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

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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

PREAMBLE

A BRIEF HISTORY OF OUR UNIVERSE

OBSERVATIONS + GENERAL THEORY OF RELATIVITY

14 b yr, COMPOSITION, EXPANDING, PAST – HOT AND DENSE

A BRIEF HISTORY OF OUR UNVIERSE

- First second – hot primordial plasma 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
- 14 billion years – Today

THE FIRST SECOND

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

Grand Unified Theory

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

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

- 10^{-11} s – Electroweak Phase Transition (E ~ 100 GeV, T ~ 10^{15} K)

- 10^{-6} s – quarks → protons, neutrons (E ~ 1 GeV, T ~ 10^{13} K)

- 1 s – Primordial Nucleosynthesis begins (E~ 1 MeV, T ~ 10^{10} K)

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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 x 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)

MATTER-ANTIMATTER ASYMMETRY OF THE UNIVERSE

- ANTIMATTER RULED OUT TILL d~1000 Mpc
- SIZE OF OBSERVABLE UNIVERSE ~ 14000 Mpc

(1 Mpc = 3 x 10^{19} km = 3 x 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
- WHERE DID THE ANTIMATTER GO? WHY THIS ASYMMETRY TODAY?
- DISEQUILIBRIUM IN THE EARLY UNIVERSE

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

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

$r_M > r_A$, 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

BEYOND STANDARD MODEL PARTICLES

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 ($k_B T > M$) ($k_B = 1$)

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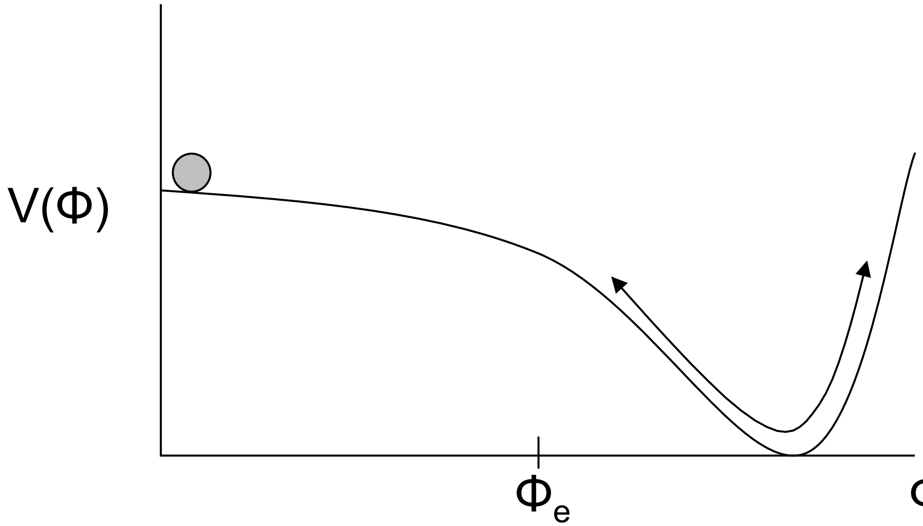
INFLATION and REHEATING

