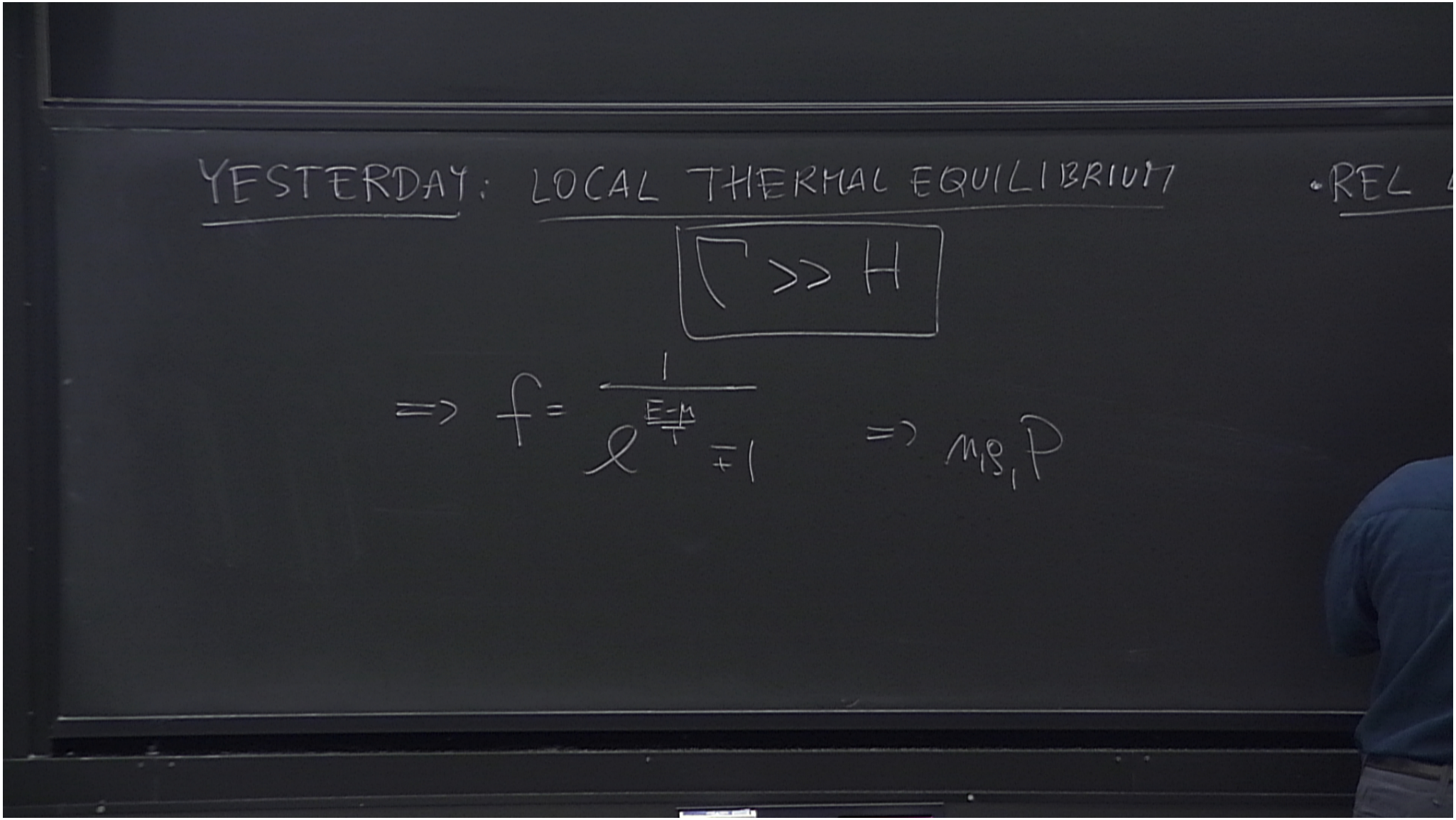
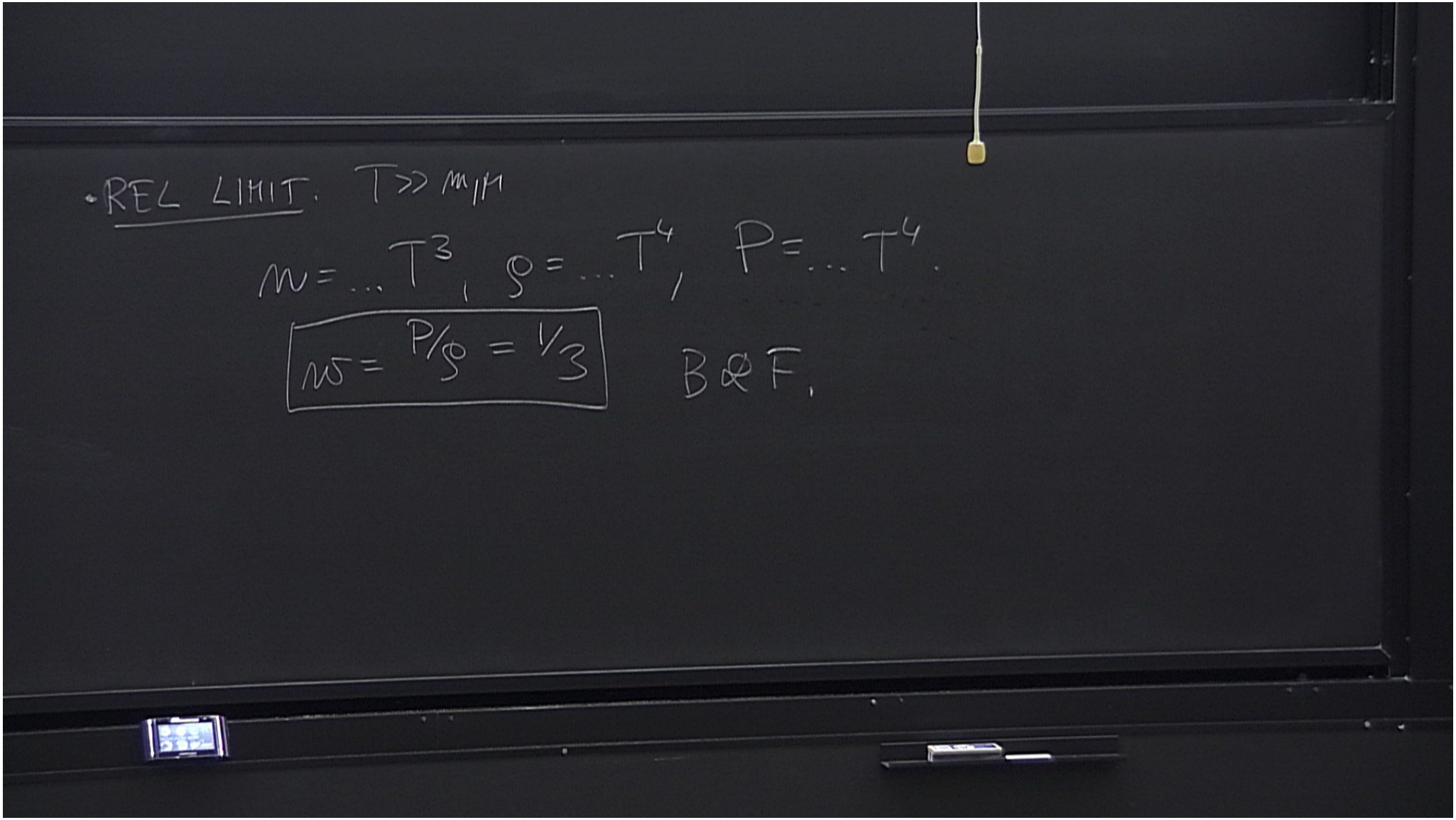
Title: PSI 2015/2016 Cosmology - Lecture 5

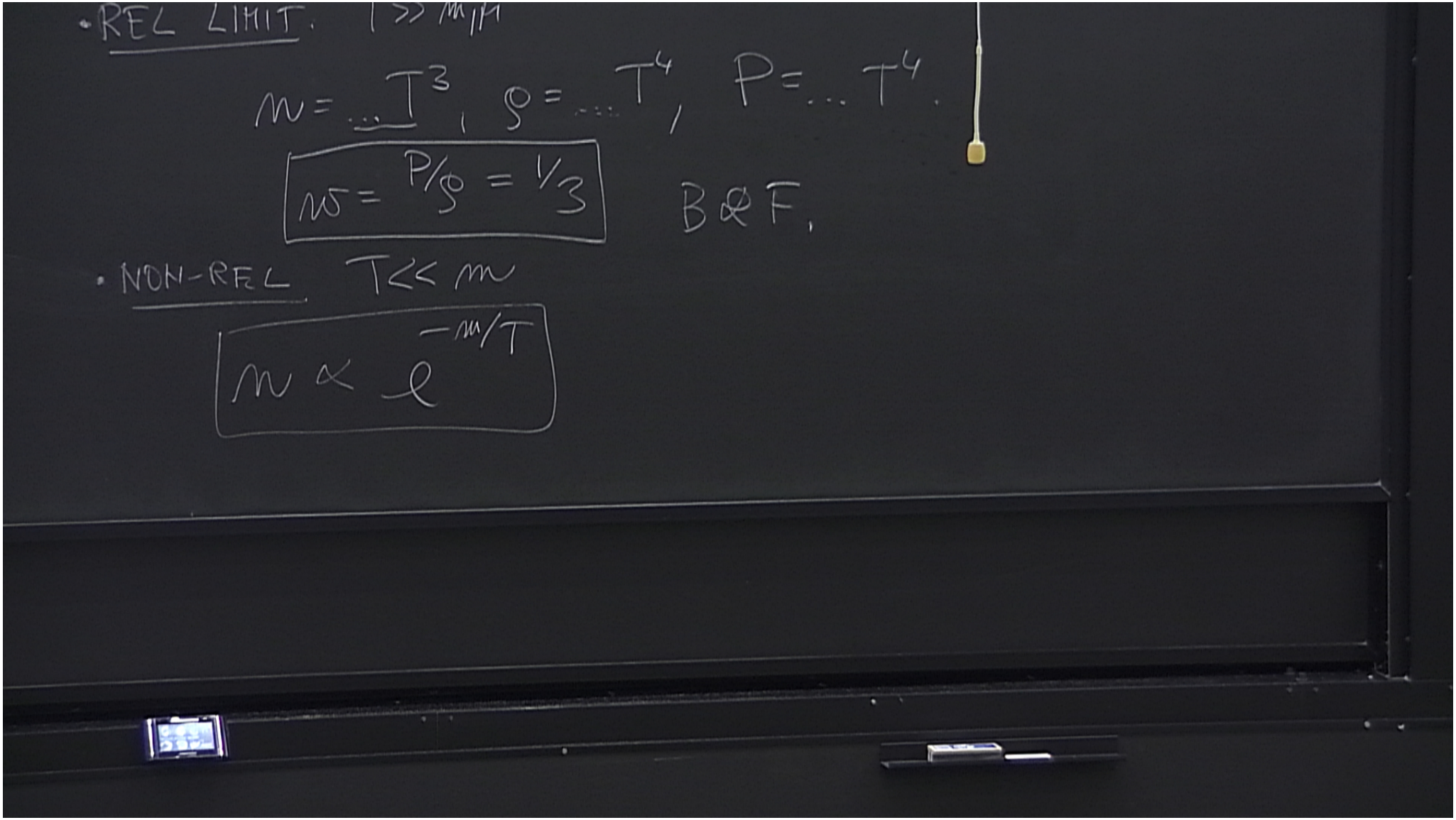
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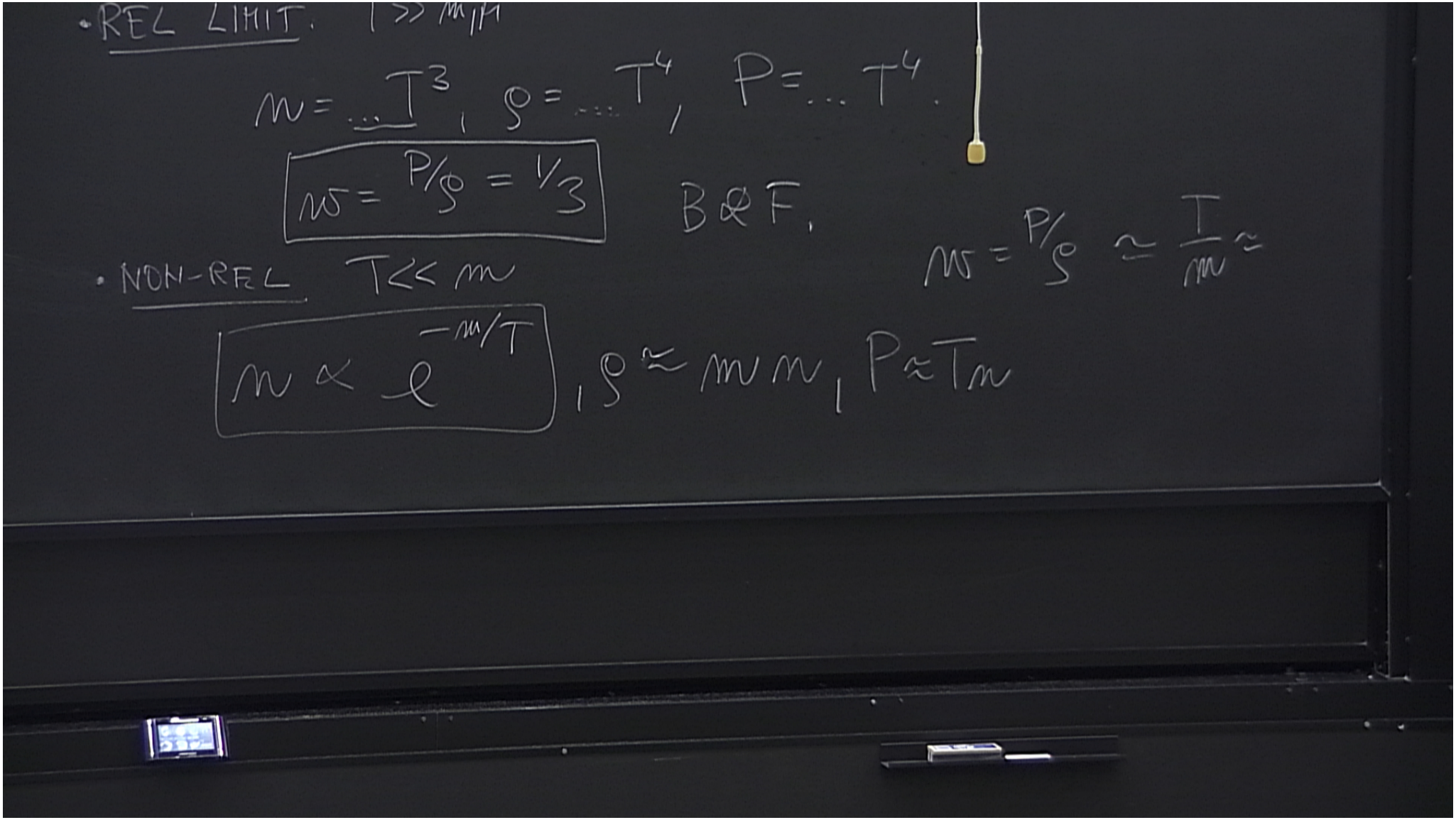
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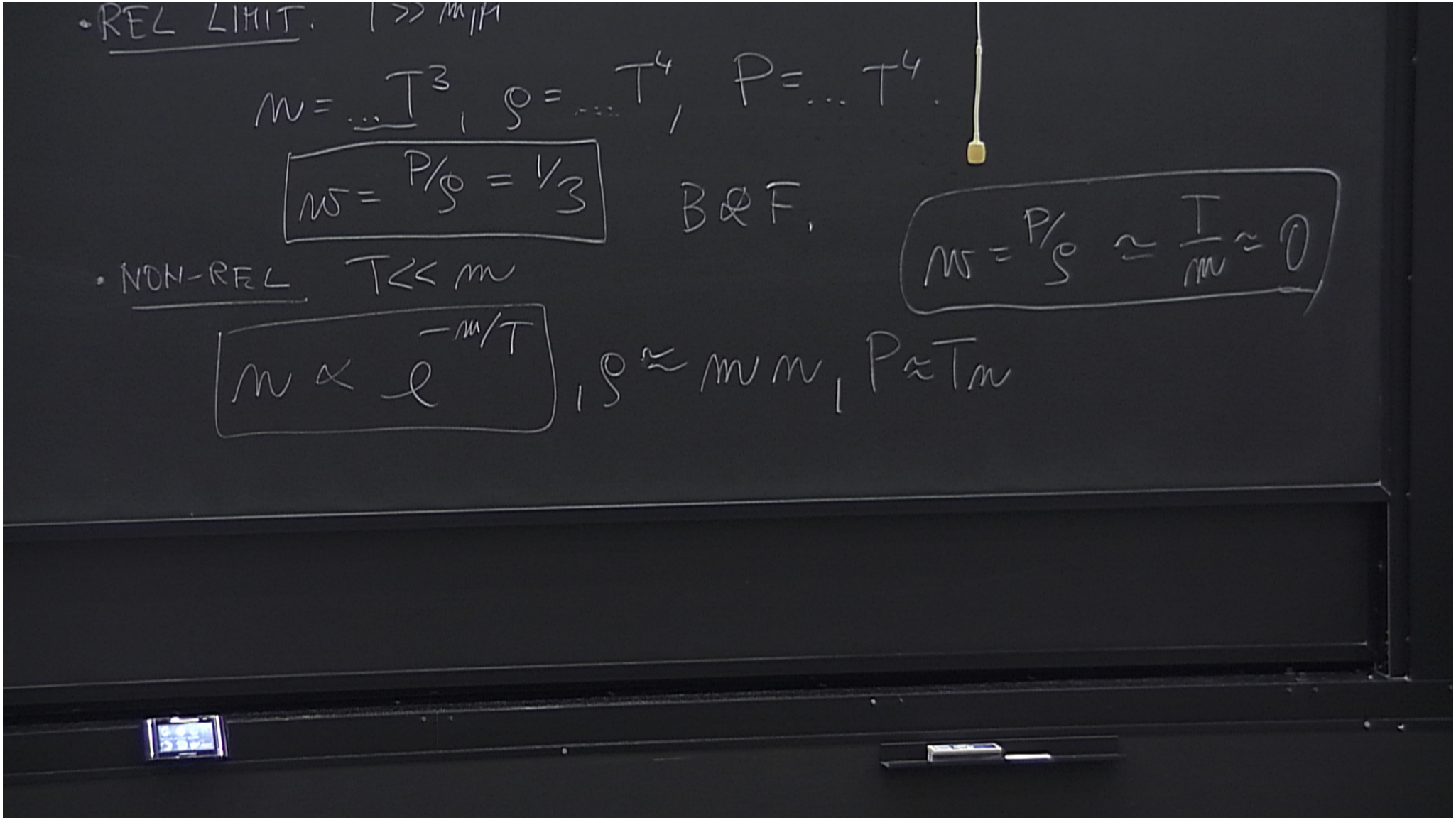
Abstract:

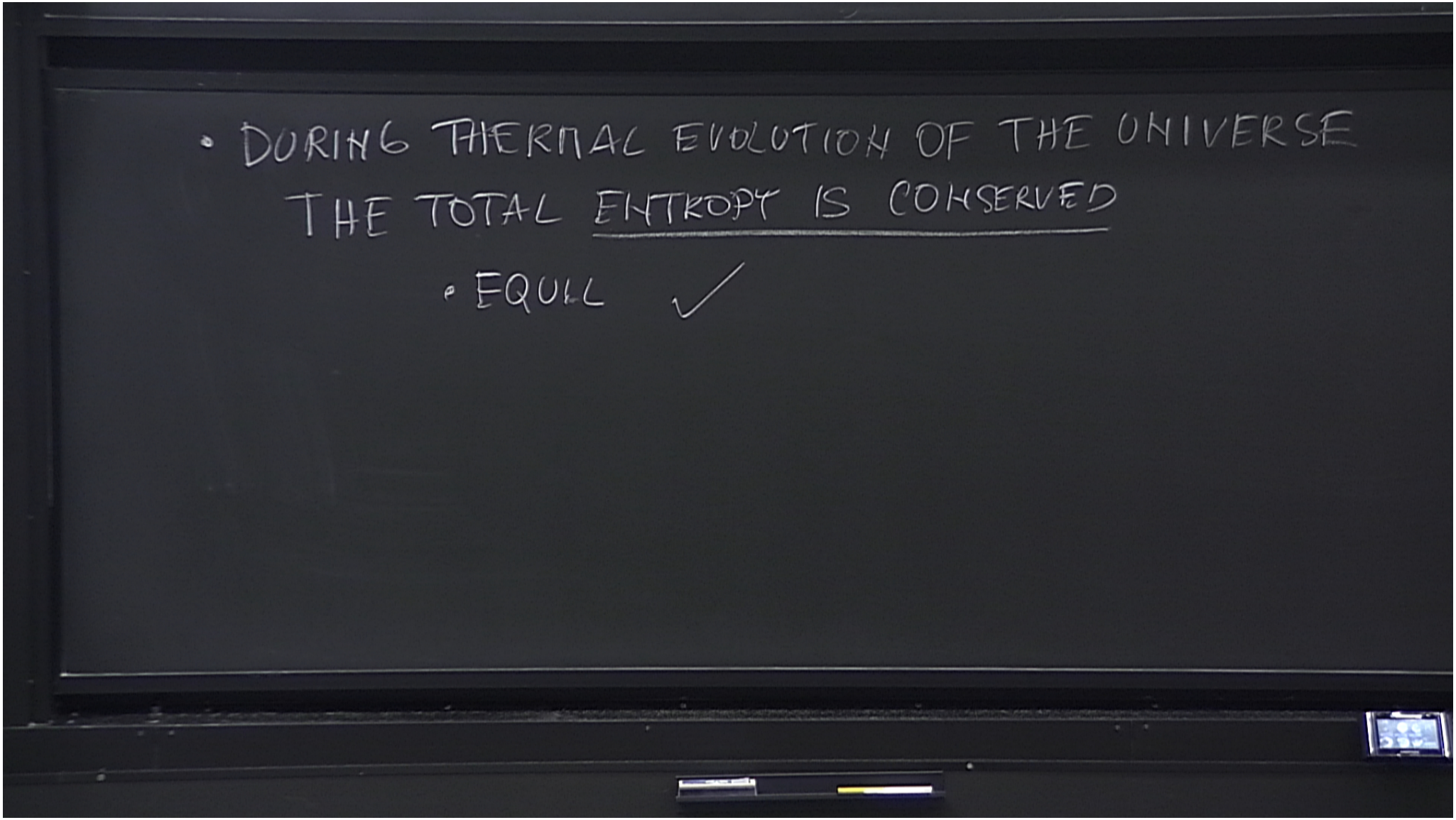

YESTERDAY: LOCAL THERMAL EQUILIBRIUM
• REL
Γ >> H
=> f = 1 / e^((E-μ)/T) ± 1
=> MB, P

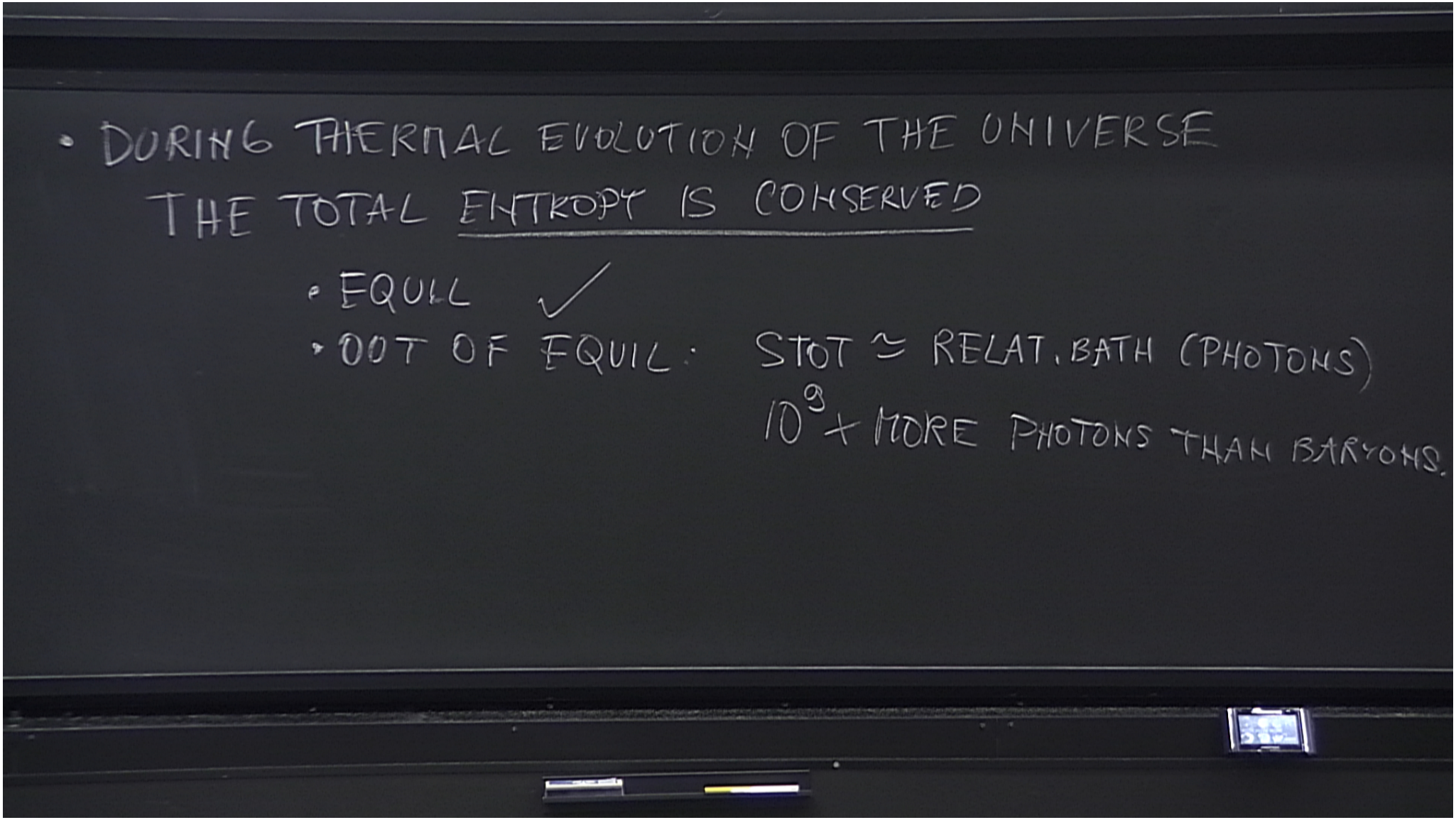

• REL LIMIT. T >> m/H
n = ... T^3, ρ = ... T^4, P = ... T^4.
w = P/ρ = 1/3
B & F.

