Dolgov

Cosmological excess (local?) of Baryons over Anti-Baryons

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-9} \qquad n_\gamma = 400\ cm^{-3}$$

BBN, visible matter

Early, at $T > 1\ GeV$ $\qquad \Omega_B \sim 5\%$

$$n_{\bar{B}} = n_B (1 - \eta) \sim n_\gamma$$

Now $n_{\bar{B}} \ll n_B$, $\quad \eta = \frac{n_B}{n_\gamma}$

Baryon number per entropy density

$$B = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{1}{7} \eta \sim 10^{-10}$$

Inflation paradigm requests the understanding of B.A.U.

3 famous conditions for Baryogenesis

Non-zero baryon asymmetry can be produced in initially baryon symmetric Universe if:

- *Baryon number B violation*
- *C and CP parity violation*
- *Departure from thermal equilibrium*

Present baryon to entropy density ratio (BBN + direct observations)

$$B = \frac{n_B}{s} = (0.6 - 1) \cdot 10^{-10}$$

A.D. Sakharov, JETP Lett. **5**, 24 (1967)

GUT Baryogenesis:

Heavy particle (X, Y-boson, ...) decays

$X, Y \to qq,\ q\ell$ $\qquad M_X \sim 10^{16}\,\mathrm{GeV}$

$$\frac{Br(X\to qq)}{Br(X\to \bar q\bar q)} = 1 + \varepsilon_{CP} \qquad \cancel{CP}$$

$$n_B - n_{\bar B} \sim \varepsilon_{CP}\, n_X \Rightarrow B \sim \frac{\varepsilon_{CP}}{g_*}$$

Out-of-equilibrium

$$\left.\frac{\Gamma_X}{H}\right|_{T=M_X} \simeq \frac{\alpha}{g_*}\,\frac{M_{Pl}}{M_X} \sim \frac{10^{17}\,\mathrm{GeV}}{M_X}$$

Problems: probably at $T\sim M_X$ X-bosons never were with a big abundance

$T\sim M_X$ seems too big for reheating temperature [non-thermal production?]

Standard Model $SU(3) \otimes SU(2) \otimes U(1)$

quarks $q = \begin{pmatrix} u \\ d \end{pmatrix}_L$ $\quad U, D \qquad U_L = C\bar{u}_R^T$

leptons $\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad E \qquad E = C\bar{e}_R^T$

Higgs $\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^+ \end{pmatrix}$, $\quad \langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{EW} \end{pmatrix}$

$v_{EW} = 247\ \text{GeV}$

$SU(2) \otimes U(1) \to U(1)_{EM}$
$W^\pm, Z$ become massive

Fermion masses:

$\bullet\, q U \varphi + \bullet\, q D \varphi + \bullet\, \ell E \varphi$ + h.c.

- Yukawa coupling constants (family index suppressed) from $\sim 10^{-5} \div$ to ~ 1.

$m_f \sim \bullet\, v_{EW}$ (modulo $\bullet$)

Grand Unification:

$SU(3) \otimes SU(2) \otimes U(1) \subset SU(5)$

$SU(5) \otimes U(1)_{B-L} \subset SO(10)$, etc. ...

$\bar{5} = (\ell, D)$, $\quad 10 = (q, U, E)$

$SU(5) \to SM$ at $M_X \simeq 10^{16}\ \text{GeV}$

New gauge bosons (X, Y - dinosaurs),
Higgses $\varphi \sim 24$-plet of $SU(5)$,
B & L breaking triplets...

Baryogenesis through Leptogenesis

- *Sphaleron processes violate B and L*

$$O_{B+L} = \prod_i (q_i q_i q_i \ell_i)$$

But,

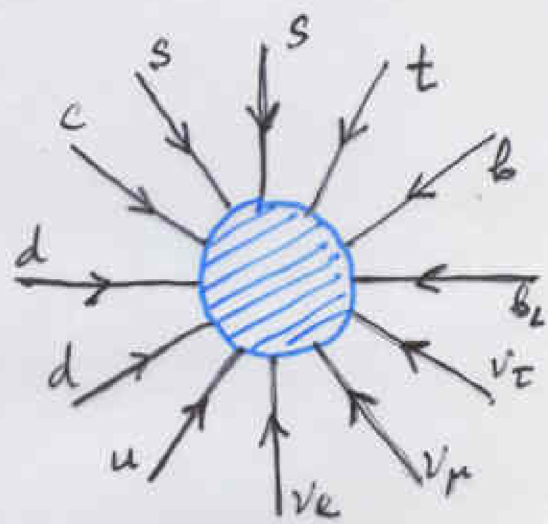
- *$B-L$ is conserved by sphalerons and all SM interactions* – $U(1)_{BL}$ anomaly free

- *Thermal equilibrium from $T \sim 10^{11}$ GeV to $T \sim 100$ GeV:*

$$B = a\,(B-L)\,, \qquad a \sim 1$$

Necessary to generate initial $B-L$ rather than just B:

$$B - L \sim 10^{-10}$$



V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).

B & L violation in general

(X, Y-boson, heavy Higgs mediated)

$\not{B}$: $^{d=6}$ $\frac{1}{M^2} qqq\ell$, etc. $B-L=0$

proton decay $M > 10^{15}$ GeV

N-mediated

$\not{L}$: $^{d=5}$ $\frac{1}{M} \ell\ell\varphi\varphi$ $B-L \neq 0$

$M \sim 10^{13 \div 14}$ GeV

Small Majorana masses for neutrinos

$$m_\nu \sim \cdot \frac{v_{EW}^2}{M}$$

$(\ell\varphi)$ = gauge invariant (spinor)

$(\ell\varphi)(\ell\varphi)$ = Lorentz invariant

$\Delta B = 2$: $^{d=9}$ $\frac{1}{M^5} qqqqqq$ $n-\tilde{n}$ oscillation

$(\Delta L = 0)$

$M \sim 10^7$ GeV

(or even $M \sim 1$ TeV)

* Weinberg. 1979

Seesaw Scheme & Heavy Neutrinos

$$\mathcal{L} = -h_{ia}\,\ell_i\,N_a\,\phi + \text{h.c.} - \tfrac{1}{2}M_a\,N_a\,N_a$$

ϕ Higgs doublet, $\langle\phi\rangle = v \sim 100$ GeV
ℓ_i, $i = 1, 2, 3$, lepton doublets,
N_a, $a = 1, 2, 3, ..K$, heavy singlet fermions (RH neutrinos)

$$\mathcal{M} = \begin{pmatrix} 0 & \hat{m}_D \\ \hat{m}_D^T & \hat{M} \end{pmatrix}, \quad \hat{m}_D = \hat{h}v, \quad \hat{M} = \hat{g}M$$

