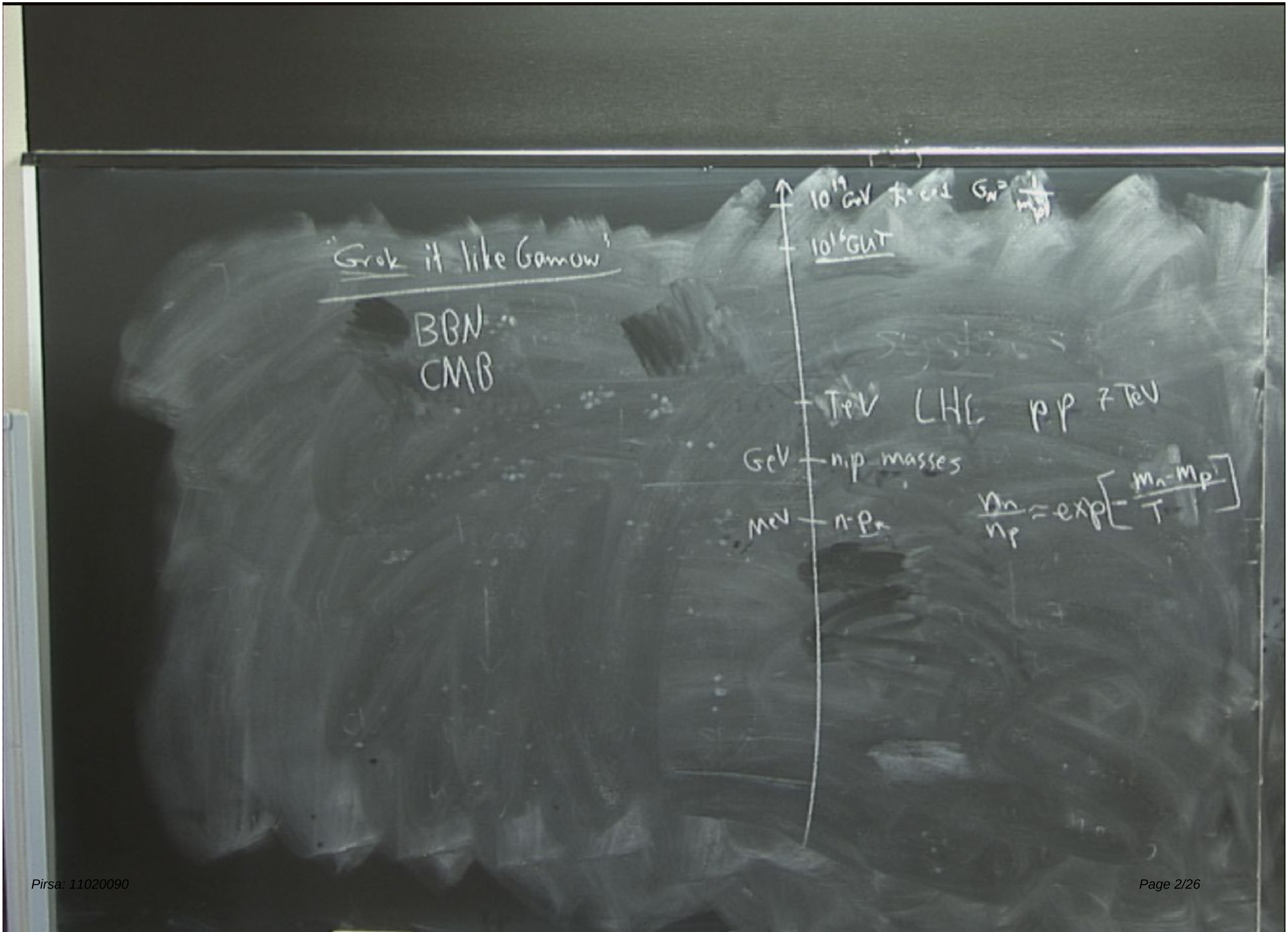
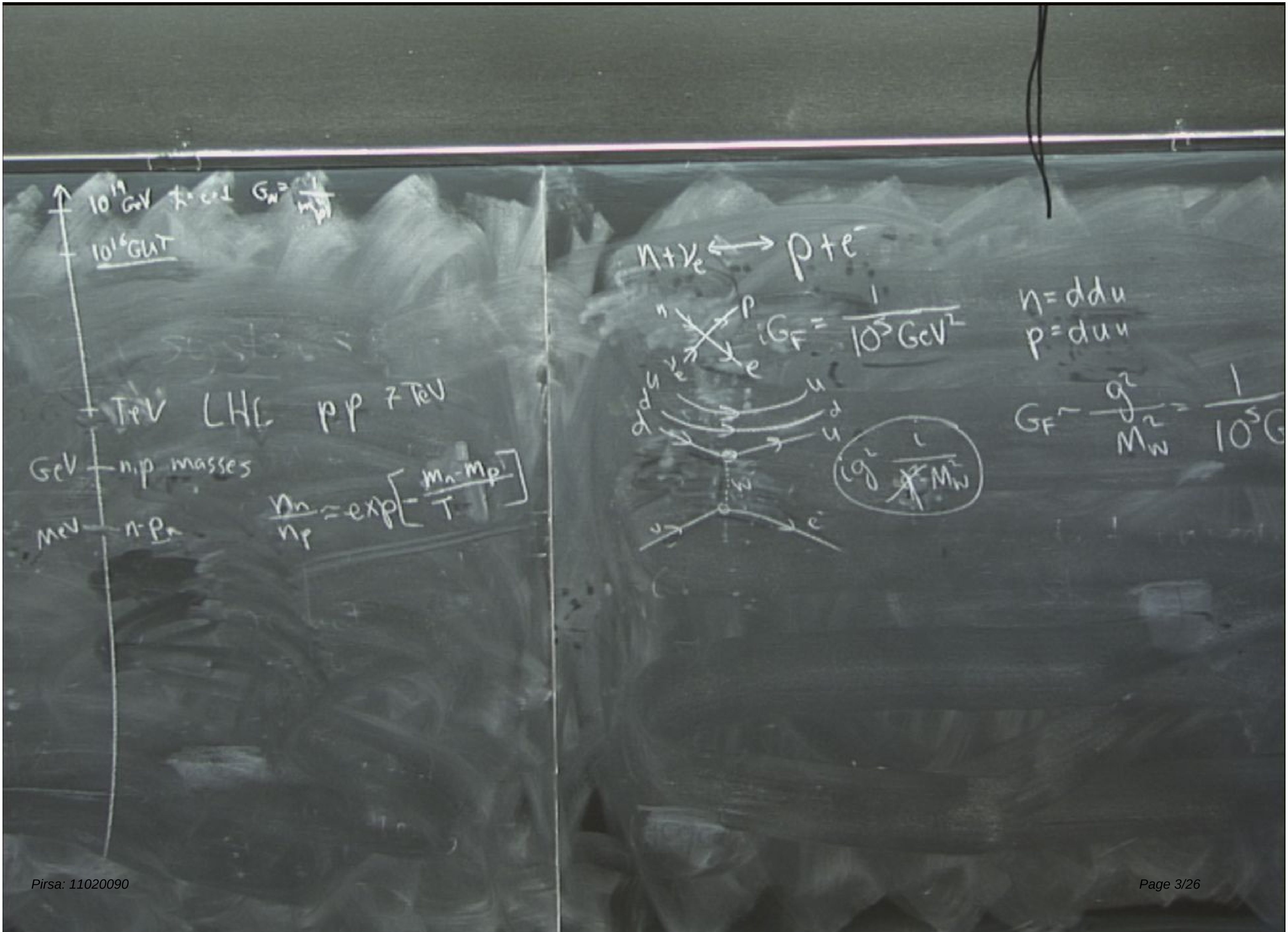
Title: Cosmology Review - Lecture 9

