



Fantastic Beasts
and Where to
Find Them ...
or
Alice in the
Mirrorland

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

Backup

Fantastic Beasts and Where to Find Them ... or Alice in the Mirrorland

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SW 13: Hot Topics in Modern Cosmology
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Introduction

Disclaimer:

- No torsioning of gravity
- No Ghost-fighting
- No entangled (poor) Cats ...

In short, no Sado-Mazo no transgressions

- All innocent and peaceful as stories of Alice or Harry

Open your mind, relax and go downstream

Tomorrow never knows



Bright & Dark Sides of our Universe

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Today's Universe: flat $\Omega_{\text{tot}} \approx 1$ (*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: $\Omega_M/\Omega_\Lambda \simeq 0.45$, ($\Omega_M = \Omega_D + \Omega_B$)
 $\rho_\Lambda \sim \text{Const.}$, $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*

Anthropic 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. But the Wurstle has two Ends ...

Dark sector ... similar to our luminous sector?

For observable particles *very complex physics !!*

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

photon, electron, nucleons (quarks), neutrinos, gluons, $W^\pm - Z$, Higgs ...

long range EM forces, confinement scale Λ_{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 Λ'_{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 chinese, **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.





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

Two parities

Fermions and anti-fermions :

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

$B=1/3 \quad L=1 \quad B=1/3 \quad L=1$



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

$B=-1/3 \quad L=-1 \quad B=-1/3 \quad L=-1$



Twin Fermions and anti-fermions :

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

$B'=1/3 \quad L'=1 \quad B'=1/3 \quad L'=1$



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

$B'=-1/3 \quad L'=-1 \quad B'=-1/3 \quad L'=-1$



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

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

PZ_2 symmetry ($L, R \rightarrow R, L$): $Y' = Y^* \quad B \rightleftharpoons B' \rightarrow B \rightleftharpoons B' \rightleftharpoons B \rightleftharpoons B'$

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

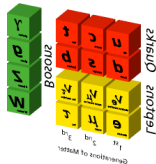
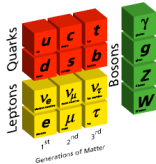
$$G \times G'$$

Regular world

Mirror world

Elementary Particles

Elementary Particles



- Two identical gauge factors, e.g. $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}}$
- Exact parity $G \rightarrow G'$: **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** \mathcal{L}_{mix}

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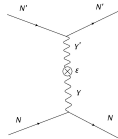
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\mathcal{L}_{mix} : possible portals to M World

- **Kinetic mixing of photons** $\epsilon F^{\mu\nu} F'_{\mu\nu}$
Makes mirror matter nanocharged ($q \sim \epsilon$)
 $\epsilon < 3 \times 10^{-7}$ (EXP) $\epsilon < 5 \times 10^{-9}$ (COSM)
GUT: $\frac{1}{M^2} (\Sigma G^{\mu\nu}) (\Sigma' G'_{\mu\nu})$ $\epsilon \sim \left(\frac{M_{\text{GUT}}}{M} \right)^2$



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

SUSY: $\frac{1}{M}(\phi_1 \phi_2)(\phi'_1 \phi'_2)$
 $\lambda \sim M_{\text{SUSY}}/M$
or NMSSM (Twin Higgs)
 $\lambda S(\phi_1 \phi_2 + \phi'_1 \phi'_2) + \Lambda S + \dots$

- **Neutrino-neutrino'** $D = 5$: $\frac{1}{M}(l\phi)(l'\phi')$ $(\Delta L, \Delta L' = 1)$
Weinberg: $\frac{1}{M}(l\phi)(l\phi)$ $(\Delta L = 2)$ $\frac{1}{M}(l'\phi')(l'\phi')$ $(\Delta L' = 2)$

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



– 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 :

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

But M World is OK if : **Z.B., Comelli, Villante, 2001**

(A) after inflation M world was born colder than O world

(B) all particle interactions between M and O sectors are so feeble that cannot bring them into equilibrium in later epochs

(C) two systems evolve adiabatically with the universe expansion (no entropy production); the temperature ratio T'/T remains \sim constant.

If $x = T'/T \ll 1$, BBN is OK $75\% \text{ H} + 25\% \text{ } ^4\text{He}$

In turn, for M world this implies helium domination: **$25\% \text{ H}' + 75\% \text{ } ^4\text{He}'$** .



Hydrogen Lifetime ? Helium Abundance ?

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*Two things are infinite: the universe and human stupidity;
but I'm not sure about the universe* – A. Einstein

*Two things are infinite: the universe and alien stupidity;
but I'm not sure about the universe* – B. Zweistein

*There is more stupidity than hydrogen in the universe,
and it has a longer lifetime* – Frank Zappa

*There is more stupidity than helium in the universe,
and it has a larger binding energy* – Appaz Knarf



Brief Cosmology of Mirror World

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$T'/T < 0.5$ is enough to concord with the BBN limits

Cosmological limits are more severe, requiring $T'/T < 0.2$ or so.

Because of $T' < T$, in mirror photons decouple much earlier than ordinary photons, and after that M matter behaves for the structure formation and CMB anisotropies essentially as CDM. This concurs M matter with WMAP/Planck, BAO, $Ly-\alpha$ etc. if $T'/T < 0.2$ or so.

Halo problem – if $\Omega'_B \simeq \Omega_B$, M matter makes ~ 20 % of DM, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)

But perhaps 100 % ? if $\Omega'_B \simeq 5\Omega_B$: – M world is helium dominated, and the star formation and evolution can be much faster. Halos could be viewed as mirror elliptical galaxies, with our matter inside forming disks.

