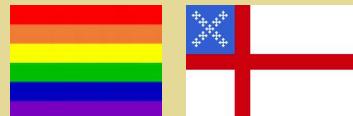


# *Electric Dipole Moments II*



M.J. Ramsey-Musolf

*Wisconsin-Madison*



## NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

<http://www.physics.wisc.edu/groups/particle-theory/>

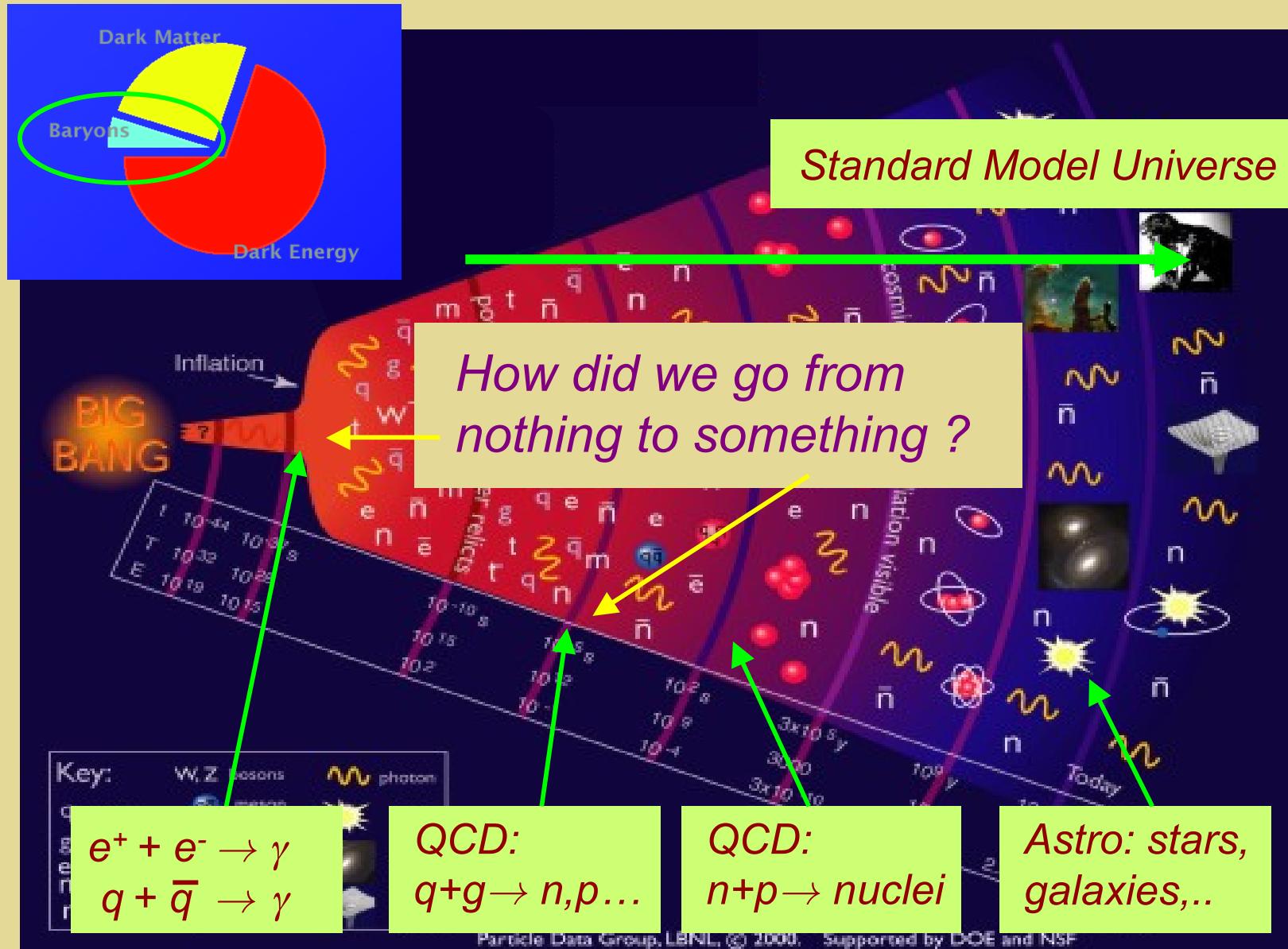
TUM Excellence Cluster, May 2013

# *Outline*

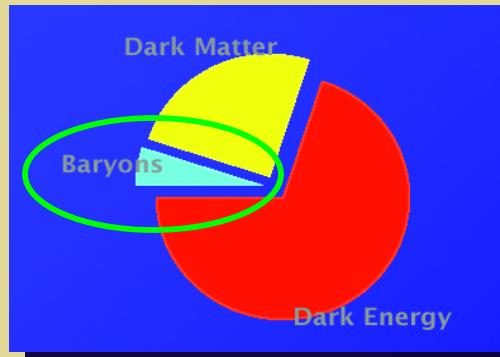
1. *Baryon Asymmetry: General Considerations*
2. *Electroweak Phase Transition*
3. *CP-Violation & EDMs*

# *I. Baryon Asymmetry: General Considerations*

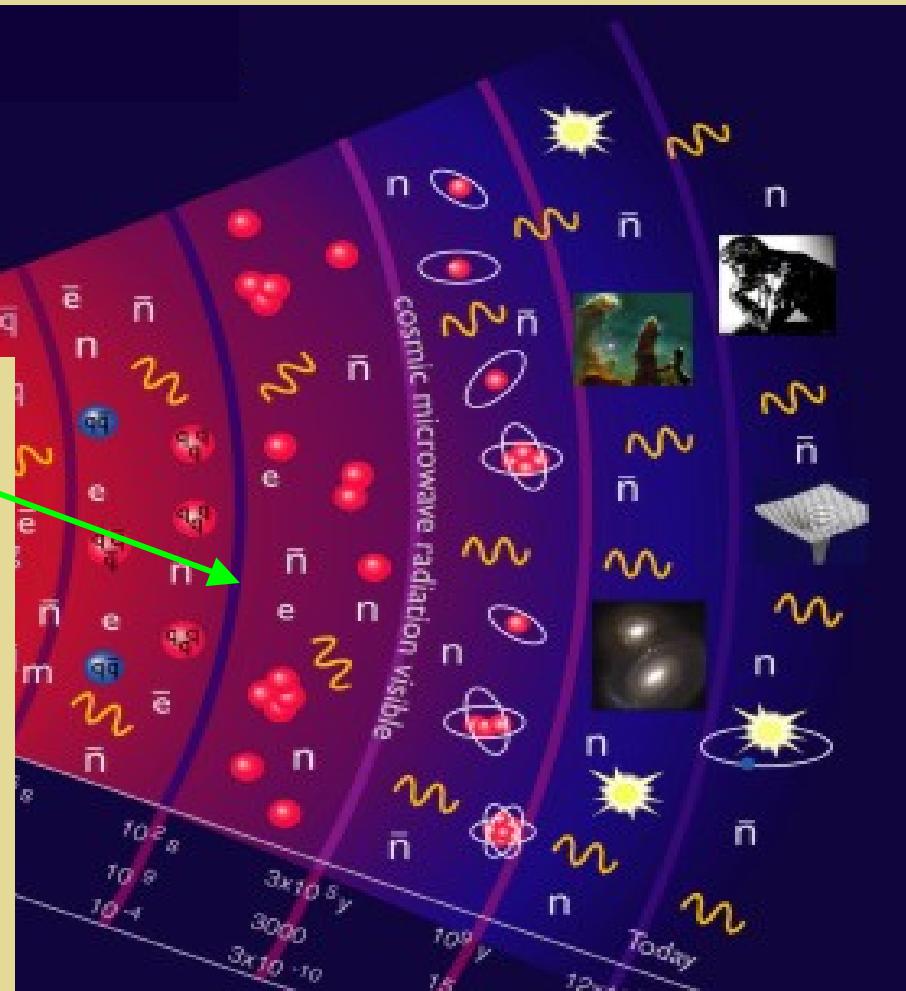
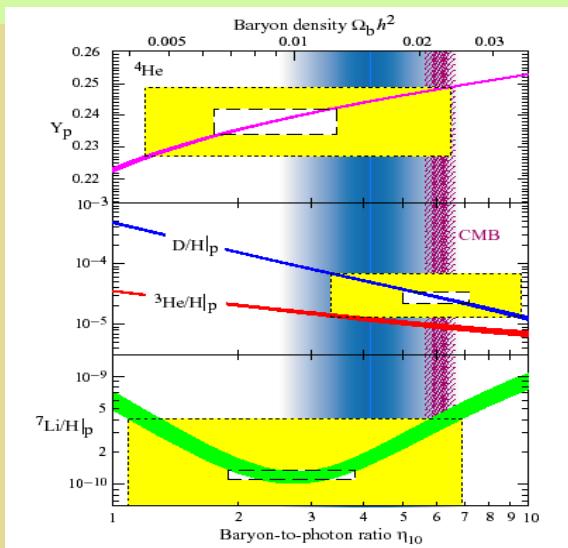
# Cosmic Baryon Asymmetry



# Cosmic Baryon Asymmetry

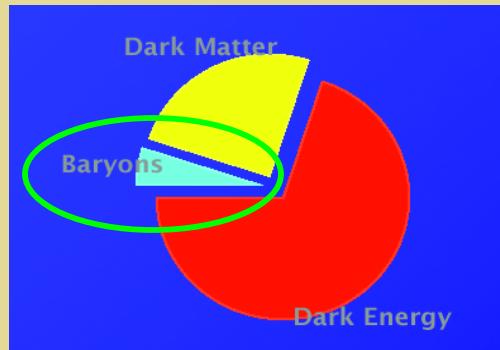


*Big Bang Nucleosynthesis:  
Light element abundances  
depend on  $Y_B$*

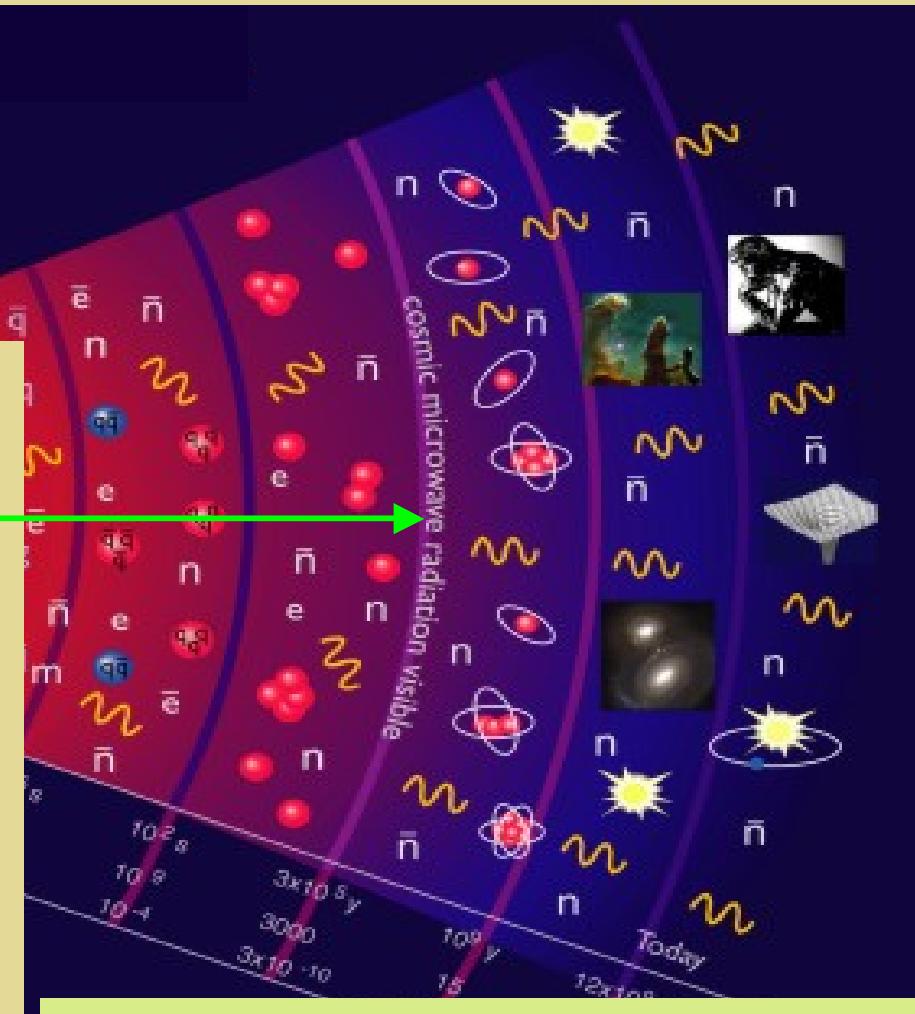
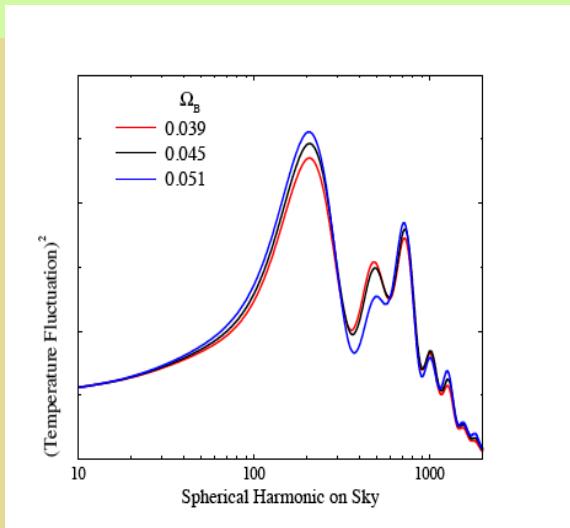


$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

# Cosmic Baryon Asymmetry

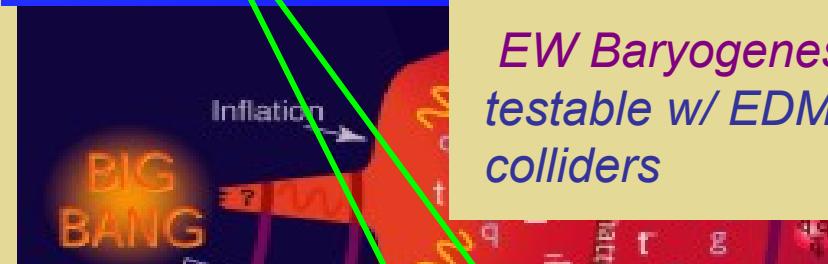
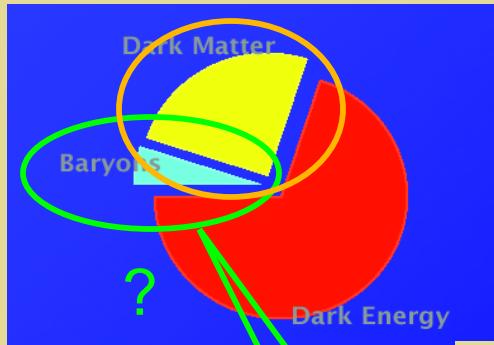


*Cosmic Microwave Bcknd:  
Shape of anisotropies  
depends on  $Y_B$*



$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

# What is the Origin of Matter



Leptogenesis:  
less testable,  
look for  
ingredients w/  $\nu s$

Baryogenesis: When?  
CPV? SUSY? Neutrinos?



Can new TeV scale  
physics explain the  
abundance of matter ?

