Windows to Parallel Dark World ?

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Cosmic Coincidence & Fine Tuning Problems

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

- $\Omega_{\rm B} \simeq 0.04$ observable matter – Baryons !
- $\Omega_{\rm D} \simeq 0.20$ dark matter: – WIMPS? Axions? ....
- $\Omega_{\Lambda} \simeq 0.75$ dark energy: – Λ-term? 5th-essence? ....

A. coincidence of matter $\Omega_{\rm M}$=$\Omega_{\rm D}$+$\Omega_{\rm B}$ and dark energy Ω_{Λ}: $\Omega_{\rm M}/\Omega_{\Lambda} \simeq 0.3$

... $\rho_{\Lambda} \sim$ Const., $\rho_{\rm M} \sim a^{-3}$; why $\rho_{\rm M}/\rho_{\Lambda} \sim 1$ – just Today?

Antrophic answer: if not Today, then it could be Yesterday or Tomorrow ...

B. Fine Tuning between visible $\Omega_{\rm B}$ and dark $\Omega_{\rm D}$ matter: $\Omega_{\rm B}/\Omega_{\rm D} \simeq 0.2$

... $\rho_{\rm B} \sim a^{-3}$, $\rho_{\rm D} \sim a^{-3}$; why $\rho_{\rm B}/\rho_{\rm D} \sim 1$ – Yesterday Today & Tomorrow?

– Difficult question ... popular models for primordial Baryogenesis (GUT-B, Lepto-B, Spont. B, Affleck-Dine B, EW B, ...) have no feeling for popular DM candidates (Wimp, Wimpzilla, axion, axino, gravitino ...)

– How Baryon Asymmetry could knew about Dark Matter? – again anthropic (landscaped) Fine Tunings in Particle Physics and Cosmology? Just for our good?

Give a human face to dark matter ....

For observable particles .... very complex physics !!

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

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

long range EM forces, confinement scale $\Lambda_{\rm QCD}$, weak scale M_W

... matter *vs.* antimatter (B-conserviolation, C/CP ... *Sakharov*)

... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

What if dark matter comes from extra gauge sector ... which is not ad hoc simple system but it is complex structure alike the observable one?

Parallel gauge sector: – $G' = SU(3)' \times SU(2)' \times U(1)'$?

photon$'$, electron$'$, nucleons$'$ (quarks$'$), $W' - Z'$, gluons$'$?

... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?

... asymmetric dark matter (B$'$-conserviolation, C/CP ...) ?

... existence of twin nuclei, atoms, molecules ... life ... twin Homo Sapiens?

Dark gauge sector ... similar to our particle sector? ... or exactly the same?

.... two (or more) parallel branes in extra dimensions? $E_8 \times E'_8$?

who knows ..... but let us imagine !

"Imagination is more important than knowledge..." *A. Einstein*

Parallel/Mirror/Twin World(s)

Parity (L $\leftrightarrow$ R) in Weak Ints. restored by Mirror fermions — Lee & Yang '56

Mirror fermions = hidden sector — Kobzarev Okun Pomeranchuk '66

hidden sector similar to our but not exact copy — Nishijima, Saffouri '65

$SU(10) \to SU(5) \times SU(5)$ and Alice strings — Schwarz' 82

- Two identical gauge factors, $G \times G'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ – $SU(5) \times SU(5)'$, *etc* .
- Can naturally emerge in string theory: O & M matter fields localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$
- Exact parity $G \leftrightarrow G'$: Mirror matter is dark (for us), but its particle physics we know exactly (on our skin) – no new parameters!

- Mirror sector $=$ a duplicate of our particle sector ...

all particles: $e,\ p,\ n,\ \nu,\ \gamma,\dots$ have invisible twins $e',\ p',\ n',\ \nu',\ \gamma',\dots$ with exactly the same mass spectrum and interaction constants

Gravity is a common force between two sectors ... while mirror particles are dark for us (do not interact with our photon).

So, mirror matter is a natural candidate for (asymmetric) dark matter (not CDM) !!

Dissipative DM, but not excluded by cosmological tests — Z.B., Comelli, Villante, 2000

Testing parallel world (worlds)

Numerous potential consequences worth of theoretical and experimental studies can be classified in three main parts:

- *Cosmological implications: mirror matter as dark matter, with specific implications for baryogenesis and dark matter genesis, evolution of the Universe, formation and structure of galaxies, gravitational lensing and microlensing, etc.*

- *Oscillation phenomena between ordinary and mirror particles which can be observable in laboratories: any neutral particle, elementary (as photon or neutrino) or composite (as the neutron or hydrogen atom) can mix with its mass degenerate twin leading to a matter disappearance (or appearance) phenomena*

- *Experimental direct and indirect searches of dark matter: mirror hydrogen, helium (and some mirror nuclei) as dark matter, different interaction portals are possible. The low region 1-5 GeV of dark matter masses is practically unexplored. Dark antimatter (we do not know the sign of baryon asymmetry in parallel sector): e.g. mirror hydrogen to antihydrogen transition. Signals in indirect search as for laboratory search.*

Para-world (or worlds) as dark matter

Mirror particles are dark for us (do not interact with our photon)
and gravity is a common force between two sectors ....
So, mirror matter is a natural candidate for dark matter !! but not CDM
Dissipative DM, but not excluded by cosmological tests *Z.B., Comelli, Villante, 2000*

- *Mirror microphysics $=$ our microphysics*
  but mirror cosmology $\neq$ our cosmology *Mirror Sector should be colder*
  $T'/T < 0.5$ *(BBN),* $T'/T < 0.3$ *(CMB+LSS)*

- *There can be* feeble *interactions between ordinary and mirror particles:*
  (Give dark matter detection a chance – DAMA & CRESST?)
  But these should be feeble *enough for not to equilibrate* T *and* T'

- *B & L violating interactions most interesting:*

– they can co-generate in Early Universe both baryon and mirror-baryon asymmetries, naturally explaining $\Omega'_B/\Omega_B \sim 5$ *...*
– At lower energies, they can be tested experimentally via mixing phenomena between ordinary and mirror particles: *neutrino–mirror neutrino (active–sterile), neutron–mirror neutron mixing ...*

Possible interactions between O & M particles **(besides gravity)**

any neutral particle (elementary or composite) can mix its mirror twin ... exactly degenerate in mass

Can be induced by exchange of extra gauge singlet particles or common gauge fields acting with both O & M particles ...

- photon - mirror photon kinetic mixing $\varepsilon F^{\mu\nu} F'_{\mu\nu}$ Holdom '86

mirror particles become "millicharged" $Q' \sim \varepsilon Q$ *relative to our photon*

$\longrightarrow$ *positronium - mirror positronium mixing* ($e^+e^- \to e'^+e'^-$) *Glashow '86*

and BBN bound $\varepsilon < 3 \times 10^{-8}$, Carlson, Glashow '87

now ... BBN : $\varepsilon < 2 \times 10^{-9}$, Structures : $\varepsilon < 3 \times 10^{-10}$ ZB, Lepidi, '08

- meson - mirror meson mixing: $\pi^0 - \pi^{0\prime}$, $K^0 - K^{0\prime}$, $\rho^0 - \rho^{0\prime}$, *etc.*

$\frac{1}{M^2}(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d)(\overline{u}'\gamma^5 u' - \overline{d}'\gamma^5 d')$, $\frac{1}{M^2}(\overline{d}\gamma^5 s)(\overline{d}'\gamma^5 s')$ $(\Delta S = 1)$

... *analogous to* $\frac{1}{M^2}(\overline{d}\gamma^5 s)(\overline{d}\gamma^5 s) \longrightarrow K^0 - \bar{K}^0$ mixing $(\Delta S = 2)$

Phenom. limits: $M > 10$ TeV $(\pi^0 - \pi^{0\prime})$, $M > 100$ TeV $(K^0 - K^{0\prime})$

Lepton & baryon number violating interactions

- neutrino - mirror neutrino mixing $(\nu - \nu')$ – effective operators :

  $\frac{1}{M}(l\phi)(l'\phi')$ $\quad (\Delta L = 1, \Delta L' = 1)$ active-sterile mixing

  analogous to $\frac{1}{M}(l\phi)^2 \quad (\Delta L = 2)$, $\quad \frac{1}{M}(l'\phi')^2 \quad (\Delta L' = 2)$

  – operators that generate neutrino Majorana masses via seesaw mechanism

- neutron - mirror neutron mixing $(n - n')$ – effective operators :

  $\frac{1}{M^5}(udd)(u'd'd')$, $\quad (\Delta B = 1, \Delta B' = 1)$

  c.f. operators $\frac{1}{M^5}(udd)^2 \quad (\Delta B = 2)$, $\quad \frac{1}{M^5}(u'd'd')^2 \quad (\Delta B' = 2)$
  which generate neutron - antineutron mixing

- hydrogen - mirror hydrogen mixing – effective operators :

  $\frac{1}{M^8}(udde)(u'd'd'e')$, $\quad (\Delta B = 1, \Delta L = 1; \Delta B' = 1, \Delta L' = 1)$

  c.f. operators $\frac{1}{M^8}(udde)^2 \longrightarrow$ *hydrogen - antihydrogen atom mixing*

BBN demands : **was Alice's guess correct?**

Mirror particle physics $\equiv$ ordinary particle physics

but .... mirror cosmology $\neq$ ordinary cosmology

- *at the BBN epoch,* $T \sim 1$ *MeV,* $g_* = g_*^{SM} = 10.75$
  as contributed by the γ, $e^\pm$ *and 3* ν *species :* $N_\nu = 3$
- *if* $T' = T$, *mirror world would give the same contribution:*
  $g_*^{\rm eff} = 2 \times g_*^{SM} = 21.5$ *– equivalent to* $\Delta N_\nu = 6.14$!!!
- *If* $T' < T$, *then* $g_*^{\rm eff} \approx g_*^{SM}(1 + x^4)$, $x = T'/T$ $\longrightarrow \Delta N_\nu = 6.14 \cdot x^4$
  E.g. $\Delta N_\nu < 0.4$ *requires* $x < 0.5$; *for* $x = 0.2$ $\Delta N_\nu \simeq 0.01$
- *Paradigm – different initial conditions & weak contact :*
  – after inflation O and M worlds are (re)heated non-symmetrically, $T' < T$

