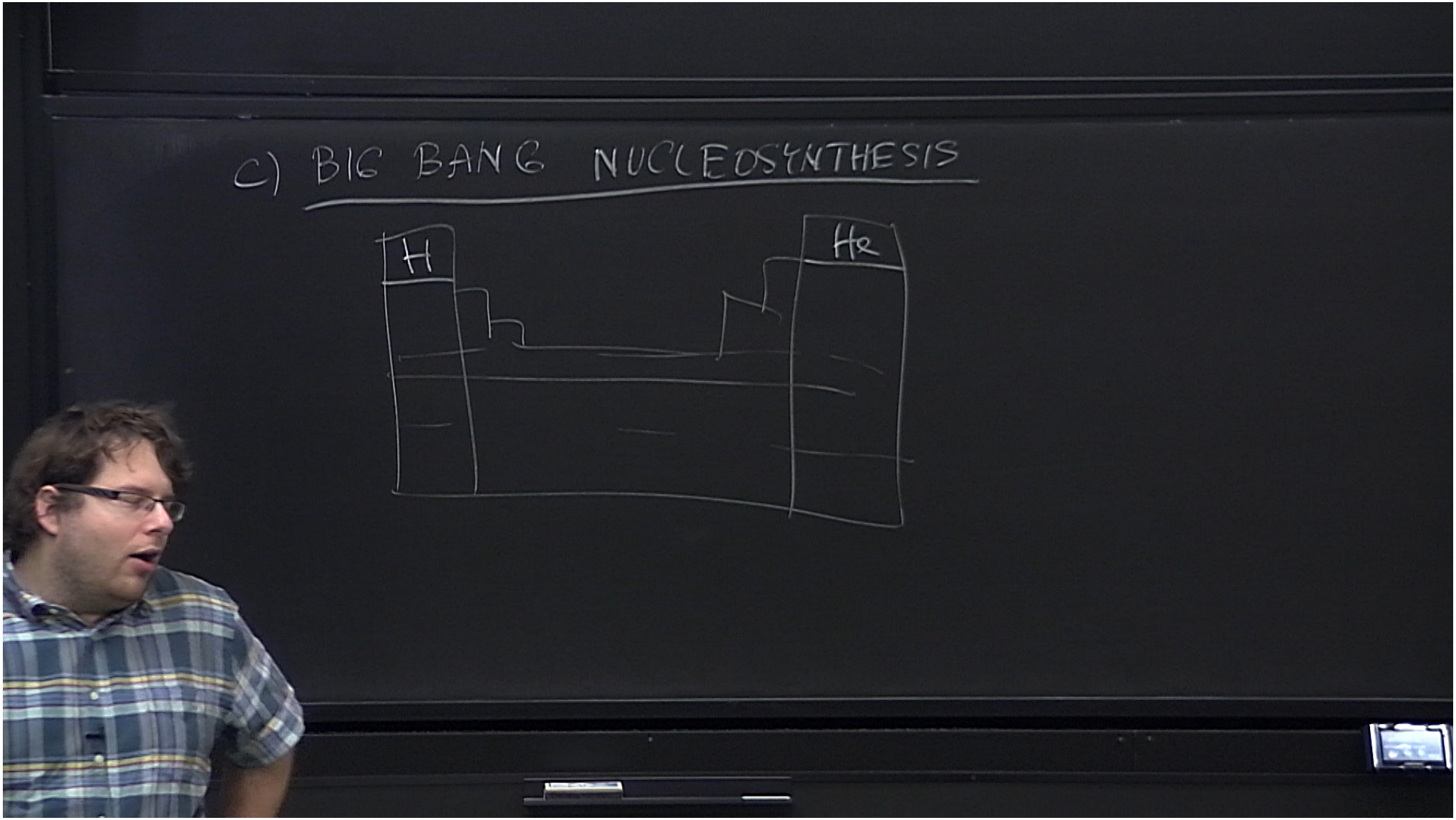
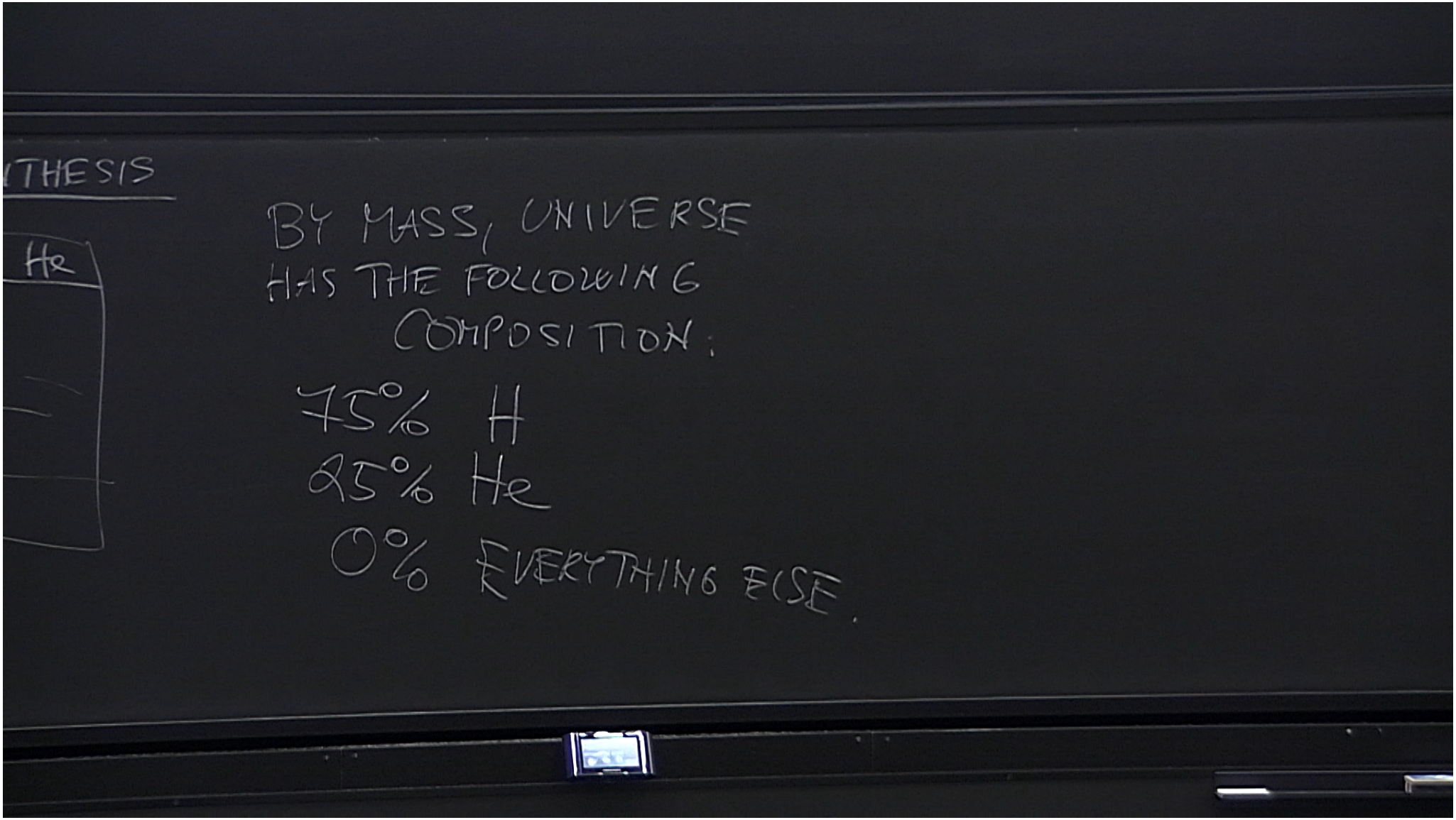
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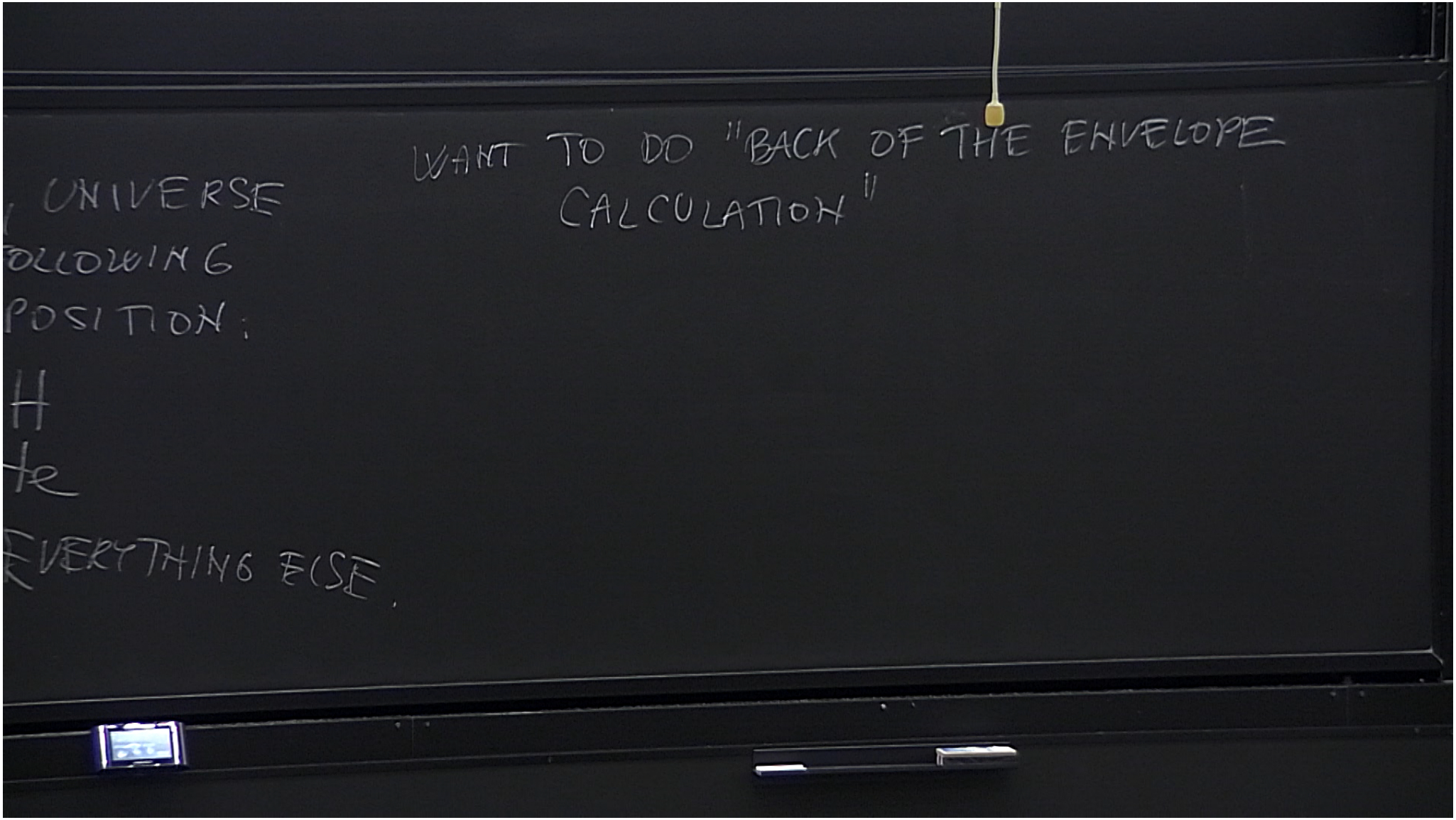
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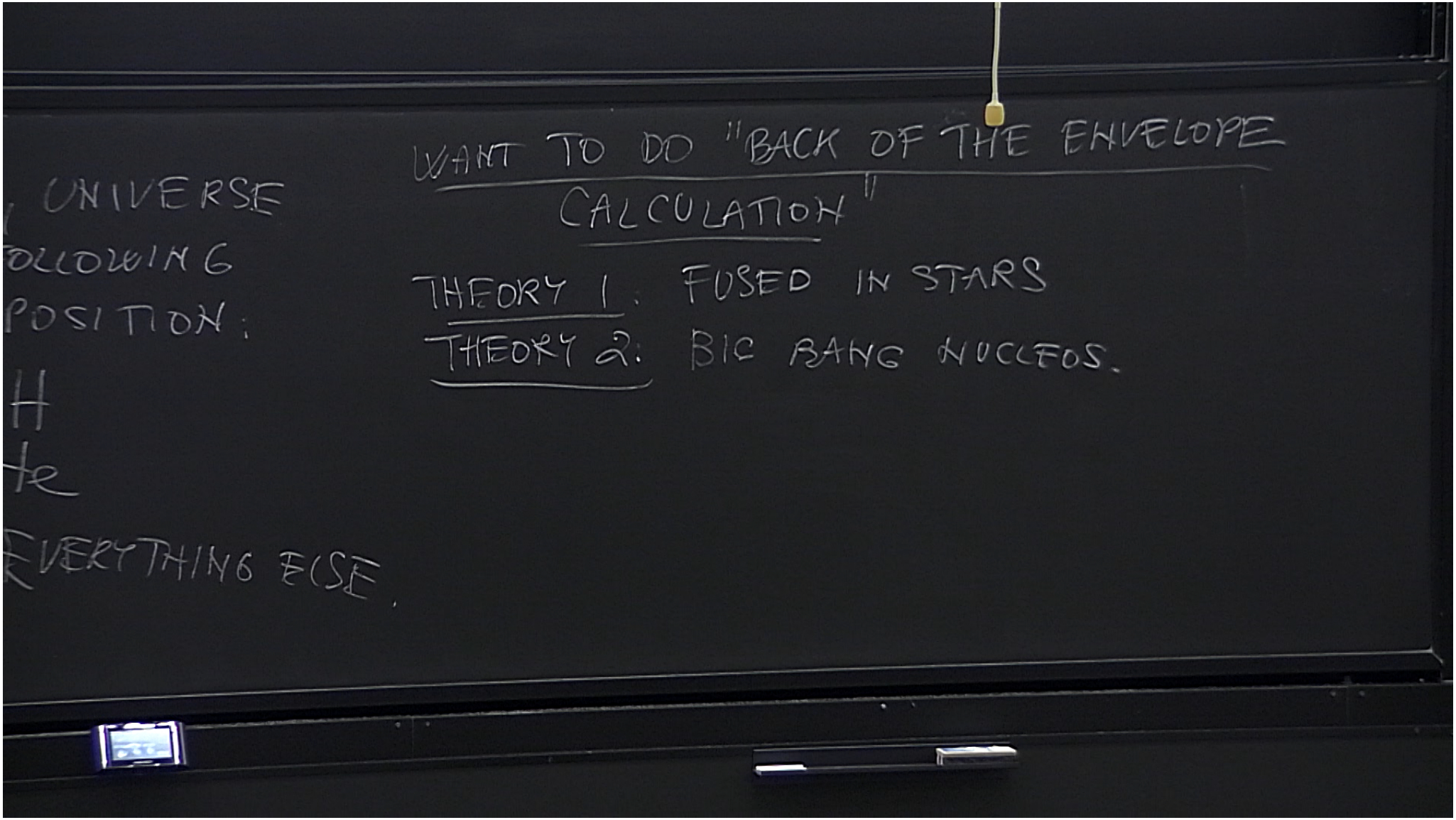
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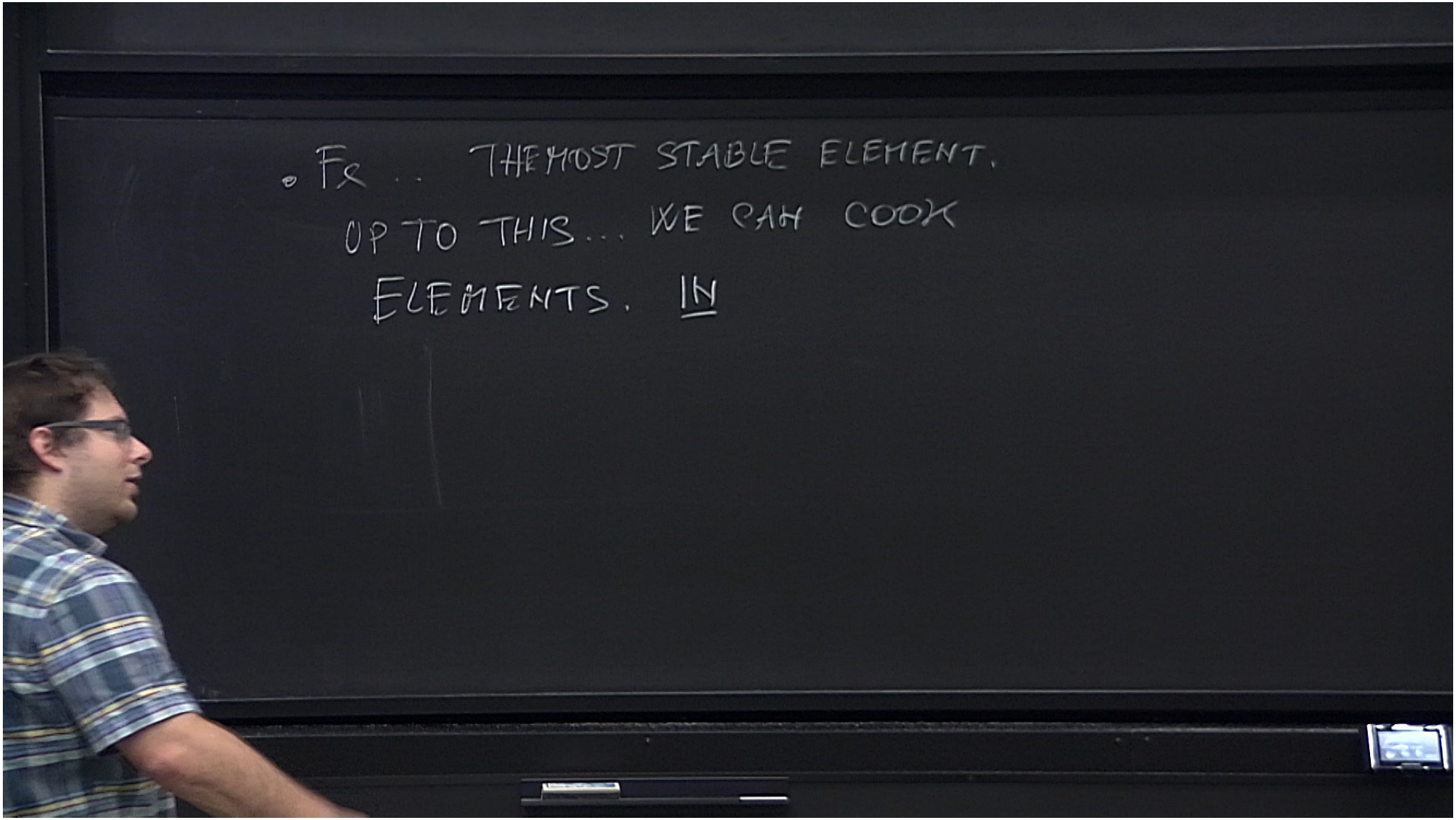
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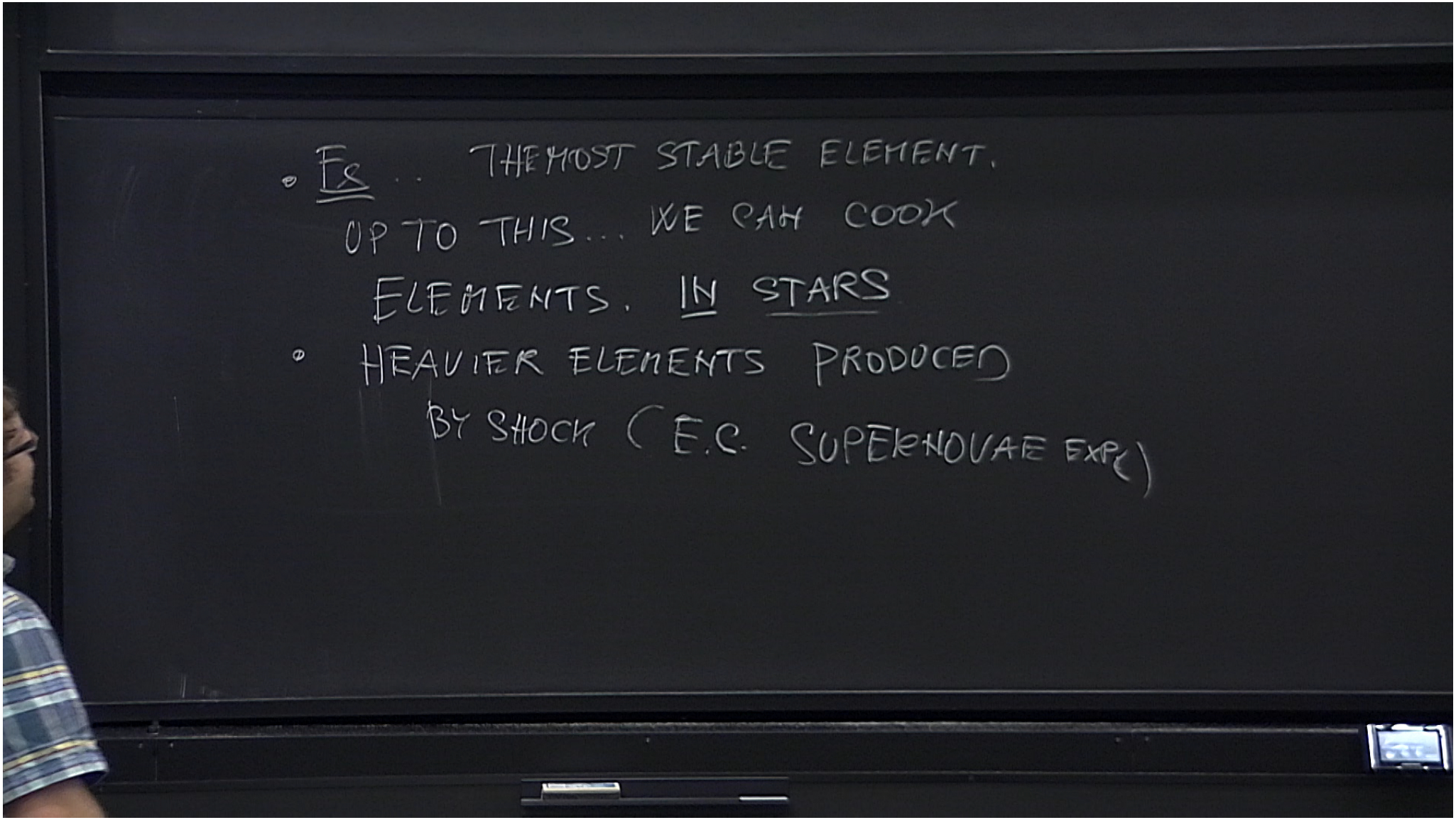

