Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

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

Parallel/Mirror Dark World

(Fantastic Beasts and Where to Find Them)

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Introduction

Open your mind, relax and go downstream .....

Tomorrow never knows

Bright & Dark Sides of our 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, 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

Everything has the End. The Wurstle has two Ends ...

Our 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-L violation, CP ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !
Best of the possible Worlds .... (Candid, Frank and Uncontrived)

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′-L′ violation, CP ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?
Another Best of the possible Worlds? (Maybe Candide had a twin?)

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.

$E_8 \times E'_8$

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

Two parities

Fermions and anti-fermions :

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

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

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

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

Twin Fermions and anti-fermions :

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

B′=1/3 L′=1 B′=1/3 L′=1

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

B′=-1/3 L′=-1 B′=-1/3 L′=-1

$$\mathcal{L}_{\rm Yuk} = \bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi \quad + \quad \text{h.c.}$$
$$\mathcal{L}_{\rm Yuk} = \bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi' \quad + \quad \text{h.c.}$$

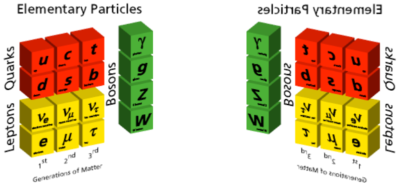
Z_2 symmetry $(L, R \to L, R)$: $\quad Y' = Y \qquad B - B' \to -(B - B')$

PZ_2 symmetry $(L, R \to R, L)$: $\quad Y' = Y^* \qquad B - B' \to B - B'$

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

$$G \times G'$$

Regular world | Mirror world



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- Exact parity $G \to G'$: no new parameters in dark Lagrangian $\mathcal{L}'$
- MM is dark (for us) and has the same gravity
- MM is identical to standard matter, (asymmetric/dissipative/atomic) but realized in somewhat different cosmological conditions: $T'/T \ll 1$.
- New interactions between O & M particles $\quad \mathcal{L}_{mix}$

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

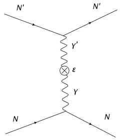
these terms can be limited (only) by experiment/cosmology !

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

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

$\epsilon < 3 \times 10^{-7}$ (EXP) $\quad \epsilon < 5 \times 10^{-9}$ (COSM)

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



Can induce galactic magnetic fields Z.B., Dolgov, Tkachev, 2013

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

$\lambda < 10^{-7}$ (COSM)

SUSY: $\frac{1}{M}(\phi_1\phi_2)(\phi'_1\phi'_2)$

$\lambda \sim M_{\rm SUSY}/M$

or NMSSM (Twin Higgs)

$\lambda S(\phi_1\phi_2 + \phi'_1\phi'_2) + \Lambda S + \ldots$

- Neutrino-neutrino′ (active-sterile) mixing – discussed later

- Neutron-neutron′ mixing – discussed later

– 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 :

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

But all is OK if : Z.B., Comelli, Villante, 2000

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); so as the universe expands the temperature ratio $T'/T \simeq$ constant

$T'/T < 0.5$ 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′

Brief Cosmology of Mirror World

- CMB & (linear) structure formation epoch

Since $x = T'/T \ll 1$, mirror photons decouple before M-R equality: $z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq \frac{1100}{x}$
After that (and before M–reionization) M matter behaves as colisionless CDM and $T'/T < 0.2$ is consistent with /Planck, BAO, Ly-α etc.

- Cosmic dawn

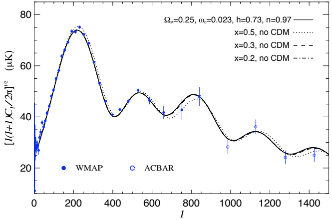
M world is colder (and helium dominated), the first M star formation can be faster which can make earlier reionization of M sector ($z'_{\rm r} \simeq 20$ or so vs $z_{\rm r} = 10 \div 6$). Heavy first M stars ($M \sim 10^3 M_\odot$ and fast formation of central BH – Quasars? EDGES 21 cm at $z \simeq 17$?

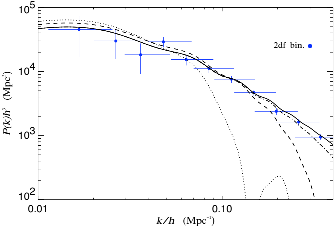
- Galaxy halos?

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 inside forming disks.

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)

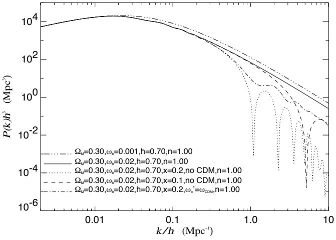
CMB and LSS power spectra





ZB, Ciarcelluti, Comelli, Villante, 2003

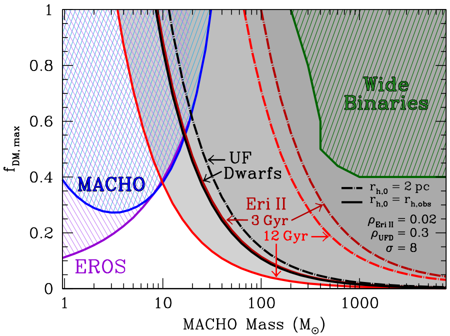
$$z'_{\rm dec} \simeq x^{-1} z_{\rm dec} \simeq \frac{1100}{x}$$



Acoustic oscillations and Silk damping scales:
$x = T'/T = 0.5,\ 0.3,\ 0.2$

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



GW events without any optical counterpart

point 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 ?

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

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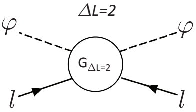
Chapter I

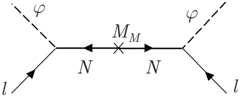
Neutrino – mirror neutrino mixings

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

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

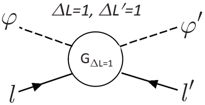
M is the (seesaw) scale of new physics beyond EW scale.





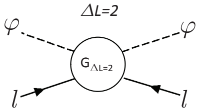
- Neutrino -mirror neutrino mixing – (active - sterile mixing)

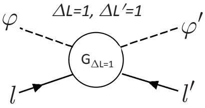
L and L' violation: $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$, $\frac{1}{M}(l'\bar{\phi}')(l'\bar{\phi}')$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$



Mirror neutrinos are natural candidates for sterile neutrinos

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.

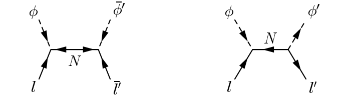
- These processes should be out-of-equilibrium
- Violate baryon numbers in both worlds, $B - L$ and $B' - L'$
- Violate also CP, given complex couplings

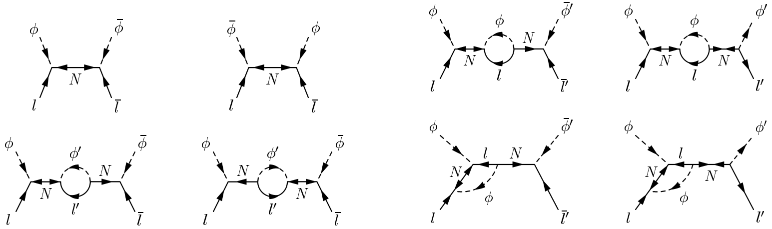
Green light to celebrated conditions of Sakharov

Co-leptogenesis:

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



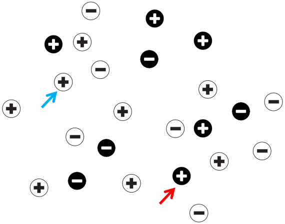


Complex Yukawa couplings $Y_{ij}l_iN_j\bar{\phi} + Y'_{ij}l'_iN_j\bar{\phi}' + \mathrm{h.c.}$

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,
PZ_2 (Mirror) symmetry $\rightarrow Y' = Y^*$

Co-leptogenesis: Mirror Matter as hidden Anti-Matter   Z.B., arXiv:1602.08599

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



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

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

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

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

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

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

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

Mirror (PZ_2): $\quad Y' = Y^* \quad \to \quad \Delta\sigma' = -\Delta\sigma \quad \to \quad B, B' > 0$

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 $\quad \to \quad n_{BL} = n'_{BL}$

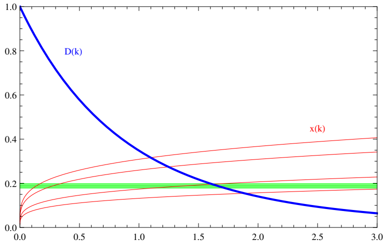
$$\Omega'_B = \Omega_B \simeq 10^3 \frac{J M_{Pl} T_R^3}{M^4} \simeq 10^3 J \left(\frac{T_R}{10^{11}\ \rm GeV}\right)^3 \left(\frac{10^{13}\ \rm GeV}{M}\right)^4$$

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.

