

CP Violation and the Origin of Matter

THE BIG PICTURE

I. What is the BARYON ASYMMETRY OF THE UNIVERSE?

- i) Data 1 min
- ii) Theory 34 min

II. Where does it come from?

What does it have to do with CP
Violation and particle physics?

- i) GUTS 30 min
- ii) Electroweak Physics 40 min
- iii) Others 10 min
- iv) Conclusions & Prospects 5 min

Lecture 1

Lecture 2

WHAT IS THE UNIVERSE MADE OF?

Energy Density in massive stuff

$$0.01 \leq \Omega_0 \equiv \frac{\rho_0}{\rho_{\text{crit}}} \leq 3$$

ρ_{crit}

$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G_N}$

$$\frac{3H_0^2}{8\pi G_N}$$

We Believe: ρ_0 is all matter

+ dark stuff*

QUESTIONS

How do we know

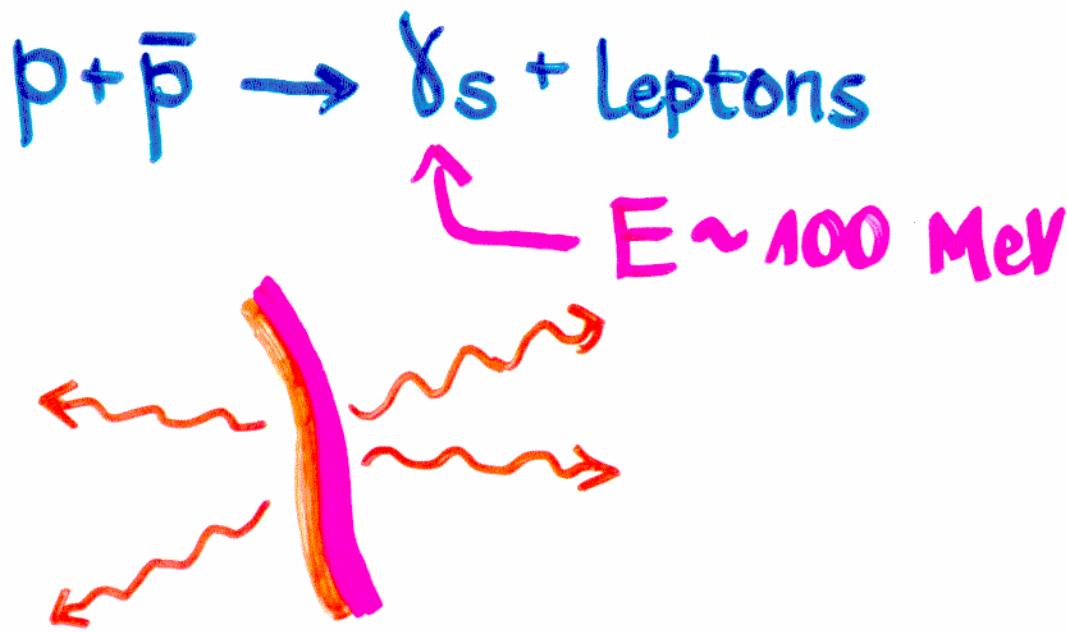
so all matter ?

Why is

so all matter ?

★ CP VIOLATION ?