If so, how will we  
know ?

Key:	
$W, Z$	bosons
q quark	meson
g gluon	photon
e electron	star
$\mu$ muon	galaxy
$\tau$ tau	black hole
$\bar{n}$ neutrino	atom
ion	

Particle Data

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

# *Ingredients for Baryogenesis*



- *B violation (sphalerons)*
- *C & CP violation (BSM)*
- *Out-of-equilibrium or CPT violation (BSM)*

# *Ingredients for Baryogenesis*



*Standard Model      BSM*

- |  |   |   |
|--|---|---|
| • <i>B violation (sphalerons)</i>                  | ✓ | ✓ |
| • <i>C &amp; CP violation (BSM)</i>                | ✗ | ✓ |
| • <i>Out-of-equilibrium or CPT violation (BSM)</i> | ✗ | ✓ |

# *Ingredients for Baryogenesis*



*Scenarios: leptogenesis,  
EW baryogenesis, Affleck-  
Dine, asymmetric DM, cold  
baryogenesis, post-  
sphaleron baryogenesis...*

	<i>Standard Model</i>	<i>BSM</i>
• <i>B violation (sphalerons)</i>	✓	✓
• <i>C &amp; CP violation (BSM)</i>	✗	✓
• <i>Out-of-equilibrium or CPT violation (BSM)</i>	✗	✓

# *EW Baryogenesis: Standard Model*

## Weak Scale Baryogenesis

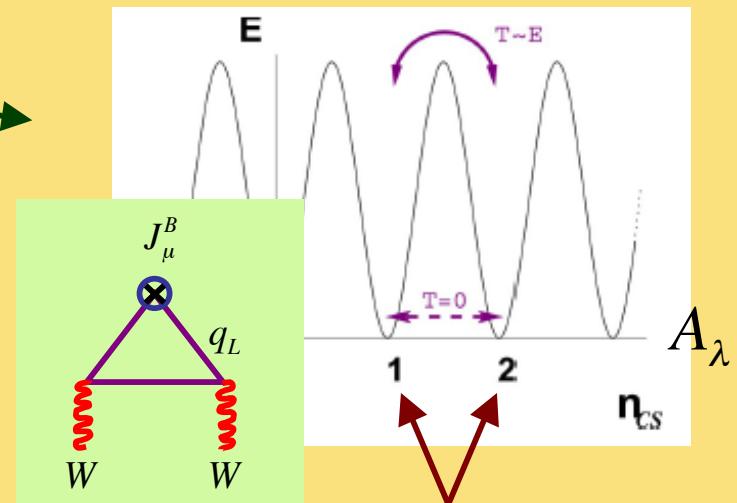
- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*



*Sakharov, 1967*

*Kuzmin, Rubakov, Shaposhnikov  
McLerran, ...*

## Anomalous Processes



Different vacua:  $\Delta(B+L) = \Delta N_{cs}$

*Sphaleron Transitions*

# ***EW Baryogenesis: Standard Model***

*Shaposhnikov*

## *Weak Scale Baryogenesis*

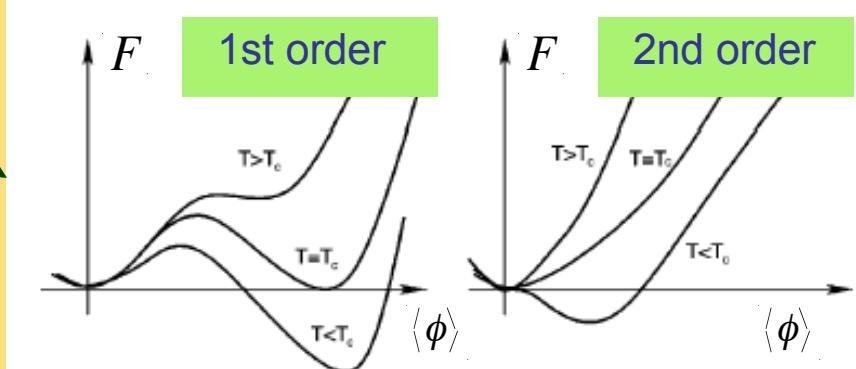
- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*



*Sakharov, 1967*

- *CP-violation too weak*
- *No EWPT*

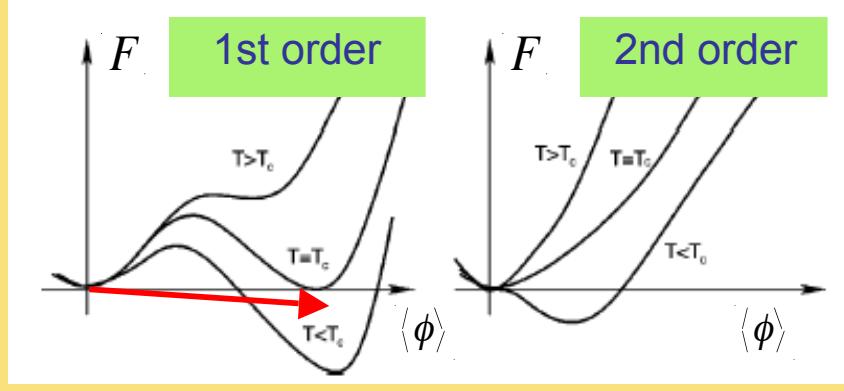
$$J = s_{12} s_{13} s_{23} c_{12} c_{13}^2 c_{23} \sin \delta_{13}$$
$$= (2.88 \pm 0.33) \times 10^{-5}$$
$$\frac{m_t^4}{M_W^4} \frac{m_b^4}{M_W^4} \frac{m_c^2}{M_W^2} \frac{m_s^2}{M_W^2} \approx 3 \times 10^{-13}$$



Increasing  $m_h$  →

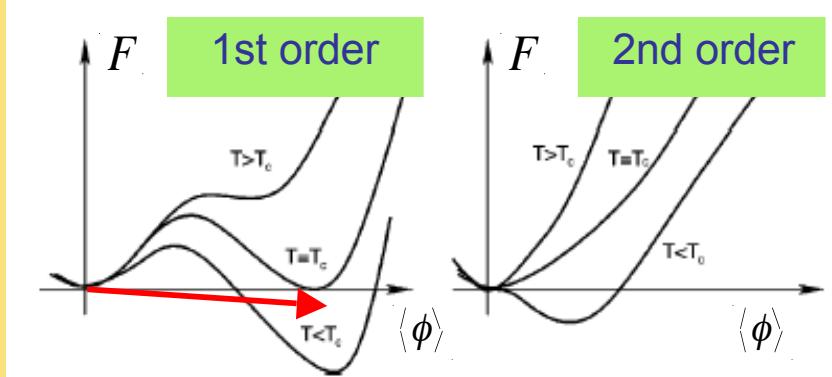
## *II. Electroweak Phase Transition*

# EW Phase Transition: New Scalars & CPV

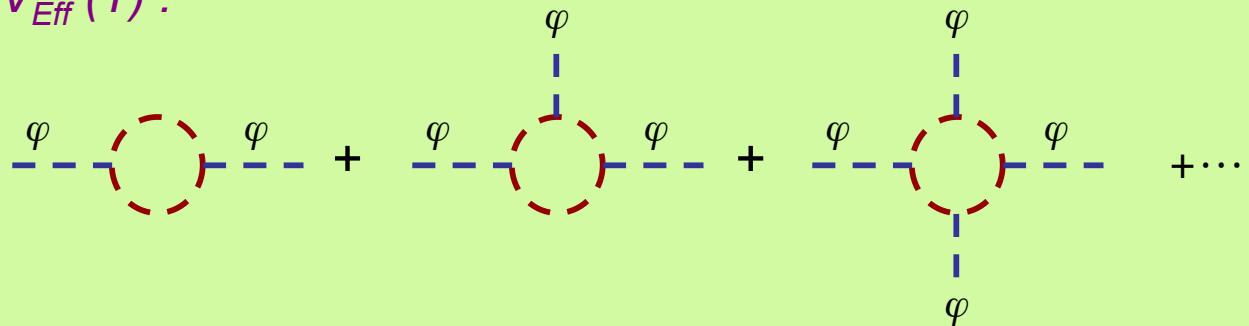


*Increasing  $m_h$*   $\longrightarrow$

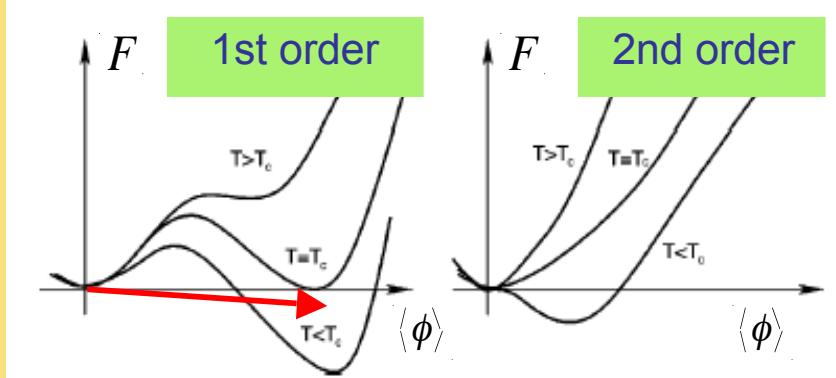
# EW Phase Transition: New Scalars & CPV



$V_{Eff}(T) :$



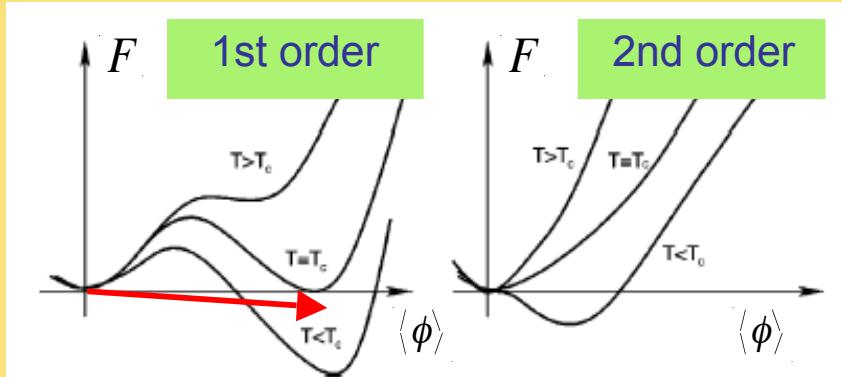
# EW Phase Transition: New Scalars & CPV



Increasing  $m_h$   $\longrightarrow$

$\longleftarrow$  New scalars

# EW Phase Transition: New Scalars & CPV



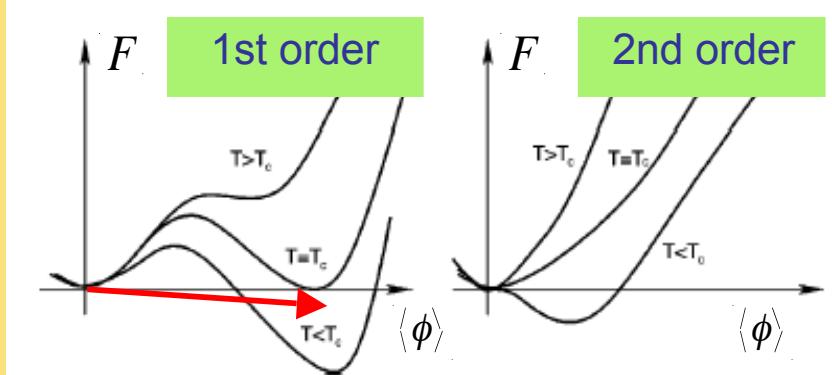
"Strong" 1<sup>st</sup> order EWPT

Increasing  $m_h$   $\longrightarrow$

$\longleftarrow$  New scalars

Baryogenesis  
Gravity Waves  
Scalar DM  
LHC Searches

# EW Phase Transition: New Scalars & CPV



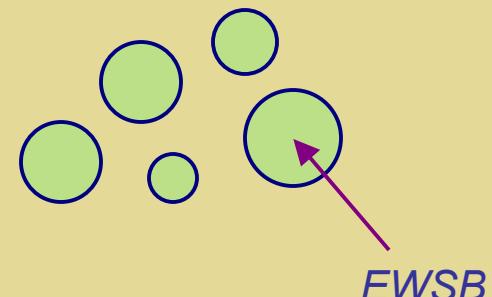
Increasing  $m_h$   $\longrightarrow$

$\longleftarrow$  New scalars

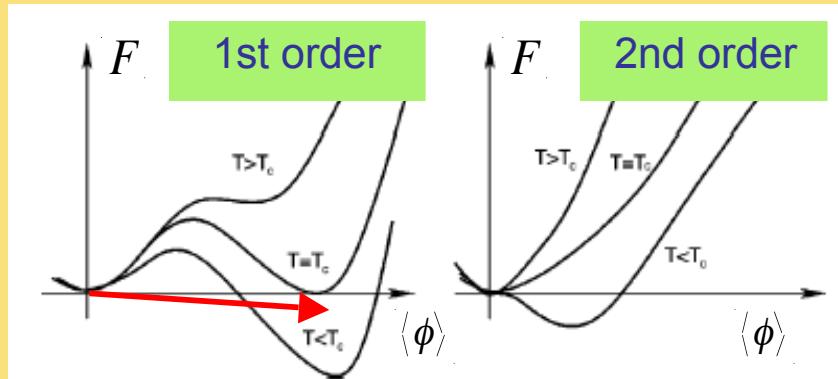
Baryogenesis  
Gravity Waves  
Scalar DM  
LHC Searches

“Strong” **1<sup>st</sup> order EWPT**

Bubble nucleation



# EW Phase Transition: New Scalars & CPV

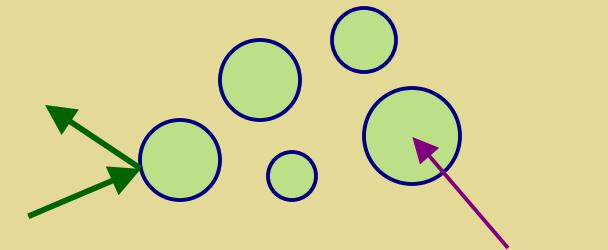


Increasing  $m_h$   $\longrightarrow$   
 $\longleftarrow$  New scalars

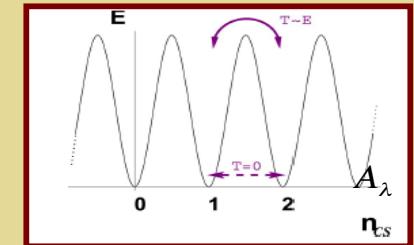
Baryogenesis  
 Gravity Waves  
 Scalar DM  
 LHC Searches