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

should be solved with Γ:



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

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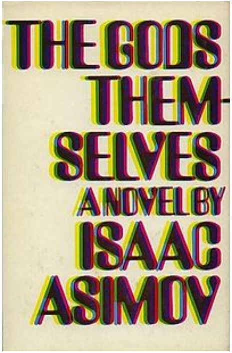
Sign of mirror BA: Free Energy from DM ?

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 .... E.g. $n' \to \bar{n}$ produces our antimatter from mirror DM

Two civilisations can agree to built scientific reactors and exchange neutrons ... and turn the energy produced by each reactor in 1000 times more energy for parallel world .. and all live happy and healthy ...

Isaak Asimov



First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

Chapter II

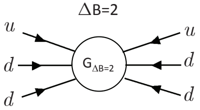
Neutron – mirror neutron mixing

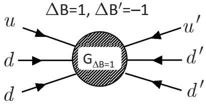
B violating operators between O and M particles in $\mathcal{L}_{\rm mix}$

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)

$$\frac{1}{M^5}(udd)(udd) \text{ and } \frac{1}{M^5}(udd)(u'd'd') \quad (+ \text{h.c.})$$





Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 2)$
$n(udd) \to \bar{n}'(\bar{u}'\bar{d}'\bar{d}'), \ n'(udd) \to \bar{n}(\bar{u}\bar{d}\bar{d})$ $(\Delta B = 1, \ \Delta B' = -1)$

Neutron– antineutron mixing

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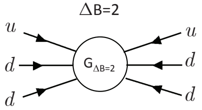
Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units
comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



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

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

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

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Zurab Berezhiani

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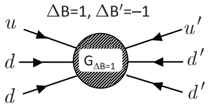
Neutron – mirror neutron mixing

Effective operator $\frac{1}{M^5}(udd)(u'd'd') \quad \to \quad$ mass mixing $\epsilon n C n' + \text{h.c.}$

violating B and B' – but conserving $\quad B - B'$



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

Key observation: *$n - \bar{n}'$ oscillation cannot destabilise nuclei:*
$(A, Z) \to (A-1, Z) + n'(p'e'\bar{\nu}')$ 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. $\tau_{n\bar{n}'} > 2.5 \times 10^8$ s for neutron – antineutron oscillation)

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

Neutron – mirror neutron oscillation probability

Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

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

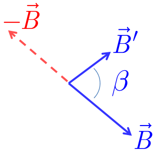
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

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

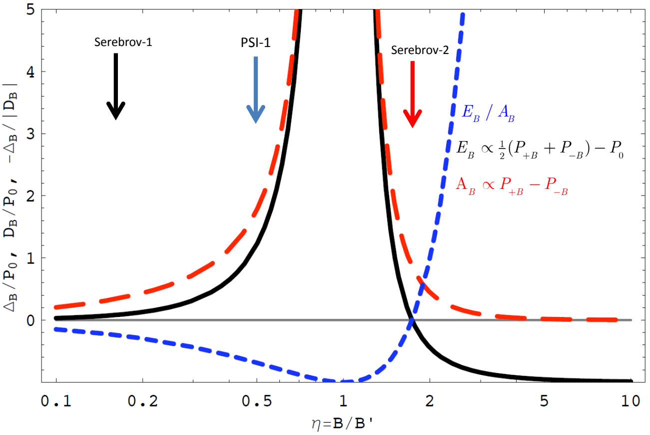


where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

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

A and E are expected to depend on magnetic field

E.g. assume B'=0.12 Gauss



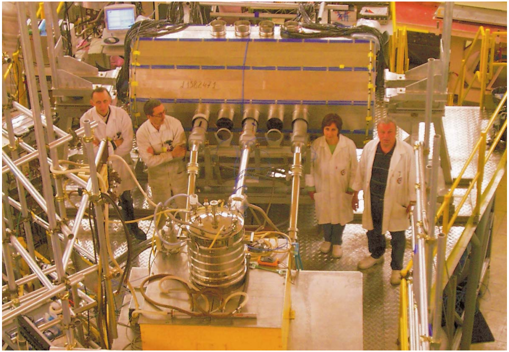
Earth mirror magnetic field via the electron drag mechanism

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.

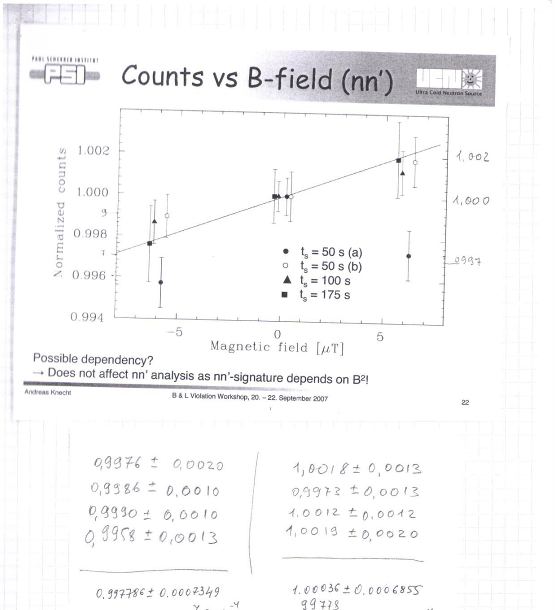
Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

Experiments

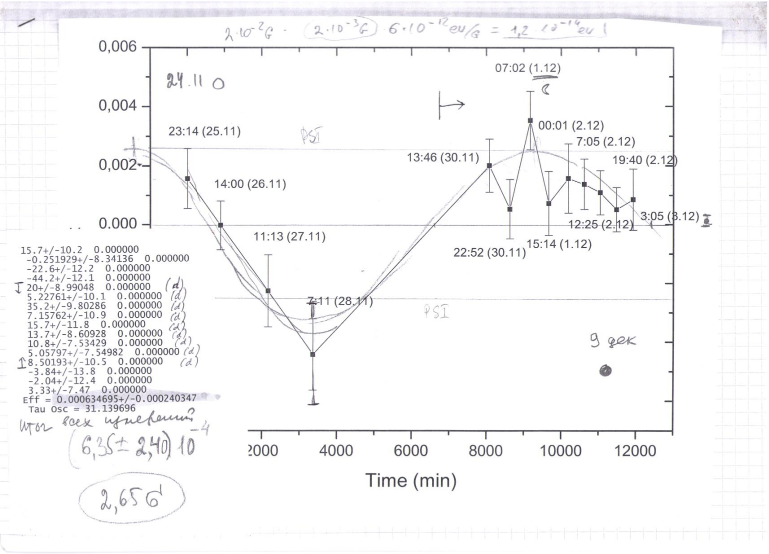
Several experiment were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN



Serebrov experiment III – Cheking PSI Anomaly



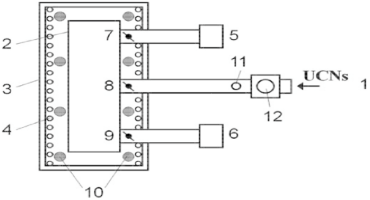
Serebrov's Fax



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.