GAMMA RAYS



∴ Point Sources of Gamma Rays

$$\text{Flux} \propto n \bar{n}$$

→ constrains product

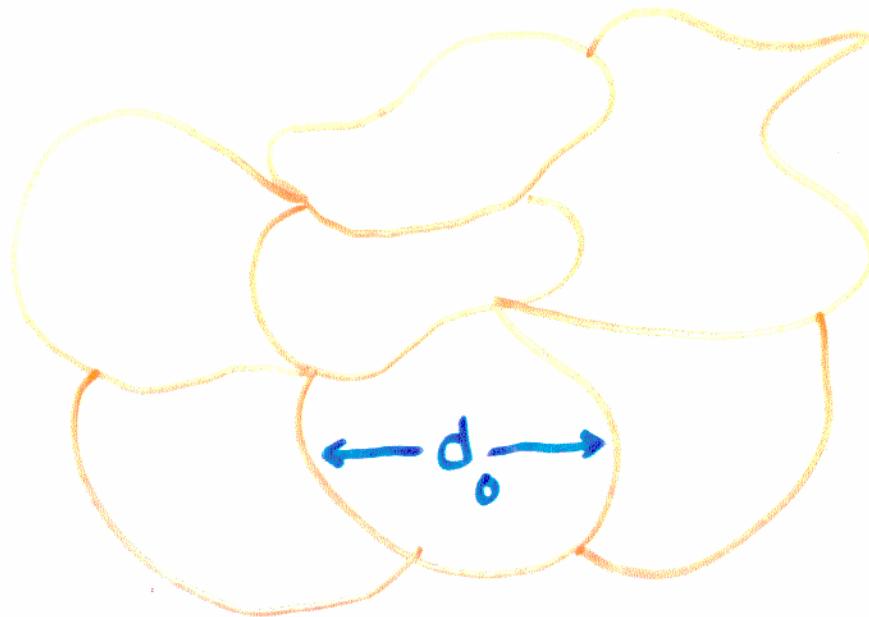
CONTINUOUS MATTER TRAIL

All Matter in the local
neighborhood ← Virgo Cluster

~ 20 Mpc*

L_{universe} ~ 3,000 Mpc

DOMAINS OF ANTIMATTER?



$$d_o \gtrsim 20 \text{ Mpc}$$

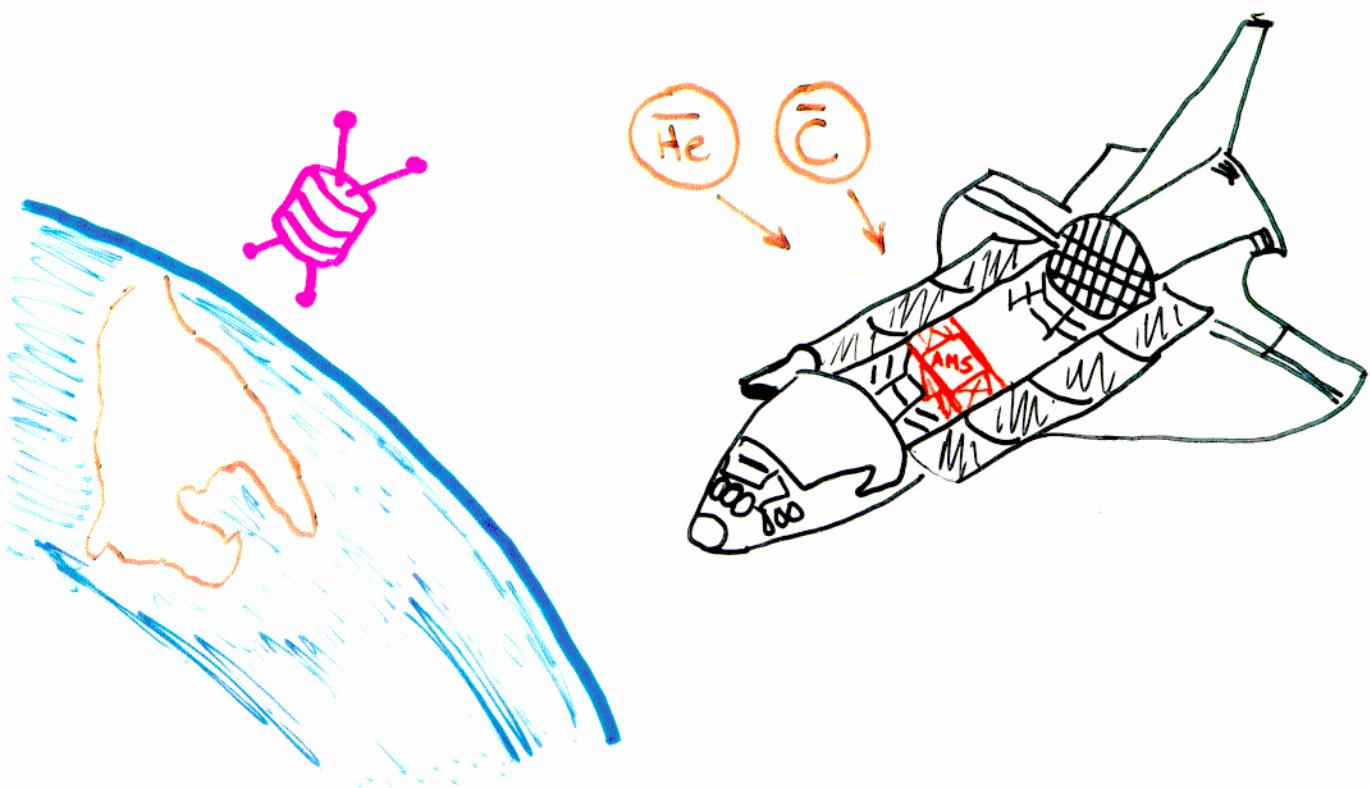
BETTER LIMITS ?

