Neutron - Mirror Neutron Oscillation:

how fast It might be?

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Cosmic Coincidence & Fine Tuning Problems

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

- $\Omega_B \simeq 0.04$ observable matter – Baryons !
- $\Omega_D \simeq 0.20$ dark matter: – WIMPS? Axions? ....
- $\Omega_\Lambda \simeq 0.75$ dark energy: – Λ-term? 5th-essence? ....

A. coincidence of matter $\Omega_M = \Omega_D + \Omega_B$ and dark energy Ω_Λ: $\Omega_M/\Omega_\Lambda \simeq 0.3$

$\cdot$ $\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$; why $\rho_M/\rho_\Lambda \sim 1$ – just Today?

Antrophic answer: if not Today, then it could be Yesterday or Tomorrow ...

B. Fine Tuning between visible Ω_B and dark Ω_D matter: $\Omega_B/\Omega_D \simeq 0.2$

$\cdot$ $\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$; why $\rho_B/\rho_D \sim 1$ – Yesterday Today & Tomorrow?

Difficult question ... popular models for the primordial Baryogenesis (GUT-B, Lepto-B, Spont. B, Affleck-Dine B, EW B, ...) have no feeling for the popular DM candidates (Wimp, Wimpzilla, axion, axino, gravitino ...)

– How Baryon Asymmetry could knew about Dark Matter? – again anthropic (landscaped) Fine Tunings in Particle Physics and Cosmology? Just for our good?

Visible vs. Dark matter

- Visible matter: $\rho_{\rm B} = n_{\rm B} M_B$, $M_B \simeq 1$ GeV – nucleons, $\eta = n_B/n_\gamma \sim 10^{-9}$

– in Baryogenesis models η depends on several factors, like CP-violating constants, particle degrees of freedom, mass scales, particle interaction strength and goodness of out-of-equilibrium.... and in some models (e.g. Affleck-Dine) on the initial conditions as well ...

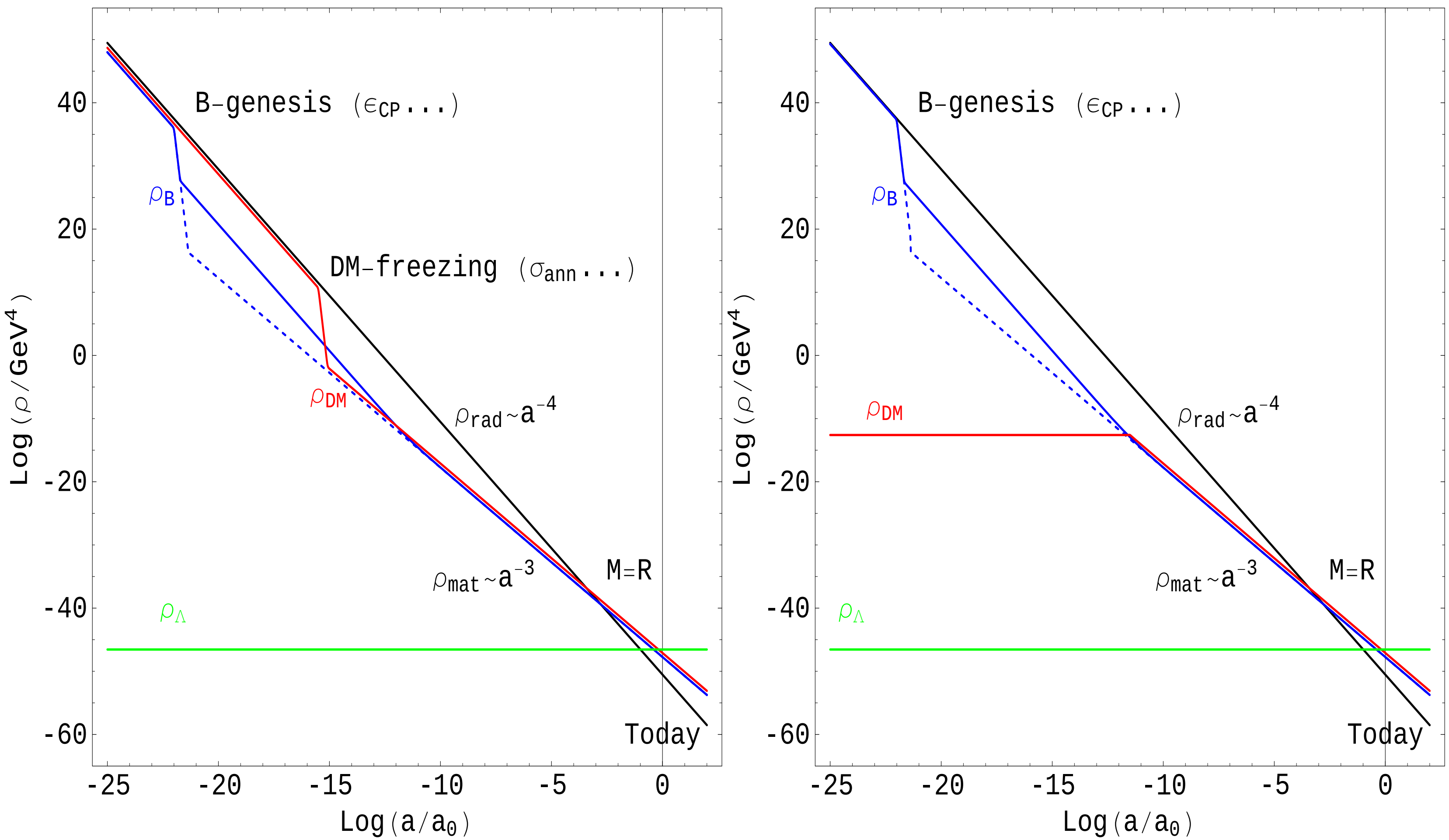
- Dark matter: $\rho_{\rm D} = n_X M_X$, but $M_X = ?$, $n_X = ?$

