Title: Cosmology (Review) - Lecture 13

Date: Feb 09, 2012 11:30 AM

URL: http://pirsa.org/12020027

Abstract:



Relic → Hot Thermal
→ Cold Thermal
→ Non-Thermal

$$\int d^4x \sqrt{-g}\,\mathcal{L} = \int d^4x \sqrt{-g}\left[\mathcal{L}_{known} - \frac{1}{2} g^{\mu\nu} D_\mu\varphi D_\nu\varphi - V(\varphi)\right]$$

$$S_\varphi = \int d^4x \left[-\frac{1}{2}\eta^{\mu\nu}\partial_\mu\varphi\,\partial_\nu\varphi - V(\varphi)\right] \rightarrow \delta S = \int d^4x \left[-\eta^{\mu\nu}\left(\partial_\mu\varphi\,\partial_\nu\delta\varphi\right.\right.$$

$$= \int d^4x \left[\eta^{\mu\nu}\partial_\mu\partial_\nu\varphi - V'(\varphi)\right]\delta\varphi$$

$t, \vec{x}$ $a(t)$ $q(\vec{x}, t)$ $\varphi(t)$

$)-V'(\varphi)\delta\varphi\Big]$ $\eta \to g$ $\partial_\mu \to \nabla_\mu$

$]\delta\varphi$

$$-\eta^{\mu\nu}\partial_\mu\partial_\nu\varphi - V'(\varphi) = 0$$

$\partial_\mu \to \Gamma_\mu$

$$\hookrightarrow -g^{\mu\nu}\nabla_\mu\nabla_\nu\varphi - V'(\varphi) = 0$$

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

$t, \vec{x}$ $a(t)$ $q(\vec{x},t)$ $\varphi(t)$ $T_{\mu\nu} \to T^{SM}_{\mu\nu} + T^{scalar}_{\mu\nu}$ $T^{\mu\nu}{}_{;\nu} = 0$

$\eta \to g$ $\partial_\mu \to \nabla_\mu$

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

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

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

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

$-\eta^{\mu\nu}\partial_\mu\partial_\nu\varphi - V'(\varphi) = 0$

$\partial_\mu \to \nabla_\mu$

$-g^{\mu\nu}\nabla_\mu\nabla_\nu\varphi - V'(\varphi) = 0$

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

$\ddot{x} + 2\gamma\dot{x} + \omega^2 x = 0$

$\gamma \gtrsim \omega$

$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$

$H(t)$

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

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

$\ddot{\varphi}$

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

$\ddot{f} + \omega^2(t) f = 0$



$H \gg m$

$H = m$

$H \ll m$

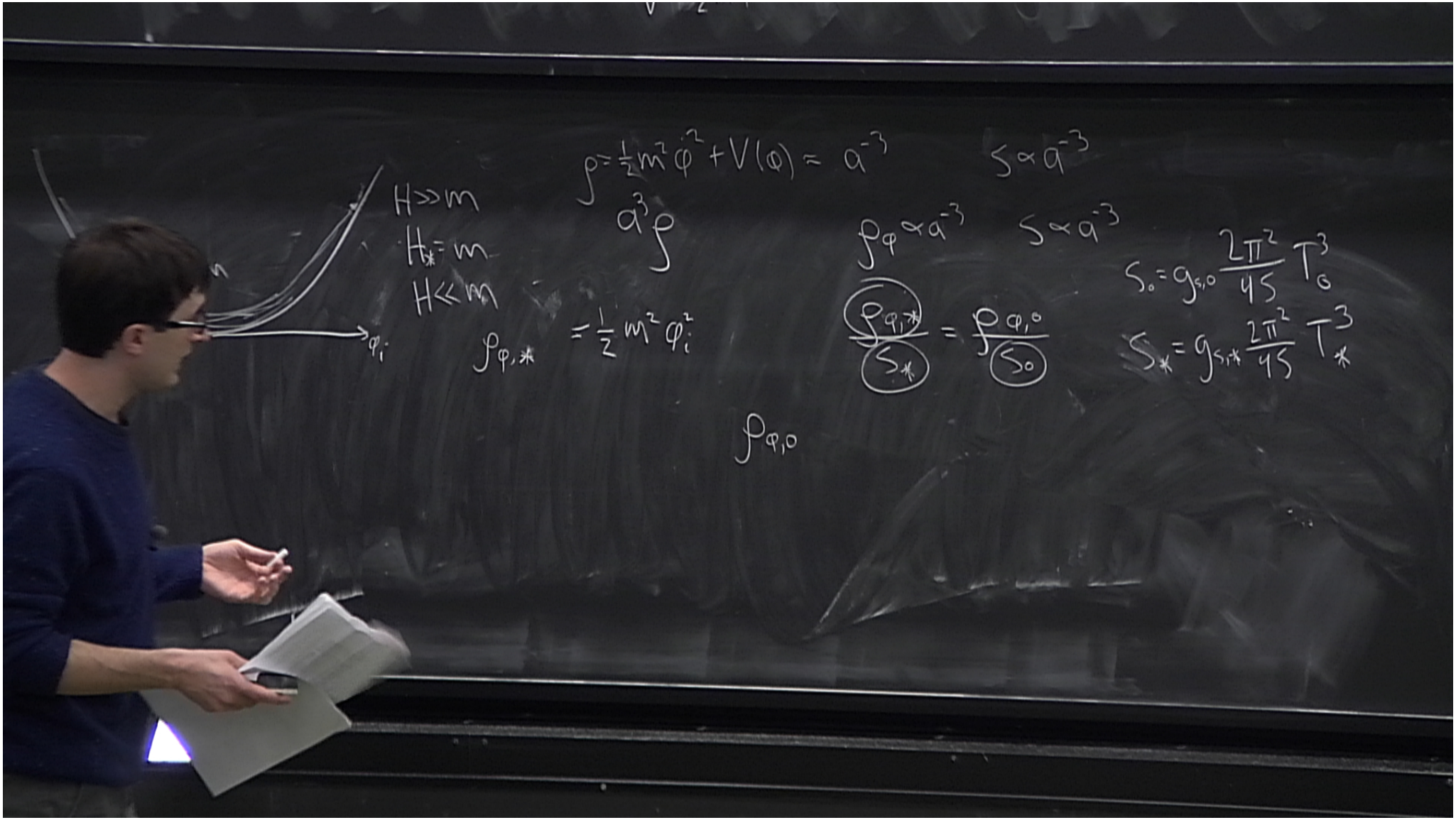
$\ln(\dot{\varphi}) = -3\ln(a) + \text{const}$