- Composition of Cosmic Rays

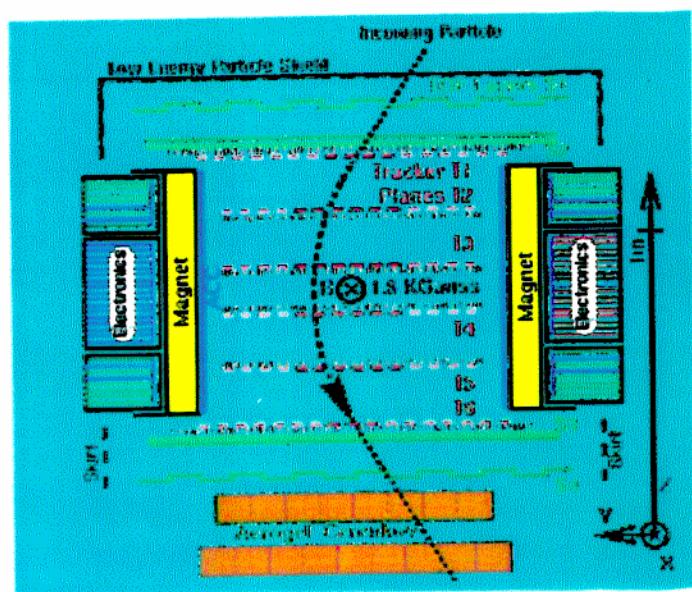
$$\frac{\bar{P}}{P} \sim 10^{-4}$$

All Secondaries

Anti-Nuclei ?



AMS
Alpha
magnetic
spectrometer



FURTHER LIMITS ?

- point source γ s with $E_{\gamma} \approx 100 \text{ MeV}$
constrains overlap $n\bar{n}$.
but $n\bar{n}$ fall off beyond
20 Mpc ← Virgo Cluster
- BUT: $n\bar{n}$ larger in the past!
∴ Search for γ s from the
EARLY UNIVERSE:
 - i) $E_{\gamma} \ll 100 \text{ MeV}$ (redshift)
 - ii) Diffuse (Every direction sees many boundaries)



PHOTONS FROM THE EARLY UNIVERSE

$t \sim 10^3$ s $y \sim 1100$



Evolve Domains



$t \sim 10^6$ s

$y \sim 20$

Evolve Photons



$t \sim 5 \cdot 10^9$ s

$y = 1$

Matter-Radiation
Decoupling

$n + \bar{n}$ uniform!

