More on Flavor Gauge Symmetry

Zurab Berezhiani

University of L'Aquila and LNGS

Folks to Dare Meeting @ Tbilisi, 26 Sept. 2017

based on work with Benedetta Belfatto

Standard Model on T-shirts

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Fermions (= matter): quarks and leptons, *3 generations*

Bosons (= interactions): gauge fields + God's particle – Higgs

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Yuk} + \mathcal{L}_{\rm Higgs}$$

Standard Model vs. P, C, T and B & L

Fermions:

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad u_R, \ d_R, \quad e_R$$

B=1/3 L=1 B=1/3 L=1

Anti-Fermions:

$$\bar{q}_R = \begin{pmatrix} \bar{u}_R \\ \bar{d}_R \end{pmatrix}, \quad \bar{l}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; \qquad \bar{u}_L, \ \bar{d}_L, \quad \bar{e}_L$$

B=-1/3 L=-1 B=-1/3 L=-1

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yuk}$$ CPT is OK (Local Lagrangian)

P $(\Psi_L \to \Psi_R)$ & C $(\Psi_L \to \bar{\Psi}_L)$ broken by gauge interactions

CP $(\Psi_L \to \bar{\Psi}_R)$ broken by complex Yukawas $Y = Y_{ij}^{u,d,e}$

$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$

There are no renormalizable interactions which can break B and L !

SM is too good: natural, economic, and experimentally tested

- Renormalizability (one can control radiative corrections)
- Origin of Mass: Higgs condensate $\langle\phi^0\rangle = v/\sqrt{2}$, $v = 246$ GeV and its radial mode H: Higgs $m_H \approx 125$ GeV

Weak Boson masses: $M_W = \frac{1}{2}gv$, $M_Z = \frac{1}{2}\left(g^2 + g'^2\right)^{1/2} v$,

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$ – ... think about the limit $g' \to 0$!

Quarks & Lepton masses $m_e, m_u, m_d, \dots m_t$ are all $\propto v \sim 100$ GeV
$M^f_{ij} = \frac{v}{\sqrt{2}} Y^f_{ij}$, $(f = u, d, e, \ \ i,j = 1,2,3)$ $\quad \tilde{V}_f^\dagger M^f V_f = M^f_{\rm diag}$

- CKM mixing $V_{\rm CKM} = V_u^\dagger V_d$: misaligned Yukawas Y^u_{ij} and Y^d_{ij}
- CP-violation: complex Yukawas $Y^{u,d}_{ij}$
- Baryon and lepton conservation: no Yukawas break B and L – accidental global $U(1)_B$ and $U(1)_L$
- Flavor conservation in neutral currents (Z, H): Yukawas $Y^{u,d,e}_{ij}$ proportional to mass matrices $M^{u,d,e}_{ij}$ (one Higgs)

CKM mixing

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

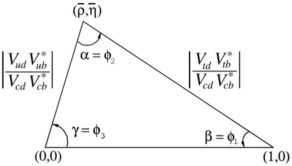
Standard parametrization (3 angles and CP-phase)

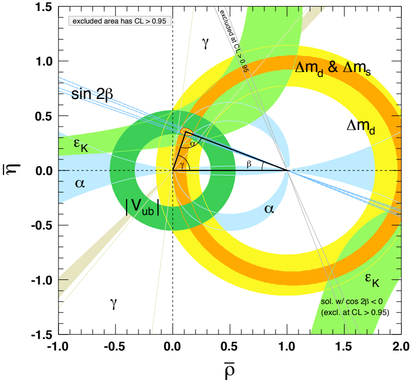
$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

or

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity Triangle: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$





SM has problems ... their solutions create other problems

• Origin of gauge constants, charge quantization, relation to gravity:
– Grand Unification, String theory
→ Weinberg angle, proton decay
→ problem of hierarchies

• Hierarchy problem: stability of electroweak (Higgs) mass scale $M_H \sim 100$ GeV (N.B. no problem with QCD scale $\Lambda_{\rm QCD} \sim 100$ MeV)
– SUSY, Technicolor, etc.
→ New particles and new phenomena at TeV scale
→ "too much" flavor changing and CP-violation (EDM's)

• Strong CP-problem: $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$ in non-perturbative QCD vacuum
$\theta \sim 1$ expected vs. $\theta < 10^{-10}$ – exp. DEMON (EDM of neutron) – Peccei-Quinn symmetry $U(1)_{PQ}$, in different model realizations
→ axion – with rich phenomenological implications
→ origin of global $U(1)_{PQ}$, hierarchy problem: $V_{PQ} \gg v$, "new" flavor changing processes $\mu \to ea$ etc.

SM has problems ... creating other problems

• Lepton and Baryon numbers: how are violated ? ... deep connection to the origin of baryon asymmetry in the Universe

• Dark matter: from where it comes ? can it be detectable ? (can it have interactions to normal matter or self-interactions ?) Why cosmological of DM is so close to baryon fraction ? $\Omega_{DM}/\Omega_B \simeq 5$ Maybe DM abundance is also related to some kind of baryon asymmetry, co-generated together with ordinary baryon asymmetry ?

Baryon & Lepton violation

• B & L can be violated only in higher order (non-renormalizable) terms

$\frac{1}{M} ll\phi\phi$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$

$\frac{1}{M^2} qqql$ etc. $(\Delta L = 1,\ \Delta B = 1\ )$ – proton decay $p \to \pi^0 e^+$, $p \to \pi^+ \nu$ etc.

$\frac{1}{M^5} qqqqqq$ etc. $(\Delta B = 2,\ \Delta B = 1\ )$ – neutron-antineutron oscillation $n(udd) \to \tilde{n}(\bar{u}\bar{d}\bar{d})$

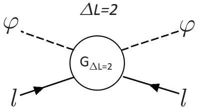
coming from new physics related to scale $M \gg v_{\rm EW}$

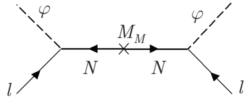
• B & L can be (non-perturbatively) violated only in (very) higher order terms due to $U(1)_B$ and $U(1)_B$ anomalies ('t Hooft) but $B - L$ must be conserved !

Baryogenesis requires new physics:

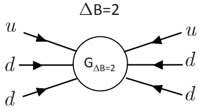
B & L can be violated only in higher order (non-renormalizable) terms

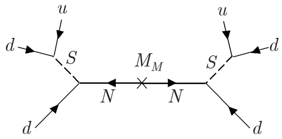
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$





- $\frac{1}{M^5}(udd)(udd)$ $(\Delta B = 2)$ – neutron-antineutron oscillation $n \to \bar{n}$





can originate from new physics related to scale $M \gg v_{\mathrm{EW}}$ via seesaw

Family problems ... for solving other problems

- Family problems: 3 families? Hierarchy of fermion masses and CKM mixing? CP-violation? Why $\tan\theta_{12} \approx \sqrt{m_d/m_s}$, etc.

- Neutrino masses: Why so small? Why large mixing?

Let us start to from resolving family problems ... and then think to resolve other problems

Gauge Flavor symmetry and origin of inter-family hierarchy

$q_i \sim (3,2)_{\frac{1}{6}}, \; \bar{u}_i \sim (\bar{3},1)_{-\frac{2}{3}}, \; \bar{d}_i \sim (\bar{3},1)_{\frac{1}{3}}; \quad l_i \sim (1,2)_{-\frac{1}{2}}, \; \bar{e}_i \sim (1,1)_1$

– L – (left set): Particle basis + anti-RH neutrino $\bar{N}_i \sim (1,1)_0$

$\bar{q}^i \sim (\bar{3},\bar{2})_{-\frac{1}{6}}, \; u^i \sim (3,1)_{\frac{2}{3}}, \; d^i \sim (3,1)_{-\frac{1}{3}}; \quad \bar{l}^i \sim (1,2)_{\frac{1}{2}}, \; e^i \sim (1,1)_{-1}$

– R – (right set): Anti-particle basis + RH-neutrino $N^i \sim (1,1)_0$

$i = 1,2,3$ family index – gauge horizontal $SU(3)$ symmetry between families? $q_i \sim 3$, $\bar{q}^i \sim \bar{3}$ etc.