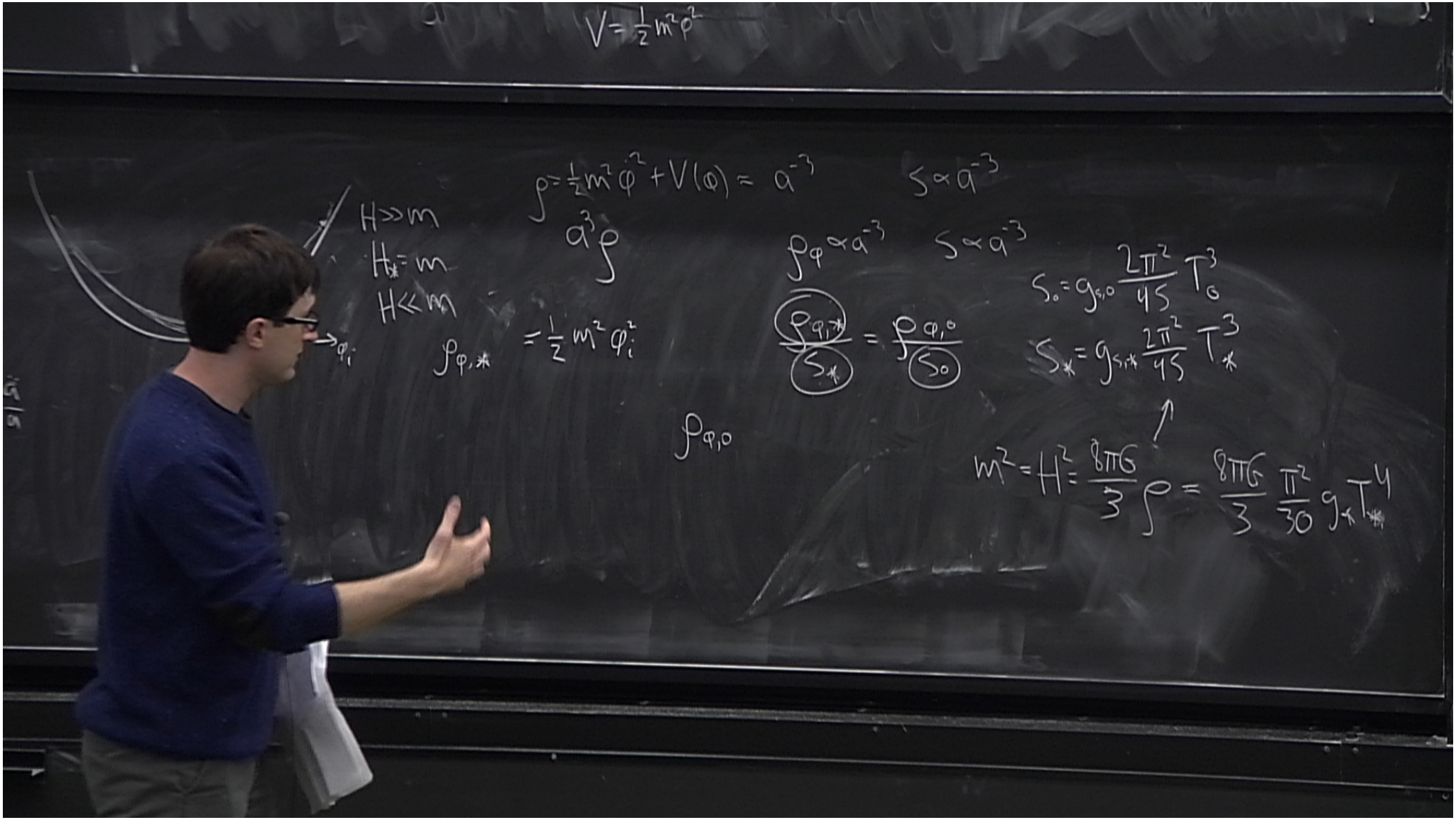
$\omega^2(t) = m^2 + (\,)\left(\frac{\dot{a}}{a}\right)^2 + (\,)\frac{\ddot{a}}{a}$

