

# Gravitinos, Reheating and the Matter-Antimatter Asymmetry of the Universe

Raghavan Rangarajan  
Physical Research Laboratory  
Ahmedabad, India

with R. Arya, N. Mahajan, N. Sahu, A. Sarkar

# OUTLINE

- OUR UNIVERSE – PRESENT AND PAST
- MATTER-ANTIMATTER ASYMMETRY OF THE UNIV
- INFLATION AND REHEATING
- GRAVITINO PROBLEM AND  $T_{\text{REH}}$

REHEATING, GRAVITINOS AND THE M-A  
ASYMMETRY

- RESOLVING THE GRAVITINO PROBLEM
- CONCLUSION

# OUR UNIVERSE

OBSERVATIONS + GENERAL THEORY  
OF RELATIVITY

PRESENT AND PAST

FUTURE ?

# THE PRESENT

14 b yr

COMPOSITION – PHOTONS AND NEUTRINOS  
LUMINOUS MATTER (p,n,e)  
DARK MATTER  
DARK ENERGY

EXPANDING

# EXPANSION OF OUR UNIVERSE

- ALL DISTANT GALAXIES ARE MOVING AWAY FROM EACH OTHER (HUBBLE 1929)
- NOT BECAUSE OF INTRINSIC VELOCITIES BUT BECAUSE **SPACE IS EXPANDING**

**GENERAL RELATIVITY** (SPACE INFLUENCED BY MATTER IN IT, DYNAMIC )

# EXPANSION OF OUR UNIVERSE

ISOTROPIC AND HOMOGENEOUS

Rate of expansion  $\propto$  (ave. energy density)<sup>1/2</sup>

Evolution and expansion also depends on the composition of the universe (rel or non-rel, ..)

- **WHATEVER DOMINATES DETERMINES THE NATURE OF EVOLUTION**

# COMPOSITION OF OUR UNIVERSE

- PHOTONS AND NEUTRINOS – NEGLIGIBLE
- PROTONS, NEUTRONS AND ELECTRONS – 5%
- DARK MATTER – 25%
- DARK ENERGY – 70% ACCELERATING

# COMPOSITION OF OUR UNIVERSE

- PHOTONS AND NEUTRINOS –  
NEGLIGIBLE (First 70 k)
- PROTONS, NEUTRONS AND  
ELECTRONS – 5%
- DARK MATTER – 25% (70 k – 9 b yr)
- DARK ENERGY – 70% ACCELERATING



# PAST

**PRESENT** -- 14 b yr, COMPOSITION, EXPANDING

+ GENERAL RELATIVITY

**PAST** – DENSE AND HOT, EXPANDING FAST

GO BACK IN TIME, HOTTER, PARTICLES MORE  
ENERGETIC, IN ELEMENTARY FORMS

GALAXIES AND STARS -- TODAY

ATOMS → NUCLEI → FUNDAMENTAL PARTICLES

# A BRIEF HISTORY OF OUR UNIVERSE

- First second – hot primordial gas of electrons, .. photons, quarks/protons, neutrons, dark matter, ...
- 1 s – 3 min – **light nuclei** (helium, lithium, ..)
- 400,000 years – Atoms form, **CMBR**
- 300 million years – First stars form
- 1 billion years – First galaxies form
- 9 billion years – Solar system formed, DE
- 14 billion years – Today

# UNIVERSE AS A PARTICLE PHYSICS LABORATORY

CURRENT COLLIDERS  $E \sim \text{TeV}$ , BSM  $> 1 \text{ TeV}$

ENERGY OF PARTICLES IN THE FIRST  
MICROSECOND IS HIGHER

CAN APPLY NEW PARTICLE PHYSICS  
THEORIES IN THE FIRST MICROSECOND

THEN AND NOW  
STUDY REACTIONS, PREDICT TODAY

**PARTICLE COSMOLOGY**

# THE FIRST SECOND

- $10^{-44}$  s – Planck time ( $E \sim 10^{19}$  GeV) [Q Gravity]

## Grand Unified Theory

- $10^{-38}$  s – GUT Phase Transition ( $E \sim 10^{16}$  GeV,  $T \sim 10^{29}$  K)

## Standard Model [q, l, H, GB] /Modified SM

- $10^{-11}$  s – Electroweak Phase Transition ( $E \sim 100$  GeV,  $T \sim 10^{15}$  K)
- $10^{-6}$  s – quarks  $\rightarrow$  protons, neutrons ( $E \sim 1$  GeV,  $T \sim 10^{13}$  K)
- 1 s – Primordial Nucleosynthesis begins ( $E \sim 1$  MeV,  $T \sim 10^{10}$  K)

