Summary

Introduction: Dark Matter from a Parallel World

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

Mirror Matter: some physical and astrophysical implications

Zurab Berezhiani

University of L'Aquila and LNGS

Portotoz 2021, 21-24 Sept. 2021

Contents

1 Introduction: Dark Matter from a Parallel World

2 Chapter I: *Neutrino - mirror neutrino mixings*

3 Chapter II: *neutron – mirror neutron mixing*

4 Chapter IV: $n - n'$ and Neutron Stars

Introduction

Everything can be explained by the Standard Model !

... but there should be more than one Standard Models

Bright & Dark Sides of our Universe

- $\Omega_B \simeq 0.05$ 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, AD-B, 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

Visible vs. Dark matter: $\Omega_D/\Omega_B \sim 1$?

Visible matter from Baryogenesis

B ($B - L$) & CP violation, Out-of-Equilibrium

$\rho_B = n_B m_B$, $m_B \simeq 1$ 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.

- Sakharov 1967

Dark matter: $\rho_D = n_X m_X$, but $m_X = ?$, $n_X = ?$

n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

Axion	$m_a \sim 10^{-5}$ eV $\quad n_a \sim 10^4 n_\gamma$ - CDM
Neutrinos	$m_\nu \sim 10^{-1}$ eV $\quad n_\nu \sim n_\gamma$ - HDM (×)
Sterile ν'	$m_{\nu'} \sim 10$ keV $\quad n_{\nu'} \sim 10^{-3} n_\nu$ - WDM
Mirror baryons	$m_{B'} \sim 1$ GeV $\quad n_{B'} \sim n_B$ - ???
WIMP	$m_X \sim 1$ TeV $\quad n_X \sim 10^{-3} n_B$ - CDM
WimpZilla	$m_X \sim 10^{14}$ GeV $\quad n_X \sim 10^{-14} n_B$ - CDM

Dark Matter from a Parallel World

Our observable particles: (Best of the possible Worlds ....)
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? + GUT ? ...)
electron, nucleons (quarks), neutrinos, gluons, Higgs
QED photon/long range, QCD gluons/confining, Weak W, Z/short range
... matter *vs.* antimatter (CP + B/B-L violation ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

Dark matter: a parallel sector ? (Best of the possible Dark Worlds ...)
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT '? Seesaw ?)
... dark matter (CP + B′/B′-L′ violation ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?

Call it Yin-Yang (in chinise, dark-bright) duality

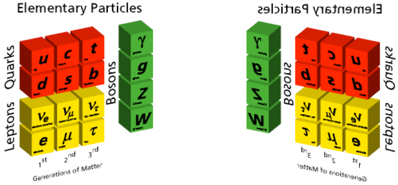
describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E_8'$

$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

$G \quad \times \quad G'$

Regular world — Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Mirror sector ($\mathcal{L}'$) is dark – or perhaps grey? ($\mathcal{L}_{\rm mix} \rightarrow$ portals)
- MM is similar to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions ($T'/T \ll 1$)
- $G \to G'$ symmetry (Z_2 or Z_2^{LR}): no new parameters in $\mathcal{L}'$ spont. broken?
- Cross-interactions between O & M particles
  $\mathcal{L}_{mix}$: new operators – new parameters! limited only by experiment!

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

Two possible parities: with and without chirality change

Fermions and anti-fermions :

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

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

$\updownarrow$ CP

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

B=–1/3 L=–1 B=–1/3 L=–1

Twin Fermions/anti-fermions :

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

B′=–1/3 L′=–1 B′=–1/3 L′=–1

$\updownarrow$ CP

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

B′=1/3 L′=1 B′=1/3 L′=1

$$\mathcal{L}_{\rm Yuk} = F_L Y \bar{F}_L \phi \; + \; \text{h.c.} \qquad \mathcal{L}'_{\rm Yuk} = F'_L Y' \bar{F}'_L \phi' \; + \; \text{h.c.}$$

Z_2: $L(R) \leftrightarrow L'(R')$: $Y'_{u,d,e} = Y_{u,d,e}$ $\quad$ B+B′ $\to$ −(B+B′)

Z_2^{LR}: $L(R) \leftrightarrow R'(L')$: $Y'_{u,d,e} = Y^*_{u,d,e}$ $\quad$ B+B′ $\to$ B+B′ $\quad Z_2^{LR} = Z_2 \times$ CP

– Sign of baryon asymmetry (BA)?

Ordinary BA is positive: $\mathcal{B} = \mathrm{sign}(n_b - n_{\bar{b}}) = 1$
– as produced by (unknown) baryogenesis a la Sakharov!

