Title: Cosmology Lecture

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Collection: Cosmology 2023/24

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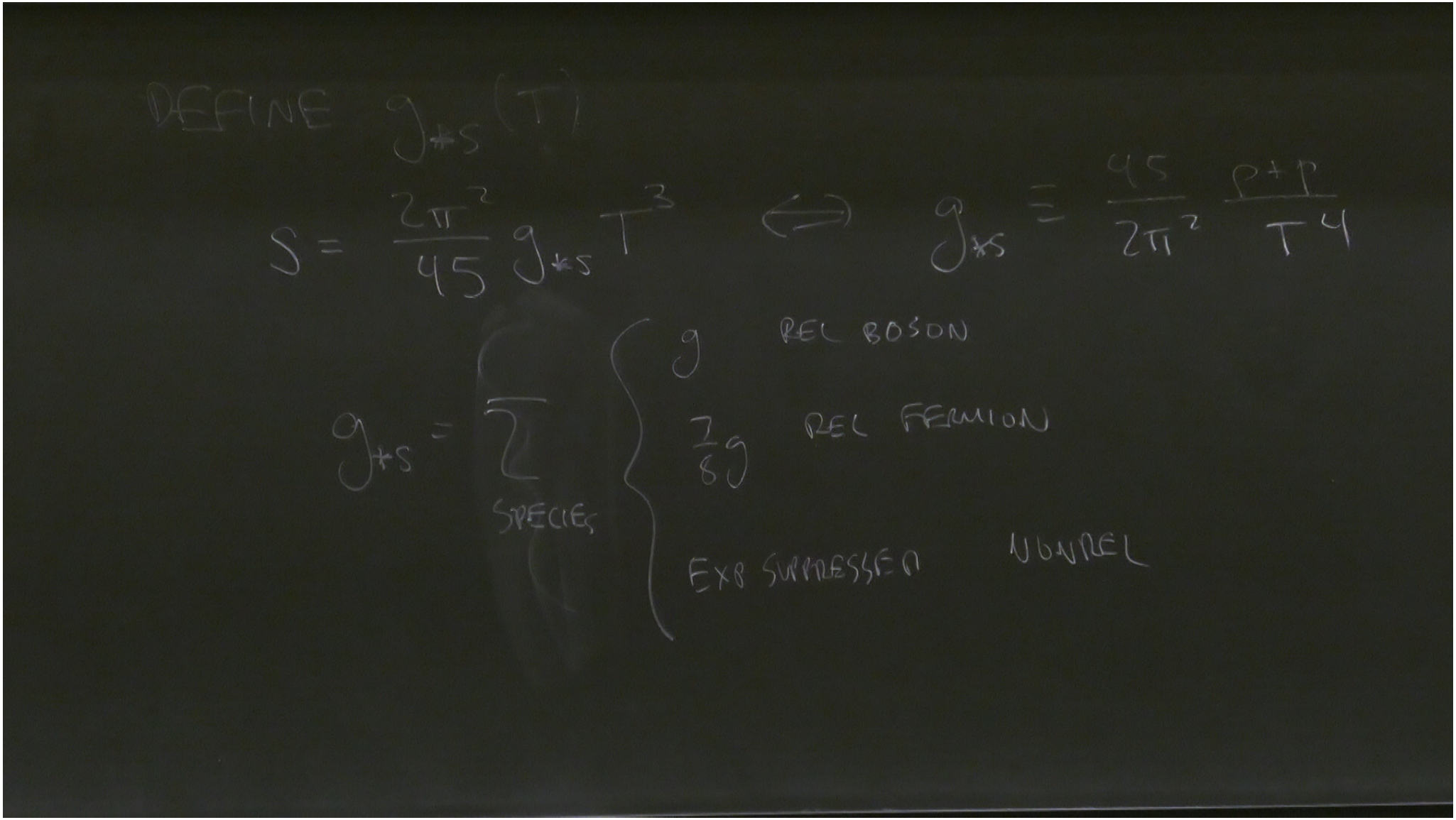
$$\begin{Bmatrix} \rho(T) \\ n(T) \\ p(T) \end{Bmatrix} = \sum_{\text{SPECIES}} \frac{g}{2\pi^2} \int dq\, q^2 f_q \begin{Bmatrix} E_q \\ 1 \\ q^2/3E_q \end{Bmatrix}$$