c) BIG BANG NUCLEOSYNTHESIS
H
He

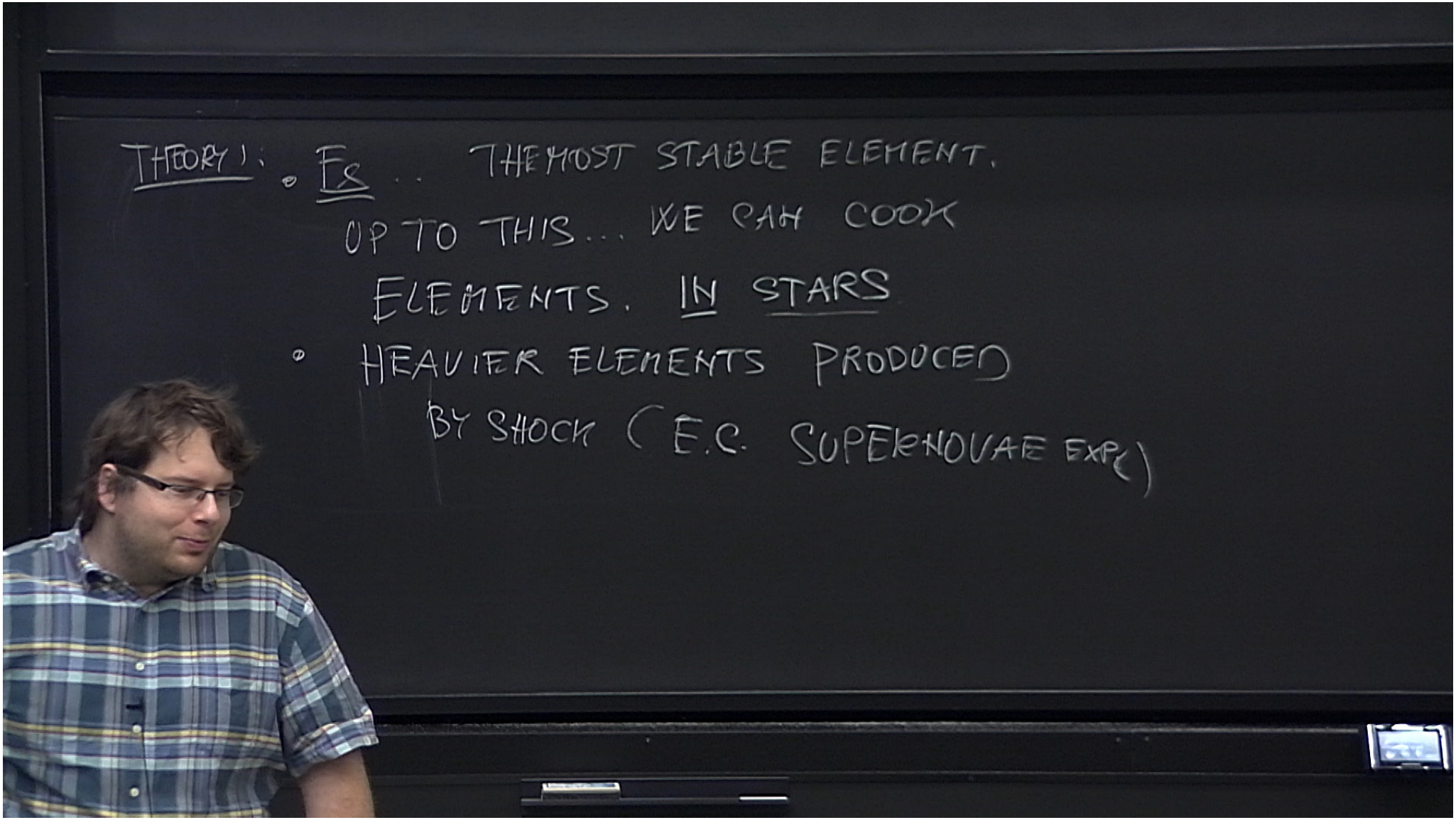

THESIS
He
BY MASS, UNIVERSE HAS THE FOLLOWING COMPOSITION:
75% H
25% He
0% EVERYTHING ELSE.

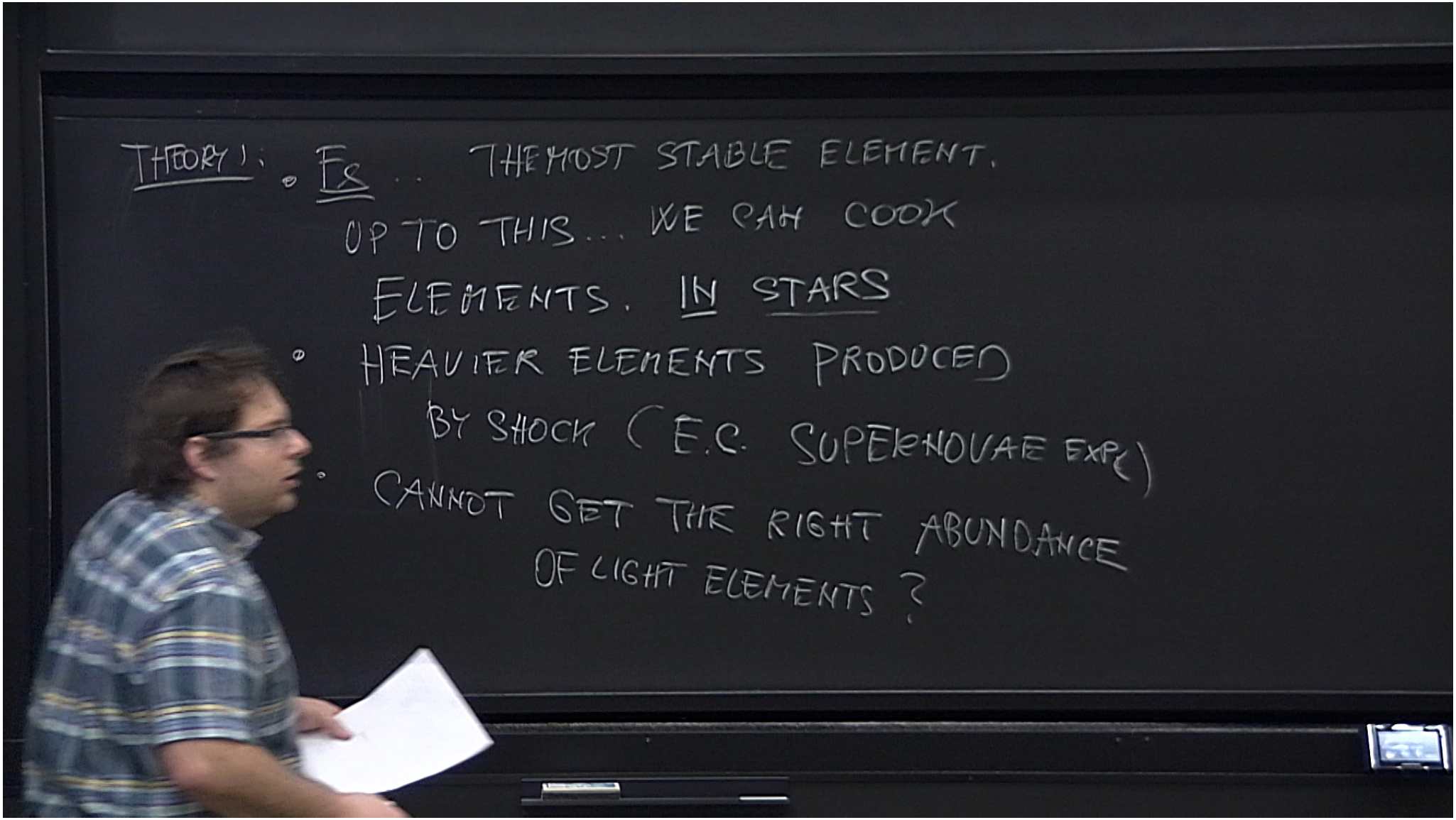

UNIVERSE
OLLOWING
POSITION:
H
te
VERYTHING ELSE.
WANT TO DO "BACK OF THE ENVELOPE
CALCULATION"

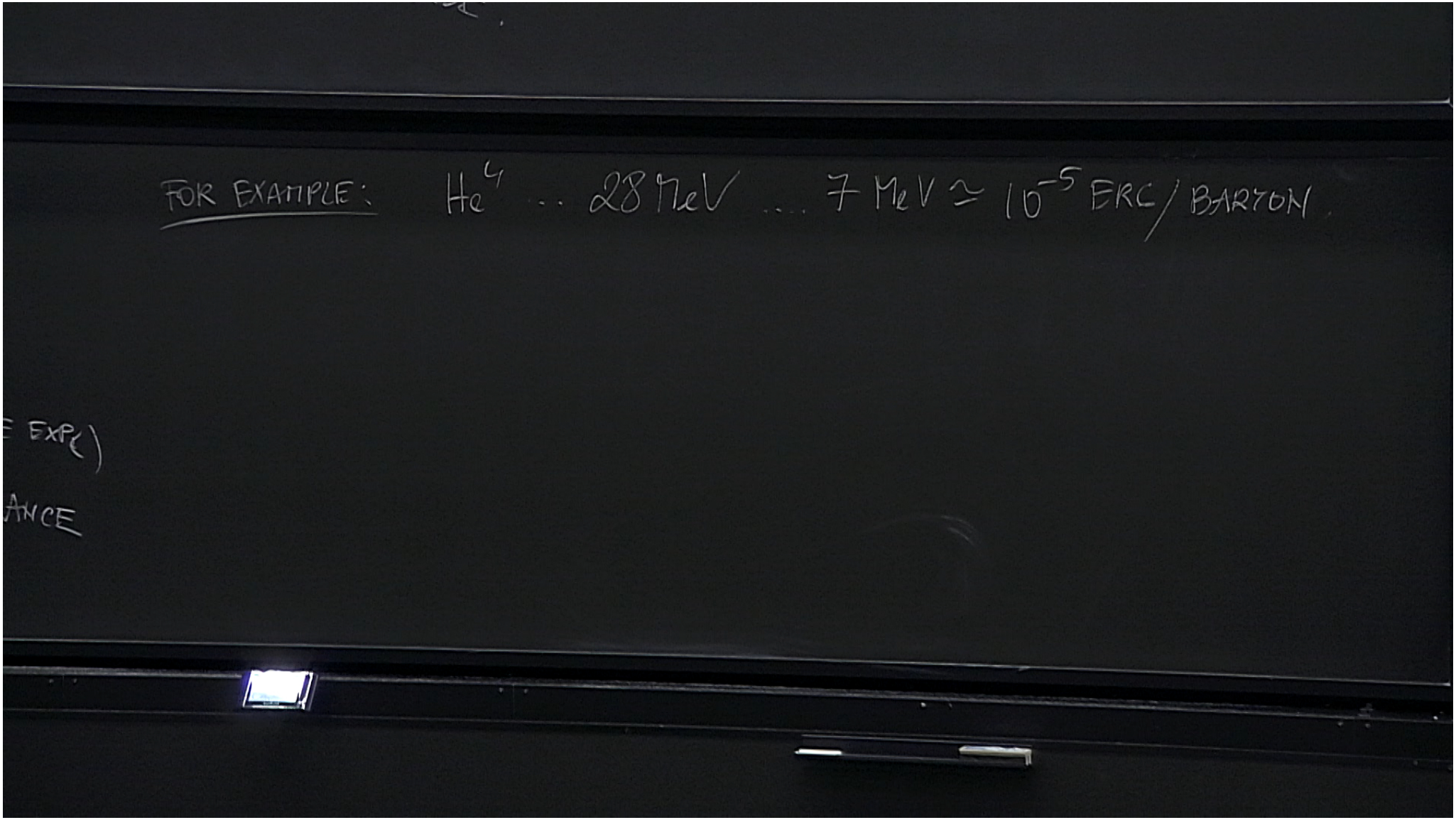

UNIVERSE
OLLOWING
POSITION:
H
te
VERYTHING ELSE.
WANT TO DO "BACK OF THE ENVELOPE CALCULATION"
THEORY 1: FUSED IN STARS
THEORY 2: BIG BANG NUCLEOS.

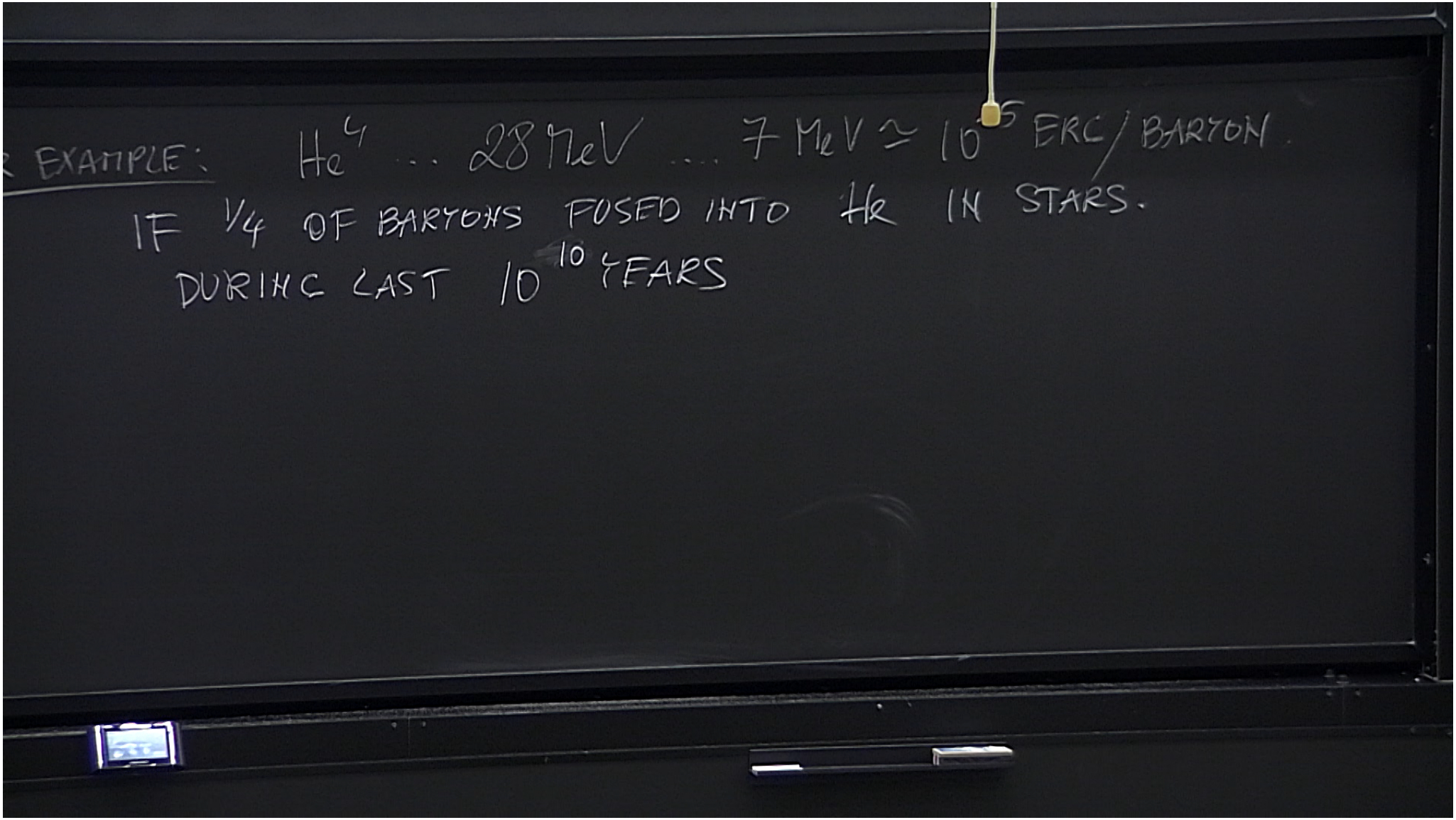

• Fe .. THE MOST STABLE ELEMENT.
UP TO THIS ... WE CAN COOK
ELEMENTS. IN

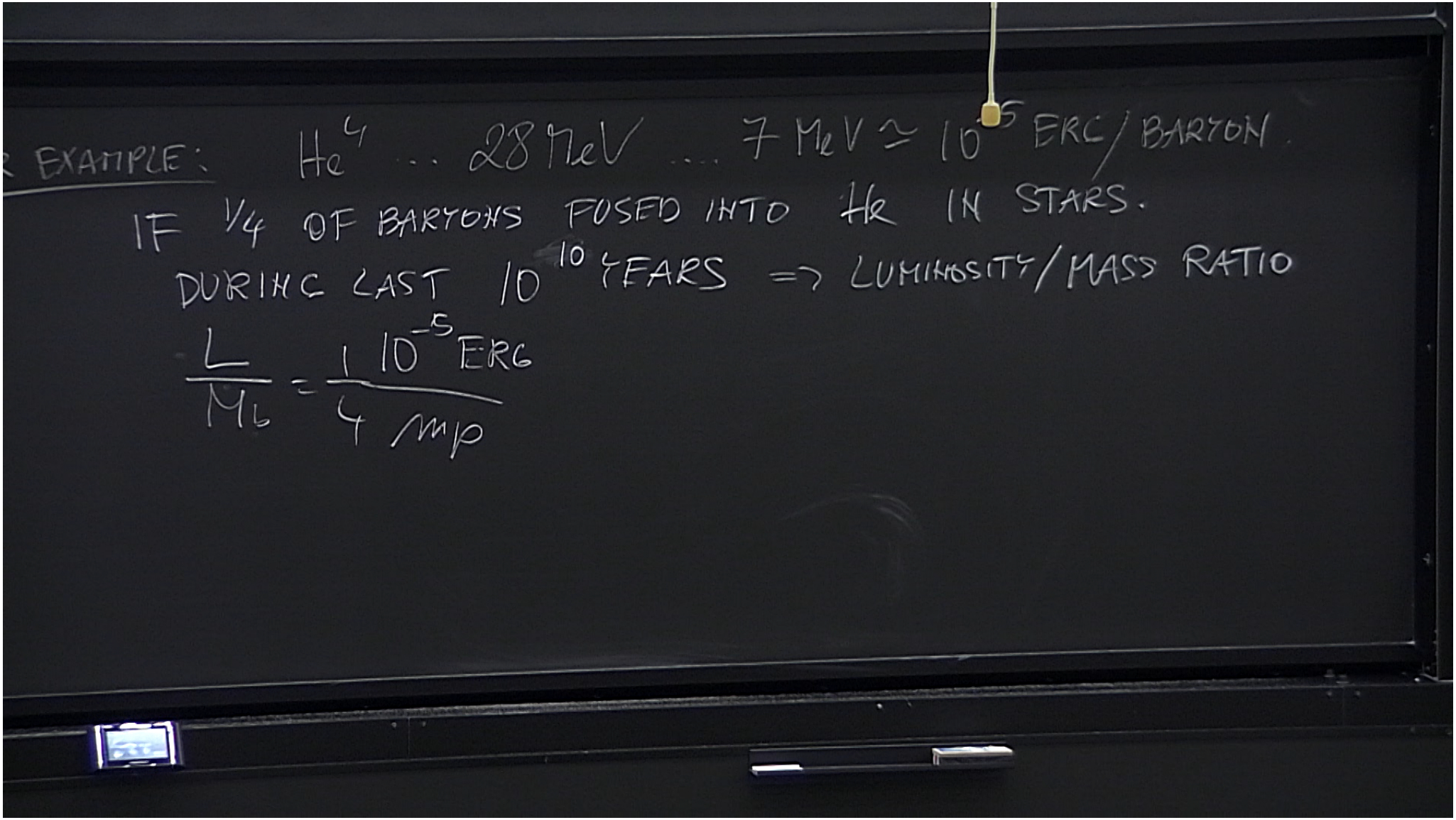

• Fe .. THE MOST STABLE ELEMENT.
UP TO THIS ... WE CAN COOK
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• HEAVIER ELEMENTS PRODUCED
BY SHOCK (E.G. SUPERNOVAE EXP.)