Sign of mirror BA, $\mathcal{B}' = \mathrm{sign}(n_{b'} - n_{\bar{b}'})$, is a priori unknown!

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in $\mathcal{L}_{\rm mix}$
E.g. EW baryogenesis or leptogenesis $N \to \ell\phi$ and $N' \to \ell'\phi'$

Z_2: $\to Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = -1$
– O and M sectors are CP-identical in same chiral basis! O=left, M=left

Z_2^{LR}: $\to Y'_{u,d,e} = Y^*_{u,d,e}$ i.e. $\mathcal{B}' = 1$
– O sector in L-basis is identical to M sector in R-basis! O=left, M=right

In the absence of cross-interactions in $\mathcal{L}_{\rm mix}$ we cannot measure sign of BA or chirality in weak interactions of M sector – so all remains academic ...

But switching on cross-interactions, violating B and B′ – but conserving say B+B′ as e.g. neutron–mirror neutron $(n - n')$ mixing: $\epsilon\bar{n}n' + \mathrm{h.c.}$
$Z_2^{LR} \to \mathcal{B}' = 1 \quad \to \quad n' \to n$ M matter → O matter
$Z_2 \to \mathcal{B}' = -1 \quad \to \quad \bar{n}' \to \bar{n}$ M (anti)matter → O antimatter

– All you need is ... M world colder than ours !

For a long time M matter was not considered as a real candidate for DM: naively assuming that exactly identical microphysics of O & M worlds implies also their cosmologies are exactly identical :

- $T' = T, \quad g'_* = g_* \quad \to \quad \Delta N_\nu^{\rm eff} = 6.15$ 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)

But all is OK if : Z.B., Dolgov, Mohapatra, 1995 *(broken* Z_2*)*
Z.B., Comelli, Villante, 2000 *(exact* Z_2*)*

A. after inflation M world was born colder than O world, $T'_R < T_R$
B. any interactions between M and O particles are feeble and cannot bring two sectors into equilibrium in later epochs
C. two systems evolve adiabatically (no entropy production): $T'/T \simeq$const

$T'/T < 0.5$ from BBN, but cosmological limits $T'/T < 0.2$ or so.

$x = T'/T \ll 1 \quad \Longrightarrow \quad$ in O sector 75% H $+$ 25% ^{4}He

$\Longrightarrow \quad$ in M world 25% H$'$ $+$ 75% ^{4}He$'$

For broken Z_2, DM can be compact H' atoms or n' with $m \simeq 5$ GeV or (sterile) mirror neutrinos $m \sim$ few keV Z.B., Dolgov, Mohapatra, 1995

Brief Cosmology of Mirror World

Z.B., Comelli, Villante, 2000

• CMB & (linear) structure formation epoch

Since $x = T'/T \ll 1$, mirror photons decouple before M-R equality:
$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq 1100\,(T/T')$

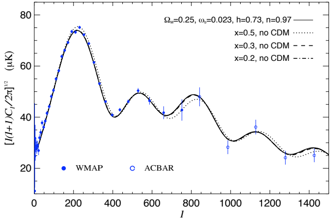
After that (and before M–reionization) M matter behaves as collisionless CDM and $T'/T < 0.2$ is consistent with Planck, BAO, Ly-α etc.

• Cosmic dawn: M world is colder (and helium dominated), the first M star can be formed earlier and reionize M sector ($z'_{\rm r} \simeq 20$ or so vs $z_{\rm r} \simeq 10$).
– EDGES 21 cm at $z \simeq 17$?
Heavy first M stars ($M \sim 10^{3\div5} M_\odot$) as seeds of central BH – Quasars?

• Galaxy halos? 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 dominated by BH and M stars, with our matter forming disks inside.
Maybe not always: Galaxies with missing DM, or too many DM, etc. ?

Because of $T' < T$, the situation $\Omega'_B \simeq 5\Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (as we show below)

CMB and LSS power spectra

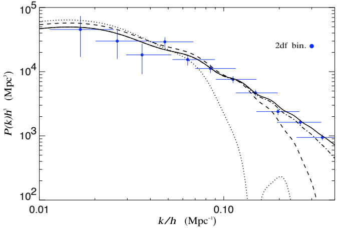


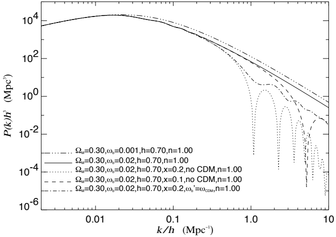
ZB, Ciarcelluti, Comelli, Villante, 2003

