Title: Cosmology (2021/2022)

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Collection: Cosmology (2021/2022)

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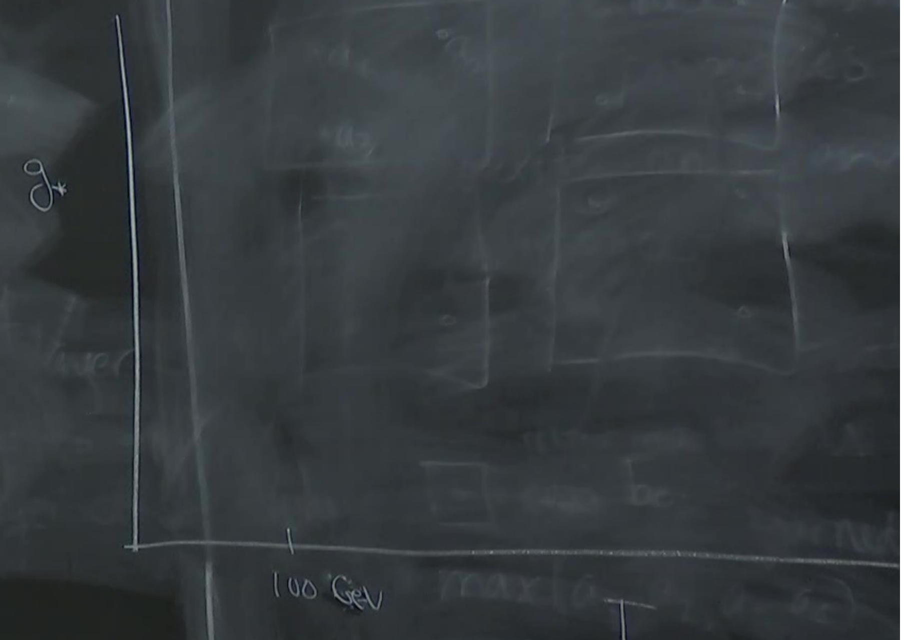
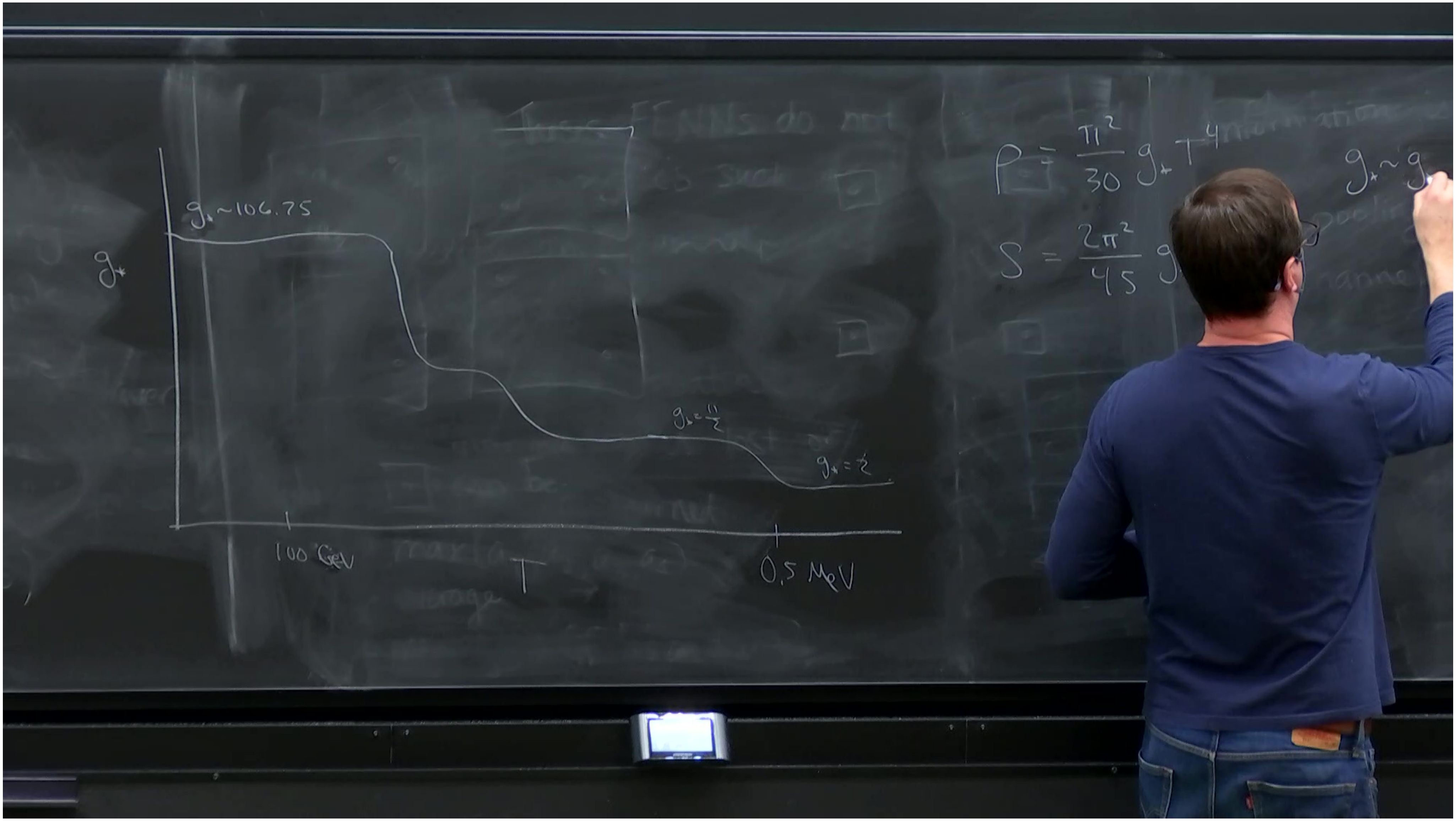
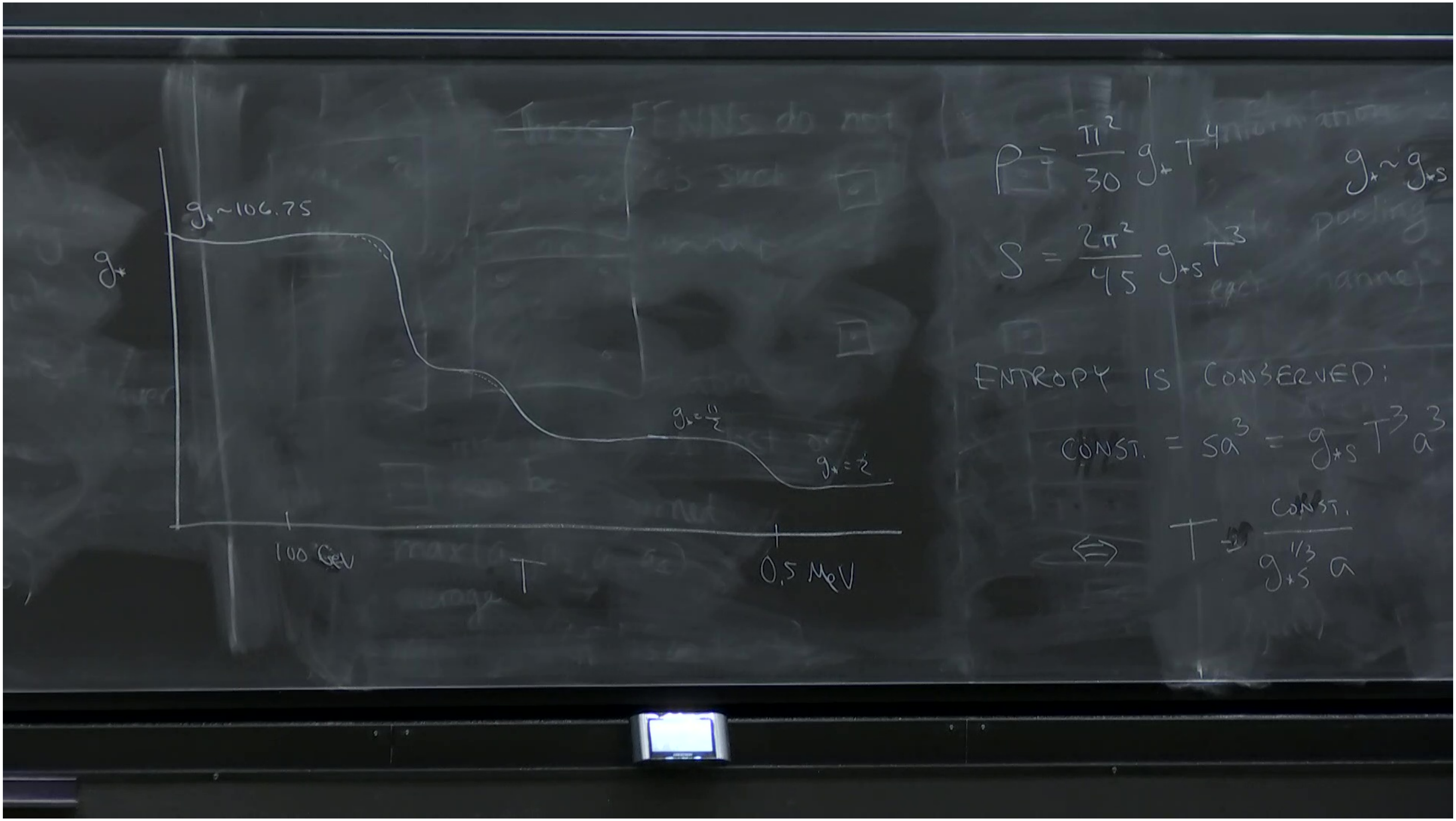
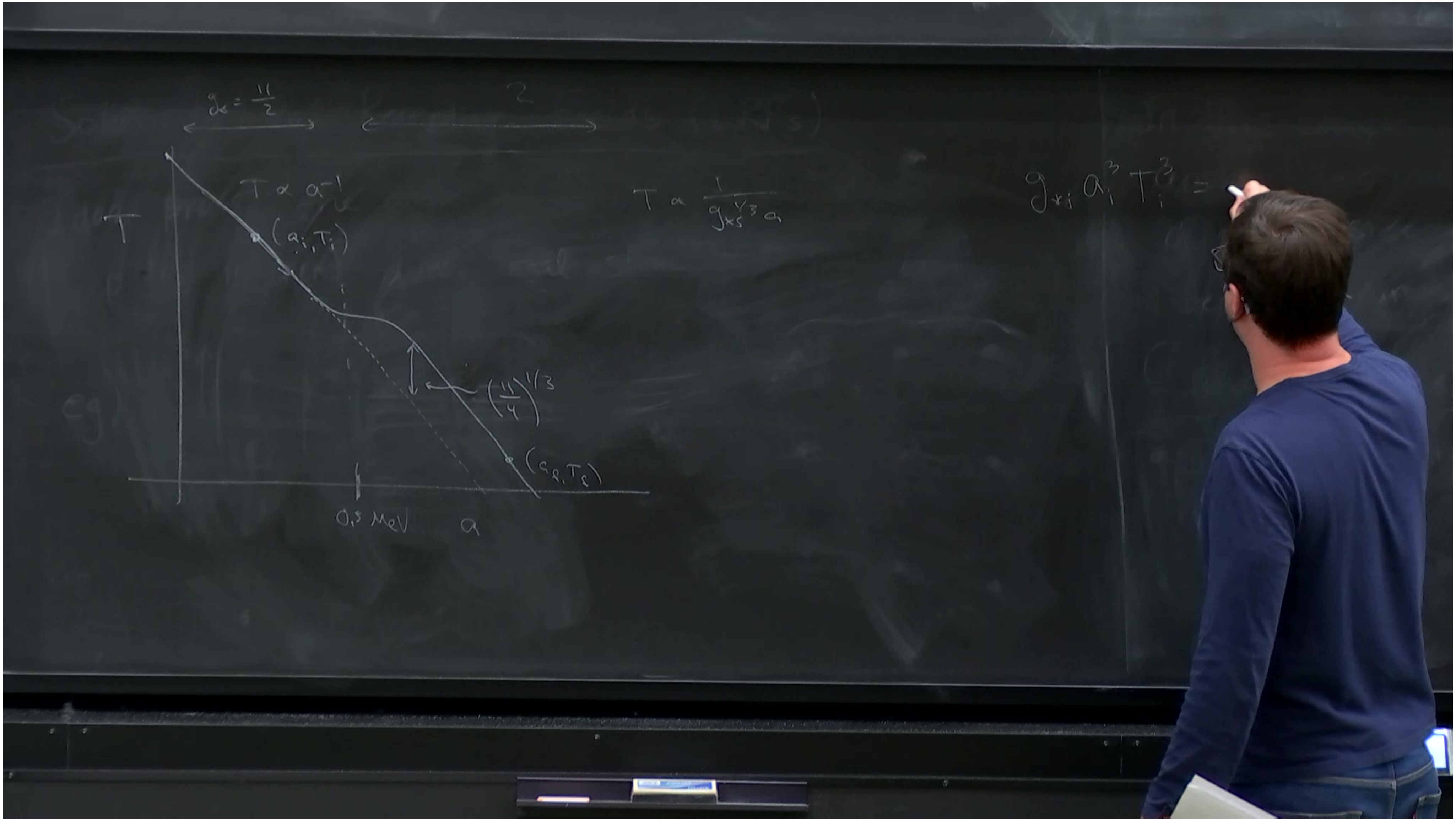
Abstract: This class is an introduction to cosmology. We'll cover expansion history of the universe, thermal history, dark matter models, and as much cosmological perturbation theory as time permits.

