



TBA (Twin
Baryon
Asymmetry):
Astrophysical
and other
implications

Zurab Berezhiani

Summary

Intro: Big
Challenges for
SM

TBA and DM
from Parallel
'Mirror' World

Neutron – mirror
neutron
oscillation $n - n'$

$n \leftrightarrow n'$ in
Neutron Stars

$n - n'$ in
UHECR

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TBA (Twin Baryon Asymmetry): Astrophysical and other implications

Zurab Berezhiani

University of L'Aquila and LNGS

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Big Challenges

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Big Challenges to the SM (and BSM) that require the physics Beyond BSM

- $\Omega_{\text{DM}}/\Omega_B \simeq 5$?
- Who injects anti-nuclei in cosmic rays (AMS 2) ?
- EECR: where do they all come from?
And where do they all belong?



1st challenge: Visible & Dark matter in the Universe

- $\Omega_B \simeq 0.05$ observable matter: **electron, proton, neutron !**
- $\Omega_D \simeq 0.25$ dark matter: **WIMP? axion? sterile ν ? ...**
- $\Omega_\Lambda \simeq 0.70$ dark energy: **Λ -term? Quintessence?**
- $\Omega_R < 10^{-3}$ relativistic fraction: **relic photons and neutrinos**

Matter – dark energy coincidence: $\Omega_M/\Omega_\Lambda \simeq 3/7$, ($\Omega_M = \Omega_D + \Omega_B$)
 $\rho_\Lambda \sim \text{Const.}$, $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*

Anthropic explanation: if not *Today*, then *Yesterday* or *Tomorrow*.

Baryon and dark matter Fine Tuning: $\Omega_D/\Omega_B \simeq 5$
 $\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$: *why* $\rho_D/\rho_B \sim 1$ - *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 BA and DM? Not appealing: looks as Fine Tuning



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

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

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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 $m_X n_X \simeq 5 m_B n_B$?

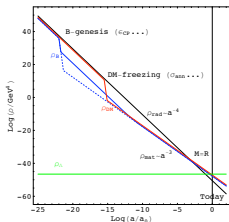
n_X is model dependent: DM particle mass and interaction strength
(production and annihilation cross sections), freezing conditions, etc.

- | | | |
|------------------|------------------------------|-------------------------------------|
| • 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 |

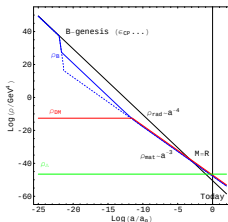


How these Fine Tunings look ...

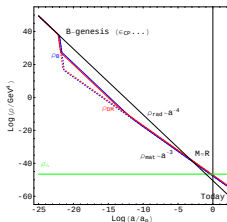
B-genesis + WIMP



B-genesis + axion



B-cogenesis



$$m_X n_X \sim m_B n_B$$

$$m_X \sim 10^3 m_B$$

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

Fine Tuning?

$$m_a n_a \sim m_B n_B$$

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

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

Fine Tuning?

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

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

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

Natural ?

Two different New Physics for B-genesis and DM ?

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



Parallel sector

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TBA and DM from Parallel 'Mirror' World:

Going Beyond BSM – coming to another SM:



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

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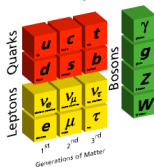
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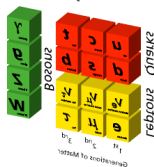
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Regular world $G \times G'$ + universal gravity
Mirror world

Elementary Particles



Elementary Particles



- Two identical gauge sectors, e.g. $SU(5) \times SU(5)'$, with identical Lagrangians: $\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}}$

- Exact parity $G \leftrightarrow G'$: **no new parameters in $\mathcal{L}'$** (parallel branes, etc.)

Beyond SM: $G \rightarrow G' = \text{BSM}$ Beyond BSM: $G' \rightarrow G = \text{SM}$
Beyond² = 1

- 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** $\mathcal{L}_{\text{mix}}$
new parameters – constrained only by experimental and astrophysical limits



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

Fermions and anti-fermions :

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

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



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

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



Twin Fermions and anti-fermions :

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

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



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

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



$$\mathcal{L}_{\text{Yuk}} = \bar{u}_L Y_u q_L \bar{\phi} + \bar{d}_L Y_d q_L \phi + \bar{e}_L Y_e l_L \phi + \text{h.c.}$$

$$\mathcal{L}'_{\text{Yuk}} = \bar{u}'_L Y'_u q'_L \bar{\phi}' + \bar{d}'_L Y'_d q'_L \phi' + \bar{e}'_L Y'_e l'_L \phi' + \text{h.c.}$$

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

$$PZ_2 = Z_2 \times CP \text{ symmetry } (L, R \rightarrow R, L): \quad Y' = Y^* \Rightarrow B \equiv B' \Rightarrow B \equiv B'$$

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Mixed interactions – Naturalness and BSM Physics

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$G \times G'$ complemented by concepts of SUSY, GUT, $U(1)_{PQ}$ etc.

Cross-interactions between two sectors – smallness of dimensionless couplings

- $\mathcal{L}_{\text{mix}} = \epsilon F^{\mu\nu} F'_{\mu\nu} \rightarrow \mathcal{L}_{\text{mix}} = \frac{\Sigma \Sigma'}{M_P^2} G^{\mu\nu} G'_{\mu\nu}$ in GUT e.g. $SU(5) \times SU(5)'$

$$\epsilon = \frac{\langle \Sigma \rangle \langle \Sigma' \rangle}{M_P^2} \ll 1 \quad (\epsilon < 10^{-9} \text{ cosmological limit – BBN})$$

- $\mathcal{L}_{\text{mix}} = \lambda (H^\dagger H) (H'^\dagger H') \rightarrow W_{\text{mix}} = \frac{1}{M_P} (H_1 H_2) (H'_1 H'_2) + \text{SSB in SUSY}$

$$\lambda \sim M_{\text{SSB}}/M \ll 1 \quad (\lambda < 10^{-7} \text{ cosmological limit – BBN})$$

- $D = 5$ operators $\frac{1}{M} \ell \ell' H H'$

Neutrino portal: sterile neutrinos as mirror neutrinos – also as origin of baryon asymmetry (see further ...)



In turn use for Naturalness Problems in BSM Physics

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- Flavor – Gauged chiral symmetry between families, e.g. $G_H = SU(3)_H$ (or $SU(3)_L \times SU(3)_R$ etc.)

Fermion mass from operators $\frac{\bar{\chi}^{ij}}{\Lambda} d_i^c q_j H$ etc. (or $\frac{\Lambda}{\chi_{ij}} d_i^c q_j H$ etc.)

– UV-complete by integrating out heavy VL fermions **Z.B., PLB 1983**

Fermion mass and mixing pattern stem from VEV hierarchy of flavons χ_{ij}
 $SU(3)_H \times U(1)_{\text{gl}} \rightarrow SU(2)_H \times U(1)'_{\text{gl}} \rightarrow U(1)_{\text{PQ}} \rightarrow \text{nothing}$
 (accidental global $U(1)$ by complex reps. of $SU(3)_H$ originates
 Peccei-Quinn $U(1)$, with flavor-changing axion etc.) – $Y_d = \frac{\langle \chi \rangle}{\Lambda}$ etc.

Now imagine that G_H is acting between two sectors:

$SM \times SM' \times SU(3)_H + PZ_2$ symmetry $\rightarrow SU(3)_H$ becomes vector-like
 – its anomalies cancel between ordinary and mirror fermions. (also flavons
 χ and $\bar{\chi}$ become chiral superfields, with $\chi \leftrightarrow \bar{\chi}$ under PZ_2)

Can realize MFV scenario in the context of SUSY quark-squark
 alignment: $\hat{M}_d^2 = m^2 + m_1^2 Y_d^\dagger Y_d + \dots$, $A_d = \mu Y_d + \mu_1 Y_d Y_d^\dagger Y_d + \dots$ etc.
 by analyticity of F-terms while gauge D terms are exactly cancelled by
 PZ_2 symmetry, $\langle \chi \rangle = \langle \bar{\chi} \rangle$ **Z.B., PLB 1998**

Gauge flavor bosons and FC phenomena, also as portal to DM

- Common $U(1)_{\text{PQ}}$ between two sectors – heavy axion as portal to DM

Z.B., Gianfagna, Giannotti, 2000, also Rubakov 1998 in different context



– 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 all is OK if :

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

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

$$\begin{aligned}
 x = T'/T \ll 1 & \implies \text{in O sector } 75\% \text{ H} + 25\% \text{ } ^4\text{He} \\
 & \implies \text{in M world } 25\% \text{ H}' + 75\% \text{ } ^4\text{He}'
 \end{aligned}$$

For broken PZ_2 , DM can be compact H' atoms or n' with $m \simeq 5 \text{ GeV}$ or (sterile) mirror neutrinos $m \sim \text{few keV}$

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Brief Cosmology of Mirror World

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- CMB & (linear) structure formation epoch

Since $x = T'/T \ll 1$, mirror photons decouple before M-R equality:

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

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

- Cosmic dawn: M world is colder (and helium dominated), the first M star can be formed earlier and reionize M sector ($z'_r \simeq 20$ or so vs $z_r = 10 \div 6$). – EDGES 21 cm at $z \simeq 17$?
Heavy first M stars ($M \sim 10^3 M_\odot$) and formation of central BH – Quasars?

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

Maybe not always: Galaxies with missing DM, or too many DM, etc. ?

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



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.

