SEPT. '10

ERICE

ELECTROWEAK BARYOGENESIS

MICHAEL G. SCHMIDT

HEIDELBERG

- (SHORT) GENERAL INTRODUCTION
- SOME OLD AND MORE RECENT MODELS

  MODIFIED SM, MSSM, nMSSM, BMSSM...

  EDM's

AT THE END OF INFLATION OUR UNIVERSE WAS WASTE AND VOID

MATTER THAN CREATED IN PRE/REHEATING (UNDER CONTROL!)

NAIVELY: SAME AMOUNT OF MATTER / ANTIMATTER

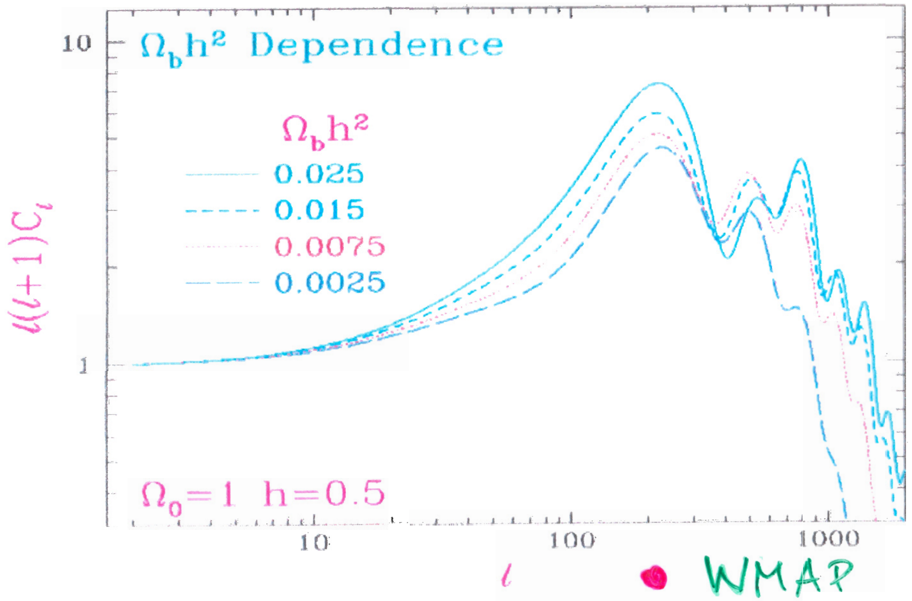
PAIR ANNIHILATION →

$$\frac{n_B}{n_\gamma} \sim \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

OBSERVED

$$\frac{n_B}{n_\gamma} = (6.21 \pm 0.16)\, 10^{-10}$$

ALMOST NO $\bar{B}$



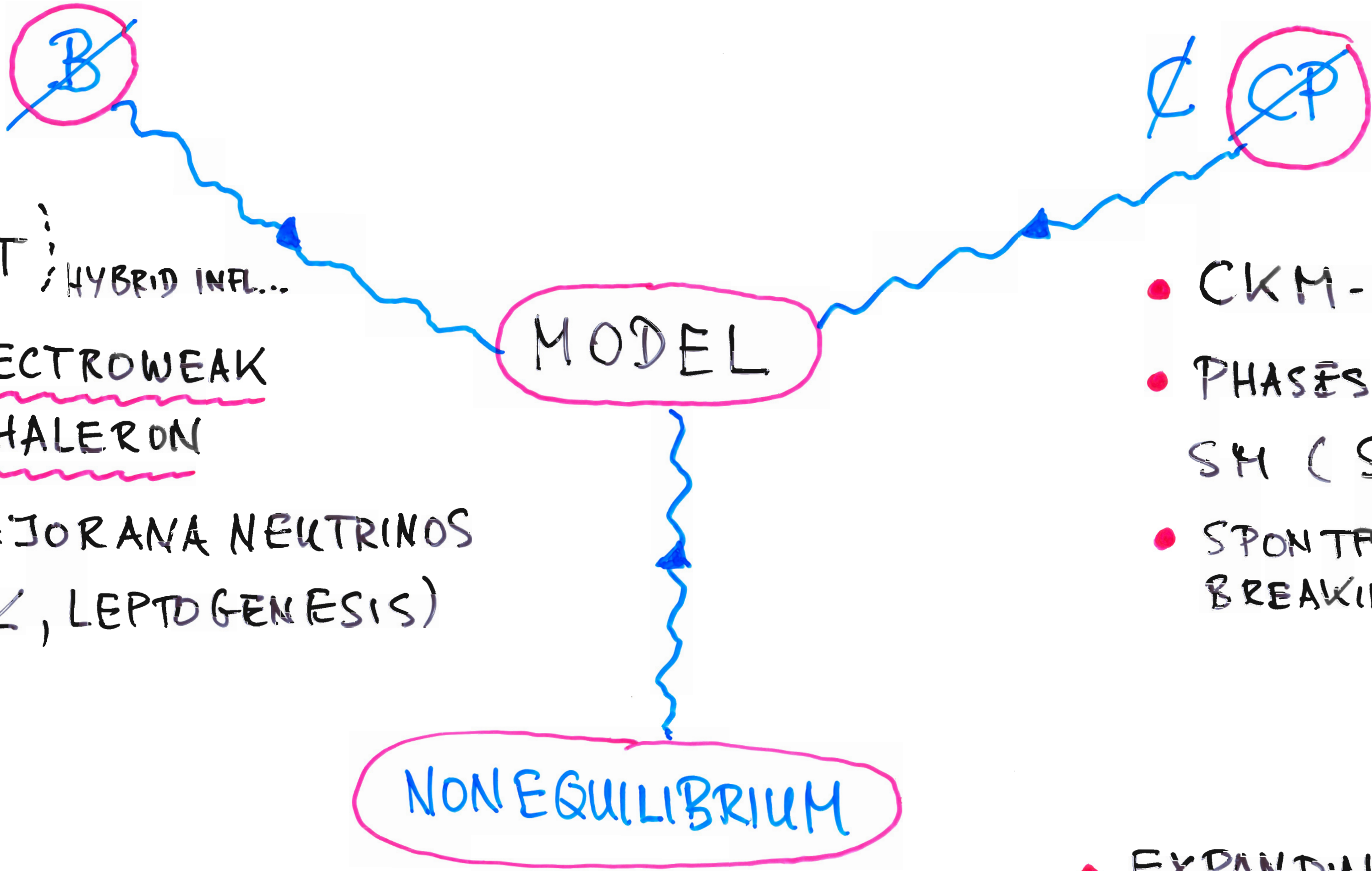
- EARLY NUCLEOSYNTHESIS
- WMAP

$n_B - n_{\bar{B}}$ ASYMMETRY HAS TO BE CREATED!