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CANNOT GET THE RIGHT ABUNDANCE
OF LIGHT ELEMENTS ?


FOR EXAMPLE: He^4 .. 28 MeV ... 7 MeV $\simeq 10^{-5}$ ERG / BARYON
EXP( )
ANCE


EXAMPLE: He^4 ... 28 MeV ... 7 MeV $\simeq 10^{-5}$ ERG/BARYON
IF 1/4 OF BARYONS FUSED INTO He IN STARS.
DURING LAST 10^{10} YEARS

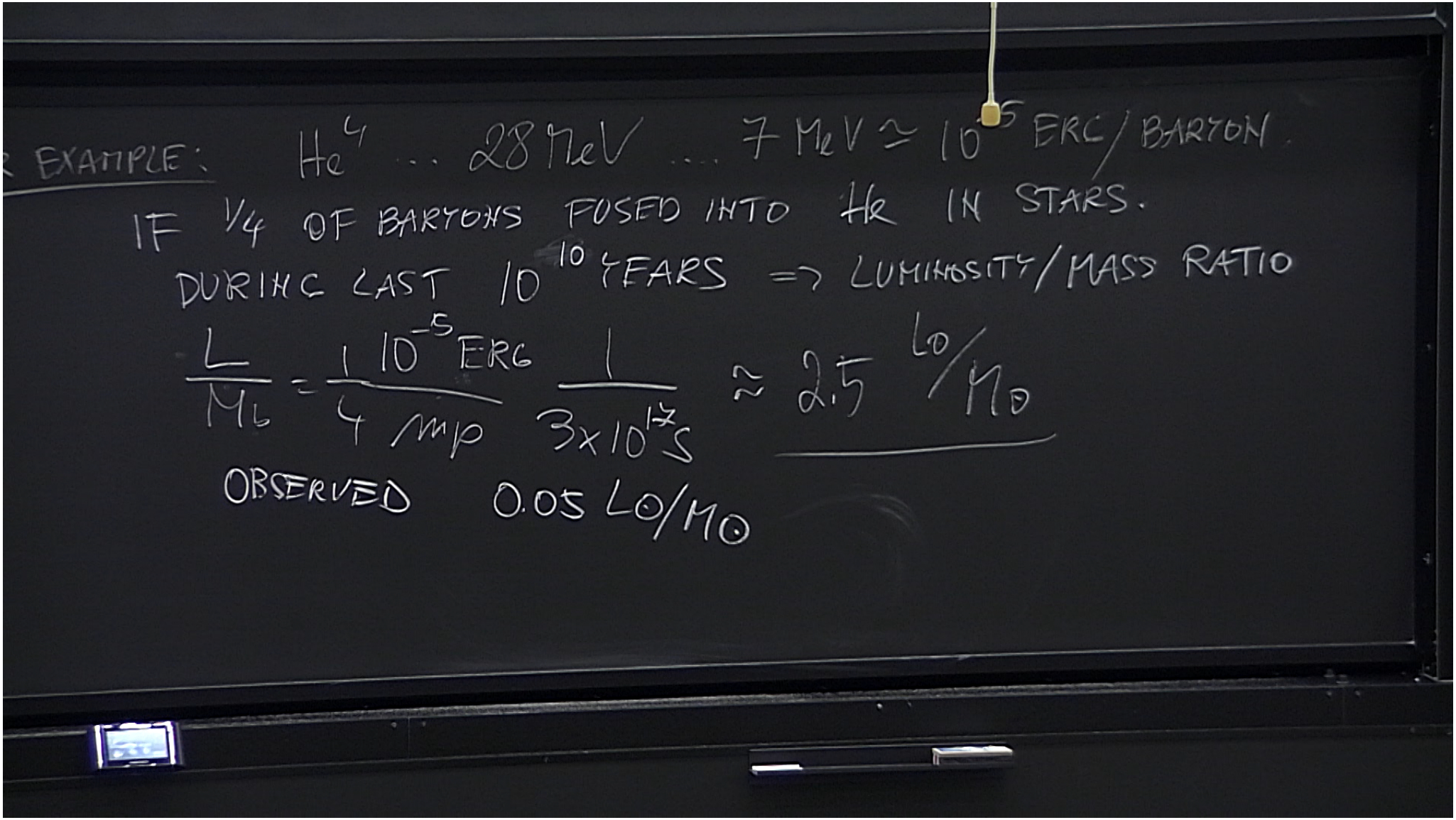

EXAMPLE: He^4 .. 28 MeV ... 7 MeV $\simeq 10^{-5}$ ERG/BARYON
IF 1/4 OF BARYONS FUSED INTO He IN STARS.
DURING LAST 10^{10} YEARS => LUMINOSITY/MASS RATIO
$\frac{L}{M_b} = \frac{1}{4} \frac{10^{-5} \text{ ERG}}{m_p}$

EXAMPLE: He^4 .. 28 MeV ... 7 MeV $\simeq 10^{-5}$ ERG/BARYON

IF 1/4 OF BARYONS FUSED INTO He IN STARS.

DURING LAST 10^{10} YEARS $\Rightarrow$ LUMINOSITY/MASS RATIO

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


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OBSERVED 0.05 $L_\odot/M_\odot$

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OBSERVED $0.05\ L_\odot/M_\odot \Rightarrow 0.5\%$ OF He FUSED IN STARS.

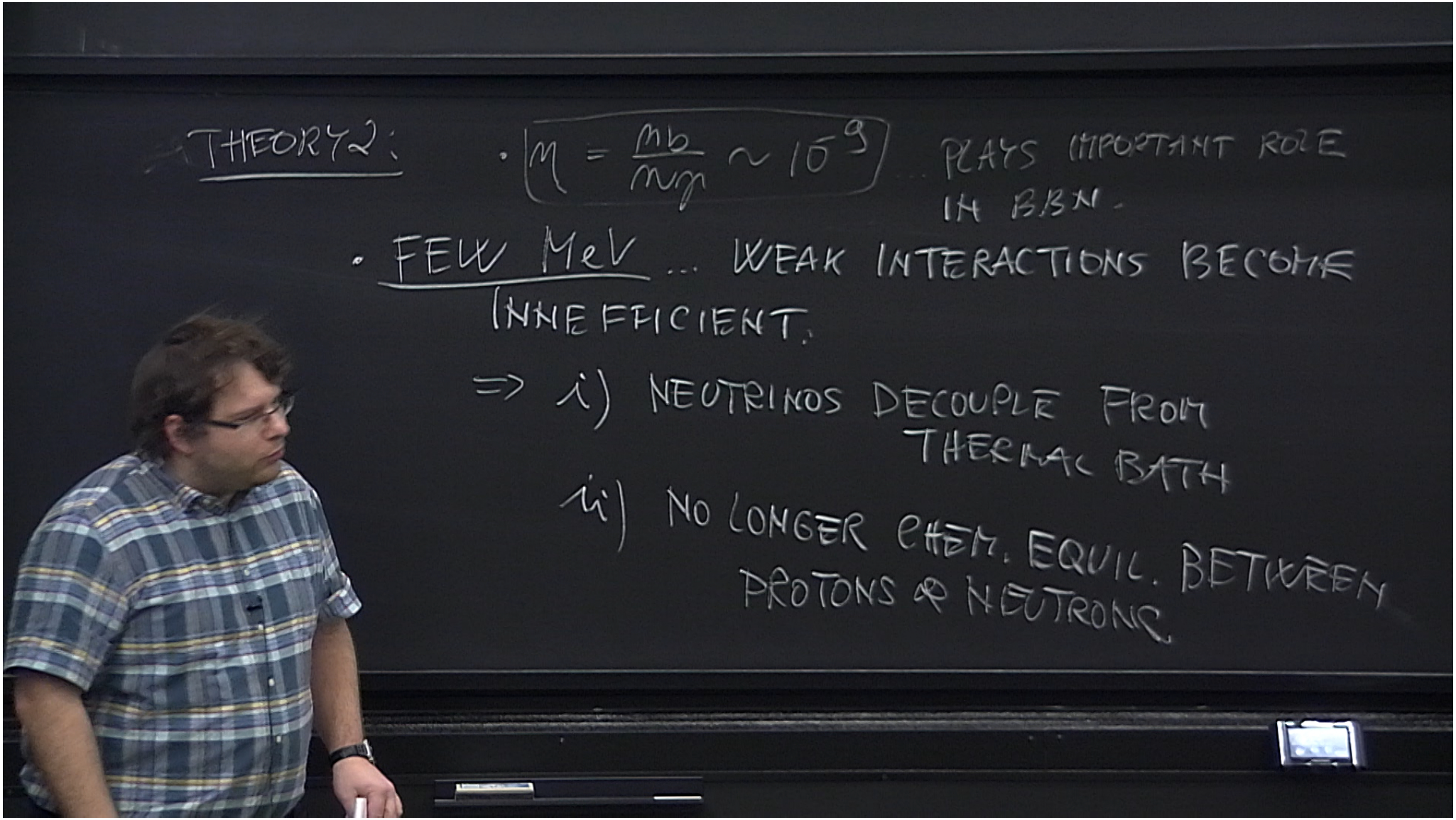
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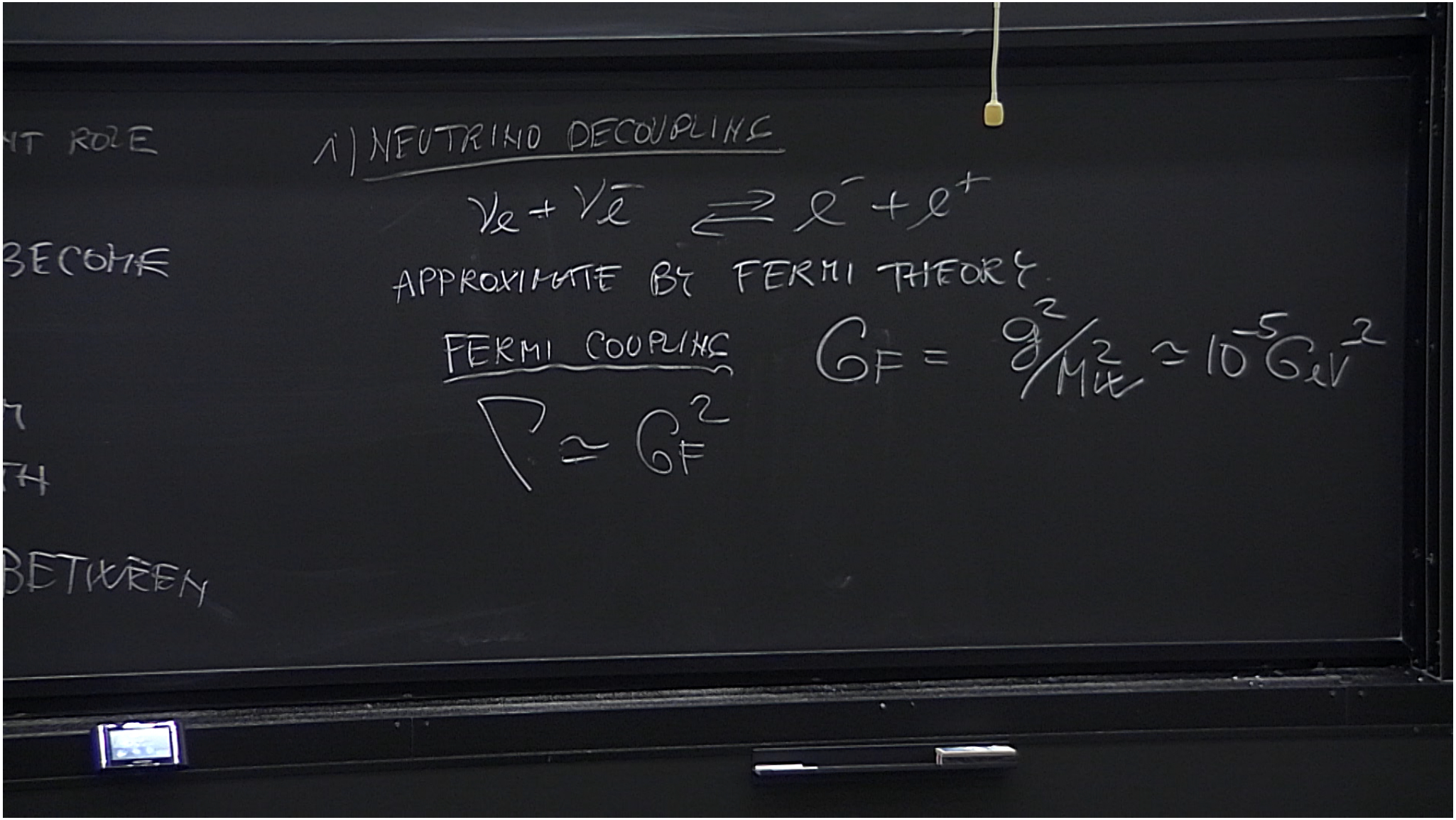
IF 1/4 OF BARYONS FUSED INTO He IN STARS.

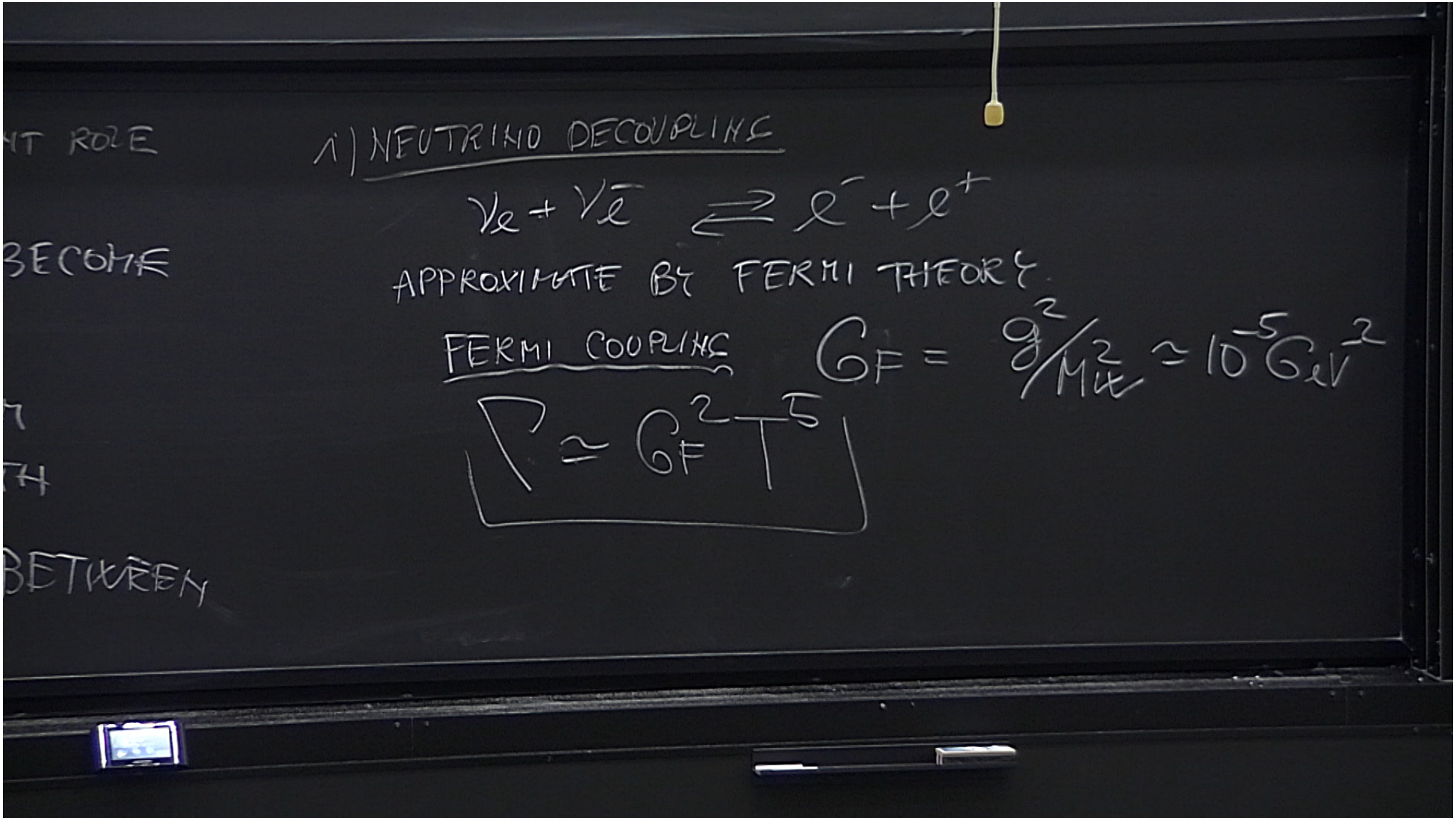
DURING LAST 10^{10} YEARS $\Rightarrow$ LUMINOSITY/MASS RATIO