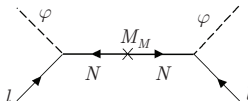
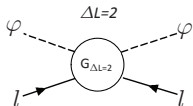
The most interesting interaction terms in $\mathcal{L}_{\text{mix}}$ are the ones which violate B and L of both sectors. [Neutral particles, elementary \(as e.g. neutrino\) or composite \(as the neutron or hydrogen atom\) can mix with their mass degenerate \(sterile\) twins:](#) matter disappearance (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\$.](#)



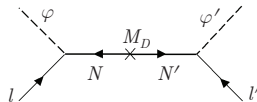
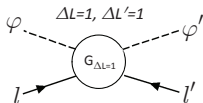
B-L violation in O and M sectors: Active-sterile mixing

- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ ($\Delta L = 2$) – 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)
Akhmedov, Z.B. and Senjanovic, 1992,
Foot and Volkas 1995, Z.B. and Mohapatra, 1995

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

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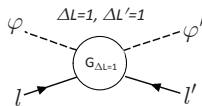
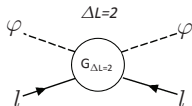
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L and L' violating operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ lead to processes $l\phi \rightarrow \bar{l}\bar{\phi}$ ($\Delta L = 2$) and $l\phi \rightarrow \bar{l}'\bar{\phi}'$ ($\Delta L = 1,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



Asymmetric reheating: our world is heated and mirror is empty:
but $l\phi \rightarrow \bar{l}'\bar{\phi}'$ heat also mirror world (but with $T' < T$)

- 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 in both sectors **Z.B. and Bento, PRL 87, 231304 (2001)**
naturally explaining $\Omega'_B \simeq 5 \Omega_B$ **Z.B., IJMP A19, 3775 (2004)**



Co-leptogenesis:

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

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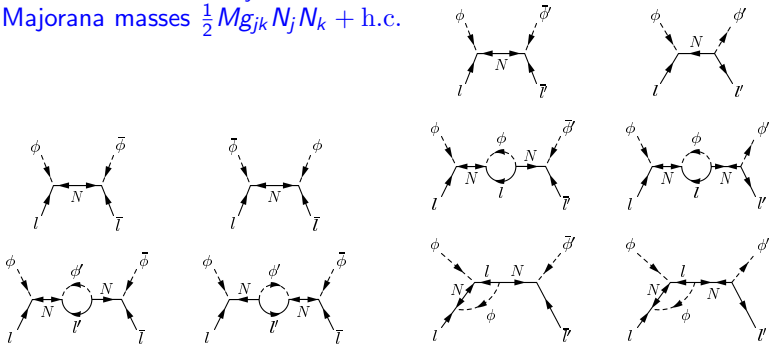
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Operators $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ and $\frac{1}{M}(l\bar{\phi})(l'\bar{\phi}')$ via seesaw mechanism –
heavy RH neutrinos N_j with
Majorana masses $\frac{1}{2}Mg_{jk}N_jN_k + \text{h.c.}$



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

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



Co-leptogenesis: Mirror Matter as Dark Anti-Matter

Z.B., arXiv:1602.08599

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

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

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

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

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

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

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

Mirror PZ_2 : $Y' = Y^* \rightarrow \Delta\sigma' = -\Delta\sigma \rightarrow B, B' > 0$

If $k = \left(\frac{\Gamma}{H}\right)_{T=T_R} \ll 1$

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



Cogenesis: $\Omega'_B \simeq 5\Omega_B$

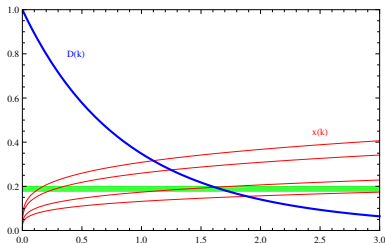
Z.B. 2003

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

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

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

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

Sign of BA is same for two sectors: $B > 0 \rightarrow B' > 0$
in other terms, both sectors are left-handed

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– Sign of mirror baryon asymmetry ?

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

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

Imagine a baryogenesis mechanism *separately* acting in O and M sectors!
– without involving cross-interactions in $\mathcal{L}_{\text{mix}}$

E.g. leptogenesis $N \rightarrow \ell\phi$ and $N' \rightarrow \ell'\phi'$

$Z_2: \rightarrow Y'_{u,d,e} = Y_{u,d,e}$ i.e. $\mathcal{B}' = 1$

– O and M sectors are CP-identical in same chiral basis O=left, M=left

$Z_2^{LR}: \rightarrow Y'_{u,d,e} = Y_{u,d,e}^*$ i.e. $\mathcal{B}' = -1$

– O sector in L-basis is identical to M sector in R-basis O=left, M=right

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

But switching on cross-interactions, violating B/L & B'/-L' – as mixings
neutron–neutron' $\epsilon nn' + \text{h.c.}$ $\Delta(B-B') = 0$ or $\nu\nu' + \text{h.c.}$ $\Delta(L-L') = 0$
 $\mathcal{B}' = -1 \rightarrow \bar{n}' \rightarrow n$ M (anti)matter $\rightarrow$ O matter but $\bar{\nu}' \rightarrow \bar{\nu}$
 $\mathcal{B}' = 1 \rightarrow n' \rightarrow \bar{n}$ M matter $\rightarrow$ O antimatter but $\nu' \rightarrow \nu$



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

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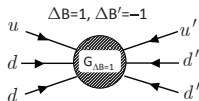
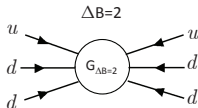
Ordinary quarks u, d (antiquarks $\bar{u}, \bar{d}$)
Mirror quarks u', d' (antiquarks $\bar{u}', \bar{d}'$)

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

$$\frac{1}{M^5}(udd)(udd)$$

&

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



Oscillations $n \rightarrow \bar{n}$ ($\Delta B = 2$)

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



Neutron– antineutron mixing

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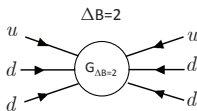
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Majorana mass of neutron $\epsilon(n^T C n + \bar{n}^T C \bar{n})$ violating B by two units
comes from six-fermions effective operator $\frac{1}{M^5}(udd)(udd)$



It causes transition $n(udd) \rightarrow \bar{n}(\bar{u}\bar{d}\bar{d})$, 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

$$\epsilon < 2.5 \times 10^{-24} \text{ eV} \rightarrow \tau > 2.7 \times 10^8 \text{ s}$$

$$\epsilon < 7.5 \times 10^{-24} \text{ eV} \rightarrow \tau > 0.9 \times 10^8 \text{ s}$$

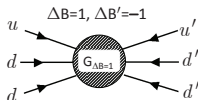
O, SK 2015

direct limit free n



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

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. $\tau > 10 \text{ yr}$ for neutron – antineutron oscillation)

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

Z.B. and Bento, PRL 96, 081801 (2006)

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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 are bound in nuclei

$n \rightarrow \bar{n}'$ conversions are effective only for free neutrons.

– it cannot occur for neutrons bound in nuclei – energy conservation!

Free neutrons are present only in

- Reactors & Spallation Facilities (challenge $\tau_{n\bar{n}'} < \tau_{dec} \simeq 10^3$ s)
- UHE Cosmic Rays: $p + \gamma \rightarrow n + \pi^+$, $N_A + \gamma \rightarrow N_{A-1} + n$
- $n \rightarrow \bar{n}'$ can take place in Neutron Stars (gravitationally bound)
– conversion of NS into mixed ordinary/mirror NS



Neutron – mirror neutron oscillation probability

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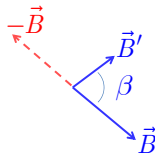
$$H = \begin{pmatrix} m_n + V_n + \mu_n \mathbf{B} \sigma & \epsilon \\ \epsilon & m_n + V'_n + \mu_n \mathbf{B}' \sigma \end{pmatrix}$$

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

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

Z.B. Eur.Phys.J C 64, 421 (2009)



Experiments

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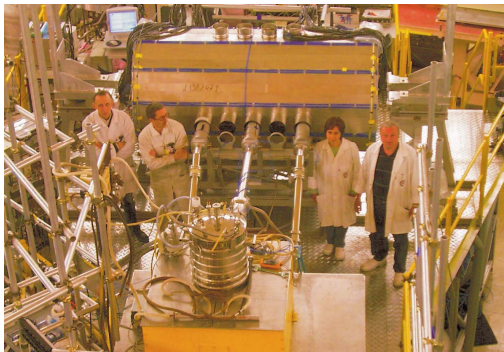
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Several experiment were done, 3 by PSI group, most sensitive by the Serebrov's group at ILL, with 190 l beryllium plated trap for UCN

5.3 σ anomaly in asymmetry



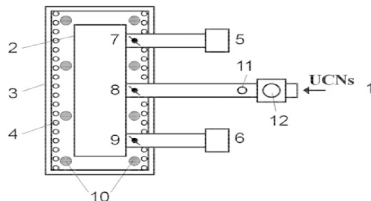
I myself have done another experiment with this chamber at ILL
– it was a fun!



