Split Fermions & Leptogenesis

Gilad Perez

LBNL, UC Berkeley

Y. Grossman & G.P., PRD **69**, (03) 015011;

Y. Nagatani & G.P., hep-ph/0401070;

Y. Grossman, R. Harnik, G.P., M. Schwartz & Z. Surujon, hep-ph/0407260.

Outline

- Twisted Split fermions.
- Leptogenesis.
- Conclusions.

Motivation

Why split fermions?

- Solution of the flavor puzzle.
- Suppression of proton decay.

$$\Updownarrow$$

Hierarchies without symmetries.

Requirements & pre-assumptions

- **Universal extra (flat) *stable* dimension.**
  (Higgs in the bulk)
- Localization $\Leftrightarrow$ 5D translation breaking.

$$\Downarrow$$

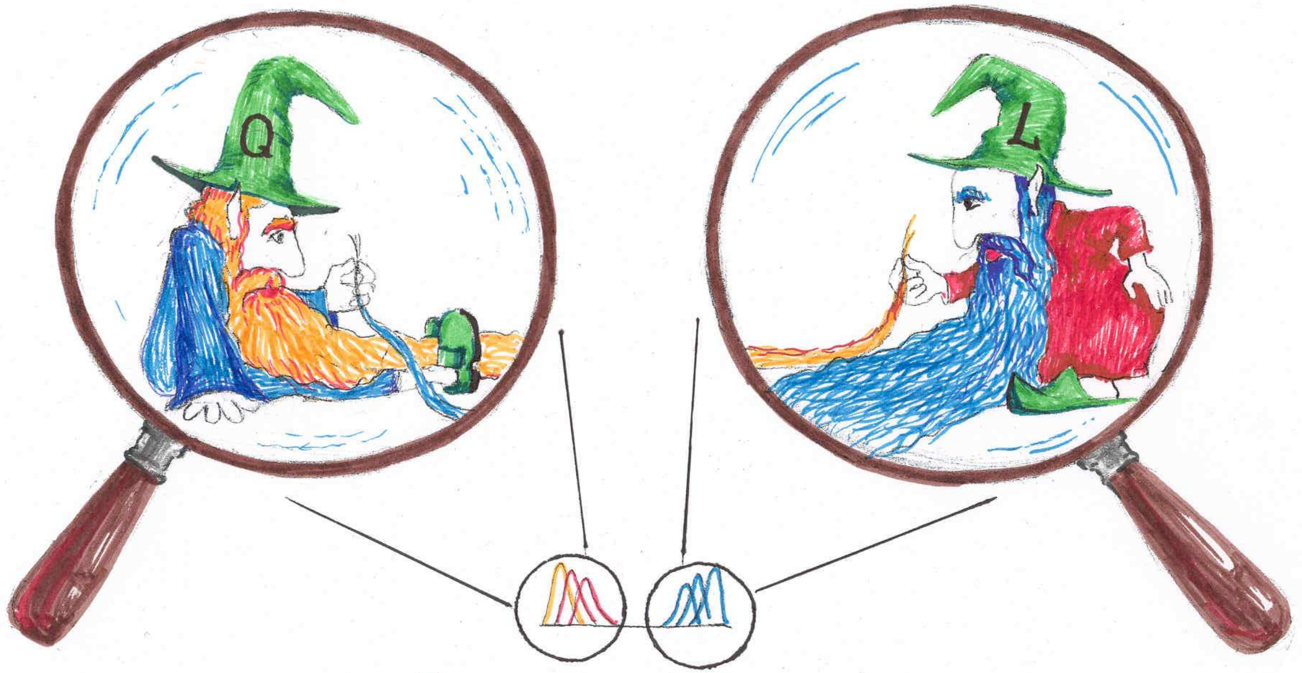
Separation $\Leftrightarrow$ Flavor violation.

$$\Updownarrow$$

Flavor hierarchy and mixing.

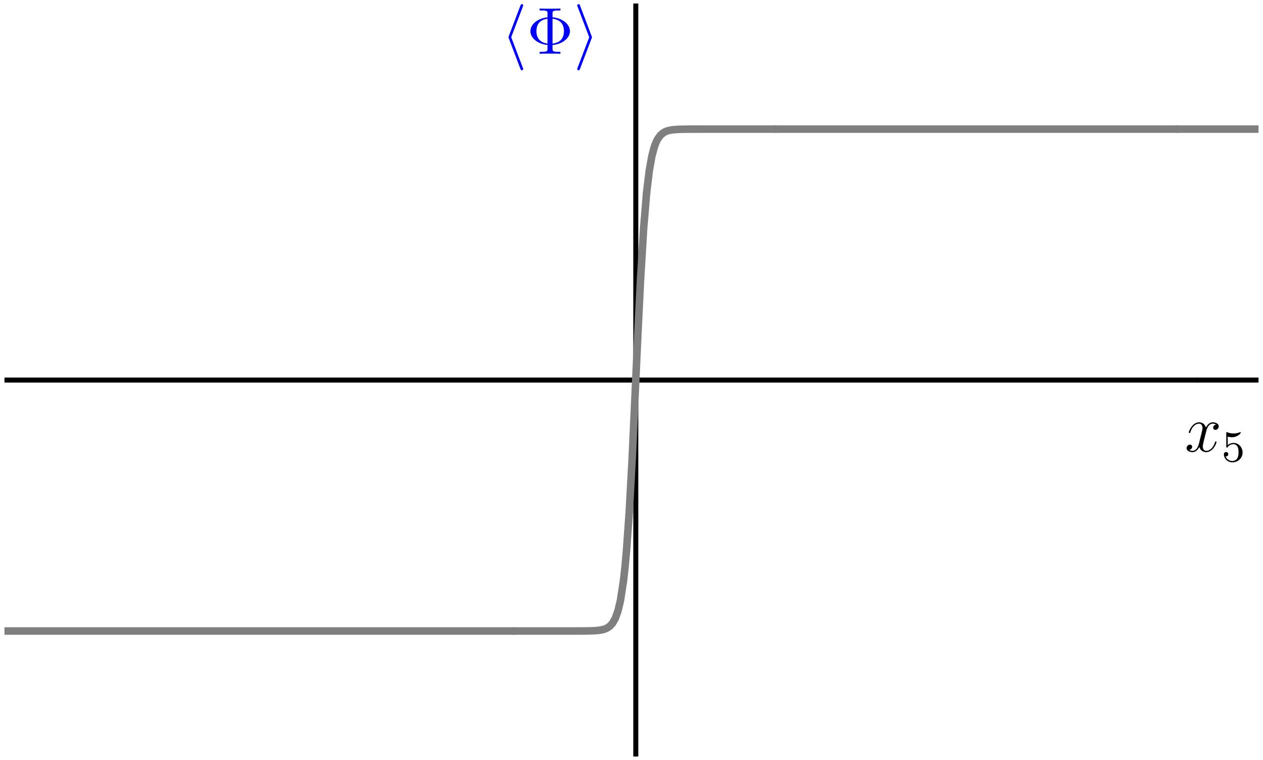
Split fermions - requirements

Separation



Basic Idea - fermion **localization**

- $\langle\Phi\rangle$, SM singlet, in a domain wall scenario:



$$\langle\Phi(x_5=\infty)\rangle = -\langle\Phi(x_5=-\infty)\rangle = V\ .$$

Localizing the fermions

- $\langle \Phi(x_5) \rangle$ is of a domain wall shape.

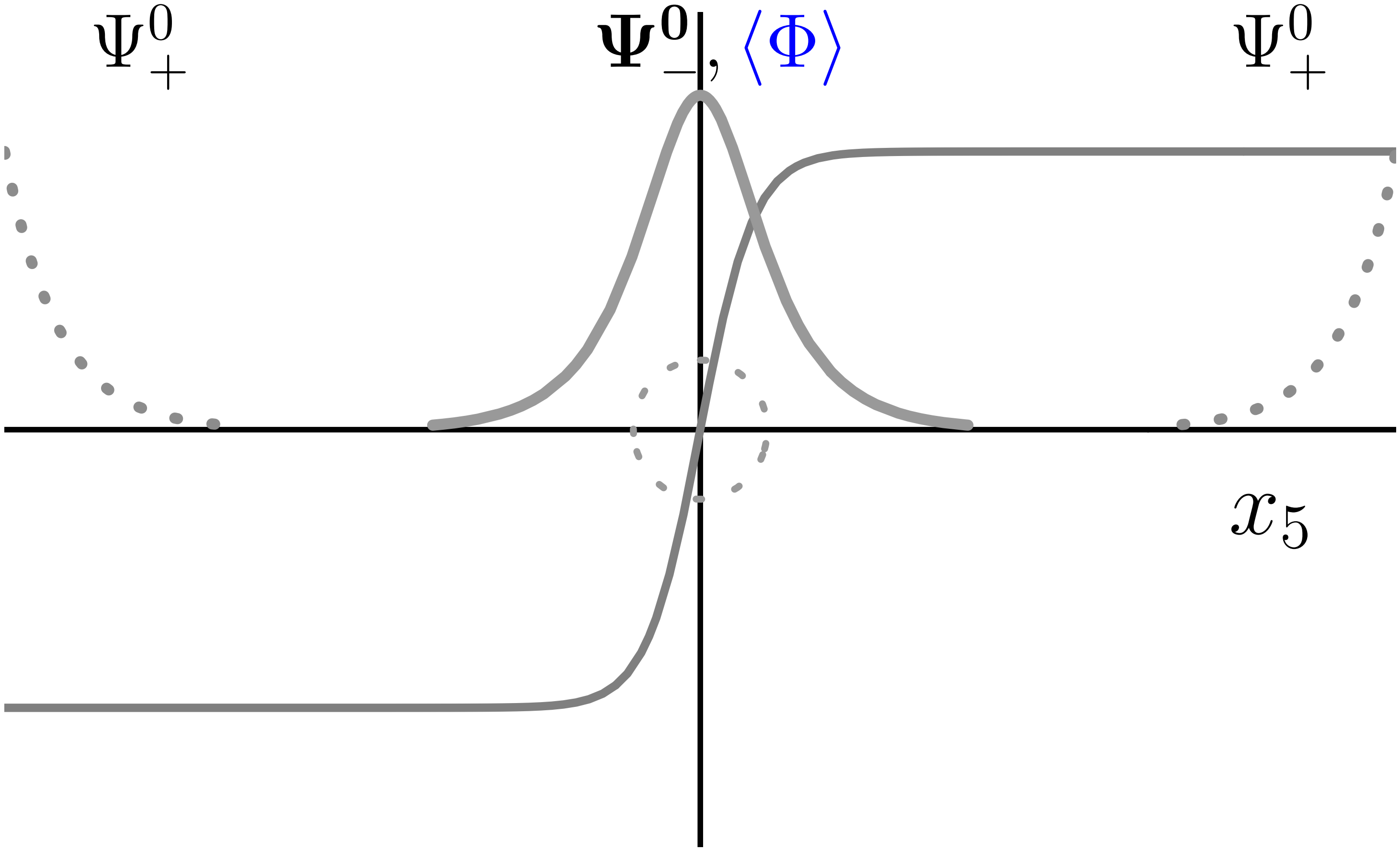
- Yukawa interactions are:

$$\mathcal{S}_5 = \int dx_5 \bar{\Psi} \left[i\gamma^5 \partial_5 + \Phi(x_5) \right] \Psi$$

- Euler-Lagrange eqs. $\Rightarrow$ **2** zero modes.

