


Baryogenesis at Electroweak scale and EDM in MSSM



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YL, S. Profumo, M. Ramsey-Musolf,
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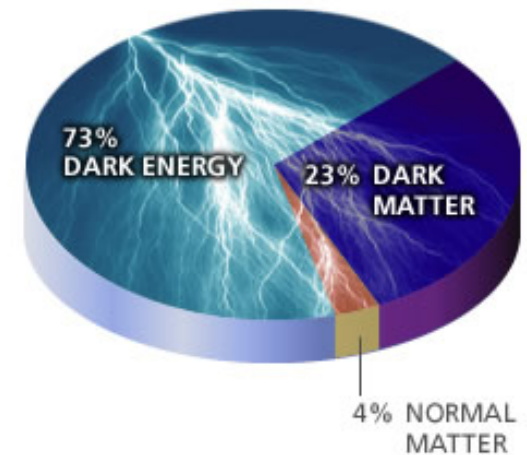
Outline

- Electroweak baryogenesis in MSSM
 - Why ruled out in SM? ➤ Why possible in MSSM?
 - What does it require in MSSM?
- The interplay between EWB and EDM in MSSM
 - Chargino-neutralino two-loop: the most relevant contribution;
 - Bino-driven EWB with highly suppressed EDMs;
- Conclusion

The origin of matter and energy

- Baryon asymmetry of Universe:

$$Y_B = \frac{\rho_B}{s_\gamma} = \frac{(7.3 \pm 2.5) \times 10^{-11}}{(9.2 \pm 1.1) \times 10^{-11}} \quad \begin{array}{l} \text{(BBN)} \\ \text{(WMAP)} \end{array}$$



- Sakharov conditions:

- Baryon number violation;
- C and CP violation;
- Departure from thermal equilibrium.

Scenarios of baryogenesis

- Planck scale baryogenesis;
- GUT baryogenesis;
- Baryogenesis via leptogenesis;
- Afleck-Dine baryogenesis;
- Electroweak baryogenesis; → most testable scenario!

EWBG fails in SM, but viable in MSSM.

- EWBG fails in SM:
 - Electroweak phase transition is not first order.
 - Not enough CP violation.
- EWGB is viable in MSSM: (Huet and Nelson, PRD, 53, 4578, 1996)
 - New bosonic degrees of freedom (stops) help on 1st order phase transition.
 - New CP violation source exist in MSSM.

EWB in MSSM

- Strong 1st order phase transition: (Carena, et al. 2008)

➤ Light Higgs: $m_H < 125$ GeV;

➤ Light RH stop: $m_{t_R} < 125$ GeV; ➤ Heavy LH stop: $m_{t_L} > 10$ TeV;

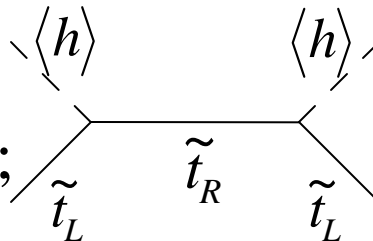
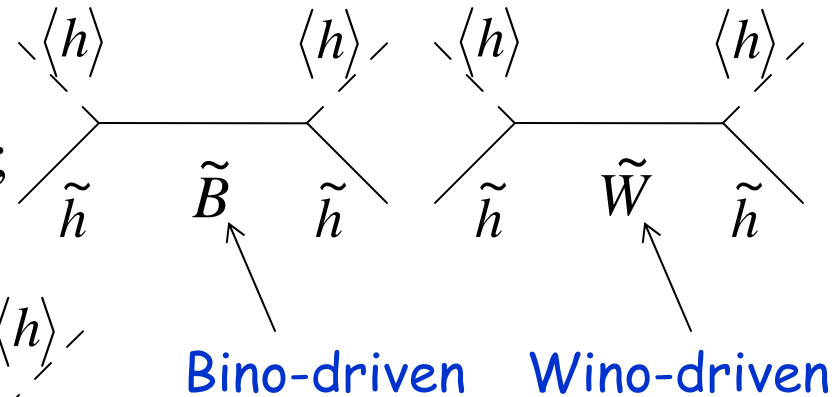
- Extra CP violation phase:

➤ Chargino-neutralino sector:

$$\phi_1 = \text{Arg}(\mu M_1 b^*); \phi_2 = \text{Arg}(\mu M_2 b^*);$$

➤ Stop sector:

$$\phi_{\tilde{t}} = \text{Arg}(\mu^* \cot \beta + A_t);$$

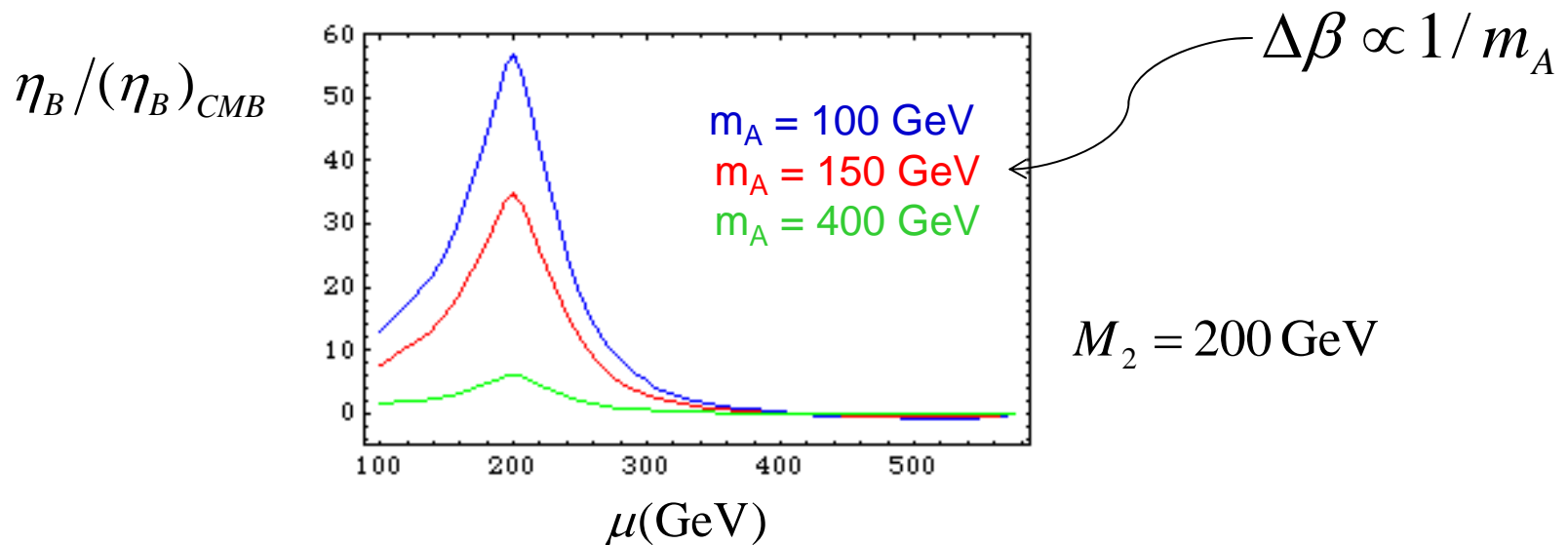


EWB in MSSM

• Resonant enhancement of CP violation:

(Carena, et al. 1997,2001; Lee, et al. 2004)

- Chargino-neutralino scenario $|\mu| \approx |M_{1,2}|$ preferred!
- Stop scenario $M_{\tilde{t}_L} \approx M_{\tilde{t}_R}$ not preferred!



Crucial parameters in chargino-neutralino scenario: $\phi_1, \phi_2, m_A, |\mu|, |M_{1,2}|$

Can large phases and small mass scales survive EDM bounds?

EDM - probe of CP violation

- Electric dipole moment:

P and T violation $\xrightarrow{\text{CPT}}$ P and CP violation

- Experimental searches:

	SM values	Current bounds	Future reach
d_e	$\leq 10^{-40} e \text{ cm};$	$\leq 1.6 \times 10^{-27} e \text{ cm};$	$\sim 10^{-30} e \text{ cm};$
d_n	$\leq 10^{-30} e \text{ cm};$	$\leq 2.9 \times 10^{-26} e \text{ cm};$	$\sim 10^{-28} e \text{ cm};$
$d_A(^{199}\text{Hg})$	$\leq 10^{-33} e \text{ cm};$	$\leq 3.1 \times 10^{-29} e \text{ cm};$	$\sim 10^{-29} e \text{ cm};$

Various contributions to EDMs.

New CP violation sources:

CP violating phases in MSSM

Studied, but incomplete

CP-odd operators:

C^{4f}

d_e

$d_{u,d}$

d^{3G}

$\tilde{d}_{u,d}$

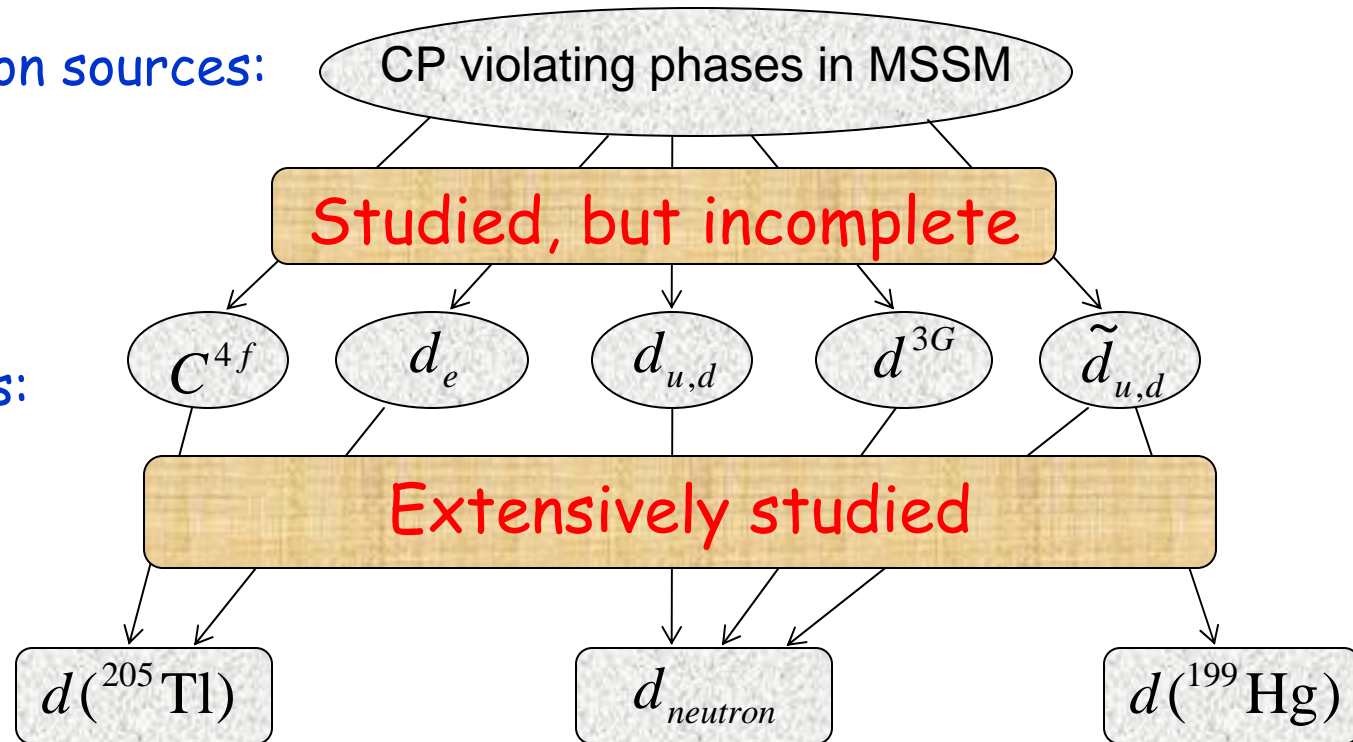
Extensively studied

Neutron and atom EDMs:

$d(^{205}\text{Tl})$

d_{neutron}

$d(^{199}\text{Hg})$



How to suppress various EDM?

CP odd op.	Phases	Compatibility condition
C^{4f}	$\phi_{1,2,3}, \phi_{\tilde{f}}$	$\tan \beta \lesssim 30$
d^G	$\phi_3, \phi_{\tilde{f}}$	$\phi_3, \phi_{\tilde{f}} \lesssim 10^{-2}$
$d_{u,d,e}^{1-loop}$	$\phi_{1,2,3}, \phi_{\tilde{f}}$	$m_{\tilde{q}_{1,2}}, m_{\tilde{l}_{1,2}} \gtrsim 10 \text{ TeV}$
$\tilde{d}_{u,d}^{1-loop}$	$\phi_{1,2,3}, \phi_{\tilde{f}}$	$m_{\tilde{q}_{1,2}}, m_{\tilde{l}_{1,2}} \gtrsim 10 \text{ TeV}$
$d_{u,d,e}^{2-loop}(\tilde{t}, \tilde{b}, \tilde{\tau})$	$\phi_{\tilde{f}}$	$\phi_{\tilde{f}} \lesssim 10^{-2}$
$\tilde{d}_{u,d}^{2-loop}(\tilde{t}, \tilde{b})$	$\phi_{\tilde{f}}$	$\phi_{\tilde{f}} \lesssim 10^{-2}$
$d_{u,d,e}^{2-loop}(\chi^{\pm,0})$	$\phi_{1,2}^?$	Not obvious.

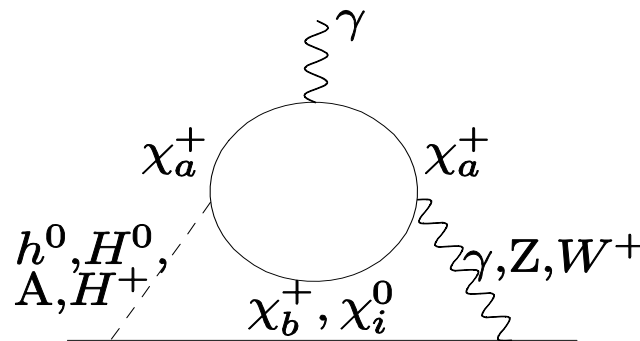
Full calculation is needed.

