MSSM Electroweak Baryogenesis and EDMs

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Outline

1. Overview of electroweak baryogenesis in SUSY and relevant constraints from the intensity, energy, and cosmic frontiers

2. Higgsino-Gaugino Sources

3. Sfermion Sources

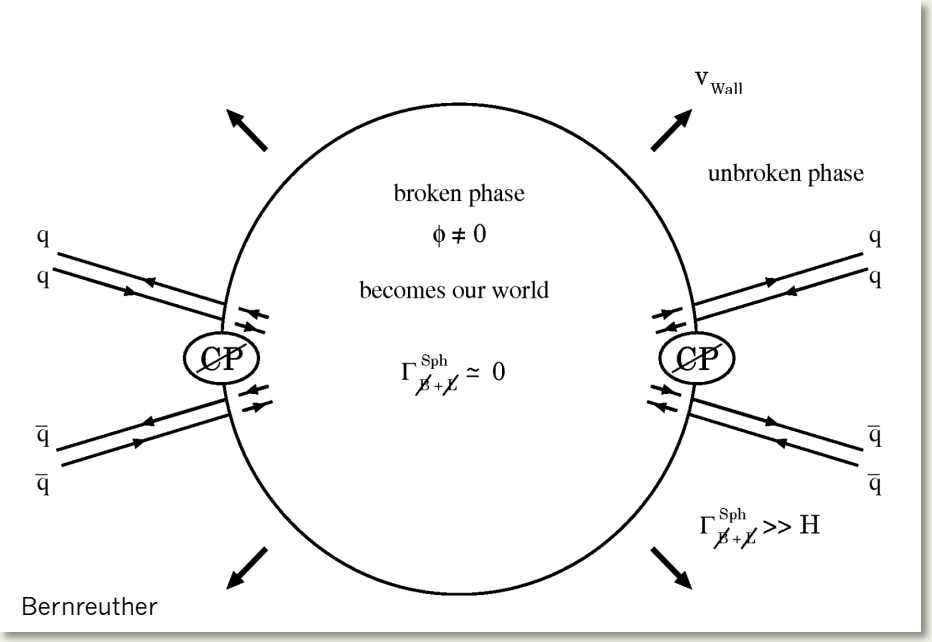
4. Summary and Conclusions

SUSY EWB Overview

-Microphysical mechanism for generation of the asymmetry must satisfy the "Sakharov conditions":

1. *B*-violation
2. *C*-, *CP*-violation
3. *"Arrow of time"*

-SM provides a teaser for baryogenesis at the electroweak scale but...

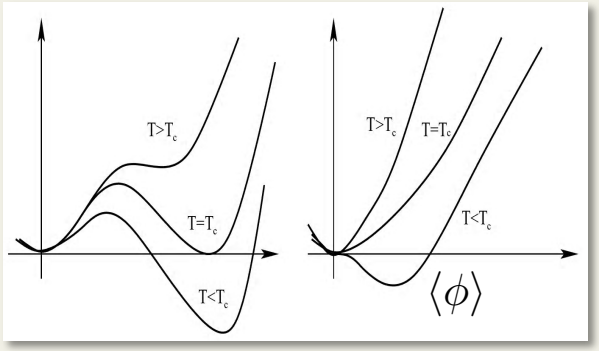


not enough CPV and no first order electroweak phase transition

SUSY EWB Overview

-Supersymmetry can provide new sources of CP-violation and a first order EWPT

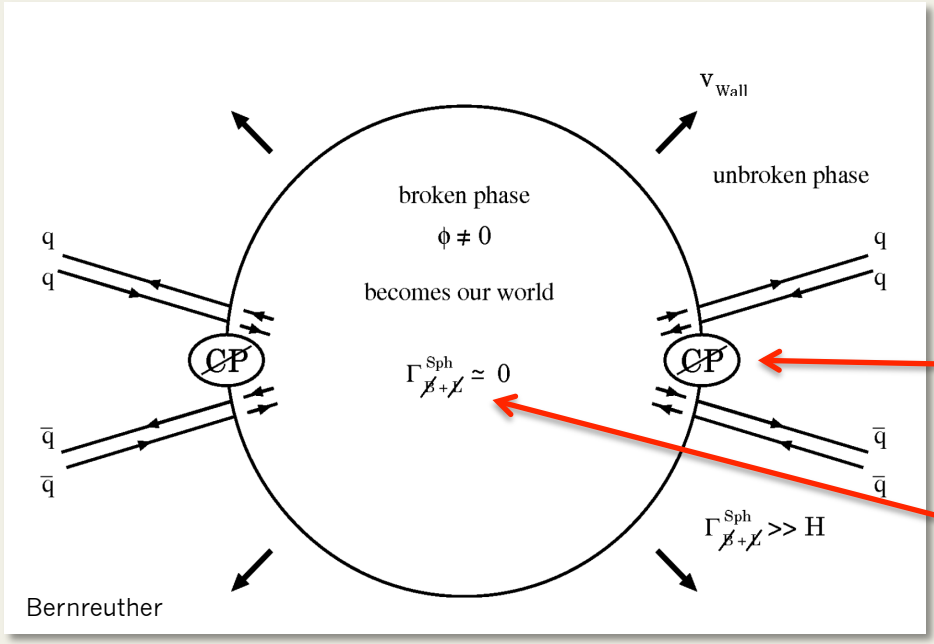
-*E.g.* MSSM has 40 new CP-violating phases (SUSY-breaking masses, couplings, etc)



