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BARYOGENESIS

THE ORIGIN OF MATTER IN OUR UNIVERSE

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COSMOLOGY / ASTROPHYSICS $\Leftrightarrow$ ELEMENTARY PARTICLE PHYSICS

WEINBERG "FIRST THREE MIN."

NEW OBSERVATIONS

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

THEORETICAL EXPLANATIONS

INFLATION ⇝ FLUCTUATIONS → STRUCTURE FORMATION

DARK MATTER / ENERGY → STRUCTURE FORMATION

STILL NOT VERY SPECIFIC HINTS FOR ELEM. PARTICLE PHYSICS

- BARYON ASYMMETRY

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} = \left(6.1 \pm {}^{0.4}_{0.3}\right) 10^{-10}$$ FROM WMAP

IN AGREEMENT WITH PRIMORDIAL NUCLEOSYNTHESIS

STRONGER CONNECTION TO ELEM. P. PHYSICS

(BEYOND THE SM NEEDED !?)

ESTIMATE OF n_B

- STAR MATTER (LUMINOUS) GAS CLOUDS ....

- EARLY NUCLEOSYNTHESIS OF LIGHT ELEMENTS

$p + e^- \leftrightarrow n + \gamma$

$n + p \leftrightarrow D + \gamma$ Deuterium ($T > 10^6$ eV $\sim 10^{10}$ °K, $t > 1$ sec)

$D + D \leftrightarrow {}^4He + \gamma$ Helium

$D + p \leftrightarrow {}^3He + \gamma$

$D + n \leftrightarrow {}^3H + \gamma$ Tritium

⋮

Lithium

MORE RECENT

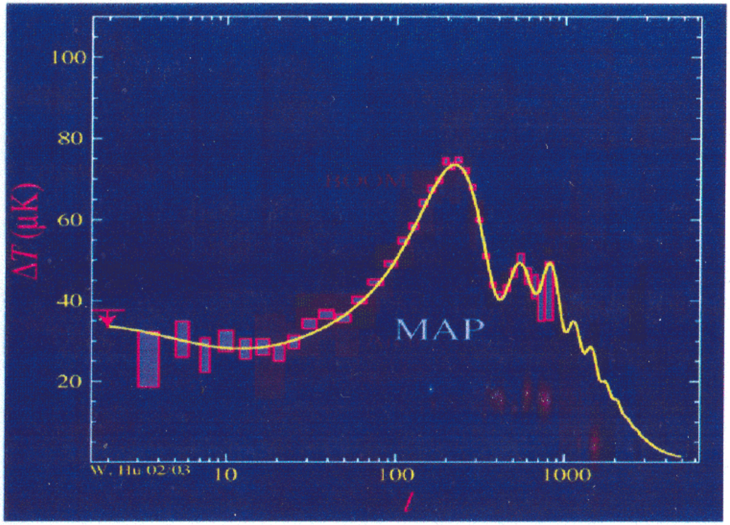
- POSITION AND HEIGHT OF ACOUSTIC PEAKS IN DISTRIBUTION OF ΔT-FLUCTUATIONS OF THE COSMIC MICROWAVE BACKGROUND (WMAP-Data)

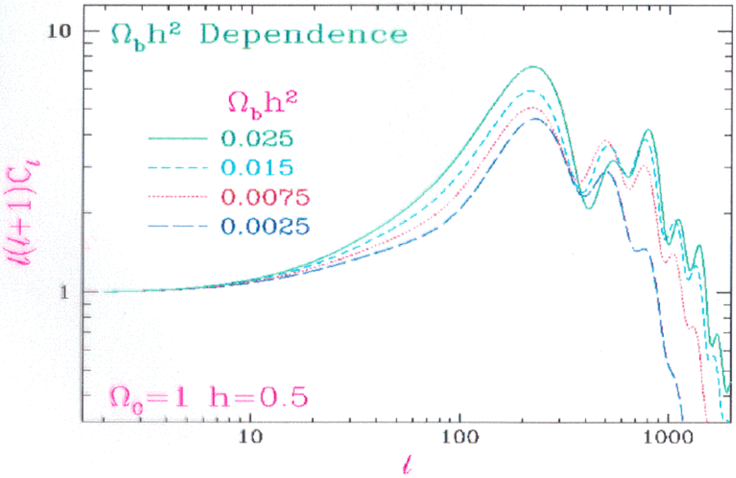
$\Omega_B \sim 0.04$!

($\Omega_{Lum} \lesssim 0.01$)

n_B INFLUENCES SOUND VELOCITY AT RECOMBINATION TIME !

Baryonic matter and cmbr





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

INFLATION

- SOLVES CAUSALITY PROBLEM IN BIG BANG TH.
- $\Omega = 1$ $(\rho = \rho_c)$
  FLAT UNIVERSE
- CREATES FLUCTUATIONS LEADING TO STRUCTURE FORMATION

NO PARTICLES LEFT AFTER EXPONENTIAL GROWTH

HAVE TO CREATE BARYON ASYMMETRY

$n_B \sim \Delta n_B = n_B - n_{\bar{B}}$ ~~$n_{\bar{B}}$~~ SMALL $\frac{n_{\bar{B}}}{n_\gamma} \lesssim 10^{-18}$

AFTER PAIR ANNIHILATION

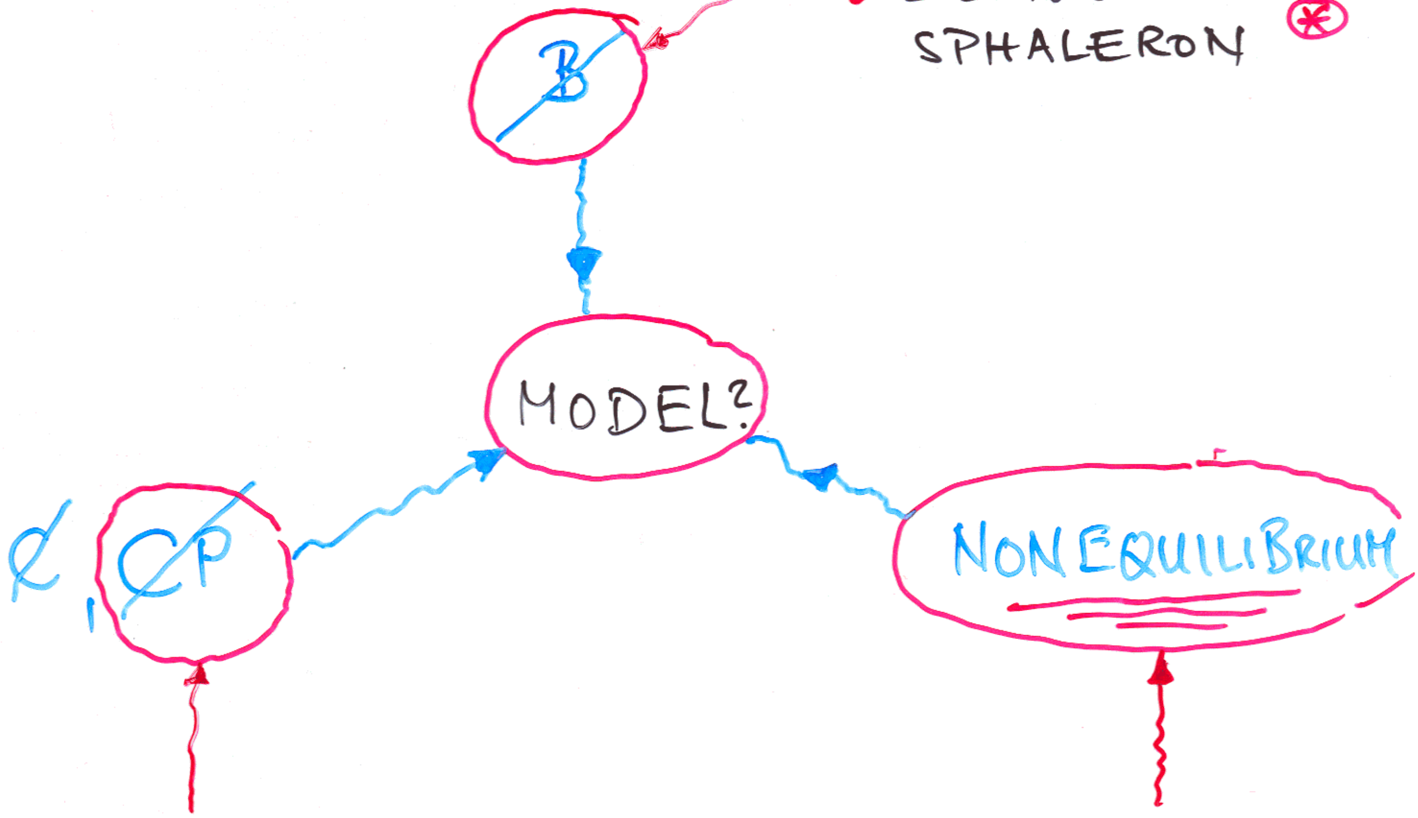
SAKHAROV NECESSARY CRITERIA

- B-VIOLATION ✓ (→ KOLB WOLFRAM...)
- C, CP-VIOLATION
  In the absence of preference for matter/antimatter B nonconserving reactions will produce B and $\bar{B}$ at the same rate
- NONEQUILIBRIUM
  Chemical potential for nonconserved q.n. vanishes
  $m_B = m_{\bar{B}}$ (CPT) → same thermal distribution

- BARYOGENESIS

SAKHAROV '67

- GUT, MAJORANA NEUTR. ($\not L$)
- ELECTROWEAK SPHALERON ⊛



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

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

⊛ POSSIBLE IN SM?

SHAPOSHNIKOV

PROGRAM

SOME IMPORTANT MODELS

- ELECTROWEAK BARYOGENESIS (SM, MSSM, NMSSM nMSSM)
- LEPTOGENESIS
- AFFLECK-DINE BARYOGENESIS
- COHERENT BARYOGENESIS
- COLD BARYOGENESIS ALMOST THE SM

TECHNICAL POINTS NEEDED

- ~~STANDARD~~ short MODEL
- SPHALERON TRANSITION (always needed)
- THERMAL HISTORY ~~OF~~ short UNIVERSE (always needed)
- PHASE TRANSITION (ELWK.)
- ~~SUPER~~ short SYMMETRY
- TRANSPORT EQS. (~~BOLTZMANN~~ short ...)
- MAJORANA NEUTRINOS

- ELECTROWEAK THEORY

INSIDE THE STANDARD MODEL

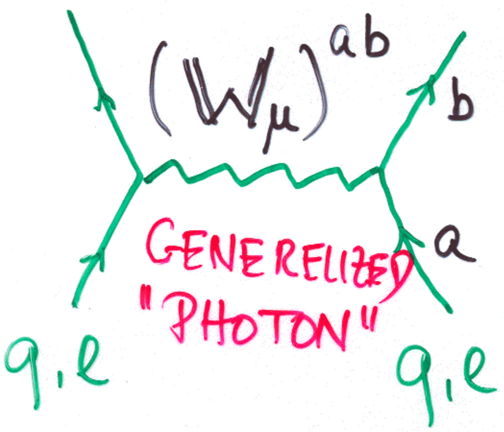
OF ELEMENTARY PARTICLE PH.

THREE GENERATIONS OF QUARKS AND LEPTONS

$$3\times \quad \begin{pmatrix}\nu \\ e^-\end{pmatrix}_{\text{LEFT HANDED}}, \quad \begin{pmatrix}u \\ d\end{pmatrix}^{a=1,2,3\ (\text{COLOR})}_{L}, \quad e^-_R,\ u^a_R,\ d^a_R$$

TABLE

WEAK (ELWK) FORCES MEDIATED BY WEAK GAUGE BOSONS COUPLING TO L.H. QUARKS + LEPTONS



$\underline{a,b=1,2}$

$$SU(2)_{\text{WEAK}} \times U(1)_Y \times SU(3)_{\text{COLOR}}$$

MIXING

$$W_\mu = \sum_{i=1}^{3} W_\mu^i \tau_i \ ; \qquad \mathcal{L} = \frac{1}{2}\operatorname{tr} F_{\mu\nu}F^{\mu\nu}$$

The Fundamental Fermions

(a) Leptons

Lepton	**Symbol**	**Charge (e)**	**Mass (GeV/c^2)**
Electron	e^-	−1	$5{\cdot}1099906(15) \times 10^{-4}$
e-Neutrino	ν_e	0	$<1.8 \times 10^{-8}$
Muon	μ^-	−1	0.10565839(6)
μ-Neutrino	ν_μ	0	$<2.5 \times 10^{-4}$
Tau	τ^-	−1	1.7841(32)
τ-Neutrino	ν_τ	0	$<3.5 \times 10^{-2}$

(b) Quarks

Quark flavor	**Symbol**	**Charge (e)**	**Mass (GeV/c^2)**
Down	d	$-\frac{1}{3}$	0.008
Up	u	$\frac{2}{3}$	0.004
Strange	s	$-\frac{1}{3}$	0.15
Charm	c	$\frac{2}{3}$	1.2
Bottom	b	$-\frac{1}{3}$	4.7
Top	t	$\frac{2}{3}$	$\gtrsim 40$

The masses are given in the usual particle-physics units $1\ \text{GeV}/c^2 = 1.782662 \times$

The Fundamental Bosons

Name	**Symbol**	**Spin ($\hbar$)**	**Mass (GeV/c^2)**	**Charge (e)**
Graviton	G	2	0	0
Photon	γ	1	0	0
Charged weak bosons	$W^\pm$	1	81.0(1.3)	±1
Neutral weak boson	Z	1	92.4(1.8)	0
Gluons	$g_1, \ldots, g_8$	1	0	0
Higgs	H	0	?	0

$$F_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g_{WEAK} [W_\mu, W_\nu]$$

LIKE IN E-DYN. BUT WITH SELFCOUPLING

! MASSIVE W-BOSONS (FIELD / PARTICLES)

(~ 80 GEV) → "WEAK" INTERACTION

COUPLING TO A DOUBLET OF COMPLEX SCALAR "HIGGS" FIELDS $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ WITH A (CLASSICAL!) (AMPLITUDE)^2:

$\langle \phi^+ \phi \rangle$

GAUGE COUPL. g_w^2

→ LATER!

