ORIGIN OF MATTER

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Outline

- INTRODUCTION AND SM RESULTS
- EWBG IN THE MSSM
- NETWORK RESULTS
  - Baryogenesis
  - Leptogenesis

INTRODUCTION AND SM RESULTS

- 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:

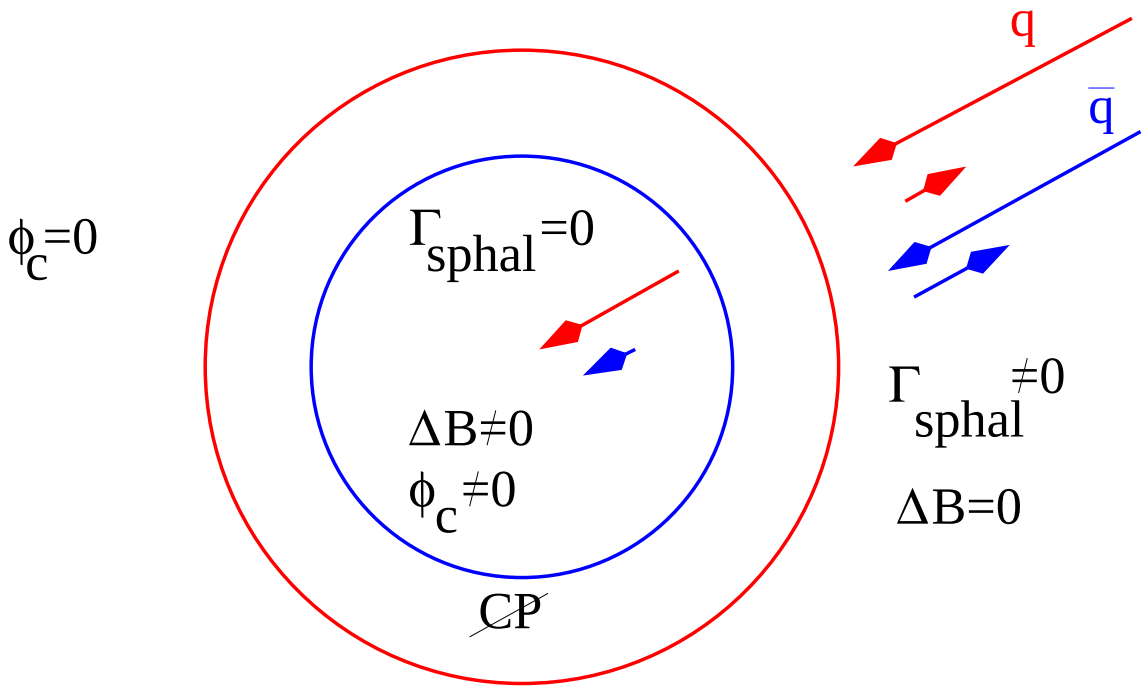
[a] A.D. Sakharov, JETPL 91B (1967) 24

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

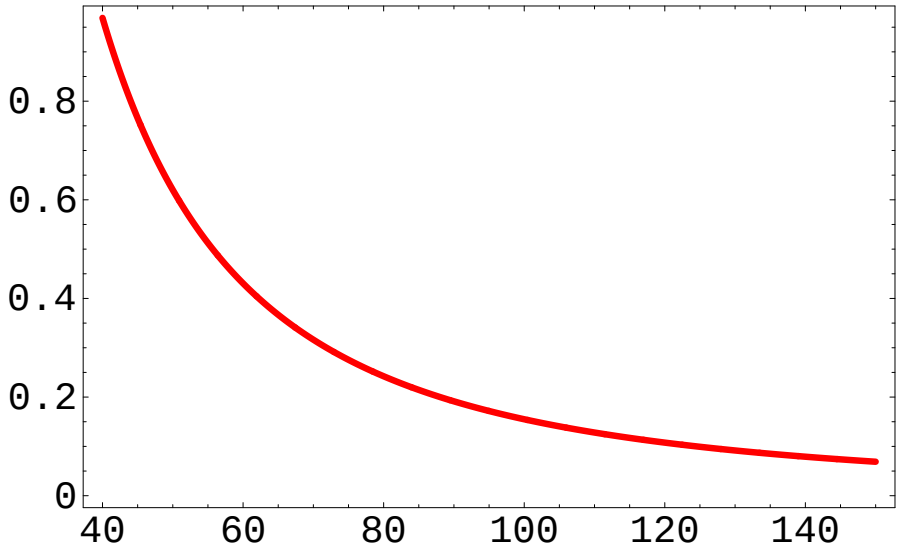
FIRST ORDER PHASE TRANSITION

- A nice mechanism for the 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

EWBG IN THE MSSM

- The lesson we learned up to now is that new physics (extra particles) has to be added to the SM one (ones)

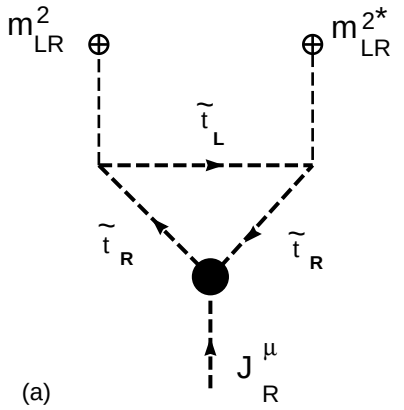
- The obvious candidates are

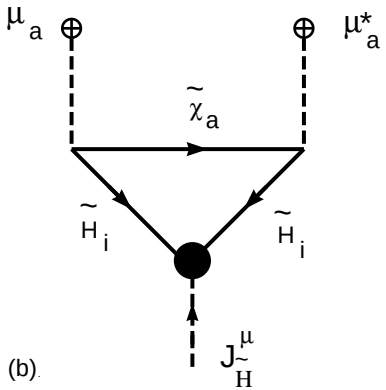
BOSONS STRONGLY COUPLED TO THE HIGGS SECTOR

- Bosons have $n = 0$ Matsubara modes and thus they contribute to the cubic terms in the finite-temperature potential and to create a first order phase transition

- Bosons appear in supersymmetric extensions of the SM: in particular STOPS who are strongly coupled to the Higgs sector (as the top quark itself)

- In the MSSM there is the so-called light stop window [a] where:
  - BAU is produced by fermions: charginos and neutralinos. It is barely consistent with WMAP results for $\mathcal{O}(1)$ phases.





[a] M. Carena, M. Quiros, C.E.M. Wagner, PLB380 (1996) 81

- Strong first order phase transition is triggered by bosons: stops and Higgses.
- In particular BAU is not erased in the broken phase if
  - Right-handed stop are light: $\sim m_t$ not to shield the phase transition
  - The SM-like Higgs is light enough

