Challenges of Light Dark matter: What, Why, Which, Where, When, and How ?

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Contents

Cosmic Concordance and Dark Side of the Universe

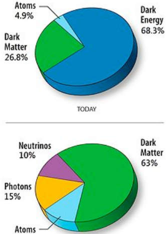
Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* and multi-component:

- $\Omega_B \simeq 0.05$ 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? ....
- $\Omega_R < 10^{-3}$ relativistic fraction: relic photons and neutrinos

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?*



Baryogenesis requires BSM Physics:
(GUT-B, Lepto-B, Affleck-Dine, EW B ...)
Dark matter requires BSM Physics:
(Wimp, Wimpzilla, sterile ν, axion, ...)

Different physics for B-genesis and DM?
Not very appealing: looks as Fine Tuning

Questions to dark matter ...

- Is it related to other fundamental problems requiring new physics?
- Does it match the appropriate relic density ($\Omega_{DM} \simeq 0.25$)? Can it tell why DM and baryon fractions are comparable, $\Omega_B/\Omega_{DM} \simeq 0.2$?
- Is it consistent with astrophysical tests (BBN, CMB, LSS, etc.) ?
- Is it cold (or warm)? Or it can be self-interacting and dissipative ?
- Can it form star like compact objects or massive Black Holes?
- Is it stable? Or it can be decaying with $t \sim 10$ Gyr?
- Is it neutral? Or it can have some tiny electric charges?
- Can it be probed via direct detection? by which detectors?
- Can it be probed by indirect signals, as gamma astronomy, cosmic rays, UHE neutrinos?
- Can it be produced experimentally, at LHC or other facilities?

Dark matter requires new physics

Standard Model has no candidate for dark matter

massive neutrino (~ 20 eV) was a natural "standard" candidate of HDM...
– but in 80's it was excluded by astrophysical observations
and later on directly 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**

In 80's a new *Strada Maestra* was opened – $\mathcal{SUSY}$
– well-motivated theoretical concept promising to be a highway for solving many fundamental problems, brought to a natural and *almost "Standard"* candidate WIMP – **undead, but looks useless**

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

Half-motivated candidate sterile neutrino of keV mass as WDM – **is alive, but of rather poor testability**

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

Apart of exception which I discuss below, and which may resolve the tantalizing question: do baryogenesis and dark matter require two different new physics, or just one can be enough?

Why $\Omega_D/\Omega_B \sim 1$? Or why $m_B \rho_B \sim m_X \rho_X$?

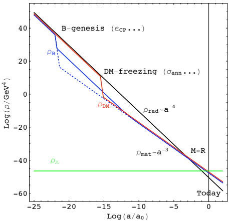
Visible matter from Baryogenesis (*Sakharov*)
B ($B-L$) & CP violation, Out-of-Equilibrium
$\rho_B = m_B n_B$, $m_B \simeq 1$ GeV, $\eta = n_B/n_\gamma \sim 10^{-9}$
η is model dependent on several factors:
coupling constants and CP-phases, particle degrees of freedom, mass scales and out-of-equilibrium conditions, etc.

Dark matter: $\rho_D = m_X n_X$, but $m_X = ?$, $n_X = ?$ and why $m_X n_X = 5 m_B n_B$?
n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

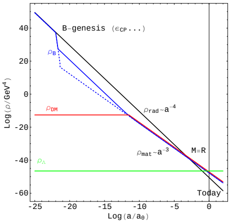
Axion	$m_a \sim 10^{-5}$ eV $n_a \sim 10^4 n_\gamma$ - CDM
Sterile ν'	$m_{\nu'} \sim$ keV $n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
WIMP	$m_X \sim$ TeV $n_X \sim 10^{-3} n_B$ - CDM
WimpZilla	$m_X \sim$ ZeV $n_X \sim 10^{-12} n_B$ - CDM
Mirror baryons	$m_{B'} = m_B$ $n_{B'} = 5 n_B$ - DSIDAAM
Asym. M baryons	$m_{B'} = 5 m_B$ $n_{B'} = n_B$ - DSIDAAM

How these Fine Tunings look ...