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

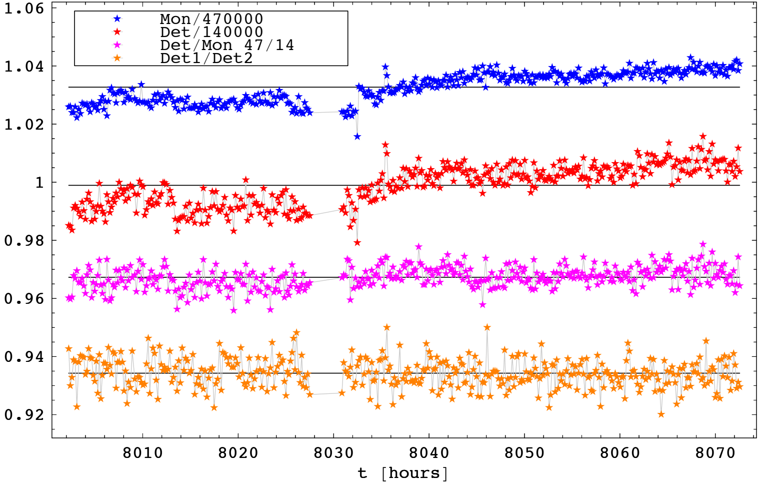
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

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

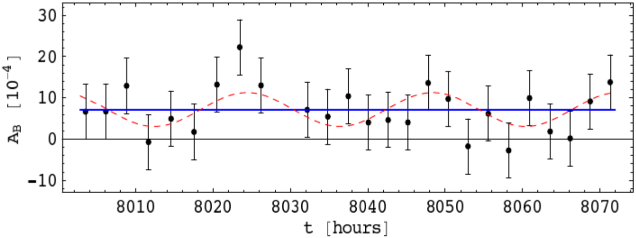
Serebrov III – Drifts of detector and monitor counts

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Serebrov III – magnetic field vertical

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Analysis pointed out the presence of a signal:

$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

interpretable by $n \to n'$ with $\tau_{nn'} \sim 2 - 10s$‘ and $B' \sim 0.1G$

Z.B. and Nesti, 2012

Neutron – mirror neutron oscillation

Eur. Phys. J. C (2012) 72:1974
DOI 10.1140/epjc/s10052-012-1974-5

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

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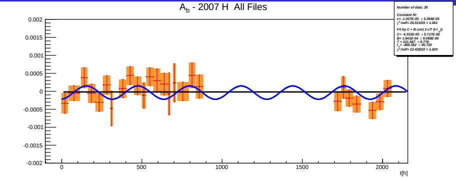
Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron traps, where they can be revealed by the magnetic field dependence of n–n' transition probability. In this work we reanalyze the experimental data acquired by the group of A.P. Serebrov at Institute Laue–Langevin, and find a dependence at more than 5σ away from the null hypothesis. This anomaly can be interpreted as oscillation of neutrons to mirror neutrons with a timescale of few seconds, in the presence of a mirror magnetic field order 0.1 G at the Earth. This result, if confirmed by future experiments, will have deepest consequences for fundamental particle physics, astrophysics and cosmology.

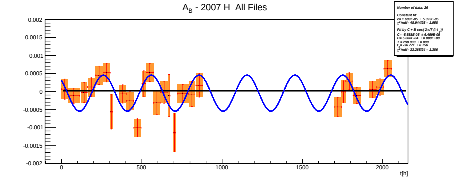
Parallel matter can be a viable candidate for dark matter [7–9]. Certain $B-L$ and CP violating processes between ordinary and mirror particles can generate the baryon asymmetries in both sectors [10–12] which scenario can naturally explain the relation $\Omega_D/\Omega_B \simeq 5$ between the dark and visible matter fractions in the Universe [13–16]. Such interactions can be mediated by heavy messengers coupled to both sectors, as right-handed neutrinos [10–12] or extra gauge bosons/gauginos [17].[1] In the context of extra dimensions, ordinary and mirror sectors can be modeled as two parallel three-dimensional branes and particle processes between them mediated by the bulk modes or "baby branes" can be envisaged [24].

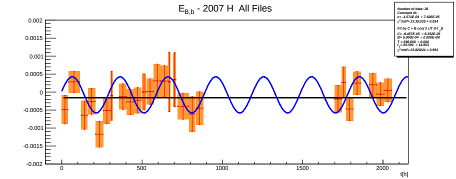
On the other hand, these interactions can induce mixing phenomena between ordinary and mirror particles. In fact, any *neutral* particle, *elementary or composite*, may oscillate

Serebrov II – magnetic field Horizontal

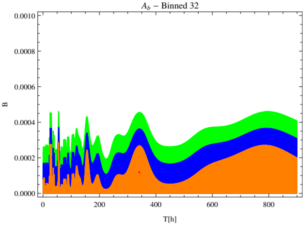
$$\{b_-, B_-, B_+, b_+, b_+, B_+, B_-, b_-\}\ ,\ B = 0.2\ \mathrm{G}\ ,\ b < 10^{-3}\ \mathrm{G}$$

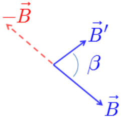


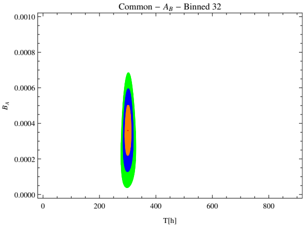


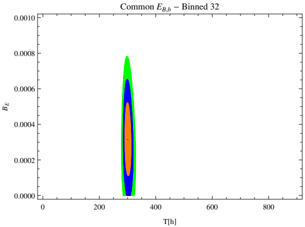


Serebrov 2007 – magnetic field Horizontal

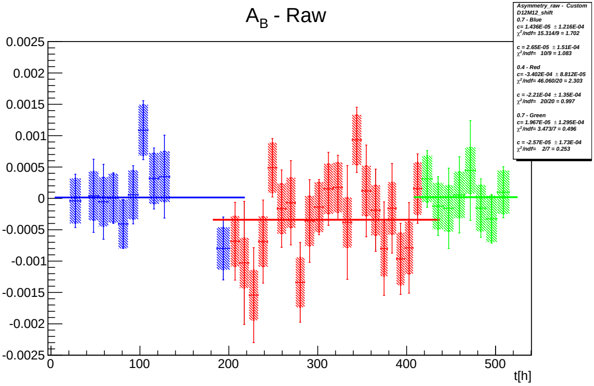




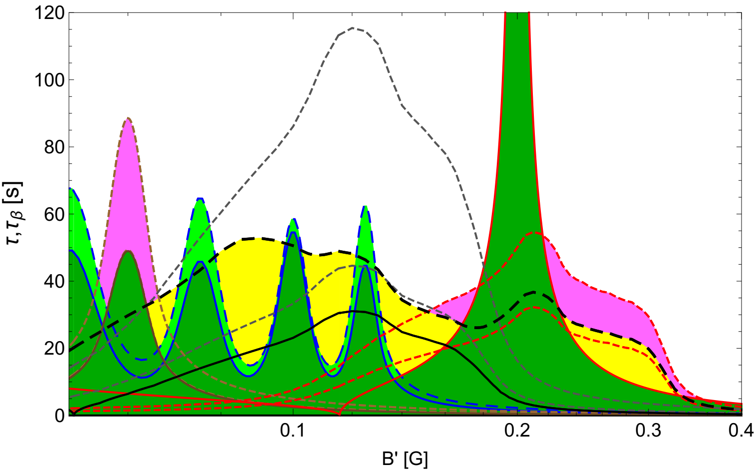




My own neasurements 2014 at ILL – with Biondi, Geltenbort et al.



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
- In Cosmic Rays
- 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

Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

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

Chapter III

$n - n'$ and Neutron Stars

Z.B., Biondi, Mannarelli, Tonelli

Neutron Stars: $n - n'$ conversion

Two states, n and n'

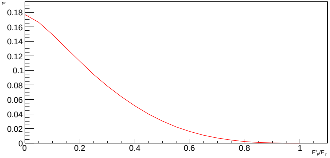
$$H = \begin{pmatrix} m_n + V_n + \mu_n \mathbf{B}\sigma & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

$$nn \to nn' \text{ with probability } P_{nn'} = \frac{1}{2}\sin^2 2\theta_{nn'} = 2\left(\frac{\epsilon}{E_F - E'_F}\right)^2$$

$$E_F \simeq (n/n_s)^{2/3} \times 60 \text{ MeV}, \quad n_s = 0.16 \text{ fm}^{-3} \quad E'_F = \ldots . n'$$

$$\Gamma_0 = \langle \sigma v_F \rangle n \eta_0 P_{nn'}(0) \simeq \left(\frac{a}{1\,\mathrm{fm}}\right)^2 \left(\frac{\varepsilon}{10^{-14}\,\mathrm{eV}}\right)^2 \times 10^{-13}\ \mathrm{yr}^{-1}$$



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

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

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

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

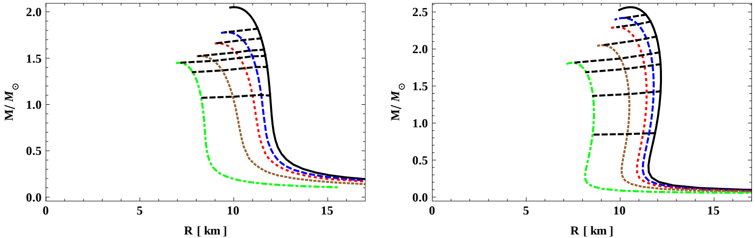
$$\rho = \rho_1 + \rho_2 \ \& \ p = p_1 + p_2, \qquad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