→ DERIVATION IN BAUMANN NOTES

$$sa^3 = \text{CONST.} \qquad s(T) = \frac{\rho(T)+p(T)}{T}$$

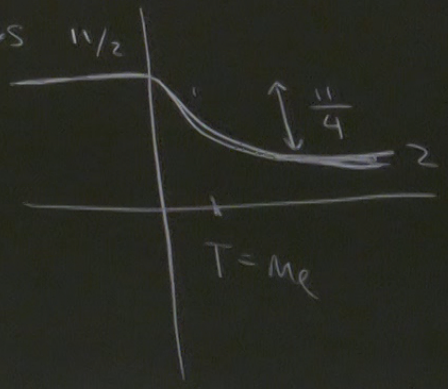

DEFINE $g_{*S}(T)$
$S = \frac{2\pi^2}{45} g_{*S} T^3 \iff g_{*S} = \frac{45}{2\pi^2} \frac{\rho + p}{T^4}$
$g_{*S} = \sum_{\text{SPECIES}}$
g REL BOSON
$\frac{7}{8} g$ REL FERMION
EXP SUPPRESSED NONREL

ENTROPY CONSERVATION $s(T)\,a^3 = \text{CONST.}$

$$g_{*S}\, a^3 T^3 = \text{CONST} \iff \boxed{T \propto g_{*S}^{-1/3}\, a^{-1}}$$

$$T \gg m_e: \quad g_{*S} = \underbrace{2}_{\text{PHOTON}} + \underbrace{2\tfrac{7}{8}}_{e^-} + \underbrace{2\tfrac{7}{8}}_{e^+} = \frac{11}{2}$$

$$T \ll m_e: \quad g_{*S} = \underbrace{2}_{\text{PHOTON}}$$



log T

1 MeV

T = me
= 0.5 MeV

Γ = NEUTRINO INTERACTION RATE

= INTERACTIONS PER NEUTRINO PER UNIT TIME

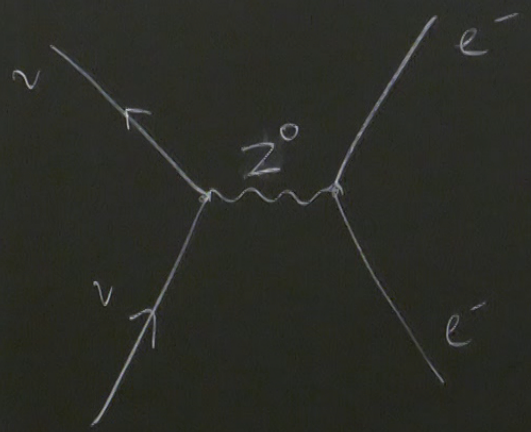
H = HUBBLE EXPANSION RATE $\frac{\dot{a}}{a}$

$\Gamma \gg H$: NEUTRINOS ARE THERMAL

$\Gamma \ll H$: NEUTRINOS "DECOUPLED"

