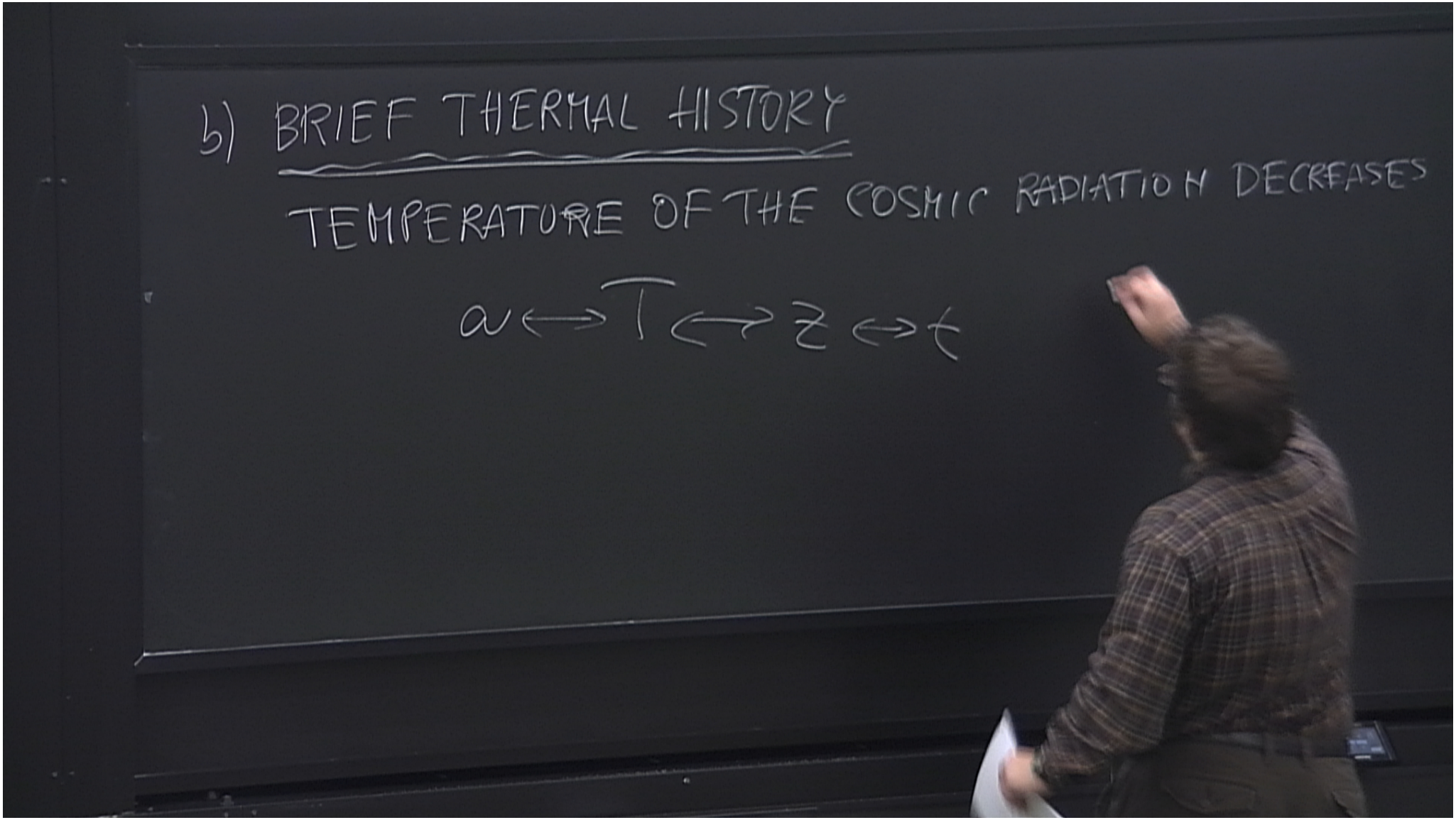
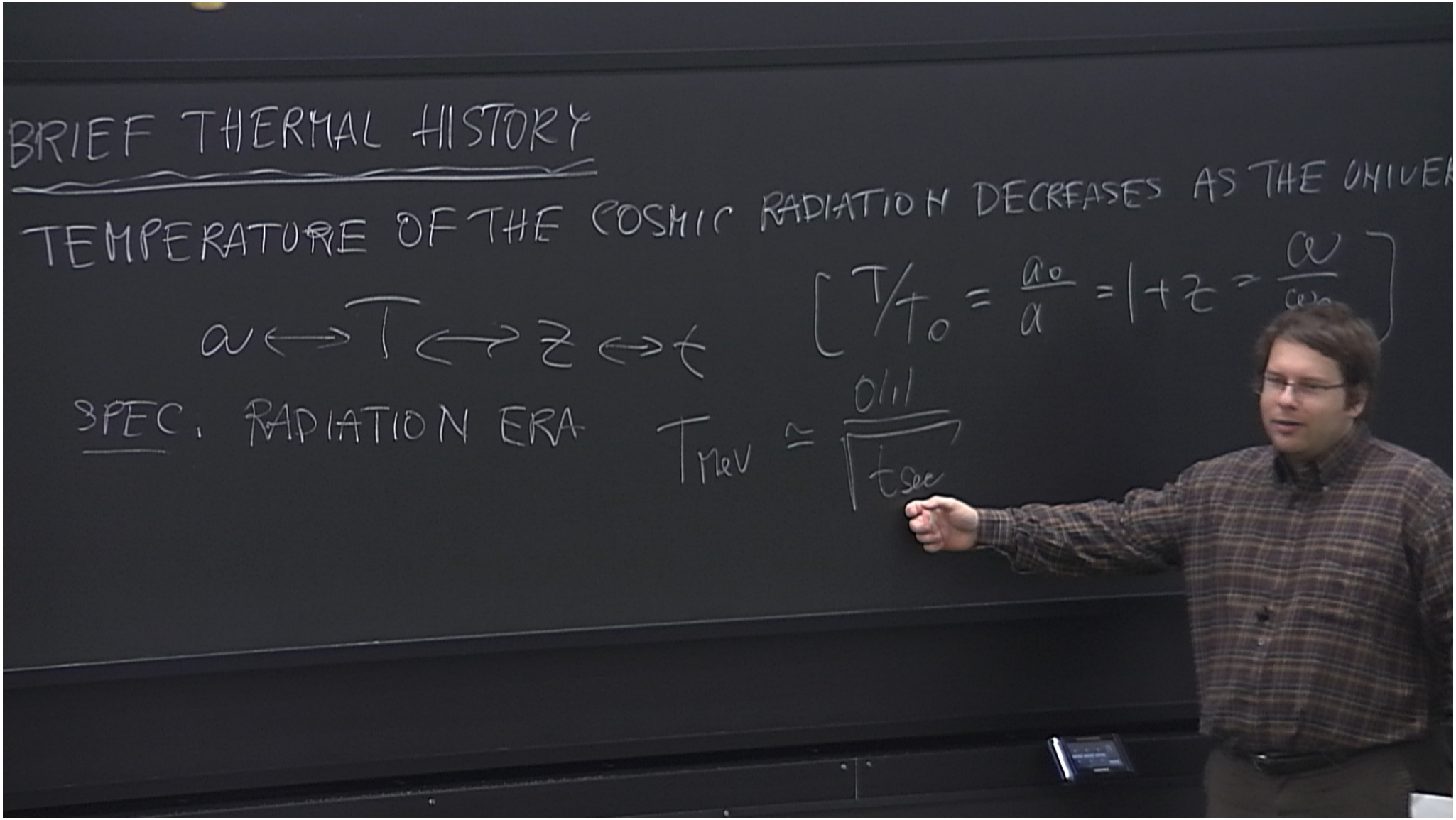
Title: Cosmology Review-5

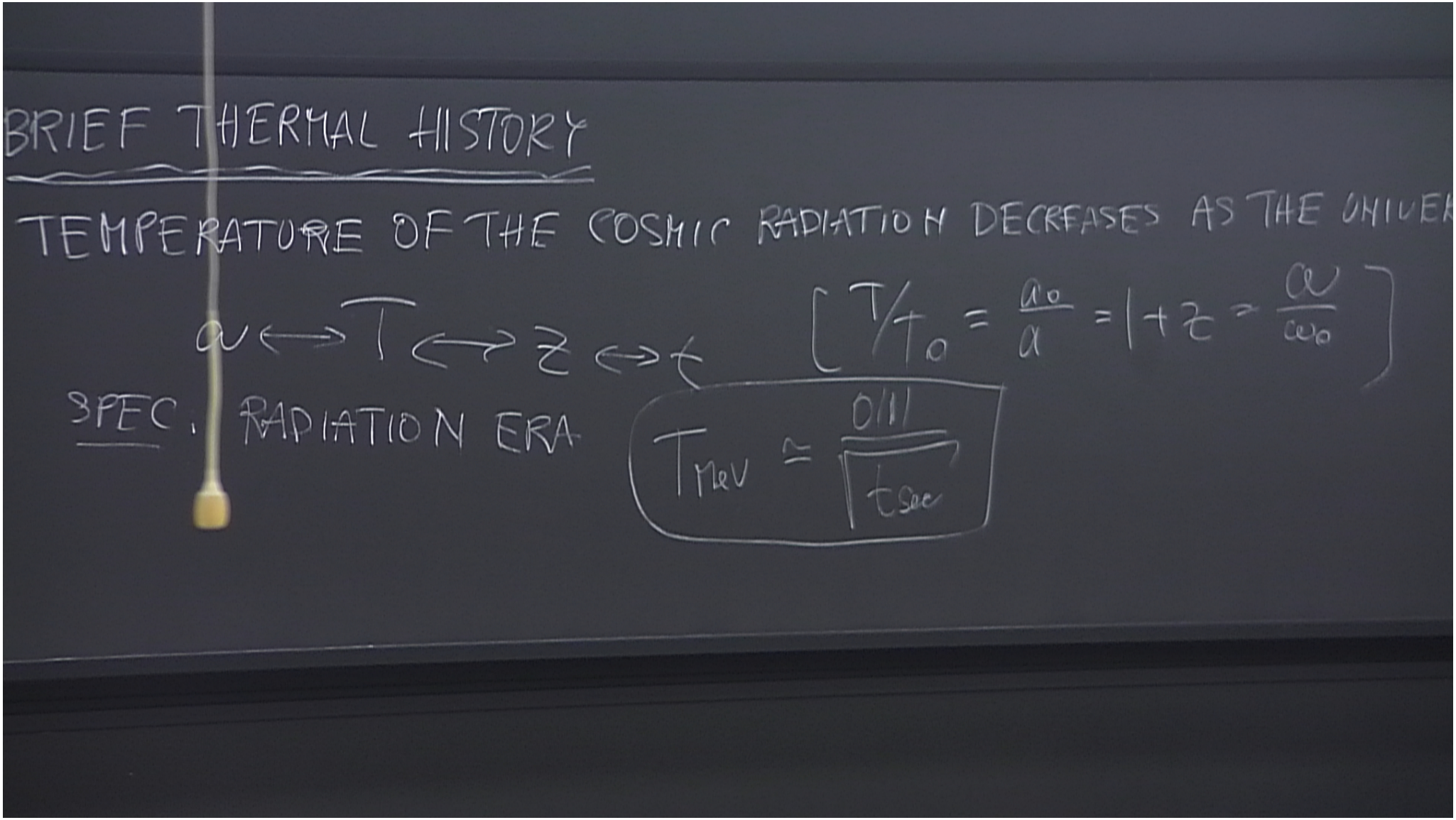
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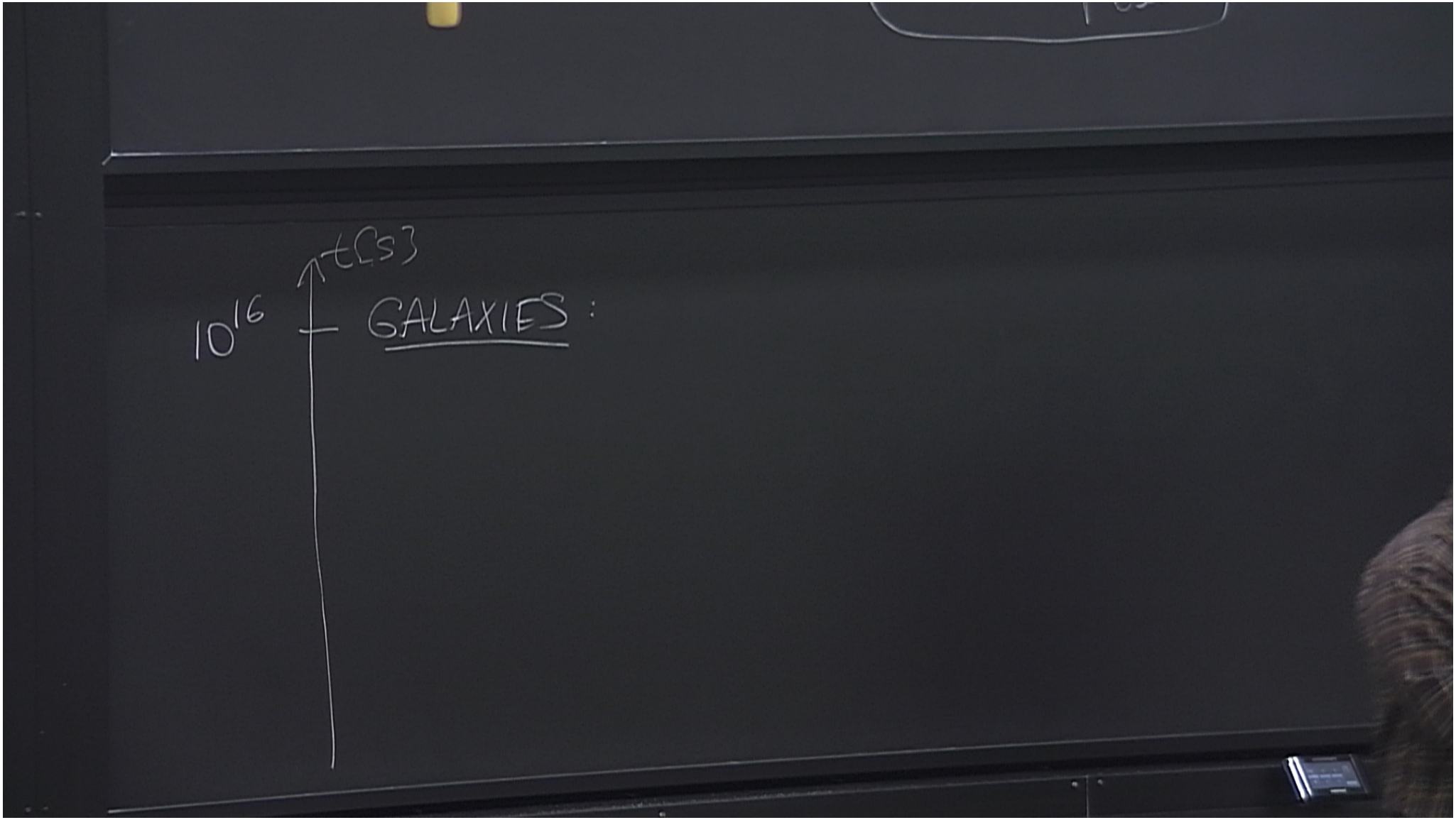
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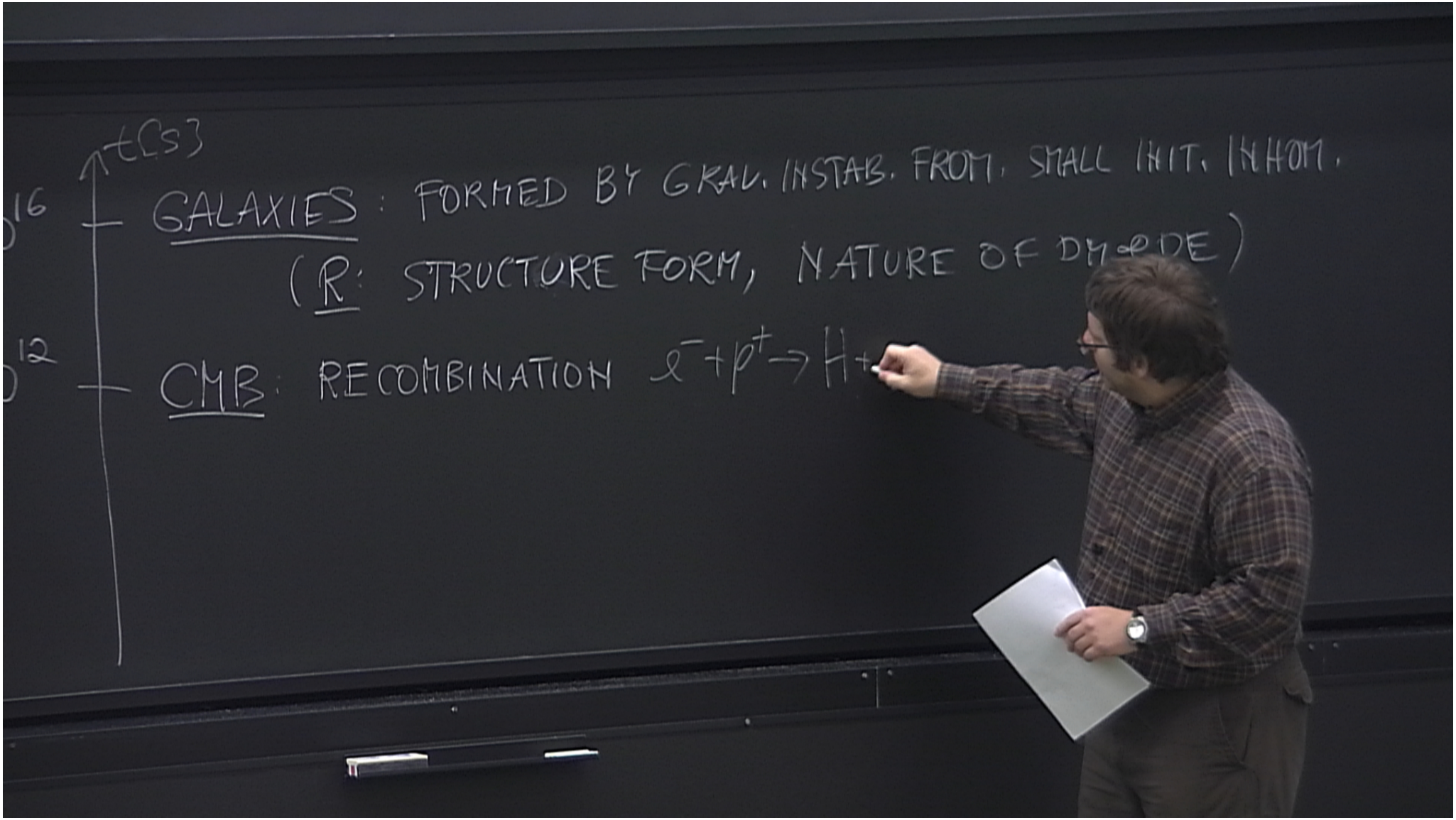
Abstract:

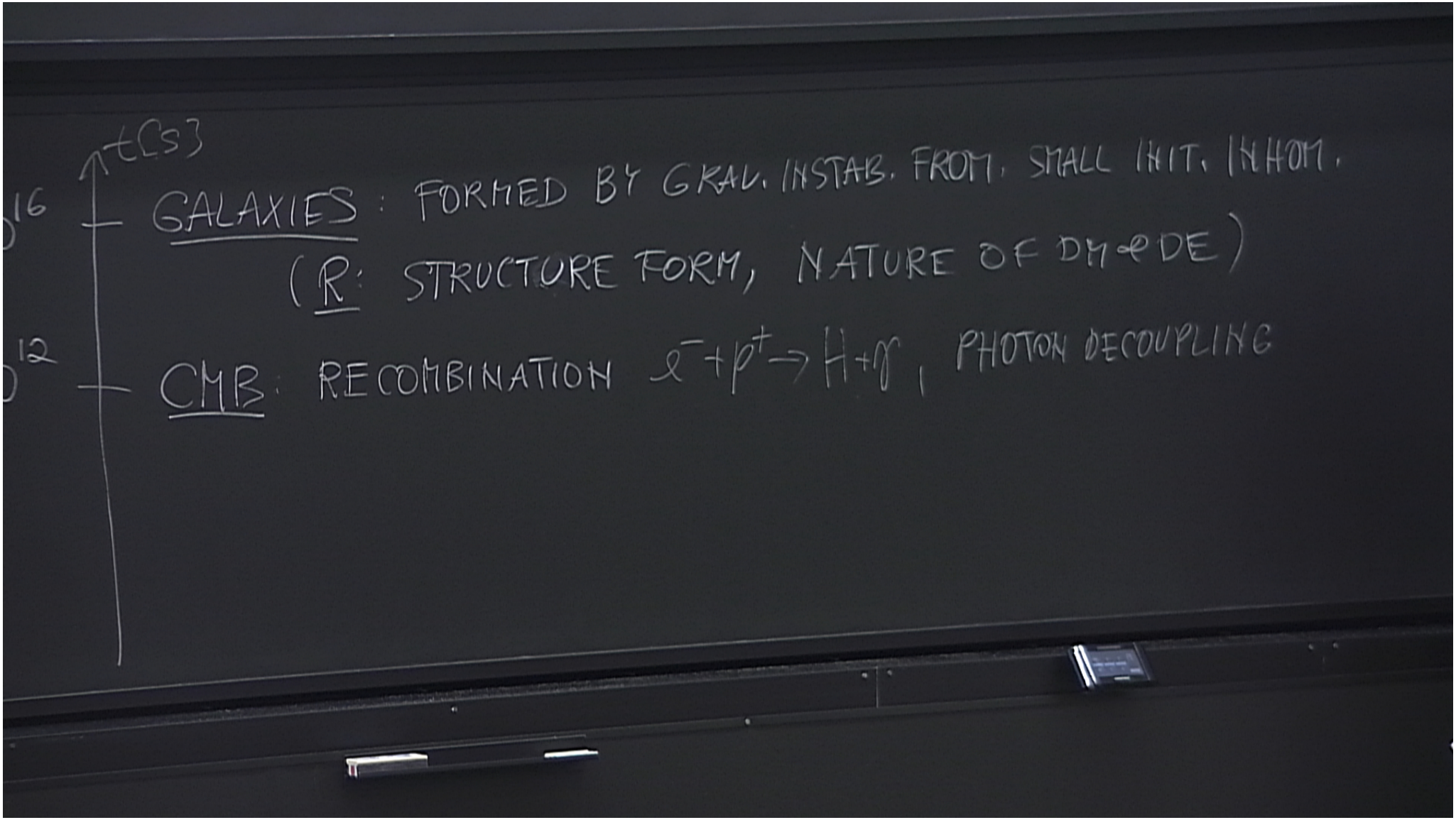

b) BRIEF THERMAL HISTORY
TEMPERATURE OF THE COSMIC RADIATION DECREASES
a ↔ T ↔ z ↔ t

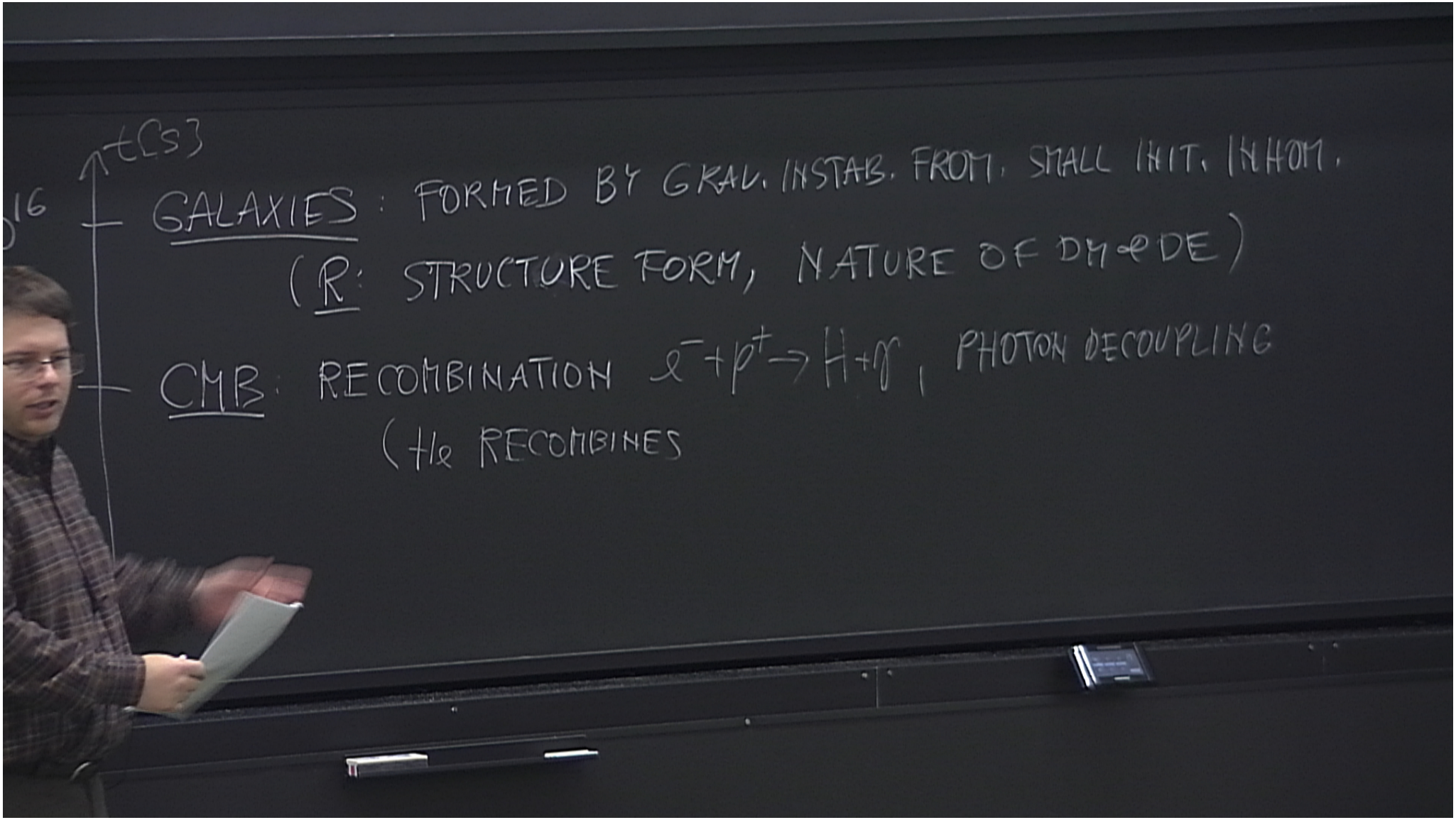

BRIEF THERMAL HISTORY
TEMPERATURE OF THE COSMIC RADIATION DECREASES AS THE UNIVER
a ⟷ T ⟷ z ⟷ t
[T/T0 = a0/a = 1+z = ω/ω
SPEC. RADIATION ERA
TMeV ≃ 0.1 / √tsec

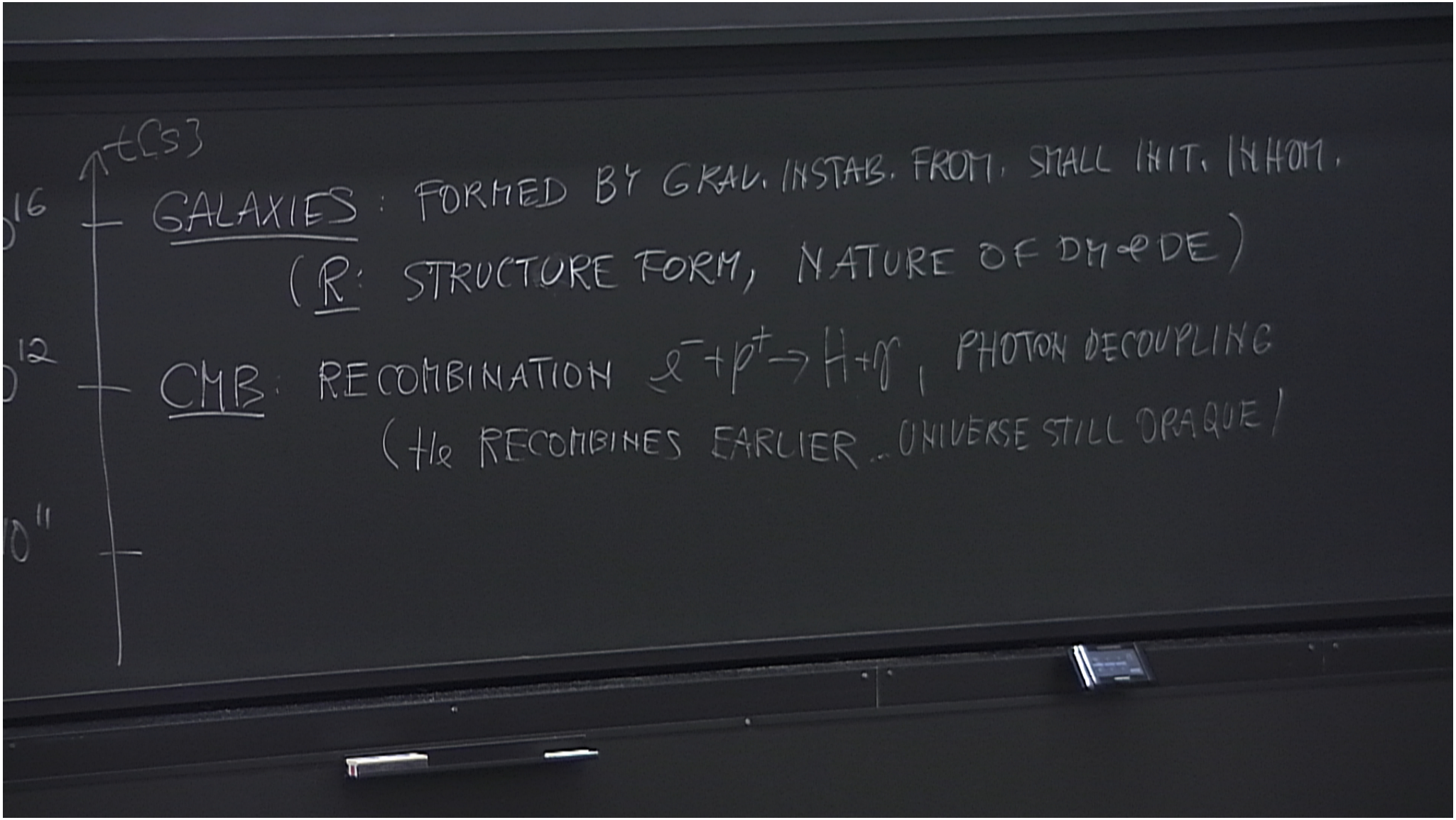

BRIEF THERMAL HISTORY
TEMPERATURE OF THE COSMIC RADIATION DECREASES AS THE UNIVER
$a \longleftrightarrow T \longleftrightarrow z \longleftrightarrow t$
$\left[T/T_0 = \frac{a_0}{a} = 1+z = \frac{\omega}{\omega_0} \right]$
SPEC. RADIATION ERA
$T_{MeV} \simeq \frac{0.1}{\sqrt{t_{Sec}}}$

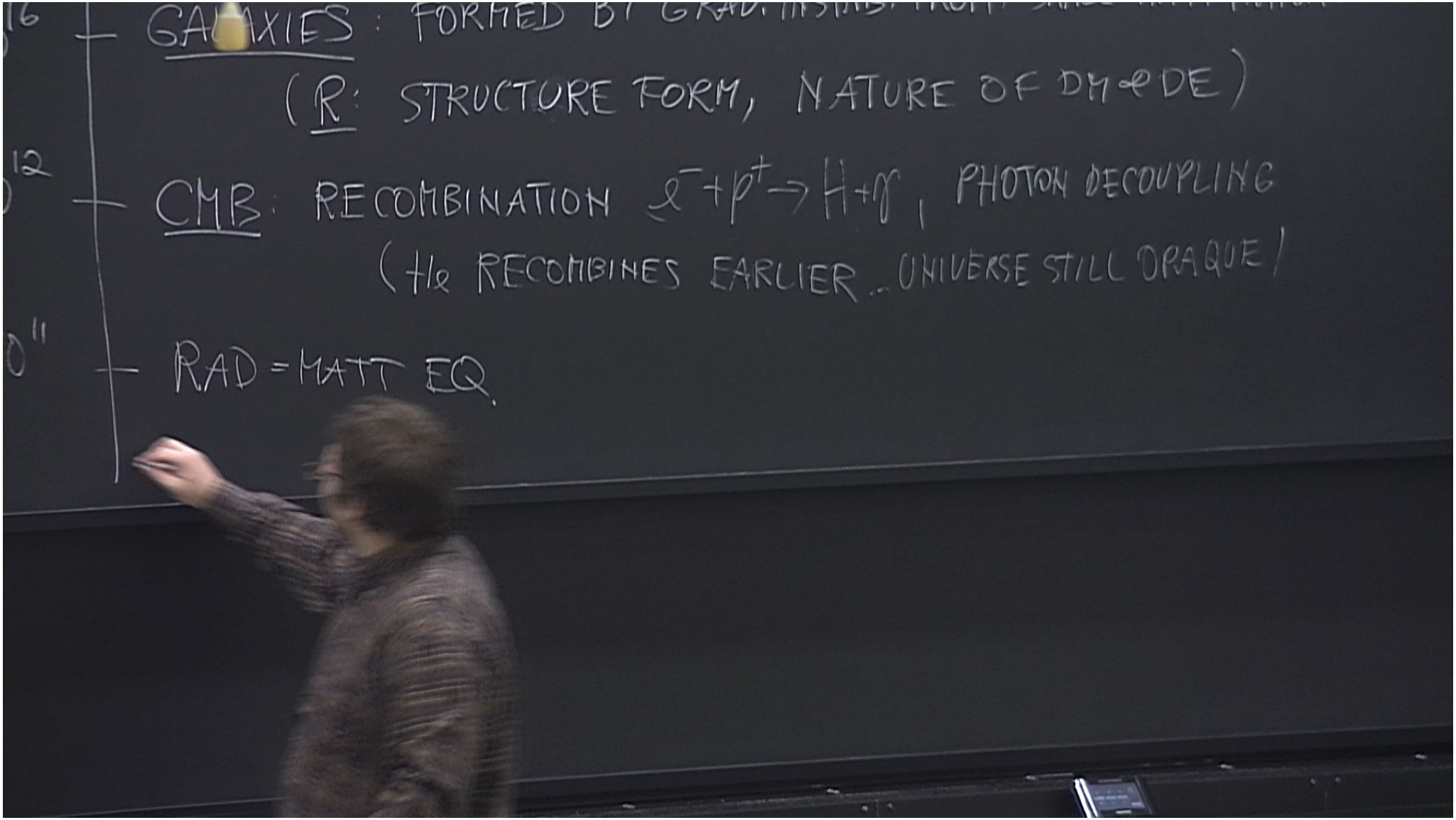

10^{16}
t[s]
GALAXIES:

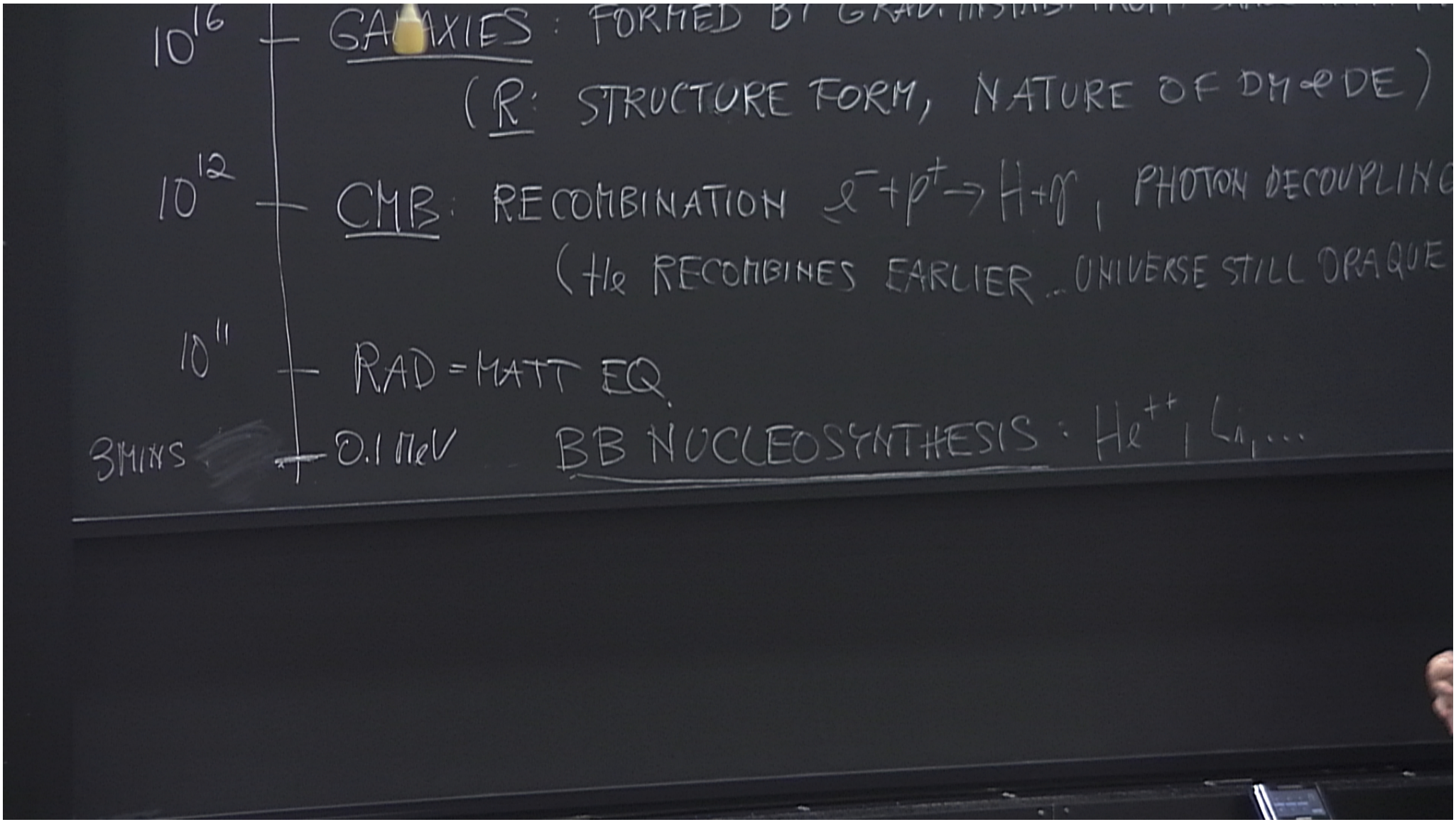

t[s]
16
12
GALAXIES: FORMED BY GRAV. INSTAB. FROM SMALL INIT. INHOM.
(R: STRUCTURE FORM, NATURE OF DM & DE)
CMB: RECOMBINATION $e^- + p^+ \rightarrow H +$

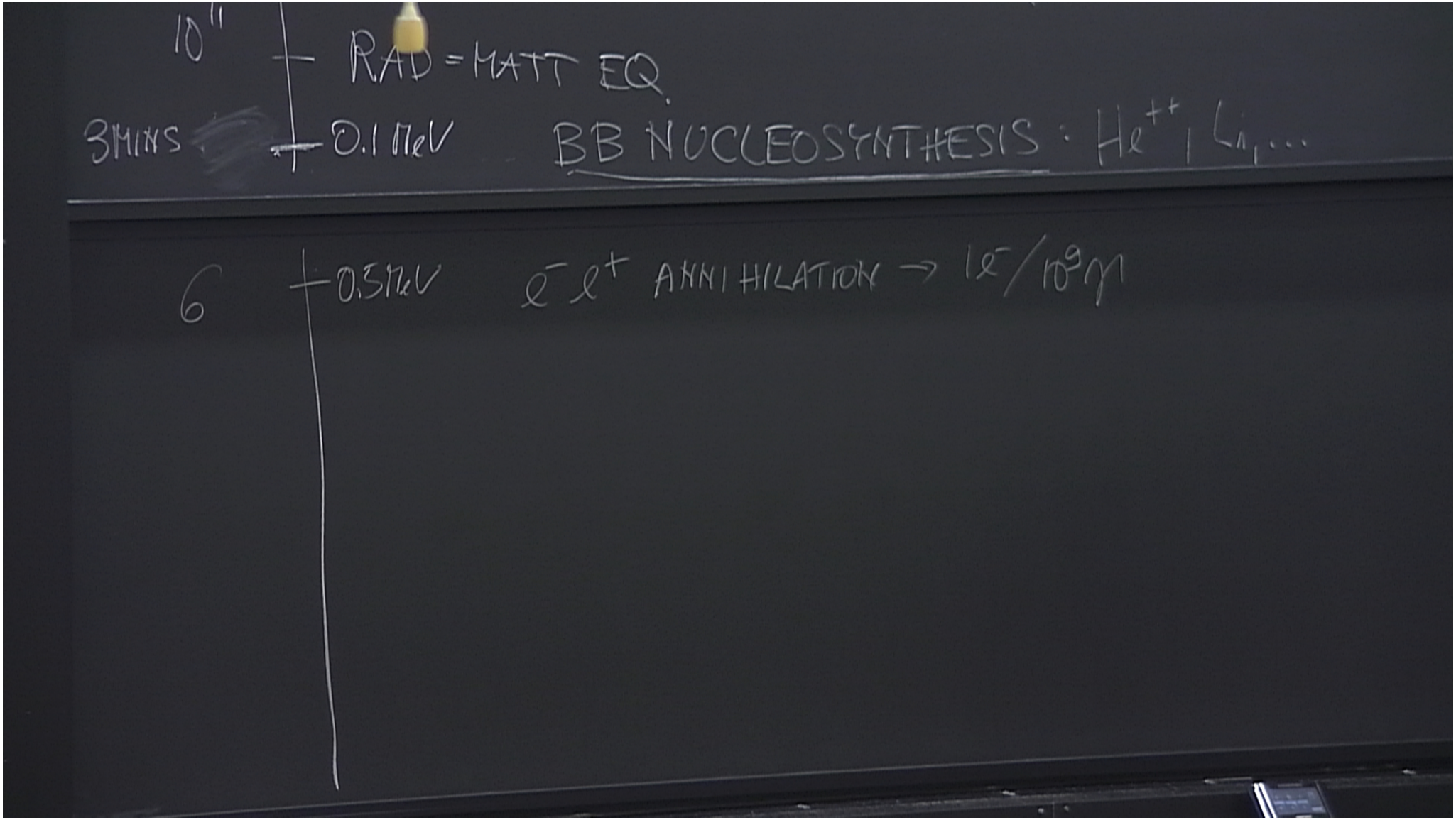

t[s]
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GALAXIES: FORMED BY GRAV. INSTAB. FROM SMALL INIT. INHOM.
(R: STRUCTURE FORM, NATURE OF DM & DE)
CMB: RECOMBINATION $e^- + p^+ \rightarrow H + \gamma$, PHOTON DECOUPLING