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



Experimental and observational manifestations

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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}_{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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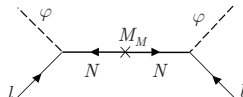
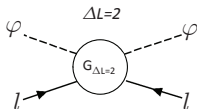
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Neutrino – mirror neutrino mixings

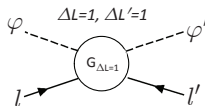


B-L violation in O and M sectors: Active-sterile mixing

- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ ($\Delta L = 2$) – 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 $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$

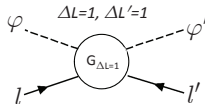
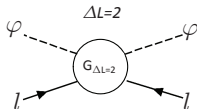


Mirror neutrinos are natural candidates for sterile neutrinos



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

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 $l\phi \rightarrow \bar{l}\bar{\phi}$ ($\Delta L = 2$) and $l\phi \rightarrow \bar{l}'\bar{\phi}'$ ($\Delta L = 1, \Delta L' = 1$)



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

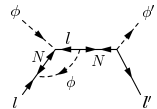
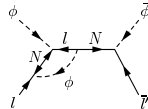
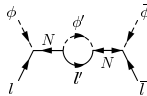
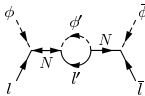
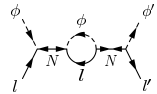
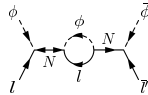
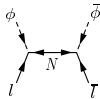
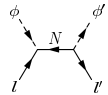
Green light to celebrated conditions of Sakharov



Co-leptogenesis:

Z.B. and Bento, PRL 87, 231304 (2001)

Operators $\frac{1}{M}(\bar{l}\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(\bar{l}\bar{\phi})(l'\bar{\phi}')$ via seesaw mechanism – heavy RH neutrinos N_j with Majorana masses $\frac{1}{2}Mg_{jk}N_jN_k + \text{h.c.}$



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

Z_2 (Xerox) symmetry $\rightarrow Y' = Y$,

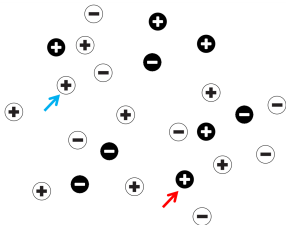
PZ_2 (Mirror) symmetry $\rightarrow Y' = Y^*$



Co-leptogenesis: Mirror Matter as hidden Anti-Matter

Z.B., arXiv:1602.08599

Hot O World \rightarrow *Cold M World*



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

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

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

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

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

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

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

$$\text{Mirror (PZ}_2\text{): } Y' = Y^* \rightarrow \Delta\sigma' = -\Delta\sigma \rightarrow B, B' > 0$$

$$\text{Xerox (Z}_2\text{): } Y' = Y \rightarrow \Delta\sigma' = \Delta\sigma = 0 \rightarrow B, B' = 0$$

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

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

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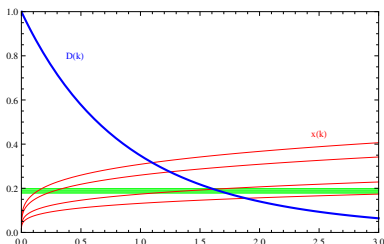
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If $k = \left(\frac{\Gamma_2}{H}\right)_{T=T_R} \sim 1$, Boltzmann Eqs.

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

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



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Chapter II

Neutron – mirror neutron mixing



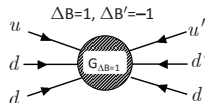
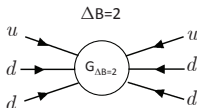
B violating operators between O and M particles in \mathcal{L}_{mix}

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)

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



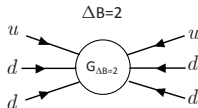
Oscillations $n(udd) \leftrightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ ($\Delta B = 2$)

$n(udd) \rightarrow \bar{n}'(\bar{u}'\bar{d}'\bar{d}')$, $n'(udd) \rightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$ ($\Delta B = 1, \Delta B' = -1$)



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

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

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

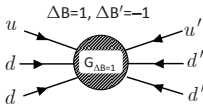
Present bounds on ϵ from nuclear stability

$$\begin{aligned} \epsilon < 1.2 \times 10^{-24} \text{ eV} &\rightarrow \tau > 1.3 \times 10^8 \text{ s} && \text{Fe, Soudan 2002} \\ \epsilon < 2.5 \times 10^{-24} \text{ eV} &\rightarrow \tau > 2.7 \times 10^8 \text{ s} && \text{O, SK 2015} \end{aligned}$$



Neutron – mirror neutron mixing

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



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

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 $\epsilon^{-1} = \tau_{n\bar{n}'} \sim 1 \text{ s}$
without contradicting experimental and astrophysical limits.
(c.f. $\tau_{n\bar{n}'} > 2.5 \times 10^8 \text{ s}$ 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

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Free Neutrons: Where to find Them ?

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

But most of neutrons bound in nuclei

$n \rightarrow \bar{n}'$ or $n' \rightarrow \bar{n}$ 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 $n' \rightarrow \bar{n}$ can solve Lithium problem)

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



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Z.B., Biondi, Mannarelli, Tonelli



Neutron Stars: $n - n'$ conversion

Two states, n and n'

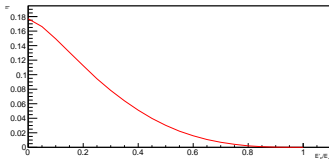
$$H = \begin{pmatrix} m_n + V_n + \mu_n \mathbf{B} \sigma & \varepsilon \\ \varepsilon & m'_n + V'_n - \mu_n \mathbf{B}' \sigma \end{pmatrix}$$

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

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

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

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



$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \quad \frac{dN_2(t)}{dt} = \Gamma N_1$$

$$N_1 + N_2 = \text{Const.}$$



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

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

$$T_{\mu\nu} = T_{\mu\nu}^1 + T_{\mu\nu}^2 = \text{diag}(\rho g_{tt}, p g_{rr}, pr^2, pr^2 \sin^2 \theta)$$

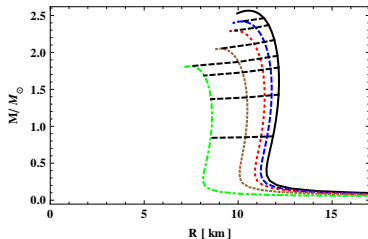
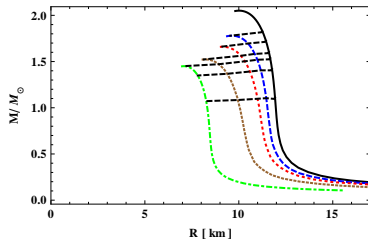
$$\rho = \rho_1 + \rho_2 \quad \& \quad p = p_1 + p_2, \quad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