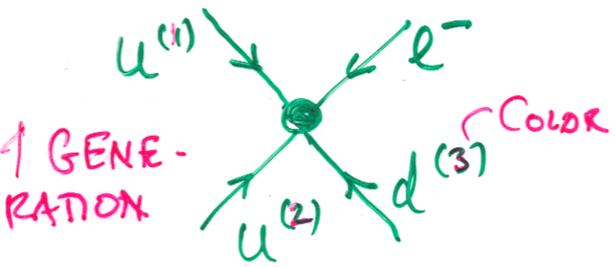
- PHASE TRANSITIONS

→ THERMODYNAMICS, STATISTICAL MECHANICS

GINZBURG - LANDAU THEORY ... HUANG, SCHWABEL

• SPHALERON TRANSITION IN ELWK.TH

$SU(2)_{WEAK}$ HAS TOPOLOGICAL NONTRIVIAL GAUGE FIELD CONFIGURATIONS (WINDING NUMBERS, CHERN-SIMONS NUMBER....) INDUCING TUNNELING BETWEEN QUARK- AND LEPTON DOUBLETS, VIOLATING B+L

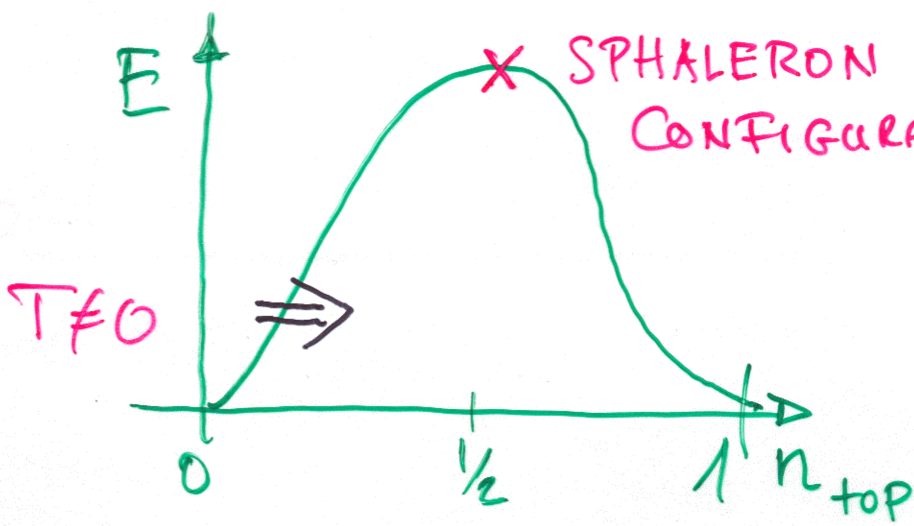


INSTANTON INDUCED AT T=0

$$e^{-8\pi^2/g_w^2}$$

Instanton action

ALSO: THERMAL TRANSITION VIOLATES B+L



$\phi(T)/T$

$$\Gamma \sim T^4 e^{-\frac{m_W(T)}{\alpha_W kT}}$$

UNSUPPRESSED IN HOT PHASE WITH $\phi(T)=0$

SOME ARGUMENTS FOR B+L VIOLATION

- QUANTUM ANOMALY

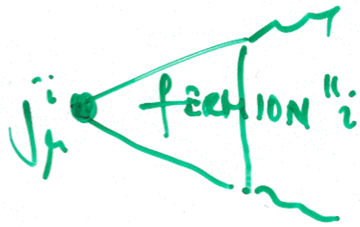
$$\int d^4x\, \partial_\mu (\underbrace{\bar{\psi}_L^i \gamma^\mu \psi_L^i}_{j_\mu^i}) = \frac{1}{64\pi^2} \int d^4x\, F_{\mu\nu}^A \tilde{F}^{\mu\nu A}$$

U(1) CURRENT OF $SU_W(2)$ DOUBLETS

GAUSS $= Q^i(+\infty) - Q^i(-\infty)$

CHANGE IN TOPOLOG- QUANTUM NUMBER

$n = (1), 2, \ldots$ instanton



- $(\partial_\mu \mathbb{1} + i g A_\mu)\psi_\lambda = \lambda \psi_\lambda$ (with D_μ marked over the operator) DIRAC EIGENFUNCTIONS

$\#\ \lambda = 0$ ZEROMODES $= \#$ TOPOL. QUANTUM NUMBER OF A_μ (ATIYA-SINGER)

$$\int [d\psi]\, e^{i\int L(\psi)}$$

(GRASSMANN)

$$\psi = \sum_{\lambda \neq 0} c_\lambda \psi_\lambda + c_0 \psi_0$$

(GRASSMANN!)

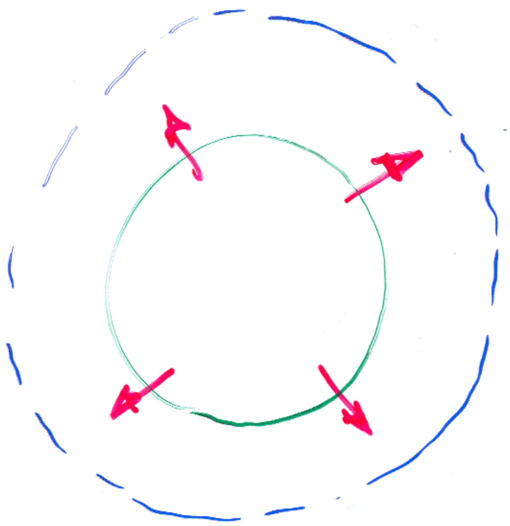
$$= \prod_{\lambda \neq 0} \int dc_\lambda \int dc_0\, e^{\text{"}c_0 \text{ indep."}} \overset{!}{=} 0$$

NEED FURTHER C_0

- THE EARLY UNIVERSE

How to reach the temperature of the electrow. P.T. ?

- IT IS HOMOGENEOUS
- IT COOLS DOWN IN EXPANDING
- IT WAS <u>VERY</u> HOT!



T_γ TODAY ~ 2.7°K

- A SHORT STORY OF THE (VERY) EARLY UNIVERSE AND BARYOGENESIS

- EINSTEIN EQ. IN SYMM. UNIVERSE (Robertson-Walker)

- RADIATION DOMINANCE

$$\left[\begin{array}{l} H^2 = \left(\frac{\dot{R}(t)}{R}\right)^2 = \frac{K}{8}\,\rho_{RAD} \quad (\sim T^4) \\ \rho_{RAD}\,R^4 = C \quad (\rho_{RAD} \sim T^4) \end{array}\right.$$

STEFAN-BOLTZMANN

$\rightsquigarrow$ "RT-LAW"

$$R(t) = \left(\frac{4KC}{3}\right)^{1/4} t^{1/2}$$

$$RT \sim \text{const.} \qquad T \sim t^{-1/2}$$

$1\ \text{GeV} \sim 10^{13}\ {}^\circ K$

100 keV $\xrightarrow{\times 10^6}$ 100 GeV

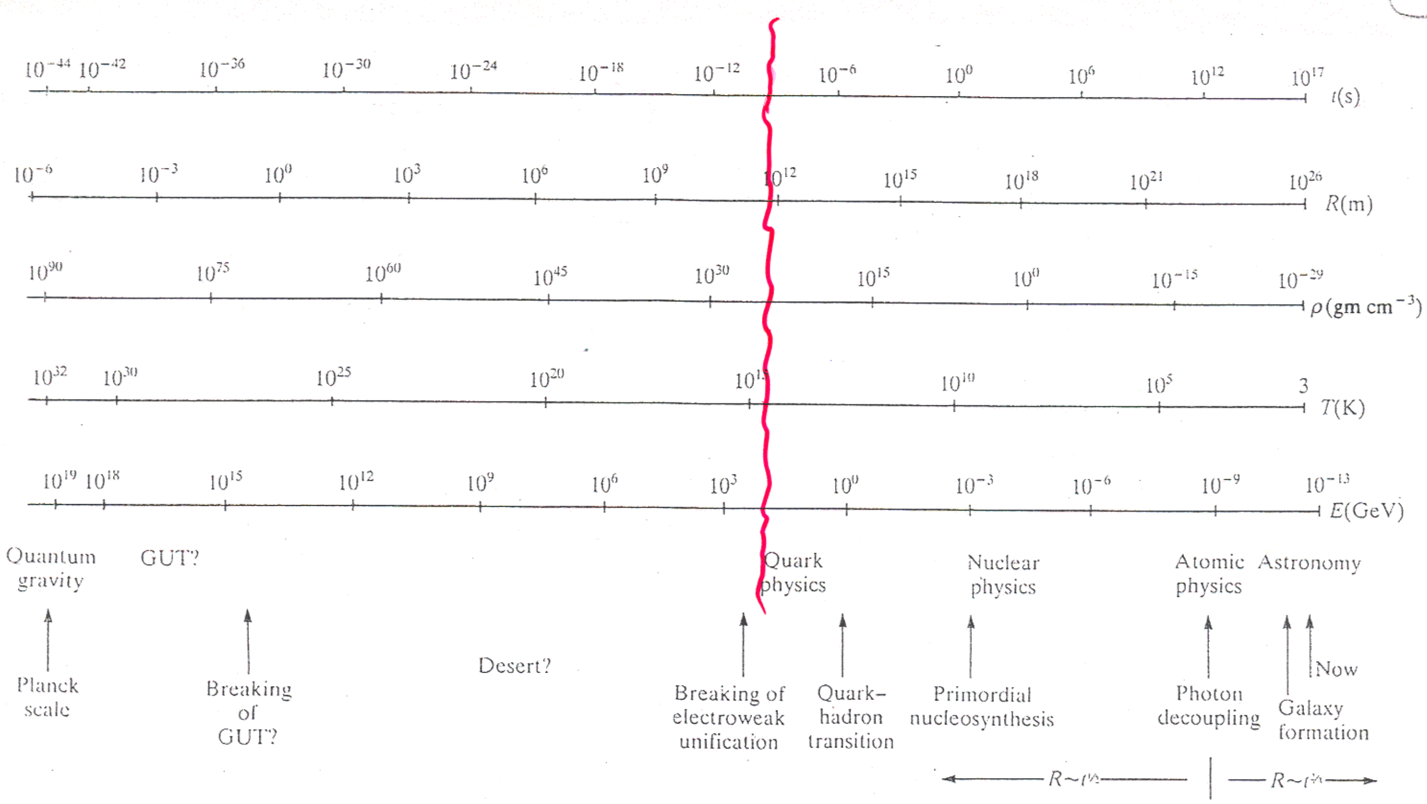
"FIRST THREE MINUTES" sec (WEINBERG)

10^{-12} sec

STILL LABORATORY ENERGY

$R \sim 10^{13}$ cm

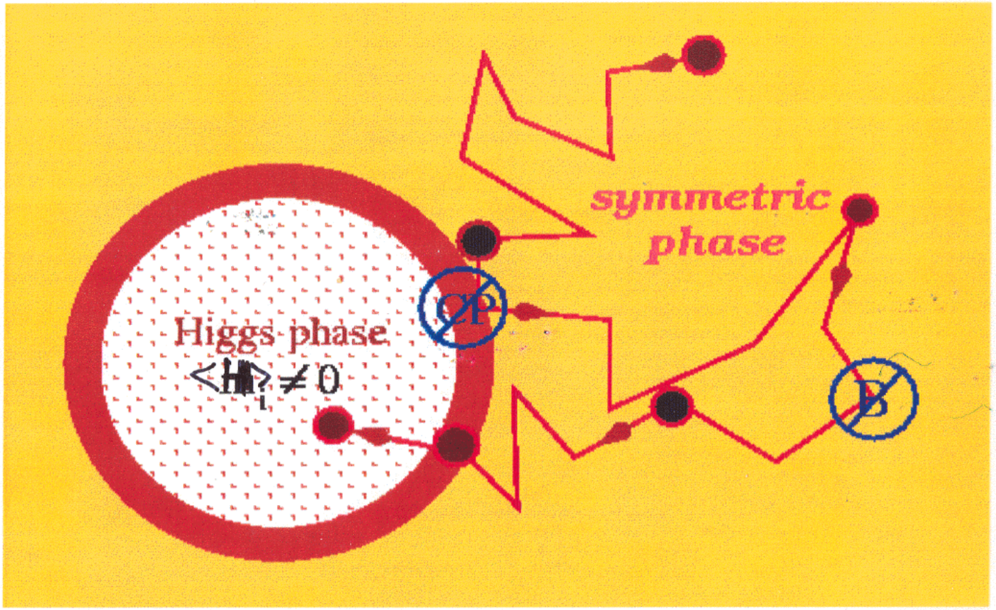
$$\Omega = \rho/\rho_c \qquad \rho_c = 3H^2/8\pi G$$



The "history" of the universe from the Planck time to the present, showing how the size of the presently observable universe R, the average density ρ, the temperature T, and the energy per particle kT, have varied with time t according to the hot big bang model. Some of the major "events" and the dominant type of physics in each epoch are indicated.

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)

NEED
- STRONG B-VIOLATION IN HOT ("UNBROKEN") PHASE
- FREEZOUT OF B-VIOLATION IN LOW TEMPERATURE ("HIGGS") PHASE ($\Gamma_{SPH} < H$)

⇒ STRONG FIRST ORDER P.T.

! IT TURNED OUT THAT IN THE SM THERE IS NO STRONG 1. ORDER P.T.

→ LATER

BUT : POSSIBLE IN VARIANTS OF THE SM:

"BEYOND THE SM"

MSSM MINIMAL SUPERSYMMETRIC SM

NMSSM NEXT TO ...

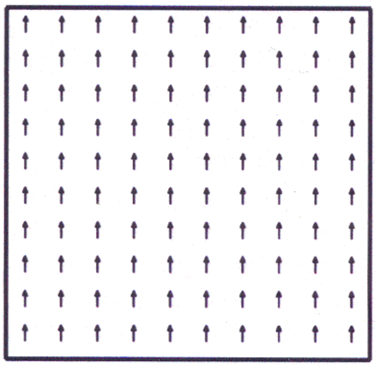
nMSSM NEARLY ...