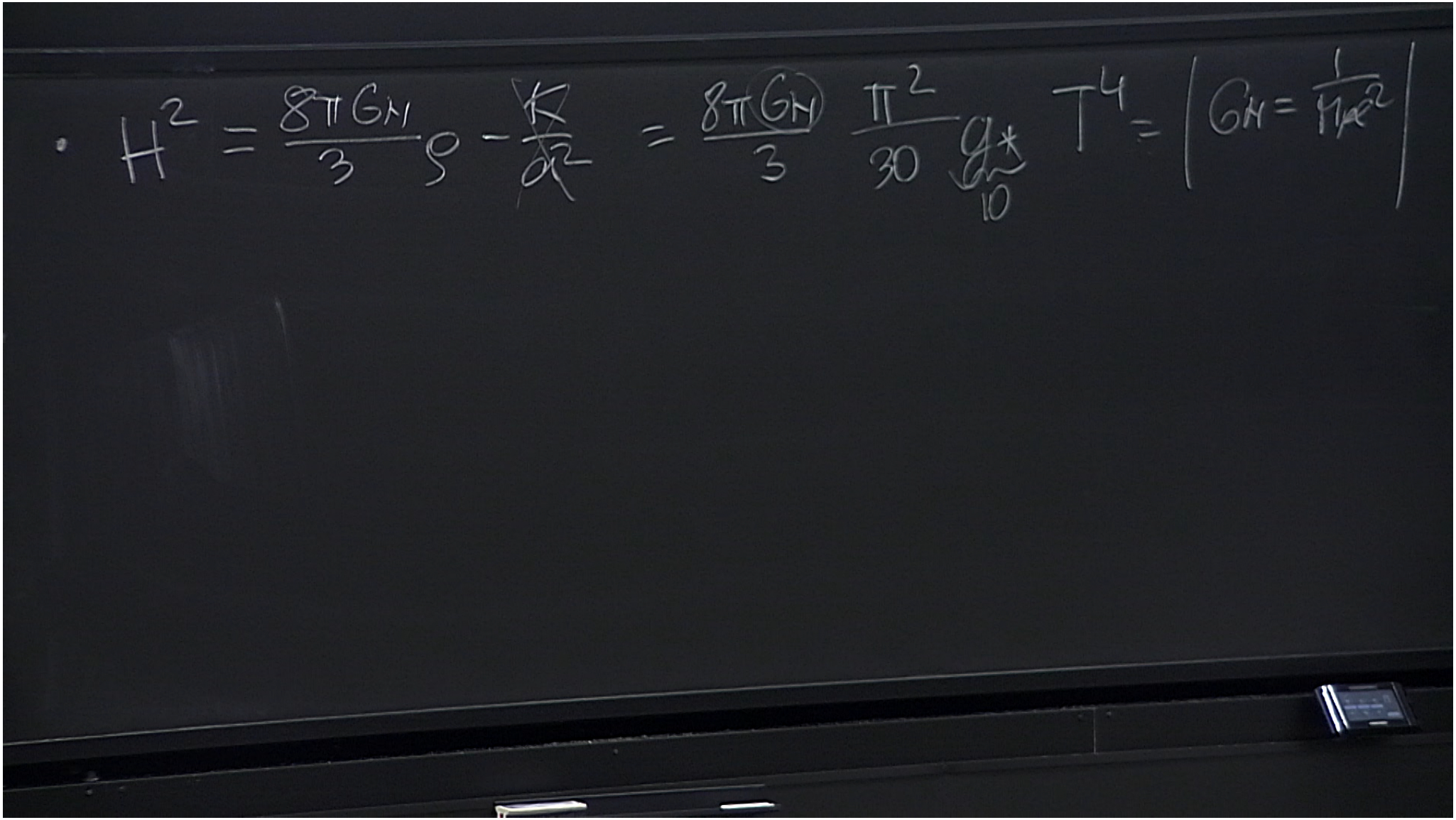
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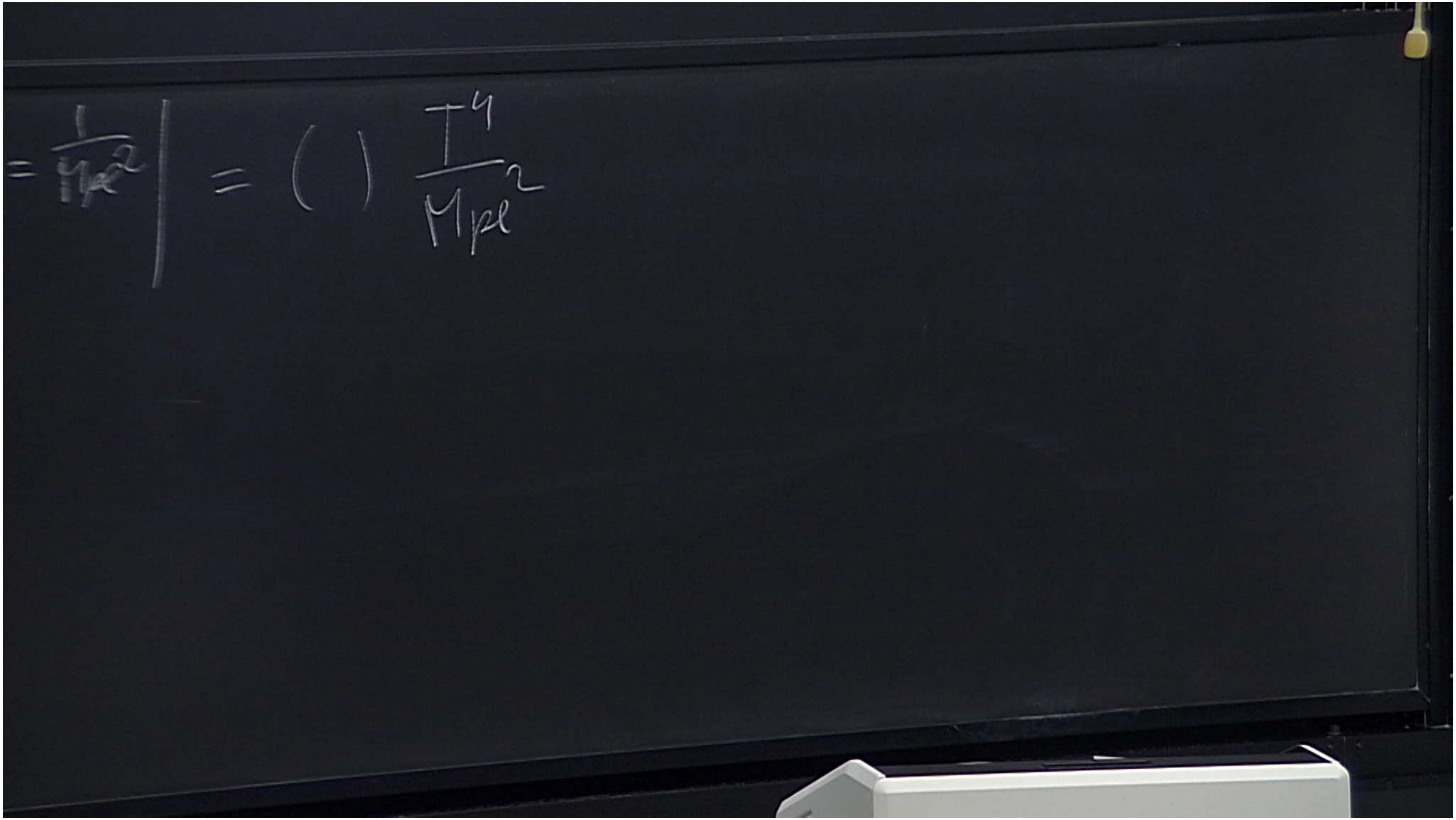
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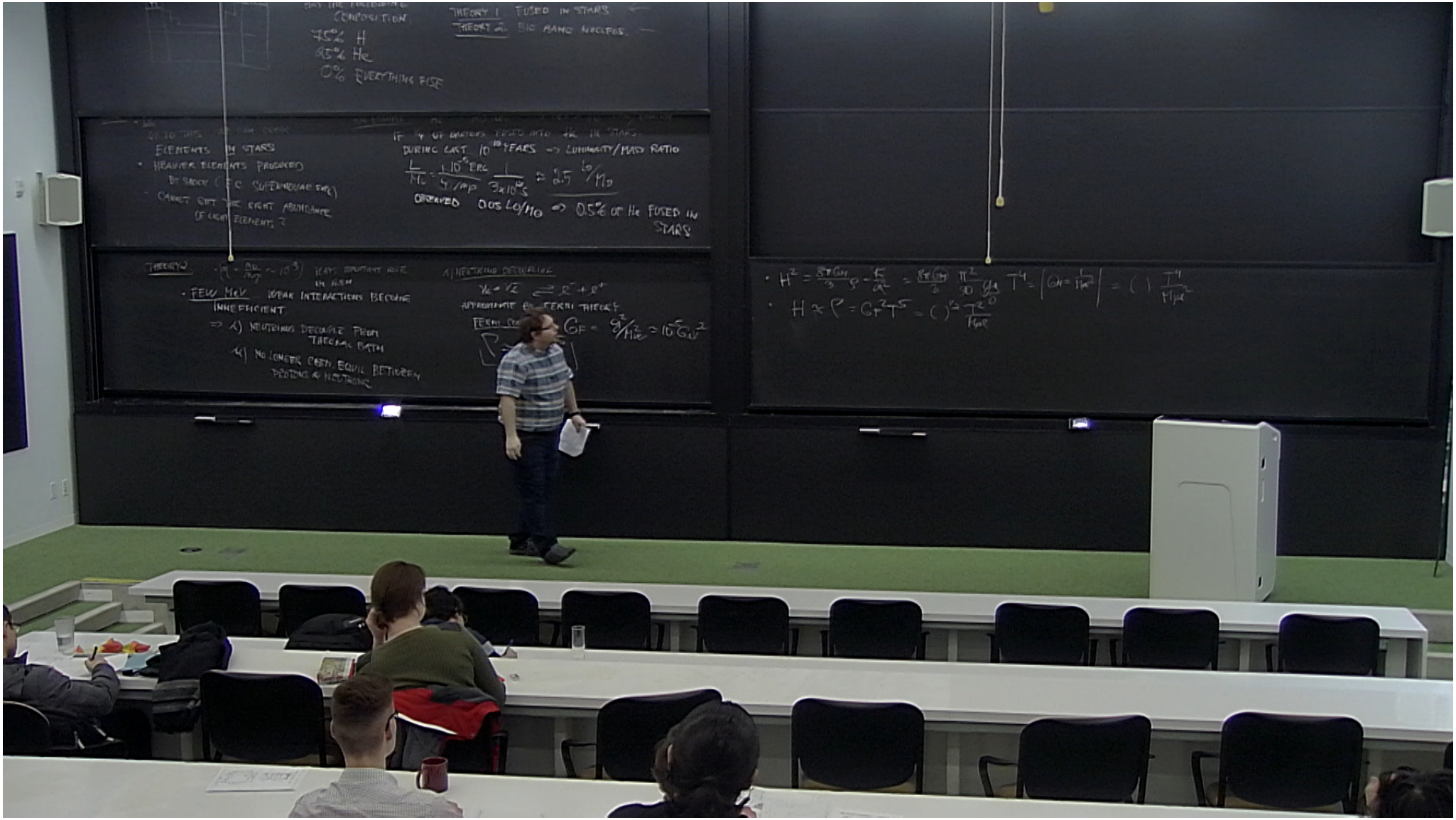

THEORY2:
$\eta = \frac{n_b}{n_\gamma} \sim 10^{-9}$
PLAYS IMPORTANT ROLE IN BBN.
FEW MeV ... WEAK INTERACTIONS BECOME INNEFFICIENT.
=> i) NEUTRINOS DECOUPLE FROM THERMAL BATH
ii) NO LONGER CHEM. EQUIL. BETWEEN PROTONS & NEUTRONS

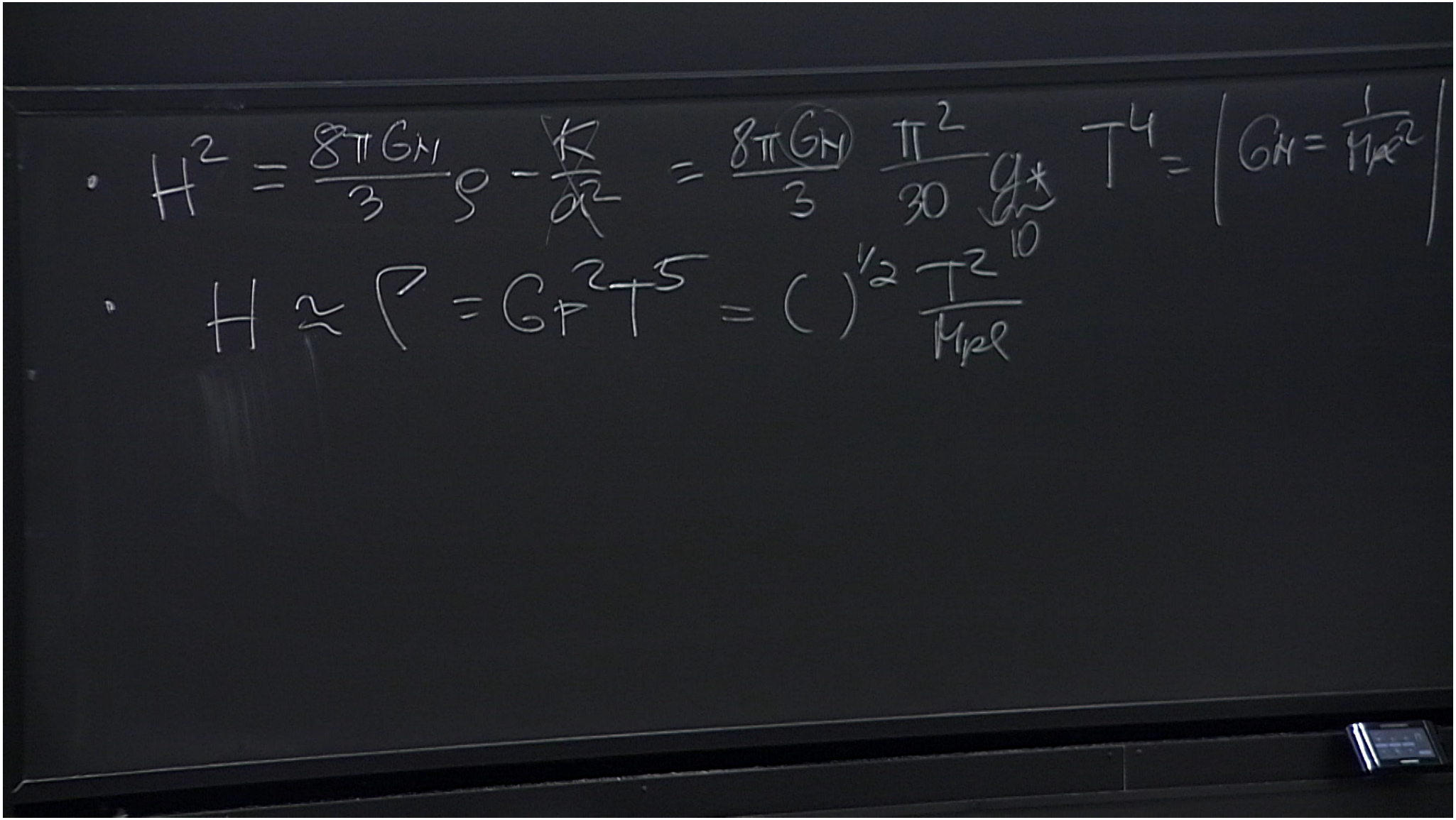

NT ROLE
BECOME
TH
BETWEEN
1) NEUTRINO DECOUPLING
$\nu_e + \bar{\nu}_e \rightleftarrows e^- + e^+$
APPROXIMATE BY FERMI THEORY
FERMI COUPLING
$G_F = g^2/M_W^2 \simeq 10^{-5}\,GeV^{-2}$
$\Gamma \simeq G_F^2$

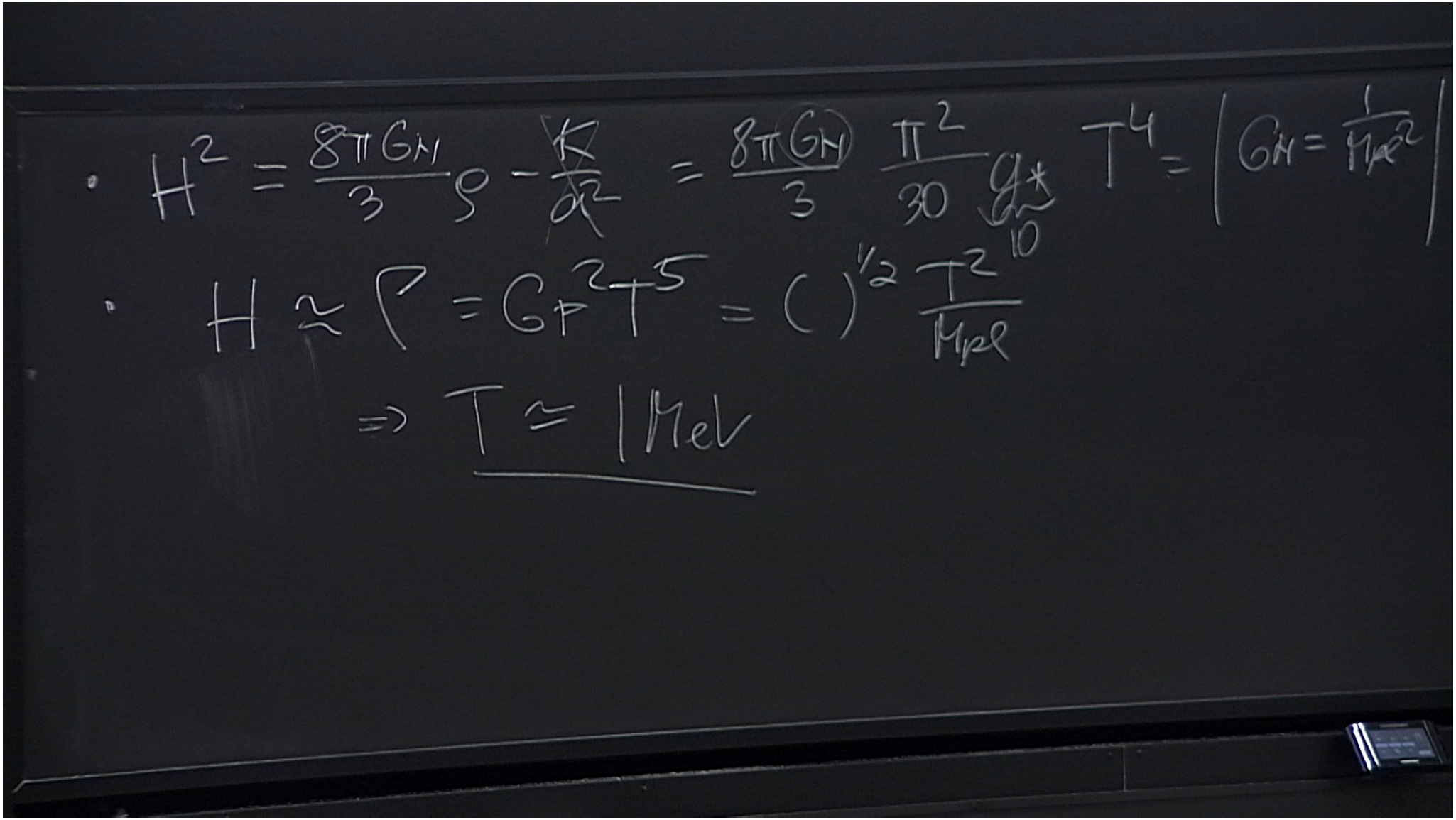

NT ROLE
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APPROXIMATE BY FERMI THEORY
FERMI COUPLING $G_F = g^2/M_W^2 \simeq 10^{-5}\,GeV^{-2}$
$\Gamma \simeq G_F^2 T^5$


