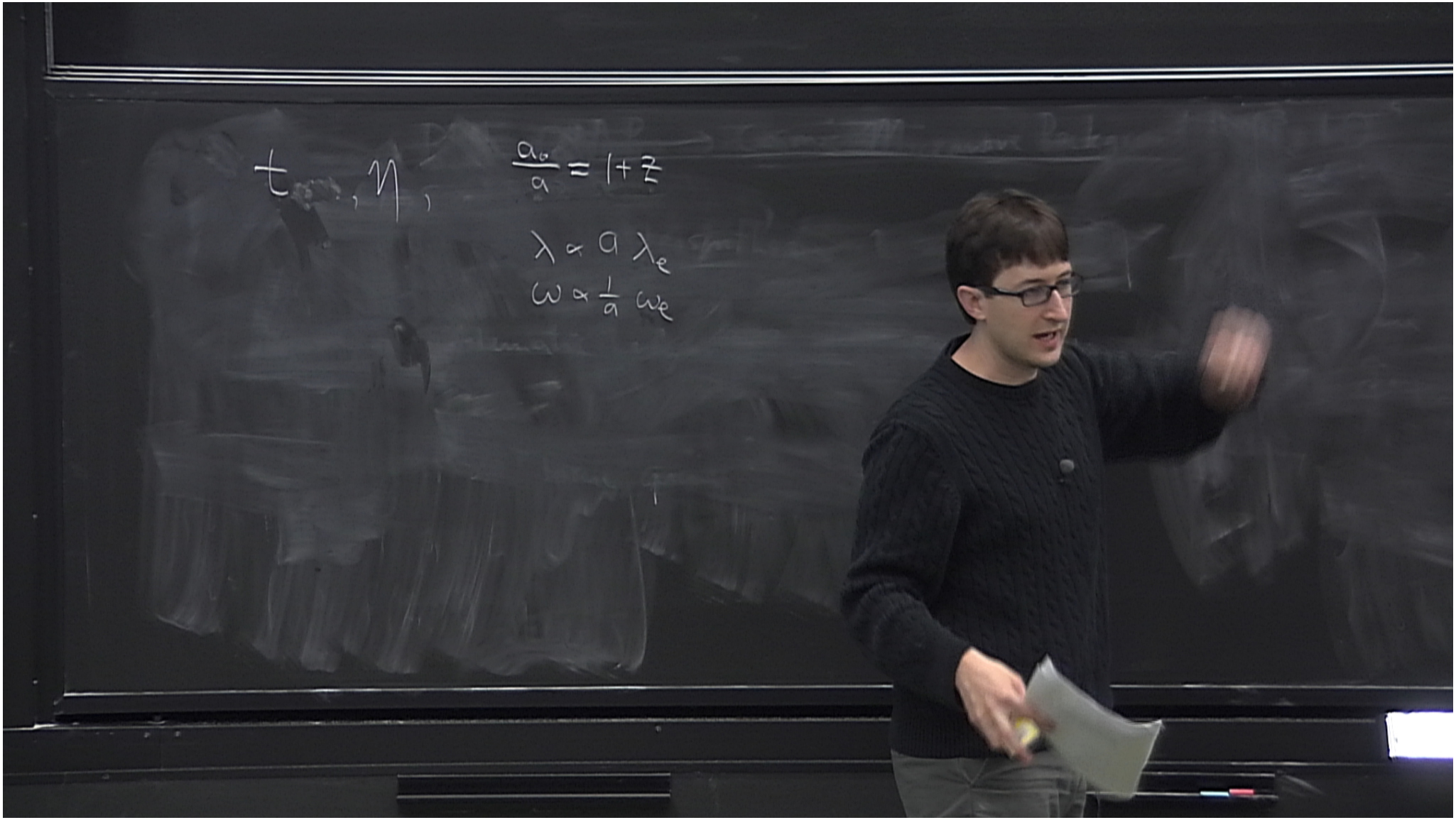
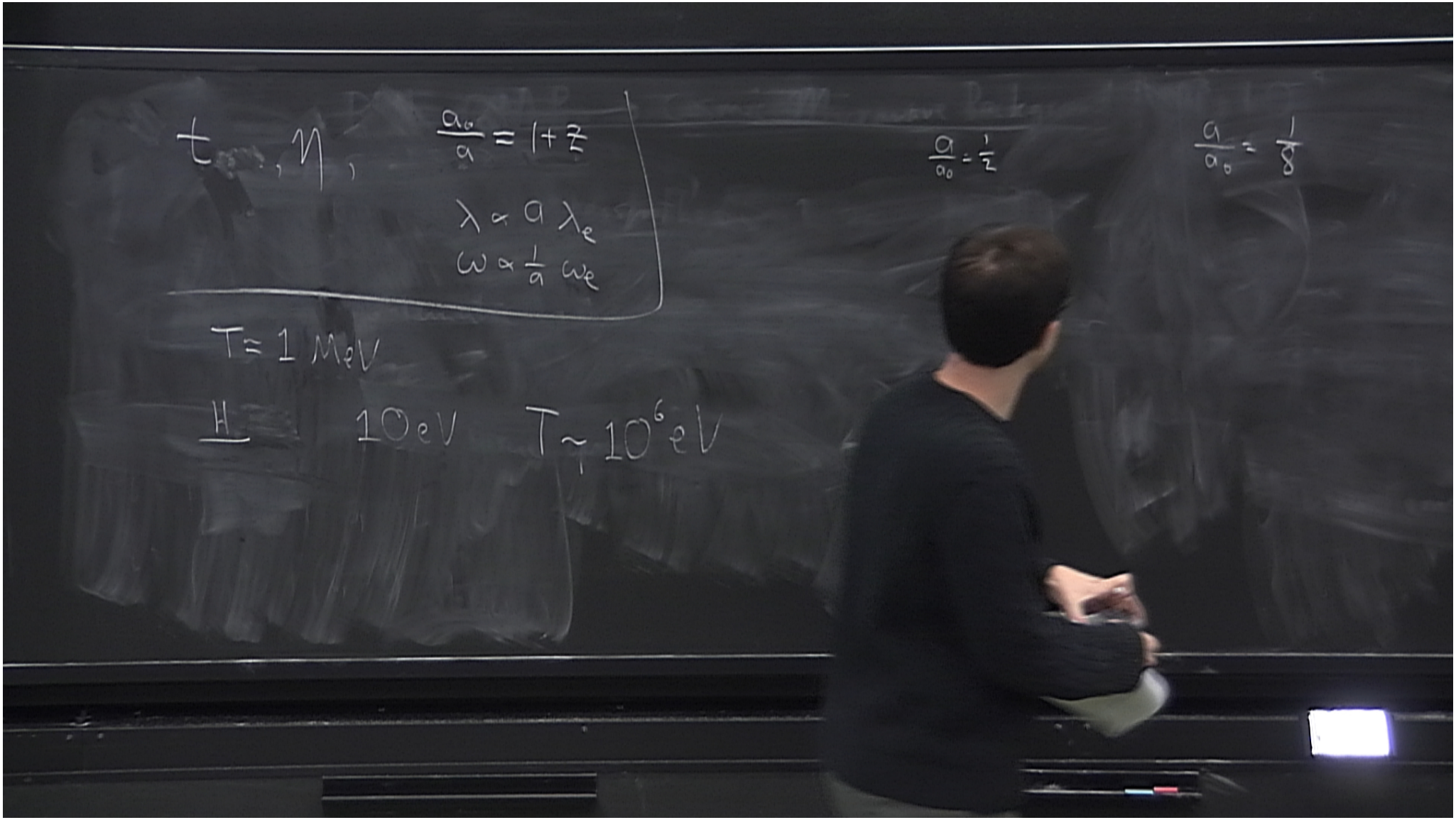
Title: Cosmology (Review) - Lecture 9

