SANTA BARBARA
FEB./MARCH '08

QUANTUM TRANSPORT EQUATIONS AND BARYGENESIS IN THE EARLY UNIVERSE

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COSMOLOGY $\Longleftrightarrow$ ELEMENTARY PARTICLE PHYSICS

ASTROPHYSICS

BEYOND WEINBERG'S "FIRST THREE MINUTES"

FASCINATING NEW OBSERVATIONS

- CMB (WMAP..)
- GALAXIES WITH LARGE REDSHIFTS SUPERNOVAE
- GRAVITATIONAL LENSING DEFECTS

FLUCTUATIONS $\leftrightarrow$ INFLATION

$\downarrow$

STRUCTURE FORMATION

$\uparrow$

DARK MATTER/ENERGY $\leftrightarrow$ SUSY ?

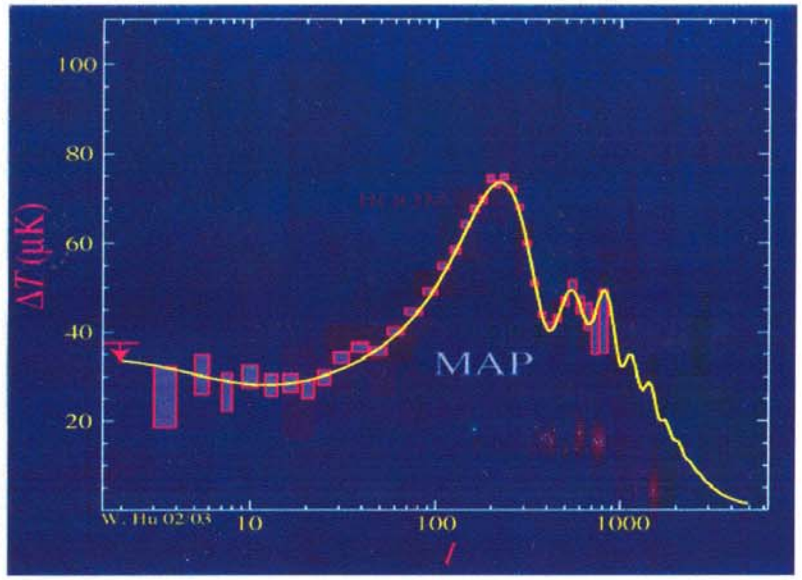
! • BARYON ASYMMETRY

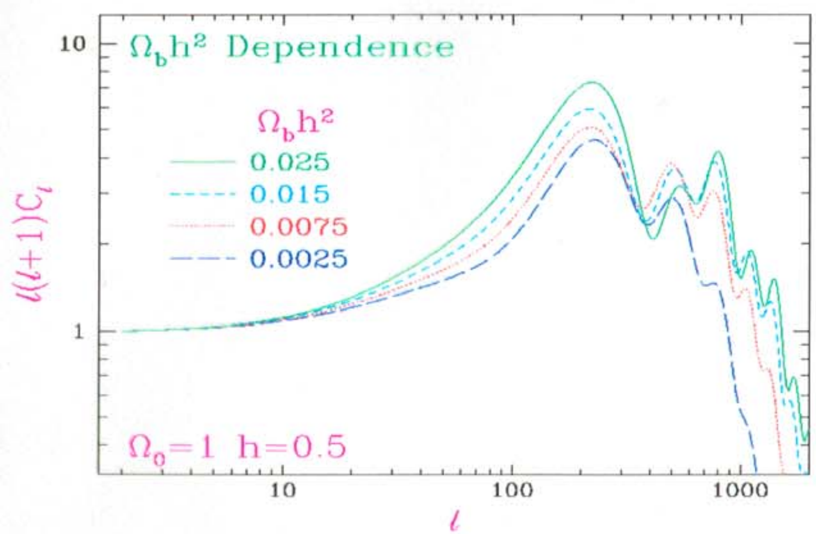
$$\eta = \frac{N_B}{N_\gamma} = \left(6.5 \pm {}^{0.4}_{0.3}\right) 10^{-10}$$ FROM WMAP

IN AGREEMENT WITH PRIMORDIAL NUCLEOSYNTHESIS

ALWAYS "BEYOND THE SM" REQUIRED

Baryonic matter and cmbr





***baryons:** increase compression **(odd)** peaks, decrease rarefaction peaks*

- BARYO GENESIS

SAKHAROV '67

$\cancel{B}$

- GUT, MAJORANA NEUTR. $\cancel{L}$
- ELECTROWEAK SPHALERON ⊛

MODEL?

$\cancel{C}$, $\cancel{CP}$

- KM - MATRIX ⊛
- PHASES IN NONSTAND.-TH
- SPONTANEOUS BREAKING

NONEQUILIBRIUM

- EXPANDING UNIVERSE
- OUT OF EQUIL. DECAY
- PHASE TRANSITION ⊛

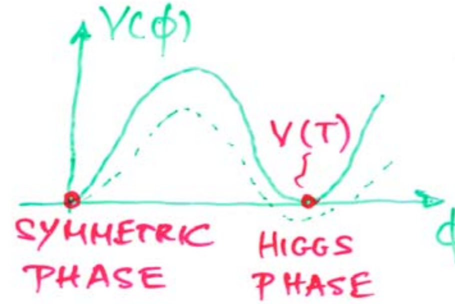
⊛ POSSIBLE IN SM?

SHAPOSHNIKOV

CONSIDER TWO MODELS $\Rightarrow$ TRANSPORT!

- ELECTROWEAK BARYOGENESIS

NEED • 1. ORDER PHASE-TR.



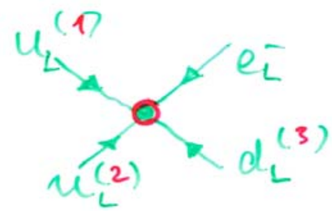
$T_c \sim 100\,GeV$

$t \sim 10^{-12}\,sec$

$R \sim 10^{13}\,cm$

• SPHALERON TRANSITION (SM)

$\cancel{B+L}$



(here: one generation)

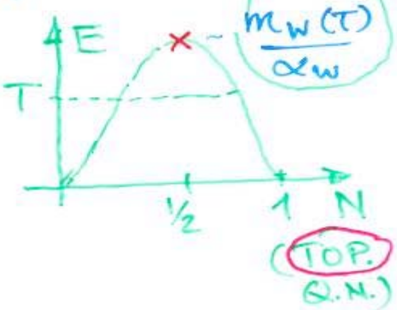
- COHERENT BARYOGENESIS

• CREATION OF A CHARGE ASYMMETRY AT THE END OF (HYBRID) INFLATION.

• LEPTON NUMBER VIOLATION BY HEAVY MAJORANA-NEUTRINO

$T \neq 0$: "SPHALERON" THERMAL TRANSITION

$$\Gamma_{\cancel{B}} \sim .. (\alpha_W T)^4 \exp\left(-.. \frac{V(T)}{T}\right) \qquad V(T) \sim \frac{m_W(T)}{\alpha_W}$$



- UNSUPPRESSED IN SYMMETRIC (HOT) PHASE $(V=0)$
- $(B+L)$ - VIOLATING

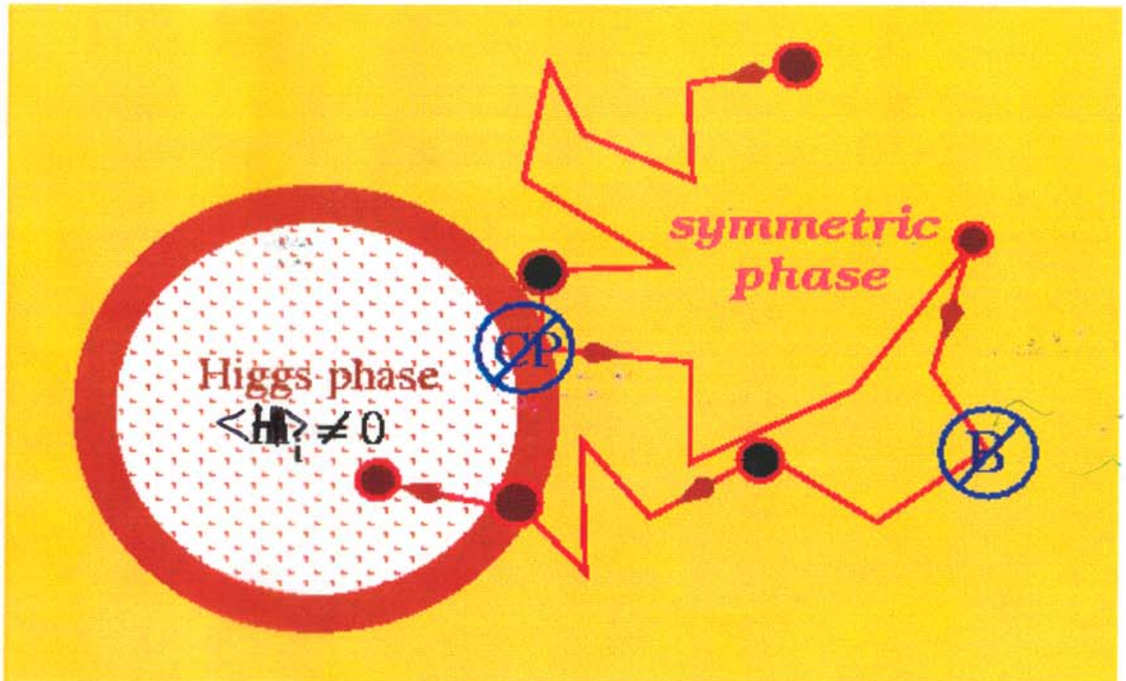
$B-L=0$?