Fermion Localization

One zero-mode is localized around the "zero" of $\langle \Phi \rangle$!!



Arkani-Hamed-Schmaltz model

PRD (00).

Chirality- Infinite 5D, a 0-mode projected out.

Localization- Strong translation violation, $\langle \Phi \rangle \propto x_5$.

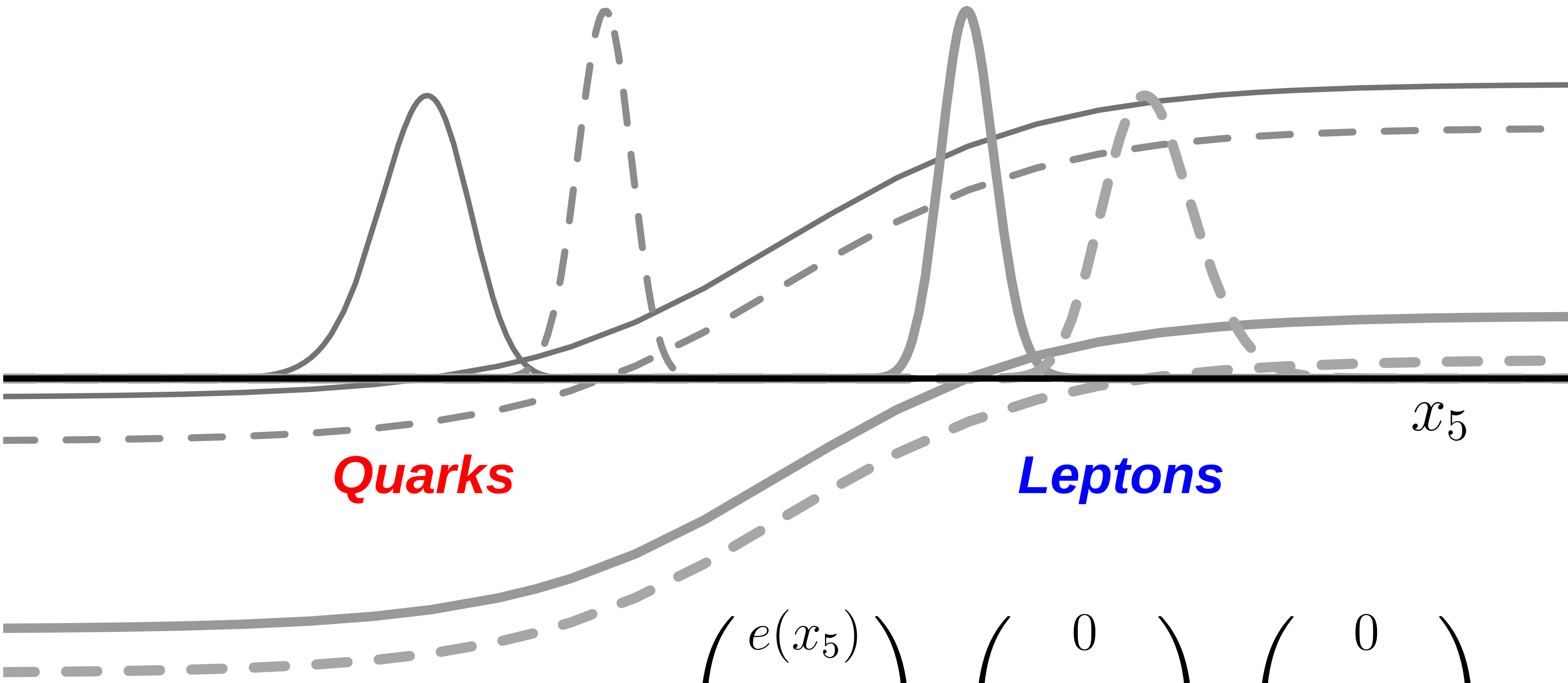
Separation- Flavor violating masses, M_i:

$$\mathcal{L}_{5D} = \Sigma_i \left[\bar{\Psi}_i \left(f \Phi + \mathbf{M}_i \right) \Psi_i \right]$$

$$\Downarrow$$

2 Flavor violating sources, U(3)$\longrightarrow$U(1)^3

The AS model



$$L_\alpha \propto \begin{pmatrix} e(x_5) \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ \mu(x_5) \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ \tau(x_5) \end{pmatrix}$$

Twisted split fermions

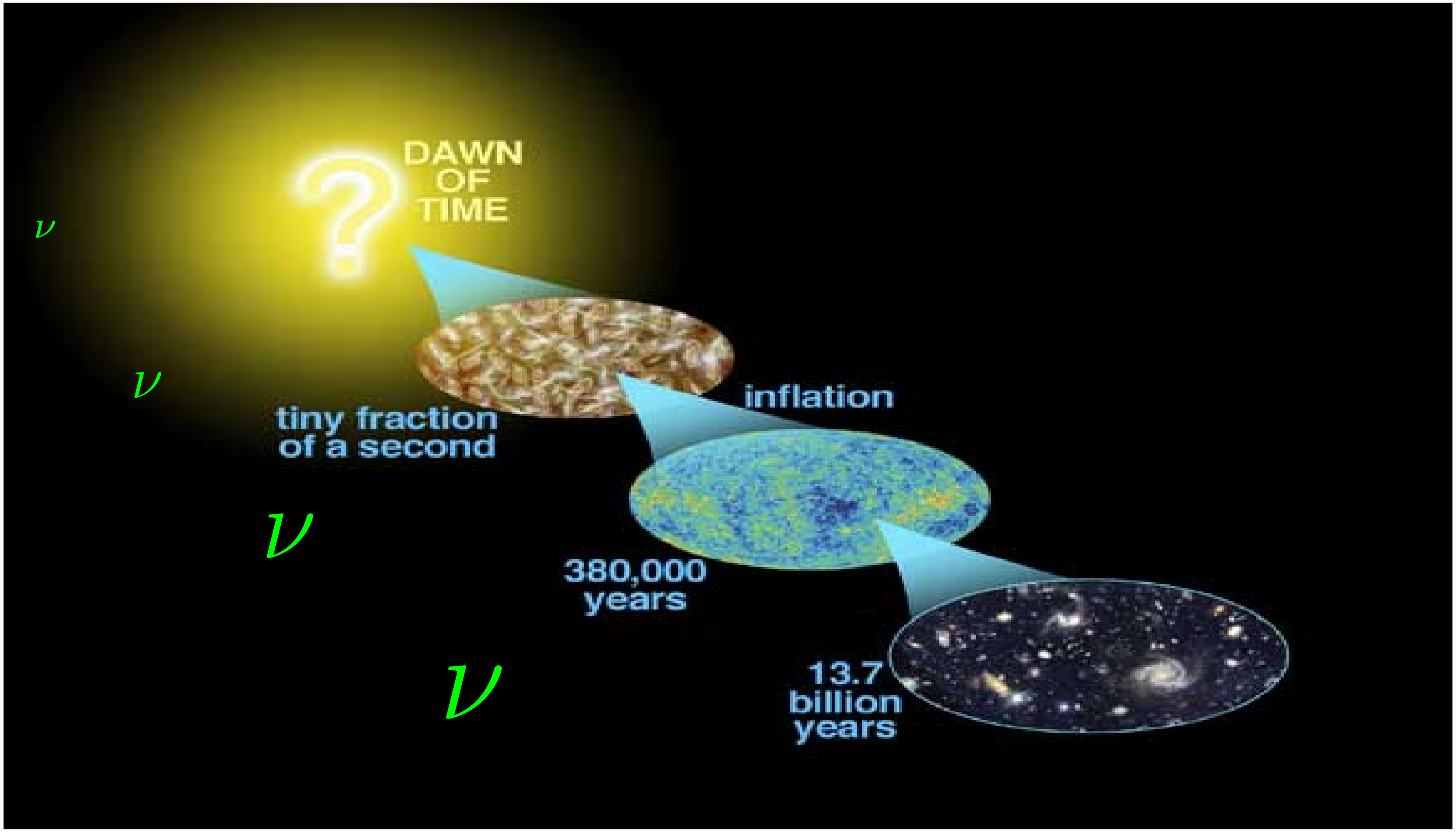
Grossman, Harnik, G.P., Schwartz & Surujun

Twisted split fermions

- Generically: $\mathcal{L}_{5D} = \bar{\Psi}_i \left(f_{ij} \Phi + \mathbf{M}_{ij} \right) \Psi_j$.
- Sym': U(3) $\xrightarrow{\widetilde{\mathbf{M}}}$ U(1) , $\quad \widetilde{\mathbf{M}} \equiv f\Phi + \mathbf{M}$.
- Twist: $\Psi^0_{\alpha i} \propto P \exp \left[\int dx_5 \, \widetilde{\mathbf{M}}(x_5) \right]_{\alpha i}$.
- CPV phase $\Leftrightarrow$ diag(f) + U(1)^3($\mathbf{M}$)U(1)^3.

Leptogenesis

Nagatani & G.P. (04).



Baryogenesis & split fermions

Main Idea: **Bulk scalar baryogenesis**

- Φ, SM singlet.
- At $T > T_c \Longrightarrow \langle\Phi\rangle = 0 \Longrightarrow$ B,L$\neq$ 0.
- At $T \leq T_c \Longrightarrow \langle\Phi\rangle = f(x_5)$:
  - 1st order phase transition (PT).
  - Fermion localization $\rightarrow$ B,L$\sim$ 0.

