Title: Cosmology (2021/2022)

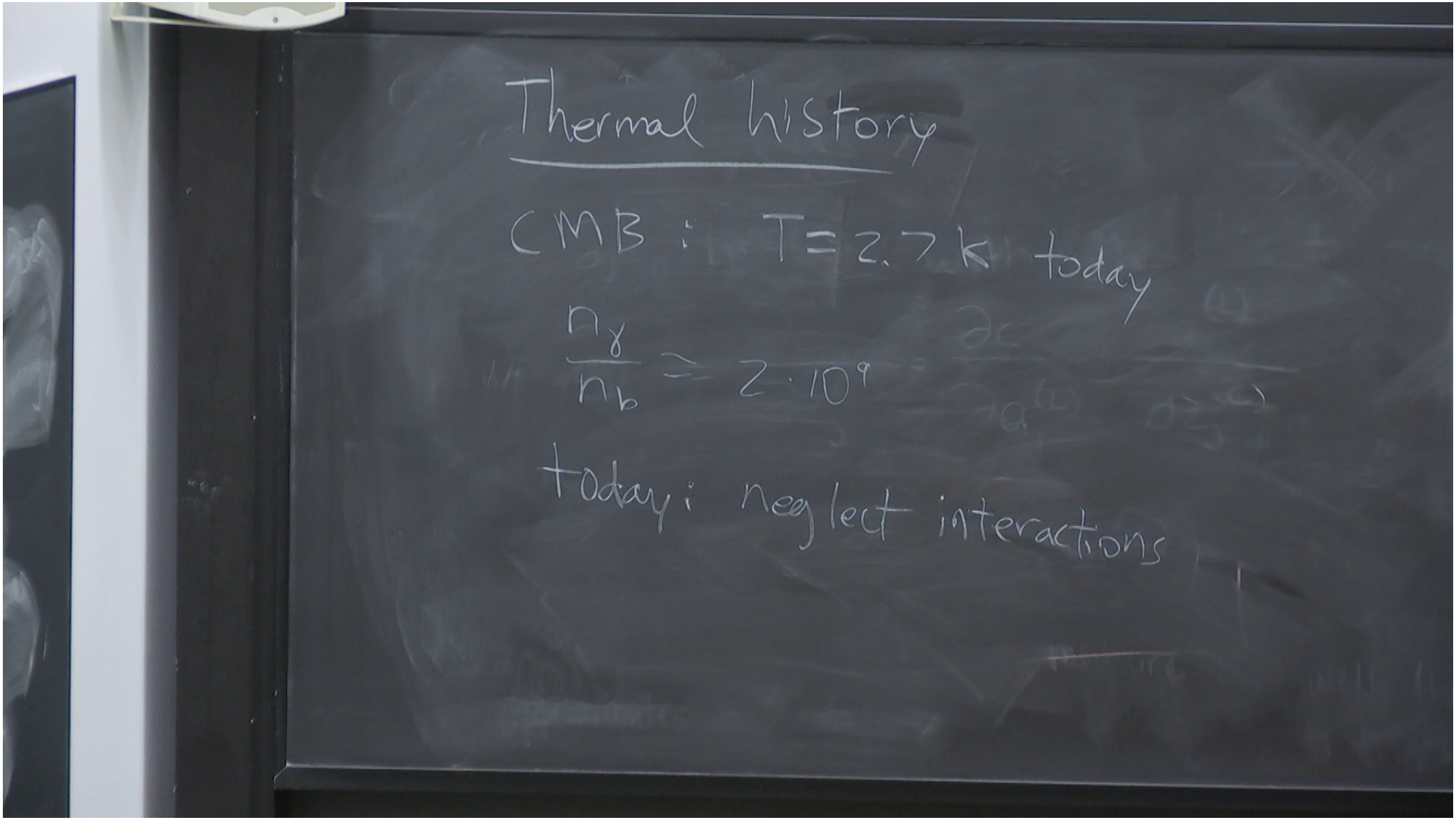
Speakers: Kendrick Smith, Gang Xu

Collection: Cosmology (2021/2022)

Date: April 12, 2022 - 2:30 PM

URL: https://pirsa.org/22040080

Abstract: This class is an introduction to cosmology. We'll cover expansion history of the universe, thermal history, dark matter models, and as much cosmological perturbation theory as time permits.


Thermal history
CMB : T = 2.7 K today
$\frac{n_\gamma}{n_b} \simeq 2 \cdot 10^9$
today: neglect interactions