I.E. FREESTREAMS ON AN FRW GEODESIC

$\rho_\nu \propto a^{-4}$



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

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

Γ = ν INTERACTION RATE

$= n_e \sigma v_\nu$

$\sim (T^3)$

Γ = INTERACTION RATE

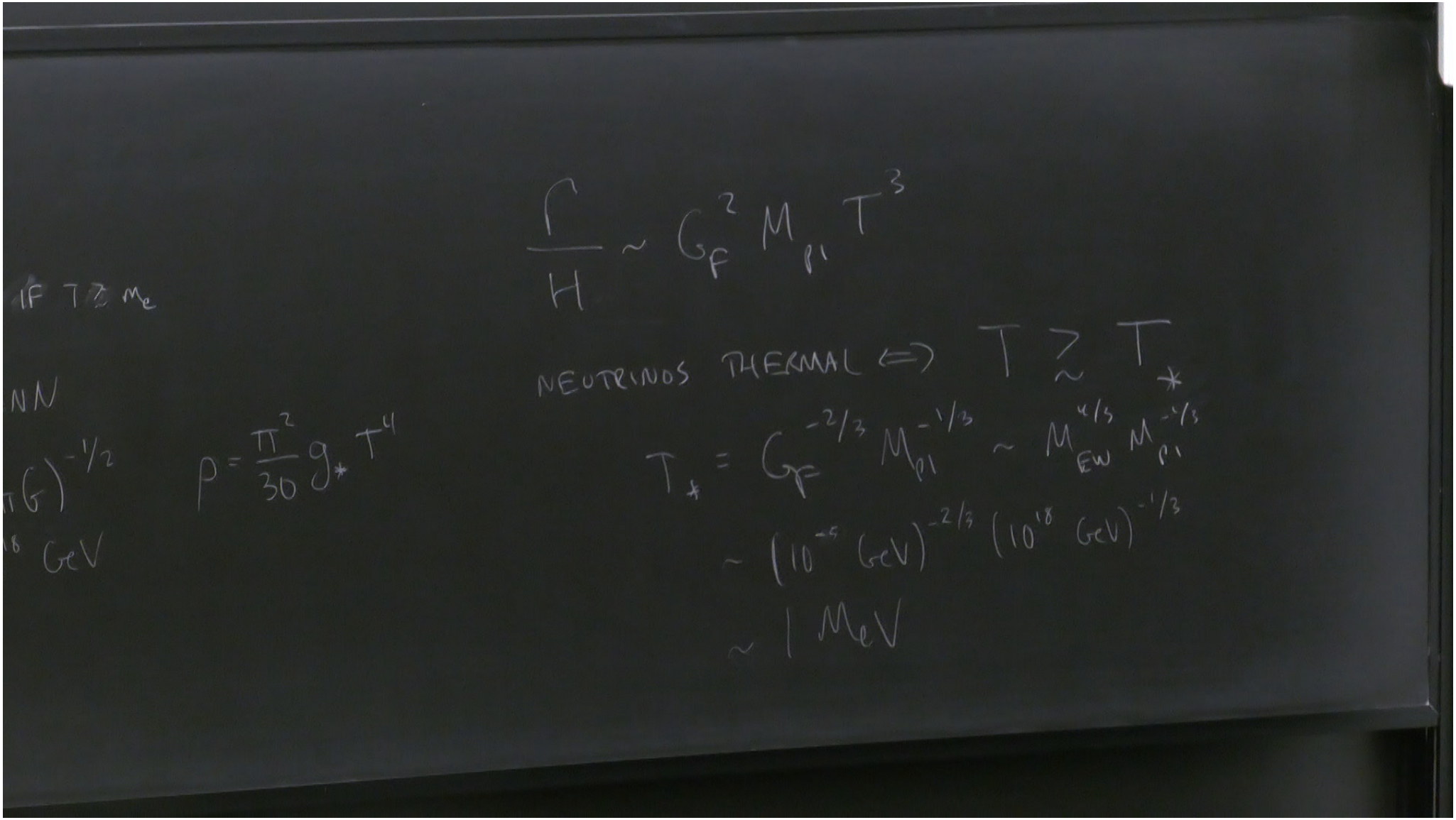
$= n_e \sigma v_\nu$

$\sim (T^3)(G_F^2 T^2)(1)$ $\quad n_e \sim T^3$ IF $T \gtrsim m_e$

$|H| \sim (G\rho)^{1/2}$ $\quad$ FRIEDMANN

$\sim (M_{Pl}^{-2} T^4)^{1/2}$ $\quad M_{Pl} = (8\pi G)^{-1/2}$ $\quad \rho = \frac{\pi^2}{30} g_* T^4$

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


IF T ≳ m_e
NN
ρ = π²/30 g_* T⁴
Γ/H ~ G_F² M_Pl T³
NEUTRINOS THERMAL ⟺ T ≳ T_*
T_* = G_F^{-2/3} M_Pl^{-1/3} ~ M_EW^{4/3} M_Pl^{-1/3}
~ (10^{-5} GeV)^{-2/3} (10^{18} GeV)^{-1/3}
~ 1 MeV