“Strong” **1<sup>st</sup> order EWPT**

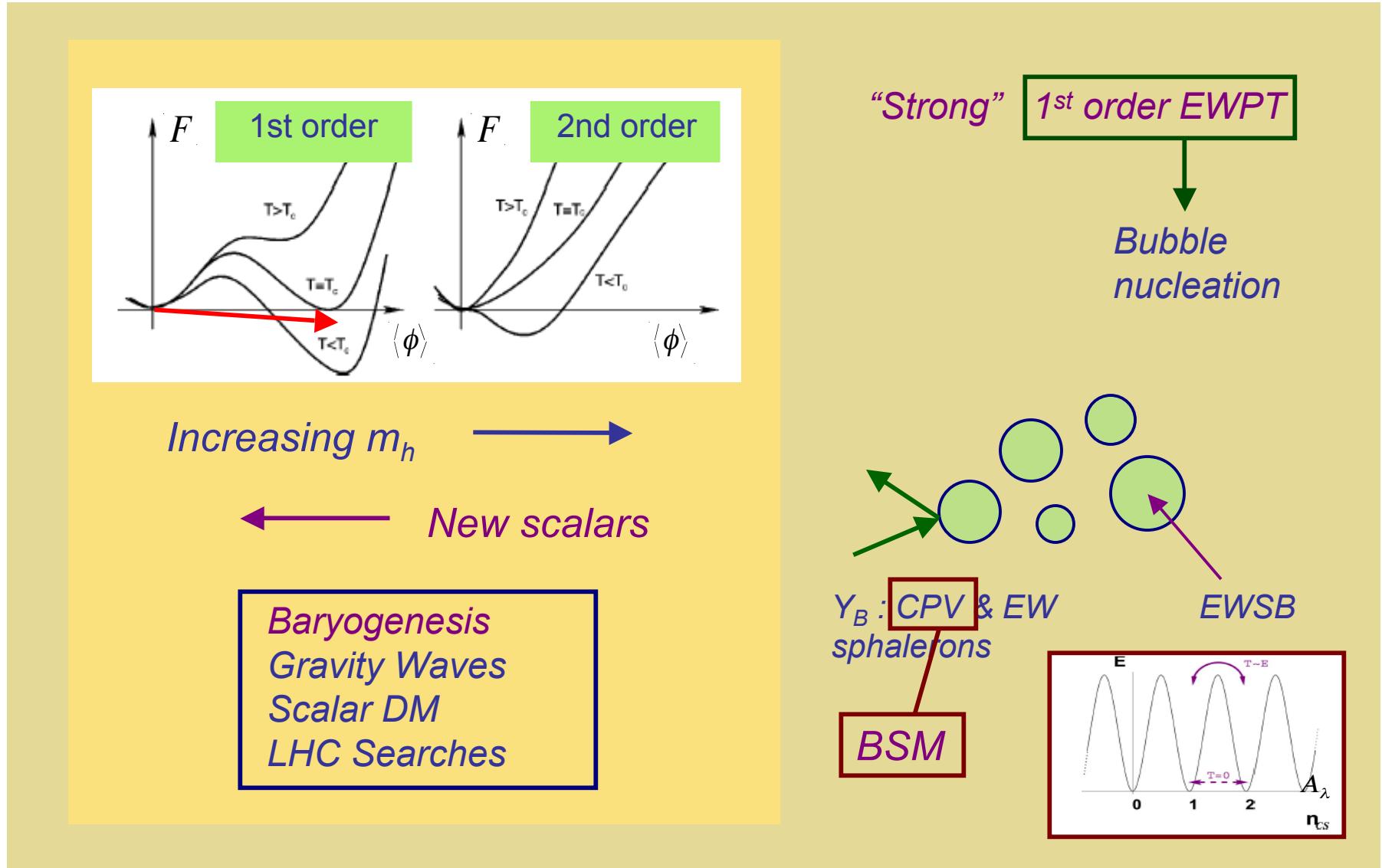
Bubble  
nucleation



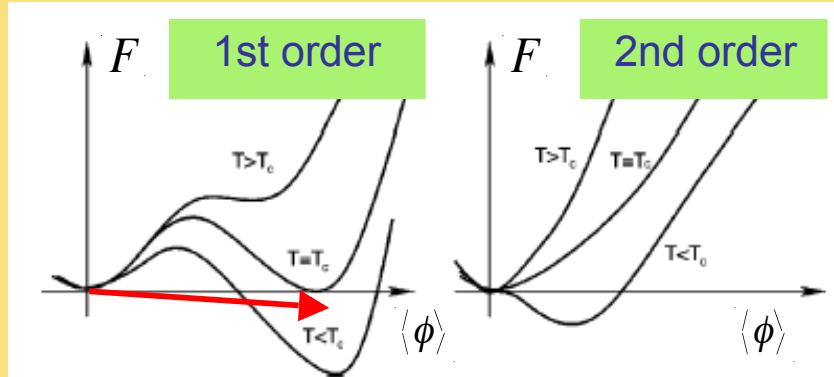
$Y_B$  : CPV & EW sphalerons      EWSB



# EW Phase Transition: New Scalars & CPV



# EW Phase Transition: New Scalars & CPV

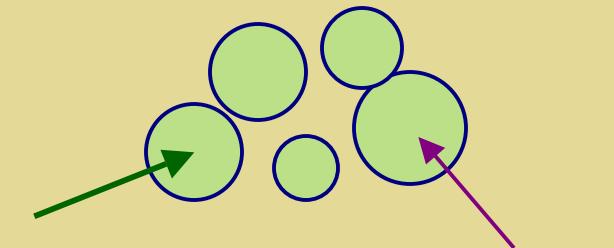


*Increasing  $m_h$*  → ← *New scalars*

*Baryogenesis*  
*Gravity Waves*  
*Scalar DM*  
*LHC Searches*

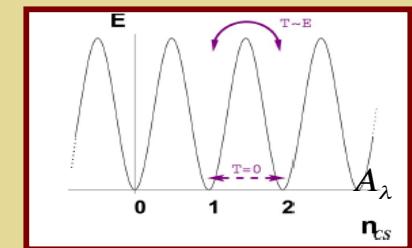
“Strong” **1<sup>st</sup> order EWPT**

*Bubble nucleation*

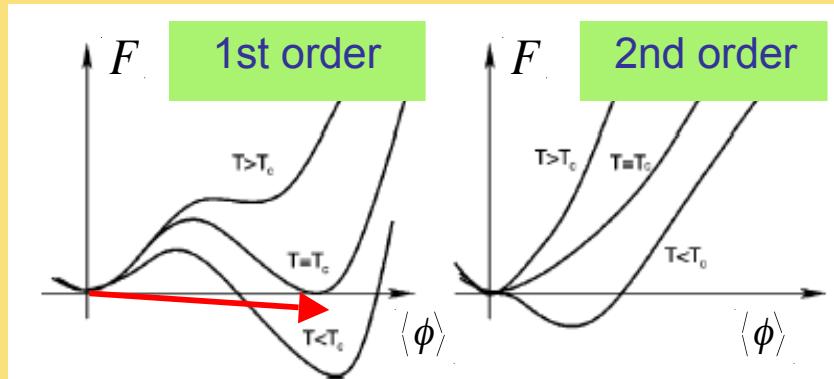


$Y_B$  : diffuses  
into interiors

EWSB



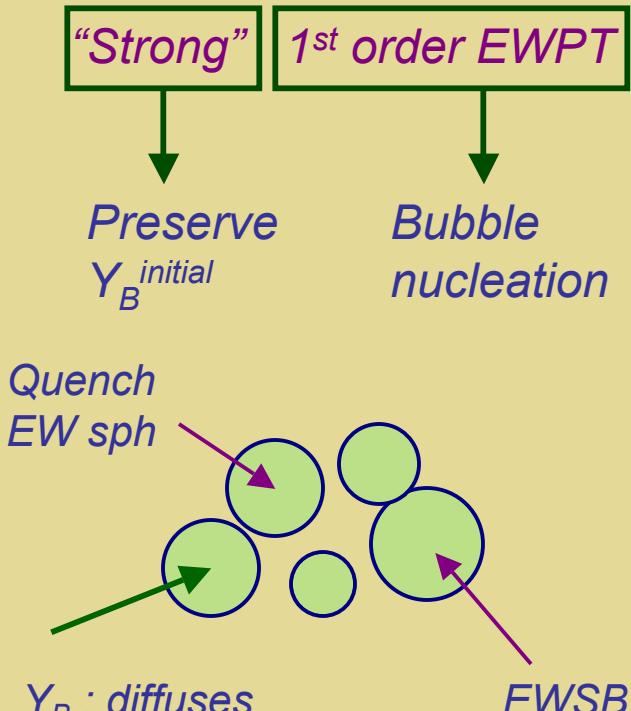
# EW Phase Transition: New Scalars & CPV



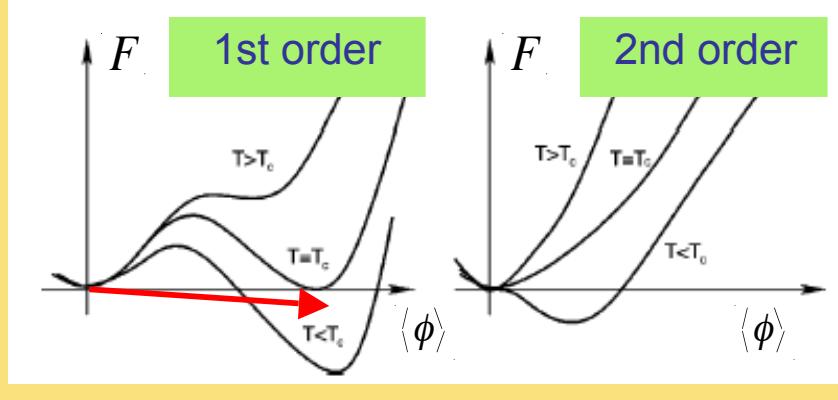
Increasing  $m_h$   $\longrightarrow$

$\longleftarrow$  New scalars

Baryogenesis  
Gravity Waves  
Scalar DM  
LHC Searches



# *EW Phase Transition: St'd Model*

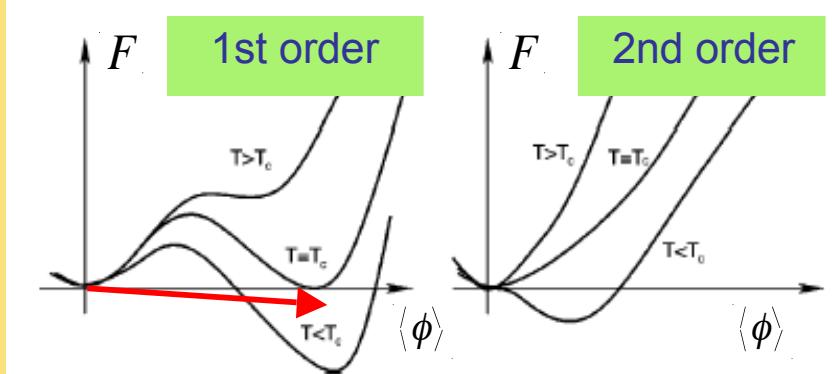


*Lattice: Endpoint*

Lattice	Authors	$M_h^C$ (GeV)
4D Isotropic	[76]	$80 \pm 7$
4D Anisotropic	[74]	$72.4 \pm 1.7$
3D Isotropic	[72]	$72.3 \pm 0.7$
3D Isotropic	[70]	$72.4 \pm 0.9$

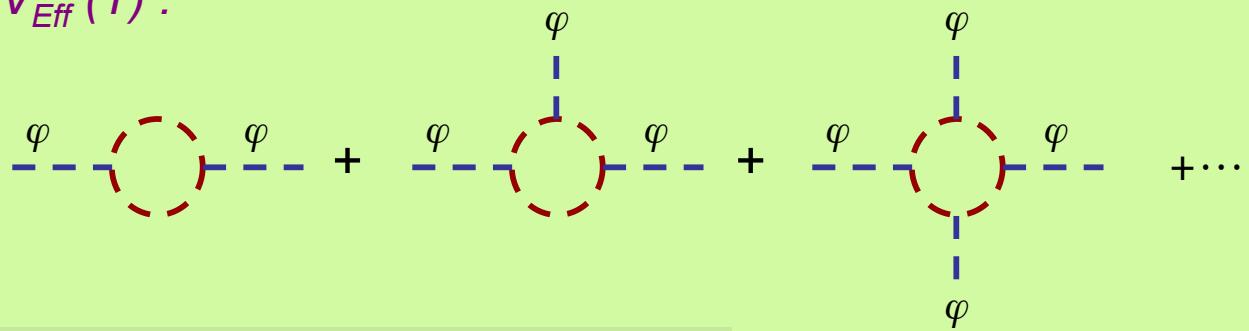
*S'td Model: 1<sup>st</sup> order EWPT  
requires light Higgs*

# EW Phase Transition: New Scalars & CPV



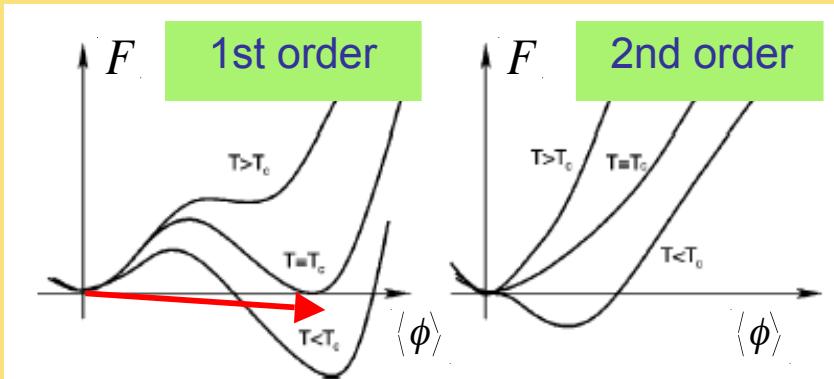
MSSM

$V_{Eff}(T) :$



Light RH stop w/ special  $M_{\tilde{t}_R}^2$

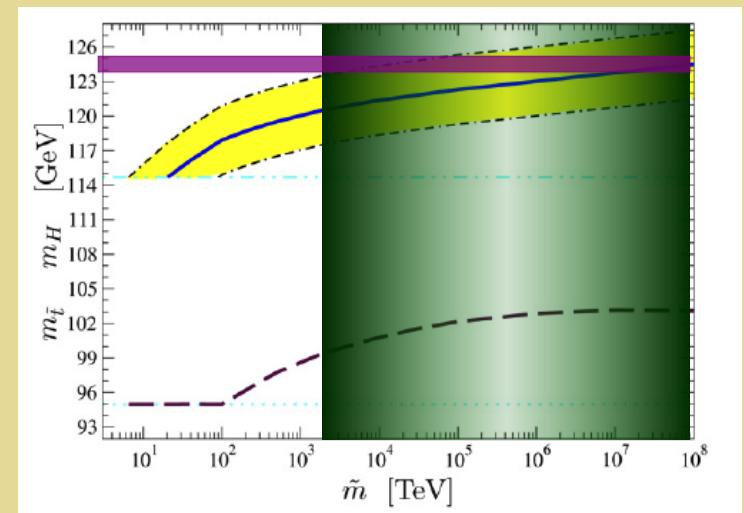
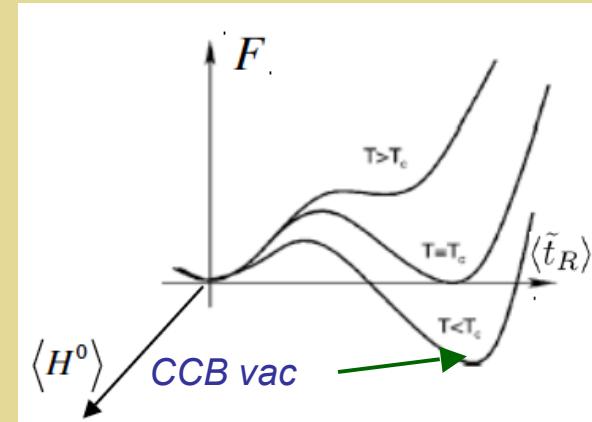
# EW Phase Transition: MSSM



