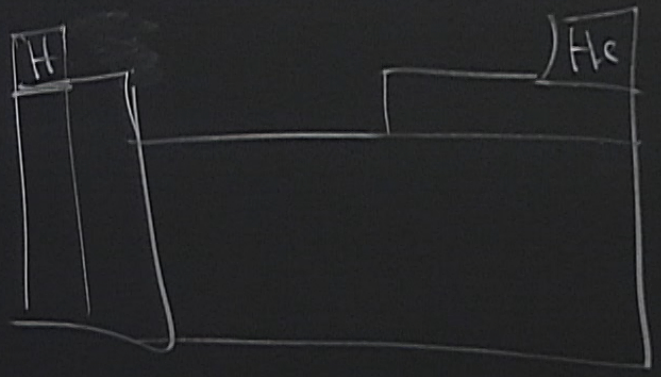
Title: PSI 17/18 - Cosmology - Lecture 6

Date: Feb 05, 2018 09:00 AM

URL: http://pirsa.org/18020015

Abstract:

c) BIG BANG NUCLEOSYNTHESIS (BBN)

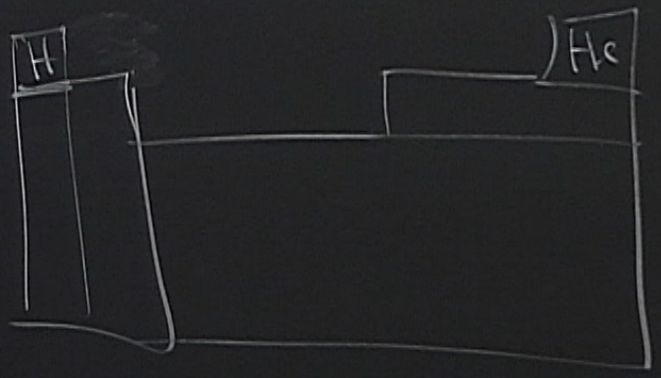


75% H

25% He

(BY MASS, NUMBER OF BARYONS)

C) BIG BANG NUCLEOSYNTHESIS (BBN)

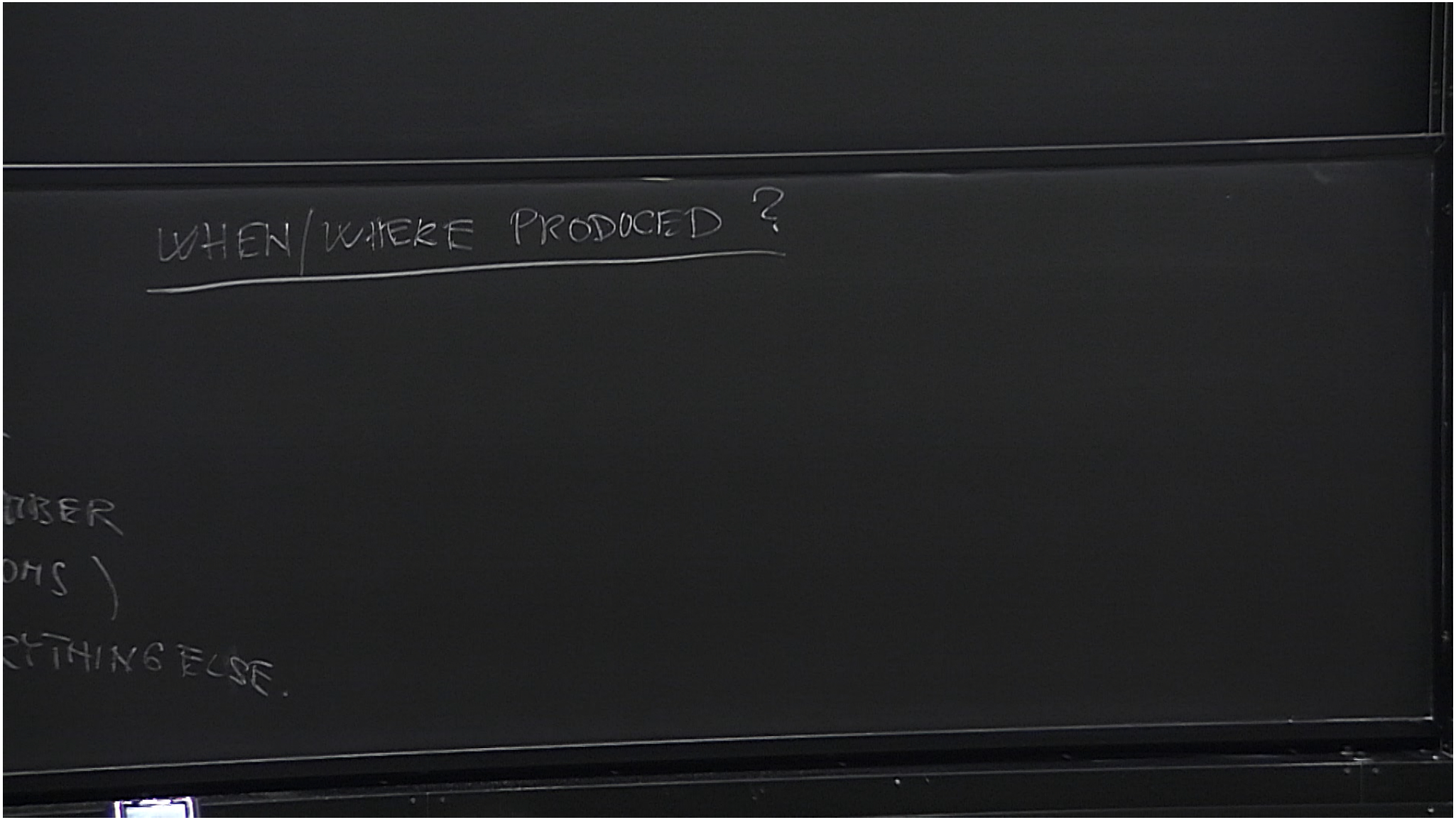


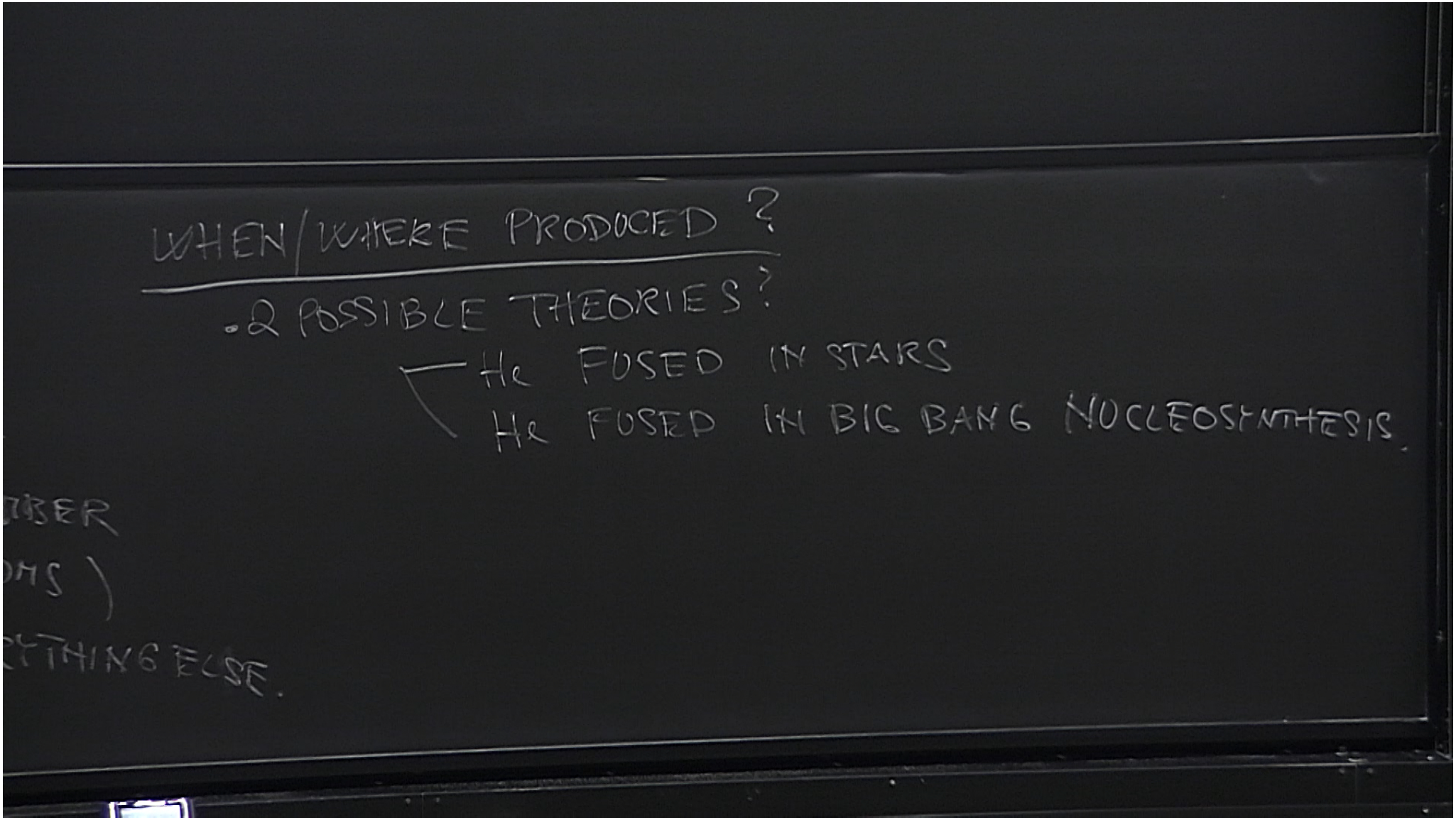
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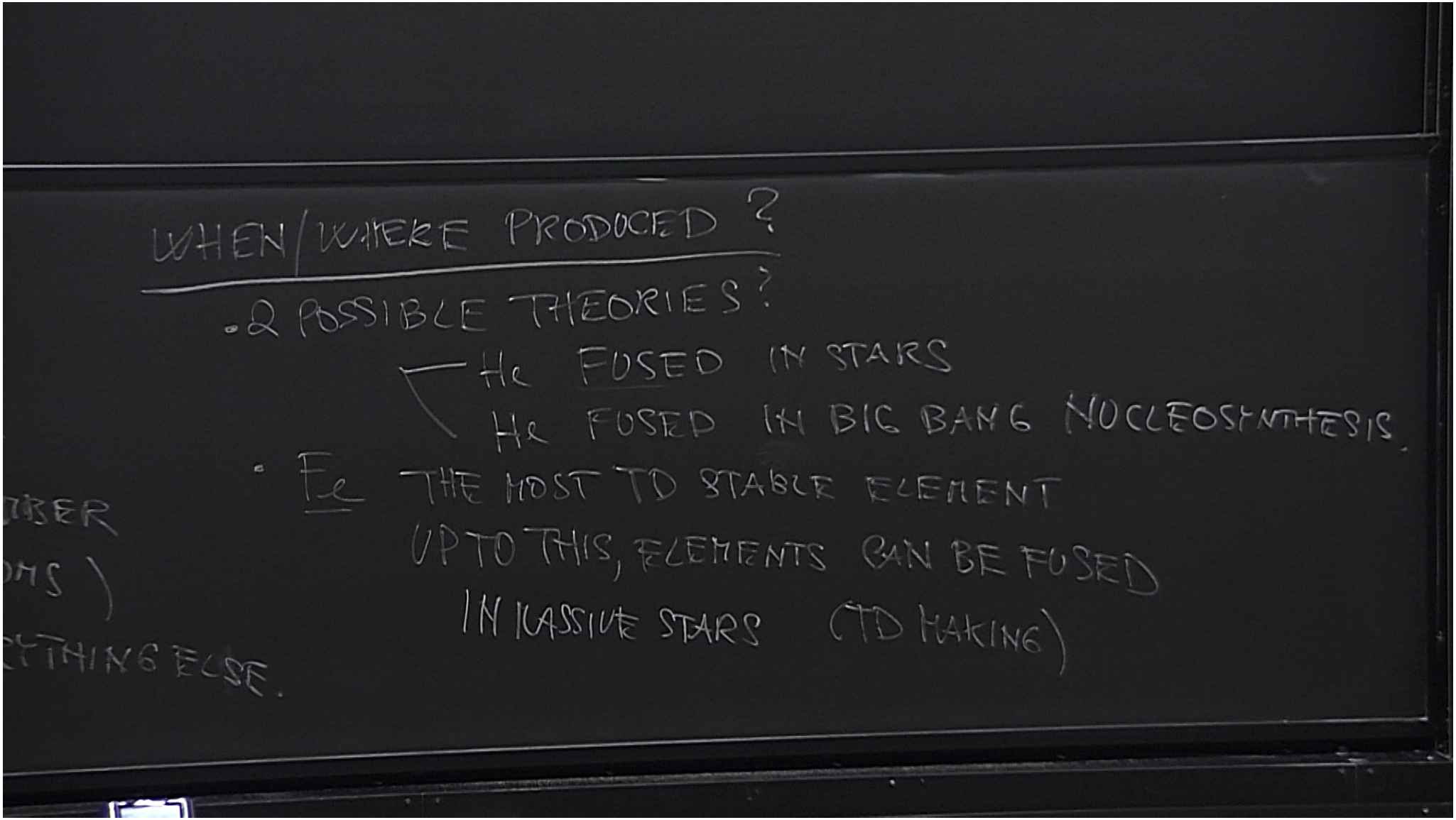
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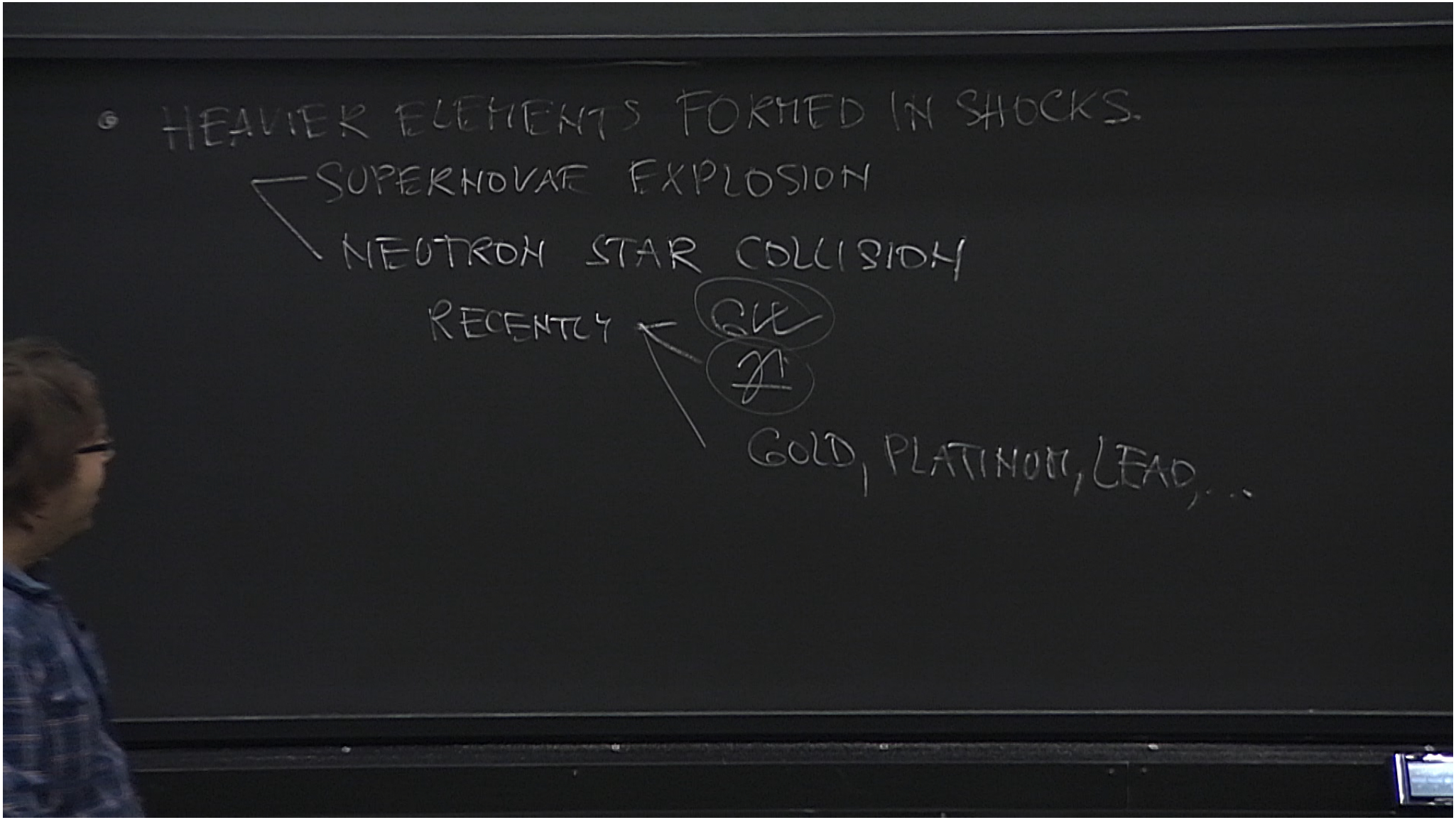
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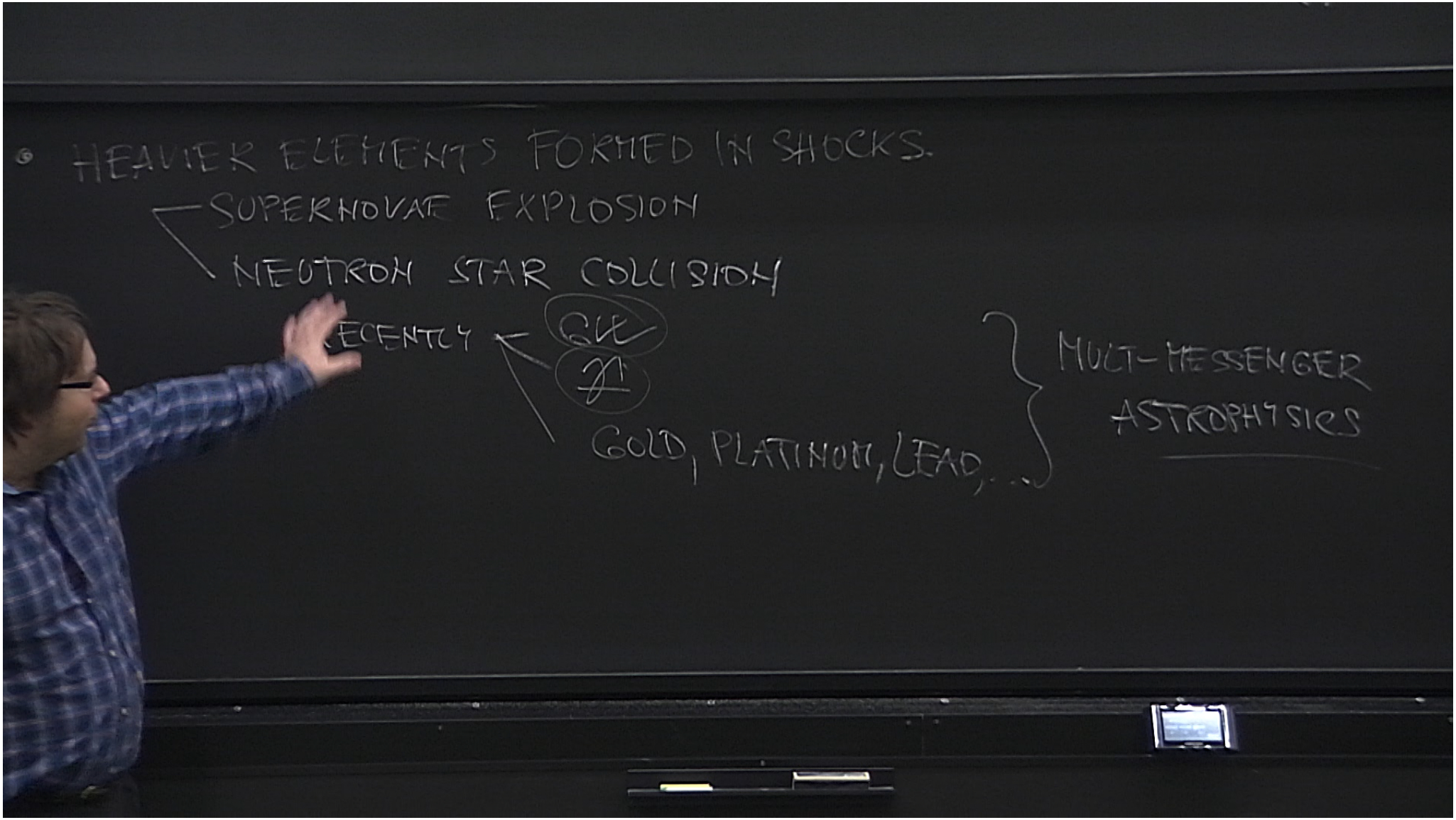
0% EVERYTHING ELSE.

