CP Violation

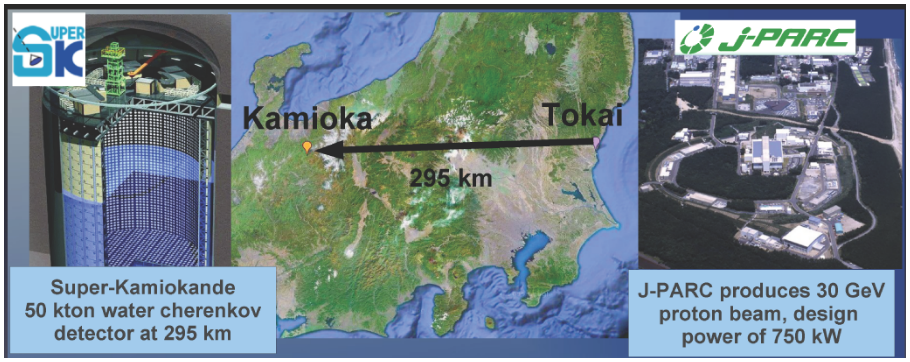
CP Violation in Neutrino Oscillation

- With leptonic Dirac CP phase $\delta \neq 0$ ➜ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

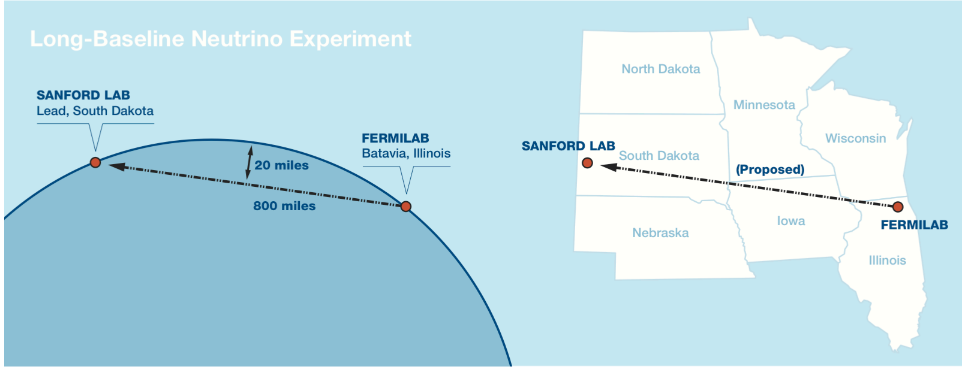
$$P\,(\nu_\alpha \rightarrow \nu_\beta) \neq P\,(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$$

- One of the major scientific goals at current and planned neutrino experiments

T2K



DUNE/LBNF



CP Violation in Neutrino Oscillation

- Oscillation Probability for neutrino (anti-neutrino) mode:

$$\begin{aligned} \mathrm{P}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) &= \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\,(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin^2(\Delta m^2_{ij}L/4E) \\ &\quad \overset{+}{(-)} 2\sum_{i>j} \mathrm{Im}\,(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin(\Delta m^2_{ij}L/2E) \end{aligned}$$

- CP violation:

$$\Delta P_{\nu\bar{\nu}\,\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31},$$

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$$

$$J_{\alpha\beta} \equiv \Im(U_{\alpha 1}U^*_{\alpha 2}U^*_{\beta 1}U_{\beta 2}) = \pm J, \quad J \equiv s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

Jarlskog invariant for lepton sector

CP Violation in Nature

☞ ~~CP~~ so far only observed in flavor sector

➥ it appears natural to seek connection between flavor physics & ~~CP~~

☞ flavor structure may be explained by (non–Abelian discrete) flavor symmetries

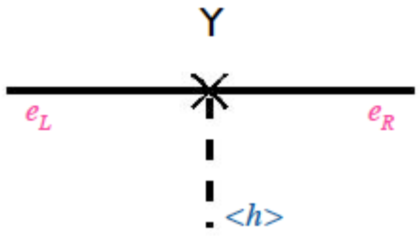
non–Abelian discrete (flavor) symmetry $G \leftrightarrow$ ~~CP~~

Origin of CP Violation

- CP violation ⇔ complex mass matrices

$$\overline{U}_{R,i}(M_u)_{ij}Q_{L,j} + \overline{Q}_{L,j}(M_u^\dagger)_{ji}U_{R,i} \xrightarrow{\mathcal{CP}} \overline{Q}_{L,j}(M_u)_{ij}U_{R,i} + \overline{U}_{R,i}(M_u)^*_{ij}Q_{L,j}$$

- Conventionally, CPV arises in two ways:
  - Explicit CP violation: complex Yukawa coupling constants Y
  - Spontaneous CP violation: complex scalar VEVs <h>



- **Complex CG coefficients in certain discrete groups ⇒ explicit CP violation**
  - CPV in quark and lepton sectors purely from complex CG coefficients

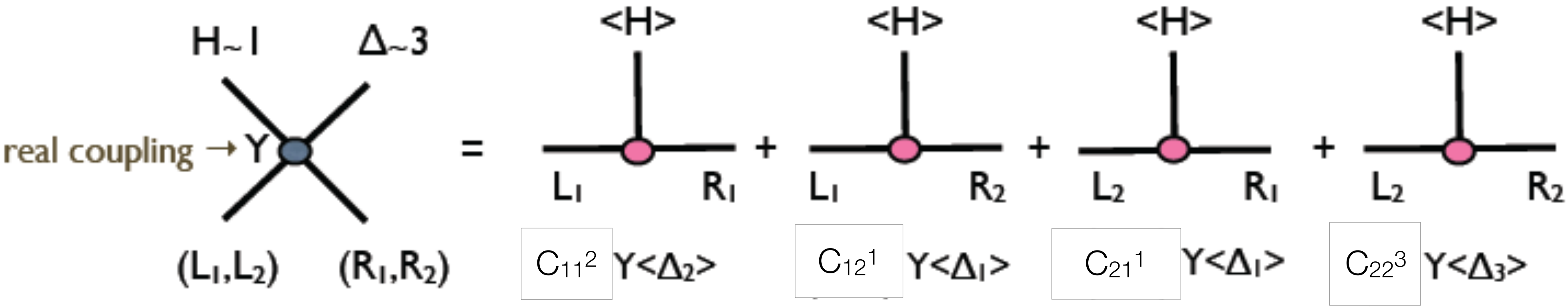
CG coefficients in non-Abelian discrete symmetries
➪ relative strengths and phases in entries of Yukawa matrices
➪ mixing angles and phases (and mass hierarchy)

Group Theoretical Origin of CP Violation

M.-C.C., K.T. Mahanthappa
Phys. Lett. B681, 444 (2009)

Basic idea

Discrete symmetry ***G***



$C_{ij}{}^{k}$: complex CG coefficients of ***G***

- if Z_3 symmetric ⇒ $\langle\Delta_1\rangle = \langle\Delta_2\rangle = \langle\Delta_3\rangle \equiv \langle\Delta\rangle$ real
- Complex effective mass matrix: **phases determined by group theory**

$$M = \begin{array}{cc} \begin{matrix} L_1 & L_2 \end{matrix} & \\ \begin{pmatrix} C_{11}{}^{2} & C_{21}{}^{1} \\ C_{12}{}^{1} & C_{22}{}^{3} \end{pmatrix} Y\langle\Delta\rangle & \begin{matrix} R_1 \\ R_2 \end{matrix} \end{array}$$

CP Transformation

- Canonical CP transformation

$$\phi(x) \xrightarrow{\mathcal{C}\mathcal{P}} \eta_{\mathcal{C}\mathcal{P}}\ \phi^*(\mathcal{P}x)$$

freedom of re–phasing fields

- Generalized CP transformation

Ecker, Grimus, Konetschny (1981); Ecker, Grimus, Neufeld (1987);
Grimus, Rebelo (1995)

$$\Phi(x) \xrightarrow{\widetilde{\mathcal{C}\mathcal{P}}} U_{\mathrm{CP}}\,\Phi^*(\ \mathcal{P}\ \ x)$$

unitary matrix

Generalized CP Transformation

- ☞ setting w/ discrete symmetry G

G and CP transformations do not commute

- ☞ generalized CP transformation

Feruglio, Hagedorn, Ziegler (2013); Holthausen, Lindner, Schmidt (2013)

