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

Raghavan Rangarajan
Physical Research Laboratory
Ahmedabad

OUTLINE

- THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE
- INFLATION AND REHEATING
- THE GRAVITINO PROBLEM, AND T_{reh}

  REHEATING, GRAVITINOS AND THE M-A ASYMMETRY

- SOLUTIONS TO THE GRAVITINO PROBLEM
- GRAVITINO PROBLEM AGAIN

  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 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)

MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

- ANTIMATTER RULED OUT TILL d~1000 Mpc
- SIZE OF OBSERVABLE UNIVERSE $\sim ct_U = 4000$ Mpc

(1 Mpc = 3×10^{19} km = 3×10^{6} lt-yr)

MATTER-ANTIMATTER ASYMMETRY OF THE UNIV

MATTER-ANTIMATTER ASYMMETRY

- EARLY TIMES ($t < 1$ s = PRIM. NUCL.) EQUAL AMOUNTS OF MATTER AND ANTIMATTER

- WHY THIS ASYMMETRY TODAY? WHERE DID THE ANTIMATTER GO?

MATTER-ANTIMATTER ASYMMETRY

- EARLY TIMES ($t < 1$ s = PRIM. NUCL.) EQUAL AMOUNTS OF MATTER AND ANTIMATTER

- WHY THIS ASYMMETRY TODAY? WHERE DID THE ANTIMATTER GO?

- DISEQUILIBRIUM IN THE EARLY UNIVERSE

  $100\ M + 100\ A \rightarrow 103\ M + 101\ A \rightarrow 2\ M$

$$X \rightarrow M \qquad\qquad X \rightarrow A$$

$r_M > r_A$, GET MORE MATTER THAN ANTIMATTER

MATTER-ANTIMATTER ASYMMETRY

- X = GUT GAUGE/HIGGS BOSONS
  - GUT BARYOGENESIS MASS ($M_X \sim 10^{16}$ GeV)
- X = HEAVY RIGHT HANDED MAJORANA NEUTRINOS
  - LEPTOGENESIS MODELS

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

1 GeV = PROTON MASS

MATTER-ANTIMATTER ASYMMETRY

WHEREFROM

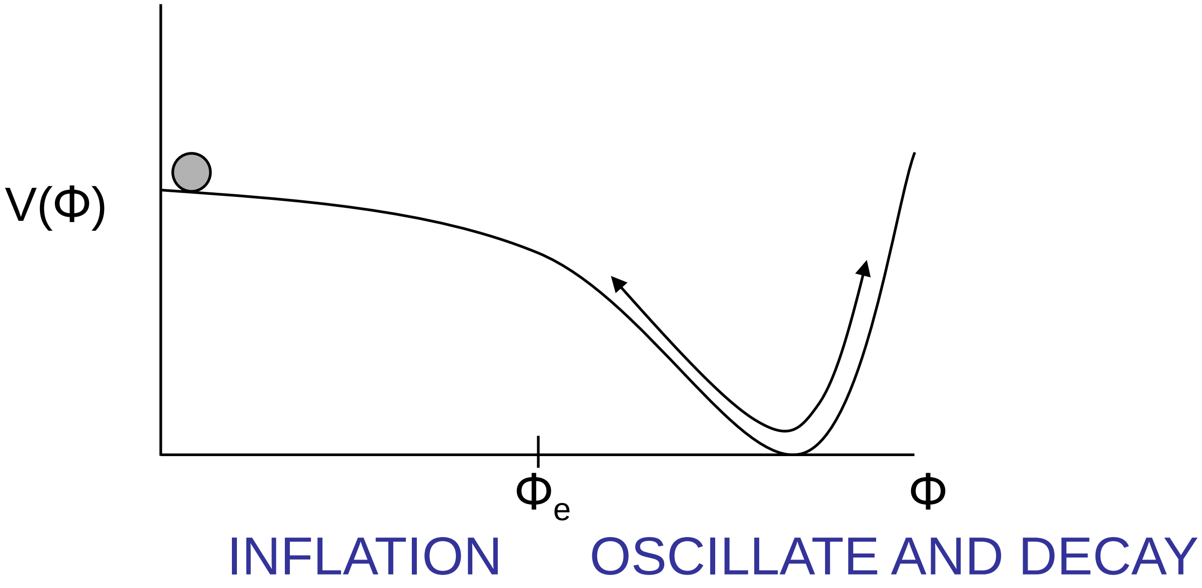
- GUT GAUGE/HIGGS BOSONS ($M_X \sim 10^{16}$ GeV)
- HEAVY RIGHT HANDED MAJORANA NEUTRINOS ($M_N \sim 10^{10}$ GeV) ?

1 GeV = PROTON MASS

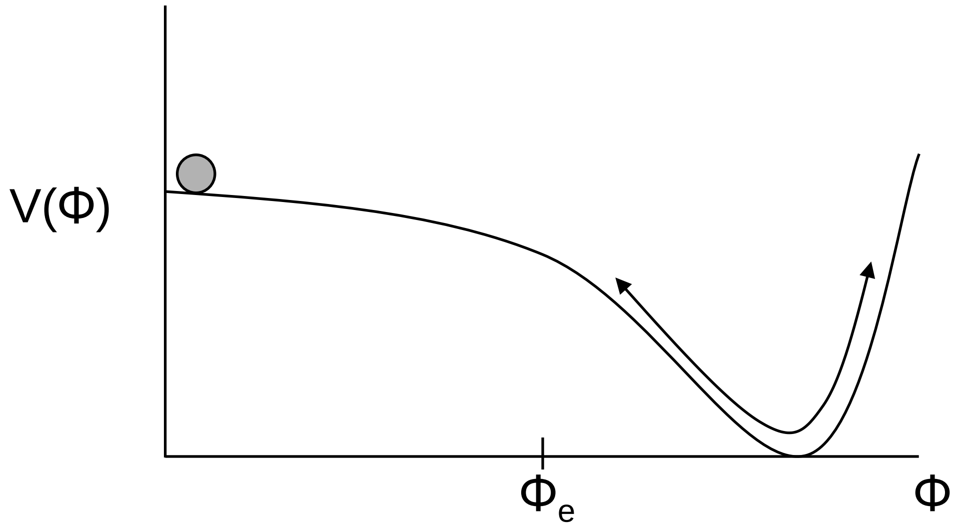
INFLATION and REHEATING

INFLATION – PERIOD OF ACCELERATED EXPANSION IN THE EARLY UNIVERSE (t ~ 10^{-38} s or later)

ASSOCIATED WITH THE DYNAMICS OF A SLOWLY VARYING FIELD CALLED THE INFLATON Φ



INFLATION and REHEATING



INFLATION   OSCILLATE AND DECAY (REHEATING)

DURING INFLATION, R~ exp(H t)   [R IS THE SCALE FACTOR, $d(t) = d_i\, R(t)$]

n OF ALL SPECIES → 0

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

REHEATING

OUTLINE

- THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE
- INFLATION AND REHEATING
- THE GRAVITINO PROBLEM, AND T_{reh}

  REHEATING, GRAVITINOS AND THE M-A ASYMMETRY

- SOLUTIONS TO THE GRAVITINO PROBLEM
- GRAVITINO PROBLEM AGAIN

  CONCLUSION

GRAVITINOS

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

SUPERSYMMETRY

- EXTENSION OF THE STANDARD MODEL (GAUGE HIERARCHY)

- SUPERPARTNERS: FERMION – BOSON

PHOTON – PHOTINO, ELECTRON – SELECTRON
(EQUAL m, IF SUSY)

LOCAL SUPERSYMMETRY: SUPERGRAVITY

GRAVITON – GRAVITINO $(\tilde{G})$

BROKEN $(m_{\tilde{G}} : \mathrm{eV} - \mathrm{TeV})$

GRAVITINOS

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

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

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 $^4He,\ ^3He,\ D$
  (NUCLEOSYNTHESIS)

GRAVITINO PROBLEM(S)

GRAVITINOS

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

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

COSMOLOGICAL CONSEQUENCES (m, n)

