Mirror Matter

cogenesis of two worlds

Zurab Berezhiani

Università di L'Aquila and LNGS Gran Sasso, Italy

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Dark Side of the Universe

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

- $\Omega_{\rm B} \simeq 0.05$ observable matter: electron, proton, neutron
- $\Omega_{\rm D} \simeq 0.25$ dark matter: who are? WIMP? axion? sterile ν? ...
- $\Omega_{\Lambda} \simeq 0.70$ dark energy: what is? Λ-term? Quintessence? ....

A. coincidence of matter $\Omega_{\rm M}$=$\Omega_{\rm D}$+$\Omega_{\rm B}$ and dark energy Ω_{Λ}: $\Omega_{\rm M}/\Omega_{\Lambda} \simeq 0.4$

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

Antrophic answer: if not Today, then it would happen Yesterday or Tomorrow.

B. Fine Tuning between baryon $\Omega_{\rm B}$ and dark $\Omega_{\rm D}$ matter: $\Omega_{\rm B}/\Omega_{\rm D} \simeq 0.2$

... $\rho_{\rm B} \sim a^{-3}$, $\rho_{\rm D} \sim a^{-3}$; why $\rho_{\rm B}/\rho_{\rm D} \sim 1$ – Yesterday Today & Tomorrow?

– Difficult question ... popular models for primordial Baryogenesis

GUT-B, Lepto-B, Spont. B, Affleck-Dine B, EW B ... *All on Sakharov's idea ...*

have no relation to popular DM candidates

Wimp, Wimpzilla, WDM (sterile ν), axion, gravitino ... *All trully neutral ...*

– How Baryogenesis could know about Dark Matter?

– Again anthropic? Again Fine Tunings in Particle Physics and Cosmology?

Visible vs. Dark matter: $\Omega_D/\Omega_B \simeq 5$ *?*

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

  Sakharov's conditions: B $(B-L)$ & CP violation, Out-of-Equilibrium

– 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 ...

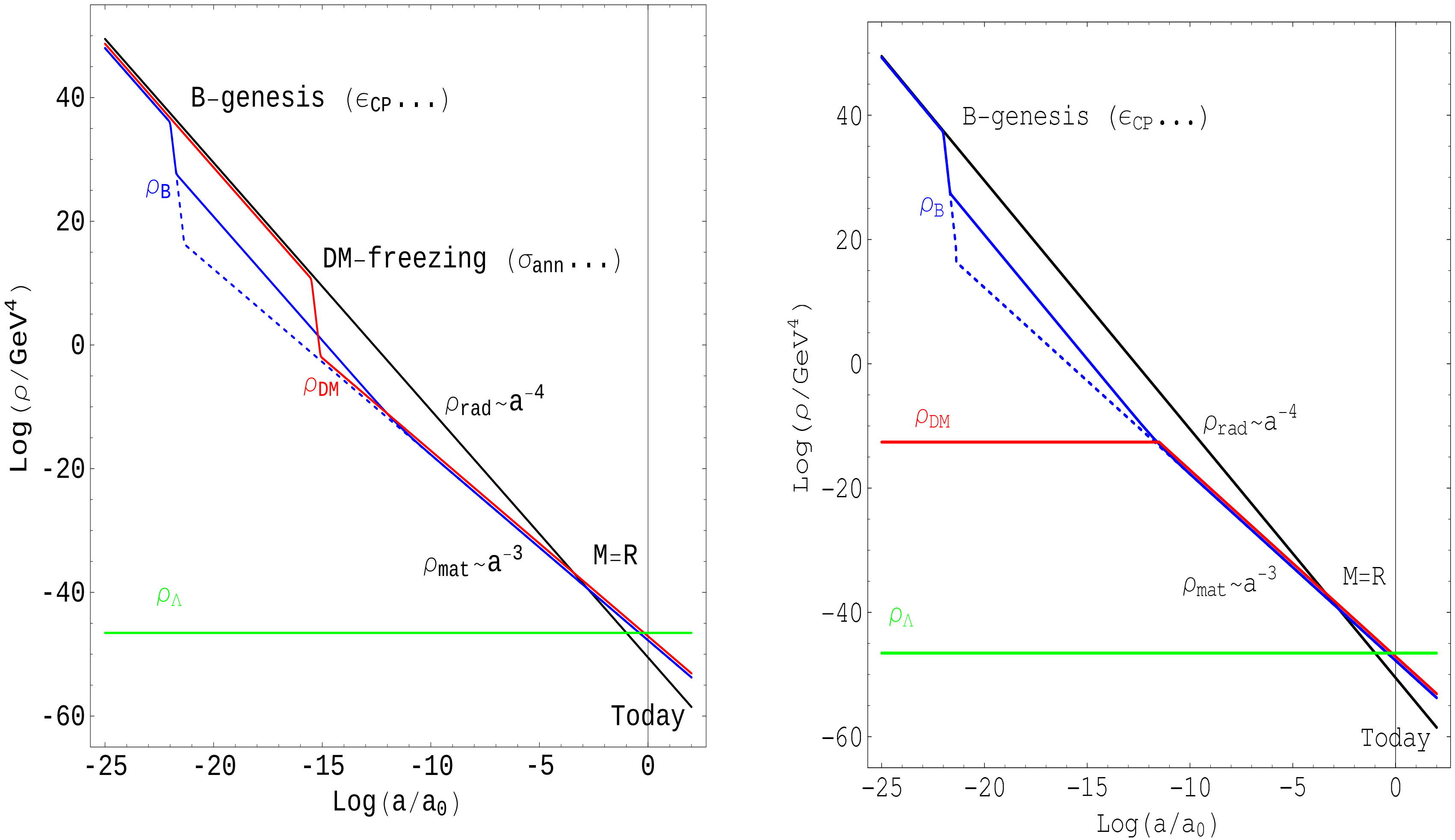
- Dark matter: $\rho_{\rm D} = n_X M_X$, but $M_X = ?$, $n_X = ?$

– wide spectrum of possibilities ...
Axion: $M_X \sim 10^{-5}$ eV, Sterile ν WDM: $M_X \sim 1$ keV, Wimp: $M_X \sim 1$ TeV,
Wimpzilla: $M_X \sim 10^{14}$ GeV ... but $M_X \sim 1$ GeV and $n_X \sim n_B$?

– 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 ...

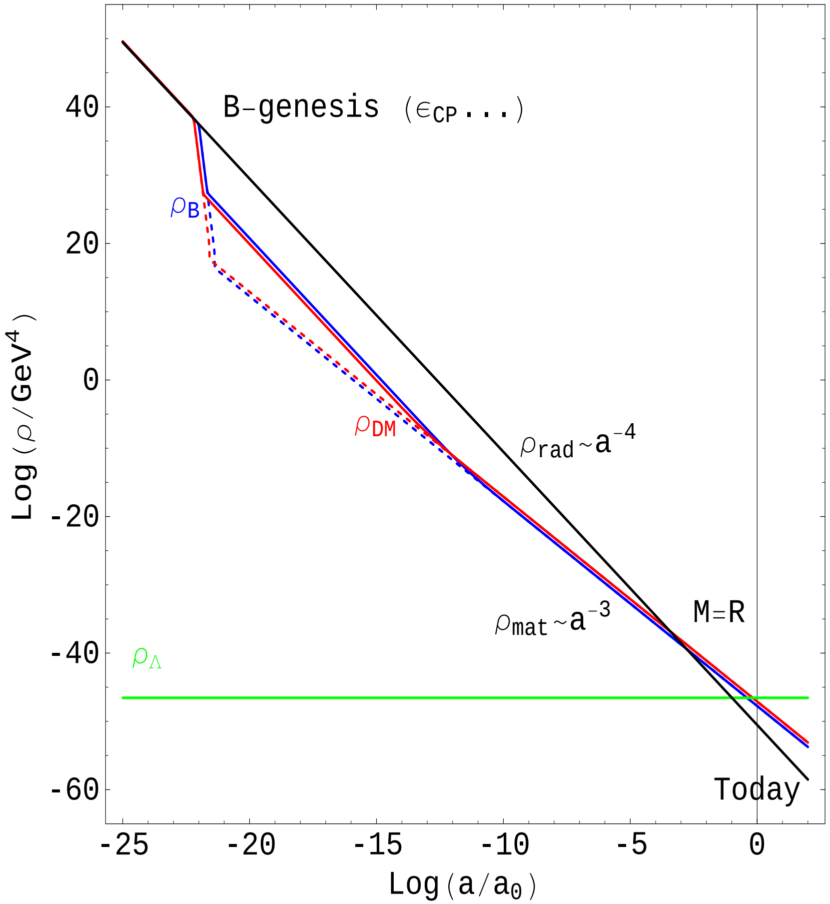
How then the mechanisms of Baryogenesis and Dark Matter synthesis, having different particle physics and corresponding to different epochs, could know about each-other? – How $\rho_B = n_B M_B$ could match $\rho_X = n_X M_X$ so intimately?

Cosmological evolution: B *vs.* D – demonstrating Fine Tuning



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

Unified origin of B and D? Cogenesis



Observable and dark matter co-genesis: both based on Baryon asymmetry ?

- *Dark particle masses/properties are similar to baryon ones:* $M_X \sim M_B$
- *Dark & B asymmetries are generated by one process and* $n_X \sim n_B$

so that $\frac{\rho_X}{\rho_B} = \frac{M_X n_X}{M_B n_B} \sim 1$ *- dark gauge sector with* B' *asymmetry*

Parallel hidden sector vs. observable sector ?

For observable particles .... very complex physics !!

Gauge $G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? RH neutrinos ?)

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, C/CP ... *Sakharov*)

... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

What if dark matter comes from extra gauge sector ... which is not ad hoc simple system but it is complex structure alike the observable one?

Parallel gauge sector: – $G' = SU(3)' \times SU(2)' \times U(1)'$?

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, C/CP ...) ?

... existence of twin nuclei, atoms, molecules ... life ... twin Homo Sapiens?

Dark gauge sector ... similar to our particle sector? ... or exactly the same?