Chargino-neutralino 2-loop EDM: diagrams

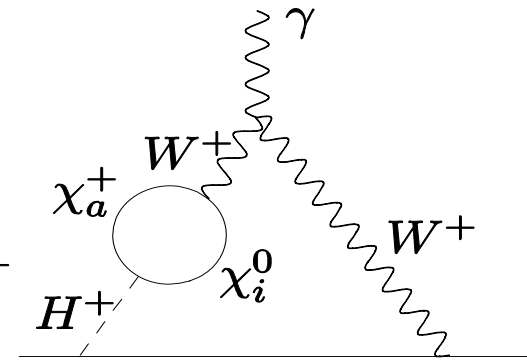
• Complete diagrams:

➤ Calculated:

$\gamma h, \gamma H, \gamma A, Zh, ZH$



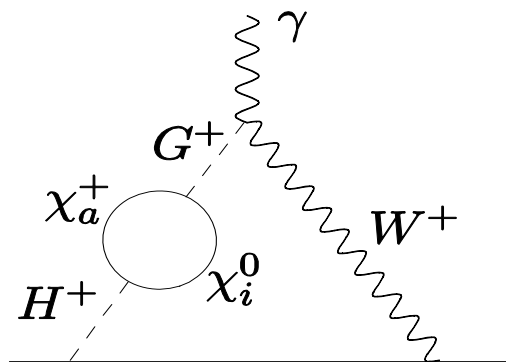
(a)



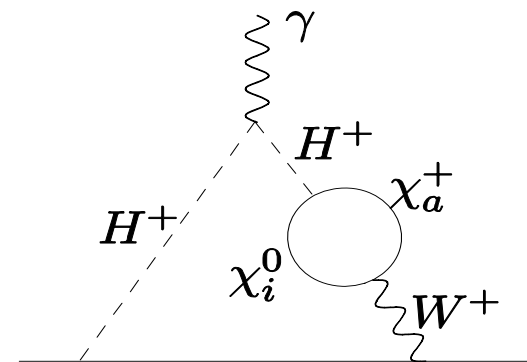
(b)

➤ Uncalculated:

ZA, WH^\pm



(c)



(d)

Chargino-neutralino 2-loop EDM: gauge choice

- Non-linear R_ξ gauge:

$$L_{g.f.}^{\text{nonlinear } R_\xi} = -\frac{1}{2\xi} |(\partial_\mu - ieA_\mu)W^{\mu+} - i\xi M_W \phi^+|^2$$

K. Fujikawa, PRD, 1973; J. Romao, A. Barroso, PRD, 1987
 M. Gavela, G. Girardi, C. Malleville, P. Sorba, Nucl. Phys.B, 1981

- No $G^\pm W^\mp \gamma$ coupling: diagram (c) vanishes.
- Taking the non-linear Landau gauge ($\xi \rightarrow 0$) limit: diagram (d) vanishes.

Chargino-neutralino 2-loop EDM: upper-loop structures

- Ward-identity consistent structures:

$$P^{\mu\nu} = \varepsilon^{\mu\nu\alpha\beta} q_\alpha l_\beta$$

$$T^{\mu\nu} = l^\mu q^\nu - l \cdot q g^{\mu\nu}$$

- Structures for each contributions:

$$\gamma h, Z h, \gamma H, Z H : P^{\mu\nu}$$

$$\gamma A, Z A : T^{\mu\nu}$$

$$W H^\pm : T^{\mu\nu} + P^{\mu\nu}$$

Chargino-neutralino 2-loop EDM: analytic result

$$d_f^{\gamma S} = \frac{eQ_f\alpha^2 c_f^S}{8\sqrt{2}\pi^2 s_W^2} \frac{m_f}{M_W m_S^2} \sum_{a=1}^2 \text{Im}(D_{S,aa}^R) M_{\chi_a^+} \int_0^1 dx \frac{1}{x(1-x)} j\left(0, \frac{r_{aS}}{x(1-x)}\right), \quad (1)$$

$$d_f^{ZS} = \frac{e\alpha^2 (T_{3fL} - 2s_W^2 Q_f) c_f^S}{16\sqrt{2}\pi^2 c_W^2 s_W^4} \frac{m_f}{M_W m_S^2} \times \sum_{a,b=1}^2 \text{Im}(G_{ab}^R D_{S,ba}^R - G_{ab}^L D_{S,ba}^L) M_{\chi_b^+} \int_0^1 dx \frac{1}{x} j\left(r_{ZS}, \frac{xr_{aS} + (1-x)r_{bS}}{x(1-x)}\right), \quad (2)$$