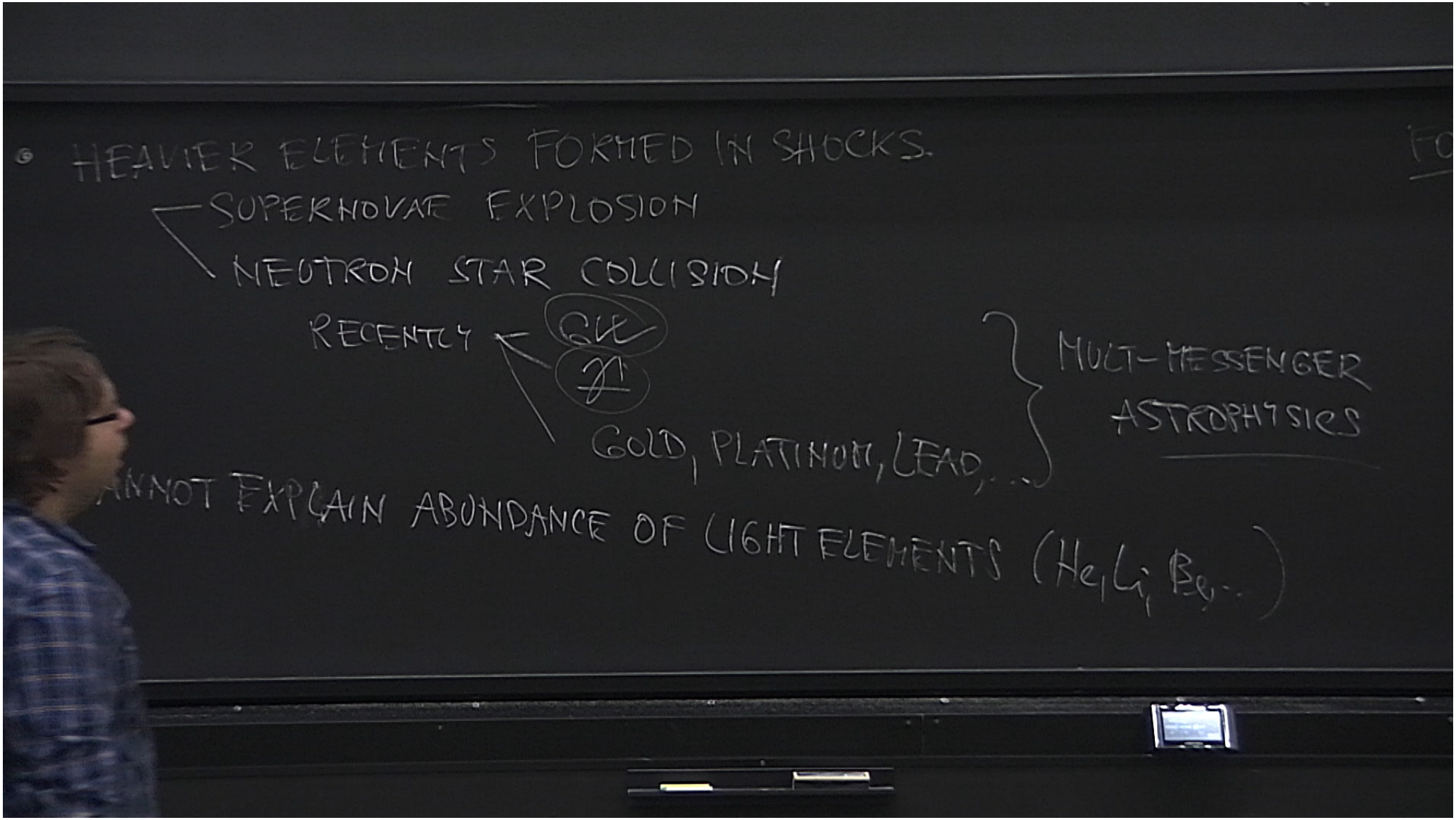

WHEN/WHERE PRODUCED ?
IBER
OMS)
RYTHING ELSE.

