ORIGIN OF MATTER

M. QUIROS

OXFORD

September 26, 2008

Outline

- INTRODUCTION AND SM RESULTS
- NETWORK RESULTS
  - Electroweak Baryogenesis $B + L \neq 0$
  - Leptogenesis $B - L \neq 0$

INTRODUCTION AND SM RESULTS

- The problem is the dynamical origin of the matter-antimatter asymmetry

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

- Conditions for baryogenesis were stated by Sakharov in 1967 [a]
  - B-violation
  - C and CP violation
  - Departure from thermal equilibrium
-

> Kuzmin, Rubakov and Shaposhnikov considered in 1985 the possibility of baryogenesis at the electroweak phase transition (EWPT)

- The question that created lot of excitement in the physics community was:

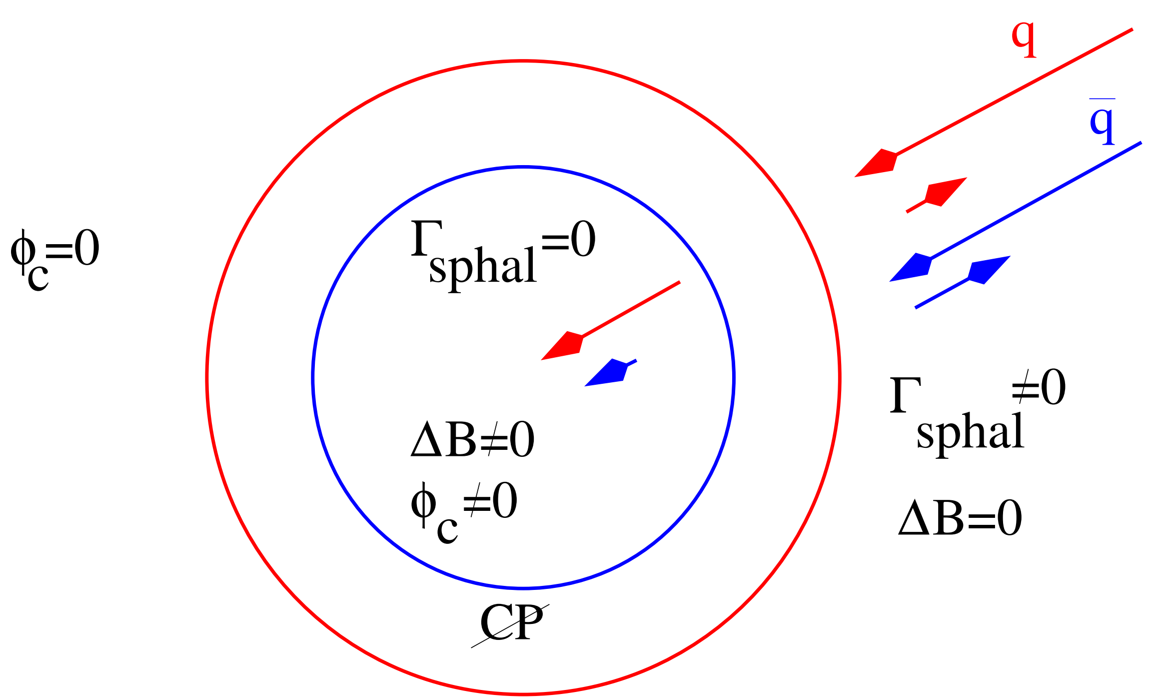
[a] A.D. Sakharov, JETPL 91B (1967) 24

CAN THE SM PRODUCE BARYOGENESIS?

