Title: Cosmology Lecture

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OBSERVATIONS DEMAND TWO-COMPONENT DARK SECTOR

1) "HOT" COMPONENT (RELATIVISTIC AT $0.3\ \text{eV} \lesssim T \lesssim 10\ \text{eV}$)

2) "COLD" COMPONENT (NON RELATIVISTIC AT $T \sim 1\ \text{keV}$)

HOT COMPONENT

- AT EARLY TIMES ($T \gtrsim 0.3\ \text{eV}$ OR $a \lesssim 10^{-3}$)

$$\rho_{hot} = N_{eff} \cdot 2 \cdot \frac{7}{8} \cdot \frac{\pi^2}{30} \left[\left(\frac{4}{11}\right)^{1/3} \frac{T_{CMB}}{a} \right]^4$$

DEFINES N_{eff}

$T_{CMB} = 2.726\ \text{K}$

$$N_{eff} = 2.99 \pm 0.17 \quad (\text{CMB})$$

- TODAY $\Omega_{hot} \lesssim 0.003$ (GRAVITATIONAL STRUCTURE)

K SECTOR

V ≲ T ≲ 10 eV)

T ~ 1 keV)

DEFINES N_{eff}

$T_{CMB} = 2.726$ K

STRUCTURE)

- BOTH CONSTRAINTS ARE SATISFIED BY 3 SPECIES OF SM NEUTRINOS IF $\Sigma m_\nu \lesssim 0.12$ eV

$$\Omega_\nu = \frac{\Sigma m_\nu}{46 \text{ eV}} \quad [\text{HW1}]$$

- SM PREDICTS $N_{eff} = 3.046$ NOT $N_{eff} = 3$

- OTHER LIGHT RELICS CONTRIBUTE (NONTRIVIAL TO DERIVE)

$$N_{eff} = \frac{8}{7} g_*^{relic} \left(\frac{g_*^{dec}}{10.75} \right)^{-4/3} \qquad g_*$$

BOTH CONSTRAINTS ARE SATISFIED BY 3 SPECIES OF SM NEUTRINOS IF $\Sigma m_\nu \lesssim 0.12\ eV$