Sakharov conditions A.D. Sakharov, JETP Lett. (67).

(i) Baryon (B) violation.

(ii) CP violation (CPV).

(iii) Deviation from thermal equilibrium.

Sakharov conditions A.D. Sakharov, JETP Lett. (67).

(i) Baryon (B) violation - Masiero, *et. al.* (00); Chung & Dent (02).

Overlap between leptons $\longrightarrow$ L **+** sphalerons.

(ii) CP violation (CPV).

(iii) Deviation from thermal equilibrium.

Sakharov conditions A.D. Sakharov, JETP Lett. (67).

(i) Baryon (B) violation -

Overlap between leptons $\rightarrow$ L **+** sphalerons!

(ii) CP violation (CPV) -

Twisted $\widetilde{\mathbf{M}}$: $\bar{L}\,(f\Phi + \mathbf{M})\,L \rightarrow$ CPV!

(iii) Deviation from thermal equilibrium.

Sakharov conditions A.D. Sakharov, JETP Lett. (67).

(i) Baryon (B) violation -

Overlap between leptons $\to$ L + sphalerons!

(ii) CP violation (CPV) -

Bulk scalar Yukawas $\bar{L}L\,(f\Phi + M) \to$ CPV!

(iii) Deviation from thermal equilibrium -

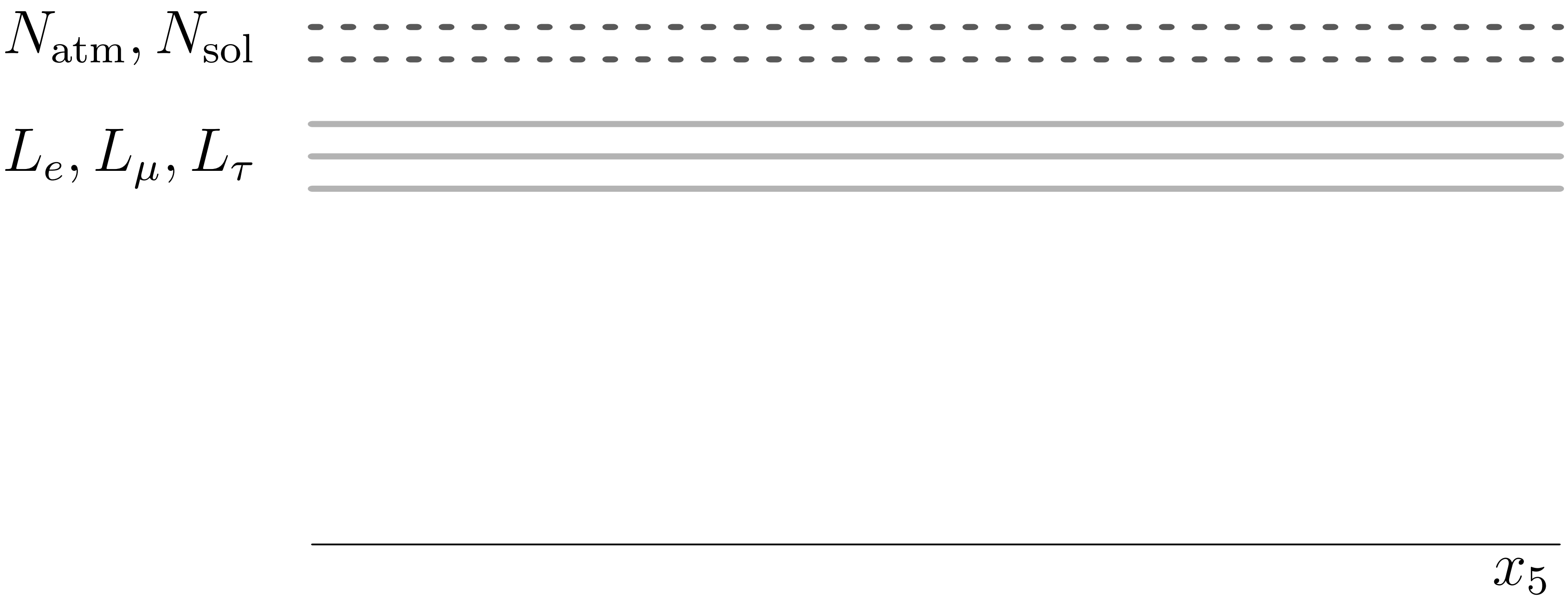
$\langle\Phi\rangle = 0 \to \langle\Phi\rangle = \chi(x_5) \Longleftrightarrow$ 1st order PT!

Lepton/Baryon violation

- At $T \geq T_c \sim R^{-1} \Rightarrow$ large L violation.
- At $T = 0 \Rightarrow$ tiny L violation.

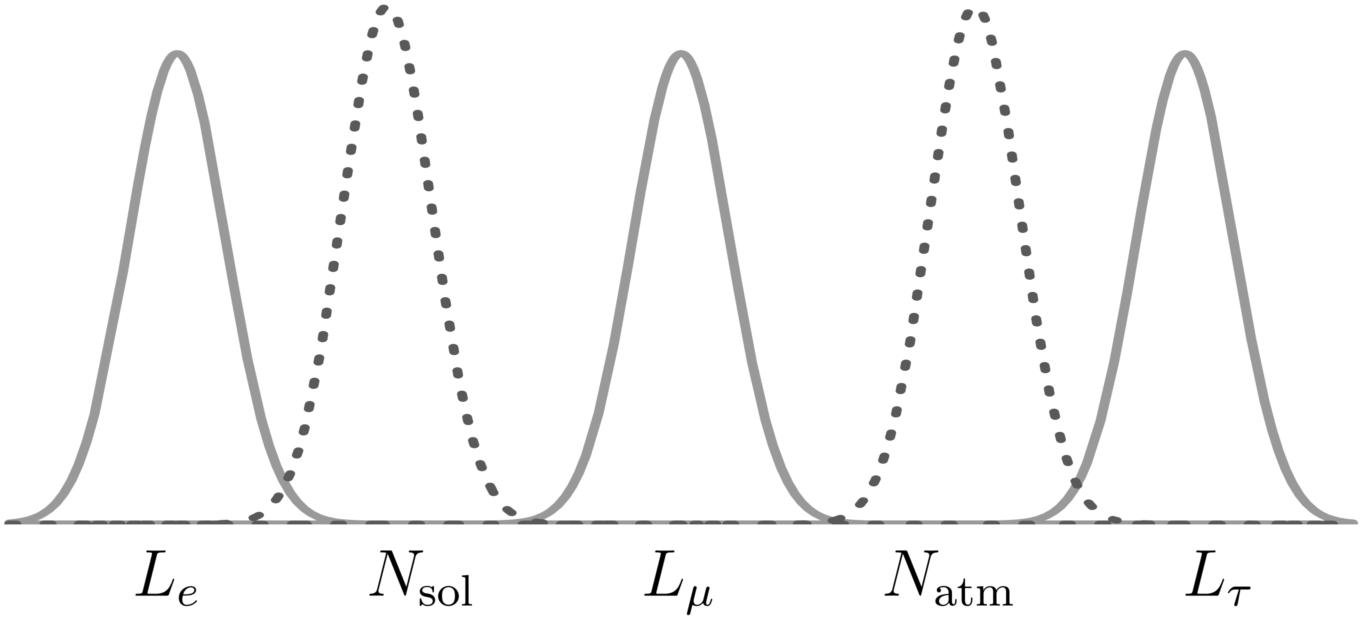
$T \geq T_c \Rightarrow$ ***large L***

- $\langle \Phi \rangle = 0 \Rightarrow$ Large overlaps!



$T \ll T_c \Rightarrow$ ***tiny L***

- $\langle \Phi \rangle = f(x_5) \Rightarrow$ small overlaps!



M. Raidal & A. Strumia, PLB (03)

Deviation from equilibrium

Effective potential in 5D $\Longrightarrow$

1st order Phase Transition:

$$V(\Phi) = \frac{a^2}{6}\Phi^6 - \frac{b^2}{4}\Phi^4 + \frac{c^2}{2}(T)\Phi^2\,.$$