(BUT: $\cancel{L}$ BY MAJORANA NEUTR.)

- ELECTROWEAK BARYOGENESIS DURING FIRST ORDER PHASE TRANSITION

Electroweak baryogenesis at a strong 1st order transition

CHARGE TRANSPORT



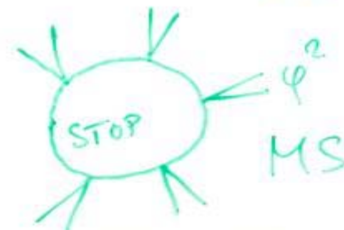
- expanding bubbles of higgs phase
- CP violation on bubble walls ⇒ CREATE CHIRAL ASYMM.
- B violation in symmetric phase (SPHALERON)

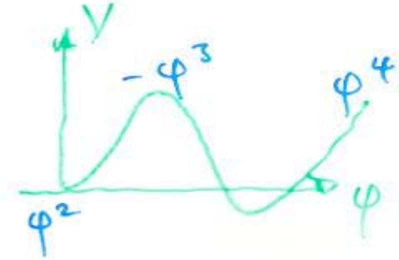
ELECTROWEAK BARYOGENESIS

SM - KM - $\cancel{CP}$ VERY SMALL

NO PHASE TRANSITION
FOR $m_h \gtrsim m_W$ (~"CROSSOVER")

SUPER SYMMETRIC VARIANTS
INCREASE "φ^3" TERM





BÖDEKER
LAINE
JOHN
SCH.
HUBER
SCH.

NMSSM
nMSSM

GET STRONG I. ORDER
PHASE TRANSITION

- EXPLICITE CP-VIOLATION

MSSM : - IN HIGGSINO-Gaugino mass MATRIX BY COMPLEX M_2, μ

- IN STOP-SYSTEM (VIA A_t, A_μ)

$\Rightarrow$ RESTRICTIONS BY EXP. BOUNDS ON n.e.d.m!

- SPONTANEOUS VIOLATION OF CP IN HIGGS EFF. POTENTIAL (T-DEPENDENT!)

"TRANSITIONAL CP-VIOLATION" JUST IN THE BUBBLE WALL REGION NEAR THE CRITICAL TEMPERATURE OF THE P.T.

$\Rightarrow$ <u>NO</u> RESTRICTION BY EXP. BOUNDS ON n.e.d.m

DOES EXIST IN NMSSM

DOES <u>NOT</u> EXIST IN MSSM

HUBER
JOHN
LAINE
SCH.

ELECTROWEAK BARYOGENESIS

- A VERY CONCRETE STEP BY STEP PROCEDURE

- (MULTIDIM.) HIGGS-FIELD CRITICAL BUBBLE
- TRANSITION PROBABILITY $..e^{-S_{eff}}$

- SUPER COOLING / NUCLEATION TEMPERATURE ("ONE BUBBLE / UNIVERSE")
- STATIONARY EXPANSION V_{WALL}.. ; PROFILE

  "DEFLAGRATION"

  HIGGS | SYMM. PHASE

  $\longrightarrow V_{WALL}$

OUR SUBJECT TODAY

- TRANSPORT IN PRESENCE OF MOVING PHASE BOUNDARY WITH CP VIOLATING EFFECTS

  QUANTUM TRANSPORT EQS. FOR CHARGINOS

- DIFFUSION EQS. TO PRODUCE CHIRAL ASYMMETRY $n_{q_L} - n_{\bar{q}_L}$

- $\not{B}$ BY "HOT" SPHALERON OF ELWK. THEORY IN FRONT OF BUBBLE WALL

- DIFFUSION IN PRESENCE OF MOVING WALL

! "THICK WALL" : $d \gg$ MEAN FREE PATH

$p \sim T \gg \frac{1}{d}$ THERMAL PART. (RELATIVISTIC)

$\rightsquigarrow$ QUASICLASSICAL DESCRIPTION ?!
DERIVATIVE EXPANSION

NEED ORDER $\hbar$ BECAUSE OF $\cancel{CP}$, DIRAC - PARTICLES

- NAIV EXSPECTATION : WKB - APPROXIMATION

$$\ldots(\;)\, e^{-i/\hbar \int^{z} p_z(z')\, dz'}$$

CLINE, JOYCE, KAINULAINEN

HUBER, SCH.

SIMPLIFICATION : $m = |m|\, e^{i\theta}$

LATER: COMPLEX MASS MATRIX M

$M = V M_{DIAG} U^{+}$

- PROBLEM : $p_{KIN} \neq p_{CANONICAL}$ IN CASE OF $\cancel{CP}$

GET SPLIT IN PART. / ANTIPART.,

USE THIS IN CLASSICAL TRANSPORT (BOLTZMANN) EQS. ?

NEED FIRST PRINCIPLE DERIVATION OF TRANSPORT / CONSTRAINT EQS. !

- FIRST PRINCIPLE DERIV. OF SEMICLASSICAL FORCE (KAINULAINEN, PROKOPEC, SCH., WEINSTOCK)

REAL TIME / KELDISH FORMALISM/

FOR FERMIONIC FIELDS WITH MASS

$$m(x) = m_R(x) + i\, m_I(x) = |m|\, e^{i\theta(x)} \; ! \quad \cancel{CP}$$

$$\mathcal{L} = i\bar{\psi}\not{\partial}\psi - \bar{\psi}_L m \psi_R - \bar{\psi}_R m^* \psi_L + \mathcal{L}_{int}$$

CENTRAL: $G^{<}_{\alpha\beta}(u,v) = i\langle \bar{\psi}_\beta(v)\psi_\alpha(u)\rangle$

WIGNER TRANSFORM

$$G^{<}(\underbrace{x,k}) = \int d^4r\, e^{ikr}\, G^{<}(x+\tfrac{r}{2}, x-\tfrac{r}{2})$$

BAYM-KADANOFF

~ "CLASSICAL PHASE SPACE" ?!

$$\Rightarrow \boxed{(\hat{\not{k}} - \hat{m}_0 - i\,\hat{m}_5\gamma^5)\, G^{<} = \overset{\text{LATER}}{C}} \to 0$$

$$\hat{k}_\mu = k_\mu + \tfrac{i}{2}\partial_\mu \qquad \hat{m}_{0,5} = m_{R,I}(x)\, e^{-\frac{i}{2}\overleftarrow{\partial}_x\cdot\partial_k}$$

WALL FRAME

$m = m(z)$

DERIVATIVE EXPANSION ~ $\hbar$-EXP.

CONSERVED SPIN s $\perp$ WALL

$z = x_3$

WALL

$$-i\gamma^0 G^< = \sum_s \frac{1}{4}\sigma^a \times \rho^b \, g^s_{ab}$$

REAL PART OF DIRAC EQ. $\Rightarrow$ CONSTRAINT EQS

IMAGINARY PART $\Rightarrow$ TRANSPORT EQS.

CE - ELIMINATE... $\longrightarrow$ g^s_{00} EQ.

$$\left[k^2 - |m(x)|^2 + \frac{s}{\tilde{k}_0} |m(x)|^2 \theta' \right] g^s_{00} = 0$$

$\tilde{k}_0 = \operatorname{sign} k_0 \left(k_0^2 - \vec{k}_\parallel^{\,2}\right)^{1/2}$

FIRST ORDER DERIV. EXP.

SOL. $$g^s_{00} = \frac{2\pi}{Z_s} f_s(\omega_s, k_z, z)\, \delta(k_0 - \omega_s)$$ + neg. frequ.