- In fact the SM contains all the ingredients required by Sakharov's conditions
  - Baryon number is perturbatively conserved in the SM but it is non-perturbatively violated: sphalerons at finite temperature
  - C and CP violating phases are present in the SM: the CKM phase
  - The out-of-equilibrium conditions are present in the bubble wall in a

FIRST ORDER PHASE TRANSITION

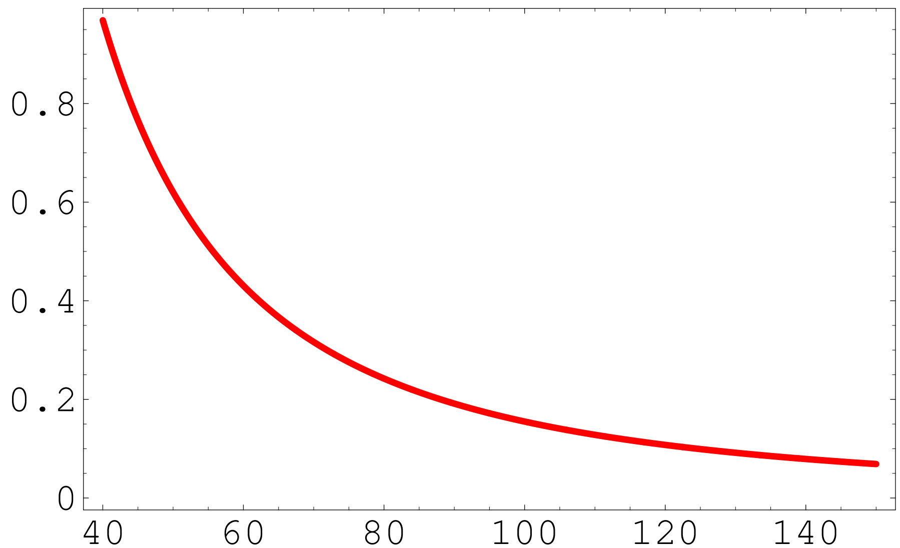
- A nice mechanism for the (electroweak) generation of the baryon asymmetry of the universe (BAU) was suggested by Cohen, Kaplan and Nelson in 1993 using CP violating interactions of fermions with the domain wall of a bubble. In this way the reflection and transmission coefficients of fermions and anti-fermions scattering off the CP violating wall are different



- If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase $\Rightarrow$ $\boxed{\frac{\phi_c}{T_c} \geq 1}$

- Although the SM contains all the ingredients for EWBG it fails quantitatively because:

  - The phase transition is not strong enough. Would a BAU be generated it would be erased by weak sphalerons in the broken phase. In fact the strength of the phase transition strongly depends on the Higgs mass and for present experimental limits it is extremely weak. A one-loop (improved by hard thermal loops) result is plotted



  - The CP violation provided by the CKM phase is too small to generate the required BAU

BAU $\Rightarrow$ NEW PHYSICS

ELECTROWEAK BARYOGENESIS

- It is triggered by sphalerons: i.e. $B - L = 0$ and $B + L \neq 0$
- It can be easily falsified at LHC
- It does not work in the SM
- Two possible avenues are explored
  - Extensions of the SM with hidden sectors (singlets under the SM gauge group)
  - Minimal Supersymmetric extension of the SM (MSSM) with extra sources of CP violation: it works under very special conditions
    - Refining the bounds of the MSSM
    - NMSSM

LEPTOGENESIS

- It is triggered by Majorana masses for right-handed neutrinos: $L \neq 0$.
- Sphalerons will process $B \neq 0$ out of $L \neq 0$
- New sources of CP violating phases in the neutrino mass matrix
- It requires out-of-equilibrium conditions in right-handed neutrino decays
- Requires conditions on the amount of CP violation and neutrino masses
- Mechanism is enhanced if some masses are very close to each other: resonant leptogenesis
- Important role of flavors such that only some $L_f \neq 0$: flavored leptogenesis
- In GUT's leptogenesis starts from $G \supseteq SO(10)$

NETWORK RESULTS: ELECTROWEAK BARYOGENESIS

SM WITH HIDDEN SECTORS

- J. R. Espinosa and M. Quiros, “Novel effects in electroweak breaking from a hidden sector,” Phys. Rev. D **76** (2007) 076004 [arXiv:hep-ph/0701145].
- J. R. Espinosa, T. Konstandin, J. M. No and M. Quiros, arXiv:0809.3215 [hep-ph].