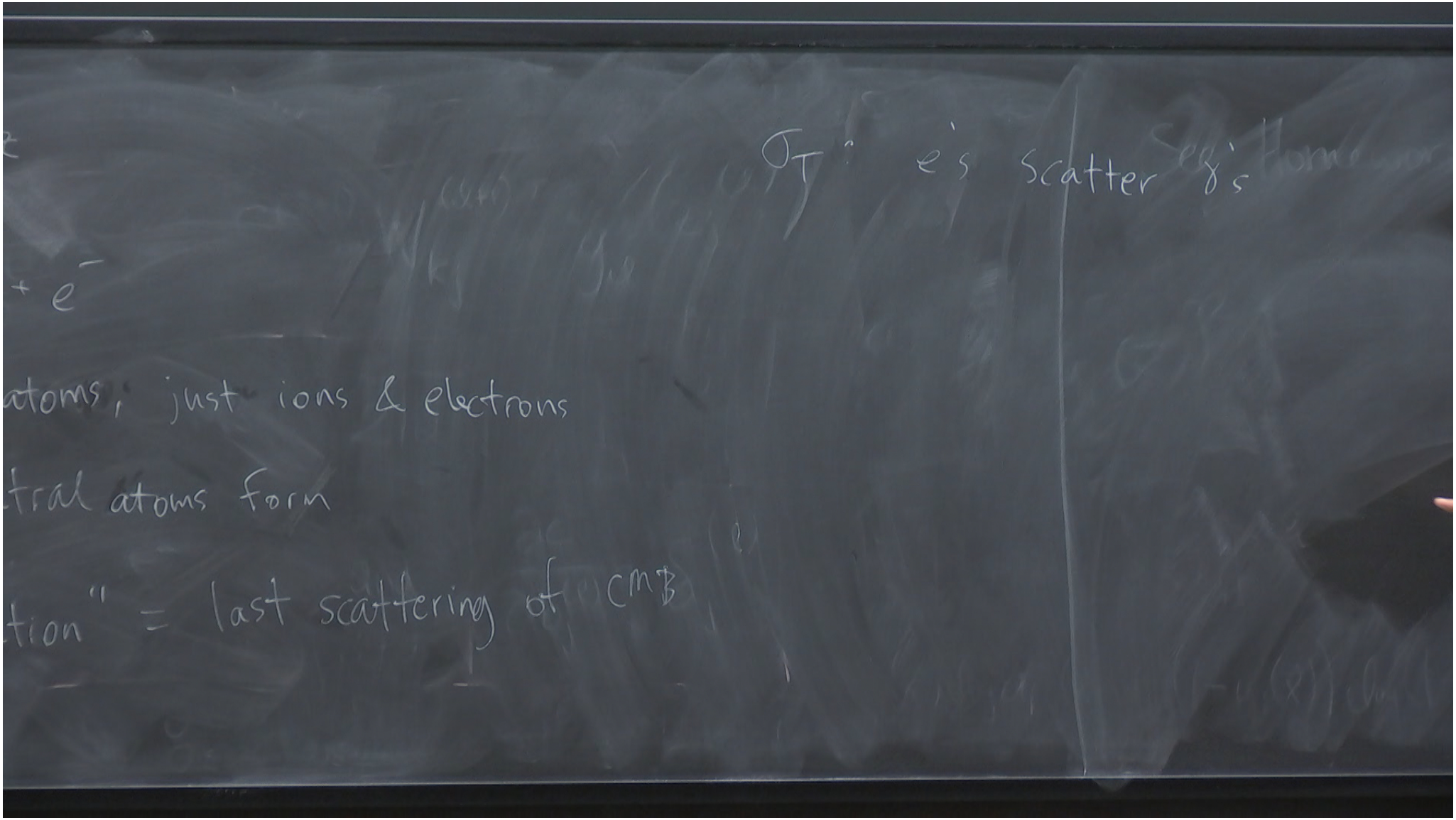
$E_\gamma \propto 1+z$

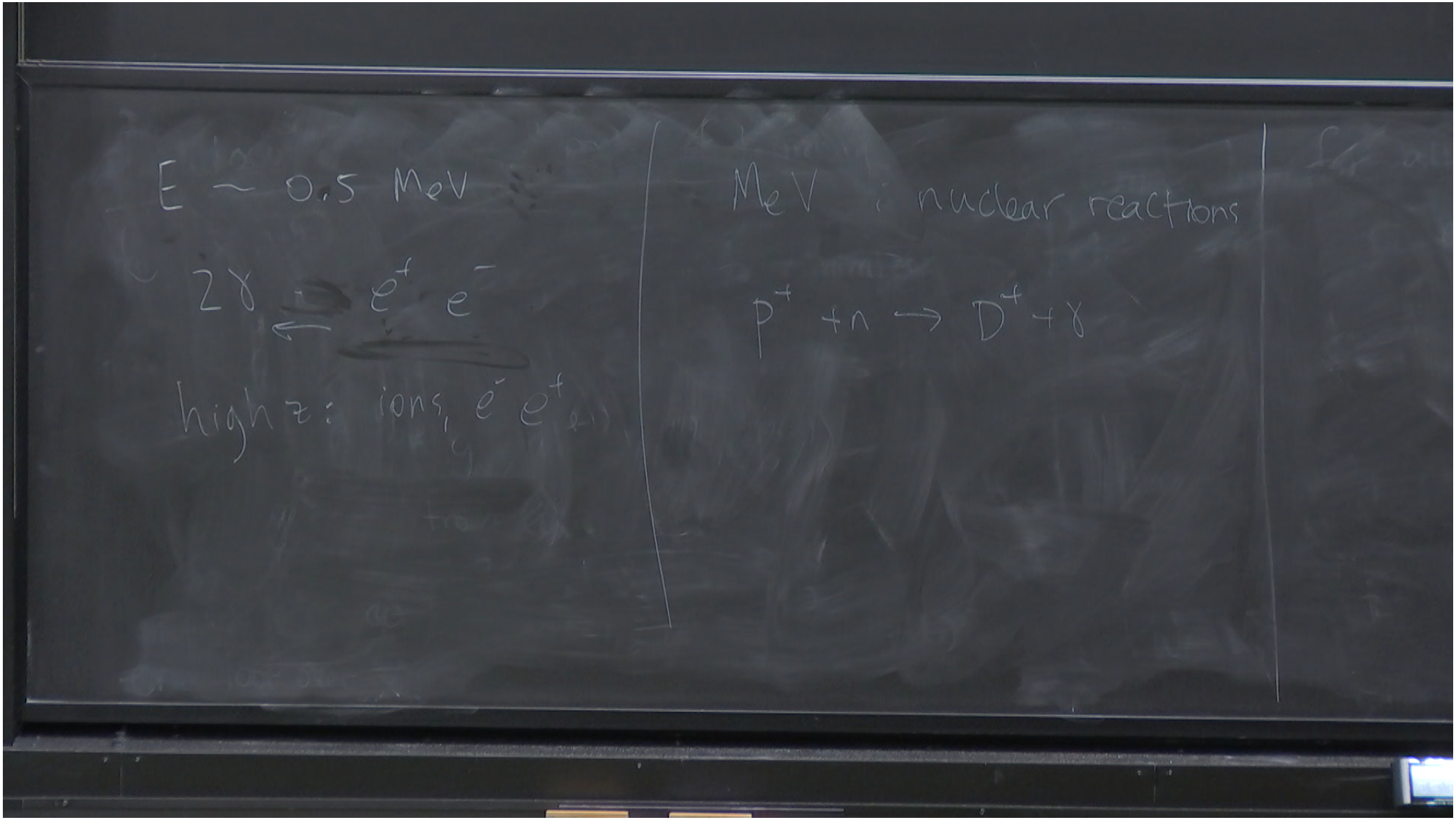
$H + \gamma \rightarrow p^+ + e^-$

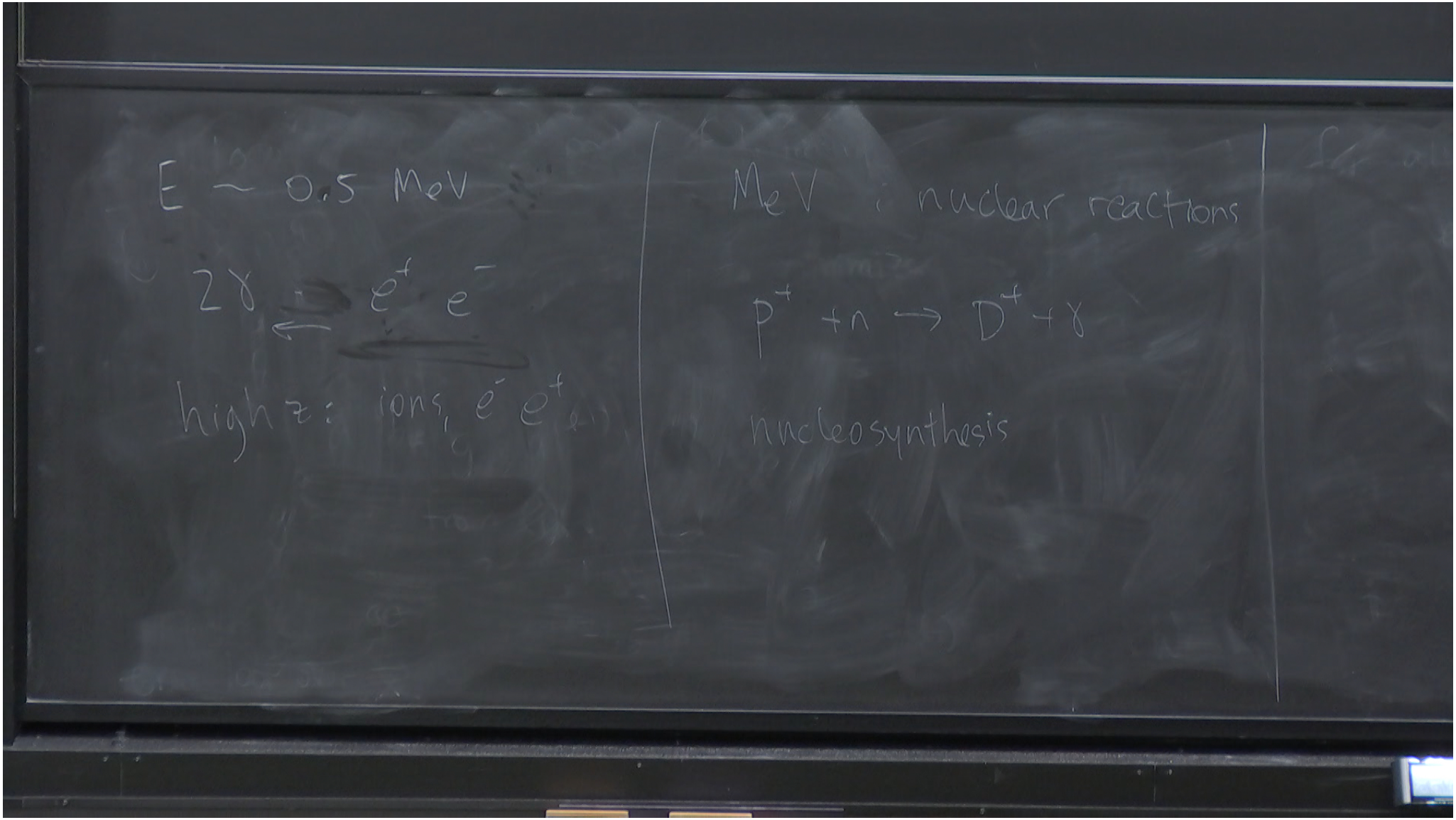
high z: no atoms, just ions & electrons

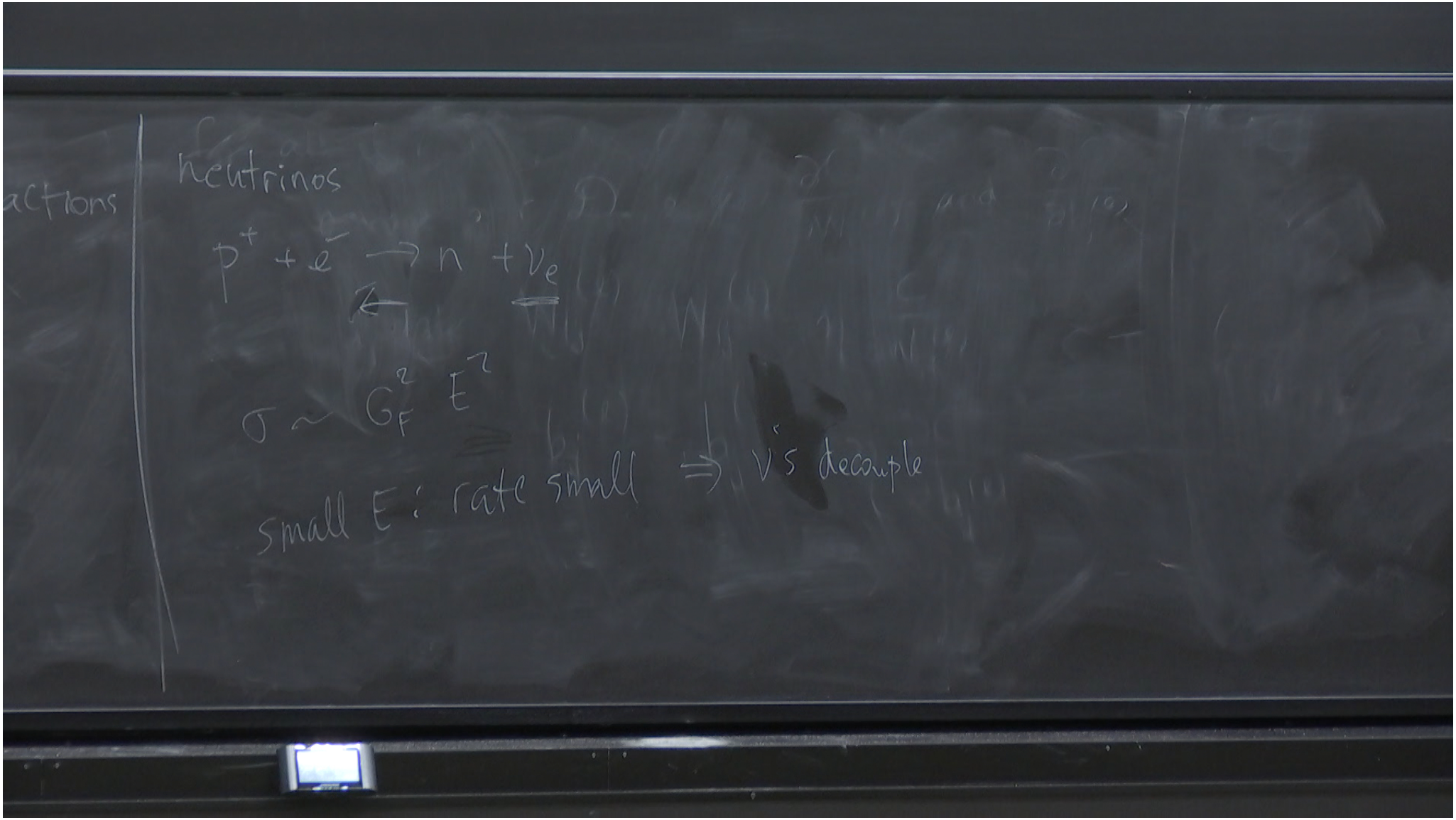
low z: neutral atoms form

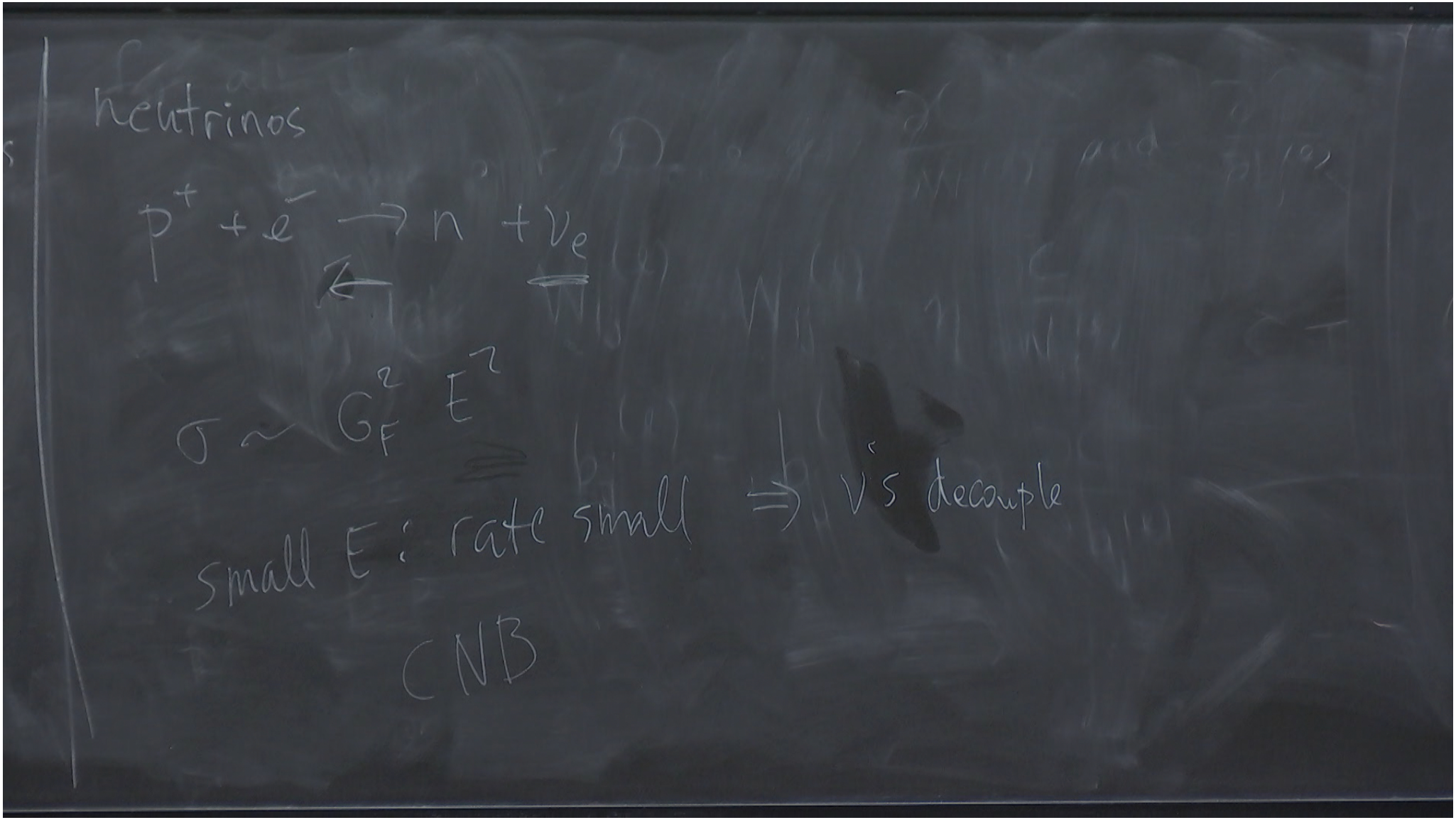
"recombination"


σ_T: e's scatter γ's
$+ e^-$
atoms; just ions & electrons
tral atoms form
tion" = last scattering of CMB


E ~ 0.5 MeV
2γ ⟵ e+ e−
high z: ions, e− e+
MeV : nuclear reactions
p+ + n → D+ + γ


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nucleosynthesis


actions
neutrinos
$p^+ + e^- \rightarrow n + \nu_e$
$\sigma \sim G_F^2 E^2$
small E: rate small $\Rightarrow$ ν's decouple