$\rightarrow$ DISPERSION RELATION

$$\boxed{\omega_s = \omega_0 - s|m|^2\theta' \left(2\omega_0\left(\omega_0^2 - \vec{k}_\parallel^{\,2}\right)^{1/2}\right)^{-1}}$$

$\omega_0 = \left(\vec{k}^2 + |m|^2\right)^{1/2}$

TE - USE CE AND ELIMINATE $\rightarrow g_{00}^s$ EQ.

$$\left[k_z \partial_z - \frac{1}{2} |m|^{2\prime} \partial_{k_z} - \frac{1}{2} (|m|^2 \theta')' \partial_{k_z} \right] g_{00}^s = 0$$

SECOND ORDER DERIV. EXP.

$\rightarrow$ VLASOV EQ. FOR f_s

$$\boxed{v_s \partial_z f_s + F_s \partial_{k_z} f_s = 0}$$

WITH $v_s = \dfrac{k_z}{\omega_s}$ GROUP VELOCITY

$$F_s = -\frac{|m|^{2\prime}}{2\omega_s} + \boxed{\frac{s(|m|^2\theta')'}{2\omega_0(\omega_0^2 - \vec{k}_{\parallel}^2)^{1/2}}}$$

CP VIOLATING

SEMICLASSICAL FORCE

ROUGH AGREEMENT WITH WKB (k_{kin} !)

CAN BOOST TO PLASMA FRAME

- MASS MATRIX: FLAVOR OSCILLATIONS

"CHARGINOS"

MSSM: HIGGSINO - GAUGINO MIXING

$$\psi_R = \begin{pmatrix} \tilde{W}_R^+ \\ \tilde{h}_{1,R} \end{pmatrix}, \quad \psi_L = \begin{pmatrix} \tilde{W}_L^+ \\ \tilde{h}_{2,L} \end{pmatrix}$$

$$\mathcal{L} = \bar{\psi}\, i\gamma\cdot\partial\, \psi - \bar{\psi}_L\, m\, \psi_R - \bar{\psi}_R\, m^+ \psi_L$$

$$m(x) = \begin{pmatrix} m_2 & g H_2^*(x) \\ g H_1^*(x) & \mu_c \end{pmatrix}$$

WALL ⇒ X-DEPENDENCE

CP-VIOL. PHASES

CE: ARE ALREADY NONALGEBRAIC IN FIRST ORDER $\hbar$

CAN WRITE KINETIC EQS. FOR CHIRAL DENSITIES WITHOUT USE OF CE (k_0 INDEPENDENCE!)

(KONSTANDIN, PROKOPEC, SCH.; SECO '04 '05)

"FLAVOR" ROTATION"

$$m(x) \to m_{\mathrm{diag.}} = U\, m\, V^+$$

$$m m^+ \to m_d^2 = U\, m m^+\, U^+$$

$$m^+ m \to \ldots$$

- FLAVOR ROTATION OF MASS MATRIX

$$m \to \overset{\text{DIAG}}{m_d} = \mathcal{U} m V^+$$

(CP. NEUTRINO PHYSICS!)

$$m m^+ \to m_d^2 = \mathcal{U} m m^+ \mathcal{U}^+$$

$$m^+ m \to m_d^2 = V m^+ m V^+$$

NOT DIAG.!

- $g_{R/L} = g_0 \pm g_3$, $g_N = g_1 + i g_2$

$g_i \leftrightarrow g_{ab}$

$$\left.\begin{array}{l} g_{R/L} = g_0 \pm g_3 \\ g_N = g_1 + i g_2 \end{array}\right\} \to \begin{array}{l} g_L \to \mathcal{U} g_L \mathcal{U}^+ = \text{"}g_{Ld}\text{"} \\ g_R \to V g_R V^+ = \text{"}g_{Rd}\text{"} \\ g_N \to \mathcal{U} g_N V^+ = \text{"}g_{Nd}\text{"} \end{array}$$

$g_R = g_R^D + g_R^T$, g_R^D DIAGONALIZED LIKE m^+m

CONSTRUCT PROJECTORS

SEPARATE CONSTRAINTS / DISP. REL.
NONLOCAL IN HIGHER DERIVATIVE ORDERS

- OBTAIN {$\boxed{\text{KINETIC EQS.}}$} IN STATIONARY CASE WITHOUT INSERTING CONSTRAINTS (k_0 INDEP.)

- CP-VIOLATING SOURCES

CP DOES NOT COMMUTE WITH FLAVOR-ROTATIONS

! CP $\to$ Q : $\quad Q\, g(k,x)\, Q^+ = CP\, g^T(k,x)\, CP^+$
$= g(-\bar{k}, \bar{x})$ $\quad \vec{\bar{x}} = -\vec{x}$ ..

FERMIONS IN $g^{sT}_{R,L}$ — NONDIAGONAL IN MASS - EIGEN ST. BASIS

CP-VIOLATING TRANSPORT EQ. ALREADY IN ORDER $\hbar$!

LINEAR RESPONSE

$$g^{sT}_{R,L} = g_{eq} + \delta g^{s}_{R,L} \quad , \quad g_{eq} = \frac{2\pi |k_0| \delta(k^2 - m_d^2)}{e^{\beta k_0} + 1}$$

$$\Rightarrow \boxed{k_z \partial_z \delta g^{sT}_R + \frac{i}{2}[m_d^2, \delta g^{sT}_R] + k_0 \Gamma_h \delta g^{sT}_R = S^s_R}$$

IN MASS E. BASIS

DAMPING FOR B.C.

WITH
$$S^s_R = -s \frac{k_z^2}{\tilde{k}_0}[VV^{+\prime}, g_{eq}] - s/4\tilde{k}_0 [V(m^+m - m^+m')V^+, g_{eq}] + s\, k_z/4\tilde{k}_0 \{V(m^+m)'V^+, g_{eq}\}$$

(AND $R \leftrightarrow L$, $U \leftrightarrow V$, $s \leftrightarrow -s$)
AND CP/Q -TRANSFORMED EQS.

$\Rightarrow$ CP-VIOLATING CURRENTS (VECTOR, AXIAL V.)

$\hbar$ - TYPICAL : $\sim \mathrm{Im}(m_2 \mu_c)(u_2 \partial_z u_1 - u_1 \partial_z u_2) \times$ Integral

$u_{1,2} = g|H_{1,2}|$

$\hbar^2$ FOR COMPARISON

$$\sim \mathrm{Im}(m_2 \mu_c)(u_2 \partial_z^2 u_1 + u_1 \partial_z^2 u_2) \times \text{Integral}$$

- BOSONIC CASE ("EXERCISE")
  (KLEIN-GORDON EQ. ...)

$$\left[\vec{k}^2 + i k_z \partial_z + \frac{1}{4}\partial_z^2 - M^2 - \frac{i}{2} M^{2\prime} \partial_{k_z}\right] \Delta^<(k,z) = \mathcal{C}_{\text{coll.}}$$

BAYM-KADANOFF-EQ.
FIRST ORDER IN DERIV.
SELF-ENERGY TERM NEGLECTED

$$\Delta^{<+} = -\Delta^<$$

HERMITEAN + ANTIHERM. PART

→ CE $\quad (\vec{k}^2 + \frac{1}{4}\partial_z^2)\Delta^< - \frac{1}{2}\{M^2, \Delta^<\} - \frac{i}{4}[M^{2\prime}, \partial_{k_z}\Delta^<] = 0$

TE $\quad k_z \partial_z \Delta^< + \frac{i}{2}[M^2, \Delta^<] - \frac{1}{4}\{M^{2\prime}, \partial_{k_z}\Delta^<\} = \mathcal{C}$

IN DIAGONAL MASS-BASIS

$$\Delta_d^< \to \Delta_d^D,\ \Delta_d^T$$

IN LOWEST (NO) DERIVATIVE ORDER

CE $\quad (\vec{k}^2 + M_d^2)\Delta_d^D = 0$

$\quad (\vec{k}^2 - \Lambda^2/k_z^2 - \frac{1}{2}\operatorname{tr} M_d^2)\Delta_d^T = 0$

SEPARATE SPECTRUM!

$$\Lambda = (\operatorname{tr} M^2 - 4 \det M^2)^{1/2}$$

TE $\quad k_z \partial_z \Delta_d^D = 0 \quad \to \quad \Delta_d^D = \text{const.}$

$\quad k_z \partial_z \Delta_d^T + \frac{i}{2}[M_d^2, \Delta_d^T] = 0 \quad \Rightarrow$ FLAVOR ROTATION

LIKE NEUTRINO OSCILLATIONS (CREATE FLAVOR E.S. → MASS E.S.)

