Title: PSI 2016/2017 Cosmology (Review) - Lecture 5

Date: Feb 06, 2017 10:15 AM

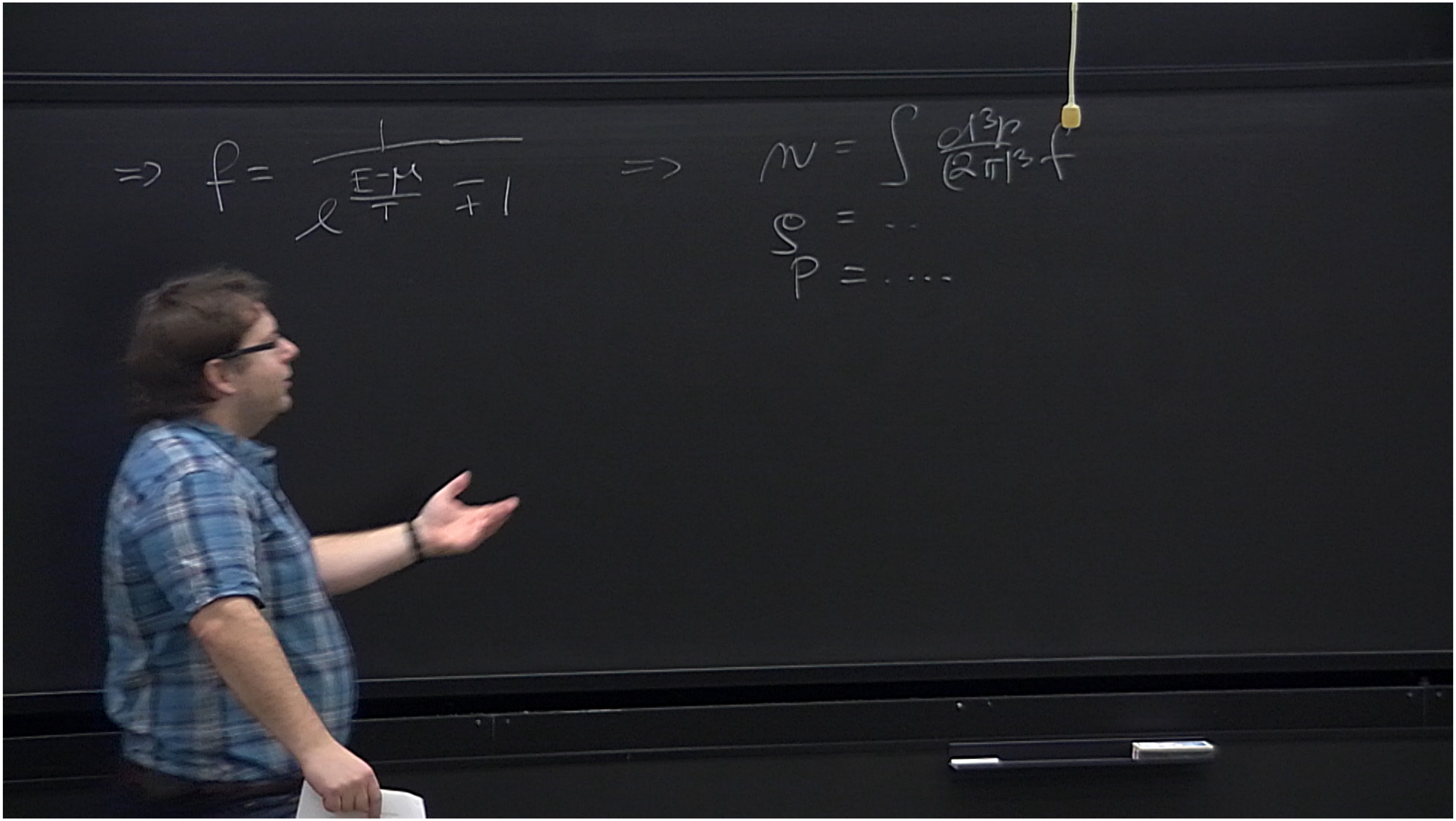
URL: http://pirsa.org/17020053

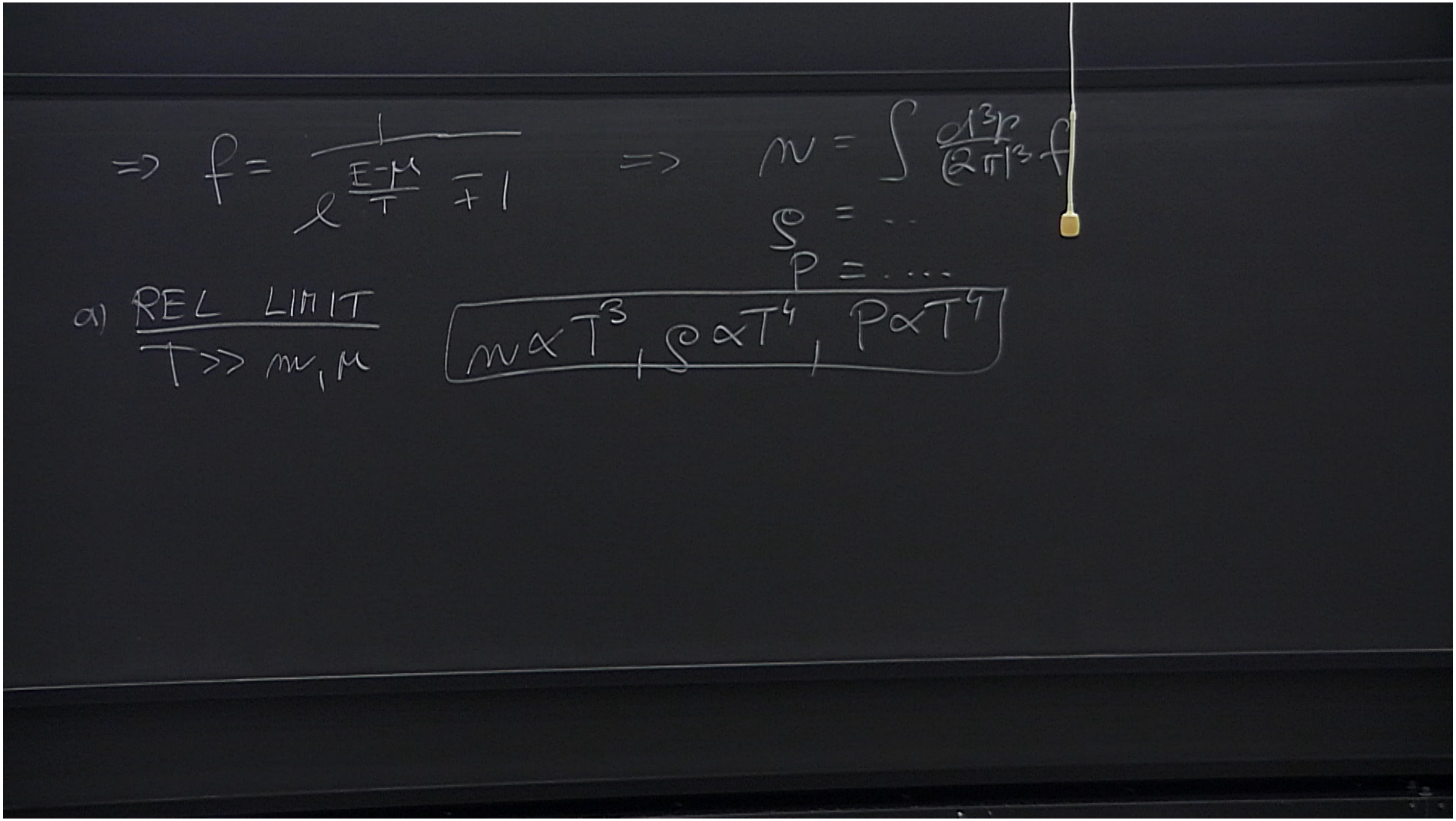
Abstract:

LAST TIME: TD's IN EXPANDING UNIVERSE

AS UNIVERSE IS EXPANDING WE DON'T REALLY HAVE EQUILIBRIUM, BUT "LOCAL THERMAL EQUILIBRIUM"

$$\boxed{\Gamma \gg H}$$


=> f = 1 / (e^((E−μ)/T) ∓ 1)
=> n = ∫ d³p/(2π)³ f
ρ = ..
P = ...


⇒ $f = \frac{1}{e^{\frac{E-\mu}{T}} \mp 1}$ ⇒ $n = \int \frac{d^3p}{(2\pi)^3} f$
$\rho = \ldots$
$P = \ldots$
a) REL LIMIT
$T \gg m, \mu$
$n \propto T^3, \rho \propto T^4, P \propto T^4$

$$\Rightarrow \quad f = \frac{1}{e^{\frac{E-\mu}{T}} \mp 1} \quad \Rightarrow \quad n = \int \frac{d^3p}{(2\pi)^3} f$$