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

Neutron Stars: observational $M - R$

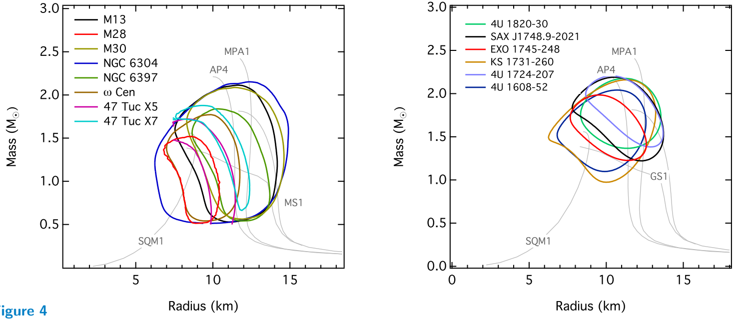


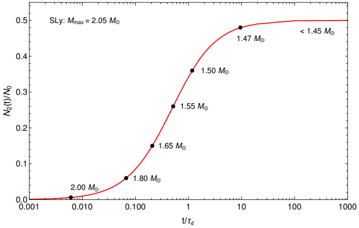
Figure 4

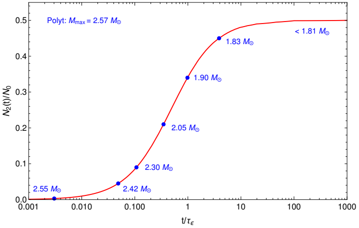
The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative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

Neutron Stars: Evolution to mixed star

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

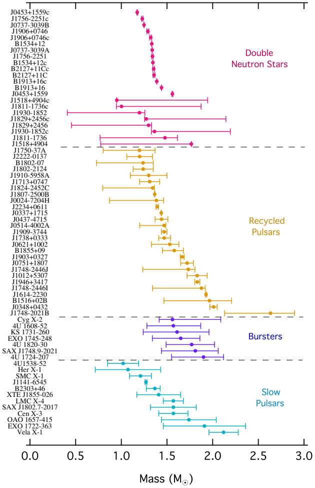
Initial state $N_1 = N_0,\ N_2 = 0$ final state $N_1 = N_2 = N_0/2$

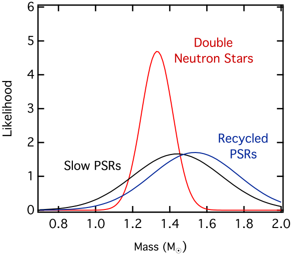




NS-NS merger: can be at the origin of heavy *trans-Iron* elements

Neutron Stars: mass distribution





Parallel/Mirror Dark World
(Fantastic Beasts and Where to Find Them)
Zurab Berezhiani
Summary
Introduction: Mirror Matter
Chapter I: *Neutrino - mirror neutrino mixings*
Chapter II: *neutron – mirror neutron mixing*
Chapter III: $n - n'$ and Neutron Stars

Chapter IV

$n - n'$ and UHECR

Z.B., Biondi, Gazizov

UHECR and GZK cutoff

Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

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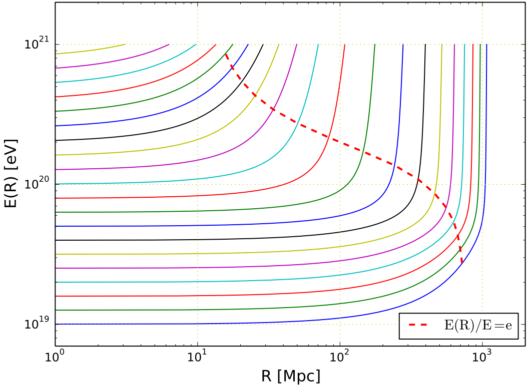
GZK cutoff:

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 $E > 10^{20}\ {\rm eV} = 100$ EeV

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

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

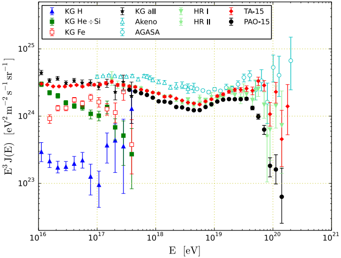


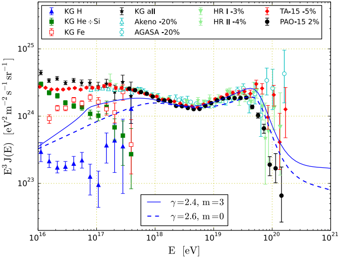
UHECR and GZK cutoff

Two giant detectors see UHECR spectra different at $E > E_{\rm GZK}$

Pierre Auger Observatory (PAO) – South hemisphere
Telescope Array (TA) – North hemisphere

At $E < E_{\rm GZK}$ two spectra are perfectly coincident
by relative energy shift ≈ 8 %





+ older detectors: AGASA, HiRes, etc. (all in north hemisphere)

Events with $E > 100$ EeV were observed
Cosmic Zevatrons exist in the Universe – but where is GZK cutoff?

But also other discrepancies are mounting ...

- Who are carriers of UHECR ?

PAO and TA see different chemical content: TA is compatible with protons at all energies, PAO insists UHECR become heavier nuclei above $E > 10$ EeV or so – perhaps new physics ?

- Different anistropies from North and South ?

TA excludes isotropic distribution at $E > 57$ EeV, observes hot spot for events $E > E_{\rm GZK}$ (which spot is cold for $E < E_{\rm GZK}$) . PAO anisotropies not so prominent: warm spot around Cen A, but observe dipole for $E > 10$ EeV – are two skies realy different ?

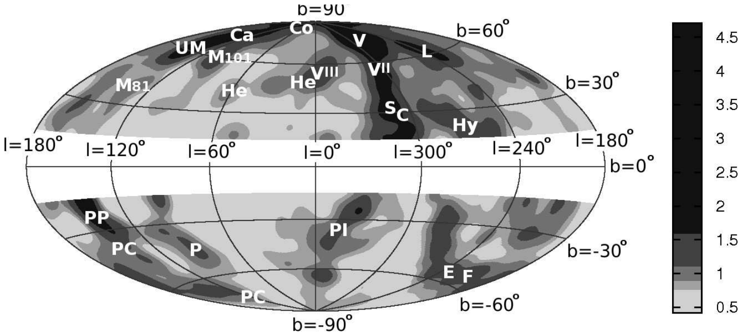
- From where highest energy events do come ?

$E > 100$ EeV are expected from local supercluster (Virgo, UM, PP etc.) and closeby structures. But they do not come from these directions. TA observes small angle correlation for $E > 100$ EeV events (2 doublets), which may indicate towards strong source – from where they come?

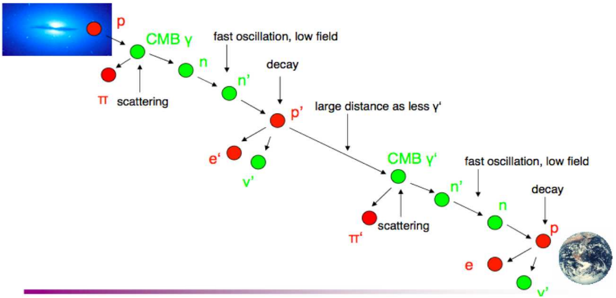
- Excess of cosmogenic photons ?

Standard GZK mechanism of UHECR produces too much cascades – contradicts to Fermi-LAT photon spectrum at $E \sim 1$ TeV – local Fog ?

From where highest energy CR are expected ?



$n - n'$ oscillation and UHECR propagation



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 in the UHECR propagation

Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

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Baryon number is not conserved in propagation of the UHECR

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

In the intergalactic space magnetic fields are extremely small.

