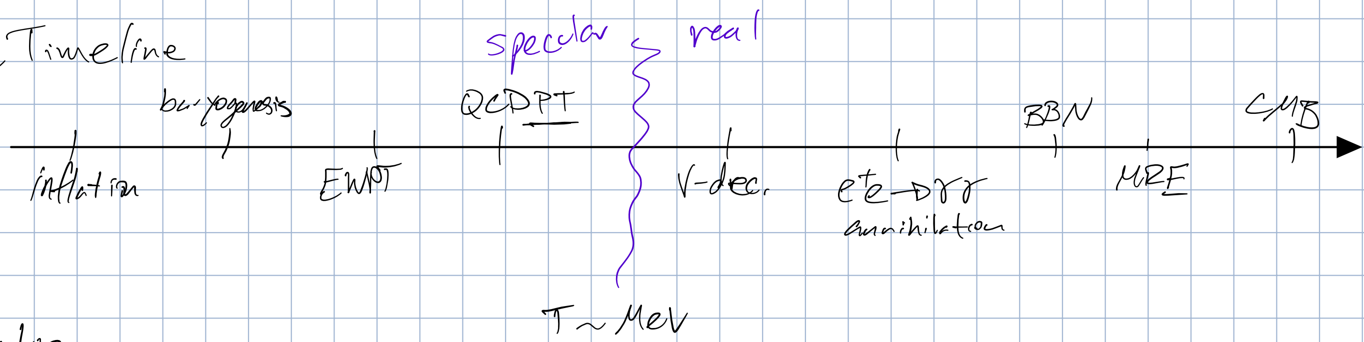
PT – phase transition

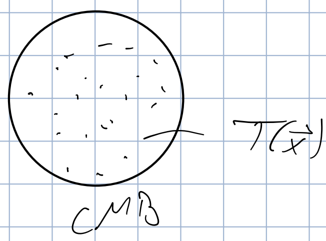
Cosmic Timeline



○ Inflation

T = temp

Horizon problem



$a(t) = e^{H \cdot t}$ $H \to$ constant

Flatness

$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\left(\rho + \frac{k}{a^2}\right)$

curvature
will parallel lines meet?

$\rho \propto a^{-3}, a^{-4}$

$k < 0$	open	lines diverge
$k = 0$	flat	
$k > 0$	closed	

Fields go under quantum fluctuations

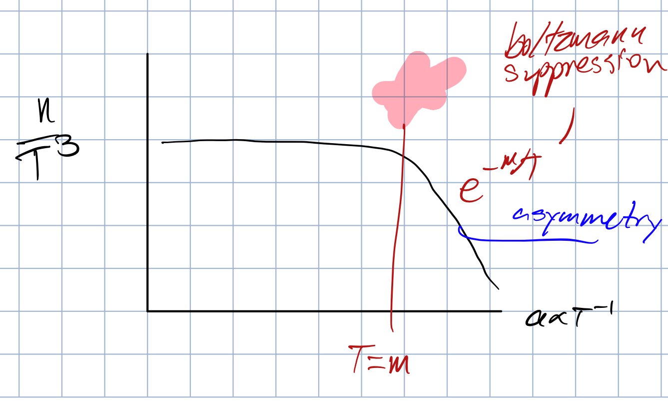
$E + \Delta E$ $1/100{,}000$

Baryogenesis

matter – antimatter asymmetry

$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = 6 \cdot 10^{-10} \approx 10^{-9}$

$T_{Baryog} = ?$ $\gtrsim 1\,MeV$



hella model

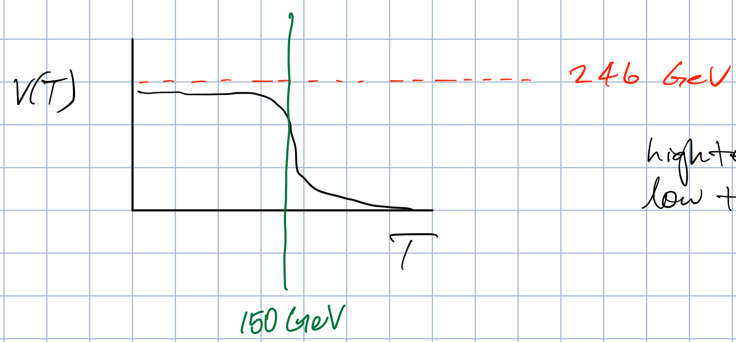
Electroweak Phase Transition (EWPT)

$m_i = y_i \cdot v$ — Higgs Vacuum Expectation Value $= 246$ GeV

"Yukawa coupling" (y_i)

like moving thru molasses

if $T > 150$ GeV



high temp, $v \to 0$
low temp, $v \to 246$ GeV

QCD Phase Transition

Strong Force theory (binds nuclei)

$T > \Lambda_{QCD} = 200$ MeV

quarks, gluons

if $T \ll m_i$

$$n_i(T) = \underbrace{g_i}_{\text{degeneracy}} \left(\frac{m_i T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_i - \overbrace{\mu}^{\text{chemical potential}})}{T}\right]$$

$E \approx m_i$

$T < 200$ MeV

protons, neutrons, confinement

$\mu_{particle} = -\mu_{antiparticle}$

$m_{proton} = m_p \approx m_{neutron} = m_n \approx$ GeV $\xrightarrow{\text{protons}}$ $n_p = g_p^{\,2} \left(\frac{m_p \cdot T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_p - \mu_p)}{T}\right]$

nonrelativistic particles

$$n_{\bar{p}} = g_p \left(\frac{m_p \cdot T}{2\pi}\right)^{3/2} \exp\left[-\frac{(m_p + \mu_p)}{T}\right]$$

as temp $\to 0$, $n_{\bar{p}} \to 0$

10^{-9}

$n_p \approx n_p - n_{\bar{p}} = \eta \cdot n_\gamma \cdot \left(\frac{1}{2}\right)$