↑ CBR COBE

← matter-antimatter
combustion

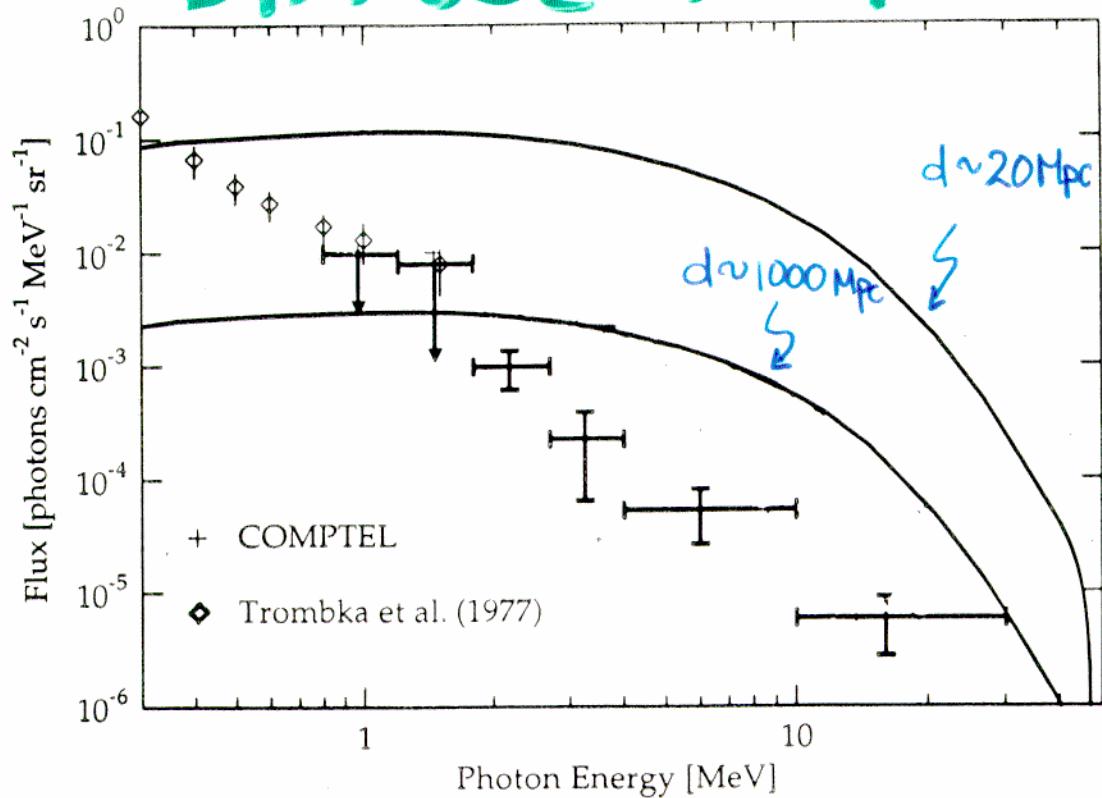
Structure
Formation

$n \leftrightarrow \bar{n}$
separate

Today

$E_\gamma \sim 0.1 \rightarrow 1$ MeV

DIFFUSE γ -RAY BACKGROUND



$d > 1000 \text{ Mpc} \rightarrow$ not so diffuse

$d < 20 \text{ Mpc} \rightarrow$ not so good

HOW BIG IS THIS ASYMMETRY

and what does it have to do
with CP violation?

$$\eta \equiv \frac{n_B + n_{\bar{B}}}{n_\chi} \leftarrow \text{Roughly independent of Universe Expansion}$$

A THEORISTS VIEW

:

IS THE ASYMMETRY SIGNIFICANT ?



$T \geq 1 \text{ GeV}$

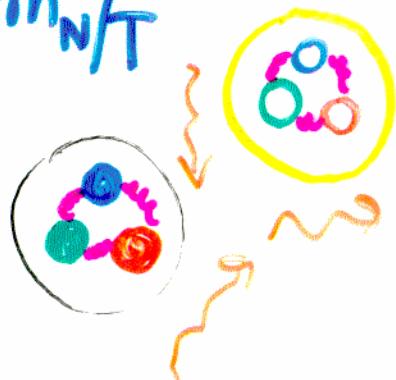
$$n_g \simeq n_g \simeq n_{\bar{g}} \simeq T^3$$



$20 \text{ MeV} < T \leq 1 \text{ GeV}$

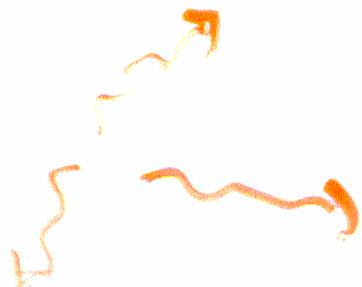
$$n_N \simeq n_{\bar{N}} \simeq (Tm)^{3/2} e^{-m_N/T}$$

$$n_g \simeq T^3$$



$T \sim 2 \cdot 10^5 \text{ eV}$

$$\frac{n_N + n_{\bar{N}}}{n_g} \sim 10^{-20}$$



AN EXPERIMENTALISTS VIEW

$$\eta = \frac{n_B + n_{\bar{B}}}{n_g} \stackrel{\text{Stars}}{\approx} \frac{n_B}{n_g} \gtrsim 10^{-10} *$$