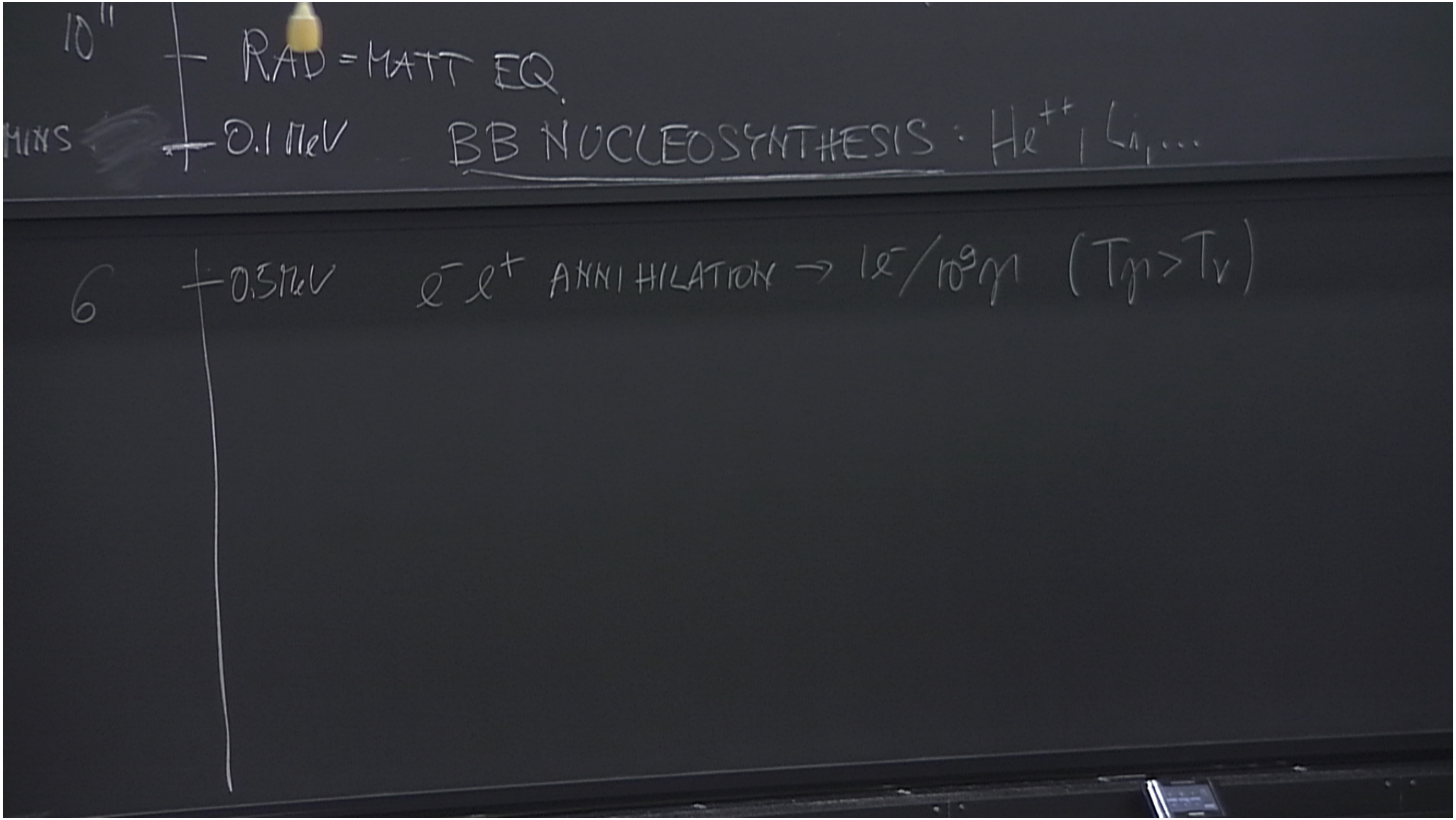

t[s]
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GALAXIES: FORMED BY GRAV. INSTAB. FROM SMALL INIT. INHOM.
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CMB: RECOMBINATION $e^- + p^+ \rightarrow H + \gamma$, PHOTON DECOUPLING
(He RECOMBINES

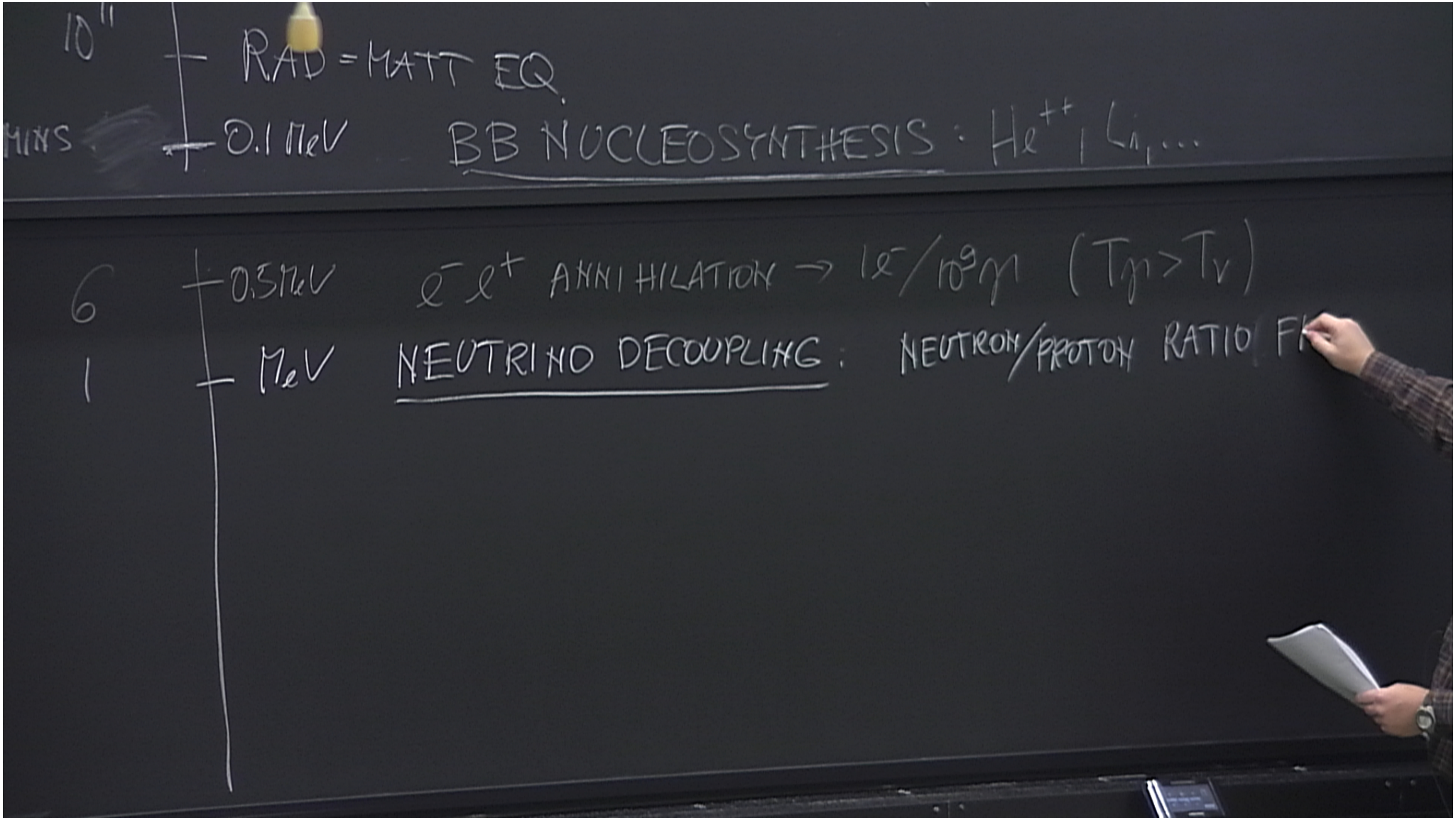

t[s]
16
12
10 11
GALAXIES: FORMED BY GRAV. INSTAB. FROM SMALL INIT. INHOM.
(R: STRUCTURE FORM, NATURE OF DM & DE)
CMB: RECOMBINATION $e^- + p^+ \rightarrow H + \gamma$, PHOTON DECOUPLING
(He RECOMBINES EARLIER .. UNIVERSE STILL OPAQUE!

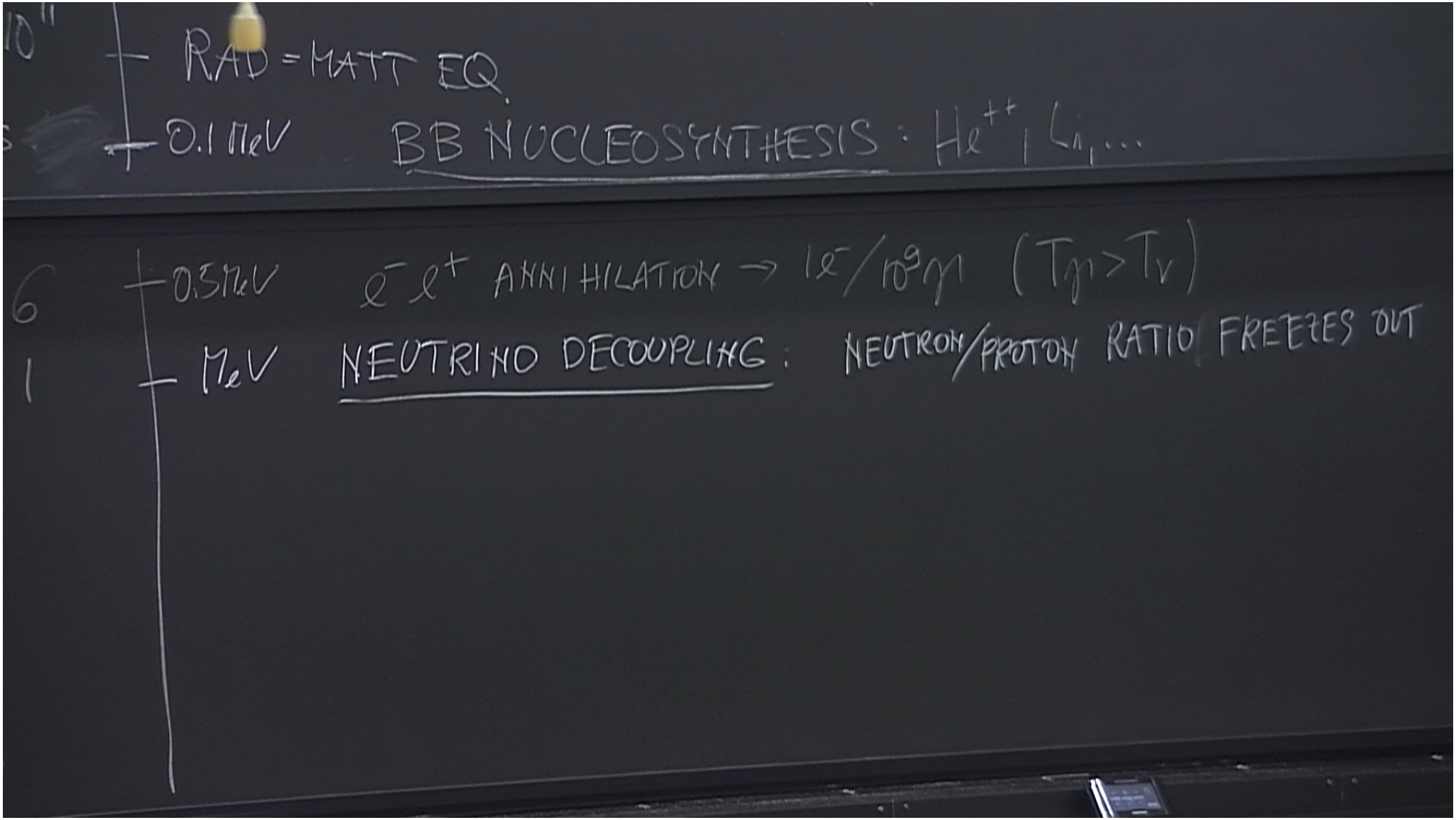

16
GALAXIES: FORMED BY GRAV. INSTAB. FROM
(R: STRUCTURE FORM, NATURE OF DM & DE)
12
CMB: RECOMBINATION $e^- + p^+ \rightarrow H + \gamma$, PHOTON DECOUPLING
(He RECOMBINES EARLIER.. UNIVERSE STILL OPAQUE!
11
RAD = MATT EQ.

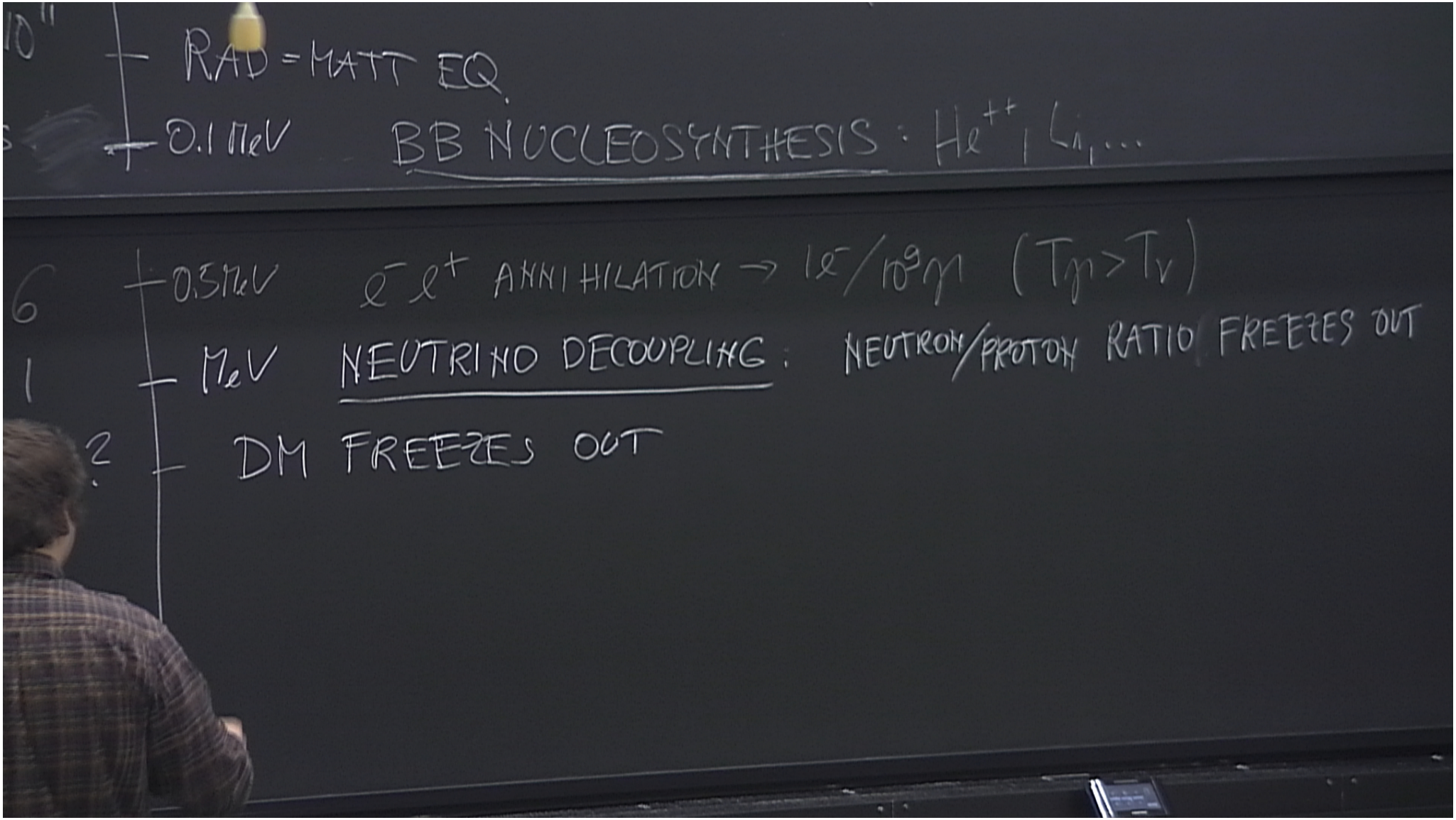

10^{16}
GALAXIES: FORMED BY
(R: STRUCTURE FORM, NATURE OF DM & DE)
10^{12}
CMB: RECOMBINATION $e^- + p^+ \rightarrow H + \gamma$, PHOTON DECOUPLING
(He RECOMBINES EARLIER.. UNIVERSE STILL OPAQUE
10^{11}
RAD = MATT EQ.
3MINS
0.1 MeV
BB NUCLEOSYNTHESIS: He^{++}, Li, ...

