Dark matter in CP-violating Supersymmetry

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Abstract. Supersymmetry provides ideal candidates for explaining the dark matter mystery of our universe. Compelling cold dark matter (CDM) candidates are the neutralino, gravitino and the superpartner of the elusive axion, the axino. The LSP neutralino is perhaps the best motivated candidate for CDM and the popular SUSY models can be in agreement with accelerator and WMAP data. Supersymmetric CP-violating phases, although phenomenologically and theoretically interesting, especially for baryogenesis scenarios, are tightly constrained by electric dipole moment (EDM) data. Two-loop renormalization group equation (RGE) running from the unification to the electroweak scale renormalizes the gaugino mass phases with important consequences for EDMs. In minimal CP-violating extensions of mSUGRA, with non-universal boundary conditions at the unification scale, EDMs and WMAP data can be simultaneously satisfied for large values of the phases in regions where neutralinos annihilate through a rapid Higgs resonance. These regions of the parameter space are accessible to LHC.

1. Introduction
Dark matter (DM) and dark energy (DE) are perhaps the biggest mysteries of modern Cosmology. There is supporting evidence for the existence of dark matter by various astrophysical sources. These include binding of galaxies in clusters, rotation curves of galaxies, large scale structure simulations and observations from high-z supernovae, colliding clusters of galaxies, gravitational lensing and so on. Certainly the most direct and accurate evidence comes from the WMAP sattelite by measuring the anisotropies of the cosmic microwave background (CMB). We know, at a very high confidence level, that dark matter comprises 23% of the total matter-energy density of the universe while the major portion, about \( \sim 72\% \), is dark energy and only 4.6% is composed of matter observed in the laboratory. The standard cosmological model, \( \Lambda CDM \)-model, is in agreement with the astrophysical data which measure a cold dark matter (CDM) abundance [1, 2]

\[
\Omega_{DM} h^2 = 0.111^{+0.011}_{-0.015} \ (2\sigma) .
\]

Hot dark matter (HDM), like Standard Model (SM) neutrinos, is almost ruled out by observations. Neutrinos have a tiny mass and if they account for the total DM, \( \Omega_{\nu} h^2 \sim 0.1 \), the sum of their masses turns out to be \( \sum m_\nu \sim 10 \ eV \). This is too small for clustering in dwarf halos, which requires \( \sum m_\nu > 120 \ eV \), and too large, as it arises from studies of structure formation and other astrophysical sources, which put upper limits \( \sum m_\nu < \mathcal{O}(1) \ eV \). In particular from galaxy clustering measurements, CMB and observations of Lyman-\( \alpha \) forest a limit \( \sum m_\nu < 0.7 \ eV \) is implied. However non-SM like neutrinos certainly are not ruled out.
On the other hand CDM has been established by various observations and analyses which include Via Lactea II simulations [3] for the study of DM in Milky Way, observations of proto-galaxies by the Very Large Telescope [4] and so on.

Thermal or non-thermal relics created in the early universe may constitute part or all of the observed DM. These can be weakly interacting massive particles (WIMP) [5] in the mass range $10 \text{ GeV} < M_\chi < \text{few TeV}$ which naturally yield relic densities in the right ball park, $\Omega_{\text{DM}} h^2 \sim 0.1$. This is often quoted as the WIMP miracle. Among the WIMP candidates are the Lightest Supersymmetric Particle (LSP) occurring in supersymmetric models, like neutralinos for instance, heavy neutrino-like particles, Kaluza-Klein (KK) excitations in extra dimensional theories, lightest T-odd particles in little Higgs models and other perhaps more exotic proposals. SuperWIMPs interact with smaller strength than WIMPs, gravitationally or other, and can be also good DM candidates. Among these are the gravitino, the axino, superpartner of the axion, KK gravitons and so on (for a review see [6]).

Non-WIMP candidates include the axion [7, 8, 9], in the mass range $m_a \simeq 10^{-5} - 10^{-3} \text{ eV}$ [10]. The lower bound produces too high a relic density and the upper bound stems from limits on stellar cooling. Axion is a perfect well motivated CDM candidate which couples weakly to two photons. On going experiments like ADMX [11], and CAST [12] have put limits on its coupling to photons and its mass but its discovery is still lacking. Other non-WIMP candidates are the Wimpzillas, Cryptons, Q-balls, Black Hole remnants and other very massive astrophysical objects, as well as, moduli fields in String Theories or other proposed massive objects, or particles, that are not part of the Standard Model.

Supersymmetry (SUSY) is a renormalizable extension of the SM and provides an elegant mechanism for the stabilization of the Higgs mass. It is an indispensable ingredient of String Theories, it is phenomenologically interesting, since it predicts a plethora of new particles which may be discovered at LHC, and it does not conflict with precision data. On the contrary precision electroweak data show a preference to SUSY [13], while gauge coupling unification is consistent with low energy supersymmetry, indicating that SUSY is perhaps the proper framework to encompass all particle forces in a unified manner. Besides these, and other theoretical virtues, it is cosmologically interesting since it predicts well motivated candidates for dark matter. SUSY with conserved R-parity offers and ideal WIMP candidate, the neutralino LSP, if it is the lightest particle. Also the gravitino, superpartner of the graviton, of the spontaneously broken local supersymmetry may also a viable candidate along with the axino, the superpartner of the axion, or the superpartner of a sterile neutrino.

In this work we will mainly focus on the LSP neutralino. Its relic density is calculated by solving Boltzmann equation, in a manner that is well prescribed in the literature. At very high universe temperatures the neutralinos are in thermal equilibrium with the cosmic soup. However as the universe expands and cools neutralinos fall out of thermal equilibrium at the freezing point defined as the temperature at which the expansion rate of the universe equals to the neutralino annihilation rate. Below this temperature the density of the neutralinos is diluted only by the expansion of the universe and their total number is locked. In the context of the popular supersymmetric models the restrictions imposed by the WMAP data, have been extensively studied and regions of the parameter space describing these models have been delineated, which are compatible with the cosmological observations, as well as, all other accelerator data. The main cosmologically allowed regions in the mSUGRA are the focus-point, the rapid Higgs annihilation funnel, the co-annihilation and the bulk region. Its of this bears it own phenomenological features. Although much effort has been expended towards studying models conserving CP symmetry in their supersymmetric sector, the appearance of possible CP-violating sources, which have supersymmetric origin, deserves more attention opening a window to physics which is phenomenologically rich.
2. Dark matter searches

Dark matter can be detected in non-accelerator experiments by direct or indirect searches.