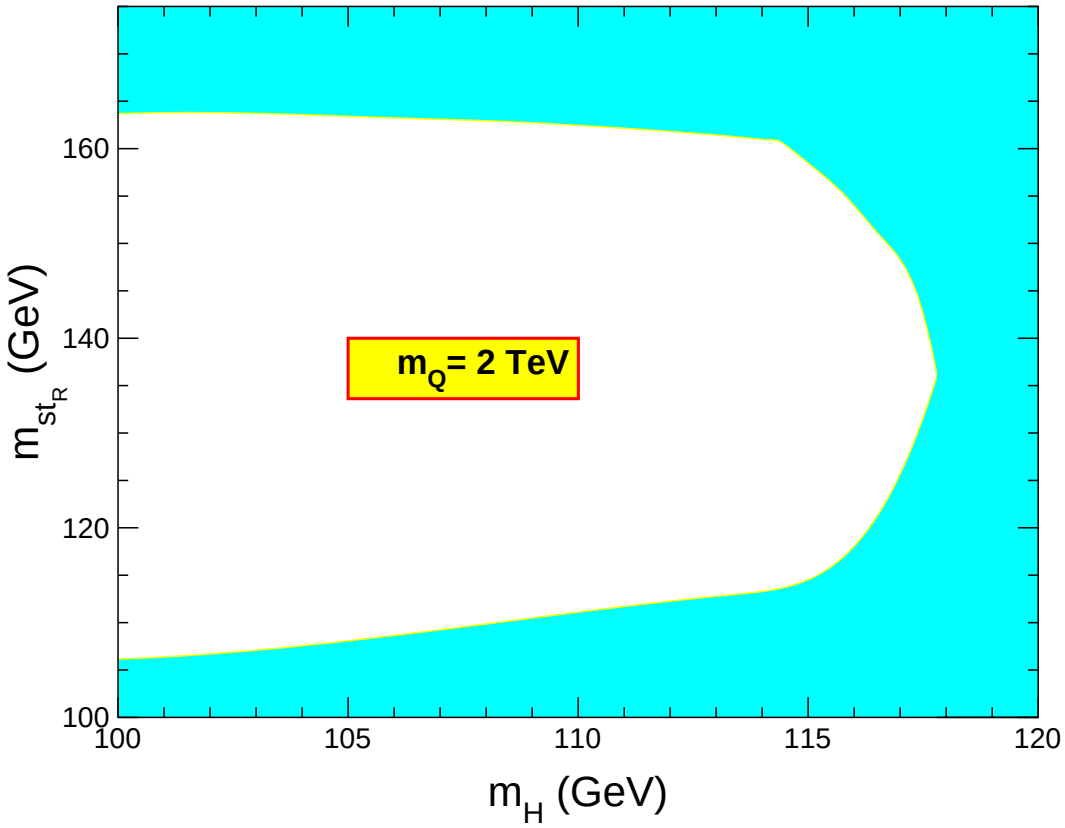
$\Uparrow$

Only 1/2 of the radiative corrections are sizeable

THIS PRODUCES THE STRONGEST CONSTRAINT ON THE MSSM

- Lighter neutralino is a candidate to Dark Matter

- The baryogenesis window for the MSSM is on the verge of experimental limits



- An obvious way out is to enlarge the MSSM with extra scalars: NMSSM, . . .

- But present experimental results are pushing the scale of supersymmetry breaking upwards

NETWORK RESULTS (FROM OCT. 1 2006)

1. BARYOGENESIS

1. Baryogenesis in the MSSM, nMSSM and NMSSM, Stephan J. Huber, Thomas Konstandin, Tomislav Prokopec, Michael G. Schmidt, Nucl.Phys.A785:206-209,2007& Nucl.Phys.B757:172-196,2006

We analyze the nMSSM ($W = SH_1H_2 - m^2S$) with CP violation in the singlet sector. We study the static and dynamical properties of the electroweak phase transition. We conclude 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. For this we determine the shape of the nucleating bubbles, including the profiles of CP-violating phases. The baryon asymmetry is calculated using the advanced transport theory to first and second order in gradient expansion presented recently. Still, first and second generation sfermions must be heavy to avoid large electric dipole moments.

2. Novel Effects in Electroweak Breaking from a Hidden Sector, Jose Ramon Espinosa, Mariano Quiros, hep-ph/0701145

The Higgs boson offers a unique window to hidden sector fields S_i, singlets under the Standard Model gauge group, via the renormalizable interactions $|H|^2 S_i^2$. We prove that such interactions can provide new patterns for electroweak breaking, including radiative breaking by dimensional transmutation consistent with LEP bounds, and trigger the strong enough first order phase transition required by electroweak baryogenesis.