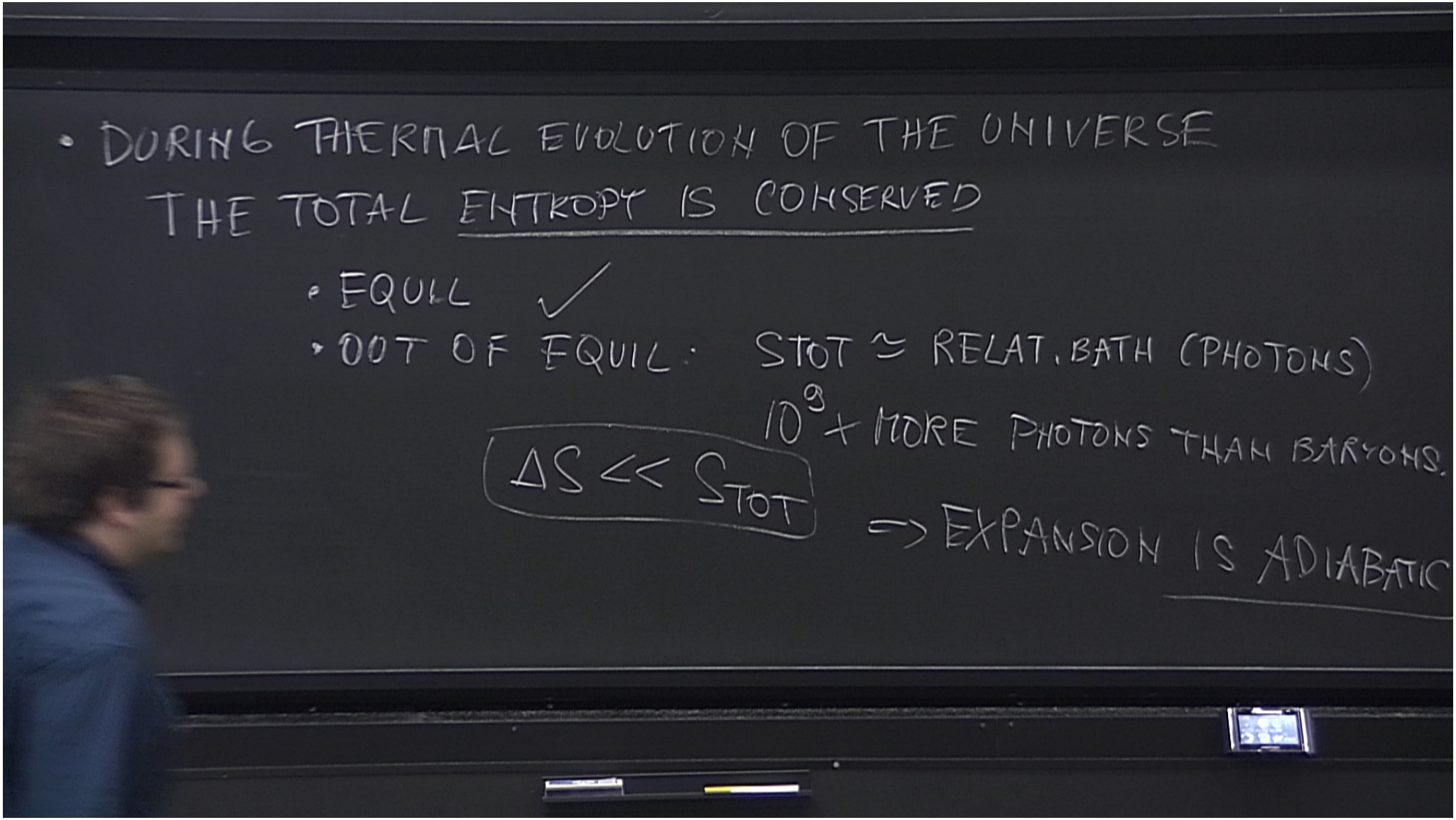

• REL LIMIT. T >> m/H
n = ... T^3, ρ = ... T^4, P = ... T^4.
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B & F.
• NON-REL T << m
n ∝ e^{-m/T}

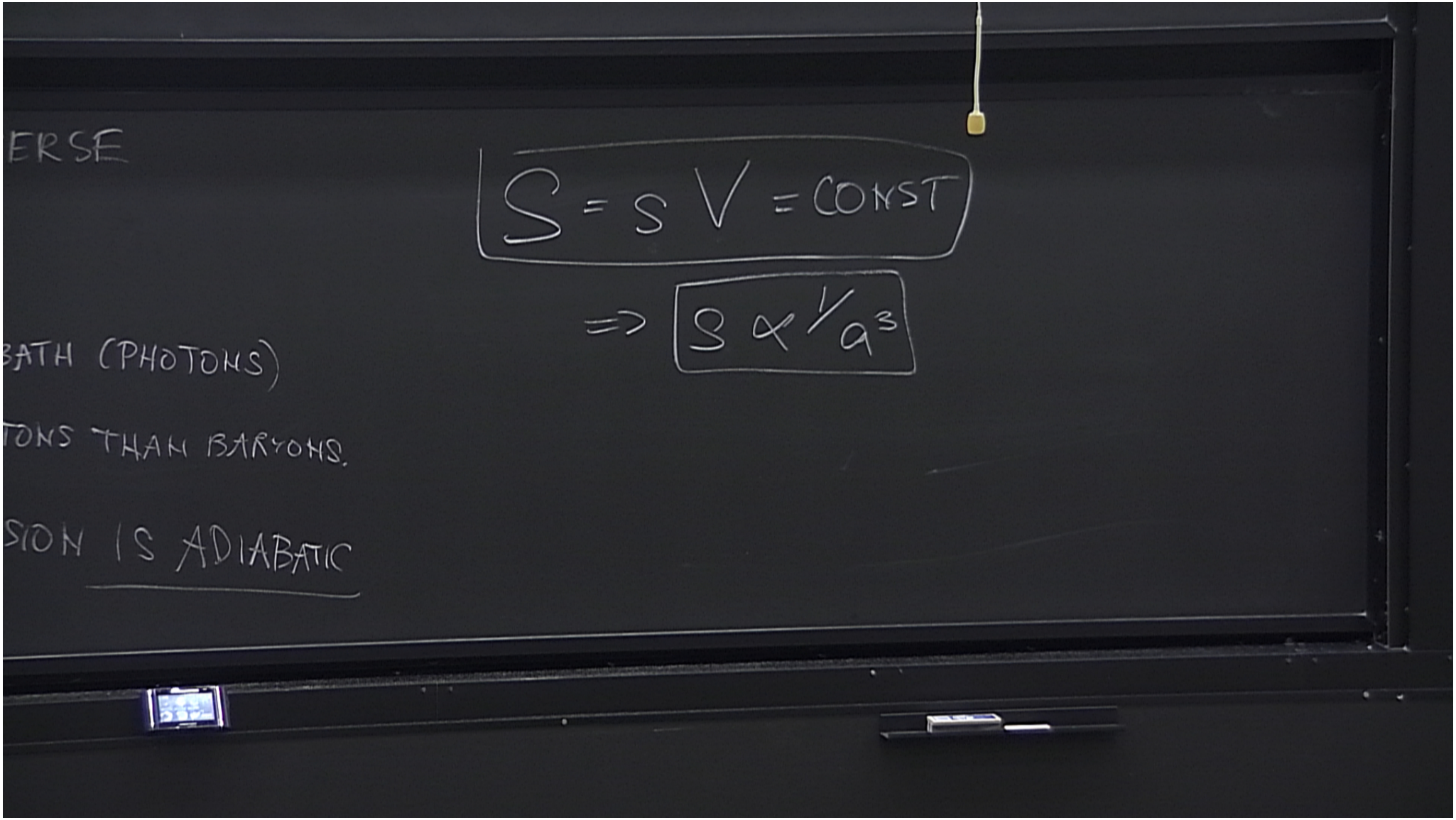

• REL LIMIT. T >> m/H
n = ... T^3, ρ = ... T^4, P = ... T^4.
w = P/ρ = 1/3
B & F.
• NON-REL T << m
n ∝ e^{-m/T}, ρ ≃ m n, P ≃ T n
w = P/ρ ≃ I/m ≃


• REL LIMIT. T >> m/μ
n = ... T³, ρ = ... T⁴, P = ... T⁴.
w = P/ρ = 1/3
B&F.
w = P/ρ ≃ I/m ≃ 0
• NON-REL T << m
n ∝ e^(−m/T), ρ ≃ m n, P ≃ T n


• DURING THERMAL EVOLUTION OF THE UNIVERSE
THE TOTAL ENTROPY IS CONSERVED
• EQUIL


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THE TOTAL ENTROPY IS CONSERVED
• EQUIL ✓
• OUT OF EQUIL: STOT ≃ RELAT. BATH (PHOTONS)
10^9 × MORE PHOTONS THAN BARYONS.


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THE TOTAL ENTROPY IS CONSERVED
• EQUIL ✓
• OUT OF EQUIL: STOT ≃ RELAT. BATH (PHOTONS)
10^9 × MORE PHOTONS THAN BARYONS.
ΔS << STOT
⇒ EXPANSION IS ADIABATIC


ERSE
$S = s\,V = \text{CONST}$
$\Rightarrow s \propto 1/a^3$
BATH (PHOTONS)
TONS THAN BARYONS.
SION IS ADIABATIC

- CONSIDER A BATH OF REL. SPECIES & NEGLECT μ'S.
  $\Rightarrow \rho = \rho(T)$, $P = P(T)$, $s = s(T)$.

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$$\frac{\partial P}{\partial T} = \frac{\rho + P}{T} \qquad (H1)$$

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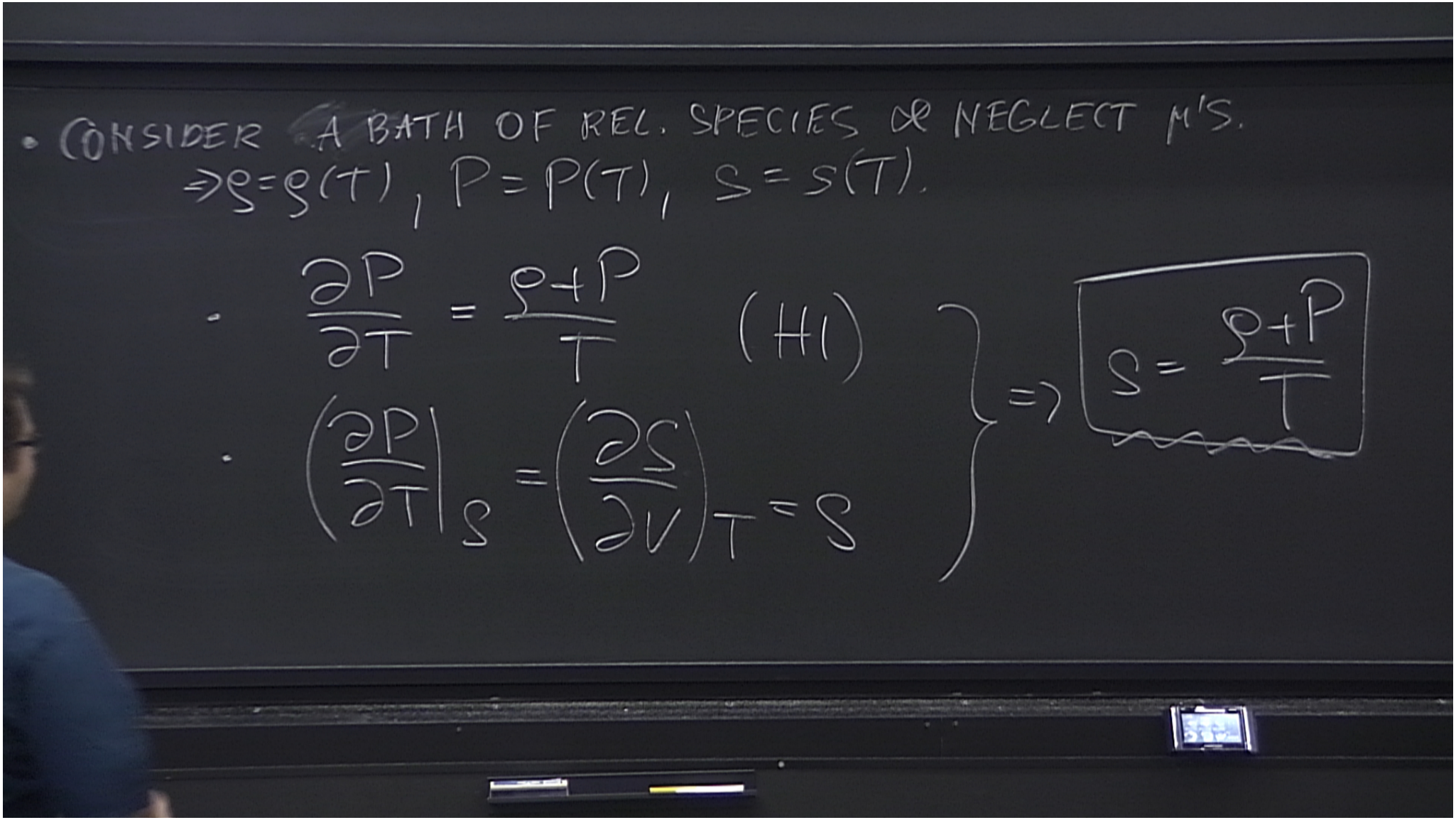
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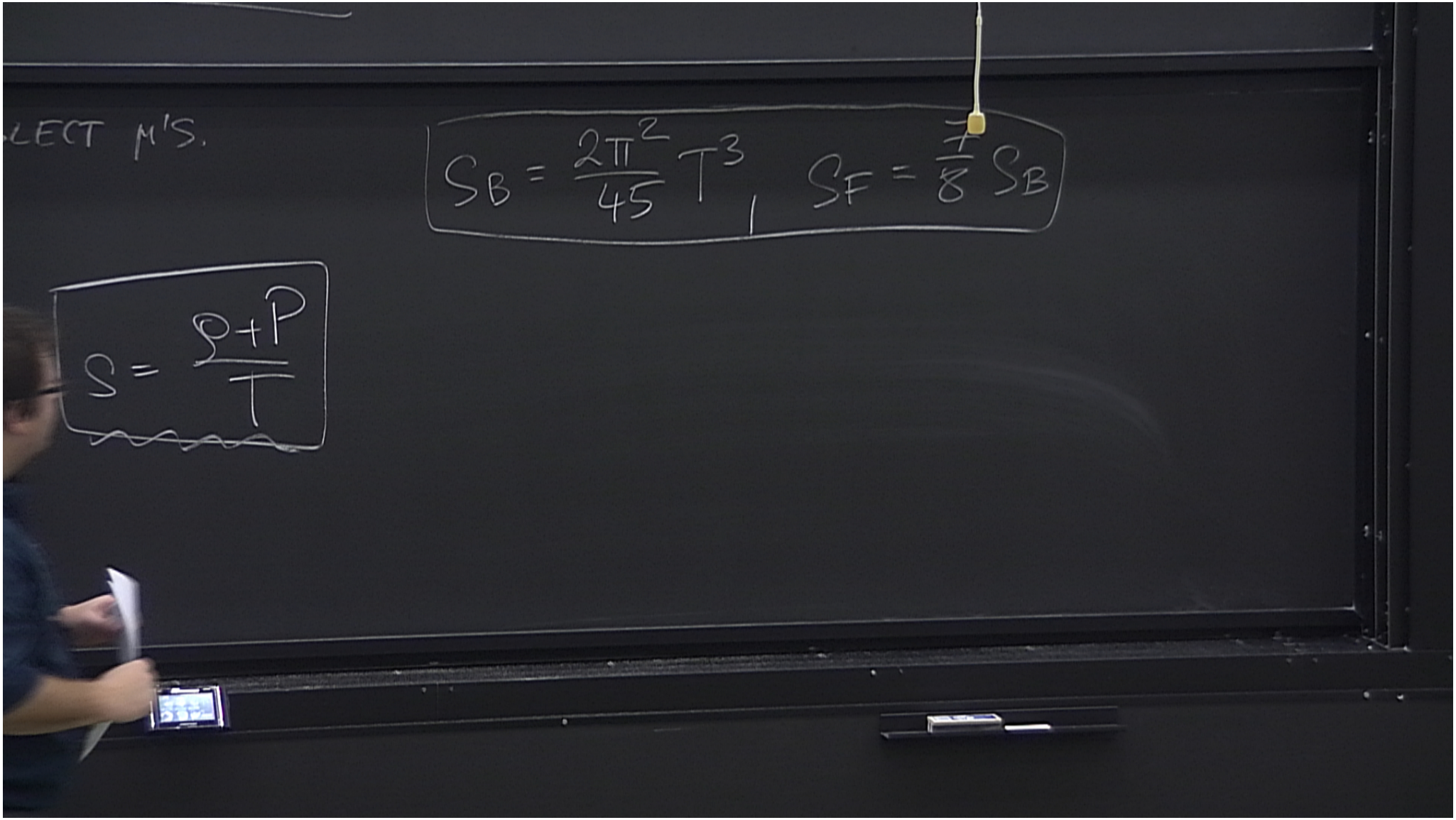
$$\left(\frac{\partial P}{\partial T}\right)_S = \left(\frac{\partial S}{\partial V}\right)_T$$

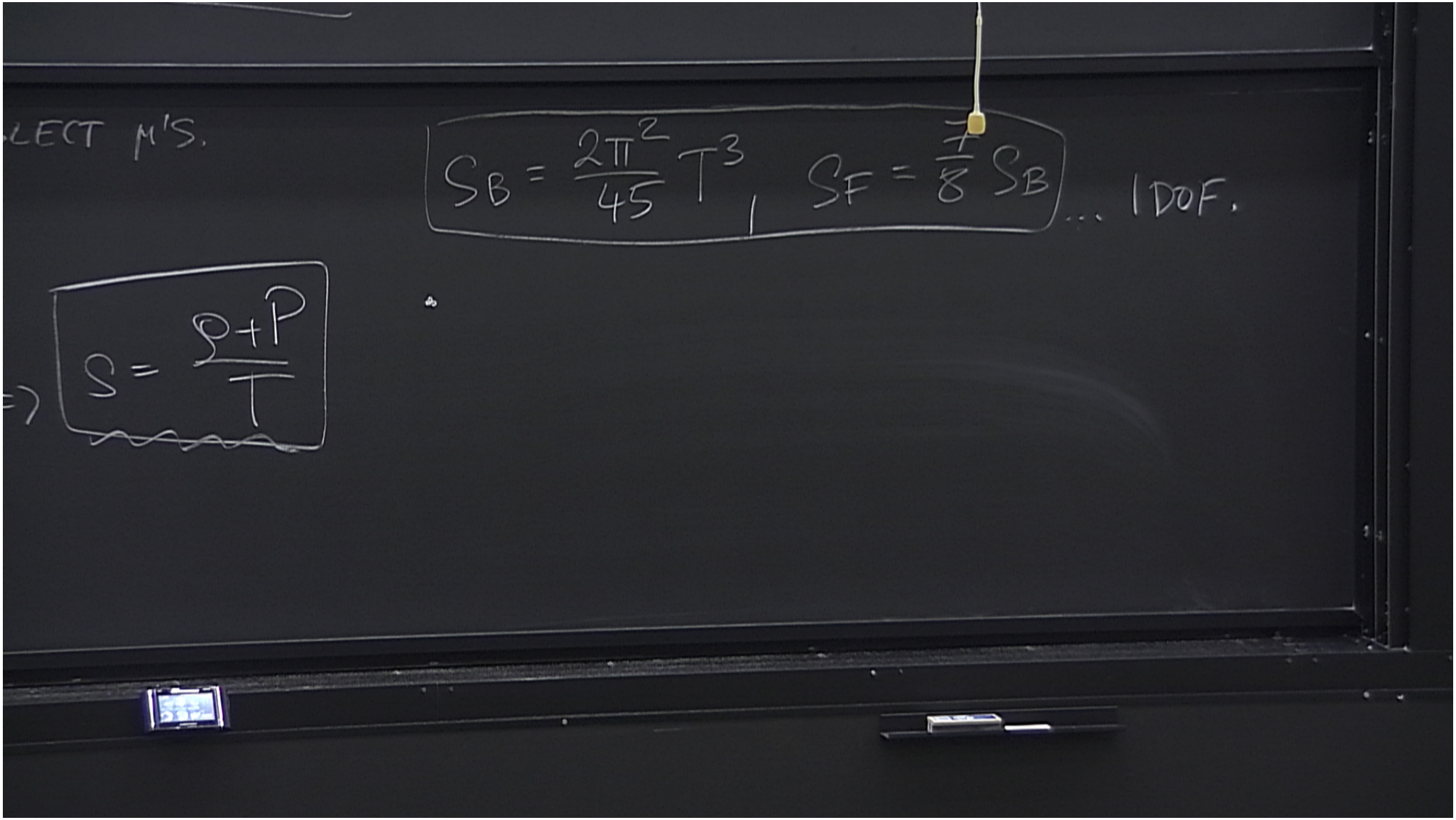
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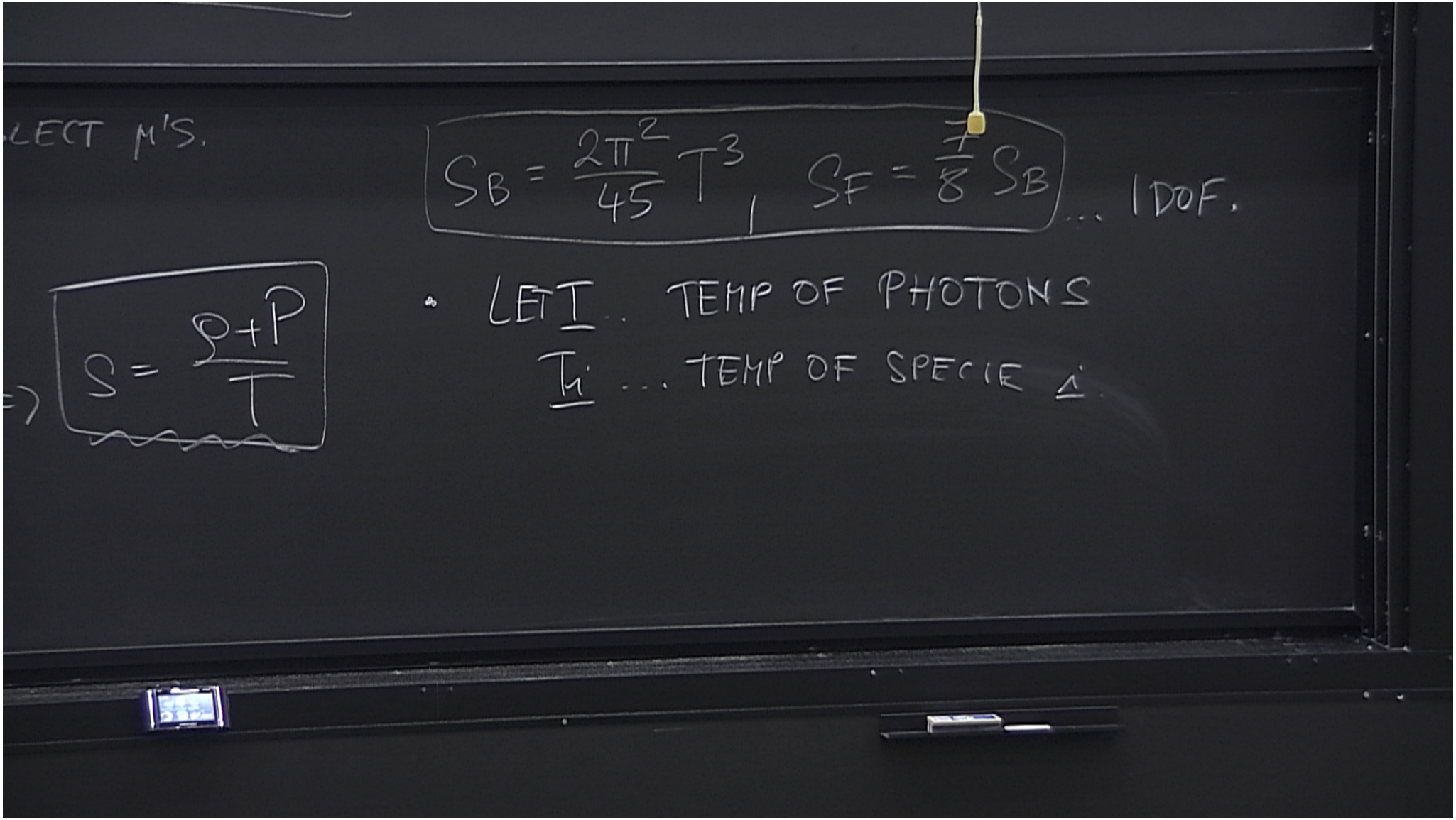
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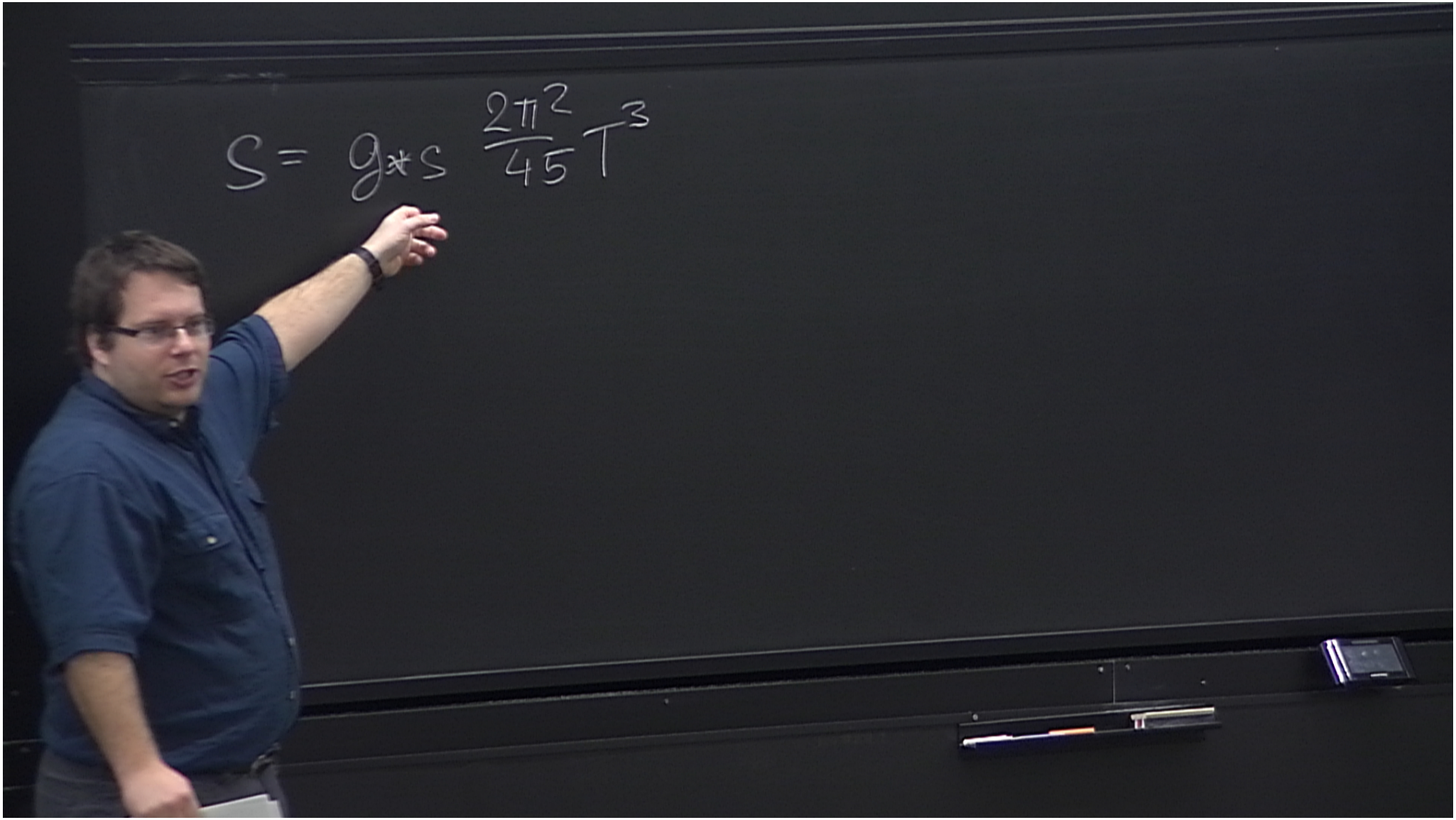
- $$\left(\frac{\partial P}{\partial T}\right)_S = \left(\frac{\partial S}{\partial V}\right)_T = S$$


• CONSIDER A BATH OF REL. SPECIES & NEGLECT M'S.
⇒ ρ = ρ(T), P = P(T), S = S(T).
$\frac{\partial P}{\partial T} = \frac{\rho + P}{T}$ (H1)
$\left(\frac{\partial P}{\partial T}\right)_S = \left(\frac{\partial S}{\partial V}\right)_T = S$
⇒
$S = \frac{\rho + P}{T}$


LECT M'S.
$S_B = \frac{2\pi^2}{45} T^3$, $S_F = \frac{7}{8} S_B$
$S = \frac{\rho + P}{T}$


LECT M'S.
$S_B = \frac{2\pi^2}{45} T^3$, $S_F = \frac{7}{8} S_B$ ... 1 DOF.
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LECT M'S.
$\rho_B = \frac{2\pi^2}{45} T^3$, $\rho_F = \frac{7}{8} \rho_B$ ... 1 DOF.
$s = \frac{\rho + P}{T}$
LET T ... TEMP OF PHOTONS
T_i ... TEMP OF SPECIE i

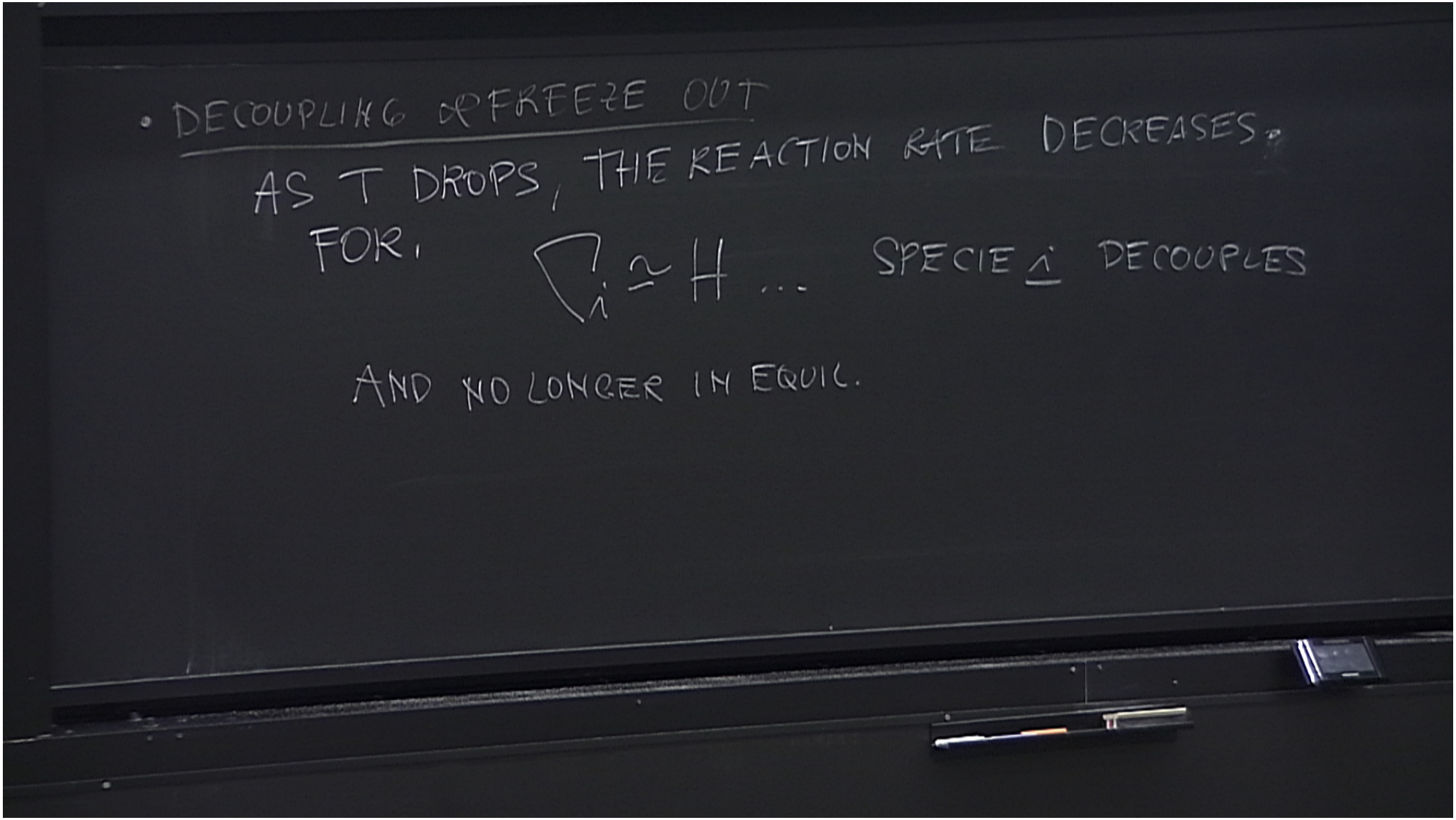

$S = g_{*S} \frac{2\pi^2}{45} T^3$

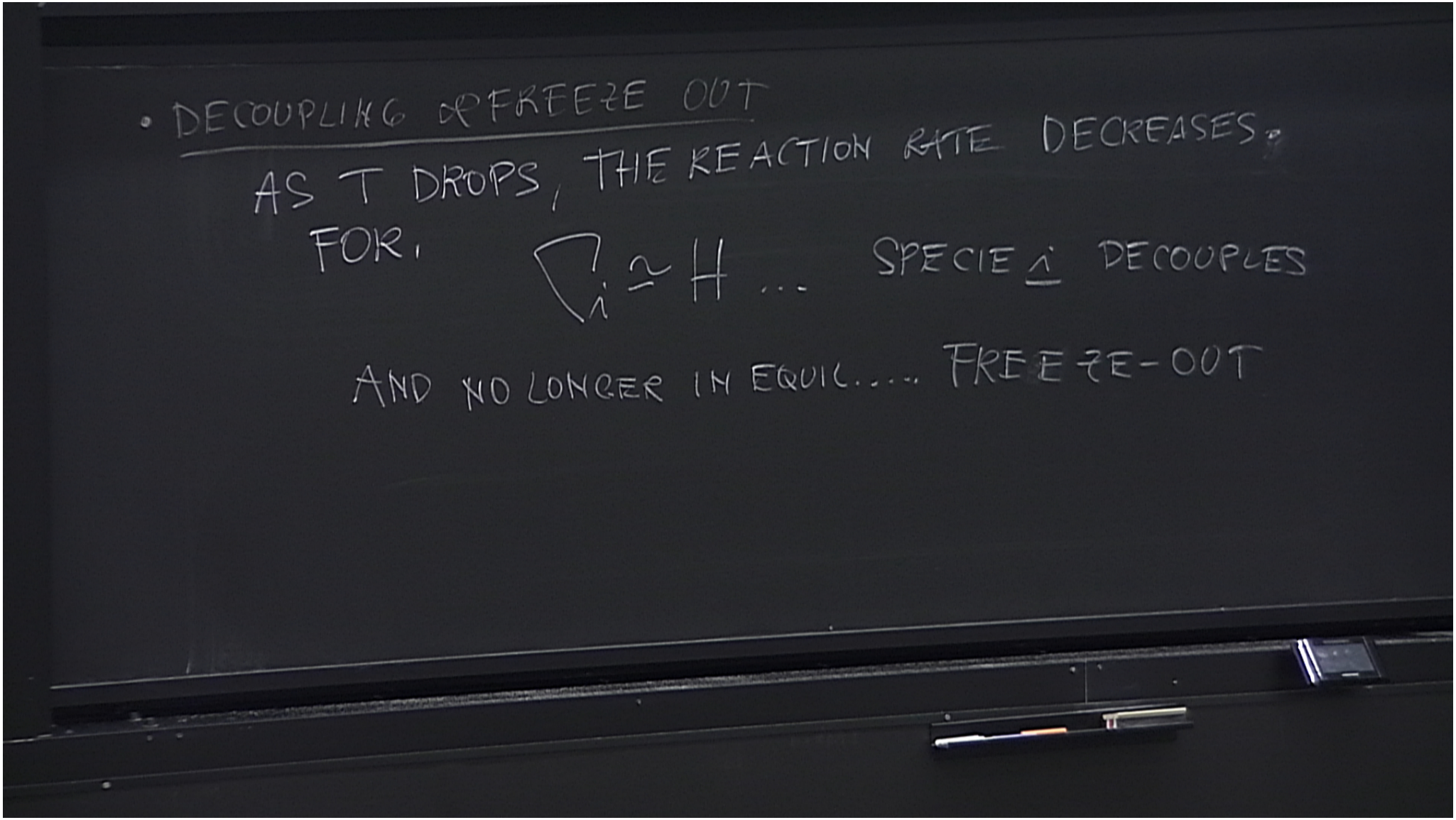
$$s = g_{*s} \frac{2\pi^2}{45} T^3 \quad , \quad g_{*s} = \sum_{\text{BOSONS}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{\text{FERMIONS}} g_i \left(\frac{T_i}{T}\right)^3$$