Effective operator

$$\frac{A_{ij}}{2M}\,\ell_i\ell_j\phi\phi + \text{h.c.}\,, \quad A = hg^{-1}h^T,$$

generates neutrino masses

$$m^{\nu}_{ij} = A_{ij}\frac{v^2}{M} \sim A_{ij}\left(\frac{10^{15}\ \text{GeV}}{M}\right) \times 10^{-2}\ \text{eV}$$

M. Gell-Mann, P. Ramond, R. Slansky, 1979;
T. Yanagida, 1979

Heavy Neutrino Decay

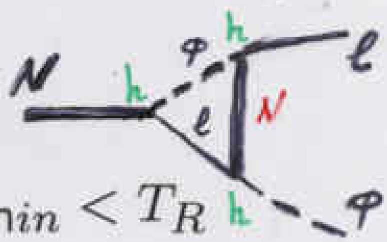
- $B-L$ *is violated by the* N *Majorana masses and thus in decays* $N \to \ell\phi\,,\ \overline{\ell\phi}$

- CP *violation in* $N\ell\phi$ *Yukawa couplings*

$$\Gamma(N \to \ell\phi) \neq \Gamma(N \to \overline{\ell\phi})$$

- *out-of-equilibrium condition: late decay*
  $\Gamma_N < H \quad (T \sim M_N)$

$\Rightarrow$ **generates $B-L$ asymmetry**



N must be produced thermally, $M_{\rm min} < T_R$ or non-thermally (resonant inflaton decay)

$T_R \lesssim 10^9\,GeV$ in SUSY

$$K = \left.\frac{\Gamma_{dec}}{H}\right|_{T\approx M} \sim \frac{h^2}{40\, g_*^{1/2}}\,\frac{M_{Pl}}{M} < 1 \;\Rightarrow\; B-L \sim \epsilon_{CP}\, g_*^{-1}$$

$$m_\nu \sim \frac{h^2 v^2}{M} < .1\,eV \qquad M < T_R$$

M. Fukugita, T. Yanagida, Phys. Lett. **B174**, 45 (1986)
review: W. Buchmüller, M. Plümacher, Int. J. Mod. Phys. A **15**, 5047 (2000)

$$\mathcal{L} = f_{ij}\, l_i\, E_j\, \varphi_1 + h_{ij}\, l_i\, N_j\, \varphi_2 + \frac{1}{2} M_{ij} N_i N_j$$

$$l \hat{f} E \varphi_1 + l \hat{h} N \varphi_2 + \frac{M}{2} N \hat{g} N$$

$$\hat{m}_e = \hat{f} v_1 \qquad \hat{m}_D = \hat{h} v_2 \qquad \hat{M} = \hat{g} M$$

see-saw mechanism:

$$\hat{m}_\nu = \hat{m}_D \hat{M}^{-1} \hat{m}_D^T = \frac{v^2}{M} \hat{h} \hat{g}^{-1} \hat{h}^T \quad (\times \sin^2\beta)$$

$$\tan\beta = \frac{v_2}{v_1}$$

Convenient choice of basis

$\hat{m}_e$, $\hat{M}$ diagonal

$$\hat{m}_e = \begin{array}{c c} & \begin{array}{ccc} E_1 & E_2 & E_3 \end{array} \\ \begin{array}{c} l_1 \\ l_2 \\ l_3 \end{array} & \begin{pmatrix} f_1 & & 0 \\ & f_2 & \\ 0 & & f_3 \end{pmatrix} \end{array} \times v_1 \qquad \begin{array}{c c} & \begin{array}{ccc} N_1 & N_2 & N_3 \end{array} \\ \begin{array}{c} N_1 \\ N_2 \\ N_3 \end{array} & \begin{pmatrix} g_1 & & 0 \\ & g_2 & \\ 0 & & g_3 \end{pmatrix} \end{array} \times M$$

$$\hat{m}_D = \begin{array}{c c} & \begin{array}{ccc} N_1 & N_2 & N_3 \end{array} \\ \begin{array}{c} l_1 \\ l_2 \\ l_3 \end{array} & \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{33} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \end{array} \times v_2 \left. \vphantom{\begin{pmatrix} a \\ b \\ c \end{pmatrix}} \right\} \text{remains non-diag. and } \underline{\text{complex}}$$

CP-violation in N decays. $N \to \ell\varphi, \bar{\ell}\bar{\varphi}$

$$\Gamma(N \to \ell\varphi) = \frac{1}{2}(1+\varepsilon_1)\Gamma$$

$$\Gamma(N \to \bar{\ell}\bar{\varphi}) = \frac{1}{2}(1-\varepsilon_1)\Gamma$$

$N = N_1$ - lightest among N

$$\varepsilon_1 = \frac{3}{16\pi} \frac{\mathrm{Im}\left[h^+ h\, g^{-1} (h^+ h)^*\right]_{11}}{(h^+ h)_{11}}$$

Recalling that $\hat{m}_\nu = \hat{m}_D \hat{M}^{-1} \hat{m}_D^T = \frac{v^2}{M} h g^{-1} h$

$$\varepsilon_1 = \frac{3}{16\pi} \frac{\mathrm{Im}\left[\hat{m}_D^+ \hat{m}_\nu m_D\right]_{11}}{v^2 \tilde{m}_1}$$

$$\tilde{m}_1 = \frac{(\hat{m}_D^+ \hat{m}_D)_{11}}{M_1} = (h^+ h)_{11} \frac{v^2}{g_1 M}$$

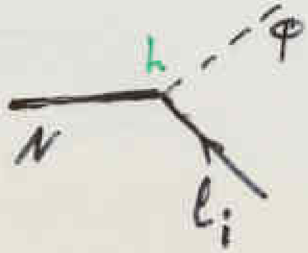
$\Big[$ does not $=$ $m_{11} = (\hat{m}_D^+ \hat{M}^{-1} \hat{m}_D)_{11}$

$= (h^+ g^{-1} h)_{11} \frac{v^2}{M} \Big]$

Out-of-equilibrium conditions

Decay: $\Delta L = 1$

$N \to \ell_i \varphi$



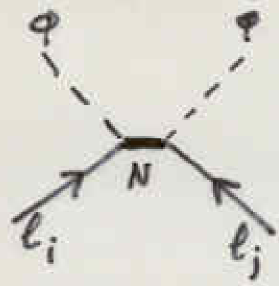
$$\Gamma_{dec} = \frac{1}{8\pi} (h h^{+})_{11} M_1 \quad < H = 1.66 g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$K_1 = \left.\frac{\Gamma_{dec}}{H}\right|_{T=M_1} \simeq \frac{M_{Pl}}{4 g_*^{1/2} v^2} \tilde{m}_1 \quad \lesssim 1$$

$$\tilde{m}_1 \lesssim 10^{-3} eV$$

Scattering: $\Delta L = 2$

$\ell_i \varphi \leftrightarrow \bar{\ell}_j \bar{\varphi}$



at $T \lesssim M_1$

$$\Gamma_{\Delta L=2} = \sigma_{\Delta L=2} \cdot n_{eq} \simeq \frac{Tr(A^{+}A)}{\pi^3 M^2} T^3 \qquad A = h g^{-1} h$$