– too wide spectrum of possibilities ...
Axion: $M_X \sim 10^{-5}$ eV; Wimp: $M_X \sim 1$ TeV; Wimpzilla: $M_X \sim 10^{14}$ GeV ...

– in relative models n_X depends on varios factors, like equilibrium status and particle degrees of freedom, particle masses and interaction strength (production and annihilation cross sections).... and in some models (e.g. Axion or Wimpzilla) on the initial conditions as well ...

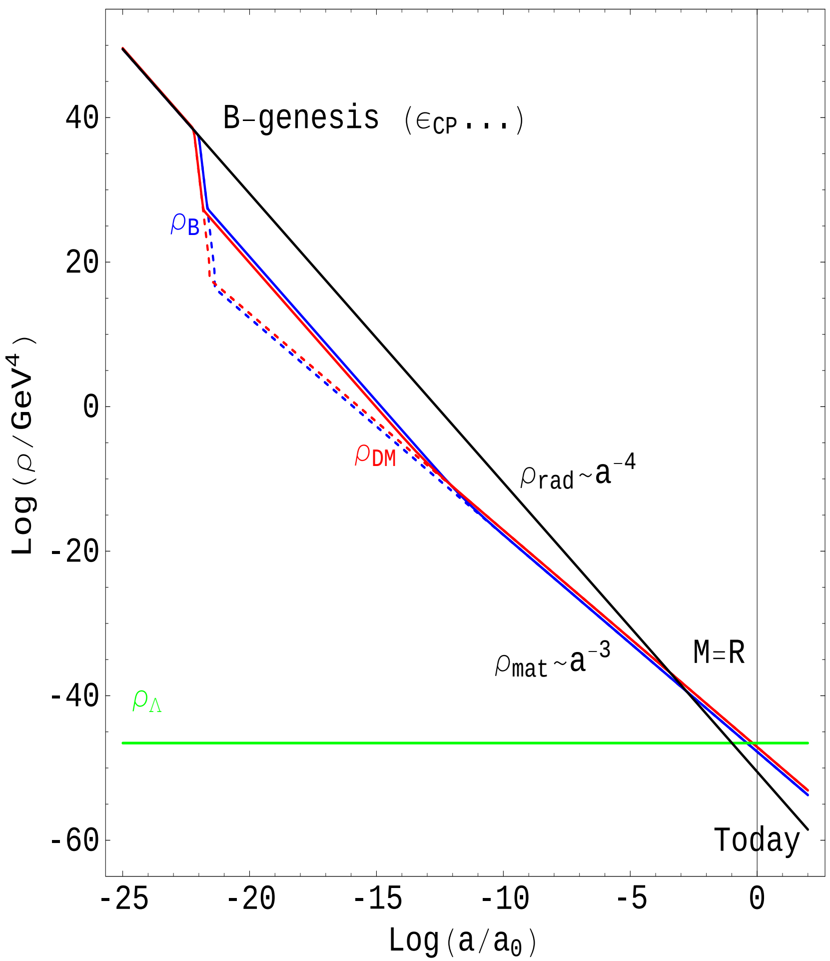
How then the mechanisms of Baryogenesis and Dark Matter synthesis, having different particle physics and corresponding to different epochs, could know about each-other? – How $\rho_B = n_B M_B$ could match $\rho_X = n_X M_X$ so intimately?

B vs. D – Fine Tuning demonstration



Evolution of the Baryon number ($\cdots$) in e.g. Leptogenesis scenario confronted to the evolution of the Dark Matter density (—) in the scenarios of WIMP (left pannel) and Axion (right pannel)

Unified origin of B and D? Both fractions at one shoot?



$$\frac{\rho_X}{\rho_B} = \frac{M_X n_X}{M_B n_B} \sim 1$$ *can be natural*

- if DM properties are similar to baryon ones: namely $M_X \sim M_B$
- and both fractions are generated by same mechanism so that $n_X \sim n_B$

"Through the Looking-Glass" **Lewis Carroll**

'Now, if you'll only attend, Kitty, and not talk so much, I'll tell you all my ideas about Looking-glass House. There's the room you can see through the glass – that's just the same as our drawing-room, only the things go the other way... the books are something like our books, only the words go the wrong way: I know that, because I've held up one of our books to the glass, and then they hold up one in the other room. I can see all of it – all but the bit just behind the fireplace. I do so wish I could see that bit! I want so to know whether they've a fire in the winter: you never can tell, you know, unless our fire smokes, and then smoke comes up in that room too – but that may be only pretence, just to make it look as if they had a fire...