- ☞ invariant contraction/coupling in A_4 or T'

$$\left[\phi_{\mathbf{1}_2} \otimes (x_{\mathbf{3}} \otimes y_{\mathbf{3}})_{\mathbf{1}_1}\right]_{\mathbf{1}_0} \propto \phi\,\left(x_1 y_1 + \omega^2 x_2 y_2 + \omega\, x_3 y_3\right)$$

$\omega = \mathrm{e}^{2\pi\,\mathrm{i}/3}$

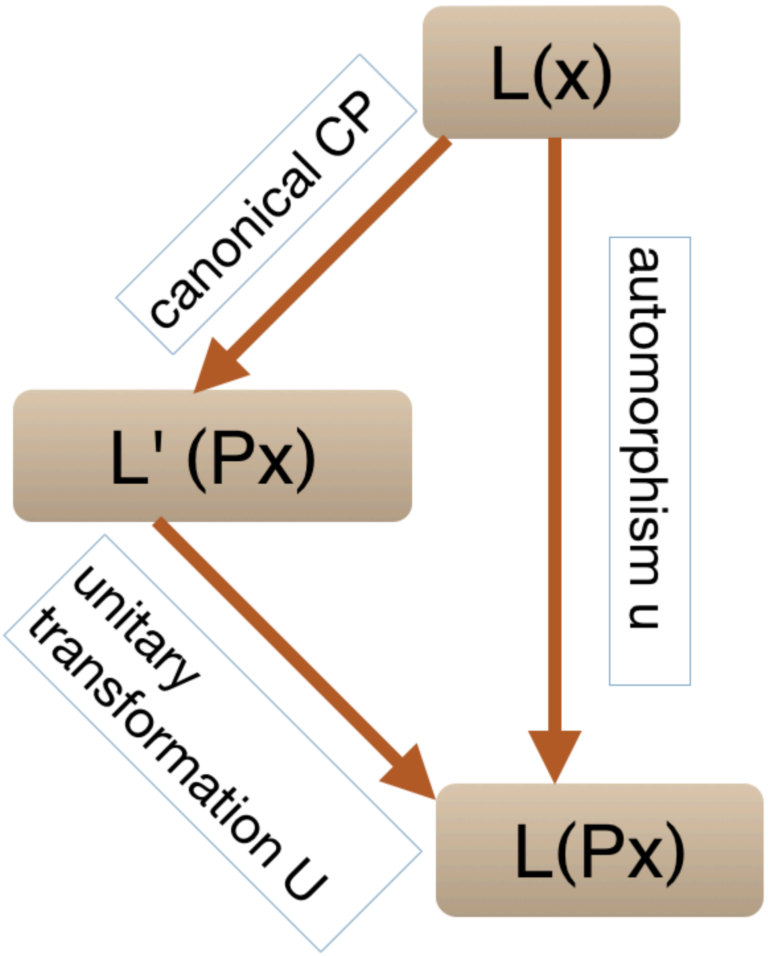
- ☞ canonical CP transformation maps A_4/T' invariant contraction to something non–invariant

➥ need generalized CP transformation $\widetilde{\mathcal{CP}}$: $\phi \xmapsto{\widetilde{\mathcal{CP}}} \phi^*$ as usual but

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \xmapsto{\widetilde{\mathcal{CP}}} \begin{pmatrix} x_1^* \\ x_3^* \\ x_2^* \end{pmatrix} \quad \& \quad \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} \xmapsto{\widetilde{\mathcal{CP}}} \begin{pmatrix} y_1^* \\ y_3^* \\ y_2^* \end{pmatrix}$$

Physical CP vs. Generalized CP Transformations

complex CGs ➪ G and physical CP transformations do not commute


L(x)

canonical CP

L' (Px)

automorphism u

unitary transformation U

L(Px)

Generalized CP transformation:

$$\Phi(x) \xrightarrow{\widetilde{\mathcal{CP}}} U_{\mathrm{CP}}\,\Phi^{*}(\,\mathcal{P}\;x)$$

contains all reps in model

Necessary Consistency condition:

Holthausen, Lindner, Schmidt (2013)

$$\rho\big(u(g)\big) \;=\; U_{\mathrm{CP}}\;\rho(g)^{*}\,U_{\mathrm{CP}}^{\dagger} \quad \forall\, g \in G$$

Physical CP vs. Generalized CP Transformations

complex CGs ➪ G and physical CP transformations do not commute

$$\begin{tikzcd}
 & L(x) \arrow[dl, "\text{canonical CP}"'] \arrow[dd, "\text{automorphism } u"] \\
L'(Px) \arrow[dr, "\text{unitary transformation } U"'] & \\
 & L(Px)
\end{tikzcd}$$

Generalized CP transformation:

$$\Phi(x) \xmapsto{\widetilde{\mathcal{CP}}} U_{\mathrm{CP}}\,\Phi^*(\,\mathcal{P}\;x)$$

Necessary Consistency condition:

Holthausen, Lindner, Schmidt (2013)

$$\rho\big(u(g)\big) = U_{\mathrm{CP}}\;\rho(g)^*\,U_{\mathrm{CP}}{}^\dagger \quad \forall\, g \in G$$

However, GCP may not correspond to physical CP transformation

➪ for GCP = physical CP: more stringent consistency condition

Physical CP vs. Generalized CP Transformations

- generalized CP transformation $\Phi(x) \xmapsto{\widetilde{\mathcal{CP}}} U_{\mathrm{CP}}\,\Phi^*(\,\mathcal{P}\;x)$
- Necessary consistency condition

$$\rho\big(u(g)\big) \;=\; U_{\mathrm{CP}}\;\rho(g)^*\,{U_{\mathrm{CP}}}^\dagger \quad \forall\, g \in G$$

Holthausen, Lindner, Schmidt (2013)

- **Necessary and sufficient consistency condition**

M.-C.C., M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner (2014)

$$\boxed{\rho_{\boldsymbol{r}_i}\big(u(g)\big) \;=\; U_{\boldsymbol{r}_i}\,\rho_{\boldsymbol{r}_i}(g)^*\,U_{\boldsymbol{r}_i}^\dagger \quad \forall\, g \in G \text{ and } \forall\, i} \quad \Longleftrightarrow \quad \boxed{\textbf{physical CP}}$$

Physical CP vs. Generalized CP Transformations

- generalized CP transformation

$$\Phi(x) \xmapsto{\widetilde{\mathcal{CP}}} U_{\mathrm{CP}}\,\Phi^*(\,\mathcal{P}\;x)$$

- Necessary consistency condition

$$\rho\big(u(g)\big) \;=\; U_{\mathrm{CP}}\;\rho(g)^*\,{U_{\mathrm{CP}}}^\dagger \quad \forall\, g \in G$$

Holthausen, Lindner, Schmidt (2013)

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⟷ **physical** CP

u has to be a **class-inverting**, **involuntary** automorphism of G

➪ non-existence of such automorphism in certain groups

➪ calculable (explicit) physical CP violation in generic settings

The Bickerstaff-Damhus automorphism (BDA)