$$\hat{m}_\nu = A \frac{v^2}{M}$$

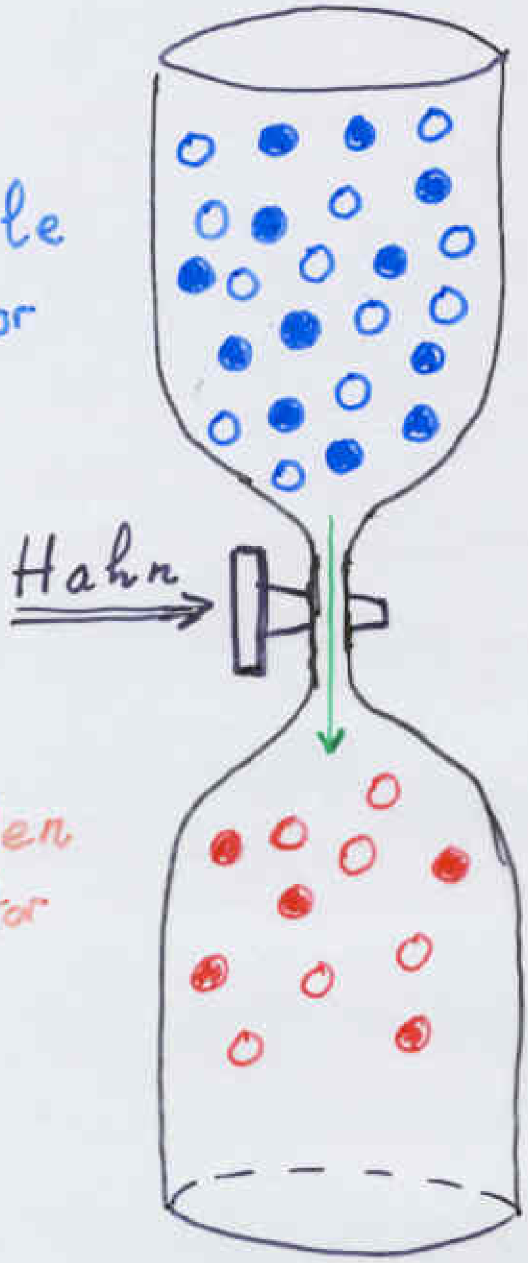
$$K_2 = \left.\frac{\Gamma_{\Delta L=2}}{H}\right|_{T<M} \simeq \frac{M_{Pl}\, Tr(\hat{m}_\nu^{+} \hat{m}_\nu)}{1.66 \pi^3 v^4} T \lesssim 1$$

$$Tr(\hat{m}_\nu^{+} m_\nu) = \sum_i m_{\nu_i}^2 < (0.2\, eV)^2 \cdot \left(\frac{10^{12} GeV}{T}\right)$$

Particle - Antiparticle, $\cancel{CP}$

Sand - Clock

Visible Sector



Hidden Sector

$B\text{-}L_{init} = 0$

$(n_{\circ} - n_{\bullet})_{init} = 0$

$(n_{\circ} - n_{\bullet})_{final} \neq 0$

$\uparrow$

$R_{\circ} - R_{\bullet} \neq 0 \qquad \cancel{CP}$

Also

$n_{\circ} - n_{\bullet} \neq 0$

in general

$\bullet$ B-asymmetry = Matter — $\Omega_B = 2 \div 5\ \%$

$\bullet$ B'-asymmetry = Dark Matter $\quad \Omega'_B \geq \Omega_B$

$\Omega_{DM} = 15 \div 50\ \%$

$\sim 30\ \%$

Ordinary (Visible) World

Hidden (Invisible) Shadow World

$$G = SU(3) \otimes SU(2) \otimes U(1) \quad \otimes \quad G' = SU(?) \otimes \ldots$$

$q,\ \ell,\ \varphi \ldots\ldots \qquad \ldots\ldots\ \ell',\ \varphi', \ldots$

$\ell\varphi$ = gauge invariant $\qquad X' (= \ell'\varphi')$ also

$$\frac{1}{M}(\ell\varphi)^2 = \frac{g_{ij}}{M}\,\ell_i\varphi\,\ell_j\varphi \qquad \frac{1}{M}(\ell'\varphi')^2 = \frac{g'_{kn}}{M}\,\ell'_k\varphi'\,\ell'_n\varphi'$$

ordinary (active) neutrino masses

Hidden (sterile) neutrino masses

Akhmedov, Z.B., Senjanovic 92

$$\frac{1}{M}(\ell\varphi)(\ell'\varphi') = \frac{g''_{ik}}{M}\,\ell_i\varphi\,\ell'_k\varphi'$$

mixing term between ordinary (active) – hidden (sterile) ν's.

ν - ν' oscillation

$\Delta L = 1$: $\quad \ell\varphi \to \ell'\varphi'$

$\qquad \bar{\ell}\bar{\varphi} \to \bar{\ell}'\bar{\varphi}'$

$\cancel{CP}$

$$\Gamma(\ell\varphi \to X') \neq \Gamma(\bar{\ell}\bar{\varphi} \to X')$$

Collisional mechanism (the lepton number leaking from ordinary to hidden sector)

$\Delta B = 1$:

$qqq \to q'q'q'$

Out-of-Equilibrium ?

Big Bang Nucleosynthesis (BBN)

Weak reactions in equilibrium, $p + e \to n + \nu_e, \ldots$

implies at temperature $T > m_e, Q$

$$\left(\frac{n}{p}\right)_{EQ} \simeq \exp\left(-\frac{Q}{T}\right) \qquad Q = m_n - m_p \simeq 1.3\ \text{MeV}$$

We know $\Gamma_W \simeq G_F^2 T^5$ — S-Model

$$H \simeq 3 \frac{\sqrt{\rho}}{M_{Pl}} \qquad = \text{S-cosmology}$$

$$\rho_{BBN} = \frac{\pi^2}{30} \cdot g_* T^4 \qquad \text{at } T \sim 1\ \text{MeV},\ t \sim 1\,s$$

g_* = Number of particle degrees of freedom

$$H = 1.66\, g_*^{1/2} \frac{T^2}{M_{Pl}}$$

In S-Model $g_*^{SM} = 10.75$ $(\gamma, e^+e^-, \nu_{e,\mu,\tau})$

$$\Delta N_\nu = 1 \Rightarrow \Delta g_* = 1.75$$

$$\frac{\Gamma_W}{H} \sim \left(\frac{T}{0.8\ \text{MeV}}\right)^3 \qquad T_{freeze} \simeq 0.8\ \text{MeV}$$

Perfectly agrees with observed abundance of the primordial ^4He: $Y_4 \simeq 0.24$

as well as De, Li, etc.

