Baryogenesis and Leptogenesis

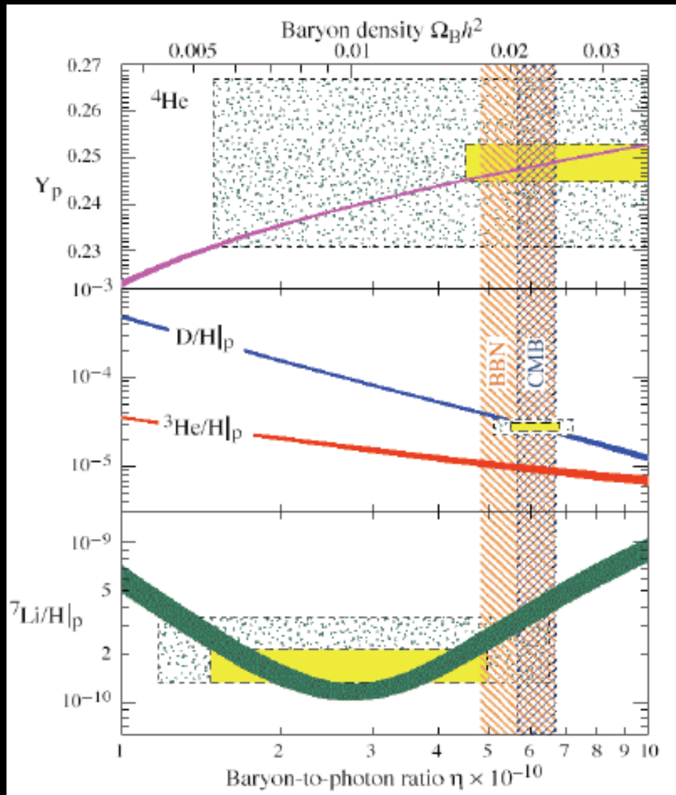
Antonio Riotto
INFN Padova and CERN

Discrete 2010, Rome

The baryon asymmetry

$$\boxed{\frac{n_B}{s} = \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{s} = (8.7 \pm 0.3) \cdot 10^{-11}}$$

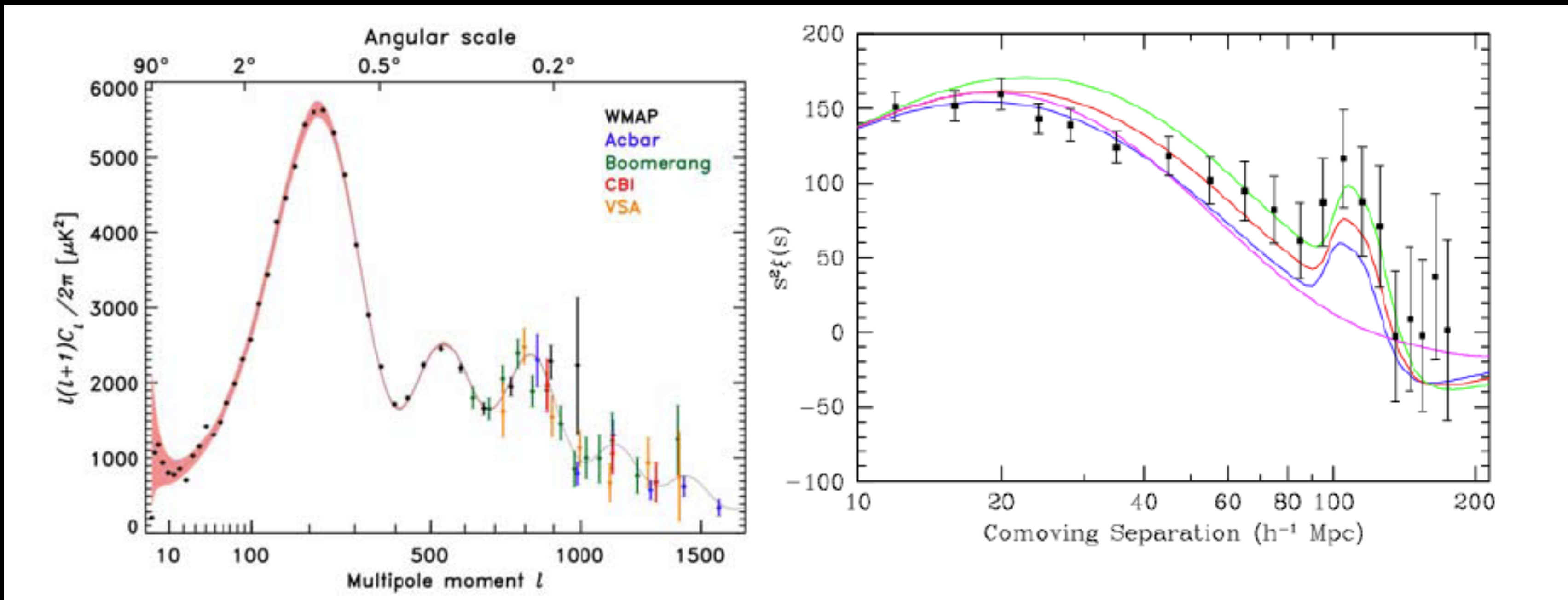
Reasonable agreement between CMB anisotropy, LSS and nucleosynthesis



The baryon asymmetry

$$\boxed{\frac{n_B}{s} = \frac{n_{\mathrm{b}} - n_{\overline{\mathrm{b}}}}{s} = (8.7 \pm 0.3) \cdot 10^{-11}}$$

Reasonable agreement between CMB anisotropy, LSS and nucleosynthesis



Why it is interesting

- Signal of physics beyond the Standard Model
- Might be testable: possible connections to neutrino physics, electroweak physics (LHC), gravity waves
- If successful, probe the Universe at very early epochs, like nucleosynthesis does for the age of the Universe ~ 1 sec

Why it is problematic

- It is only one number: different from DM (direct and indirect detection, collider)

Plan of the talk

- Short introduction to Sacharov's conditions
- Why the SM fails
- Leptogenesis and its testable predictions
- Electoweak baryogenesis and its testable predictions
- Conclusions

Sakharov's conditions (1967)

- Baryon number violation
- C- and CP-violation
- Out-of-equilibrium

Baryon number violation

$$[H, B] = 0 \Rightarrow \dot{B} = 0 \Rightarrow B = B_{\mathrm{in}} = 0$$

C- and CP-violation

$$C\colon\ i \longrightarrow f \text{ goes into } \bar{i} \longrightarrow \bar{f}$$

$$CP \text{ (or } T\text{): } i(\mathbf{r}_i, \mathbf{p}_i, \mathbf{s}_i) \to f(\mathbf{r}_f, \mathbf{p}_f, \mathbf{s}_f) \text{ goes into}$$

$$f(\mathbf{r}_f, -\mathbf{p}_f, -\mathbf{s}_f) \to i(\mathbf{r}_i, -\mathbf{p}_i, -\mathbf{s}_i)$$

Out-of-equilibrium conditions

$$B_{\mathrm{EQ}} \propto (m_X T)^{3/2} \exp(-M_X/T) \sinh(\mu_X/T) \text{ and } X\bar{X} \to \gamma\gamma$$

$$\Rightarrow \mu_X = 0$$

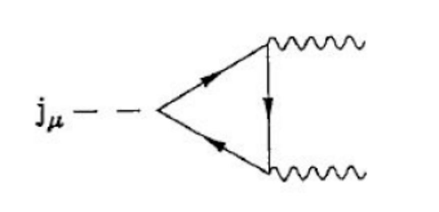
Baryon and lepton number violation: already in the SM