2.1. Direct detection of DM

The WIMPs in the galactic halo have a local relic density $\rho_{\text{CDM}} \approx 0.3 \text{GeV/cm}^3$ and can be scattered elastically by target nuclei whose recoil can be detected by ionization or phonon signal, in cryogenic materials like Germanium, or scintillation light if the target materials are noble gases [14, 15, 16]. CDMS, CDMS II 2008 Ge [17], XENON10 [18] have already put limits on the spin independent (s.i.) elastic cross section covering a larger area of previous experiments (CRESST, EDELWEISS, WARP, ZEPLIN), excluding already a large portion in the $\sigma_{\text{s.i.}} - m_{\text{WIMP}}$ plane predicted by the popular SUSY schemes, as is seen in figures 1 and 2 (talk by A. Rubbia in this conference). Also bounds on the spin-dependent (s.d.) cross sections have been put by XENON10 [19] and COUPP [20] experiments.

The DAMA/LIBRA experiment, by measuring the yearly modulation of the effect, has detected a signal consistent with the existence of DM in the galactic halo [21]. This however is not confirmed by the other experiments. Their results however cannot be directly compared in a model independent way and the situation still remains unclear.

In the mSUGRA the spin-independent cross section falls with the LSP mass, $m_{\text{LSP}}$, ranging between $10^{-8} \text{pb}$ and $10^{-10} \text{pb}$, for $m_{\text{LSP}}$ between 200 GeV and 800 GeV. In models predicting DM with an enhanced Higgsino component the cross section is larger, $\sim 10^{-8} \text{pb}$, even for large LSP masses. The projected sensitivity of next round experiments, superCDMS, XENON100, XENONIT, LUX, WARP will reach $10^{-9} - 10^{-10} \text{pb}$ for $m_{\text{LSP}} < 800 \text{GeV}$. Also some experiments will use materials with low atomic weight, like fluorine for instance, which are sensitive to the spin-dependent part of the elastic cross section. Therefore in the coming years direct detection experiments, by improving their sensitivities and by using diverse target materials, are likely to detect DM if it has supersymmetric origin.

![Figure 1](http://uninfofs.brown.edu/Gaitskell.Macie.Filipin.pdf)  
**Figure 1.** CDMS limits on the spin independent cross section compared with those of other experiments [17].

![Figure 2](http://uninfofs.brown.edu/Gaitskell.Macie.Filipin.pdf)  
**Figure 2.** Present and projected limits by XENON and CDMS experiments, from ref. [22].
2.2. Indirect detection of DM

Indirect detection of DM is a complementary way to discover it. WIMP – WIMP annihilation in the galactic halo may be observed through production of gamma rays, neutrinos and antimatier. Production of jets in $WIMP + WIMP \rightarrow q\bar{q}$ and eventually $\gamma$-rays may be observed by HESS and Fermi/GLAST. Neutrino telescopes ANTARES, IceCube, NESTOR, SuperK and eventually KM3Net will search for high energy neutrinos. $\gamma$-ray measurements by EGRET \[23\] in the galactic center provides evidence of an excess in the $10 - 50 \text{ GeV}$ range \[24\]. PAMELA is searching for positrons and antiprotons by measuring the cosmic flux of anti-particles. Recent results from PAMELA \[25\] have caused some excitement since they show that positrons, in the $10 - 80 \text{ GeV}$ range, are in excess over the background as is seen in figure 3. This confirms previous

![Figure 3](image1.png)  
**Figure 3.** Fraction of $e^+$ measured by PAMELA compared with data from other experiments, \[25\]

indications by HEAT \[26\] and AMS-01 \[27\], at a much higher confidence. A similar excess is not observed however in the antiproton energy spectrum. The ATIC project has measured the spectrum of electrons and positrons together in the energy range $20 - 2000 \text{ GeV}$ and found a broad bump between $300 \text{ GeV}$ and $800 \text{ GeV}$ \[28\]. ATIC does not distinguish between $e^-$ and $e^+$ so it is crucial to determine what fraction of the excess is due to $e^+$. If this signal is finally confirmed it may attributed to DM annihilation in the center of our galaxy. However it seems that neutralino DM, owing mainly to its Majorana nature, is incapable of explaining the phenomenon and other mechanism should be perhaps invoked to fit the data. In a first attempt to fit the data, in \[29\] a minimal model is assumed in which the dark matter candidate is a fermion pentaplet, with respect the weak $SU(2)$ group, carrying zero weak hypercharge, see figure 4. PAMELA data has recently attracted the interest of many authors and the literature is already proliferated by works in which the effect is analysed, and various candidates and mechanisms are proposed which explain the data \[29, 30, 31, 32, 33, 34, 35\].

![Figure 4](image2.png)  
**Figure 4.** A minimal dark matter fermion 5-plet model fitting PAMELA data, \[29\]

2.3. Supersymmetric DM in colliders

Particle physicists would like to see DM be discovered in colliders. The LSP neutralino in R-parity conserving SUSY theories is a leading candidate and may be detected at collider searches, if it exists, and in particular at the LHC. Detectable events may arise from heavier than the LSP
states that decay, via multi-step cascade processes, to the lightest neutralino which leaves its imprint via missing energy. Squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) are among the heavy strongly interacting states and if not extremely heavy will have large production cross sections with pairs of squarks and gluinos in the final state, i.e. $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$. In mSUGRA with $100 \, fb^{-1}$ integrated luminosity the LHC reach for low $m_0$ extends to $M_{1/2} < 1.4 \, TeV$, corresponding to gluino and squark masses $m_{\tilde{q}, \tilde{g}} \approx 3 \, TeV$. For large $m_0$ sfermions are too heavy to be produced and the LHC reach comes only from gluino pair production for values of $M_{1/2}$ up to $700 \, GeV$, equivalent to a gluino mass $m_{\tilde{g}} \approx 2 \, TeV$. Note that the reach of the LHC is rather insensitive to the particular supersymmetric model under consideration, as long as the produced gluino and squarks decay via multi-cascade processes to the neutralino DM. [6].