'How would you like to leave in the Looking-glass House, Kitty? I wander if they'd give you milk in there? But perhaps Looking-glass milk isn't good to drink? Now we come to the passage: it's very like our passage as far as you can see, only you know it may be quite on beyond. Oh, how nice it would be if we could get through into Looking-glass House! Let's pretend there's a way of getting through into it, somehow ... Why, it's turning into a sort of mist now, I declare! It'll be easy enough to get through ...'

–Alice said this, and in another moment she was through the glass... she was quite pleased to find that there was a real fire in the fireplace... 'So I shall be as worm here as I was in my room,' thought Alice: 'warmer, in fact, there'll be no one here to scold me away from the fire'.

"Looking-Glass Universe" – Mirror World

Imagine a parallel "Mirror" sector of particles, a hidden duplicate of ordinary sector, coupled to us by gravity — hence candidate of DM

Kobzarev, Okun, Pomeranchuk '66
Blinnikov, Khlopov '83

Two identical gauge factors, $G \times G'$, with the identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ (exact parity under $G \leftrightarrow G'$)

$SU(3)\times SU(2)\times U(1) \quad \times \quad SU(3)'\times SU(2)'\times U(1)'$, Foot, Lew, Volkas '91

or better GUT×GUT$'$: $SU(5) \times SU(5)'$, $SO(10) \times SO(10)'$, *etc* .

- Can naturally emerge in string theory: O & M matter fields localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$

- Exact parity $G \leftrightarrow G'$: Mirror matter is dark (for us), and its particle physics we know exactly – no new parameters!

- Spontaneously broken $G \leftrightarrow G'$: different weak scales $M_W' \neq M_W$ shadow DM with rescaled particle spectrum – one extra parameter $\zeta = M_W'/M_W$

Z.B. & Mohapatra '95
Z.B., Dolgov & Mohapatra '96

Mirror Particles and two parities: simple and mirror

$SU(3)\times SU(2)\times U(1)$ gauge (g, W, Z, γ) & Higgs (ϕ) fields	$\times$	$SU(3)'\times SU(2)'\times U(1)'$ gauge (g', W', Z', γ') & Higgs (ϕ') fields

quarks (B=1/3)	leptons (L=1)	|	quarks (B′=1/3)	leptons (L′=1)
$q_L = (u,d)^t_L$	$l_L = (\nu, e)^t_L$	|	$q'_L = (u',d')^t_L$	$l'_L = (\nu', e')^t_L$
$u_R \;\; d_R$	e_R	|	$u'_R \;\; d'_R$	e'_R
		|		
$\widetilde{\text{quarks}}$ (B=-1/3)	$\widetilde{\text{leptons}}$ (L=-1)	|	$\widetilde{\text{quarks}}$ (B′=-1/3)	$\widetilde{\text{leptons}}$ (L′=-1)
$\tilde{q}_R = (\tilde{u},\tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$	|	$\tilde{q}'_R = (\tilde{u}',\tilde{d}')^t_R$	$\tilde{l}'_R = (\tilde{\nu}', \tilde{e}')^t_R$
$\tilde{u}_L \;\; \tilde{d}_L$	$\tilde{e}_L$	|	$\tilde{u}'_L \;\; \tilde{d}'_L$	$\tilde{e}'_L$

$$- \quad \mathcal{L}_{\rm Yuk} = f_L Y \tilde{f}_L \phi + \tilde{f}_R Y^* f_R \tilde{\phi} \quad \Big| \quad \mathcal{L}'_{\rm Yuk} = f'_L Y' \tilde{f}'_L \phi' + \tilde{f}'_R Y'^* f'_R \tilde{\phi}'$$

- D-parity: $L \leftrightarrow L',\; R \leftrightarrow R',\;\; \phi \leftrightarrow \phi'$ – $Y' = Y$ • *identical xero copy*
- M-parity: $L \leftrightarrow R',\; R \leftrightarrow L',\;\; \phi \leftrightarrow \tilde{\phi}'$ – $Y' = Y^\dagger$ • *mirror (chiral) copy*

BBN constraint

Mirror particle physics $\equiv$ ordinary particle physics

but .... mirror cosmology $\neq$ ordinary cosmology

- *at the BBN epoch,* $T \sim 1$ *MeV,* $g_* = g_*^{SM} = 10.75$
  (as contributed by the γ, $e^\pm$ *and 3* ν *species)*
- *if* $T' = T$*, mirror world would give the same contribution:*
  $g_*^{\rm eff} = 2 \times g_*^{SM} = 21.5$ *– equivalent to* $\Delta N_\nu = 6.14$
- *If* $T' < T$, *then* $g_*^{\rm eff} \approx g_*^{SM}(1 + x^4)$, $x = T'/T$ *–*
  hence mirror world contributes as $\Delta N_\nu = 6.14 \cdot x^4$
  E.g. $\Delta N_\nu < 0.4$ *requires* $x < 0.5$; *for* $x = 0.2$ $\Delta N_\nu \simeq 0.01$
- *A paradigm:*
  – after inflation O and M worlds are (re)heated in non-symmetric way, with $T' < T$
  – particle processes between O and M particles are slow enough and are out-of-equilibrium
  – both sectors evolve adiabatically, without significant entropy production, hence $x = T'/T$ *remains nearly constant at later times*

