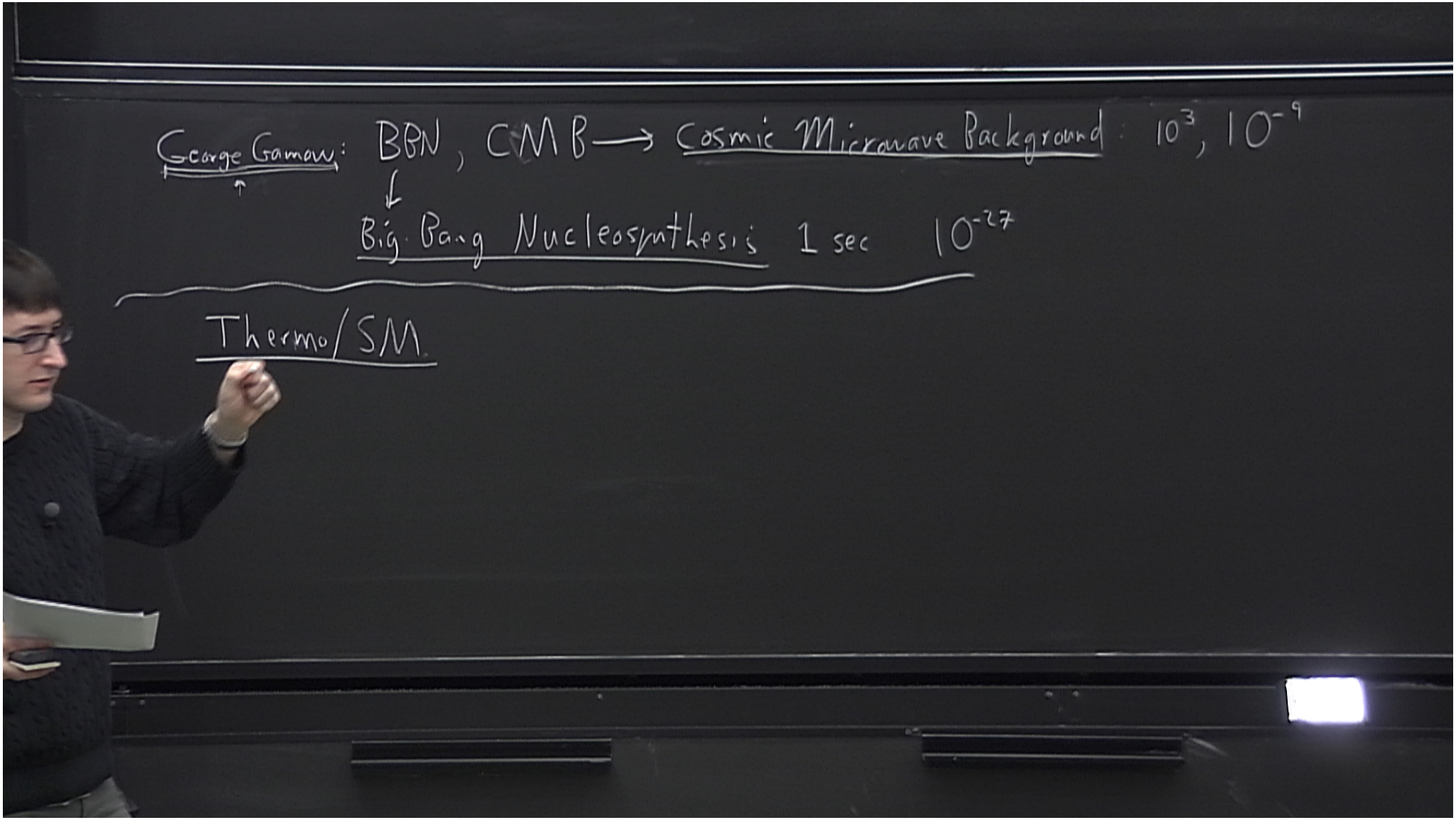
Title: Cosmology (Review) - Lecture 8

Date: Feb 03, 2012 09:00 AM

URL: http://pirsa.org/12020021

Abstract:


George Gamow: BBN, CMB → Cosmic Microwave Background 10^3, 10^{-9}
Big Bang Nucleosynthesis 1 sec 10^{-27}
Thermo/SM

George Gamow: BBN, CMB → Cosmic Microwave Background 10^3, 10^{-9}

↓

Big Bang Nucleosynthesis 1 sec 10^{-27}

$\vec{p} \to E$

$T_i \gg m_i, \mu_i$

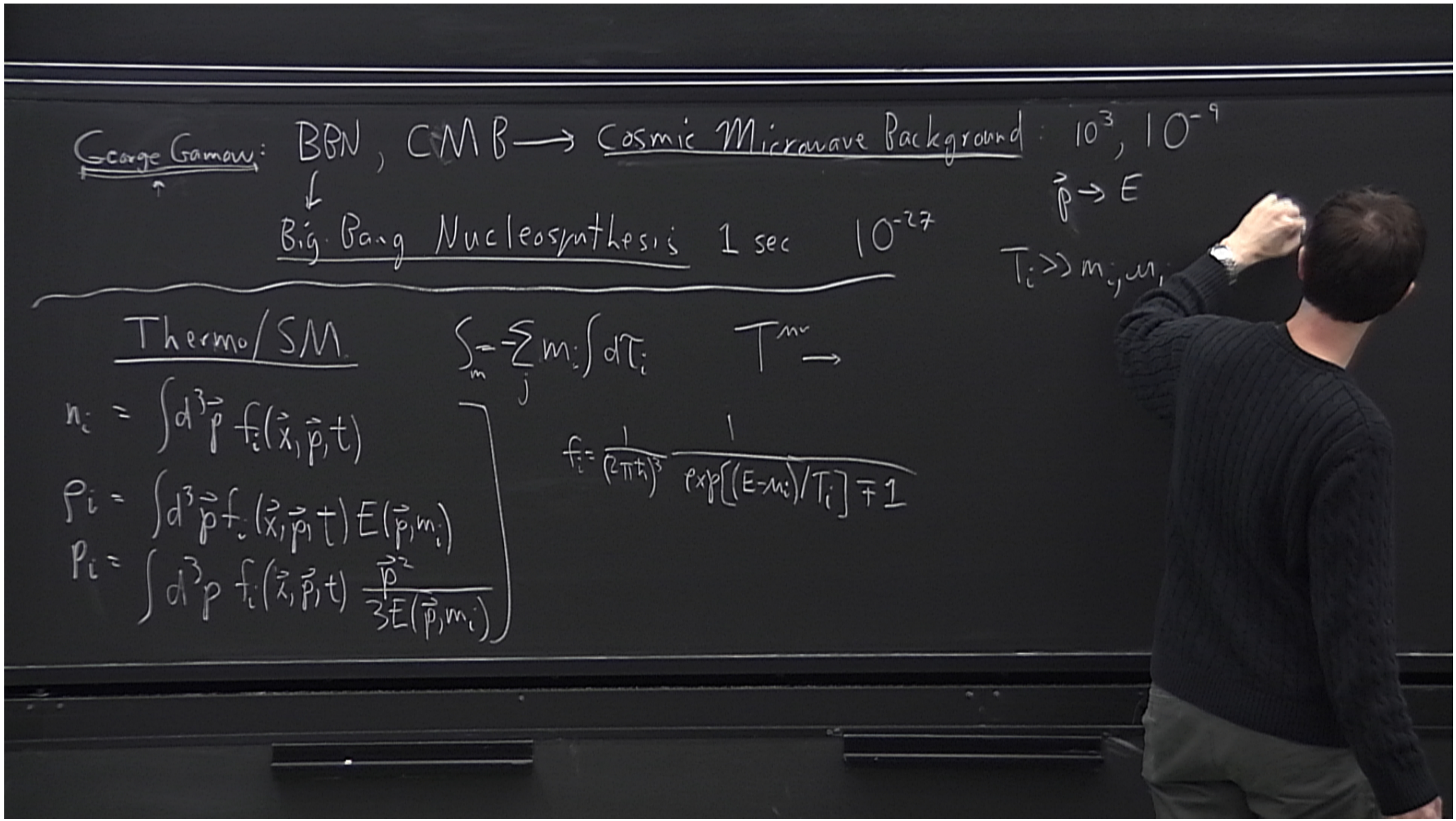
Thermo/SM $\quad S_m = -\sum_j m_j \int d\tau_j \quad T^{\mu\nu} \to$

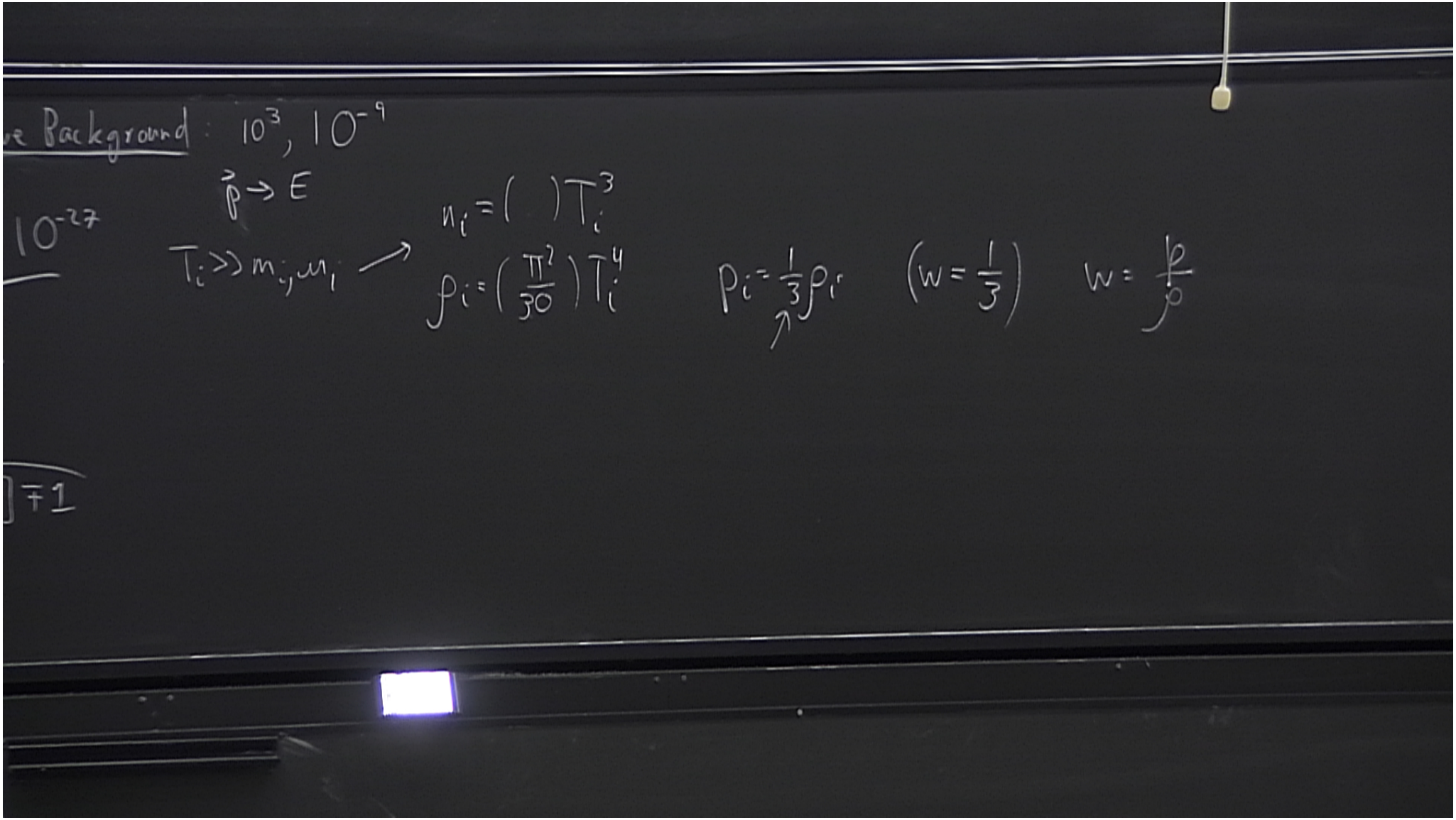
$$n_i = \int d^3\vec{p}\, f_i(\vec{x}, \vec{p}, t)$$

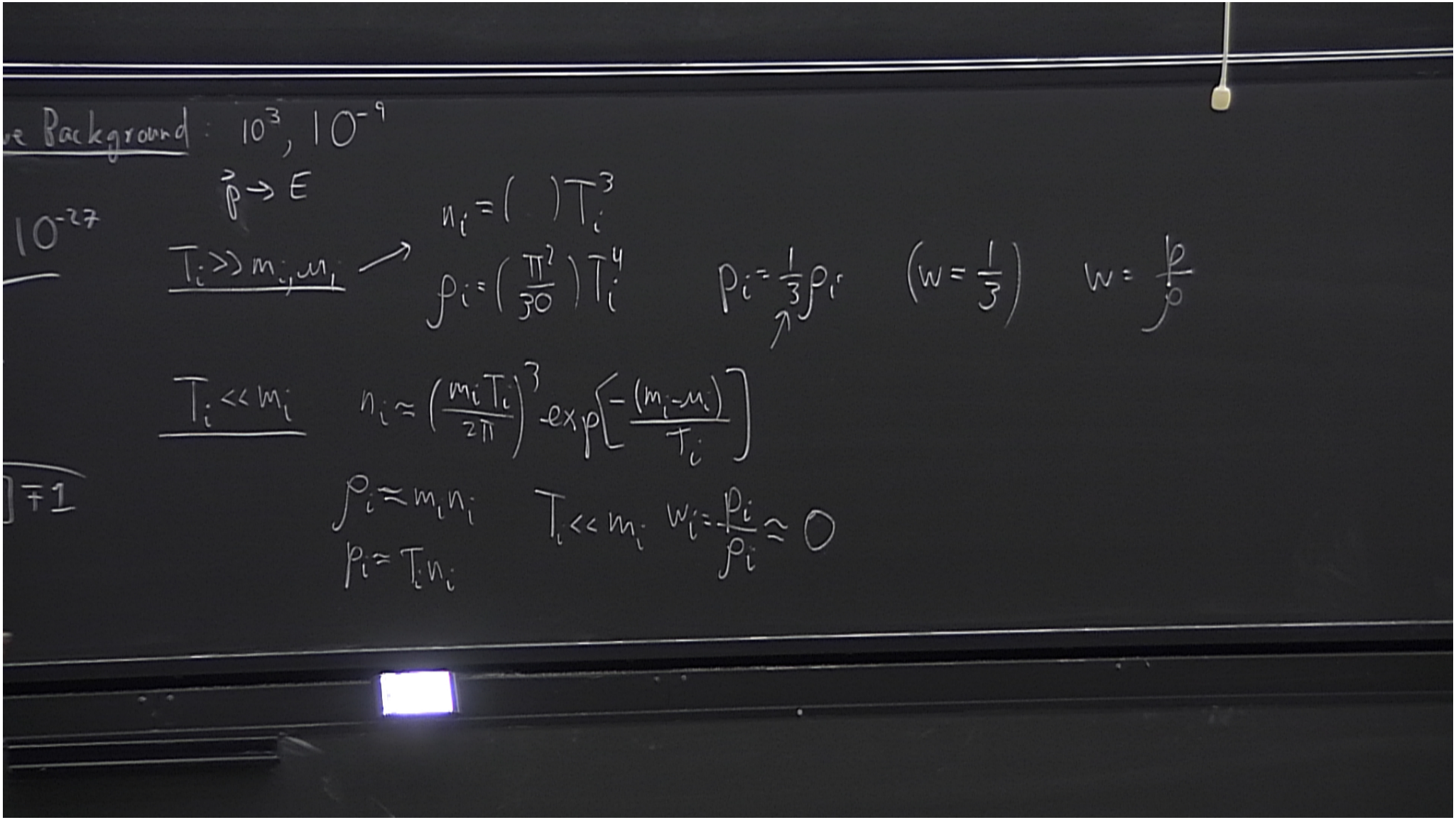
$$\rho_i = \int d^3\vec{p}\, f_i(\vec{x}, \vec{p}, t)\, E(\vec{p}, m_i)$$

