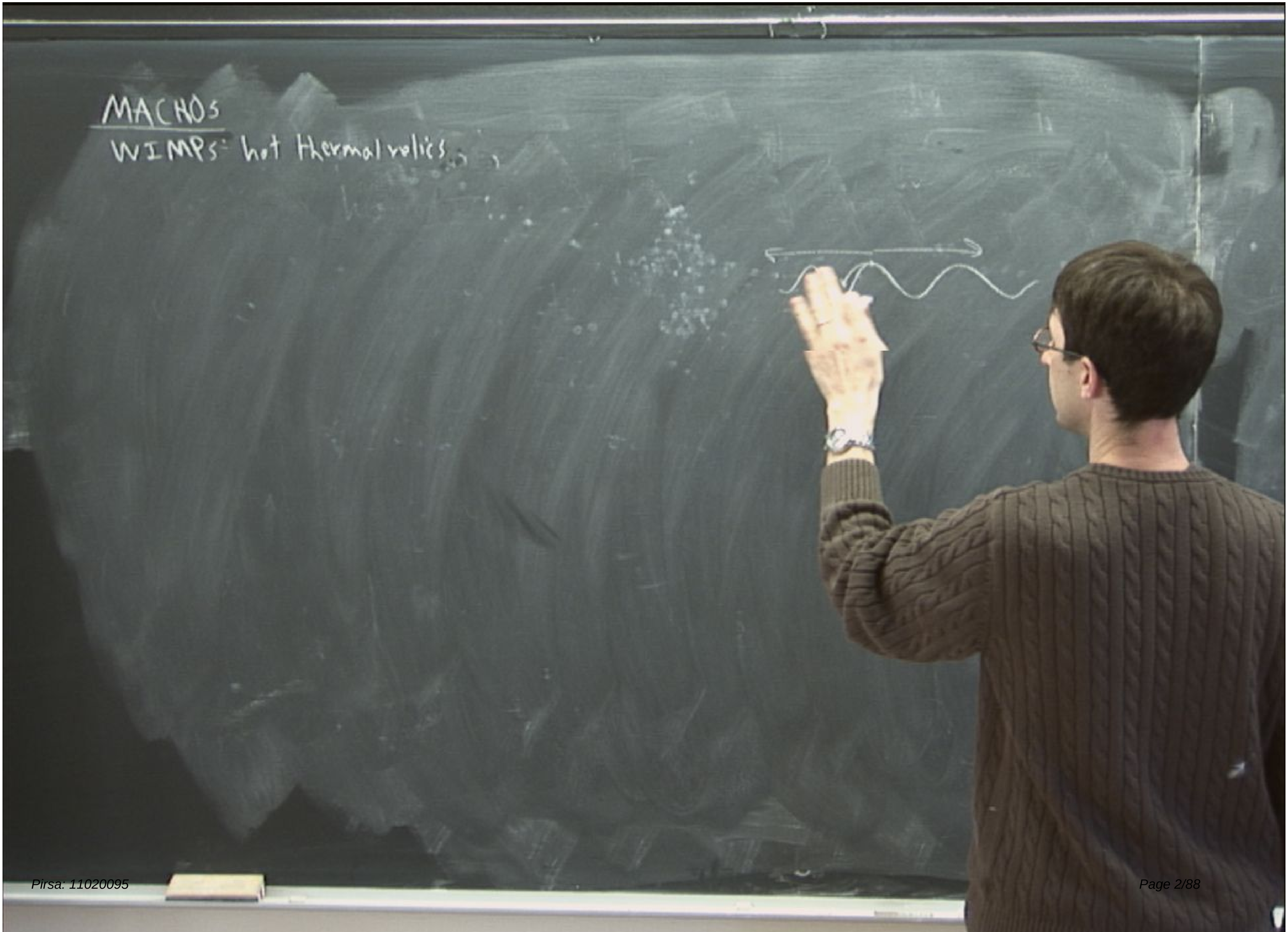
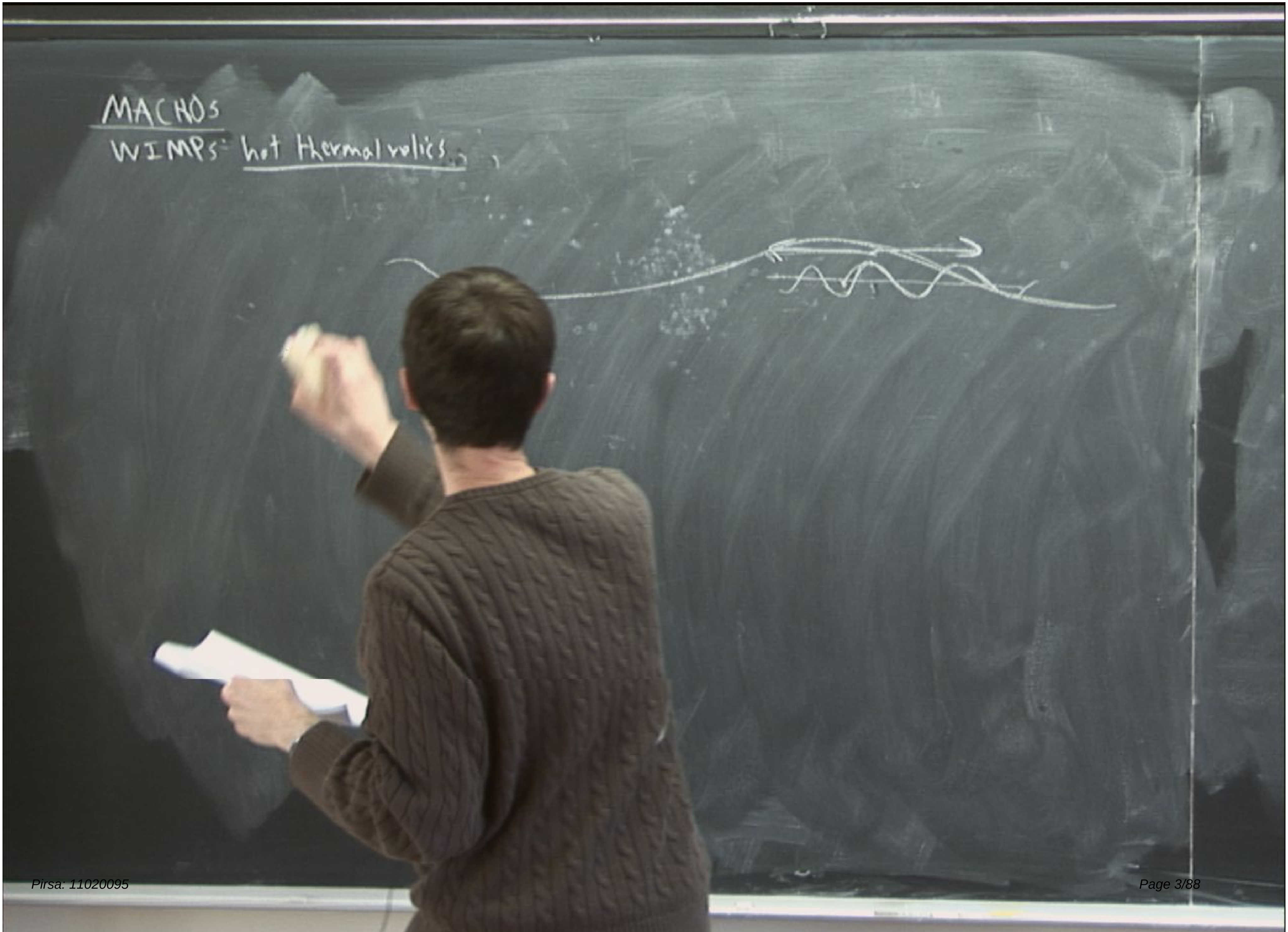
Title: Cosmology Review - Lecture 12

Date: Feb 08, 2011 11:30 AM

URL: http://pirsa.org/11020095

Abstract:


MACHOs
WIMPs: hot thermal relics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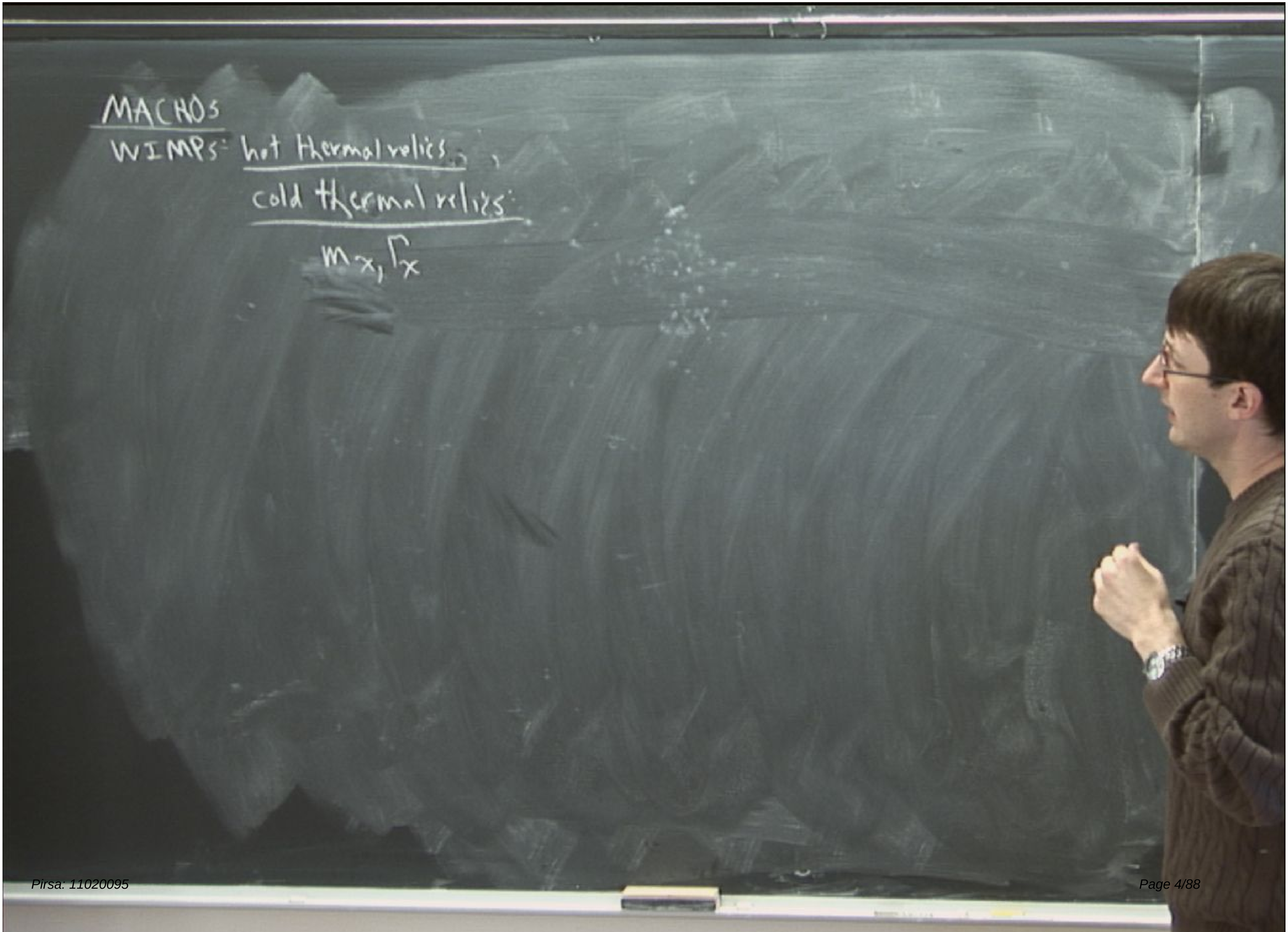
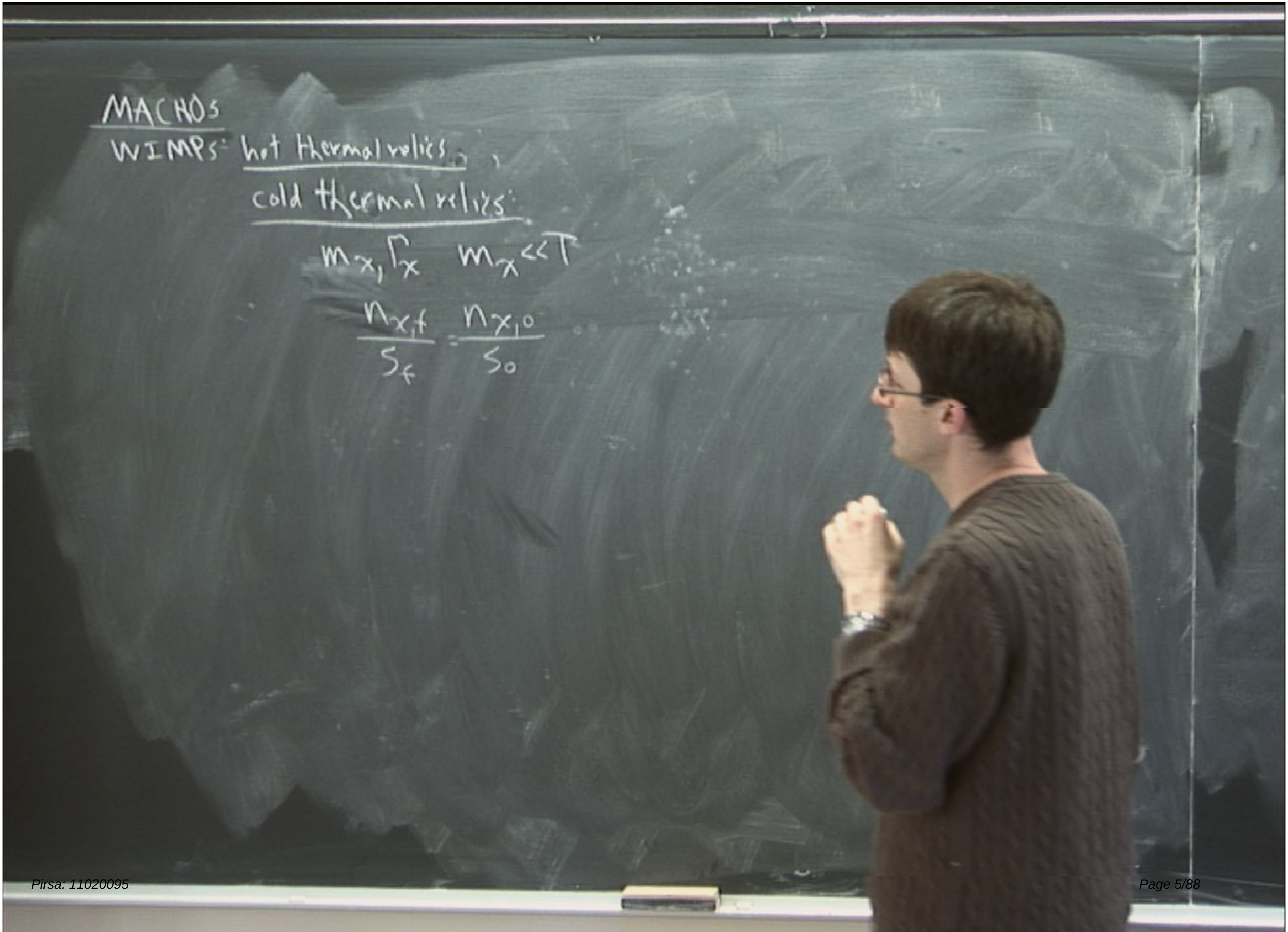

MACHOs
WIMPs: hot thermal relics
cold thermal relics:
m_X, Γ_X


MACHOs
WIMPs: hot thermal relics
cold thermal relics
$m_\chi, \Gamma_\chi \quad m_\chi \ll T$
$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$

MACHOs

WIMPs: hot thermal relics

cold thermal relics:

$m_\chi, \Gamma_\chi \quad m_\chi \ll T$

$$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0} \quad \rho_{\chi,0} = m_\chi n_{\chi,0}$$

$$0.25 = \frac{\rho_{\chi,0}}{\rho_{crit,0}}$$

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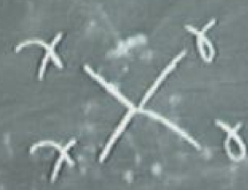

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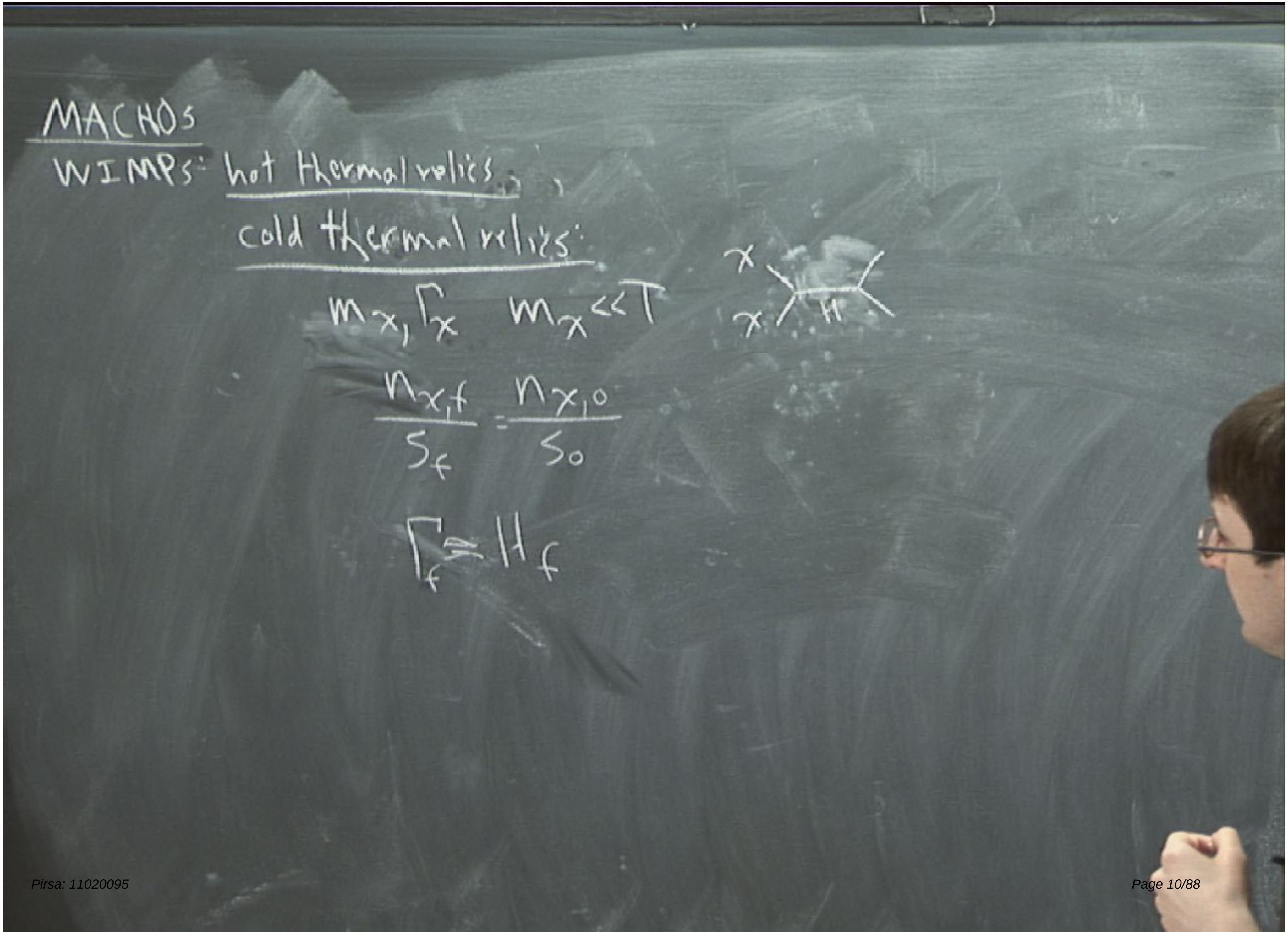
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cold thermal relics:
m_χ, Γ_χ $m_\chi << T$
$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$
$\Gamma_f \simeq H_f$
χ
χ
H

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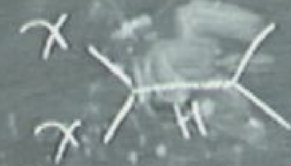

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MACHOs

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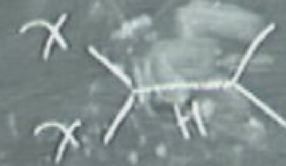

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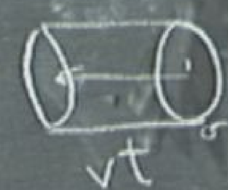

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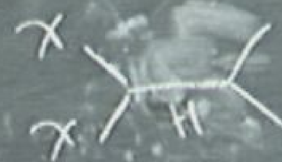
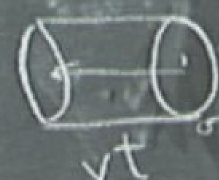


$$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$$



$\sigma v t n_\chi = 1$

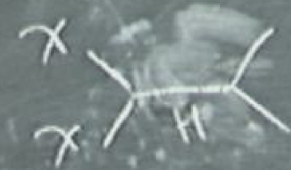
$\Gamma_f \approx H_f$

CHOs

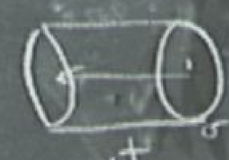
IMPs: hot thermal relics

cold thermal relics:

$m_\chi, \Gamma_\chi \quad m_\chi \ll T$



$$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$$



$\sigma v \, n_\chi = \frac{1}{t} = \Gamma$

$\Gamma_f \approx H_f$

ot thermal relics

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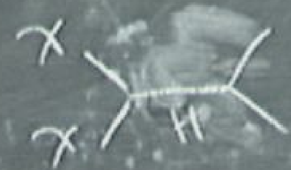
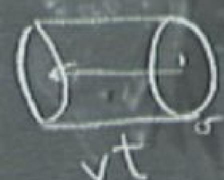
$m_\chi, \Gamma_\chi \quad m_\chi \ll T$



$$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$$

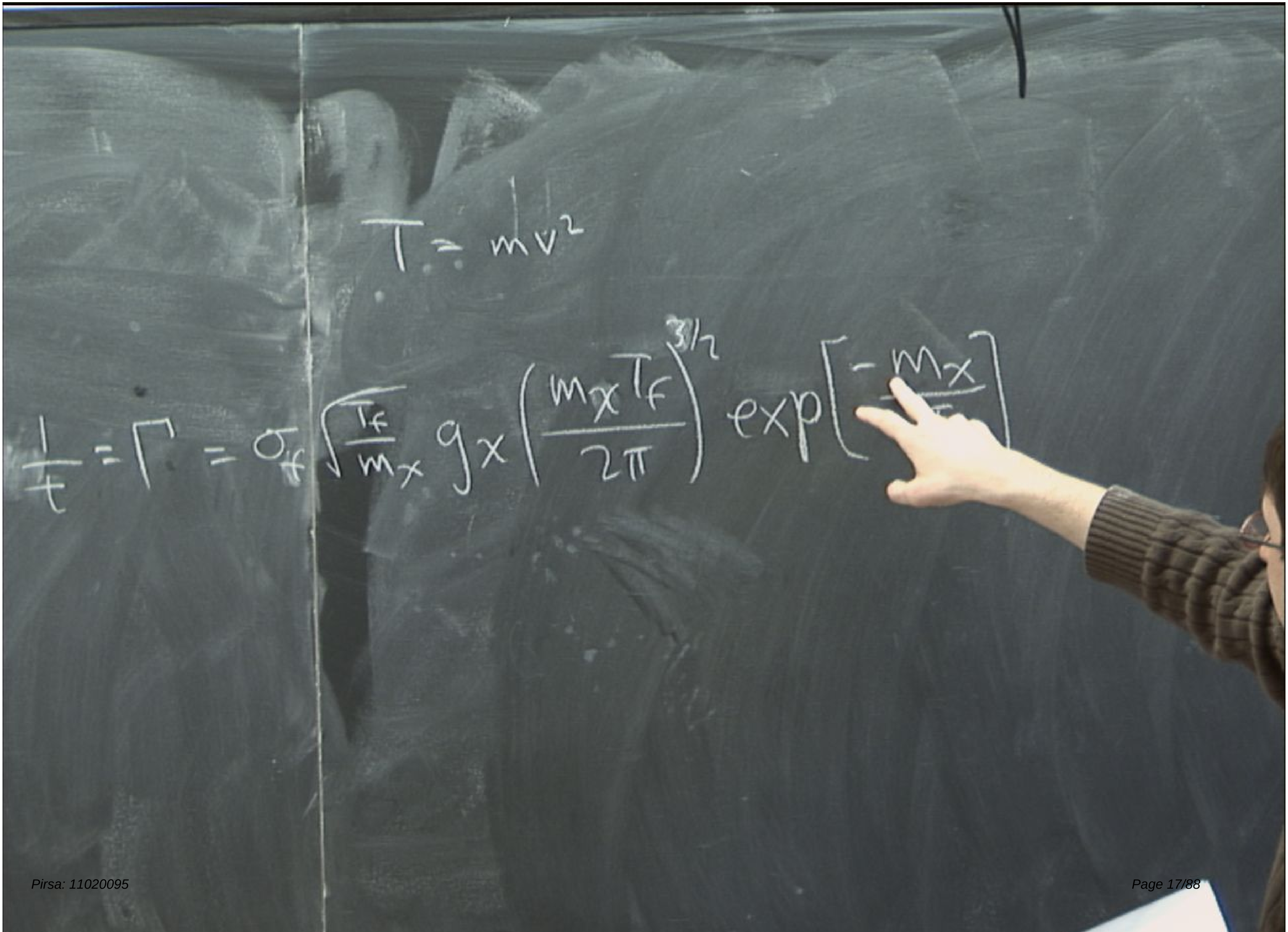


$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma$$

$$\Gamma_f \approx H_f$$

$$T = mv^2$$

$$\langle \sigma v \rangle n_x = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_x}}$$


$T = mv^2$
$\frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_x}}\, g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-m_x\right]$

$$T = mv^2$$

$$\frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_x}}\, g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right]$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho = g_*$$

$$T = mv^2$$

$$\frac{T_f}{m_x} g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right] =$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g_* \frac{\pi^2}{30} T_f^4$$

$$\Big)^{3/2} \exp\left[-\frac{m_x}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g_* \frac{\pi^2}{30} T_f^4$$

$$x_f = \frac{m_x}{T_f}$$

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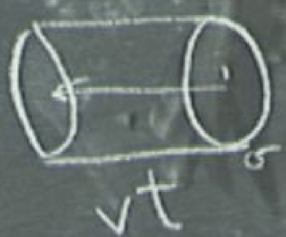

$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, g x \Big($$

$$x_f = \ln\Big[\;\ldots\; m_{pl}\, m_\chi\, \sigma_f \Big]$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho$$

$$\Gamma = H$$

$$x_f = \frac{m_\chi}{T_f}$$

$$\left[\frac{m_\chi}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$$

Vol. 1
QFT

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g$$

$$T = mv^2$$

$$\sigma_f \sqrt{\frac{T_f}{m_x}} \underbrace{g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right]} = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$$

$H^2 = \frac{8}{3}$

$T = mv^2$

$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, \underbrace{g_\chi \left(\frac{m_\chi T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_\chi}{T_f}\right]} = \sqrt{\frac{8\pi}{3}}$$

$$= \ln\left[\quad m_{pl}\, m_\chi\, \sigma_f \right]$$

$$\frac{n_{\chi,f}}{\frac{2\pi^2}{45} g_f}$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g_{*}\frac{\pi^2}{30}T_f^4$$

$$\Gamma = H$$

$$x_f = \frac{m_x}{T_f}$$

$$\exp\left[-\frac{m_x}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$$

$g_{s,f}$ g_f

x,f

f

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g_f \frac{\pi^2}{30} T_f^4$$

$$\Gamma = H$$

$m v^2$

$$x_f = \frac{m_x}{T_f}$$

$$x\left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$$

$$\boxed{g_{s,f} = g_f}$$

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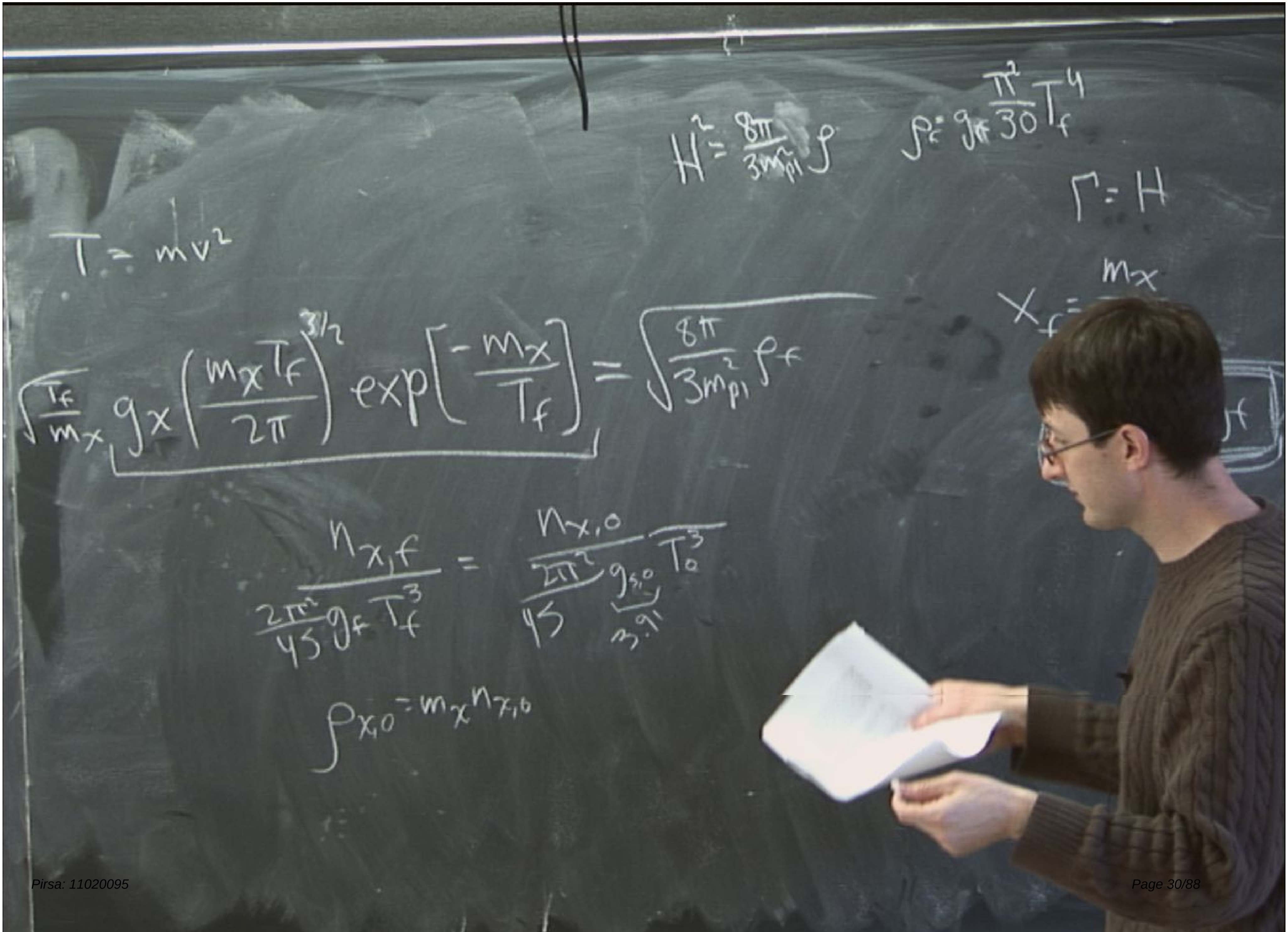
$$\frac{n_{x,f}}{\frac{2\pi^2}{45} g_f T_f^3} = \frac{n_{x,0}}{\frac{2\pi^2}{45} \underbrace{g_{s,0}}_{3.91} T_0^3}$$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$x_f = \frac{m_\chi}{}$
$\sqrt{\frac{T_f}{m_\chi}}\, g_\chi \left(\frac{m_\chi T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_\chi}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\rho_f}$
$\frac{n_{\chi,f}}{\frac{2\pi^2}{45} g_f T_f^3} = \frac{n_{\chi,0}}{\frac{2\pi^2}{45} g_{s,0} T_0^3}$
3.91
$\rho_{\chi,0} = m_\chi n_{\chi,0}$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho \qquad \rho_f = g_f \frac{\pi^2}{30} T_f^4$$