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:

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



Serebrov III – magnetic field vertical

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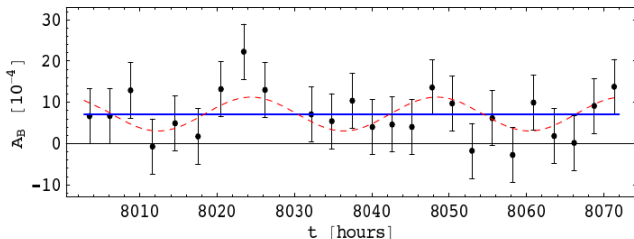
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Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



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



My own experiment at ILL – Z.B., Biondi, Geltenbort et al. 2018

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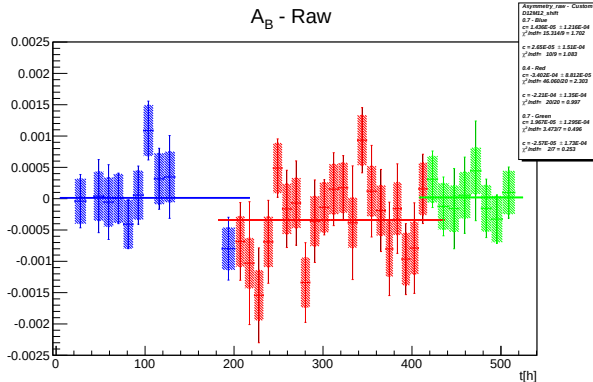
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$\sim 4\sigma$ anomaly in asymmetry reduced to 2.7σ



ZB, Biondi, Geltenbort et al, at ILL, Eur. Phys. J. C. 2018

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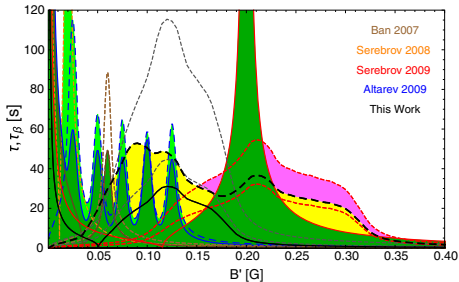
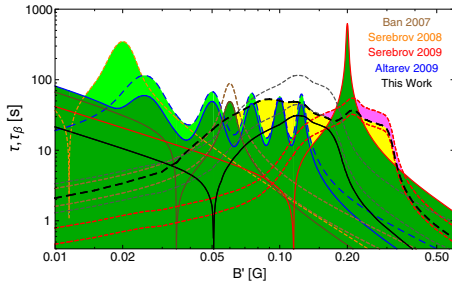
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nEDM Collaboration at PSI, 2021

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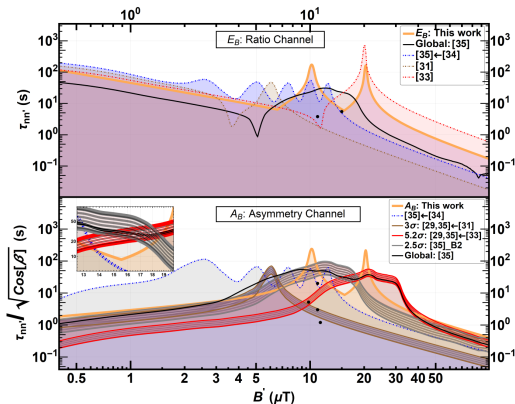
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Limits and prospects on $n - n'$ oscillation

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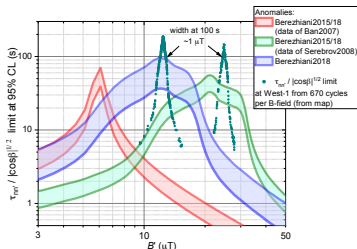
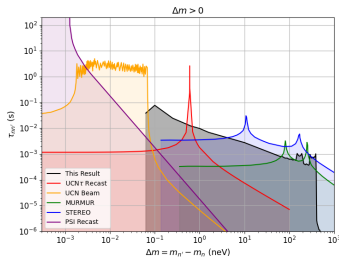
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$n - n'$ search in new experiments at PSI, ILL and ESS targeting

$\tau_{nn'} \sim 100 - 200$ s N. Ayres et al. [PSI collaboration], 2021

limits from the Neutron Star surface heating: $\tau_{nn'} > 1 - 10$ s

Z.B., Biondi, Mannarelli and Tonelli, Eur. Phys. J. C 81, 1036 (2021)

$\tau \sim 1$ s $\rightarrow \epsilon \sim 10^{-15}$ eV $\rightarrow M \sim 10$ TeV

$-\frac{1}{M^5}(udd)(u'd'd')$ and underlying new physics at LHC?



$n \leftrightarrow n'$ in Neutron Stars

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$n \leftrightarrow n'$ in Neutron Stars and antinuclei in cosmic rays

*ZB, Biondi, Mannarelli and Tonelli, 'Neutron-mirror neutron mixing and neutron stars,' Eur. Phys. J. C **81**, no.11, 1036 (2021)*

*ZB, 'Antistars or Antimatter Cores in Mirror Neutron Stars?,' Universe **8**, no.6, 313 (2022)*



Neutron Star transformation by $n - n'$ conversion

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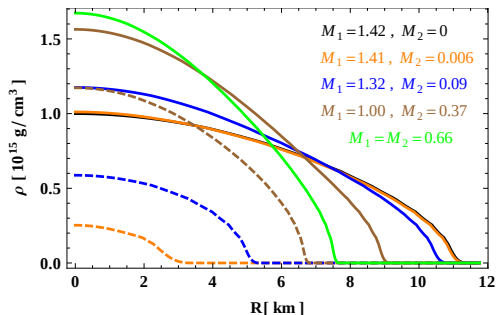
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$$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma \quad N + N' = N_0 \quad \text{remains Const.}$$

$$\text{Initial state } N = N_0, N' = 0 \quad \text{final state } N = N' = \frac{1}{2} N_0$$



ZB, Biondi, Mannarelli, Tonelli, arXiv: 2012.15233



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

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

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

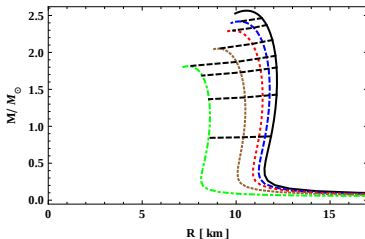
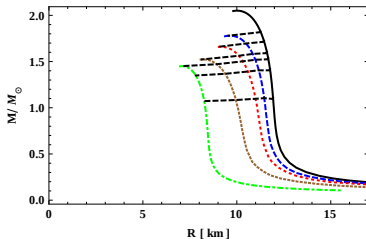
$$\rho = \rho_1 + \rho_2 \quad \& \quad p = p_1 + p_2, \quad p_\alpha = F(\rho_\alpha)$$

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

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

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

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



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



Neutron Stars: $n - n'$ conversion

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Two states, n and n'

$$H = \begin{pmatrix} E(n_b) & \varepsilon \\ \varepsilon & E'(n_{b'}) \end{pmatrix}$$

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

Fermi degenerate neutron liquid $p_F \simeq (n_b/0.3 \text{ fm}^{-3})^{2/3} \times 400 \text{ MeV}$

$nn \rightarrow nn'$ with rate $\Gamma = 2\theta^2 \eta \langle \sigma v \rangle n_b$

$$\frac{dN}{dt} = -\Gamma N \quad \frac{dN'}{dt} = \Gamma N \quad N + N' = N_0 \text{ remains Const.}$$

$$\tau_\epsilon = \Gamma^{-1} \sim \epsilon_{15}^{-2} \times 10^{15} \text{ yr} \quad N'/N_0 = t/\tau_\epsilon$$

for $t = 10^{10} \text{ yr}$, $\tau_\epsilon = 10^{15} \text{ yr}$ gives M fraction 10^{-5}
 $\sim 10^{52}$ nucleons – few Earth mass

$$\dot{\epsilon} = \frac{E_F N}{\tau_\epsilon} = \left(\frac{10^{15} \text{ yr}}{\tau_\epsilon} \right) \times 10^{31} \text{ erg/s} \quad \text{NS heating – surface T}$$



2nd challenge: Antinuclei in Cosmic Rays – AMS-02

Eight anti-helium candidates were observed by AMS-02:

6 helium-3 and 2 helium-4 low energies ($E \sim \text{GeV}$)

$$\Phi(\overline{\text{He}})/\Phi(\text{He}) \sim 10^{-8} \quad (\text{c.f. } \Phi(\overline{p})/\Phi(p) \sim 10^{-4})$$
$$\Phi(\text{He}) \sim 10^3 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

– no anti-deuteron candidate

Discovery of a single **anti-He4** nucleus challenges all known physics.

AMS-02 signal (once published) should point to highly non-trivial
New Physics

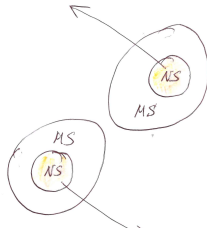
LHC: $\overline{p}$ are abundantly produced as secondaries in pp collisions
anti-deuteron and anti-triton/He3 also (but in tiny amounts)
– no anti-He4 was ever seen at the LHC ...

Some *ad hoc* tuned DM models (BSM) could explain the flux of
ant-He3 – but impossible for anti-He4 !



My hypothesis ...

- Neutron stars (NS) exist and NS-NS gravitational mergers are observed
- $n \rightarrow \bar{n}'$ transition would produce M-matter core in NS. Limits from surface T implies $\tau_\epsilon > 10^{15-16}$ yr. So in 10^{10} yr a 'planetary' mass of mirror egg will be produced inside the NS. This will not affect much NS-NS merger pattern.
- There should exist dark 'mirror' neutron stars (NS') built of mirror neutrons n' . $n' \rightarrow \bar{n}$ transition produces (our) antimatter "eggs" inside NS' – a planetary mass antistar inside NS'
- NS'-NS' mergers "liberate" the anti-nuclei with $v \sim c$





How large the antinuclear flux can be ?