NEXT ORDER IN GRADIENT EXP.

CE : NOT ALGEBRAIC ANYMORE

$-$ FOR $\Delta_d^{<Q}$

TE :
$$\boxed{k_z \partial_z \Delta_d^< + k_z [\Sigma_1, \Delta_d^<] + \frac{i}{2} [M_d^2, \Delta_d^<] - \frac{1}{4} \{ M_d^{2\prime} + \frac{1}{2} [\Sigma_1, M_d^2], \partial_{k_z} \Delta_d^< \} = C_d}$$

$\Sigma_1 = U^+ U'$

! CP DOES NOT COMMUTE WITH FLAVOR ROTATION

U

CP $\Rightarrow$ "Q"-TRANSFORMATION : BASIS INDEPENDENT

$$\Delta^{<Q} := \Delta^{<CP*}$$

NEED EQUATION FOR $(\Delta^{<Q} - \Delta^<)$ FOR ~~CP~~-SOURCE

LINEAR RESPONSE : $\delta \Delta_d^< = \Delta_d^< - \Delta_{eq}^<$

($M_d^{2\prime}$, Σ_1 FIRST ORDER)

$$i \Delta_{eq}^< (k_\mu) = 2\pi \delta (k^2 - M_d^2) \, \mathrm{sign}(k_0) \underbrace{\frac{1}{e^{\beta k_0} - 1}}_{f_{BE}}$$

$$\Rightarrow k_z \partial_z \delta \Delta_d^T + \frac{i}{2} [M_d^2, \delta \Delta_d^T] \underbrace{- C_d}_{\text{DAMPING}}$$
$$= - k_z [\Sigma_1, \Delta_{eq}^<]^T + \frac{1}{4} \{ M_d^{2\prime} + [\Sigma_1, M_d^2], \partial_{k_z} \Delta_{eq}^< \}^T$$

ONLY T-PART CONTRIBUTES IN $(\delta \Delta_d^< - \delta \Delta_d^{<Q})$

- COLLISION TERMS

PROKOPEC
SCH.
WEINSTOCK

- DRIVE SYSTEM BACK TO EQUILIBRIUM (OUR "T")
- ALSO GENERATE CP- ASYMMETRY (LESS IMPORTANT)

ATTENTION!

- CHARGINO BARYOGENESIS

- (ASYMMETRIC) CHARGINOS DECAY INTO QUARKS + LEPTONS

$\Rightarrow$ DIFFUSION EQUATIONS

HUET
NELSON

CAREN A
MORENO
QUIROS
SECO
WAGNER

- SPHALERON TRANSITION :
  LEFT HANDED QUARKS + LEPTONS
  AND CP - TRANSFORMS
  PRODUCE BARYON ASYMMETRY

$$n_B = -\frac{3\,\Gamma_{\text{WEAK SPH.}}}{v_{W\,eff}} \int_{-\infty}^{0} dz\, \underbrace{n_L(z)}_{n_L = 5 n_Q + 4 n_T} \exp\left(z \frac{15 \Gamma_{ws}}{4 v_w}\right)$$

V. DIFFUSION EQUATIONS

Using our formalism, we can deduce the CP-violating particle densities in the chargino sector. To evaluate the baryon asymmetry in the broken phase, we need to compute the density of left-handed quarks and leptons n_L in front of the wall. These densities couple to the weak sphaleron and produce a net baryon number.

To determine how the CP-violating currents are transported from the charginos to the left-handed quarks and leptons we use a system of coupled diffusion equations as derived in [15], and later adapted in [12, 19] and [9]. The diffusion equations are

$$\begin{aligned} v_w n_Q' &= D_q n_Q'' - \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h}{k_H}\right] - \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right] \\ &\quad -6\,\Gamma_{ss} \left[2\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\frac{n_Q + n_T}{k_B}\right] \end{aligned} \tag{51}$$

$$\begin{aligned} v_w n_T' &= D_q n_T'' + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h}{k_H}\right] + \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right] \\ &\quad +3\,\Gamma_{ss} \left[2\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\frac{n_Q + n_T}{k_B}\right] \end{aligned} \tag{52}$$

$$v_w n_H' = D_h n_H'' + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h}{k_H}\right] - \Gamma_h \frac{n_H}{k_H} \tag{53}$$

$$v_w n_h' = D_h n_h'' + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h}{k_H}\right] - (\Gamma_h + 4\Gamma_\mu)\frac{n_h}{k_H}\,, \tag{54}$$

where n_T denotes the density of the left-handed top and stop particles, n_Q the remaining left-handed quarks and squarks and n_H and n_h the sum and difference of the two Higgsino densities n_{H_1} and n_{H_2}. The quantities k_i are statistical factors defined by $n_i = k_i\,\mu_i \frac{T_c^2}{6}$ (μ_i

* MSSM

T. KONSTANDIN
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M. G. SCH.
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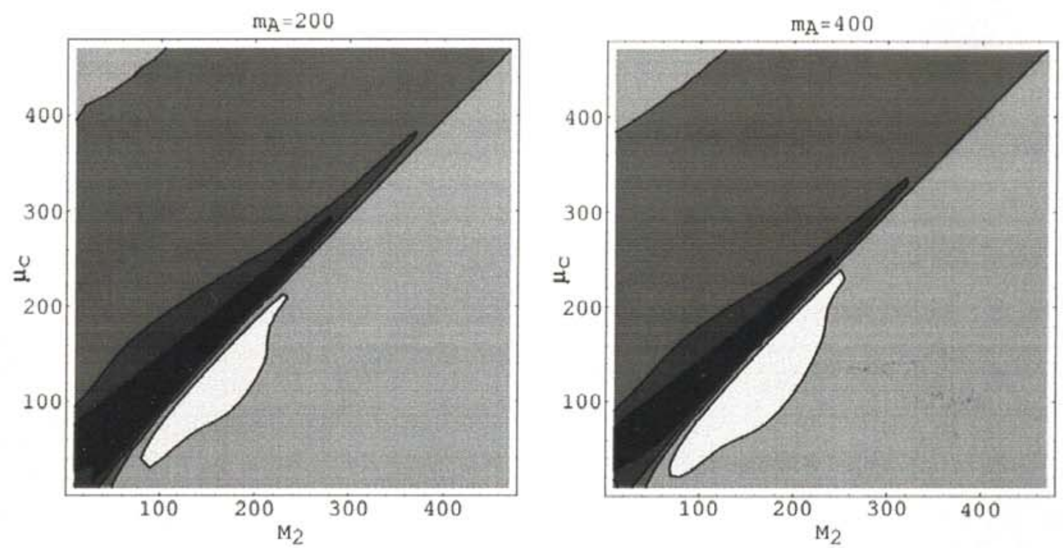


FIG. 5: The baryon-to-entropy ratio $\eta_{10} = 10^{10} \times \eta$ in the (M_2, μ_c) parameter space from (0 GeV,0 GeV) to (400 GeV,400 GeV). For the left plot the value $m_A = 200$ GeV is used, for the right plot $m_A = 400$ GeV. The black region denotes $\eta_{10} > 1$, where baryogenesis is viable. The other four regions are bordered by the values of η_{10}, $\{-0.5, 0, 0.5, 1\}$, beginning with the lightest color.