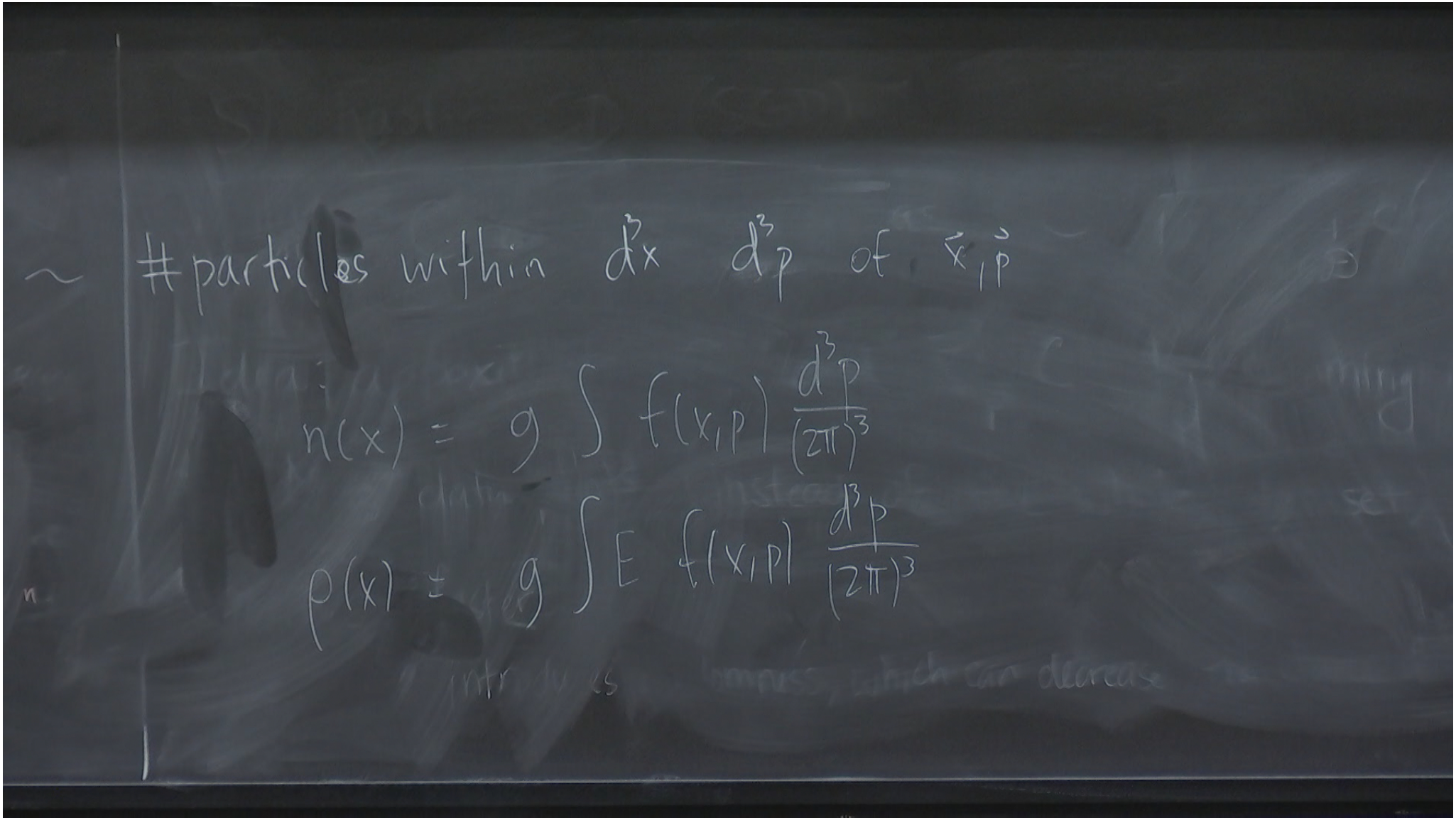

neutrinos
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CNB

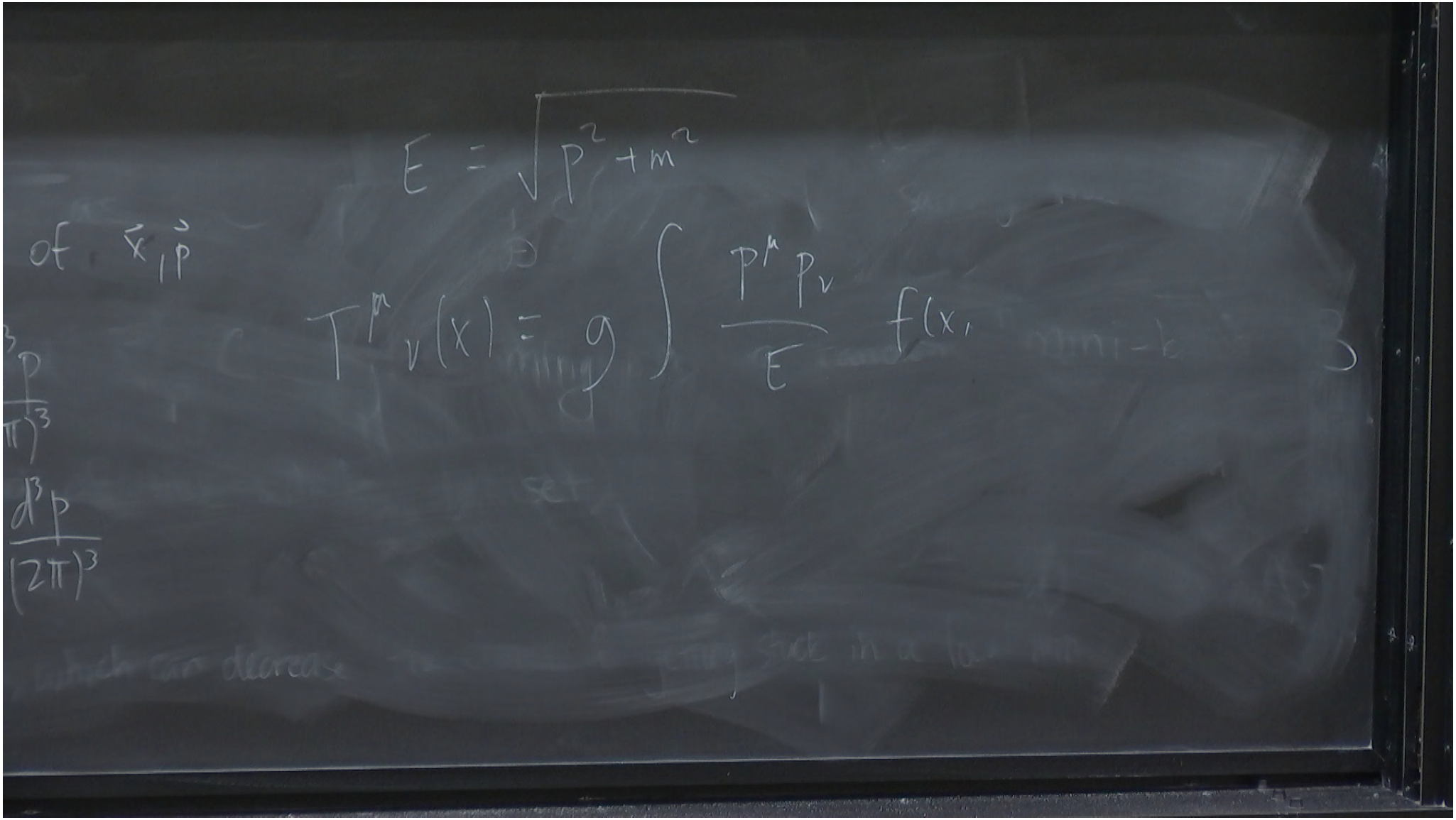
Thermal history

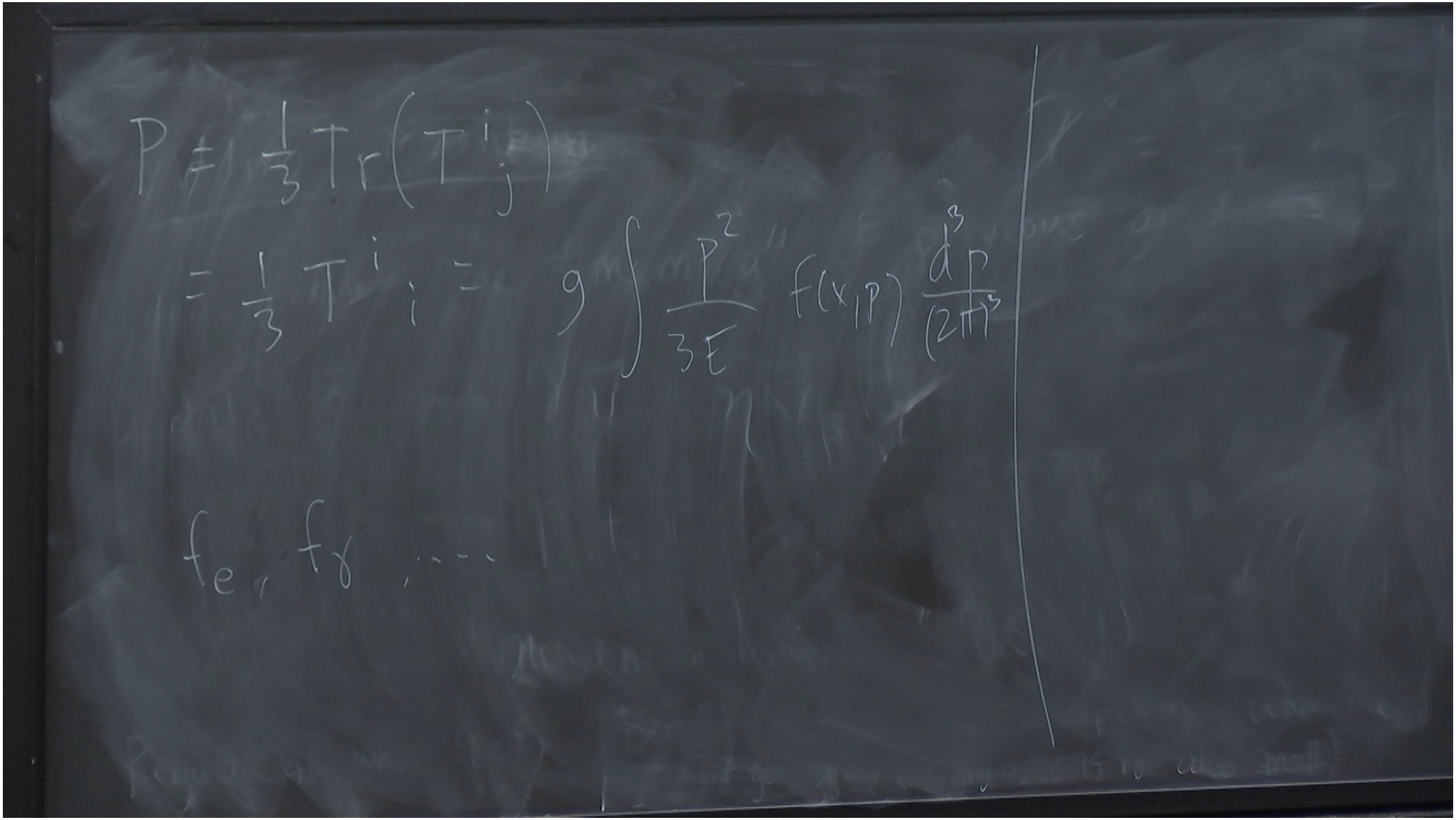
distribution function $f(x, p, t)\,\frac{d^3x\,d^3p}{(2\pi)^3} \sim$

units : $c = \hbar = 1$

$[\text{length}] = [\text{time}] = \frac{1}{[\text{mass}]}$


~ #particles within d^3x d^3p of $\vec{x}, \vec{p}$
$n(x) = g \int f(x,p) \frac{d^3p}{(2\pi)^3}$
$\rho(x) = g \int E f(x,p) \frac{d^3p}{(2\pi)^3}$


$E = \sqrt{p^2 + m^2}$
of $\vec{x}, \vec{p}$
$T^{\mu}{}_{\nu}(x) = g \int \frac{p^{\mu} p_{\nu}}{E} f(x,$
$\frac{d^3p}{(2\pi)^3}$
$\frac{d^3p}{(2\pi)^3}$


$P = \frac{1}{3} Tr(T^i_j)$
$= \frac{1}{3} T^i_i = g \int \frac{p^2}{3E} f(x,p) \frac{d^3p}{(2\pi)^3}$
$f_e, f_\gamma, \ldots$

evolution: Boltzmann eqn.

