# *SUSY Baryogenesis, EDMs, & Dark Matter: A Systematic Approach*


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| | |
|---|---|
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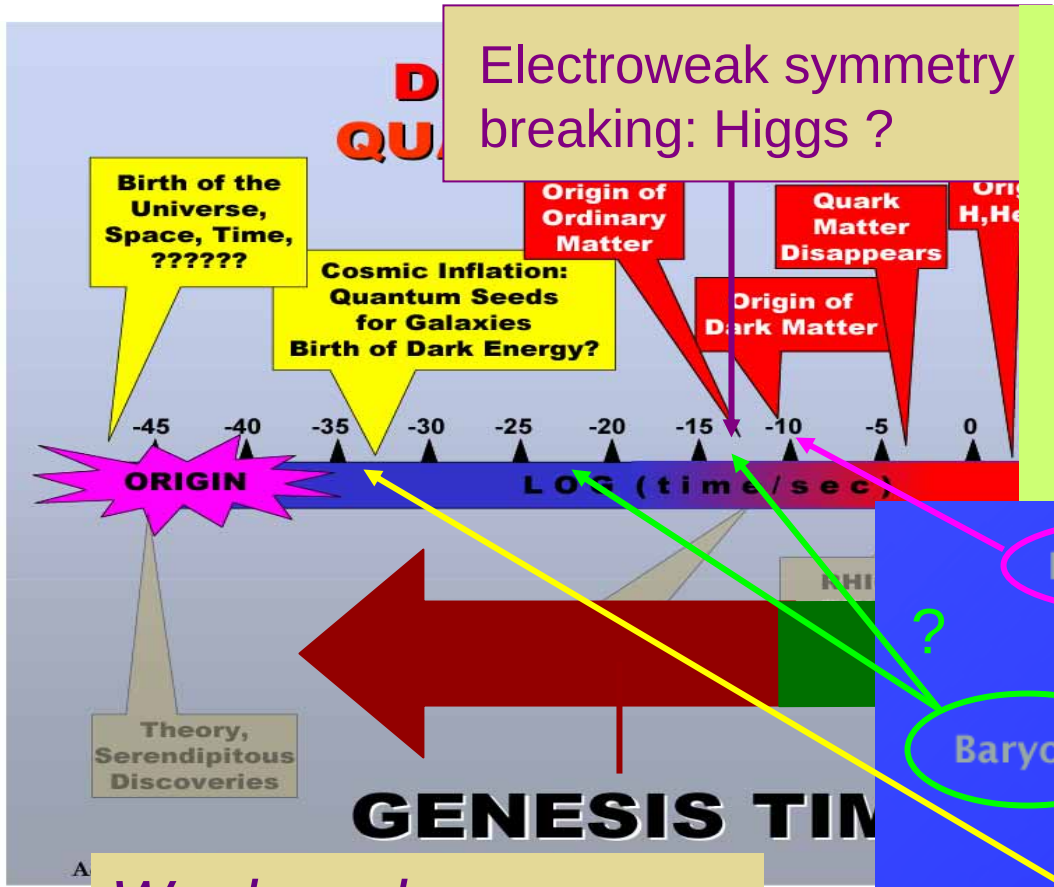
*PRD 71: 075010 (2005),*
*hep-ph/0603058 (PRD),*
*hep-ph/0603246 (JHEP)*

# The Origin of Matter & Energy




Electroweak symmetry breaking: Higgs ?