2-HIGGS MODELS

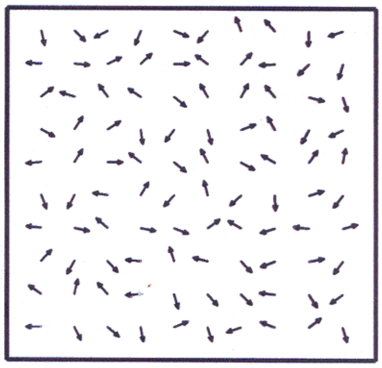
COSMOLOGY MIGHT REQUIRE TO MODIFY THE SM ANYWAY!

Symmetry Restoration

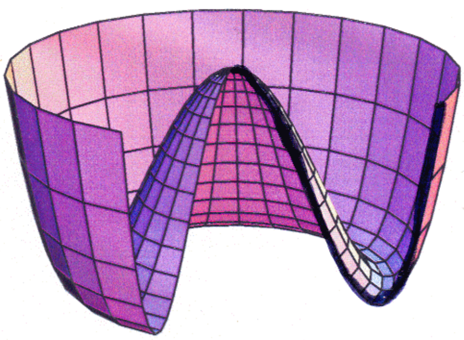
Low Temperature



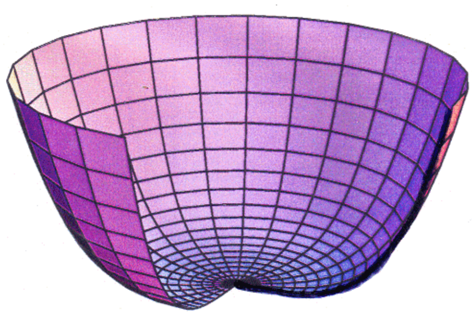
High Temperature

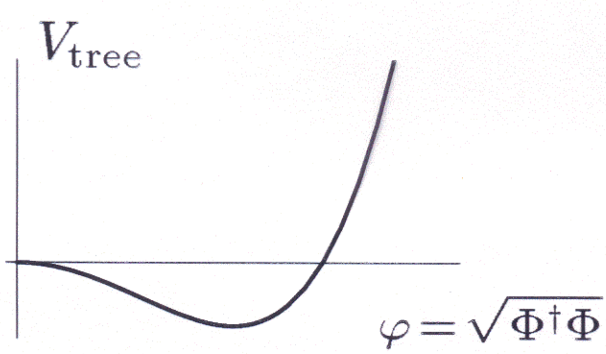


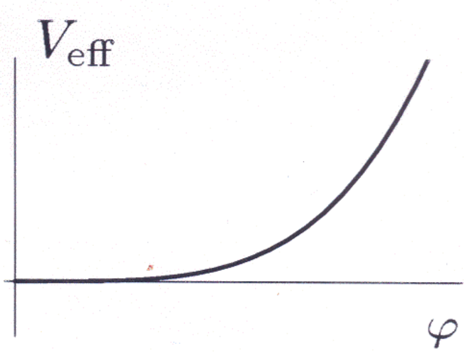
Broken Symmetry



Restored Symmetry

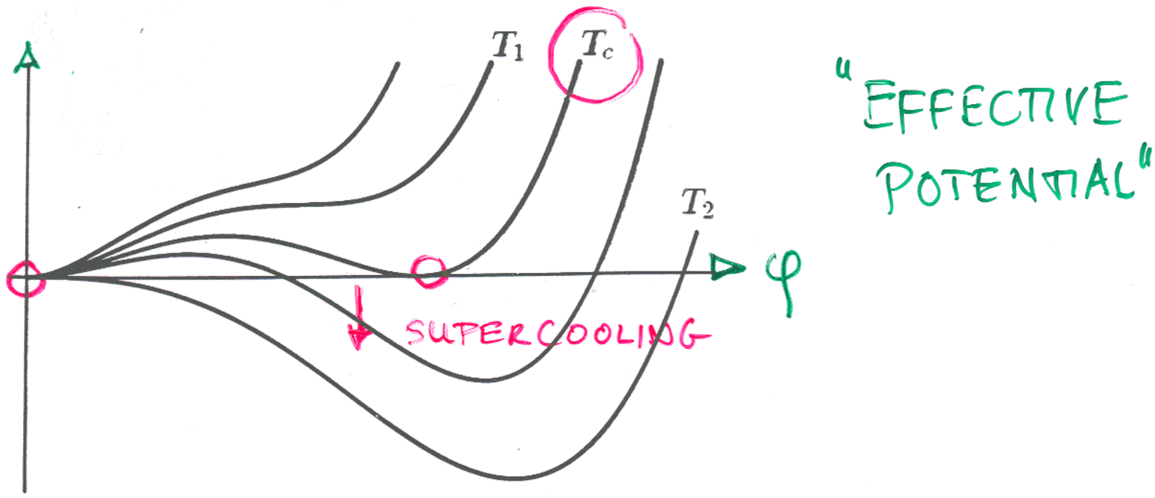






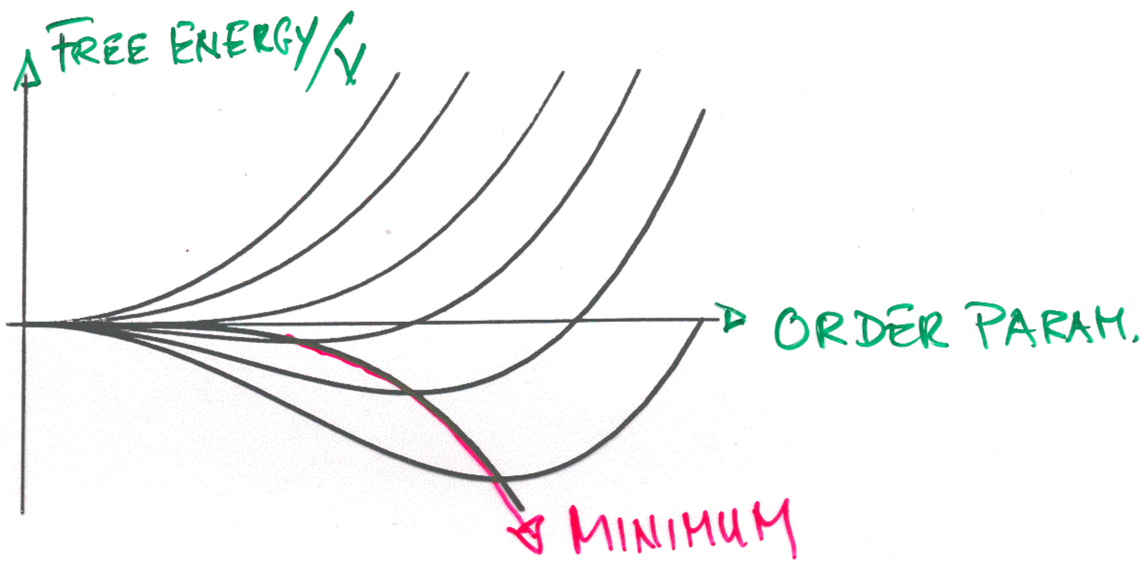
First Versus Second Order

first order:



The field value at the global minimum jumps at the critical temperature (bubble nucleation).
There are deviations from the thermodynamic equilibrium.

second order:

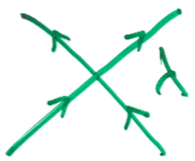


The field value at the global minimum departs continuously from 0 at the critical temperature.

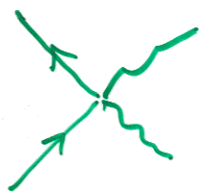
THE EFFECTIVE HIGGS POTENTIAL AT $T \neq 0$

"TREE" COUPLING

$\mu^2 \phi^+ \phi$



$\frac{\lambda}{4} (\phi^+ \phi)^2$



$g_w^2 A_\mu^2 \phi^+ \phi$ $\qquad m^2_{\text{GAUGE B.}} = \frac{1}{4} g_w^2 \langle \phi^+ \phi \rangle$

$$\phi = \underbrace{\langle \phi \rangle}_{\text{CLASSICAL}} + \phi_Q$$

SIMPLE : CALCULATE GRANDCANONICAL POT. OF GAUGE BOSONS (+ HIGGSES...)

$$Z_J = \sum_{N=0}^{\infty} \sum_{\{n_{\vec p}\}, \sum_p n_{\vec p} = N} e^{-\beta (E\{n_{\vec p}\} - \mu N)} \qquad \mu \to 0$$

$$\beta = \frac{1}{kT}$$

$$E\{n_{\vec p}\} = \sum_{\vec p} n_{\vec p} \left(\epsilon_{\vec p} = (m_G^2(\phi) + \vec p^2)^{1/2} \right)$$

$$Z_J = \prod_{\vec p} \sum_{n_{\vec p}=0}^{\infty} e^{-\beta(\epsilon_{\vec p} - \mu) n_{\vec p}} = \prod_{\vec p} \frac{1}{1 - e^{-\beta(\epsilon_p - \mu)}}$$

"QUANTUM BOSON GAS"

$$\mu = 0$$

$$J = -\frac{1}{\beta} \ln Z_J = V_1(\phi) =$$

$$= \frac{1}{\beta} \int \frac{d^3p}{(2\pi)^3} \ln\left(1 - e^{-\beta\left(m_G^2(\phi) + \vec{p}^2\right)^{1/2}}\right)$$

$$= \underbrace{\ldots T^4}_{\text{STEFAN-BOLTZMANN}} + \ldots T^2 m_G^2(\phi) - \ldots T \left(m_G^2(\phi)\right)^{3/2}$$

$$- \ldots m_G^4 \ln \frac{m_G^2}{T^2} + \ldots$$

$\sim + g_w^2 \, \phi^+ \phi \, T^2$! "$-\phi^3$-TERM"

REMEMBER

$$V = V_0 + V_1$$

FIRST ORDER P.T. ?

SIMILAR: "DEBYE" MASS $\sim g^2 T^2$
OF LONGITUDINAL GAUGE BOS. ("A_0")
NOT OF TRANSVERSAL

MORE CLEAN: THERMO FIELD THEORY

DISCUSS INFRARED-BEHAVIOR WITH MASSLESS TRANSV. GB! $\phi \to 0$

COMPARE

$$Z = \mathrm{tr}\,\rho = \sum_n \langle n | e^{-\beta H} | n \rangle$$

WITH QUANTUM MECH. TRANSITION $i \to j$

$$\langle j | e^{iHt/\hbar} | i \rangle$$

($\hbar \to 1$ later)

$\beta \simeq -it/\hbar$,

$$\left.\begin{aligned} x(0) &= x_i \\ x(t) &= x_j \end{aligned}\right\} \Rightarrow x(0) = x(\beta)$$

PERIODIC

"EUCLIDEAN TIME" it.

Quantum Field Th. $\rightsquigarrow$ ThermoFIELDTH.

$$\phi(x_4, \vec{x}) = \phi(x_4 + \beta, \vec{x})$$

(x_4: euclid.)

FOURIER-TRANSFORM

$$\int \frac{dp_4}{2\pi} \to \frac{1}{\beta} \sum_n$$

$p_4 \beta = 2\pi n$

$(n = 0, \pm 1, \ldots$

MATSUBARA FREQ. FOR BOSONS

FEYNMAN-PROPAGATOR

$$\frac{1}{\vec{p}^2 - p_0^2 + m^2} \to \frac{1}{(2\pi n T)^2 + \vec{p}^2 + m^2}$$

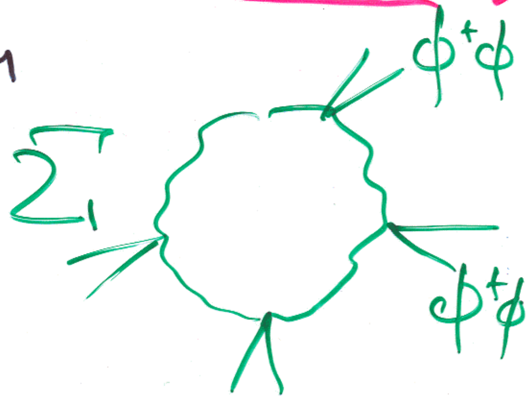
EFFECTIVE POTENTIAL

$$T \sum_{n=-\infty}^{+\infty} \int \frac{d^3p}{(2\pi)^3} \ln\left((2\pi n T)^2 + p^2 + m^2\right)$$

$$= (T=0 \text{ piece}) + \frac{1}{\beta} \int \frac{d^3p}{(2\pi)^3} \ln\left(1 - e^{-\beta(m^2+\vec{p}^{\,2})^{1/2}}\right)$$

See above!

$n=0$ GIVES "ϕ^3"-TERM
(3 DIM.)



FOR $\langle \phi^+\phi \rangle \to 0$

(GAUGE BOSON CONDENSATE IMPORTANT ?!)

HAVE INFRARED PROBLEMS FOR MASSLESS GAUGE BOSONS

$n=0$:
$$\frac{1}{\vec{p}^{\,2} + .. g^2T^2}$$

AVOIDS IR-DIVERGENCE

"HARD THERMAL LOOPS"
}
FOR LONGITUDINAL GAUGE FIELDS

$n \neq 0$ MODES (MASSIVE $2\pi n T$!)

INFLUENCE THE EFF. ACTION OF $n=0$

$\Rightarrow$ "INTEGRATE OUT" $n \neq 0$

OBTAIN EFFECTIVE 3-DIMENSIONAL TH.

NAIV: $\int_0^\beta dt_E \int d^3x \rightarrow \frac{1}{T} \int d^3x$

HAVE TO PERFORM 1/2-LOOP PERTURBATION THEORY (O.K.!) TO OBTAIN "DIMENSIONALLY REDUCED" THEORY $\Rightarrow$ AGAIN GAUGE THEORY WITH HIGGS FIELD, NOW 3D – "TRUNCATED"

$\rightsquigarrow$ FIG.