- ANNIHILATION EVENTS
  - e^+e^- $T \sim m_e \sim 0.5$ MeV
  - $\mu^+\mu^-$ $T \sim m_\mu \sim 100$ MeV
- DECOUPLING EVENTS ("FREEZEOUT")
  - ν $T \sim 1$ MeV
  - DM ?
- "BINDING" EVENTS
  - RECOMBINATION $T \sim 0.3$ eV
  - BBN $T \sim 0.1$ MeV




g* ~ 106.75
g*
g* = 11/2
g* = 2
100 GeV
0.5 MeV
T
ρ = π²/30 g* T⁴
S = 2π²/45 g
g* ~ g


g* ~ 106.75
g*
g* = 11/2
g* = 2
100 GeV
T
0.5 MeV
ρ = π²/30 g* T⁴
s = 2π²/45 g*s T³
g* ~ g*s
ENTROPY IS CONSERVED:
CONST. = sa³ = g*s T³ a³
⟺ T ∝ CONST. / (g*s^(1/3) a)


$g_* = \frac{11}{2}$
2
$T \propto a^{-1}$
(a_i, T_i)
$\left(\frac{11}{4}\right)^{1/3}$
(a_f, T_f)
0.5 MeV
a
T
$T \propto \frac{1}{g_{*s}^{1/3} a}$
$g_{*i} a_i^3 T_i^3 =$