MAXIMAL CP-VIOLATION

RESTRICTIONS BY exp. n/e - ELECTRIC DIPOL LIMITS

$$\eta_{10} = \frac{n_B}{s_\gamma} \times 10^{10}$$

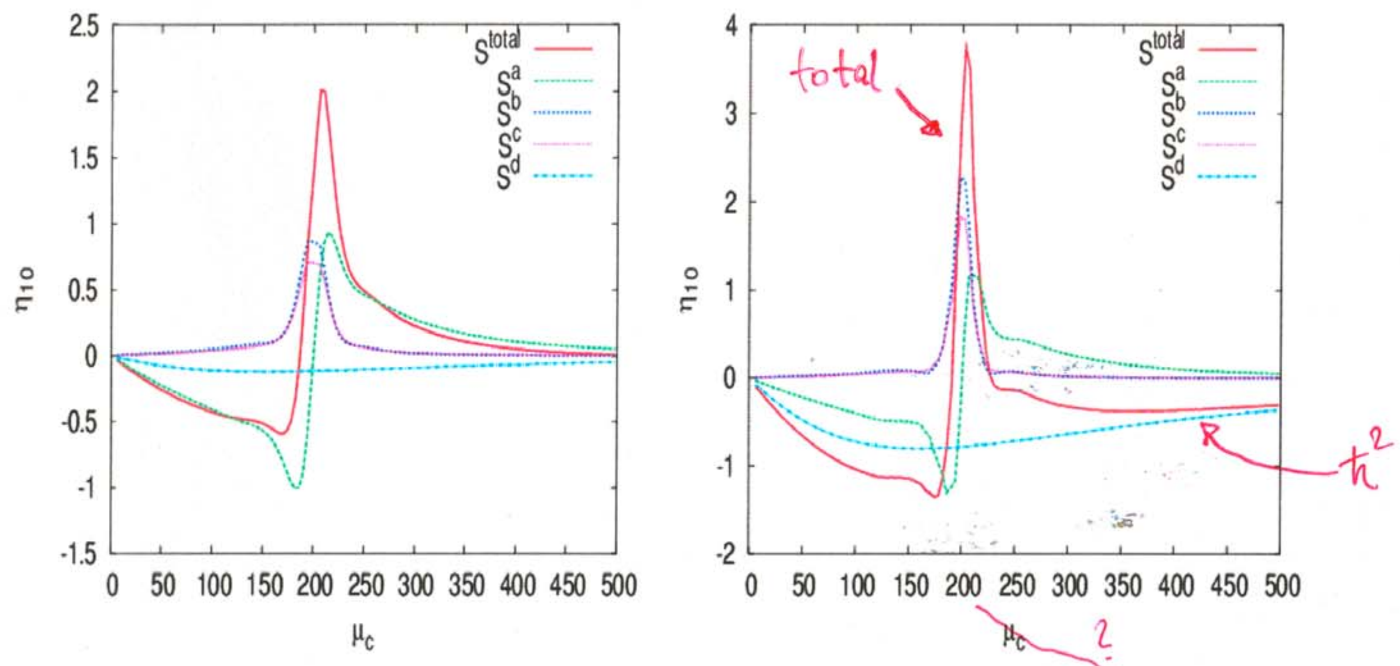


FIG. 2: This plot shows the first and second order sources as a function of μ_c with $M_2 = 200$ GeV. The plot on the left are the sources with the damping, $\Gamma = \alpha_w T_c$, while on the right plot, $\Gamma = 0.25\alpha_w T_c$.

MAXIMAL CP-VIOLATION ASSUMED

ELECTRIC DIPOLE MOMENT FROM MSSM

The current measurement bound of the electron electric dipole moment (EDM)

Regan et al, Phys. Rev. Lett. 88:071805, 2002

$|d_e|$ 1.6×10^{-27} ecm

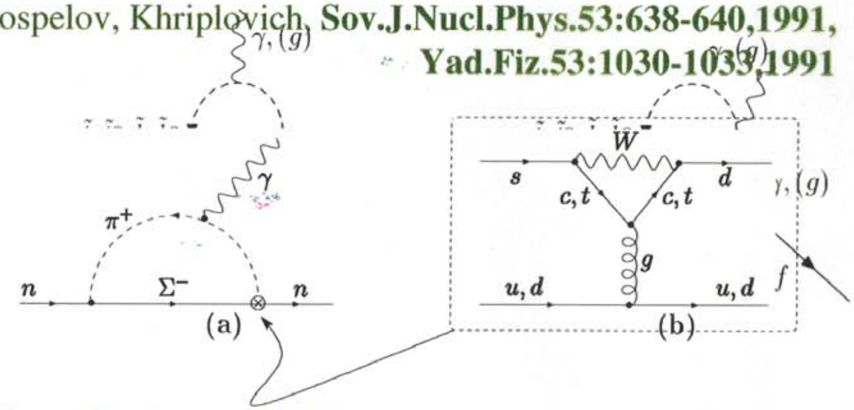
The standard model (MSM) value for eEDM (4 loop)

d_e^{CKM} 1×10^{-38} ecm

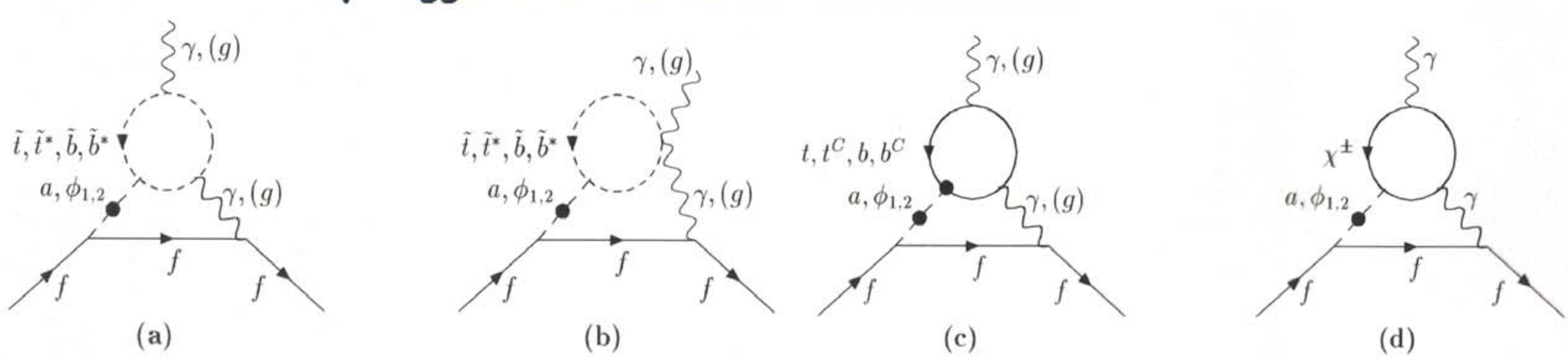
Pospelov, Khriplovich, Sov.J.Nucl.Phys.53:638-640,1991, Yad.Fiz.53:1030-1033,1991

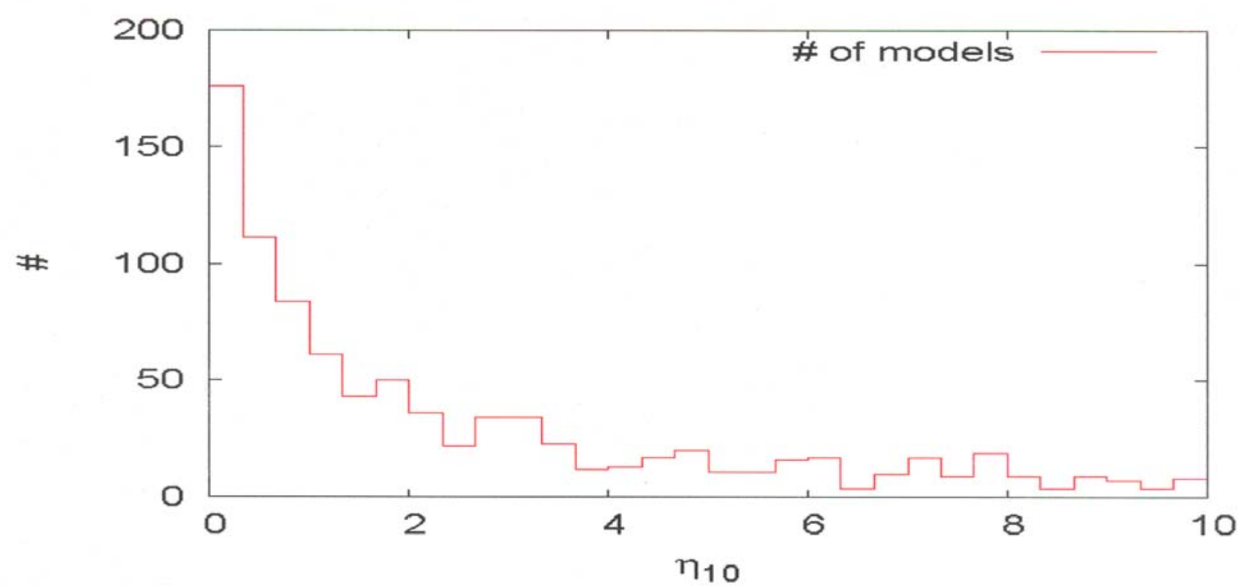
The standard model (MSM) value for neutron EDM (2 loop penguin)

$d_n^{CKM} \sim 1\times10^{-32}$ ecm



The MSSM 2 loop Higgs contribution for electron EDM





Produced baryon asymmetry in random nMSSM models.

HUBER '06
KONSTANDIN
PROKOPEC
SCHMIDT

- "COHERENT BARYOGENESIS" B. GARBRECHT, T. PROKOPEC, M.G. SCH.