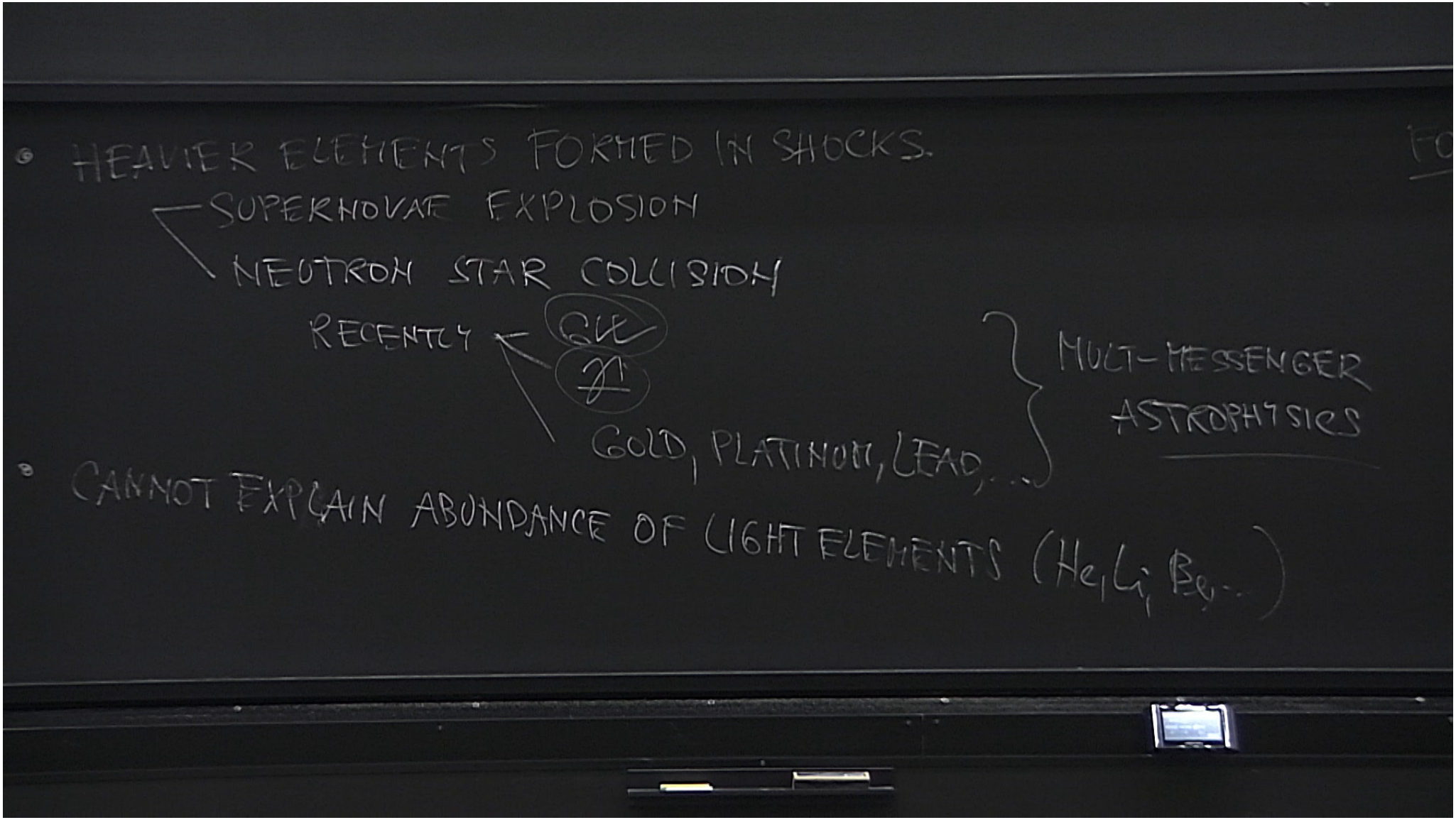

WHEN/WHERE PRODUCED ?
-2 POSSIBLE THEORIES?
He FUSED IN STARS
He FUSED IN BIG BANG NUCLEOSYNTHESIS.
MBER
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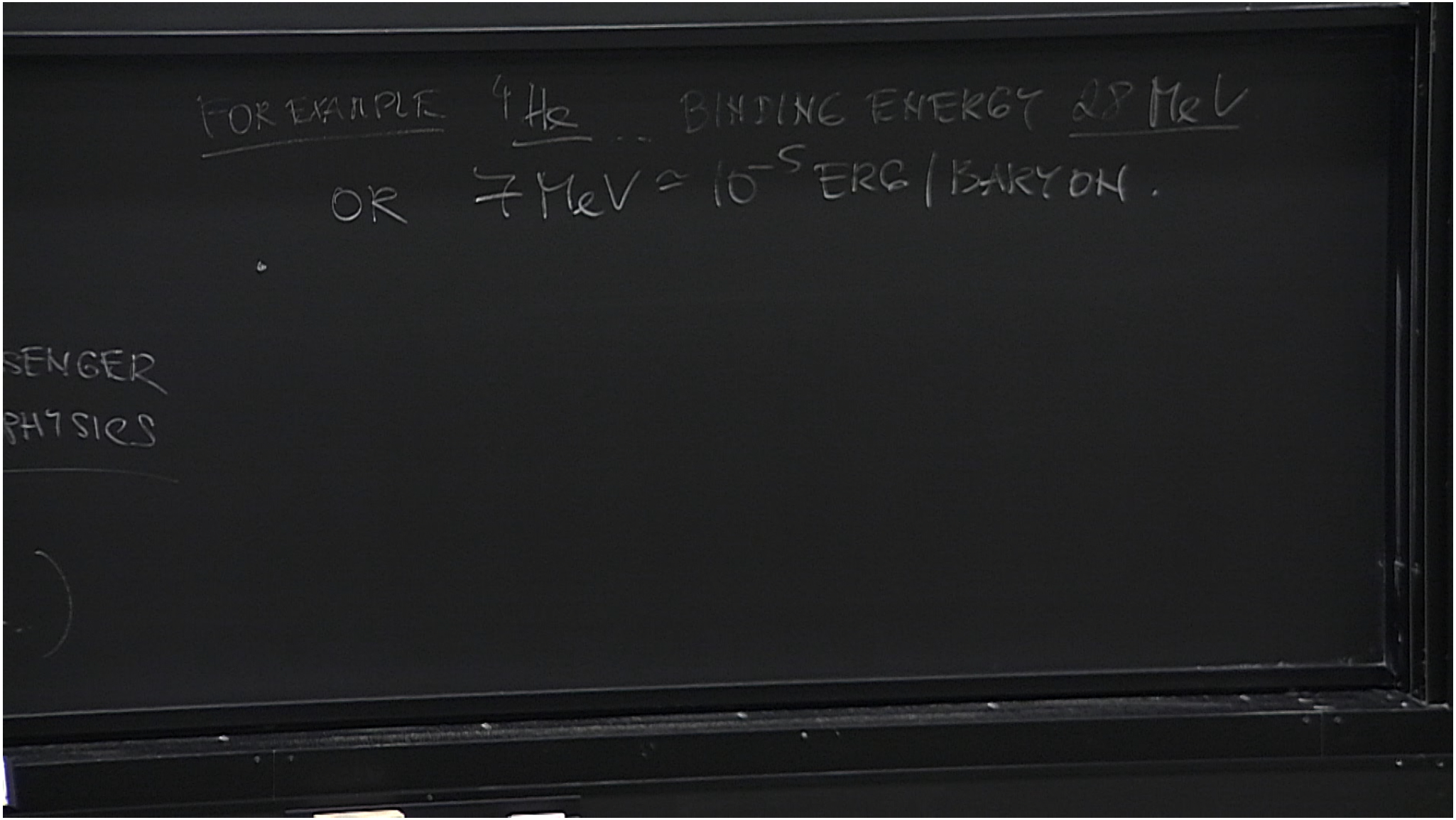

WHEN/WHERE PRODUCED ?
-2 POSSIBLE THEORIES?
He FUSED IN STARS
He FUSED IN BIG BANG NUCLEOSYNTHESIS.
Fe THE MOST TO STABLE ELEMENT
UP TO THIS, ELEMENTS CAN BE FUSED
IN MASSIVE STARS (TO MAKING)


HEAVIER ELEMENTS FORMED IN SHOCKS.
SUPERNOVAE EXPLOSION
NEUTRON STAR COLLISION
RECENTLY
GOLD, PLATINUM, LEAD, ...


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FOR EXAMPLE 4He ... BINDING ENERGY 28 MeV
OR 7 MeV ≈ 10^{-5} ERG / BARYON.
SENGER
PHYSICS

FOR EXAMPLE ^4He ... BINDING ENERGY 28 MeV

OR 7 MeV $\simeq 10^{-5}$ ERG / BARYON.

- ASSUME THAT 25% OF BARYONS FUSED TO He IN STARS, DURING HISTORY OF UNIVERSE

$\simeq t = 10^{10}$ YEARS $(3 \times 10^{17}$ S)

SENGER
PHYSICS

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$L =$

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$M_b = N_b\, m_p$

LUMINOSITY TO MASS RATIO

$$\frac{L}{M_b} \simeq 0.25 \frac{10^{-5}\,\mathrm{ERG}}{m_p \times 3\times10^{17}\,\mathrm{S}} \simeq 2.5 \frac{L_\odot}{M_\odot}$$

OBSERVED: $\frac{L}{M_b} \leq 0.05 \frac{L_\odot}{M_\odot}$

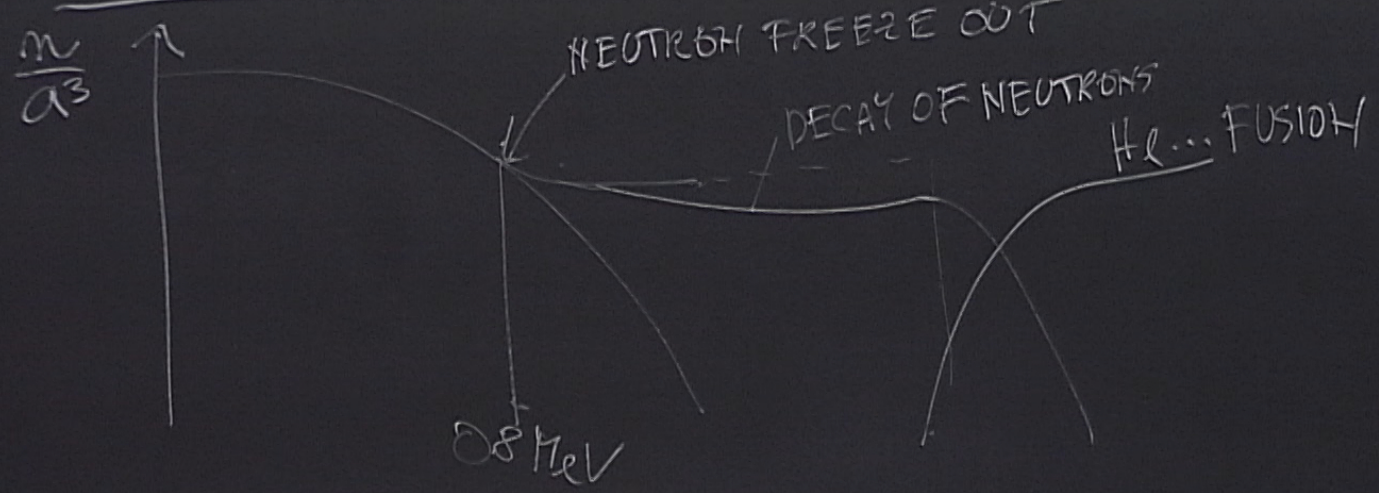
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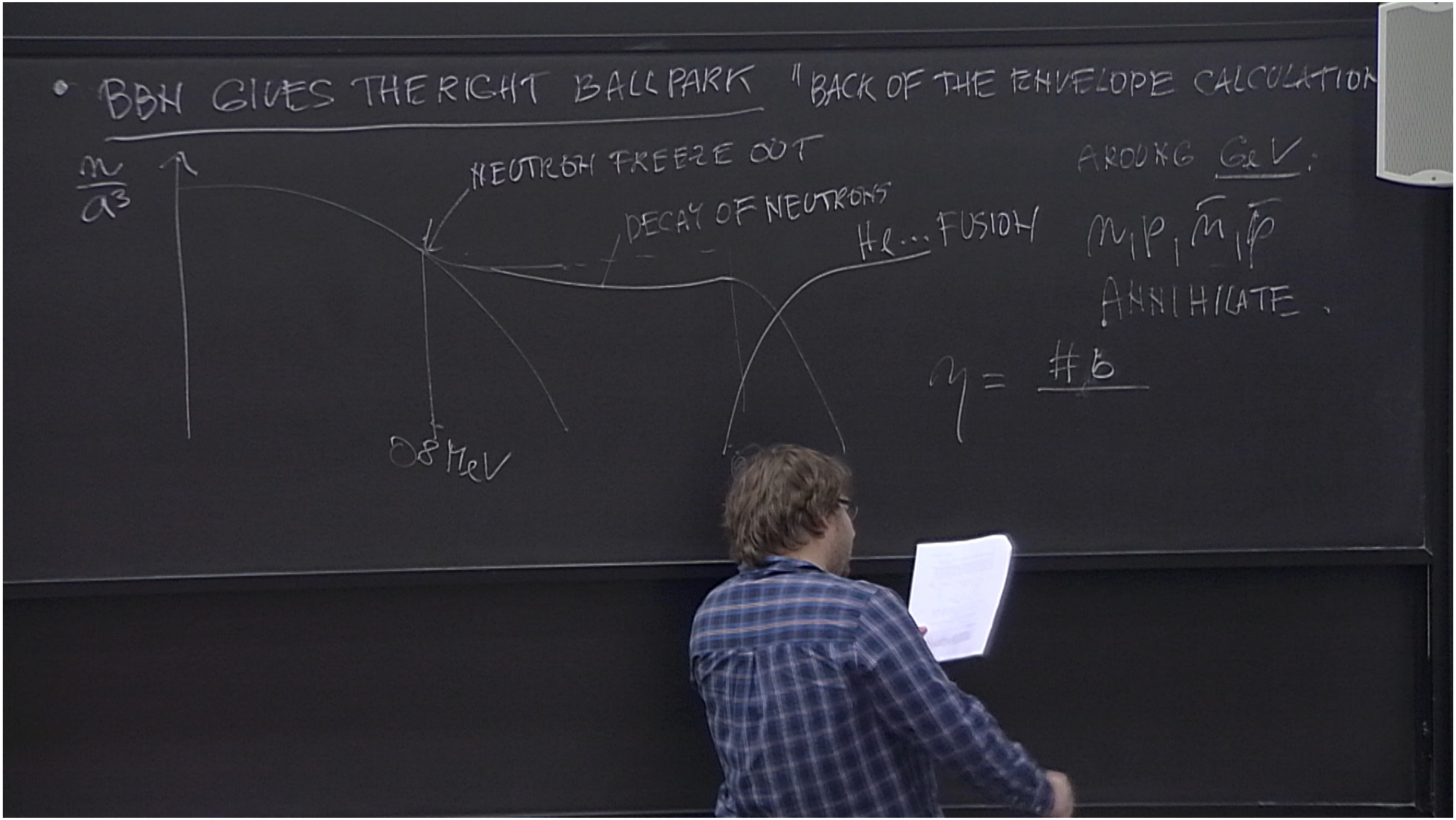
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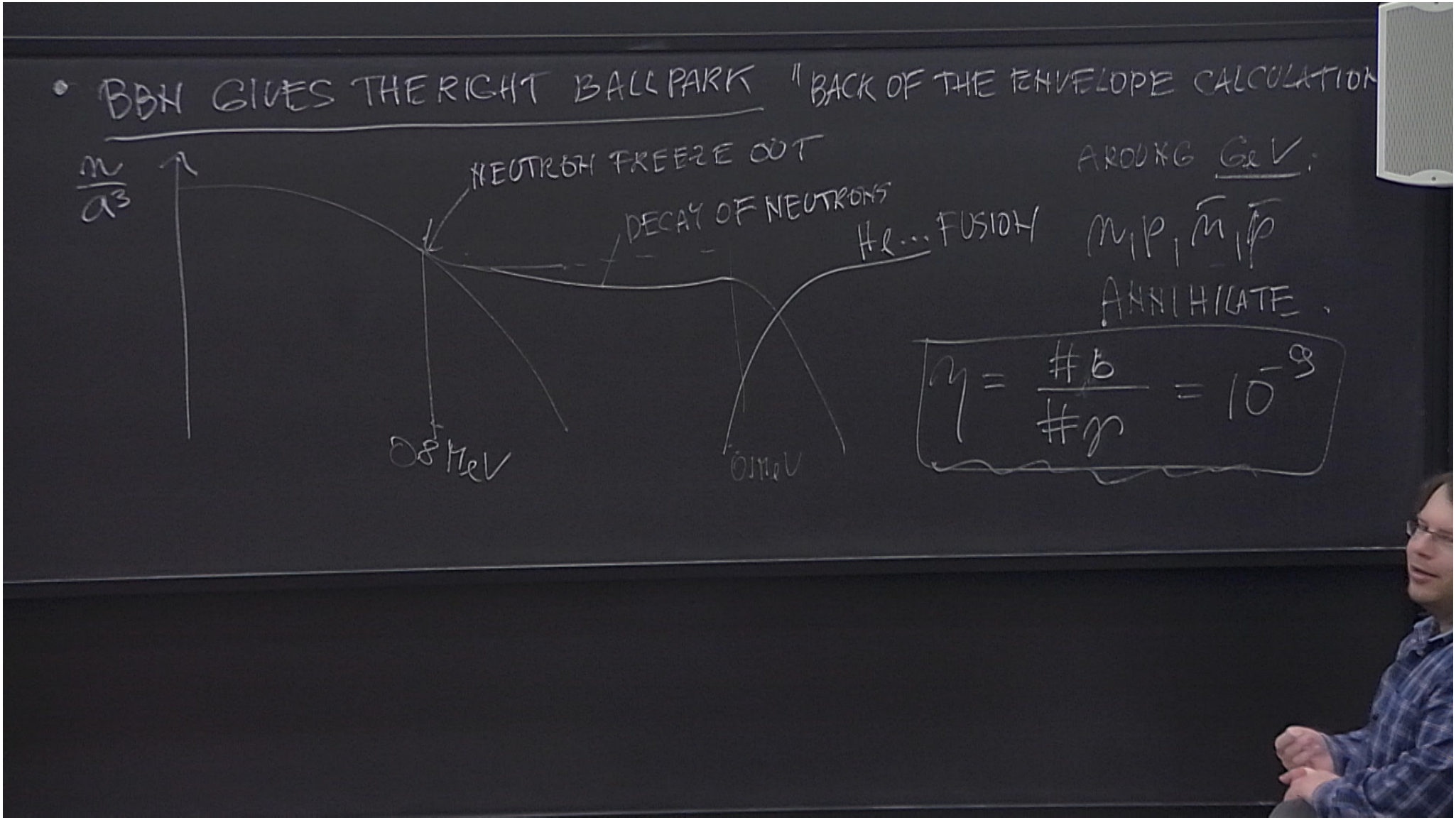
OBSERVED: $\frac{L}{M_b} \leq 0.05 \frac{L_\odot}{M_\odot}$