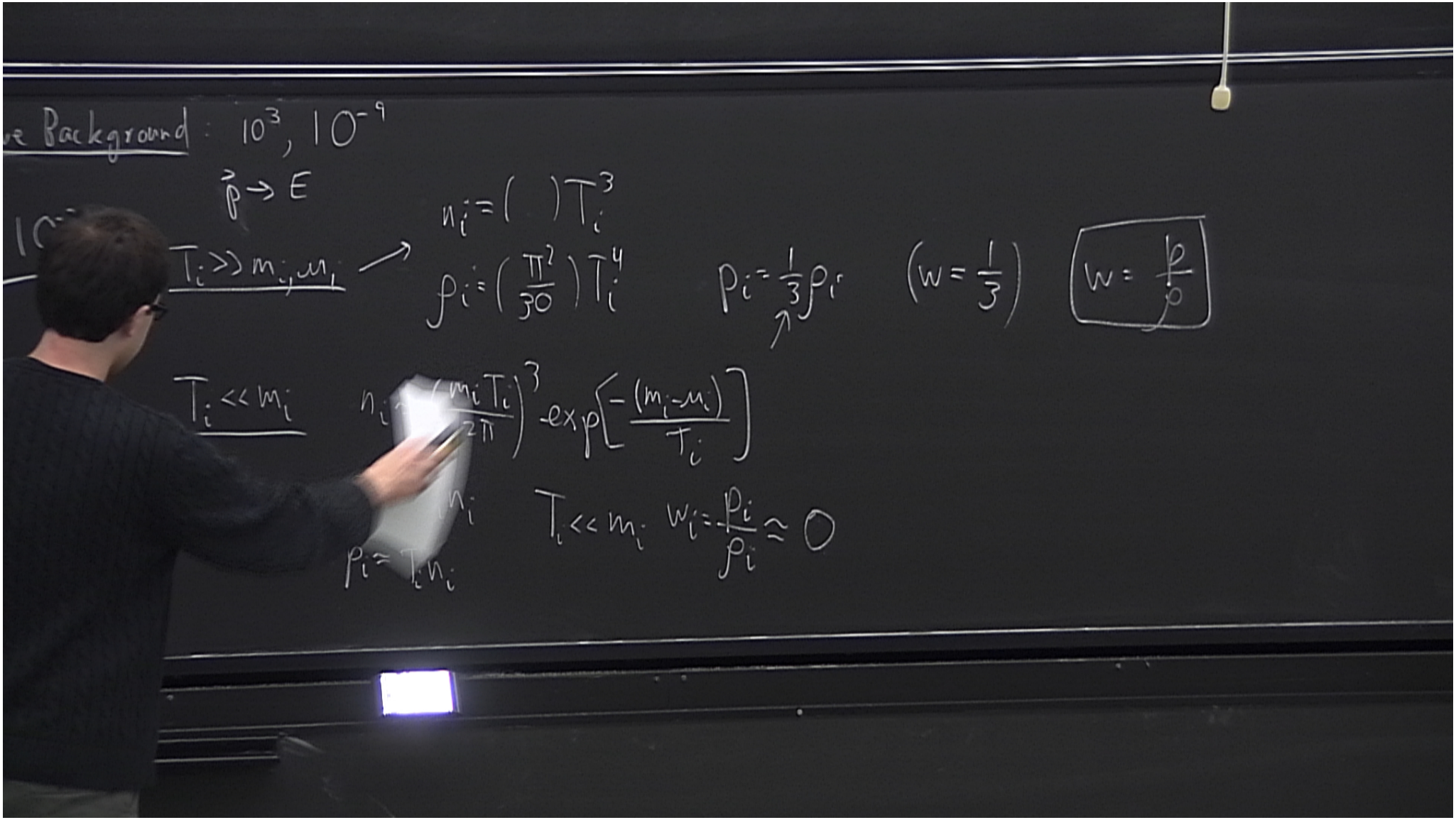
$$P_i = \int d^3p\, f_i(\vec{x}, \vec{p}, t)\, \frac{\vec{p}^2}{3E(\vec{p}, m_i)}$$

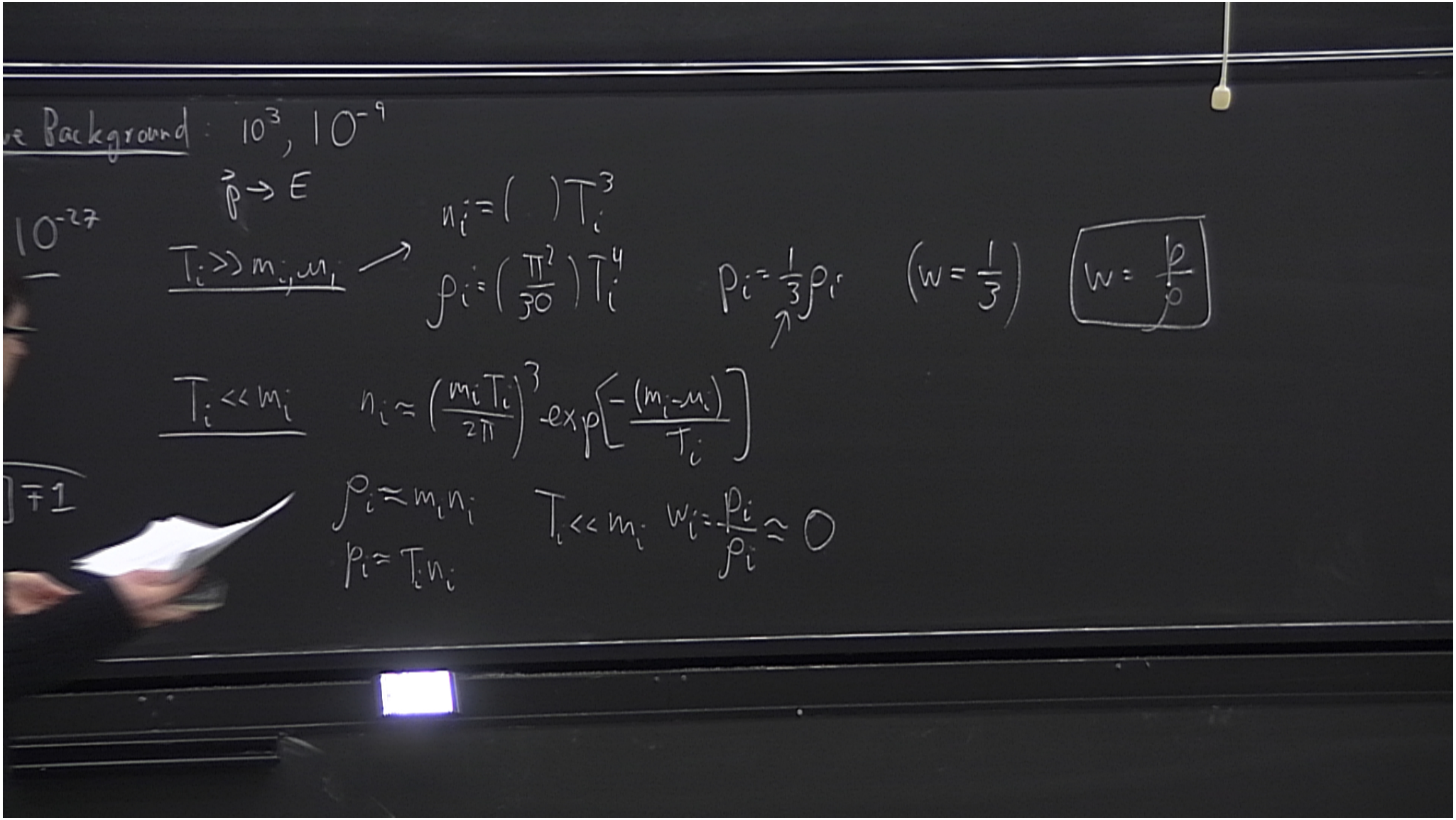
$$f_i = \frac{1}{(2\pi\hbar)^3} \frac{1}{\exp\left[(E-\mu_i)/T_i\right] \mp 1}$$




e Background: $10^3, 10^{-9}$
$\vec{p} \to E$
10^{-27}
$T_i \gg m_i, \mu_i \rightarrow$
$n_i = (\ ) T_i^3$
$\rho_i = \left(\frac{\pi^2}{30}\right) T_i^4$
$p_i = \frac{1}{3}\rho_i \quad \left(w = \frac{1}{3}\right) \quad w = \frac{p}{\rho}$
∓ 1


e Background: $10^3, 10^{-9}$
$\vec{p} \to E$
10^{-27}
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$p_i = \frac{1}{3}\rho_i$
$(w = \frac{1}{3})$
$w = \frac{p}{\rho}$
$T_i \ll m_i$
$n_i \approx \left(\frac{m_i T_i}{2\pi}\right)^3 \exp\left[-\frac{(m_i - \mu_i)}{T_i}\right]$
∓ 1
$\rho_i \approx m_i n_i$
$T_i \ll m_i$
$w_i = \frac{p_i}{\rho_i} \approx 0$
$p_i = T_i n_i$


Background: $10^3, 10^{-9}$
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n_i
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∓ 1
$\rho_i \approx m_i n_i$
$p_i = T_i n_i$
$T_i \ll m_i$ $w_i = \frac{p_i}{\rho_i} \approx 0$

$10^3, 10^{-9}$

$dE = TdS - PdV$

$\rho \to E$

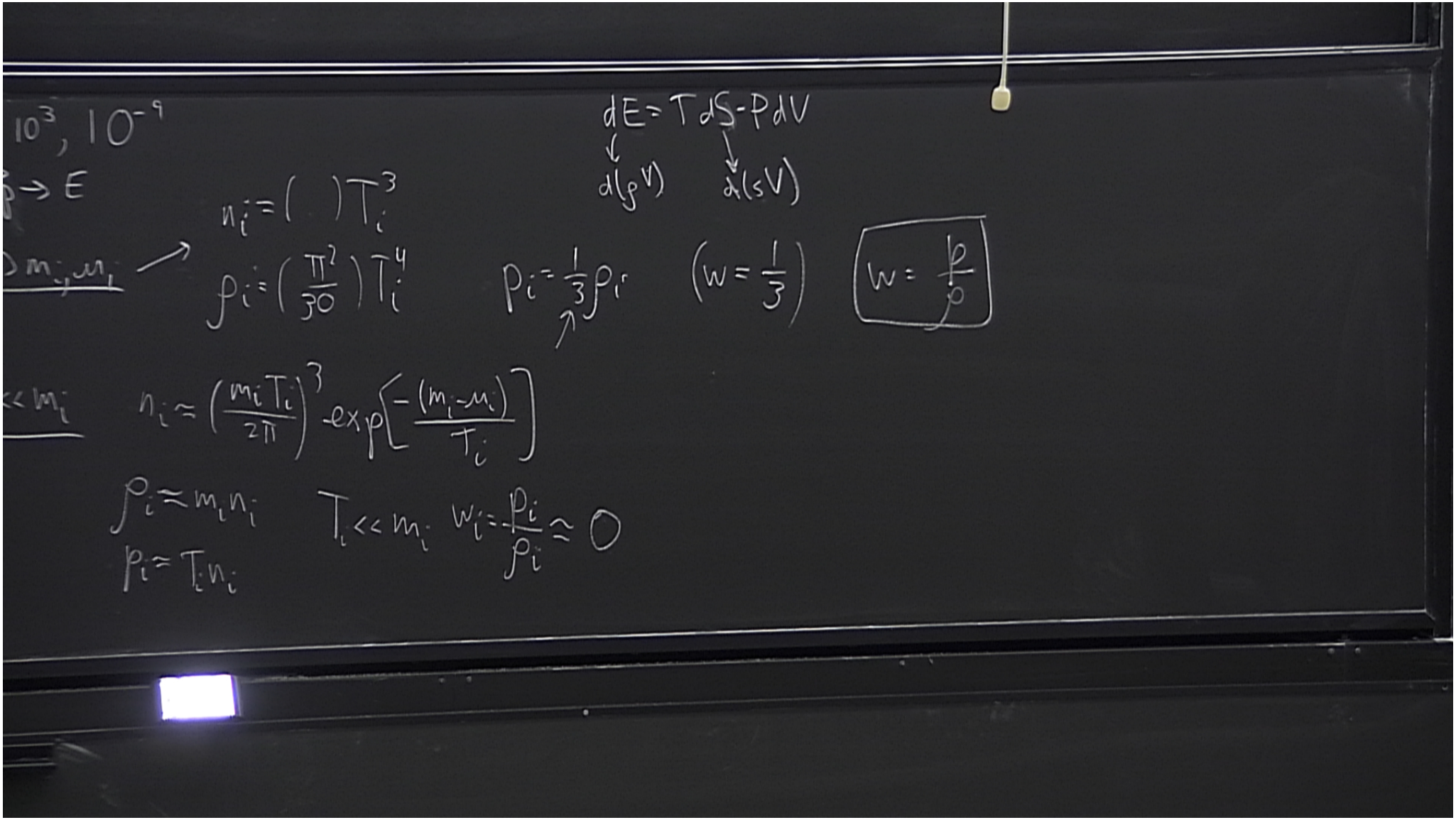
$n_i = (\ )T_i^3$

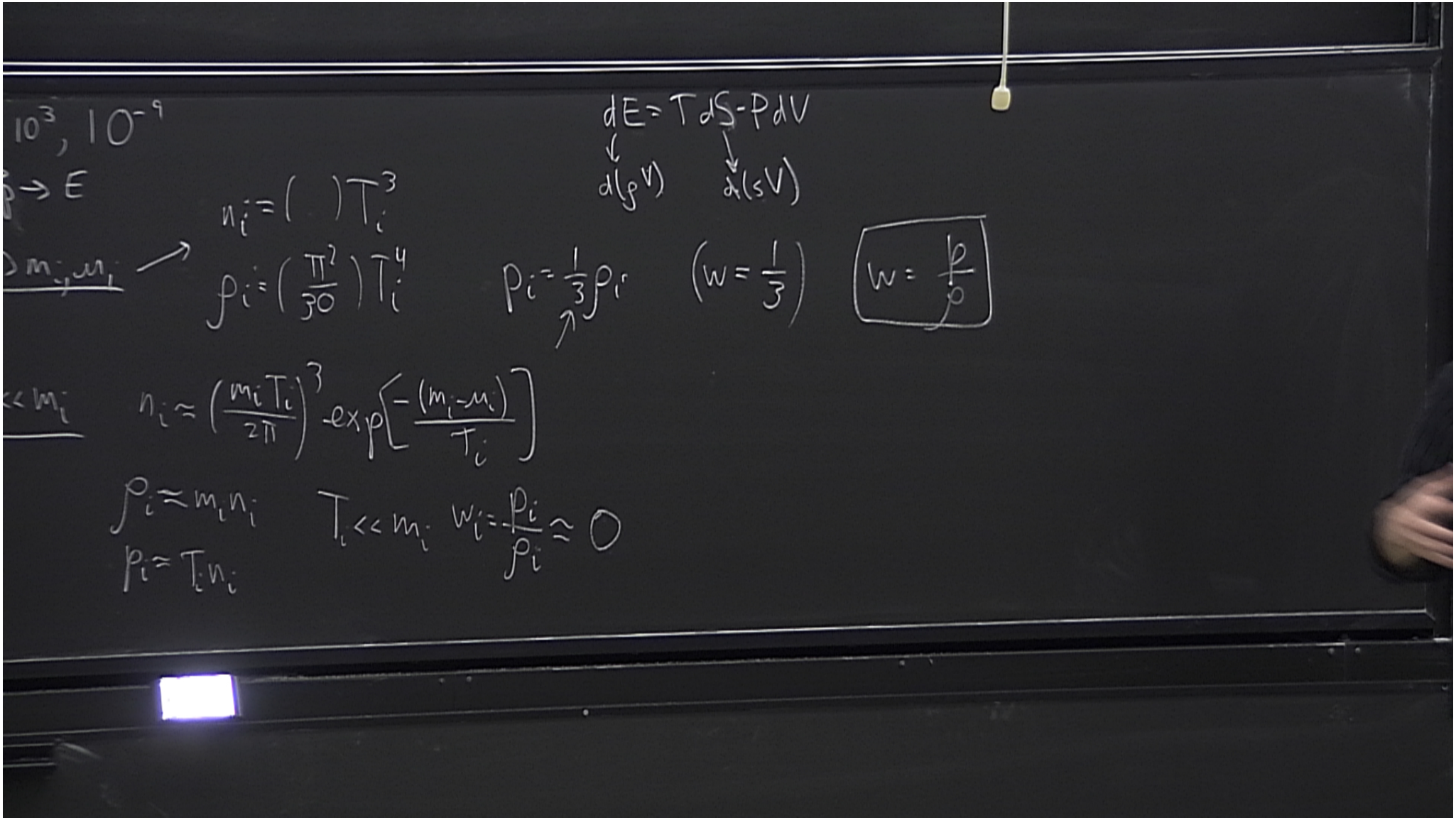
$m_i, \mu_i \rightarrow$ $\rho_i = \left(\frac{\pi^2}{30}\right) T_i^4$ $\quad p_i = \frac{1}{3}\rho_i$ $\quad (w = \frac{1}{3})$ $\quad \boxed{w = \frac{p}{\rho}}$