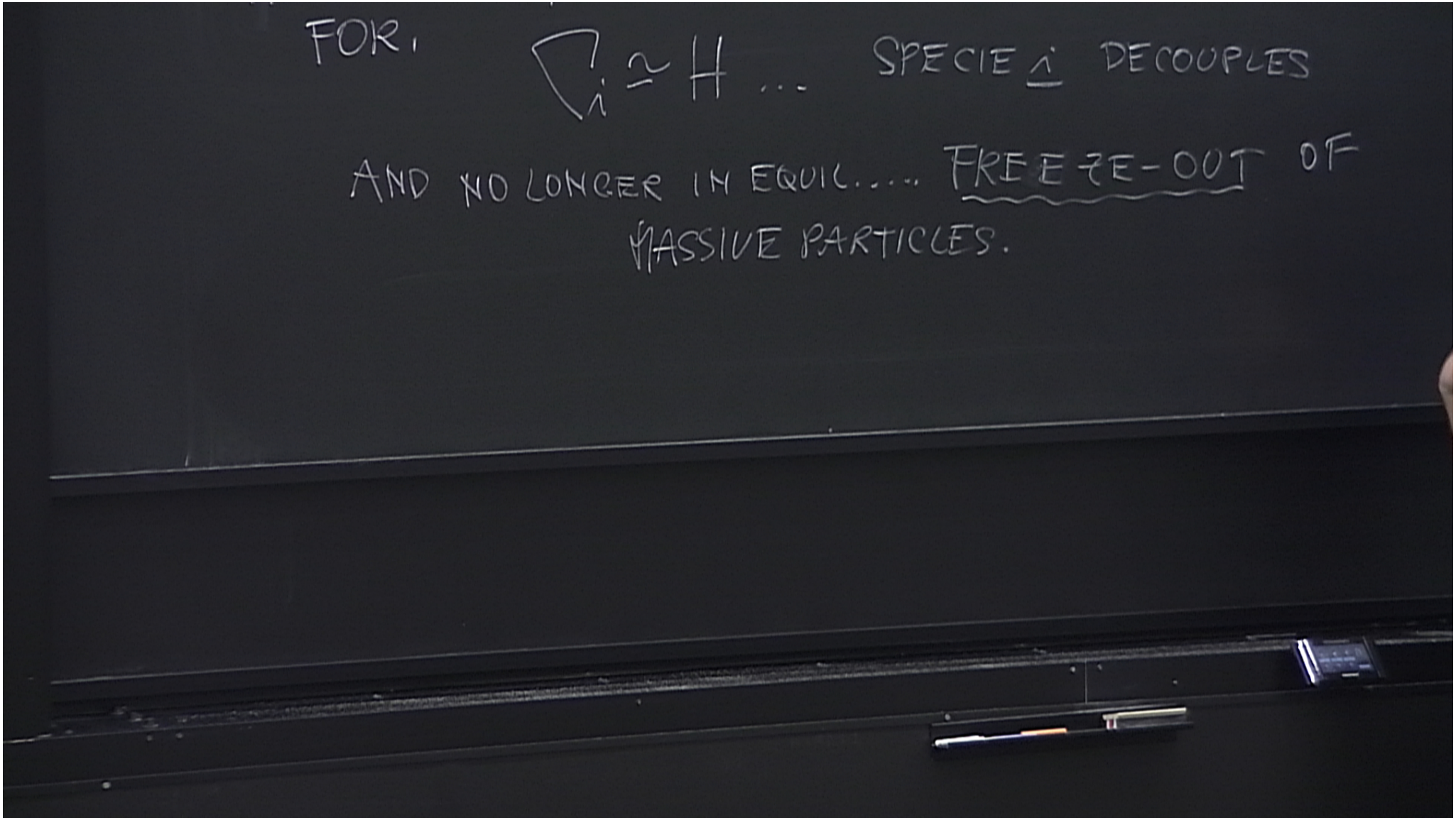
$$\rho = g_* \frac{\pi^2}{30} T^4$$

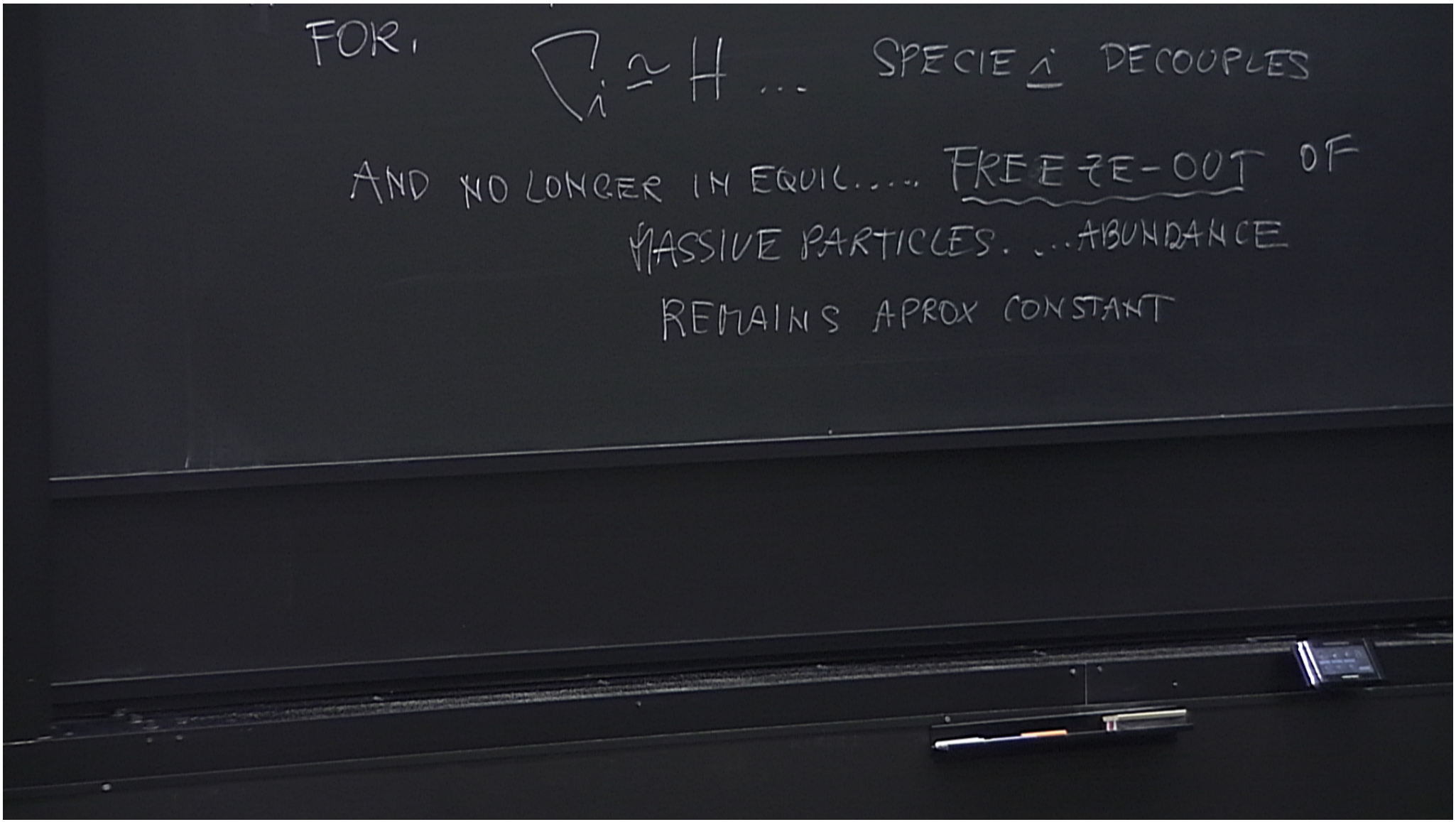
$$s = g_{*s}\,\frac{2\pi^2}{45}T^3 \quad , \quad g_{*s} = \sum_{\text{BOSONS}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8}\sum_{\text{FERMIONS}} g_i \left(\frac{T_i}{T}\right)^3$$

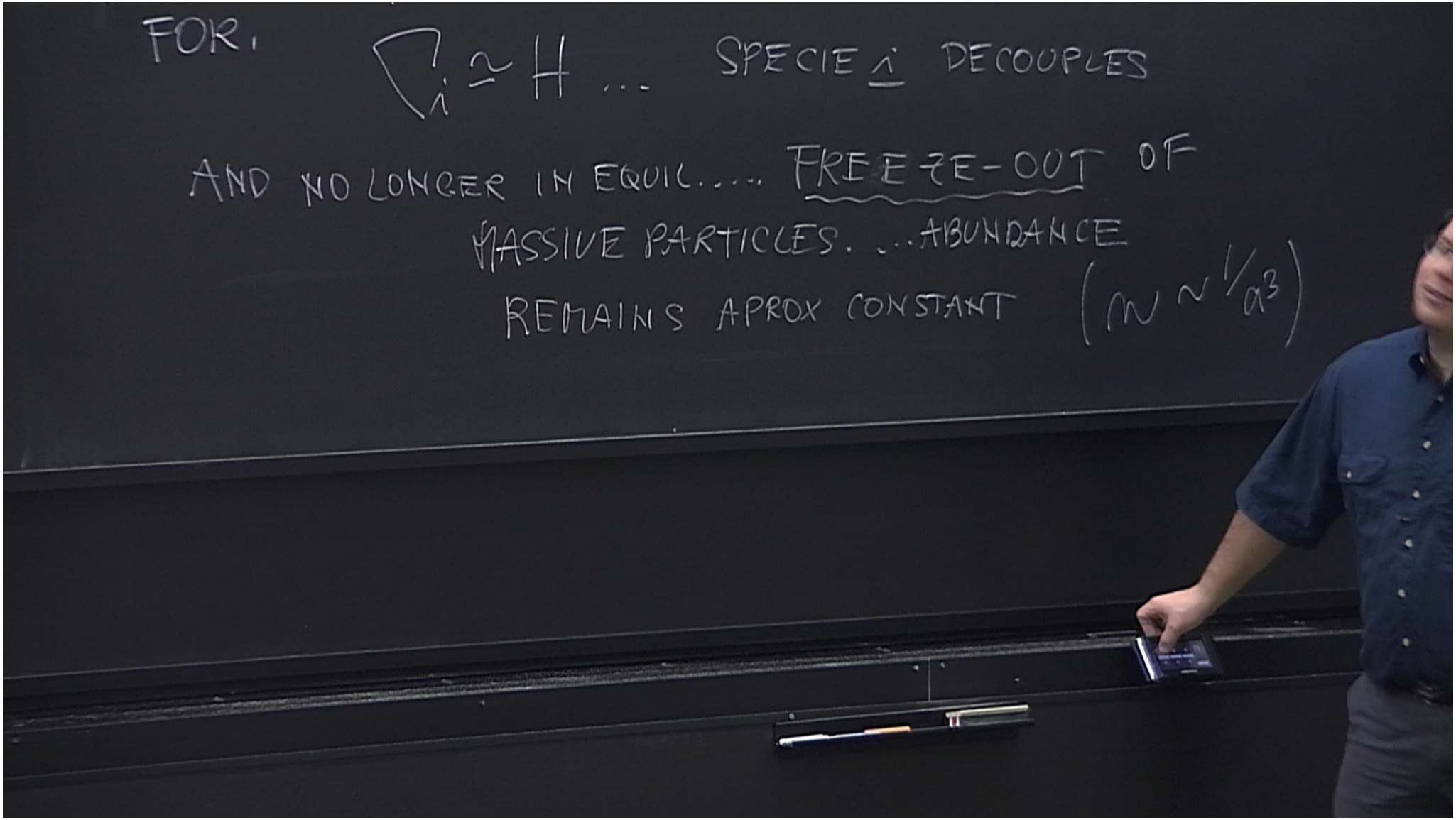
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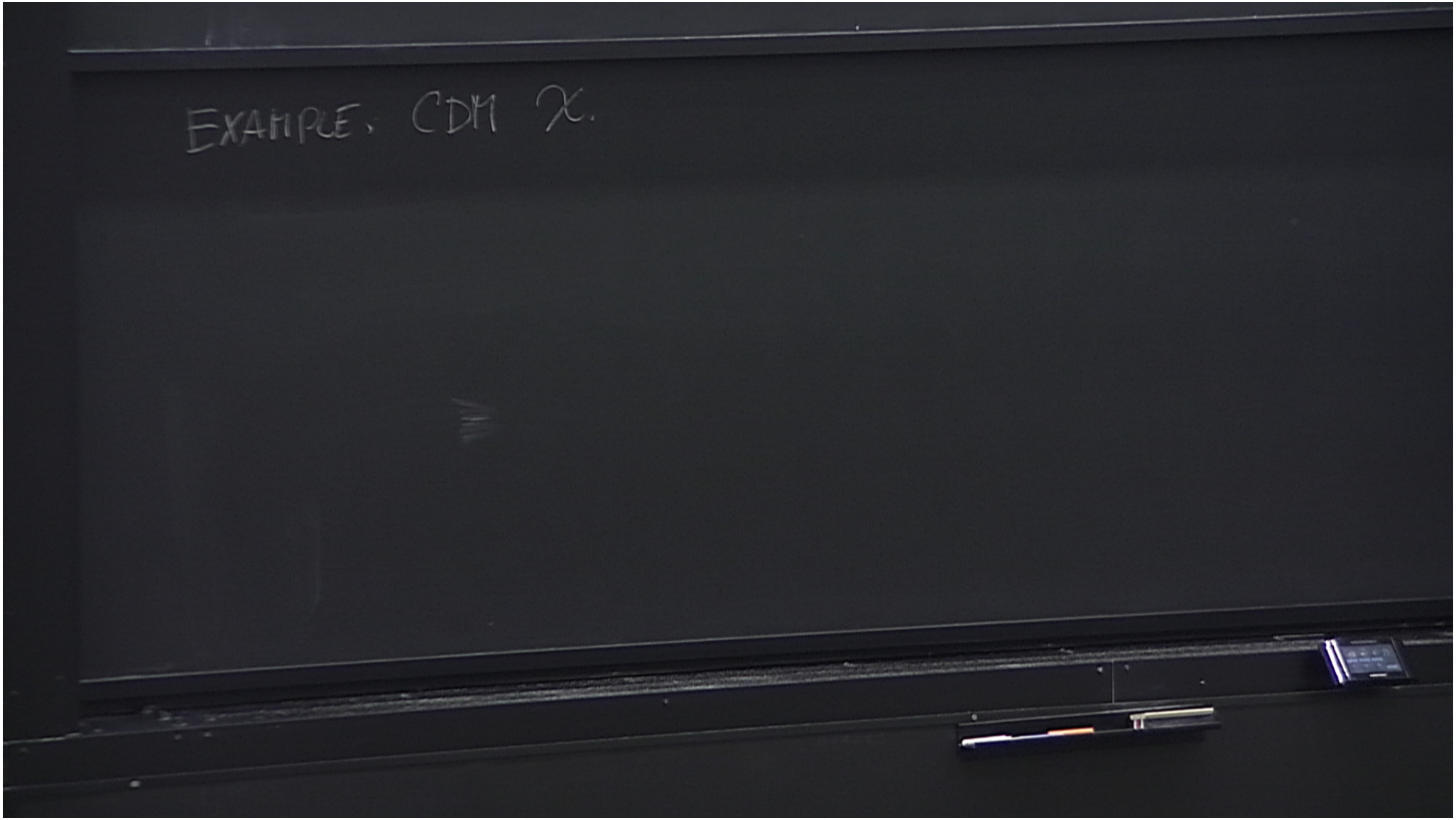

• DECOUPLING & FREEZE OUT
AS T DROPS, THE REACTION RATE DECREASES.
FOR, $\Gamma_i \simeq H$ ... SPECIE i DECOUPLES
AND NO LONGER IN EQUIL.

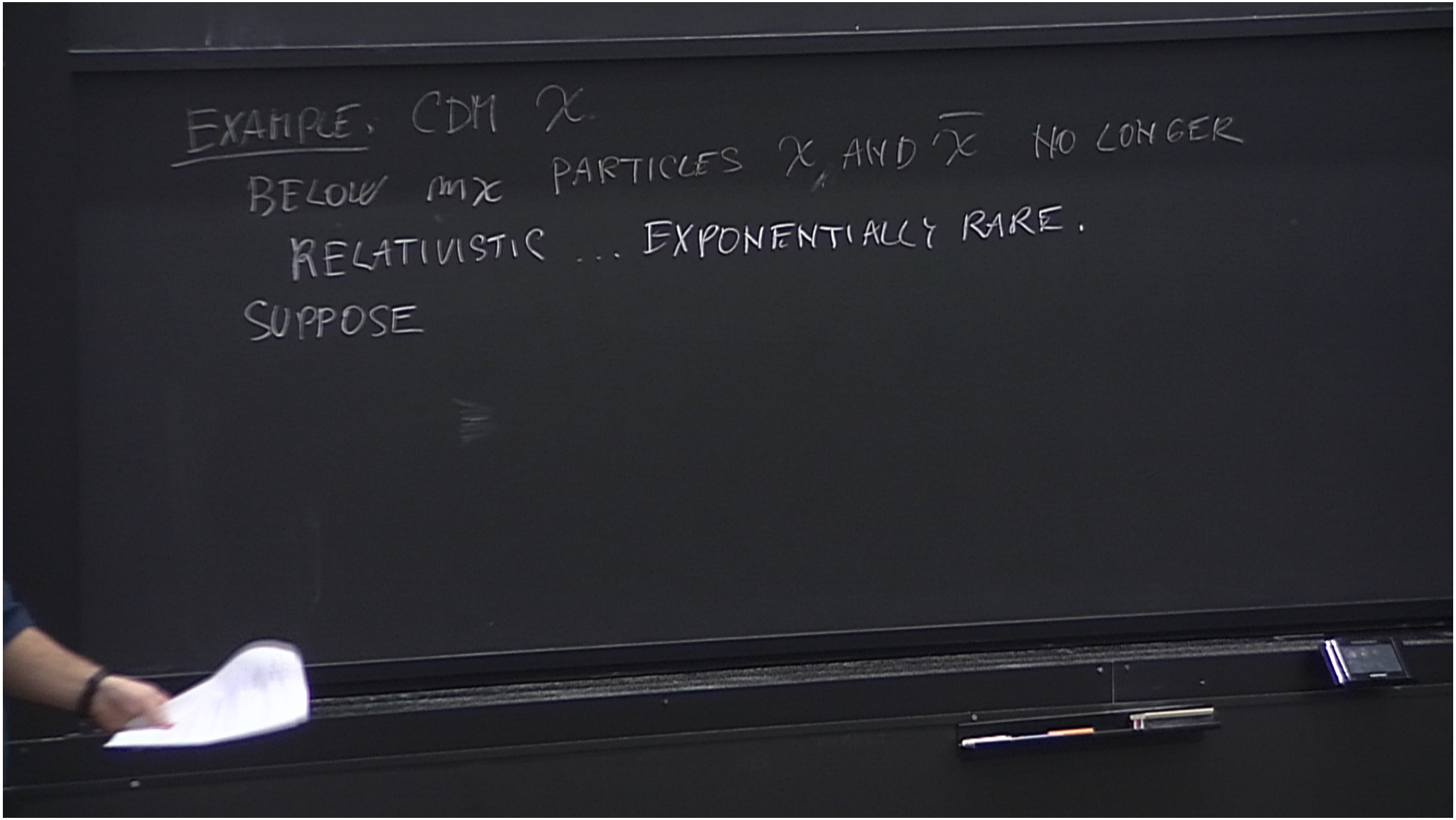

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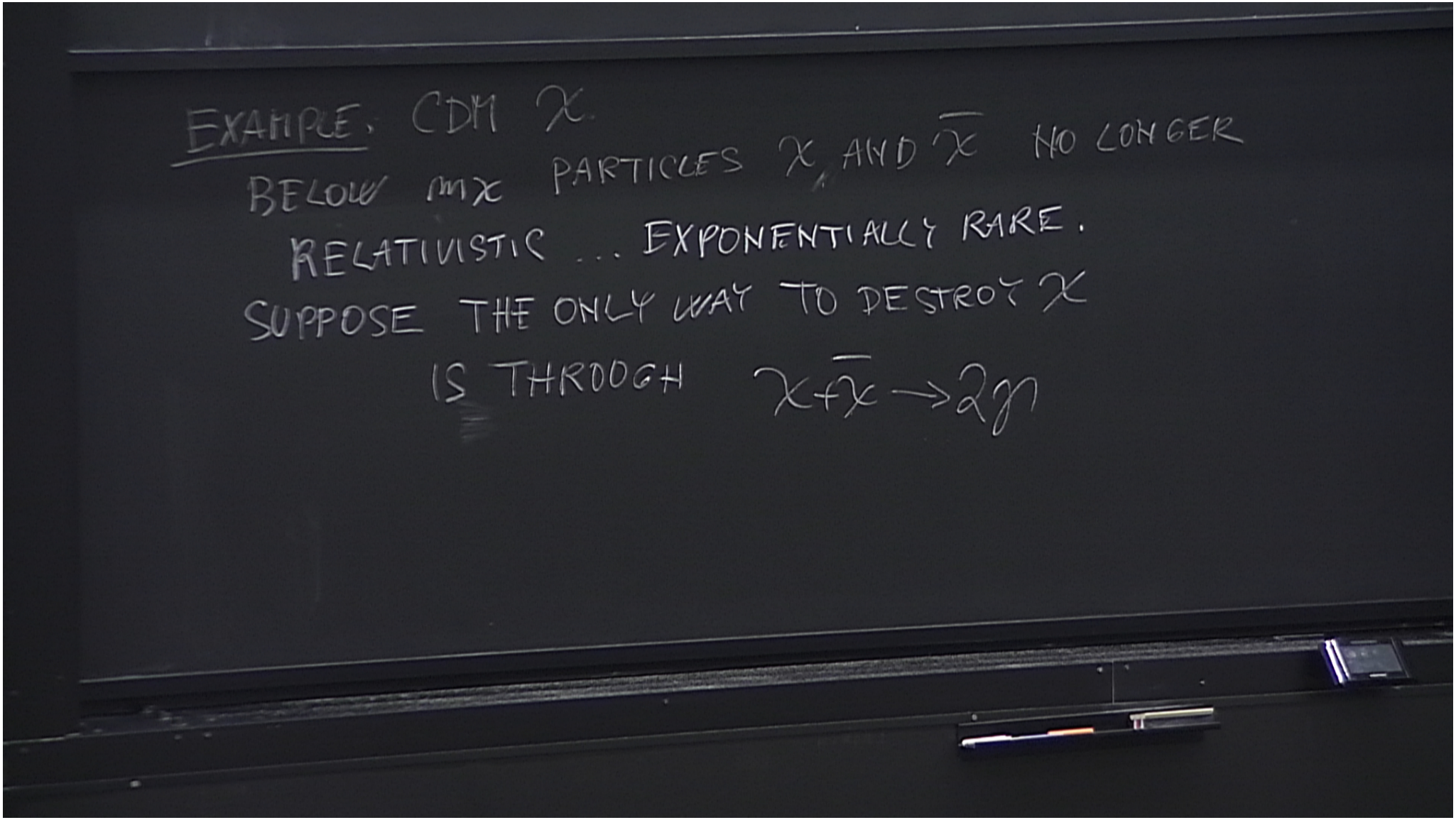

FOR. $\Gamma_i \simeq H$ ... SPECIE i DECOUPLES
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MASSIVE PARTICLES.

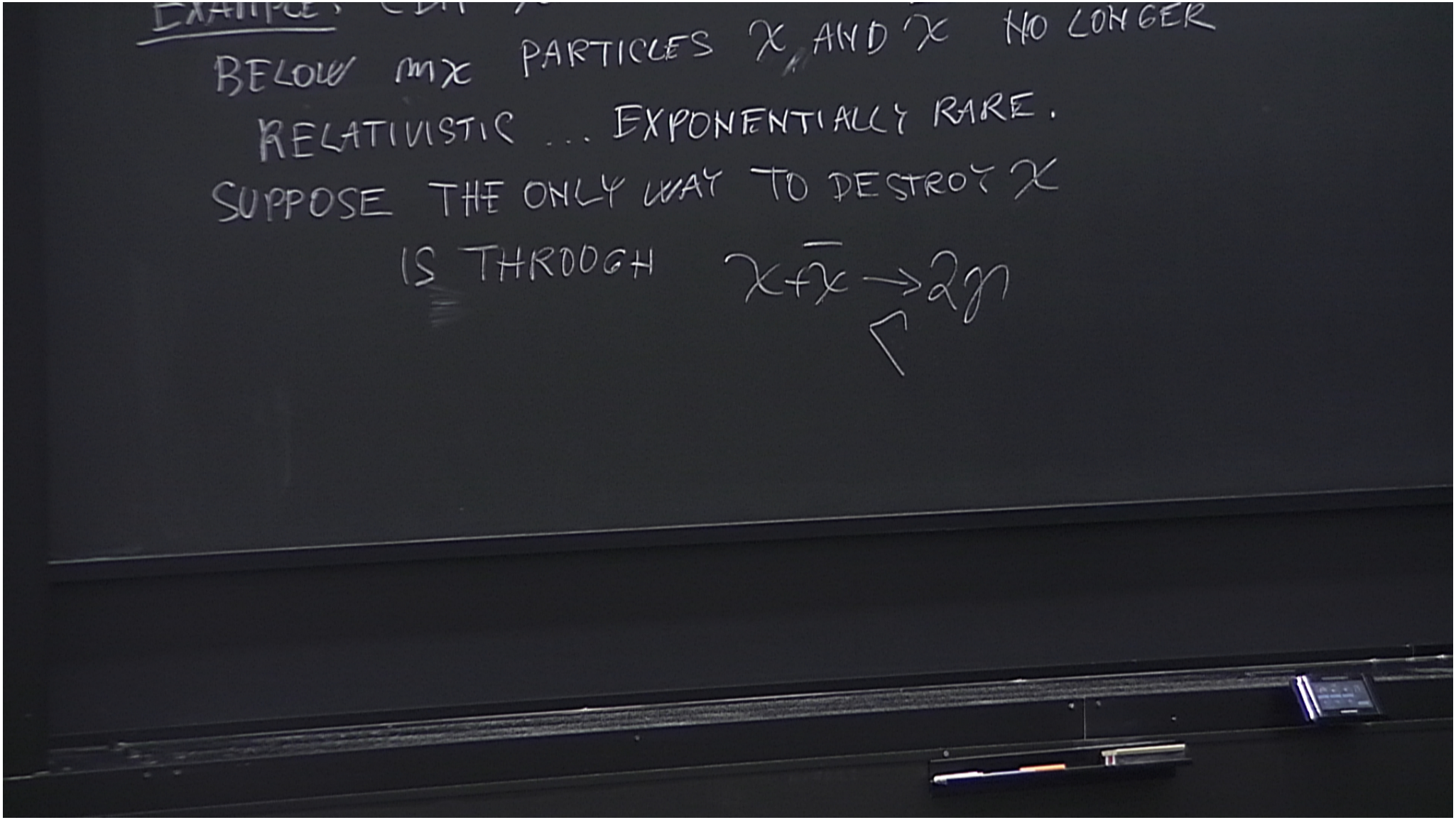

FOR. $\Gamma_i \simeq H$ ... SPECIE i DECOUPLES
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MASSIVE PARTICLES. ...ABUNDANCE
REMAINS APROX CONSTANT