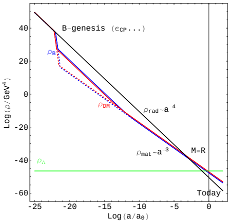
B-genesis + WIMP



B-genesis + axion



B-cogenesis



$m_X n_X \sim m_B n_B$
$m_X \sim 10^3 m_B$
$n_X \sim 10^{-3} n_B$
Fine Tuning?

$m_a n_a \sim m_B n_B$
$m_a \sim 10^{-13} m_B$
$n_a \sim 10^{13} n_B$
Fine Tuning?

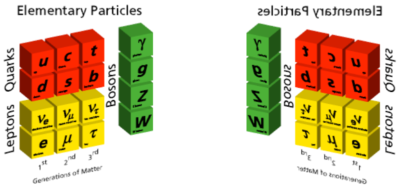
$m_{B'} n_{B'} \sim m_B n_B$
$m_{B'} \sim m_B$
$n_{B'} \sim n_B$
Natural ?

Two different New Physics for B-genesis and DM ?
Or co-genesis by the same Physics explaining why $\Omega_{DM} \sim \Omega_B$?

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

$G \times G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. SM $\times$ SM$'$ or $SU(5) \times SU(5)'$, 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 $\quad \mathcal{L}_{mix}$
- Natural in string/brane theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

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.

$E_8 \times E'_8$

Is existence of mirror world compatible with cosmology ?

For a long while mirror matter was not considered as a real candidate for dark matter: M world was naively taken to have not only exactly identical microphysics as O sector but also exactly identical cosmology:

- $T' = T, \quad g'_* = g_* \quad \to \quad \Delta N_\nu^{\rm eff} = 6.15$ vs. $\Delta N_\nu^{\rm eff} < 0.5$ (BBN)
- $n'_B/n'_\gamma = n_B/n_\gamma \ (\eta' = \eta) \quad \to \quad \Omega'_B = \Omega_B$ vs. $\Omega'_B/\Omega_B \simeq 5$ (DM)

If $x = T'/T \ll 1$, BBN is OK $\quad \to \quad$ Cosmological Paradigm:

(A) at the Big Bang (i.e. after inflation) the M world was born with smaller temperature than O world

(B) all interactions between M and O particles are feeble enough and cannot bring two sectors into equilibrium after reheating

(C) no entropy production by 1st order phase transitions which could heat M world: two systems evolve adiabatically over the universe expansion and their temperature ratio T'/T remains nearly constant.

but then $n'_B/n'_\gamma = n_B/n_\gamma$ and $n'_\gamma/n_\gamma = (T'/T)^3 \quad \Omega'_B/\Omega_B \simeq x^3 \ll 1$!!!

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

However ...

Understanding of astronomy, optics, and physics, a rumor about the four planets seen by the very celebrated mathematician Galileo Galilei with his telescope, shown to be unfounded.

Francesco Sizzi, crlticlsm of Galileo's discovery of the Jupiter's moons

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 concords M matter with WMAP/Planck, BAO, Ly-α etc. if $T'/T < 0.25$ or so.

Halo problem – if $\Omega'_B \simeq \Omega_B$, M matter makes ~ 20 % of DM, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)
But perhaps 100 % ? if $\Omega'_B \simeq 5\Omega_B$: – M world is helium dominated, and the star formation and evolution can be much faster. Halos could be viewed as mirror elliptical galaxies, with our matter inside forming disks.