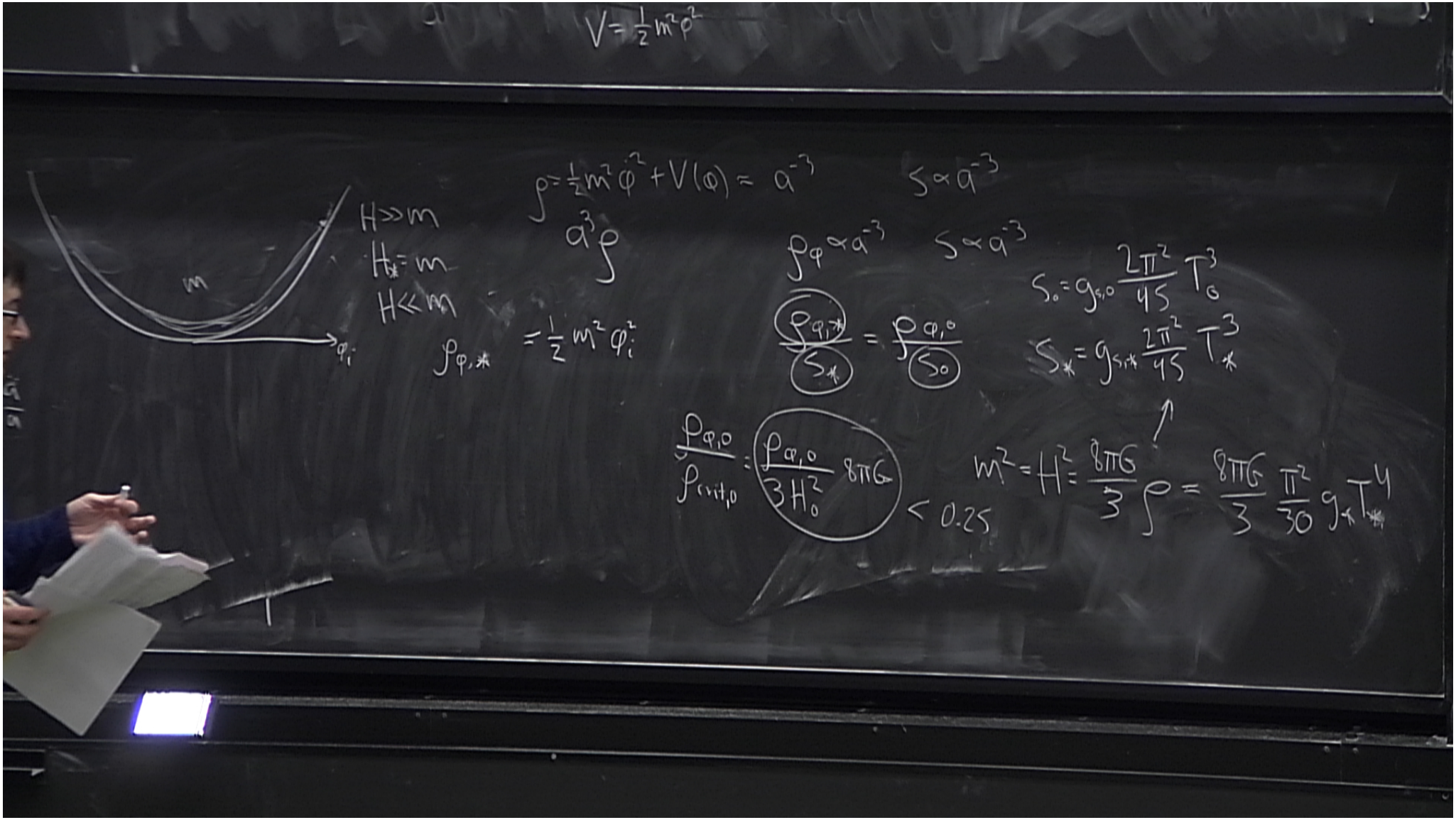
$\dot{\varphi} \propto a^{-3}$

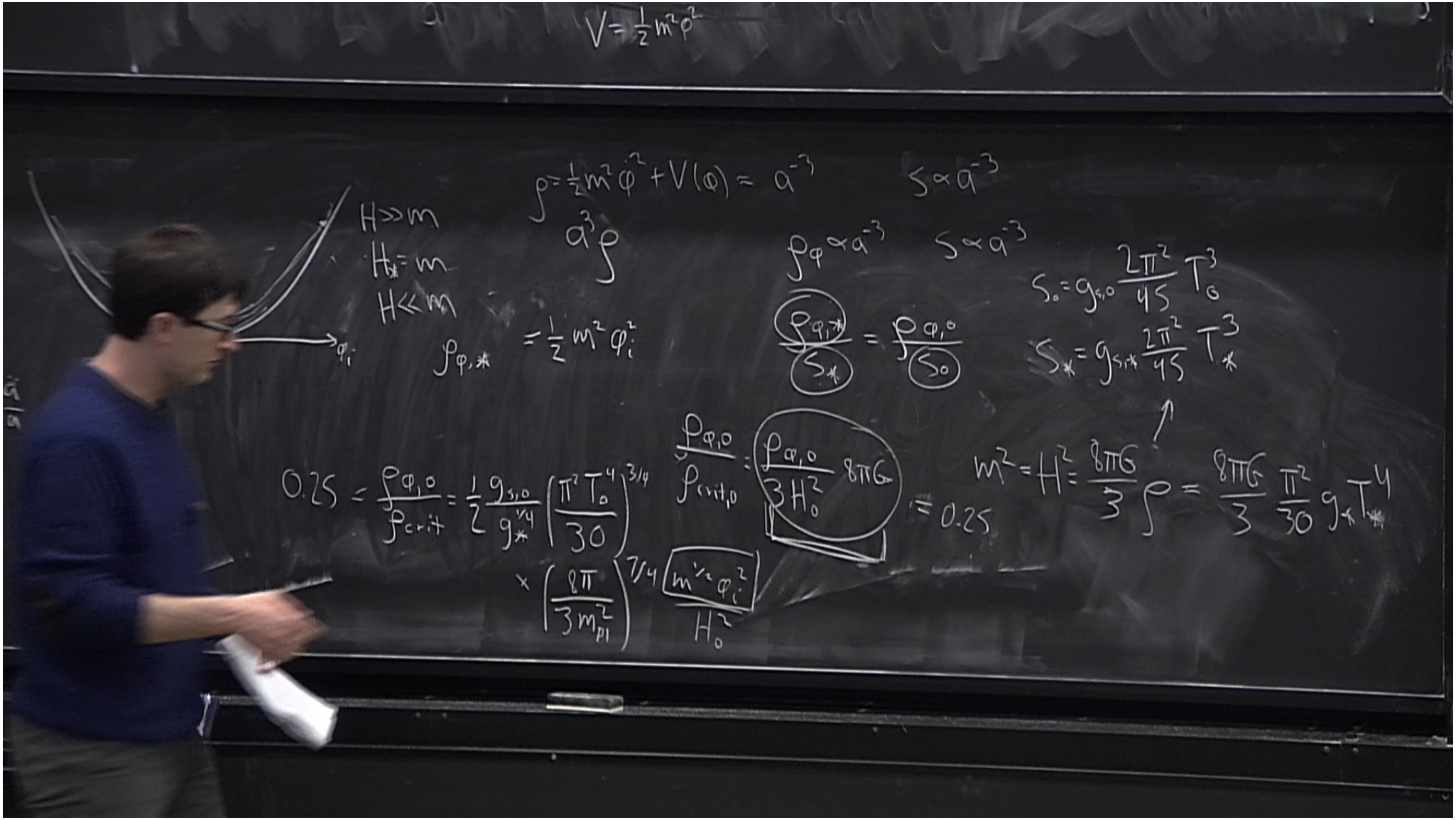
$\frac{\dot{\omega}}{\omega^2} \ll 1$

$f \propto e^{\pm i m t}$

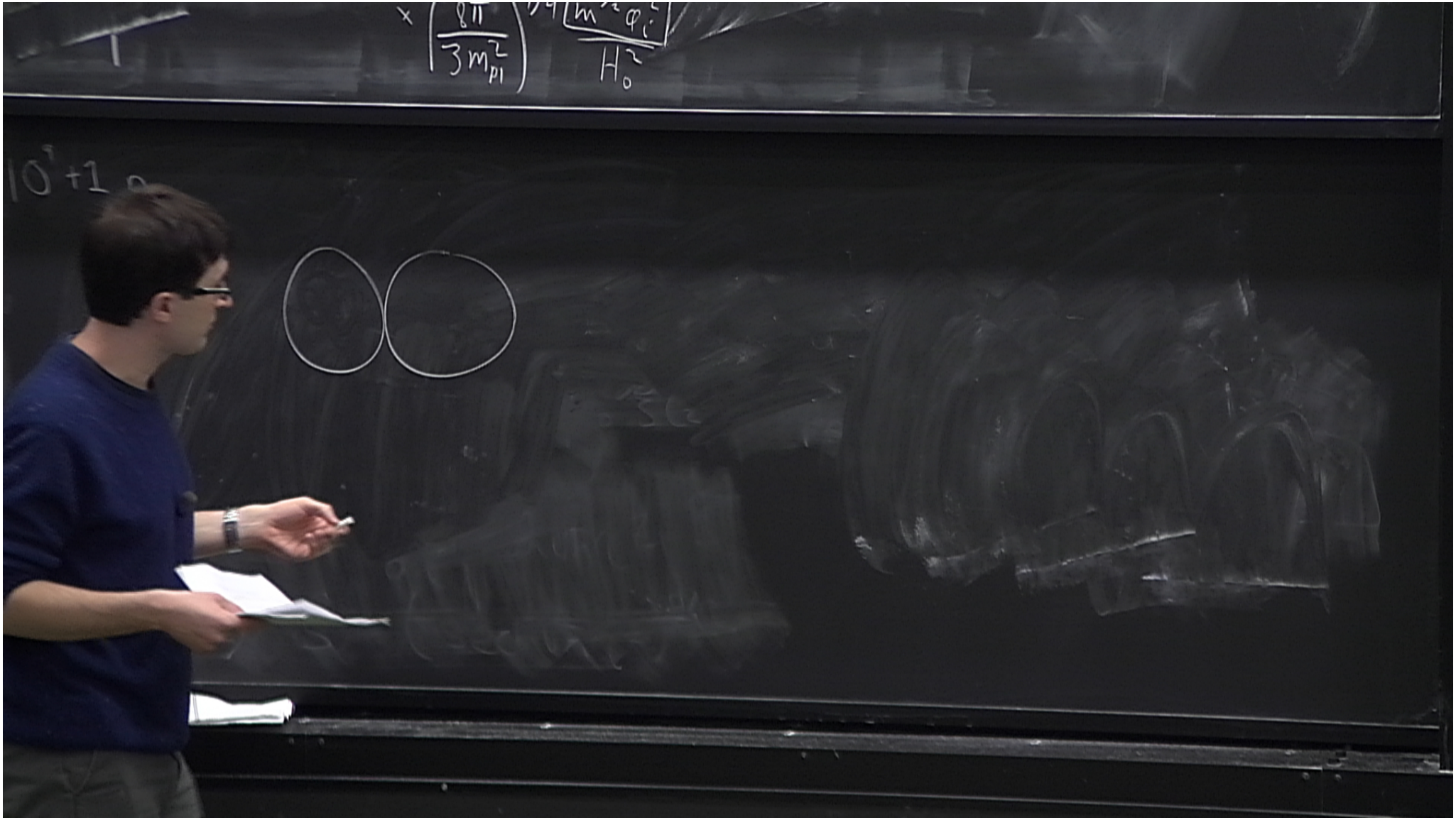

$\rho = \frac{1}{2}m^2\varphi^2 + V(\varphi) \propto a^{-3}$
$s \propto a^{-3}$
$a^3\rho$
$H \gg m$
$H_* = m$
$H \ll m$
φ_i
$\rho_{\varphi,*} = \frac{1}{2}m^2\varphi_i^2$
$\rho_\varphi \propto a^{-3}$
$s \propto a^{-3}$
$\frac{\rho_{\varphi,*}}{s_*} = \frac{\rho_{\varphi,0}}{s_0}$
$s_0 = g_{s,0}\frac{2\pi^2}{45}T_0^3$
$s_* = g_{s,*}\frac{2\pi^2}{45}T_*^3$
$\rho_{\varphi,0}$