But for relativistic neutrons transverse component of B is enhanced by Lorentz factor: $B_{\rm tr} = \gamma B$ $(\gamma \sim 10^{11}$ for $E \sim 100$ EeV)

Average oscillation probability: $P_{nn'} = \frac{1}{1+q(E)}$

$$q = 0.45 \times \left(\frac{\tau_{nn'}}{1\ {\rm s}}\right)^2 \times \left(\frac{B_{\rm tr} - B'_{\rm tr}}{1\ {\rm fG}}\right)^2 \times \left(\frac{E}{100\ {\rm EeV}}\right)^2$$

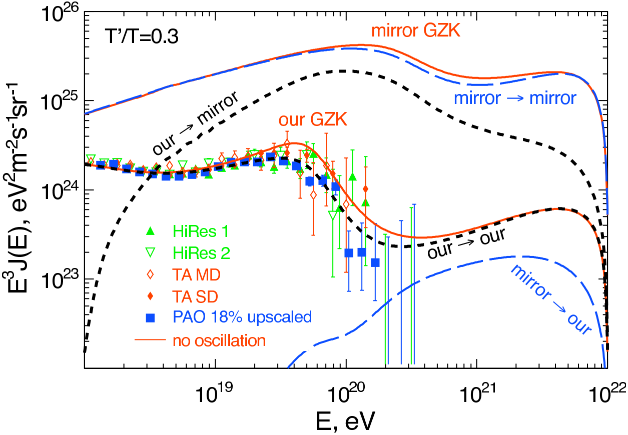
If $q(E) < 1$, $n - n'$ oscillation becomes effective

$\frac{n'_{\rm CMB}}{n_{\rm CMB}} = \left(\frac{T'}{T}\right)^3 \ll 1$ $\frac{n'_{\rm EBL}}{n_{\rm EBL}} \sim 1$ M-star formation & evolution

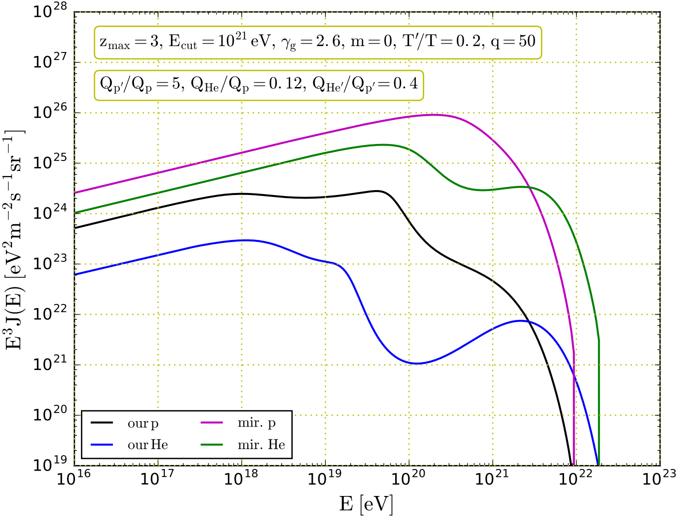
Earlier (than GZK) cutoff in cosmic rays

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

Baryon number is not conserved in propagation of the UHECR



Ordinary and Mirror UHECR



Swiss Cheese Model: Mirror CRs are transformed into ordinaries in nearby Voids. Z.B., Biondi, Gazizov, 2018

Summary

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Chapter II: neutron – mirror neutron mixing

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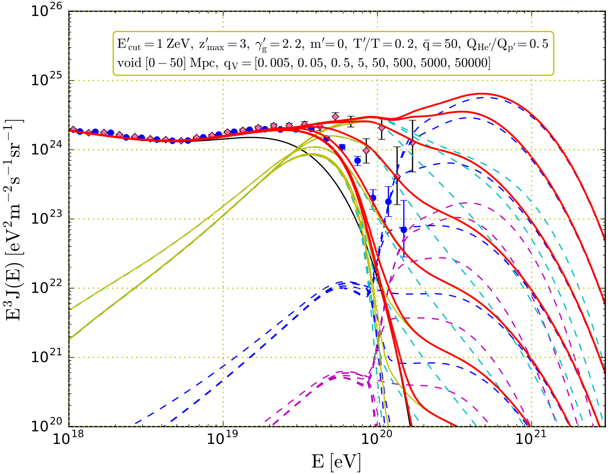
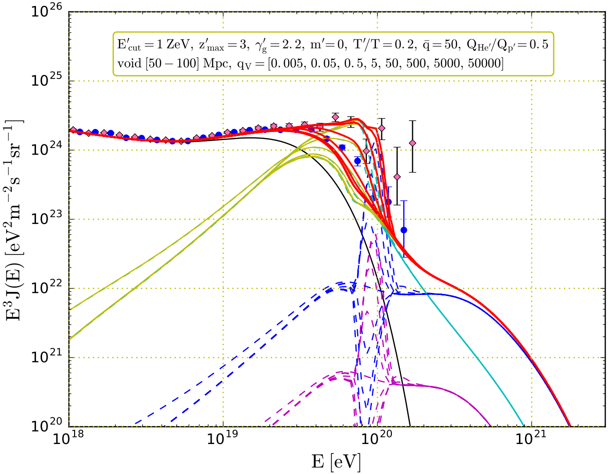
$n \to n'$ probability depends on magnetic field in Void: $P_{nn'} = \frac{1}{1+q(E)}$

Adjacent Void (0–50 Mpc) $\quad q = 0.5 \times \left(\frac{\tau_{nn'}}{1\ \mathrm{s}}\right)^2 \left(\frac{B_{\rm tr} - B'_{\rm tr}}{1\ \mathrm{fG}}\right)^2 \left(\frac{E}{100\ \mathrm{EeV}}\right)^2$



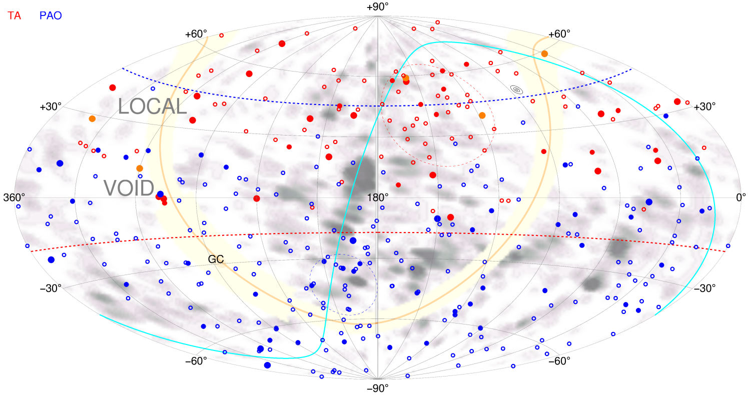
More distant Void (50–100 Mpc)



Is northern sky (TA) is more "voidy" than the Southern sky (PAO) ?

Arrival directions TA and PAO events of $E > 100$ EeV

- TA 2008-14 $\quad E > 100$ EeV, $\quad 80 \div 100$ EeV, $\quad 57 \div 80$ EeV
- Pierre Auger 2004-14 $\quad$ .... the same for $1.1 \times E$



TA events: autocorrelations & with tracers

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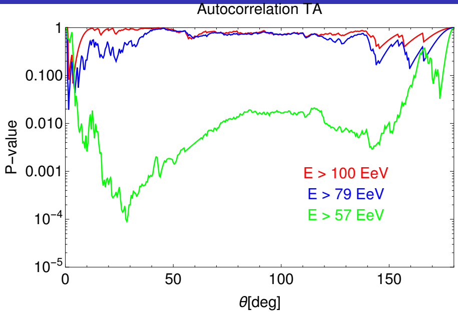
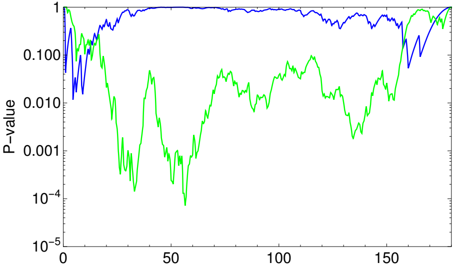
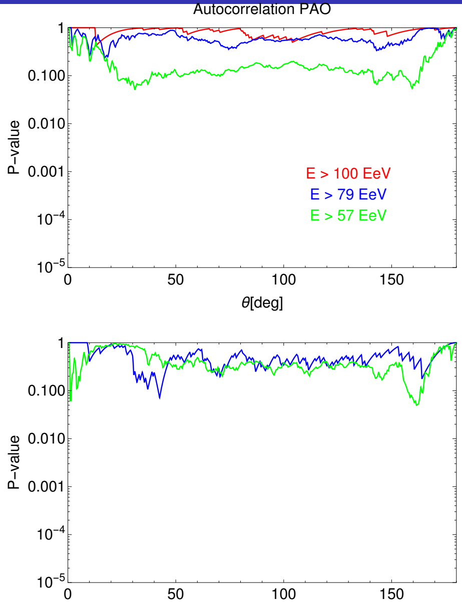




Auger events: autocorrelations & with tracers



Are North Sky and South Sky different ?