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- $\Phi_{\bar{b}} \sim R(\text{NS}' - \text{NS}') \times N_{\bar{b}}^{\text{NS}} \times \tau_{\text{surv}} \times c$

Merger rate:

$$R(\text{NS}' - \text{NS}') \sim R(\text{NS} - \text{NS}) \sim 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Amount of antibarions produced in NS'

$$N_{\bar{b}} \sim N_0 \times (t_{\text{NS}}/\tau_{\varepsilon}) \sim 3 \cdot 10^{52} \times (t_{\text{NS}}/10^{10} \text{ yr}) (10^{15} \text{ yr}/\tau_{\varepsilon})$$

Survival time:

$$\tau_{\text{surv}} = (n_p \langle \sigma_{\text{ann}} v \rangle)^{-1} \simeq 3 \cdot 10^{14} \times (1 \text{ cm}^{-3}/n_p) \quad t_{\text{NS}}, \tau_{\text{surv}} < 14 \text{ Gyr}$$

- $\Phi_{\bar{b}} \sim \left(\frac{R}{10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left(\frac{N_{\bar{b}}}{10^{53}} \right) \left(\frac{\tau_{\text{surv}}}{10^{17} \text{ s}} \right) \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$



Antinuclei in Cosmic Rays ... AMS-02

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6 helium-3 and 2 helium-4 with energies $\sim$ GeV

$$\Phi(\overline{\text{He}})/\Phi(\text{He}) \sim 10^{-8} \quad - \text{no anti deuteron candidate}$$

Discovery of a single **anti-He-4** nucleus challenges all known physics.

AMS-02 signal (once published) will bring to a revolution in Physics

STing promised that AMS-02 will publish the anti-nuclei data as soon as they see first **anti-carbon**



My scenario is optimistic – this depends in burning conditions in antimatter core for nuclear reactions – depends on age, central density etc. – First it should start to produce helium as in the Sun (without initial Helium) – but then it can go to produce C-N-O and perhaps further ...

Everything is as simple as possible – but not simpler



Chapter IV

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$n - n'$ and Extreme Energy Cosmic Rays:
where do they all come from? and where do they all
belong?

*ZB and Bento, 'Fast neutron: Mirror neutron oscillation and ultra high energy cosmic rays,' Phys. Lett. B **635**, 253 (2006)*

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



Cosmic Rays from low to highest energies

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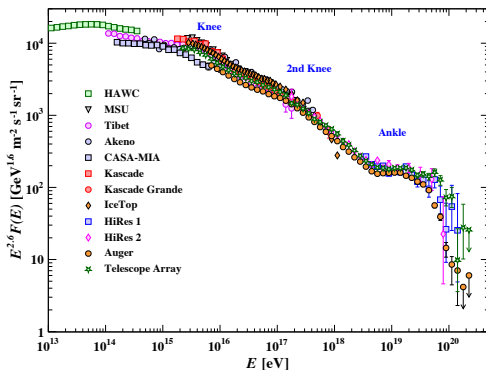
$n - n'$ in
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$E \sim 1 \text{ GeV} = 10^9 \text{ eV}$ low energies
 $E < 1 \text{ TeV} = 10^{12} \text{ eV}$ moderate energies
 $E < 1 \text{ PeV} = 10^{15} \text{ eV}$ knee – galactic CR
 $E > 1 \text{ EeV} = 10^{18} \text{ eV}$ UHECR: extragalactic
 $E > 50 \text{ EeV}$ (GZK cutoff)

Events $E > 100 \text{ EeV} = 10^{20} \text{ eV}$ (EECR) were observed
– Cosmic Zevatrons exist somewhere in the Universe





UHECR as protons and GZK cutoff

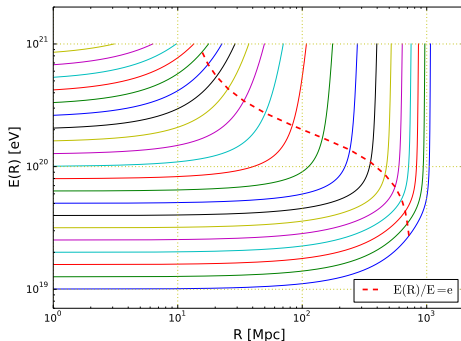
GZK cutoff:

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 $p + \pi^-$)



$E > 100 \text{ EeV} \rightarrow d_{\text{eff}} = 50 \text{ Mpc}$, $E > 200 \text{ EeV} \rightarrow d_{\text{eff}} = 20 \text{ Mpc}$

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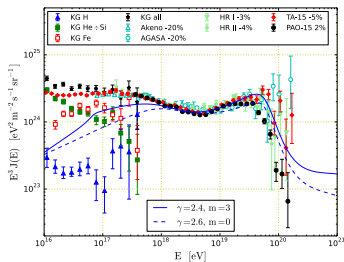
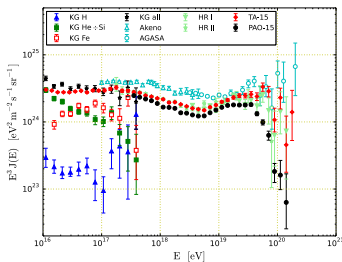
3rd challenge: Extragalactic cosmic rays (UHECR)

Two giant detectors:

Pierre Auger Observatory (PAO) – South hemisphere

Telescope Array (TA) – North hemisphere

At $E < E_{GZK} \approx 50$ EeV two spectra are perfectly coincident by relative energy shift $\approx 10\%$ – but remain discrepant at $E > E_{GZK}$
 – $E > 100$ EeV: $N_{PAO} = 36$ $N_{TA} = 28$
 $N_{PAO}/N_{TA} \approx 1.2$ while $N_{PAO}/N_{TA} \approx 6$ was expected!



+ older detectors: AGASA, HiRes, etc. (e.g. $N_{AGASA} = 11$)
 (all in north hemisphere)



But also other problems are mounting ...

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- Who are carriers of UHECR? (chemical content)

Chemical content: extragalactic UHECR are protons for $E = 1 \div 10$ EeV.
But UHECR become gradually heavier nuclei above $E > 10$ EeV or so
Disappointing Model – or perhaps new physics?

- Different anistropies from North and South?

TA disfavors isotropic distribution at $E > 57$ EeV, observes hot spot for $E > E_{\text{GZK}}$. PAO anisotropies not prominent: a spot around Cen A and warm spot at NGC 253 – are two skies really different?

- Arrival directions?

$E > 100$ EeV are expected from local supercluster (Virgo cluster etc.) and/or closeby structures. But they do not come from these directions.
TA has small angle correlation for $E > 100$ EeV events (3 doublets) which may indicate towards strong sources – but no sources are associated
– where do they all come from?

- Who are cosmic Zevatrons?

Several candidates on Hillas Plot (AGN, HBL, SBG, GRB etc.)
– but no reliable acceleration mechanism



Big Challenge – Isotropic arrival directions of EECR

PDF vs data – $E > 100$ events from the middle of Nowhere!

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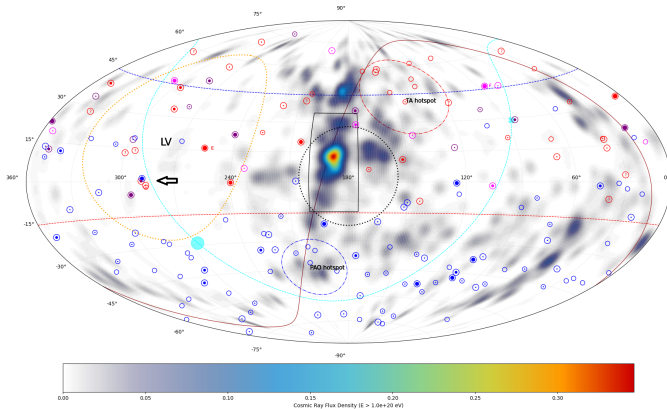
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PDF for arrival directions from sources $d < 70$ Mpc (2Mass catalog)
 $E > 100$ events PAO, TA, AGASA and others (big circles) + $E = 80 \div 100$
(smaller circles) – practically isotropic and evidently many from LV + small
scale clustering (doublets, triplets and even a quadruplet)
– and nothing from Virgo!





2019: From my slides at TEVPA 2019, Sydney

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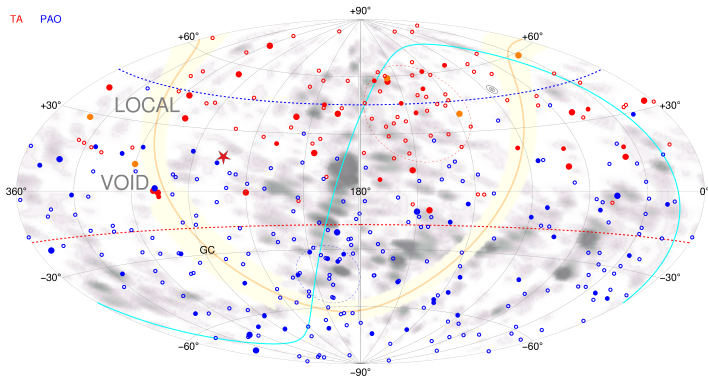
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UHECR $E > 100$ EeV (big circles) + all super GZK events $E > 60$ EeV
TA - 10 events, PAO - 8 events (data till 2015)

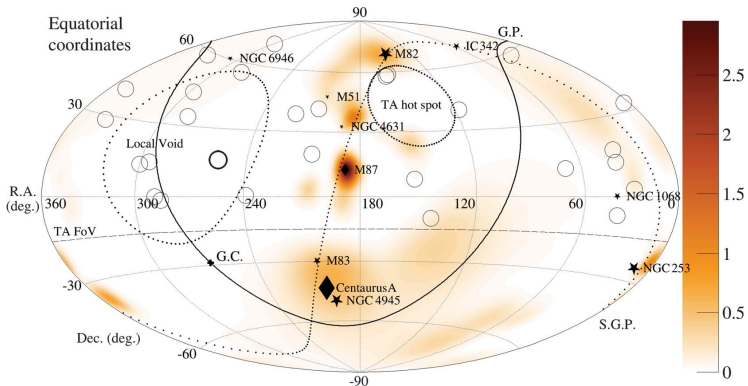


Eye: $E = 320$ EeV Fly'e Eye Monster **Father McKenzie** (FM)
Star $E = 244$ EeV TA Energy Recordsman **Eleanor Rigby** (ER)
+ 2 AGASSA events $E > 200$ EeV + 2 PAO & 2 TA events $E > 165$ EeV
– Where do they all come from... and where do they all belong?