The baryon and the lepton asymmetry are accidental symmetries of the SM at the tree-level:

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = 0$$

They are however anomalous, that is they are violated at the quantum level:

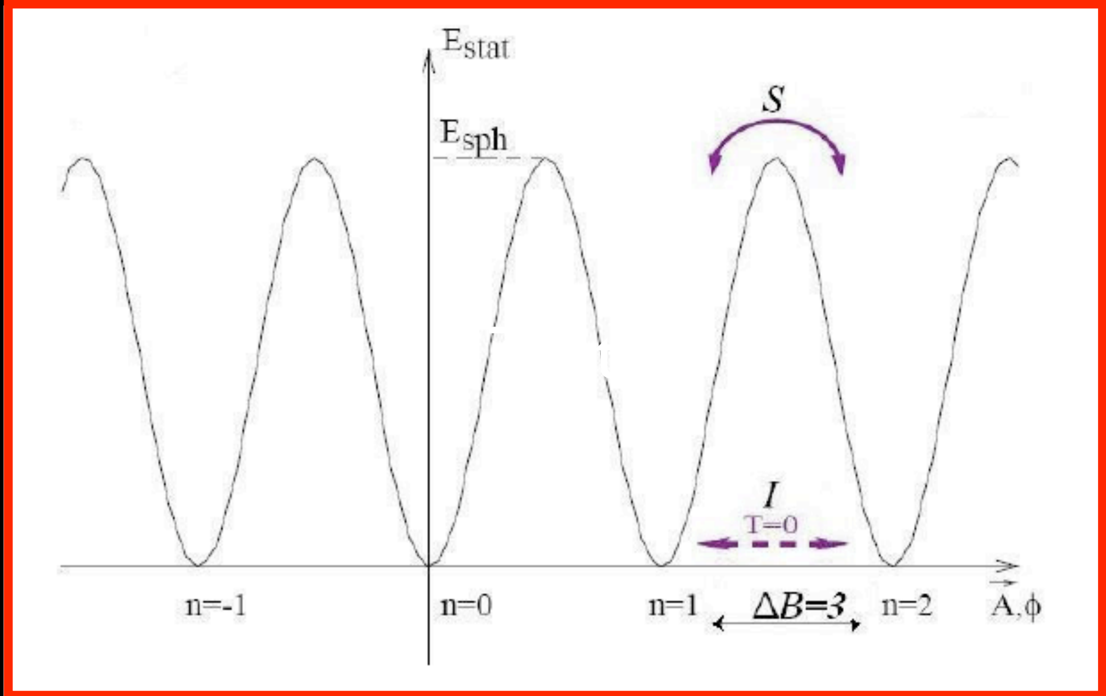
$$\boxed{\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right)}$$



If the RHS acquires is vacuum expectation value, the baryon and the lepton numbers are violated

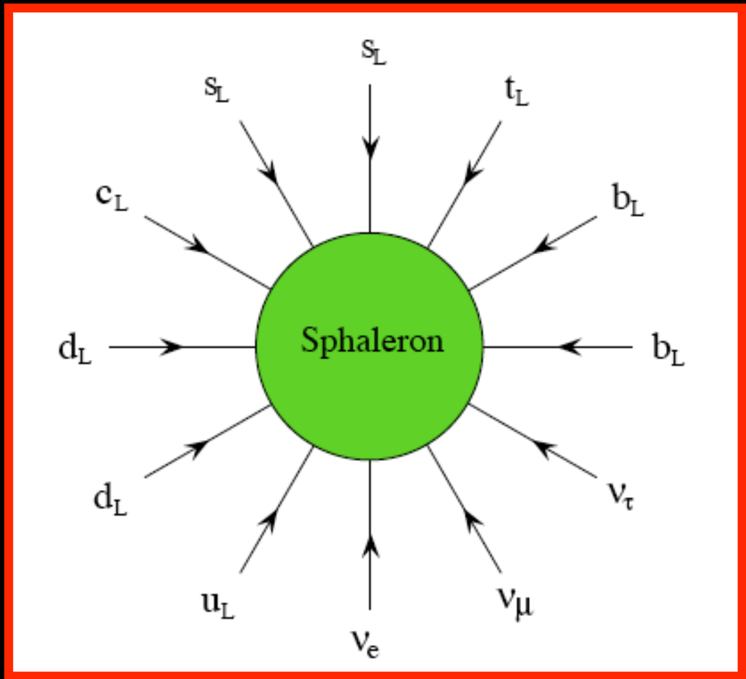
Sphalerons

$(B+L)$-violated, but $(B-L)$ conserved



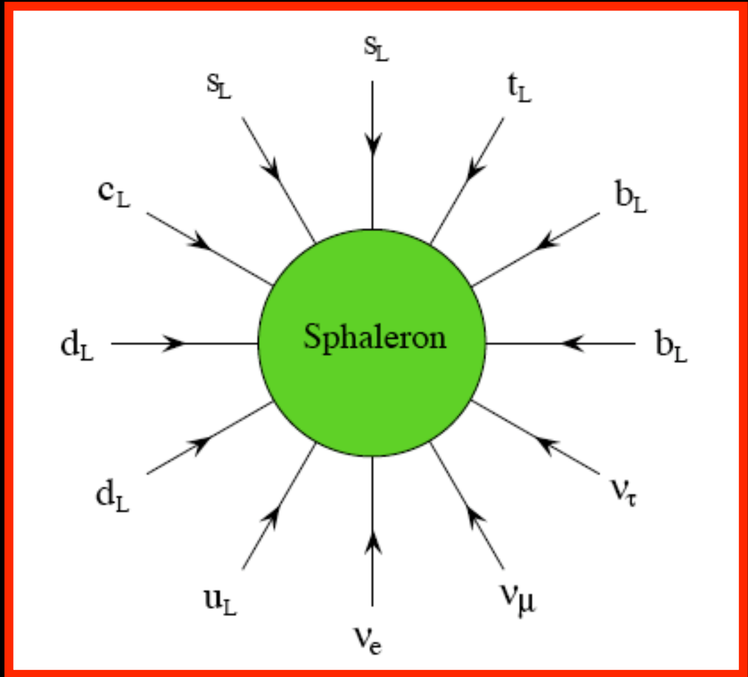
Gauge configurations mediate the the jump from one vacuum to the other, thus violating the baryon number

At high temperatures sphaleron gauge configurations are thermally activated and have size $\ell_{\rm sp} \sim 1/(g_2^2 T)$



$$T \gg M_W : \quad \frac{\Gamma_{\rm sp}}{V} \sim \frac{1}{\ell_{\rm sp}^4} \sim (\alpha_W T)^4$$

At low temperatures sphaleron gauge configurations are Boltzmann suppressed and have size $\ell_{\rm sp} \sim 1/(g_2 \langle H \rangle)$



$$T \ll M_W : \ \frac{\Gamma_{\rm sp}}{V} \sim (\alpha_W T)^4 \exp\left(-E_{\rm sp}/T\right), \ E_{\rm sp} \sim M_W/g_2 \sim \langle H \rangle$$

Sphalerons are switched off if $\langle H \rangle / T > 1$

All popular baryogenesis mechanisms use SM sphalerons as source of the baryon number violation

$$\boxed{\dot{B} \propto -\Gamma_{\rm sp}\left(B - B_{\rm EQ}\right)}$$

if fermions are present

Sphalerons push the system to the equilibrium value of the baryon number $B_{\rm EQ}$: if there are N particles and M interactions in equilibrium, there are $(N-M)$-conserved charges:

$$B_{\rm EQ} = \sum_{i=1}^{N-M} \langle Q_i \rangle$$

connection to DM?