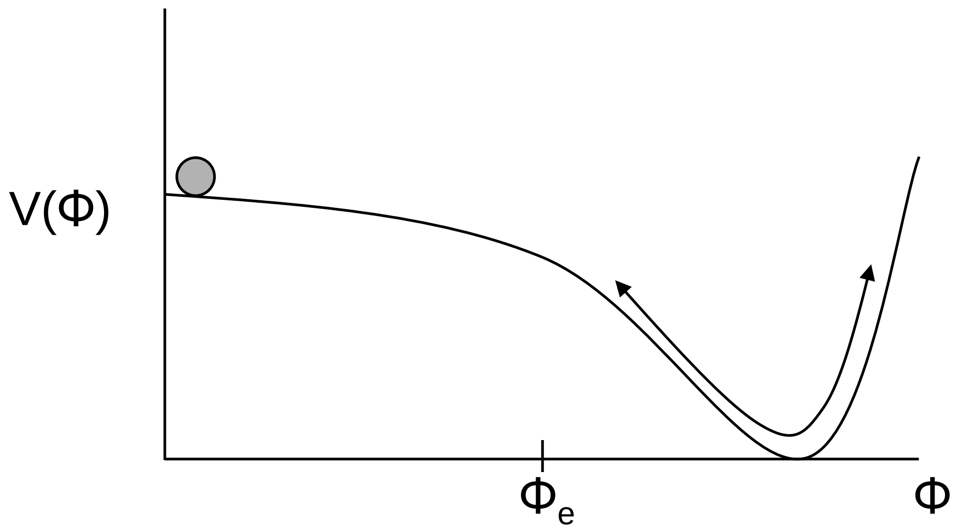
- STABLE : AFFECTS EXPANSION RATE, $\rho_{\tilde{G}} > \rho_c$ (L/H)
- UNSTABLE : AFFECT EXPANSION RATE PRIOR TO DECAY

  DECAY PRODUCTS $\rho > \rho_c$

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

GRAVITINO PROBLEM(S) => UPPER BOUND ON $\rho_{\tilde{\mathbf{G}}} \propto \mathbf{n}_{\tilde{\mathbf{G}}}$

STANDARD PICTURE OF GRAVITINO PRODUCTION



INFLATION $\rightarrow$ REHEATING (OSC. + DECAY) $(\mathrm{T}_{\mathrm{reh}})$

$\rightarrow$ RADIATION DOMINATED UNIV
(Relativistic particles)

THERMAL SCATTERING $\rightarrow \tilde{G}$
(gluons, quarks, squarks, gluinos)

STANDARD CALC OF GRAVITINO PRODUCTION

CALCULATE GRAVITINO PRODUCTION IN THE RAD DOM ERA

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

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

$\Rightarrow$ UPPER BOUND ON $\mathrm{T}_{\mathrm{reh}}$ OF 10^{6-9} GeV (MASS 100 GeV – 10 TeV)

1 GeV $=10^{13}$ K

REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

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

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

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 $10^{6\text{-}9}$ 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 TEMPERATURE IS A PROBLEM FOR GUT BARYOGENESIS AND LEPTOGENESIS

OUTLINE

- THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE
- INFLATION AND REHEATING
- THE GRAVITINO PROBLEM, AND T_{reh}

REHEATING, GRAVITINOS AND THE M-A ASYMMETRY

- SOLUTIONS TO THE GRAVITINO PROBLEM
- GRAVITINO PROBLEM AGAIN

CONCLUSION

SOLUTIONS

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

POPULAR – RELATED TO LIGHT NEUTRINO MASSES

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

SOLUTIONS

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 $\tilde{G}$

CAN INCREASE *N*

OR

SUPPRESS $\tilde{G}$

SOLUTIONS

INCREASE *N*

RESONANCE LEPTOGENESIS

SOFT LEPTOGENESIS

PREHEATING (WORKS FOR GUT BARYOGENESIS TOO)

DETAILED VIEW OF REHEATING

DECREASE $\tilde{G}$

DELAYED THERMALISATION DURING REHEATING DUE TO SUSY FLAT DIRECTIONS

SUSY FLAT DIRECTIONS

STANDARD MODEL , *H* SCALAR (SPIN 0)

SCALAR POTENTIAL IN SUSY IS A FUNCTION OF

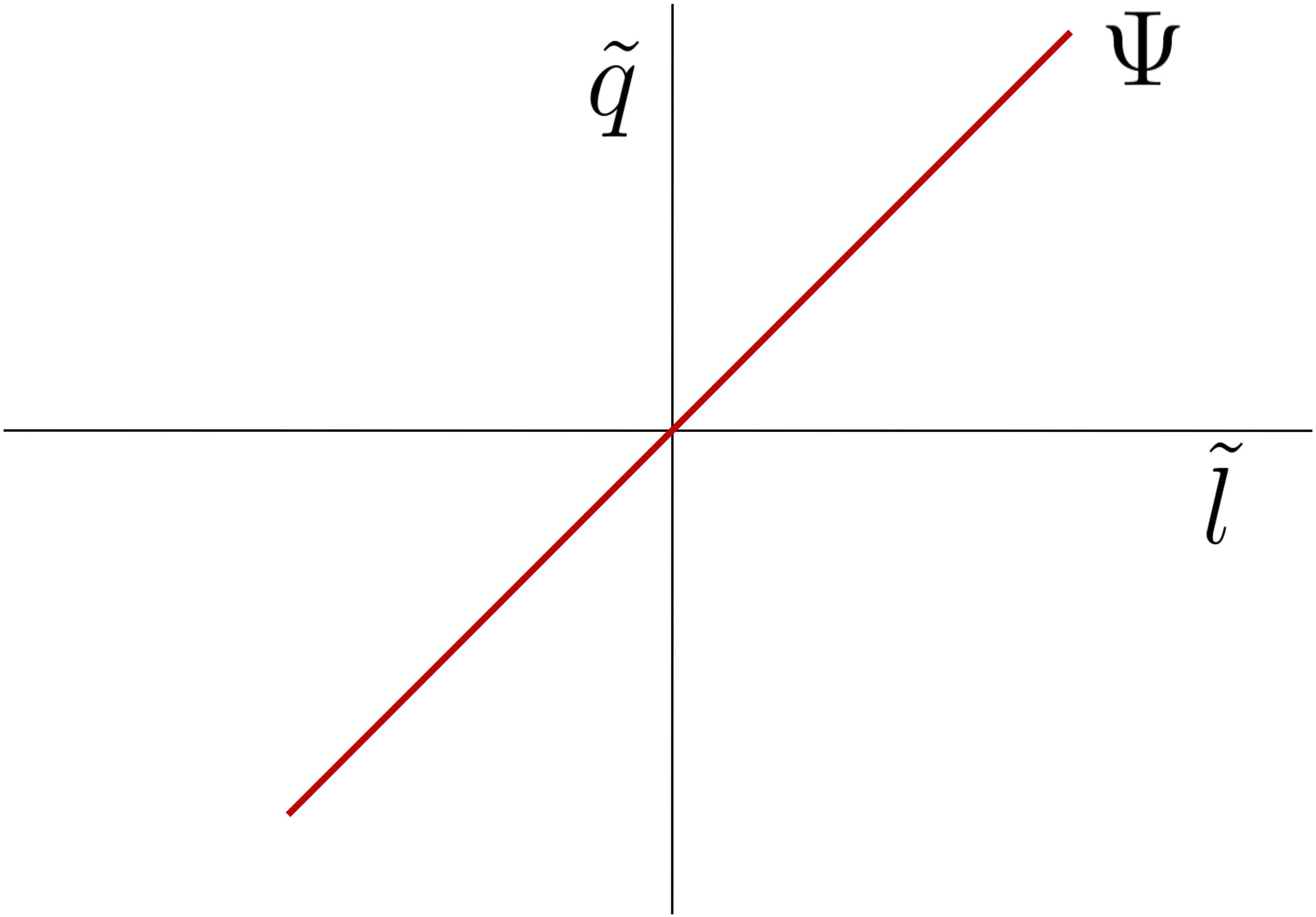
$$(H_u, H_d, \tilde{q}_i, \tilde{l}_i)$$

DIRECTIONS IN FIELD SPACE OF SCALARS ALONG WHICH THE SCALAR POTENTIAL VANISHES — FLAT DIRECTIONS

UDD: $\langle \tilde{u}_L \rangle = \psi, \ \langle \tilde{s}_L \rangle = \psi, \ \langle \tilde{b}_L \rangle = \psi$ PHASES

REPRESENTED BY A FIELD Ψ (AFFLECK-DINE FIELD) WITH VEV ψ

SUSY FLAT DIRECTIONS



COSMOLOGICAL CONSEQUENCES

NON-ZERO VALUE OF ψ GIVES MASS TO GAUGE BOSONS (BREAKS GAUGE SYMMETRY),

e.g., $$L \supset \tilde{q}^* \tilde{q} A A$$

COSMOLOGICAL CONSEQUENCES

NON-ZERO VALUE OF ψ GIVES MASS TO GAUGE BOSONS (BREAKS GAUGE SYMMETRY),

e.g., $L \supset \tilde{q}^* \tilde{q} A A$

IF ALL GAUGE BOSONS GET MASS [LLddd, QuQue], IT SLOWS DOWN THERMALISATION AFTER INFLATION.