2023 Monster event - 'Amaterasu' - Telescope Array

$E > 244$ EeV (big circle) + 27 events $E > 100$ EeV (circles)



now PAO has published now 36 events with $E > 100$ EeV



Local Universe: Local Void and other guys around

...

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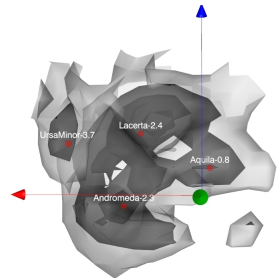
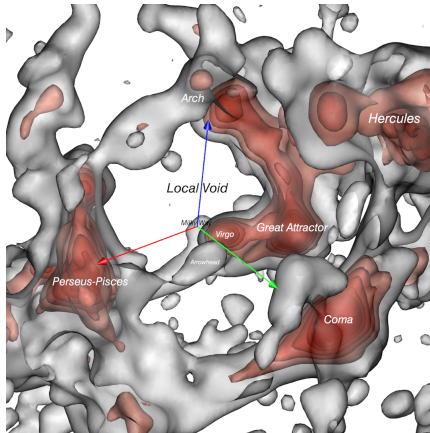
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Local Universe within 150 Mpc (SG coordinates X, Y, Z)

Local Void - $\Delta X \times \Delta Y \times \Delta Z \simeq 70 \times 50 \times 60 \simeq 2 \times 10^5 \text{ Mpc}^3$



Sculptor Void - $\Delta X \times \Delta Y \times \Delta Z \simeq 190 \times 90 \times 140 \simeq 2 \times 10^6 \text{ Mpc}^3$.



$n - n'$ oscillation and UHECR propagation

TBA (Twin Baryon Asymmetry): Astrophysical and other implications

Zurab Berezhiani

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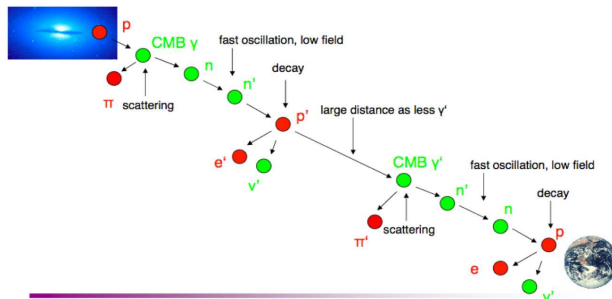
Neutron – mirror neutron oscillation $n - n'$

$n \leftrightarrow n'$ in Neutron Stars

$n - n'$ in UHECR

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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 $p' + \gamma' \rightarrow n' + \pi'^+$ $l'_{\text{mfp}} \sim (T/T')^3 l_{\text{mfp}} \gg 5 \text{ Mpc}$



Ordinary and Mirror UHECR

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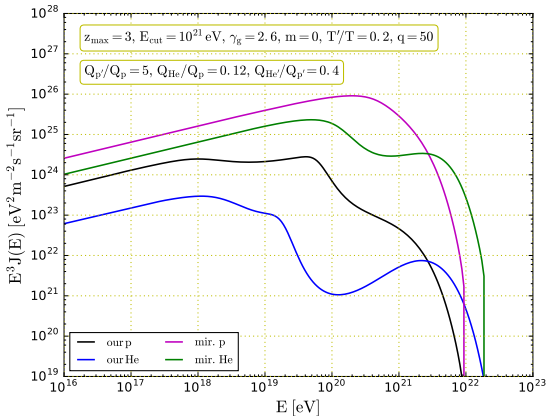
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$$\frac{n'_{\text{CMB}}}{n_{\text{CMB}}} = \left(\frac{T'}{T}\right)^3 \ll 1 \quad \rightarrow \quad \frac{\ell'_{\text{mfp}}}{\ell_{\text{mfp}}} \simeq \left(\frac{T}{T'}\right)^3 \gg 1$$





$n - n'$ oscillation in the UHECR propagation

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Baryon number **is not conserved** in propagation of the UHECR

$$H = \begin{pmatrix} \gamma\mu_n \mathbf{B}\sigma & \epsilon \\ \epsilon & \gamma\mu_n \mathbf{B}'\sigma \end{pmatrix} \times (\gamma = E/m_n)$$

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:

$$P_{nn'} = \sin^2 2\theta_{nn'} \sin^2(\ell/\ell_{\text{osc}}) \simeq \frac{1}{2} [1 + Q(E)]^{-1} \quad \tan 2\theta_{nn'} = \frac{2\epsilon}{\gamma\mu_n \Delta B}$$

$$Q = (\gamma\Delta B/2\epsilon)^2 \approx 0.5 \left(\frac{\tau_{nn'}}{1 \text{ s}}\right)^2 \left(\frac{\Delta B}{1 \text{ fG}}\right)^2 \left(\frac{E}{100 \text{ EeV}}\right)^2 \quad \Delta B = |B_{\text{tr}} - B'_{\text{tr}}|$$

$$\text{If } q = 0.5 \left(\frac{\tau_{nn'}}{1 \text{ s}}\right)^2 \left(\frac{\Delta B}{1 \text{ fG}}\right)^2 < 1,$$

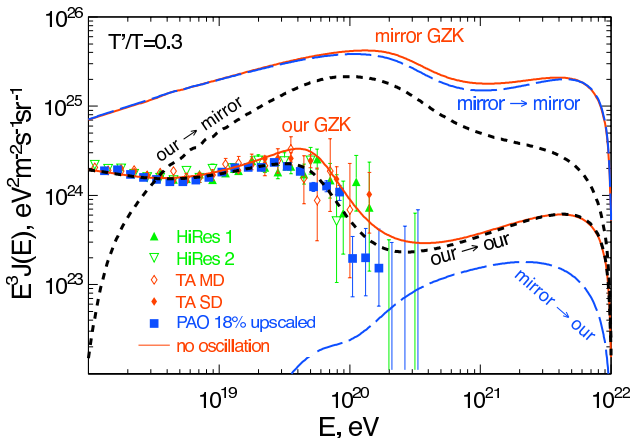
$n - n'$ oscillation becomes effective for $E = 100$ EeV



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: Mirror CRs are transformed into ordinaries in nearby Voids.

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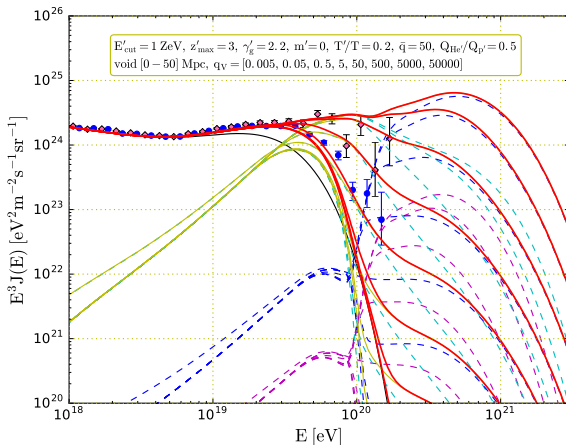
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Adjacent Void (0–50 Mpc) $q = 0.5 \times \left(\frac{\tau_{nn'}}{1 \text{ s}} \right)^2 \left(\frac{B_{\text{tr}} - B'_{\text{tr}}}{1 \text{ fG}} \right)^2$





Today: UHECR $E > 100$ EeV: PAO + TA

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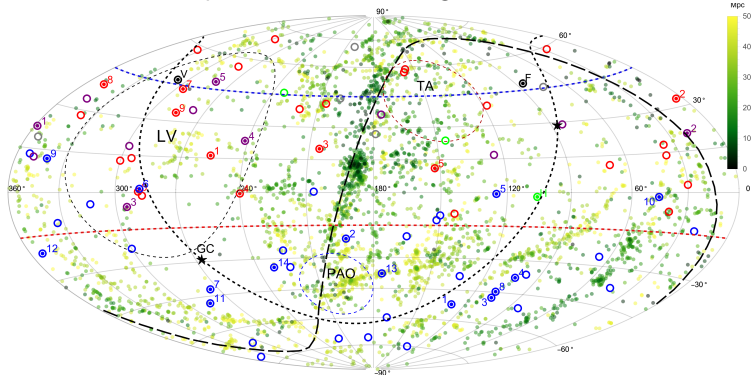
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Galaxies $d < 50$ Mpc fro 2MASS catalog



TA – 28 events (red circles)
PAO – 36 events (blue circles)

AGASA + others 17 events (purple)



Summary (From my talk at TEVPA 2019)

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The UHECR spectra observed by TA and PAO are perfectly concordant (after 10% rescaling) at energies up to 10 EeV ... but become increasingly discordant at higher energies, very strongly above the GZK cutoff (60 EeV)

The discrepancy can be due to difference between the N- and S-skies!
N-sky is well structured, with prominent overdensities and large voids ...
S-sky is more amorphous with diffuse galaxies ...

It is unlikely that PAO–TA discrepancy is due to different power of sources within the GZK radius (no correlation with the galaxy distribution at $E > 80$ EeV, no event from the Virgo or Fornax clusters, etc.)

But it can be explained in "Swiss Cheese" model: UHECR above 80 – 100 EeV are born from mirror UHECR via $n' - n$ conversion in nearby voids within the radius $\sim 50 - 100$ Mpc (**Voids = small magnetic fields**)

The TA signal at super-GZK energies is boosted by prominent Voids in N-hemisphere. This can also explain intermediate scale anisotropies (20-30 degrees) in the TA arrival directions Interestingly, the TA/PAO spectra are concordant in the common sky ...