  – processes between O - M particles are slow enough & stay Out-of-Equilibrium

  – both sectors evolve adiabatically, without significant entropy production

  So $x = T'/T$ *is nearly independent of time* *(* $T'_{\rm CMB}/T_{\rm CMB}$ *today)*

BBN: $\Delta N_\nu/6.14 = x^4 \ll 1$ $\longrightarrow$ BBN$'$: $\Delta N'_\nu/6.14 = x^{-4} \gg 1$

^{1}H 75%, ^{4}He 25% *vs.* ^{1}H$'$ 25%, ^{4}He$'$ 75%

Z. Berezhiani, D. Comelli, F. Villante, Phys. Lett. B 503, 362 (2001)

Co-baryo/leptogenesis between O & M sectors

E.g. D=5 effective operators (active sterile neutrino system)

$$\frac{A}{M} ll\phi\phi + \frac{A'}{M} l'l'\phi'\phi' + \frac{D}{M} ll'\phi\phi'$$

- They generate also processes like $l\phi \to \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \to \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) satisfying Sakharov's 3 conditions for baryogenesis

  A. violate B-L – *by definition*

  B. violate CP – *complex Yukawa constants y_{ia}*

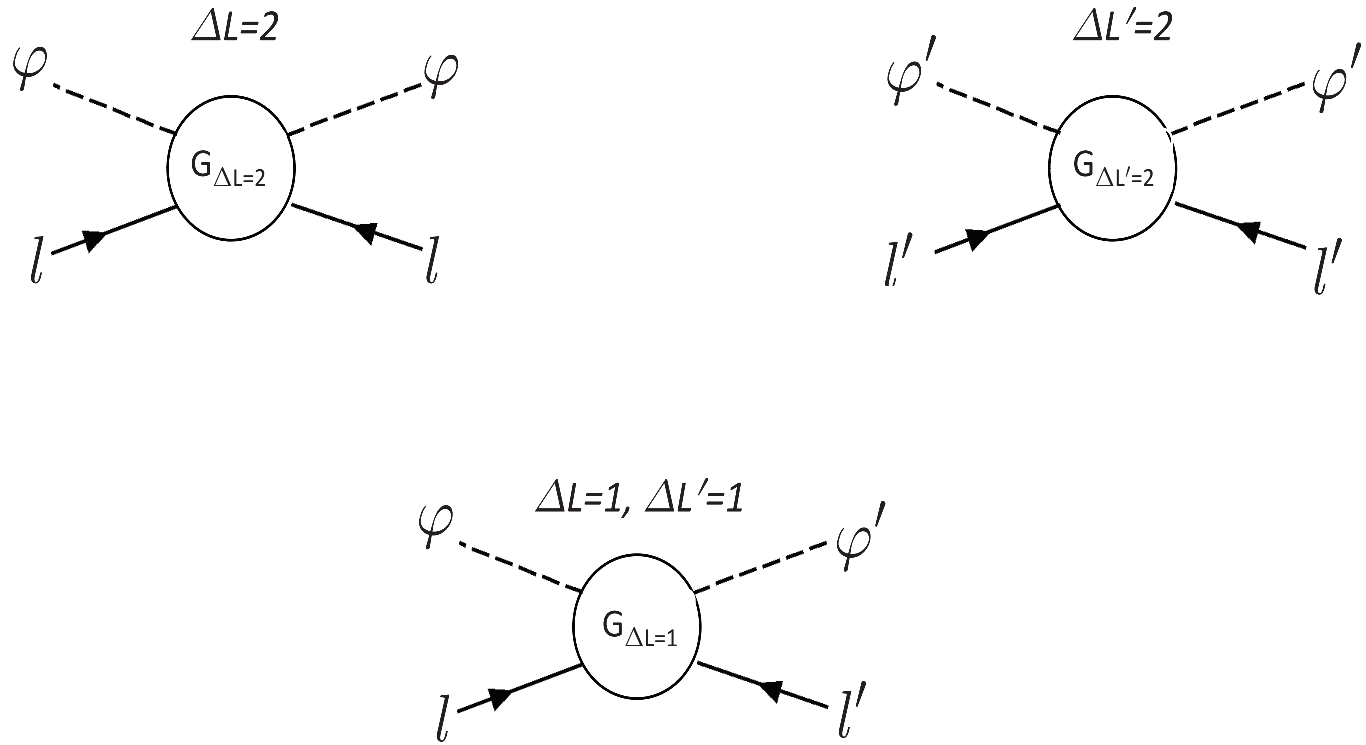
  C. out-of-equilibrium – *already implied by the BBN*

  and thus generate B-L$\neq$0 ($\to$ B$\neq$0 by sphalerons) for ordinary matter
- The same reactions generate B$'$-L$'$ $\neq$0 ($\to$ B$'$$\neq$0) in Mirror sector.

Both matter fractions: observable and dark, can be generated at one shoot !!

L. Bento, Z. Berezhiani, PRL 87, 231304 (2001)

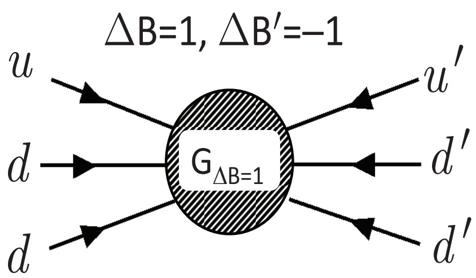
Sterile neutrinos come from parallel hidden sector

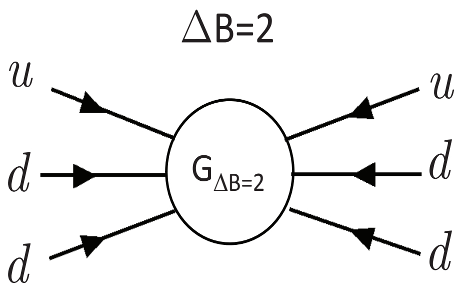


Effective $D=5$ operators $\frac{A}{M}(l\phi)(l\phi) \; + \; \frac{A'}{M}(l'\phi')(l'\phi') \; + \; \frac{D}{M}(l\phi)(l'\phi')$

Baryon number violation: $\Delta B = 1$

any neutral particle, elementary or composite, can mix its mass degenerate twin





- baryon - mirror baryon mixings *($n - n'$, $\Lambda - \Lambda'$ etc.)* ZB, Bento, '05

  $\frac{1}{M^5}(udd)(u'd'd')$, six-fermion interaction ($\Delta B = 1$, $\Delta B' = 1$)

  - *analogous to 6-fermion operators* $\frac{1}{M^5}(udd)^2$ ($\Delta B = 2$),

  inducing neutron - antineutron mixing

  $\tau_{n\bar{n}} > 10^8$ s $\qquad \tau_{nn'} = ?$

$n - n'$ oscillation: surprising possibility

PRL **96,** 081801 (2006) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2006

Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?

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We discuss the phenomenological implications of the neutron (n) oscillation into the mirror neutron (n'), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal n-n' oscillation in vacuum with a characteristic time τ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular, for the propagation of ultra high energy cosmic rays.

Experimental & astrophysical bounds

- ILL experiment for $n-\tilde{n}$ oscillation search in flight: $t \simeq 0.1$ s, $B < 10^{-4}$G
  - no $\tilde{n}$ event found, $\tau_{n\tilde{n}} > 0.86 \times 10^{8}$ s (~ 3 yr) *Baldo Ceolin et al. '94*

  as for $n - n'$: about 5% neutron deficit was observed, so taking
  $P_{nn'}(t) \simeq (t/\tau_{nn'})^2 < 10^{-2}$: $\tau_{nn'} > 1$ s
- $n - n'$ – anomalous UCN loses, $\eta < 2 \cdot 10^{-6}$: $\tau_{nn'} > 0.2$ s
- Nuclear Stability: no limit for $\tau_{nn'}$
- BBN bound: $\tau_{nn'} > 1$ s , neutron star stability: $\tau_{nn'} > 10^{-2}$ s

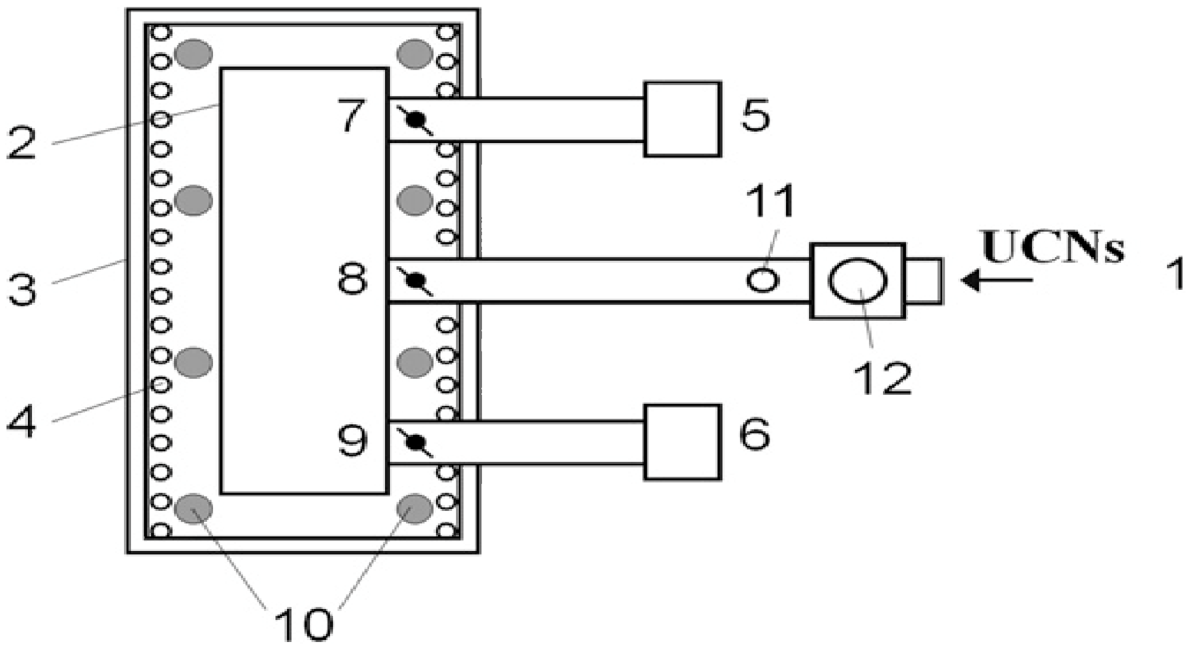
Recent Experimental search: comparing the neutron losses at different B