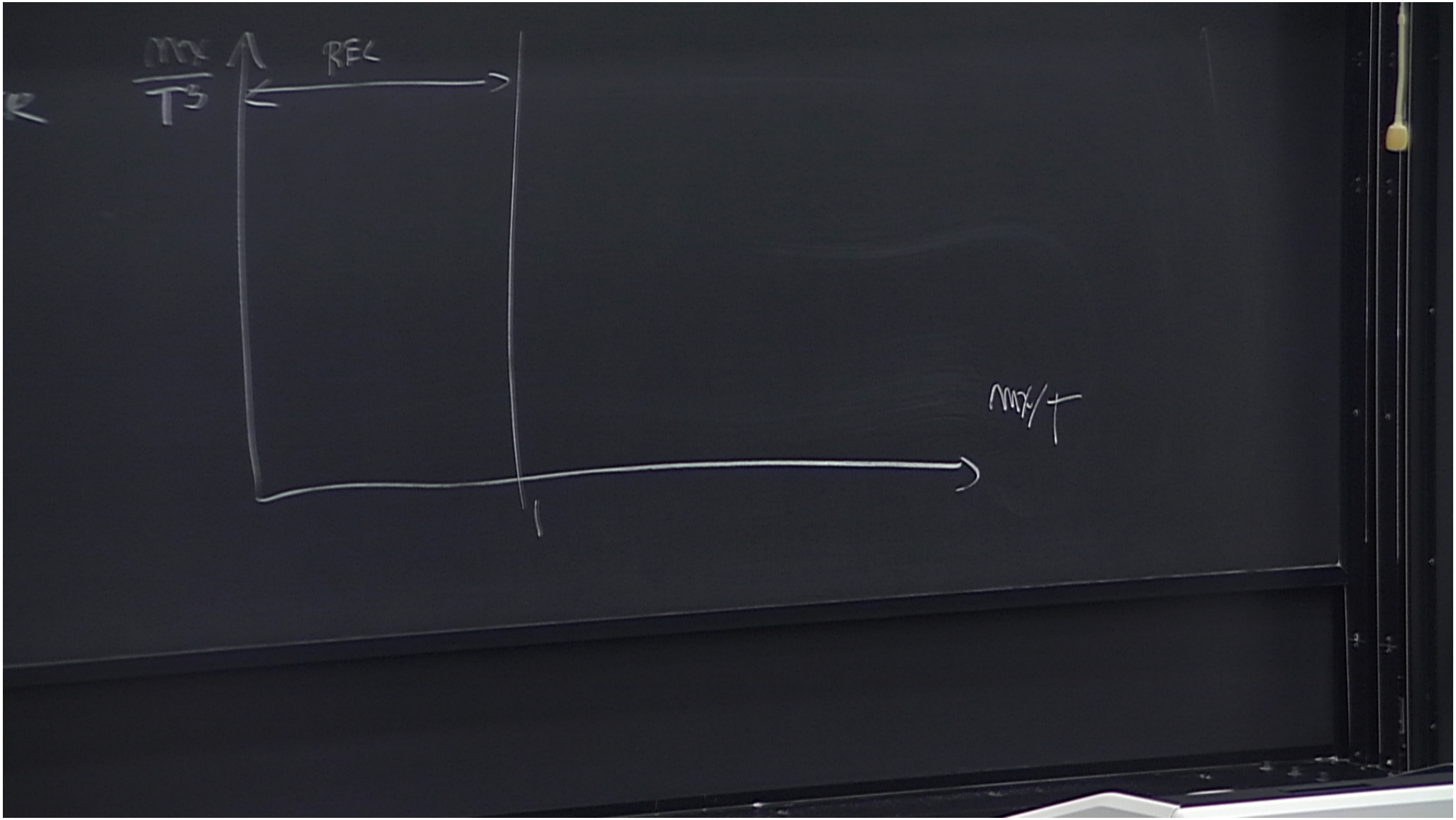

FOR. $\Gamma_i \simeq H$ ... SPECIE i DECOUPLES
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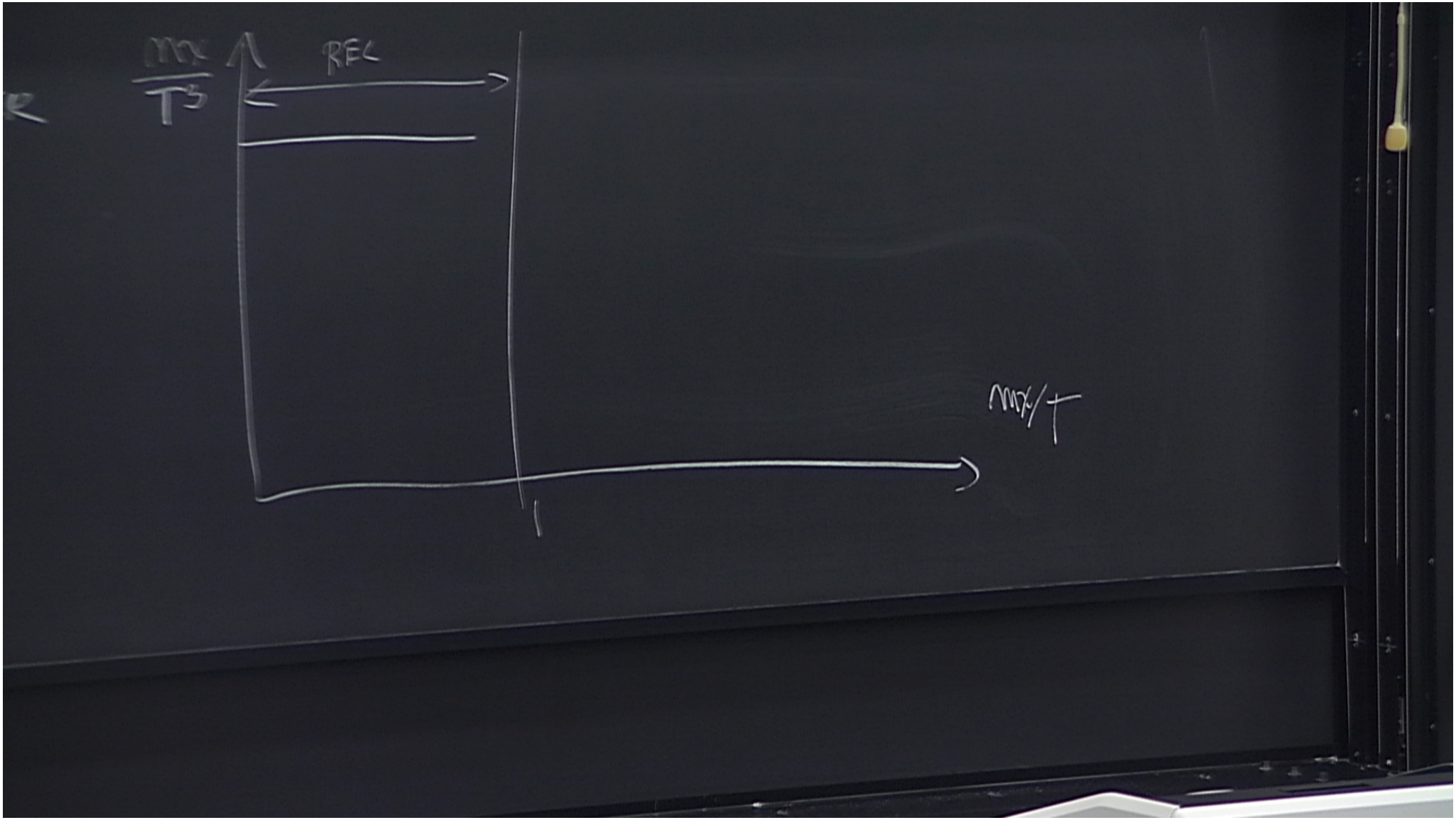

EXAMPLE: CDM χ.

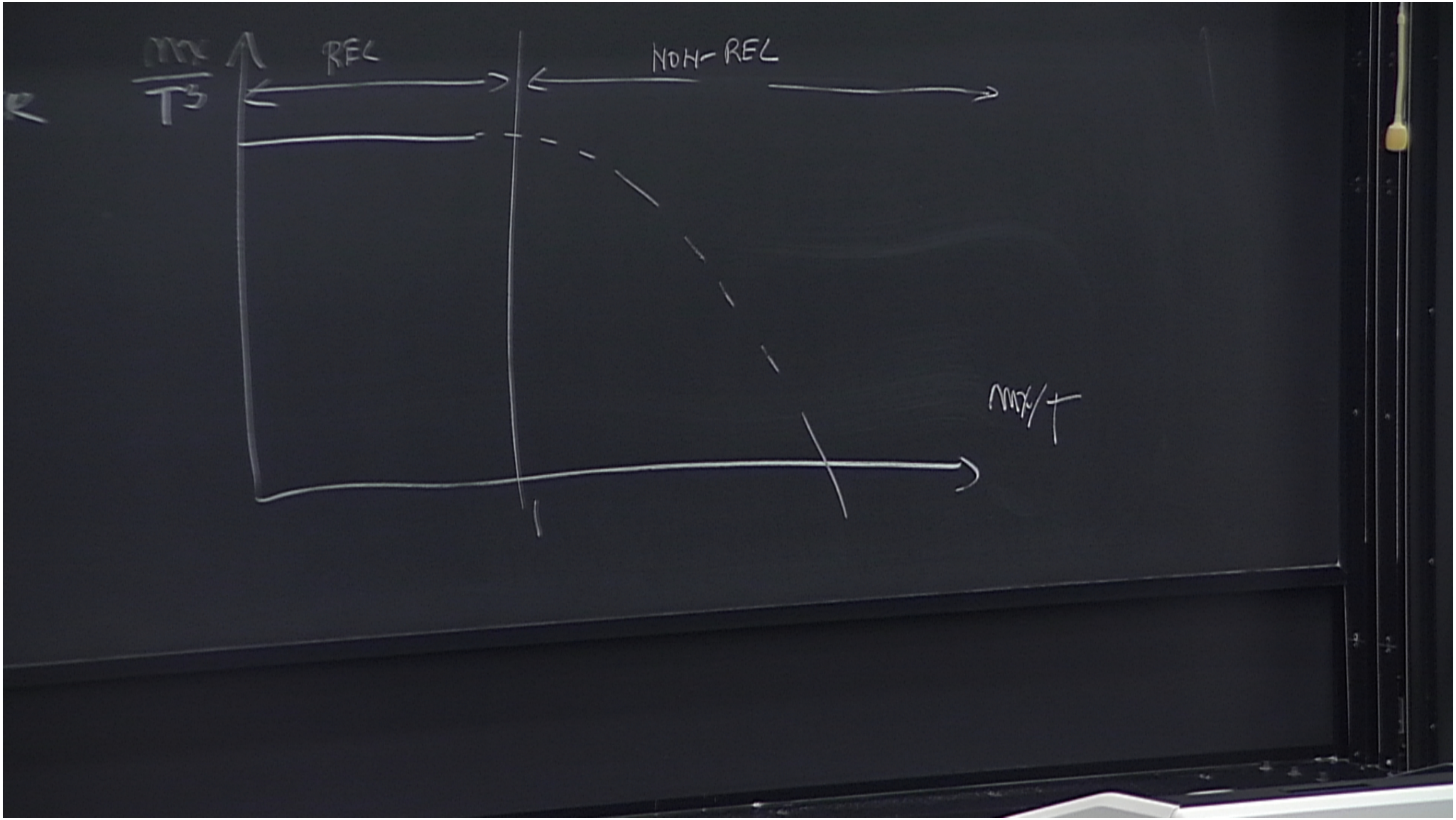

EXAMPLE: CDM χ.
BELOW m_χ PARTICLES χ, AND $\bar{\chi}$ NO LONGER
RELATIVISTIC ... EXPONENTIALLY RARE.
SUPPOSE

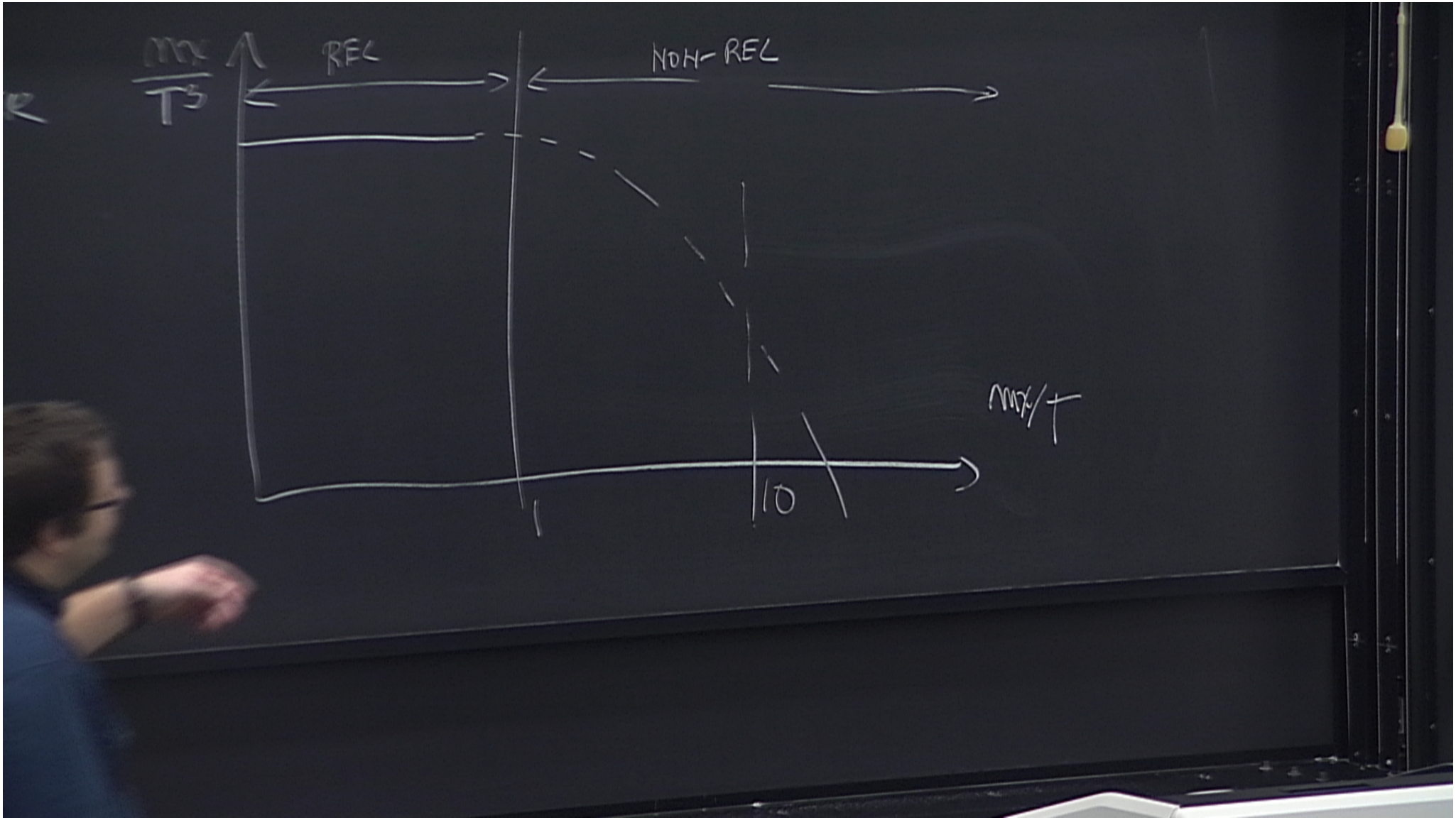

EXAMPLE: CDM χ.
BELOW m_χ PARTICLES χ, AND $\bar{\chi}$ NO LONGER
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SUPPOSE THE ONLY WAY TO DESTROY χ
IS THROUGH $\chi + \bar{\chi} \to 2\gamma$

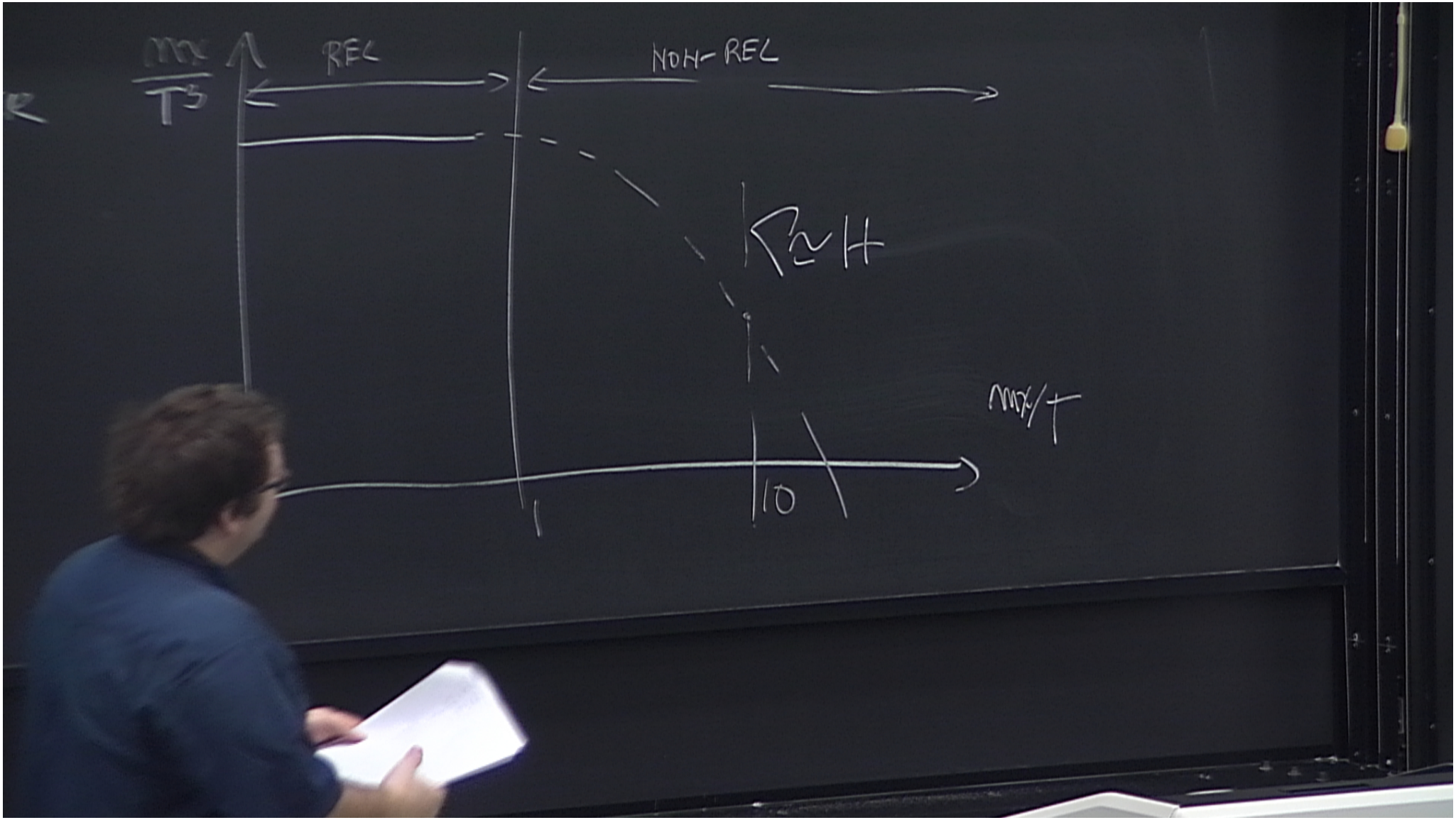

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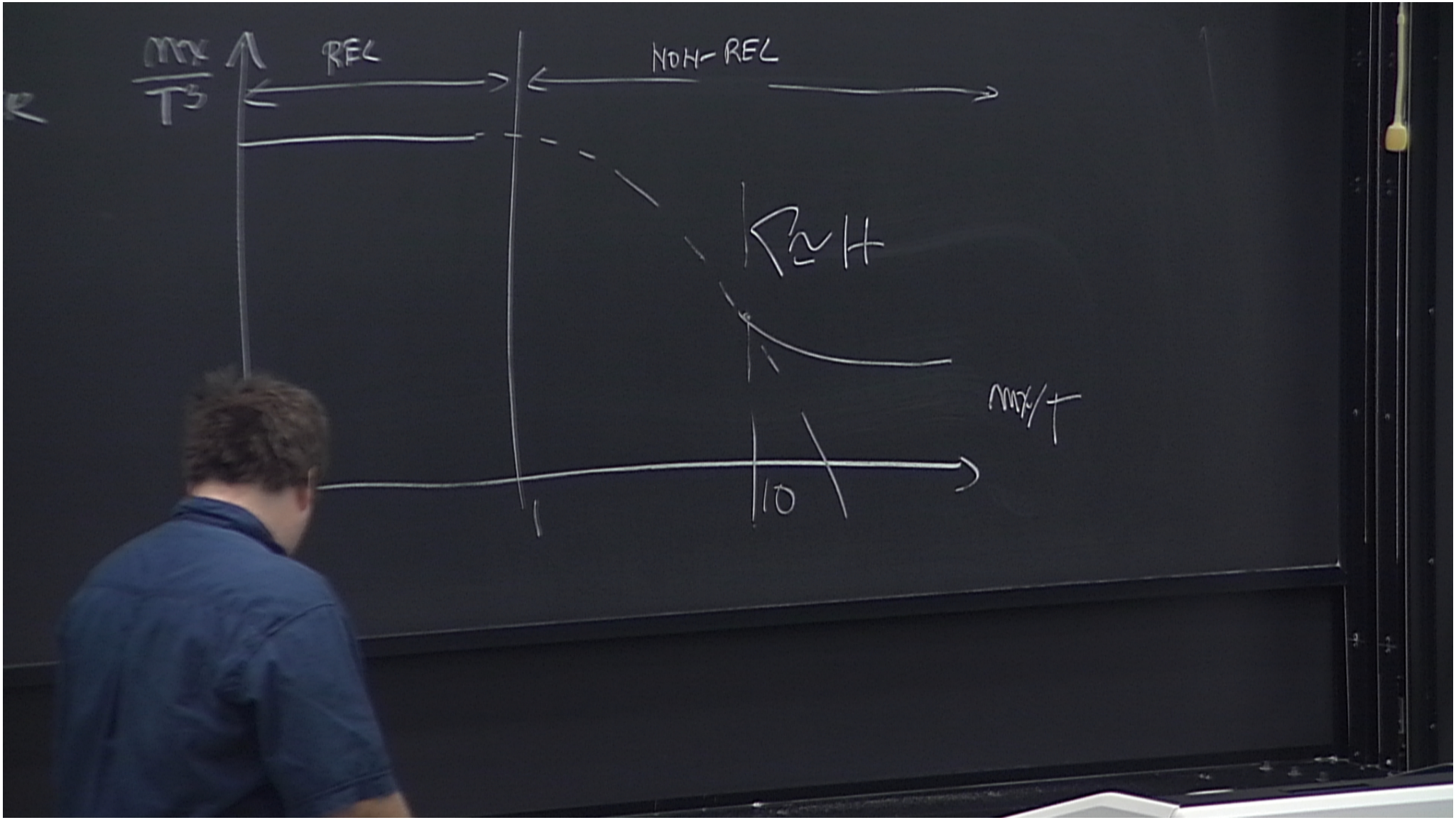