If nature is supersymmetric the neutralino LSP emerges as the prominent CDM candidate, provided that R-parity is conserved. However within the context of supersymmetric theories other options are available. The gravitino LSP can be also a good DM candidate [36, 37, 38, 39, 40, 41]. Gravitinos, which are thermally produced in the early universe, constitute CDM, while those that are produced by the decays of the next-to-lightest SUSY particle (NLSP) constitute Warm/Hot DM. However scenarios with gravitino dark matter face potential cosmological problems by the presence of NLSP at the time of Big Bang Nucleosynthesis (BBN), whose decays may dissociate light nuclei. This problem may be avoided if gravitino is much lighter than the NLSP neutralino, or if the NLSP is the stau, in which case the BBN constraints are weaker, although still significant [42, 43, 44, 45, 46]. However even in this case charged NLSPs form bound states with light nuclei leading to overproduction of $^6Li$, an effect known as catalyzed BBN, implying severe upper limits on the staus abundance before they decay [47]. Another resolution is to assume that R-parity is tinely violated, inducing stau decays to SM particles with small lifetimes, so that they decay before nucleosynthesis [48, 49, 50].

The axinos interact more weakly than a WIMP and similarly to the gravitinos can constitute CDM or Warm/Hot DM [51, 52, 53, 54, 55, 56, 57]. In this case, due to the smallness of the Peccei-Quinn scale, the decays of the NLSP are characterized by lifetimes $10^{-2} \, sec$ and occur before BBN, posing therefore no problems for nucleosynthesis. Recently there has been a revived interest in the axino DM since it may reconcile Yukawa-unification modes, that predict over-abundance of neutralino DM, with the WMAP data [58].

Concluding this section, in the following years direct and indirect DM searches, and in a complementary way LHC experiments, will possibly shed light to the mystery of dark master and identify its nature, whose detection will mark the beginning of a new exciting era in Astroparticle and Particle Physics.

3. CP-violation in SUSY

3.1. CP-violation, Baryogenesis and EDM constraints

Supersymmetric models and their corresponding predictions for neutralino DM have been extensively studied. However models encompassing CP-violation have not been studied to the same extent. Sources of CP-violations, other than this residing in the Cabbibo-Kobayashi-Maskawa (CKM) mixing matrix, posses very interesting theoretical and phenomenological features [59, 60, 61]:

- They are important for electroweak baryogenesis
- Affect the predictions for LSP relic densities
- Produce electric dipole moments for elementary fermions and Atoms
- Affect the sparticle spectrum
- Have a large impact on Higgs-boson phenomenology
- Have impact on $B_s \to \mu^+\mu^-$ and $B \to K\phi$ decays
Supersymmetric CP-violating phases can be observed in collider physics [62] through, squark and gluino production, squark decays, like $\tilde{t} \to t + l^+l^- + \tilde{\chi}$ which is observable at LHC [63], or $e^+ + e^- \to f \bar{f}$ [64], observable at ILC.

CKM phase is known to be too small to account for the observed baryon asymmetry of the universe (BAU). Therefore one has to consider additional CP-violating sources. Phases accommodated in SUSY parameters are welcome for baryogenesis which can take place via a first order electroweak (EW) phase transition. Leptogenesis [65] is another alternative (talk by A. Pilaftsis at this conference).

Squark/slepton driven EW baryogenesis requires a stop mass in the range $120 \text{ GeV} < m_{\tilde{t}} < m_t$ while phase transition becomes too weak for a Higgs mass $m_H > 120 \text{ GeV}$. These leave a narrow window for the mechanism to take effect [66, 67].

Higgsino/Gaugino driven baryogenesis is an alternative scenario [68]. The effect is resonantly enhanced for values $|\mu| \sim |M_{1,2}|$, where $M_{1,2}$ are the Bino and Wino soft masses. Then for successful baryogenesis the relevant phases $\arg(\mu M_{1,2})$ need be larger than $O(10^{-2})$. However even such small phases may overproduce EDMs which put very stringent constraints on CP-violating phases. This is the SUSY CP-problem which can be encoded by

$$\delta_{CP} \left( \frac{1 \text{ TeV}}{M_{\text{SUSY}}} \right) << 1 \quad (1)$$

having the meaning that either CP-violating phases are very small, $\delta_{CP} << 1$, or the supersymmetry breaking scale is very large, $M_{\text{SUSY}} >> \text{TeV}$, beyond LHC reach, so that the above constraint is observed. However the cancellation mechanism, for which we will talk about later, evades this constraint.

EDMs are probes of CP-violation and new physics [69]. Upper limits put on them, by various experiments, translate into constraints on the phases, or particular combinations of them. The experimentally measured EDMs are those of neutron, Thallium and Mercury and the bounds imposed [70] are shown in table 1.

| Element       | Bound on EDM          |
|---------------|-----------------------|
| neutron       | $|d_n| < 2.9 \times 10^{-26} \text{ e} \cdot \text{cm}$ |
| $^{205}\text{Tl}$ paramagnetic | $|d_{\text{Tl}}| < 9.0 \times 10^{-25} \text{ e} \cdot \text{cm}$ |
| $^{199}\text{Hg}$ diamagnetic   | $|d_{\text{Hg}}| < 2.0 \times 10^{-28} \text{ e} \cdot \text{cm}$ |

The bound on Thallium EDM translates into a bound on the electron’s EDM, $|d_e| < 1.6 \times 10^{-27} \text{ e} \cdot \text{cm}$. Future experiments will impose additional constraints by measurements of the EDM of Deuteron with a projected sensitivity $|d_D| < (1.0 - 3.0) \times 10^{-27} \text{ e} \cdot \text{cm}$, [71, 72].

