$



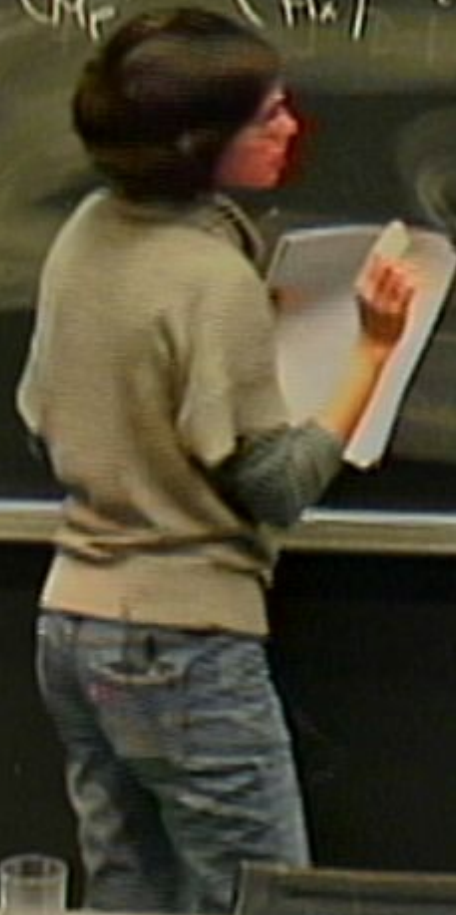
$$\frac{H_v^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_v}{H_v} \right)^2 \ln \dots \right)$$

$$\text{---} \quad \frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{10V}}{\mu_{1R}} \right) + \dots \right)$$

$$\text{---} \quad \frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{10V}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_x}{\mu_{1R}} \right) \right)$$


$$\text{---} \quad \frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{\mu_{102}} \right) + \dots \right)$$

$$\text{---} \quad \frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_x}{\mu_{102}} \right) \right)$$




$$\text{---} \text{---} \frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{10V}}{\mu_{12}} \right) + \dots \right)$$

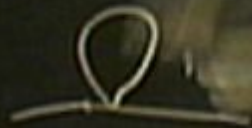
$$\text{---} \text{---} \frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{10}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_x}{\mu_{10}} \right) \right)$$




$$\frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{\mu_{102}} \right) + \dots \right)$$




$$\frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_x}{\mu_{102}} \right) \right)$$

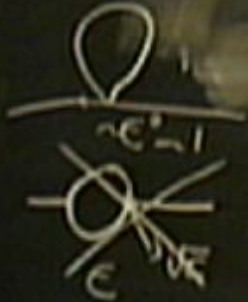





$$\frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{\mu_{102}} \right) + \dots \right)$$




$$\frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{\mu_{100}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{H_p} \right)^2 \ln \left(\frac{H_x}{\mu_{102}} \right) \right)$$






$$\frac{H_x^2}{2k^3} \left(1 - \frac{1}{2\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{\mu_{UV}}{\mu_{IR}} \right) + \dots \right)$$




$$\frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{\mu_{UV}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{H_x}{\mu_{IR}} \right) \right)$$

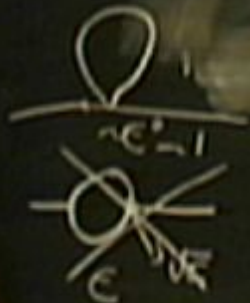




$$\frac{H_x^2}{2k^3} \left[1 - \frac{1}{2\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{\mu_{UV}}{\mu_{IR}} \right) + \dots \right]$$



$$\frac{H_x^2}{2k^3} \left(1 + \frac{1}{6\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{\mu_{UV}}{H_x} \right) + \frac{1}{2\pi^2} \left(\frac{H_x}{M_p} \right)^2 \ln \left(\frac{H_x}{\mu_{IR}} \right) \right)$$



$$\langle \delta\phi_{k_1} \delta\phi_{k_2} \rangle$$

$$\langle \delta\phi_{k_1} \delta\phi_{k_2} \rangle$$

$$\int (\vec{r}, t) = SN$$



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$$\int (\vec{x}, \vec{e}) = N_{\phi} \delta\phi +$$