Roughly

$$B = \cancel{\frac{B+L}{2}} + \frac{B-L}{2}$$

Generic expression

$$\boxed{\frac{n_B}{s} \simeq \alpha_W^4 \cdot \delta_{\mathrm{CP}} \cdot f_{\mathrm{NEQ}} \simeq 10^{-7} \delta_{\mathrm{CP}} \cdot f_{\mathrm{NEQ}}}$$

Why SM fails
(one reason, among others)

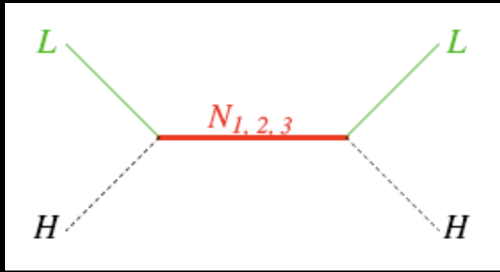
$$
\begin{aligned}
\delta_{\mathrm{CP}} &\sim \frac{(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)}{T^6} \\
&\times \frac{(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)}{T^6} \\
&\sim \frac{m_t^4 m_c^2 m_b^4 m_s^2}{T^{12}} \\
&\sim 10^{-20}
\end{aligned}
$$

Leptogenesis

See-saw mechanism

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left(\frac{M_i}{2} \overline{N}_i^c N_i + \lambda_{i\alpha} N_i L_\alpha H + {\rm h.c.} \right)$$

$$\begin{aligned} N_i &= {\rm Right-handed\ neutrinos}\ (i = 1,2,3) \\ L_\alpha &= {\rm Left-handed\ lepton\ doublets}\ (\alpha = 1,2,3) \\ H &= {\rm Higgs\ doublet} \end{aligned}$$



Minkowski; Yanagida; Gell-Mann; Ramond; Slansky; Glashow; Mohapatra; Senjanovic

$$\boxed{\begin{aligned} m_\nu &= m_D^T \frac{1}{M} m_D = U^* D_m U^\dagger,\ m_D = \lambda \langle H \rangle \\ U &= {\rm low-energy\ lepton\ PMNS\ matrix} \end{aligned}}$$

Neutrino get light masses and lepton number is violated

Leptogenesis can be implemented in several ways

- Type I: hierarchical RH neutrinos
- Type II and III: adding extra heavy d.o.f. which contribute to light neutrino masses
- Resonant leptogenesis: almost degenerate RH neutrinos
- Thermal: RH neutrinos generated from scatterings in the thermal bath
- Non-thermal: RH neutrinos generated from some non-equilibrium event

Leptogenesis can be implemented in several ways

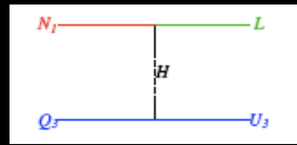
- Type I: hierarchical RH neutrinos
- Type II and III: adding extra heavy d.o.f. which contribute to light neutrino masses
- Resonant leptogenesis: almost degenerate RH neutrinos
- Thermal: RH neutrinos generated from scatterings in the thermal bath
- Non-thermal: RH neutrinos generated from some non-equilibrium event

Out-of-equilibrium decay scenario

Scatterings

Fukugita and Yanagida

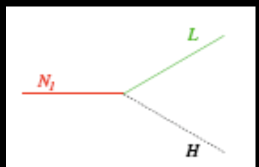
$$\boxed{\begin{aligned} Y'_{N_1} &= -(D+S)\left(Y_{N_1} - Y^{\rm eq}_{N_1}\right) \\ Y_{\mathcal{L}} &= \epsilon_1\left(Y_{N_1} - Y^{\rm eq}_{N_1}\right) - W_{\rm ID} Y_{\mathcal{L}} \end{aligned}}$$

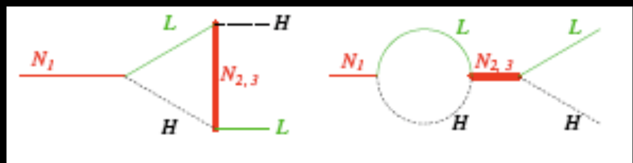


Wash-out term from inverse decays

$$\begin{aligned} D, W_{\rm ID} &\propto K \equiv \frac{\sum_\alpha \Gamma(N_1 \rightarrow L_\alpha H)}{H(M_1)} \\ &= \left(\frac{\widetilde{m}_1}{3\times 10^{-3}\,{\rm eV}}\right) \end{aligned}$$

CP violation in decays

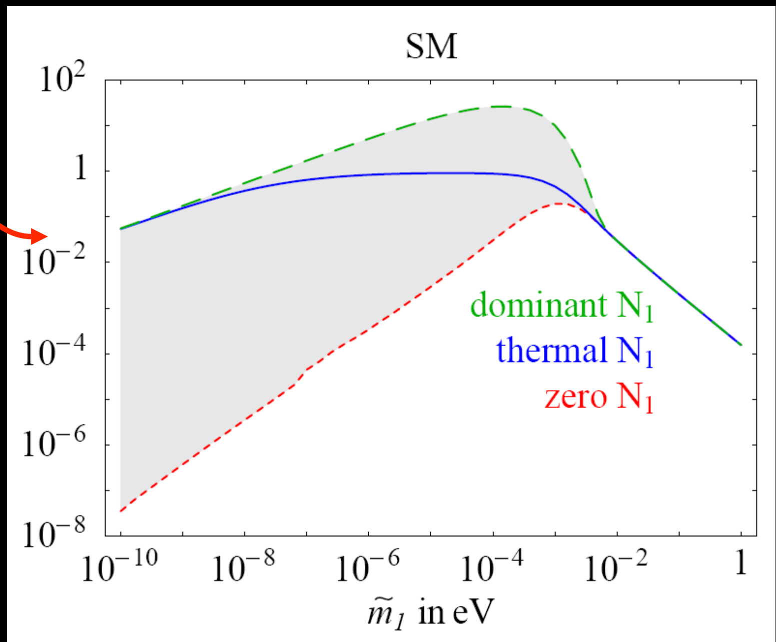




$$\begin{aligned} \epsilon_1 &= \frac{\sum_\alpha \left[\Gamma(N_1 - \rightarrow L_\alpha H) - \Gamma(N_1 \rightarrow \bar{L}_\alpha \bar{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \rightarrow L_\alpha H) + \Gamma(N_1 - \rightarrow \bar{L}_\alpha \bar{H})\right]} \\ &\propto \sum_j {\rm Im}\left(\lambda\lambda^\dagger\right)^2_{1j} \frac{M_1}{M_j} \end{aligned}$$