REL

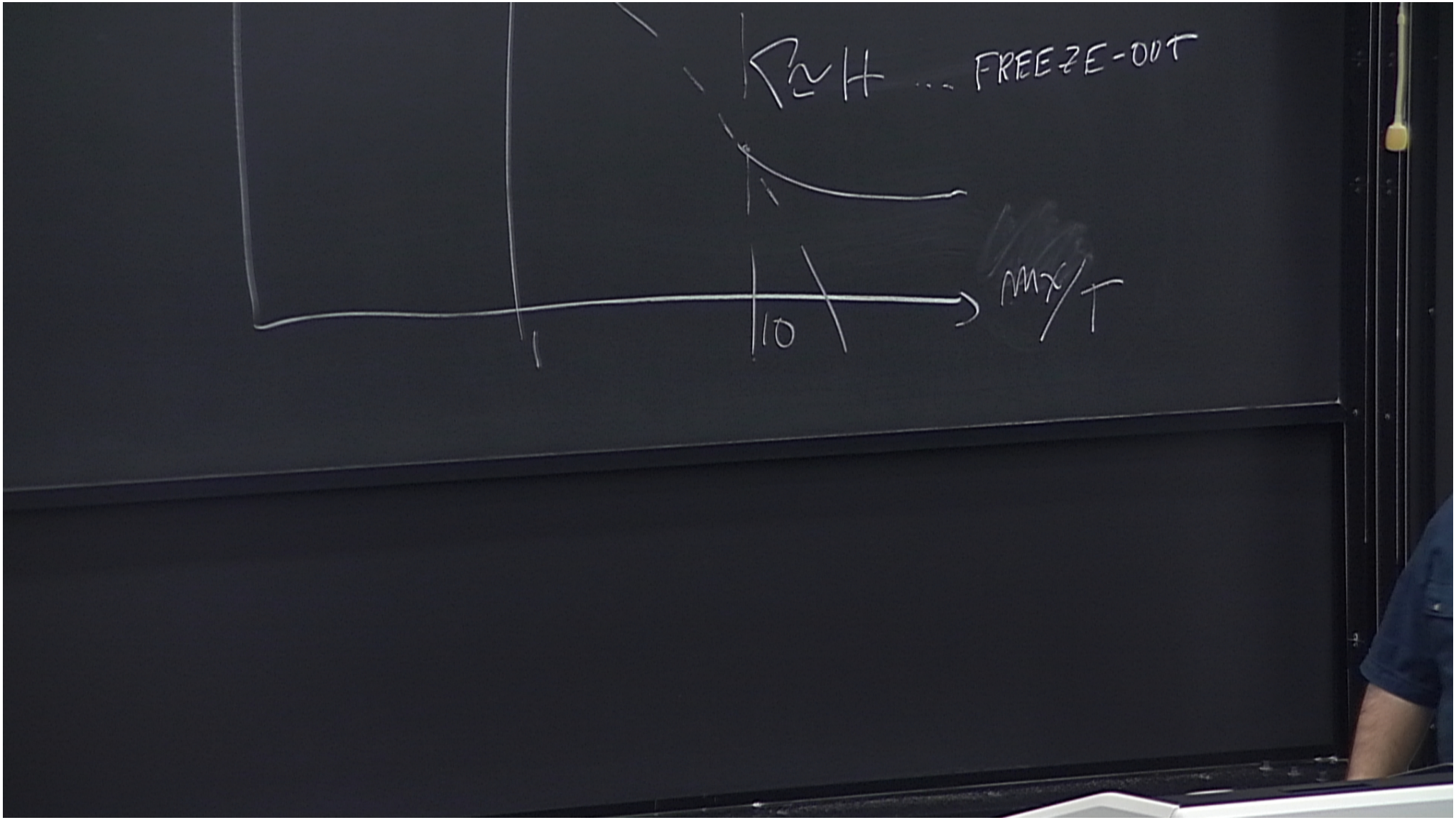

REL

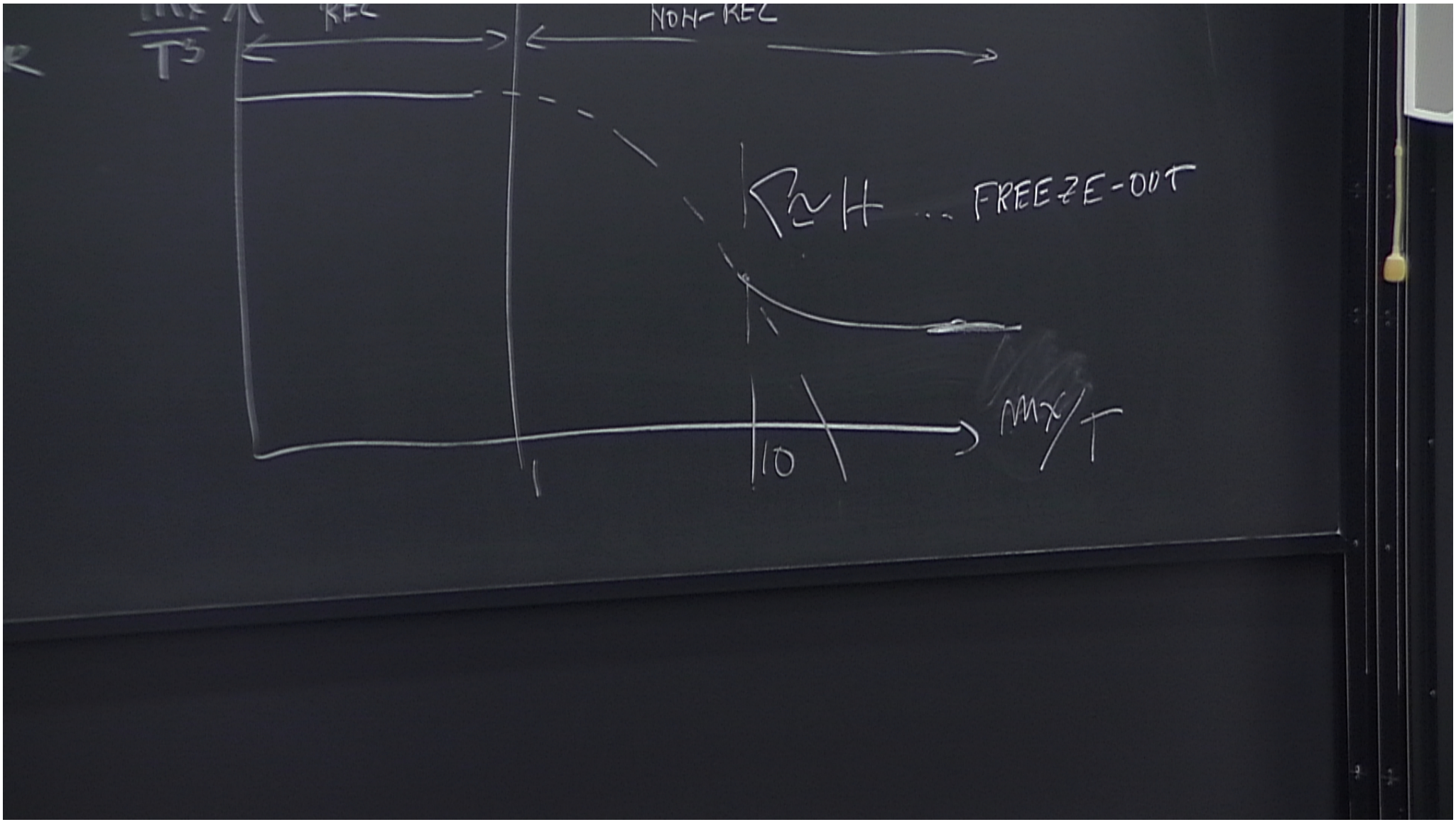

REL
NON-REL

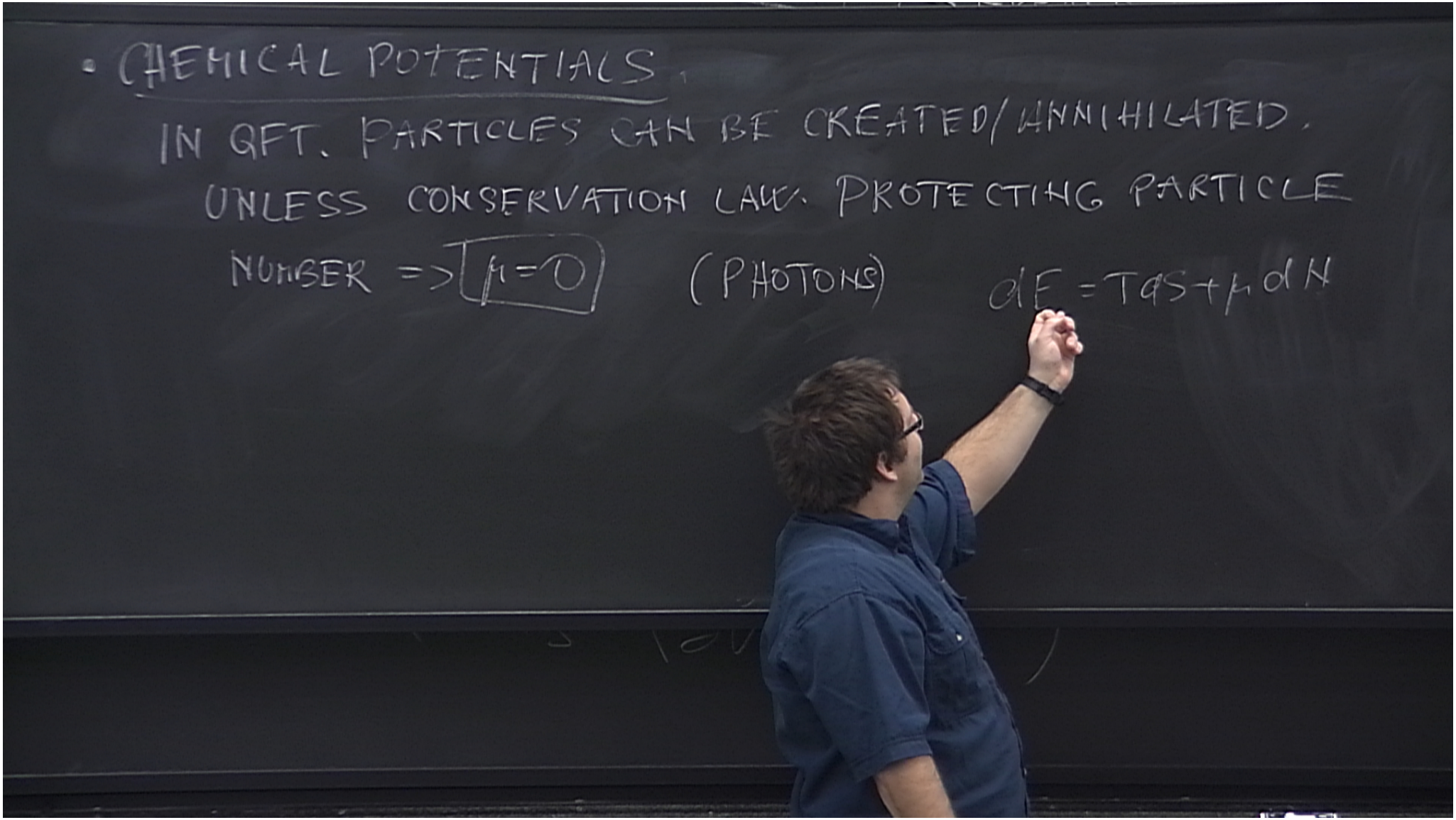

REL
NON-REL
1
10

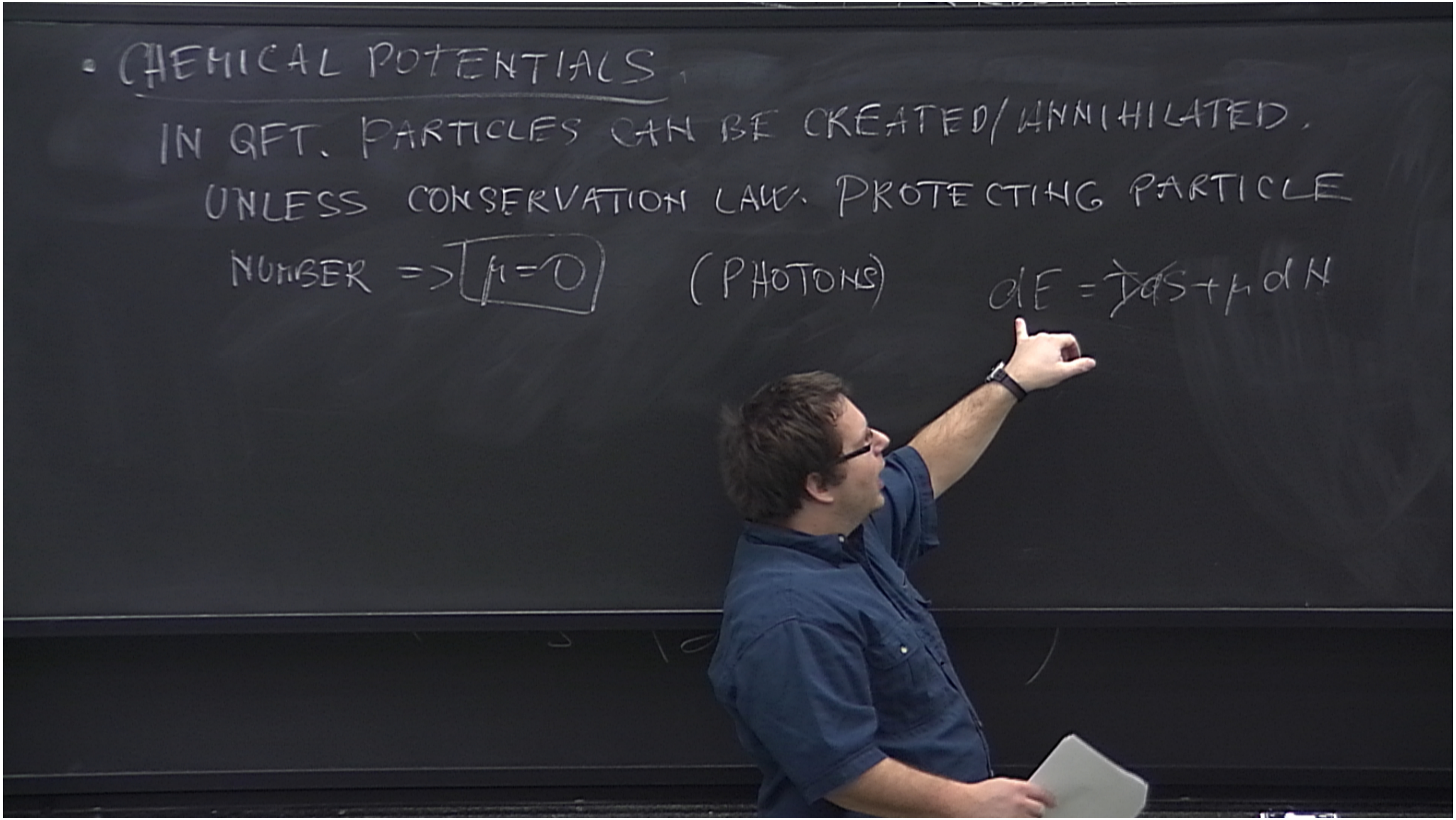

REL
NON-REL
P≃H
10

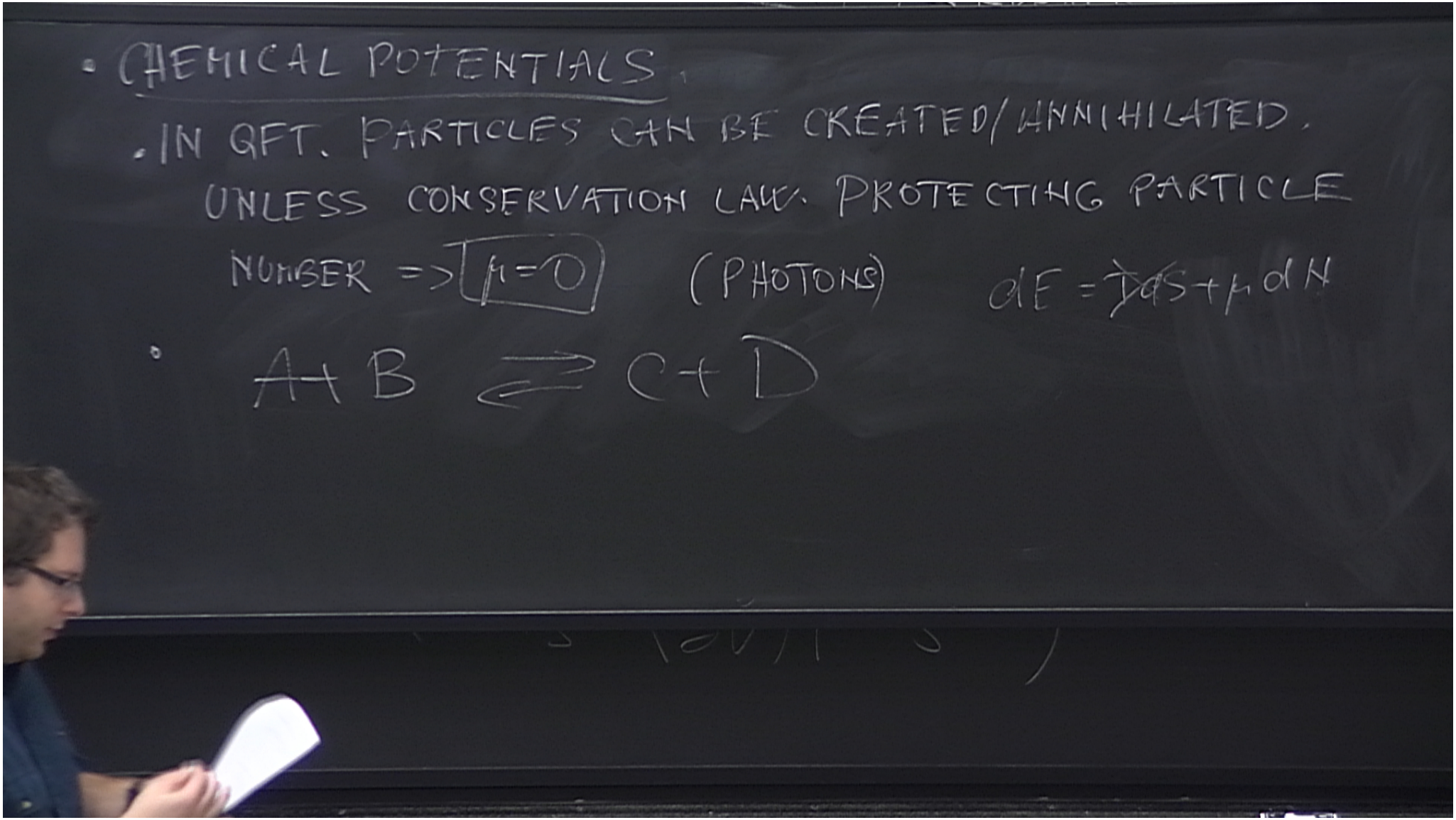

REL
NON-REL
10


Γ ≃ H ... FREEZE-OUT
1
10
mx/T


REL
NON-REL
T3
Γ ≃ H ... FREEZE-OUT
10
mx/T

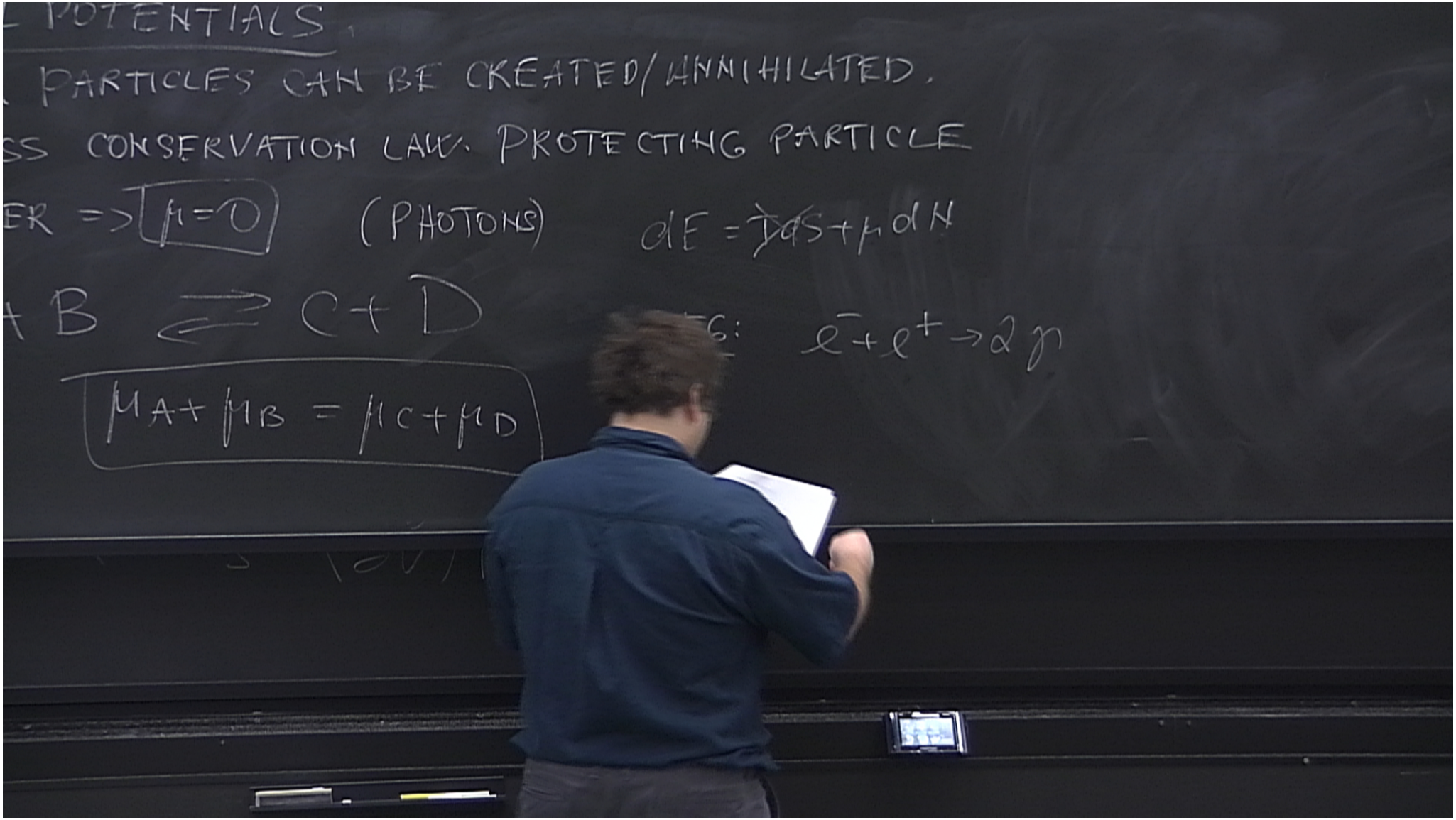

• CHEMICAL POTENTIALS.
IN QFT. PARTICLES CAN BE CREATED/ANNIHILATED.
UNLESS CONSERVATION LAW. PROTECTING PARTICLE
NUMBER => μ=0 (PHOTONS)
dE = TdS + μ dN

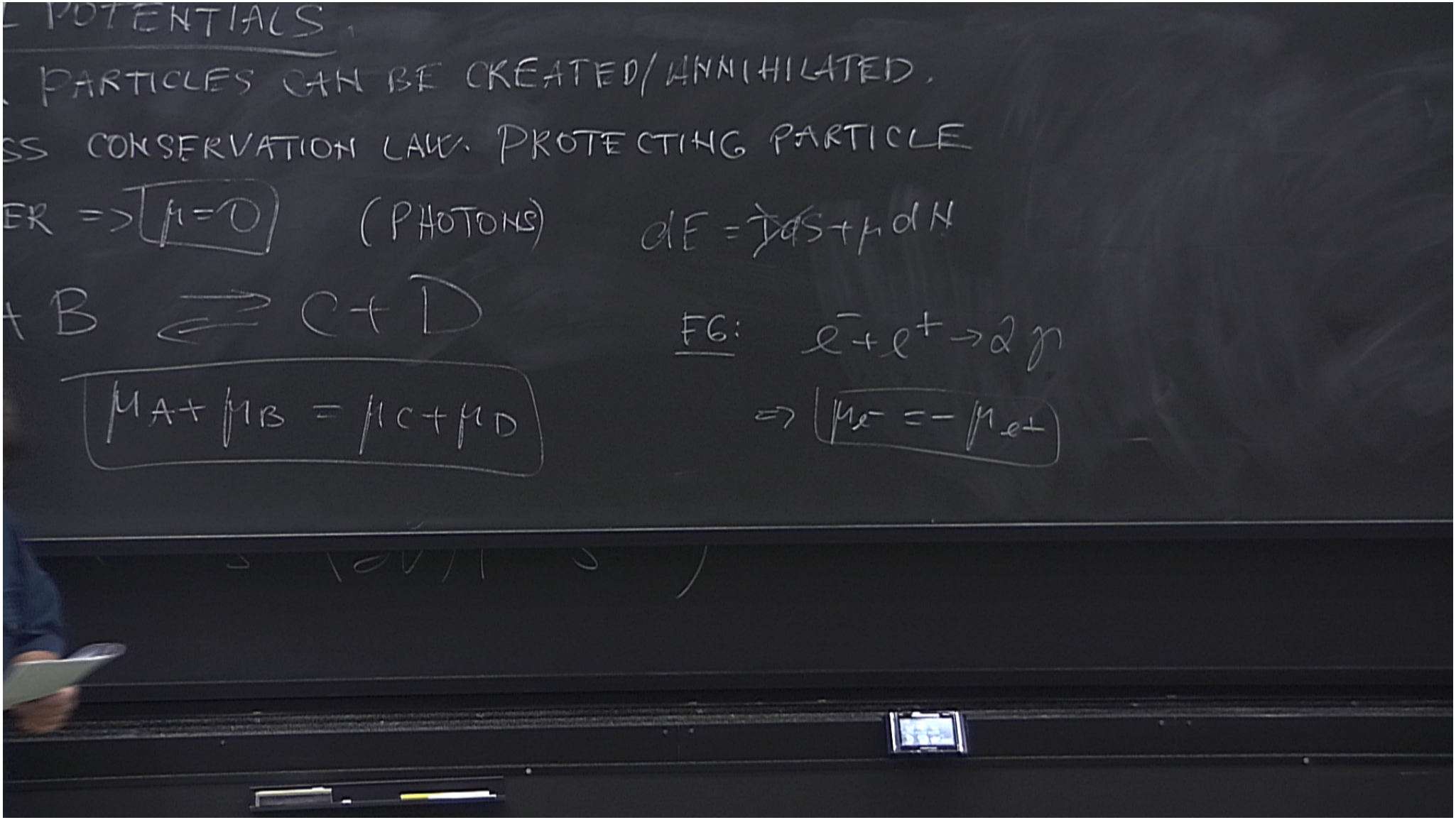

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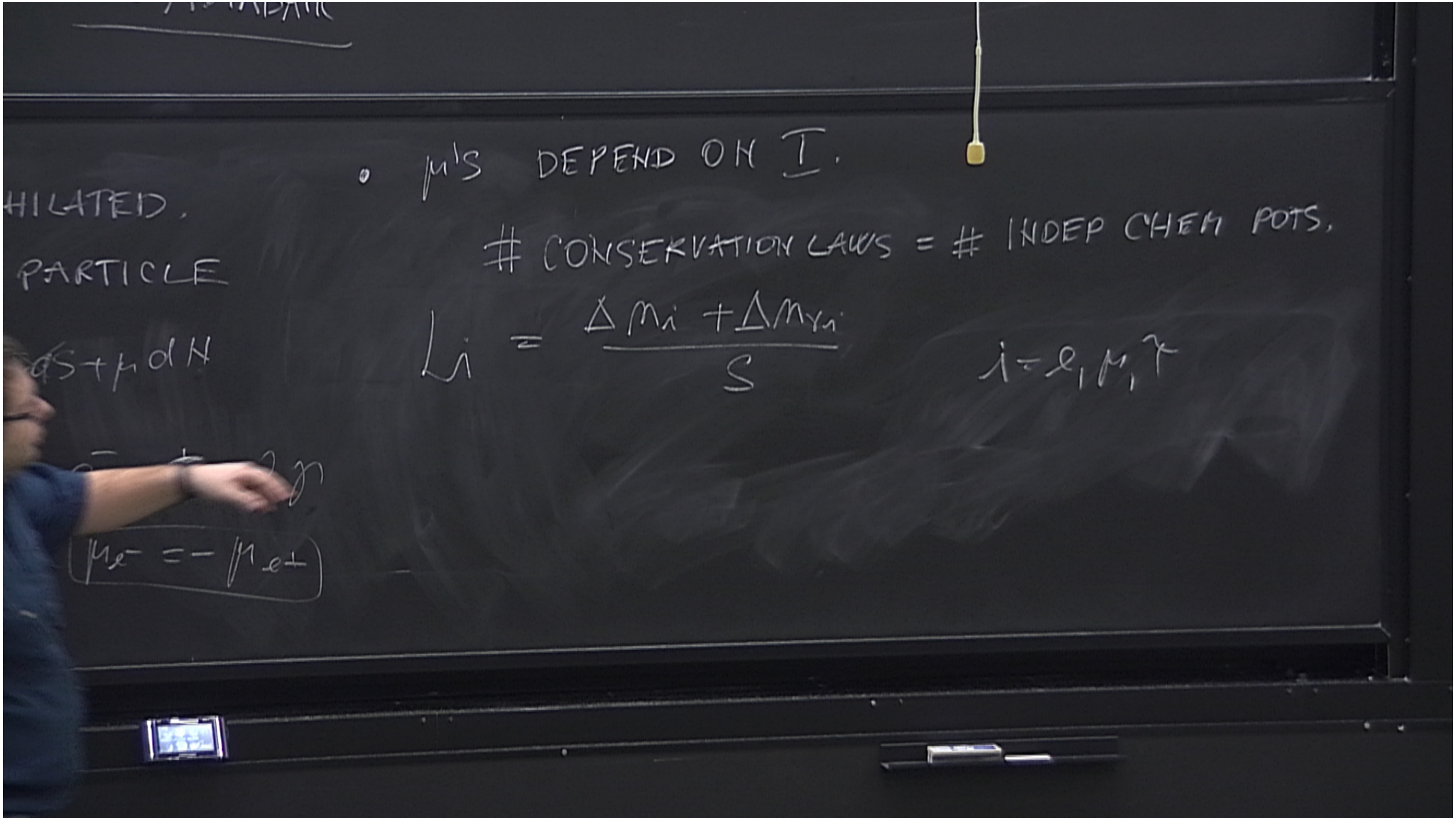

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. IN QFT. PARTICLES CAN BE CREATED/ANNIHILATED.
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NUMBER => μ=0 (PHOTONS) dE = TdS + μ dN
A + B ⇌ C + D

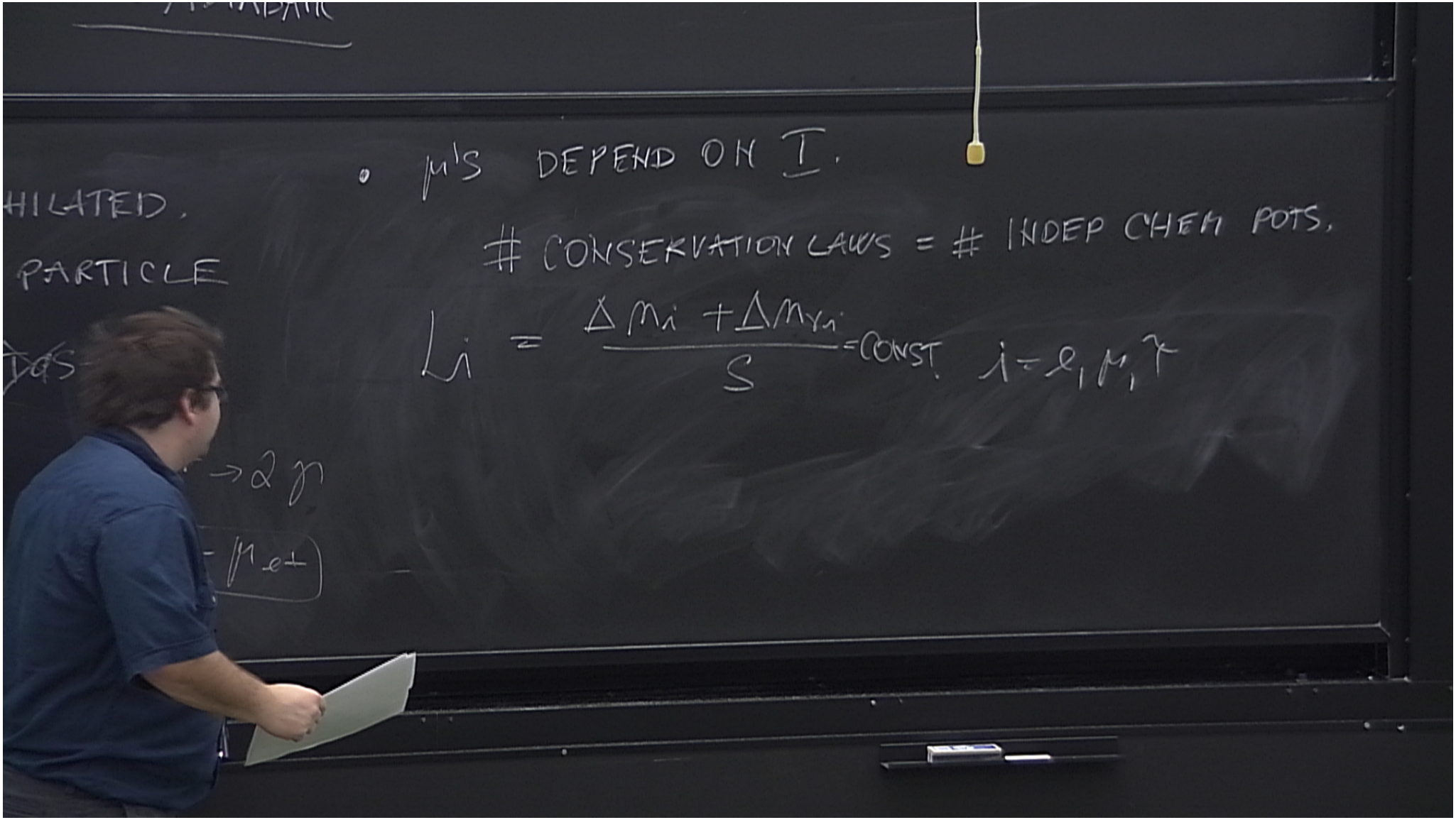
- CHEMICAL POTENTIALS.
  - IN QFT. PARTICLES CAN BE CREATED/ANNIHILATED. UNLESS CONSERVATION LAW. PROTECTING PARTICLE NUMBER => $\mu = 0$ (PHOTONS) $dE = TdS + \mu\, dN$
  - $A + B \rightleftharpoons C + D$

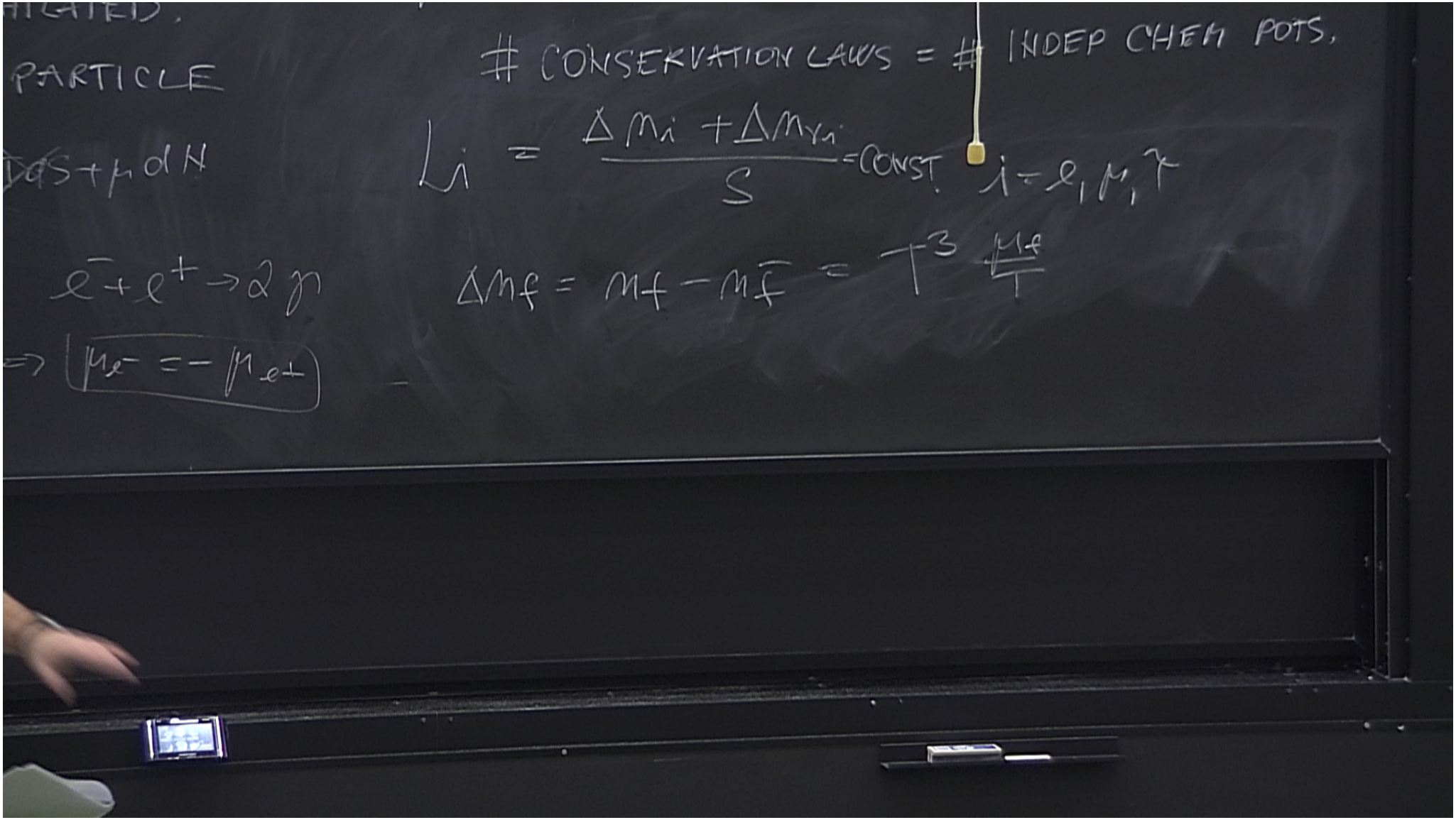
$$\mu_A + \mu_B = \mu_C + \mu_D$$

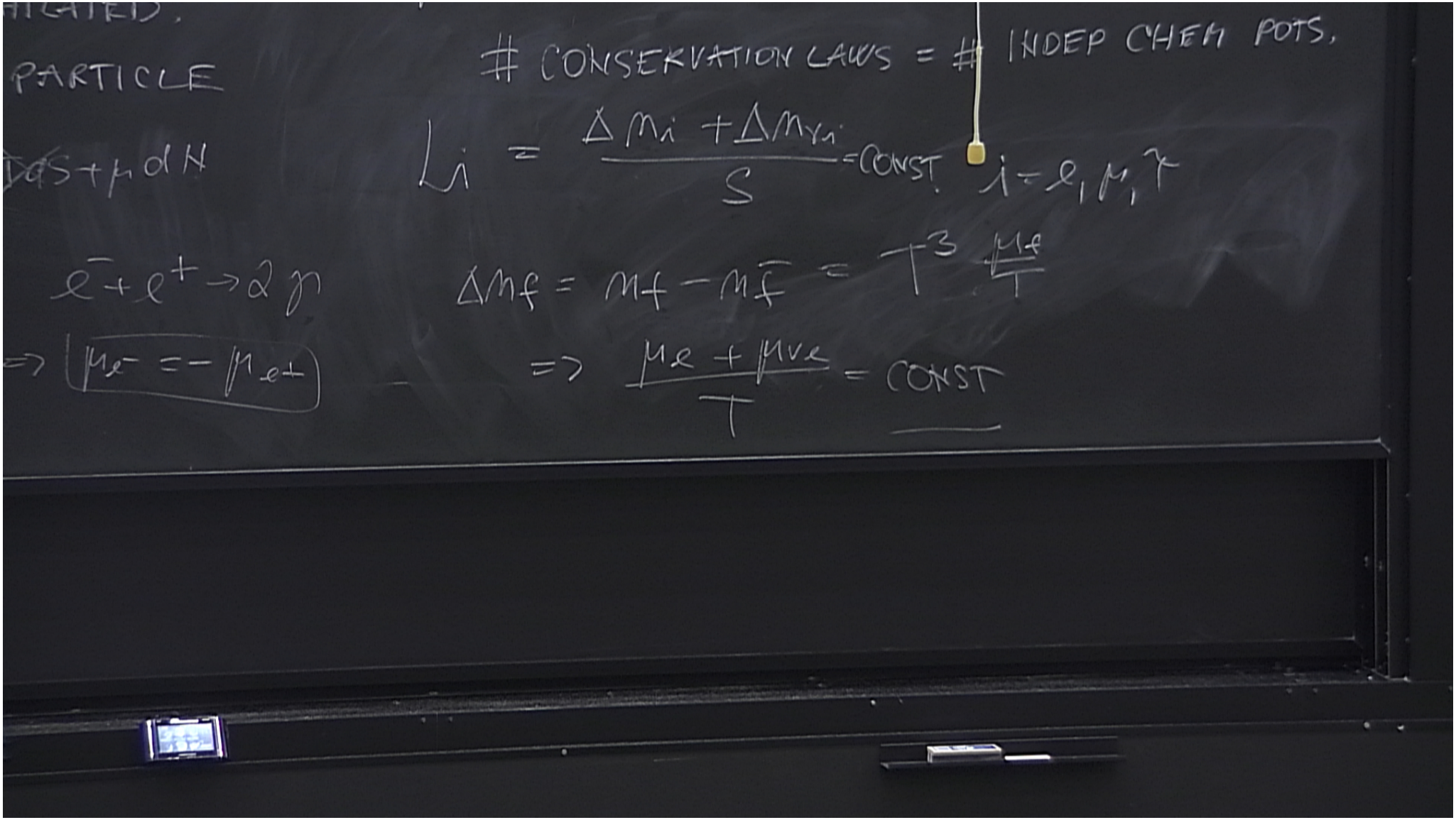

POTENTIALS.
PARTICLES CAN BE CREATED/ANNIHILATED.
SS CONSERVATION LAW. PROTECTING PARTICLE
ER => μ=0 (PHOTONS)
dE = TdS + μ dN
+B ⇌ C+D
e⁻ + e⁺ → 2γ
μA + μB = μC + μD