$$\Gamma = H$$

$$T = mv^2$$

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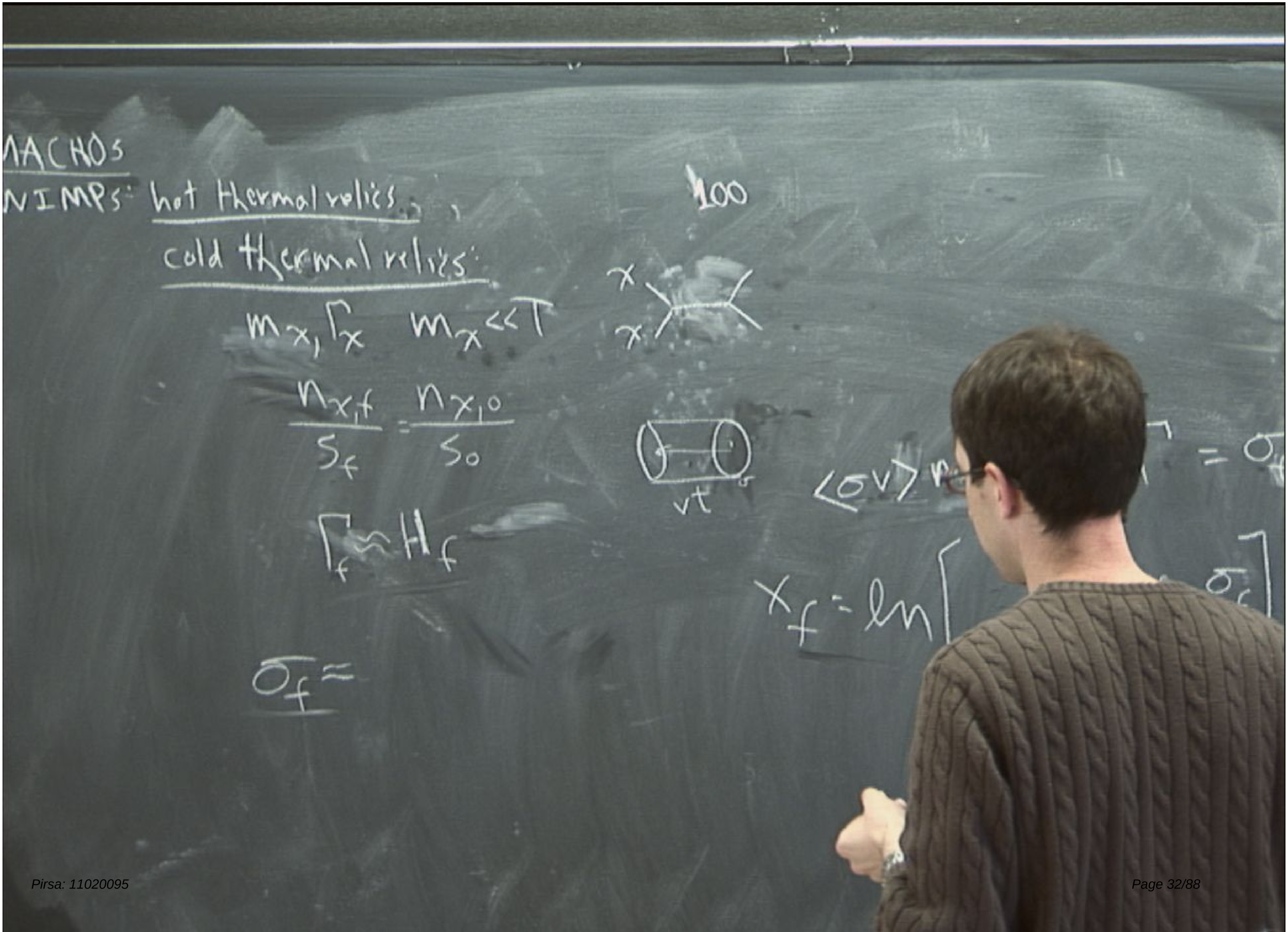
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$\Gamma_f \approx H_f$
$\sigma_f =$
100
χ
χ
vt
$\langle \sigma v \rangle$ n
$= \sigma_f$
$x_f = \ln[$

MACHOS

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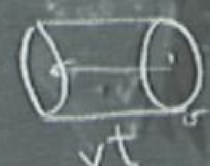
$\Gamma_f \simeq H_f$

$\sigma_f =$

100 GeV $\quad M_W, M_Z, H$



$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma =$

$x_f = \ln\left[\; m_{pl} m_\chi \sigma_f \right.$

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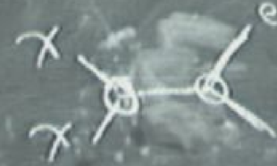
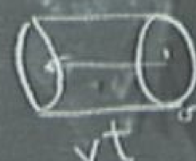


$$g^2 \frac{1}{M^2} \sim G_F$$



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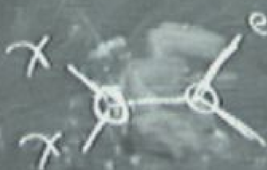
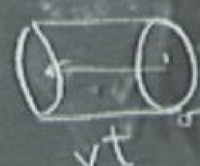


$$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\mathrm{GeV}^2}$$



$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f$$

$$x_f = \ln\left[\quad m_{pl} m_\chi \sigma_f \right]$$

...nal relics

...ermal relics:

$n_\chi, \Gamma_\chi \quad m_\chi \ll T$

$$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$$

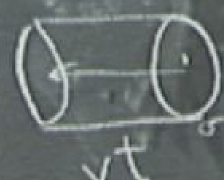
$$\Gamma_f \simeq H_f$$

$\sigma_f \simeq$

100 GeV $\quad M_W, M_Z, H$

$$\sigma \sim |M|^2$$

$$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\mathrm{GeV}^2}$$



$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}$$

$$x_f = \ln\left[\; \cdot \; m_{pl}\, m_\chi\, \sigma_f \right]$$

T

$\sigma \sim |M|^2$

100 GeV $\quad \underline{M_W, M_Z}, \underline{H}$

$\frac{n_{\chi}}{s}$

$m_\chi \ll T$

$\chi\chi \to e$

$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\mathrm{GeV}^2}$

$T = mv^2$

$\frac{n_{\chi,0}}{s_0}$

$vt \quad \sigma$

$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, g_\chi \left(\frac{m_\chi}{\ldots} \right.$

$x_f = \ln\left[\quad m_{pl}\, m_\chi\, \sigma_f \right]$

$$\sigma \sim |\mathcal{M}|^2 m_\chi^2$$

GeV

$100 \quad \underline{M_W, M_Z}, \underline{H}$

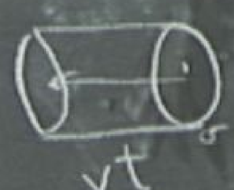
...ies:

$m_\chi \ll T$

$$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\mathrm{GeV}^2}$$

$$T = m v^2$$

$$\frac{n_{\chi,0}}{s_0}$$



$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, g_\chi \Big(\frac{m_\chi}{\cdots}$$

...f

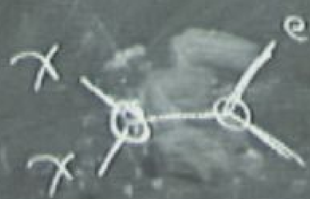
$$x_f = \ln\Big[\; m_{pl} m_\chi \sigma_f \Big]$$

$\sigma \sim |\mathcal{M}|^2 m_\chi^2 \sim G_F^2 m_\chi^2$

100 GeV $\quad M_W, M_Z, H$

...ies:

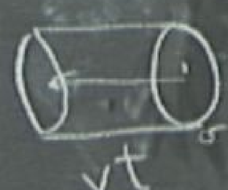
$m_\chi << T$



$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\mathrm{GeV}^2}$

$T = m v^2$

$\frac{n_{\chi,0}}{s_0}$



$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, g \ldots \left(m_\chi \ldots \right.$

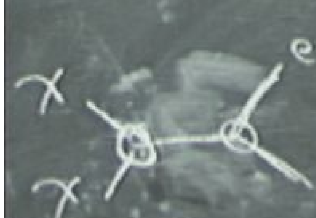
n_f

$x_f = \ln\left[\; m_{pl} m_\chi \sigma_f \; \right]$

$$\sigma \sim |M|^2 m_\chi^2 \sim G_F^2 m_\chi^2$$

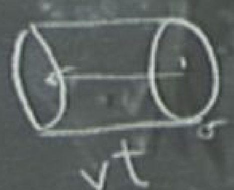
$\uparrow_p$ 1 GeV

100 GeV $\underline{M_W, M_Z, H}$



$$g^2 \frac{1}{M^2} \sim G_F \sim \frac{1}{10^5\,\text{GeV}^2}$$

$$T = m v^2$$

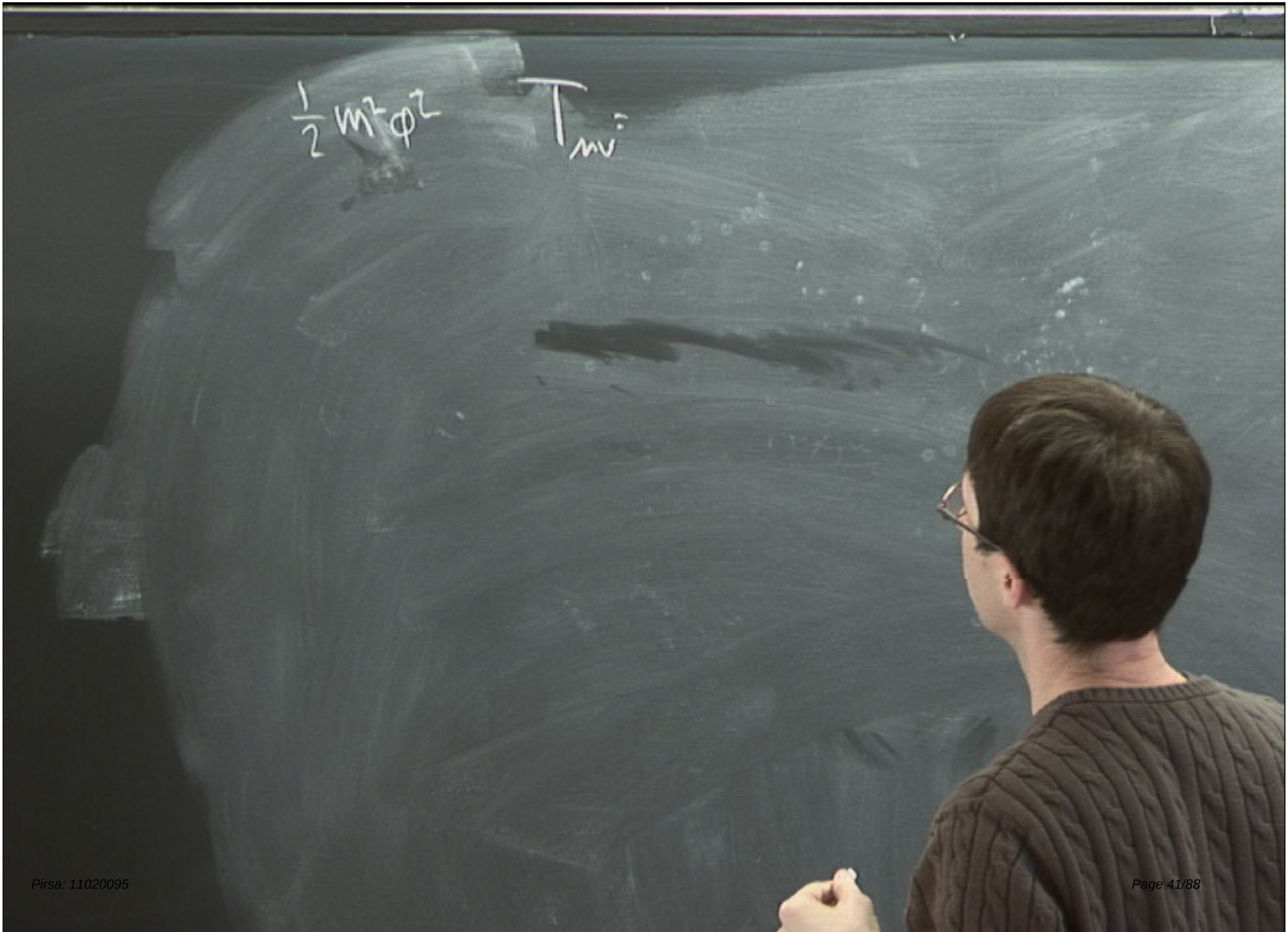


$$\langle \sigma v \rangle n_\chi = \frac{1}{t} = \Gamma = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, \underline{g_\chi \left(\frac{m_\chi T_f}{2\pi}\right)^{3/2} \mathrm{ex}}$$

$$x_f = \ln\left[\; m_p\, m_\chi\, \sigma_f \right]$$

$$\frac{n_{\chi,f}}{\frac{2\pi^2}{45} g_f T}$$

$\rho_{\chi,0}$


$\frac{1}{2} m^2 \phi^2$
$T_{\mu\nu} =$

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

$T_{\mu\nu} = \ldots$

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

$T_{\mu\nu} = \dots$

$T^{\mu}{}_{\nu} =$

$\frac{1}{2} m^2 \phi^2$ $\quad T_{\mu\nu} = \ldots \quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