MASS SCALES

M_H, T $\Rightarrow$ $g_w T$ $\Rightarrow$ $g_w^2 T$

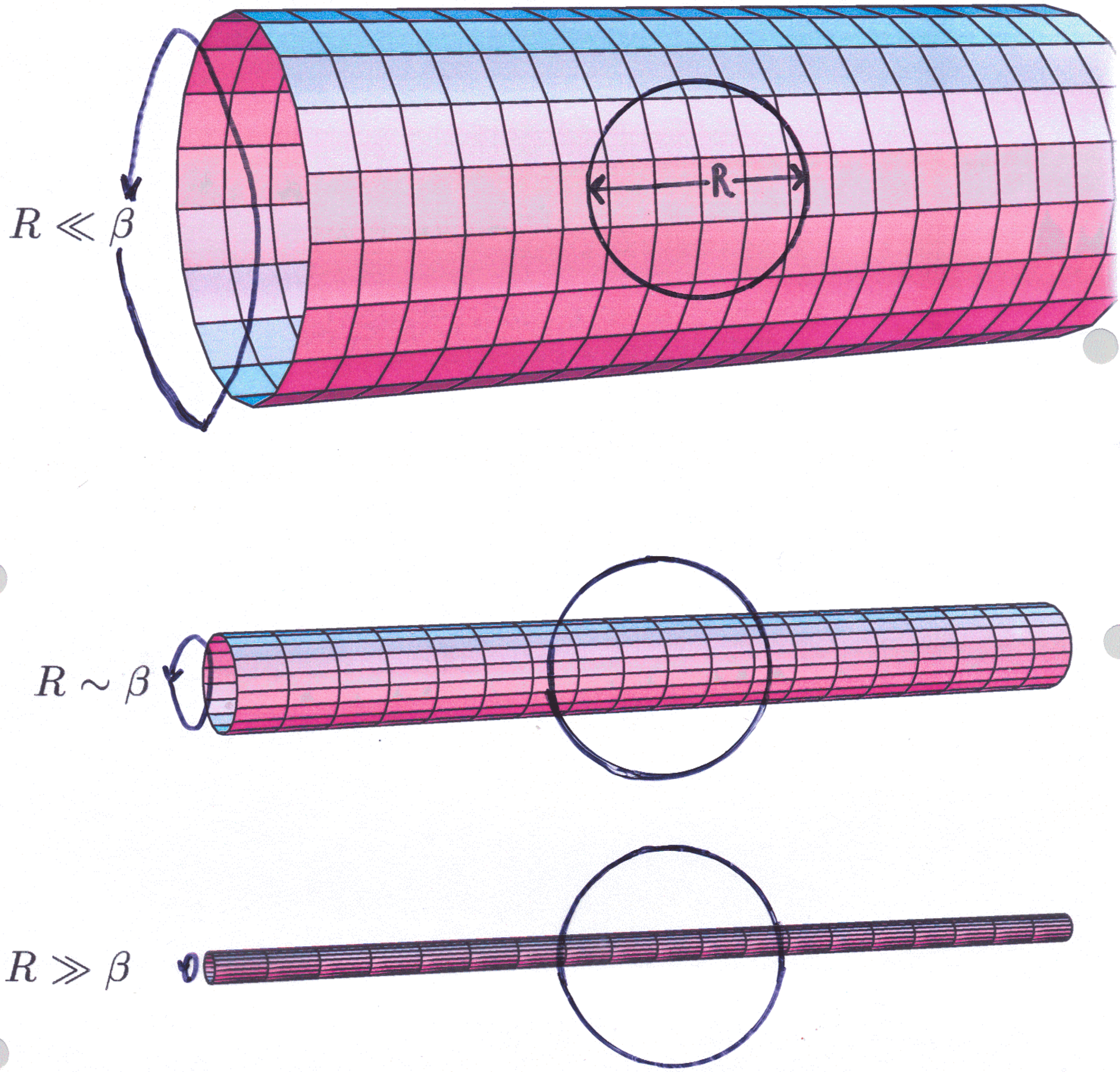
{ MATSUBARA ~ T, OTHER MASSIVE STATES — DEBYE — 3D THEORY

CAN BE STRONGLY IR SENSITIVE (TRANSVERSAL GAUGE BOSONS!)

$\rightsquigarrow$ LATTICE GAUGE TH. CALCUL.

$\beta = \frac{1}{T}$

Dimensional Reduction

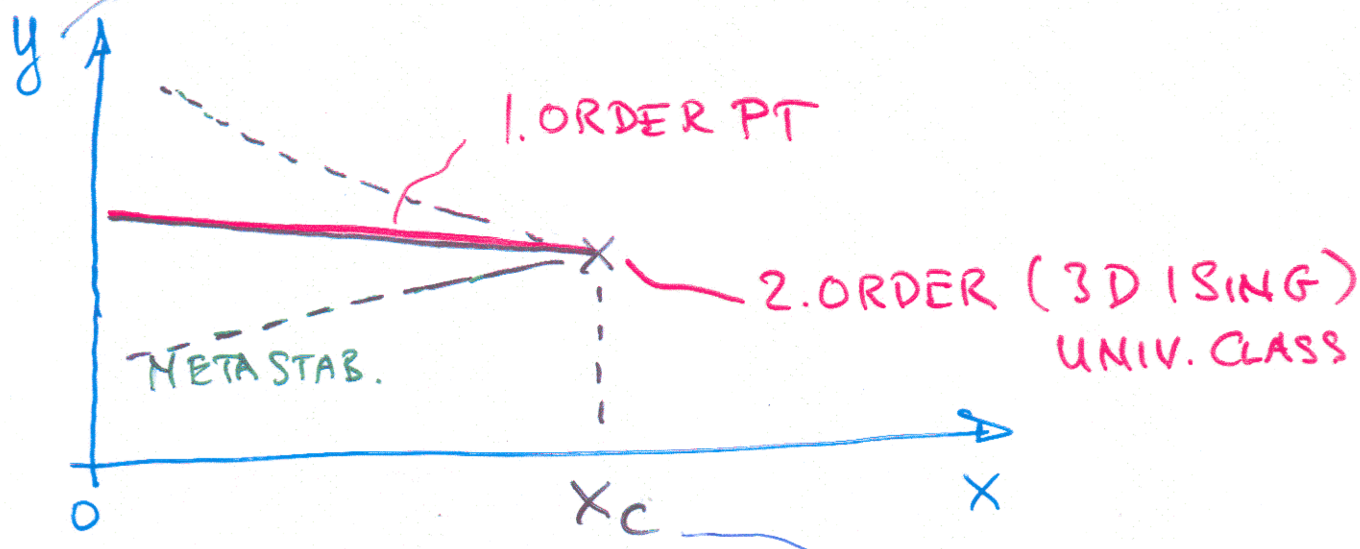


$$\mathcal{L} = \frac{1}{4} W_{ij}^a W_{ij}^a + (D_i\phi)^+(D_i\phi) + m_3^2 \phi^+\phi + \lambda_3 (\phi^+\phi)^2 + \ldots$$

g_3^2 "=" g_4^2 "T" $+ \ldots$

$x = \lambda_3 / g_3^2$, $y = m_3^2(g_3^2) / g_3^4$

HIGGS-MASS DEP. $\sim (T - T_c^*)$



"CROSS-OVER" at $m_H \gtrsim m_W$

NO PHASE TRANSITION

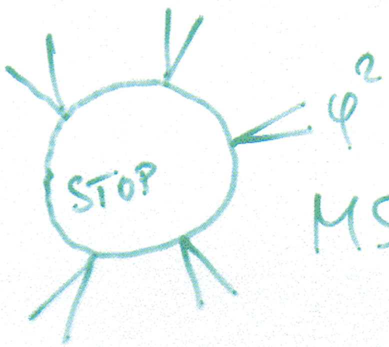
ELECTROWEAK BARYOGENESIS

SM – CKM – ~~CP~~ VERY SMALL
(BUT !! SEE LATER)

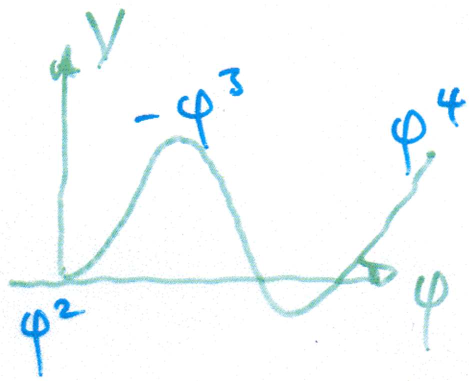
NO PHASE TRANSITION – Kajantie, Laine, Rummukainen
FOR $m_h \gtrsim m_W$ ("~CROSSOVER")

⇝

SUPERSYMMETRIC VARIANTS
INCREASE "φ^3" TERM



MSSM



Bödeker, Laine, John, Sch. /

GET STRONG 1. ORDER PHASE TRANSITION

Huber, Sch. – NMSSM
nMSSM

SUSY "MINIMAL" MODEL ("MSSM") (*) (8')

$H \rightarrow H_1, H_2, \tilde{H}_1, \tilde{H}_2$ HIGGSINOS

$q \rightarrow q, sq$ SQUARKS

$\ell \rightarrow \ell, s\ell$ SLEPTONS

$g \rightarrow g, \tilde{g}$ GAUGINOS

STANDARD MODEL COUPLINGS + SOFT SUSY-BREAKING PARAM.

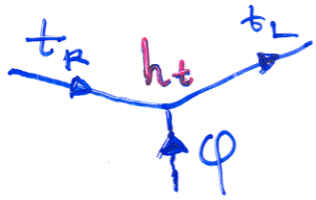
IN LOOP:

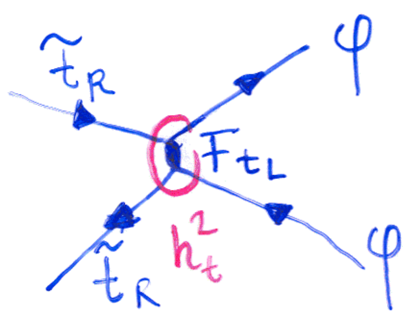
$$m^2_{\tilde{t}_R} = m^2_u + m^2_{top} + (m^2_{THERMAL})$$

m^2_u: SUSY BREAKING MASS

$m^2_{top} \sim h_t^2 \varphi^2$

$m^2_{THERMAL} \sim T^2$





MSSM WITH STRONG FIRST ORDER PT

$\left(\frac{v(T_c)}{T_c} \gtrsim 1\right)$

- $m_h \lesssim$ .. 110 GeV.. $\longrightarrow \tan\beta$
  - experim. $m_h \gtrsim 108$ GeV (m_{A_0} depend.)

    ((CERN = 114 GeV ??))

- 160 GeV $\lesssim m_{stop_R} \lesssim m_{top}$ (conservativ. ..) avoid $stop_R$-condensate
  - experim. $m_{stop_R} \gtrsim 100$ GeV ($m_{Neutrelino}$ depend.)

LOWERING THE EXPER. HIGGS-MASS BOUND WITH STRONG CP-VIOLATION

PILAFTSIS WAGNER

MODEL CAN BE RULED OUT BY EXPER. IN THE NEAR FUTURE - OR CONFIRMED!

NMSSM

STRONG FIRST ORDER PT. EVEN FOR $m_h \rightsquigarrow 120$ GeV!

REDUCTION OF EXP. m_H-bound BY H-SINGLET MIXING

LARGE PARAMETER SPACE

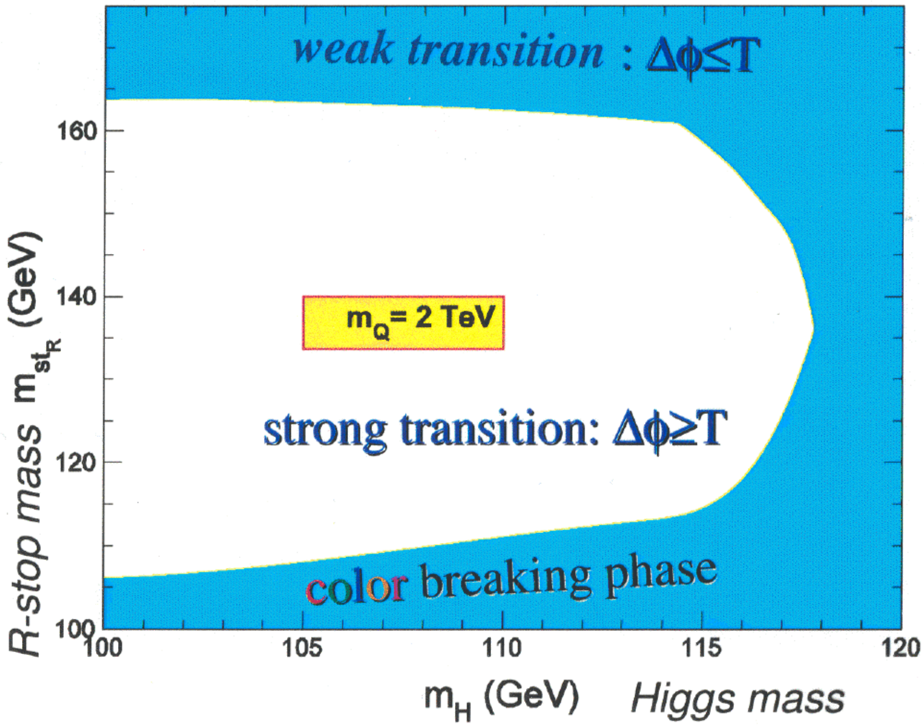
S. HUBER

M.G. SCH.

Strong first order transition in MSSM

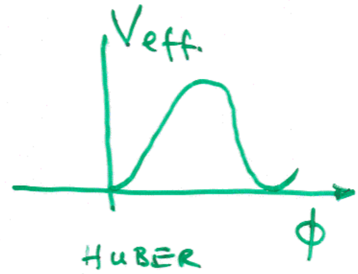
allowed "triangle" for MSSM:

Carena, Quiros, Seco, Wagner, 2000



ELECTROWEAK BARYGENESIS – A CONCRETE PROCEDURE!

- CRITICAL BUBBLE (1. ORDER P.T. !)
  - MULTIDIMENSIONAL IN FIELDS (HIGGS)



HUBER, JOHN, LAINE, SCH.