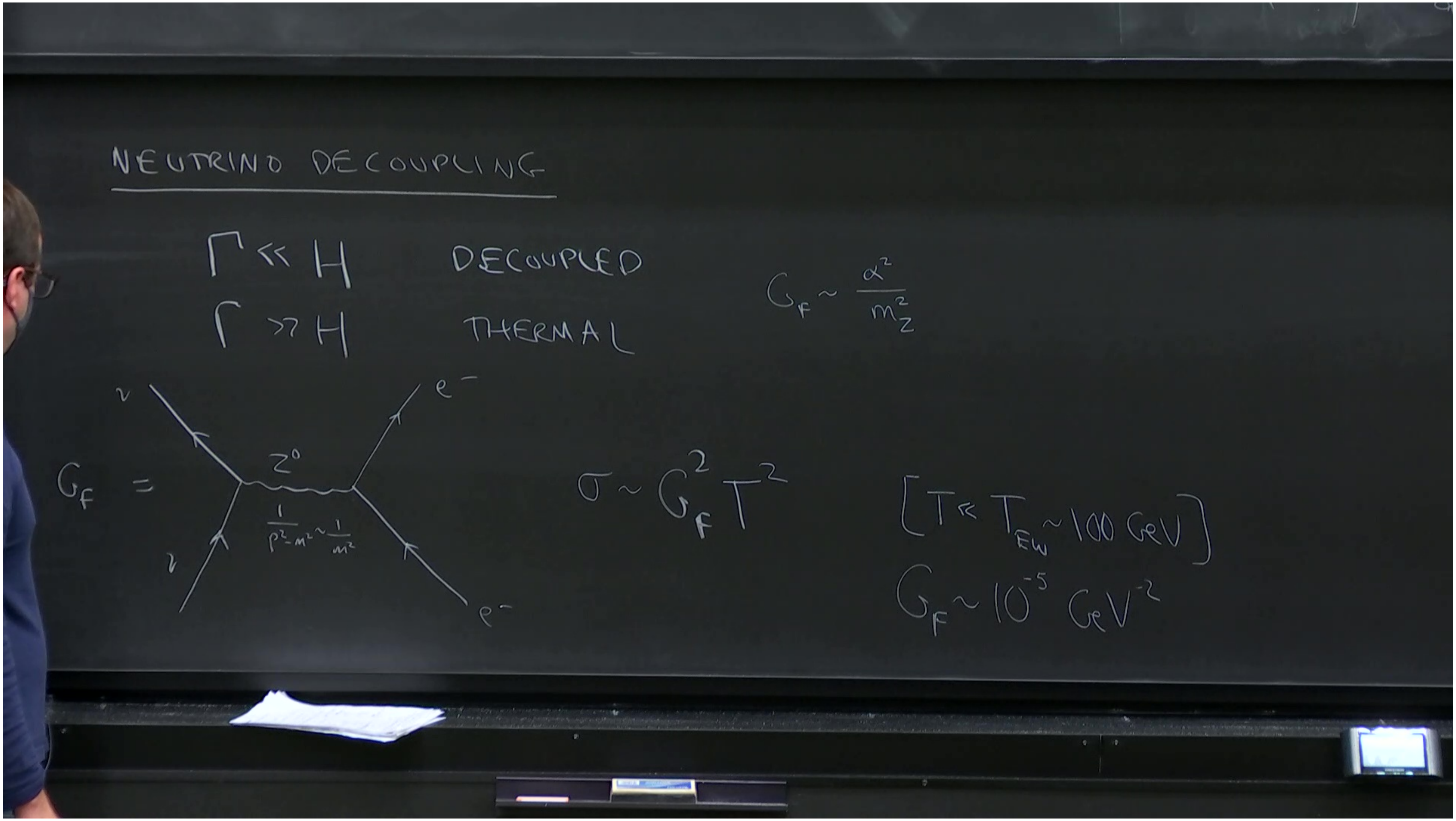
$$\propto \frac{1}{g_{*s}^{1/3}\, a}$$

$$g_{*i}\, a_i^3\, T_i^3 = g_{*f}\, a_f^3\, T_f^3$$

$$T_f = \left(\frac{g_{*i}}{g_{*f}}\right)^{1/3} \frac{T_i\, a_i}{a_f}$$

$$= \left(\frac{11/2}{2}\right)^{1/3} \frac{T_i\, a_i}{a_f}$$

$$= \left(\frac{11}{4}\right)^{1/3} \frac{T_i\, a_i}{a_f}$$


NEUTRINO DECOUPLING
Γ ≪ H DECOUPLED
Γ ≫ H THERMAL
G_F ~ α²/m_Z²
ν
e⁻
Z⁰
G_F =
1/(p²−m²) ~ 1/m²
ν
e⁻
σ ~ G_F² T²
[T ≪ T_EW ~ 100 GeV]
G_F ~ 10⁻⁵ GeV⁻²

UPLING

DECOUPLED

THERMAL

e^-

e^-

$G_F \sim \frac{\alpha^2}{m_Z^2}$

$\Gamma \sim n_e \sigma v$

$\sigma \sim G_F^2 T^2$

$[T \ll T_{EW} \sim 100\ \mathrm{GeV}]$

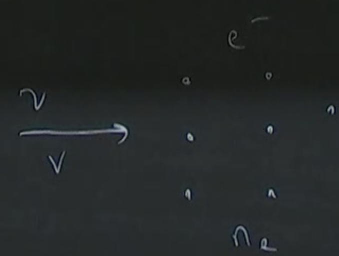
$G_F \sim 10^{-5}\ \mathrm{GeV}^{-2}$

$\frac{T_i a_i}{a_f}$

$n_e \sigma v$

$[\,T^3\,][\,G_F^2 T^2\,][\,1\,]$

$\left(\frac{8\pi G}{3}\rho_{tot}\right.$



$\Gamma = n_e \sigma v$

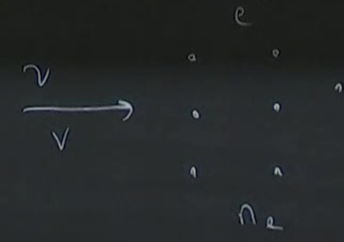
$$n_e = g\int \frac{d^3q}{(2\pi)^3}\,\frac{1}{e^{E_q/T}+1} \qquad T \gg m_e$$

$$= \frac{3g\zeta(3)}{4\pi^2}\,T^3 \qquad [HW]$$

$$\sim T^3$$

$$= \left(\frac{11}{4}\right)^{1/3} \frac{T_i a_i}{a_f}$$

$$M_{pl} = (8\pi G)^{-1/2} \sim 10^{18}\ \text{GeV}$$



$$\Gamma \sim n_e \sigma v$$

$$\sim [\ T^3\ ][\ G_F^2 T^2][\ 1\ ]$$

$$H = \left(\frac{8\pi G}{3}\rho_{tot}\right)^{1/2}$$

$$\sim \left(\frac{1}{3M_{pl}^2}\frac{\pi^2}{30} g_* T^4\right)^{1/2}$$

$$\sim \frac{T^2}{M_{pl}}$$

$$n_e = g\int \frac{d^3q}{(2\pi)^3}\frac{1}{e^{E_q/T}+1}$$

$$= \frac{3g\zeta(3)}{4\pi^2}T^3$$

$$\sim T^3$$

$[T \ll T_{EW} \sim 100\ \text{GeV}]$

$G_F \sim 10^{-5}\ \text{GeV}^{-2}$

CONDITION FOR DECOUPLING

$$1 \sim \frac{\Gamma}{H} \sim \frac{G_F^2 T_*^5}{M_{Pl}^{-1} T_*^2}$$

$$T_* \sim G_F^{-2/3} M_{Pl}^{-1/3} \sim \boxed{1\ MeV} \sim \boxed{0.8\ MeV}$$

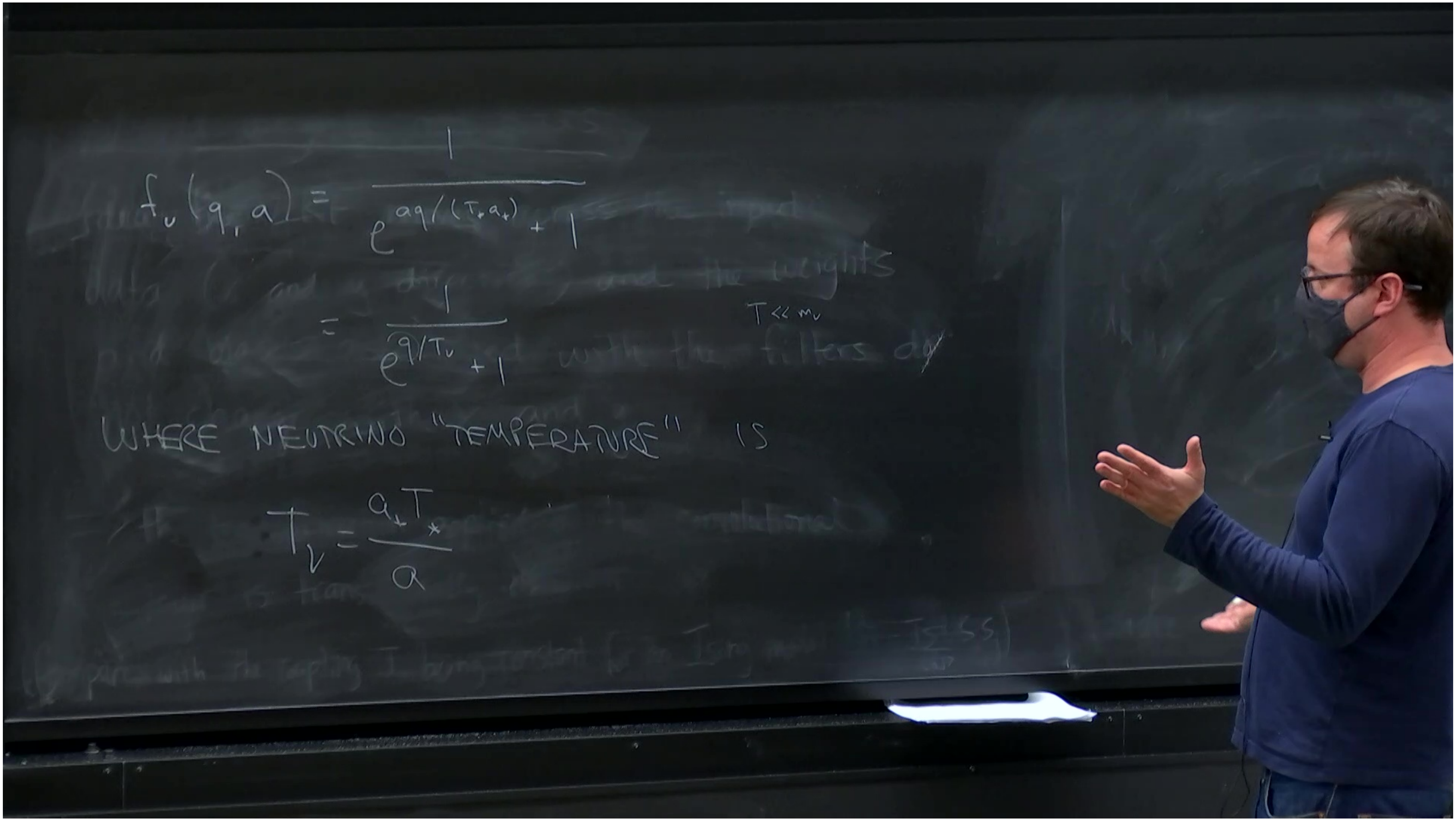
$e^+e^- \sim 0.5$ MeV

WHAT HAPPENS TO NE

LET'S ASSUME DECOUPLING IS INSTANTANEOUS AT $T \sim T_*$

AT DECOUPLING: $f_\nu(q, a_*) = \dfrac{1}{e^{q/T_*} + 1}$ $\qquad q \approx E_q$

AFTER DECOUPLING: $f_\nu(q, a) = f_\nu\left(\dfrac{a q}{a_*}, a_*\right)$


$f_\nu(q, a) = \frac{1}{e^{aq/(T_* a_*)} + 1}$
$= \frac{1}{e^{q/T_\nu} + 1}$
$T \ll m_\nu$
WHERE NEUTRINO "TEMPERATURE" IS
$T_\nu = \frac{a_* T_*}{a}$

