The origin of baryons

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Introduction and SM results

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

Matter-antimatter

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

- Conditions for baryogenesis were stated by Sakharov in 1967 [1]

Baryogenesis conditions

- B-violation
- C and CP violation
- Departure from thermal equilibrium

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

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

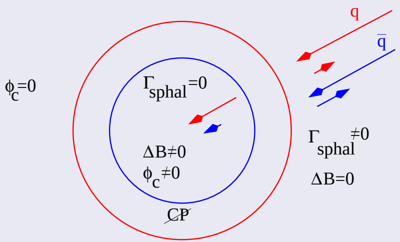
FIRST ORDER PHASE TRANSITION

- This question created lot of excitement in the physics community

ELECTROWEAK BARYOGENESIS

- A nice mechanism for the (electroweak) generation of the BAU was suggested by Cohen, Kaplan and Nelson in 1993. The reflection and transmission coefficients of fermions and anti-fermions scattering off the CP violating wall are different

EWBG

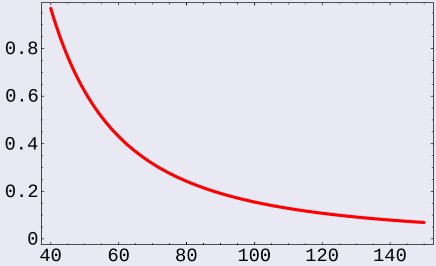


- If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase $\Rightarrow \dfrac{\phi_c}{T_c} \geq 1$

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

EWBG in the SM

- 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. At one-loop



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

In summary EWBG

- Is triggered by sphalerons: i.e. $B-L=0$ and $B+L\neq 0$
- It does not work in the SM
- Two possible avenues are currently 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
  - Those special conditions lead to investigations on BMSSM: NMSSM, nMSSM,..
- They can be easily falsified at LHC

BAU $\Rightarrow$ NEW PHYSICS

LEPTOGENESIS

Leptogenesis requires new physics and is an alternative to EWBG

- 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 $G \supseteq SO(10)$

Results on EWBG

Some results on EWBG

- Hidden sectors: SM singlets
- MSSM
- Confining/deconfining phase transition in RS models
- Studies on first-order phase transitions
- Affleck-Dine BAU
- Cold EWBG

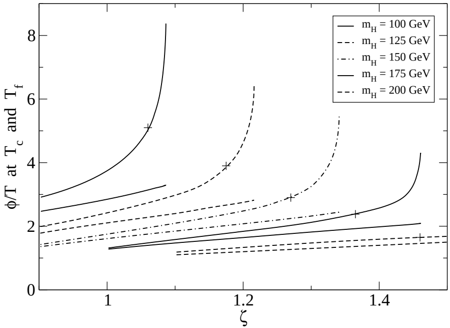
HIDDEN SECTORS

- 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, "Some Cosmological Implications of Hidden Sectors," Phys. Rev. D **78** (2008) 123528 [arXiv:0809.3215 [hep-ph]]
- Extensions of the Standard Model with hidden sector scalars coupled to the Higgs boson

$$V = \sum_i \left(\frac{1}{2} m_{S_i}^2 + \zeta_i^2 H^\dagger H\right) S_i^2 + m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- 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

Strength of the phase transition



T_c (lower curves: degeneracy temp) and T_f (upper curves: end of phase transition)

MSSM

M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, "The Baryogenesis Window in the MSSM," Nucl. Phys. B **812** (2009) 243 [arXiv:0809.3760 [hep-ph]].

- Although the EWBG scenario may not be realized within the Standard Model, it can be accommodated within the MSSM provided there are new CP-violating phases and the lightest stop is lighter than the top-quark
- This work contains an update of the values of the stop ($m_{\tilde{t}}$) and Higgs (m_H) masses consistent with the requirements of electroweak baryogenesis based on an analysis that makes use of the RGE improved Higgs and stop potentials