NECESSARY CONDITIONS (SAKHAROV '67)

- B-VIOLATION
- C/CP-VIOLATION: IF NO PREF. FOR MATTER IN $\not{B}$ REACTIONS: $n_B = n_{\bar{B}}$
- NONEQUILIBRIUM: WITH EQUIL. AND CPT → SAME THERMAL DISTRIB. FOR $B, \bar{B}$!

- BARYOGENESIS



- GUT ; HYBRID INFL...
- ELECTROWEAK SPHALERON
- MAJORANA NEUTRINOS (L̸, LEPTOGENESIS)

- CKM-MATRIX OF SM
- PHASES IN EXTENDED SM (SUSY...)
- SPONTANEOUS BREAKING

- EXPANDING UNIVERSE
  OUT OF EQUILIBRIUM DECAY
- PHASE TRANSITION

! ALL INTIMATELY CONNECTED
- WITH ELEMENTARY PARTICLE PHYSICS

SM - ELWK. PHASE TRANSITION? SHAPOSHNIKOV '87

• SPHALERON TRANSITION

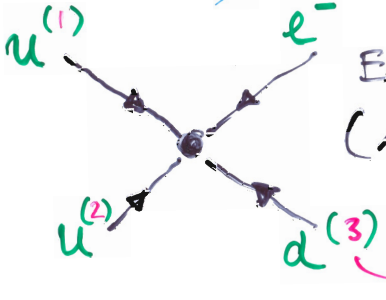
$SU(2)_L$ GAUGE THEORY IN SM VIOLATES B+L
(B-L CONSERVING)

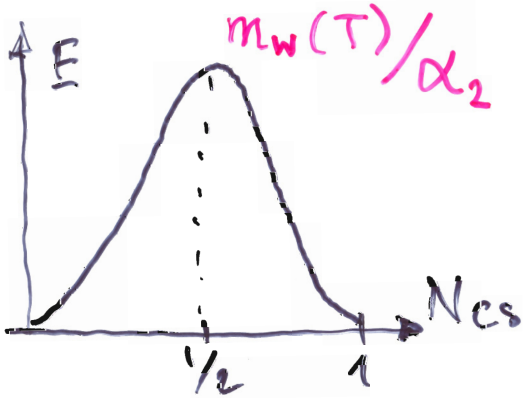
$$\frac{d}{dt}\int d^3x\, j_0^B \sim \frac{d}{dt} N_{CS}$$

⇒ • INSTANTON INDUCED TUNNELING IN N_{CS} $(N \to N \pm 1)$

$$\sim e^{-8\pi^2/g_2^2}$$

EXTREMELY SMALL !!





• THERMAL SPHALERON TRANSITIONS

$$\Gamma_B \sim \ldots \alpha_2 (\alpha_2 T)^4 \exp\left(-\frac{v(T)}{T}\right)$$

KLINKHAMER MANTON

BÖDEKER, MOORE, RUMMUKAINEN

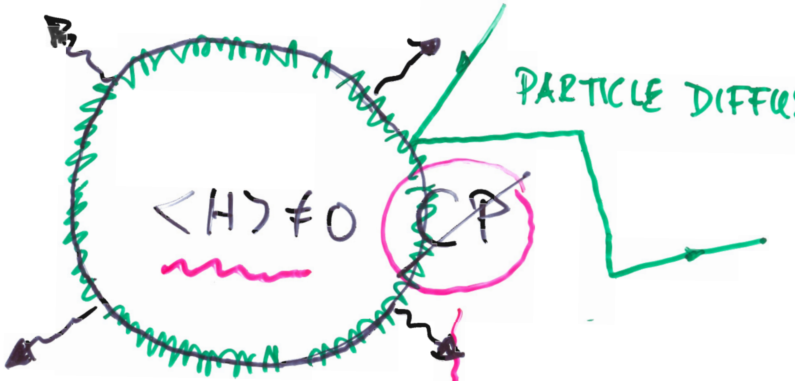
$v \sim \langle H \rangle$

TWO VERSIONS:
- • EXPON. SUPPRESSED IN HIGGS PHASE ($v(T) \neq 0$)
- • UNSUPPRESSED IN SYMMETRIC PHASE ($\langle H \rangle = 0$)

TWO FACES:
- • B-ASSYM. WIPED OUT IN EQUILIBRIUM ($B-L=0$)
- • B-ASSYM. GENERATED IN NONEQUILIBRIUM

PROMINENT USE IN ELECTROWEAK BARYOGENESIS AT A STRONG FIRST ORDER PHASE TRANSITION FROM THE SYMM. PHASE ($\langle H \rangle = 0$) TO THE HIGGS PHASE ($\langle H \rangle \neq 0$) WITH THE CHARGE TRANSPORT MECHANISM.

$B - L = 0$



BUBBLE EXPANSION

CREATE CHIRAL ASYMMETRY IN BUBBLE WALL

$\langle H \rangle = 0$ SYMM. PHASE

$\not{B}$ "HOT" SPHALERON

CREATE BARYON ASSYMETRY

FREEZE OUT OF B: NEED $v(T)/T \gtrsim 1$ "STRONG 1.O."