- TRANSITION PROBABILITY (LANGER FORMAL.) $\sim \ldots e^{-S_{eff}}$
- SUPERCOOLING
  NUCLEATION TEMPERATURE ("1 BUBBLE/UNIVERSE")
- STATIONARY EXPANSION OF BUBBLE

HIGGS ¦ SYMM. PHASE
$\rightarrow V_W$

$V_W = ?$, WALL-PROFILE
DEFLAGATION

BUBBLE PRESSURE = – FRICTION
$\rightsquigarrow V_W, \delta f_{NONEQUIL.}$

"OUR" SUBJECT

- DIFFUSION IN PRESENCE OF MOVING BUBBLE WALL ⇐ QUANTUM BOLTZMANN EQ
  MOORE, PROKOPEC, JOHN, SCH.
- WITH CP-VIOLATING WALL OR (MSSM) EXPLICIT ~~CP~~ INTERACTION

GENERATES CHIRAL ASYMMETRY

$$n_{q_L} - n_{\bar{q}_L}$$

- ~~B~~ BY "HOT" SPHALERON OF ELWK. THEORY IN FRONT OF BUBBLE WALL

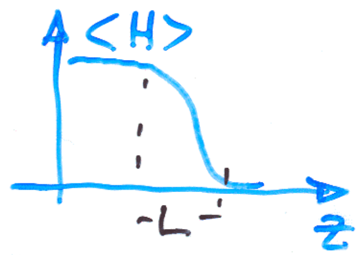
TRANSPORT EQS.

• $\left(\frac{\partial}{\partial t} + \underbrace{\frac{d\vec{x}}{dt}}_{\vec{v}}\cdot\vec{\nabla}_x + \underbrace{\frac{d\vec{p}}{dt}}_{\text{FORCE}}\cdot\vec{\nabla}_p\right) \overbrace{f(\vec{x},\vec{p},t)}^{\text{prob. in phase space}} = \text{COLLISION TERM}$

BOLTZMANN EQ.

CP-VIOLATING FORCE IN BUBBLE WALL.

WE HAVE "THICK WALL"



• $L \gg \frac{1}{T}$

→ EXSPECT WKB APPROXIMATION O.K. ("QUASICLASSICAL)

• CP-VIOLATION IS $\hbar$-EFFECT (QUANTUM EFF.)

→ "QUANTUM BOLTZMANN EQS." BAYM-KADANOFF EQS.

CONSIDER CORRELATORS (GREENS FUNCTIONS..)

$\langle \phi(\vec{x}',t')\,\phi(\vec{x},t)\rangle_\Omega$ ← ENSEMBLE

$\vec{X} = \frac{\vec{x}+\vec{x}'}{2}$, $\Delta\vec{x} = \vec{x}'-\vec{x}$ $\xrightarrow{FT}$ $\vec{p}$ ⇝ "$f(\vec{X},T,\vec{p},E)$"

$T = \frac{t+t'}{2}$, $\Delta t = t'-t$ "WIGNER TRANSFORM" → E

- "SIMPLE" WITH CP-VIOLATING DIRAC MASS

$$m = |m| e^{i\theta}, \quad m = m(z) \rightarrow |m|(z), \; \theta(z)$$

$$F_z = -\frac{|m|^{2\,\prime}}{\cdots} + s\frac{(|m|^2 \theta')'}{\cdots}$$

← CP viol. $\hbar \frac{d}{dx}\theta$

- MSSM

$$M = \begin{pmatrix} m_2 & g H_2 \\ g H_1 & \mu \end{pmatrix}$$

MASS-MATRIX IN CHARGINO-HIGGSINO SYSTEM

m_2, μ: CP-VIOLATING PHASES

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

NOTE

QUANTUM TRANSPORT EQS. NOW ALSO USED IN LEPTOGENESIS

* MSSM

T. KONSTANDIN
T. PROKOPEC
M.G. SCH.
M. SECO

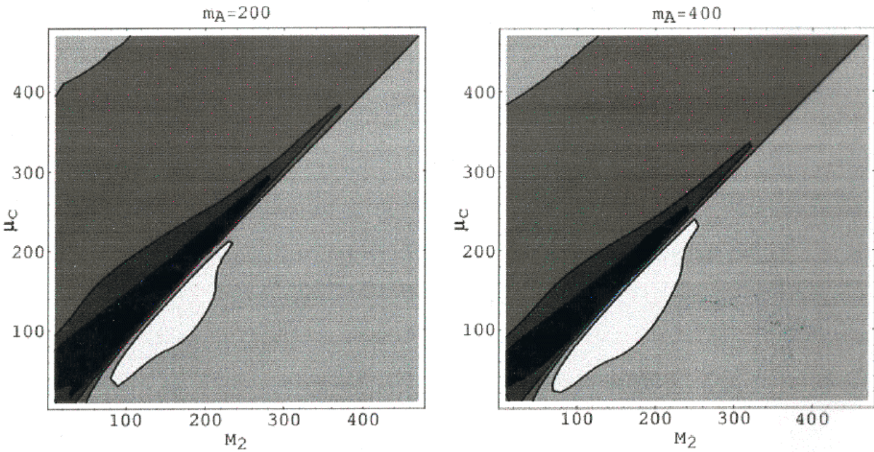


FIG. 5: The baryon-to-entropy ratio $\eta_{10} = 10^{10} \times \eta$ in the (M_2, μ_c) parameter space from (0 GeV,0 GeV) to (400 GeV,400 GeV). For the left plot the value $m_A = 200$ GeV is used, for the right plot $m_A = 400$ GeV. The black region denotes $\eta_{10} > 1$, where baryogenesis is viable. 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

$|d_e| \lesssim 1.6\ 10^{-27}$ e cm
Regan et al PRL 88 071805, 2002

! RESTRICTIONS BY exp. n/e - ELECTRIC DIPOL LIMITS
~ CP-VIOL. PHASE < 0.1

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

$$|d_e| \quad 1.6\times10^{-27}\,\mathrm{ecm}$$

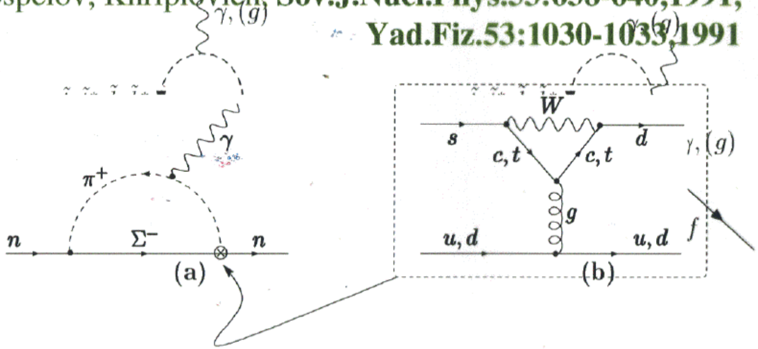
The standard model (MSM) value for eEDM (4 loop)

$$d_e^{CKM} \quad 1\times10^{-38}\,\mathrm{ecm}$$

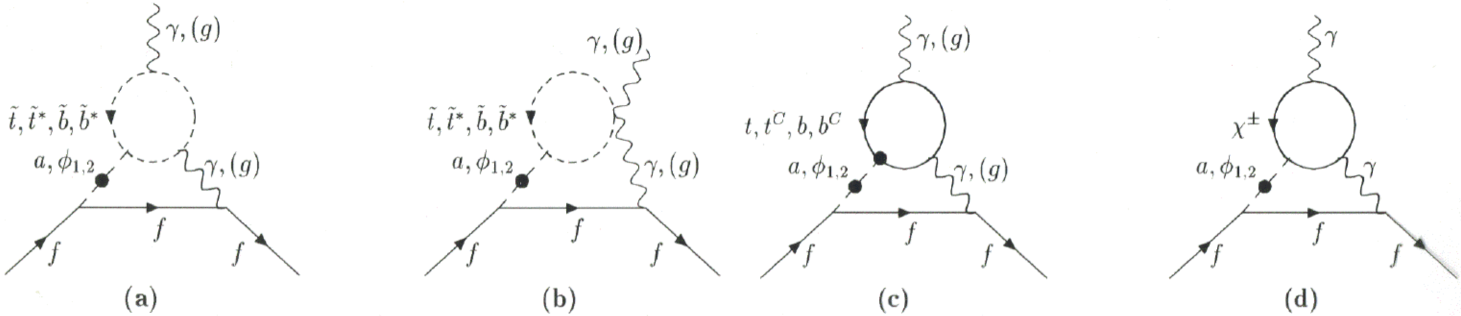
Pospelov, Khriplovich, Sov.J.Nucl.Phys.53:638-640,1991,
Yad.Fiz.53:1030-1033,1991

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

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



The MSSM 2 loop Higgs contribution for electron EDM



MSSM

"superpotential"

$$W = y^{(e)}_{\cdot\cdot}\, H_1 \epsilon L_{\cdot}\, \bar{e}_{\cdot} + y^{(d)}_{\cdot\cdot}\, H_1 \epsilon Q_{\cdot}\, \bar{d}_{\cdot}$$

$$+ y^{(u)}_{\cdot\cdot}\, H_2 \epsilon Q_{\cdot}\, \bar{u}_{\cdot} \quad + \mu\, H_1 \epsilon H_2$$

NMSSM

$$W = W_{MSSM} + \lambda S\, H_1 \epsilon H_2 - m^2 S + \frac{k}{3!} S^3$$

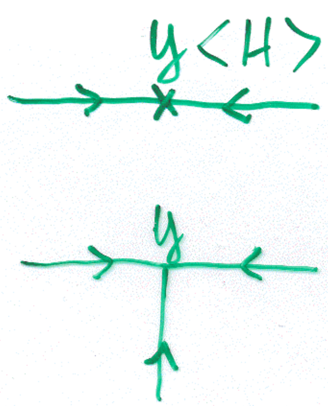
$$(+ \mu\, H_1 \epsilon H_2)$$

---

nMSSM

$$W = W_{MSSM} + \lambda S\, H_1 \epsilon H_2 - m^2 S$$

+ SUSY BREAKING TERMS (SOFT)



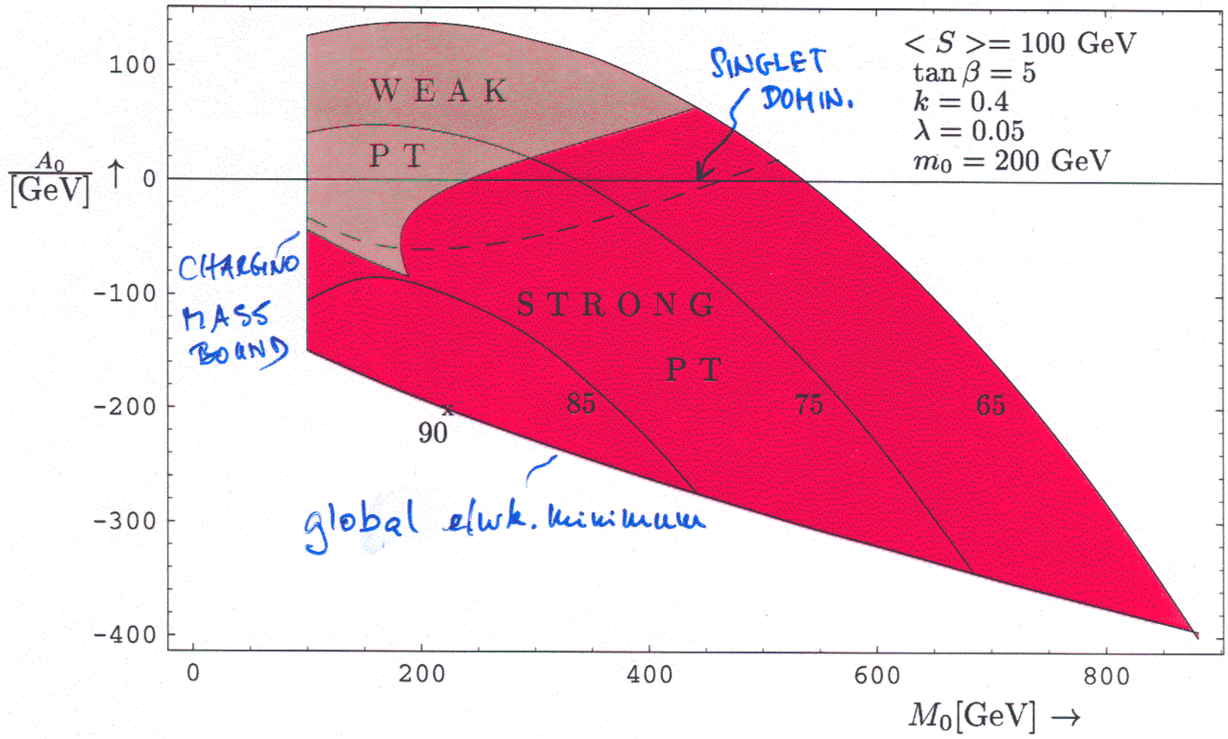
$$H_1 = (H_1^0, H_1^-)$$

$$H_2 = (H_2^+, H_2^0)$$

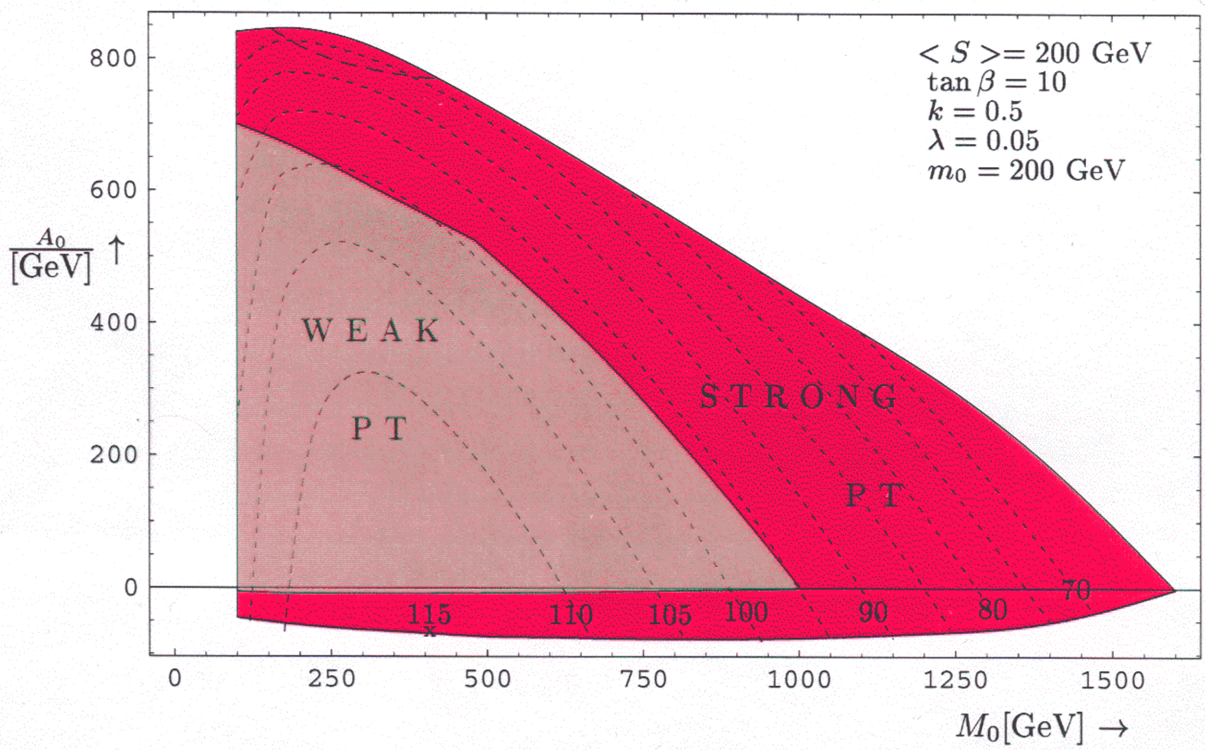
NMSSM | RESULTS for strength of the PT :