.... two (or more) parallel branes in extra dimensions? $E_8 \times E'_8$?

who knows ..... but let us imagine !

"Imagination is more important than knowledge..." *A. Einstein*

Parallel/Mirror/Twin World(s)

- Two identical gauge factors, $G \times G'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ – $SU(5) \times SU(5)'$, *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), but its particle physics we know exactly (on our skin) – no new parameters!

- Asymmetric mirror world: spont. broken parity $G \leftrightarrow G'$:

$\langle \phi' \rangle \gg \langle \phi \rangle \longrightarrow (M'_W \gg M_W)$ ZB, Mohapatra & Dolgov, '95-96

Lepton/quark masses rescale $\propto M'_W/M_W$, neutrino masses $\propto (M'_W/M_W)^2$, but baryon masses $\propto \Lambda'/\Lambda \sim (M'_W/M_W)^{1/3}$ – *Asymmetric DM, sterile* ν *WDM, Strong CP & axidragon, SUSY little Higgs – accidental global* $U(4)$*, etc.*

Parallel Sector, Twin Particles & Mirror Parity

$SU(3)\times SU(2)\times U(1)$ 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)
$q_L = (u,d)^t_L$	$l_L = (\nu, e)^t_L$	|	$q'_L = (u',d')^t_L$	$l'_L = (\nu', e')^t_L$
$u_R \quad d_R$	e_R	|	$u'_R \quad d'_R$	e'_R
$\widetilde{\text{quarks}}$ (B=-1/3)	$\widetilde{\text{leptons}}$ (L=-1)	|	$\widetilde{\text{quarks}}$ (B′=-1/3)	$\widetilde{\text{leptons}}$ (L′=-1)
$\tilde{q}_R = (\tilde{u},\tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu},\tilde{e})^t_R$	|	$\tilde{q}'_R = (\tilde{u}',\tilde{d}')^t_R$	$\tilde{l}'_R = (\tilde{\nu}',\tilde{e}')^t_R$
$\tilde{u}_L \quad \tilde{d}_L$	$\tilde{e}_L$	|	$\tilde{u}'_L \quad \tilde{d}'_L$	$\tilde{e}'_L$

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

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

Para-world (or worlds) as dark matter

- *Parallel/twin/mirror sector: a duplicate of our particle sector ...*
its particles species have exactly the mass spectrum and interaction constants (strong, weak & electromagnetic) exactly identical to that of ordinary particles

- *Mirror particles are dark for us: do not interact with our photon* γ
(reciprocally, our particles do not interact with mirror photon γ' *)*

- *Gravity is a common force between two sectors ....*
Thus, mirror matter is a natural candidate for dark matter !!

- *Mirror microphysics* $=$ *our microphysics*
but mirror cosmology $\neq$ *our cosmology   Mirror Sector should be colder*
$T'/T < 0.5$ *(BBN),* $T'/T < 0.3$ *(CMB+LSS)*

- *There can be feeble interactions between ordinary and mirror particles:*
(Give dark matter detection a chance – DAMA & CRESST?)
But these should be feeble enough for not to equilibrate T *and* T'

- *B & L violating interactions most interesting: they can co-generate in Early Universe both baryon and para-baryon asymmetries, with* $\Omega'_B/\Omega_B \sim 5$ *naturally*

- *At lower energies, these induce mixings between ordinary particles and their twins:*
neutrino–paraneutrino (active–sterile) neutrino mixing, neutron–paraneutron mixing ...

BBN demands : **Paraworld is colder**

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 :* $N_\nu = 3$
- *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* $g_*^{\rm eff} \approx g_*^{SM}(1 + x^4)$, $x = T'/T$ $\longrightarrow \Delta N_\nu = 6.14 \cdot x^4$
  E.g. $\Delta N_\nu < 0.4$ *requires* $x < 0.5$; *for* $x = 0.2$ $\Delta N_\nu \simeq 0.01$
- *Paradigm – different initial conditions & weak contact :*
  – after inflation O and M worlds are (re)heated non-symmetrically, $T' < T$

  – processes between O - M particles are slow enough & stay Out-of-Equilibrium

  – both sectors evolve adiabatically, without significant entropy production

  So $x = T'/T$ *is nearly independent of time (*$T'_{\rm CMB}/T_{\rm CMB}$ *today)*

BBN: $\Delta N_\nu/6.14 = x^4 \ll 1$ $\longrightarrow$ BBN$'$: $\Delta N'_\nu/6.14 = x^{-4} \gg 1$

^{1}H 75%, ^{4}He 25% *vs.* ^{1}H$'$ 25%, ^{4}He$'$ 75%

Z. Berezhiani, D. Comelli, F. Villante, Phys. Lett. B 503, 362 (2001)

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 [Z.B., Comelli & Villante '01]

- *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: $x < x_{\rm eq} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

- *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:*

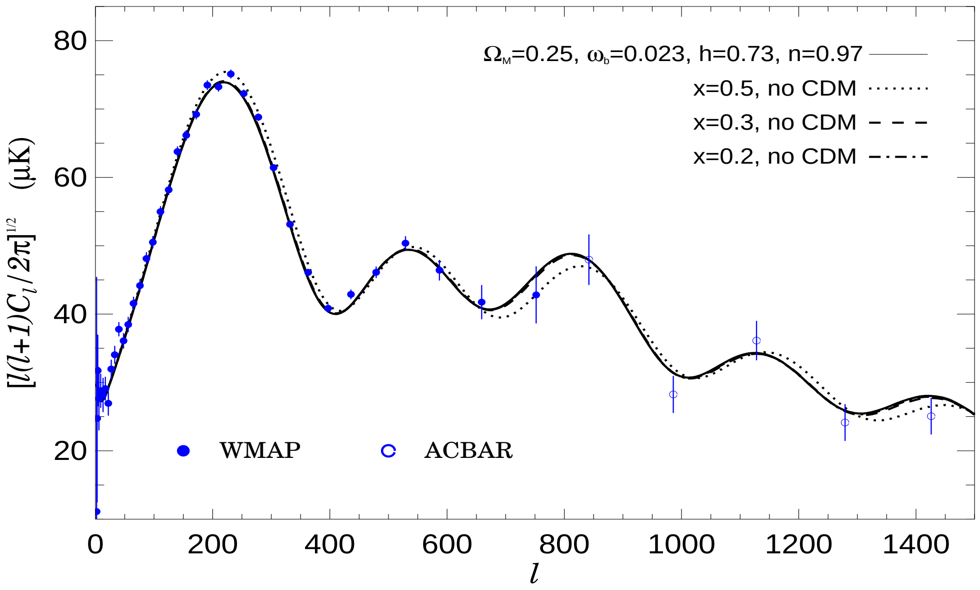
$\lambda'_S \sim 5 x_{\rm eq}^{5/4} (x/x_{\rm eq})^{3/2} (\Omega_M h^2)^{-3/4}$ *Mpc*

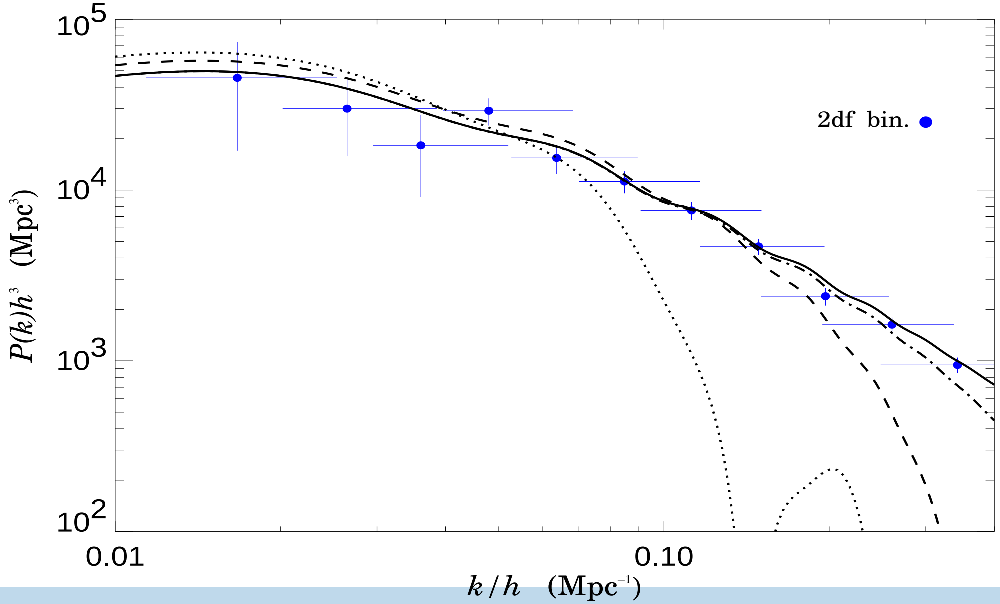
Hence the structures formation at 1 Mpc scales (galaxies) implies $x < 0.2$

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 fast due to different temperature and chemical content (in fact, mirror sector is dominated by Helium).*

