Title: Cosmology (Review) - Lecture 11

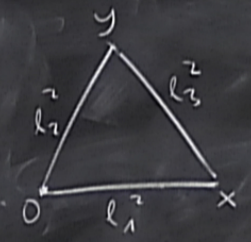
Date: Feb 07, 2012 11:30 AM

URL: http://pirsa.org/12020026

Abstract:

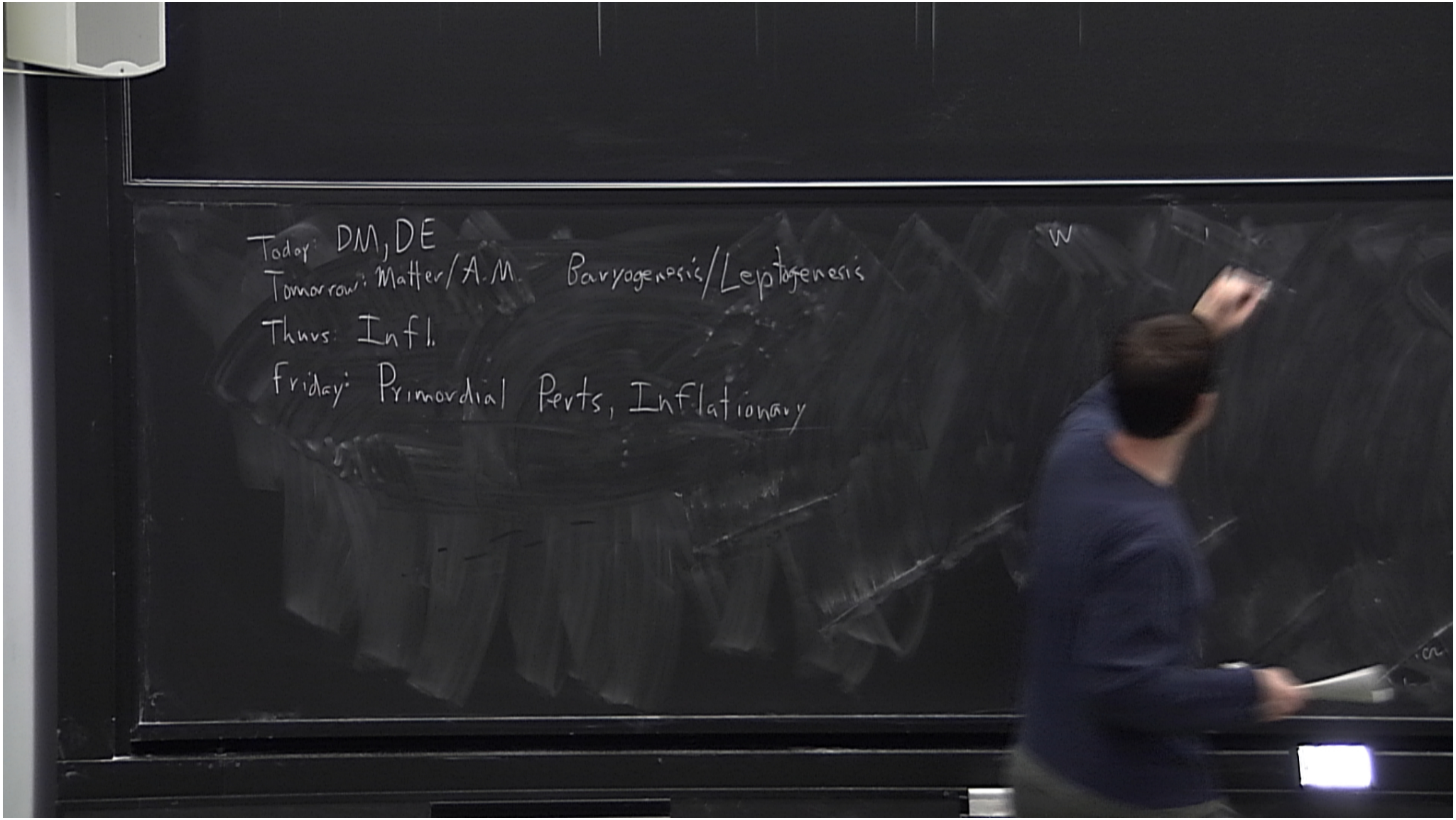
1) connectivity of T
2) edge lengths

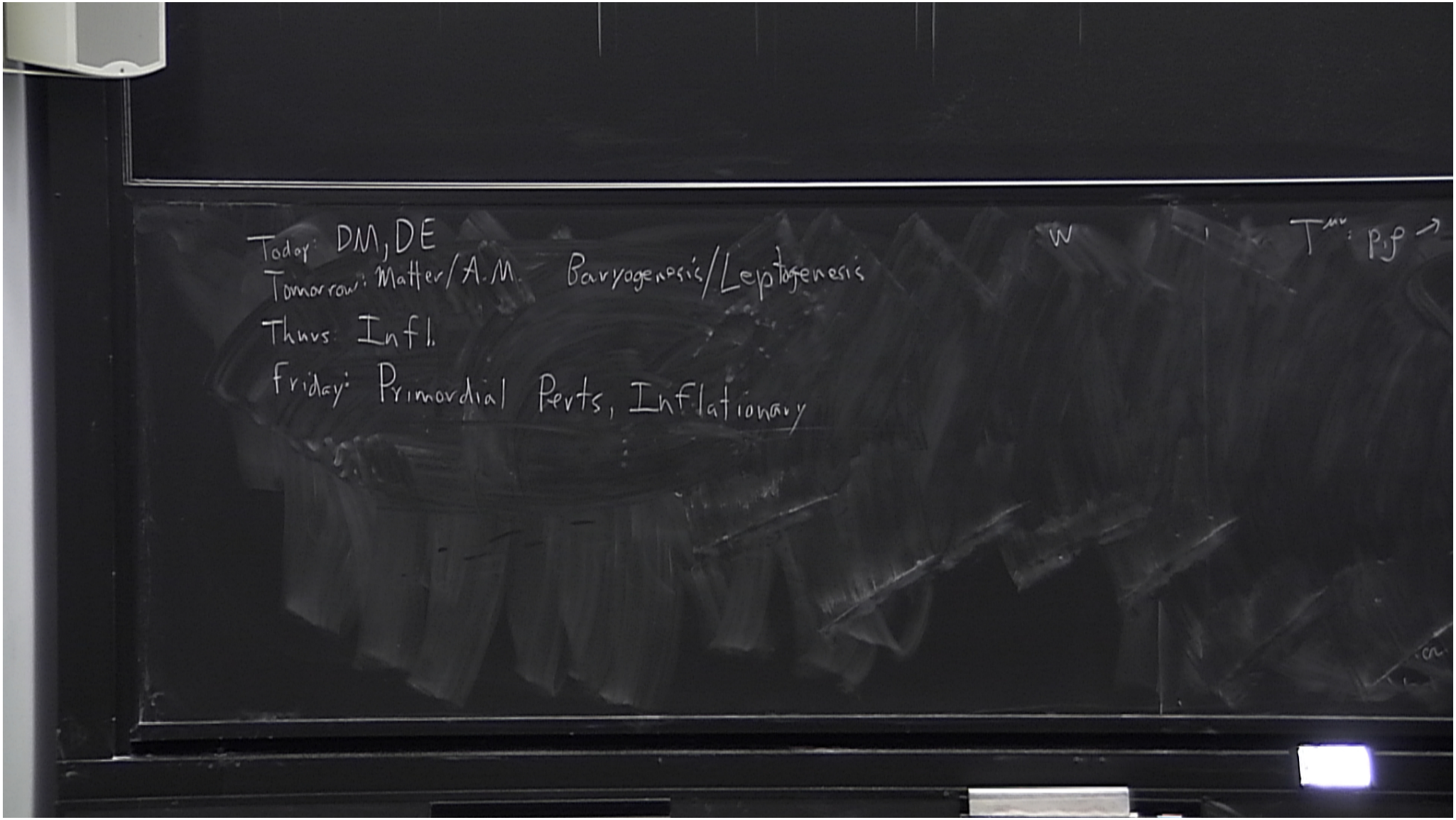
ex.

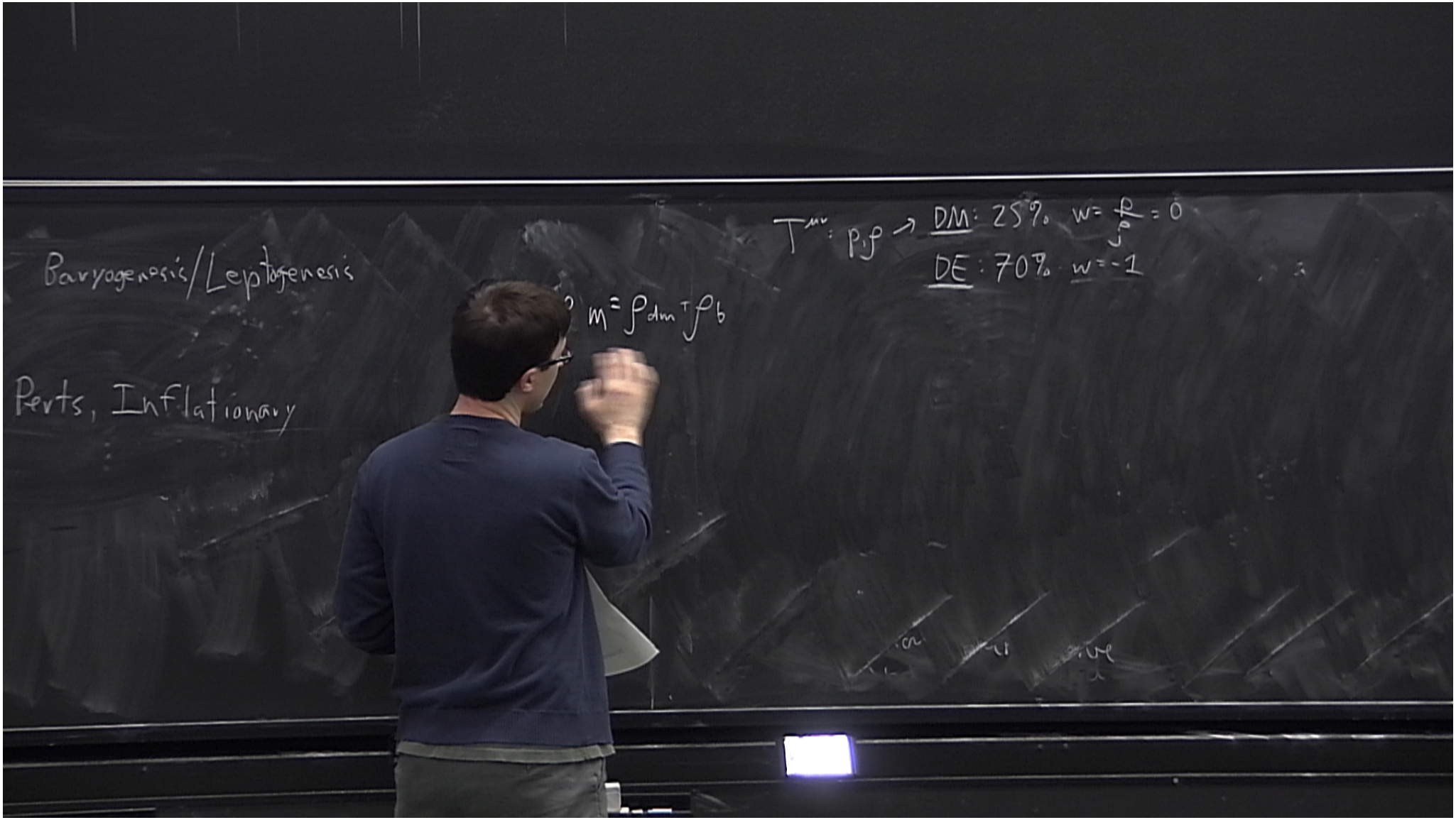


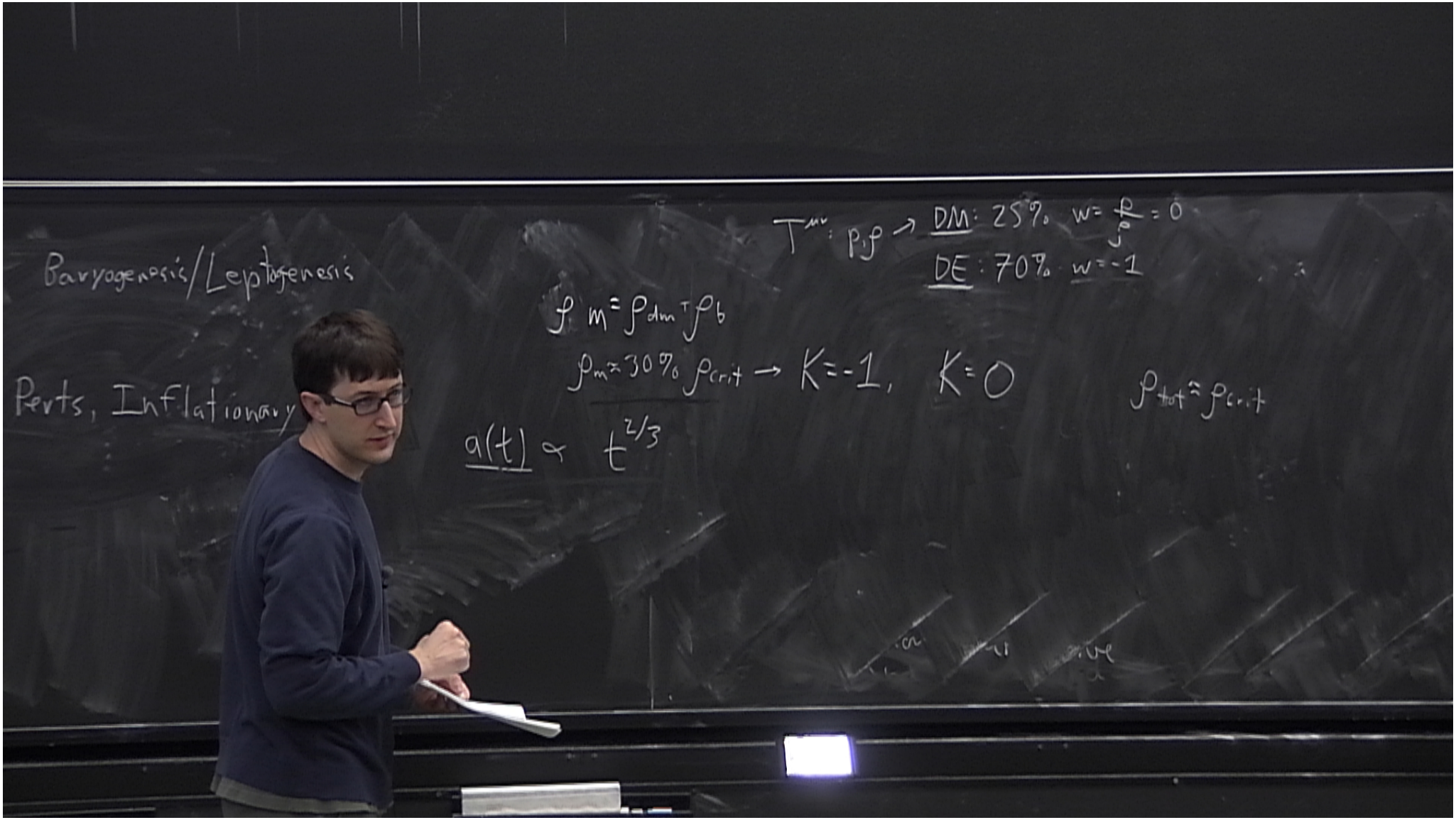
$$\Rightarrow g_{\mu\nu} = \begin{pmatrix} l_1^2 & \frac{1}{2}(l_1^2+l_2^2-l_3^2) \\ \frac{1}{2}(l_1^2+l_2^2-l_3^2) & l_2^2 \end{pmatrix}$$