COULD FOSE AT MOST 0.5% He IN STARS

- BBN GIVES THE RIGHT BALLPARK "BACK OF THE ENVELOPE CALCULATION"




• BBN GIVES THE RIGHT BALLPARK "BACK OF THE ENVELOPE CALCULATION
n/a3
NEUTRON FREEZE OUT
DECAY OF NEUTRONS
He... FUSION
0.8 MeV
AROUND GeV:
n, p, n̄, p̄
ANNIHILATE.
η = #6


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n/a3
NEUTRON FREEZE OUT
DECAY OF NEUTRONS
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AROUND GeV:
n, p, n̄, p̄
ANNIHILATE.
η = #b/#γ = 10^-9
.8 MeV
.1MeV

FUSE AT MOST 0.5% He
IN STARS

FEW MeV: WEAK INTERACTIONS BECOME
INEFFICIENT:

IN STARS 0.5% He

FEW MeV: WEAK INTERACTIONS BECOME INEFFICIENT:

i) NEUTRINOS DECOUPLE FROM THE REST OF BATH

ii) CHEMICAL EQ. BETWEEN PROTONS & NEUTRONS NO LONGER MAINTAINED.



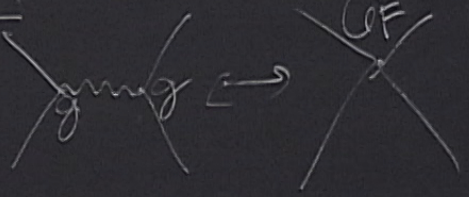
i) $\nu_e + \bar{\nu}_e \rightleftarrows e^- + e^+$

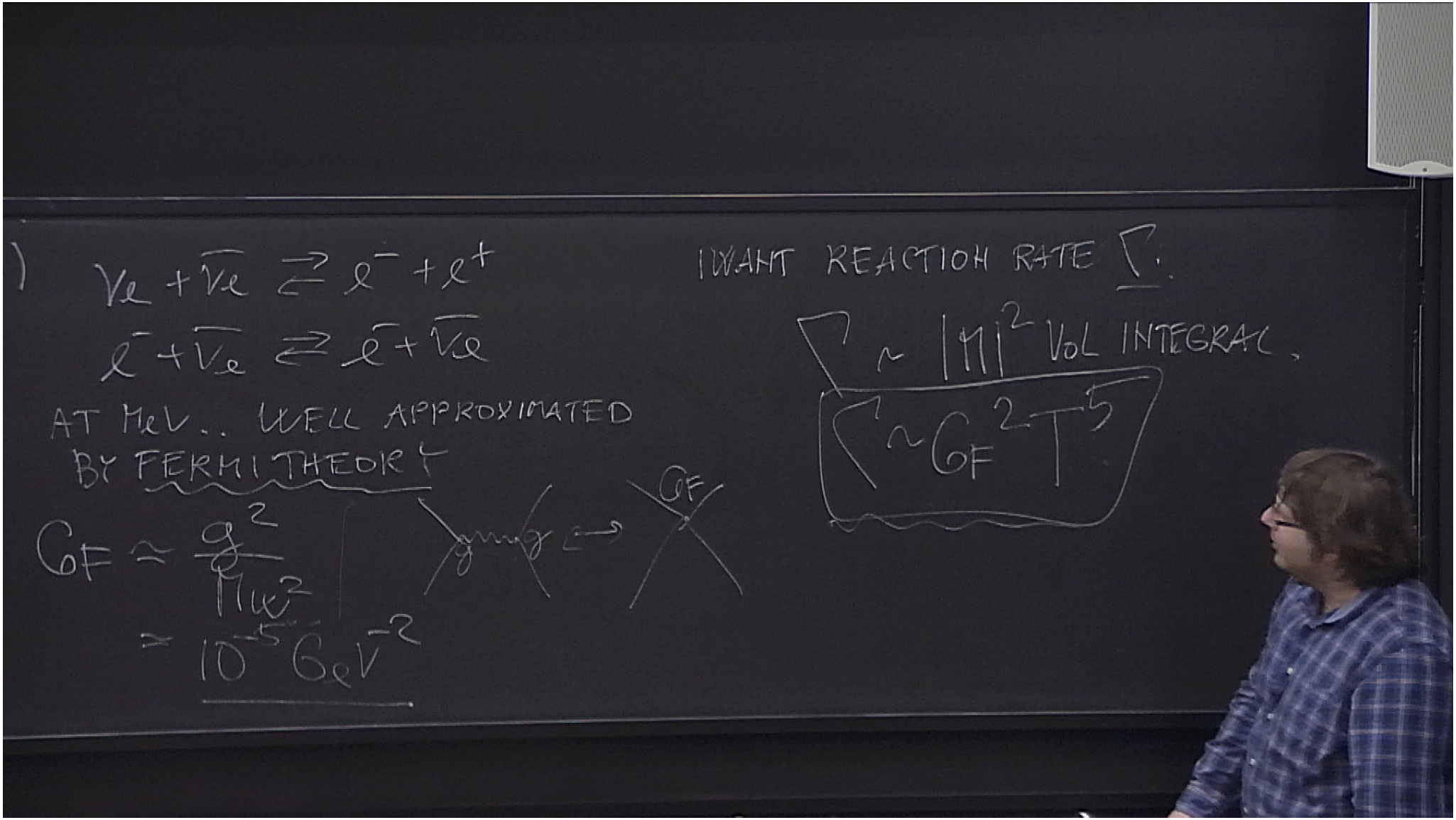
$e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$

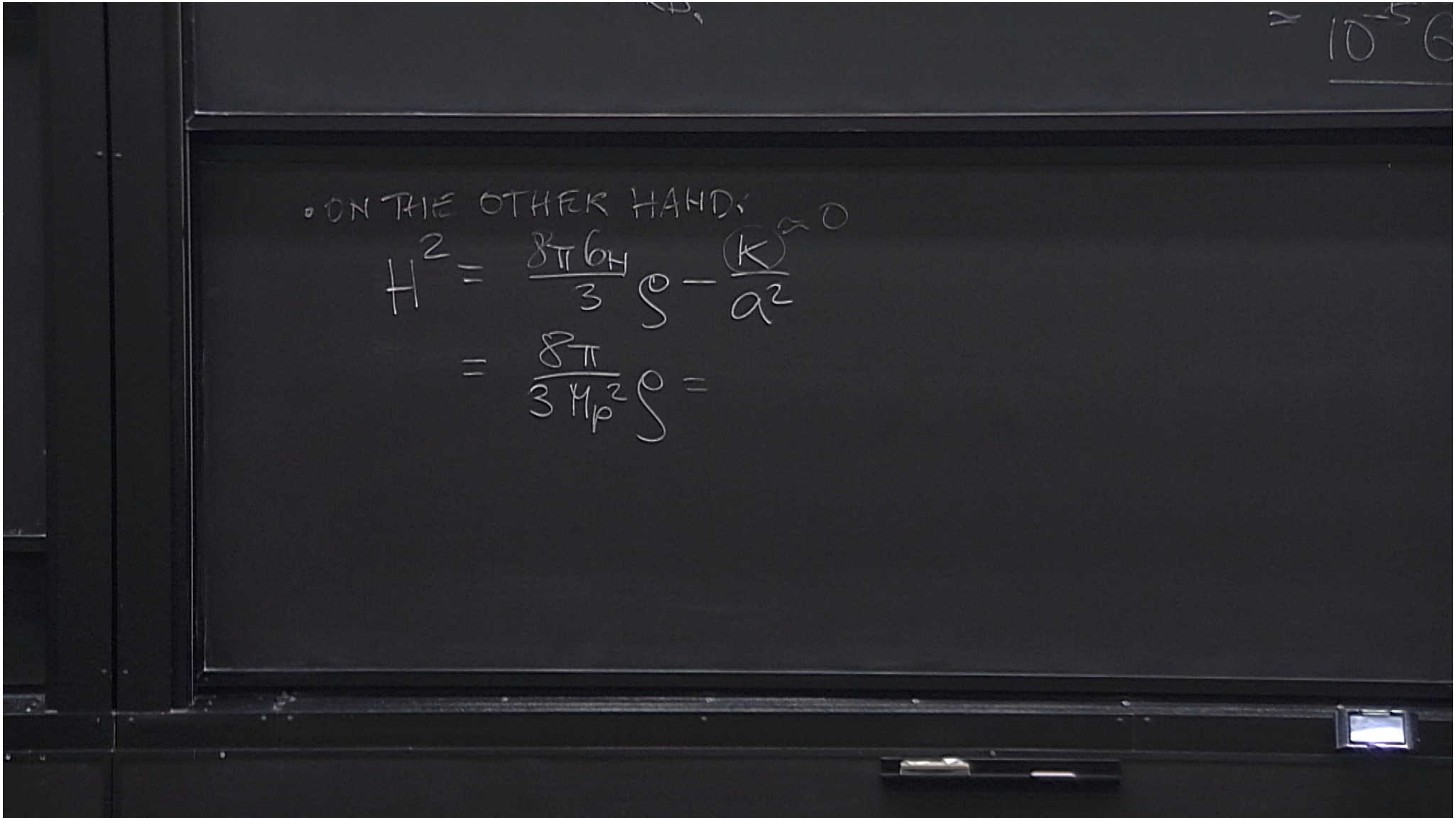
AT MeV.. WELL APPROXIMATED BY FERMI THEORY

$G_F \approx \frac{g^2}{M_W^2}$

$\approx 10^{-5}\ \mathrm{GeV}^{-2}$




$\nu_e + \bar{\nu}_e \rightleftarrows e^- + e^+$
$e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$
AT MeV.. WELL APPROXIMATED BY FERMI THEORY
$G_F \approx \frac{g^2}{m_W^2}$
$\approx 10^{-5}\,\mathrm{GeV}^{-2}$
$g \to G_F$
I WANT REACTION RATE Γ.
$\Gamma \sim |\mathcal{M}|^2$ VOL INTEGRAL.
$\Gamma \sim G_F^2 T^5$