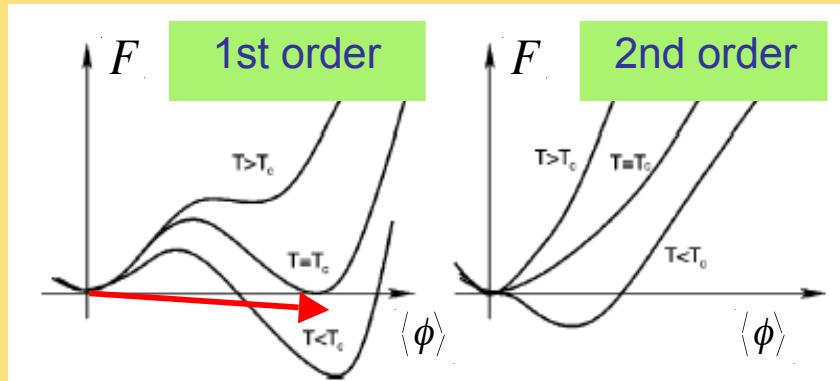
*Increasing  $m_h$*  →  
← *New scalars*

MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable



# EW Phase Transition: New Scalars

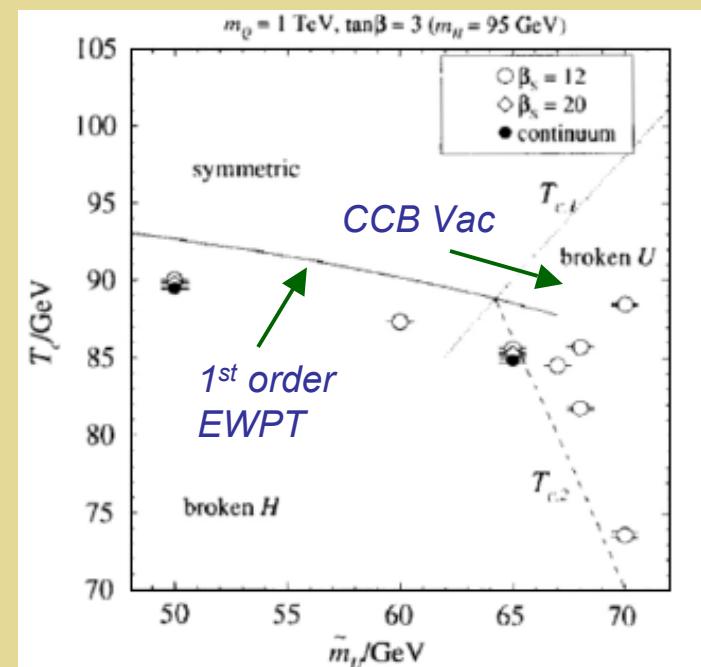


*Increasing  $m_h$*  →  
← *New scalars*

MSSM: Light RH stops

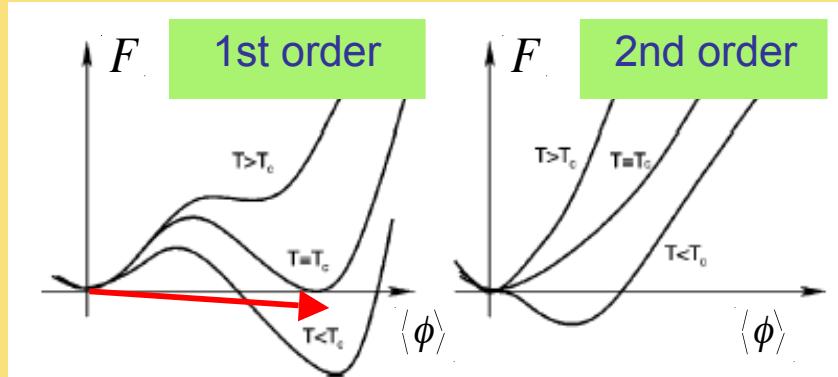
PT: Carena et al, ...

Lattice: Laine, Rummukainen



Decreasing RH stop mass →

# EW Phase Transition: Higgs Portal



Increasing  $m_h$   $\longrightarrow$   
 $\longleftarrow$  New scalars

$$\mathcal{O}_4 = \lambda_{\phi H} \phi^\dagger \phi H^\dagger H + \dots$$

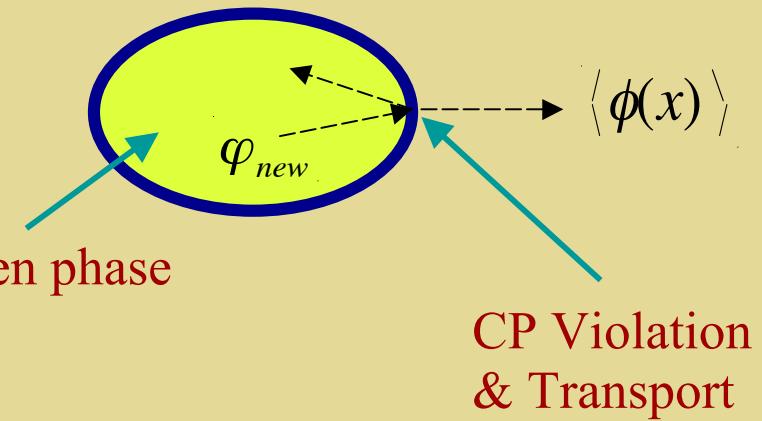
- Renormalizable
- $\phi$ : singlet or charged under  $SU(2)_L \times U(1)_Y$
- Generic features of full theory (NMSSM, GUTS...)
- More robust vacuum stability
- Novel patterns of SSM

### ***III. CPV: EDMs & Flavor***

# *CPV in EW Baryogenesis*

Unbroken phase

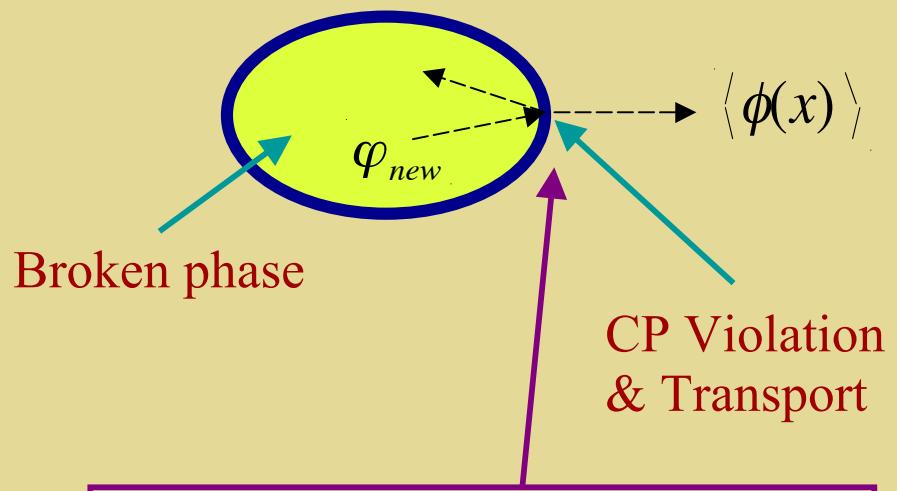
Broken phase



CP Violation  
& Transport

# *CPV in EW Baryogenesis*

Unbroken phase



*Transport: A Competition R-M et al*

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C}) \quad CPV$$

$$\Gamma(A + B \leftrightarrow C) \quad Chem\ Eq$$

$$\Gamma(A + B \leftrightarrow A + B) \quad Diffusion$$

# **Quantum Kinetic Equations**

## **CPV Sources**

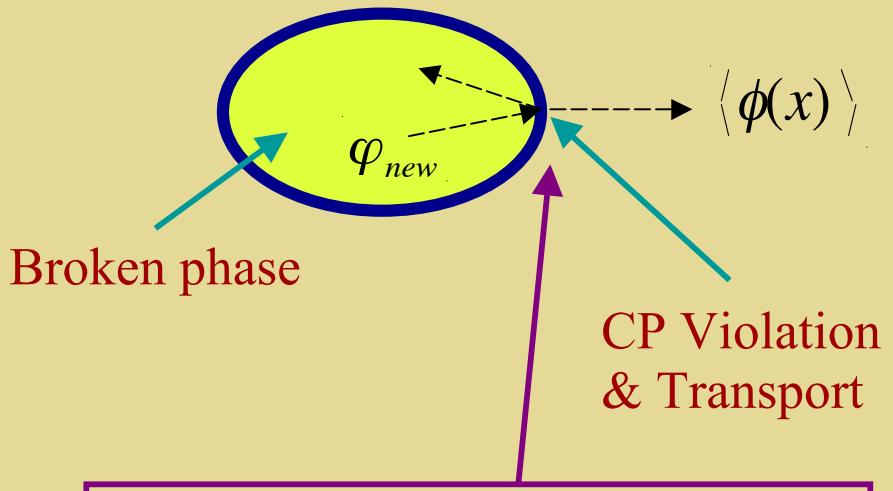
*Kinetic eq (approx) in Wigner space:*

$$2k \cdot \partial_X G^<(k, X) = -i[M^2(X), G^<(k, X)] - 2[k \cdot \Sigma, G^<(k, X)] + \Lambda[G(k, X)]$$

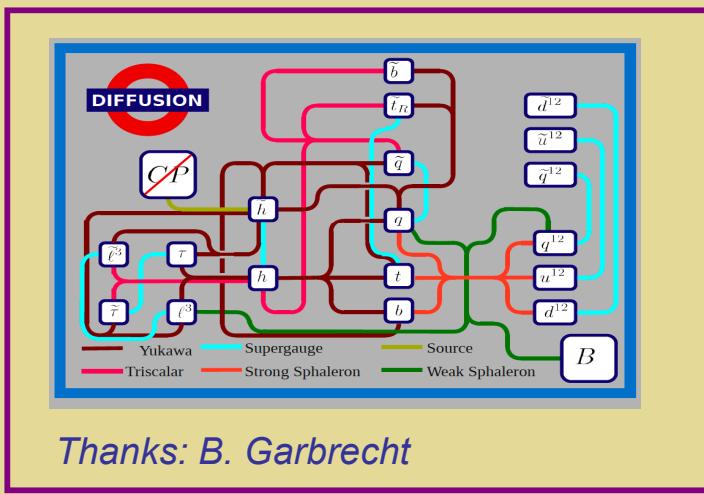
*The  $G(k, X)$  are matrices in flavor space*

# CPV in EW Baryogenesis

Unbroken phase



MSSM:  $\sim 30$  Coupled Eqns



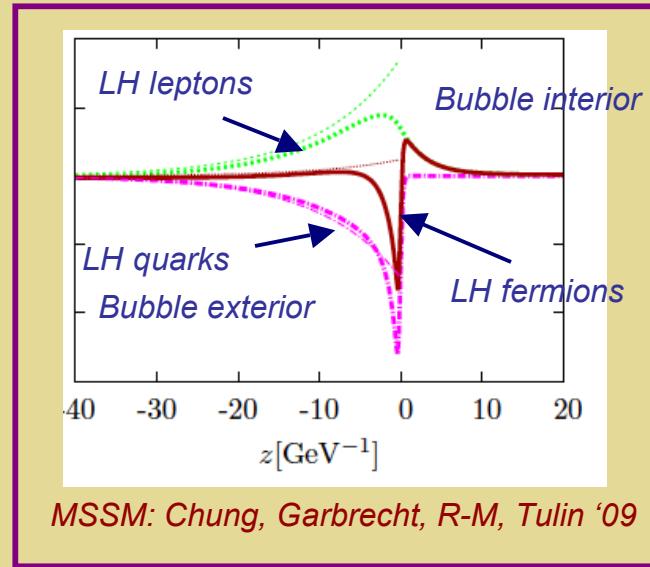
Transport: A Competition R-M et al

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C}) \quad CPV$$

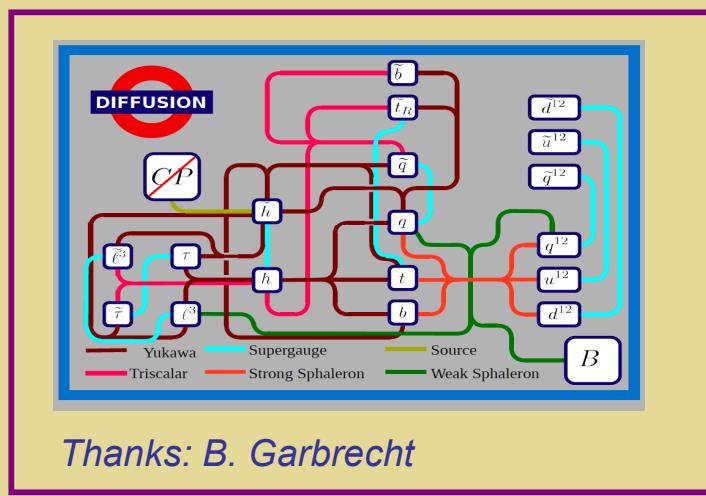
$$\Gamma(A + B \leftrightarrow C) \quad Chem\ Eq$$

$$\Gamma(A + B \leftrightarrow A + B) \quad Diffusion$$

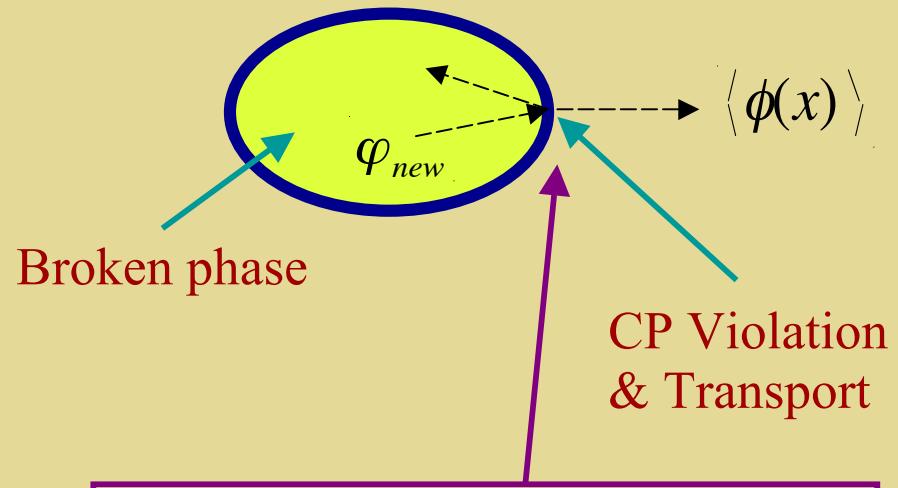
# CPV in EW Baryogenesis



MSSM:  $\sim 30$  Coupled Eqns



Unbroken phase



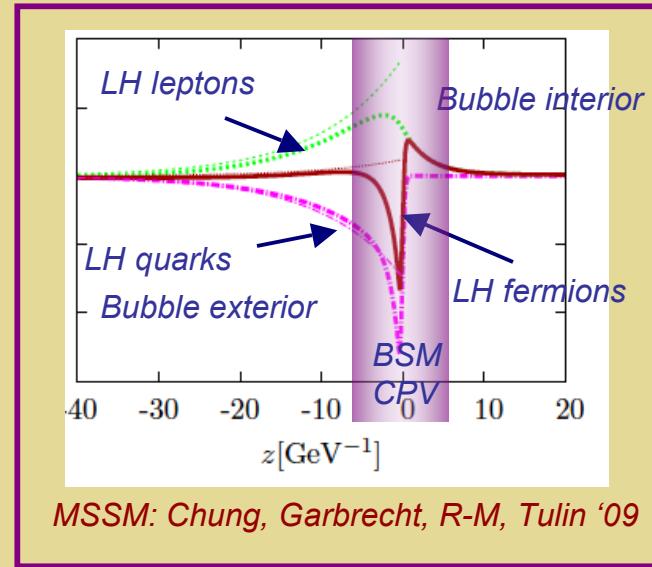
Transport: A Competition R-M et al

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C}) \quad \text{CPV}$$

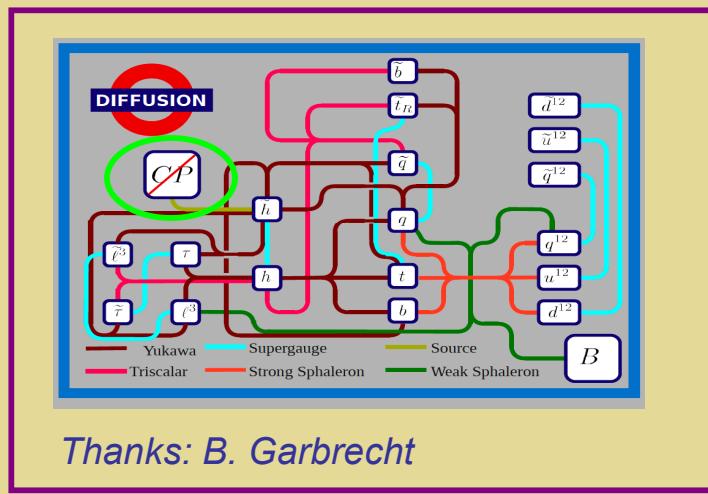
$$\Gamma(A + B \leftrightarrow C) \quad \text{Chem Eq}$$