  Cosmological implications of extensions of the Standard Model with hidden sector scalars coupled to the Higgs boson are studied. Special emphasis on the conformal case, in which the electroweak symmetry is broken radiatively with a Higgs mass above the experimental limit. The refined analysis of the electroweak phase transition strengthens the prediction of a strongly first-order phase transition as required by electroweak baryogenesis. Gravitational wave production and the possibility of low-scale inflation as well as a viable dark matter candidate are considered

- G. Nardini, M. Quiros and A. Wulzer, “A Confining Strong First-Order Electroweak Phase Transition,” JHEP **0709** (2007) 077 [arXiv:0706.3388 [hep-ph]].

  In the Randall-Sundrum model where the radion is stabilized by a Goldberger-Wise (GW) potential there is a supercooled transition. When the Higgs is localized at the IR brane the electroweak phase transition is delayed and becomes a strong first-order one where the Universe expands by a few e-folds. This generates the possibility of having the out-of-equilibrium condition required by electroweak baryogenesis in the electroweak phase transition

- B. Hassanain, J. March-Russell and M. Schvellinger, “Warped Deformed Throats have Faster (Electroweak) Phase Transitions,” JHEP **0710** (2007) 089 [arXiv:0708.2060 [hep-th]].

  The dynamics of the finite-temperature phase transition for warped Randall-Sundrum(RS)-like throat models related to the Klebanov-Tseytlin solution is found. For infrared branes stabilized near the tip of the throat, the bounce action has a mild N^2 dependence, where N is the effective number of degrees of freedom of the holomorphic theory. In addition, the bounce action is not enhanced by large numbers. These features allow the transition to successfully complete over a wider parameter range than for Goldberger-Wise stabilized RS models.

NETWORK RESULTS: ELECTROWEAK BARYOGENESIS

MSSM

- M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, arXiv:0806.4297 [hep-ph].
- M. Carena, G. Nardini, M. Quiros and C.E.M. Wagner, “The baryogenesis window in the MSSM”

  An allowed window in the $(m_{\tilde{t}}, m_H)$-plane, consistent with all present experimental data, where there is a strongly first-order electroweak phase transition and where the electroweak vacuum is metastable but sufficiently long-lived is found. In particular there are absolute upper bounds on the Higgs and stop masses, $m_H < 125$ GeV and $m_{\tilde{t}} < 125$ GeV, implying that this scenario will be probed at the LHC.

NETWORK RESULTS: ELECTROWEAK BARYOGENESIS

nMSSM

- Stephan J. Huber, Thomas Konstandin, Tomislav Prokopec, Michael G. Schmidt, Nucl.Phys.A785:206-209,2007 & Nucl.Phys.B757:172-196,2006

  The nMSSM ($W = SH_1H_2 - m^2S$) with CP violation in the singlet sector is analyzed. It is concluded that electroweak baryogenesis in this model is generic in the sense that if the present limits on the mass spectrum are applied, no severe additional tuning is required to obtain a strong first-order phase transition and to generate a sufficient baryon asymmetry. Still, first and second generation sfermions must be heavy to avoid large electric dipole moments.

NETWORK RESULTS: LEPTOGENESIS

CP VIOLATION AND LEPTOGENESIS

- S. Pascoli, S. T. Petcov and A. Riotto, “Connecting low energy leptonic CP-violation to leptogenesis,” Phys. Rev. D **75** (2007) 083511 [arXiv:hep-ph/0609125]; S. Pascoli, S. T. Petcov and A. Riotto, “Leptogenesis and low energy CP violation in neutrino physics,” Nucl. Phys. B **774** (2007) 1 [arXiv:hep-ph/0611338].
- E. Molinaro and S. T. Petcov, “The Interplay Between the ’Low’ and ’High’ Energy CP-Violation in Leptogenesis,” arXiv:0803.4120 [hep-ph].