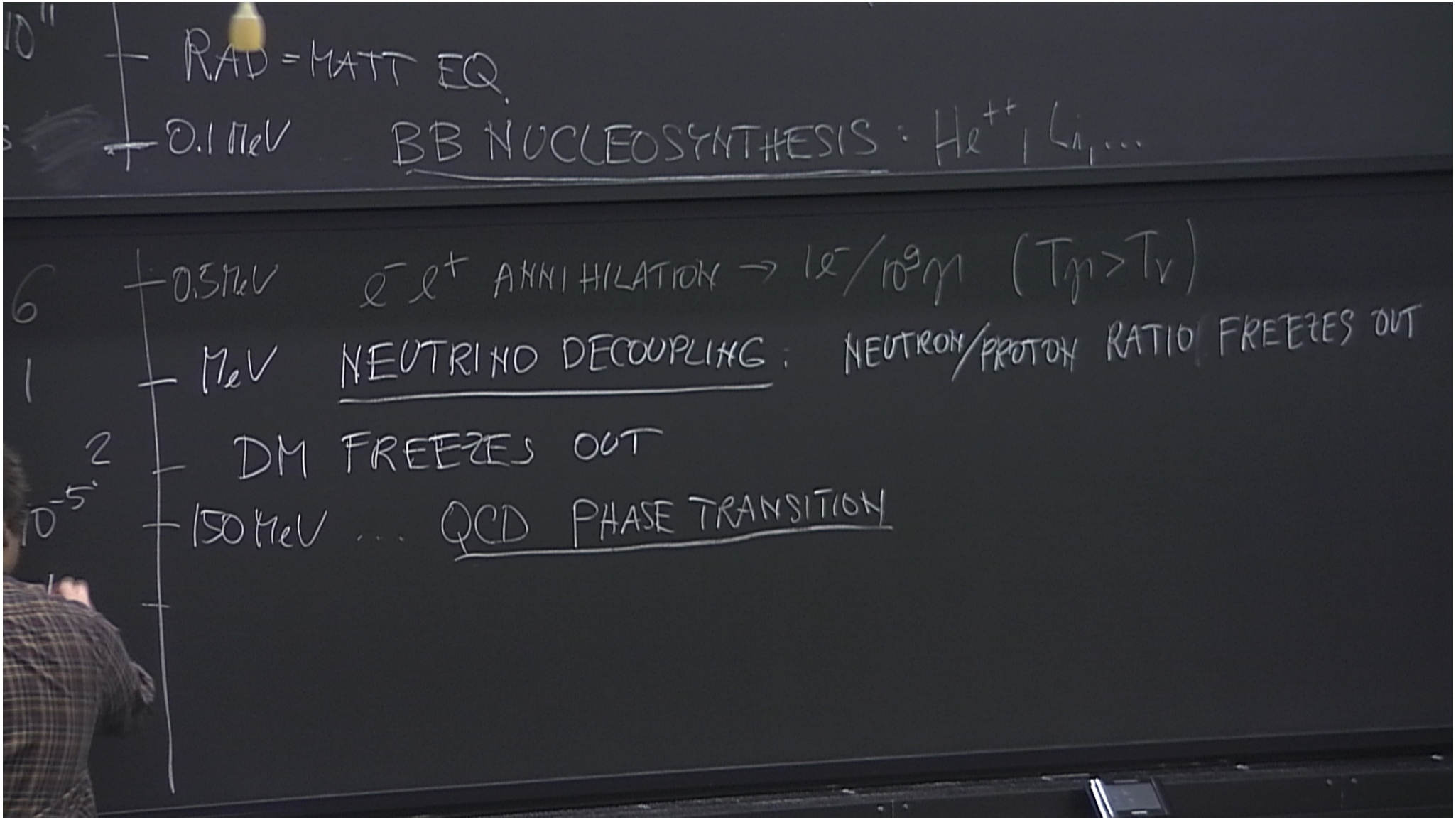

10^11
RAD = MATT EQ.
3MINS
0.1 MeV
BB NUCLEOSYNTHESIS : He^++, Li, ...
6
0.5MeV
e⁻ e⁺ ANNIHILATION → 1e⁻/10⁹γ

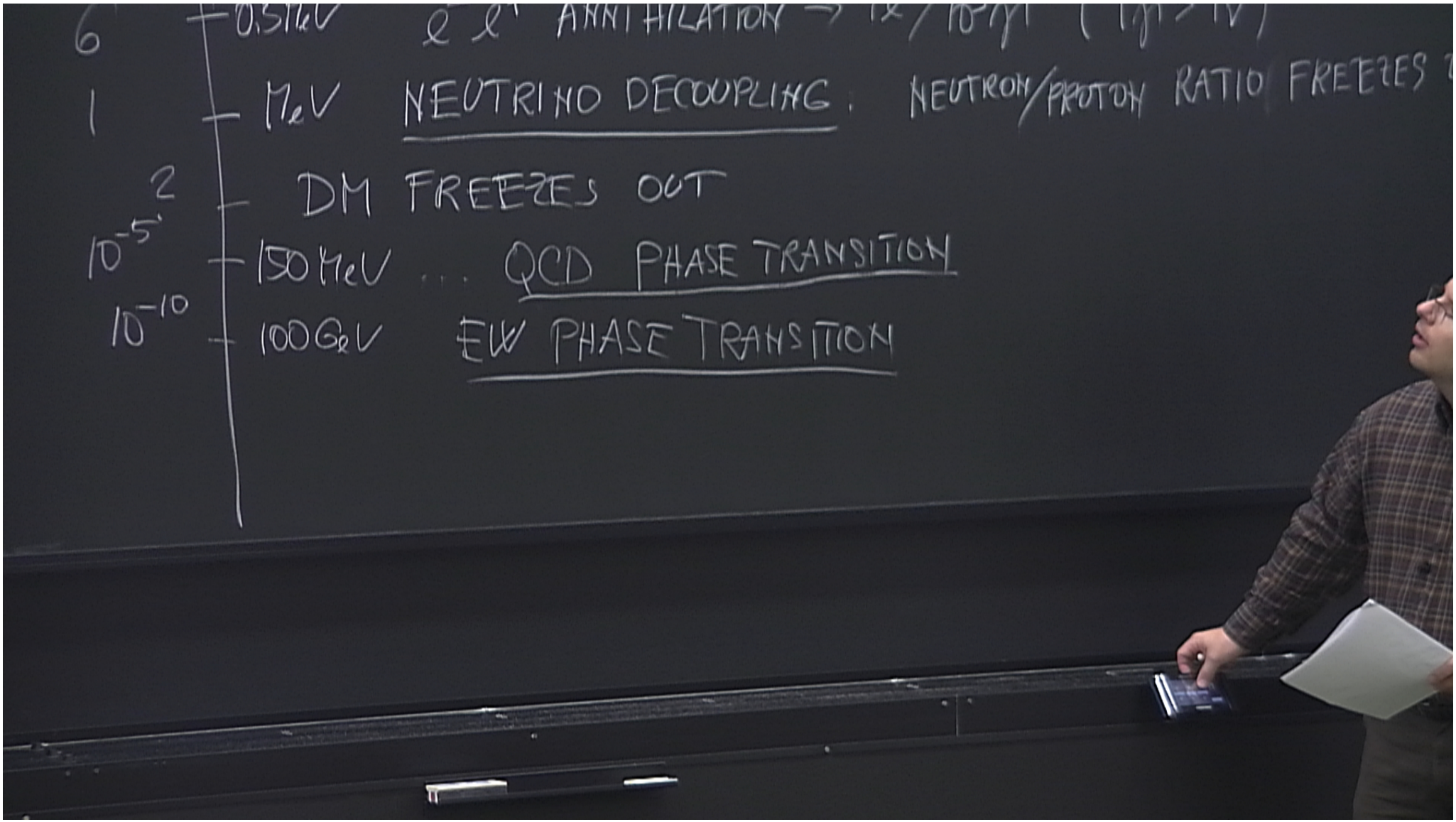

10^11
RAD = MATT EQ.
0.1 MeV
BB NUCLEOSYNTHESIS : He^++, Li, ...
6
0.5 MeV
e^- e^+ ANNIHILATION → 1e^-/10^9 γ (T_γ > T_ν)

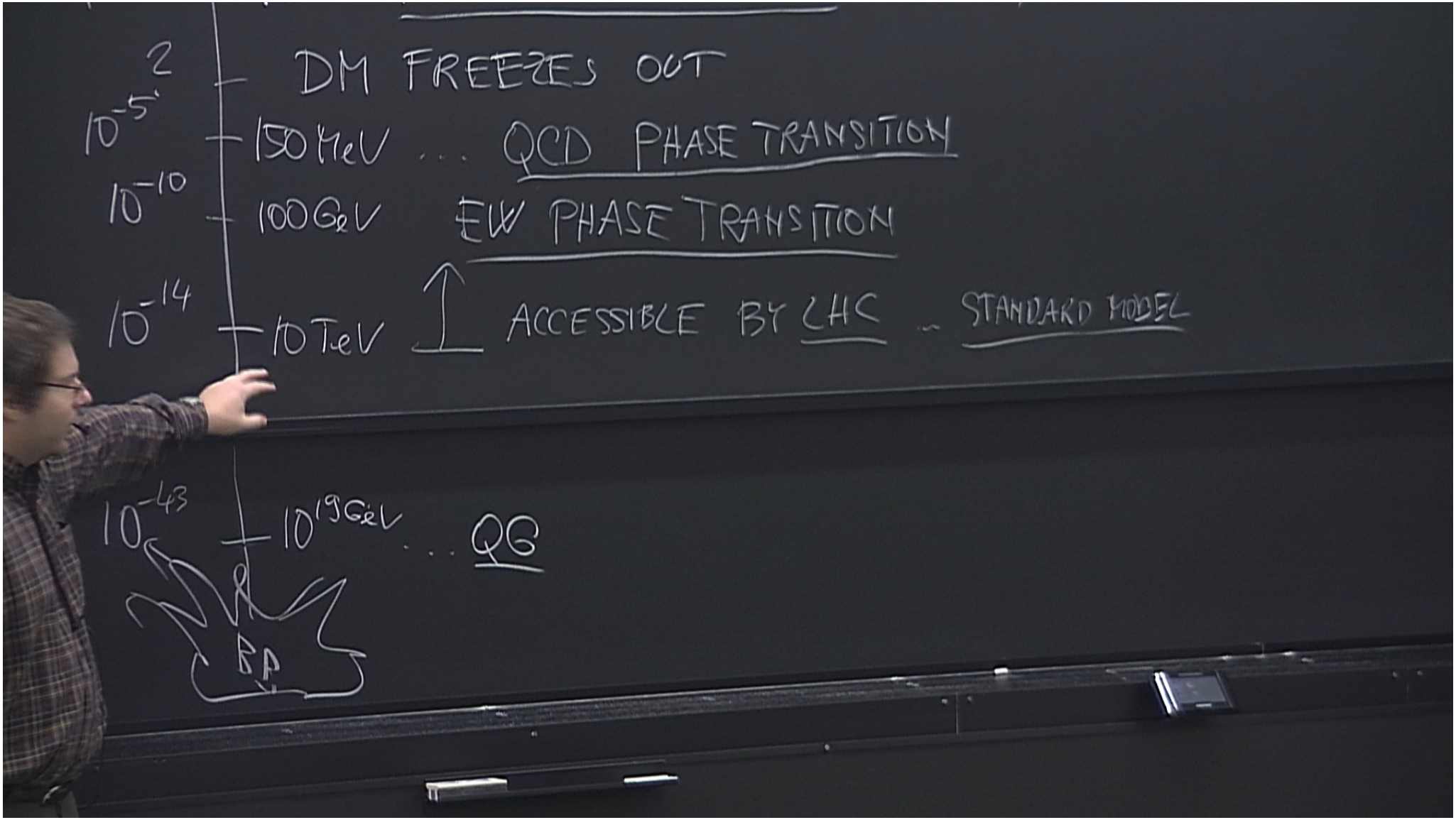

10^11
RAD = MATT EQ.
MINS
0.1 MeV
BB NUCLEOSYNTHESIS : He++, Li, ...
6
0.5MeV
e- e+ ANNIHILATION → 1e-/10^9 γ (Tγ > Tν)
1
MeV
NEUTRINO DECOUPLING :
NEUTRON/PROTON RATIO

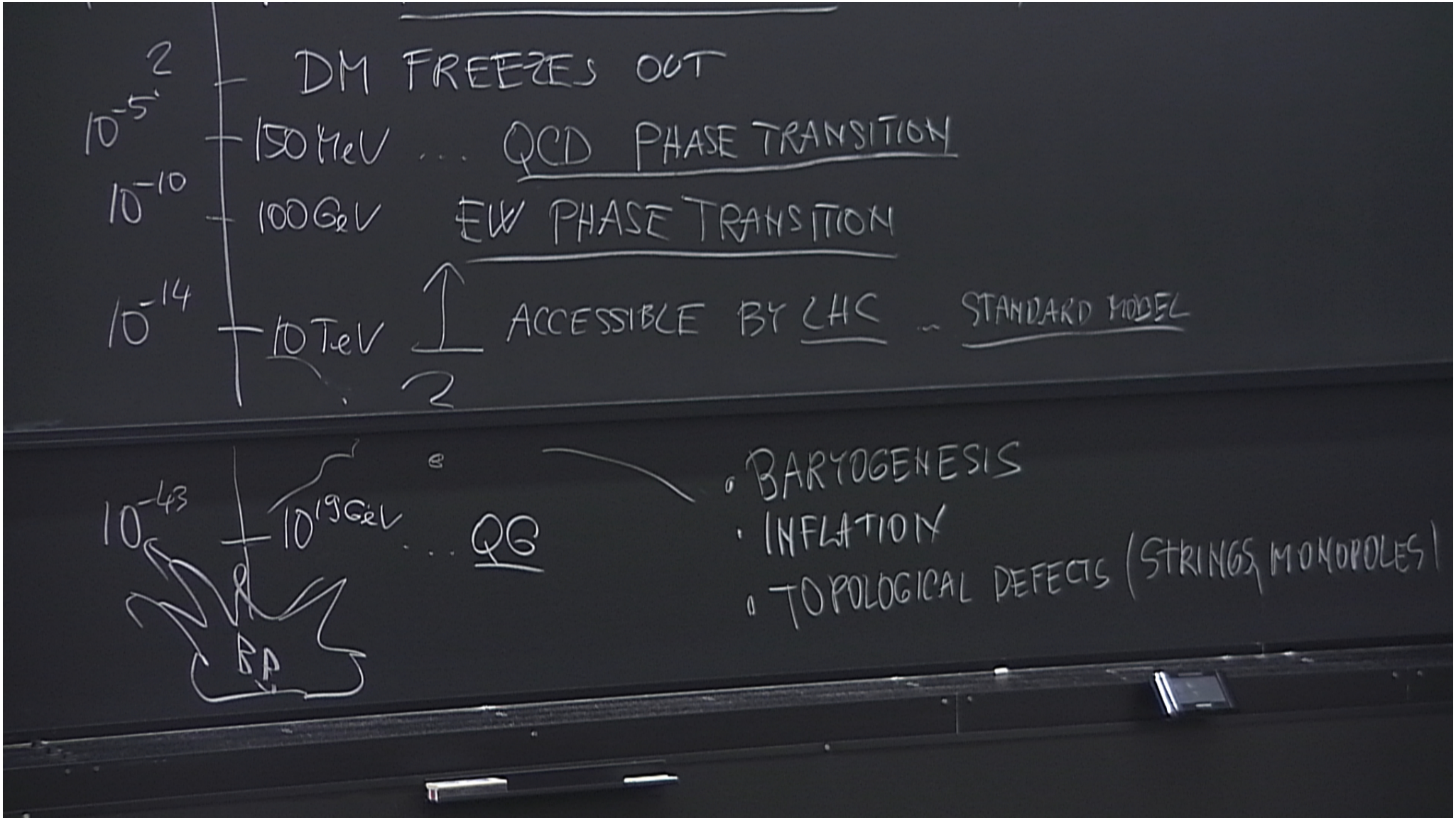

RAD = MATT EQ.
0.1 MeV
BB NUCLEOSYNTHESIS : He^{++}, L_i, ...
0.5 MeV
$e^- e^+$ ANNIHILATION → $1e^-/10^9\gamma$ ($T_\gamma > T_\nu$)
MeV
NEUTRINO DECOUPLING: NEUTRON/PROTON RATIO FREEZES OUT

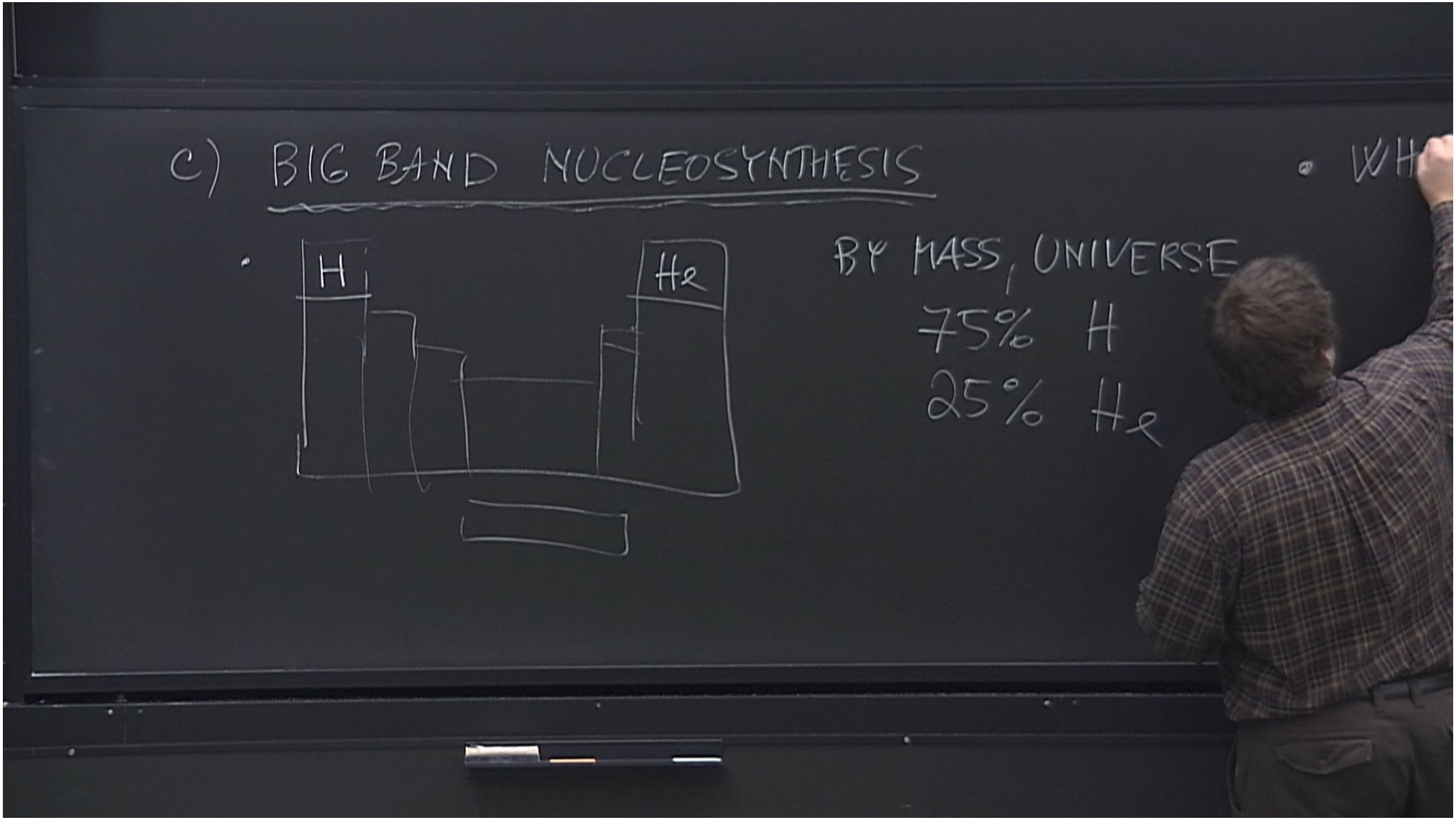

RAD = MATT EQ.
0.1 MeV
BB NUCLEOSYNTHESIS : He^{++}, Li, ...
0.5 MeV
$e^- e^+$ ANNIHILATION → $1e^-/10^9\gamma$ ($T_\gamma > T_\nu$)
MeV
NEUTRINO DECOUPLING: NEUTRON/PROTON RATIO FREEZES OUT
DM FREEZES OUT

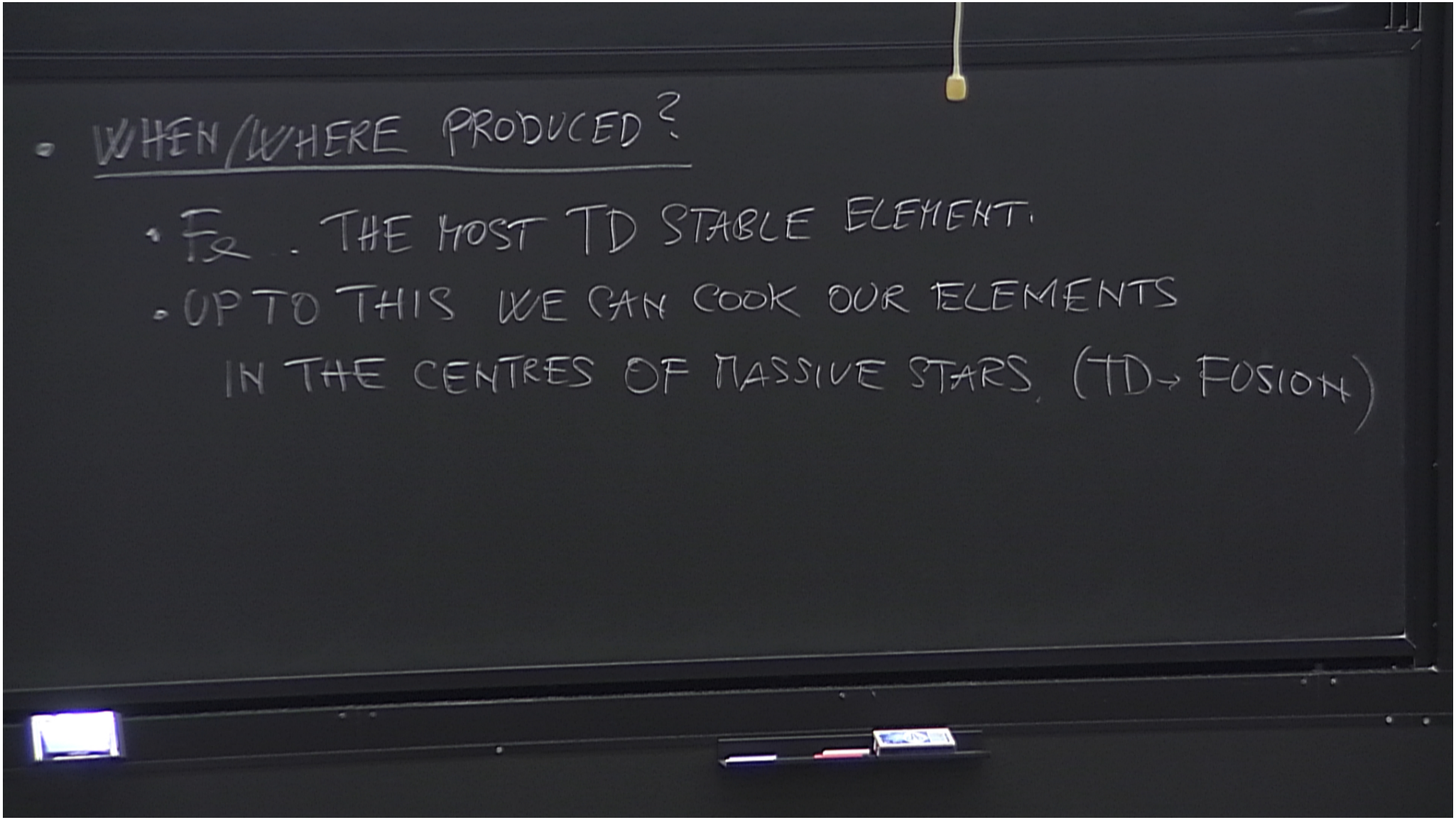

RAD = MATT EQ.
0.1 MeV BB NUCLEOSYNTHESIS : He^{++}, Li_4, ...
0.3 MeV $e^- e^+$ ANNIHILATION → $1e^-/10^9\gamma$ ($T_\gamma > T_\nu$)
MeV NEUTRINO DECOUPLING: NEUTRON/PROTON RATIO FREEZES OUT
DM FREEZES OUT
150 MeV ... QCD PHASE TRANSITION

