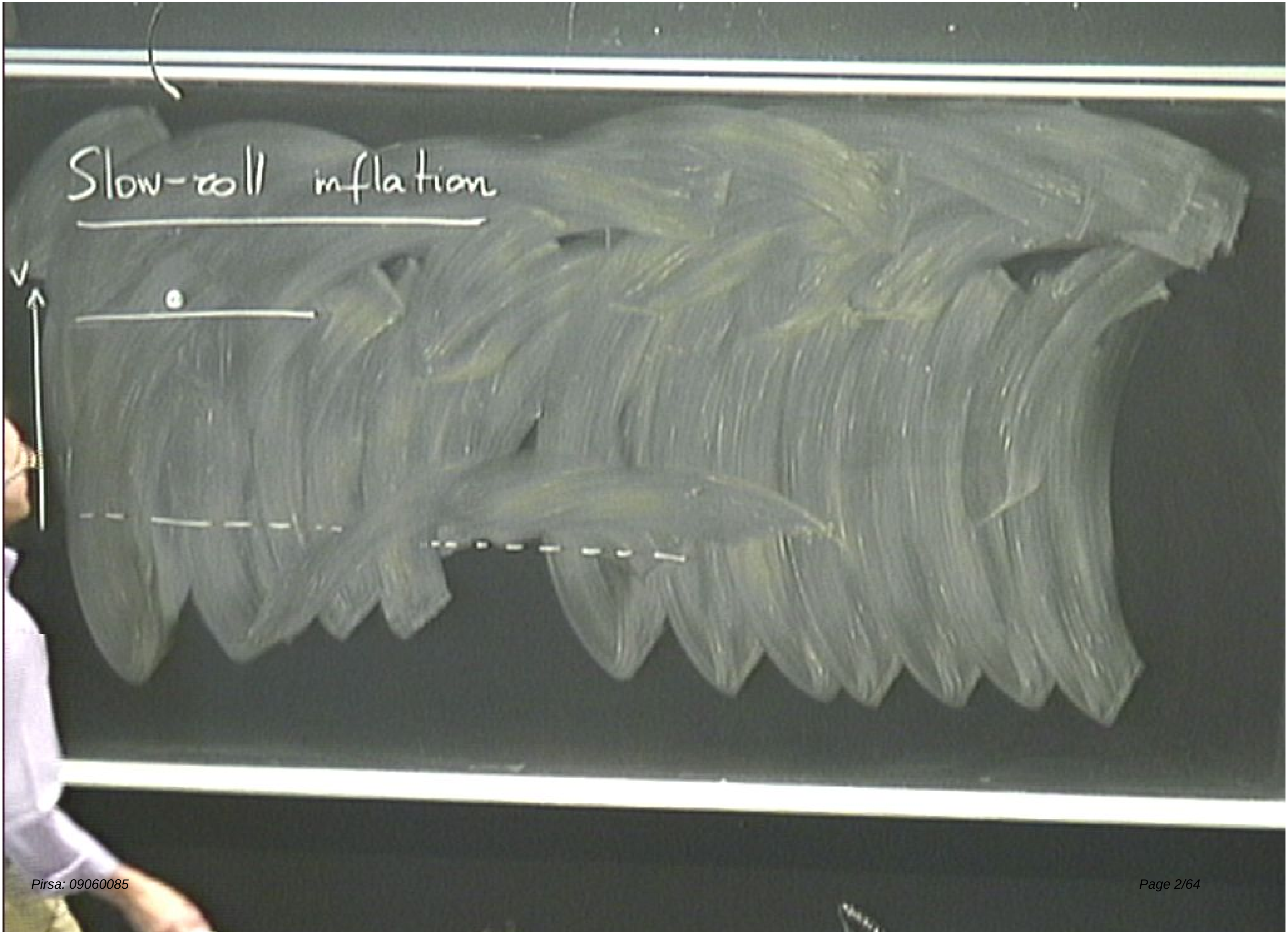
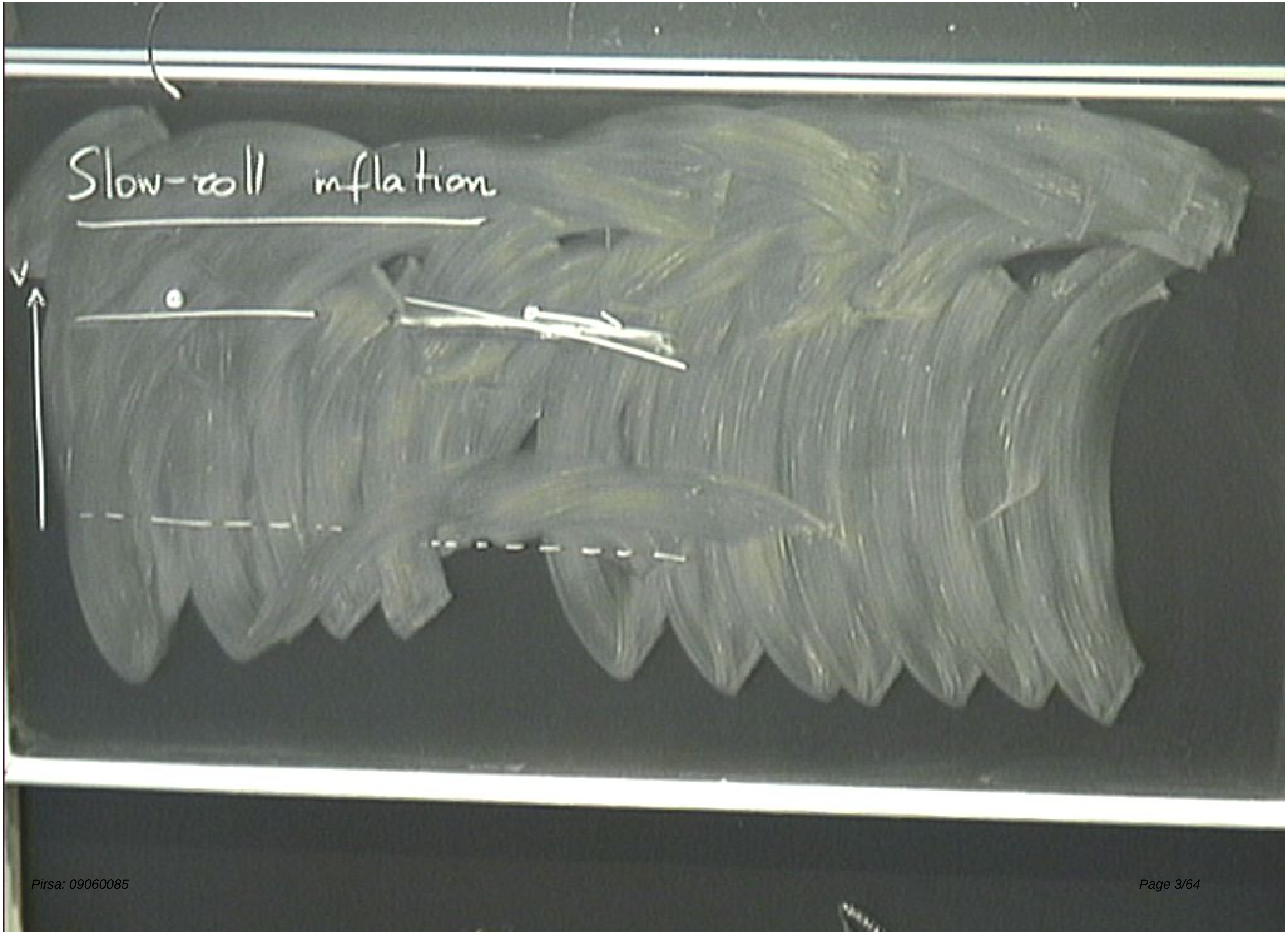
Title: Inflationary Cosmology - Lecture 2

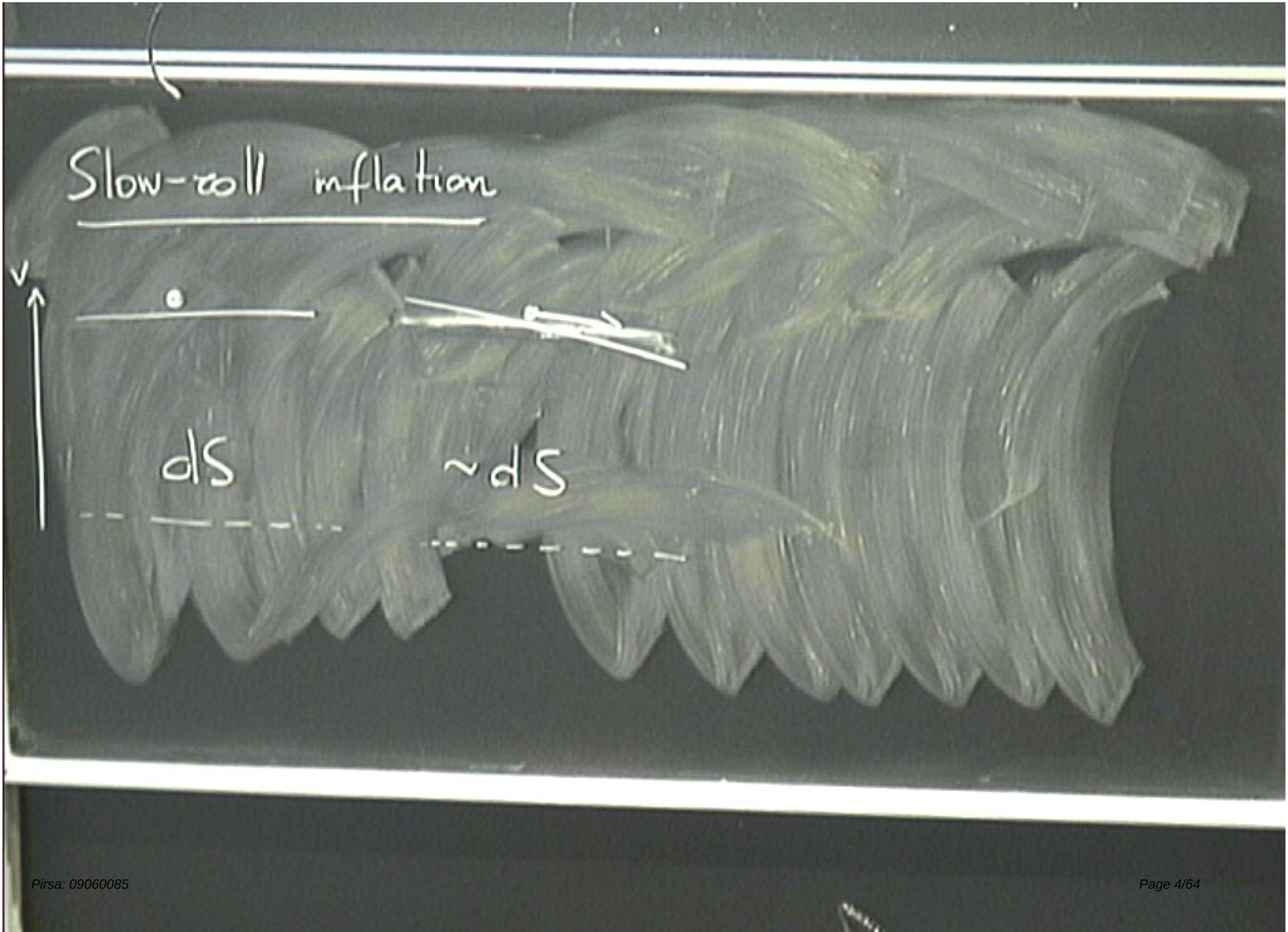
Date: Jun 30, 2009 10:00 AM

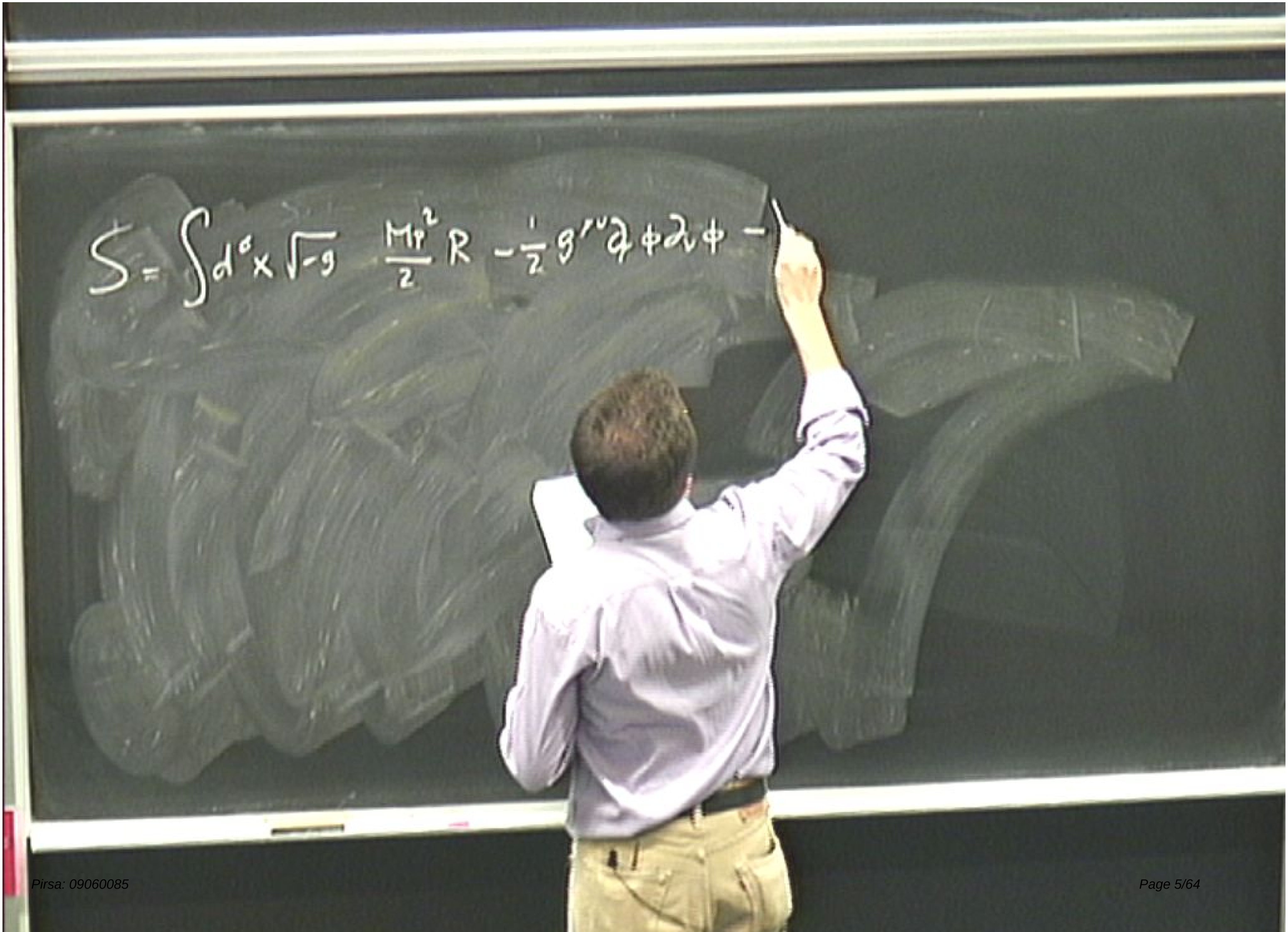
URL: http://pirsa.org/09060085

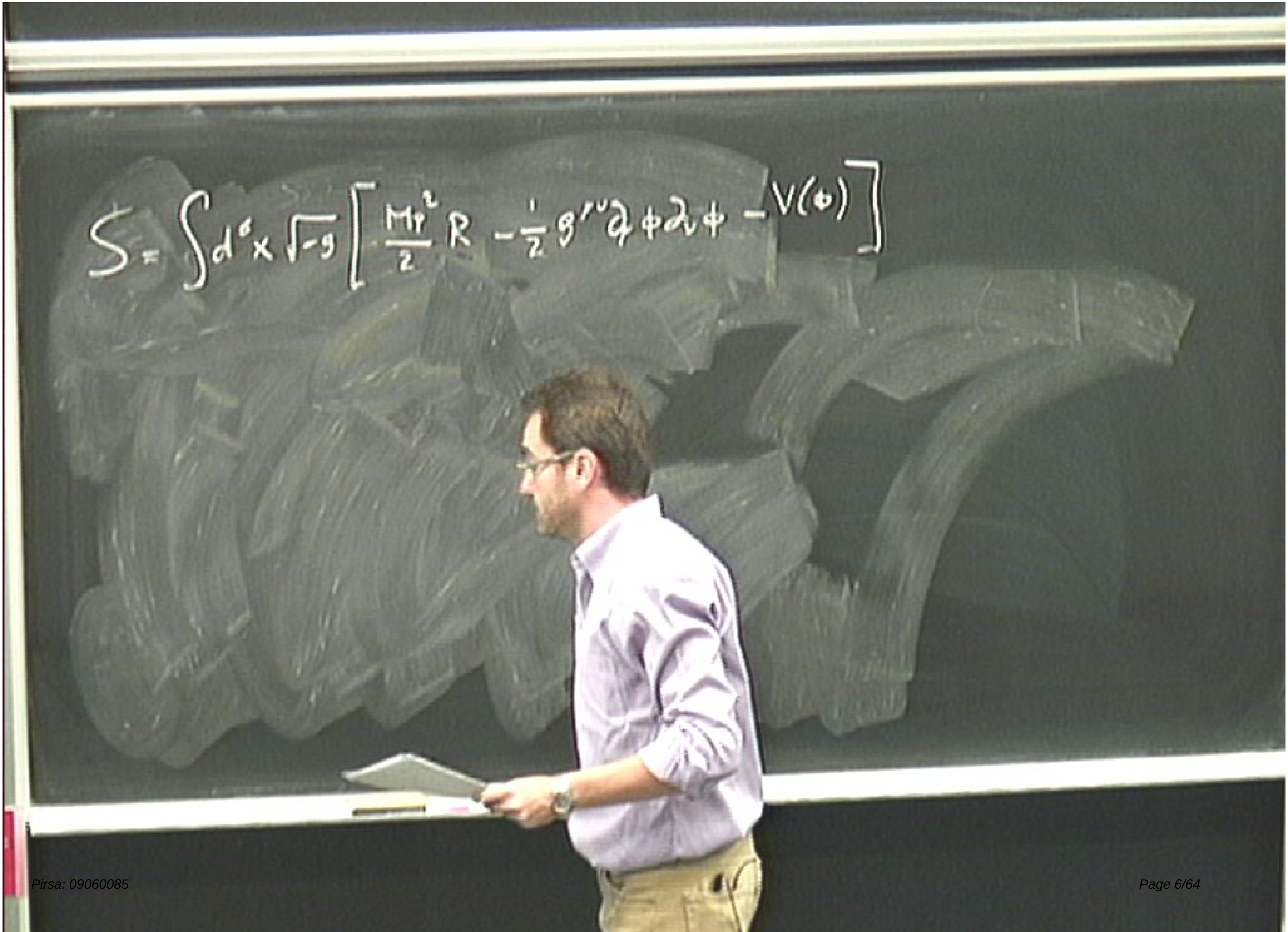
Abstract:

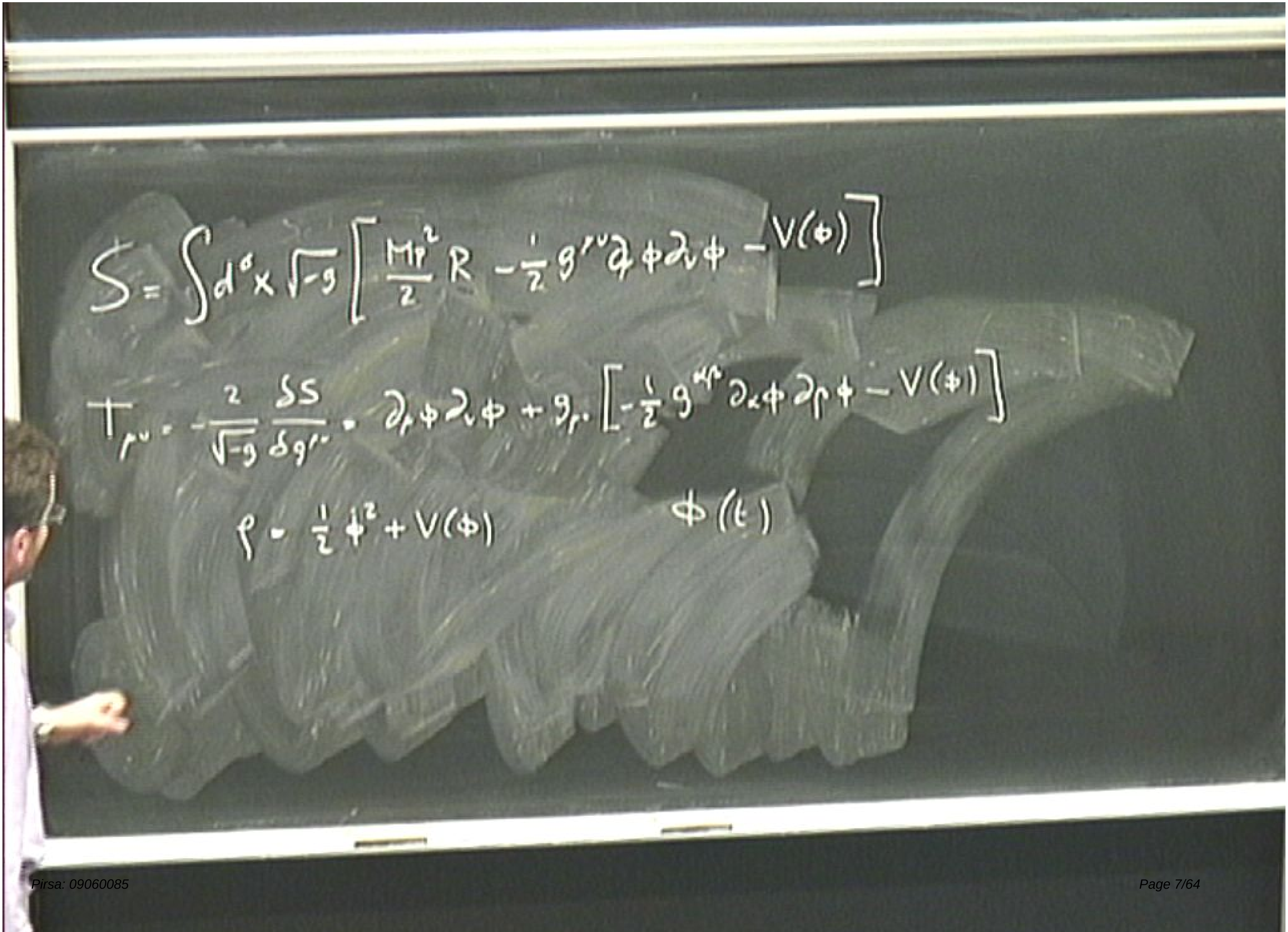

Slow-roll inflation
V


Slow-roll inflation
V


Slow-roll inflation
V
dS
~dS


$S = \int d^4x \sqrt{-g} \ \frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi -$


$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$


$S = \int d^4x \sqrt{-g} \left[\frac{M_p^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$
$T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g^{\mu\nu}} = \partial_\mu \phi \partial_\nu \phi + g_{\mu\nu} \left[-\frac{1}{2} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi - V(\phi) \right]$
$\rho = \frac{1}{2} \dot{\phi}^2 + V(\phi)$
$\phi(t)$

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$$\phi(t)$$

$$\begin{cases} \rho = \frac{1}{2} \dot{\phi}^2 + V(\phi) \\ p = \frac{1}{2} \dot{\phi}^2 - V(\phi) \end{cases}$$

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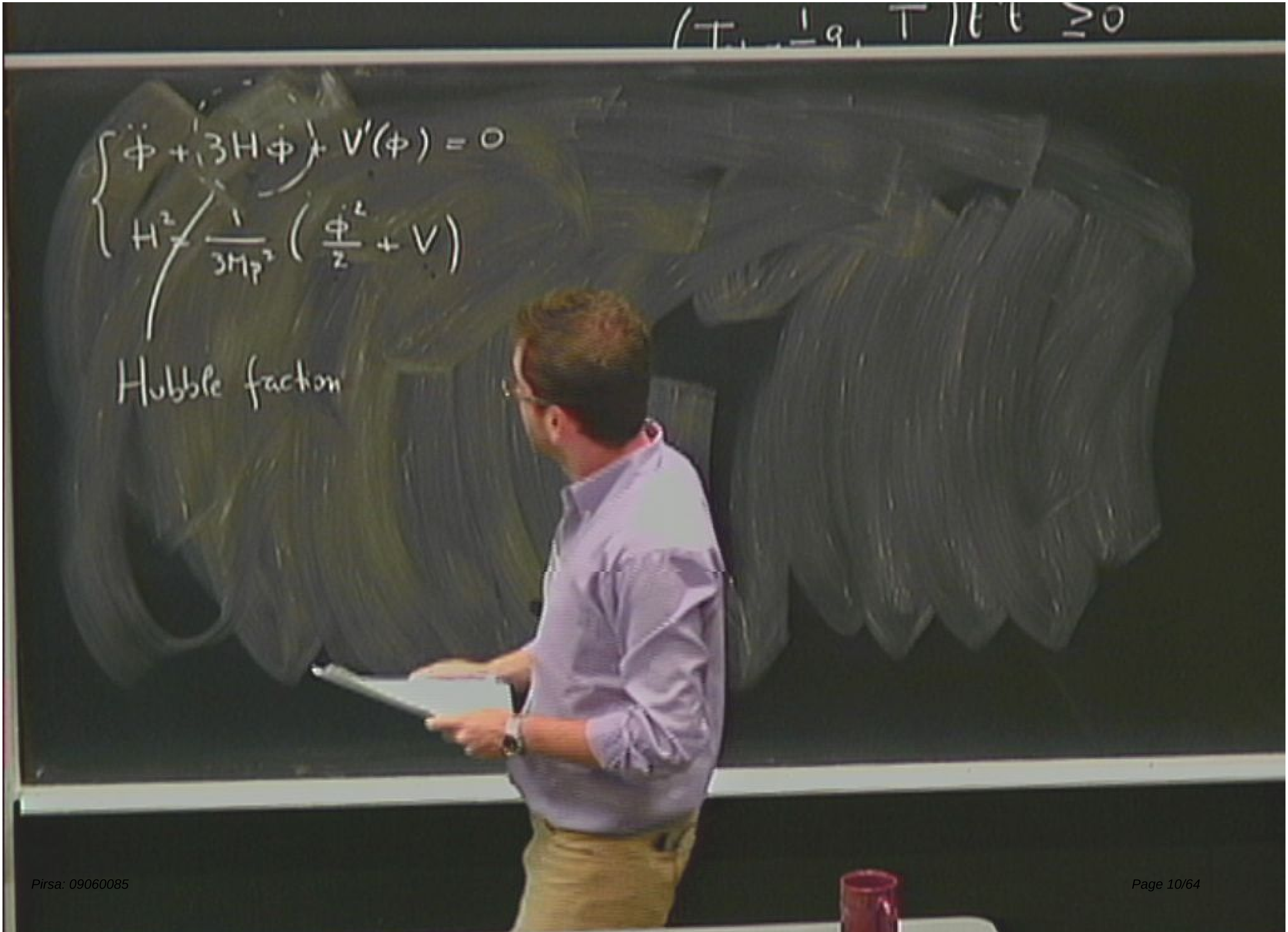
$$\phi(t)$$

$$\begin{cases} \rho = \frac{1}{2} \dot{\phi}^2 + V(\phi) \\ p = \frac{1}{2} \dot{\phi}^2 - V(\phi) \end{cases}$$

$$\frac{\dot{\phi}^2}{2} \ll V \qquad \text{slow-roll}$$



$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$
$H^2 = \frac{1}{3M_p^2}\left(\frac{\dot{\phi}^2}{2} + V\right)$
Hubble fraction

$$\left(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T\right) t^\mu t^\nu \geq 0$$

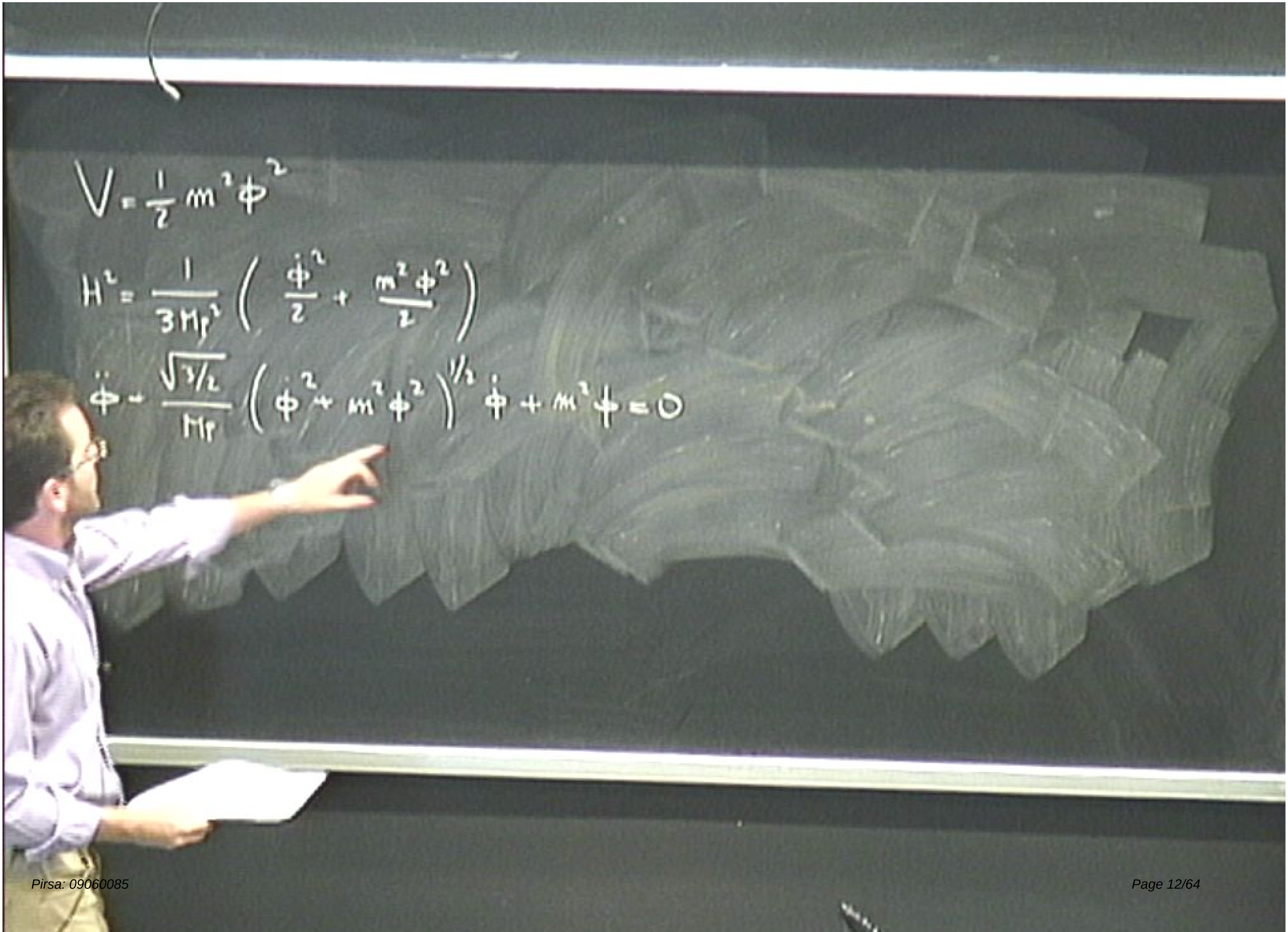
$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \\ H^2 = \dfrac{1}{3M_p^2}\left(\dfrac{\dot{\phi}^2}{2} + V\right) \end{cases}$$

Hubble friction

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$\rho_K \propto a^{-6}$$

$$\dot{\phi} \propto a^{-3}$$


$V = \frac{1}{2} m^2 \phi^2$
$H^2 = \frac{1}{3 M_P^2} \left(\frac{\dot{\phi}^2}{2} + \frac{m^2 \phi^2}{2} \right)$
$\ddot{\phi} + \frac{\sqrt{3/2}}{M_P} \left(\dot{\phi}^2 + m^2 \phi^2 \right)^{1/2} \dot{\phi} + m^2 \phi = 0$

$$V = \frac{1}{2} m^2 \phi^2$$

$$H^2 = \frac{1}{3 M_P^2} \left(\frac{\dot{\phi}^2}{2} + \frac{m^2 \phi^2}{2} \right)$$

$$\ddot{\phi} + \frac{\sqrt{3/2}}{M_P} \left(\dot{\phi}^2 + m^2 \phi^2 \right)^{1/2} \dot{\phi} + m^2 \phi = 0$$

$$\ddot{\phi} = \frac{d\dot{\phi}}{d\phi} \dot{\phi} \qquad \frac{d\dot{\phi}}{d\phi} = -\frac{1}{\dot{\phi}} \left[\sqrt{3/2}\, \frac{\dot{\phi}}{M_P} \left(\dot{\phi}^2 + m^2 \phi^2 \right)^{1/2} + m^2 \phi \right]$$