$$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq 1100\,(T/T')$$

⟵ imprint of $\Delta N_{\rm eff}$

imprint of M-baryon oscillations



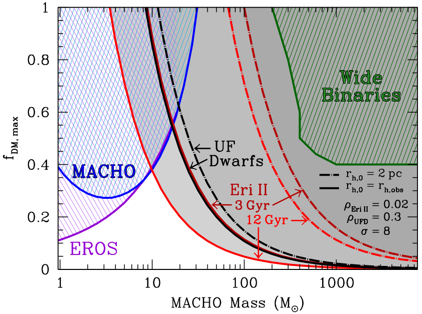


Acoustic oscillations and Silk damping scales: $x = 0.5,\ 0.3,\ 0.2$

$x < 0.2$: Galaxies with $M < 10^{8\div 9} M_\odot$ will be damped

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, M neutron stars and BH = Machos)
Microlensing limits: $f \sim 20 - 40$ % for $M = 1 - 10\ M_\odot$,
$f \sim 100$ % is allowed for $M = 20 - 200\ M_\odot$



GW events without any optical counterpart

Massive BH compact binaries, $M \sim 10 - 100\ M_\odot$

Can such objects be formed from MM?

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, BH-Ns and NS-NS binaries?
And perhaps large seeds for central BH in overdense regions?

Experimental and observational manifestations

A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.

- Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
- Easier formation and faster evolution of stars: Dark matter disk? Galaxy halo as mirror elliptical galaxy? Microlensing ? Neutron stars? Black Holes? Binary Black Holes? Central Black Holes?

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

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

Possible portals to Mirror World: $\mathcal{L}_{\rm mix}$

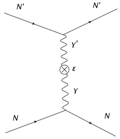
can be limited (only) by experiment/cosmology !

- Kinetic mixing of photons $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Makes mirror matter nanocharged ($q \sim \epsilon$)

$\epsilon < 5 \times 10^{-8}$ (EXP) $\quad \epsilon < 10^{-9}$ (COSM) $\quad$ (Exact Z_2)

GUT: $\frac{1}{M^2}(\Sigma G^{\mu\nu})(\Sigma' G'_{\mu\nu}) \quad \epsilon \sim \left(\frac{M_{GUT}}{M}\right)^2$



Portal for DM detection, can induce DM capture by stars/planest, can induce galactic magnetic fields Z.B., Dolgov, Tkachev, 2013

- Higgs-Higgs′ coupling $\lambda(\phi^\dagger\phi)(\phi'^\dagger\phi') \quad \lambda < 10^{-7}$ (COSM)

SUSY: $\quad W \sim \frac{1}{M}(\phi_1\phi_2)(\phi'_1\phi'_2) + F/D$- terms, $\quad \lambda \sim M_{\rm SUSY}/M$

SUSY Twin Higgs $\lambda S(\phi_1\phi_2 + \phi'_1\phi'_2 - \Lambda^2) + \dots \quad$ global $SU(4)$

$\langle\phi'\rangle \gg \langle\phi\rangle \quad$ Higgs = PGB $\quad$ ZB 05, Falkowksi Pokorski Schmalz 06

Non-SUSY version of twin-Higgs Chacko et al, 2005

- Common Peccei-Quinn symmetry: $\quad Z_2$ & $U(1)_{\rm PQ}$ @ PeV scale

  axion $m_a \sim 10$ MeV (axidragon) $\quad$ Z.B., Gianfagna, Giannotti 2000

  another version: asymmetric $SU(5) \times SU(5)$ Rubakov 1998

- Chiral family gauge symmetry $SU(3)_H$ ZB and Chkareuli 82

$f_L(q_L,\ell_L) \sim 3$, $f^c_L(u^c_L,d^c_L,e^c_L) \sim 3$ – $(\bar{5},3)+(10,3)$ in $SU(5)\times SU(3)_H$

Fermion mass generation requires $SU(3)_H$ breaking: $\frac{\chi}{M} H f_L f^c_L + \mathrm{h.c.}$

$Y_f = \langle\chi\rangle/M \quad 3\times 3 = 6+\bar{3} \quad \rightarrow \quad \chi = \bar{6},\ 3$

$$U(3)_H \to U(2)_H \to U(1)_H \to I \qquad \langle\chi\rangle = \begin{pmatrix} 0 & \chi_{12} & 0 \\ -\chi_{12} & 0 & \chi_{23} \\ 0 & -\chi_{23} & \chi_{33} \end{pmatrix}$$

Operators $\frac{\chi}{M} H f_L f^c_L + \mathrm{h.c.}$ obtained integrating out heavy fermions.