- Hypothesis of horizontal hierarchies: Z.B., Chkareuli 1982 Z.B. 1983

Family symmetry is chiral: fermions cannot get masses without its breaking! The SM Yukawa structures $Y_{u,d,e}$, i.e. the mass hierarchy between families and pattern of weak mixing angles, follows the VEV structure breaking $U(3) = SU(3)_{\rm loc} \times U(1)_{\rm glob}$

$U(3) \to U(2) \to U(1) \to \text{Nothing}$

$V_3 \gg V_2 \gg V_1 \gg v_{EW}$ $\qquad V_3 : V_2 : V_1 \sim m_3 : m_2 : m_1$

Effective operators for fermion masses

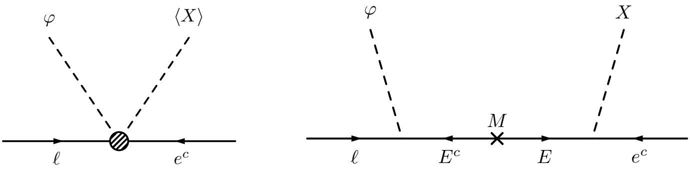
Effective operators for fermion masses (Projective couplings)

$$\frac{1}{M} X_u^{ji} \phi\, u_j^c q_i + \frac{1}{M} X_d^{\alpha i} \bar{\phi}\, d_\alpha^c q_i + \frac{1}{M} X_e^{\beta k} \bar{\phi}\, l_\beta e_k^c$$

where $X_{u,d,e}$ are horizontal scalars (flavons) which VEVs break family symmetries, ϕ is ordinary SM Higgs doublet

$$Y_u \sim \frac{\langle X_u \rangle}{M}, \quad Y_d \sim \frac{\langle X_d \rangle}{M}, \quad Y_e \sim \frac{\langle X_e \rangle}{M}$$

can be induced by "universal seesaw" mechanism by exchange of heavy fermions with quantum numbers of quarks and leptons: $U + U^c$, $D + D^c$, $E + E^c$ Z.B. 1983



How many family $SU(3)$'s can be introduced ?

- SM allows maximal (per fermion type) chiral symmetry

$$SU(3)_q \times SU(3)_u \times SU(3)_d \times SU(3)_l \times SU(3)_e \quad (\times SU(3)_N \ ?)$$

$$q_i \sim 3_q, \quad \bar{u}_j \sim 3_u, \quad \bar{d}_\alpha \sim 3_d; \quad l_\beta \sim 3_l, \quad \bar{e}_k \sim 3_e \ , \qquad \bar{N}_a \sim 3_N$$

No renormalizable terms are allowed for fermion masses – one has to introduce (non-renormalizable) effective operators

$$\left(\frac{X_u}{M}\phi q u^c + \frac{X_d}{M}\bar{\phi} q d^c + \frac{X_e}{M}\bar{\phi} e^c l\right) + \left(\frac{X_\nu}{M}\phi l N + \frac{X_N}{2} N N\right) + \text{h.c.}$$

Horizontal scalars (Flavons):

$$X_u \sim (\bar{3}_u, \bar{3}_q), \ X_d \sim (\bar{3}_d, \bar{3}_q), \ X_e \sim (\bar{3}_e, \bar{3}_l), \ X_\nu \sim (\bar{3}_N, \bar{3}_l), \ X_N \sim \bar{6}_N$$

$$\frac{1}{M}\langle X_{u,d,e,\nu}\rangle \to Y_{u,d,e,\nu}, \qquad \langle X_N \rangle \to M_N$$

- Minimal chiral symmetry motivated by GUT $SO(10) \times SU(3)_F$

$$F_i = (q, l, \bar{u}, \bar{d}, \bar{e}, \bar{N})_i \sim 16_i \qquad \text{flavons} \quad X_{u,d,e,\nu} \sim \bar{3} \times \bar{3} = \bar{6}_{\rm sym} + 3_{\rm asym}$$

$$\frac{X_6^{\{ij\}}}{M}(10 + 126) \cdot 16_i 16_j + \frac{X_3^{[ij]}}{M} \cdot 120 \cdot 16_i 16_j + \text{h.c.}$$

Gauged Flavor: $SU(5) \times SU(3)_{\bar{5}\mathrm{plet}} \times SU(3)_{10\mathrm{plet}}$

- medium chiral family symmetry motivated by $SU(5)$ GUT

$\bar{5}_\alpha = (\bar{d}, l)_\alpha \qquad 10_i = (q, \bar{u}, \bar{e})_i$

Gauge family symmetry $SU(3)_{\bar{5}\mathrm{plet}} \times SU(3)_{10\mathrm{plet}}$

i.e. we identify $SU(3)_{q,u,e} = SU(3)_{10}$ and $SU(3)_{d,l} = SU(3)_{\bar{5}}$

$q_i, \bar{u}_i, \bar{e}_i \sim 3_q, \qquad l_\alpha, \bar{d}_\alpha \sim 3_l$

Flavons: 3 triplets of $SU(3)_e$ and $SU(3)_l$: $\xi^i_n \sim \bar{3}_e$ and $\eta^a_n \sim \bar{3}_l$

effective operators

$$\sum_n \left(\frac{\xi^j_n \xi^i_n}{M^2} \bar{\phi} \bar{u}_j q_i + \frac{\eta^\alpha_n \xi^i_n}{M^2} \phi \bar{d}_\alpha q_i + \frac{\xi^i_n \eta^\alpha_n}{M^2} \phi \bar{e}_i l_\alpha + \frac{\eta^\alpha_n \eta^\beta_n}{M^2} \bar{\phi} \bar{\phi} l_\alpha l_\beta \right) + \text{h.c.}$$

$$Y_u^{ij} \sim \sum_n \frac{1}{M^2} \langle \xi^j_n \xi^i_n \rangle$$

$$Y_d^{\alpha i} \simeq Y_e^{i\alpha} \sim \sum_n \frac{1}{M^2} \langle \eta^\alpha_n \xi^i_n \rangle$$

$$Y_\nu^{\alpha\beta} \sim \sum_n \frac{1}{M} \langle \eta^\alpha_n \eta^\beta_n \rangle$$

Fermion mass pattern

Imagine there is no (or almost no) hierarchy in breaking
$U(3)_l \to U(2)_l \to U(1)_l \to$Nothing : $\quad U_3 > U_2 > U_1$

$$\langle \eta_A \rangle = U_3 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \langle \eta_B \rangle = U_2 \begin{pmatrix} 0 \\ S \\ C \end{pmatrix}, \quad \langle \eta_C \rangle = U_1 \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

But breaking $U(3)_e$ breaking is strongly hierarchical
$U(3)_e \to U(2)_e \to U(1)_e \to$Nothing : $\quad V_3 \gg V_2 \gg V_1$

$$\langle \xi_A \rangle = V_3 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \langle \xi_B \rangle = V_2 \begin{pmatrix} 0 \\ s \\ c \end{pmatrix}, \quad \langle \xi_C \rangle = V_1 \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

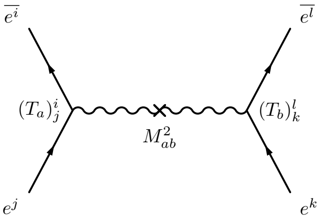
$$V_1/V_2 \sim V_2/V_3 = \epsilon \sim 1/20, \qquad |c|^2 + |s|^2 = |x|^2 + |y|^2 + |z|^2 = 1$$