FR Munich, Schmidt et al. Procs. B&L-violation'07, Berkeley
ILL Grenoble, Ban et al. Phys.Rev.Lett. 99, 161603 (2007)
ILL Grenoble, Serebrov et al. Phys.Lett. B663, 181 (2008)
ILL Grenoble, Altarev et al. Phys.Rev. D 80, 032003 (2009)
ILL Grenoble, Bodek et al. NIM A611, 141 (2009)
ILL Grenoble, Serebrov et al. NIM A611, 137 (2009)
ILL Grenoble, Z.B et al., 2013 paper in preparation

$\tau_{nn'} > 414$ s if $B' = 0$
not valid if there is mirror magnetic field $B' > 10$ mG !!!

Experiments of Serebrov at ILL, Grenoble

Serebrov et al. (I) Phys.Lett. B 663, 181 (2008); (II) NIM A611, 137 (2009)



Comparing the losses for different magnetic fields in the UCN trap, Volume = 190 l, two detectors and monitor in the guide (PF2 MAMBA).

Collision frequency $\nu \approx 11\,s^{-1}$ *(m.f.p.* $t_f \sim 0.1\,s$*)*
effective holding time $t_s = 370\,s$ *(collision No.* $n_s = \nu t_s \approx 4000$*)*

About 4 month of measurements (each exp. I and exp. II)

Reach to $n - n'$ *oscillation probability down to* $\Delta P \sim 3 \times 10^{-8}$

2-nd experiment of Serebrov

Serebrov et al. NIM A611, 137 (2009)

Comparing the losses for different magnetic fields:

Horizontal magnetic field (measurements about 3 month) *repeating sequences*

$B_+, b_+, b_-, B_-; B_-, b_-, b_+, B_+$

B *large magnetic field* ($B = 0.2$ G)

b *small (zero) magnetic field* ($b = 0.2,\ 0.7, 3.0,\ 5.6,\ 12$ mG)

Directional $(+-)$ *asymmetry* $A_B = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$

(expected vanishing for small field, $A_b \approx 0$*)*

– *compatible with 0 within* 1σ, $A_B = (0.1 \pm 0.5) \times 10^{-4}$ *(but see later!)*

Large-small asymmetry $E_{Bb} = \frac{N_{\vec{B}} + N_{-\vec{B}}}{N_{\vec{b}} + N_{-\vec{b}}} - 1 \approx (P_B - P_b)\nu t_s,$

– 2σ *deviation:* $E = -(1.5 \pm 0.75) \times 10^{-4}$

Vertical magnetic field (incomplete 2 weeks) *repeating sequences*

$B_+, B_-, B_-, B_+; B_-, B_+, B_+, B_-$

– *only large field,* $B \simeq 0.2$ G & $B \simeq 0.4$ G

Up-down $(+-)$ *asymmetry* $A_B = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$

- 3σ *deviation reported:* $A_B = (3.8 \pm 1.2) \cdot 10^{-4}$ *something was wrong here*

We reanalized the data ...

Thanks to A. Serebrov for data records

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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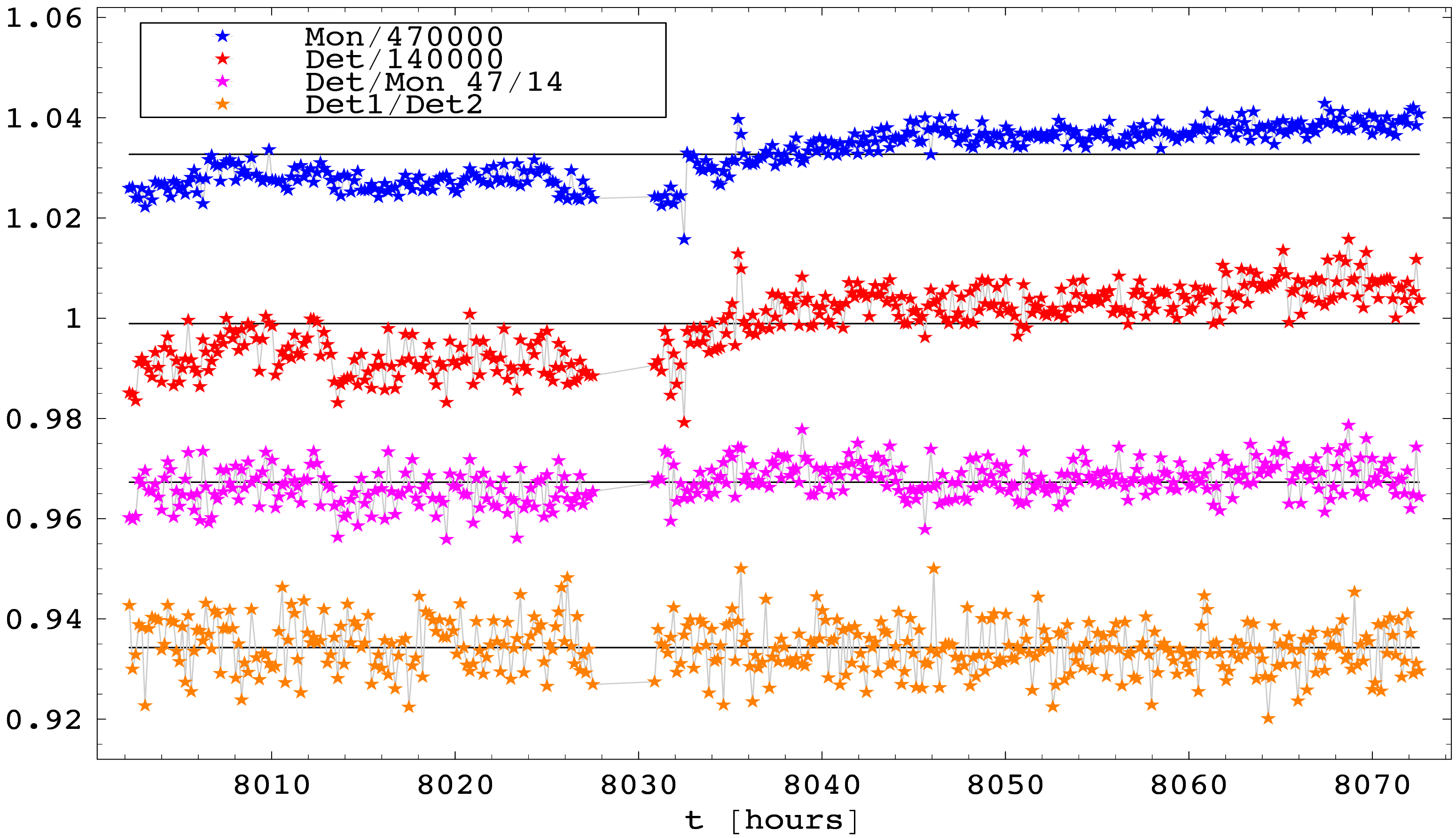
Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron 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

Measurements at $B \approx 0.2$ G

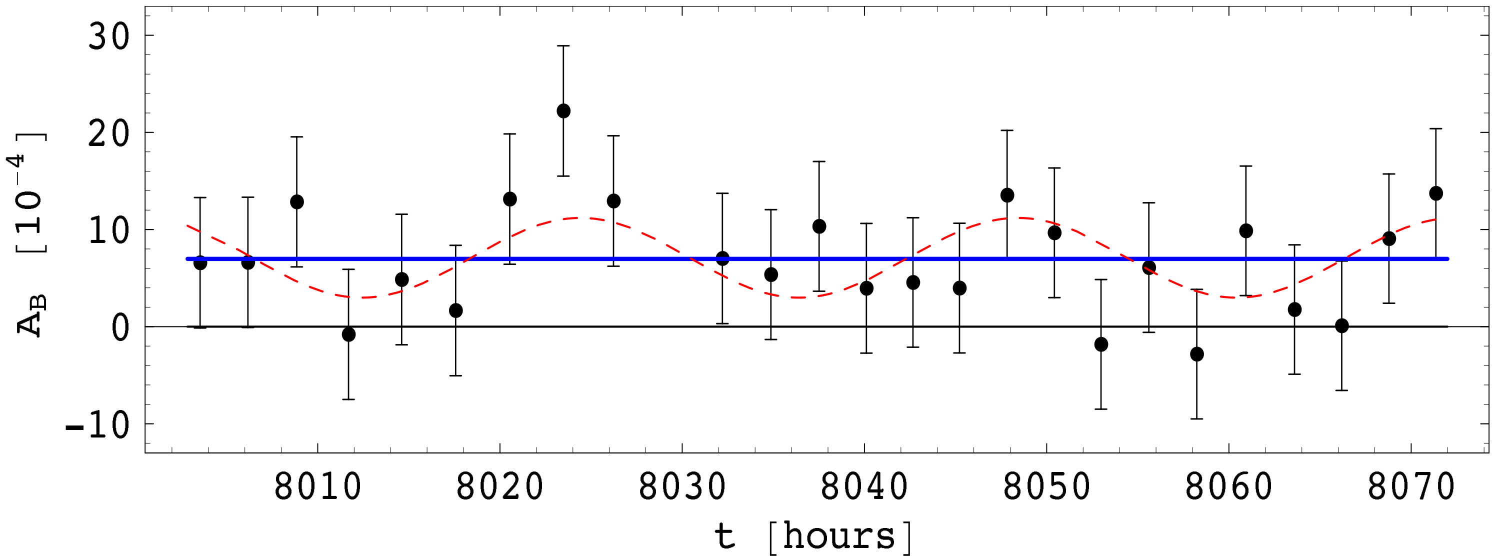


Det/Mon = Const $\chi^2_{\mathrm{dof}} = 1.4$ Det1/Det2 = Const $\chi^2_{\mathrm{dof}} = 1.0$