Conservative limit: $\Delta N_\nu < 1$

$\Delta g_* < 1.75$

Ordinary sector (T) + hidden (T')

$$\rho_{BBN} \simeq \frac{\pi^2}{30}\left(g_* T^4 + g'_* T'^4\right) = \frac{\pi^2}{30} g_*^{eff} T^4$$

$$g_*^{eff} = g_*^{SM} + g'_* \left(\frac{T'}{T}\right)^4 = 10.75 + g'_* x^4$$

g'_* – Number of particle degrees in hidden sector (at temperature T')

$$\boxed{x = \frac{T'}{T}}$$

BBN limit $\Delta N_\nu < 1$ $\quad \Delta g_* < 1.75$

$\Downarrow$

contribution of 1 Weyl spinor (ℓ')

$$\Delta g_* = g'_* x^4 < 1.75 \qquad g'_* \geq 1.75$$

$$\boxed{x < 1} \Longrightarrow \boxed{T' < T}$$

$$\boxed{x < \left(\frac{1.75}{g'_*}\right)^{1/4} < 0.64} \text{ if } g'_* = g_* = 10.75$$

Out-of-Equilibrium condition:

- Ordinary and hidden sectors have different temperatures: $T > T'$
- Rate of process $\Gamma(\ell\varphi \to \ell'\varphi')$ should be smaller than Hubble parameter $H \simeq 1.66\, g_* \frac{T^2}{M_{Pl}}$

Notations

- The (post-inflation) reheating temperatures of the two sectors are different
  Kolb, Seckel, Turner, 85 — Berezhiani, Dolgov, Mohapatra 96
- The two sectors evolve with separately conserved entropy densities $\boxed{s' \ll s}$ = are not in equilibrium

free parameter of the model $\rightarrow$ $x \equiv \left(\frac{s'}{s}\right)^{1/3} = \left(\frac{T_0'}{T_0}\right)$

$$s = \frac{2\pi^2}{45} g_s(T)\, T^3 \quad ; \quad s' = \frac{2\pi^2}{45} g_s'(T')\, T'^3$$

$$\rho = \frac{\pi^2}{30} g_*(T)\, T^4 \quad ; \quad \rho' = \frac{\pi^2}{30} g_*'(T')\, T'^4$$

$$\forall t \qquad \frac{T'}{T} = x \cdot \left(\frac{g_s(T)}{g_s'(T')}\right)^{1/3}$$

- The Hubble constant is given as a function of T and T' by

$$\forall t \qquad H(t) = 1.66 \sqrt{\bar{g}_*(T)}\, T^2 = 1.66 \sqrt{\bar{g}_*'(T')}\, T'^2$$

where:

$$\bar{g}_*(T) = g_*(T)\left\{1 + x^4\right\} \cong g_*(T) \qquad \text{O- observer}$$

$$\bar{g}_*'(T') = g_*'(T')\left\{1 + x^{-4}\right\} \cong g_*'(T')\, x^{-4} \qquad \text{M- observer}$$

Model: Yukawa Couplings

$$\mathcal{L} = -h_{ia}\,\ell_i\,N_a\,\phi + \text{h.c.} - \tfrac{1}{2}M_{ab}N_aN_b$$

$$-\,h'_{ka}\,\ell'_k N_a\,\phi' + \text{h.c.}$$

N_a: Heavy singlet Majorana neutrinos

$$M_{ab} \to M_a = g_a M$$

$G = SU(2)\otimes U(1)$:

$$\phi = \begin{pmatrix} \phi^0 \\ \phi^+ \end{pmatrix},\ \ell_i = \underbrace{\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L}_{\text{leptons}}\ ;\ \bar{\ell}_i = \underbrace{\begin{pmatrix} \bar{\nu}_i \\ \bar{e}_i \end{pmatrix}_R}_{\text{anti-leptons}} = C\,\overline{\ell}^{\,T}$$

$G' = SU(2)'\otimes U(1)'$:

$$\phi' = \begin{pmatrix} \phi'^0 \\ \phi'^+ \end{pmatrix},\ \ell'_k = \begin{pmatrix} \nu'_j \\ e'_j \end{pmatrix}_L ;\ \bar{\ell}'_j = \begin{pmatrix} \bar{\nu}'_j \\ \bar{e}'_j \end{pmatrix}_R = C\,\overline{\ell'}^{\,T}$$

Effective operators:

$$\frac{A_{ij}}{2M}\ell_i\ell_j\phi\phi + \frac{D_{ik}}{M}\ell_i\ell'_k\phi\phi' + \frac{A'_{kn}}{2M}\ell'_k\ell'_n\phi'\phi' + \text{h.c.}$$

with the coupling constant matrices
$A = hg^{-1}h^T,\quad A' = h'g^{-1}h'^T,\quad D = hg^{-1}h'^T$

*) G' can be any gauge group, just needed $\ell'\phi'$ to be gauge invariant

Seesaw mechanism
for active-sterile neutrino system:

$$M_\nu = \begin{pmatrix} m_\nu & m_{\nu\nu'} \\ m^T_{\nu\nu'} & m_{\nu'} \end{pmatrix} = \frac{1}{M} \begin{pmatrix} Av^2 & Dvv' \\ D^T vv' & A'v'^2 \end{pmatrix}$$

$\langle\phi\rangle = v \sim 100$ GeV, $\quad \langle\phi'\rangle = v'$,

Sterile neutrinos = mirror neutrinos

Explains why sterile neutrinos are light
(same grounds as active neutrinos)
and origin of the active-sterile mixing

$$m_\nu \simeq A \left(\frac{10^{13}\,\mathrm{GeV}}{M}\right) \times 1\,\mathrm{eV}$$

$$m'_\nu \simeq A' \cdot z^2 m_\nu \qquad\qquad z = v'/v$$

$$\tan\theta_{\nu\nu'} \simeq \frac{2Dvv'}{A'v'^2 - Av} \simeq \frac{2Dz}{A'z^2 - A} \simeq \frac{2D}{A'z^2}$$

for $z \gg 1$

E. Akhmedov, Z. Berezhiani, G. Senjanovič, Phys. Rev. Lett. **69** , 3013 (1992).
Z. Berezhiani and R. Mohapatra, Phys. Rev. **D** 52, 6607 (1995).