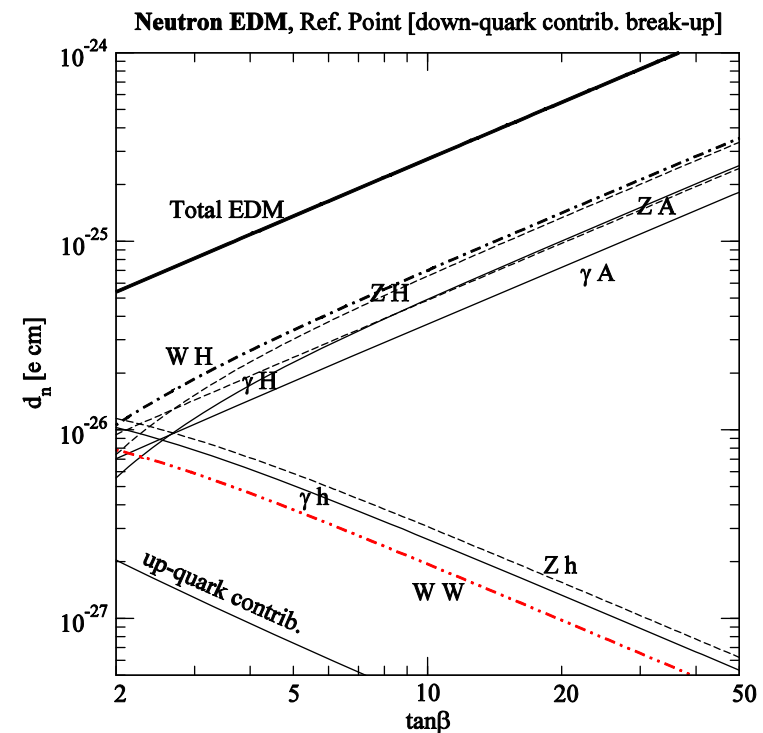
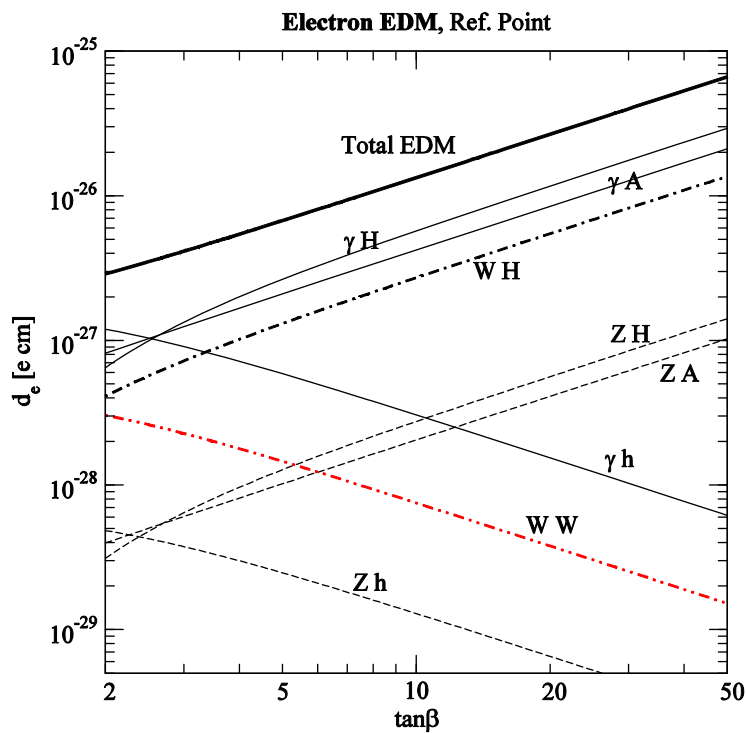
$$d_f^{\gamma A^0} = \frac{eQ_f\alpha^2 c_f^{A^0}}{8\sqrt{2}\pi^2 s_W^2} \frac{m_f}{M_W m_{A^0}^2} \sum_{a=1}^2 \text{Im} E_{aa}^R M_{\chi_a^+} \int_0^1 dx \frac{1-2x+2x^2}{x(1-x)} j\left(0, \frac{r_{aA^0}}{x(1-x)}\right), \quad (3)$$

$$d_f^{ZA^0} = \frac{e\alpha^2 (T_{3fL} - 2s_W^2 Q_f) c_f^{A^0}}{16\sqrt{2}\pi^2 c_W^2 s_W^4} \frac{m_f}{M_W m_{A^0}^2} \times \sum_{a,b=1}^2 \text{Im}(G_{ab}^R E_{ba}^R + G_{ab}^L E_{ba}^L) M_{\chi_b^+} \int_0^1 dx \frac{1-x}{x} j\left(r_{ZA^0}, \frac{xr_{aA^0} + (1-x)r_{bA^0}}{x(1-x)}\right), \quad (4)$$

