Baryogenesis and Leptogenesis

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Dark Candles ICTS-TIFR Bengaluru, 9 June 2017

Overview

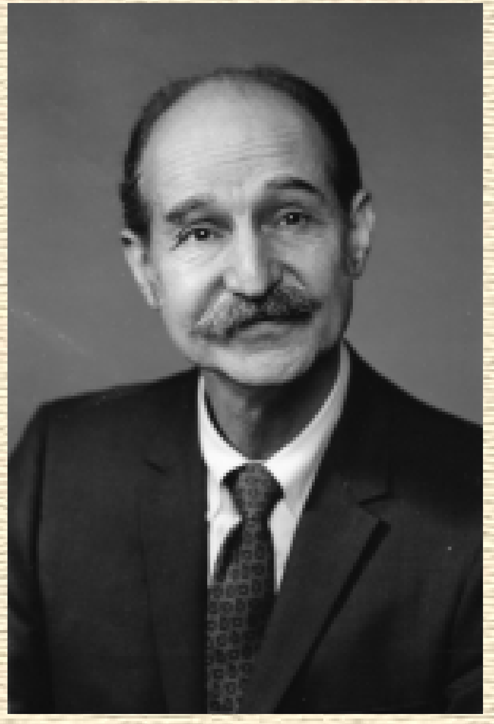
- Three paradigms of baryogenesis :
  - GUT decay ... essentially thermal, high scale
  - TeV scale ... essentially non-thermal, low scale
  - Leptogenesis ... combination of possibilities
- Sphaleron physics
  - MSSM status
- Leptogenesis – the thermal case
  - Compatibility with inflation and supersymmetry
  - CP violation from to light neutrino data
- Leptogenesis – Resonance enhancement; soft-term leptogenesis
- Affleck-Dine mechanism – SUSY flat directions and B-genesis
- Leptogenesis – the non-thermal case; D-parity breaking
- Comprehensive models – DM, BAU, inflation ...

Genesis of “baryogenesis”

The cosmology – nuclear physics connection

- “Alpher, Bethe and Gamow” paper estiamtes He to H ratio 1948
- Alpher and Hermann estimate 5K as the temperature of residual photons 1949

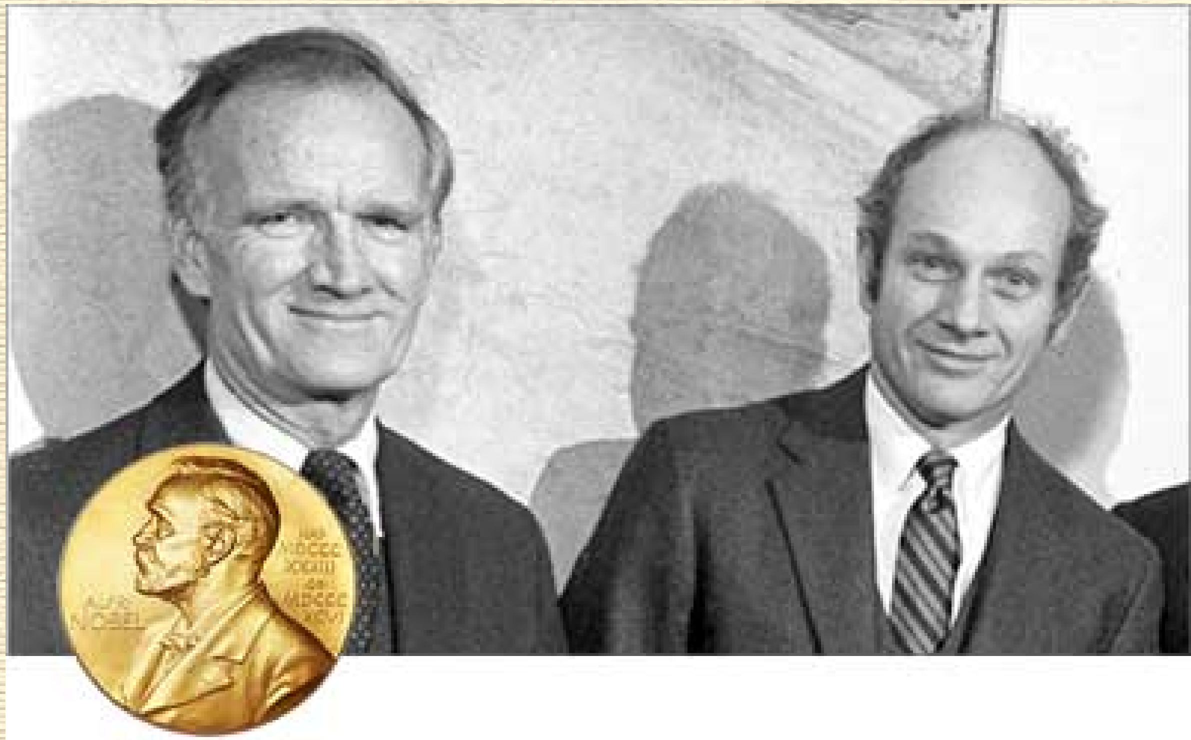




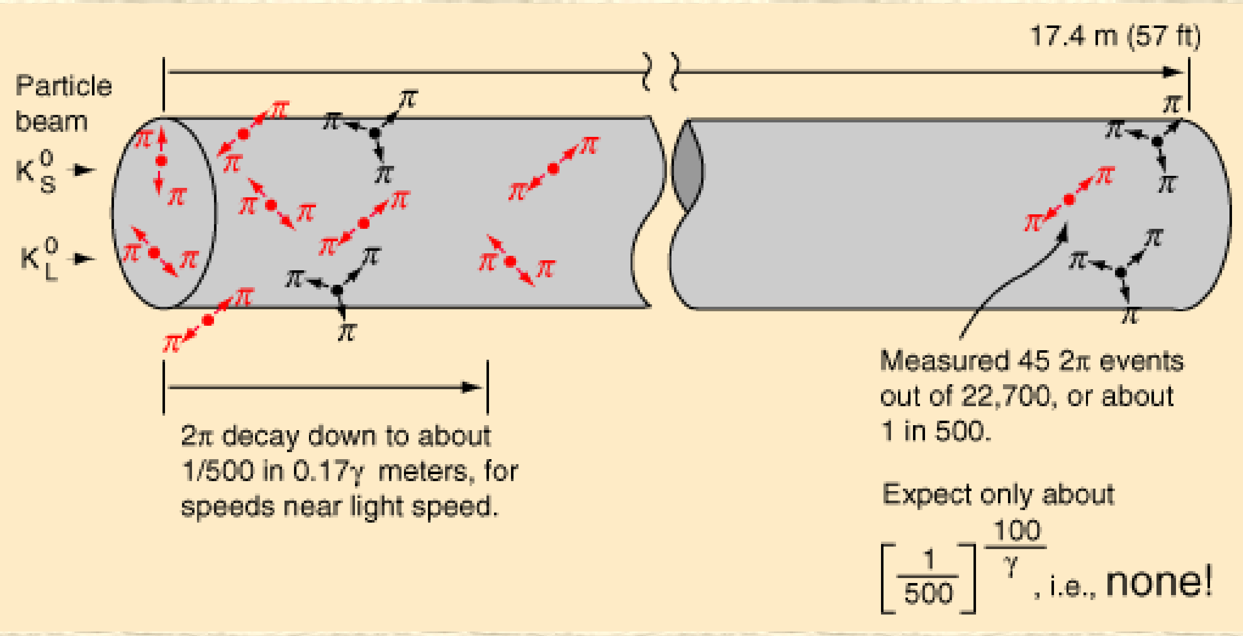
Gamow; Alpher; Herman

One concerns the MeV scale, the other concerns the eV scale!