$$\rho = \ldots$$

$$P = \ldots.$$

a) <u>REL LIMIT</u>

$T \gg m, \mu$

$$n \propto T^3, \quad \rho \propto T^4, \quad P \propto T^4$$

$$w = P/\rho = 1/3$$

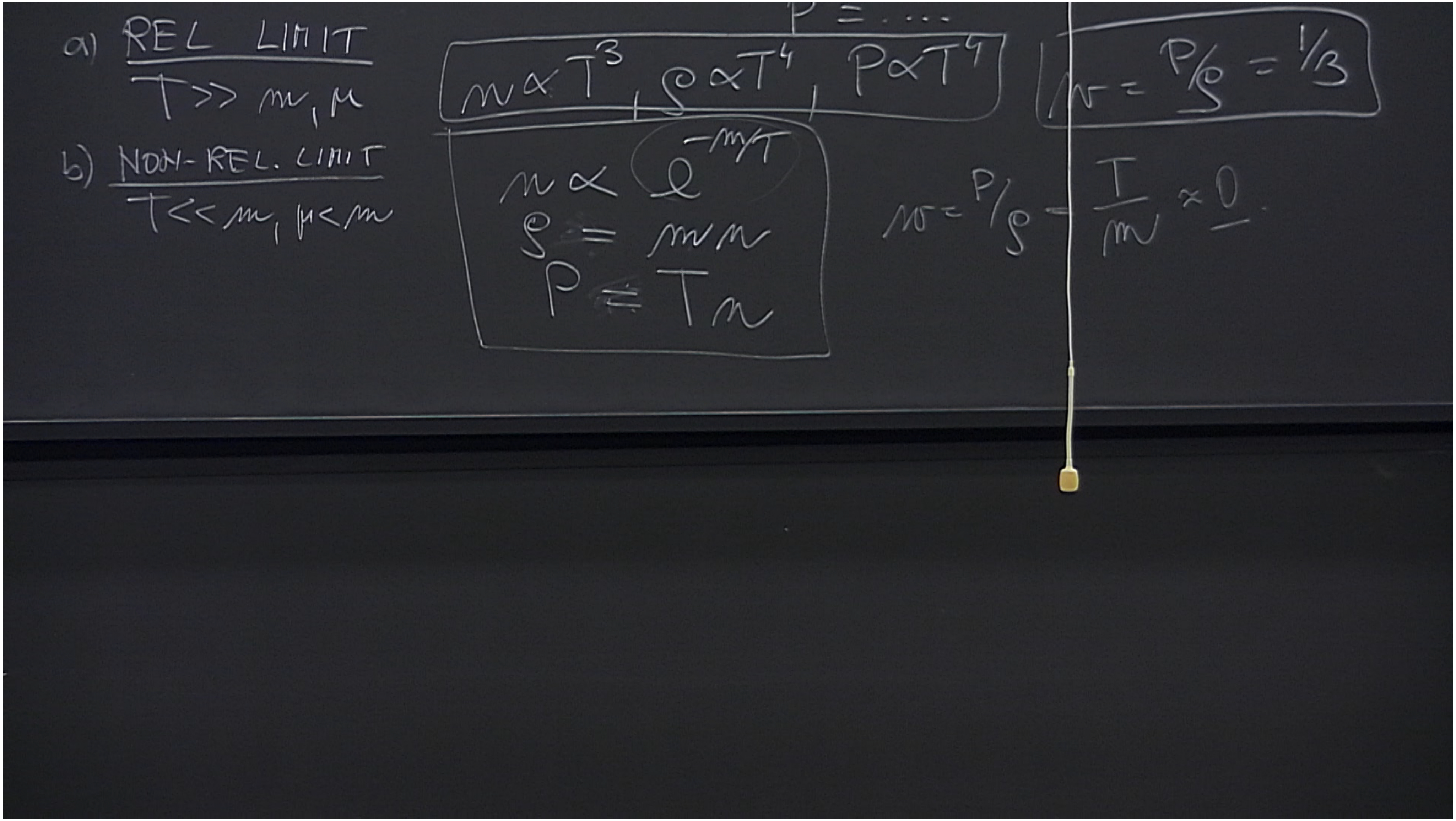
b) <u>NON-REL. LIMIT</u>

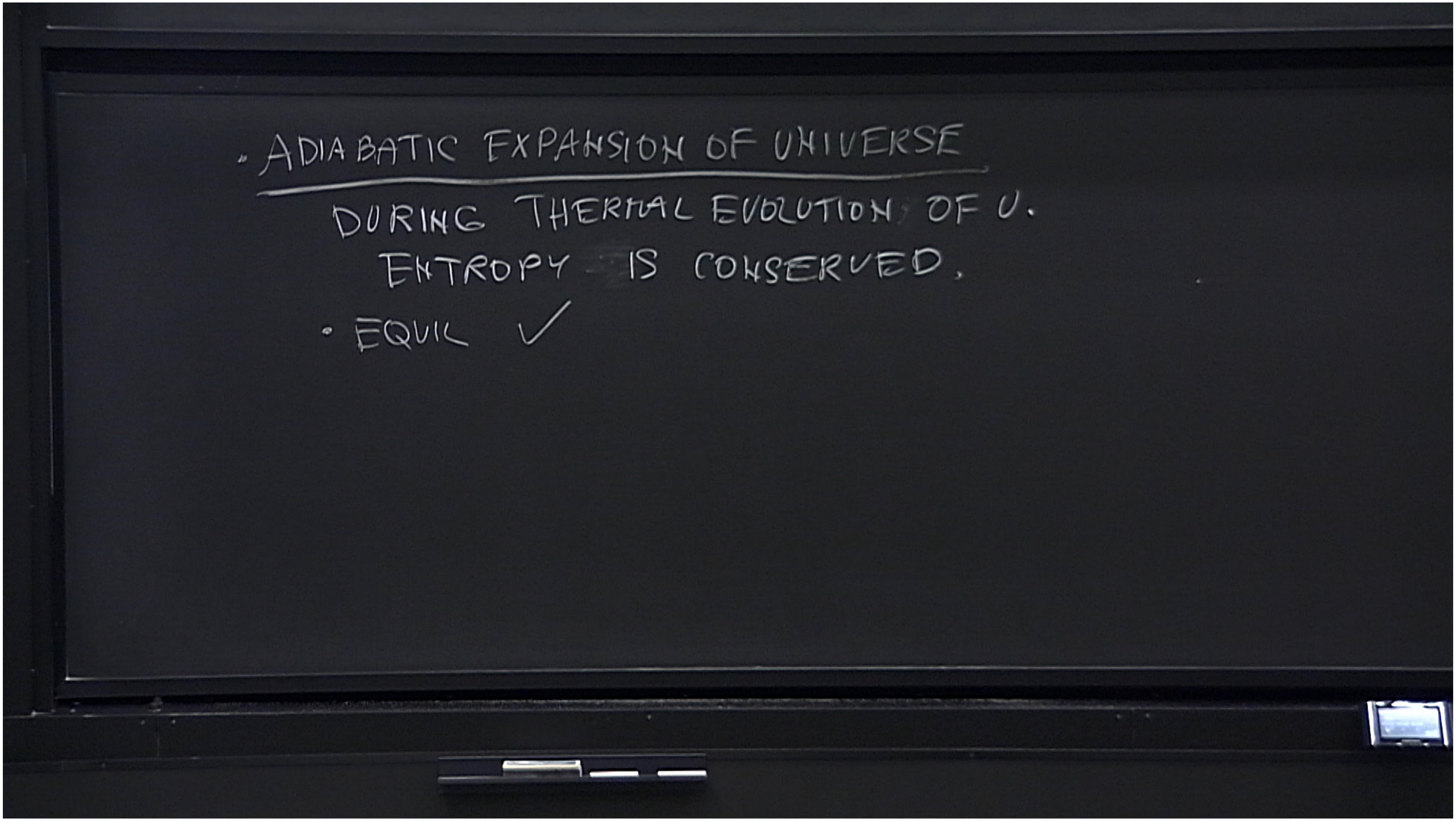
$T \ll m, \; \mu < m$

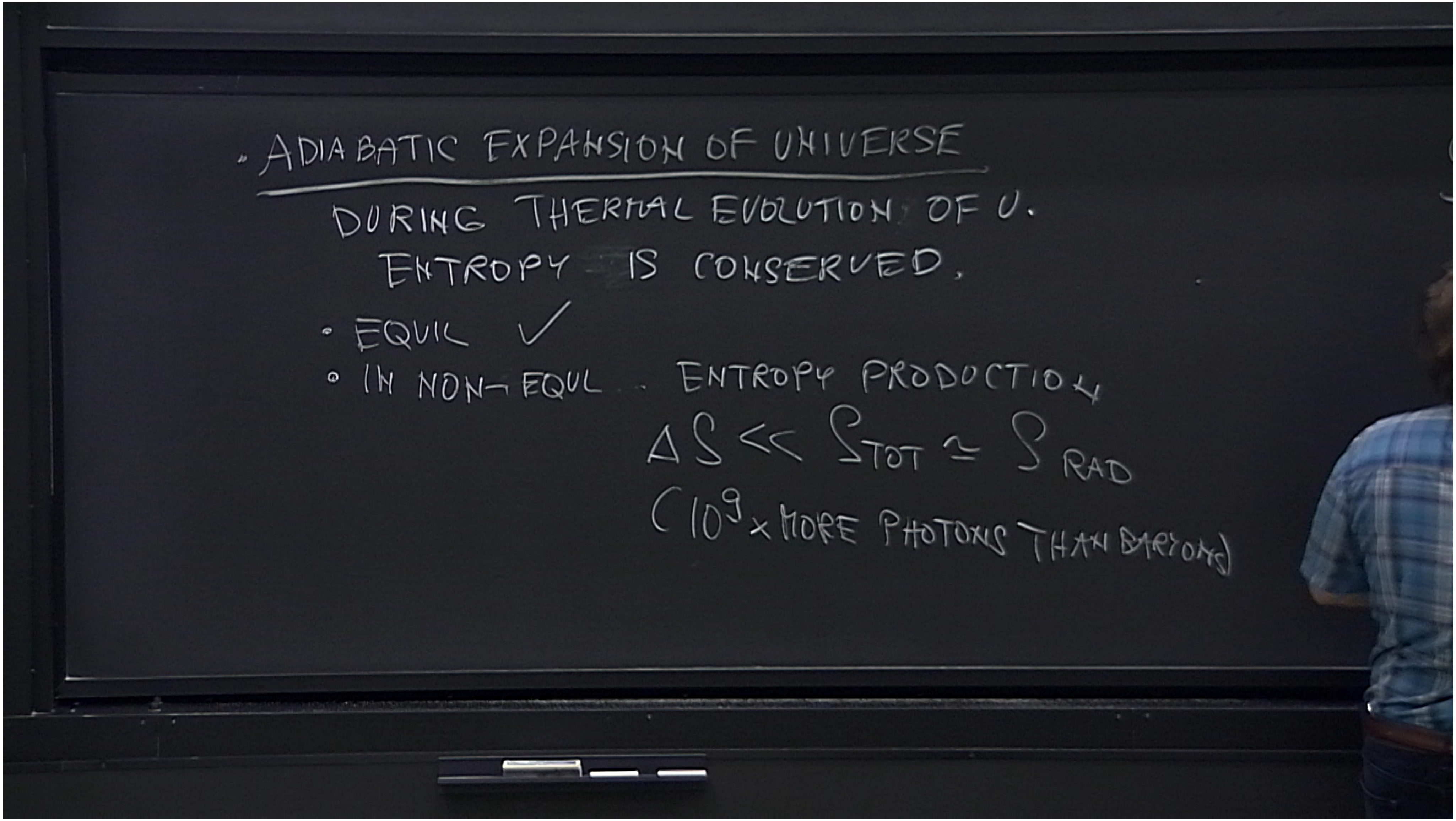
$$n \propto e^{-m/T}$$

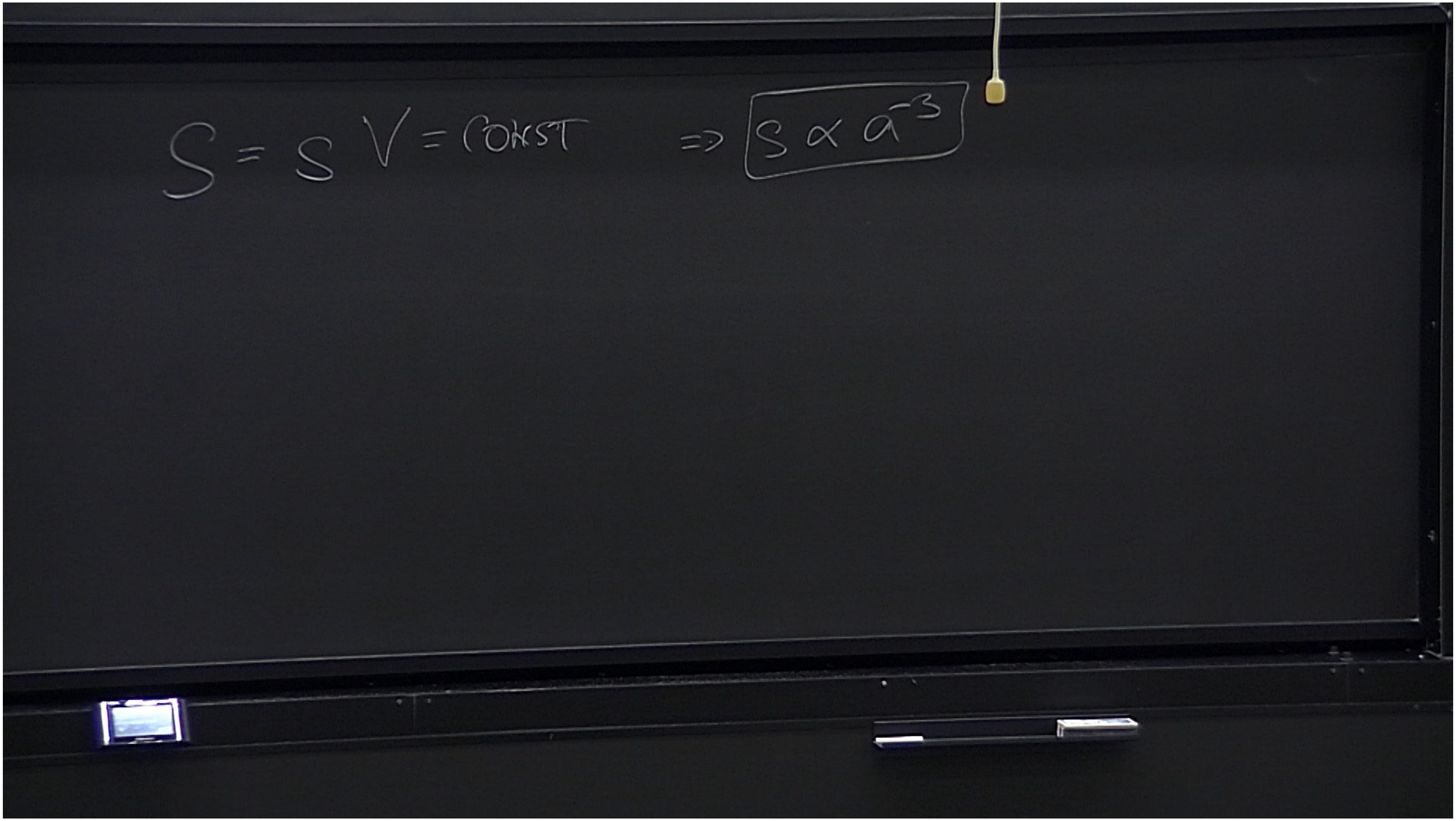
$$\rho \simeq m n$$

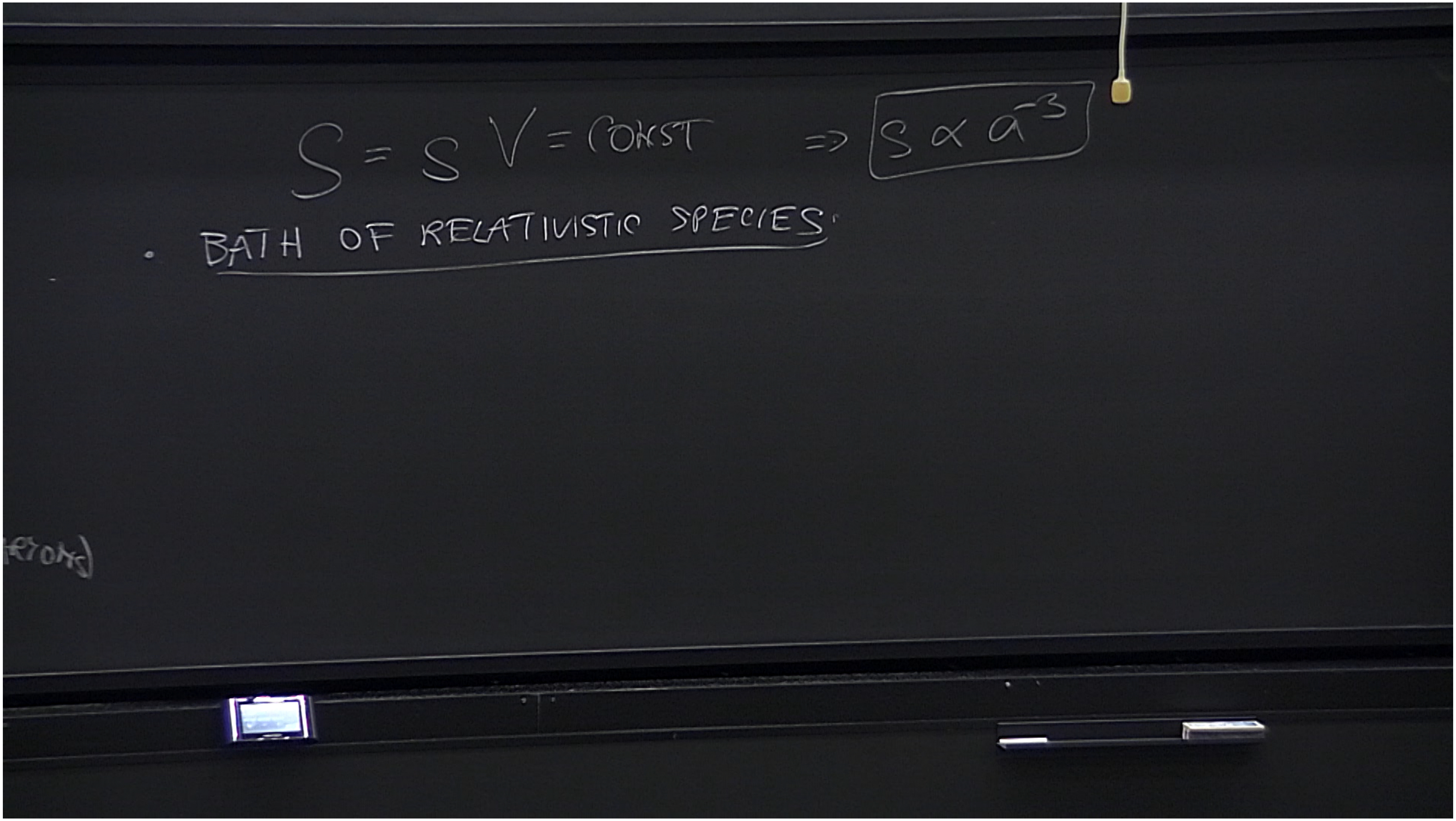
$$P \simeq T n$$

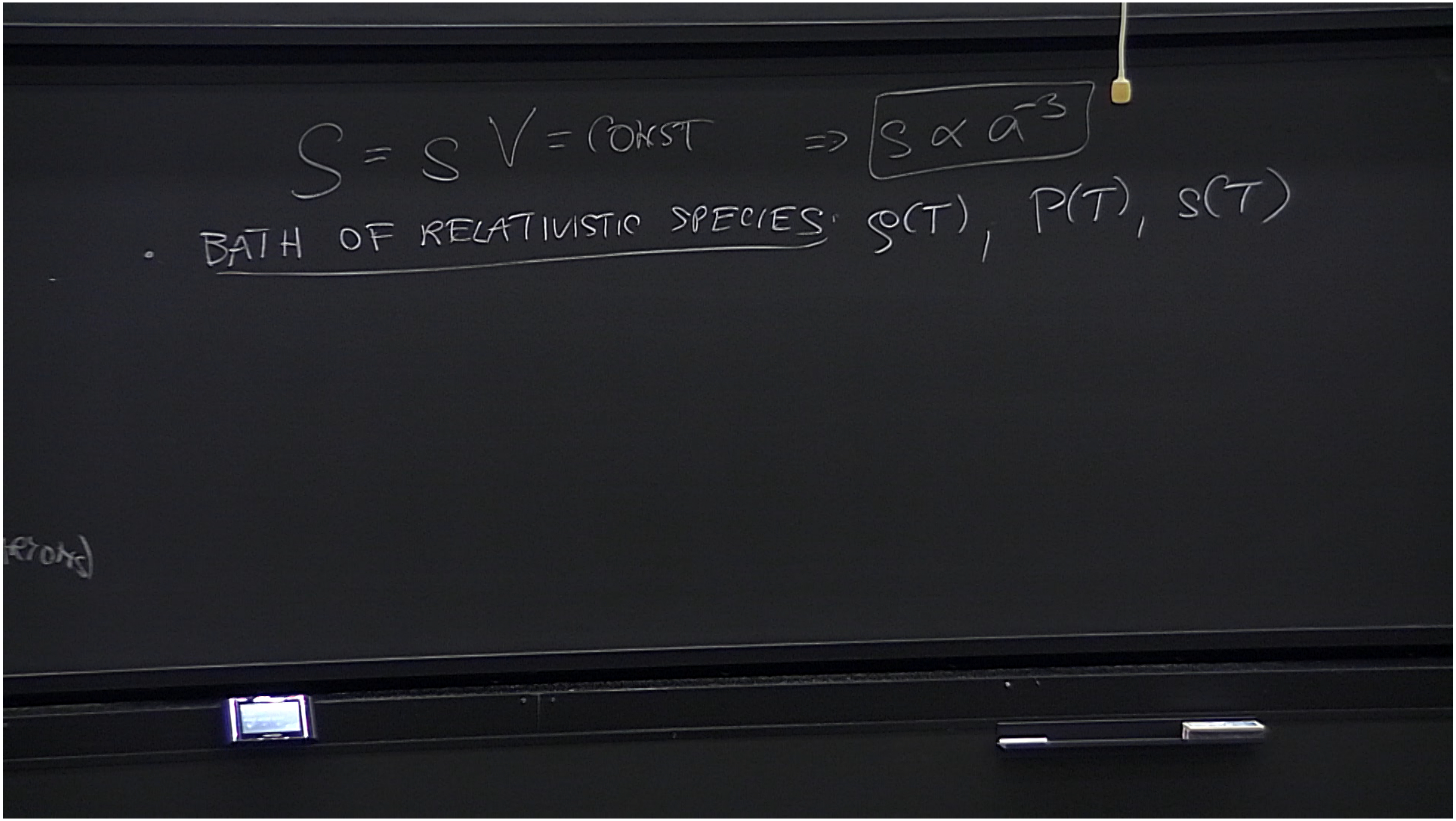

a) REL LIMIT
$T >> m, \mu$
b) NON-REL. LIMIT
$T << m, \mu < m$
$P = \ldots$
$n \propto T^3, \rho \propto T^4, P \propto T^4$
$w = P/\rho = 1/3$
$n \propto e^{-m/T}$
$\rho = m n$
$P = T n$
$w = P/\rho = \frac{T}{m} \approx 0$