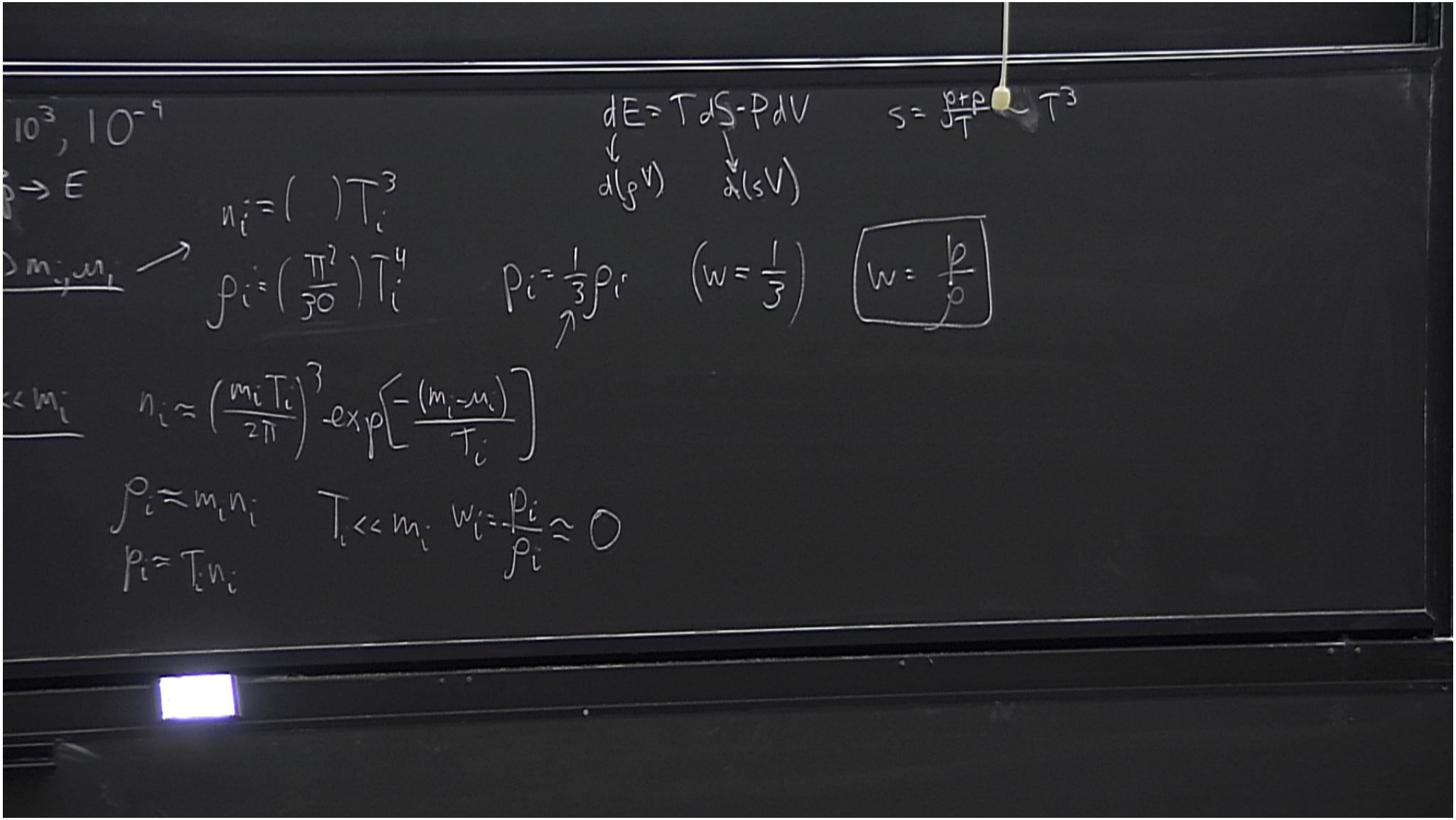
$T \ll m_i$ $\quad n_i \approx \left(\frac{m_i T_i}{2\pi}\right)^3 \exp\left[-\frac{(m_i - \mu_i)}{T_i}\right]$

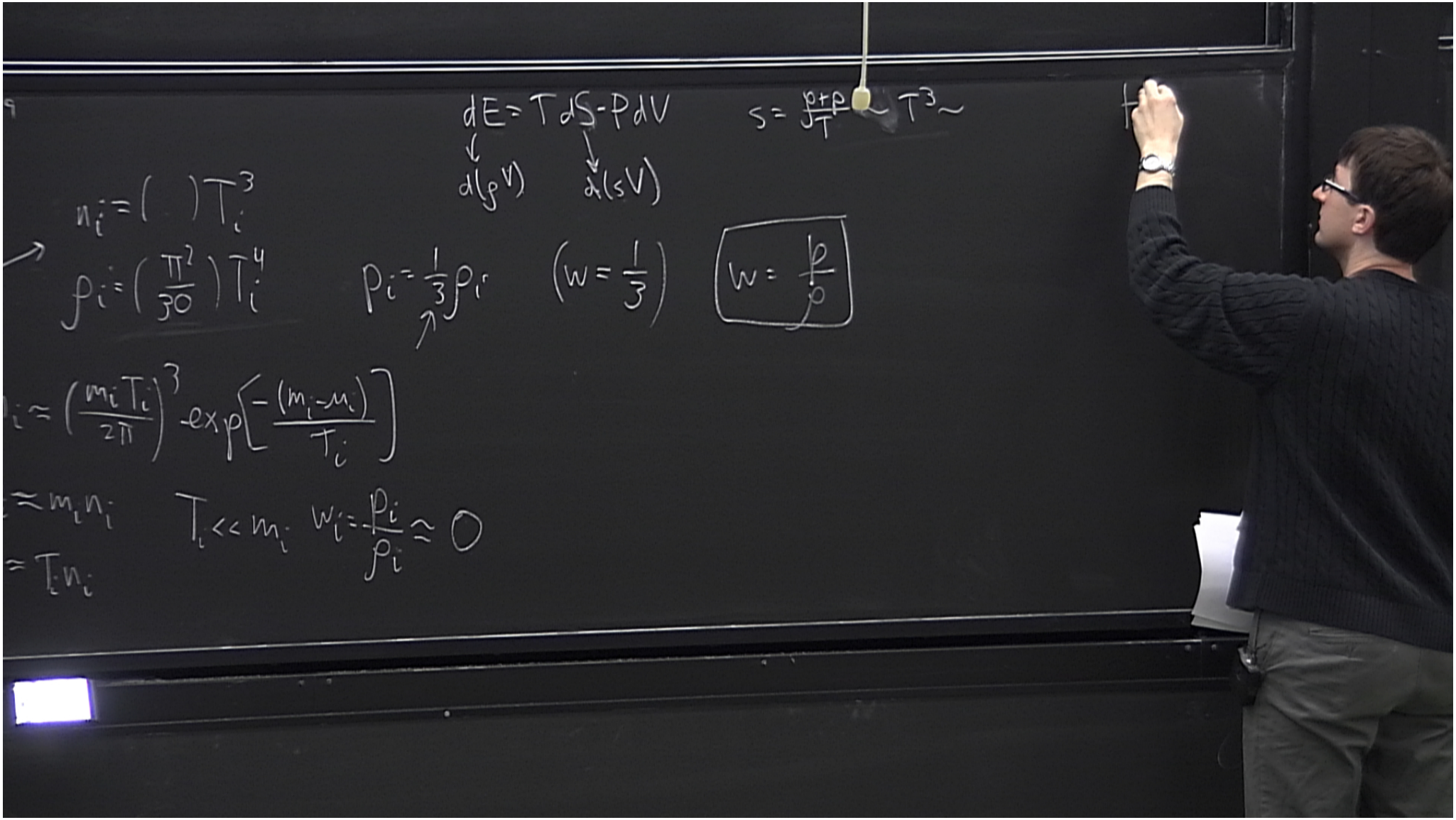
$\rho_i \approx m_i n_i$ $\quad T_i \ll m_i$ $\quad w_i = \frac{p_i}{\rho_i} \approx 0$