$(T_* a_*) + 1$

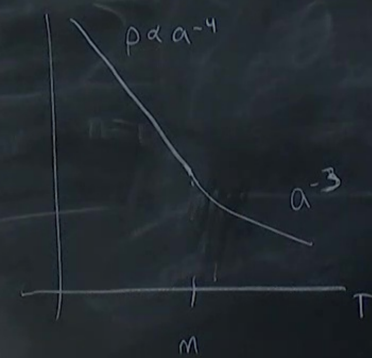
$+1$

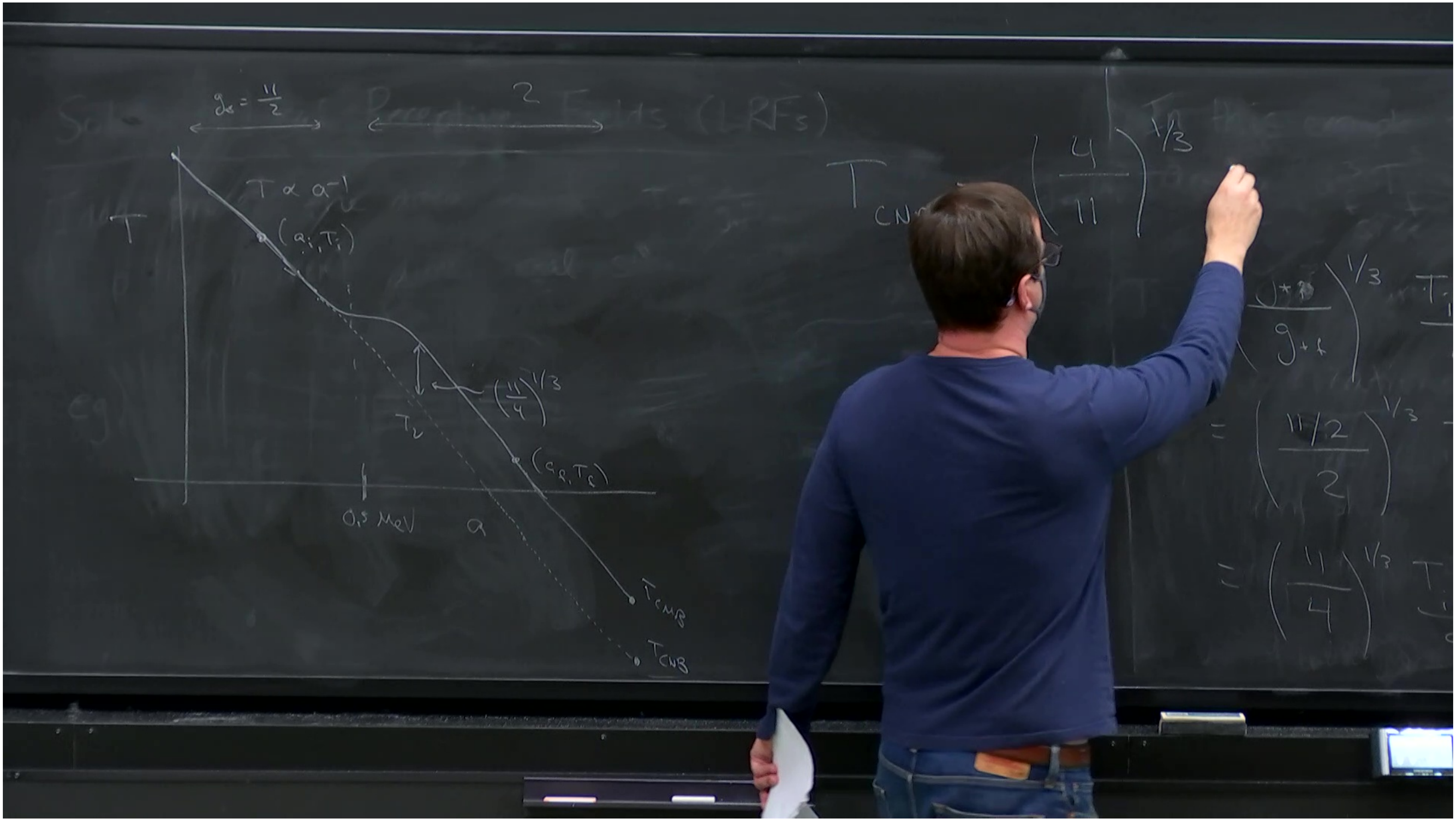
"TEMPERATURE" IS

$$n = g \int \frac{d^3 q}{(2\pi)^3} \frac{1}{e^{aq/(T_* a_*)} + 1}$$

$$q' = aq$$

$$= a^{-3} g \underbrace{\int \frac{d^3 q'}{(2\pi)^3} \frac{1}{e^{q'/(T_* a_*)} + 1}}_{\text{CONSTANT IN } a}$$



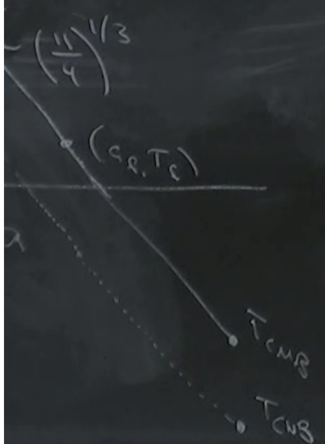


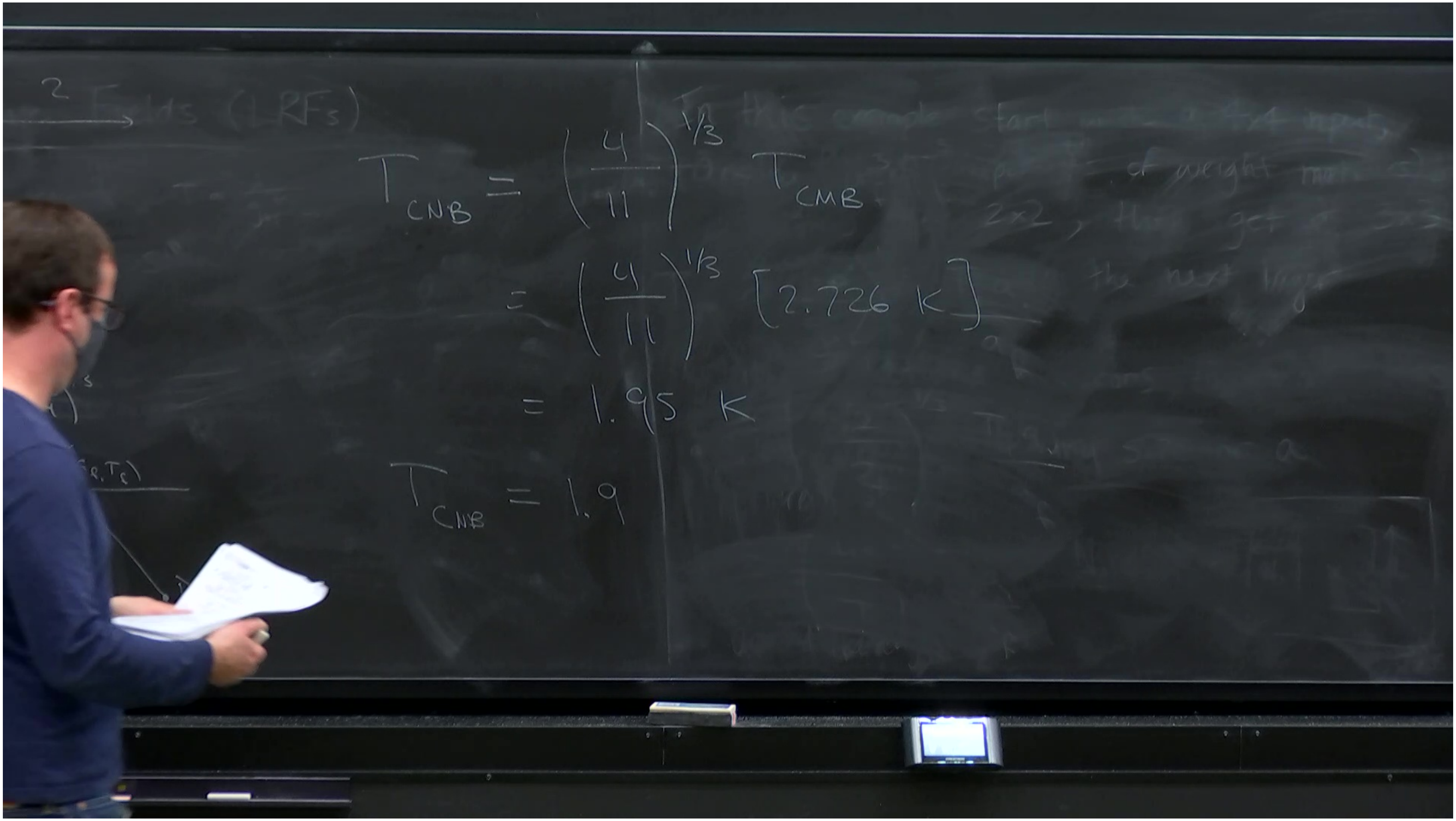
(LRFs)
T ∝ a⁻¹
(aᵢ, Tᵢ)
(11/4)^1/3
(a₀, T₀)
0.5 MeV
a
T_CNB
T_CNB
(4/11)^1/3
(11/2 / 2)^1/3
(11/4)^1/3