$$\Gamma(A + B \leftrightarrow A + B) \quad \text{Diffusion}$$

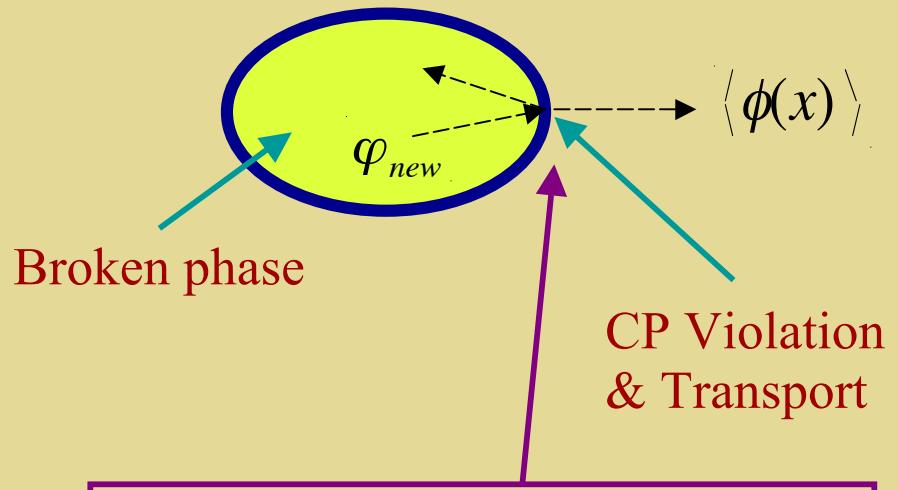
# CPV in EW Baryogenesis



MSSM:  $\sim 30$  Coupled Eqns



Unbroken phase



Transport: A Competition R-M et al

$$\Gamma(A + B \rightarrow C) \neq \Gamma(\bar{A} + \bar{B} \rightarrow \bar{C}) \quad \text{CPV}$$

$$\Gamma(A + B \leftrightarrow C) \quad \text{Chem Eq}$$

$$\Gamma(A + B \leftrightarrow A + B) \quad \text{Diffusion}$$

# Illustrative Study: MSSM

*Chargino Mass Matrix*

$$\mathbf{M}_C = \begin{pmatrix} CPV \\ M_2 & m_w \sqrt{2} \cos \beta \\ m_w \sqrt{2} \sin \beta & \mu \end{pmatrix}$$

*Neutralino Mass Matrix*

$$\mathbf{M}_N = \begin{pmatrix} M_1 & 0 & -m_z \cos \beta \sin \theta_W & m_z \cos \beta \cos \theta_W \\ 0 & M_2 & m_z \sin \beta \sin \theta_W & -m_z \sin \beta \cos \theta_W \\ -m_z \cos \beta \sin \theta_W & m_z \cos \beta \cos \theta_W & 0 & -\mu \\ m_z \sin \beta \sin \theta_W & -m_z \sin \beta \cos \theta_W & -\mu & 0 \end{pmatrix}$$

$\sin \phi_\mu = \text{Arg}(\mu M_1 b^*) = \text{Arg}(\mu M_2 b^*)$

# Illustrative Study: MSSM

Chargino Mass Matrix

$$M_C = \begin{pmatrix} M_2 & m_w \sqrt{2} \cos \beta \\ m_w \sqrt{2} \sin \beta & \mu \end{pmatrix}$$

CPV

$\frac{g v_d(x)}{\sqrt{2}}$

$\frac{g v_u(x)}{\sqrt{2}}$

$T \sim T_{EW}$ : scattering  
of  $\tilde{H}, \tilde{W}$  from  
background field

$T \ll T_{EW}$ : mixing  
of  $\tilde{H}, \tilde{W}$  to  $\tilde{\chi}^+, \tilde{\chi}^0$

Neutralino Mass Matrix

$$M_N = \begin{pmatrix} M_1 & 0 & -m_z \cos \beta \sin \theta_W & m_z \cos \beta \cos \theta_W \\ 0 & M_2 & m_z \sin \beta \sin \theta_W & -m_z \sin \beta \cos \theta_W \\ -m_z \cos \beta \sin \theta_W & m_z \cos \beta \cos \theta_W & 0 & -\mu \\ m_z \sin \beta \sin \theta_W & -m_z \sin \beta \cos \theta_W & -\mu & 0 \end{pmatrix}$$

$$\sin \phi_\mu = \text{Arg}(\mu M_1 b^*) = \text{Arg}(\mu M_2 b^*)$$

# Illustrative Study: MSSM

*Chargino Mass Matrix*

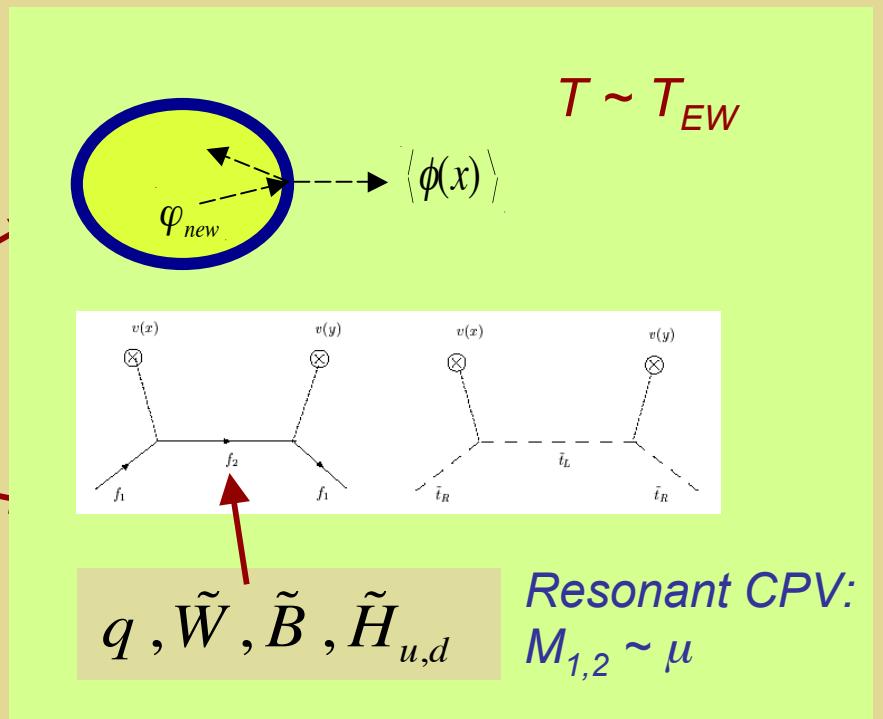
$$M_C = \begin{pmatrix} M_2 & m_w \sqrt{2} \cos \beta \\ m_w \sqrt{2} \sin \beta & \mu \end{pmatrix}$$

CPV

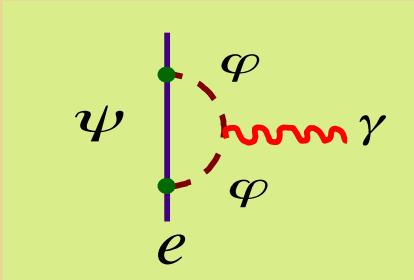
*Neutralino Mass Matrix*

$$M_N = \begin{pmatrix} M_1 & 0 & 0 & -\mu \\ 0 & M_2 & m_z \sin \beta \sin \theta_W & m_z \sin \beta \sin \theta_W \\ -m_z \cos \beta \sin \theta_W & m_z \cos \beta \cos \theta_W & -m_z \sin \beta \sin \theta_W & 0 \\ m_z \sin \beta \sin \theta_W & -m_z \sin \beta \sin \theta_W & 0 & 0 \end{pmatrix}$$

$$\sin \phi_\mu = \text{Arg}(\mu M_1 b^*) = \text{Arg}(\mu M_2 b^*)$$



# EDM Probes: EWB Implications

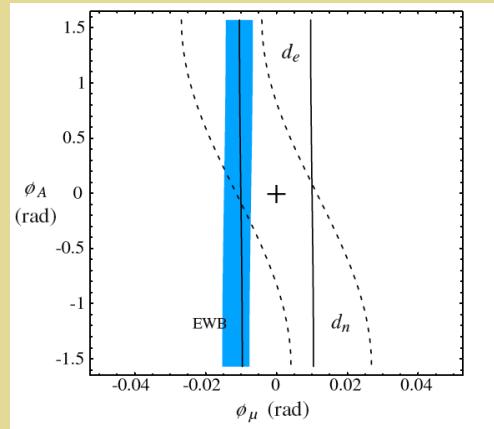


$$\sin\phi_{CP} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

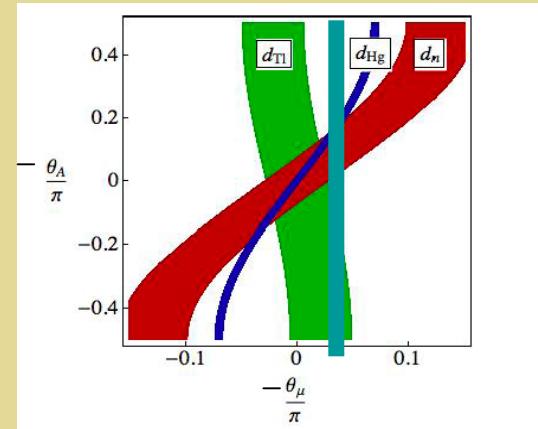
$$M < 500 \text{ GeV} \rightarrow \sin\phi_{CP} < 10^{-2}$$

*Universal  
gaugino  
phases*

$\text{Arg}(\mu M_i b^*) =$   
 $\text{Arg}(\mu M_j b^*)$

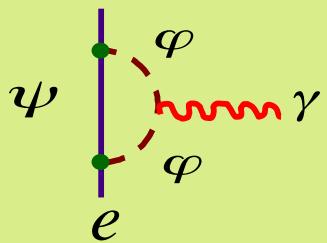


Cirigliano, R-M, Tulin, Lee '06



Ritz CIPANP 09 +  
Cirigliano, R-M, Tulin, Lee '06

# *EDM Probes: EWB Implications*



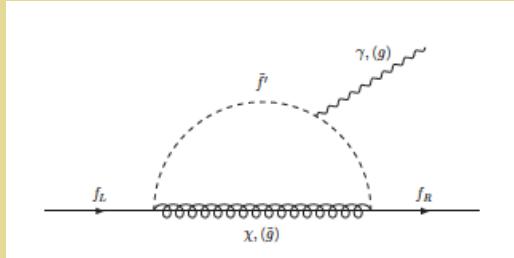
$$\sin\phi_{CP} \sim 1 \rightarrow M > 5000 \text{ GeV}$$

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*Viable EWB & CPV:*

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

# *EDM Probes: EWB Implications*

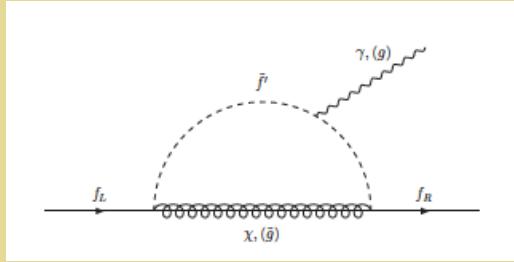


*Heavy sfermions: LHC  
consistent & suppress  
1-loop EDMs*

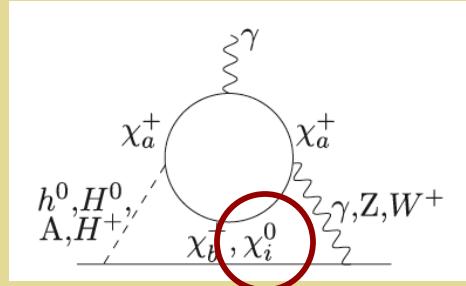
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*Sub-TeV EWB-inos: LHC & EWB -  
viable but non-universal phases*

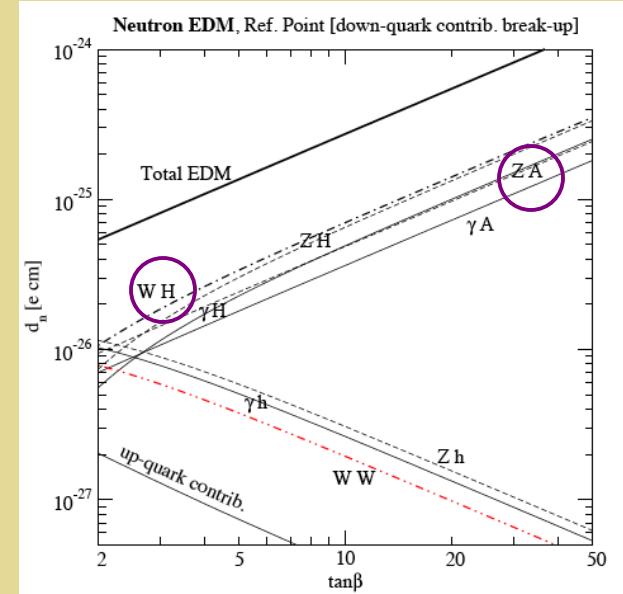
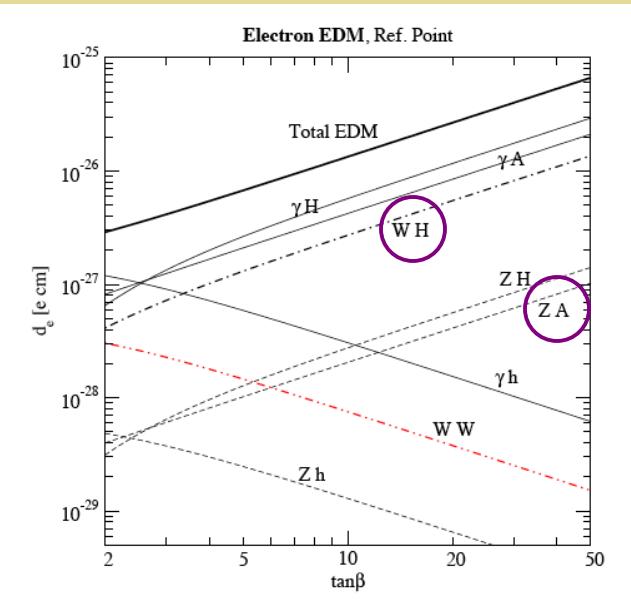
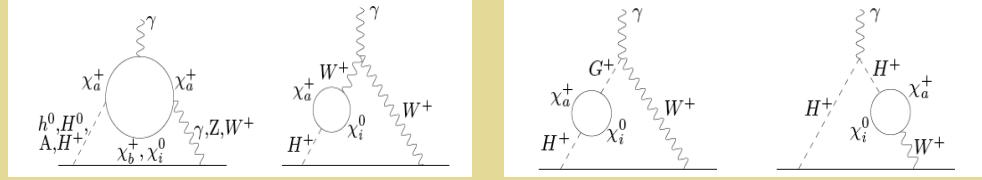
*Viable EWB & CPV:*