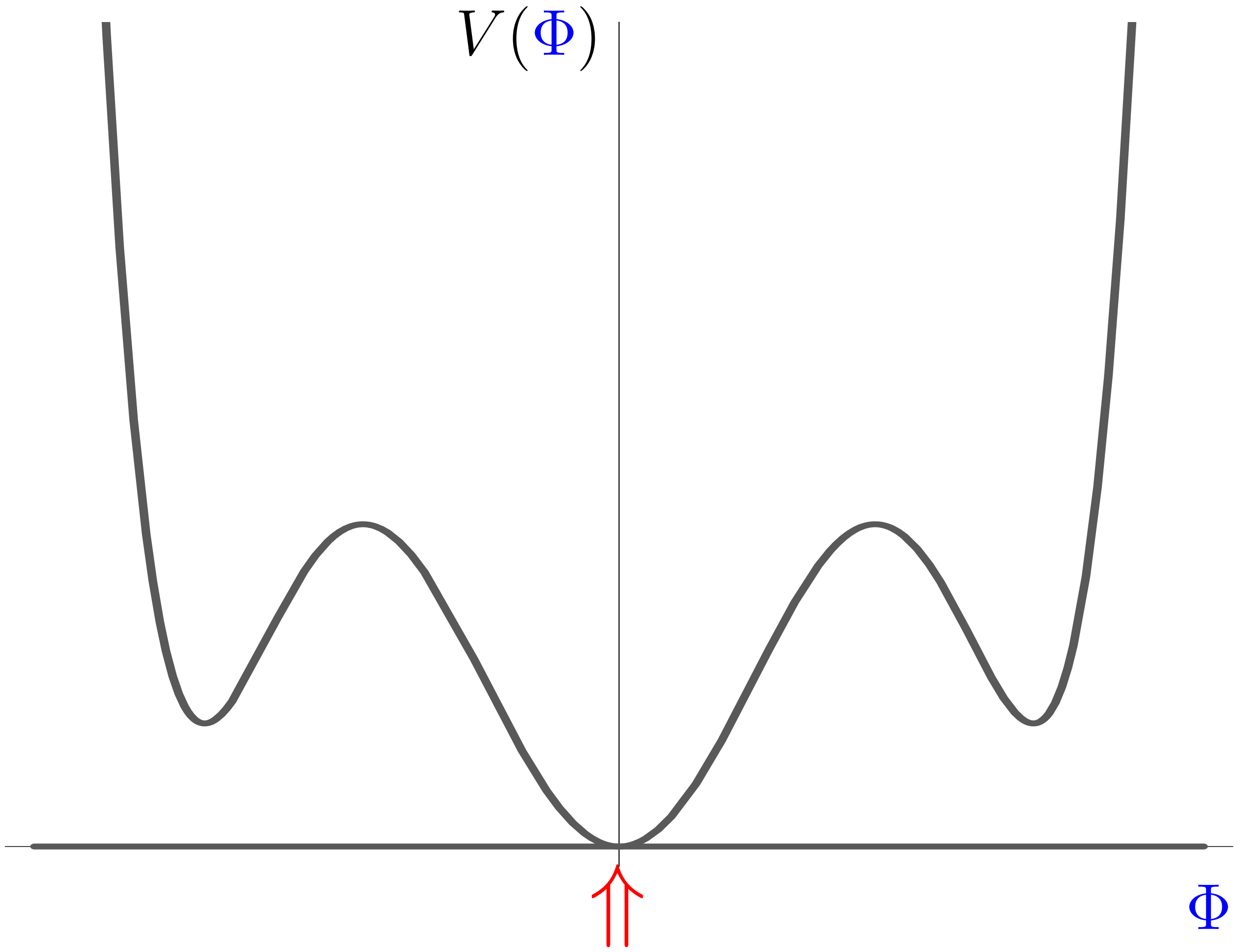
1st order Phase Transition

$$V(\Phi) = \frac{a^2}{6}\Phi^6 - \frac{b^2}{4}\Phi^4 + \frac{c^2}{2}(T)\Phi^2 \,.$$

- $c(T > T_c) < \frac{b^2}{2a} \Rightarrow$ 3 minima
- $c(T_c) = \frac{\sqrt{3}b^2}{4a} \Rightarrow$ 3 Separated vacua!
- $c(T \ll T_c) < \frac{\sqrt{3}b^2}{4a} \Rightarrow \langle\Phi\rangle = f(x_5)$

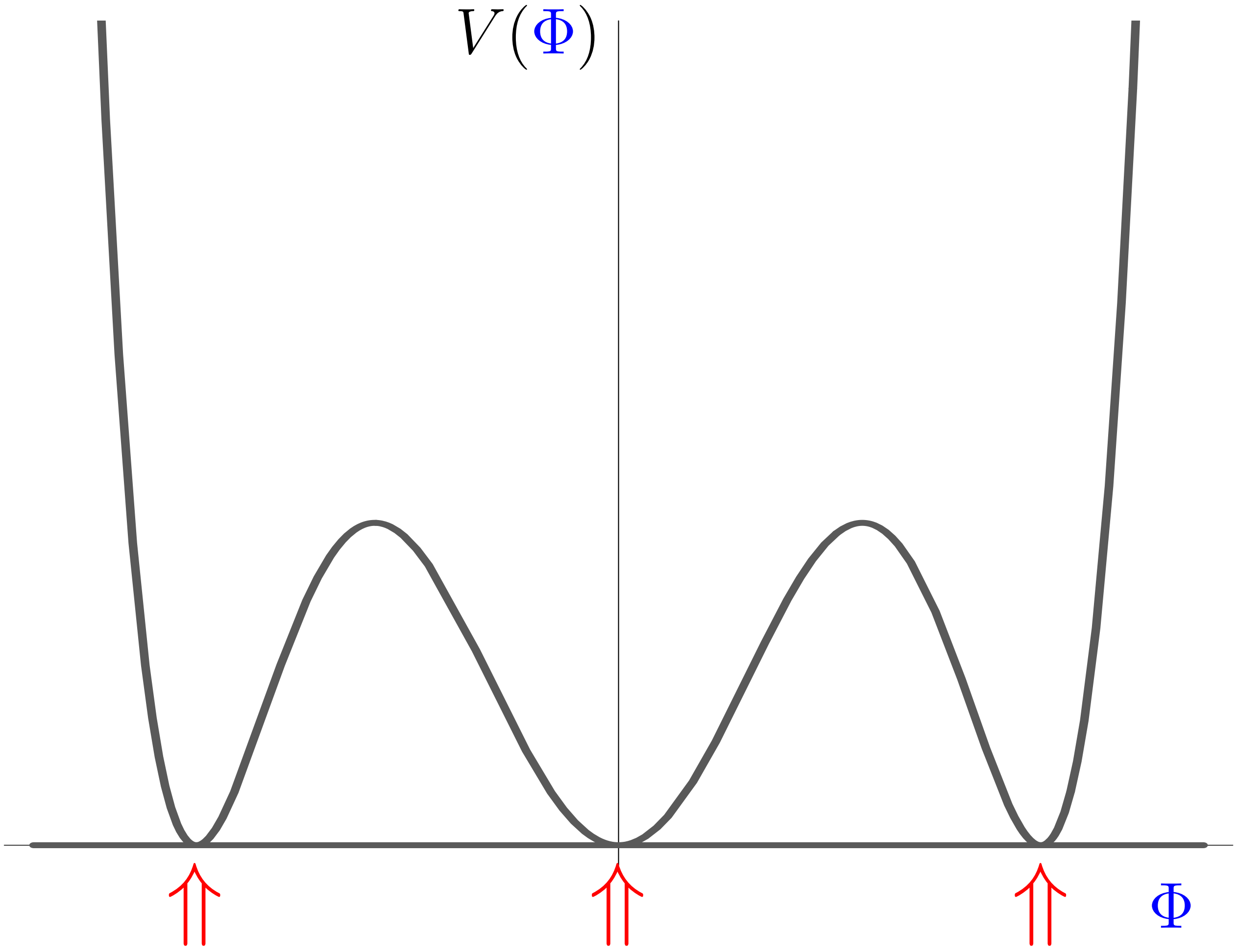
High T - $\langle\Phi\rangle = 0$

$$c(T > T_c) < \frac{b^2}{2a} \;\rightarrow\; 3\ \mathrm{minima}$$



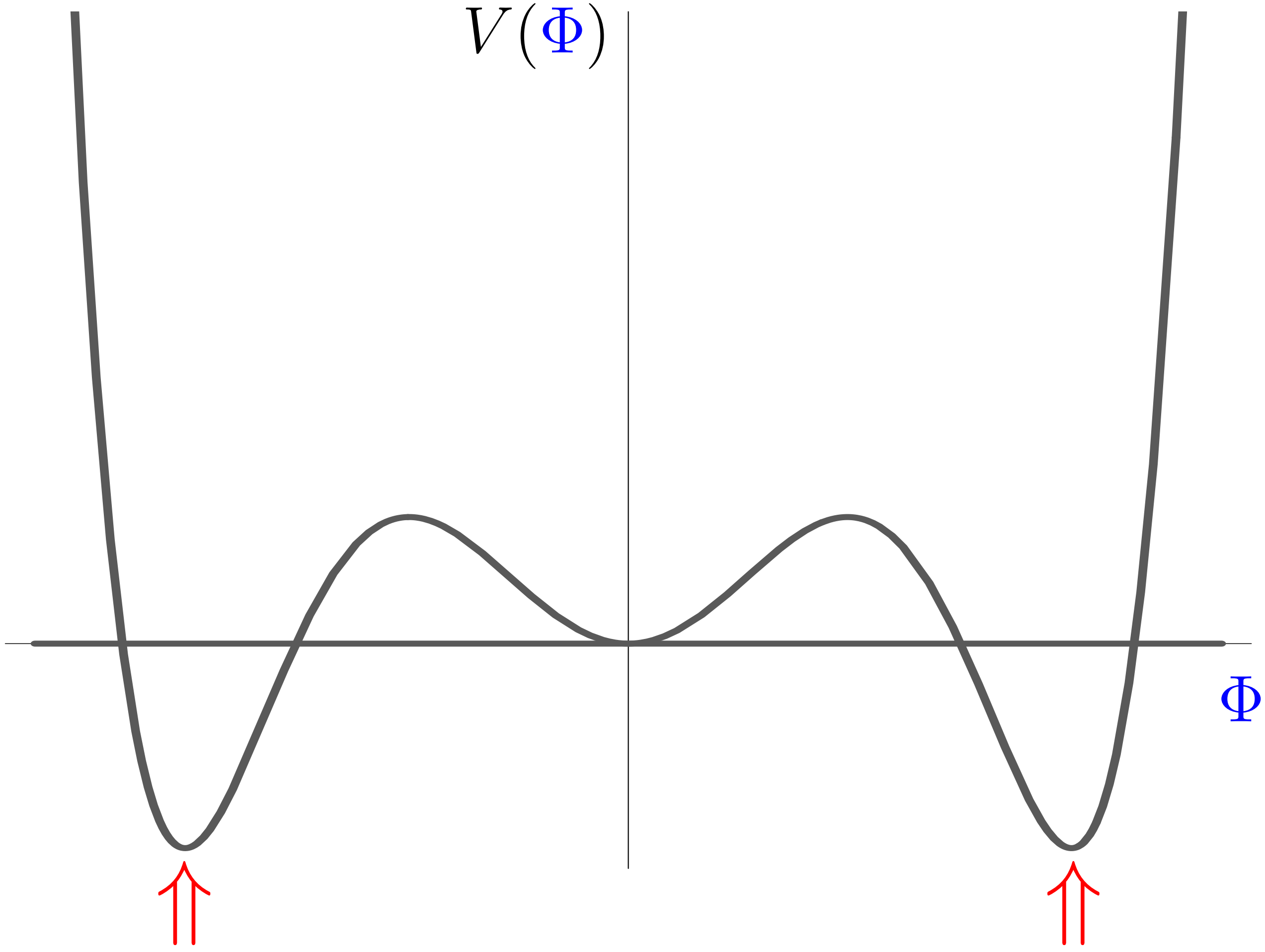
Critical T - Separated Vacua

$$c(T = T_c) = \frac{\sqrt{3}b^2}{4a} \quad \rightarrow \quad 3 \text{ equal minima}$$



Low T - $\langle \Phi \rangle \neq 0$

$$c(T \ll T_c) < \frac{\sqrt{3}b^2}{4a} \;\rightarrow\; \langle \Phi \rangle = f(x_5)$$



Estimation of L,B

- Crude estimate of B: Cohen, Kaplan & Nelson, ARNPS (93)

$$\frac{n_b}{s} \sim \left[\frac{g_{\mathrm{B}}^2(T_c)}{g_*(T_c)}\right] \times [\theta_{CP}] \sim \mathcal{O}\left(10^{-10}\right) \quad .$$