Then one obtains $\quad m_u : m_c : m_t \sim \epsilon^4 : \epsilon^2 : 1,$
$m_e : m_\mu : m_\tau \sim m_d : m_s : m_b \sim \epsilon^2 : \epsilon : 1$
and respectively small quark mixings: $\sin\theta^q_{ij} \sim m_i/m_j$
$m_{\nu 1} < m_{\nu 2} < m_{\nu 3}$ without significant hierarchy,
and large neutrino mixing angles $\tan\theta^\nu_{12}, \tan\theta^\nu_{23} \sim 1$

Flavor changing induced by horizontal gauge bosons

Consider effects of $SU(2)_e$ gauge bosons in the limit $V_3 \gg V_2$
Three gauge bosons $\Theta_{1,2,3} \to \Theta^{\pm}, \Theta_3$ have equal masses,
$M_\Theta \approx \frac{1}{2} g V_2$ and induce effective operators with RH-currents

$$\frac{G_H}{\sqrt{2}} \overline{\psi}\gamma^\mu(1+\gamma_5)\tau^a\psi \cdot \overline{\psi}\gamma_\mu(1+\gamma_5)\tau^a\psi, \qquad \psi = \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}, \qquad \frac{G_H}{G_F} = \left(\frac{v_{EW}}{V_2}\right)^2$$



No flavor changing in flavor basis: $\psi_i \bar{\psi}_j \to \psi_i \bar{\psi}_j$ or $\psi_i \psi_j \to \psi_i \psi_j$
Can be Fierzed to $\overline{\psi}\gamma^\mu(1+\gamma_5)\psi \cdot \overline{\psi}\gamma_\mu(1+\gamma_5)\psi$

Custodial symmetry, allows scales $\sim$ TeV for new physics
Z.B., Dvali, 1998

Flavor changing induced by horizontal gauge bosons

Mixing with 3-rd family induces violation of custodial symmetry:

$$\begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}_R = \begin{pmatrix} V_{1e} & V_{1\mu} & V_{1\tau} \\ V_{2e} & V_{2\mu} & V_{2\tau} \\ V_{3e} & V_{3\mu} & V_{3\tau} \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

Gives rise to Flavor-changing operators

$$\frac{G_{\mu eee}}{\sqrt{2}} \bar{e}\gamma^\mu(1+\gamma_5)\mu \cdot \bar{e}\gamma_\mu(1+\gamma_5)e \qquad \text{decay } \mu \to eee$$

$$\frac{G_{\mu e\mu e}}{\sqrt{2}} \bar{e}\gamma^\mu(1+\gamma_5)\mu \cdot \bar{e}\gamma_\mu(1+\gamma_5)\mu \qquad \text{conversion } \mu\bar{e} \to e\bar{\mu}$$

with $G_{\mu eee}/G_H = R$ and $G_{\mu e\mu e}/G_H = R^2$
where $R \approx |V_{3e}^* V_{3\mu}| \sim \epsilon^3 \sim (m_e m_\mu / m_\tau^2) \sim 10^{-4}$

$\mathrm{Br}(\mu \to 3e) < 10^{-12} \quad \to \quad G_{\mu eee}/G_F = R(v_{EW}/V_2)^2 < 10^{-6}$
$V_2 > \left(\frac{R}{10^{-6}}\right)^{1/2} v_{EW} \simeq 1$ TeV !!!

However, muonium–antimuonium conversion is hopelessly small:
$G_{\mu e\mu e}/G_F = RG_{\mu e\mu e}/G_F < 10^{-10}$ vs. exp. bound
$G_{\mu e\mu e}/G_F < 3 \times 10^{-3}$ $\qquad \bar{s}d \to \bar{d}s \ (K^0 \to \bar{K}^0) \qquad V_2 > 3$ TeV

Compositeness limit: $\frac{1}{\Lambda^2}(\bar{e}\bar{e}ee)$ etc. $\quad \Lambda > 6$ TeV or so

Flavor changing with τ-lepton

Mixing with 3-rd family

$$\begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}_R = \begin{pmatrix} V_{1e} & V_{1\mu} & V_{1\tau} \\ V_{2e} & V_{2\mu} & V_{2\tau} \\ V_{3e} & V_{3\mu} & V_{3\tau} \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

Gives rise to Flavor-changing operators involving τ

$$\frac{G_{\tau eee}}{\sqrt{2}} \overline{e}\gamma^\mu(1+\gamma_5)\tau \cdot \overline{e}\gamma_\mu(1+\gamma_5)e \qquad \text{decay } \tau \to eee$$

$$\frac{G_{\tau\mu ee}}{\sqrt{2}} \overline{\mu}\gamma^\mu(1+\gamma_5)\tau \cdot \overline{e}\gamma_\mu(1+\gamma_5)e \qquad \text{decay } \tau \to \mu ee$$

$$G_{\tau eee}/G_H = R_e \approx |V_{3e}^* V_{3\tau}| \sim \epsilon^2 \sim 10^{-3}$$

$$G_{\tau\mu ee}/G_H = R_\mu \approx |V_{3\mu}^* V_{3\tau}| \sim \epsilon \sim 0.03$$

Experimentally $\frac{Br(\tau\to\mu ee)}{Br(\tau\to\mu\bar{\nu}_\mu\nu_\tau)} < 10^{-6}$

$$G_{\tau\mu ee}/G_F = R_\mu (v_{EW}/V_2)^2 < 10^{-3}$$

$$V_2 > \left(\frac{R_\mu}{10^{-3}}\right)^{1/2} v_{EW} \simeq 1 \text{ TeV again !!!}$$

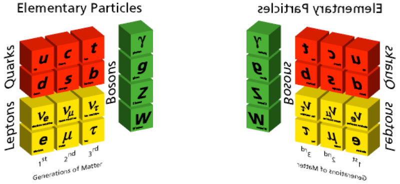
Are there some stronger FC effects ?

... Let us recall about gauge anomalies ... what cancels them ?

$SU(3) \times SU(2) \times U(1)$ & $SU(3)' \times SU(2)' \times U(1)'$

$G \times G'$

Regular world | Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- M sector is dark (for us) and the gravity is a common force (with us)
- M matter looks as non-standard for dark matter but it is truly standard in direct sense, just as our matter (self-interacting/dissipative/asymmetric)
- New interactions are possible between O & M particles $\mathcal{L}_{mix}$
- Natural in string/brane theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

$SU(3) \times SU(2) \times U(1)$ vs. $SU(3)' \times SU(2)' \times U(1)'$

generalized P and C parities

Fermions and anti-fermions :

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}; \qquad u_R,\ d_R, \quad e_R$$

B=1/3 L=1 B=1/3 L=1

$$\bar{q}_R = \begin{pmatrix} \bar{u}_R \\ \bar{d}_R \end{pmatrix}, \quad \bar{l}_R = \begin{pmatrix} \bar{\nu}_R \\ \bar{e}_R \end{pmatrix}; \qquad \bar{u}_L,\ \bar{d}_L, \quad \bar{e}_L$$

B=-1/3 L=-1 B=-1/3 L=-1

Twin Fermions and anti-fermions :

$$q'_L = \begin{pmatrix} u'_L \\ d'_L \end{pmatrix}, \quad l'_L = \begin{pmatrix} \nu'_L \\ e'_L \end{pmatrix}; \qquad u'_R,\ d'_R, \quad e'_R$$

B=1/3 L=1 B=1/3 L=1

$$\bar{q}'_R = \begin{pmatrix} \bar{u}'_R \\ \bar{d}'_R \end{pmatrix}, \quad \bar{l}'_R = \begin{pmatrix} \bar{\nu}'_R \\ \bar{e}'_R \end{pmatrix}; \qquad \bar{u}'_L,\ \bar{d}'_L, \quad \bar{e}'_L$$

B=-1/3 L=-1 B=-1/3 L=-1

$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$
$$(\bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi') + (u'_R Y'^*_u \bar{q}'_R \phi' + d'_R Y'^*_d \bar{q}'_R \bar{\phi}' + e'_R Y'^*_e \bar{l}'_R \bar{\phi}')$$