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

Two 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

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

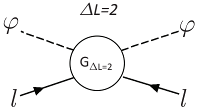
Doubling symmetry $(L,R\to L,R$ parity$)$: $Y'=Y$ $\quad B-B'\to-(B-B')$

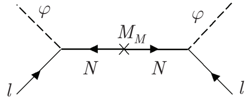
Mirror symmetry $(L,R\to R,L$ parity$)$: $Y'=Y^*$ $\quad B-B'\to B-B'$

Baryogenesis requires new physics:

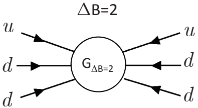
B & L can be violated only in higher order (non-renormalizable) terms

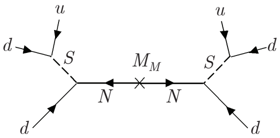
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$





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



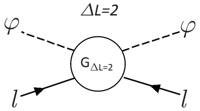


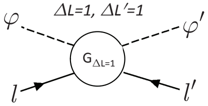
can originate from new physics related to scale $M \gg v_{\rm EW}$ via seesaw

L and B violating operators between O and M particles

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

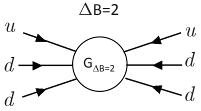
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

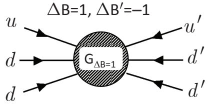




M is the (seesaw) scale of new physics beyond EW scale.
Mirror neutrinos are most natural candidates for sterile neutrinos

- Neutron -mirror neutron mixing – (Active - sterile neutrons) B and B' violating operators: $\frac{1}{M^5}(udd)(udd)$ and $\frac{1}{M^5}(udd)(u'd'd')$





L and L' violating operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ lead to processes $l\phi \to \bar{l}\bar{\phi}$ $(\Delta L = 2)$ and $l\phi \to \bar{l}'\bar{\phi}'$ $(\Delta L = 1,\ \Delta L' = 1)$

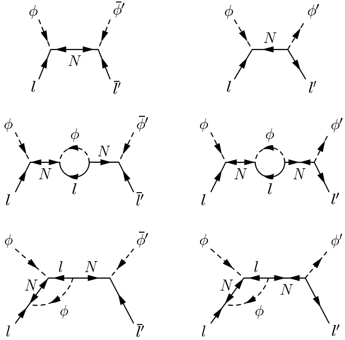
After inflation, our world is heated and mirror world is empty: but ordinary particle scatterings transform them into mirror particles, heating also mirror world.

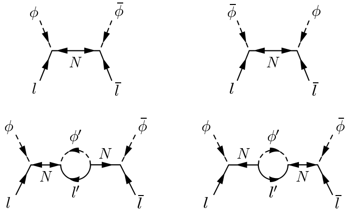
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

Green light to celebrated conditions of Sakharov

Theory of cogenesis: Z.B. and Bento, PRL 87, 231304 (2001)

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 $\frac{1}{2}Mg_{jk}N_jN_k + \mathrm{h.c.}$





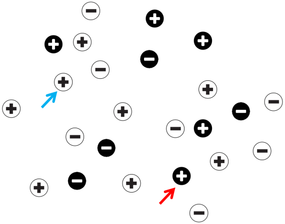
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

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

Cogenesis: Mirror Matter as hidden Anti-Matter

Z.B., arXiv:1602.08599

Hot O World $\longrightarrow$ *Cold M World*



$$\frac{dn_{\rm BL}}{dt} + (3H+\Gamma)n_{\rm BL} = \Delta\sigma\, n_{\rm eq}^2$$

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

$$\sigma(l\phi \to \bar{l}\bar{\phi}) - \sigma(\bar{l}\,\bar{\phi} \to l\phi) = \Delta\sigma$$

$$\sigma(l\phi \to \bar{l}'\bar{\phi}') - \sigma(\bar{l}\,\bar{\phi} \to l'\phi') = -(\Delta\sigma + \Delta\sigma')/2 \quad \to \quad 0 \quad (\Delta\sigma = 0)$$

$$\sigma(l\phi \to l'\phi') - \sigma(\bar{l}\,\bar{\phi} \to \bar{l}'\bar{\phi}') = -(\Delta\sigma - \Delta\sigma')/2 \quad \to \quad \Delta\sigma \quad (0)$$