Estimation of L,B

- Crude estimate of B: Cohen, Kaplan & Nelson, ARNPS (93)

$$\frac{n_b}{s} \sim \left[\frac{g_{\rm B}^2(T_c)}{g_*(T_c)}\right] \times [\theta_{CP}] \sim \mathcal{O}\left(10^{-10}\right) .$$

- SM: Huet & Sather, PRD (95)

$$\frac{n_b}{s} \sim \left[\frac{\alpha_W^4(M_W)}{100}\right] \times \left[J\,\frac{m_b^4 m_c^2 m_s^2}{T^8}\right] \lesssim 10^{-27}$$

- Split Fermions:

$$\frac{n_b}{s} \lesssim \left[\frac{\varepsilon_{\rm L}^4}{100}\right] \times [{\rm F}({\rm R}, \Phi_{1,2})]$$

θ_{CP} in the thin wall

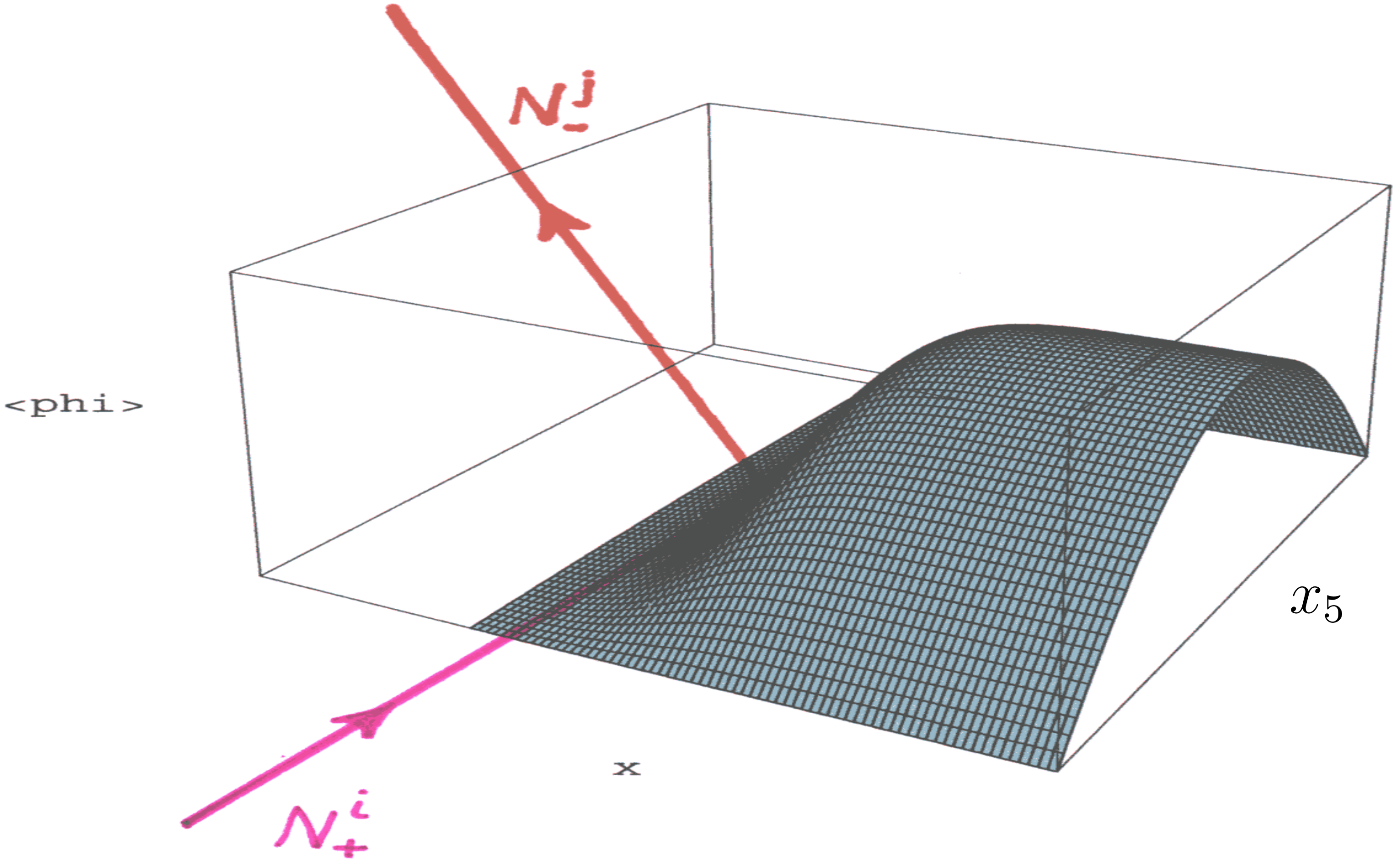
♣ CPT + unitarity:

$$\theta_{CP} \propto \int \frac{dp_3}{2\pi} \left[n^{\mathrm{f}}(0, p_3) - n^{\mathrm{f}}(1, p_3') \right] \times \Delta^{CP}(E) \,,$$

$$\Delta^{CP}(E) \sim \mathrm{Tr} \left[R^{\dagger}_{0,1^+} R_{0,1^+} - R^{\dagger}_{1^+,0} R_{1^+,0} \right] .$$

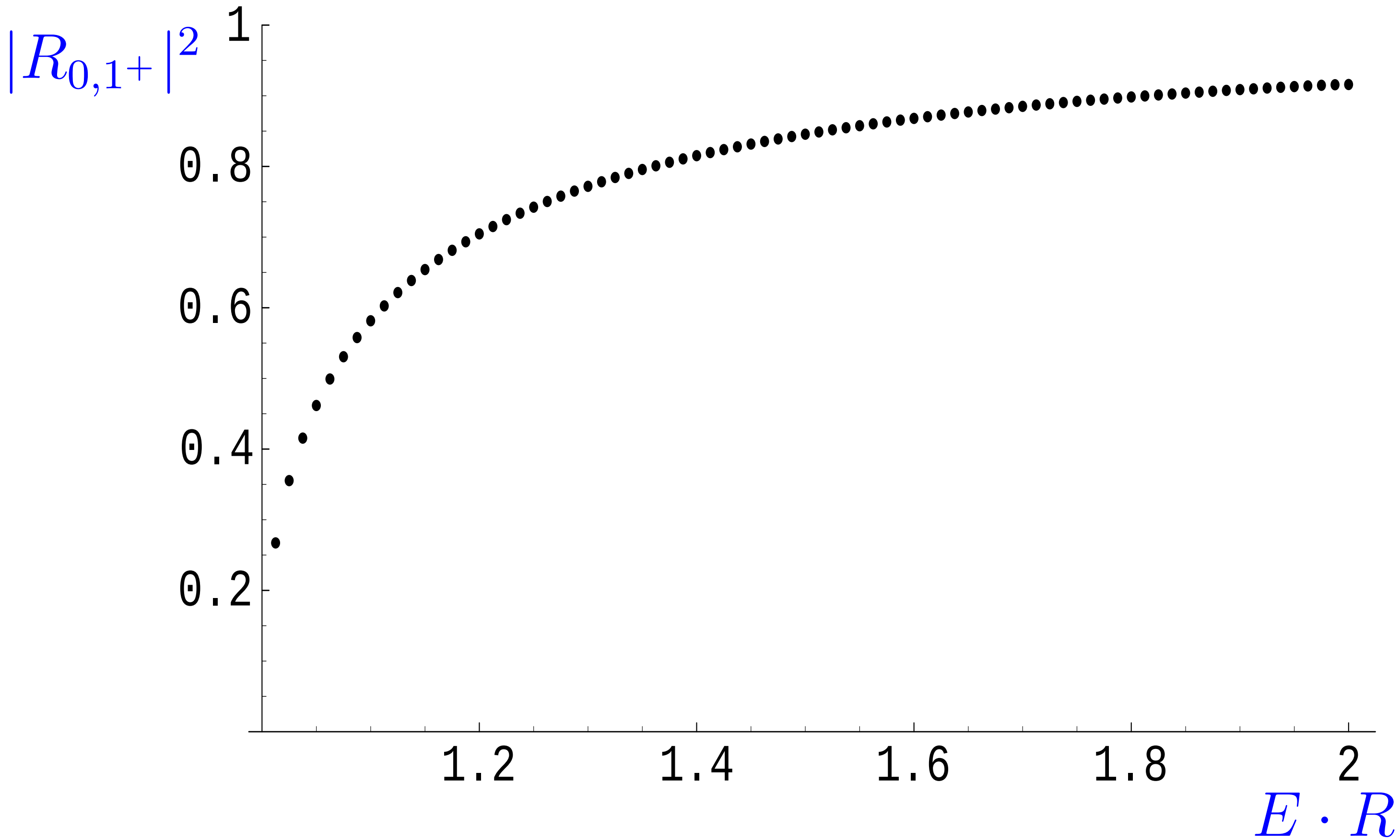
Dynamics- Interaction with the bubble

KK$_\pm$ modes have different Reflection coefficients:



The energy dependence of $|R_{0,1^+}|^2$

Sizable reflection is found!