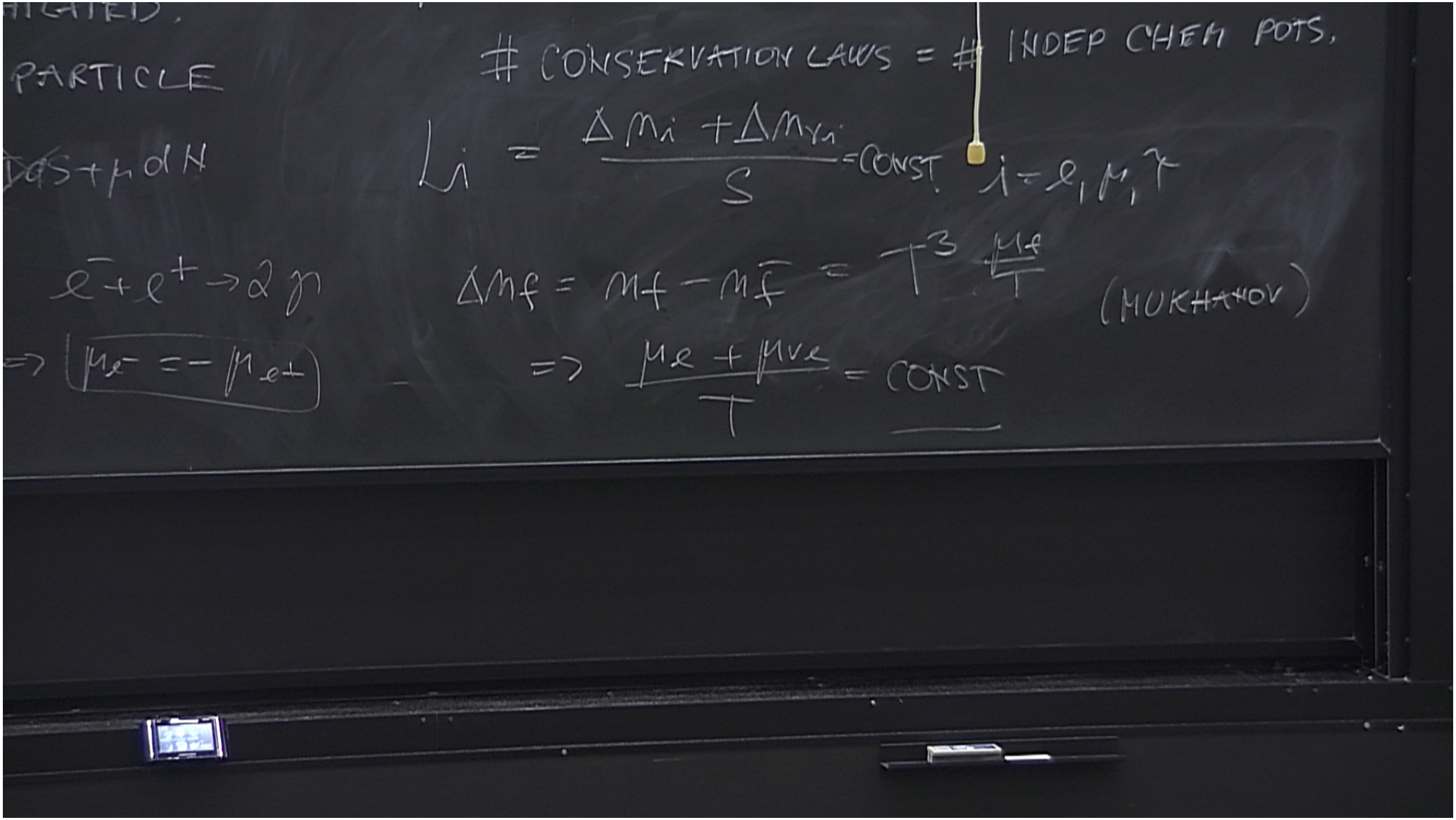

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FG: e⁻ + e⁺ → 2γ
=> μe⁻ = −μe⁺


HILATED.
PARTICLE
$\mu_{e^-} = -\mu_{e^+}$
• μ'S DEPEND ON $\underline{I}$.
CONSERVATION LAWS = # INDEP CHEM POTS.
$L_i = \frac{\Delta M_i + \Delta M_{ri}}{S}$
$i = e, \mu, \tau$


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$\rightarrow 2\gamma$
μ_{e^+}


PARTICLE
CONSERVATION LAWS = # INDEP CHEM POTS.
$dS + \mu\, dN$
$L_i = \frac{\Delta n_i + \Delta n_{\gamma i}}{S} = \text{CONST.}$ $i = e, \mu, \tau$
$e^- + e^+ \to 2\gamma$
$\Delta n_f = n_f - n_{\bar{f}} = T^3 \frac{\mu_f}{T}$
$\Rightarrow \boxed{\mu_{e^-} = -\mu_{e^+}}$

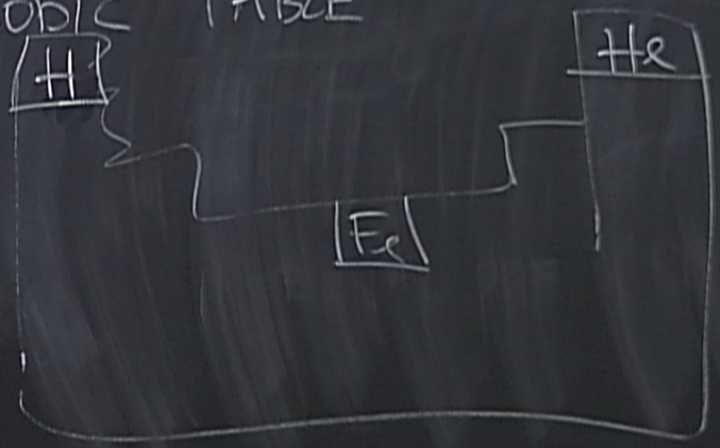

PARTICLE
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SUPPOSE THE ONLY WAY TO DESTRO[illegible]

c) BIG BANG NUCLEOSYNTHESIS

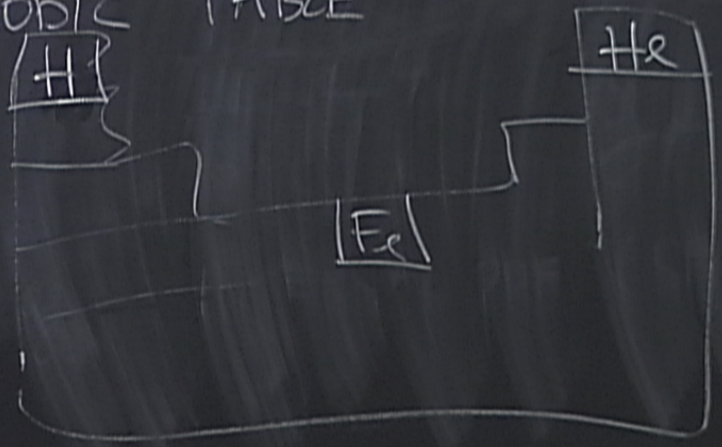
- PERIODIC TABLE



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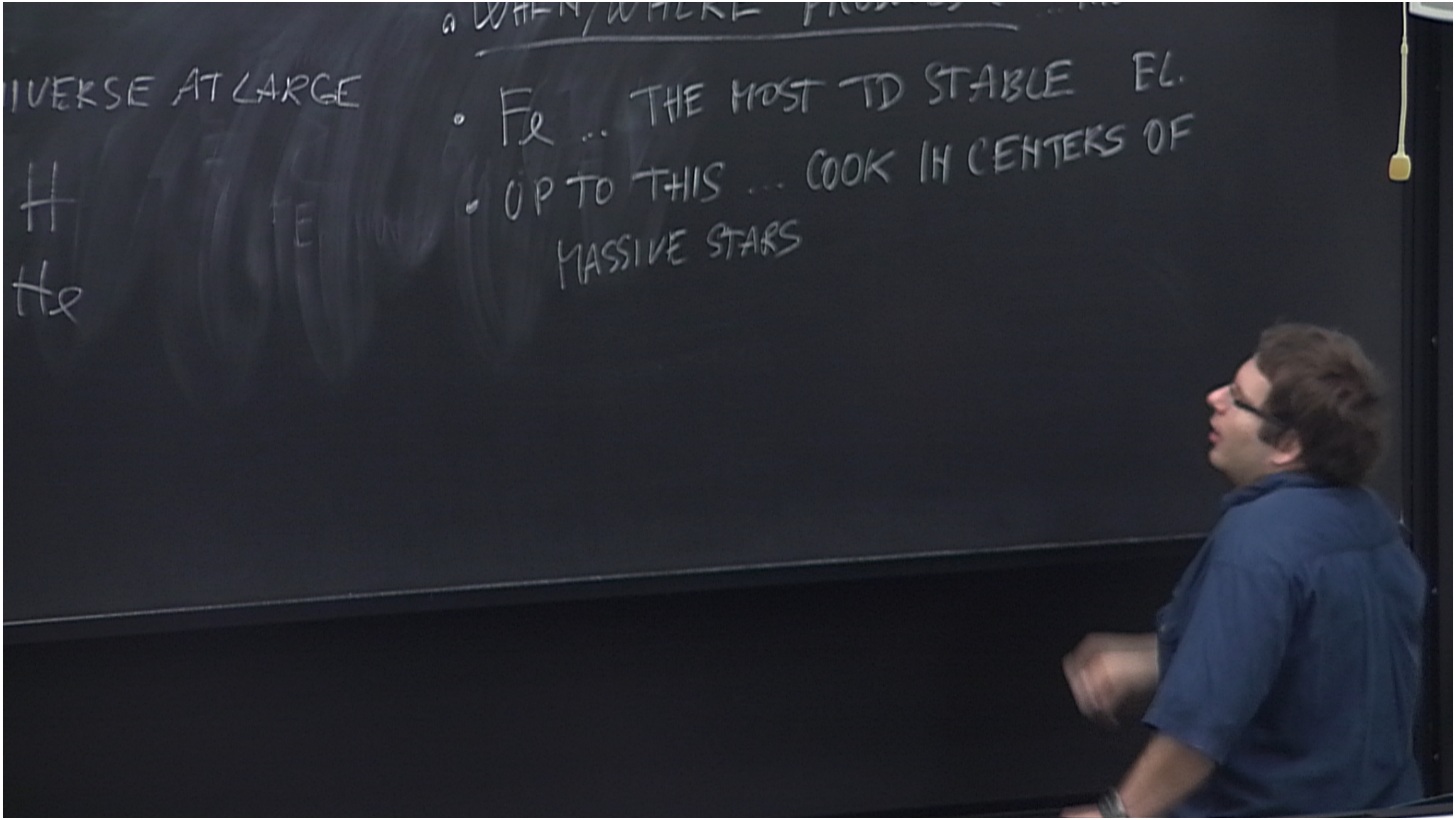