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# Heavy Sfermions: Two-loop EDMs

One loop EDMs suppressed in heavy sfermion regime

Li, Profumo, R-M: PRD 78:075009 (2008)



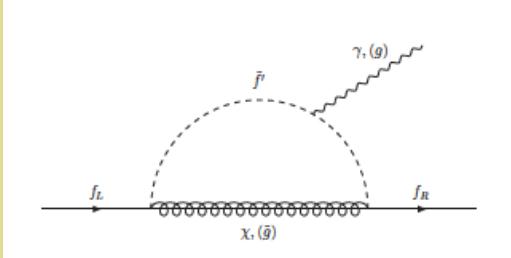
$$m_A=300 \text{ GeV}, \mu=300 \text{ GeV}, M_2=2M_1=290 \text{ GeV}$$

$$d_n = \sum_K H_k(g_i, M_i) \sin \phi_k$$

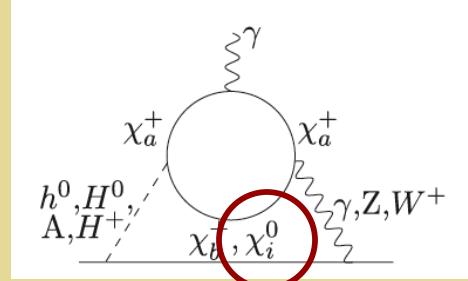


WH Loops dominate for neutron & comparable to  $\gamma H$ ,  $\gamma A$  for electron

# *EDM Probes: EWB Implications*

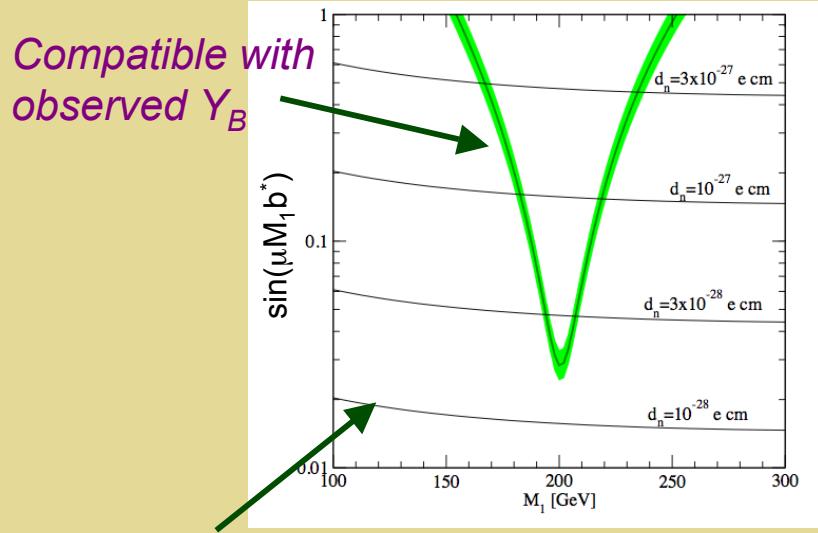


*Heavy sfermions: LHC  
consistent & suppress  
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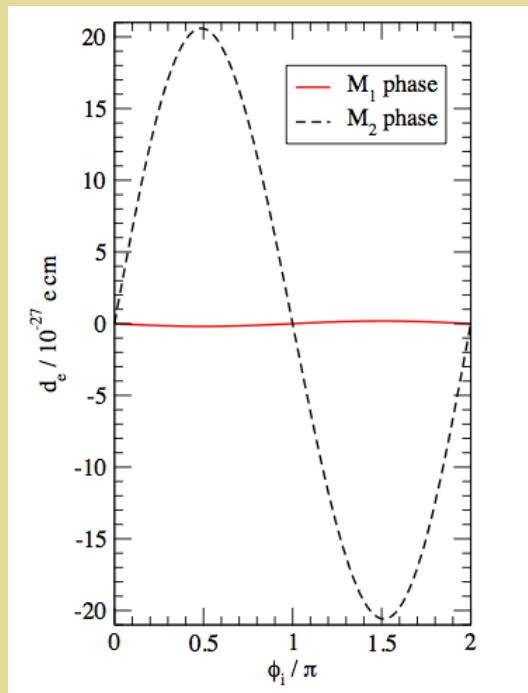
- Viable EWB & CPV:*
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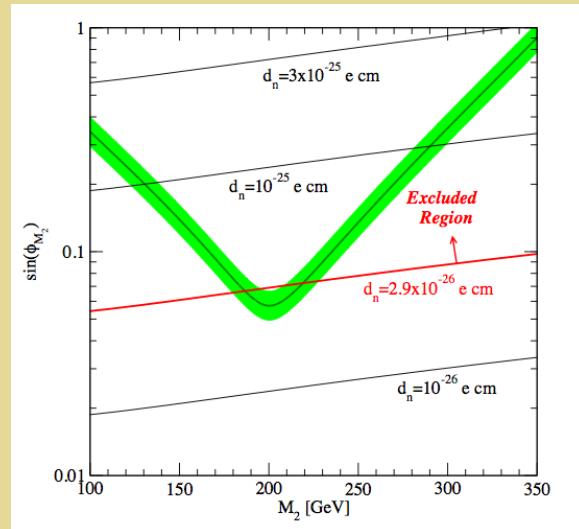
*Li, Profumo, RM*

# EDMs & EWB: 2 Loop Regime

$\text{Arg}(\mu M_1 b^*) \neq \text{Arg}(\mu M_2 b^*)$

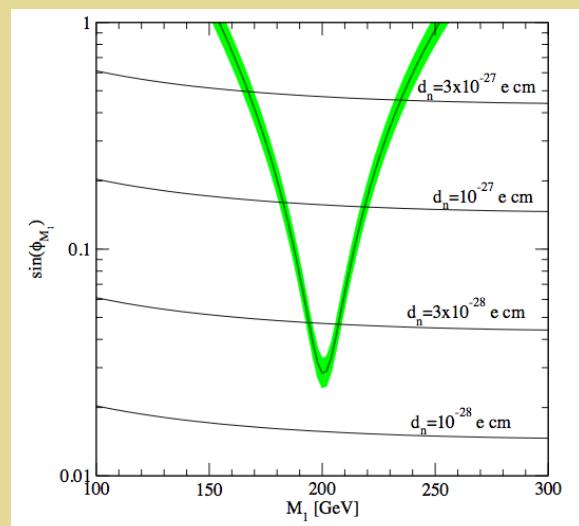


Weak dependence of  
 $d_e$ ,  $d_n$  on  $\text{Arg}(\mu M_1 b^*)$



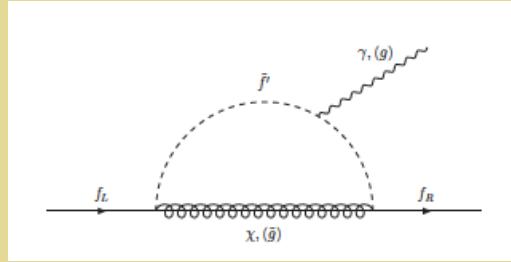
Li, Profumo, R-M: PLB  
673:95 (2009)

Res  $\chi^+$  EWB not  
compatible with  $d_n$

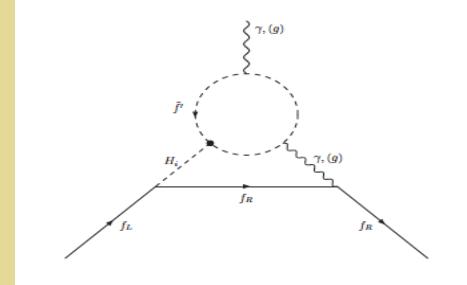


Res & non-res  $\chi^0$   
EWB compatible  
with future  $d_n$ , light  
 $m_A$ , & moderate  
 $\tan\beta$

# EDM Probes: EWB Implications

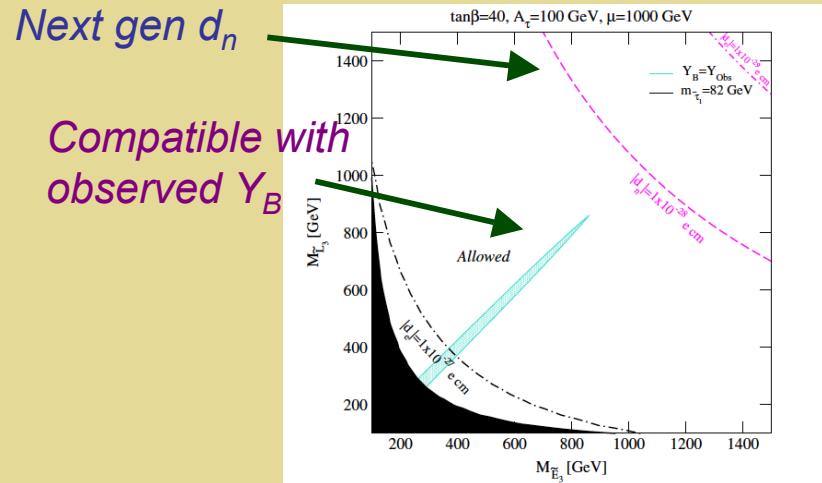


*Light staus: LHC consistent & suppress 1-loop EDMs*



*No CEDM (<sup>199</sup>Hg): EWB-viable but  $m_H \rightarrow$  New scalars for EWPT*

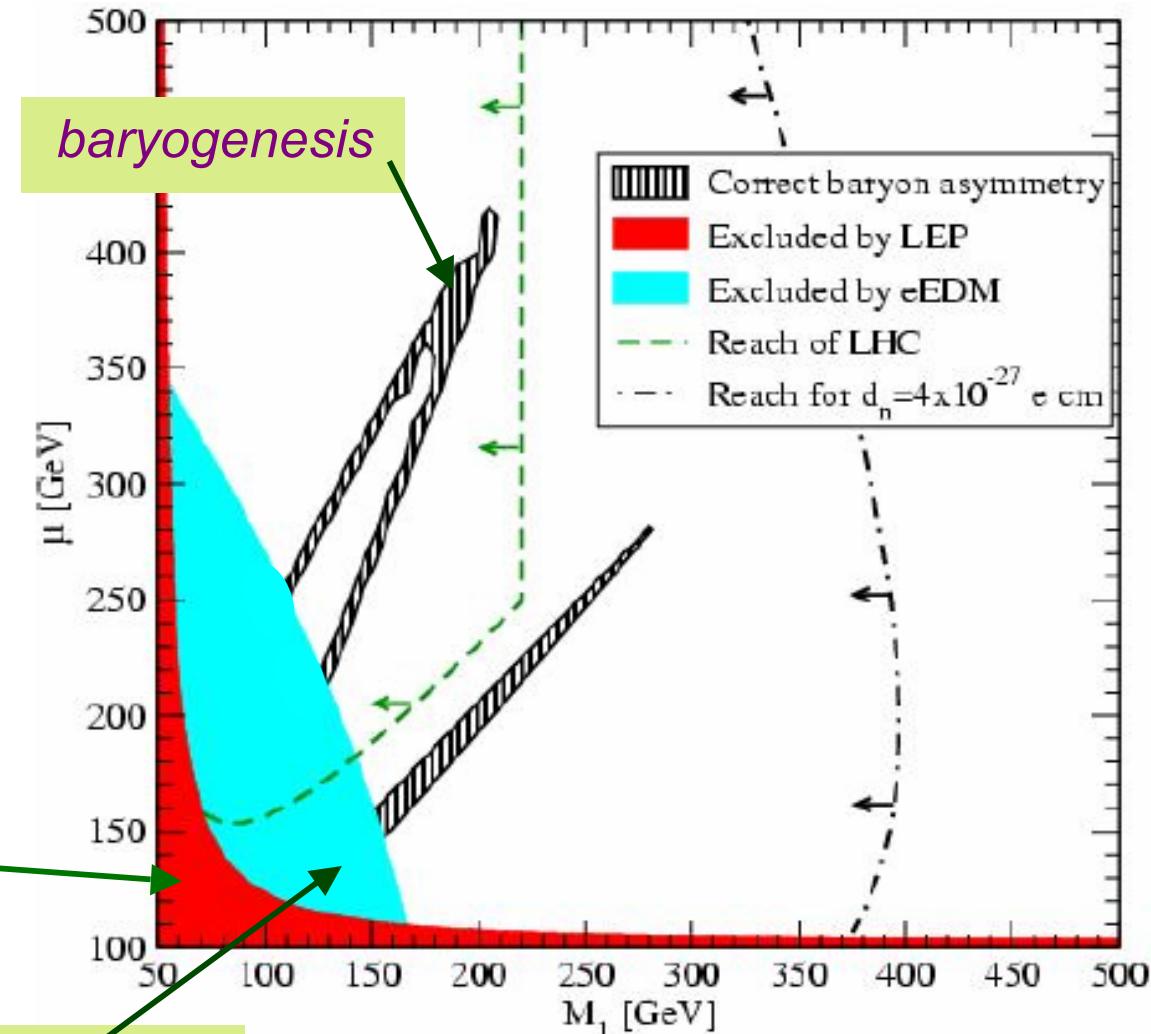
- Viable EWB & CPV:**
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*Kozaczuk, Wainwright, Profumo, RM*