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$$\int (\vec{x}, t) = N_\phi \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$



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$$\int (\mathcal{L}, \epsilon) = N_{\phi} \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\langle \sum_{k_1} \sum_{k_2} \dots \rangle$$

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$$\int (\vec{x}, t) = N_\phi \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\langle S_{\vec{k}_1}, S_{\vec{k}_2} \rangle \sim N_\phi^2 N_{\phi\phi} \int \frac{d^3q}{(2\pi)^3} B(k_1, q, |\vec{k}_2 - \vec{q}|) + \frac{1}{2} (N_{\phi\phi})^2 \int \frac{d^3q}{(2\pi)^3} P(q) P(|\vec{k}_2 - \vec{q}|)$$



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$$\int (\vec{x}, t) = N_\phi \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\langle \dots \rangle \sim N_\phi^{(1)} N_{\phi\phi} \int \frac{d^3q}{(2\pi)^3} B(k_i, q, |\vec{k}_i - \vec{q}|) + \frac{1}{2} (N_{\phi\phi})^2 \int \frac{d^3q}{(2\pi)^3} P(q) P(|\vec{k}_i - \vec{q}|) + \dots$$



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$$\int (\vec{x}, t) = N_{\phi} \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\langle \int_{\vec{x}_i} \dots \rangle = N_{\phi}^{(i)} N_{\phi\phi} \int \frac{d^3q}{(2\pi)^3} \mathcal{B}(k_i, q, |\vec{k}_i - \vec{q}|) \\ + \frac{1}{2} (N_{\phi\phi})^2 \int \frac{d^3q}{(2\pi)^3} P(q) P(|\vec{k}_i - \vec{q}|) \\ + N^{(i)} N^{(j)} P(k) \int \frac{d^3q}{(2\pi)^3} P(q)$$

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$$\int (\vec{x}, t) = N_\phi \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\langle S_{\vec{k}_1} S_{\vec{k}_2} \rangle \sim N_\phi^{(1)} N_{\phi\phi} \int \frac{d^3q}{(2\pi)^3} B(\vec{k}_1, \vec{q}, |\vec{k}_2 - \vec{q}|) + \frac{1}{2} (N_{\phi\phi})^2 \int \frac{d^3q}{(2\pi)^3} P(\vec{q}) P(|\vec{k}_2 - \vec{q}|) + N_\phi^{(1)} N_\phi^{(1)} P(k) \int \frac{d^3q}{(2\pi)^3} P(\vec{q})$$



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$$\int \frac{d^3 q}{q^3 |\mathbf{R} - \mathbf{q}|^3} \quad \langle \sum_{i_1} \sum_{i_2} \rangle \sim \left(N_{\phi}^{(1)} N_{\phi}^{(2)} \right) \int \frac{d^3 q}{(2\pi)^3} \mathcal{B}(k_i, q, |\mathbf{R} - \mathbf{q}|)$$

$$+ \frac{1}{2} (N_{\phi\phi}^{(1)})^2 \int \frac{d^3 q}{(2\pi)^3} P(q) P(|\mathbf{R} - \mathbf{q}|)$$

$$+ N_{\phi\phi}^{(1)} N_{\phi\phi}^{(2)} P(k) \int \frac{d^3 q}{(2\pi)^3} P(q)$$

$N_{\phi} \sim \frac{1}{\sqrt{c}}$
 $N_{\phi\phi} \sim c^0$
 $N_{\phi\phi\phi} \sim \sqrt{c}$