Bento, Z.B., 2001

The Collisional Leaking Mechanism

- *$B-L$ is violated by N Majorana masses and Yukawa couplings to mirror leptons* $N\ell'\phi'$

$\Delta L = \Delta(B-L) = 1$ reactions

$$\ell\phi\,(\overline{\ell}\overline{\phi}) \;\rightarrow\; \ell'\phi'\,,\;\overline{\ell}'\overline{\phi}'$$

mediated by heavy neutrinos N at $T \ll M_N$

- *CP violation in* $N\ell\phi$ *and* $N\ell'\phi'$ *Yukawa couplings*

$$\sigma(\ell\phi \rightarrow X') \neq \sigma(\overline{\ell}\overline{\phi} \rightarrow X')$$

generates a $B-L$ asymmetry if

- *The standard particles (leptons, Higgs) are in thermal equilibrium* (at $T \sim T_R \ll M_N$) *and the mirror particles are out-of-equilibrium*:

$$T'_R < T_R, \qquad n_{X'} \ll n_X$$

* $B-L$ **is created as leptons escape (leak) from the standard to the mirror sector**

Reactions between two systems

$\ell\varphi \to \bar{\ell}'\bar{\varphi}'$ dominant reaction $(\sim \frac{1}{M})$

$\Delta L = 1$ reaction rate: $\Gamma_1 = \sigma_1 n_{eq}$

$$\sigma_1 = \sum_{\text{iso,fl}} \sigma(\ell\phi \to \bar{\ell}'\bar{\phi}') = \frac{Q_1}{8\pi M^2}, \quad n_{eq} = \frac{1.2\,T^3}{\pi^2}$$

$$Q_1 = \mathrm{Tr}(D^\dagger D) = \mathrm{Tr}[(h'^\dagger h')g^{-1}(h^\dagger h)^* g^{-1}].$$

Hubble parameter $H = 1.66 g_*^{1/2} T^2 / M_{Pl}$

Out-of-equilibrium condition:

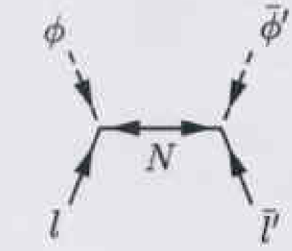
$$K_1 = \left(\frac{\Gamma_1}{2H}\right)_R \simeq 1.5 \cdot 10^{-3} \frac{Q_1 T_R M_{Pl}}{g_*^{1/2} M^2} < 1$$

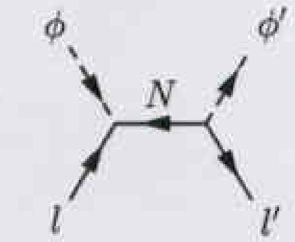
$$M_{12} > Q_1^{1/2} T_9^{1/2}$$

$M_{12} \equiv (M/10^{12}\ \text{GeV}), \quad T_9 \equiv (T_R/10^9\ \text{GeV});$
in the SM: $g_* \simeq 100$
in the MSSM: $g_* \simeq 200$

$\Delta L = 1$

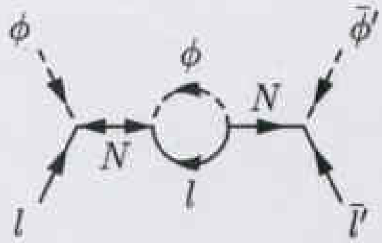
$\sim \frac{1}{M}$

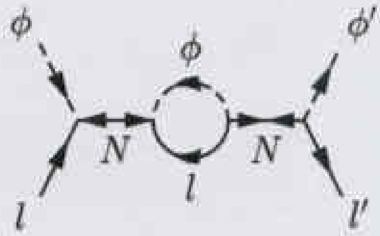




$\sim \frac{\hat{p}}{M^2}$

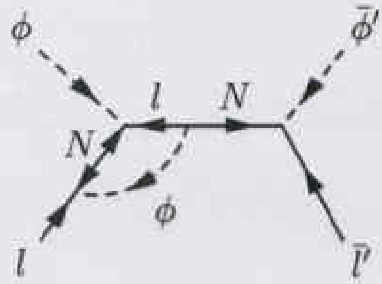
$\sim \frac{\hat{p}}{M^3}$

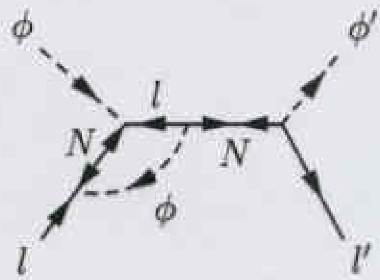




$\sim \frac{1}{M^2}$

$\sim \frac{\hat{p}}{M^3}$





$\sim \frac{1}{M^2}$

$l\phi \to \bar{l}'\bar{\phi}'$ $\qquad$ $l\phi \to l'\phi'$

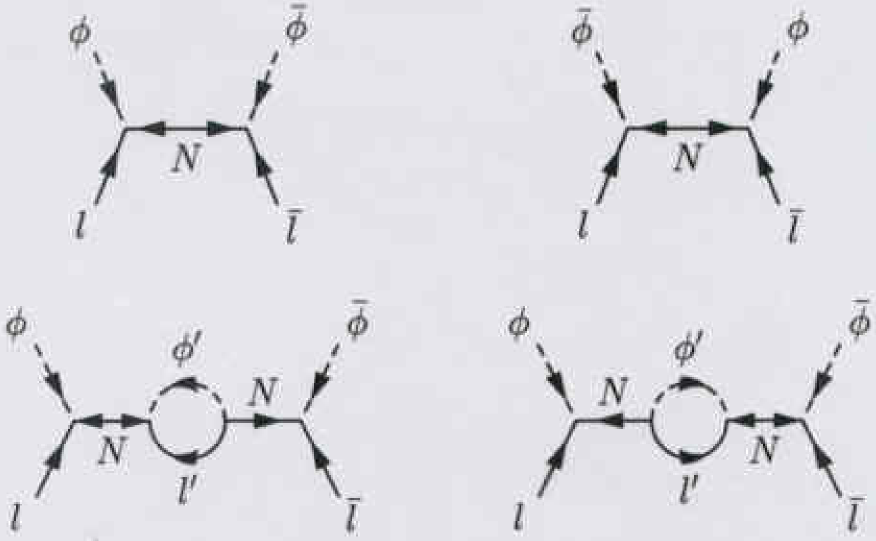
$\Delta\sigma(l\phi \to \bar{l}'\bar{\phi}') \sim \frac{p^2}{M^4}$ $\qquad$ $\Delta\sigma(l\phi \to l'\phi') \sim \frac{p^2}{M^4}$