$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2} = \frac{8\pi G_N}{3}\frac{\pi^2}{30}g_{10}^* T^4 = \left| G_N = \frac{1}{M_{Pl}^2} \right|$


$= \frac{1}{M_{pl}^2} \Big| = ( ) \frac{T^4}{M_{pl}^2}$


COMPOSITION
75% H
25% He
0% EVERYTHING ELSE
THEORY I FUSED IN STARS
THEORY II BIG BANG NUCLEOS
ELEMENTS IN STARS
HEAVIER ELEMENTS PRODUCED
BY SHOCK (EG SUPERNOVAE EXPL)
CANNOT GET THE RIGHT ABUNDANCE
OF LIGHT ELEMENTS ?
DURING LAST 10^{10} YEARS => LUMINOSITY/MASS RATIO
OBSERVED 0.05 $L_\odot/M_\odot$ => 05% OF He FUSED IN STARS
THEORY
FEW MeV WEAK INTERACTIONS BECOME INEFFICIENT
=> A) NEUTRINOS DECOUPLE FROM THERMAL BATH
B) NO LONGER EQUIL BETWEEN PROTONS & NEUTRONS
A) NEUTRINO DECOUPLING
APPROXIMATE BY FERMI THEORY
$H^2 = \frac{8\pi G\rho}{3} \rho = \frac{E}{a^2} = \frac{8\pi G}{3} \frac{\pi^2}{30} g_* T^4 = \left| GM = \frac{1}{M_{Pl}^2} \right| = ( ) \frac{T^4}{M_{Pl}^2}$
$H \approx P = G_F^2 T^5 = ( )^5 \frac{T^{10}}{M_{Pl}^5}$


$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2} = \frac{8\pi G_N}{3}\frac{\pi^2}{30} g_* T^4 = \left| G_N = \frac{1}{M_{PL}^2} \right|$
$H \simeq \Gamma = G_F^2 T^5 = ()^{1/2} \frac{T^2}{M_{PL}}$


$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2} = \frac{8\pi G_N}{3}\frac{\pi^2}{30} g_*^{10} T^4 = \left| G_N = \frac{1}{M_{PL}^2} \right|$
$H \simeq \Gamma = G_F^2 T^5 = ()^{1/2} \frac{T^2}{M_{PL}}$
$\Rightarrow T \simeq 1\,\text{MeV}$

$$H \simeq \Gamma = G_F^2 T^5 = ()^{1/2} \frac{T^2}{M_{Pl}}$$

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iii) CHEMICAL EQUIL BETWEEN p & n:

$$p^+ + e^- \rightleftarrows n + \nu_e$$

$$H \simeq \Gamma = G_F^2 T^5 = ()^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Rightarrow T \simeq 1\,\text{MeV}$$

iii) CHEMICAL EQUIL BETWEEN p & n:

STOP... T

$$p^+ + e^- \rightleftarrows n + \nu_e$$

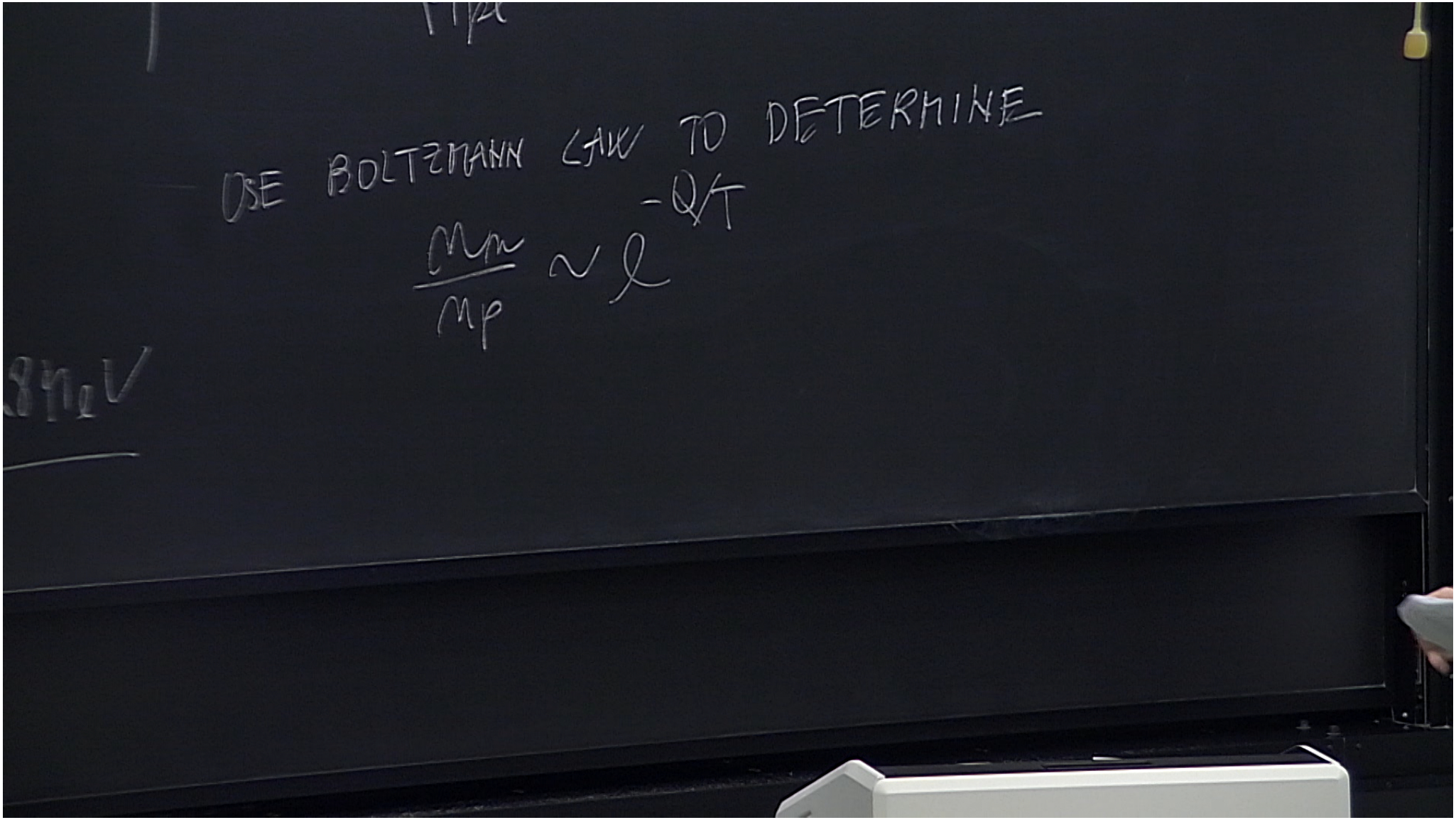
$$H \simeq \Gamma = G_F^2 T^5 = ()^{1/2} \frac{T^2}{M_{Pl}}$$

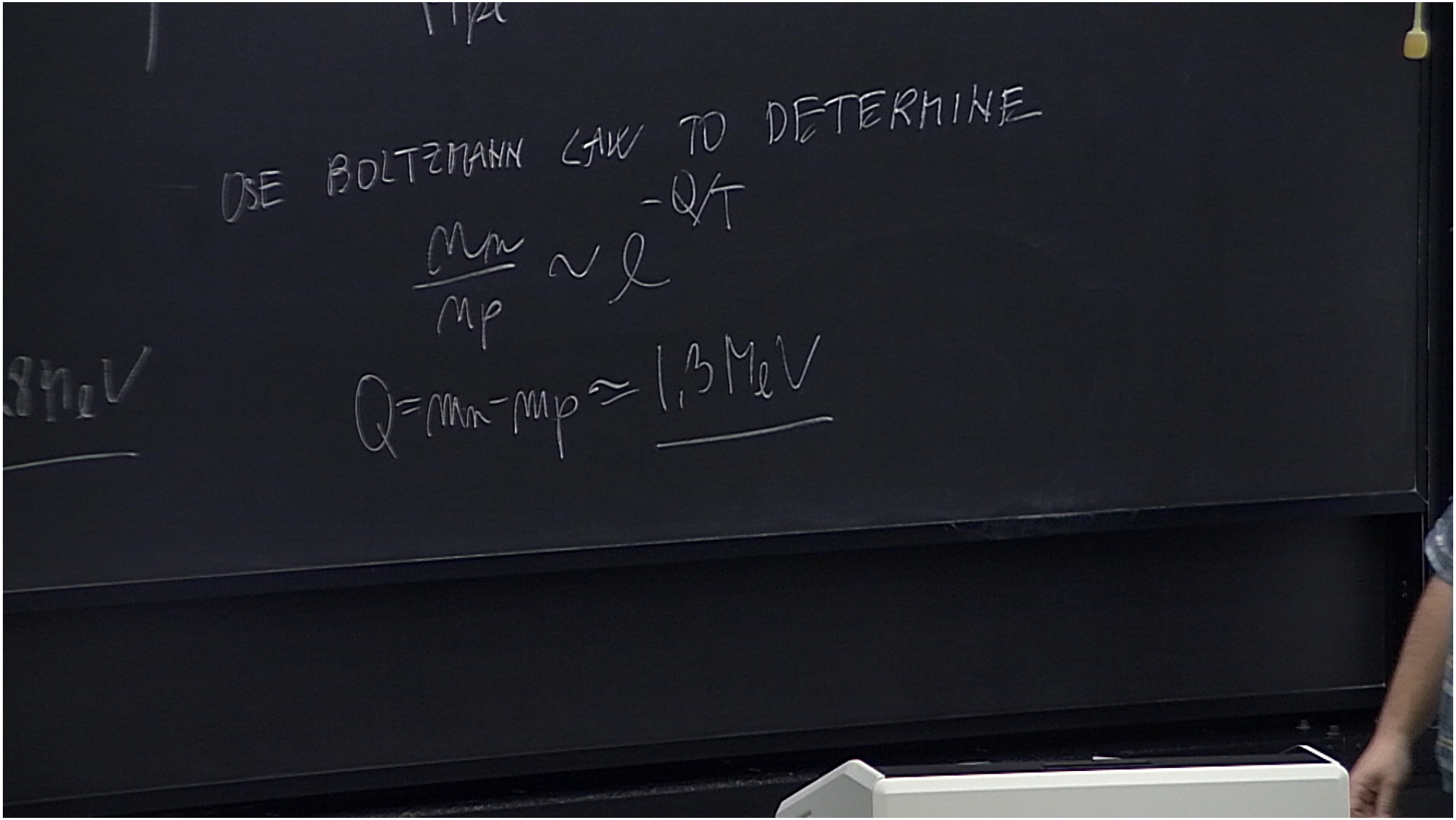
$$\Rightarrow T \simeq 1\,\text{MeV}$$

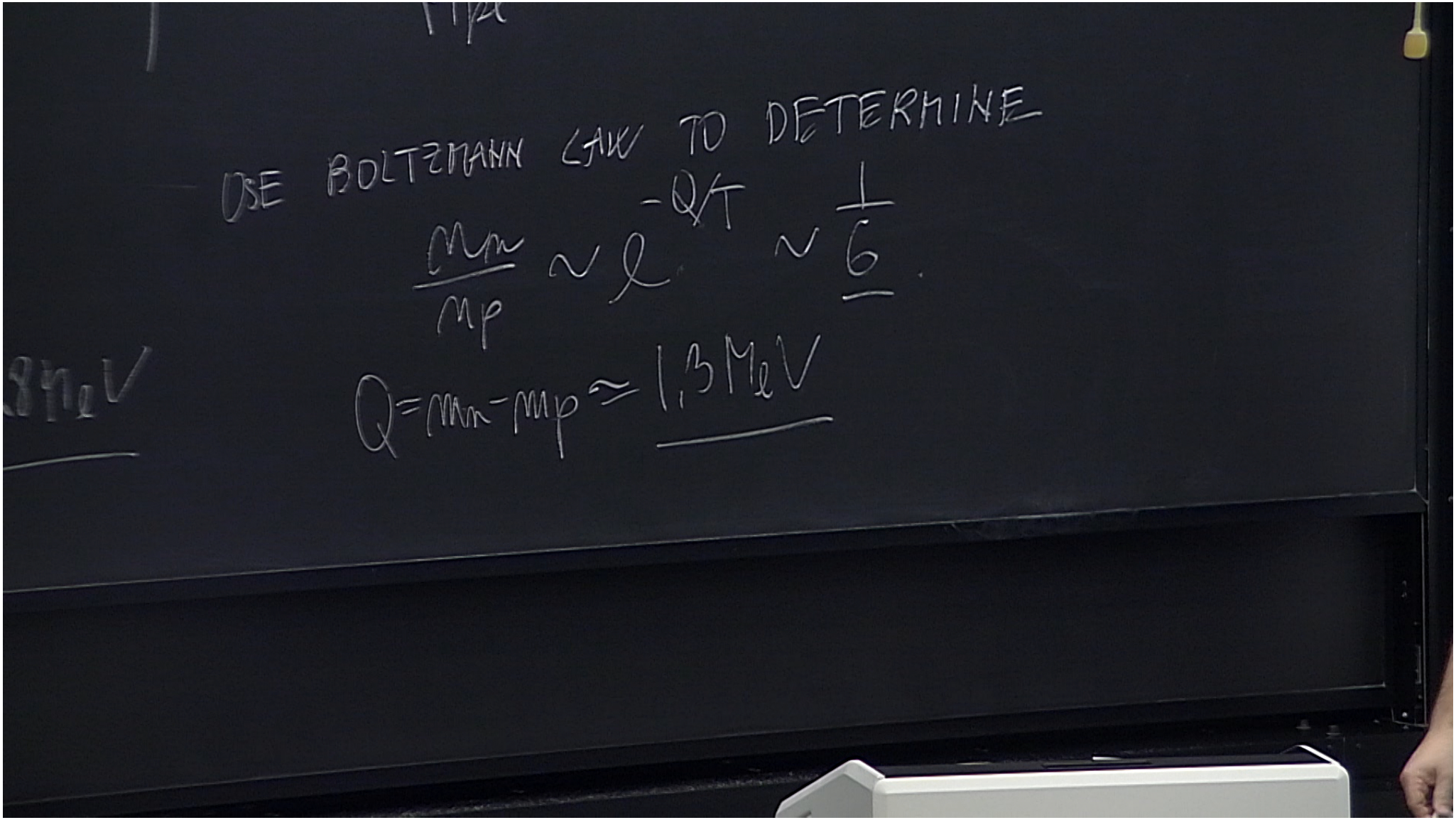
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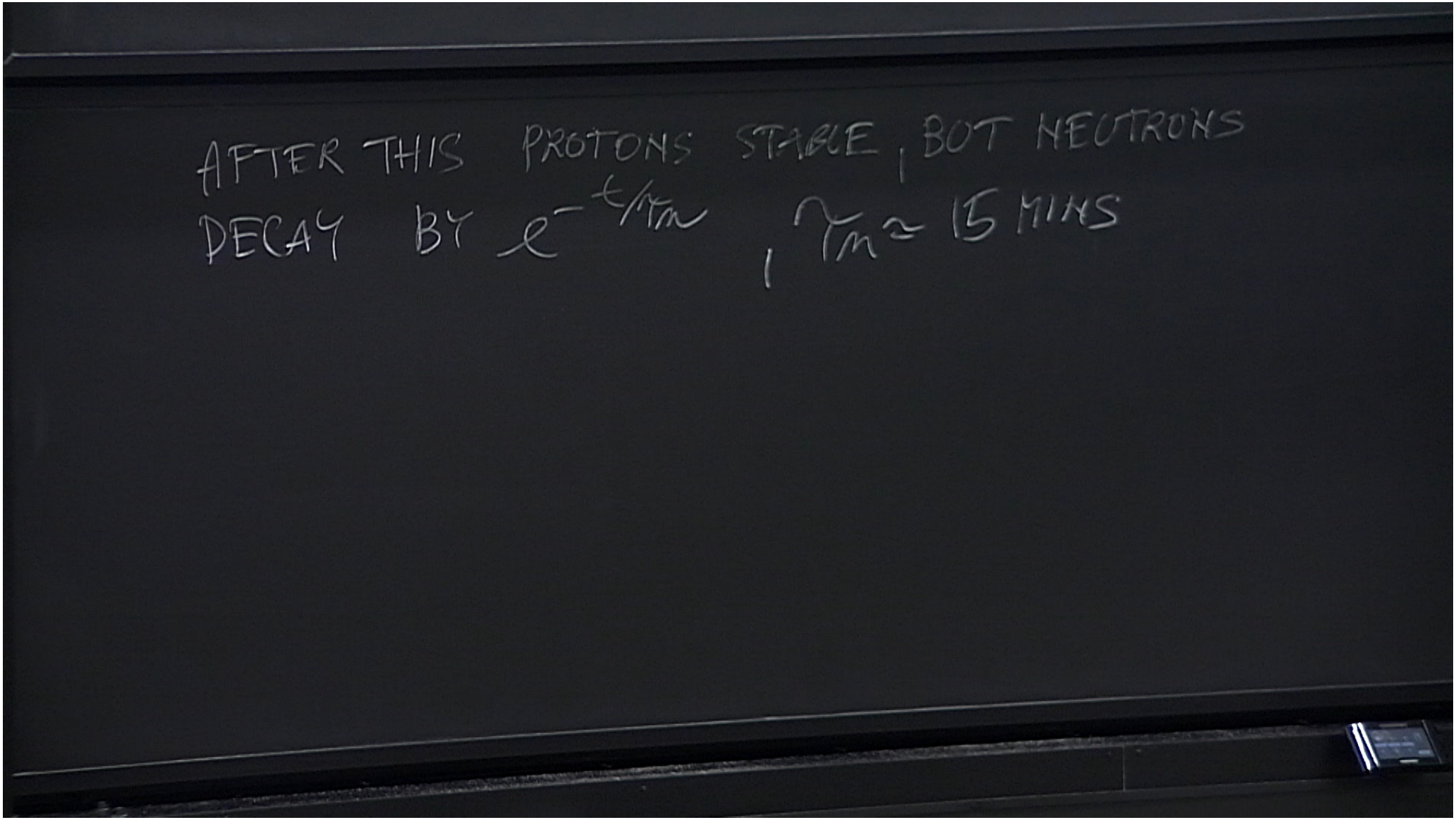
STOP... $T \simeq 0.8\,\text{MeV}$