It was commonly thought that the observation of low energy leptonic CP-violating phases would not automatically imply the existence of a baryon asymmetry in the leptogenesis scenario. This conclusion does not generically hold when the issue of flavour is relevant and properly taken into account in leptogenesis.

We illustrate the possible correlations between the baryon asymmetry of the Universe and i) the magnitude of CP-violation in neutrino oscillations, or ii) the effective Majorana mass in neutrinoless double beta decay, in the cases when the only source of CP-violation is respectively the Dirac or the Majorana phases in the neutrino mixing matrix.

NETWORK RESULTS: LEPTOGENESIS

m_ν AND LEPTOGENESIS

- S. M. West, "Neutrino Masses And Tev Scale Resonant Leptogenesis From Supersymmetry Breaking," Mod. Phys. Lett. A **21** (2006) 1629.
- E. Molinaro, S. T. Petcov, T. Shindou and Y. Takanishi, "Effects of Lightest Neutrino Mass in Leptogenesis," Nucl. Phys. B **797** (2008) 93 [arXiv:0709.0413 [hep-ph]].

It is shown, in particular, that if the lightest neutrino mass m_3 in the case of inverted hierarchical spectrum lies the interval $5 \times 10^{-4} eV < m_3 < 7 \times 10^{-3} eV$, the predicted baryon asymmetry can be larger by a factor of ~ 100 than the asymmetry corresponding to negligible $m_3 \cong 0$. As consequence, we can have successful thermal leptogenesis for $5 \times 10^{-6} eV < m_3 < 5 \times 10^{-2}$ eV

NETWORK RESULTS: LEPTOGENESIS

EDM AND LEPTOGENESIS

- F. R. Joaquim, I. Masina and A. Riotto, “Observable electron EDM and leptogenesis,” Int. J. Mod. Phys. A **22** (2007) 6253 [arXiv:hep-ph/0701270].

  In the context of the minimal supersymmetric seesaw model, the CP-violating neutrino Yukawa couplings might induce an electron EDM. The same interactions may also be responsible for the generation of the observed baryon asymmetry of the Universe via leptogenesis. We identify in a model-independent way those patterns within the seesaw models which predict an electron EDM at a level probed by planned laboratory experiments and show that negative searches on $\tau \longrightarrow e\gamma$ decay may provide the strongest upper bound on the electron EDM. We also conclude that a possible future detection of the electron EDM is incompatible with thermal leptogenesis, even when flavour effects are accounted for

NETWORK RESULTS: LEPTOGENESIS

QUANTUM BOLZMAN EFFECTS IN LEPTOGENESIS

- A. De Simone and A. Riotto, "On Resonant Leptogenesis," JCAP **0708** (2007) 013 [arXiv:0705.2183 [hep-ph]]; A. De Simone and A. Riotto, "Quantum Boltzmann Equations and Leptogenesis," JCAP **0708** (2007) 002 [arXiv:hep-ph/0703175].
- V. Cirigliano, A. De Simone, G. Isidori, I. Masina and A. Riotto, "Quantum Resonant Leptogenesis and Minimal Lepton Flavour Violation," JCAP **0801** (2008) 004 [arXiv:0711.0778 [hep-ph]].

It has been recently shown that the quantum Boltzmann equations may be relevant for the leptogenesis scenario. In particular, they lead to a time-dependent CP asymmetry which depends upon the previous dynamics of the system. This memory effect in the CP asymmetry is particularly important in resonant leptogenesis where the asymmetry is generated by the decays of nearly mass-degenerate right-handed neutrinos. We study the impact of the nontrivial time evolution of the CP asymmetry in resonant leptogenesis, both in the one-flavour case and with flavour effects included. We show that significant qualitative and quantitative differences arise with respect to the case in which the time dependence of the CP asymmetry is neglected.