Discovery of CP violation at Brookhaven National Lab 1963

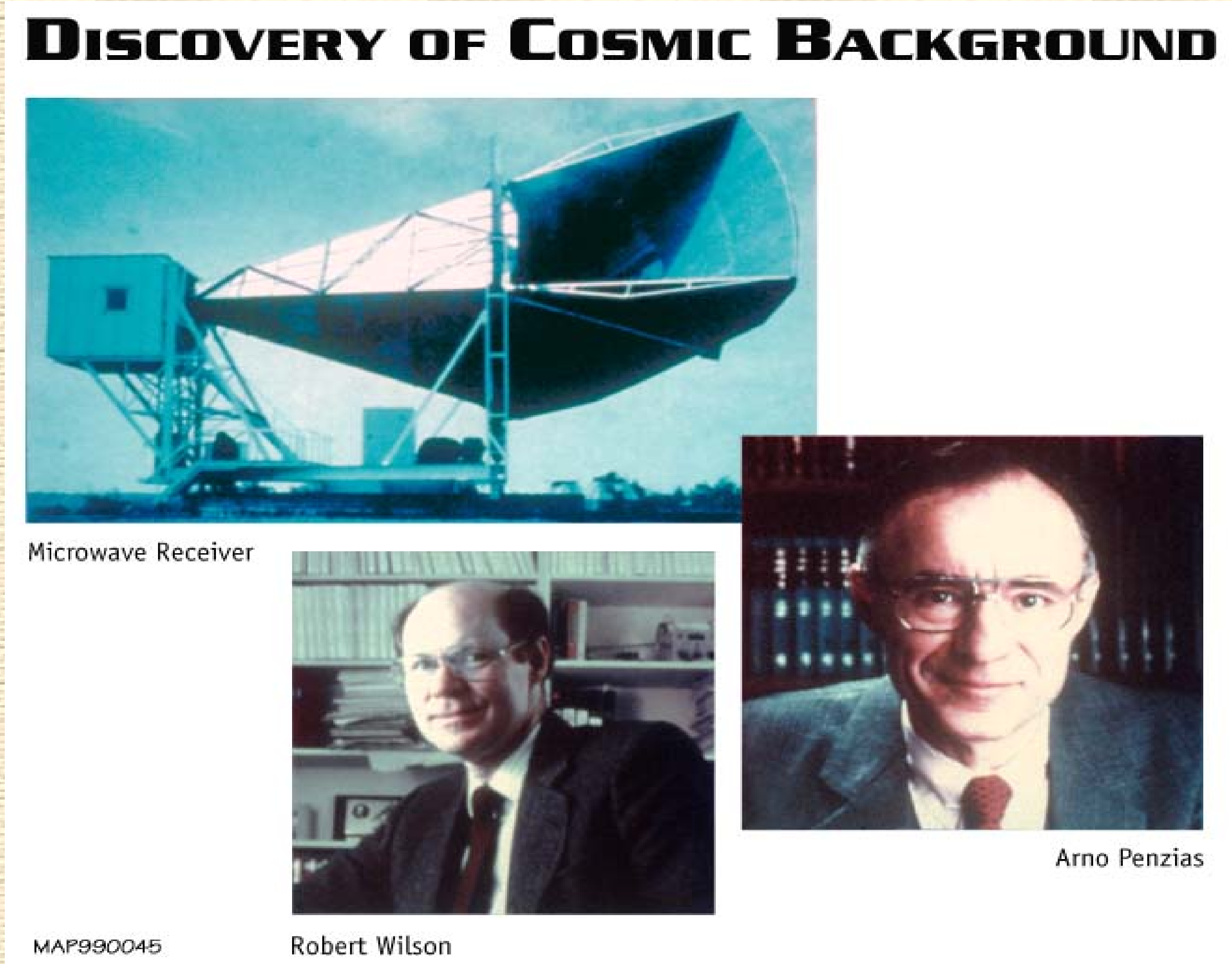


Nobel 1980



(schematic courtsy hyperphysics website Georgia State U.)

Cosmic Microwave Background Radiation discovered 1965



Nobel 1978

Postdicting Baryon asymmetry

Matter- antimatter asymmetry apparent ...

but above discoveries opened up the possibility of explaining quantitatively the number

$$\frac{n_B}{s} \cong 10^{-9}$$

Weinberg's comment in Brandeis lectures "Dynamic and Algebraic Symmetries" 1964;

Specific model Sakharov 1967

Current status

From Nucleosynthesis calculations and
observed obundances of D, ^{3}He, ^{4}He and ^{7}Li,

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \cong 5 \times 10^{-10}; \qquad 0.017 < \Omega_B h^2 < 0.024$$

$$H_0 \equiv h 100\,\mathrm{km}/s/\mathrm{Mpc}; \qquad h \cong 0.7$$

Note from random fluctuations at the QCD scale, the residual η would be 10^{-17}
From WMAP data,

$$\Omega_B h^2 \cong 0.022$$

The candle is ...

→ Half lit ... $\sim 10^{-9}$

→ Half dark ... $\ll 1$

Genesis of baryogenesis

(Sakharov 1967; Yoshimura; Weinberg 1978)

1. There should exist baryon number B violating interaction

$$X \rightarrow qq \qquad \Delta B_1 = \frac{2}{3}$$
$$\bar{q}\bar{l} \qquad \Delta B_2 = -\frac{1}{3}$$

2. Charge conjugation C must be violated

$$\mathcal{M}(X \rightarrow qq) \neq \mathcal{M}(\bar{X} \rightarrow \bar{q}\bar{q})$$

3. CP violation

$$r_1 = \frac{\Gamma(X \rightarrow qq)}{\Gamma_1 + \Gamma_2} \neq \frac{\bar{\Gamma}(\bar{X} \rightarrow \bar{q}\bar{q})}{\bar{\Gamma}_1 + \bar{\Gamma}_2} = \bar{r}_1$$

4. Out of equilibrium conditions
   Reverse reactions don't get the time to reverse the products

Net baryon asymmetry

$$\begin{aligned} B &= \Delta B_1 r_1 && + \Delta B_2(1-r_1) \\ &\quad +(-\Delta B_1)\bar{r}_1 && + (-\Delta B_2)(1-\bar{r}_1) \\ &= (\Delta B_1 - \Delta B_2)(r_1 - \bar{r}_1) \end{aligned}$$

- GUTs generically involve new gauge forces which mediate B violation
- Higgs scalar interactions can be natural source of CP violation
- The Particle Physics rates and expansion rate of the Universe compete

$$\Gamma_X \cong \alpha_X m_X^2 / T; \qquad H \cong g_*^{1/2} T^2 / M_{\rm Pl}$$

Soon, by 1990, protons not decaying :-(
GUT BGenesis not happening :-(:-(

TeV scale baryogenesis

- B and L are known to be accidental symmetries of SM at tree level
- $B+L$ turns out to be anomalous

$$Tr(T^a\{\tau^b,\tau^c\}) \neq 0$$

- Anomalous processes can proceed by tunneling (Klinkhammer and Manton 1983)

$$\Gamma_{\text{sphaleron}} \sim \exp\{-S^E_{\text{sphaleron}}\}$$

at a finite temperature at a rate

$$\Gamma^T_{\text{sphaleron}} \sim \exp\{-E_{\text{sphaleron}}/kT\}$$

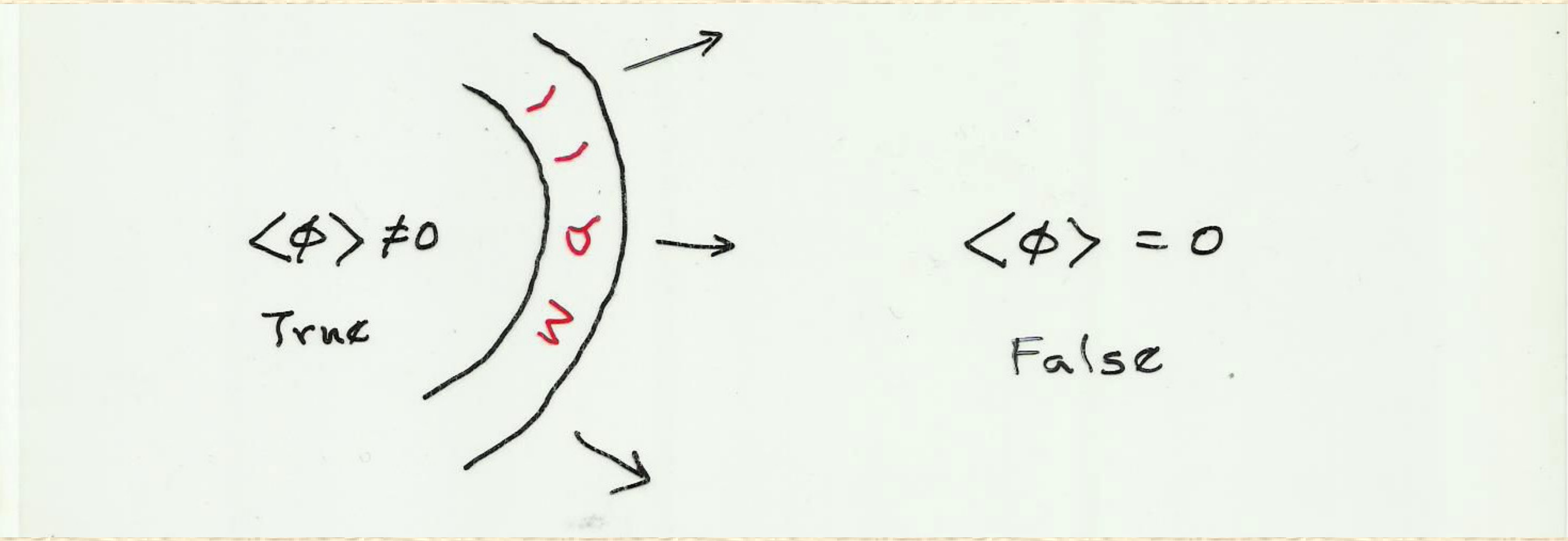
where

$$S_{\text{sphaleron}}, E_{\text{sphaleron}} \sim \frac{1}{\alpha^2_{\text{EW}}} M_W \sim 5\,\text{TeV}$$

- Anomalous processes unsuppressed for $T \gg M_W$

- Two conclusions : (Kuzmin-Rubakov-Shaposhnikov 1986)
  - Any $B + L$ generated at high scale will be erased
  - ... there is a way to violate $B + L$ just as we cool below M_W
- Expansion rate H too slow at electroweak scale – need another source of out of equilibrium conditions –> First Order Phase Transition (FOPT)
- First order phase transition in SM requires Higgs mass to be $\lesssim 90$GeV ...