$S_F \sim \frac{\hat{p} + M}{p^2 - M^2}$ $\qquad$ $p^2 \ll M^2$

$\sim \frac{1}{M}$

$\sim \frac{\hat{p}}{M^2}$

$\Delta L = 2$



$\sim \frac{1}{M}$

$\sim \frac{\hat\rho}{M^3}$

$l\phi \to \bar l \bar\phi$

CPT symmetry

$$\sigma(\ell\phi \to everything) = \sigma(\overline{\ell}\overline{\phi} \to everything).$$

$$\begin{aligned}
&\sigma(\ell\phi \to X') - \sigma(\overline{\ell}\overline{\phi} \to X') + && (\Delta L = 1)\\
&\sigma(l\phi \to \overline{\ell}\overline{\phi}) - \sigma(\overline{\ell}\overline{\phi} \to l\phi) + && (\Delta L = 2)\\
&\sigma(l\phi \to l\phi) - \sigma(\overline{\ell}\overline{\phi} \to \overline{\ell}\overline{\phi}) = 0 && (\Delta L = 0)
\end{aligned}$$

$$\begin{aligned}
\Delta\sigma_2 \equiv \sum_{\text{iso,fl}} \sigma\left(\ell\,\phi \to \overline{\ell}\,\overline{\phi}\right) - \sigma\left(\overline{\ell}\overline{\phi} \to \ell\,\phi\right)\\
= \frac{3\,S}{32\,\pi^2 M^4} J_{CP} \qquad = -\Delta\sigma_1
\end{aligned}$$

$$J_{CP} = \mathrm{Im}\,\mathrm{Tr}\left\{h'^{\dagger}\,h'\,g^{-2}\,h^{\dagger}\,h\,g^{-1}\,(h^{\dagger}\,h)^{*}\,g^{-1}\right\}$$

$$\Delta\Gamma \equiv \Delta\Gamma_{(\Delta L=2)} = -\Delta\Gamma_{(\Delta L=1)}$$

$$\frac{dL}{dt} \propto 1\times(-\Delta\Gamma) + 2\times\Delta\Gamma = +\Delta\Gamma$$

$$\Delta\Gamma = \Gamma\left(\ell\,\phi \to X'\right) - \Gamma\left(\overline{\ell}\,\overline{\phi} \to X'\right) \simeq \Delta\sigma\, n_{\text{eq}}$$

$B-L$ Asymmetry

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \Delta\Gamma n_{\text{eq}} = \frac{9J_{CP}\langle S\rangle_T}{128\pi^2 M^4} n_{\text{eq}}^2$$

integrating from the reheating temperature T_R to lower temperatures $T \ll T_R$ with

$$H = \frac{1}{2t} = \frac{1.66\, g_*^{1/2} T^2}{M_{Pl}}, \quad n_{\text{eq}} = \frac{1.2\, T^3}{\pi^2},$$
$$\langle S\rangle_T = 17\, T^2$$

we obtain $B-L$ density per entropy unit:

$$B - L = \frac{n_{B-L}}{s} \simeq 0.07 \left[\frac{\Delta\Gamma}{g_* H}\right]_{T=T_R}$$

$s = \frac{2\pi^2}{45} g_* T^3$ is the entropy density

About 1.5 times larger contribution comes from period $T > T_R$ when the Universe is still dominated by the inflaton oscillations:
scale factor $\propto t^{2/3}$, entropy $\propto t^{5/4}$.

Final result:

$$B - L \simeq 3 \cdot 10^{-3} \frac{J_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}$$

taking $g_* \simeq 100$

$$B - L \simeq 300\, J_{CP} \frac{T_9^3}{M_{12}^4} \times 10^{-10}$$

Upper limit

$$B - L < 300\, J_{CP} \frac{T_9}{Q^2} \times 10^{-10};$$
$$Q^2 = \max\{Q_1^2, 6Q_2^2)$$

Compatible with the gravitino thermal production bound $T_R <$ few $\times\, 10^9$ GeV

Fitting the data

- *Input*

$$h \sim h' \sim \frac{1}{10} - \frac{1}{3}$$

$$M_i \sim 10^{12} - 10^{14} \text{ GeV}$$

$$T_i \sim 10^{11} - 10^{9} \text{ GeV}$$

- *Output*

$$m_\nu^2 \sim 10^{-3} - 1 \text{ eV}^2$$

$$\Gamma \left(X \to X'\right)_{\Delta L=1} \sim \frac{1}{10} H$$

$$\frac{B-L}{S} \sim 10^{-10}$$

The mirror Universe

$$\text{VISIBLE SECTOR} \longrightarrow G \times G' \longleftarrow \text{MIRROR SECTOR}$$

G, G' = Identical groups

$E_8 \times E_8'$ String

THE TWO WORLDS INTERACT ONLY GRAVITATIONALLY

- Microphysics is the same in the two sectors
- (Macrophysics) [Cosmology] <u>must</u> be different, since the two sectors must have different temperatures

$$\rho_{BBN} = \frac{\pi^2}{30} \cdot g_* \cdot T^4 \cdot \left\{ 1 + \left(\frac{T'}{T} \right)^4 \right\} \qquad x = \frac{T'}{T}$$

$$g_* = 10.75 \qquad \Delta g = \bar{g}_* - 10.75 = 1.75\,\Delta N_\nu$$

$$\Delta N_\nu \lesssim 1 \longrightarrow \boxed{x = \frac{T'}{T} \lesssim 0.64}$$

$$\Delta g \lesssim 1.75$$

Equivalent picture – parallel brane world, $G = G'$
Arkani-Hamed, Dimopulos, Dvali, Kaloper, 99

One can travel from ordinary to parallel world via cosmic (Alice) strings!
Dvali, Kogan, Shifman, 00

$$J_{CP} = \mathrm{Im}\, \mathrm{Tr}\left\{ h'^{+} h' g^{-2} h^{+} h\, g^{-1} (h^{+} h)^{*} g^{-1} \right\}$$

$$J'_{CP} = \mathrm{Im}\, \mathrm{Tr}\left\{ h^{+} h\, g^{-2} h'^{+} h' g^{-1} (h'^{+} h')^{*} g^{-1} \right\}$$

Mirror Matter $\quad f \leftrightarrow \bar{f}_{(R)}$

$$h' = h^{*}$$

$$J_{CP} = J'_{CP} \neq 0$$

$J_{CP} \neq 0 \longrightarrow$ Baryon Asymmetry, $B \neq 0$

$$\Omega_B \sim \Omega_B^{0} \cdot e^{-K} \sim 5\% \qquad K = \sqrt{K_1^2 + 6K_2^2}$$