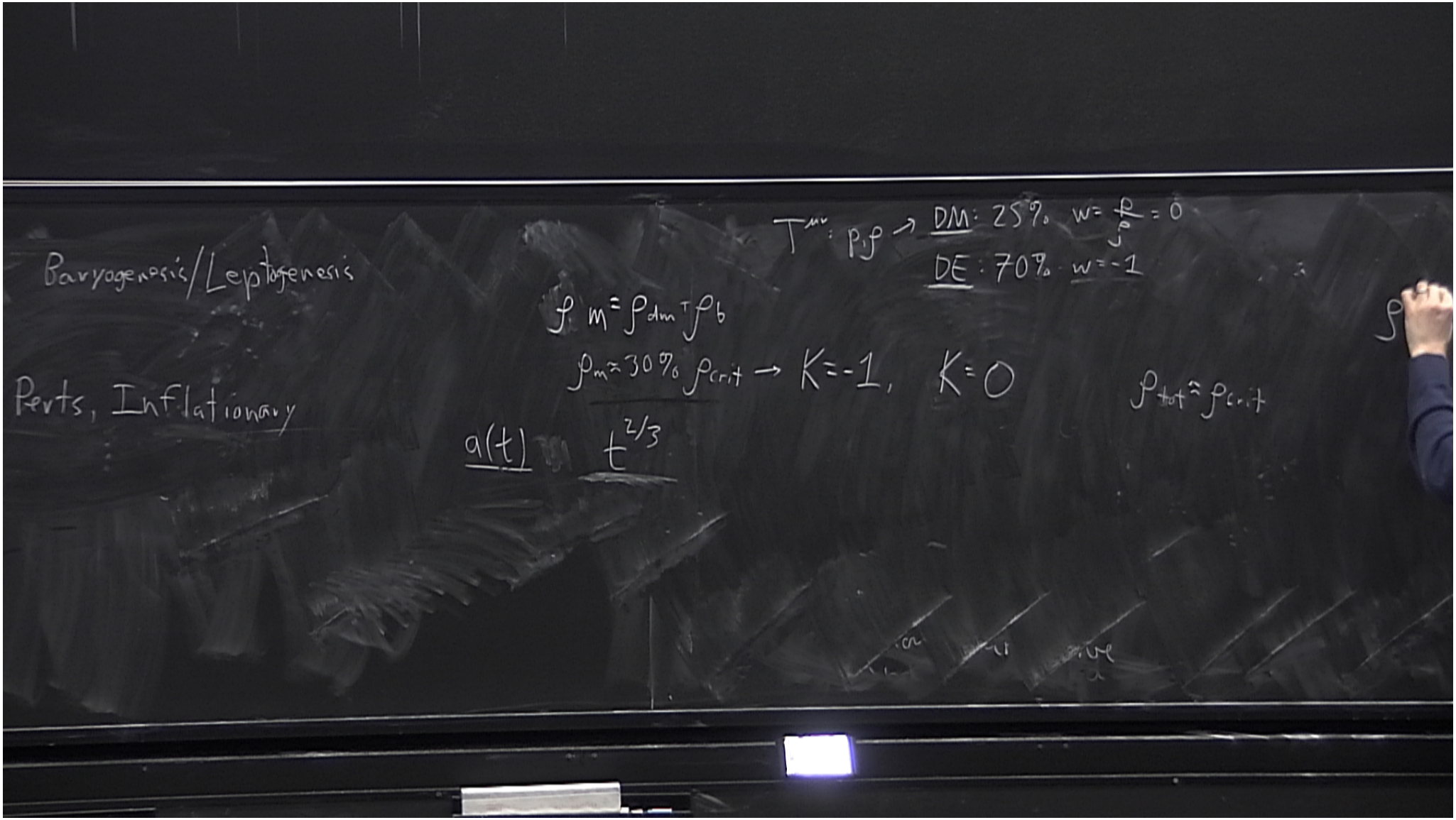


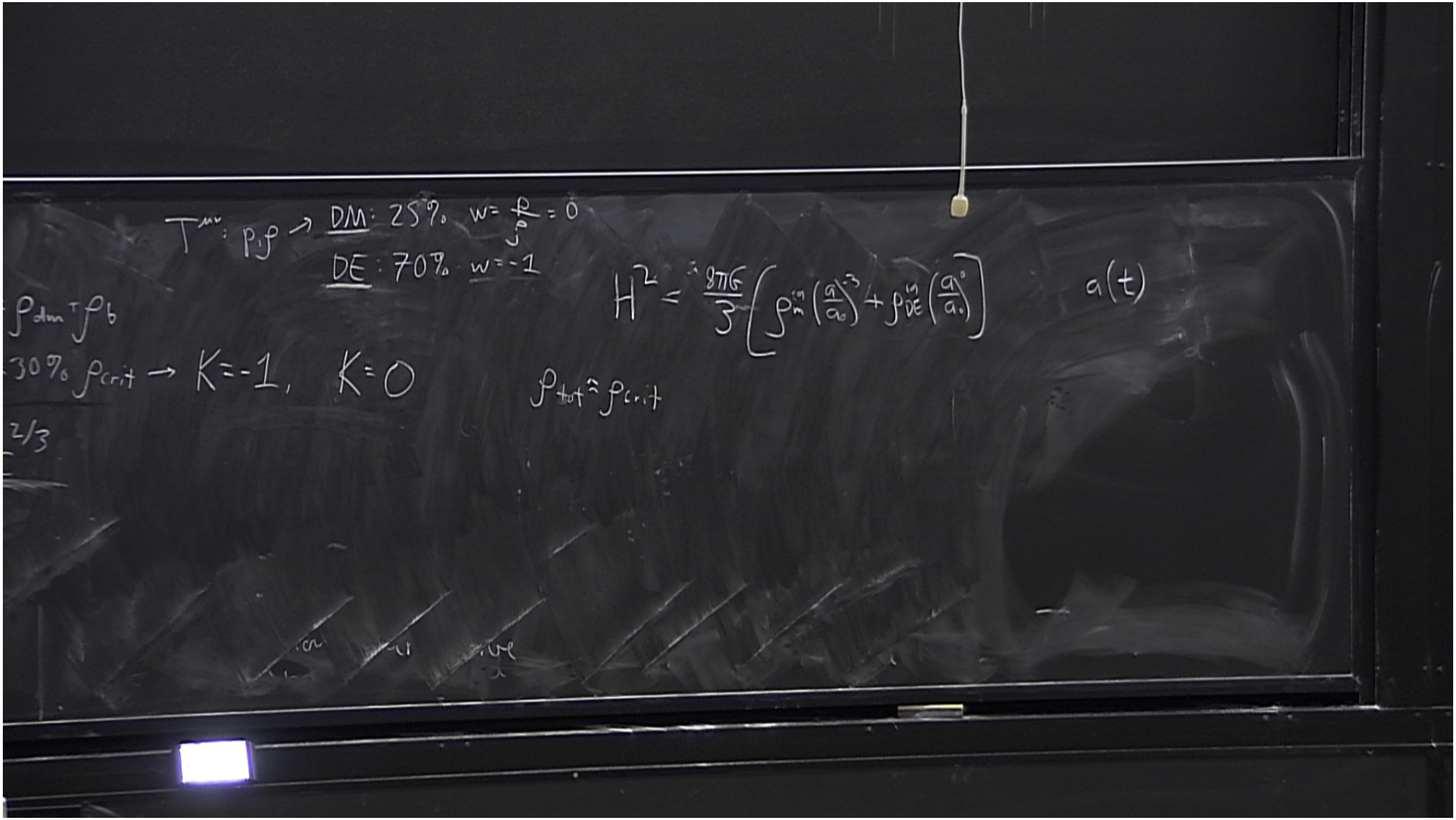

Today: DM, DE
Tomorrow: Matter/A.M. Baryogenesis/Leptogenesis
Thurs: Infl.
Friday: Primordial Perts, Inflationary

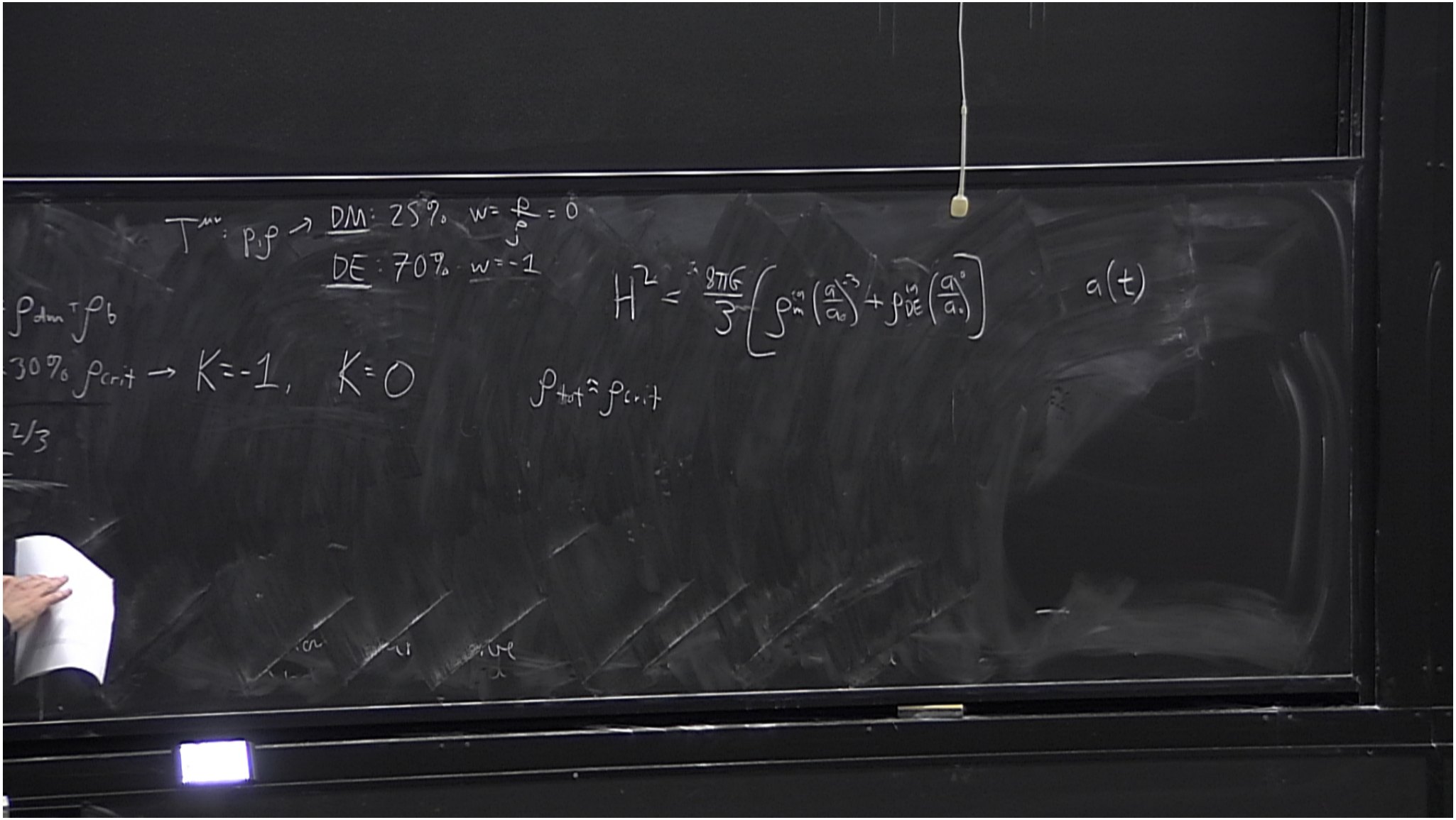

Today: DM, DE
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Thurs: Infl.
Friday: Primordial Perts, Inflationary
w
$T^{\mu\nu}$: p, ρ

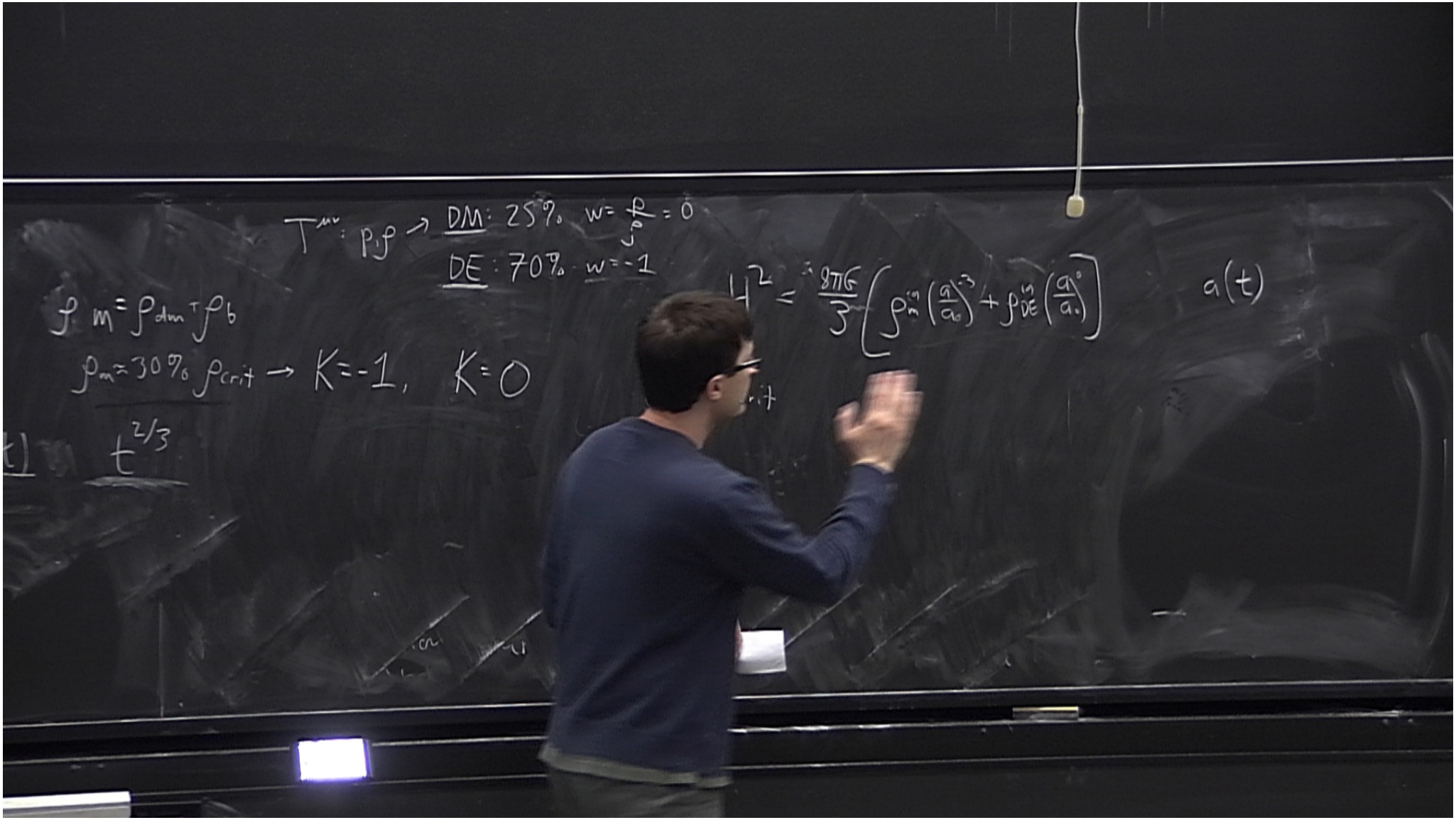

Baryogenesis/Leptogenesis
Perts, Inflationary
$T^{\mu\nu}$: $P, \rho \rightarrow$ DM: 25% $w = \frac{P}{\rho} = 0$
DE: 70% $w = -1$
$m = \rho_{dm} + \rho_b$