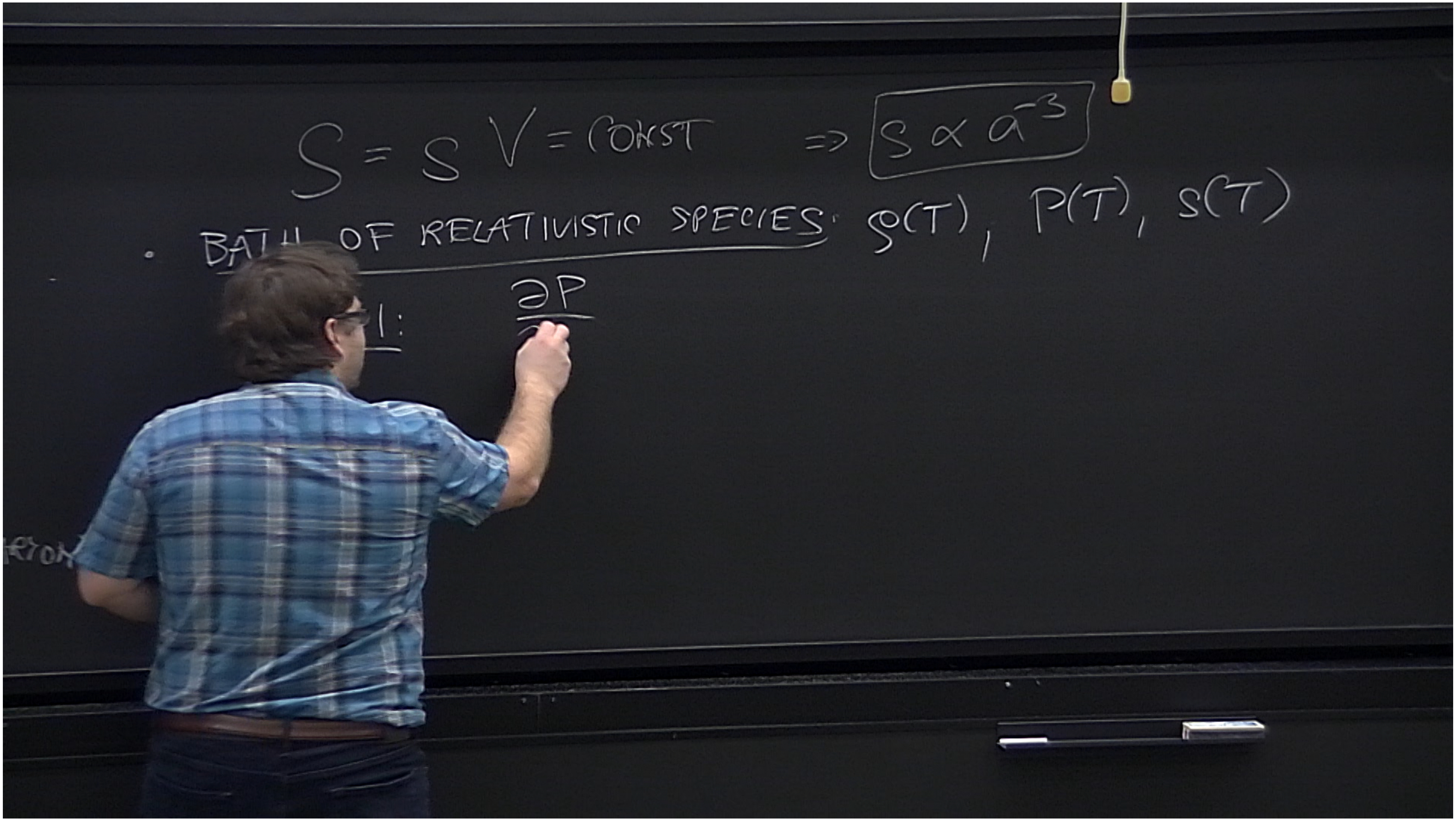

• ADIABATIC EXPANSION OF UNIVERSE
DURING THERMAL EVOLUTION OF U.
ENTROPY IS CONSERVED.
• EQUIL ✓


• ADIABATIC EXPANSION OF UNIVERSE
DURING THERMAL EVOLUTION OF U.
ENTROPY IS CONSERVED.
• EQUIL ✓
• IN NON-EQUL .. ENTROPY PRODUCTION
ΔS << S TOT ≃ S RAD
(10^9 × MORE PHOTONS THAN BARYONS)


$S = s\,V = \text{CONST} \Rightarrow s \propto a^{-3}$

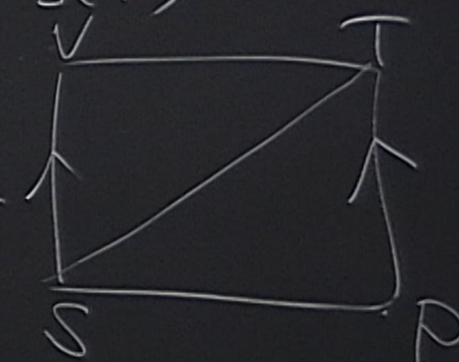

S = s V = CONST ⇒ s ∝ a^-3
• BATH OF RELATIVISTIC SPECIES:


$S = s V = \text{CONST} \Rightarrow s \propto a^{-3}$
• BATH OF RELATIVISTIC SPECIES: $\rho(T)$, $P(T)$, $s(T)$


S = s V = CONST
$\Rightarrow s \propto a^{-3}$
BATH OF RELATIVISTIC SPECIES: ρ(T), P(T), s(T)
∂P

$$S = sV = \text{CONST} \Rightarrow \boxed{s \propto a^{-3}}$$

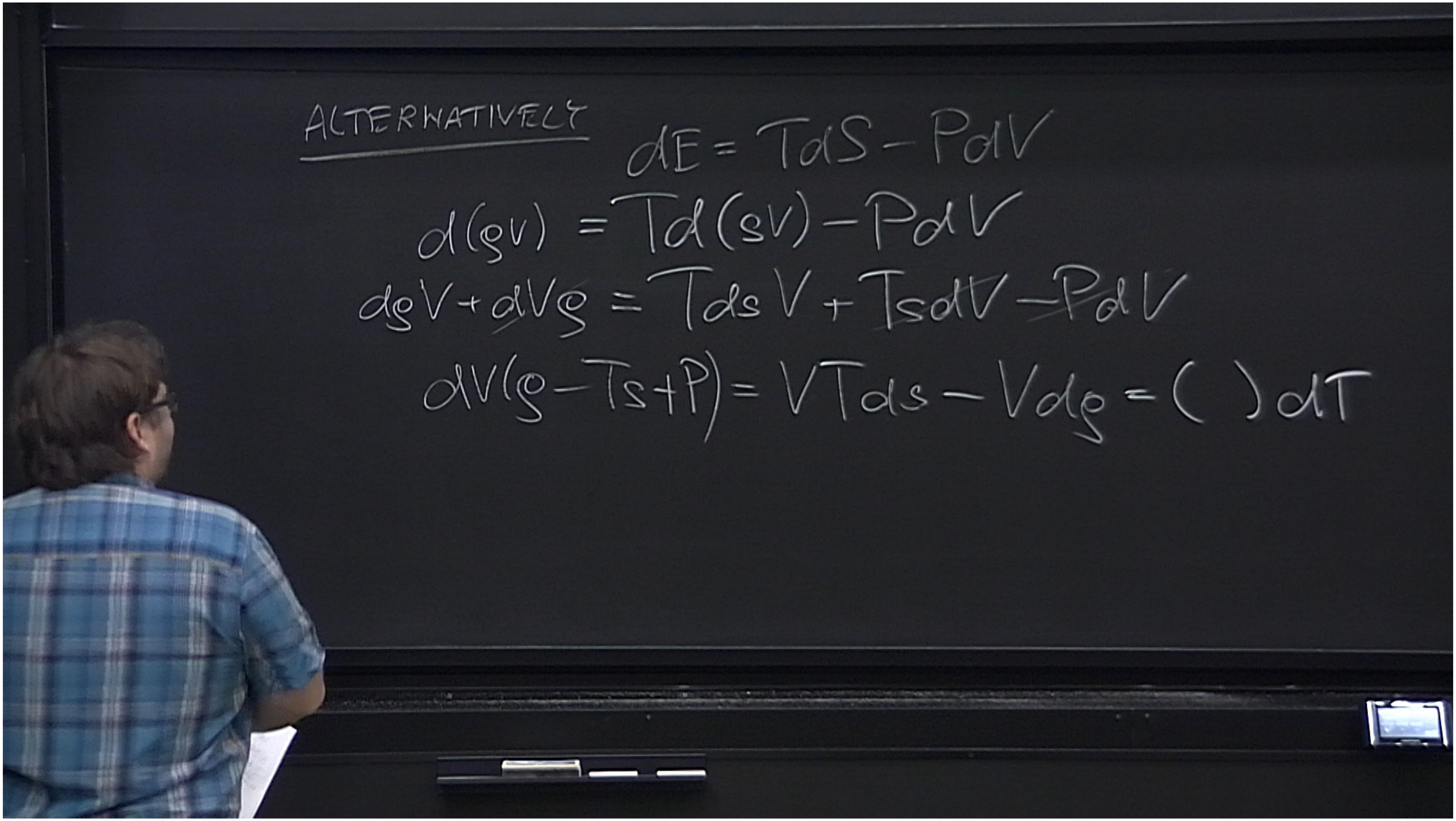
• BATH OF RELATIVISTIC SPECIES: $\rho(T)$, $P(T)$, $s(T)$

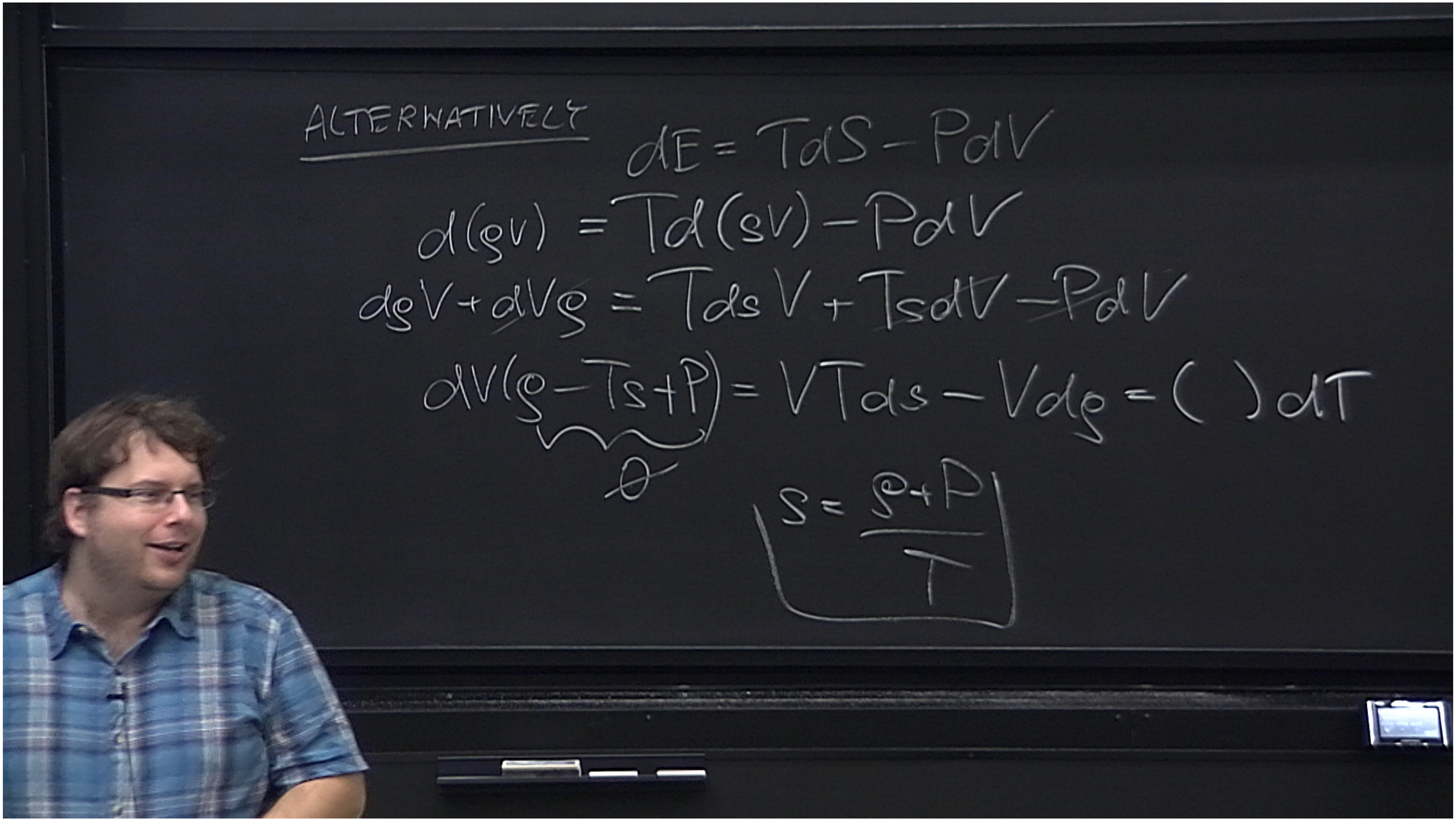


HI: $$\left(\frac{\partial P}{\partial T}\right)\Big|_S = \frac{\rho+P}{T} = \left(\frac{\partial S}{\partial V}\right)\Big|_P = \left(\frac{\partial S}{\partial V}\right)\Big|_T$$

$$= s$$

$$\boxed{s = \frac{\rho+P}{T} \propto T^3}$$


ALTERNATIVELY
dE = TdS − PdV
d(ρV) = Td(sV) − PdV
dρV + dVρ = TdsV + TsdV − PdV
dV(ρ − Ts + P) = VTds − Vdρ = ( ) dT