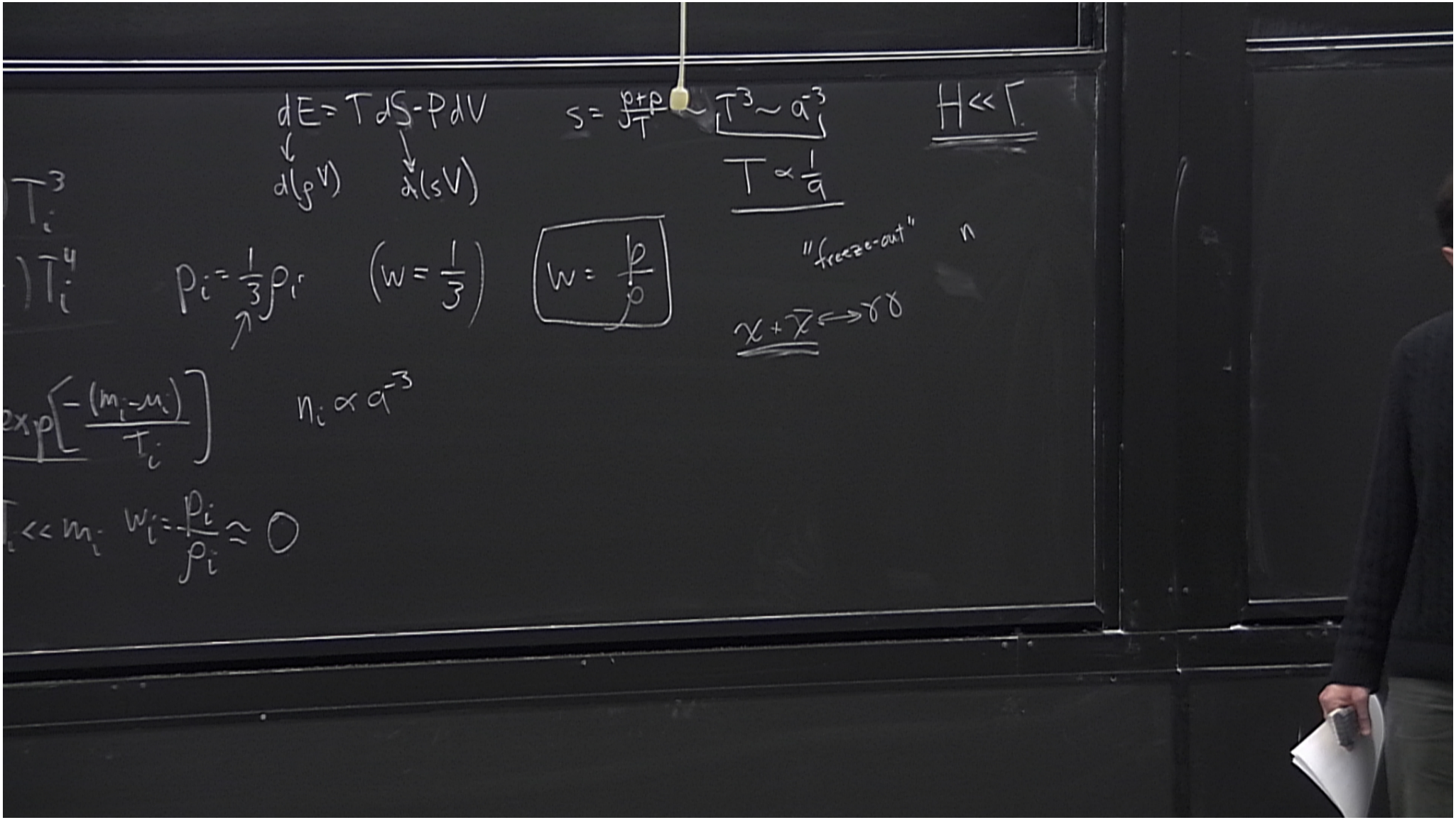
$p_i \approx T_i n_i$

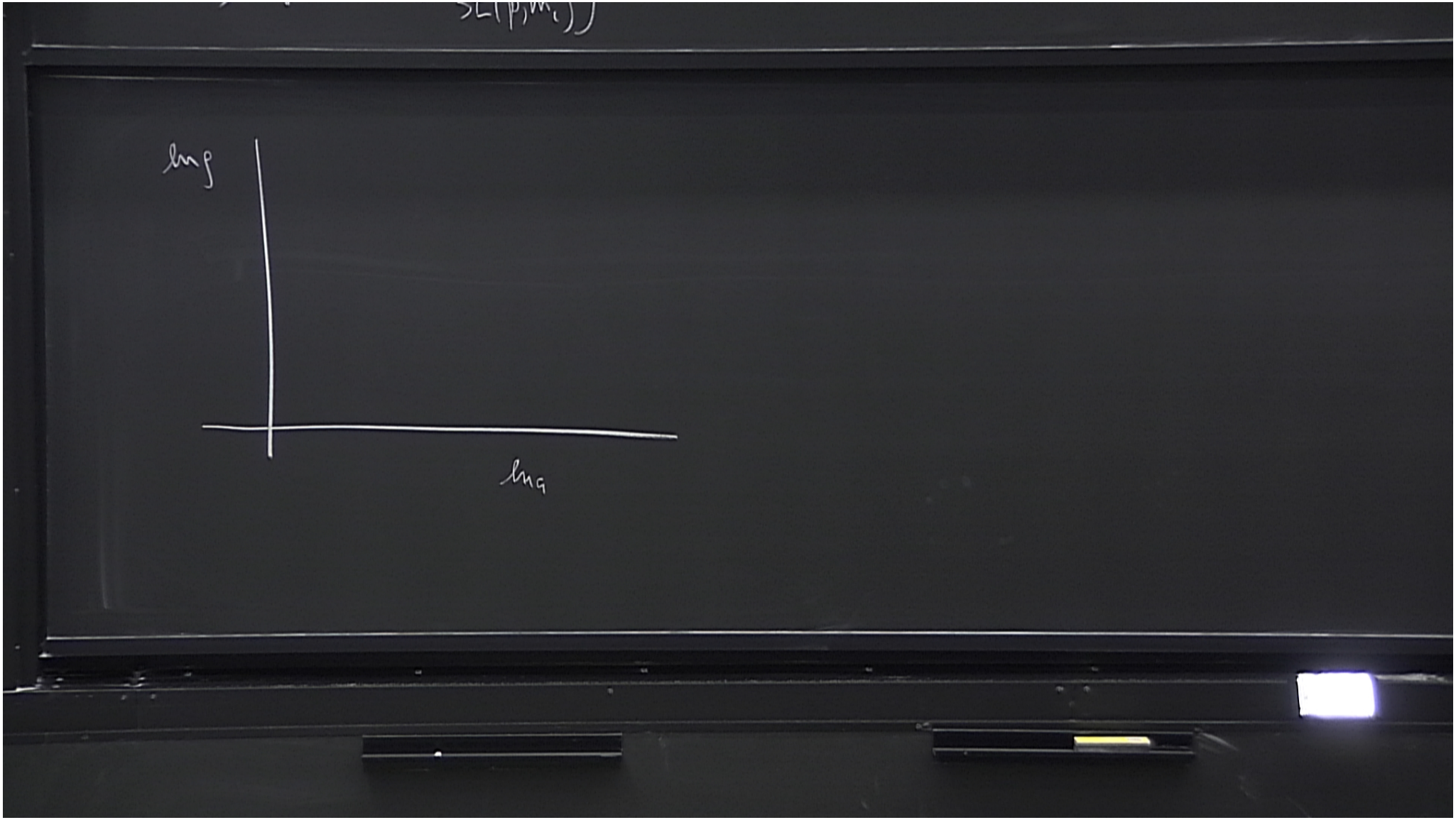

$10^3, 10^{-9}$
$\rho \to E$
m_i, μ_i
$n_i = (\ ) T_i^3$
$\rho_i = \left(\frac{\pi^2}{30}\right) T_i^4$
$dE = T dS - P dV$
$d(\rho V)$
$d(sV)$
$p_i = \frac{1}{3}\rho_i$
$(w = \frac{1}{3})$
$w = \frac{p}{\rho}$
$\ll m_i$
$n_i \approx \left(\frac{m_i T_i}{2\pi}\right)^3 \exp\left[-\frac{(m_i - \mu_i)}{T_i}\right]$
$\rho_i \approx m_i n_i$
$T_i \ll m_i$
$w_i = \frac{p_i}{\rho_i} \approx 0$
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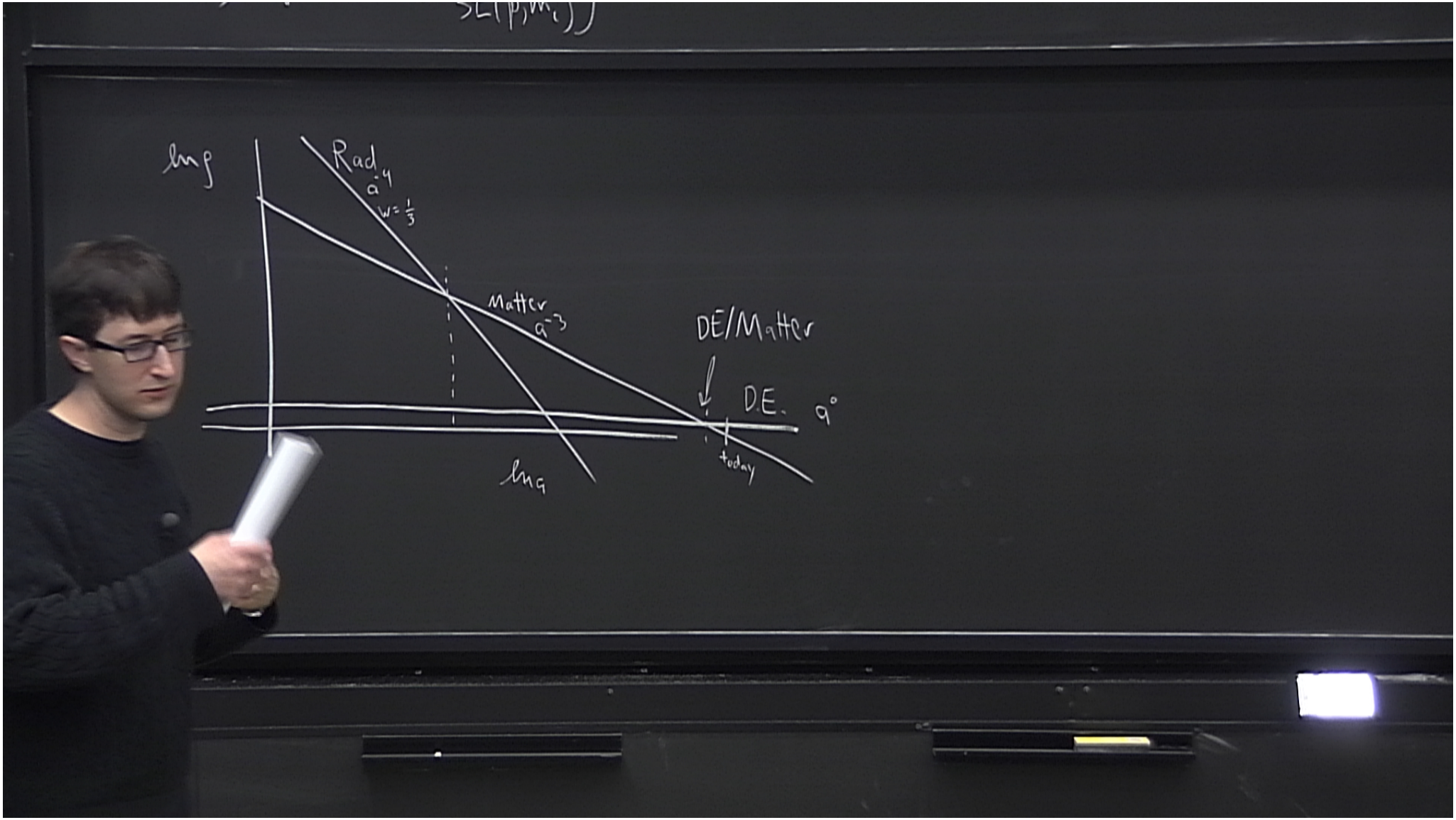

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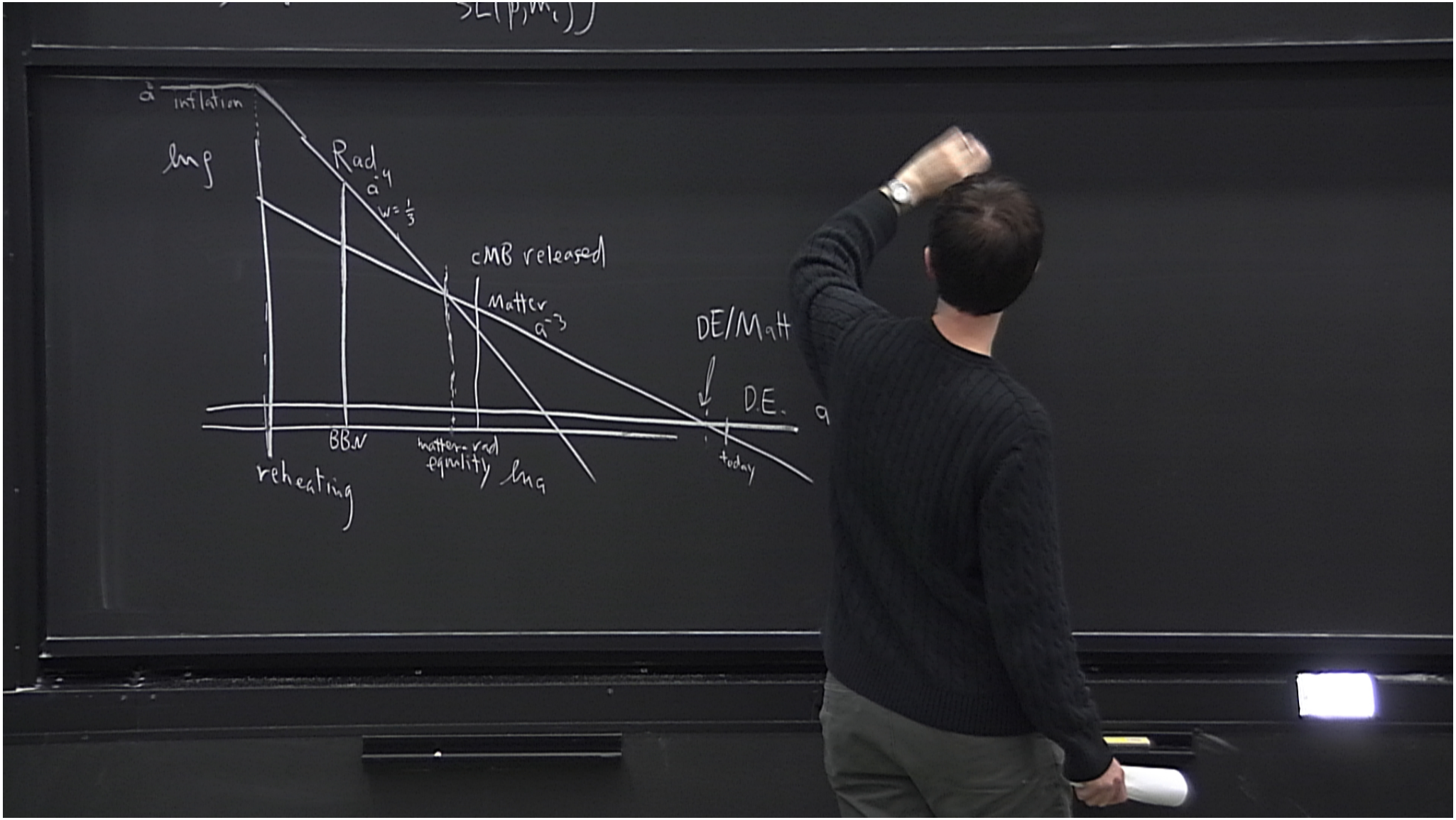

$10^3, 10^{-9}$
$\rho \to E$
m_i, μ_i
$n_i = (\ ) T_i^3$
$\rho_i = \left(\frac{\pi^2}{30}\right) T_i^4$
$dE = T dS - P dV$
$d(\rho V)$
$d(sV)$
$s = \frac{p+\rho}{T} \sim T^3$
$p_i = \frac{1}{3}\rho_i \quad (w = \frac{1}{3})$
$w = \frac{p}{\rho}$
$\ll m_i$
$n_i \approx \left(\frac{m_i T_i}{2\pi}\right)^3 \exp\left[-\frac{(m_i - \mu_i)}{T_i}\right]$
$\rho_i \approx m_i n_i \quad T_i \ll m_i \quad w_i = \frac{p_i}{\rho_i} \approx 0$
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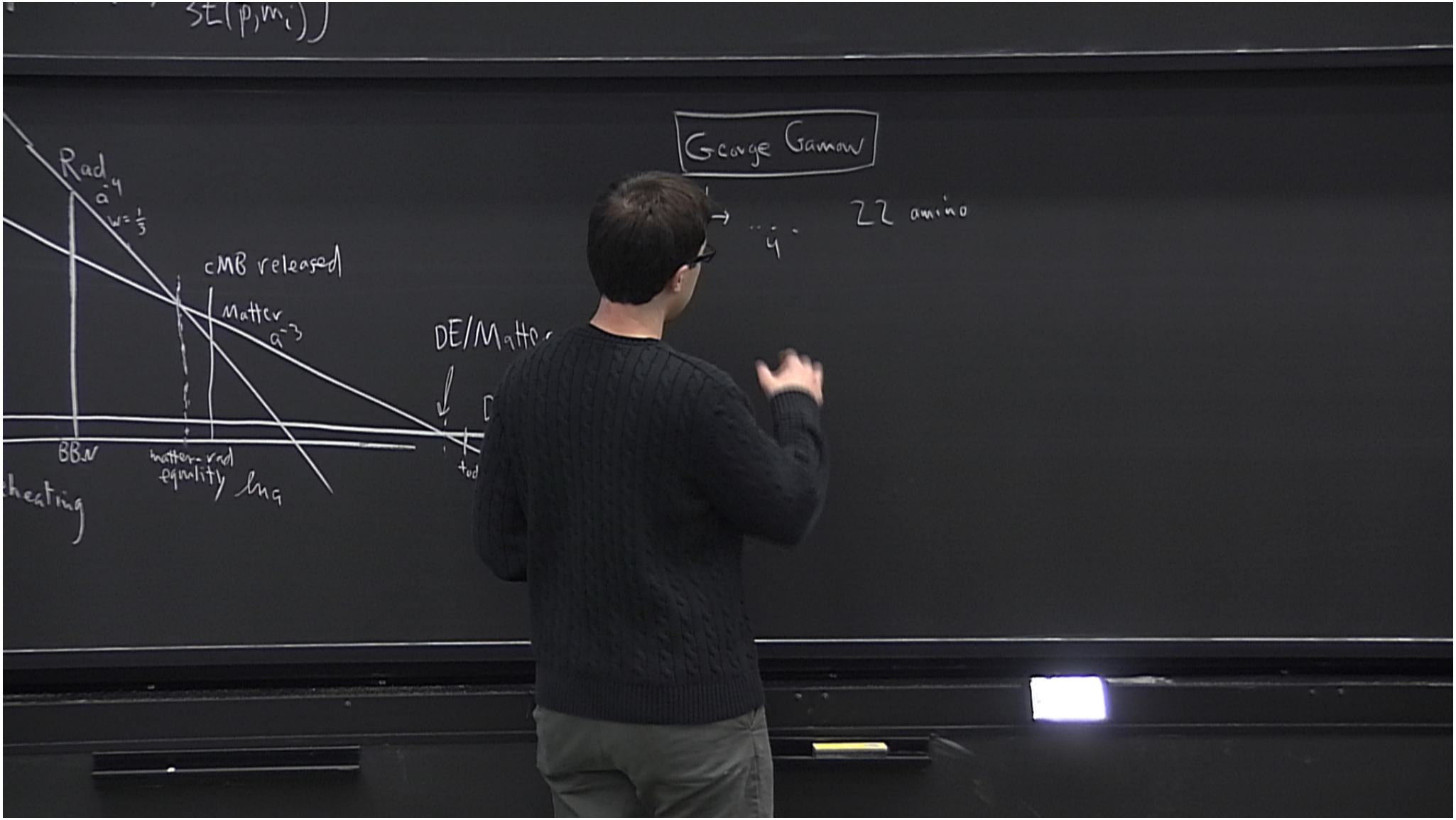

dE = T dS - P dV
d(ρV)
d(sV)
s = (ρ+p)/T ~ T^3 ~
n_i = ( ) T_i^3
ρ_i = (π^2/30) T_i^4
p_i = 1/3 ρ_i
(w = 1/3)
w = p/ρ
≈ (m_i T_i / 2π)^3 exp[- (m_i - μ_i) / T_i]
≈ m_i n_i
= T_i n_i
T_i << m_i
w_i = p_i/ρ_i ≈ 0


dE = TdS - PdV
d(ρV)
d(sV)
s = (ρ+p)/T
T³ ~ a⁻³
T ∝ 1/a
H ≪ Γ
T_i³
T_i⁴
p_i = 1/3 ρ_i
(w = 1/3)
w = p/ρ
"freeze-out"
n
x + x̄ ↔ γγ
exp[-(m_i - μ_i)/T_i]
n_i ∝ a⁻³
T_i ≪ m_i
w_i = p_i/ρ_i ≈ 0


ln p
ln q


ln ρ
Rad
a^-4
w = 1/3
Matter
a^-3
DE/Matter
D.E.
today
ln a


inflation
ln ρ
Rad
a^{-4}
$w = \frac{1}{3}$
CMB released
Matter
a^{-3}
DE/Matt
D.E.
BBN
matter-rad equality
today
reheating
ln a

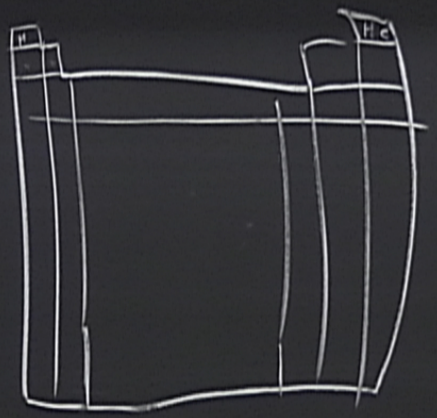

George Gamow
Rad
a^{-4}
$w = \frac{1}{3}$
CMB released
Matter
a^{-3}
DE/Matter
BBN
matter-rad equality
22 amino



