Baryogenesis and EDMs:
Constraints on CP Violation Beyond the Standard Model

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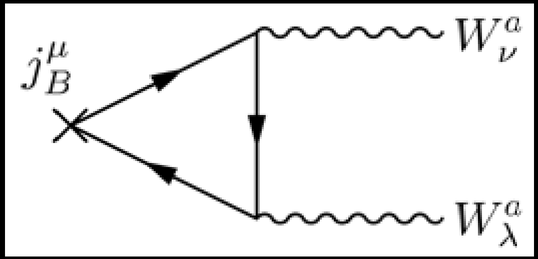
Outline

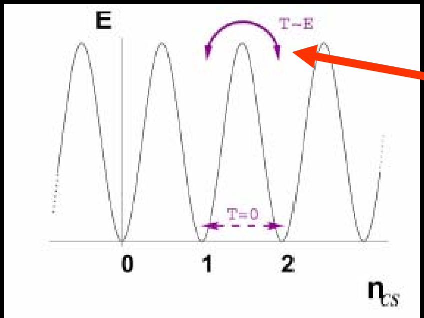
- **Electroweak Baryogenesis**
  - ***Model scenario: MSSM Baryogenesis***
  - ***Transport Equations from QFT***
  - ***Resonantly-Enhanced Sources***
  - ***Higgs-to-baryon conversion***
- **EDM Constraints**
  - ***MSSM Loops***
  - ***Constraints on EWB***

Baryogenesis during Bubble Nucleation

Kuzmin, Rubakov, Shaposhnikov;
Cohen, Kaplan, Nelson;
Joyce, Prokopec, Turok

- "Bubble" nucleation of regions of broken EW phase
- Baryon number violating sphalerons active outside bubbles



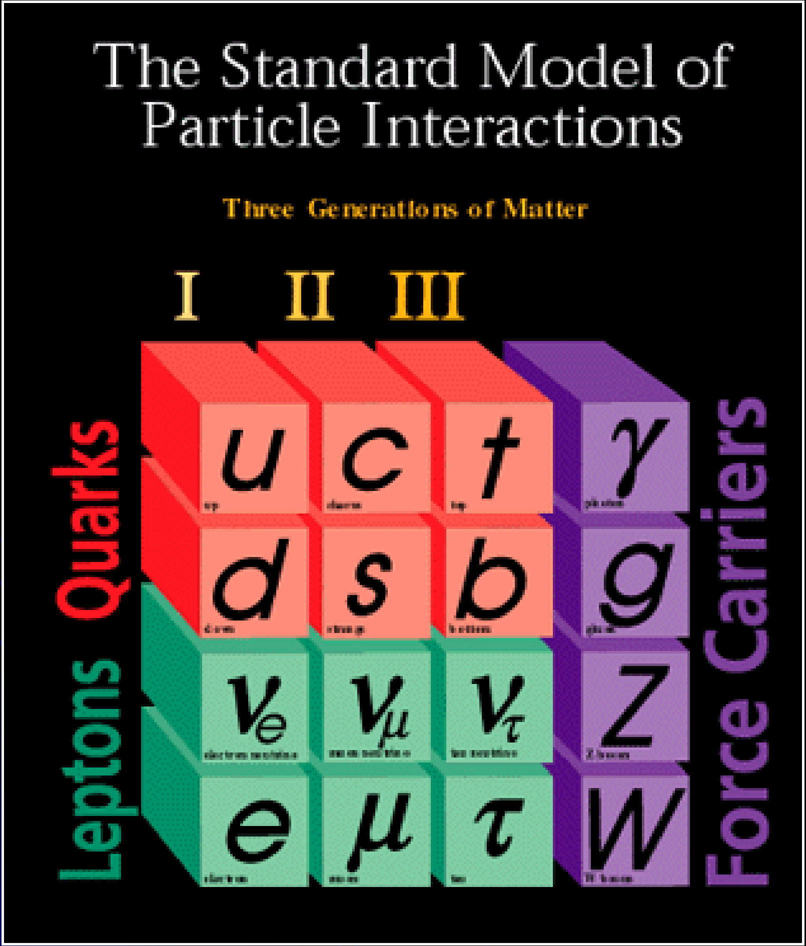


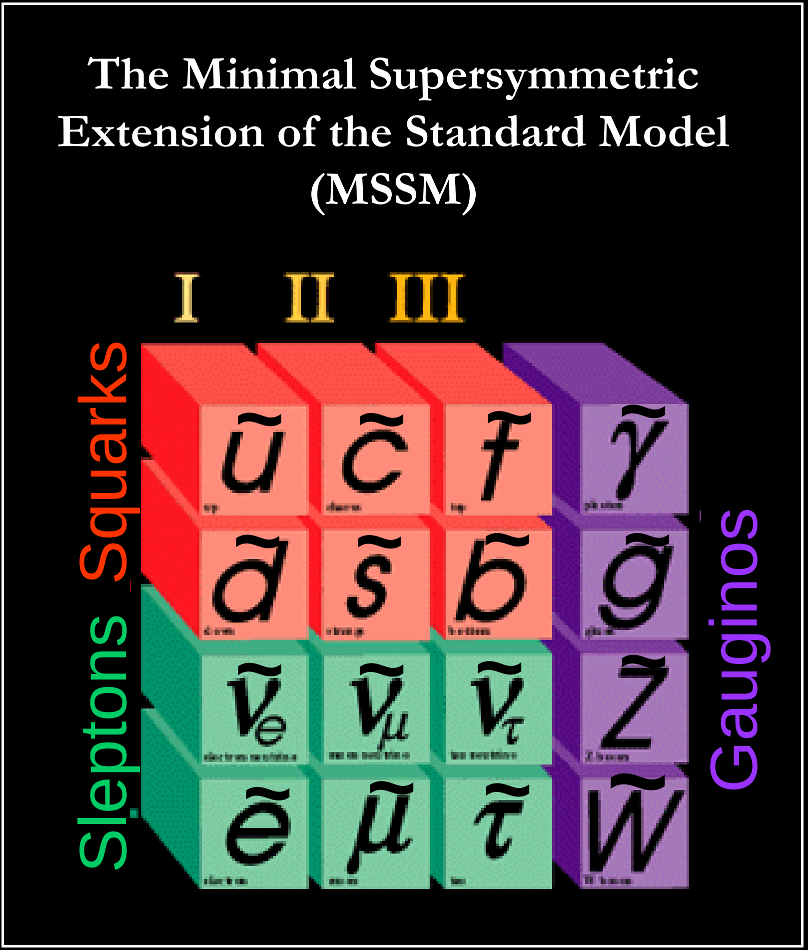
$$\Delta B = \Delta L$$
$$= N_F \Delta n_{CS}$$