# THE FIRST SECOND

- $10^{-44}$  s – Planck time ( $E \sim 10^{19}$  GeV) [Q Gravity]

## Grand Unified Theory

- $10^{-38}$  s – GUT Phase Transition ( $E \sim 10^{16}$  GeV,  $T \sim 10^{29}$  K) ■

## Standard Model [q, l, H, GB] /Modified SM

- $10^{-11}$  s – Electroweak Phase Transition ( $E \sim 100$  GeV,  $T \sim 10^{15}$  K) ■
- $10^{-6}$  s – quarks  $\rightarrow$  protons, neutrons ( $E \sim 1$  GeV,  $T \sim 10^{13}$  K)
- 1 s – Primordial Nucleosynthesis begins ( $E \sim 1$  MeV,  $T \sim 10^{10}$  K)

# OUTLINE

- OUR UNIVERSE – PRESENT AND PAST
- MATTER-ANTIMATTER ASYMMETRY OF THE UNIV
- INFLATION AND REHEATING
- GRAVITINO PROBLEM AND  $T_{\text{REH}}$
- REHEATING, GRAVITINOS AND THE M-A ASYMM
- RESOLVING THE GRAVITINO PROBLEM
- CONCLUSION

# MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

- SOLAR SYSTEM — PROBES, INTERACTION OF SOLAR WIND WITH PLANETS
- MILKY WAY — COSMIC RAYS
- CLUSTER (20 Mpc) — GALACTIC COLLISIONS  
(1 Mpc =  $3 \times 10^6$  lt-yr) INTERGALACTIC HOT PLASMA
- UP TO 1000 Mpc — COSMIC DIFFUSE GAMMA RAY SPECTRUM  
(ANNIHILATIONS AT BOUNDARY FROM  $z=1000$  TO 20 – 380,000 YR TO 100 MILLION YR) (Cohen, de Rujula, Glashow)<sup>16</sup>



# MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

- ANTIMATTER RULED OUT TILL  $d \sim 1000$  Mpc
- SIZE OF OBSERVABLE UNIVERSE  $\sim 14000$  Mpc

$$(1 \text{ Mpc} = 3 \times 10^{19} \text{ km} = 3 \times 10^6 \text{ lt-yr})$$

MATTER-ANTIMATTER ASYMMETRY OF THE  
UNIV

# HOW GENERATE ASYMMETRY?

- EARLY TIMES ( $t \ll 1 \text{ s} = \text{PRIM. NUCL.}$ ) EQUAL AMOUNTS OF MATTER AND ANTIMATTER
- WHERE DID THE ANTIMATTER GO? WHY THIS ASYMMETRY TODAY?
- DISEQUILIBRIUM IN THE EARLY UNIVERSE  
 $100 M + 100 A \rightarrow 103 M + 101 A \rightarrow 2 M$



$r_M > r_A$ , GET MORE MATTER THAN ANTIMATTER

# MATTER-ANTIMATTER ASYMMETRY

- X = GUT (GRAND UNIFIED THEORY) BOSONS
  - GUT BARYOGENESIS MASS ( $M_X \sim 10^{16}$  GeV)
- X = HEAVY NEUTRINOS
  - LEPTOGENESIS MODELS MASS ( $M_N \sim 10^{10}$  GeV)

MASS EXPRESSED AS MASS ENERGY  $M c^2$

1 GeV = PROTON MASS  $\sim 10^{-27}$  kg

# MATTER-ANTIMATTER ASYMMETRY

## WHEREFROM

- GUT BOSONS ( $M_X \sim 10^{16}$  GeV)
- HEAVY NEUTRINOS ( $M_N \sim 10^{10}$  GeV) ?

1 GeV = PROTON MASS

# MATTER-ANTIMATTER ASYMMETRY

## WHEREFROM

- GUT BOSONS ( $M_X \sim 10^{16}$  GeV)
- HEAVY NEUTRINOS ( $M_N \sim 10^{10}$  GeV) ?

1 GeV = PROTON MASS

In the hot early Universe when temperatures were very high ( $k_B T > M$ ) ( $k_B=1$ )

# OUTLINE

- OUR UNIVERSE – PRESENT AND PAST
- MATTER-ANTIMATTER ASYMMETRY OF THE UNIV
- INFLATION AND REHEATING
- GRAVITINO PROBLEM AND  $T_{\text{REH}}$
- REHEATING, GRAVITINOS AND THE M-A ASYMM
- RESOLVING THE GRAVITINO PROBLEM
- CONCLUSION

# INFLATION

PERIOD OF *ACCELERATED* EXPANSION IN  
THE EARLY UNIVERSE ( $t \sim 10^{-38}$  s or later)

HOW AND WHY?