MACHOs as mirror stars – *microlensing:* $M_{\rm av} = 0.5\, M_\odot$

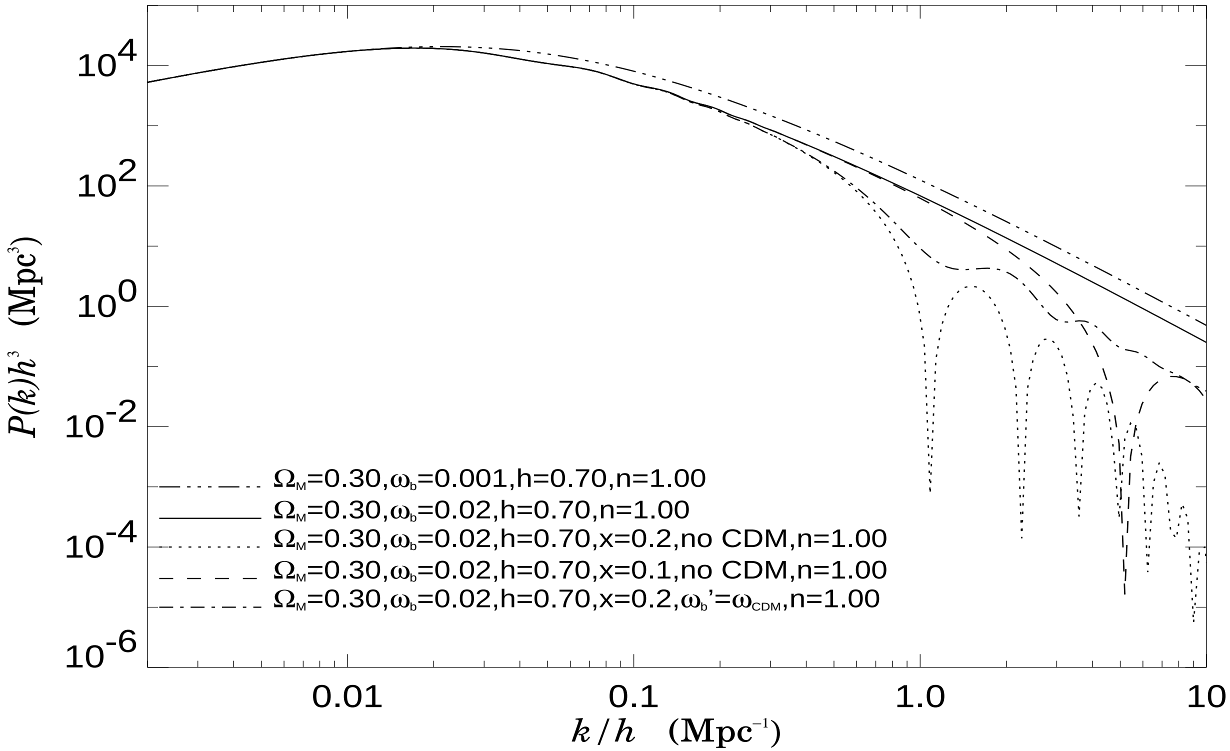
CMB & LSS power spectra





LSS power spectra

Z.B., Ciarcelluti, Comelli & Villante, ’03



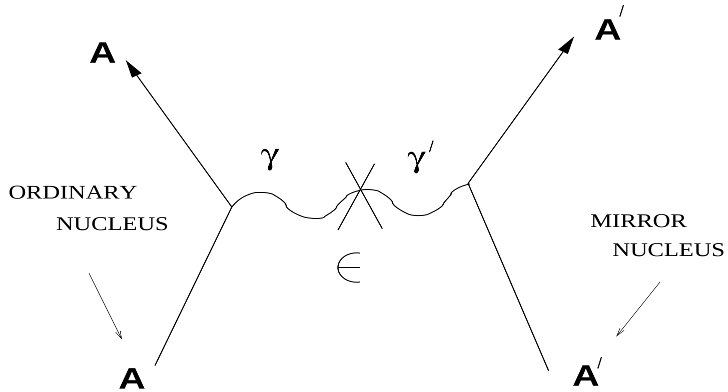
Possible interactions between O & M particles (besides gravity) can be induced at tree level by exchange of extra gauge singlet particles or common gauge fields acting with both O & M particles ... and these interactions can lead to particle mixing phenomena between O & M sectors: any neutral particle (elementary or composite) can have mass/kinetic mix its degenerate twin

- photon - mirror photon kinetic mixing $\varepsilon F^{\mu\nu} F'_{\mu\nu}$ Holdom '86

mirror particles become "millicharged" $Q' \sim \varepsilon Q$ *relative to our photon* $\longrightarrow$
BBN bound $\varepsilon < 3 \times 10^{-8}$, Carlson, Glashow '87

BBN now : $\varepsilon < 2 \times 10^{-9}$, *Structures :* $\varepsilon < 3 \times 10^{-10}$ ZB, Lepidi, '08

Natural in GUTs: $\frac{\alpha}{M_{Pl}^2}(\Sigma G)(\Sigma' G') \longrightarrow \varepsilon = \alpha s_W^2 \frac{\langle \Sigma \rangle^2}{M_{Pl}^2} < 10^{-8} - 10^{-9}$



Good for dark matter detection (DAMA) Foot '04

Testable O-ps - O-ps′ mixing ($e^+e^- \to e'^+e'^-$) *to* $\varepsilon \sim 10^{-9}$ Crivelli et al.'10

meson - mirror meson mixing: $D = 6$ operators

any neutral particle, elementary or composite, can mix its mass degenerate twin

- $\pi^0 - \pi^{0\prime}$, $\quad \rho^0 - \rho^{0\prime}$, *etc.*

  $\frac{1}{M^2}(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d)(\overline{u}'\gamma^5 u' - \overline{d}'\gamma^5 d')$,

  $\frac{1}{M^2}(\overline{u}\gamma^\mu u - \overline{d}\gamma^\mu d)(\overline{u}'\gamma_\mu u' - \overline{d}'\gamma_\mu d')$

  Phenom. limit: $\quad M > 10$ TeV $\quad (\pi^0 - \pi^{0\prime} \to 2\gamma'$ invisible)

- $K^0 - K^{0\prime}$ *etc.*

  $\frac{1}{M^2}(\overline{d}\gamma^5 s)(\overline{d}'\gamma^5 s') \qquad (\Delta S = 1)$

  C.f. $\quad \frac{1}{M^2}(\overline{d}\gamma^5 s)(\overline{d}\gamma^5 s) \quad \longrightarrow \quad K^0 - \bar{K}^0$ mixing $\quad (\Delta S = 2)$

  Phenom. limit: $\quad M > 100$ TeV $\quad (K^0 - K^{0\prime})$

● *Can be induced via exchange of flavor gauge bosons ($SU(3)_{\rm fl}$ etc.) interacting with both our and mirror quarks/leptons* : *helping for Flavor Problem: custodial symmetry, minimality of flavor violation in SUSY (SSB terms allignment), anomaly cancellation for chiral $SU(3)_{\rm fl}$, Vanishing D-term, etc.*

● *In the context of TeV scale gravity the gauge flavour bosons can live in extra dimensions (between parallel branes)*

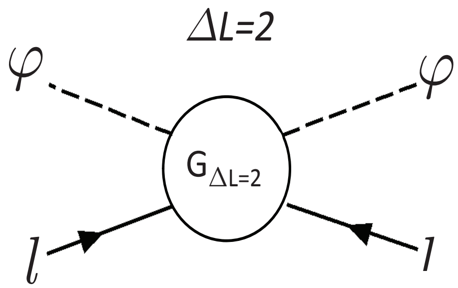
Lepton number violating interactions: $D = 5$ operators

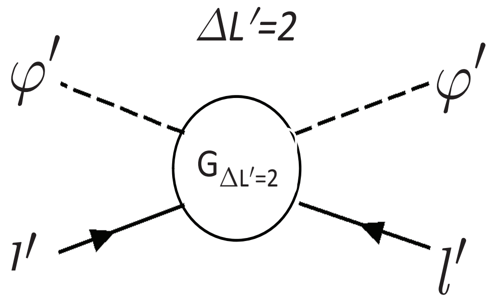
neutrino - mirror neutrino mixing $(\nu - \nu')$ – effective operators :

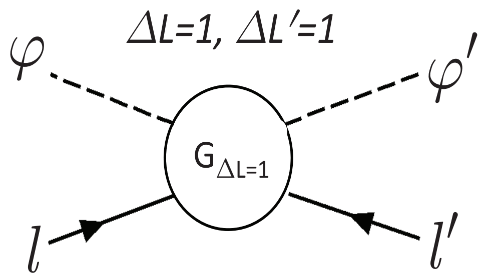
Akhmedov, ZB, Senjanovic, 1992; ZB, Mohapatra, 1995

$$\frac{1}{M}(l\phi)(l'\phi') \qquad (\Delta L = 1, \Delta L' = 1)$$

C.f. $\frac{1}{M}(l\phi)^2 \quad (\Delta L = 2)$, $\frac{1}{M}(l'\phi')^2 \quad (\Delta L' = 2)$ *for Majorana masses*







Lepton number violating interactions: $D = 5$ *operators*

- neutrino - mirror neutrino mixing $(\nu - \nu')$

$$\frac{A}{M}(l\phi)^2 \quad (\Delta L = 2), \quad \frac{A'}{M}(l'\phi')^2 \quad (\Delta L' = 2)$$ *for Majorana masses*

$$\frac{D}{M}(l\phi)(l'\phi') \qquad (\Delta L = 1, \Delta L' = 1)$$

Inserting VEVs $\langle\phi\rangle = v$ *and* $\langle\phi'\rangle = v'$,
we get $\nu - \nu'$ *(active-sterile) mixing*

$$\begin{pmatrix} \hat{m}_\nu & \hat{m}_{\nu\nu'} \\ \hat{m}^t_{\nu\nu'} & \hat{m}_{\nu'} \end{pmatrix} = \begin{pmatrix} \frac{Av^2}{M} & \frac{Dvv'}{M} \\ \frac{D^t vv'}{M} & \frac{A'v'^2}{M} \end{pmatrix}$$

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

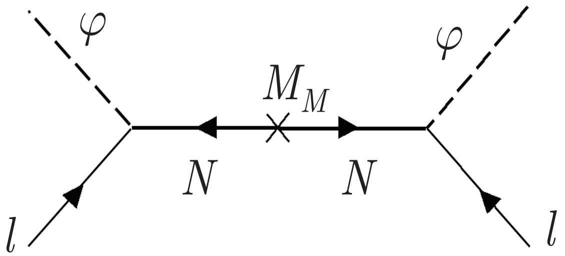
- $v' = v$: $\quad m_{\nu'} = m_\nu$ *and maximal mixing* $\theta_{\nu\nu'} = 45°$;
- $v' > v$: $\quad m_{\nu'} \sim (v'/v)^2 m_\nu$ *and small mixing* $\theta_{\nu\nu'} \sim v/v'$;