$$d_f^{WH^\pm} = -\frac{e\alpha^2 c_f^{H^\pm}}{32\pi^2 s_W^4 c_W} \frac{m_f}{M_W m_{H^\pm}^2} \sum_{a=1}^2 \sum_{i=1}^4 \int_0^1 dx \frac{1}{1-x} j\left(r_{WH^\pm}, \frac{r_{aH^\pm}}{1-x} + \frac{r_{iH^\pm}}{x}\right) \left[(\text{Im}(M_{ai}^L N_{ai}^{L*} + M_{ai}^R N_{ai}^{R*}) M_{\chi_a^+} x^2 + \text{Im}(M_{ai}^R N_{ai}^{L*} + M_{ai}^L N_{ai}^{R*}) M_{\chi_i^0} (1-x)^2) \right. \\ \left. + (\text{Im}(M_{ai}^L N_{ai}^{L*} - M_{ai}^R N_{ai}^{R*}) M_{\chi_a^+} x + \text{Im}(M_{ai}^R N_{ai}^{L*} - M_{ai}^L N_{ai}^{R*}) M_{\chi_i^0} (1-x)) \right]. \quad (5)$$

Chargino-neutralino 2-loop EDM: numerical result

- ZA and WH are dominant contributions



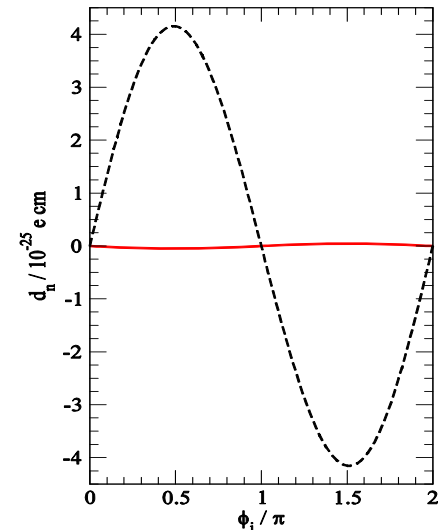
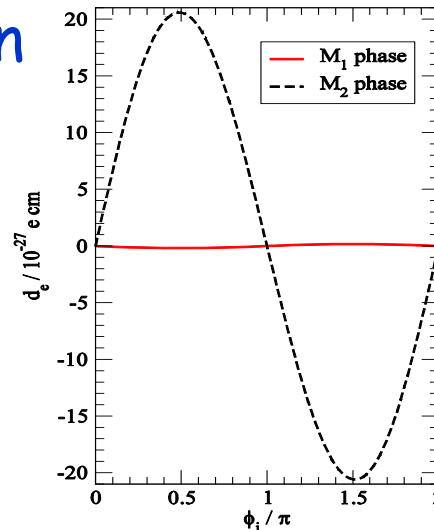
Ref. point: $M_1 = 145\text{GeV}$, $M_2 = 290\text{GeV}$, $|\mu| = 300\text{GeV}$, $\phi_1 = \phi_2 = \frac{\pi}{2}$, $m_{A^0} = 300\text{GeV}$