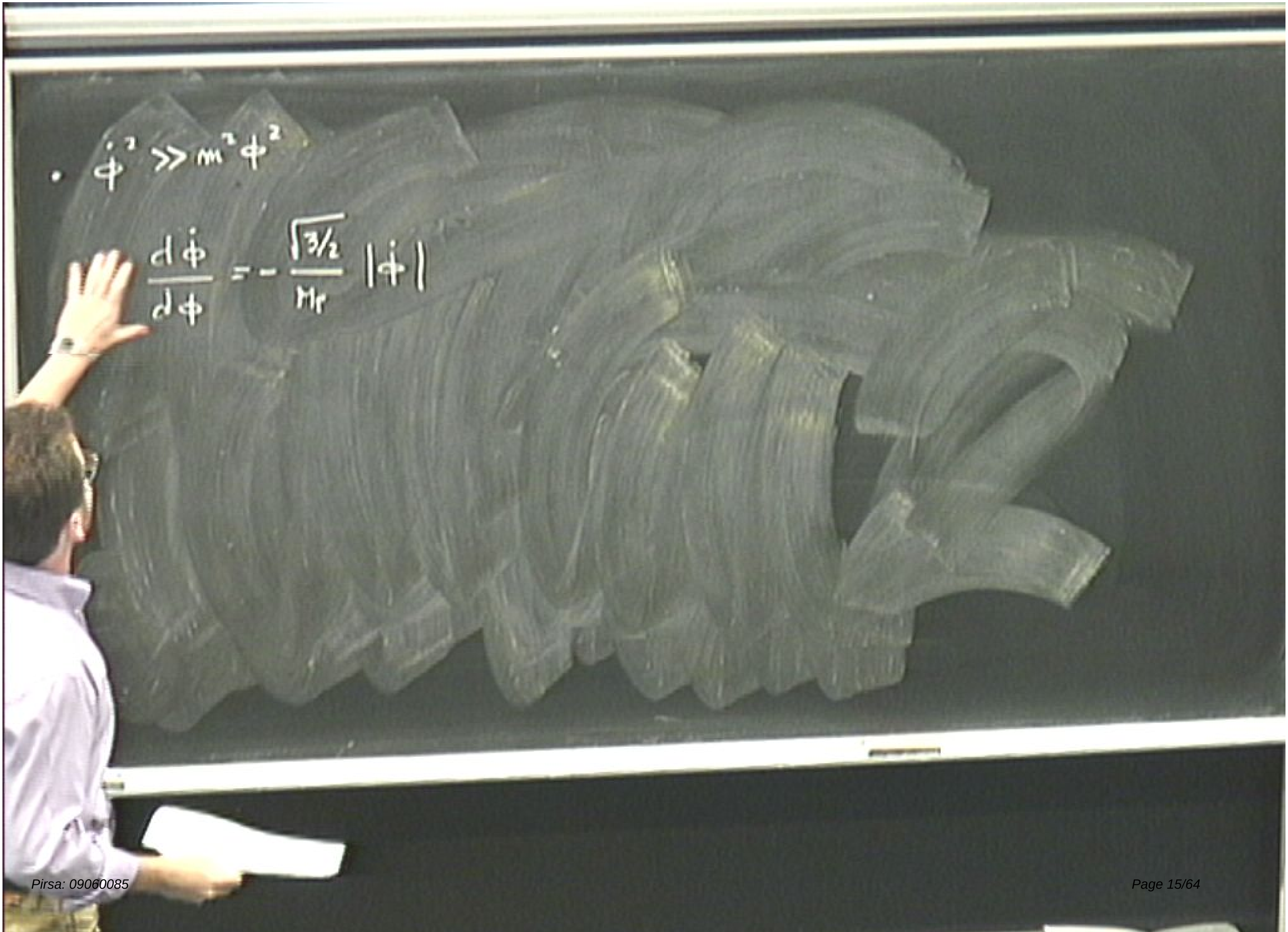
$$V = \frac{1}{2} m^2 \phi^2$$

$$H^2 = \frac{1}{3M_P^2}\left(\frac{\dot\phi^2}{2} + \frac{m^2\phi^2}{2}\right)$$

$$\boxed{\phi \gg M_P}$$

$$\ddot\phi + \frac{\sqrt{3/2}}{M_P}\left(\dot\phi^2 + m^2\phi^2\right)^{1/2}\dot\phi + m^2\phi = 0$$

$$\ddot\phi = \frac{d\dot\phi}{d\phi}\dot\phi \qquad \frac{d\dot\phi}{d\phi} = -\frac{1}{\dot\phi}\left[\sqrt{3/2}\,\frac{\dot\phi}{M_P}\left(\dot\phi^2 + m^2\phi^2\right)^{1/2} + m^2\phi\right]$$


• $\dot{\phi}^2 \gg m^2 \phi^2$
$\frac{d\dot{\phi}}{d\phi} = -\frac{\sqrt{3/2}}{M_P} |\dot{\phi}|$

- $\dot{\phi}^2 \gg m^2 \phi^2$ Kinetic domination

$$\frac{d\dot{\phi}}{d\phi} = -\frac{\sqrt{3/2}}{M_P} |\dot{\phi}|$$

- $m^2 \phi^2 \gg \dot{\phi}^2$

- $\dot{\phi}^2 \gg m^2\phi^2$ Kinetic domination

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$$\frac{d\dot{\phi}}{d\phi} \approx 0 \qquad \frac{d\dot{\phi}}{d\phi} \propto \frac{\sqrt{3/2}}{M_P}\,\dot{\phi}\, m\phi + m^2\phi \Rightarrow \dot{\phi} = -\sqrt{\frac{2}{3}}\, m M_P$$

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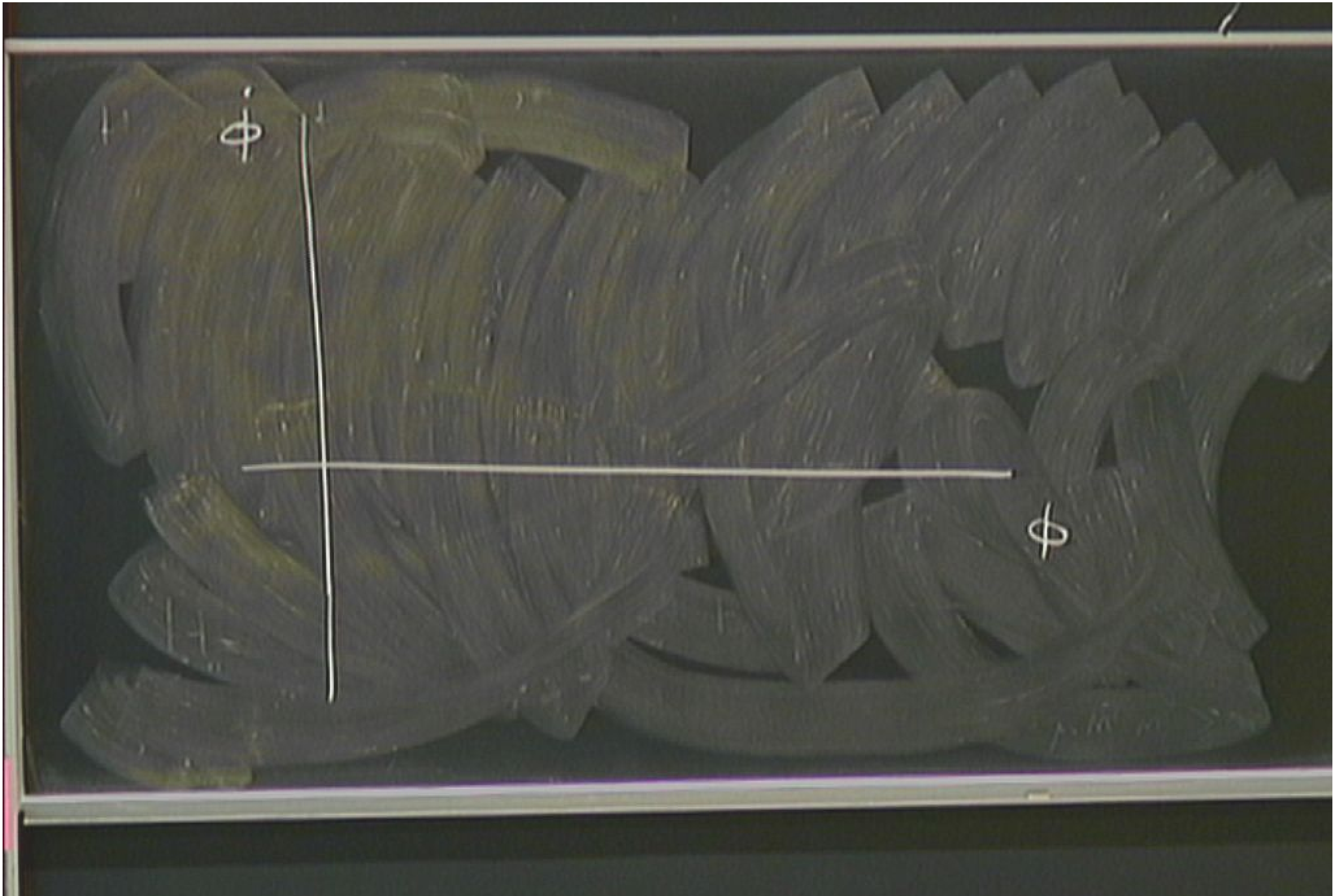
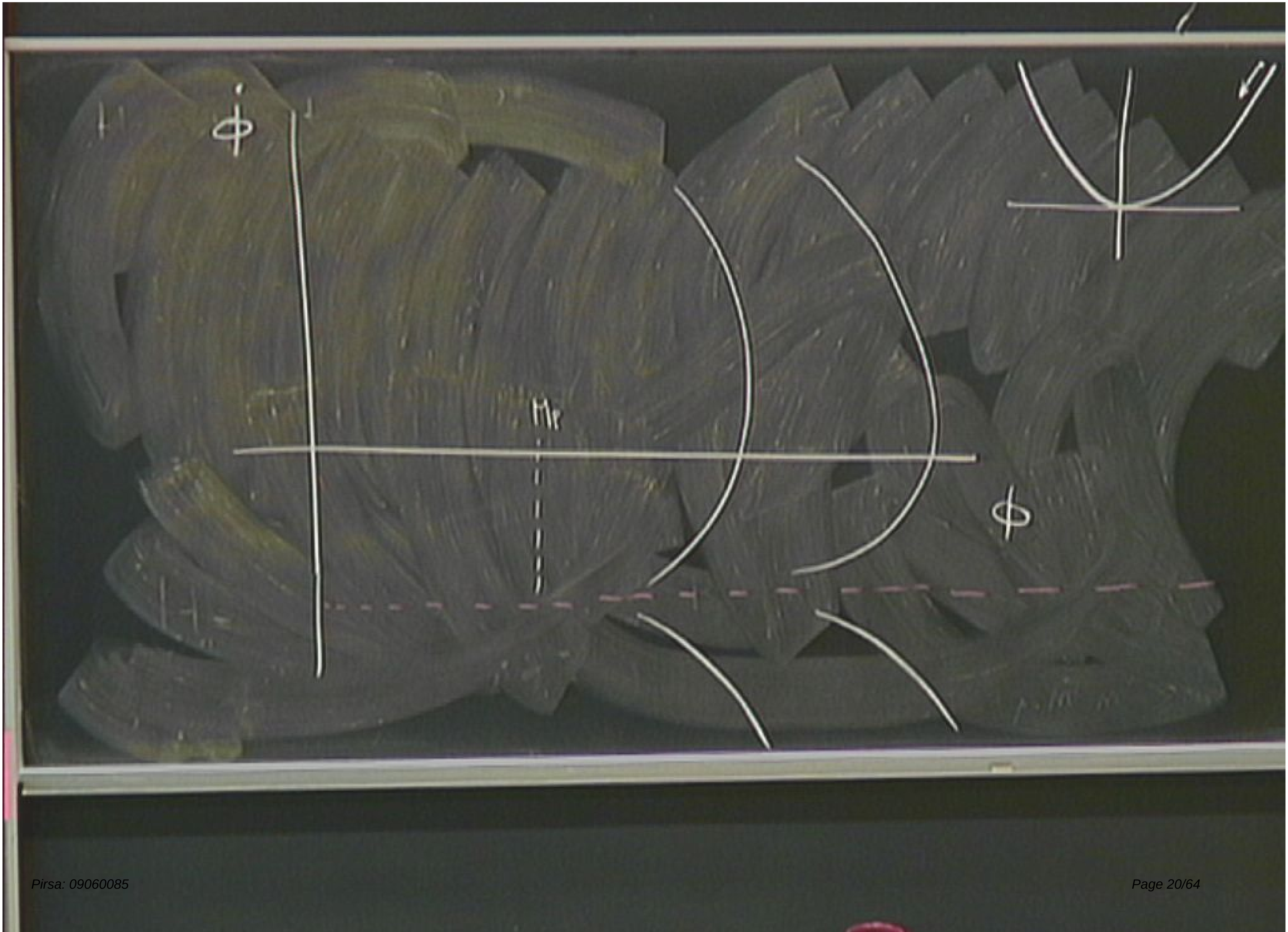
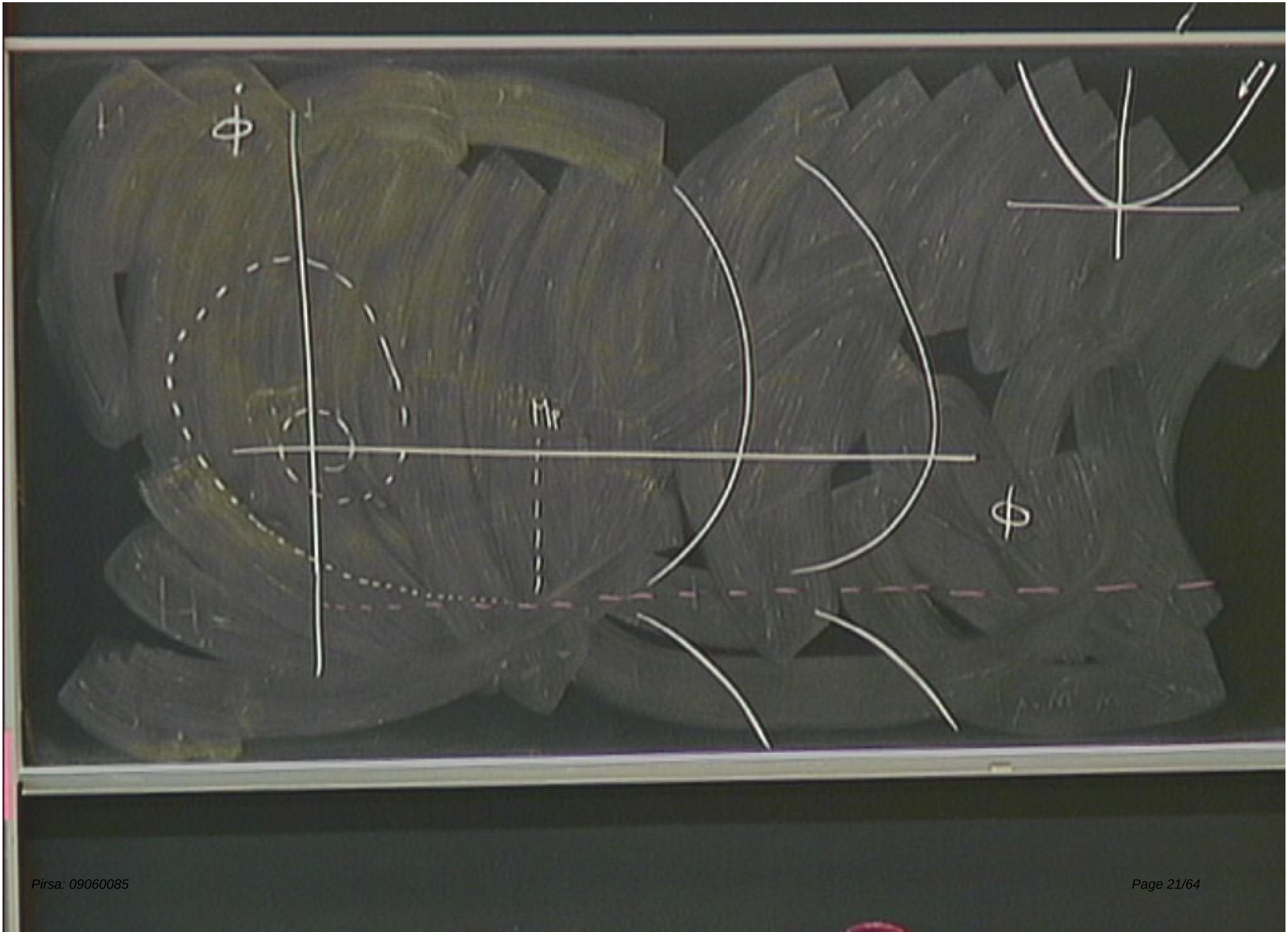
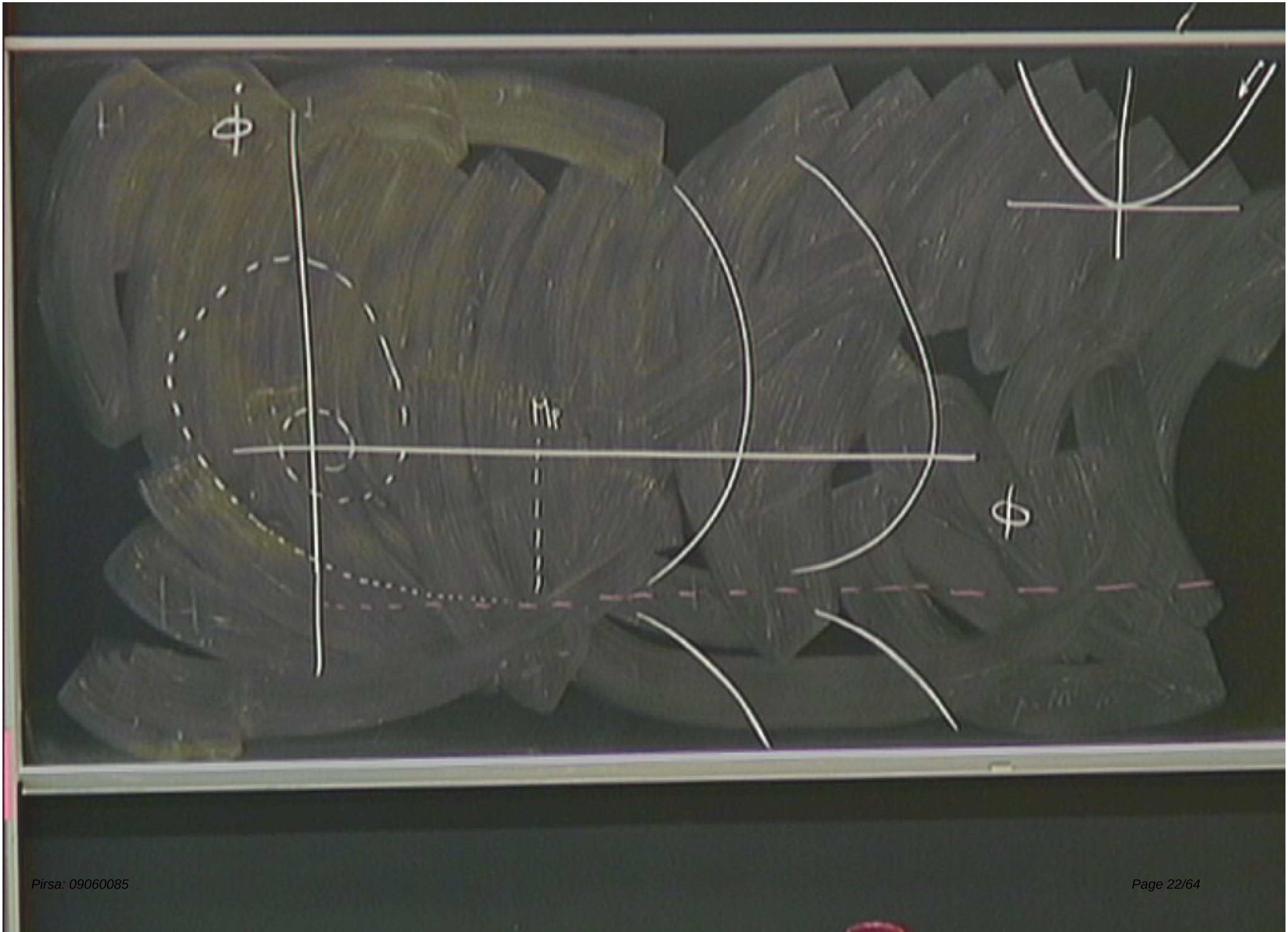
$$\frac{\dot{\phi}^2}{2} \sim m^2 M_P^2 \ll \frac{1}{2} m^2 \phi^2 = V$$