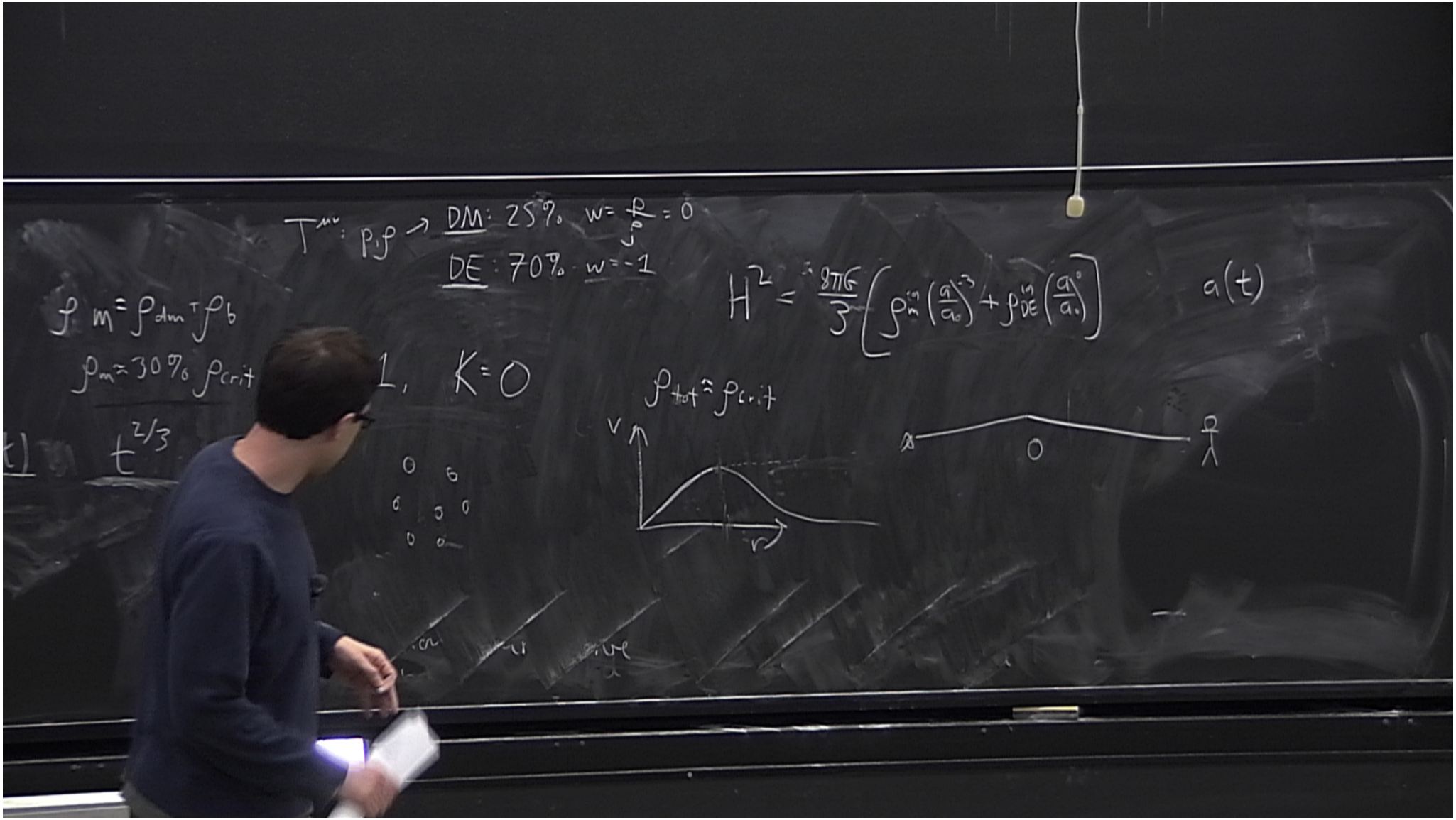

Baryogenesis/Leptogenesis
Perts, Inflationary
$T^{\mu\nu}$: P, ρ → DM: 25% $w = \frac{P}{\rho} = 0$
DE: 70% $w = -1$
$\rho_m = \rho_{dm} + \rho_b$
$\rho_m \approx 30\% \rho_{crit} \rightarrow K = -1, \quad K = 0$
$\rho_{tot} \approx \rho_{crit}$
$a(t) \propto t^{2/3}$

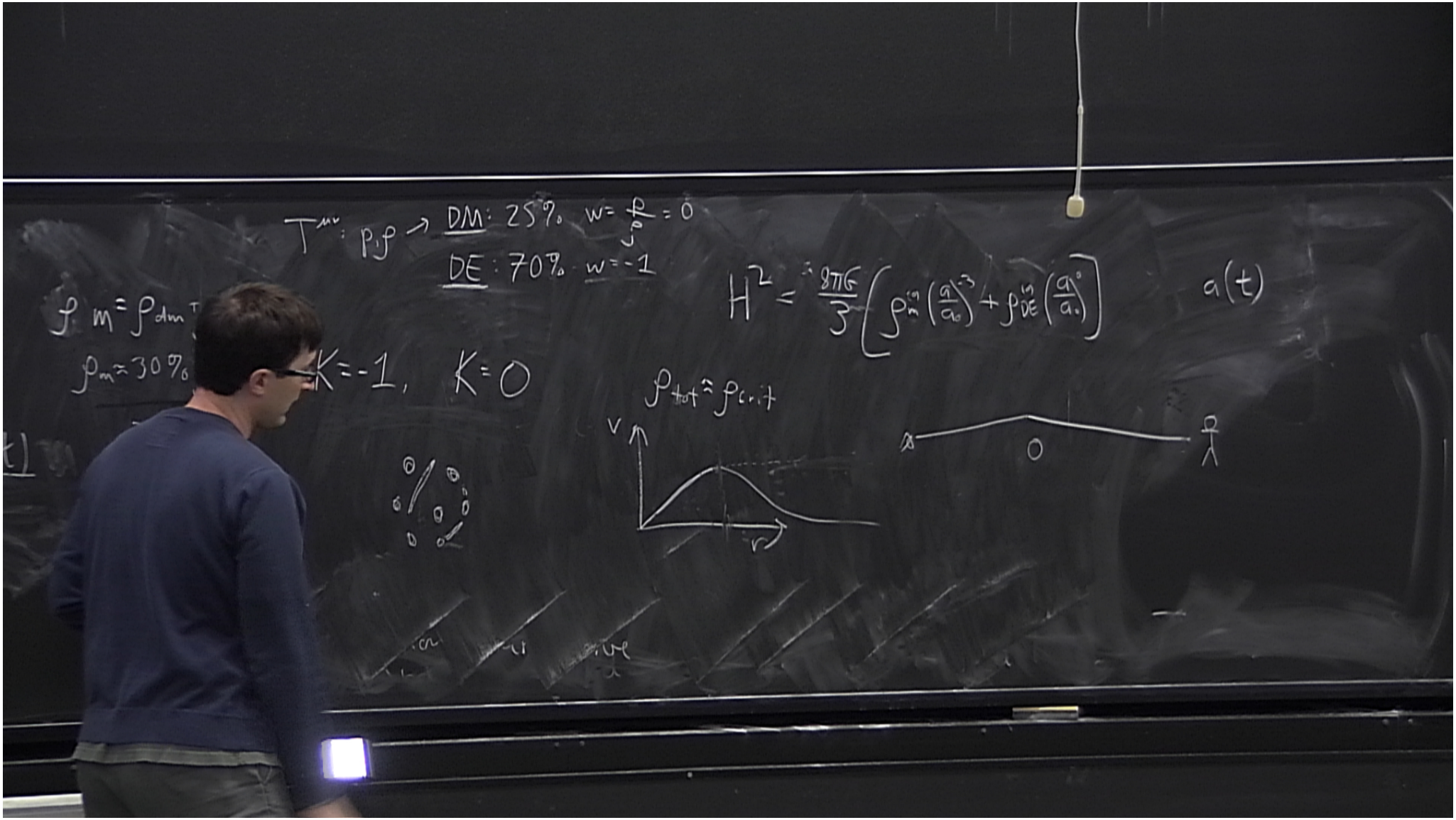

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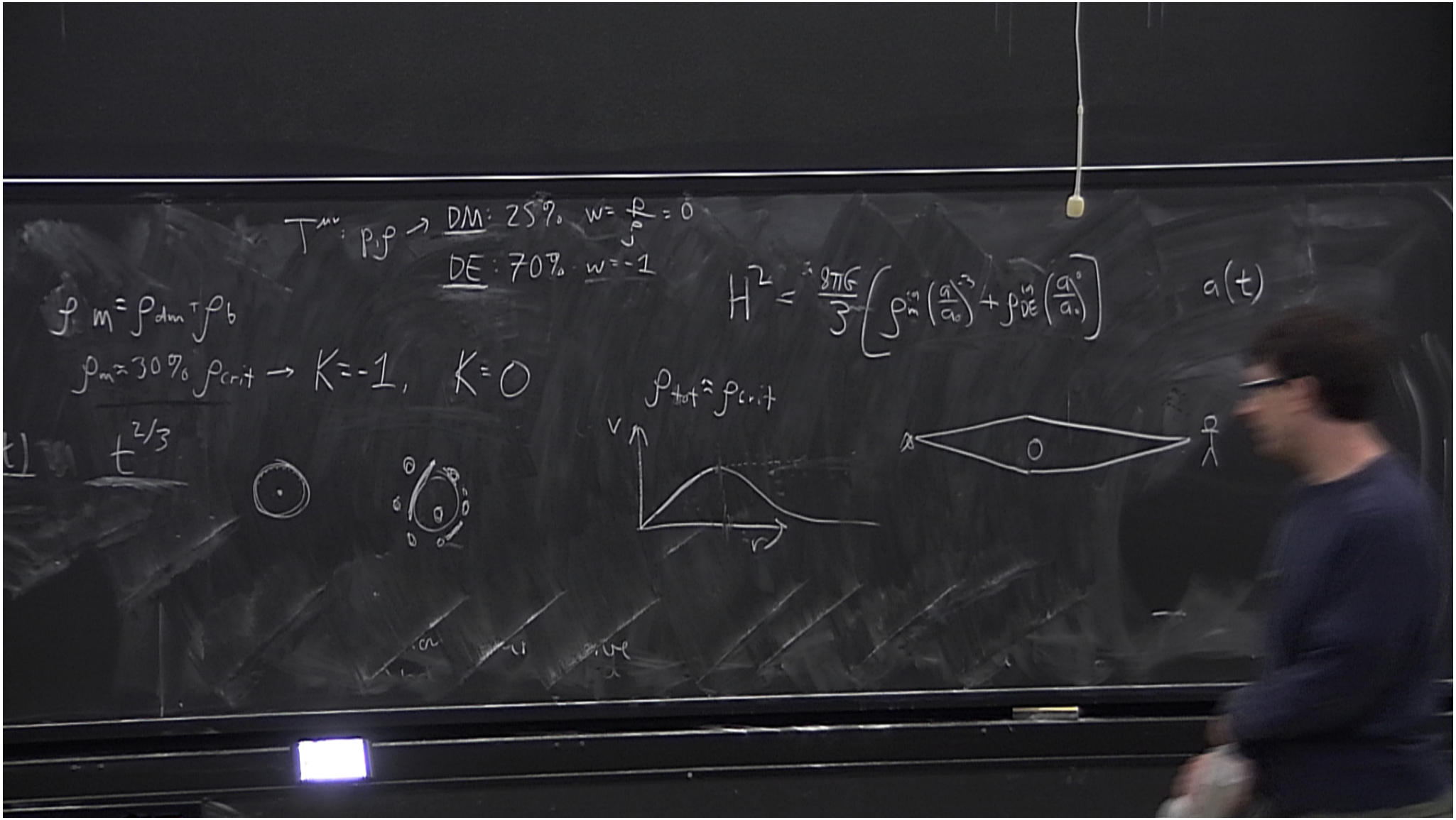

$T^{\mu\nu}$: $\rho, p \rightarrow$ DM: 25% $w = \frac{p}{\rho} = 0$
DE: 70% $w = -1$
$H^2 = \frac{8\pi G}{3}\left[\rho_m^{in}\left(\frac{a}{a_0}\right)^{-3} + \rho_{DE}^{in}\left(\frac{a}{a_0}\right)^{0}\right]$
$a(t)$
ρ_{dm}, ρ_b
30% $\rho_{crit} \rightarrow K=-1, \quad K=0$
$\rho_{tot} \approx \rho_{crit}$
2/3

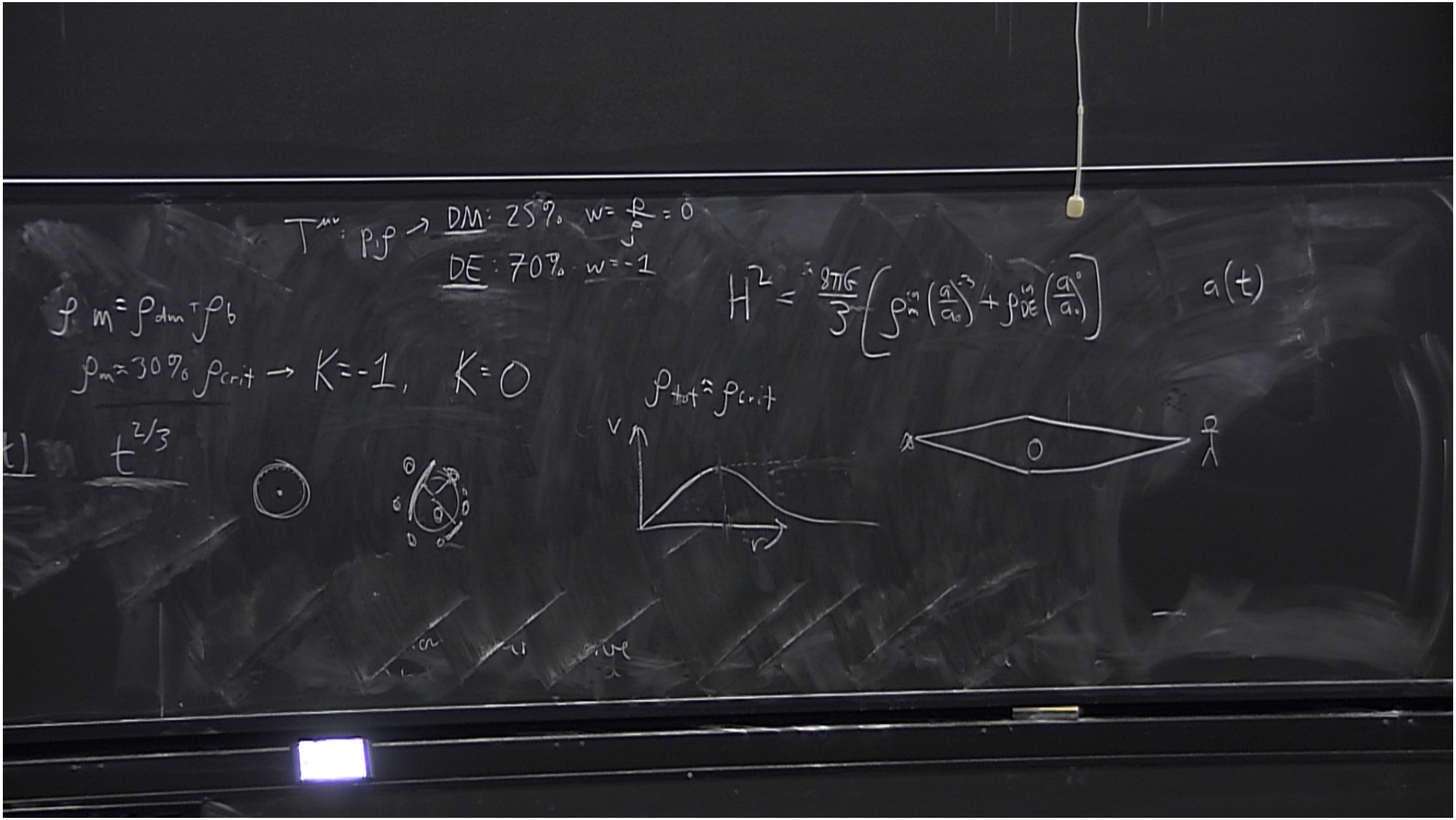

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DE: 70% $w = -1$
$H^2 = \frac{8\pi G}{3}\left[\rho_m^{(0)}\left(\frac{a}{a_0}\right)^{-3} + \rho_{DE}^{(0)}\left(\frac{a}{a_0}\right)^{0}\right]$
$a(t)$
ρ_{dm} ρ_b
30% $\rho_{crit} \rightarrow K=-1, \quad K=0$
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2/3