Gamow

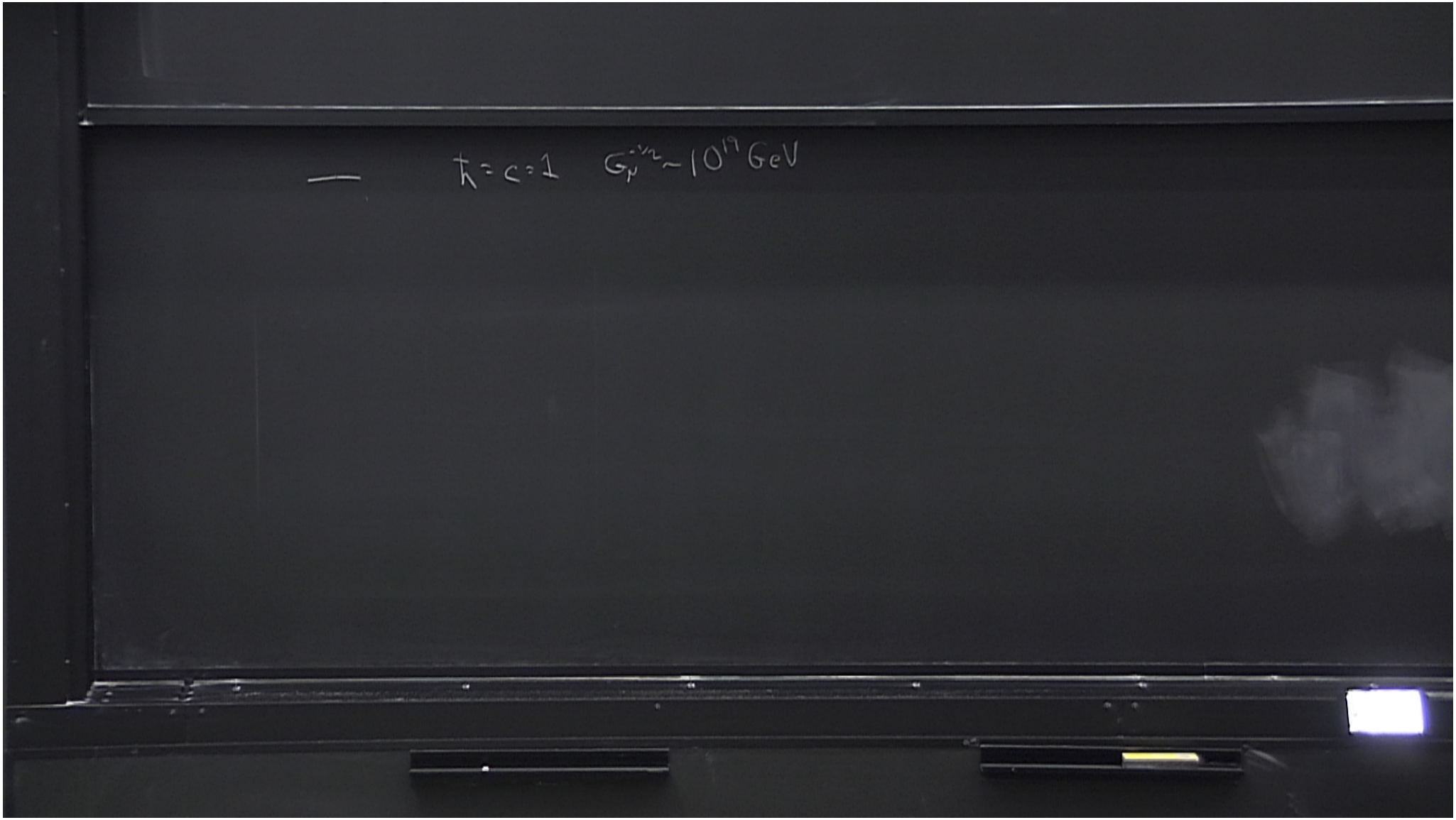
22 amino

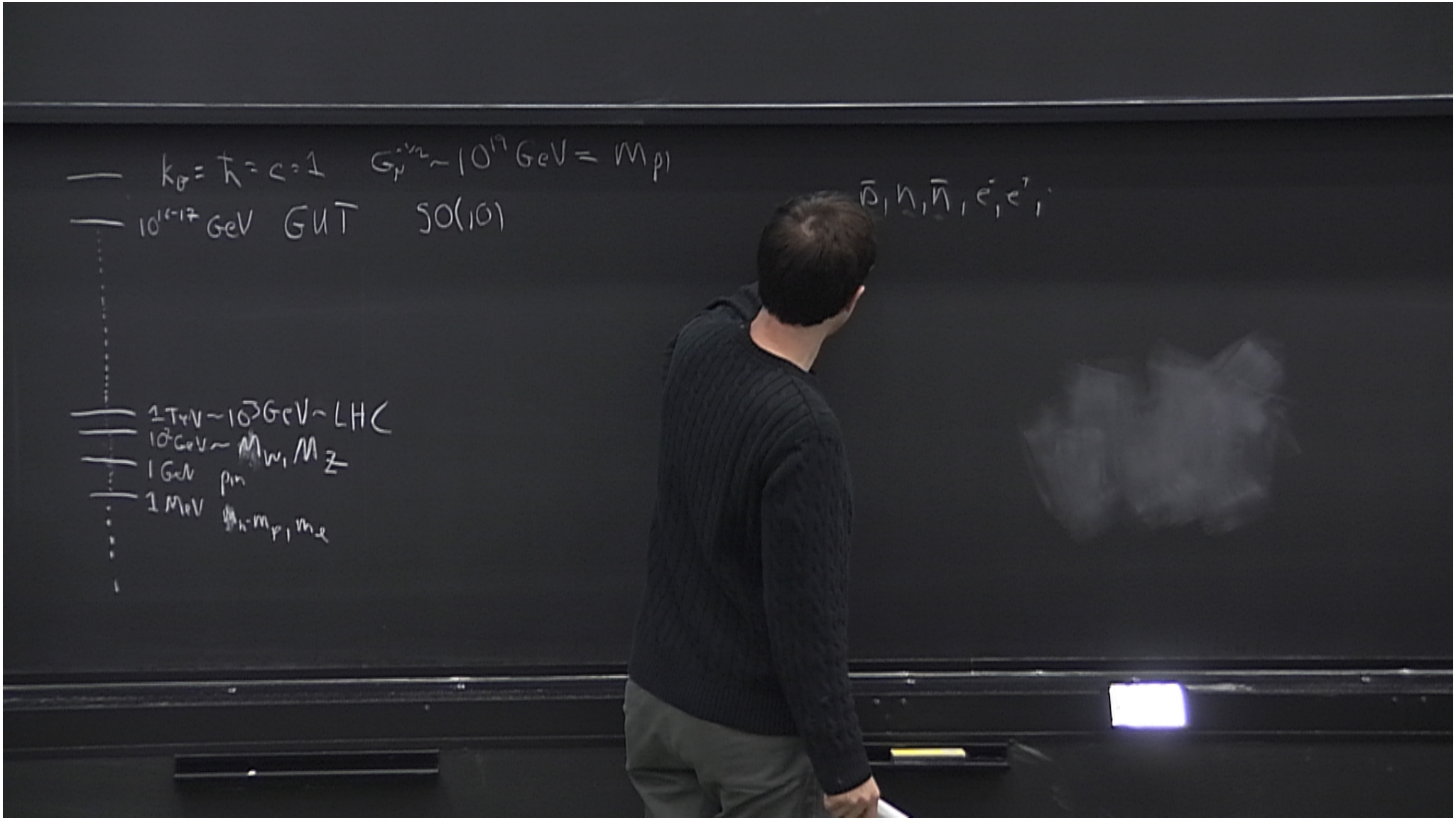
Fermi, Gamow, Fowler, Hoyle, Bethe

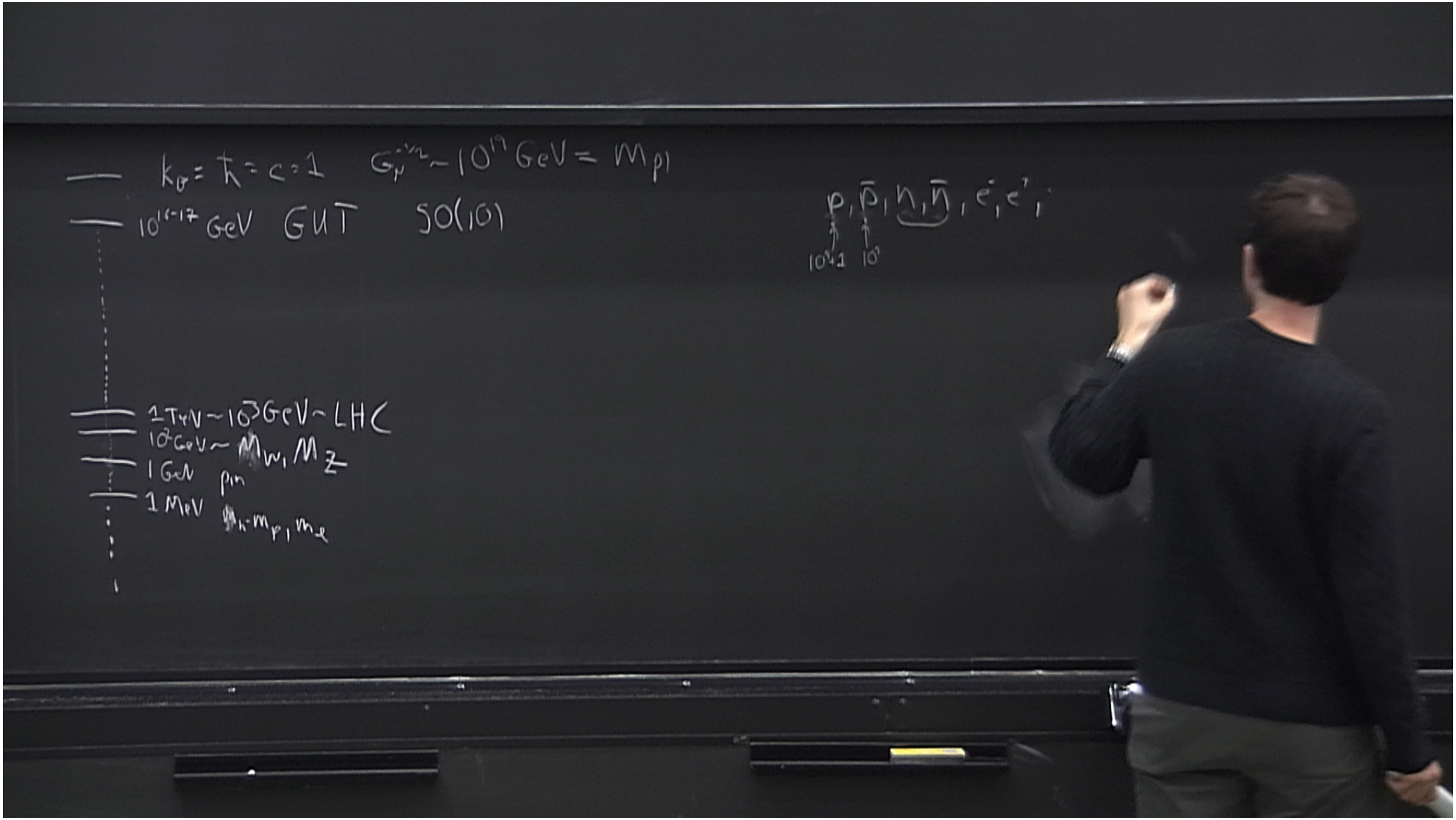


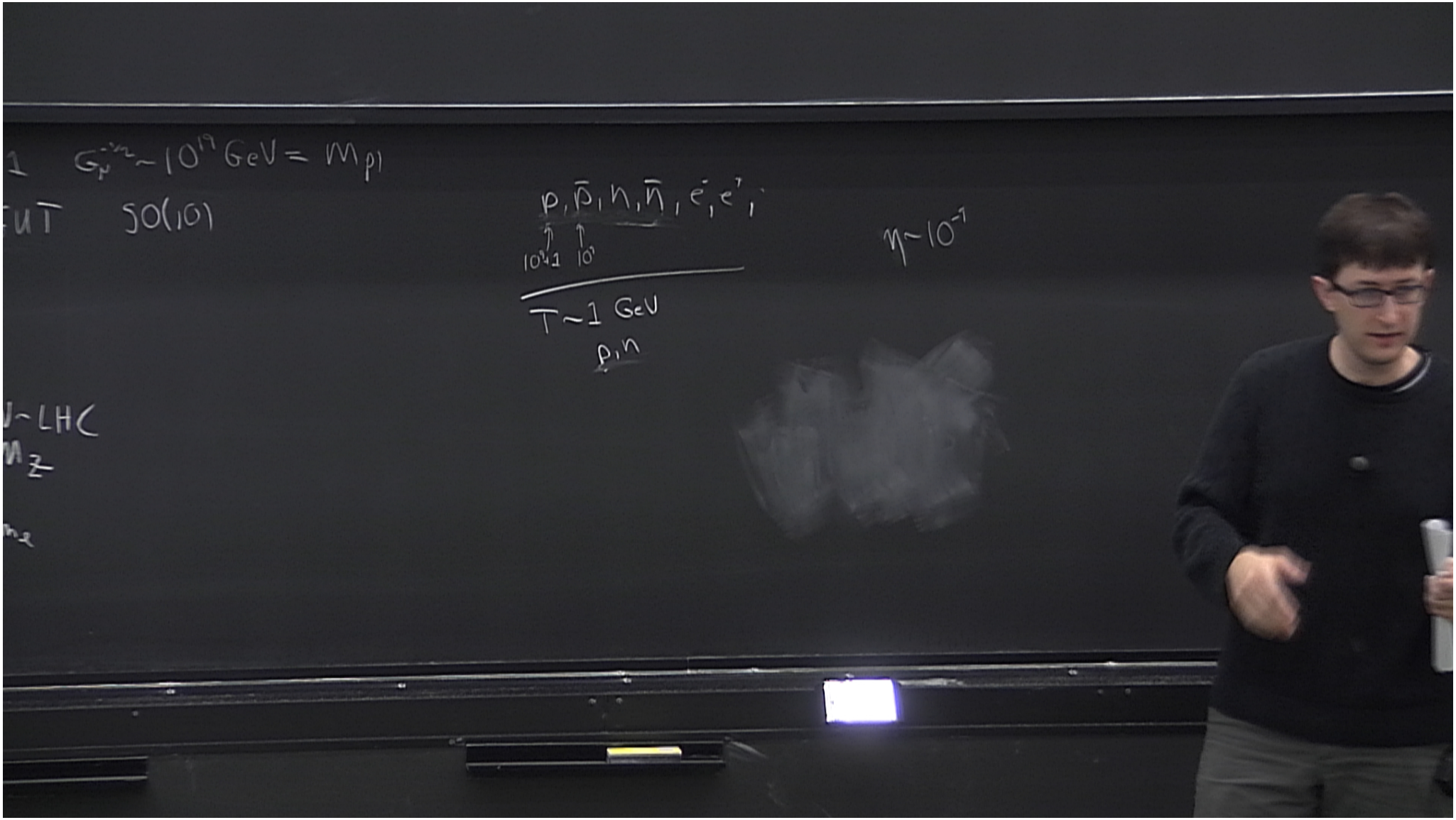
Iron

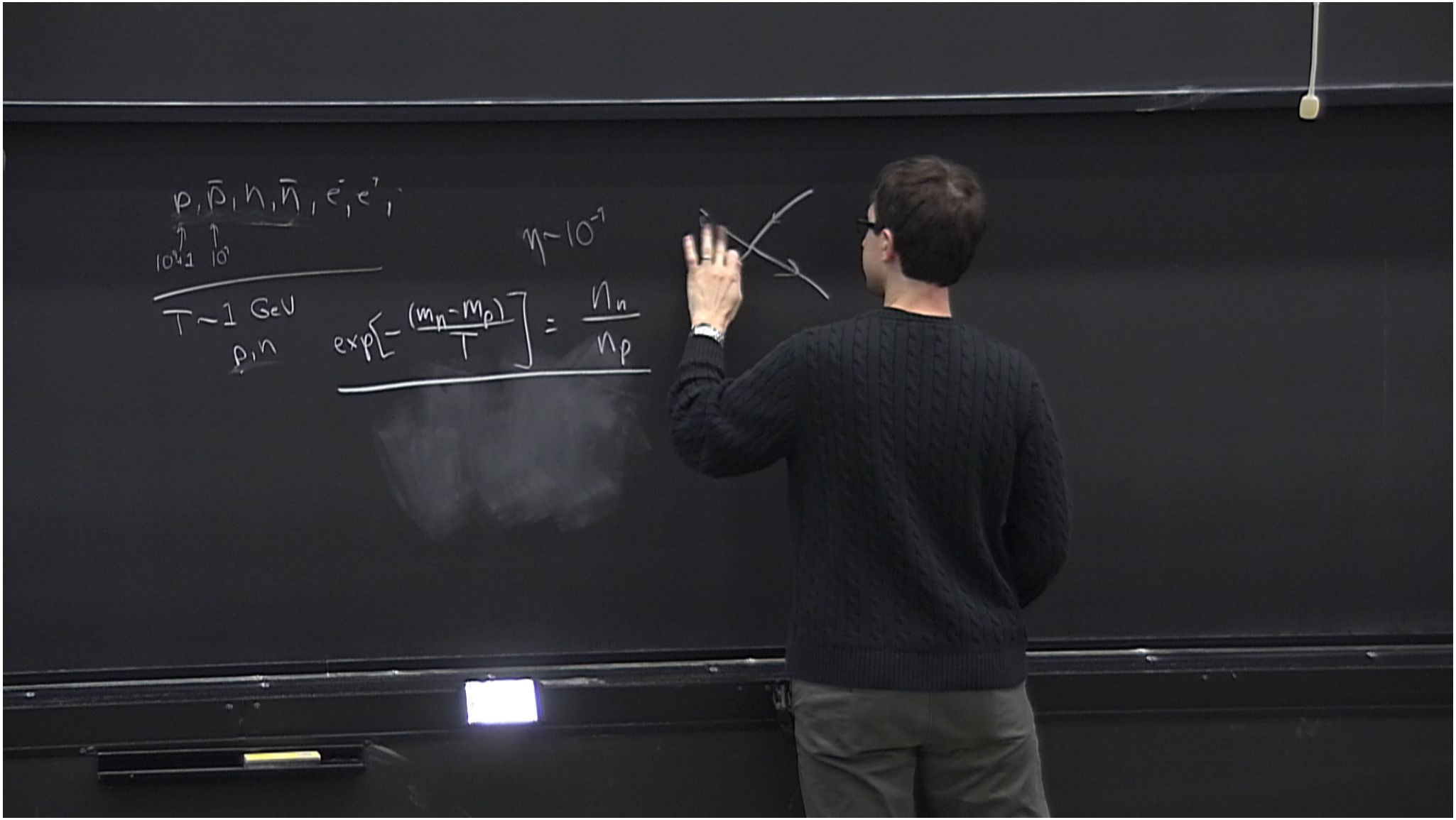
Uranium, Thorium, Plutonium


$\hbar = c = 1$ $G_N^{-1/2} \sim 10^{19}$ GeV


$k_B = \hbar = c = 1$ $G_N^{-1/2} \sim 10^{19}$ GeV $= M_{Pl}$
10^{16-17} GeV GUT SO(10)
$\bar{p}, n, \bar{n}, e^-, e^+$
1 TeV $\sim 10^3$ GeV $\sim$ LHC
10^2 GeV $\sim M_W, M_Z$
1 GeV ρ_m
1 MeV $\Phi_n \cdot m_p, m_e$


$k_B = \hbar = c = 1$ $G_N^{-1/2} \sim 10^{19}$ GeV $= M_{Pl}$
10^{16-17} GeV GUT SO(10)
1 TeV $\sim 10^3$ GeV $\sim$ LHC
10^2 GeV $\sim M_W, M_Z$
1 GeV ρ_{in}
1 MeV m_n, m_p, m_e
$p, \bar{p}, n, \bar{n}, e, e^+$
10^{24} 1 10^{33}


$G_F^{-1/2} \sim 10^{19}\,\mathrm{GeV} = M_{Pl}$
SO(10)
$p, \bar{p}, n, \bar{n}, e^-, e^+$
10^{-1} 10^{1}
$T \sim 1$ GeV
p, n
$\eta \sim 10^{-7}$
$\sim$ LHC
M_Z


p, p̄, n, n̄, e⁻, e⁺
10^-1
10^-9
η ~ 10^-9
T ~ 1 GeV
p, n