one-flavour

$$Y_{\mathcal{L}} \simeq 10^{-3} \epsilon_1 \eta(\widetilde{m}_1)$$



G.F. Giudice, A. Notari, M. Raidal, A.R., A. Strumia, 2004

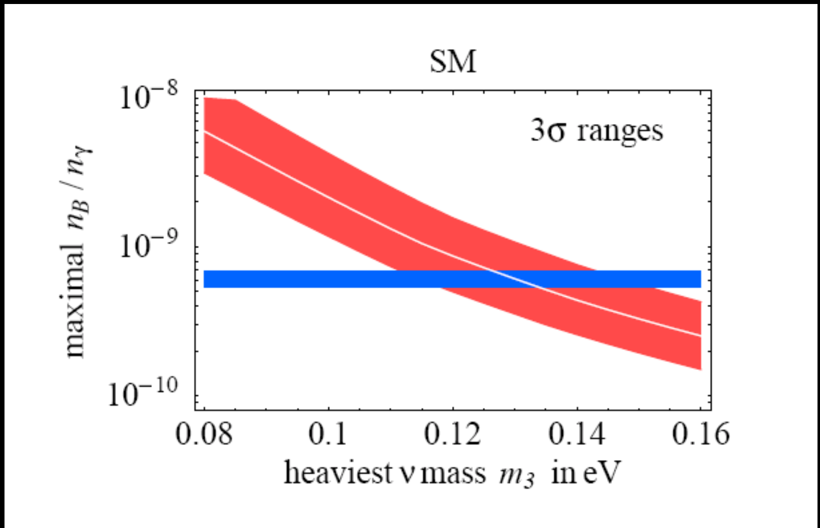
Upper bound on light neutrino masses (hierarchical RH neutrinos)

$$\epsilon_1 \leq \frac{3 M_1 \Delta m^2_{\rm atm}}{8\pi \langle H \rangle^2 \overline{m}}, \quad \overline{m} = {\rm Tr}\, m_\nu$$

A. Ibarra and S. Davidson, 2002

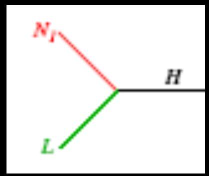
If $\overline{m}$ increases, M_1 must increase, but at some point $\Delta L = 2$ scatterings are in equilibrium, at $T \approx M_1 > 10^{10} (\mathrm{eV}/\overline{m})^2$ GeV

$$\boxed{\overline{m} \leq 0.15 \quad \mathrm{eV}}$$



G.F. Giudice, A. Notari, M. Raidal, A.R., A. Strumia, 2004

Flavours are relevant in leptogenesis



How is it possible that the flavour in the, say, tau flavour is washed out by inverse decays involving the electron and the muon flavour ?

$$W_{\rm ID} Y_{\mathcal{L}} \propto -K Y_{\mathcal{L}} = -(K_e + K_\mu + K_\tau)(Y_e + Y_\mu + Y_\tau)$$

When is the one-flavour approximation valid?

- Tau Yukawa coupling induces interactions in equilibrium at temperatures 10^{12} GeV

- At temperatures above 10^{12} GeV, there is no notion of flavour : different flavours are not distinguishable. The only meaningful flavour is the total lepton (= one - flavour)

For $M_1 < 10^{12}$ GeV the one single approximation is not correct and flavours have to be accounted for

A. Abada, S. Davidson, F-X. Josse-Michaux, M. Losada and A.R., 2006; E. Nardi, Y. Nir, E. Roulet and J. Racker, et al., 2006

When flavour effects are included:

$$Y_B \propto \sum_\alpha \epsilon_\alpha \eta\left(\widetilde{m}_\alpha\right) \text{ and not to } \sum_\alpha \epsilon_\alpha \sum_\beta \eta\left(\widetilde{m}_\beta\right)$$

- The baryon asymmetry can be a factor (10-100) larger
- The upper bound on light neutrino masses disappears:

$$\epsilon_\alpha \leq \frac{3M_1\overline{m}}{8\pi\langle H\rangle^2}$$

From observing some CP-violation in the neutrino sector can we conclude that leptogenesis is at work?

High energy
$M_i(3+0)+\lambda(9+6)$
18 parameters

Low energy
$D_m(3+0)+U(3+3)$
9 parameters

$$\boxed{18-9=9 \text{ parameters are lost}}$$

Use the orthogonal parametrization: $\lambda = \sqrt{M} \cdot R \cdot D_m \cdot U^\dagger$

One-flavour regime:

$$\epsilon_1 \propto \mathrm{Im}\left(\sum_\alpha m_\alpha^2 R_{1\alpha}^2\right)$$

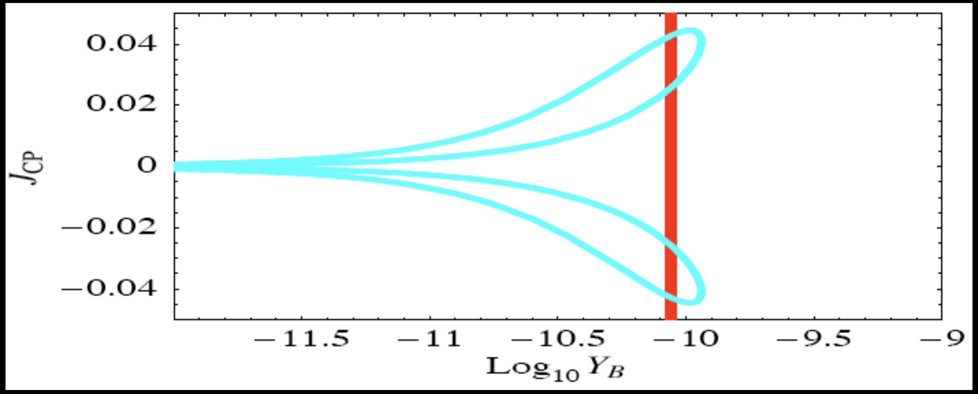
Flavoured regime:

$$\boxed{\epsilon_\alpha \propto \mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{\alpha\beta}^* U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}$$

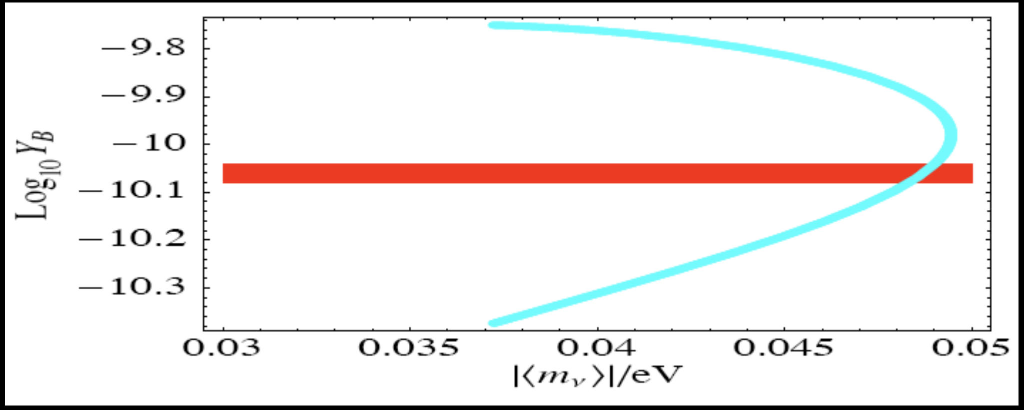
If leptonic low-energy CP-violation is present
the CP-violation in leptogenesis is not zero

Leptogenesis from the low-energy Dirac phase

$$Y_B \propto c_{23}^2 s_{12} s_{13} \left|\sin\delta\right| \propto J_{\rm CP}$$