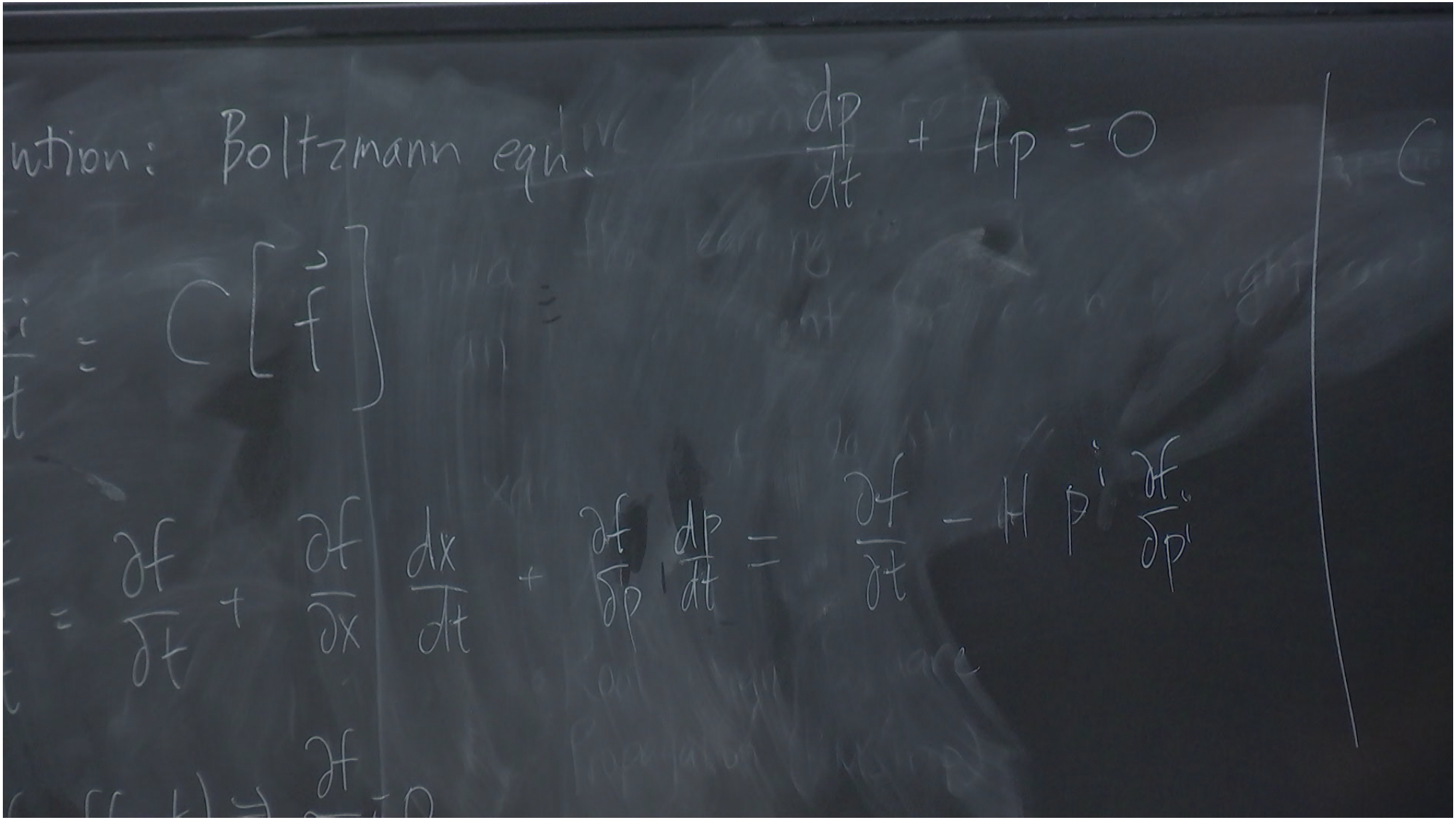
$$\frac{dp}{dt} + Hp =$$

$$\frac{d^3p}{(2\pi)^3}$$

$$\frac{df_i}{dt} = C[\vec{f}]$$

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x}\frac{dx}{dt} + \frac{\partial f}{\partial p}\frac{dp}{dt}$$

$$f = f(p,t) \Rightarrow \frac{\partial f}{\partial x} = 0$$


ution: Boltzmann eqn.
$\frac{dp}{dt} + Hp = 0$
$= C[\vec{f}]$
$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x}\frac{dx}{dt} + \frac{\partial f}{\partial p}\frac{dp}{dt} = \frac{\partial f}{\partial t} - H p \frac{\partial f}{\partial p}$

$$\frac{dp}{dt} + Hp = 0$$

$$\frac{\partial f}{\partial p}\frac{dp}{dt} = \frac{\partial f}{\partial t} - H p^i \frac{\partial f}{\partial p^i}$$

