Title: Lecture - Cosmology, PHYS 621

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Subject: Cosmology

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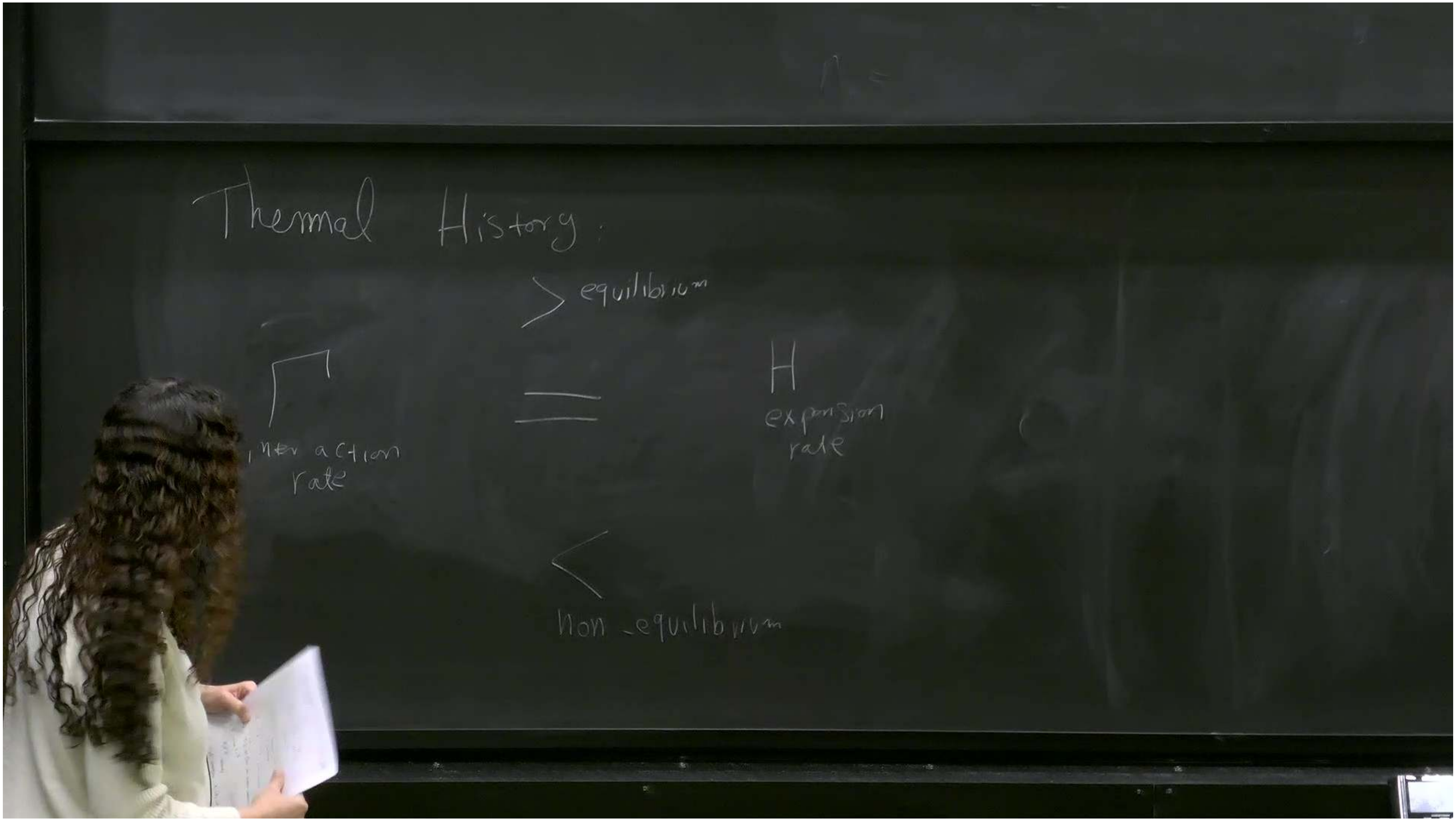
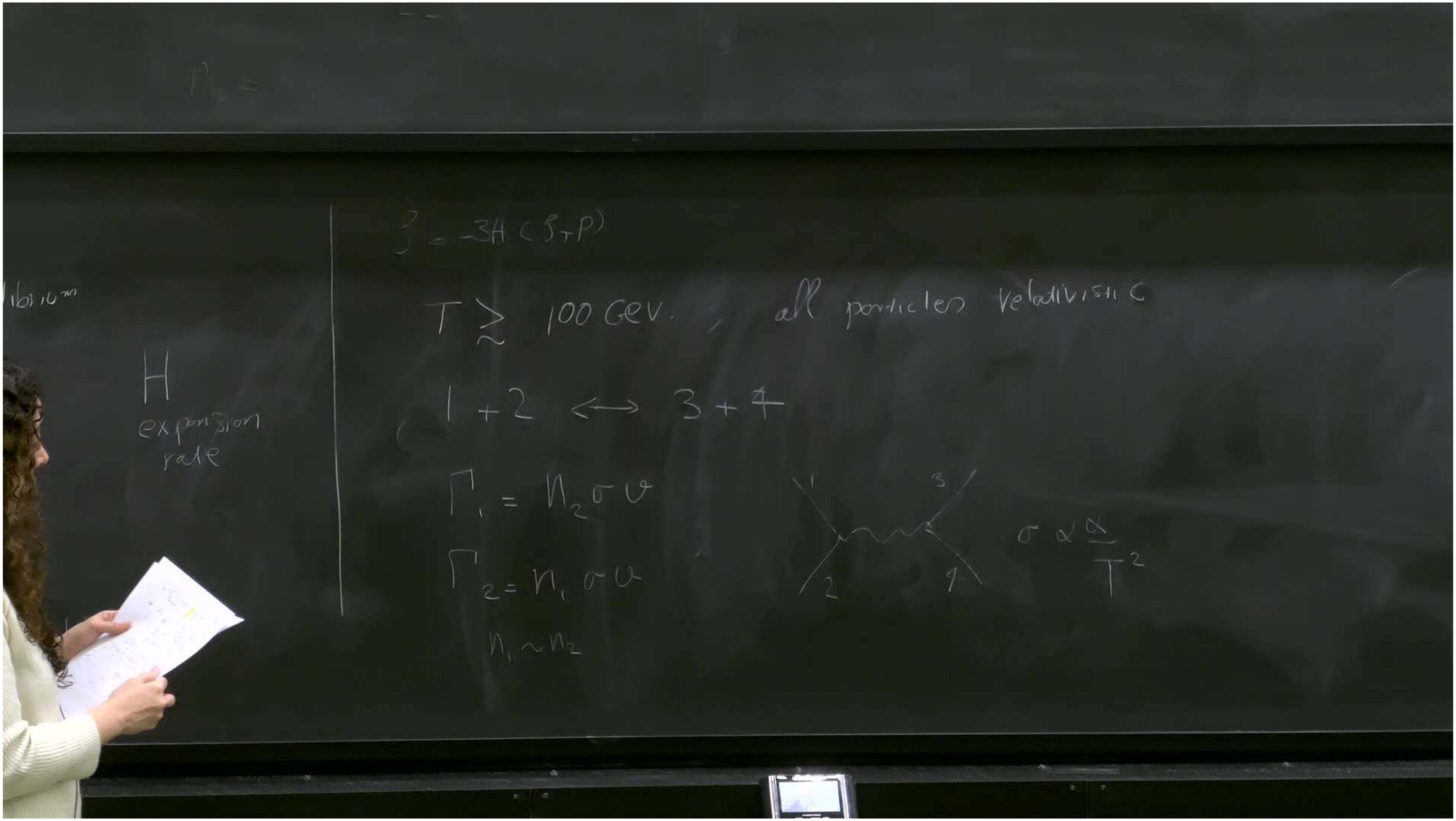
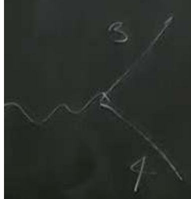