  - SCALAR FIELD CONDENSATE ← WITHOUT B/L CHARGE!
    INDUCES TIME DEPENDENT
    MASS (MATRIX) IN COSMOLOGY
  - COHERENT PARTICLE PRODUCTION
    BY NONADIABATICAL TIME DEPENDENCE
    OF SCALAR COND.
  - CERTAIN CHARGE NUMBERS TRANS-
    FORMED TO B-L
  - ~~CP~~ OF MASS MATRIX ⇒
    ASYMMETRY ⇒ BARYON ASYM.

FRAMEWORK AGAIN! CONSIDER "QUANTUM BOLTZMANN EQS."

(SCHWINGER - KELDISH CTP ...)

⇒ MATRIX - EQS.

FOR FERMIONS / BOSONS

$\boxed{z \leftrightarrow t}$

WIGNER FUNCTIONS

(CLOSEST TO CLASSICAL PHASE SPACE DISTRIBUTIONS)

$$iG^<(k, \underline{\underline{x}})_{ab} = \int d^4r\, e^{ik\cdot r} \langle | \bar{\psi}_b(\underline{\underline{x}} - \tfrac{r}{2})\, \psi_a(\underline{\underline{x}} + \tfrac{r}{2}) | \rangle$$

a, b: species

$$(i\gamma^0 G^<)^+ = i\gamma^0 G^<$$

DIRAC-EQ. WITH TIME DEPENDENT MASS-MATRIX

$$\boxed{\left(\not{k} + \tfrac{i}{2}\gamma^0 \partial_t - (M_H(t) + i\gamma^5 M_A(t))\, e^{-\frac{i}{2}\overleftarrow{\partial_t}\partial_{k_0}}\right)_{ac} iG^<_{cb} = 0}$$

$$M_H = \tfrac{1}{2}(M + M^+)\ ; \quad M_A = \tfrac{1}{2i}(M - M^+)$$

- $M(t)$ AND $\frac{dM(t)}{dt}$ .. : CP-VIOLATING PHASES CANNOT BE SIMULTANEOUSLY REMOVED

BEYOND "JARLSKOG"

- THE HELICITY OPERATOR $\hat{h} = \hat{k}\cdot\gamma^0\vec{\gamma}\gamma^5$ COMMUTES WITH DIRAC-OPERATOR

SAME AS BEFORE WITH $z \rightarrow t$!

- DECOMPOSE

$$-i\gamma^0 G_h^< = \frac{1}{4}\left(\mathbb{1} + h\,\hat{\vec{k}}\cdot\vec{\sigma}\right) \otimes \rho^\mu\, g_{\mu h}$$

PAULI-M.

- PROJECT DIRAC-EQ. WITH ρ^μ
- TAKE 0-th MOMENT $\quad f_{\mu h} = \int_{-\infty}^{+\infty} \frac{dk_0}{2\pi}\, g_{\mu h}$

MATRIX EQS

$$\Rightarrow \boxed{\begin{aligned}
&\dot{f}_{0h} + i\left[M_H, f_{1h}\right] + i\left[M_A, f_{2h}\right] = 0\\
&\dot{f}_{1h} + 2h|\vec{k}|\, f_{2h} + i\left[M_H, f_{0h}\right] - \left\{M_A, f_{3h}\right\} = 0\\
&\dot{f}_{2h} - 2h|\vec{k}|\, f_{1h} + \left\{M_H, f_{3h}\right\} + i\left[M_A, f_{0h}\right] = 0\\
&\dot{f}_{3h} - \left\{M_H, f_{2h}\right\} + \left\{M_A, f_{1h}\right\} = 0
\end{aligned}}$$

EXACT (WITHOUT COLLISION T.)

INITIAL COND.: NO FERMIONS FOR $t \to -\infty$

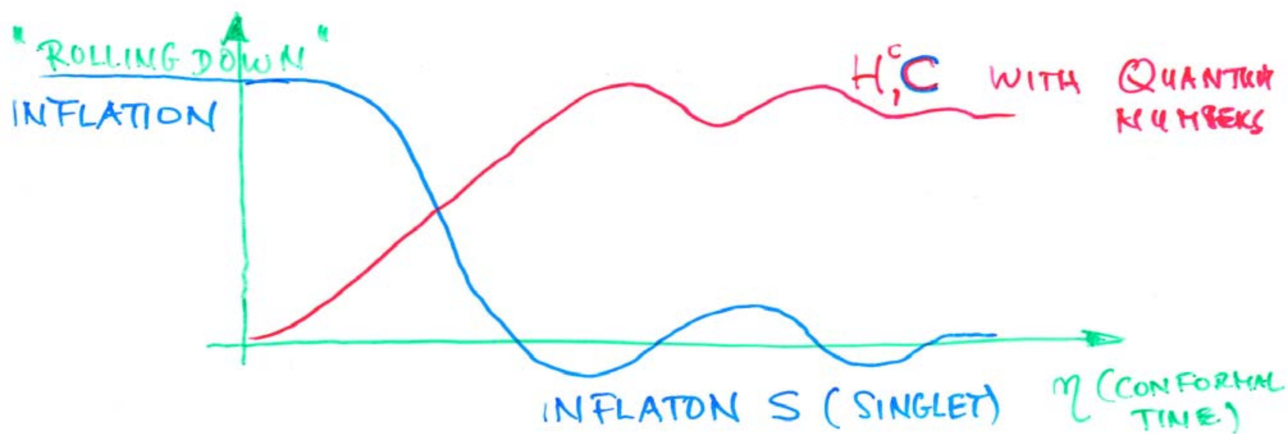
$\langle 0 | \dots | 0 \rangle$
HEISENB. P.

$f_{0h}^{aa}(|\vec{k}|, t)$ IS 0th COMPONENT OF VECTOR CURRENT

$\Rightarrow$ CHARGE OF MODE WITH MOM. k AND HELICITY h $= q_{ah}(k,t)$

$\sum_a q_{ah}(k,t)$ CONSERVED (YUKAWA INT. $\to U(1)$)

- APPLICATION : HYBRID INFLATION (SUPERSYM.)



GUT - WATERFALL

EXAMPLES :

- PATI - SALAM : $G_{PS} = SU(4) \times SU(2)_L \times SU(2)_R$ "COLOR"

$$\underbrace{SU(3)_C \times U(1) \quad U(1)}_{U(1)_Y}$$

- $SO(10) \longrightarrow SM$

$$W_{\text{SUPERPOT.}} \supset \kappa S\,(\bar{H}^c H^c - \mu^2) + \ldots$$ CP-VIOL. COUPLINGS

$\bar{C}\ C$

$H^c = (\bar{4}, 1, 2)$ $\quad$ $C = [16]$

PATI-SALAM $\quad$ SO(10)

HYBRID INFLATION

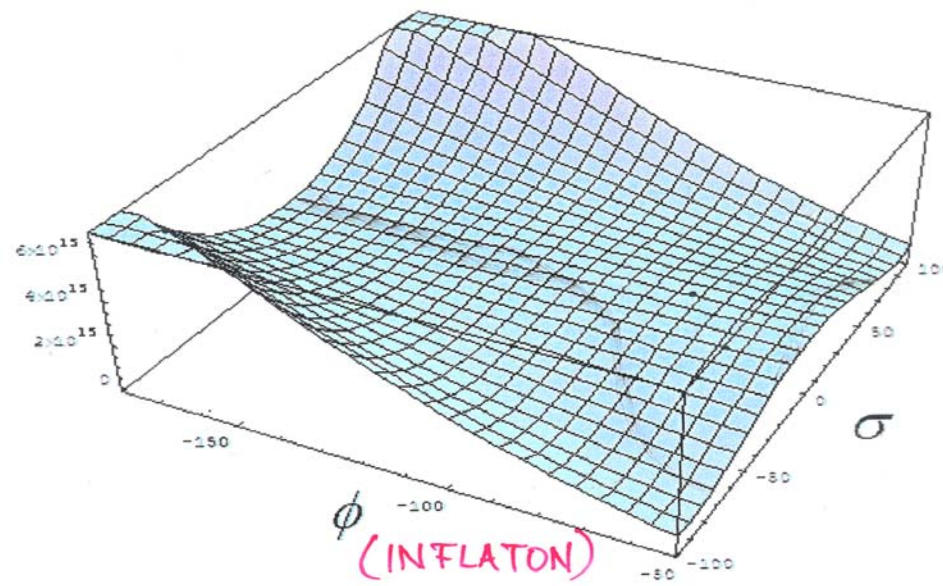


Figure 1: Hybrid Potential, using $m_{pl} = 10^9$, $\lambda = 10^4$, $g = 8 \cdot 10^3$, $m = 1.5 \cdot 10^{-5} m_{pl}$, and $M = 10^{-3} \cdot m_{pl}$.