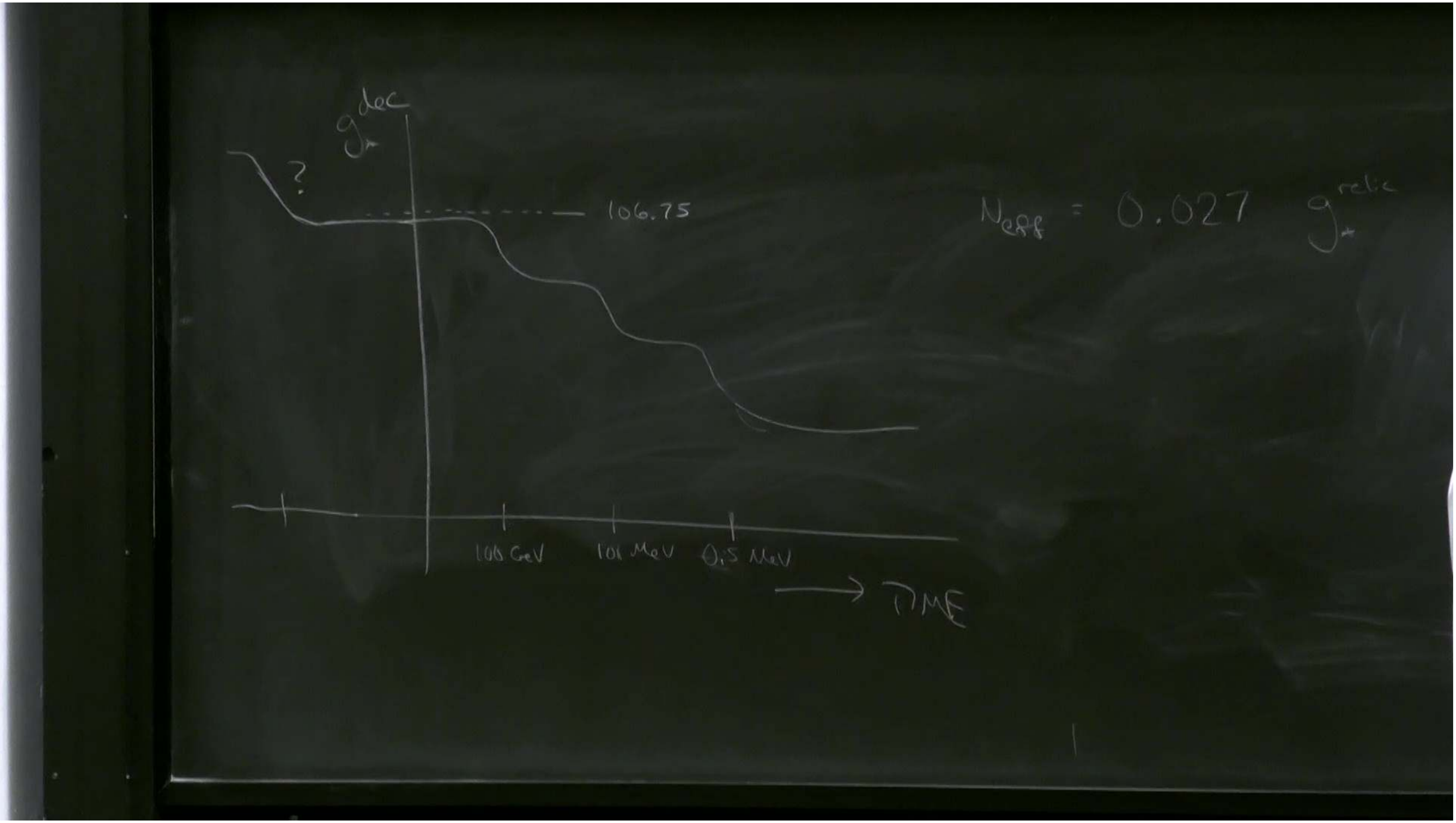
$$\Omega_\nu = \frac{\Sigma m_\nu}{46\ eV} \quad [HW1]$$

- SM PREDICTS $N_{eff} = 3.046$ NOT $N_{eff} = 3$
- OTHER LIGHT RELICS CONTRIBUTE (NONTRIVIAL TO DERIVE) → IF $T_f \gg 1\ MeV$, $m_f \ll T_f$

$$N_{eff} = \frac{8}{7} g_*^{relic} \left(\frac{g_*^{dec}}{10.75} \right)^{-4/3}$$

$$g_*^{relic} = \begin{cases} g & \text{BOSON} \\ \frac{7}{8} g & \text{FERMION} \end{cases}$$

g_*^{dec} = "g_* OF THE PLASMA AT DECOUPLING" ~ 10



g_*^{dec}
?
106.75
$N_{eff} = 0.027\ g_*^{relic}$
100 GeV
100 MeV
0.5 MeV
TIME

COMPONENT

1) LARGE TODAY!