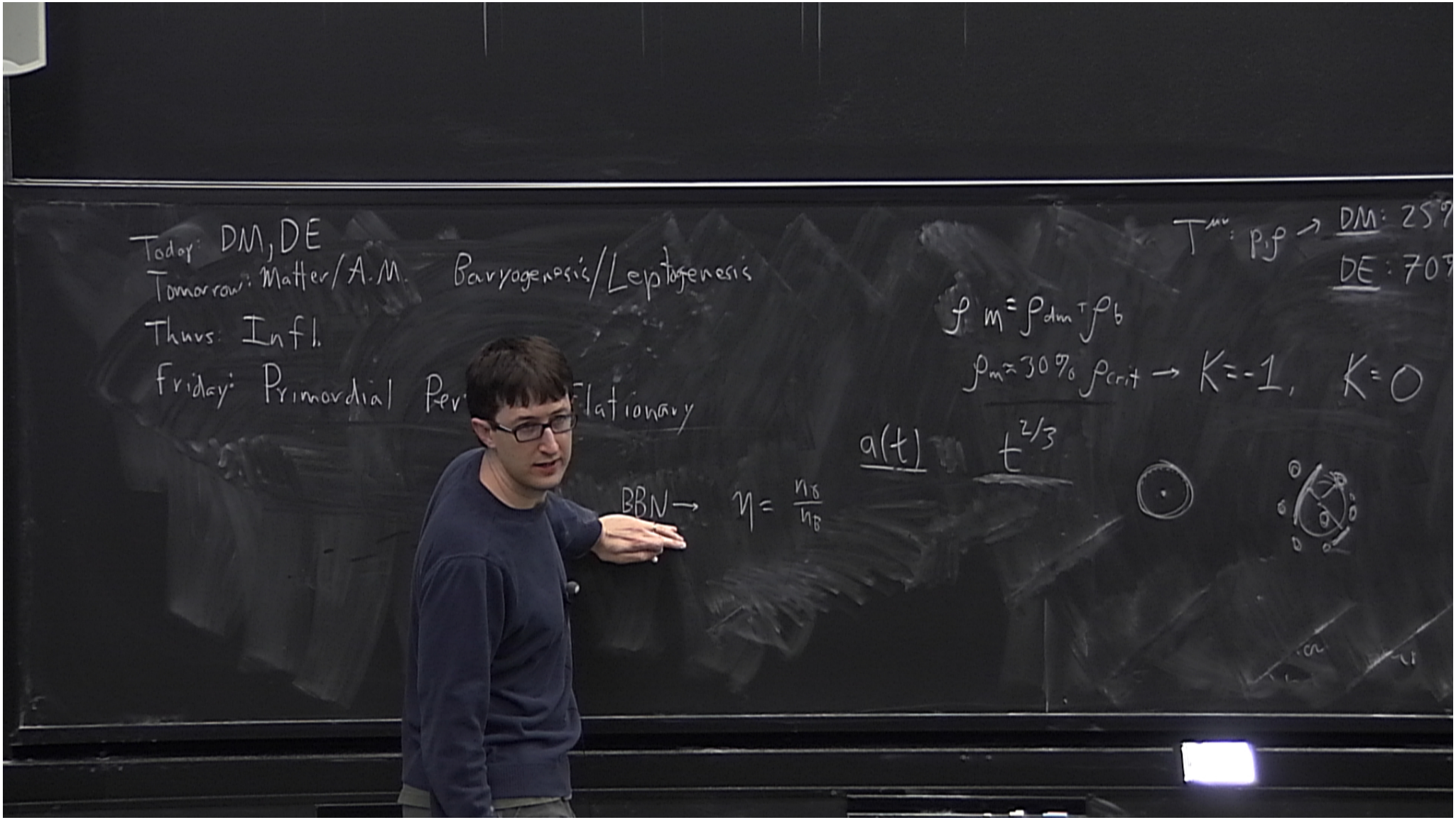

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$\rho_m \approx 30\% \rho_{crit} \rightarrow K = -1, \quad K = 0$
$t^{2/3}$
$H^2 = \frac{8\pi G}{3}\left(\rho_{m_0}\left(\frac{a}{a_0}\right)^{-3} + \rho_{DE}\left(\frac{a}{a_0}\right)^{0}\right)$
$a(t)$


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$\rho_m = \rho_{dm} + \rho_b$
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$\rho_{tot} \approx \rho_{crit}$
$t^{2/3}$
V
r
O


$T^{\mu\nu}$: $\rho, p \rightarrow$ DM: 25% $w = \frac{p}{\rho} = 0$
DE: 70% $w = -1$
$H^2 = \frac{8\pi G}{3}\left[\rho_m^0 \left(\frac{a}{a_0}\right)^{-3} + \rho_{DE}^0 \left(\frac{a}{a_0}\right)^{0}\right]$
$a(t)$
$\rho_m = \rho_{dm}$
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V
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O


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v
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O


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v
r
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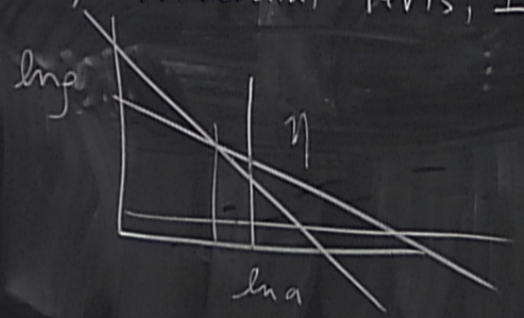

Today: DM, DE
Tomorrow: Matter/A.M. Baryogenesis/Leptogenesis
Thurs: Infl.
Friday: Primordial Per
flationary
BBN → η = n_B / n_B
T^μν: ρ, p → DM: 25%
DE: 70%
ρ_m = ρ_dm + ρ_b
ρ_m ≈ 30% ρ_crit → K = -1, K = 0
a(t) t^2/3

Today: DM, DE

Tomorrow: Matter/A.M. Baryogenesis/Leptogenesis

Thurs: Infl.

Friday: Primordial Perts, Inflationary



$T^{\mu\nu}$: $P, \rho \rightarrow$ DM: 25%

DE: 70%

$\rho_m = \rho_{dm} + \rho_b$

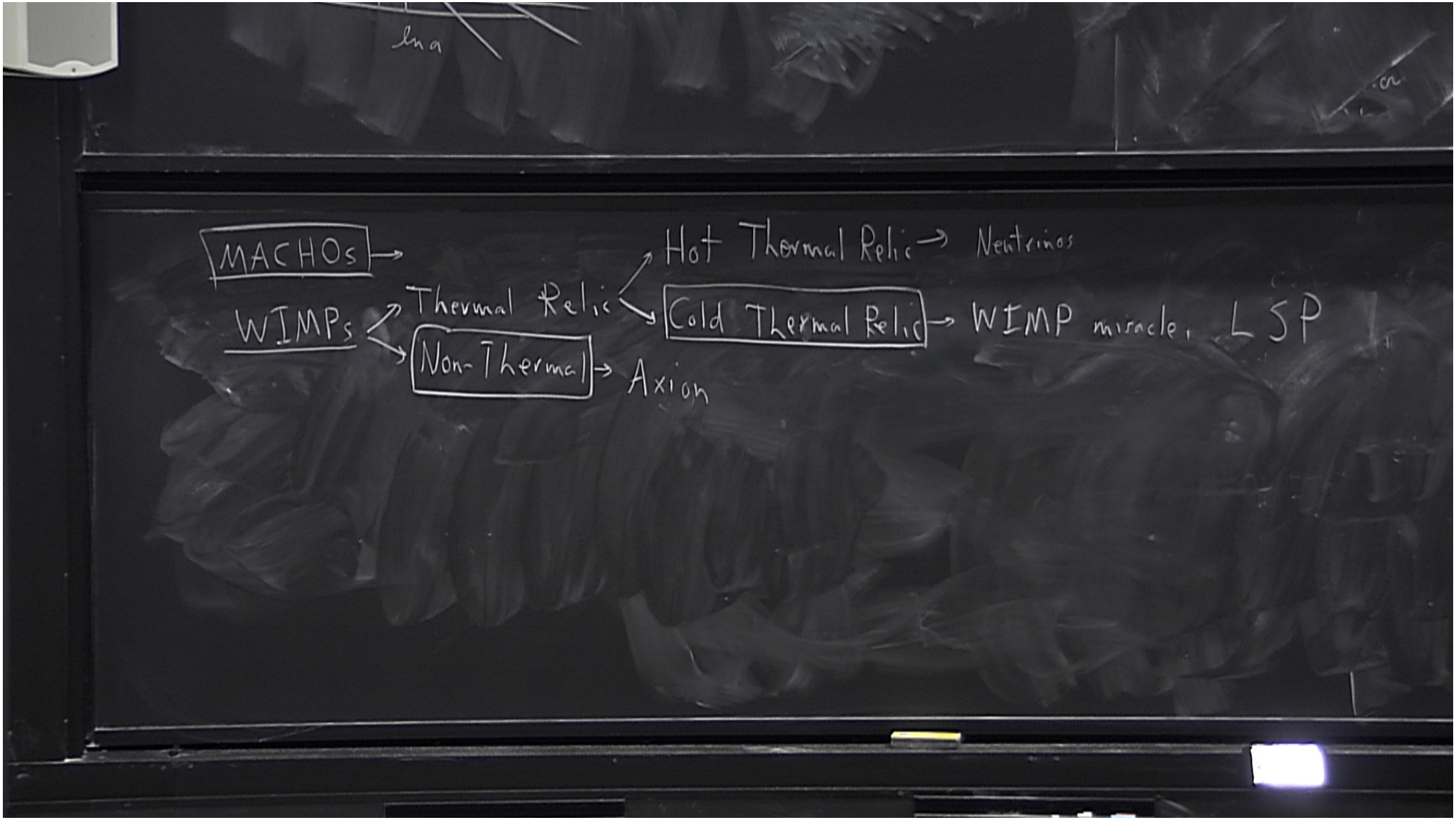
$\rho_m \approx 30\% \rho_{crit} \rightarrow K = -1, \; K = 0$