$\propto T^{-3}$ Zeta fn

$\longrightarrow n_p(T)$

Neutrino Decoupling (ν-dec)

$\nu = \{ \nu_e, \nu_\mu, \nu_\tau \}$
3 "flavors"
each w/ antineutrino

$Q_\nu = 0 \quad m_\nu \approx 0$

$\Downarrow$

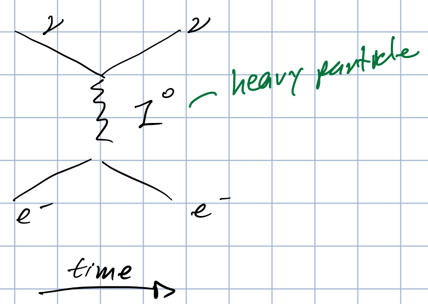
$\bar{\nu} = \{ \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \}$

numdensity: $n_\nu = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{p/T}+1}$ # spinstates $g_\nu = 1$

feels weak force, only interacts w/ 1 polarization states

$n_\nu \propto T^3$ (just like photons)

Weak Force



Z & W bosons
$m_Z \approx m_W$
~100 GeV

Fermi Constant: $G_F^{-1/2} = m_Z \sim m_W$

$G_F \equiv 1.15 \cdot 10^{-5}\ GeV^{-2}$

like G, but for weak force

Short range $10^{-15} m \sim fm$

$V(r) \sim \frac{\sqrt{G_F}}{r} e^{-m_Z r}$ (potential)

$r \ll \frac{1}{m_Z} \rightarrow V(r) \propto \frac{1}{r}$ (Coulumb)

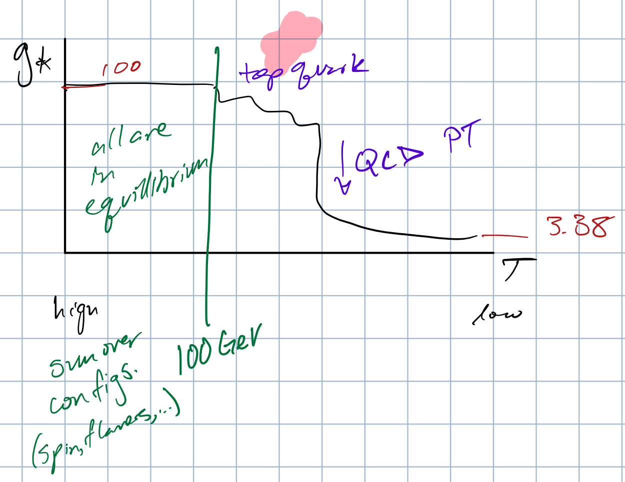
$r \gg \frac{1}{m_Z} \rightarrow V(r) \propto e^{-m_Z r}$ (Yukawa)

$T \gg MeV \rightarrow n_\nu \propto T^3$
radiation dominated
$\downarrow$

effective species

$H = \left(\frac{8\pi}{3} G\rho\right)^{1/2}$ $\qquad \rho_{rad} = \frac{\pi^2 \cdot g_* \cdot T^4}{30}$ $\qquad g_*(T) = \sum_{boson} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{fermion} g_i \left(\frac{T_i}{T}\right)^4$

photon temp. $\qquad$ integer spin $\qquad$ 1/2 spin



top quark becomes Boltzmann suppressed

channel energy & entropy to other particles

ρ_{rad} – who is in the bath? keep losing # particles b/c of energy changes

$H(T) \approx 1.66 \cdot \sqrt{g_*} \cdot \frac{T^2}{m_{pl}}$ —— planck mass : $m_{pl} = 1.22 \cdot 10^{19}\ GeV = G^{-1/2}$

ν - interaction rate ?

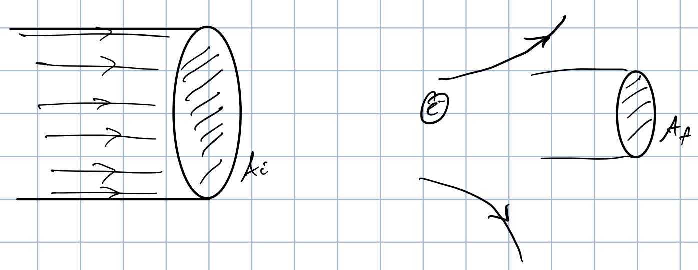
$R_\nu >> H(T)$? equillibrium
$R_\nu << H(T)$? decoupling

$R \equiv n \cdot \sigma \cdot v$ $\qquad$ (units inverse time)
$[\text{volume}]^{-1} \cdot [\text{area}] \cdot [c]$ speed of light

σ : x-section $\qquad [cm]^2$: $[GeV]^{-2}$

scattering time

how much of beam is deflected b/c of particle



$\sigma \equiv A_f - A_i$

$\langle \sigma(E_{beam}) \rangle \rightarrow \langle \sigma \rangle (T)$
thermal avg

expansion vs interaction

now traveling unimpeded

$R_\nu = n_e(T) \cdot \underbrace{\sigma(T)}_{\text{weak force}} \cdot v$
$= T^3 \cdot (G_F^2 \cdot T^2)$
$= G_F^2 T^5$ $\qquad$ more temp, more interaction → nice

$R_\nu = H \longrightarrow T_{decoupling} = \left(\frac{1.66 \cdot \sqrt{g_*}}{M_{pl}\, G_F^2}\right)^{1/3} \approx 1\,MeV$

$n_\nu(T) \propto T_{decl.}^3 \cdot a^{-3}$ for all time $\longrightarrow$ Cosmic Neutrino Background