# INFLATION

EARLY UNIVERSE: RADIATION + SCALAR FIELD  $\phi$

RAD DOMINATE, UNIV EVOLVES ACCORDINGLY

ENERGY DENSITY OF RADIATION DECREASES

ENERGY DENSITY OF  $\phi$  IS  $\dot{\phi}^2/2 + V(\phi) \approx V(\phi)$

SLOWLY CHANGING  $\sim$  CONSTANT

WHEN  $\phi$  DOMINATES, DETERMINES EVOL OF UNIV



# INFLATION

IN AN EXPANDING UNIVERSE  $d(t) \sim d_1 R(t)$

EINSTEIN'S EQN GIVES  $R(t)$  FOR RAD/INFLATON

DURING RADIATION DOMINATED ERA ,  $R \sim t^{1/2}$

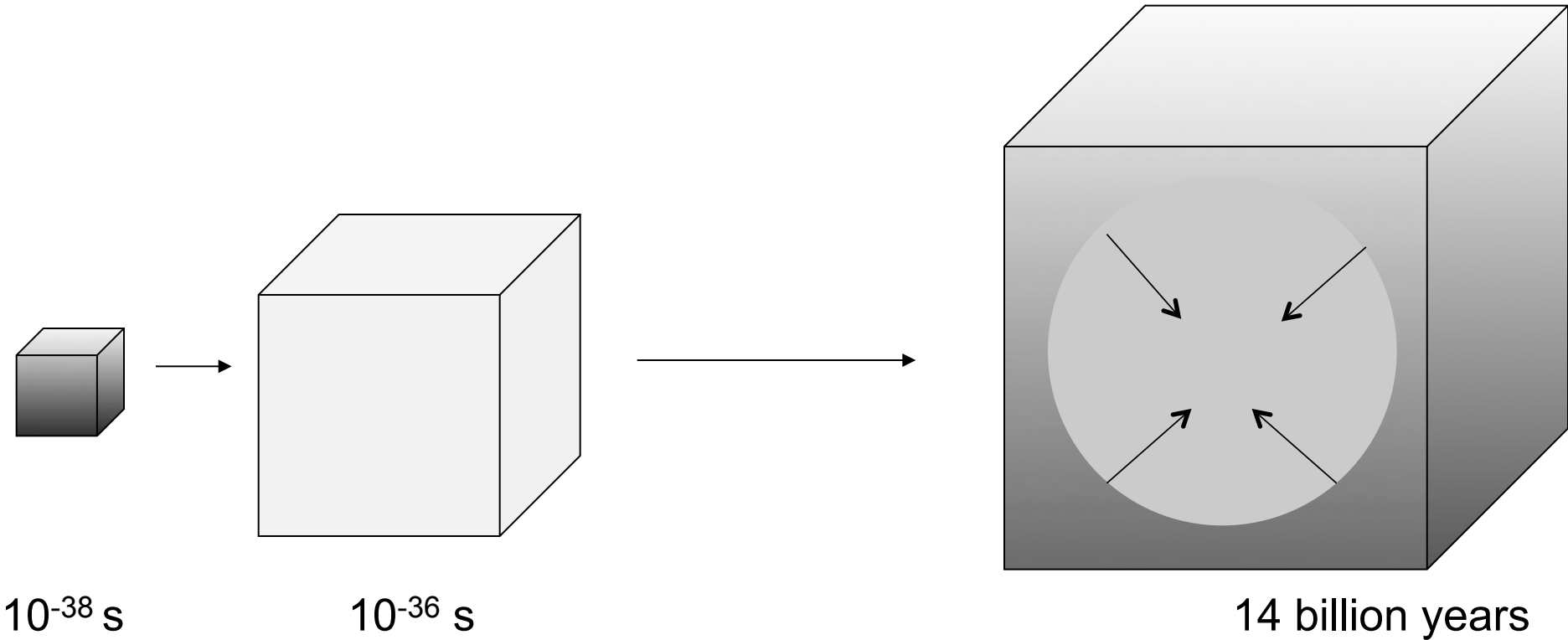
DURING INFLATION,  $V(\phi) \sim \text{CONST}$ ,  $R \sim \exp(H_i t)$

$H_i$  IS THE HUBBLE PARAMETER

DURING INFLATION,  $V_f \sim 10^{90} V_i$  (IN  $10^{-36}$  s !!)