Mirror Baryons as Dark Matter

As far as Mirror Baryons are dark (in terms of ordinary photons), they could constitute Dark Matter of the Universe

- *Once $x < 1$, mirror photons decouple earlier than our photons:* $z'_{\rm dec} \simeq \frac{1}{x} z_{\rm dec}$

However, if the DM is entirelly due to mirror baryons, then the large scale structure (LSS) formation requires that mirror photons must decouple before Matter-Radiation Equality epoch: $x < x_{\rm eq} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

If this condition is satisfied, then

- *mirror Jeans scale λ'_J becomes smaller than the Hubble horizon before Matter-Radiation Equality*

- *mirror Silk scale is smaller than the one for the normal baryons:*

$\lambda'_S \sim 5 x_{\rm eq}^{5/4} (x/x_{\rm eq})^{3/2} (\Omega_M h^2)^{-3/4}$ *Mpc* *[Z.B., Comelli & Villante '01]*

Hence the structures formation at 1 Mpc scales (galaxies) implies $x < 0.2$

N.B. Since mirror baryons constitute dissipative dark matter, the formation of the extended halos can be problematic, but perhaps possible if the star formation in the mirror sector is rather fast due to different temperature and chemical content (in fact, BBN in mirror sector is much faster, and in consequence it is dominated by Helium (up to 80 %) rather than Hydrogen).

O & M interactions besides gravity

- Higgs-Higgs′ quartic: $\lambda(\phi^\dagger\phi)(\phi'^\dagger\phi')$

could be interesting for the Higgs physics at the LHC ... but BBN: $\lambda < 10^{-8}$!

reaction $\phi\tilde{\phi} \to \phi'\tilde{\phi}'$ *should not bring mirror sector in equilibrium with our particles*

... natural in SUSY : *lowest order mixed Higgs term is* ***D=5*** *operator*

$W = \frac{1}{M_{Pl}}(\phi_u\phi_d)(\phi'_u\phi'_d)$ – *in superpotential*

- Photon-photon′ kinetic mixing: $\varepsilon F^{\mu\nu}F'_{\mu\nu}$

mirror particles become "millicharged" $Q' \sim \varepsilon Q$ *relative to our photon* *Holdom '86*

process $e^+e^- \to e'^+e'^-$ *testable in positronium physics down to* $\varepsilon \sim 10^{-7}$

Glashow '86, Gninenko '94

$N'N$ *nuclear scattering testable in DM detectors down to* $\varepsilon \sim 5\cdot 10^{-9}$ *Foot '03*

but BBN: *(*$e^+e^- \to e'^+e'^-$ *reaction)* $\varepsilon < 3\cdot 10^{-8}$ *Carlson & Glashow '87*

and CMB+LSS: $\varepsilon < 10^{-9}$ *if mirror baryons constitute DM* *Z.B. & Lepidi '07*

... natural in GUT : *lowest order mixed gauge term is* ***D=6*** *operator*

$\mathcal{L} \sim \frac{\Sigma\Sigma'}{M_{Pl}^2}G^{\mu\nu}G'_{\mu\nu}$ – *e.g.* $\Sigma^{(\prime)}, G^{(\prime)}_{\mu\nu} \sim 24$*-plets* *in* $SU(5)\times SU(5)'$

O & M neutrino mixing

Mixed *D=5* effective operators — Z.B. & Mohapatra '95

$$\frac{A}{M} ll\phi\phi_{(\Delta L=2)} + \frac{A'}{M} l'l'\phi'\phi'_{(\Delta L'=2)} + \frac{D}{M} ll'\phi\phi'_{(\Delta L=1,\Delta L'=1)}$$

Substituting VEVs $\langle\phi\rangle = v$ *and* $\langle\phi'\rangle = v'$, *we get* $\nu - \nu'$ *mixing*

$$\begin{pmatrix} \hat{m}_\nu & \hat{m}_{\nu\nu'} \\ \hat{m}^t_{\nu\nu'} & \hat{m}_{\nu'} \end{pmatrix} = \frac{1}{M} \begin{pmatrix} Av^2 & Dvv' \\ D^t vv' & A'v'^2 \end{pmatrix}$$ – *active-sterile* ν *system*

[M-parity: $A' = A^*$, $D = D^\dagger$; D-parity: $A' = A$, $D = D^t$]

- $v' = v$: $m_{\nu'} = m_\nu$ *and maximal mixing* $\theta_{\nu\nu'} = 45°$; — Foot & Volkas '95
- $v' > v$: $m_{\nu'} \sim (v'/v)^2 m_\nu$ *and small mixing* $\theta_{\nu\nu'} \sim v/v'$;

e.g. $v'/v \sim 10^2$: $\sim$ *keV sterile neutrinos as WDM* — Z.B., Dolgov, Mohapatra '96