- CP-violating interactions active inside bubble walls
- n_L created in wall, diffuses outside, induces baryon number violation

$$\partial_t \rho_B(x) - D_q \nabla^2 \rho_B(x) \propto -n_F \Gamma_{\rm sph}[n_L(x) + R\rho_B(x)]$$

Supersymmetry





Viability of MSSM Baryogenesis

- First-order phase transition for $m_H \lesssim 120\ \mathrm{GeV}$
  - Hints of higher limit?
- LEP limit $m_H \gtrsim 114\ \mathrm{GeV}$
- First-order PT also requires one light top squark
  - Precision electroweak requires heavy $\tilde{t}_L$
  - So $\tilde{t}_R$ must be light
  - Difficult to generate large CPV squark source with disparate masses
  - Rely on Higgsino source instead…
- Extensions of MSSM with extra light scalar (e.g. NMSSM) can strengthen phase transition and allow degenerate squarks
  - enhancing CP-violating squark source

Densities in MSSM Baryogenesis

- Densities for supermultiplets:

$$Q = n_{t_L} + n_{\tilde{t}_L} + n_{b_L} + n_{\tilde{b}_L}$$
$$T = n_{t_R} + n_{\tilde{t}_R}$$
$$B = n_{b_R} + n_{\tilde{b}_R}$$
$$H = n_{H_u} + n_{\tilde{H}_u} - n_{H_d} - n_{\tilde{H}_d}$$
$$h = n_{H_u} + n_{\tilde{H}_u} + n_{H_d} + n_{\tilde{H}_d}$$

Assume supergauge interactions keep superpartners in chemical equilibrium

- Relate particle densities to chemical potentials:

$$n_i = g_i \int \frac{d^3k}{(2\pi)^3} [n_{B,F}(\omega_{\mathbf{k}}, \mu_i) - n_{B,F}(\omega_{\mathbf{k}}, -\mu_i)]$$
$$\Rightarrow n_i = \frac{k_i T^2}{6} \mu_i$$

Transport Equations

- Coupled transport equations for particle densities:

Huet, Nelson (1995):

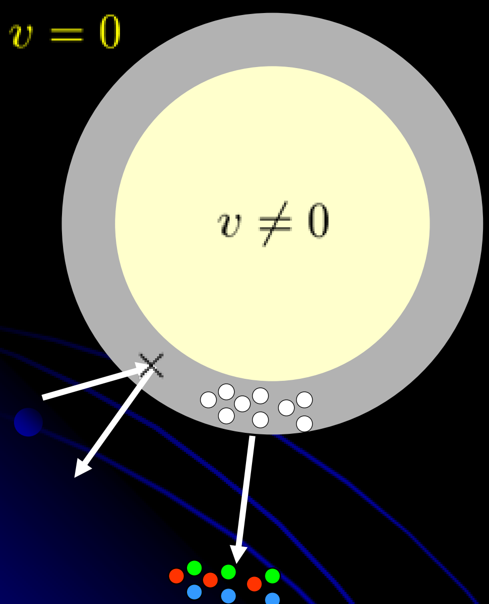
$$\partial_\mu J_i^\mu = S_i^{CP}(\mu_i) + S_i^{\not{CP}} + S_i^{\text{s.s.}}$$

$$\Downarrow$$

$$v_w T' - D_q T'' = S_{\tilde{t}_R}^{\not{CP}} - S^{\text{s.s.}} + \Gamma_M^-(\mu_Q - \mu_T) + \Gamma_Y(\mu_Q - \mu_T + \mu_H)$$

$$v_w Q' - D_q Q'' = -S_{\tilde{t}_R}^{\not{CP}} + 2S^{\text{s.s.}} - \Gamma_M^-(\mu_Q - \mu_T) - \Gamma_Y(\mu_Q - \mu_T + \mu_H)$$

$$v_w H' - D_h H'' = S_{\tilde{H}}^{\not{CP}} - \Gamma_H \mu_H - \Gamma_Y(\mu_Q - \mu_T + \mu_H)$$



$S_{\tilde{H}}^{\not{CP}} \gg S_{\tilde{t}_R}^{\not{CP}}$

$D_h \gg D_q$

CP violating sources

Relaxation rates

Higgs-(s)quark flavor transfer

Higgsino source dominates in MSSM, Γ_Y transfers it to (s)quark sector

Derive from Field Theory

- **Derive transport equations for particle densities:**
  - **Thermal expectation values of currents:**

$$\langle \partial_\mu j^\mu(x) \rangle \quad \textbf{where} \quad \langle \mathcal{O}(x) \rangle = \frac{1}{Z}\,\mathrm{Tr}\Big[e^{-\beta \mathcal{F}}\mathcal{O}(x)\Big]$$