exp[-(m_n - m_p)/T] = n_n/n_p

$p, \bar{p}, n, \bar{n}, e^-, e^+, \ldots$

10^{-1} 10^{9}

$\eta \sim 10^{-9}$

$T \sim 1$ GeV

p, n

$$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p}$$



$p, \bar{p}, n, \bar{n}, e^-, e^+$

10^{-1} 10^{1}

$\eta \sim 10^{-7}$

$T \sim 1$ GeV

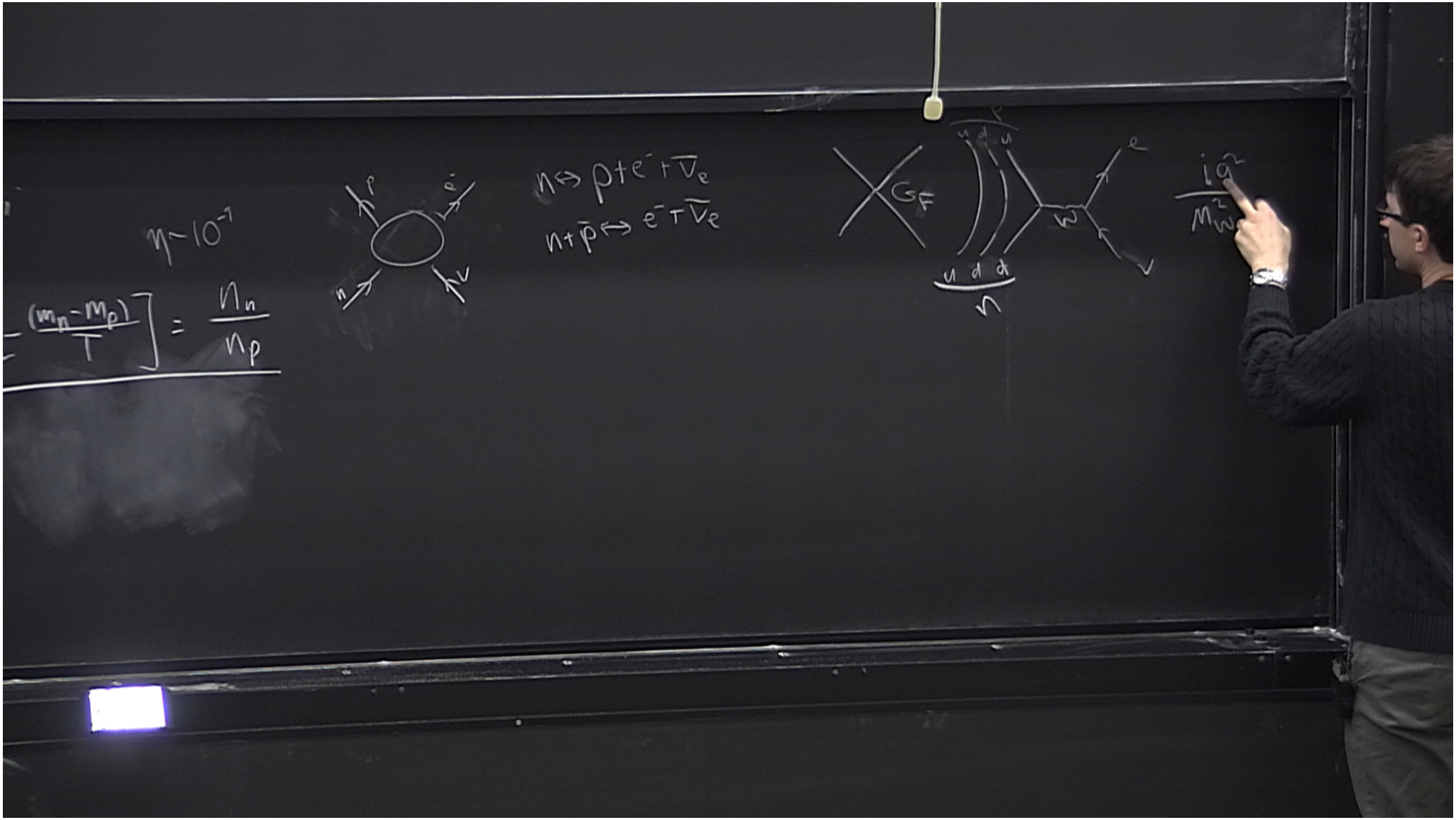
p, n

$$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p}$$



$n \leftrightarrow p + e^- + \bar{\nu}_e$

$n + \bar{p} \leftrightarrow e^- + \bar{\nu}_e$

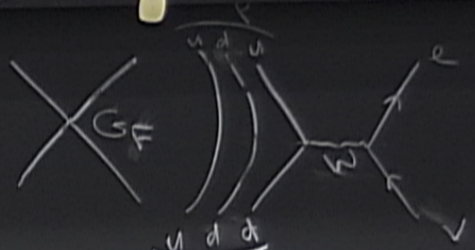

$\eta \sim 10^{-7}$
$\frac{(m_n - m_p)}{T}\Big] = \frac{n_n}{n_p}$
$n \Leftrightarrow p + e^- + \bar{\nu}_e$
$n + \bar{p} \Leftrightarrow e^- + \bar{\nu}_e$
G_F
$\frac{ig^2}{M_W^2}$

$\eta \sim 10^{-7}$



$n \leftrightarrow p + e^- + \bar{\nu}_e$

$n + \bar{p} \leftrightarrow e^- + \bar{\nu}_e$



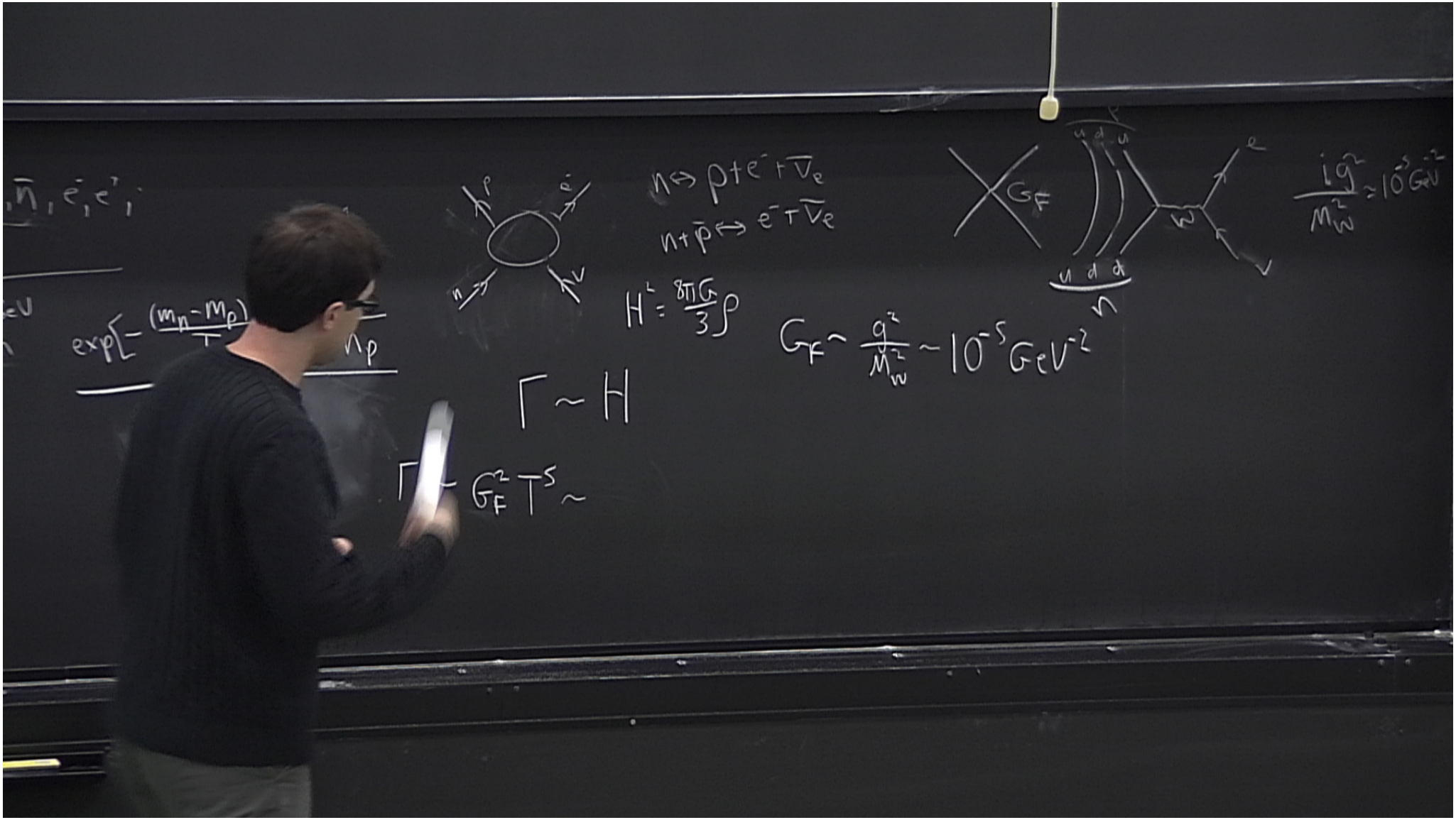
$\frac{iq^2}{M_W^2} \simeq 10^{-5} GeV^{-2}$

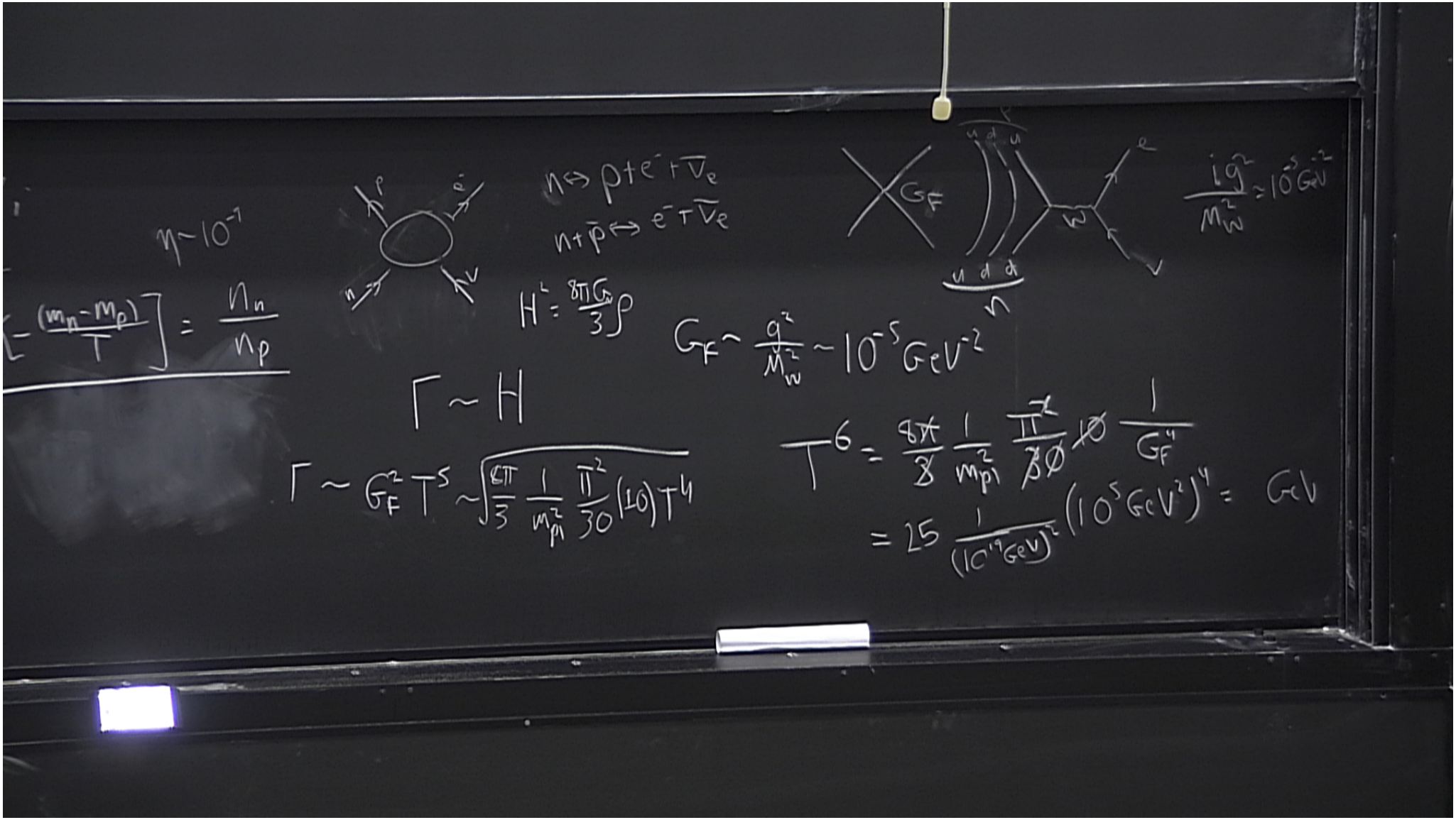
$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p}$