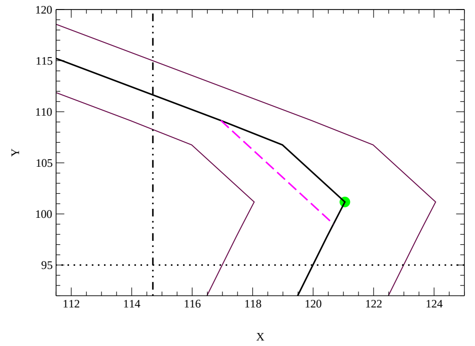
- Allowed window

Absolute window

$m_H \lesssim 127$ GeV and $m_{\tilde{t}} \lesssim 120$ GeV

consistent with all present experimental data, where there is a strong first-order phase transition

$y = m_{\tilde{t}}/\text{GeV}$, $x = m_H/\text{GeV}$



conf/deconf PT in RS models

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

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 EWBG

- T. Konstandin, G. Nardini and M. Quiros, "Gravitational backreaction effects on the holographic phase transition," arXiv:1007.1468 [hep-ph]
- For the case of thermal tunneling

$$S_3/T \gtrsim 61.5 \times (N^2 - 1) \left(\frac{v_1^2}{M^3} \right)^{-3/4}$$

or

Thermal tunneling

$$N \lesssim 6.8$$

- For the case of quantum tunneling one finds

$$S_4 \gtrsim 54.3 \times (N^2 - 1) \left(\frac{v_1^2}{M^3} \right)^{-1} ,$$

Quantum tunneling

$$N \lesssim 12.5$$

First-order phase transitions

- A complete and general analysis is done in: José R. Espinosa, Thomas Konstandin, José M. No and Géraldine Servant, "Energy Budget of Cosmological First-order Phase Transitions," arXiv:1004.4187 [hep-ph]
- Different regimes are considered in all generality

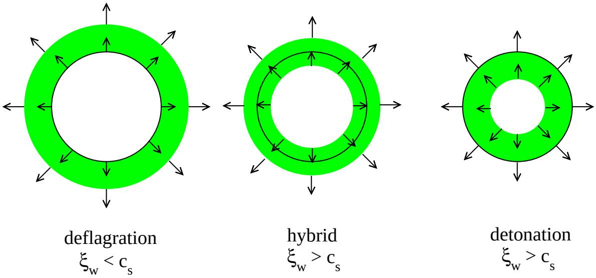


Figure: Pictorial representation of expanding bubbles of different types. The black circle is the phase interface (bubble wall). In green we show the region of non-zero fluid velocity.

The energy budget turns out to be:

η=friction parameter
$\alpha_N \propto$ false Higgs vacuum energy$/T_N^4$

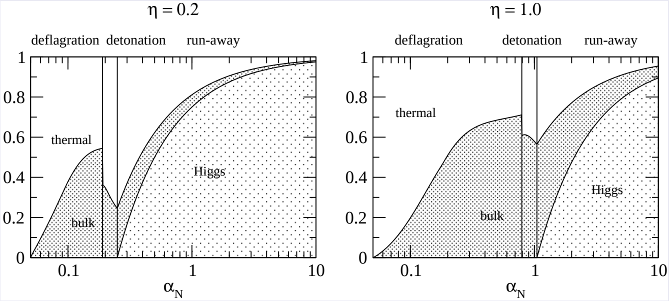


Figure: The energy budget for $\eta = 0.2$ and $\eta = 1.0$. The different contributions (from top to bottom) are thermal energy, bulk fluid motion and energy in the Higgs field. The last two components can potentially produce anisotropic stress in the plasma and subsequently gravity waves.

AFFLECK-DINE BARYOGENESIS

- John McDonald, "Enhanced Dark Matter Annihilation Rate for Positron and Electron Excesses from Q-ball Decay," Phys. Rev. Lett. **103**, 151301 (2009) [arXiv:0904.0969 [hep-ph]]
- Q-ball decay in Affleck-Dine baryogenesis models can account for dark matter when the annihilation cross-section is sufficiently enhanced to explain the positron and electron excesses observed by PAMELA, ATIC
- A flat direction of dimension d is described by an effective superpotential

$$W = \frac{\lambda \Phi^d}{d! M^{d-3}}$$

- The baryon asymmetry is generated by Affleck-Dine baryogenesis: oscillations of Φ

- The reheating temperature necessary to account for the observed baryon asymmetry