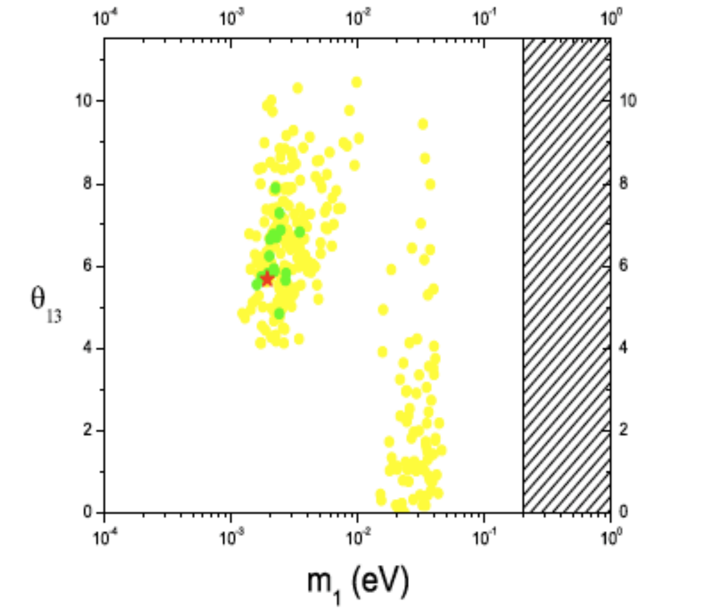


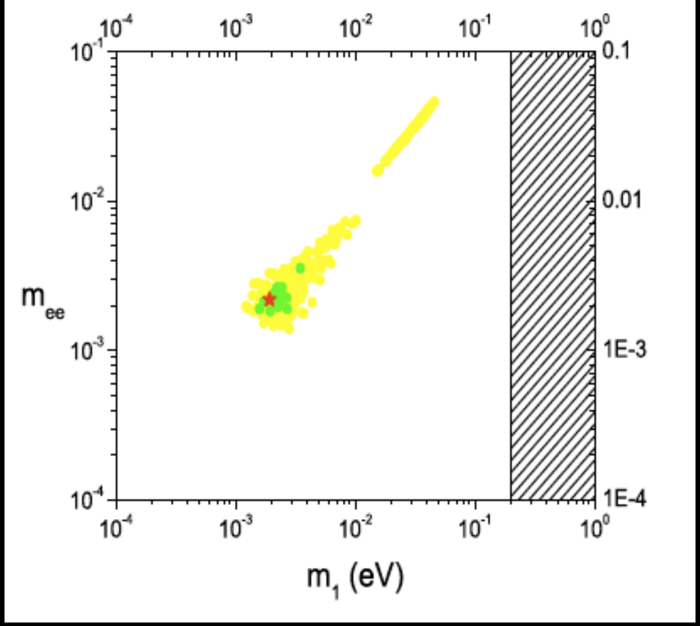
Leptogenesis from the low-energy Majorana phase



S. Pascoli, S. Petcov and A.R., 2004

The see-saw mechanism is naturally embedded in SO(10)





$\theta_{13} > 5^\circ$

$\theta_{13} \sim 7^\circ + (\theta_{23} - 45^\circ)/3$

A 3σ discovery of $\theta_{13} > 8^\circ$ will imply a given value for θ_{23}

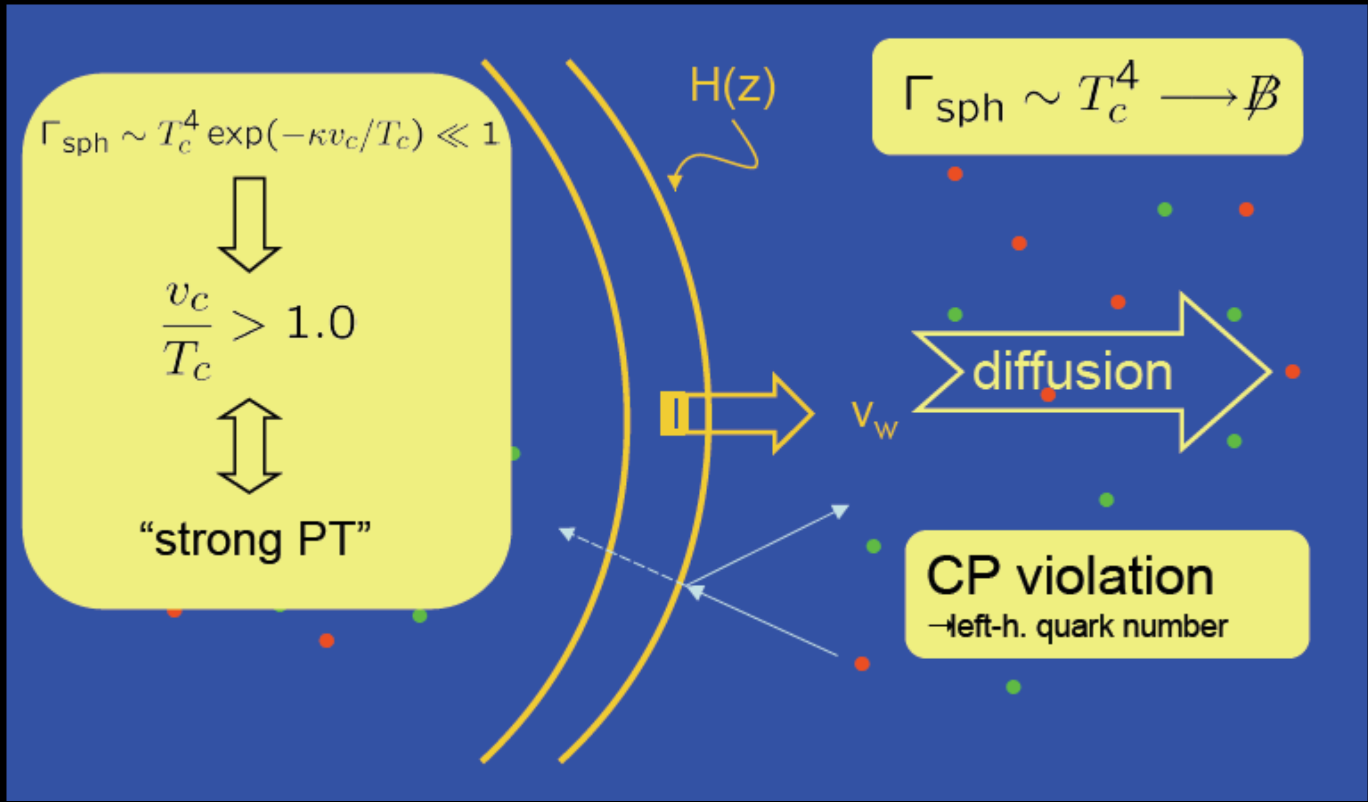
P. Di Bari and A.R., to appear

Leptogenesis and testability

- Lepton number violation: direct production of RH neutrinos (hard)
- Lepton number violation: detection of $0\nu 2\beta$ decays (requires IH or quasi degenerate ν's). If $\overline{m}$ measured by cosmology, say ~ 0.2 eV and no $0\nu 2\beta$ seen, leptogenesis strongly disfavoured (no Majorana)
- If leptonic CP-violation is seen: circumstantial evidence for leptogenesis
- If leptonic CP-violation not seen: leptogenesis is not ruled out