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



Neutron Stars: observational $M - R$

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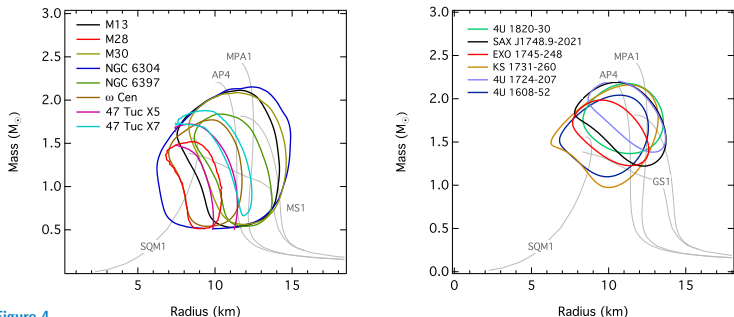


Figure 4

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

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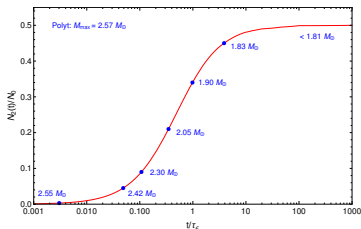
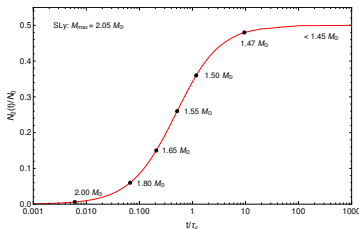
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$$\frac{dN_1(t)}{dt} = -\Gamma N_1 \quad \frac{dN_2(t)}{dt} = \Gamma N_1$$

Initial state $N_1 = N_0, N_2 = 0$

$$N_1 + N_2 = \text{Const.}$$

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

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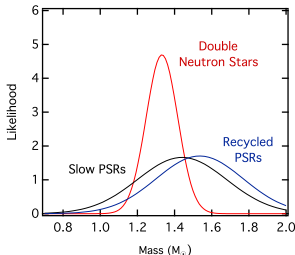
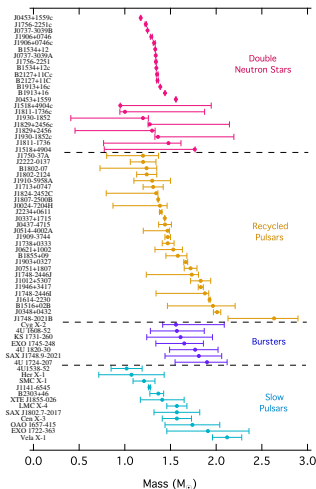
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Z.B., Biondi, Gazizov



UHECR and GZK cutoff

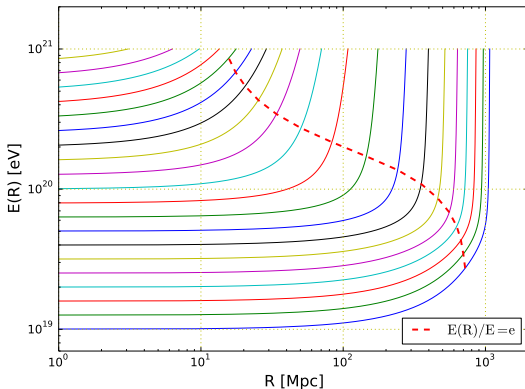
GZK cutoff:

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

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

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

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



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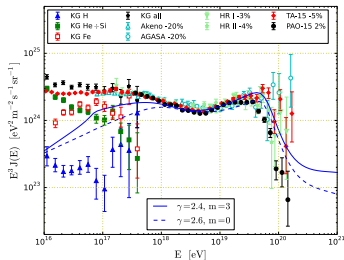
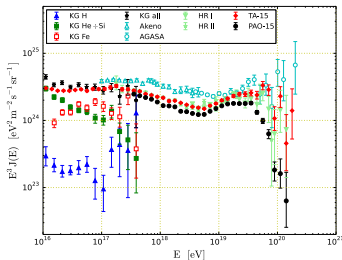


UHECR and GZK cutoff

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

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

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



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

Events with $E > 100 \text{ EeV}$ 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 $E > E_{\text{GZK}}$ (which spot is cold for $E < E_{\text{GZK}}$) . PAO anisotropies not so prominent: warm spot around Cen A, but observe dipole for $E > 10$ EeV – are two skies really 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 ?

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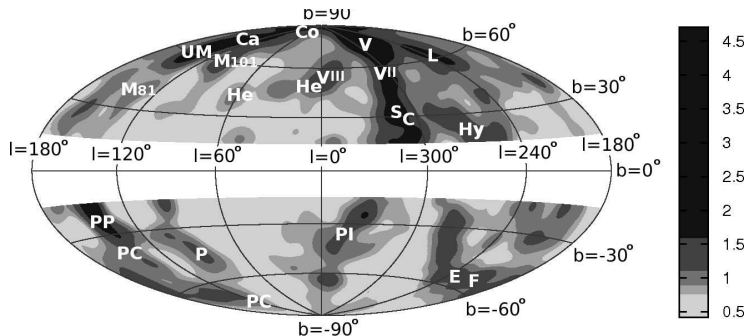
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Ordinary and Mirror UHECR