Doubling symmetry $(L, R \to L, R$ parity): $Y' = Y \quad B - B' \to -(B - B')$

Mirror symmetry $(L, R \to R, L$ parity): $Y' = Y^* \quad B - B' \to B - B'$

$[SU(3) \times SU(2) \times U(1)] \times [SU(3)' \times SU(2)' \times U(1)'] +$ Flavor

$SU(3)_e \times SU(3)_l$: anomalies cancelled between two sectors

$q_L, \bar{u}_L, \bar{e}_L \sim 3_e, \quad l_L, \bar{d}_L \sim 3_l$

$\bar{q}_R, u_R, e_R \sim \bar{3}_e, \quad \bar{l}_R, d_R \sim \bar{3}_l$

$q'_L, \bar{u}'_L, \bar{e}'_L \sim \bar{3}_e, \quad l'_L, \bar{d}'_L = \bar{3}_l$

$\bar{q}'_R, u'_R, e'_R \sim 3_a, \quad \bar{l}'_R, d'_R = 3_l$

Mirror parity $(L, R \to R, L)$: flavon fields $\chi_L \to \chi_R = (\bar{\chi}_L)^+$

Effective operators

$$W = \frac{1}{M}(\bar{u} X_u q \bar{\phi} \ + \ \bar{d} X_d q \phi \ + \ \bar{e} X_e l \phi) + \text{h.c.}$$
$$W' = \frac{1}{M}(\bar{u}' \bar{X}_u q' \bar{\phi}' + \bar{d}' \bar{X}_d q' \phi' + \bar{e}' \bar{X}_e l' \phi') + \text{h.c.}$$

$X_e \sim (\bar{3}_e, \bar{3}_l), \quad \bar{X}_e \sim (3_e, 3_l) \quad \frac{X_e}{M} \to Y_e$, etc.

Quark & lepton Yukawas in both sectors determined by the pattern of flavon VEVs $\langle \chi \rangle$ Z.B. 1996

Mirror parity and MFV – a deviation

- Generically, SUSY flavor limits require $M_{SUSY} > 100$ TeV or so ...

But assuming the gauge symmetry $SU(3) \times \ldots$ between 3 fermion families can be obtained quark-squark mass allignment: universal relations like

$$\tilde{m}_d^2 = m_0^2 + m_1^2 (Y_d^\dagger Y_d) + m_2^2 (Y_d^\dagger Y_d)^2, \qquad A_d = A_0 Y_d + A_1 Y_d (Y_d^\dagger Y_d), \text{ etc.}$$

Z.B. 1996, Anselm, Z.B. 1997, Z.B., Rossi, 2000

later on (2002) coined as Minimal Flavor Violation (MFV)

$F-$terms can be easily handled
gauge $D-$ terms give problems

If flavour symmetry $SU(3) \times \ldots$ is shared between two sectors:
flavon superpotential: $W_H = \mu \chi \bar{\chi} + \lambda(\chi^2 + \bar{\chi}^3) \quad \to \quad \langle \chi \rangle = \langle \bar{\chi} \rangle$

D-terms of flavor $SU(3)$ vanish because of mirror parity   Z.B. 1996

LHC – run II: can SUSY be just around the corner?

Standard picture of SUSY (2 Higgses with $m \sim 100$ GeV + Higgsinos) has gone ! *One* Higgs discovered by LHC perfectly fits the SM Higgs ... already at LEP epoch many theorists felt that $M_{SUSY} < 1$ TeV was problematic

- SUSY induced proton decays $(D=5)$ require $M_{SUSY} > 1$ TeV or so
- SUSY induced CP-violation: electron EDM, $M_{SUSY} > 1$ TeV or so
- But gauge coupling crossing requires $M_{SUSY} < 10$ TeV or so

Z.B. Chianese, Miele, 2015

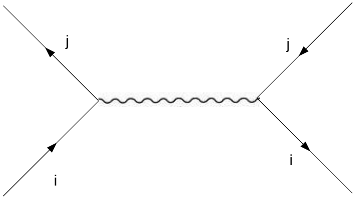
SUSY at scale of few TeV is still the best choice for BSM physics: maybe SUSY is indeed just around the corner?

Remains *Little* hierarchy problem – 2 orders Fine Tuning – between $M^2_{\rm Higgs} \sim (100~{\rm GeV})^2$ and $M^2_{\rm SUSY} \sim (1~{\rm TeV})^2$

muonium–mirror muonium oscillation

FC operators induced by horizontal gauge bosons between two sectors

$\frac{G_H}{\sqrt{2}}\overline{\psi}\gamma^\mu(1+\gamma_5)\sigma^a\psi \cdot \overline{\psi'}\gamma_\mu(1-\gamma_5)\sigma^a\psi', \quad \psi=(e_1,e_2),\ \psi'=(e'_1,e'_2),$
with $G_H/G_F = \left(v_{EW}/V_2\right)^2$

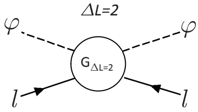


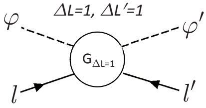
Process $\mu\bar{e} \to \mu'\bar{e}'$ unsuppressed: $G_H/G_F = \left(v_{EW}/V_2\right)^2 > 5\cdot 10^{-2}$
Muonium–mirror muonium oscillation can be searched via invisible channel of muonium decay Gninenko et al., 2013

Interesting possibility – along with positronium–mirror positronium oscillation search This Conf. talk of Crivelli

$\mathcal{L}_{\mathrm{mix}}$: L and B violating operators

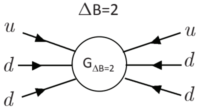
• Neutrino -mirror neutrino mixing $\frac{1}{M}(l^\alpha \bar{\phi})(l'_\alpha \bar{\phi}')$ is allowed while $\frac{1}{M}(l^\alpha \bar{\phi})(l^\beta \bar{\phi})$ is forbidden by $SU(3)_l$ $\rightarrow \frac{\eta_\alpha \eta_\beta}{M^3}(l^\alpha \bar{\phi})(l^\beta \bar{\phi})$

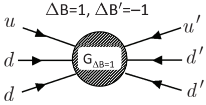




Neutrinos can be Dirac (or pseudo-Dirac) particles with L component living in ordinary world and R component in Mirror world

• Neutron -mirror neutron mixing $\frac{1}{M^5}(u^i d^\alpha d^\beta)(u'_i d'_\alpha d'_\beta)$ is allowed while $\frac{1}{M^5}(u^i d^\alpha d^\beta)^2$ is forbidden by $SU(3)_e \times SU(3)_l$





Let me take you down ... to neutron mixings

The Mass Mixing $\epsilon(\bar{n}n' + \bar{n}'n)$ from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$ unsuppressed by familyy symmetry, and can be much stronger that $n - \bar{n}$ mixing
violates B and B' – but conserving $B - B'$

$$\epsilon = \langle n|(udd)(u'd'd')|n'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{10 \ {\rm TeV}}{M}\right)^5 \times 10^{-15} \ {\rm eV}$$

Oscillations $n \to \bar{n}'$ (regeneration $n \to \bar{n}' \to n$) ...

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

Surprisingly, $n - \bar{n}'$ oscillation can be as fast as $\tau_{nn'} = \epsilon^{-1} \sim 1$ s, without contradicting any experimental and astrophysical limits. C.f. $\tau_{n\bar{n}} > 10^8$ s.

Yin-Yang Theory: Dark sector ... similar to our luminous sector?

For observable particles .... *very complex physics !!*
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? Seesaw ?)
photon, electron, nucleons (quarks), neutrinos, gluons, $W^{\pm} - Z$, Higgs ...
long range EM forces, confinement scale $\Lambda_{\rm QCD}$, weak scale M_W
... matter *vs.* antimatter (B-conserviolation, CP ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

If dark matter comes from extra gauge sector ... it is as *complex*:
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT '? Seesaw ?)
photon′, electron′, nucleons′ (quarks′), $W' - Z'$, gluons′ ?
... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?
... asymmetric dark matter (B′-conserviolation, CP ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?

