Gravity Wave signatures of Electroweak Phase Transition in Split NMSSM

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Standard Model: Major Problems

Gauge fields (interactions): $\gamma, W^\pm, Z, g$

Three generations of matter: $L = (\nu_L, e_L), e_R; Q = (u_L, d_L), d_R, u_R$

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO)
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage
  - Dark energy ($\Omega_\Lambda$)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity
  - ... 

Split NMSSM can explain all above in green
Outline

1. Dark Matter Problem
2. Baryon Asymmetry of the Universe (BAU)
3. Supersymmetric models
4. Split SUSY: viable and cosmologically interesting
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Dark Matter Properties \[ p = 0 \]

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition, \( T \approx 1 \text{ eV} \) (either Cold or Warm, \( v_{RD/MD} \lesssim 10^{-3} \))
3. (almost) collisionless
4. (almost) electrically neutral

Among the known particles

Only neutrinos (at least two species are massive) could fit
Unfortunately neutrinos do not fit (If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition, $T \sim 1$ eV (either Cold or Warm, $\nu_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

To be collected inside galaxies

If not: for bosons for fermions

Pauli blocking:

$$f(p, x) = \rho_x(x) \cdot \frac{1}{M_x} \cdot \frac{1}{\left(\sqrt{2\pi} M_x v_x\right)^3} \cdot e^{-\frac{p^2}{2M_x^2 v_x^2}} \bigg|_{p=0} \leq \frac{g_x}{(2\pi)^3}$$

$$M_x \gtrsim 750 \text{ eV}$$
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Matter-antimatter asymmetry

\[ \eta_B \equiv \frac{n_B}{n_{\gamma}} \approx 6 \times 10^{-10} \]

\[ \eta_B \sim \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \]
Baryogenesis

Sakharov conditions of successful baryogenesis

- B-violation \((\Delta B \neq 0)\) \(XY \ldots \rightarrow X' Y' \ldots B\)
- C- & CP-violation \((\Delta C \neq 0, \Delta CP \neq 0)\) \(\bar{X} \bar{Y} \ldots \rightarrow \bar{X}' \bar{Y}' \ldots \bar{B}\)
- processes above are out of equilibrium \(X' Y' \ldots B \rightarrow XY \ldots\)

Analyses of BBN, CMB and LSS data reveal similar results, so we need baryon asymmetry production before \(T \approx 1 \text{ MeV}\)

Electroweak baryogenesis within the SM ???
B is violated, since the baryon current is anomalous

\[ \partial^\mu j^B_\mu = 3 \frac{g^2}{32\pi^2} \varepsilon_{\mu\nu\lambda\rho} V^a_{\mu\nu} V^a_{\lambda\rho}, \]

\[ V^a_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc} V^b_\mu V^c_\nu \]

Anomaly: only left fermions couple to fields \( V^a_\mu \).

\[ \Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3 x \partial^\mu j^B_\mu = 3 \int_{t_i}^{t_f} d^4 x \frac{g^2}{32\pi^2} \varepsilon_{\mu\nu\lambda\rho} V^a_{\mu\nu} V^a_{\lambda\rho}, \]

Strong fields are needed: \( V^a_{\mu\nu} \propto \frac{1}{g} \). Energies of such configurations (EW sphalerons) are \( \propto \frac{1}{g^2} \).

Sphalerons are in equilibrium with plasma above EW scale, at temperatures

\[ 100 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV} \]
$CP$ is violated by CKM-phase

$$V_{CKM} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}
\end{pmatrix},$$

where $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$ are mixing angles, $i, j = 1, 2, 3$, and $\theta_{13}$ is the $CP$-violating phase.
Phase transitions of the I and II orders
Baryons are produced on the bubble walls
However, with numbers we have in the SM

(Higgs boson mass, top-quark mass, CKM-elements, etc)

EW baryogenesis does not work
**CP violation is too mild**

\[ V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}, \]

where \( c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij} \) are mixing angles, \( i, j = 1, 2, 3 \), and \( \theta_{13} \) is the \( CP \)-violating phase

\[ s_{12} = 0.2254, \quad s_{13} = 0.0035, \quad s_{23} = 0.04118, \quad \delta_{13} = 69^\circ \pm 5^\circ. \]

Phase is always multiplied by a small modulos
EW transition is not of the I order