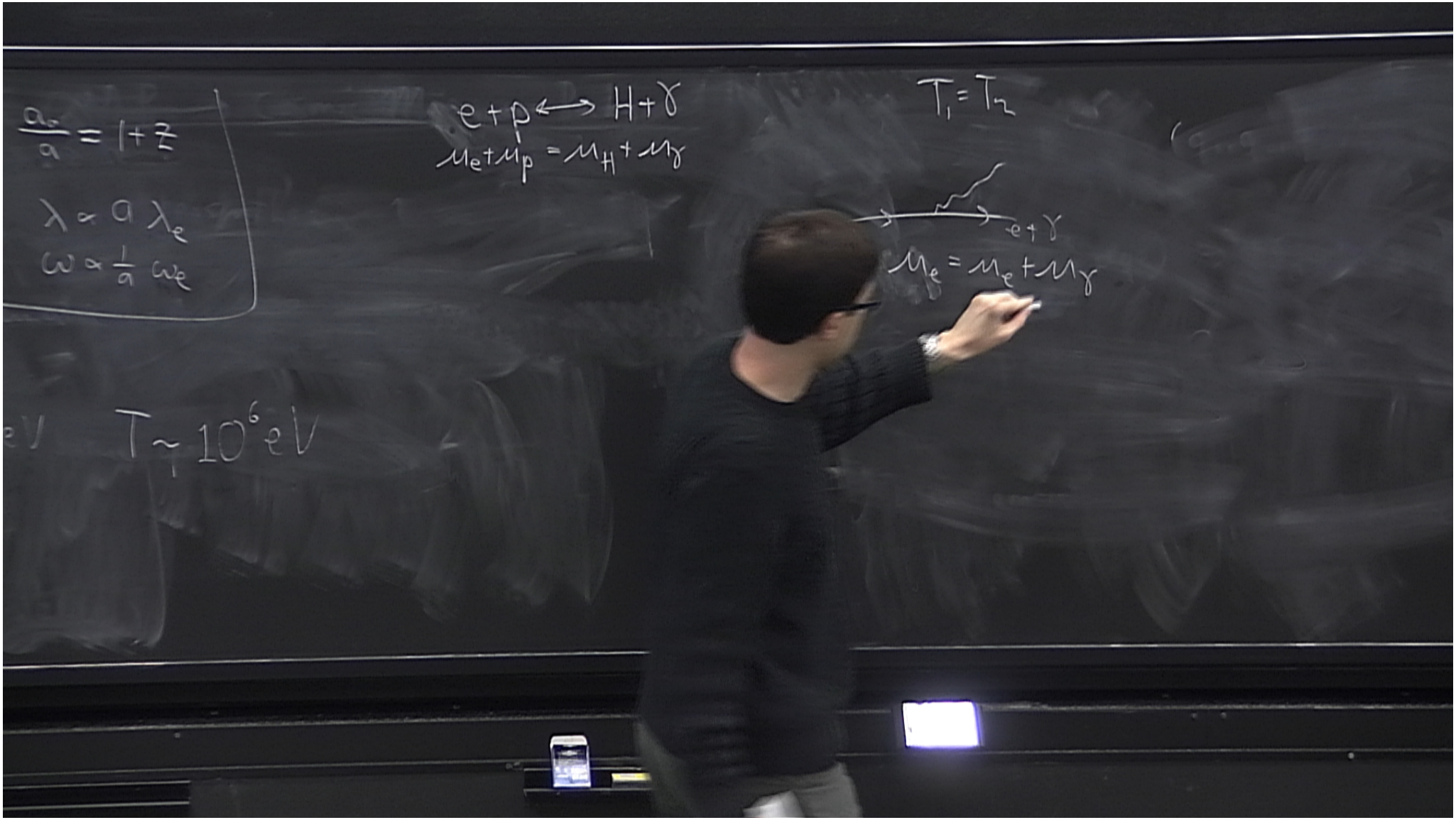
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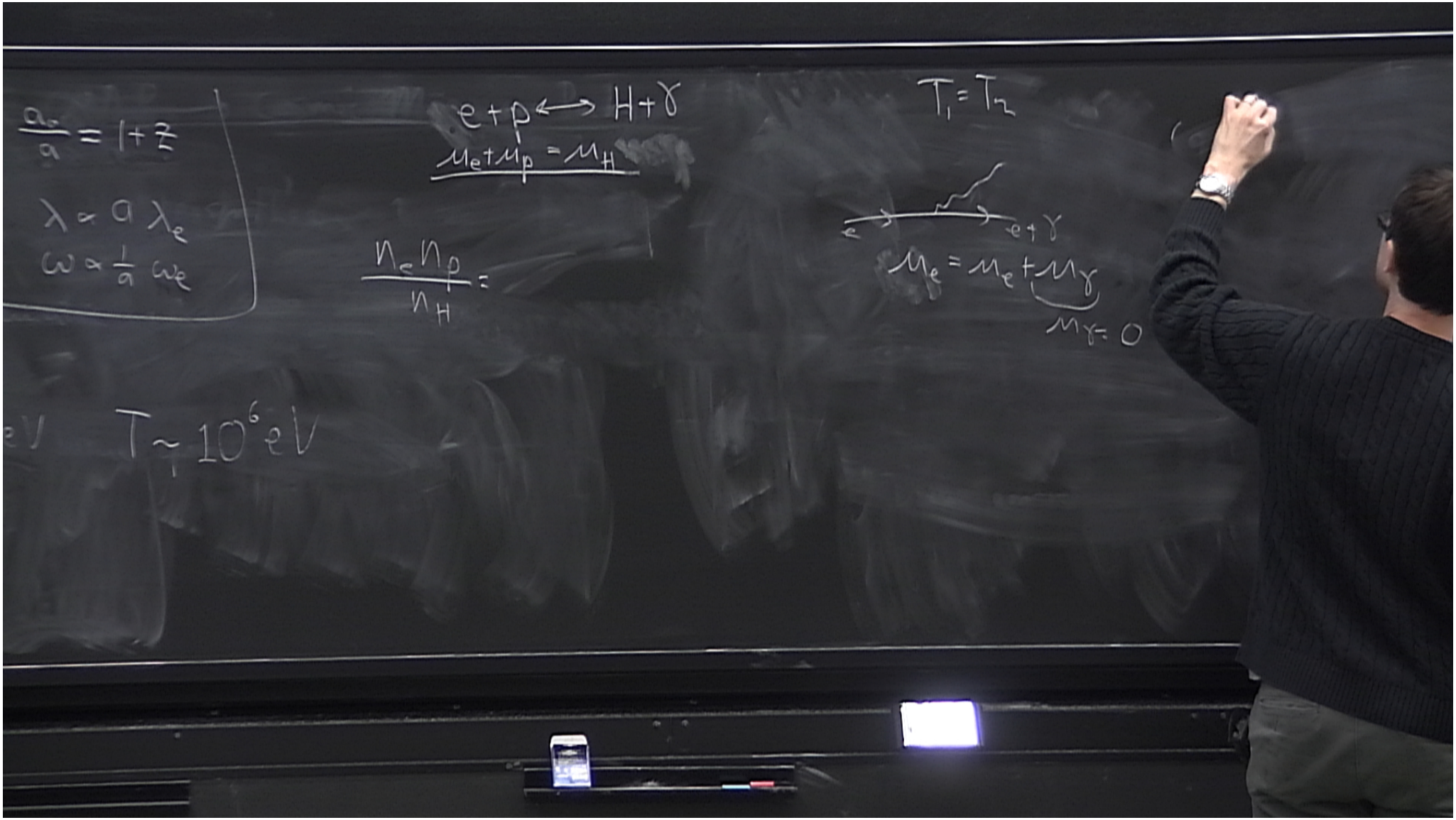
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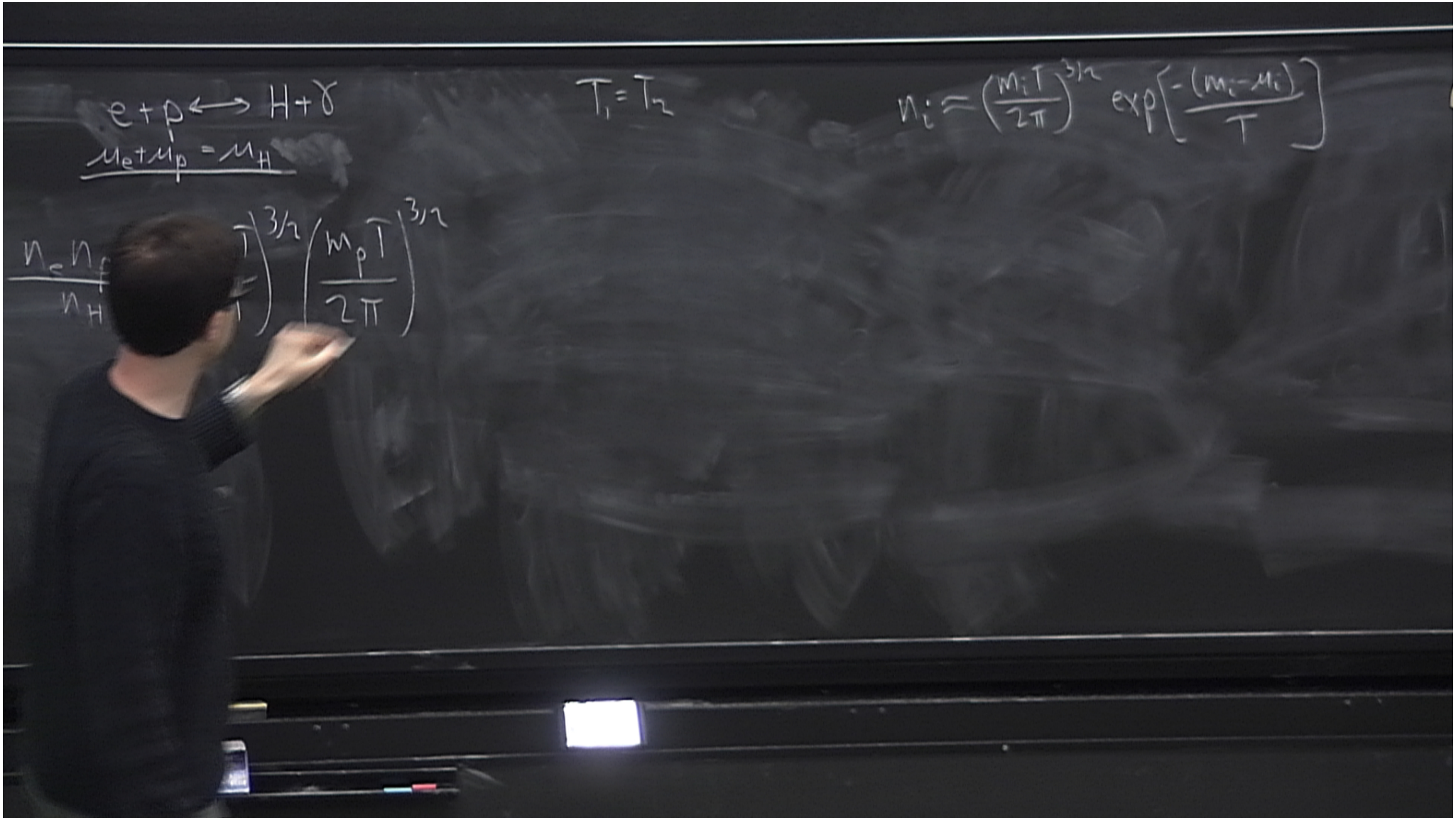
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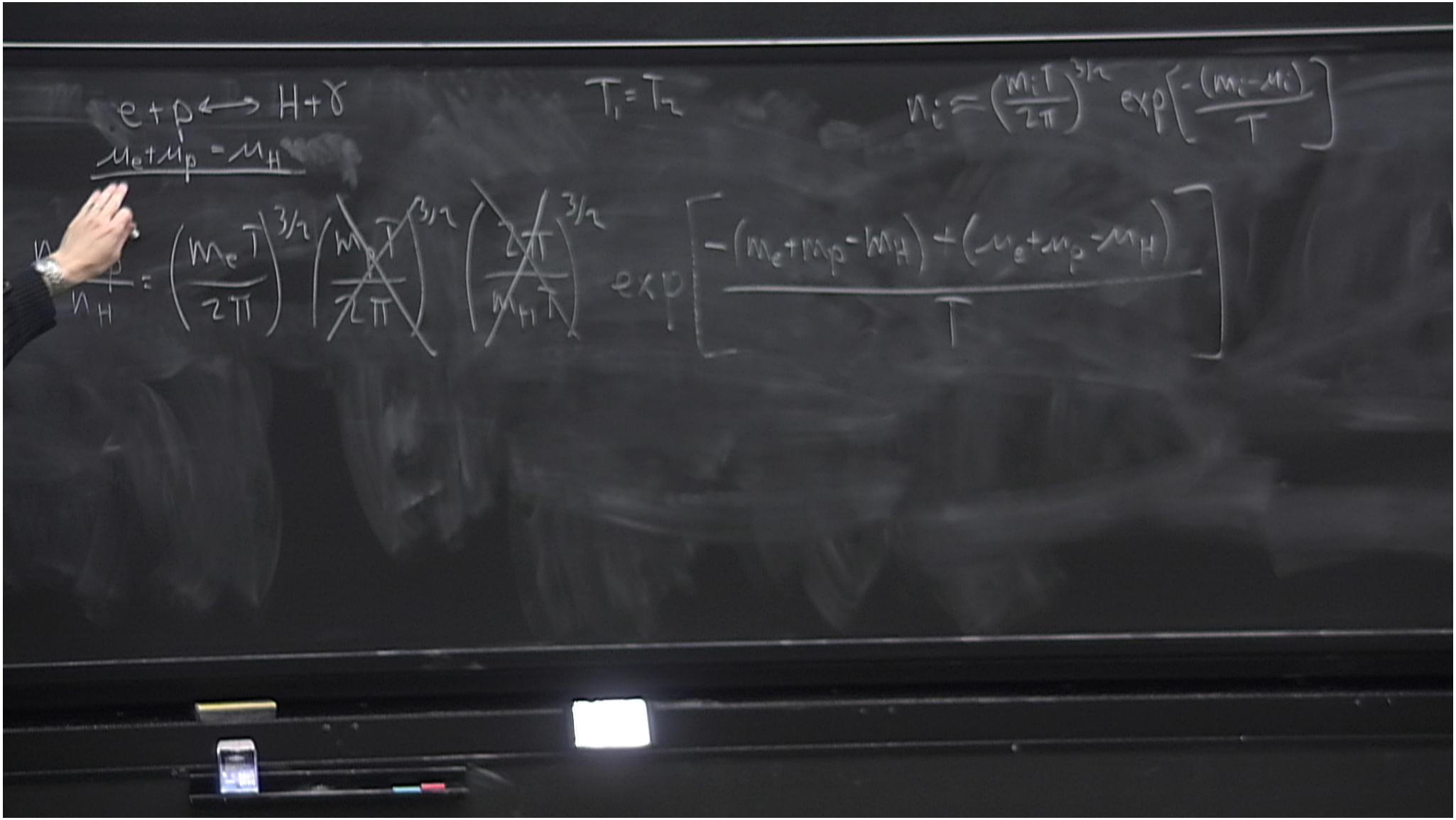