3. A Confining Strong First-Order Electroweak Phase Transition, Germano Nardini, Mariano Quiros, Andrea Wulzer, 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 from a deconfined to a confined phase at temperatures orders of magnitude below the typical Standard Model critical temperature. 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. We have studied numerically the region of the GW parameter space where the theory is consistent and the latter possibility is realized. We have found that in most of the parameter space the nucleation temperature is so low that sphalerons are totally inactive inside the bubbles. The condition for sphalerons to be inactive after reheating imposes an upper bound on the reheating temperature that is weaker for heavy Higgs bosons so that the out-of-equilibrium condition seems to favor heavy over light Higgses. The condition for sphalerons to be active outside the bubbles puts an upper bound on the number of e-folds at the phase transition, roughly consistent with the critical value required by low-scale inflation to solve the cosmological horizon problem.

4. Warped Deformed Throats have Faster (Electroweak) Phase Transitions, Babiker Hassanain, John March-Russell, Martin Schvellinger, arXiv:0708.2060 [hep-th]

We study the dynamics of the finite-temperature phase transition for warped Randall-Sundrum(RS)-like throat models related to the Klebanov-Tseytlin solution. We find that, for infrared branes stabilized near the tip of the throat, the bounce action has a mild N^2 dependence, where $N(y) \sim [M_5 L(y)]^{3/2}$ is the effective number of degrees of freedom of the holographic dual QFT, and where L(y) is the local curvature radius, which decreases in the infrared. 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. Due to the increase of L(y) in the ultraviolet, the throat has a reliable gravitational description even when the number of infrared degrees of freedom is small. We also comment on aspects of the thermal phase transition in Higgsless models, where the gauge symmetry breaking is achieved via boundary conditions. Such models include orbifold-GUT models and the Higgsless electroweak symmetry breaking theories of Csaki et al., with Standard Model gauge fields living in the bulk.

LEPTOGENESIS

1. The Seesaw with many right-handed neutrinos, John R. Ellis, Oleg Lebedev, arXiv:0707.3419 [hep-ph]

There are no upper limits on the possible number of massive, singlet (right–handed) neutrinos that may participate in the seesaw mechanism, and some string constructions motivate seesaw models with up to O(100) right–handed neutrinos. In this case, the seesaw mass scale can be significantly higher than that in the traditional scheme with just 3 right–handed neutrinos. We consider the possible phenomenological implications of such models, in particular, for lepton-flavour violation and electric dipole moments. Since the neutrino masses depend on the Majorana mass scale linearly, while supersymmetric loop corrections depend on it logarithmically, the magnitude of lepton-flavour- and CP-violating transitions may increase with the multiplicity of the right–handed neutrinos and may be enhanced by orders of magnitude. We also point out that, in the context of leptogensis, the bounds on the reheating temperature and the lightest neutrino mass get relaxed compared to those in the case of 3 right–handed neutrinos.

2. CP and Lepton-Number Violation in GUT Neutrino Models with Abelian Flavour Symmetries, John R. Ellis, Mario E. Gomez, Smaragda Lola, JHEP 0707:052,2007.

We study the possible magnitudes of CP and lepton-number-violating quantities in specific GUT models of massive neutrinos with different Abelian flavour groups, taking into account experimental constraints and requiring successful leptogenesis. We discuss SU(5) and flipped SU(5) models that are consistent with the present data on neutrino mixing and upper limits on the violations of charged-lepton flavours and explore their predictions for the CP-violating oscillation and Majorana phases. In particular, we discuss string-derived flipped SU(5) models with selection rules that modify the GUT structure and provide additional constraints on the operators, which are able to account for the magnitudes of some of the coefficients that are often set as arbitrary parameters in generic Abelian models.

3. On Resonant Leptogenesis, Andrea De Simone, Antonio Riotto, arXiv:0705.2183 [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.

4. Quantum Boltzmann Equations and Leptogenesis, Andrea De Simone, Antonio Riotto, JCAP 0708:002,2007

The closed time-path formalism is a powerful Green's function formulation to describe non-equilibrium phenomena in field theory and it leads to a complete non-equilibrium quantum kinetic theory. We make use of this formalism to write down the set of quantum Boltzmann equations relevant for leptogenesis. They manifest memory effects and off-shell corrections. In particular, memory effects lead to a time-dependent CP asymmetry whose value at a given instant of time depends upon the previous history of the system. This result is particularly relevant when the asymmetry is generated by the decays of nearly mass-degenerate heavy states, as in resonant or soft leptogenesis.