First order → Second order

Increasing m_h →

← Additional scalars



Sources of CP-violation?

Mechanism for strongly 1st order EWPT?

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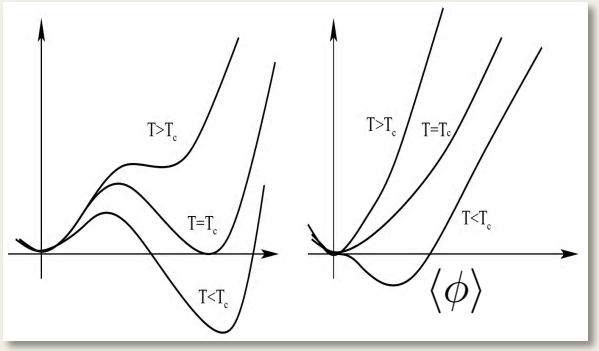

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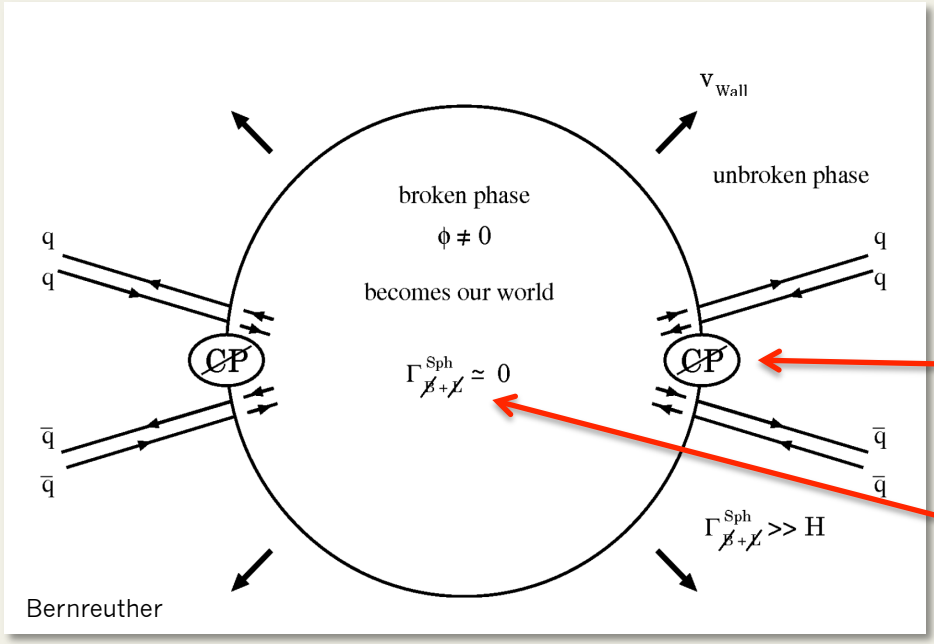


This talk

Sources of CP-violation?

Mechanism for strongly 1st order EWPT?