Generic requirements on bubble walls :



Whatever be the order parameter of the transition, e.g., 2 Higgs doublets,

- Thick wall, slow bubbles : scalar condensate with transient CP phase; sphalerons fit in the wall (Turok, Zadrozni 1992)
- Thin wall, fast bubbles : CP phase as before, fermions scatter asymmetrically from the walls (Cohen, Kaplan and Nelson 1993)

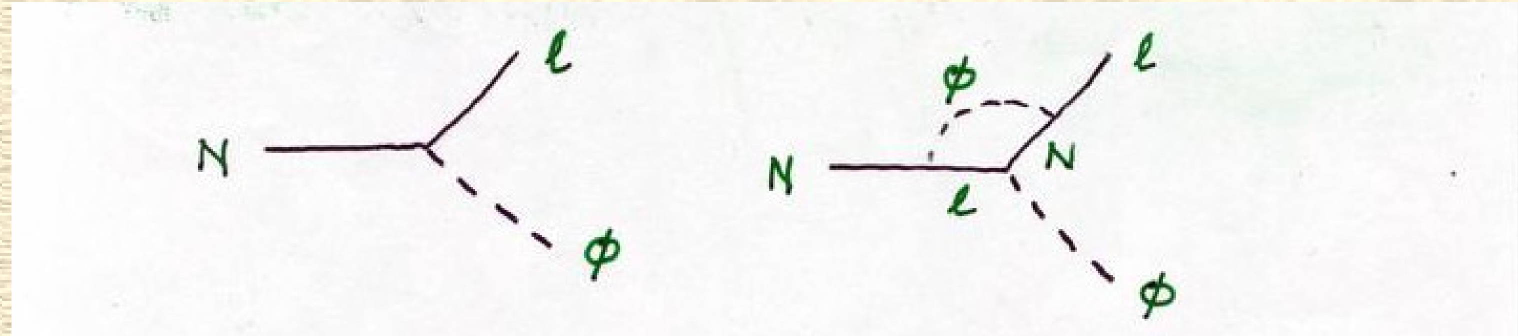
In either case we need to go beyond the SM :

- → CKM phase acquired at the wall; but magnitude too small
- → At least two scalars as order parameters of the phase transition. Minimal model : 2 Higgs Doublets
- → MSSM realistic and adequate but in tension with 7 TeV data
- → Observational possibility – Gravitational waves from bubble wall decays (Grojean, Servant, Caprini, Durrer 2009)

Leptogenesis - thermal case

(Fukugita and Yanagida 1986)

- Out of equilibrium decay of heavy Majorana neutrinos

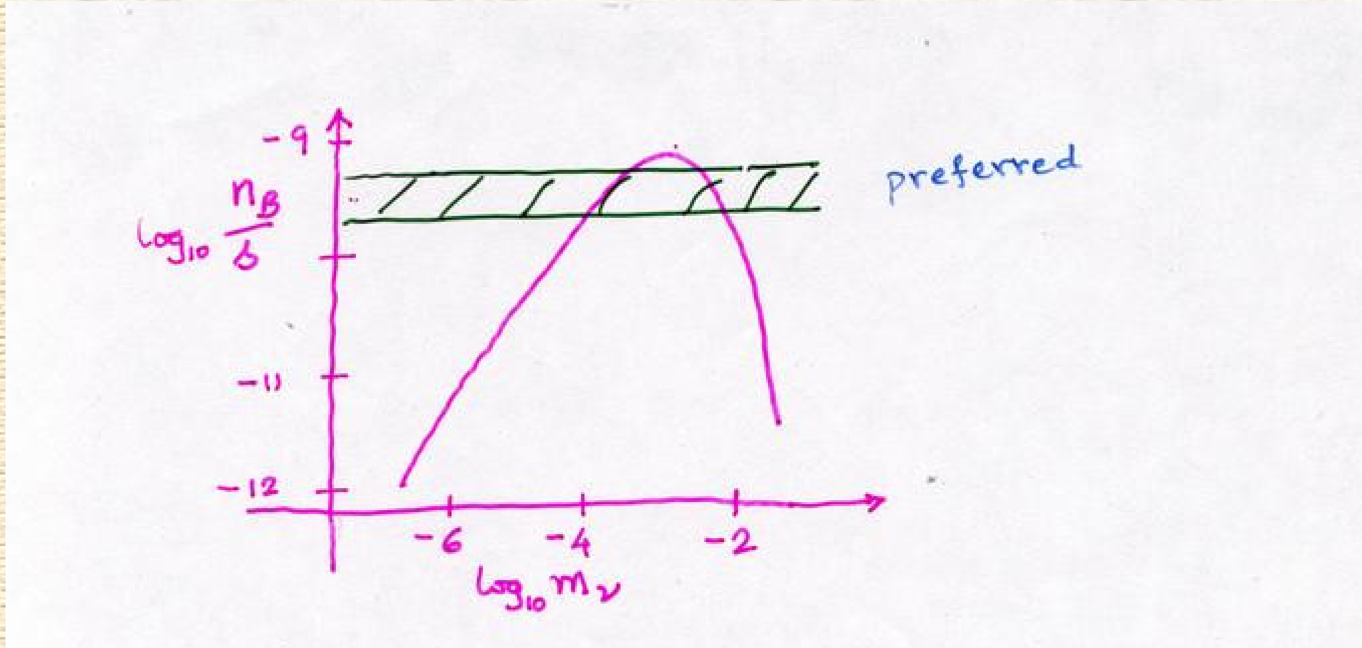


- Easy to arrange CP violation due to complex vacuum expectation values of scalar fields producing the mass

$$\frac{r-\bar{r}}{r} \sim \frac{1}{v^2 m_{_D}^2} \mathrm{Im}(m_{_D}^\dagger m_{_D})^2$$

- Need to have comparable, faster, expansion rate of the Universe

Thermal leprogenesis in SO(10) (Buchmuller, Di Bari, Plumacher)



m_ν too small : Yukawa couplings too small to bring heavy N into equilibrium
m_ν too large : Erasure processes too efficient

$$M_N \gtrsim O(10^9)\mathrm{GeV}\left(\frac{2.5\times 10^{-3}}{Y_N}\right)\left(\frac{0.05\mathrm{eV}}{m_\nu}\right)$$

$M_N \gtrsim 10^9$ GeV – does not sit well with hierarchy in non-SUSY case

– Tension with with SUSY unification gravitino overproduction

Mass and CP phase constraint

The mass M determining the decay rate enters the CP violating diagrams; M is connected to light ν mass through see-saw.

- Analysis of see-saw formula with three generations taken into account show, for thermal leptogenesis, (Davidson and Ibarra 2002)

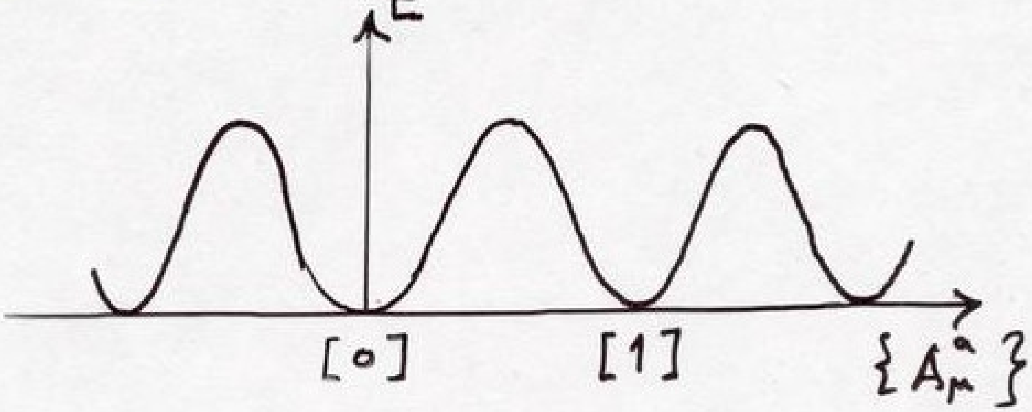
$$|\varepsilon_{CP}| \leqslant 10^{-7}\left(\frac{M_1}{10^9\mathrm{GeV}}\right)\left(\frac{m_3}{0.05\mathrm{eV}}\right)$$

- This can be too small for producing the asymmetry

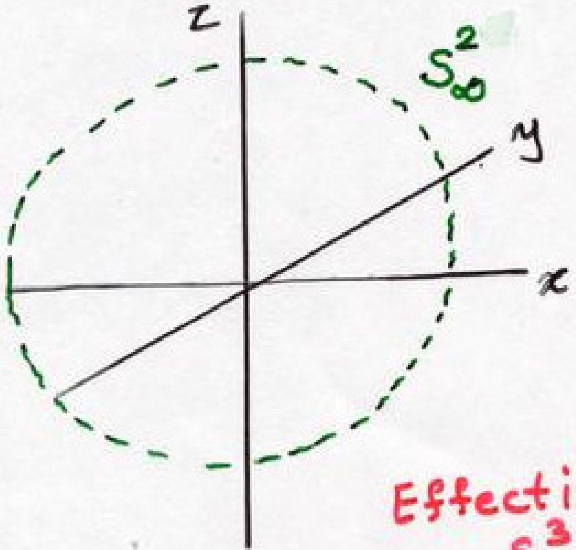
Details of : Anomalous violation of $B + L$