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$$\int \frac{d^3 q}{q^3 |\mathbf{R} - \mathbf{q}|^3} \quad \int (\mathbf{x}, t) = N_\phi \delta\phi + \frac{1}{2} N_{\phi\phi} \delta\phi^2 + \dots$$

$$\int \frac{d^3 q}{q^3} \quad \langle S_{\mathbf{r}_1} S_{\mathbf{r}_2} \rangle \sim \underbrace{N_\phi N_{\phi\phi}}_{N_\phi \sim \frac{1}{\sqrt{c}} \quad N_{\phi\phi} \sim c^0 \quad N_{\phi\phi\phi} \sim \sqrt{c}} \int \frac{d^3 q}{(2\pi)^3} \mathcal{B}(\mathbf{k}_1, \mathbf{q}, |\mathbf{R} - \mathbf{q}|)$$
$$+ \frac{1}{2} (N_{\phi\phi})^2 \int \frac{d^3 q}{(2\pi)^3} P(\mathbf{q}) P(|\mathbf{R} - \mathbf{q}|)$$
$$+ N^{(4)} N^{(3)} P(t) \int \frac{d^3 q}{(2\pi)^3} P(\mathbf{q})$$

$$P(X, \phi)$$

$$P = X - V$$

(12)

$$P_x, P_{xx}, P_{x\phi}$$

$$C_s =$$

$$P(X, \phi)$$

$$P = X - V$$

$$\textcircled{D} P_x, P_{xx}, P_{x\phi}$$

$$z = \frac{P_x}{P_x + 2XP_{xx}}$$

$$P(X, \phi)$$

$$P = X - V$$

(DRI)

P_x, P_{xx}, P_{xf}

$\frac{1}{C_S}$

$$C_S^2 = \frac{P_x}{P_x + 2XP_u}$$

$$P(X, \phi)$$

$$P = X - V$$

(DB)