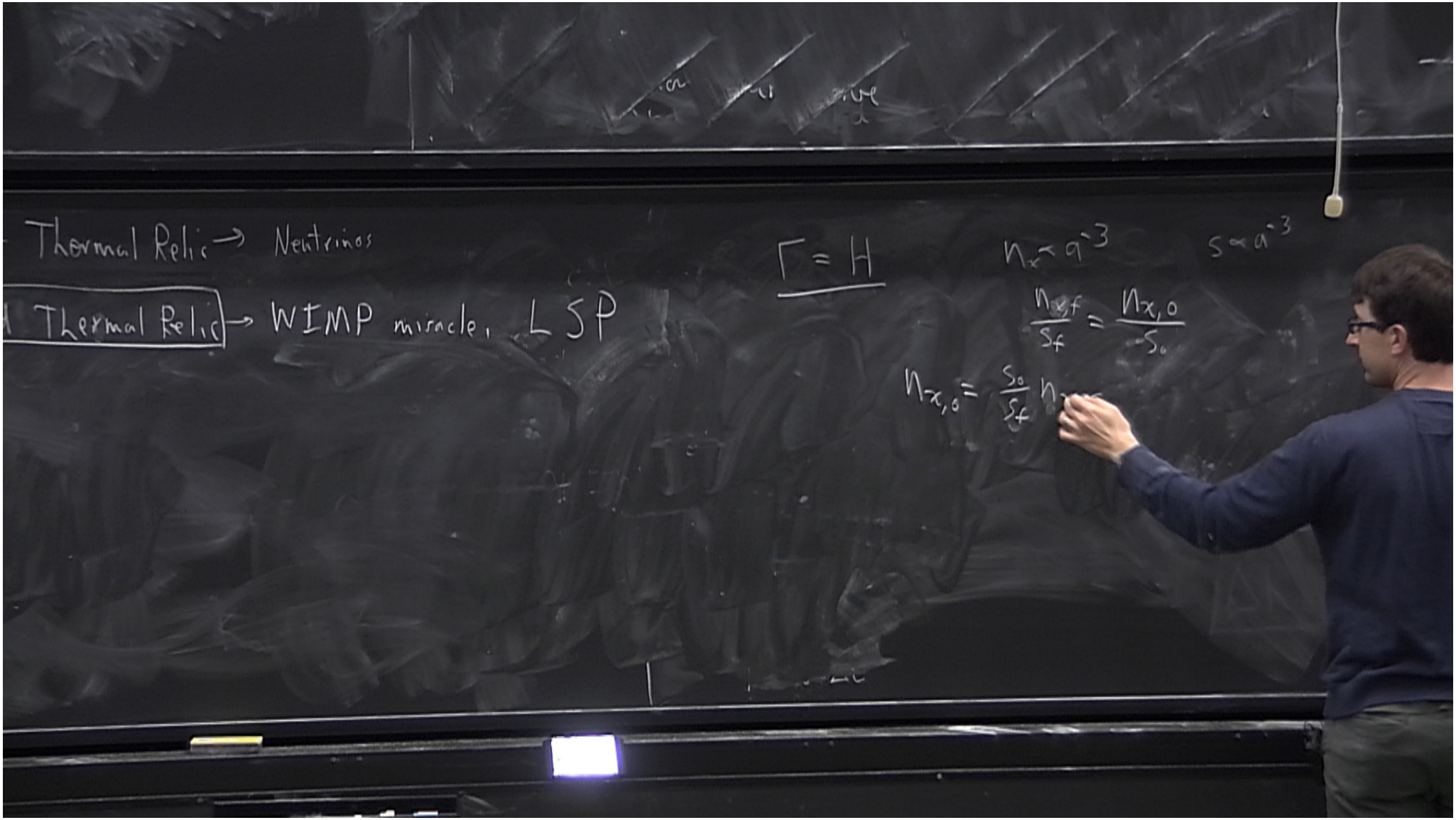
$a(t) \quad t^{2/3}$

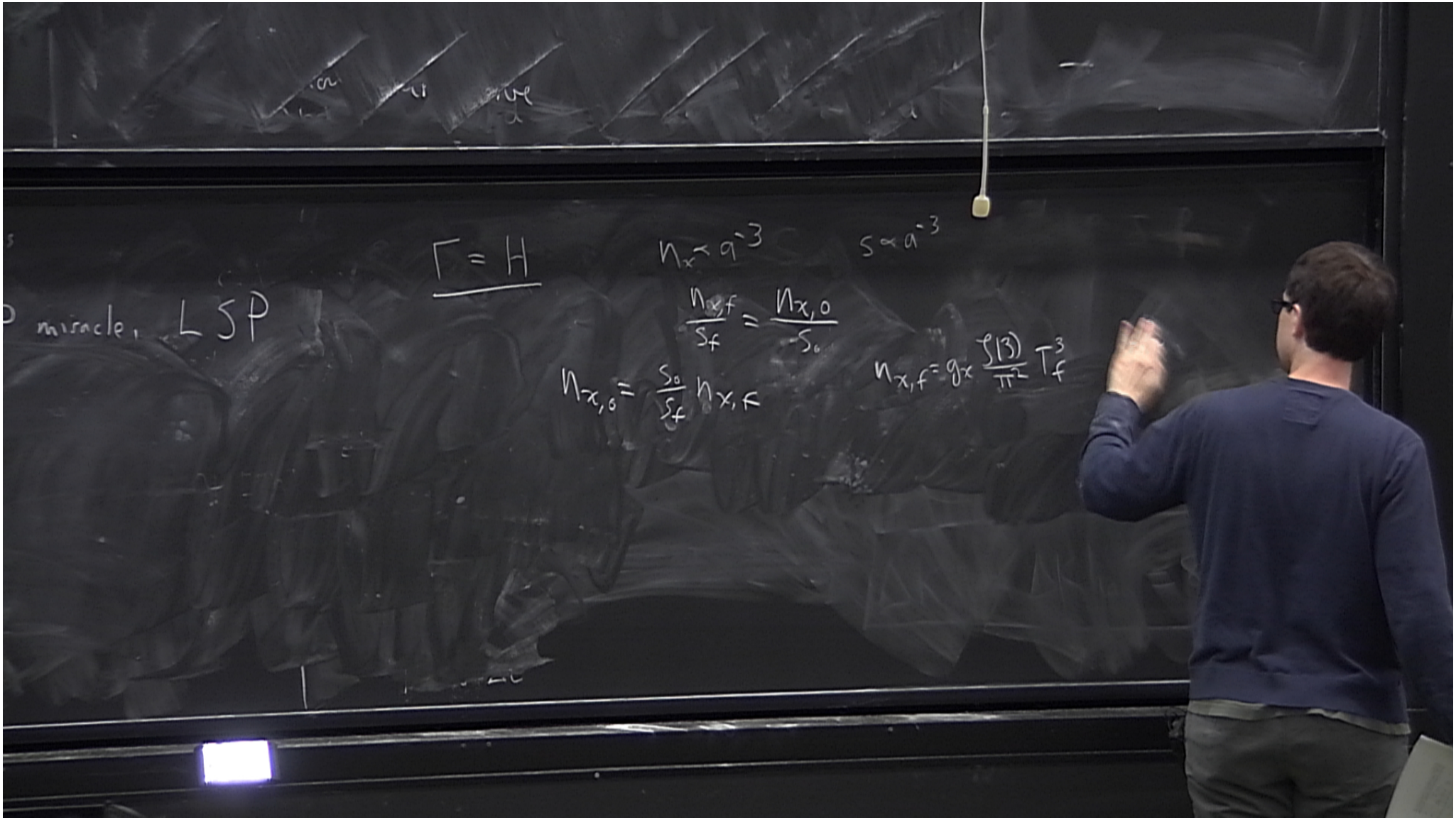
BBN $\rightarrow \eta = \frac{n_b}{n_\gamma} \rightarrow 5\%$

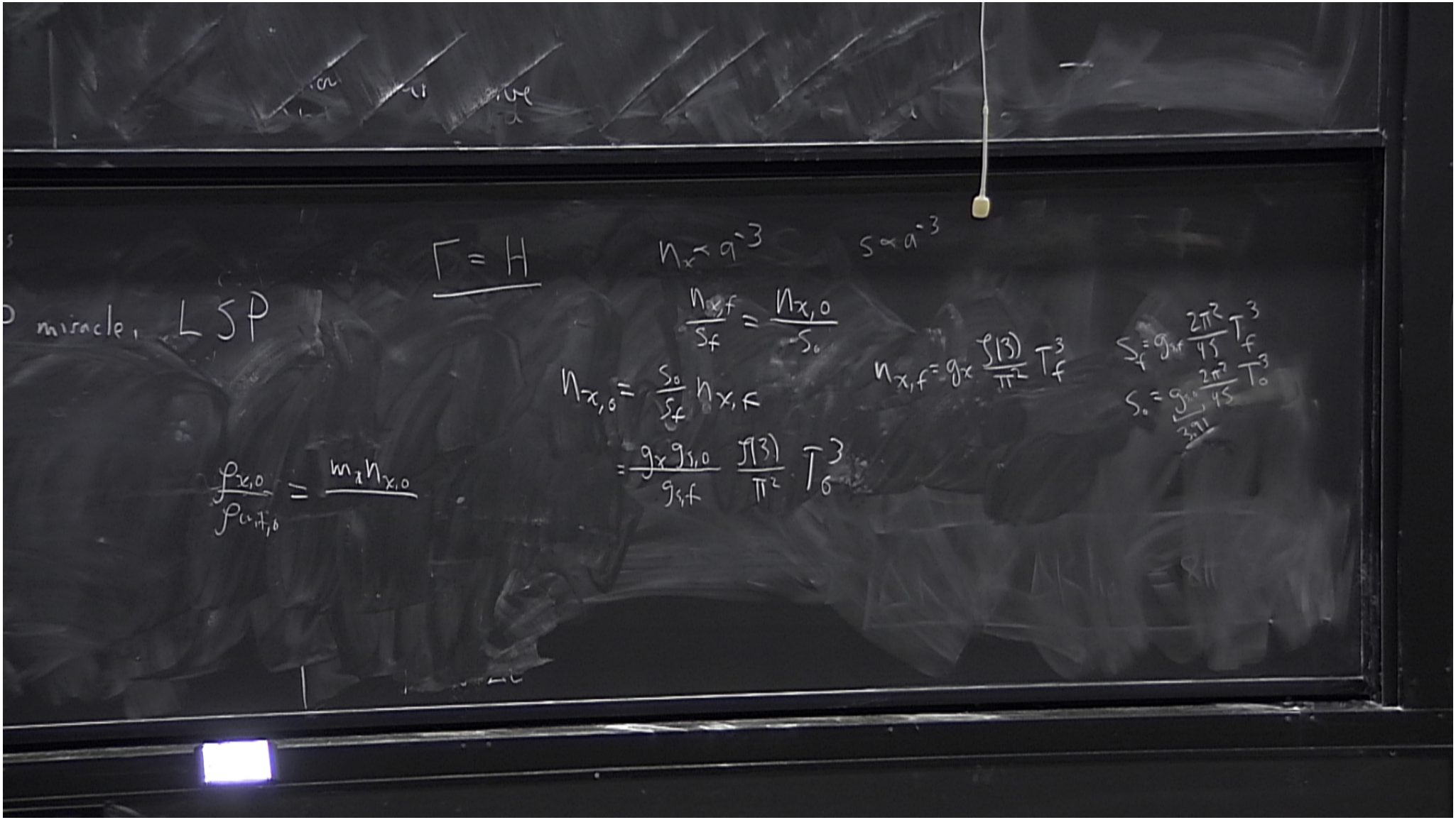


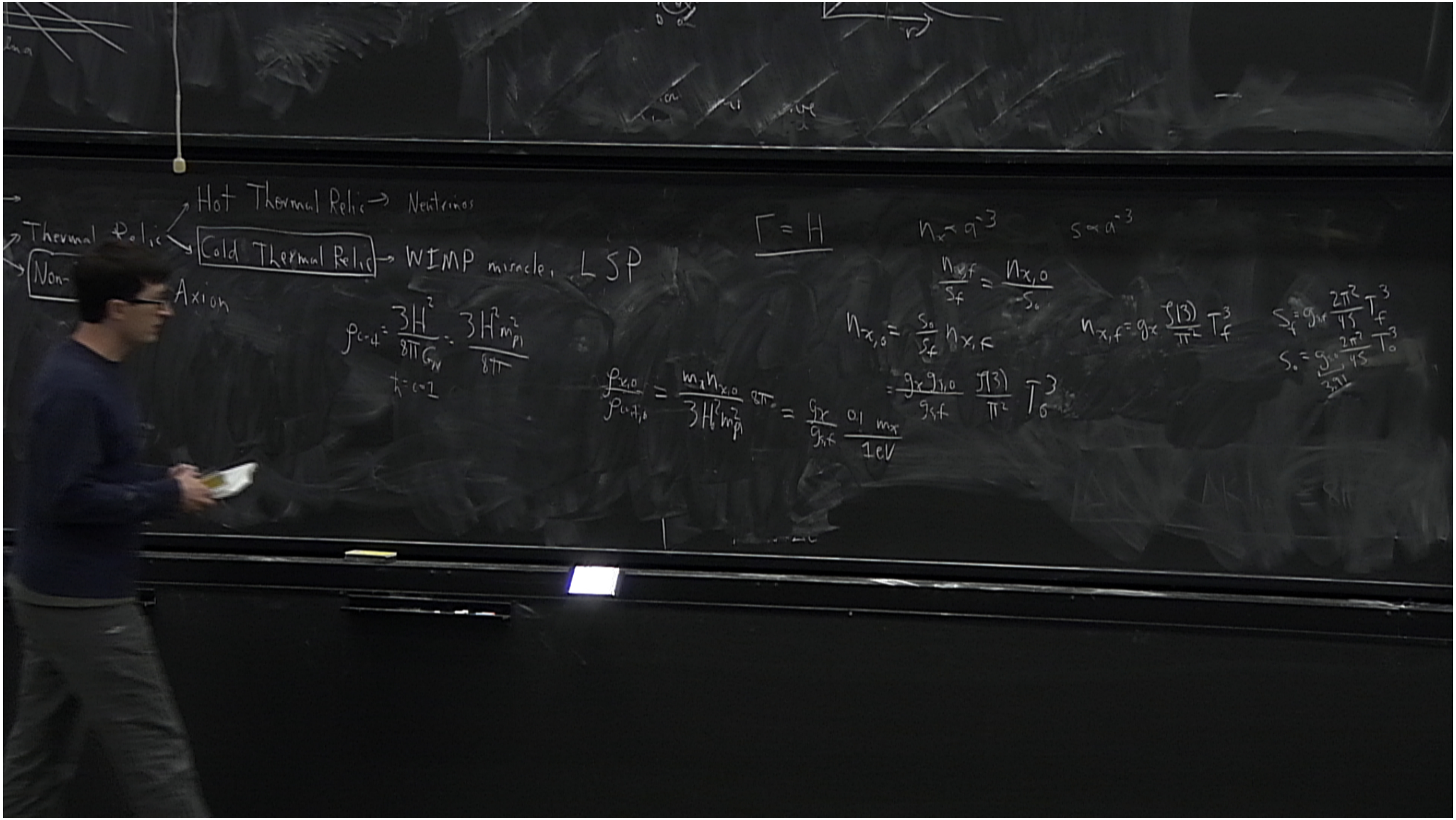


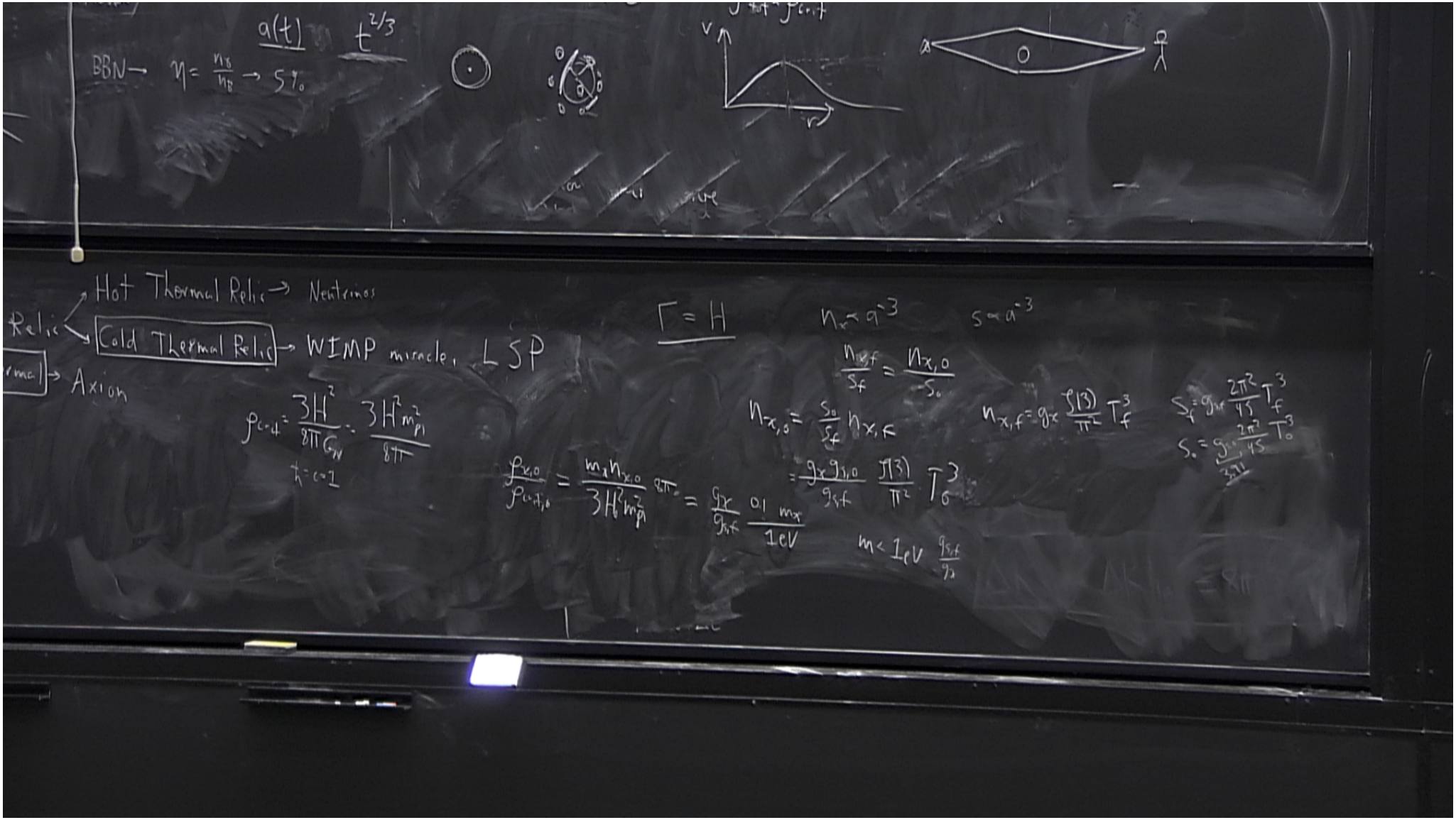

MACHOs
WIMPs
Thermal Relic
Non-Thermal
Axion
Hot Thermal Relic
Neutrinos
Cold Thermal Relic
WIMP miracle, LSP