THEOR. DESCRIPTION WITH (QUANTUM) BOLTZMANN EQS. (BAYM-KADANOFF)

+ DIFFUSION EQS. ; CP-VIOLATION $\rightarrow \hbar, \hbar^2$.. EFFECTS

T. KONSTANDIN
T. PROKOPEC
M. G. SCH.
S. WEINSTOCK

IN THE SM ??

- FIRST ORDER P.T. : NAIVELY, YES

WITH THERMAL MASS $\pm\phi^2 T^2$

BUT IR-EFFECT FOR $\phi_{HIGGS} \to 0$

NON PERTURBATIVE EFF. 3-D-THEORY

WITH COUPLING $g_2^2 T$ → LATTICE

⇝ NO PHASETRANS. FOR $m_H \gtrsim m_W$

- CP-VIOLATION

JARLSKOG-DETERMINANT

PERTURBATIVE IN Q-MASSES!

SMALL!

$$\Delta_{CP} = J\,(m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2)(m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2) / v^{12} \approx 10^{-19}$$

T^{12} ?

WITH

$$J = \mathrm{Im}\,(V_{ud} V_{dc}^{+} V_{cb} V_{bu}^{+}) = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta$$

$\approx (3.0 \pm 0.3)\, 10^{-5}$ NOT SO SMALL

? CKM

? MISSLEADING AT SMALL TEMPERATURES

IN A TACHYONIC ELECTROWEAK TRANSITION ⇝ "COLD BARYOGENESIS"

J. SMIT
A. TRANBERG

- DERIVE CP-VIOLATING TERM(S) IN BOSONIZED SM, INTEGRATING OUT FERMIONS (SECOND ORDER DERIVATIVE EXPANSION, WORLD LINE METHOD) $\sum_i$ 3 GENER

$$S_{CP} = \frac{1}{8(4\pi)^2}\frac{3}{16}\,[J]\,\kappa^{CP}\,\epsilon^{\mu\nu\lambda\sigma}\,\frac{1}{\tilde{m}_c^2}\times\int d^4x\left[Z_\mu W^+_{\nu\lambda} W^-_\alpha \left(W^+_\sigma W^-_\alpha + W^+_\alpha W^-_\sigma\right) + c.c.\right]$$

$[J] \sim 10^{-5}$!

OUTER GAUGE B. + HIGGS-F.

$\kappa^{CP} \simeq 9.87$ (NONPERT. EXPRESSION IN q-MASSES)

A. HERNANDEZ
T. KONSTANDIN
M.G. SCH.

- INTRODUCE HIGGS INSTABILITY AT SMALL TEMPERATURES (→ LOW SCALE HYBRID INFLATION ...) → TACHYONIC MODES
SOLVE CLASSICAL GAUGE-HIGGS EQS. AND MONITOR GENERATION OF CS NUMBER ("BARYOGENESIS")

A. TRANBERG +

LOOKS PROMISING (PROBLEMS: DERIVATIVE EXP. + CUT OFF IN IR)

NOTE: PT IN THE RANDALL-SUNDRUM MODEL WITH VERY FLAT RADION STABILIZING POTENTIAL → VERY STRONG SUPERCOOLING T_N

$v/T_N \gtrsim 1$, EASY

("LOW SCALE INFLATION")

NARDINI
QUIROS
WULZER

CREMINELLI
NICOLIS
RATTAZZI

BEYOND THE SM

SHAPOSHNIKOV ET AL.
BERNREUTER
CLINE '06
FROMME, HUBER, SENIUCH '06

Motivation?

- **TWO-HIGGS DOUBLET MODEL(S)**

  "EXTRA" HIGGS WITH MASS ~300 GeV
  STRONGLY COUPLED TO LIGHT HIGGS → STRONG 1. ORDER PT
  SPONTENEOUS + EXPLICIT CP-VIOL.
  "THICK WALL" ($p \sim T \ll 1/D$) → QUASICLASSICAL/WKB

- **SUPERSYMMETRIC MODELS**

  - MSSM MOST POPULAR

    INCLUDE GAUGE SINGLET

  - NMSSM $W = W_{MSSM} + \lambda S H_1 H_2 - m^2 S + \frac{k}{3!} S^3 + \{\mu H_1 H_2\}$ — HUBER, SCH.; FUNAKUBO ET AL.
  - nMSSM $W = W_{MSSM} + \lambda S H_1 H_2 - m^2 S$ + (SOFT) SUSY BREAKING TERMS — HENON, MORRISEY, WAGNER '04; HUBER, KONSTANDIN, PROKOPEC, SCH. '06
  - μνSSM $S \to \tilde{\nu}_i$ CHUNG, LONG
  - BMSSM HIGHER DIM. OPERATORS IN EFF. POTENTIAL BLUM, NIR..

→ TREE-LEVEL EFFECTS

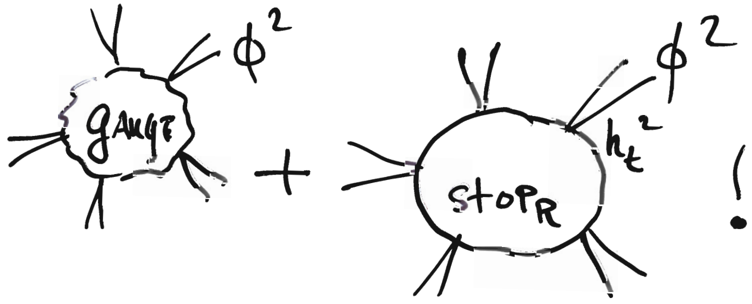
MSSM

INCREASE "ϕ^3" - TERM WITH A LIGHT $stop_R \equiv u$ IN THE LOOP

$$m^2_{LOOP} = \tilde{m}_u^2 + \underbrace{\ldots T^2}_{POS.} \simeq \text{SMALL!}$$

LAB. $$m^2_{STOP_R} = \underbrace{\tilde{m}_u^2}_{NEG.!} + \underbrace{h_t^2 \phi^2}_{m^2_{TOP}} < m^2_{TOP}$$

CARENA, QUIROS, WAGNER



GET ALSO (INTERMEDIATE?!) COLORED PHASE

- LOWEST HIGGS IS SM-LIKE! ⇒ EXPER. BOUNDS! $m_H \gtrsim 114.4$ GeV

LIGHT HIGGS BOSON?