S. HUBER
M.G. SCH.

$\langle S \rangle = 100$ GeV



$\langle S \rangle = 200$ GeV

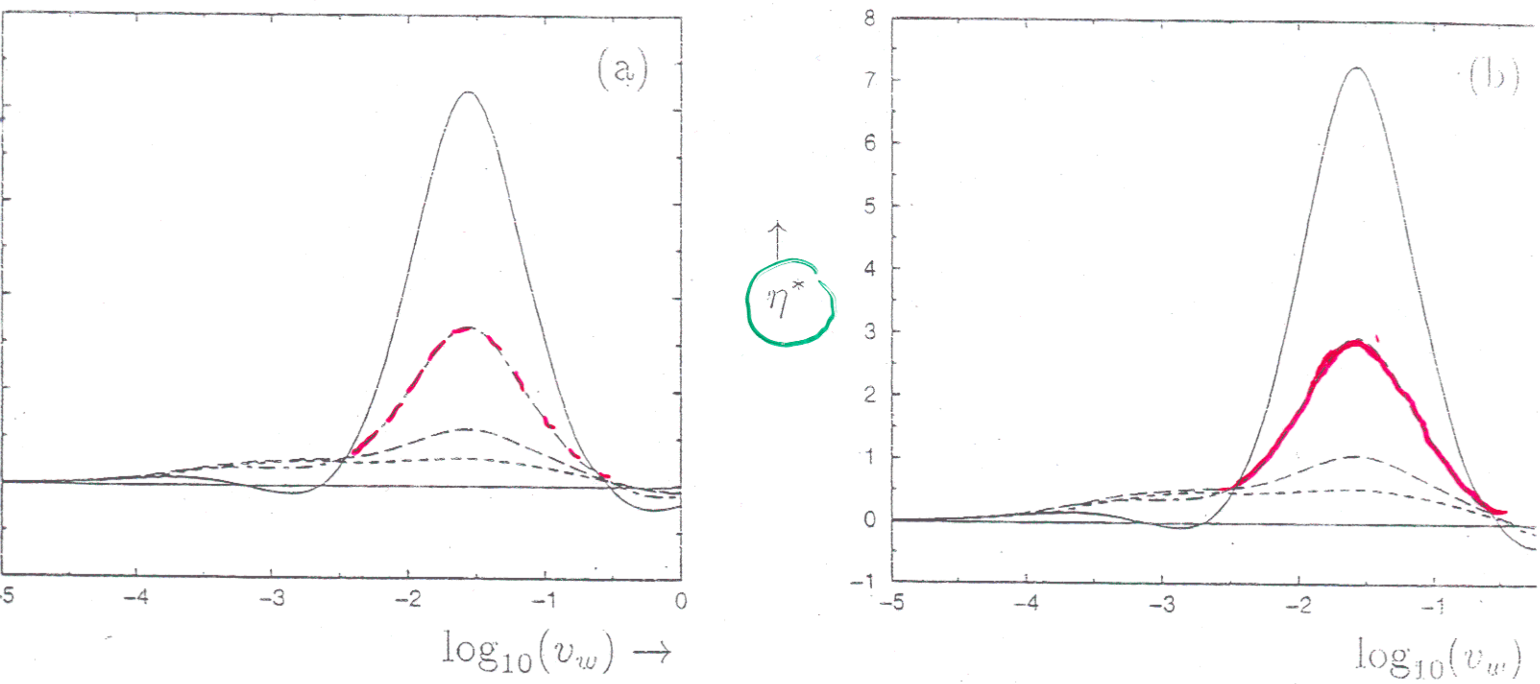


$M_H^{max} = 115$ GeV and $\frac{v_c}{T_c} > 1$

$\eta^* = \eta_B / \eta_{B\,observed}$

NMSSM

S. HUBER
M. SCH.

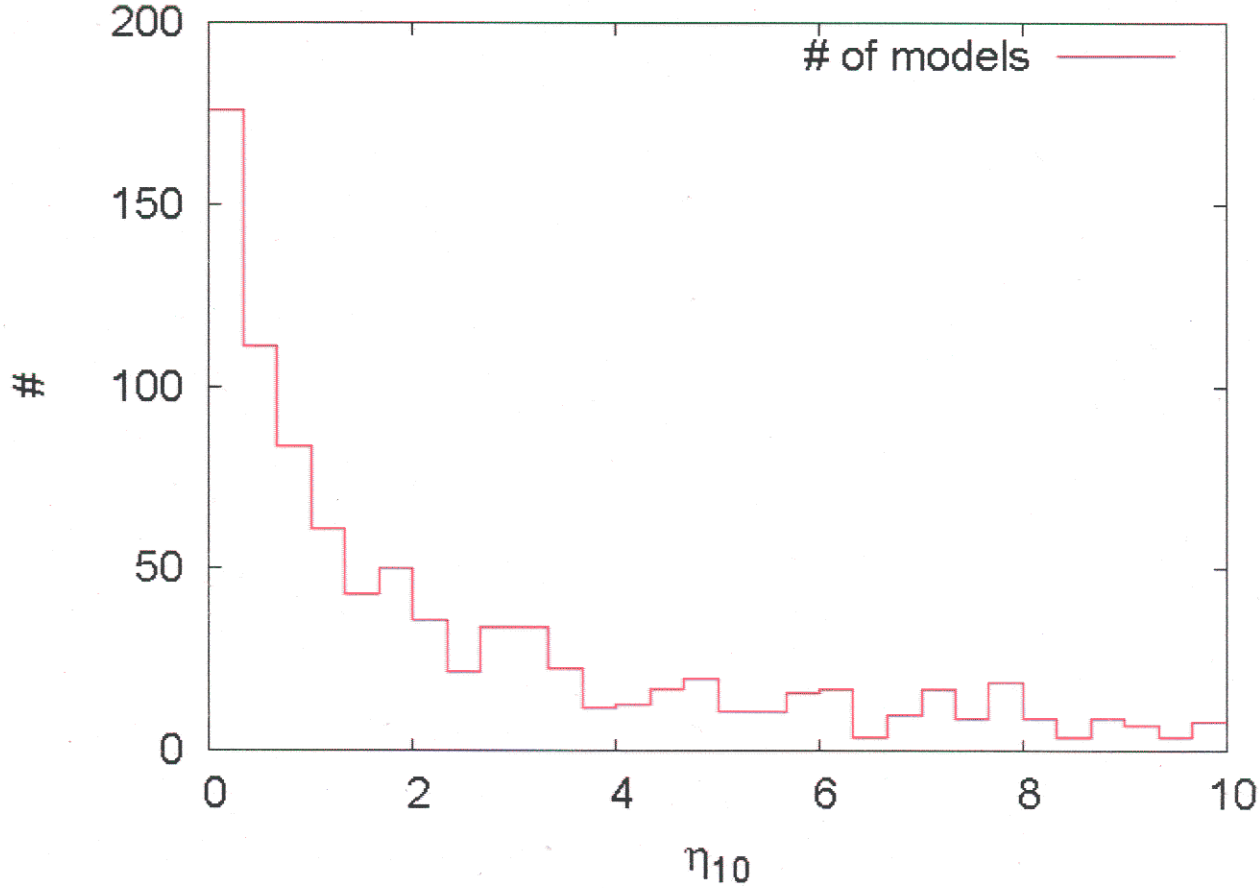


ure 10: The chargino contribution to the baryon asymmetry in units of 2 ×
a function of the wall velocity for different values of the wall thickness
$T, 10/T, 5/T, 3/T$ (from below). We use the squark spectrum C and the ex
explicit CP-violation considered in the context of fig. 6. (b): The same quanti
transitionally CP-violating bubble wall of fig. 7 and the squark spectrum D.

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{135\,\Gamma_{SPHALERON}}{g^* 2\pi^2 v_w T} \int_0^\infty dz\, \mu_{B_L}(z)$$

IN FRONT OF WALL

(η^* IN UNITS OF 2×10^{-11}!)



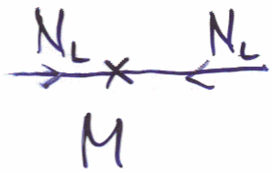
Produced baryon asymmetry in random nMSSM models.

HUBER '06
KONSTANDIN
PROKOPEC
SCHMIDT

$\eta_{10} \simeq 1$ exp.

• MAJORANA NEUTRINOS N

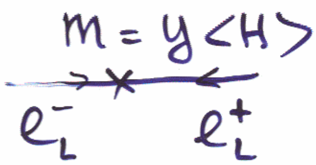
(preparing for leptogen.)



$$\mathcal{L} = \ldots \frac{1}{2} \overline{N^c} M N$$

* MAJORANA MASS VIOLATES LEPTON NUMBER!

"Weyl note."



$$\mathcal{L} = \ldots \overline{e}_R m e_L$$

DIRAC MASS (IN DIRAC NOTATION)

data

$$\Delta m_{21}^2 = m_{sol}^2 = (7.9 \pm 0.3)\, 10^{-5}\, eV^2$$

$$\Delta m_{32}^2 = m_{atm}^2 = (2.6 \pm 0.2)\, 10^{-3}\, eV^2$$

DIRAC SPINOR $\begin{pmatrix} \chi_{1L} \\ \chi_{2L}^{c} \end{pmatrix}$

MAJORANA SPINOR $\begin{pmatrix} \chi_{1L} \\ \chi_{1L}^{c} \end{pmatrix}$

SEESAW MECHANISM

$$(\nu_L \; N) \begin{pmatrix} 0 & \underbrace{m}_{y\langle H\rangle} \\ m^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$\Rightarrow$ diagonal.

$$\text{"}m_\nu\text{"} \approx \frac{m^2}{M}$$

$$\text{"}m_N\text{"} \sim M$$

LEPTOGENESIS

- INCLUDING FLAVOUR

$$y_i^{(\ell)} \, (\mathbb{H} \, \epsilon \, \mathbb{L}_i) \, \bar{e}_i \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$+ \lambda_{ik} \, (\mathbb{H}^* \, \mathbb{L}_i) \, N_k$$

$$+ \frac{1}{2} M_i \, N_i N_i$$

$$\mathbb{H} = \begin{pmatrix} H^- \\ H^0 \end{pmatrix}$$

(WEYL NOT.)