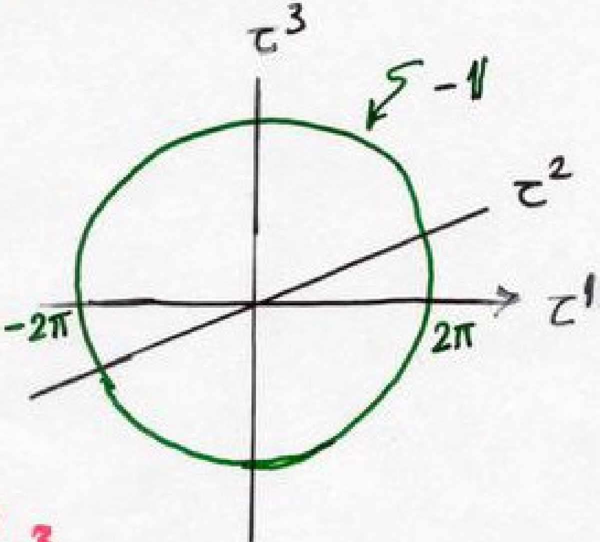
- Gauge theories are non-linear and possess a non-trivial vacuum structure (Jackiw-Rebbi 1973; Polyakov 1976; Klimkhammer-Manton; Soni 1984)

"Large" gauge transformations



$$U^{[1]}_{J\text{-}R} = \frac{\lambda^2 - r^2}{\lambda^2 + r^2} + i\,\frac{2\,\vec{\tau}\cdot\vec{r}\,\lambda}{\lambda^2 + r^2}$$





Effectively $S^3 \rightarrow S^3$

Each vacuum characterised by

$$N_g = \int d^3x \, K^0$$

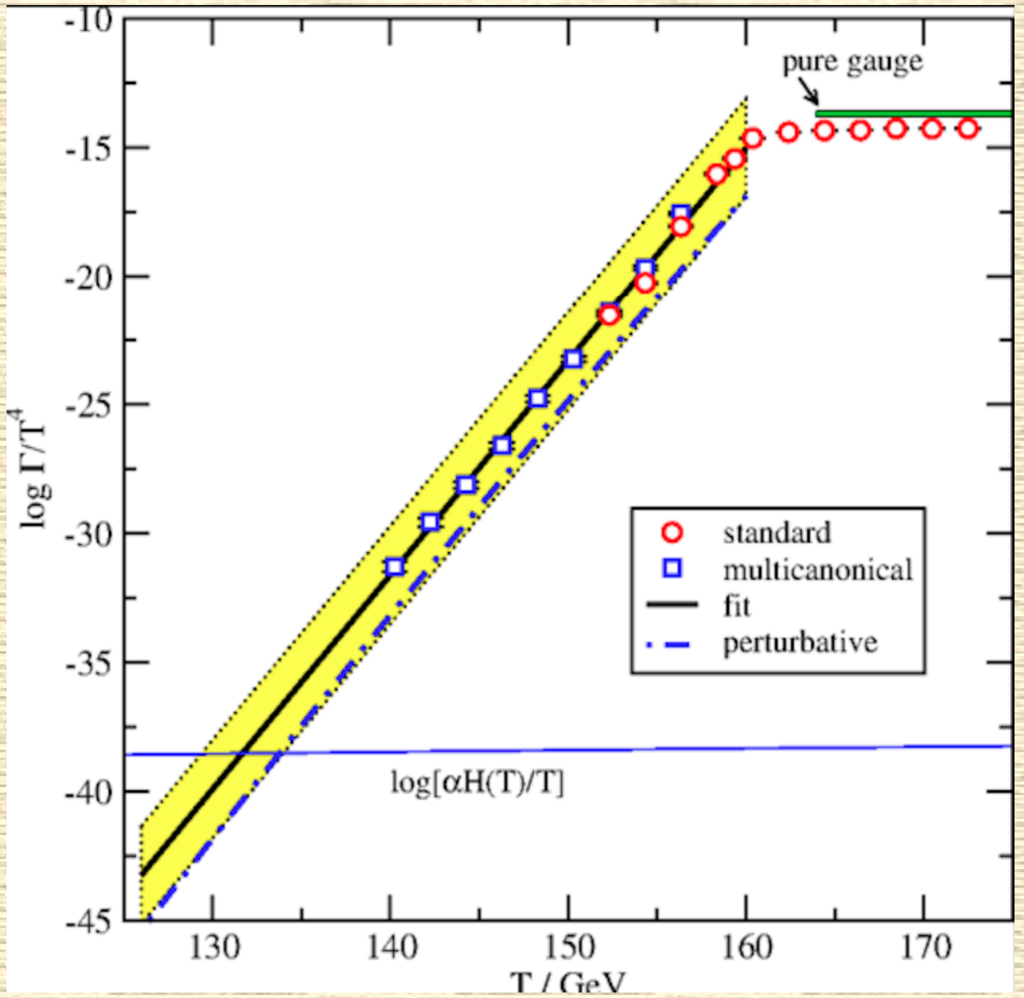
where

$$K^\mu = \mathrm{Tr} \, \varepsilon^{\mu\nu\rho\sigma} \left(A_\nu \partial_\rho A_\sigma - \frac{2}{3} A_\nu A_\rho A_\sigma \right)$$

Interestingly, if there are chiral fermions coupled to this gauge field, then their axial current turns out to be anomalous in QFT, resulting in

$$\Delta N_F = \Delta N_g$$

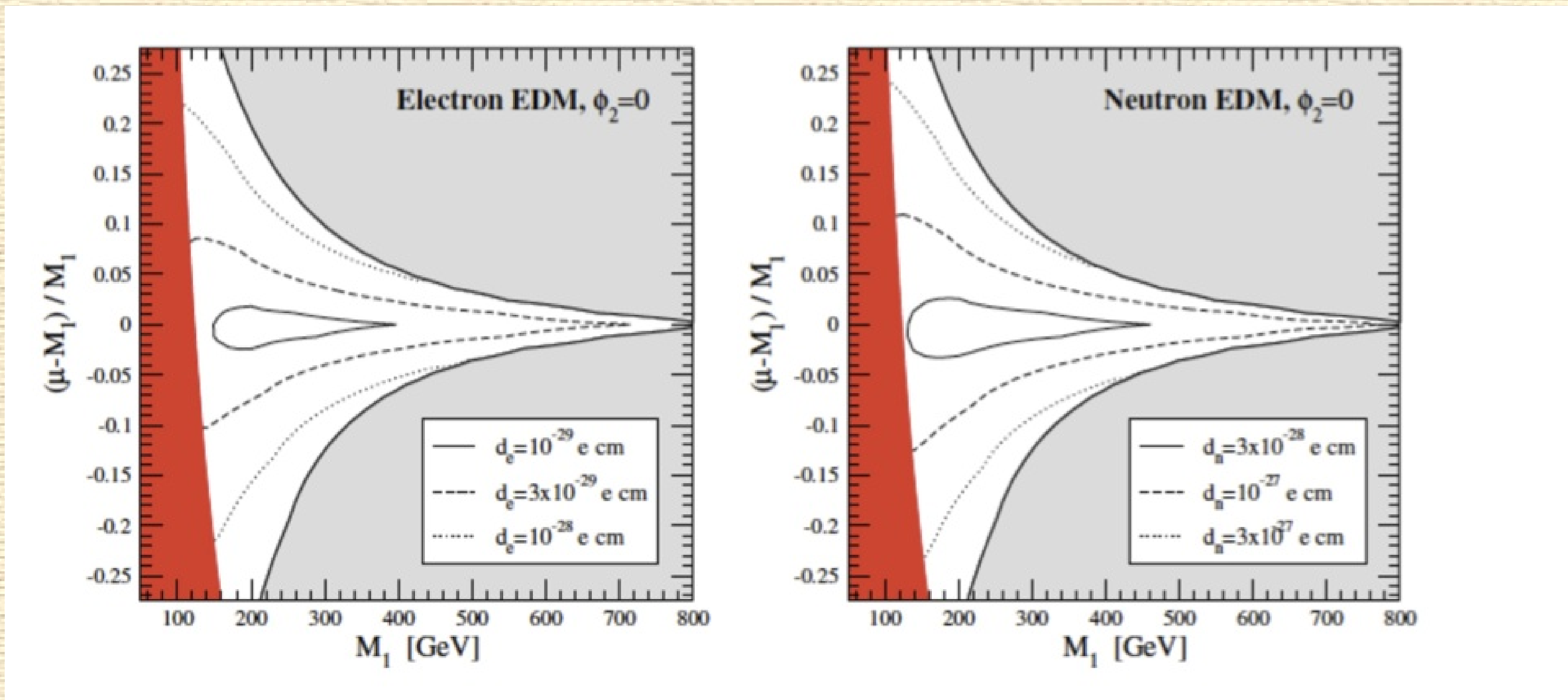
Sphaleron rate with Higgs boson, D>2012



Rummukainen et al (2014)

But "sphaleron" B+L violation possible at colliders!! (Shaposhnikov 199x)