$g_{hZZ} / g_{h^{SM}ZZ} = \sin(\beta - \alpha)$ SMALL? FUNAKUBO, SENAHA

EVEN SMALLER WITH STRONG ~~CP~~?

- BUT NOT SUFFICIENT BARYOGENESIS! PILAFTSIS WAGNER

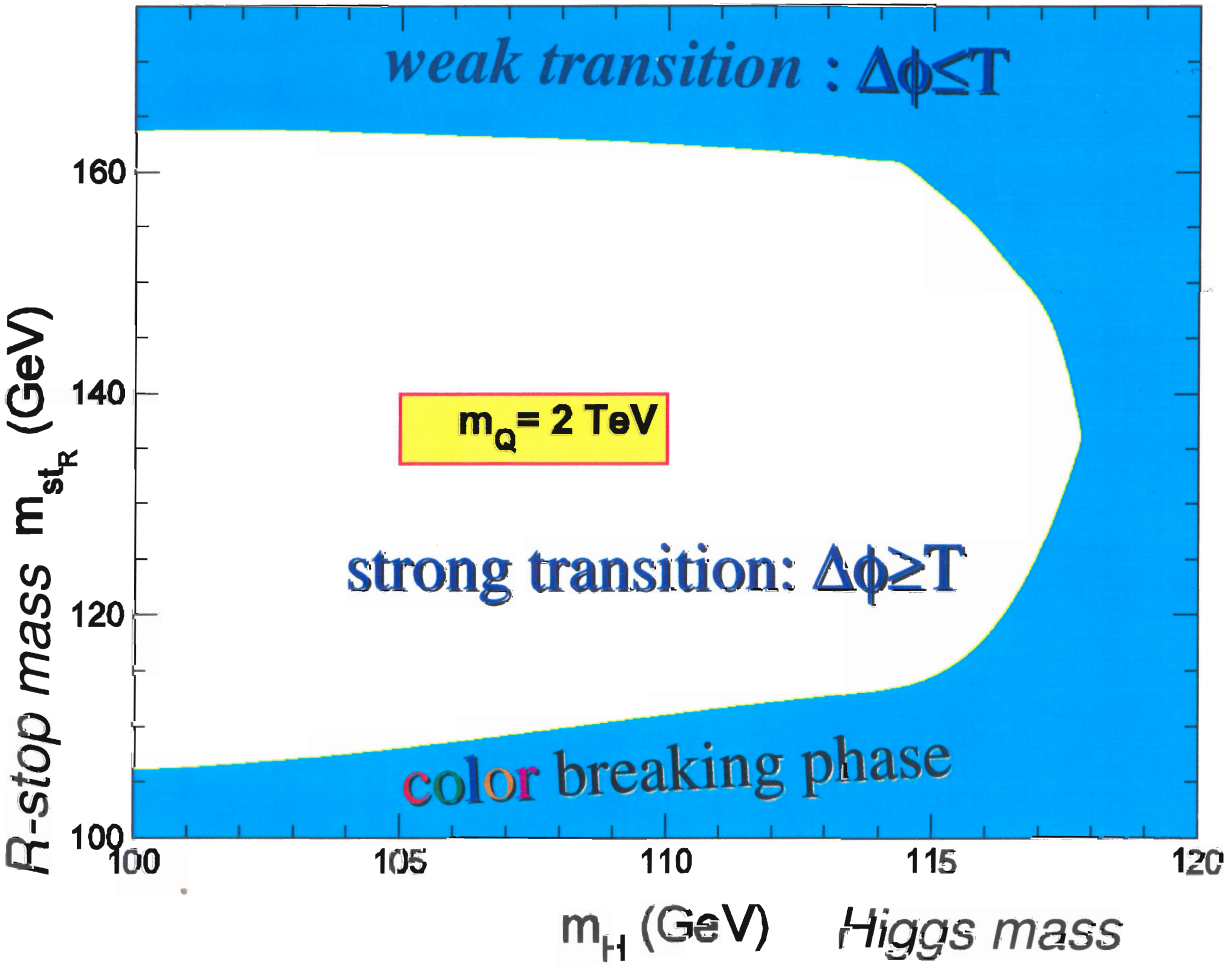
BODEKER ET AL.
LAINE RUMMUKAINEN

- CAN GET STRONG 1. ORDER PT TO HIGGS PHASE : $\frac{v(T)}{T} \gtrsim 1$

Strong first order transition in MSSM

allowed "triangle" for MSSM:

Carena, Quiros, Seco, Wagner, 2000



CARENA, NARDINI, QUIRÓS, WAGNER

'09 ANALYSE IN 1-LOOP IMPROVED (DAISY, "2-LOOP" LOG'S) THEORY THE PHASE DIAGRAM. FIND EXTENSION OF "ALLOWED" REGION IN ($m_{stop_R} - m_H$) ADMITTING QUASI STABLE H-VACUA FOR LARGE SUSY MASS SCALE $\tilde{m}$

(NOT IN EFF. 3D THEORY)

AGAINST DECAY INTO COLORED PHASE

(THUS ALSO SUPPRESSING EDM)