$J'_{CP} = J_{CP} \Rightarrow$ M-Baryon Asymmetry, $B' \neq 0$

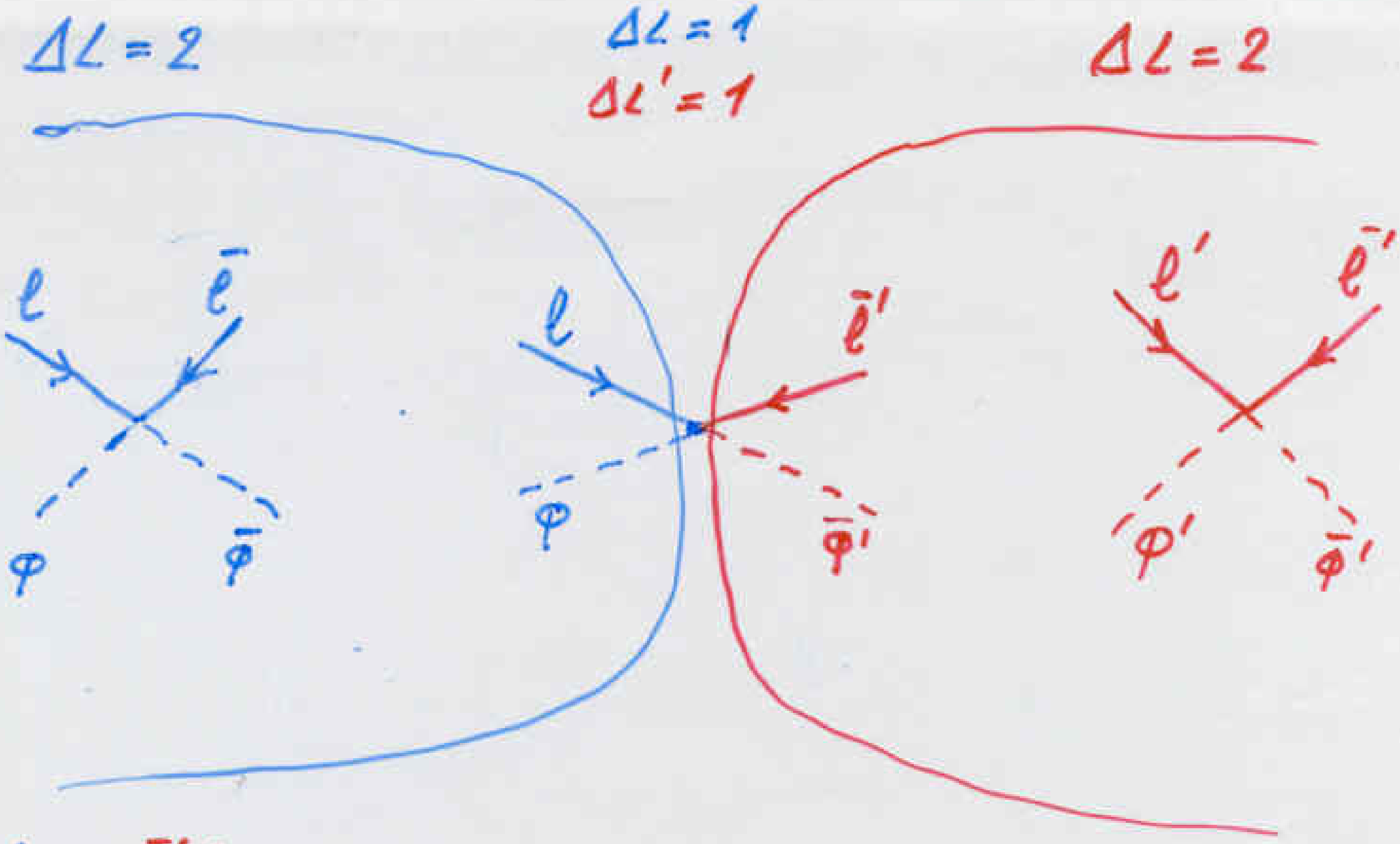
Dark Matter (self-interacting)

$$\Omega'_B \sim \Omega_B^{0} e^{-K'} \sim \Omega_B \cdot e^{K}$$

Naturally could be ~ 10 times more!

$$\Omega'_B \simeq \Omega_B e^{K}$$

$$K \sim 1$$



$\ell\varphi \to \bar\ell'\bar\varphi'$

$\Delta L = 1$:

$$K_1 = \left(\frac{\Gamma_1}{2H}\right)_{T=T_R} \simeq 10^{-3}\,\frac{T_R M_{Pl}}{g_*^{1/2} M^2}\, Q_1 \lesssim 1$$

$$Q_1 = \mathrm{Tr}\left[(h'^{+}h')\,g^{-1}\,(h^{+}h)^{*}\,g^{-1}\right]$$

$\ell\varphi \to \bar\ell\bar\varphi$

$\Delta L = 2$:

$$K_2 = \left(\frac{\Gamma_2}{2H}\right)_{T=T_R} \simeq \frac{\sqrt{6}\,Q_2}{Q_1}\,K_1 \lesssim 1$$

$$Q_2 = \mathrm{Tr}\left[(h^{+}h)\,g^{-1}\,(h^{+}h)^{*}\,g^{-1}\right]$$

$\ell'\varphi' \to \bar\ell\bar\varphi$

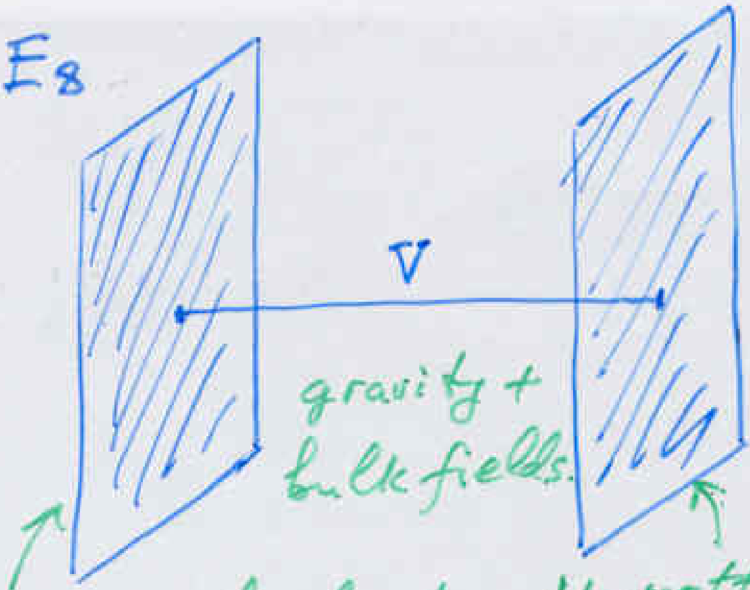
$\Delta L' = 1$:

$$K_1' = \left(\frac{\Gamma_1'}{2H}\right)_{T=T_R} \simeq \left(\frac{T_R'}{T_R}\right)^3 K_1 = x^3 K_1 < 1$$

$\ell'\varphi' \to \bar\ell'\bar\varphi'$

$\Delta L' = 2$:

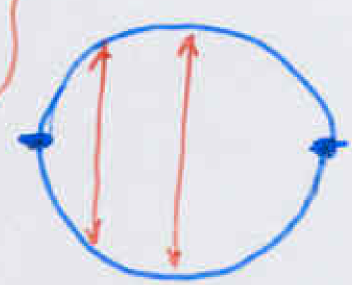
$$K_2' = \left(\frac{\Gamma_2'}{2H}\right)_{T=T_R} \simeq x^3\,\frac{Q_2'}{Q_2}\,K_2 \sim x^3 K_2 < 1$$



Witten $E_8 \times E_8'$ from M-theory

O-Matter localized
q, l, φ + gauge fields

M-matter localized
q', l', φ' + gauge' fields



orbifold S_1/Z_2

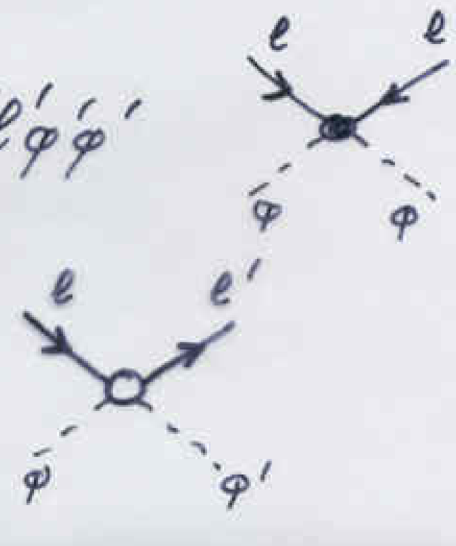
$\alpha \to -\alpha$

In warped compactification possibilities of bigravity (Dark matter seen only from large distances).