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

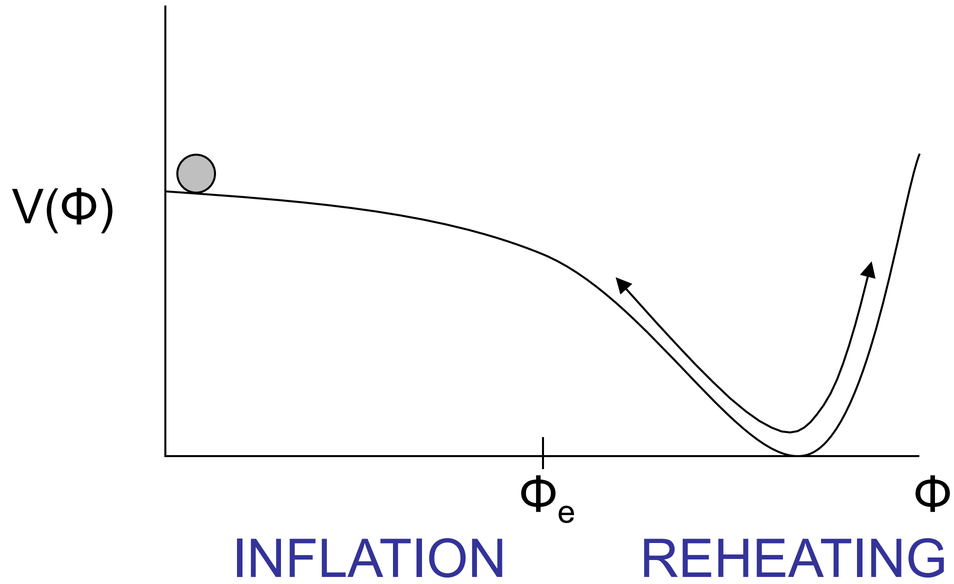
ASSOCIATED WITH THE DYNAMICS OF A SLOWLY VARYING FIELD CALLED THE INFLATON Φ



SLOW ROLL OSCILLATE AND DECAY

ENERGY DENSITY DOMINATES, DETERMINES EVOL OF UNIV

INFLATION and REHEATING



DURING INFLATION, R~ exp(H t) [R IS THE SCALE FACTOR, In expanding Univ d ~ d_1 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

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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 (spacetime dep) 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)

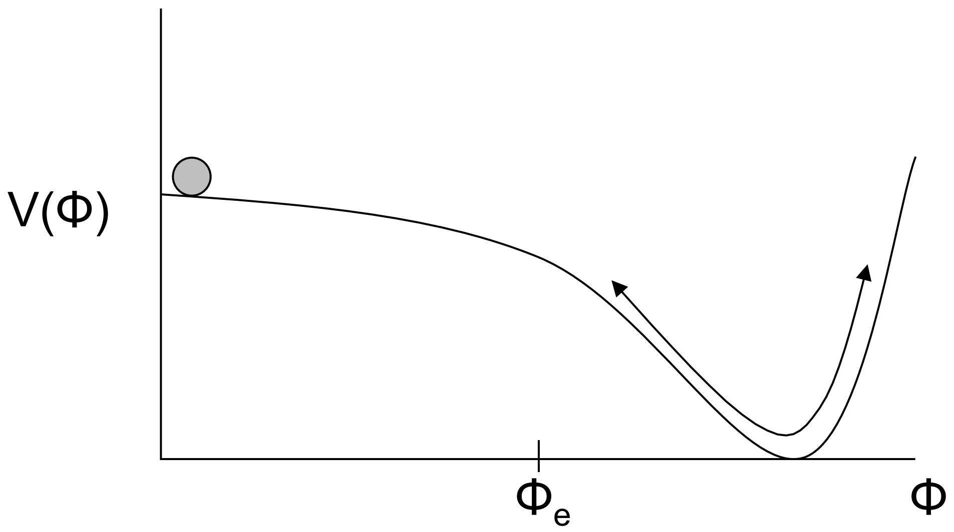
- STABLE : AFFECTS EXPANSION RATE, $\rho_{\tilde{G}} > \rho_c$ (L/H)
- UNSTABLE : AFFECT EXPANSION RATE PRIOR TO DECAY

  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 → REHEATING (OSC. + DECAY) $(\mathrm{T_{reh}})$

→ RADIATION DOMINATED UNIV
(Relativistic particles)

THERMAL SCATTERING → $\tilde{G}$
(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 T_{reh} OF 10^{6-9} GeV (MASS 100 GeV – 10 TeV)

$k_B T$ in GeV $k_B=1$ 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

1 GeV $=10^{13}$ K

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

1 GeV = PROTON MASS

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

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

REHEATING, GRAVITINOS AND MATTER-ANTIMATTER ASYMMETRY

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

LOW REHEAT TEMPERATURE IS A PROBLEM FOR GUT BARYOGENESIS AND LEPTOGENESIS

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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)

SOLUTIONS

INCREASE *N*

DETAILED VIEW OF REHEATING

DECREASE $\tilde{G}$

DELAYED THERMALISATION DURING REHEATING
DUE TO SUSY FLAT DIRECTIONS

SOLUTIONS

INCREASE *N*

DETAILED VIEW OF REHEATING

DECREASE $\tilde{G}$

DELAYED THERMALISATION DURING REHEATING DUE TO SUSY FLAT DIRECTIONS

NEW GRAVITINO PROBLEM

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

SOLUTION 1

INCREASE *N*

DETAILED VIEW OF REHEATING

NEUTRINO PRODUCTION DURING REHEATING

STANDARD CALC OF PRODUCTION ASSUMES INSTANTANEOUS INFLATON DECAY AND REHEATING.

$$\mathrm{T} \to \mathrm{T}_{\mathrm{max}} \to \mathrm{T}_{\mathrm{reh}}$$

$\mathrm{T}_{\mathrm{reh}}$ IS THE FINAL TEMPERATURE AT THE END OF REHEATING

$\mathrm{T}_{\mathrm{max}}$ CAN BE AS HIGH AS 1000 $\mathrm{T}_{\mathrm{reh}}$. CAN BE USED TO CREATE ENOUGH NEUTRINOS