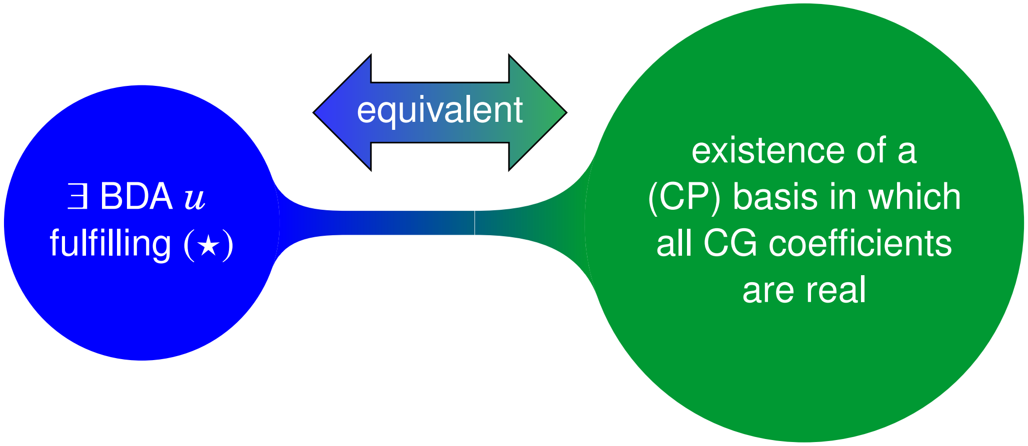
- Bickerstaff-Damhus automorphism (BDA) $\boldsymbol{u}$

Bickerstaff, Damhus (1985)

$$\rho_{\boldsymbol{r}_i}(u(g)) \quad = \quad U_{\boldsymbol{r}_i}\ \rho_{\boldsymbol{r}_i}(g)^*\, U_{\boldsymbol{r}_i}^\dagger \quad \forall\, g \in G \text{ and } \forall\, i \qquad (\,\star\,)$$

unitary & symmetric

- BDA vs. Clebsch-Gordan (CG) coefficients



equivalent

$\exists$ BDA u fulfilling $(\star)$

existence of a (CP) basis in which all CG coefficients are real

Twisted Frobenius-Schur Indicator

- How can one tell whether or not a given automorphism is a BDA?
- Frobenius-Schur indicator:

$$\mathrm{FS}(\boldsymbol{r}_i) := \frac{1}{|G|}\sum_{g\in G}\chi_{\boldsymbol{r}_i}(g^2) = \frac{1}{|G|}\sum_{g\in G}\mathrm{tr}\left[\rho_{\boldsymbol{r}_i}(g)^2\right]$$

$$\mathrm{FS}(\boldsymbol{r}_i) = \begin{cases} +1, & \text{if } \boldsymbol{r}_i \text{ is a real representation,} \\ 0, & \text{if } \boldsymbol{r}_i \text{ is a complex representation,} \\ -1, & \text{if } \boldsymbol{r}_i \text{ is a pseudo–real representation.} \end{cases}$$

- Twisted Frobenius-Schur indicator

Bickerstaff, Damhus (1985); Kawanaka, Matsuyama (1990)

$$\mathrm{FS}_u(\boldsymbol{r}_i) = \frac{1}{|G|}\sum_{g\in G}\left[\rho_{\boldsymbol{r}_i}(g)\right]_{\alpha\beta}\left[\rho_{\boldsymbol{r}_i}(u(g))\right]_{\beta\alpha}$$

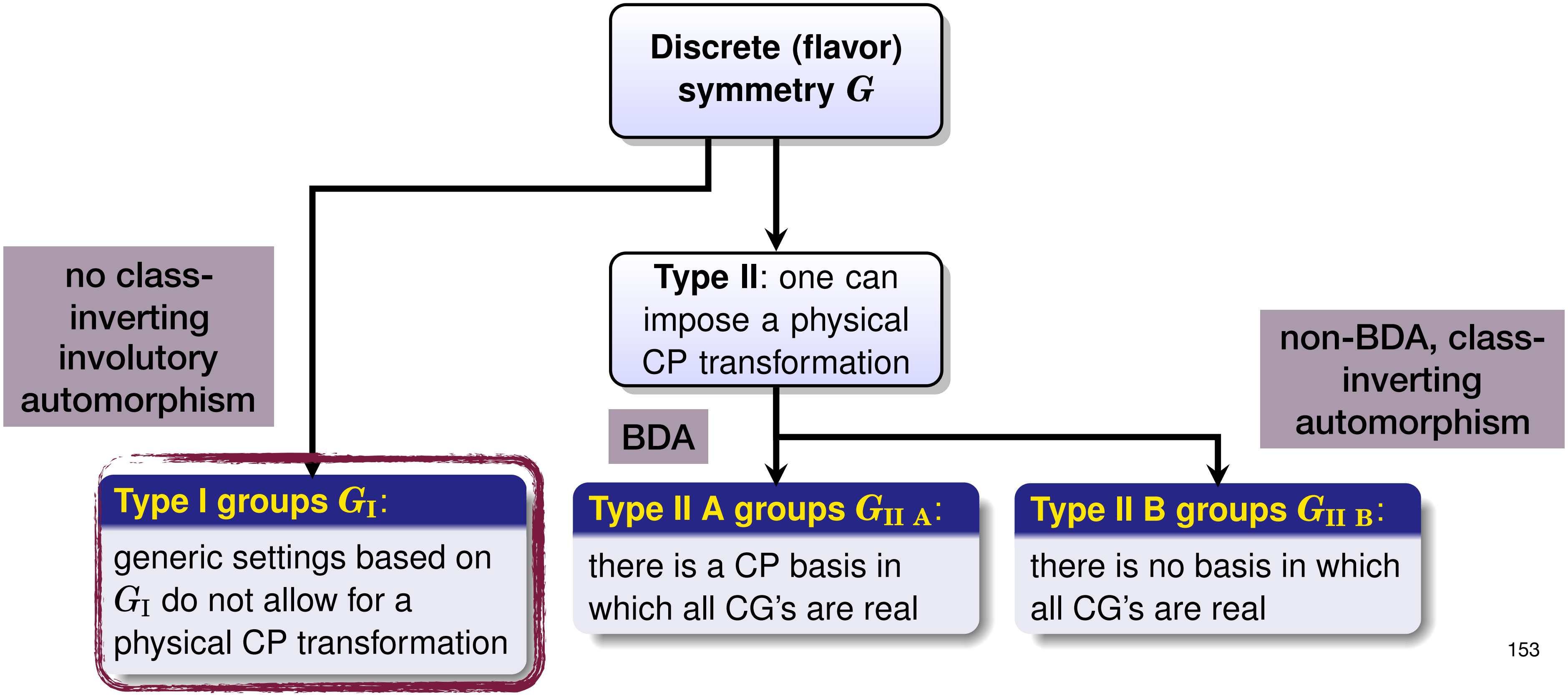
- $$\mathrm{FS}_u(\boldsymbol{r}_i) = \begin{cases} +1 \quad \forall\, i, & \text{if } u \text{ is a BDA,} \\ +1 \text{ or } -1 \quad \forall\, i, & \text{if } u \text{ is class–inverting and involutory,} \\ \text{different from } \pm 1, & \text{otherwise.} \end{cases}$$

A Novel Origin of CP Violation

M.-C.C, M. Fallbacher, K.T. Mahanthappa,
M. Ratz, A. Trautner, NPB (2014)

- **For discrete groups that do not have class-inverting, involutory automorphism, CP is generically broken by complex CG coefficients (Type I Group)**
- **Non-existence of such automorphism ⇔ Physical CP violation**

CP Violation from Group Theory!