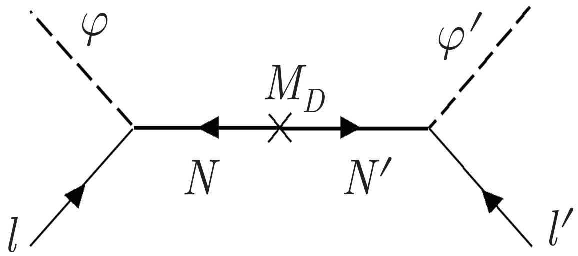
e.g. $v'/v \sim 10^2$*:* $\sim$ *keV sterile neutrinos as WDM* Z.B., Dolgov, Mohapatra '96

- $A, A' = 0$ *($L - L'$ conserved) light Dirac neutrinos*

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

Mixed Seesaw between O & M sectors





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

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

  Yukawas are genetically complex

  D-*parity:* $y' = y$, M-*parity:* $y' = y^\dagger$

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

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

Leptogenesis between O & M sectors

- In the Early Universe, after post-inflationary reheating, these interactions generate also processes like $l\phi(\tilde{l}\tilde{\phi}) \to \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \to \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) satisfying Sakharov's 3 conditions

  A. violate B-L – *by definition (only L)*

  B. violate CP – *complex Yukawa constants*

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

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

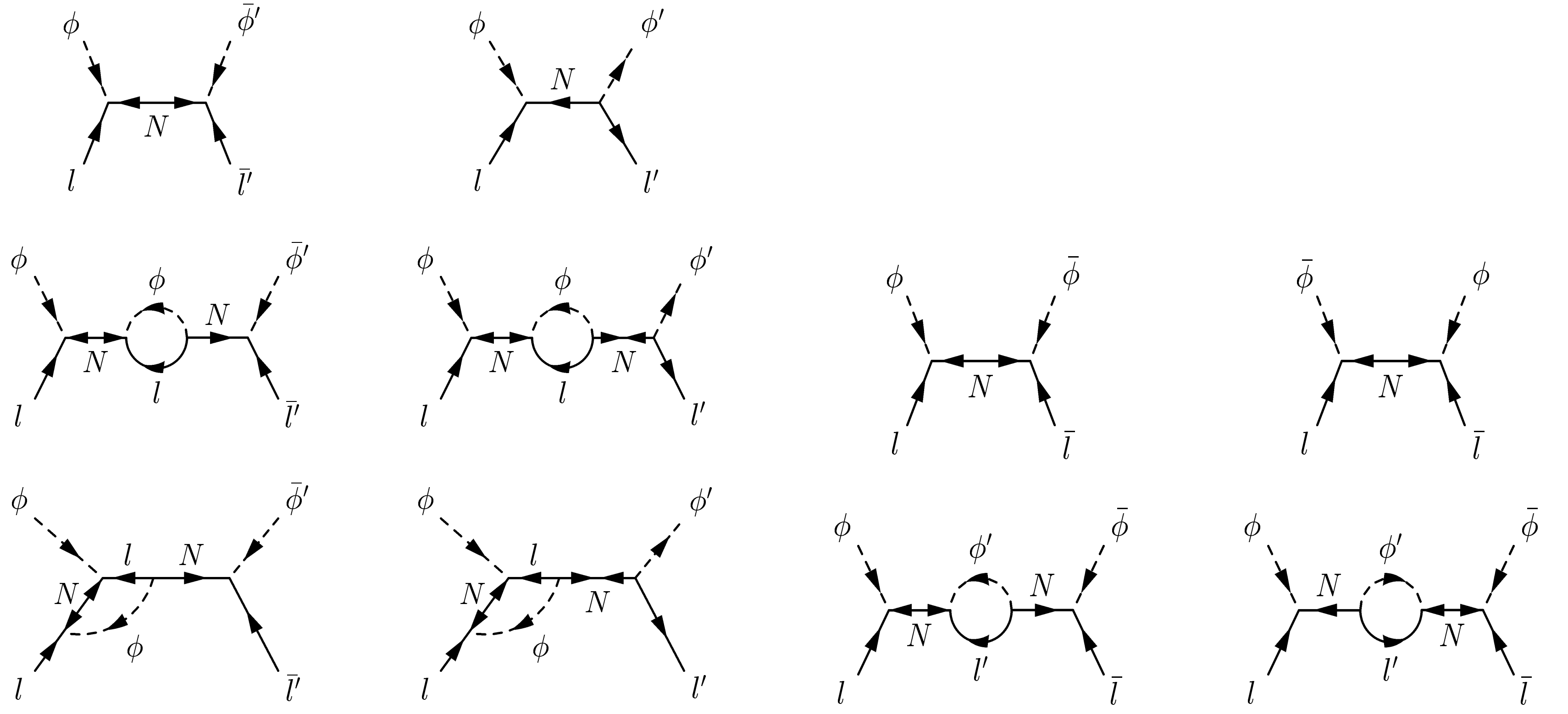
- The same reactions generate B$'$-L$'$ $\neq$0 ($\to$ B$'\neq$0) in dark sector.

Ordinary and mirror Baryon asymmetries can be generated at one shoot !!

Baryon & Dark matter Co-genesis

CP violation in ΔL=1 and ΔL=2 processes

L. Bento, Z. Berezhiani, PRL 87, 231304 (2001)



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

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

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

Evolution for (B-L)$'$ and (B-L) $\quad T_R \ll M$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} + \Gamma n_{B-L} = \frac{3}{4}\Delta\sigma\, n_{\rm eq}^2$$

$$\frac{dn'_{B-L}}{dt} + 3Hn'_{B-L} + \Gamma' n'_{\rm B-L} = \frac{3}{4}\Delta\sigma'\, n_{\rm eq}^2$$

$\Gamma \propto n'_{\rm eq}/M^2$ is the effective reaction rate of $\Delta L' = 1$ and $\Delta L' = 2$ processes

$$\Gamma'/\Gamma \simeq n'_{\rm eq}/n_{\rm eq} \simeq x^3\ ; \qquad x = T'/T$$

$\Delta\sigma' = -\Delta\sigma = \frac{3\varepsilon_{CP}\, S}{32\pi^2 M^4}$, *where* $S \sim 16T^2$ *is the c.m. energy square*

$$Y_{BL} = D(k)\cdot Y_{BL}^{(0)}; \qquad Y'_{BL} = D(k')\cdot Y_{BL}^{(0)}$$

Damping factors $D(k)$ *and* $D(k')$*:* $\qquad k = \left[\frac{\Gamma_{\rm eff}}{H}\right]_{T=T_R}, \qquad k' = kx^2$

$Y_{BL}^{(0)} \approx 2\times 10^{-3}\frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}$: $\qquad T_R$ *is (re)heating temperature*

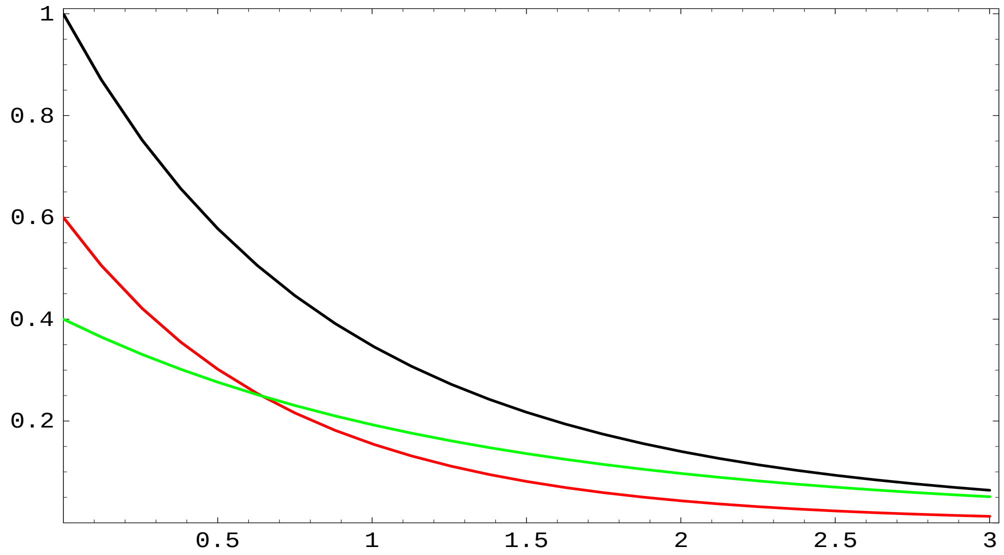
$Y_{BL}^{(0)} \sim 10^{-9}$ at $M \sim 10^{12}$ GeV, $T_R \sim 10^9$ GeV, $\varepsilon_{CP} \sim 10^{-3}$.

$M'_B = M_B$ ... but $n'_B > n_B$ $k \sim 1$ – borderline out-of-equili

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

$$k = \left[\frac{\Gamma_{\rm eff}}{H}\right]_{T=T_R}, \qquad k' = kx^2, \qquad x = \frac{T'}{T} < 0.5 \qquad (T_R = T_{\rm Reheat})$$

$D(k) < D(k') \approx 1$: lower limit $\frac{\Omega'_B}{\Omega_B} = \frac{D(k')}{D(k)} > 1$ Z.B. '03