Thermal History:
> equilibrium
Γ
interaction rate
=
H
expansion rate
<
non-equilibrium


$\dot{\rho} = -3H(\rho + P)$
librium
H
expansion rate
$T \gtrsim 100$ GeV, all particles relativistic
$1 + 2 \longleftrightarrow 3 + 4$
$\Gamma_1 = n_2 \sigma v$
$\Gamma_2 = n_1 \sigma v$
$n_1 \sim n_2$
1
3
2
4
$\sigma \propto \frac{\alpha}{T^2}$

particles relativistic

$$\Gamma_{ew/strong} \sim T^3 \times \frac{\alpha^2}{T^2} \sim \alpha^2 T$$

$$H^2 = \frac{1}{3M_p^2}\rho_r \sim \frac{T^4}{3M_p^2} \qquad (k_B = 1)$$



$$\sigma \propto \frac{\alpha^2}{T^2}$$

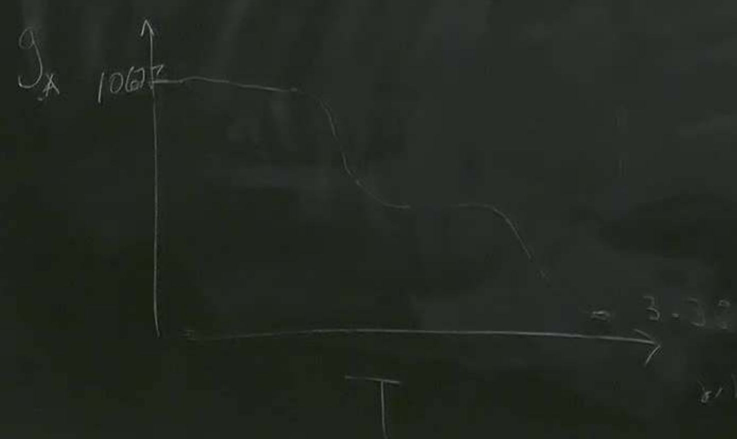
$$H \sim T^2 / M_p$$

$$\Gamma / H \sim \alpha^2 \frac{M_p}{T} \sim \frac{10^{16}\,\text{GeV}}{T}$$

$\propto T^3$

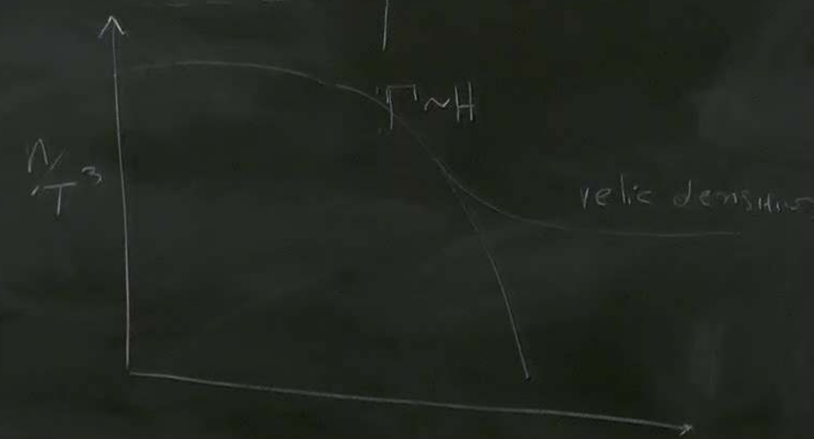
eq: $100_{\text{GeV}} < T < 10^{15}\,\text{GeV}$

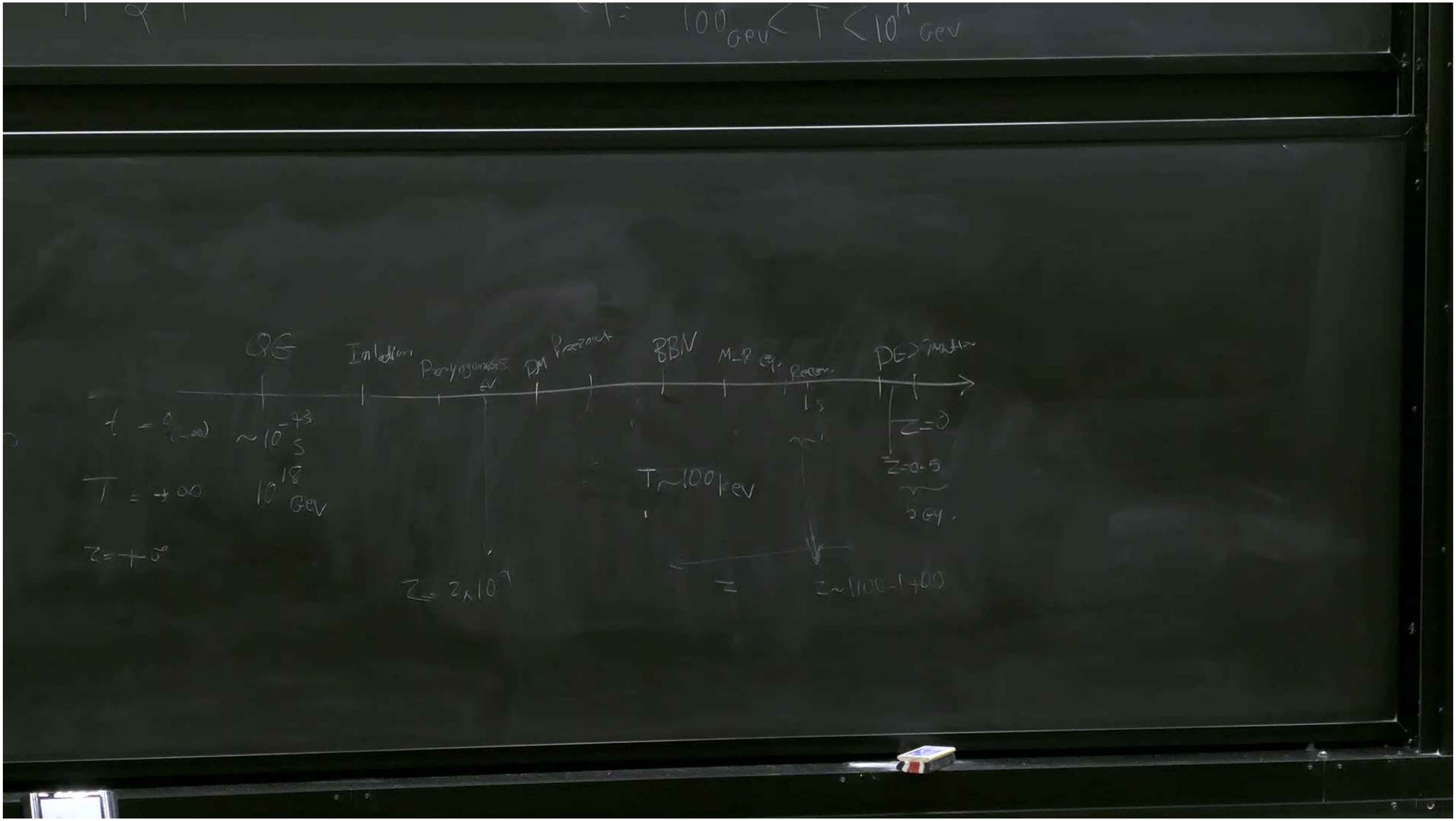
$$\rho_r = \frac{\pi^2}{30} g_*(T)\, T^4$$