ADISORN ADULPRAVITCHAI

SUPERSYMM. PATI-SALAM MODEL WITH HYBRID INFLATION

NEED B-L VIOLATION (OTHERWISE "SPHALERON WASH OUT")

- $G_{PS} = SU(4)_c \times SU(2)_L \times SU(2)_R \subset SO(10)$

$$SU(4)_c \Downarrow SU(3)_c \times U(1), \qquad SU(2)_R \Downarrow U(1)$$

JEANNEROT
KHALIL
LAZARIDES
SHAFI

SENOGUZ
SHAFI

- GUT-SECTOR

$$H^c = (\bar{4}, 1, 2) \qquad \bar{H}^c = (4, 1, \bar{2})$$

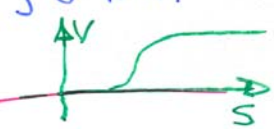
$$S = (1,1,1) \qquad G = (6_{as}, 1, 1) \to D_3 + \bar{D}_{\bar{3}}$$

$$H^c = \left.\underbrace{\begin{pmatrix} u^c_{H_1} & u^c_{H_2} & u^c_{H_3} & \nu^c_H \\ d^c_{H_1} & d^c_{H_2} & d^c_{H_3} & e^c_H \end{pmatrix}}_{SU(4)_c}\right\} SU(2)_R$$

"SMOOTH" HYBRID INFLATION

"INFLATON"

- $$W \supset \kappa\, S\left(\bar{H}^c H^c - \mu^2\right) - \beta S \left(\frac{\bar{H}^c H^c}{M_S}\right)^2 + \varphi\, G H^c H^c + \xi\, G \bar{H}^c \bar{H}^c + \kappa_G\, S G^2$$



POT. MIN. : $\langle G \rangle = 0$, $\langle \nu^c_H \rangle = \langle \nu^{c\,*}_{\bar{H}} \rangle$ (D-TERM!)

$$V = 2\Big|\underbrace{S}_{\neq 0}\, \nu^{c*}_H \underbrace{\left(\kappa - 2\beta \frac{|\nu^c_H|^2}{M_S^2}\right)}_{=0 \text{ DURING INFLATION}}\Big|^2 + \Big|\overbrace{\kappa\left(|\nu^c_H|^2 - \mu^2\right) - \beta \frac{|\nu^c_H|^4}{M_S^2}}^{=0 \text{ FOR SUSY-VAC.}}\Big|^2$$

- DIRAC FERMIONS

$$\chi_1 = \begin{pmatrix} -d^c_H \\ \overline{\overline{D}} \end{pmatrix} \qquad \chi_2 = \begin{pmatrix} -D \\ \bar{d}^c_H \end{pmatrix}$$

MASS - MATRIX $\quad (\bar{\chi}_1 \; \bar{\chi}_2) \begin{pmatrix} \cdots \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$

$$\begin{pmatrix} \mathrm{Re}\langle \nu^c_H \rangle \underline{\underline{\xi}} & (m_d + m_G)/2 \\ (m_d + m_G)/2 & \mathrm{Re}\langle \nu^c_H \rangle \underline{\underline{\xi}} \end{pmatrix} + i\gamma^5 \begin{pmatrix} -\mathrm{Jm}\langle \nu^c_H \rangle \underline{\underline{\xi}} & i(m_d + m_G)/2 \\ -i(m_d - m_G)/2 & -\mathrm{Jm}\langle \nu^c_H \rangle \underline{\underline{\xi}} \end{pmatrix}$$

$m_d = \langle S \rangle \left(\kappa/2 - \beta \langle |\nu^c_H| \rangle^2 / M_S^2 \right) \qquad m_G = 4\kappa_G \langle S \rangle$

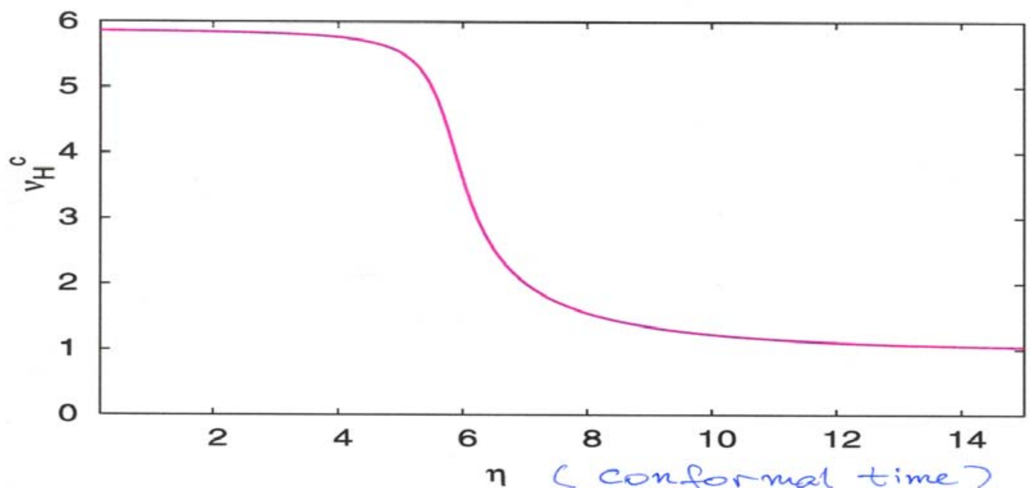
$\rightarrow 0$ FOR SUSY-MINIMUM $(S \rightarrow 0)$

- FOR $\xi \neq \xi^*$: GENERATE CHARGE $q_1 = -q_2$ $\rightarrow$FIG.
  ($\langle \nu^c_H \rangle$ REAL CONV.) (summed over color)
- B-L ASYMMETRY GENERATED IN $\chi_{1,2}$ DECAY TO ORDINARY MATTER

$F^c = (\bar{4}, 1, 2)$ LEPTONS + (R.H) QUARKS

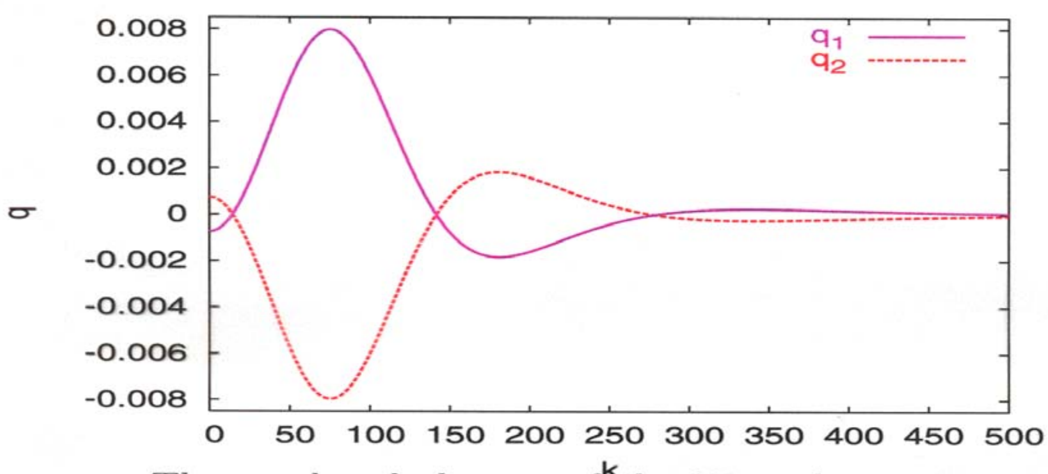
$$= \begin{pmatrix} u_1^c & u_2^c & u_3^c & \nu^c \\ d_1^c & d_2^c & d_3^c & e^c \end{pmatrix} \leftarrow \text{MAJORANA-NEUTRINO}$$

Coherent Baryogenesis in Hybrid Inflation



(conformal time)

Evolution of the field ν_H^c.



The produced charges of the Dirac fermions χ_{1j}, χ_{2j}, summed over both helicities.