$\Omega_c = 0.266 \pm 0.005$ COLD DARK MATTER

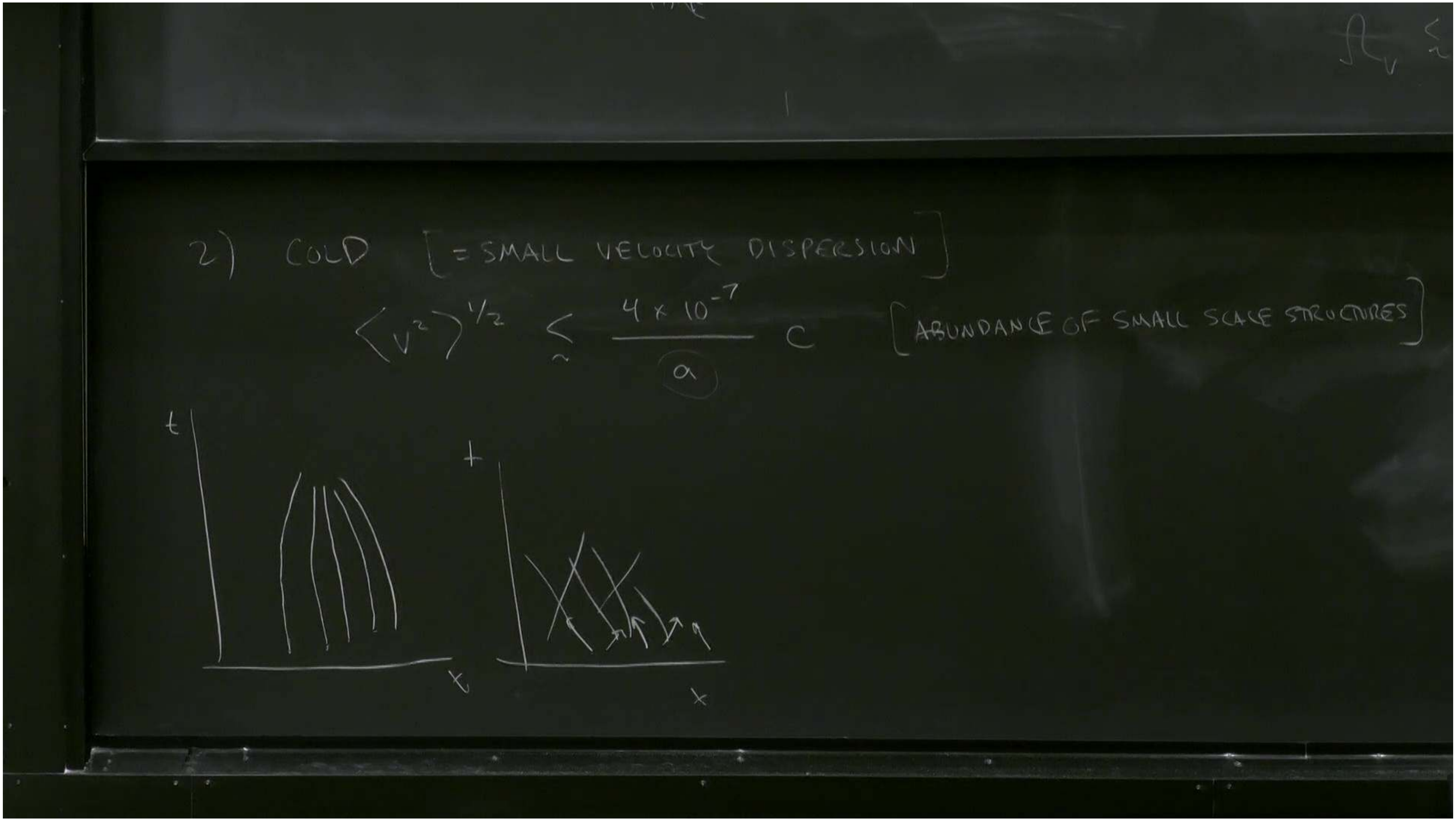
FOR COMPARISON:

$\Omega_b = 0.045 \pm 0.003$ "BARYONIC" MATTER = NONRELATIVISTIC

$\Omega_\Lambda = 0.689 \pm 0.006$ COSMOLOGICAL CONSTANT

$\Omega_\gamma = 5 \times 10^{-5}$ PHOTONS

$\Omega_\nu \lesssim 0.003$ NEUTRINOS


2) COLD [= SMALL VELOCITY DISPERSION]
$\langle v^2 \rangle^{1/2} \lesssim \frac{4 \times 10^{-7}}{a} c$
[ABUNDANCE OF SMALL SCALE STRUCTURES]
t
x
t
x

CAN THE CDM BE A 4TH NEUTRINO SPECIES?