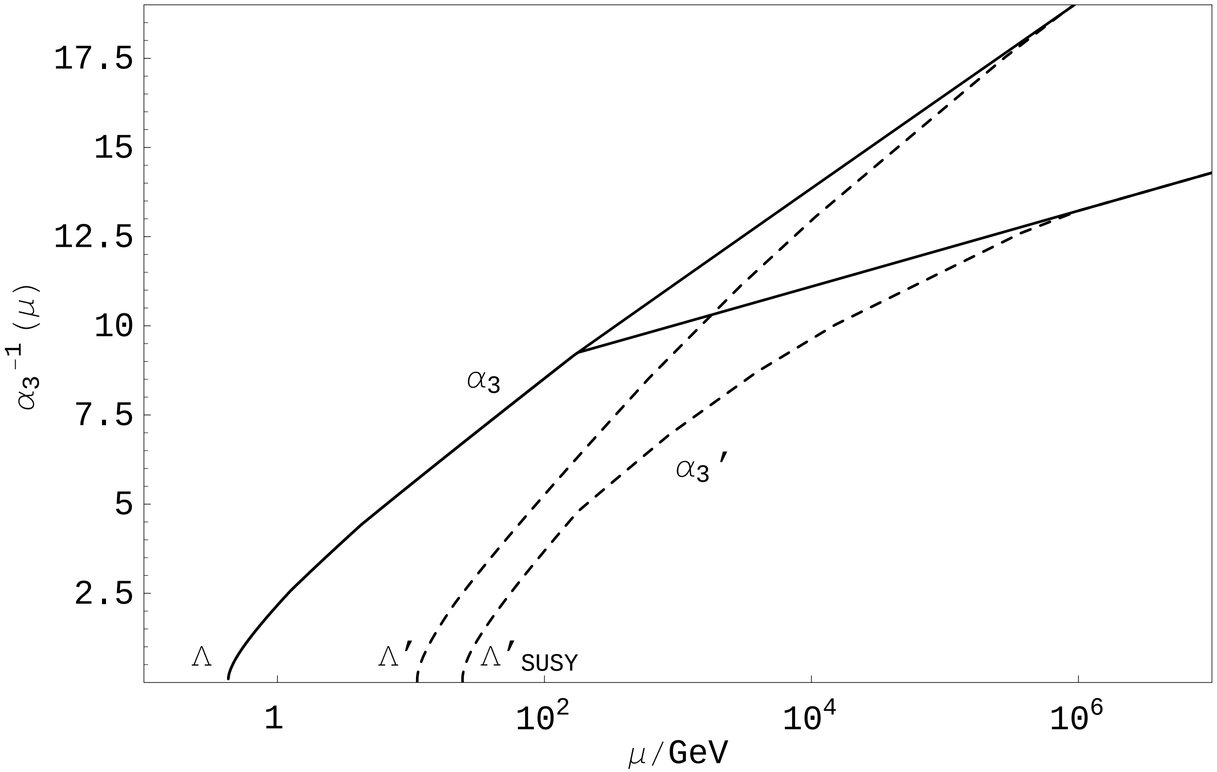


BBN: $x < 0.5 \quad \longrightarrow \quad k \le 4$; LSS: $x < 0.2 \quad \longrightarrow \quad k \le 1.5$

upper limit $\frac{\Omega'_B}{\Omega_B} = \frac{1}{D(k)} < 5 - 10$

$n'_B = n_B$ .... but $M'_B > M_B$

Spont. broken M parity: $v' \gg v$ Z.B., Dolgov & Mohapatra '96



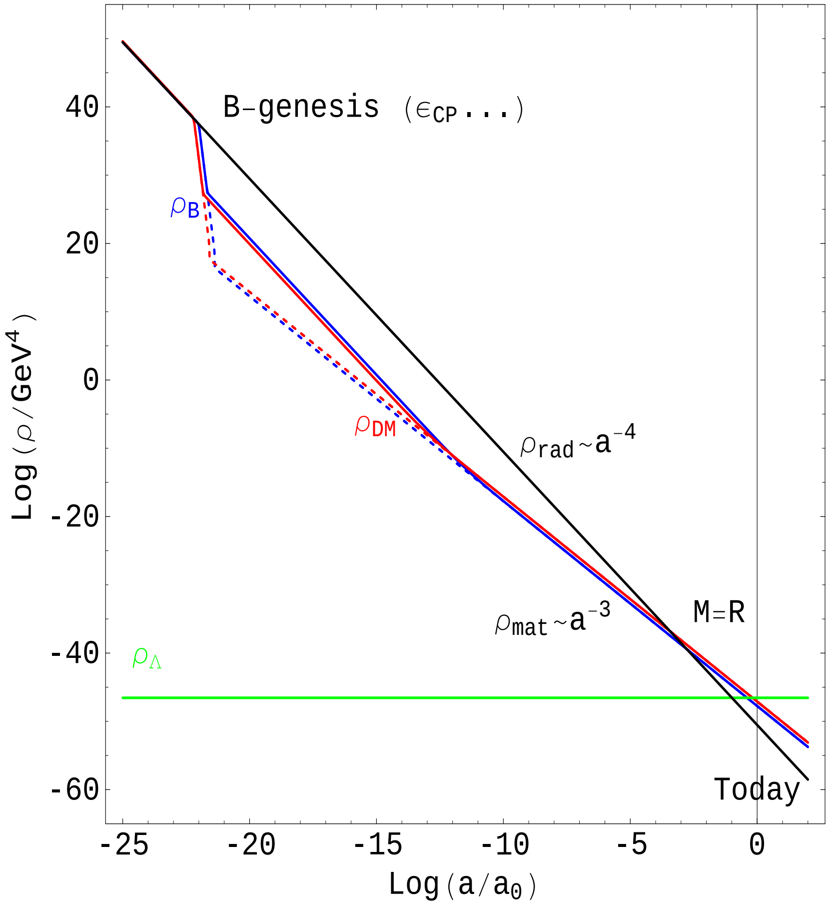
$n'_B \simeq n_B$ $k < 1$ (robust non-equilibrium)

$M'_N/M_N \simeq (\Lambda'/\Lambda)$ changes slowly with M'_W

$m'_e/m_e \simeq M'_W/M_W$ changes fastly with M_W.

– Properties of MB's get closer to CDM : $M'_W \sim 10$ TeV ?

Cogenesis of B & B': unified origin of matter & dark matter

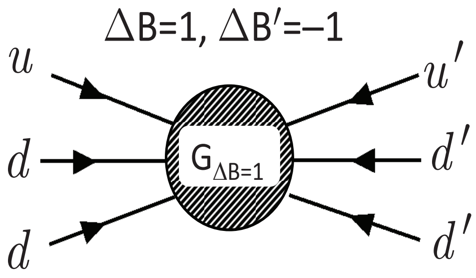


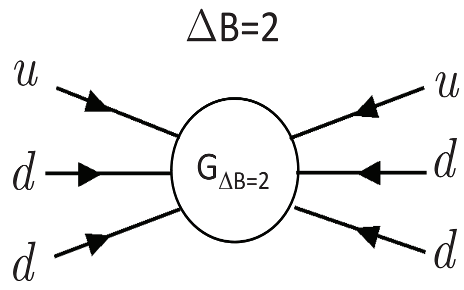
Observable and mirror matter co-genesis:
both based on Baryon asymmetry ....

- *mirror particle masses/properties are similar to baryon ones:* $M'_B = M_B$
- *Dark & B asymmetries are generated by one process and* $n'_B \geq n_B$

so that $\dfrac{\rho'_B}{\rho_B} = \dfrac{M'_B n'_B}{M_B n_B} \geq 1$ *- dark gauge sector with B' asymmetry*

Baryon number violating operators: $D = 9$





any neutral particle, elementary or composite, can mix its mass degenerate twin

- baryon - mirror baryon mixings *($n - n'$, $\Lambda - \Lambda'$ etc.)* ZB, Bento, '05

  $\frac{1}{M^5}(udd)(u'd'd')$, six-fermion interaction $(\Delta B = 1, \Delta B' = 1)$

  - *6-fermion operators* $\frac{1}{M^5}(udd)^2$ $(\Delta B = 2)$,

  inducing neutron - antineutron mixing Kuzmin '70, Glashow '79

  Marshak & Mohapatra '80

$\tau_{n\bar{n}} > 10^8$ s $\tau_{nn'} = ?$

$n - n'$ oscillation: surprising possibility

PRL **96,** 081801 (2006) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2006

Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?

Zurab Berezhiani[1,*] and Luís Bento[2,†]

[1]*Dipartimento di Fisica, Università di L'Aquila, I-67010 Coppito, AQ, Italy and Laboratori Nazionali del Gran Sasso, INFN, I-67010 Assergi, AQ, Italy*

[2]*Faculdade de Ciências, Centro de Física Nuclear da Universidade de Lisboa, Universidade de Lisboa, Avenida Professor Gama Pinto 2, 1649-003 Lisboa, Portugal*

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We discuss the phenomenological implications of the neutron (n) oscillation into the mirror neutron (n'), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal n-n' oscillation in vacuum with a characteristic time τ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular, for the propagation of ultra high energy cosmic rays.

Experimental & astrophysical bounds

- ILL experiment for $n - \tilde{n}$ oscillation search in flight: $t \simeq 0.1$ s, $B < 10^{-4}$G
  – no $\tilde{n}$ event found, $\tau_{n\tilde{n}} > 0.86 \times 10^8$ s $(\sim 3$ yr$)$ *Baldo Ceolin et al. '94*

  as for $n - n'$: about 5% neutron deficit was observed, so taking $P_{nn'}(t) \simeq (t/\tau_{nn'})^2 < 10^{-2}$: $\tau_{nn'} > 1$ s
- $n - n'$ – anomalous UCN loses, $\eta < 2 \cdot 10^{-6}$: $\tau_{nn'} > 0.2$ s
- Nuclear Stability: no limit for $\tau_{nn'}$
- BBN bound: $\tau_{nn'} > 1$ s , neutron star stability: $\tau_{nn'} > 10^{-2}$ s

Experimental sensitivities were analyzed Pokotilovsky, Phys.Lett. B639, 214 (2006)