$$C[f] \sim \Gamma f$$

Fast: $\Gamma \gg H$

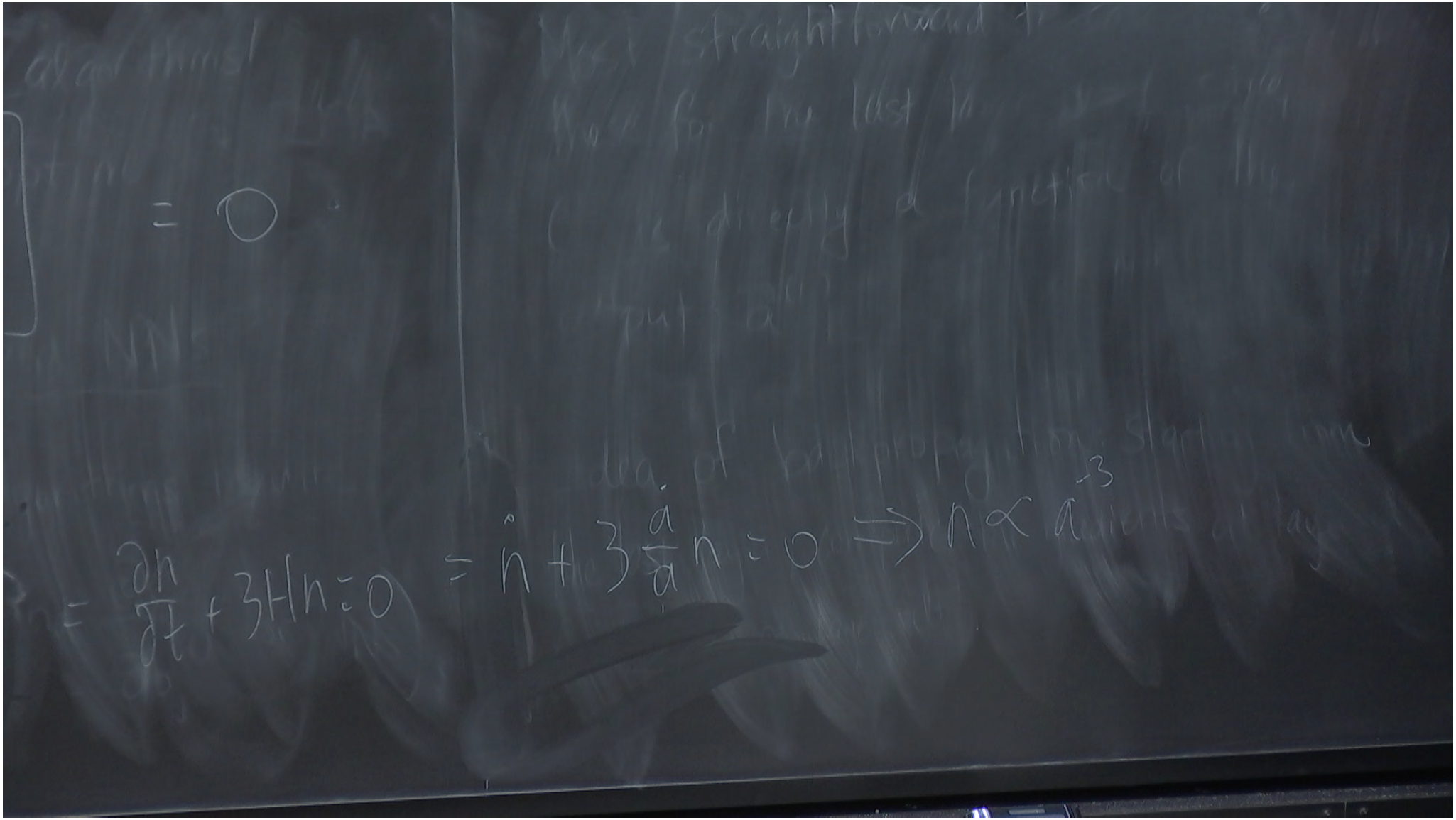
Slow: $\Gamma \ll H$

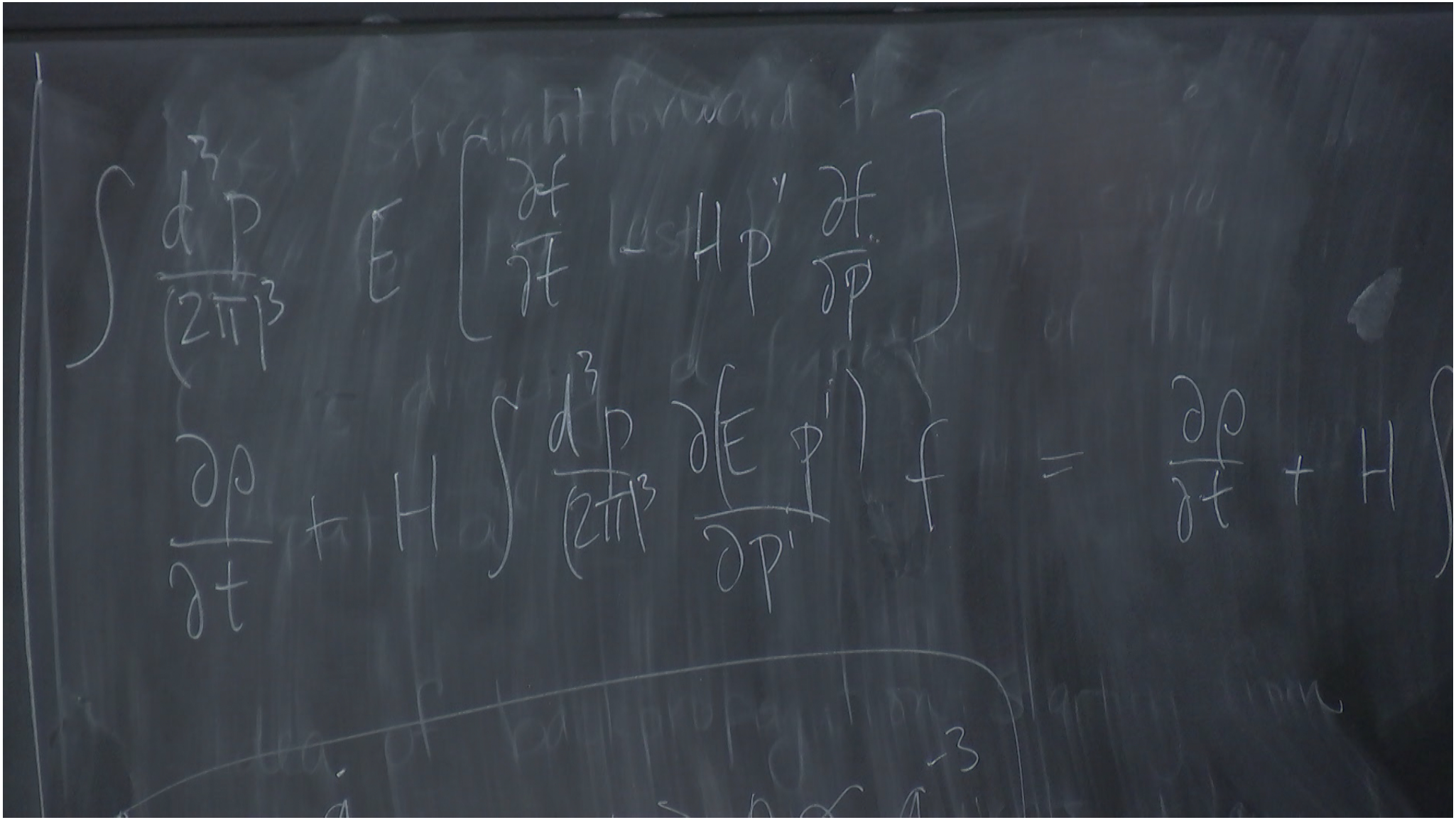
Suppose: $C[f] = 0$

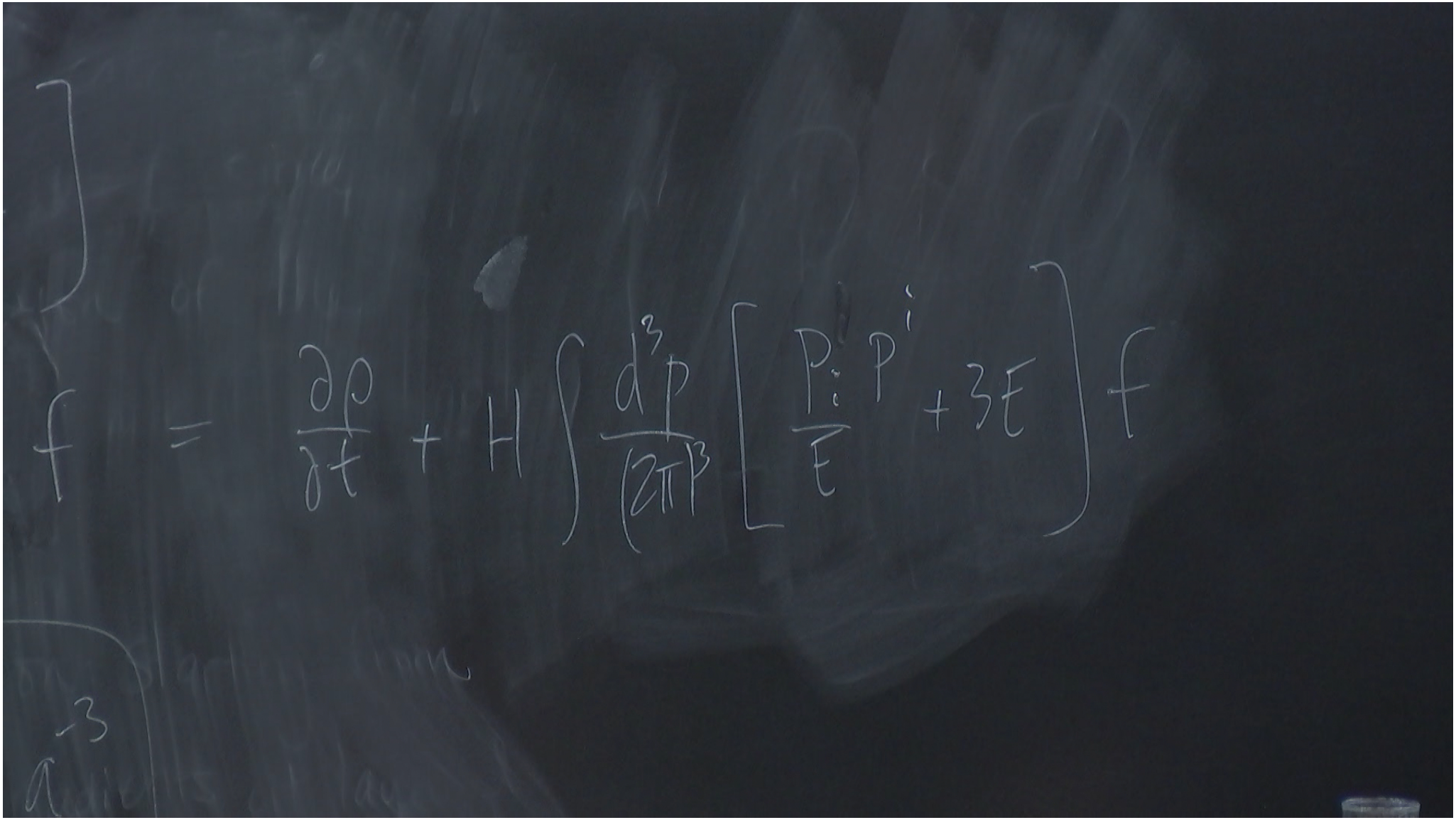
$$\int \frac{d^3p}{(2\pi)^3} \left[\frac{\partial f}{\partial t} - H p^i \frac{\partial f}{\partial p^i} \right] = 0$$