t , η ,
$\frac{a_0}{a} = 1+z$
$\lambda \propto a\,\lambda_e$
$\omega \propto \frac{1}{a}\,\omega_e$

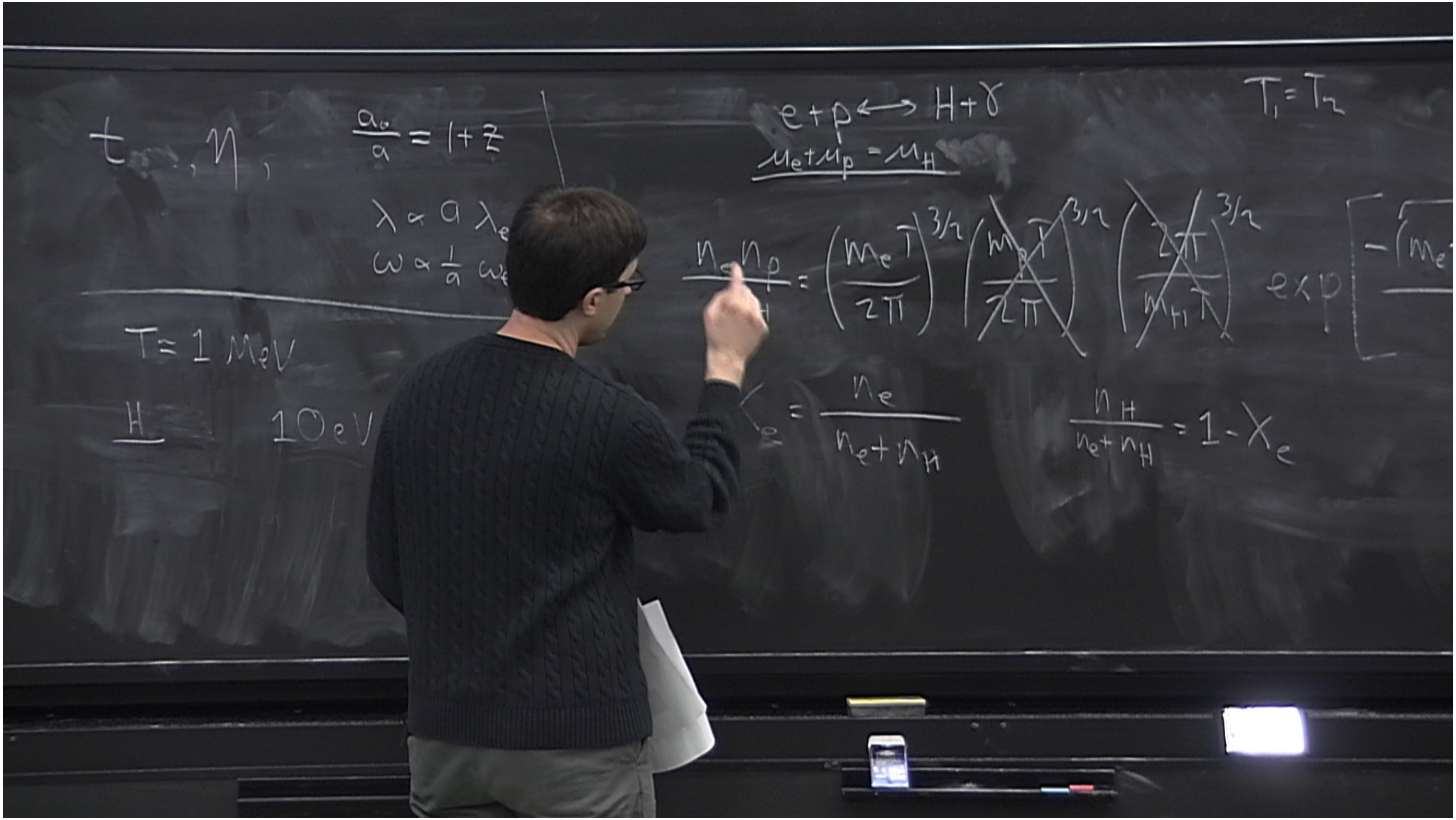

t , η ,
$\frac{a_0}{a} = 1+z$
$\lambda \propto a\,\lambda_e$
$\omega \propto \frac{1}{a}\,\omega_e$
$\frac{a}{a_0} = \frac{1}{2}$
$\frac{a}{a_0} = \frac{1}{8}$
T = 1 MeV
H 10 eV $T \sim 10^6$ eV