# WHY?

## HORIZON PROBLEM -- ISOTROPY OF CMBR



# INFLATION AND REHEATING

DURING INFLATION,  $V_f \sim 10^{90} V_i$

$n$  OF ALL SPECIES  $\rightarrow 0$ . COLD

AFTER SOME TIME ( $10^{-36}$ s) THE INFLATON FIELD OSCILLATES AND DECAYS

INFLATON DECAY PRODUCTS THERMALISE,  $T_{\text{reh}}$   
THERMAL BATH HAS  $q, l, h, dm$ , BSM INCLUDING  
GUT PARTICLES AND HEAVY NEUTRINOS

REHEATING

THEREAFTER, ONCE AGAIN RAD DOMINATED

# WHY BELIEVE?

CMBR DATA CLEARLY INDICATES THAT SOME EVENT LIKE INFLATION DID HAPPEN

INFLATION PREDICTS SOME ANISOTROPY  
-- SEEN

(INFLATION ALSO PREDICTS PRIMORDIAL GRAVITATIONAL WAVES - NOT YET DETECTED)

# OUTLINE

- OUR UNIVERSE – PRESENT AND PAST
- MATTER-ANTIMATTER ASYMMETRY OF THE UNIV
- INFLATION AND REHEATING
- GRAVITINO PROBLEM AND  $T_{\text{REH}}$
- REHEATING, GRAVITINOS AND THE M-A ASYMM
- RESOLVING THE GRAVITINO PROBLEM
- CONCLUSION

# GRAVITINOS

$\tilde{G}$  = SUPERSYMMETRIC PARTNER OF THE GRAVITON

## SUPERSYMMETRY

- EXTENSION OF THE STANDARD MODEL (GAUGE HIERARCHY)
- SUPERPARTNERS: FERMION – BOSON

PHOTON – PHOTINO, ELECTRON – SELECTRON,  
QUARKS – SQUARKS

(EQUAL  $m$ , IF SUSY)

GRAVITON – GRAVITINO (**SUPERGRAVITY**)

CAVEAT: NO SUSY PARTICLE SEEN YET, LHC ?

# GRAVITINOS

$\tilde{G}$  = SUPERSYMMETRIC PARTNER OF THE GRAVITON

PRODUCED AFTER INFLATION  $t \sim 10^{-38}$  s ( $m_{\tilde{G}}$  : eV – TeV)

## COSMOLOGICAL CONSEQUENCES (m, n)

- STABLE : AFFECTS EXPANSION RATE,  $\rho_{\tilde{G}} > \rho_c$  (L/H)
- UNSTABLE : AFFECT EXPANSION RATE PRIOR TO DECAY

DECAY PRODUCTS  $\rho > \rho_c$

DESTROY LIGHT ELEMENTS  ${}^4\text{He}$ ,  ${}^3\text{He}$ ,  $D$   
(NUCLEOSYNTHESIS)

## GRAVITINO PROBLEM(S)

# GRAVITINOS

$\tilde{G}$  = SUPERSYMMETRIC PARTNER OF THE GRAVITON

PRODUCED AFTER INFLATION  $t \sim 10^{-34}$  s ( $m_{\tilde{G}} : \text{eV} - \text{TeV}$ )

## COSMOLOGICAL CONSEQUENCES (m, n)

- STABLE : AFFECTS EXPANSION RATE,  $\rho_{\tilde{G}} > \rho_c$  (L/H)
- UNSTABLE : AFFECT EXPANSION RATE PRIOR TO DECAY

DECAY PRODUCTS  $\rho > \rho_c$

DESTROY LIGHT ELEMENTS  ${}^4\text{He}, {}^3\text{He}, D$   
(NUCLEOSYNTHESIS)