[AFTER (PARTIAL) DIAGONALIZATION]

ASSUME: "M_1" IN THERMAL EQUILIBRIUM

$(M_{2,3} \gg M_1)$

* OUT OF EQUILIBRIUM DECAY $\quad \Gamma_{DECAY} < H$

HAVE 3 CP-PHASES (ONE OF CKM TYP)

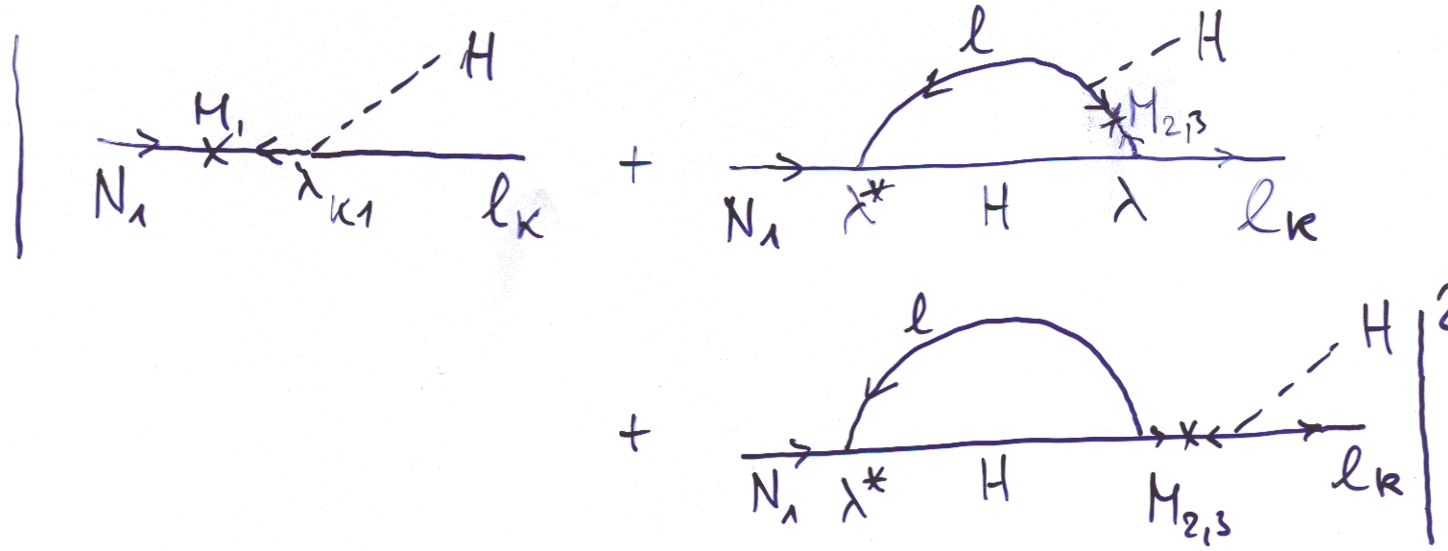
* ⇒ CP VIOLATING DECAY

$T_{REHEAT} \gtrsim M_1/5$ (DANGEROUS FOR SUSY "GRAVITINO PROBLEM")

$$\epsilon_K := \frac{\Gamma(N_1 \to H + \ell_K) - \Gamma(N_1 \to \bar{H} \bar{\ell}_K)}{\ldots + \ldots}$$

W. BUCHMÜLLER
? "DARK MATTER"

NEED TREE / ONELOOP INTERFERENCE



$$\epsilon_k = \frac{3 M_1}{16\pi v_H^2 [\lambda^+\lambda]_{11}} \mathrm{Im}\{[\lambda]_{k1}[m^+\lambda]_{k1}\}$$

RELATED TO NEUTRINO MASS

$$\Gamma_i = \frac{1}{8\pi}(\lambda^+\lambda)_{ii} M_i$$

LEPTON ASYMMETRY $\xrightarrow{\text{SPHALERON}}$ BARYON ASYMMETRY

$M_1 > 10^9$ GeV NEEDED

WASH OUT FOR $\tilde{m}_1 = \frac{v_H^2(\lambda^+\lambda)_{11}}{M_1} \gtrsim m^* = 10^{-3}$ eV

BARYON ASYM. THEN IS INDEPENDENT OF INITIAL N_1 ABUNDANCE AND BARYON ASSYM.

ALSO: NONTHERMAL LEPTOGENESIS

(LEPTOGEN.

BOLTZMANN EQS. (SIMPLE CASE!)

$$\frac{dN_{N_1}}{dz} = -(D+S)\left(N_{N_1} - N_{N_1}^{\text{EQUIL.}}\right)$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D\left(N_{N_1} - N_{N_1}^{\text{EQUIL.}}\right) - W N_{B-L}$$

$z = M_1/T$, $D = \Gamma_D/Hz$, $S = \Gamma_S/Hz$

$W = \Gamma_W/Hz$

INCREASING z ~ DECREASING T ~ INCREASING TIME

$$B = \frac{8N_f + 4}{22N_f + 1}(B-L)$$

(N_f = 3 FAM.)

IN EQUILIBRIUM, SINCE CHEMICAL POTENTIAL LEFT

$T \gg v_H$

AFFLECK-DINE BARYOGENESIS / LEPTOGENESIS

MSSM → SCALAR SUPERPARTNERS OF LEPTONS AND QUARKS

→ SCALAR FIELD ϕ_i POTENTIAL

$$V = \underbrace{\sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2}_{\text{F-TERM}} + \underbrace{\frac{1}{2} g^{a2} \left(\sum_i \phi_i^* T^a \phi_i\right)}_{\text{D-TERM}}$$

+ SUSY BREAKING

e.g. $W = \ldots\ y_i^{(\ell)}\ \mathbb{L}_i \epsilon H_1 \bar{\ell}_i$

$$\Rightarrow |y_i^{(\ell)}|^2\ |\underbrace{\mathbb{L}_i \epsilon H_1}_{}|^2$$

"$\underline{\underline{\phi}}$" CARRIES LEPTON NUMBER

FLAT DIRECTION WITHOUT EXPANSION OF UNIVERSE AND SUSY-BREAKING

"ϕ-CONDENSATE" ROLLING DOWN POTENTIAL

$$\ddot{\phi}(t) + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \qquad \left(H = \frac{1}{2t} \quad \text{IF RAD. DOM.}\right)$$

START $V = m^2 |\phi|^2$

(i) $H \gg m$ STRONG DAMPING

(ii) $H \ll m$ ϕ-OSCILLATION OF RE / Im ϕ ← ROTATING ϕ

ϕ-SHRINKING IN TIME

(iii) INTERACTION TERMS

CP-VIOLATING (the b and c terms):

$$|\phi|^4 + b\,\phi^3\phi^* + c\,\phi^4 + c.c.$$

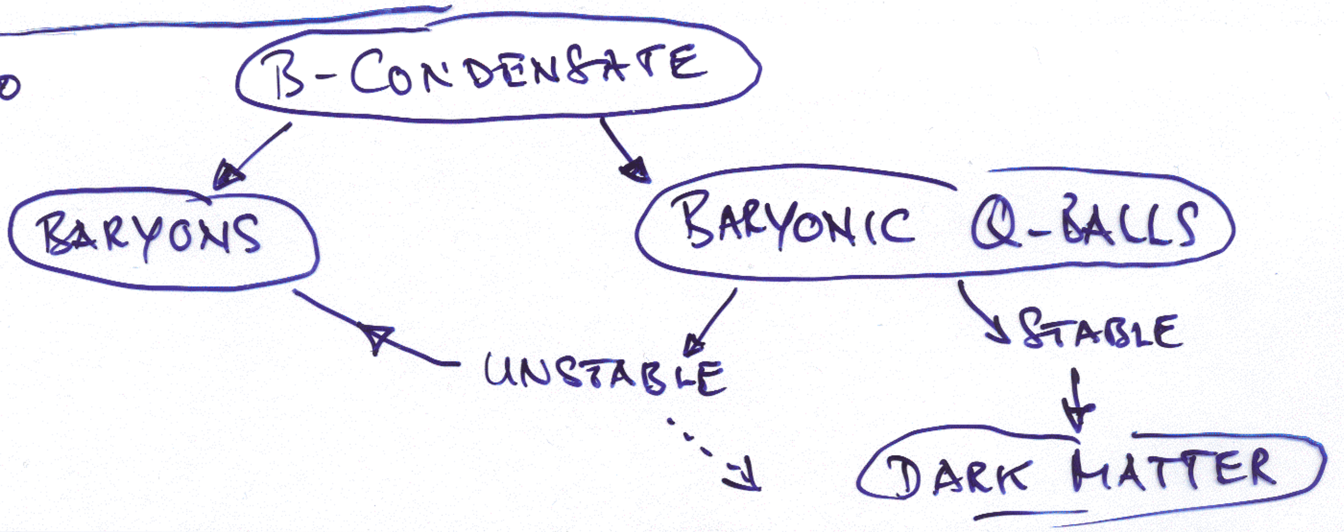
GIVE PERTURBATIONS, CP-VIOLATING EFFECT (VIOL. OF "ANGULAR MOMENTUM") FOR A LIMITED TIME CREATES LEPTON NUMBER $\sim i\,\phi^* \overleftrightarrow{\partial_0} \phi$

(iv) CONDENSATE (HERE Lept.) DESTABILIZES (BARYONIC IN OTHER TERMS)

DECAY INTO <u>LEPTONS</u> WITH ASYMM.

$\xrightarrow{\text{SPHALERON}}$ <u>BARYON</u> ASYMMETRY

A180



- "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 NON ADIABATICAL 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...)

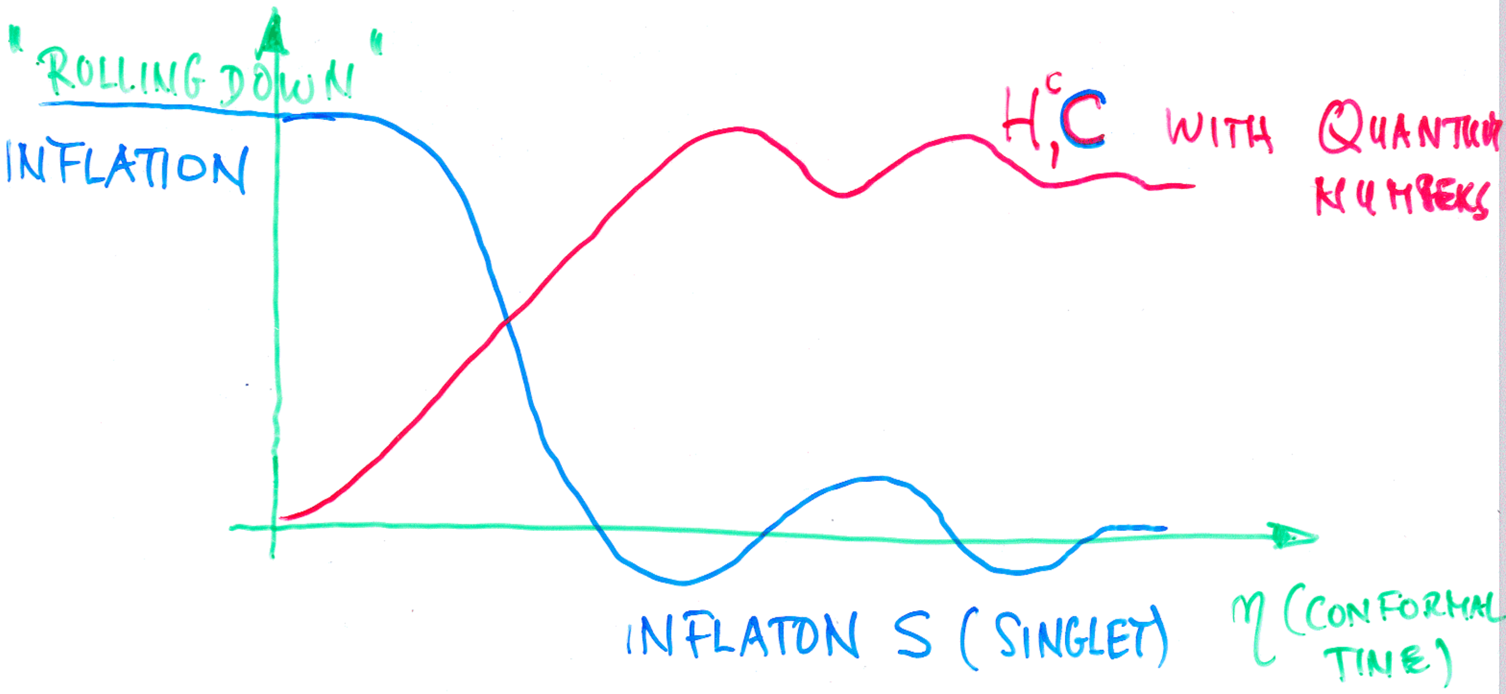
→ MATRIX-EQS.

FOR FERMIONS / BOSONS

$z \leftrightarrow t$

- APPLICATION : HYBRID INFLATION (SUPERSYM.)

→ FIG.



GUT - WATERFALL

EXAMPLES :

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

"COLOR"

$SU(4) \to SU(3)_C \times U(1)$, $SU(2)_R \to U(1)$; $U(1) \times U(1) \to U(1)_Y$

- $SO(10) \to SM$

$$W_{\text{SUPERPOT.}} \supset \kappa S \left(\bar{H}^c H^c - \mu^2 \right) + \ldots$$

CP-VIOL. COUPLINGS

$\bar{C}\ C$

$H^c = (\bar{4}, 1, 2)$ PATI-SALAM

$C = [16]$ SO(10)