Bosons $$j^\mu_\phi = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*)$$

Fermions $$j^\mu_\psi = i\bar{\psi}\gamma^\mu\psi$$

Closed Time Path QFT

- Expectation value in given "in" state:

$$\langle n | S_{\rm int}^\dagger T\{\mathcal{O}(x) S_{\rm int}\} | n \rangle$$

$$S_{\rm int} = T \exp\left(i \int d^4x\, \mathcal{L}_{\rm int} \right)$$

$$\Downarrow$$

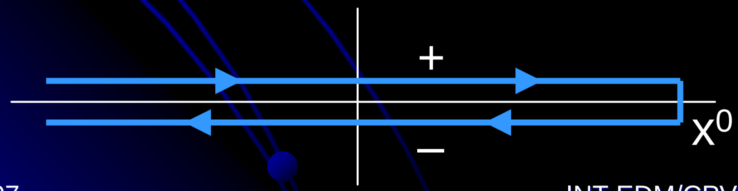
$$\langle n | \mathcal{P} \left\{ \mathcal{O}_+(x) \exp\left(i \int d^4x\, \mathcal{L}_+ - i \int d^4x\, \mathcal{L}_- \right) \right\} | n \rangle$$

$$\Downarrow$$

"path-ordering"

$$\langle n | \mathcal{P} \left\{ \mathcal{O}(x) \exp\left(i \int_{\mathcal{C}} d^4x\, \mathcal{L} \right) \right\} | n \rangle$$

Four Green's functions:

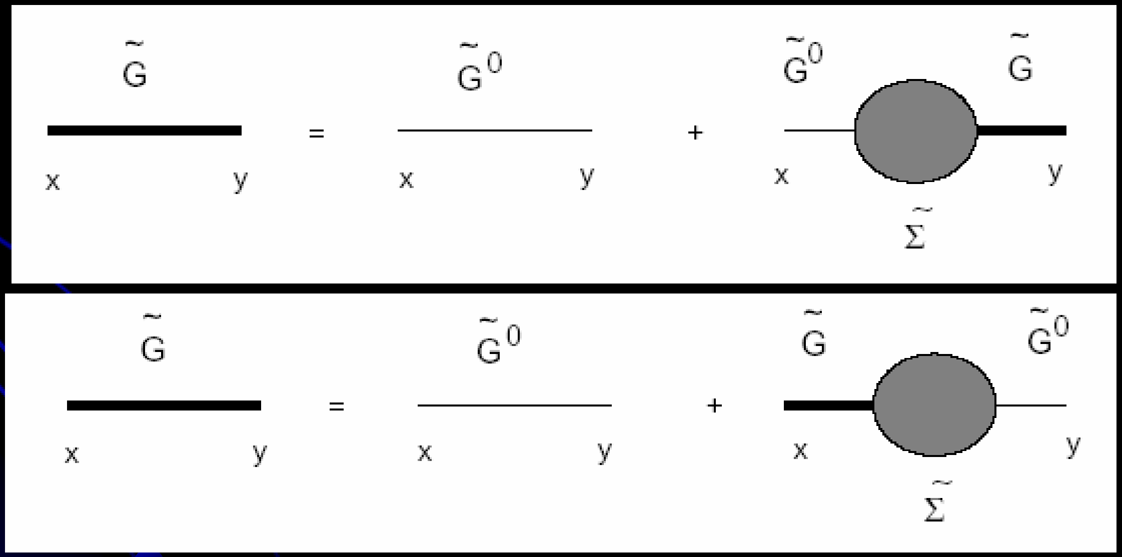


$$\Longrightarrow \quad \tilde{G}(x,y) = \begin{pmatrix} G^{++} & -G^{+-} \\ G^{-+} & -G^{--} \end{pmatrix}$$

Schwinger-Dyson Equations

$$\tilde{G}(x,y) = \tilde{G}^0(x,y) + \int d^4z \int d^4w\, \tilde{G}^0(x,z)\tilde{\Sigma}(z,w)\tilde{G}(w,y)$$

$$\tilde{G}(x,y) = \tilde{G}^0(x,y) + \int d^4z \int d^4w\, \tilde{G}(x,z)\tilde{\Sigma}(z,w)\tilde{G}^0(w,y)$$



Quantum Transport Equations

- Schwinger-Dyson equations imply transport equations:

$$\frac{\partial n}{\partial X^0} + \nabla \cdot \mathbf{j}(X)$$

$$= \int d^3z \int_{-\infty}^{X^0} dz^0 [\Sigma^>(X,z) G^<(z,X) - G^>(X,z)\Sigma^<(z,X)$$