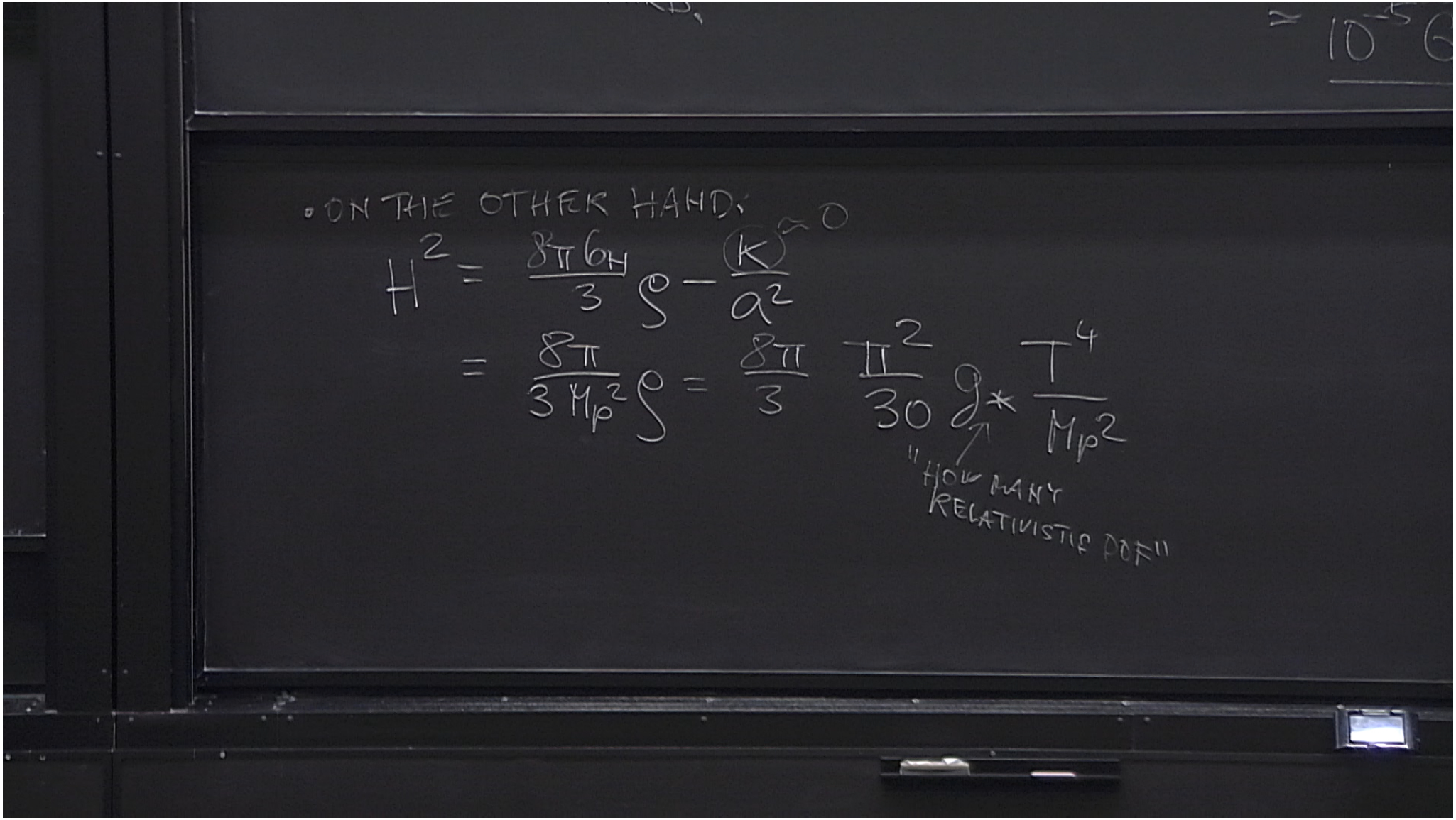

• ON THE OTHER HAND:
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} \simeq 0$
$= \frac{8\pi}{3M_p^2}\rho =$

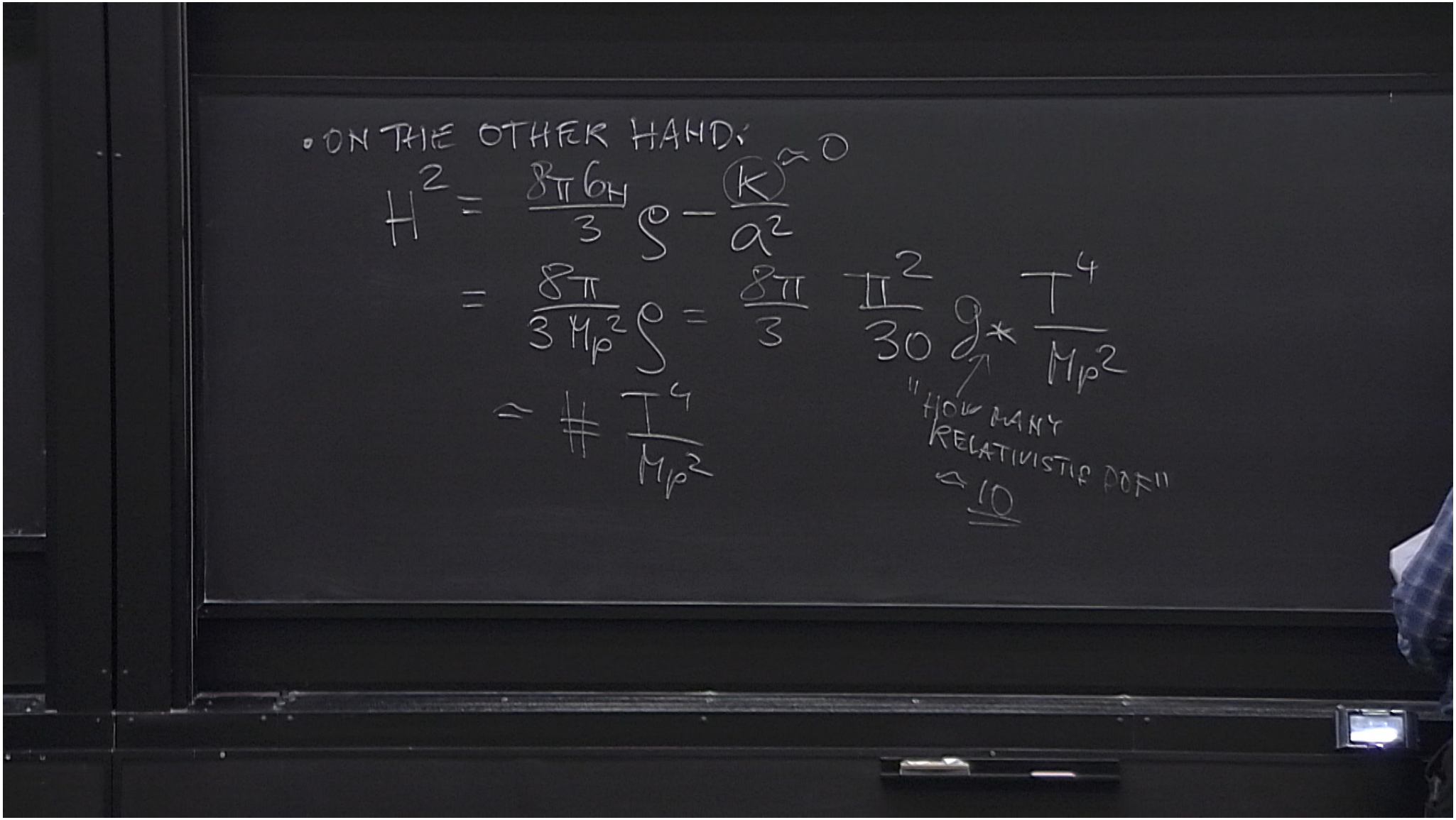
$\sim 10^{-5}$ G

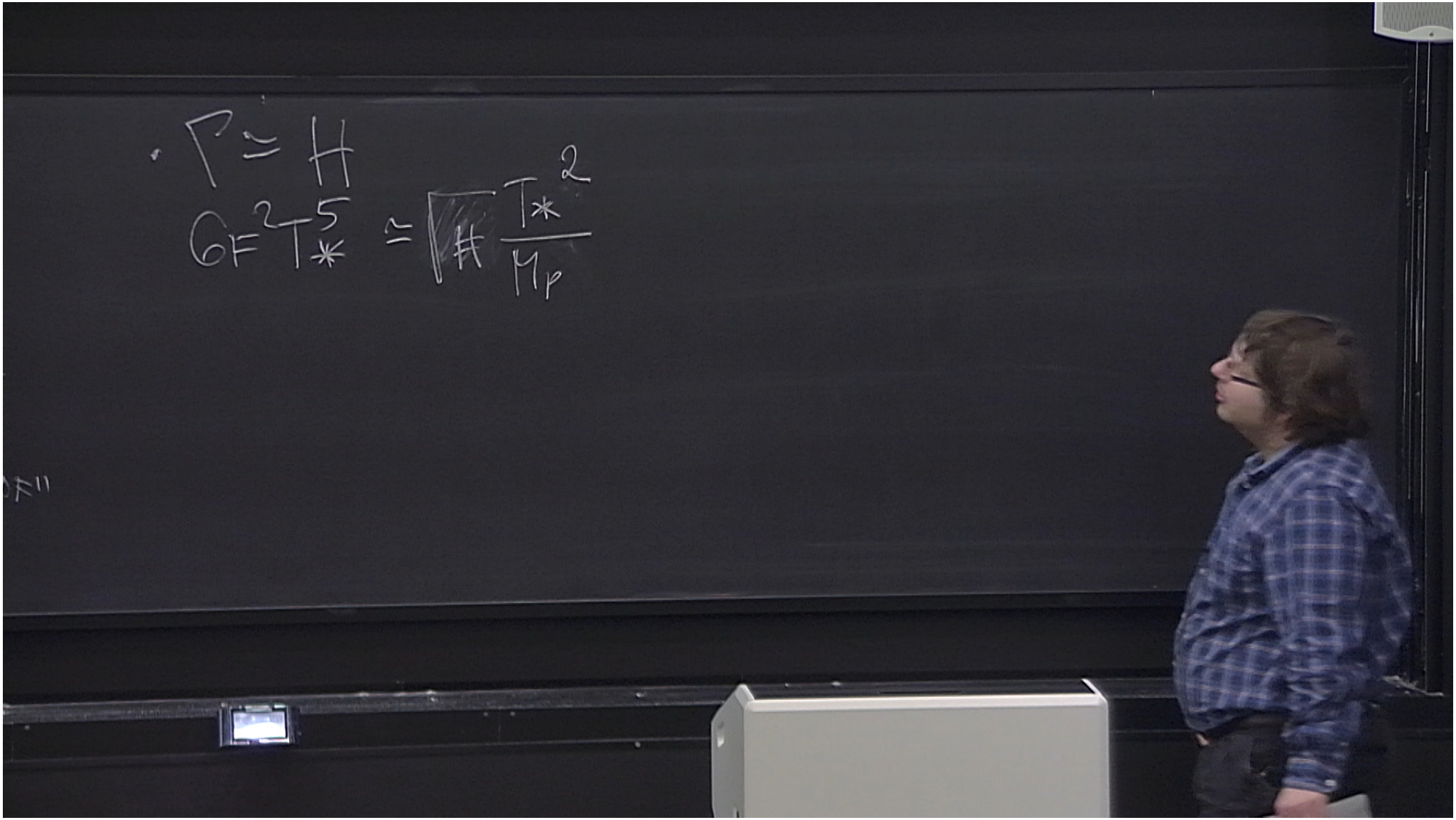
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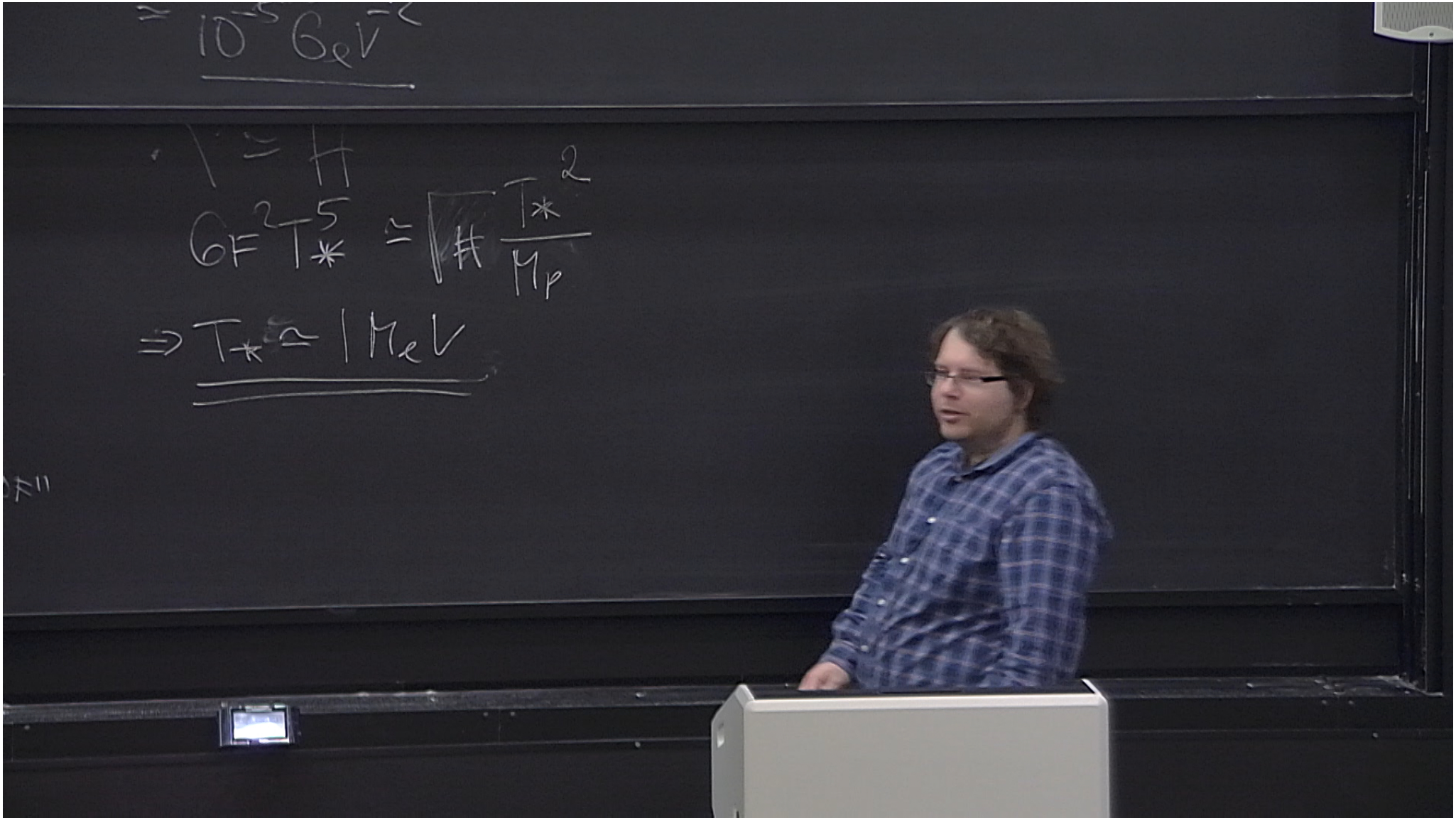
$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} \quad (k \simeq 0)$$