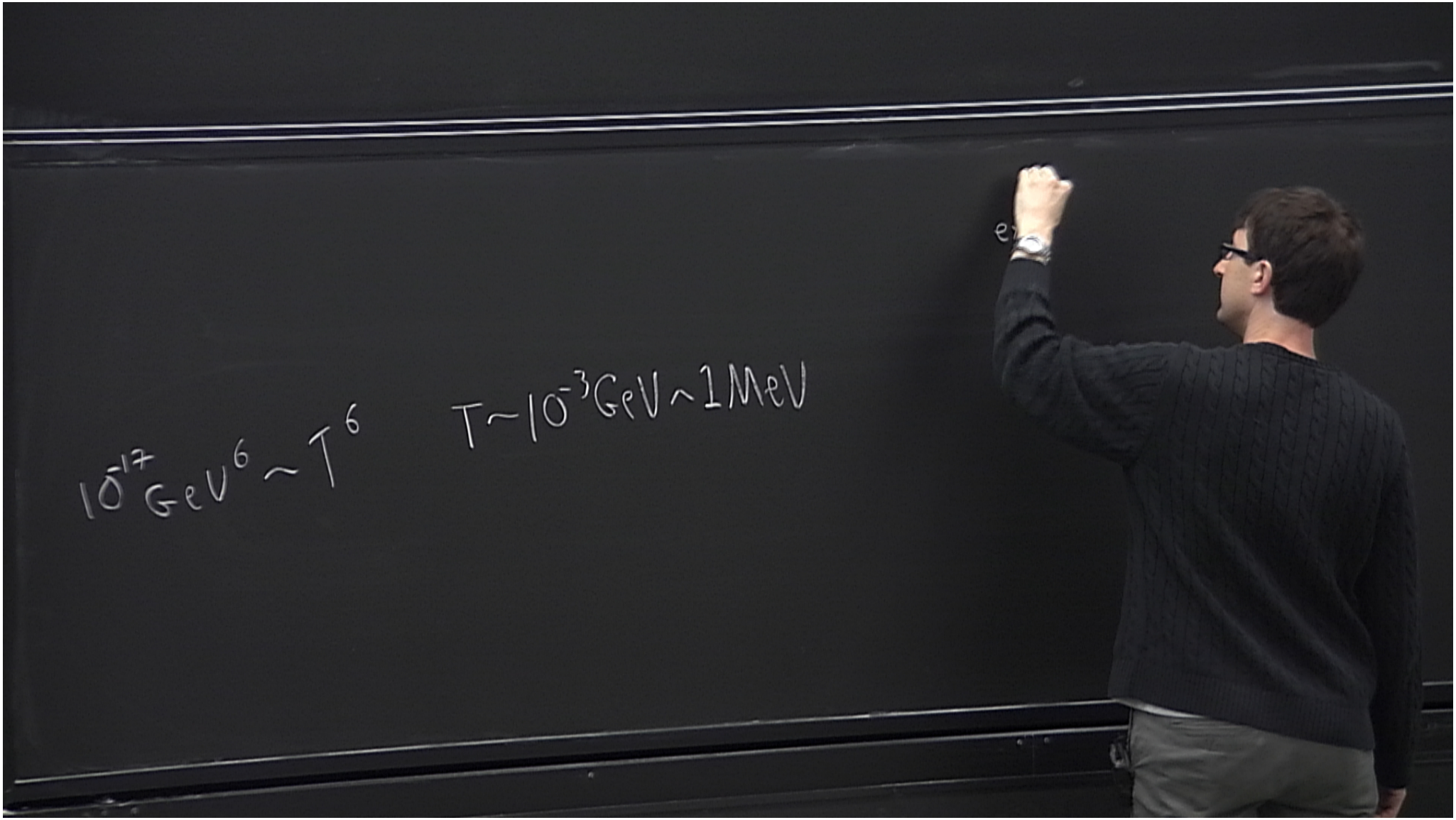
$G_F \sim \frac{q^2}{M_W^2} \sim 10^{-5} GeV^{-2}$

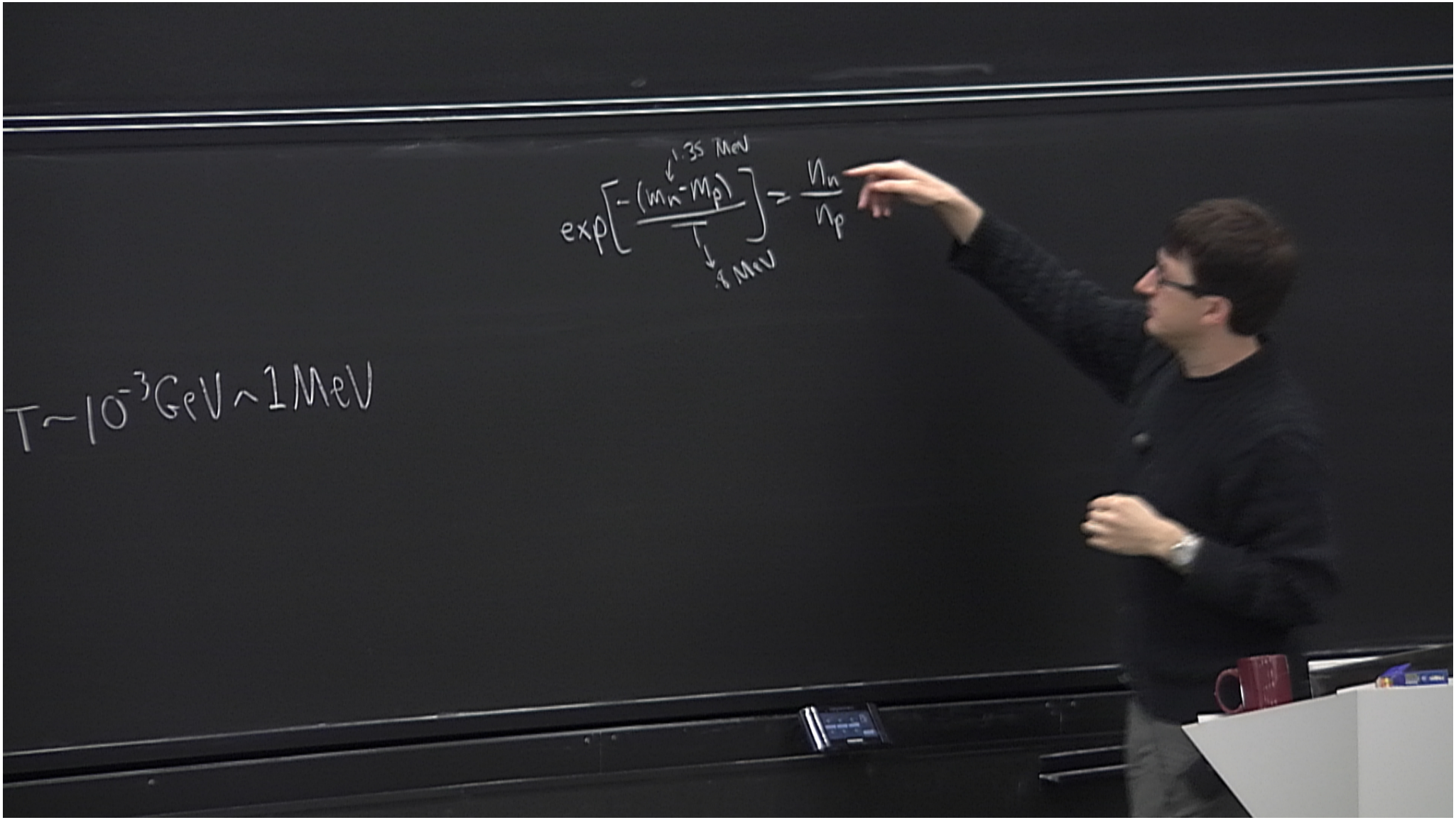
$\Gamma \sim H$

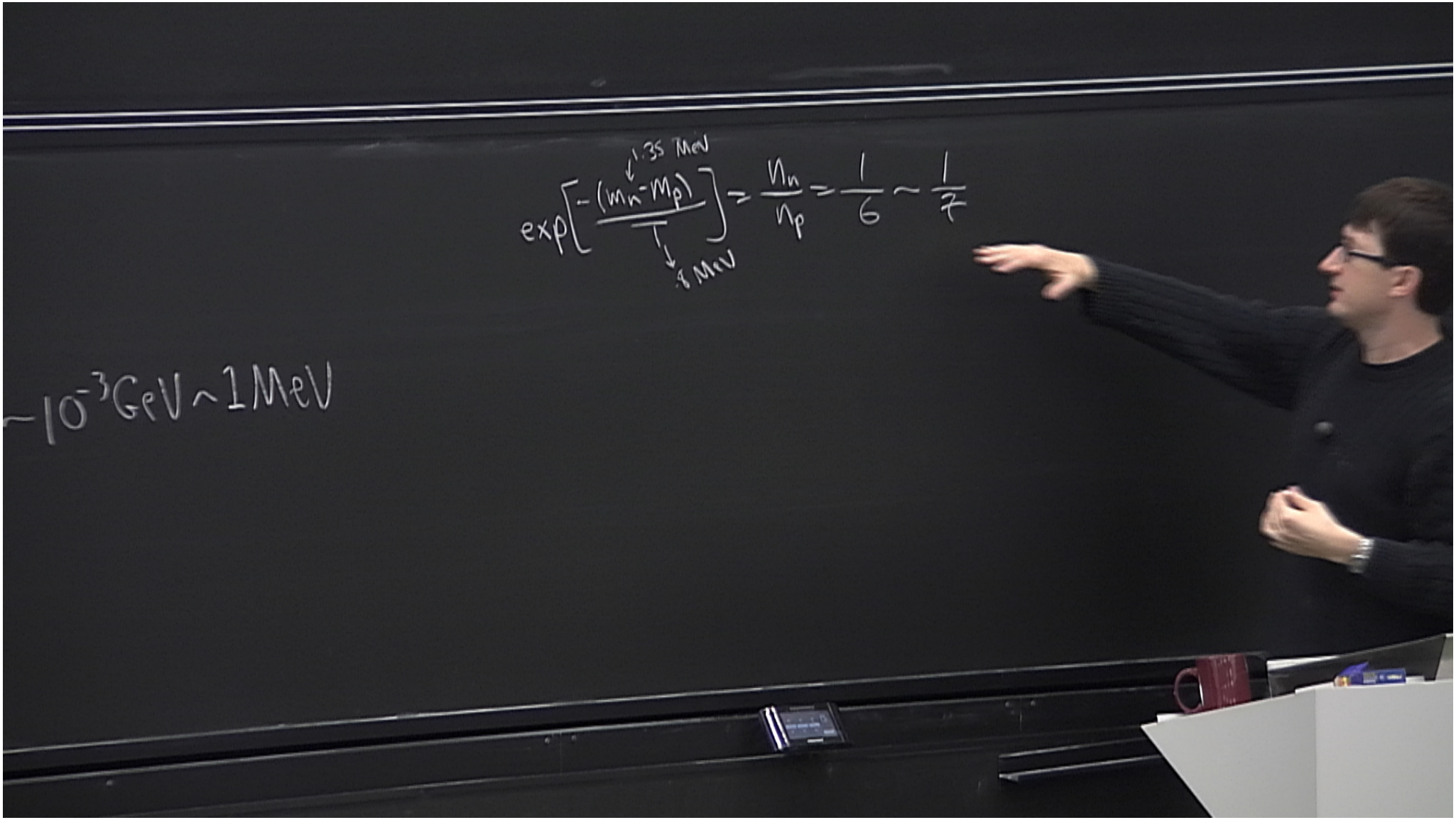
$\Gamma \sim G_F^2 T^5$

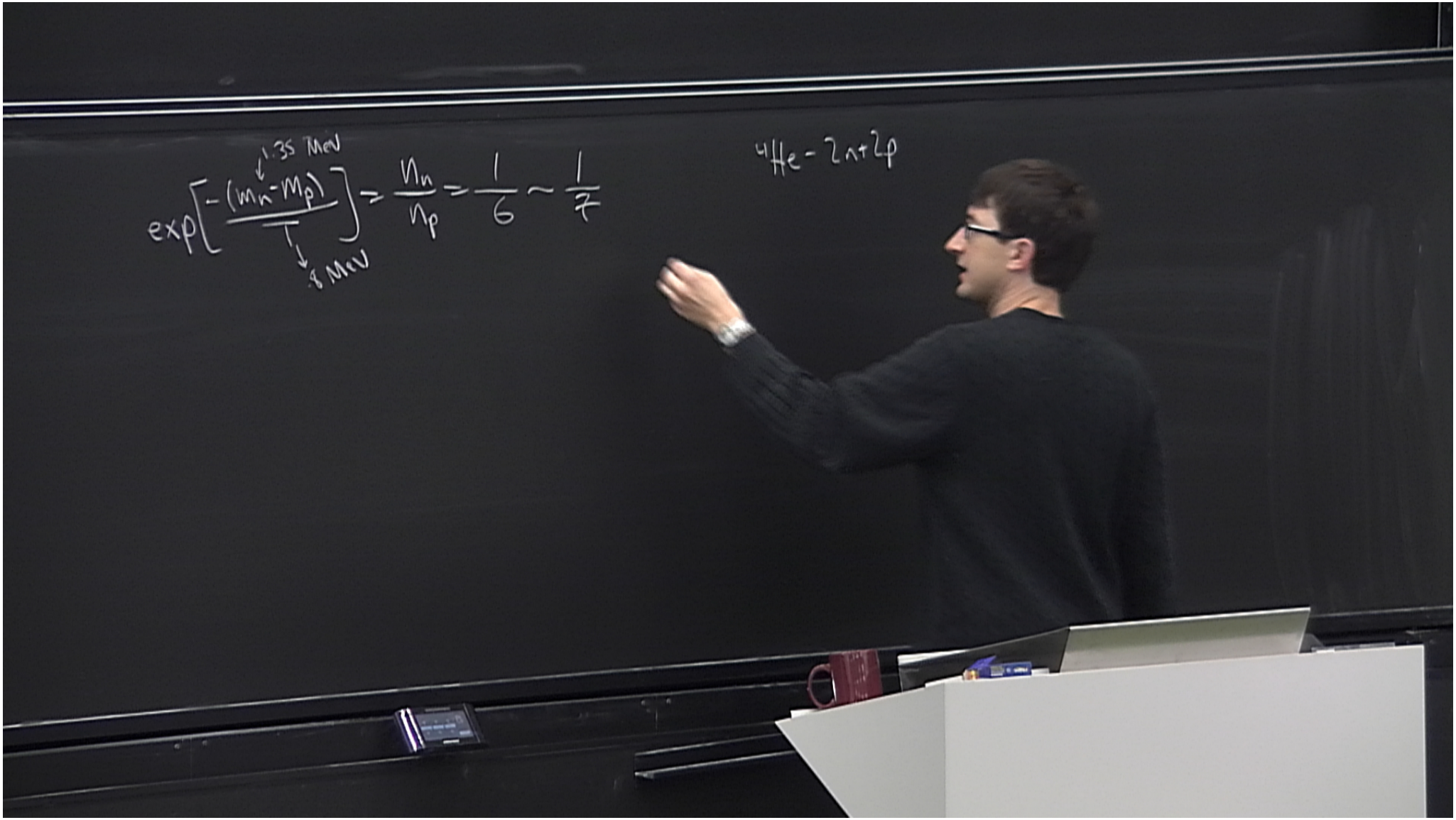

$n \to p + e^- + \bar{\nu}_e$
$n + \bar{p} \to e^- + \bar{\nu}_e$
$H^2 = \frac{8\pi G}{3}\rho$
$G_F \sim \frac{g^2}{M_W^2} \sim 10^{-5}\,\mathrm{GeV}^{-2}$
$\frac{ig^2}{M_W^2} \simeq 10^{-5}\,\mathrm{GeV}^{-2}$
$\Gamma \sim H$
$\Gamma \sim G_F^2 T^5 \sim$
$\exp\left[-\frac{(m_n - m_p)}{T}\right]$
n_p