Results of our analysis

Z.Berezhiani, Nesti, Magnetic anomaly in UCN trapping: signal for neutron oscillation to parallel world? Eur. Phys. J. 72, 1974 (2012)

Up-down asymmetry $A = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s, \quad \nu t_s \approx 4000$



- at $B \simeq 0.2$ G : $A_B = (7.0 \pm 1.3) \times 10^{-4} \quad (\chi^2_{\rm dof} = 0.9) \qquad (5.2\sigma)$!!

– calibration in free flow mode show no evidence for systematic effects, with $\pm 2 \times 10^{-5}$

- at $B \simeq 0.4$ G : $A_B = (-0.3 \pm 2.4) \times 10^{-4}$ Resonance ?

Points to $n - n'$ oscillation with $\tau_{nn'} = 2 - 10$ s and $B' \simeq 0.1$ G

Our analysis for horizontal field   (preliminary)

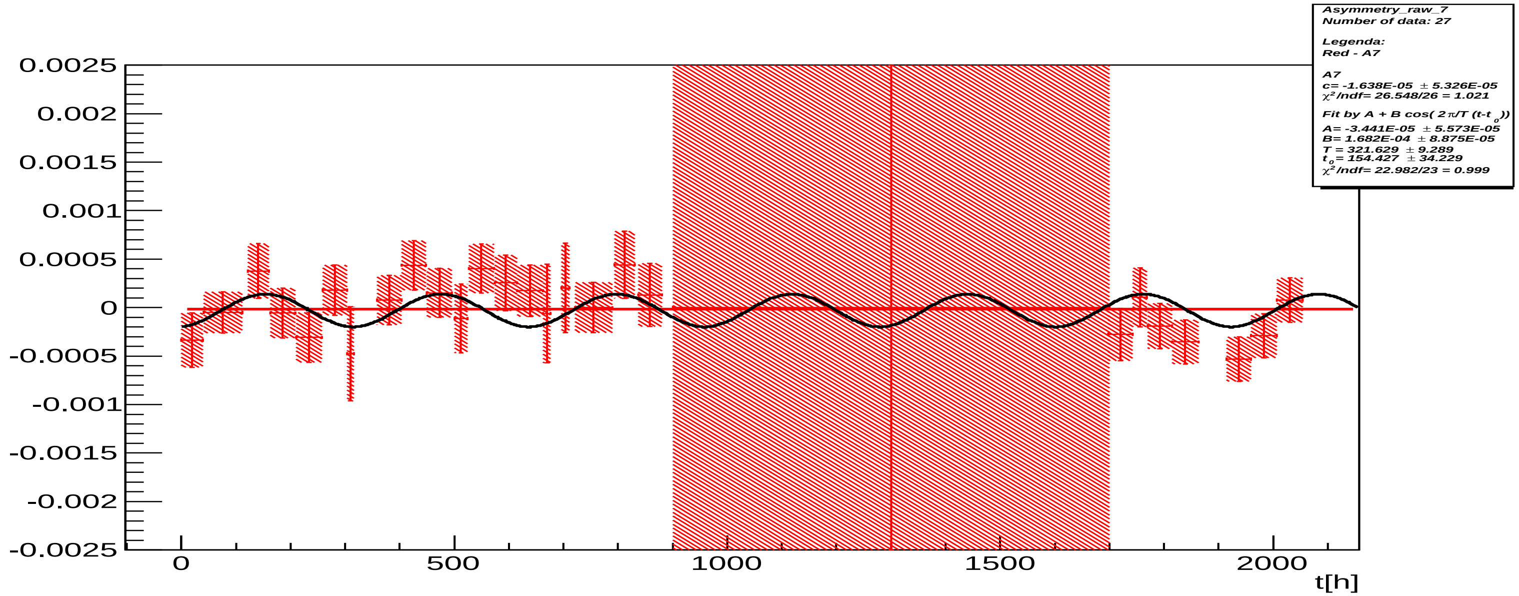
sequences $B_+, b_+, b_-, B_-; B_-, b_-, b_+, B_+$

B large magnetic field ($B = 0.2$ G)

b small (zero) magnetic field ($b = 0.2,\ 0.7, 3.0,\ 5.6,\ 12$ mG)

$+-$ asymmetry at small field $A_b = \frac{N_{b+} - N_{b-}}{N_{b+} + N_{b-}} = (D_b \cos\beta)\nu t_s$

Zero result expected !! ... and Zero is obtained !!



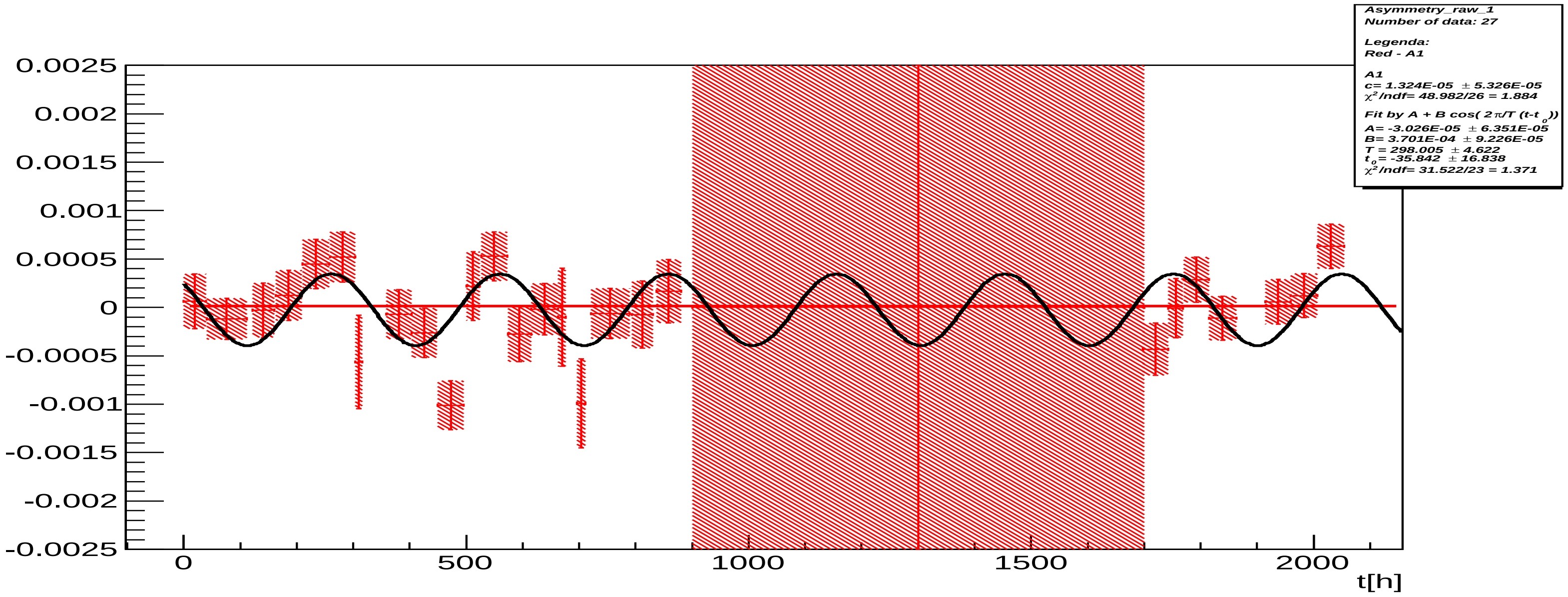
Constant fit $A_b = (-1.6 \pm 5.3) \times 10^{-5}$ with $\chi^2_{\rm dof} = 1.0$

and no significant hint for time modulation .....