YL, S. Profumo, M. Ramsey-Musolf, arXiv:0806.2693

Chargino-neutralino 2-loop EDM: bino v.s. wino contribution

- Very different contribution from bino and wino phases

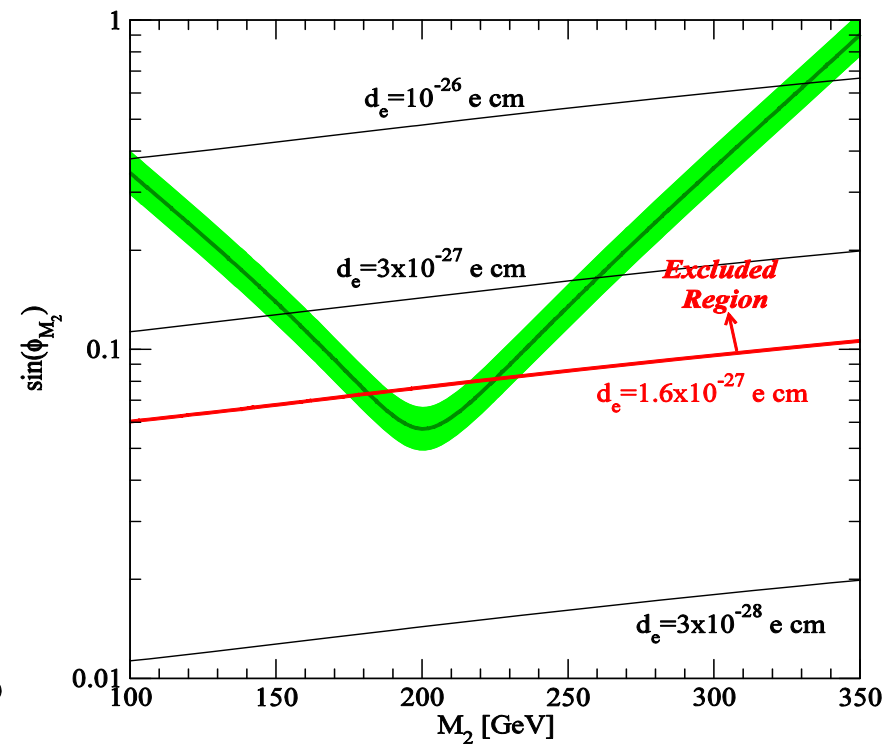
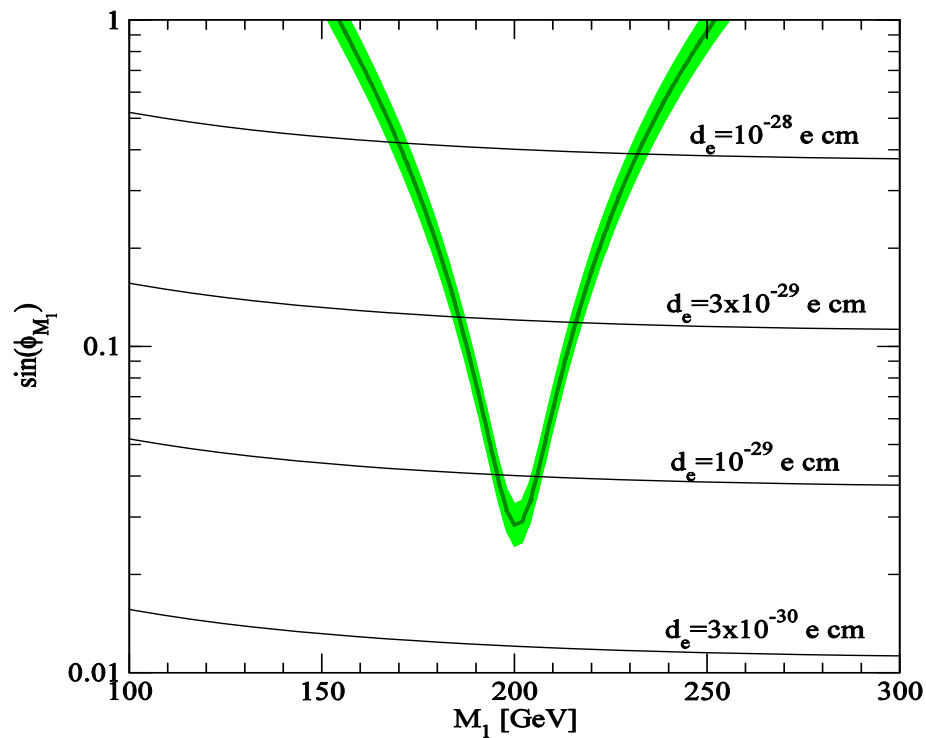
$$\frac{d(\phi_1)}{d(\phi_2)} \approx \frac{1}{50}$$



- Suppression is due to many aspects:
 - Neutralino only appears in WH and WW: 20%
 - In WH and WW: $(g' / g)^2 = \tan^2 \theta_W \approx 0.3$
 - Another factor of 0.3 is presumably from that, in WH and WW, W boson only couple to wino and higgsino.