ALTERNATIVELY
dE = TdS − PdV
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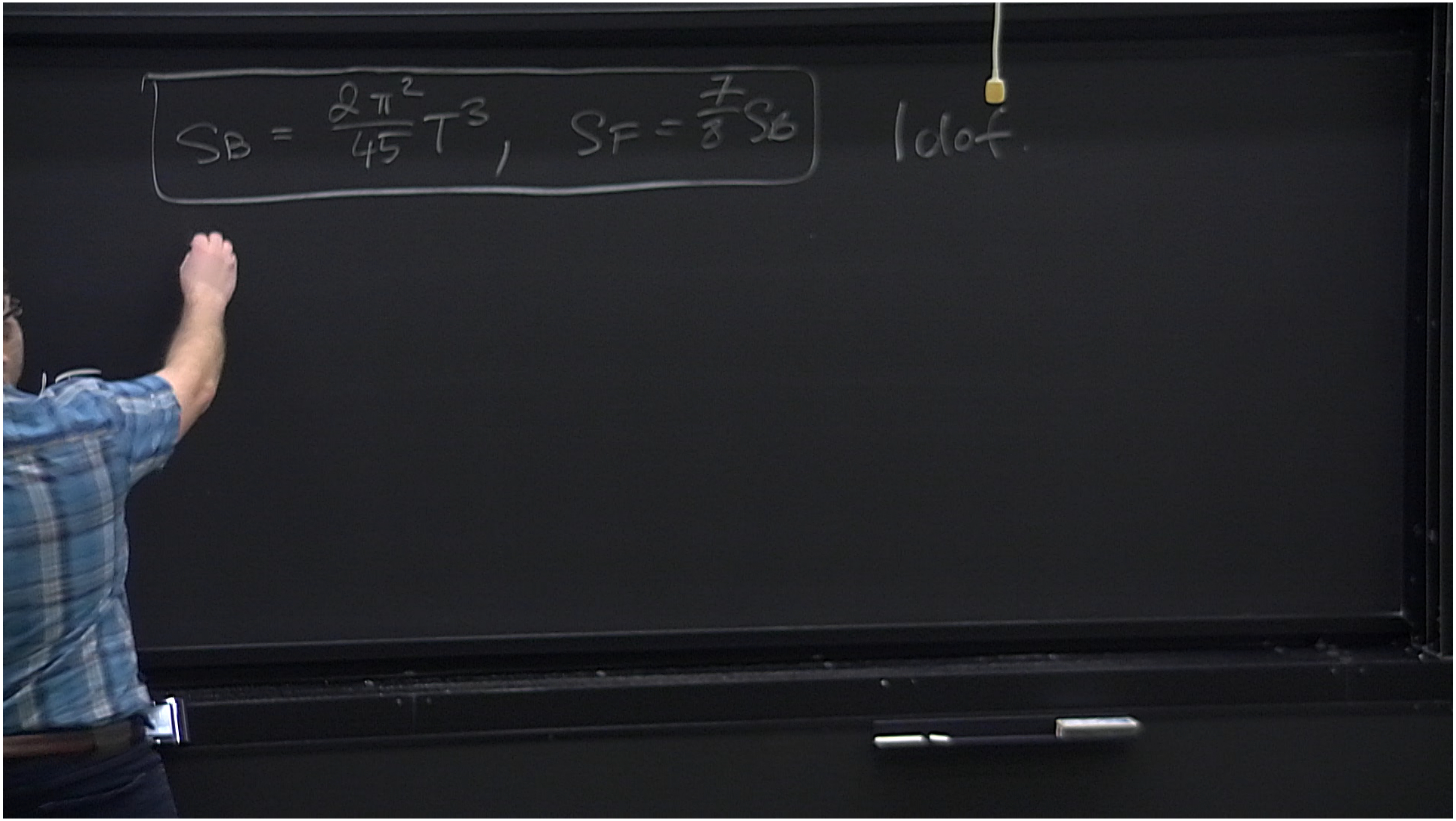
dρV + dVρ = TdsV + TsdV − PdV
dV(ρ − Ts + P) = VTds − Vdρ = ( ) dT
θ
s = (ρ + P)/T


$s_B = \frac{2\pi^2}{45} T^3, \quad s_F = \frac{7}{8} s_B$
1 dof.

$$S_B = \frac{2\pi^2}{45} T^3, \quad S_F = \frac{7}{8} S_B$$ 1 dof.

TYPICALLY ... BATH OF MANY SPECIES. DENOTE T. TEMPERATURE OF PHOTONS. T_i.. TEMPERATURES OF OTHER SPECIES

dT $\Rightarrow$ $$S = g_{*S} \frac{2\pi^2}{45} T^3$$

$$S_B = \frac{2\pi^2}{45} T^3 , \quad S_F = \frac{7}{8} S_B$$

1 dof.

TYPICALLY ... BATH OF MANY SPECIES. DENOTE T .. TEMPERATURE OF PHOTONS. T_i .. TEMPERATURES OF OTHER SPECIES

dT

$$\Rightarrow \quad S = g_{*S} \frac{2\pi^2}{45} T^3 , \quad g_{*S} = \sum_{\text{BOSONS}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{\text{FERM.}} g_i \left(\frac{T_i}{T}\right)^3$$

$$S_B = \frac{2\pi^2}{45} T^3, \quad S_F = \frac{7}{8} S_B$$

1 dof.

TYPICALLY ... BATH OF MANY SPECIES. DENOTE T ... TEMPERATURE OF PHOTONS. T_i .. TEMPERATURES OF OTHER SPECIES

dT

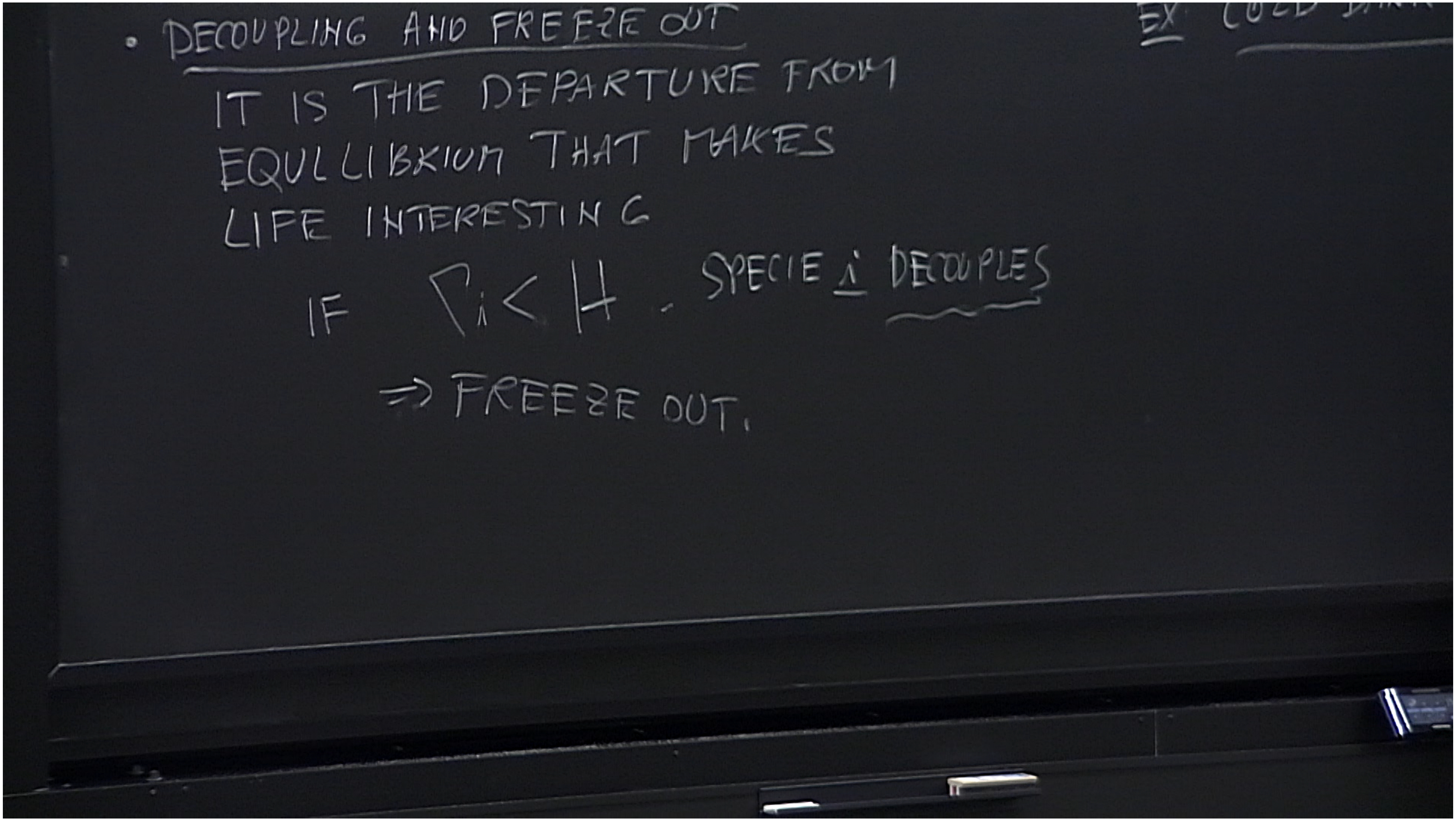
$$\Rightarrow S = g_{*S} \frac{2\pi^2}{45} T^3, \quad g_{*S} = \sum_{\text{BOSONS}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{\text{FERM.}} g_i \left(\frac{T_i}{T}\right)^3$$

$$\rho = g_* \frac{\pi^2}{30} T^4, \quad g_* = \sum_{\text{BOSONS}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{\text{FERM}} g_i \left(\frac{T_i}{T}\right)^4$$