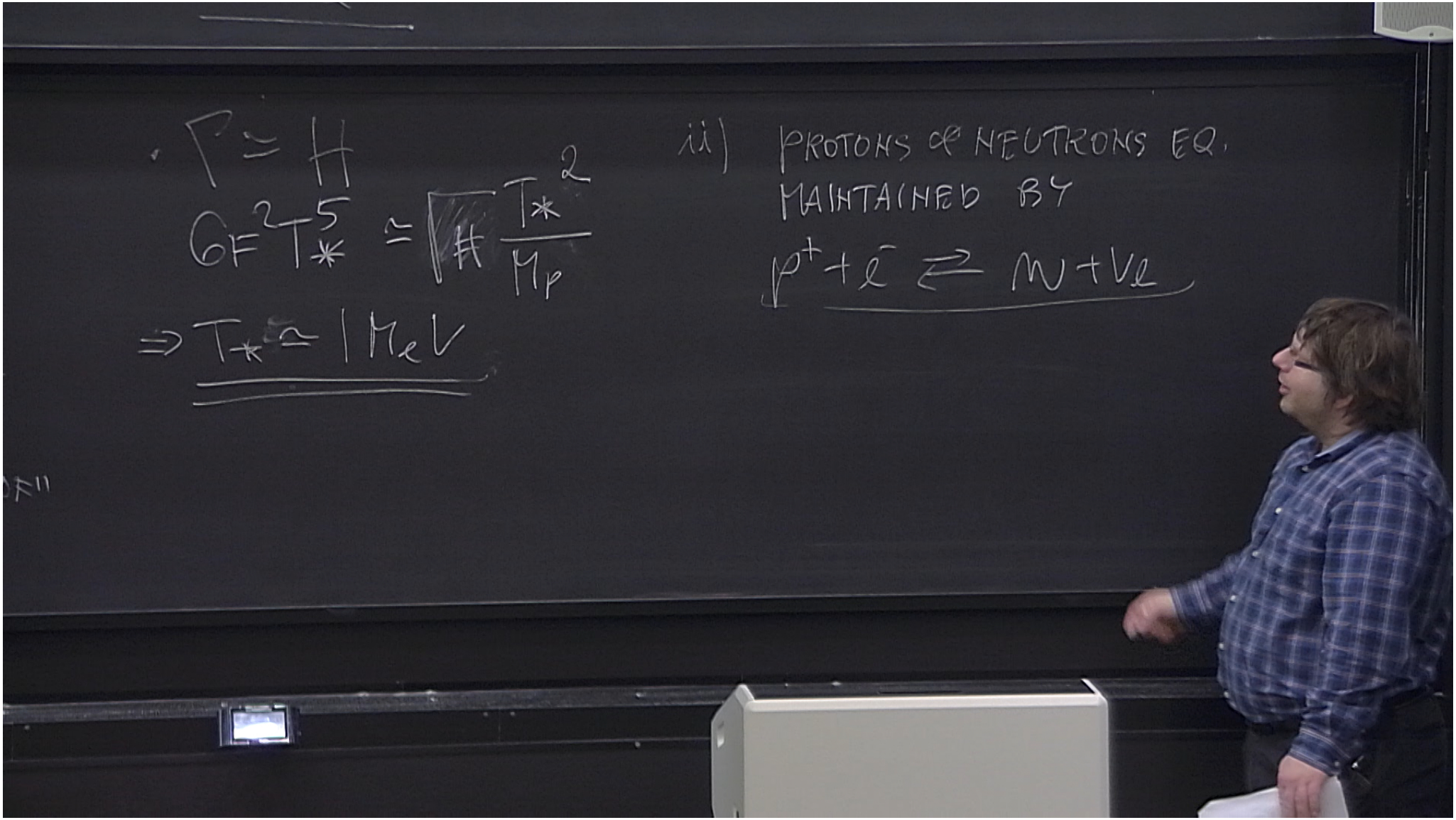
$$= \frac{8\pi}{3M_p^2}\rho = \frac{8\pi}{3}\,\frac{\pi^2}{30}\,g_*\,\frac{T^4}{M_p^2}$$

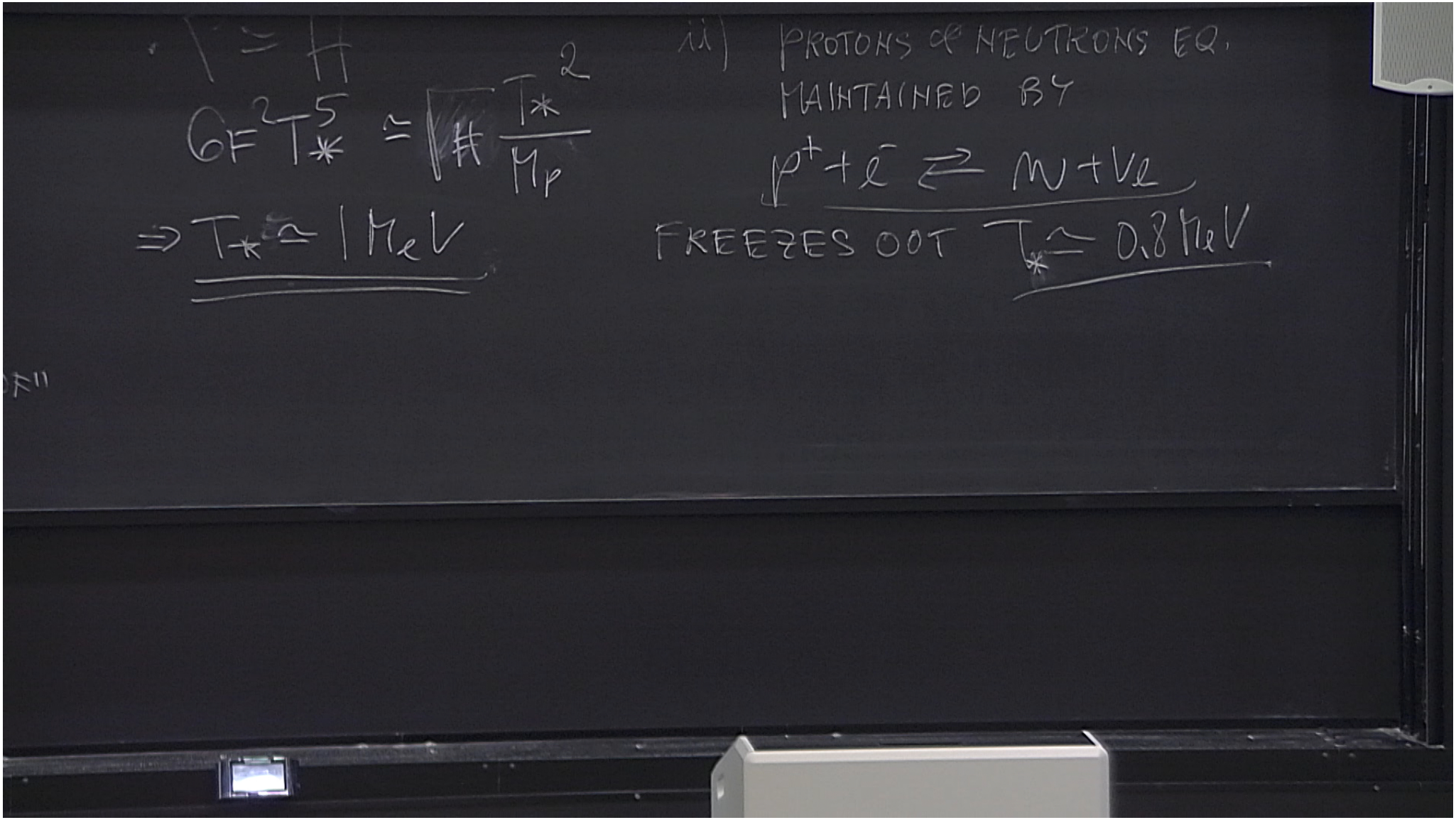

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"HOW MANY RELATIVISTIC DOF"

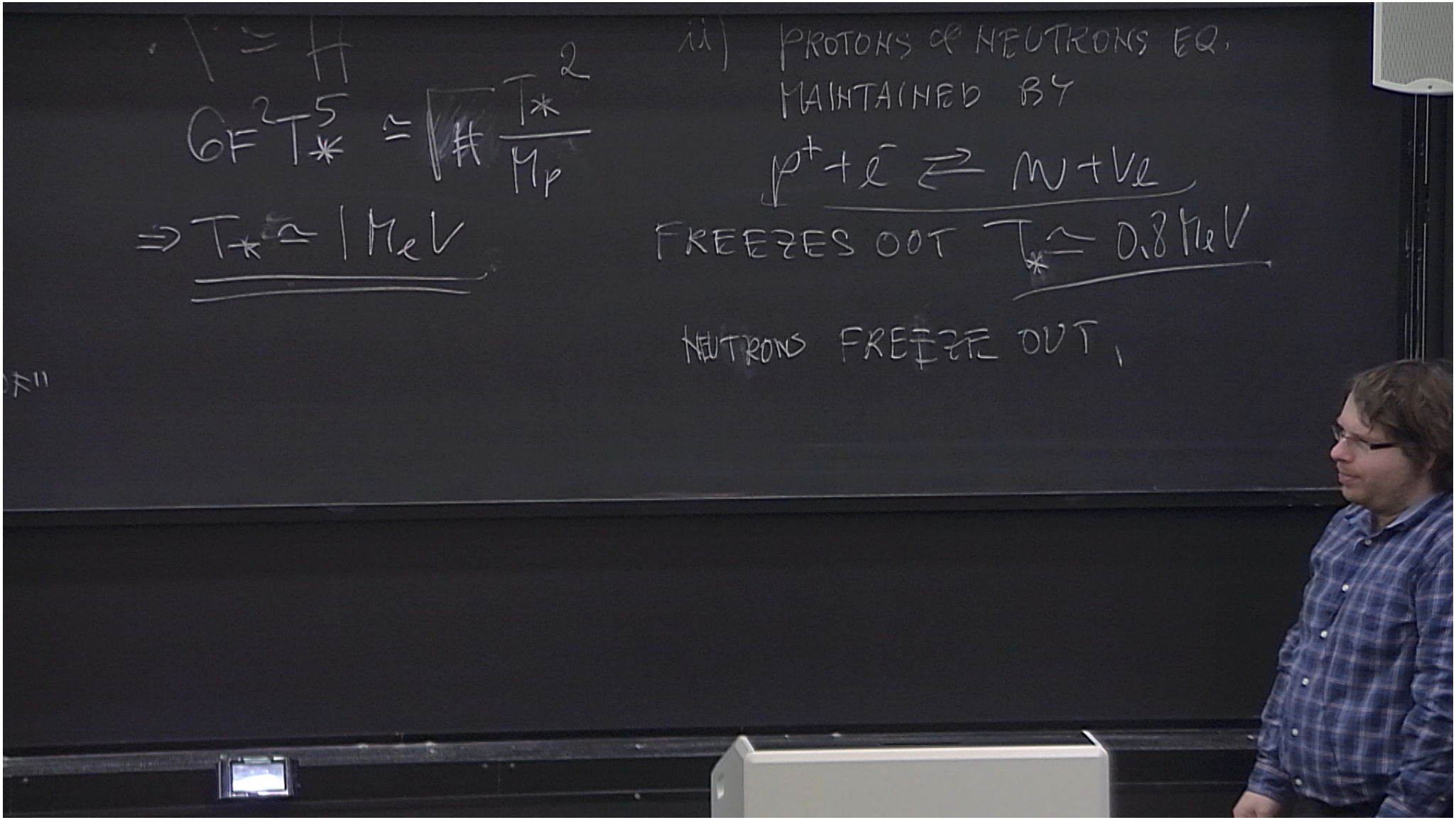

• ON THE OTHER HAND:
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} \simeq 0$
$= \frac{8\pi}{3M_P^2}\rho = \frac{8\pi}{3}\frac{\pi^2}{30}g_* \frac{T^4}{M_P^2}$
$\simeq \# \frac{T^4}{M_P^2}$
"HOW MANY RELATIVISTIC DOF"
$\lesssim 10$


$\Gamma \simeq H$
$G_F^2 T_*^5 \simeq \sqrt{\#} \frac{T_*^2}{M_P}$


$\simeq 10^{-5}\,\mathrm{GeV}^{-2}$
$\Gamma \simeq H$
$G_F^2 T_*^5 \simeq \sqrt{\#}\,\frac{T_*^2}{M_P}$
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ii) PROTONS & NEUTRONS EQ. MAINTAINED BY
$p^+ + e^- \rightleftarrows n + \nu_e$


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FREEZES OUT $T_* \simeq 0.8\,MeV$