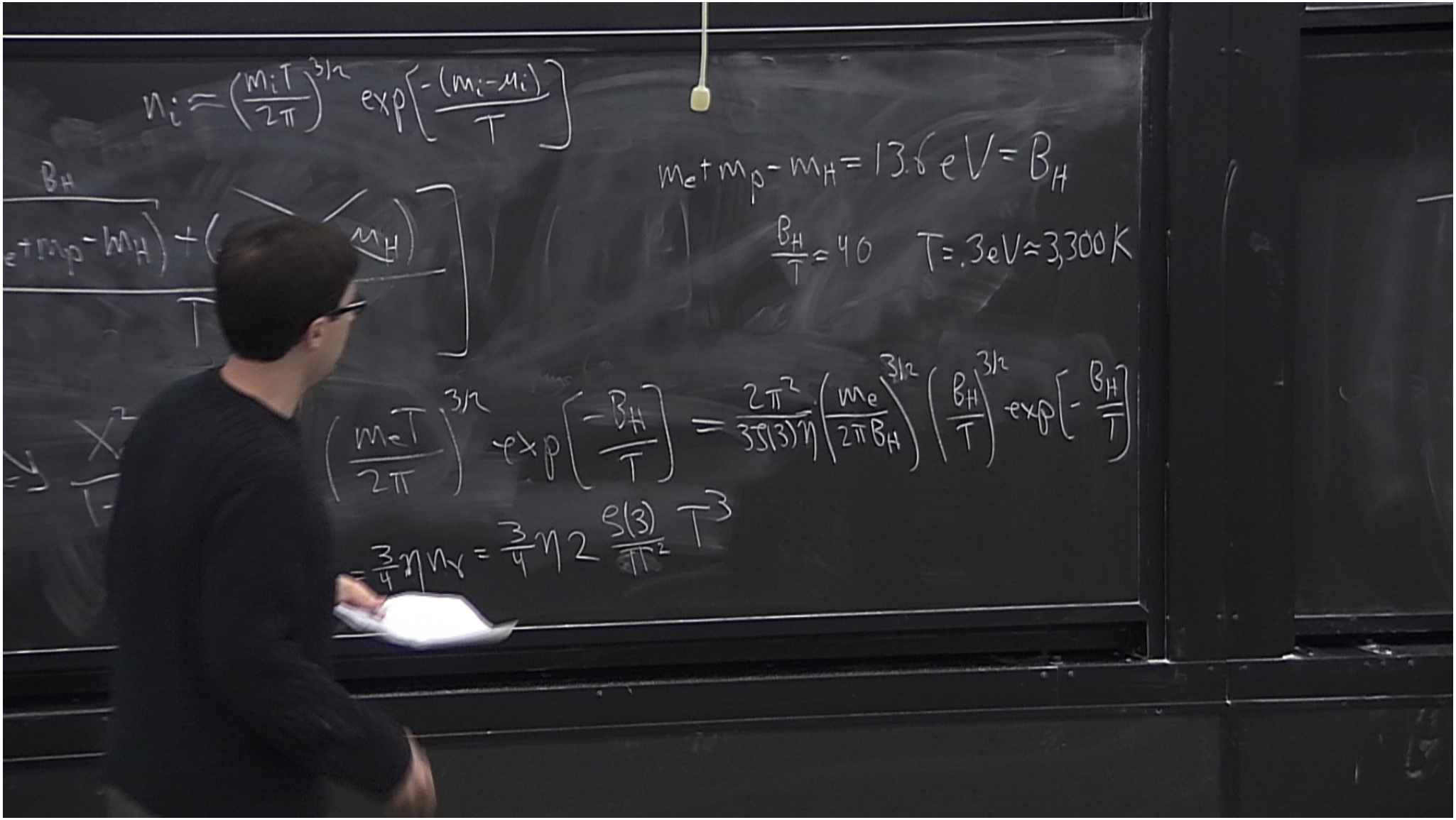

$\frac{a_0}{a} = 1+z$
$\lambda \propto a\,\lambda_e$
$\omega \propto \frac{1}{a}\,\omega_e$
$e+p \longleftrightarrow H+\gamma$
$\mu_e+\mu_p = \mu_H+\mu_\gamma$
$T_1 = T_2$
$e+\gamma$
$\mu_e = \mu_e+\mu_\gamma$
$T \sim 10^6\,eV$

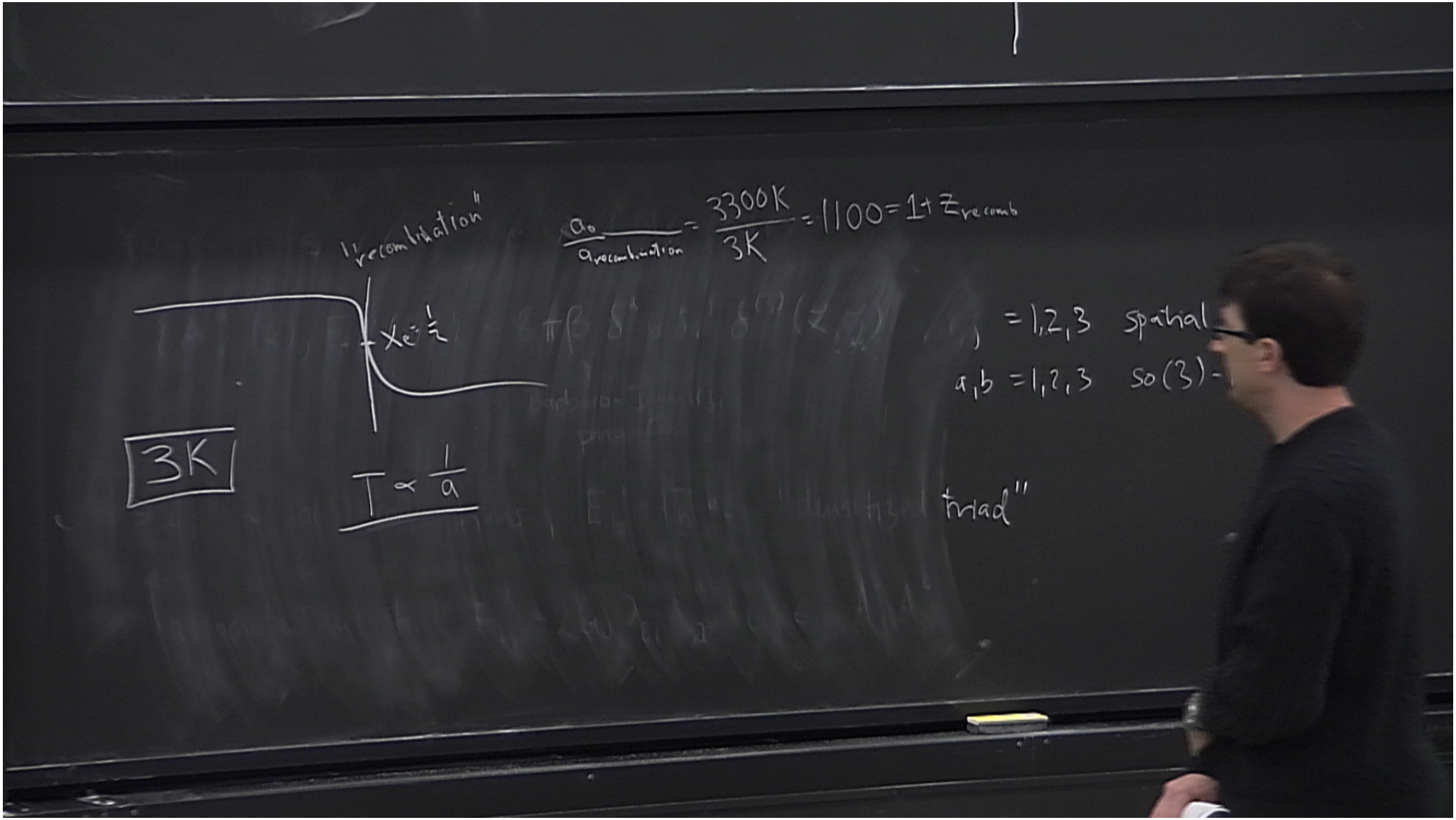

$\frac{a_0}{a} = 1+z$
$\lambda \propto a\,\lambda_e$
$\omega \propto \frac{1}{a}\,\omega_e$
$e + p \longleftrightarrow H + \gamma$
$\mu_e + \mu_p = \mu_H$
$\frac{n_e n_p}{n_H} =$
$T_1 = T_2$
$e + \gamma$
$\mu_e = \mu_e + \mu_\gamma$
$\mu_\gamma = 0$
$T \sim 10^6\,eV$

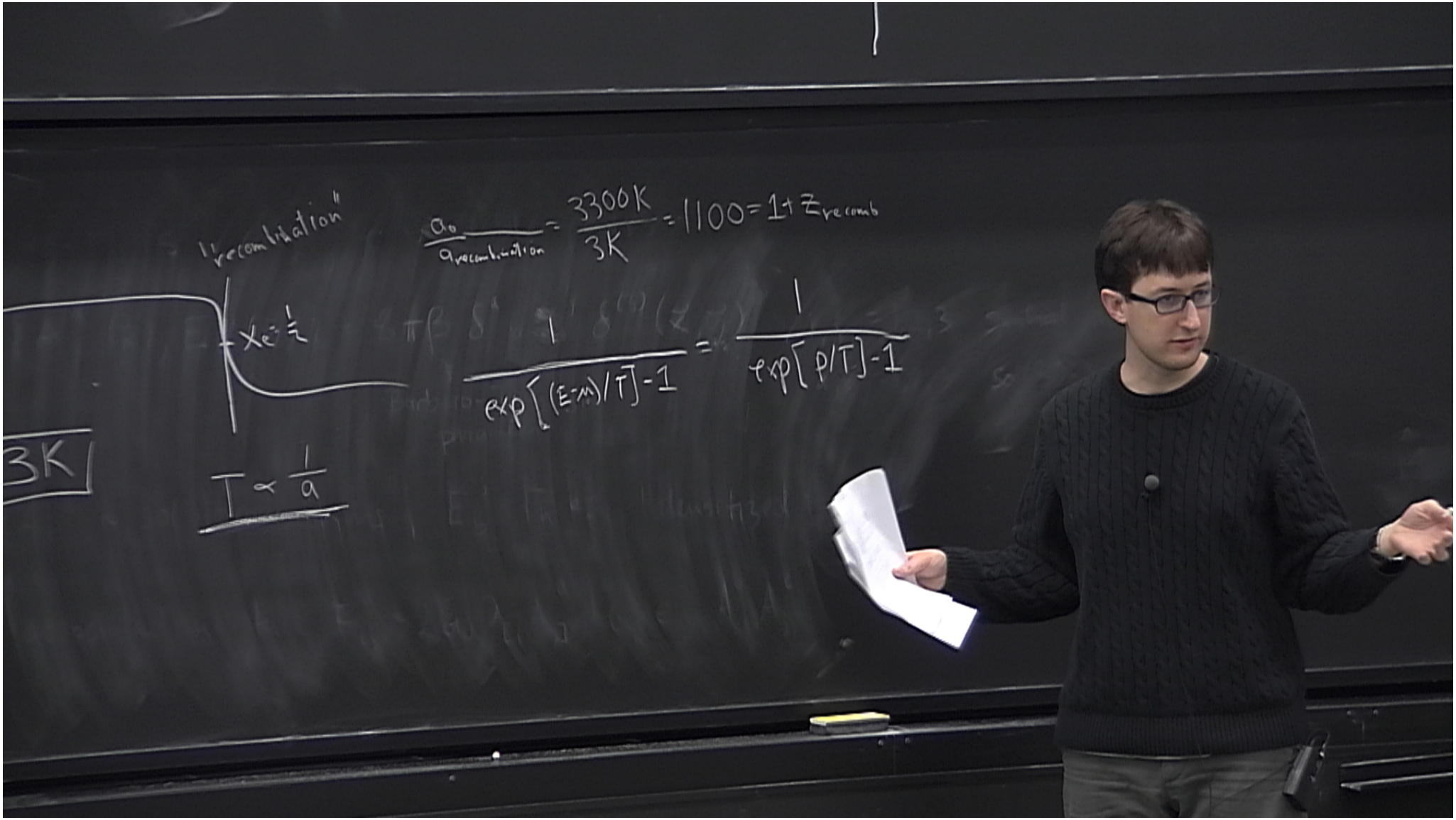

e + p ⟷ H + γ
$T_1 = T_2$
$n_i \simeq \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_i - \mu_i)}{T}\right]$
$\mu_e + \mu_p = \mu_H$
$\frac{n_e}{n_H} = \frac{n_f}{}$
$\left(\frac{T}{}\right)^{3/2} \left(\frac{m_p T}{2\pi}\right)^{3/2}$