$$P_x, P_{xx}, P_{xf}$$

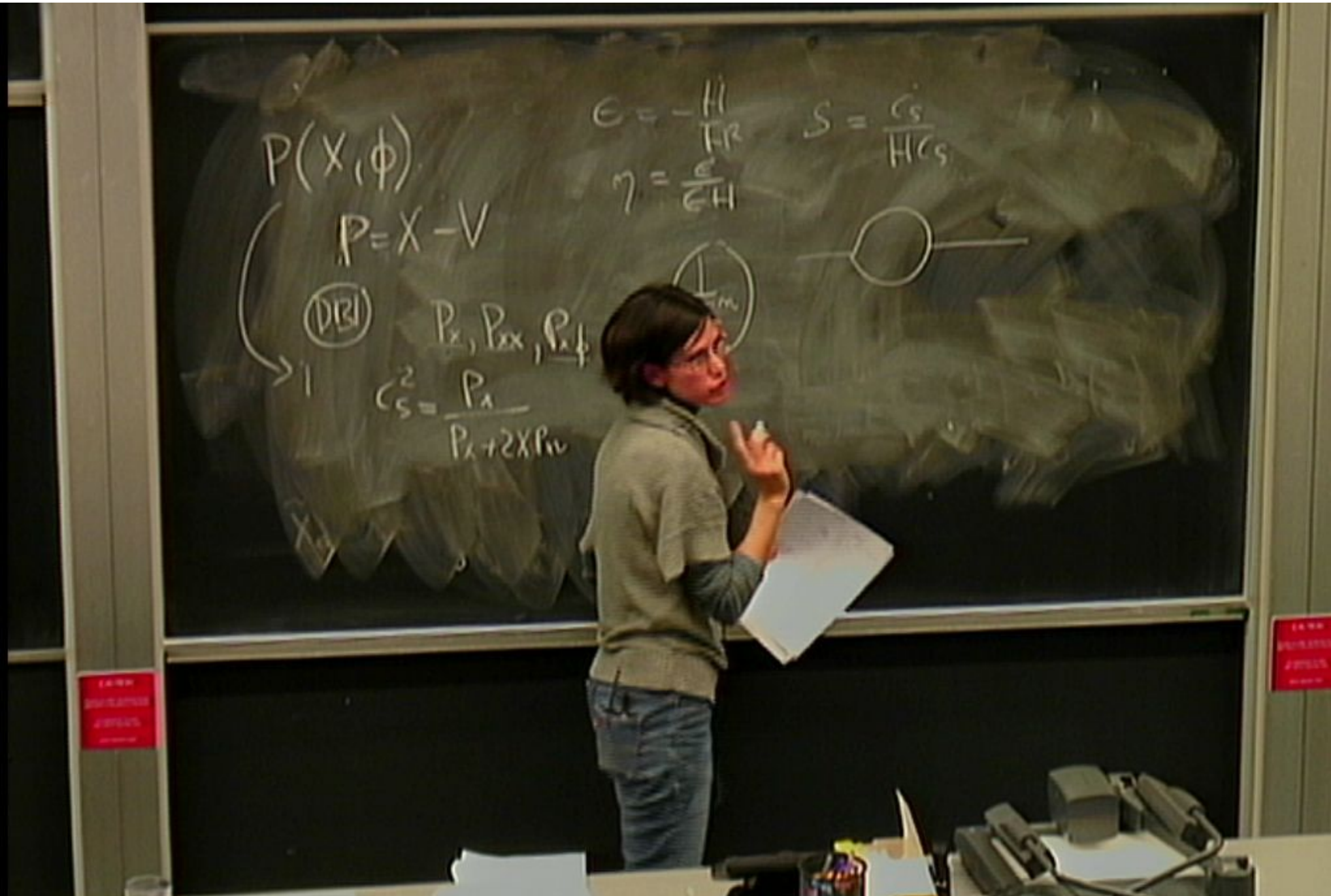
$$C_s^2 = \frac{P_x}{P_x + 2XP_{xx}}$$

$$\epsilon = -\frac{H}{FR}$$

$$\eta = \frac{\epsilon}{\epsilon H}$$

$$S = \frac{C_s}{HC_s}$$

$$\left(\frac{1}{C_s} \right)$$



$$P(X, \phi)$$

$$P = X - V$$

(DRI)