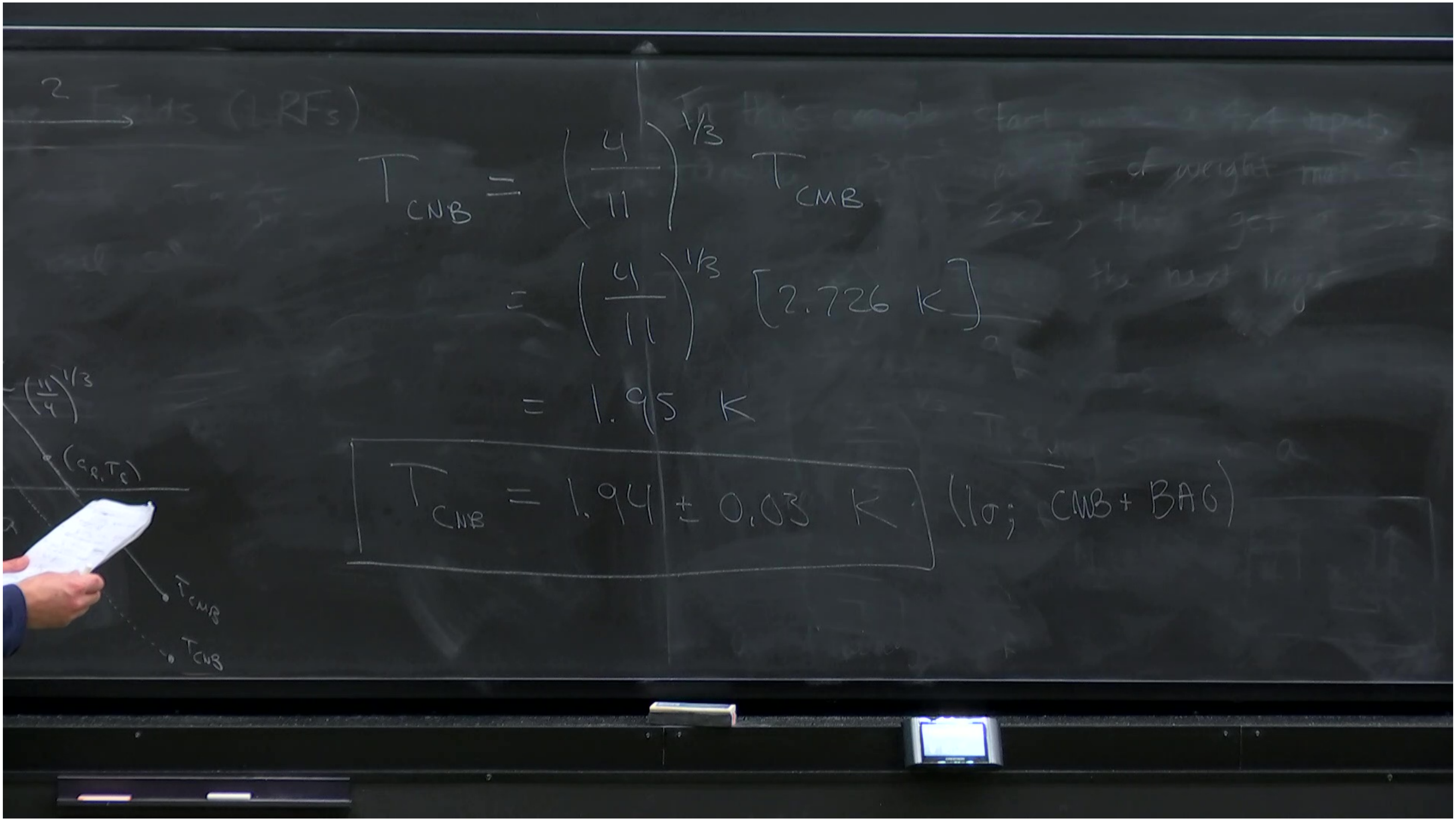
$$T_{CNB} = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

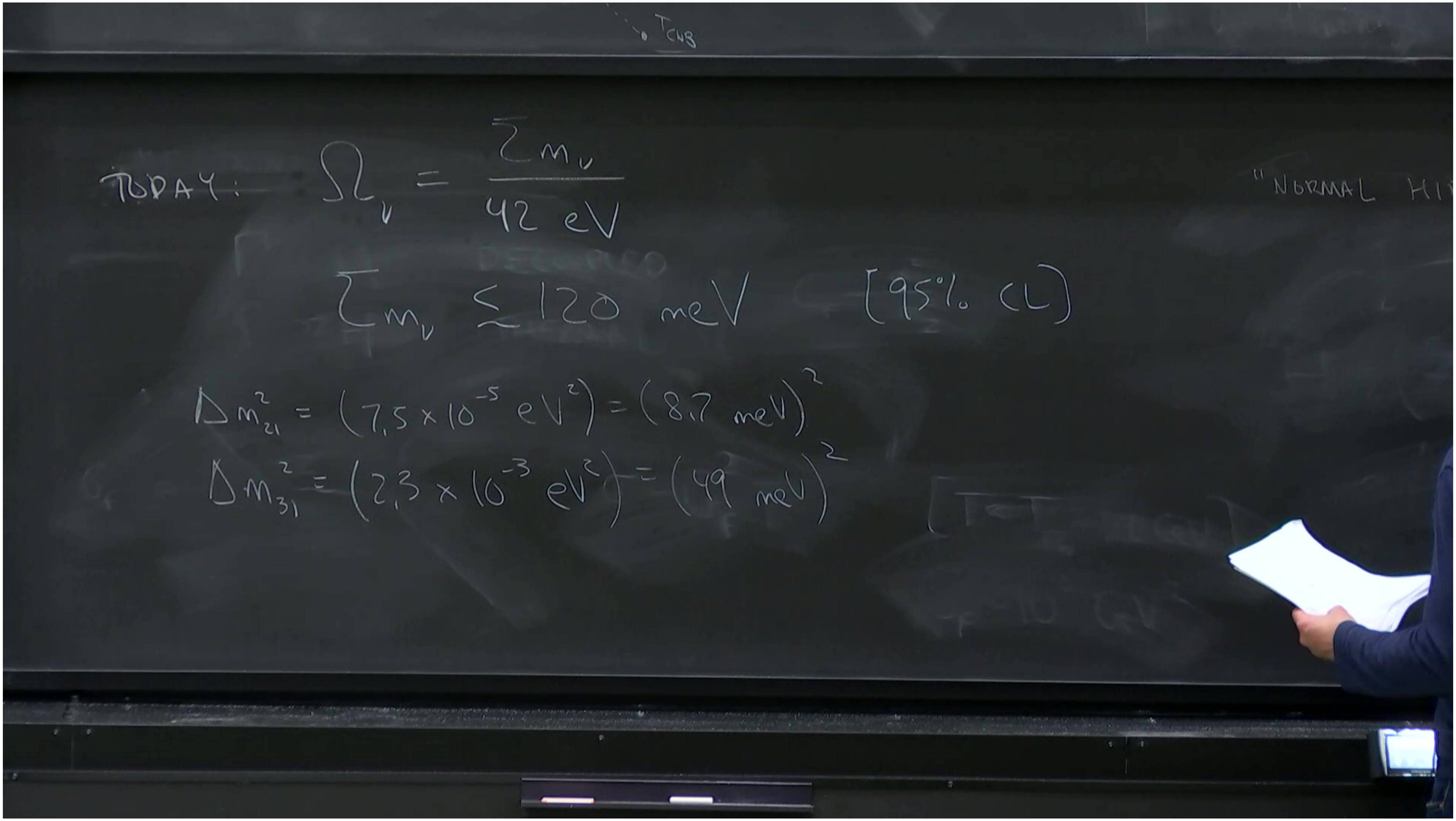
$$= \left(\frac{4}{11}\right)^{1/3} [2.726\ \mathrm{K}]$$