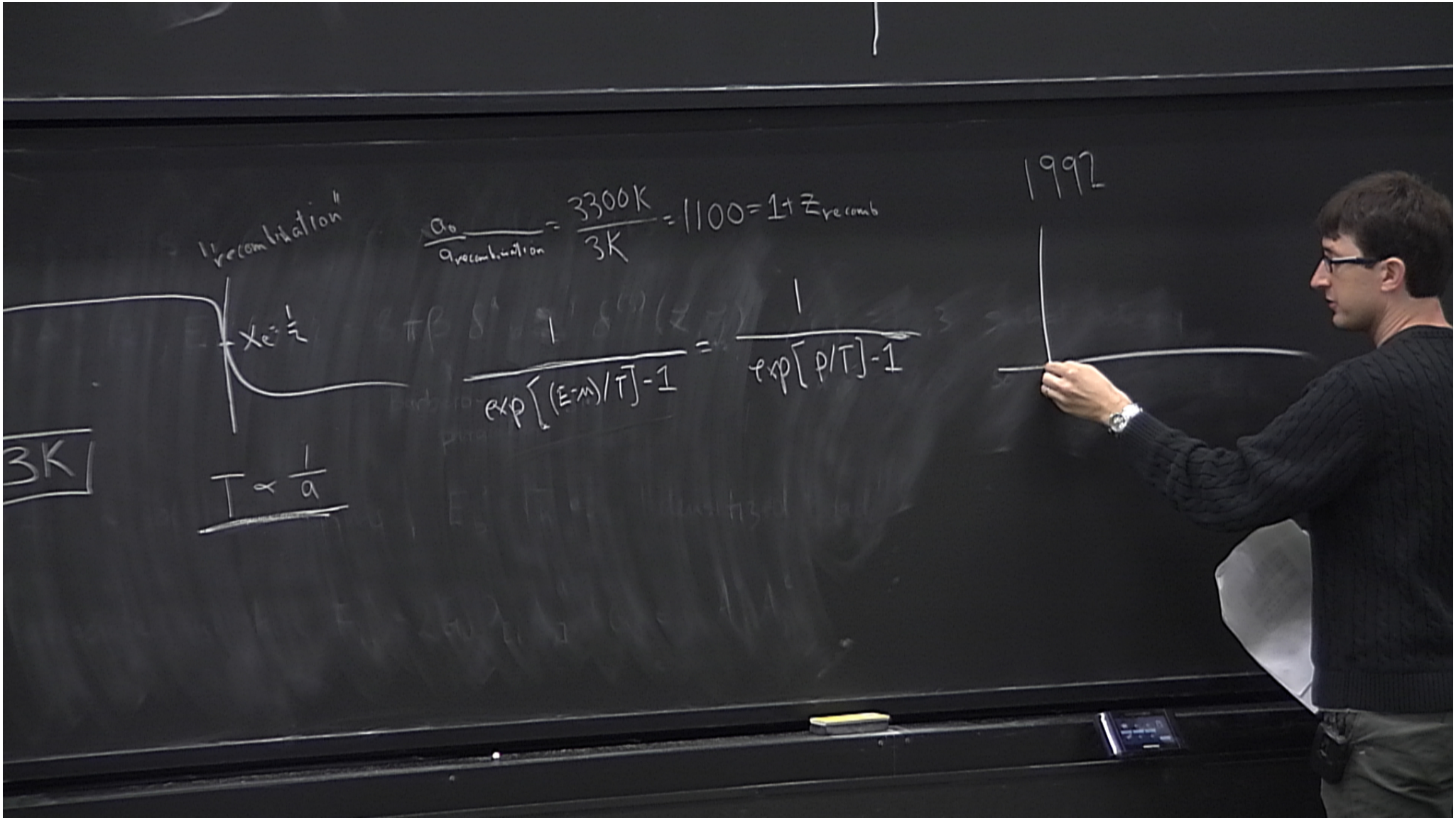

e + p ⟷ H + γ
$T_1 = T_2$
$n_i \simeq \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_i - \mu_i)}{T}\right]$
$\mu_e + \mu_p = \mu_H$
$\frac{n_e n_p}{n_H} = \left(\frac{m_e T}{2\pi}\right)^{3/2} \left(\frac{m_p T}{2\pi}\right)^{3/2} \left(\frac{2\pi T}{m_H T}\right)^{3/2} \exp\left[\frac{-(m_e + m_p - m_H) + (\mu_e + \mu_p - \mu_H)}{T}\right]$

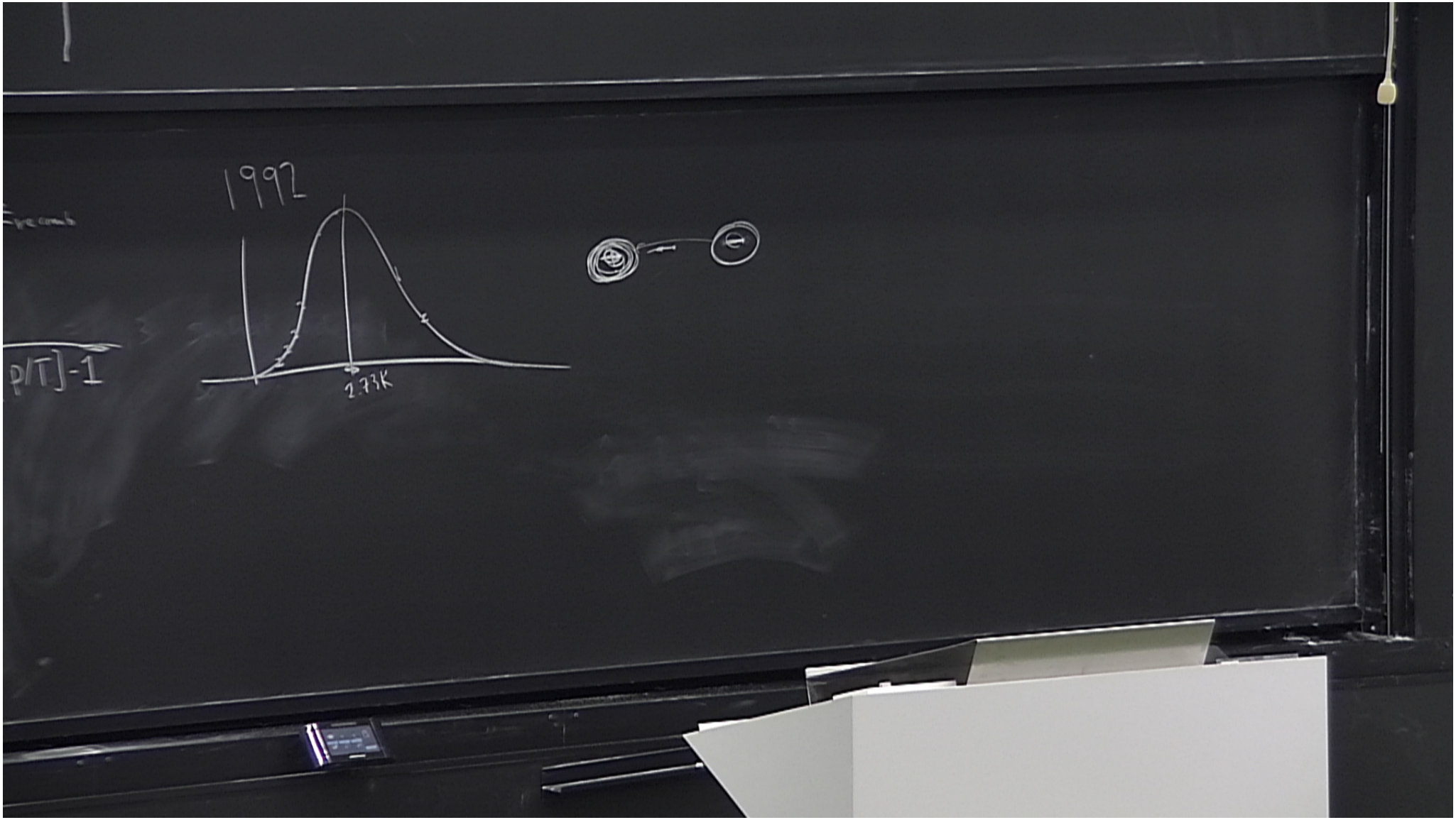

$\frac{a_0}{a} = 1+z$
$e+p \leftrightarrow H+\gamma$
$T_1 = T_2$
$\mu_e + \mu_p = \mu_H$
$\lambda \propto a\,\lambda_e$
$\omega \propto \frac{1}{a}\,\omega_e$
$\frac{n_e n_p}{n_H} = \left(\frac{m_e T}{2\pi}\right)^{3/2} \left(\frac{m_p T}{2\pi}\right)^{3/2} \left(\frac{2\pi T}{m_{H1} T}\right)^{3/2} \exp\left[-\left(m_e\right.\right.$
$T = 1\ MeV$
H $10\,eV$
$= \frac{n_e}{n_e + n_H}$
$\frac{n_H}{n_e + n_H} = 1 - X_e$