### 3.2. CP-violating phases

We shall consider supersymmetric models having the content of the MSSM, allowing for CP-violations in the Lagrangian which is split, in the usual manner, into its supersymmetric and its soft SUSY breaking part,

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (2)$$
\( \mathcal{L}_{\text{soft}} \) encodes all information for the breaking of supersymmetry. Global \( U(3) \)-rotations can be used to eliminate redundant phases from the quark and lepton Yukawa sector and only one complex CKM phase is left. In the limit of vanishing Higgs multiplet mixing, \( \mu = 0 \), the supersymmetric part is invariant under a global \( U_{PQ}(1) \) Peccei-Quinn type symmetry and a global \( U_R(1) \) symmetry \[60\] under which the multiplets carry the charges appearing in table 2. It is customary to trade the symmetry \( U_R(1) \) for the combination \( U_R - PQ(1) \) and this is the reason the corresponding charges are also displayed.

These rotations are neither symmetries of the supersymmetric part of the Lagrangian \( \mathcal{L}_{\text{SUSY}} \) when \( \mu \neq 0 \), nor of its soft SUSY breaking part \( \mathcal{L}_{\text{soft}} \), and can be used to rotate away further phases. We shall focus on CP-violating models with minimal flavor violation, coined CPMFV for short, in which all flavor mixings occur within the CKB matrix. Furthermore we shall pursue a top-down approach according to which the boundary conditions, for the magnitudes and phases of the unknown soft SUSY breaking parameters, are set at the unification scale. This scheme is pertinent to a unified description that determines the theory at Planckian energies. Then the number of the parameters is reduced, like in mSUGRA, and their low energy values are extracted by running the appropriate renormalization group equations. A subclass of CPMFV models are those with universal boundary conditions for the magnitudes of the soft SUSY breaking parameters, but not their phases. These are very economic, they conform with flavor changing neutral currents and minimally extend the complex mSUGRA models, often termed cmSUGRA in literature \[59\]. This class of models has been studied in \[73\] and \[74\].

| Multiplet | \( PQ \)-charge | \( R \)-charge | \( (R - PQ) \)-charge |
|-----------|-----------------|----------------|---------------------|
| Higgs     | 1               | 1              | 0                   |
| Quark / Lepton | - 1/2 | 1/2            | - 1/2              | 1 | 0 |
| Vector    | 0               | 0              | -1                  |

Table 2. \( U(1) \) charges of multiplets

Which phases are rotated away by the \( U_{PQ}(1) \) and \( U_R(1) \)-rotations is a matter of choice. In cmSUGRA due to the fact that the values of the trilinear and gaugino masses are equal, one remains with two phases at the unification scale, and the scheme usually adopted is to consider the basis in which \( \phi_{\mu} = \text{arg}(\mu) \) and \( \phi_{A} = \text{arg}(A_0) \) are the unrotated phases. The phase of \( \mu, \phi_{\mu} \), is known to be severely constrained by the EDM bounds, unlike the phase \( \phi_{A} \) of \( A_0 \) which is less constrained. In the CPMFV case twelve phases remain, since we do not impose universality of the trilinear scalar couplings and the gaugino masses at the unification scale, in general. Therefore in this scheme more options are available and such models have a richer phenomenology.

Certainly any basis is as good as another but whatever the choice physical quantities depend on twelve invariant combinations, namely

\[
\text{arg}(\mu M_a m_3^{2\nu}) , \text{arg}(\mu A_i m_3^{2\nu}) .
\]

In equation (3) \( M_a, a = 1, 2, 3, \) are the gaugino soft masses, \( A_i, i = e, \mu, \tau, u, c, t, d, s, b, \) are the flavor diagonal trilinear scalar couplings and \( m_3^{2\nu} \) is the soft Higgs mixing parameter. Therefore there are twelve invariant combinations in all.
The phases run with the energy scale as can be seen by considering their RGEs. Exception to that is the $\mu$ phase which does not run at all. The phases of the soft trilinear couplings run already at one loop while the gaugino phases start running at the two loop level. In particular at two loops there are contributions to the RGEs of the bino and wino masses, $M_1, M_2$, mixing electroweak and strong interactions which are accompanied by large group factors, as is seen in equation (4), where the ellipses stand for the rest of the contributions [75].

\[
\frac{dM_1}{d\ln Q} = \ldots - \frac{1}{(4\pi)^2} \frac{176}{5} \alpha_1 \alpha_3 (M_3 + M_1) \ldots
\]

\[
\frac{dM_2}{d\ln Q} = \ldots - \frac{1}{(4\pi)^2} 48 \alpha_2 \alpha_3 (M_3 + M_2) \ldots.
\]

Unlike their corresponding one-loop expressions, the RGEs for $M_1, M_2$ are not multiplicative and their phases do not remain constant with the energy scale. In particular they are affected by the presence of the gluino mass $M_3$. A non-vanishing gluino phase at the unification scale, $M_{GUT}$, may produce non-vanishing bino and wino phases $\text{arg}(M_{1,2}) \sim 10^{-1} - 10^{-2}$, even if the latter are zero at $M_{GUT}$ [74]. These values although small, due to their two-loop nature, are slightly larger than expected, due to the presence of the large group factors in the RGEs, and at any rate adequately large for EDMs and for Higgsino / Gaugino baryogenesis [68].

An immediate consequence of this is the impact on the electron’s EDM which is affected by the gluino phase due to the two-loop RGE running, which as said is absent at one loop [74]. We remark that the gluino phase is important for other reasons too. It is observable in gluino production processes [60], via its decays, and in $e^+e^-$ annihilation processes to a fermion-antifermion pair [64, 59]. Besides it greatly affects neutralino relic densities through its impact on the bottom mass corrections [76], in the large $\tan\beta$ regime, and also important for the cancellation mechanism implemented to make EDM contributions small [77]. Therefore if its value has to be non-vanishing, for theoretical and/or phenomenological reasons, its impact on the electron’s EDM should be watched [74].