Automatic global symmetry $U(1)_H = U(1)_{PQ}$ ZB, 83-85

– axion with flavor and lepton violating couplings

(axion=familon=majoron) rich phenomenology ZB + Khlopov 90-91

SUSY: natural "quark-squark" alignment: Yukawa-SSB (F-terms)

$\tilde{m}^2 = m_S^2(1+Y^\dagger Y+\ldots)$, $\quad A = m_S Y$ viable SUSY @ TeV scale

ZB 96, Anselm and ZB 96, ZB and Rossi, 2000

coined as MFV in D'Ambrosio Giudice Isidori 2002

F-terms ($SU(3)_H$= global). D-term problem if $SU(3)_H$ is local

Gauge Flavor Symmetry as a portal

Mirror sector $\to$ automatic cancellation of $SU(3)_H$ anomaly:

$f_L, f_L^c \sim 3, \quad f_L', f_L'^c \sim \bar{3}$

if M-sector right-handed, $Z_2^{LR} = Z_2 \times CP$

in SUSY: flavons $\chi_L \sim \bar{6},\ 3$ + mirror flavons $\bar{\chi}_L \sim 6,\ \bar{3}$

$W = \frac{\chi_L}{M} H f_L f_L^c + \frac{\bar{chi}_L}{M} H' f_L' f_L'^c$

$SU(3)_H$ D-terms are vanishing by mirror symmetry: $\langle\chi\rangle = \langle\bar{\chi}\rangle$

MFV @ work achieved ZB 96, Z.B. and Rossi, 2000

valid both for exact mirror $\langle\phi'\rangle = \langle\phi\rangle$ or $\langle\phi'\rangle \neq \langle\phi\rangle$ (e.g. twin Higgs)
makes viable SUSY @ TeV scale

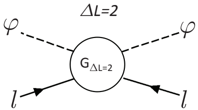
Flavor gauge bosons @ TeV scale: DM direct detection
$\pi^0 \to \pi^{0\prime}$, $K^0 \to K^{0\prime}$, $e\bar{\mu} \to e'\bar{\mu}'$ etc. Z.B., Belfatto 2019

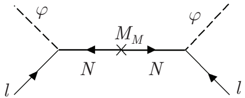
Chapter I

Neutrino – mirror neutrino mixings

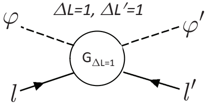
B-L violation in O and M sectors: Active-sterile mixing

- $\frac{A}{M}(\ell\phi)(\ell\phi)$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$
M is the (seesaw) scale of new physics beyond EW scale.





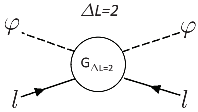
- Neutrino -mirror neutrino mixing – (active - sterile mixing)
L and L' violation: $\frac{A}{M}(\ell\phi)(\ell\phi)$, $\frac{A}{M}(\ell'\phi')(\ell'\phi')$ and $\frac{B}{M}(\ell\phi)(l\ell'\phi')$

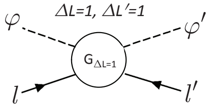


Mirror neutrinos naturally sterile neutrinos: $\langle\phi'\rangle/\langle\phi\rangle \sim 10 \div 10^2$
ZB and Mohapatra 95, ZB, Dolgov and Mohapatra 96

Co-leptogenesis: B-L violating interactions between O and M worlds

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





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

Mirror Matter: some physical and astrophysical implications

Zurab Berezhiani

Summary

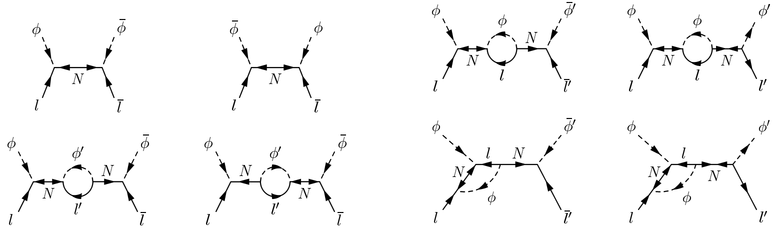
Introduction: Dark Matter from a Parallel World

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

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



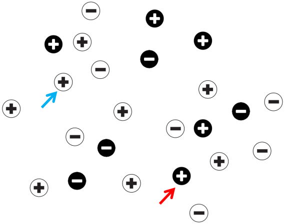
Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,
Z_2^{LR} (Mirror) symmetry $\rightarrow Y' = Y^*$

Co-leptogenesis: Mirror Matter as Dark Anti-Matter

Z.B., arXiv:1602.08599

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



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

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

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

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

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

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

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

Mirror (Z_2^{LR}): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B > 0,\ B' < 0$