*Baryogenesis: When? SUSY? Neutrinos? CPV?*

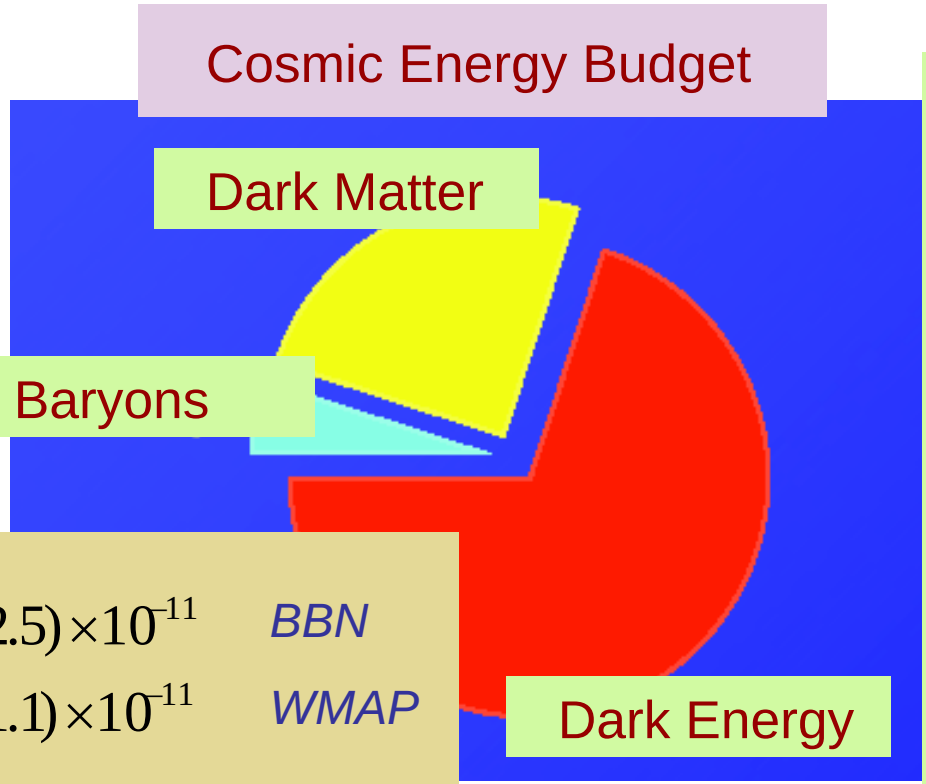
*WIMPy D.M.: Related to baryogenesis?*

*"New gravity"? Grav baryogenesis ?*

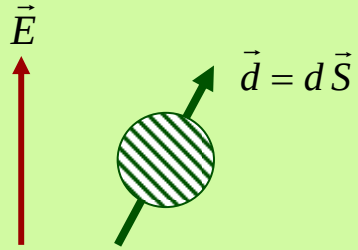

Cosmic Energy Budget

*Weak scale baryogenesis can be tested experimentally*

# *What is the origin of baryonic matter ?*




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




$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd
by CPT theorem

*What are the quantitative implications of new EDM experiments for explaining the origin of the baryonic component of the Universe ?*

# EDM Probes of New CP Violation

*See Pospelov, Plaster*

CKM

| $f$ | $d_{SM}$ | $d_{exp}$ | $d_{future}$ |
|---|---|---|---|
| $e^-$ | $< 10^{-40}$ | $< 1.6\times10^{-27}$ | $\rightarrow 10^{-31}$ |
| $n$ | $< 10^{-30}$ | $< 6.3\times10^{-26}$ | $\rightarrow 10^{-29}$ |
| $^{199}Hg$ | $< 10^{-33}$ | $< 2.1\times10^{-28}$ | $\rightarrow 10^{-32}$ |
| $\mu$ | $< 10^{-28}$ | $< 1.1\times10^{-18}$ | $\rightarrow 10^{-24}$ |

*Also $^{225}Ra$, $^{129}Xe$, $d$*

If new EWK CP violation is responsible for abundance of matter, will these experiments see an EDM?

# *Baryogenesis and EDMs: Theoretical Tasks*

- *Attaining reliable computations that relate particle physics models of new CP-violation to EDMs of complex systems (neutron, atoms, nuclei)*

  *Nonperturbative QCD, atomic & nuclear structure*

- *Attaining reliable (systematic) computations of the baryon asymmetry from fundamental particle physics theories with new CP-violation*

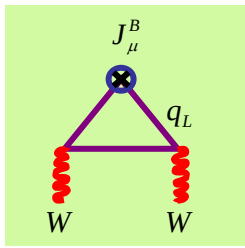
  - *Non-equilibrium quantum transport*
  - *Non-zero T and $\mu$*
  - *Spacetime dynamics of cosmic phase transitions*

*Equally difficult but less studied* → *This talk series*

# Baryogenesis: New Electroweak Physics

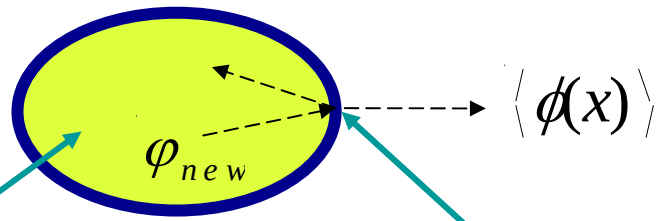
Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics




Unbroken phase

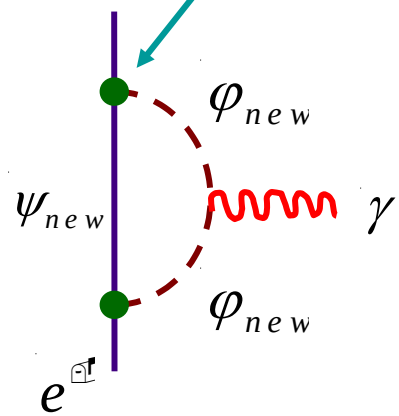
Topological transitions




Broken phase

1st order phase transition

CP Violation




*Theoretical Issues:*

*Transport at phase boundary (non-eq QFT)*

*Bubble dynamics (numerical)*

*Strength of phase transition (beyond MSSM)*

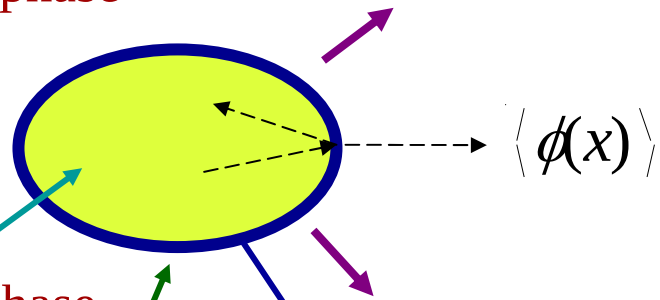
*EDMs: many-body physics & QCD*

# Systematic Baryogenesis

*Cohen, Kaplan, Nelson*
*Joyce, Prokopec, Turok*

Unbroken phase

Topological transitions




Broken phase

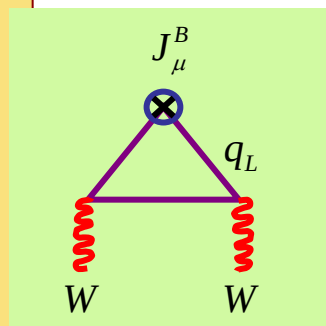
1st order phase transition

*"snow"*

$n_L$ produced in wall & diffuses in front

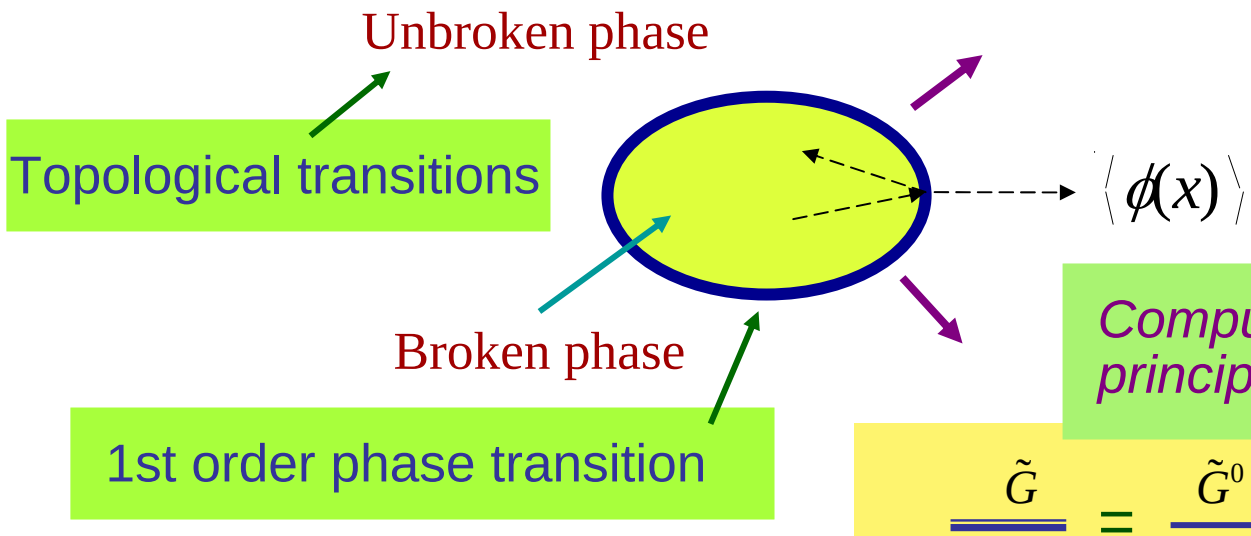
$$\frac{\partial \rho_B}{\partial t} - D\nabla^2 \rho_B = -\Gamma_{WS} F_{WS}(x)\left[n_L(x) + R\rho_B\right]$$