CP

$\kappa = 0.007$ $\beta = 1$	$\mu = 2.0 \times 10^{16}\mathrm{GeV}$	$\zeta = 0.12i$ $\xi = 0.12$	$M_S = 50\mu$ $\Gamma = 0.1\mu$

REALISTIC PARAMETERS OF SENOGUZ/SHAFI - INFLATION

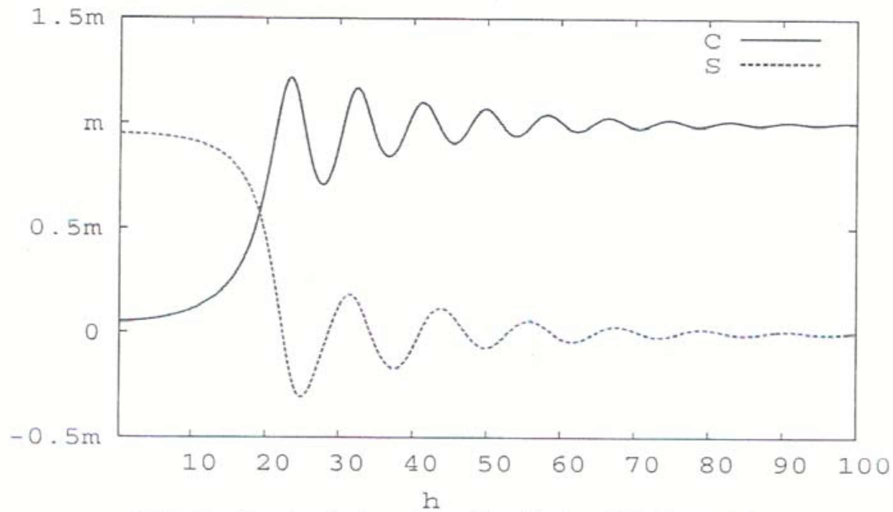


FIG. 1: Epoch of phase transition in the SO(10)-model

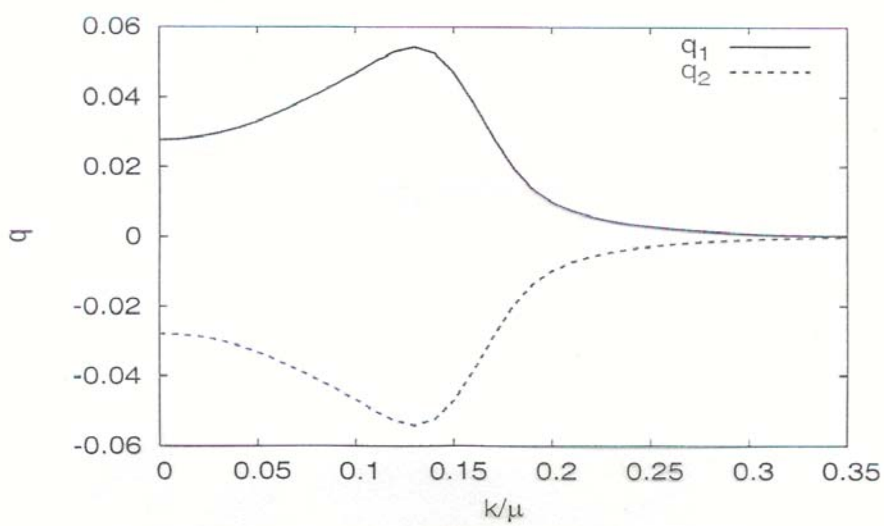


FIG. 2: The produced charges for the multiplet $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$.

- COUPLINGS

(i) $\gamma \underbrace{F^c \bar{H}^c}_{\text{SINGLET}} F^c \bar{H}^c / M_s$ → MAJORANA MASS FOR ν

$\chi_1 \Rightarrow$ $d^c_{\bar{H}} \xrightarrow[\langle \nu^c_{\bar{H}} \rangle]{} d + \nu_{\text{MAJORANA}}$

SCALAR FERMION

NO ~~CP~~ DECAY REQUIRED AS IN LEPTOGENESIS! (WITH TREE - ONE LOOP INTERFERENCE)

(ii) $\delta\, F^c H^c F^c H^c / M_s$

$\epsilon^{\cdots\cdot}$

$\epsilon^{\cdot\cdot}$

$\chi_2 \Rightarrow$ $\overline{d^c_H} \xrightarrow[\langle \nu^c_H \rangle]{} \bar{u}\ \bar{d}$

$\rightsquigarrow$ $B\text{-}L = -\frac{2}{3} q_2 + \frac{1}{3} q_1 = q_1$

AFTER SPHALERON PROCESSES

$$B = \frac{10}{31}(B-L)$$

ESTIMATE

VACUUM ENERGY $\rho = \left[\kappa^2 \frac{M_s^2}{4\beta} - \kappa\mu^2\right]^2 \rightsquigarrow \pi^2 g^* T_R^4/30$

$S < 2\pi^2 g^* T_R^3/45$

$B/n_\gamma > 10^{-10}$ EASILY

DETAILED REHEATING CALCULATION

$$\boxed{\frac{n_B}{s} = \frac{3}{4}\,\frac{n_B^{(0)}\,T_R}{V_0} \simeq 1\times 10^{-10}} \quad (*)$$

MORE DETAILED EVALUATION

$n_B^{(0)} \sim 1.5\ 10^{45}\ \mathrm{GeV}^3$ baryonic density produced at preheating (sum. q from fig. $\times 3$ (colors) $\times \frac{1}{3}$ (sphal.))

$T_R = \left(\frac{90}{\pi^2 g^*}\right)^{1/4} \sqrt{\Gamma M_{Pl}} \sim 2.7 \cdot 10^9\ \mathrm{GeV}$ REHEATING TEMPERATURE

WITH $\Gamma \sim \frac{1}{8\pi} m_{\nu_{H}^c} \left(\gamma_1 \langle \nu_H^c \rangle / M_S\right)^2 \sim 15\ \mathrm{GeV}$

INFLATON DECAY

$\langle \nu_H^c \rangle \to M_1$ MAJOR. NEUTRINO MASS ; $m_{\nu_H^c} \sim 4 \cdot 10^{14}\ \mathrm{GeV}$

V_0 ENERGY DENSITY AFTER INFLATION $\simeq 3 \cdot 10^{64}\ \mathrm{GeV}^4$

$s = 2\pi^2 g^* T_R^3/45$ ENTROPY DENSITY

$(*)$ $n_B/s = n_B^{(0)}/s \ \underbrace{\left(\frac{a_0}{a_R}\right)^3 \left(H_R/H_0\right)^2}$ MATTER DOMINANCE

$H_0^2 = \frac{1}{3} V_0/m_{Pl}^2 \qquad H_R^2 = \pi^2 g^* T_R^4/30\,/3m_{Pl}^2$

- NONTHERMAL LEPTOGENESIS (IN SAME MODEL)

$\langle \nu_H^c \rangle \to$ MAJORANA NEUTRINO MASS AFTER PREHEATING

$\left.\begin{array}{l} \text{LIGHTEST MASS } M_1 = 3.9 \times 10^{10}\ \text{GeV} \\ \qquad \text{COMPARE } T_R \sim 2.7 \cdot 10^{9}\ \text{GeV} \end{array}\right\}$ NONTHERMAL!

MAXIMAL MIXING AND CP VIOLATION VIA
1-LOOP INTERFERENCE

$$\frac{n_L}{s} \lesssim 3 \cdot 10^{-10} \frac{T_R}{m_{\nu_H^c}} \left(\frac{M_1}{10^6\,\text{GeV}}\right)\left(\frac{m_{\nu_3}}{0.04\,\text{eV}}\right)$$

$$\approx 8 \times 10^{-11}$$

$\Rightarrow \frac{n_B}{s} \lesssim 3 \times 10^{-11}$ SMALLER! (SENOGUZ / SHAFI)

CONCLUSIONS

- MODELS FOR THE GENERATION OF A BARYON ASYMMETRY HAVE TO COMBINE DETAILED INFORMATIONS FROM ELEM. PARTICLE PHYSICS, COSMOLOGY, AND QUANTUM (AT LEAST $\hbar$) TRANSPORT THEORY
- TRY TO NARROW DOWN TO MODELS EXPLAINING ALSO OTHER FEATURES IN COSMOLOGY (INFLATION...) AND ELEM. PARTICLE PHYSICS (GUT'S ...)
- MOST ASPECTS: <u>BEYOND</u> THE SM!
- COMMON FEATURE: $B+L \Rightarrow 0$ BY HOT SPHALERON IN EQUILIBRIUM
- B-GENERATION
  - * IN (MODIFIED) ELECTROWEAK THEORY AT PHASE BOUNDARY
  - * AT GUT / INFLATION ENERGIES BY NONEQUILIBRIUM AND L-VIOLATING MAJORANA NEUTRINOS

TRANSPORT!

EXITING FIELD AT THE BORDERLINE BETWEEN COSMOLOGY AND ELEM. PARTICLE PHYSICS