Xerox (Z_2): $\quad Y' = Y \quad \to \quad \Delta\sigma' = \Delta\sigma = 0 \quad \to \quad B, B' = 0$

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

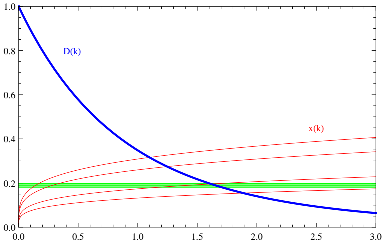
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ {\rm GeV}}\right)^3 \left(\frac{10^{13}\ {\rm GeV}}{M}\right)^4$$

Cogenesis: $\Omega'_B \simeq 5\Omega_B$ Z.B. 2003

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

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

should be solved with Γ:



$D(k) = \Omega_B/\Omega'_B$, $x(k) = T'/T$ 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

Mirror Matter: some physical and astrophysical implications

Zurab Berezhiani

Summary

Introduction: Dark Matter from a Parallel World

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

Chapter II

Neutron – mirror neutron mixing

B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

Summary

Introduction: Dark Matter from a Parallel World

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

Ordinary quarks $u,\ d$ (antiquarks $\bar{u},\ \bar{d}$)
Mirror quarks $u',\ d'$ (antiquarks $\bar{u}',\ \bar{d}'$)

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

$$\frac{1}{M^5}(udd)(udd) \qquad \& \qquad \frac{1}{M^5}(udd)(u'd'd')$$

Oscillations $n \to \bar{n}$ $(\Delta B = 2)$
Oscillations $n \to \bar{n}'$ $(\Delta B = 1,\ \Delta B' = -1)$ $B + B'$ is conserved

Summary

Introduction: Dark Matter from a Parallel World

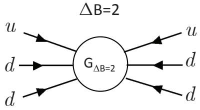
Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

Neutron– antineutron mixing

Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



It causes transition $n(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$, with oscillation time $\tau = \epsilon^{-1}$

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

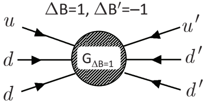
Key moment: *$n - \bar{n}$ oscillation destabilizes nuclei:*
$(A, Z) \to (A-1, \bar{n}, Z) \to (A-2, Z/Z-1) + \pi's$

Present bounds on ϵ from nuclear stability

$\varepsilon < 1.2 \times 10^{-24}$ eV	$\to$	$\tau > 1.3 \times 10^8$ s	Fe, Soudan 2002
$\varepsilon < 2.5 \times 10^{-24}$ eV	$\to$	$\tau > 2.7 \times 10^8$ s	O, SK 2015
$\varepsilon < 7.5 \times 10^{-24}$ eV	$\to$	$\tau > 0.9 \times 10^8$ s	direct limit free n

Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \rightarrow \quad$ mass mixing $\epsilon n C n' + \mathrm{h.c.}$
violating B and B' – but conserving $B - B'$



$$\epsilon = \langle n|(udd)(u'd'd')|\bar{n}'\rangle \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \sim \left(\frac{1 \text{ TeV}}{M}\right)^5 \times 10^{-10} \text{ eV}$$

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \rightarrow (A-1, Z) + n'(p'e'\bar{\nu}')$ forbidden by energy conservation
(In principle, it can destabilise Neutron Stars)

For $m_n = m_{n'}$, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1$ s
without contradicting experimental and astrophysical limits.
(c.f. $\tau > 10$ yr for neutron – antineutron oscillation)

Neutron disappearance $n \rightarrow \bar{n}'$ and regeneration $n \rightarrow \bar{n}' \rightarrow n$
can be searched at small scale 'Table Top' experiments

Neutron – mirror neutron oscillation probability

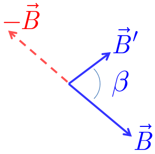
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

Earth mirror magnetic field via the electron drag mechanism

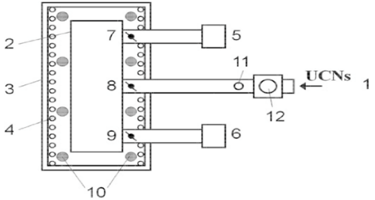
Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.
Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.
Circular electric currents emerge which can generate magnetic field.
Modifying mirror Maxwell equations by the source (drag) term, one gets $B' \sim \epsilon^2 \times 10^{15}$ G before dynamo, and even larger after dynamo.

Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

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.