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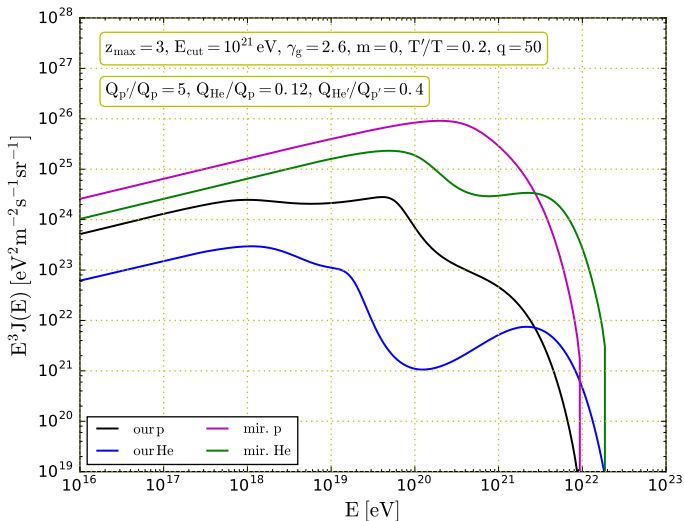
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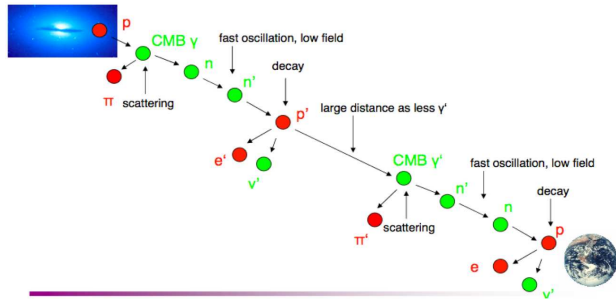
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$n - n'$ oscillation and UHECR propagation



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

- A. $p + \gamma \rightarrow p + \pi^0$ or $p + \gamma \rightarrow n + \pi^+$ $P_{pp,pn} \approx 0.5$ $l_{\text{mfp}} \sim 5 \text{ Mpc}$
- B. $n \rightarrow n'$ $P_{nn'} \simeq 0.5$ $l_{\text{osc}} \sim \left(\frac{E}{100 \text{ EeV}}\right) \text{ kpc}$
- C. $n' \rightarrow p' + e' + \bar{\nu}'_e$ $l_{\text{dec}} \approx \left(\frac{E}{100 \text{ EeV}}\right) \text{ Mpc}$
- D. $p' + \gamma' \rightarrow p' + \pi'^0$ or $p' + \gamma' \rightarrow n' + \pi'^+$ $l'_{\text{mfp}} \sim (T/T')^3 l_{\text{mfp}} \gg 5 \text{ Mpc}$



$n - n'$ oscillation in the UHECR propagation

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: $B_{\text{tr}} = \gamma B$ ($\gamma \sim 10^{11}$ for $E \sim 100$ EeV)

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

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

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

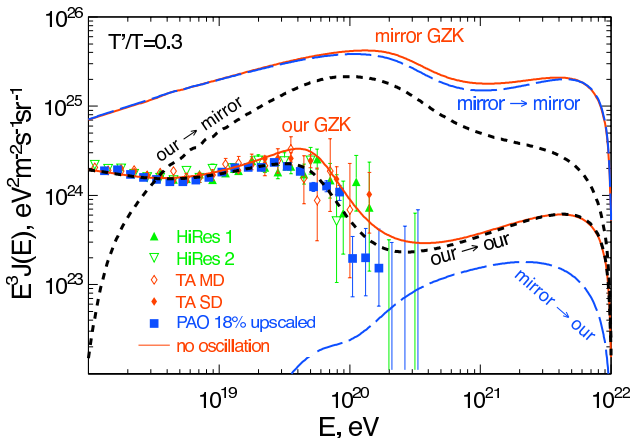
$$\frac{n'_{\text{CMB}}}{n_{\text{CMB}}} = \left(\frac{T'}{T} \right)^3 \ll 1 \quad \frac{n'_{\text{EBL}}}{n_{\text{EBL}}} \sim 1 \quad \text{M-star formation \& evolution}$$



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





Swiss Cheese Model: UHECR from Voids – adjacent Void

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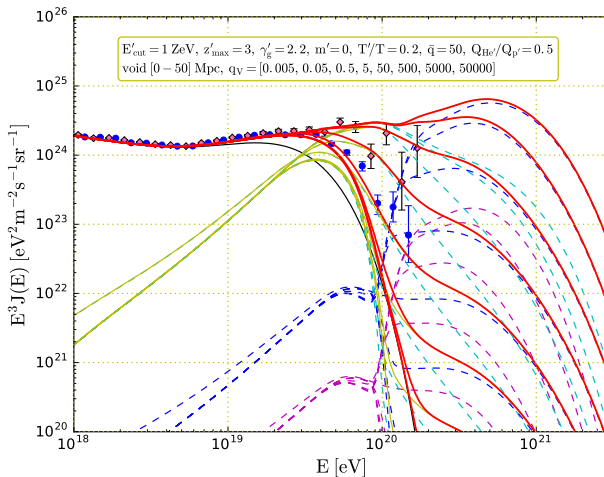
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More distant Void

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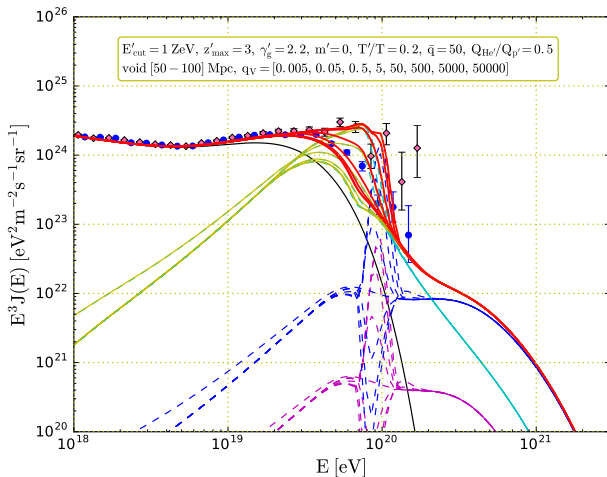
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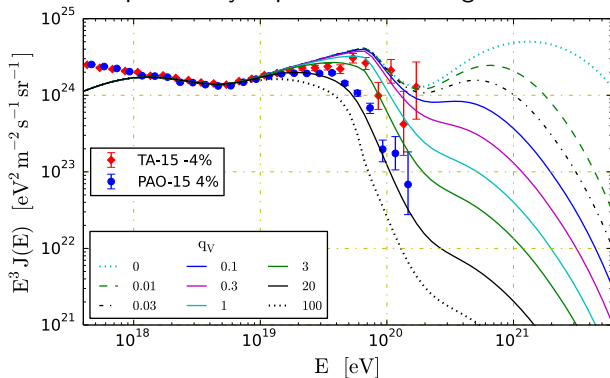
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Z.B., Biondi, Gazizov, 2018

Mirror CRs are transformed into ordinaries in nearby Voids. $n - n'$ oscillation probability depends on the magnetic fields in the Voids.