- $A, A' = 0$ ($L - L'$ *conserved*) *light – Dirac neutrinos* — Z.B. & Bento '05

with L *components in ordinary sector and* R *components in mirror sector*

Mixed Seesaw and Leptogenesis between O & M sectors

- Heavy gauge singlet fermions $N_a, \quad a = 1, 2, 3, ...$ with large Majorana mass terms $M_{ab} = g_{ab}M$, can equally talk with both O and M leptons

$$\mathcal{L}_{\rm Yuk} = y_{ia}\phi l_i N_a \; + \; y'_{ia}\phi' l'_i N_a \; + \; \tfrac{1}{2} M g_{ab} N_a N_b \; + \; \text{h.c.} \; ;$$

(M-*parity:* $\quad y' = y^\dagger$; D-*parity:* $\quad y' = y$)

- D=5 effective operators $\frac{A}{M} ll\phi\phi \; + \; \frac{A'}{M} l'l'\phi'\phi' \; + \; \frac{D}{M} ll'\phi\phi'$ emerge after integrating out heavy states N, where

$$A = yg^{-1}y^t, \quad A' = y'g^{-1}y'^t, \quad D = yg^{-1}y'^t$$

- They generate also processes like $l\phi \to \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \to \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) satisfying Sakharov's 3 conditions for baryogenesis

  A. violate B-L – *by definition*

  B. violate CP – *complex Yukawa constants* y_{ia}

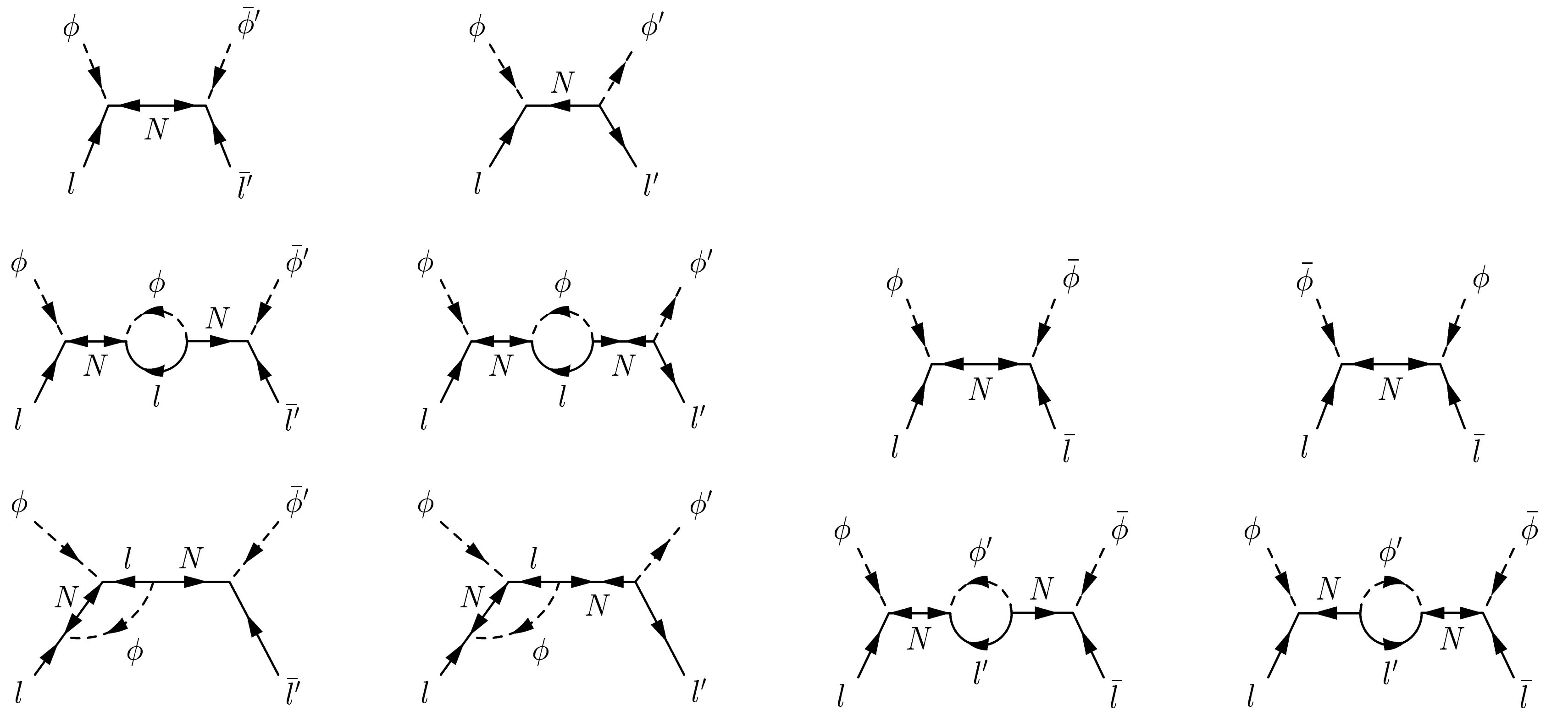
  C. out-of-equilibrium – *already implied by the BBN*

  and thus generate B-L$\neq$0 ($\to$ B$\neq$0 by sphalerons) for ordinary matter

- The same reactions generate B$'$-L$'$ $\neq$0 ($\to$ B$'\neq$0) in Mirror sector.