Stars
 Microwave
 Background

$\eta_{\text{expt}} \gg \eta_{\text{theory}}$

* Nucleosynthesis

$$4 \cdot 10^{-10} \lesssim \eta \lesssim 7 \cdot 10^{-10}$$

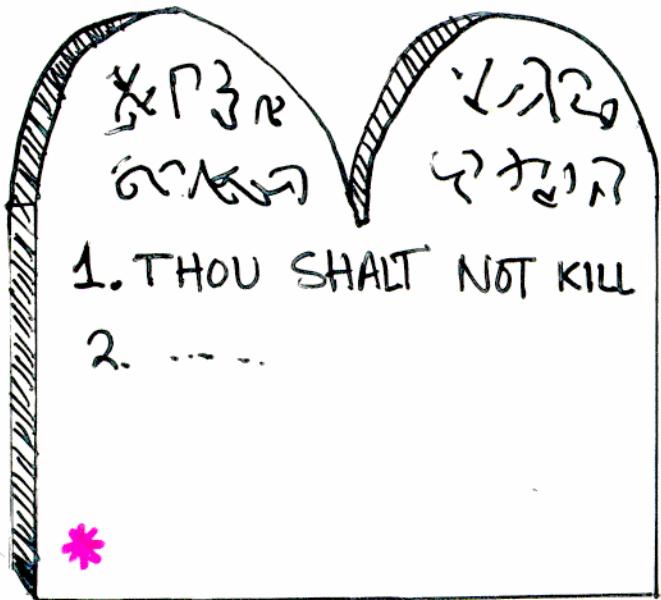
AVOIDING CATASTROPHE

$T \gg \text{GeV}$: $n_B > n_{\bar{B}}$ ASYMMETRY
↓ mate
 $n_B > 0$

→ THE UNIVERSE CONTAINS
'STUFF' BECAUSE OF A
BARYON ASYMMETRY OF THE
UNIVERSE !

Is this a sign of
CP Violation?

INITIAL CONDITION



* Oh, and by the way

THOU SHALT HAVE 1 FEWER ANTI-BARYON
FOR EVERY BILLION BARYONS

- 1) Peculiar
- 2) Initial Conditions Distasteful
- 3) Inconsistent with Inflation!

BARYO GENESIS

The dynamical generation of the Baryon Asymmetry during the evolution of the universe.

Assume: $B=0$ ($T \gg 1 \text{ MeV}$)



$B \neq 0$ ($T \sim 3 \cdot 10^4 \text{ eV}$)

NECESSARY INGREDIENTS

(Sakharov 1967!)