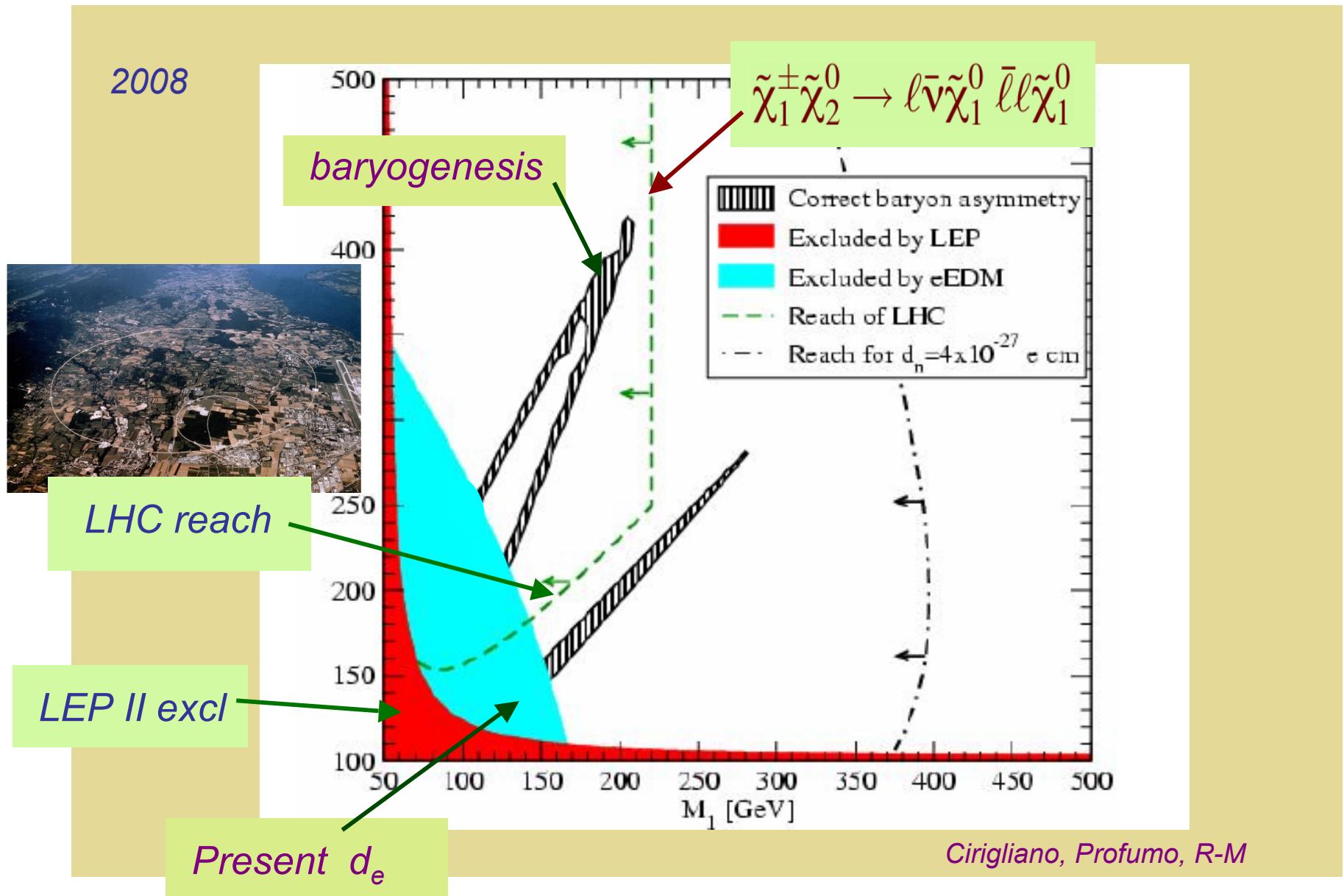
# MSSM Baryogenesis: EDMs & LHC

2008

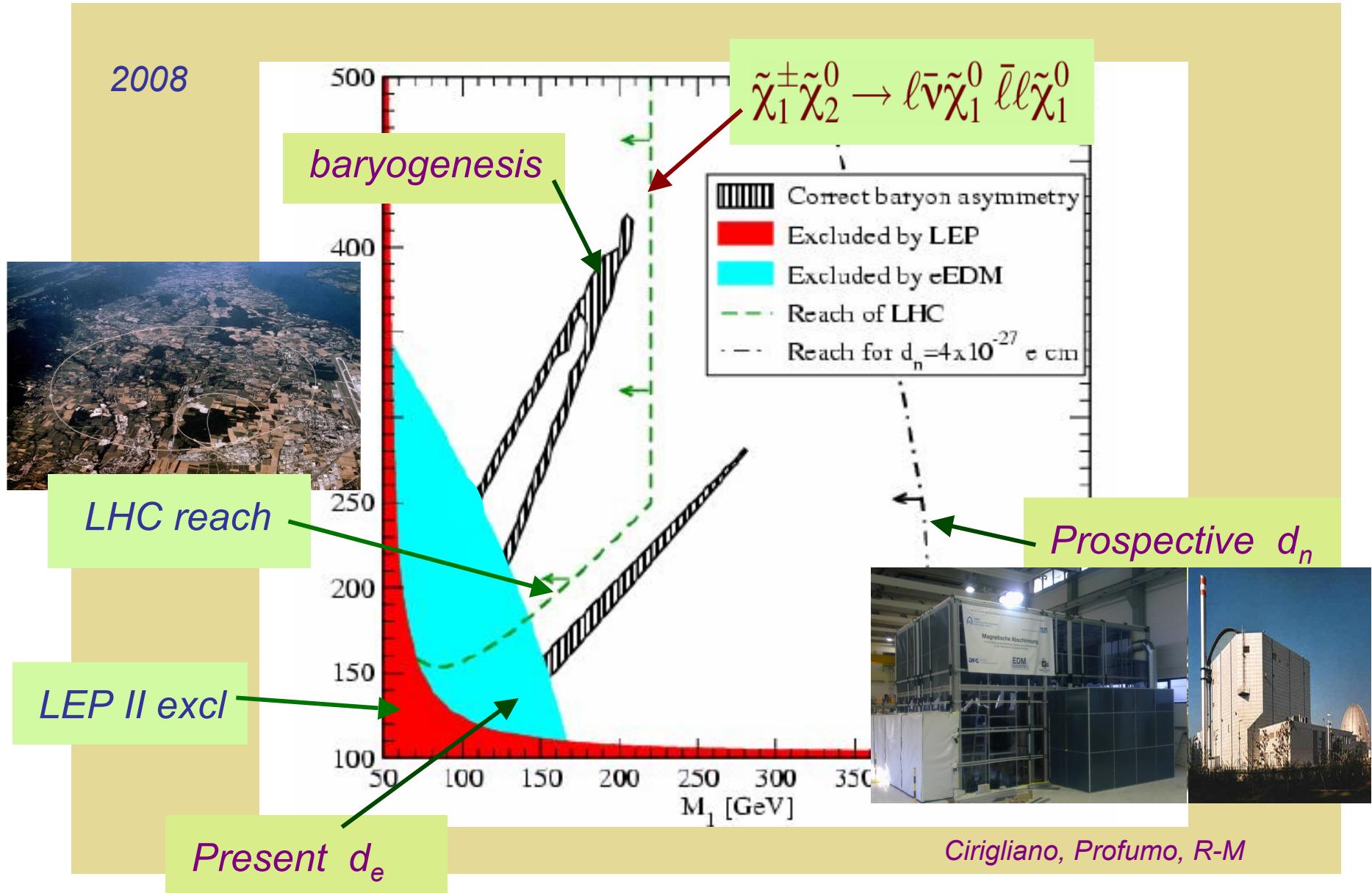


Cirigliano, Profumo, R-M

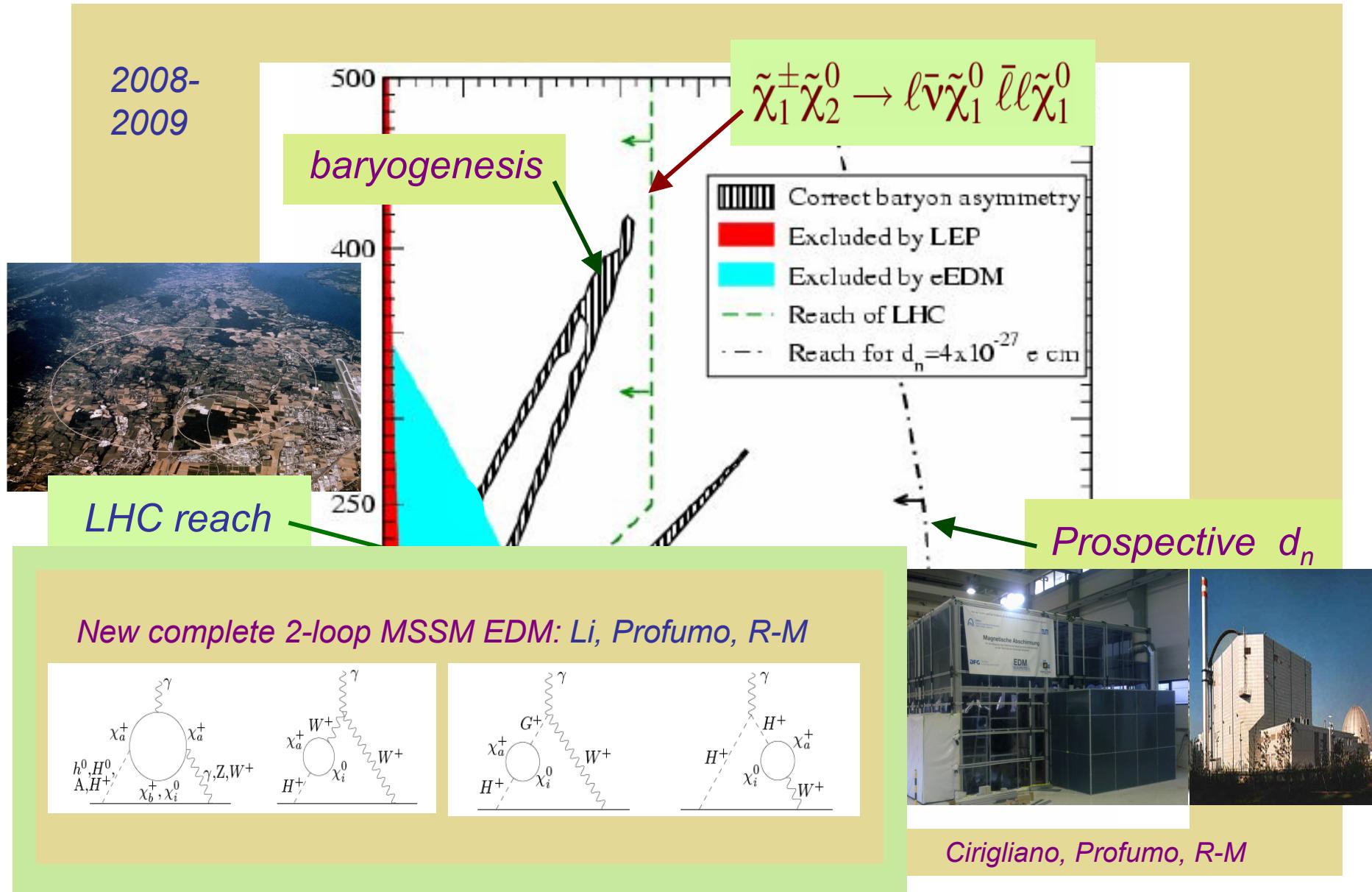
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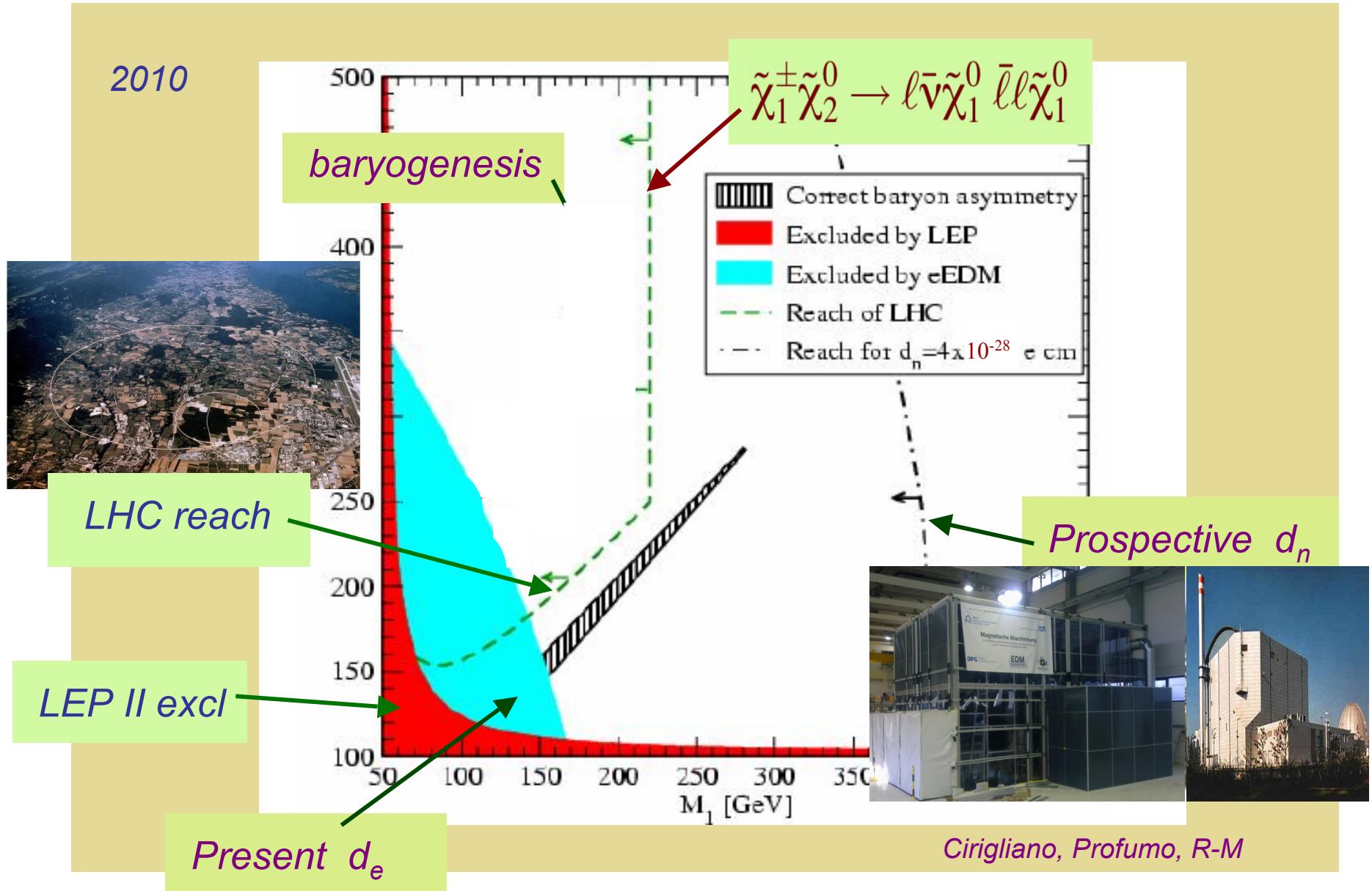
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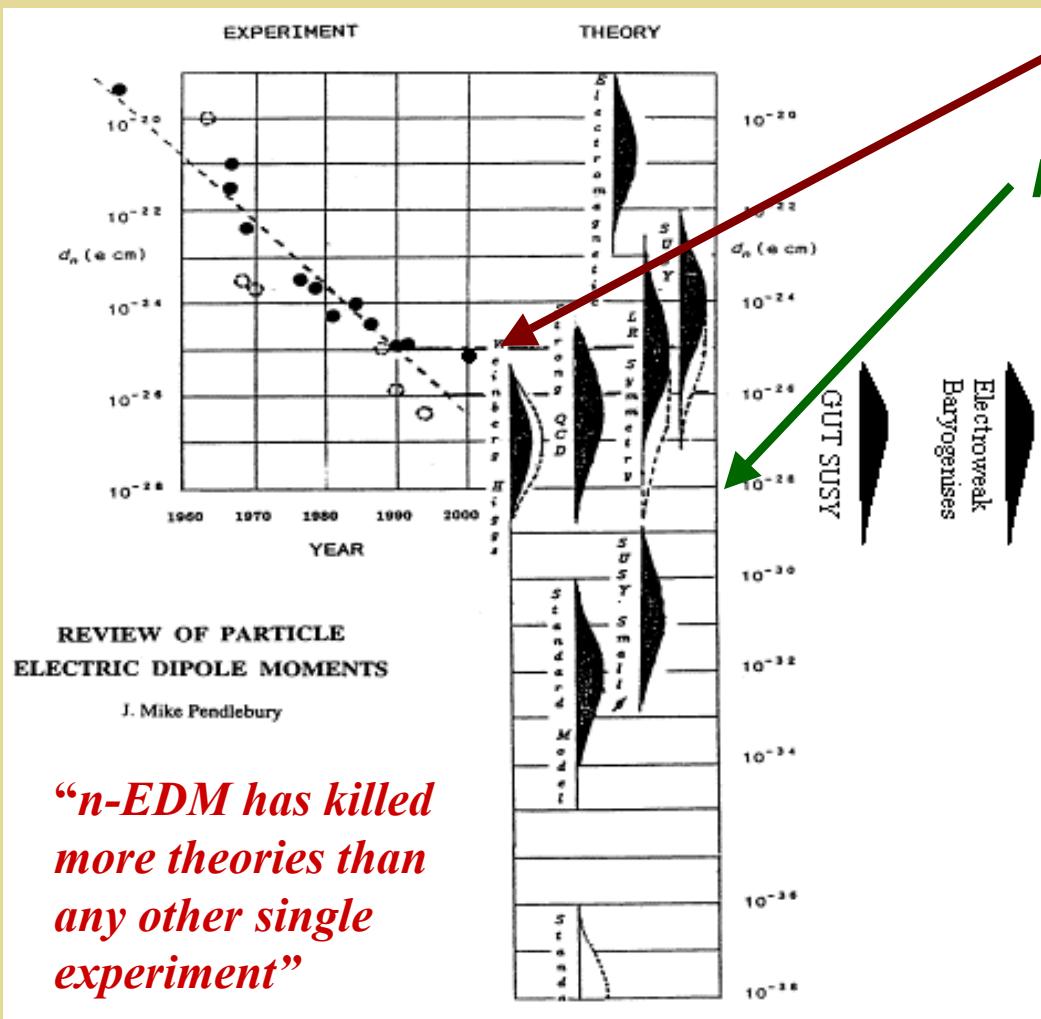
# MSSM Baryogenesis: EDMs & LHC