Both matter fractions: observable and dark, can be generated at one shoot !!

CP violation in ΔL=1 and ΔL=2 processes



$$\varepsilon_{CP} = \mathrm{Im\,Tr}[(y^\dagger y)^* g^{-1}(y'^\dagger y')g^{-2}(y^\dagger y)g^{-1}]$$
$$\varepsilon'_{CP} = \mathrm{Im\,Tr}[(y'^\dagger y')^* g^{-1}(y^\dagger y)g^{-2}(y'^\dagger y')g^{-1}]$$

Z.B. and Bento '01

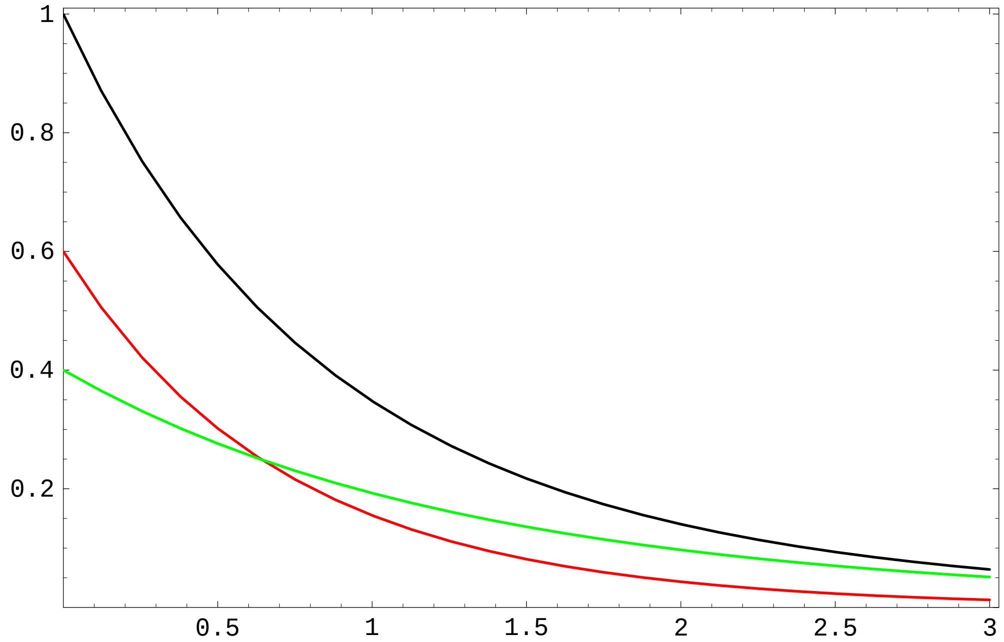
$\varepsilon_{CP} \longrightarrow \varepsilon'_{CP}$ *when* $y \longrightarrow y'$

- D-*parity:* $y' = y$, $\varepsilon_{CP} = 0$;
- M-*parity:* $y' = y^\dagger$ $\varepsilon_{CP} \neq 0$

Leptogenesis: $M'_B = M_B$ ... but $\Omega'_B \geq \Omega_B$

$$B = D(k) \cdot Y^{(0)}, \quad B' = D(kx^3) \cdot Y^{(0)}; \quad Y^{(0)} \approx \frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4} \cdot 10^{-3}$$

$$k = [\Gamma_{\rm eff}/H]_{T=T_R}, \quad x = T'/T \approx 1.2\,(k/g_*)^{1/4} \quad (T_R = T_{\rm Reheating})$$

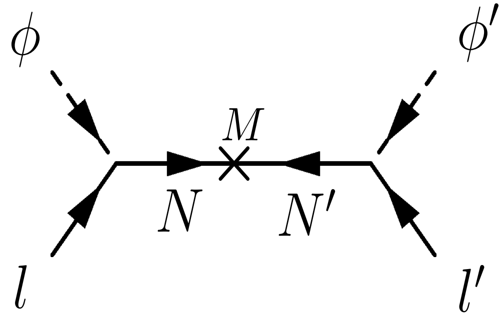


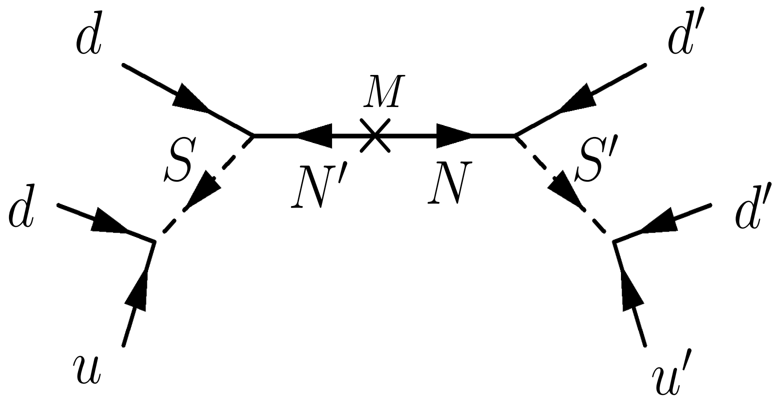
BBN: $x < 0.5 \quad \to \quad k \leq 4;$ LSS: $x < 0.2 \quad \to \quad k \leq 1.5$

Thus Ordinary/Mirror matter ratio can vary within $\frac{\Omega_B}{\Omega'_B} = D(k) \simeq 0.2 - 1$

Leptogenesis or Baryogenesis?