My hypothesis is testable with the new data of TA/PAO at higher statistics on $E > 100$ EeV events for which typical "voidity" radius is ~ 50 Mpc



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Implication for cosmogenic neutrinos. Mirror Sector is Helium dominated, and in mirror UHECR ${}^4\text{He}'$ can be more than p' . So neutrons can be produced also by ${}^4\text{He}' + \gamma' \rightarrow {}^3\text{He}' + n'$. Subsequent decay $n' \rightarrow p'e'\bar{\nu}'$ and (sterile-active) oscillation $\nu' \rightarrow \nu$ can produce large flux of cosmogenic neutrinos which may explain astrophysical neutrino flux of IceCube above 100 TeV at higher redshifts

$n - n'$ conversion also has interesting implications for the neutron stars (gradual conversion of the neutron stars into mixed ordinary-mirror stars till achieving "fifty-fifty" mixed twin star configuration with $\sqrt{2}$ times smaller radius and maximal mass ...

Remarkably, it can be tested in laboratories via looking for anomalous (magnetic field dependent) disappearance of the neutrons (for which there already exist some experimental indications, most remarkable at the 5.2σ level) due to $n \rightarrow n'$ conversion and "walking through the wall" experiments ($n \rightarrow n' \rightarrow n$ regeneration). $n - n'$ oscillation can be also related to the neutron lifetime puzzle.



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

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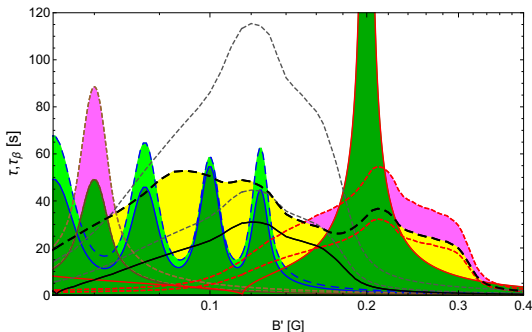
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limits from the Neutron Star surface heating: $\tau_{nn'} > 1 - 10$ s

Z.B., Biondi, Mannarelli and Tonelli, Eur. Phys. J. C 81, 1036 (2021)

$$q = 0.5 \left(\frac{\tau_{nn'}}{1 \text{ s}} \right)^2 \left(\frac{\Delta B}{1 \text{ fG}} \right)^2 \geq 1 \text{ implies } \Delta B \leq 1 \text{ fG for } \tau_{nn'} \simeq 1 \text{ s}$$

In turn, $\Delta B > 10^{-17}$ G implies $\tau_{nn'} < 100$ s

Optimism for $n - n'$ search in new experiments at PSI, ILL and ESS
targeting $\tau_{nn'} \sim 100 - 200$ s

N. Ayres et al. [PSI collaboration], 2021



Transforming Dark Matter into Antimatter: n or $\bar{n}$?

TBA (Twin
Baryon
Asymmetry):
Astrophysical
and other
implications

Zurab Berezhiani

Summary

Intro: Big
Challenges for
SM

TBA and DM
from Parallel
'Mirror' World

Neutron – mirror
neutron
oscillation $n - n'$

$n \leftrightarrow n'$ in
Neutron Stars

$n - n'$ in
UHECR

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Cross-interactions can induce mixing of neutral particles between two sectors, e.g. $\nu - \nu'$ oscillations (M neutrinos = sterile neutrinos)

Oscillation $n \rightarrow n'$ can be very effective process, **faster than the neutron decay**. For certain parameters it can explain the neutron lifetime problem, 4.5σ discrepancy between the decay times measured by different experimental methods (bottle and beam), or anomalous neutron losses observed in some experiments and paradoxes in the UHECR detections

$n \rightarrow n'$ transition can have observable effects on neutron stars. It creates dark cores of M matter in the NS interiors, or eventually can transform them into maximally mixed stars with equal amounts of O and M neutrons

Such transitions in mirror NS create O matter cores. If baryon asymmetry in M sector has opposite sign, transitions $\bar{n}' \rightarrow \bar{n}$ create antimatter cores which can be seen by LAT **by accreting ordinary gas** and explain the origin of anti-helium nuclei in cosmic rays **supposedly seen by AMS2**



Getting Energy from Dark Parallel World

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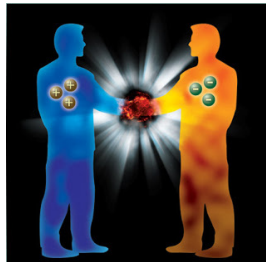
I argued that in O and M worlds baryon asymmetries can have same signs: $B > 0$ and $B' > 0$. Since $B - B'$ is conserved, our neutrons have transition $n \rightarrow \bar{n}'$ (which is the antiparticle for M observer)

while n' (of M matter) oscillates $n' \rightarrow \bar{n}$ into our antineutron

Neutrons can be transformed into antineutrons, but (happily) with low efficiency: $\tau_{n\bar{n}} > 10^8$ s

dark neutrons, before they decay, can be effectively transformed into our antineutrons in controllable way, by tuning vacuum and magnetic fields, if $\tau_{n\bar{n}'} < 10^3$ s

$E = 2m_n c^2 = 3 \times 10^{-3}$ erg
per every $\bar{n}$ annihilation



Two civilisations can agree to built scientific reactors and exchange neutrons ... we could get plenty of energy out of dark matter !

E.g. mirror source with 3×10^{17} n/s (PSI) $\longrightarrow$ power = 100 MW



Asimov Machine: the "Pump"

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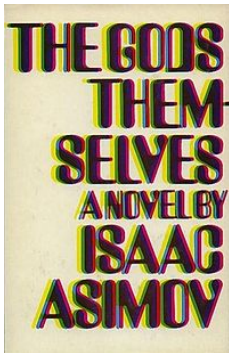
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First Part: Against Stupidity ...

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

Third Part: ... Contend in Vain?

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

Radiochemist Hallam constructs the "Pump": a cheap, clean, and apparently endless source of energy functioning by the matter exchange between our universe and a parallel universe

His "discovery" was inspired by beings of parallel (mirror) world where stars were very old and so too cold – they had no more energy resources and were facing full extinction ...



$$2 \times 2 = 4 !$$

Z.B., Eur.Phys.J C81:33 (2021), arXiv:2002.05609

4 states: $n, \bar{n} : n', \bar{n}'$ and mixing combinations:

$$n \longleftrightarrow \bar{n} \quad (\Delta B = 2) \quad \& \quad n' \longleftrightarrow \bar{n}' \quad (\Delta B' = 2)$$

$$n \longleftrightarrow n' \quad + \quad \bar{n}' \longleftrightarrow \bar{n} \quad \Delta(B - B') = 0$$

$$n \longleftrightarrow \bar{n}' \quad + \quad n' \longleftrightarrow \bar{n} \quad \Delta(B + B') = 0$$

Full Hamiltonian is 8×8 :

$$\begin{pmatrix} m_n + \mu \vec{B} \vec{\sigma} & \epsilon_{n\bar{n}} & \epsilon_{nn'} & \epsilon_{n\bar{n}'} \\ \epsilon_{n\bar{n}} & m_n - \mu \vec{B} \vec{\sigma} & \epsilon_{n\bar{n}'} & \epsilon_{nn'} \\ \epsilon_{nn'} & \epsilon_{n\bar{n}'} & m'_n + V'_n + \mu' \vec{B}' \vec{\sigma} & \epsilon_{n\bar{n}} \\ \epsilon_{n\bar{n}'} & \epsilon_{nn'} & \epsilon_{n\bar{n}} & m'_n + V'_n - \mu' \vec{B}' \vec{\sigma} \end{pmatrix}$$

Present bounds on oscillation time $\tau_{n\bar{n}} = \epsilon^{-1}$:

$$\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s} \quad (\text{free } n), \quad \tau_{n\bar{n}} > 4.7 \times 10^8 \text{ s} \quad (\text{bound } n)$$

$$P_{n\bar{n}}(t) = \frac{t^2}{\tau_{n\bar{n}}^2} = \left(\frac{10^8 \text{ s}}{\tau_{n\bar{n}}} \right)^2 \left(\frac{t}{0.1 \text{ s}} \right)^2 \times 10^{-18}$$



Shortcut for $n \rightarrow \bar{n}$ via $n \rightarrow n' \rightarrow \bar{n}$

Consider case when direct $n - \bar{n}$ mixing simply absent: $\epsilon_{n\bar{n}} = 0$

Anyway, $n \rightarrow \bar{n}$ emerges as second order effect via $n \rightarrow n' \bar{n}' \rightarrow \bar{n}$

$$\bar{P}_{n\bar{n}} = \bar{P}_{nn'} \bar{P}_{n\bar{n}'}$$

$$\bar{P}_{nn'} = \frac{2\epsilon_{nn'}^2 \cos^2(\beta/2)}{(\Omega - \Omega')^2} + \frac{2\epsilon_{nn'}^2 \sin^2(\beta/2)}{(\Omega + \Omega')^2}, \quad \bar{P}_{n\bar{n}'} = \frac{2\epsilon_{n\bar{n}'}^2 \sin^2(\beta/2)}{(\Omega - \Omega')^2} + \frac{2\epsilon_{n\bar{n}'}^2 \cos^2(\beta/2)}{(\Omega + \Omega')^2}$$

where β is the (unknown) angle between the vectors $\vec{B}$ and $\vec{B}'$

Disappearance experiments measure the sum $P_{nn'} + P_{n\bar{n}'} \propto \epsilon_{nn'}^2 + \epsilon_{n\bar{n}'}^2$

$n - \bar{n}$ transition measures the product $P_{n\bar{n}} = P_{nn'} P_{n\bar{n}'} \propto \epsilon_{nn'}^2 \epsilon_{n\bar{n}'}^2$

From the ILL'94 limit $P_{n\bar{n}} < 10^{-18}$ (measured at $B = 0$) we get

$$\tau_{nn'} \tau_{n\bar{n}'} > \frac{2 \times 10^9}{\Omega'^2} \approx \left(\frac{0.5 \text{ G}}{B'} \right)^2 \times 100 \text{ s}^2$$

E.g. $\tau_{nn'} \tau_{n\bar{n}'} \sim 1$ second is possible if $B' \sim 5 \text{ G}$

Limits become even weaker if $\Delta m > 0.1 \text{ neV}$

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How good the shortcut can be?