Electron EDM and SUSY CP violation



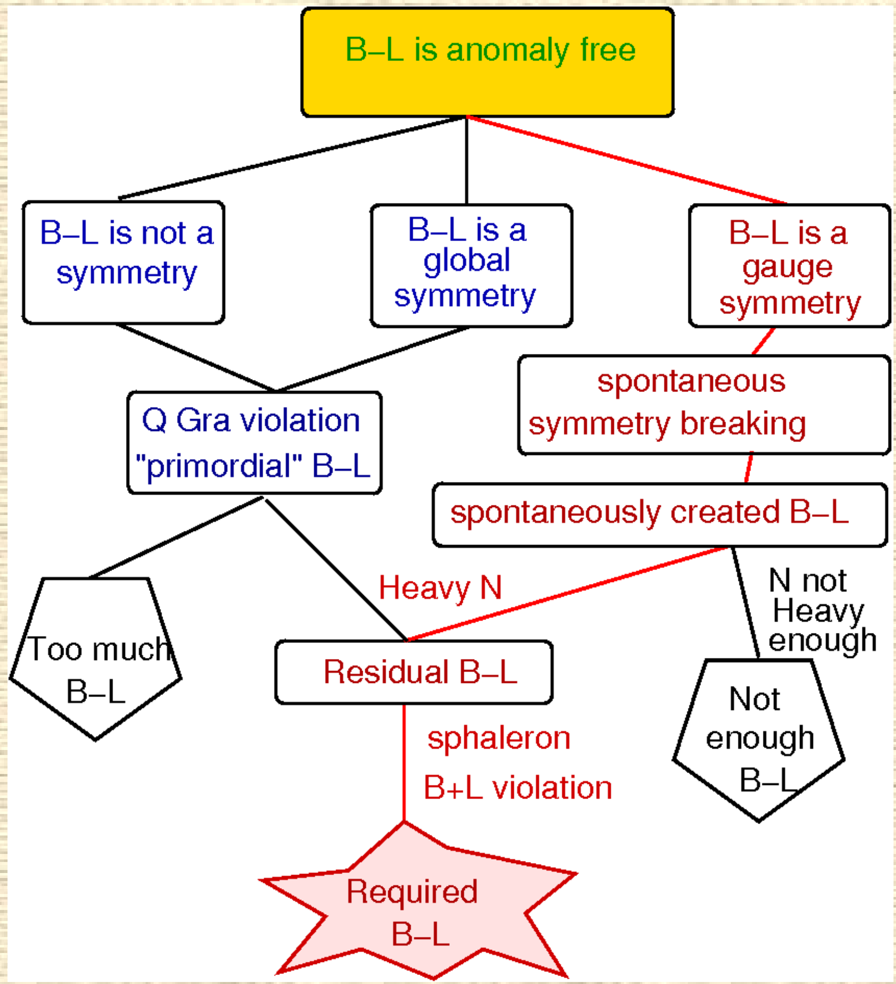
Morrissey and Ramsey-Musolf (2012)

$$d_f \simeq \sin\delta_{\rm CP}\left(\frac{m_f}{\rm MeV}\right)\left(\frac{1{\rm TeV}}{M}\right)^2 \times 10^{-26} e\,{\rm cm}$$

With $M \sim 500$GeV for sufficient abundance at 100GeV, $\delta_{\rm CP} \sim 0.01$ and not adequate source of baryon asymmetry from the walls.

SUSY partner becoming heavy (split SUSY) can suppress the one-loop EDM, yet preserve B-genesis –> untestable from EDM.

What choices did der Alte have?



Salvaging leptogenesis

Precursors ... relative importance of the diagrams producing CP

"Resonant" leptogenesis (Pilaftsis 1997)

$$\mathcal{L}_{\rm Yuk} = -\sum_{i,j=1}^{3} \left(h^{\nu}_{ij} \bar{L}_i \tilde{\Phi} \frac{(1+\gamma^5)}{2} N_j + \hat{h}^{l}_{ij} \bar{L}_i \Phi \frac{(1+\gamma^5)}{2} l_i + h.c. \right)$$

A. Pilaftsis, T.E.J. Underwood / Nuclear Physics B 692 (2004) 303–345 305

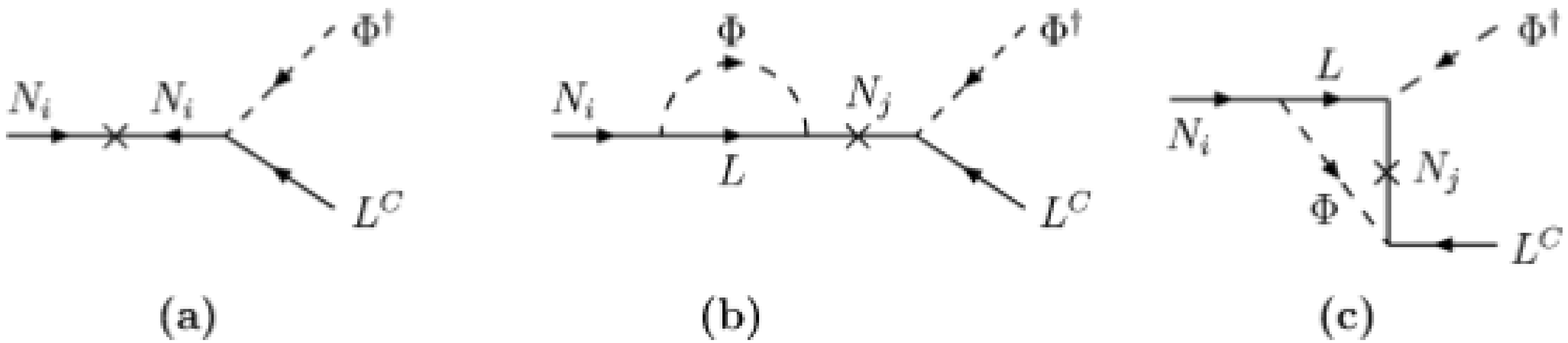
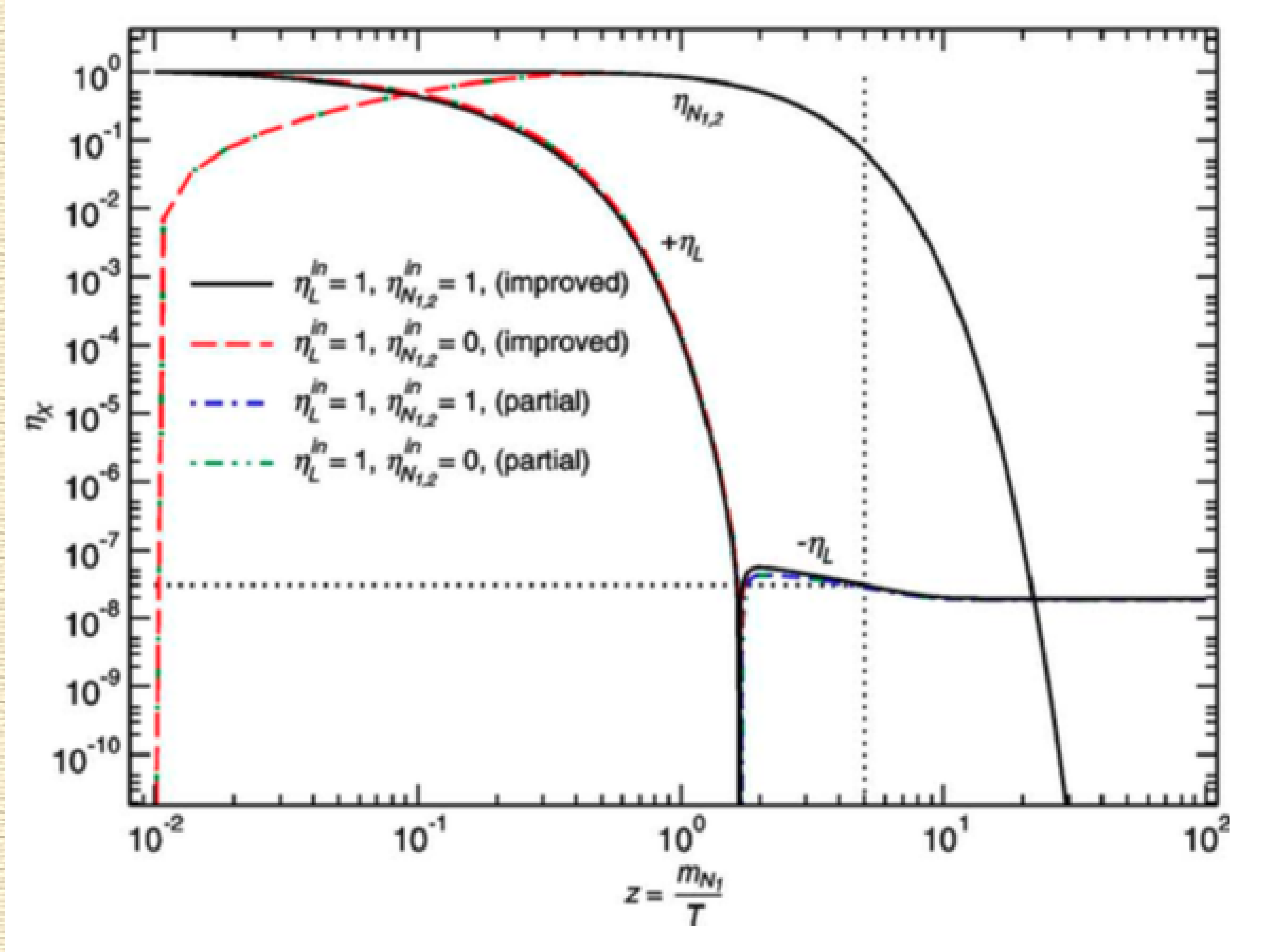


Fig. 1. Feynman diagrams contributing to the L-violating decays of heavy Majorana neutrinos, $N_i \to L^C \Phi^\dagger$, where L and Φ represent lepton and Higgs-boson iso-doublets, respectively: (a) tree-level graph, and one-loop (b) self-energy and (c) vertex graphs.

- CP violation from interference of tree level and absorptive part of the loop diagrams
  - → "ϵ-type" (originating in oscillation) from self energy diagram
  - → "ϵ'-type" (also involving decay) from the vertex diagram
- ϵ-type much larger and can be order 1 if the mass difference of the heavy neutrinos of the order of their decay widths.