5. Observable Electron EDM and Leptogenesis. F.R. Joaquim, I. Masina, A. Riotto, 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.

6. On the impact of flavour oscillations in leptogenesis, Andrea De Simone, Antonio Riotto, JCAP 0702:005,2007.

When lepton flavour effects in thermal leptogenesis are active, they introduce important differences with respect to the case in which they are neglected, the so-called one-flavour approximation. We investigate analytically and numerically the transition from the one-flavour to the two-flavour case when the τ-lepton flavour becomes distinguishable from the other two flavours. We study the impact of the oscillations of the asymmetries in lepton flavour space on the final lepton asymmetries, for the hierarchical right-handed neutrino mass spectrum. Flavour oscillations project the lepton state on the flavour basis very efficiently. We conclude that flavour effects are relevant typically for $M_1 < 10^{12}$ GeV, where M_1 is the mass of the lightest right-handed neutrino.

7. Leptogenesis and Low Energy CP Violation in Neutrino Physics, S. Pascoli, S.T. Petcov, Antonio Riotto, Nucl.Phys.B774:1-52,2007

Taking into account the recent progress in the understanding of the lepton flavour effects in leptogenesis, we investigate in detail the possibility that the CP-violation necessary for the generation of the baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana CP-violating phases in the PMNS neutrino mixing matrix U, and thus is directly related to the low energy CP-violation in the lepton sector (e.g., in neutrino oscillations, etc.). We first derive the conditions of CP-invariance of the neutrino Yukawa couplings lambda in the see-saw Lagrangian, and of the complex orthogonal matrix R in the "orthogonal" parametrisation of lambda. We show, e.g. that under certain conditions i) real R and specific CP-conserving values of the Majorana and Dirac phases can imply CP-violation, and ii) purely imaginary R does not necessarily imply breaking of CP-symmetry. We study in detail the case of hierarchical heavy Majorana neutrino mass spectrum, presenting results for three possible types of light neutrino mass spectrum: i) normal hierarchical, ii) inverted hierarchical, and iii) quasi-degenerate. Results in the alternative case of quasi-degenerate in mass heavy Majorana neutrinos, are also derived. The minimal supersymmetric extension of the Standard Theory with right-handed Majorana neutrinos and see-saw mechanism of neutrino mass generation is discussed as well. We illustrate the possible correlations between the baryon asymmetry of the Universe and i)

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.

8. Effects of Lightest Neutrino Mass in Leptogenesis. E. Molinaro, S.T. Petcov, T. Shindou, Y. Takanishi, arXiv:0709.0413 [hep-ph]

The effects of the lightest neutrino mass in “flavoured” leptogenesis are investigated in the case when the CP-violation necessary for the generation of the baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana phases in the neutrino mixing matrix U. The type I see-saw scenario with three heavy right-handed Majorana neutrinos having hierarchical spectrum is considered. The “orthogonal” parametrisation of the matrix of neutrino Yukawa couplings, which involves a complex orthogonal matrix R, is employed. Results for light neutrino mass spectrum with normal and inverted ordering (hierarchy) are obtained. It is shown, in particular, that if the matrix R is real and CP-conserving and 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 $\sim$ 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 even if R is real and the only source of CP-violation in leptogenesis is the Majorana and/or Dirac phase(s) in U.