$F_{WS}$ (x) !0 deep inside bubble



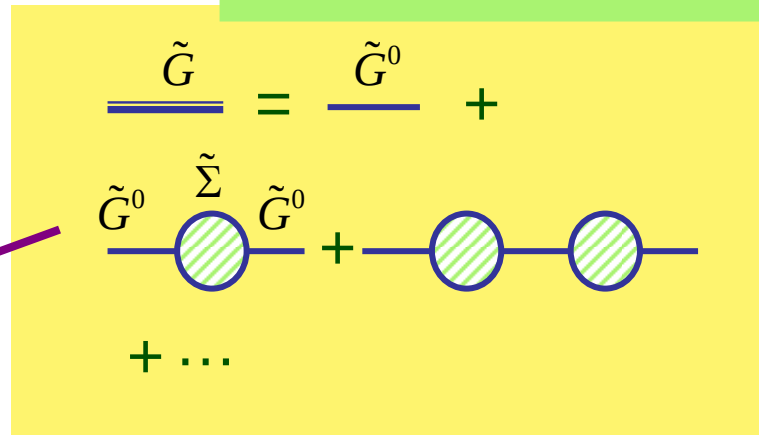
# Systematic Baryogenesis

*Riotto*
*Carena et al*
*Lee, Cirigliano, Tulin, R-M*
*Konstandin et al*




*Compute from first principles given $\mathcal{L}_{new}$*

$$\frac{\partial n_i}{\partial t} - D\nabla^2 n_i = S\left(n_j, T, \varphi, \tilde{M}\right)$$




Quantum Transport Equation

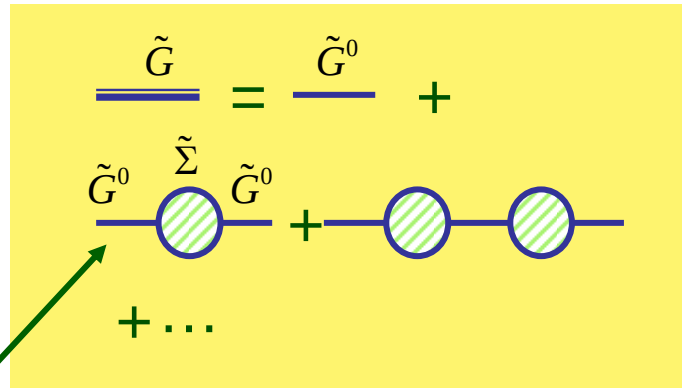
Schwinger-Dyson Equations

# Systematic Baryogenesis

*Departure from equilibrium*

- *Non-adiabatic evolution of states & degeneracies*

$$_{out}\langle 0| = {}_{in}\langle 0|S^\dagger \neq e^{i\alpha}({}_{in}\langle 0|)$$




*Generalized Green's Functions: Closed Time Path*

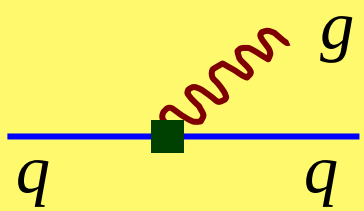
- *Non-thermal distributions*

*Exploit scale hierarchy: expand in scale ratios* $\varepsilon$

$$f_i(E) = f_0(E, \mu_i, T) + \varepsilon f'(E) + \cdots$$

# *Scale Hierarchy*

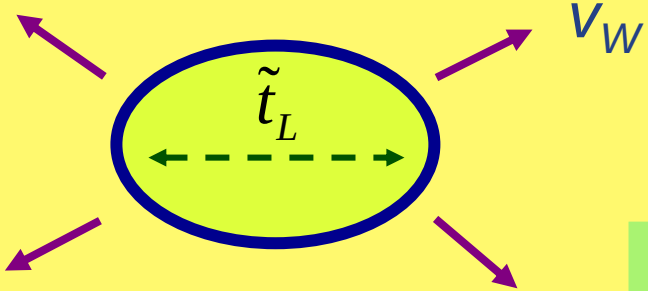
T > 0: Degeneracies




M(T)

$\Gamma_P(T)$

$v_W > 0$: Non-adiabaticity




Time Scales

Plasma time:

$\tau_P \sim 1/\Gamma_P$

Decoherence time:

$\tau_d \sim 1/(v_W k)$

*e.g., particle in an expanding box*

# Scale Hierarchy

Time scales:

$\tau_{int} \sim 1/\omega \qquad \tau_P \sim 1/\Gamma_P \qquad \tau_d \sim 1/(v_w k)$

$\Gamma_P \sim 3C_f \alpha T/ 8 \qquad \omega^2 \sim m^2 + 2\pi\alpha\, C_f\, T^2 + k^2$

$k / \omega < 1 \qquad v_w \sim 0.1$

$\varepsilon_p = \tau_{int} / \tau_P \sim \Gamma_P / \omega \qquad << 1$

$\varepsilon_d = \tau_{int} / \tau_d \sim v_w k / \omega \qquad << 1$

Energy scales:

$\varepsilon_\mu = \mu / T \qquad << 1$

# Quantum Transport Equations

$$\partial_X^\mu j_\mu(X) = \int d^3z \int_{-\infty}^{X_0} dz_0 \left[ \Sigma^>(X,z) G^<(z,X) - G^>(X,z) \Sigma^<(z,X) + \cdots \right]$$

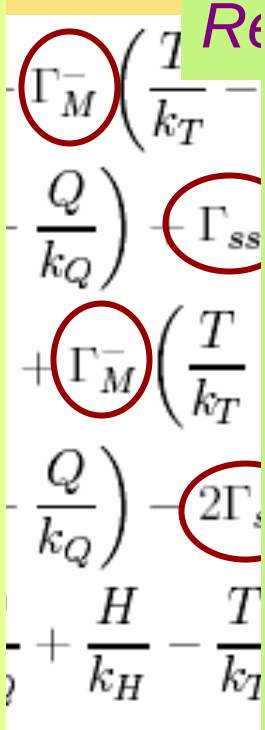
Approximations

- neglect $O(\varepsilon^3)$ terms

Expand

Cl

Re



From S-D Equations:

- $S^{CPV}$

  Riotto, Carena et al, Lee et al

- $\Gamma_M$, $\Gamma_H$, $\Gamma_Y$

  Lee et al

Numerical work:

- $\Gamma_{SS}$

currents

violation in

and baryon sectors

# *Some Results: Preview*

# Baryon Number (Illustrative, MSSM)

$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi_\mu + \phi_A)$$

$$F_1 \propto \frac{S_{\tilde{H}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

$$F_2 \propto \frac{S_{\tilde{t}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