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

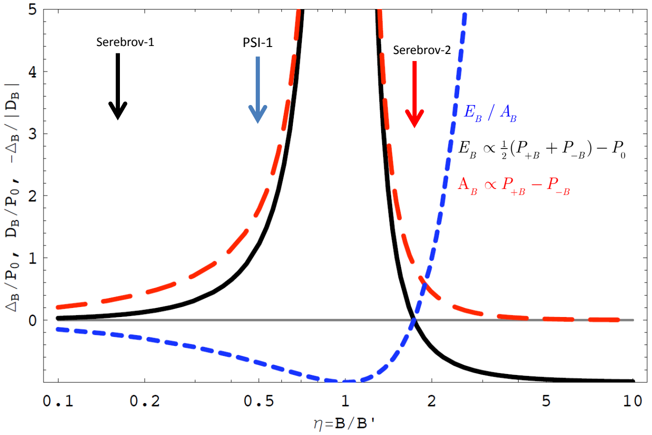
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

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

A and E are expected to depend on magnetic field

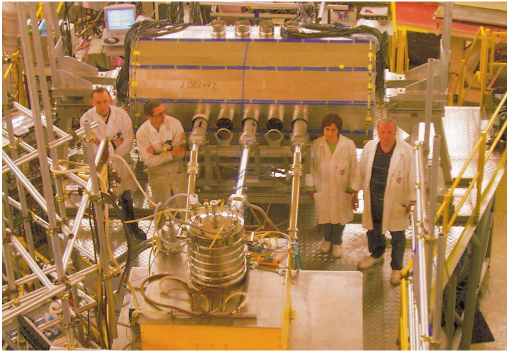
E.g. assume B'=0.12 Gauss



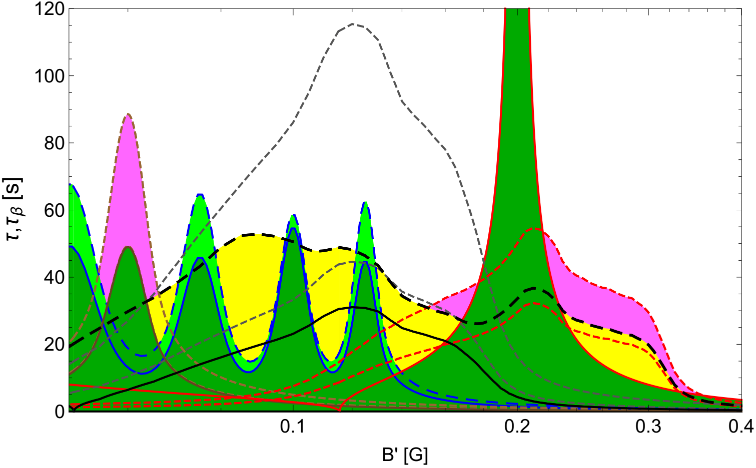
Experiments

8 experiment were done at ILL/PSI, 3+1 by PSI group, 2+1 by Serebrov group with 190 l beryllium plated trap for UCN

New experiments are underway at PSI, ILL and ORNL



Exp. limits on $n - n'$ oscillation time – ZB et al, Eur. Phys. J. C. 2018



Free Neutrons: Where to find Them ?

Neutrons are making 1/7 fraction of baryon mass in the Universe.

But most of neutrons bound in nuclei ....

$n \to \bar{n}'$ or $n' \to \bar{n}$ conversions can be seen only with free neutrons.

Free neutrons are present only in

- Reactors and Spallation Facilities (experiments are looking for)
- In Cosmic Rays ($n - n'$ can reconcile TA and Auger experiments)
- During BBN epoch (fast $n' \to \bar{n}$ can solve Lithium problem)

– Transition $n \to \bar{n}'$ can take place for (gravitationally) Neutron Stars – conversion of NS into mixed ordinary/mirror NS

Mirror Matter: some physical and astrophysical implications

Zurab Berezhiani

Summary

Introduction: Dark Matter from a Parallel World

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

Chapter IV: $n - n'$ and Neutron Stars

Chapter IV

$n - n'$ and Neutron Stars (and Mirror Neutron stars)

Z.B., Biondi, Mannarelli, Tonelli, arXiv:2012.15233

Z.B., arXiv:2106.11203

Neutron Stars: $n - n'$ conversion

Two states, n and n'

$$H = \begin{pmatrix} m_n + V_n + \mu_n \mathbf{B}\sigma & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

$$n_1 = \cos\theta n + \sin\theta n', \quad n_2 = \sin\theta n - \cos\theta n', \quad \theta \simeq \frac{\epsilon}{V_n - V'_n}$$

$$V_n = 2\pi a n_b / m_n \simeq \xi a_3 \times 125 \text{ MeV} \qquad \xi = n_b/n_s \ (n_s = 0.16/\text{ fm}^3)$$

$$E_F \simeq \xi^{2/3} \times 60 \text{ MeV}, \qquad (V'_n < V_n, \quad E'_F < E'_F)$$

$$nn \to nn' \text{ with rate } \Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b, \qquad \sigma = 4\pi a^2$$