φ
φ

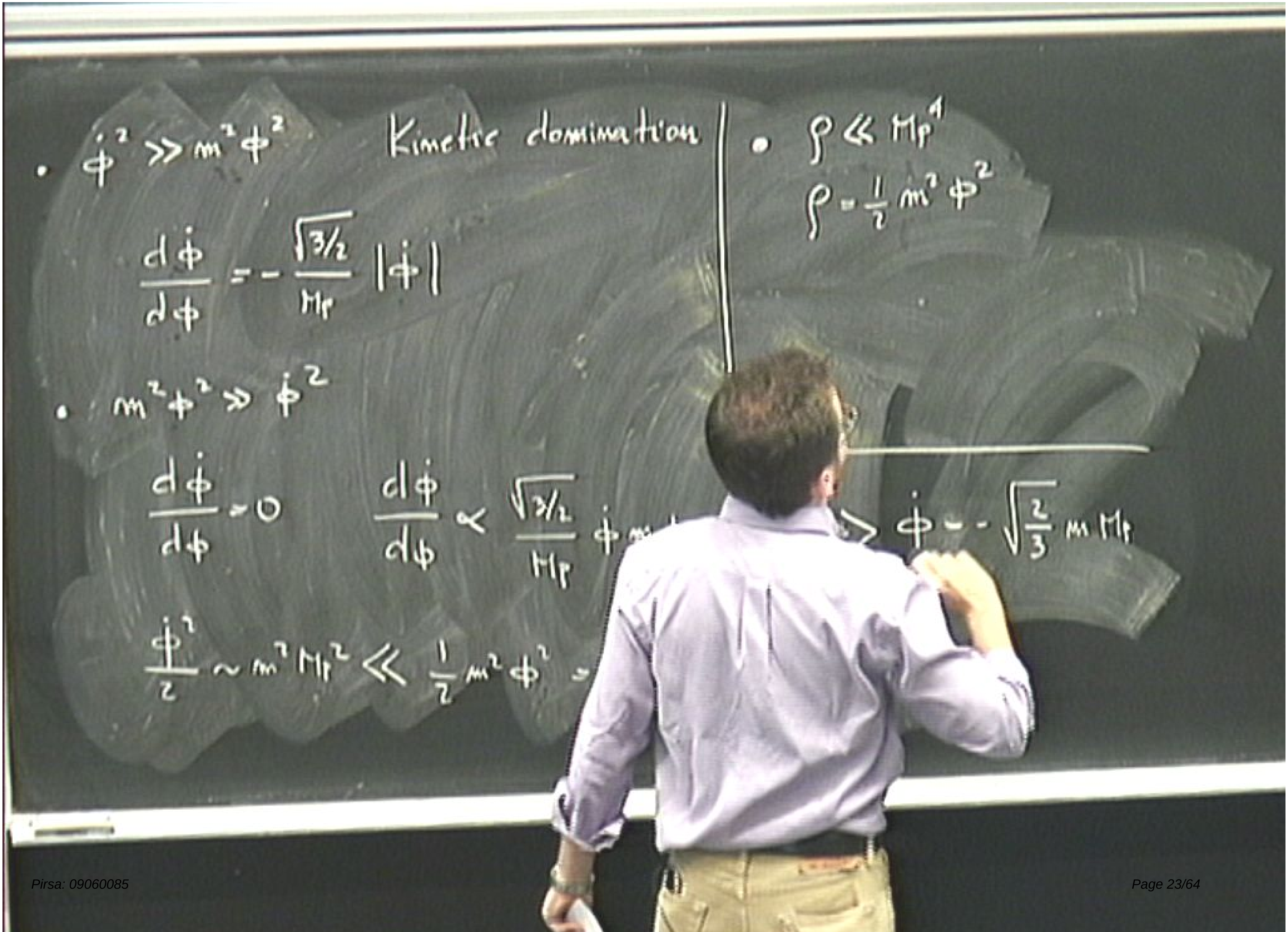

ϕ̇
ϕ



φ
m_r
φ



φ
M_P
φ


$\dot\phi^2 \gg m^2\phi^2$
Kinetic domination
$\frac{d\dot\phi}{d\phi} = -\frac{\sqrt{3/2}}{M_P}|\dot\phi|$
$m^2\phi^2 \gg \dot\phi^2$
$\frac{d\dot\phi}{d\phi} \approx 0$
$\frac{d\dot\phi}{d\phi} \propto \frac{\sqrt{3/2}}{M_P}\dot\phi$
$\dot\phi = -\sqrt{\frac{2}{3}}\, m M_P$
$\frac{\dot\phi^2}{2} \sim m^2 M_P^2 \ll \frac{1}{2}m^2\phi^2$
$\rho \ll M_P^4$
$\rho = \frac{1}{2}m^2\phi^2$

- $\dot{\phi}^2 \gg m^2\phi^2$ Kinetic domination

$$\frac{d\dot{\phi}}{d\phi} = -\frac{\sqrt{3/2}}{M_P}\,|\dot{\phi}|$$

- $m^2\phi^2 \gg \dot{\phi}^2$

$$\frac{d\dot{\phi}}{d\phi} \simeq 0 \qquad \frac{d\dot{\phi}}{d\phi} \propto \frac{\sqrt{3/2}}{M_P}\,\dot{\phi}\, m\,\phi + m^2\phi \Rightarrow \dot{\phi} \simeq -\sqrt{\frac{2}{3}}\, m M_P$$

$$\frac{\dot{\phi}^2}{2} \sim m^2 M_P^2 \ll \frac{1}{2} m^2\phi^2 = V$$

- $\rho \ll M_P^4$

$$\rho = \frac{1}{2} m^2 \phi^2 \qquad m \simeq 10^{13}\,\mathrm{GeV}$$

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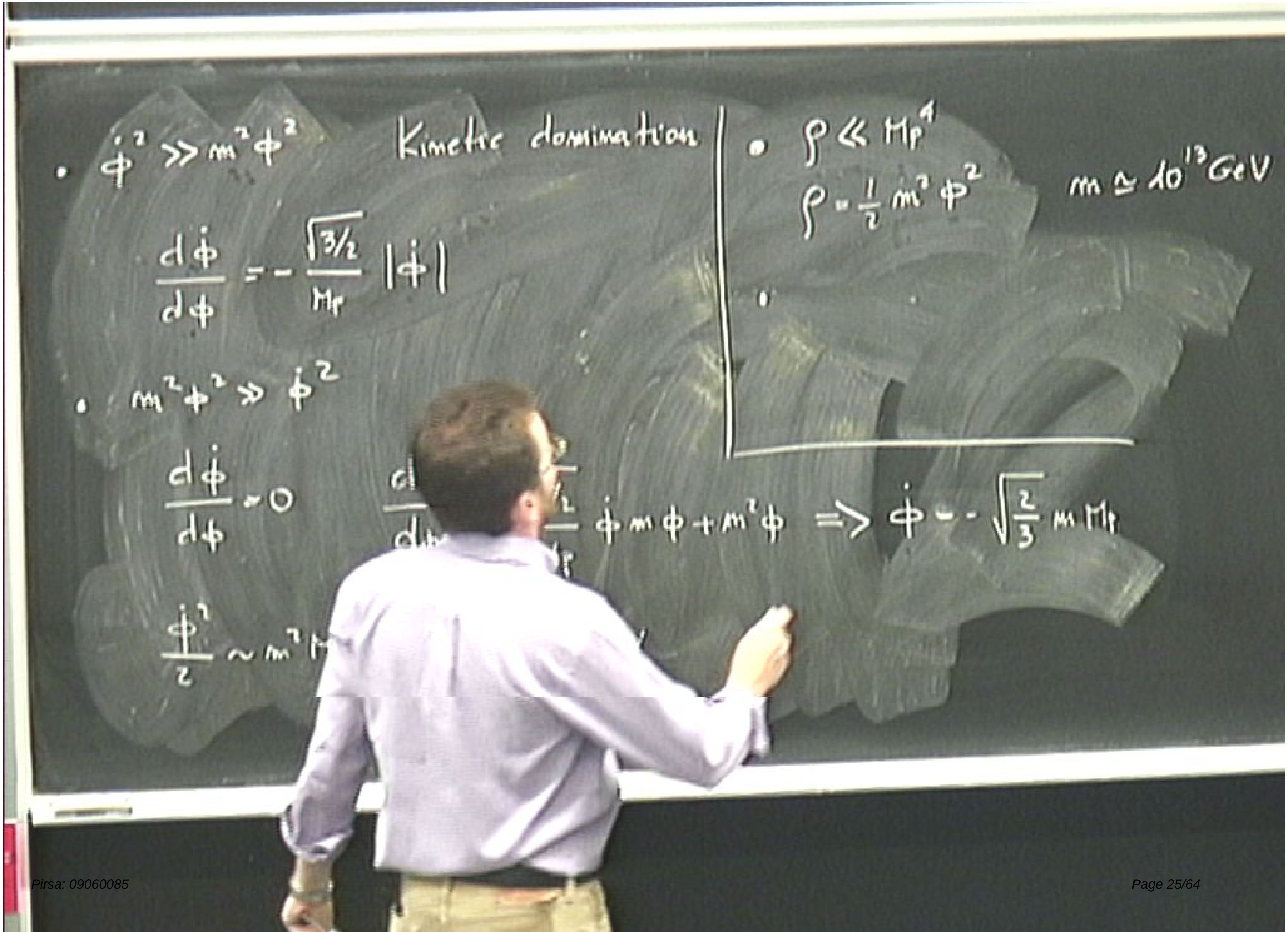

Kinetic domination
• $\dot\phi^2 \gg m^2\phi^2$
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• $m^2\phi^2 \gg \dot\phi^2$
$\frac{d\dot\phi}{d\phi} \simeq 0$
$\dot\phi\, m\phi + m^2\phi \Rightarrow \dot\phi = -\sqrt{\frac{2}{3}}\, m M_P$
$\frac{\dot\phi^2}{2} \sim m^2$
• $\rho \ll M_P^4$
$\rho = \frac{1}{2}m^2\phi^2$
$m \simeq 10^{13}$ GeV

- $\dot{\phi}^2 \gg m^2 \phi^2$ Kinetic domination

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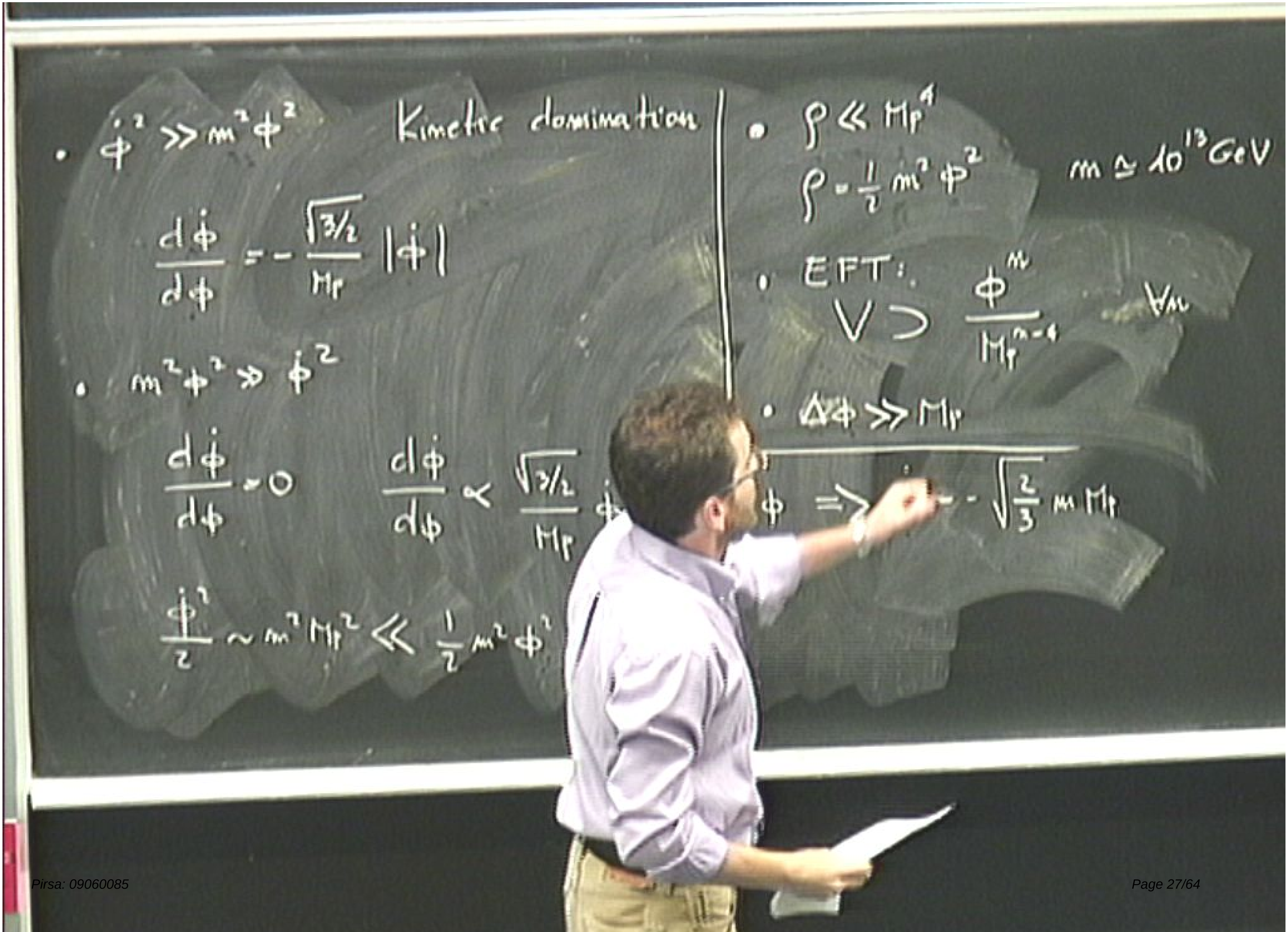
- $\rho \ll M_P^4$

$\rho = \frac{1}{2} m^2 \phi^2$ $m \simeq 10^{13}$ GeV

- EFT:

$$V \supset \frac{\phi^n}{M_P^{n-4}}$$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• $\rho \ll M_P^4$
$\rho = \frac{1}{2}m^2\phi^2$
$m \simeq 10^{13}$ GeV
• EFT: $V \supset \frac{\phi^n}{M_P^{n-4}}$ $\forall n$
• $\Delta\phi \gg M_P$
$\Rightarrow$
$-\sqrt{\frac{2}{3}}\, m M_P$