*Higgsinos*

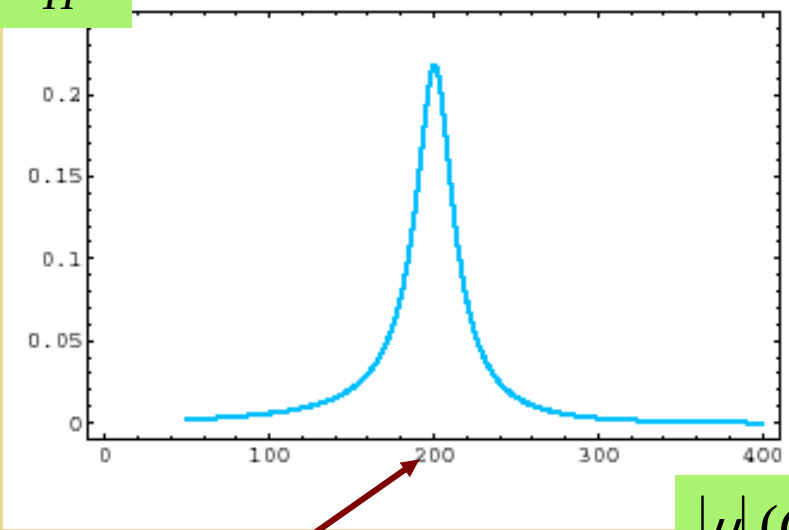
*Squarks*

*MSSM EWB: Higgsino-Gaugino driven*

# Resonant CPV & Relaxation

$\hat{S}_{\tilde{H}}$

CP violation



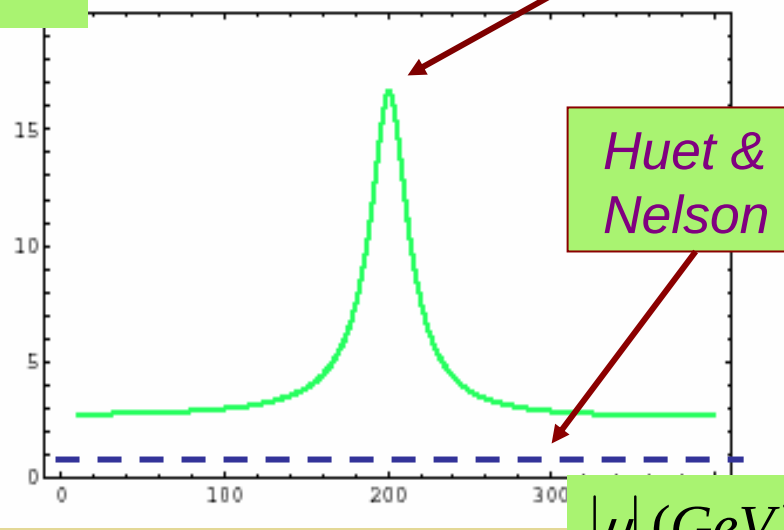

$|\mu|\,(GeV)$

$M_{\tilde{W}}$

$R_{\Gamma}$

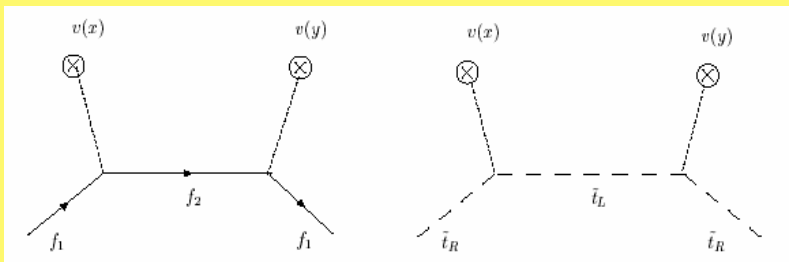
Relaxation

$M_{\tilde{W}}$




Huet & Nelson

$|\mu|\,(GeV)$




$\tilde{H} \leftrightarrow \tilde{W}$

$$F_1 \propto \frac{S_{\tilde{H}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

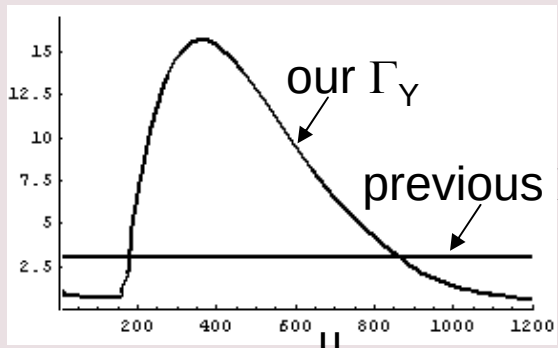
See C. Lee talk

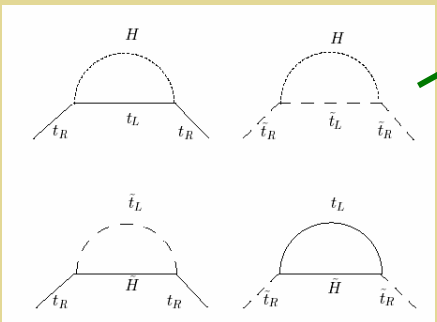
# Baryon Number & $\Gamma_Y$

See S. Tulin talk

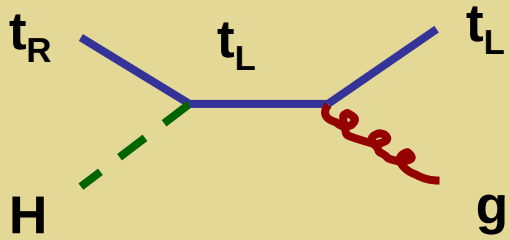
$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi$$

$$F_i = F_i^\infty \left[ 1 + \Delta\left(\frac{\Gamma_H}{\Gamma_Y}\right) \right]$$