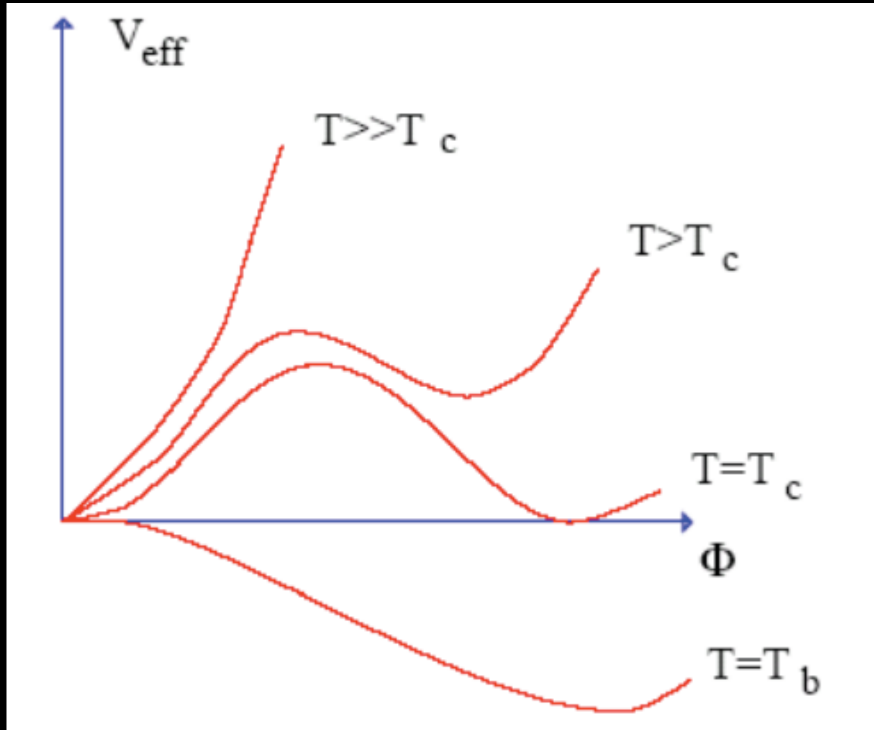
Electroweak baryogenesis

First collisions at CERN



$$\frac{n_B}{s} \sim \alpha_W^4 \delta_{\rm CP} f_{\rm NEQ}(v_{\rm wall}) = \mathcal{O}\left(10^{-10}\right) \text{ naturally}$$

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- $E(T)$ from boson (thermal) loops
- $\frac{\langle H \rangle}{T} \sim \frac{E}{\lambda} \Rightarrow$ light Higgs

Electroweak baryogenesis naturally implemented in the MSSM

- Extra CP-violation provided by the phases of in the chargino and Higgsino sectors

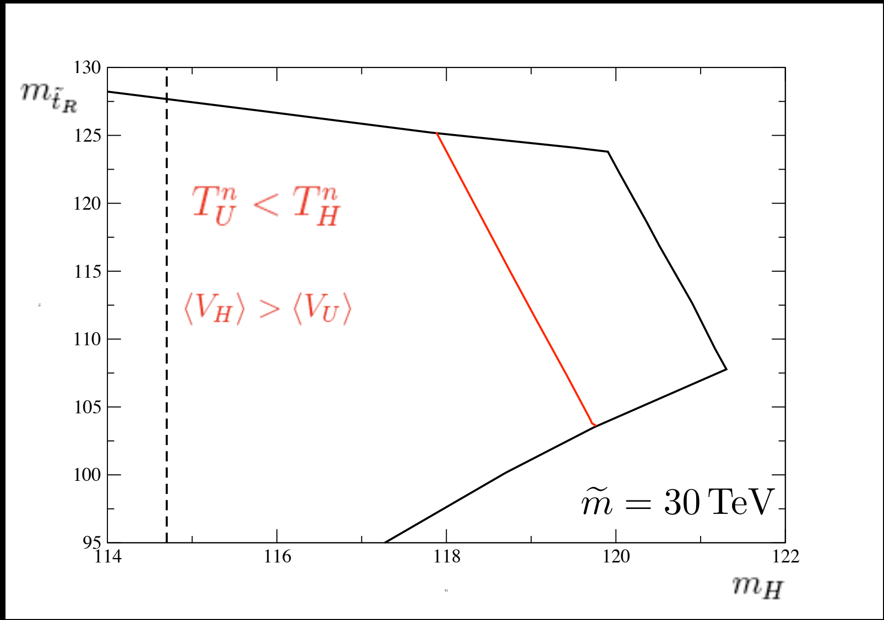
- Bosonic loops provided by light RH stops

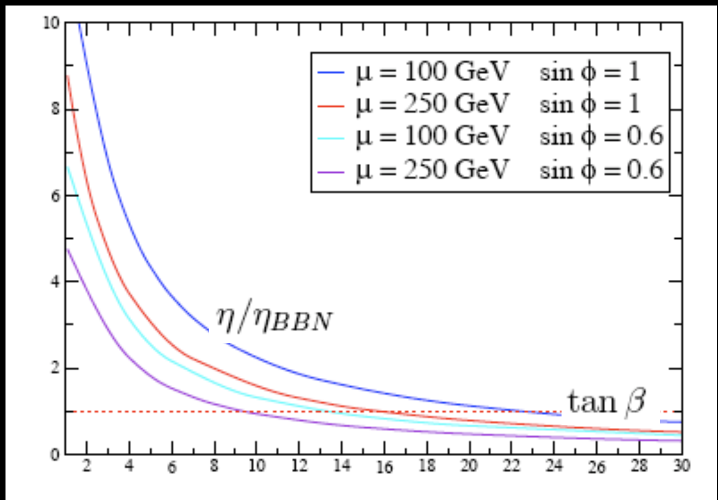
- The lightest neutral Higgs can be light enough

- Sphalerons push the baryon number to its equilibrium value B_{EQ} generated by the Higgsino and stop charges