$$-\Sigma^<(X,z) G^>(z,X) + G^<(X,z)\Sigma^>(z,X)]$$

CP-violating and conserving interactions enter self-energies

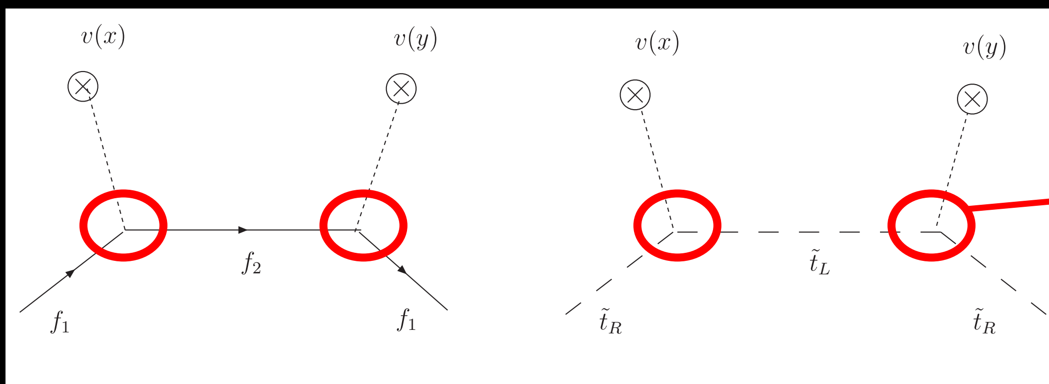
integral over entire history of system

slowly varying in *X:* $v(X), \mu_i(X)$

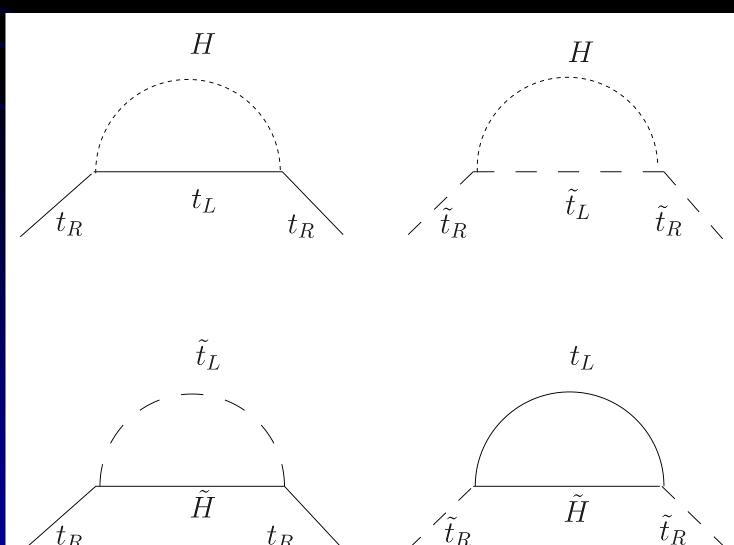
$$G^>_{\tilde{t}_R}(x,y) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot(x-y)} [1 + n_B(k^0 - \mu_{\tilde{t}_R})] \rho_{\tilde{t}_R}(k)$$

Examples of Self-Energies

- Fermion and scalar interactions with Higgs vevs, Higgs particles, and Higgsinos



contribution to $S^{\not{CP}}_{\tilde{t}_R}$ Γ_M



$$\mathcal{L}_{\rm MSSM} \supset y_t \tilde{t}_L (A_t H_u^0 - \mu^* H_d^{0*}) \tilde{t}_R^*$$

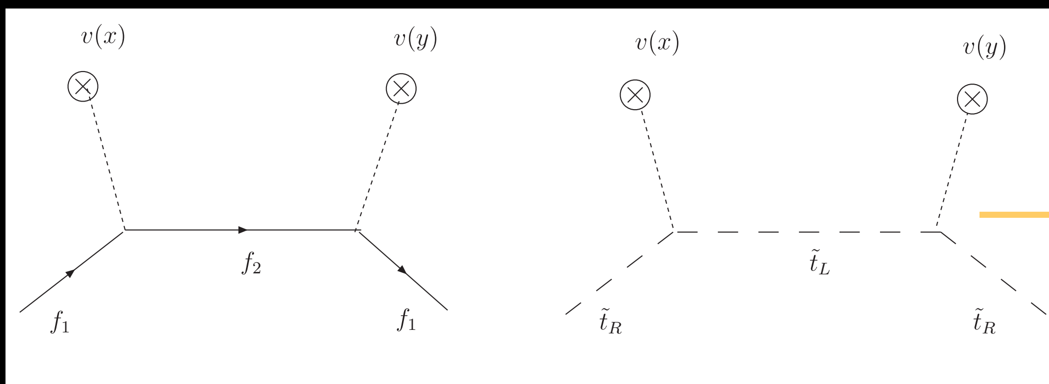
$$A_t = |A_t| e^{i\phi_A} \qquad \mu = |\mu| e^{i\phi_\mu}$$

(only two phases in minimal supergravity SUSY-breaking scenario)

contribution to Γ_Y

Resonances and Enhancements

- Quantum Effects give resonances in sources and relaxation rates, enhanced Yukawa transfer rate

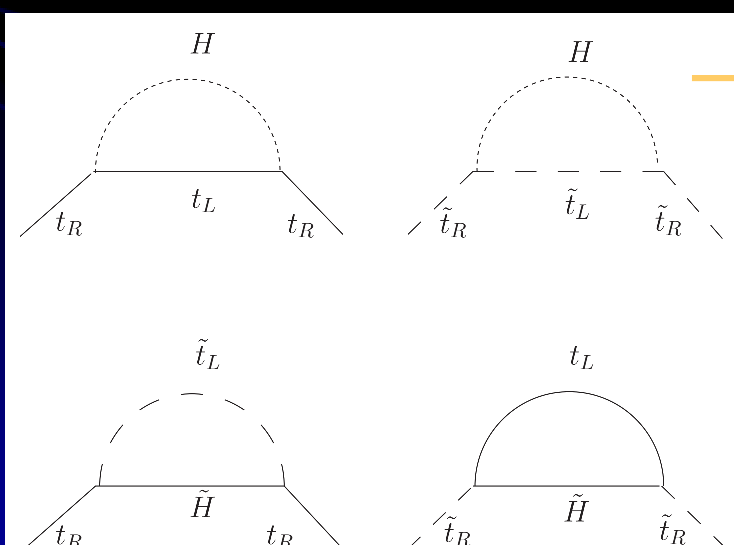


$$S^{\not{CP}}_{\tilde{t}_R} \sim \frac{1}{(m_{\tilde{t}_L} - m_{\tilde{t}_R})^2}$$