SUPPRESSES GRAVITINO PRODUCTION

ALLAHVERDI AND MAZUMDAR

(FLAT DIRECTION DECAYS BEFORE EWSB t~10^{-11} s)

COSMOLOGICAL CONSEQUENCES

GRAVITINOS PRODUCED BY SCATTERING OF INFLATON DECAY PRODUCTS

$n_{\tilde{G}}$ DEPENDS ON n OF SCATTERERS

STANDARD PICTURE:

INFLATON DECAYS $\rightarrow n_0 \rightarrow$ THERMALISE

KINETIC EQM n_0

CHEMICAL EQM n_1

FLAT DIRECTIONS THAT BREAK ALL GAUGE SYMM

INFLATON DECAYS $\rightarrow n_0 \rightarrow$ DELAYED THERMALISATION

$$n \sim n_0 \ll n_1 \qquad [10^4]$$

DILUTE PLASMA, $n_{\tilde{G}} \downarrow\downarrow$ $\qquad$ $N \downarrow$

RESULTS

SUPPRESSED GRAVITINO PRODUCTION DUE TO

A) DILUTE PLASMA
B) PHASE SPACE SUPPRESSION

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

OUTGOING GLUON/GLUINO HEAVY

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

RESULTS

SUPPRESSED GRAVITINO PRODUCTION DUE TO

A) DILUTE PLASMA
B) PHASE SPACE SUPPRESSION

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

COMPLETE SHUT OFF

PRODUCTION AFTER THE FLAT DIRECTION DECAYS IS NOT LARGE $\propto T_f$ [10^5 GeV] [RR, A. SARKAR]

ALTERNATE SCENARIO WITH SUSY FLAT DIRECTIONS

- **GRAVITINO OVER-PRODUCTION**

GRAVITINO PROBLEM AGAIN!

- IF A FLAT DIRECTION GIVES MASS TO SOME BUT NOT ALL GAUGE BOSONS, THERMALISATION WILL OCCUR

- CONSIDERED SUCH A FLAT DIRECTION [H_u H_d]

PHOTONS, GLUONS AND PHOTINOS AND GLUINOS LIGHT

QUARKS AND SQUARKS HEAVY

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

GRAVITINO PROBLEM AGAIN!

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

- RESONANT PRODUCTION OF GRAVITINOS WHEN

$$E_{\tilde{g}} + E_q \approx m_{\tilde{q}}$$

- GRAVITINO ABUNDANCE GENERATED IS VERY LARGE AND GREATER THAN THE COSMOLOGICAL UPPER BOUND FOR MOST PARAMETER SPACE

GRAVITINO PROBLEM AGAIN!

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

- RESONANT PRODUCTION OF GRAVITINOS WHEN

$$E_{\tilde{g}} + E_q = m_{\tilde{q}}$$

- GRAVITINO ABUNDANCE GENERATED IS VERY LARGE AND GREATER THAN THE COSMOLOGICAL UPPER BOUND FOR MOST PARAMETER SPACE

- COSMOLOGICAL UPPER BOUND IS $Y < 10^{-14}$

- FOR DIFFERENT SETS OF PARAMETERS

$Y = 10^{-8}$ — 10^{-2}

GRAVITINO PROBLEM AGAIN!

- LARGE VALUES FOR SUSY FLAT DIRECTIONS IS GENERIC. EXACERBATED GRAVITINO PROBLEM

- HAVE TO INVOKE EARLY DECAY OF FLAT DIRECTIONS TO AVOID CONFLICT

[MAHAJAN, RR, A. SARKAR]

CONCLUSION

1. POPULAR MODELS OF GENERATING THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE REQUIRE A LARGE REHEAT TEPERATURE 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

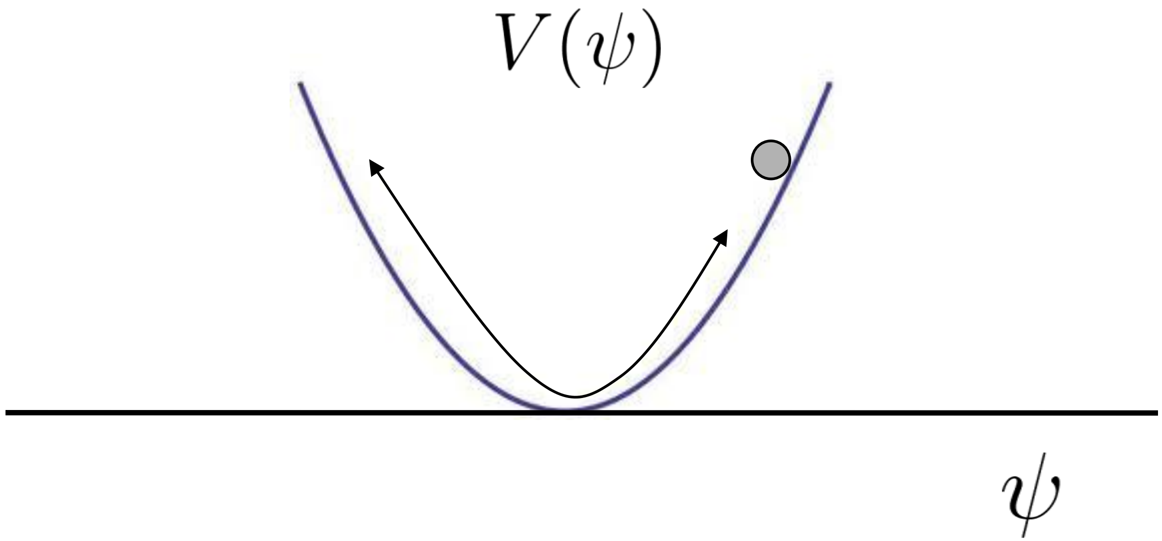
CONCLUSION

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

5. GRAVITINO ABUNDANCE IN A THERMAL UNIVERSE WITH FLAT DIRECTIONS CAN BE LARGE – NEW SOURCE OF THE GRAVITINO PROBLEM

(DETAILS OF SUSY MODEL)

SUSY FLAT DIRECTIONS



FLAT DIRECTION → QUADRATIC POT WITH CURV m_0

$\psi_0 \neq 0$ DUE TO QUANTUM FLUCTUATIONS DURING INFLATION; OTHER REASONS

WHEN H ~ m_0 , Ψ OSCILLATES, $\psi \sim 1/R^{3/2}$

THEN IT DECAYS (BEFORE t_{EW})

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

Raghavan Rangarajan
Physical Research Laboratory
Ahmedabad, India

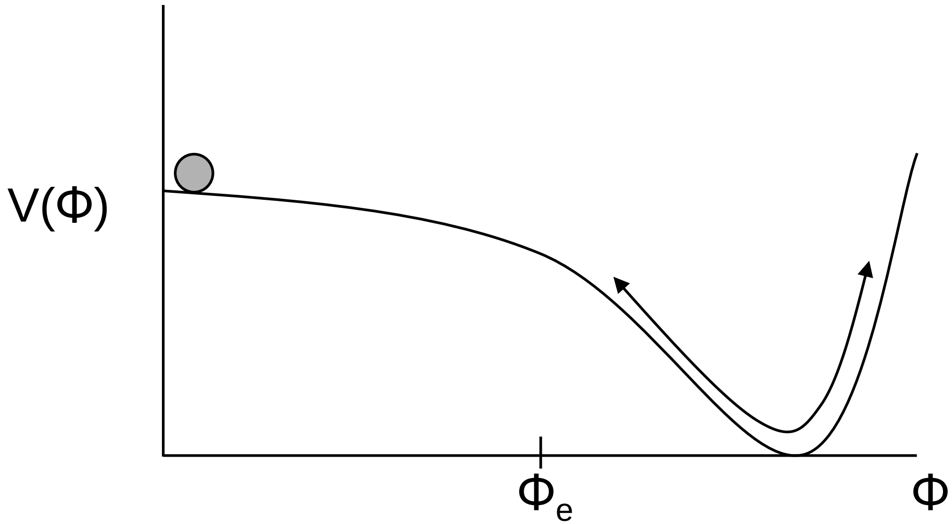
with N. Sahu, A. Sarkar, N. Mahajan

SOLUTION 1

INCREASE *N*

DETAILED VIEW OF REHEATING

UPTIL NOW ASSUMED INSTANTANEOUS INFLATON DECAY AND REHEATING.