But for large field, $B = 0.2$ G ....

sequences $B_+, b_+, b_-, B_-; B_-, b_-, b_+, B_+$

$+-$ asymmetry at large field $A_B = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$



Constant fit $A_B = (-1.4 \pm 5.3) \times 10^{-5}$ *but with* $\chi^2_{\rm dof} = 1.9$

while time periodic fit $A_B \propto C + A\cos\left(2\pi \frac{t - t_0}{T}\right)$ gives

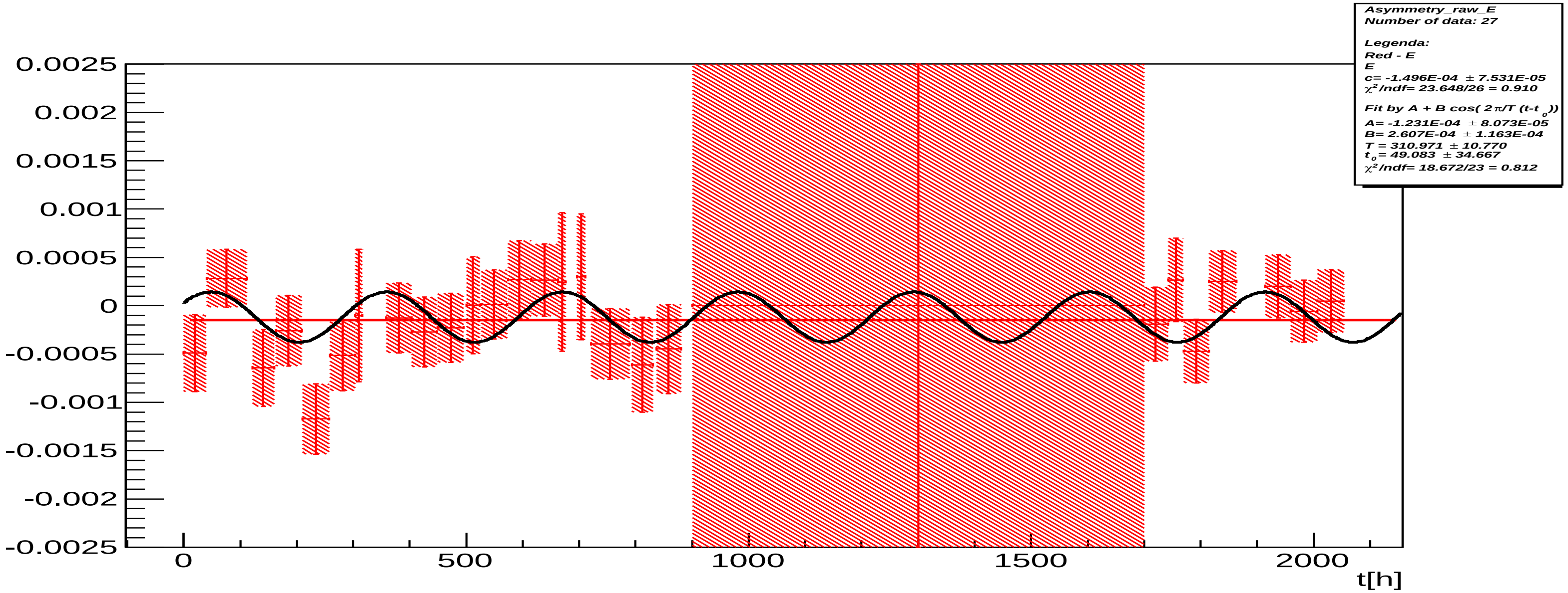
$C = (-3.0 \pm 6.3) \times 10^{-5}, \quad A = (-37.0 \pm 9.2) \times 10^{-5} \quad (4\sigma)$

and $T = 298 \pm 5$ h – *with* $\chi^2_{\rm dof} = 1.3$

And comparing large B and small b fields ....

sequences $B_+, b_+, b_-, B_-; B_-, b_-, b_+, B_+$

Large-small asymmetry $E_{Bb} = \frac{N_{\vec{B}}+N_{-\vec{B}}}{N_{\vec{b}}+N_{-\vec{b}}} - 1 \approx (P_B - P_b)\nu t_s,$

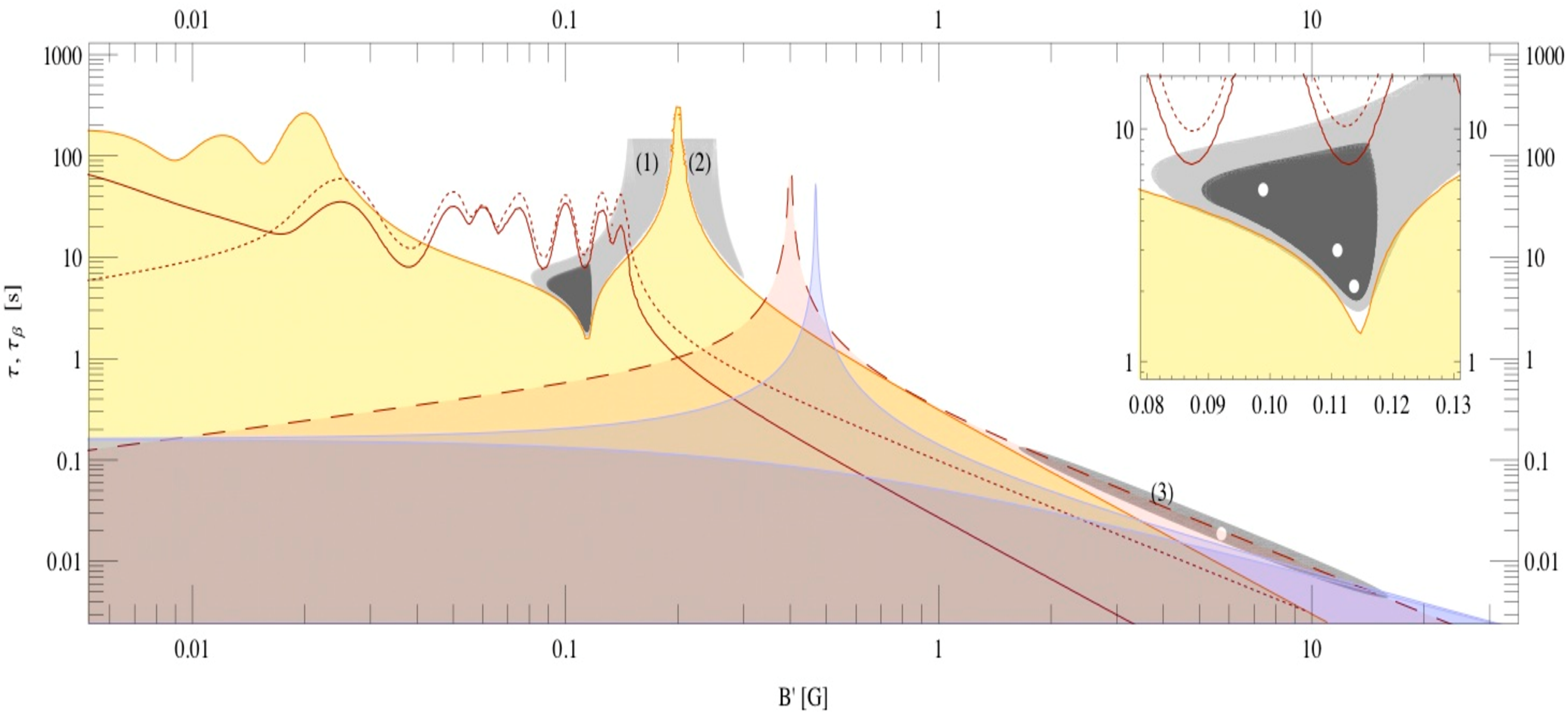


Constant fit: $E_{Bb} = -(1.5 \pm 0.75) \times 10^{-4}$ *with* $\chi^2_{\rm dof} = 1.1$ (2σ)

and time periodic fit $E_{Bb} \propto C + A\cos\left(2\pi\frac{t-t_0}{T}\right)$ gives
$C = (-1.3 \pm 8.0) \times 10^{-5}$, $A = (-26 \pm 11) \times 10^{-5}$ (2.5σ)
and $T = 310 \pm 11$ h – *with* $\chi^2_{\rm dof} = 0.8$
(while for A_B we had $T = 298 \pm 5$ h !!)

Global analysis if signals are time variable ...

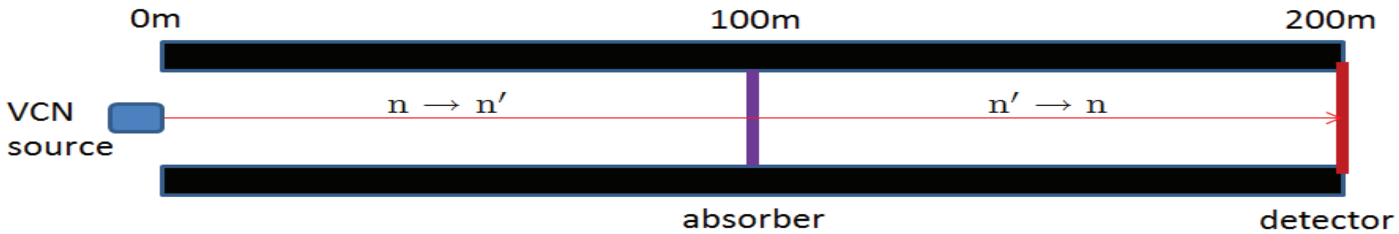
Experiments PSI 1,2,3 also indicate about 3σ anomalies near $B \sim 0.1$ G
Last experiment at ILL (summer 2013) shows 4σ deviation *(Preliminary)*



$B' \sim 0.1$ G but its value may vary in time within 50%, and its direction in 100%. $\tau \sim 1-10$ s ?????

Mirror magnetic field of Earth maybe generated by a tiny friction of matter and captured dark matter – *analogous to* Z.B., Dolgov, Tkachev, 2013

IRIDE @ LNF, BNL (?) .... ESS (intensity, pulse shape)



To maximize the neutron observation time the proposed experiment can involve a beam of very cold neutrons, VCN, produced by the ESS. Neutrons with assumed velocities between 50 to 500 m/s will travel along a 100+100 meter evacuated tube with a neutron absorber placed in the middle, so that no initial neutrons should be in the second volume. The detector located at the end of the second hundred meters will detect regenerated neutrons. In order to select the resonance case the tube must be placed within a homogenous tunable magnetic field.