Riotto (1998)

$$\Gamma^-_M \sim \frac{1}{m_{\tilde{t}_L} - m_{\tilde{t}_R}}$$

Cirigliano, CL, Ramsey-Musolf (2005)

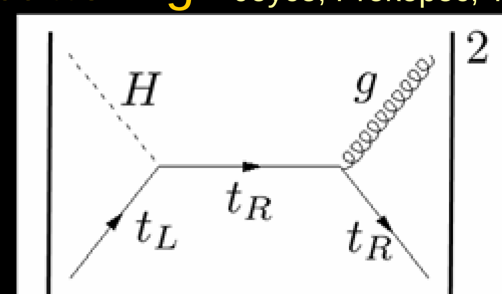


First calculation of Γ_Y at $\mathcal{O}(\alpha_s^0)$

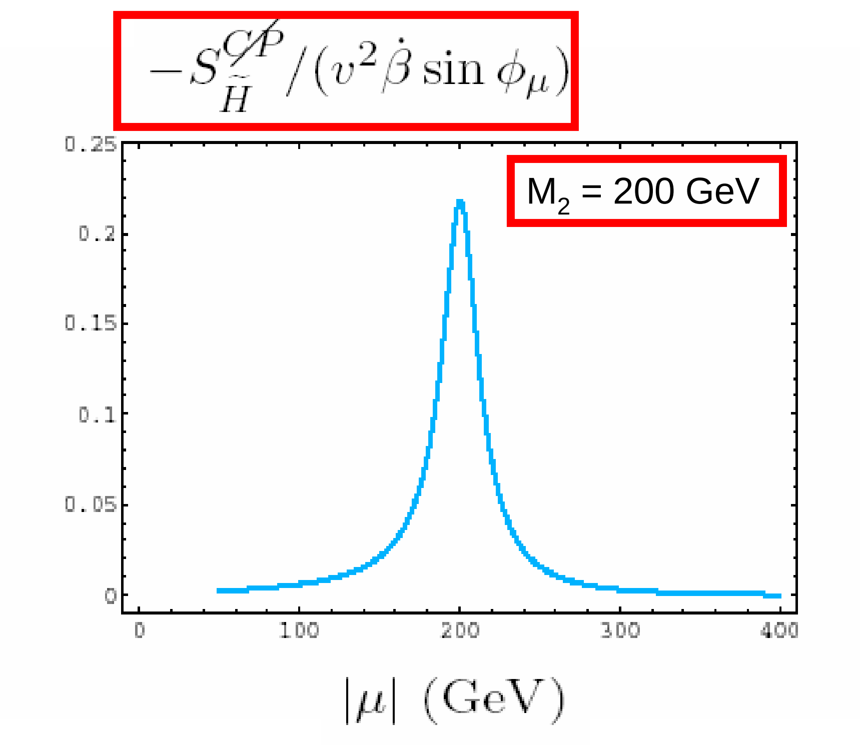
Cirigliano, CL, Ramsey-Musolf, Tulin (2006)

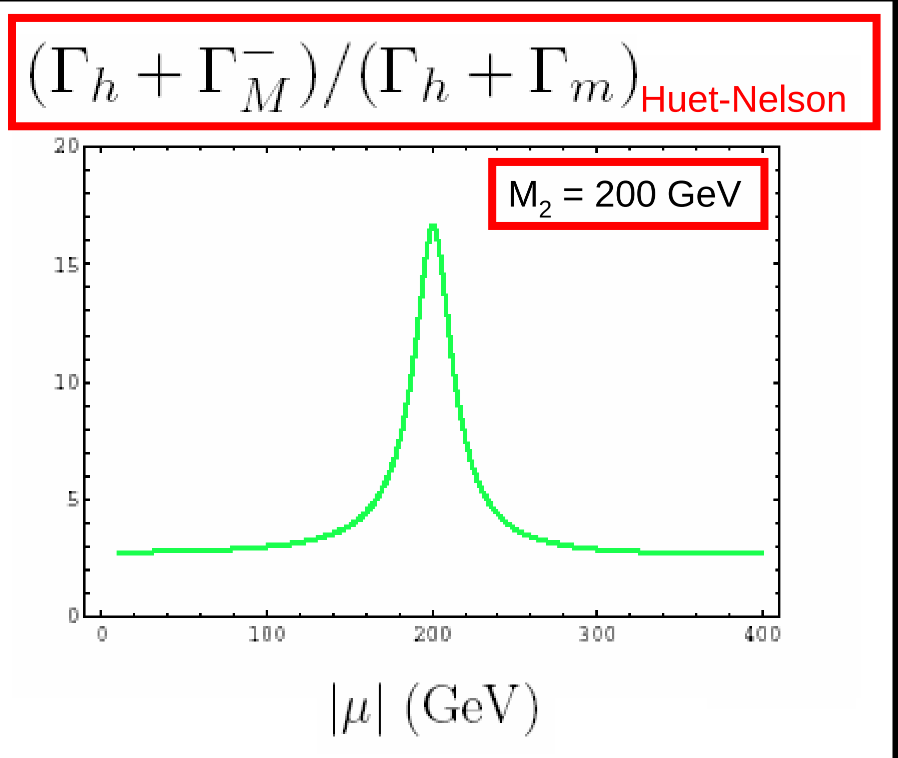
cf. gluon scattering Joyce, Prokopec, Turok (1994)

$\Gamma_Y \propto$



Higgsino Source and Relaxation





$$\rho_B(\bar{z} > 0) \propto \frac{S^{\not{CP}}_{\tilde{H}} + S^{\not{CP}}_{\tilde{t}_R}}{\sqrt{\Gamma_h + \Gamma^-_M}}$$

Resonant enhancements of relaxation terms mitigate but do not cancel out those of CP-violating sources