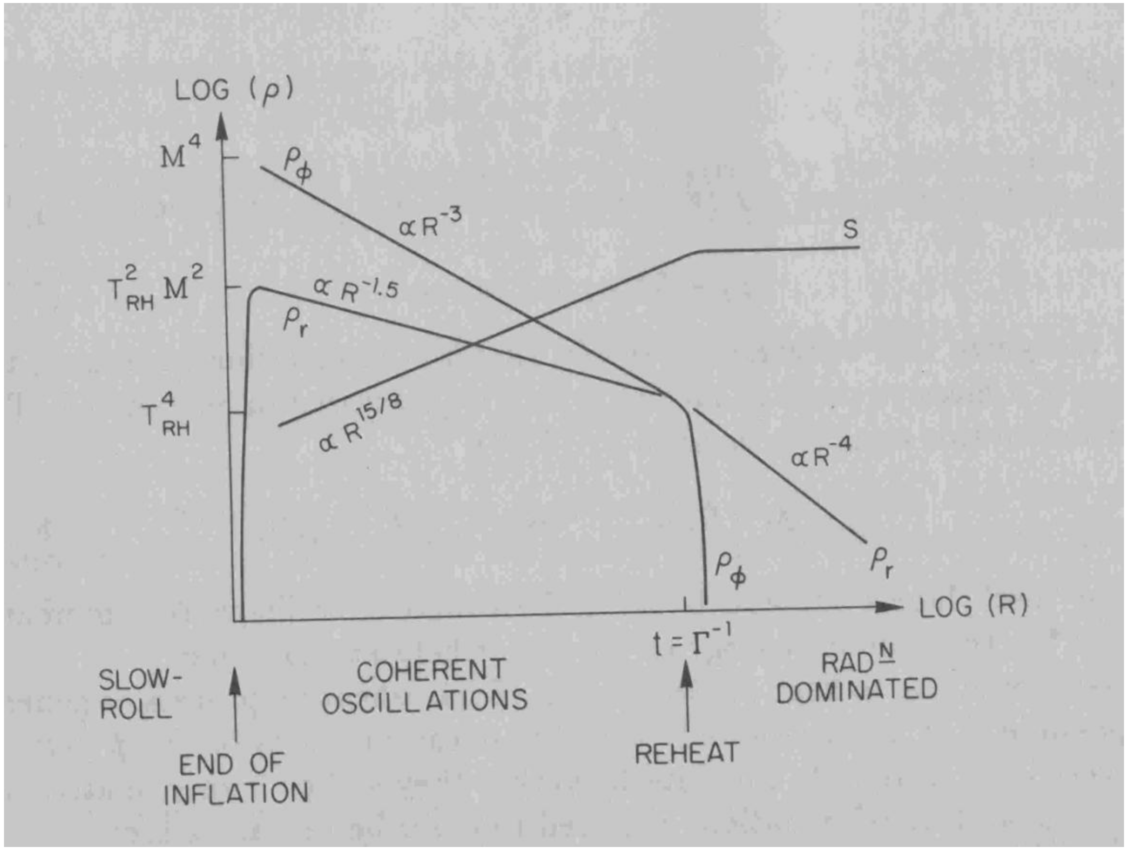
INFLATON OSCILLATES. AT $t = \Gamma_\phi^{-1},\ \mathrm{T}: 0 \to \mathrm{T}_{\rm reh}$

T_{reh} IS INITIAL AND MAX TEMP OF RAD DOM ERA

$\mathrm{T}_{\rm reh} < M_N$ PROBLEM FOR LEPTOGENESIS

STANDARD CALC OF N PRODUCTION ALSO ASSUMES INSTANTANEOUS INFLATON DECAY AND REHEATING.

QUADRATIC INFLATON POTENTIAL DURING REHEATING



$$\rho_r \propto T^4$$

$$T \rightarrow T_{max} \rightarrow T_{reh}$$

KOLB & TURNER

T_{reh} IS THE FINAL TEMPERATURE AT THE END OF REHEATING

THE SOLUTION

$\mathrm{T}_{\mathrm{max}}$ CAN BE AS HIGH AS 1000 $\mathrm{T}_{\mathrm{reh}}$

SO SUFFICIENT NUMBER OF HEAVY RIGHT-HANDED NEUTRINOS (*N*) WITH $M_N \sim 10\,\mathrm{T}_{\mathrm{reh}}$ CAN BE PRODUCED DURING REHEATING

CHUNG ET AL, DELEPINE AND SARKAR, GIUDICE ET AL

IF $\mathrm{T_{max}}$ CAN ENHANCE NEUTRINO PRODUCITON, CAN IT ALSO

ENHANCE GRAVITINO PRODUCTION ?

IF $n_{\tilde{G}}$ (RAD DOM ERA) $\propto \mathrm{T_{reh}}$ (MAX TEMP OF RAD DOM ERA),

WILL $n_{\tilde{G}}$ (REHEATING ERA) $\propto \mathrm{T_{max}}$?

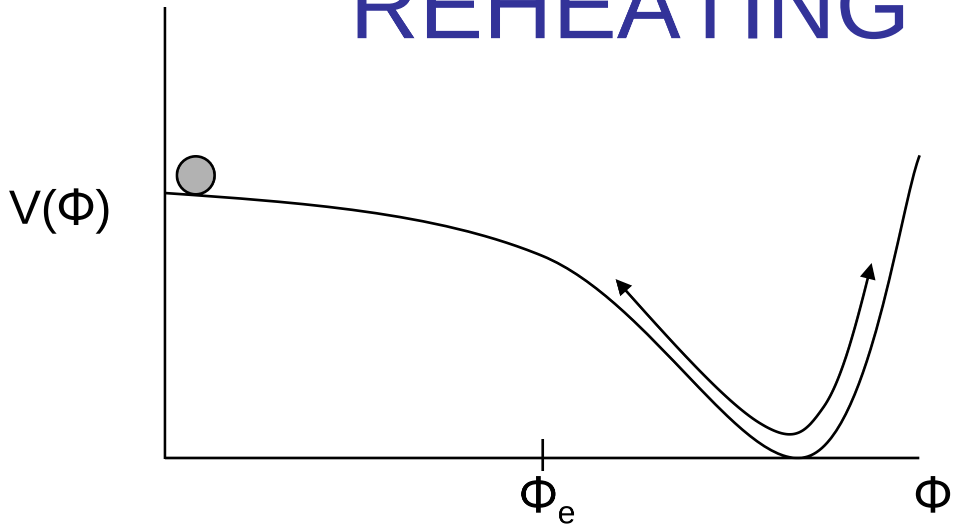
IF $n_{\tilde{G}}(\mathrm{REH}) \gg n_{\tilde{G}}(\mathrm{RD}),$ GET BOUNDS ON $\mathrm{T_{max}}$

-- THEN THE PROBLEM FOR LEPTOGENESIS CAN REAPPEAR

CALCULATE $n_{\tilde{G}}$ (REH)

- EXPECT $n_{\tilde{G}}(\mathrm{T_{MAX}})$
- $n_{\tilde{G}}(\mathrm{REH}) >, < n_{\tilde{G}}(\mathrm{RD})$

GRAVITINO PRODUCTION DURING REHEATING



INFLATON DECAYS AND DECAY PRODUCTS THERMALISE QUICKLY $\Rightarrow \mathrm{T}(t)$

$$\frac{dn_{\tilde{G}}}{dt} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2$$

$$\dot{\mathrm{T}}\,\frac{dn_{\tilde{G}}}{d\mathrm{T}} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2$$

$$\frac{dn_{\tilde{G}}}{dt} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v| \rangle n^2$$

$H =$ HUBBLE PARAMETER (DILUTION DUE TO EXPANSION)