# MSSM Baryogenesis: EDMs & LHC



# *EDMs: What We May Learn*

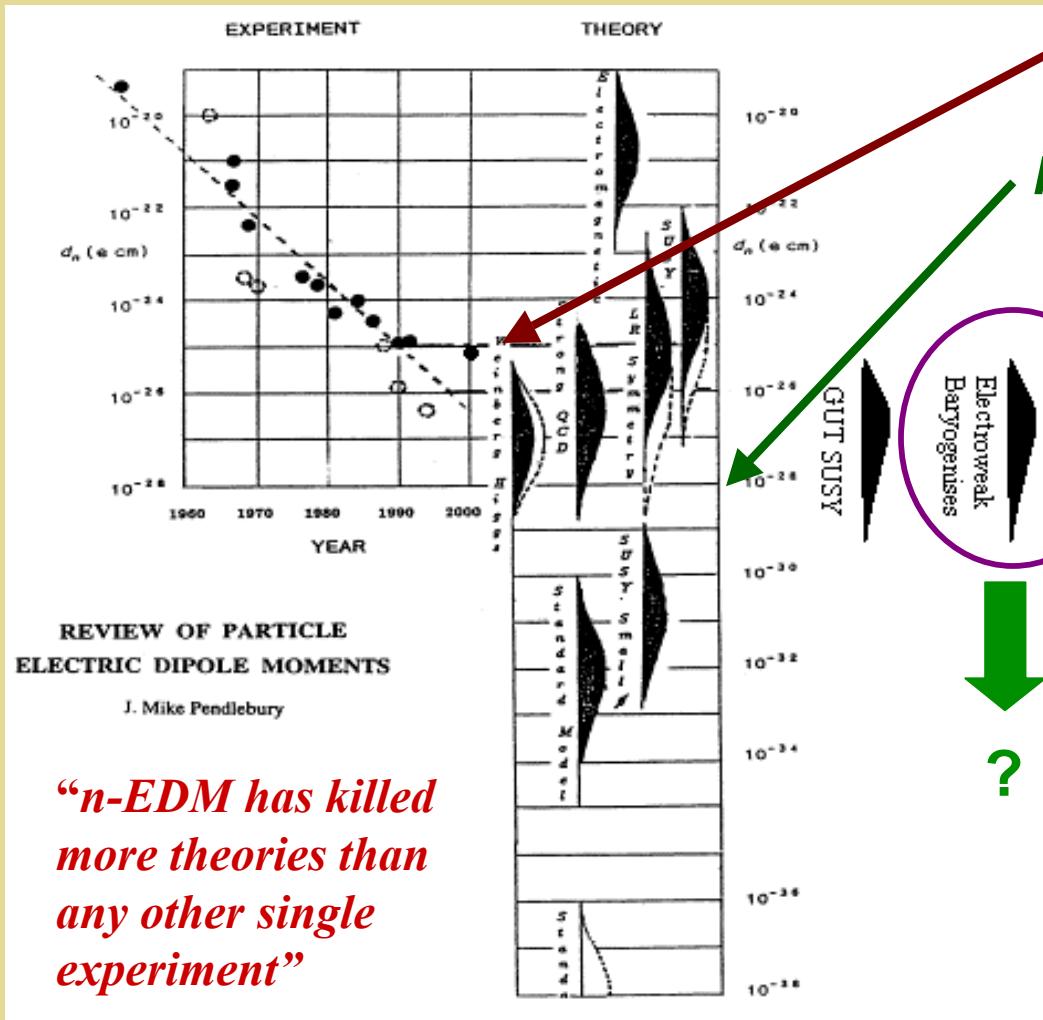


*Present n-EDM limit*

*Proposed n-EDM limit*

*Matter-Antimatter Asymmetry in the Universe:*

# EDMs: What We May Learn



Present  $n$ -EDM limit

Proposed  $n$ -EDM limit

GUT SUSY

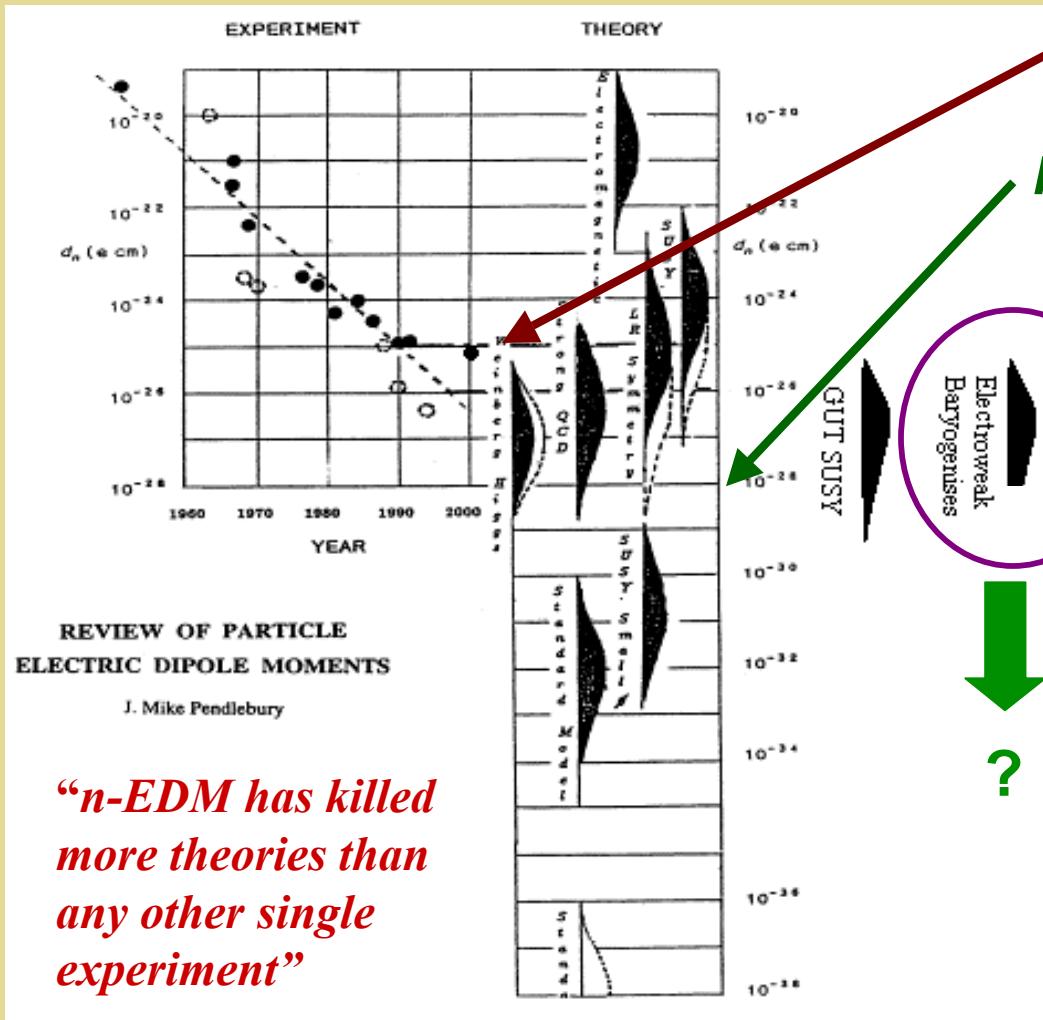
Electroweak Baryogenesis

?

Matter-Antimatter Asymmetry in the Universe:

Theory: How robust ?  
Can EDMs kill EW baryogenesis ?

# EDMs: What We May Learn



Present  $n$ -EDM limit

Proposed  $n$ -EDM limit

Electroweak Baryogenesis

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Matter-Antimatter Asymmetry in the Universe:  
MSSM

Theory: How robust ?  
Can EDMs kill EW baryogenesis ?

# *Flavored CPV & EWB*

*CPV & 2HDM*

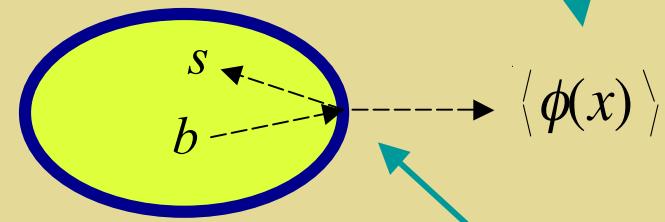
$$\begin{aligned}\mathcal{L} = & -y_{ij}^u \bar{Q}^i (\epsilon H_u^\dagger) u_R^j - y_{ij}^d \bar{Q}^i H_u d_R^j \\ & - \lambda_{ij}^u \bar{Q}^i H_d u_R^j - \lambda_{ij}^d \bar{Q}^i (\epsilon H_d^\dagger) d_R^j + h.c..\end{aligned}$$

*Liu, R-M, Shu '11;  
see also Tulin &  
Winslow '11; Cline  
et al '11*

*Viable EWB & CPV:*

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- *CPV is flavor non-diag*

Combination  
of  $H_{u,d}$  vevs



CP Violation  
& Transport

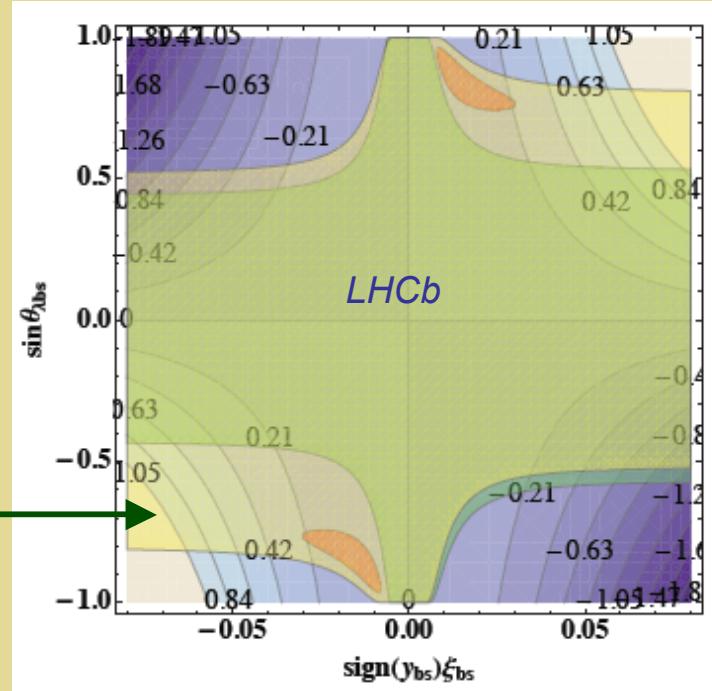
# Flavored CPV & EWB

CPV & 2HDM

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Liu, R-M, Shu '11;  
see also Tulin &  
Winslow '11; Cline  
et al '11

constant  $n_B / s$



Viable EWB & CPV:

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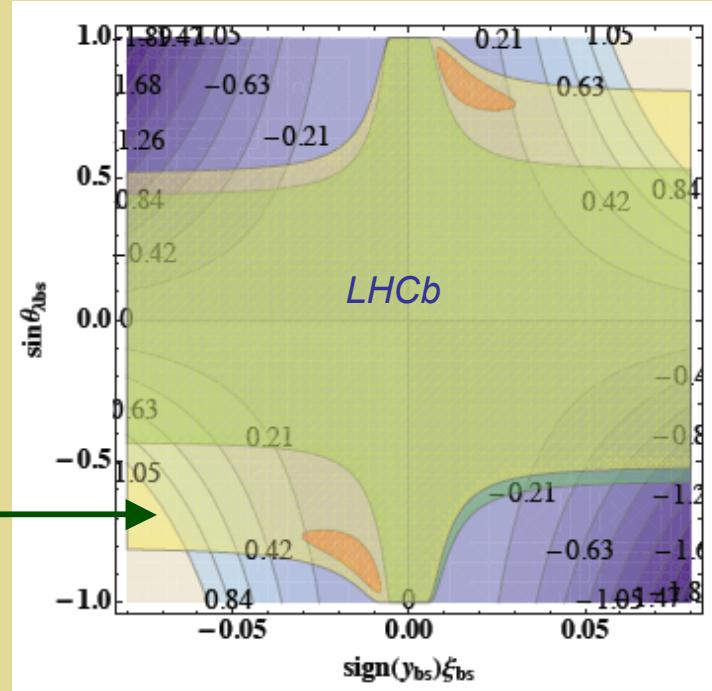
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Liu, R-M, Shu '11;  
see also Tulin &  
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constant  $n_B / s$



Viable EWB & CPV:

- EDMs are 2-loop
- CPV is flavor non-diag

Largely unexplored:  
flavored EWB