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:26 (22pp), 2012 April HUCHRA ET AL.

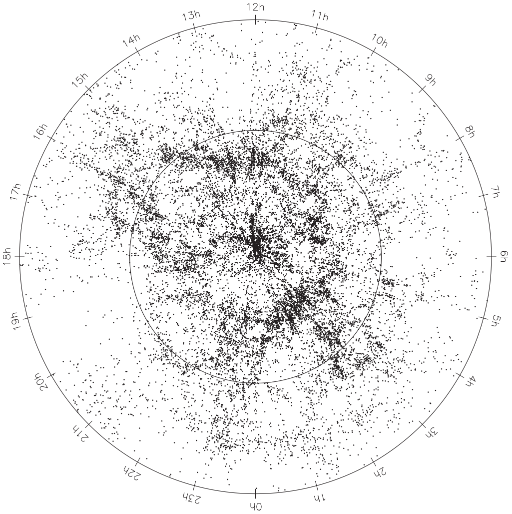


Figure 7. Hockey Puck plot—a full cylinder section—of 2MRS in the north celestial cap. The view is looking downward from the NCP, the thickness of the "puck" is 8000 km s^{-1}, and its radius is 15,000 km s^{-1}.

Are South Sky and North Sky different ?

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:26 (22pp), 2012 April HUCHRA ET AL.

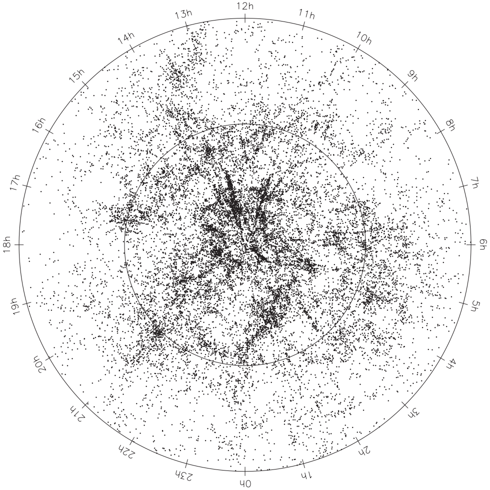


Figure 8. Same as Figure 7 but for the south celestial cap.

Parallel/Mirror Dark World

(Fantastic Beasts and Where to Find Them)

Zurab Berezhiani

Summary

Introduction: Mirror Matter

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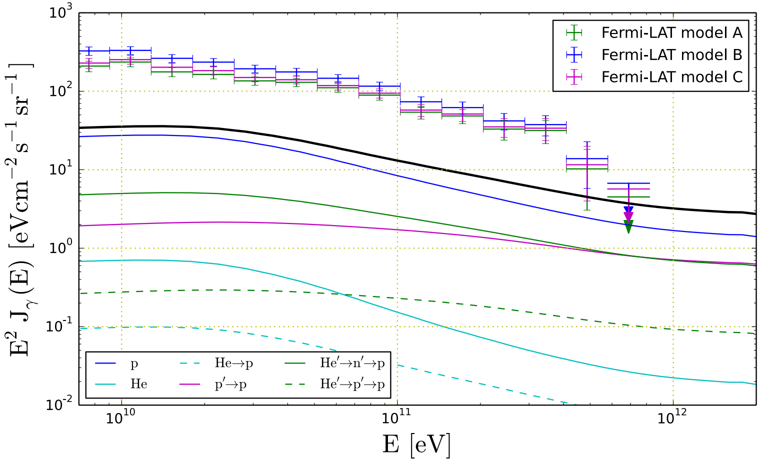
Backup

Cosmogenic gammas vs Fermi-LAT IGRB spectrum



Serenpidity: *Who are you, Mr. DM ?*

- Have you relations with other (fundamental) problems? *Yes*
- Do you manage to match your Ω to $5\,\Omega_B$? *Yes*
- Are you cold? Or self-interacting & dissipative? *Depends when...*
- Are you neutral? Or you have electric charges? *Depends which...*
- Do you agree with astrophysical tests (BBN, CMB, LSS, ...) ? *Yes*
- Can you form halos, stars & massive Black Holes? *Yes*
- Are you directly detectable? Can you be converted in visible? *Yes*
- Do you send indirect signals via cosmic rays & gammas? *Yes*
- Can you be produced at LHC or other experimental facilities? *Yes*

– Let me guess, is your name Susy? *No! but I know her very well*

– Are you heavy or light? *Well, I'm just normal ...*

– Are you stable? *Stable enough... but my longevity also has limits*

– Are you really dark? *Well, it's relative ... to someone I'm blond*

– Are you single? *I'm a family ...*

B-genesis and DM require new physics: but which ?

Why $\Omega_D/\Omega_B \sim 1$?

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 $m_X = ?$, $n_X = ?$

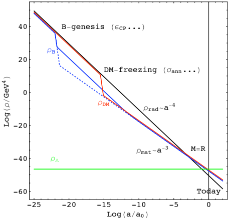
and why $m_X n_X = 5 m_B n_B$?

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

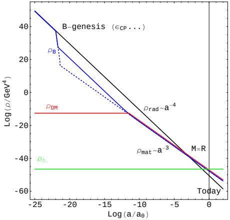
• Axion	• $m_a \sim$ meV	$n_a \sim 10^4 n_\gamma$	– CDM
• Neutrinos	• $m_\nu \sim$ eV	$n_\nu \sim n_\gamma$	– HDM ($\times$)
• Sterile ν'	• $m_{\nu'} \sim$ keV	$n_{\nu'} \sim 10^{-3} n_\nu$	– WDM
• WIMP	• $m_X \sim$ TeV	$n_X \sim 10^{-3} n_B$	– CDM
• WimpZilla	• $m_X \sim$ ZeV	$n_X \sim 10^{-12} n_B$	– CDM

How these Fine Tunings look ...

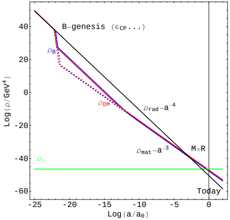
B-genesis + WIMP



B-genesis + axion



B-cogenesis

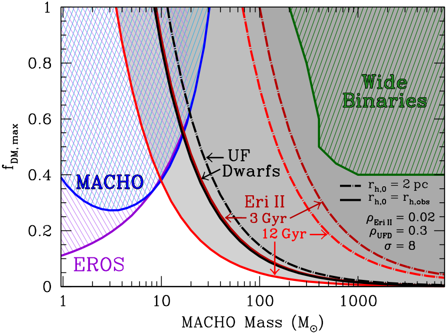


B-genesis + WIMP	B-genesis + axion	B-cogenesis
$m_X n_X \sim m_B n_B$	$m_a n_a \sim m_B n_B$	$m_{B'} n_{B'} \sim m_B n_B$
$m_X \sim 10^3 m_B$	$m_a \sim 10^{-13} m_B$	$m_{B'} \sim m_B$
$n_X \sim 10^{-3} n_B$	$n_a \sim 10^{13} n_B$	$n_{B'} \sim n_B$
Fine Tuning?	Fine Tuning?	Natural ?

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

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



GW events without any optical counterpart

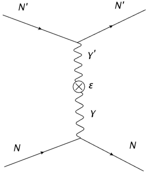
point towards massive BH compact binaries, $M \sim 10 - 30\ M_\odot$ and radius $R \sim 10 R_\odot$

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 ?

Discussing $\mathcal{L}_{\text{mix}}$: possible portal between O and M particles

- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$



Experimental limit $\epsilon < 4 \times 10^{-7}$
Cosmological limit $\epsilon < 5 \times 10^{-9}$

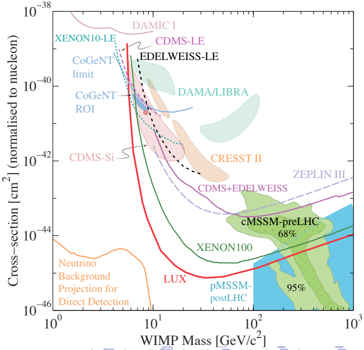
Makes mirror matter nanocharged ($q \sim \epsilon$)
A promising portal for DM direct detection Foot, 2003

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

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

or

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



OM-MM interactions in the Early Universe after recombination

After recombination fractions $\sim 10^{-4}$ of OM and $\sim 10^{-3}$ of MM remains ionized. $\gamma - \gamma'$ kinetic mixing $\rightarrow$ Rutherford scatterings $ep' \to ep'$, $ee' \to ee'$ etc

Relative motion (rotation) of O and M matter drags electrons but not protons/ions which are much heavier. So circular electric currents emerge which can generate magnetic field. MHD equations with the source (drag) term induces magnetic seeds $B, B' \sim 10^{-15}$ G in galaxies/clusters then amplified by dynamo. So magnetic fields $\sim \mu$G can be formed in very young galaxies Z.B., Dolgov, Tkachev, 2013

MM capture by Earth can induce mirror magnetic field in the Earth, even bigger than ordinary 0.5 G.