Transfer of Higgs Source to Baryons

- CP-violating Higgsino source transferred to baryons via Yukawa or tri-scalar interactions

$$v_w H' - D_h H'' = S_{\tilde{H}}^{CP\!\!\!/} - \Gamma_H \mu_H - \Gamma_Y (\mu_Q - \mu_T + \mu_H)$$

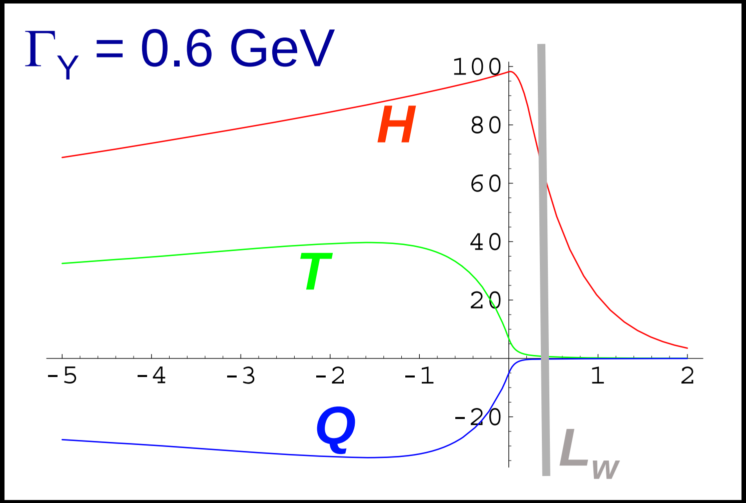
- Efficient diffusion of Higgs number into sphaleron-active region

$$D_h \sim 100/T \gg D_q \sim 6/T$$

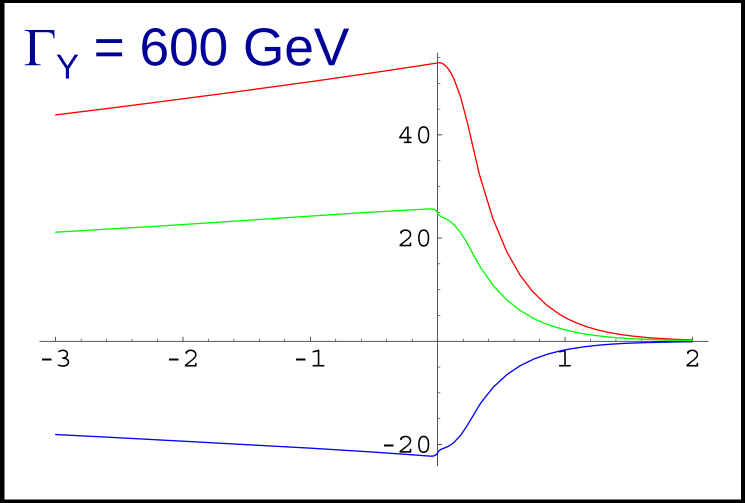
- Conversion to baryons unsuppressed outside bubble wall

$$v_w Q' - D_q Q'' \approx -\Gamma_{\tilde{M}} (\mu_Q - \mu_T) - \Gamma_Y (\mu_Q - \mu_T + \mu_H)$$