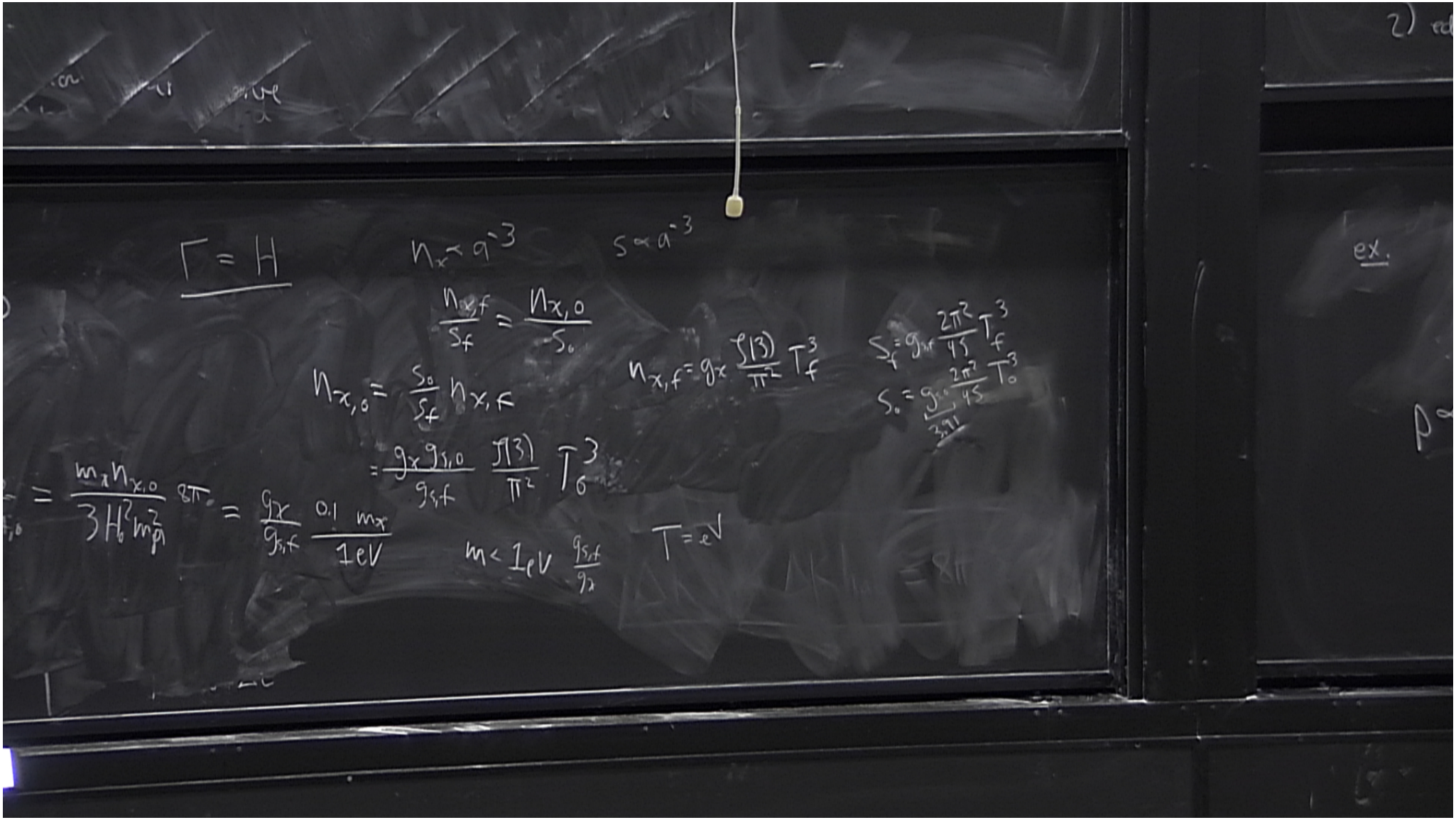

Thermal Relic → Neutrinos
Thermal Relic → WIMP miracle, LSP
Γ = H
$n_x \propto a^{-3}$
$s \propto a^{-3}$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f}$

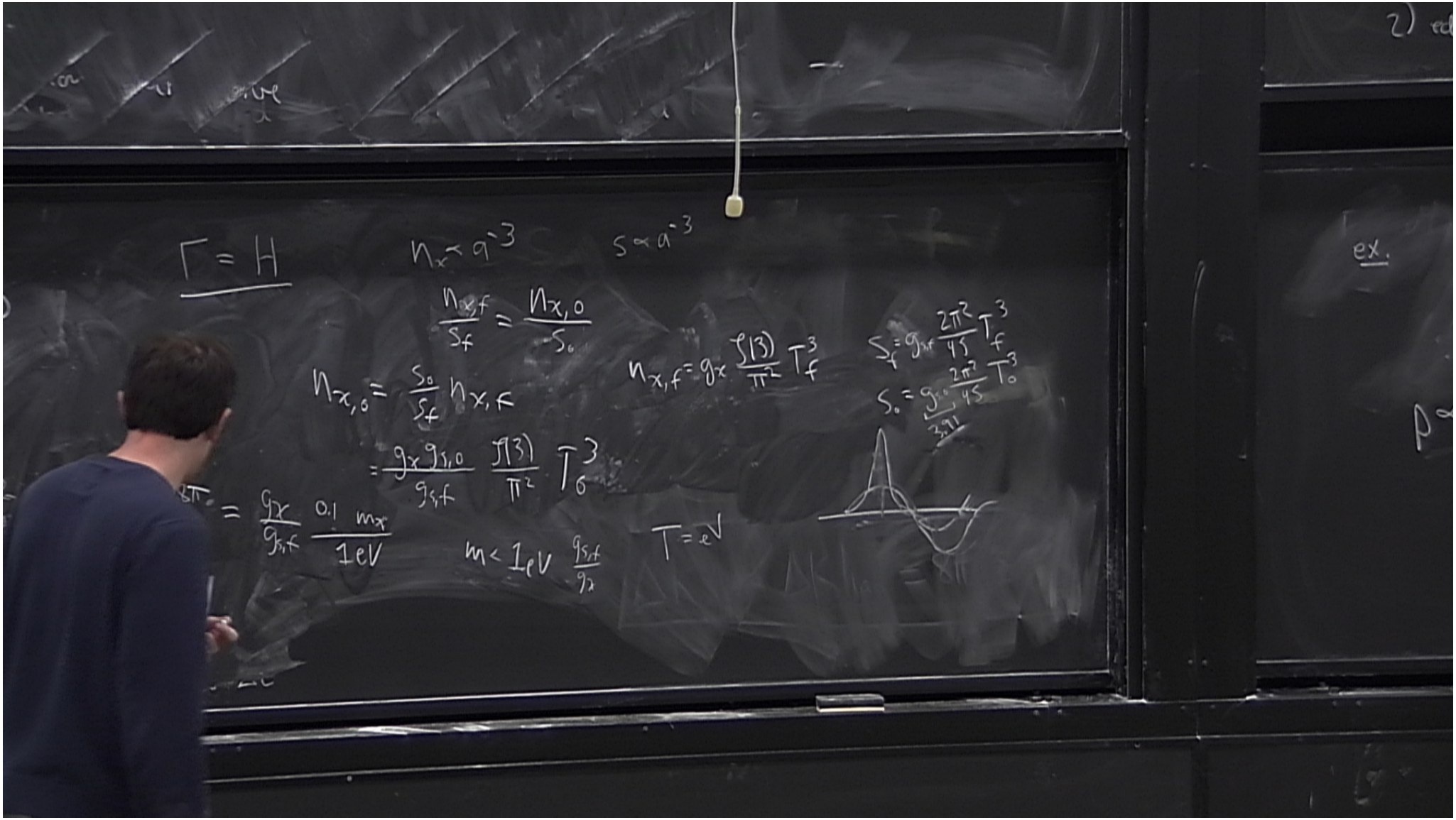

Γ = H
$n_x \propto a^{-3}$
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$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f}$
$n_{x,f} = g_x \frac{\zeta(3)}{\pi^2} T_f^3$
miracle, LSP

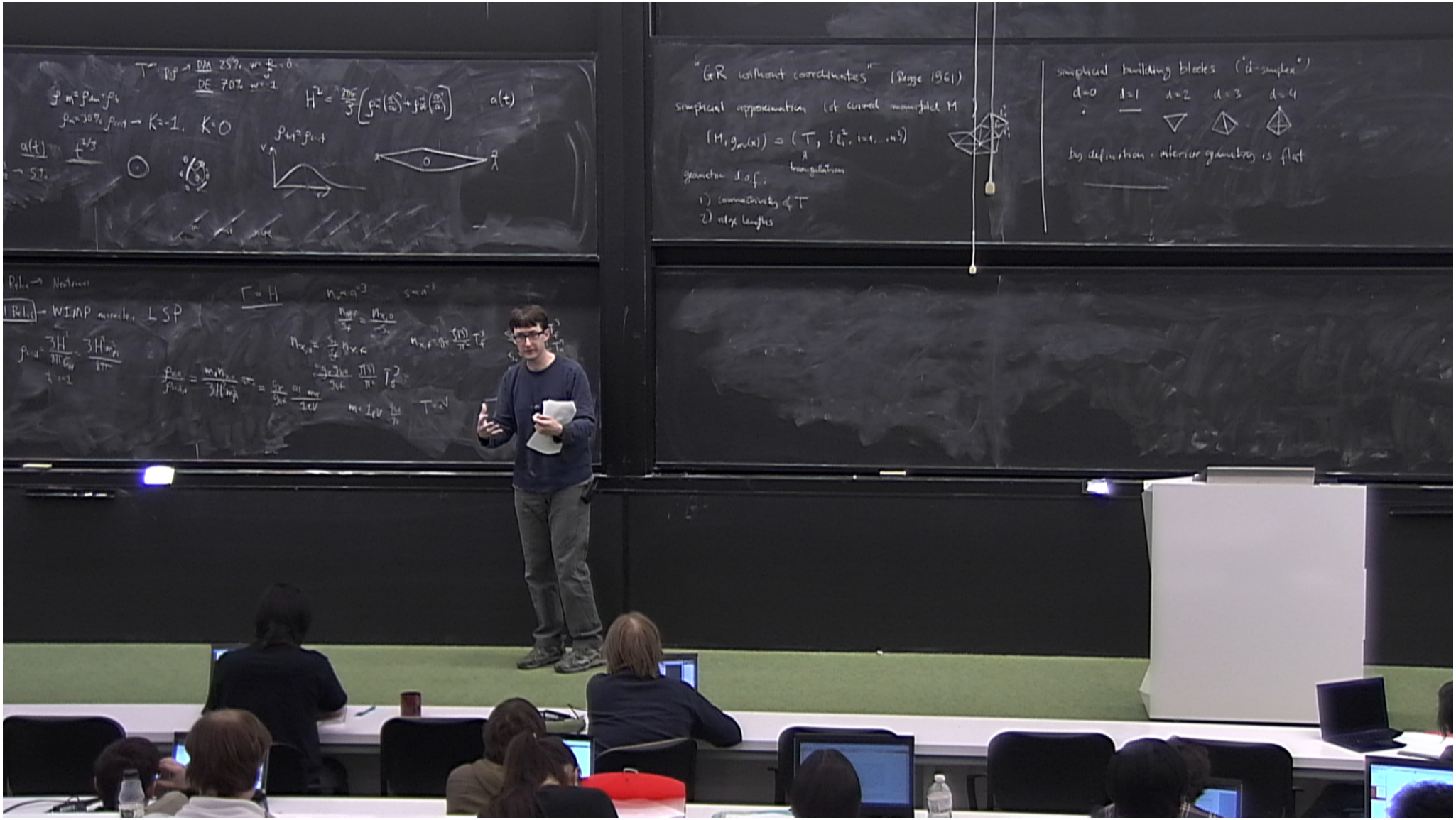

miracle, LSP
$\Gamma = H$
$n_x \sim a^{-3}$
$s \propto a^{-3}$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f}$
$= \frac{g_x g_{s,0}}{g_{s,f}} \frac{\zeta(3)}{\pi^2} T_0^3$
$n_{x,f} = g_x \frac{\zeta(3)}{\pi^2} T_f^3$
$s_f = g_{s,f} \frac{2\pi^2}{45} T_f^3$
$s_0 = \frac{g_{s,0}}{3.91} \frac{2\pi^2}{45} T_0^3$
$\frac{\rho_{x,0}}{\rho_{crit,0}} = \frac{m_x n_{x,0}}{}$

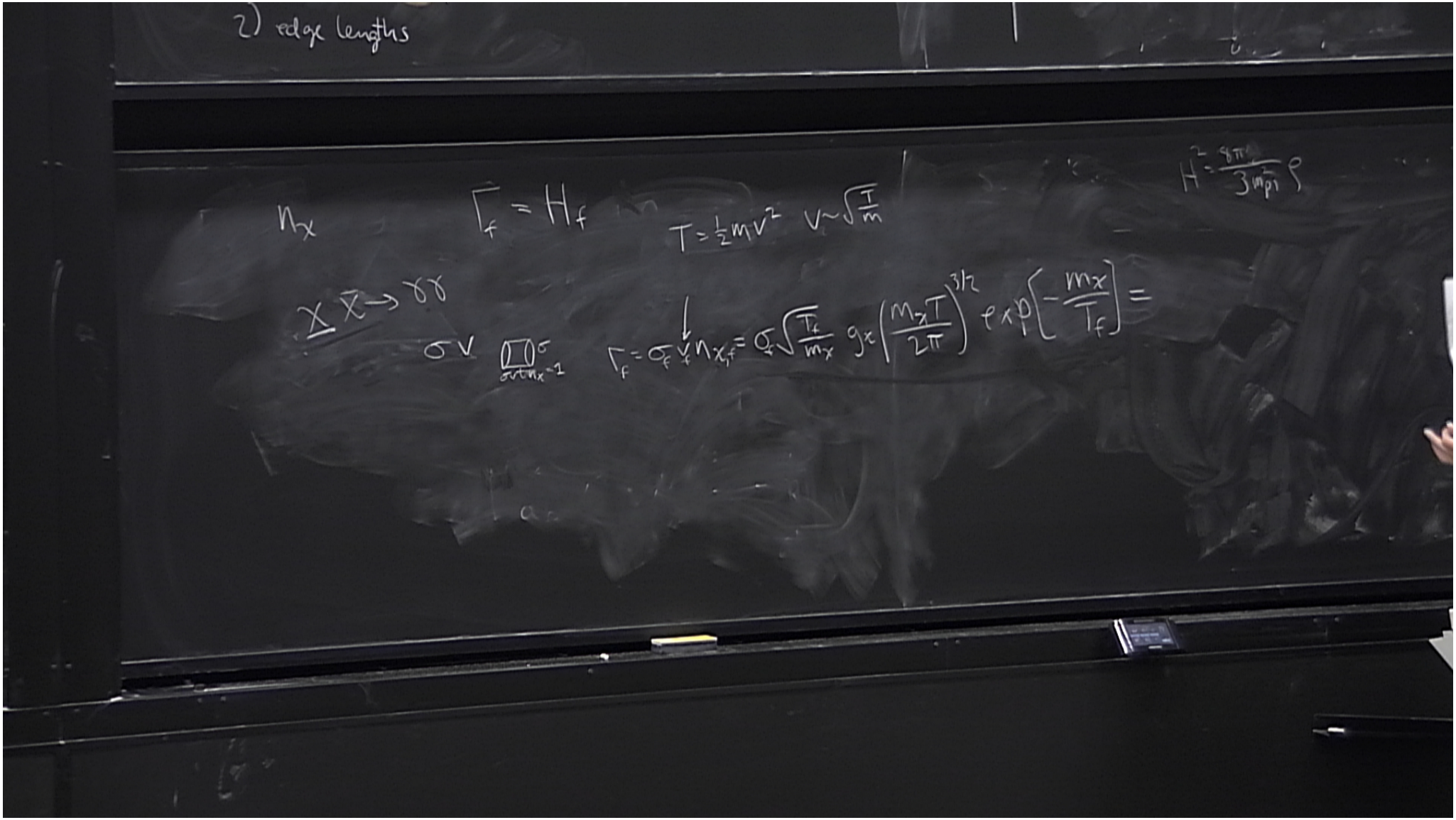

Hot Thermal Relic → Neutrinos
Thermal Relic
Cold Thermal Relic → WIMP miracle, LSP
Non-
Axion
Γ = H
$n_x \propto a^{-3}$
$s \propto a^{-3}$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$\rho_{c=1} = \frac{3H^2}{8\pi G_N} = \frac{3H^2 m_{Pl}^2}{8\pi}$
$\hbar = c = 1$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f}$
$n_{x,f} = g_x \frac{\zeta(3)}{\pi^2} T_f^3$
$s_f = g_{*s} \frac{2\pi^2}{45} T_f^3$
$s_0 = g_{*s,0} \frac{2\pi^2}{45} T_0^3$
$\frac{g_{*s,0}}{3.91}$
$\frac{\rho_{x,0}}{\rho_{c=1,0}} = \frac{m_x n_{x,0}}{3H_0^2 m_{Pl}^2} 8\pi = \frac{g_x}{g_{*s,f}} \frac{0.1\ m_x}{1\text{eV}}$
$= \frac{g_x g_{s,0}}{g_{s,f}} \frac{\zeta(3)}{\pi^2} T_0^3$