(See e.g. 1206.2942 for a review)

-Constraints on CP-sources from intensity, energy, and cosmic frontier

Observational Constraints

Intensity frontier:

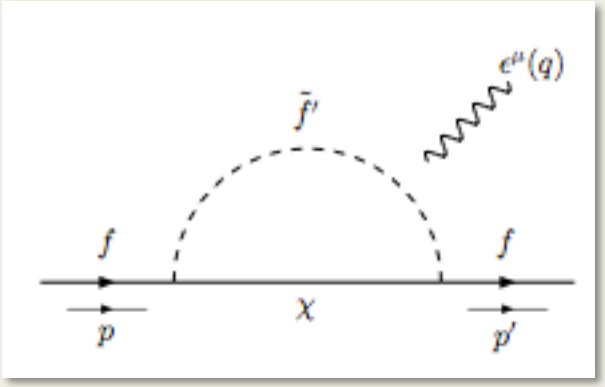
-Electric Dipole Moments sensitive to CP-violation

$$H = -\mu_f^B \mathbf{B}\cdot\frac{\mathbf{S}}{S} - d_f^E \mathbf{E}\cdot\frac{\mathbf{S}}{S} \longrightarrow \mathcal{L} = -d_f^E \frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

P-odd, *T*-odd (*CP*-odd)

$$\mathcal{L}_{(C)EDM} = -\frac{i}{2}d_f^E F^{\mu\nu}\bar{f}\sigma_{\mu\nu}\gamma_5 f - \frac{i}{2}d_q^C G^{a\mu\nu}\bar{q}\sigma_{\mu\nu}\gamma_5 T^a q$$

(Chromo-EDM)



-EDM can be induced at one-loop and beyond. With heavy sfermions, two-loop contributions can still be sizable

Energy frontier:

-Collider searches constrain new SUSY degrees of freedom which must be light (O (100 GeV)) to avoid thermal suppression near the EWPT

-Predictions for mass and properties of observed 126 GeV Higgs affected by new particles

Cosmic Frontier:

-Light gauginos for CPV sources have implications for dark matter

Observational Constraints

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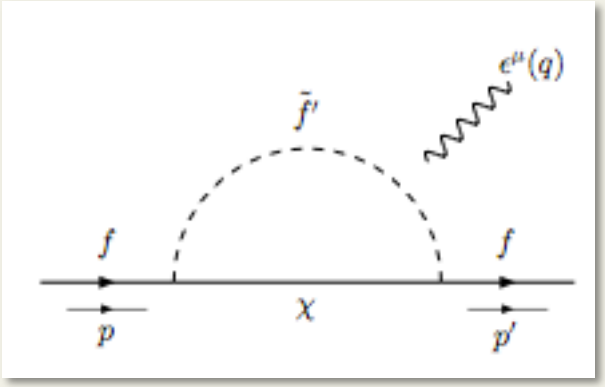

-EDM can be induced at one-loop and beyond. With heavy sfermions, two-loop contributions can still be sizable

Sensitive to the same CPV phase and interactions relevant for EWB

Energy frontier:

-Collider searches constrain new SUSY degrees of freedom which must be light (O(100 GeV)) to avoid thermal suppression near the EWPT

Also depend on details of spectrum beyond EWB requirements

-Predictions for mass and properties of observed 126 GeV Higgs affected by new particles

Cosmic Frontier:

Depends on source

-Light gauginos for CPV sources have implications for dark matter

Observational Constraints

What do these constraints imply for MSSM EWB and what can we hope to learn?

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What do these constraints imply for MSSM EWB and what can we hope to learn?

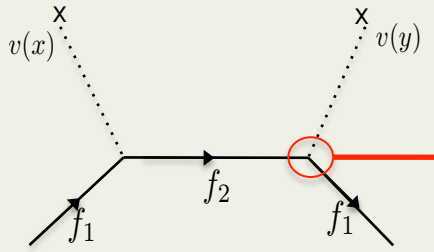
Consider both Higgsino-gaugino and scalar sources

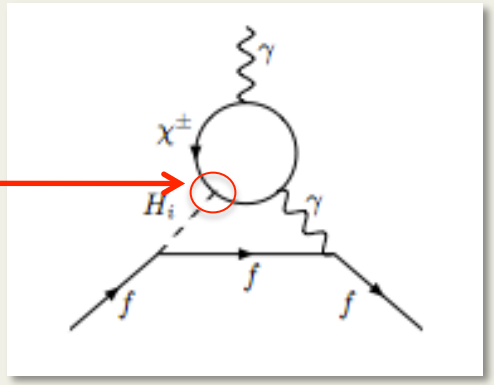
Higgsino-Gaugino Sources

-Higgsino-gaugino sources: Relative CP-violating phase in $M_{1,2}$ and μ

$$\mathcal{L}_{\rm int} \supset -\frac{g_2}{\sqrt{2}}\bar{\Psi}_{\widetilde{H}^0}\left[v_d(x)P_L + e^{i\phi}v_u(x)P_R\right]\Psi_{\widetilde{W}^0} - g_2\bar{\Psi}_{\widetilde{H}^+}\left[v_d(x)P_L + e^{i\phi}v_u(x)P_R\right]\Psi_{\widetilde{W}^+} + h.c. + \text{bino terms}$$