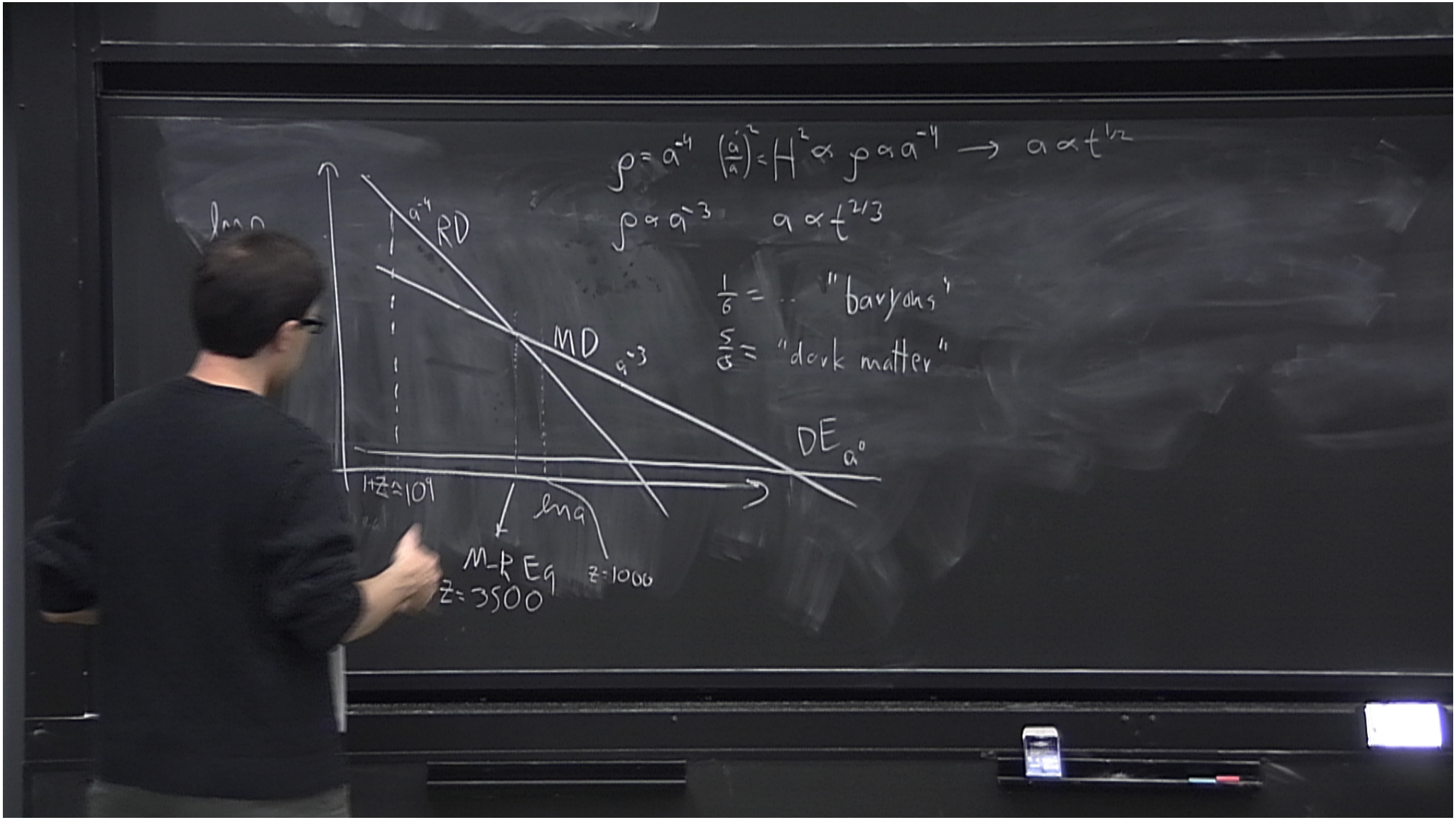

$n_i \simeq \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_i - \mu_i)}{T}\right]$
$m_e + m_p - m_H = 13.6\,eV = B_H$
$\frac{B_H}{T} = 40 \quad T = .3eV \approx 3{,}300K$
$\left(\frac{m_e T}{2\pi}\right)^{3/2} \exp\left[-\frac{B_H}{T}\right] = \frac{2\pi^2}{3\zeta(3)}\eta\left(\frac{m_e}{2\pi B_H}\right)^{3/2}\left(\frac{B_H}{T}\right)^{3/2}\exp\left[-\frac{B_H}{T}\right]$
$= \frac{3}{4}\eta n_\gamma = \frac{3}{4}\eta 2 \frac{\zeta(3)}{\pi^2} T^3$

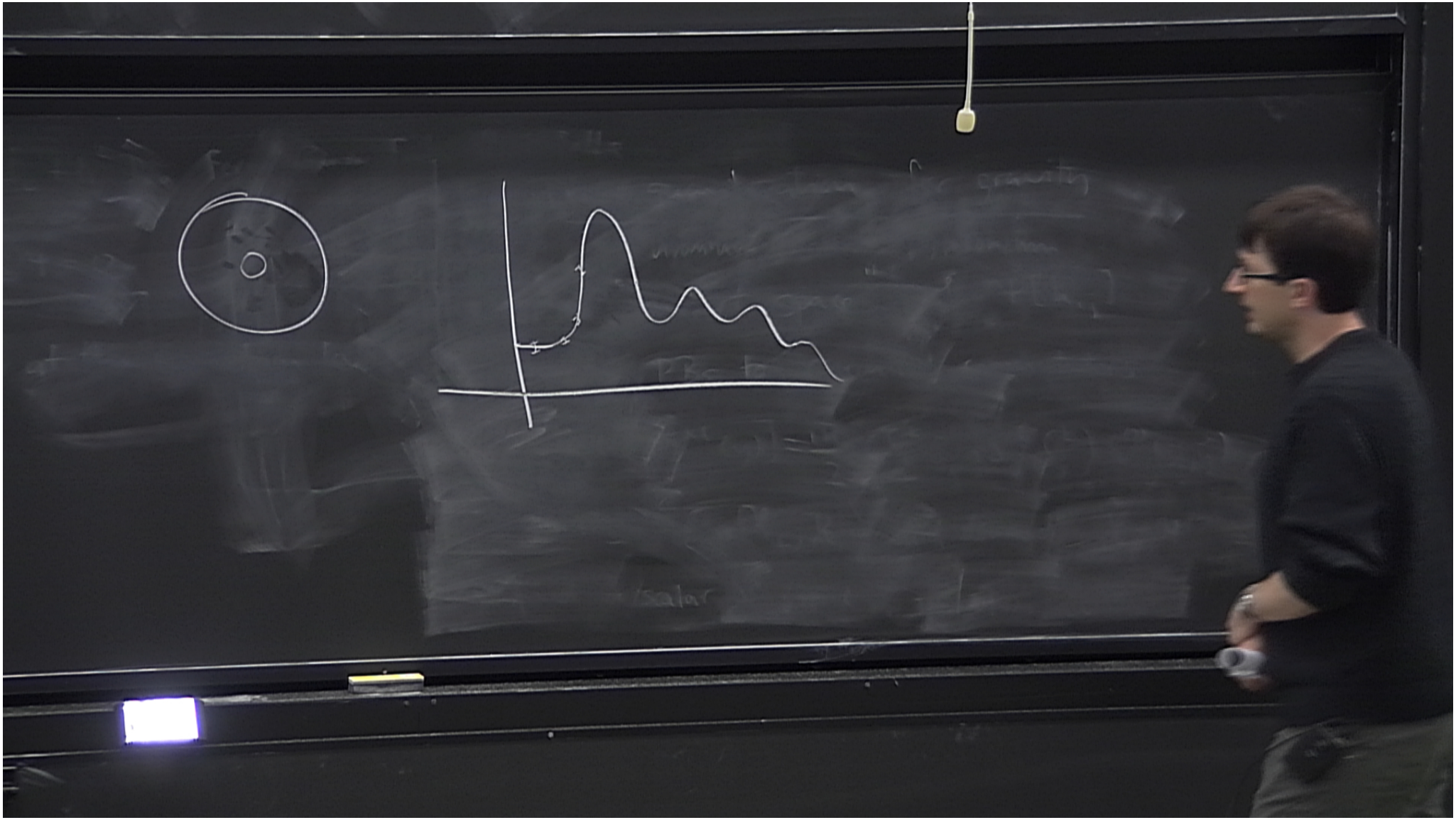

"recombination"
$\frac{a_0}{a_{recombination}} = \frac{3300K}{3K} = 1100 = 1 + z_{recomb}$
$x_e \sim \frac{1}{2}$
3K
$T \propto \frac{1}{a}$
$= 1,2,3$ spatial
$a,b = 1,2,3$ so(3)-
triad"