Discrete (flavor) symmetry G

no class-inverting involutory automorphism

Type I groups G_{I}:

generic settings based on G_{I} do not allow for a physical CP transformation

Type II: one can impose a physical CP transformation

BDA

Type II A groups $G_{\mathrm{II\ A}}$:

there is a CP basis in which all CG's are real

non-BDA, class-inverting automorphism

Type II B groups $G_{\mathrm{II\ B}}$:

there is no basis in which all CG's are real

Examples

M.-C.C., M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner (2014)

- Type I: all odd order non-Abelian groups

group	$\mathbb{Z}_5 \rtimes \mathbb{Z}_4$	T_7	$\Delta(27)$	$\mathbb{Z}_9 \rtimes \mathbb{Z}_3$
SG	(20,3)	(21,1)	(27,3)	(27,4)

- Type IIA: dihedral and all Abelian groups

group	S_3	Q_8	A_4	$\mathbb{Z}_3 \rtimes \mathbb{Z}_8$	T′	S_4	A_5
SG	(6,1)	(8,4)	(12,3)	(24,1)	(24,3)	(24,12)	(60,5)

- Type IIB

group	$\Sigma(72)$	$((\mathbb{Z}_3 \times \mathbb{Z}_3) \rtimes \mathbb{Z}_4) \rtimes \mathbb{Z}_4$
SG	(72,41)	(144,120)

Novel Origin of CP (Time Reversal) Violation

M.-C.C, M. Fallbacher,
K.T. Mahanthappa, M. Ratz,
A. Trautner, NPB (2014)

complex CGs ⇨ CP symmetry cannot be defined for certain groups (Type I)

CP Violation from Group Theory!

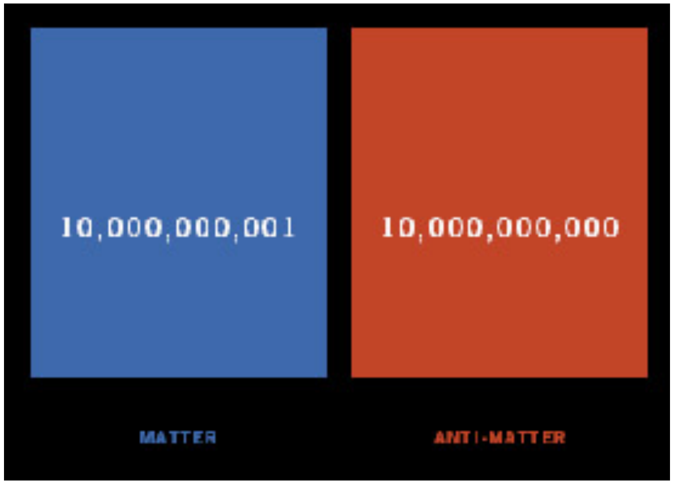
The Plan

- Part I: Neutrinos in the SM; What do We Know from Experiments
- Part II: Neutrinos Mass in BSM
- Part III: Neutrino Mixing and Leptonic CP Violation
- **Part IV: Baryogenesis through Leptogenesis**

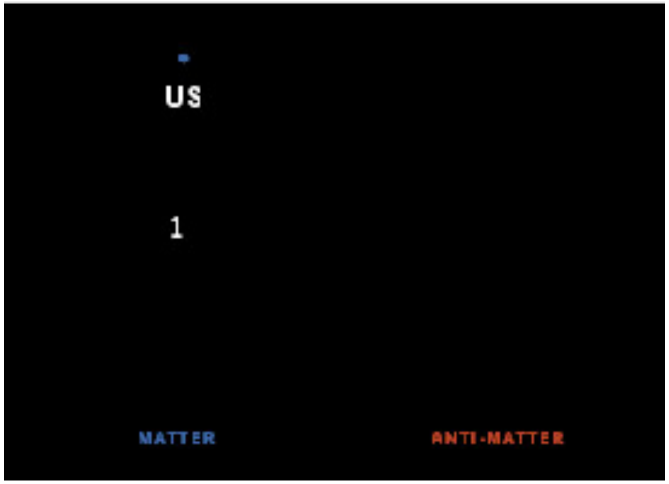
References

- A. Riotto, hep-ph/9901362
- M. Trodden, hep-ph/0411301
- W. Büchmuller, hep-ph/0502169
- “TASI 2006 Lectures on Leptogenesis,” M.-C. Chen, hep-ph/0703087

Three Sakharov Conditions



Early Universe



Universe Now

[Picture credit: H. Murayama]

- **Baryon number can be generated dynamically, if**
    - violation of baryon number
    - violation of Charge (C) and Charge Parity (CP)
    - departure from thermal equilibrium

Baryon Number Asymmetry beyond SM

- Within the SM:
  - CP violation in quark sector not sufficient to explain the observed matter-antimatter asymmetry of the Universe
  - accidental symmetries L_e, L_μ, L_τ, total L
  - massless neutrinos, no cLFV

- **neutrino oscillation ⇒ non-zero neutrino masses**
  - physics beyond the Standard Model
  - new CP phases in the neutrino sector

- neutrino masses open up a new possibility for baryogenesis Fukugita, Yanagida, 1986

Leptogenesis

Sources of CP Violation: SM

- SM: CP is not exact symmetry in weak interactions (Kaon & B-meson systems)
- charged current interactions in weak basis

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U}_L \gamma^\mu D_L W_\mu + h.c. \qquad \text{where } U_L = (u, c, t)_L \text{ and } D_L = (d, s, b)_L$$

- rotate to mass basis

$$\text{diag}(m_u, m_c, m_t) = V_L^u M^u V_R^u \qquad U'_L \equiv V_L^u U_L \text{ and } D'_L \equiv V_L^d D_L$$

$$\text{diag}(m_d, m_s, m_d) = V_L^d M^d V_R^d \, . \qquad U_{CKM} \equiv V_L^u (V_L^d)^\dagger$$

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U}'_L U_{CKM} \gamma^\mu D'_L W_\mu + h.c.$$

Sources of CP Violation: MSSM

- soft SUSY breaking terms → new sources of CPV
- superpotential of MSSM

$$W = \mu \hat{H}_1 \hat{H}_2 + h^u \hat{H}_2 \hat{Q} \hat{u}^c + h^d \hat{H}_1 \hat{Q} \hat{d}^c + h^e \hat{H}_1 \hat{L} \hat{e}^c$$

- parameters in soft SUSY breaking sector
  - tri-linear couplings:

$$\Gamma^u H_2 \widetilde{Q} \widetilde{c}^c + \Gamma^d H_1 \widetilde{Q} \widetilde{d}^c + \Gamma^e H_1 \widetilde{L} \widetilde{e}^c + h.c. \qquad \Gamma^{(u,d,e)} \equiv A^{(u,d,e)} \cdot h^{(u,d,e)}$$

  - bi-linear coupling in Higgs sector: $\mu B H_1 H_2$
  - gaugino masses: M_i for $i = 1, 2, 3$
  - soft scalar masses: $\widetilde{m}_f$
- cMSSM w/ mSUGRA → 2 physical phases → soft leptogenesis

$$\phi_A = \mathrm{Arg}(AM), \quad \phi_\mu = -\mathrm{Arg}(B)$$

Observation of Neutrino Oscillations

$\Rightarrow$ CP violation in lepton sector

$\Rightarrow$ Leptogenesis

Leptonic CP Violation

- Seesaw Lagrangian at high energy (in the presence of RH neutrinos)

$$\mathcal{L} = \overline{\ell}_{L_i} i\gamma^\mu \partial_\mu \ell_{L_i} + \overline{e}_{R_i} i\gamma^\mu \partial_\mu e_{R_i} + \overline{N}_{R_i} i\gamma^\mu \partial_\mu N_{R_i} \\ + f_{ij}\overline{e}_{R_i}\ell_{L_j}H^\dagger + h_{ij}\overline{N}_{R_i}\ell_{L_j}H - \frac{1}{2}M_{ij}N_{R_i}N_{R_j} + h.c.$$

in f_{ij} and M_{ij} diagonal basis →

h_{ij} general complex matrix: { 9-3 = 6 mixing angles
9-3 = 6 physical phases

- Low energy effective Lagrangian (after integrating out RH neutrinos)

$$\mathcal{L}_{eff} = \overline{\ell}_{L_i} i\gamma^\mu \partial_\mu \ell_{L_i} + \overline{e}_{R_i} i\gamma^\mu \partial_\mu e_{R_i} + f_{ii}\overline{e}_{R_i}\ell_{L_i}H^\dagger + \frac{1}{2}\sum_k h^T_{ik}h_{kj}\ell_{L_i}\ell_{L_j}\frac{H^2}{M_k} + h.c.$$

in f_{ij} diagonal basis →

h_{ij} symmetric complex matrix: { 6-3 = 3 mixing angles
6-3 = 3 physical phases

- high energy → low energy:

Standard Leptogenesis

- most general Lagrangian in lepton sector

$$\mathcal{L}_Y = f_{ij}\overline{e}_{R_i}\ell_{L_j}H^\dagger + h_{ij}\overline{\nu}_{R_i}\ell_{L_j}H - \frac{1}{2}(M_R)_{ij}\overline{\nu}^c_{R_i}\nu_{R_j} + h.c.$$

- mass generation

$$m_\ell = fv, \quad m_D = hv \ll M_R$$

- see-saw mechanism in neutrino sector $\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$
- resulting effective masses

$$\nu \simeq V_\nu^T \nu_L + V_\nu^* \nu_L^c, \quad N \simeq \nu_R + \nu_R^c$$

$$m_\nu \simeq -V_\nu^T m_D^T \frac{1}{M_R} m_D V_\nu, \quad m_N \simeq M_R$$

- basic idea:
  - T < M_R: out-of-equilibrium decays of N → ΔL
  - sphaleron processes: ΔL → ΔB

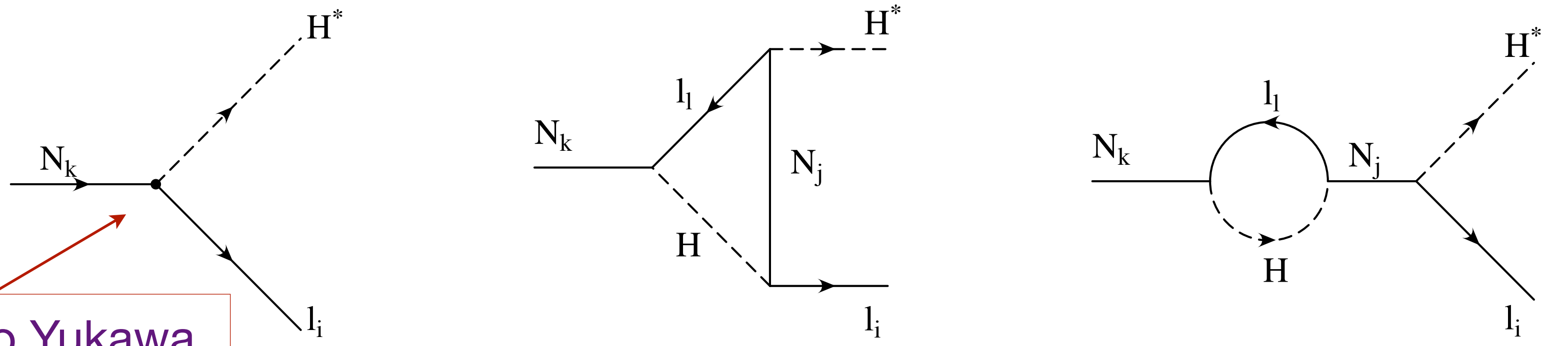
Luty, 1992; Covi, Roulet, Vissani, 1996; Flanz et al, 1996; Plumacher, 1997; Pilaftsis, 1997;

Buchmuller, Plumacher, 1998;
Buchmuller, Di Bari, Plumacher, 2004

Standard Leptogenesis

Fukugita, Yanagida, 1986

- CP asymmetry in RH heavy neutrino decay:
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry ΔL



Neutrino Yukawa coupling

leptons antileptons

$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}$$

Leptonic CP violation ⇒ ΔL ∝ $\left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]$ ≠ 0

Standard Leptogenesis - washout

- final amount of asymmetry $$Y_L \equiv \frac{n_L - \overline{n}_L}{s} = \kappa \frac{\epsilon_1}{g_*}$$
- k: parametrizing washout effects
  - out of equilibrium condition $$\Gamma_{D_1} < H\Big|_{T=M_1}$$
  - asymmetry can be washed out by inverse decays and scattering processes
    - Boltzmann equations
- EW Sphaleron effects ΔL → ΔB
  - final B asymmetry

$$\boxed{Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} = cY_{B-L} = \frac{c}{c-1} Y_L}$$