· CPV sources arise from higgsino-gaugino interactions with Higgs vevs:





-Assuming sfermions heavy, EDM from 2-loop Barr-Zee diagrams

-EDM depends on same couplings and masses as CPV sources, so powerful probe for EWB

· Compute source using vev-insertion scheme (see e.g. Lee et. al., 0412354, Michael Ramsey-Musolf's talk):

Thermal suppression for masses much above 100 GeV

$$S^{\not CP}_{\widetilde{H}^\pm} = \frac{g_2^2}{\pi^2}v(x)^2\dot{\beta}(x)M_2\mu\sin\phi\int_0^\infty \frac{dkk^2}{\omega_{\widetilde{H}}\omega_{\widetilde{W}}}\,\mathrm{Im}\left\{\frac{n_F(\mathcal{E}_{\widetilde{W}}) - n_F(\mathcal{E}^*_{\widetilde{H}})}{(\mathcal{E}_{\widetilde{W}} - \mathcal{E}^*_{\widetilde{H}})^2} - \frac{n_F(\mathcal{E}_{\widetilde{W}}) + n_F(\mathcal{E}_{\widetilde{H}})}{(\mathcal{E}_{\widetilde{W}} + \mathcal{E}_{\widetilde{H}})^2}\right\}$$

Resonant for degenerate masses

Higgsino-Gaugino Sources

-Lightest neutralino can be viable DM candidate → consider Higgsino-gaugino EWB parameter space with a "well-tempered" neutralino (determines μ for given $M_{1,2}$)

(JK, Profumo, and Wainwright, 1208.5166)

-Assume only light gauginos/Higgsinos and possibly RH stop with other sfermions heavy

-Solve set of quantum Boltzmann equations for LH charge density; SU(2) sphalerons convert LH density to B+L density

-Impose EDM constraints from CPV phase $\phi_{M_{1,2}} \equiv \mathrm{Arg}(\mu M_{1,2} b^*)$. Largest contribution to e-EDM from 2-loop Barr-Zee diagrams. Current limit (YbF): $d_e < 1.05 \times 10^{-27} e \cdot cm$

-Impose bounds from dark matter direct- and indirect-detection

Higgsino-Gaugino Sources

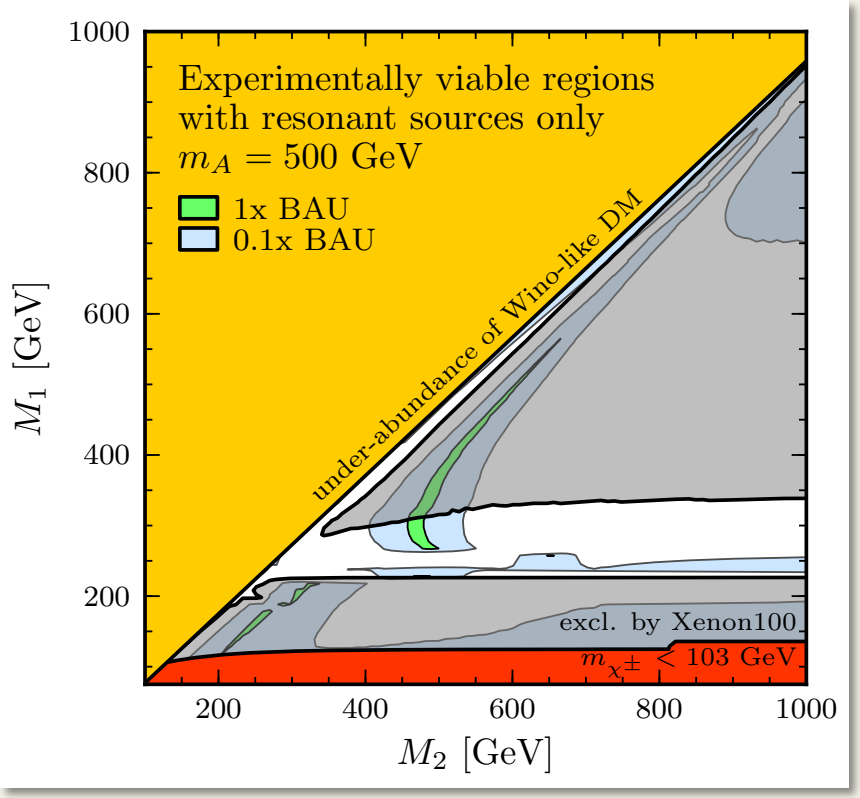
-Putting it all together:

-Narrow range of parameter space, but there are still MSSM regions that can account for both the BAU through Higgsino-gaugino sources and a viable neutralino DM candidate

-EDM and dark matter constraints are complementary, making very specific predictions independent of the EWPT

-Modest improvements in direct detection and EDM measurements should probe all available parameter space*. E.g. sensitivity of ACME experiment by the end of this year expected to reach an order of magnitude smaller EDMs than the current limit.

See JK, Profumo, and Wainwright, 1208.5166



*Several caveats (sign of μ, strange quark content of proton, etc.). Of course relaxing the relic density requirement opens up more parameter space, but still highly constrained (see e.g. Cirigliano et. al 0910.4589)

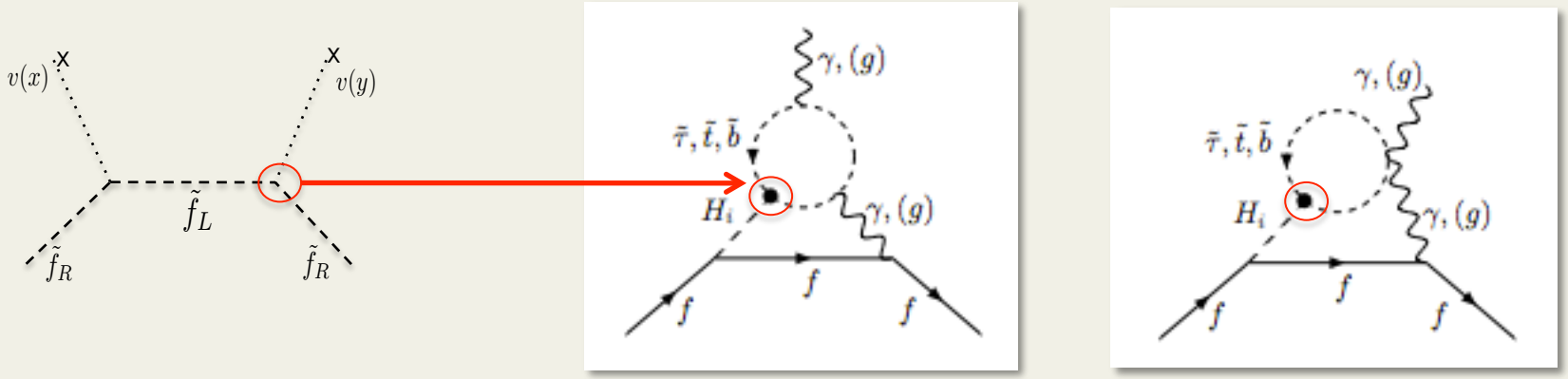
Scalar Sources

-Another possibility: **sfermionic** CP-violating sources

JK, Profumo, Ramsey-Musolf, and Wainwright, 1206.4100

$$\mathcal{L} \supset \; y_t \tilde{t}_L \tilde{t}_R^* (A_t H_u^0 - \mu^* H_d^{0*}) + y_b \tilde{b}_L \tilde{b}_R^* (A_b H_d^0 - \mu^* H_u^{0*})$$
$$+ y_\tau \tilde{\tau}_L \tilde{\tau}_R^* (A_\tau H_d^0 - \mu^* H_u^{0*}) - b H_u^0 H_d^0 + h.c.,$$

Note:Chromo-EDM contribution present for squarks



-Compute CPV source for transport equations in vev-insertion scheme for stops, sbottoms, and staus

$$S_{\tilde{t}}^{CPV}(x) = \frac{N_C y_t^2}{2\pi^2} \mathrm{Im}(\mu A_t) v^2(x) \dot{\beta}(x) \int_0^\infty \frac{dk k^2}{\omega_R \omega_L} \mathrm{Im}\left[\frac{n_B(\mathcal{E}_R^*) - n_B(\mathcal{E}_L)}{(\mathcal{E}_L - \mathcal{E}_R^*)^2} + \frac{n_B(\mathcal{E}_R) + n_B(\mathcal{E}_L)}{(\mathcal{E}_L + \mathcal{E}_R)^2} \right]$$