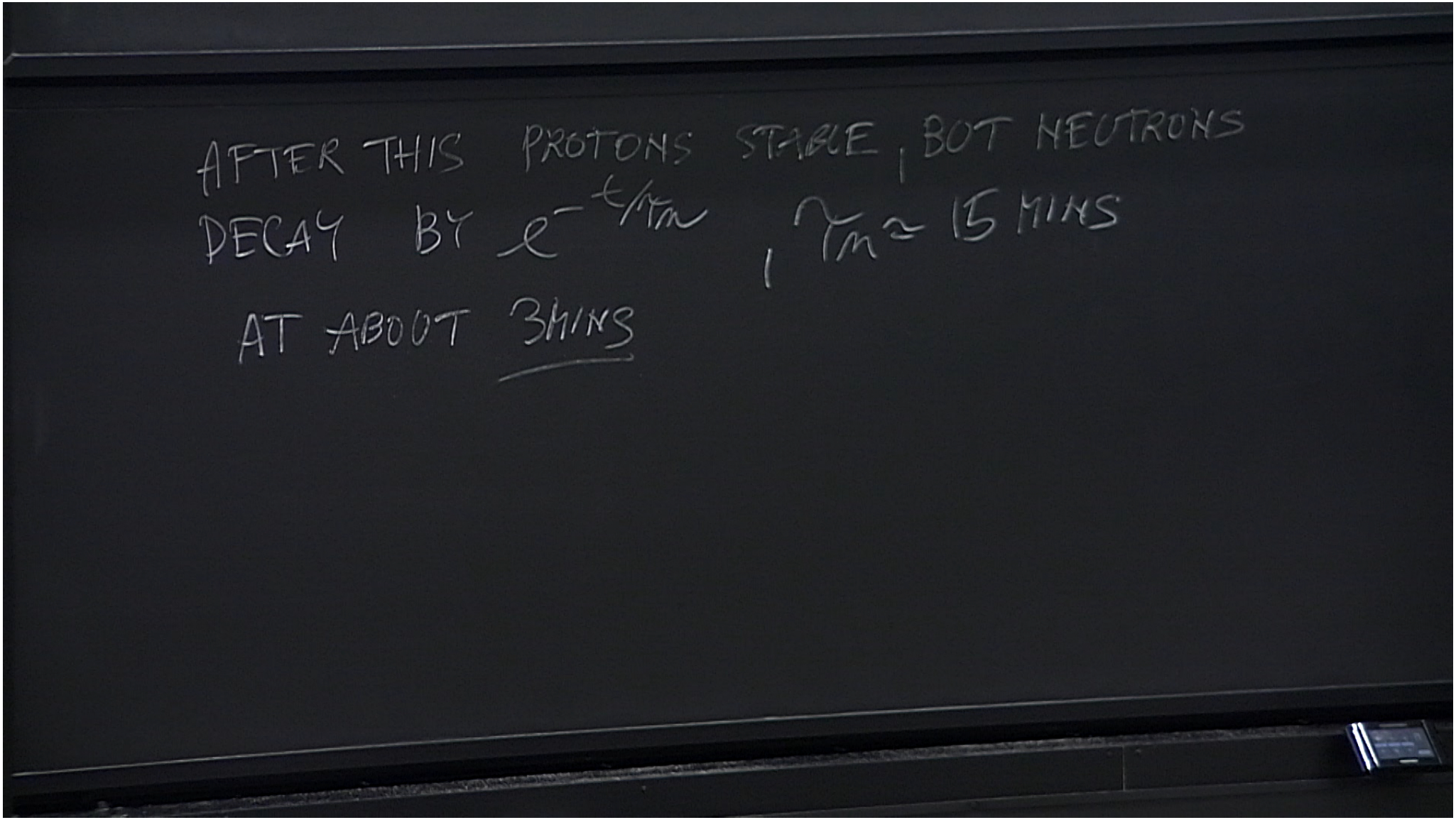
$$p^+ + e^- \rightleftarrows n + \nu_e$$


USE BOLTZMANN GAW TO DETERMINE
$\frac{n_m}{n_p} \sim e^{-Q/T}$


USE BOLTZMANN LAW TO DETERMINE
$\frac{n_n}{n_p} \sim e^{-Q/T}$
$Q = m_n - m_p \simeq 1{,}3\,MeV$

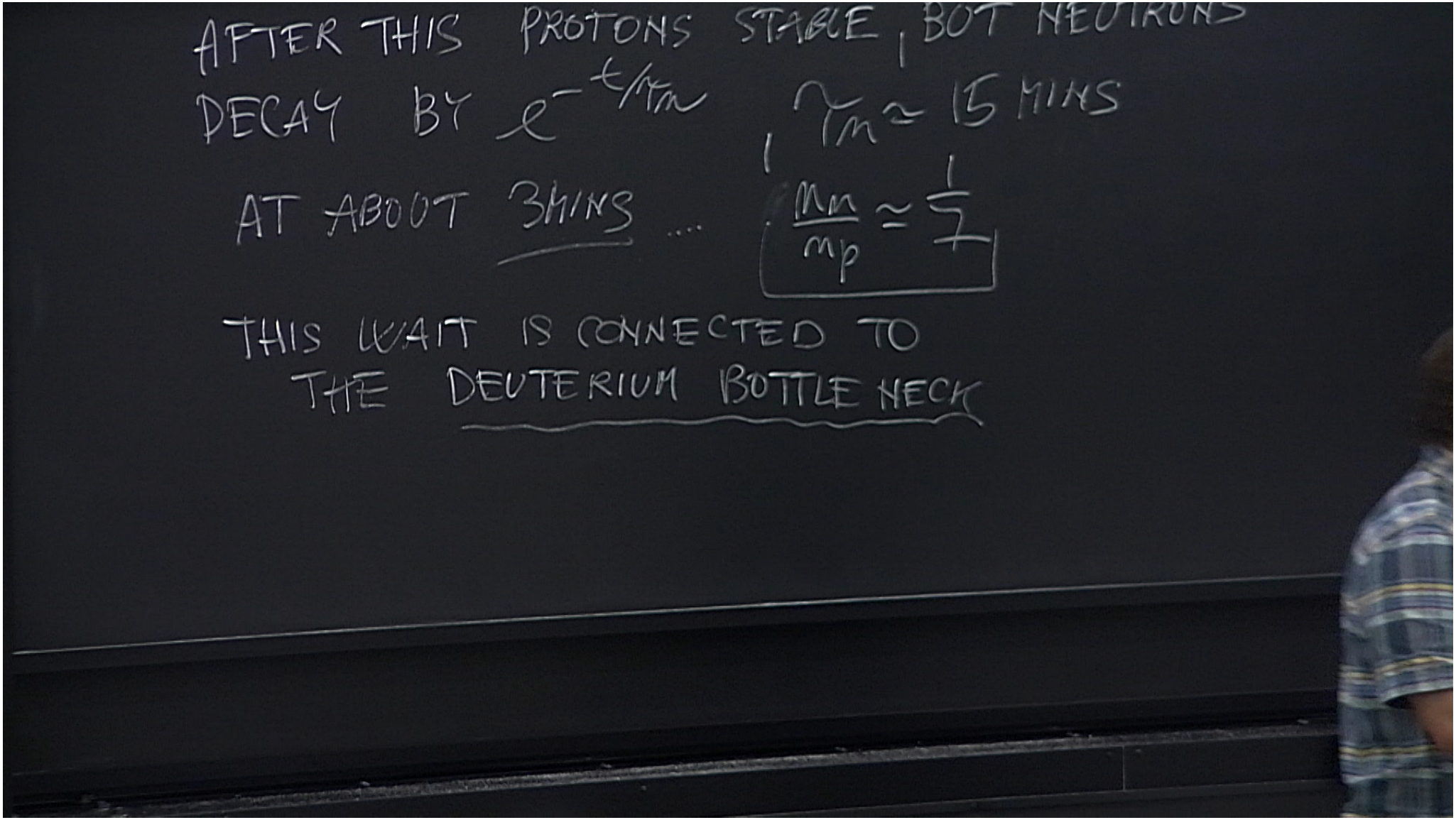

USE BOLTZMANN GAW TO DETERMINE
$\frac{n_n}{n_p} \sim e^{-Q/T} \sim \frac{1}{6}$
$Q = m_n - m_p \simeq 1{,}3\,\mathrm{MeV}$


AFTER THIS PROTONS STABLE, BOT NEUTRONS
DECAY BY e^{-t/τ_n}, $\tau_n \simeq 15$ MINS


AFTER THIS PROTONS STABLE, BOT NEUTRONS
DECAY BY e^{-t/τ_n}, $\tau_n \simeq 15$ MINS
AT ABOUT 3MINS

AFTER THIS PROTONS STABLE, BUT NEUTRONS DECAY BY e^{-t/τ_n}, $\tau_n \simeq 15$ MINS

AT ABOUT 3MINS ... $\frac{n_n}{n_p} \simeq \frac{1}{7}$


AFTER THIS PROTONS STABLE, BOT NEUTRONS
DECAY BY e^{-t/τ_n} , $\tau_n \simeq 15$ MINS
AT ABOUT 3MINS ... $\frac{n_n}{n_p} \simeq \frac{1}{7}$
THIS WAIT IS CONNECTED TO
THE DEUTERIUM BOTTLE NECK

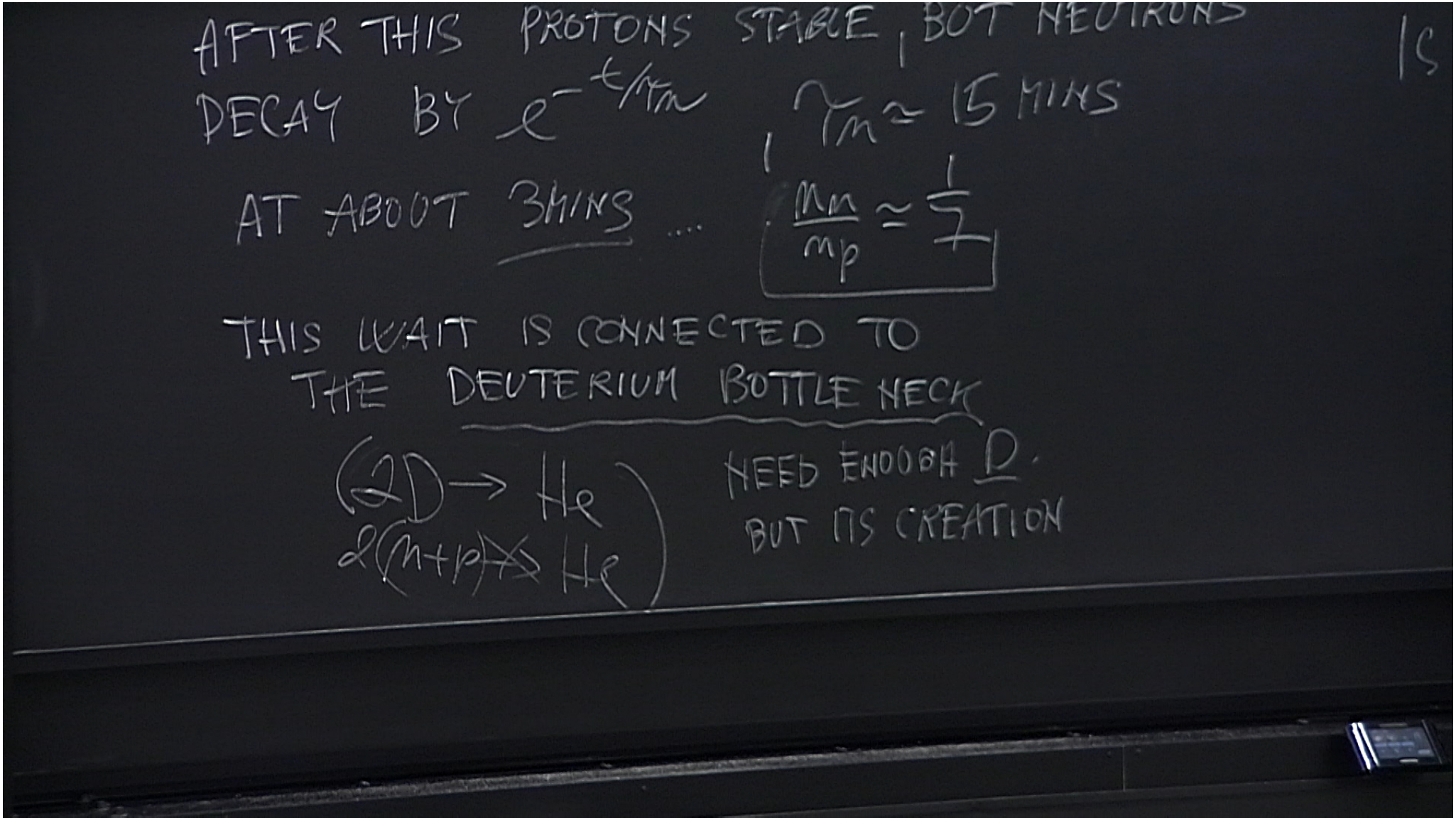
AFTER THIS PROTONS STABLE, BOT NEUTRONS DECAY BY e^{-t/τ_n}, $\tau_n \simeq 15$ MINS

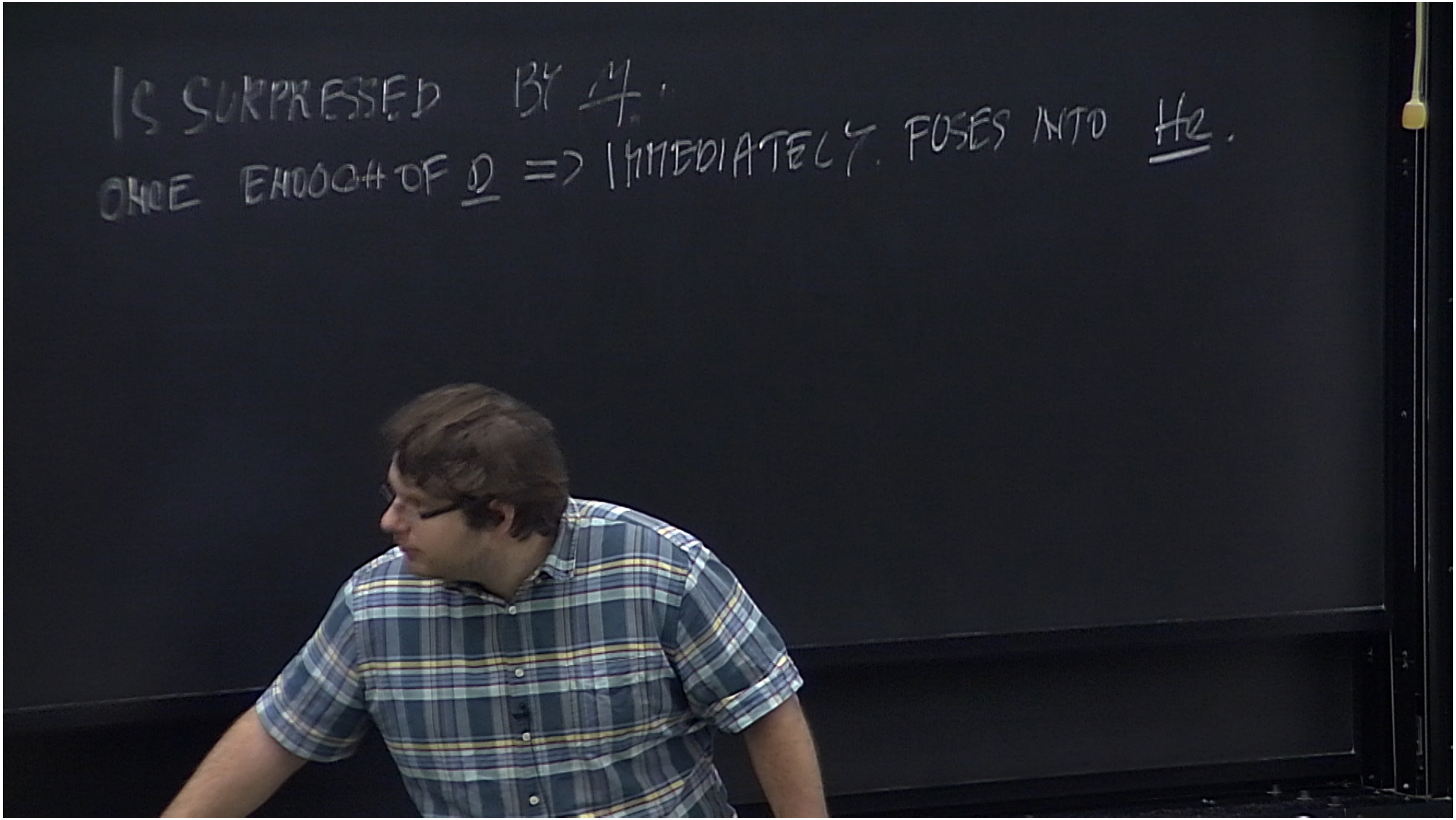
AT ABOUT 3MINS ... $\frac{n_n}{n_p} \simeq \frac{1}{7}$

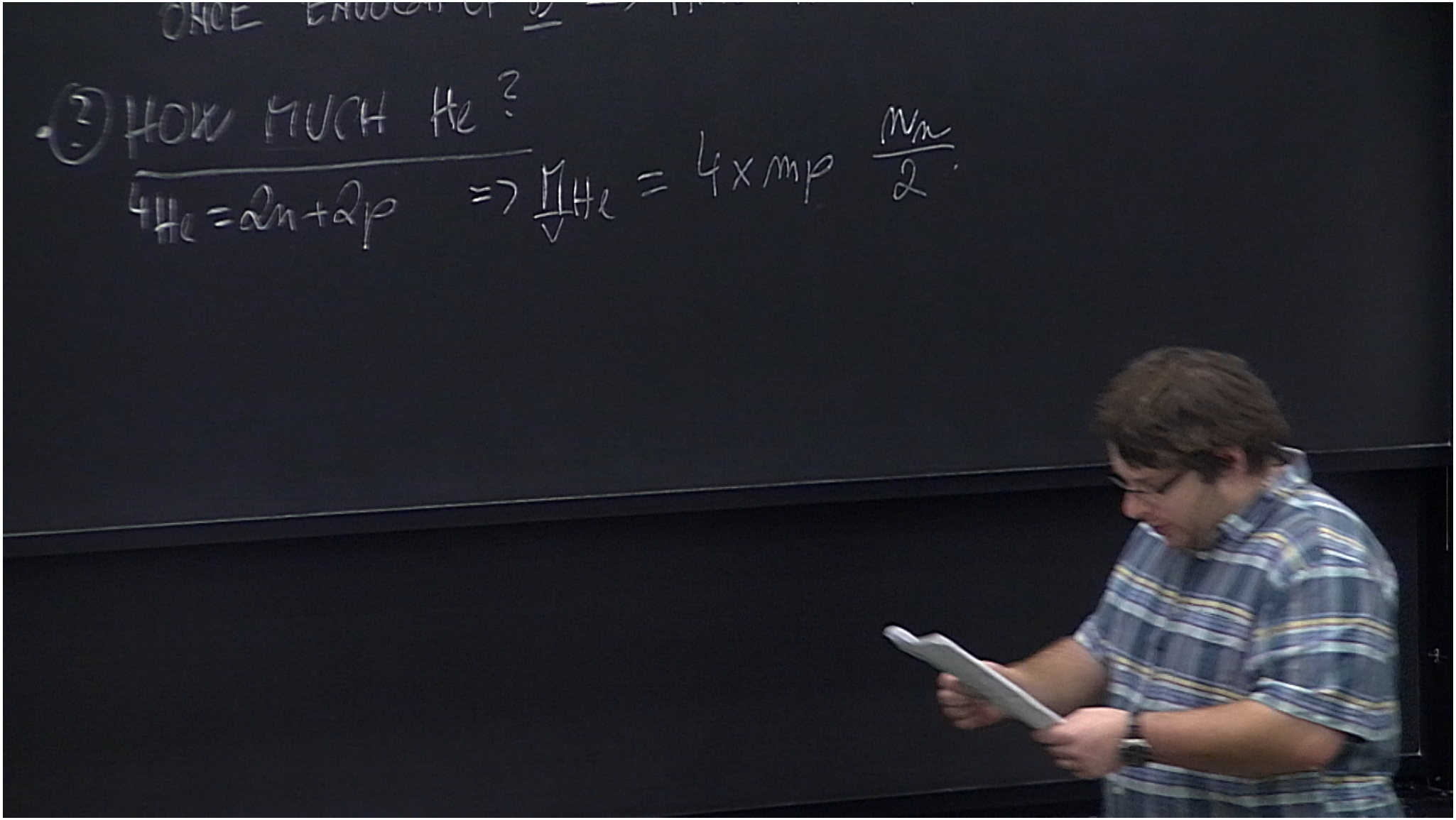
THIS WAIT IS CONNECTED TO THE DEUTERIUM BOTTLE NECK

$(^2D \rightarrow {}^4He$

$2(n+p) \not\rightarrow {}^4He)$


AFTER THIS PROTONS STABLE, BOT NEUTRONS
DECAY BY e^{-t/τ_n} , $\tau_n \approx 15$ MINS
AT ABOUT 3MINS ... $\frac{n_n}{n_p} \approx \frac{1}{7}$
THIS WAIT IS CONNECTED TO
THE DEUTERIUM BOTTLE NECK
$2D \rightarrow He$
$2(n+p) \rightarrow He$
NEED ENOUGH D.
BUT ITS CREATION