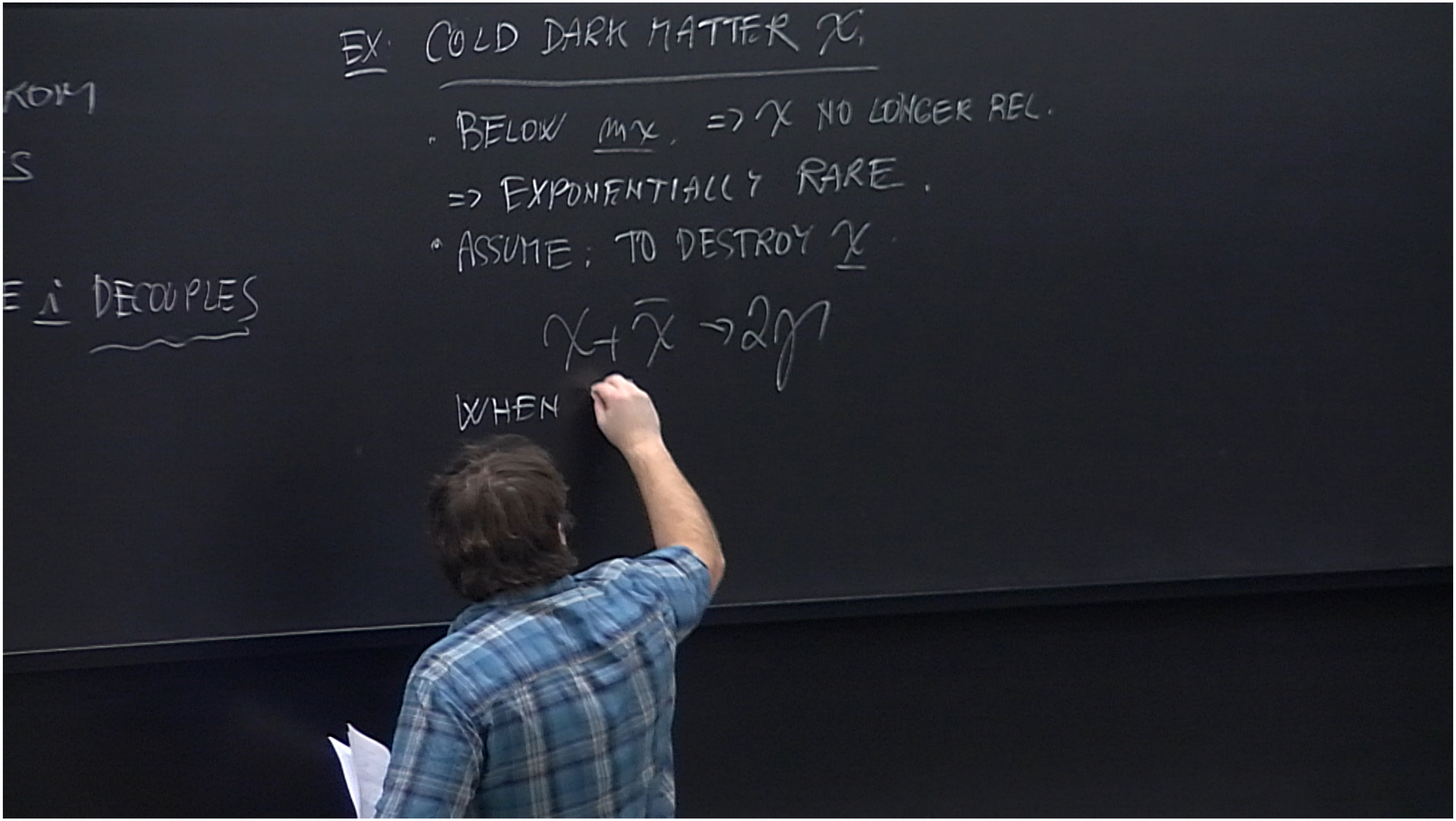
• DECOUPLING AND FREEZE OUT

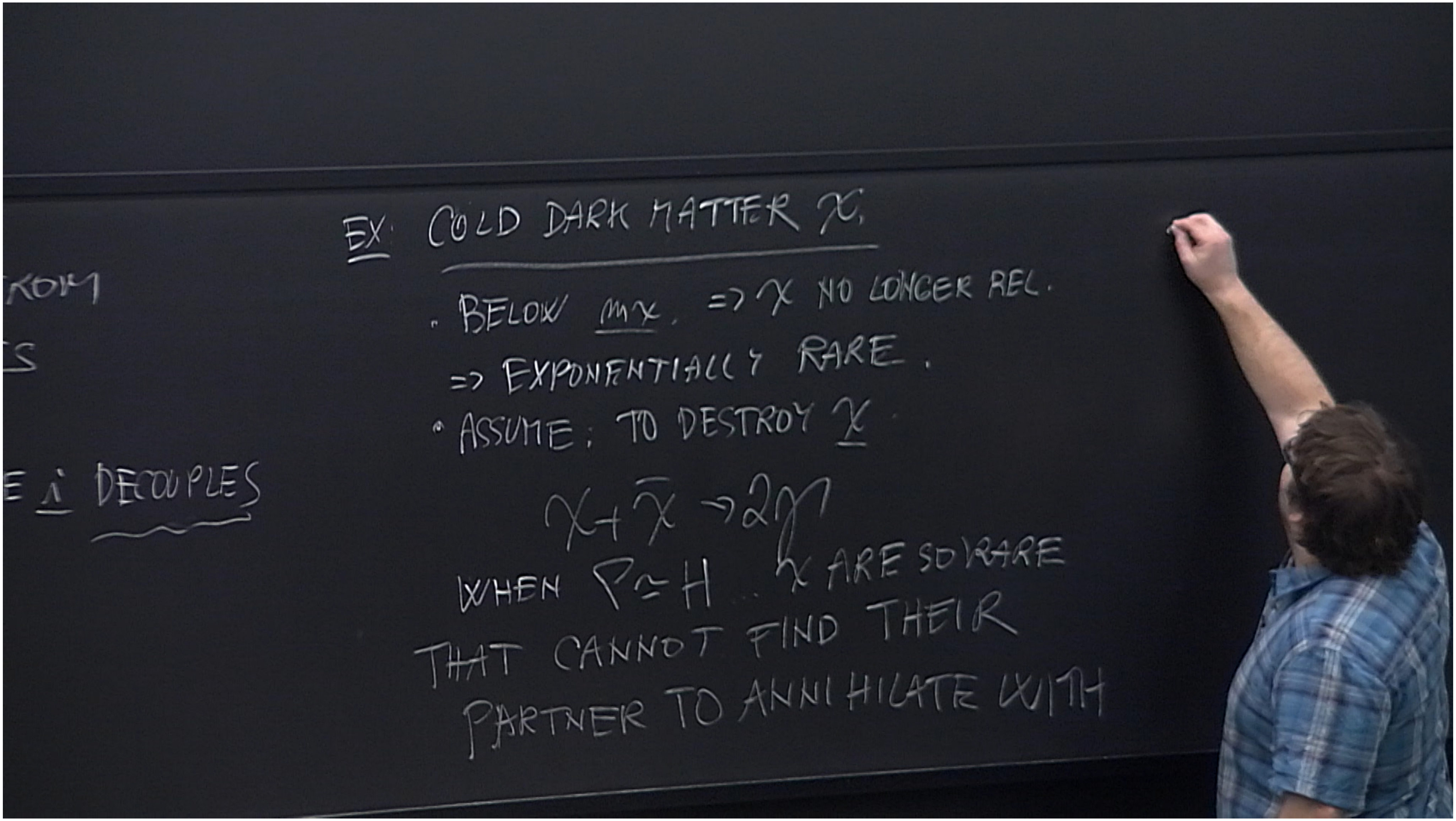
IT IS THE DEPARTURE FROM EQULLIBRIUM THAT MAKES LIFE INTERESTING

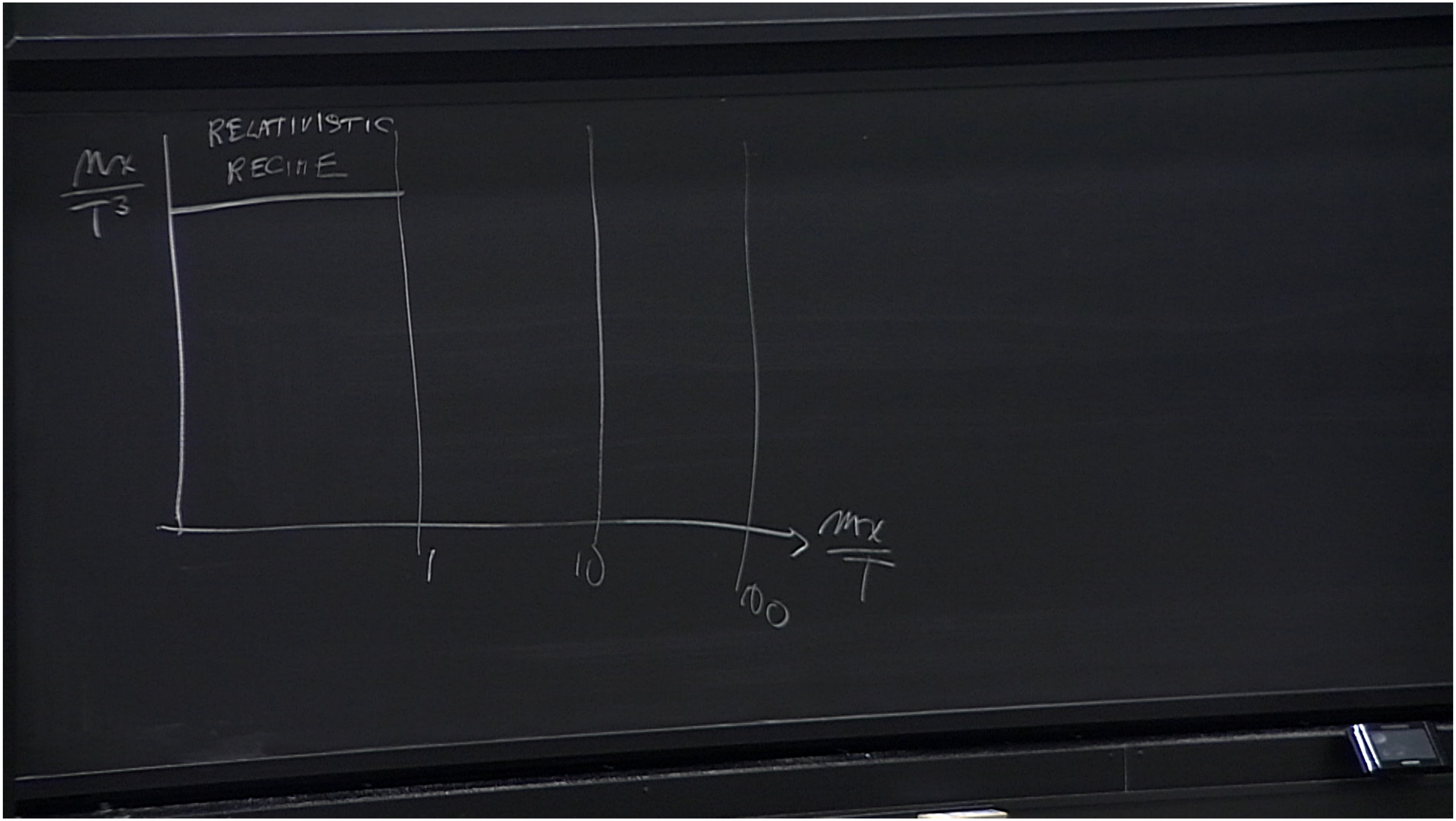
IF $\Gamma_i < H$, SPECIE i DECOUPLES

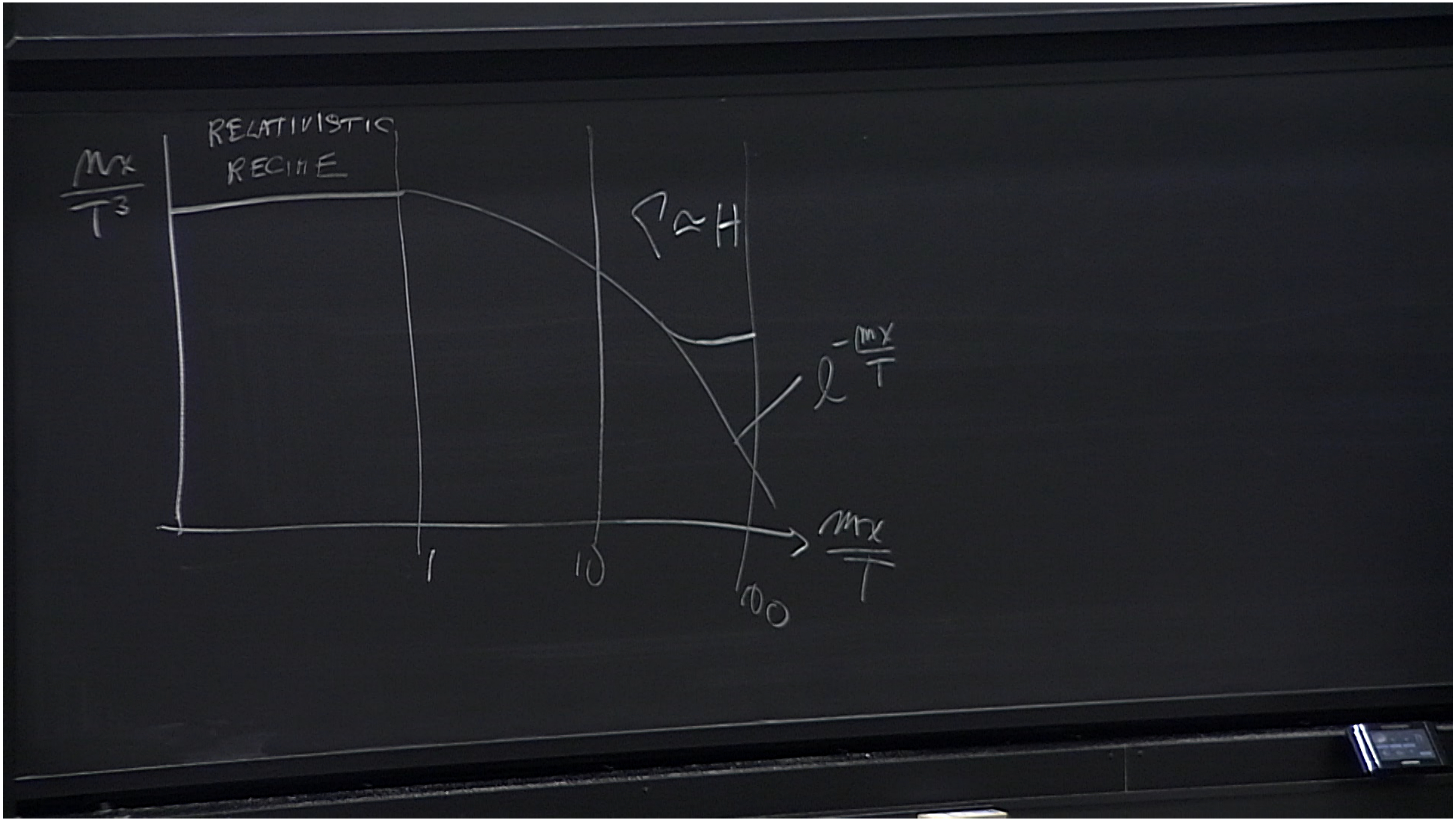


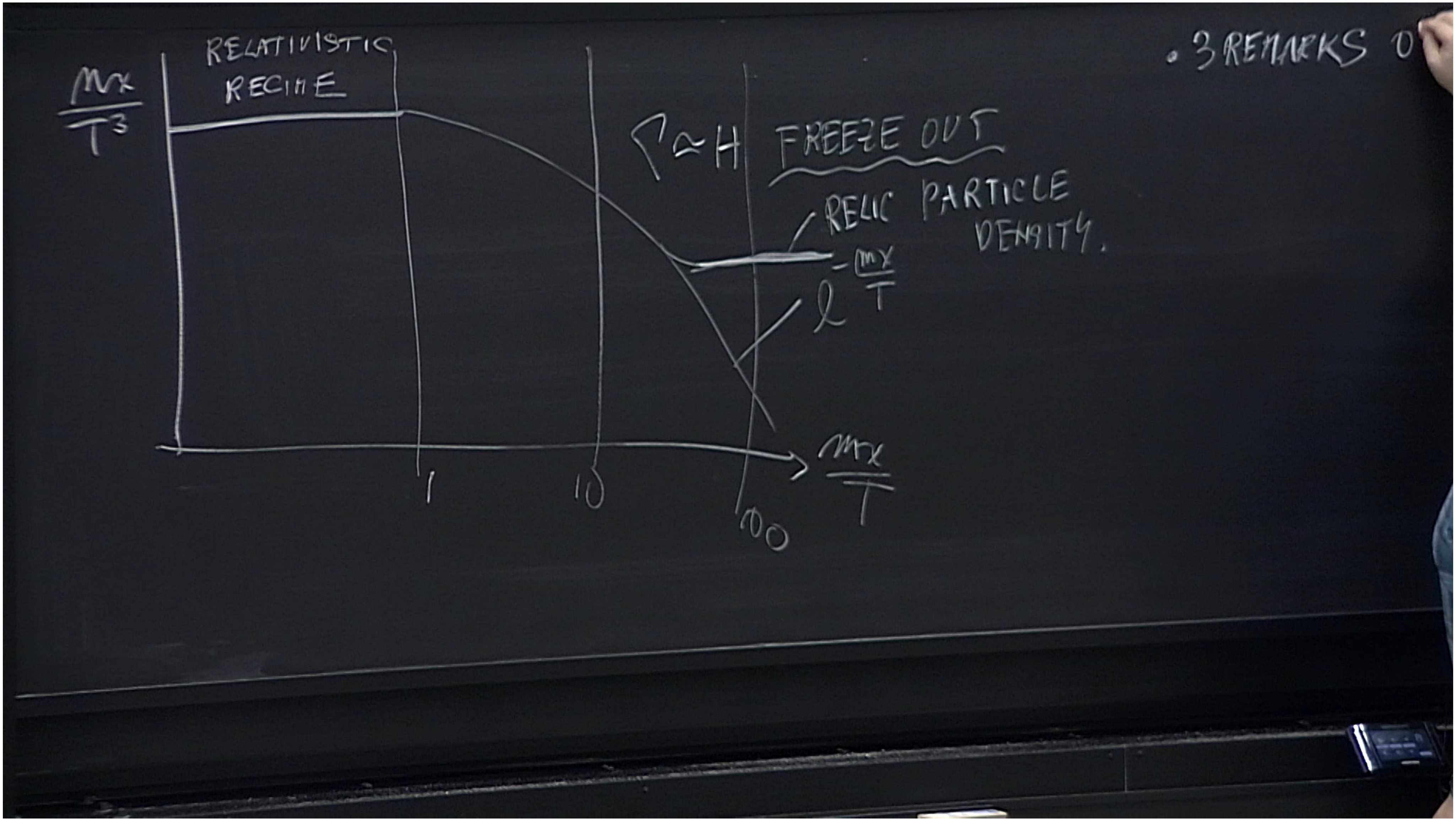
• DECOUPLING AND FREEZE OUT
IT IS THE DEPARTURE FROM
EQULLIBRIUM THAT MAKES
LIFE INTERESTING
IF Γi < H . SPECIE i DECOUPLES
⇒ FREEZE OUT.
EX