$\frac{1}{2}m^2\phi^2$ $\quad T_{\mu\nu} = \ldots$ $\quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

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

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$\frac{1}{2} m^2 \phi^2$ $\quad T_{\mu\nu} = \ldots$ $\quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$ $\quad T^{\mu\nu}$

$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

$Q \quad j^{\mu}(x) = (\rho, \vec{j})$

$\frac{1}{2}m^2\phi^2$ $\quad \underline{T_{\mu\nu}} = \ldots$ $\quad T^\mu{}_\nu = \mathrm{diag}(-\rho, p, p, p)$

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

$p = \frac{1}{2}\dot\phi^2 - V(\phi)$

$T^{\mu\nu}$

$Q \quad j^\mu(x) = (\rho, \vec{j})$

$j^\mu{}_{,\mu} = 0$

$\ldots$ $T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

$V(\phi)$ $T^{\mu\nu}$

$V(\phi)$

$\underline{Q}$ $j^{\mu}(x) = (\rho, \vec{j})$

$\underline{j^{\mu}{}_{;\mu} = 0}$ $\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{j}$

$\bigcirc$

$$T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$$

$V(\phi)$

$V(\phi)$

$$T^{\mu\nu}{}_{;\nu} = 0$$

Q $\quad j^{\mu}(x) = (\rho, \vec{j})$

P^{μ} $\quad \boxed{j^{\mu}{}_{;\mu} = 0}$ $\quad \frac{\partial \rho}{\partial t} = \vec{\nabla} \cdot \vec{j}$

$$T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$$

$V(\phi)$

$V(\phi)$

$$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p)$$

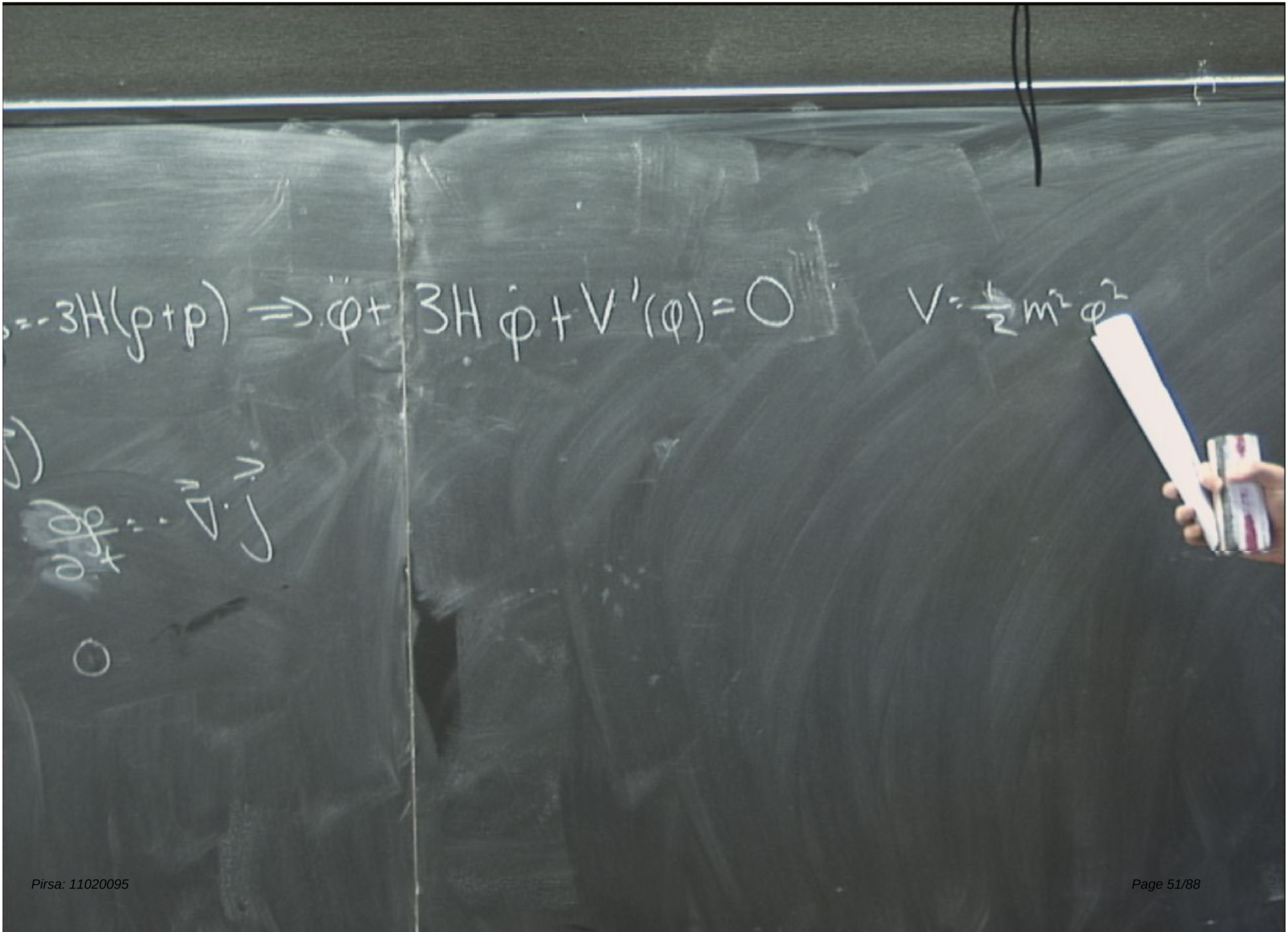
Q

$$j^{\mu}(x) = (\rho, \vec{j})$$

P^{μ}

$$\boxed{j^{\mu}{}_{;\mu} = 0}$$

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{j}$$


= -3H(ρ+p) ⇒ φ̈ + 3H φ̇ + V'(φ) = 0
V = ½ m² φ²
∂ρ/∂t = - ∇·j
0

x $\quad V(x) = \frac{1}{2} m\omega^2 x^2$ $\quad m$

$$= -3H(\rho + p) \Rightarrow \ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0 \qquad V = \frac{1}{2}m^2\varphi^2$$