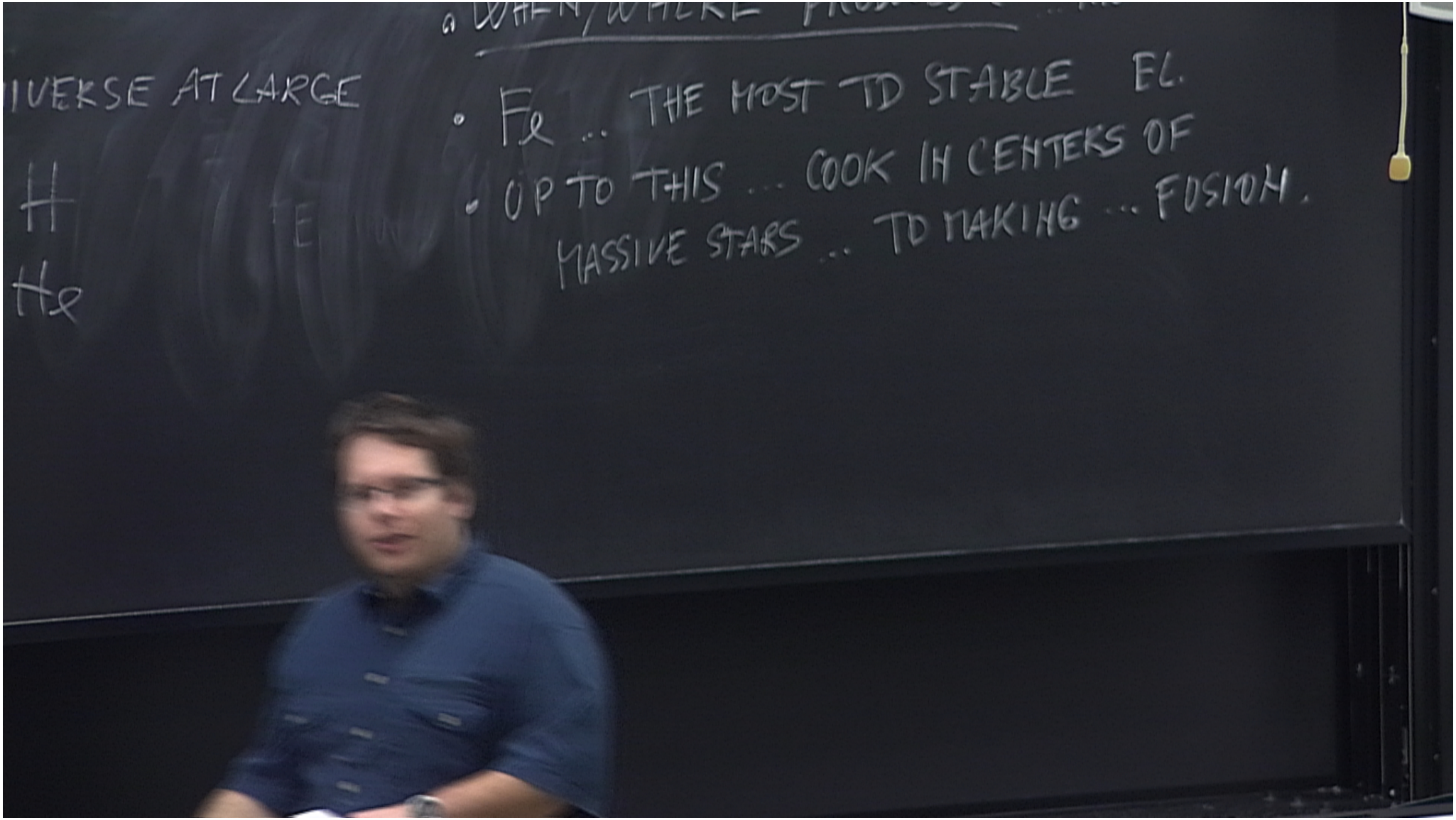
BY MASS, UNIVERSE AT LARGE

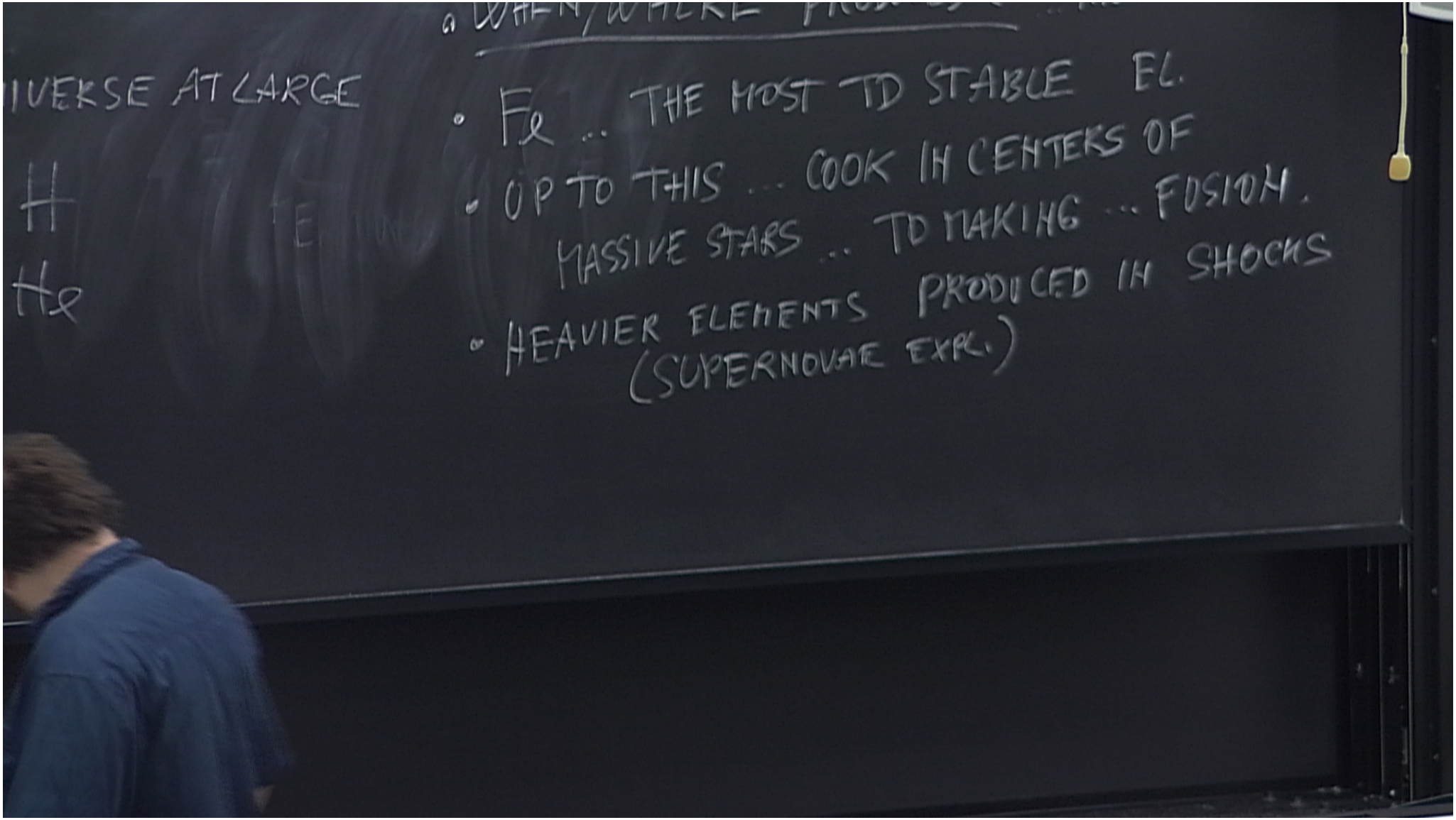
75% H

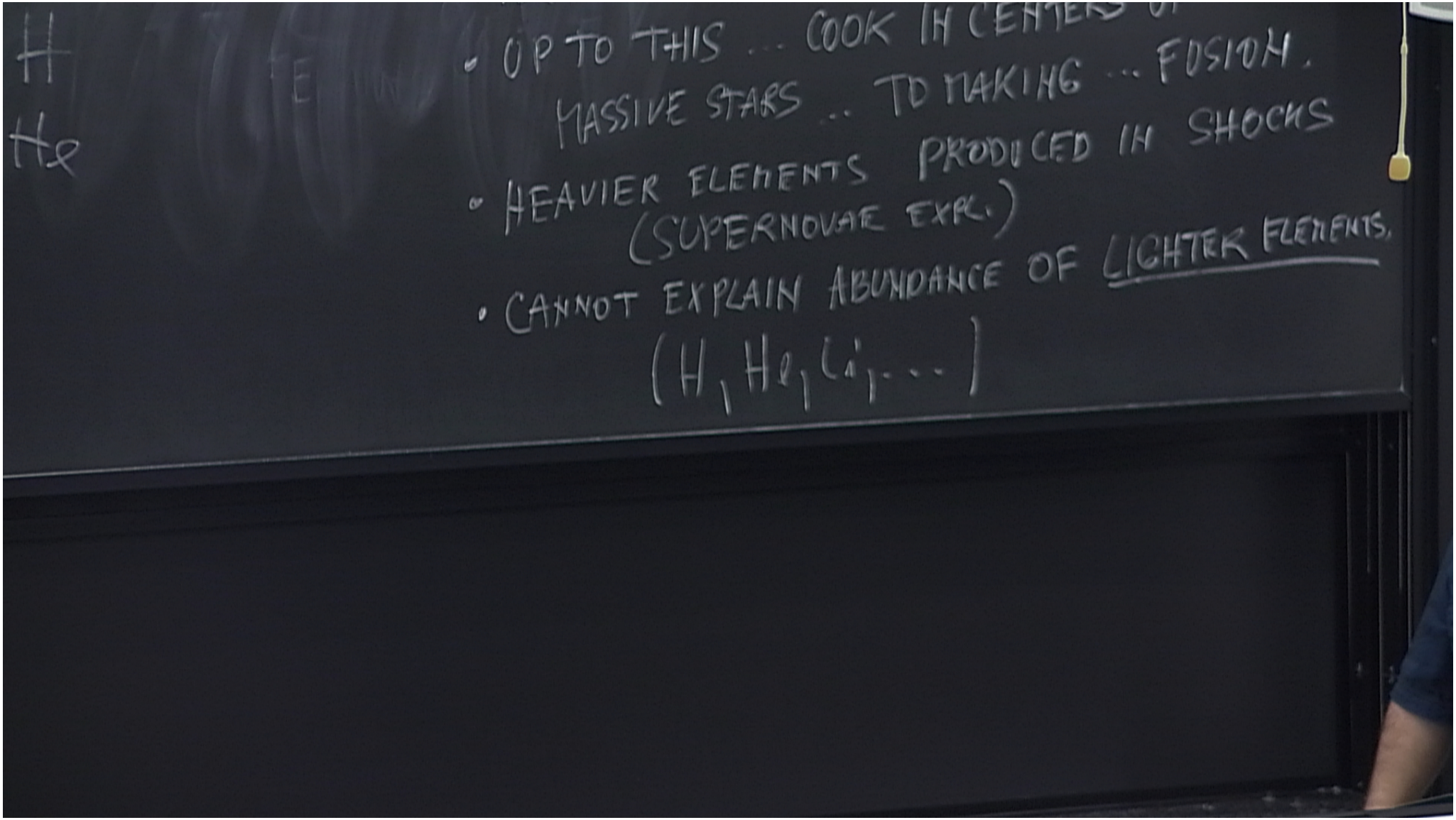
25% He

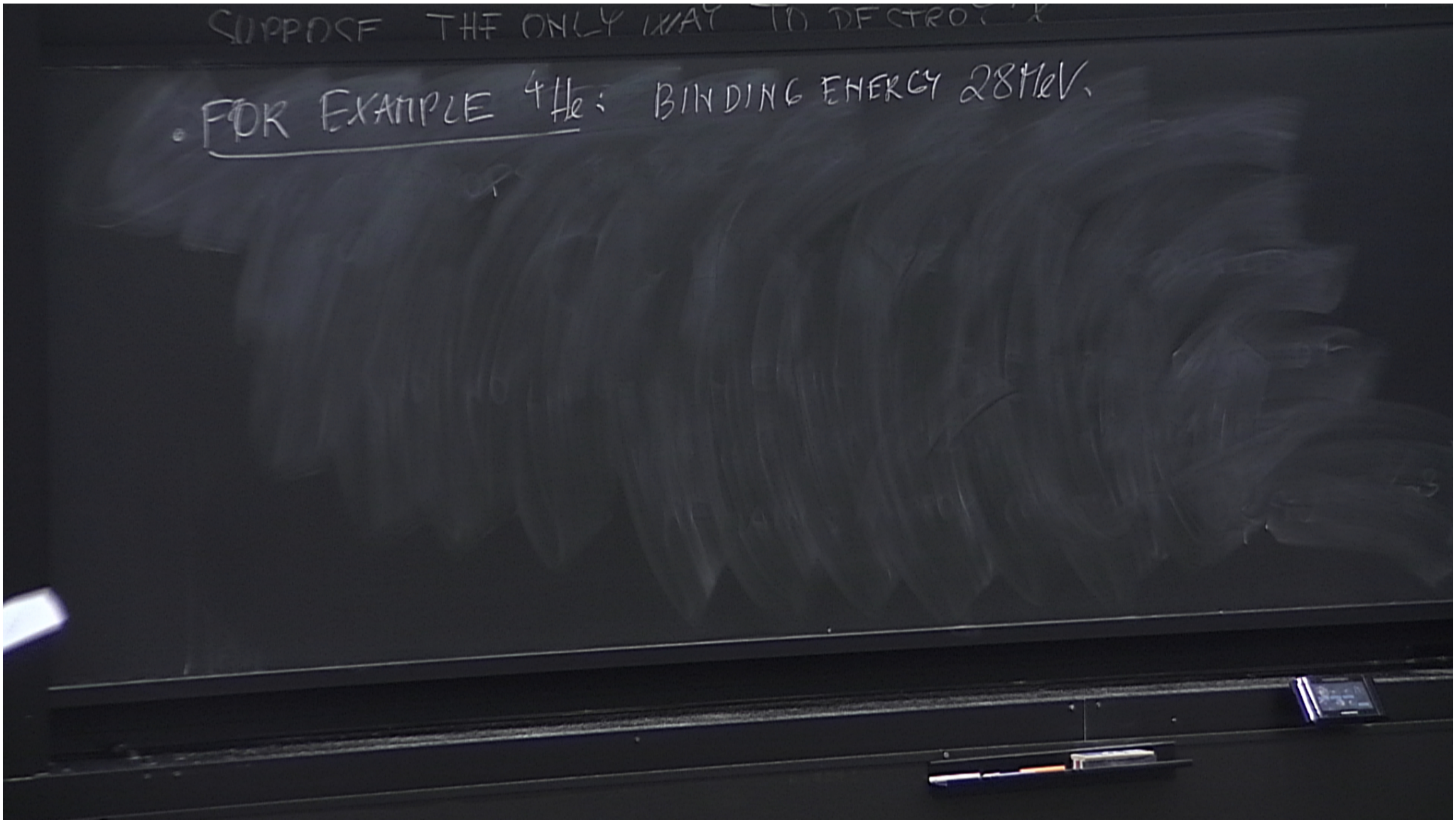

WHEN/WHERE PRODUCED?
MID 20th CENT.
IVERSE AT LARGE
H
He

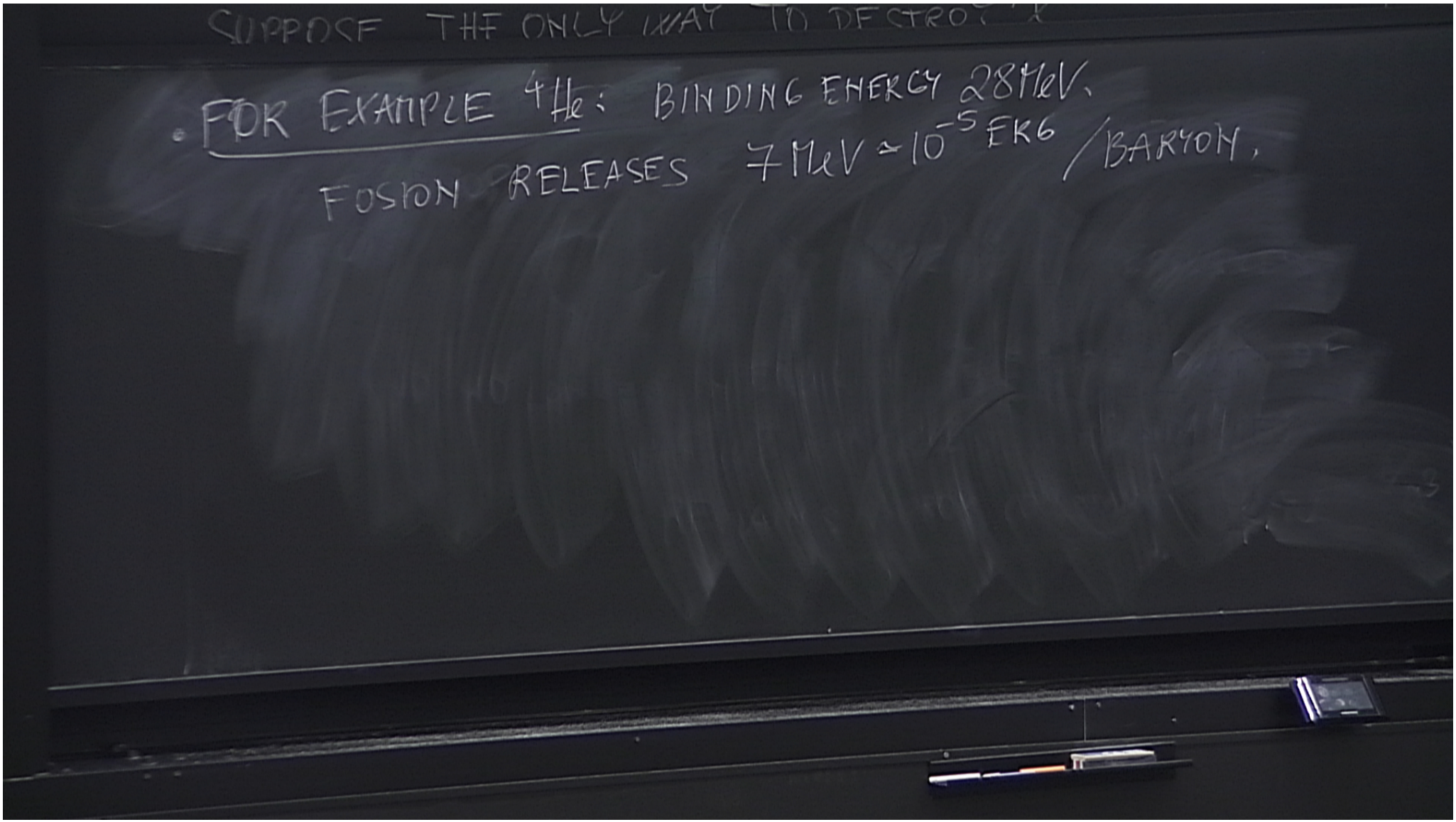

IVERSE AT LARGE
H
He
• Fe ... THE MOST TD STABLE EL.
• UP TO THIS ... COOK IN CENTERS OF
MASSIVE STARS

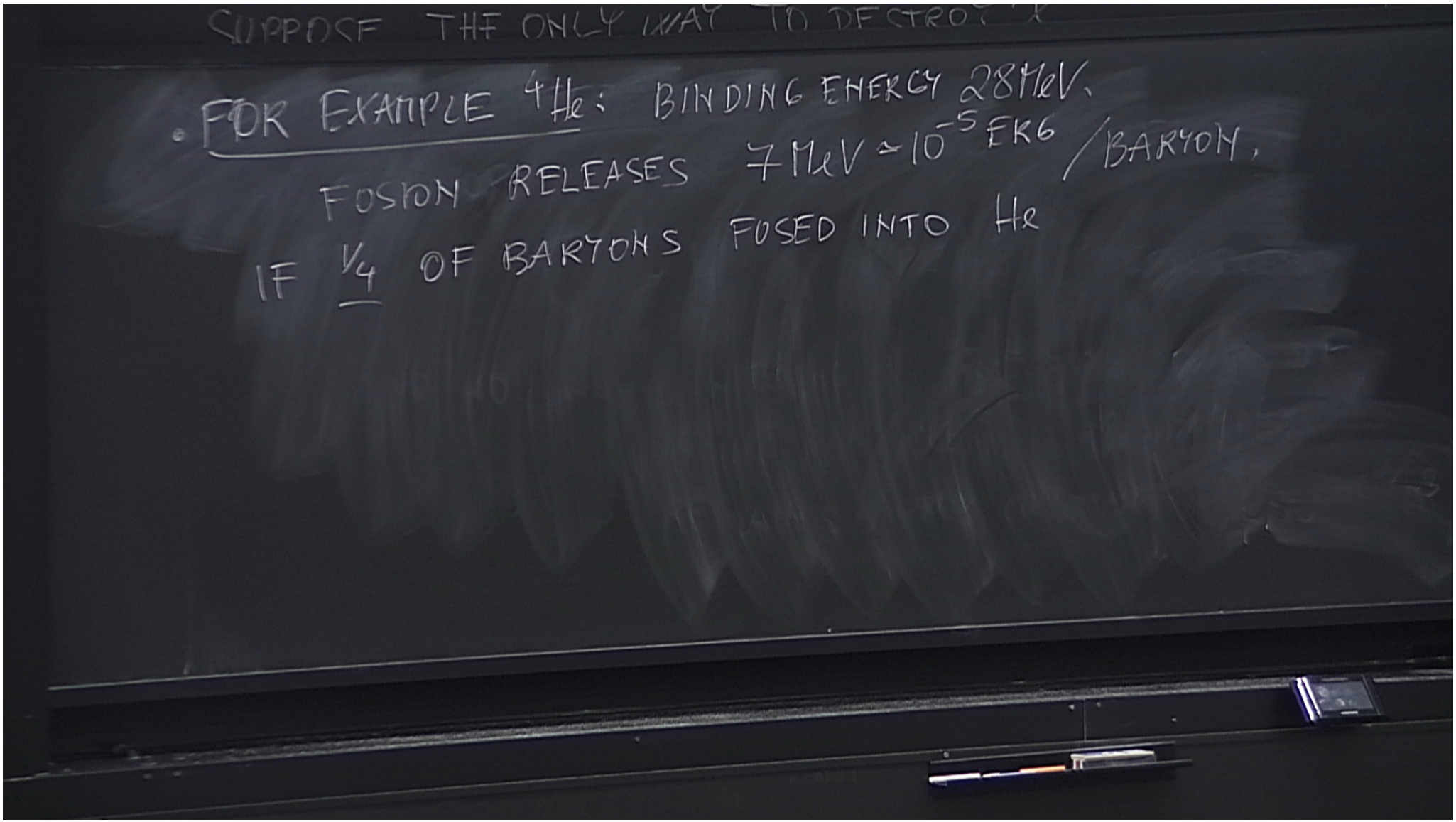

IVERSE AT LARGE
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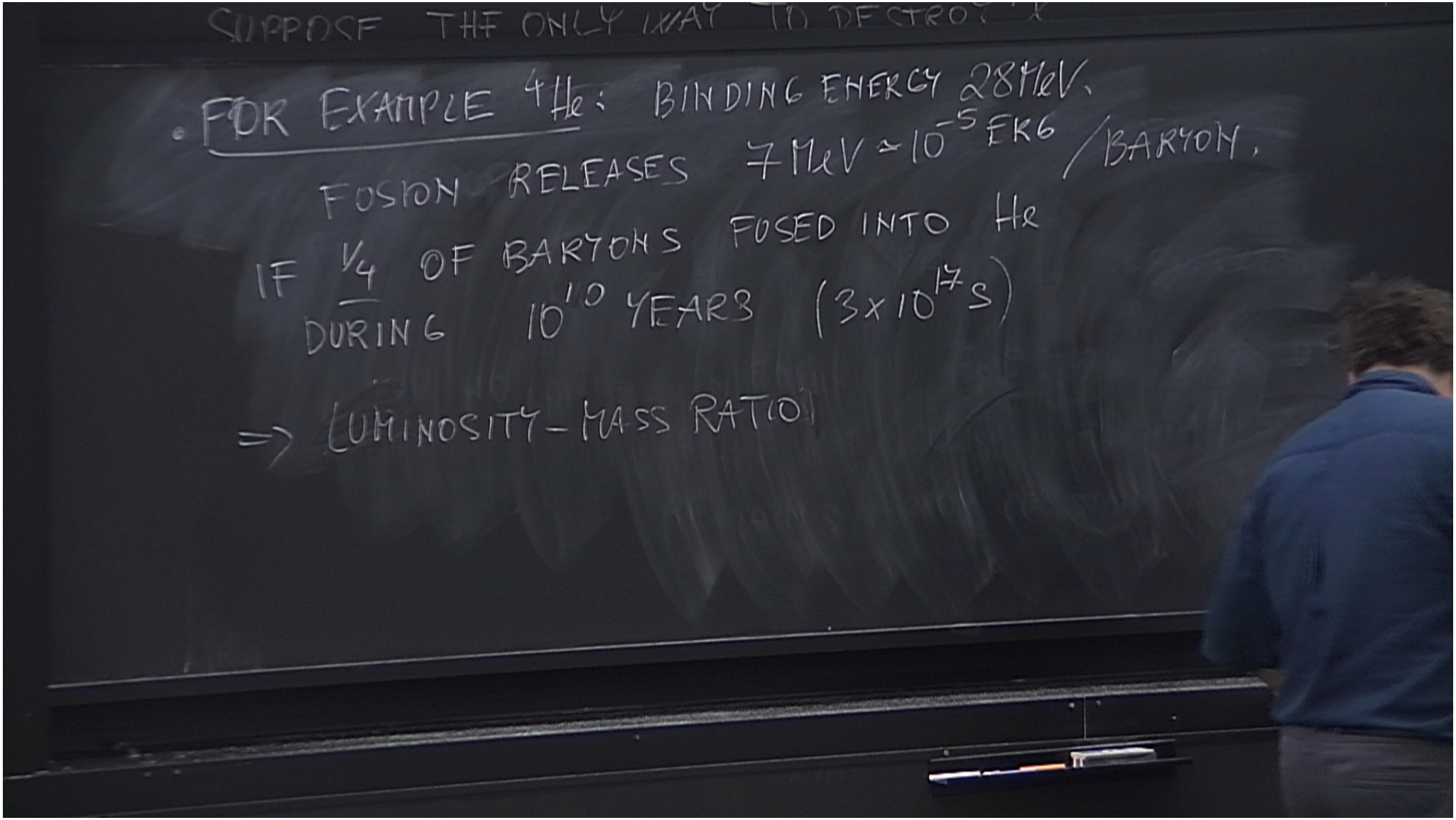

IVERSE AT LARGE
H
He
WHEN/WHERE
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• UP TO THIS ... COOK IN CENTERS OF MASSIVE STARS ... TO MAKING ... FUSION.
• HEAVIER ELEMENTS PRODUCED IN SHOCKS (SUPERNOVAE EXPL.)


H
He
- UP TO THIS ... COOK IN CENTERS
MASSIVE STARS .. TO MAKING ... FUSION.
- HEAVIER ELEMENTS PRODUCED IN SHOCKS
(SUPERNOVAE EXP.)
- CANNOT EXPLAIN ABUNDANCE OF LIGHTER ELEMENTS.
(H, He, Li, ...)


SUPPOSE THE ONLY WAY TO DESTRO
• FOR EXAMPLE ^4He: BINDING ENERGY 28MeV.


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DURING 10^{10} YEARS (3×10^{17} s)
=> LUMINOSITY - MASS RATIO

FUSION RELEASES $7\,MeV \simeq 10^{-5}$ ERG / BARYON,

IF $\frac{1}{4}$ OF BARYONS FUSED INTO He

DURING 10^{10} YEARS $(3\times10^{17}\,s)$

$\Rightarrow$ LUMINOSITY-MASS RATIO:

$$\frac{L}{M_{BAR}} = \frac{1}{4}\,\frac{10^{-5}\ \text{ERG}}{m_p}\,\frac{1}{3\times10^{17}\,s}$$

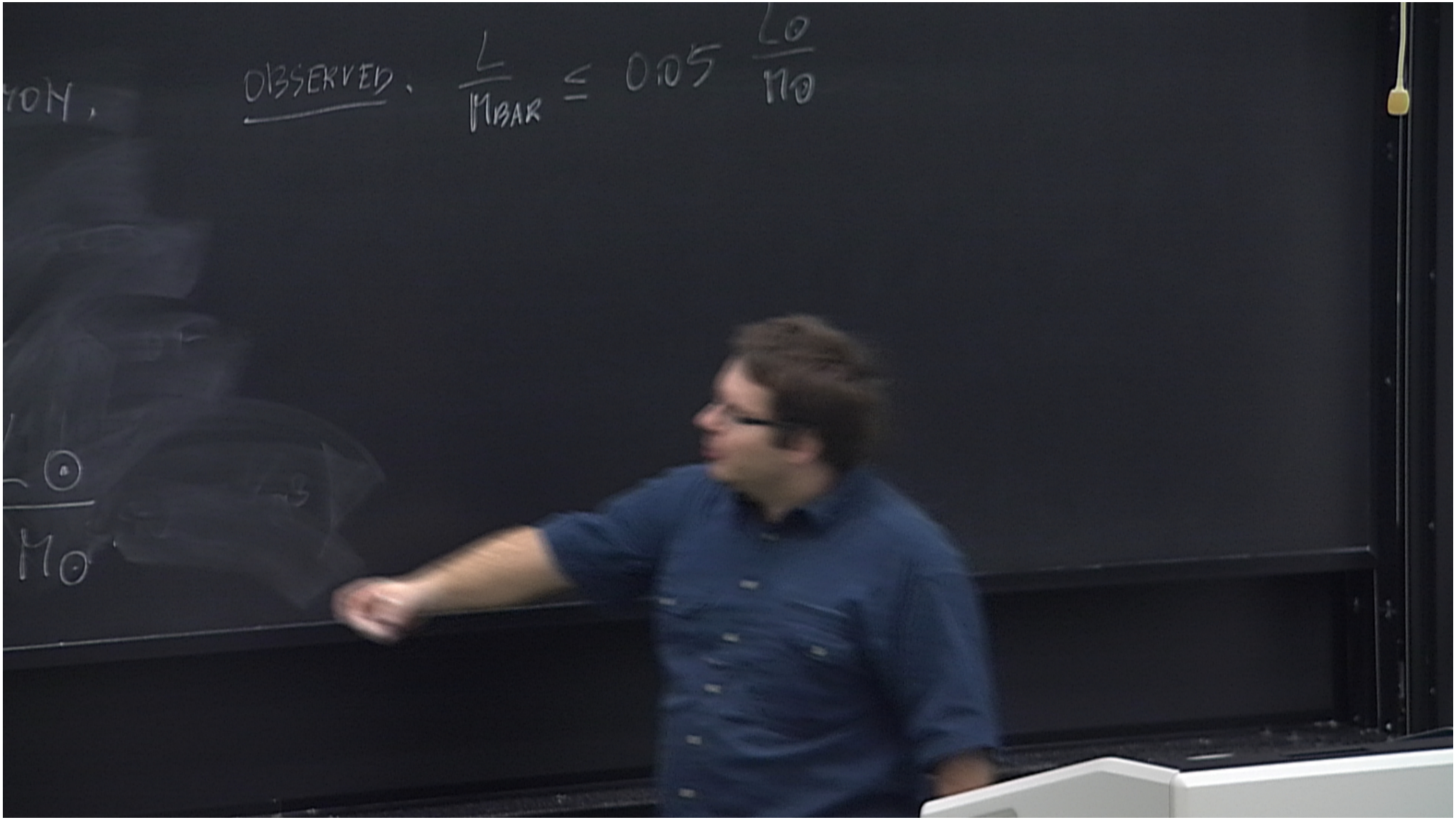
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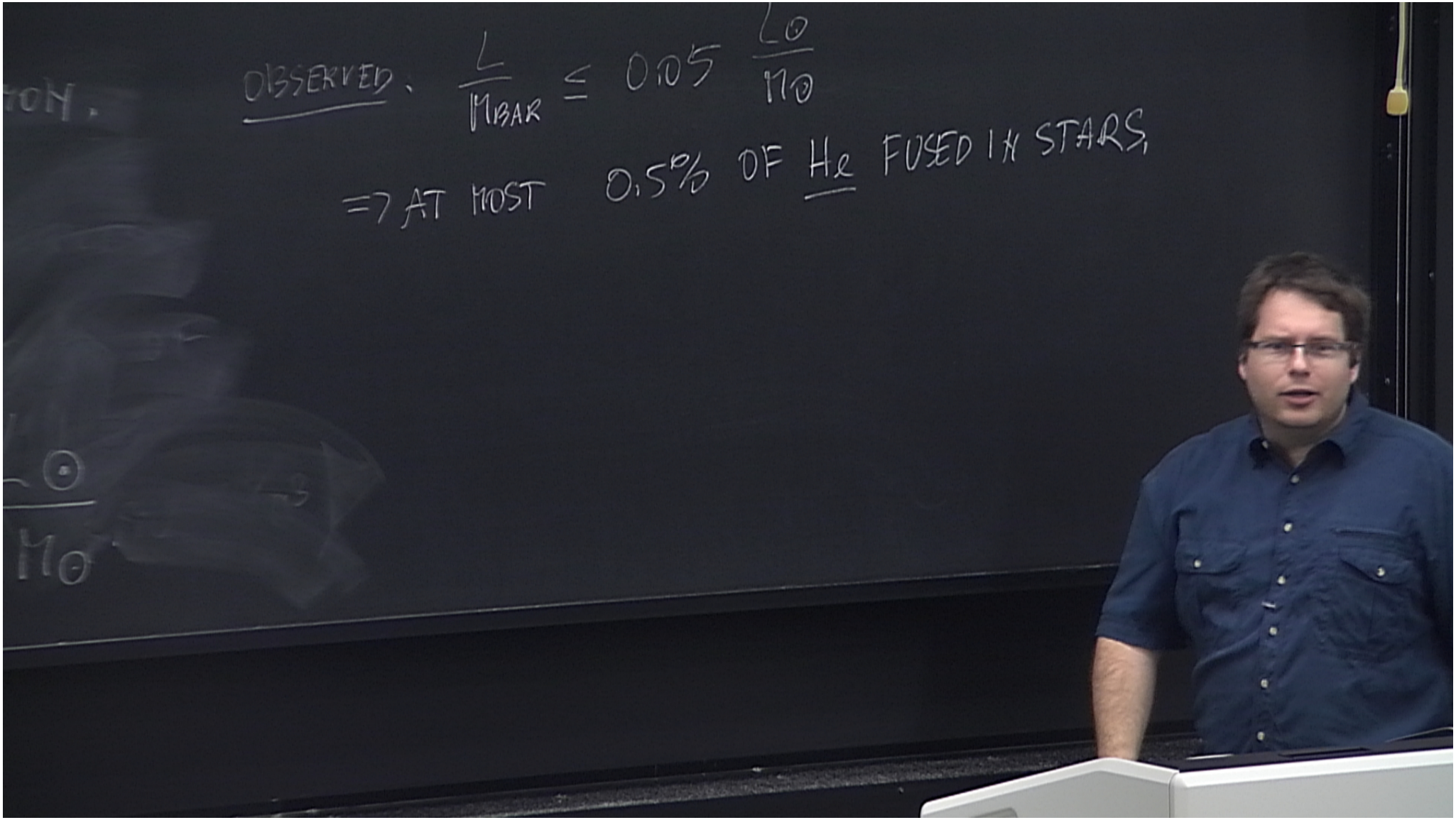
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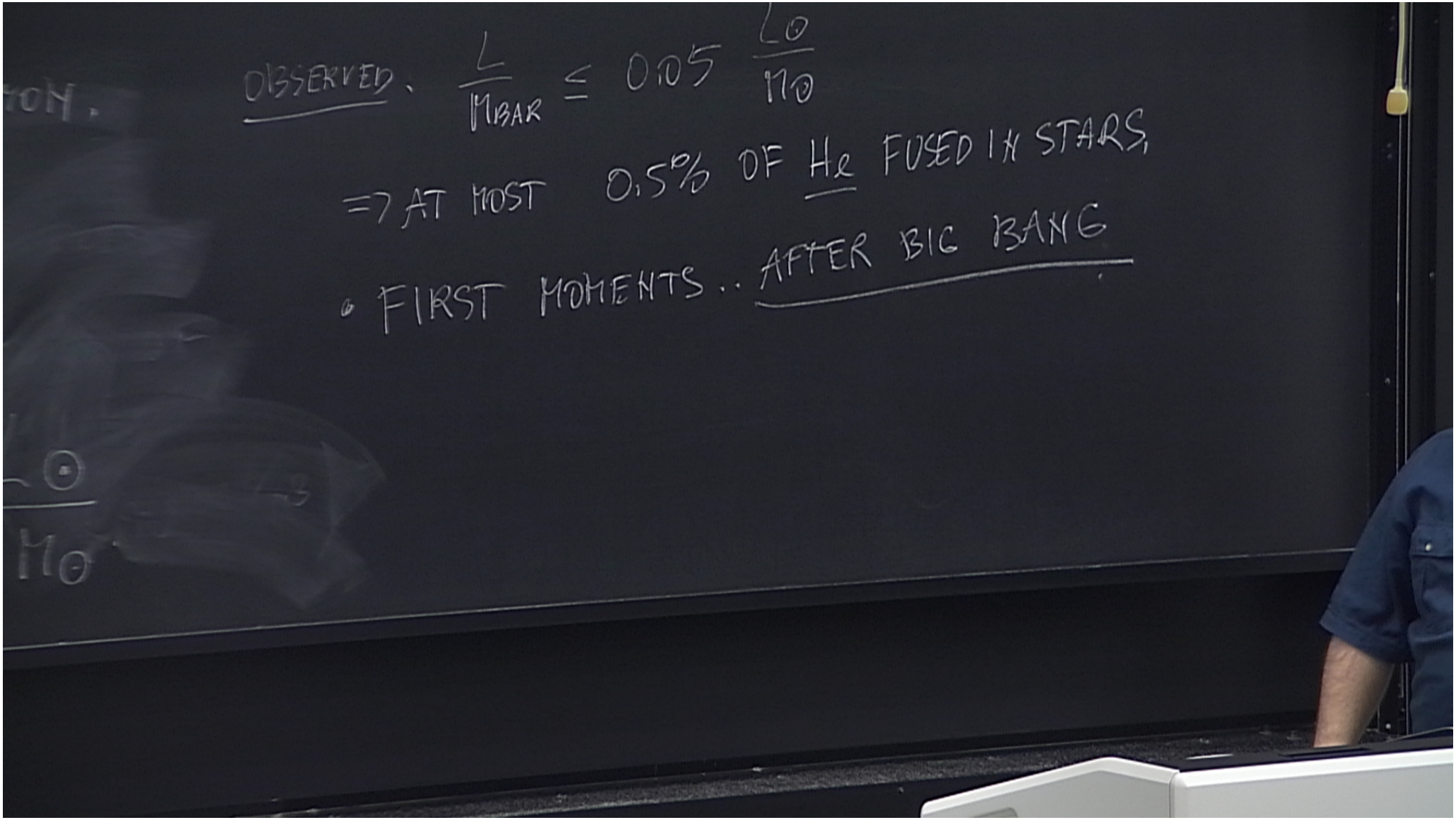
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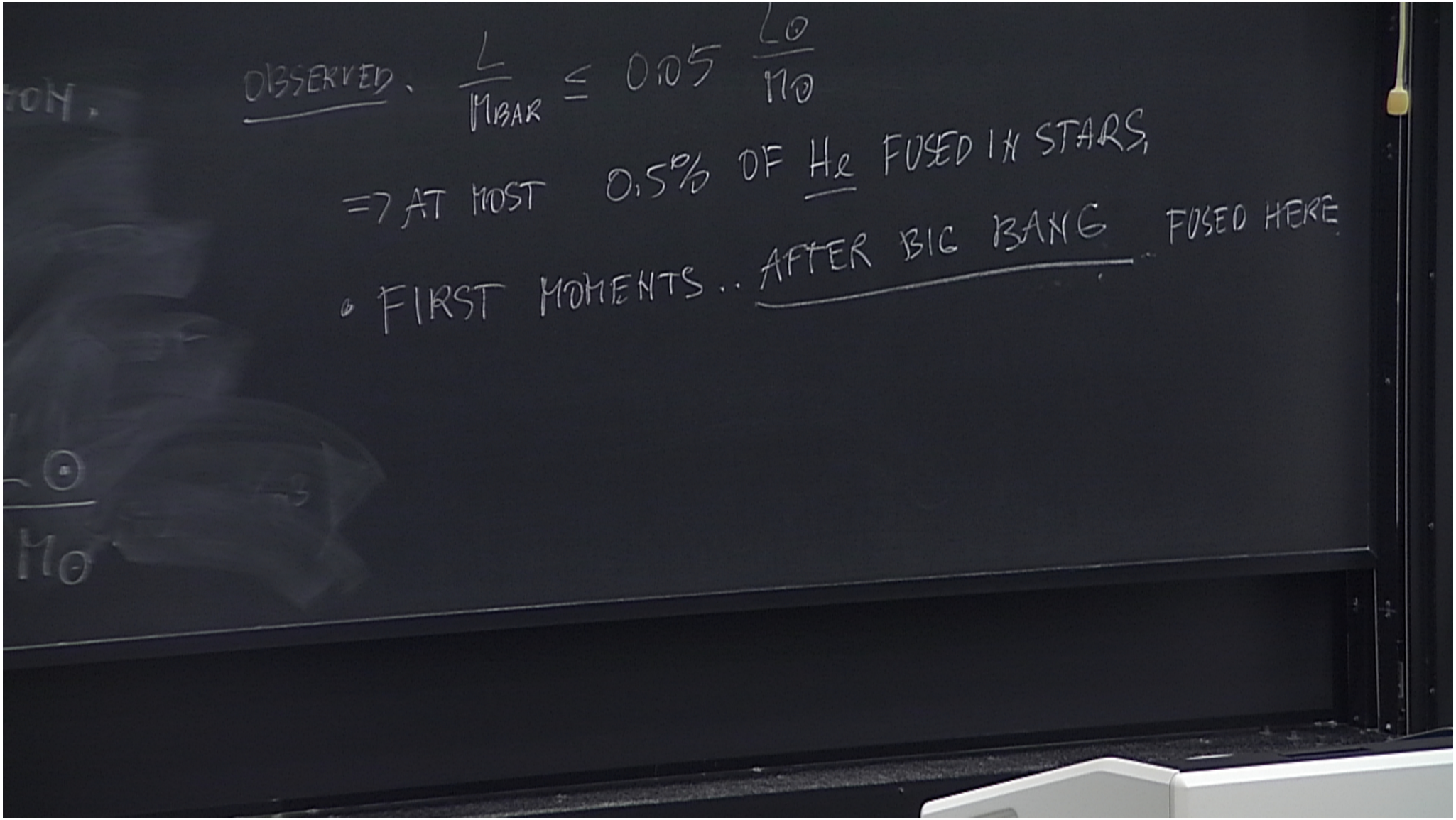
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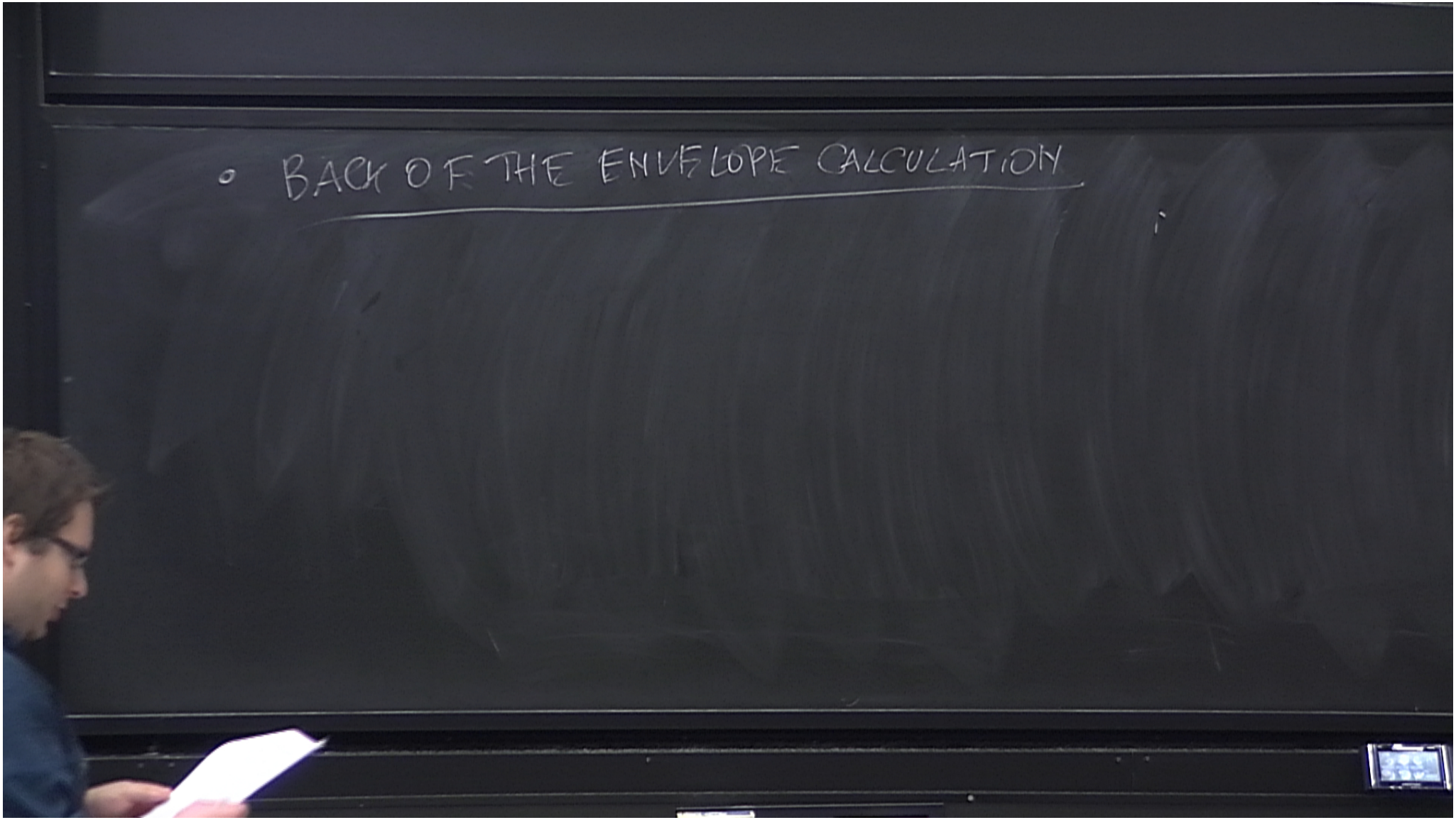
$$\frac{L}{M_{BAR}} = \frac{1}{4}\,\frac{10^{-5}\ \text{ERG}}{m_p}\,\frac{1}{3\times10^{17}\,s} \simeq 2.5\,\frac{L_\odot}{M_\odot}$$