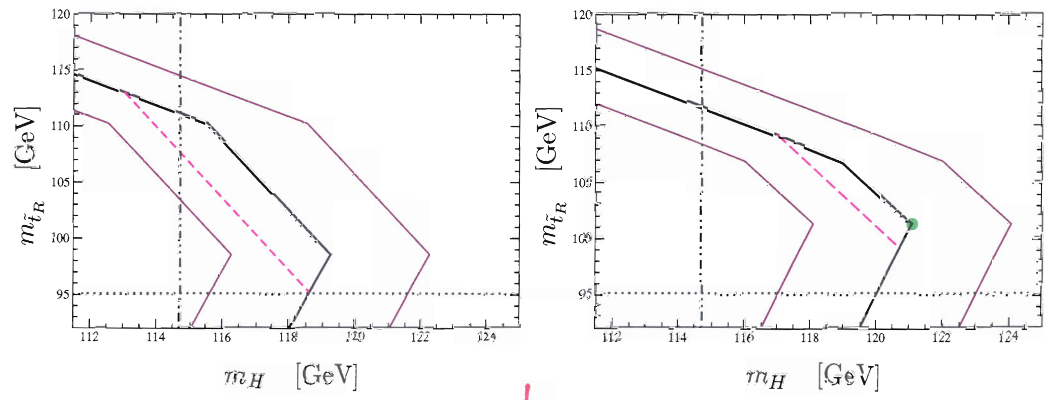


Figure 3: Window where $\phi(T_H^c)/T_H^c \geq 0.9$ and $T_R^c \geq T_U^c + 1.6$ GeV in the m_H-$m_{\tilde{t}}$ plane for $\tilde{m} = 500$ TeV (left panel) and $\tilde{m} = 8000$ TeV (right panel). The allowed region is below the solid lines and dashed lines for $\tan\beta \leq 15$ and $\tan\beta \leq 5$, respectively. The thick solid line is obtained by ignoring the Higgs mass uncertainty, while the solid thin lines is obtained by including an uncertainty of 3 GeV in the Higgs mass computation. The Higgs (stop) mass lower bound is marked by a dotted–dashed (dotted) straight line. In green (right panel) the point that will be numerically analyzed in the tunneling analysis.

- $m_H, m_{stop_R} \lesssim 125$ GeV

- CP-VIOLATION IN THE MSSM : IN THE HIGGSINO-GAUGINOS, STOP$_L$ - STOP$_R$

$$M(z) = \begin{pmatrix} M_2 & g_2 \langle H_2(z) \rangle \\ g_2 \langle H_1(z) \rangle & \mu_c \end{pmatrix}$$

$(\mu H_1 H_2)$

EXPLICIT BREAKING BY M_2 / μ_c PHASES

NO SPONTANEOUS BREAKING IN HIGGS SECTOR

z-DEPENDENCE IN BUBBLE WALL

PHASES LIMITED BY edm's !

NOTE — FOR SINGLET S : $\mu_c(S)$!

— $M_2 \to M_1$ (BINO) ?!

PHASE !

(MUCH LESS RESTRICTIVE FOR EDM's)

CIRIGLIANO, LI, PROFUMO, RAMSEY-MUSOLF

"edm"

- ELECTRIC DIPOL MOMENTS ARE A MEASURE FOR CP VIOLATION

IN PARTICULAR THE NEUTRON edm IS VERY SENSITIVE TO CP VIOLATIONS NEEDED FOR ELECTROWEAK BARYOGENESIS

exper. $d_n \lesssim 2.9 \times 10^{-26}\ e\ cm$

TO BE IMPROVED!

D. DUBBERS
M. G. SCH.
RMP

SM $d_n^{CKM} \simeq 10^{-32}\ e\ cm$ VERY SMALL

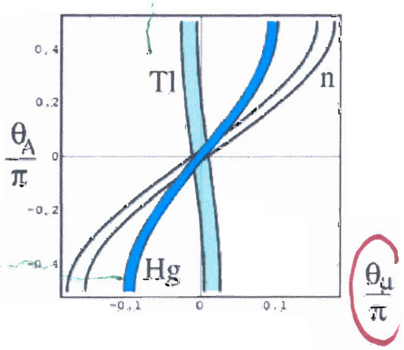
MSSM: exp.: ALREADY VERY RESTRICTIVE

IBRAHIM
NATH

BIG 2

$$M_{susy} \underset{1\text{-LOOP}}{\gtrsim} (\sin\theta_\mu \tan\beta - \sin\theta_A) \cdot 1.5\ TeV$$

^{205}Tl



^{199}Hg

FOR SMALL SUSY-BREAKING SCALE M_{susy}

WELL.. BUT..

- UNIVERSAL SUSY BREAKING?
- BIG SQUARK MASSES
- SIZABLE 2-LOOP CONTRIB.
- CANCELLATIONS ?
- HIGHER DIMENSIONAL TERMS ?
- BINO-MASS CP

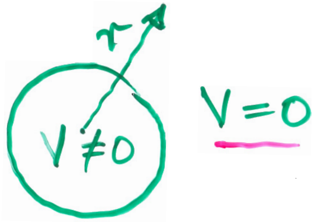
ELLIS
LEE
PILAFTSIS
LI
PROFUMO
RAMSEY-MUSOLF

In supersymmetric (SUSY) extensions of the Standard Model, particle EDMs are naturally large. In a two-parameter minimal SUSY-model (MSSM), particle EDMs depend only on two phase angles θ_A and θ_μ. Shown are experimental atomic and neutron EDM limits that strongly constrain these phases to near the origin $\theta_A = \theta_\mu = 0$ where the three bands of the figure cross – much too small for electroweak baryogenesis. From Pospelov and Ritz (2005)

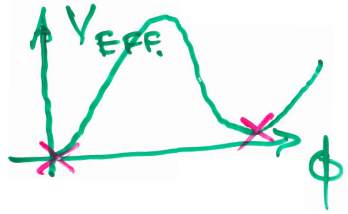
CONDITIONS FOR A STRONG FIRSTORDER ELWK. P.T. MUCH EASIER TO FULFILL IN THE NMSSM, nMSSM ⇒ TREE LEVEL "Φ^3" ($H, S \ldots$)

GIVEN SUCH A STRONG PHASE TRANSITION THE PROCEDURE TO OBTAIN A BARYON ASYMMETRY HAS QUITE A FEW STEPS, BUT ALL OF THEM VERY CONCRETE AND FEASABLE

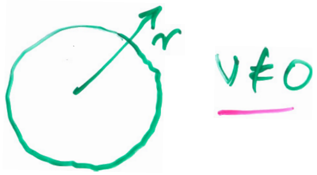
- CRITICAL BUBBLE (MULTIDIM. IN HIGGS FIELDS) ("DET"!)