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{j}$$

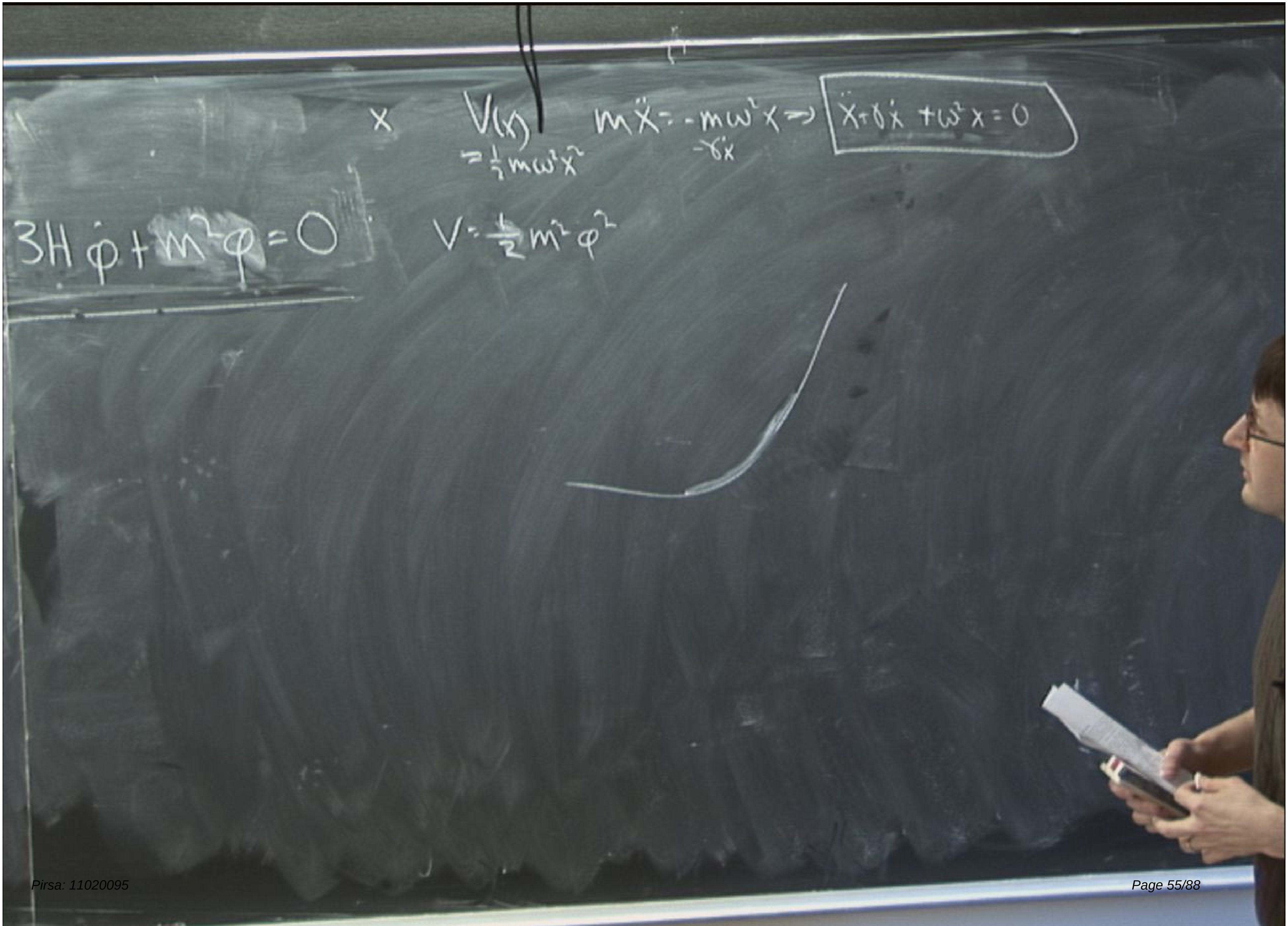
0

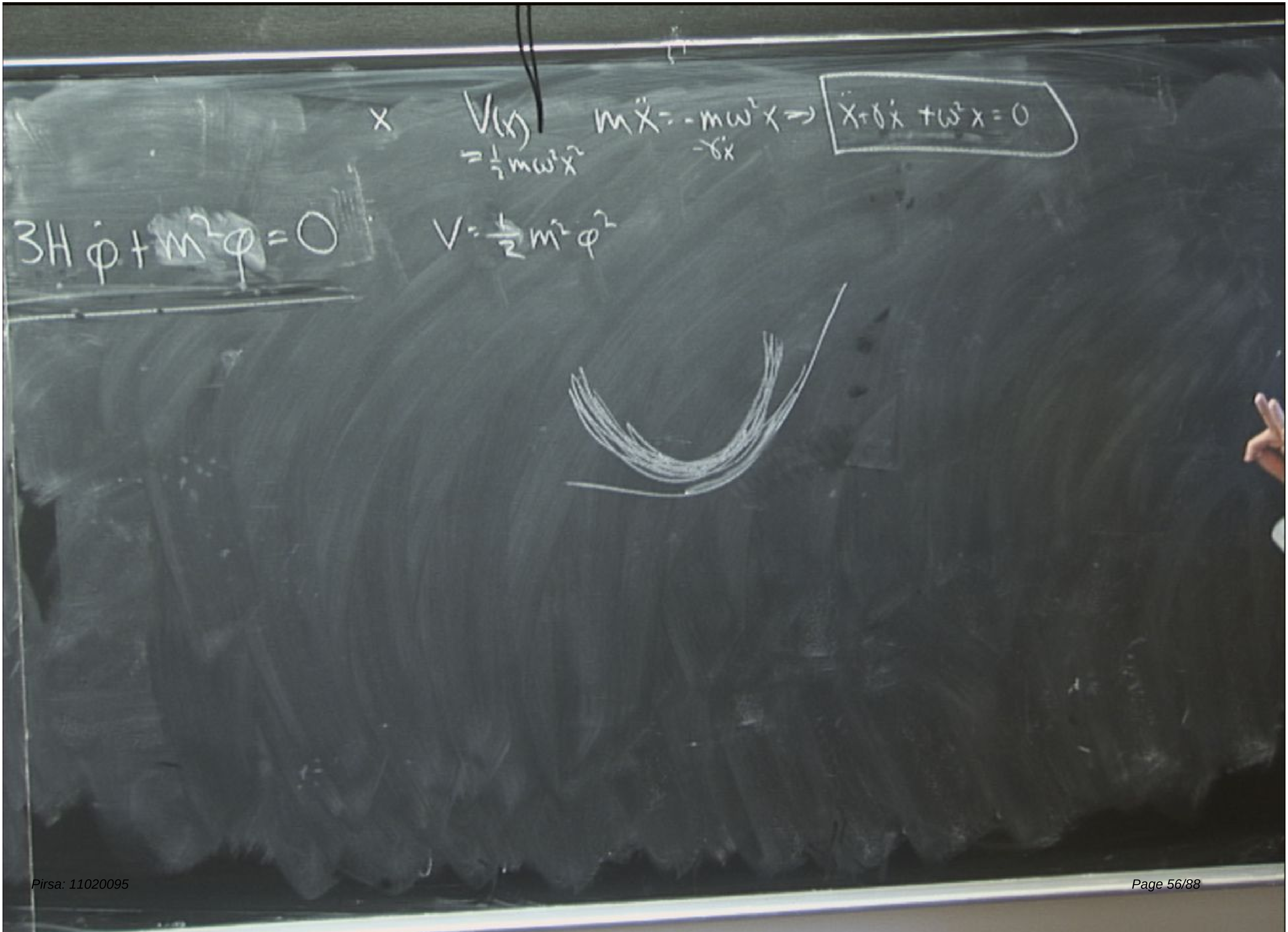
$x \qquad V(x) = \frac{1}{2} m\omega^2 x^2 \qquad m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \ddot{x} + \gamma\dot{x} + \omega^2 x = 0$

$\ldots {}^2\varphi = 0 \qquad V = \frac{1}{2} m^2 \varphi^2$

$x \quad V(x) = \frac{1}{2} m\omega^2 x^2 \quad m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x = 0}$

$3H\dot{\varphi} + m^2\varphi = 0 \qquad V = \frac{1}{2} m^2 \varphi^2$


x
$V(x) = \frac{1}{2} m\omega^2 x^2$
$m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \ddot{x} + \gamma\dot{x} + \omega^2 x = 0$
$3H\dot{\varphi} + m^2\varphi = 0$
$V = \frac{1}{2} m^2 \varphi^2$


x
$V(x) = \frac{1}{2} m\omega^2 x^2$
$m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x = 0}$
$3H\dot{\varphi} + m^2\varphi = 0$
$V = \frac{1}{2} m^2 \varphi^2$

$x \qquad V(x) = \frac{1}{2} m\omega^2 x^2 \qquad m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x =}$

$H(\rho + p) \Rightarrow \underline{\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0} \qquad V = \frac{1}{2} m^2 \varphi^2$

$\frac{\partial\rho}{\partial t} = -\vec{\nabla}\cdot\vec{j}$

0

$\frac{1}{2}m^2\phi^2$ $\quad$ $T_{\mu\nu} = \dots$ $\quad$ $T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

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

$$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow$$

Q $\quad$ $j^{\mu}(x) = (\rho, \vec{j})$

P^{μ} $\quad$ $\boxed{j^{\mu}{}_{;\mu} = 0}$ $\quad$ $\frac{\partial \rho}{\partial t} \dots \vec{\nabla}\cdot\vec{j}$

(ρ, p, ρ)

$0 \to \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$

x $\quad V(x) = \frac{1}{2}m\omega^2 x^2$ $\quad m\ddot{x}$

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

$j^\mu = (\rho, \vec{j})$

$\partial_\mu j^\mu = 0 \qquad \frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\vec{j}$

$\frac{\ddot{\varphi}}{\dot{\varphi}} = -3H \Rightarrow \dot{\varphi} \propto a^{-3}$

$\frac{1}{2} m^2 \phi^2$ $\qquad T_{\mu\nu} = \dots \qquad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

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

$$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p$$

$Q \qquad j^{\mu}(x) = (\rho, \vec{j})$

$P^{\mu} \qquad \boxed{j^{\mu}{}_{;\mu} = 0} \qquad \frac{\partial \rho}{\partial t} \cdots \nabla$

$$m = H_i = \sqrt{\frac{8\pi}{3 m_{pl}^2} g_* T_i^4}$$

$x \qquad V(x) = \frac{1}{2} m\omega^2 x^2 \qquad m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x = 0}$

$\varphi = 0 \qquad V = \frac{1}{2} m^2 \varphi^2 \qquad \varphi = a^{-3/2} u \qquad \dot{\varphi} = a^{-3/2}\dot{u} - \frac{3}{2} a^{-5/2} \dot{a} u$

$\Rightarrow \dot{\varphi} \propto a^{-3}$

$\ddot{u} + (\qquad) u$

x

$V(x) = \frac{1}{2} m\omega^2 x^2$

$m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x = 0}$

a^{-3}

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

$\varphi = a^{-3/2} u$

$\dot{\varphi} = a^{-3/2}\dot{u} - \frac{3}{2} a^{-5/2} \dot{a} u$

$\ddot{u} + \left(-\frac{c}{t^2} + m^2\right) u = 0$

$\varphi = a^{-3/2} \cos mt$

$\frac{1}{2}m^2\phi^2$ $\quad T_{\mu\nu} = \ldots \quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

3

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

$$T^{\mu\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\phi}$$

Q $\quad j^{\mu}(x) = (\rho, \vec{j})$

P^{μ} $\quad \boxed{j^{\mu}{}_{;\mu} = 0} \quad \frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\vec{j}$

$$m = H_i = \sqrt{\frac{8\pi}{3m_{pl}^2} g_* T_i^4}$$

$T_{\mu\nu} = \dots$

$T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

$+V(\phi)$

$- V(\phi)$

$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\phi} + 3H\dot{\phi}$

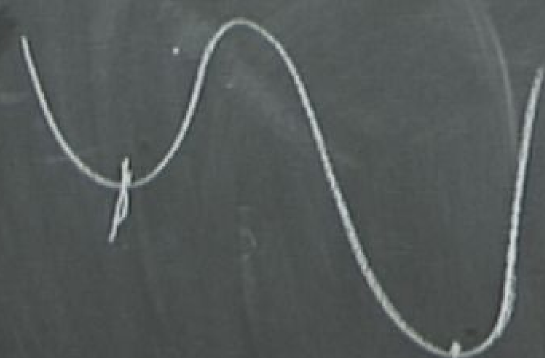
Q $\quad j^{\mu}(x) = (\rho, \vec{j})$

$\frac{\ddot{\phi}}{\dot{\phi}} \dots$

P^{μ} $\quad \boxed{j^{\mu}{}_{;\mu} = 0}$ $\quad \frac{\partial \rho}{\partial t} \dots \vec{\nabla} \cdot \vec{j}$

ϕ_i

$= H_i = \sqrt{\frac{8\pi}{3 m_{pl}^2} g_* T_i^4}$



x $\quad V(x) = \frac{1}{2} m\omega^2 x^2$ $\quad m\ddot{x} = -m\omega^2 x - \gamma\dot{x} \Rightarrow \boxed{\ddot{x} + \gamma\dot{x} + \omega^2 x = 0}$

$3H\dot{\varphi} + m^2\varphi = 0$ $\quad V = \frac{1}{2} m^2 \varphi^2$ $\quad \varphi = a^{-3/2} u$ $\quad \dot{\varphi} = a^{-3/2}\dot{u} - \frac{3}{2} a^{-5/2} \dot{a} u$

$\frac{\ddot{\varphi}}{\dot{\varphi}} = -3H \Rightarrow \dot{\varphi} \propto a^{-3}$

$\ddot{u} + \left(\frac{c}{t^2} + m^2\right) u = 0$

$\varphi = a^{-3/2} \cos mt$

$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$

$\frac{1}{2} m^2 \phi^2$ $\quad T_{\mu\nu} = \dots \quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

3

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

$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

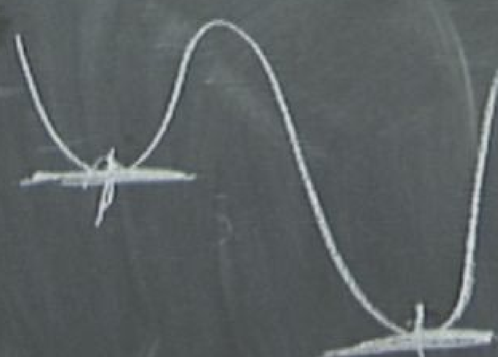
$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\phi}$

$Q \quad j^{\mu}(x) = (\rho, \vec{j})$

$P^{\mu} \quad \boxed{j^{\mu}{}_{;\mu} = 0} \quad \frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \vec{j}$

$m = H_i = \sqrt{\frac{8\pi}{3 m_{pl}^2} g_* T_i^4}$

O



$\frac{1}{2}m^2\phi^2$ $\quad T_{\mu\nu} = \ldots \quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