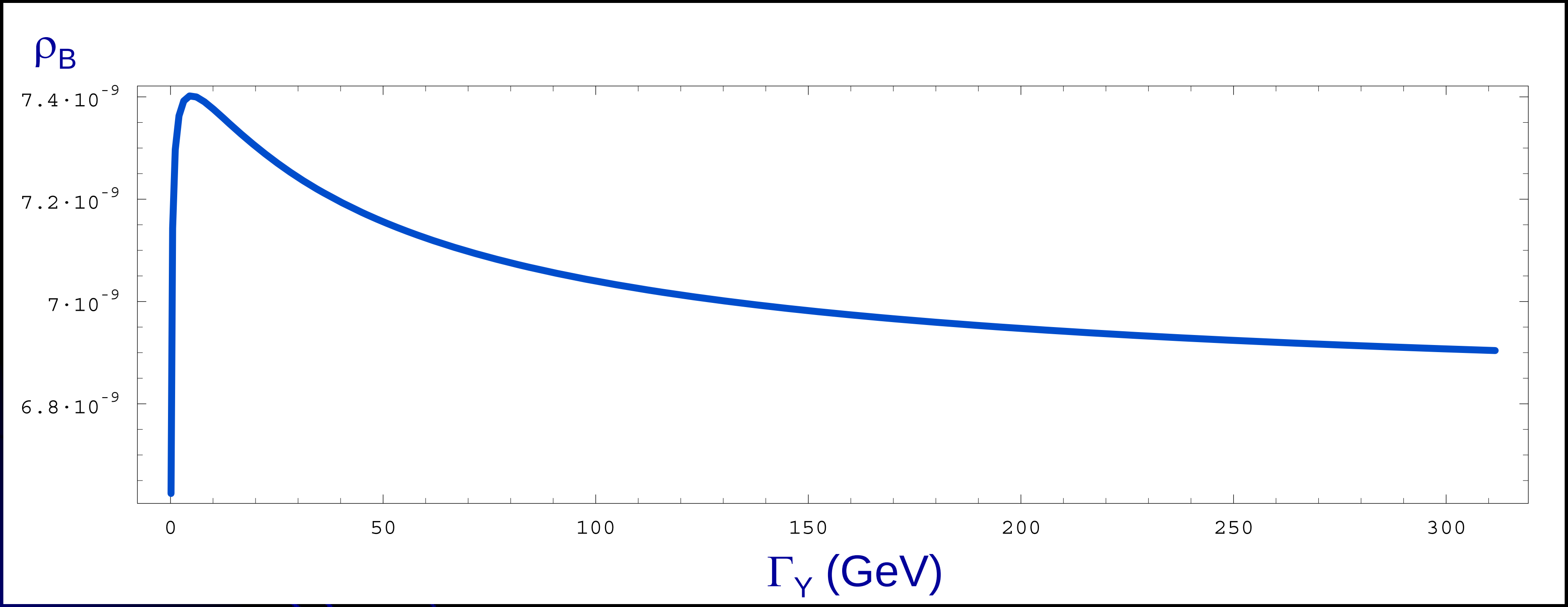
Solution for Densities



Γ_M = 46 GeV
Γ_H = 25 GeV

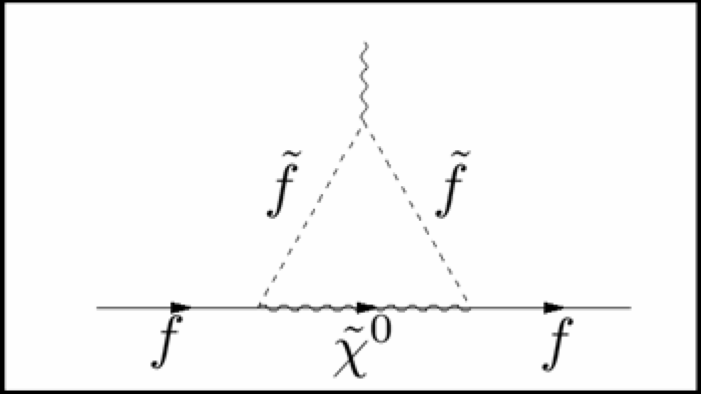


Solution for Baryon Density



Electric Dipole Moments

- One-loop MSSM graphs generating EDMs:

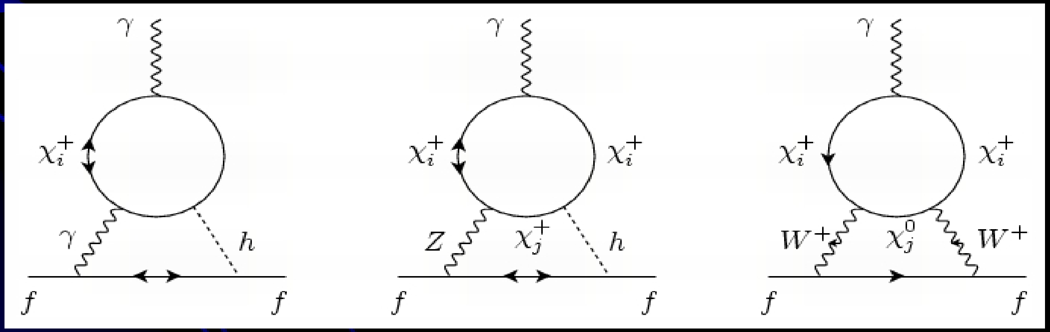


Ibrahim, Nath

Suppressed for large values of sfermion masses $m_{\tilde{f}}$

- Two-loop graphs independent of sfermion masses

Chang, Chang, Keung; Pilaftsis; Giudice, Romanino



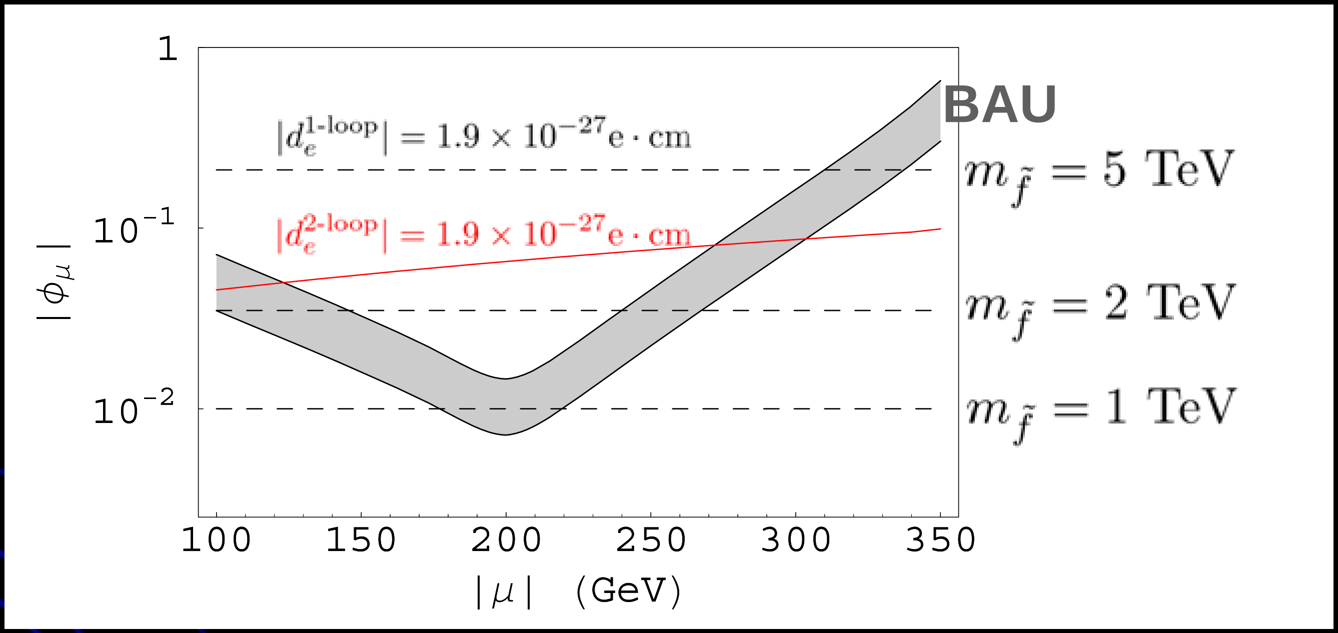
Independent of $m_{\tilde{f}}$

Dominant for

$$m_{\tilde{f}} \gtrsim 2 - 3\ \text{TeV}$$

Combined BAU & EDM constraints

$$\mathcal{L}_{\rm SUSY} \supset |\mu| e^{i\phi_\mu} (\widetilde{H}_d^0 \widetilde{H}_u^0 - \widetilde{H}_d^- \widetilde{H}_u^+) - \frac{1}{2} M_2 \bar{\psi}_W \psi_W$$