$n \to n' \to n$ near resonance $P_{nn'} \times P_{n'n} \sim (t/\tau)^4 \sim 10^{-6}$

Concluding: *What if $n - n'$ will turn true really ...*

– Need for new $n \to n'$ exps. with bigger statistics and careful systematics

- *search for $n \to n' \to n$ regeneration,*
- *or Lorentz-violation in the neutron precession – (B-dependent corrections to μ_n)*

are positive .... $n - n'$ oscillation – window to parallel world !! *Fundamental for particle physics, astrophysics and cosmology, and even for geophysics.... News:*

- *Who is dark matter, its nature, its detection, identity of sterile ν's*
- *Primordial co-genesis of matter and dark matter:* $\Omega_{B'} \sim 5\Omega_B$
- *impact for Big Bang Nucleosynthesis, CMB and cosmological structure formation*
- *Dark matter in Galaxies: Halo as mirror elliptic galaxy, Machos, dark supernove*
- *Dark matter capture by the solar system and the Earth ...*
- *origin of magnetic fields in galaxies, stars and even planets ? ...*
- *$n - n'$ in cosmic rays, in solar flares, at the BBN, in neutron stars, etc.*
- *Other Ordinary - mirror particle oscillations:* *e.g.* $\Lambda \to \Lambda'$, $K \to K'$, ...
  or for hydrogen atom $\mathrm{H} \to \mathrm{H}'$, etc. + *regeneration*
  but also particle- antiparticle oscillations $n \to \tilde{n}$, $\Lambda \to \tilde{\Lambda}$, $\mathrm{H} \to \tilde{\mathrm{H}}$ etc.
- *underlying TeV scale physics can be tested at the LHC and meson factories*

- *..... can provide a free source of energy ?* A. Asimov, "The Gods Themselves"

What's Next for LNGS

Study of potential consequences of particle regeneration or appearance in low background conditions:

- *Regeneration of neutrons from solar flares: $n \to n' \to n$ in underground chamber with controlled magnetic field*

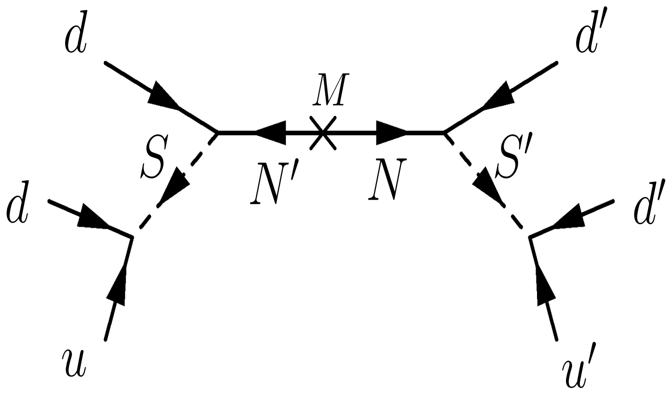
- *Search for millicharged DM captured in the Earth via induced EM phenomena rotating disk.*

- *Dark antimatter: Appearance of antiparticles (antineutron, antihydrogen) from mirror sector in underground chamber with controlled magnetic field. observation of antineutrino burst from explosions of mirror SN.*

Baryon number violating operators: $D = 9$

- $\frac{1}{M^5}(udd)(u'd'd')$, six-fermion interaction ($\Delta B = 1$, $\Delta B' = 1$) induces he neutron - mirror neutron mass mixing $\epsilon\,(\overline{n}n' + \overline{n}'n)$,
$\epsilon \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \simeq \left(\frac{10\,\rm TeV}{\mathcal{M}}\right)^5 \cdot 10^{-15}\,\rm eV \qquad \mathcal{M} \sim 10\,\rm TeV$

• *6-fermion operators* $\frac{1}{M^5}(udd)^2$ $(\Delta B = 2)$, *inducing neutron - antineutron mixing,* can also be obtained with Majorana mass insertion, $\mu \ll M$



induced by heavy singlet N "seesaw"
u, d and u', d' ordinary and mirror quarks
S, S' color triplet scalars (squarks?))
– can generate B (and B′) asymmetry
via processes $dS \to d'S'$ *etc.*
even below TeV scale (adult Early Universe)

$\mathcal{M} \sim (M_S^4 M_N)^{1/5} \sim 10\,\rm TeV$ *– can be achieved in Seesaw*
if $M_S, M_N \sim 10\,\rm TeV$, *or* $M_N \sim 10^7\,\rm GeV$ *and* $M_S \sim 1\,\rm TeV$

Testable at LHC?

ZB, Bento, '05

Neutron - Mirror neutron mixing

- $n - n'$ oscillation in vacuum: maximal mixing $\theta = 45^\circ$

and oscillation time $\tau_{nn'} = \epsilon^{-1} \sim \left(\frac{\mathcal{M}}{10\,\mathrm{TeV}}\right)^5 \times 1\,\mathrm{s}$

$$P_{nn'}(t) = \sin^2\left(\frac{t}{\tau_{nn'}}\right) \times \exp\left(-\frac{t}{\tau_{\mathrm{dec}}}\right)$$

... can be fast, $\tau_{nn'} \sim 1\mathrm{s}$ ... faster then neutron decay, $\tau_{\mathrm{dec}} = 880$ s

... similar to neutron - antineutron oscillation but limits on $n - \bar{n}$ are strong:

Direct experimental Search: $\tau_{n\bar{n}} > 0.86 \times 10^8$ s   Baldo Ceolin et al., '95

Nuclear stability: $\tau_{n\bar{n}} > 1.3 \times 10^8$ s   PDG '2011

c.f. $\tau_p > 10^{33}$ *yr (!!)* *for proton decay* $(\Delta B = 1)$

!!! N.B. Nuclear Stability

- $n - \tilde{n}$ destabilizes nuclei: $(A, Z) \to (A-1, Z, \tilde{n}) \to (A-2, Z) + \pi$'s

$\tau_{n\tilde{n}} > 10^8$ s or so ...

- $n - n'$ does not: $(A, Z) \to (A-1, Z) + n'$ forbidden

for stable nuclei by energy conservation ! – no restriction for $\tau_{nn'}$!

Neutron - antineutron oscillation in external fields

Effective (non-relativistic) 4×4 Hamiltonian for $n - \tilde{n}$ oscillation

$$H = \begin{pmatrix} m + V_{\rm g} + V_n - i(\frac{\Gamma}{2} + W_n) + \mu\vec{B}\vec{\sigma} & \epsilon \\ \epsilon & m + V_{\rm g} + V_{\tilde{n}} - i(\frac{\Gamma}{2} + W_{\tilde{n}}) - \mu\vec{B}\vec{\sigma} \end{pmatrix}$$

- CPT: $m_{\tilde{n}} = m_n, \Gamma_{\tilde{n}} = \Gamma_n, \quad \mu_{\tilde{n}} = -\mu_n = 1.91\mu_N$
- Grav. potentials $V_{\rm g}^{\tilde{n}} = V_{\rm g}^{n}$
- Magnetic field: *creates Energy gap* $|\mu B| = B[{\rm G}] \times 6 \cdot 10^{-12}\ {\rm eV} = 9000\ {\rm s}^{-1}$

$n - \tilde{n}$ oscillation probability in magnetic field $\vec{B}$

$$P_{n\tilde{n}}(t) = \frac{\epsilon^2}{\omega^2 + \epsilon^2} \sin^2(\sqrt{\omega^2 + \epsilon^2}\, t) \approx \frac{\epsilon^2}{\omega^2} \sin^2(\omega t) \qquad \omega = |\mu B|,$$

When $\omega t \ll 1$: $\quad P_{n\tilde{n}}(t) = (t/\tau_{n\tilde{n}})^2, \quad \tau_{n\tilde{n}} = \epsilon^{-1}$

Magnetic field suppression is needed : for $t \sim 0.1$ s, $B < 10^{-4}$ G

Neutron - Mirror neutron oscillation in external fields

Effective (non-relativistic) 4×4 Hamiltonian for $n - n'$ oscillation

$$H = \begin{pmatrix} m + V_\mathrm{g} + V_\mathrm{m} - i(\frac{\Gamma}{2} + W_\mathrm{m}) + \mu\vec{B}\vec{\sigma} & \epsilon \\ \epsilon & m' + V'_\mathrm{g} + V'_\mathrm{m} - i(\frac{\Gamma'}{2} + W'_\mathrm{m}) + \mu'\vec{B}'\vec{\sigma} \end{pmatrix}$$

- Exact mirror parity: $m' = m$, $\Gamma' = \Gamma$, $\mu' = \mu = -1.91\mu_N$
- Grav. potentials $V'_\mathrm{g} = V_\mathrm{g}$
- but there are magnetic fields: $\vec{B}' \neq \vec{B}$: at Earth $B \simeq 0.5\ \mathrm{G}$

In magnetic fields $\vec{B}$ and $\vec{B}'$, the oscillation probability becomes

$$P(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2}\cos^2\frac{\beta}{2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}\sin^2\frac{\beta}{2},$$

ZB, EPJ C64, 421 (2009)

$\omega = \frac{1}{2}|\mu B|$, $\omega' = \frac{1}{2}|\mu B'|$, β *angle between* $\vec{B}$ *and* $\vec{B}'$, $\tau = \tau_{nn'} = \epsilon^{-1}$

Energy gap $\omega = \frac{1}{2}|\mu B| = B[\mathrm{G}] \times 3 \cdot 10^{-12}\ \mathrm{eV} = 4500\ \mathrm{s}^{-1}$

At the resonance, $B = B'$, when $\omega t \ll 1$: $P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2 \cos^2\frac{\beta}{2}$,

Experimental strategy for searching $n \to n'$

Coherent neutron interaction with matter gives "optical" potential $V \sim \mathrm{few} \times 10^{-7}$ eV. Thus, if $V > 0$, ultra-cold neutrons (UCN) with $E_{\mathrm{kin}} < V$. i.e. $v <$ few m/s are reflected from the surface.