**GRAVITINO PROBLEM(S) => UPPER BOUND ON  $\rho_{\tilde{G}} \propto n_{\tilde{G}}$**  32



# STANDARD PICTURE OF GRAVITINO PRODUCTION

RAD

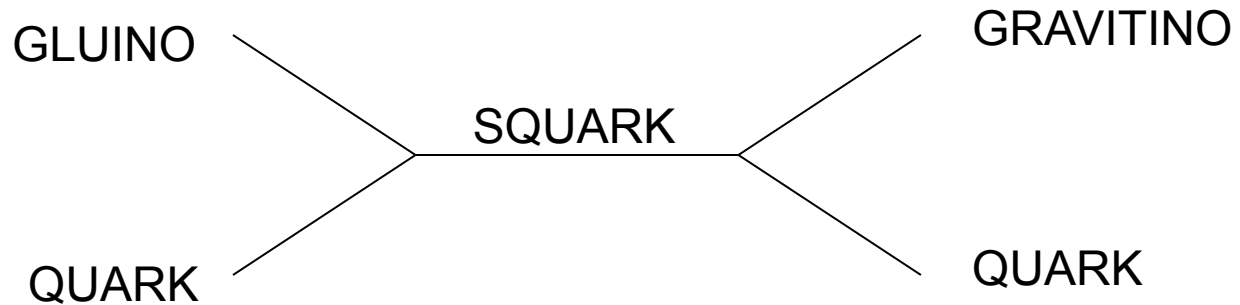
INFLATION  $\rightarrow$  REHEATING (OSC. + DECAY)  
( $T_{\text{reh}}$ )

$\rightarrow$  RADIATION DOMINATED UNIV  
(Relativistic particles)

THERMAL SCATTERING  $\rightarrow \tilde{G}$

(gluons, quarks, squarks, gluinos)

# STANDARD PICTURE OF GRAVITINO PRODUCTION



$$\tilde{g} + q \longrightarrow \tilde{q}^* \longrightarrow \tilde{G} + q$$

$$q + \bar{q} \rightarrow g + \tilde{G}$$

$$q + \bar{q} \rightarrow \tilde{g} + \tilde{G}$$

$$\tilde{q} + \bar{q} \rightarrow \tilde{g} + \tilde{G}$$

$$\langle \Sigma_{\text{tot}} | v \rangle = G_N \alpha$$

PRADLER AND STEFFEN

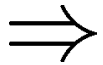
$$G_N = 1/M_{Pl}^2$$

# STANDARD CALC OF GRAVITINO PRODUCTION

CALCULATE GRAVITINO PRODUCTION IN THE  
RAD DOM ERA

MAINLY PRODUCED AT THE BEGINNING OF THE  
RAD DOM ERA WHEN  $T \sim T_{\text{reh}}$  AND  $n_{\tilde{G}} \propto T_{\text{reh}}$ .

UPPER BOUND ON  $n_{\tilde{G}}$



UPPER BOUND ON  $T_{\text{reh}}$  OF  $10^6\text{--}9$  GeV  
(MASS 100 GeV – 10 TeV)

$$k_B T \text{ in GeV} \quad k_B = 1 \quad 1 \text{ GeV} = 10^{13} \text{ K}$$

# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

- THE UPPER BOUND ON THE REHEAT TEMPERATURE  $10^{6-9}$  GeV TO SUPPRESS GRAVITINO PRODUCTION

$$1 \text{ GeV} = 10^{13} \text{ K}$$

# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

- THE UPPER BOUND ON THE REHEAT TEMPERATURE  $10^{6-9}$  GeV TO SUPPRESS GRAVITINO PRODUCTION
- MATTER-ANTIMATTER ASYMMETRY GENESIS MODELS REQUIRE HEAVY X, MASS  $10^{10}$ ,  $10^{16}$  GeV

1 GeV = PROTON MASS

# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

- THE UPPER BOUND ON THE REHEAT TEMPERATURE  $10^{6-9}$  GeV TO SUPPRESS GRAVITINO PRODUCTION
- MATTER-ANTIMATTER ASYMMETRY GENESIS MODELS REQUIRE HEAVY X, MASS  $10^{10}$ ,  $10^{16}$  GeV

DIFFICULT TO HAVE ENOUGH HEAVY X IN THE RADIATION DOMINATED UNIV AFTER REHEATING

# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

- THE UPPER BOUND ON THE REHEAT TEMPERATURE  $10^{6-9}$  GeV TO SUPPRESS GRAVITINO PRODUCTION
- MATTER-ANTIMATTER ASYMMETRY GENESIS MODELS REQUIRE HEAVY X, MASS  $10^{10}$ ,  $10^{16}$  GeV

DIFFICULT TO HAVE ENOUGH HEAVY X IN THE RADIATION DOMINATED UNIV AFTER REHEATING

$$n_X \sim \exp(- M c^2/k_B T)$$



# REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

- THE UPPER BOUND ON THE REHEAT TEMPERATURE  $10^{6-9}$  GeV TO SUPPRESS GRAVITINO PRODUCTION
- MATTER-ANTIMATTER ASYMMETRY GENESIS MODELS REQUIRE HEAVY X, MASS  $10^{10}$ ,  $10^{16}$  GeV