Scalar Sources

-Stop sources: compute baryon asymmetry over stop mass plane

-CEDMs dominate; strongest constraints from neutron and 199 Hg:

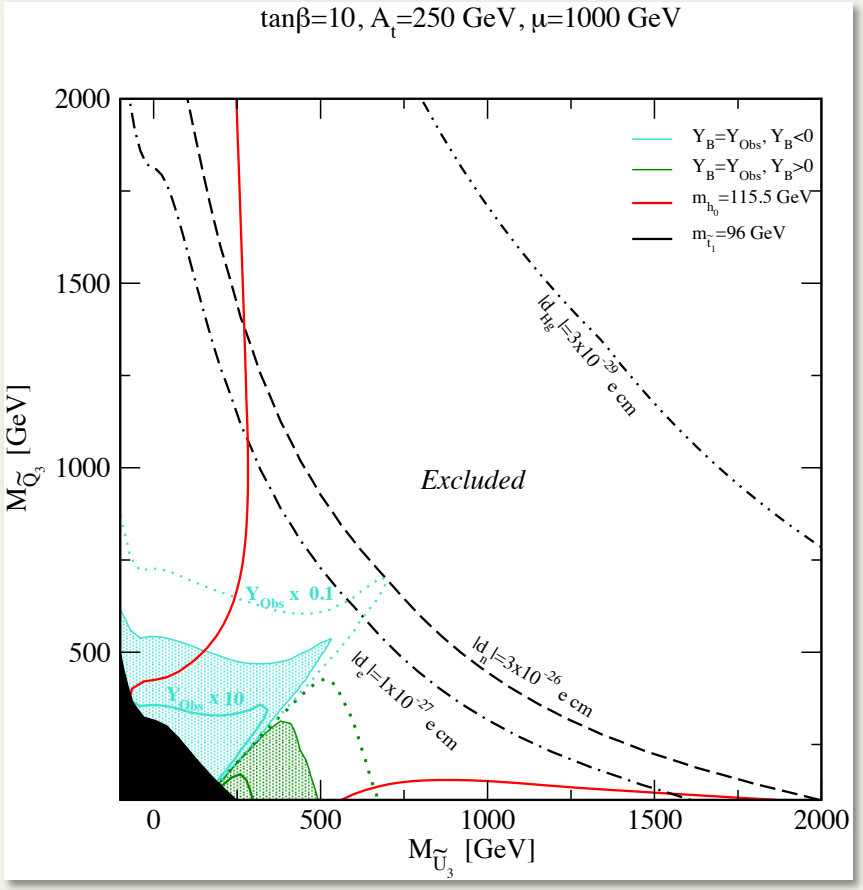
$$|d_{Hg}| < 3 \times 10^{-29} e \text{ cm}$$
$$|d_n| < 2.9 \times 10^{-26} e \text{ cm}$$

-Considerable uncertainty due to strong dynamics

Nuclear Schiff moment πNN vertices

$$d_{\rm Hg} = (1.8 \times 10^{-3} \text{ GeV}^{-1}) e g_{\pi NN}^{(1)} + 10^{-2} d_e^E + (3.5 \times 10^{-3} \text{GeV}) e C_S + (4 \times 10^{-4} \text{ GeV}) e \left[C_P + \left(\frac{Z-N}{A} \right)_{\rm Hg} C_P' \right],$$

Atomic physics



-Also uncertainties in computation of BAU (vev-insertion tends to overestimate the asymmetry)