$\Sigma_{\rm tot} =$ TOTAL CROSS SECTION FOR GRAVTINO PRODUCTION

$v =$ RELATIVE VELOCITY OF THE INCOMING PARTICLES

$\langle \quad \rangle$ THERMAL AVERAGING

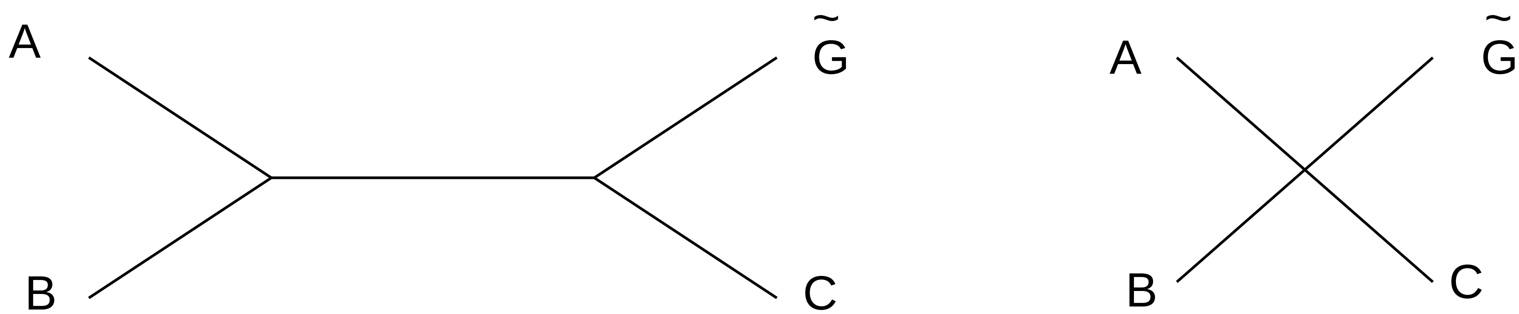
$n = \frac{1.2}{\pi^2}\,{\rm T}^3$ NUMBER DENSITY OF SCATTERERS

IGNORED DECAY $\tau \sim 10^{7-8}\,(100{\rm GeV}/m_{\tilde{G}})\,{\rm s}$

FOR $m_{\tilde{G}} \sim 100{\rm GeV}\,, \tau \sim 1\,{\rm yr}$ DECAY NOT RELEVANT

CALCULATION OF $\langle\Sigma_{\rm tot}|v|\rangle$

$\tilde{G}$ PRODUCED BY THE SCATTERING OF INFLATON DECAY PRODUCTS



e.g. $q+\bar{\tilde{q}}\to g+\tilde{G}$ $\quad q+\bar{q}\to\tilde{g}+\tilde{G}$ $\quad \tilde{q}+\bar{\tilde{q}}\to\tilde{g}+\tilde{G}$

$$\langle\Sigma_{\rm tot}|v|\rangle=\alpha/M_{Pl}^2$$

PRADLER AND STEFFEN

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

$$\dot{\mathrm{T}}\,\frac{dn_{\tilde{G}}}{d\mathrm{T}} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2$$

$$\rho_r \sim R^{-\frac{3}{2}} \Rightarrow \mathrm{T} \sim R^{-\frac{3}{8}} \sim t^{-1/4}$$

[R IS THE SCALE FACTOR]

$$R \sim t^{\frac{2}{3}}$$

SOLVE FROM $\mathrm{T}_{\rm max}$ TO $\mathrm{T}_{\rm reh}$.

$$n_{\tilde{G}}(\mathrm{T}_{\rm reh}) = 0.007\,\frac{\alpha}{M_{Pl}^2}\frac{\mathrm{T}_{\rm max}^4\mathrm{T}_{\rm reh}^2}{H_{\rm max}} \qquad \text{for } \mathrm{T}_{\rm max} \gg \mathrm{T}_{\rm reh}$$

$$Y_{\tilde{G}}(\mathrm{T}_{\rm reh}) = \frac{n_{\tilde{G}}(\mathrm{T}_{\rm reh})}{s(\mathrm{T}_{\rm reh})} \quad = 0.01\,g_{\rm reh}^{-1}\,\frac{\alpha}{M_{Pl}^2}\,\frac{\mathrm{T}_{\rm max}^4}{H_{\rm max}\mathrm{T}_{\rm reh}}$$

RESULTS

INCLUDE GRAVITINO PRODUCTION IN THE RAD DOM ERA FROM $\mathrm{T_{reh}}$ TO $\mathrm{T_f}$. SOLVE BOLTZMANN EQN IN RD ERA.

$$Y_{\tilde{G}}(\mathrm{T_f}) = Y_{\tilde{G}}(\mathrm{T_{reh}}) + 0.02\, g_{\mathrm{reh}}^{-3/2}\, \frac{\alpha}{M_{Pl}}\, \mathrm{T_{reh}} \qquad \mathrm{T_f} \ll \mathrm{T_{reh}}$$

EARLIER $Y_{\tilde{G}}(\mathrm{T_{reh}})$ SET TO 0

$$Y_{\tilde{G}}(\mathrm{T_f}) = 0.03\, g_{\mathrm{reh}}^{-1}\, \frac{\alpha}{M_{Pl}^2} \left[0.4\, \frac{\mathrm{T_{max}^4}}{H_{\mathrm{max}} \mathrm{T_{reh}}} + 0.6\, g_{\mathrm{reh}}^{-\frac{1}{2}}\, M_{Pl} \mathrm{T_{reh}} \right]$$

$$T_{\rm max} \simeq 0.8\, g_*^{-\frac{1}{4}} M_{\rm I}^{\frac{1}{2}} \left(\Gamma_\phi M_{Pl}\right)^{\frac{1}{4}}$$

M_I = SCALE OF INFLATION ≤ 10^{16} GeV $\qquad \rho_\phi = M_I^4$

Γ_ϕ = DECAY RATE OF THE INFLATON

g_* = NUMBER OF REL. DEG. OF FREEDOM ~ 230 IN MSSM

$$T_{\rm reh} \simeq 0.55\, g_{*{\rm reh}}^{-\frac{1}{4}} \left(M_{Pl}\Gamma_\phi\right)^{\frac{1}{2}}$$

$$H_{\rm max} \simeq \sqrt{\frac{8\pi}{3}} \frac{M_I^2}{M_{Pl}}$$

KOLB AND TURNER

2 INDEPENDENT VARIABLES

$$Y_{\tilde{G}}(\mathrm{T_f}) = 0.03\, g_{\mathrm{reh}}^{-1}\, \frac{\alpha}{M_{Pl}^2}\, \left[0.4\, \frac{\mathrm{T}_{\mathrm{max}}^4}{H_{\mathrm{max}} \mathrm{T}_{\mathrm{reh}}} + 0.6\, g_{\mathrm{reh}}^{-\frac{1}{2}}\, M_{Pl} \mathrm{T}_{\mathrm{reh}} \right]$$

$$H_{\mathrm{max}} = 2.0\, g_*^{\frac{1}{2}}\, \frac{\mathrm{T}_{\mathrm{max}}^4}{\mathrm{T}_{\mathrm{reh}}^2\, M_{Pl}}$$

$$Y_{\tilde{G}}(\mathrm{T_f}) = 0.007\, g_{\mathrm{reh}}^{-3/2} \frac{\alpha}{M_{Pl}} [\mathrm{T}_{\mathrm{reh}} + 3.0\, \mathrm{T}_{\mathrm{reh}}]$$

- DEPENDENCE ON T_{max} CANCELS OUT [UNEXPECTED]

$$Y_{\tilde{G}}(\mathrm{T_f}) = 0.03\, g_{\mathrm{reh}}^{-1}\, \frac{\alpha}{M_{Pl}^2} \left[0.4\, \frac{\mathrm{T_{max}^4}}{H_{\mathrm{max}} \mathrm{T_{reh}}} + 0.6\, g_{\mathrm{reh}}^{-\frac{1}{2}}\, M_{Pl} \mathrm{T_{reh}} \right]$$

$$H_{\mathrm{max}} = 2.0\, g_*^{\frac{1}{2}}\, \frac{\mathrm{T_{max}^4}}{\mathrm{T_{reh}^2}\, M_{Pl}}$$

$$Y_{\tilde{G}}(\mathrm{T_f}) = 0.007\, g_{\mathrm{reh}}^{-3/2} \frac{\alpha}{M_{Pl}} [\mathrm{T_{reh}} + 3.0\, \mathrm{T_{reh}}]$$