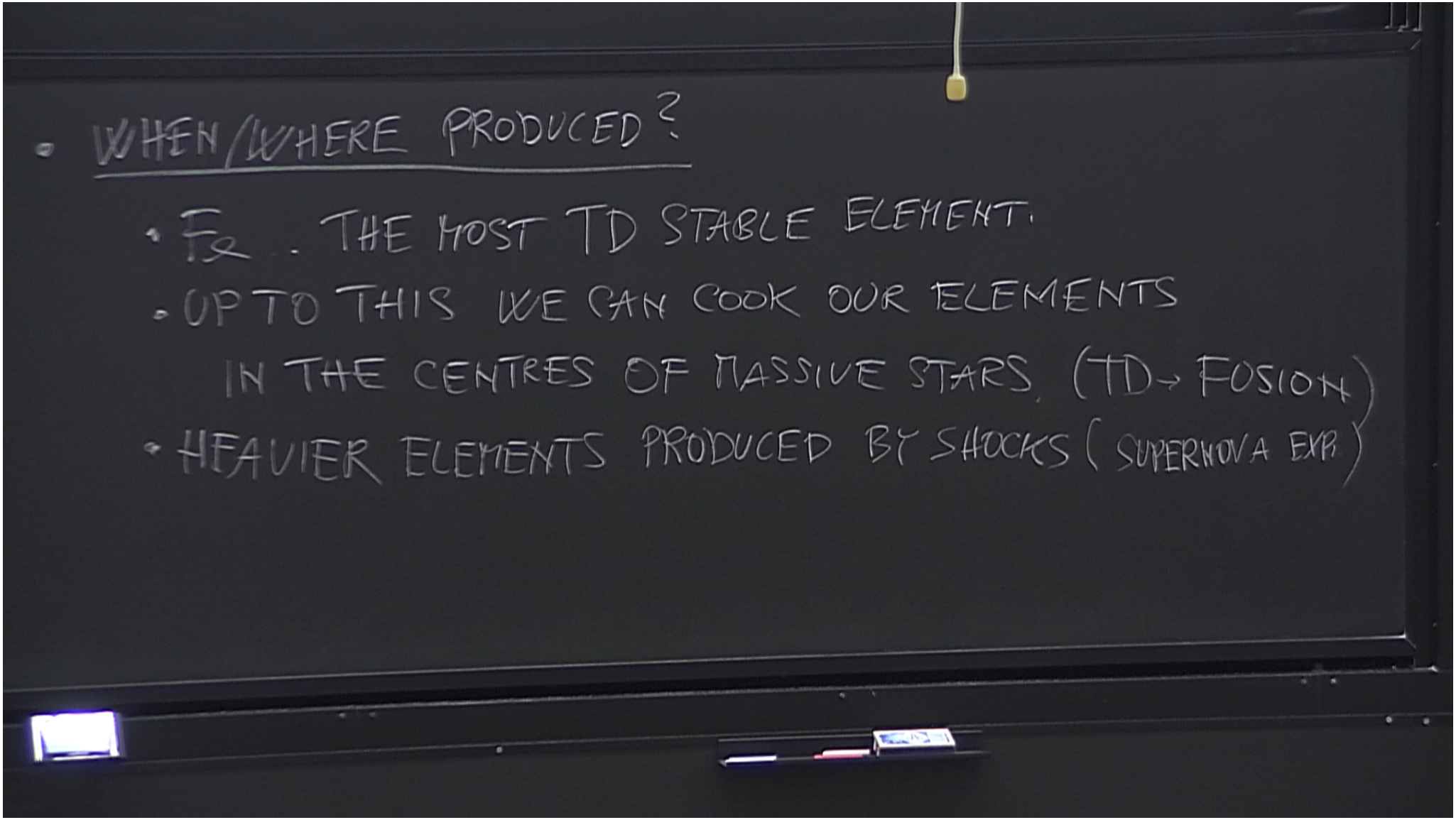

0.5 MeV
e⁺e⁻ ANNIHILATION
1 MeV
NEUTRINO DECOUPLING.
NEUTRON/PROTON RATIO FREEZES
DM FREEZES OUT
10⁻⁵ s
150 MeV ... QCD PHASE TRANSITION
10⁻¹⁰ s
100 GeV
EW PHASE TRANSITION

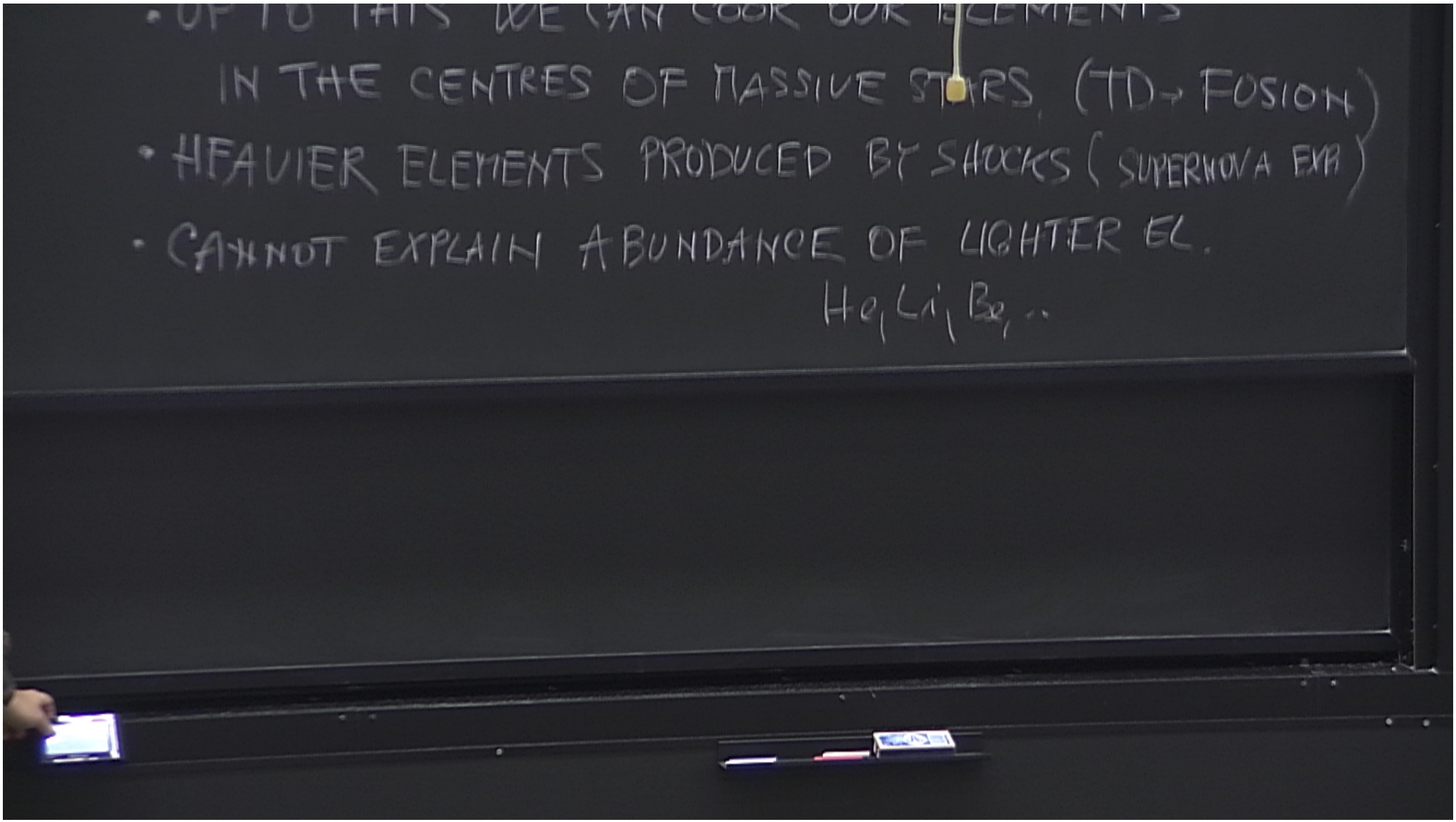

DM FREEZES OUT
150 MeV ... QCD PHASE TRANSITION
100 GeV EW PHASE TRANSITION
10 TeV ACCESSIBLE BY LHC ... STANDARD MODEL
10^19 GeV ... QG
BA

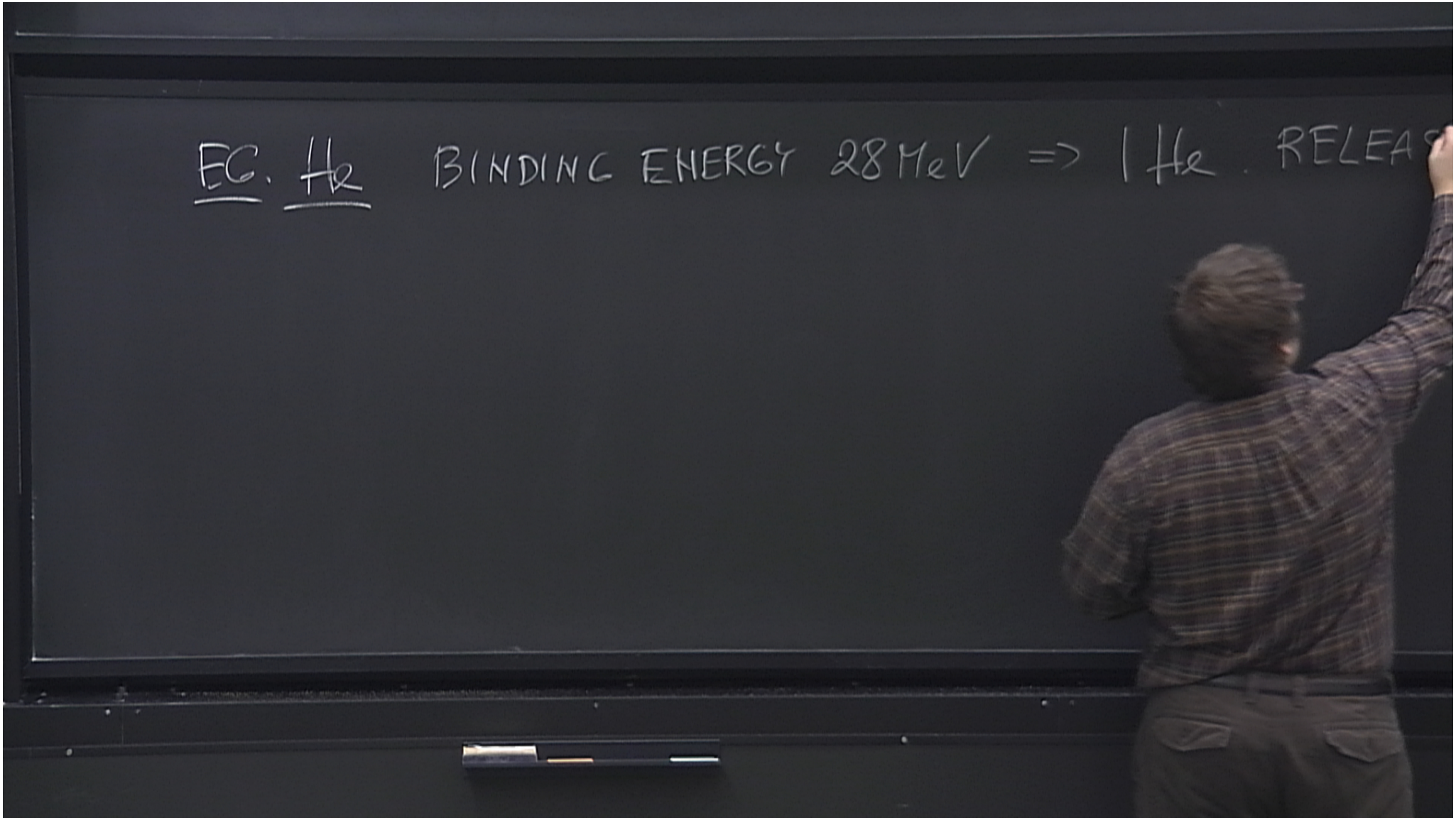

DM FREEZES OUT
10^{-5} 150 MeV ... QCD PHASE TRANSITION
10^{-10} 100 GeV EW PHASE TRANSITION
10^{-14} 10 TeV ACCESSIBLE BY LHC ... STANDARD MODEL
10^{-43} 10^{19} GeV ... QG
• BARYOGENESIS
• INFLATION
• TOPOLOGICAL DEFECTS (STRINGS, MONOPOLES)

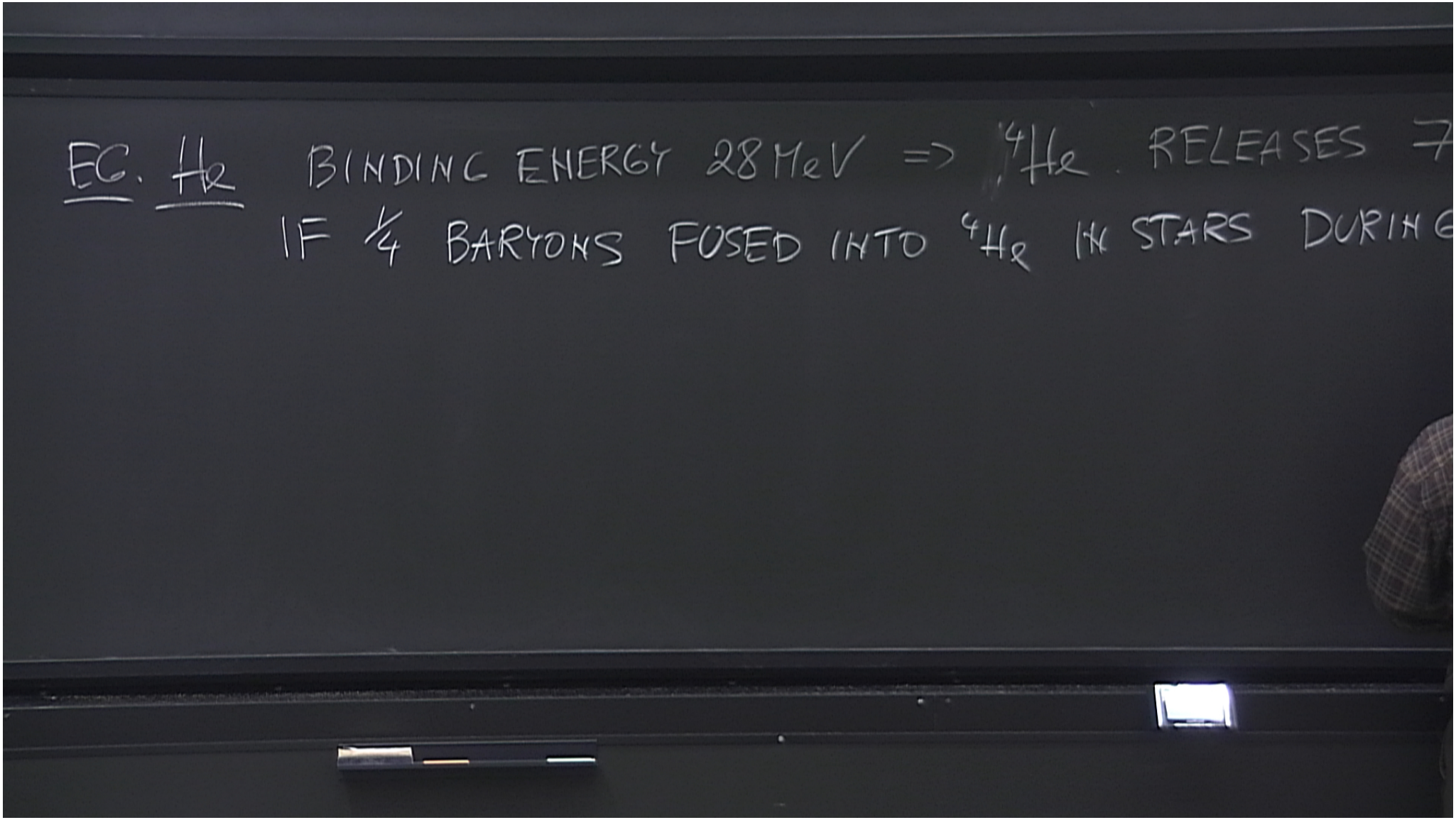

c) BIG BAND NUCLEOSYNTHESIS
H
He
BY MASS, UNIVERSE
75% H
25% He

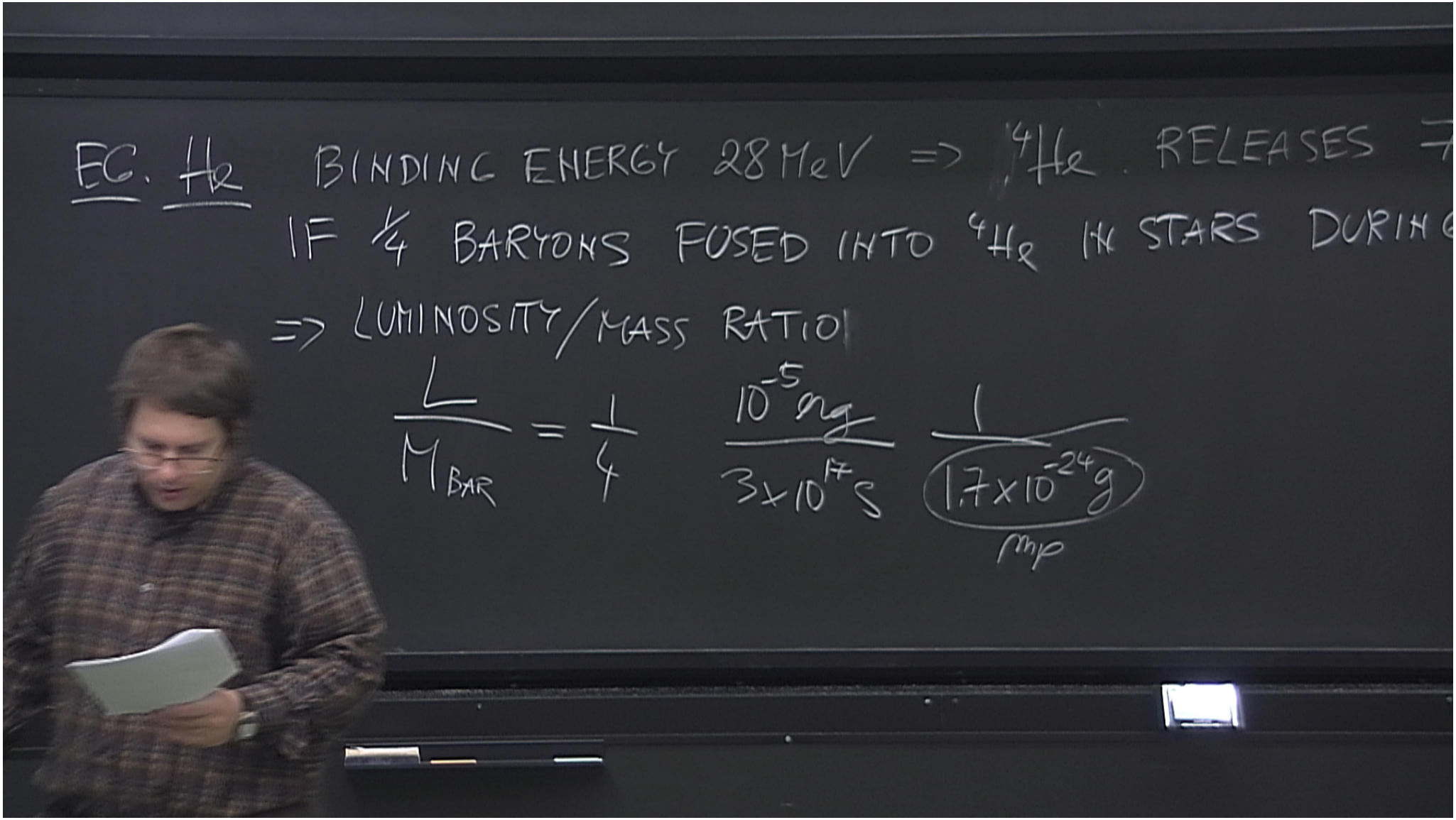

WHEN/WHERE PRODUCED?
Fe. THE MOST TD STABLE ELEMENT.
UP TO THIS WE CAN COOK OUR ELEMENTS
IN THE CENTRES OF MASSIVE STARS. (TD→ FOSION)


WHEN/WHERE PRODUCED?
Fe . THE MOST TD STABLE ELEMENT.
UP TO THIS WE CAN COOK OUR ELEMENTS
IN THE CENTRES OF MASSIVE STARS. (TD→ FOSION)
HEAVIER ELEMENTS PRODUCED BY SHOCKS (SUPERNOVA EXP.)


