Gravity Wave signatures of Electroweak Phase Transition in Split NMSSM

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Standard Model: Major Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

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

Split NMSSM can explain all above in green

Outline

Outline

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition, $T \simeq 1\,\text{eV}$ (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
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3. (almost) collisionless
4. (almost) electrically neutral

To be collected inside galaxies

If not: for bosons

for fermions

Pauli blocking: $M_X \gtrsim 750\,\text{eV}$

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Big|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Outline

Matter-antimatter asymmetry

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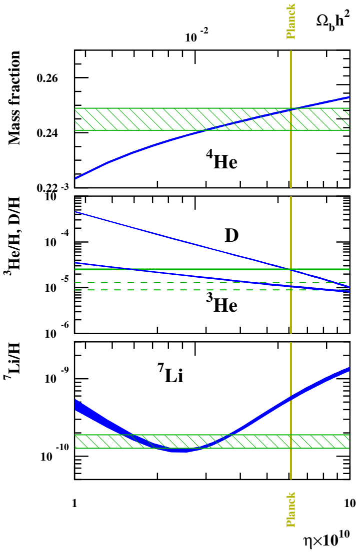
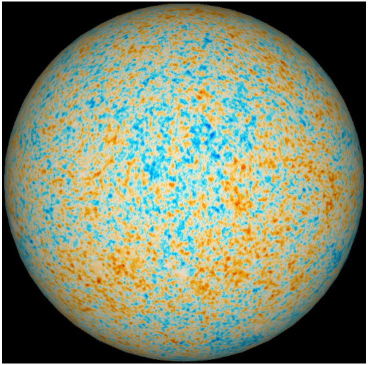


$$\eta_B \equiv \frac{n_B}{n_\gamma} \approx 6\times10^{-10}$$

$$\eta_B \sim \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}}$$



Baryogenesis

Sakharov conditions of successful baryogenesis

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

Analyses of BBN, CMB and LSS data reveal similar results, so

we need baryon asymmetry production before $T \simeq 1$ MeV

Electroweak baryogenesis within the SM ???

B is violated, since the baryon current is anomalous

$$\partial^\mu j_\mu{}^{\mathrm{B}} = 3\frac{g^2}{32\pi^2}\varepsilon_{\mu\nu\lambda\rho} V^{a\ \mu\nu} V^{a\ \lambda\rho} \ ,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc} V^b_\mu V^c_\nu$ refer to $SU(2)_{\mathrm{W}}$

Anomaly: only left fermions couple to fields V^a_μ.

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

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

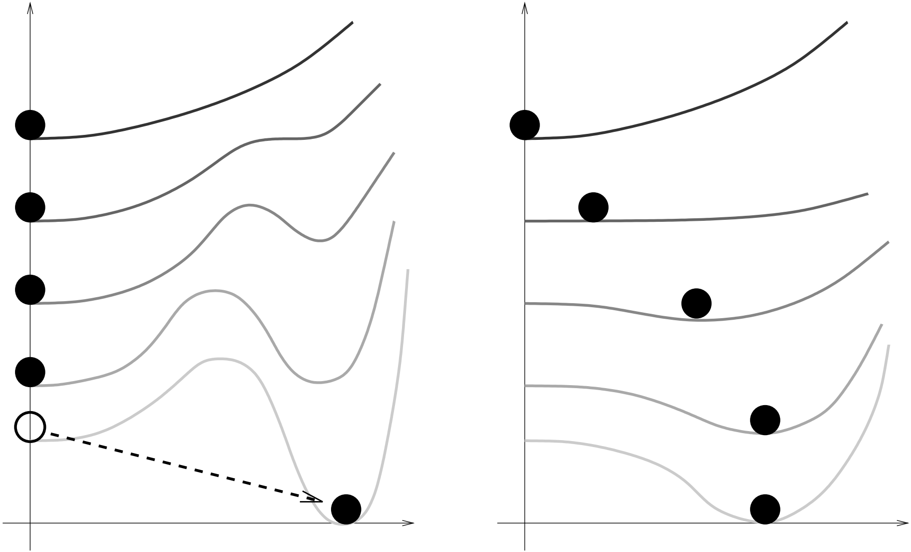
$$100\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\ \mathrm{GeV}$$