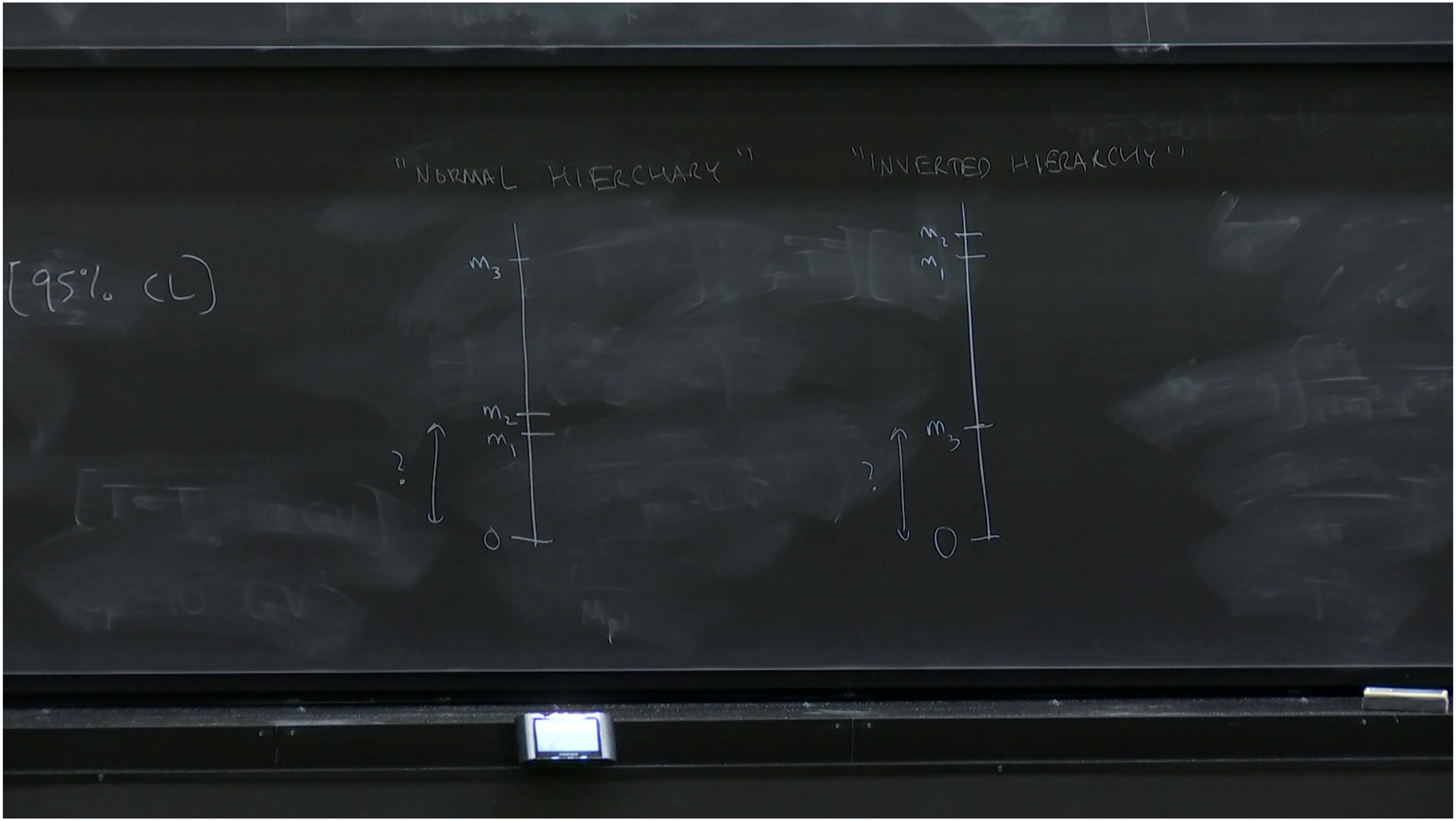
$$= 1.95\ \mathrm{K}$$

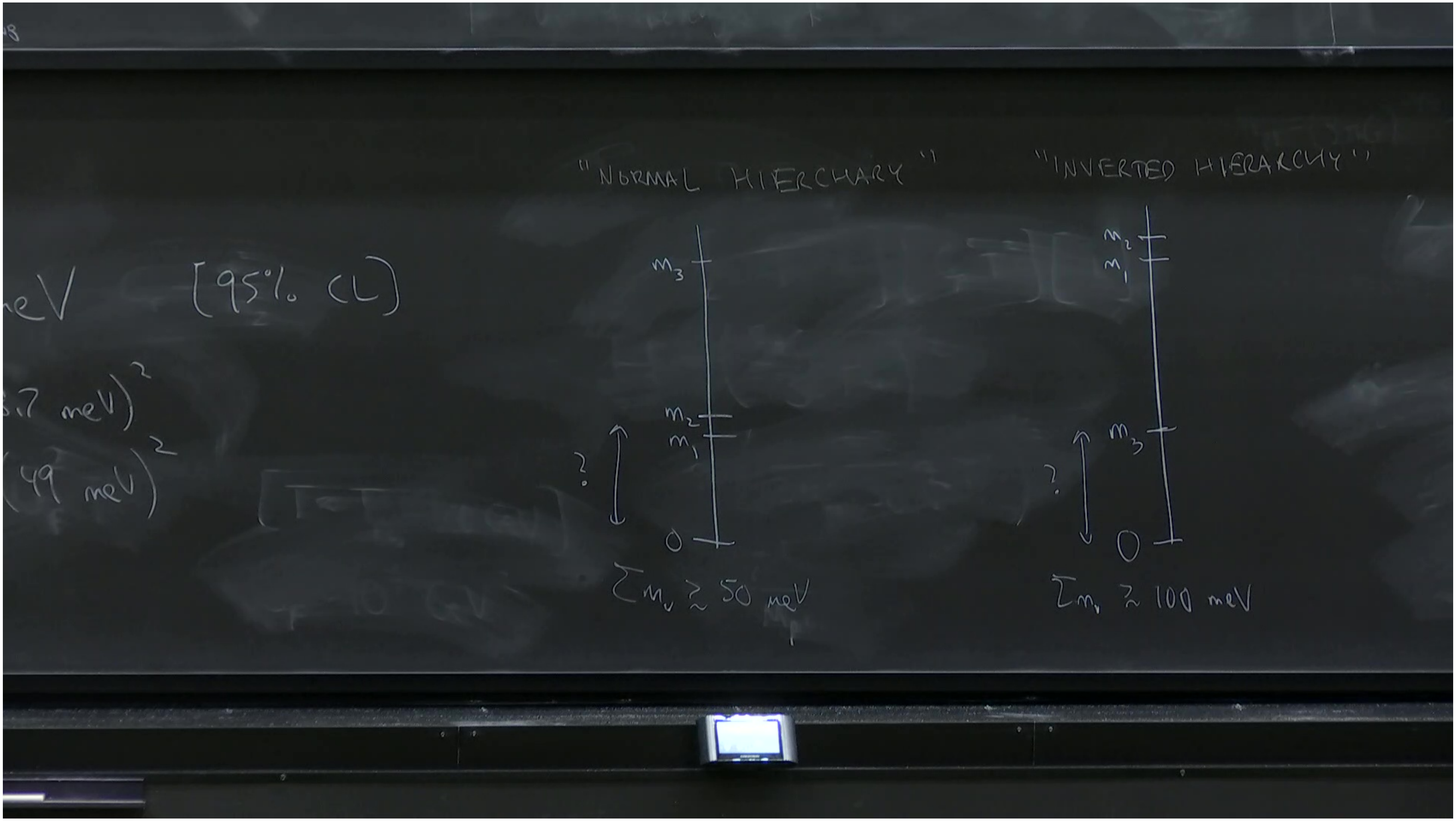



$T_{CNB} = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$
$= \left(\frac{4}{11}\right)^{1/3} [2.726\ K]$
$= 1.95\ K$
$T_{CNB} = 1.9$


$T_{CNB} = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$
$= \left(\frac{4}{11}\right)^{1/3} [2.726\ K]$
$= 1.95\ K$
$\boxed{T_{CNB} = 1.94 \pm 0.03\ K}$ (1σ; CMB + BAO)
$\left(\frac{11}{4}\right)^{1/3}$
(a_R, T_R)
T_{CMB}
T_{CNB}


$T_{C\nu B}$
TODAY: $\Omega_\nu = \frac{\sum m_\nu}{42\ eV}$
"NORMAL HI
$\sum m_\nu \lesssim 120$ meV [95% CL]
$\Delta m^2_{21} = (7.5 \times 10^{-5}\ eV^2) = (8.7\ meV)^2$
$\Delta m^2_{31} = (2.3 \times 10^{-3}\ eV^2) = (49\ meV)^2$