CHUNG ET AL, DELEPINE AND SARKAR, GIUDICE ET AL

GRAVITINO PRODUCTION DURING REHEATING

STANDARD CALC OF PRODUCTION ASSUMES INSTANTANEOUS INFLATON DECAY AND REHEATING.

$$\mathrm{T} \rightarrow \mathrm{T}_{\mathrm{max}} \rightarrow \mathrm{T}_{\mathrm{reh}}$$

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$\mathrm{T}_{\mathrm{max}}$ CAN BE AS HIGH AS 1000 $\mathrm{T}_{\mathrm{reh}}$. CAN BE USED TO CREATE ENOUGH NEUTRINOS

IF A LARGE T_{max} CAN ENHANCE NEUTRINO PRODUCTION, CAN IT ALSO ENHANCE GRAVITINO PRODUCTION ?

GRAVITINO PRODUCTION DURING REHEATING

SOLVED THE INTEGRATED BOLTZMANN EQUATION FOR GRAVITINO PRODUCTION DURING REHEATING

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

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

$q - \tilde{q}, g - \tilde{g}$ Superpartners

RESULTS

SOLVED THE INTEGRATED BOLTZMANN EQUATION FOR GRAVITINO PRODUCTION DURING REHEATING

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

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

DEPENDENCE ON T_{max} CANCELS OUT [UNEXPECTED]

ABUNDANCE GENERATED IS LARGE, BUT LESS THAN THE COSMOLOGICAL BOUND ON THE GRAVITINO ABUNDANCE

SOLUTION IS VIABLE

RR, SAHU

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NEW SCENARIO OF GRAVITINO PRODUCTION

IN THE PRESENCE OF SUSY FLAT DIRECTIONS

IN SOME CASES, SUPPRESS PRODUCTION

IN OTHER CASES, EXCESSIVE PRODUCTION

SUSY FLAT DIRECTIONS

STANDARD MODEL , *H* SCALAR (SPIN 0)
MINIMISE V, <*H*> ≠ 0 => *q, l, W, Z* GET MASS
HIGGS MECHANISM

SCALAR POTENTIAL *V* IN SUSY IS A FUNCTION OF

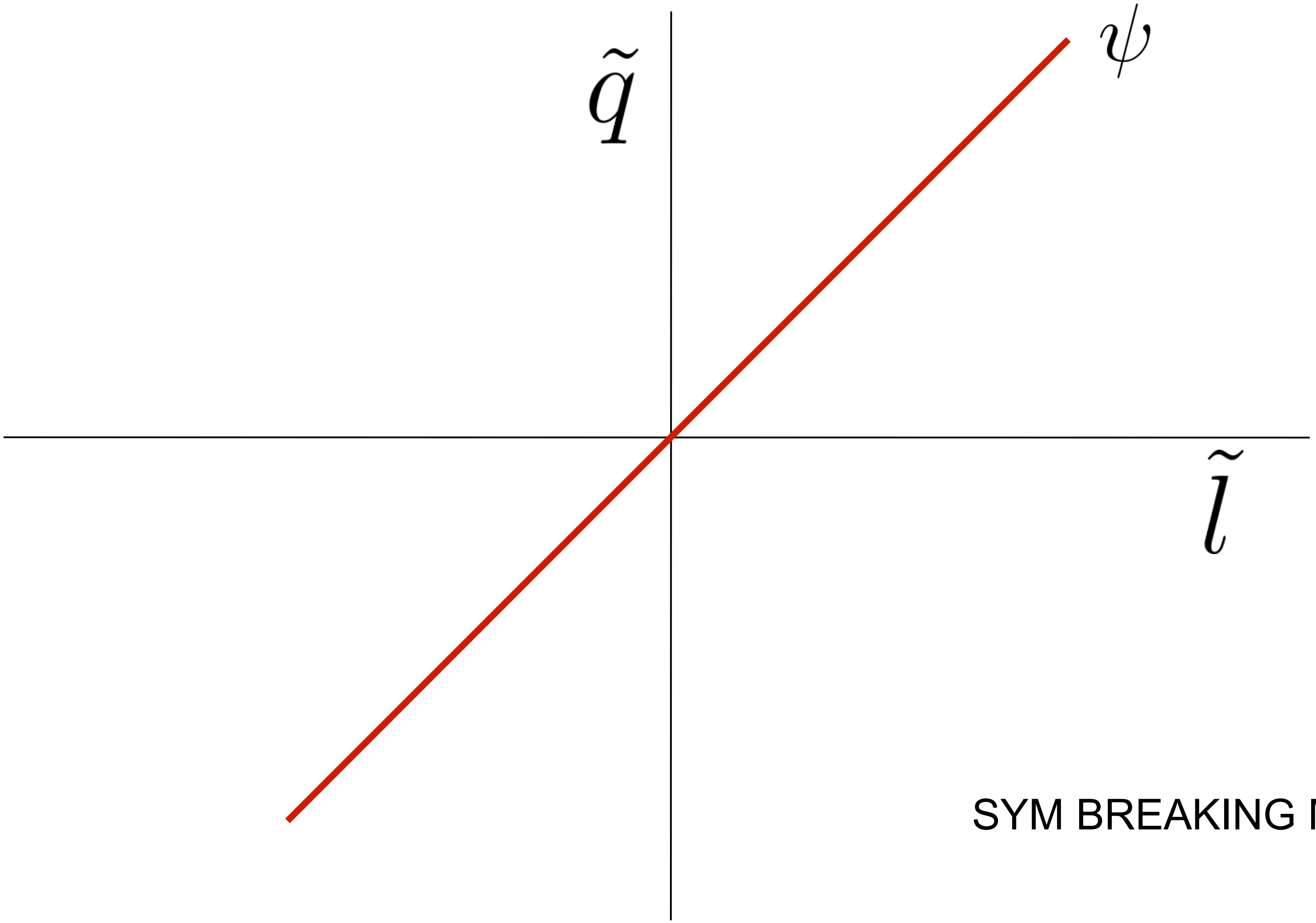
$$(H_u, H_d, \tilde{q}_i, \tilde{l}_i)$$