Are North Sky and South Sky different ?

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 199:26 (22pp), 2012 April

HUCHRA ET AL.

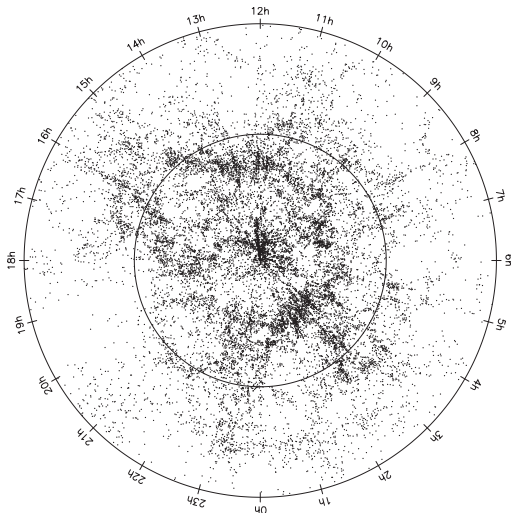


Figure 7. Hockey Puck plot—a full cylinder section—of 2MRS in the north celestial cap. The view is looking downward from the NCP, the thickness of the “puck” is 8000 km s^{-1} , and its radius is $15,000 \text{ km s}^{-1}$.

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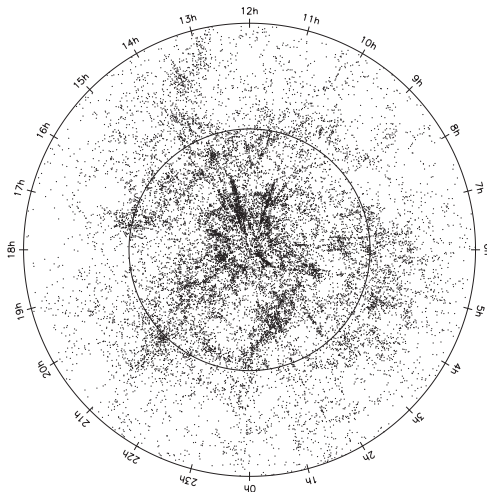


Figure 8. Same as Figure 7 but for the south celestial cap.

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

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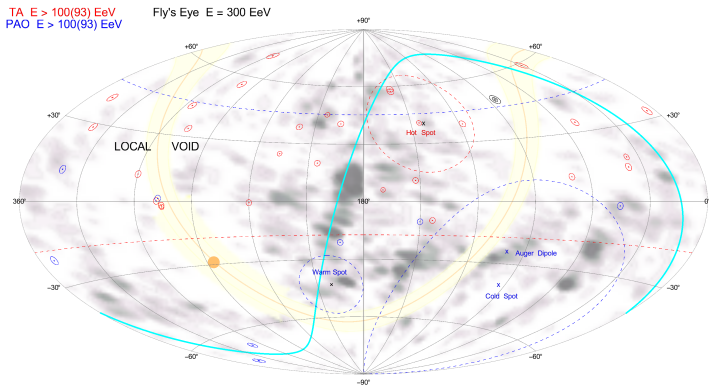
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Arrival directions of $E > 80$ EeV events

Fantastic Beasts
and Where to
Find Them ...
or
Alice in the
Mirrorland

Zurab Berezhiani

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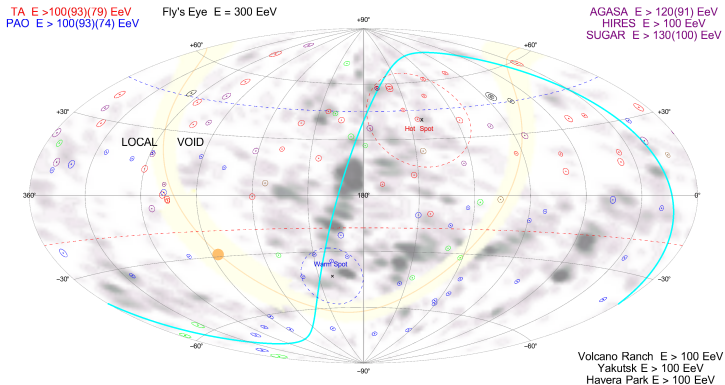
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Correlations: arrival directions with AGN+RG vs. TA $E > 100$ EeV

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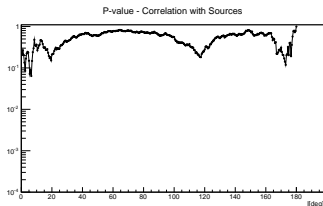
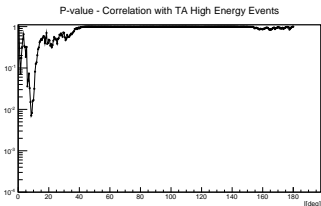
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Cosmogenic gammas vs Fermi-LAT IGRB spectrum