D=5 *operator* $\frac{1}{M} l l' \phi \phi'$ *($\Delta L = 1$)* *induced by heavy singlet* N *"seesaw" exchange (l, ϕ and l', ϕ' ordinary and mirror lepton and Higgs doublets)* *– can generate B-L (and B′-L′) asymmetry via processes* $l\phi \to l'\phi'$ Z.B. and Bento '01





Z.B. and Bento '05

D=9 *operator* $\frac{1}{\mathcal{M}^5}(udd)(u'd'd')$ *($\Delta B = 1$)* *induced by heavy singlet* N *"seesaw" (u, d and u', d' ordinary and mirror R-quarks, S, S' color triplet scalars (squarks?))* *– can generate B-L (and B′-L′) asymmetry via processes* $dS \to d'S'$

Neutron - Mirror neutron mixing

Operators like $\frac{1}{\mathcal{M}^5}(udd)(u'd'd')$ *and* $\frac{1}{\mathcal{M}^5}(qqd)(q'q'd')$ *induce the neutron - mirror neutron mass mixing* $\delta m\,(\overline{n}n' + \overline{n}'n)$, *with* $\delta m \sim \left(\frac{10\,\mathrm{TeV}}{\mathcal{M}}\right)^5 \cdot 10^{-15}\,\mathrm{eV}$

- $n - n'$ *oscillation in vacuum:*

maximal mixing $\theta = 45^\circ$ *and oscillation time* $\tau_{\rm osc} = \delta m^{-1} \sim \left(\frac{\mathcal{M}}{10\,\mathrm{TeV}}\right)^5\ \mathrm{s}$

... similar to neutron - antineutron oscillation

Kuzmin '70, Glashow '79

Marshak & Mohapatra '80

but experimental limits on $n - \bar{n}$ *are strong:* $\tau_{n\bar{n}} > 10\,\mathrm{yr}$ *, while* $n - n'$ *is still allowed to be rather fast, faster then neutron decay:* $\tau_{nn'} < 10\,\mathrm{min}$

Can be interesting if $\mathcal{M} \sim (M_S^4 M_N)^{1/5} \sim 10\,\mathrm{TeV}$ *In the "seesaw" model –*
E.g. if $M_S, M_N \sim 10\,\mathrm{TeV}$, *or* $M_N \sim 10^{12}\,\mathrm{TeV}$ *and* $M_S \sim 100\,\mathrm{GeV}$

(see diagram of the previous page)

!!! N.B. Nuclear Stability

- $n - \tilde{n}$ *destabilizes nuclei:* $(A, Z) \to (A-1, Z, \tilde{n}) \to (A-2, Z) + \pi$*'s*

$\tau_{n\tilde{n}} > 10\,\mathrm{yr}$ *or so ...*

- $n - n'$ *does not:* $(A, Z) \to (A-1, Z) + n'$ ***not allowed** by phase space !*

gives no restriction for $\tau_{nn'}$ *!*

Neutron - Mirror neutron oscillation in magnetic field

Effective (non-relativistic) Hamiltonian for $n - n'$ oscillation

$$H = \begin{pmatrix} m - i\,\Gamma/2 + V + \mu(\boldsymbol{\sigma}\cdot\boldsymbol{B}) & \delta m \\ \delta m & m' - i\,\Gamma'/2 + V' \end{pmatrix}$$

- Exact mirror parity: masses $m' = m$ and widths $\Gamma' = \Gamma$
- Grav. potentials are the same: $V' = V$, but $\mu = -1.91\mu_N$:

$|\mu B| \simeq 6 \cdot 10^{-12}\ \mathrm{eV/G}$ (Earth magnetic field $B \simeq 0.5\ \mathrm{G}$)

Take $\boldsymbol{B} = (0, 0, B)$ across z-axis, $(\boldsymbol{\sigma}\boldsymbol{B}) = B\sigma_z = \mathrm{diag}(B, -B)$

$$H = \begin{pmatrix} m \mp 2\omega_B & \delta m \\ \delta m & m \end{pmatrix}$$ diagonal in the basis $(\psi_+, \psi_-, \psi'_+, \psi'_-)$

– Energy gap $2\omega_B = |\mu B| \simeq B[\mathrm{G}] \times 6 \cdot 10^{-12}\ \mathrm{eV}$

