Dark World:

Dark atoms, dark neutrinos, dark neutrons ....

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Heisenberg – an intelligent question

W. Heisenberg, Introduction to the Unified Field Theory of Elementary Particles, 1965

In last chapter (Weak Interactions), Heisenberg questions the origin of massless neutrino. Neutrino is a neutral particle but this does not mean that it must be massless. (Chiral) neutrino can make a (Majorana) mass with antineutrino state. Why then it is massless ?

And then he suggests the following:
" ... this makes to think that the neutrino might play a role of a Goldstone particle emerging due to asymmetry of a ground state ... though here the usual Goldstone argumentation needs to be modified ... and arguments according to which Goldstone particles must be bosons, probably will be rendered invalid ... In this view, interpretation of neutrino as a Goldstone particle looks very appealing. On the other hand, theory of weak interactions does not exist yet ... "

A crazy idea .... and even wrong !!!
NOW we know that neutrinos are not Goldstones

Yet, there are many crazy ideas around that are not even wrong ...

Standard Model – an intelligent design

Gauge Symmetry $SU(3) \times SU(2) \times U(1)$

gauge fields: G(luons), W, Z, γ & Higgs field(s): $\phi = (H_u, H_d)$

quarks (B=1/3)	leptons (L=1)	|	$\widetilde{\text{quarks}}$ (B′=-1/3)	$\widetilde{\text{leptons}}$ (L=-1)
$q_L = (u, d)^t_L$	$l_L = (\nu, e)^t_L$	|	$\tilde{q}_R = (\tilde{u}, \tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$
$u_R \quad d_R$	$e_R \quad (N_R\ ?)$	|	$\tilde{u}_L \quad \tilde{d}_L$	$\tilde{e}_L \quad (\tilde{N}_L\ ?)$
Higgs: ϕ		|	$\widetilde{\text{Higgs}}$: $\tilde{\phi}$	

Fermion masses $\mathcal{L}_{\rm Yuk} = f_L Y \tilde{f}_L \phi + \tilde{f}_R Y^* f_R \tilde{\phi}$ *(natural flavor cons.)*

- CP: $L \leftrightarrow \tilde{R}, \; R \leftrightarrow \tilde{L}, \quad \phi \leftrightarrow \tilde{\phi}$ – complex conjugation

  $\mathcal{L}_{\rm Yuk}$ breaks CP once Yukawa constants Y are complex

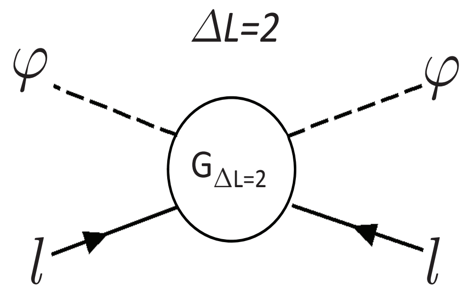
- Standard Model has a protective symmetry for masses of ν's – accidental global $U(1)$ of lepton number which is violated by $D = 5$ operator

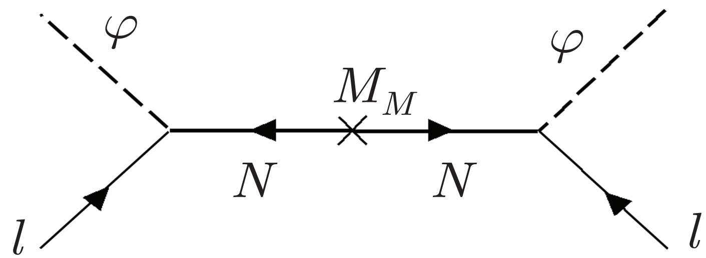
$\frac{A}{M}(l_L\phi)(l_L\phi)$ + h.c. $(\Delta L = 2)$ *and so* $m_\nu \sim v_W^2/M$ S. Weinberg 79