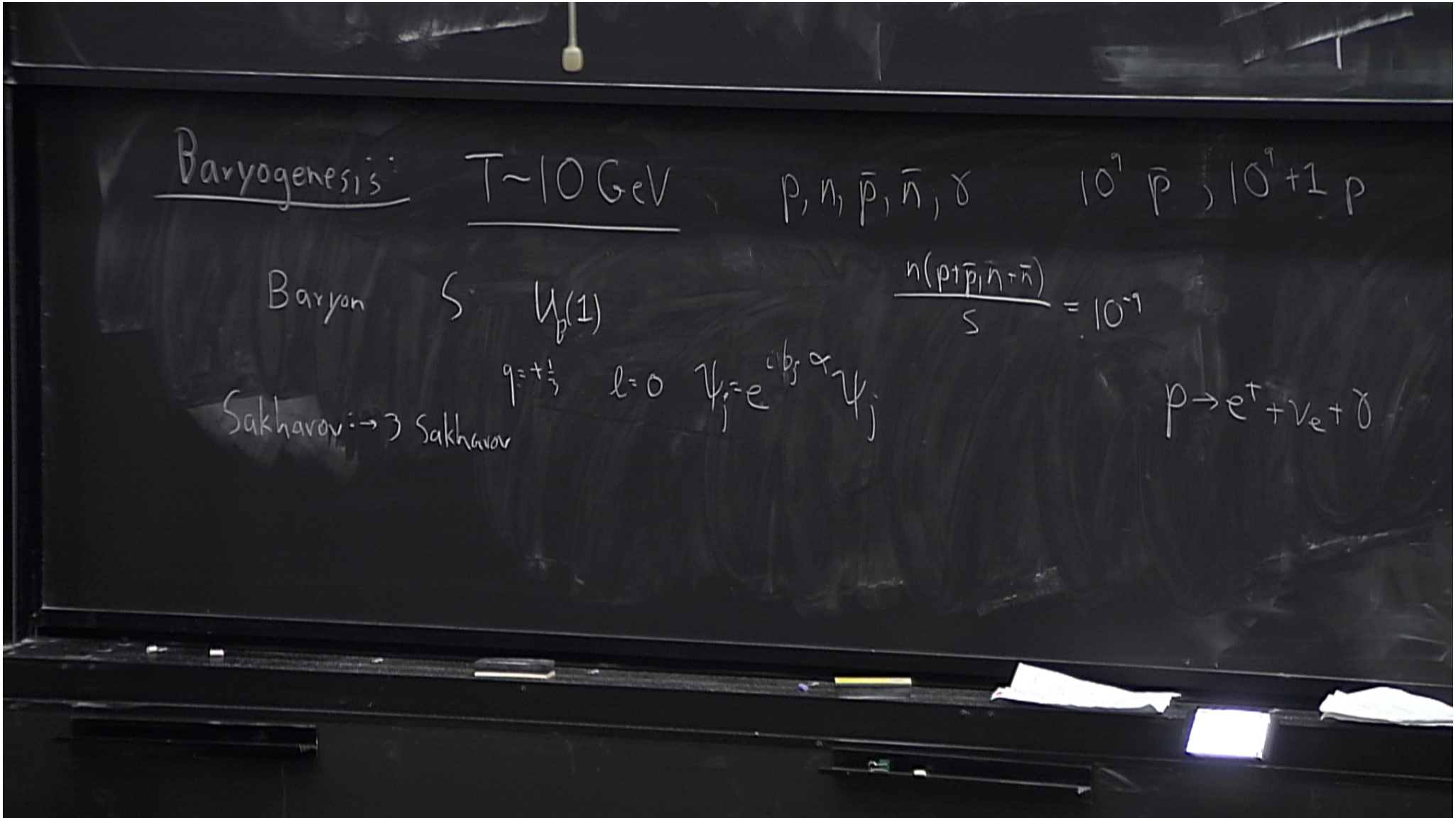

$V = \frac{1}{2} m^2 \phi^2$
$\rho = \frac{1}{2} m^2 \phi^2 + V(\phi) \approx a^{-3}$
$a^3 \rho$
$s \propto a^{-3}$
$H \gg m$
$H = m$
$H \ll m$
ϕ_i
$\rho_{\phi,*} = \frac{1}{2} m^2 \phi_i^2$
$\rho_\phi \propto a^{-3}$
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$\frac{\rho_{\phi,*}}{s_*} = \frac{\rho_{\phi,0}}{s_0}$
$\rho_{\phi,0}$
$s_0 = g_{s,0} \frac{2\pi^2}{45} T_0^3$
$s_* = g_{s,*} \frac{2\pi^2}{45} T_*^3$
$m^2 = H^2 = \frac{8\pi G}{3} \rho = \frac{8\pi G}{3} \frac{\pi^2}{30} g_* T_*^4$

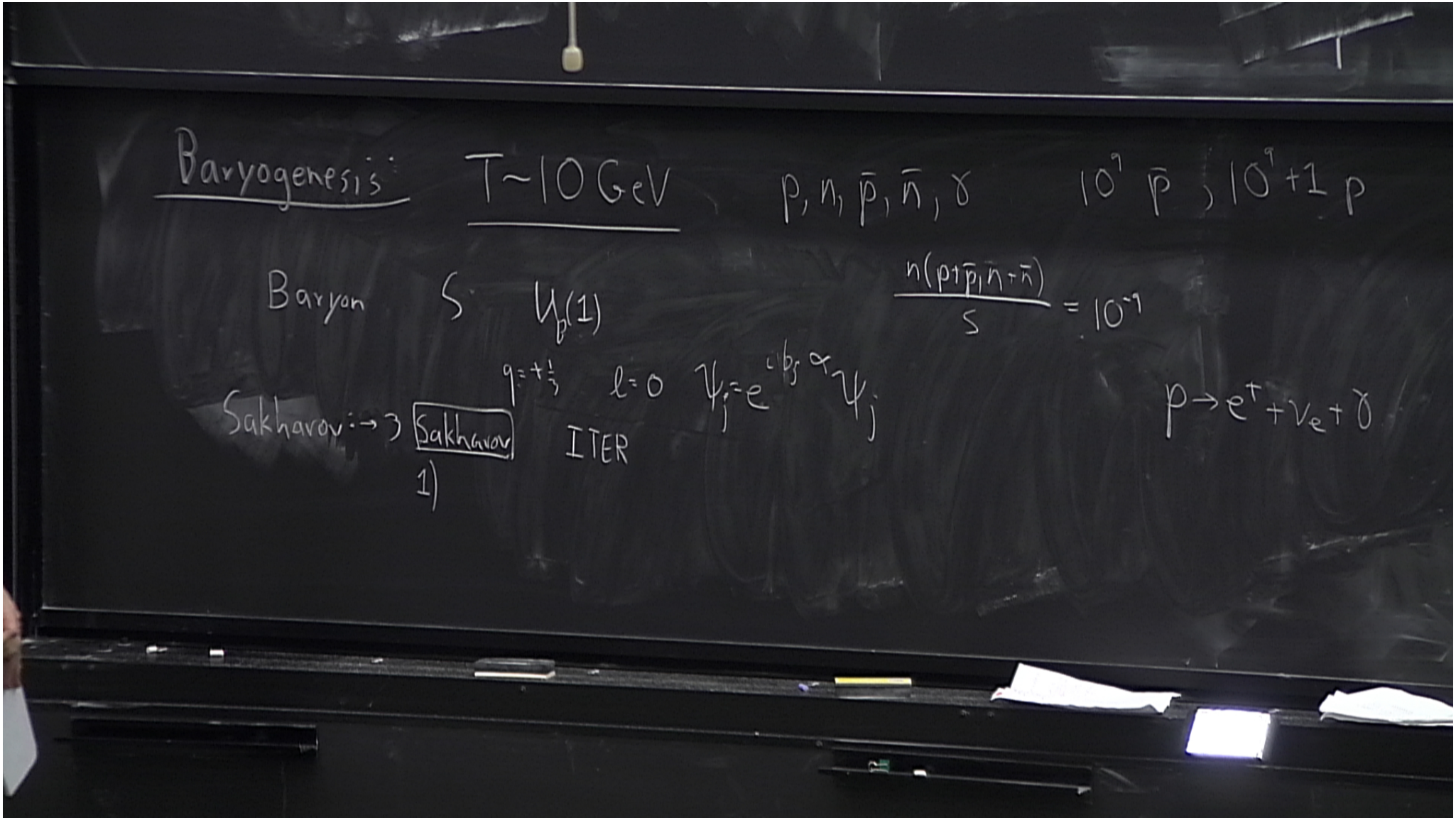

$V = \frac{1}{2} m^2 \phi^2$
$\rho = \frac{1}{2} m^2 \phi^2 + V(\phi) \approx a^{-3}$
$s \propto a^{-3}$
$a^3 \rho$
$\rho_\phi \propto a^{-3}$
$s \propto a^{-3}$
$H \gg m$
$H = m$
$H \ll m$
m
ϕ_i
$\rho_{\phi,*} = \frac{1}{2} m^2 \phi_i^2$
$\frac{\rho_{\phi,*}}{s_*} = \frac{\rho_{\phi,0}}{s_0}$
$s_0 = g_{s,0} \frac{2\pi^2}{45} T_0^3$
$s_* = g_{s,*} \frac{2\pi^2}{45} T_*^3$
$\frac{\rho_{\phi,0}}{\rho_{crit,0}} = \frac{\rho_{\phi,0}}{3H_0^2} 8\pi G < 0.25$
$m^2 = H^2 = \frac{8\pi G}{3} \rho = \frac{8\pi G}{3} \frac{\pi^2}{30} g_* T_*^4$