- $\dot\phi^2 \gg m^2\phi^2$ Kinetic domination

$$\frac{d\dot\phi}{d\phi} = -\frac{\sqrt{3/2}}{M_P}|\dot\phi|$$

- $m^2\phi^2 \gg \dot\phi^2$

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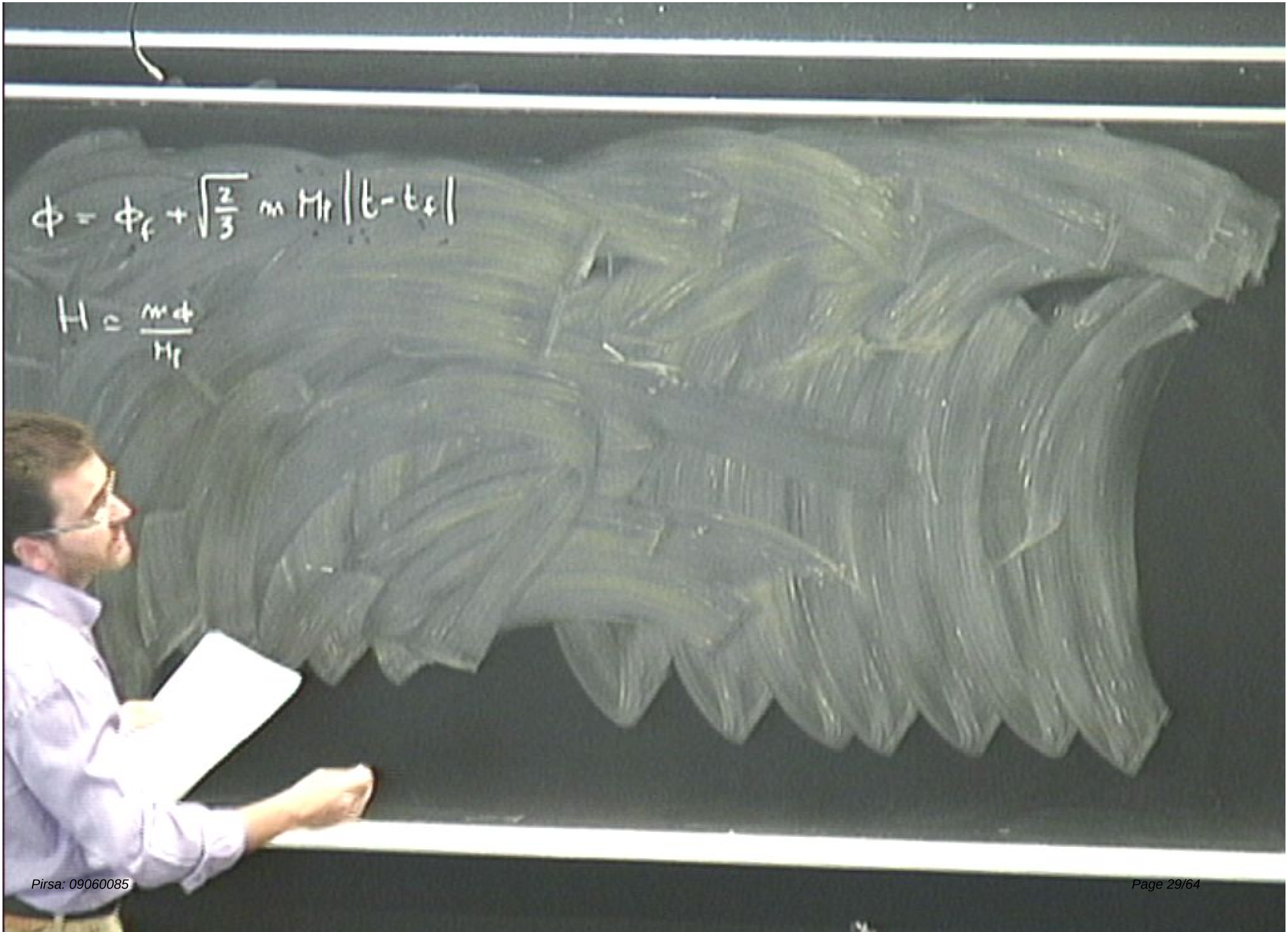
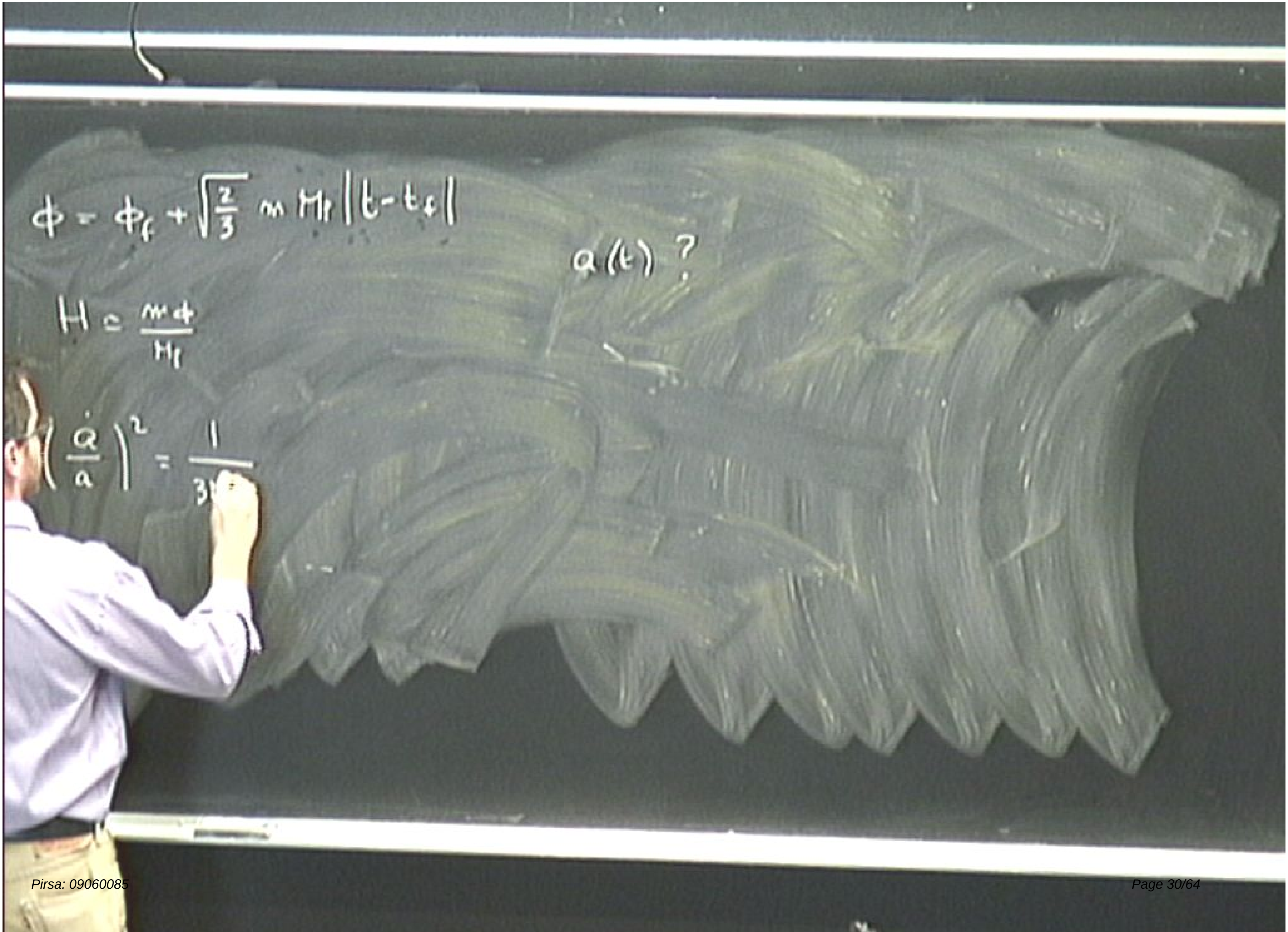
- $\rho \ll M_P^4$

$\rho = \frac{1}{2}m^2\phi^2$ $\qquad m \simeq 10^{13}\,\mathrm{GeV}$

- EFT: $V \supset \frac{\phi^n}{M_P^{n-4}} \quad \forall n$

- $\Delta\phi \gg M_P \Longleftrightarrow$ Observable GWs


φ = φ_f + √(2/3) m M_P |t − t_f|
H ≃ mφ / M_P


$\phi = \phi_f + \sqrt{\frac{2}{3}}\, m M_P \,||t - t_f||$
$a(t)$?
$H \simeq \frac{m\phi}{M_P}$
$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}$

$$\phi = \phi_f + \sqrt{\frac{2}{3}}\, m M_P \,|t - t_f|$$

$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\,\frac{2}{3}\,\frac{1}{2}\, m^4 M_P^2\, |t - t_f|^2$$

$$a(t) = e^{\frac{m^2}{6}|t - t_f|^2}$$

$$\phi = \phi_f + \sqrt{\frac{2}{3}}\, m\, M_P\, |t - t_f|$$

$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

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$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\,\frac{2}{3}\,\frac{1}{2}\, m^4 M_P^2\, |t - t_f|^2$$

$$\frac{\dot{H}}{H^2} = \frac{1}{m^2 |t - t_f|^2} \sim \frac{1}{N}$$

$$a(t) = e^{\frac{m^2}{6}|t - t_f|^2};\quad N$$

$$\phi = \phi_f + \sqrt{\tfrac{2}{3}}\, m M_P \,|t - t_f|$$

$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

$$\left(\frac{\dot a}{a}\right)^2 = \frac{1}{3M_P^2}\,\frac{2}{3}\,\frac{1}{2}\, m^4 M_P^2\, |t - t_f|^2$$

$$a(t) = e^{\frac{m^2}{6}|t - t_f|^2} \; ; \; N$$

$$\frac{\dot H}{H^2} = \frac{1}{m^2 |t - t_f|^2} \sim \frac{1}{N}$$

$\sim dS$

$$\phi = \phi_f + \sqrt{\frac{2}{3}}\, m M_P \left| t - t_f \right|$$

$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_P^2}\,\frac{2}{3}\,\frac{1}{2}\, m^4 M_P^2 \left| t - t_f \right|^2$$

$$a(t) = e^{\frac{m^2}{6}\left| t - t_f \right|^2} ; \quad N$$

$$\frac{\dot{H}}{H^2} = \frac{1}{m^2 \left| t - t_f \right|^2} \sim \frac{1}{N}$$

$\sim dS$

$$\phi = \phi_f + \sqrt{\frac{2}{3}}\, m M_P |t - t_f|$$

$a(t)$?

$$H \simeq \frac{m\phi}{M_P}$$

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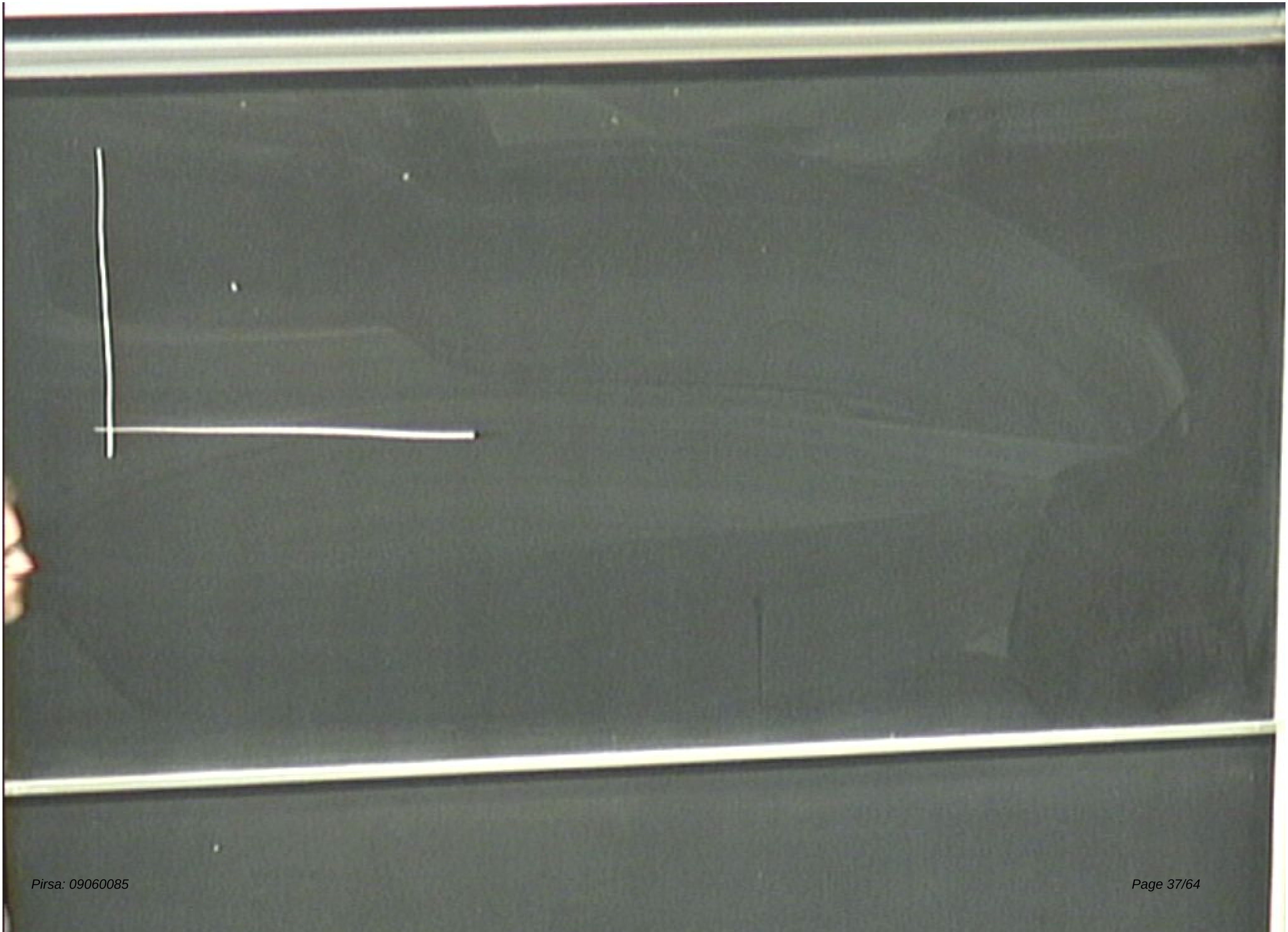
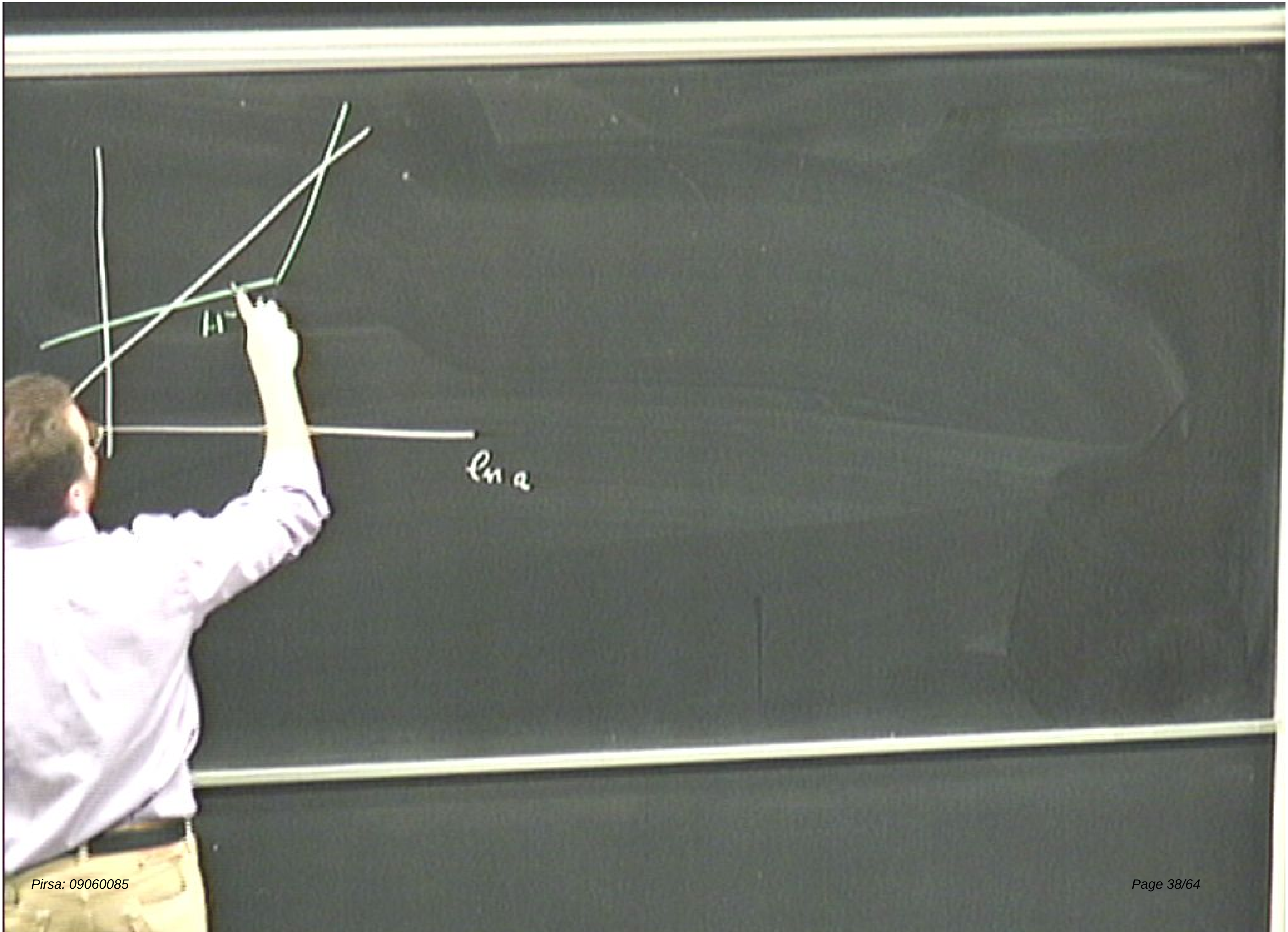
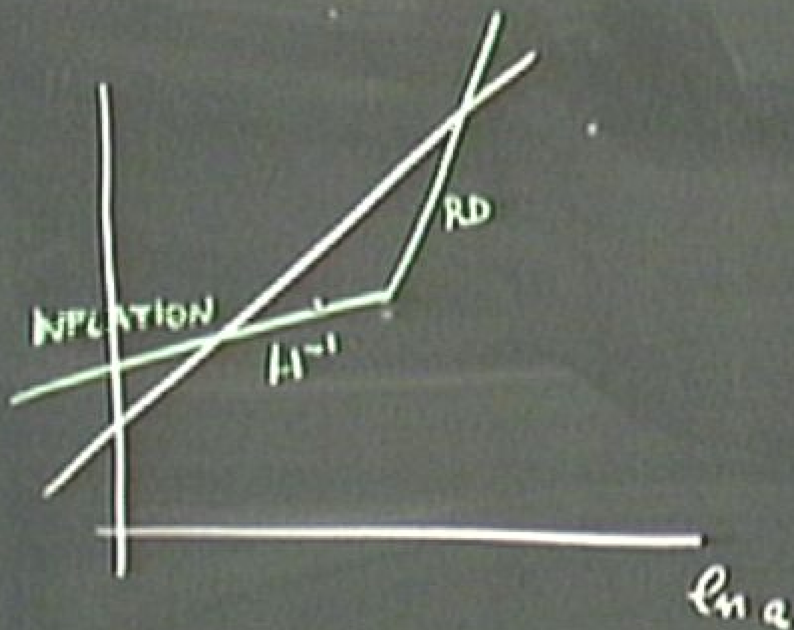
$$a(t) = e^{\frac{m^2}{6}|t - t_f|^2};\ N$$