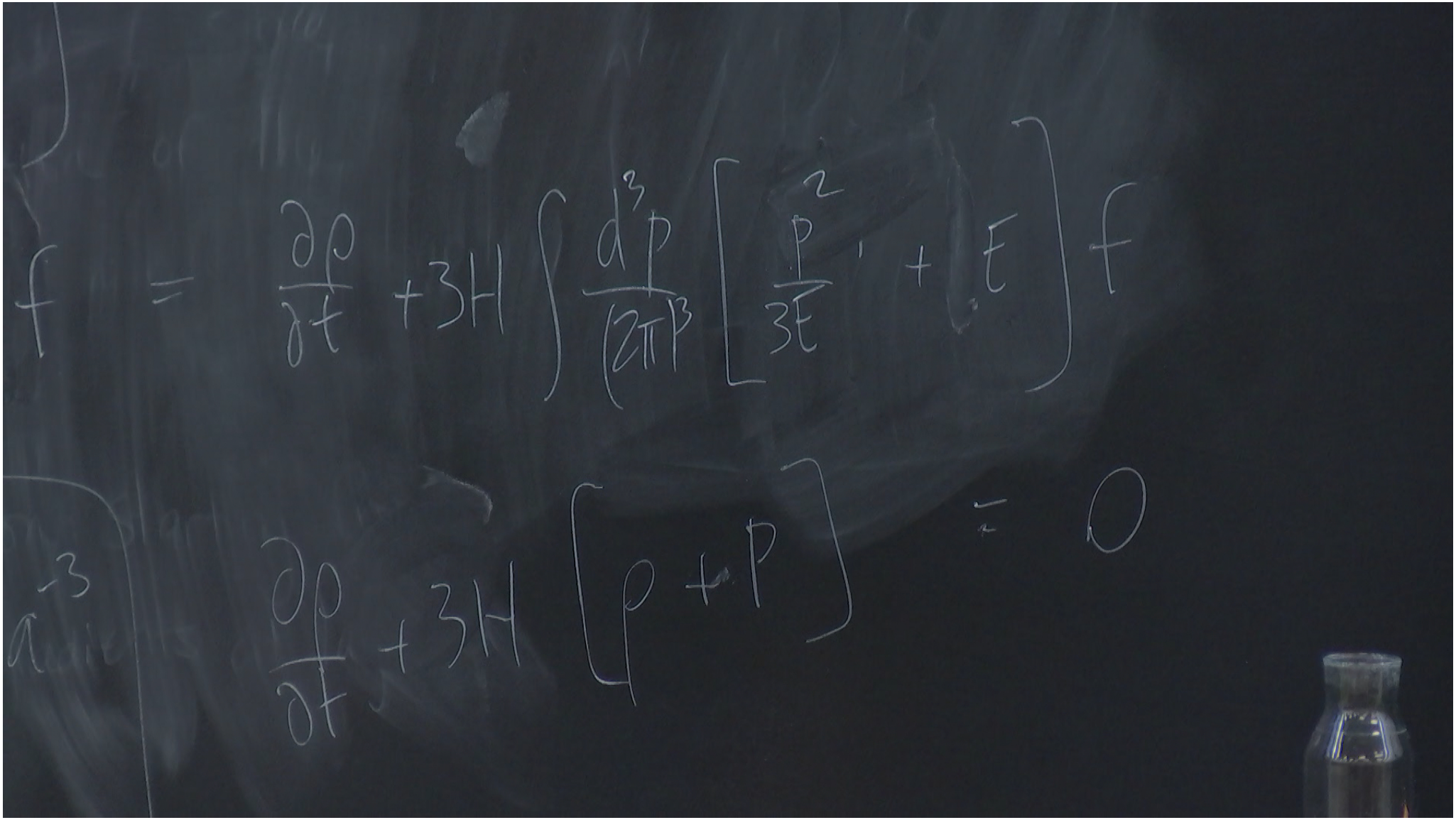
$$\frac{\partial n}{\partial t} - H \int \frac{d^3p}{(2\pi)^3} p^i \frac{\partial f}{\partial p^i}$$

$$\frac{\partial n}{\partial t} + 3H \int \frac{d^3p}{(2\pi)^3} f$$


$= 0$
straight forward
$= \frac{\partial n}{\partial t} + 3Hn = 0 = \dot{n} + 3\frac{\dot{a}}{a}n = 0 \Rightarrow n \propto a^{-3}$

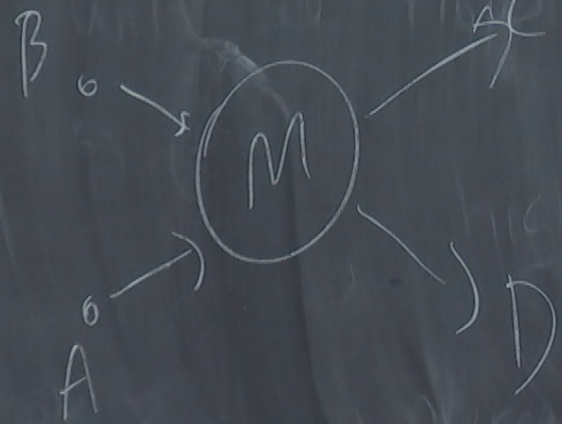

straight forward
$\int \frac{d^3p}{(2\pi)^3} E \left[\frac{\partial f}{\partial t} - Hp \frac{\partial f}{\partial p} \right]$
$\frac{\partial \rho}{\partial t} + H \int \frac{d^3p}{(2\pi)^3} \frac{\partial (E\, p^i)}{\partial p^i} f = \frac{\partial \rho}{\partial t} + H \int$
-3


$f = \frac{\partial \rho}{\partial t} + H \int \frac{d^3p}{(2\pi)^3} \left[\frac{p_i p^i}{E} + 3E \right] f$

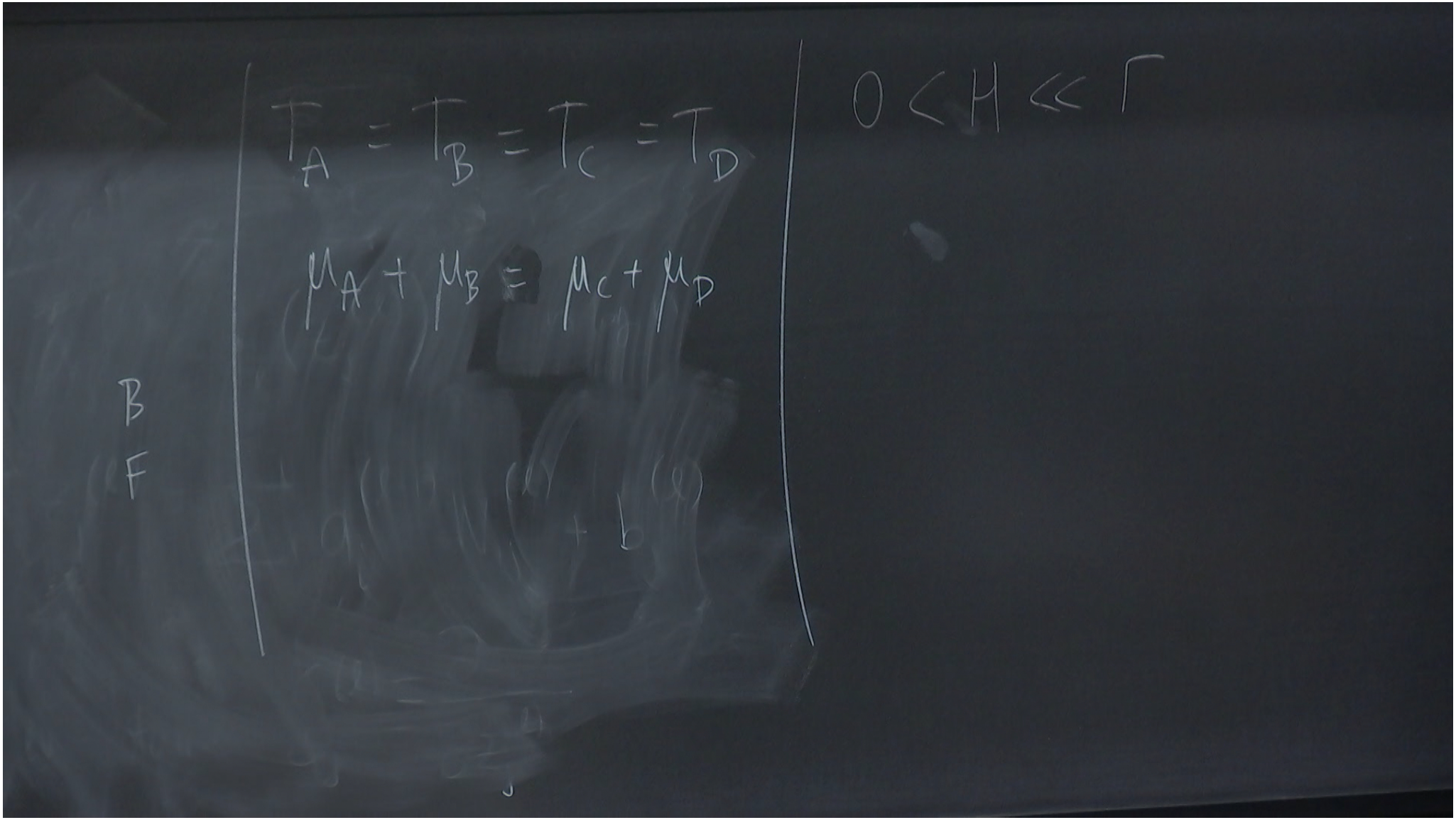

$f = \frac{\partial \rho}{\partial t} + 3H \int \frac{d^3p}{(2\pi)^3} \left[\frac{p^2}{3E} + E \right] f$
$\frac{\partial \rho}{\partial t} + 3H \left[\rho + P \right] = 0$
a^{-3}