Reflection coefficients & Δ^{CP}

- Solving the Dirac eq. and matching the W.F's:

$$|R_{0,1^+}|^2 = \mathcal{O}(1) \cdot F(E) \qquad 1 < ER < 2\,.$$

$$\Downarrow$$

$$n_{\mathrm{L}} \sim e^{-2T_C R} \times \mathcal{O}(0.1)\,.$$

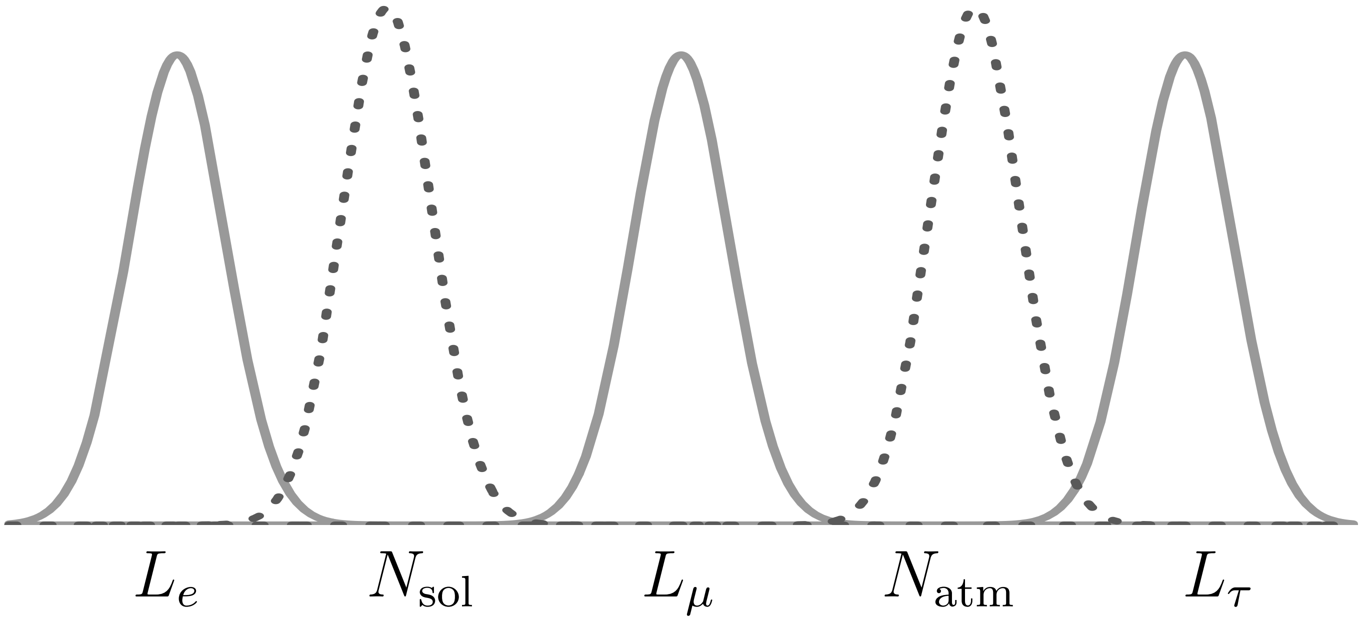
L/B Violation ?

Recall that:

$$\frac{n_b}{s} \sim \left[\frac{g^2_{\mathrm{B}}(T_c)}{g_*(T_c)} \right] \times [\theta_{CP}]$$

Lepton flavor model

- Minimal see-saw model.



M. Raidal & A. Strumia, PLB (03)

Lepton violation

- Consider $\mathcal{L}_{\rm L}$ of approximate U(1)$_{\rm L}$:

$$\mathcal{L}_{\rm L} = \varepsilon_{\rm L}^6 \frac{HH}{M} LL + \varepsilon_{\rm L}^2 \, \epsilon_{ij} L_i N_j^c H + \varepsilon_{\rm L}^2 M' N N$$

$$Q(L) = 3 \,, \qquad Q(N) = 1 \,.$$

Lepton violation

- Consider $\mathcal{L}_{\rm L}$ of approximate U(1)$_{\rm L}$:

$$\mathcal{L}_{\rm L} = \varepsilon_{\rm L}^6 \frac{HH}{M} LL + \varepsilon_{\rm L}^2 \, \epsilon_{ij} L_i N_j^c H + \varepsilon_{\rm L}^2 M' N N$$

- To have a successful see-saw:

$$\frac{\varepsilon_{\rm L}^6}{M} \lesssim \frac{\sqrt{\Delta m^2_{\rm Sol}}}{5} \quad \Rightarrow$$

$$\varepsilon_{\rm L} \lesssim 0.05 \left(\frac{M}{10^3\,\mathrm{TeV}} \right)^{\frac{1}{6}} .$$

Final estimate B=?

Split Fermions:

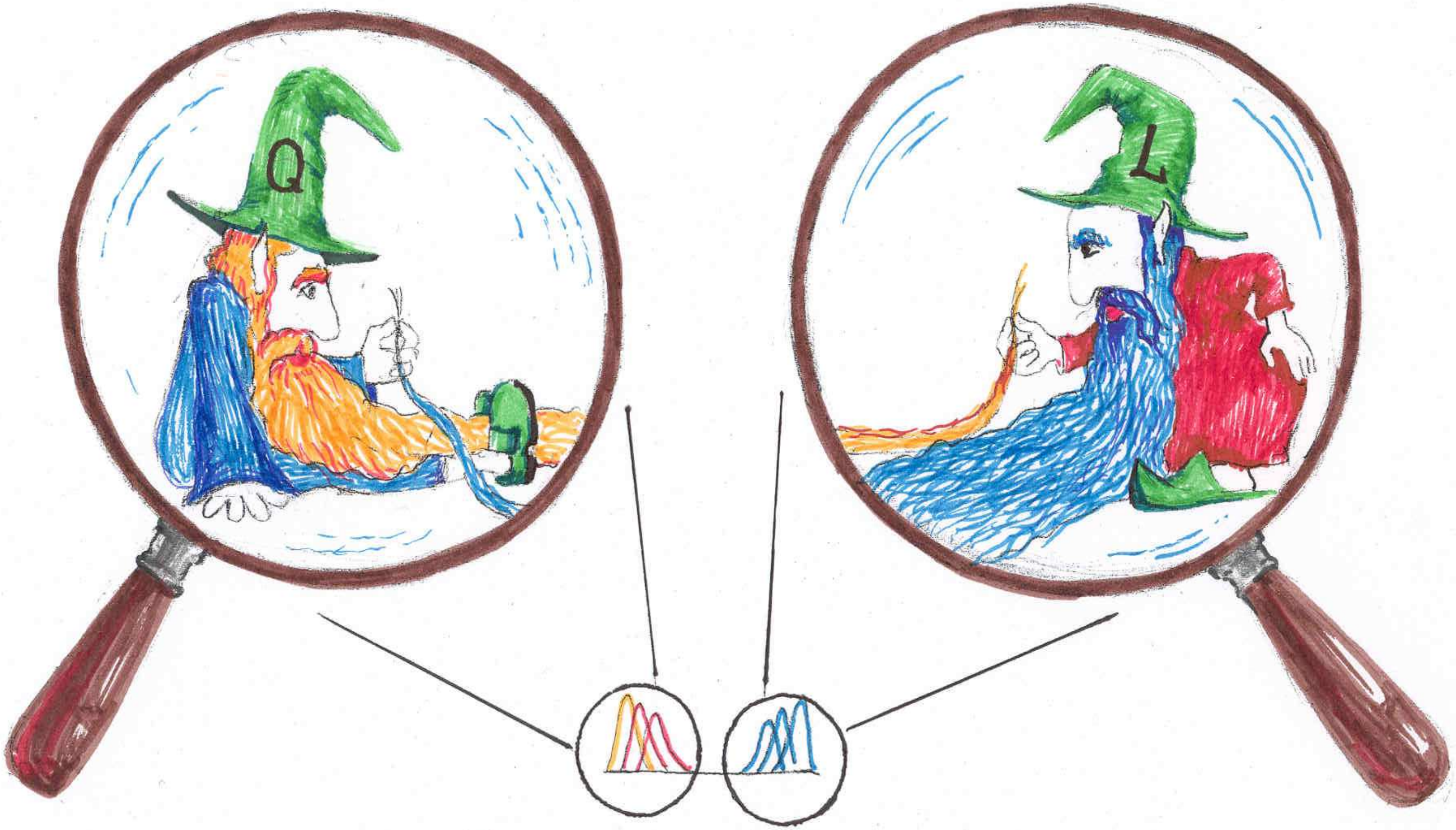
$$\frac{n_b}{s} \lesssim \left[\frac{\varepsilon_{\mathrm{L}}^4}{10^2}\right] \times \left[e^{-2} \cdot \mathrm{F}(\mathrm{R}, \Phi_{1,2})\right] \lesssim 10^{-10}$$

Conclusion

- Split fermions (flavor puzzle) $\Rightarrow$ twisting.
- Split fermions framework may yield a new lepto/baryogenesis type.
- Flavor parameters & CPV are connected.

Twisted split fermions & leptogenesis

Gilad Perez



Finite dimension - Realistic model

Georgi, Grant & Hailu, (01);
Kaplan & Tait, (01).

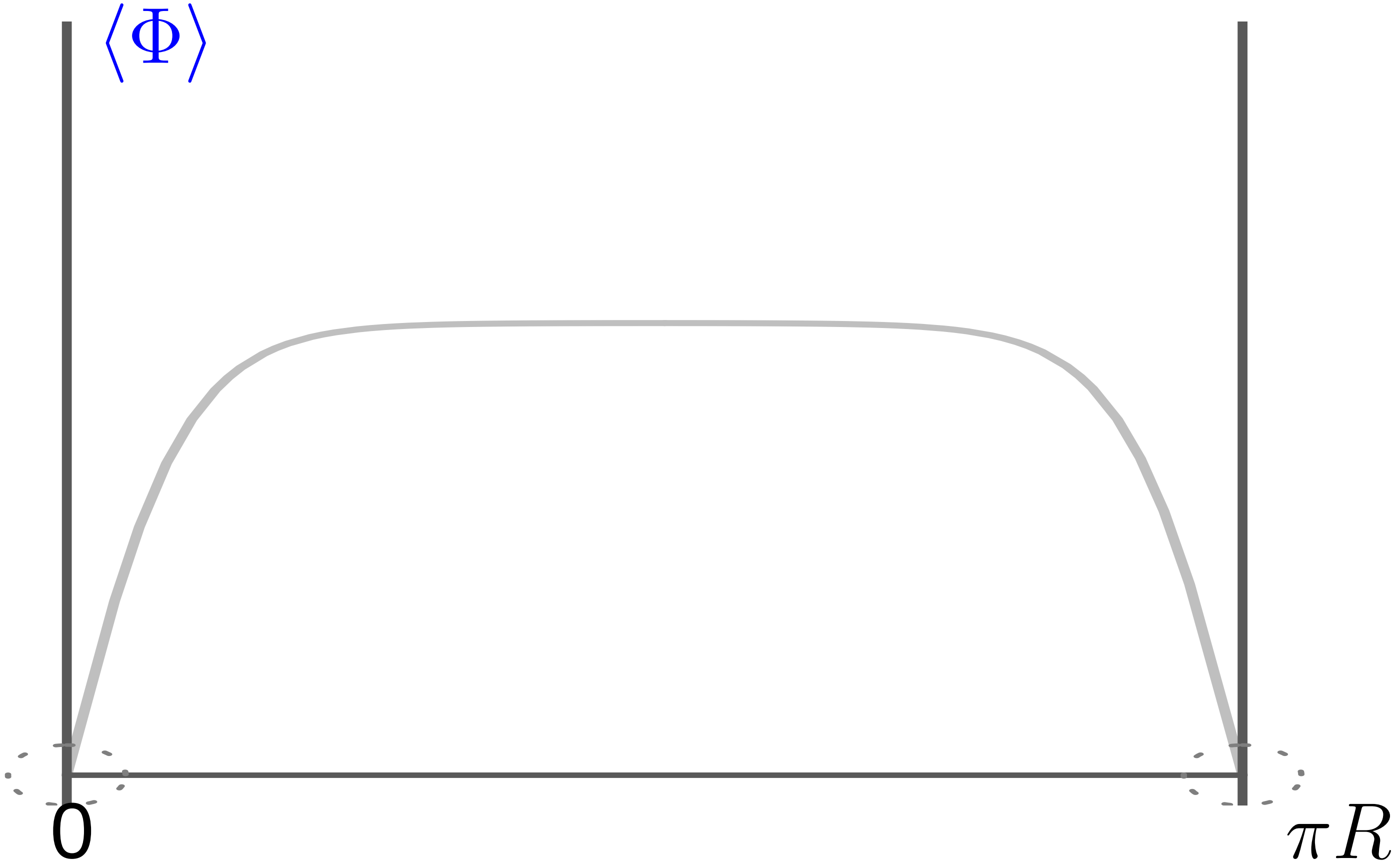
The 5D is orbifold: S_1/Z_2 (no translation sym').