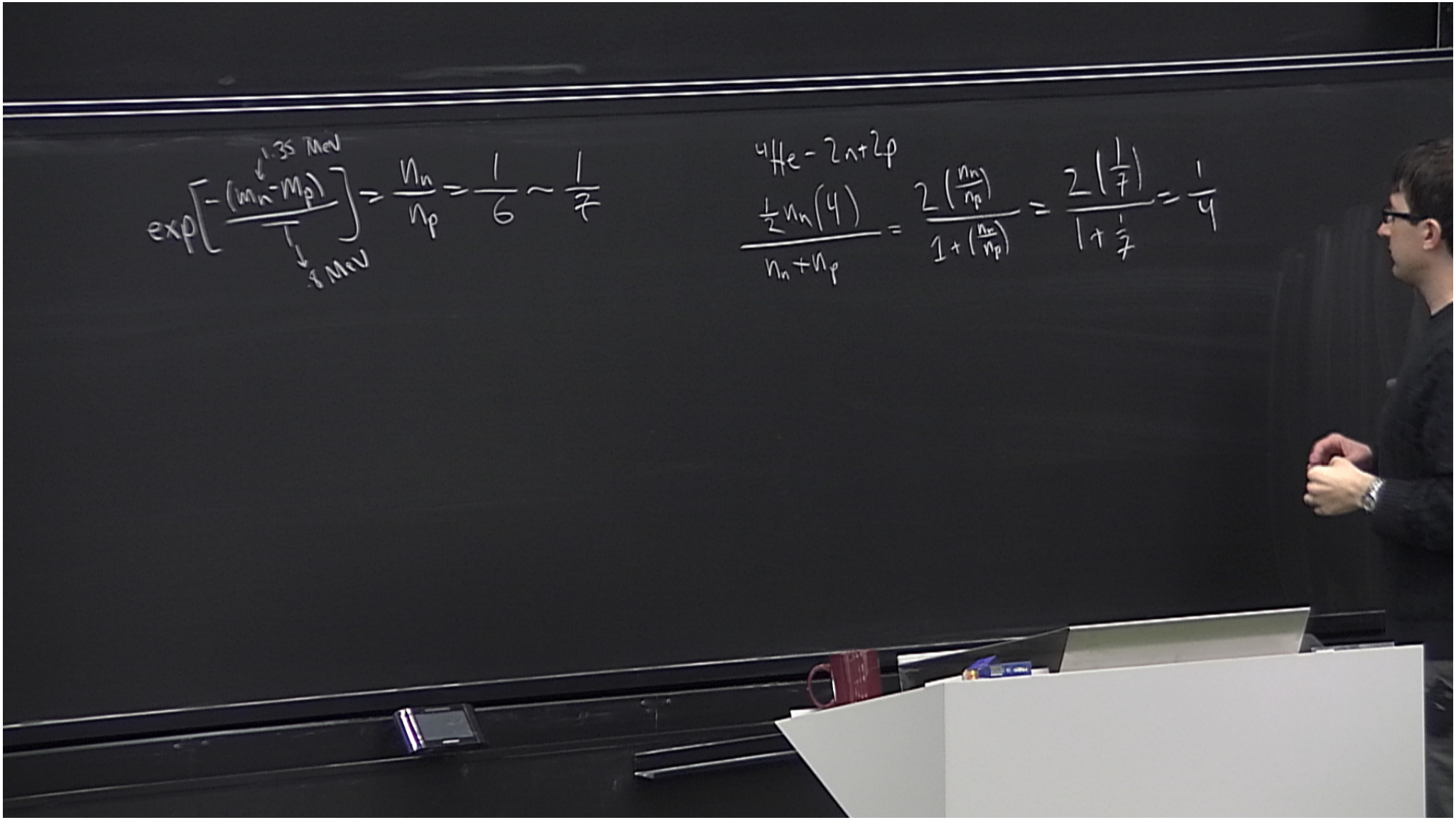

$\eta \sim 10^{-7}$
$\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p}$
$n \to p + e^- + \bar{\nu}_e$
$n + \bar{p} \to e^- + \bar{\nu}_e$
$H^2 = \frac{8\pi G_N}{3}\rho$
G_F
$\frac{iq^2}{M_W^2} \simeq 10^{-5}\,GeV^{-2}$
$G_F \sim \frac{g^2}{M_W^2} \sim 10^{-5}\,GeV^{-2}$
$\Gamma \sim H$
$\Gamma \sim G_F^2 T^5 \sim \sqrt{\frac{8\pi}{3}\frac{1}{m_{pl}^2}\frac{\pi^2}{30}(10)}\,T^4$
$T^6 = \frac{8}{3}\frac{1}{m_{pl}^2}\frac{\pi^2}{30}\,10\,\frac{1}{G_F^4}$
$= 25\,\frac{1}{(10^{19}\,GeV)^2}(10^5\,GeV^2)^4 = GeV$

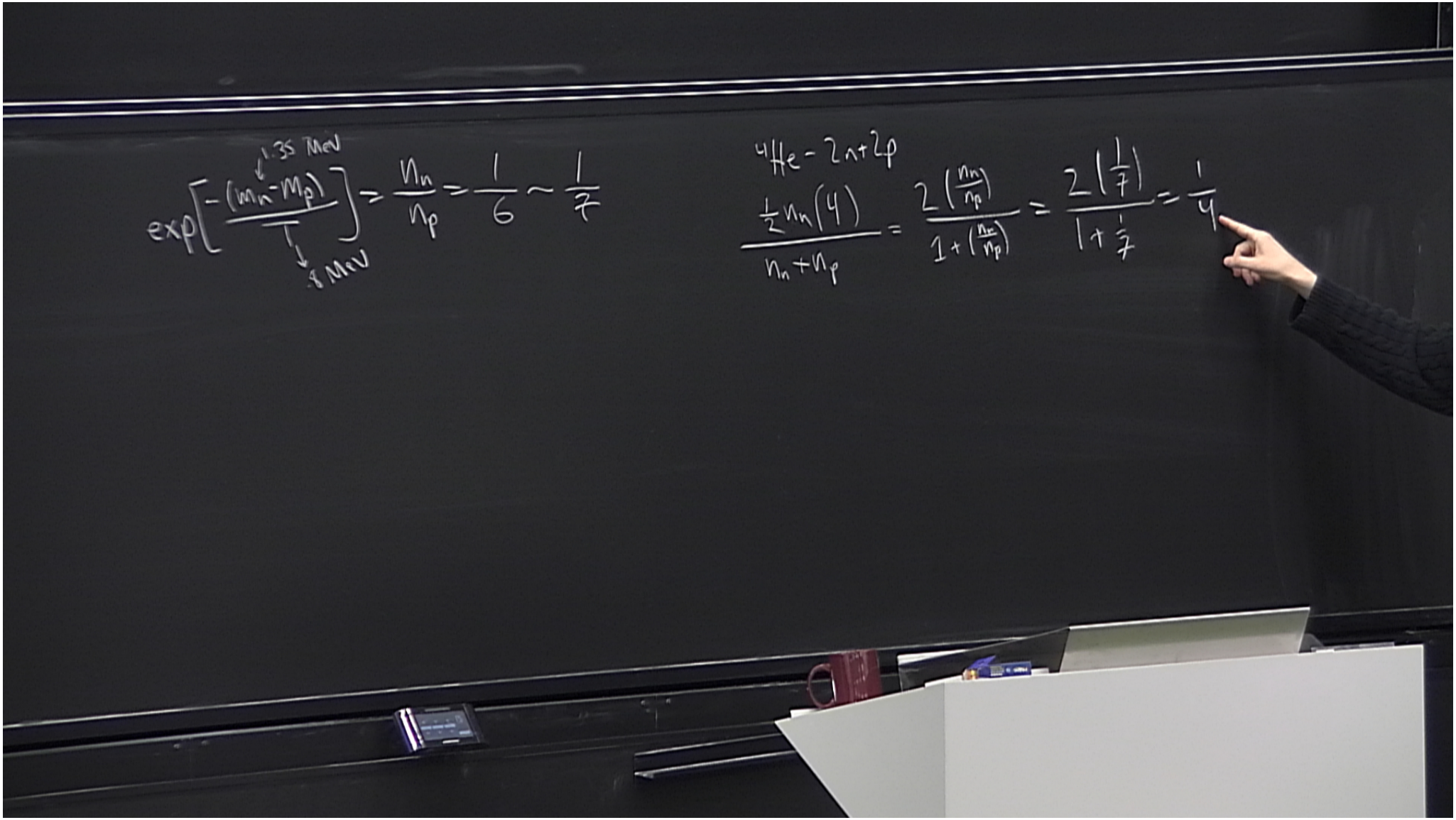

$10^{-17}\,GeV^6 \sim T^6$
$T \sim 10^{-3}\,GeV \sim 1\,MeV$

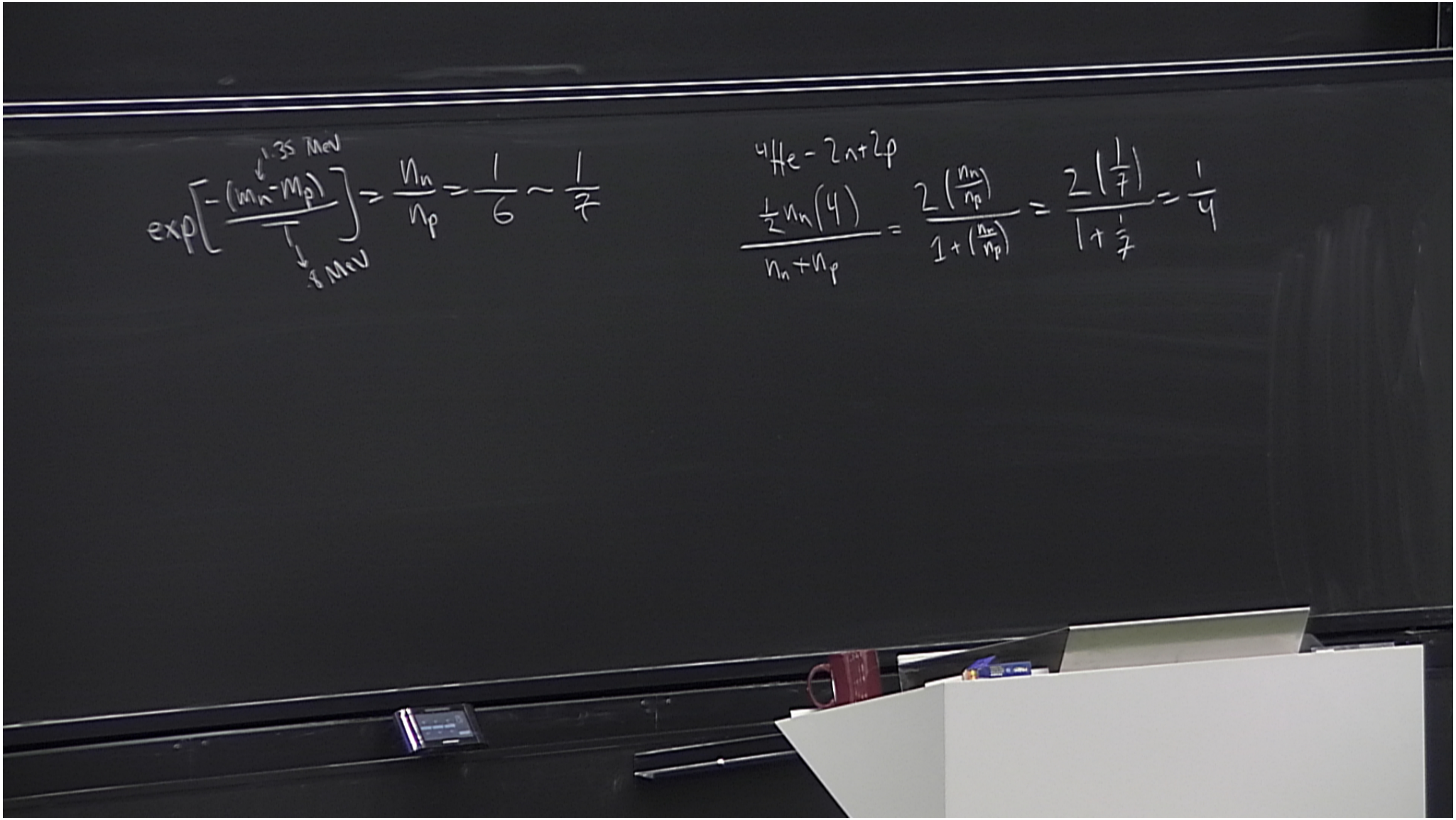

$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p}$
1.35 MeV
1 MeV
$T \sim 10^{-3}\,\mathrm{GeV} \sim 1\,\mathrm{MeV}$


$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p} = \frac{1}{6} \sim \frac{1}{7}$
1.35 MeV
.8 MeV
$\sim 10^{-3}\,\text{GeV} \sim 1\,\text{MeV}$


$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p} = \frac{1}{6} \sim \frac{1}{7}$
1.35 MeV
.8 MeV
$^4He - 2n + 2p$


$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p} = \frac{1}{6} \sim \frac{1}{7}$
1.35 MeV
.8 MeV
$^4He - 2n + 2p$
$\frac{\frac{1}{2} n_n (4)}{n_n + n_p} = \frac{2\left(\frac{n_n}{n_p}\right)}{1 + \left(\frac{n_n}{n_p}\right)} = \frac{2\left(\frac{1}{7}\right)}{1 + \frac{1}{7}} = \frac{1}{4}$


$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p} = \frac{1}{6} \sim \frac{1}{7}$
1.35 MeV
.8 MeV
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$\exp\left[-\frac{(m_n - m_p)}{T}\right] = \frac{n_n}{n_p} = \frac{1}{6} \sim \frac{1}{7}$
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.8 MeV
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$\frac{\frac{1}{2} n_n (4)}{n_n + n_p} = \frac{2\left(\frac{n_n}{n_p}\right)}{1 + \left(\frac{n_n}{n_p}\right)} = \frac{2\left(\frac{1}{7}\right)}{1 + \frac{1}{7}} = \frac{1}{4}$