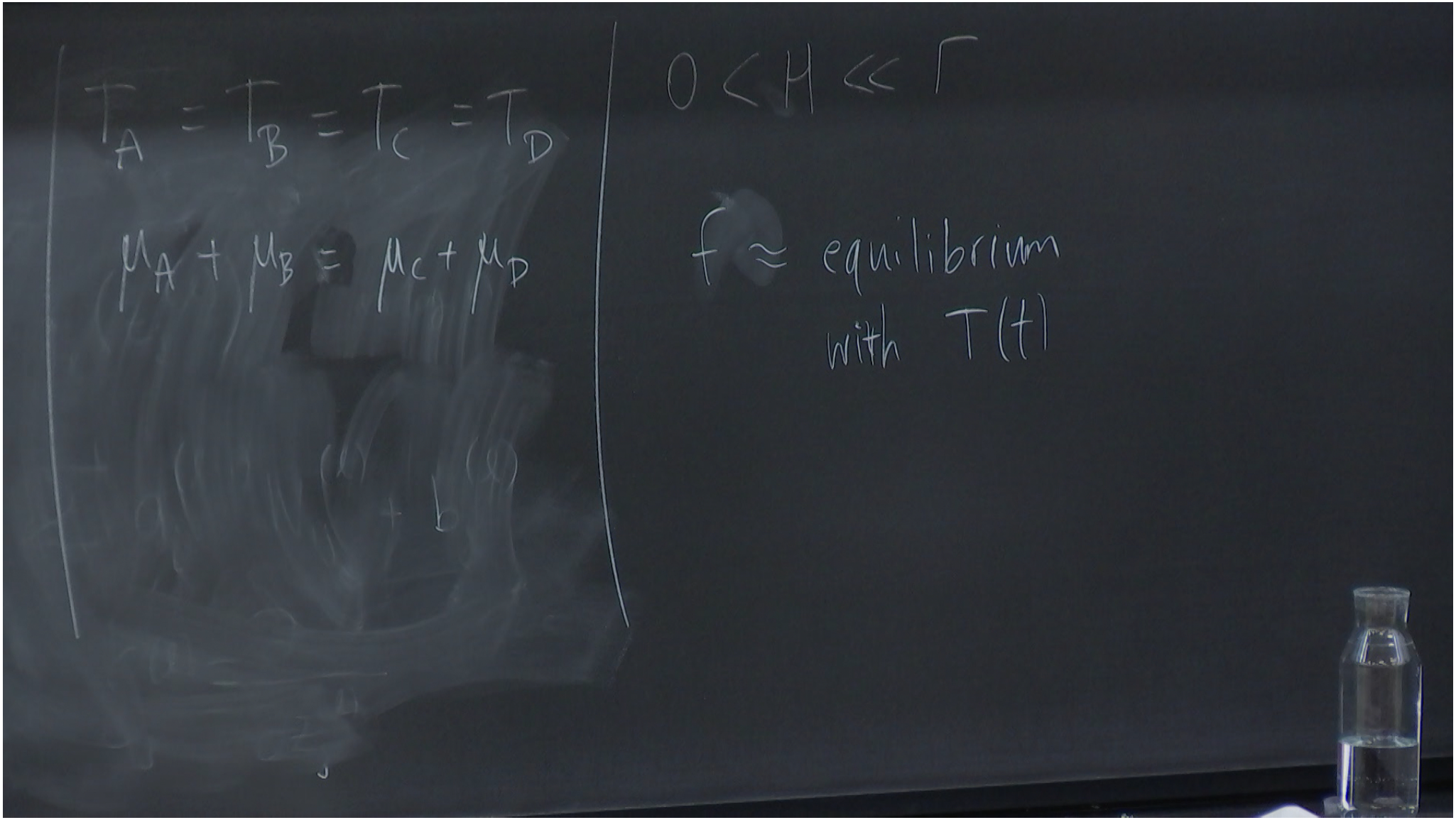
Fast: $\Gamma >> H$

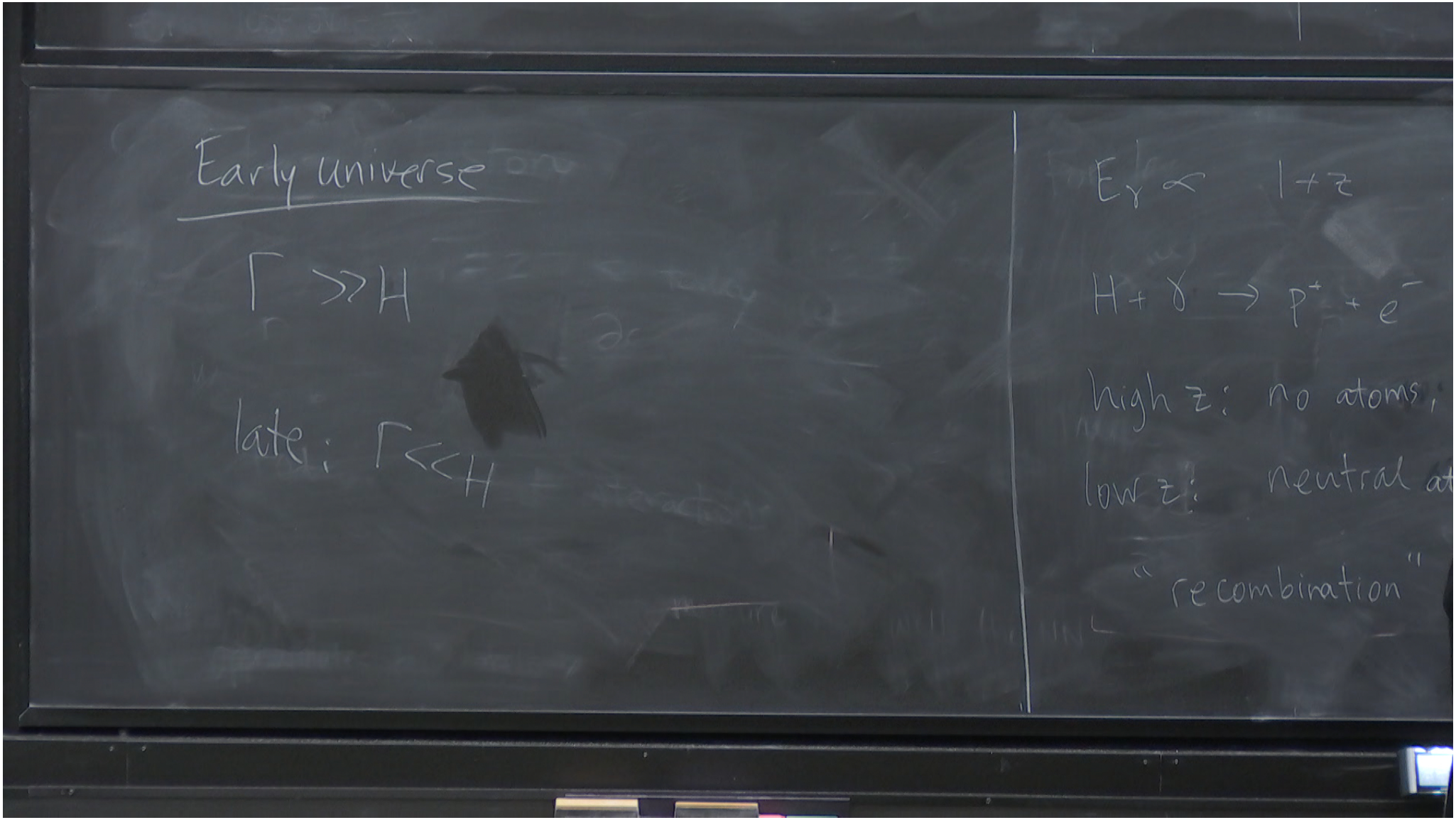
$H = 0$; $f \rightarrow$ equilibrium



$$f(p) = \frac{1}{e^{(E-\mu)/T} \mp 1}$$


$T_A = T_B = T_C = T_D$
$\mu_A + \mu_B = \mu_C + \mu_D$
$0 < H \ll \Gamma$
B
F


$T_A = T_B = T_C = T_D$
$\mu_A + \mu_B = \mu_C + \mu_D$
$0 < H \ll \Gamma$
$f \approx$ equilibrium with $T(t)$


Early universe
$\Gamma \gg H$
late: $\Gamma \ll H$
$E_\gamma \propto 1+z$
$H + \gamma \rightarrow p^+ + e^-$
high z: no atoms;
low z: neutral at
"recombination"