DIRECTIONS IN FIELD SPACE OF SCALARS ALONG WHICH THE SCALAR POTENTIAL IS MINIMISED

V' = 0, POTENTIAL IS FLAT — FLAT DIRECTIONS

[POTENTIAL IS CONSTANT AND ZERO ALONG FLAT DIRECTION]

SUSY FLAT DIRECTIONS



SYM BREAKING MINIMA

Any point on this line minimises the potential – parametrised by ψ. Note that each point corresponds to a different vacuum

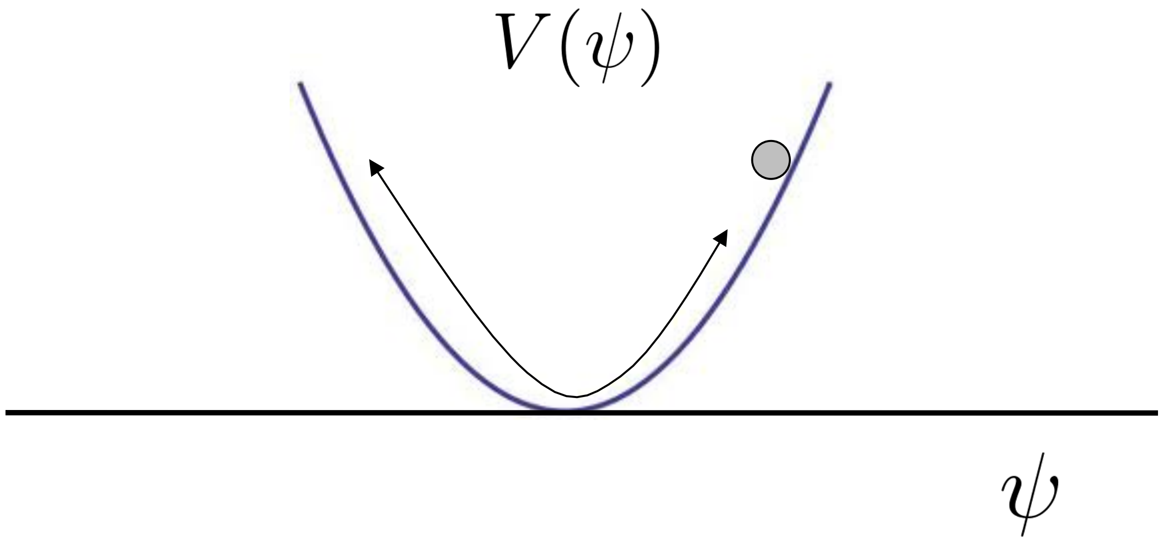
SUSY FLAT DIRECTIONS

FLAT DIRECTION CORRESPONDING TO

$\tilde{q}$ = ψ, $\tilde{l}$ = ψ PHASES

REPRESENTED BY A COMPLEX SCALAR FIELD ψ
(AFFLECK-DINE FIELD)