• UP TO THIS WE CAN COOK OUR ELEMENTS
IN THE CENTRES OF MASSIVE STARS (TD→ FUSION)
• HEAVIER ELEMENTS PRODUCED BY SHOCKS (SUPERNOVA EXP)
• CANNOT EXPLAIN ABUNDANCE OF LIGHTER EL.
H, Li, Be, ..


EG. ^4_2He BINDING ENERGY 28 MeV => ^1_1He . RELEA


EG. He BINDING ENERGY 28 MeV => 4He RELEASES 7
IF 1/4 BARYONS FUSED INTO 4He IN STARS DURIN


EC. He BINDING ENERGY 28 MeV => ^4He RELEASES
IF ¼ BARYONS FUSED INTO ^4He IN STARS DURIN
=> LUMINOSITY/MASS RATIO
$\frac{L}{M_{BAR}} = \frac{1}{4} \frac{10^{-5} erg}{3 \times 10^{17} s} \frac{1}{1.7 \times 10^{-24} g}$
mp

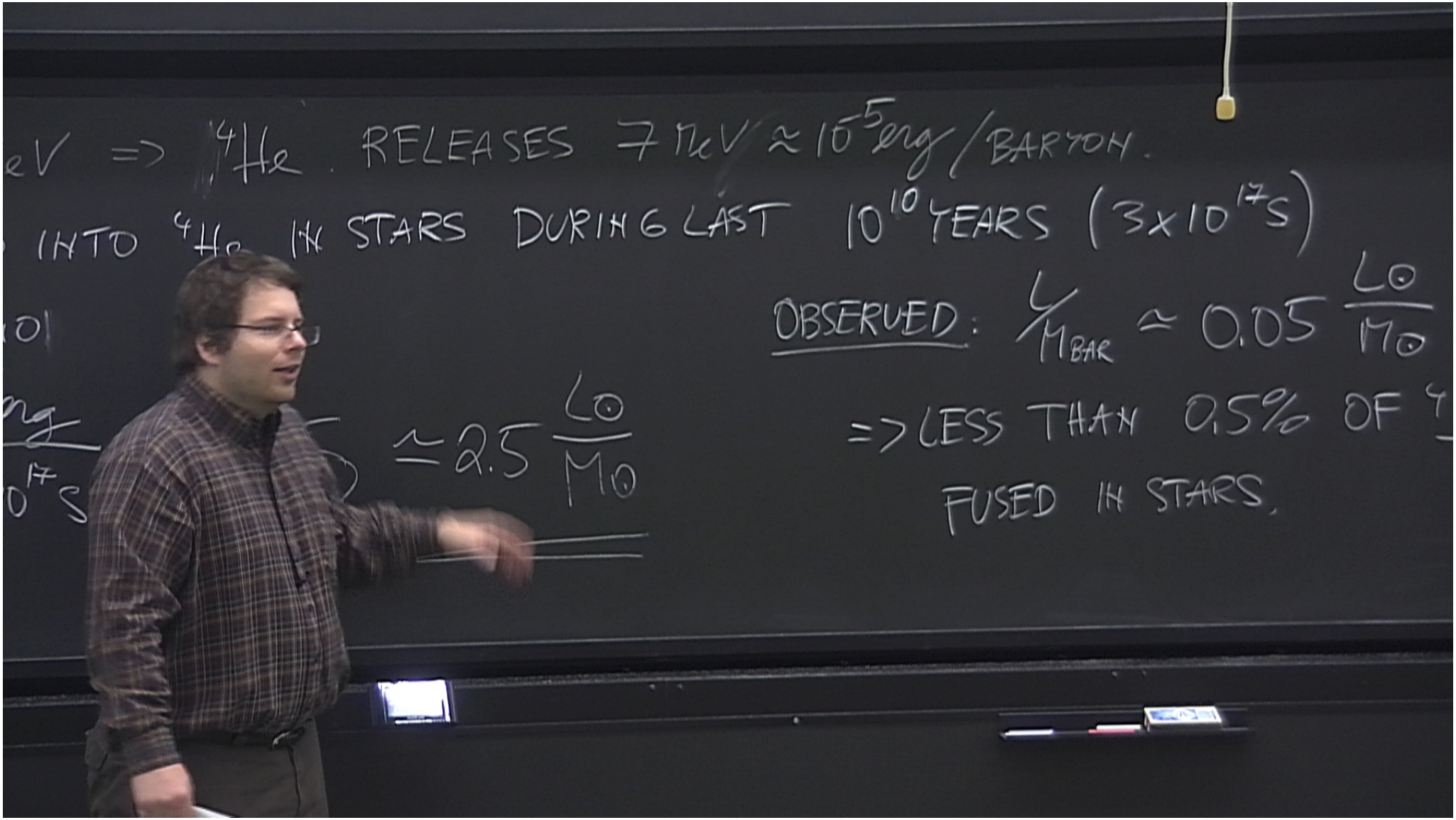
EG. H_2 BINDING ENERGY 28 MeV => ^4He RELEASES 7

IF ¼ BARYONS FUSED INTO ^4He IN STARS DURING

=> LUMINOSITY/MASS RATIO

$$\frac{L}{M_{BAR}} = \frac{1}{4}\,\frac{10^{-5}\,erg}{3\times10^{17}\,s}\,\frac{1}{1.7\times10^{-24}\,g}\simeq 2.5\,\frac{L_\odot}{M_\odot}$$

m_p


eV => ^4He RELEASES 7 MeV $\approx 10^5$ erg / BARYON.
INTO ^4He IN STARS DURING LAST 10^{10} YEARS (3×10^{17} s)
OBSERVED: $L/M_{BAR} \simeq 0.05 \frac{L_\odot}{M_\odot}$
$\simeq 2.5 \frac{L_\odot}{M_\odot}$
=> LESS THAN 0.5% OF
FUSED IN STARS.

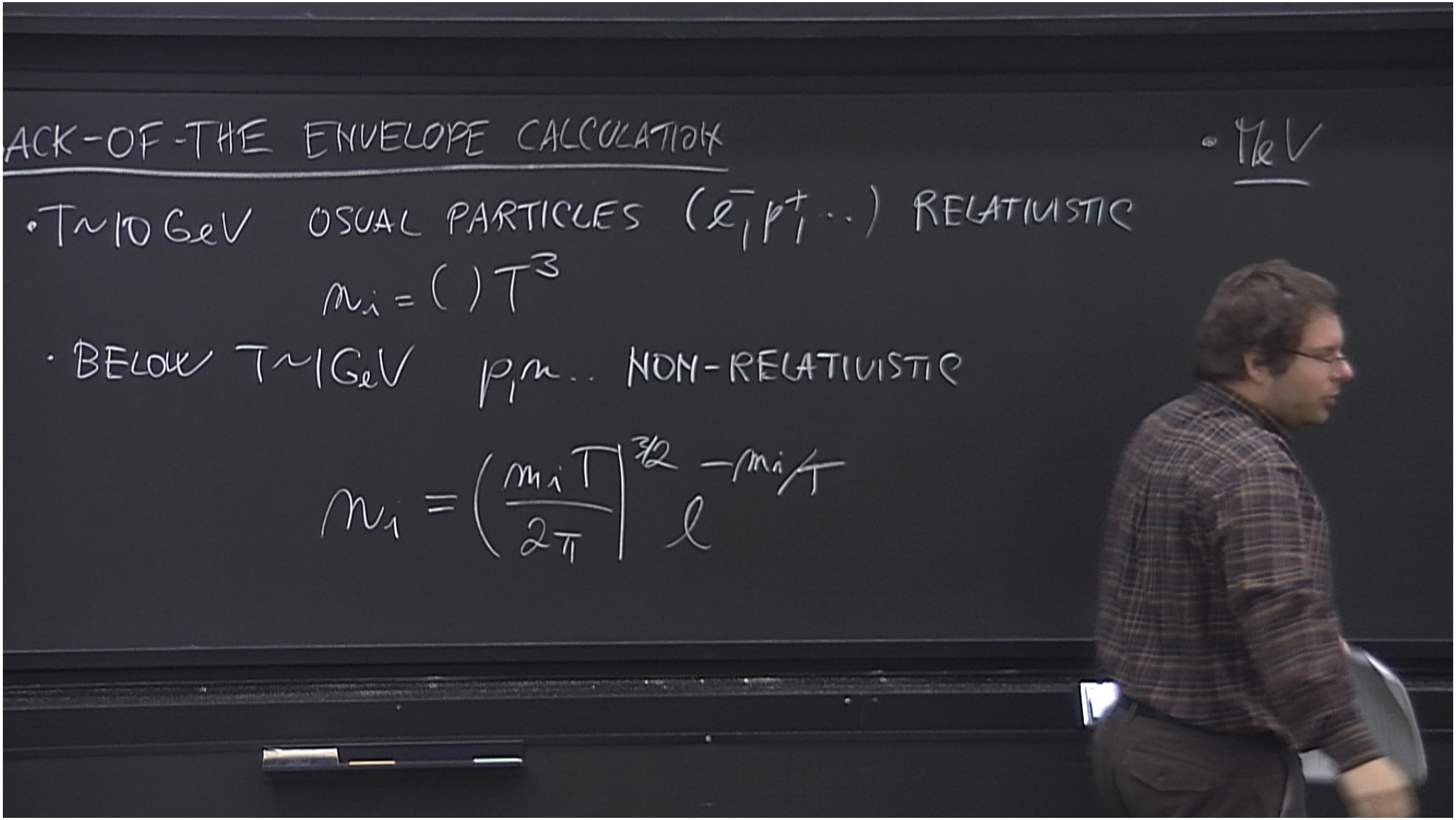
- BACK-OF-THE ENVELOPE CALCULATION

  - $T \sim 10$ GeV OSUAL PARTICLES ($e^-, p^+ \ldots$) RELATIVISTIC

    $n_i = (\ ) T^3$

  - BELOW $T \sim 1$ GeV $p, n \ldots$ NON-RELATIVISTIC

    $$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$


ACK-OF-THE ENVELOPE CALCULATION
• 1 GeV
• T~10 GeV OSUAL PARTICLES (e⁻, p⁺ ..) RELATIVISTIC
$n_i = ( ) T^3$
• BELOW T~1 GeV p, n .. NON-RELATIVISTIC
$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$

-OF-THE ENVELOPE CALCULATION

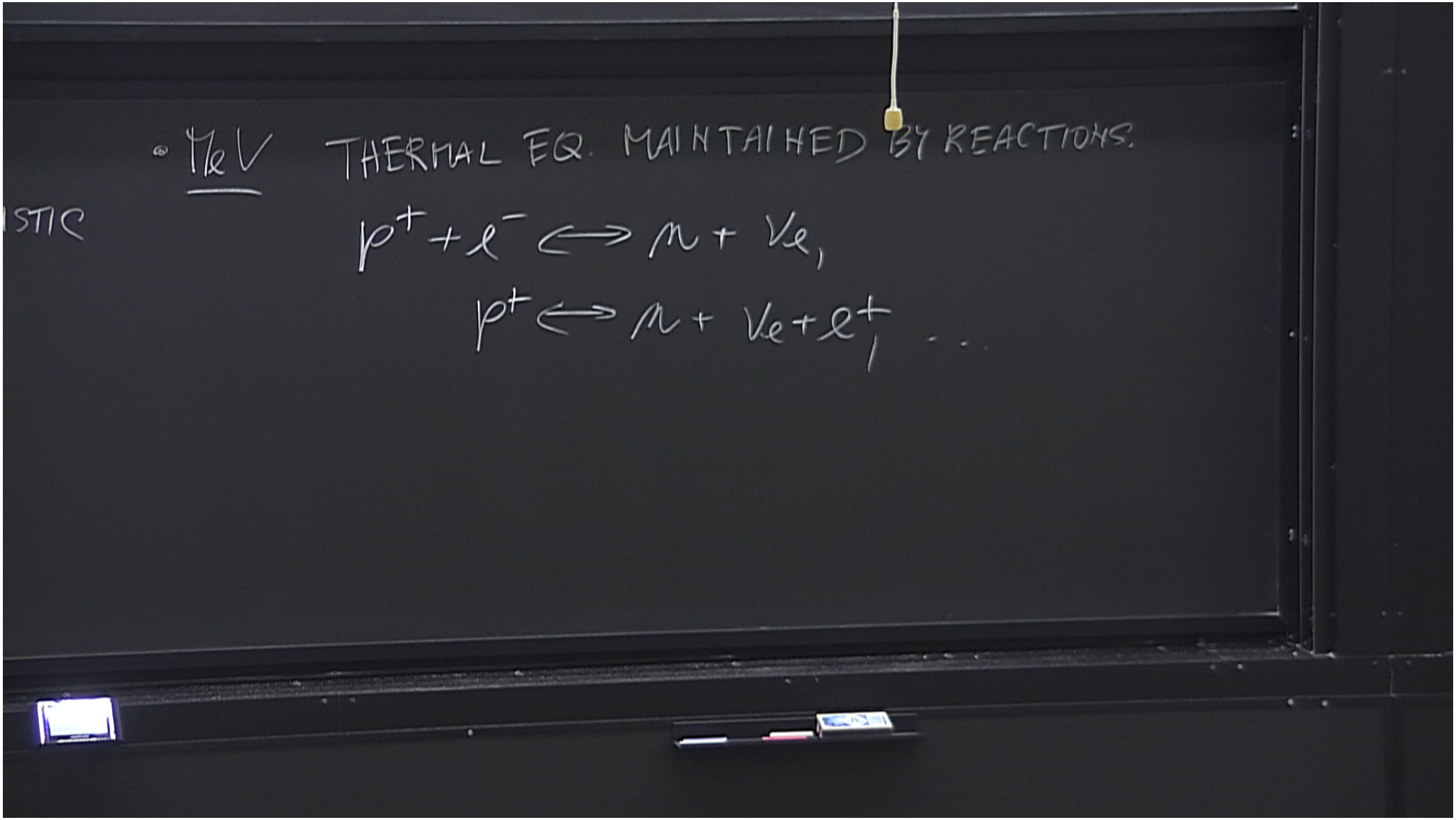
~ 10 GeV USUAL PARTICLES ($e^-, p^+ \ldots$) RELATIVISTIC

$n_i = (\ )\, T^3$

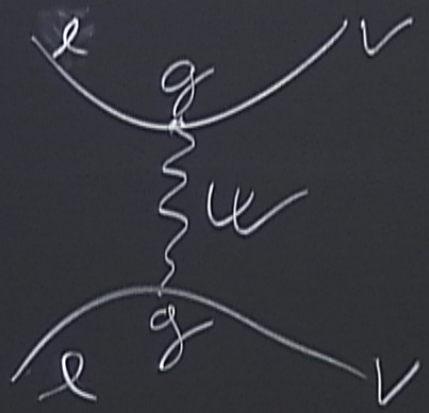
BELOW $T \sim 1$ GeV $p, n \ldots$ NON-RELATIVISTIC

$$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$

• 1 GeV THERM


• MeV THERMAL EQ. MAINTAINED BY REACTIONS.
STIC
$p^+ + e^- \leftrightarrow n + \nu_e$,
$p^+ \leftrightarrow n + \nu_e + e^+$, ...