– $M \gg v_W$ is a cutoff scale from relevant "New Physics" beyond SM

– A is "Yukawa" matrix determining mass and mixing pattern of ν's

Seesaw





No N*:* *Effective* $D = 5$ *operator* $\frac{A_{ij}}{M}(l_i\phi)(l_j\phi)$

With N*:* $D = 4$ *terms* $\mathcal{L}_\nu = y_{ia}\phi l_i N_a + \frac{1}{2} M g_{ab} N_a N_b$

$A = y g^{-1} y^t$ *Effective operators obtained by integrating out heavy* N_a*,* $a = 1, 2, \ldots$ *fermions, gauge singlets with Majorana mass terms* $M g_{ab} N_a N_b$ *and Yukawa (Dirac) couplings* $l_i y_{ia} N_a \phi$ *(*M *overall mass scale and* g_{ab}, y_{ia} *Yukawa matrices)*

• BAU via leptogenesis: Decay $N \to l\phi$ violates $B - L$, violates CP: $\Gamma(N \to l\phi) - \Gamma(N \to \tilde{l}\tilde{\phi}) \neq 0$ due to complex Yukawas y and may be out of equilibrium at $T \sim M$.

Fukugita, Yanagida, 86

However, present experimental data indicate to some anomalies (Reactor neutrino anomaly, Gallium anomaly, LSND, etc.)

For explaining them, theorists invoke some light fermion specie(s), SM singlets but having significant oscillation with neutrinos, and coined them by less sexy name sterile neutrino (sneutrino)

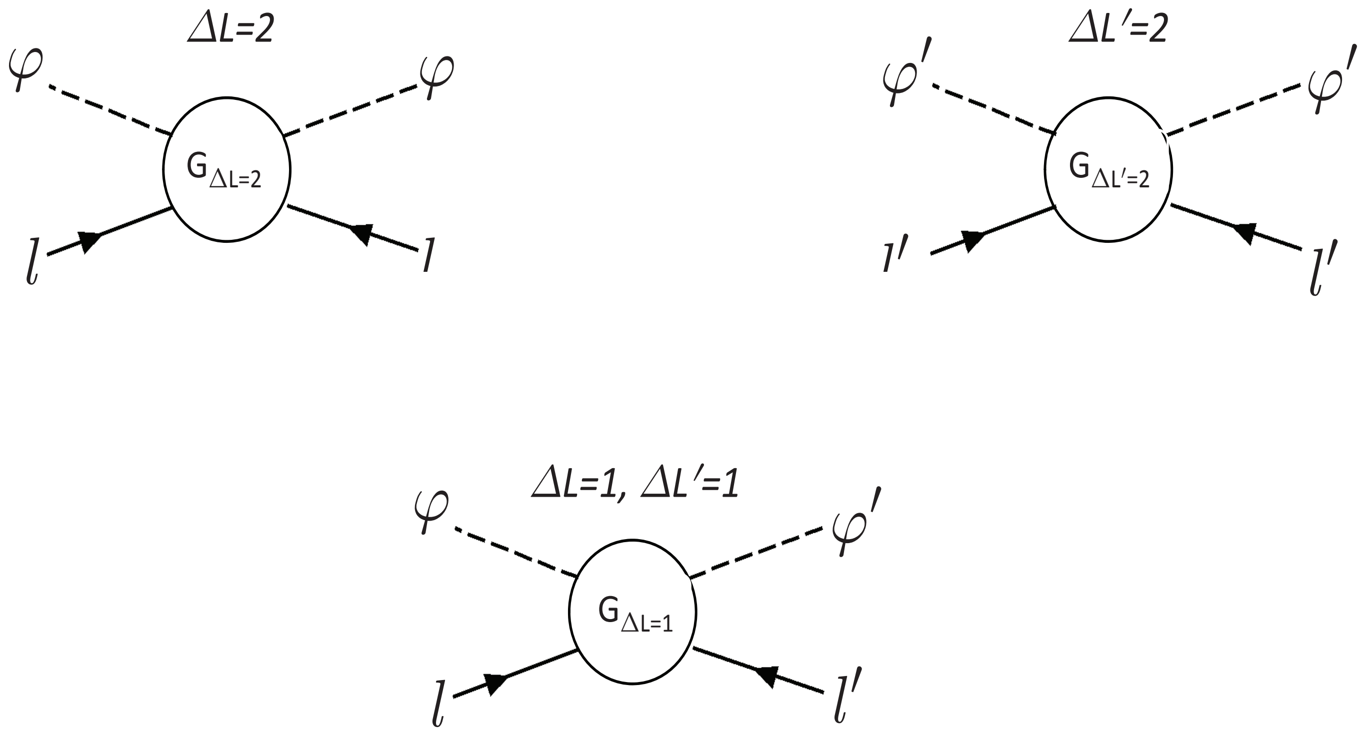
WDM: ν_s with $m \sim$ keV. Mixing with normal nu's ? (3.5 keV excess)