Reheating temperature

d	$\kappa_d T_R$
4	$1.4 \times 10^9\ GeV$
5	$1.1 \times 10^4 \left(\frac{m}{TeV}\right)^{1/3}\ GeV$
6	$29 \left(\frac{m}{TeV}\right)^{1/2}\ GeV$
7	$0.85 \left(\frac{m}{TeV}\right)^{3/5}\ GeV$
8	$0.08 \left(\frac{m}{TeV}\right)^{2/3}\ GeV$

Table: Reheating temperature as a function of d for successful Affleck-Dine baryogenesis

$$\kappa_d = \left(\frac{(d-1)!^2}{\lambda^2\,(d-1)}\right)^{1/(d-2)}, \quad T_R = \text{reheating temp}$$

- Recent observations of a cosmic-ray positron excess by PAMELA and an electron excess by ATIC are consistent with dark matter of mass $\sim 1\ TeV$ which annihilates primarily to leptons and which has an annihilation cross-section enhanced relative to the thermal relic cross-section by a factor $\sim 10^3$
- When combined with Affleck-Dine baryogenesis Q-balls can provide a common origin for the baryon asymmetry and dark matter, with the scalars of the Q-ball decaying to the lightest SUSY particles (LSPs) and baryons
- Generally the LSP density produced by Q-ball decay is initially too large, requiring subsequent annihilation. It is shown that the required annihilation cross-section can naturally be consistent with an enhancement factor $\sim 10^3$

- The enhancement factor as a function of Q-ball decay temperature is therefore given by

$$B_{ann} = 10^3 \left(\frac{10.75}{g(T_d)}\right)^{1/2} \left(\frac{m_\chi}{1\ TeV}\right) \left(\frac{50\ MeV}{T_d}\right)$$

- Thus the enhancement factor is the right order of magnitude when dark matter comes from Q-ball decay and the decay temperature is in the range $T_d \sim 10 - 100\ MeV$
- This has been proven to be the case and

T_d

$$T_d \approx 55\ MeV \left(\frac{10.75}{g(T_d)}\right)^{1/4} \left(\frac{m}{1\ TeV}\right)^{5/4}$$

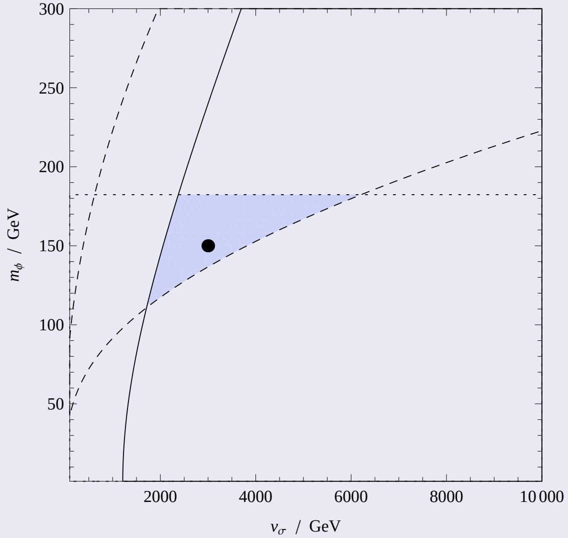
COLD EWBG

- K. Enqvist, P. Stephens, O. Taanila and A. Tranberg, "Fast Electroweak Symmetry Breaking and Cold Electroweak Baryogenesis," arXiv:1005.0752 [astro-ph.CO]
- The observed baryon asymmetry could be explained if the electroweak transition is cold rather than hot with $T \ll 100\,\text{GeV}$, and if the transition itself is a fast quench rather than adiabatic
- Recent analytical work and numerical simulations have indicated that in such a cold environment, Standard Model CP-violation is much larger than at electroweak temperatures and is indeed strong enough to account for the BAU
- In Cold EWBG most of the baryon asymmetry is produced at the initial quench when the Higgs field is rapidly falling down the slope of the potential.