CP is violated by CKM-phase

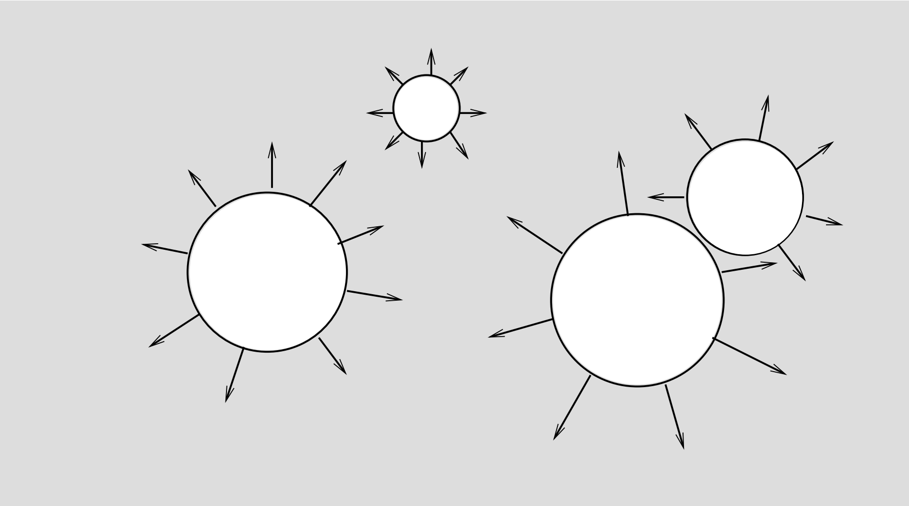
$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}}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

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

$$s_{12} = 0{,}2254, \;\; s_{13} = 0{,}0035,$$
$$s_{23} = 0{,}04118, \;\; \delta_{13} = 69^\circ \pm 5^\circ.$$

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,

— whashing out any asymmetry

Outline

Supersymmetry is a symmetry of bosons and fermions

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

- SUSY exhanges bosons and fermions:

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

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

  they become superpartners

- In supersymmetric theory

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

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

  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

$$\text{Dirac fermion } \Psi : 4\, d.o.f. \longrightarrow \text{complex scalars } \phi_+ , \phi_-$$
$$\text{massless vector } A_\mu : 2\, d.o.f. \longrightarrow \text{Majorana fermion } \lambda$$

- superpartners are of the same masses

$$m\bar{\Psi}\Psi \longrightarrow m^2 \phi_+^* \phi_+ + m^2 \phi_-^* \phi_- \,, \qquad M_A = M_\lambda = 0 \,,$$

- and exhibit the same interactions $\mathscr{L}$ is a scalar !!

$$e A_\mu \bar{\Psi}\gamma^\mu \Psi \longrightarrow ie A^\mu \left(\phi_+ \partial_\mu \phi_+^* - \phi_+^* \partial_\mu \phi_+\right) - ie A^\mu \left(\phi_- \partial_\mu \phi_-^* - \phi_-^* \partial_\mu \phi_-\right)$$
$$e A_\mu \bar{\psi}_+ \bar{\sigma}^\mu \psi_+ - e A_\mu \bar{\psi}_- \bar{\sigma}^\mu \psi_- \longrightarrow -ie\sqrt{2}\left(\phi_+ \bar{\psi}_+ \bar{\lambda} - \phi_- \bar{\psi}_- \bar{\lambda}\right) + \text{h.c.}$$
$$\text{total derivative} \longleftarrow e^2 A_\mu A^\mu \phi_+^* \phi_+ + e^2 A_\mu A^\mu \phi_-^* \phi_-$$
$$\text{total derivative} \longleftarrow -e^2 \frac{1}{2}\left(\phi_+^* \phi_+ - \phi_-^* \phi_-\right)^2$$

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

gluons, g	$\longleftrightarrow$	gluino, $\tilde{g}$
photon, γ	$\longleftrightarrow$	photino, $\tilde{\gamma}$
weak gauge bosons, $W^{\pm}, Z$	$\longleftrightarrow$	winos, zino, $\tilde{W}^{\pm}, \tilde{Z}$
quarks, leptons, q, l	$\longleftrightarrow$	squarks, sleptons, $\tilde{q}, \tilde{l}$
	e.g.	
r.h. electron, e_R	$\longleftrightarrow$	r.h. selectron, $\tilde{e}_R$
l.h. top, t_L	$\longleftrightarrow$	l.h. stop, $\tilde{t}_L$
neutrino, ν	$\longleftrightarrow$	sneutrino, $\tilde{\nu}$
SM Higgs boson	$\longleftrightarrow$	higgsino
to avoid the anomaly		due to higgsino set
two Higgs doublets, h, H, A, $H^{\pm}$	$\longleftrightarrow$	neutral $\tilde{h}$, $\tilde{H}$ and charged $\tilde{H}^{\pm}$ or $\chi^0_{1,2}$ and $\chi^{\pm}$ higgsinos