DEFINE $f_\nu(q, a)$ = MEAN OCCUPATION NUMBER

APPROXIMATION: INSTANTANEOUSLY DECOUPLE AT $T = T_*$

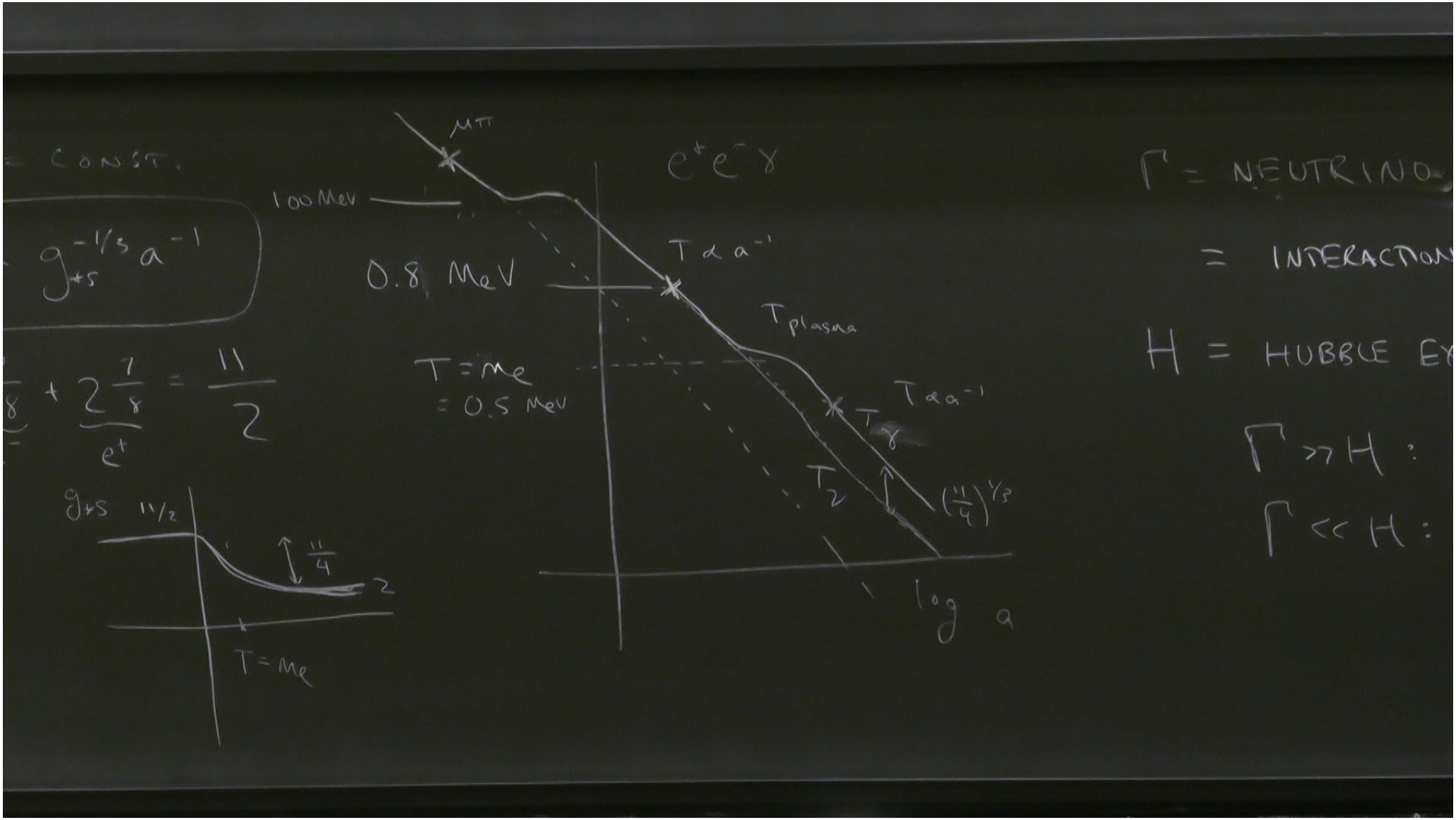
- AT $a = a_*$, NEUTRINOS ARE THERMAL

$$f_\nu(q, a_*) = \frac{1}{e^{E_q/T_*} + 1} \approx \frac{1}{e^{q/T_*} + 1} \qquad T_* \gg m_\nu$$

- FOR $a \geq a_*$, NEUTRINOS FREESTREAM WITH $q \propto a^{-1}$

$$f_\nu(q, a) = f_\nu\left(\frac{a}{a_*} q, a_*\right)$$

$$= \left[e^{(aq)/(a_* T_*)} + 1\right]^{-1}$$


CONST.
$g_{*S}^{-1/3} a^{-1}$
$\frac{\gamma}{\gamma} + 2\frac{\gamma}{e^+} = \frac{11}{2}$
g_{*S} 11/2
$\frac{11}{4}$
2
T = Me
100 MeV
0.8 MeV
T = Me
= 0.5 MeV
$e^+e^-\gamma$
$T \propto a^{-1}$
T_{plasma}
$T \propto a^{-1}$
T_γ
T_2
$(\frac{11}{4})^{1/3}$
log a
Γ = NEUTRINO
= INTERACTION
H = HUBBLE EX
Γ >> H :
Γ << H :