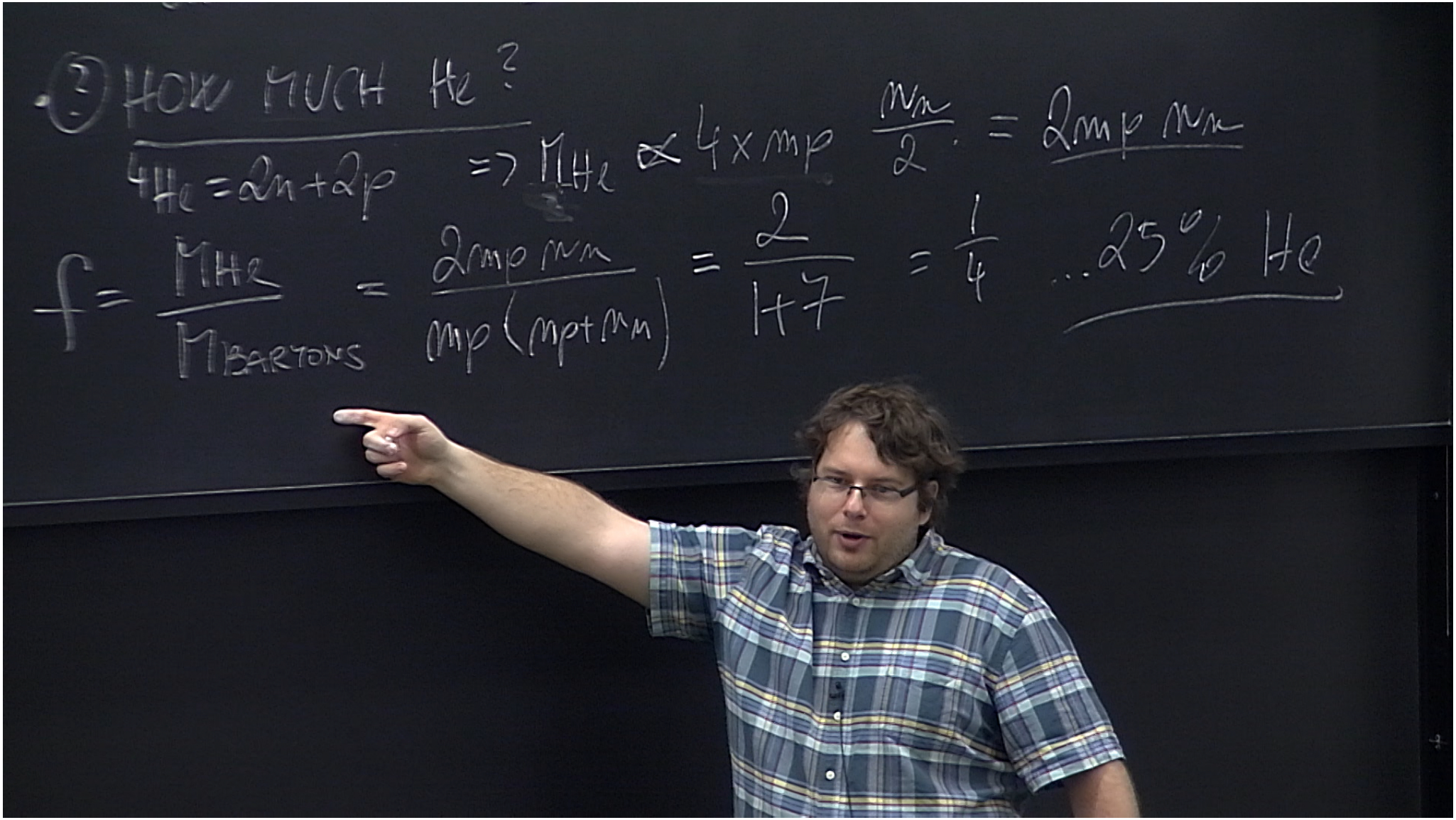

IS SUPPRESSED BY 4.
ONCE ENOUGH OF D => IMMEDIATELY FUSES INTO He.

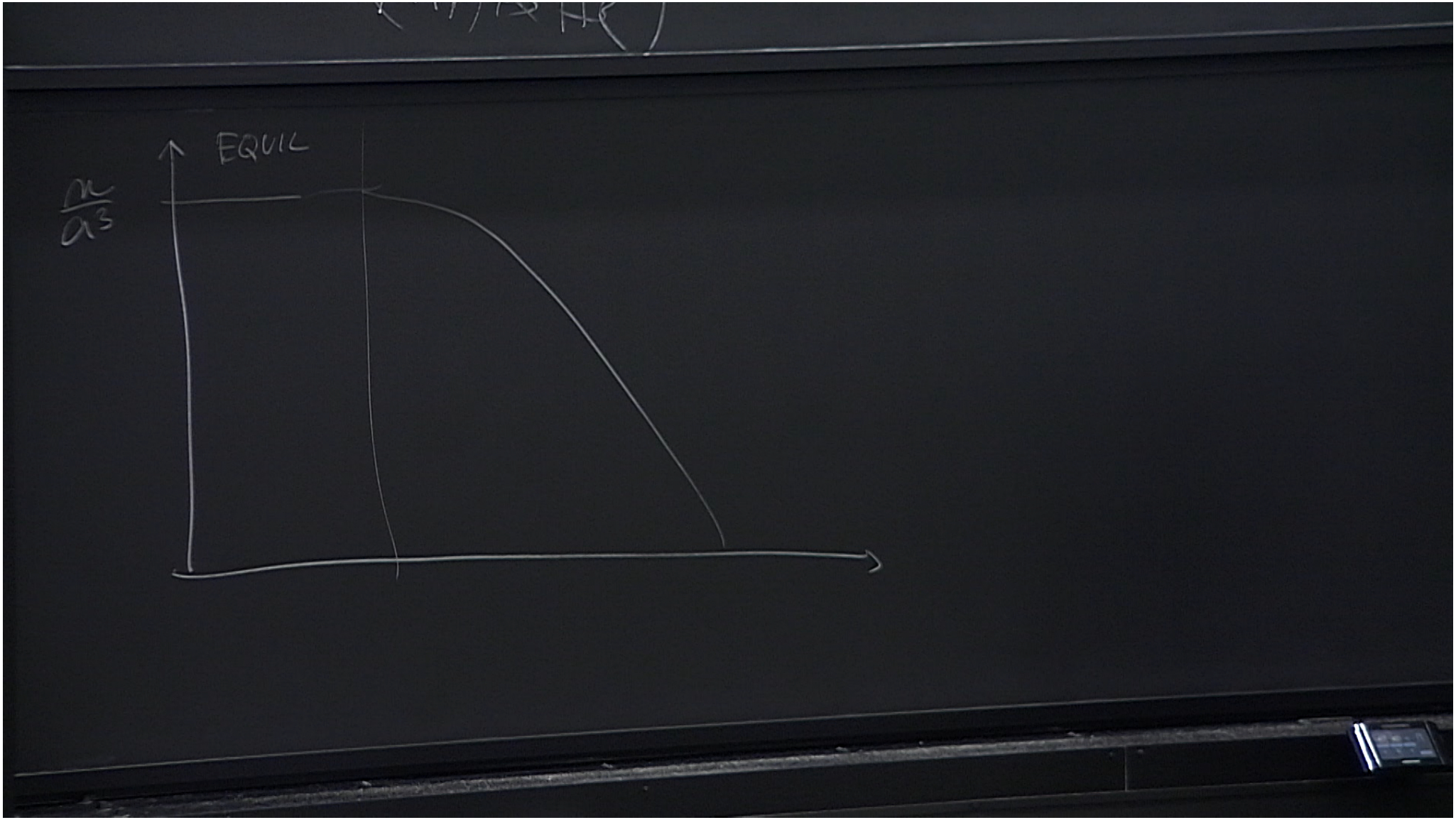

ONCE
(3) HOW MUCH He?
$m_{He} = 2n + 2p$ => $\overline{m}_{He} = 4 \times m_p \frac{m_n}{2}$.

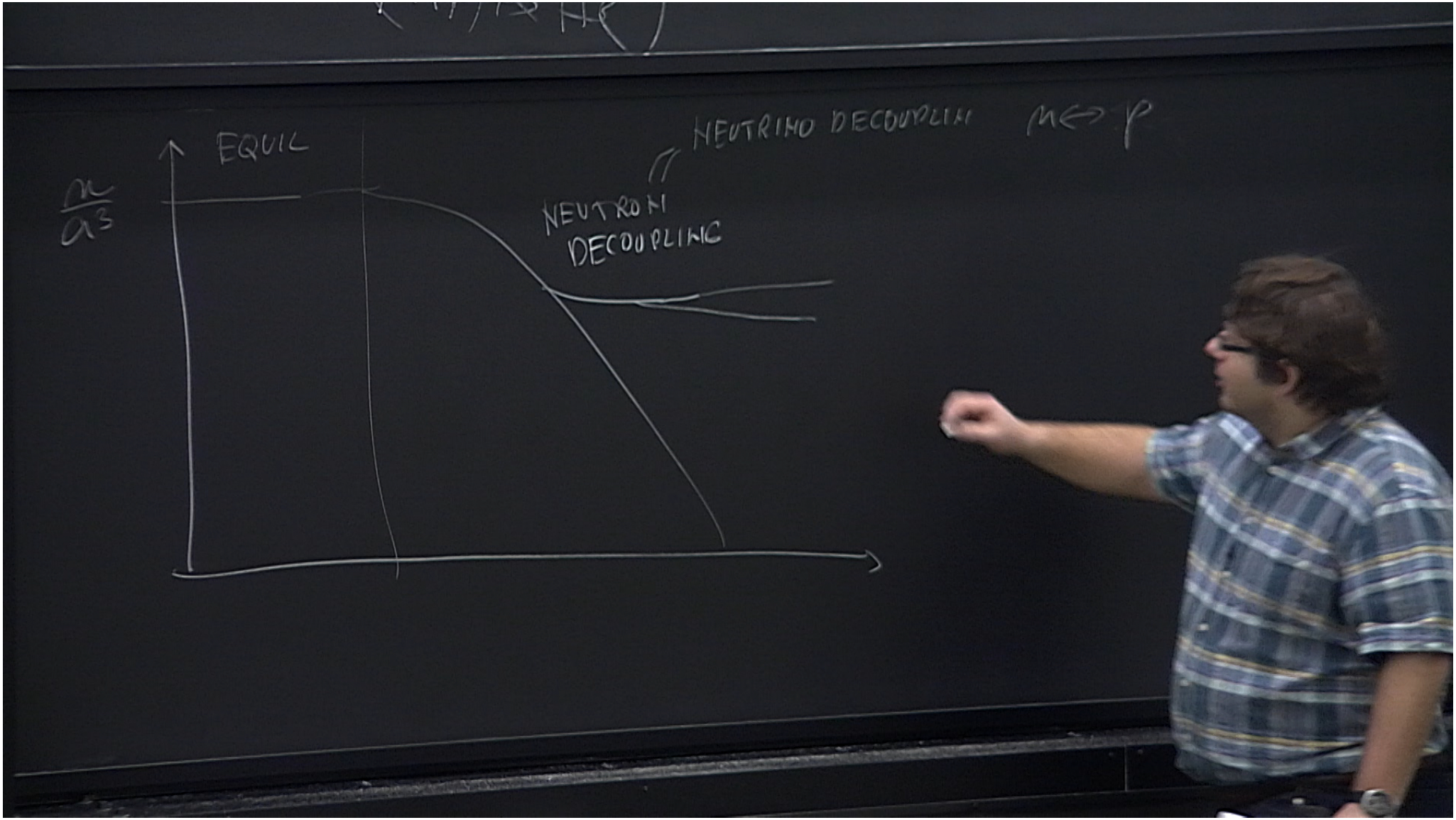
③ HOW MUCH He?

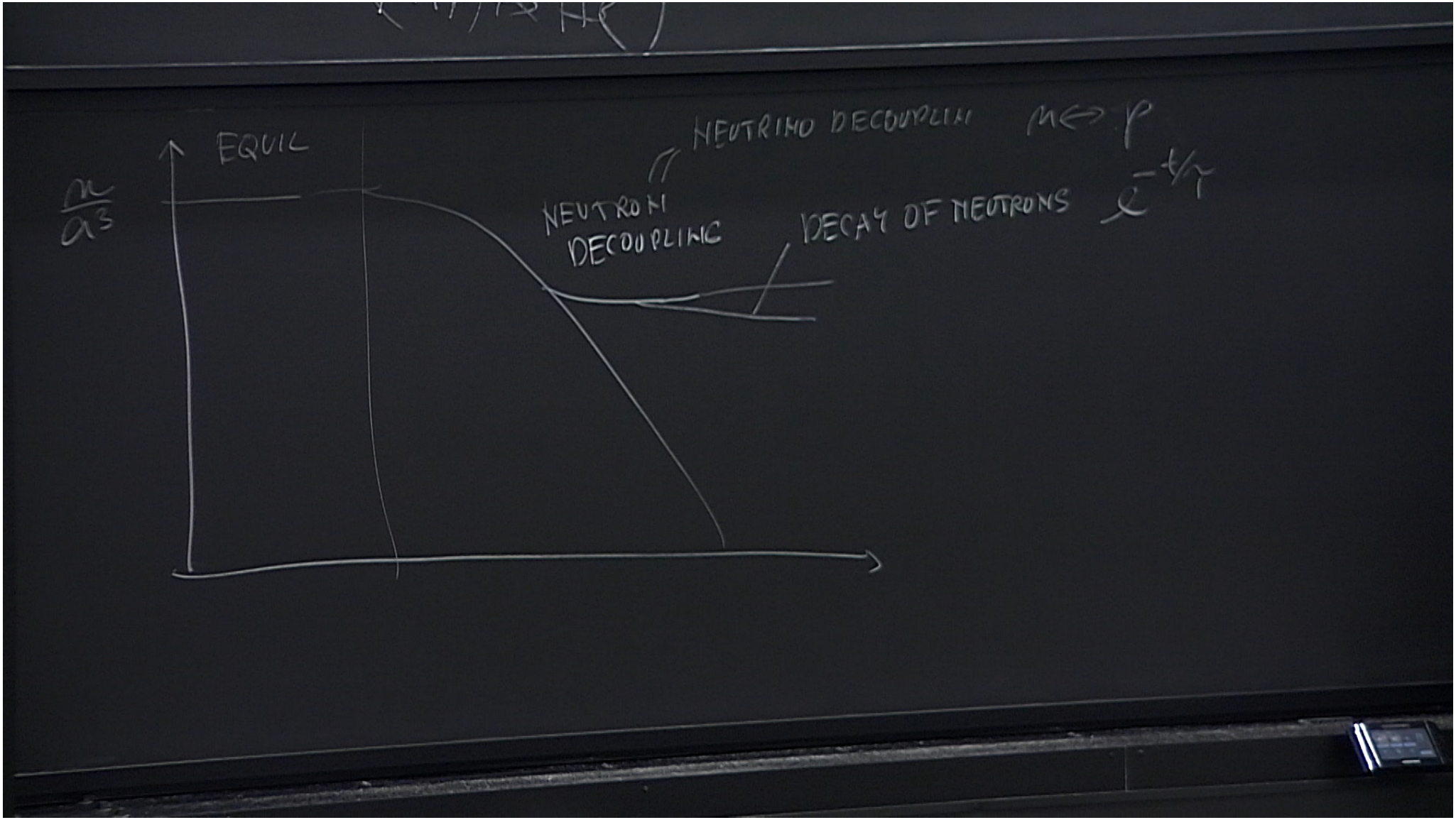
$^4He = 2n + 2p \Rightarrow M_{He} = 4 \times m_p \frac{n_n}{2} = 2 m_p n_n$

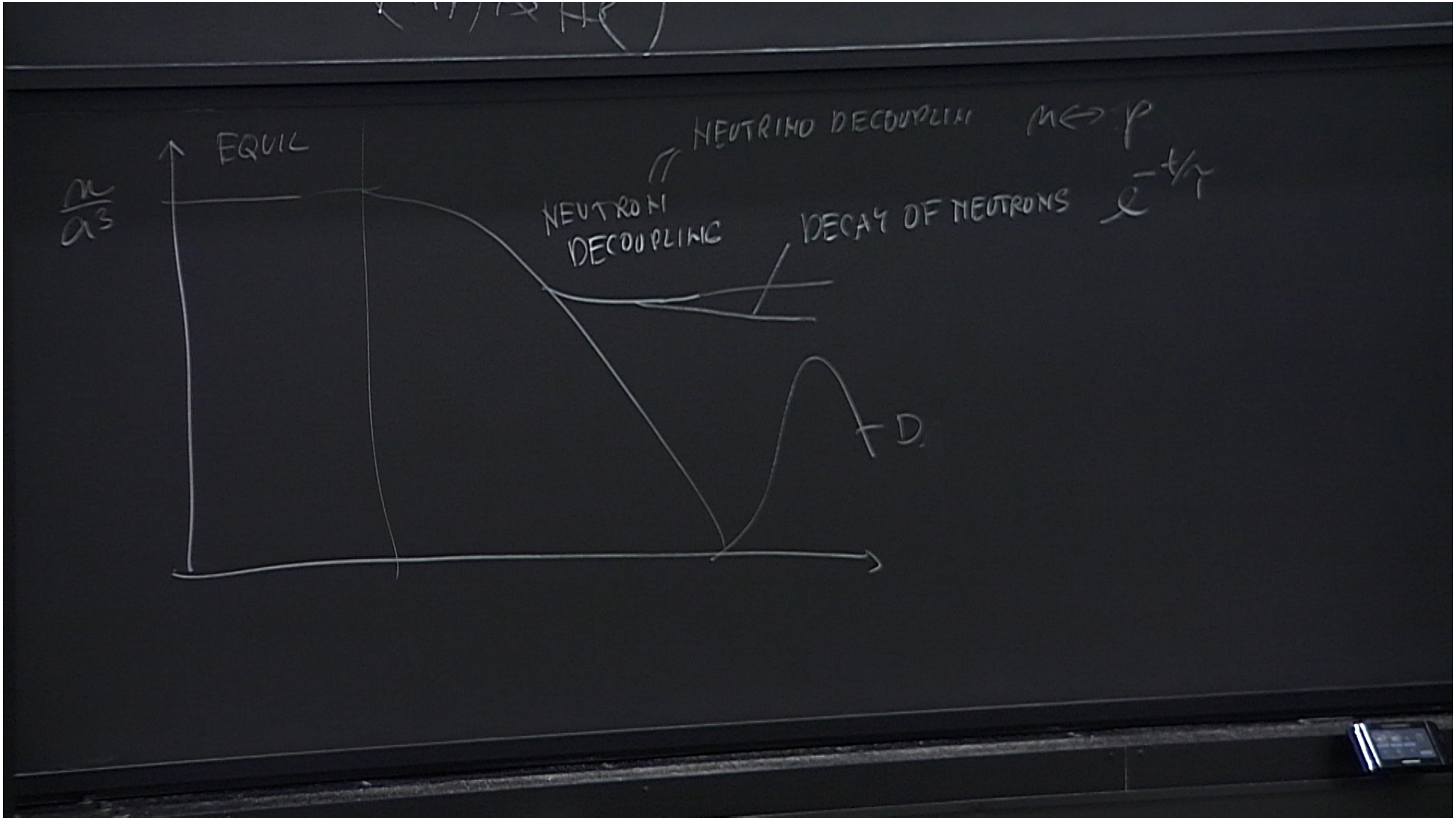
$f = \frac{M_{He}}{M_{BARYONS}} = \frac{2 m_p n_n}{m_p (n_p + n_n)} = \frac{2}{1+7} = \frac{1}{4}$ ...25% He