Scalar Sources

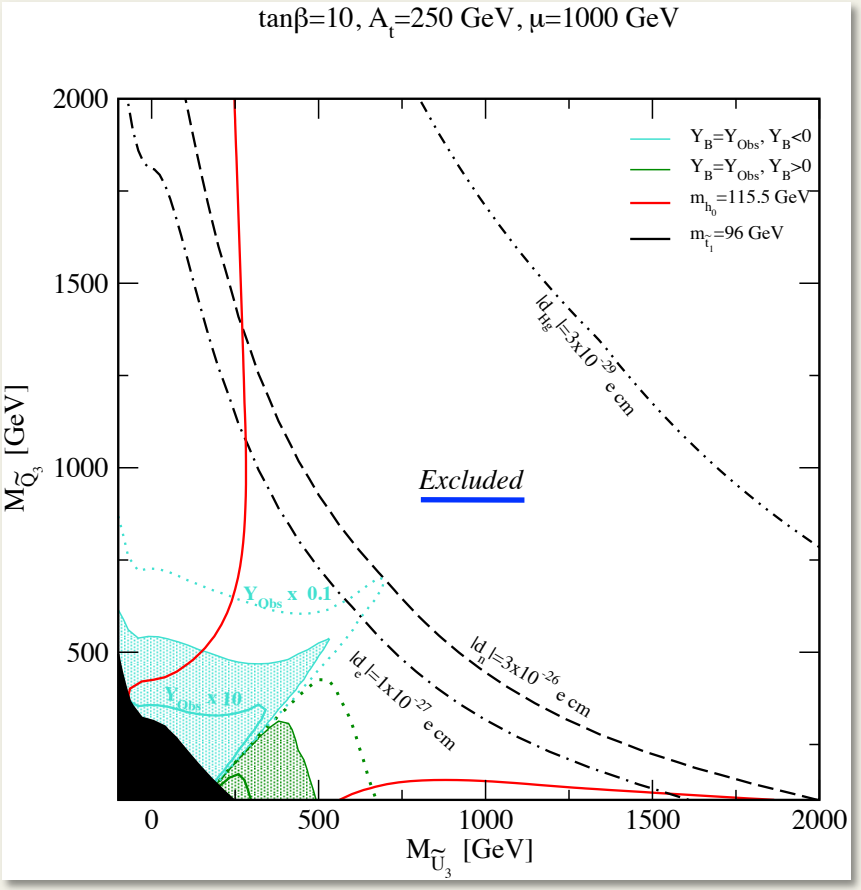
-Stop sources:

-Even with an order of magnitude uncertainty in the EDMs and an order of magnitude larger BAU, stop sources still **solidly ruled out by EDM constraints alone**

-Also disfavored by 125 GeV Higgs: EDMs ~ $|\mu|, |A_t|$ and Boltzmann suppressed for heavy stops

-Direct searches for stops constrain the low-mass regions already excluded by EDMs

-**Sbottoms also ruled out by EDMs**

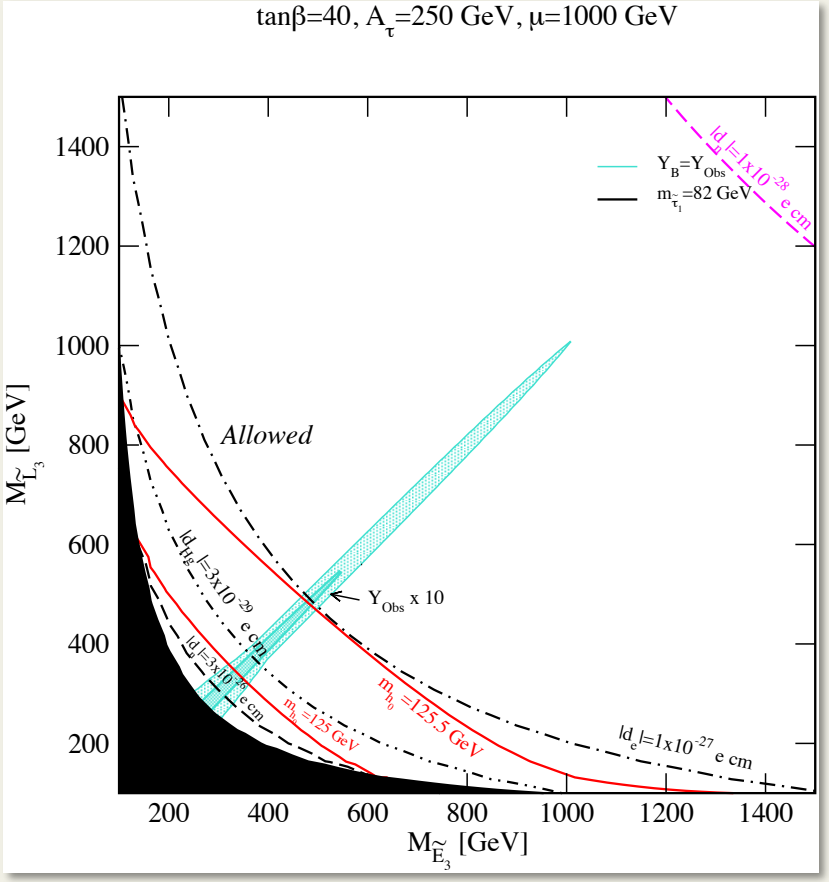


Scalar Sources

- What about staus? For sizable tanβ, y_τ enhanced

$$S^{CPV}_{\tilde{\tau}}(x) = -\frac{y_\tau^2}{2\pi^2}\,\mathrm{Im}(\mu A_\tau)v^2(x)\dot{\beta}(x) \times \int_0^\infty \frac{dkk^2}{\omega_R\omega_L}\,\mathrm{Im}\left[\frac{n_B(\mathcal{E}_R^*)-n_B(\mathcal{E}_L)}{(\mathcal{E}_L-\mathcal{E}_R^*)^2}+\frac{n_B(\mathcal{E}_R)+n_B(\mathcal{E}_L)}{(\mathcal{E}_L+\mathcal{E}_R)^2}\right]$$