Thus, the UCN can be stored in the trap: The material wall of the trap acts as a potential well

If in the trap, during a free flight ($t_f \sim 0.1$ s) between the wall collisions n oscillates to n', than it each wall collision it disappears from the trap with a mean probability $P(\vec{B})$

$$\frac{dN}{dt} = \Gamma_{\mathrm{eff}} N \quad \rightarrow \quad N(t) = N(0) \times e^{-\Gamma_{\mathrm{eff}} t}$$

$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{dec}} + \eta_{\mathrm{loss}} \nu + P(\vec{B}) \nu$, $\nu = 1/t_f \sim 10$ s^{-1} collision frequency.

For different magnetic fields $\vec{B}_1$ and $\vec{B}_2$, all regular (B-independent) contributions as well as $N(0)$ cancel out in the ratio $\frac{N_1(t)}{N_2(t)} = \frac{N(0)e^{-\Gamma_{1\mathrm{eff}} t}}{N(0)e^{-\Gamma_{2\mathrm{eff}} t}} = e^{-(P_1 - P_2)\nu t}$

Asymmetry $A_B = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx \frac{1}{2}(P_{\vec{B}} - P_{-\vec{B}})\nu t_s = D_B \cos\beta \nu t_s,$

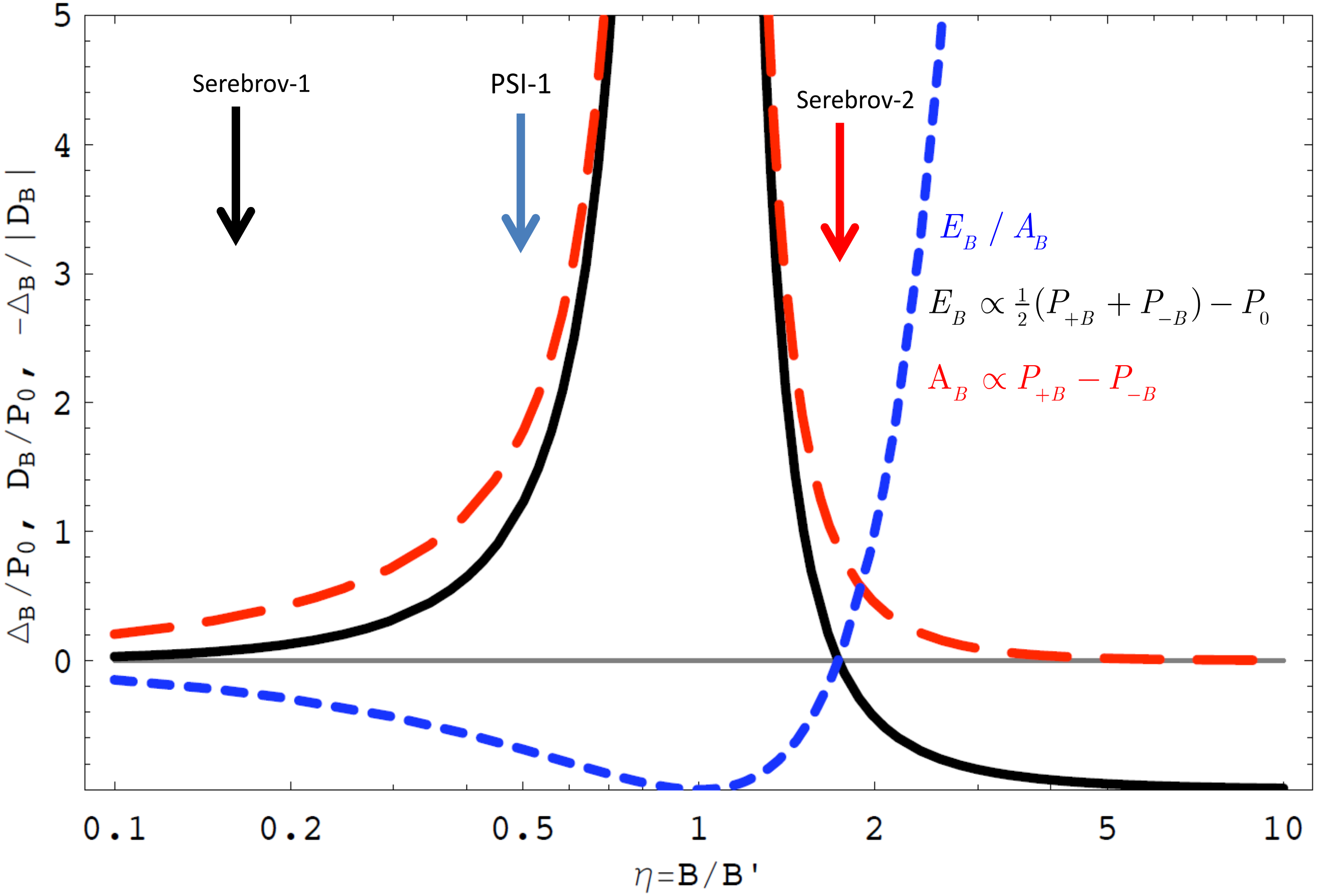
On-off Effectivity $E_B = 1 - \frac{N_{\vec{B}} + N_{-\vec{B}}}{2N_0} \approx \Delta_B \nu t_s,\ \Delta_B = \frac{1}{2}(P_{\vec{B}} + P_{-\vec{B}}) - P_0$

Effectivity of D_B and Δ_B

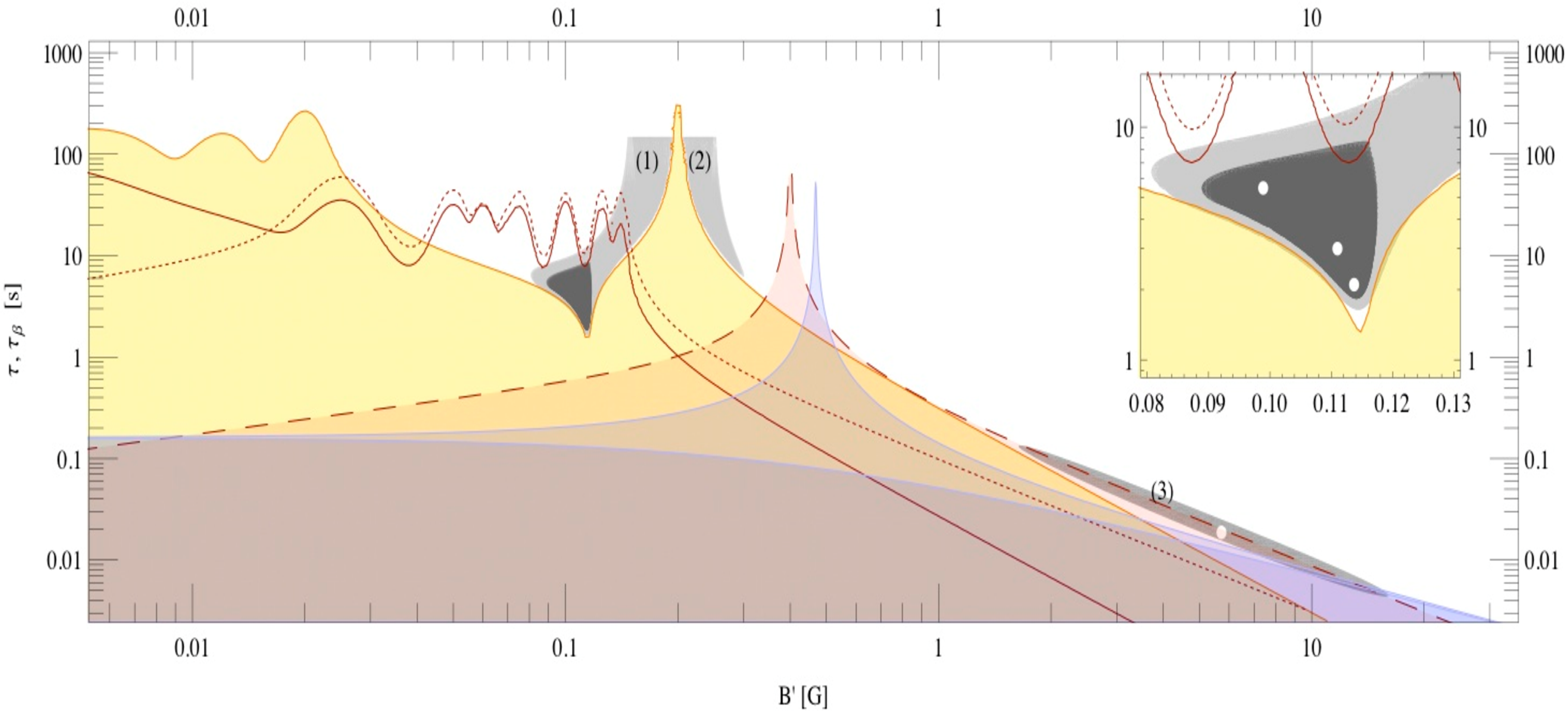
Z.B., Eur. Phys. J. C64, 421 (2009)

$$P_0 = \frac{\epsilon^2}{2\omega'^2} = \frac{2}{\tau^2_{nn'}|\mu B'|^2}$$

E.g. assume B'=0.12 Gauss



Global analysis – *assuming constant mirror field B'*



$B' \sim 0.1$ G , $\tau/\cos\beta \sim 2 - 10$ s ?????

Can the Earth possess mirror magnetic field?
.... Why not if mirror matter is dark matter ... and it can be captured by the Earth with $\sigma \sim 1$ pb (DAMA/Libra etc.)