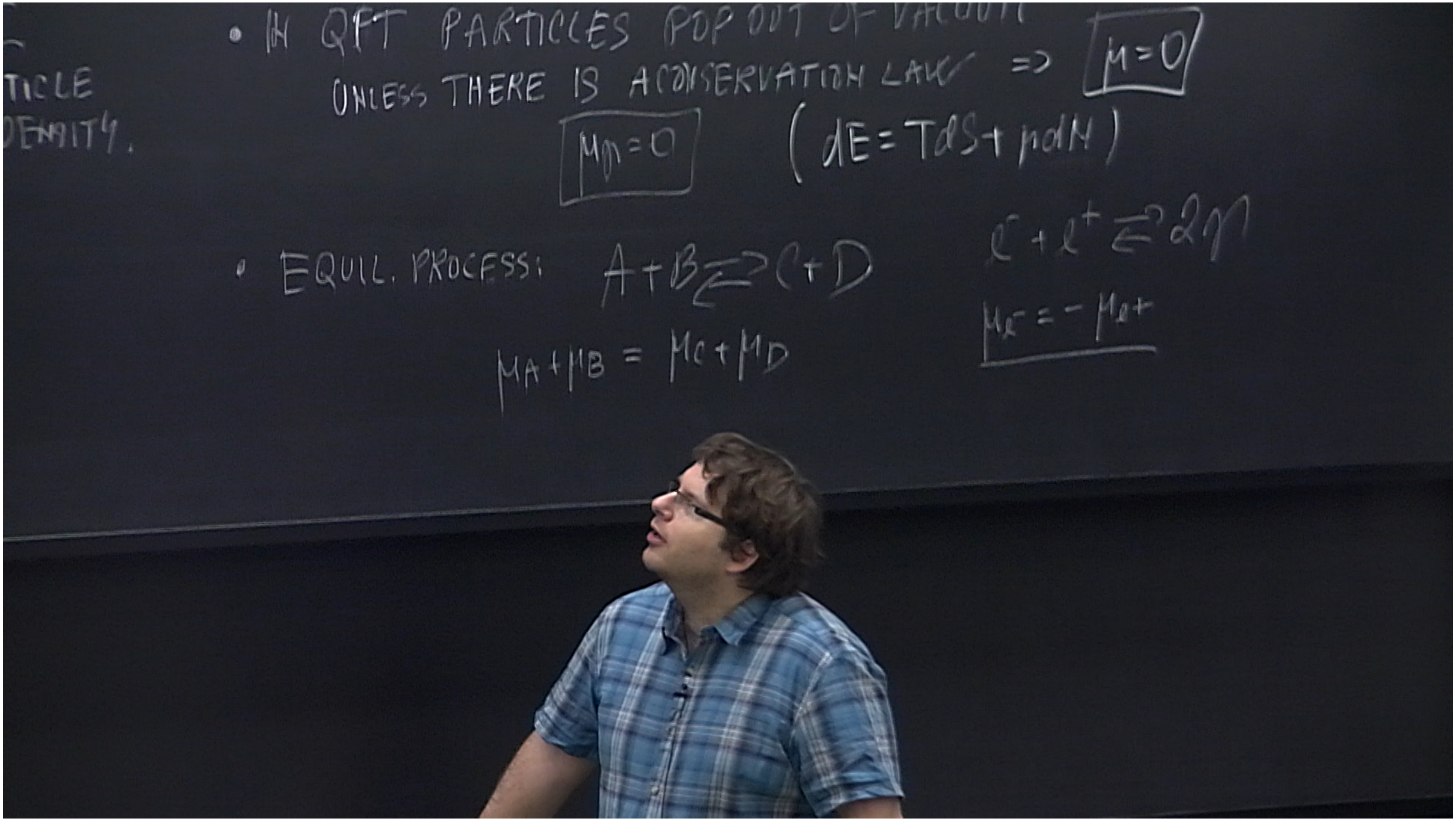

EX. COLD DARK MATTER χ:
• BELOW mχ ⇒ χ NO LONGER REL.
⇒ EXPONENTIALLY RARE.
• ASSUME: TO DESTROY χ
χ + χ̄ → 2γ
WHEN
DECOUPLES

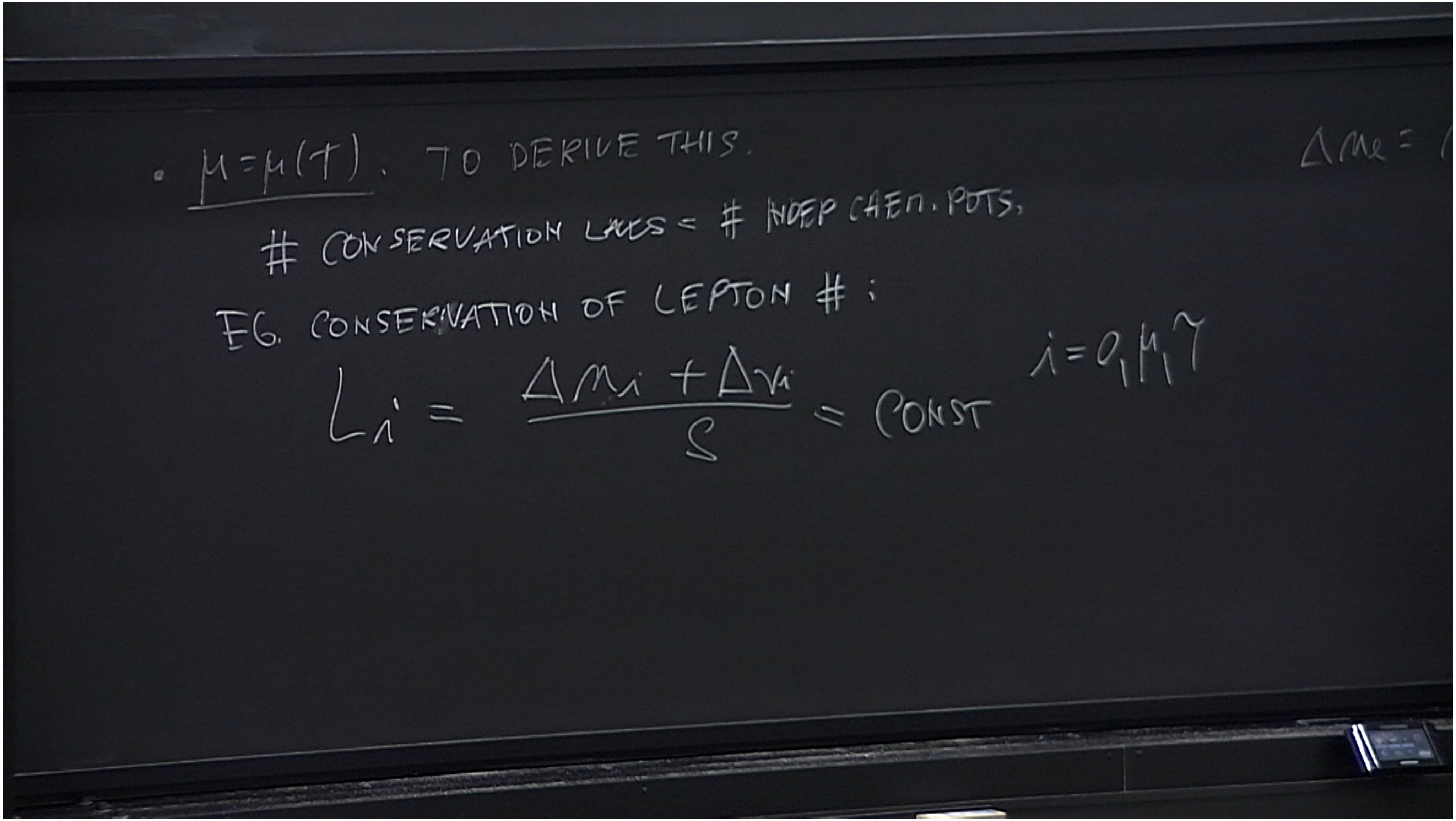

EX: COLD DARK MATTER χ.
• BELOW mχ. => χ NO LONGER REL.
=> EXPONENTIALLY RARE.
• ASSUME: TO DESTROY χ.
χ + χ̄ → 2γ
WHEN Γ ≃ H .. χ ARE SO RARE
THAT CANNOT FIND THEIR
PARTNER TO ANNIHILATE WITH
DECOUPLES


RELATIVISTIC
REGIME
mx/T^3
mx/T
1
10
100


RELATIVISTIC
REGIME
mx
T3
ρ≃H
e^-mx/T
mx
T
1
10
100


RELATIVISTIC REGIME
FREEZE OUT
RELIC PARTICLE DENSITY.
1
10
100
• 3 REMARKS O


TICLE
DENSITY.
• IN QFT PARTICLES POP OUT OF
UNLESS THERE IS A CONSERVATION LAW $\Rightarrow$ $\mu = 0$
$\mu_\gamma = 0$
$(dE = TdS + \mu dN)$
• EQUIL. PROCESS: $A + B \rightleftarrows C + D$
$\mu_A + \mu_B = \mu_C + \mu_D$
$e^- + e^+ \rightleftarrows 2\gamma$
$\mu_{e^-} = -\mu_{e^+}$



• $\mu = \mu(T)$. TO DERIVE THIS.
CONSERVATION LAWS = # INDEP CHEM. POTS.
EG. CONSERVATION OF LEPTON # :
$L_i = \frac{\Delta n_i + \Delta \nu_i}{s} = \text{CONST}$ $i = e, \mu, \tau$
$\Delta n_e =$

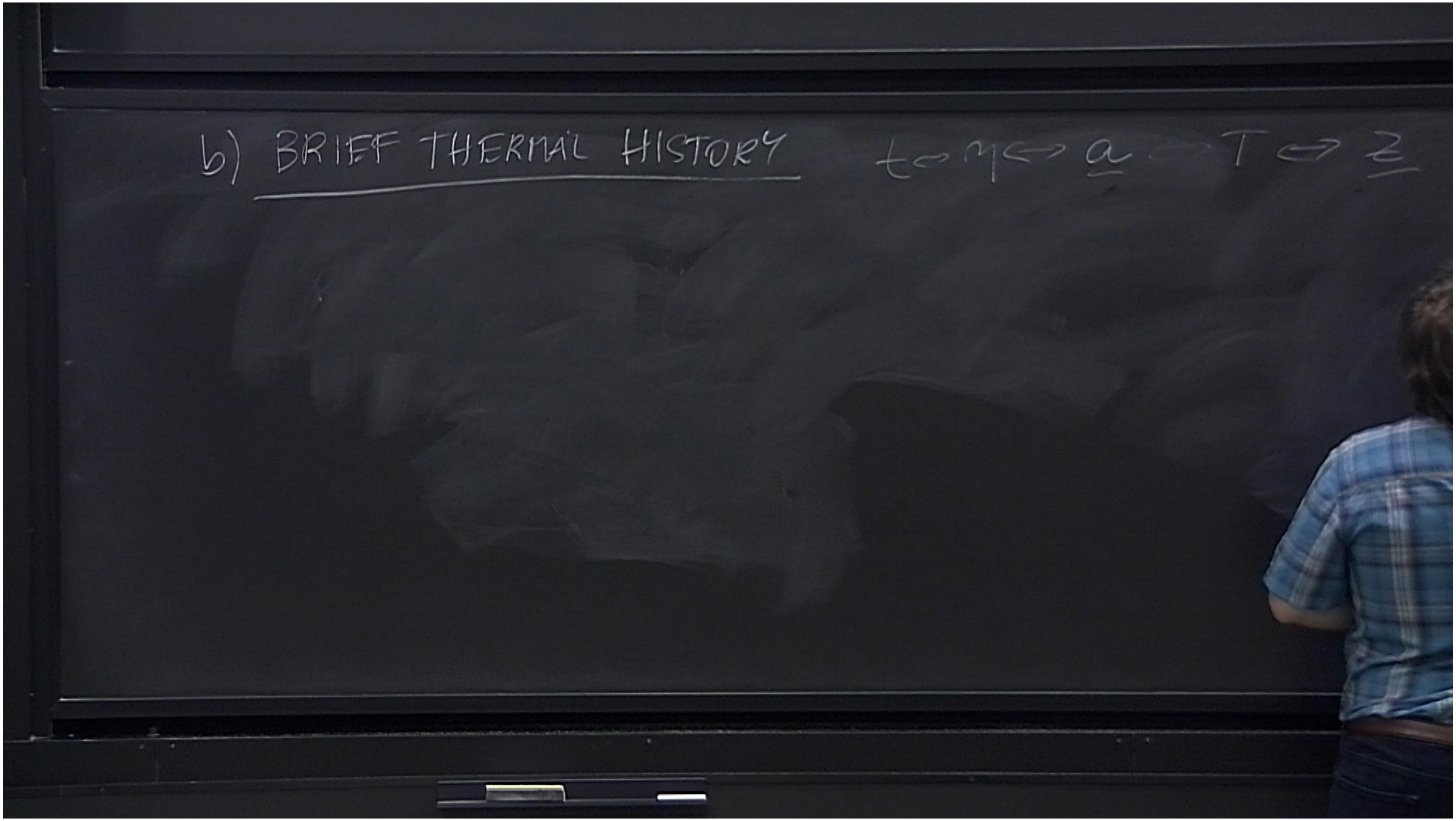
$\Delta \mu_e = \mu_e - \bar{\mu}_e \propto T^3 \frac{\mu_e}{T}$