$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \qquad \frac{dN_2(t)}{dt} = \Gamma N_1 \qquad N_1 + N_2 = \text{Const.}$$

$$\tau_\epsilon = \Gamma^{-1} = \epsilon_{15}^{-2} a_R \left(\frac{M}{1.5 \, M_\odot} \right)^{2/3} \times 10^{15} \text{ yr}$$

$$\dot{\mathcal{E}} = \Gamma E_F N_b = \epsilon_{15}^2 \left(\frac{M}{1.5 \, M_\odot} \right) \times 10^{31} \text{ erg/s} \qquad \text{NS heating – surface T}$$

Mixed Neutron Stars: TOV and $M - R$ relations

$$g_{\mu\nu} = \mathrm{diag}(-g_{tt}, g_{rr}, r^2, r^2 \sin^2\theta) \qquad g_{tt} = e^{2\phi},\ g_{rr} = \frac{1}{1-2m/r}$$

$$T_{\mu\nu} = T^1_{\mu\nu} + T^2_{\mu\nu} = \mathrm{diag}(\rho g_{tt}, p g_{rr}, p r^2, p r^2 \sin^2\theta)$$

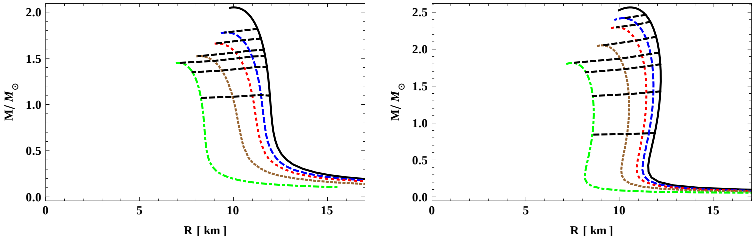
$$\rho = \rho_1 + \rho_2 \ \&\ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \ \to\ \frac{dm_{1,2}}{dr} = 4\pi r^2 \rho_{1,2} \qquad m = m_1 + m_2$$

$$\frac{d\phi}{dr} = -\frac{1}{\rho+p}\frac{dp}{dr} \ \to\ \frac{dp_1/dr}{\rho_1+p_1} = \frac{dp_2/dr}{\rho_2+p_2}$$

$$\frac{dp}{dr} = (\rho+p)\frac{m+4\pi p r^3}{2mr-r^2}$$

$$(m_1 \neq 0, m_2 = 0)_{\mathrm{in}} \to (m_1 = m_2)_{\mathrm{fin}} \qquad r \to \frac{r}{\sqrt{2}}, \quad m_\alpha \to \frac{m_\alpha}{2\sqrt{2}}$$

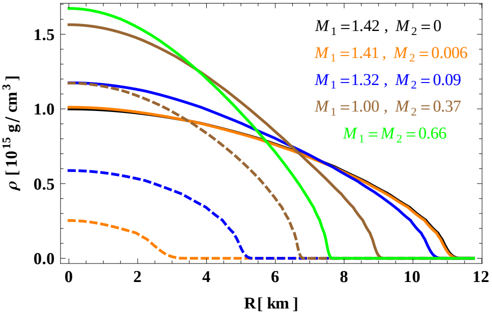


$$\sqrt{2} \text{ rule:} \quad M^{\max}_{\mathrm{mix}} = \frac{1}{\sqrt{2}} M^{\max}_{\mathrm{NS}} \qquad R_{\mathrm{mix}}(M) = \frac{1}{\sqrt{2}} R_{\mathrm{NS}}(M)$$

Neutron Star transformation

$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \qquad \frac{dN_2(t)}{dt} = \Gamma N_1 \qquad N_1 + N_2 = \text{Const.}$$

Initial state $N_1 = N_0,\ N_2 = 0$ final state $N_1 = N_2 = N_0/2$



Hybrid stars: in quark matter (color-superconducting phase) transition is not energetically farorable. But in neutron liquid shell it can occur and create the M matter core in the HS interior.