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NEUTRONS FREEZE OUT,

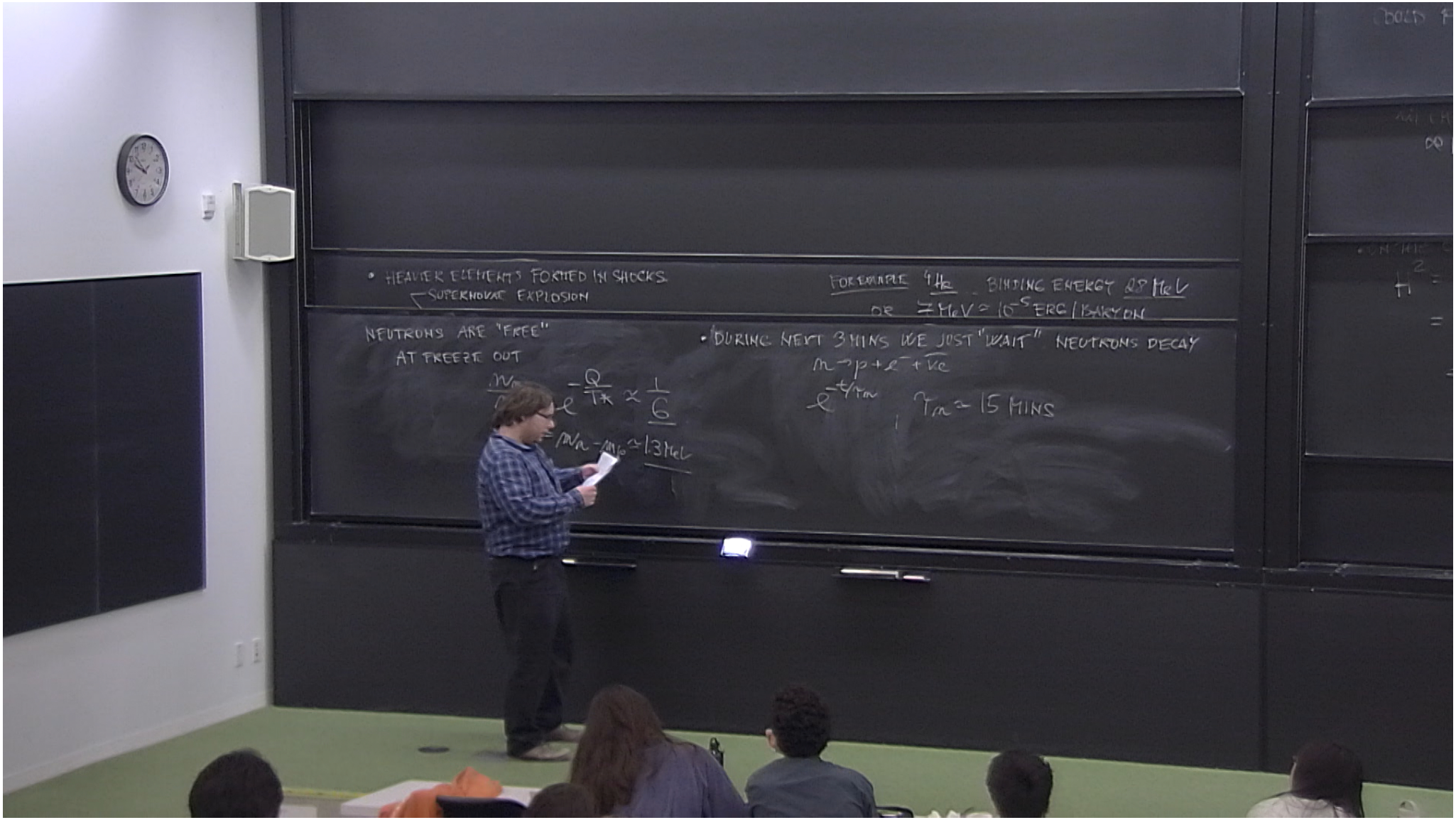
- HEAVIER ELEMENTS FORMED IN SHOCKS.
  - SUPERNOVAE EXPLOSION

NEUTRONS ARE "FREE" AT FREEZE OUT

- DURING NE

$$\frac{n_n}{n_p} = e^{-\frac{Q}{T_*}} \approx \frac{1}{6}$$

$$Q = m_n - m_p \simeq 1.3\,\text{MeV}$$


• HEAVIER ELEMENTS FORMED IN SHOCKS
SUPERNOVAE EXPLOSION
FOR EXAMPLE ^4He BINDING ENERGY 28 MeV
OR $\simeq$ MeV $\simeq 10^5$ ERG / BARYON
NEUTRONS ARE "FREE"
AT FREEZE OUT
$e^{-\frac{Q}{T_*}} \propto \frac{1}{6}$
$m_n - m_p \simeq 1.3$ MeV
• DURING NEXT 3 MINS WE JUST "WAIT" NEUTRONS DECAY
$n \to p + e^- + \bar{\nu}_e$
e^{-t/τ_n}, $\tau_n \simeq 15$ MINS

FOR EXAMPLE ^{4}He ... BINDING ENERGY 28 MeV

OR $\frac{7}{4}$ MeV $\simeq 10^{-5}$ ERG / BARYON

- DURING NEXT 3 MINS WE JUST "WAIT". NEUTRONS DECAY

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$e^{-t/\tau_n} \qquad \tau_n \simeq 15 \text{ MINS}$$

FOR EXAMPLE ^{4}He ... BINDING ENERGY 28 MeV

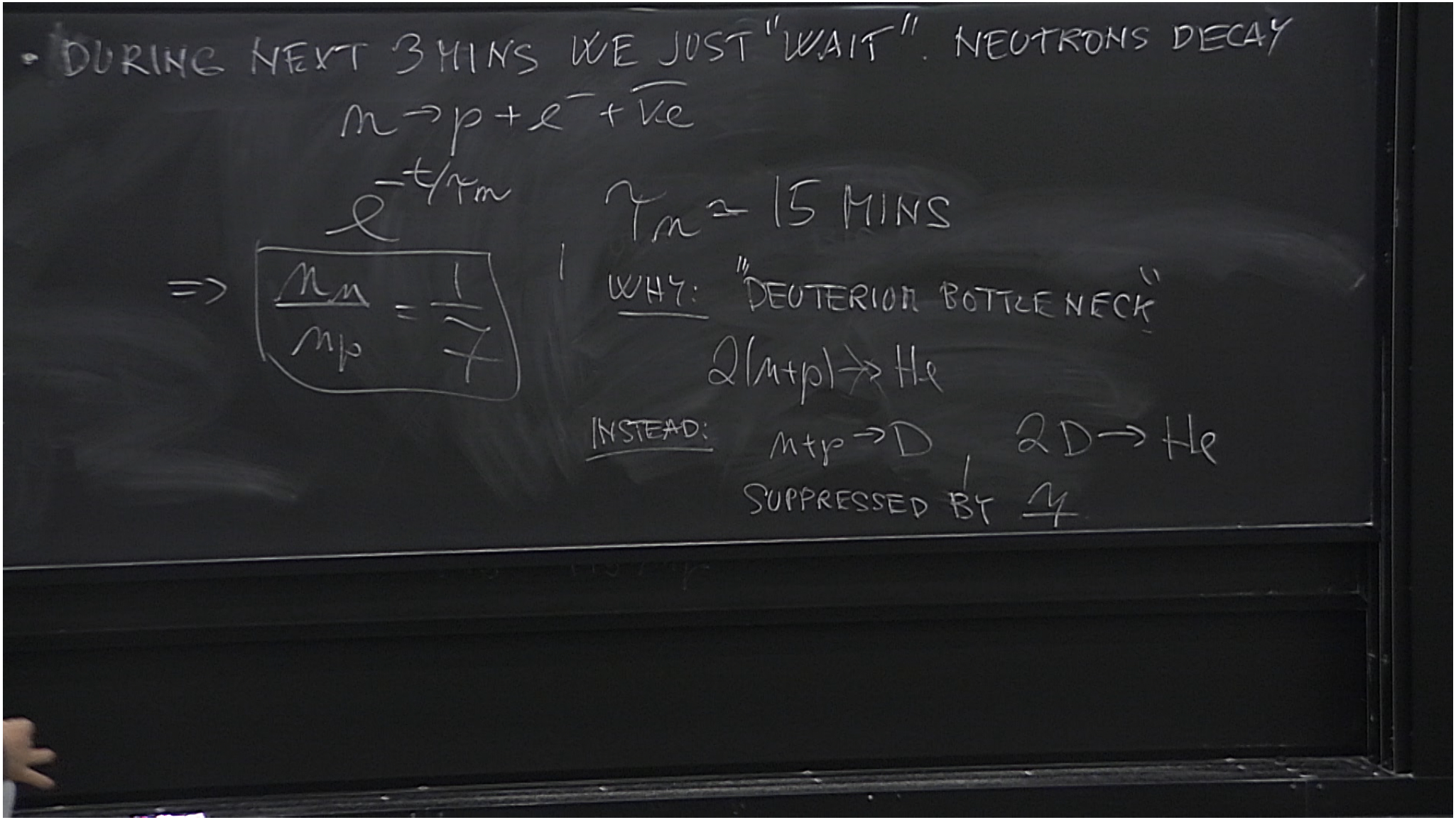
OR $\frac{1}{7}$ MeV $\simeq 10^{-5}$ ERG / BARYON

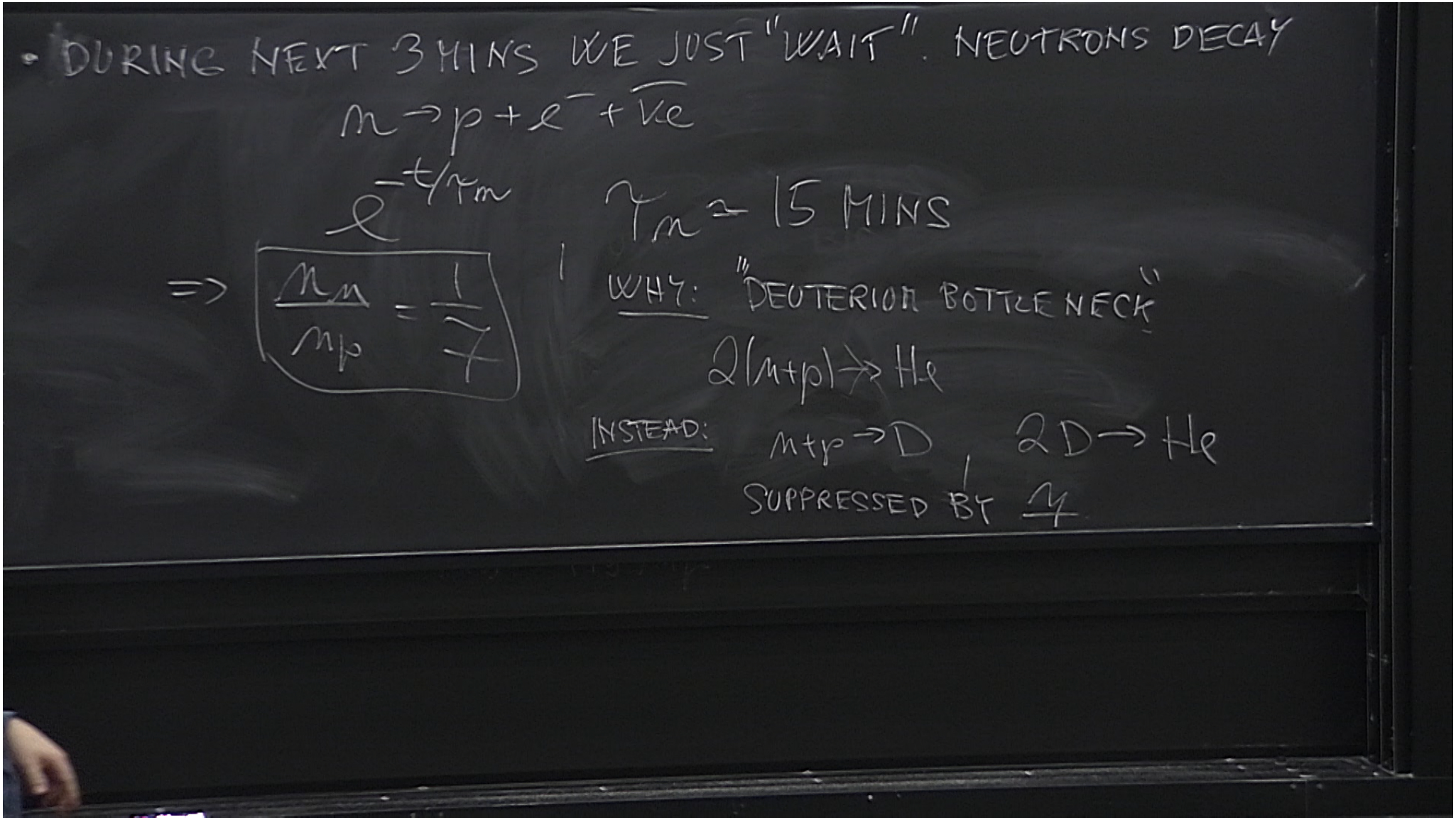
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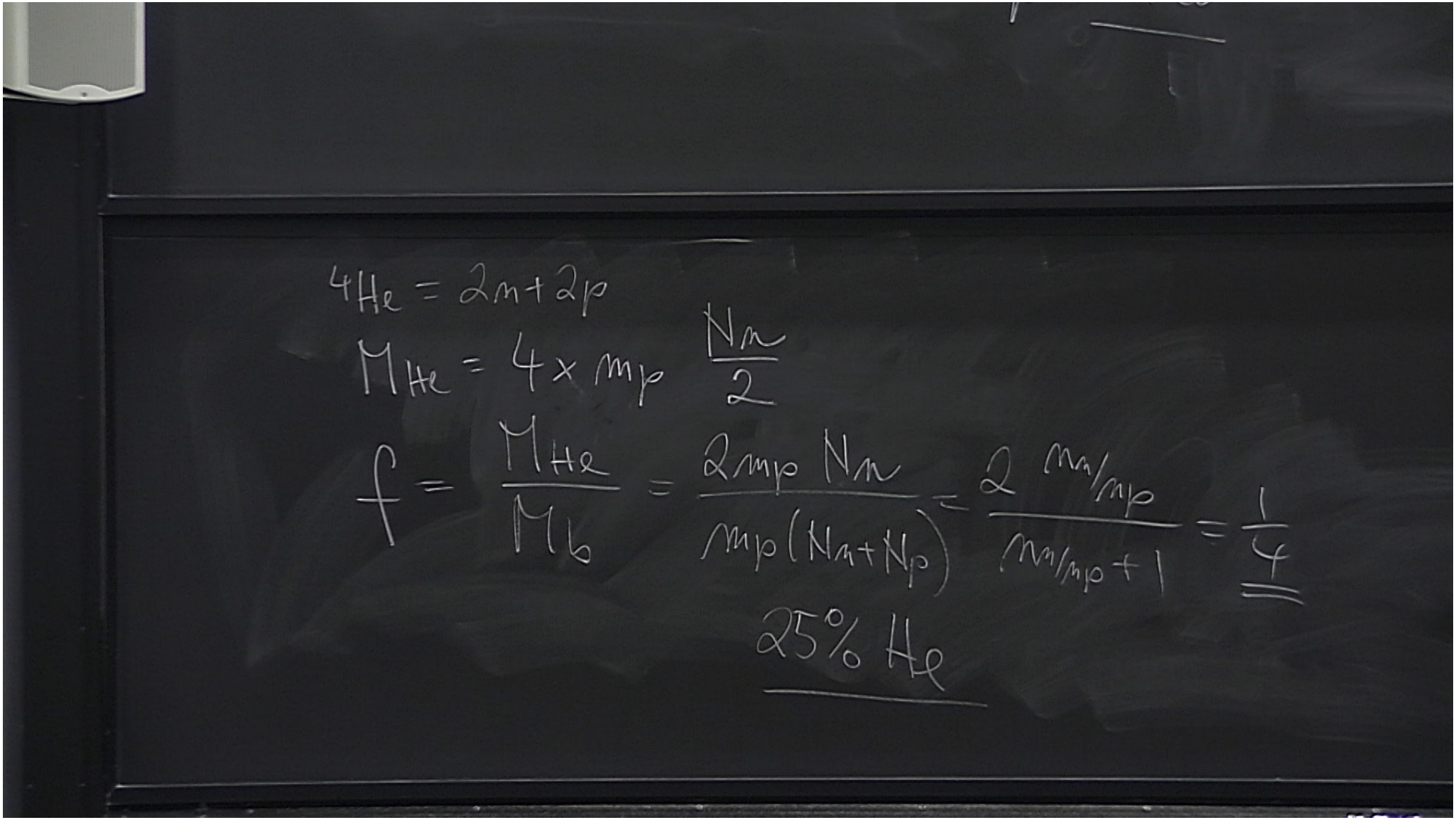
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$$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$$