"NORMAL HIERCHARY"
"INVERTED HIERARCHY"
[95% CL]
m_3
m_2
m_1
?
0
m_2
m_1
m_3
?
0



"NORMAL HIERCHARY"
"INVERTED HIERARCHY"
eV [95% CL]
.7 meV)²
(49 meV)²
m₃
m₂
m₁
?
0
Σm_ν ≳ 50 meV
Σm_ν ≳ 100 meV

"EFFECTIVE" NUMBER OF NEUTRINO SPECIES

$$N_{eff} = 2.99 \pm 0.17 \quad (1\sigma)$$

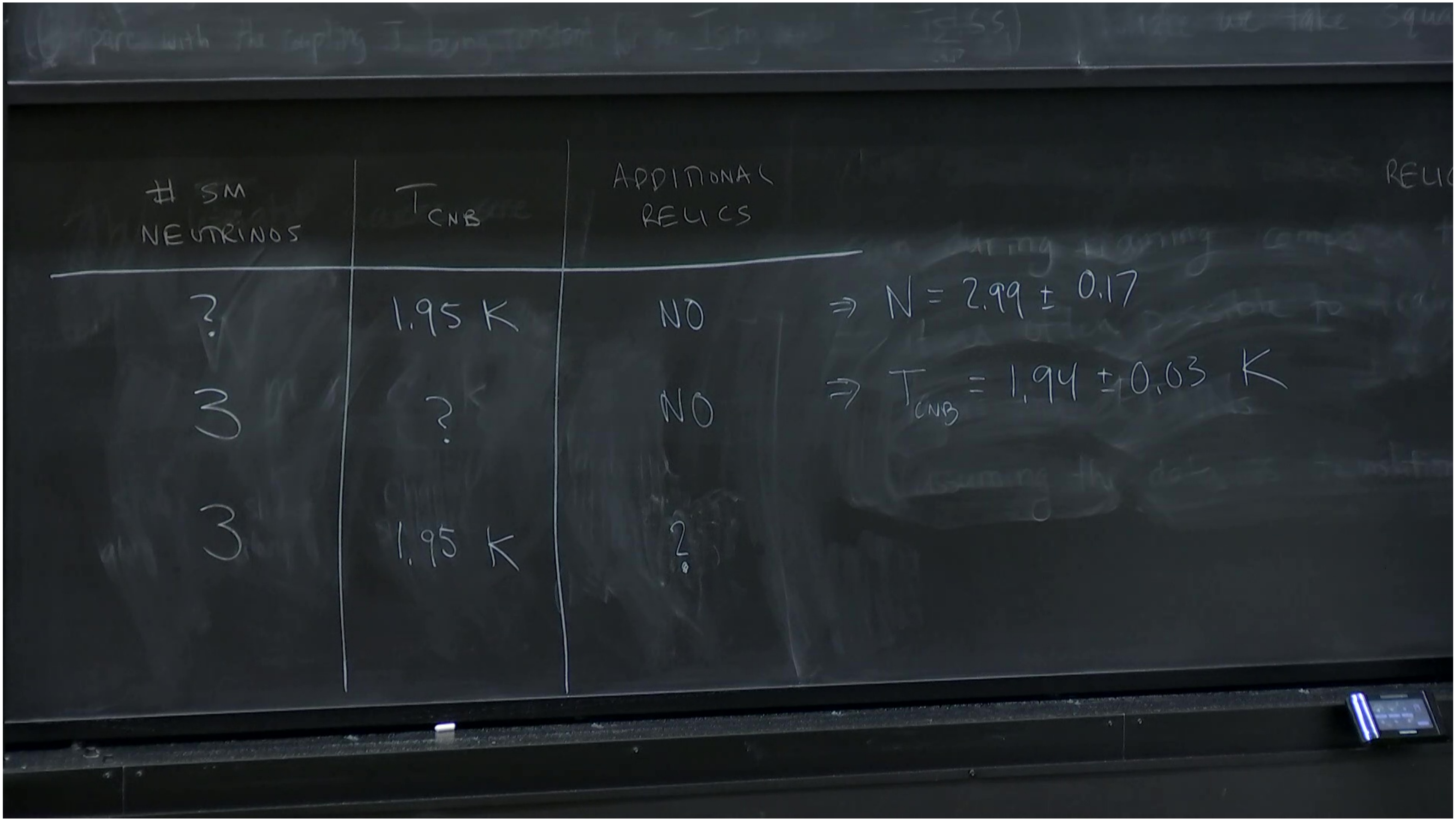
ρ_{relic} = ENERGY DENSITY OF <u>DECOUPLED</u> <u>RELATIVISTIC</u> SPECIES AT $T \sim 1$ eV

$$= N_{eff} \times \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} \frac{\pi^2}{30} T_\gamma^4$$