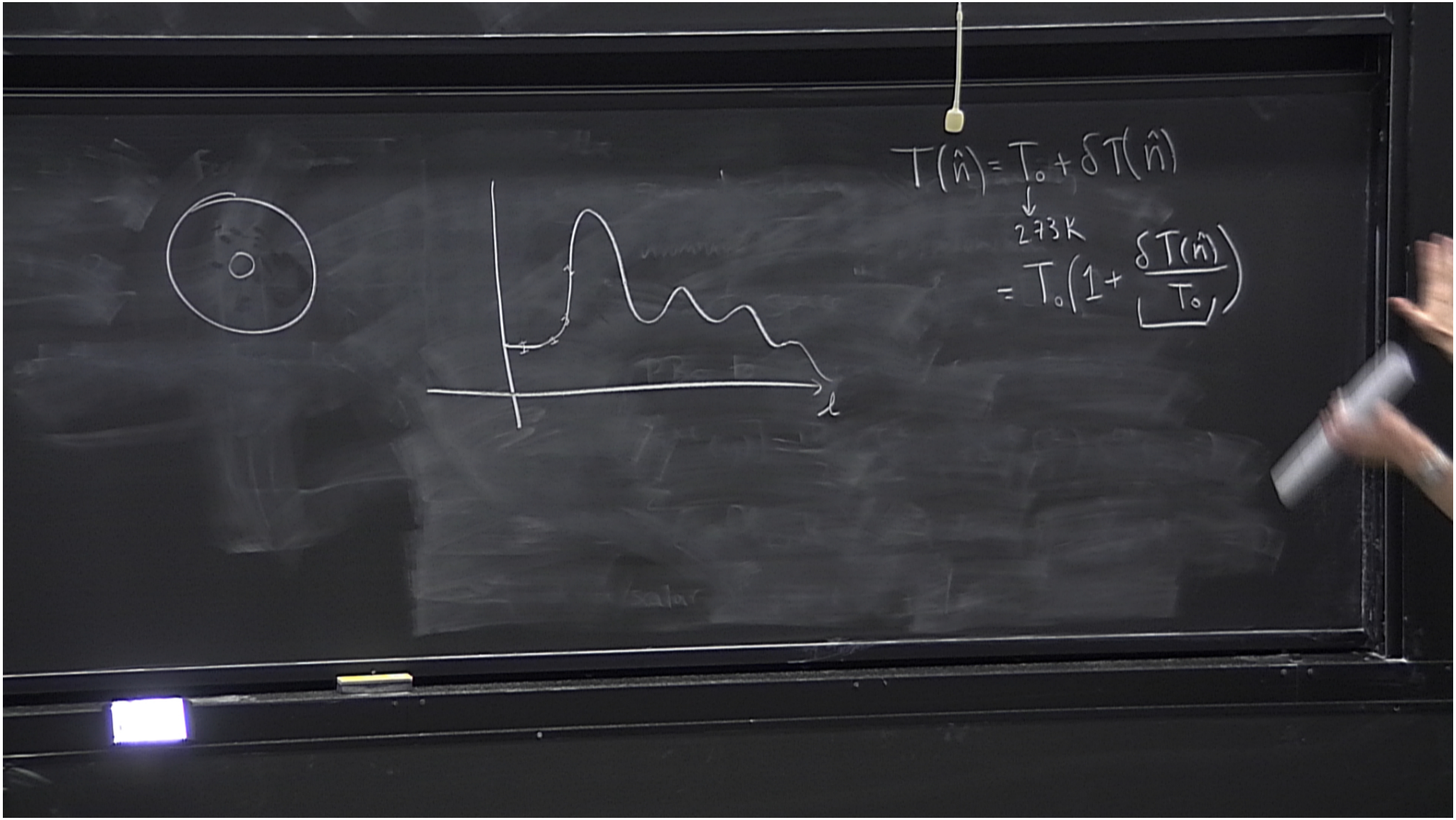

"recombination"
$\frac{a_0}{a_{recombination}} = \frac{3300K}{3K} = 1100 = 1 + z_{recomb}$
$Xe^{-\frac{1}{z}}$
$\frac{1}{\exp[(E-\mu)/T]-1} = \frac{1}{\exp[p/T]-1}$
3K
$T \propto \frac{1}{a}$

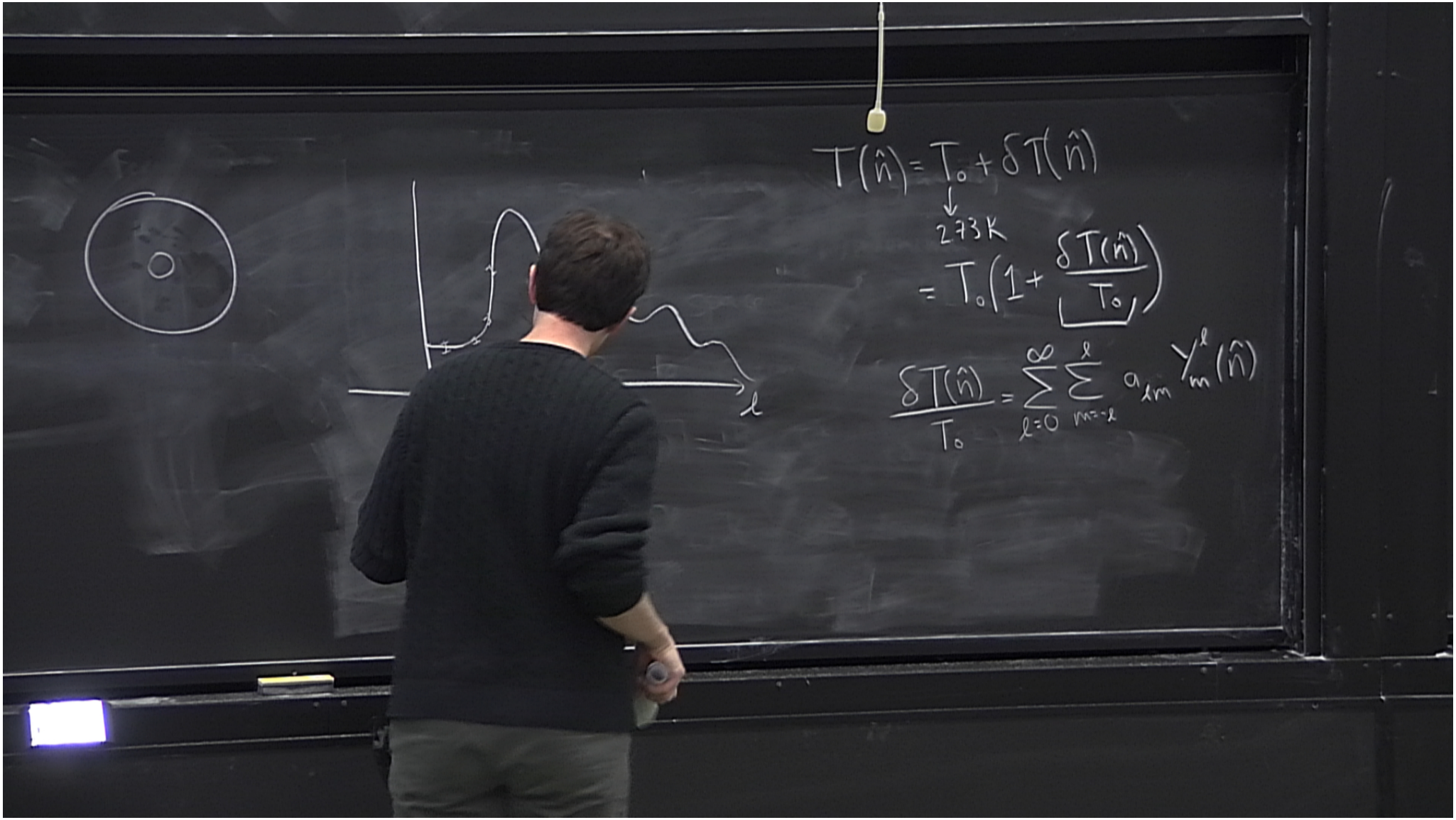

"recombination"
$\frac{a_0}{a_{recombination}} = \frac{3300K}{3K} = 1100 = 1 + z_{recomb}$
$Xe^{-\frac{1}{z}}$
$\frac{1}{\exp[(E-\mu)/T]-1} = \frac{1}{\exp[p/T]-1}$
3K
$I \propto \frac{1}{a}$
1992