Let us call it Yin-Yang Theory

in chinise, Yin-Yang means dark-bright duality

describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

Resume: If flavour symmetry $SU(3) \times \ldots$ is a portal to mirror sector

• Anomaly cancellation of between ordinary and mirror fermions

• SUSY flavor problem can be settled via MFV (safe D-terms)

• Flavor gauge bosons (and gauginos) can be as light as few TeV ... and mediate interesting new flavor changing phenomena:

muonium disappearance $\mu\bar{e} \to \mu'\bar{e}'$ $(\pi^0 \to \pi^{0\prime},\ K^0 \to K^{0\prime}$ etc.)

Maybe relevant for recent anomalies in B-decays: $B \to K^*\mu\mu$ etc.

$n \to n'$ oscillation of the neutron or regeneration $n \to n' \to n$
non-linear dependence of the neutron precession frequency on applied magnetic field (due to $n - n'$ mixing)

• DM direct detection: Flavor gauge bosons mediate scattering of mirror DM (atoms, electrons) on ordinary atoms, also with FC

and many cosmological and astrophysical implications:
BBN, DM properties, origin of cosmic rays and cosmic antimatter, etc.

Fine

Thank You !

Backup

Dark matter requires new physics

Standard Model has no candidate for dark matter

massive neutrino (~ 20 eV) was a natural "standard" candidate of "hot" dark matter (HDM) forming cosmological structures (Pencakes) – but it was excluded by astrophysical observations in 80's, and later on by the neutrino experiments! – **RIP**

In about the same period the BBN limits excluded dark matter in the form of invisible baryons (dim stars, etc.) – **RIP**

Then a new *Strada Maestra* was opened – $\mathcal{SUSY}$
– well-motivated theoretical concept promising to be a highway for solving many fundamental problems, brought a natural and *almost "Standard"* candidate WIMP – **undead, but looks useless**

Another well-motivated candidate, Axion, emerged from Peccei-Quinn symmetry for solving strong CP problem – **alive, but seems confused**

All other candidates in the literature are *ad hoc !*

Apart one exception –
which may answer to tantalizing question: do baryogenesis and dark matter require two different new physics, or just one can be enough?

Cosmic Concordance and Dark Side of the Universe

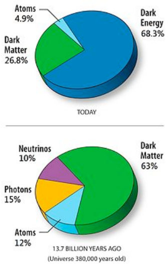
Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component:

- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....

Matter – dark energy *coincidence:* $\Omega_M/\Omega_\Lambda \simeq 0.45$, $(\Omega_M = \Omega_D + \Omega_B)$
$\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*

Antrophic explanation: if not *Today*, then *Yesterday* or *Tomorrow.*

Baryon and dark matter *Fine Tuning:* $\Omega_B/\Omega_D \simeq 0.2$
$\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$: *why* $\rho_B/\rho_D \sim 1$ - *Yesterday Today & Tomorrow?*



– How Baryogenesis could know about Dark Matter? popular models for primordial Baryogenesis (GUT-B, Lepto-B, Affleck-Dine B, EW B ...) have no relation to popular DM candidates (Wimp, Wimpzilla, sterile ν, axion, gravitino ...)

– Anthropic? Another Fine Tuning in Particle Physics and Cosmology?

Coincidence of luminous and dark matter fractions: why $\Omega_D/\Omega_B \sim 1$? or why $m_B \rho_B \sim m_X \rho_X$?

Visible matter from Baryogenesis (*Sakharov*)
B ($B-L$) & CP violation, Out-of-Equilibrium
$\rho_B = m_B n_B, \;\; m_B \simeq 1$ GeV, $\;\; \eta = n_B/n_\gamma \sim 10^{-9}$

η is model dependent on several factors:
coupling constants and CP-phases, particle degrees of freedom, mass scales and out-of-equilibrium conditions, etc.

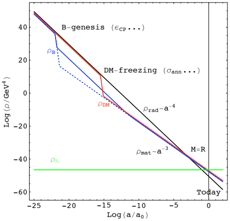
Dark matter: $\;\; \rho_D = m_X n_X$, but $m_X = ?$, $\;\; n_X = ?$
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

- Axion
- Neutrinos
- Sterile ν'
- Para-baryons
- WIMP
- WimpZilla

- $m_a \sim 10^{-5}$ eV $\quad n_a \sim 10^4 n_\gamma$ - CDM
- $m_\nu \sim 10^{-1}$ eV $\quad n_\nu \sim n_\gamma$ - HDM $(\times)$
- $m_{\nu'} \sim 10$ keV $\quad n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
- $m_{B'} \simeq 1$ GeV $\quad n_{B'} \sim n_B$ - SIDDM
- $m_X \sim 1$ TeV $\quad n_X \sim 10^{-3} n_B$ - CDM
- $m_X \sim 10^{14}$ GeV $\quad n_X \sim 10^{-14} n_B$ - CDM

How these Fine Tunings look ...

B-genesis + WIMP



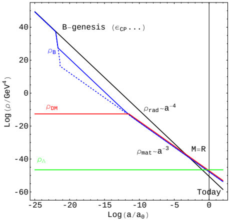
$m_X n_X \sim m_B n_B$

$m_X \sim 10^3 m_B$

$n_X \sim 10^{-3} n_B$

Fine Tuning?

B-genesis + axion



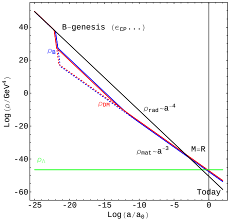
$m_a n_a \sim m_B n_B$

$m_a \sim 10^{-13} m_B$

$n_a \sim 10^{13} n_B$

Fine Tuning?

B-cogenesis



$m_{B'} n_{B'} \sim m_B n_B$

$m_{B'} \sim m_B$

$n_{B'} \sim n_B$

Natural ?

Can mirror matter be dark matter ?

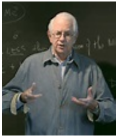
In spite of evident beauty of Yin-Yang dual picture, for a long while mirror matter was not taken as a real candidate for dark matter. There were real reasons for that: if O and M sectors have exactly identical microphysics and also exactly identical cosmologies, then one expected:

- Equal temperatures, $T' = T$, $g'_* = g_*$ $\rightarrow$ $\Delta_\nu^{\rm eff} = 6.15$ against BBN limits

- equal baryon asymmetries, $\eta' = \eta$ $(n'_B/n'_\gamma = n_B/n_\gamma)$ and so $\Omega'_B = \Omega_B$ while $\Omega'_B/\Omega_B \simeq 5$ is needed for dark matter

If $T' \ll T$? BBN is OK
but $\eta' = \eta$ implies $\Omega'_B \simeq (T'/T)^3 \Omega_B \ll \Omega_B$

Such a mirror universe "can have no influence on the Earth and therefore would be useless and therefore does not exist"
S. Glashow, citing Francesco Sizzi



M baryons can be dark matter. If parallel world is colder than ours, all problems can be settled   Z.B., Comelli, Villante, 2000

It is enough to accept a simple paradigm: at the Big Bang the M world was born with smaller temperature than O world; then over the universe expansion their temperature ratio T'/T remains constant.

$T'/T < 0.5$ is enough to concord with the BBN limits and do not affect standard primordial mass fractions: 75% H + 25% ^{4}He.
Cosmological limits are more severe, requiring $T'/T < 0.2$ os so.
In turn, for M world this implies helium domination: 25% H$'$ + 75% ^{4}He$'$.

Because of $T' < T$, the situation $\Omega'_B > \Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

Because of $T' < T$, in mirror photons decouple much earlier than ordinary photons, and after that M matter behaves for the structure formation and CMB anisotropies essentially as CDM. This concordes M matter with WMAP/Planck, BAO, Ly-α etc. if $T'/T < 0.25$ or so.

Halo problem – Mirror matter can be ~ 20 % of dark matter, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)
But perhaps 100 % ? – M world is helium dominated, and the star formation and evolution should be much faster. Halos could be viewed as mirror elliptical galaxies, with our matter inside forming disks.