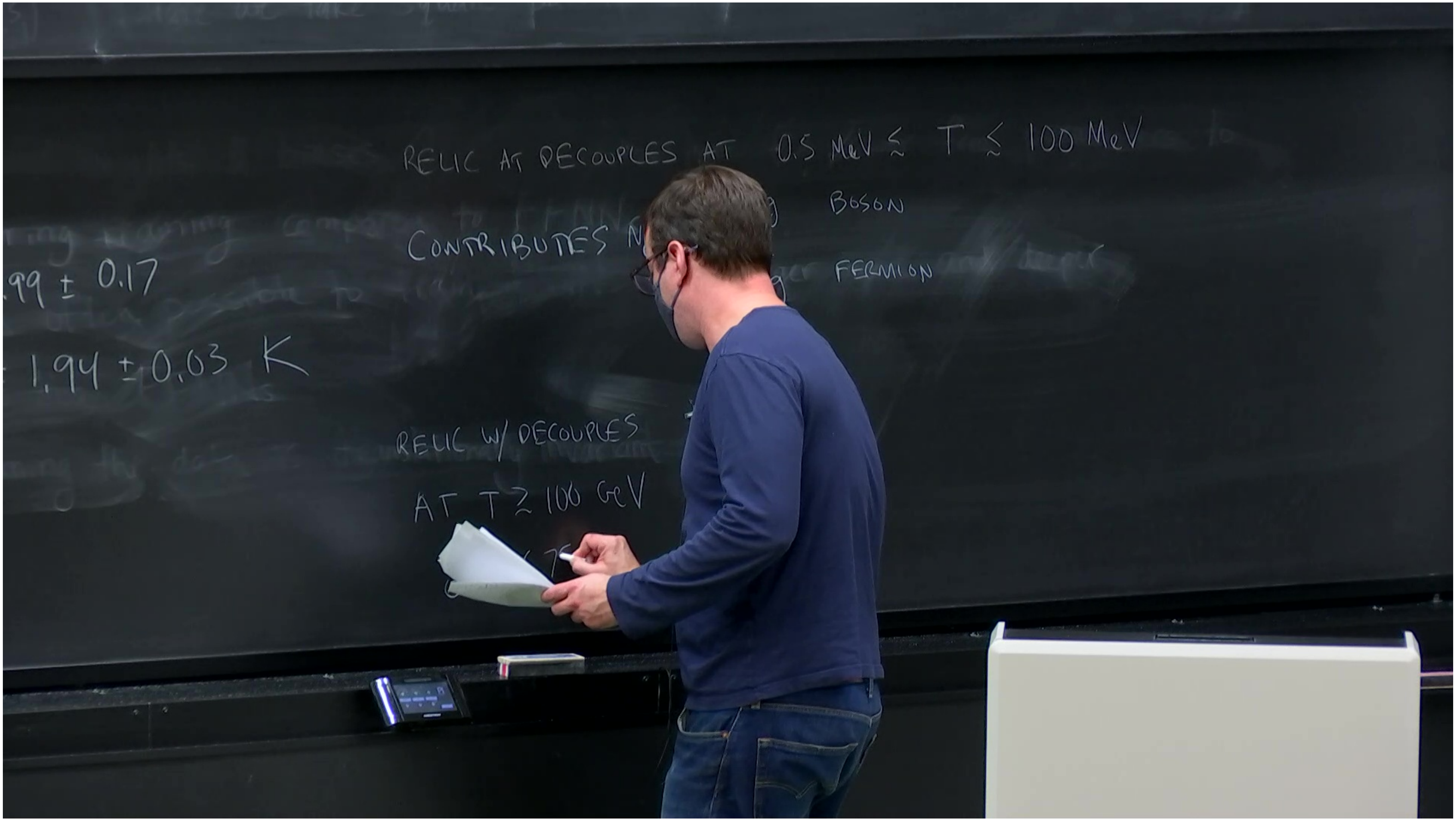
DEFINITION OF N_{eff}

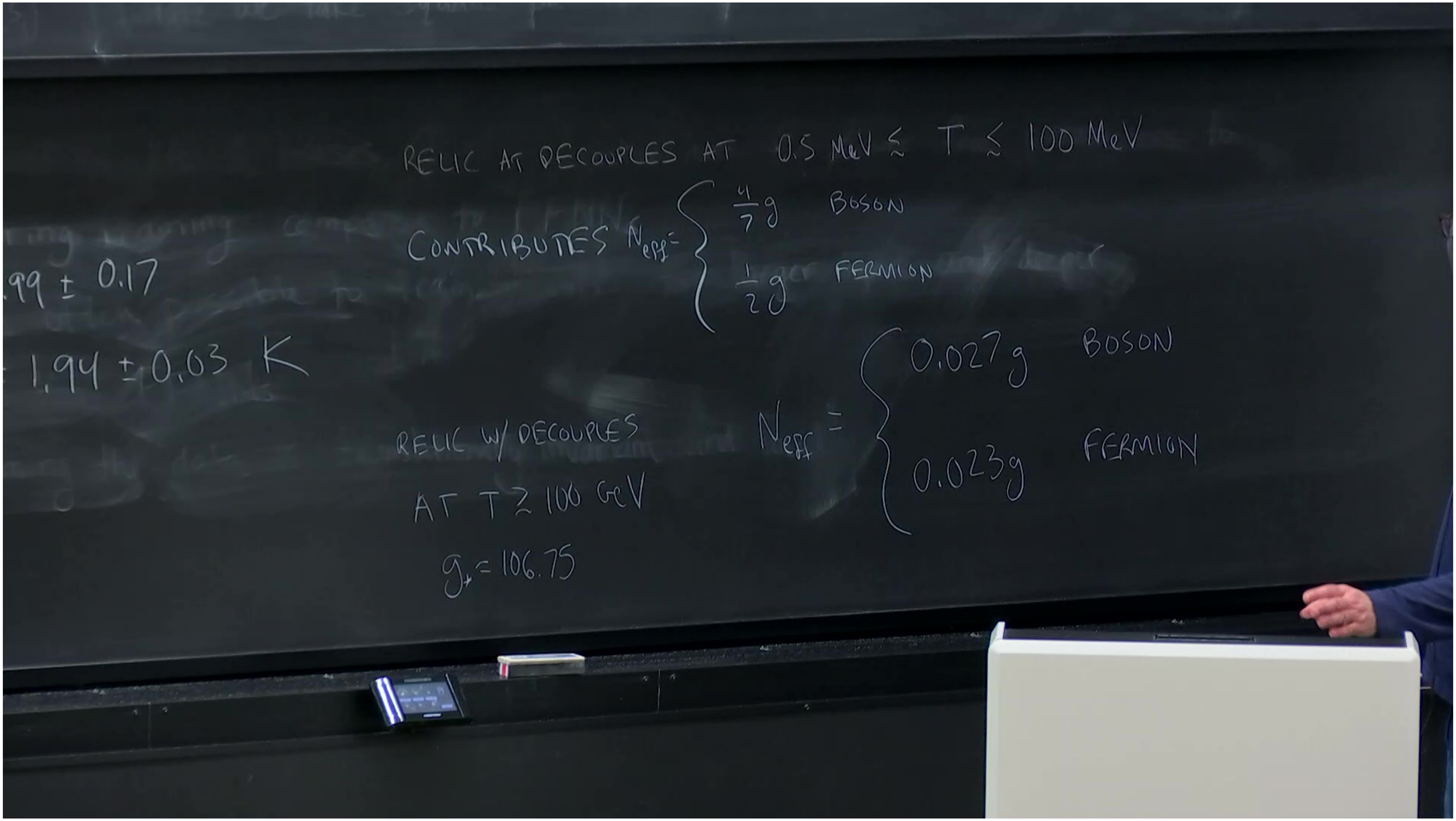
A RELIC WITH

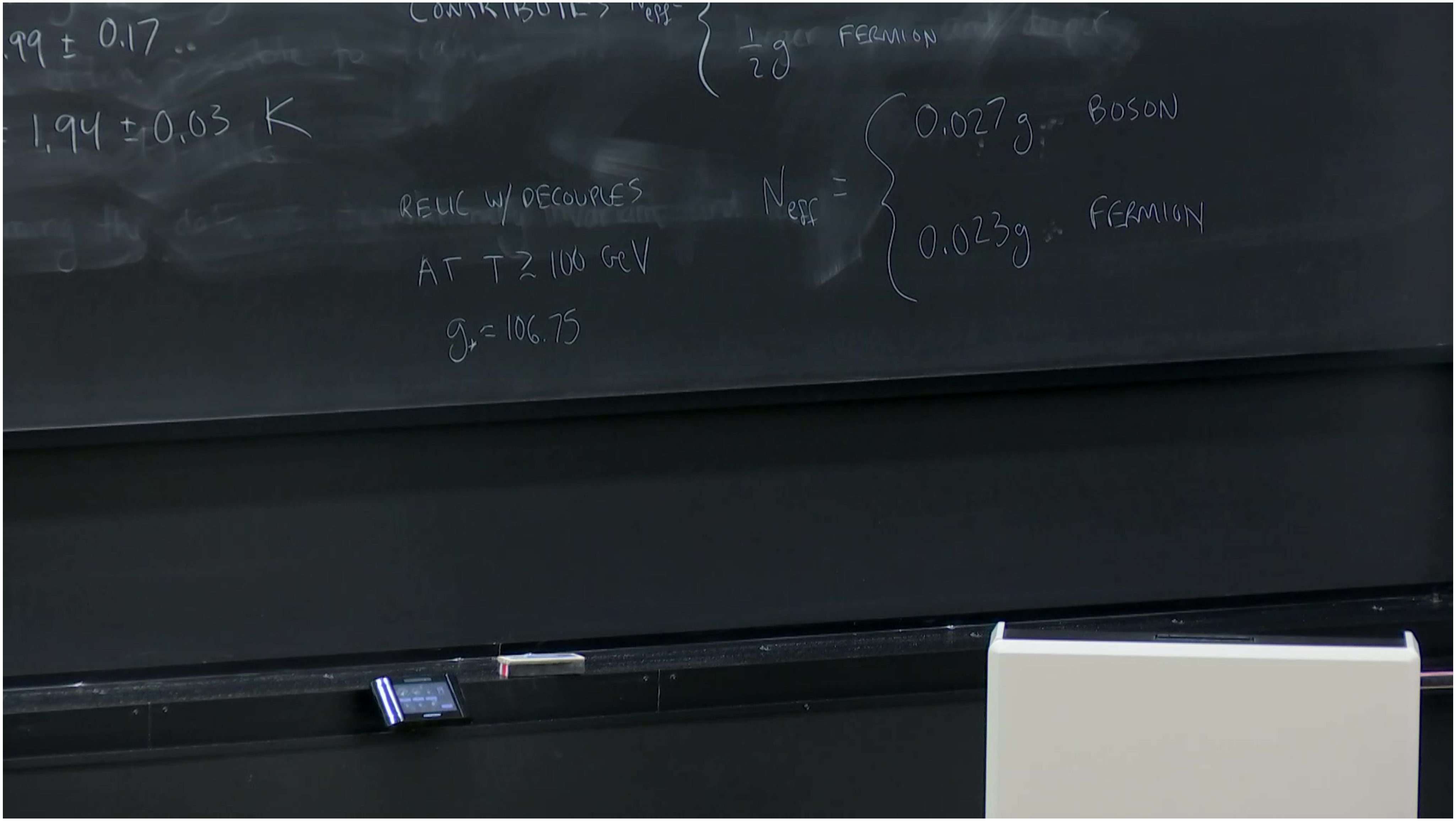
CONTRIBUTES N_{eff}



SM NEUTRINOS
T CNB
ADDITIONAL RELICS
? 1.95 K NO
3 ? NO
3 1.95 K ?
⇒ N = 2.99 ± 0.17
⇒ T CNB = 1.94 ± 0.03 K


RELIC AT DECOUPLES AT 0.5 MeV ≲ T ≲ 100 MeV
BOSON
CONTRIBUTES
FERMION
.99 ± 0.17
1.94 ± 0.03 K
RELIC W/ DECOUPLES
AT T ≳ 100 GeV


RELIC AT DECOUPLES AT 0.5 MeV ≲ T ≲ 100 MeV
CONTRIBUTES N_eff = 4/7 g BOSON
1/2 g FERMION
.99 ± 0.17
1.94 ± 0.03 K
RELIC W/ DECOUPLES
AT T ≳ 100 GeV
g* = 106.75
N_eff = 0.027g BOSON
0.023g FERMION


CONTRIBUTES N_{eff} =
.99 ± 0.17
$\frac{1}{2}g$ FERMION
1.94 ± 0.03 K
0.027g BOSON
RELIC W/ DECOUPLES
N_{eff} =
0.023g FERMION
AT T ≳ 100 GeV
$g_* = 106.75$