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

$$\Delta\sigma' = \Delta\sigma(Y \to Y')$$

Mirror (LR): $Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B, B' > 0$

Xerox (LL): $Y' = Y \quad \to \quad \Delta\sigma' = \Delta\sigma = 0 \quad \to \quad B, B' = 0$

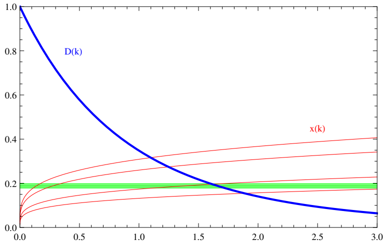
If $k = \left(\frac{\Gamma}{H}\right)_{T=T_R} \ll 1$, neglecting Γ in eqs $\quad \to \quad n_{BL} = n'_{BL}$

$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ \mathrm{GeV}}\right)^3 \left(\frac{10^{13}\ \mathrm{GeV}}{M}\right)^4$$

If $k = \left(\frac{\Gamma_2}{H}\right)_{T=T_R} \sim 1$, Boltzmann Eqs.

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

should be solved with Γ:



$D(k) = \Omega_B/\Omega'_B$, $\qquad x(k) = T'/T$ for different $g_*(T_R)$ and Γ_1/Γ_2.

So we obtain $\Omega'_B = 5\Omega_B$ when $m'_B = m_B$ but $n'_B = 5n_B$

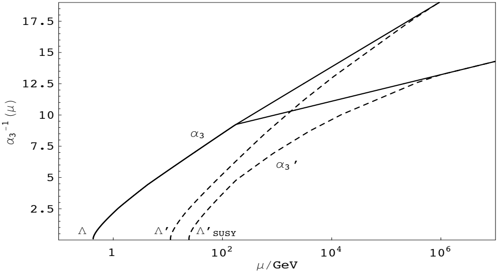
– the reason: mirror world is colder

$\Omega'_B \simeq 5\Omega_B$ when $n'_B = n_B$ but $m'_B = 5m_B$

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

broken M parity: $v'/v \sim 10^2$ $\quad v' \sim 10$ TeV, $v \sim 100$ GeV

Z.B., Dolgov & Mohapatra '96



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

$M'_N/M_N \sim (\Lambda'/\Lambda) \sim (v'/v)^{0.3} \sim 5$ –- $M_N \sim 5$ *GeV*

$m'_e/m_e \sim v'/v \sim 10^2$ – $m'_e \sim 100$ *MeV*

– Properties of MB's get closer to CDM : but also WDM from mirror neutrinos ?

$m'_\nu/m_\nu \simeq (v'/v)^2 \sim 1$ *keV*

Spontaneous M-parity breaking: $v' \gg v$

can be used for solving "little hierarchy problem" – "Twin Higgs" mechanism

SUSY Twin Higgs using M sector — Z.B., 2005, Alice adventures ...
Without SUSY, adjusted ad hoc — Chacko, Goh, Harnik, 2006, PRL
SUSY twin Higgs using L-R model — Falkowski, Pokorski, Schmalz, 2007

SUSY Twin Higgs

$SU(2) \times U(1) \times SU(2)' \times U(1)'$ – Gauge symmetry of two sectors

Mirror Z_2 symmetry gives automatic global symmetry $U(4)$ in Higgs sector – consider superpotential
$W = \lambda S(H_1 H_2 + H_1' H_2' + mS - \Lambda^2) + ...\qquad + g^2(D^2 + D'^2)$
Take $\Lambda \sim 10$ TeV and assume that SUSY breaking spurion $\eta = M_S \theta^2$ is odd against Xerox symmetry, $\eta \to -\eta$.