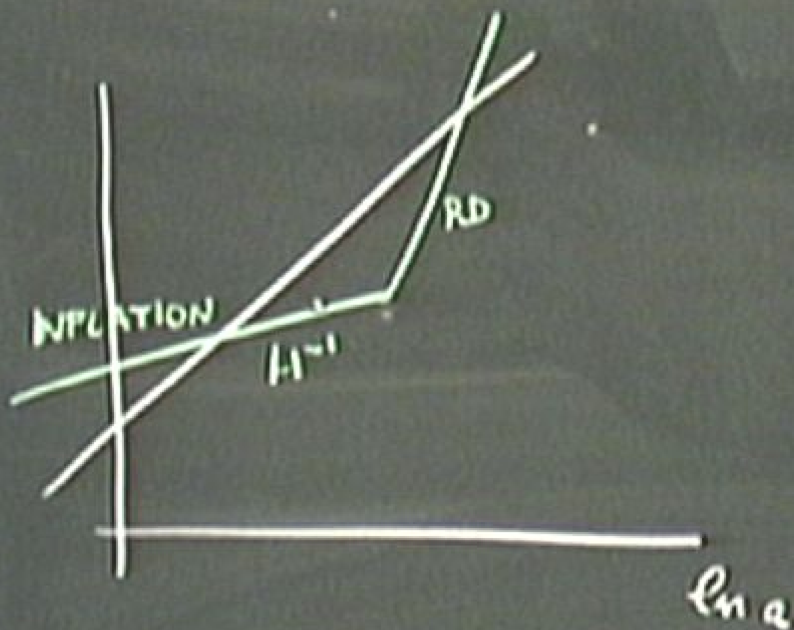
$\sim dS$



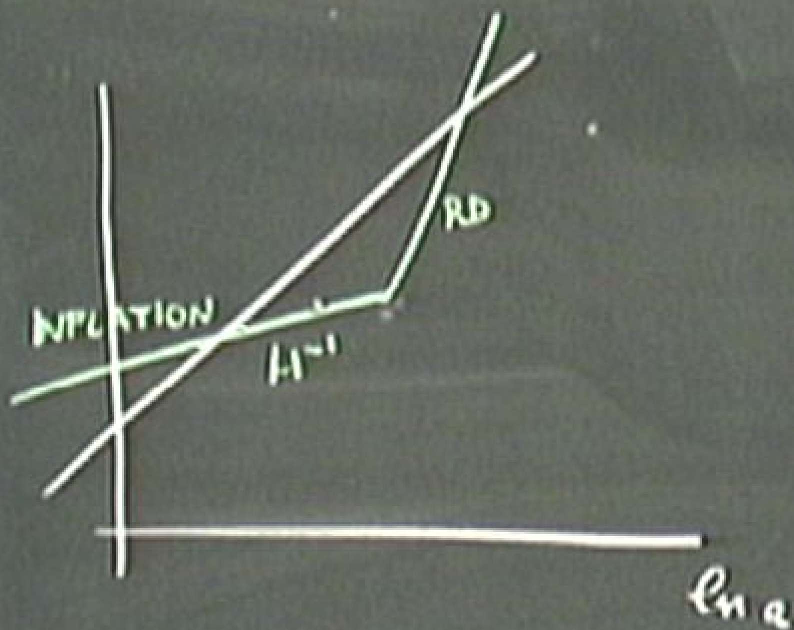

ln a



$$\frac{H^{-1}_{end}\, a_0/a_e}{H_0^{-1}}$$

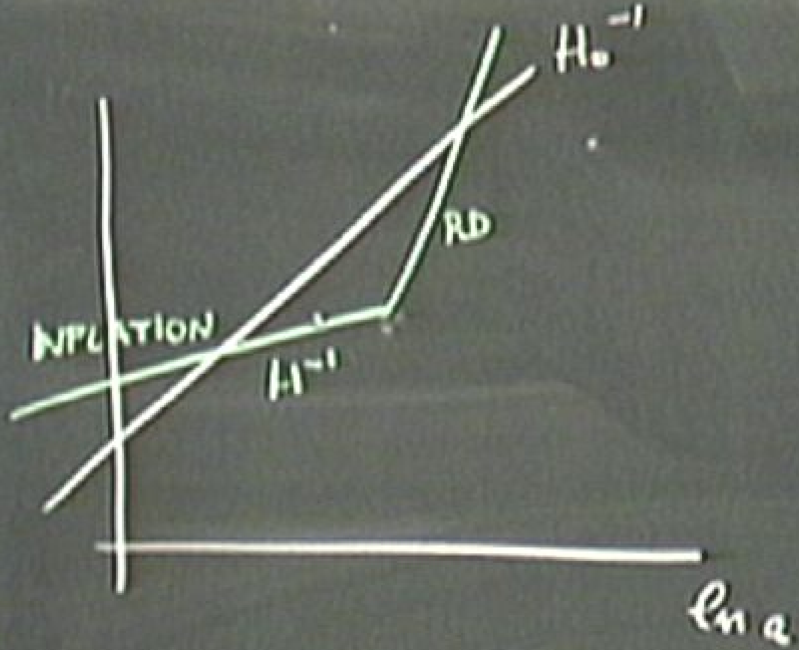


$$\frac{H^{-1}_{end}\; a_0/a_e \;\; RD}{H_0^{-1}} =$$



$$\frac{H^{-1}_{end}\; a_0/a_e \;\; RD}{H_0^{-1}} = \frac{T_0}{T_e}$$

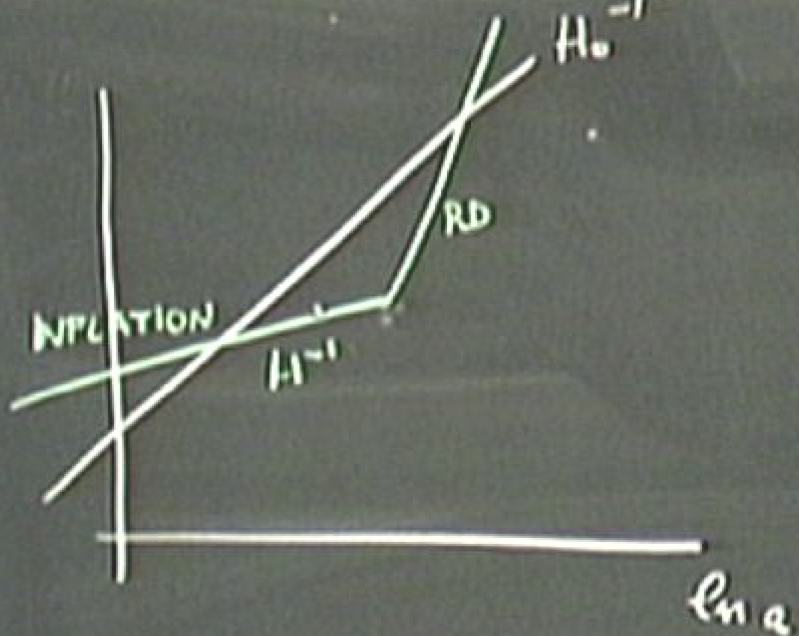
$$T_e \sim 10^{13}\,\text{GeV}$$



$$N = \log 10^{28} = 64$$

$$\frac{H^{-1}_{end}\, a_0/a_e \;\; \mathrm{RD}}{H_0^{-1}} = \frac{T_0}{T_e} \simeq 10^{-28}$$

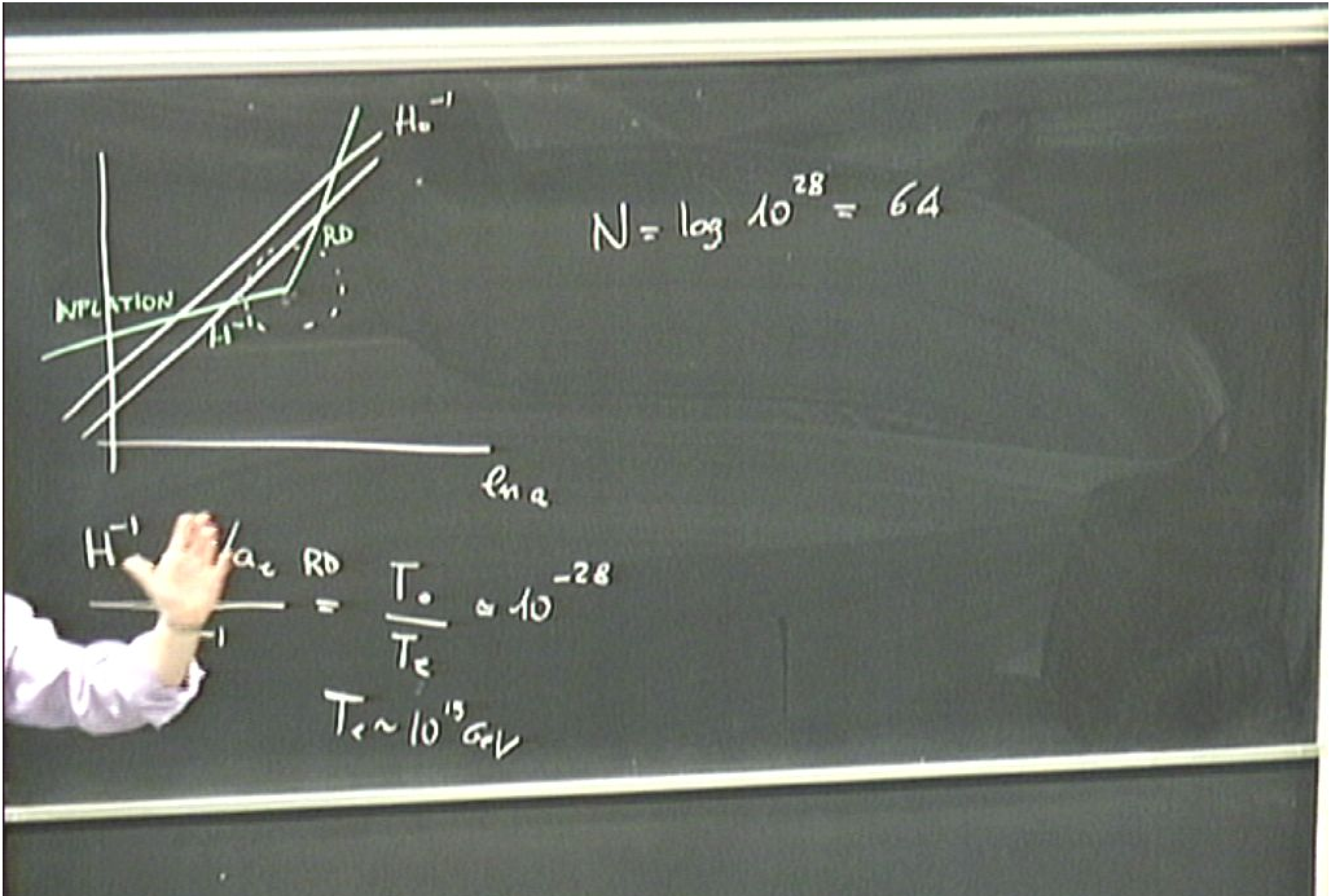
$$T_e \sim 10^{13}\,\mathrm{GeV}$$

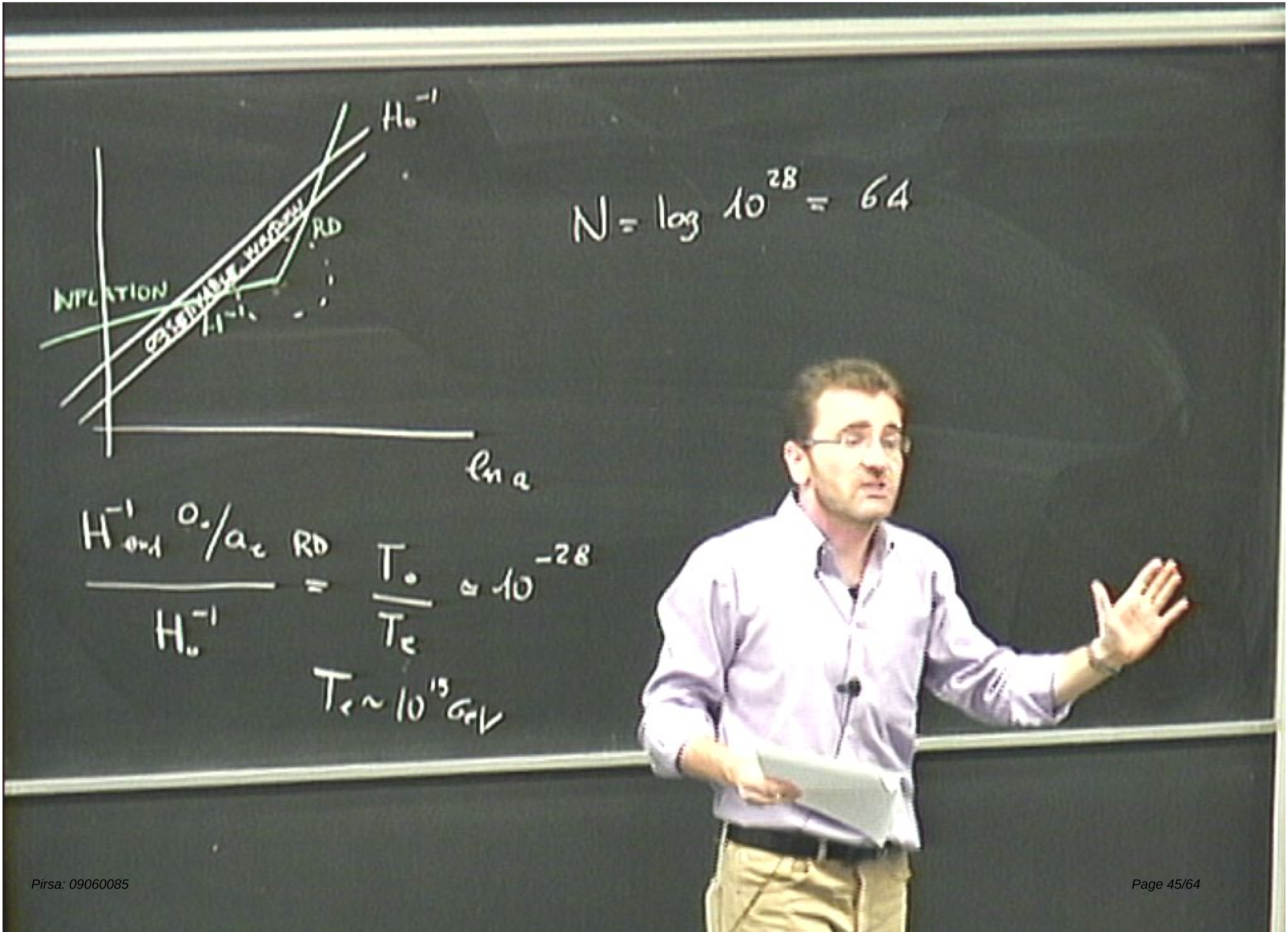


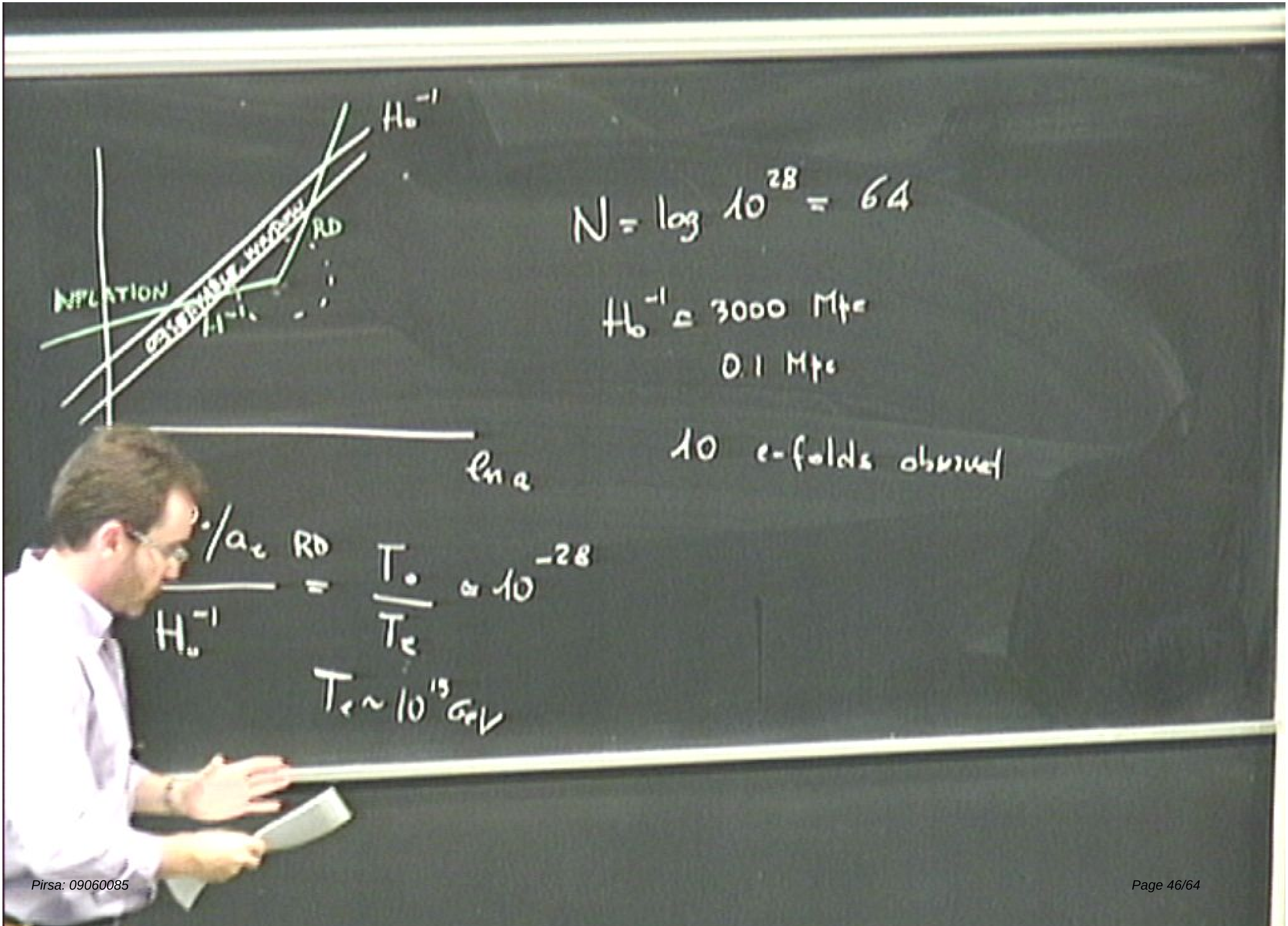
$$N = \log 10^{28} = 64$$

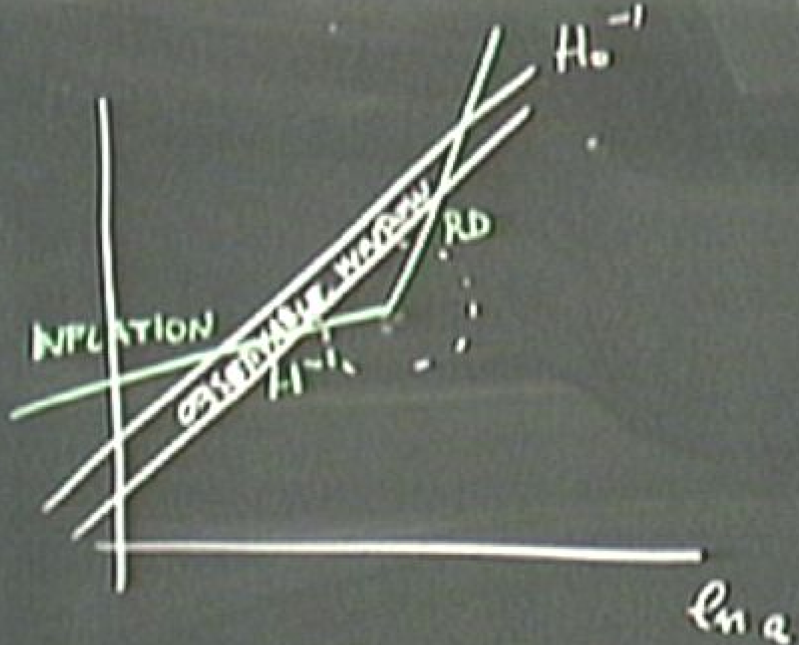
$$\frac{H^{-1}_{end}\; a_0/a_e \;\; RD}{H_0^{-1}} = \frac{T_0}{T_e} \approx 10^{-28}$$

$$T_e \sim 10^{15}\,\mathrm{GeV}$$


H_0^{-1}
RD
INFLATION
ln a
N = log 10^28 = 64
RD
= T_0 / T_e ≈ 10^-28
T_e ~ 10^15 GeV