- DEPENDENCE ON T_{max} CANCELS OUT [UNEXPECTED]

- GRAVITINO PRODUCTION DURING REHEATING IS COMPARABLE (1/3) TO THAT IN THE RADIATION DOMINATED ERA [UNEXPECTED]

COMPARISON WITH NUMERICAL ANALYSIS

KAWASAKI, KOHRI AND MOROI

NUMERICAL FIT TO FINAL

$$Y_{\tilde{G}} \simeq 1.9 \times 10^{-12} \times \left(\frac{\mathrm{T_{reh}}}{10^{10}\ \mathrm{GeV}} \right) \times \left[1 + 0.045 \ln \left(\frac{\mathrm{T_{reh}}}{10^{10}\ \mathrm{GeV}} \right) \right] \left[1 - 0.028 \ln \left(\frac{\mathrm{T_{reh}}}{10^{10}\ \mathrm{GeV}} \right) \right]$$

SAME FUNCTIONAL FORM

GIUDICE, RIOTTO AND TKACHEV: SIMILAR RELATIVE MAGNITUDES

IMPLICATIONS FOR LEPTOGENESIS

NO LARGE ENHANCEMENT IN TOTAL GRAVITINO PRODUCTION

CHANGE IN THE BOUND ON THE REHEAT TEMPERATURE   (FACTOR OF 4/3)

$$\mathrm{T}_{\mathrm{max}} \sim \mathrm{T}_{\mathrm{reh}}^{\frac{1}{2}}$$

NO NEW CONSTRAINTS ON T_{max} DUE TO GRAVITINO PRODUCTION DURINGIN REHEATING

SO NOT AFFECT SCENARIO OF PRODUCTION OF HEAVY NEUTRINOS DURING REHEATING

SOLUTION 2

DECREASE $\tilde{G}$

DELAYED THERMALISATION DURING REHEATING DUE TO SUSY FLAT DIRECTIONS

SUSY FLAT DIRECTIONS

STANDARD MODEL , *H* SCALAR (SPIN 0)

<*H*> ≠ 0 => *q, l, W, Z* GET MASS

IN SUPERSYMMETRIC STANDARD MODEL, HAVE

$$H_u, H_d, \tilde{q}_i, \tilde{l}_i$$

FOR SOME COMB. OF THESE SCALARS, THEIR INITIAL VALUE IN THE EARLY UNIVERSE AFTER INFLATION, NEED NOT BE 0 (Q FLUC, OTHER)

$$\langle \tilde{u} \rangle = \psi, \ \langle \tilde{s} \rangle = \psi, \ \langle \tilde{b} \rangle = \psi$$

FLAT DIR

ψ DECREASES IN TIME, AND THEN DISAPPEARS (FLAT DIRECTION DECAY, BEFORE EWSB)

EARLIER INFLATON DECAYS AND DECAY PRODUCTS THERMALISE QUICKLY

$$q + \bar{\tilde{q}} \to g + \tilde{G} \qquad q + \bar{q} \to \tilde{g} + \tilde{G} \qquad \tilde{q} + \bar{\tilde{q}} \to \tilde{g} + \tilde{G}$$

$$\dot{n}_{\tilde{G}} + 3Hn_{\tilde{G}} = \langle \Sigma_{\mathrm{tot}} |v| \rangle n^2 \qquad n \sim T^3$$

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

$f_{1,2}$ PARTICLE DISTRIBUTION FUNCTIONS FOR INCOMING PARTICLES

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

$$q + \bar{\tilde{q}} \to g + \tilde{G} \qquad q + \bar{q} \to \tilde{g} + \tilde{G} \qquad \tilde{q} + \bar{\tilde{q}} \to \tilde{g} + \tilde{G}$$

- DISTRIBUTION FUNCTIONS

$$f_i = C_i \delta \left(E_i - \frac{m_I}{2} \frac{R_d}{R} \right) \qquad \text{for } t_d < t < t_{kin}$$

$$= \exp \left(- \frac{E_i - \xi_i}{T} \right) \qquad \text{for } t_{kin} < t < t_{thr}$$

- PHASE SPACE SUPPRESSION

OUTGOING GAUGE BOSON/ GAUGINO HEAVY

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

- SO FAR SEEN TWO SOLUTIONS OF THE GRAVITINO PROBLEM – INCREASING NEUTRINO, SUPPRESSING GRAVITINO

- **ALTERNATE SCENARIO**

ALTERNATE SCENARIO

- IF FLAT DIRECTION VEV DOES NOT BREAK ALL GAUGE SYMMETRIES, THERMALISATION WILL OCCUR

- CONSIDER A SCENARIO WITH H_u H_d FLAT DIRECTION. $SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM}$

- QUARK AND SQUARK HEAVY (NR), $m \approx h\psi$

$$m_{\tilde{q}}^2 - m_q^2 = m_S^2 \qquad m_S^2 \sim T^2 \ll m_{q,\tilde{q}}^2$$

- GLUINOS LIGHT (m ~ gT, REL), THERMAL DISTRIBUT.

GRAVITINO PROBLEM AGAIN!

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

- RESONANT PRODUCTION OF GRAVITINOS AS SQUARK CAN GO ON SHELL
- GRAVITINO ABUNDANCE GENERATED IS VERY LARGE AND GREATER THAN THE COSMOLOGICAL UPPER BOUND FOR MOST PARAMETER SPACE
- COSMOLOGICAL UPPER BOUND IS $Y < 10^{-14}$
- FOR DIFFERENT SETS OF PARAMETERS

$Y = 10^{-8}$ — 10^{-2}

GRAVITINO PROBLEM AGAIN!

- LARGE VEVS FOR SUSY FLAT DIRECTIONS IS GENERIC. EXACERBATED GRAVITINO PROBLEM
- HAVE TO INVOKE EARLY DECAY OF FLAT DIRECTIONS TO AVOID CONFLICT

CONCLUSION

4. NEUTRINOS GENERATED DURING REHEATING ~ GRAVITINO ABUNDANCE GENERATED NOT TOO LARGE

5. GRAVITINO ABUNDANCE GENERATED IN A NON-THERMAL UNIVERSE IN THE PRESENCE OF FLAT DIRECTIONS IS SUPPRESSED

6. GRAVITINO ABUNDANCE IN A THERMAL UNIVERSE WITH FLAT DIRECTIONS CAN BE LARGE – NEW SOURCE OF THE GRAVITINO PROBLEM (DETAILS OF SUSY MODEL)

OUTLINE

- THE MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE
- INFLATION AND REHEATING
- THE GRAVITINO PROBLEM, AND T_{reh}

  REHEATING, GRAVITINOS AND THE M-A ASYMMETRY

- A WAY OUT: DETAILED VIEW OF REHEATING
- ANOTHER WAY OUT: DELAYED THERMALISATION
- GRAVITINO PROBLEM AGAIN

  CONCLUSION

REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

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

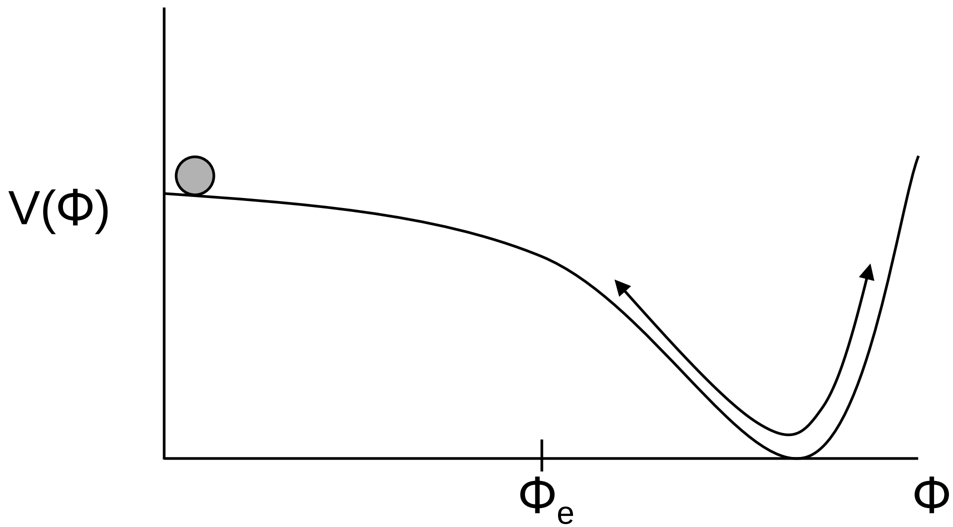
- MATTER-ANTIMATTER ASYMMETRY GENESIS MODELS REQUIRE HEAVY X, MASS 10^{10}, 10^{16} GeV