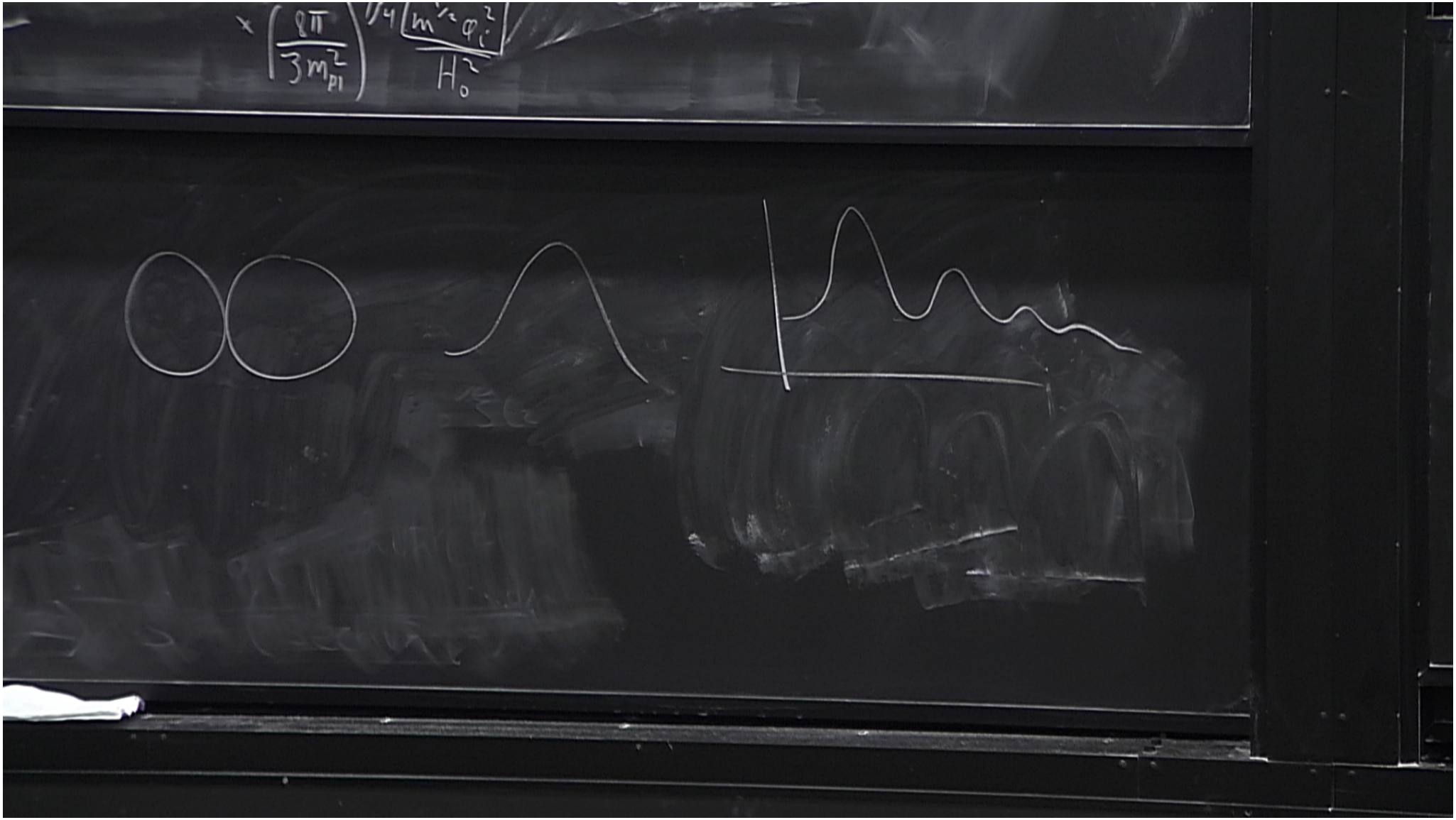

$V = \frac{1}{2} m^2 \phi^2$
$\rho = \frac{1}{2} m^2 \phi^2 + V(\phi) \propto a^{-3}$
$S \propto a^{-3}$
$a^3 \rho$
$H \gg m$
$H = m$
$H \ll m$
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$\rho_{\phi,*} = \frac{1}{2} m^2 \phi_i^2$
$\rho_\phi \propto a^{-3}$
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$\frac{\rho_{\phi,*}}{S_*} = \frac{\rho_{\phi,0}}{S_0}$
$S_0 = g_{s,0} \frac{2\pi^2}{45} T_0^3$
$S_* = g_{s,*} \frac{2\pi^2}{45} T_*^3$
$0.25 \leq \frac{\rho_{\phi,0}}{\rho_{crit}} = \frac{1}{2} \frac{g_{s,0}}{g_*^{1/4}} \left(\frac{\pi^2 T_0^4}{30} \right)^{3/4} \times \left(\frac{8\pi}{3 m_{pl}^2} \right)^{1/4} \frac{m^{1/2} \phi_i^2}{H_0^2}$
$\frac{\rho_{\phi,0}}{\rho_{crit,0}} = \frac{\rho_{\phi,0}}{3H_0^2} 8\pi G = 0.25$
$m^2 = H^2 = \frac{8\pi G}{3} \rho = \frac{8\pi G}{3} \frac{\pi^2}{30} g_* T_*^4$