Huet, Nelson; Carena, Quiros, Riotto, Vilja, Wagner, 1999

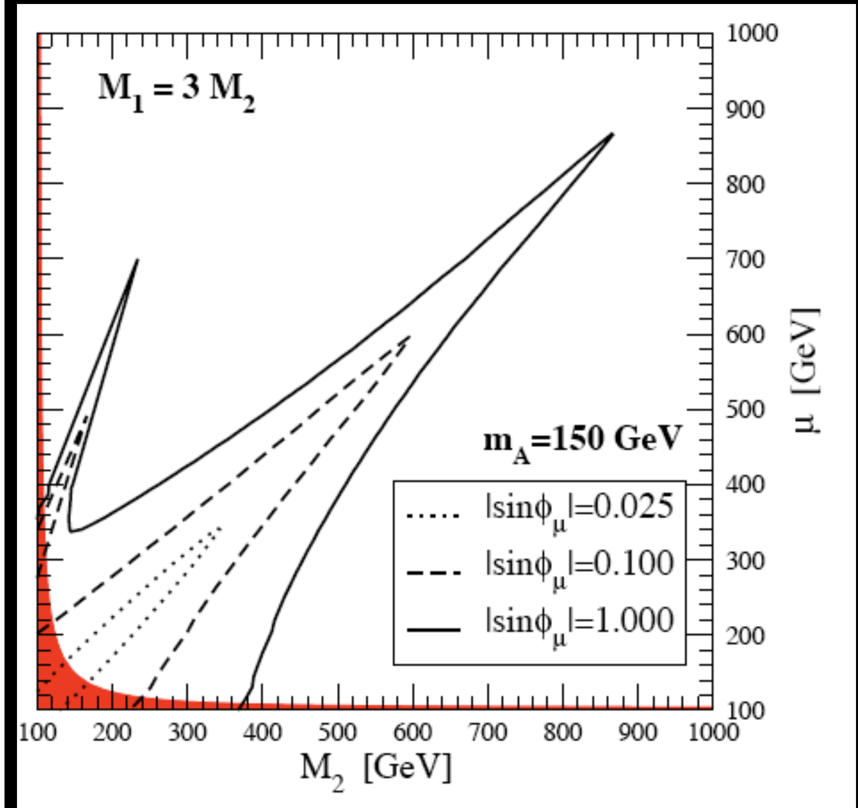
MSSM baryogenesis window

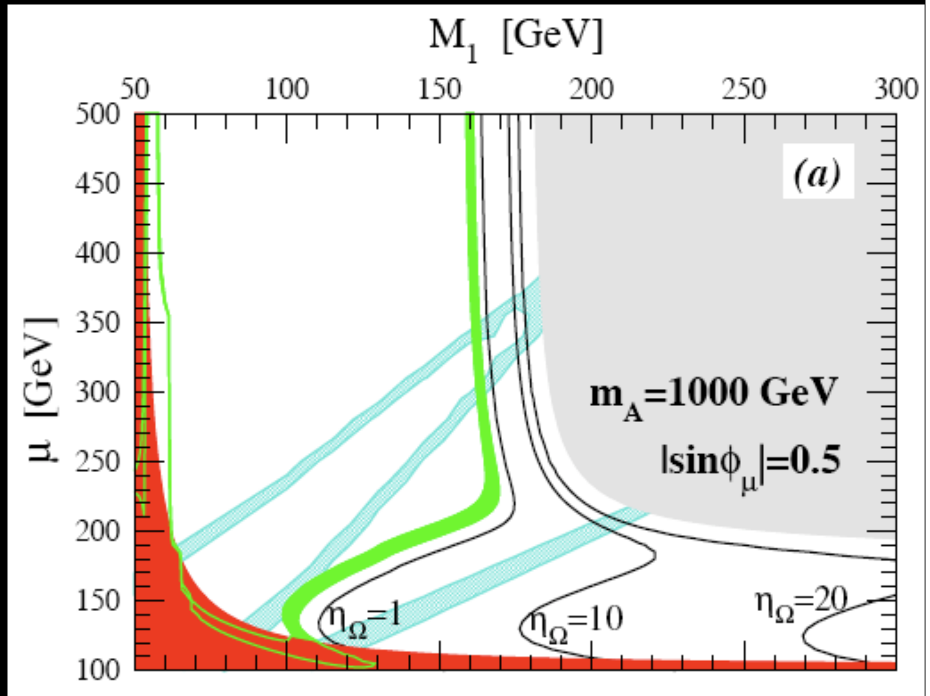


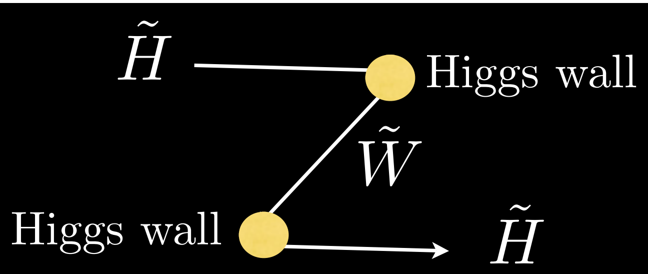


M. Carena, G. Nardini,
M. Quiros and C. Wagner,
2009

Electron EDM (one- and two-loop)