- TRANSITION PROBABILITY (LANGER FORM.) $\sim e^{-S_{EFF}}$

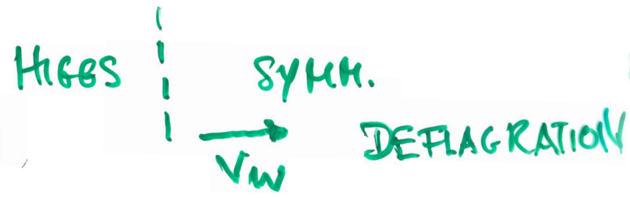


- SUPERCOOLING ("1 BUBBLE/UNIVERSE")
  NUCLEATION TEMPERATURE
- SPHALERON RATE (MULTIDIM. IN HIGGS F.) (FLUCTUATIONS!)



- STATIONARY EXPANSION OF BUBBLE

→ $V_W = ?$, WALL PROFILE — V_W SMALL! BIG? (GRAVITY WAVES)



- DIFFUSION IN PRESENCE OF MOVING WALL

→ WITH CP-VIOLATING WALL OR EXPLICIT ~~CP~~ INTERACTION

! (QUANTUM) BOLTZMANN EQS., GENERATE CHIRAL ASYMMETRY $n_{q_L} - n_{\bar{q}_L}$

KONSTANDIN
PROKOPEC
M.G.SCH.
/WEINSTOCK

* MSSM : SOLVE THE BK EQS.

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

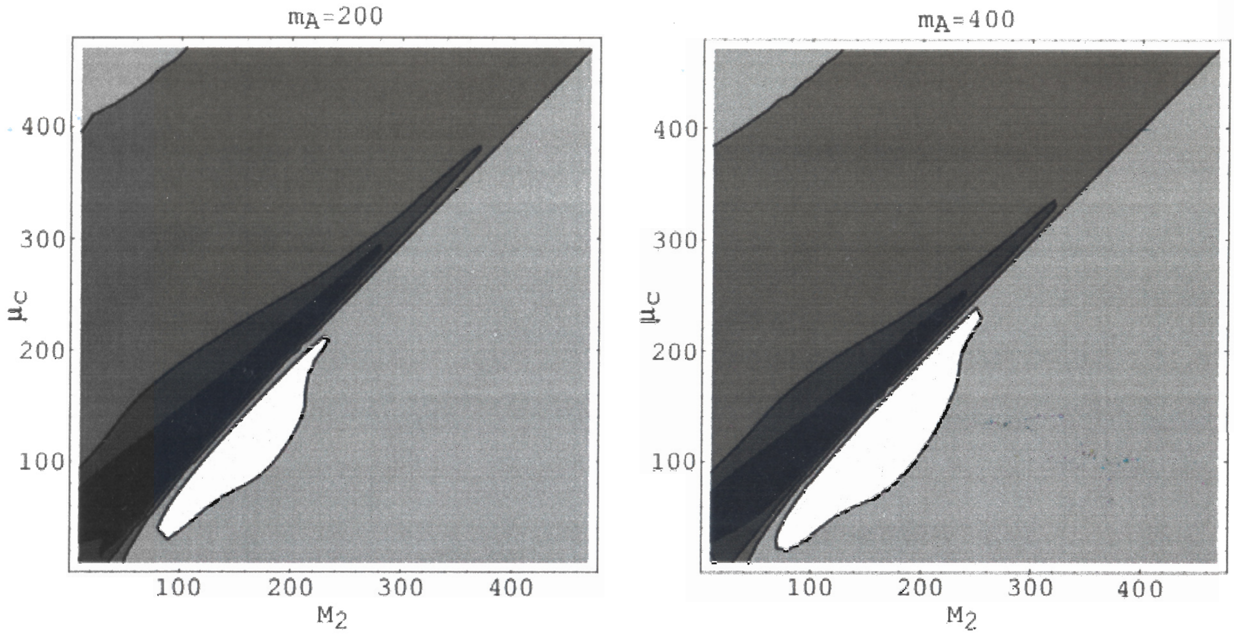


FIG. 5: The baryon-to-entropy ratio $\eta_{10} = 10^{10} \times \eta$ in the (M_2, μ_c) parameter space from (0 GeV,0 GeV) to (400 GeV,400 GeV). For the left plot the value $m_A = 200$ GeV is used, for the right plot $m_A = 400$ GeV. The black region denotes $\eta_{10} > 1$, where baryogenesis is viable.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