In figure 5 we display the dependence of the electron’s EDM as function of the gluino phase for some particular inputs. The experimentally allowed area is the yellow stripe at the bottom of the figure. A strong dependence on the gluino phase, $\xi_3$, is observed allowing values of $\xi_3$ in the vicinity of $\pm \pi$ and 0.

**Figure 5.** The ratio of the electron EDM to its experimental limit as function of the gluino phase $\xi_3$ at $M_{GUT}$. The remaining phases are zero. The values of the parameters are displayed in the figure. $m_0, M_{1/2}, A_0$ are the magnitudes of the soft parameters which are taken equal at $M_{GUT}$.

Except the phases discussed previously there is an additional source of CP-violation that needs be discussed. This is due to the misalignment of the two Higgs expectation values (vev).
The two vevs are not aligned and their relative orientation is, in general, non-vanishing and cannot be rotated away. The relative angle $\theta$ of the two vevs is determined from the minimization conditions of the effective potential and is not an arbitrary parameter [78, 59]. If the remaining CP-violating phases are set to zero this is also zero, but when the others are switched on this is non-vanishing. Solving the minimization conditions at the tree level its value is vanishing but with the one-loop contributions to the scalar potential taken into account this turns out to be non-zero. It should be noted that a non-zero $\theta$ emerges even if the Higgs mixing parameter $m^2_3$ is taken real at the minimization scale by using appropriate rotations. In other words the presence of $\theta$ is related to the dependence of the one-loop scalar potential on the CP-odd parts of the Higgs scalars rather than to the complexity of the parameter $m^2_3$. Certainly one can maintain $\theta$ vanishing at every loop order, by introducing appropriate counter-terms, as is done in other approaches, but in principle both approaches are equivalent.

The angle $\theta$ is expected to be small, since it arises from loop corrections to the potential, but it has large impact on phenomenology [78, 59]. Chargino, neutralino, sfermion mass matrices, as well as, EDMs and quark chromoelectric moments depend on it through the combination, $\theta + \text{arg}(\mu)$. Also certain couplings depend on it. It also enhances Higgs decay widths to $b\bar{b}$, affecting therefore neutralino relic densities when the dominant process is LSP annihilation through a Higgs resonance [59].

In figure 6, for some particular inputs, we display the values of $\theta$ and the electron’s EDM, $d_e$, as functions of $\tan\beta$. The dashed-dotted and dotted lines correspond to values of $d_e$ with and without the contribution of the angle $\theta$ respectively. Although $\theta$ is small, in the entire range of $\tan\beta$ considered, the discrepancy between the two lines displayed is striking for values of $\tan\beta > 40$ [74].

![Figure 6](image_url)

**Figure 6.** The angle $\theta$ and the electron’s EDM, with and without the inclusions of $\theta$, for the inputs shown on the figure, as functions of $\tan\beta$. $m_0, M_{1/2}, A_0$ are the magnitudes of the soft parameters which are taken equal.

4. Dark Matter and CP-violation

4.1. Reconciling EDM and WMAP data

The importance of supersymmetric CP-violation in conjunction with dark matter observations by WMAP has been the subject of several works (for a review see [59]). Constrained supersymmetric models, like cmSUGRA, as well as models with Yukawa unification [79, 80, 81, 76, 73] have been studied in detail. Also unconstrained MSSM models with $CP$ have been studied and large phases can be in agreement with the electron and neutron EDM and also with the WMAP data. It has been shown that the presence of $CP$ modifies, by as much as 100%, the predictions for the relic density in a direct way [82]. The neutralino relic density is also affected in an indirect way by the corrections to the bottom mass, which are large in the large
tan $\beta$ regime. The SUSY threshold corrections to the bottom mass have a large impact on the cosmologically allowed domains and are sensitive to the values of the phases chosen, among these the gluino phase which, as we have already discussed, affects through two-loop RGEs the phases of the remaining gauginos. In [74] the DM predictions for the neutralino LSP were studied and large $\mathcal{CP}$ phases were sought, compatible with the EDM constraints, duly taking into account the presence of the vev misaligning angle $\theta$ and the RGE dependence of the phases involved. The two-loop running of the phases, from high to low scales, may induce corrections to the phases that have a large impact on EDMs, as we have already discussed, and this is implemented in the approach followed in [74]. The impact of the trilinear coupling phases to the phases of the gaugino mass parameters has been the subject of [83]. Among other subtleties that affect the numerical analysis are the Higgs masses and their decay widths, that depend on the $\tilde{m}$ parameters has been the subject of [83]. Among other subtleties that affect the numerical analysis are the Higgs masses and their decay widths, that depend on the $\mathcal{CP}$ phases, and also on the bottom and top quark masses. The whole scheme is also sensitive to the top mass whose experimental value is now considerably lower than the value used in earlier works. An updated analysis of the constrained MSSM, when CP is conserved, using the currently known top quark mass has been already carried out [84].

For $\tan \beta < 40$ the regions of the parameter space compatible with the cosmological data are the "focus" and the "coannihilation" regions. For higher values of $\tan \beta$, of particular importance is the paired LSP neutralino annihilation into a fermion-antifermion pair through a rapid Higgs resonance. In the CP-conserving case regions on which this effect takes place span a large portion of the parameter space and open for large $\tan \beta > 40$. It would be interesting to see, in the $\mathcal{CP}$-case, if these "funnel" regions extent to values of $m_0, M_{1/2}$ where EDMs are mass suppressed, being at the same time small enough to be accessible at LHC, for large values of the phases involved. The "funnels" track the line on which

$$\frac{M_{Higgs}}{2 m_\chi} = 1,$$

where $m_\chi$ is the LSP neutralino mass, and their shape and location depend sensitively on:

- Higgs masses $M_{Higgs}$, which are sensitive to the top mass, $m_t$
- Higgs decay widths $\Gamma_H$, which depend on the CP-odd phases
- Bottom mass $m_b$, whose threshold corrections depend on the CP-odd phases.