DIFFICULT TO PRODUCE HEAVY X

IN THE RAD DOMINATED UNIV AFTER REHEATING

LOW REHEAT TEMPERATURE IS A PROBLEM FOR GUT BARYOGENESIS AND LEPTOGENESIS

SUMMARY OF THE PROBLEM



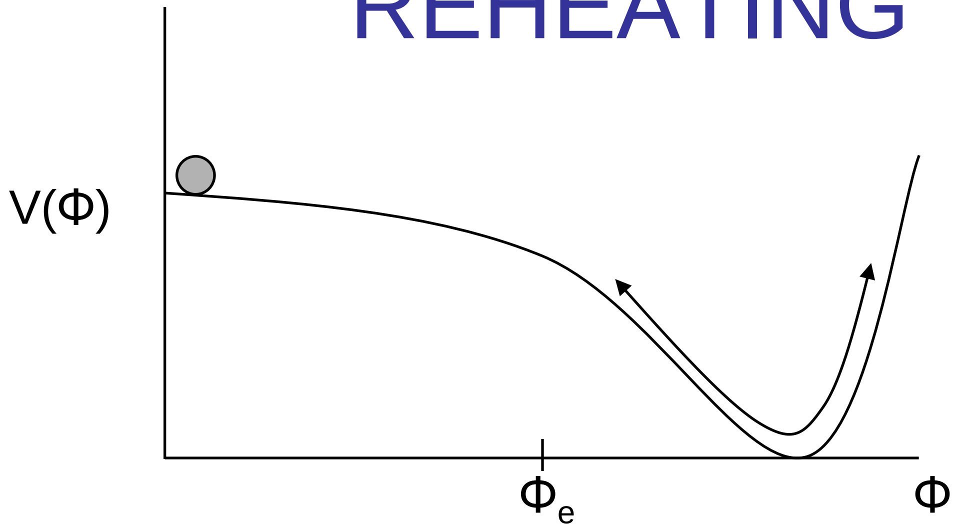
INFLATION $\rightarrow$ REHEATING $(\mathrm{T_{reh}})$

$\rightarrow$ RADIATION DOMINATED UNIV

THERMAL SCATTERING $\rightarrow \tilde{G}$
$\rightarrow N$

UPPER BOUND ON $\mathrm{T_{reh}}$ TO SUPPRESS $\tilde{G}$ SUPPRESSES N TOO

GRAVITINO PRODUCTION DURING REHEATING



INFLATON DECAYS AND DECAY PRODUCTS THERMALISE QUICKLY

$$\frac{dn_{\tilde{G}}}{dt} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot} |v| \rangle n^2$$

$$\frac{dn_{\tilde{G}}}{dt} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v| \rangle n^2$$

$H =$ HUBBLE PARAMETER (DILUTION DUE TO EXPANSION)

$\Sigma_{\rm tot} =$ TOTAL CROSS SECTION FOR GRAVTINO PRODUCTION

$v =$ RELATIVE VELOCITY OF THE INCOMING PARTICLES

$\langle \quad \rangle$ THERMAL AVERAGING

$n = \frac{1.2}{\pi^2}\,{\rm T}^3$ NUMBER DENSITY OF SCATTERERS

IGNORED DECAY $\tau \sim 10^{7-8}\,(100{\rm GeV}/m_{\tilde{G}})\,{\rm s}$

FOR $m_{\tilde{G}} \sim 100{\rm GeV}\,, \tau \sim 1\,{\rm yr}$ DECAY NOT RELEVANT

QUARTIC POTENTIAL

- REDONE FOR A QUARTIC POTENTIAL $R \sim t^{1/2}$
- $H(T),\ \rho_\phi(T),\ \rho_r(T)$ DIFFERENT

$$Y_{\tilde{G}}(\mathrm{REH}) = \frac{1}{2} Y_{\tilde{G}}(\mathrm{RD})$$

CONCLUSION

- OBTAINED AN ANALYTIC EXPRESSION FOR GRAVITINO PRODUCTION DURING REHEATING
- THE ABUNDANCE IS OF THE SAME ORDER AS THAT DURING THE RADIATION DOMINATED ERA (THE STANDARD CALC)
- THE DEPENDENCE ON $\mathrm{T_{max}}$ CANCELS OUT
- NO NEW CONSTRAINTS ON LEPTOGENESIS MODELS INVOKING $\mathrm{T_{max}}$

$$\dot{\mathrm{T}}\,\frac{dn_{\tilde{G}}}{d\mathrm{T}} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2$$

$$n \sim \mathrm{T}^3\,, \quad \text{NEED } \dot{\mathrm{T}} \text{ AND } H(T)$$

QUADRATIC INFLATON POTENTIAL DURING REHEATING, $R \sim t^{\frac{2}{3}}$

$$\rho_r \sim R^{-\frac{3}{2}} \Rightarrow \mathrm{T} \sim R^{-\frac{3}{8}} \sim t^{-1/4}$$ [R IS THE SCALE FACTOR]

$$\dot{\mathrm{T}} = -\frac{3}{8} T H_{\rm max} \left(\frac{\mathrm{T}}{\mathrm{T}_{\rm max}}\right)^4$$

$$H = \frac{\dot{R}}{R} = -\frac{8}{3}\frac{\dot{\mathrm{T}}}{\mathrm{T}} = H_{\rm max}\left(\frac{\mathrm{T}}{\mathrm{T}_{\rm max}}\right)^4 \,.$$

$$\dot{\mathrm{T}}\,\frac{dn_{\tilde{G}}}{d\mathrm{T}} + 3Hn_{\tilde{G}} = \langle\Sigma_{\rm tot}|v|\rangle n^2$$

$$n \sim \mathrm{T}^3\,, \quad \text{NEED } \dot{\mathrm{T}} \text{ AND } H(T)$$

QUADRATIC INFLATON POTENTIAL DURING REHEATING, $R \sim t^{\frac{2}{3}}$

$$\rho_r \sim R^{-\frac{3}{2}} \Rightarrow \mathrm{T} \sim R^{-\frac{3}{8}} \sim t^{-1/4}$$ [R IS THE SCALE FACTOR]

SOLVE FROM $\mathrm{T}_{\rm max}$ TO $\mathrm{T}_{\rm reh}$.

$$n_{\tilde{G}}(\mathrm{T}_{\rm reh}) = 0.007\,\frac{\alpha}{M_{Pl}^2}\frac{\mathrm{T}_{\rm max}^4\mathrm{T}_{\rm reh}^2}{H_{\rm max}} \qquad \text{for } \mathrm{T}_{\rm max} \gg \mathrm{T}_{\rm reh}$$

$$Y_{\tilde{G}}(\mathrm{T}_{\rm reh}) = \frac{n_{\tilde{G}}(\mathrm{T}_{\rm reh})}{s(\mathrm{T}_{\rm reh})} \quad = 0.01\,g_{\rm reh}^{-1}\,\frac{\alpha}{M_{Pl}^2}\,\frac{\mathrm{T}_{\rm max}^4}{H_{\rm max}\mathrm{T}_{\rm reh}}$$

$$\dot{\mathrm{T}}\,\frac{dn_{\tilde{G}}}{d\mathrm{T}} + 3Hn_{\tilde{G}} = \langle\Sigma_{\rm tot}|v|\rangle n^2$$

$$\dot{\mathrm{T}},\; H(\mathrm{T}),\; n \sim \mathrm{T}^3$$

$$\mathrm{T} \sim R^{-\frac{3}{8}} \qquad R \sim t^{\frac{2}{3}}$$ [R IS THE SCALE FACTOR]

SOLVE FROM $\mathrm{T}_{\rm max}$ TO $\mathrm{T}_{\rm reh}$.