Recent Experimental search: comparing the neutron losses at different B

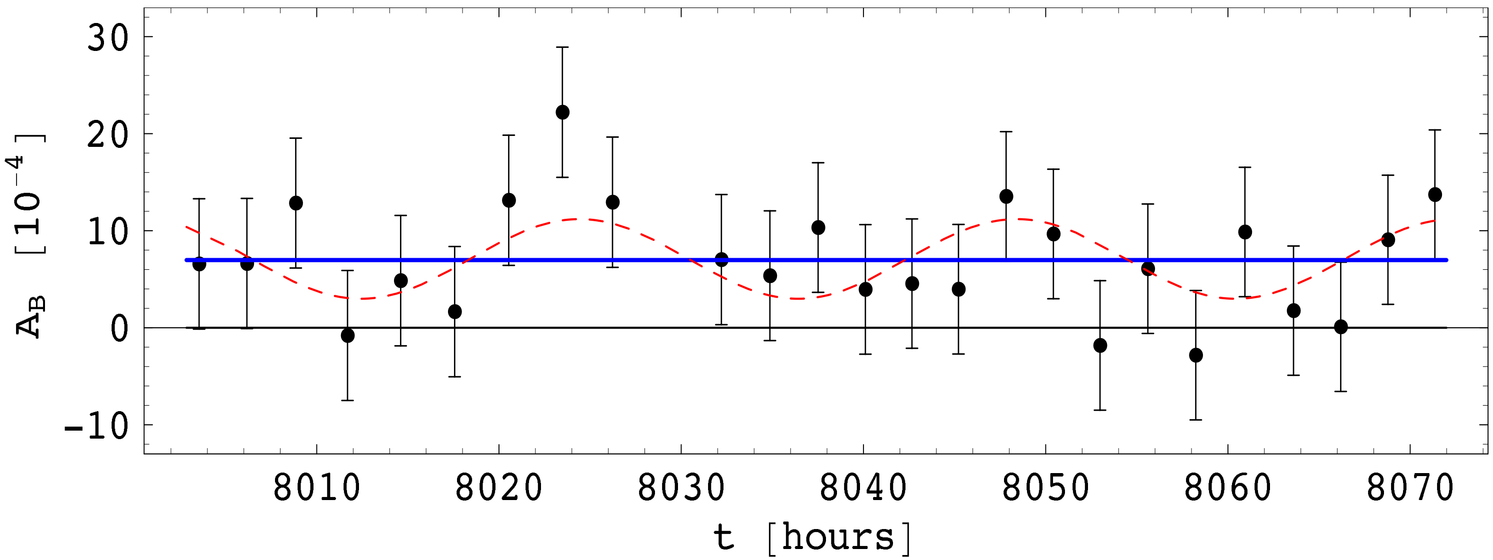
FR Munich, Schmidt et al. Procs. B&L-violation'07, Berkeley
ILL Grenoble, Ban et al. Phys.Rev.Lett. 99, 161603 (2007)
ILL Grenoble, Serebrov et al. Phys.Lett. B663, 181 (2008)
ILL Grenoble, Altarev et al. Phys.Rev. D 80, 032003 (2009)
ILL Grenoble, Bodek et al. NIM A611, 141 (2009)
ILL Grenoble, Serebrov et al. NIM A611, 137 (2009)

$\tau_{nn'} > 414$ s if $B' = 0$ – not valid if $B' > 1$ mG (or $V' \neq V$)

Can be origin of discrepancy between neutron lifetime measurements

Measurements in vertical magnetic field

Measurements of asymmetry $A = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$, *where* $\nu t_s \approx 4000$



- at $B \simeq 0.2$ G : $A_B = (7.0 \pm 1.3) \times 10^{-4}$ $(\chi^2_{\rm dof} = 0.9)$ (5.2σ)

– calibration in free flow mode show no evidence for systematic effects

- at $B \simeq 0.4$ G : $A_B = (-0.3 \pm 2.4) \times 10^{-4}$ Resonance ?

Points to $n - n'$ oscillation with $\tau_{nn'} = 2 - 10$ s and $B' \simeq 0.1$ G

Other experiments also indicate about 3σ anomalies about $B \sim 0.1$ G

Neutron - Mirror neutron mixing

- $n - n'$ oscillation in vacuum: maximal mixing $\theta = 45°$

and oscillation time $\tau_{nn'} = \epsilon^{-1} \sim \left(\frac{\mathcal{M}}{10\,\mathrm{TeV}}\right)^5 \times 1\,\mathrm{s}$

$$P_{nn'}(t) = \sin^2\left(\frac{t}{\tau_{nn'}}\right) \times \exp\left(-\frac{t}{\tau_{\mathrm{dec}}}\right)$$

... can be fast, $\tau_{nn'} \sim 1\mathrm{s}$ ... faster then neutron decay, $\tau_{\mathrm{dec}} = 880$ s

... similar to neutron - antineutron oscillation but limits on $n - \bar{n}$ *are strong:*

Direct experimental Search: $\tau_{n\bar{n}} > 0.86 \times 10^8$ s Baldo Ceolin et al., '95

Nuclear stability: $\tau_{n\bar{n}} > 1.3 \times 10^8$ s PDG '2011

c.f. $\tau_p > 10^{33}$ *yr (!!) for proton decay* $(\Delta B = 1)$

!!! N.B. Nuclear Stability

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

$\tau_{n\tilde{n}} > 10^8$ s or so ...

- $n - n'$ does not: $(A, Z) \to (A-1, Z) + n'$ forbidden

for stable nuclei by energy conservation ! – no restriction for $\tau_{nn'}$!

Neutron - Mirror neutron oscillation in external fields

Effective (non-relativistic) 4×4 Hamiltonian for $n - n'$ oscillation

$$H = \begin{pmatrix} m + V_{\rm g} + V_{\rm m} - i(\frac{\Gamma}{2} + W_{\rm m}) + \mu \vec{B}\vec{\sigma} & \epsilon + \mu_\epsilon(\vec{B} + \vec{B}')\vec{\sigma} \\ \epsilon + \mu_\epsilon(\vec{B} + \vec{B}')\vec{\sigma} & m' + V'_{\rm g} + V'_{\rm m} - i(\frac{\Gamma'}{2} + W'_{\rm m}) + \mu' \vec{B}'\vec{\sigma} \end{pmatrix}$$

- Exact mirror parity: $m' = m$, $\Gamma' = \Gamma$, $\mu' = \mu = -1.91\mu_N$
- Grav. potentials $V'_{\rm g} = V_{\rm g}$, but not in bi-gravity — ZB, Pilo, Rossi, 09
- but there are magnetic fields: $\vec{B}' \neq \vec{B}$: at Earth $B \simeq 0.5$ G

In magnetic fields $\vec{B}$ and $\vec{B}'$, the oscillation probability becomes ($\mu_\epsilon = 0$)

$$P(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2}\cos^2\frac{\beta}{2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}\sin^2\frac{\beta}{2},$$

ZB, EPJ C64, 421 (2009)

$\omega = \frac{1}{2}|\mu B|$, $\omega' = \frac{1}{2}|\mu B'|$, β *angle between* $\vec{B}$ *and* $\vec{B}'$.

Energy gap $\omega = \frac{1}{2}|\mu B| = B[\mathrm{G}] \times 3 \cdot 10^{-12}\ \mathrm{eV} = 4500\ \mathrm{s}^{-1}$

At the resonance, $B = B'$, when $\omega t \ll 1$: $P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2\frac{\beta}{2}$,

$\tau_{nn'} = \epsilon^{-1}$

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$\tau_{nn'} > 414$ s if $B' = 0$ – not valid if $B' > 1$ mG (or $V' \neq V$)

Can be origin of discrepancy between neutron lifetime measurements

Experimental strategy for searching $n \to n'$

Coherent neutron interaction with matter gives "optical" potential $V \sim \text{few} \times 10^{-7}$ eV. Thus, if $V > 0$, ultra-cold neutrons (UCN) with $E_{\text{kin}} < V$. i.e. $v <$ few m/s are reflected from the surface.

Thus, the UCN can be stored in the trap (e.g. beryllium or nickel). The material wall of the trap acts as a potential well

If in the trap, during a free flight ($t_f \sim 0.1$ s) between the wall collisions n oscillates to n', than it each wall collision it disappears from the trap with a mean probability $P(\vec{B})$

$$\frac{dN}{dt} = \Gamma_{\text{eff}} N \quad \to \quad N(t) = N(0) \times e^{-\Gamma_{\text{eff}} t}$$

$\Gamma_{\text{eff}} = \Gamma_{\text{dec}} + \eta_{\text{loss}}\nu + P(\vec{B})\nu$, $\nu = 1/t_f \sim 10$ s^{-1} collision frequency.

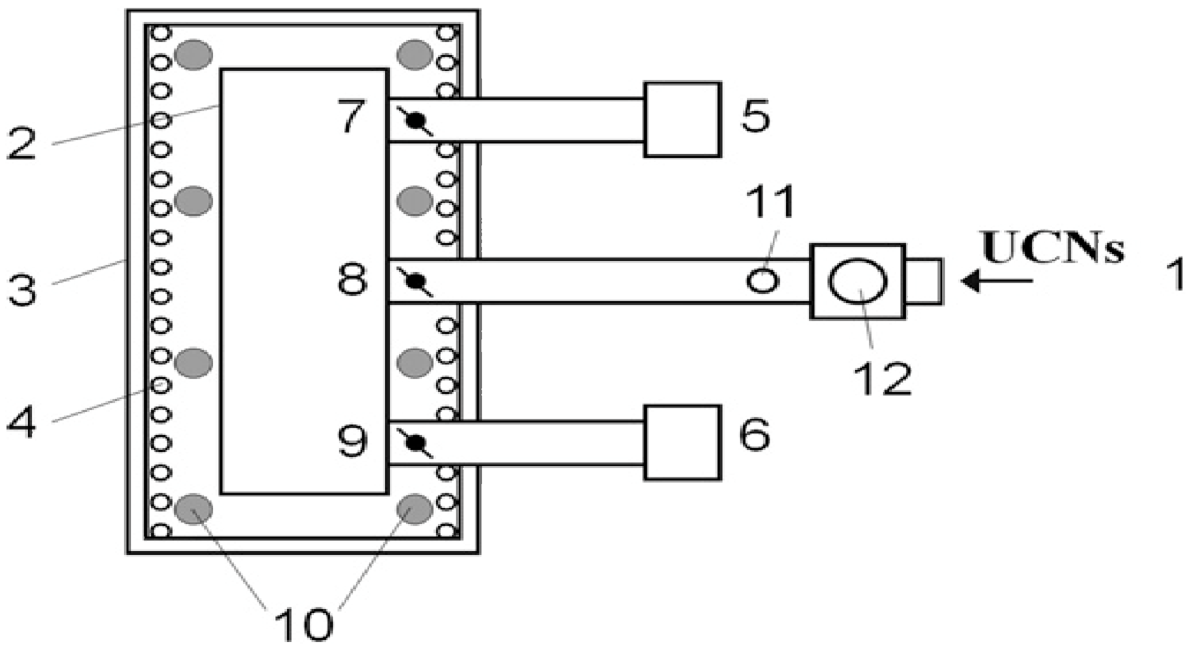
For different magnetic fields $\vec{B}_1$ and $\vec{B}_2$, all regular (B-independent) contributions as well as $N(0)$ cancel out in the ratio $\frac{N_1(t)}{N_2(t)} = \frac{N(0)e^{-\Gamma_{1\text{eff}} t}}{N(0)e^{-\Gamma_{2\text{eff}} t}} = e^{-(P_1-P_2)\nu t}$

Up down asymmetry $A_B = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx (D_B \cos\beta)\nu t_s$,

On-off asymmetry $E_{Bb} = \frac{N_{\vec{B}} + N_{-\vec{B}}}{N_{\vec{b}} + N_{-\vec{b}}} - 1 \approx (P_B - P_b)\nu t_s$,

2-nd experiment of Serebrov

ILL Grenoble, Serebrov et al. NIM A611:137 (2009)



Comparing the losses for different magnetic fields in the UCN trap, Volume = 190 l, two detectors and monitor in the guide (PF2 EDM).