Scanning the parameter space it proves rather difficult to satisfy WMAP and EDM constraints simultaneously. This is shown in figure 7, for fixed SUSY inputs, and $\tan \beta = 50$. The common magnitudes of the soft scalar and gaugino masses are $m_0, M_{1/2} = 500 \text{ GeV}$. The magnitude of the common trilinear coupling has been taken $A_0 = 100 \text{ GeV}$. We have fixed the wino phase, $\xi_2$, and vary the bino and the gluino phases $\xi_1, \xi_3$. All other phases are taken zero at the unification scale, $M_{GUT}$, with the exception of the phase of the Higgs mixing parameter $m_3^2$. Throughout our analysis, the phase of $m_3^2$ is rotated away, at the scale at which the minimization conditions are solved, and therefore its phase at $M_{GUT}$ is not zero but is extracted by running the RGEs. One clearly sees from figure 7 that the electron and neutron EDM bounds are both satisfied in the small gray shaded area, but that of Mercury cannot be simultaneously satisfied. The WMAP data on the DM relic density are satisfied only within a small region located at the center of the figure which stays afar from the region allowed by the electron and neutron EDMs. This figure is representative of the difficulty one encounters with in trying to satisfy WMAP and EDM data. In figure 8 we display the projection on the $\xi_1, \xi_3$ plane of a random sample of one million $\xi_{1,2,3}$ points, with the other phases taken zero. We take $\tan \beta = 50$ and the common magnitudes of the soft parameters are $M_{1/2} = 480 \text{ GeV}, m_0 = 500 \text{ GeV}$, and $A_0 = 100 \text{ GeV}$. The gray points are those for which all accelerator bounds are observed, and the black those for which, in addition, the neutralino relic density is $\Omega_{\chi} h_0^2 < 0.122$. The yellow points are their subset yielding a relic density in the WMAP range $0.096 < \Omega_{\chi} h_0^2 < 0.122$. Concerning EDMs, only

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Since the text is an excerpt from a scientific paper, the full context and analysis are crucial for understanding the implications of the findings. The discussion involves complex theoretical aspects of particle physics, particularly focusing on supersymmetry (SUSY) and its implications for experimental constraints like the WMAP and EDM data. The authors explore the sensitivity of the model to various phases and parameters, and the limitations in simultaneously satisfying constraints from different experiments.

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for the green diamonds displayed the electron and neutron EDMs are within their experimental bounds, and of those only the two red-green diamonds satisfy all EDM bounds. From these two only one, lying at the bottom, satisfies all available data.

Figure 7. EDMs and neutralino relic density contours for the inputs shown. $\xi_1, \xi_3$ are the phases of the bino and gluino soft masses.

4.2. EDMs and the cancellation mechanism
The difficulty in satisfying the EDM constraints is due to the fact that even tiny phases overproduce their values. For arbitrary values of the phases and for $m_0, M_{1/2}$ up to 3 TeV it is hard to find regions compatible with the EDMs, although regions satisfying the WMAP data do exist within this domain. Moving towards higher values of $m_0, M_{1/2}$, where EDMs are mass suppressed, the “funnel” and the “coannihilation” cosmologically allowed regions are excluded and only the ”focus” region survives, which is compatible with all available data. However this region is not accessible to LHC. This outlines in brief the obstacles one encounters with in trying to locate points which satisfy all available experimental constraints.

The “cancellation mechanism”, first proposed in [77], can be implemented in order to find small $m_0, M_{1/2}$ values, which are within LHC reach and also compatible with the EDM data. According to it the phases can be fine tuned so that contributions of various Feynman diagrams delicately cancel each other rendering neutron and electron EDMs small. This has been applied successfully, when phases are given at the electroweak scale, and extended regions can be found by just rescaling the initial $m_0, M_{1/2}$ values for which the cancellation was successful. The same mechanism can be applied having as inputs the phases at the unification scale $M_{GUT}$ as well. However in that case a rescaling of $m_0, M_{1/2}$ does not generate EDM allowed regions. The reason is that by rescaling the values of $m_0, M_{1/2}$ to $\lambda m_0, \lambda M_{1/2}$, keeping fixed the values of the phases for which cancellation was achieved, the low energy values of the phases change too, due to their RGE running which depends on the soft masses, and the cancellation is lost. Therefore in the top-down approach one proceeds as follows. For a given set of $m_0, M_{1/2}$, and the remaining parameters, we rotate the bino phase $\xi_1(M_{GUT})$ until neutralino contributions to the electron EDM, $d_e$, which depend on the bino phase, cancel the chargino contributions which are $\xi_1$ - independent. This renders $d_e$ small. Subsequently one rotates the gluino phase, $\xi_3(M_{GUT})$, so that the neutron EDM, $d_n$, becomes small. In this way one renders small both $d_e, d_n$. This procedure assumes that the electron EDM does not depend on the gluino phase so that the second rotation does not upset the value of $d_e$ found by the first rotation. However, as we have
discussed, in the presence of the gluino phase the two-loop RGE running dislocates slightly the bino phase found in the first rotation and therefore the procedure has to be repeated so that the phases are readjusted. We should remark that the EDM of Mercury is not guaranteed to be small by this procedure. With the obtained bino and gluino phases one can scan the entire parameter space to delineate regions compatible with all EDMs. This procedure is cumbersome but feasible.

From this discussion it becomes apparent the important role a non-vanishing gluino phase plays in the cancellation mechanism, in addition to its phenomenological importance and its impact on the running of the bino and wino phases that we have discussed.