$$c_s = \frac{8N_f + 4N_H}{22N_f + 13N_H}$$

Bound on Light Neutrino Mass

- sufficient leptogenesis requires

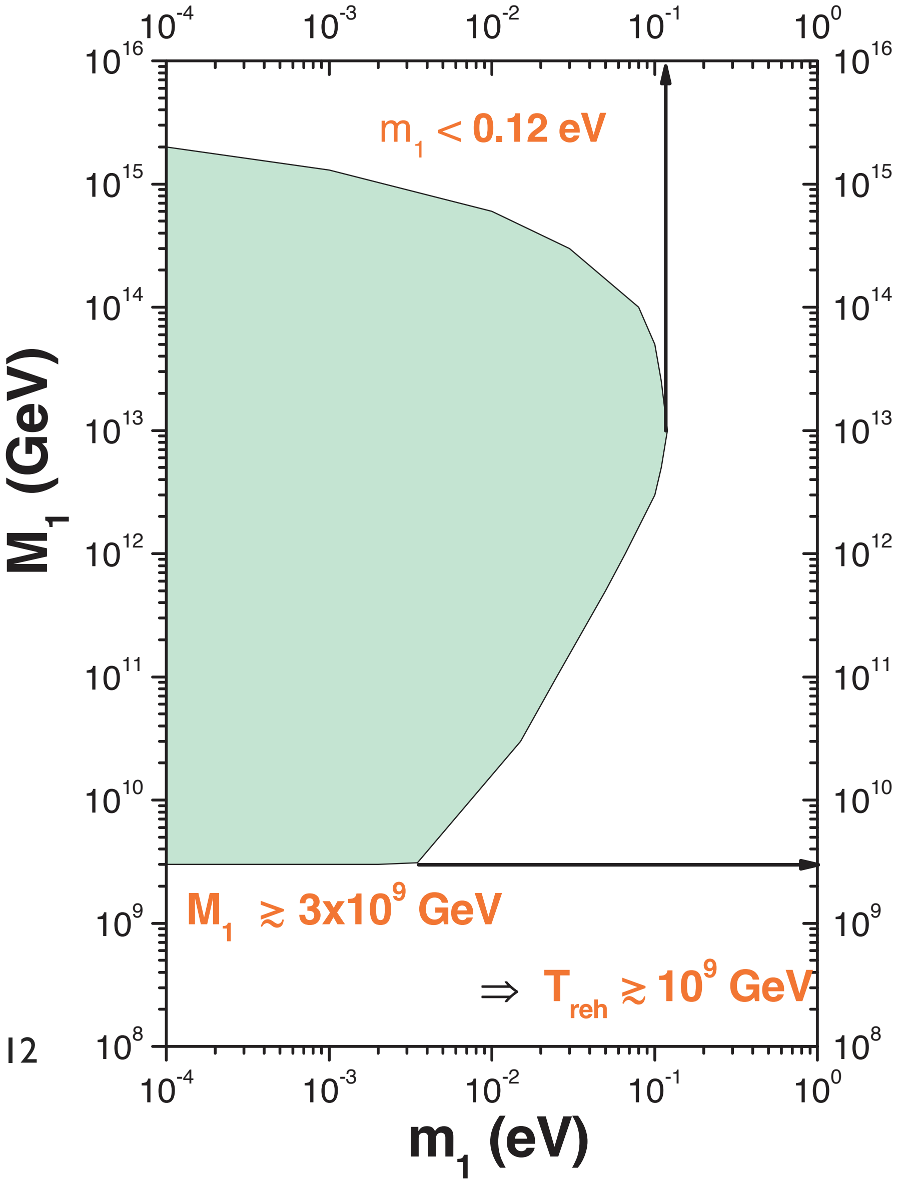
  $M_1 \gtrsim 3\text{x}10^9$ GeV

- upper bound on light neutrino mass

  $m_1 < 0.12$ eV

  - incompatible with quasi-degenerate spectrum

- constraints slightly alleviated with flavored case



P. Di Bari, 2012

Gravitino Problem

For light gravitino mass,

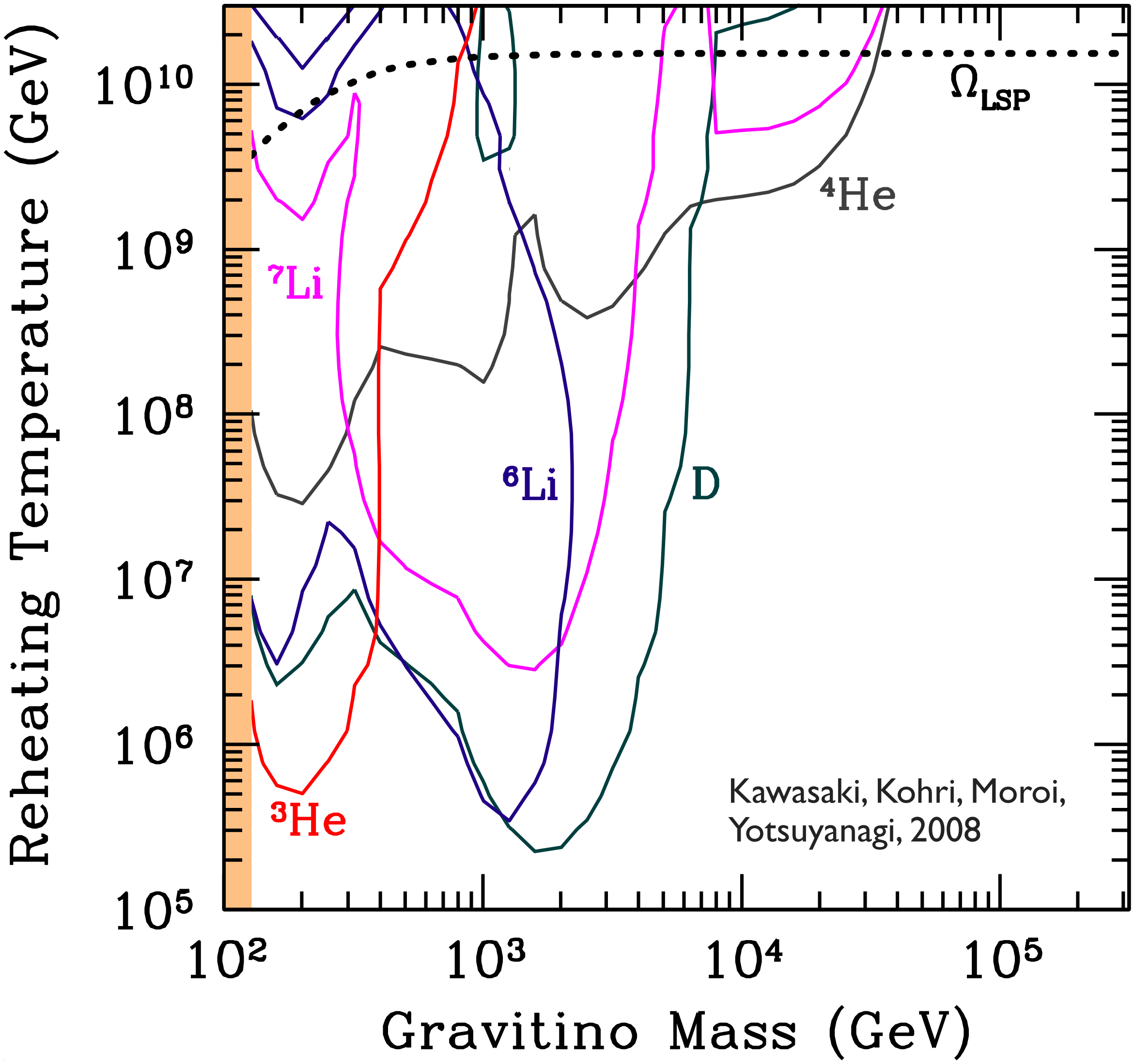
BBN constraints

⇒ $T_{RH} < 10^{(5\text{-}6)}$ GeV

tension!
(if SUSY)

Sufficient leptogenesis ⇒

$T_{RH} > M_R > 2 \times 10^9$ GeV



Kawasaki, Kohri, Moroi, Yotsuyanagi, 2008

Non-standard Scenarios

Leptogenesis ↔ Gravitino Overproduction

- resonant enhancement in self-energy diagram
    - resonant leptogenesis (near degenerate RH neutrinos)

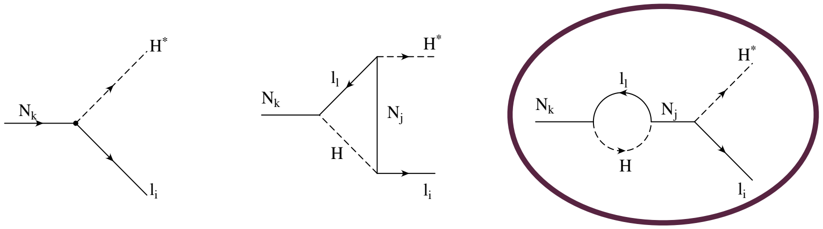
- relaxing relations between lepton number asymmetry and RH neutrino mass
    - soft leptogenesis (SUSY CP phases)

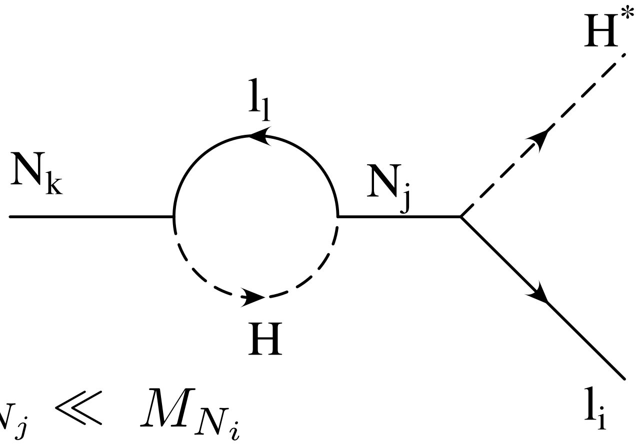
- relaxing relation between T_{RH} and R_H neutrino mass
    - non-thermal leptogenesis
        - non-thermal production of N_R by inflaton decay

Pilaftsis, 1997

Resonant Leptogenesis

- Recall: Standard Leptogenesis





- self-energy diagram dominates for $M_{N_i} - M_{N_j} \ll M_{N_i}$

$$\epsilon_{N_i}^{\text{Self}} = \frac{Im[(h_\nu h_\nu^\dagger)_{ij}]^2}{(h_\nu h_\nu^\dagger)_{ii}(h_\nu h_\nu^\dagger)_{jj}} \left[\frac{(M_i^2 - M_j^2) M_i \Gamma_{N_j}}{(M_i^2 - M_j^2)^2 + M_i^2 \Gamma_{N_j}^2} \right]$$

  - enhanced asymmetry if $M_1^2 - M_2^2 \sim \Gamma_{N_2}^2$
  - O(1) asymmetry if

$$M_1 - M_2 \sim \frac{1}{2}\Gamma_{N_{1,2}} \quad , \quad \text{assuming} \quad \frac{Im(h_\nu h_\nu^\dagger)_{12}^2}{(h_\nu h_\nu^\dagger)_{11}(h_\nu h_\nu^\dagger)_{22}} \sim 1$$

- Leptogenesis possible with M1,2 ~ TeV

Pilaftsis, Underwood, 2003

Soft Leptogenesis

Grossman,Kashti,Nir,Roulet, 03
D'Ambrosio,Giudice,Raidal, 03

- leptogenesis:
  - CP violation in decays → standard leptogenesis
  - CP violation in mixing → soft leptogenesis