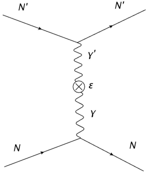
H' Higgses get VEVs $v' \sim 10$ TeV, H Higgses remain pseudo-Goldstone, then getting VEVs $v \sim 100$ GeV from SSB terms
M sector – Standard Model with $m_e' \sim (v'/v) m_e$ but $m_{p,n}' \simeq 5 m_{p,n}$ ($\Lambda'_{\rm QCD}/\Lambda_{\rm QCD}$ rescales softer with v'/v)
Dark matter can be very compact hydrogen or helium-like atoms from M sector, or even neutrons if $m_p' > m_n'$ ($\tan\beta' \neq \tan\beta$)

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

- 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 ($q \sim \epsilon$)
A promising portal for DM direct detection Foot, 2003

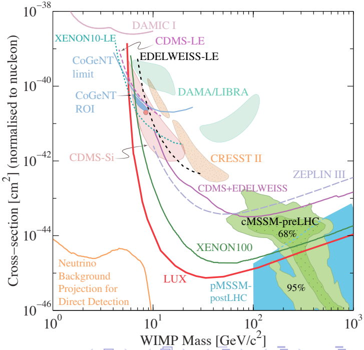


Mirror atoms: He' – 75 %, C',N',O' etc. few %
Rutherford-like scattering

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

or

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



Inducing magnetic field via the electron drag mechanism

Detection possibility of Mirror matter via photon kinetic mixing was recently studied in all details in two works with DAMA Collaboration
For asymmetric M matter, 2015   For exact M matter, 2017

Rutherford-like scattering with mirror matter due to photon-mirror photon kinetic mixing. Relative motion (rotation) of O and M matter

flows drags electrons but not 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 magnetic seed $B, B' \sim 10^{-15}$ G before dynamo, then amplified by dynamo

Such mechanism can induce magnetic fields $\sim \mu$G in very young galaxies
Z.B., Dolgov, Tkachev, 2013

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

a deviation about gauge flavor symmetries

$SU(3)_q\times SU(3)_u\times SU(3)_d\times SU(3)_l\times SU(3)_e$ *without anomalies*

$q_L\sim 3_q,\quad l_L\sim 3_l;\qquad \bar u_L\sim 3_u,\ \bar d_L\sim 3_d,\quad \bar e_L\sim 3_e$

$\bar q_R\sim \bar 3_q,\quad \bar l_R\sim \bar 3_l;\qquad u_R\sim \bar 3_u,\ d_R\sim \bar 3_d,\quad e_R\sim \bar 3_e$

$q'_L\sim \bar 3_q,\quad l'_L=\bar 3_l;\qquad \bar u'_L\sim \bar 3_u,\ \bar d'_L\sim \bar 3_d,\quad \bar e'_L\sim \bar 3_e$

$\bar q'_R\sim 3_q,\quad \bar l'_R=3_l;\qquad u'_R\sim 3_u,\ d'_R\sim 3_d,\quad e'_R\sim 3_e$

Mirror parity $(L,R\to R,L)$: flavon superfields $\chi_L\to\chi_R=(\bar\chi_L)^+$

$$W=\frac{1}{M}(\bar u\chi_u q\bar\phi\ +\ \bar d\chi_d q\phi\ +\ \bar e\chi_e l\phi)+\text{h.c.}$$
$$W'=\frac{1}{M}(\bar u'\bar\chi_u q'\bar\phi'+\bar d'\bar\chi_d q'\phi'+\bar e'\bar\chi_e l'\phi')+\text{h.c.}$$

$\chi_u\sim(\bar 3_u,\bar 3_q),\quad \bar\chi_u\sim(3_u,3_q)\quad \frac{\chi_u}{M}\to Y_u$, etc.