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e^{-t/τ_n}
$\tau_n \simeq 15$ MINS
$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$
WHY: "DEUTERIUM BOTTLENECK"
$2(n+p) \not\to He$
INSTEAD: $n+p \to D$, $2D \to He$
SUPPRESSED BY $\frac{1}{7}$


• DURING NEXT 3 MINS WE JUST "WAIT". NEUTRONS DECAY
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$2(n+p) \not\to He$
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SUPPRESSED BY $\frac{1}{7}$


4He = 2n + 2p
MHe = 4 × mp
Nn / 2
f = MHe / Mb = 2 mp Nn / mp (Nn + Np) = 2 mn/mp / mn/mp + 1 = 1/4
25% He

INSTEAD: $n+p \to D$, $2D \to He$

SUPPRESSED BY η

→ OTHER ELEMENTS ✓

BBN IS A PROBE OF FUNDAMENTAL PHYSICS

RESULT DEPENDS ON

g_*

$\frac{1}{\eta}$

INSTEAD: $n + p \to D$, $2D \to He$

SUPPRESSED BY η

- OTHER ELEMENTS ✓

BBN IS A PROBE OF FUNDAMENTAL PHYSICS

RESULT DEPENDS ON

- g_* (RELATIVISTIC PARTICLE CONTENT AT T_*)
- $\sim T_n$,

INSTEAD: $n + p \to D$, $2D \to He$

SUPPRESSED BY η

- OTHER ELEMENTS ✓

BBN IS A PROBE OF FUNDAMENTAL PHYSICS

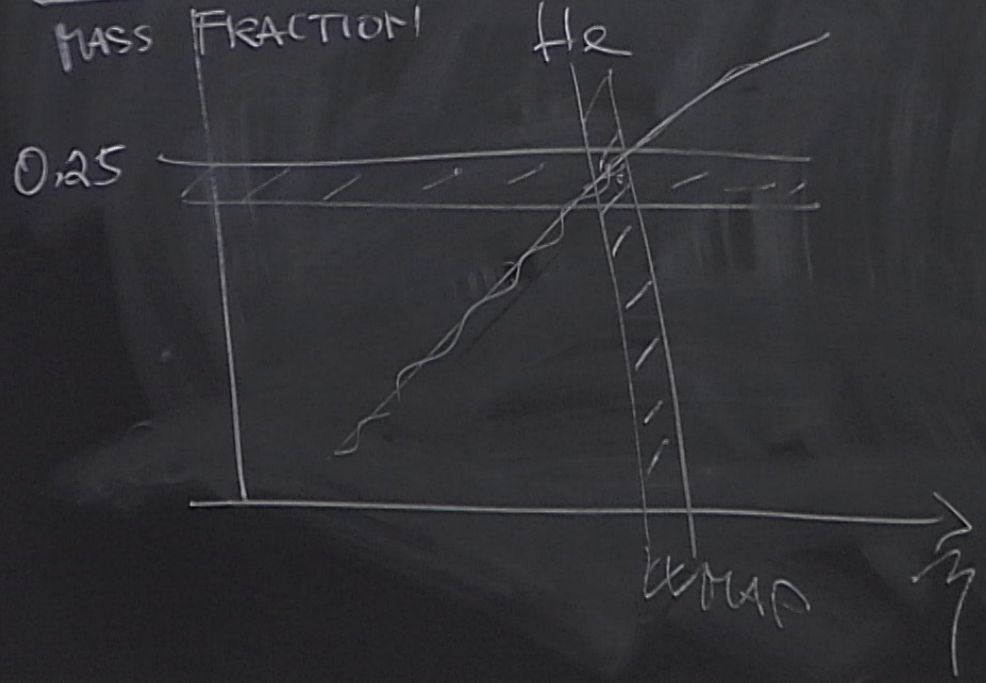
RESULT DEPENDS ON

- g_* (RELATIVISTIC PARTICLE CONTENT AT T_*)
- $\tilde{m}$, Q, η, G_N, G_F

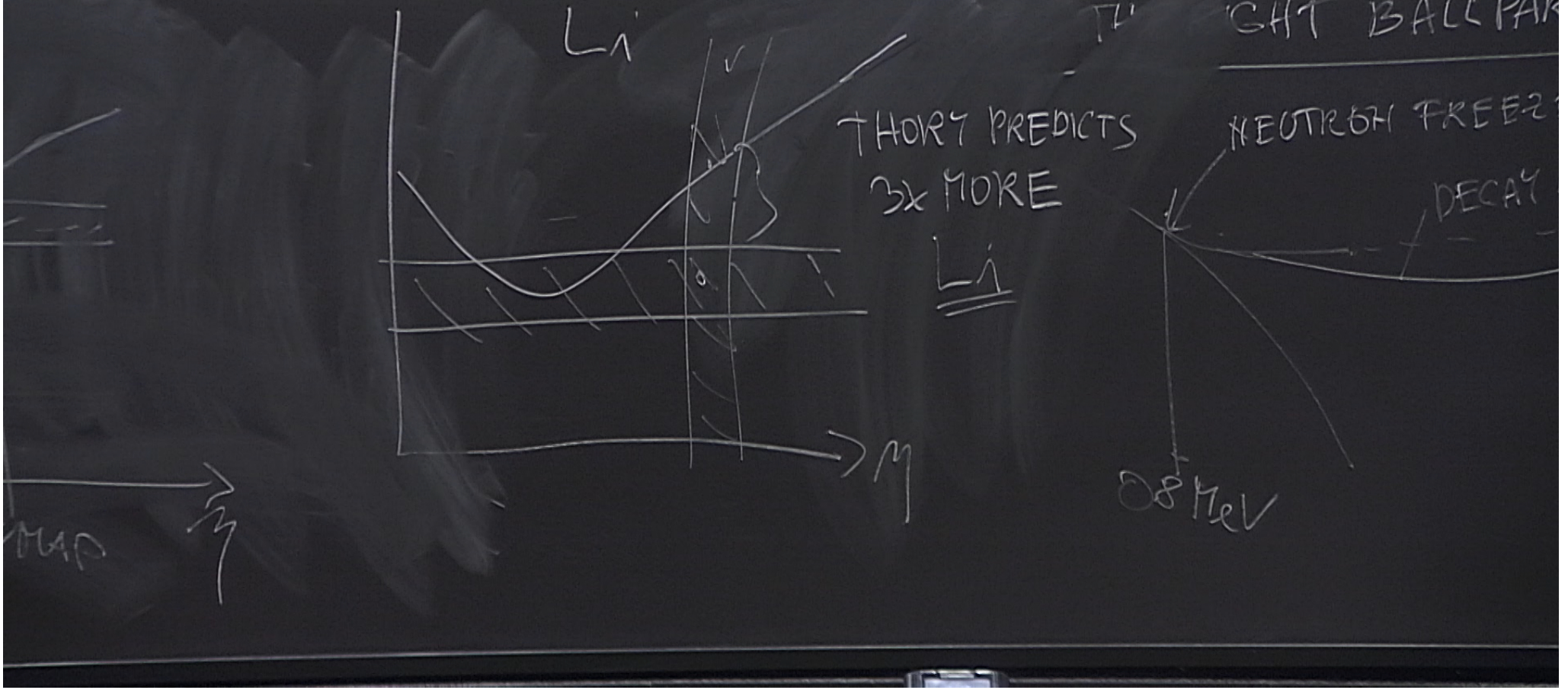
$\frac{1}{4}$

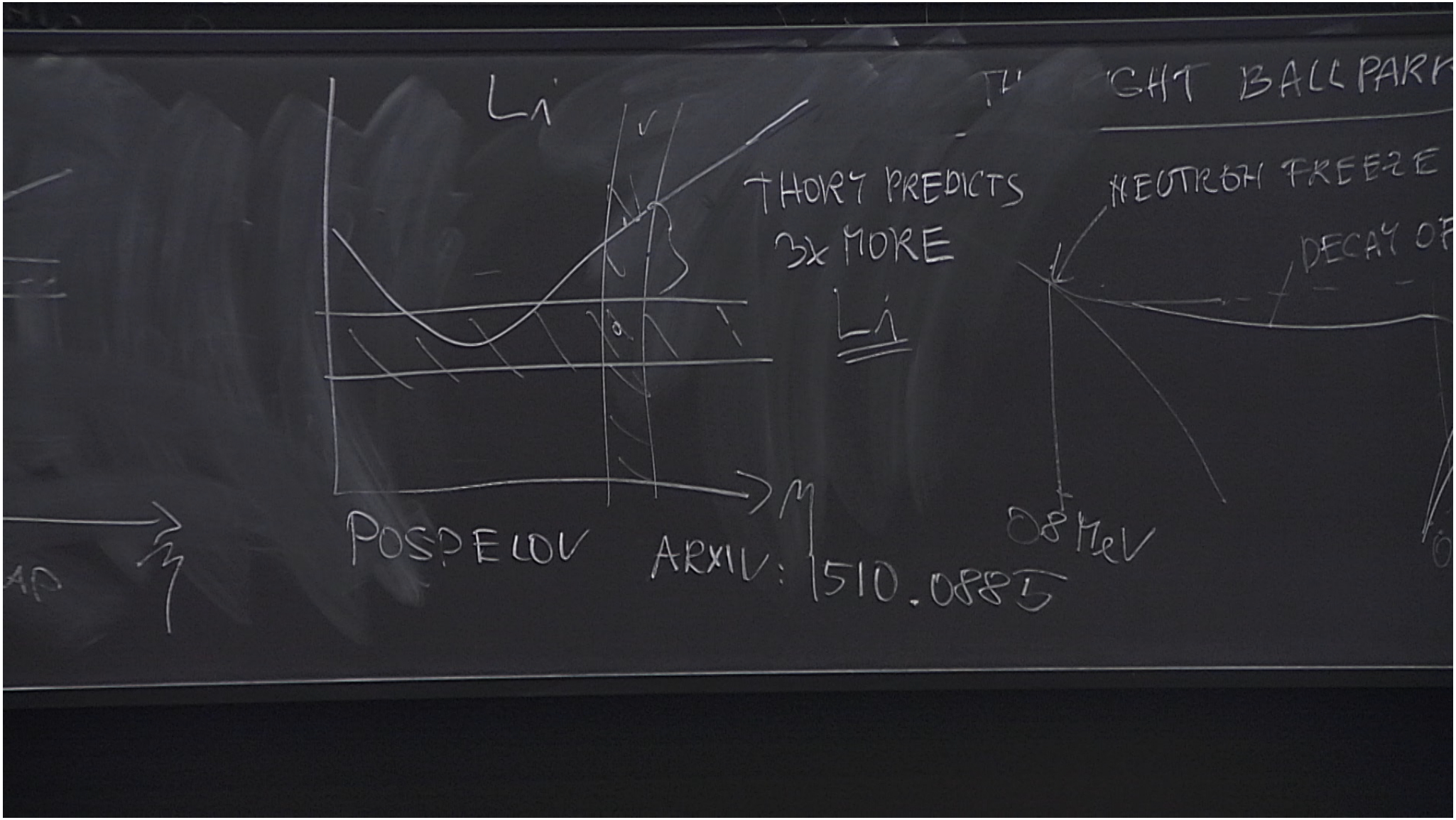
$H = \frac{8\pi}{3} \rho - \frac{a^2}{a^2} = \frac{8\pi}{3} \rho - \frac{8\pi}{3} \Pi^2 \rho T^4$

FOR EXAMPLE M:



$\frac{a^2}{8\pi} \Pi^2 \cdot T^4$ $G_F^2 T_*^5 \simeq \# \frac{T_*}{M_P}$




Li
THORY PREDICTS
3x MORE
Li
M
POSPELOV ARXIV: 1510.0885
NEUTRON FREEZE
DECAY OF
.08 MeV