Oscillation probability $P_{nn'}(t) = \sin^2 2\theta_B \sin^2(t/\tau_B) \cdot e^{-t/\tau_{\mathrm{dec}}}$

$$\sin 2\theta_B = \frac{\delta m}{\sqrt{\delta m^2 + \omega_B^2}}, \quad \tau_B = \frac{1}{\sqrt{\delta m^2 + \omega_B^2}} = \tau_0 \sin 2\theta_B, \quad \tau_0 = \delta m^{-1}$$

$n - n'$ oscillation rates

Oscillation probability in magnetic field B

$$P_{nn'}(t) = \frac{\delta m^2}{\delta m^2 + \omega_B^2} \sin^2\left(t\sqrt{\delta m^2 + \omega_B^2}\right) e^{-t/\tau_{\rm dec}}, \qquad (\omega_B = \tfrac{1}{2}|\mu B|)$$

In vacuum ($B = 0$): $\quad P_{nn'}(t) = \sin^2(t/\tau_0) \cdot e^{-t/\tau_{\rm dec}}$

($\tau_{\rm osc} = \tau_0 = \delta m^{-1}, \quad \theta_{\rm mix} = 45^\circ$)

for short times ($t \ll \tau_0$) : $\quad P_{nn'}(t) = (t/\tau_0)^2$

for longer times ($t \gg \tau_0$) : $\quad P_{nn'}(t) = \frac{1}{2}\, e^{-t/\tau_{\rm dec}}$

In medium ($B \neq 0$):

for short times ($t \ll \tau_B$) : $\quad P_{nn'}(t) = (t/\tau_0)^2$

for long times ($t \gg \tau_B$) : $\quad P_{nn'}(t) = \bar{P}_B = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + \omega_B^2}$

Magnetic field suppresses oscillation. The experiments with the reactor neutrons in free flight as well in the UCN traps could observe the difference in the neutron disappearance rates for the magnetic field on and off

for detailed discussion, see Pokotilovsky '06

Neutron - Mirror neutron mixing in astrophysics

- *primordial baryon asymmetry can be generated via $\Delta B = 1$ processes like $udd \to u'd'd'$. The same (and possibly somewhat larger) baryon asymmetry would be generated in the Mirror sector, wich could naturally explanain the origin of the baryonic and dark matter balance in the Universe: $\Omega_D \sim \Omega_B$.*

N.B. This mechanism does not require that $n - n'$ oscillation time should be necessarily small, within the present experimental reach. However, it requires that $\Delta B = 2$ processes like $udd \to \bar{u}\bar{d}\bar{d}$ should be also active though could be much slower. Hence, should the $n - n'$ oscillation detected at the level $\tau_{nn'} < 10^4$ s, (i.e. $\mathcal{M}_{nn'} \sim 10$ TeV) it would give a strong argument that $n - \bar{n}$ oscillation should also exist at the experimentally accessible level, with the relevant cutoff scale $\mathcal{M}_{n\bar{n}} \sim 100$ TeV and thus $\tau_{n\bar{n}} \sim 10^9$ s.

- *If $\tau_{nn'} < 10^3$ s, $n - n'$ oscillation provides an elegant mechanism for the transport of the ultra high energy cosmic rays at the large cosmological distances without suffering significant energy depression, and could be of interest in the search of the UHECR above the GZK cutoff and their correlation with the far distant astrophysical objects (BL Lacs, GRB's etc.)* *Z.B. & Bento '05*
- *Fast $n - n'$ oscillation could have interesting implications also for the neutrons from the solar flares* *Mohapatra,Nasri, Nussinov '05*

Experimental limits & and future search

- ILL experiment for $n - \tilde{n}$ oscillation search in flight: $t \simeq 0.1$ s, $B < 10^{-4}$G
  - no $\tilde{n}$ event found, $\tau_{n\tilde{n}} > 10^8$ s (or > 3 yr) Baldo Ceolin et al. '94

  as for $n - n'$: about 5% neutron deficit was observed, so taking

  $P_{nn'}(t) \simeq (t/\tau)^2 < 10^{-2}$, $\tau_{nn'} > 1$ s $\rightarrow$ $\delta m < 10^{-15}$ eV
- $n - n'$ – anomalous UCN loses, $\eta < 2 \cdot 10^{-6} \rightarrow \delta m < 3 \cdot 10^{-15}$ eV
- Nuclear Stability gives no limit for $\tau_{nn'}$

Recent Experimental search:

- $\tau > 2.5$ s, Munich, Schmidt et al, Feb. 2007 (unpubl.)
- $\tau > 103$ s, ILL Grenoble, Ban et al. May 2007, axXiv:0705.2336 [nucl-ex]
- $\tau > 413$ s, ILL Grenoble, Serebrov et al. June 2007, axXiv:0706.3600 [nucl-ex]

Future experiments can reach sensitivity $\tau \sim 10^4$ s

$n - n'$ oscillations can have very different experimental implications if n and n' states are not exactly degenerate at B=0. E.g. gravity is not quite universal between O and M matters, or there exist non-universal 5th forces of non-gravitational origin. Opposite effect is possible: magnetic field could enhance the oscillation instead of suppressing it.