$|d_e| \lesssim 1.6\ 10^{-27}$ ecm

Regan et al PRL 88 071805, 2002

MAXIMAL CP-VIOLATION

! RESTRICTIONS BY exp. n/e - ELECTRIC DIPOL LIMITS

~ CP-VIOL. PHASE < 0.1

QUASICLASSICAL CONTR. $\sim \hbar^2$

+ OSCILLATING "RESONANT" CONTR. $\sim \hbar$ DOMINATES

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

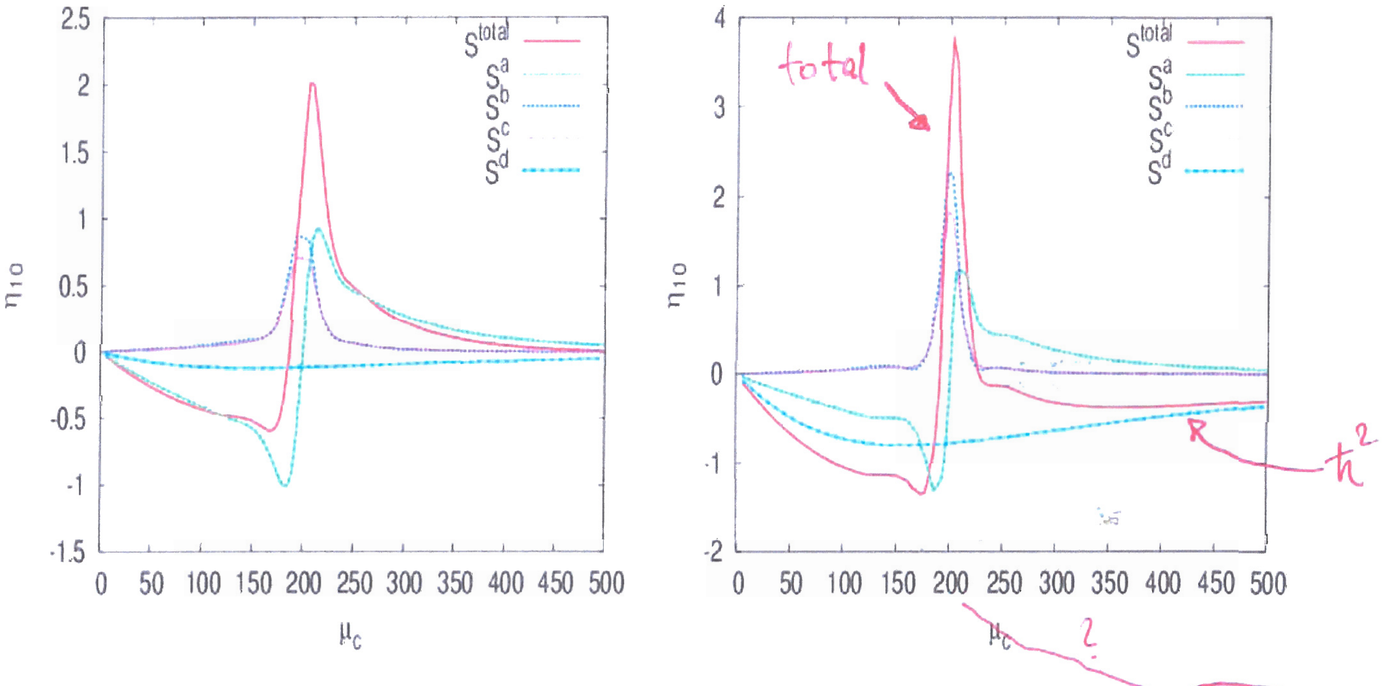


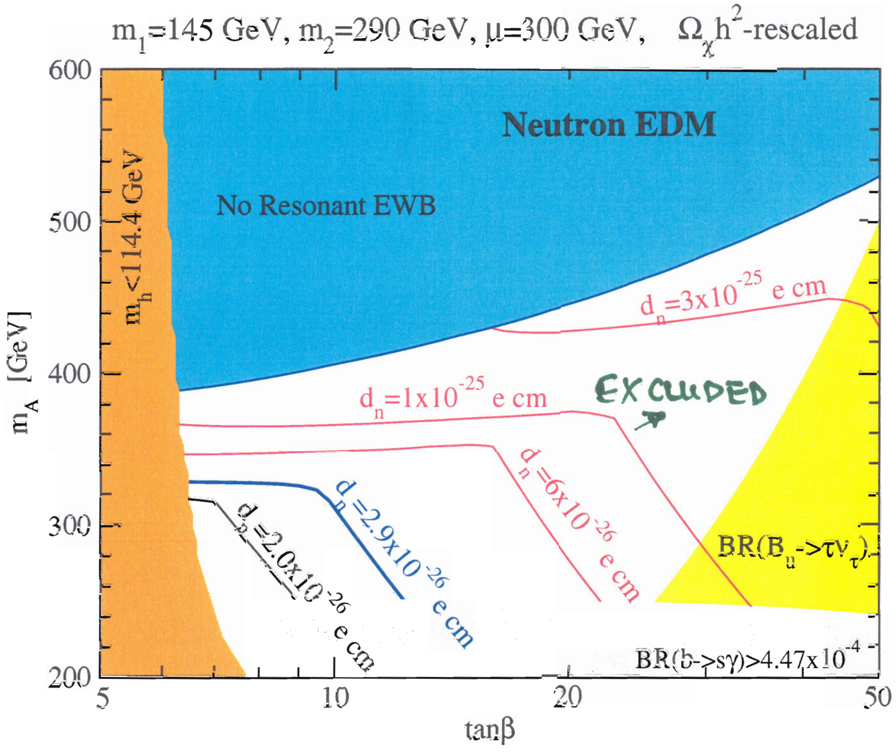
FIG. 2: This plot shows the first and second order sources as a function of μ_c with $M_2 = 200$ GeV. The plot on the left are the sources with the damping, $\Gamma = \alpha_w T_c$, while on the right plot, $\Gamma = 0.25\alpha_w T_c$.