– No bubbles

– Sphalerons remain in equilibrium for some time after transition,

— whasing out any asymmetry
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Supersymmetry is a symmetry of bosons and fermions

supercharge $\hat{Q}_{SUSY}$

- SUSY exchanges **bosons** and **fermions**:

$$
\hat{Q}_{SUSY} \text{ boson } \rightarrow \text{ fermion}
$$

$$
\hat{Q}_{SUSY} \text{ fermion } \rightarrow \text{ boson}
$$

they become **superpartners**

- In supersymmetric theory

$$
\text{bosonic d.o.f. } = \text{ fermionic d.o.f.}
$$

$$
[\hat{Q}_{SUSY}, \hat{H}] = 0
$$

**superpartners**

are of the same mass and exhibit the same interactions
How does it work? Supersymmetric QED

- the same number of d.o.f. in **bosonic** and **fermionic** sectors

  Dirac fermion $\Psi : 4 \ d.o.f. \longrightarrow$ complex scalars $\phi_+, \phi_-$

  massless vector $A_\mu : 2 \ d.o.f. \longrightarrow$ Majorana fermion $\lambda$

- superpartners are of the same masses

\[ m\bar{\Psi}\Psi \longrightarrow m^2\phi_+^*\phi_+ + m^2\phi_-^*\phi_- , \quad M_A = M_\lambda = 0 , \]

- and exhibit the same interactions

\[ eA_\mu \bar{\Psi}\gamma^\mu\Psi \longrightarrow ieA^\mu (\phi_+ \partial_\mu \phi_+^* - \phi_-^* \partial_\mu \phi_-) - ieA^\mu (\phi_- \partial_\mu \phi_-^* - \phi_-^* \partial_\mu \phi_-) \]

\[ eA_\mu \bar{\Psi}_+ \bar{\sigma}^\mu \psi_+ - eA_\mu \bar{\Psi}_- \bar{\sigma}^\mu \psi_- \longrightarrow -ie\sqrt{2} (\phi_+ \bar{\psi}_+ \bar{\lambda} - \phi_- \bar{\psi}_- \bar{\lambda}) + \text{h.c.} \]

\[ \text{total derivative} \quad \longleftrightarrow \quad e^2 A_\mu A^\mu \phi_+^*\phi_+ + e^2 A_\mu A^\mu \phi_-^*\phi_- \]

\[ \text{total derivative} \quad \longleftrightarrow \quad -e^2 \frac{1}{2} (\phi_+^*\phi_+ - \phi_-^*\phi_-)^2 \]
Most attractive features

- **Theory:** bosonic loops cancel fermionic ones
  - only logarithmic divergences remain:
  - stability of the hierarchical structure of energy scales, e.g.
  - \( M_W \ll M_{Pl} \) is stable

- **Phenomenology:** number of particles gets doubled !!
  - get new interactions but with the same coupling constants !!
SUSY: a couple is more stable and promising
### Supersymmetrizing the Standard Model  
MSSM

<table>
<thead>
<tr>
<th>Particles</th>
<th>Superpartners</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluons, $g$</td>
<td>gluino, $\tilde{g}$</td>
</tr>
<tr>
<td>photon, $\gamma$</td>
<td>photino, $\tilde{\gamma}$</td>
</tr>
<tr>
<td>weak gauge bosons, $W^\pm, Z$</td>
<td>winos, zino, $\tilde{W}^\pm, \tilde{Z}$</td>
</tr>
<tr>
<td>quarks, leptons, $q, l$</td>
<td>squarks, sleptons, $\tilde{q}, \tilde{l}$</td>
</tr>
<tr>
<td>r.h. electron, $e_R$</td>
<td>r.h. selectron, $\tilde{e}_R$</td>
</tr>
<tr>
<td>l.h. top, $t_L$</td>
<td>l.h. stop, $\tilde{t}_L$</td>
</tr>
<tr>
<td>neutrino, $\nu$</td>
<td>sneutrino, $\tilde{\nu}$</td>
</tr>
</tbody>
</table>

**SM Higgs boson**

To avoid the anomaly due to higgsino set

- two Higgs doublets, $h, H, A, H^\pm$
- neutral $\tilde{h}, \tilde{H}$ and charged $\tilde{H}^\pm$
- or $\chi_{1,2}^0$ and $\chi^\pm$ higgsinos
Problems of a supersymmetric extension

- there are no superpartners of the same mass with the same couplings
  \[ \rightarrow \quad \text{SUSY must be spontaneously broken} \]
- superpartners are heavy
  - bases are not aligned
  - Higgs makes SM particles (and superpartners) massive
  - hundred new parameters
  \[ \leftarrow \quad \text{mixing and FCNC} \]
At least a huge gap is between us
SUSY is broken and thereby even more attractive

- Higgs mass gets corrections of the types
  \[ \propto \log\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right), \quad \text{and} \quad \propto \left(\frac{m_{\tilde{t}}^2}{m_t^2} - 1\right), \]

  the superpartners must be not far from the EW-scale

- Massive, emerge in pairs \implies\ lightest superpartner is stable (LSP)
  R-parity