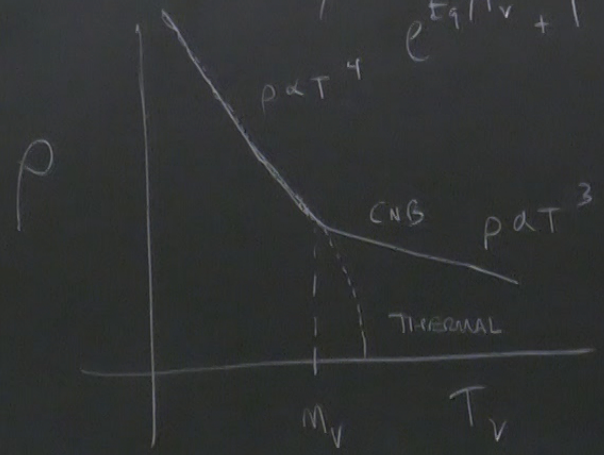
USUALLY WRITTEN THIS WAY

$$f_q = \frac{1}{e^{q/T_\nu} + 1}$$

WHERE $T_\nu \equiv \frac{a_*}{a} T_*$

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

$$\neq \frac{1}{e^{E_q/T_\nu} + 1}$$



$$\rho = \frac{g}{2\pi^2} \int dq\, q^2 f_q E_q$$

$$\Omega_\nu = \frac{\sum_\nu m_\nu}{46\ \text{eV}}$$ ←

TODAY

CURRENT BOUND:

$$\sum_{\nu} m_\nu \lesssim 120 \text{ meV} \quad [95\% \text{ CL}]$$

NEUTRINO OSCILLATION EXPERIMENTS:

$$m_2^2 - m_1^2 = (7.5 \times 10^{-5} \text{ eV}^2) = (8.7 \text{ meV})^2$$

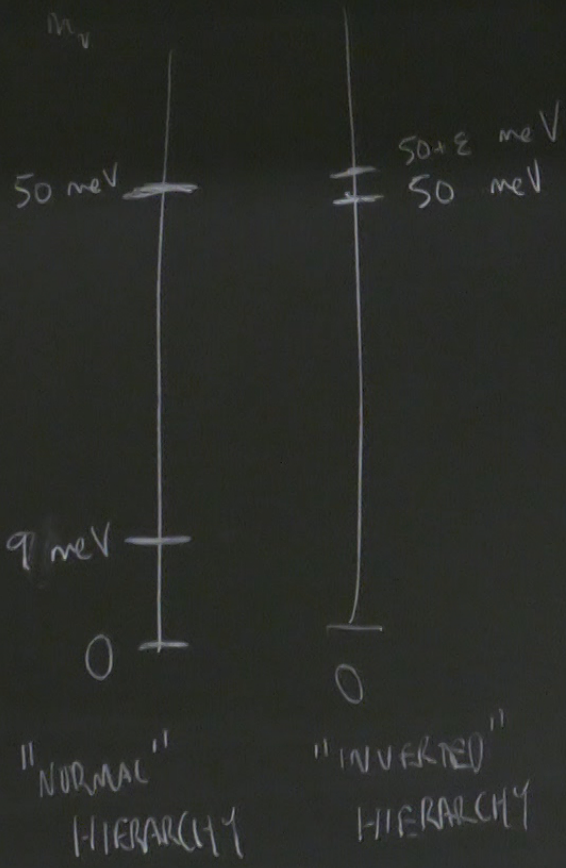
$$m_3^2 - m_2^2 = (2.3 \times 10^{-3} \text{ eV}^2) = (49 \text{ meV})^2$$