SUSY BREAKING



FLAT DIRECTION → QUADRATIC POT WITH CURV m_0

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

WHEN $t_U \sim t_F$ (OR $H \sim m_0$), ψ OSCILLATES, $\psi \sim 1/R^{3/2}$

THEN IT DECAYS (BEFORE EWSB $t \sim 10^{-11}$ s)

SOLUTION 2

DECREASE $\tilde{G}$

DELAYED THERMALISATION DURING REHEATING DUE TO SUSY FLAT DIRECTIONS

COSMOLOGICAL CONSEQUENCES

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

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

FLAT DIRECTION EXPECTATION VALUE CAN BE 10^{13} GEV OR HIGHER

THERMALISATION DUE TO PROCESSES MEDIATED BY GAUGE BOSONS – PHOTONS (EM), GLUONS (STRONG)

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, LEADING TO A DILUTE PLASMA.

SUPPRESSES GRAVITINO PRODUCTION

ALLAHVERDI AND MAZUMDAR; RR AND A. SARKAR

COSMOLOGICAL CONSEQUENCES

STANDARD PICTURE OF REHEATING:

INFLATON DECAYS $\rightarrow n_0 \rightarrow$ THERMALISE

KINETIC EQM n_0

CHEMICAL EQM n_1 $[10^4]$

FLAT DIRECTIONS:

INFLATON DECAYS $\rightarrow n_0 \rightarrow$ DELAYED THERMALISATION

$$n \sim n_0 \ll n_1$$

DILUTE PLASMA

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

$$n_{\tilde{G}} \downarrow\downarrow$$

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

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

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

RESULTS

APPROPRIATE $f_{1,2}$

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

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

COMPLETE SHUT OFF

[RR, A. SARKAR]

N↓ BUT SUFFICIENT

GRAVITINO PRODUCTION

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

- **DELAYED THERMALISATION IN THE PRESENCE OF SUSY FLAT DIRECTIONS**
  N $\downarrow$ **BUT** $\tilde{G}\downarrow\downarrow$

ALTERNATE SCENARIO WITH SUSY FLAT DIRECTIONS

- GRAVITINO OVER-PRODUCTION

ALTERNATE SCENARIO

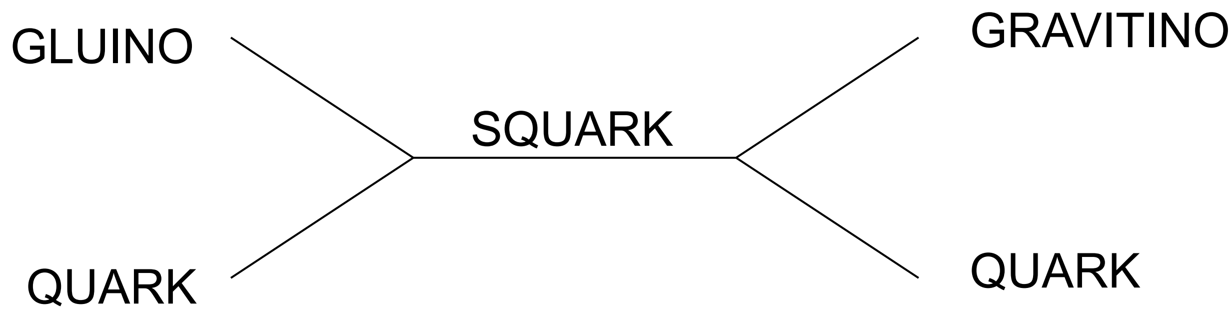
- IF FLAT DIRECTION EV DOES NOT BREAK ALL GAUGE SYMMETRIES, THERMALISATION WILL OCCUR

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

- GLUON AND GLUINO LIGHT (m ~ gT, REL), THERMAL DISTRIBUTION

- QUARK AND SQUARK HEAVY (NR), $m \approx h\psi$, $\psi > 10^{13}$ GeV

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



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

- BREIT-WIGNER RESONANCE WHEN

  Incoming energy = $E_{gluino} + E_q \approx m_{sq}$

- CROSS SECTION ~ $\dfrac{1}{(s-m_{sq}^2)^2 + m_{sq}^2\,\Gamma^2}$

$s^{1/2} = E_{gluino} + E_q$, Γ = squark decay rate

GRAVITINO PROBLEM AGAIN!

- 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 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. 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 THE SUSY MODEL)

ADJUST THE REHEAT TEMP?

- GRAVITINO ABUNDANCE DECREASES BY INCREASING T_{REH}
- STANDARD PRODUCTION – GRAVITINO ABUNDANCE INCREASES WITH T_{REH}