NO:

$$\Omega = \frac{m_\nu}{46 \text{ eV}} \left(\frac{g_*^{dec}}{10.75}\right)^{-1} \text{[HW1]} \Rightarrow m_\nu = 12 \text{ eV}$$

$$\langle v^2 \rangle^{1/2} = \sqrt{15 \frac{\zeta(5)}{\zeta(3)} \frac{T_\nu}{m_\nu}} \left(\frac{g_*^{dec}}{10.75}\right)^{-1/3}$$

$$= (6 \times 10^{-7}) \left(\frac{1 \text{ keV}}{m_\nu}\right) \left(\frac{g_*^{dec}}{10.75}\right)^{-1/3} \qquad m_\nu \gtrsim 1 \text{ keV}$$

GENERALIZE TO "HOT RELIC" $\Rightarrow$ RELATIVISTIC AT FREEZEOUT $(m \ll T_f)$

FARFETCHED: $g_*^{dec} \sim 10^3 \quad m \sim 1 \text{ keV}$

WE'LL SHOW THAT A "COLD RELIC" ($m \gg T_f$)

NATURALLY FITS THE CDM CONSTRAINTS.

SETUP. TWO PARAMS m_χ = PARTICLE MASS

σ = CROSS SECTION $\chi\bar{\chi} \leftrightarrow SM$

APPROXIMATION: INSTANTANEOUS FREEZEOUT AT T_f

DROPPING ORDER-ONE CONSTANTS THROUGHOUT!

STEP 1. COMPUTE T_f. SET $\Gamma \sim H$

SM

$$\Gamma \sim \sigma n_\chi v$$

$$\sim \sigma \left[(mT)^{3/2} e^{-m/T} \right] \left[\frac{T}{m} \right]^{1/2}$$

$$\sim \sigma m T^2 e^{-m/T}$$

$$H \sim \rho_{tot}^{1/2} M_{pl}^{-1}$$

$$\sim \left[T^4 \right]^{1/2} M_{pl}^{-1}$$

$$\sim T^2 M_{pl}^{-1}$$

$$\frac{1}{2} m v^2 \sim T$$

$$H^2 = \frac{\rho}{3 M_{pl}^2}$$

$$\rho_{tot} = g_* \frac{\pi^2}{30} T^4$$

$$1 \sim \frac{\Gamma}{H} \sim \sigma m M_{pl} e^{-m/T_f}$$

$$\Rightarrow T_f = \frac{m}{x}$$ WHERE $x = \log(\sigma m M_{pl})$

NOTE $x \gg 1$ BY ASSUMPTION

x CAN'T BE TOO LARGE SINCE $x = \log(\cdots)$

E.G. IF $m \simeq 1$ TeV $\sigma \sim 10^{-7}$ GeV^{-2} $\Rightarrow$ $x \sim 30$