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Assuming e.g. $\tau_{nn'} \tau_{n\bar{n}'} = 100$ s and $B' = 0.5$ G, we see that
ILL94-like measurement at $B = 0.45$ G (or $B = 0.49$ G) would give
 $P_{n\bar{n}} \simeq \sin^2 \beta \times 10^{-15}$ (or $P_{n\bar{n}} \simeq \sin^2 \beta \times 10^{-12}$)

To maximize $n - \bar{n}$ probability, one has to match resonance with
about 1 mG precision: we get

$$P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2 \frac{\beta}{2}, \quad P_{n\bar{n}'}(t) = \left(\frac{t}{\tau_{n\bar{n}'}}\right)^2 \sin^2 \frac{\beta}{2}$$

and

$$P_{n\bar{n}}(t) = P_{nn'}(t)P_{n\bar{n}'}(t) = \frac{\sin^2 \beta}{4} \left(\frac{t}{0.1 \text{ s}}\right)^4 \left(\frac{100 \text{ s}^2}{\tau_{nn'} \tau_{n\bar{n}'}}\right)^2 \times 10^{-8}$$

Practically no limit from nuclear stability

E.g. ^{16}O decay time predicted $\sim 10^{60}$ yr vs. present limit $\sim 10^{32}$ yr !



How effective $n \rightarrow \bar{n}$ can be?

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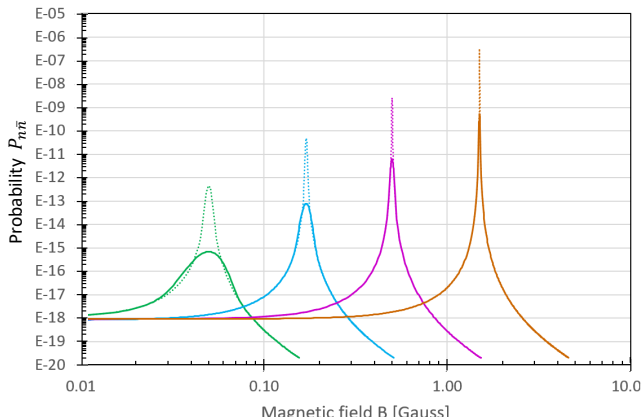
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simulations for $n - \bar{n}$ experiment with
 $t = 0.1$ s ($\ell = 100$ m as ILL) and $t = 0.02$ s ($\ell = 20$ m)



– and perhaps a chance for free energy ?



Majorana Machine

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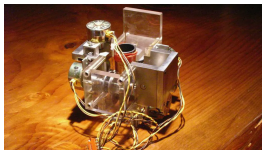
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Che cretini! Hanno scoperto il protone neutro e non se ne accorgono!

La fisica è su una strada sbagliata. Siamo tutti su una strada sbagliata...

La fantomatica macchina forse teorizzata da Ettore Majorana! Nella sua formulazione attuale violerebbe un'infinità di principi scientifici, producendo enormi quantità di energia a costo zero. Non può affatto esistere ...



Thank You ...

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It's wonderful to be here
It's certainly a thrill
You're such a lovely audience ...

We hope you have enjoyed the show
We're sorry but it's time to go
It's getting very near the end
We'd like to thank you once again





Thanks

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Many Thanks for Listening

The talk of Z.B. was supported in part by the research grant No. 2022E2J4RK "PANTHEON: Perspectives in Astroparticle and Neutrino THEory with Old and New messengers" under the program PRIN 2022 funded by the Italian Ministero dell'Università e della Ricerca (MUR) and by the European Union – Next Generation EU.



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UHECR as nuclei – but even stronger cutoff

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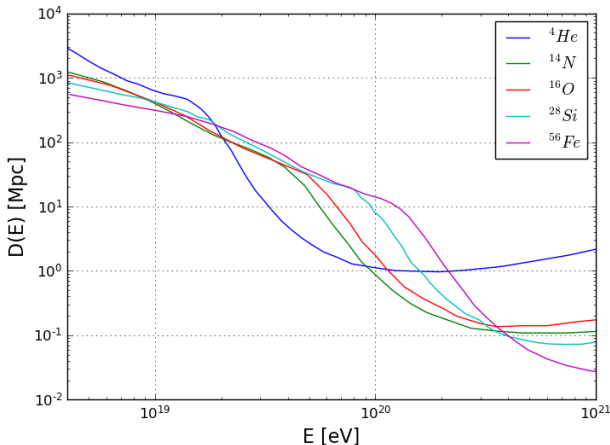
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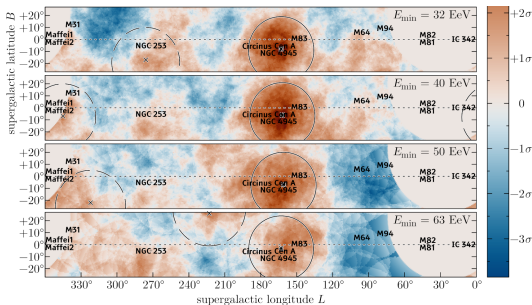
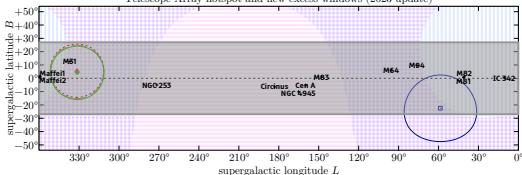
For flux $E > 100$ EeV, e.g. for oxygen we get $d_{\text{eff}} \approx 10$ Mpc,
for silicon $d_{\text{eff}} \approx 30$ Mpc, for iron $d_{\text{eff}} \approx 50$ Mpc



Association with close sources (SBG, AGN etc,)

Hot spots of TA and PAO

Telescope Array hotspot and new excess windows (2023 update)



But all spots become dim at increasing E
 – and completely disappear for $E > 100$ EeV

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Are North and South skies different ?

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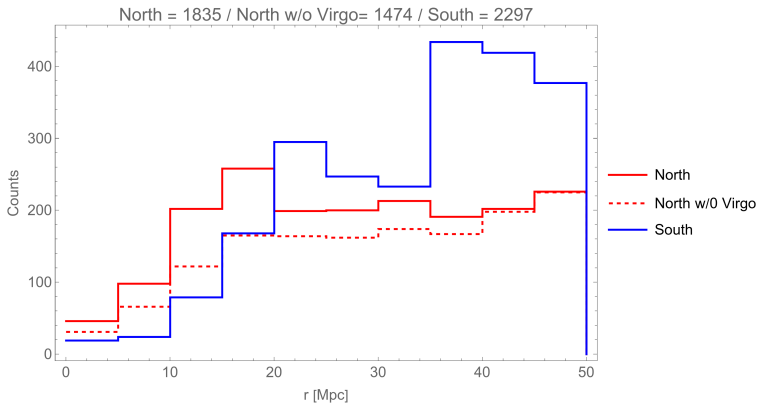
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Today: UHECR $E > 100$ EeV: PAO + TA

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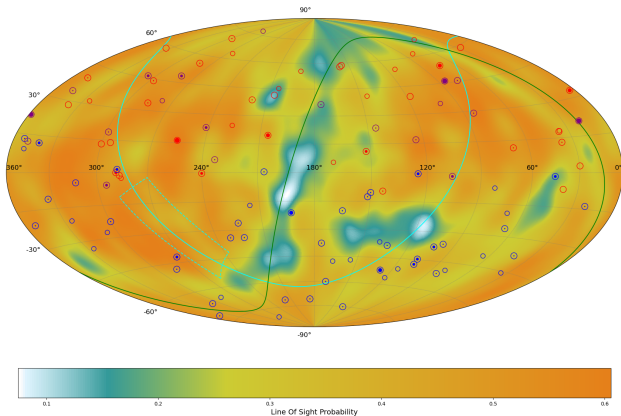
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GMF modelling: quadrupole ($B(r) \propto r^{-4}$ at $R > r_q$)
 $r_q = 10$ kpc, $\tau = 10$ s





UHECR $E > 100$ EeV ... + AGASA etc.

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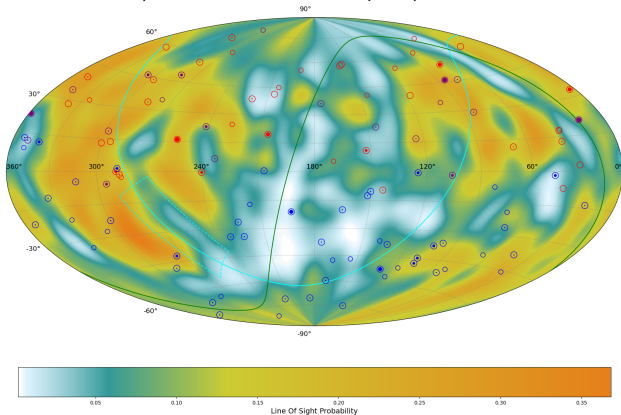
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GMF quadrupole $r_q = 20$ kpc, $\tau = 10$ s (or $r_q = 10$ kpc, $\tau = 160$ s)





UHECR $E > 100$ EeV ... + AGASA etc.