- Most natural DM candidate (WIMPs) we have

- 2 Higgs doublets can arrange EW phase transition of the I order
  additional sources of CP-violation
  \implies\ prospects for EW baryogenesis

- There are several anomalies in particle physics (and closely related) experiments:
  \( g - 2 \),
  \[ \frac{\text{Br}(B \to K^*\mu^+\mu^-)}{\text{Br}(B \to D^{(*)}\tau\nu)}, \quad \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}, \quad \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+\ell^-)} \]
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Split SUSY: heavy sfermions, light gauginos $M_{\tilde{Q}} \gg M_\lambda$

Is it possible in SUSY?

Yes, moreover, someones argued natural

- In many (simple) models where SUSY is broken spontaneously gauginos are light (massless), that was the problem
- the hierarchy $M_{\tilde{Q}} \gg M_\lambda$ is stable with respect to quantum corrections (RG-evolution)

$$\frac{dM_\lambda_i}{d \log Q^2} \propto \alpha_i M_{\lambda_i} + \alpha_i y^2 A$$

$$\frac{dM^2_{\tilde{Q}}}{d \log Q^2} \propto y^2 M^2_{\tilde{Q}} + \cdots + \alpha_i M^2_{\lambda_i}$$

$$\frac{dA_i}{d \log Q^2} \propto y^2 A_i + \cdots + \alpha_i M_{\lambda_i}$$
Split SUSY: $M_{\tilde{Q}} \gg M_\lambda$

@ 1 TeV: gauginos + higgsinos + SM-like Higgs boson

- dark matter (natural)
- gauge coupling unification (feature of Split MSSM)
- no FCNC (natural)
- stability of gauge hierarchy (LOST)
  - Though... in MSSM is lost (to some extent) as well: $(100 \text{ GeV})^2 \ll (1 \text{ TeV})^2$
  - Splitting scale is not very high in fact

out of LHC reach though
Why NMSSM? Adding 4 d.o.f. to 230...

- $\mu$-problem:
  - MSSM: $\hat{\mathcal{W}} = \mu \hat{H}_u \hat{H}_d$
  - NMSSM: $\hat{\mathcal{W}} = \hat{\mu} \hat{H}_u \hat{H}_d$

- mechanism of baryogenesis within the Split SUSY:
  - NMSSM: Electroweak

EWB does not work in MSSM:
the Higgs sector mimics SM, no EW phase transition of the I order

MSSM: new sources of $CP$-violation
NMSSM: + the strongly first order phase transition

Electroweak baryogenesis is attractive:
both ingredients can be directly tested

The main concern: SM Higgs

S.Demidov, D.G., D.Kirpichnikov (2016)
BAU in Split NMSSM

EWB works perfectly

\[ \Delta_0 = 8.3 \times 10^{-11} \] or \[ \eta_B \equiv n_B/n_\gamma = 6.2 \times 10^{-10} \]
How to test Split NMSSM?

- New particles
  - Higgs sector: new scalar
  - Neutralino sector: singlino
  - New $CP$-sources
  - EW 1st order phase transition:
    - Bubbles can produce gravitational waves
      - Contribute to EDMs
Electric dipole moments of electron and neutron

*CP*-source: the same contributions to EDMs as in Split MSSM but here one has generally two additional phases,

\[
\begin{align*}
\phi_1 &= \arg(\tilde{g}_u \tilde{g}_d^* M_2 \tilde{\mu}) , \\
\phi_2 &= \arg \left( \kappa k^* \lambda_u \lambda_d (\tilde{\mu}^*)^{-2} \right) , \\
\phi_3 &= \arg (\lambda_u \lambda_d^* \tilde{g}_u \tilde{g}_d) \\
\tilde{\mu} &= \mu + \kappa (v_s + iv_P) / \sqrt{2} \\
d_f &= d_{h\gamma} + d_{WW} + d_{hZ}
\end{align*}
\]
EDMs in Split NMSSM

a factor of 30 improvement in electron EDM for last 10 years

Also light charginos are disfavored from LHC
the rest ($m_{\chi^+} \approx 200 - 240$ GeV) can be tested in $\chi_1^+ \rightarrow \chi_1^0 + W^+$
SPlit SUSY: PHENO viable and COSMO interesting

GW in Split NMSSM

M_s = 10 TeV

M_s = 12 TeV
Conclusions:

- SUSY is wonderful and we search for it
- Split NMSSM is a viable option
- It can explain DM and BAU
- The explanation can be tested
  - @ colliders. . . light chargino
  - @ new searches for electron and neutrons
  - EDMs
  - @ gravitational interferometers