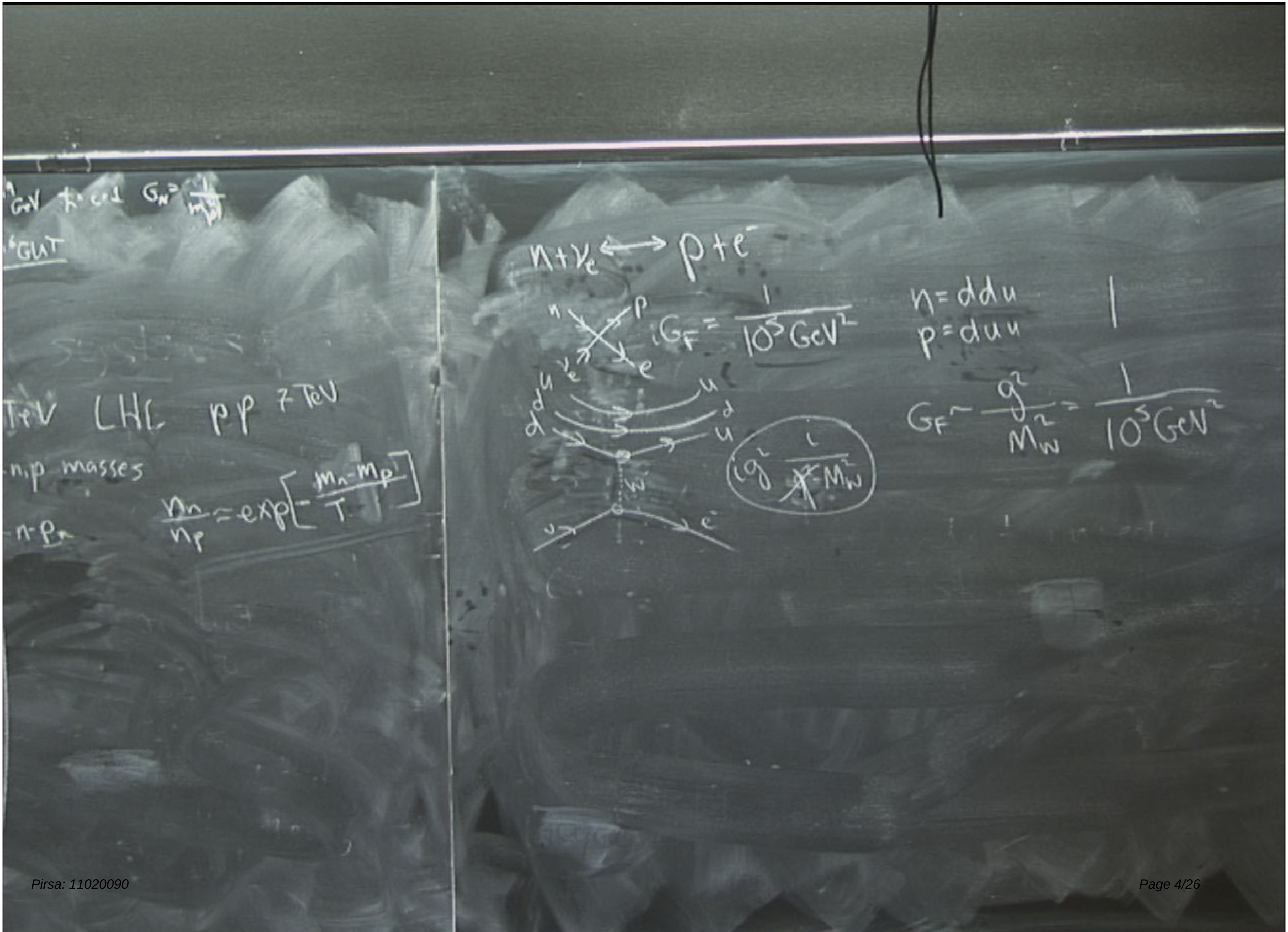
Date: Feb 03, 2011 11:30 AM

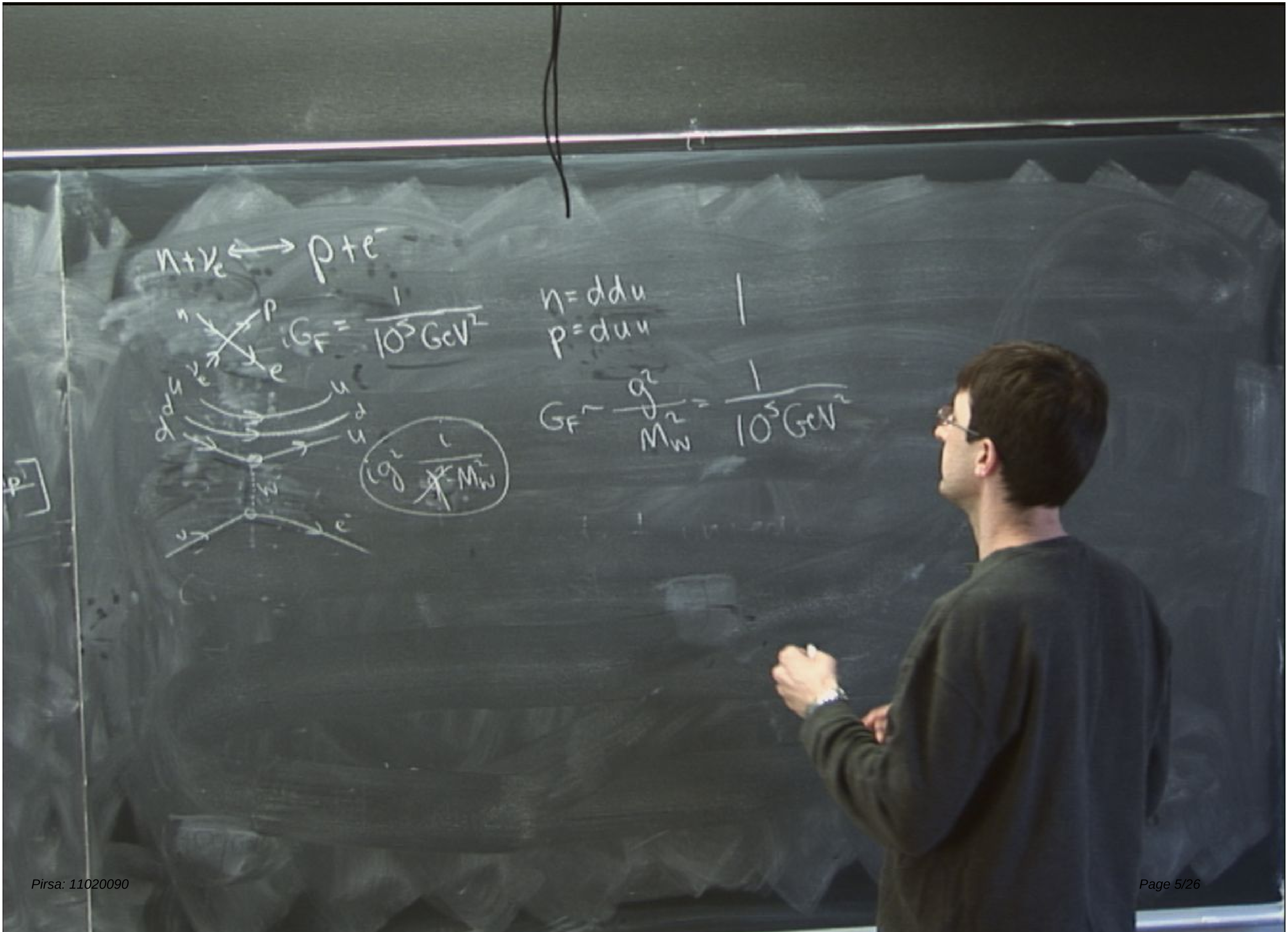
URL: http://pirsa.org/11020090

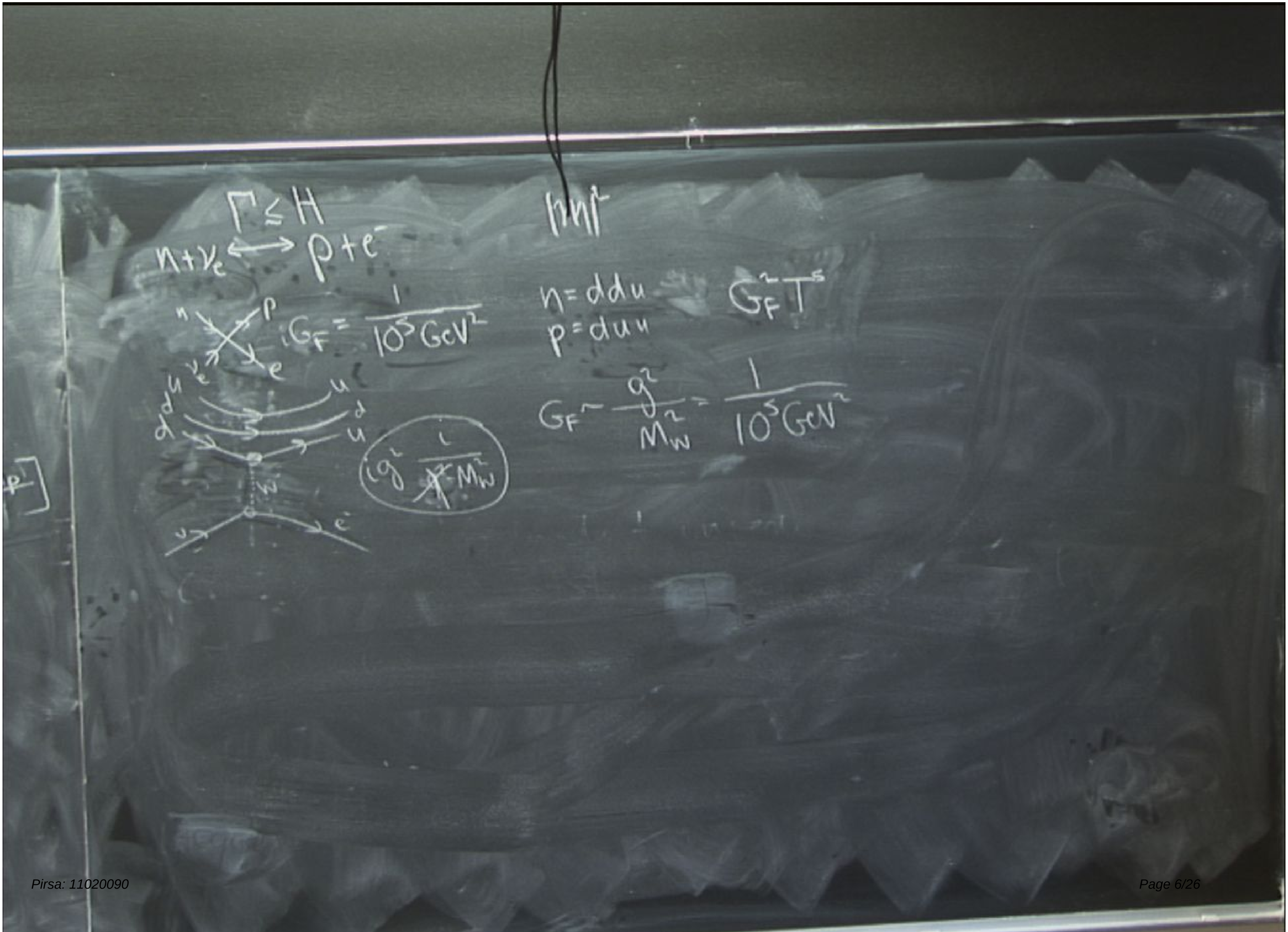
Abstract:

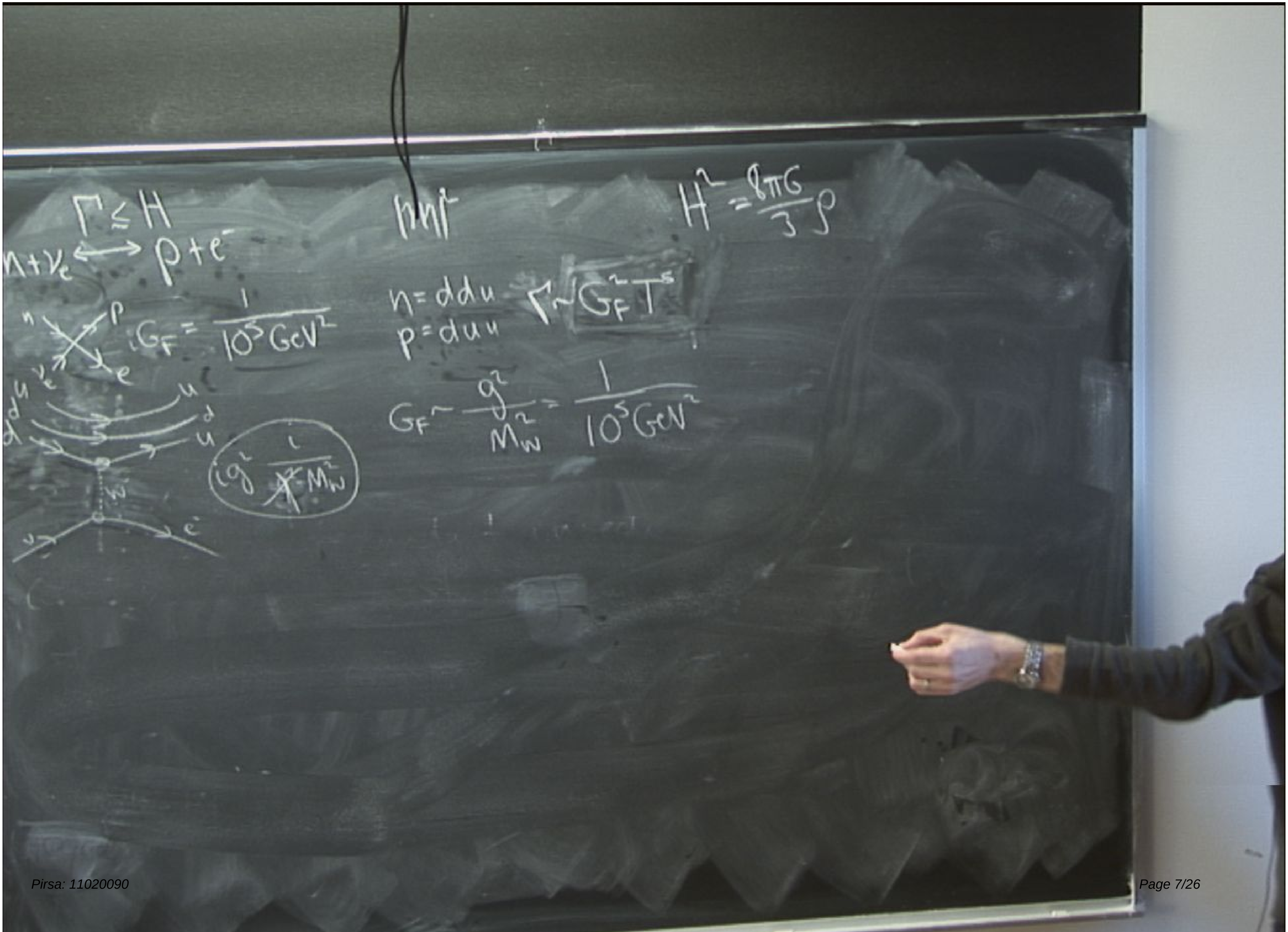

"Grok it like Gamow"
BBN
CMB
10^16 GUT
TeV LHC pp 7 TeV
GeV n,p masses
MeV n-p
n_n / n_p ≈ exp[-(m_n - m_p)/T]

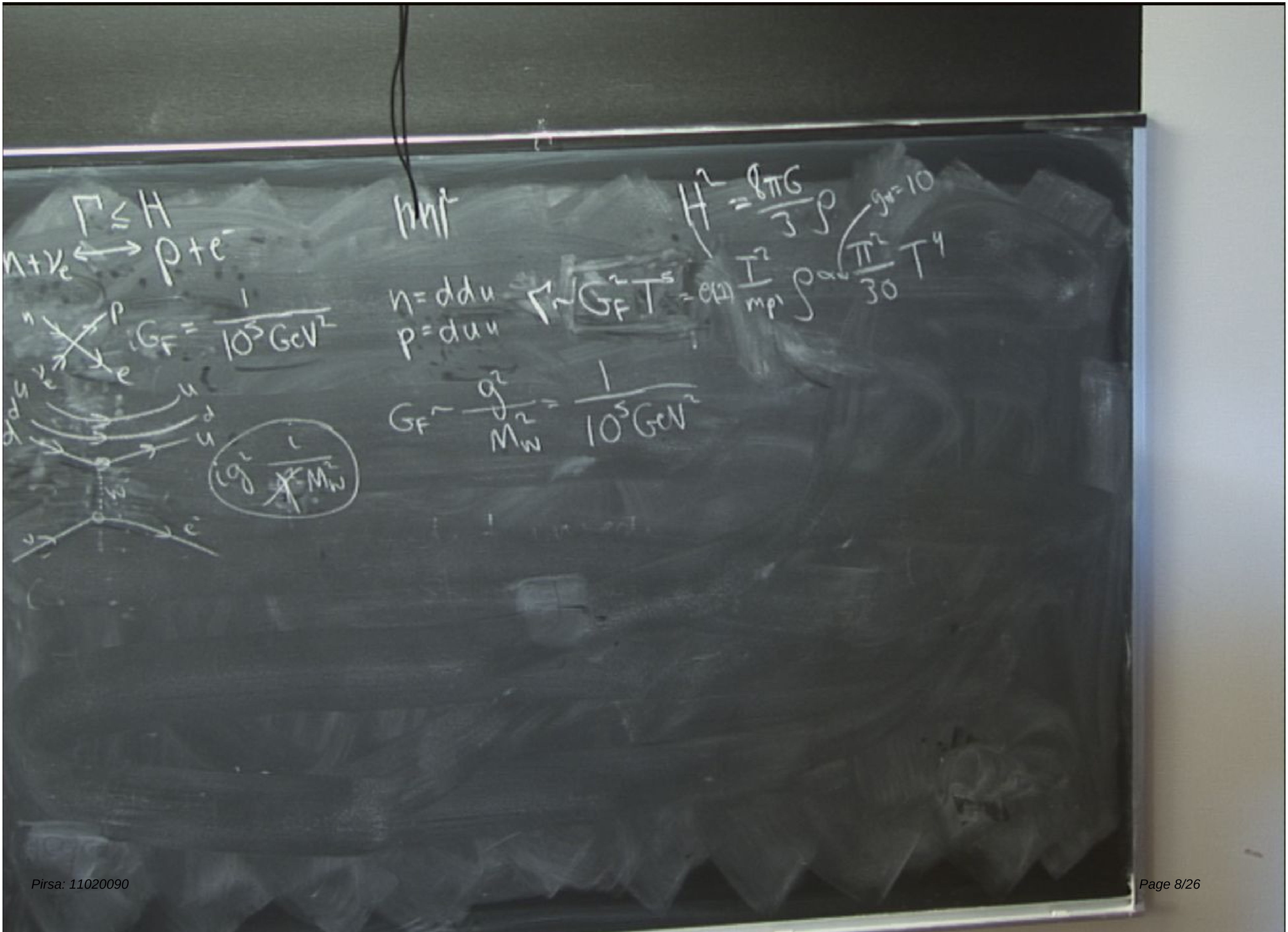

10^19 GeV
10^16 GUT
TeV LHC pp 7 TeV
GeV n, p masses
MeV n-p
n_n/n_p = exp[-(m_n-m_p)/T]
n+ν_e ⟷ p+e^-
iG_F = 1/10^5 GeV^2
n=ddu
p=duu
G_F ~ g^2/M_W^2 = 1/10^5 G
ig^2 i/(q^2-M_W^2)

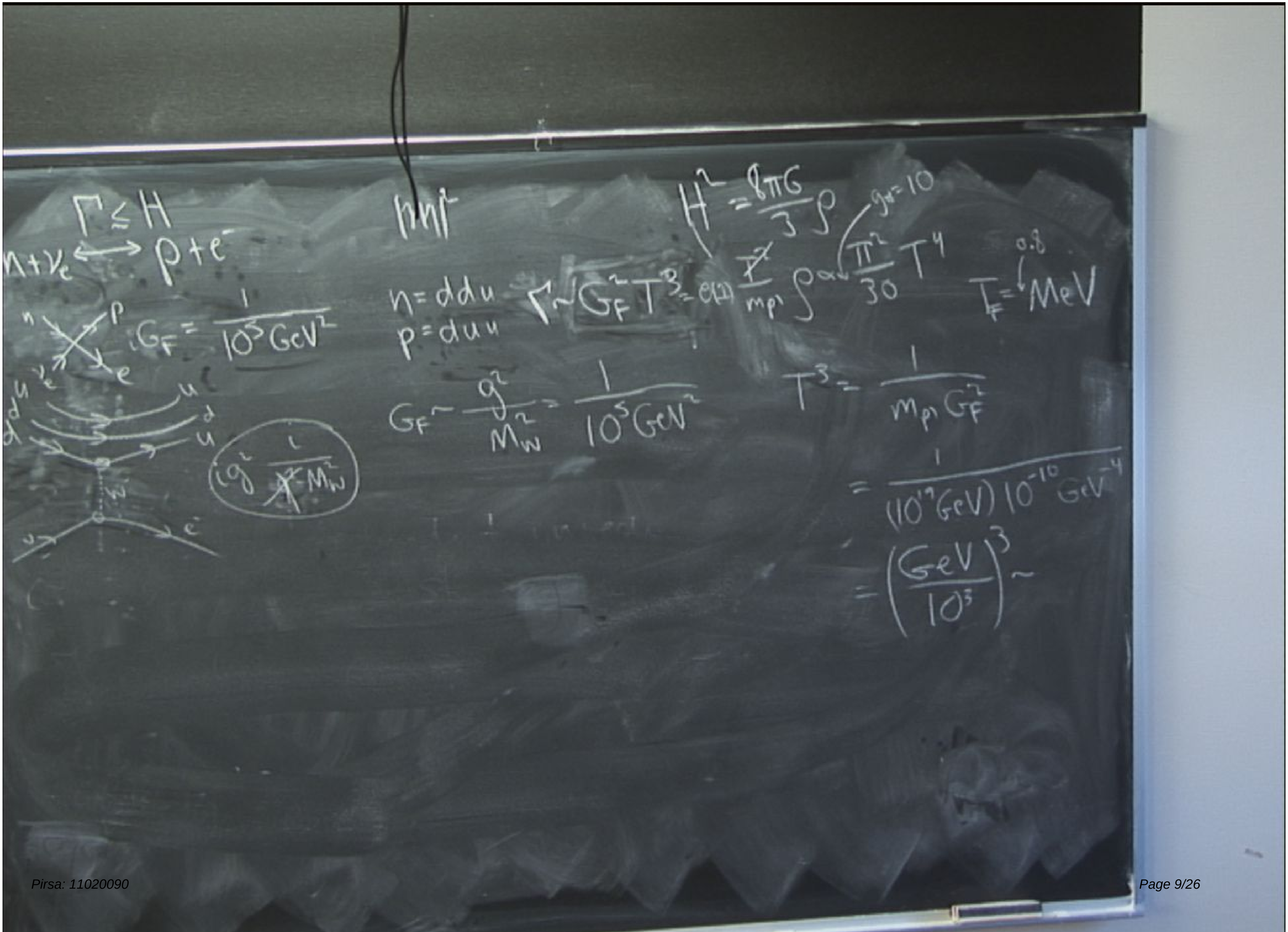

GeV ħ=c=1 G_N = 1/m_pl^2
GUT
TeV LHC pp 7 TeV
n, p masses
n_n/n_p ≃ exp[-(m_n - m_p)/T]
n + ν_e ⟷ p + e^-
iG_F = 1/(10^5 GeV^2)
n = ddu
p = duu
ig^2 i/(q^2 - M_W^2)
G_F ~ g^2/M_W^2 = 1/(10^5 GeV^2)
W


n + ν_e ⟷ p + e⁻
iG_F = 1 / 10^5 GeV^2
n = ddu
p = duu
G_F ~ g^2 / M_W^2 = 1 / 10^5 GeV^2