Up down asymmetry measured $A = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s,$

$\nu \approx 11$ s^{-1} *collision frequence,* $t_s = 370$ s *holding time,* $\nu t_s \approx 4000$

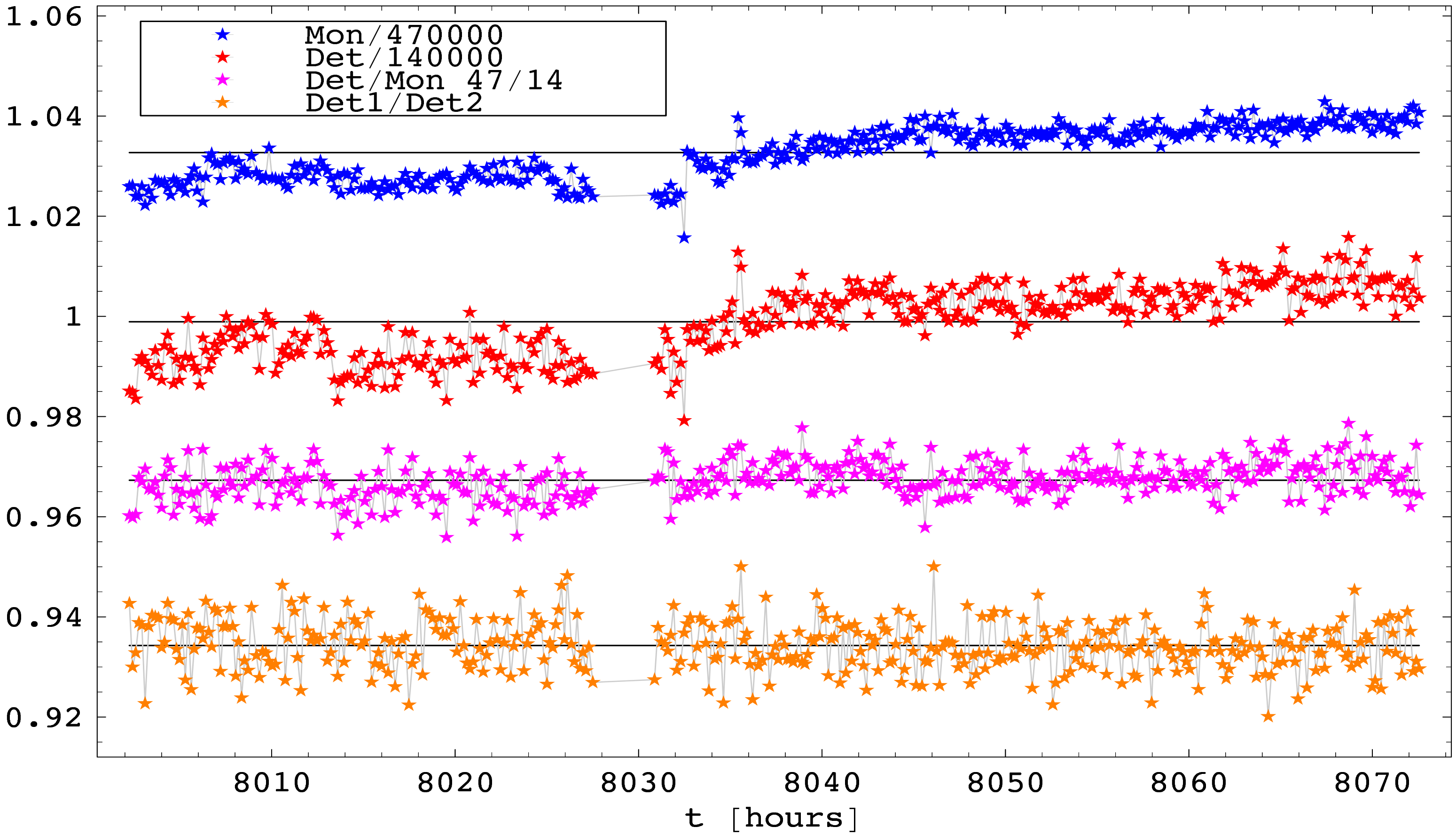
repeating sequence $B_+, B_-, B_-, B_+; B_-, B_+, B_+, B_-$

– eliminating the linear and quadratic drifts of the neutron flux $\sim 2\%$

- 3σ *deviation reported:* $A = (3.8 \pm 1.2) \cdot 10^{-4}$ *(*$B \simeq 0.2$ *G & $B \simeq 0.4$ G)*

We critically reanalized these experimental data ...

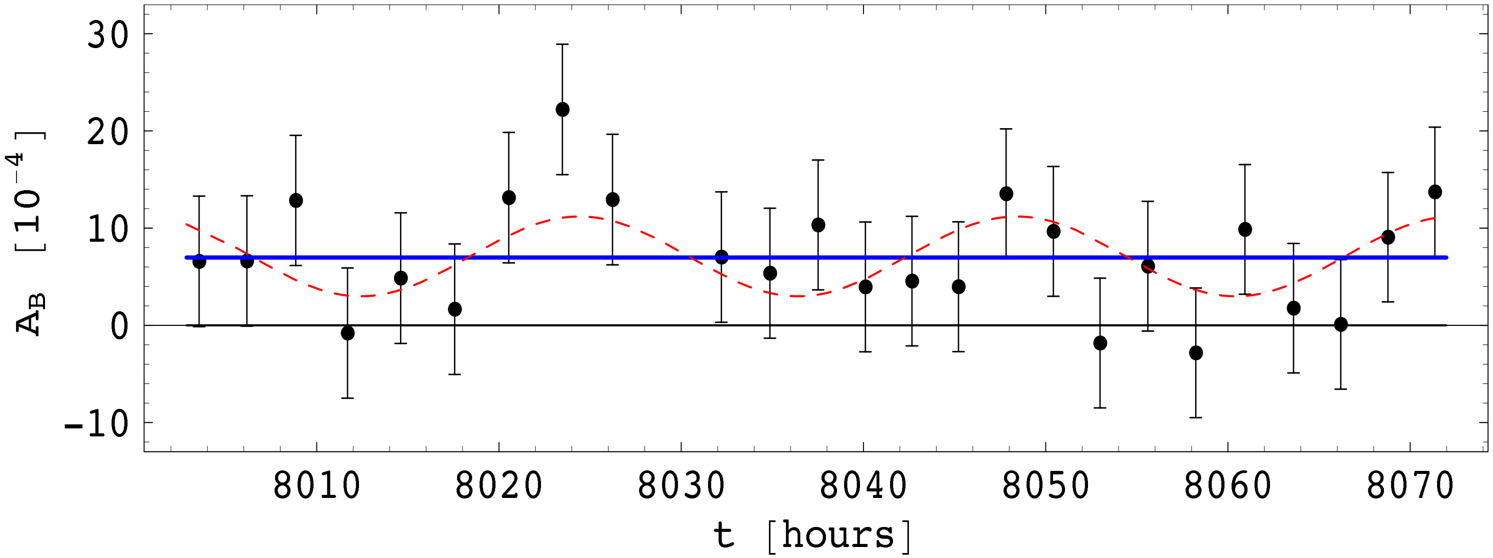
Z.Berezhiani, Nesti, *Magnetic anomaly in UCN trapping: signal for neutron oscillation to parallel world?* Eur. Phys. J. 72, 1974 (2012)



Det/Mon = Const $\chi^2_{\rm dof} = 1.4$ Det1/Det2 = Const $\chi^2_{\rm dof} = 1.0$

Measurements in vertical magnetic field

Measurements of asymmetry $A = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$, *where* $\nu t_s \approx 4000$



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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 small, within the present experimental reach. However, it requires collaboration of $\Delta B = 2$ processes like $udd \to \bar{u}\bar{d}\bar{d}$ – (neutron-antineutron $n - \tilde{n}$ oscillation, $\Lambda - \tilde{\Lambda}$, etc.). These processes 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 $n - \tilde{n}$ oscillation should also exist at the experimentally accessible level – (see talk of Y. Kamyshkov) with the relevant cutoff scale $\mathcal{M}_{n\tilde{n}} > 300$ 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 spectrum above the GZK cutoff and their correlation with the far distant astrophysical objects (BL Lacs, GRB's etc.)* *ZB and Gazizov, ArXiv*
- *Effects for the neutrons from the solar flares* *Mohapatra, Nasri, Nussinov '05*

Cosmic rays and GZK cutoff

K. Greisen, End to the cosmic ray spectrum?, Phys. Rev. Lett. 16, 748 (1966).
G. Zatsepin, V. Kuzmin, Upper limit on the spectrum of cosmic rays, JETP Lett. 4, 78 (1966).