H₀⁻¹
RD
INFLATION
OBSERVABLE UNIVERSE
ln a
N = log 10^28 = 64
H⁻¹end a₀/aₑ RD / H₀⁻¹ = T₀/Tₑ ≈ 10^-28
Tₑ ~ 10^15 GeV


H0^-1
RD
INFLATION
N = log 10^28 = 64
H0^-1 ≈ 3000 Mpc
0.1 Mpc
10 e-folds observed
ln a
RD
= T0 / Te ≈ 10^-28
H0^-1



$$N = \log 10^{28} = 64$$

$$H_0^{-1} \simeq 3000 \text{ Mpc}$$

$$0.1 \text{ Mpc}$$

10 e-folds observed

$$\frac{H^{-1}_{end}\ a_0/a_e\ \text{RD}}{H_0^{-1}} = \frac{T_0}{T_e} \simeq 10^{-28}$$

$$T_e \sim 10^{15}\,\text{GeV}$$

$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} + V'(\phi) \\ H^2 = \dfrac{1}{3M_p^2}\left(\dfrac{\dot{\phi}^2}{2} + V(\phi)\right) \end{cases} \xrightarrow{\text{SR}} \begin{cases} \dot{\phi} \simeq -\dfrac{V'}{3H} \\ H^2 \simeq \dfrac{V}{3M_p^2} \end{cases}$$

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- $\frac{1}{2}\dot{\phi}^2 \ll V$ $\qquad \frac{V'^2}{H^2} \ll V$ $\qquad \epsilon = \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2 \ll 1$

(Ex) $\epsilon = -\frac{\dot{H}}{H^2}$

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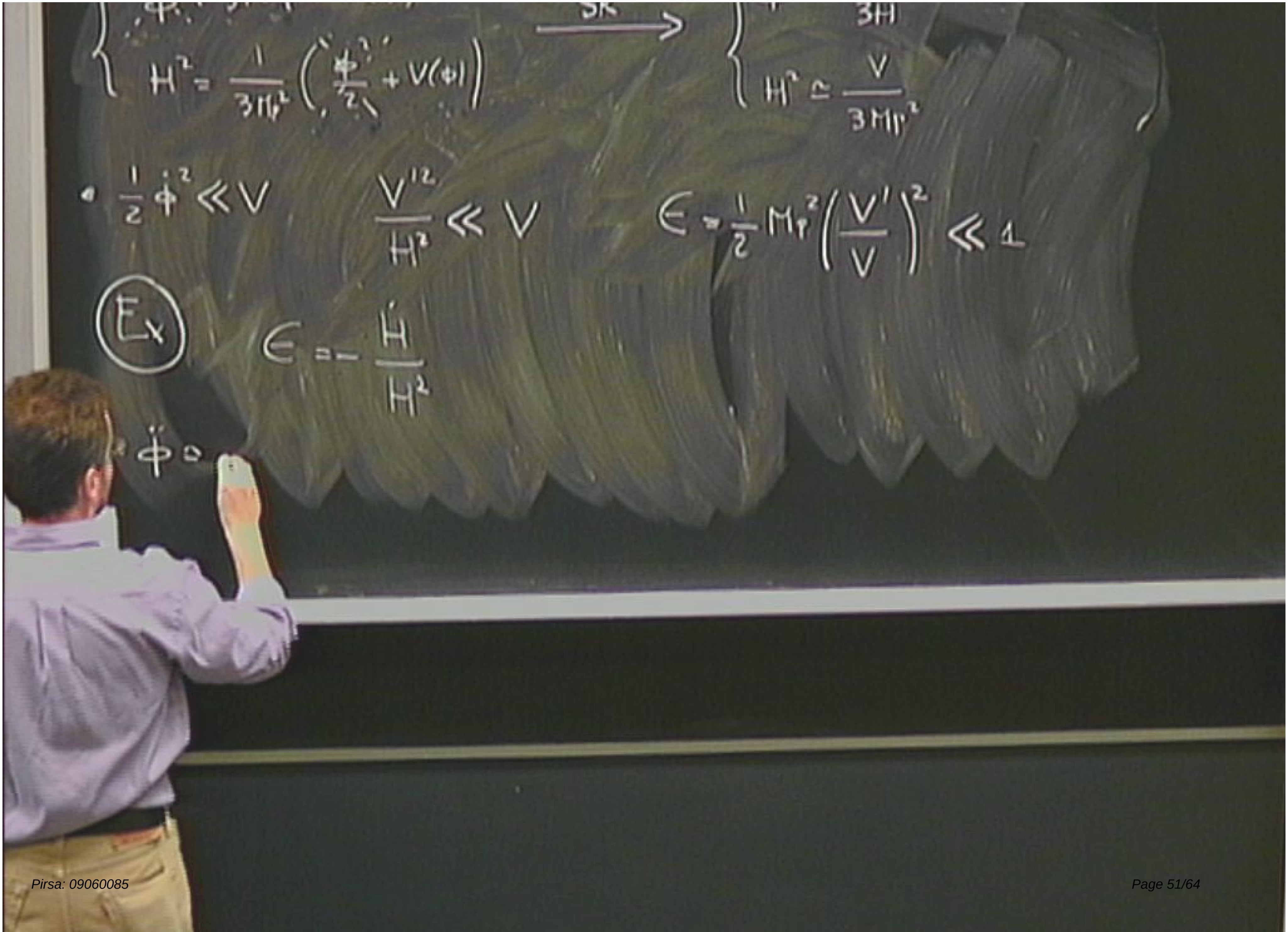
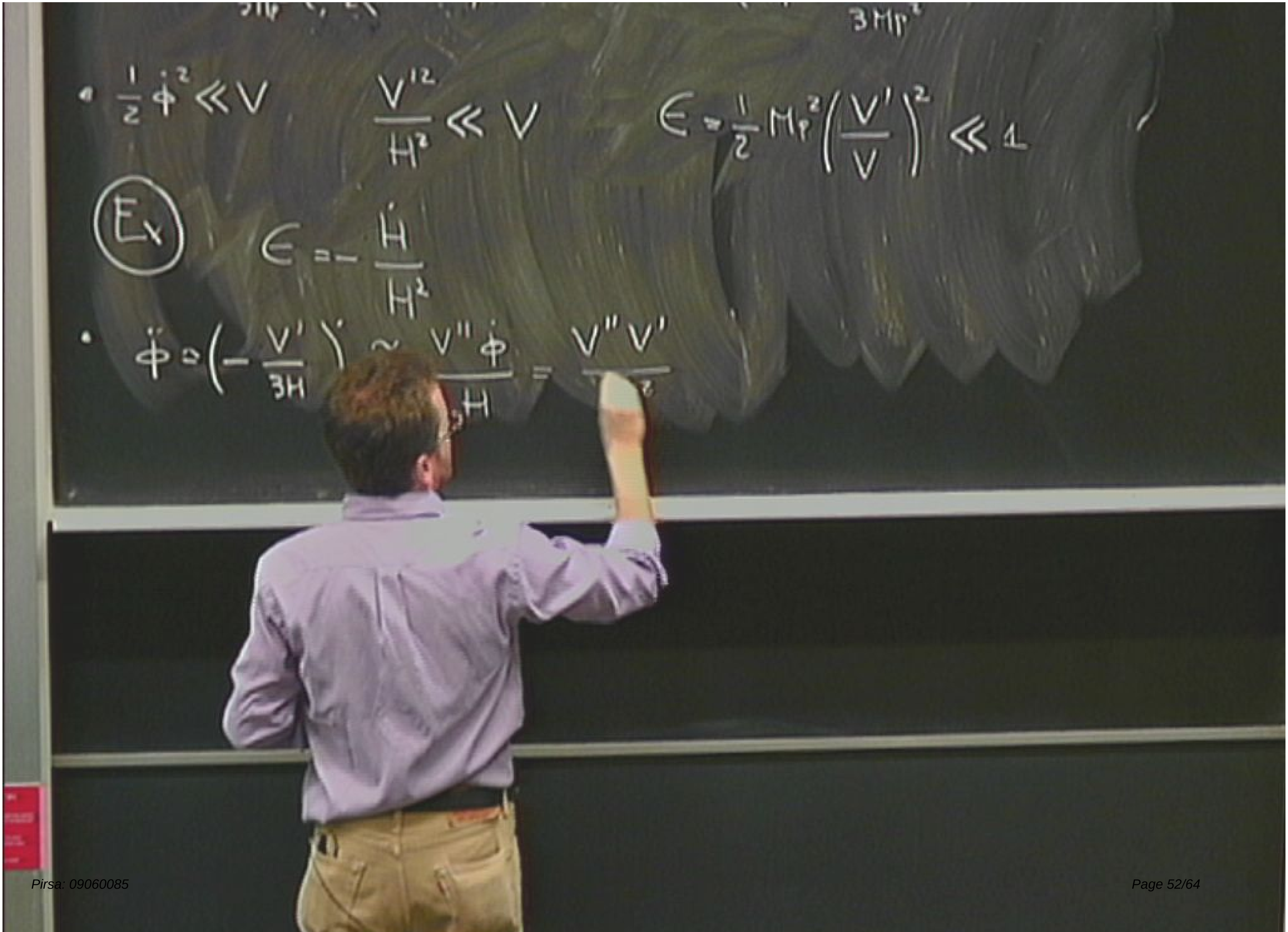
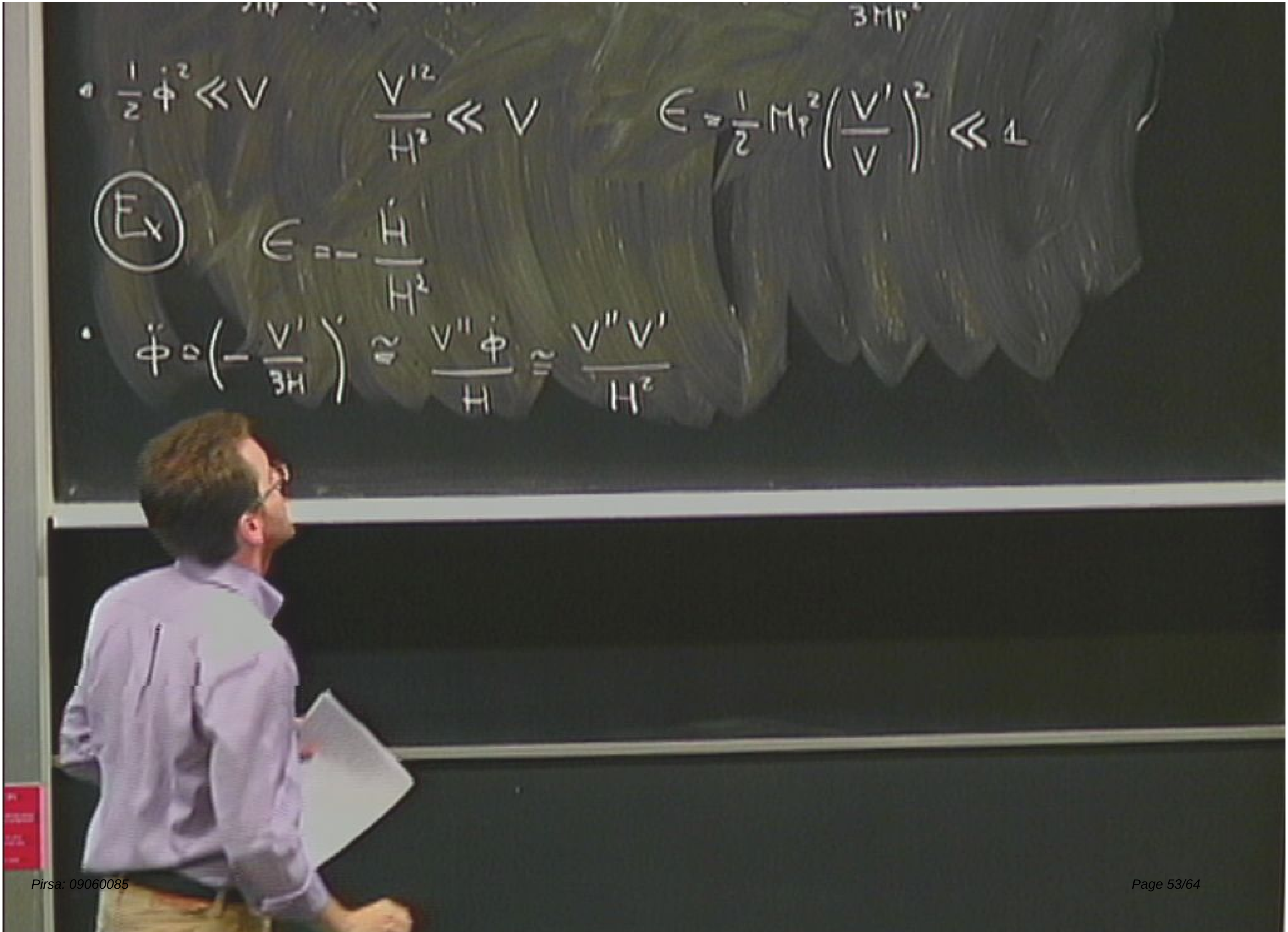
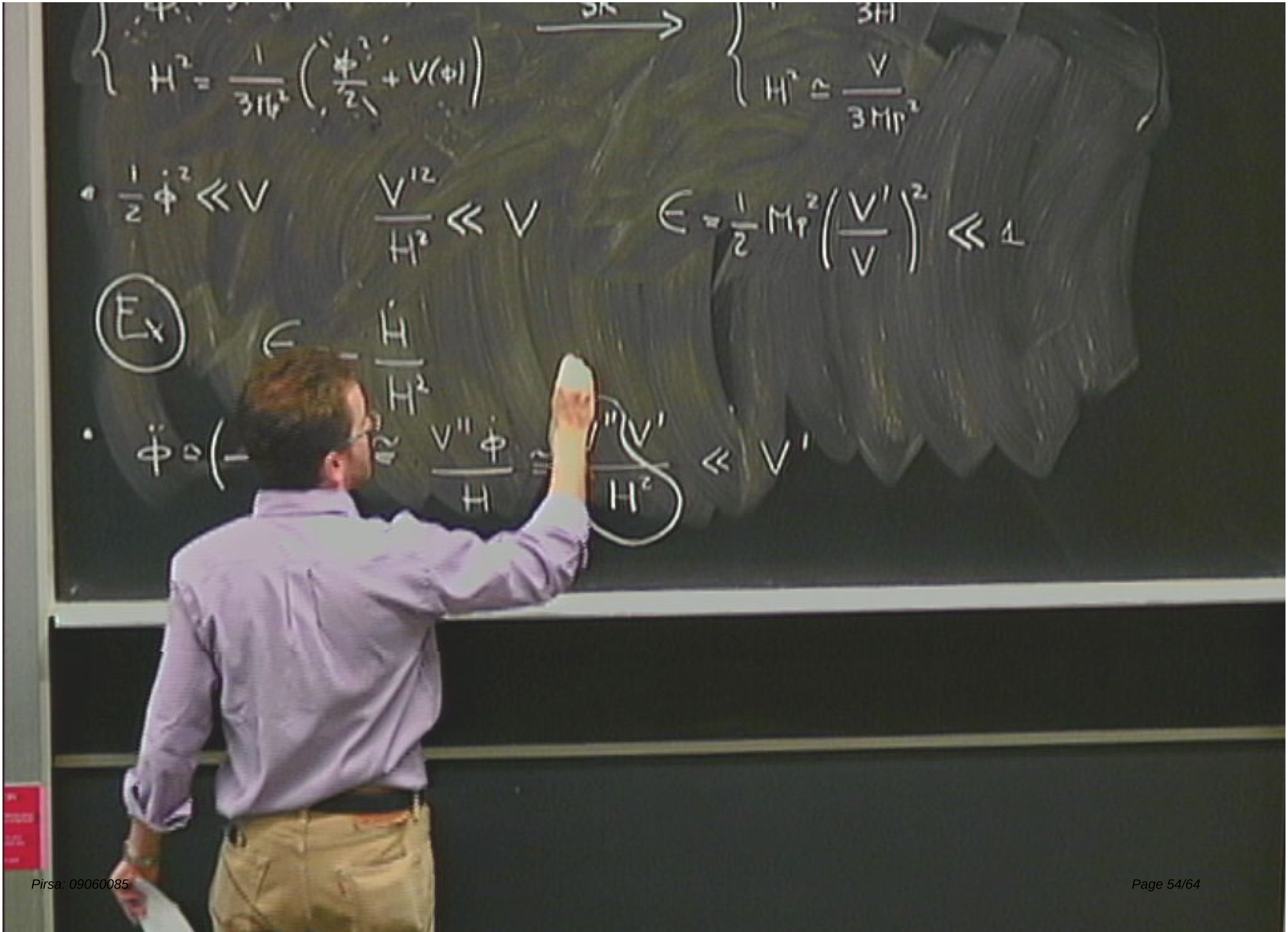