Neutron - Mirror neutron mixing in astrophysics

So $n - n'$ transition is impossible for neutrons bound in nuclei ....
it ican be tested only with free neutrons

where one can have free neutrons apart of reactors/spallation sources ?
(I already described the experimental status)

● *neutrons in ultra-high energy cosmic rays: $n \longrightarrow n'$ and $n' \longrightarrow n$ would modify the UHECR spectrum around GZK energies* *Z.B and Bento 2005, Z.B. and Gazizov 2011*

● *neutrons from the sun (solar flares): $n \longrightarrow n' \longrightarrow n$ transition could bring to neutron detection behind the Earth* *Mohapatra, Nasri and Nussinov, 2005*

● *at the BBN epoch ($t \sim 1 - 200$ s), before the capture of all survived neutrons in helium etc.: $n' \longrightarrow n$ could lead to time delayed injection of neutrons from (neutron reach) mirror sector which could solve lithium-7 problem without troubling deuterium abundance* *Coc, Uzan, Vangioni and Pospelov, 2014*

● *$n - n'$ transitions may have interesting implications for neutron stars (mass/radius problem, transition to quark stars, etc.) strongly suppressed by large chemical potential (~ 200 MeV) – good calculations are needed*

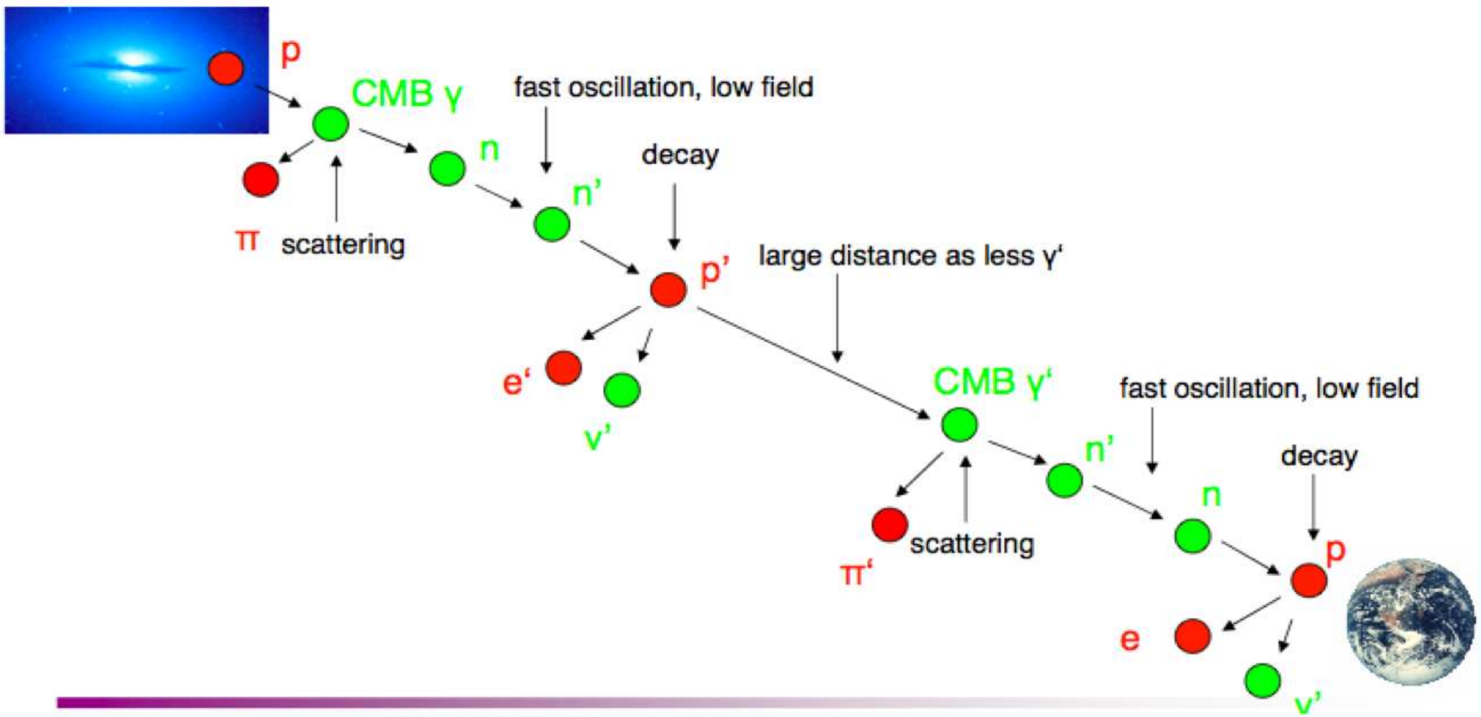
Physics underlying $n - n'$ mixing

- *Cogenesis of baryon and dark matter.* *Primordial baryon asymmetry generated via $\Delta B = 1$ processes like $udd \to u'd'd'$. The similar (and somewhat larger) baryon asymmetry is generated in the Mirror sector. This naturally explanains the origin of the baryonic and dark matter balance in the Universe: $\Omega_D \sim \Omega_B$.*

N.B. This mechanism requires collaboration of $\Delta B = 2$ processes like $udd \to \bar{u}\bar{d}\bar{d}$ – (neutron-antineutron $n - \tilde{n}$ oscillation, $\Lambda - \tilde{\Lambda}$, etc.).
They should be also active though could be much slower. Hence, should the $n - n'$ oscillation detected at the level $\tau_{nn'} < 10^3$ s, (i.e. $\mathcal{M}_{nn'} \sim 10$ TeV) it would give a strong argument that $n - \tilde{n}$ oscillation should also exist at the experimentally accessible level – with the relevant cutoff scale $\mathcal{M}_{n\tilde{n}} \sim 1$ PeV and thus $\tau_{n\bar{n}} \sim 10^9$ s.

- *Can be tested at LHC, PSI, etc.* *at least some messengers betwen udd and $u'd'd'$ must be light enough to be born at the TeV scale.*
In particular, $n - n'$ mixing maybe related to R-parity violating physics in SUSY, to flavor symmetry, etc.

$n - n'$ oscillation and propagation of UHECR



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

A. $p + \gamma \to p + \pi^0$ or $p + \gamma \to n + \pi^+$ $\quad P_{pp,pn} \approx 0.5 \quad l_{\rm mfp} \sim 5$ Mpc

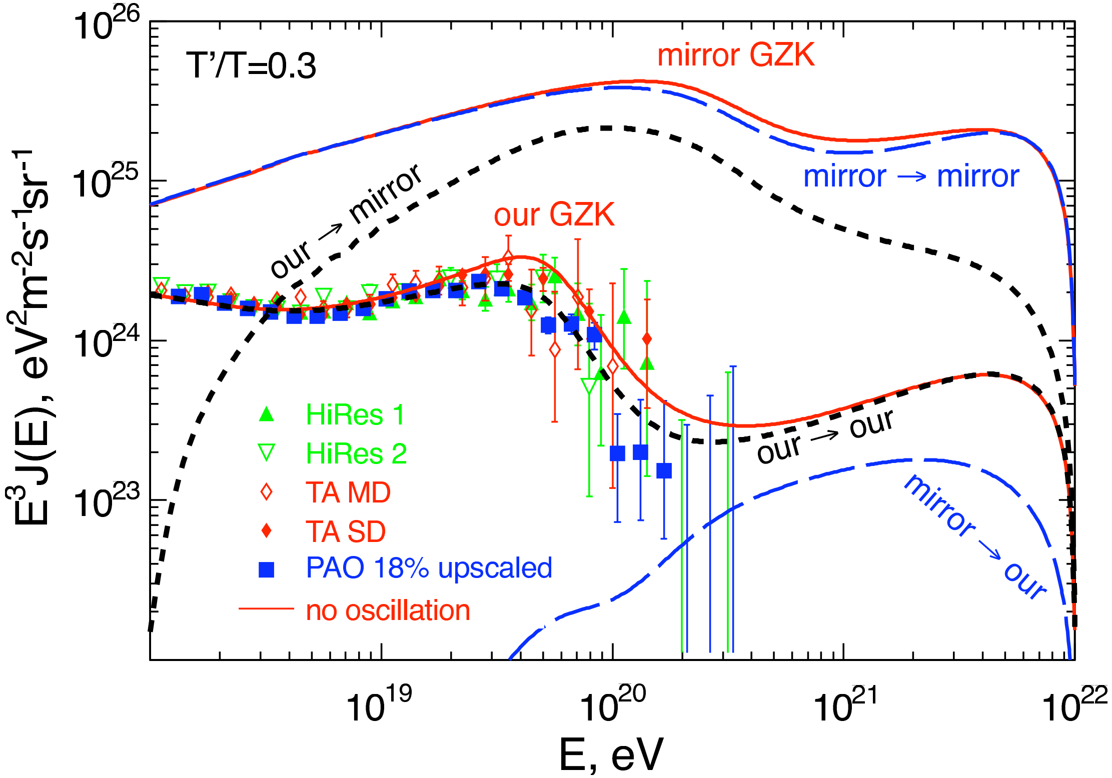
B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100\ \rm EeV}\right)$ kpc

C. $n' \to p' + e' + \bar{\nu}'_e \quad l_{\rm dec} \approx \left(\frac{E}{100\ \rm EeV}\right)$ Mpc

D. $p' + \gamma' \to p' + \pi'^0$ or $p' + \gamma' \to n' + \pi'^+ \quad l'_{\rm mfp} \sim (T/T')^3\, l_{\rm mfp} \gg 5$ Mpc

$n - n'$ oscillation and the UHECR spectrum

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



UHECR flux with $n - n'$ oscillation relative to the standard GZK prediction (normalized to "dip" model) for UHECR from ordinary and mirror sources

Auger observes cutoff of the spectrum at $E \simeq 30$ EeV, earlier than expected by GZK mechanism, $E \simeq 60$ EeV

Positive predictions for energies at $E > 100$ EeV (JEM-EUSO)