Problems of a supersymmetric extension

- there are no superpartners of the same mass with the same couplings

  $\longrightarrow$ SUSY must be spontaneously broken

- superpartners are heavy bases are not aligned
  Higgs makes SM particles (and superpartners) massive
  handred new parameters $\Longleftarrow$ 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

$$\propto \log(m_t^2/m_{\tilde{t}}^2), \quad \text{and} \quad \propto \left(m_{\tilde{t}}^2 - m_t^2\right),$$

  the superpartners must be not far from the EW-scale

- Massive, emerge in pairs $\Longrightarrow$ 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
  $\Longrightarrow$ prospects for EW baryogenesis
- There are several anomalies in particle physics (and closely related) experiments: $\mathrm{Br}(B \to K^* \mu^+ \mu^-)$
  $(g-2)$, $\Gamma(B \to D^{(*)} \tau \nu)/\Gamma(B \to D^{(*)} l \nu)$,
  $\Gamma(B \to K \mu^+ \mu^-)/\Gamma(B \to K e^+ e^-)$

Outline

Split SUSY: heavy sfermions, light gauginos $M_{\tilde{Q}} \gg M_\lambda$

Is it possible in SUSY?

N.Arkani-Hamed, S.Dimopoulos (2004)

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)

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

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

$$\frac{dA_i}{d\log Q^2} \propto y^2 A_i + \cdots + \alpha_i M_{\lambda_i}$$

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...

- μ-problem : $\mu^2\left(H_U^\dagger H_U + H_D^\dagger H_D\right)$

  MSSM: $\hat{W} = \mu \hat{H}_u \hat{H}_d$ NMSSM: $\hat{W} = \hat{N} \hat{H}_u \hat{H}_d$

- 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

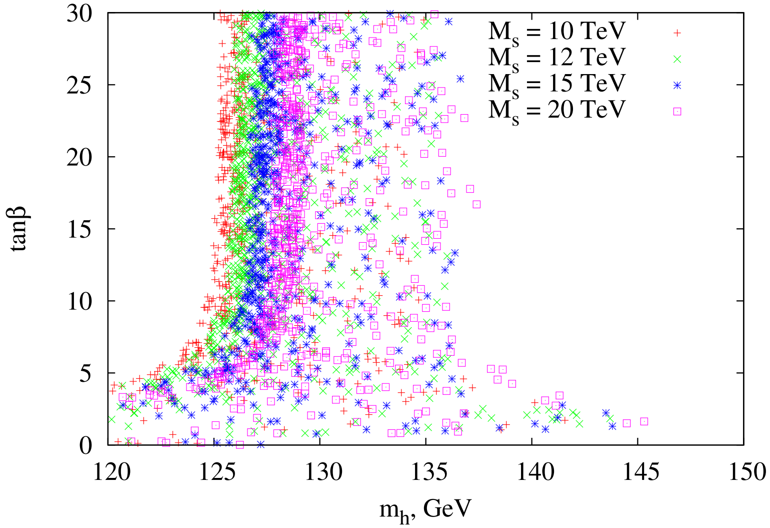
MSSM: new sources of *CP*-violation
NMSSM: + the strongly first order phase transition

Electroweak baryogenesis is attractive:
both ingredients can be directly tested

S.Demidov, D.G. (2007)