Neutron Stars: observational $M - R$

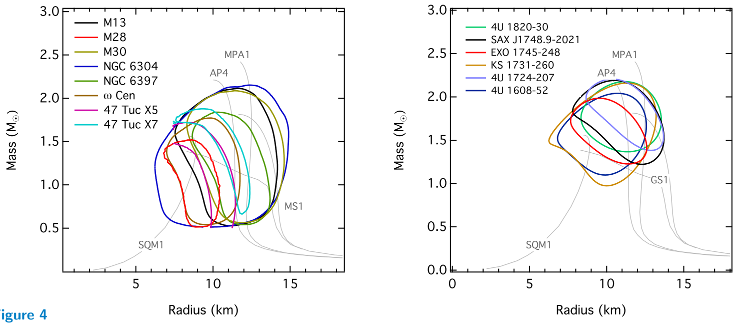
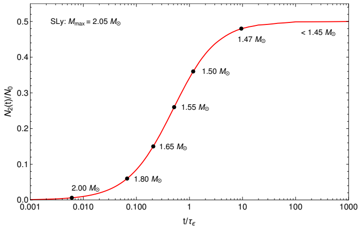
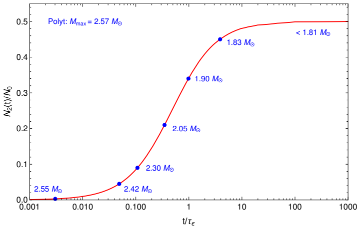


Figure 4

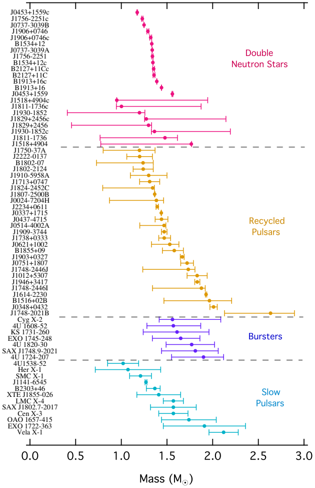
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative equations of state (see Section 4.1 and Fig. 7 for detailed descriptions.)

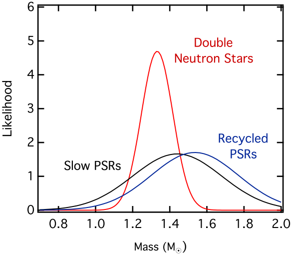
Neutron Stars Evolution to mixed star





Neutron Stars: mass distribution



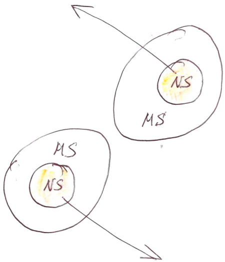


Neutron Star Mergers

NS-NS merger and kilonova (GW170817 ?)
r-processes can give heavy *trans-Iron* elements

Mirror NS-NS merger is invisible (GW190425 ? $M_{\rm tot} = 3.4 M_\odot$)

But not completely ... if during the evolution they developed small core of normal matter or antimatter (depends on the mirror BA sign) – their mergers can be origin of antinuclei for AMS-2



Antimatter Cores in Mirror Neutron stars

DUPOURQUÉ, TIBALDO, and VON BALLMOOS PHYS. REV. D **103,** 083016 (2021)

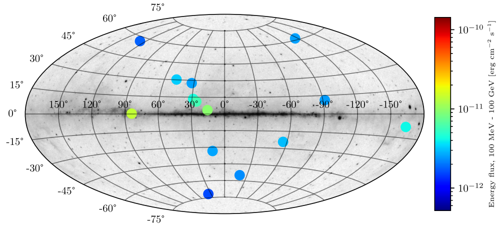


FIG. 1. Positions and energy flux in the 100 MeV–100 GeV range of antistar candidates selected in 4FGL-DR2. Galactic coordinates. The background image shows the *Fermi* 5-year all-sky photon counts above 1 GeV (image credit: NASA/DOE/Fermi LAT Collaboration).

Antimatter production rate: $\dot{N}_{\bar{b}} = \frac{N_0}{\tau_\epsilon} \simeq \epsilon_{15}^2 \left(\frac{M}{M_\odot}\right)^{2/3} \times 3 \cdot 10^{34}\ \mathrm{s}^{-1}$

ISM accretion rate: $\dot{N}_b \simeq \frac{(2GM)^2 n_{\rm is}}{v^3} \simeq \frac{10^{32}}{v_{100}^3} \times \left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right)\left(\frac{M}{M_\odot}\right)^2 \mathrm{s}^{-1}$

Annihilation γ-flux from the mirror NS as seen at the Earth:

$J \simeq \frac{10^{-12}}{v_{100}^3}\left(\frac{n_{\rm is}}{1/\mathrm{cm}^3}\right)\left(\frac{M}{1.5\,M_\odot}\right)^2\left(\frac{50\,\mathrm{pc}}{d}\right)^2 \frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s}}$ $\quad d$ – distance to source

Alternative: Antistars – Dolgov & Co. but some difference:

– the surface redshift s expected $\sim 15 \div 30$ % for the NS

– which should be absent for antistars (weak gravity)