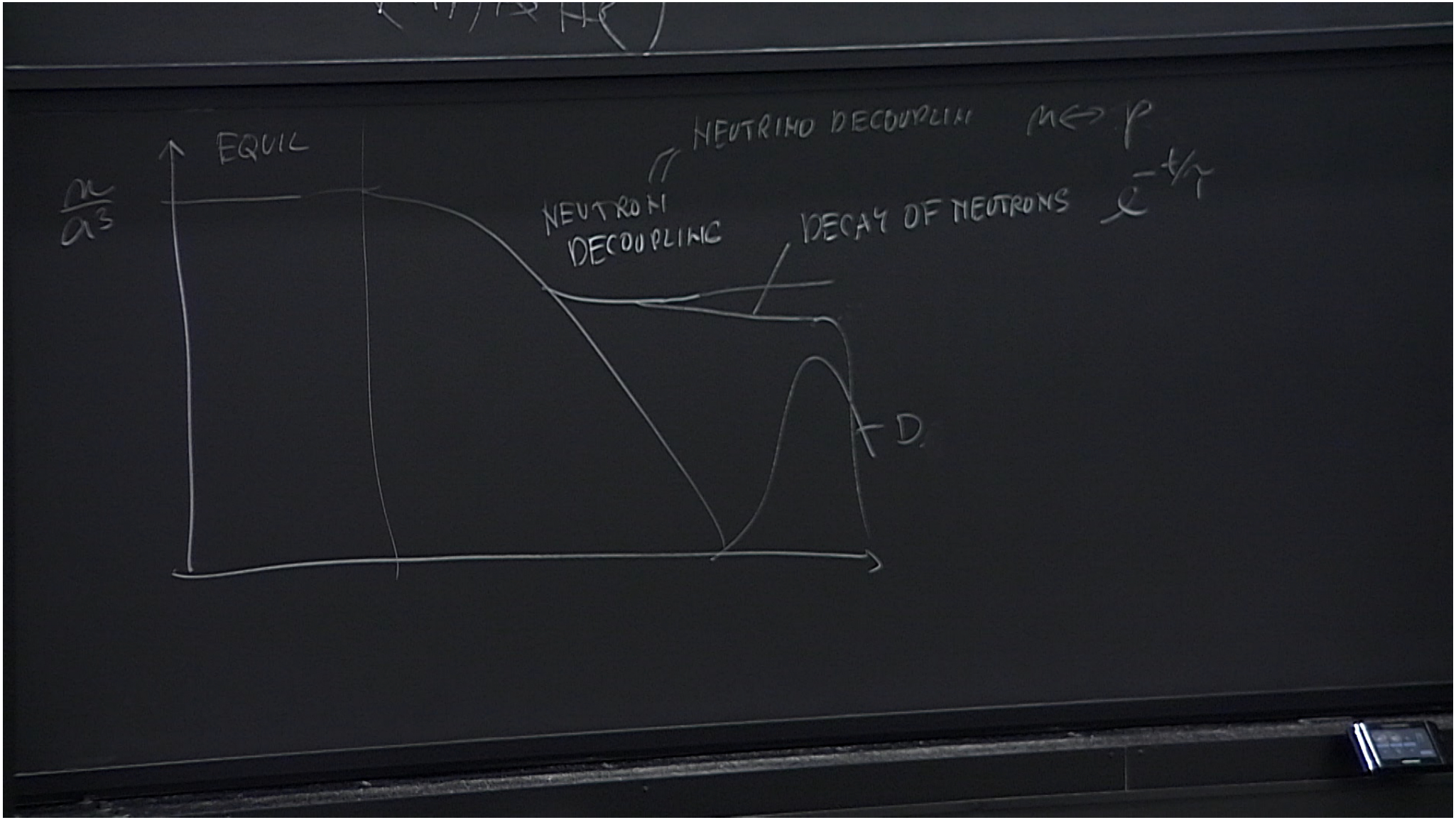

3 HOW MUCH He?
4He = 2n + 2p
=> MHe ≈ 4 x mp
nn/2 = 2 mp nn
f = MHe / MBARYONS = 2 mp nn / mp (mp + nn) = 2/17 = 1/4 ...25% He

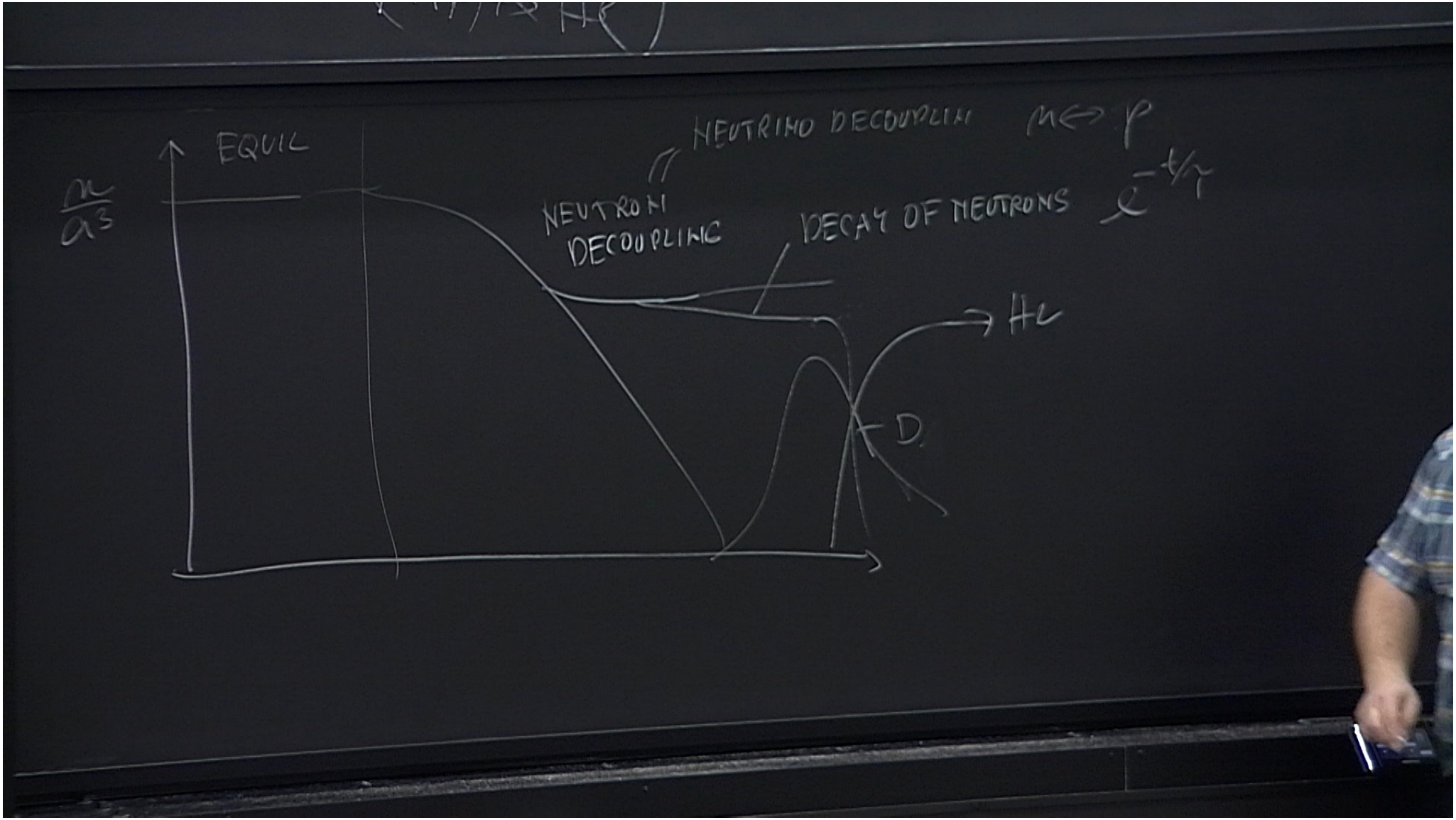

EQUIL

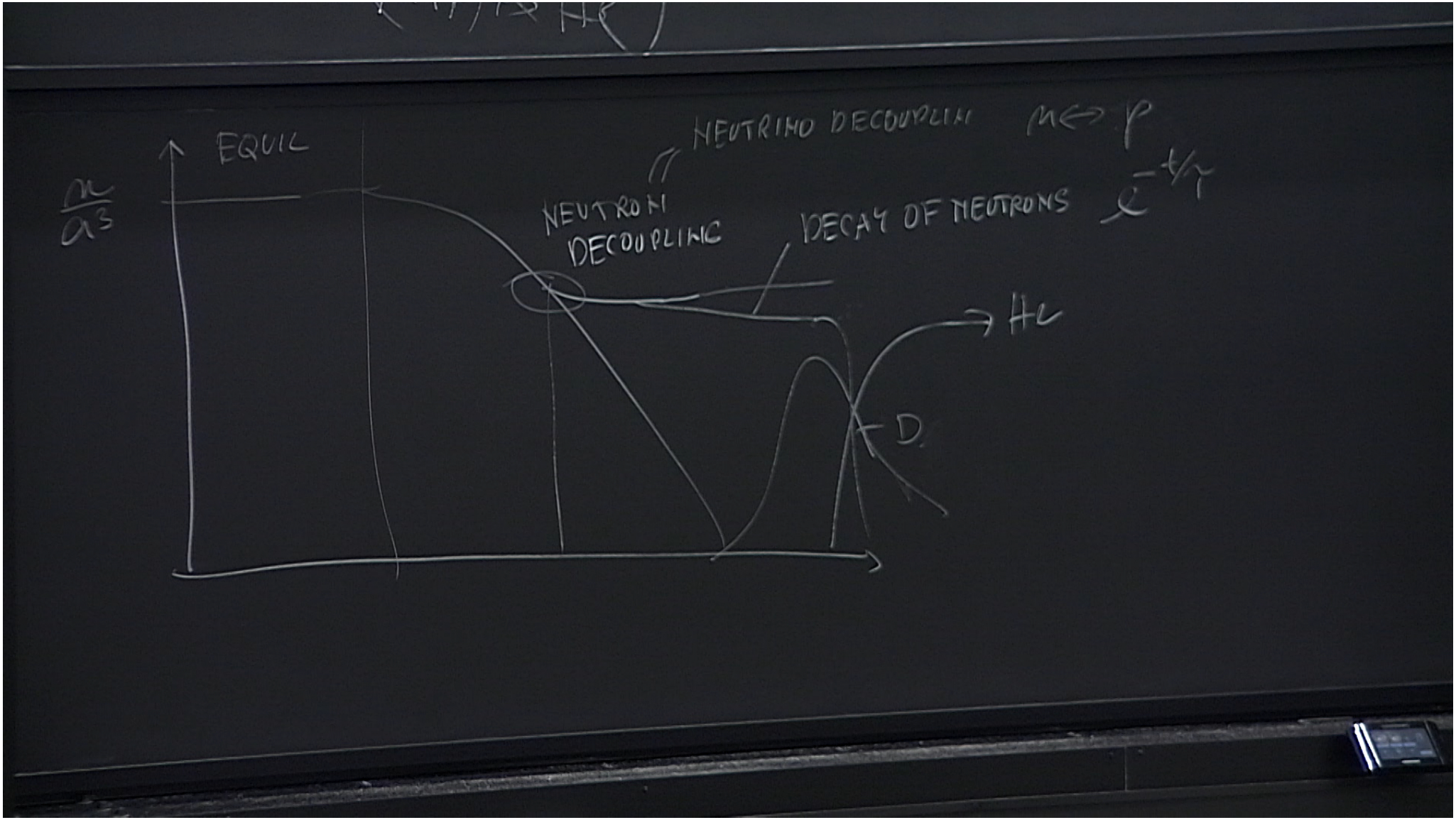

EQUIL
NEUTRINO DECOUPLING
NEUTRON
DECOUPLING

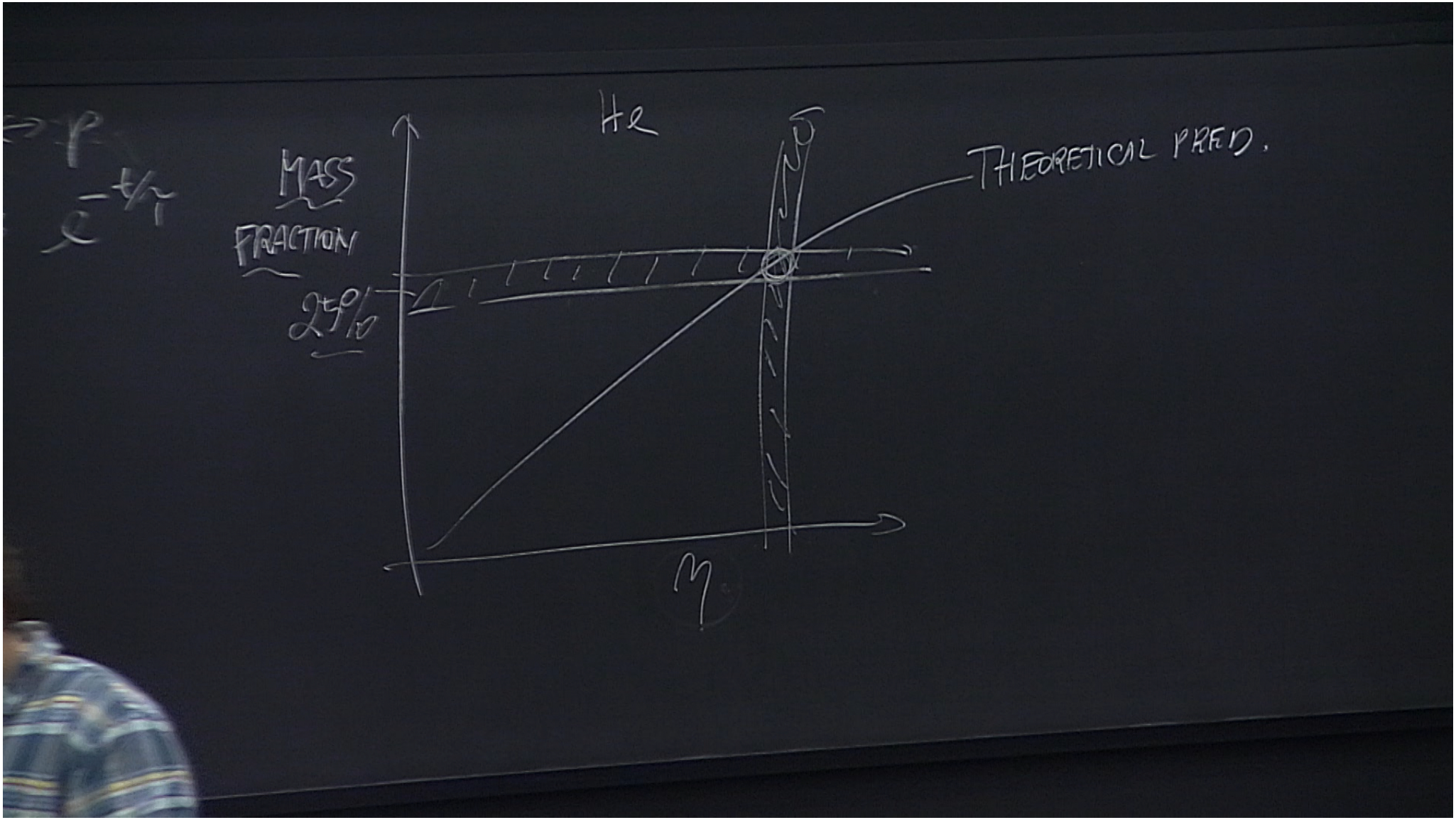

EQUIL
NEUTRINO DECOUPLING
NEUTRON DECOUPLING
DECAY OF NEUTRONS

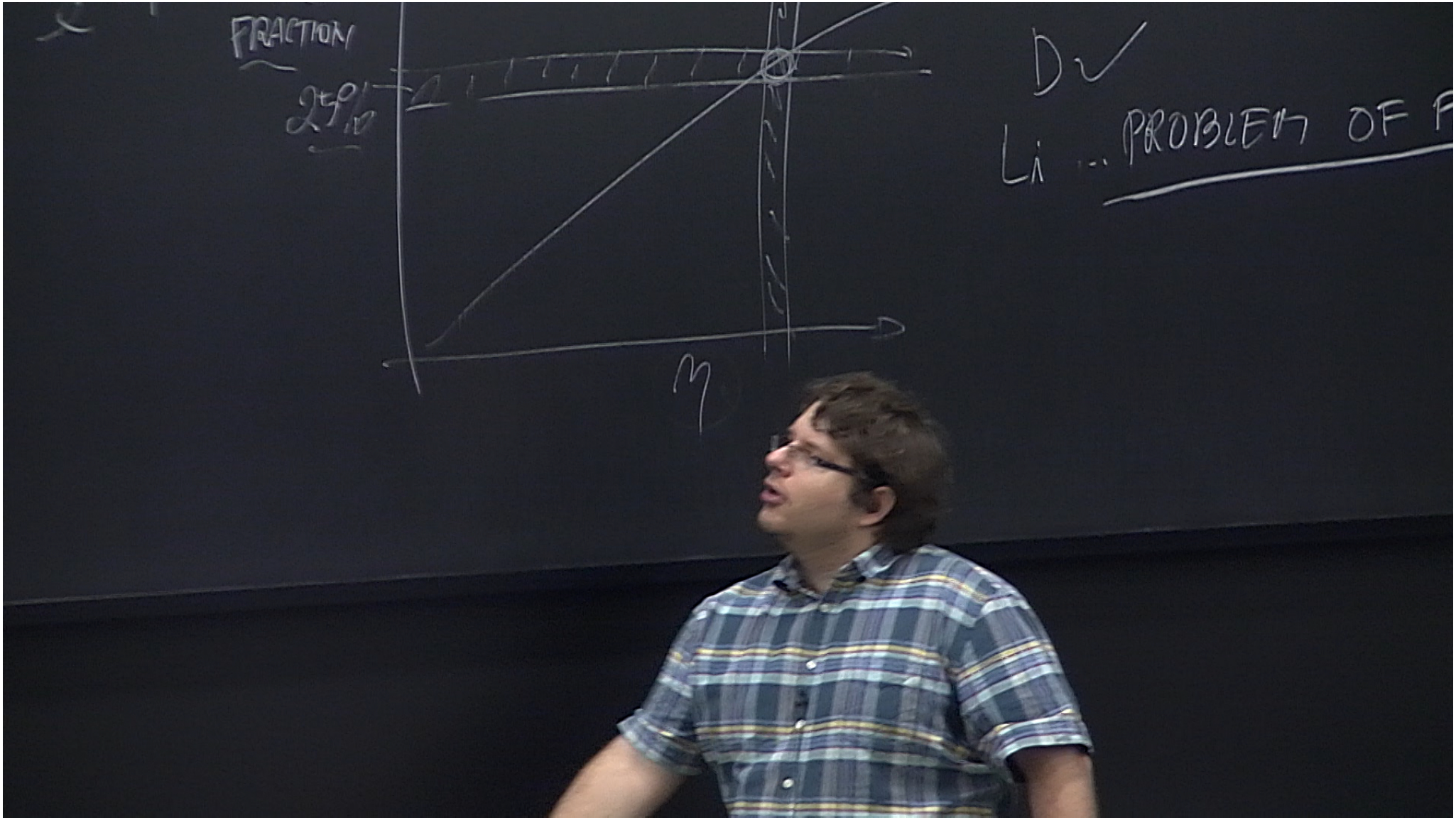

EQUIL
NEUTRINO DECOUPLING
NEUTRON DECOUPLING
DECAY OF NEUTRONS
+D.


EQUIL
NEUTRINO DECOUPLING
NEUTRON DECOUPLING
DECAY OF NEUTRONS
D


EQUIL
NEUTRINO DECOUPLING
NEUTRON DECOUPLING
DECAY OF NEUTRONS
D


EQUIL
NEUTRINO DECOUPLING
NEUTRON DECOUPLING
DECAY OF NEUTRONS
D


MASS
FRACTION
25%
He
M
THEORETICAL PRED.


FRACTION
25%
M
D✓
Li ... PROBLEM OF F

BBN CONSTRAINTS FUNDAMENTAL PHYSICS

THE FINAL FRACTION f DEPENDS ON

g_* (PARTICLE CONTENT), τ_n,

$Q = m_n - m_p$, η, G_N, ζ_F