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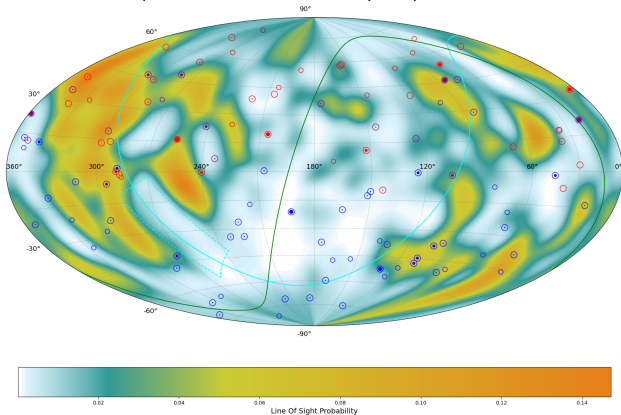
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GMF quadrupole $r_q = 30$ kpc, $\tau = 10$ s (or $r_q = 20$ kpc, $\tau = 50$ s)





Serebrov III – Drifts of detector and monitor counts

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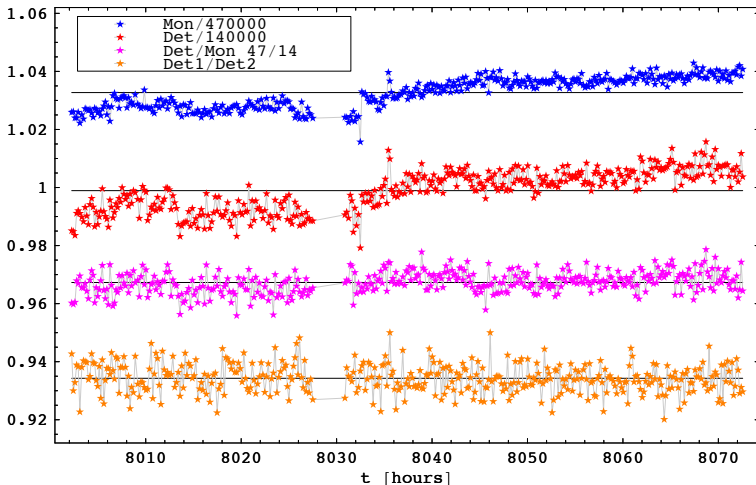
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Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G





Serebrov III – magnetic field vertical

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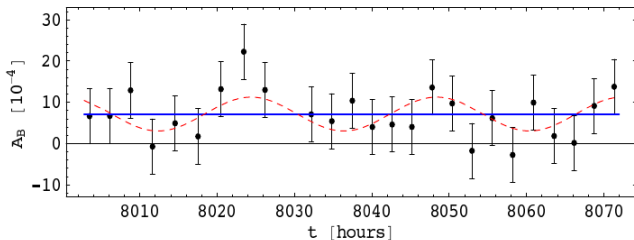
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Exp. sequence: $\{B_-, B_+, B_+, B_-, B_+, B_-, B_-, B_+\}$, $B = 0.2$ G



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



2009 – magnetic field Horizontal

large field $B_{\pm} = 0.2$ G and small field $b_{\pm} < 10^{-2}$ G

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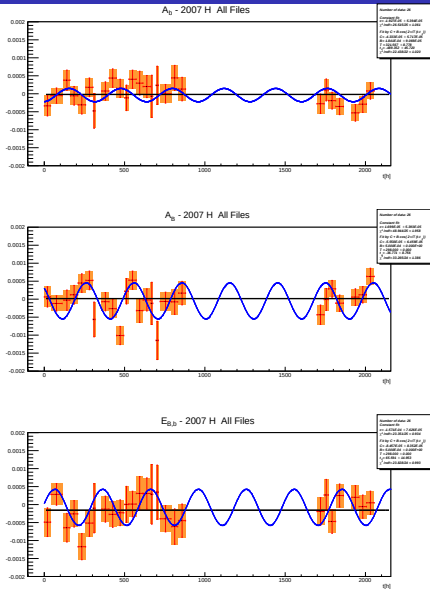
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2009 – magnetic field Horizontal

large field $B = 0.2$ G and small field $b < 10^{-2}$ G

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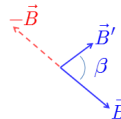
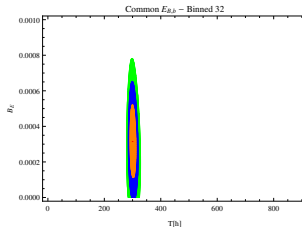
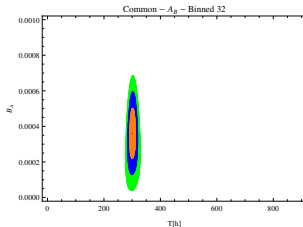
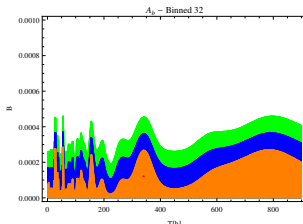
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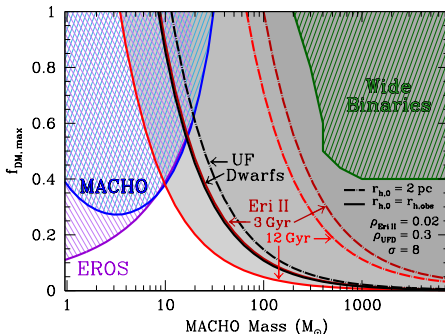
small field: $A_b \simeq 0$, but large field measurements show non-zero A_B
and E_B , both with the period $T \simeq 300$ hours
(Unpublished and not included in Fig. of exp. limits)



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 ?

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

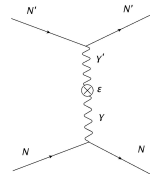
- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

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**



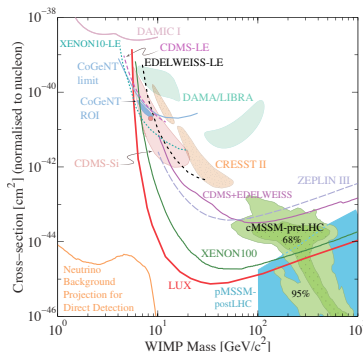
Mirror atoms: He' – 75 %,
C', N', O' etc. few %

Rutherford-like scattering

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

or

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



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OM-MM interactions in the Early Universe after recombination

TBA (Twin Baryon Asymmetry): Astrophysical and other implications

Zurab Berezhiani

Summary

Intro: Big Challenges for SM

TBA and DM from Parallel 'Mirror' World

Neutron – mirror neutron oscillation $n - n'$

$n \leftrightarrow n'$ in Neutron Stars

$n - n'$ in UHECR

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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



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

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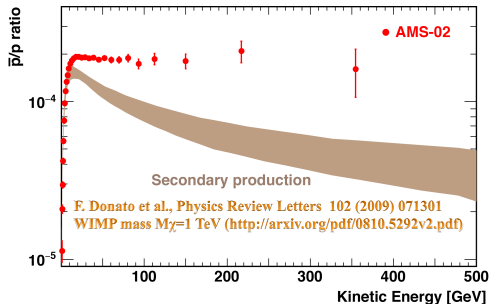
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In mirror cosmic rays, disintegration of mirror nuclei by galactic UV background or in scatterings with mirror gas, frees out mirror neutrons which then oscillate into our antineutron, $n' \rightarrow \bar{n}$, which then decays as $\bar{n} \rightarrow \bar{p} + \bar{e} + \nu_e$.

so we get antiprotons (positrons), with spectral index similar to that of protons in our cosmic rays ?





More parallel worlds ?

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Imagine there are 4 worlds all described by Standard Model, related by mirror (LR) and xerox (LL) symmetries ...

This can be used for solving little hierarchy problem, invoking also SUSY

Consider superpotential

$$W = \lambda S_1(H_1 H_2 + \Phi_1 \Phi_2 - \Lambda^2) + \lambda S_2(H'_1 H'_2 + \Phi'_1 \Phi'_2 - \Lambda^2)$$

Xerox symmetry: $H_{1,2} \rightarrow \Phi_{1,2}$, $H'_{1,2} \rightarrow \Phi'_{1,2}$

Mirror symmetry: $S_1 \rightarrow S_2$, $H_{1,2} \rightarrow H'_{1,2}$, $\Phi_{1,2} \rightarrow \Phi'_{1,2}$

Global symmetries $SU(4)_H$ and $SU(4)'_H$

Take $\Lambda \sim 10$ TeV and assume that SUSY breaking spurion $\eta = M_S \theta^2$ is odd against Xerox symmetry, $\eta \rightarrow -\eta$.

Φ 's get VEVs $v' \sim 10$ TeV, H 's remain pseudo-Goldstone, then getting VEVs $v \sim 100$ GeV

Φ sectors – Standard Models with $m_E \sim (v'/v)m_e$ but $m_{P,N} \simeq (2 \div 3)m_{p,n}$ ($\Lambda_\Phi/\Lambda_{\text{QCD}}$ rescales softer with v'/v)

Dark matter can be very compact hydrogen atoms from Φ sectors, or even neutrons if $m_P > m_N$

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



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 ...*



Is existence of mirror world compatible with cosmology ?

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

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

If $T' \ll T$, BBN is OK $\rightarrow$ Cosmological Paradigm:

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

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

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

but then $\eta' = \eta$ implies $\Omega'_B \simeq (T'/T)^3 \Omega_B \ll \Omega_B \quad !!!$

Such a mirror universe “can have no influence on the Earth and therefore would be useless and therefore does not exist”

S. Glashow, citing Francesco Sizzi



However ...

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

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

The microphysics of the postulated mirror matter should be exactly the same as that of the usual matter. However, we know that the spatial distribution of the dark matter is very different from that of the ordinary (baryonic) matter. On the face of it this makes mirror matter an implausible candidate for dark matter.

Anonimous Referee, from a referee report (PRL of course)