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

$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

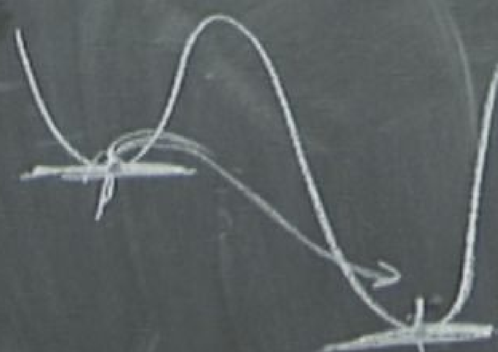
$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\phi}$

$Q \quad j^{\mu}(x) = (\rho, \vec{j})$

$P^{\mu} \quad \boxed{j^{\mu}{}_{;\mu} = 0} \quad \frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\vec{j}$

$m = H_i = \sqrt{\frac{8\pi}{3m_{pl}^2} g_* T_i^4}$

O



$e^{-S_I/\hbar}$

$\frac{1}{2}m^2\phi^2$ $\quad T_{\mu\nu} = \dots \quad T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$

3

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

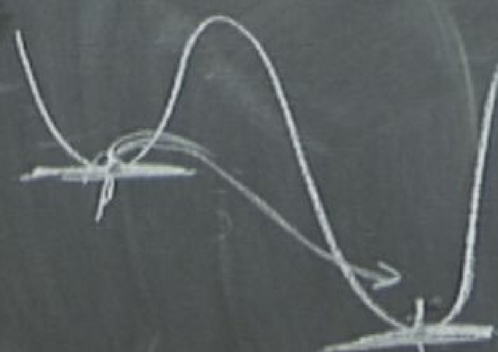
$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho} = -3H(\rho + p) \Rightarrow \ddot{\phi}$

Q $\quad j^{\mu}(x) = (\rho, \vec{j})$

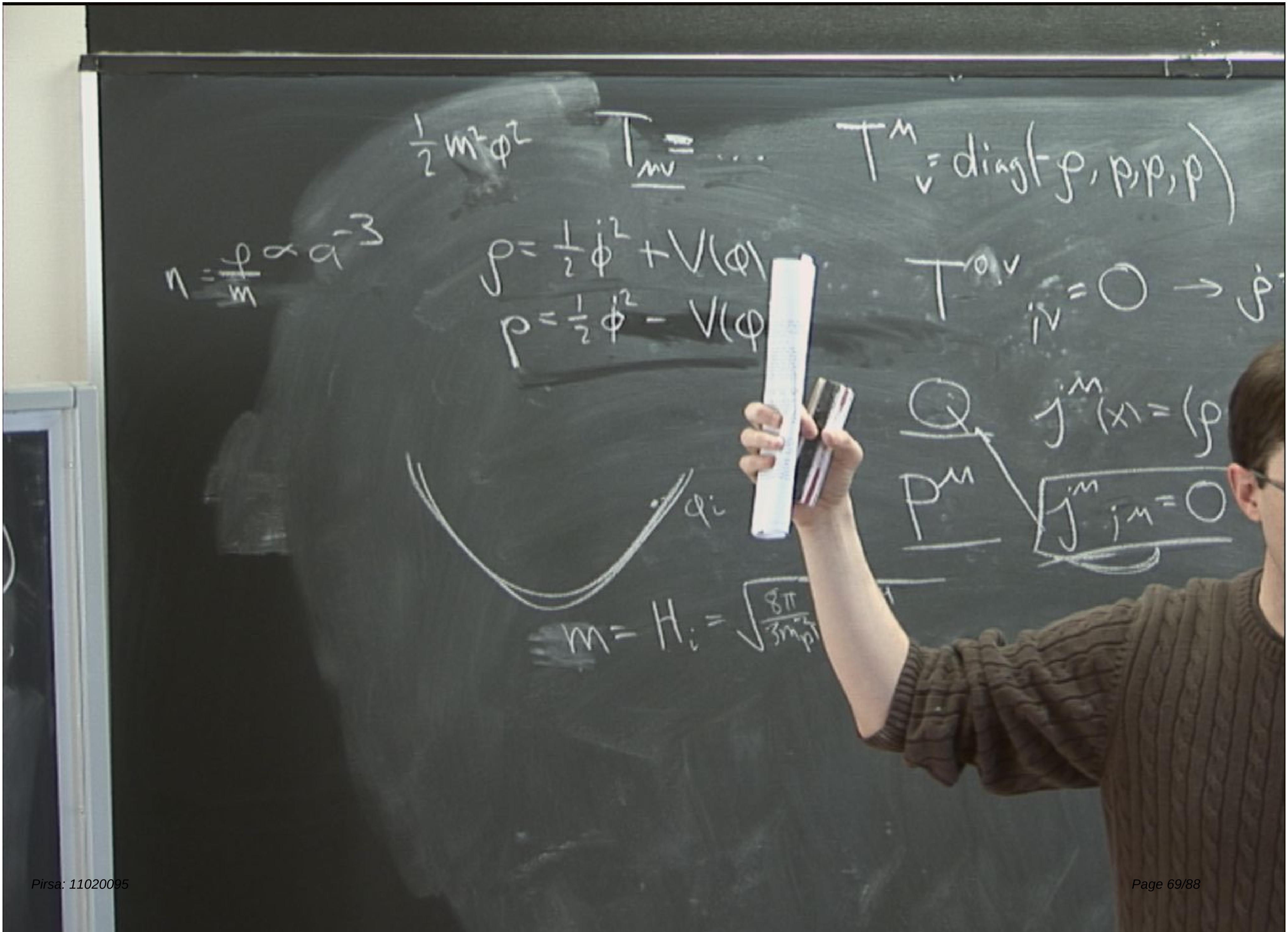
P^{μ} $\quad \boxed{j^{\mu}{}_{;\mu} = 0} \quad \frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\vec{j}$

$m = H_i = \sqrt{\frac{8\pi}{3m_{pl}^2} g_* T_i^4}$

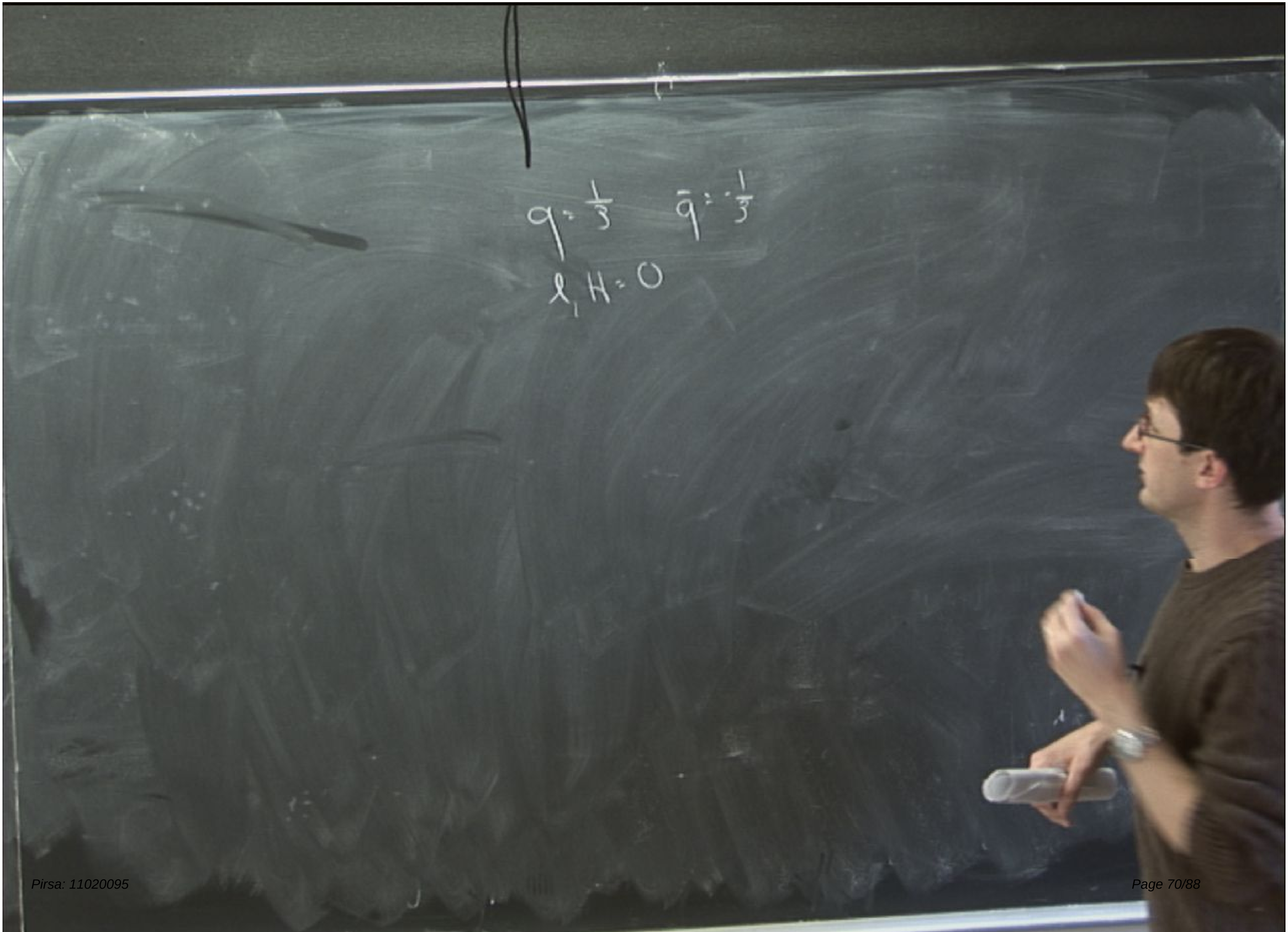


O

$e^{-S_I/\hbar}$



$\frac{1}{2} m^2 \phi^2$
$T_{\mu\nu} = \dots$
$T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$
$n = \frac{\rho}{m} \propto a^{-3}$
$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$
$p = \frac{1}{2}\dot{\phi}^2 - V(\phi$
$T^{0\nu}{}_{;\nu} = 0 \rightarrow \dot{\rho}$
Q
$j^{\mu}(x) = (\rho$
P^{μ}
$j^{\mu}{}_{;\mu} = 0$
ϕ_i
$m = H_i = \sqrt{\frac{8\pi}{3m_p^2}}$


q = 1/3   q̄ = -1/3
l, H = 0

$q = \frac{1}{3}$ $\quad \bar{q} = -\frac{1}{3}$ $\quad 3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

L

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \rightarrow n + \nu_e$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \rightarrow n + \nu_e$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \rightarrow n + \nu_e$

$T > m_p, m_n$

$p, \bar{p}, n, \bar{n}$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$ $3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

e μ τ

ν ν_μ ν_τ

$p + e \rightarrow n + \nu_e$

$T > m_p, m_n$

$p, \bar{p}, n, \bar{n}, \gamma$

$q = \frac{1}{3}$ $\quad \bar{q} = -\frac{1}{3}$ $\quad 3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \rightarrow n + \nu_e$

$T > m_p, m_n$

$p, \bar{p}, n, \bar{n}, \gamma$

$q = \frac{1}{3}$ $\quad \bar{q} = -\frac{1}{3}$ $\quad 3\left(\frac{1}{3}\right) = 1.$