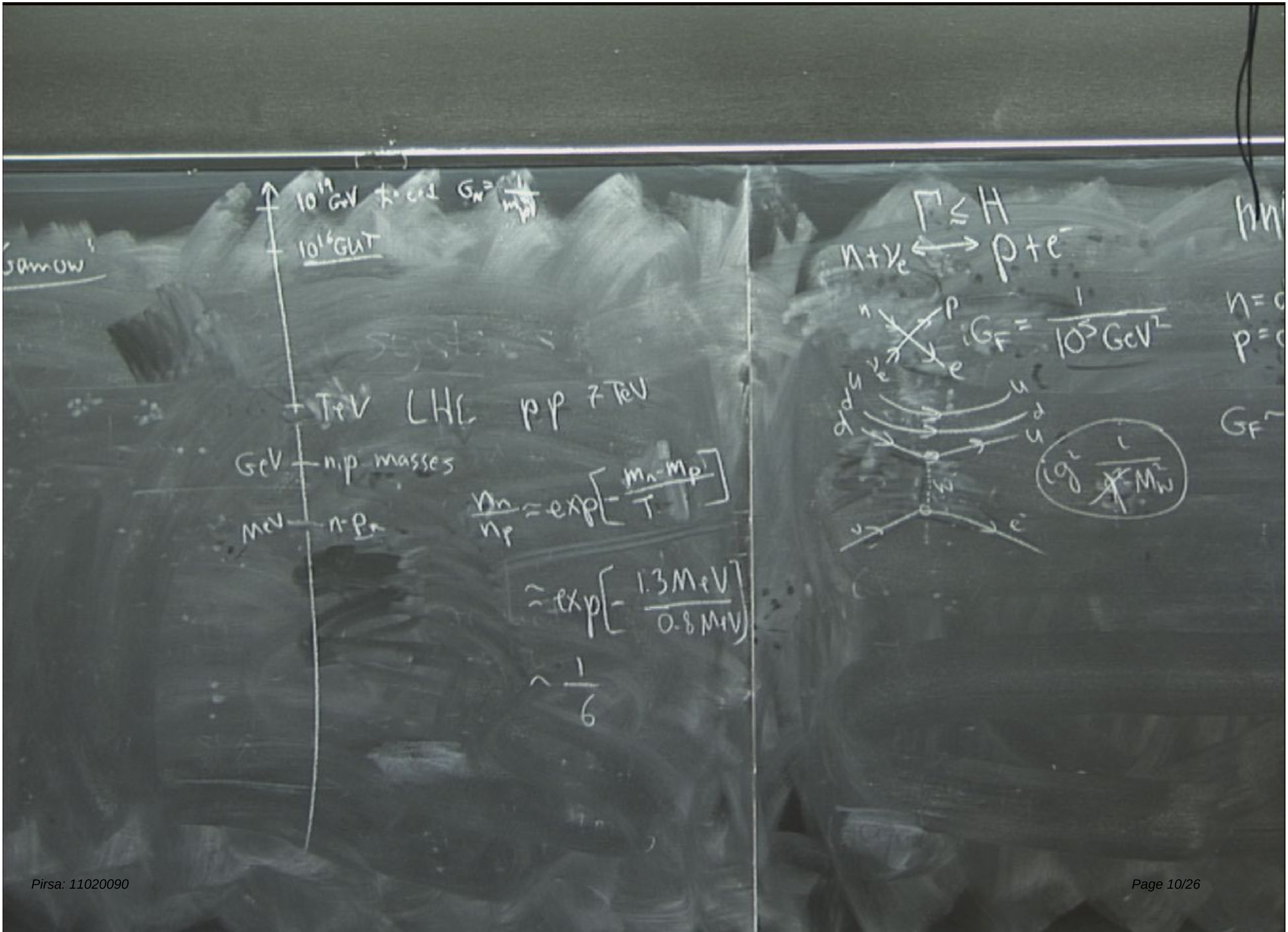

Γ ≤ H
n + νe ⟷ p + e⁻
iGF = 1 / 10⁵ GeV²
n = ddu
p = duu
GF² T⁵
GF ~ g² / MW² = 1 / 10⁵ GeV²
W


Γ ≤ H
n + ν_e ⟷ p + e⁻
G_F = 1 / 10⁵ GeV²
n = ddu
p = duu
Γ ~ G_F² T⁵
G_F ~ g² / M_W² = 1 / 10⁵ GeV²
H² = 8πG/3 ρ


Γ ≤ H
n + νe ⟷ p + e-
n = ddu
p = duu
GF = 1/10^5 GeV^2
Γ ~ GF^2 T^5
H^2 = 8πG/3 ρ
π^2/30 T^4
g* = 10
GF ~ g^2/MW^2 = 1/10^5 GeV^2



Γ ≤ H
n + ν_e ⟷ p + e⁻
G_F = 1 / 10⁵ GeV²
n = ddu
p = duu
Γ ~ G_F² T³
G_F ~ g² / M_W² = 1 / 10⁵ GeV²
H² = 8πG/3 ρ
g* = 10
π²/30 T⁴
T_F = 0.8 MeV
T³ = 1 / m_pl G_F²
= 1 / (10¹⁹ GeV) 10⁻¹⁰ GeV⁻⁴
= (GeV / 10³)³ ~



10^19 GeV
10^16 GUT
TeV LHC pp 7 TeV
GeV n, p masses
MeV n-p
nn/np ≃ exp[-(mn-mp)/T]
≃ exp[-1.3 MeV/0.8 MeV]
~ 1/6
Γ ≤ H
n + νe ⟷ p + e
iGF = 1/10^5 GeV^2
u d d u d u
W
e
ig^2 1/M_W^2