- Recall: Kaon system
  - mismatch between CP eigenstates & mass eigenstates $\Rightarrow$ CP violation
  - CP eigenstates $\frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle \pm \left|\overline{K}^0\right\rangle\right)$
  - time evolution

$$\frac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} = \mathcal{H}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} \qquad \mathcal{H} = \overset{\downarrow}{\mathcal{M}} - \frac{i}{2}\overset{\downarrow}{\mathcal{A}}$$

Soft Leptogenesis

- Mass eigenstates

$$|K_L\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$
$$|K_S\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$

- mismatch between mass eigenstates & CP eigenstates

$$\left|\frac{q}{p}\right| \neq 1\,, \quad \text{where} \quad \left(\frac{q}{p}\right)^2 = \left(\frac{2\mathcal{M}_{12}^* - i\mathcal{A}_{12}^*}{2\mathcal{M}_{12} - i\mathcal{A}_{12}}\right)$$

Soft Leptogenesis

- For soft leptogenesis

$$W = M_1 N_1 N_1 + \mathcal{Y}_{1i} L_i N_1 H_u$$

$$-\mathcal{L}_{soft} = \left(\frac{1}{2} B M_1 \widetilde{\nu}_{R_1} \widetilde{\nu}_{R_1} + A \mathcal{Y}_{1i} \widetilde{L}_i \widetilde{\nu}_{R_1} H_u + h.c. \right) + \widetilde{m}^2 \widetilde{\nu}^{\dagger}_{R_1} \widetilde{\nu}_{R_1}$$

⇒

interactions: $-\mathcal{L}_{\mathcal{A}} = \widetilde{\nu}_{R_1} (M_1 Y^*_{1i} \widetilde{\ell}^*_i H^*_u + \mathcal{Y}_{1i} \overline{\widetilde{H}}_u \ell^i_L + A \mathcal{Y}_{1i} \widetilde{\ell}_i H_u) + h.c.$

mass terms: $-\mathcal{L}_{\mathcal{M}} = (M_1^2 \widetilde{\nu}^{\dagger}_{R_1} \widetilde{\nu}_{R_1} + \frac{1}{2} B M_1 \widetilde{\nu}_{R_1} \widetilde{\nu}_{R_1}) + h.c.$

- diagonalization of mass matrix in $\widetilde{\nu}_{R_1}$ and $\widetilde{\nu}^{\dagger}_{R_1}$ basis

⇒ mass eigenstates: $\widetilde{N}_+$ and $\widetilde{N}_-$ $\quad M_{\pm} \simeq M_1 \left(1 \pm \frac{|B|}{2M_1} \right)$

mass splitting due to
SUSY breaking

Soft Leptogenesis

- time evolution of $\widetilde{\nu}_{R_1}$-$\widetilde{\nu}^\dagger_{R_1}$ system

$$\frac{d}{dt}\begin{pmatrix}\widetilde{\nu}_{R_1}\\ \widetilde{\nu}^\dagger_{R_1}\end{pmatrix} = \mathcal{H}\begin{pmatrix}\widetilde{\nu}_{R_1}\\ \widetilde{\nu}^\dagger_{R_1}\end{pmatrix} \qquad \mathcal{H} = \mathcal{M} - \tfrac{i}{2}\mathcal{A}$$

$$\mathcal{M} = \begin{pmatrix} 1 & \frac{B^*}{2M_1} \\ \frac{B}{2M_1} & 1 \end{pmatrix} M_1 \qquad \mathcal{A} = \begin{pmatrix} 1 & \frac{A^*}{M_1} \\ \frac{A}{M_1} & 1 \end{pmatrix} \Gamma_1$$

- total decay width of $\widetilde{\nu}_{R_1}$

$$\Gamma_1 = \frac{1}{4\pi}(\mathcal{Y}_\nu \mathcal{Y}_\nu^\dagger)_{11} M_1$$

Soft Leptogenesis

- eigenstates of H: $\widetilde{N}'_{\pm} = p\widetilde{N} \pm q\widetilde{N}^{\dagger}$

$$|p|^2 + |q|^2 = 1.$$

- for A12 << M12 :

$$\left(\frac{q}{p}\right)^2 = \frac{2\mathcal{M}^*_{12} - i\mathcal{A}^*_{12}}{2\mathcal{M}_{12} - i\mathcal{A}_{12}} \simeq 1 + \mathrm{Im}\left(\frac{2\Gamma_1 A}{BM_1}\right)$$

- mismatch between $(\widetilde{N}_+, \widetilde{N}_-)$ and $(\widetilde{N}'_+, \widetilde{N}'_-)$

⇒ CP violation in lepton asymmetry

non-zero CPV ⇒ $|q/p| \neq 1$

$$\Rightarrow \quad \mathrm{Im}\left(\frac{A\Gamma_1}{M_1 B}\right) \neq 0$$ i.e. SUSY breaking

Soft Leptogenesis

- total lepton number asymmetry

$$\epsilon = \frac{\sum_f \int_0^\infty [\Gamma(\widetilde{\nu}_{R_1}, \widetilde{\nu}^\dagger_{R_1} \to f) - \Gamma(\widetilde{\nu}_{R_1}, \widetilde{\nu}^\dagger_{R_1} \to \overline{f})]}{\sum_f \int_0^\infty [\Gamma(\widetilde{\nu}_{R_1}, \widetilde{\nu}^\dagger_{R_1} \to f) + \Gamma(\widetilde{\nu}_{R_1}, \widetilde{\nu}^\dagger_{R_1} \to \overline{f})]}$$

  - final states: $f = (\widetilde{L}\ H),\ (L\ \widetilde{H})$ (L=+1)

- after time integration

$$\epsilon = \left(\frac{4\Gamma_1 B}{\Gamma_1^2 + 4B^2} \right) \frac{\mathrm{Im}(A)}{M_1} \delta_{B-F}$$

δ_{B-F} : take into account thermal effects

Is Leptogenesis Possible without LNV?

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000;
Murayama, Pierce, 2002; ...

- Leptogenesis possible when neutrinos are Dirac particles
- small Dirac mass through suppressed Yukawa coupling
- Characteristics of Sphaleron effects:
  - only left-handed fields couple to sphalerons
  - sphalerons change (B+L) but not (B-L)
  - sphaleron effects in equilibrium for T > Tew
- If L stored in RH fermions can survive below EW phase transition, net lepton number can be generated even with L=0 initially
- for SM quarks and leptons: rapid left-right equilibration through large Yukawa

no net asymmetry
if B = L = 0 initially

Dirac Leptogenesis

- LR equilibration for neutrinos:
  - neutrino Yukawa coupling $\lambda \bar{\ell}_L H \nu_R$
  - rate for conversion $\Gamma_{LR} \sim \lambda^2 T$
  - for LR conversion not to be in equilibrium

$$\Gamma_{LR} \lesssim H \ , \quad \text{for} \quad T > T_{eq} \qquad\qquad H \sim \frac{T^2}{M_{\rm Pl}}$$