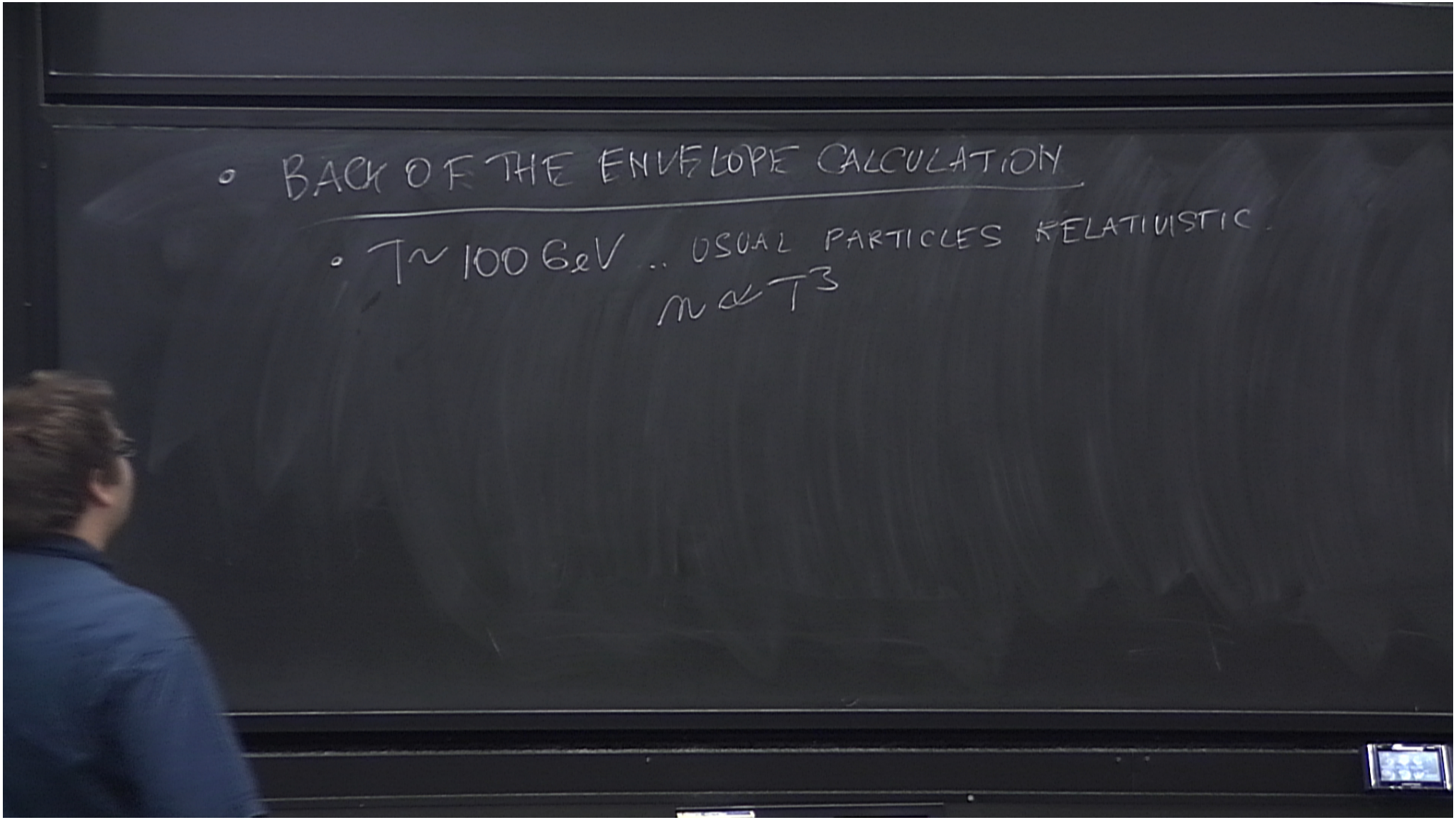

OBSERVED.
$\frac{L}{M_{BAR}} \leq 0.05 \frac{L_\odot}{M_\odot}$

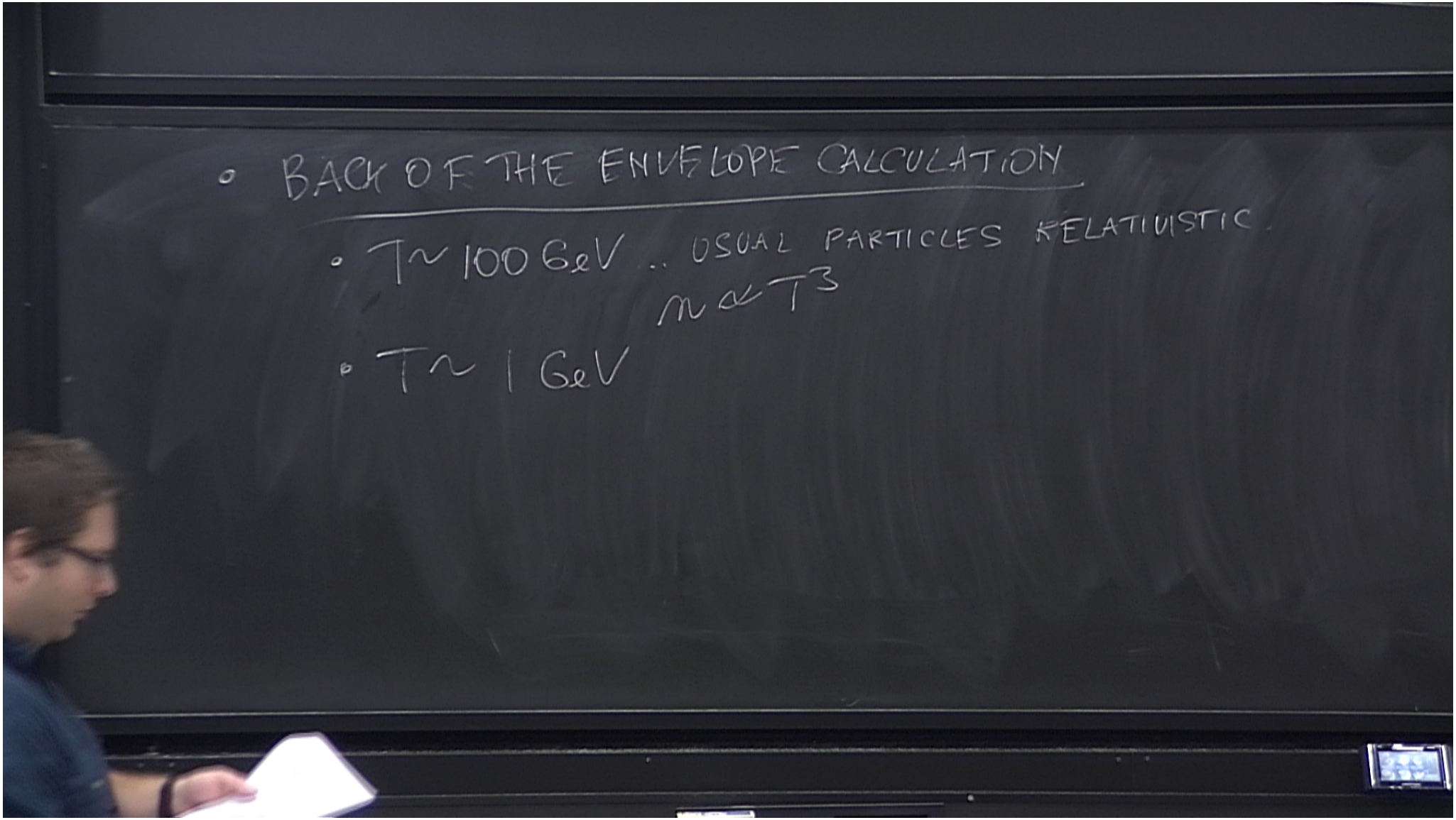

OBSERVED. $\frac{L}{M_{BAR}} \leq 0.05 \frac{L_\odot}{M_\odot}$
$\Rightarrow$ AT MOST 0.5% OF He FUSED IN STARS

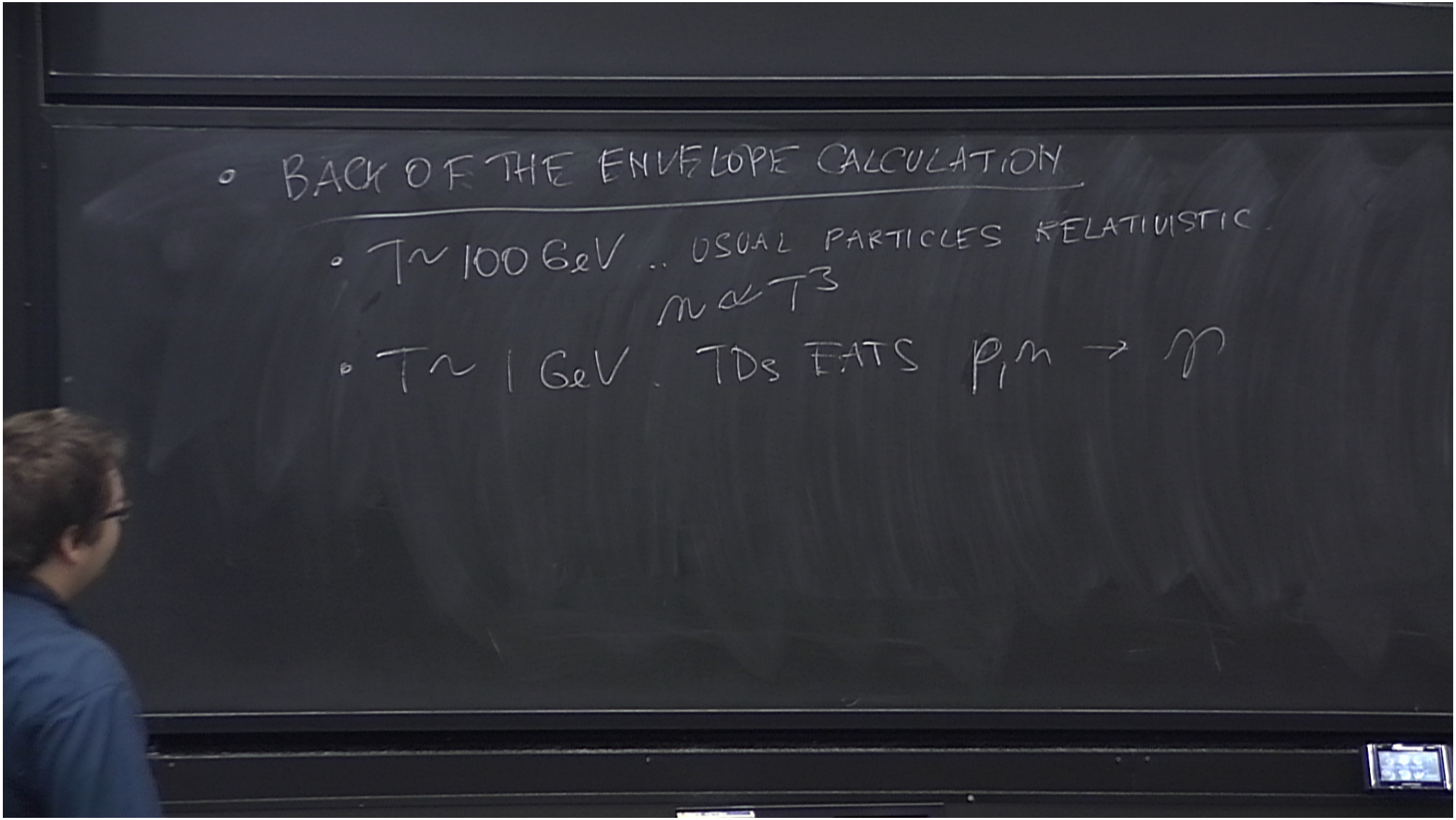

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• FIRST MOMENTS.. AFTER BIG BANG

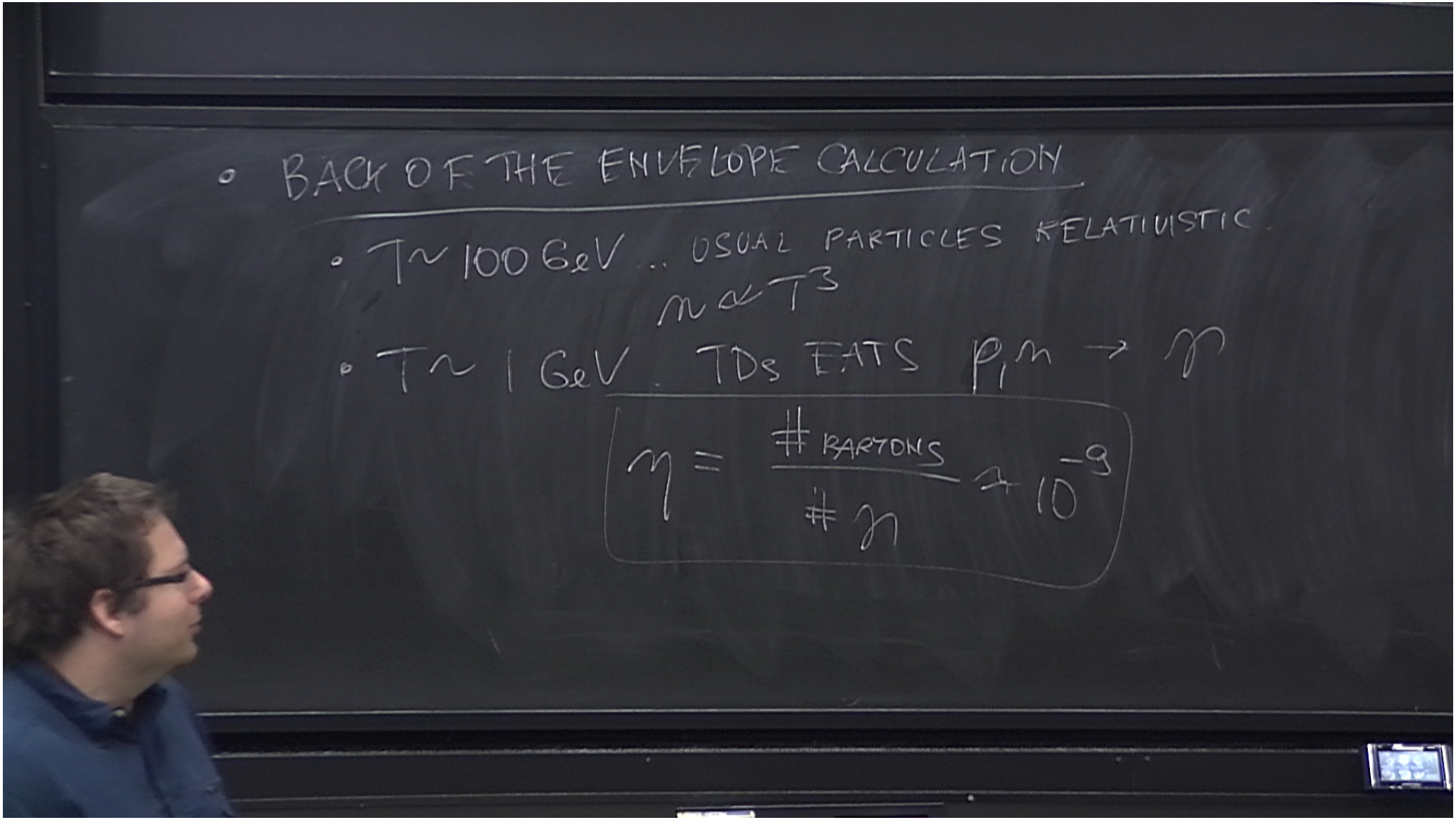

OBSERVED. $\frac{L}{M_{BAR}} \leq 0.05 \frac{L_\odot}{M_\odot}$
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• FIRST MOMENTS.. AFTER BIG BANG .. FUSED HERE

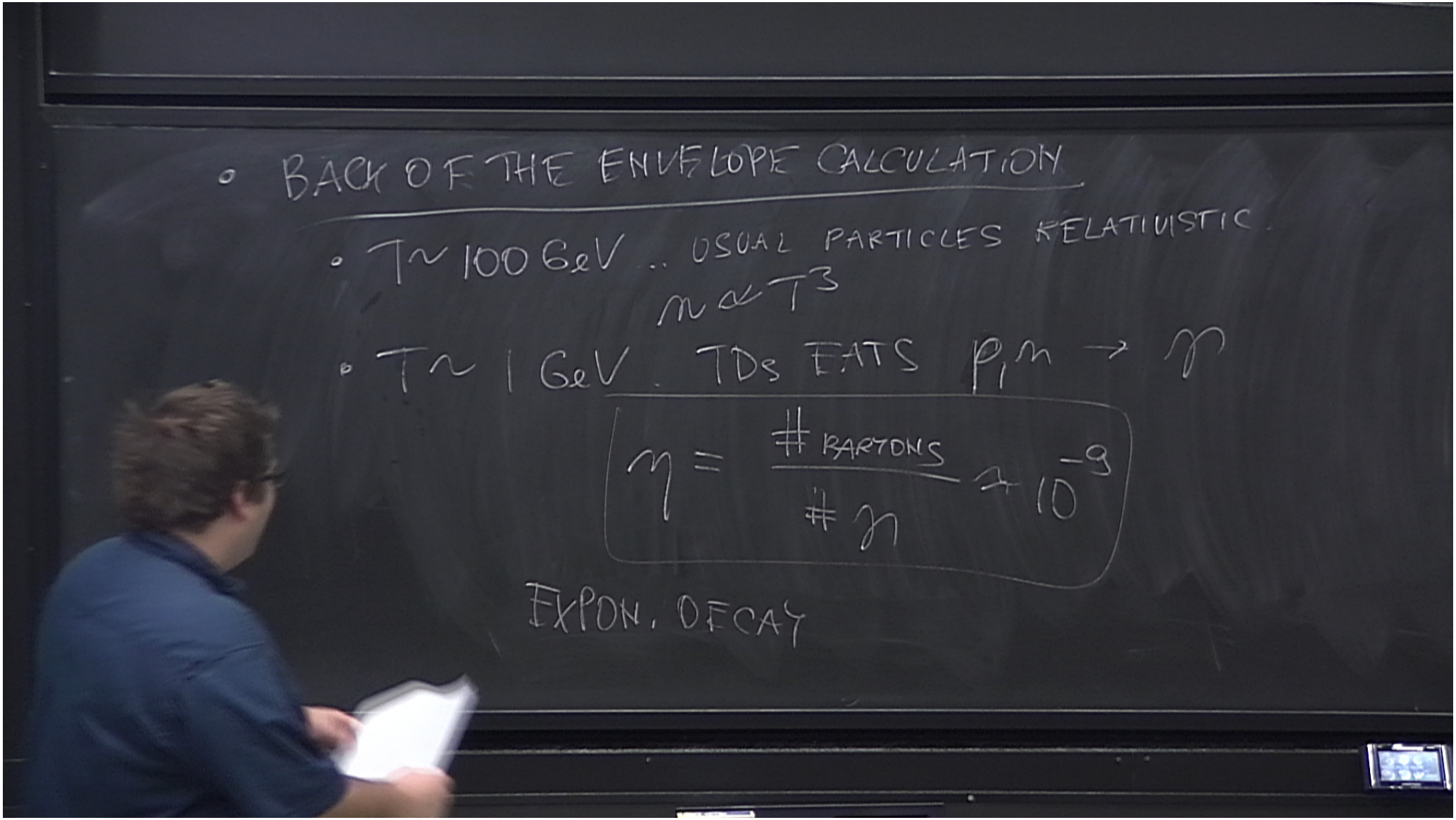

• BACK OF THE ENVELOPE CALCULATION

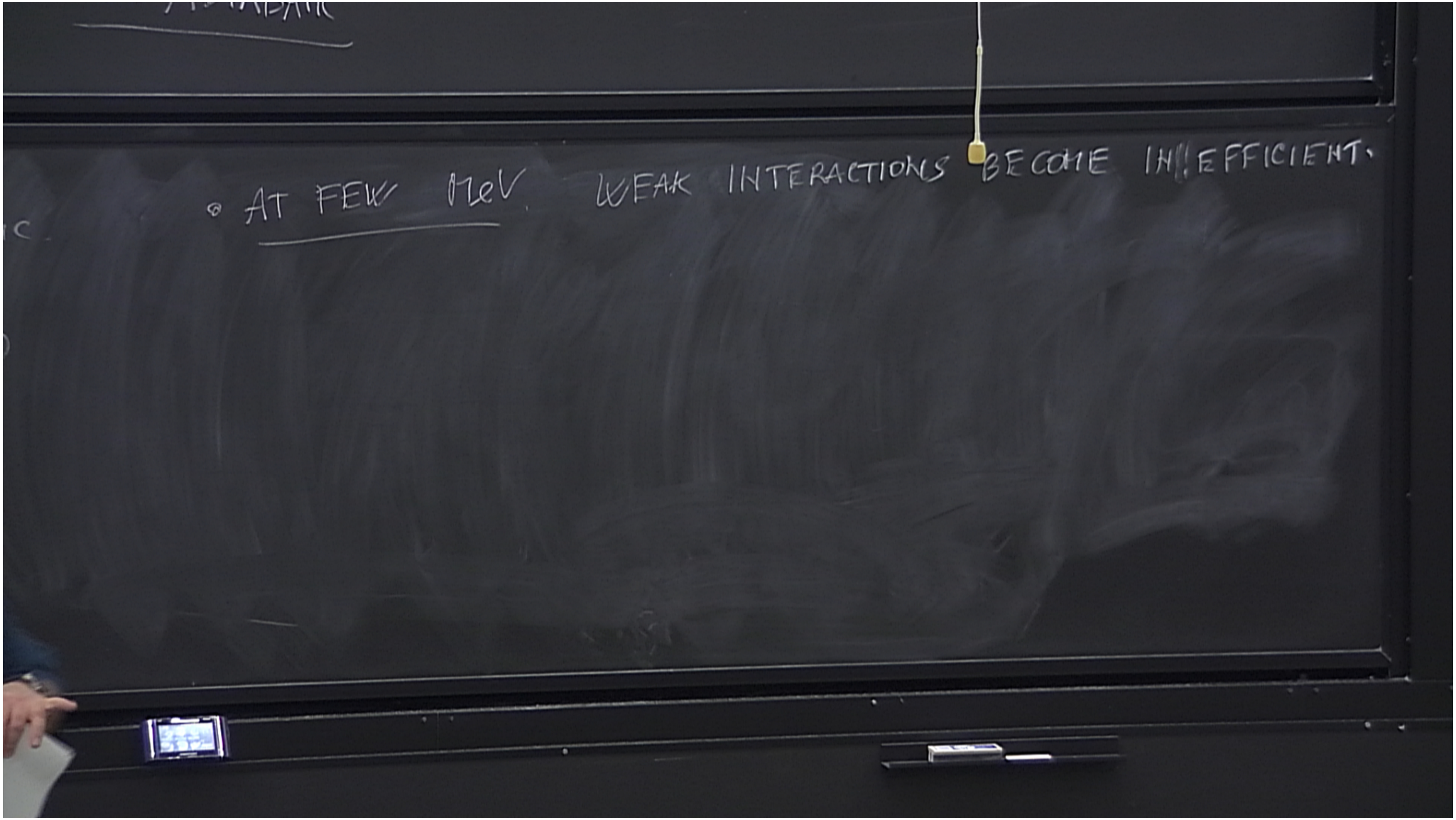

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• T ~ 100 GeV .. USUAL PARTICLES RELATIVISTIC
n ∝ T³

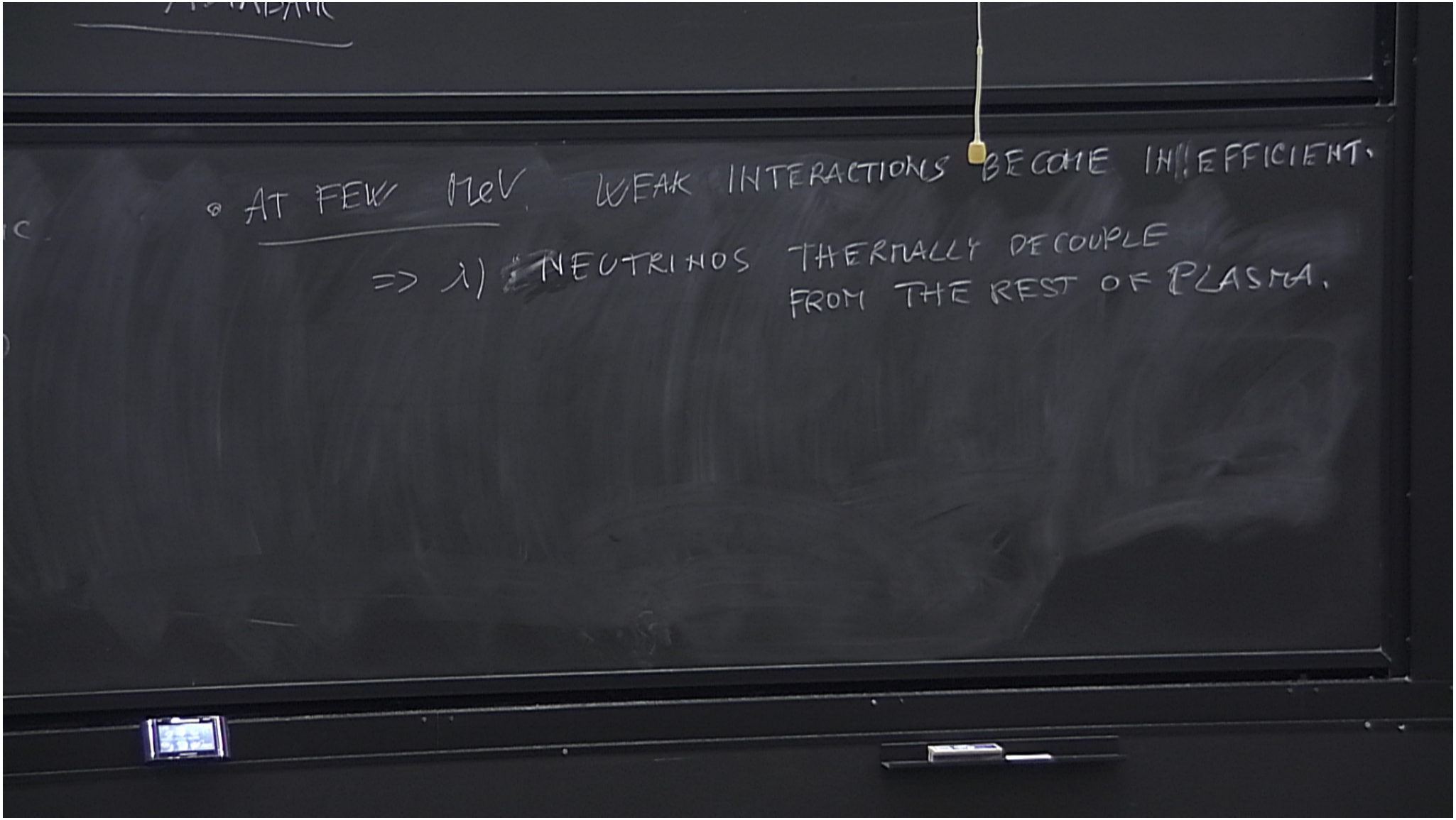

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• T ~ 1 GeV

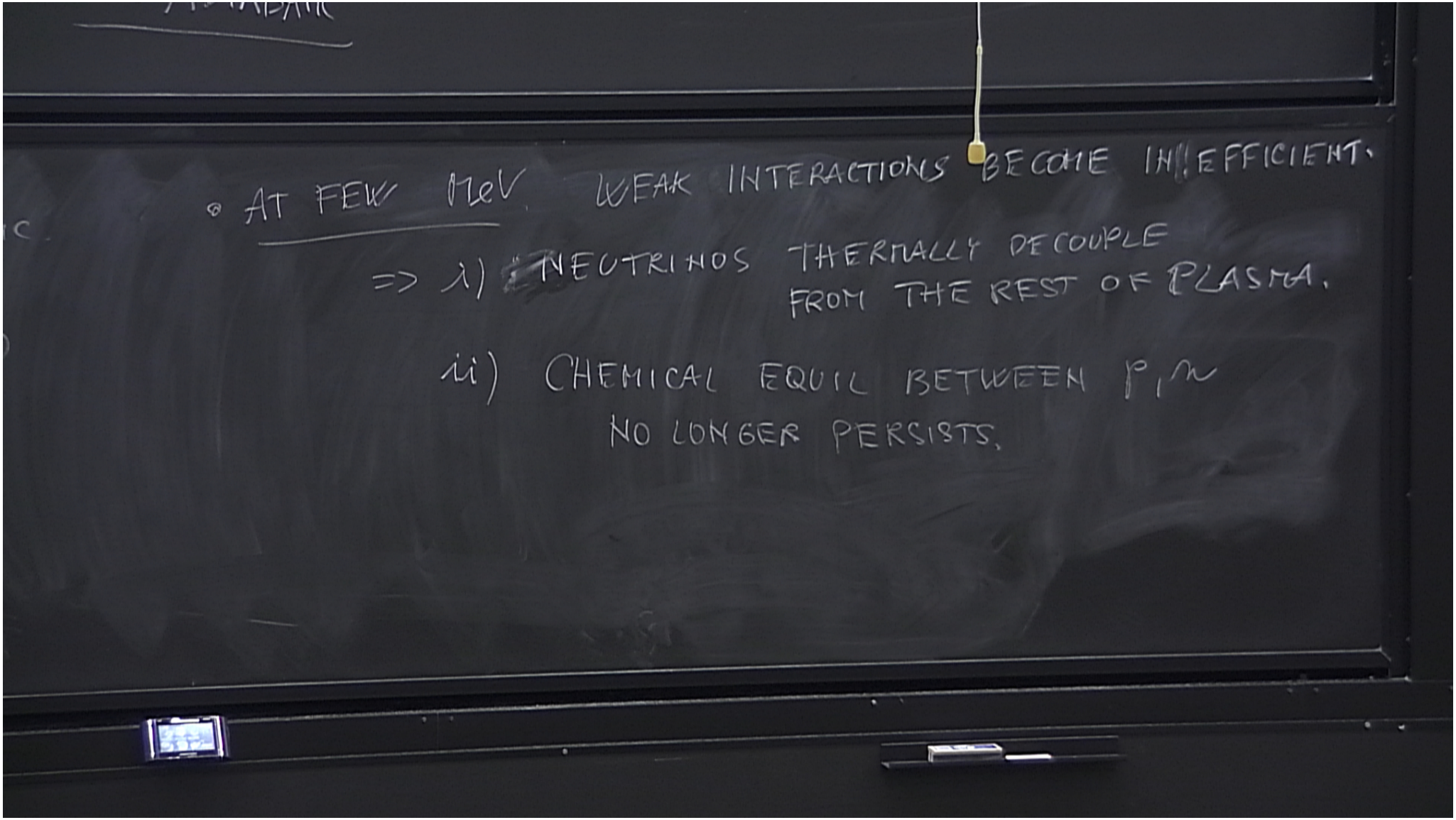

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EXPON. DECAY


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=> i) NEUTRINOS THERMALLY DECOUPLE FROM THE REST OF PLASMA.
ii) CHEMICAL EQUIL BETWEEN p, n NO LONGER PERSISTS.