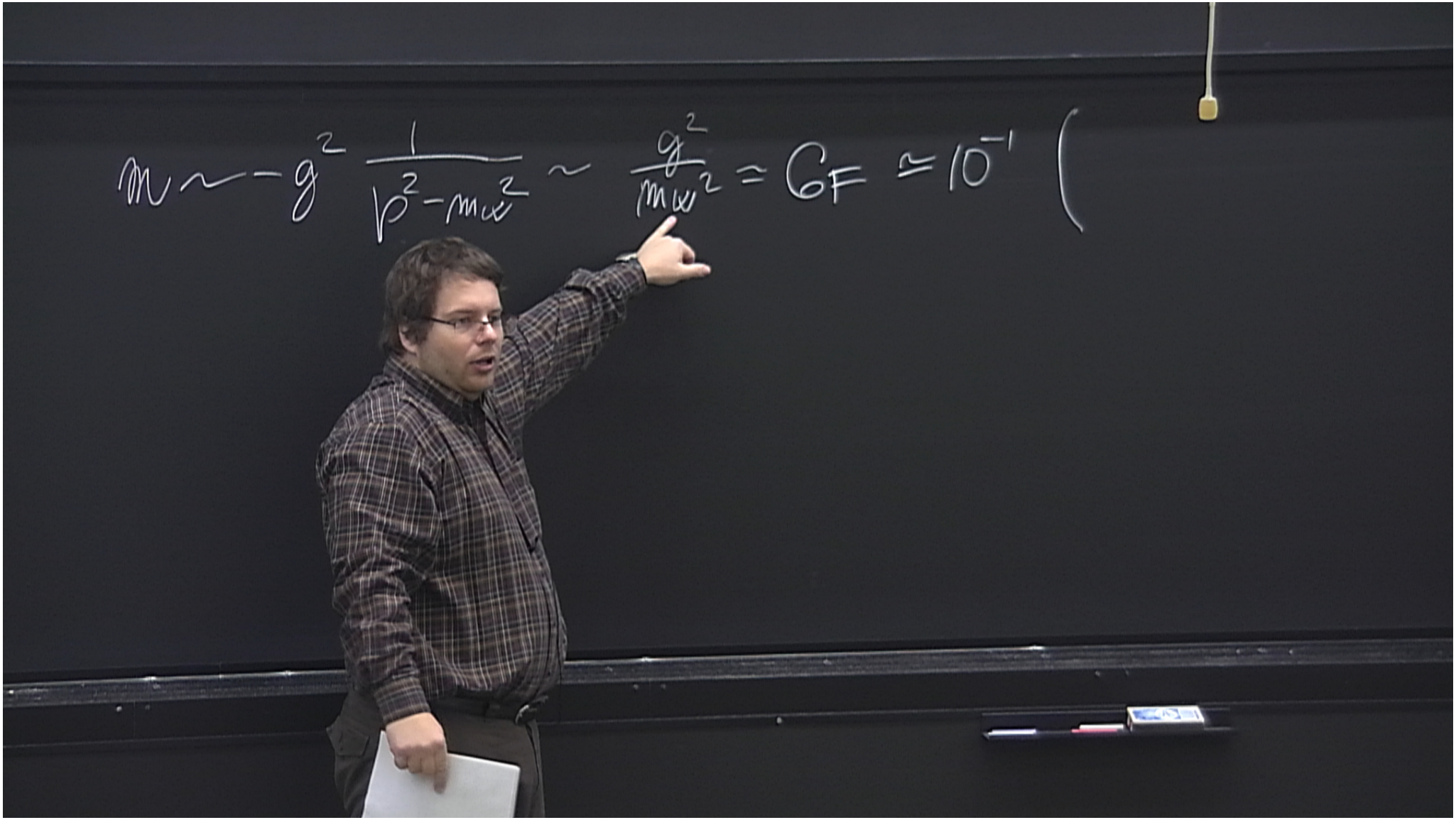
- NEUTRINO DECOUPLING

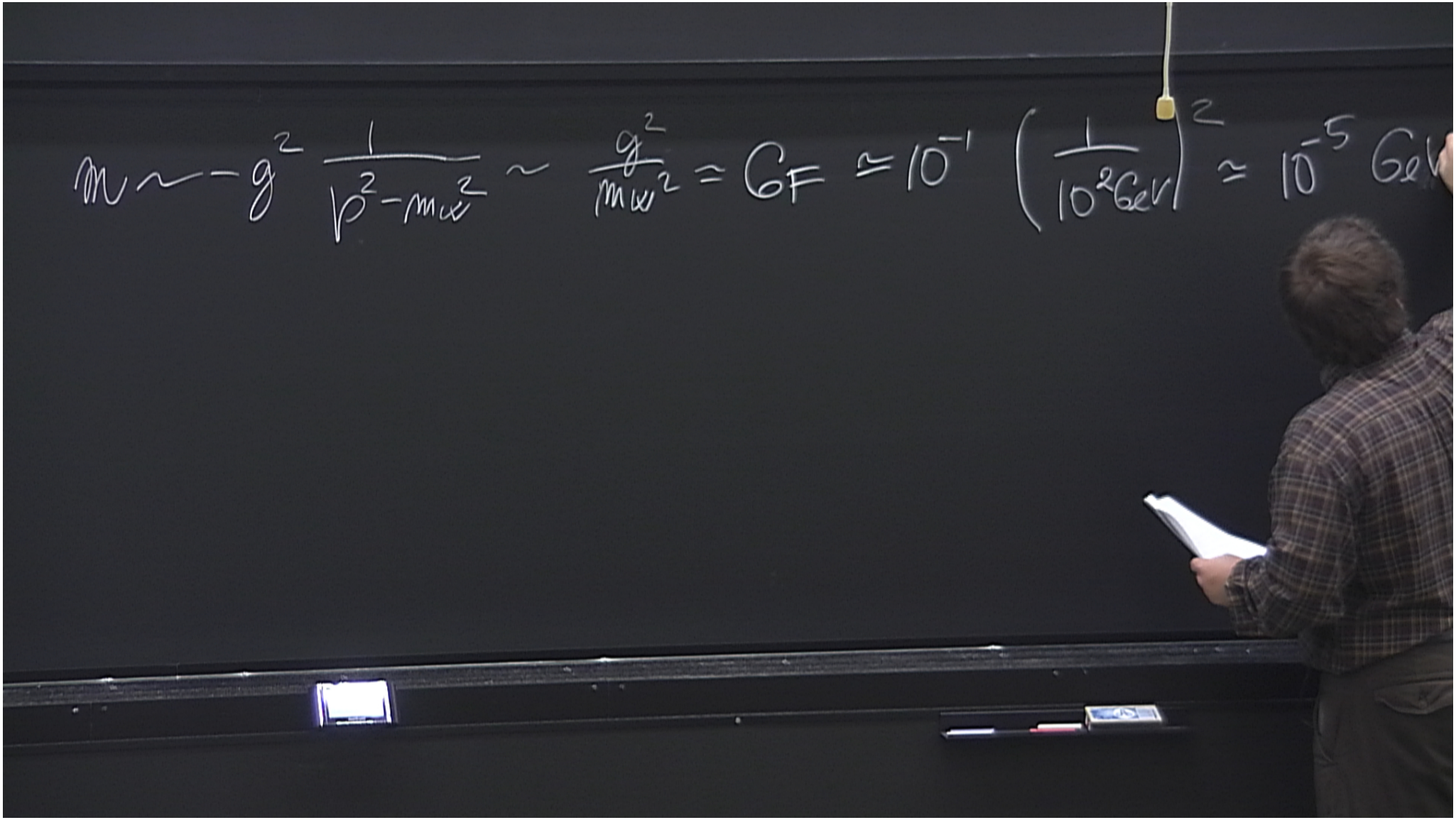


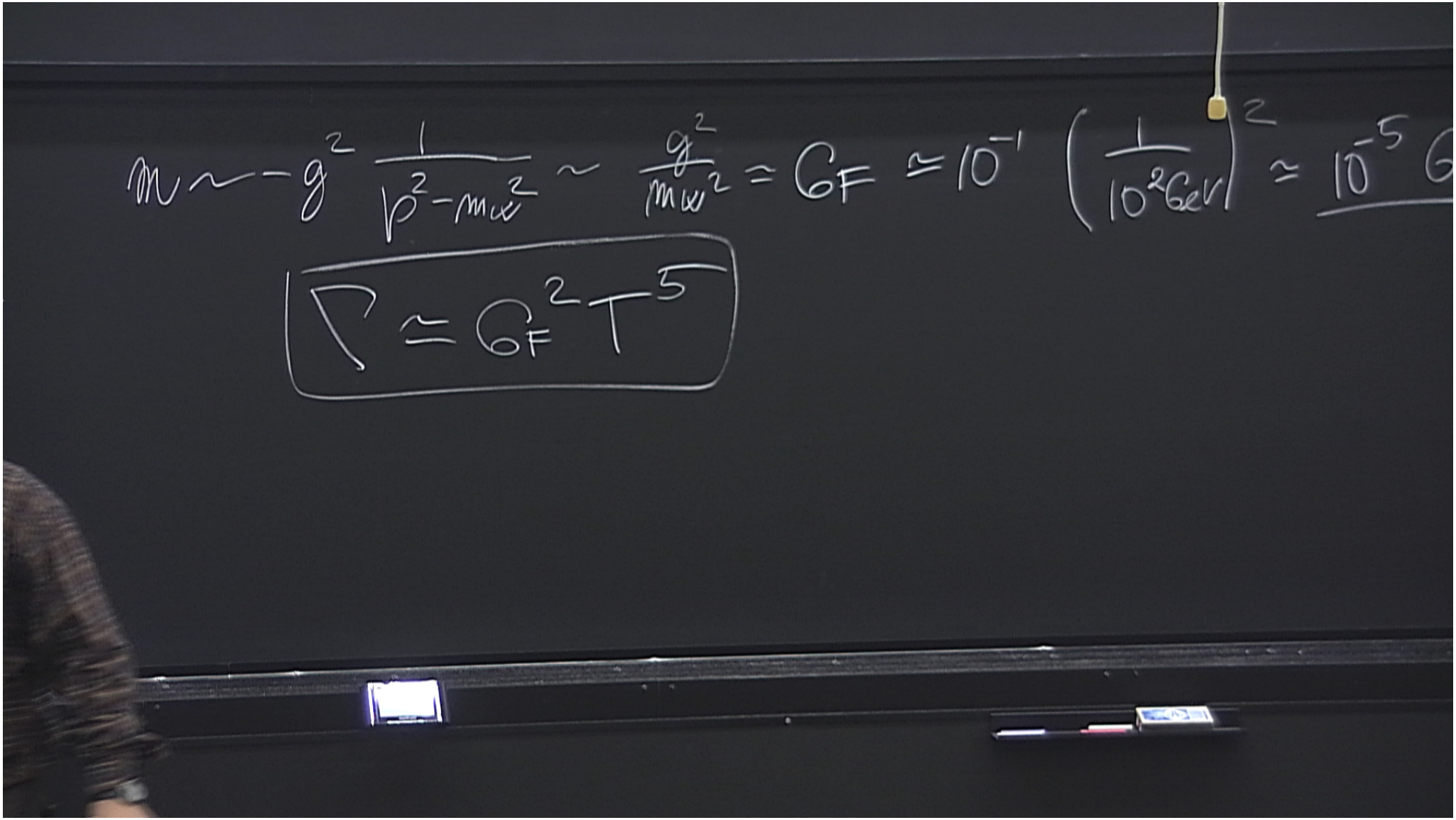
$\nu_e \bar{\nu}_e \leftrightarrow e^+ e^-$

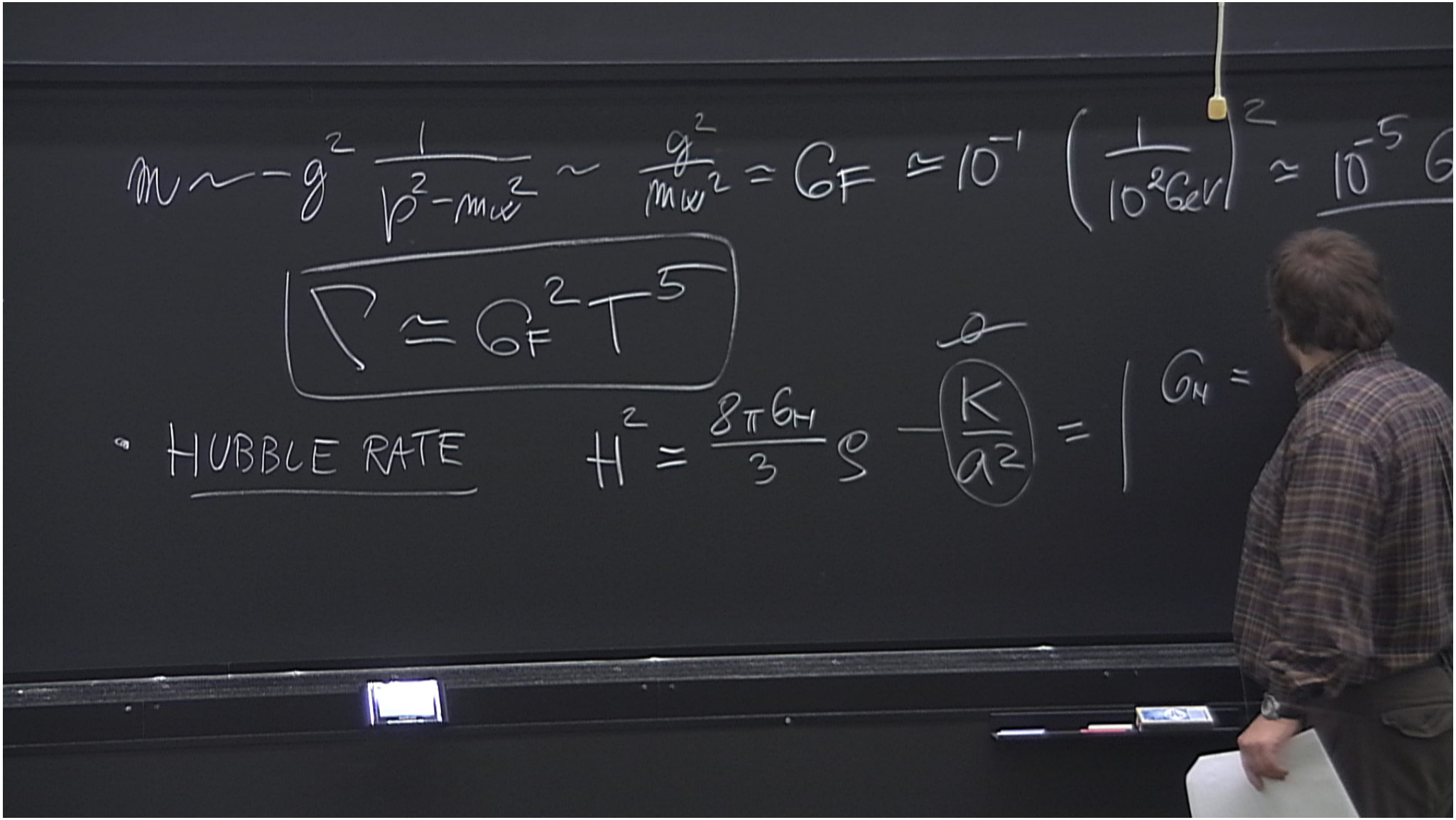
$e^- \bar{\nu}_e \leftrightarrow e^- + \bar{\nu}_e$

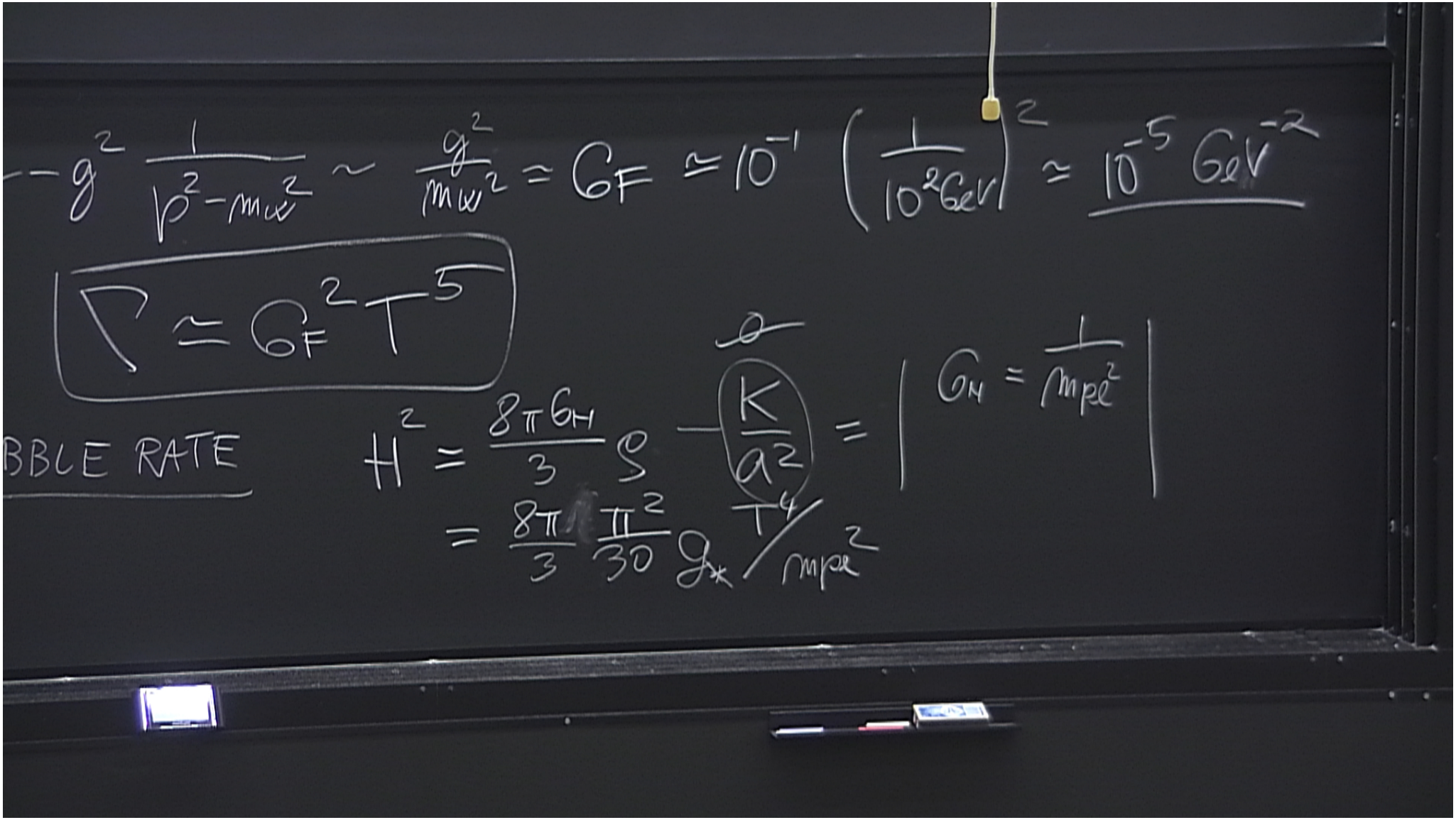
$\mathcal{M} \sim -g^2 \frac{1}{p^2 - m_W^2}$


$\mathcal{M} \sim -g^2 \frac{1}{p^2 - m_W^2} \sim \frac{g^2}{m_W^2} \simeq G_F \simeq 10^{-1}$ (


$\mathcal{M} \sim -g^2 \frac{1}{p^2 - m_W^2} \sim \frac{g^2}{m_W^2} \simeq G_F \simeq 10^{-1} \left(\frac{1}{10^2 \text{GeV}}\right)^2 \simeq 10^{-5}$ GeV


$\mathcal{M} \sim -g^2 \frac{1}{p^2 - m_W^2} \sim \frac{g^2}{m_W^2} \simeq G_F \simeq 10^{-1} \left(\frac{1}{10^2 \text{GeV}}\right)^2 \simeq 10^{-5}$ G
$\Gamma \simeq G_F^2 T^5$


$\mathcal{M} \sim -g^2 \frac{1}{p^2 - m_W^2} \sim \frac{g^2}{m_W^2} \simeq G_F \simeq 10^{-1} \left(\frac{1}{10^2 \text{GeV}}\right)^2 \simeq 10^{-5}$ G
$\Gamma \simeq G_F^2 T^5$
HUBBLE RATE $H^2 = \frac{8\pi G_N}{3} \rho - \frac{K}{a^2}$ = 1 G_N =

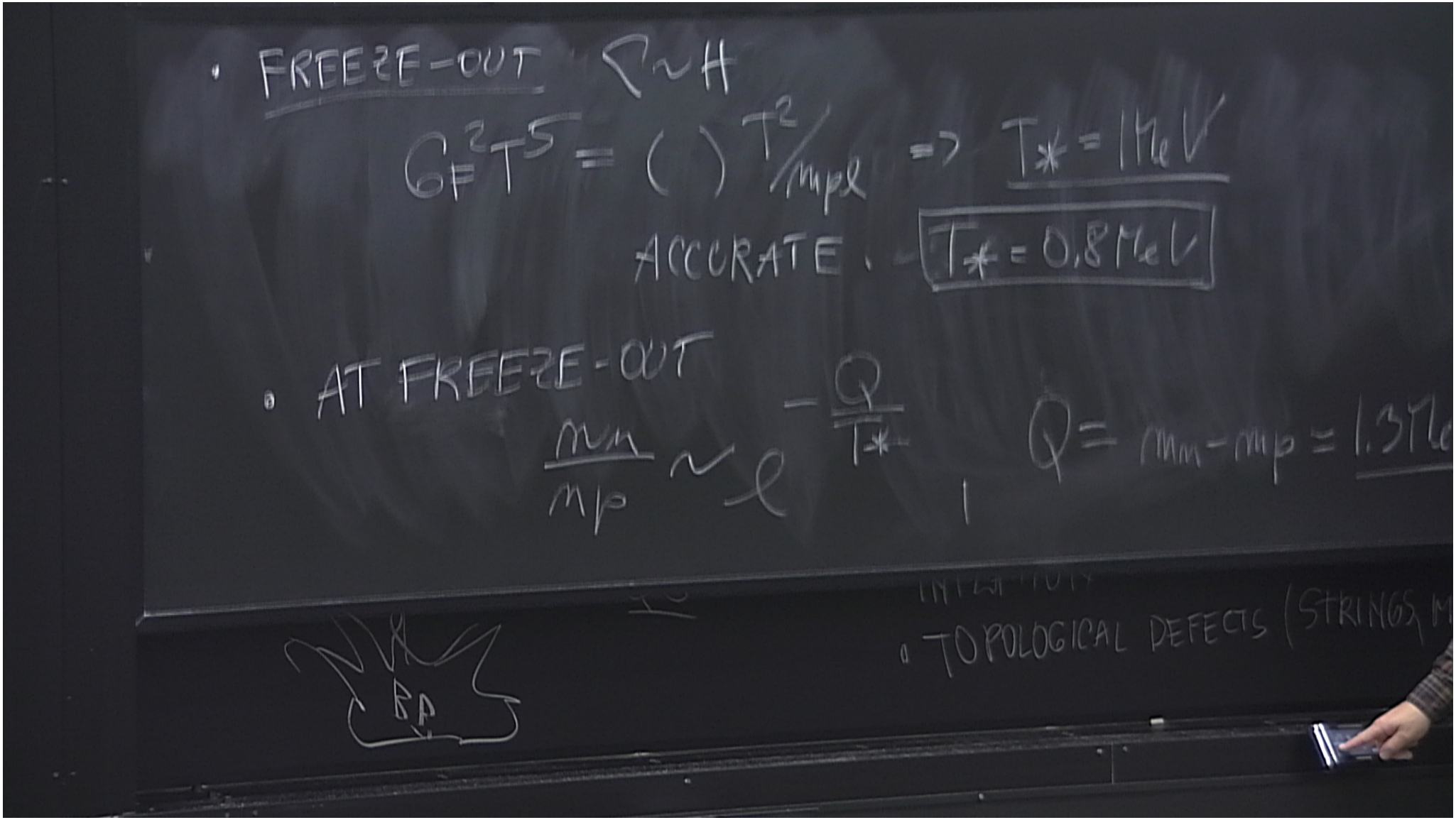

$-g^2 \frac{1}{p^2 - m_W^2} \sim \frac{g^2}{m_W^2} \simeq G_F \simeq 10^{-1} \left(\frac{1}{10^2 \text{GeV}}\right)^2 \simeq 10^{-5}\ \text{GeV}^{-2}$
$\Gamma \simeq G_F^2 T^5$
BBLE RATE
$H^2 = \frac{8\pi G_N}{3} \rho - \frac{K}{a^2} = 0$
$G_N = \frac{1}{m_{pl}^2}$
$= \frac{8\pi}{3} \frac{\pi^2}{30} g_* \frac{T^4}{m_{pl}^2}$