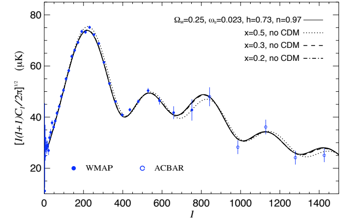
Experimental and observational manifestations

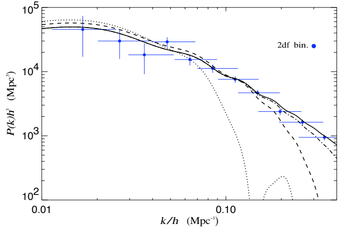
A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.
• Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
• Easier formation and faster evolution of stars: Dark matter disk? Galaxy halo as mirror elliptical galaxy? Microlensing ? Neutron stars? Black Holes? Binary Black Holes? Central Black Holes?

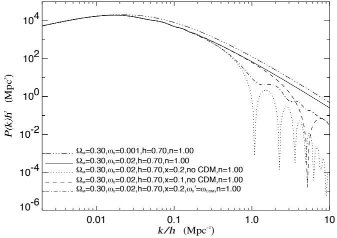
B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$, etc. Mirror helium as most abundant mirror matter particles (the region of DM masses below 5 GeV is practically unexplored). Possible signals from heavier nuclei C,N,O etc.

C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass degenerate (sterile) twins: matter disappearance (or appearance) phenomena can be observable in laboratories.
In the Early Universe, these B and/or L violating interactions can give primordial baryogenesis and dark matter genesis, with $\Omega'_B/\Omega_B = 1 \div 5$.

CMB and LSS power spectra



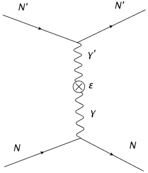




Acoustic oscillations and Silk damping at short scales: $x = T'/T < 0.2$

Discussing $\mathcal{L}_{\rm mix}$: possible portal between O and M particles

- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$



Experimental limit $\epsilon < 4 \times 10^{-7}$
Cosmological limit $\epsilon < 5 \times 10^{-9}$

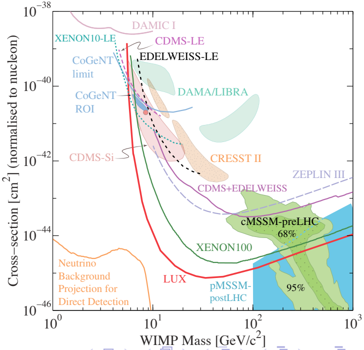
Makes mirror matter nanocharged ($q \sim \epsilon$) and is a promising interaction for dark matter direct detection

Mirror atoms: He' – 75 %, C',N',O' etc. few %
Rutherford-like scattering

$$\frac{d\sigma_{AA'}}{d\Omega} = \frac{(\epsilon\alpha ZZ')^2}{4\mu^2_{AA'} v^4 \sin^4(\theta/2)}$$

or

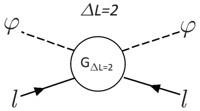
$$\frac{d\sigma_{AA'}}{dE_R} = \frac{2\pi(\epsilon\alpha ZZ')^2}{M_A v^2 E_R^2}$$

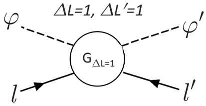


$\mathcal{L}_{\rm mix}$: L and B violating operators

- Neutrino -mirror neutrino mixing – (Active - sterile mixing)

L and L' violating operators: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

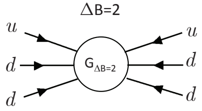


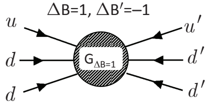


M is the (seesaw) scale of new physics beyond EW scale.
Mirror neutrinos are most natural candidates for sterile neutrinos

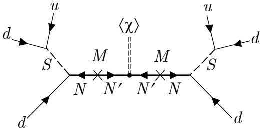
- Neutron -mirror neutron mixing – (Active - sterile neutrons) B and

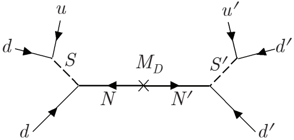
B' violating operators: $\frac{1}{M^5}(udd)(udd)$ and $\frac{1}{M^5}(udd)(u'd'd')$





Seesaw between ordinary and mirror neutrons





$$S\,u\,d + S^\dagger d\,\mathcal{N} + M_D \mathcal{N}\mathcal{N}' + \chi \mathcal{N}^2 + \chi^\dagger \mathcal{N}'^2$$

$$g_n(\chi n^T C n + \chi^\dagger n'^T C n' + \mathrm{h.c.})$$

$$\epsilon_{n\bar{n}} \sim \frac{\Lambda_{\rm QCD}^6 V}{M_D^2 M_S^4} \sim \left(\frac{10^8~\mathrm{GeV}}{M_D}\right)^2 \left(\frac{1~\mathrm{TeV}}{M_S}\right)^4 \left(\frac{V}{1~\mathrm{MeV}}\right) \times 10^{-24}~\mathrm{eV}$$

$$\tau_{n\bar{n}} > 10^8~\mathrm{s}$$

$n - n'$ oscillation with $\tau_{nn'} \sim 1$ s $\qquad \tau_{nn'} \sim \frac{V}{M_D}\tau_{n\bar{n}}$

$$\epsilon_{nn'} \sim \frac{\Lambda_{\rm QCD}^6}{M_D M_S^4} \sim \left(\frac{10^8~\mathrm{GeV}}{M_D}\right) \left(\frac{1~\mathrm{TeV}}{M_S}\right)^4 \times 10^{-15}~\mathrm{eV}$$

$$M_D M_S^4 \sim (10~\mathrm{TeV})^5$$

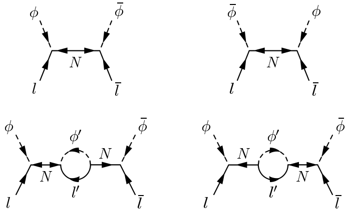
L and L' violating operators: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

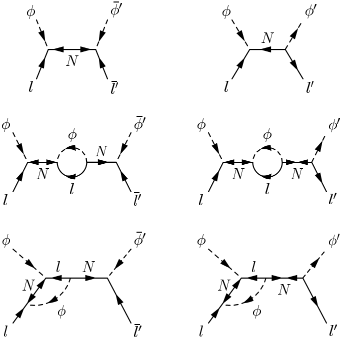
After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B-L$ and $B'-L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

Operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ via seesaw mechanism –
heavy RH neutrinos N_j with
Majorana masses $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$



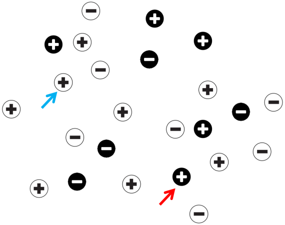


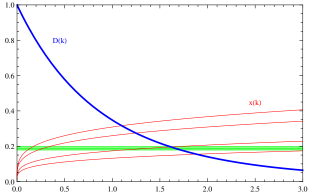
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Xerox symmetry $\rightarrow$ $Y' = Y$, Mirror symmetry $\rightarrow$ $Y' = Y^*$

Theory of cogenesis: B/L violating interactions between O and M worlds

Hot World $\longrightarrow$ *Cold World* $\quad \Omega'_B/\Omega_B = 1-5 \quad \text{if } T'/T < 0.2$





$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2 \qquad \frac{dn'_{\rm BL}}{dt} + (3H+\Gamma')n'_{\rm BL} = -\Delta\sigma'\, n_{\rm eq}^2$$

$$\sigma(l\phi \to \bar{l}'\bar{\phi}') - \sigma(\bar{l}\bar{\phi} \to l'\phi') = -(\Delta\sigma + \Delta\sigma')/2$$
$$\sigma(l\phi \to l'\phi') - \sigma(\bar{l}\bar{\phi} \to \bar{l}'\bar{\phi}') = -(\Delta\sigma - \Delta\sigma')/2$$
$$\sigma(l\phi \to \bar{l}\bar{\phi}) - \sigma(\bar{l}\bar{\phi} \to l\phi) = \Delta\sigma$$

$$\Delta\sigma = {\rm Im\,Tr}[g^{-1}(Y^\dagger Y)^* g^{-1}(Y'^\dagger Y')g^{-2}(Y^\dagger Y)] \times T^2/M^4$$
$$\Delta\sigma' = \Delta\sigma(Y \to Y')$$

Mirror (LR) symmetry: $\Delta\sigma' = -\Delta\sigma \qquad B, B' > 0$

Xerox (LL) symmetry: $\Delta\sigma' = \Delta\sigma = 0 \qquad B, B' = 0$

More parallel worlds ?