Gamow

10^{19} GeV $\hbar = c = 1$ $G_N = \frac{1}{m_{pl}^2}$

10^{16} GUT

TeV LHC pp 7 TeV

GeV — n, p masses

MeV — n-p

$$\frac{n_n}{n_p} \simeq \exp\left[-\frac{m_n - m_p}{T}\right]$$

$$\simeq \exp\left[-\frac{1.3\,\mathrm{MeV}}{0.8\,\mathrm{MeV}}\right]$$

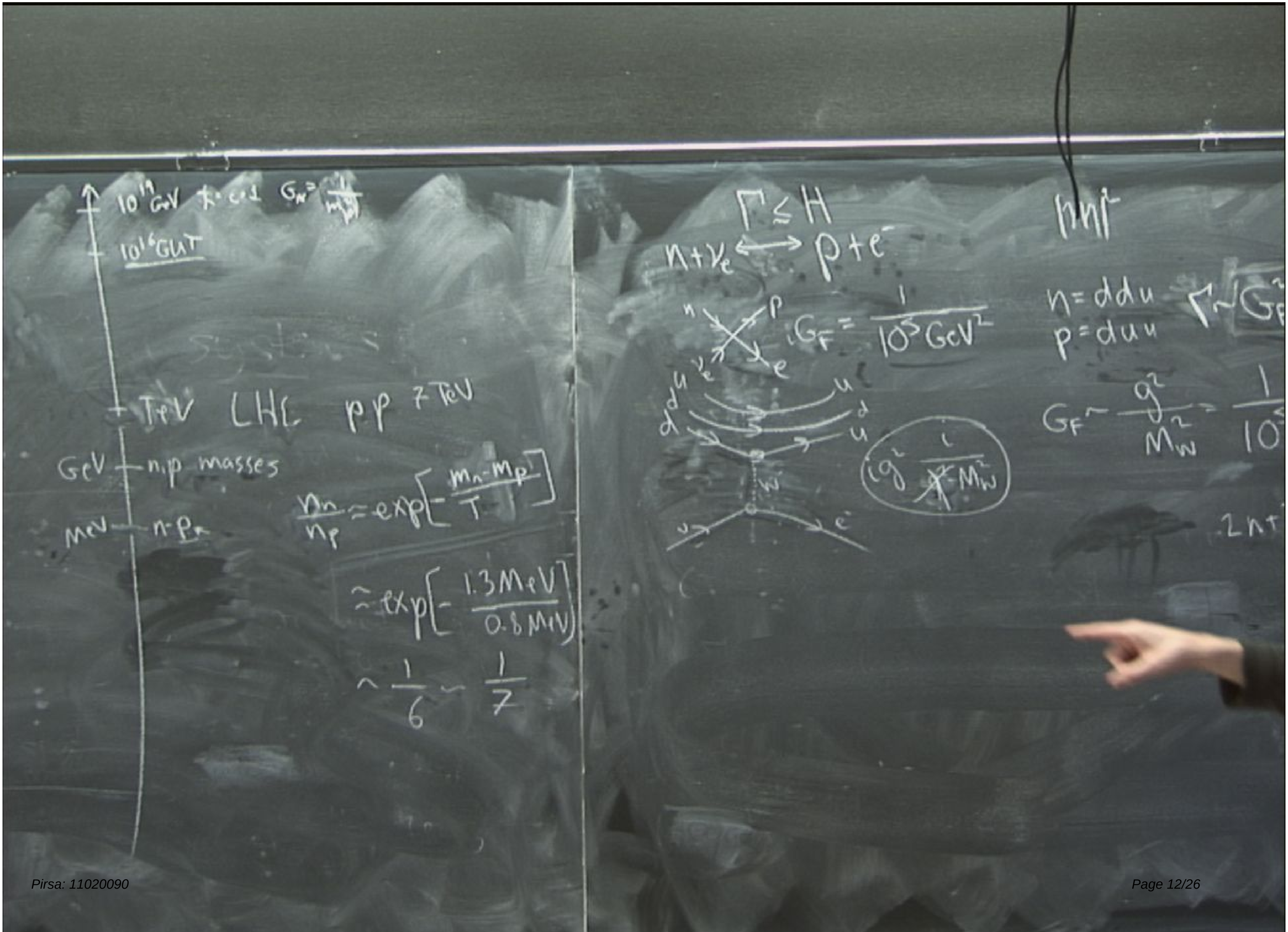
$$\sim \frac{1}{6}$$

$\Gamma \lesssim H$

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

$G_F = \frac{1}{10^5\,\mathrm{GeV}^2}$

$ig^2 \frac{1}{q^2 - M_W^2}$


10^19 GeV ħ = c = 1 G_N = 1/m_pl^2
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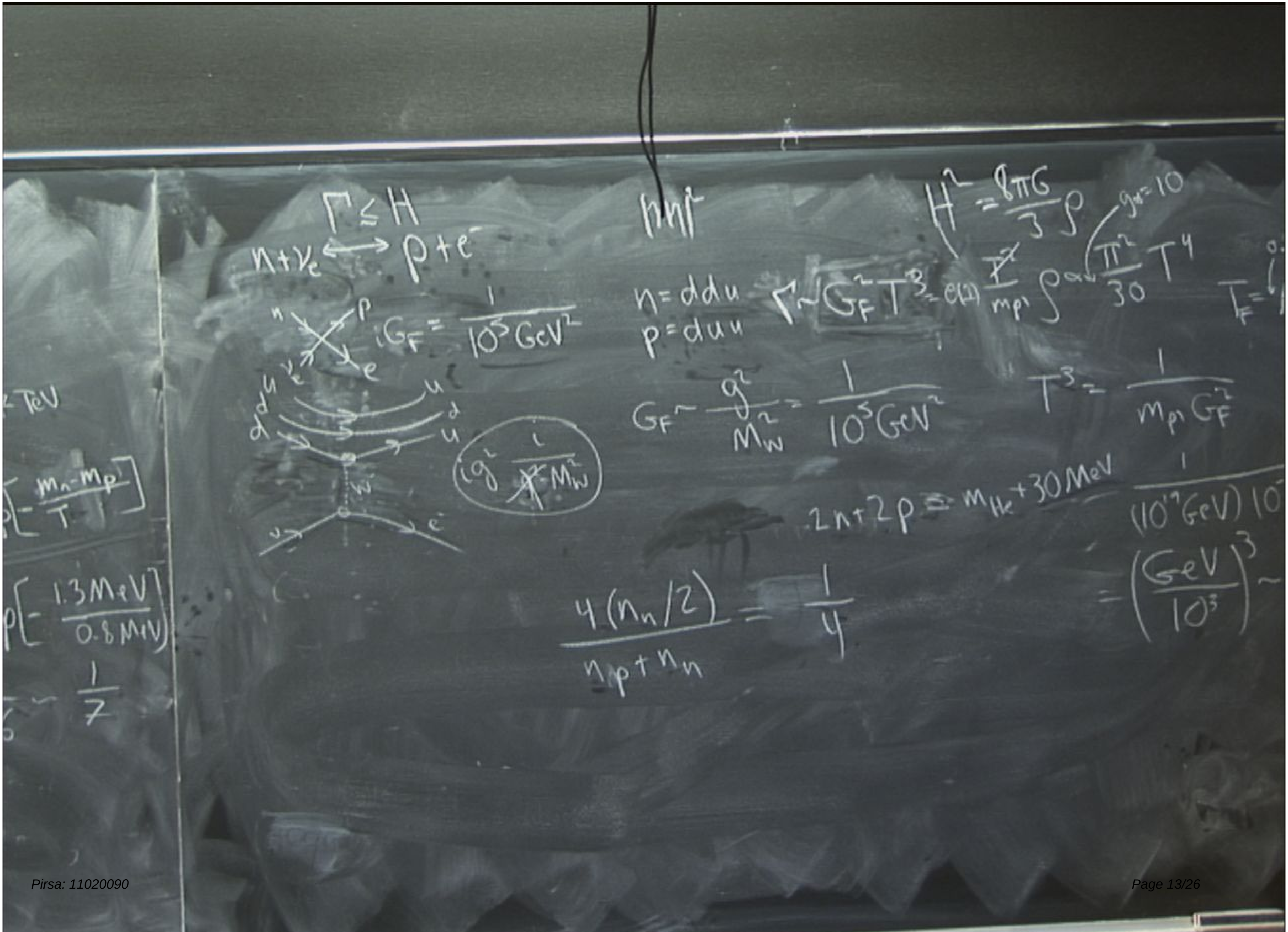
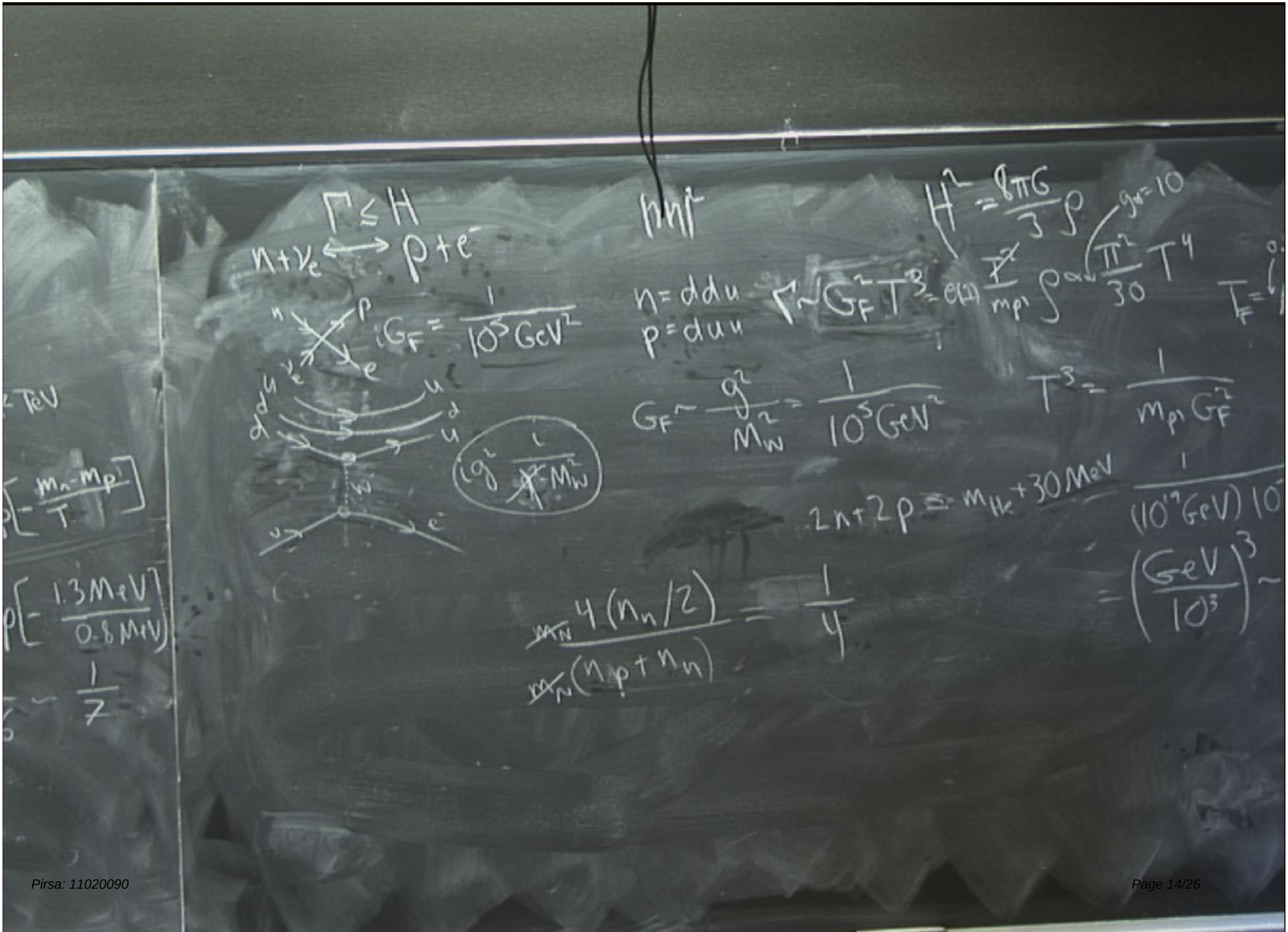
TeV LHC pp 7 TeV
GeV n, p masses
MeV n-p
n_n/n_p ≃ exp[-(m_n - m_p)/T]
≃ exp[-1.3 MeV/0.8 MeV]
~ 1/6 ~ 1/7
Γ ≤ H
n + ν_e ⟷ p + e^-
n p ν_e e
iG_F = 1/(10^5 GeV^2)
u d d u d u
W
ν e
ig^2 i/(q^2 - M_W^2)
n = ddu
p = duu
G_F ~ g^2/M_W^2



Γ ≤ H
n + ν_e ⟷ p + e⁻
iG_F = 1/(10⁵ GeV²)
n = ddu
p = duu
Γ ~ G_F² T³
H² = (8πG/3) ρ
g* = 10
ρ ∝ (π²/30) T⁴
T³ = 1/(m_pl G_F²)
G_F ~ g²/M_W² = 1/(10⁵ GeV²)
ig² i/(q² − M_W²)
2n + 2p = m_He + 30 MeV
4(n_n/2)/(n_p + n_n) = 1/4
1/((10¹⁹ GeV) 10
= (GeV/10³)³ ~
TeV
exp[−(m_n − m_p)/T]
exp[−1.3 MeV/0.8 MeV]
~ 1/7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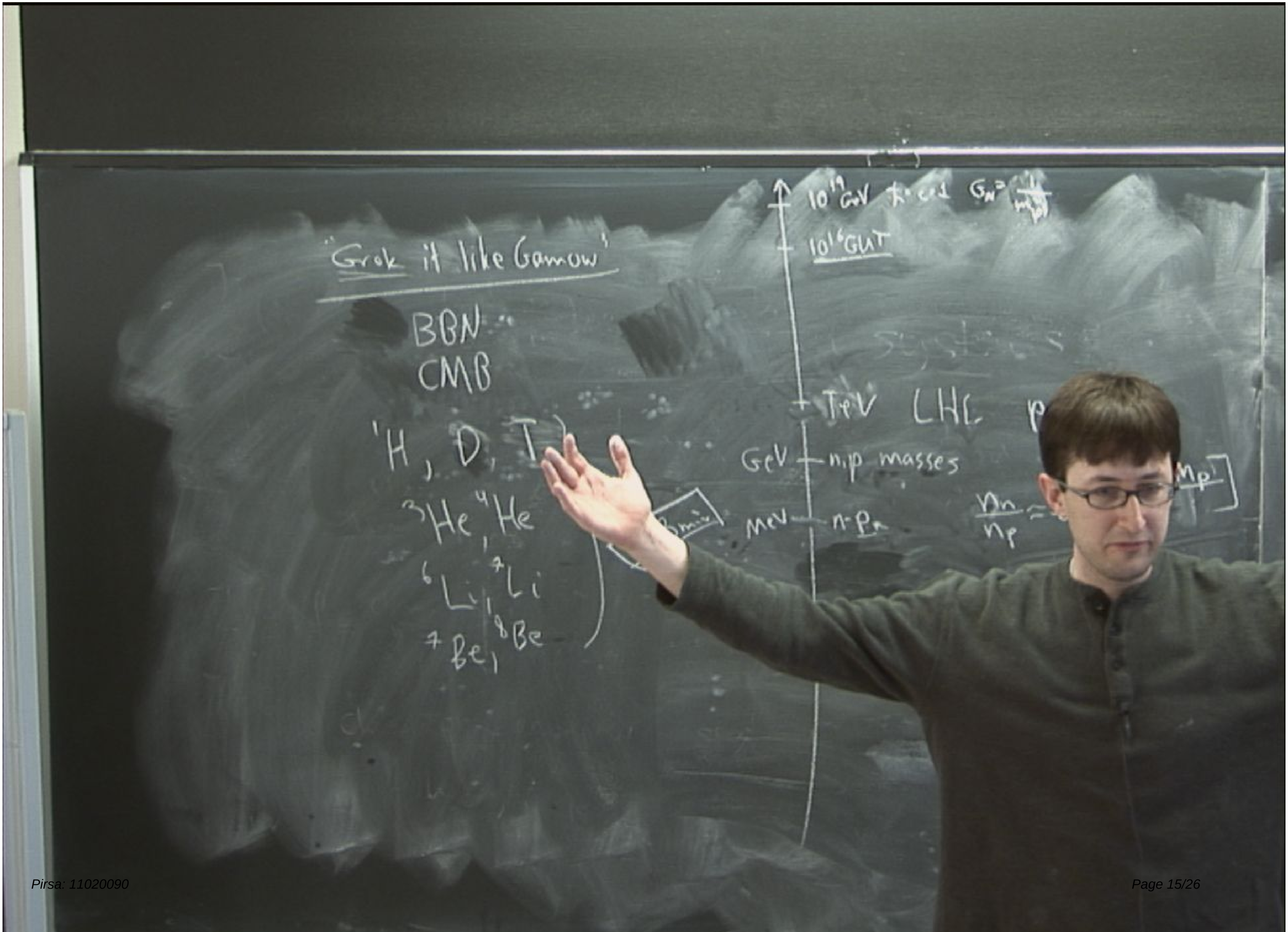
H² = 8πG/3 ρ
ρ ∝ π²/30 T⁴
g* = 10
T³ = 1 / (m_pl G_F²)
2n + 2p = m_He + 30 MeV
= (GeV / 10³)³
4 (n_n/2) / (n_p + n_n) = 1/4
1.3 MeV / 0.8 MeV
1/7
TeV