Project out a zero mode: $\Psi(-x_5) = \gamma_5 \Psi(x_5)$.

Scalar kink profile: $\Phi(-x_5) = -\Phi(x_5)$.

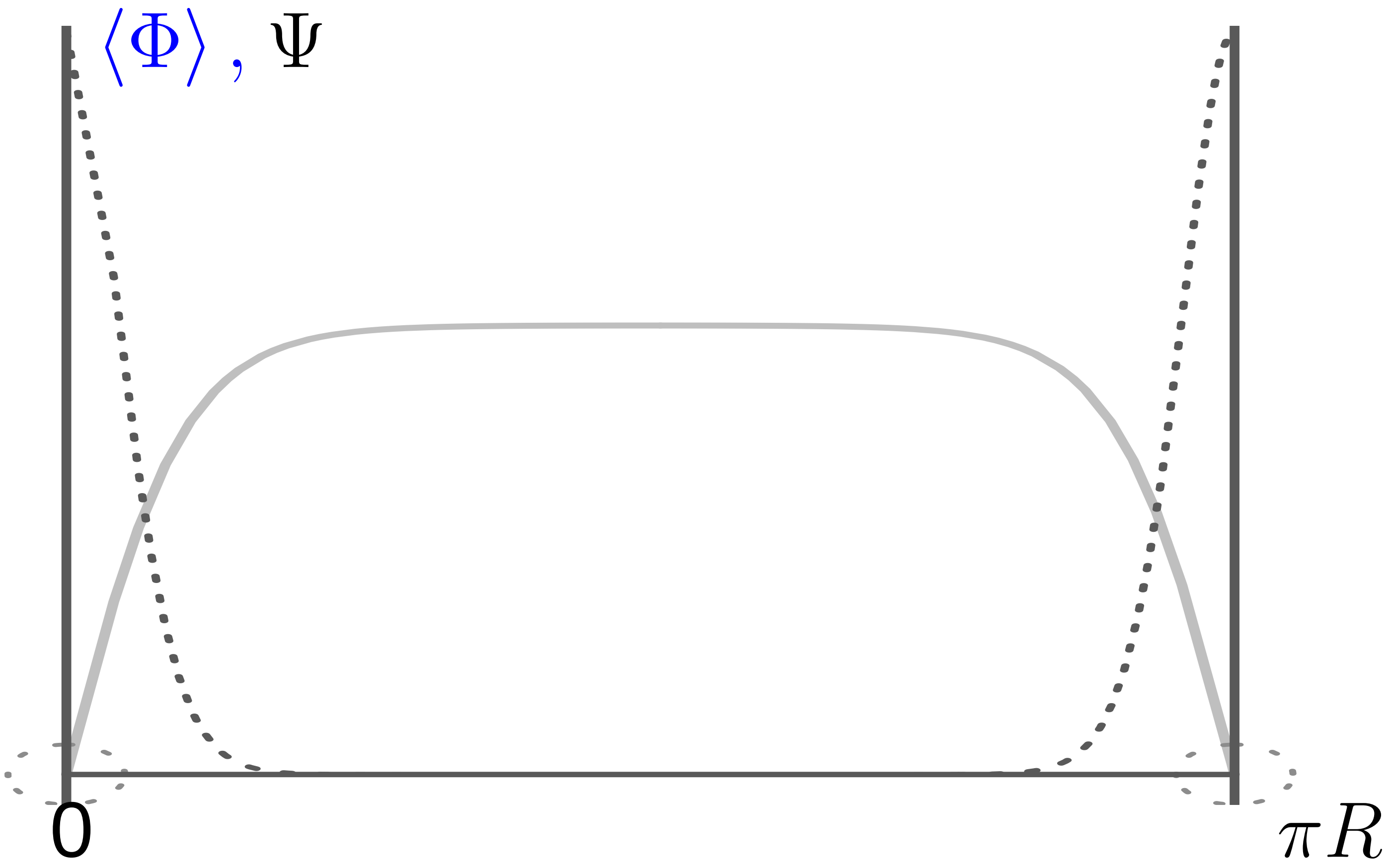
Separation ??

Translation sym' is minimally violated!



☒ ***No separation !***

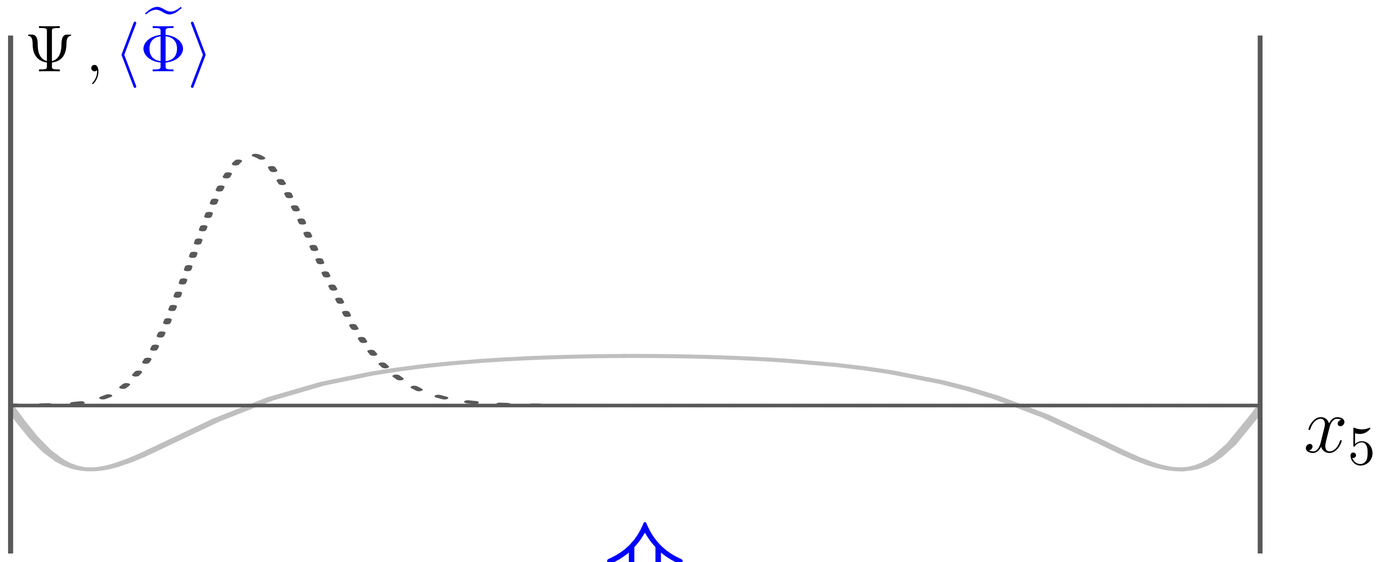
Fermions are stuck at the fixed points.



2 scalar model - Natural flavor sector

Y. Grossman & G.P., (03)

Fermion & scalars profile



$\Updownarrow$

2 Flavor violating sources!

Neutrinos parameters

$$\delta m^2_{\rm sol} \sim 7 \cdot 10^{-5}\,, \qquad \delta m^2_{\rm atm} \sim 3 \cdot 10^{-3}\,,$$

$$\theta_{12} \sim 0.6\,, \qquad \theta_{23} \sim \frac{\pi}{4}\,, \qquad \theta_{13} \lesssim 0.1\,.$$

Hierarchical pattern:

$$m_{\rm atm} = \sqrt{\delta m^2_{\rm atm}} \sim 5 \cdot 10^{-2}\,,$$

$$m_{\rm sol} = \sqrt{\delta m^2_{\rm sol}} \sim 8 \cdot 10^{-3}\,.$$

Neutrino mass matrix- minimal model

$$\mathcal{L}_{\mathrm{L}} = \frac{M_{\mathrm{atm}}}{2} N_{\mathrm{atm}}^2 + \frac{M_{\mathrm{sol}}}{2} N_{\mathrm{sol}}^2 + \lambda_{\mathrm{sol}}\, H N_{\mathrm{sol}} \left(s L_e + c\; e^{-i\phi/2} L_\mu + 0\, L_\tau\right) + \lambda_{\mathrm{atm}} H N_{\mathrm{atm}} (0 L_e + s_{\mathrm{atm}} L_\mu + c_{\mathrm{atm}} L_\tau),$$

$$m_\nu = m_{\mathrm{atm}} \begin{pmatrix} \delta s^2 & \delta s c e^{-i\phi/2} & 0 \\ \delta s c e^{-i\phi/2} & s_{\mathrm{atm}}^2 + \delta c^2 e^{-i\phi} & s_{\mathrm{atm}} c_{\mathrm{atm}} \\ 0 & s_{\mathrm{atm}} c_{\mathrm{atm}} & c_{\mathrm{atm}}^2 \end{pmatrix},$$

$$m_{\mathrm{atm}} = \frac{\lambda_{\mathrm{atm}}^2 v^2}{M_{\mathrm{atm}}}, \qquad \delta = \frac{\lambda_{\mathrm{sol}}^2 / M_{\mathrm{sol}}}{\lambda_{\mathrm{atm}}^2 / M_{\mathrm{atm}}}.$$