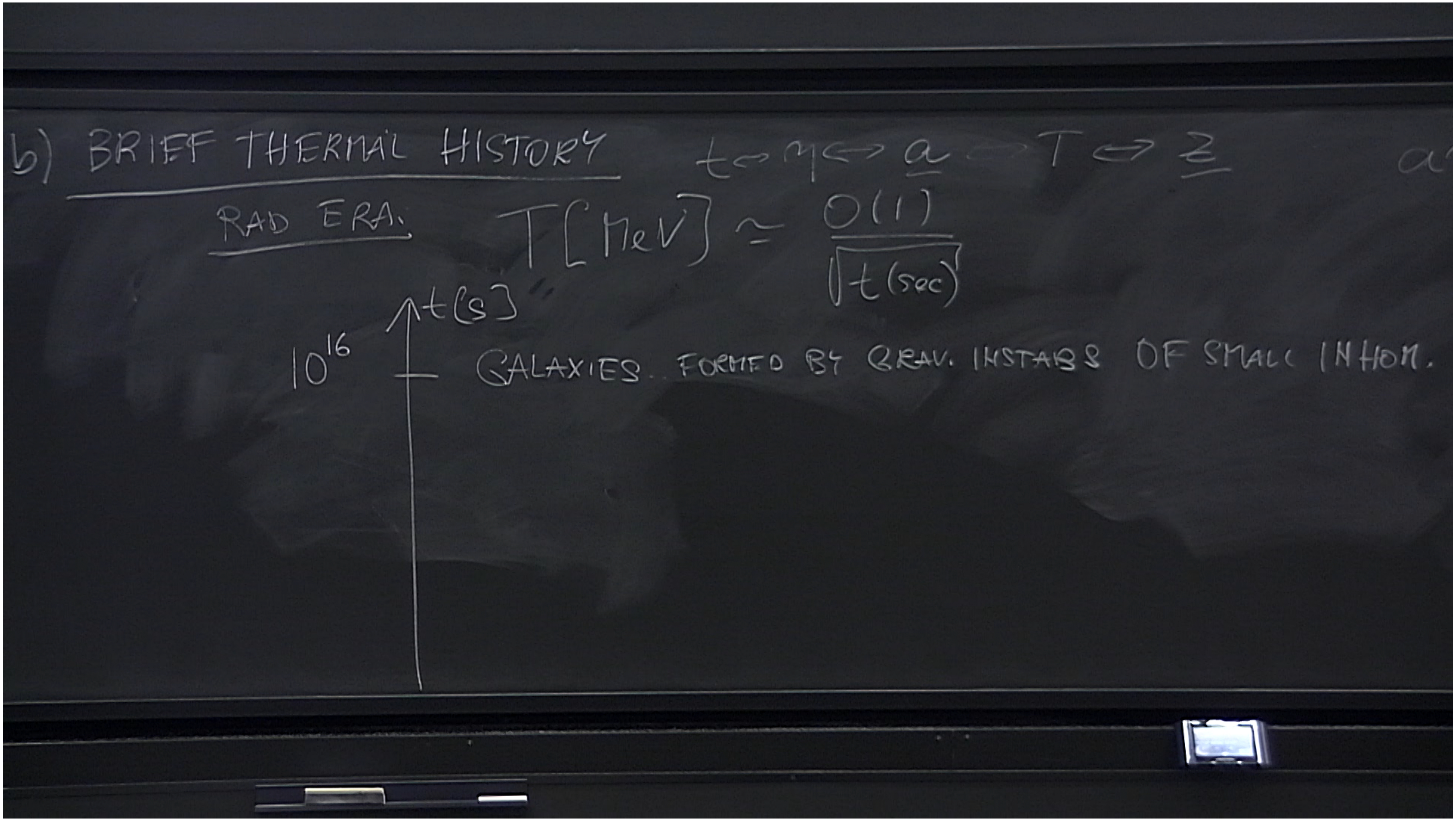
= INDEP CHEM. POTS,

$\Rightarrow \frac{\mu_e + \mu_{\nu_e}}{T} = \text{CONST}$

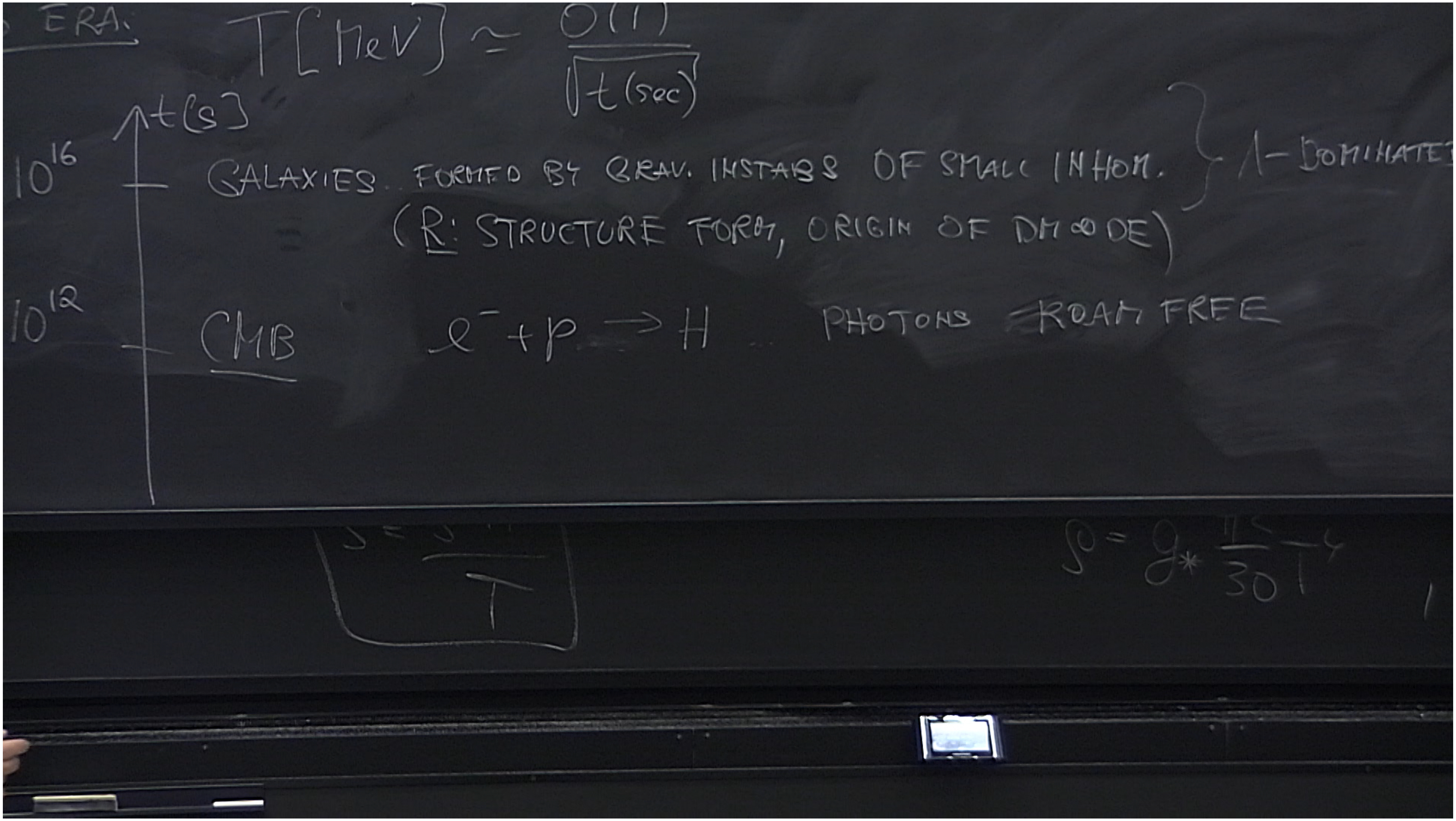
...ON # :

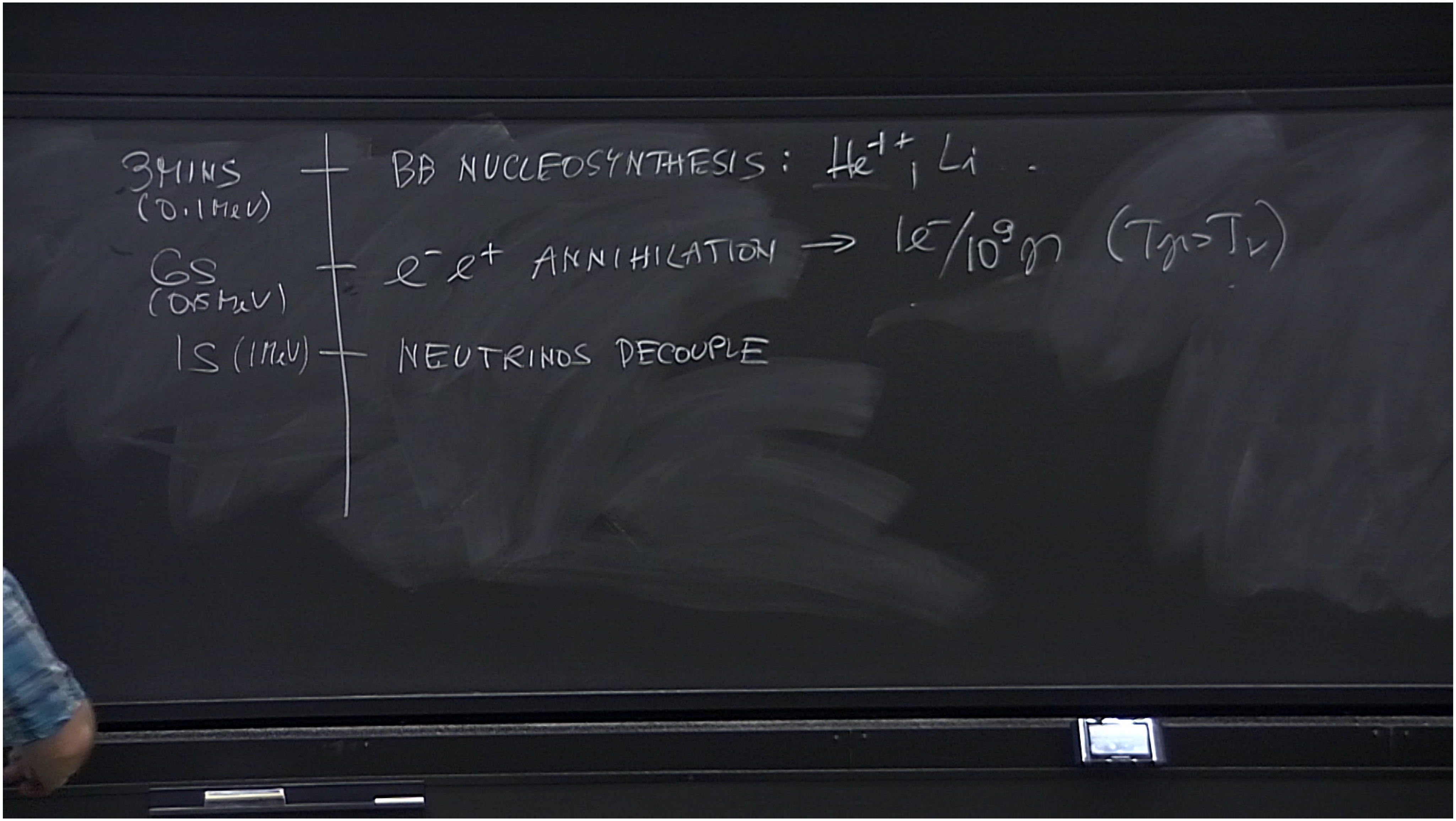
$\frac{\Delta \nu_i}{\ } = \text{CONST}$ $\quad i = e, \mu, \tau$

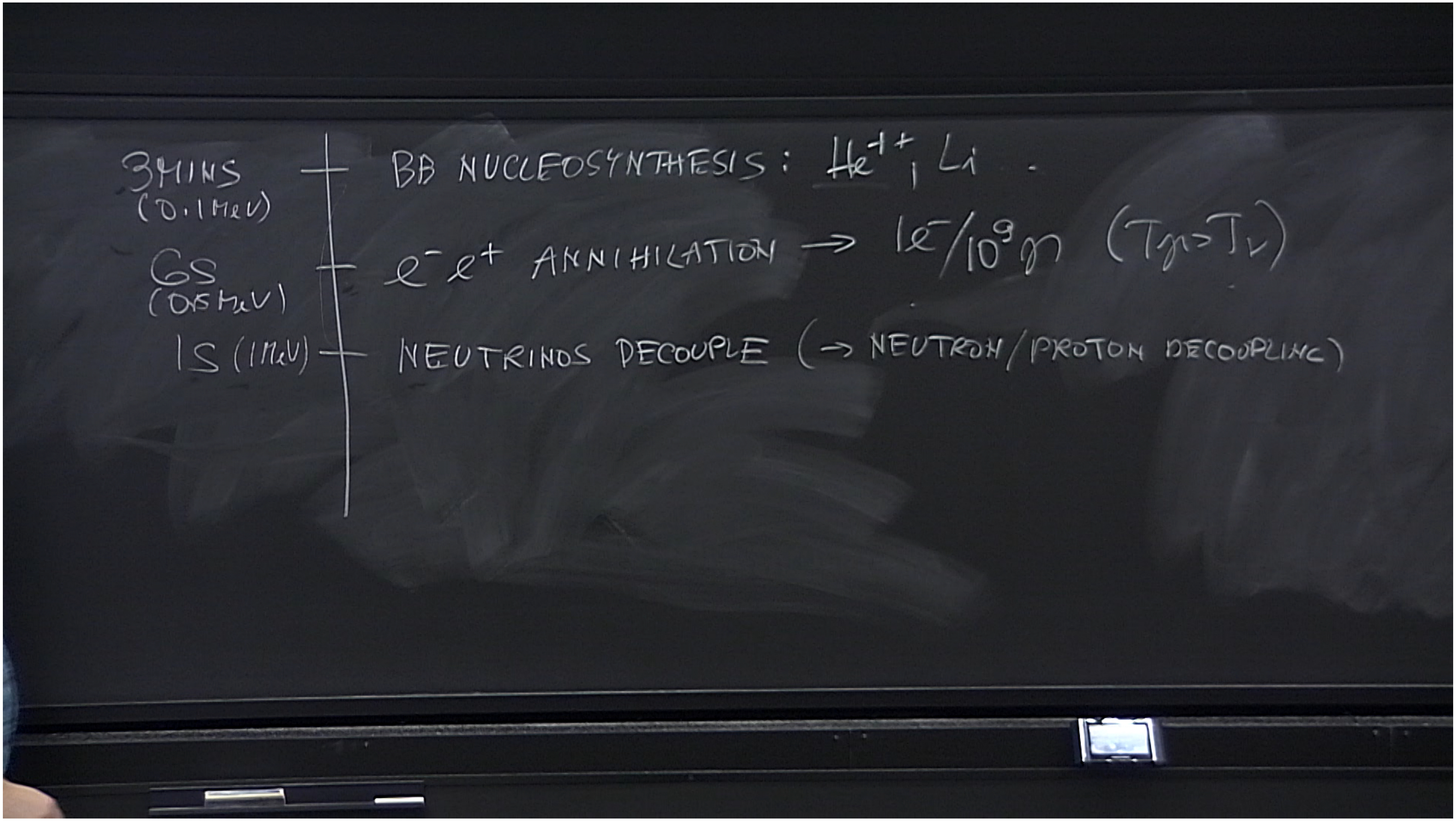

b) BRIEF THERMAL HISTORY
t ↔ η ↔ a ↔ T ↔ z



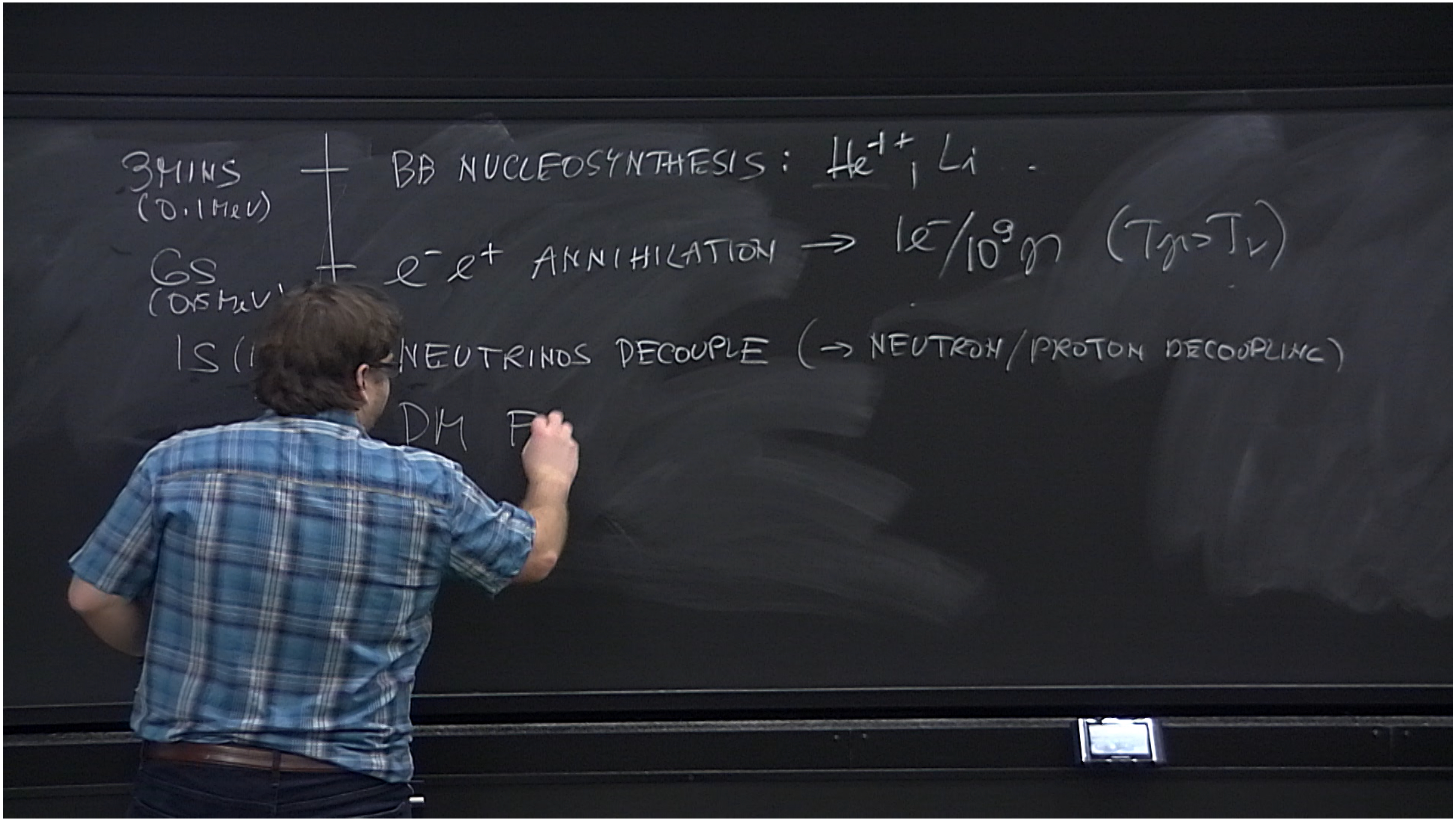
b) BRIEF THERMAL HISTORY
t ⇔ η ⇔ a ⇔ T ⇔ z
RAD ERA.
T [MeV] ≃ O(1) / √t (sec)
t [s]
10^16
GALAXIES FORMED BY GRAV. INSTABS OF SMALL INHOM.