Quark & lepton Yukawa (mass and mixing) structures is determined by the pattern and hierarchy of flavon VEVs $\langle\chi\rangle$ Z.B. 1982-83

Mirror parity and MFV

• 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

$\tilde{m}_d^2 = m_0^2 + m_1^2(Y_d^\dagger Y_d) + m_2^2(Y_d^\dagger Y_d)^2$, etc. Z.B. 1996, Anselm, Z.B., 1997

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

$F-$terms can be easily handled
gauge $D-$ terms give problems
Flavon superpotential: $W_H = \mu\chi\bar{\chi} + a\chi^2 + a^*\bar{\chi}^3 +$ h.c.
$\rightarrow$ D-terms vanish because of mirror parity

If flavour symmetry $SU(3) \times \ldots$ is shared between two sectors:

• Anomaly cancellation of between ordinary and mirror fermions

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

• Interesting phenomena mediated by flavor gauge bosons: e.g. flavor violating $e\bar{\mu} \rightarrow \bar{e}'\mu'$ disappearance of muonium), etc.

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

So called Natural 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

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 $M^2_{\rm SUSY} \sim (1~{\rm TeV})^2$

– but for it we have mirror (twin) Higgs mechanism

Experimental and observational manifestations of exactly mirror matter

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 $\Omega'_B/\Omega_B = 1 \div 5$.

The Mass Mixing $\epsilon(nCn' + \mathrm{h.c.})$ 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 $B - B'$

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

Key observation: *$n - n'$ oscillation cannot destabilise nuclei:* *$(A,Z) \to (A-1,Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation*

Surprisingly, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{nn'} \sim 1$ s, without contradicting any experimental and astrophysical limits. (c.f. $\tau_{n\bar{n}} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)
Disappearance $n \to \bar{n}'$ (regeneration $n \to \bar{n}' \to n$) can be searched at small scale 'Table Top' experiments

Summary

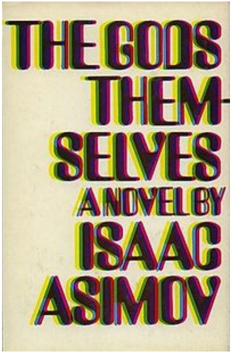
But $n' \to \bar{n}$ produces appearance of our antimatter from dark mirror matter – with a lot of interesting cosmological implications for UHECR, AMS 2 and PAMELLA, INTEGRAL positron excess, Primordial Lithium problem, etc.

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 anti-hydrogen, etc.

Two civilisations can agree to built scientific reactors and exchange neutrons ... and turn the energy produced by each reactor in 1000 times

Appendix



First Part: Against Stupidity ...

Second Part: ...The Gods Themselves ...

Third Part: ... Contend in Vain?

"Mit der Dummheit kämpfen Götter selbst vergebens!" – Friedrich Schiller

Backup

Backup

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

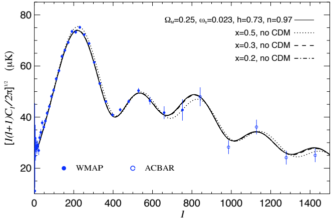
$CP\ (\Psi_L \to \bar{\Psi}_R)$ broken by complex Yukawas $Y = Y_{ij}^{u,d,e}$

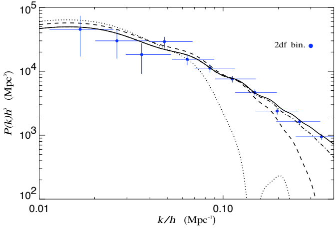
$$(\bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi) + (u_R Y_u^* \bar{q}_R \phi + d_R Y_d^* \bar{q}_R \bar{\phi} + e_R Y_e^* \bar{l}_R \bar{\phi})$$

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

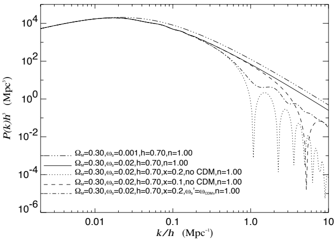
Good for our stability, Bad for baryogenesis

CMB and LSS power spectra





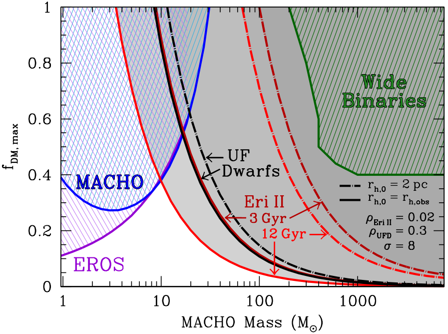
Z.B., Ciarcelluti, Comelli, Villante, 2003



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

Can Mirror stars be progenitors of gravitational Wave bursts GW150914 etc. ?