DIFFICULT TO HAVE ENOUGH HEAVY X IN THE RADIATION DOMINATED UNIV AFTER REHEATING

LOW REHEAT TEMP TO SUPPRESS GRAVITINOS IS A PROBLEM FOR GUT BARYOGENESIS AND LEPTOGENESIS

# OUTLINE

- OUR UNIVERSE – PRESENT AND PAST
- MATTER-ANTIMATTER ASYMMETRY OF THE UNIV
- INFLATION AND REHEATING
- GRAVITINO PROBLEM AND  $T_{\text{REH}}$

REHEATING, GRAVITINOS AND THE M-A ASYMM

- **RESOLVING THE GRAVITINO PROBLEM**

CONCLUSION

WE FOCUS ON **LEPTOGENESIS** MODELS –  
OUT OF EQM DECAY OF  $N$ .

POPULAR – RELATED TO LIGHT NEUTRINO MASSES

MASS  $M_N \sim 10^{10}$  GeV

# PROBLEM

TWO SPECIES NEUTRINOS AND GRAVITINOS

BOTH CREATED IN THE SAME THERMAL ENVIRONMENT

-- RADIATION DOMINATED UNIVERSE AFTER REHEATING

WANT  $N$  (M-A ASYMMETRY) BUT NOT  $\tilde{G}$  (DECAY)

# OUR QUERY

IS IT POSSIBLE TO MAKE THEORIES WITH GRAVITINOS  
(SUPERSYMMETRY/SUPERGRAVITY)

CONSISTENT WITH MODELS OF LEPTOGENESIS  
INVOLVING HEAVY NEUTRINOS

IF YES, GOOD

IF NOT, EITHER ONE OF THESE PARTICLE PHYSICS  
IDEAS WILL HAVE TO BE DISCARDED

(ASSUMPTIONS)

# SOLUTIONS

**INCREASE  $N$**

**DETAILED VIEW OF REHEATING**

[RR, SAHU]

**DECREASE  $\tilde{G}$**

**MODIFIED THERMALISATION DURING REHEATING  
DUE TO SUSY FLAT DIRECTIONS**

[RR, SARKAR]

# NEW PROBLEMS

**INCREASE  $\tilde{G}$  DUE TO SUSY FLAT DIRECTIONS/TEMP**

[MAHAJAN, RR, SARKAR; ARYA, MAHAJAN, RR]

# SOLUTION 2

DECREASE  $\tilde{G}$

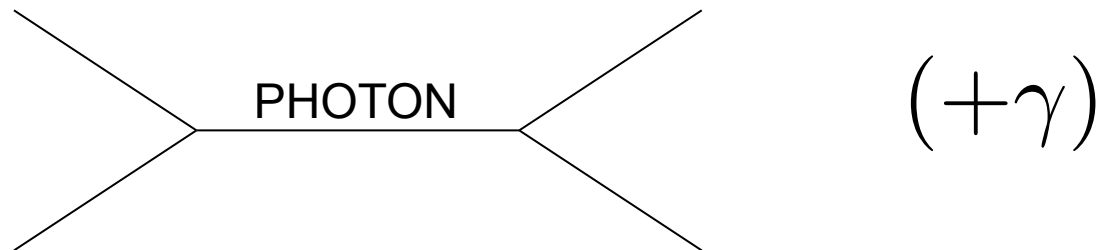
**MODIFIED THERMALISATION  
DURING REHEATING DUE TO  
SUPERSYMMETRY FIELDS**

# STANDARD THERMALISATION DURING REHEATING

INFLATON DECAY

THERMALISATION DURING REHEATING DUE TO  
ELASTIC AND INELASTIC SCATTERING

PROCESSES MEDIATED BY GAUGE BOSONS –  
PHOTONS (EM), GLUONS (STRONG), W, Z (WEAK)