Figures 9-12 were produced by use of the cancellation mechanism. The gaugino phases \(\xi_{1,2,3}\), different in each figure, were tuned by this mechanism in order to satisfy the electron and neutron EDMs for a particular \(m_0, M_{1/2}\) point. Then by keeping fixed these phases the entire \(m_0, M_{1/2}\) plane was scanned. The magnitude of the trilinear coupling is taken \(A_0 = 100\) GeV in all figures displayed. Recall that we consider a model where the soft breaking parameters have common magnitudes at the unification scale but their phases differ in general. All other phases are taken zero with the exception of figure 12 where the phase of \(\mu\) is \(\pi/2\). The boundaries of the electron, neutron and Mercury EDMs, \(d_e, \, d_n, \, d_\mu\), are designated in blue (dashed), magenta (short-dashed) and orange (dashed-dotted) lines respectively, and the allowed regions lie to the right of these boundaries pointing towards higher values of \(m_0, M_{1/2}\). The regions allowed by WMAP data are the thin green stripes colored in green. In figure 9 we have taken \(\tan \beta = 10\) and \(d_e\) excludes all values compatible with the WMAP data in the region \(m_0, M_{1/2} < 2\) TeV. Only very high values \(m_0 > 4\) TeV, \(M_{1/2} > 800\) GeV are allowed by \(d_e\) and WMAP data (not shown), lying on the focus point hyperbolic branch, which are beyond the LHC reach. In figure 10 the value of \(\tan \beta = 30\) is considerably larger. Part of the focus point region, \(M_{1/2} < 700\) GeV, is now compatible with all data and accessible to LHC. On the right of the figure a small funnel starts being formed but it is inaccessible to LHC since \(d_e\) allows only for values \(M_{1/2} > 2.2\) TeV, \(m_0 \sim 1\) TeV. Within the shadowed region the ratio \(|M_2/\mu|\) is close to unity, as required in Higgsino/Gaugino driven baryogenesis mechanism. Therefore in this region EW baryogenesis is possibly succesfull. In figure 11 \(\tan \beta = 46\) is large. A peaked funnel region has been formed, part of which is accessible to LHC. The focus point region is inaccessible to LHC since only \(m_0 > 8\) TeV is allowed by the \(d_e\) bound (not shown). The shadowed region is as in the figure 10. Figure 12 is similar to figure 11 but the phase of \(\mu\) is non-zero in this case and set to \(\pi/2\), violating therefore CP in the maximal possible way.

Therefore by the cancellation mechanism one is able to find large CP-violating phases that survive the stringent constraints imposed by the EDM data which are cosmologically allowed. However in the simple model considered here, in which the magnitudes of the soft breaking parameters are taken common at the unification scale, these are fine tuned. The amount of fine tuning can be seen in the scattered plots of figures 13, 14, where we have fixed \(m_0 = 2000\) GeV, \(M_{1/2} = 1520\) GeV, selected from figure 12, and vary the phases about their values obtained in figure 12, which correspond to the blue diamond at the center of each figure. Only the displayed scattered points (diamonds) correspond to values of the phase of the \(\mu\) parameter, \(\phi_\mu\), and the phases \(\xi_3, \xi_2\) of the gluino and the wino soft masses, that satisfy all constraints. The amount of tuning for the phases, as read from these figures, is \(O(0.05\pi)\) for \(\phi_\mu, \xi_2\) and \(\xi_3\). The bino phase \(\xi_1\) is less fine tuned \(O(0.1\pi)\) (not shown).

The conclusion is therefore that by the cancellation mechanism one can find large phases compatible with the EDM and WMAP data which are however fine-tuned, at least in the minimal supersymmetric schemes considered in this work.
5. Early Universe and DM

WIMPs with weak scale masses are excellent DM candidates. In the framework of SUSY theories, with conserved R-parity, the LSP neutralino qualifies as a WIMP particle, being perhaps the best motivated CDM candidate. Precise measurements of the CMB spectrum, and other cosmological observations, have led to a very precise determination of the DM content of the universe, constraining the various supersymmetric models proposed so far. The class of supersymmetric models in which CP-symmetry is conserved in the supersymmetric sector, can survive the stringent limits put by the cosmological observations and regions of the parameters describing the various models, which are compatible with all available data, have been delineated. In the presence of supersymmetric CP-violation, there are in addition tight constraints, by EDM measurements, but still, in this case too, such models can constitute viable supersymmetric extensions of the Standard Model.

Relic abundances of the thermally produced WIMPs depend on the annihilation cross-sections, which can be determined by particle experiments, and have been theoretically calculated in detail within the context of the supersymmetric models considered. In these
approaches it is tacitly assumed that the expansion rate of the universe is determined through Friedmann equation, and that universe is radiation dominated during decoupling of DM particles, which occurs at a freeze-out temperature $T_f$. DM particles started be thermally produced after inflation, at a temperature $T_p$ which is usually assumed to be larger than $T_f$, entailing to present day DM relic densities that are independent of $T_p$. Besides these the standard scenarios assume that for temperatures $T < T_f$ the entropy per comoving volume is conserved.

However modifying the cosmological assumptions can have a large impact on the predicted relic densities and thus non-standard scenarios have been investigated as well. These include inflationary models with low reheat temperature, models with low entropy production, and models with a modified expansion rate [85]. We shall focus on the latter which are encountered in schemes with a modified General Relativity or anisotropic universe expansion, models with a quintessence contribution to the energy-matter density of the universe or String and Brane inspired models. In some of these non-standard scenarios the relic density may differ from that predicted in the conventional approaches by many orders of magnitudes, in some cases!

If the universe is not radiation dominated after inflation and an extra component $\rho_\phi$ contributes to matter-energy density, in addition to radiation $\rho_r$, the Hubble expansion rate $H$ is

$$3 \ H^2 = 8\pi G_N \ (\rho_r + \rho_\phi) \ .$$

Then the number to entropy density ratio, $Y \equiv n/s$, satisfies a modified Boltzmann equation,

$$\frac{dY}{dT} = \xi <\sigma v> (Y^2 - Y_{eq}^2) \left[\frac{45G_N}{\pi} g_{eff}\right]^{-1/2} \left(h + \frac{T}{3} \frac{dh}{dT}\right)$$

where $Y_{eq}$ is its equilibrium value. $g_{eff}$ and $h$ count the relativistic and entropy degrees of freedom respectively. Notice the appearance of the prefactor $\xi$ in equation 7 which accounts for the modified expansion rate. In the standard scenarios, where only radiation dominates, this is set to unity. In the case under consideration this is given by

$$\xi = \left(1 + \frac{\rho_\phi}{\rho_r}\right)^{-1/2} \ .$$

**Figure 13.** Scattered plots of the $\phi_\mu$ and $\xi_3$ allowed phases. The blue diamond at the center corresponds to their values used in figure 12. The remaining inputs are as in the figure 12.