Effective operators

$$\frac{A}{M}\, l l \varphi\varphi + \frac{D}{M}\, l l' \varphi\varphi' + \frac{A'}{M}\, l' l' \varphi'\varphi'$$

$$\frac{B}{M^2}\, \bar{l} \partial l' \varphi^* \varphi' + \ldots\ldots$$



Z.B, Mazumdar, Lorenzana

RH - sneutrino decay
(in SUSY Hybrid inflation scheme).

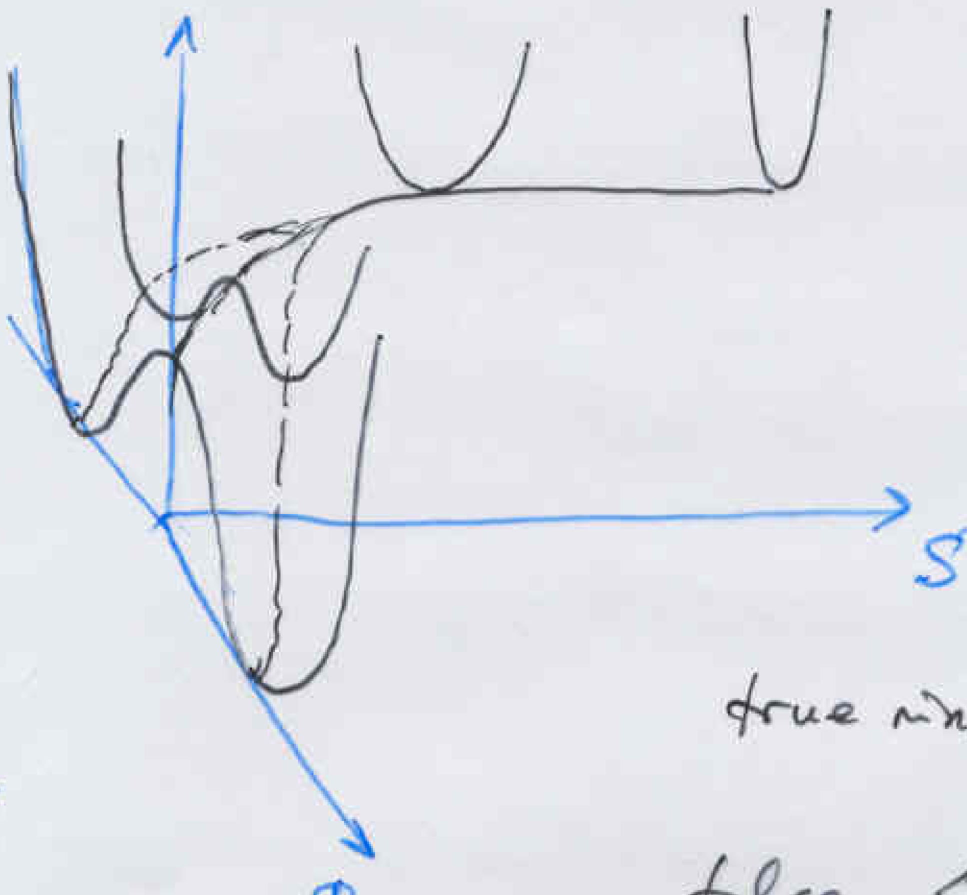
SUSY model for inflation

Dvali, Shafi, Shaefer

$$W = -\Lambda^2 S + S\Phi^2$$

S - inflaton
Φ - "orthogonal"

$\Lambda \sim 10^{15}\,\mathrm{GeV}$



true min. $\langle\Phi\rangle \sim \Lambda$
$\langle S\rangle = 0$

false, $\langle\Phi\rangle = 0$
$S > \Lambda$

Solving initial condition problem

$$W = -\Lambda^2 S + S\Phi^2 + \Phi N^2 + N \ell \varphi$$

N = RH neutrino

At inflationary stage $\langle \Phi \rangle = 0$,

$M_N = 0$, $B-L$ is restored,

$\tilde{N}$ – has initial value $\sim M_p$

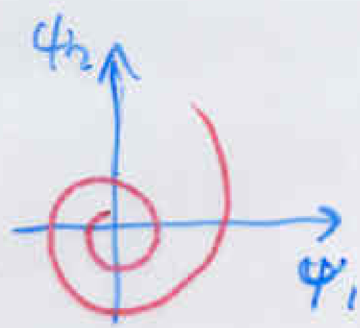
At reheating, $\langle \Phi \rangle \neq 0$, $M_N \propto \langle \Phi \rangle \sim \Lambda$

N has evolution with different frequencies for $\tilde{N} = \tilde{\psi}_1 + i\tilde{\psi}_2$

$$\ddot{\psi}_{1,2} + (3H + \Gamma)\dot{\psi}_{1,2} = -2\varphi^2 \psi_{1,2} \mp \sigma \varphi \psi_{1,2}$$

$J_\mu \simeq \tilde{N} \overleftrightarrow{\partial_\mu} N$ is non-zero

$$n_{B-L} = \frac{1}{2}\left(\psi_1 \dot{\psi}_2 - \dot{\psi}_1 \psi_2\right)$$



$$B - L \sim \alpha \frac{T_R}{M_{pl}}$$

Conclusions

$N \to \ell\varphi$ decay: $T_R > M$,

Link to ν-mass

interesting connections to ν-mass textures

$\ell\varphi \to N \to \ell'\varphi'$ scattering: $T_R < M$

link to active-sterile ν-mass pattern

$\frac{\delta B}{B} \neq 0 \qquad \left(\frac{\delta B}{B} \sim \frac{\delta T}{T}\right)$

Adiabatic + isocurvature correlated perturb.

$\frac{\delta R}{R} \neq 0, \quad \delta B = 0$ adiabatic

$\delta R = 0, \quad \frac{\delta B}{B} \neq 0$ isocurvature

$\frac{\delta\pi}{\pi} \neq 0 \qquad \pi = 3.14\ldots$? Melchiorri, yesterday

$\tilde{N} \to \ell\tilde{\varphi}$ decay at inflation exit

$\delta B \neq 0$ as in A.-D. models