The last requirement makes the QFT interpretation and calculation difficult. Resummation technique is required.



Sample results for $M_N \sim 1$TeV, $\Delta M_N / M_N \sim 10^{-9}$, $\epsilon \sim 10^{-7}$, $\eta_L \sim 1$.
The dotted line 5×10^{-7} indicates the required Lepton asymmetry so that after sphaleronic processes the required Baryon asymmetry would be produced.

“Just” Beyond the SM ?

GUT naturalness of gauge coupling unification —> see-saw M_N was expected to fit in.
But note that

$$\begin{aligned} m_N &\approx \frac{m_D^2}{m_\nu} \\ &\approx 10^{14}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2 \\ &\approx 10^{4}\mathrm{GeV}\left(\frac{0.1\mathrm{eV}}{m_\nu}\right)\left(\frac{m_D}{1\,\mathrm{MeV}}\right)^2 \end{aligned}$$

So in the absence of any suggestive high scale, may as well explore the PeV scale.

Left-right as JBSM

Just Beyond the Standard Model ... $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes U(1)_X$

$$Q = \tau_L^3 + \tau_R^3 + \frac{1}{2}X$$

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
ν_L	$+\frac{1}{2}$	0		0
e_L^-	$-\frac{1}{2}$	0		-1
ν_R	0	$+\frac{1}{2}$		0
e_R^-	0	$-\frac{1}{2}$		-1

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
u_L	$+\frac{1}{2}$	0		$+\frac{2}{3}$
d_L	$-\frac{1}{2}$	0		$-\frac{1}{3}$
u_R	0	$+\frac{1}{2}$		$+\frac{2}{3}$
d_R	0	$-\frac{1}{2}$		$-\frac{1}{3}$

Gauged $B - L$

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
$\lceil \nu_L \rceil$	$+\frac{1}{2}$	0	$-\frac{1}{2}$	0
$\lfloor e_L^- \rfloor$	$-\frac{1}{2}$	0	$-\frac{1}{2}$	-1
$\lceil \nu_R \rceil$	0	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$\lfloor e_R^- \rfloor$	0	$-\frac{1}{2}$	$-\frac{1}{2}$	-1

	τ_L^3	τ_R^3	$\frac{1}{2}X$	Q
$\lceil u_L \rceil$	$+\frac{1}{2}$	0	$+\frac{1}{6}$	$+\frac{2}{3}$
$\lfloor d_L \rfloor$	$-\frac{1}{2}$	0	$+\frac{1}{6}$	$-\frac{1}{3}$
$\lceil u_R \rceil$	0	$+\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$
$\lfloor d_R \rfloor$	0	$-\frac{1}{2}$	$+\frac{1}{6}$	$-\frac{1}{3}$

- In praise of $B - L$ ... the only conserved charge of SM which is not gauged! –> Hereby it gains the status of being gauged

Minimal SUSY L-R Model – MSLRM

The minimal set of Higgs superfields required is,

$$\begin{aligned} \Phi_i &= (1,2,2,0), & i &= 1,2, \\ \Delta &= (1,3,1,2), & \bar{\Delta} &= (1,3,1,-2), \\ \Delta_c &= (1,1,3,-2), & \bar{\Delta}_c &= (1,1,3,2), \\ \Omega &= (1,3,1,0), & \Omega_c &= (1,1,3,0) \end{aligned}$$

where the bidoublet is doubled so that the model has non-vanishing Cabibo-Kobayashi-Maskawa matrix. The number of triplets is doubled to have anomaly cancellation.

Under discrete parity symmetry the fields are prescribed to transform as,

$$\begin{aligned} Q &\leftrightarrow Q_c^*, & L &\leftrightarrow L_c^*, & \Phi_i &\leftrightarrow \Phi_i^\dagger, \\ \Delta &\leftrightarrow \Delta_c^*, & \bar{\Delta} &\leftrightarrow \bar{\Delta}_c^*, & \Omega &\leftrightarrow \Omega_c^*. \end{aligned} \tag{1}$$

The F-flatness and D-flatness conditions lead to the following set of vev's for the Higgs fields as one of the possibilities,

$$\langle\Omega_c\rangle = \begin{pmatrix} \omega_c & 0 \\ 0 & -\omega_c \end{pmatrix}, \quad \langle\Delta_c\rangle = \begin{pmatrix} 0 & 0 \\ d_c & 0 \end{pmatrix}, \quad \langle\Phi_i\rangle = \begin{pmatrix} \kappa_i & 0 \\ 0 & \kappa_i' \end{pmatrix} \tag{2}$$

This ensures spontaneous parity violation [Aulakh, Bajc, Melfo, Rasin, Senjanovic (1998 ...)] Mass scale see-saw

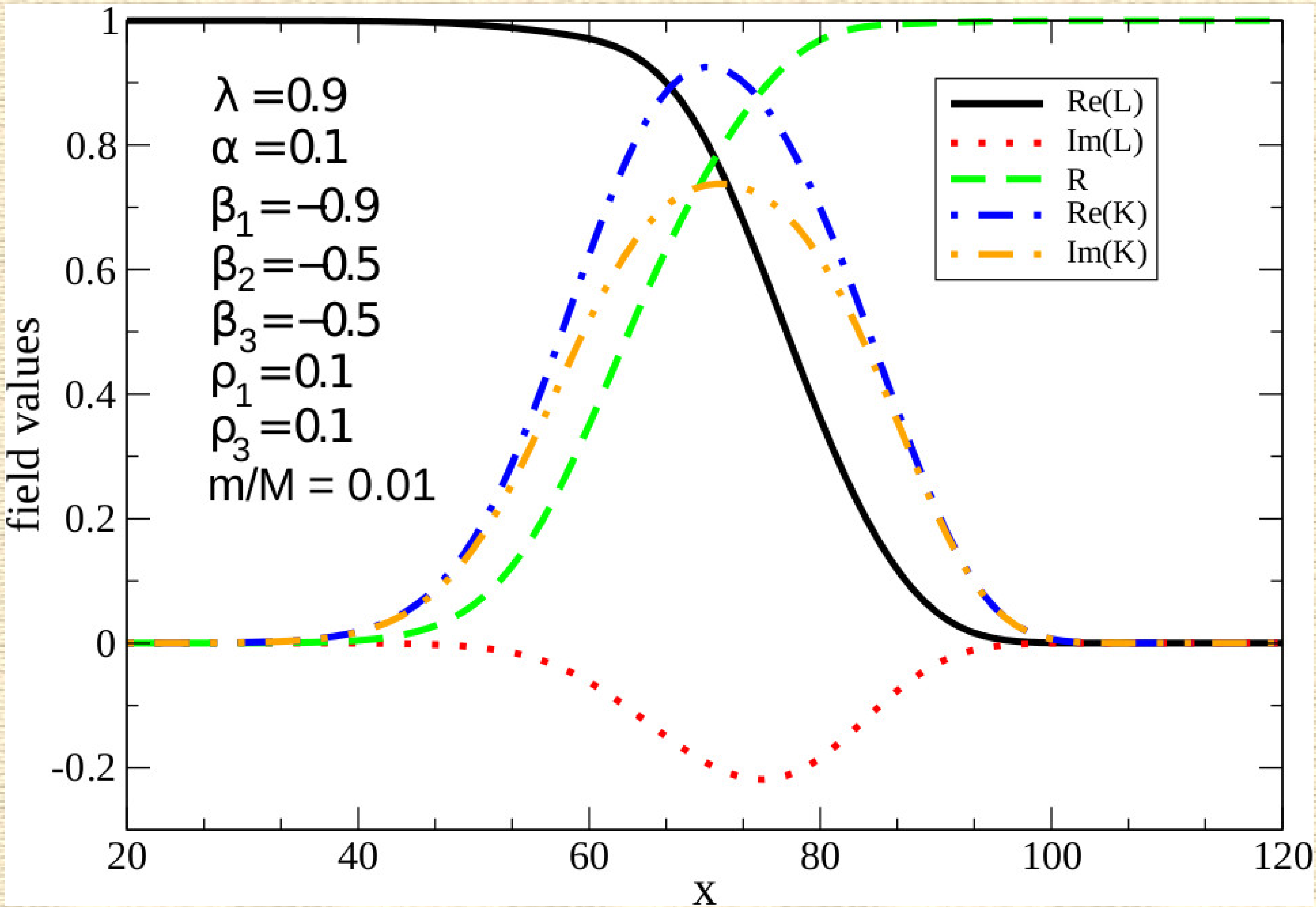
- An R symmetry ensures Ω mass terms in superpotential are vanishing, no new spurious mass scale
- Leads naturally to a see-saw relation

$$\boxed{M_{B-L}^2 = M_{EW} M_R}$$

- Leptogenesis postponed to an energy scale closer to M_{EW} not a high scale like $10^9 - 10^{14}$ GeV