  - Thus LR equilibration occur at much later time

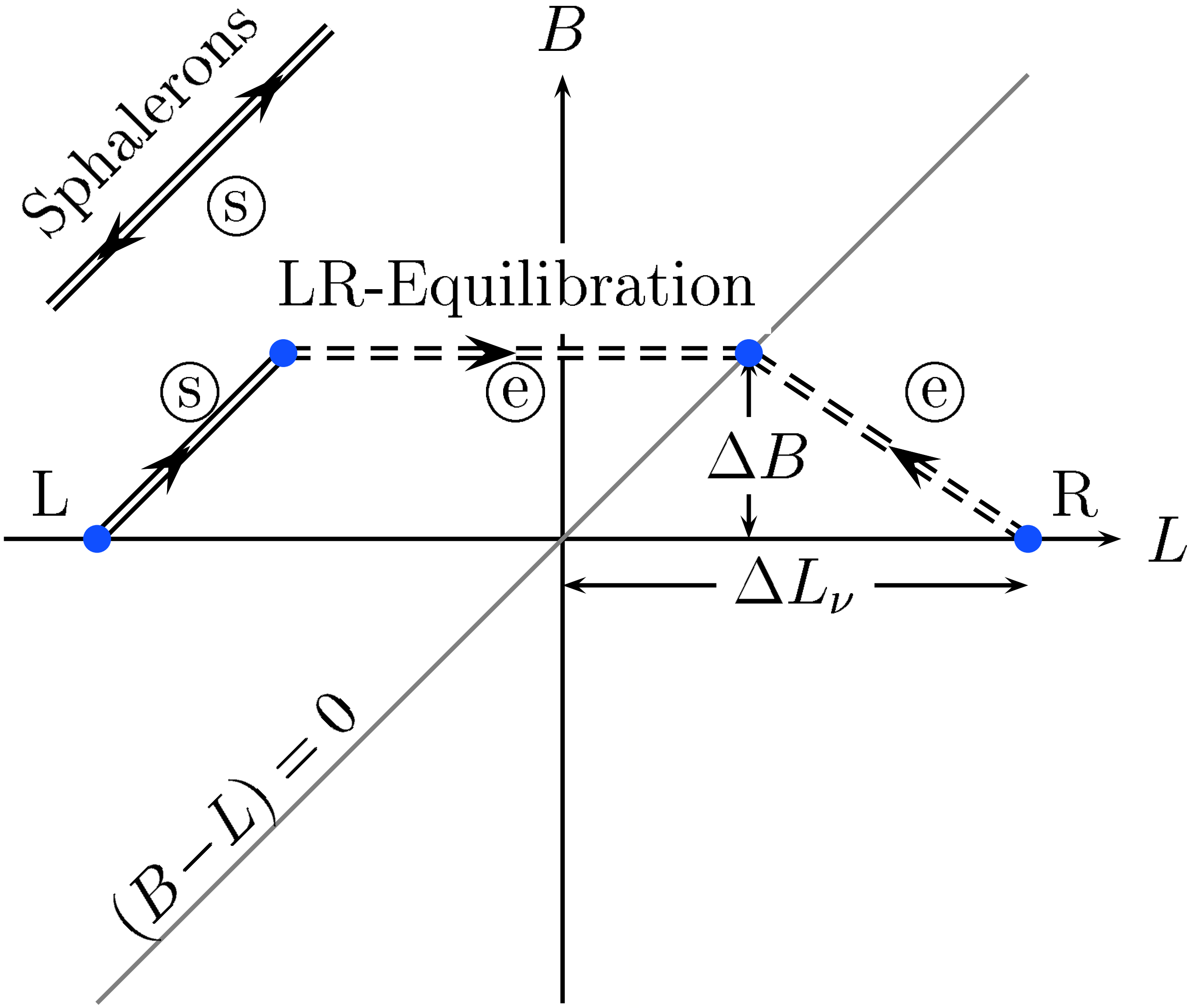
$$T \ \lesssim \ T_{eq} \ll T_{EW} \qquad \Rightarrow \qquad \lambda^2 \lesssim \frac{T_{eq}}{M_{\rm Pl}} \ll \frac{T_{EW}}{M_{\rm Pl}}$$

$$M_{\rm Pl} \sim 10^{19} \ \text{GeV} \qquad T_{EW} \sim 10^2 \ \text{GeV} \qquad \lambda < 10^{-(8\sim9)}$$

$$m_D < 10 \ \text{keV}$$

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000



Dirac Leptogenesis

K. Dick, M. Lindner, M. Ratz, D.Wright, 2000;
H. Murayama, A. Pierce, 2002

- Leptogenesis possible even when neutrinos are Dirac particles **(no ΔL = 2 violation)**

- Characteristics of Sphaleron effects:
  - only left-handed fields couple to sphalerons
  - sphalerons change (B+L) but not (B-L)
  - sphaleron effects in equilibrium for T > Tew

late time LR equilibration of neutrinos making Dirac leptogenesis possible with primordial **ΔL = 0**

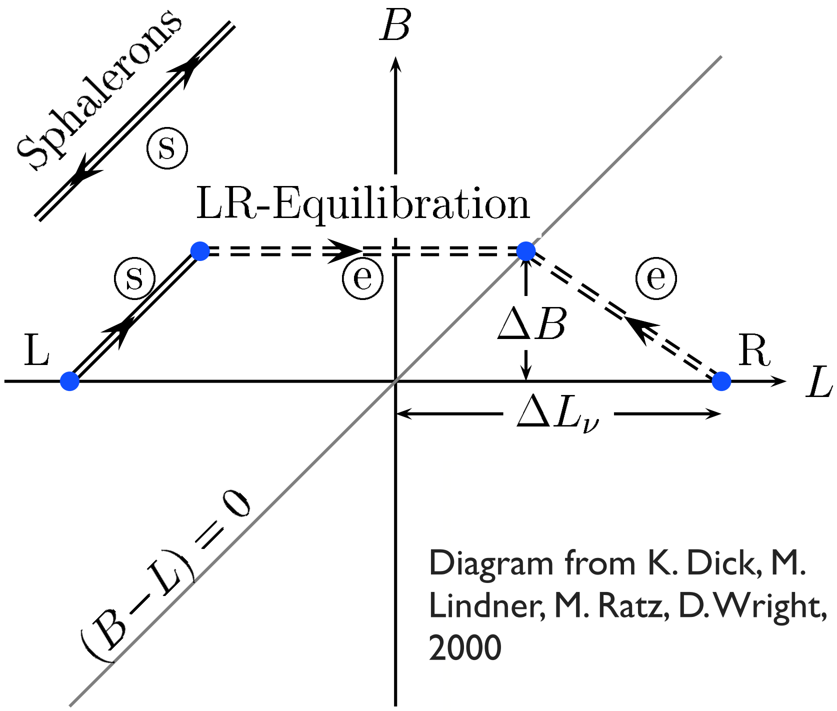


Diagram from K. Dick, M. Lindner, M. Ratz, D.Wright, 2000

Connection to Low Energy Observables

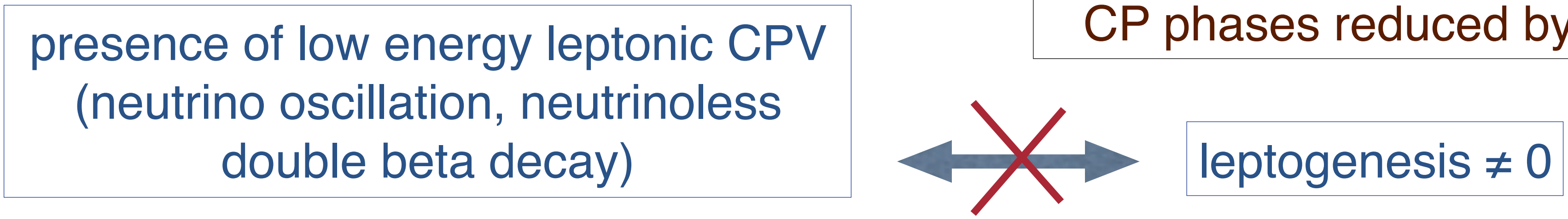
- Standard Leptogenesis: seesaw mechanism, Majorana neutrinos
- Seesaw Lagrangian at high energy (in the presence of RH neutrinos)

6 mixing angles + 6 physical phases

- Low energy effective Lagrangian (after integrating out RH neutrinos)

3 mixing angles + 3 physical phases

high energy → low energy:
numbers of mixing angles and
CP phases reduced by half



presence of low energy leptonic CPV (neutrino oscillation, neutrinoless double beta decay)

leptogenesis $\neq 0$

  - No model independent connection
  - BUT, in certain predictive models, connection can be established