Imagine there are 4 worlds all described by Standard Model, related by mirror (LR) and xerox (LL) symmetries ...

This can be used for solving little hierarchy problem, invoking also SUSY

Consider superpotential
$W = \lambda S_1(H_1H_2 + \Phi_1\Phi_2 - \Lambda^2) + \lambda S_2(H'_1H'_2 + \Phi'_1\Phi'_2 - \Lambda^2)$

Xerox symmetry: $H_{1,2} \to \Phi_{1,2}$, $H'_{1,2} \to \Phi'_{1,2}$

Mirror symmetry: $S_1 \to S_2$, $H_{1,2} \to H'_{1,2}$, $\Phi_{1,2} \to \Phi'_{1,2}$

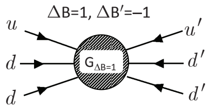
Global symmetries $SU(4)_H$ and $SU(4)'_H$
Take $\Lambda \sim 10$ TeV and assume that SUSY breaking spurion $\eta = M_S\theta^2$ is odd against Xerox symmetry, $\eta \to -\eta$.

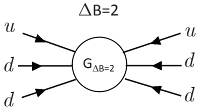
Φ's get VEVs $v' \sim 10$ TeV, H's remain pseudo-Goldstone, then getting VEVs $v \sim 100$ GeV
Φ sectors – Standard Models with $m_E \sim (v'/v)m_e$ but $m_{P,N} \simeq (2 \div 3)m_{p,n}$ ($\Lambda_\Phi/\Lambda_{\rm QCD}$ rescales softer with v'/v)
Dark matter can be very compact hydrogen atoms from Φ sectors, or even neutrons if $m_P > m_N$

Self-collisional DM with right amount $\sigma/m_N \sim 1$ b/GeV – perfect candidate for Dark matter resolving many problems of halos

The interactions able to make such cogenesis, should also lead to mixing of our neutral particles into their mass degenerate mirror twins.

The Mass Mixing $\epsilon(\bar{n}n' + \bar{n}'n)$ comes from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$, M is the scale of new physics violating B and B' – but conserving $B - B'$





$$\epsilon = \langle n|(udd)(u'd'd')|n'\rangle \sim \frac{\Lambda_{\rm QCD}^6}{M^5} \sim \left(\frac{10\ \rm TeV}{M}\right)^5 \times 10^{-15}\ \rm eV$$

Oscillations $n \to \bar{n}'$ (regeneration $n \to \bar{n}' \to n$) ... but $n' \to \bar{n}$

$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

Surprisingly, $n - n'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{nn'} \sim 1$ s, without contradicting any experimental and astrophysical limits.

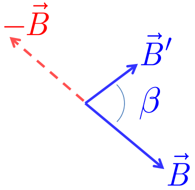
Neutron – mirror neutron oscillation probability

The probability of n-n' transition depends on the relative orientation of magnetic and mirror-magnetic fields. The latter can exist if mirror matter is captured by the Earth

$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega-\omega')t\right]}{2\tau^2(\omega-\omega')^2} + \frac{\sin^2\left[(\omega+\omega')t\right]}{2\tau^2(\omega+\omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega-\omega')t\right]}{2\tau^2(\omega-\omega')^2} - \frac{\sin^2\left[(\omega+\omega')t\right]}{2\tau^2(\omega+\omega')^2}$$

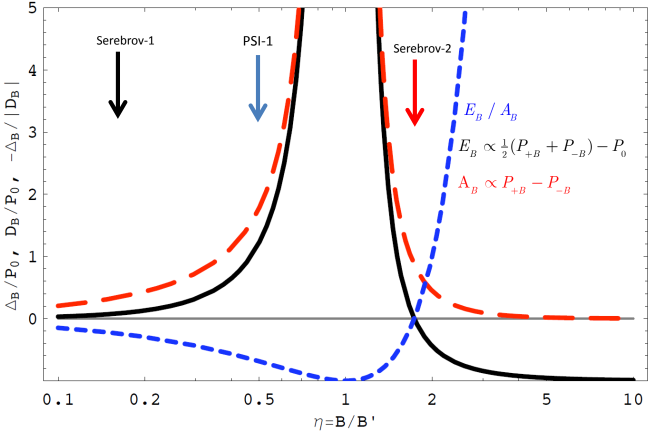


where $\omega = \frac{1}{2}|\mu B|$ and $\omega' = \frac{1}{2}|\mu B'|$; τ - oscillation time

$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis}\, d_B(t) \cdot \cos\beta \leftarrow \text{ assymetry}$$

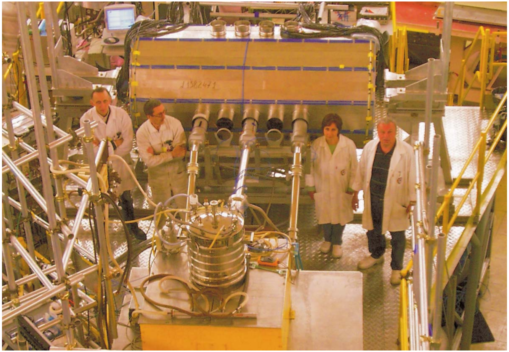
A and E are expected to depend on magnetic field

E.g. assume B'=0.12 Gauss



Experiments

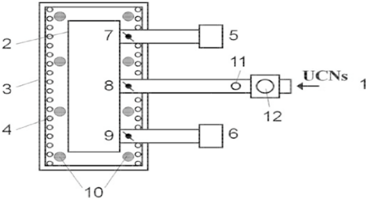
Several experiment were done, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN



Experimental Strategy

To store neutrons and to measure if the amount of the survived ones depends on the magnetic field applied.

- Fill the Trap with the UCN
- Close the valve
- Wait for T_S (300 s ...)
- Open the valve
- Count the survived Neutrons



Repeat this for different orientation and values of Magnetic field.
$N_B(T_S) = N(0)\exp\left[-\left(\Gamma + R + \bar{\mathcal{P}}_B \nu\right) T_S\right]$

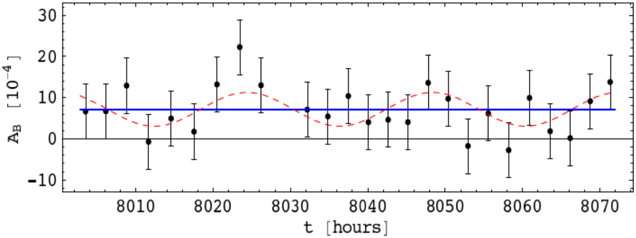
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

$$A(B, T_S) = \frac{N_B(T_S) - N_{-B}(T_S)}{N_B(T_S) + N_{-B}(T_S)} \neq 0 \qquad E(B, b, T_S) = \frac{N_B(T_S)}{N_b(T_S)} - 1 \neq 0$$

Serebrov experiment 2007 – magnetic field vertical

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Analysis pointed out the presence of a signal:

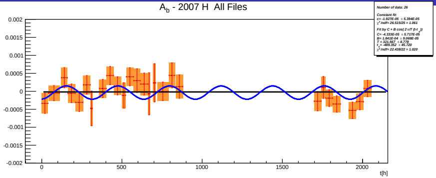
$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