Picture of Galactic halos as mirror ellipticals (Einasto density profile), O matter disk inside (M stars = Machos).
Microlensing limits: $f \sim 20 - 40$ % for $M = 1 - 10\ M_\odot$,
$f \sim 100$ % is allowed for $M = 20 - 200\ M_\odot$ but see Brandt '05



Three events without any optical counterpart

Points towards massive BH compact binaries, $M \sim 10 - 30\ M_\odot$ and radius $R \sim 10 R_\odot$

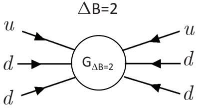
How such objects can be formed ?

M matter: 25 % Hydrogen vs 75 % Helium: M stars more compact, less opaque, less mass loses by stellar wind and evolving much faster. Appropriate for forming such BH binaries ?

Neutron– antineutron oscillation

Kuzmin 1970

The Mass Mixing $\epsilon(n^T Cn + \bar{n}^T C\bar{n})$ (Majorana mass of neutron) violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(u'd'd')$, M is the scale of new physics



$$\epsilon = \langle n|(udd)(udd)|\bar{n}\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{100\ \rm TeV}{M}\right)^5 \times 10^{-25}\ \rm eV$$

free $n - \bar{n}$ oscillation time $\tau = \epsilon^{-1}$

Key observation: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi's$

Present bounds on ϵ from nuclear stability

$\epsilon < 1.2 \times 10^{-24}$ eV $\quad\to\quad \tau > 1.3 \times 10^8$ s $\quad$ Fe, Soudan 2002
$\epsilon < 2.5 \times 10^{-24}$ eV $\quad\to\quad \tau > 2.7 \times 10^8$ s $\quad$ O, SK 2015

Neutron– antineutron oscillation Kuzmin 1970

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

Oscillation probability $P_{n\bar{n}}(t) = \frac{\epsilon^2}{\epsilon^2+\omega_B^2} \sin^2\left(t\sqrt{\epsilon^2+\omega_B^2}\right)$ where $\omega_B = \mu_n B$

If $\Omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\epsilon t)^2$

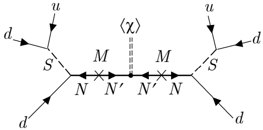
If $\Omega_B t \gg 1$, then $P_{n\bar{n}}(t) = (\epsilon/\omega_B)^2$

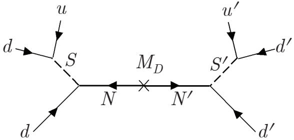
"Quasi-free" regime: for a given free flight time t, magnetic field should be properly suppressed to achieve $\omega_B t < 1$.
More suppression makes no sense !

Exp. Baldo-Ceolin et al, 1994 (ILL, Grenoble) : $t \simeq 0.1$ s, $B < 100$ nT
$\tau > 2.7 \times 10^8 \quad \to \quad \epsilon < 7.7 \times 10^{-24}$ eV

but at ESS 2 orders of magnitude better sensitivity can be achieved, down to $\epsilon \sim 10^{-25}$ eV

Seesaw between ordinary and mirror neutrons





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

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

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

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

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

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

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

Neutron – mirror neutron oscillation probability

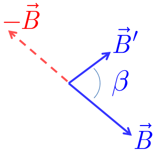
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