$$q\bar{q} \rightarrow q\bar{q}$$

$$q\bar{q} \rightarrow q\bar{q}\gamma$$



# STANDARD THERMALISATION

## INFLATON DECAY AND REHEATING:

$$\phi \rightarrow n_0$$

DECAY

$$n_0 \rightarrow n_0$$

KINETIC EQM

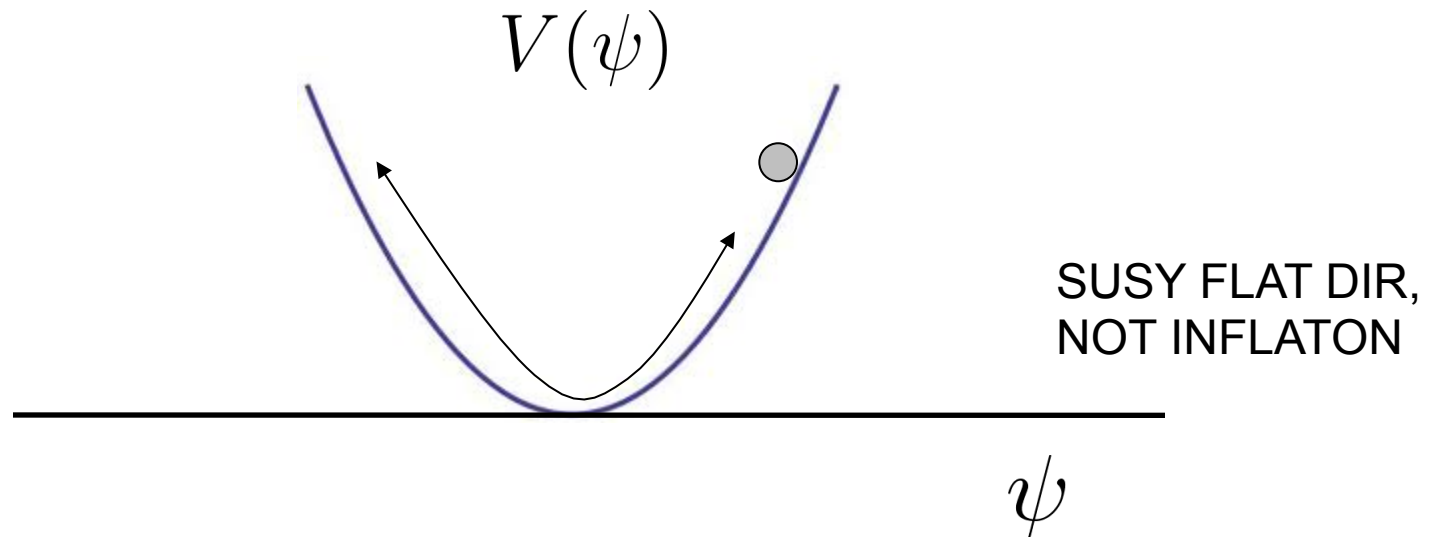
$$n_0 \rightarrow n_1$$

CHEMICAL EQM

$$n_1 = 10^4 n_0$$

# HEAVY GAUGE BOSONS

IN THE EARLY UNIVERSE A SUPERSYMMETRIC FIELD (AFFLECK-DINE FIELD) CAN GET A NON-ZERO EXPECTATION VALUE (CONDENSATE)