- No CEDM contributions; strongest constraints from *e*-EDM
- Freedom in stop sector for Higgs mass



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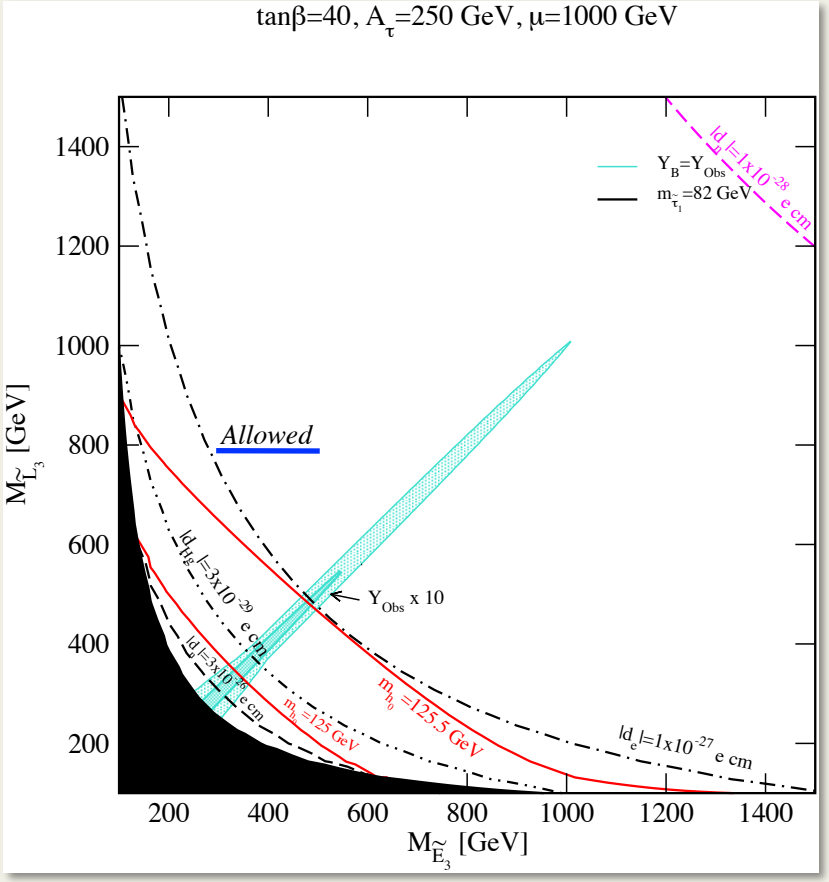
- No CEDM contributions; strongest constraints from *e*-EDM
- Freedom in stop sector for Higgs mass

-Nearly degenerate staus may be able to account for the observed baryon asymmetry and satisfy current EDM and collider constraints



-Caveats: narrow resonance (no SU(3) interactions → smaller widths), uncertainties

-Next generation of EDM experiments should probe all parameter space (see e.g. 1205.2671 for discussion of expected sensitivities)

Summary and Outlook

- CP-violating sources for MSSM electroweak baryogenesis are currently being tested on the intensity, energy, and cosmic fronts.
- Complementarity of dark matter and EDM constraints can be important for studying Higgsino-gaugino sources in the MSSM. E.g. Direct detection + *e*-EDM search results leave a small window for EWB with viable DM
- EDMs of neutral atoms and nucleons are very powerful probes for squark-sourced MSSM EWB. The CEDM contribution to the 199 Hg and neutron electric dipole moments comfortably rule out stop and sbottom sources
- Stau sources are still potentially viable. Require large tanβ and nearly degenerate soft SUSY-breaking masses. Will be tested by forthcoming results from *e*-EDM searches (this year?)
- Further work is required to reduce theoretical uncertainties in the computation of baryon asymmetry and nucleon/atomic EDMs to conclusively confirm or rule out MSSM EWB