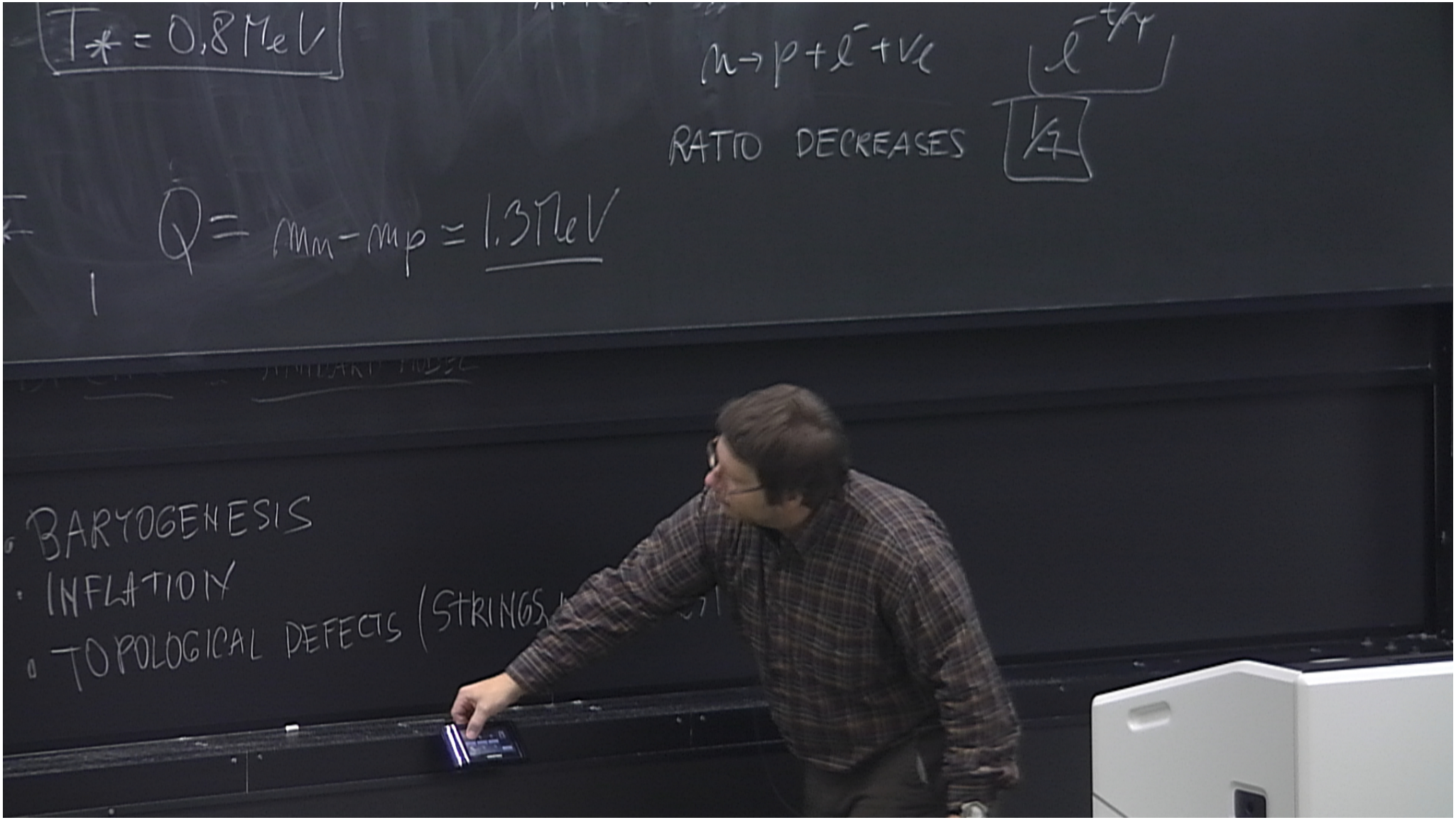
(He RECOMBINES EARLIER .. UNIVERSE STILL ORA

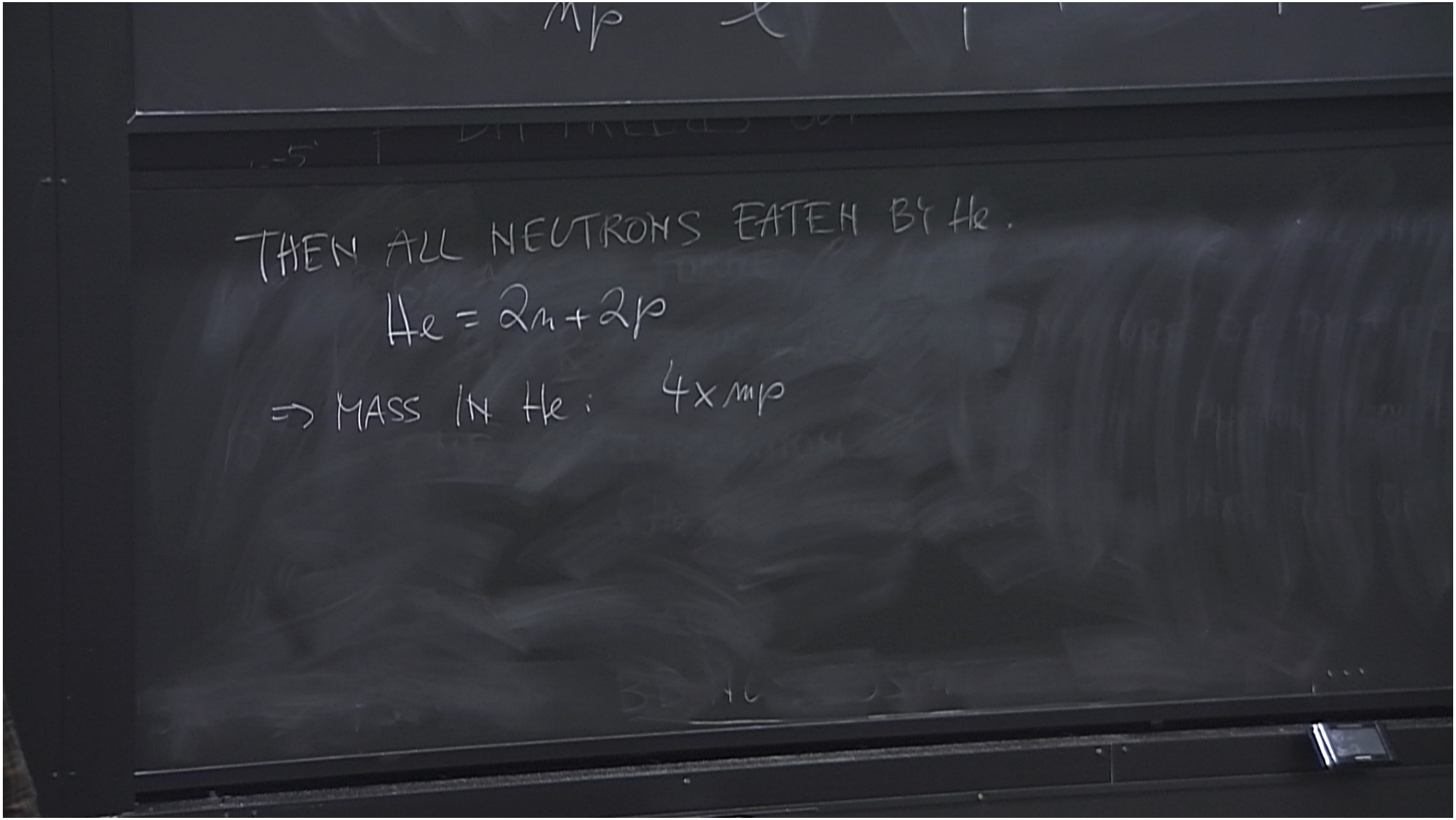
10^{11} | RAD = MATT EQ

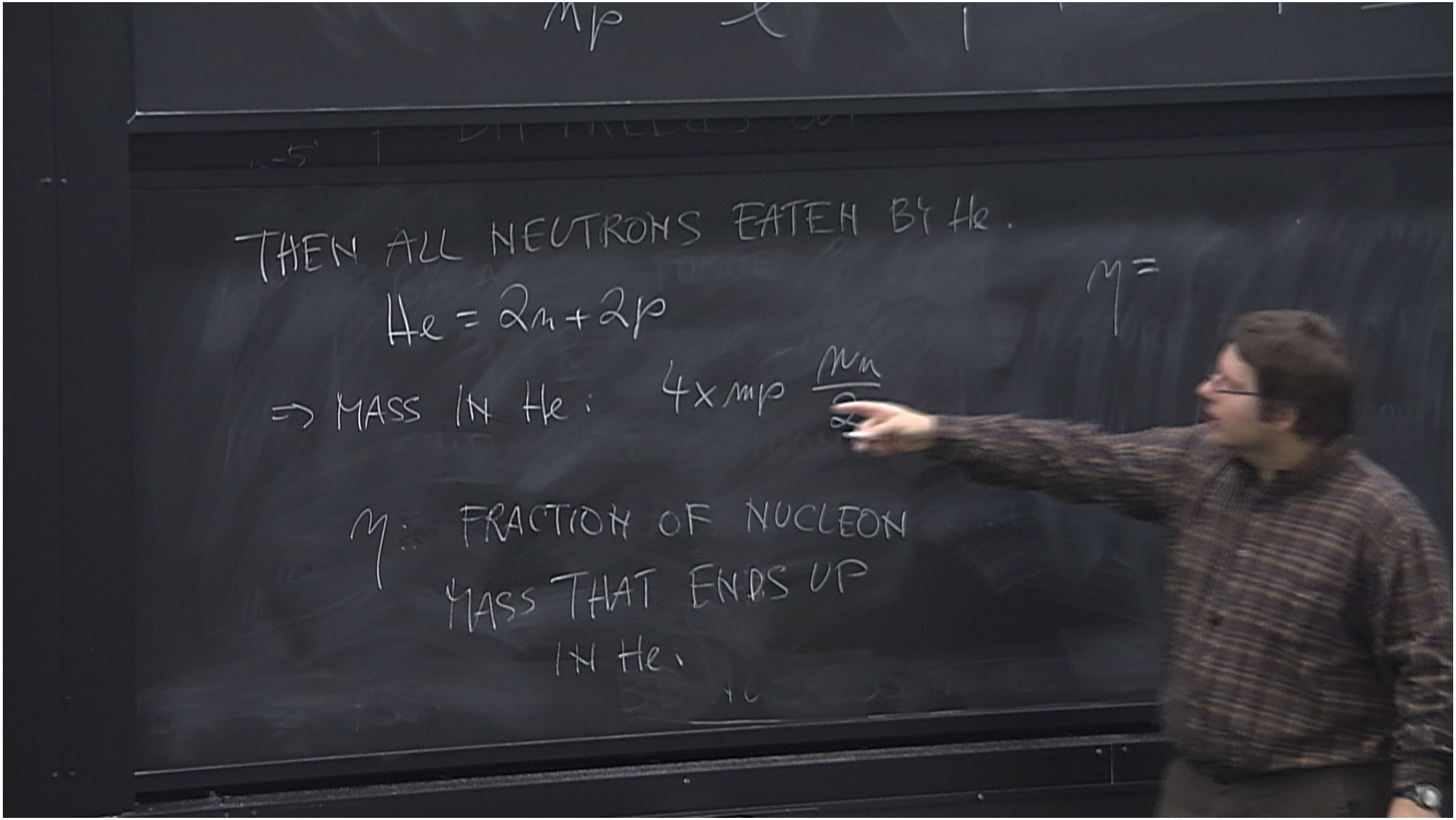
- FREEZE-OUT $\Gamma \sim H$

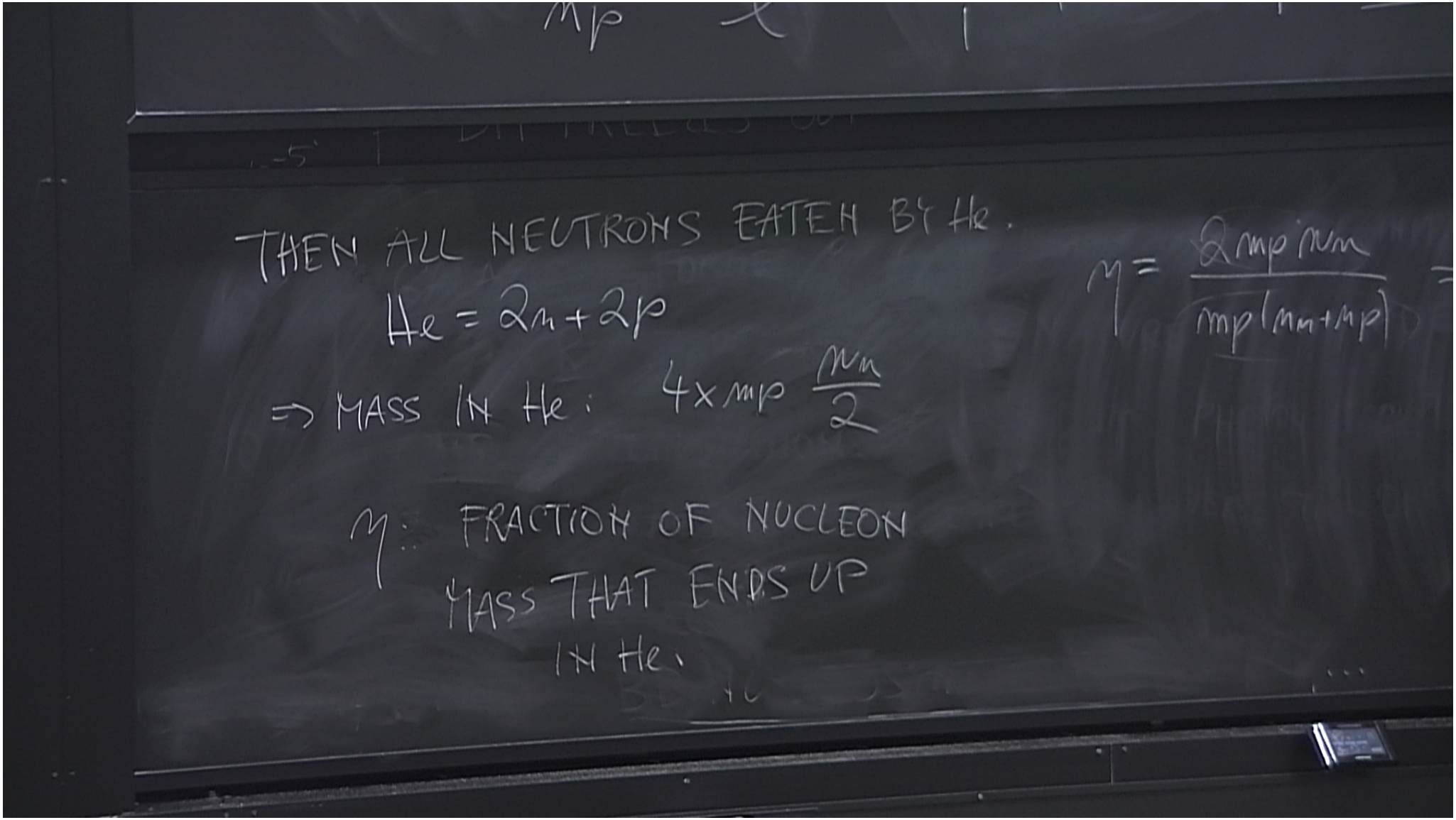
$$G_F^2 T^5 = (\,)\, T^2/m_{pl} \Rightarrow T_* = 1\,\text{MeV}$$

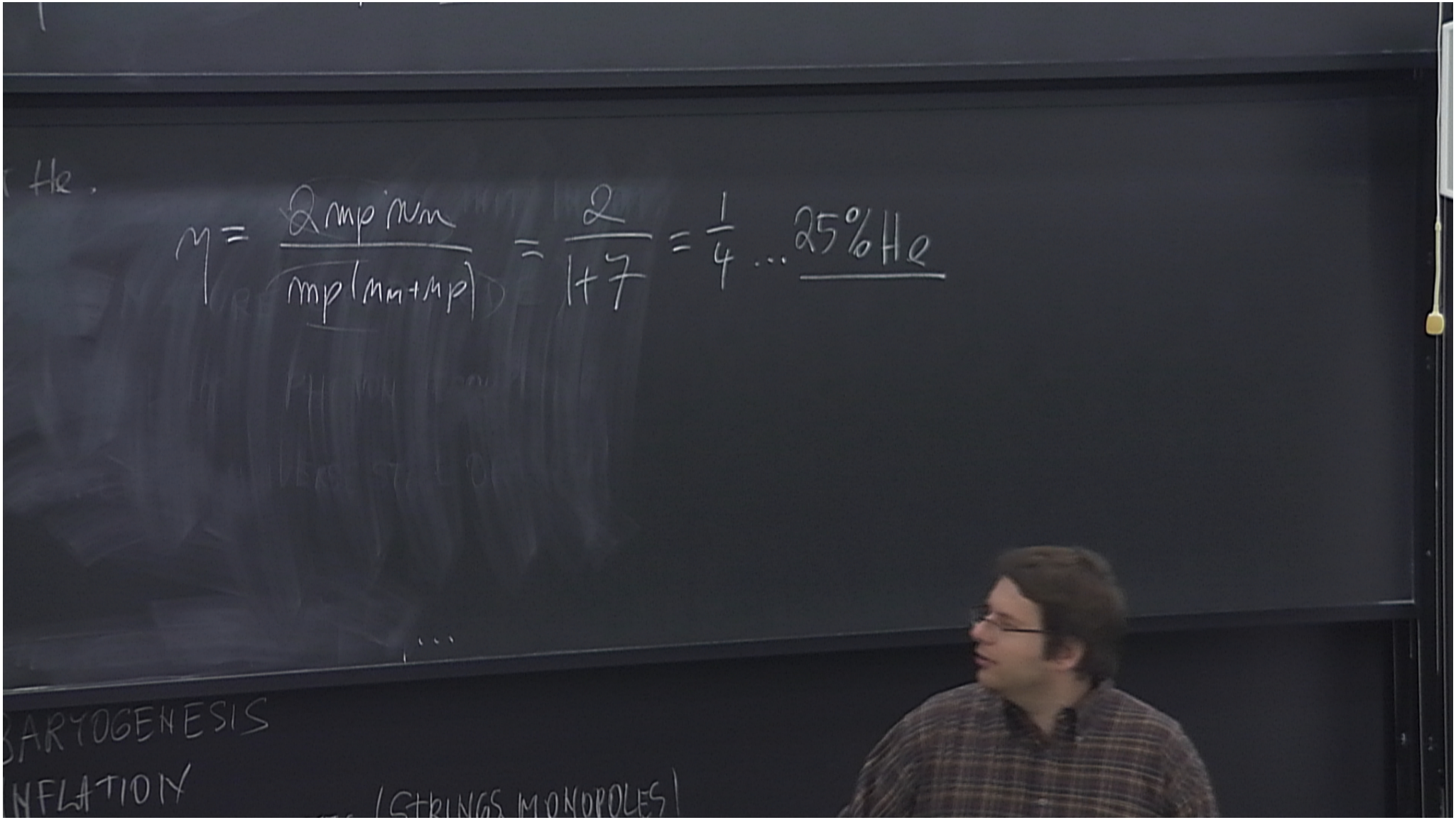

• FREEZE-OUT Γ ~ H
$G_F^2 T^5 = (\,)\, T^2/m_{pl}$ => $T_* = 1\,MeV$
ACCURATE: $T_* = 0.8\,MeV$
• AT FREEZE-OUT
$\frac{n_n}{n_p} \sim e^{-\frac{Q}{T_*}}$ $Q = m_n - m_p = 1.3\,MeV$
• TOPOLOGICAL DEFECTS (STRINGS, M


$T_* = 0.8\,MeV$
$n \to p + e^- + \nu_e$
$e^{-t/\tau}$
RATIO DECREASES
1/2
$Q = m_n - m_p \simeq 1.3\,MeV$
BARYOGENESIS
INFLATION
TOPOLOGICAL DEFECTS (STRINGS


THEN ALL NEUTRONS EATEN BY He.
He = 2n + 2p
=> MASS IN He: 4 x mp


THEN ALL NEUTRONS EATEN BY He.
He = 2n + 2p
⇒ MASS IN He: 4 x mp
η: FRACTION OF NUCLEON
MASS THAT ENDS UP
IN He.


THEN ALL NEUTRONS EATEN BY He.
He = 2n + 2p
⇒ MASS IN He: 4 × mp (mn/2)
η: FRACTION OF NUCLEON MASS THAT ENDS UP IN He.
η = 2 mp mn / mp(mn + mp)


He.
$Y = \frac{2 n_p n_n}{n_p (n_n + n_p)} = \frac{2}{1+7} = \frac{1}{4}$ ... 25% He
BARYOGENESIS
INFLATION
(STRINGS MONOPOLES)