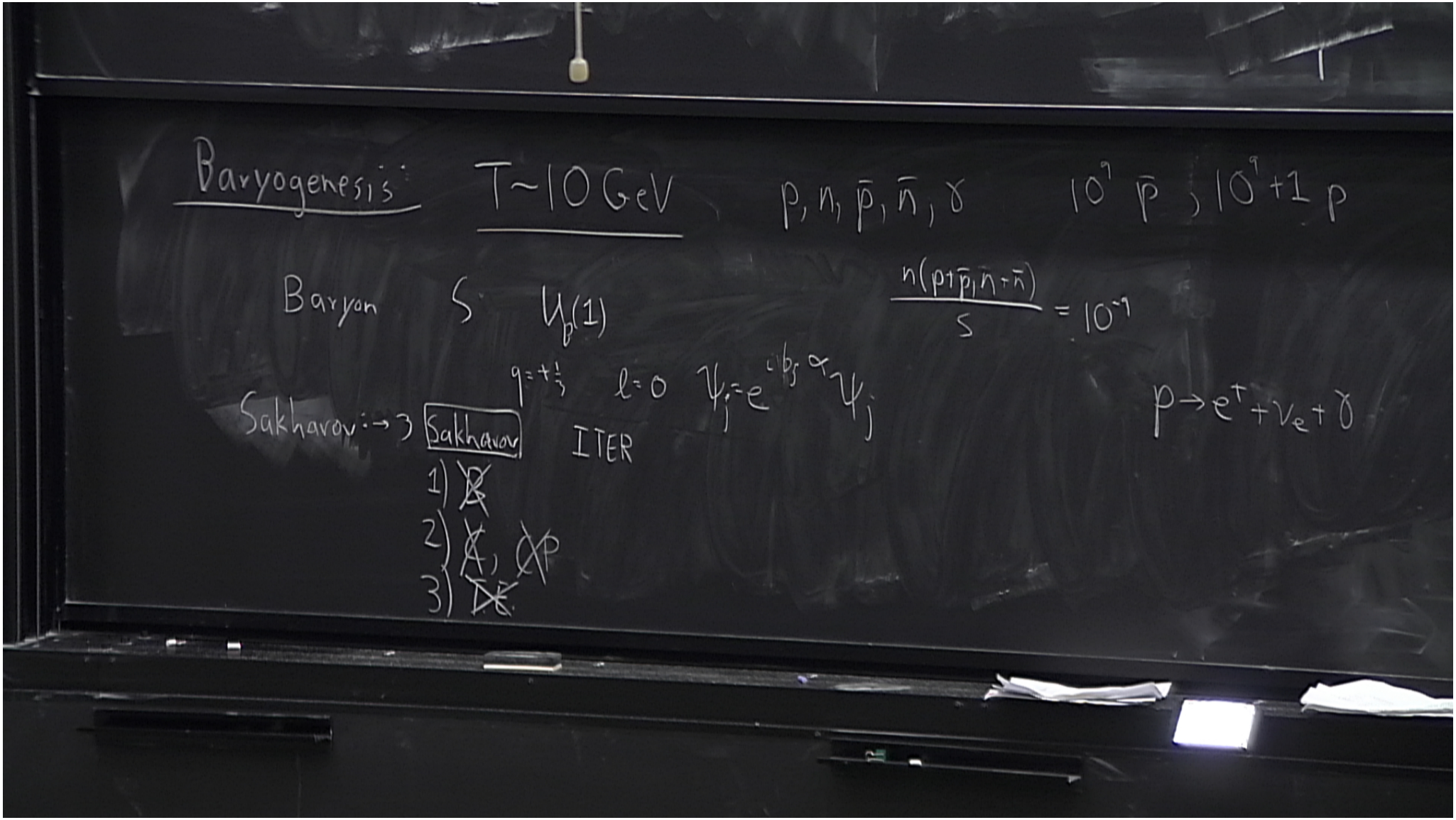

Baryogenesis
T~10 GeV
p, n, p̄, n̄, γ
10^9 p̄ ; 10^9+1 p
n(p+p̄, n+n̄) / s = 10^-9

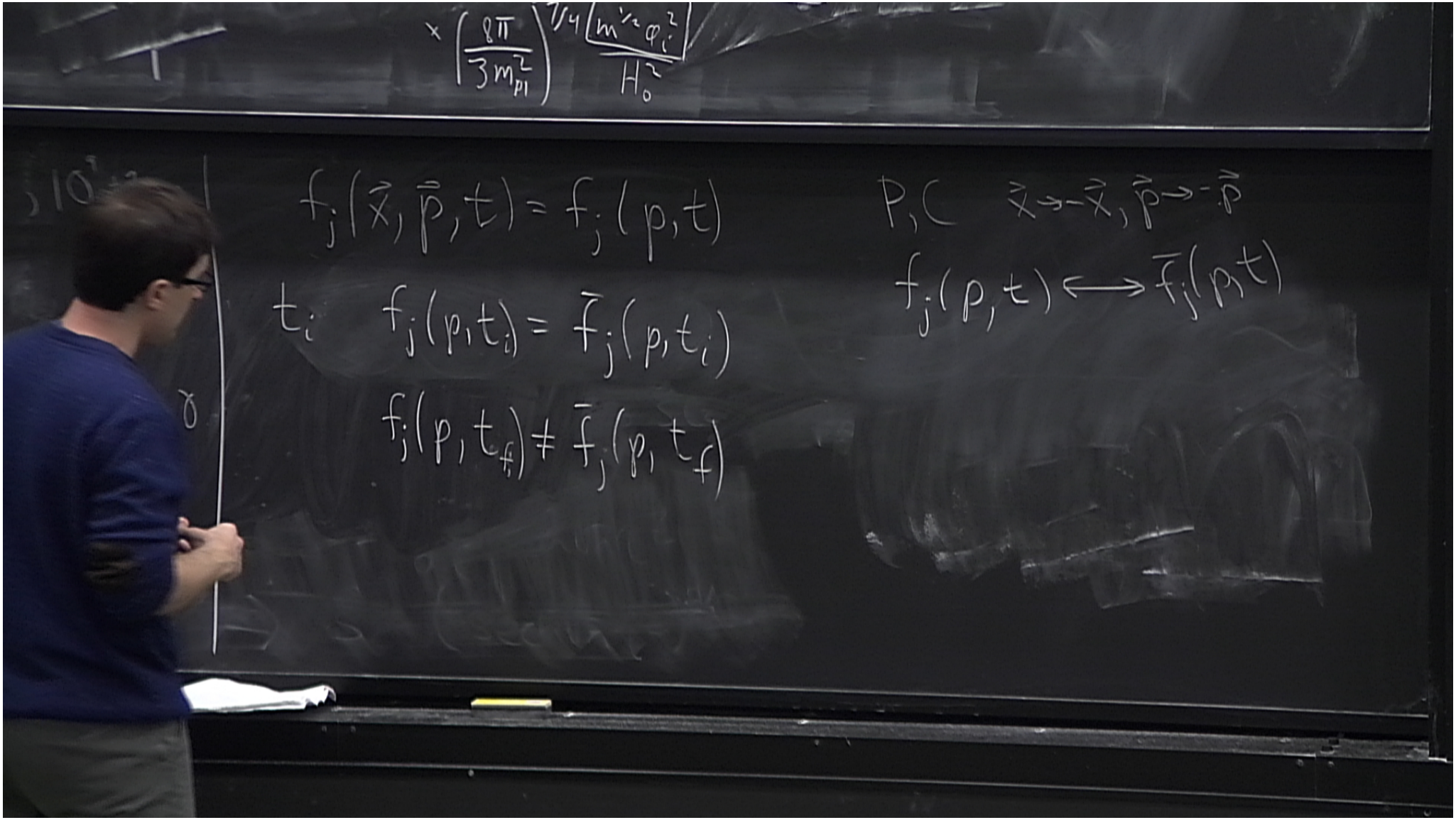

$\left(\frac{8\pi}{3m_{pl}^2}\right)$
$\frac{m^2\varphi_i^2}{H_0^2}$
10^5+1


Baryogenesis
T~10 GeV
p, n, p̄, n̄, γ
10^9 p̄ ; 10^9+1 p
Baryon
S
U_B(1)
n(p+p̄, n+n̄) / S = 10^-9
q = +1/3
ℓ = 0
ψ_j → e^{iθ_j α} ψ_j
Sakharov :→ 3 Sakharov
p → e^+ + ν_e + γ


Baryogenesis
T~10 GeV
p, n, p̄, n̄, γ
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Sakharov
1)
ITER
p → e^+ + ν_e + γ