New EDGES measurements of 21 cm emission (T-S hydrogen) indicates that at redshift $z \sim 17$ baryons were factor 2 cooler than predicted: if true, it can be beautiful implication of OM matter cooling (momentum transfer) via their Rutherford collisions with (cooler) MM

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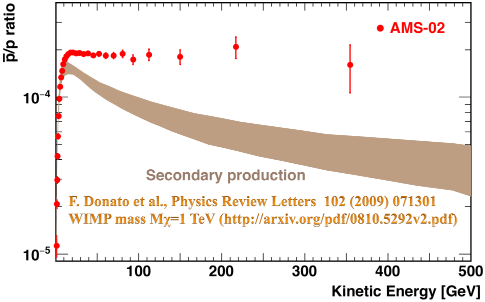
Mirror matter is a hidden antimatter: antimatter in the cosmos?

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 ?



Free neutron– antineutron oscillation

Two states, n and $\bar{n}$

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

Oscillation probability $P_{n\bar{n}}(t) = \frac{\varepsilon^2}{\omega_B^2} \sin^2(\omega_B\, t), \quad \omega_B = \mu_n B$

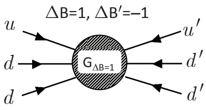
If $\omega_B t \gg 1$, then $P_{n\bar{n}}(t) = \frac{1}{2}(\varepsilon/\omega_B)^2 = \frac{(\varepsilon t)^2}{(\omega_B t)^2}$

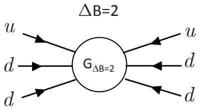
If $\omega_B t < 1$, then $P_{n\bar{n}}(t) = (t/\tau)^2 = (\varepsilon t)^2$

"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
$\tau > 2.7 \times 10^8 \quad \rightarrow \quad \varepsilon < 7.7 \times 10^{-24}$ eV
At ESS 2 orders of magnitude better sensitivity can be achieved, down to $\varepsilon \sim 10^{-25}$ eV

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

Neutron – mirror neutron oscillation probability

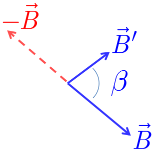
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}'\sigma \end{pmatrix}$$

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

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

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

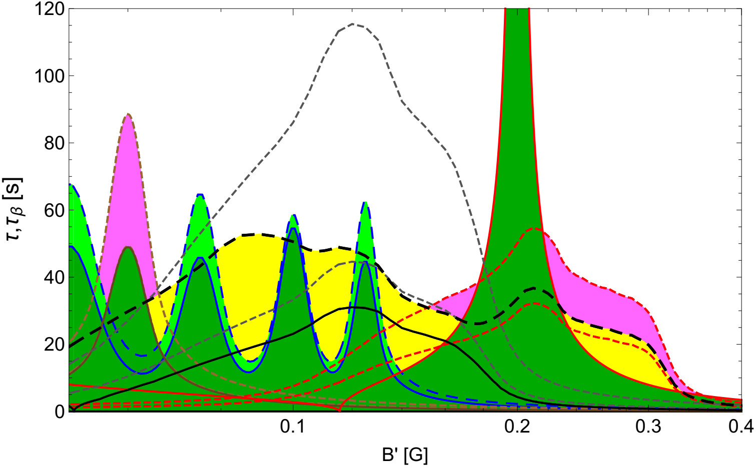
$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$



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

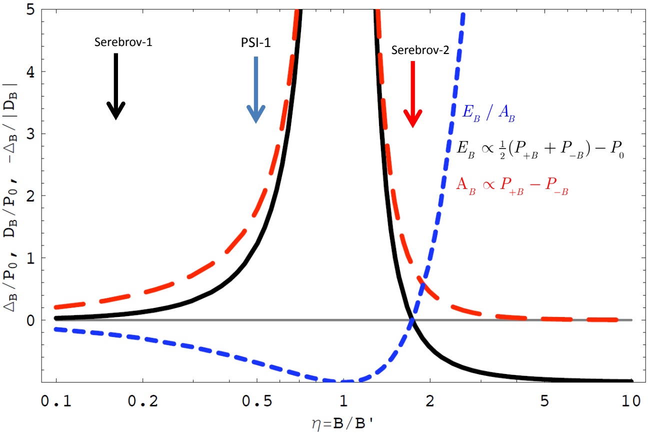
$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} = N_{collis} d_B(t) \cdot \cos\beta \leftarrow \text{ assymetry}$$

Experimental limits on $n - n'$ oscillation time



A and E are expected to depend on magnetic field

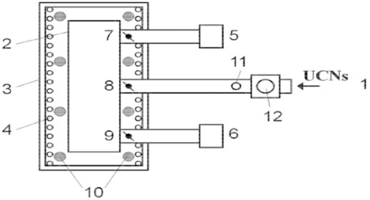
E.g. assume B'=0.12 Gauss



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.

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

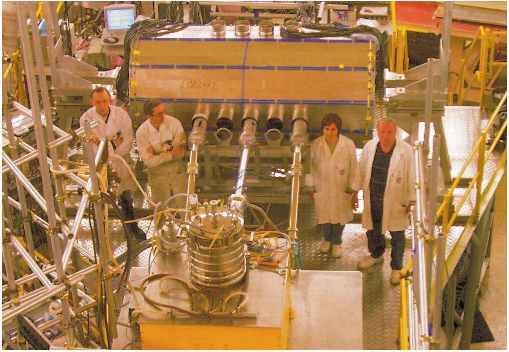
$$\frac{N_{B1}(T_S)}{N_{B2}(T_S)} = \exp\left[\left(\bar{\mathcal{P}}_{B2} - \bar{\mathcal{P}}_{B1}\right)\nu T_S\right]$$

So if we find that:

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

Experiments

Several experiment were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN



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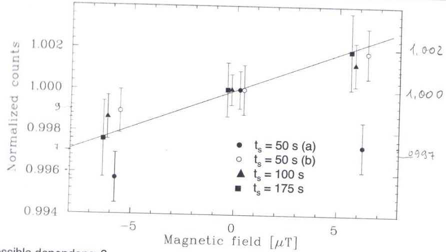
Serebrov – Cheking PSI Anomaly

PAUL SCHERRER INSTITUT PSI

Counts vs B-field (nn')

UCN Ultra Cold Neutron Source



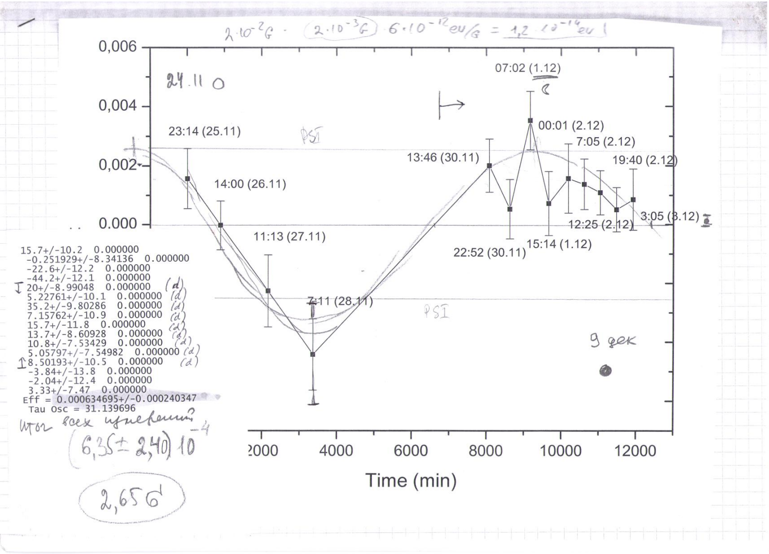
Possible dependency?

→ Does not affect nn' analysis as nn'-signature depends on B^2!