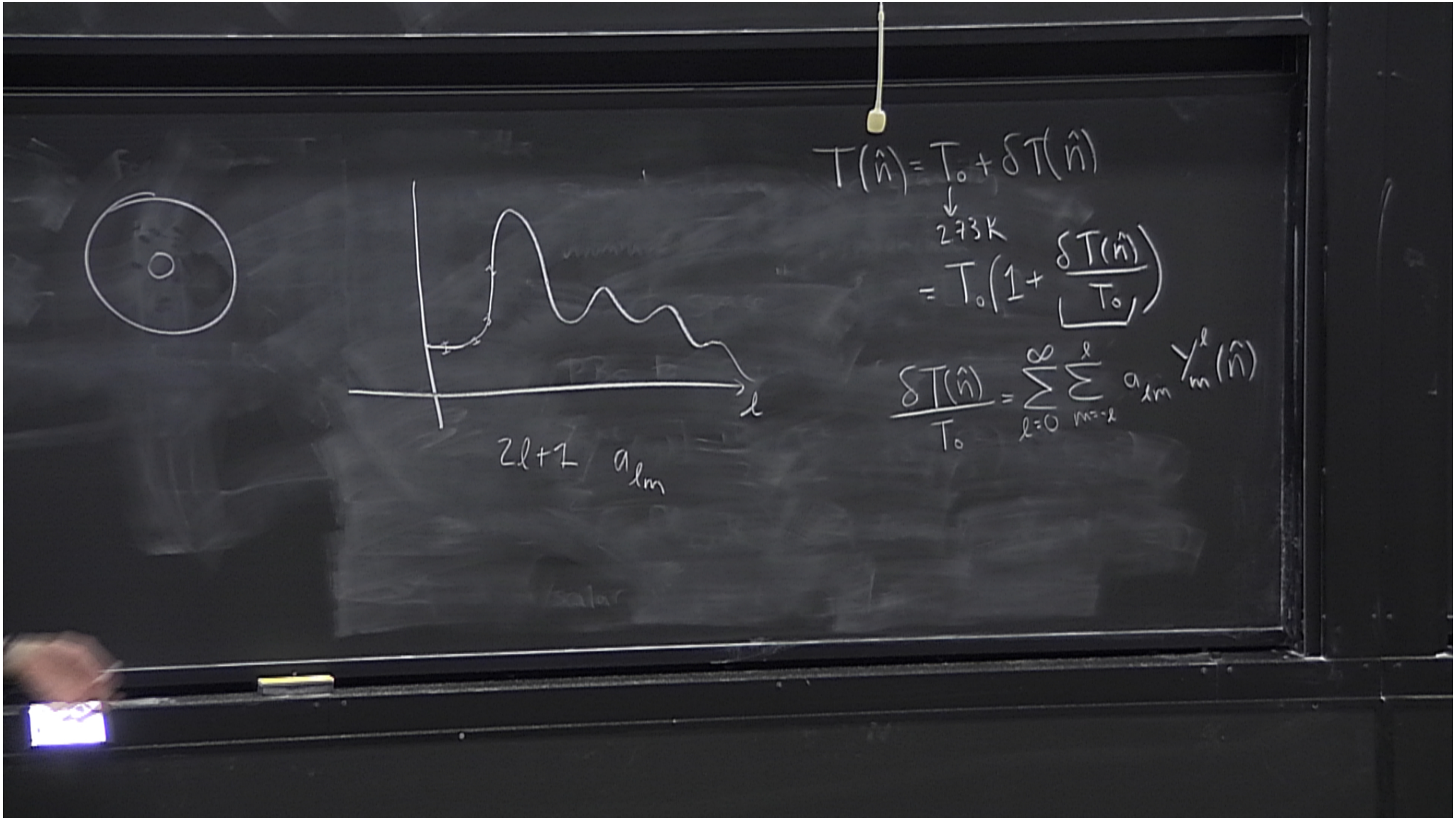

1992
2.73K
p/T]-1

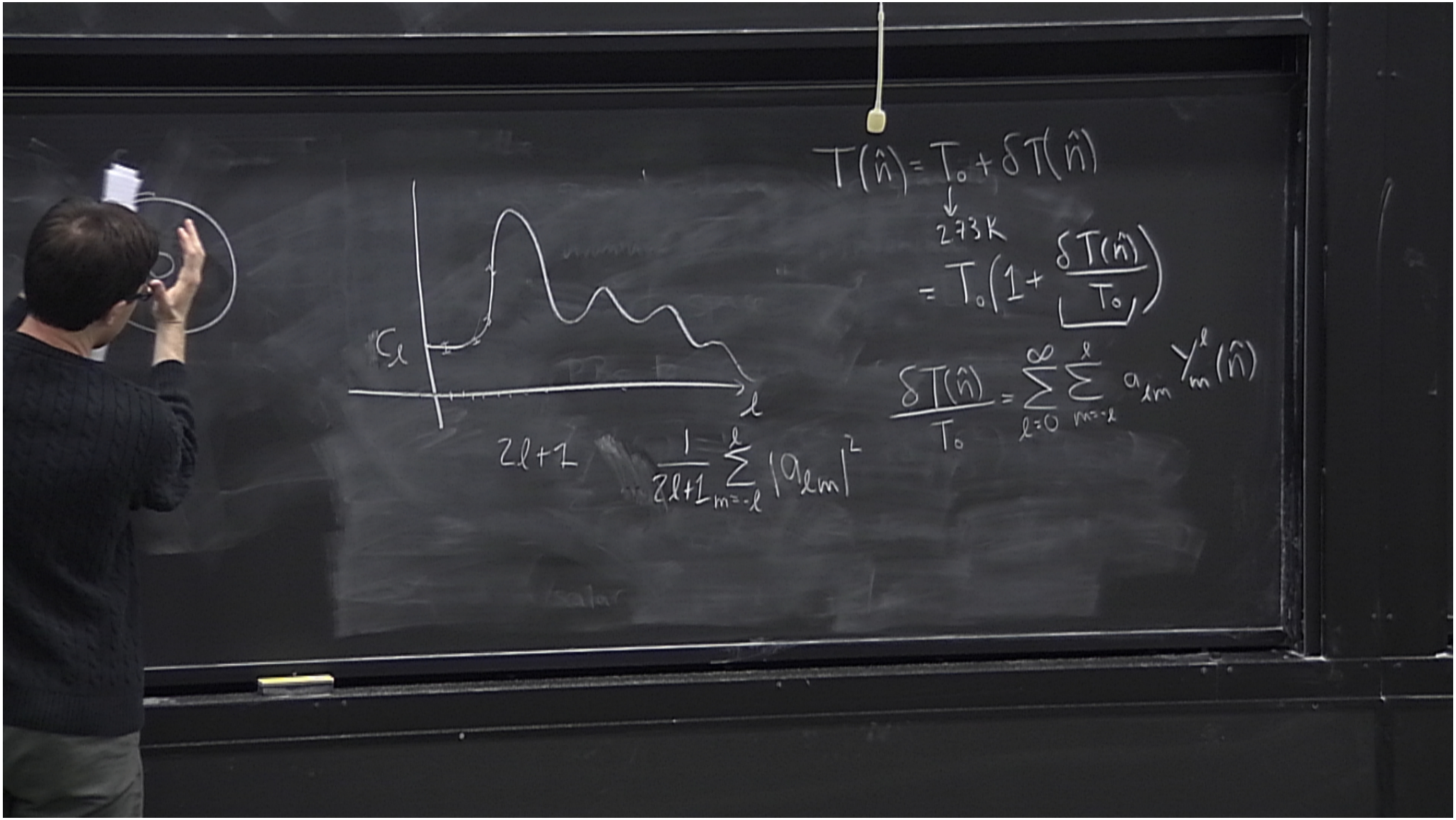

$\rho = a^{-4}$ $\left(\frac{\dot{a}}{a}\right)^2 = H^2 \propto \rho \propto a^{-4} \rightarrow a \propto t^{1/2}$
$\rho \propto a^{-3}$ $a \propto t^{2/3}$
$\frac{1}{6}$ = ... "baryons"
$\frac{5}{6}$ = "dark matter"
a^{-4} RD
MD a^{-3}
DE a^0
$1+z \approx 10^9$
$\ln a$
M-R Eq
$z = 3500$
$z = 1000$

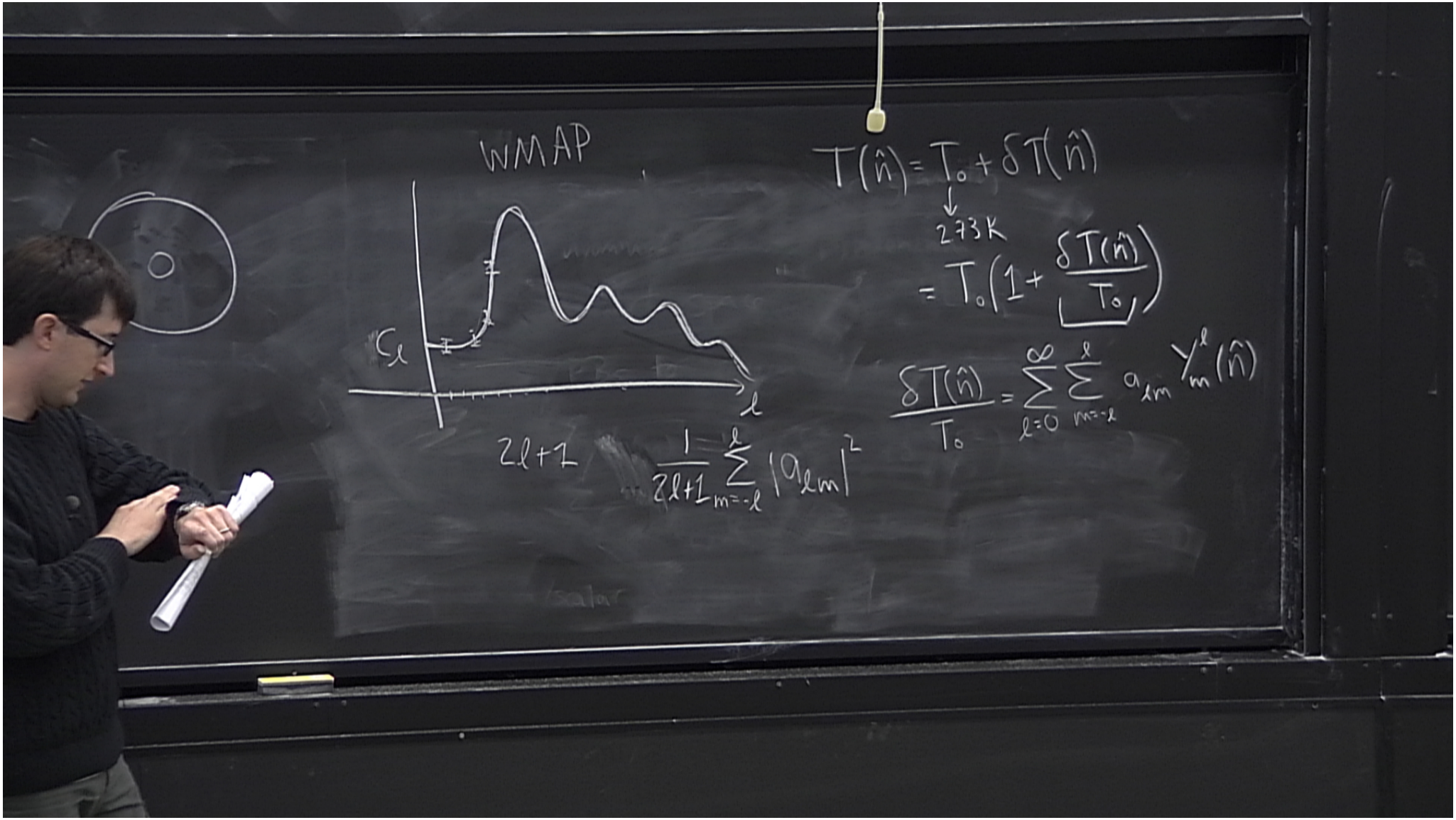

solar


$T(\hat{n}) = T_0 + \delta T(\hat{n})$
$2.73\,K$
$= T_0\left(1 + \frac{\delta T(\hat{n})}{T_0}\right)$
l


$T(\hat{n}) = T_0 + \delta T(\hat{n})$
$\downarrow$
$2.73\,K$
$= T_0\left(1 + \frac{\delta T(\hat{n})}{T_0}\right)$
$\frac{\delta T(\hat{n})}{T_0} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_m^l(\hat{n})$
l


$T(\hat{n}) = T_0 + \delta T(\hat{n})$
$2.73\,K$
$= T_0\left(1 + \frac{\delta T(\hat{n})}{T_0}\right)$
$\frac{\delta T(\hat{n})}{T_0} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm}\, Y_m^l(\hat{n})$
$2l+1$ a_{lm}
l


$T(\hat{n}) = T_0 + \delta T(\hat{n})$
$2.73\,K$
$= T_0\left(1 + \frac{\delta T(\hat{n})}{T_0}\right)$
$\frac{\delta T(\hat{n})}{T_0} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_m^l(\hat{n})$
C_l
l
$2l+1$
$\frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$


WMAP
C_ℓ
ℓ
$2\ell+1$
$\frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2$
$T(\hat{n}) = T_0 + \delta T(\hat{n})$
$2.73\,K$
$= T_0\left(1 + \frac{\delta T(\hat{n})}{T_0}\right)$
$\frac{\delta T(\hat{n})}{T_0} = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m}\, Y_m^\ell(\hat{n})$