- Baryon production essentially stops after the first oscillation, after which the coherent Higgs field starts decaying, thereby reheating the Universe. The reheating temperature should be low enough that sphaleron diffusion does not subsequently wipe out the baryon number.
- The realization of a fast quench does not appear to be possible within the Standard Mode
- If the Higgs field were coupled to some beyond-the-Standard Model fields, the situation might change
- The proposed model

$$V(\sigma,\phi) = V_0 - \frac{m_\sigma^2}{2}\sigma^2 - \frac{\lambda_4}{4}\sigma^4 + \frac{\lambda_6}{6}\sigma^6 - \frac{g^2}{2}\sigma^2\phi^2 + \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\kappa}{2}\sigma^2\xi^2 + \frac{m_\xi^2}{2}\xi^2$$

- The final result is the region



Results on leptogenesis

Some results on leptogenesis

- CP violation and leptogenesis
- m_ν and leptogenesis
- EDM and leptogenesis
- Supersymmetry and leptogenesis
- GUTs and leptogenesis
- Flavored and leptogenesis
- Review and leptogenesis

CP VIOLATION

- 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]
- 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]]
- Studies of 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

ν MASSES

- 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]]
- M. Frigerio, P. Hosteins, S. Lavignac and A. Romanino, "A new, direct link between the baryon asymmetry and neutrino masses," Nucl. Phys. B **806** (2009) 84 [arXiv:0804.0801 [hep-ph]]

It is shown, in particular, that we can have successful thermal leptogenesis for $5 \times 10^{-6} eV < m_3 < 5 \times 10^{-2}$ eV

EDM

- 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 $\tau \rightarrow e\gamma$ 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

QUANTUM BOTZMANN EFFECTS

- 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 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

SUPERSYMMETRY

- 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]]
- In particular enough baryon asymmetry is generated if

$$M_1 \geq 2 \times 10^{11}\,\mathrm{GeV} \left(\frac{10^7\,\mathrm{GeV}}{T_{\mathrm{RH}}}\right) \left(\frac{M_p}{|\phi_0|}\right)^{3/2} \left(\frac{\widetilde{m}}{100\,\mathrm{GeV}}\right)^{1/2}$$

which implies that a successful baryogenesis can occur only if

$$\phi_0 \geq 0.2\, M_p\, (10^7\,\mathrm{GeV}/\,T_{\mathrm{RH}})^{1/2}$$

ϕ_0=initial value of the flat direction in the supersymmetric scalar potential

- 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]

The sensitivity of the baryon asymmetry to the phases of the lepton mixing matrix is studied, and found that leptogenesis can work for any value of the phases. The contribution to the electric dipole moment of the electron, arising from the seesaw, is estimated and found that it is (just) beyond the sensitivity of next generation experiments ($< 10^{-29} e$ cm)

GUTS

- 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, "Successful type I Leptogenesis with SO(10)-inspired mass relations," 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 it is found $m_1 > 0.001$ 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

FLAVOURED

- A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada and A. Riotto, "Flavour issues in leptogenesis," JCAP **0604** (2006) 004
- A. Abada, S. Davidson, A. Ibarra, F. X. Josse-Michaux, M. Losada and A. Riotto, "Flavour matters in leptogenesis," JHEP **0609** (2006) 010
- S. Antusch, S. F. King and A. Riotto, "Flavour-dependent leptogenesis with sequential dominance," JCAP **0611** (2006) 011
- A. De Simone and A. Riotto, "On the impact of flavour oscillations in leptogenesis," JCAP **0702** (2007) 005
- S. Davidson, J. Garayoa, F. Palorini and N. Rius, "Insensitivity of flavoured leptogenesis to low energy CP violation," Phys. Rev. Lett. **99** (2007) 161801
- E. Molinaro and S. T. Petcov, "A Case of Subdominant/Suppressed 'High Energy' Contribution to the Baryon Asymmetry of the Universe in Flavoured Leptogenesis," Phys. Lett. B **671** (2009) 60

Flavoured leptogenesis

The impact of flavour in thermal leptogenesis, including the quantum oscillations of the asymmetries in lepton flavour space is studied. In the Boltzmann equations different numerical factors and additional terms which can affect the results significantly are found. 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)

REVIEW

Review on leptogenesis

- S. Davidson, E. Nardi and Y. Nir, "Leptogenesis," Phys. Rept. **466** (2008) 105 [arXiv:0802.2962 [hep-ph]]

SUMMARY

I have not made any statistics but the results on the problem of BAU from UniverseNet have added original and essential ingredients towards a possible experimental confirmation of the different proposed mechanisms