9. Leptonic CP violation: Zero, maximal or between the two extremes, Y. Farzan, A.Yu. Smirnov, JHEP 0701:059,2007

Discovery of the CP-violation in the lepton sector is one of the challenges of the particle physics. We search for possible principles, symmetries and phenomenological relations that can lead to particular values of the CP-violating Dirac phase, δ. In this connection we discuss two extreme cases: the zero phase, $\delta = 0$, and the maximal CP-violation, $\delta = \pm\pi/2$, and relate them to the peculiar pattern of the neutrino mixing. The maximal CP-violation can be related to the $\nu_\mu - \nu_\tau$ reflection symmetry. We study various aspects of this symmetry and introduce a generalized reflection symmetry that can lead to an arbitrary phase that depends on the parameter of the symmetry transformation. The generalized reflection symmetry predicts a simple relation between the Dirac and Majorana phases. We also consider the possibility of certain relations between the CP-violating phases in the quark and lepton sectors.

10. Sensitivity of the baryon asymmetry produced by leptogenesis to low energy CP violation. Sacha Davidson, Julia Garayoa, Federica Palorini, Nuria Rius, arXiv:0705.1503 [hep-ph]

If the baryon asymmetry of the Universe is produced by leptogenesis, CP violation is required in the lepton sector. In the seesaw extension of the Standard Model with three hierarchical right-handed neutrinos, we show that the baryon asymmetry is insensitive to the PMNS phases: thermal leptogenesis can work for any value of the observable phases. This result was well-known when there are no flavour effects in leptogenesis; we show that it remains true when flavour effects are included.

11. Quasi-degenerate neutrinos and leptogenesis from L(mu) - L(tau), E.J. Chun, K. Turzynski, hep-ph/0703070

We provide a framework for quasi-degenerate neutrinos consistent with a successful leptogenesis, based on the $L_m u - L_t a u$ flavor symmetry and its breaking pattern. In this scheme, a fine-tuning is needed to arrange the small solar neutrino mass splitting. Once it is ensured, the atmospheric neutrino mass splitting and the deviation from the maximal atmospheric mixing angle are driven by the same symmetry breaking parameter $\lambda\, 0.1$, and the reactor angle is predicted to be slightly smaller than lambda, while the Dirac CP phase is generically of order one. Given that the pseudo-Dirac nature of right-handed neutrinos is protected from the flavor symmetry breaking, a small mass splitting can be generated radiatively. For moderate values of tan(beta) 10, this allows for low-scale supersymmetric leptogenesis, overcoming a strong wash-out effect of the quasi-degenerate light neutrinos and evading the gravitino overproduction.

12. Preheating and Affleck-Dine leptogenesis after thermal inflation, Gary N. Felder, Hyunbyuk Kim, Wan-Il Park, Ewan D. Stewart, JCAP 0706:005,2007

Previously, we proposed a model of low energy Affleck-Dine leptogenesis in the context of thermal inflation. The lepton asymmetry is generated at the end of thermal inflation, which occurs at a relatively low energy scale with the Hubble parameter somewhere in the range $1\,keV < H < 1\,MeV$. Thus Hubble damping will be ineffective in bringing the Affleck-Dine field into the lepton conserving region near the origin, leaving the possibility that the lepton number could be washed out. Previously, we suggested that preheating could damp the amplitude of the Affleck-Dine field allowing conservation of the lepton number. In this paper, we demonstrate numerically that preheating does efficiently damp the amplitude of the Affleck-Dine field and that the lepton number is conserved as the result. In addition to demonstrating a crucial aspect of our model, it also opens the more general possibility of low energy Affleck-Dine baryogenesis.

13. Stability and leptogenesis in the left-right symmetric seesaw mechanism, Evgeny Khakimovich Akhmedov, Mattias Blennow, Tomas Hallgren, Thomas Konstandin, Tommy Ohlsson, JHEP 0704:022,2007

We analyze the left-right symmetric type I+II seesaw mechanism, where an eight-fold degeneracy among the mass matrices of heavy right-handed neutrinos M_R is known to exist. Using the stability property of the solutions and their ability to lead to successful baryogenesis via leptogenesis as additional criteria, we discriminate among these eight solutions and partially lift their eight-fold degeneracy. In particular, we find that viable leptogenesis is generically possible for four out of the eight solutions.