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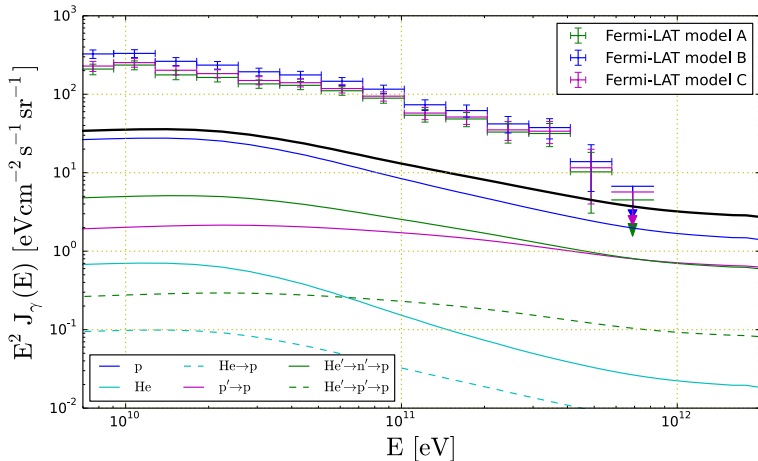
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Serenpidity: *Who are you, Mr. DM ?*

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- 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-gensis 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

$$\rho_B = m_B n_B, \quad m_B \simeq 1 \text{ GeV}, \quad \eta = n_B/n_\gamma \sim 10^{-9}$$

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



How these Fine Tunings look ...

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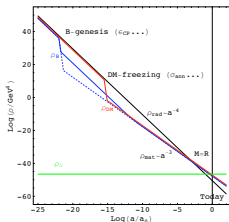
Chapter II:
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B-genesis + WIMP



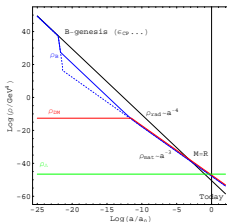
$$m_X n_X \sim m_B n_B$$

$$m_X \sim 10^3 m_B$$

$$n_X \sim 10^{-3} n_B$$

Fine Tuning?

B-genesis + axion



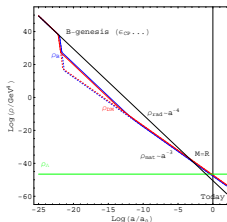
$$m_a n_a \sim m_B n_B$$

$$m_a \sim 10^{-13} m_B$$

$$n_a \sim 10^{13} n_B$$

Fine Tuning?

B-cogenesis



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

$$m_{B'} \sim m_B$$

$$n_{B'} \sim n_B$$

Natural ?

Two different New Physics for B-genesis and DM ?

Or co-genesis by the same Physics explaining why $\Omega_{DM} \sim \Omega_B$?



CMB and LSS power spectra

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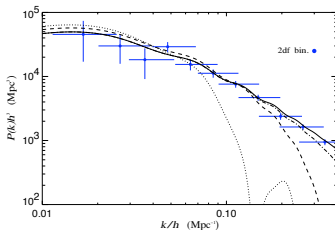
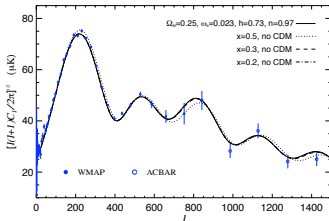
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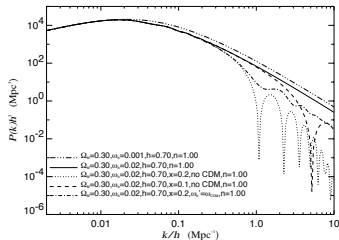
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Z.B., Ciarcelluti, Comelli, Villante, 2003



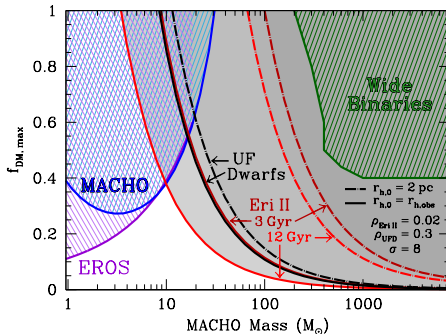
*Acoustic oscillations and Silk damping
at short scales: $x = T'/T < 0.2$*



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

Picture of Galactic halos as mirror ellipticals (Einasto density profile),
O matter disk inside (M stars = Machos).

Micro lensing 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}_{mix} : possible portal between O and M particles

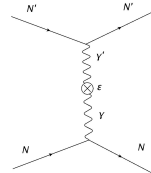
- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

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**



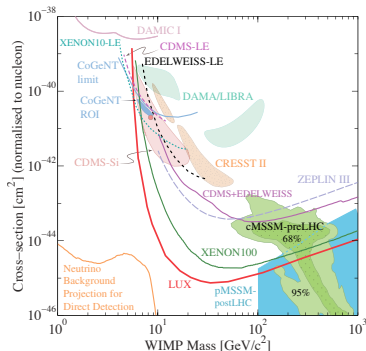
Mirror atoms: $\text{He}' - 75\%$,
 $\text{C}', \text{N}', \text{O}'$ etc. few %

Rutherford-like scattering

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

or

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





OM-MM interactions in the Early Universe after recombination

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



Free Energy from DM for the future generations ?

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$n' \rightarrow \bar{n}$ produces our antimatter from mirror 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



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

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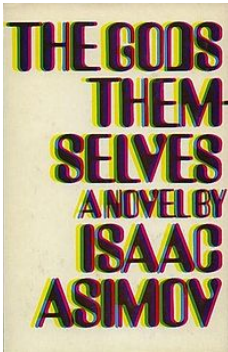
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First Part: *Against Stupidity ...*

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

Third Part: *... Contend in Vain?*

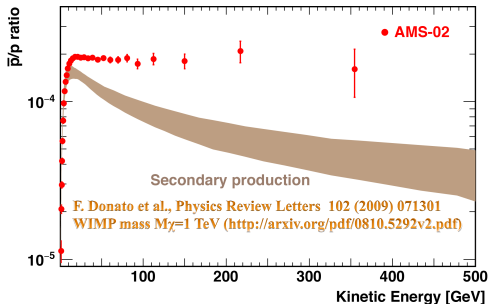
*"Mit der Dummheit kämpfen Götter
selbst vergebens!"* – Friedrich Schiller



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, $n' \rightarrow \bar{n}$, which then decays as $\bar{n} \rightarrow \bar{p} + \bar{e} + \nu_e$.