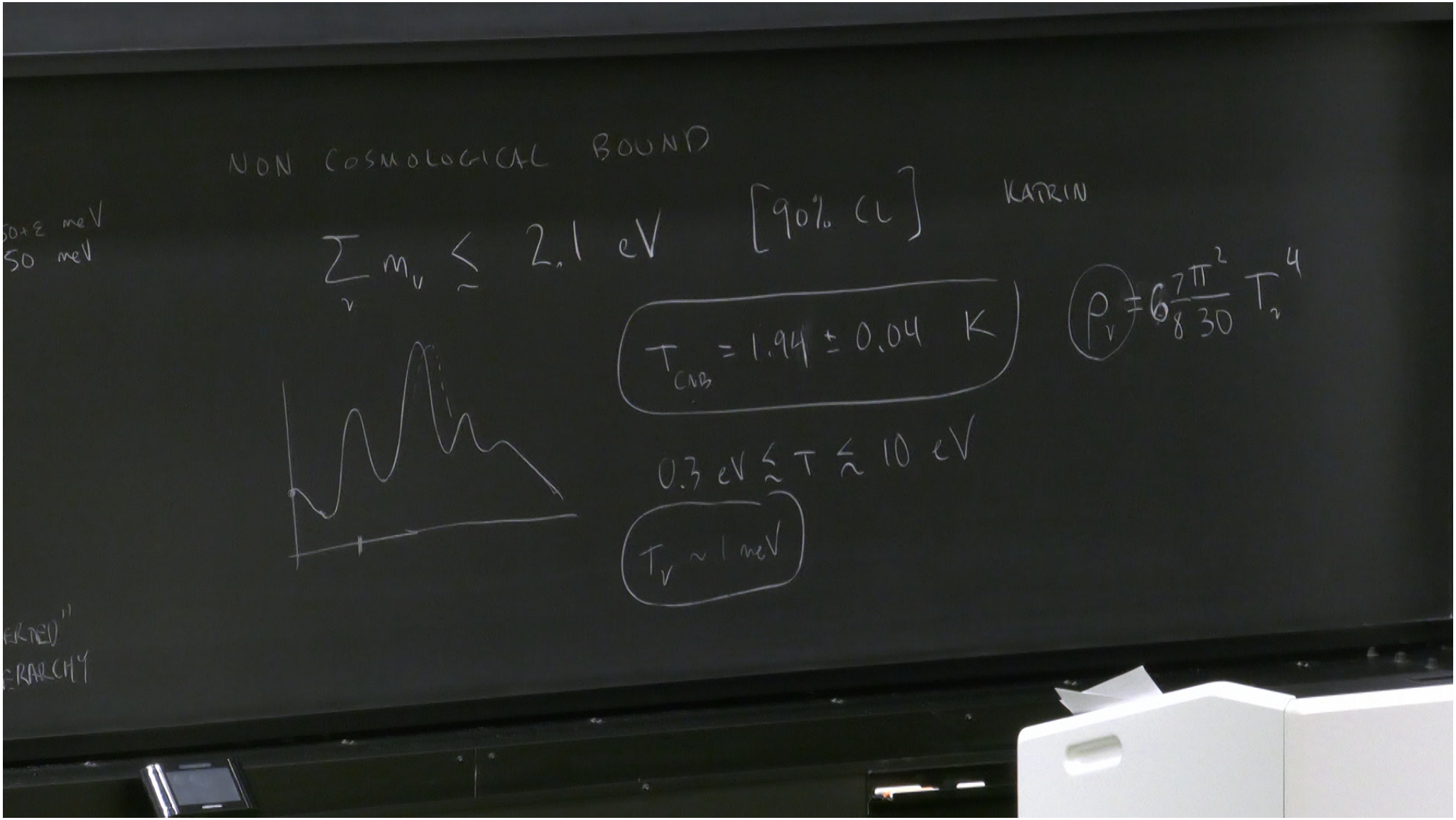
< 120 meV [95% CL]

LATION EXPERIMENTS:

$m_1^2 = (7.5 \times 10^{-5}\ \mathrm{eV}^2) = (8.7\ \mathrm{meV})^2$

$m_2^2 = (2.3 \times 10^{-3}\ \mathrm{eV}^2) = (49\ \mathrm{meV})^2$




NON COSMOLOGICAL BOUND
KATRIN
$\sum_\nu m_\nu \lesssim 2.1$ eV [90% CL]
$T_{CNB} = 1.94 \pm 0.04$ K
$\rho_\nu = 6\frac{7\pi^2}{8\,30} T_\nu^4$
0.3 eV $\lesssim T \lesssim$ 10 eV
$T_\nu \sim 1$ meV