* BARYON VIOLATION

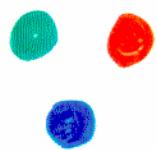
$B=0$

$t \rightarrow$
evolves

$B \neq 0$

★ C, CP VIOLATION

HOW DO WE DISTINGUISH
Quarks FROM antiQuarks

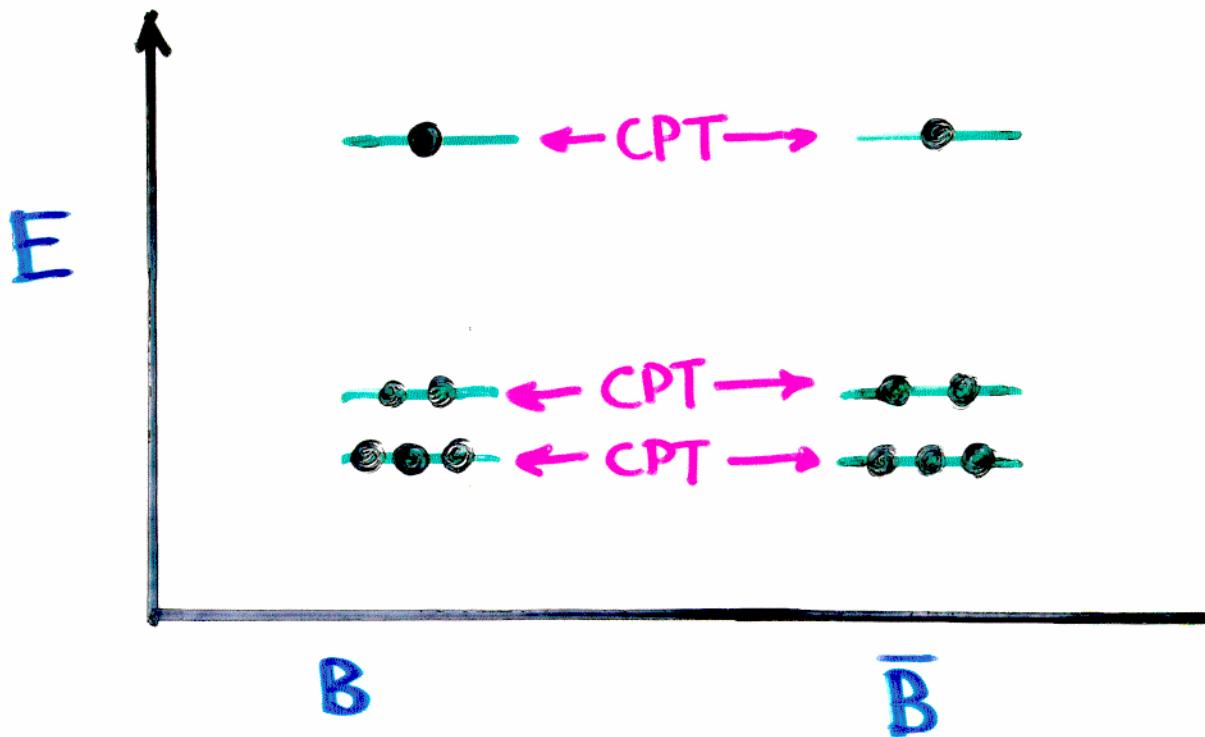


\hat{B} odd under C, CP

$$\frac{\text{Rate}[K_L^0 \rightarrow e^+ + \pi^- + \nu]}{\text{Rate}[K_L^0 \rightarrow e^- + \pi^+ + \bar{\nu}]} \approx 1.006$$

$\sim 10^{-3}$ effect

*DEPARTURE FROM THE THERMAL EQUILIBRIUM



$$\langle B \rangle = \text{Tr} \hat{B} e^{-\beta \hat{H}} = 0$$

Odd under CPT ↑ Even under CPT
 $\hat{B} \rightarrow -\hat{B}$ ↑ $\hat{H} \rightarrow \hat{H}$

WHERE DO THEY COME FROM ?