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

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

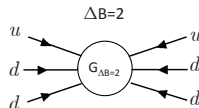
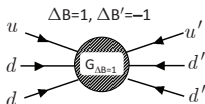
$\tau > 2.7 \times 10^8 \rightarrow \varepsilon < 7.7 \times 10^{-24}$ eV

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



Neutron – mirror neutron mixing

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



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

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

Surprisingly, $n - \bar{n}'$ oscillation can be as fast as $\epsilon^{-1} = \tau_{nn'} \sim 1 \text{ s}$, without contradicting any experimental and astrophysical limits.

(c.f. $\tau_{n\bar{n}} > 2.5 \times 10^8 \text{ s}$ for neutron – antineutron oscillation)

Disappearance $n \rightarrow \bar{n}'$ (regeneration $n \rightarrow \bar{n}' \rightarrow n$) can be searched at small scale 'Table Top' experiments



Neutron – mirror neutron oscillation probability

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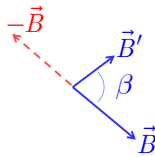
$$H = \begin{pmatrix} m_n + \mu_n \mathbf{B} \sigma & \epsilon \\ \epsilon & m_n + \mu_n \mathbf{B}' \sigma \end{pmatrix}$$

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

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

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

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



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

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



Experimental limits on $n - n'$ oscillation time

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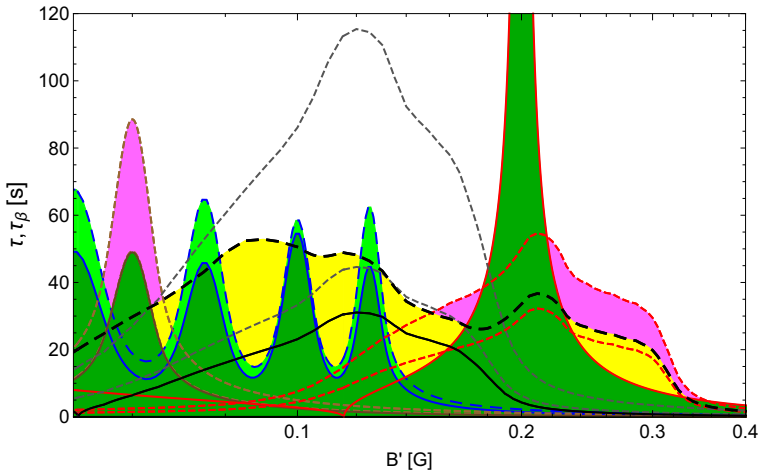
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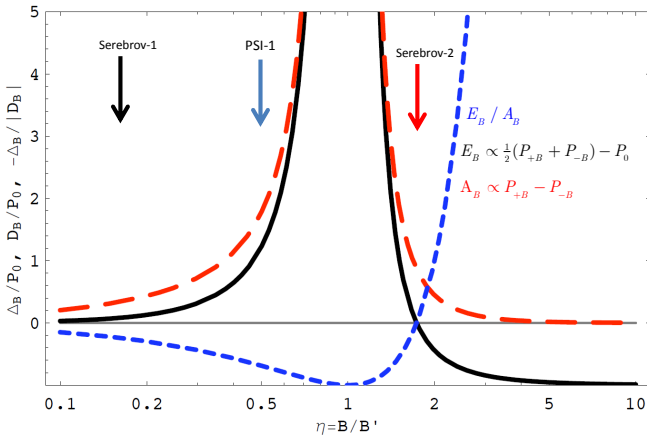
Backup





A and E are expected to depend on magnetic field

E.g. assume $B'=0.12$ Gauss

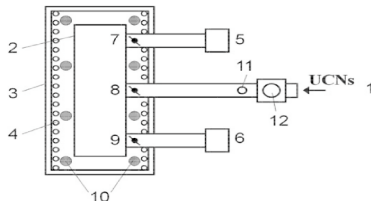




Experimental Strategy

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.

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

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

So if we find that:

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



Experiments

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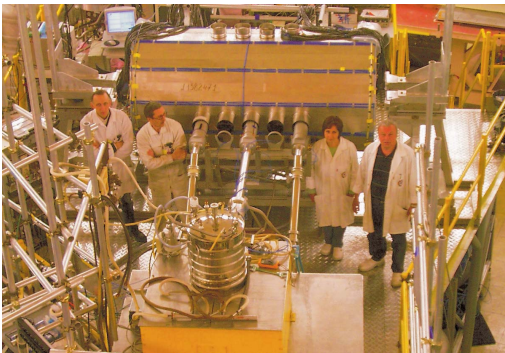
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Several experiments were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN





Serebrov – Cheking PSI Anomaly

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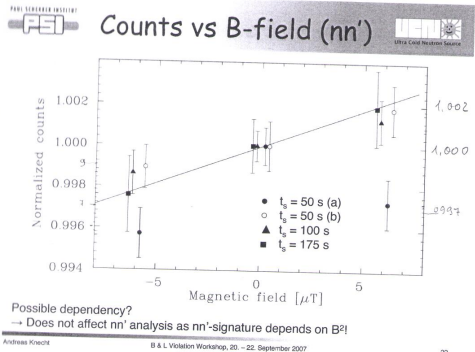
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$$\begin{aligned} 0.9976 \pm 0.0020 \\ 0.9986 \pm 0.0010 \\ 0.9990 \pm 0.0010 \\ 0.9998 \pm 0.0013 \end{aligned}$$

$$\begin{aligned} 1.0018 \pm 0.0013 \\ 0.9972 \pm 0.0013 \\ 1.0012 \pm 0.0012 \\ 1.0019 \pm 0.0020 \end{aligned}$$