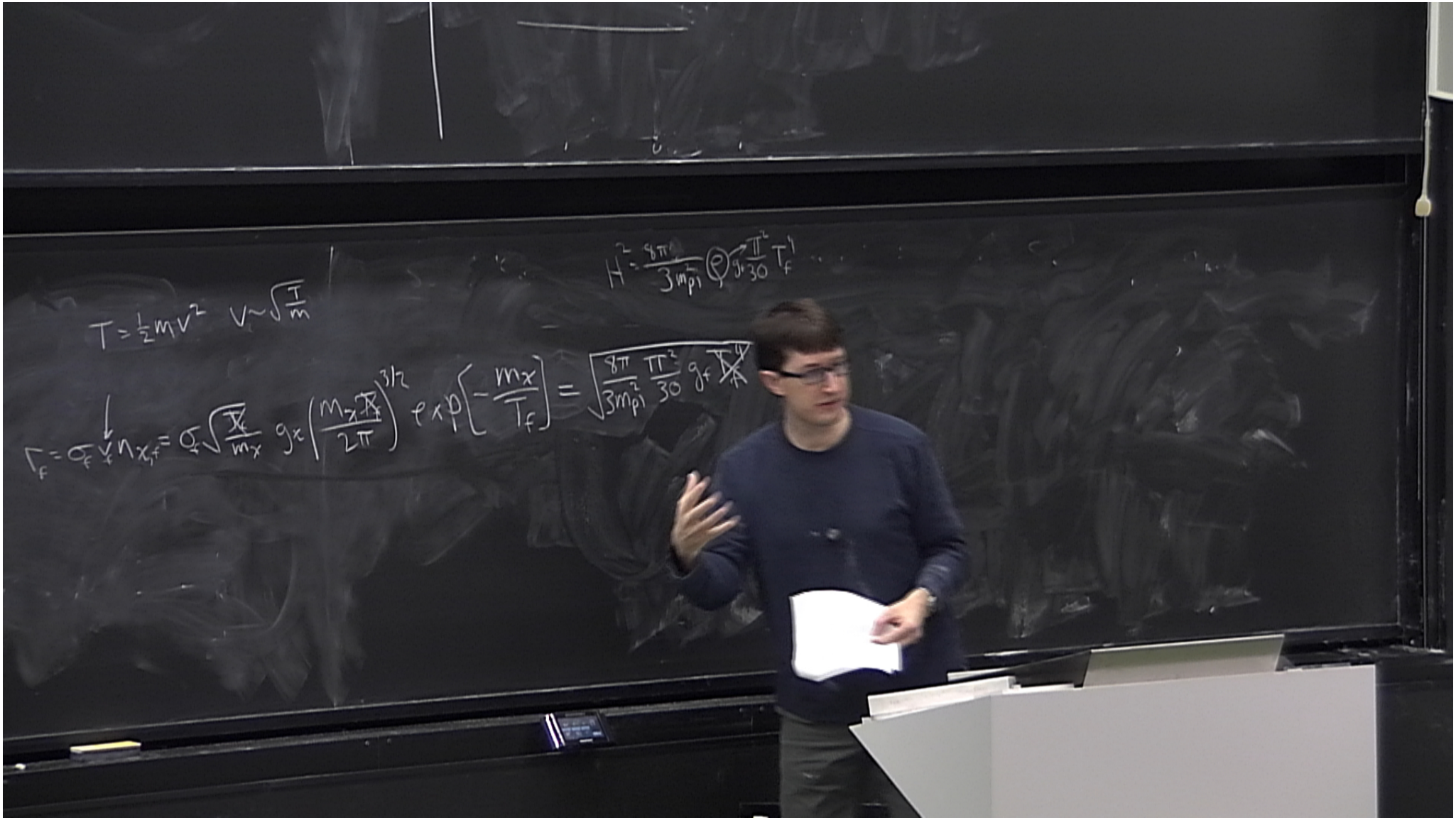

a(t) $t^{2/3}$
BBN → $\eta = \frac{n_B}{n_\gamma} \to 5\%$
v
r
Relic
Hot Thermal Relic → Neutrinos
Cold Thermal Relic → WIMP miracle, LSP
Axion
$\Gamma = H$
$n_x \propto a^{-3}$
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$\frac{3.91}{}$
$\frac{\rho_{x,0}}{\rho_{c=1,0}} = \frac{m_x n_{x,0}}{3H_0^2 m_{Pl}^2} 8\pi = \frac{g_x}{g_{s,f}} \frac{0.1\ m_x}{1\,eV}$
$= \frac{g_x g_{s,0}}{g_{s,f}} \frac{\zeta(3)}{\pi^2} T_0^3$
$m < 1\,eV \frac{g_{s,f}}{g_x}$

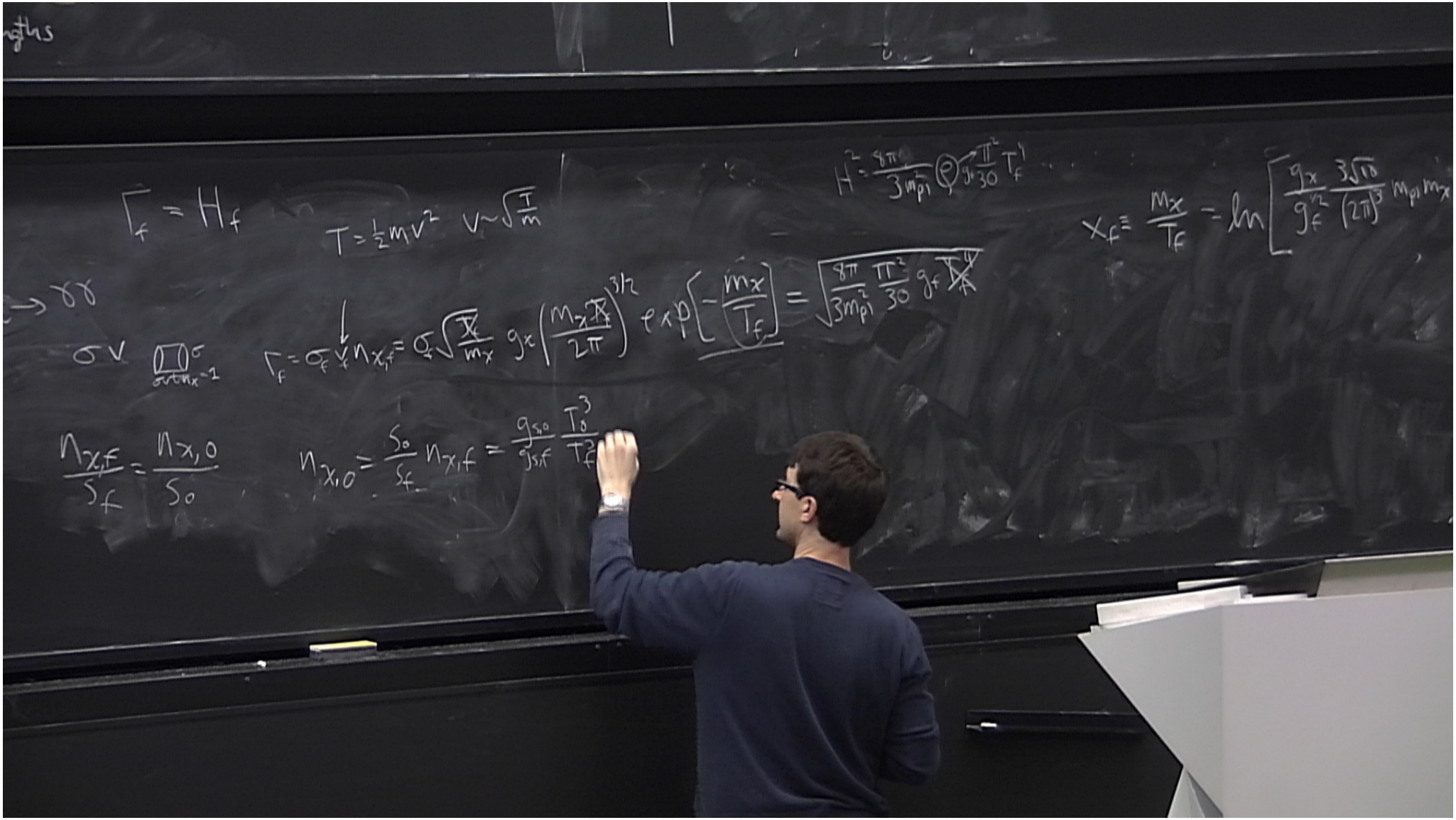

$\Gamma = H$
$n_x \propto a^{-3}$
$s \propto a^{-3}$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f}$
$= \frac{g_x}{g_{s,f}} \frac{g_{s,0}}{g_{s,f}} \frac{\zeta(3)}{\pi^2} T_0^3$
$n_{x,f} = g_x \frac{\zeta(3)}{\pi^2} T_f^3$
$s_f = g_{s,f} \frac{2\pi^2}{45} T_f^3$
$s_0 = \frac{g_{s,0}}{3.91} \frac{2\pi^2}{45} T_0^3$
$= \frac{m_x n_{x,0}}{3 H_0^2 m_{pl}^2} 8\pi = \frac{g_x}{g_{s,f}} \frac{0.1\ m_x}{1\,eV}$
$m < 1\,eV \frac{g_{s,f}}{g_x}$
$T = eV$
ex.

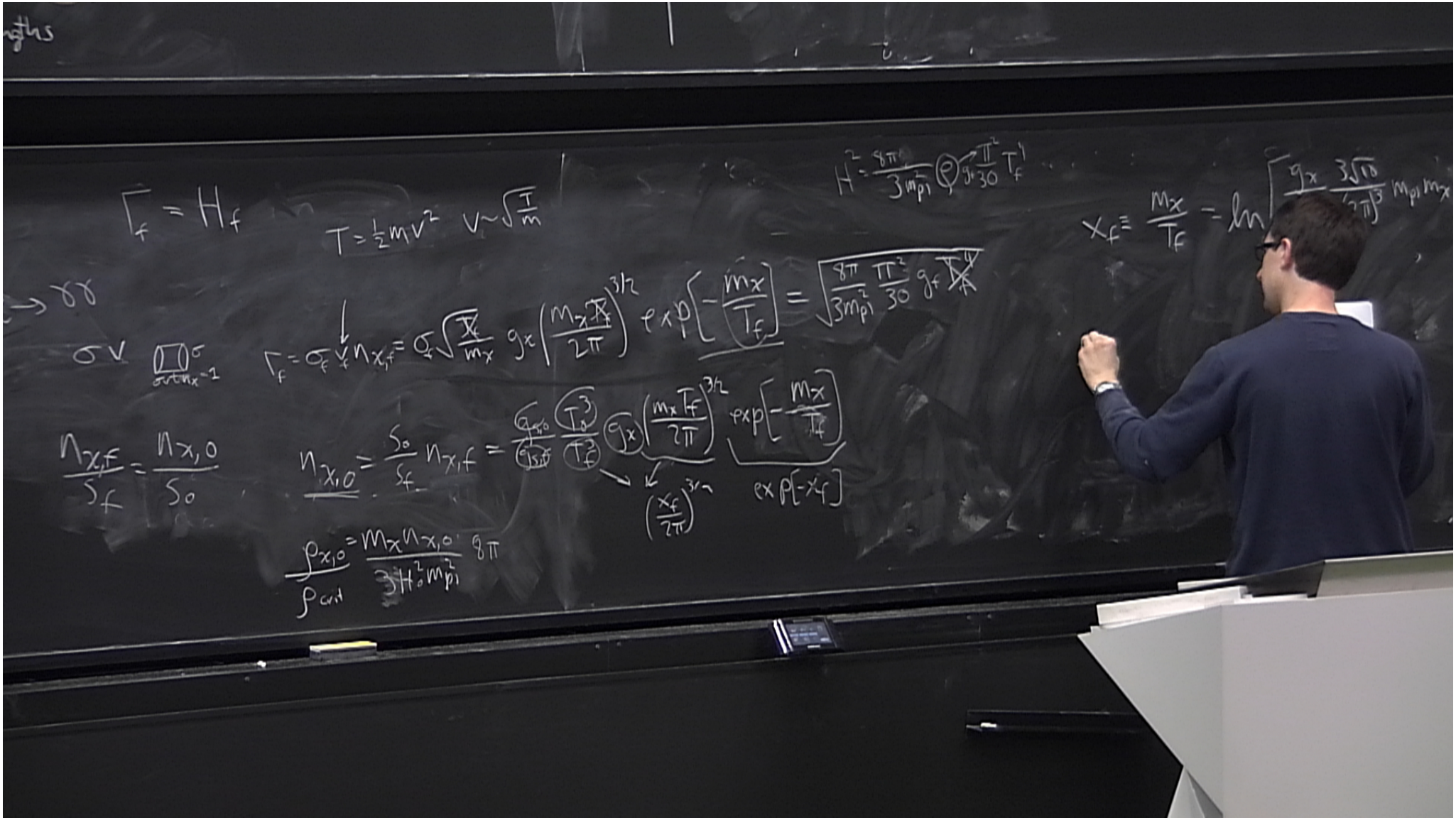

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$= \frac{g_x}{g_{s,f}} \frac{\zeta(3)}{\pi^2} T_0^3$
$n_{x,f} = g_x \frac{\zeta(3)}{\pi^2} T_f^3$
$s_f = g_{s,f} \frac{2\pi^2}{45} T_f^3$
$s_0 = \frac{g_{s,0}}{3.91} \frac{2\pi^2}{45} T_0^3$
$= \frac{g_x}{g_{s,f}} \frac{0.1\ m_x}{1eV}$
$m < 1eV \frac{g_{s,f}}{g_x}$
$T = eV$
ex.