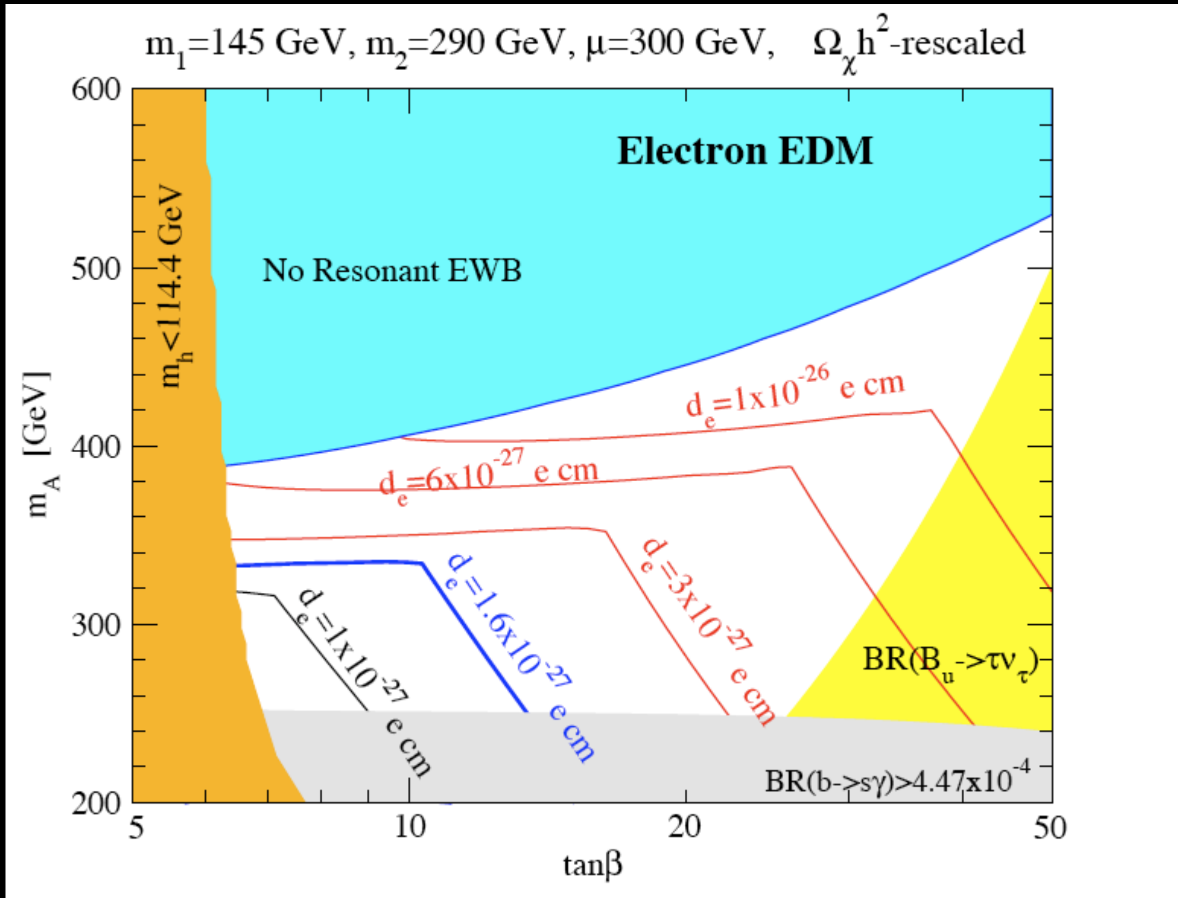






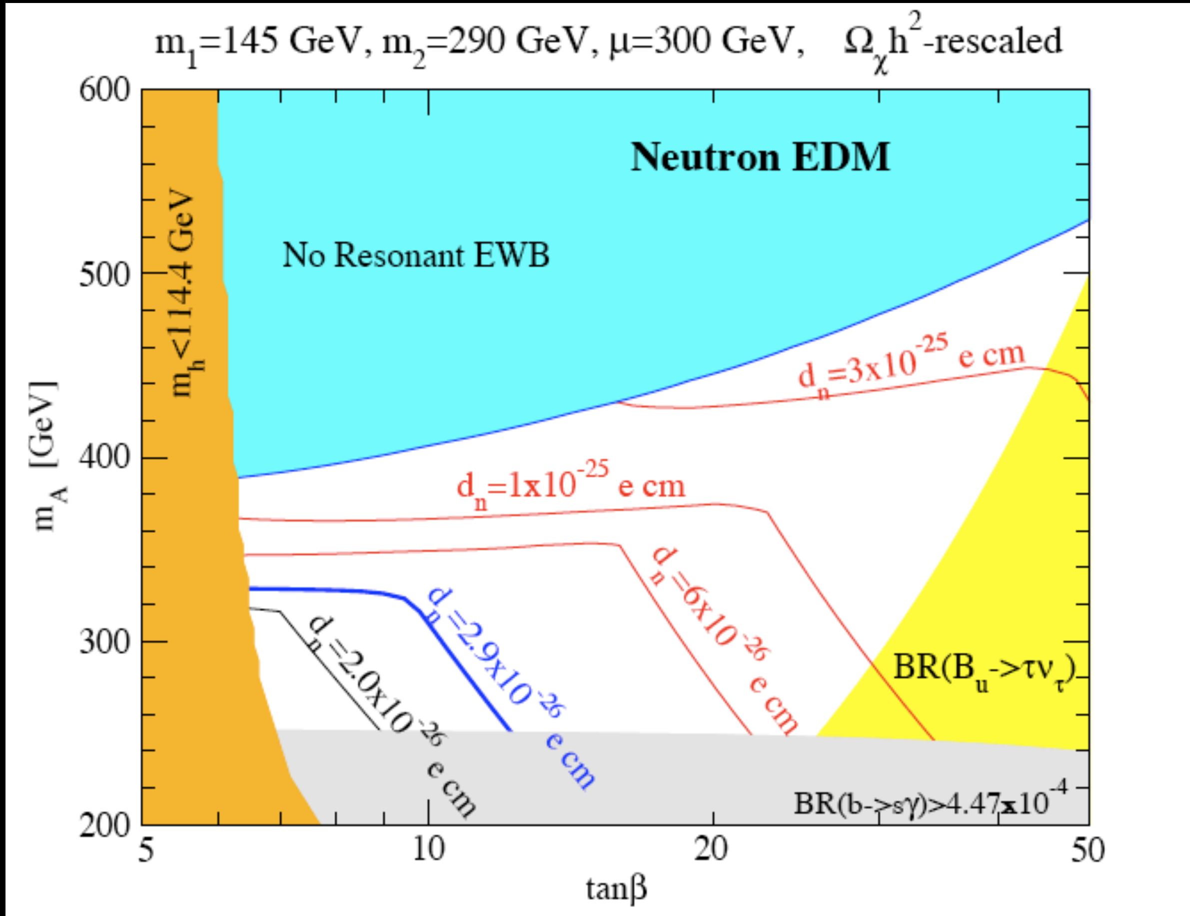
V. Cirigliano et al., 2009

Electron and Neutron EDMs



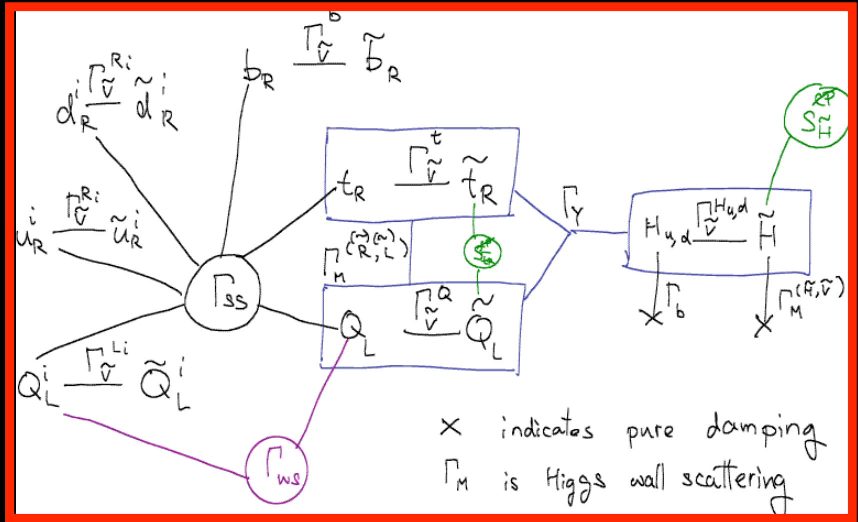
V. Cirigliano et al., 2009

Electron and Neutron EDMs



V. Cirigliano et al., 2009

Are we ready to test the MSSM EWB scenario?



- In the last seven years revision of the baryon asymmetry prediction by a factor 100-000

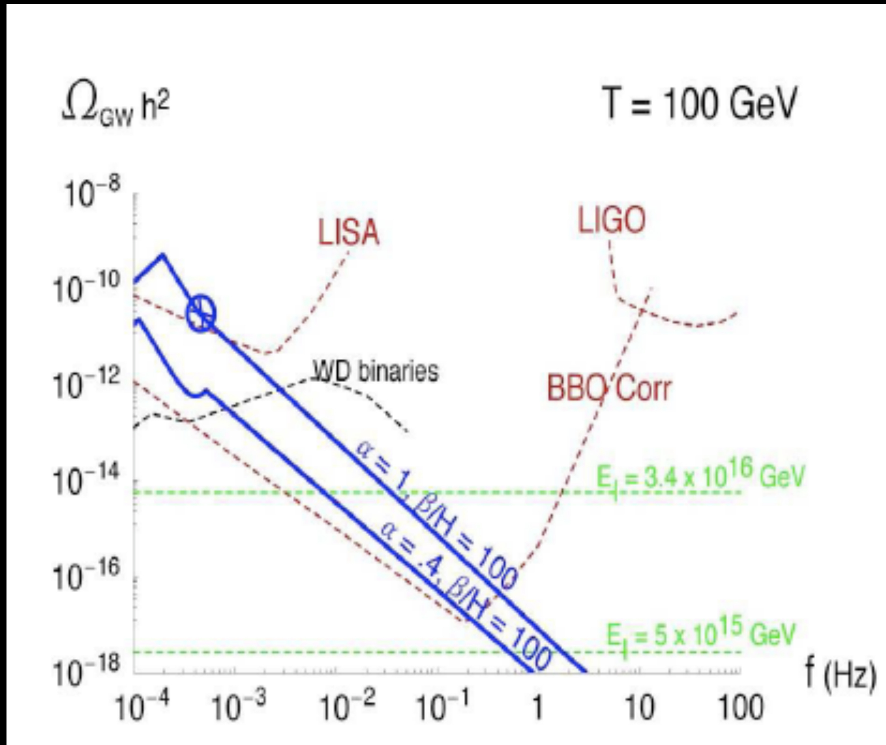
- Have to solve for Higgs profile

- Velocity of the bubble wall (IR modes of gauge bosons and stops, Landau damping, memory effects)?

EWB and testability

- Light stops with mass $m_{\tilde{t}_R} < 127$ GeV
- Light Higgs with mass $m_h < 120$ GeV
- Light Higgsinos and charginos
- Large CP-phases induce testable CP-violation in EDM's and can test the vast majority of the parameter space
- Gravity wave production

Bubble collisions at MSSM EWPT generate gravitational waves



$$\Omega_{\rm GW} h^2(f_*) \simeq 10^{-6}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\alpha}{1+\alpha}\right)^2 v_{\rm wall}^3$$

M. Maggiore, A. Nicolis and A.R., 2001

$$f_* \simeq 5\cdot 10^{-3}\,{\rm mHz}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)$$

Conclusions

- The baryon asymmetry is an indication of physics beyond the SM
- More difficult to test than DM
- If leptogenesis, the generation takes place at very high energy scales, but nevertheless testable in low-energy experiments (like GUTs vs proton decay)
- If EWB, the generation takes place at testable energy scales and testable soon at LHC and/or flavour physics