$$0.997786 \pm 0.0002349$$

$$1.00036 \pm 0.0006855$$



Serebrov experiment III – 1st Fax

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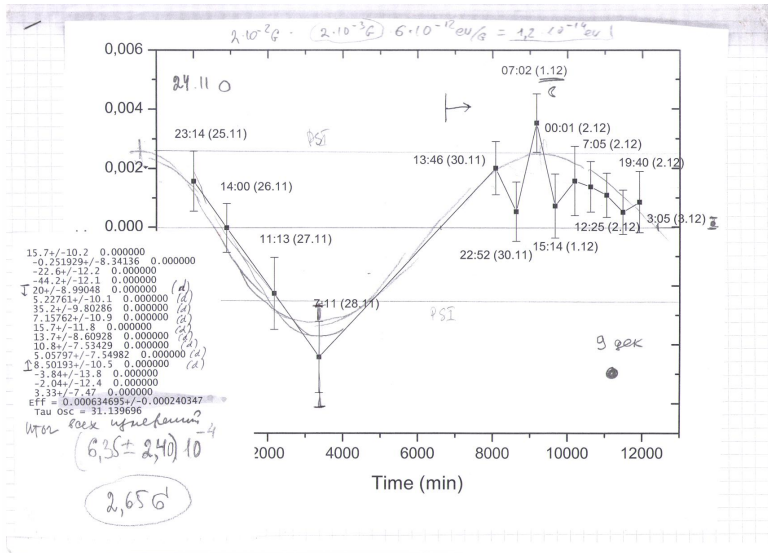
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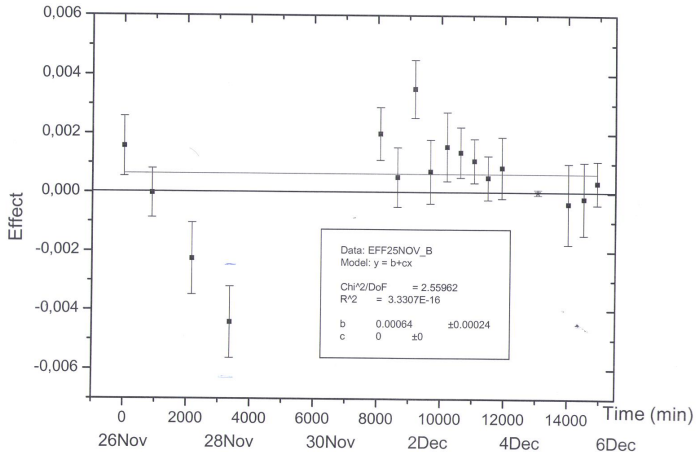
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Serebrov experiment III – 2nd Fax

Dark Matter RosettaVent (Vent)



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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

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and Where to
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or
Alice in the
Mirrorland

Zurab Berezhiani

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*neutron - mirror
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Backup



Serebrov III – Drifts of detector and monitor counts

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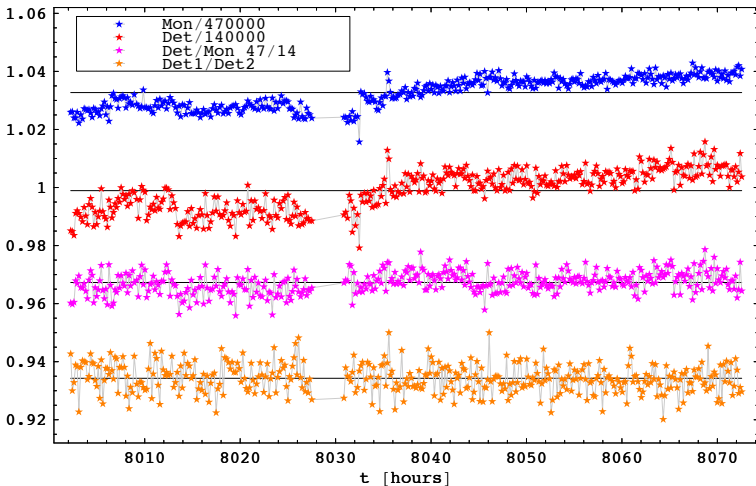
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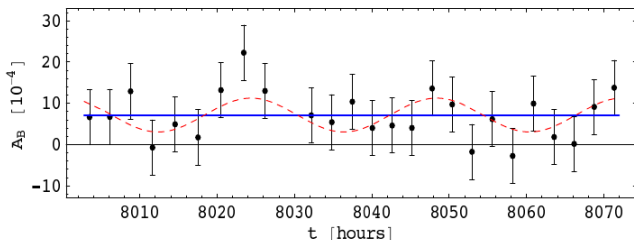
Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G





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:

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

interpretable by $n \rightarrow n'$ 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

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

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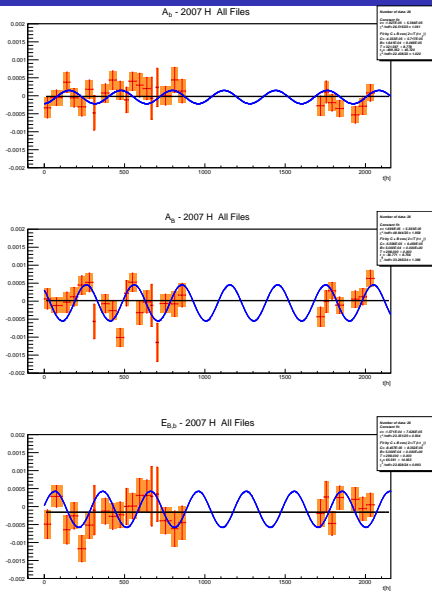
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Serebrov 2007 – magnetic field Horizontal

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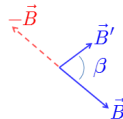
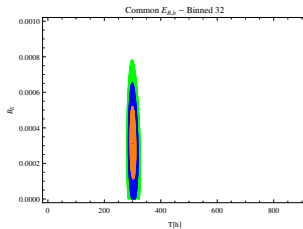
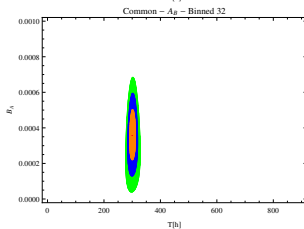
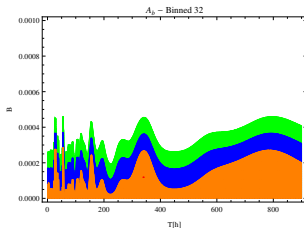
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My own measurements 2014 at ILL – with Biondi, Geltenbort et al.

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