$M_2 = 200$ GeV

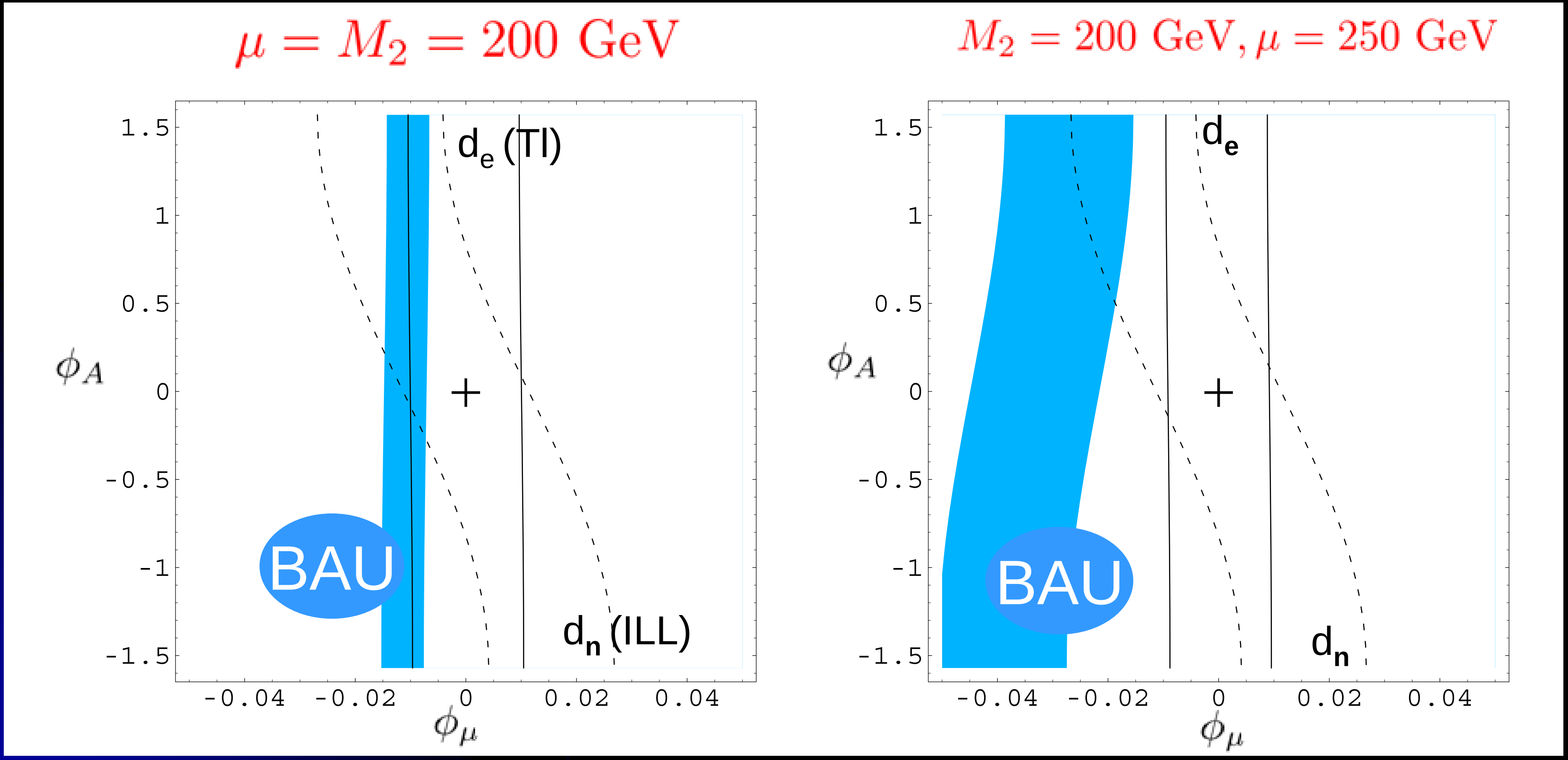
Combined BAU & EDM constraints

(1-loop)

$$\mathcal{L}_{\rm SUSY} \supset y_t \tilde{t}_L (A_t H_u^0 - \mu^* H_d^{0*}) \tilde{t}_R^* \qquad A_t = |A_t| e^{i\phi_A}$$

$$+ \mu (\widetilde{H}_d^0 \widetilde{H}_u^0 - \widetilde{H}_d^- \widetilde{H}_u^+) \qquad \mu = |\mu| e^{i\phi_\mu}$$

neutron edm calc.:
Pospelov, Ritz



The Future of Baryogenesis

- More complete, consistent calculation of BAU with non-equilibrium QFT. Still in progress...
  - Resummation of Higgs vev insertions, mixing of mass/flavor eigenstates (cf. Carena et al., Konstandin et al.)
  - Relax approximation of gauge or superpartner equilibrium (keep track of gauge, gaugino densities)
- Non-minimal supersymmetric extensions
  - More CP violating parameters
  - Extra scalar field, stronger phase transition
  - Enhanced squark source possible
- Collider and EDM searches may point to the correct scenario for baryogenesis