Non-thermal leptogenesis

Example of simulated domain walls in a Left-Right symmetric model



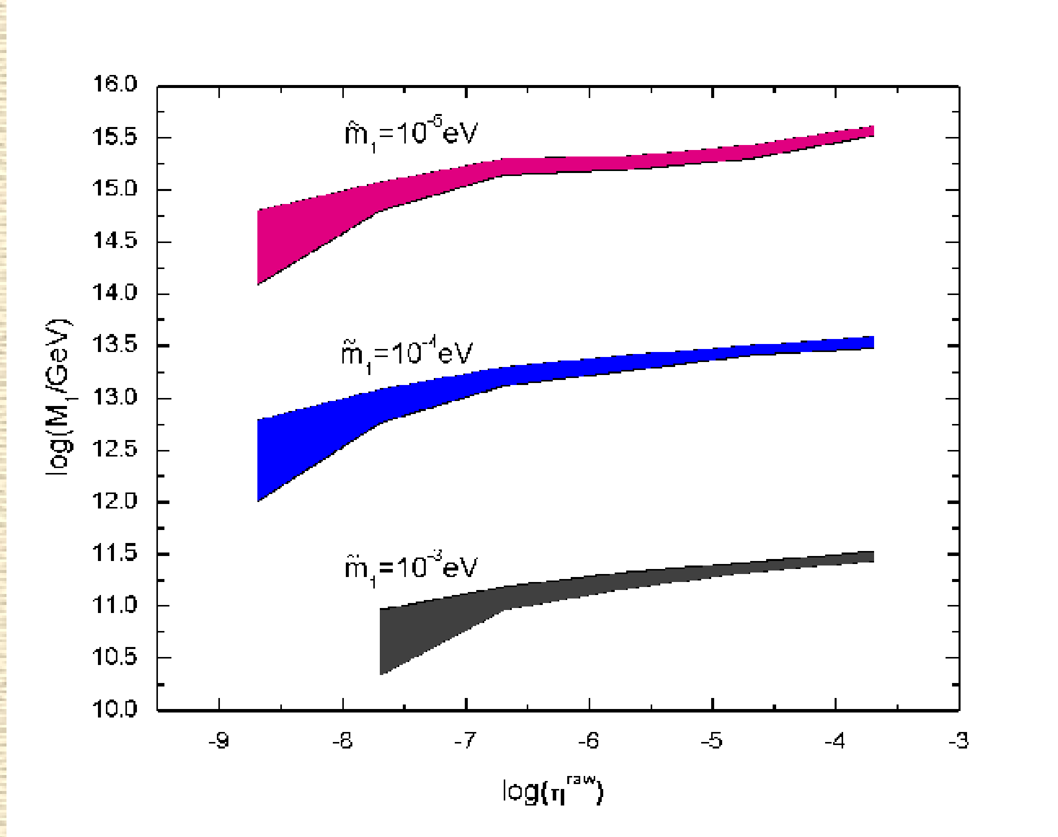
If we ask the reverse question : if the N mass is not as high as required for thermal Leptogenesis, do we still have the scope for producing baryon asymmetry?

The answer is yes. (Cline, Rabikumar and UAY, PRD 2002; Anjishnu Sarkar, UAY PRD 2003)

- The left-right symmetric model has domain walls, with sufficient CP violation provided by the scalar condensates to produce lepton number at a low scale.
- The effect is the same as having bubble walls
- Open question : relating the dynamical $O(1)$ CP phase to static phases in EDM etc.

Can this lepton asymmetry survive?

This question was answered in the affirative, solving Boltmann equations (Narendra Sahu and UAY PRD 2005)



Washout with low scale W_R

Dhuria, Hati, Rangarajan and Sarkar (2015)

Wash out factor K estimated to be in the range 10^9 to 10^{11} for $M_{W_R} \sim 2$TeV.

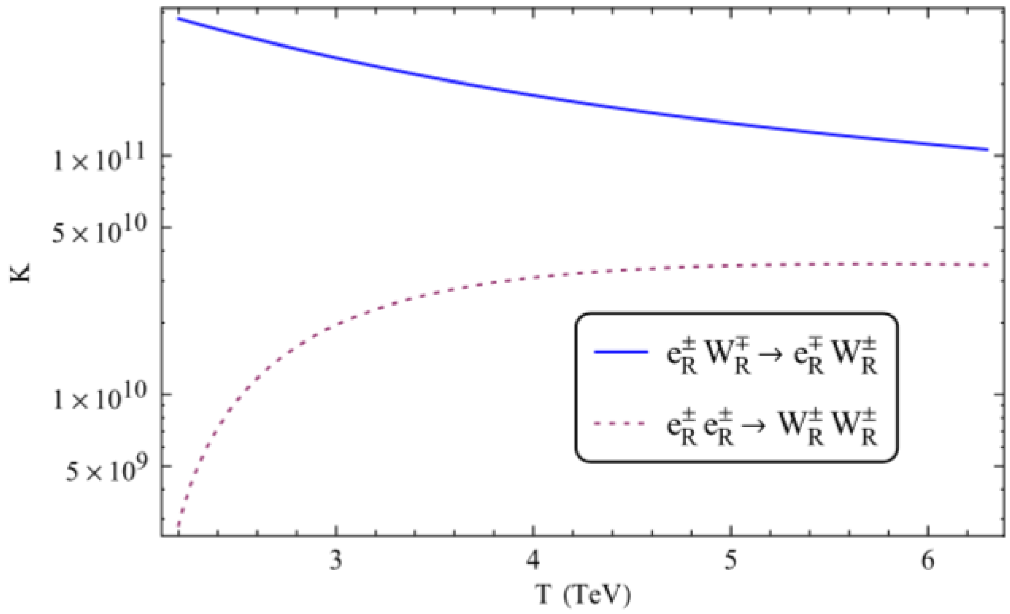
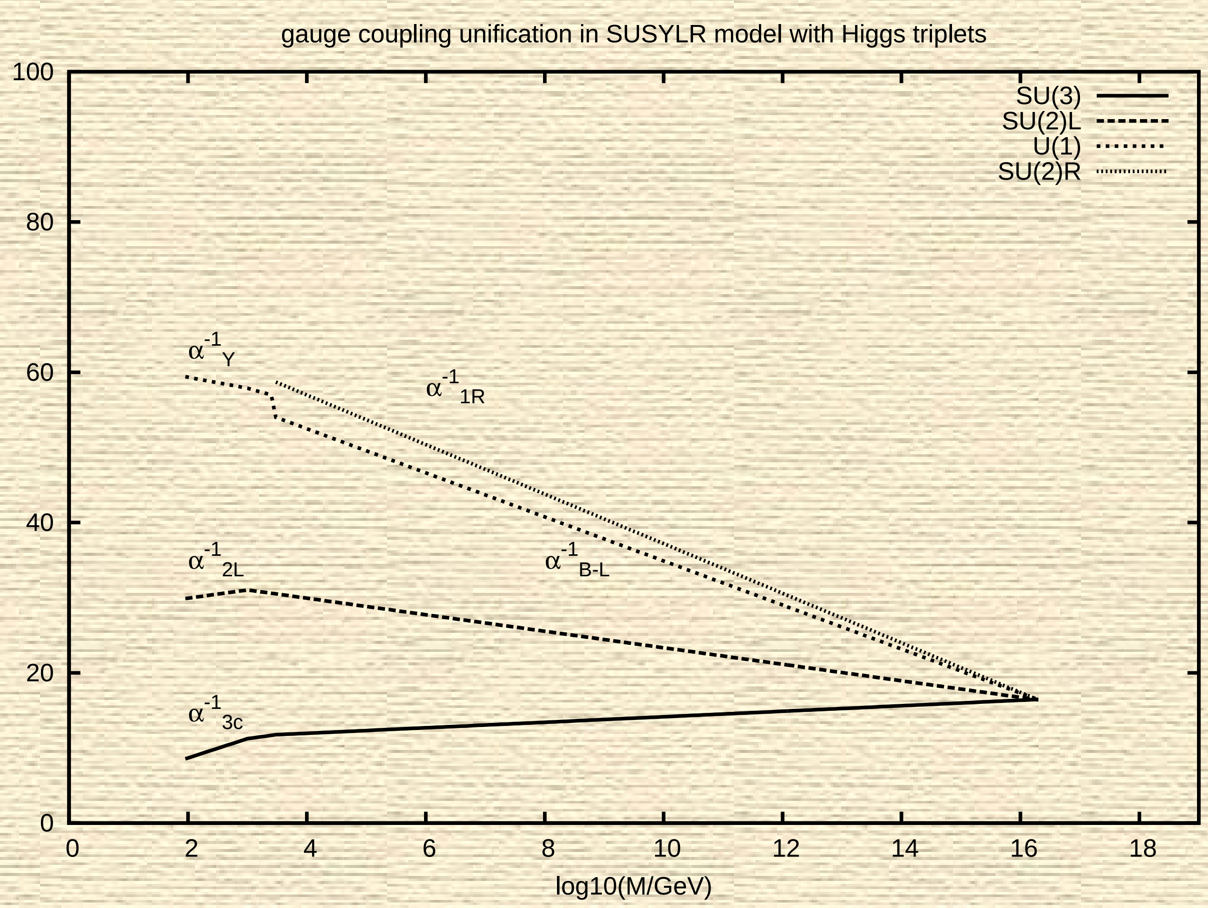


FIG. 2 (color online). Plot showing K as a function of temperature (T) with $M_{W_R} = 2.1$ TeV for the scattering processes $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ and $e_R^\pm e_R^\pm \to W_R^\pm W_R^\pm$ (including both Δ_R^{++} and N_R mediated diagrams) for $v_R > T > M_{W_R}$.

Domain wall based mechanism for $\eta_{\rm raw}$ and compatible lower bound on M_{W_R} needs to be checked in this context.