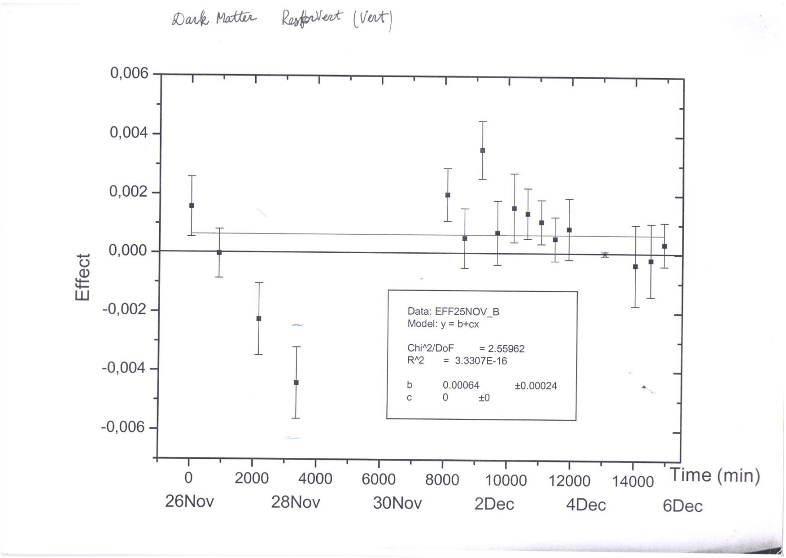
Andreas Knecht | B & L Violation Workshop, 20. – 22. September 2007 | 22

0,9976 ± 0,0020	1,0018 ± 0,0013
0,9986 ± 0,0010	0,9973 ± 0,0013
0,9990 ± 0,0010	1,0012 ± 0,0012
0,9958 ± 0,0013	1,0019 ± 0,0020
0.997786 ± 0.0007349	1.00036 ± 0.0006855
	99778

Serebrov experiment III – 1st Fax



Serebrov experiment III – 2nd Fax



Neutron – mirror neutron oscillation

Eur. Phys. J. C (2012) 72:1974
DOI 10.1140/epjc/s10052-012-1974-5

THE EUROPEAN PHYSICAL JOURNAL C

Letter

Magnetic anomaly in UCN trapping: signal for neutron oscillations to parallel world?

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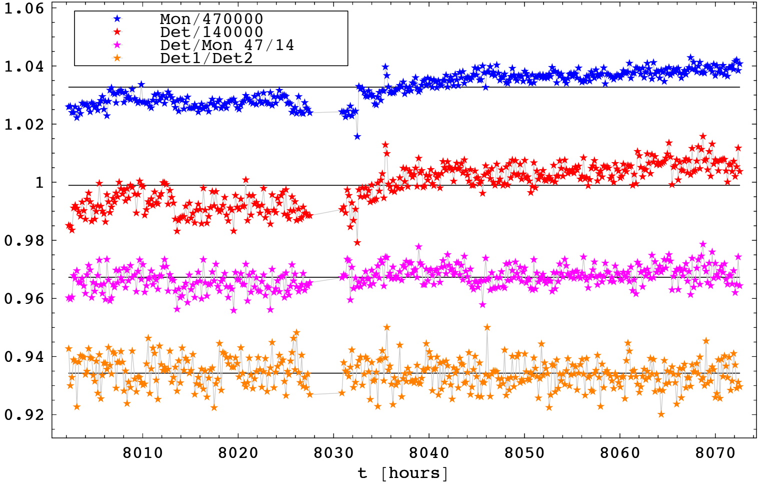
Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron traps, where they can be revealed by the magnetic field dependence of n–n' transition probability. In this work we reanalyze the experimental data acquired by the group of A.P. Serebrov at Institute Laue–Langevin, and find a dependence at more than 5σ away from the null hypothesis. This anomaly can be interpreted as oscillation of neutrons to mirror neutrons with a timescale of few seconds, in the presence of a mirror magnetic field order 0.1 G at the Earth. This result, if confirmed by future experiments, will have deepest consequences for fundamental particle physics, astrophysics and cosmology.

Parallel matter can be a viable candidate for dark matter [7–9]. Certain $B-L$ and CP violating processes between ordinary and mirror particles can generate the baryon asymmetries in both sectors [10–12] which scenario can naturally explain the relation $\Omega_D/\Omega_B \simeq 5$ between the dark and visible matter fractions in the Universe [13–16]. Such interactions can be mediated by heavy messengers coupled to both sectors, as right-handed neutrinos [10–12] or extra gauge bosons/gauginos [17].[1] In the context of extra dimensions, ordinary and mirror sectors can be modeled as two parallel three-dimensional branes and particle processes between them mediated by the bulk modes or "baby branes" can be envisaged [24].

On the other hand, these interactions can induce mixing phenomena between ordinary and mirror particles. In fact, any *neutral* particle, *elementary or composite*, may oscillate

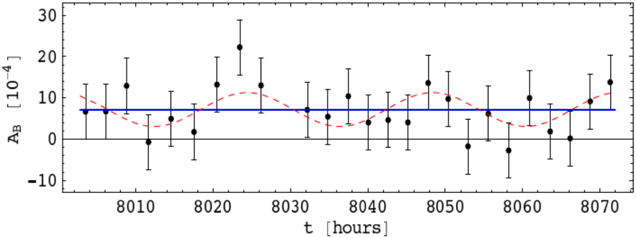
Serebrov III – Drifts of detector and monitor counts

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Serebrov III – magnetic field vertical

Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



Analysis pointed out the presence of a signal:

$$A(B) = (7.0 \pm 1.3) \times 10^{-4} \qquad \chi^2_{/dof} = 0.9 \longrightarrow 5.2\sigma$$

interpretable by $n \to n'$ with $\tau_{nn'} \sim 2 - 10s$' and $B' \sim 0.1G$

Z.B. and Nesti, 2012

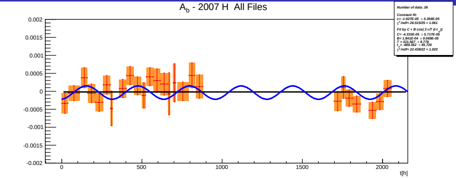
Earth mirror magnetic field via the electron drag mechanism

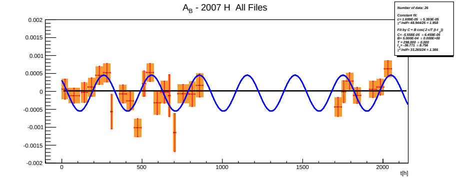
Earth can accumulate some, even tiny amount of mirror matter due to Rutherford-like scattering of mirror matter due to photon-mirror photon kinetic mixing.
Rotation of the Earth drags mirror electrons but not mirror protons (ions) since the latter are much heavier.
Circular electric currents emerge which 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.

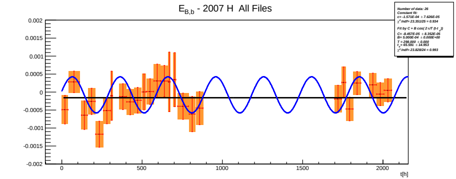
Such mechanism can also induce cosmological magnetic fields
Z.B., Dolgov, Tkachev, 2013

Serebrov II – magnetic field Horizontal

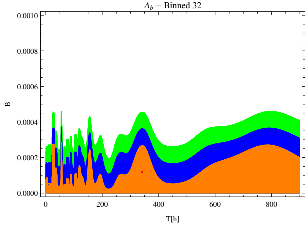
$$\{b_-, B_-, B_+, b_+, b_+, B_+, B_-, b_-\} \ , \ B = 0.2 \text{ G} \ , \ b < 10^{-3} \text{ G}$$

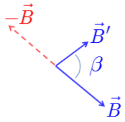


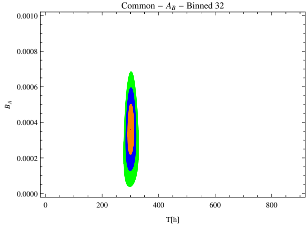


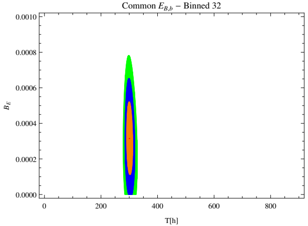


Serebrov 2007 – magnetic field Horizontal









Summary

Introduction: Mirror Matter

Chapter I: *Neutrino - mirror neutrino mixings*

Chapter II: *neutron – mirror neutron mixing*

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

My own neasurements 2014 at ILL – with Biondi, Geltenbort et al.

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