Neutrino mass matrix and the required suppression

$$\varepsilon_{\mathrm{L}}^2 \times \begin{matrix} N_{\mathrm{sun}} \\ N_{\mathrm{atm}} \end{matrix} \overset{\begin{matrix} L_e & L_\mu & L_\tau \end{matrix}}{\begin{pmatrix} \epsilon_{\mathrm{sol}} & \epsilon_{\mathrm{sol}} & 0 \\ 0 & \epsilon_{\mathrm{atm}} & \epsilon_{\mathrm{atm}} \end{pmatrix}}$$

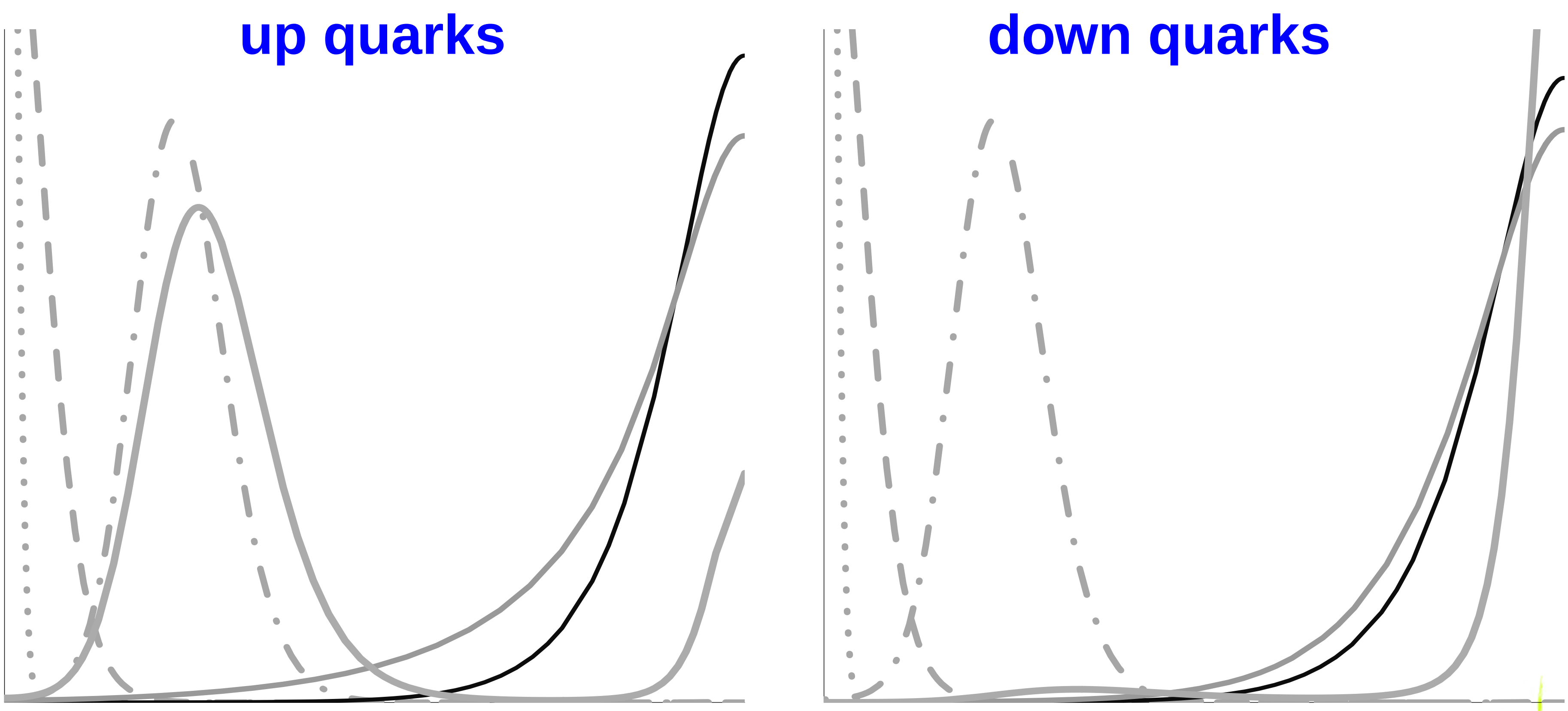
$$\varepsilon_{\mathrm{L}}{}^2 \cdot \frac{\epsilon_{\mathrm{atm}}}{M} \sim m_{\mathrm{atm}} \longrightarrow \epsilon_{\mathrm{atm}} \sim 0.02 \left(\frac{M}{10^3\,\mathrm{TeV}} \right)^{\frac{1}{3}}$$

$$\varepsilon_{\mathrm{L}}{}^2 \cdot \frac{\epsilon_{\mathrm{sol}}}{M} \sim m_{\mathrm{sol}} \longrightarrow \epsilon_{\mathrm{sol}} \sim 0.007 \left(\frac{M}{10^3\,\mathrm{TeV}} \right)^{\frac{1}{3}} .$$

A Realistic model

♣ Yukawas, $Y_{1,2}$, are flavor matrices:

$$\mathcal{L}_Y = \bar{\Psi}^i \left(Y_1^{ij} \mathbf{\Phi_1} - Y_2^{ij} \mathbf{\Phi_2} \right) \Psi^j$$



Scales

- Significant excess of L $\Rightarrow T_c \sim \frac{1}{R}$.
- FCNC & LFV bounds $\Rightarrow \frac{1}{R} \gtrsim 10^3$ TeV.

Scales

- Significant excess of L $\Rightarrow T_c \sim \frac{1}{R}$.
- FCNC & LFV bounds $\Rightarrow \frac{1}{R} \gtrsim 10^3$ TeV.
- 4D coherence length - $l_{\rm Th} \sim \frac{1}{T_c \alpha_s} \gtrsim R$.
- L violation time - $\tau_{\rm L}^{-1} \sim \varepsilon_{\rm L}^4 T_c \ll l_{\rm Th}$.
- Wall length - $l_{\rm w}^{-1} \sim \frac{v_{\rm w}}{\delta_{\rm w}} \sim (0.01 - 1) T_c$.

$l_{\rm Th} \gtrsim l_{\rm w} \Rightarrow$ Thin wall is applicable.

Reflection coefficients & Δ^{CP}

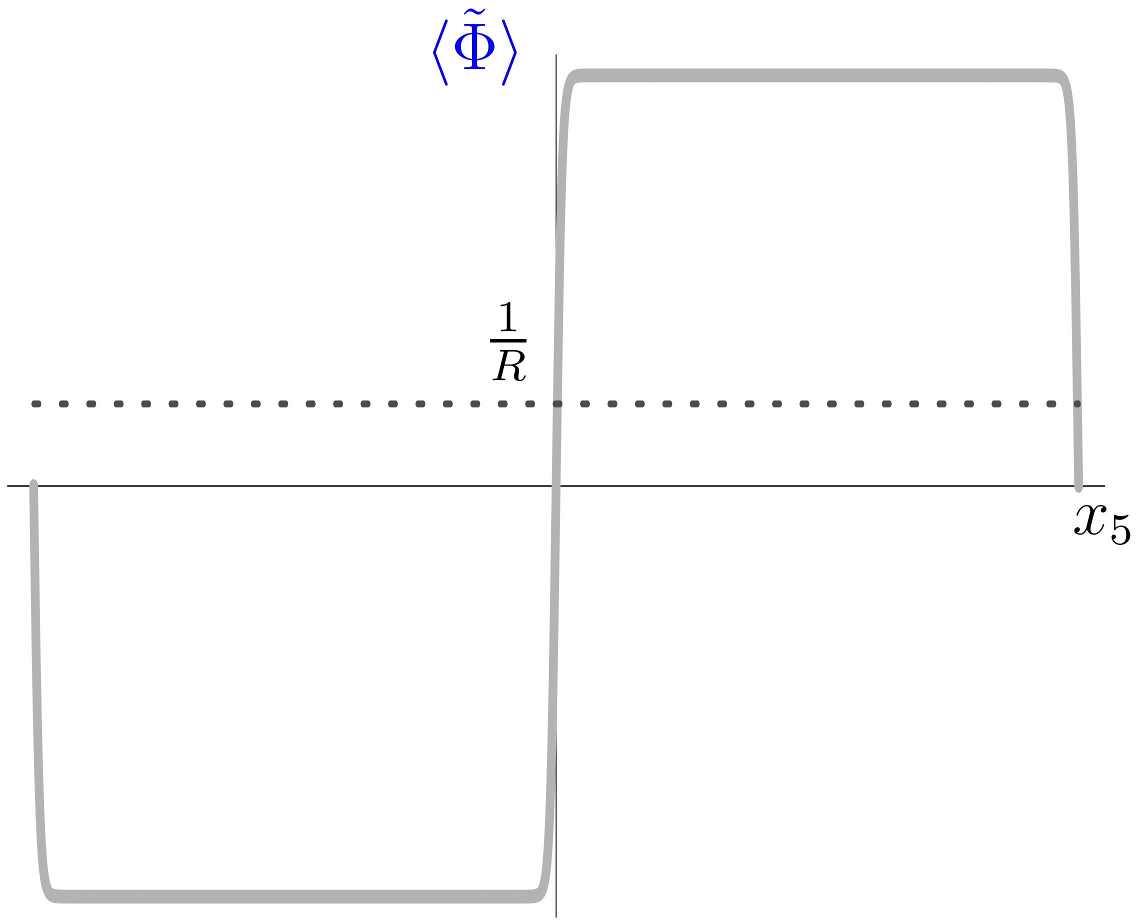
- $R_{0,1^+}$ in a single flavor model.
- Yukawas have $\mathcal{O}(1)$ CPV phase $\Rightarrow$

  $\Delta^{CP}(E) \sim |R_{0,1^+}|^2$.
- $|R_{0,1^+}|$ is approx' using -

  $$\langle\tilde{\Phi}\rangle \sim \frac{a}{R}\left[\theta(x_5) - \theta(-x_5)\right].$$

Step function approx'

Only zero modes can be transmitted.



Reflection coefficients & Δ^{CP}

- Solving the Dirac eq. and matching the W.F's:

$$|R_{0,1^+}|^2 = \mathcal{O}(1) \cdot F(E) \qquad 1 < ER < 2\,.$$

Twisted split fermions & leptogenesis

Gilad Perez