★ CP Violation

K_L^0 physics

★ Non-Equilibrium

Expanding Universe

★ B Violation

GUTS

CP VIOLATION

CKM theory in the weak interactions

Non-trivial phase in CKM matrix

BARYON VIOLATION

Naïve: proton stability rules out large B violation

∴ B violation mediated by heavy particles

$$M_\chi \gtrsim 10^{16} \text{ GeV}$$



Large

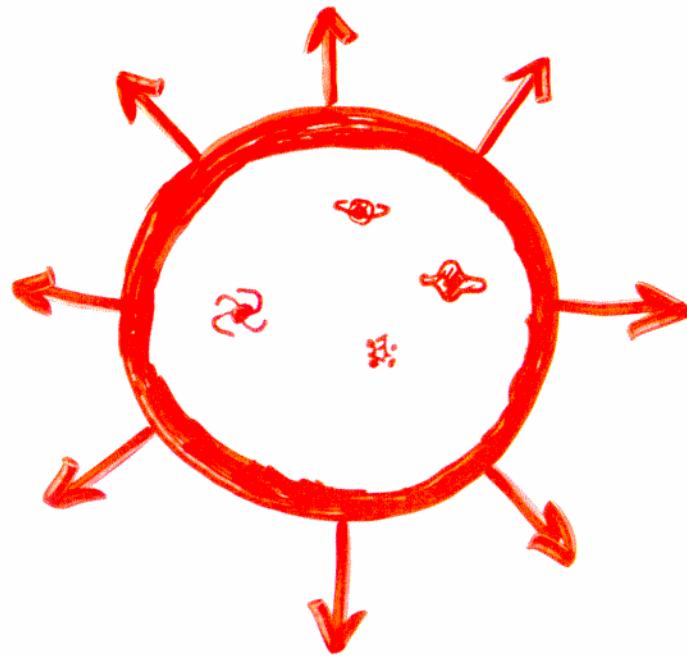
$$E \sim 10^{16} \text{ GeV}$$

Small

$$E \ll 10^{16} \text{ GeV}$$

DECOUPLING → ACCIDENTAL

DEPARTURE FROM EQUILIBRIUM



$$\text{Expansion Rate} = \frac{\dot{R}}{R} = -\frac{\dot{T}}{T} = H(t)$$

$\sim \frac{T^2}{M_{Pl}}$ ← 10^{19} GeV

- Small Except at high T

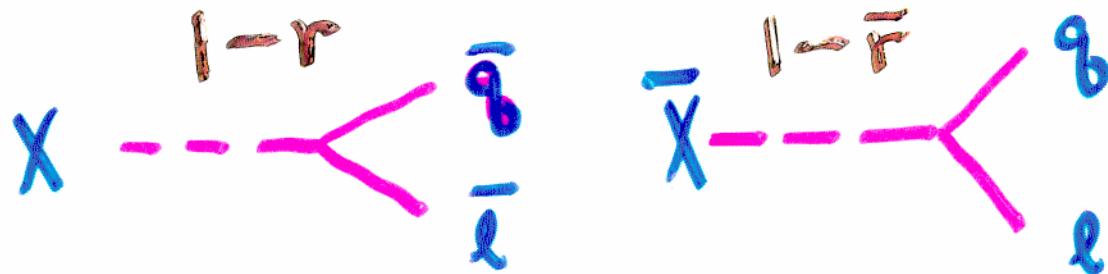
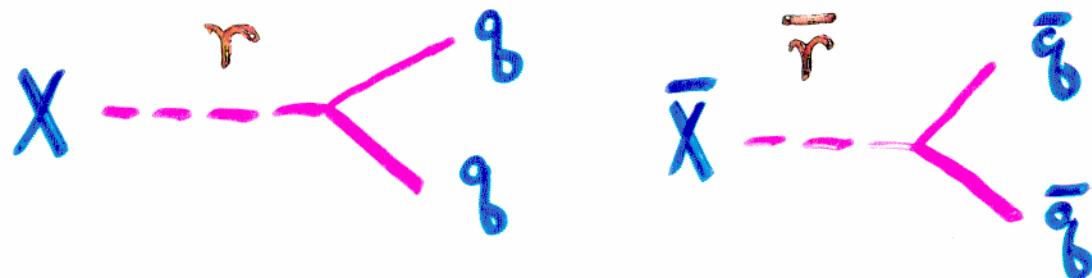
COMPARE?

SUGGESTS GUTS

Quarks & Leptons 'Unified'

∴ Gauge Bosons (and GUT Higgs Scalars)
have B Violating couplings

X, Y, H



CPT: $m_x = m_{\bar{x}}$; $\Gamma_x = \Gamma_{\bar{x}}$

~~CPT~~: $r \neq \bar{r}$ ← interference

$$\cancel{B}: B(gg) = \frac{2}{3} \quad B(\bar{g}\bar{l}) = -\frac{1}{3}$$

Thermal Distribution

$$n_x = n_{\bar{x}}$$

↓
DECAY
↓

$$B_x = n_x \left[r^{\frac{2}{3}} + (1-r) \left(-\frac{1}{3} \right) \right]$$

$$+ B_{\bar{x}} = n_{\bar{x}} \left[\bar{r} \left(-\frac{2}{3} \right) + (1-\bar{r}) \left(+\frac{1}{3} \right) \right]$$

$$n_B = n_x \cdot (r - \bar{r})$$

NON-EQUILIBRIUM

?

Thermal



Equal Rates!

SOLUTION:

$T < M_x$ $\rightarrow \dots$ small

$n_x \propto e^{-M_x/T}$ $\rightarrow \dots$ small

→ make n_x larger

OUT-OF-EQUILIBRIUM DECAY

Γ_{eq} { Decay
Annihilation

H { Expansion

$$\begin{aligned} \Gamma_{\text{eq}} &\ll H \\ \downarrow & \\ -m_x/T & \\ n_x &\gg e \end{aligned}$$

GUT BARYOGENESIS

Late (out-of-equilibrium) decays
of GUT particles (Scalars)
With CP violation in
decay amplitudes can
produce B asymmetry

!

Size? K physics?

B-factory?