HYBRID INFLATION

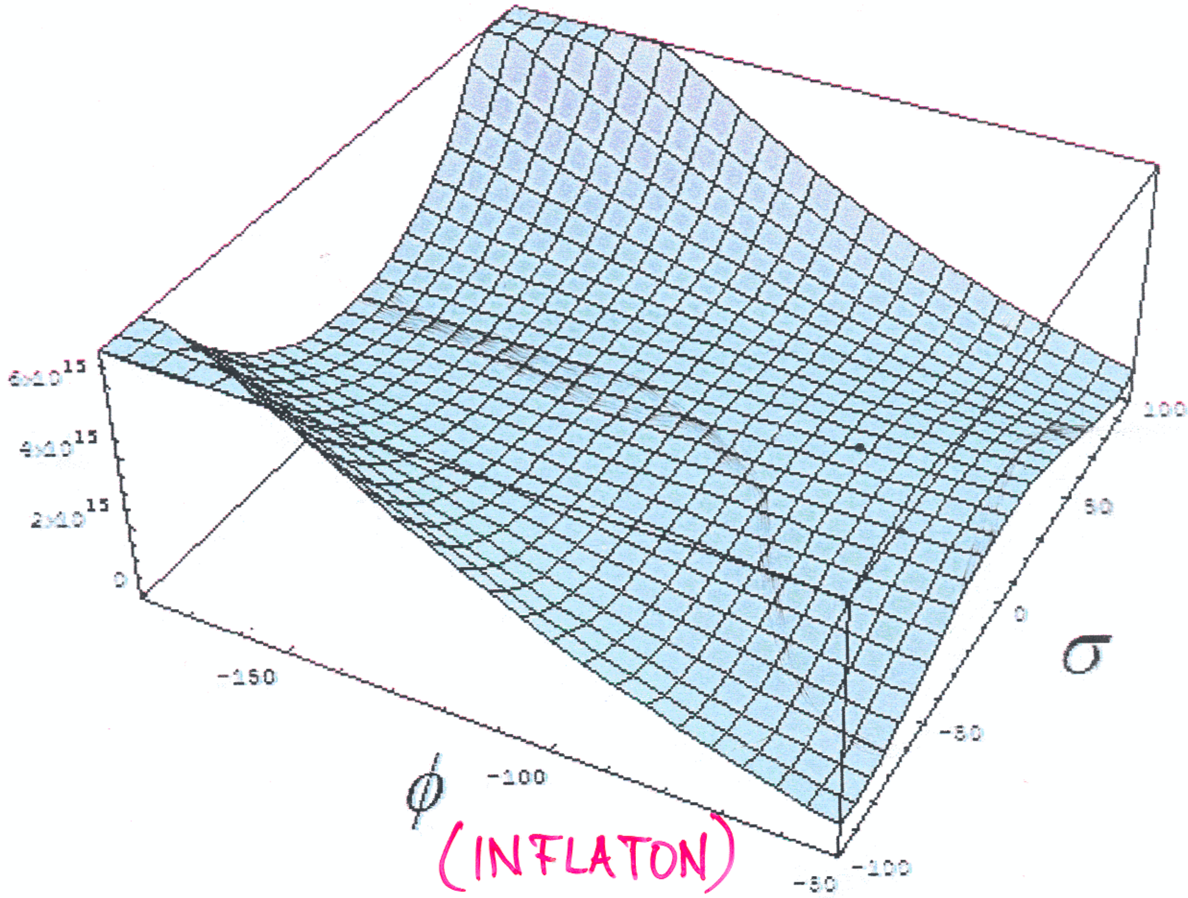
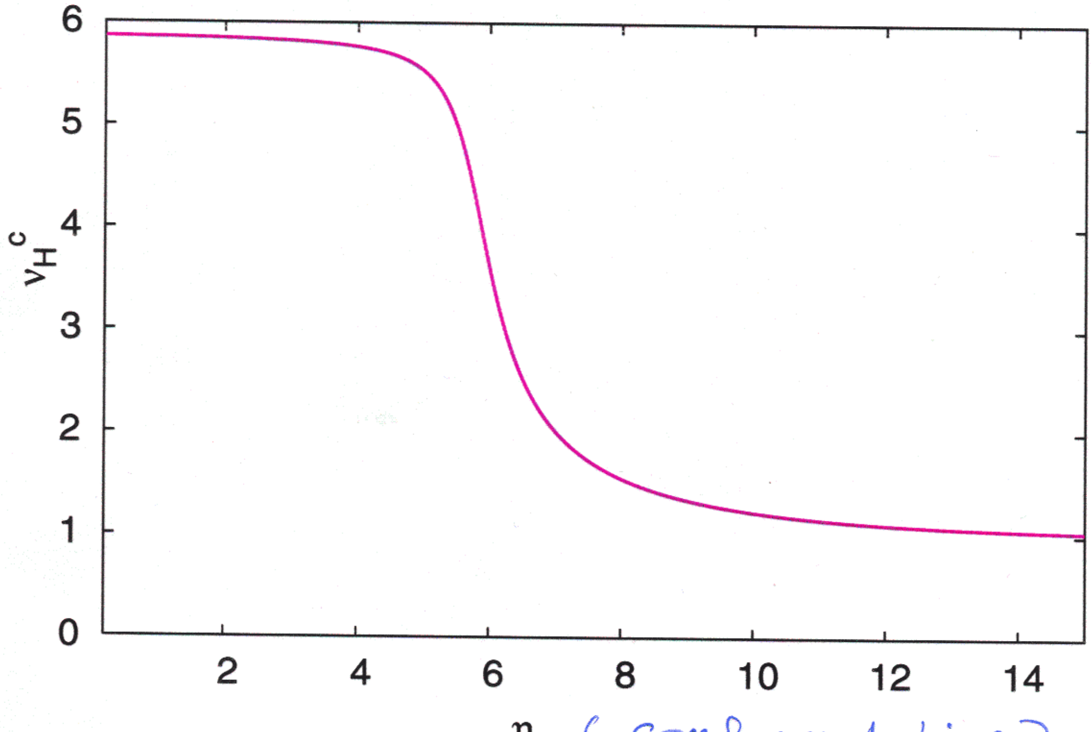


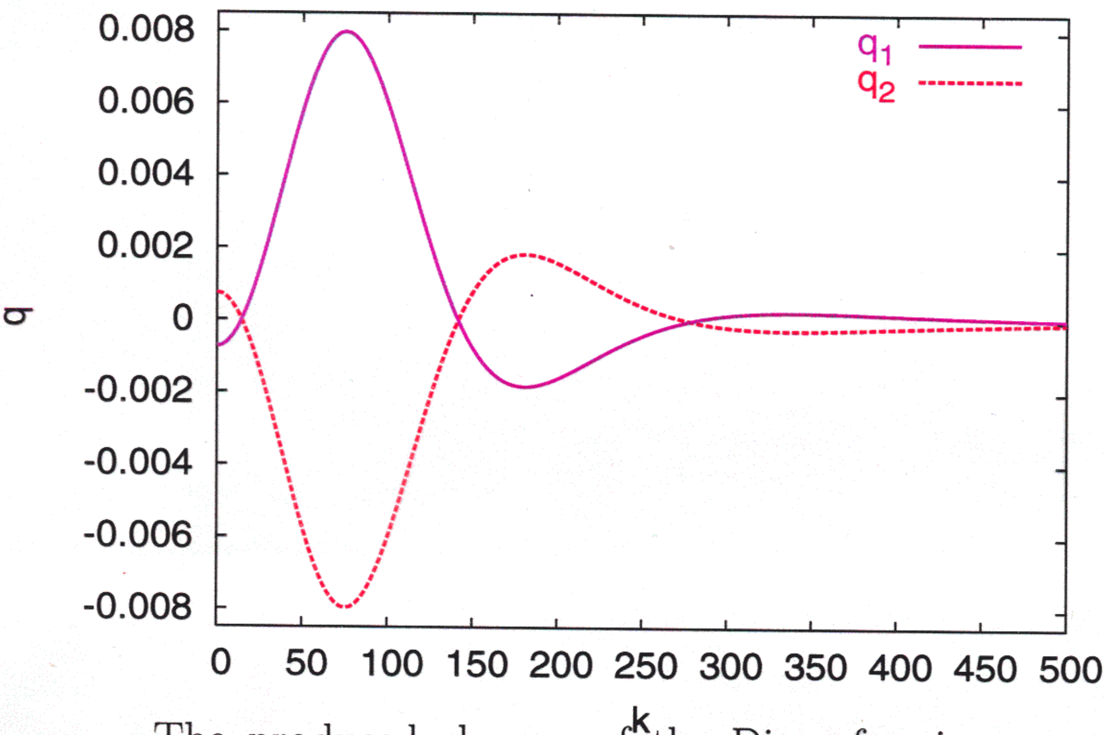
Figure 1: Hybrid Potential, using $m_{pl} = 10^9$, $\lambda = 10^4$, $g = 8 \cdot 10^3$, $m = 1.5 \cdot 10^{-5} m_{pl}$, and $M = 10^{-3} \cdot m_{pl}$.

ADISORN ADULPRAVITCHAI

Coherent Baryogenesis in Hybrid Inflation



Evolution of the field ν_H^c.



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

CP

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

REALISTIC PARAMETERS OF SENOGUZ/SHAFI-INFLATION

- COUPLINGS

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

$X_1 \Rightarrow$ $d^c_{\bar{H}} \xrightarrow{\langle \nu^c_{\bar{H}} \rangle} d + \nu_{MAJORANA}$

SCALAR   FERMION

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

(ii) $\delta \, F^c H^c F^c H^c / M_s$ $\epsilon^{\cdots\cdot}$ $\epsilon^{\cdot\cdot}$

$X_2 \Rightarrow$ $\overline{d^c_H} \xrightarrow{\langle \nu^c_H \rangle} \bar{u} \; \bar{d}$

$\curvearrowright \; B-L = -\frac{2}{3} q_2 + \frac{1}{3} q_1 = q_1$

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

- NONTHERMAL LEPTOGENESIS (IN SAME MODEL)

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

LIGHTEST MASS $M_1 = 3.9 \times 10^{10}$ GeV

COMPARE $T_R \sim 2.7 \cdot 10^9$ GeV } NONTHERMAL!

MAXIMAL MIXING AND CP VIOLATION VIA 1-LOOP INTERFERENCE

$$\frac{n_L}{s} \lesssim 3 \cdot 10^{-10} \frac{T_R}{m_{\nu_H^c}} \left(\frac{M_1}{10^6 \text{ GeV}}\right)\left(\frac{m_{\nu 3}}{0.04 \text{ eV}}\right) \approx 8 \times 10^{-11}$$

$$\Rightarrow \frac{n_B}{s} \lesssim 3 \times 10^{-11} \quad \text{SMALLER!}$$

(SENOGUZ / SHAFI)

COLD ELECTROWEAK BARYOGENESIS

ALMOST THE SM

J. SMIT
A. TRANBERG

- $\mu^2 |H|^2 \Rightarrow -\mu^2 |H|^2$

  $\langle H \rangle = 0 \Rightarrow \langle H \rangle \neq 0$

IN LOW SCALE (TEV) HYBRID INFLATION

→ REHEATING TEMP. SMALL ≪ ELWK SCALE (100 GeV

- CP VIOLATING TERM MUCH BIGGER THAN "JARLSKOG DETERMINANT" IN THE EFFECTIVE ACTION !!

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INTEGRATE OUT QUARKS

2. ORDER IN DERIVATIVE EXPANSION

(→ "WORLD LINE METHOD")

INCLUDING CKM - CP - VIOLATION

- DO CLASSICAL EVOLUTION WITH $\mu^2(t)$ IN EFFECTIVE THEORY INCLUDING CP-VIOLATING TERM ON LATTICE.

MEASURE BARYON NUMBER VIOLATION

INSPECTING

$$N_{CS}(t) - N_{CS}(0) = \frac{1}{16\pi^2} \int dt \int d^3x \, \mathrm{tr}\, F^{\mu\nu} \tilde{F}_{\mu\nu}$$

AND "HIGGS-WINDING" N_W

STATIONARY CASE (NO DERIVATIVES OF FIELDS)

$\Rightarrow$ "JARLSKOG DETERMINANT" RULES ~~CP~~

$$\Delta_{CP} = J \prod \frac{\Delta \tilde{m}_u^2}{v^2} \prod \frac{\Delta \tilde{m}_d^2}{v^2} \simeq 10^{-19}$$

v^2: ELWK SCALE; $\tilde{m}_u$: DIAGONALIZED

$\mathbb{C} = \mathcal{U}^+ D$ CKM MATRIX

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta \simeq (3.0 \pm 0.3) \times 10^{-5} !$$

$$S_{\not{CP}} = \frac{1}{8(4\pi)^2} \frac{3}{16} J \kappa^{CP} \epsilon^{\mu\nu\lambda\sigma} \int d^4x \left(Z_\mu W^+_{\nu\lambda} W^-_\alpha \times (W^+_\sigma W^-_\alpha + W^+_\alpha W^-_\sigma) + c.c. \right) \not{\tilde{m}_c^2}$$

$\kappa^{CP} \approx 9.87$ IN "BROKEN" PHASE

$$\frac{\kappa^{CP}}{\tilde{m}_c^2} \approx \frac{32}{9\tilde{m}_c^2 (\tilde{m}_c^2 - \tilde{m}_s^2)^3 (\tilde{m}_c^2 - \tilde{m}_t^2)^3 (\tilde{m}_s^2 - \tilde{m}_t^2)^2} \times$$
$$\Big(\tilde{m}_s^6 \tilde{m}_t^6 (\tilde{m}_s^2 - \tilde{m}_t^2)^2 + 3\tilde{m}_c^{14} (\tilde{m}_s^2 + \tilde{m}_t^2)$$
$$-5\tilde{m}_c^2 \tilde{m}_s^4 \tilde{m}_t^4 (\tilde{m}_s^2 - \tilde{m}_t^2)^2 (\tilde{m}_s^2 + \tilde{m}_t^2) - 12\tilde{m}_c^{12} (\tilde{m}_s^4 + \tilde{m}_t^4)$$
$$+\tilde{m}_c^4 \tilde{m}_s^2 \tilde{m}_t^2 (\tilde{m}_s^2 - \tilde{m}_t^2)^2 (13\tilde{m}_s^4 + 28\tilde{m}_s^2\tilde{m}_t^2 + 13\tilde{m}_t^4) + 18\tilde{m}_c^{10} (\tilde{m}_s^6 + \tilde{m}_t^6)$$
$$+\tilde{m}_c^8 (-12\tilde{m}_s^8 + 37\tilde{m}_s^6\tilde{m}_t^2 - 74\tilde{m}_s^4\tilde{m}_t^4 + 37\tilde{m}_s^2\tilde{m}_t^6 - 12\tilde{m}_t^8)$$
$$+\tilde{m}_c^6 (3\tilde{m}_s^{10} - 41\tilde{m}_s^8\tilde{m}_t^2 + 41\tilde{m}_s^6\tilde{m}_t^4 + 41\tilde{m}_s^4\tilde{m}_t^6 - 41\tilde{m}_s^2\tilde{m}_t^8 + 3\tilde{m}_t^{10}) \Big)$$
$$- \frac{64\, \tilde{m}_c^4 \tilde{m}_s^2 \tilde{m}_t^2 (\tilde{m}_c^2 - \tilde{m}_t^2)(\tilde{m}_c^2 - 3\tilde{m}_s^2 + 2\tilde{m}_t^2) \log\left[\frac{\tilde{m}_s^2}{\tilde{m}_c^2}\right]}{3(\tilde{m}_c^2 - \tilde{m}_s^2)^4 (\tilde{m}_s^2 - \tilde{m}_t^2)^3}$$
$$+ \frac{64\, \tilde{m}_c^4 \tilde{m}_s^2 (\tilde{m}_c^2 - \tilde{m}_s^2) \tilde{m}_t^2 (\tilde{m}_c^2 + 2\tilde{m}_s^2 - 3\tilde{m}_t^2) \log\left[\frac{\tilde{m}_t^2}{\tilde{m}_c^2}\right]}{3(\tilde{m}_c^2 - \tilde{m}_t^2)^4 (\tilde{m}_s^2 - \tilde{m}_t^2)^3}.$$

ALREADY SIMPLIFIED! $\tilde{m}_b^2 = \tilde{m}_c^2$

COMPUTER ALGEBRA

"NONPERTURBATIVE" IN $\tilde{m}$'s

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