**Figure 14.** Scattered plots of the $\phi_\mu$ and $\xi_2$ allowed phases. The blue diamond at the center corresponds to their values used in figure 12. The remaining inputs are as in the figure 12.
and its value at every epoch is determined by solving Friedmann’s equations. In models in which a quintessence scalar field carries the dark energy of the universe the maximal enhancement to the relic density, compatible with BBN bounds, turns out to be \[\Delta \Omega \equiv \frac{(\Omega - \Omega_{\text{no } \phi})}{\Omega_{\text{no } \phi}} \sim 10^6, \tag{9}\]
where \(\Omega_{\text{no } \phi}\) is the ratio of matter density to the critical density, calculated without the presence of the quintessence fields \(\phi\).

The situation of modified expansion rate is encountered in Supercritical String Cosmology (SSC), where a rolling dilaton provides with a smoothly evolving dark energy and couples to the matter density in the following way \[d \rho_m dt = -3H(\rho_m + p_m) + \dot{\phi}(\rho_m - 3p_m). \tag{10}\]

Then \(Y\) varies as \[\frac{dY}{dT} = \xi <\sigma v> (Y^2 - Y_{eq}^2) \left[\frac{45G_N}{\pi} g_{eff}\right]^{-1/2} (h + \frac{T}{3} \frac{dh}{dT}) - \frac{\dot{\phi}Y}{HT} \tag{11}\]
which yields a relic density \[\Omega = R \times \Omega_0. \tag{12}\]

In this equation \(\Omega_0\) is the density obtained by ordinary calculations, where the dilaton field is absent, and \(R\) is a cosmological correction factor given by \[R = \xi^{-1}(T_f) \exp \left(\int_{T_p}^{T_f} \frac{\dot{\phi}}{HT} dT\right) \tag{13}\]

The main consequences implied by such a modification of the standard scenario are listed below:

- For an LSP neutralino it turns out that \(R \sim O(0.1)\), for dilaton solutions which are in agreement with an accelerating universe, \(q_0 = -0.61\), with a smooth evolution of the DE in the redshift regime \(0 < z < 1.6\).
- LSP relic density is diluted by a factor of ten and regions of MSSM with too much DM are allowed!
- For a baryon the factor \(R \sim O(1)\), leaving the predictions for conventional matter relic abundances unaffected!

The phenomenological consequences for LHC searches have been studied in [90]. In particular, in the mSUGRA model and with \(\tan \beta = 10\), and a common trilinear scalar coupling \(A_0 = 100\ GeV\), the cosmologically allowed region, by WMAP data, in the \(m_0, M_{1/2}\) plane is a thin co-annihilation stripe lying above the border of the disallowed region within which the LSP is a stau. With the modification implied by 12 the cosmologically allowed region is shifted upwards towards larger values of \(m_0\). This changes the phenomenology and the signal of discovering SUSY at LHC. For the co-annihilation case the dominant decay chain for a squark is \[\tilde{q}_L \rightarrow q \chi_2^0 \rightarrow q \tau \tilde{\tau} \rightarrow q\tau \tau \chi_1^0\]
so the dominant signal is \(2\tau + \text{jet} + \not{E}_T\).
with low-energy $\tau$'s in the final state. For the SSC cosmologically allowed region, three possible neutralino decays $\tilde{\chi}_2^0$ are open

$$\tilde{\chi}_2^0 \rightarrow h_0 + \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow Z + \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau}$$

yielding different signals

$$Z + \text{jet} + E_T$$
$$h_0 + \text{jet} + E_T$$
$$2\tau + \text{jet} + E_T.$$

The last channel (tau production) in this case is characterized by high-energy $\tau$'s. Thus the final states expected at the LHC in this scenario, unlike the standard scenario, consist of $Z$ bosons, Higgs bosons, and/or high energy taus.

Therefore, modifications of the early universe evolution may have important consequences for the predictions of the DM abundances of SUSY models. In the SSC case discussed here, the time dependent dilaton not only contributes to the dark energy but also affects Boltzmann transport equation, which determines the DM content of the universe, in a dramatic way. The final states in the SSC scenario are different from those of the standard cosmology with important consequences for LHC physics.

6. Summary

Our conclusions are summarized as follows:

- CP-conserving supersymmetric models are incapable of explaining the baryon asymmetry of the universe (BAU) due to the smallness of the CKM phase. Extending mSUGRA to include $\mathcal{C}P$ is too restrictive. There are only two phases which are severely constrained by the EDM data, to values not sufficient to generate the observed BAU by the standard EW baryogenesis mechanisms.

- Departing from the simple mSUGRA-type models to models encompassing $\mathcal{C}P$, with non-universal boundary conditions, includes additional phases making such models phenomenologically interesting. The EDM constraints allow to certain combinations of phases to be relatively large, being therefore of relevance for Higgsino/Gaugino driven EW baryogenesis.

- The cancellation mechanism is an important tool to delineate regions, which are within LHC reach, reconciling EDM and WMAP data.

- In a top-down approach, the scale dependencies of the phases induce sizable effects and should be counted for. In particular the 2-loop RGE running of the phases from the GUT to EW scale affects the gaugino phases by amounts which, although small, are substantial for EDMs.

- Large phases can be measured in future experiments and are phenomenologically interesting.

Therefore, supersymmetric $\mathcal{C}P$ phases can change the picture for DM predictions of the conventional supersymmetric models and if large can be measured in future collider experiments. The origin of such phases can be sought in the underlying GUT physics, and in particular in String Theory, if we believe that low energy supersymmetry is a manifestation of a unified description of Nature at Planckian energies. Models encompassing supersymmetric $\mathcal{C}P$-violating sources deserve further detailed investigation.

The implications of a variety of mechanisms, that modify the standard early universe evolution, may have severe consequences for the calculation of DM relic abundances, and
therefore for SUSY phenomenology, which are of paramount importance for supersymmetric LHC searches. In particular the dilaton in non-critical string theories modifies the expansion rate of the universe and couples to matter in such a way that dilutes the predictions for neutralino DM by factors of $O(10)$, changing therefore the profile of DM allowed region in SUSY models.

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