Baryogenesis: T~10 GeV p, n, p̄, n̄, γ 10^9 p̄ ; 10^9+1 p
Baryon S U_B(1)
n(p+p̄, n+n̄) / S = 10^-9
q=+1/3 ℓ=0 ψ_j = e^{iθ_j} ψ_j
Sakharov :→ 3 Sakharov ITER
1)
2)
3)
p → e^+ + ν_e + γ


$\times \left(\frac{8\pi}{3m_{Pl}^2}\right)^{1/4} \frac{m^{1/2}\varphi_i^2}{H_0^2}$
$f_j(\vec{x}, \vec{p}, t) = f_j(p, t)$
$t_i \quad f_j(p, t_i) = \bar{f}_j(p, t_i)$
$f_j(p, t_f) \neq \bar{f}_j(p, t_f)$
$P, C \quad \vec{x} \to -\vec{x}, \vec{p} \to -\vec{p}$
$f_j(p, t) \longleftrightarrow \bar{f}_j(p, t)$

$$\times \left(\frac{8\pi}{3m_{Pl}^2}\right)^{1/4} \frac{m^{1/2}\varphi_i^2}{H_0^2}$$

$\cdots 10^{1} + 1\ p$

$\cdots \to e^{+} + \nu_e + \gamma$

$f_j(\vec{x}, \vec{p}, t) = f_j(p, t)$

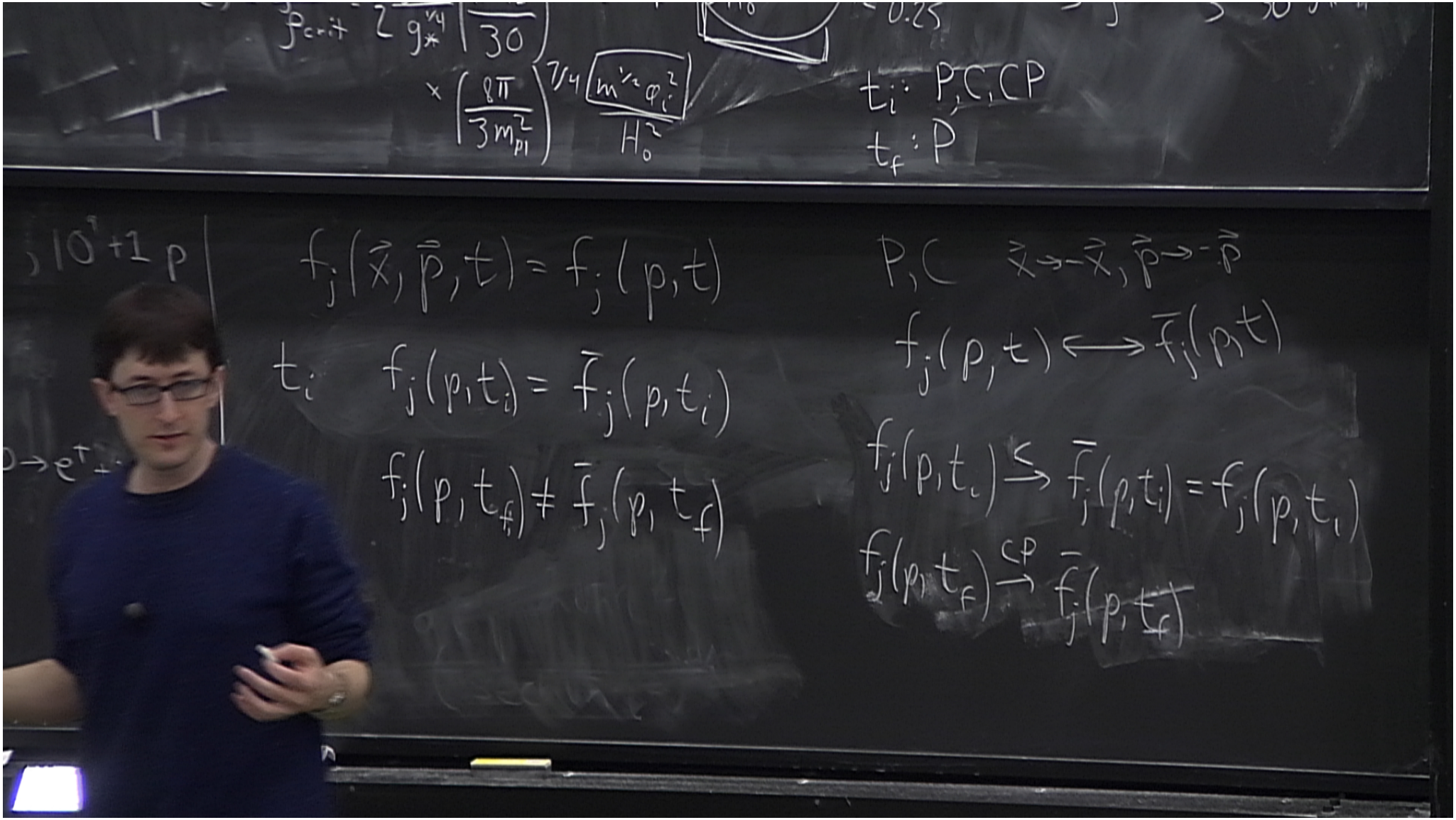
$t_i \quad f_j(p, t_i) = \bar{f}_j(p, t_i)$

$f_j(p, t_f) \neq \bar{f}_j(p, t_f)$

$P_1 C \quad \vec{x} \to -\vec{x}, \vec{p} \to -\vec{p}$

$f_j(p, t) \longleftrightarrow \bar{f}_j(p, t)$

$f_j(p, t_i) \to \bar{f}_j(p, t_i)$


ρ_{crit}
$2\,g_*^{1/4}\sqrt{\frac{\pi}{30}}$
$\times\left(\frac{8\pi}{3m_{Pl}^2}\right)^{1/4}\frac{m_i^{1/2}\varphi_i^2}{H_0^2}$
t_i: P, C, CP
t_f: P
$f_j(\vec{x},\vec{p},t) = f_j(p,t)$
t_i $f_j(p,t_i) = \bar{f}_j(p,t_i)$
$f_j(p,t_f) \neq \bar{f}_j(p,t_f)$
P, C $\vec{x}\to-\vec{x}$, $\vec{p}\to-\vec{p}$
$f_j(p,t) \longleftrightarrow \bar{f}_j(p,t)$
$f_j(p,t_i) \overset{CP}{\Rightarrow} \bar{f}_j(p,t_i) = f_j(p,t_i)$
$f_j(p,t_f) \overset{CP}{\to} \bar{f}_j(p,t_f)$