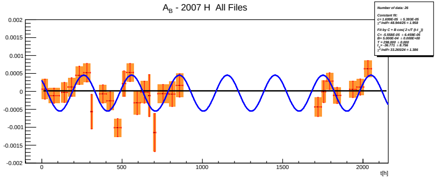
interpretable by $n \to n'$ with $\tau_{nn'} \sim 2 - 10s$‘ and $B' \sim 0.1G$

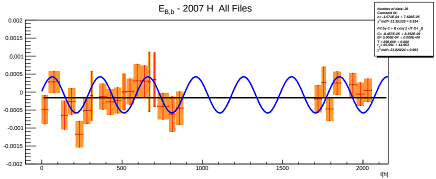
Z.B. and Nesti, 2012

Serebrov 2007 – magnetic field Horizontal

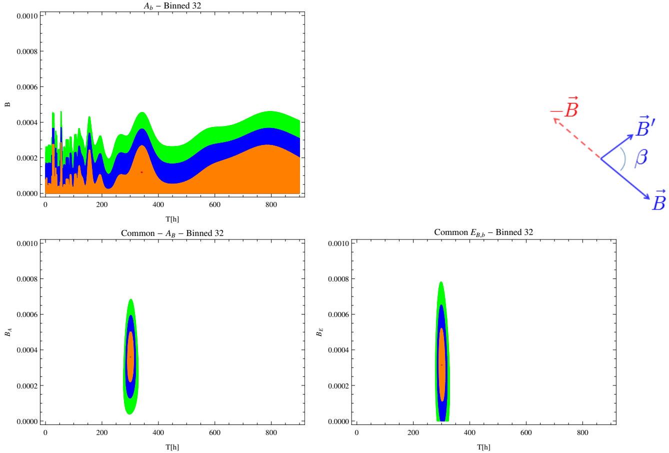
$$\{b_-, B_-, B_+, b_+, b_+, B_+, B_-, b_-\}\ ,\ B = 0.2\ \mathrm{G}\ ,\ b < 10^{-3}\ \mathrm{G}$$







Serebrov 2007 – magnetic field Horizontal



Earth mirror magnetic field via the electron drag mechanism

Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.

Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.

Circular electric currents emerge which can generate magnetic field.

Modifying mirror Maxwell equations by the source (drag) term, one gets $B' \sim \epsilon^2 \times 10^{15}$ G before dynamo, and even larger after dynamo.

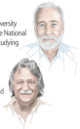
The neutron enigma ...

PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort



Geoffrey L. Greene is a professor of physics at the University of Tennessee, with a joint appointment at the Oak Ridge National Laboratory's Spallation Neutron Source. He has been studying the properties of the neutron for more than 40 years.

Peter Geltenbort is a staff scientist at the Institut Laue-Langevin in Grenoble, France, where he uses one of the most intense neutron sources in the world to research the fundamental nature of this particle.

IN BRIEF

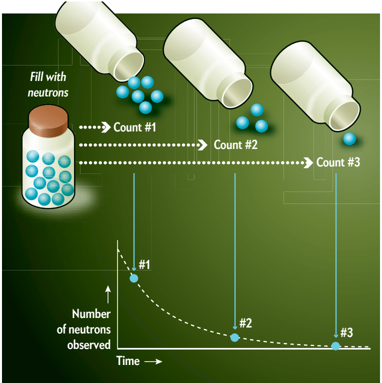
The best experiments in the world cannot agree on how long neutrons live before decaying into other particles.

Two main types of experiments are under way: bottle traps count the number of neutrons that survive after various intervals, and beam experiments look for the particles into which neutrons decay.

Resolving the discrepancy is vital to answering a number of fundamental questions about the universe.

Illustration by Bill Mayer

Two methods to measure the neutron lifetime

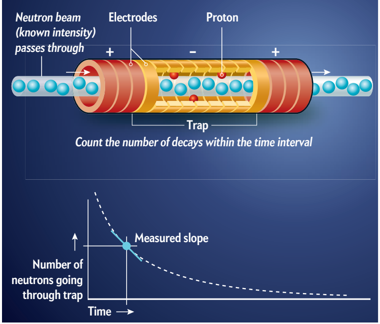


The Bottle Method

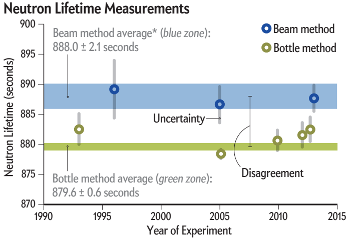
One way to measure how long neutrons live is to fill a container with neutrons and empty it after various time intervals under the same conditions to see how many remain. These tests fill in points along a curve that represents neutron decay over time. From this curve, scientists use a simple formula to calculate the average neutron lifetime. Because neutrons occasionally escape through the walls of the bottle, scientists vary the size of the bottle as well as the energy of the neutrons—both of which affect how many particles will escape from the bottle—to extrapolate to a hypothetical bottle that contains neutrons perfectly with no losses.

The Beam Method

In contrast to the bottle method, the beam technique looks not for neutrons but for one of their decay products, protons. Scientists direct a stream of neutrons through an electromagnetic "trap" made of a magnetic field and ring-shaped high-voltage electrodes. The neutral neutrons pass right through, but if one decays inside the trap, the resulting positively charged protons will get stuck. The researchers know how many neutrons were in the beam, and they know how long they spent passing through the trap, so by counting the protons in the trap they can measure the number of neutrons that decayed in that span of time. This measurement is the decay rate, which is the slope of the decay curve at a given point in time and which allows the scientists to calculate the average neutron lifetime.



Problems to meet ...



A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter and would thus seem to disappear. Such mirror matter could contribute to the total amount of dark matter in the universe. Although this idea is quite stimulating, it remains highly speculative. More definitive confirmation of the divergence between the bottle and beam methods of measuring the neutron lifetime is necessary before most physicists would accept a concept as radical as mirror matter.

Mirror matter is a hidden antimatter ...

why the neutron lifetime measured in UCN traps is smaller than that measured in beam method ?

I've taken my old calculations in the Yin-Yang dual cogenesis and finds out that, at least in simplest scenarios, the sign of mirror baryo asymmetry tells that mirror neutrons born in parallel world, oscillate into our antineutrons rather than in neutrons !
$n - \bar{n}'$ and $n' - \bar{n}$ against $n - n'$

This makes clear how discrepancy emerges – in traps our neutrons oscillate into mirror antineutrons and annihilate with the mirror gas with $\langle \sigma v/c \rangle \simeq 50$ mb. These are continuous loses which cannot be distinguished from the UCN decay. The oscillation probability at the Earth magnetic field can be order 10^{-6} which is sufficient for order second correction if the mirror gas density is about 10^{-5} atm.

Mirror matter can be transformed into our antimatter !!!

Hence, in normal conditions $n' \to n$ oscillation probabilities are tiny, mirror neutrons behave nicely and do not disturb us: everyone stays on his side of the mirror

However, under well-controlled vacuum and magnetic conditions, mirror neutrons can be transformed into our antineutrons with reasonable probabilities provided that the oscillation time $n' \to \bar{n}$ is indeed small ... the resulting annihilations give energy, and we can use it

"It does not matter how beautiful your theory is, it does not matter how smart you are ... if it is not confirmed by experiment, it's wrong"

Now it is turn of experimentalists to turn this tale into reality .... or to exclude it – at least oscillation time $\tau_{nn'} < 10^3$ s

If discovered – impact can be enormous ... One could get plenty of energy out of dark matter !

Summary

Encounter of matter and antimatter leads to immediate (uncontrollable) annihilation which can be destructive

Annihilation can take place also between our matter and dark matter, but controllable by tuning of vacuum and magnetic conditions. Dark neutrons can be transformed into our antineutrons, or dark hydrogen atom into our antihydrogen, etc.

Two civilisations can agree to built scientific reactors and exchange neutrons ... and turn the energy produced by each reactor in 1000 times more energy for parallel world .. and all live happy and healthy