STEP 2. COMPUTE Ω_c

$$\rho_f \sim m(mT_f)^{3/2} e^{-m/T_f}$$

DENSITY AT FREEZEOUT

$$\sim \frac{x^{3/2}\, T_f^3}{M_{pl}\,\sigma}$$

$$\frac{m}{T_f} = x = \log(m M_{pl} \sigma)$$

$$\rho_{c0} \sim \rho_f\, a_f^3$$

$$\sim \rho_f \left(\frac{T_{CMB}}{T_f}\right)^3$$

DENSITY TODAY

$$T_{plasma} \sim \frac{T_f\, a_f}{a}$$

WITHIN ORDER-ONE FACTOR

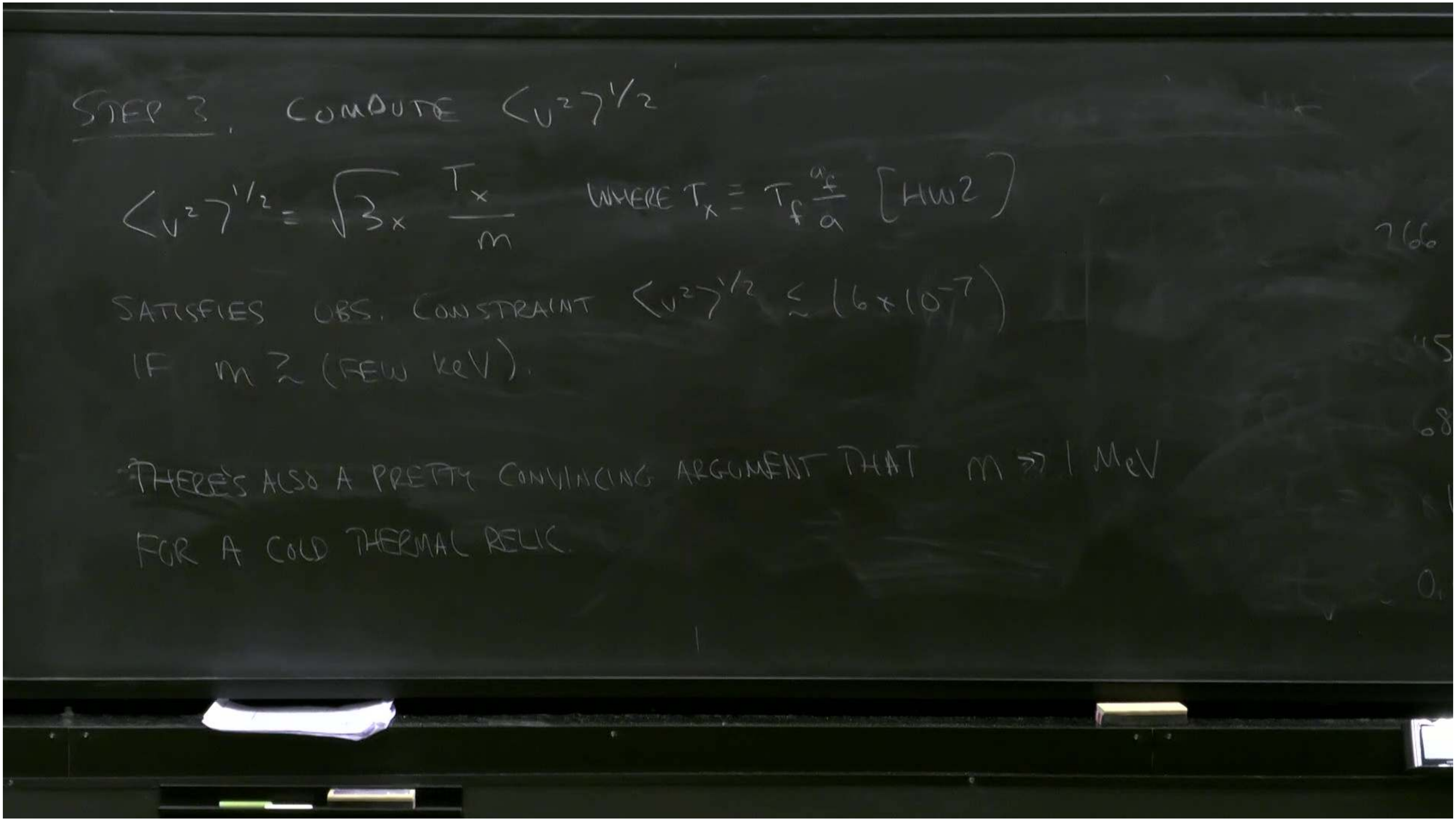
$$\sim \rho_f \left(\frac{T_{CMB}}{T_F} \right. \qquad \sim \frac{x^{3/2} T_{CMB}^3}{M_{Pl} \sigma}$$

$$\Omega_c = \frac{\rho_{c0}}{\rho_{tot,0}} = \frac{\rho_{c0}}{H_0^2 / 3M_{Pl}^2} \sim (0.25) \left(\frac{x}{30} \right)^{3/2} \left(\frac{\sigma}{10^{-7}\ \mathrm{GeV}^{-2}} \right)^{-1}$$

NEED $\sigma \sim 10^{-7}\ \mathrm{GeV}^{-2}$

WITH WEAK (I.E. LOGARITHMIC) DEPENDENCE ON m

"WIMP MIRACLE": ELECTROWEAK SCALE $\sigma \sim 10^{-7}\ \mathrm{GeV}^{-2}$ NATURALLY APPEARS


STEP 3. COMPUTE ⟨v²⟩^1/2
⟨v²⟩^1/2 = √(3 Tx / m)   WHERE Tx ≡ Tf af/a [HW2]
SATISFIES OBS. CONSTRAINT ⟨v²⟩^1/2 ≲ (6×10^-7)
IF m ≳ (FEW keV).
THERE'S ALSO A PRETTY CONVINCING ARGUMENT THAT m ≫ 1 MeV
FOR A COLD THERMAL RELIC.