$l, H = 0$

$e \quad \mu \quad \tau$

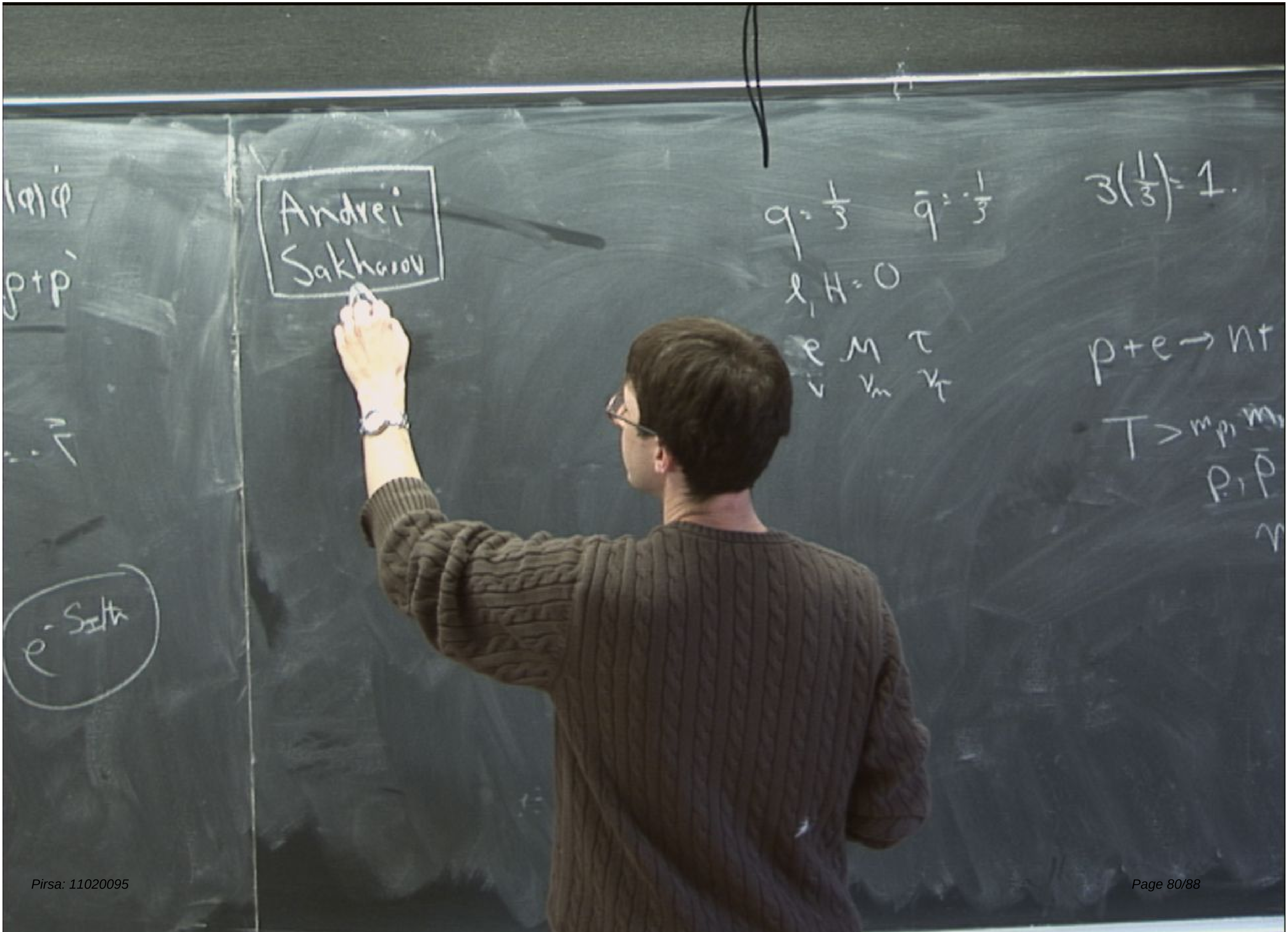
$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \to n + \nu_e$

$T > m_p, m_n$

$p, \bar{p}, n, \bar{n}, \gamma$

$\eta = \frac{n_B}{n_\gamma} \sim \underline{10^{-9}}$


Andrei
Sakharov
q = 1/3
3(1/3) = 1.
l, H = 0
e μ τ
p + e → n +

$\boxed{\text{Andrei Sakharov}}$

$q = \frac{1}{3} \qquad \bar{q} = -\frac{1}{3} \qquad 3\left(\frac{1}{3}\right) = 1.$

$\ell,\ H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \to n +$

$T > m_p, m$

$p, \bar{p}$

$e^{-S_I/\hbar}$

$(\varphi)\dot{\varphi}$

$p + p'$

$\ldots \bar{r}$

$e^{-S_E/\hbar}$

$\boxed{\text{Andrei Sakharov}}$

$n_B = n_{\bar{B}}$

$q = \frac{1}{3} \quad \bar{q} = -\frac{1}{3}$

$3(\frac{1}{3}) = 1.$

$\ell, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$p + e \to n +$

$T > m_p, m$

$p, \bar{p}$

n

$V'(\varphi)\dot{\varphi}$

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

$\vec{j})$

$\frac{\partial \rho}{\partial t} = -\vec{\nabla}$

0

$e^{-S_I/\hbar}$

$\boxed{\text{Andrei Sakharov}}$

$n_B = n_{\bar{B}}$

Sakharov conditions

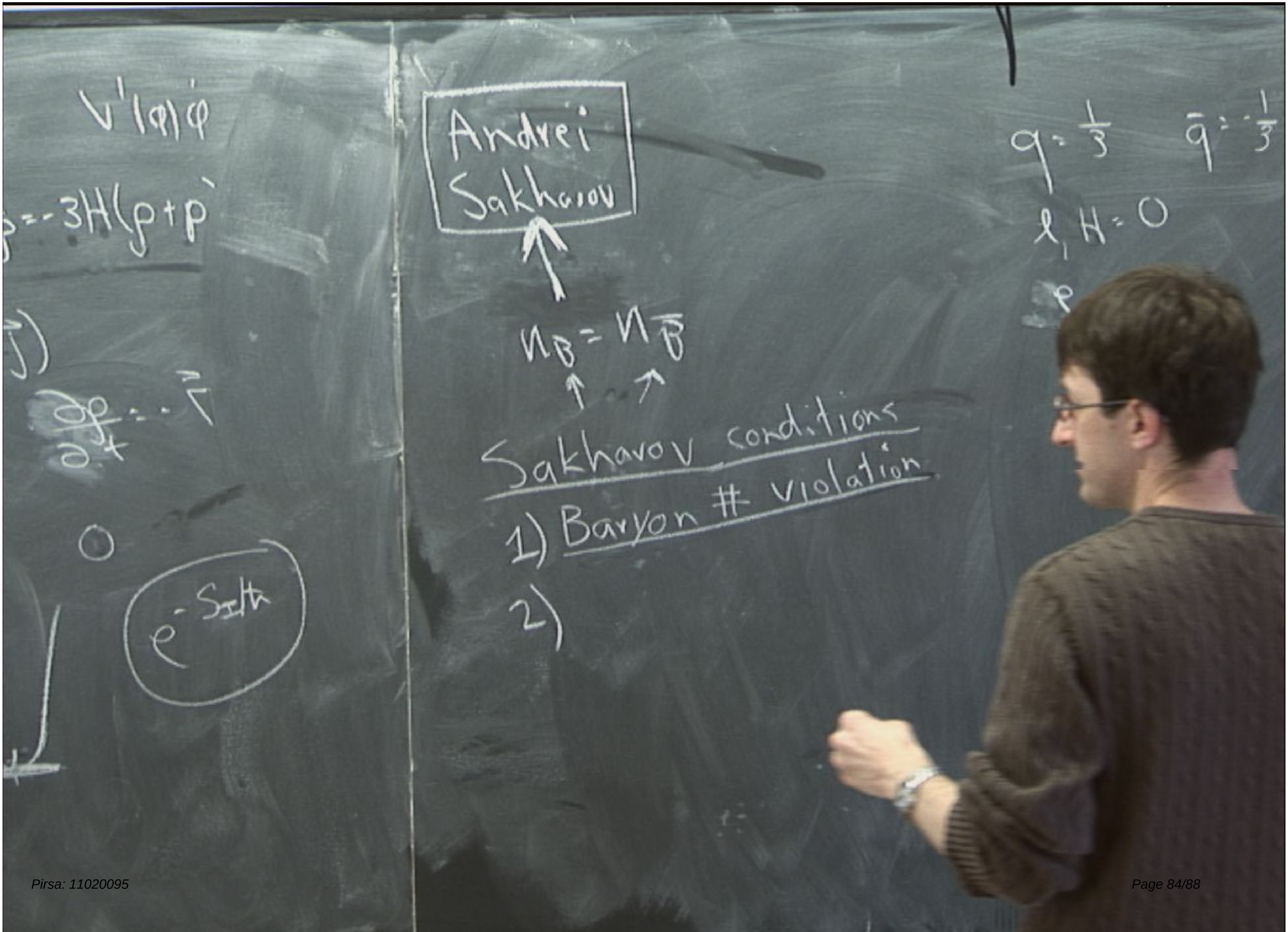
1) Baryon #

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$

$\ell, H = 0$

e μ τ

ν ν_μ ν_τ


Andrei Sakharov
$n_B = n_{\bar{B}}$
Sakharov conditions
1) Baryon # violation
2)
$q = \frac{1}{3}$
$\bar{q} = -\frac{1}{3}$
$\ell, H = 0$
$e^{-S_{Inst}}$

$V'(\varphi)\dot{\varphi}$

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

$\frac{\partial \rho}{\partial t} = -\vec{\nabla}$

$e^{-S_I/\hbar}$

$\boxed{\text{Andrei Sakharov}}$

$n_B = n_{\bar{B}}$

Sakharov conditions

1) Baryon # violation

2) C, CP

$q = \frac{1}{3}$ $\quad \bar{q} = -\frac{1}{3}$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$V'(\varphi)\dot\varphi$

$\dot\rho = -3H(\rho + p)$

$\frac{\partial \rho}{\partial t} = -\vec{\nabla}$

$\bigcirc$

$e^{-S_{I}/\hbar}$

$\boxed{\text{Andrei Sakharov}}$

$n_B = n_{\bar{B}}$

Sakharov conditions

1) Baryon # violation

2) C, CP

C, P, T CPT

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$

$\ell, H = 0$

e μ τ

ν ν_μ ν_τ

Andrei Sakharov

$n_B = n_{\bar{B}}$

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$

$\ell, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

Sakharov conditions

1) Baryon # violation

2) C, CP

C, P, T CPT

$\boxed{\text{Andrei Sakharov}}$

$n_B = n_{\bar{B}}$

Sakharov conditions

1) Baryon # violation

2) C, CP   C, P, T   CPT

3) Thermal Equil.

$q = \frac{1}{3}$ $\bar{q} = -\frac{1}{3}$

$l, H = 0$

$e \quad \mu \quad \tau$

$\nu \quad \nu_\mu \quad \nu_\tau$

$3(\frac{1}{3}$

$p + e$

T

Sith