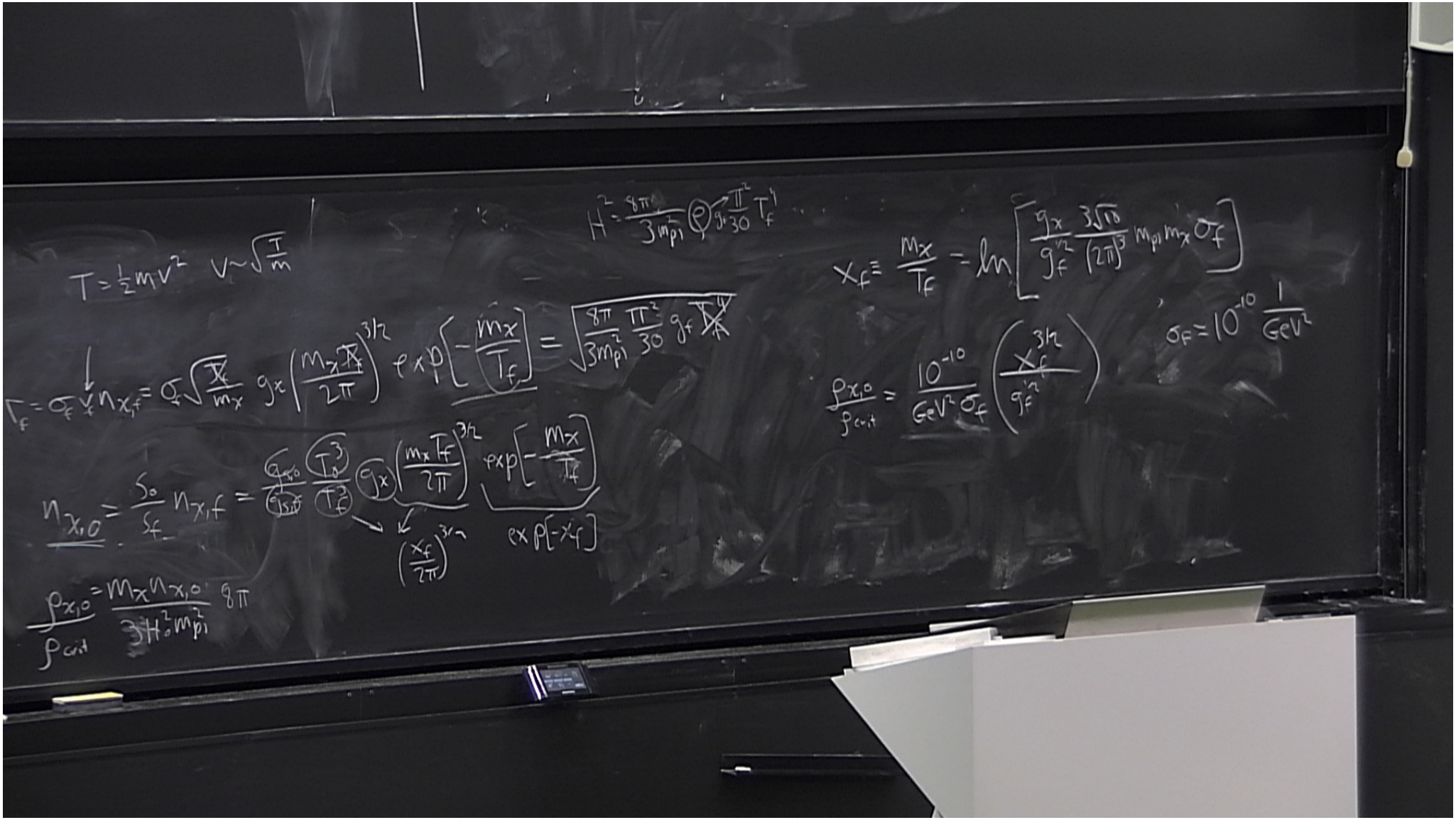

"GR without coordinates" (Regge 1961)
simplicial approximation (of curved manifold M)
geometric d.o.f.:
1) connectivity of T
2) edge lengths
simplicial building blocks ("d-simplex")
d=0
d=1
d=2
d=3
d=4
by definition: interior geometry is flat
WIMP
LSP
Neutrinos


2) edge lengths
n_χ
$\Gamma_f = H_f$
$T = \frac{1}{2} m v^2$ $v \sim \sqrt{\frac{T}{m}}$
$H^2 = \frac{8\pi}{3 m_{pl}^2} \rho$
$\chi\chi \to \gamma\gamma$
σv σ $\sigma v n_\chi^{-1}$
$\Gamma_f = \sigma_f v_f n_{\chi,f} = \sigma_f \sqrt{\frac{T_f}{m_\chi}} g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} \exp\left[-\frac{m_\chi}{T_f}\right] =$


$T = \frac{1}{2} m v^2 \quad v \sim \sqrt{\frac{T}{m}}$
$H^2 = \frac{8\pi}{3 m_{pl}^2} \rho \to g_* \frac{\pi^2}{30} T_f^4$
$\Gamma_f = \sigma_f v_f n_{\chi,f} = \sigma_f \sqrt{\frac{T_f}{m_\chi}} g_\chi \left(\frac{m_\chi T_f}{2\pi} \right)^{3/2} \exp\left[-\frac{m_\chi}{T_f} \right] = \sqrt{\frac{8\pi}{3 m_{pl}^2} \frac{\pi^2}{30} g_f T_f^4}$


$\Gamma_f = H_f$
$T = \frac{1}{2} m v^2 \quad v \sim \sqrt{\frac{T}{m}}$
$H^2 = \frac{8\pi}{3 m_{pl}^2} \rho \quad \rho \sim g_* \frac{\pi^2}{30} T_f^4$
$x_f \equiv \frac{m_x}{T_f} = \ln\left[\frac{g_x}{g_f^{1/2}} \frac{3\sqrt{10}}{(2\pi)^3} m_{pl} m_x \right]$
$\sigma v \quad \sigma \sim \frac{\sigma}{\sigma v t m_x^{-1}}$
$\Gamma_f = \sigma_f v_f n_{x,f} = \sigma_f \sqrt{\frac{T_f}{m_x}} g_x \left(\frac{m_x T_f}{2\pi} \right)^{3/2} \exp\left[-\frac{m_x}{T_f} \right] = \sqrt{\frac{8\pi}{3 m_{pl}^2}} \frac{\pi^2}{30} g_f T_f^4$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f} = \frac{g_{s0}}{g_{sf}} \frac{T_0^3}{T_f^3}$

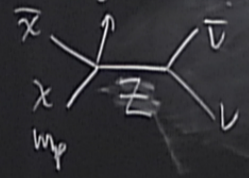

$\Gamma_f = H_f$
$T = \frac{1}{2} m v^2 \quad v \sim \sqrt{\frac{T}{m}}$
$H^2 = \frac{8\pi}{3 m_{pl}^2} \rho = \frac{8\pi}{3 m_{pl}^2} g_* \frac{\pi^2}{30} T_f^4$
$x_f \equiv \frac{m_x}{T_f} = \ln\left[\frac{g_x}{(2\pi)^3} \frac{3\sqrt{10}}{} m_{pl} m_x\right]$
σv
$\Gamma_f = \sigma_f n_{x,f} = \sigma_f \sqrt{\frac{T_f}{m_x}} g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right] = \sqrt{\frac{8\pi}{3 m_{pl}^2} \frac{\pi^2}{30} g_f}$
$\frac{n_{x,f}}{s_f} = \frac{n_{x,0}}{s_0}$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f} = \frac{g_{x,0}}{g_{s,f}} \frac{T_0^3}{T_f^3} g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right]$
$\left(\frac{x_f}{2\pi}\right)^{3/2} \quad \exp[-x_f]$
$\frac{\rho_{x,0}}{\rho_{crit}} = \frac{m_x n_{x,0}}{3 H_0^2 m_{pl}^2} 8\pi$


$T = \frac{1}{2} m v^2 \quad v \sim \sqrt{\frac{T}{m}}$
$H^2 = \frac{8\pi}{3 m_{pl}^2} \rho = \frac{8\pi}{3 m_{pl}^2} g_* \frac{\pi^2}{30} T_f^4$
$x_f \equiv \frac{m_x}{T_f} = \ln\left[\frac{g_x}{g_f^{1/2}} \frac{3\sqrt{10}}{(2\pi)^3} m_{pl} m_x \sigma_f\right]$
$\Gamma_f = \sigma_f \bar{v}_f n_{x,f} = \sigma_f \sqrt{\frac{T_f}{m_x}} g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right] = \sqrt{\frac{8\pi}{3 m_{pl}^2} \frac{\pi^2}{30} g_f T_f^4}$
$\sigma_F \simeq 10^{-10} \frac{1}{GeV^2}$
$\frac{\rho_{x,0}}{\rho_{crit}} = \frac{10^{-10}}{GeV^2 \sigma_f} \left(\frac{x_f^{3/2}}{g_f^{1/2}}\right)$
$n_{x,0} = \frac{s_0}{s_f} n_{x,f} = \frac{g_{x,0}}{g_{s,f}} \frac{T_0^3}{T_f^3} g_x \left(\frac{m_x T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_x}{T_f}\right]$
$\left(\frac{x_f}{2\pi}\right)^{3/2} \quad \exp[-x_f]$
$\frac{\rho_{x,0}}{\rho_{crit}} = \frac{m_x n_{x,0}}{3 H_0^2 m_{pl}^2} 8\pi$

2) relax lengths

n_χ $\Gamma_f = H_f$ $T = \frac{1}{2}mv^2$ $v \sim \sqrt{\frac{T}{m}}$ $H^2 = \frac{8\pi}{3m_{pl}^2}\rho$

$g \sim 0.3$ $\chi\bar{\chi} \to \gamma\gamma$

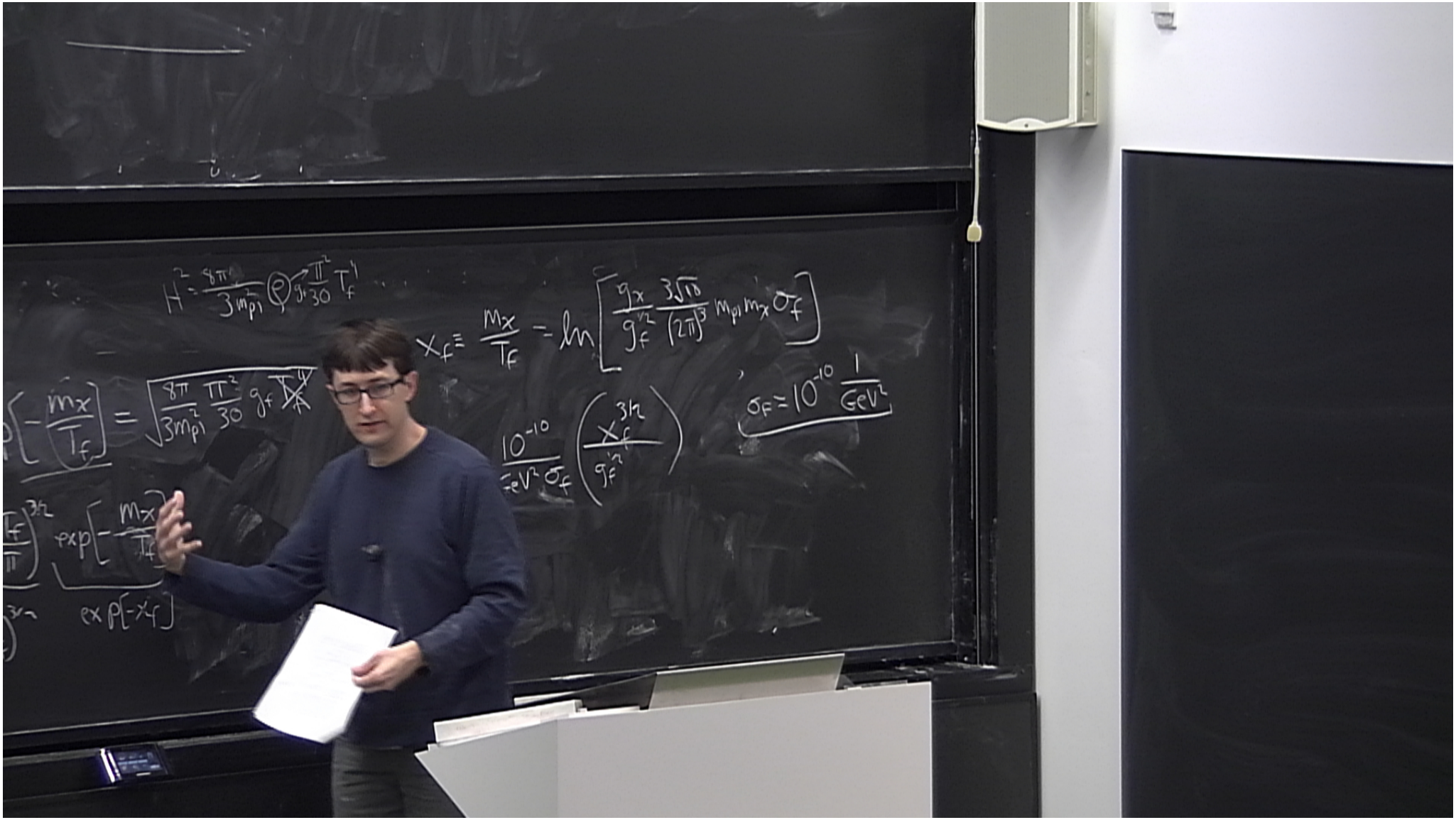


σv $\sigma \sim \frac{\sigma}{\sigma v m_\chi^{-1}}$ $\Gamma_f = \sigma_f v_f n_{\chi,f} = \sigma_f \sqrt{\frac{T_f}{m_\chi}}\, g_\chi \left(\frac{m_\chi T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_\chi}{T_f}\right] = \sqrt{\frac{8\pi}{3m_{pl}^2}\frac{\pi^2}{30}g_f}\,T_f^2$

$\frac{n_{\chi,f}}{s_f} = \frac{n_{\chi,0}}{s_0}$ $n_{\chi,0} = \frac{s_0}{s_f} n_{\chi,f} = \frac{g_{s0}}{g_{sf}}\frac{T_0^3}{T_f^3} g_\chi \left(\frac{m_\chi T_f}{2\pi}\right)^{3/2} \exp\left[-\frac{m_\chi}{T_f}\right]$

$\left(\frac{x_f}{2\pi}\right)^{3/2}$ $\exp[-x_f]$

$\frac{\rho_{\chi,0}}{\rho_{crit}} = \frac{m_\chi n_{\chi,0}}{3H_0^2 m_{pl}^2}\, g_\pi$


$H^2 = \frac{8\pi}{3m_{pl}^2}\rho = \frac{\pi^2}{30} g_* T_f^4$
$x_f \equiv \frac{m_x}{T_f} = \ln\left[\frac{g_x}{g_f^{1/2}} \frac{3\sqrt{10}}{(2\pi)^3} m_{pl} m_x \sigma_f\right]$
$\sigma_f = 10^{-10} \frac{1}{GeV^2}$
$\frac{10^{-10}}{GeV^2 \sigma_f} \left(\frac{x_f^{3/2}}{g_f^{1/2}}\right)$
$\exp\left[-\frac{m_x}{T_f}\right]$
$\exp[-x_f]$