Unification ... conditional

Aulakh-Bajc-Melfo-Rasin-Senjanovic model



Unification of coupling is achieved in this model (Debasish Borah & UAY PRD 2010)

- Breaking of $U(1)_{B-L}$ can be as low as 3 TeV

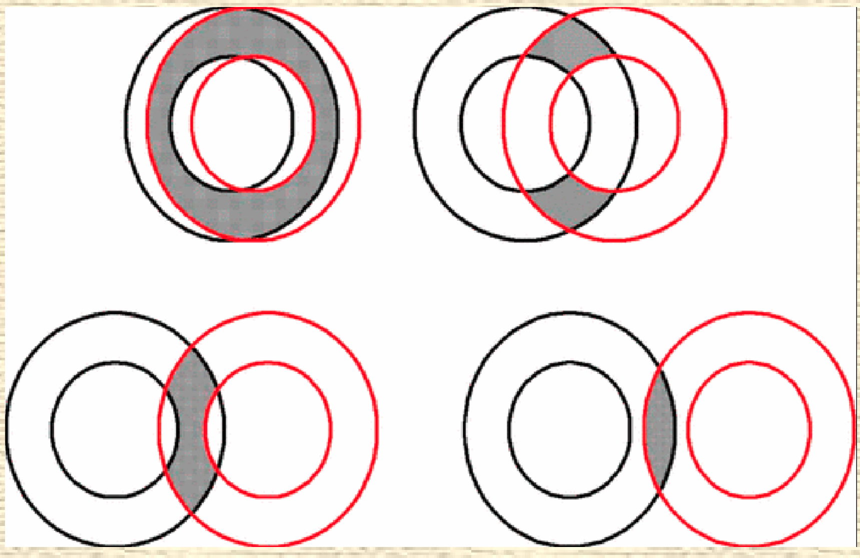
- Need to add new scalars at a higher scale. (Explored exhaustively–> Kopp, Lindner, Niro, Underwood 2009)

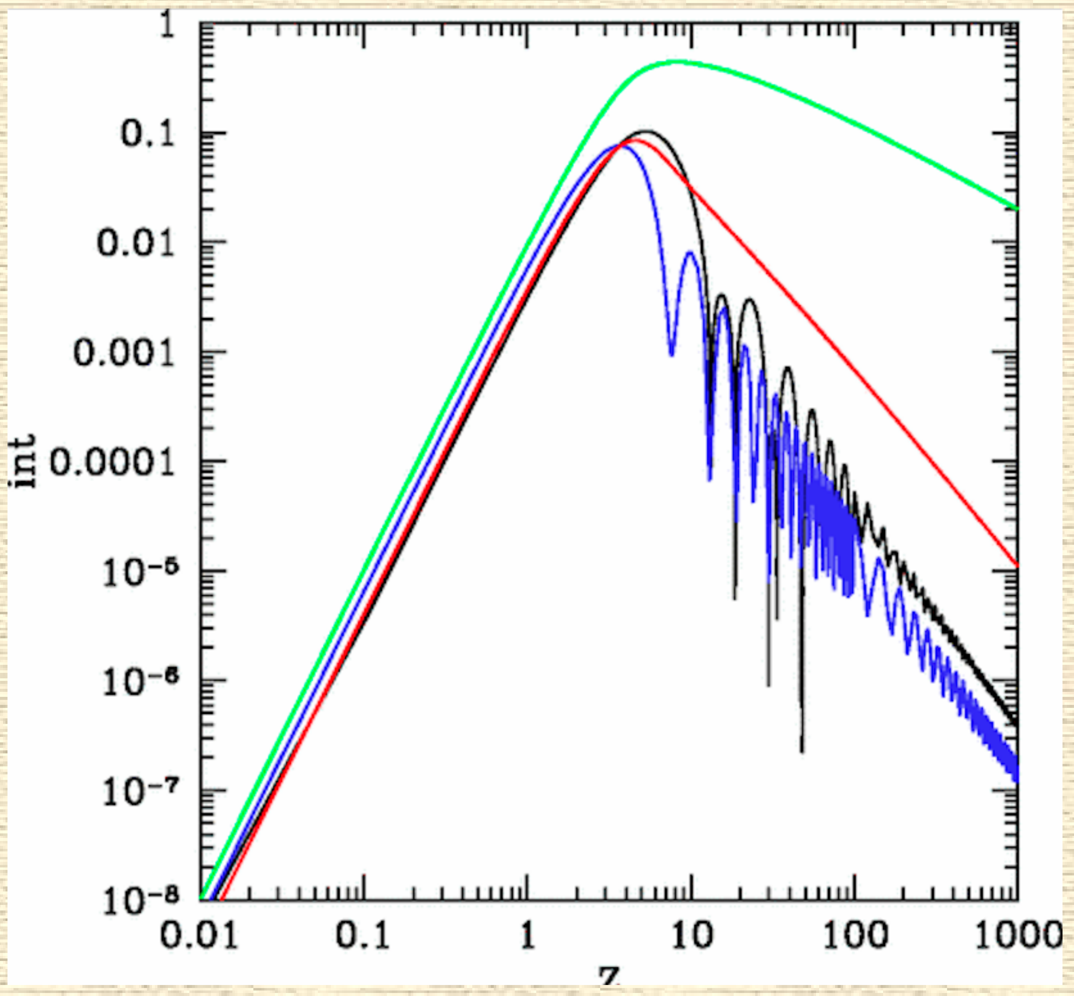
What was not covered ...

... a very very limited list

- Affleck-Dine mechanism
- Soft leptogenesis (soft SUSY breakign terms; resonant)
- "Put-it-all-together" models
  - νMSM ... Shaposhnikov
  - SM*A*S*H ... Ringwald (SM+Axion+Seesaw+Higgs portal inflation)
  - In this conference ... M K P's talk
- Connection to collider LFV ...
- Collider $(B + L)$V through sphalerons !!!

Gravitational waves as signature





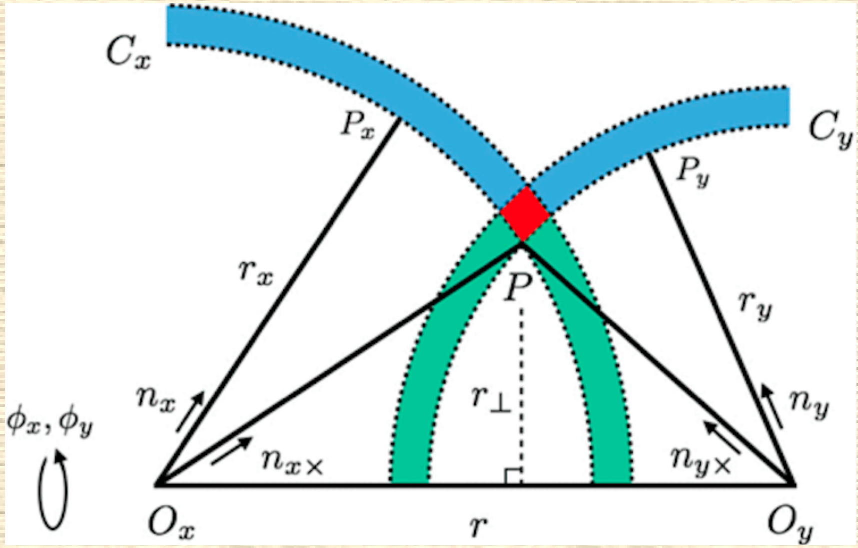
Graphical set up ...

Integrals determining the GW spectra as a function of z.

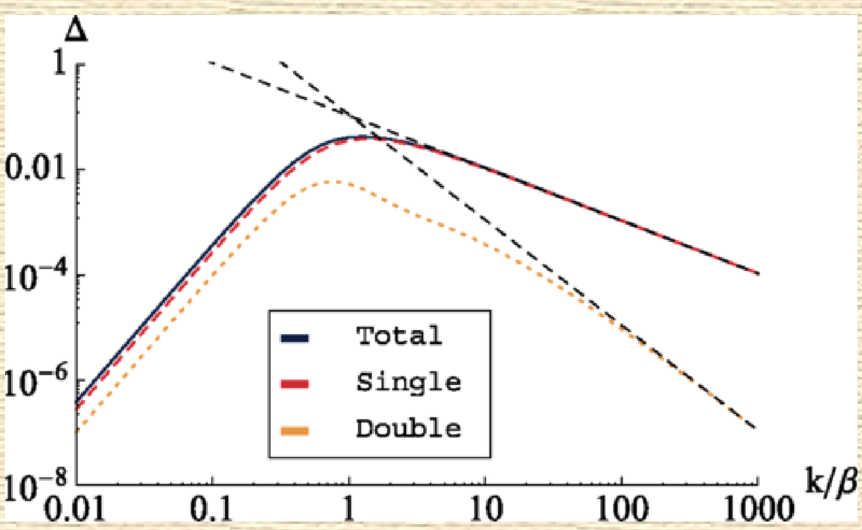
Servant, Caprini, Durrer 2009

Jinno and Takimoto 2017

Modelling the details,



Results



spectrum of Gr waves as a function of wave number

Conclusions and caveats

- Extensions beyond merely accommodating the massive neutrinos required beyond SM –> CP violation; O-o-Eq conditions
- Thermal leptogenesis is viable and appealing ...
  - needs to rely on expedients such as resonance
- Many other variants not necessarily thermal but relying details of particle interactions ... QFT subtleties
- Several collider and non-accelerator constraints ...
- "Put-it-all-together" models
- Non-thermal leptogensis natural through domain walls
- Domain wall disappearance requirement
  - constrains the model (LRSM case doen by us)
  - Gravitational waves as a signature

—> Thanks page

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