The main concern: SM Higgs

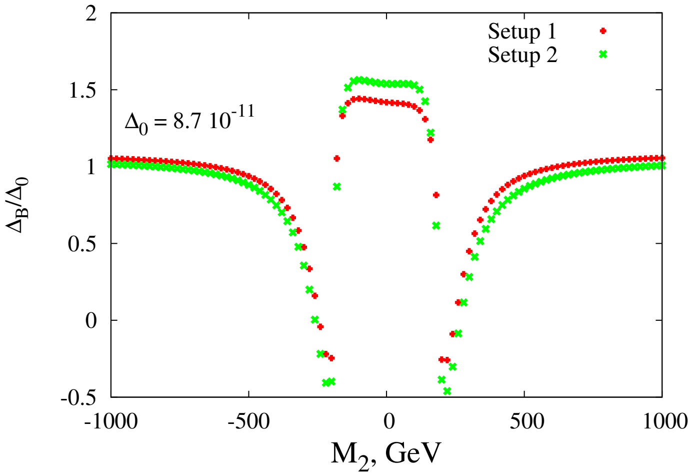
S.Demidov, D.G., D.Kirpichnikov (2016)



BAU in Split NMSSM

EWB works perfectly

2 Setups $\Delta_0 = 8.3 \times 10^{-11}$ 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 — contribute to EDMs
- EW Ist order phase transition:

  bubbles can produce gravitational waves

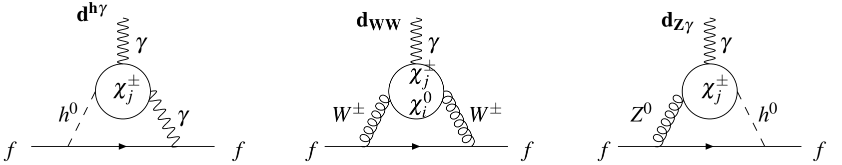
Electric dipole moments of electron and neutron

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

$$\phi_1 = \arg(\tilde{g}_u{}^* \tilde{g}_d{}^* M_2 \tilde{\mu}), \quad \phi_2 = \arg\left(\kappa k^* \lambda_u \lambda_d (\tilde{\mu}^*)^{-2}\right), \quad \phi_3 = \arg(\lambda_u \lambda_d^* \tilde{g}_u^* \tilde{g}_d)$$

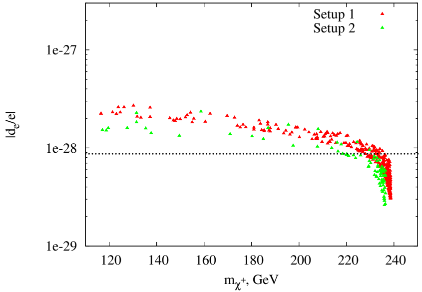
$$\tilde{\mu} = \mu + \kappa (v_s + i v_P)/\sqrt{2}$$

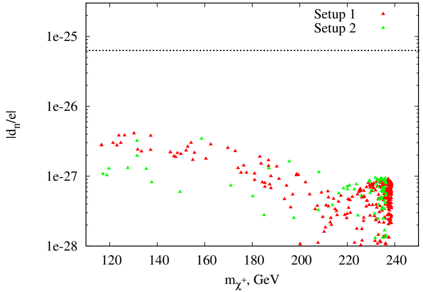
$$\mathrm{d_f} = \mathrm{d_{h\gamma}} + \mathrm{d_{WW}} + \mathrm{d_{hZ}}$$



EDMs in Split NMSSM

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



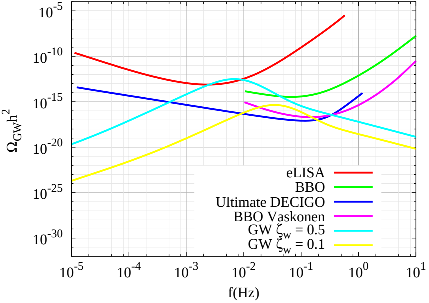


Also light charginos are disfavored from LHC

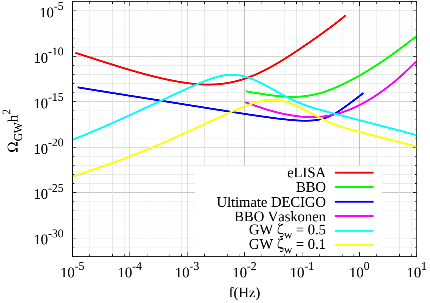
the rest ($m_{\chi^+} \simeq 200 - 240\,$GeV) can be tested in $\chi_1^+ \to \chi_1^0 + W^+$

GW in Split NMSSM

S.Demidov, D.G., D.Kirpichnikov (2017?)



$M_s = 10\,\mathrm{TeV}$



$M_s = 12\,\mathrm{TeV}$

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 serches for electron and neutrons EDMs
  @ gravitational interferometers