$$P_x, P_{xx}, P_{xf}$$

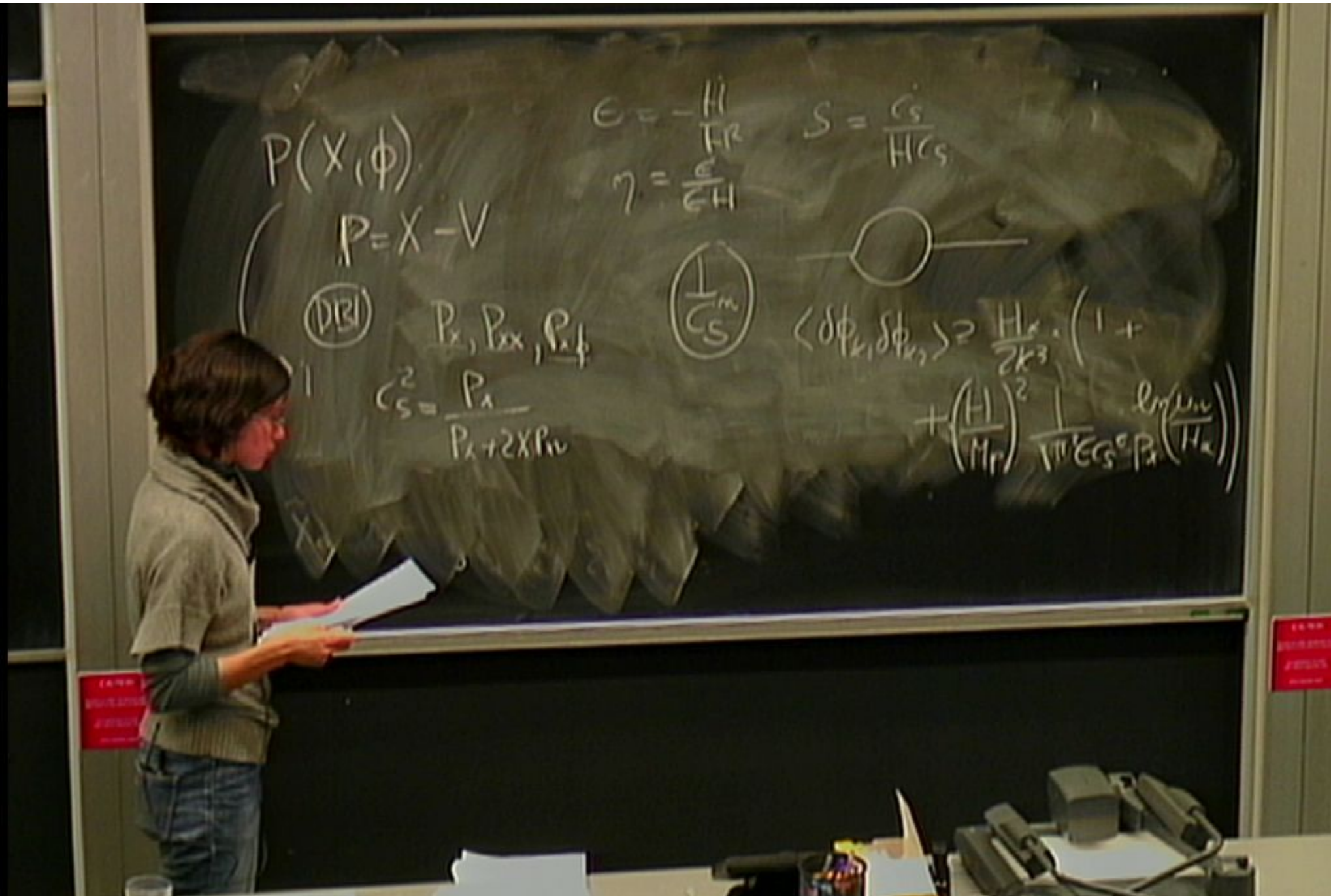
$$c_s^2 = \frac{P_a}{P_x + 2X P_u}$$

$$E = -\frac{H}{FR}$$
$$\eta = \frac{\epsilon}{\epsilon H}$$

$$S = \frac{C_s}{H C_s}$$



$P(X, \phi)$
 $P = X - V$
 $\epsilon = -\frac{H}{FR}$ $S = \frac{C_S}{HC_S}$
 $\eta = \frac{\epsilon}{\epsilon H}$
 $\langle \delta\phi_{k_1}, \delta\phi_{k_2} \rangle = \frac{H_k}{2k^3} \left(1 + \left(\frac{H}{M_r} \right)^2 \frac{1}{\sqrt{HC_S}^2 P_2} \ln \left(\frac{M_w}{H_k} \right) \right)$



$$P(X, \phi)$$

$$P = X - V$$

(DIB)

P_x, P_{xx}, P_{xf}

$$C_s^2 = \frac{P_x}{P_x + 2XP_{xx}}$$

$$E = -\frac{H}{FR}$$

$$\eta = \frac{\epsilon}{CH}$$

$$S = \frac{C_s}{HC_s}$$

$\left(\frac{1}{C_s}\right)$



$$\langle \delta\phi_{k1}, \delta\phi_{k2} \rangle = \frac{H_x}{2k^3} \left(1 + \left(\frac{H}{M_r}\right)^2 \frac{1}{\sqrt{HC_s}^2 P_x} \ln\left(\frac{U_w}{H_x}\right) \right)$$

$P(X, \phi)$
 $P = X - V$
 $\epsilon = -\frac{H}{FR}$
 $\eta = \frac{\epsilon}{EH}$
 $S = \frac{C_s}{HC_s}$
 $C_s \geq 0.9 \times 10^{-2}$
 $\langle S_{k1}, S_{k2} \rangle$
 $\left(\frac{D_{BI}}{C_s} \right)$
 P_x, P_{xx}, P_{xf}
 $C_s^2 = \frac{P_a}{P_x + 2XP_v}$
 $\delta \phi_{k2} \geq \frac{H_x}{2k^3} \cdot \left(1 + \left(\frac{H}{M_r} \right)^2 \frac{1}{\sqrt{HC_s}^6 P_x} \ln \left(\frac{M_v}{H_x} \right) \right)$