"Grok it like Gamow"
BBN
CMB
¹H, D, T
³He, ⁴He
⁶Li, ⁷Li
⁷Be, ⁸Be
10¹⁹ GeV
10¹⁶ GUT
TeV LHC
GeV
n,p masses
MeV

"Grok it like Gamow"

BBN

CMB

$^{1}H, D, T$

$^{3}He, ^{4}He$

$^{6}Li, ^{7}Li$

$^{7}Be, ^{8}Be$

1s–3min

10^{19} GeV $\hbar = c = 1$ $G_N = \frac{1}{m_{pl}^2}$

10^{16} GUT

TeV LHC pp 7 TeV

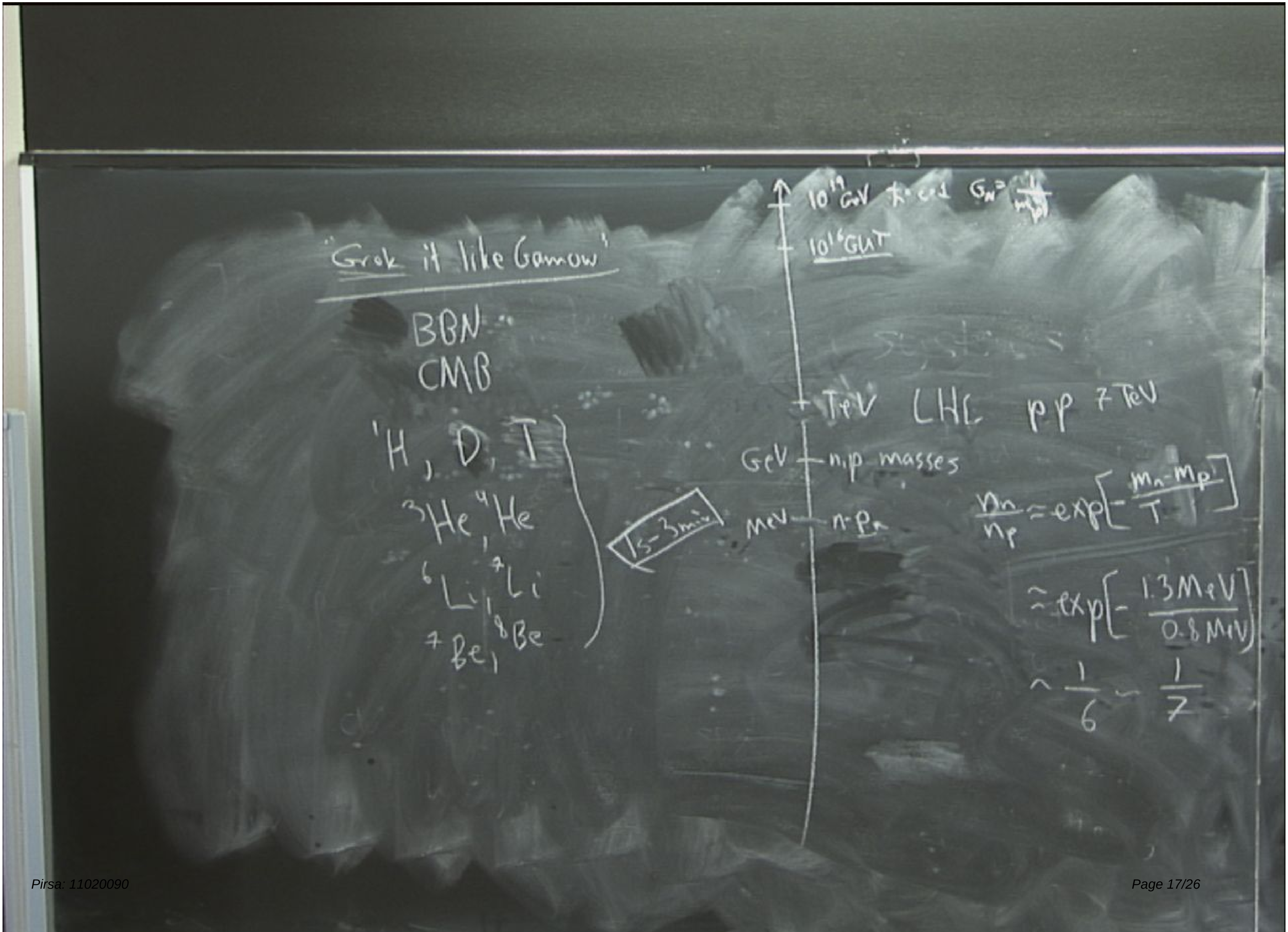
GeV — n, p masses

MeV — n–p

$$\frac{n_n}{n_p} \simeq \exp\left[-\frac{m_n - m_p}{T}\right]$$

$$\simeq \exp\left[-\frac{1.3\,MeV}{0.8\,M\ldots}\right]$$

$$\sim \frac{1}{6} \sim \frac{1}{7}$$


"Grok it like Gamow"
BBN
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1H, D, T
3He, 4He
6Li, 7Li
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1s-3min
10^19 GeV
10^16 GUT
TeV LHC pp 7 TeV
GeV n, p masses
MeV n-p
nn/np ≃ exp[-(mn-mp)/T]
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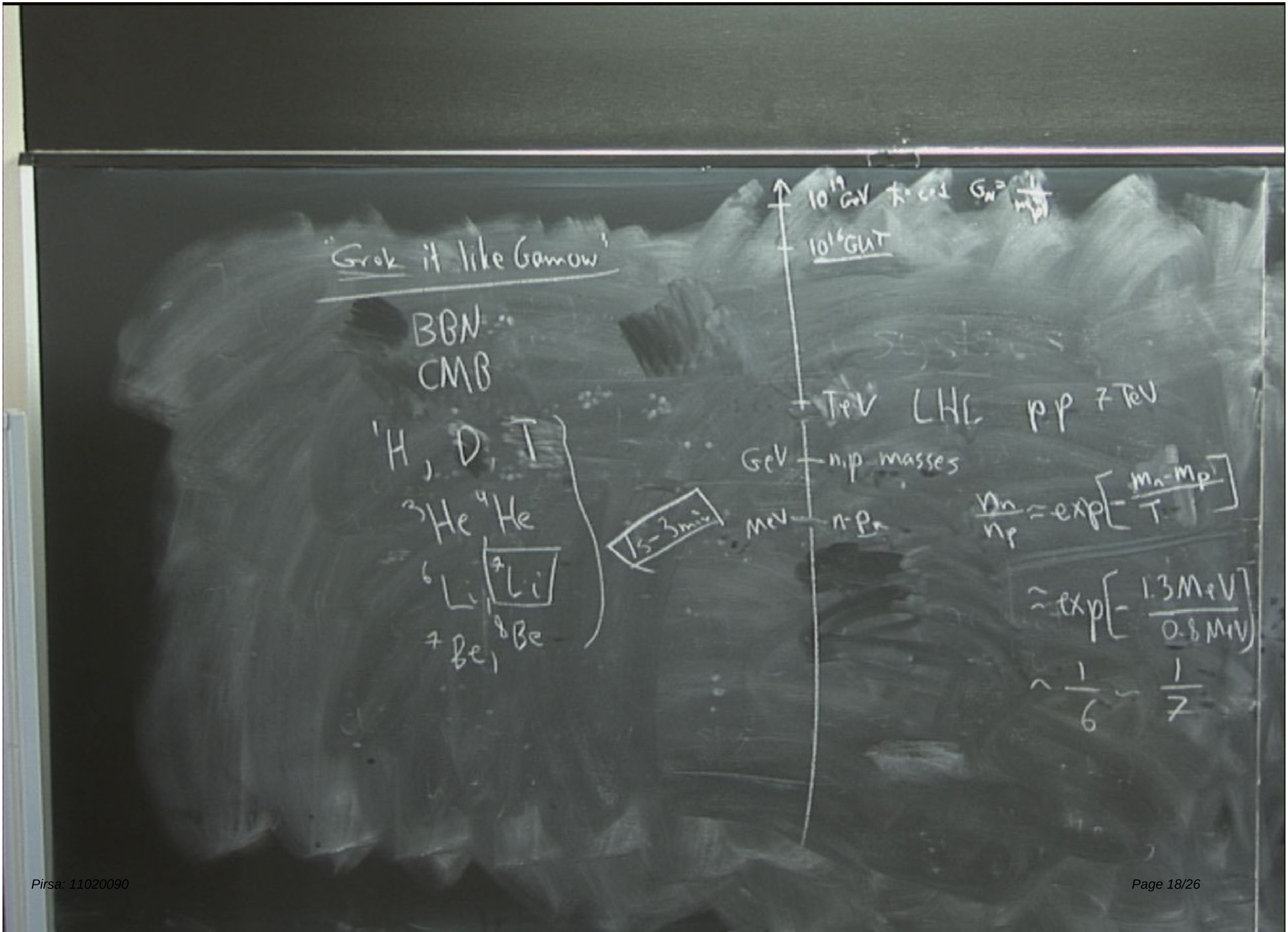
~ 1/6 ~ 1/7