ERA.
T[MeV] ≃ O(1) / √t(sec)
t[s]
10^16
GALAXIES .. FORMED BY GRAV. INSTABS OF SMALL INHOM.
(R: STRUCTURE FORM, ORIGIN OF DM & DE)
Λ-DOMINATED
10^12
CMB
e⁻ + p → H ...
PHOTONS ROAM FREE
ρ = g* π²/30 T⁴

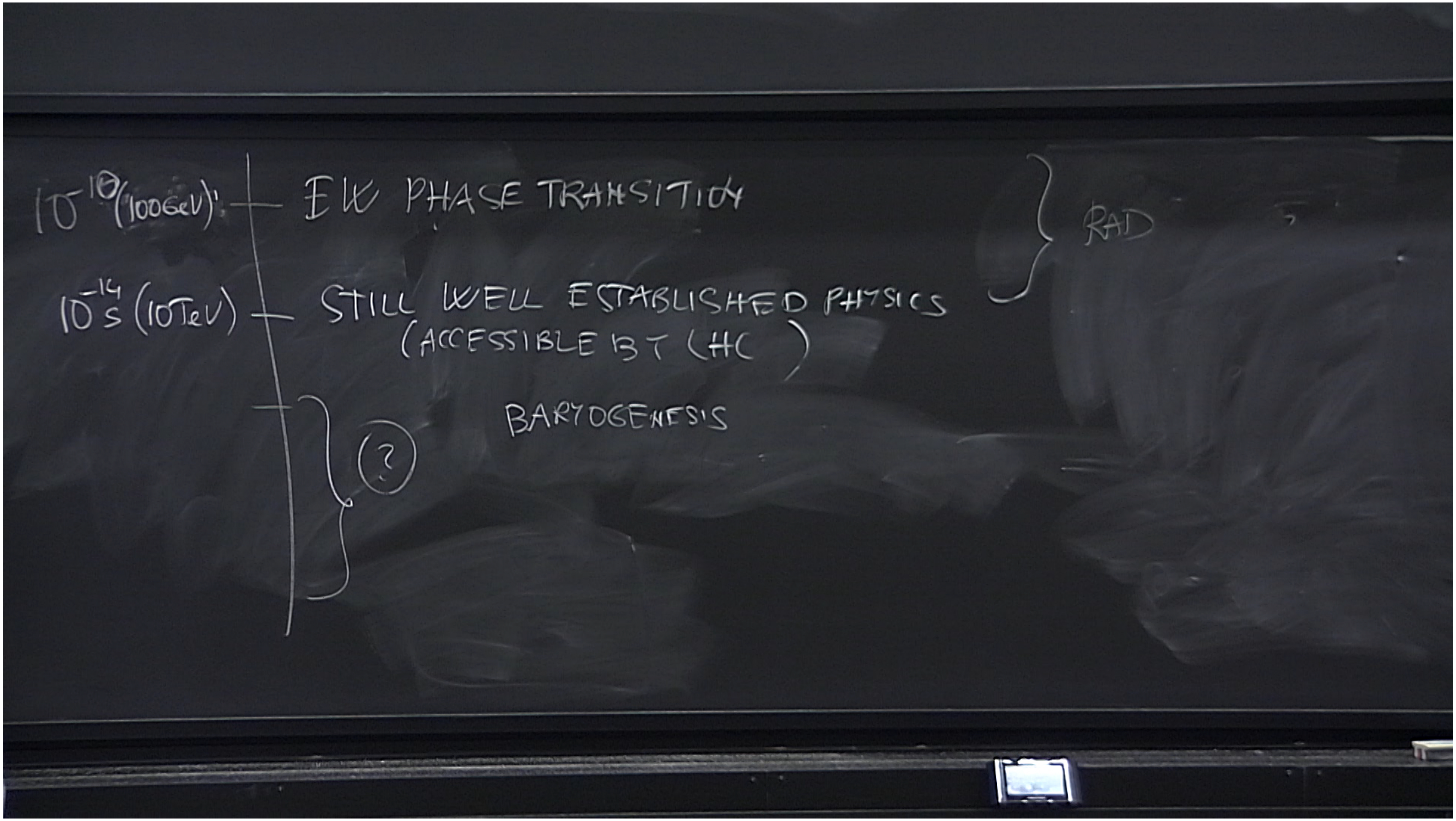

3MINS (0.1MeV)
BB NUCLEOSYNTHESIS: He⁺⁺, Li ..
6S (0.5MeV)
e⁻e⁺ ANNIHILATION → 1e⁻/10⁹γ (Tγ>Tν)
1S (1MeV)
NEUTRINOS DECOUPLE

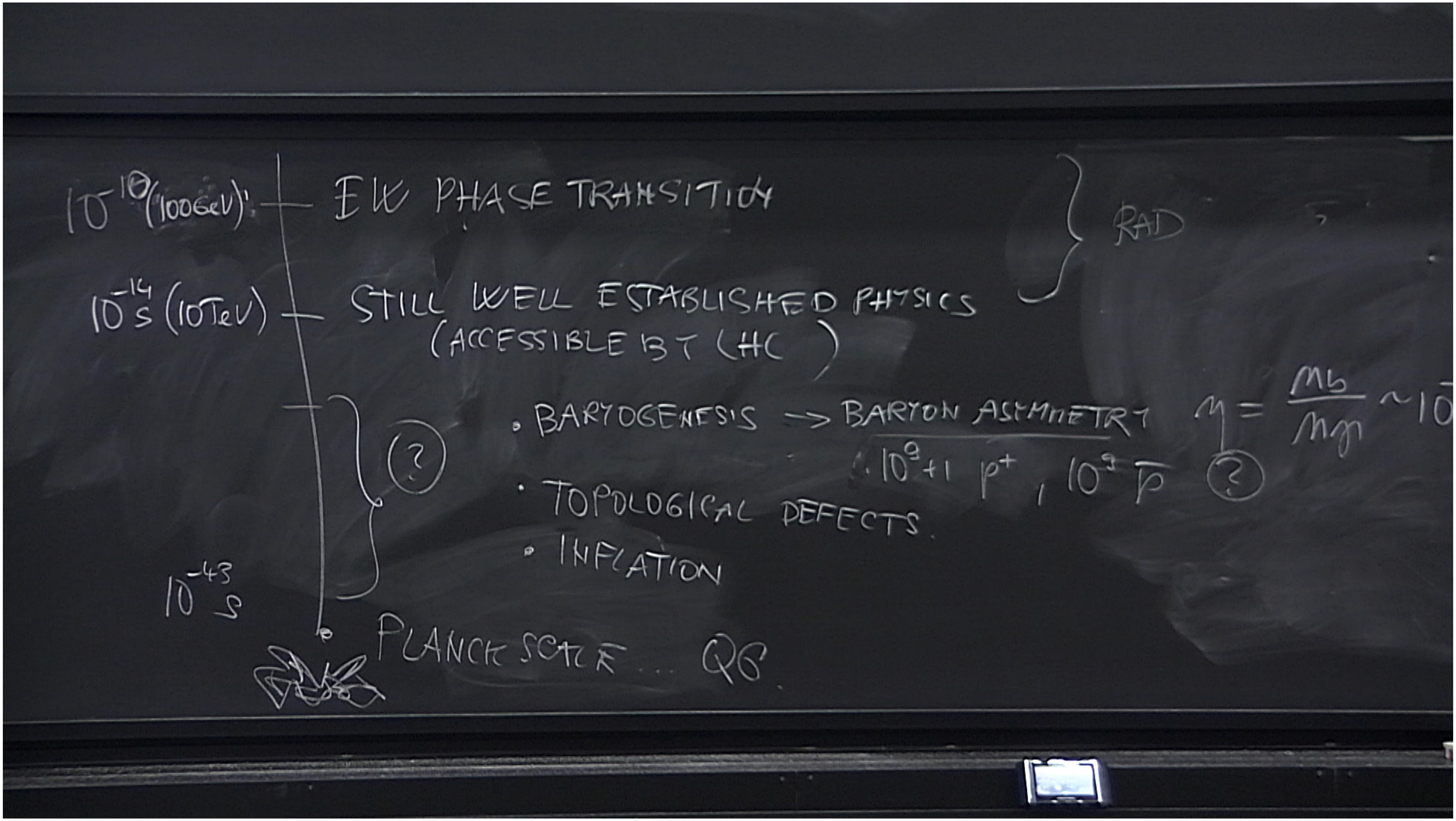


3MINS (0.1MeV) — BB NUCLEOSYNTHESIS: He++, Li ..
6S (0.5MeV) — e⁻e⁺ ANNIHILATION → 1e⁻/10⁹γ (Tγ>Tν)
1S (1MeV) — NEUTRINOS DECOUPLE (→ NEUTRON/PROTON DECOUPLING)

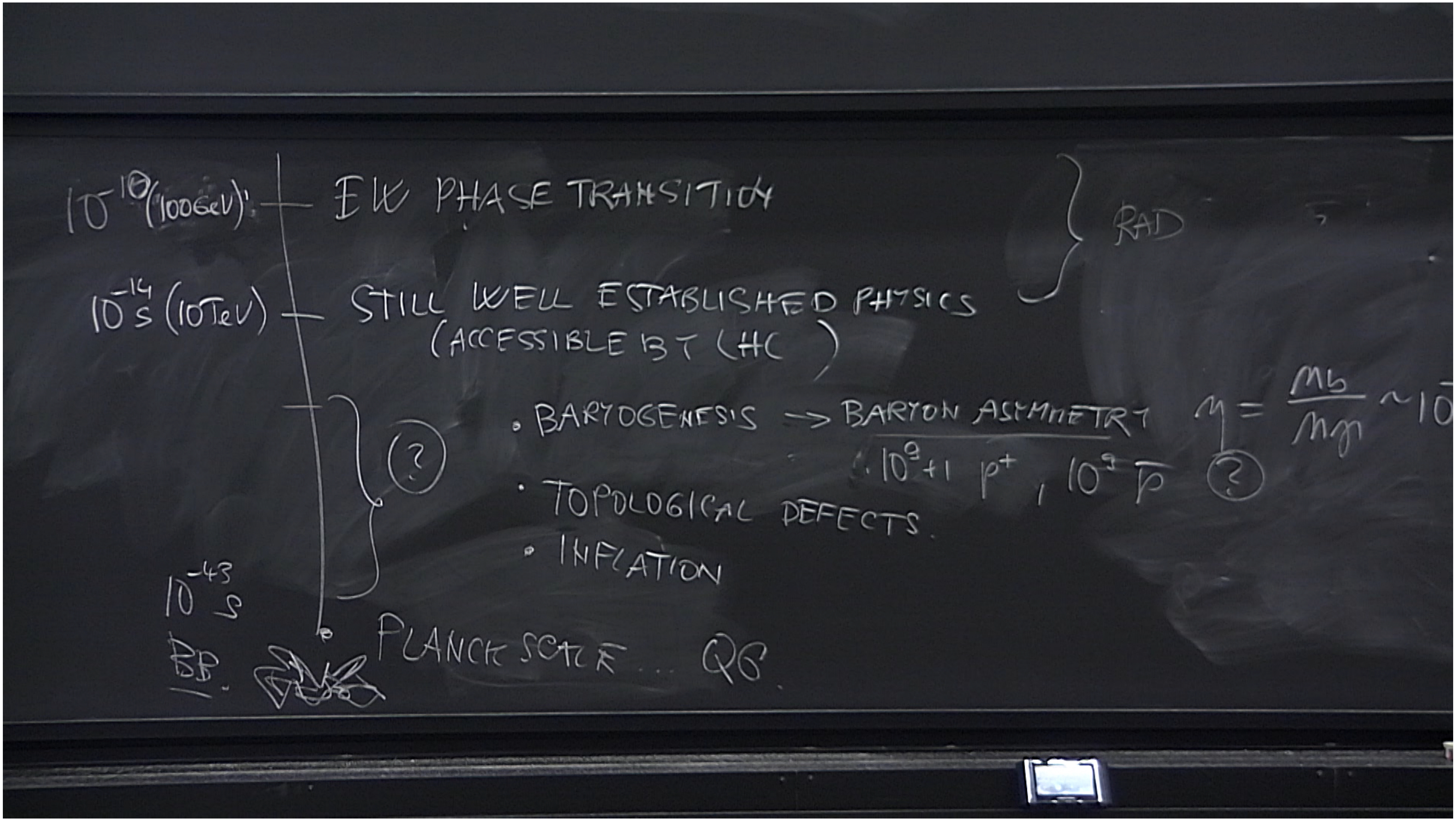


3MINS
(0.1MeV)
BB NUCLEOSYNTHESIS: He++, Li ..
6S
e- e+ ANNIHILATION → 1e-/10^9 γ (Tγ>Tν)
NEUTRINOS DECOUPLE (→ NEUTRON/PROTON DECOUPLING)
DM


10^{-10} (100GeV)
EW PHASE TRANSITION
10^{-14} s (10TeV)
STILL WELL ESTABLISHED PHYSICS
(ACCESSIBLE BY LHC)
BARYOGENESIS
?
RAD



10^-10 (100GeV) — EW PHASE TRANSITION
RAD
10^-14 s (10TeV) — STILL WELL ESTABLISHED PHYSICS
(ACCESSIBLE BY LHC)
• BARYOGENESIS → BARYON ASYMMETRY
10^9+1 p+ , 10^9 p̄
• TOPOLOGICAL DEFECTS
• INFLATION
10^-43 s
PLANCK SCALE ... QG


10^-10 (100GeV)
EW PHASE TRANSITION
RAD
10^-14 s (10TeV)
STILL WELL ESTABLISHED PHYSICS
(ACCESSIBLE BY LHC)
• BARYOGENESIS -> BARYON ASYMMETRY
10^9+1 p+, 10^9 p̄
η = nb/nγ ~10
• TOPOLOGICAL DEFECTS
• INFLATION
10^-43 s
PLANCK SCALE ... QG
BB