GZK cutoff:

Photo-pion production on the CMB if $E > E_{\rm GZK} \approx \frac{m_\pi m_p}{\varepsilon_{\rm CMB}} \approx 6 \times 10^{19}$ eV :

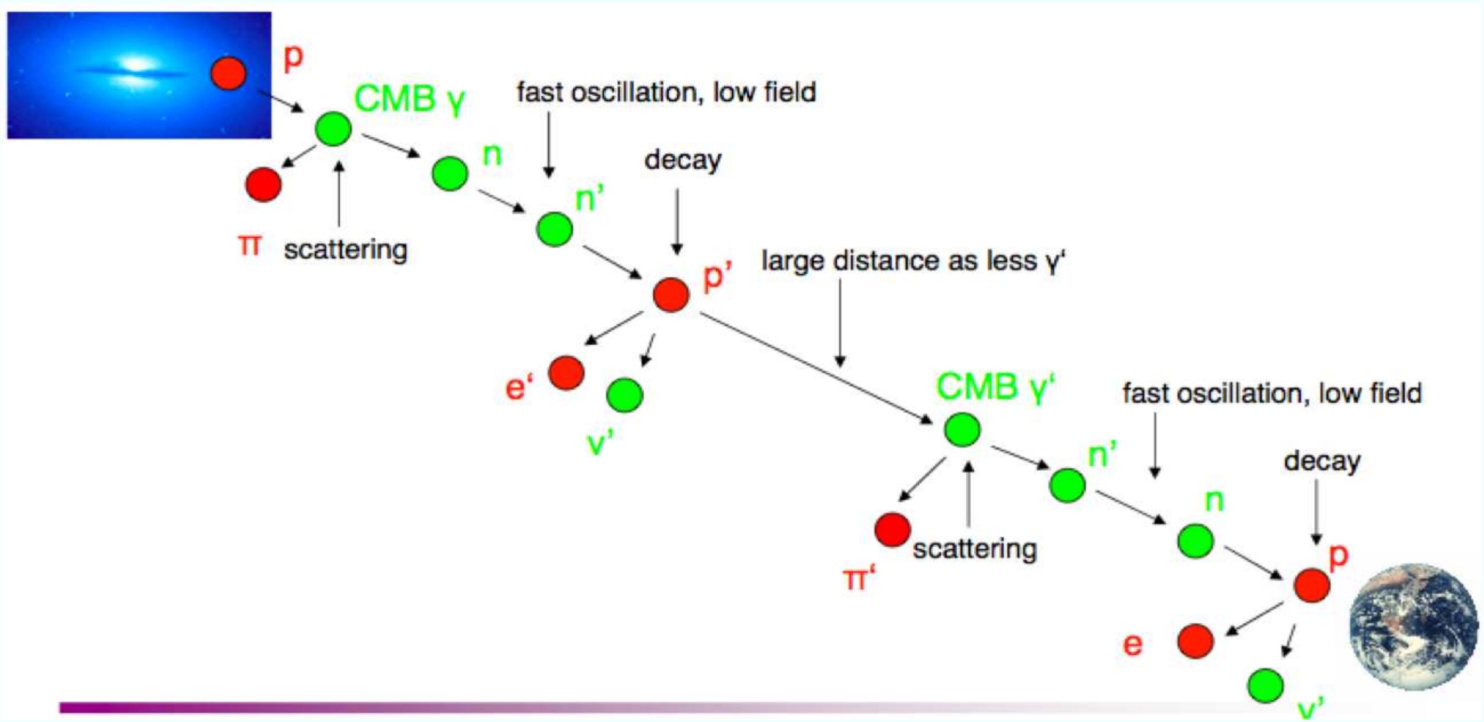
$p + \gamma \to p + \pi^0$ (or $n + \pi^+$), $\quad l_{\rm mfp} \sim 5$ Mpc for $E > 10^{20}$ eV $= 100$ EeV

Neutron decay: $n \to p + e + \bar{\nu}_e$, $\quad l_{\rm dec} = \left(\frac{E}{100 \text{ EeV}}\right)$ Mpc

Neutron on CMB scattering: $n + \gamma \to n + \pi^0$ (or $p + \pi^-$)

Presence of $n - n'$ oscillation with $\tau_{\rm osc} \ll \tau_{\rm dec}$ drastically changes situation

$n - n'$ oscillation and propagation of UHECR



Z. Berezhiani, L. Bento, Fast neutron – Mirror neutron oscillation and ultra high energy cosmic rays, Phys. Lett. B 635, 253 (2006).

A. $p+\gamma \to p+\pi^0$ or $p+\gamma \to n+\pi^+$ $\quad P_{pp,pn} \approx 0.5 \quad l_{\rm mfp} \sim 5$ Mpc

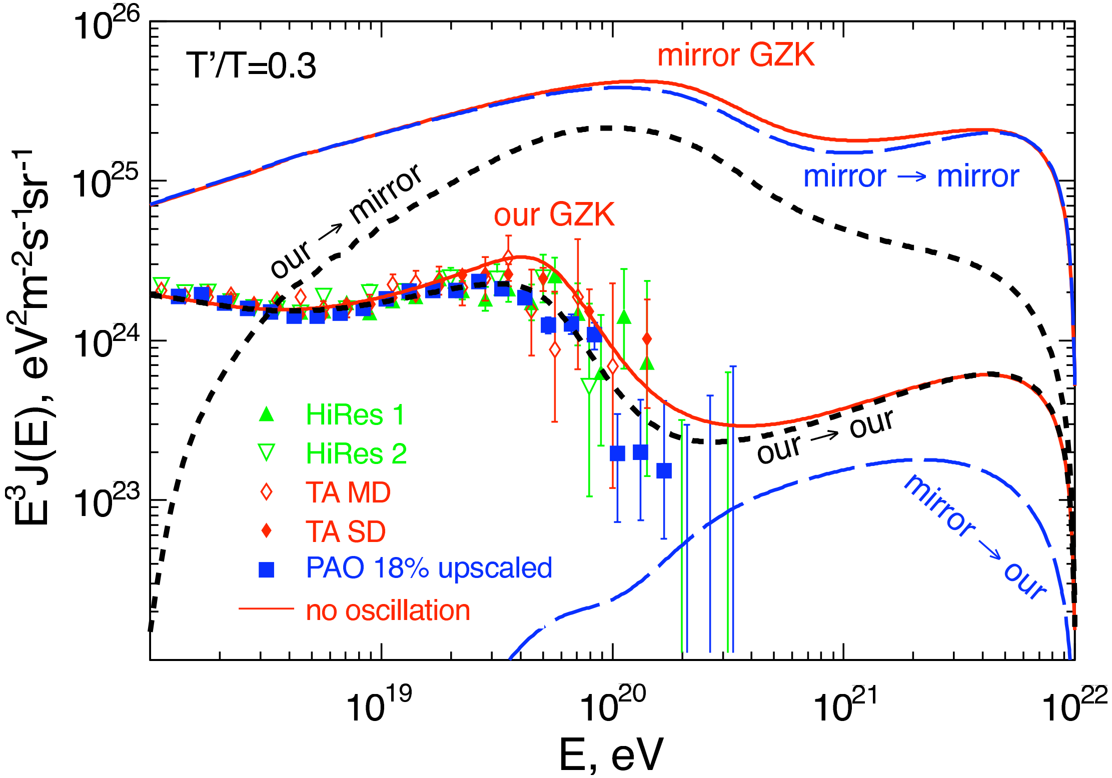
B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100\ \rm EeV}\right)$ kpc

C. $n' \to p' + e' + \bar{\nu}'_e \quad l_{\rm dec} \approx \left(\frac{E}{100\ \rm EeV}\right)$ Mpc

D. $p'+\gamma' \to p'+\pi'^0$ or $p'+\gamma' \to n'+\pi'^+ \quad l'_{\rm mfp} \sim (T/T')^3\, l_{\rm mfp} \gg 5$ Mpc

$n - n'$ oscillation and the UHECR spectrum

Z. Berezhiani, A. Gazizov, Neutron Oscillations to Parallel World: Earlier End to the Cosmic Ray Spectrum?, Eur. Phys. J. 72, 2111 (2012)



UHECR flux with $n - n'$ oscillation relative to the standard GZK prediction (normalized to "dip" model) for UHECR from ordinary and mirror sources

Auger observes cutoff of the spectrum at $E \simeq 30$ EeV, earlier than expected by GZK mechanism, $E \simeq 60$ EeV

Positive predictions for energies at $E > 100$ EeV (JEM-EUSO)

Concluding: *If this anomaly will be confirmed ...*

– Need for new $n \to n'$ exps. with bigger statistics and careful systematics

proposal for 4 month exp. with PF2 EDM submitted to ILL

but experiments need ~ 100 kEuros (at the ILL or somewhere else)? Then, if

- *search for $n \to n' \to n$ regeneration,*
- *or Lorentz-violation in the neutron precession – (B-dependent corrections to μ_n)*

are positive .... $n - n'$ oscillation – window to parallel world !! Fundamental for particle physics, astrophysics and cosmology, and even for geophysics.... News:

- *Who is dark matter, its nature, its detection, identity of sterile ν's*
- *Primordial co-genesis of matter and dark matter: $\Omega_{B'} \sim 5\Omega_B$*
- *impact for Big Bang Nucleosynthesis, CMB and cosmological structure formation*
- *Dark matter in Galaxies: Halo as mirror elliptic galaxy, Machos, dark supernove*
- *Dark matter capture by the solar system and the Earth ...*
- *origin of magnetic fields in galaxies, stars and even planets ? ...*
- *$n - n'$ in cosmic rays, in solar flares, at the BBN, in neutron stars, etc.*
- *Other Ordinary - mirror particle oscillations: e.g. $\Lambda \to \Lambda'$, $K \to K'$, ...*
  or for hydrogen atom $\mathrm{H} \to \mathrm{H}'$, etc. + regeneration
  but also particle- antiparticle oscillations $n \to \tilde{n}$, $\Lambda \to \tilde{\Lambda}$, $\mathrm{H} \to \tilde{\mathrm{H}}$ etc.
- *underlying TeV scale physics can be tested at the LHC and meson factories*
- *..... can provide a free source of energy ?* A. Asimov, "The Gods Themselves"

More than 1 parallel worlds ?? *(lke in R. Sheckley's "Mind exchanges")*