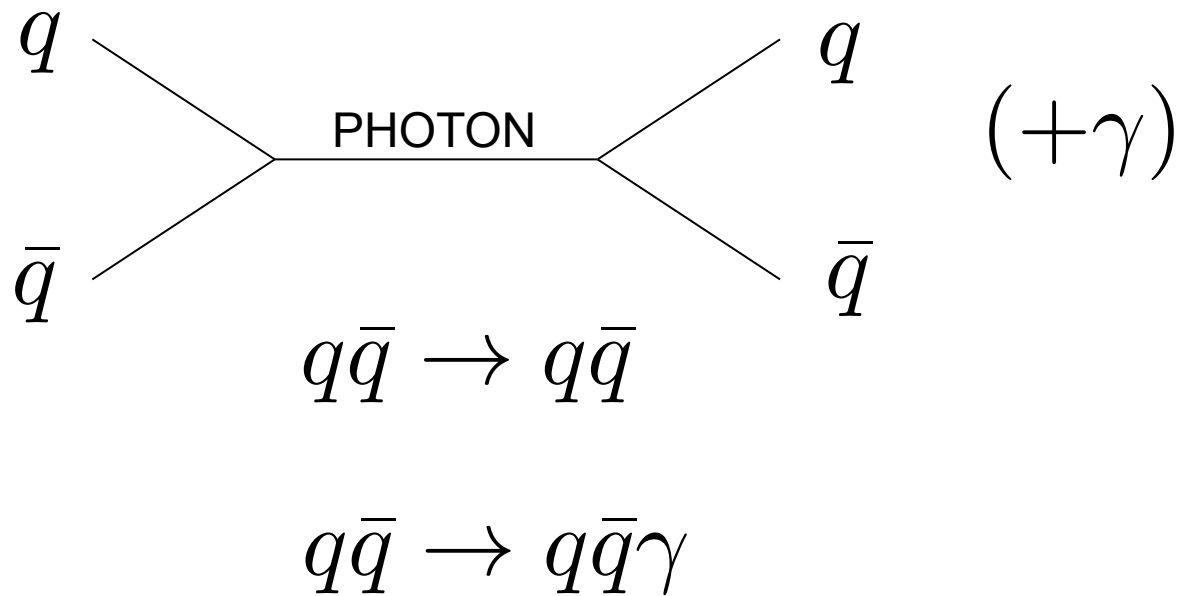


GIVES MASS TO GAUGE BOSONS

PHOTON, GLUONS, W, Z CAN BE  $10^{13}$  TIMES HEAVIER THAN THE PROTON

# MODIFIED THERMALISATION

PROCESSES MEDIATED BY GAUGE  
BOSONS – PHOTONS, GLUONS, W, Z  
SUPPRESSED



# MODIFIED THERMALISATION

INFLATON DECAY AND REHEATING:

$$\phi \rightarrow n_0$$

DECAY

DELAYED

$$n_0 \rightarrow n_0$$

KINETIC EQM

$$n_0 \rightarrow n_1$$

CHEMICAL EQM

$$n \sim n_0 \ll n_1$$

$n \downarrow$

**DILUTE PLASMA**

# GRAVITINO SUPPRESSION

$n_{\downarrow}$  DILUTE PLASMA



GRAVITINOS PRODUCED BY SCATTERING OF  
INFLATON DECAY PRODUCTS [n.n]

$n_{\tilde{G}} \downarrow\downarrow$  ALLAHVERDI AND MAZUMDAR; RR AND A. SARKAR

LATER A-D FIELD DECAYS, GB MASSLESS, THERMAL.  
FINAL REHEAT TEMPERATURE LOW

# OBTAINING THE GRAVITINO ABUNDANCE

$$q + \bar{q} \rightarrow g + \tilde{G} \quad q + \bar{q} \rightarrow \tilde{g} + \tilde{G} \quad \tilde{q} + \bar{\tilde{q}} \rightarrow \tilde{g} + \tilde{G}$$

## INTEGRATED BOLTZMANN EQUATION

$$\text{NOW, } \dot{n}_{\tilde{G}} = -3Hn_{\tilde{G}} + \int d\Pi_1 d\Pi_2 f_1 f_2 W_{12}(s)$$

$$W_{12}(s) \propto \sigma_{CM}$$

$f_{1,2}$  PARTICLE DISTRIBUTION FUNCTIONS FOR INCOMING PARTICLES – APPROPRIATE NON-THERMAL

# RESULTS

## SUPPRESSED GRAVITINO PRODUCTION DUE TO

A) DILUTE PLASMA

B) PHASE SPACE SUPPRESSION

$$q + \bar{q} \rightarrow g + \tilde{G} \quad q + \bar{q} \rightarrow \tilde{g} + \tilde{G} \quad \tilde{q} + \bar{\tilde{q}} \rightarrow \tilde{g} + \tilde{G}$$

OUTGOING GLUON/GLUINO HEAVY

GRAVITINO PRODUCTION SHUTS OFF WHEN THE ENERGY OF INCOMING QUARKS/SQUARKS  $< m_{g,\tilde{g}}$

# RESULTS

SUPPRESSED GRAVITINO PRODUCTION

$$Y_{\tilde{G}} = 4 \times 10^{-18}, 10^{-20} < 10^{-14}$$

COMPLETE SHUT OFF

[RR, A. SARKAR]

N↓ BUT SUFFICIENT



# CONCLUSION

1. POPULAR MODELS OF GENERATING THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE REQUIRE A LARGE REHEAT TEMPERATURE AFTER INFLATION
2. BUT THAT GENERATES TOO MANY GRAVITINOS IN THE UNIVERSE
3. COSMOLOGISTS ARE LOOKING FOR MECHANISMS TO ENHANCE NEUTRINO ABUNDANCE/SUPPRESS GRAVITINO ABUNDANCE

# CONCLUSION

4. GRAVITINO ABUNDANCE GENERATED IN A NON-THERMAL UNIVERSE IN THE PRESENCE OF SUPERSYMMETRY FIELDS IS SUPPRESSED

# SYMBIOSIS BETWEEN THE BIG AND THE SMALL

- USE COSMOLOGY TO CONSTRAIN PARTICLE PHYSICS THEORY –  
    SUPERSYMMETRY → GRAVITINOS
- INVOKE PARTICLE PHYSICS THEORIES TO EXPLAIN COSMOLOGICAL PHENOMENA –  
    M-AM ASYMMETRY