NETWORK RESULTS: LEPTOGENESIS

SUPERSYMMETRIC LEPTOGENESIS

- S. Khalil and A. Masiero, "Radiative B-L symmetry breaking in supersymmetric models," Phys. Lett. B **665** (2008) 374 [arXiv:0710.3525 [hep-ph]].
- G. F. Giudice, L. Mether, A. Riotto and F. Riva, "Supersymmetric Leptogenesis and the Gravitino Bound," Phys. Lett. B **664** (2008) 21 [arXiv:0804.0166 [hep-ph]].
- S. Davidson, J. Garayoa, F. Palorini and N. Rius, "CP Violation in the SUSY Seesaw: Leptogenesis and Low Energy," arXiv:0806.2832 [hep-ph].

  We study the sensitivity of the baryon asymmetry to the phases of the lepton mixing matrix, and find that leptogenesis can work for any value of the phases. We also estimate the contribution to the electric dipole moment of the electron, arising from the seesaw, and find that it is (just) beyond the sensitivity of next generation experiments ($< 10^{-29} e$ cm). The fourteen dimensional parameter space is efficiently explored with a Monte Carlo Markov Chain, which concentrates on the regions of interest.

NETWORK RESULTS: LEPTOGENESIS

LEPTOGENESIS AND GUT'S

- M. Frigerio, P. Hosteins, S. Lavignac and A. Romanino, “A new, direct link between the baryon asymmetry and neutrino masses,” arXiv:0804.0801 [hep-ph].
- P. Di Bari and A. Riotto, arXiv:0809.2285 [hep-ph].

  Some conditions on the low energy parameters have to be satisfied in order for inverse processes involving the lightest right-handed neutrino not to wash-out the asymmetry. In particular we find $m_1 > 0.001$ eV, where m_1 is the mass of the lightest left-handed neutrino and that non-vanishing values of the mixing angle θ_{13} are preferred in the case of a normal fully hierarchical spectrum of light neutrinos

NETWORK RESULTS: LEPTOGENESIS

FLAVOURED LEPTOGENESIS

- A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada and A. Riotto, "Flavour issues in leptogenesis," JCAP **0604** (2006) 004 [arXiv:hep-ph/0601083].
- A. Abada, S. Davidson, A. Ibarra, F. X. Josse-Michaux, M. Losada and A. Riotto, JHEP **0609** (2006) 010 [arXiv:hep-ph/0605281].
- S. Antusch, S. F. King and A. Riotto, "Flavour-dependent leptogenesis with sequential dominance," JCAP **0611** (2006) 011 [arXiv:hep-ph/0609038].
- A. De Simone and A. Riotto, "On the impact of flavour oscillations in leptogenesis," JCAP **0702** (2007) 005 [arXiv:hep-ph/0611357].
- S. Davidson, J. Garayoa, F. Palorini and N. Rius, "Insensitivity of flavoured leptogenesis to low energy CP violation," Phys. Rev. Lett. **99** (2007) 161801 [arXiv:0705.1503 [hep-ph]].
- E. Molinaro and S. T. Petcov, "A Case of Subdominant/Suppressed 'High Energy' Contribution in Flavoured Leptogenesis," arXiv:0808.3534 [hep-ph].

NETWORK RESULTS: LEPTOGENESIS

FLAVOURED LEPTOGENESIS

We study the impact of flavour in thermal leptogenesis, including the quantum oscillations of the asymmetries in lepton flavour space. In the Boltzmann equations we find different numerical factors and additional terms which can affect the results significantly. The upper bound on the CP asymmetry in a specific flavour is weaker than the bound on the sum. This suggests that – when flavour dynamics is included – there is no model-independent limit on the light neutrino mass scale,and that the lower bound on the reheat temperature is relaxed by a factor $\sim$ (3 - 10)

NETWORK RESULTS: LEPTOGENESIS

REVIEW ON LEPTOGENESIS

- S. Davidson, E. Nardi and Y. Nir, “Leptogenesis,” arXiv:0802.2962 [hep-ph].

NETWORK STATISTICS ON THE ORIGIN OF MATTER

- Number of papers: 28
- Number of citations: 507
- Average number of citations: 18