$$n_{\tilde{G}}(\mathrm{T}_{\rm reh}) = 0.007\,\frac{\alpha}{M_{Pl}^2}\frac{\mathrm{T}_{\rm max}^4\mathrm{T}_{\rm reh}^2}{H_{\rm max}} \qquad \text{for } \mathrm{T}_{\rm max} \gg \mathrm{T}_{\rm reh}$$

$$Y_{\tilde{G}}(\mathrm{T}_{\rm reh}) = \frac{n_{\tilde{G}}(\mathrm{T}_{\rm reh})}{s(\mathrm{T}_{\rm reh})} \quad = 0.01\,g_{\rm reh}^{-1}\,\frac{\alpha}{M_{Pl}^2}\,\frac{\mathrm{T}_{\rm max}^4}{H_{\rm max}\mathrm{T}_{\rm reh}}$$

IMPLICATIONS FOR LEPTOGENESIS

NO LARGE ENHANCEMENT IN TOTAL GRAVITINO PRODUCTION

THOUGH $\mathrm{T_{max}} \gg \mathrm{T_{reh}}$, AND $n_{\tilde{G}}(REH) < n_{\tilde{G}}(RD)$

- NO LARGE CHANGE IN THE BOUND ON THE REHEAT TEMPERATURE

UPPER BOUND ON $\mathrm{T_{reh}}$ OF $10^{6-9}\mathrm{GeV}$ GOES DOWN BY 4/3

- $\mathrm{T_{max}} \sim \mathrm{T_{reh}^{\frac{1}{2}}}$ SO NOT AFFECT PRODUCTION OF HEAVY

NEUTRINOS AT $\mathrm{T_{max}}$

GRAVITINO PRODUCTION

- **DETAILED VIEW OF REHEATING**
  N$\uparrow\uparrow$ **BUT** $\tilde{G}\uparrow$

- **DELAYED THERMALISTION IN THE PRESENCE OF SUSY FLAT DIRECTIONS**

SUSY FLAT DIRECTIONS

SCALAR POTENTIAL IN SUSY IS A FUNCTION OF

$$(\tilde{q}, \tilde{l}, H_u, H_d)$$

DIRECTIONS IN FIELD SPACE OF SCALARS ALONG WHICH THE SCALAR POTENTIAL VANISHES

$$\langle \tilde{u} \rangle = \psi, \ \langle \tilde{s} \rangle = \psi, \ \langle \tilde{b} \rangle = \psi$$ PHASES

CALLED FLAT DIRECTIONS AS THE POTENTIAL IS FLAT AS YOU VARY THE VALUE OF ψ

INITIAL VALUE NEED NOT BE 0 (Q FLUC, OTHER)
ψ DECREASES IN TIME, AND THEN DISAPPEARS (DECAYS)

SUSY FLAT DIRECTIONS

SUSY BREAKING LIFTS THE POTENTIAL OF Ψ – GIVES MASS TO THE FIELD

INITIAL VALUE OF THE FIELD MAY BE AWAY FROM 0

WHEN H < m_{ψ} THE FIELD OSCILLATES IN ITS POTENTIAL

FINALLY Ψ DECAYS, GAUGE SYMMETRIES RESTORED

COSMOLOGICAL CONSEQUENCES

NON-ZERO VALUE OF THE FIELD Ψ GIVES MASS TO GAUGE BOSONS, e.g.,

$$L \supset \tilde{q}^* \tilde{q} A A$$

COSMOLOGICAL CONSEQUENCES

NON-ZERO VALUE OF THE FIELD Ψ GIVES MASS TO GAUGE BOSONS, e.g.,

$$L \supset \tilde{q}^* \tilde{q} A A$$

IF ALL GAUGE SYMMETRIES BROKEN [LLddd, QuQue], IT SLOWS DOWN THERMALISATION AFTER INFLATION.

DILUTE PLASMA. AFFECTS GRAVITINO PRODUCTION

ALLAHVERDI AND MAZUMDAR

EARLIER INFLATON DECAYS AND DECAY PRODUCTS THERMALISE QUICKLY

$$q + \bar{\tilde{q}} \to g + \tilde{G} \qquad q + \bar{q} \to \tilde{g} + \tilde{G} \qquad \tilde{q} + \bar{\tilde{q}} \to \tilde{g} + \tilde{G}$$

$$\dot{n}_{\tilde{G}} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2 \qquad n \sim T^3$$

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

$$W_{12}(s) = 4p_{12} \sqrt{s} \; \sigma_{CM}(s)$$

$$p_{12} = \left[s - (m_1 + m_2)^2\right]^{1/2} \left[s - (m_1 - m_2)^2\right]^{1/2} / [2\sqrt{s}]$$

$$s = (E_1 + E_2)^2_{CM}$$

- FLAT DIRECTION HAS A LARGE INITIAL VEV (DURING INFLATION)

- AFTER INFLATION, LARGE GAUGE BOSON MASS, SLOWS DOWN THERMALISATION

  DELAYED t_{KIN}

  DELAYED t_{CHEM}

- VEV DECREASES AND FINALLY FLAT DIRECTION DECAYS AT t_f .

  GAUGE SYMMETRIES RESTORED ($t_f \ll t_{EW}$)

RESULTS

- m_0 = 100 GeV < Γ_ψ = 10^4 GeV, $t_0 > t_d$

  NO GRAVITINO PRODUCTION EVEN AFTER THERMALISATION TILL THE FLAT DIRECTIONS DECAYS, DUE TO PHASE SPACE SUPPRESSION

  PRODUCTION AFTER THE FLAT DIRECTION DECAYS IS STANDARD $\propto T_f$ [10^5 GeV]

  LOW

RESULTS

- m_0 = 100 GeV > Γ_ψ = 10 GeV, $t_0 < t_d$

SUPPRESSED GRAVITINO PRODUCTION TILL THERMALISATION

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

NO GRAVITINO PRODUCTION AFTER THERMALISATION TILL THE FLAT DIRECTION DECAYS

PRODUCTION AFTER THE FLAT DIRECTION DECAYS IS NOT LARGE $\propto T_f$ [10^5 GeV]

GRAVITINO PROBLEM AGAIN!

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

- RESONANT PRODUCTION OF GRAVITINOS AS SQUARK CAN GO ON SHELL

- GRAVITINO ABUNDANCE GENERATED IS VERY LARGE AND GREATER THAN THE COSMOLOGICAL UPPER BOUND FOR MOST PARAMETER SPACE

GRAVITINO PROBLEM AGAIN!

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

- RESONANT PRODUCTION OF GRAVITINOS AS SQUARK CAN GO ON SHELL
- GRAVITINO ABUNDANCE GENERATED IS VERY LARGE AND GREATER THAN THE COSMOLOGICAL UPPER BOUND FOR MOST PARAMETER SPACE
- COSMOLOGICAL UPPER BOUND IS $Y < 10^{-14}$
- FOR DIFFERENT SETS OF PARAMETERS

$$Y = 10^{-8} \text{ — } 10^{-2}$$

RESULTS

- GRAVITINO ABUNDANCE SUPPRESSED

- LEPTOGENESIS IN THE NON-THERMAL UNIVERSE?

DILUTE PLASMA AFFECTS NUMBER DENSITY OF HEAVY RIGHT HANDED NEUTRINOS TOO

BUT SUFFICIENT TO CREATE REQUIRED BARYON ASYMMETRY

ALLAHVERDI AND MAZUMDAR

CONCLUSION

1. GRAVITINO ABUNDANCE GENERATED DURING REHEATING ~ ABUNDANCE GENERATED AFTERWARDS

2. GRAVITINO ABUNDANCE GENERATED IN A NON-THERMAL UNIVERSE IN THE PRESENCE OF FLAT DIRECTIONS IS SUPPRESSED

3. GRAVITINO ABUNDANCE IN A THERMAL UNIVERSE WITH FLAT DIRECTIONS CAN BE LARGE

CONCLUSION

4. NEUTRINOS GENERATED DURING REHEATING ~ GRAVITINO ABUNDANCE GENERATED NOT TOO LARGE (WITH SOME UNEXPECTED RESULTS)

5. GRAVITINO ABUNDANCE GENERATED IN A NON-THERMAL UNIVERSE IN THE PRESENCE OF FLAT DIRECTIONS IS SUPPRESSED (NEW CAUSES)

6. GRAVITINO ABUNDANCE IN A THERMAL UNIVERSE WITH FLAT DIRECTIONS CAN BE LARGE – NEW SOURCE OF THE GRAVITINO PROBLEM