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

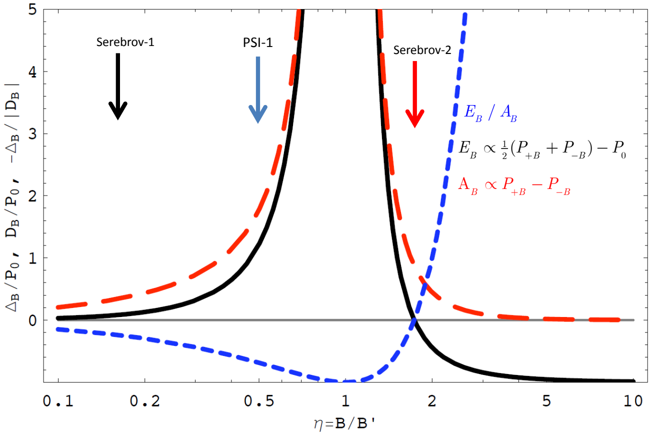


where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

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

A and E are expected to depend on magnetic field

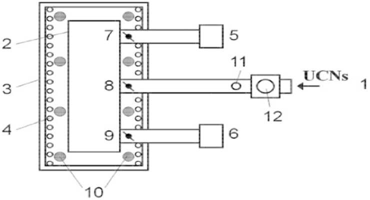
E.g. assume B'=0.12 Gauss



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.

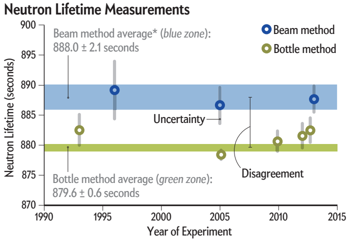
$N_B(T_S) = N(0)\exp\left[-\left(\Gamma + R + \bar{\mathcal{P}}_B\nu\right) T_S\right]$

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

So if we find that:

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

Problems to meet ...

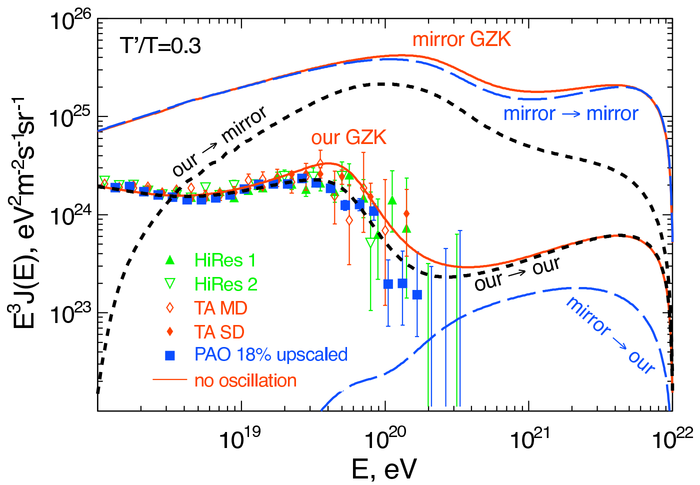


A few theorists have taken this notion seriously. Zurab Berezhiani of the University of L'Aquila in Italy and his colleagues have suggested such a secondary process: a free neutron, they propose, might sometimes transform into a hypothesized "mirror neutron" that no longer interacts with normal matter 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.

Why the neutron lifetime measured in UCN traps is smaller than that measured in beam method ? Missing decay channel seems impossible (neutron would be unstable also in nuclei).
But $n \to n'$ conversion can be plausible explanation
$+$ beta-decay of n' in invisible channel

$n - n'$ oscillation in itself cannot destabilise nuclei:
$(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation

Neutron – mirror neutron oscillation in cosmic rays



I Mirror matter is a hidden antimatter ... : antimatter in the cosmos?

In mirror cosmic rays, disintegration of mirror nuclei by galactic UV background or in scatterings with mirror gas, frees out mirror neutrons which the oscillate into our antineutron, $n' \to \bar{n}$, which then decays as $\bar{n} \to \bar{p} + \bar{e} + \nu_e$.
so we get antiprotons (positrons), with spectral index similar to that of protons in our cosmic rays ?