relativistic | non-relativistic

$T \gg m$ | $T \ll m$




100 GeV < T < 10^17 GeV
QG
Inflation
Baryogenesis
DM Freezeout
BBN
M-R eq.
Recom.
DE > matter
~10^-43 s
10^18 GeV
T ~ 100 keV
Z = 2x10^9
z ~ 1100-1400
z = 0
z = 0.5

$\Delta x \Delta p > h$

$(\Delta x \Delta p)^3_{min} = h^3$

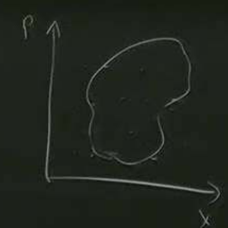
$N =$ phase space # states $= \frac{VP}{h^3}$

$(\vec{x}, \vec{p})$

$n_p = \frac{N}{P} = \frac{V}{h^3} = \frac{L^3}{h^3}$

$n_{p.s} = \frac{N}{PV} = 1/h^3$

g. internal D.O.F.



density of states: $\frac{g}{h^3} = \frac{g}{(2\pi)^3}$

$\hbar = h/2\pi = 1$

$n = \frac{g}{(2\pi)^3} \int_p f_{(p)} d^3 p$

distribution function $f(\cancel{x}, \vec{p}, \cancel{t}) = f(p)$

$|\vec{p}|$

$\int dx^3 dp^3 \; f_{(\;)} \; E(\vec{p}, \vec{x}, t)$

$\rho = \frac{g}{(2\pi)^3} \int d^3 p \; f(p) E(p)$

P

density of states: $\frac{g}{h^3} \underset{\hbar = h/2\pi = 1}{=} g/(2\pi)^3$

distribution function $f(\cancel{x}, \vec{p}, \cancel{t}) = f(p)$

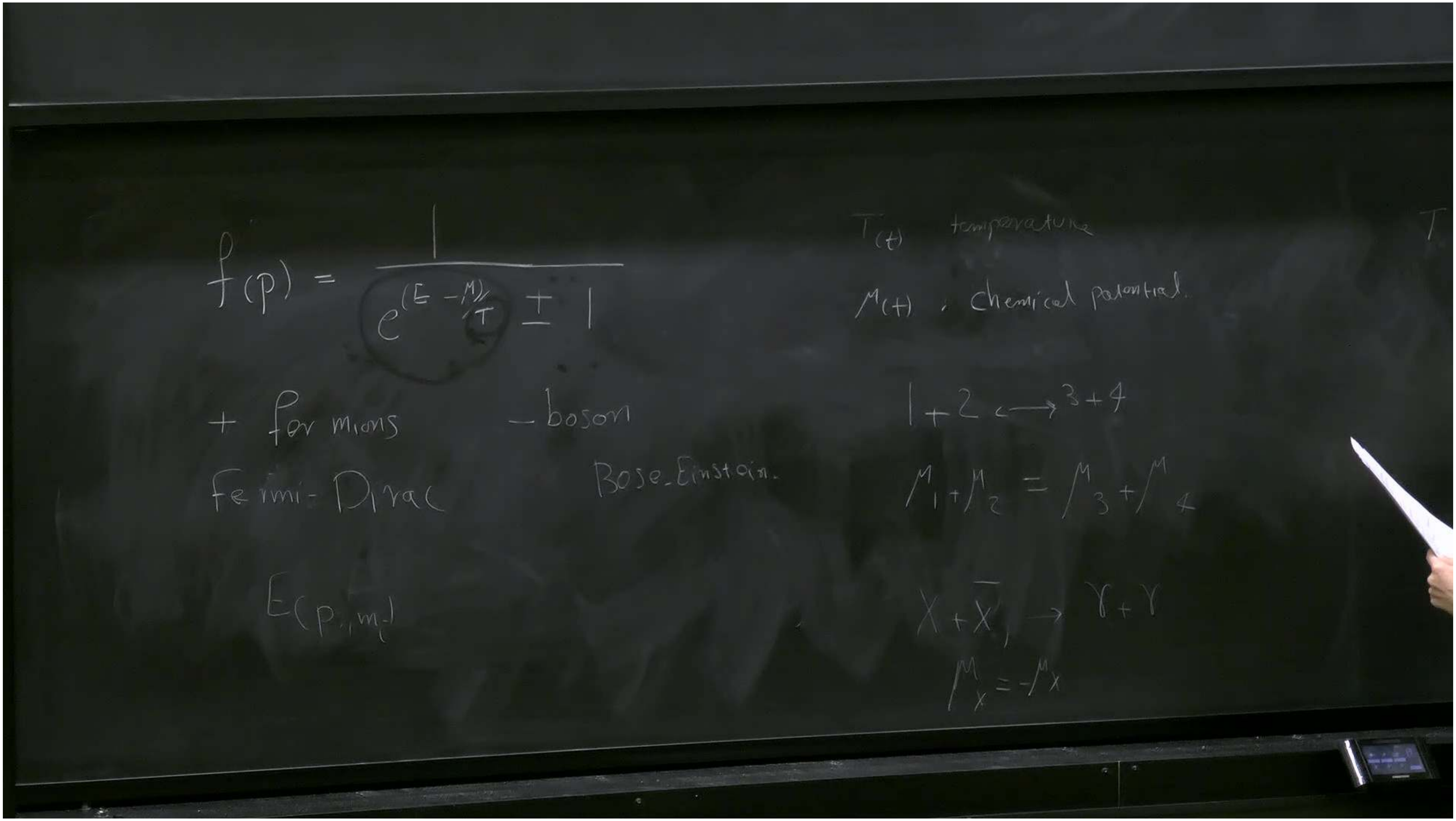
$\vec{p} \downarrow |p|$

$\int dx^3 dp^3 \ f_{(\ )} \ , \ E(\vec{p},\vec{x},t)$

$\rho = \frac{g}{(2\pi)^3} \int d^3p \ f(p) \, E(p)$

$P = g/(2\pi)^3 \int d^3p \ f(p) \ \frac{p^2}{3E(p)}$

$E = \sqrt{m^2 + p^2}$


f(p) = 1 / (e^((E − μ)/T) ± 1)
T(t) temperature
μ(t) : chemical potential.
+ fermions
− boson
Fermi-Dirac
Bose-Einstein.
E(p_i, m_i)
1 + 2 ⟷ 3 + 4
μ1 + μ2 = μ3 + μ4
X + X̄ → γ + γ
μ_X̄ = −μ_X

$T \ll m$

$$f(p) \simeq e^{-(E-\mu)/T}$$ M-B distribution

$$\frac{m}{T} \ll 1 \Rightarrow m \simeq 0 \qquad d^3p = 4\pi\, p^2 dp$$

$$n = \frac{g}{2\pi^2} \int dp\, p^2 \cdot \frac{1}{e^{\frac{\sqrt{p^2+m^2}}{T}} \pm 1}$$

$$\rho = \quad '' \quad '' \quad '' \quad \sqrt{p^2+m^2}$$

$$x = m/T \qquad \xi = p/T \qquad n = \frac{g\,T^3}{2\pi^2} I_\pm(x)$$

$$\rho = g\,T^4 \; J_\pm(x)$$