MAXIMAL CP-VIOLATION ASSUMED

MSSM

"LIMITS ON THE SIZE OF edm's exist, AND ARE TYPICALLY ON THE SAME ORDER, OR ABOVE, THE EXPECTED SENSITIVITY OF THE NEXT GENERATION OF EXPERIMENTAL SEARCHES, IMPLYING THE MSSM BARYOGENESIS WILL BE SOON CONCLUSIVELY TESTED"

CLPR



FROM V. CIRIGLIANO, Y. LI, S. PROFUMO, M.J. RAMSEY-MUSOLF
JHEP 01(2010) 002

- NONUNIVERSAL gaugino-HIGGSINO PHASES (..BINO-MASS..)
- REANALYSIS OF DIFFUSION PROCESSES LEADING FROM gaugino-Higgsino → l.h. quarks NEEDED FOR THE SPHALERON TRANSITION

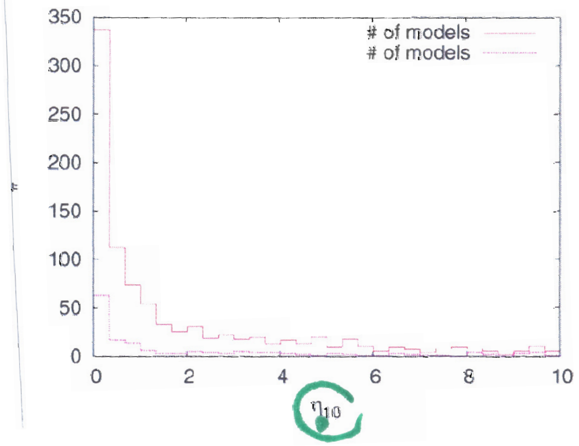
b, τ CONTRIBUTION, SUSY NONDEGENERACY ...

CHUNG, GARBRECHT, RAMSEY-MUSOLF, TULIN '09

HUBER
KONSTANDIN
PROKOPEC
SCH.
'06

- THE nMSSM (WITH A SINGLET "HIGGS" S) EASILY ALLOWS FOR A STRONG 1. ORDER P.T. FROM TREE-LAGR.!
(... QUITE A FEW PARAMETERS ...) edm - BOUNDS FOR CP-VIOLATION ARE VERY RESTRICTIVE.

"RANDOM CHOICE"



The number # of results for the analysis of the baryon asymmetry of the universe for large M_2 = 1 TeV, in dependence of the baryon-entropy abundance parameter $\eta_{10}^s = (n_B / s)\times 10^{10}$. Approximately 50% of the parameter sets predict a value of the baryon asymmetry higher than the observed value $\eta_{10}^s = 0.87$. The bottom line corresponds to the small number of parameter sets (4.8%) that fulfill current bounds at the electron EDM with 1 TeV sfermions. From Huber *et al.* (2006).

- **HIGHER DIMENSION OPERATORS** IN AN EFFECTIVE THEORY INCLUDING THE SM

"ϕ^{3}" ! → STRONG 1. ORDER

$$V(H) = -\mu^2 H^+H + \frac{\lambda}{4}(H^+H)^2 + \frac{1}{\Lambda^2}(H^+H)^3$$

$$+ \frac{Z_{ij}^u}{\Lambda_{CP}^2}(H^+H)\, u_i^c Q_j H + \dots$$

↖ CP-VIOLATING

ZHANG

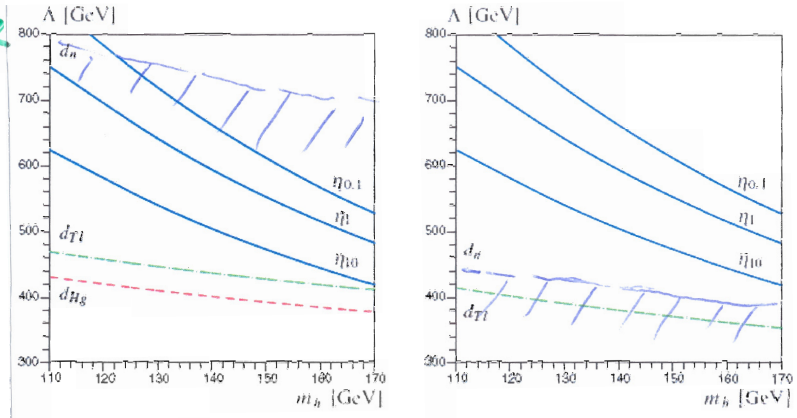
BÖDEKER FROMME HUBER SENIUCH

GROJEAN SERVANT WELLS

(FROM 2H DOUBLET MODEL ?)

$\Lambda \sim \Lambda_{CP}$?

STRONG edm BOUNDS



HUBER POSPELOV RITZ '07

... EDM constraints on electroweak baryogenesis for an extended SM Higgs sector. Shown are the Higgs masses m_h and scales Λ of new physics excluded (shaded areas) by the present EDM limits for neutron d_n, thallium d_{Tl}, and mercury d_{Hg}. (a) In the minimal scenario, the observed baryon asymmetry $\eta_1 = 6 \cdot 10^{-10}$ is excluded by the present limit on the neutron EDM d_n (and so is one tenth and ten times η_1). (b) Therefore, additional *CP*-odd sources must be introduced to lower the exclusion limits. From Huber *et al.* (2007).

- ALSO IN THE MSSM SUCH OPERATORS HELP TO OBTAIN STRONG 1. ORDER P.T.

$$W_{DST} = \frac{\lambda_1}{M}(H_u H_d)^2 + \frac{\lambda_2}{M}\theta^2 m_{susy}(H_u H_d)^2$$

DINE, SEIBERG, THOMAS

"BMSSM" (Beyond)

BLUM NIR '08

SPONTANEOUS CP VIOLATION IN HIGGS SECTOR!

CONCLUSIONS

- BARYOGENESIS TIGHTLY CONNECTS COSMOLOGY AND ELEMENTARY PARTICLE PHYSICS
- ELECTROWEAK BARYOGENESIS INGREDIENTS WILL BE TESTED IN THE NEAR FUTURE BOTH BY HIGH ENERGY / COLLIDER EXPERIMENTS AND BY LOW ENERGY EDM MEASUREMENTS !
- ALL STEPS TOWARDS MODELING ELWK. BARYOGENESIS MANAGEABLE - THOUGH TECHNICALLY DEMANDING
- MSSM - BARYOGENESIS STRONGLY CONSTRAINED RULED OUT SOON ?
- BUT THERE ARE VARIOUS OTHER POSSIBILITIES - MODIFIED SSM'S, 2HIGGS ... -