Comparing bino- and wino-driven EWB

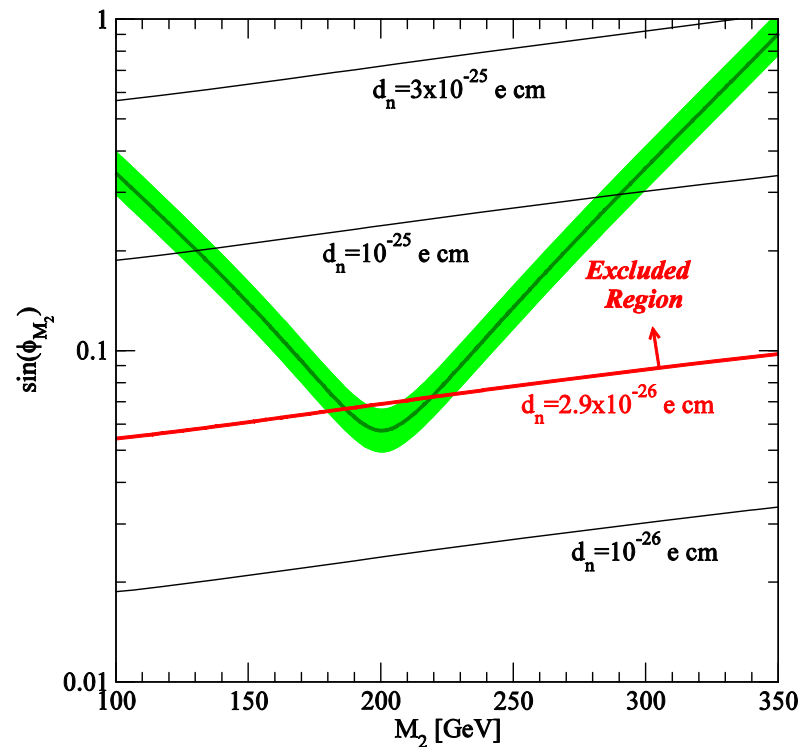
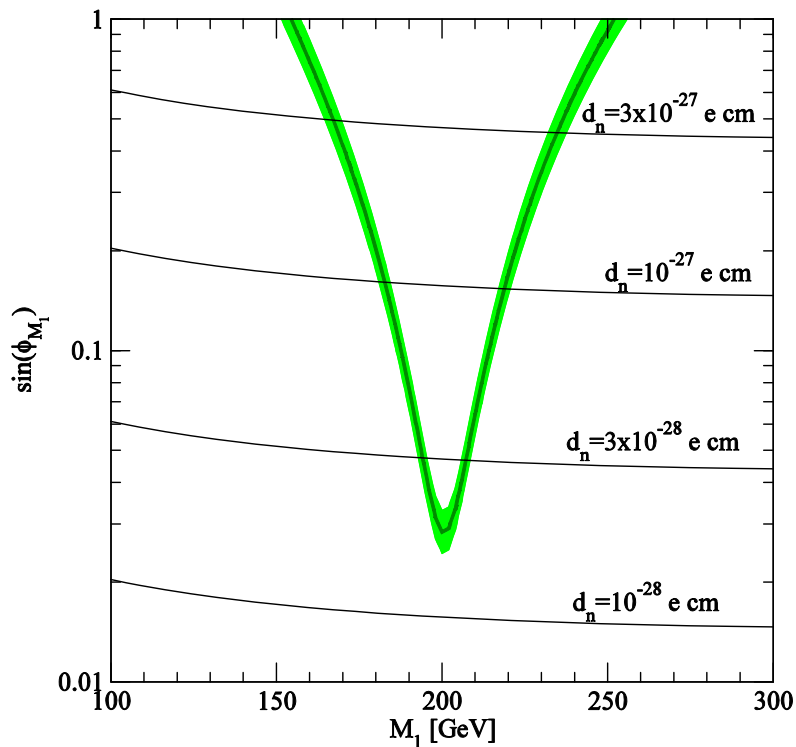
- Electron EDM:



Ref. point: $M_1 = 95$ GeV, $M_2 = 190$ GeV, $|\mu| = 200$ GeV, $\tan\beta = 10$, $m_{A^0} = 300$ GeV

Comparing bino- and wino-driven EWB

- Neutron EDM:



Ref. point: $M_1 = 95\text{GeV}$, $M_2 = 190\text{GeV}$, $|\mu| = 200\text{GeV}$, $\tan\beta = 10$, $m_{A^0} = 300\text{GeV}$

Bino-driven EWB can happen with highly suppressed EDMs!

Compatibility between EWB and EDM?

CP odd op.	phases	Compatibility condition
C^{4f}	$\phi_{1,2,3}, \phi_{\tilde{f}}$	$\tan \beta < 30$
d^G	$\phi_3, \phi_{\tilde{f}}$	$\phi_3, \phi_{\tilde{f}} < 10^{-2}$
$d_{u,d,e}^{1-loop}$	$\phi_{1,2,3}, \phi_{\tilde{f}}$	$m_{\tilde{q}_{1,2}}, m_{\tilde{l}_{1,2}} > 10 \text{ TeV}$
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$d_{u,d,e}^{2-loop}(\tilde{t}, \tilde{b}, \tilde{\tau})$	$\phi_{\tilde{f}}$	$\phi_{\tilde{f}} < 10^{-2}$
$\tilde{d}_{u,d}^{2-loop}(\tilde{t}, \tilde{b})$	$\phi_{\tilde{f}}$	$\phi_{\tilde{f}} < 10^{-2}$
$d_{u,d,e}^{2-loop}(\chi^{\pm,0})$	$\phi_{1,2}$	$\phi_1 \approx 1, \phi_2 < 10^{-2}$ Not obvious.

Bino-driven EWB scenario!

Conclusions & outlook

- EWB in SM is ruled out, but EWB in MSSM, either bino-driven or wino-driven, remains possible.
- EWB in MSSM is strongly constrained by EDM experiments.
- We calculate the full chargino-neutralino 2-loop EDMs, which is the most relevant part to EWB in MSSM.
- We observe that the bino-driven EWB is much less constrained from EDM bounds than wino-driven EWB.
- A scan over the full parameter space will give an absolute lower bound on EDM that is consistent with EWB.

Thank you !!!