"Grok it like Gamow"
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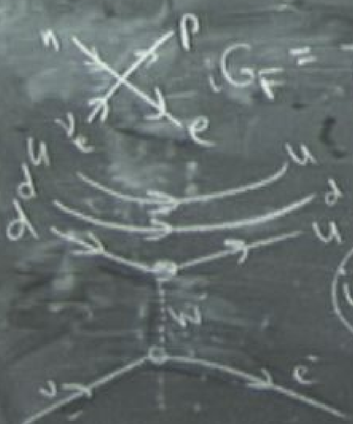
1s–3min
10¹⁹ GeV
10¹⁶ GUT
TeV LHC pp 7 TeV
GeV n, p masses
MeV n-p
$\frac{n_n}{n_p} \simeq \exp\left[-\frac{m_n - m_p}{T}\right]$
$\simeq \exp\left[-\frac{1.3\,MeV}{0.8\,MeV}\right]$
$\sim \frac{1}{6} - \frac{1}{7}$

$\Gamma \leq H$

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



$G_F = \frac{1}{10^5\,\text{GeV}^2}$

$ig^2 \frac{i}{q^2 - M_W^2}$

$n = ddu$

$p = duu$

$\Gamma \sim G_F^2 T^5 = O(1) \frac{T^2}{m_{pl}}$

$H^2 = \frac{8\pi G}{3}\rho$

$\rho \approx g_* \frac{\pi^2}{30} T^4, \quad g_* = 10$

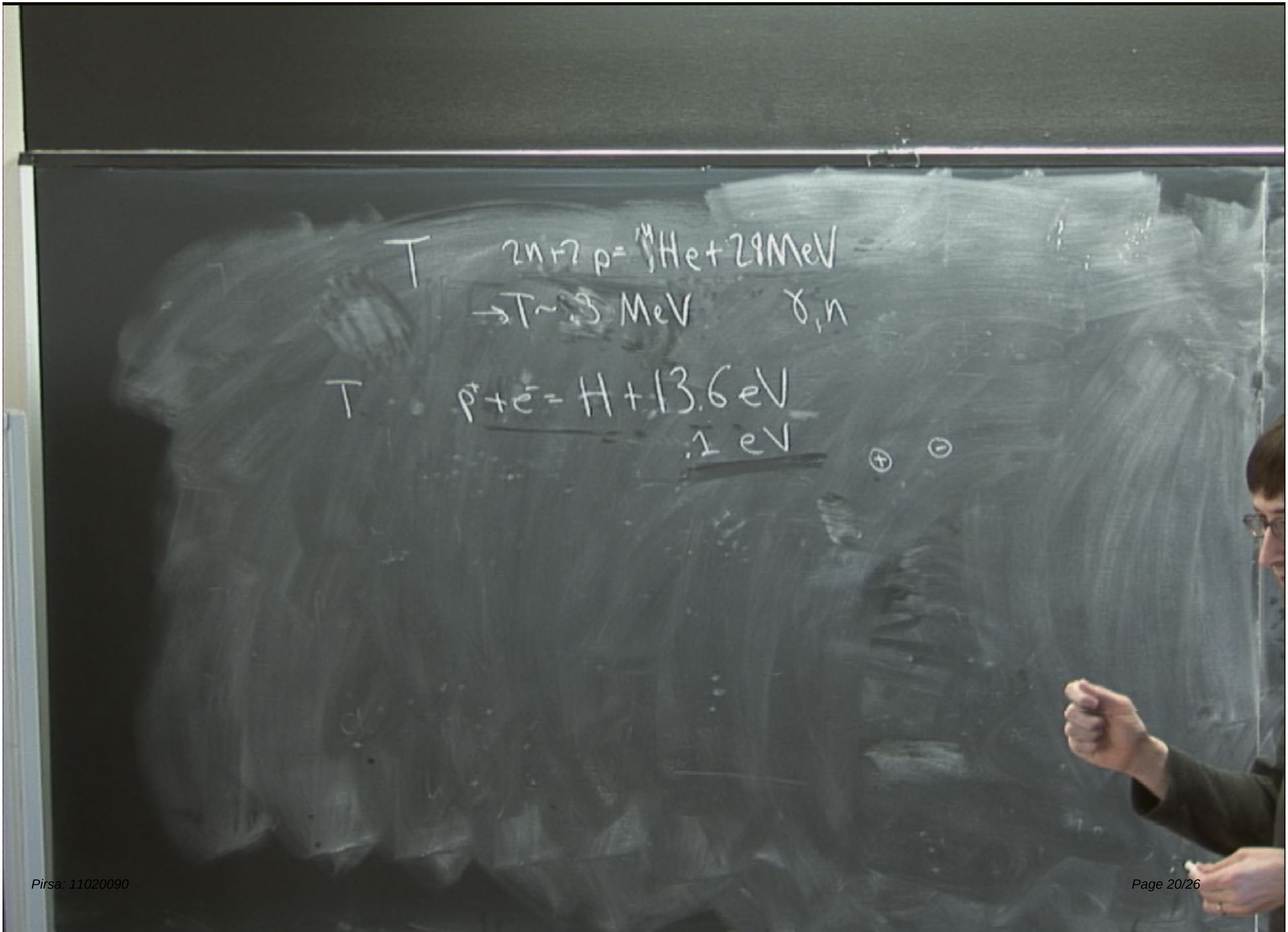
$T_F = 1\,\text{MeV}$ (0.8)

$G_F \sim \frac{g^2}{M_W^2} = \frac{1}{10^5\,\text{GeV}^2}$

$T^3 = \frac{1}{m_{pl} G_F^2} = \frac{1}{(10^{19}\,\text{GeV})\,10^{-10}\,\text{GeV}^{-4}} = \left(\frac{\text{GeV}}{10^3}\right)^3 \sim$

$2n + 2p = m_{He} + 30\,\text{MeV}$

$\frac{m_N\, 4(n_n/2)}{m_N (n_p + n_n)} = \frac{1}{4}$


T 2n+2p = ⁴He + 28MeV
→T ~ .3 MeV γ, n
T p⁺+e⁻ = H + 13.6 eV
.1 eV

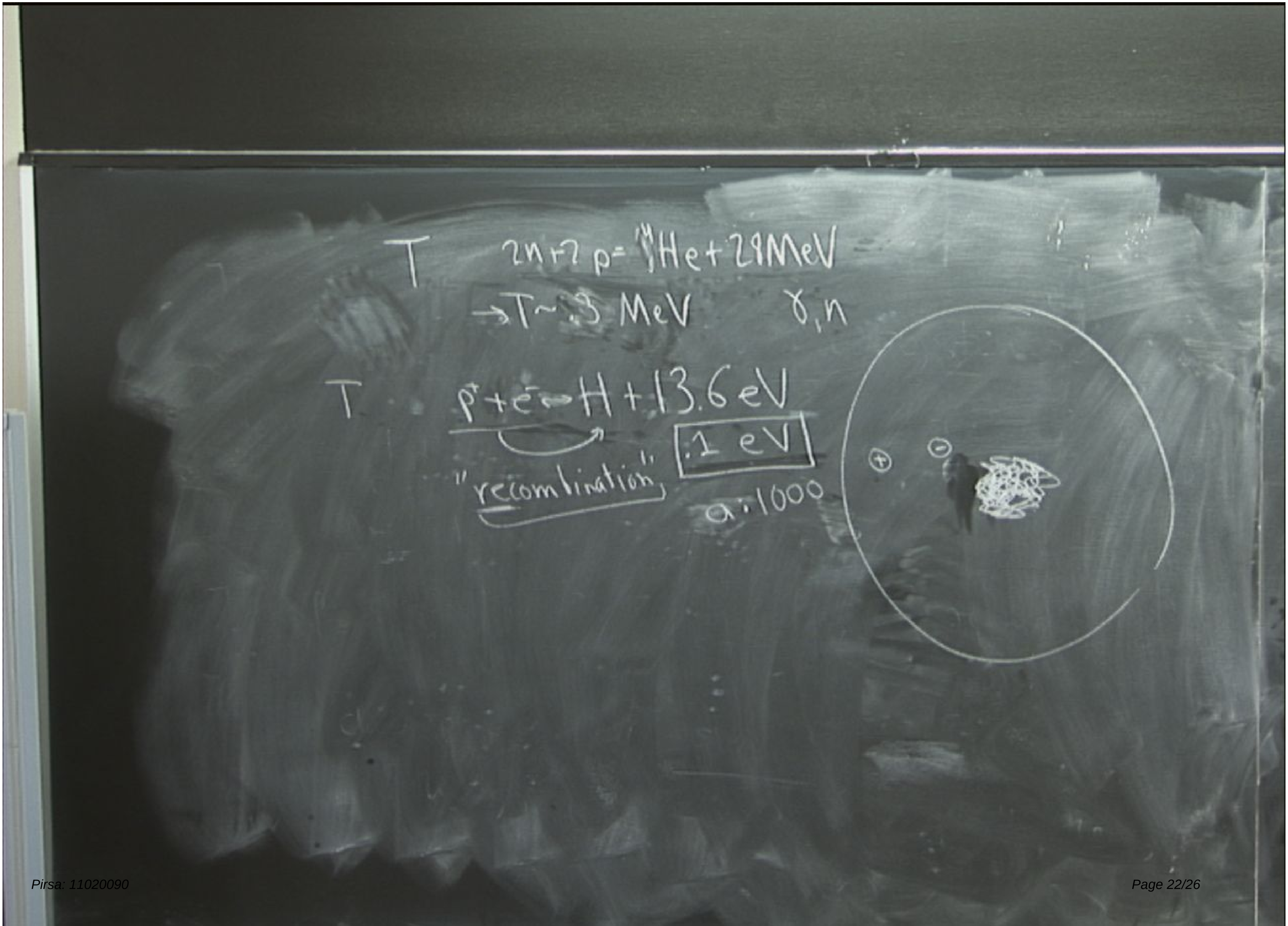
$T \quad 2n + 2p = {}^{4}_{2}He + 28\,MeV$