$H^2 = \frac{1}{3M_p^2}\left(\frac{\dot\phi^2}{2} + V(\phi)\right)$
SR
$H^2 \simeq \frac{V}{3M_p^2}$
3H
$\frac{1}{2}\dot\phi^2 \ll V$
$\frac{V'^2}{H^2} \ll V$
$\epsilon = \frac{1}{2} M_p^2 \left(\frac{V'}{V}\right)^2 \ll 1$
Ex
$\epsilon = -\frac{\dot H}{H^2}$
$\ddot\phi \simeq$


• ½ φ̇² ≪ V
V'²/H² ≪ V
ε = ½ Mp² (V'/V)² ≪ 1
Ex
ε = − Ḣ/H²
• φ̈ ≃ (− V'/3H)˙ ~ V''φ̇/H = V''V'



$\bullet\ \frac{1}{2}\dot{\phi}^2 \ll V$
$\frac{V'^2}{H^2} \ll V$
$\epsilon \approx \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 \ll 1$
Ex
$\epsilon = -\frac{\dot{H}}{H^2}$
$\bullet\ \ddot{\phi} \approx \left(-\frac{V'}{3H}\right)^{\cdot} \approx \frac{V''\dot{\phi}}{H} \approx \frac{V''V'}{H^2}$


$H^2 = \frac{1}{3M_p^2}\left(\frac{\dot\phi^2}{2} + V(\phi)\right)$
$H^2 \simeq \frac{V}{3M_p^2}$
$\frac{1}{2}\dot\phi^2 \ll V$
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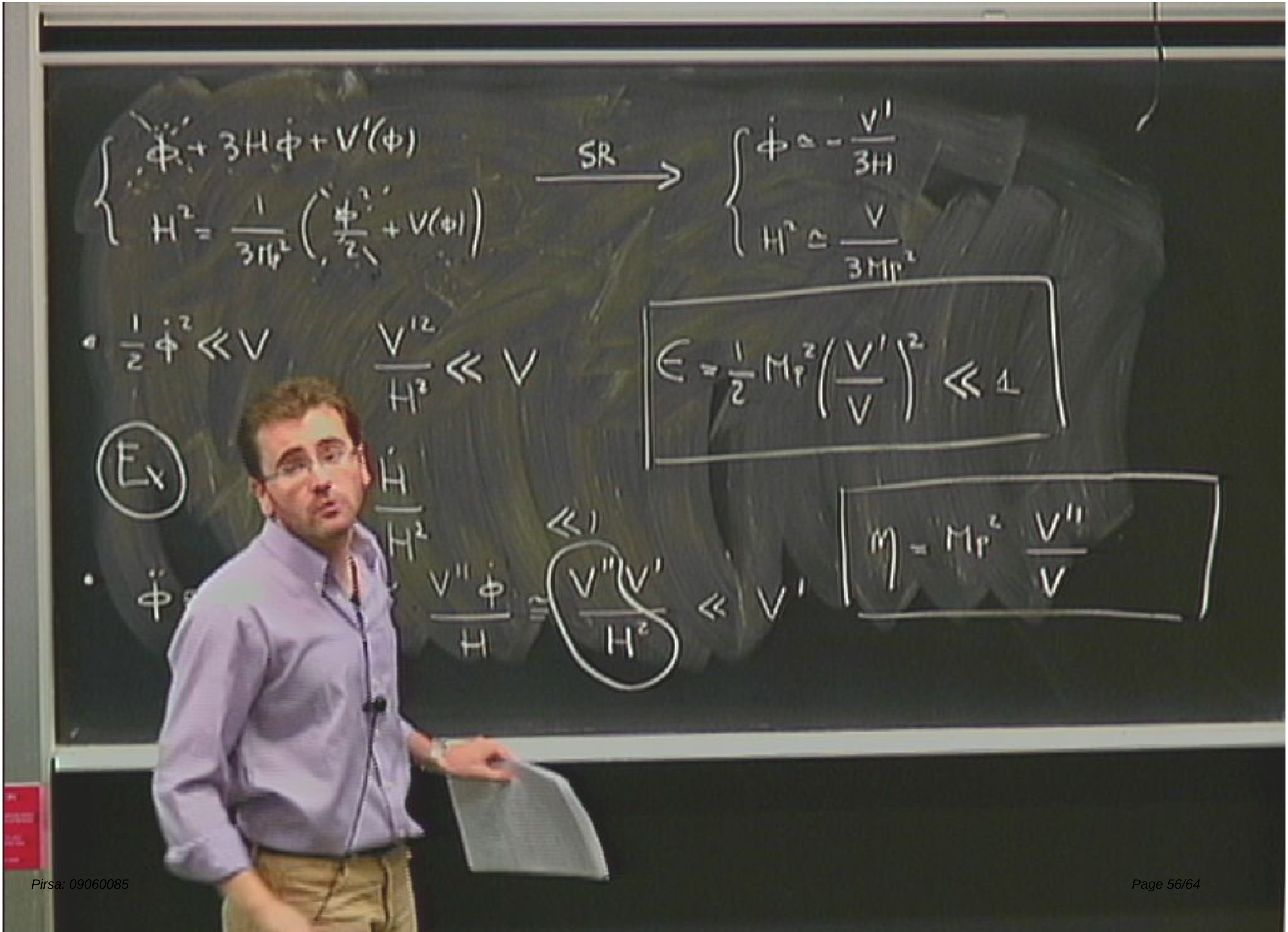
Ex
$\epsilon = -\frac{\dot H}{H^2}$
$\ddot\phi \simeq \frac{V''\dot\phi}{H} \simeq \frac{V''V'}{H^2} \ll V'$

$$\left\{ H^2 = \frac{1}{3M_P^2}\left(\frac{\dot\phi^2}{2} + V(\phi)\right) \right. \xrightarrow{\quad} \left\{ H^2 \simeq \frac{V}{3M_P^2} \right.$$

- $\frac{1}{2}\dot\phi^2 \ll V \qquad \frac{V'^2}{H^2} \ll V \qquad \epsilon = \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 \ll 1$

(Ex) $\epsilon = -\frac{\dot H}{H^2}$

- $\ddot\phi \simeq \left(-\frac{V'}{3H}\right)^{\cdot} \simeq \frac{V''\dot\phi}{H} \simeq \frac{V''V'}{H^2} \ll V'$ ($\ll 1$)



SR
Ex

$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} + V'(\phi) \\ H^2 = \frac{1}{3M_p^2}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) \end{cases} \xrightarrow{SR} \begin{cases} \dot{\phi} \simeq -\frac{V'}{3H} \\ H^2 \simeq \frac{V}{3M_p^2} \end{cases}$$

- $\frac{1}{2}\dot{\phi}^2 \ll V \qquad \frac{V'^2}{H^2} \ll V$

$$\boxed{\epsilon = \frac{1}{2} M_p^2 \left(\frac{V'}{V}\right)^2 \ll 1}$$

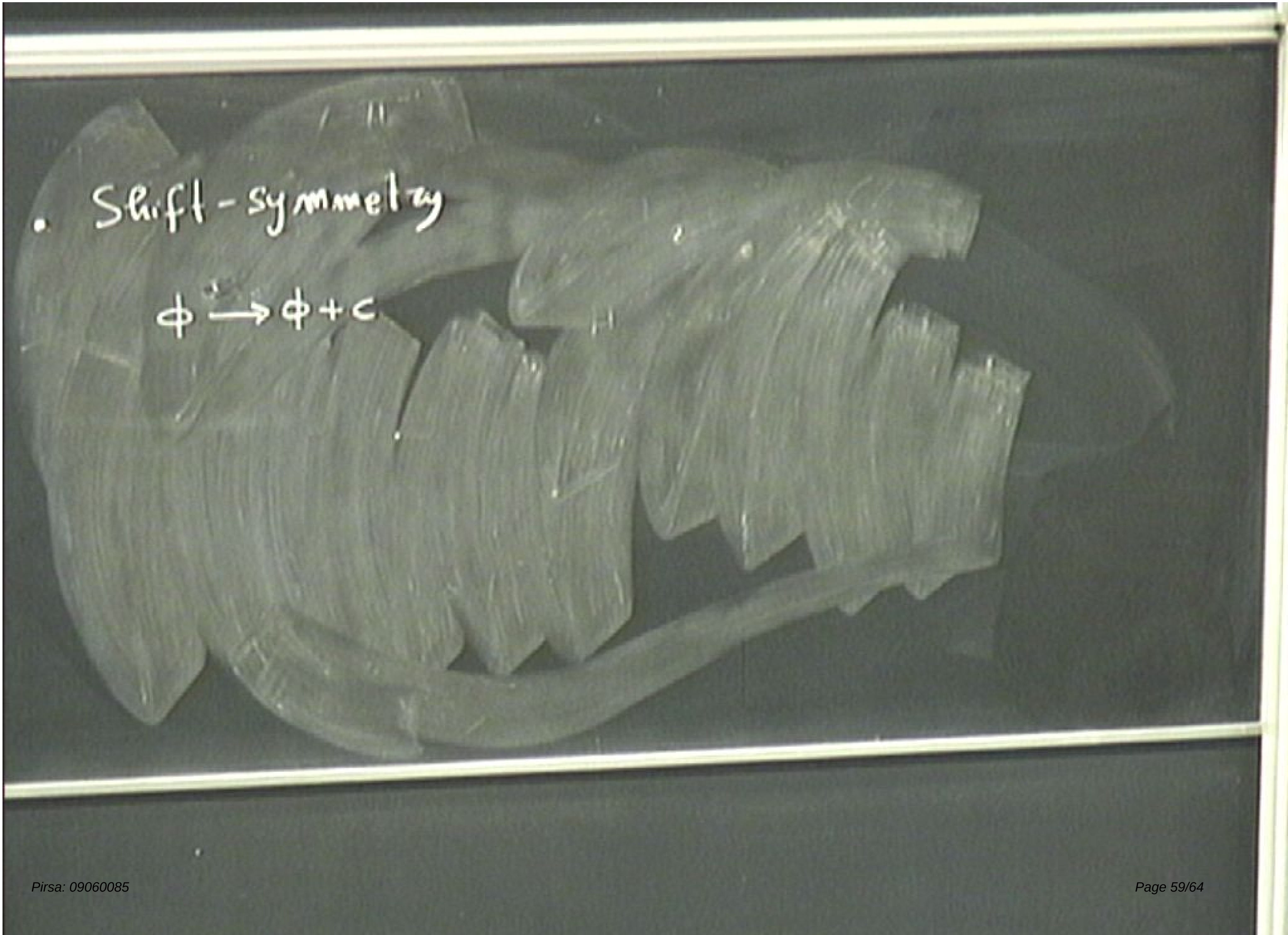
Ex $\quad \epsilon = -\frac{\dot{H}}{H^2}$

- $\ddot{\phi} \simeq \left(-\frac{V'}{3H}\right)^{\cdot} \simeq \frac{V''\dot{\phi}}{H} \simeq \frac{V''V'}{H^2} \ll V'$ $\quad (\ll 1)$

$$\boxed{\eta = M_p^2 \frac{V''}{V}}$$

• Shift-symmetry

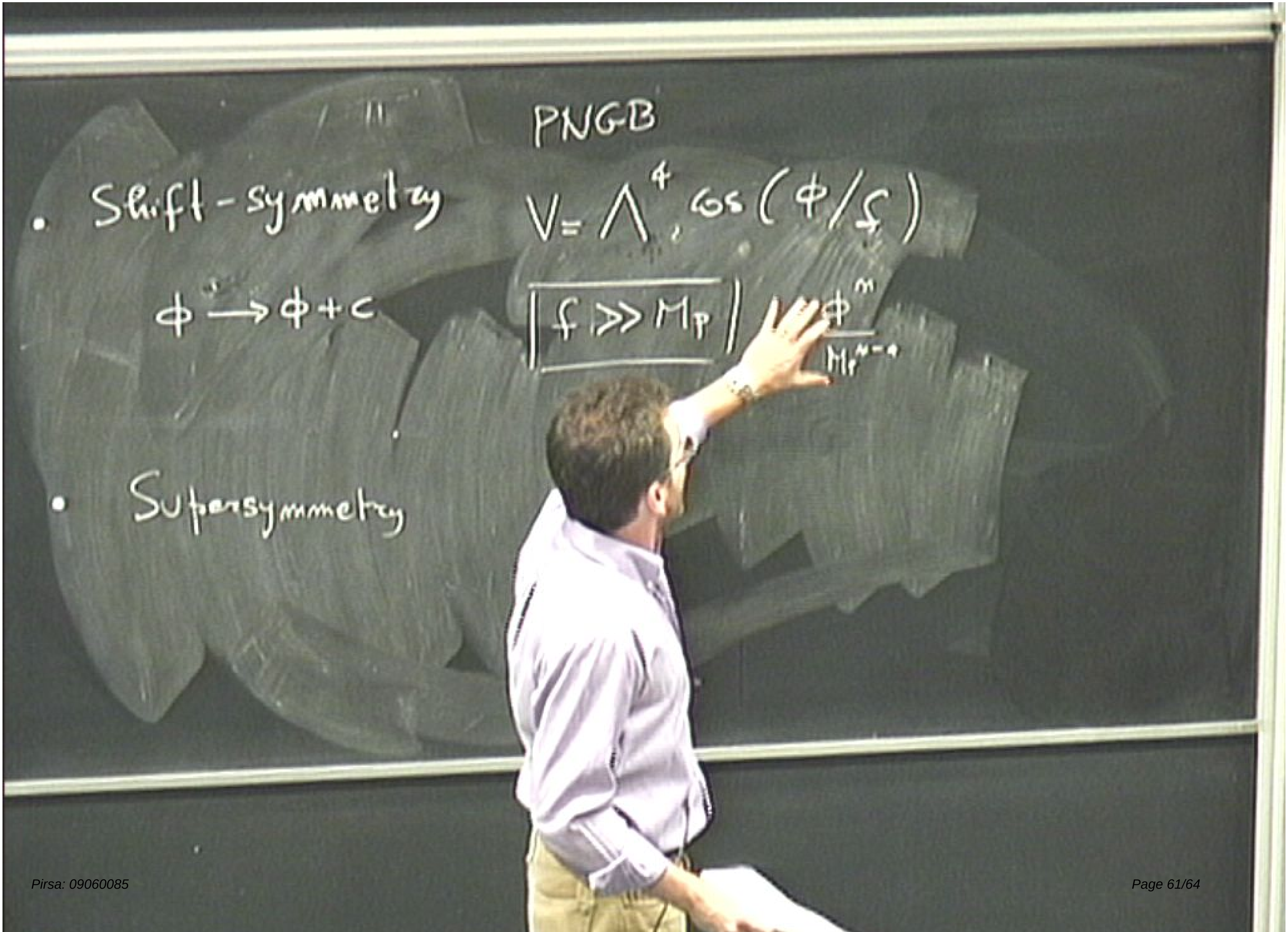
$$\phi \longrightarrow \phi + c$$


• Shift - symmetry
$\phi \longrightarrow \phi + c$

- Shift-symmetry

  $\phi \longrightarrow \phi + c$

- Supersymmetry


PNGB
• Shift-symmetry
V = Λ^4 cos(φ/f)
φ → φ + c
f >> Mp
φ^n / Mp^(n-4)
• Supersymmetry

PNGB

- Shift-symmetry $V = \Lambda^4 \cos(\phi/f)$

  $\phi \to \phi + c$ $\quad \boxed{f \gg M_P} \quad \frac{\phi^n}{M_P^{n-4}}$

- Supersymmetry: $V = e^{K/M_P^2}\left[(K^{-1})^i{}_j L_i L^j - 3\frac{|W|^2}{M_P^2}\right]$

  ↓ GR

  Supergravity $\quad L_i = W_i + K_i \frac{W}{M_P^2}$

PNGB

- Shift-symmetry $\quad V = \Lambda^4 \cos(\phi/f)$

$\phi \to \phi + c \qquad \boxed{f \gg M_p} \qquad \frac{\phi^n}{M_p^{n-4}} \qquad K = \phi^\dagger \phi$

- Supersymmetry: $\quad V = e^{K/M_p^2}\left[(K^{-1})^i{}_j L_i L^j - 3\frac{|W|^2}{M_p^2}\right]$

↓ GR

Supergravity $\qquad L_i = W_i + K_i \frac{W}{M_p^2}$

PNGB

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$\swarrow$ GR

Supergravity $\quad L_i = W_i + K_i \frac{W}{M_p^2}$