$O(\alpha_s^0)$




$O(\alpha_s)$

Cirigliano, Lee, R-M, Tulin

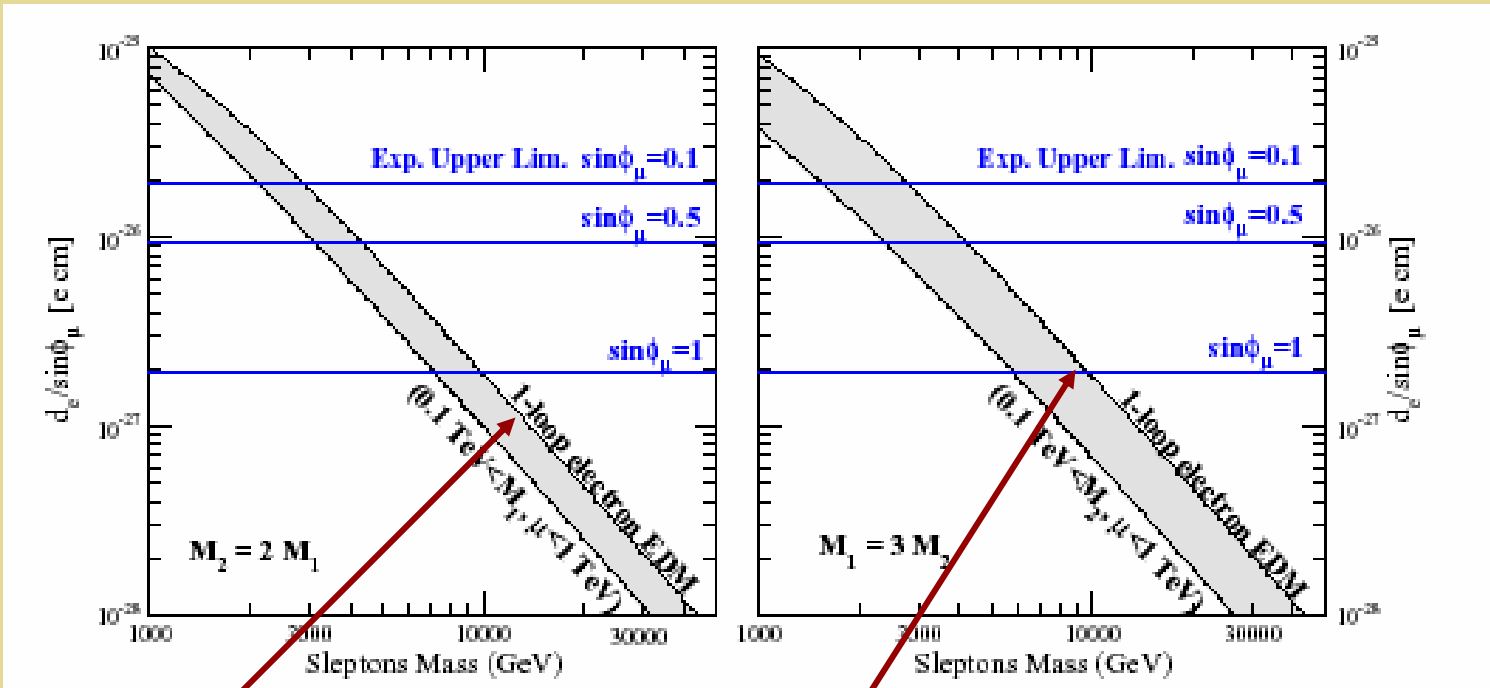
Joyce, Prokopec, Turok

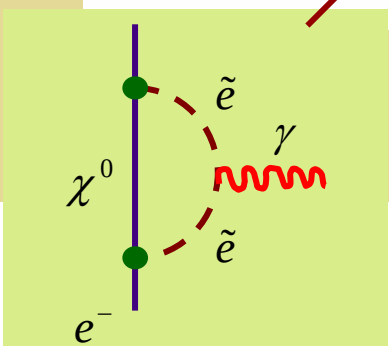
# EDM constraints & SUSY CPV

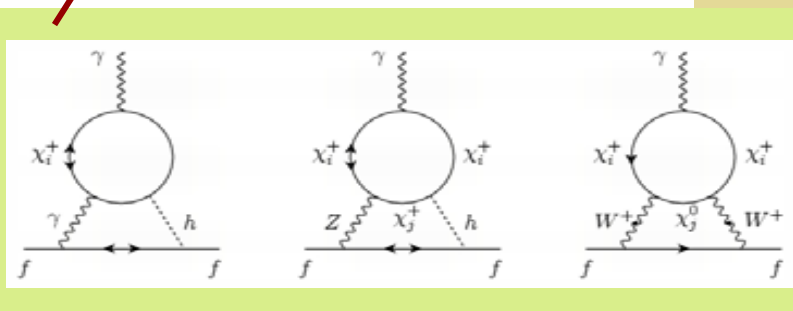
See C. Lee talk

See S. Profumo talk

## One-loop vs. Two-loop EDMs



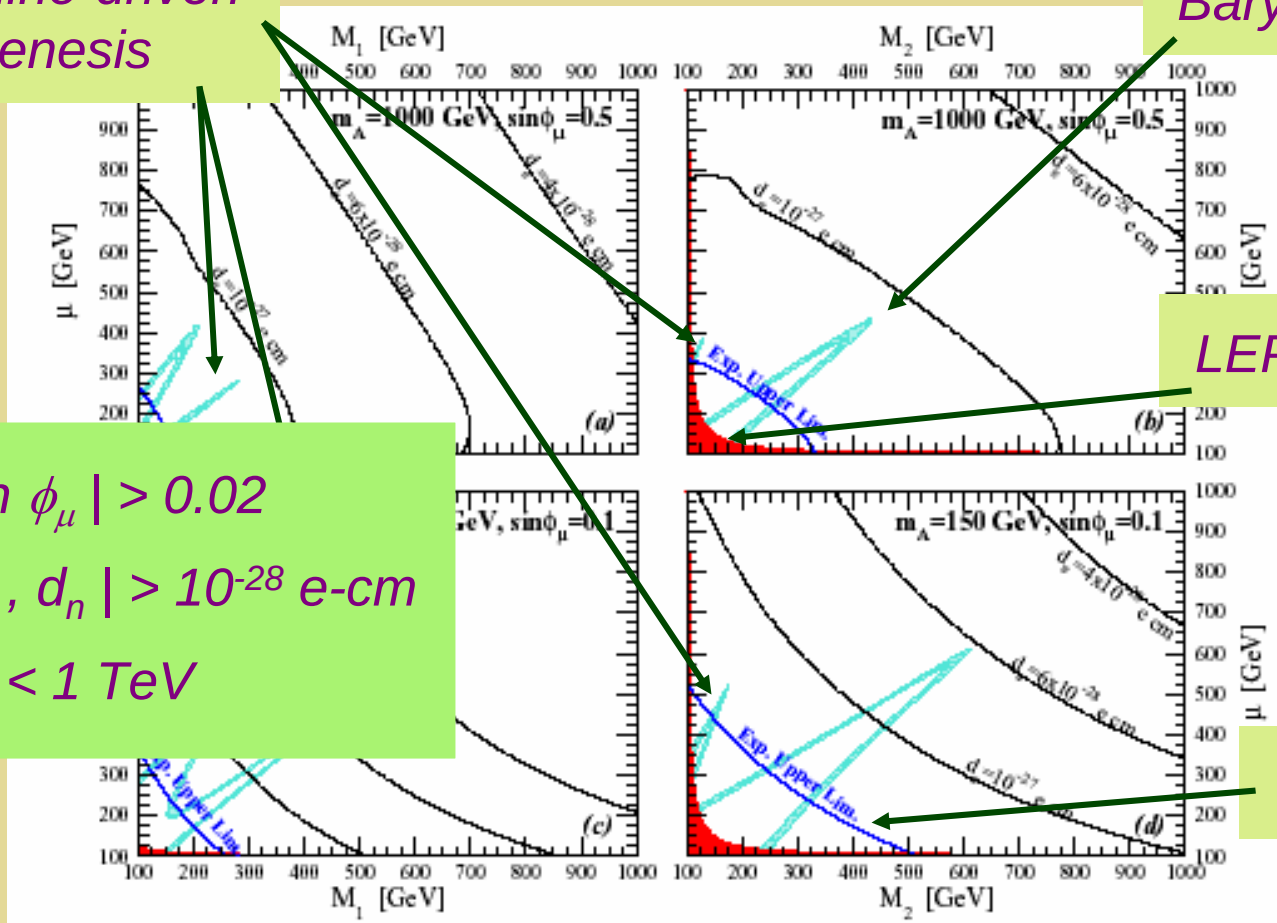



# EDM constraints & SUSY CPV

DM Considerations

Neutralino-driven baryogenesis

Baryogenesis




LEP II Exclusion

$|\sin\phi_\mu| > 0.02$

$|d_e, d_n| > 10^{-28}$ e-cm

$M_\chi < 1$ TeV

Two loop $d_e$

SUGRA: $M_2 \sim 2M_1$

AMSB: $M_1 \sim 3M_2$

See Profumo talk

# *Conclusions*

- *New EDM experiments can test -- and possibly rule out -- EWB as a paradigm for explaining the BAU provided sufficiently reliable computations of $Y_B$ can be performed*
- *Progress is being made in obtaining systematic computations of $Y_B$ by computing all relevant transport coefficients in a consistent framework*
- *There exists a rich phenomenology involving cosmology, EDMs, LHC, ILC in SUSY and beyond as well as additional formal work to be undertaken*