$\rightarrow T \sim .3\,MeV \qquad \gamma, n$

$T \quad p^{+} + e^{-} = H + 13.6\,eV$

"recombination" $\boxed{.1\,eV}$

$a \cdot 1000$


T
2n+2p= ⁴He+29MeV
→T~.3 MeV
γ,n
T
p⁺+e⁻→H+13.6eV
.1 eV
"recombination"
a:1000
+
−

$$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{\mu_i - m_i}{T}\right]$$

$$\frac{n_p n_e}{n_H}$$

$$n = 2\,\frac{\zeta(3)}{\pi^2}\,T^3$$

$$X_e = \frac{n_e}{n_e + n_H}$$

$$p^+ + e^- \longleftrightarrow H + \gamma \quad (+2\gamma)$$

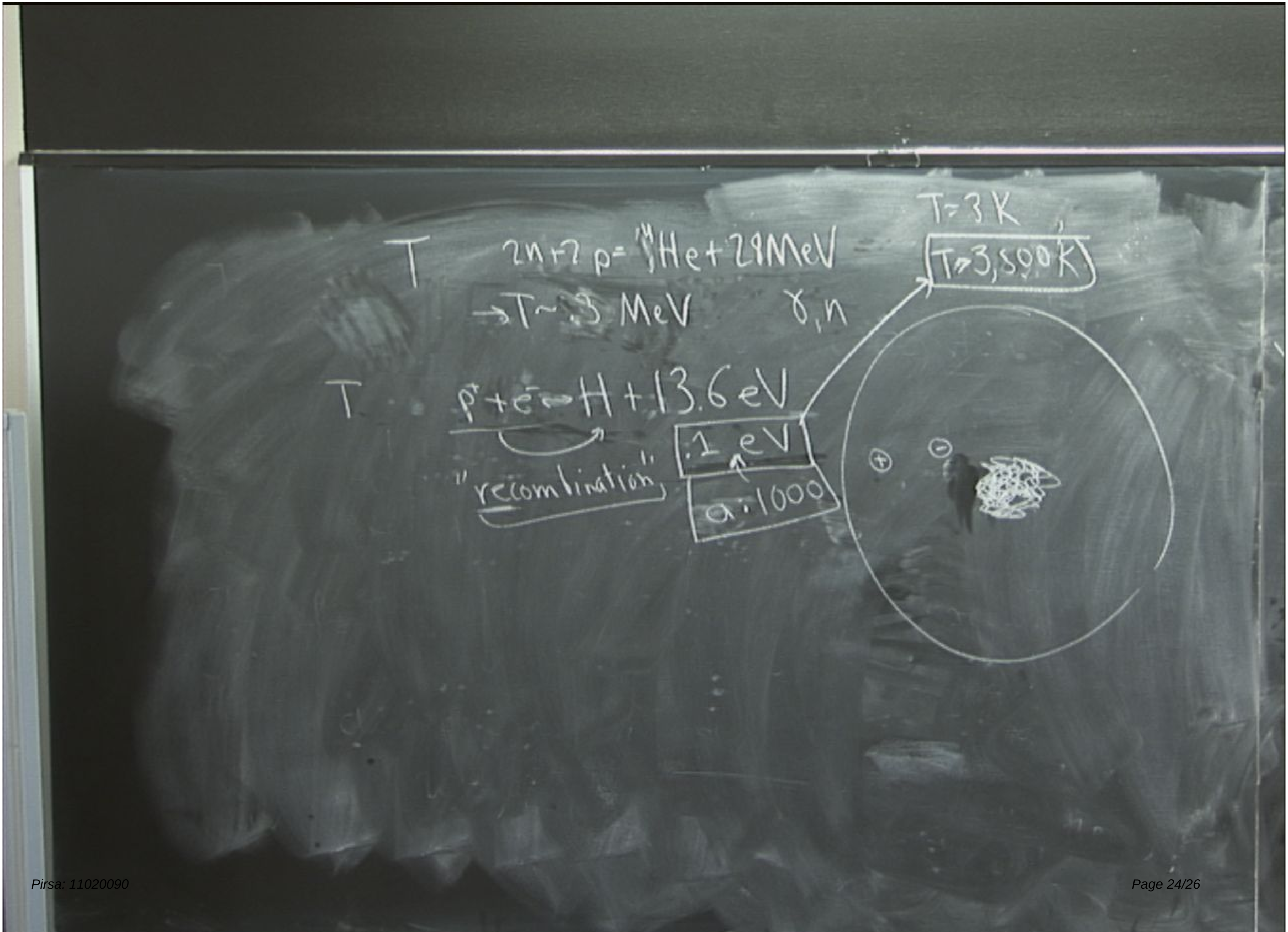
$$dA = S\,dT - P\,dV + \mu_i\,dN_i + \dots + \mu_p N_p + \mu_e N_e + \mu_\nu N_\nu + \mu_H N_H$$

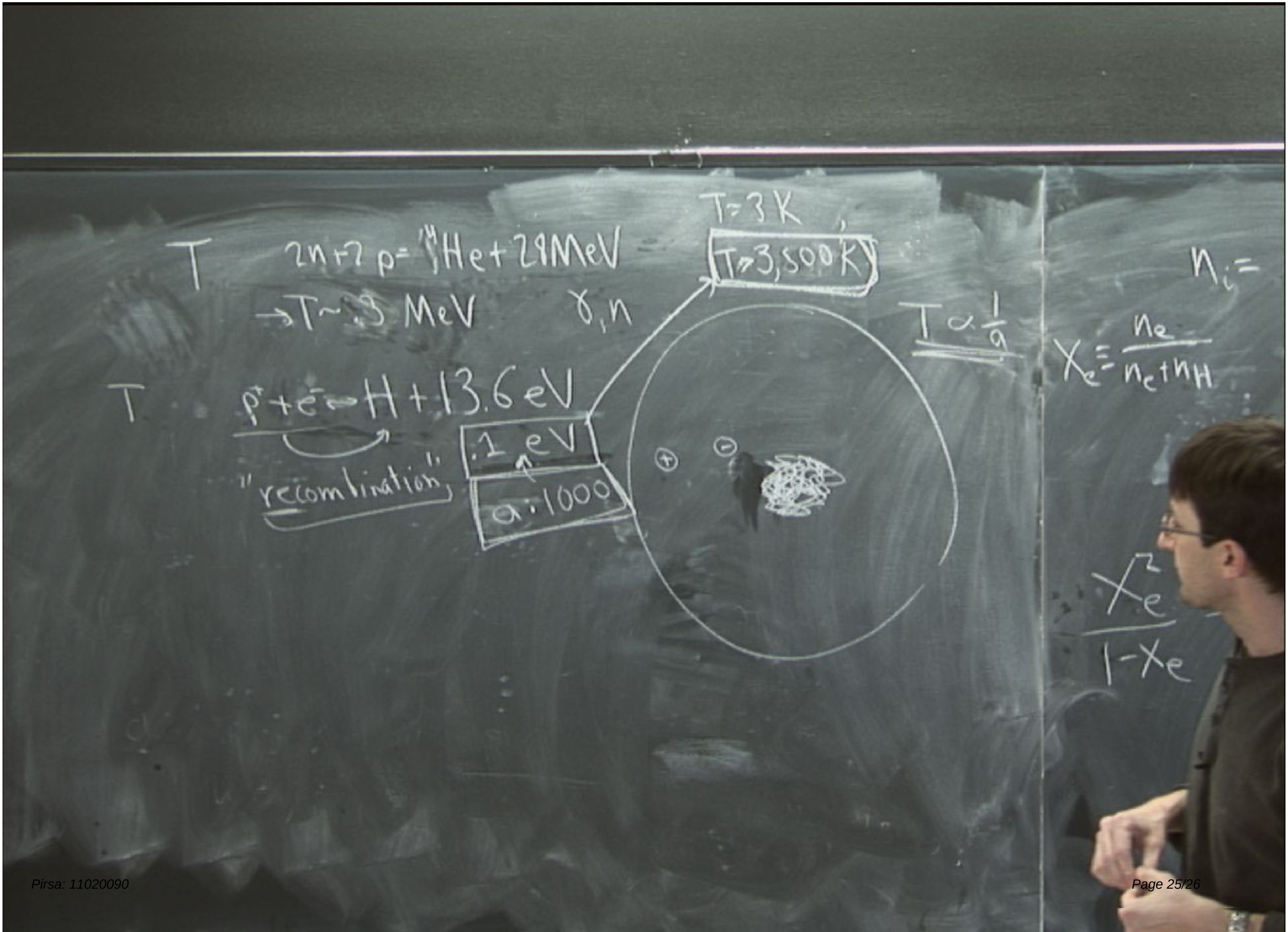
$$\boxed{\mu_p + \mu_e = \mu_H + \mu_\gamma + \dots}$$

$$\frac{X_e^2}{1 - X_e} = \frac{n_e^2}{n_H} = \left(\frac{m_p T}{2\pi}\right)^{3/2} \left(\frac{m_e T}{2\pi}\right)^{3/2} \left(\frac{2\pi}{m_H T}\right)^{3/2} \exp\left[\frac{m_H - m_p - m_e}{T}\right]$$

$$= \left(\frac{m_e T}{2\pi}\right)^{3/2} \exp\left(-\frac{B_H}{T}\right) \frac{1}{\frac{3}{4}\eta n_\gamma}$$

$$=$$


T
2n+2p = He + 28MeV
→T ~ .3 MeV
γ, n
T = 3 K
T ≈ 3,500 K
T
p + e → H + 13.6 eV
.1 eV
"recombination"
a·1000


T=3 K
T≈3,500 K
T
2n+2 p= He+28MeV
→T~.3 MeV
γ, n
T ∝ 1/a
n_i =
X_e = n_e / (n_e + n_H)
T
p+e → H + 13.6 eV
.1 eV
"recombination"
a≈1000
X_e^2 / (1-X_e)

$$n_i = \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[\frac{\mu_i - m_i}{T}\right]$$

$$\frac{n_p n_e}{n_H}$$

$$n = 2\frac{\zeta(3)}{\pi^2} T^3$$

$$\frac{1}{a}$$

$$X_e \equiv \frac{n_e}{n_e + n_H}$$

$$p^+ + e^- \longleftrightarrow H + \gamma \quad (+2\gamma)$$

$$\mu_p + \mu_e = \mu_H + \mu_\gamma + \dots$$

$$dA = SdT - PdV + \mu_i dN_i + \dots$$
$$+ \mu_p N_p + \mu_e N_e + \mu_\nu N_\nu + \mu_H N_H$$

$$\frac{X_e^2}{1 - X_e} = \frac{n_e^2}{n_H} = \left(\frac{m_p T}{2\pi}\right)^{3/2} \left(\frac{m_e T}{2\pi}\right)^{3/2} \left(\frac{2\pi}{m_H T}\right)^{3/2} \exp\left[\frac{m_H - m_p - m_e}{T}\right]$$

$$= \left(\frac{m_e T}{2\pi}\right)^{3/2} \exp\left(-\frac{B_H}{T}\right) \frac{1}{\frac{3}{4}\eta n_\gamma}$$

$$=$$