Immediate questions arise:
- why these SM singlet ν_s are light ?
- why these have a reasonable mixing with active neutrinos ?
- and finally, who are these guys ?

Some theorists argued that RH neutrinos of seesaw can be light *(without really asking why these must fasten belt for obeying such a strong diet .... or, as we call it, Fine Tuning)*

Others invented chimeras: Goldstino, dilatino, modulino, axino, saxino ... which could be massless (or enough light) ... but these have no reason to have large mixing with active neutrinos ... and require again Fine Tunings for imposing such mixing without destroying experimental consistency

Sterile neutrinos come from parallel dark world



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

Sterile ν's are light by same motive as active ν's – and sizeably mixed with the latter

Akhmedov, ZB, Senjanovic, 92

ZB, Mohapatra, 95

Heisenberg's interpretation of neutrino as a Goldstone particle was certainly crazy ... but not stupid at all....

This idea has triggered the works of D.V. Volkov and collaborators which brought to the discovery of the concepts of Supersymmetry and super-Higgs mechanism seven years after (in 1972). In fact, particle that Heisenberg had in mind was Goldstino. And, later on, broken SUSY brought a natural candidate for dark matter ... LSP

However, this idea was not useful for neutrinos. The neutrinos found their way to be light without help of SUSY, just due to the Standard Model structure.

Now, concerning status of SUSY, what about dark matter ...
and what about baryogenesis ?

Parallel hidden sector vs. observable sector ?

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*

Dark Side of the Universe

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

- $\Omega_{\rm B} \simeq 0.05$ observable matter: electron, proton, neutron
- $\Omega_{\rm D} \simeq 0.25$ dark matter: who are? WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: what is? Λ-term? Quintessence? ....

A. coincidence of matter $\Omega_{\rm M}$=$\Omega_{\rm D}$+$\Omega_{\rm B}$ and dark energy Ω_Λ: $\Omega_{\rm M}/\Omega_\Lambda \simeq 0.4$

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

Antrophic answer: if not Today, then it would happen Yesterday or Tomorrow.

B. Fine Tuning between baryon $\Omega_{\rm B}$ 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 ... *All on Sakharov's idea ...*

have no relation to popular DM candidates

Wimp, Wimpzilla, WDM (sterile ν), axion, gravitino ... *All trully neutral ...*

– How Baryogenesis could know about Dark Matter?

– Again anthropic? Again Fine Tunings in Particle Physics and Cosmology?

Visible vs. Dark matter: $\Omega_D/\Omega_B \simeq 5$ *?*

- Visible matter: $\rho_{\rm B} = n_{\rm B} M_B$, $M_B \simeq 1$ GeV – nucleons, $\eta = n_B/n_\gamma \sim 10^{-9}$

  Sakharov's conditions: $B\ (B-L)$ & CP violation, Out-of-Equilibrium

– in Baryogenesis models η depends on several factors, like CP-violating constants, particle degrees of freedom, mass scales, particle interaction strength and goodness of out-of-equilibrium.... and in some models (e.g. Affleck-Dine) on the initial conditions as well ...

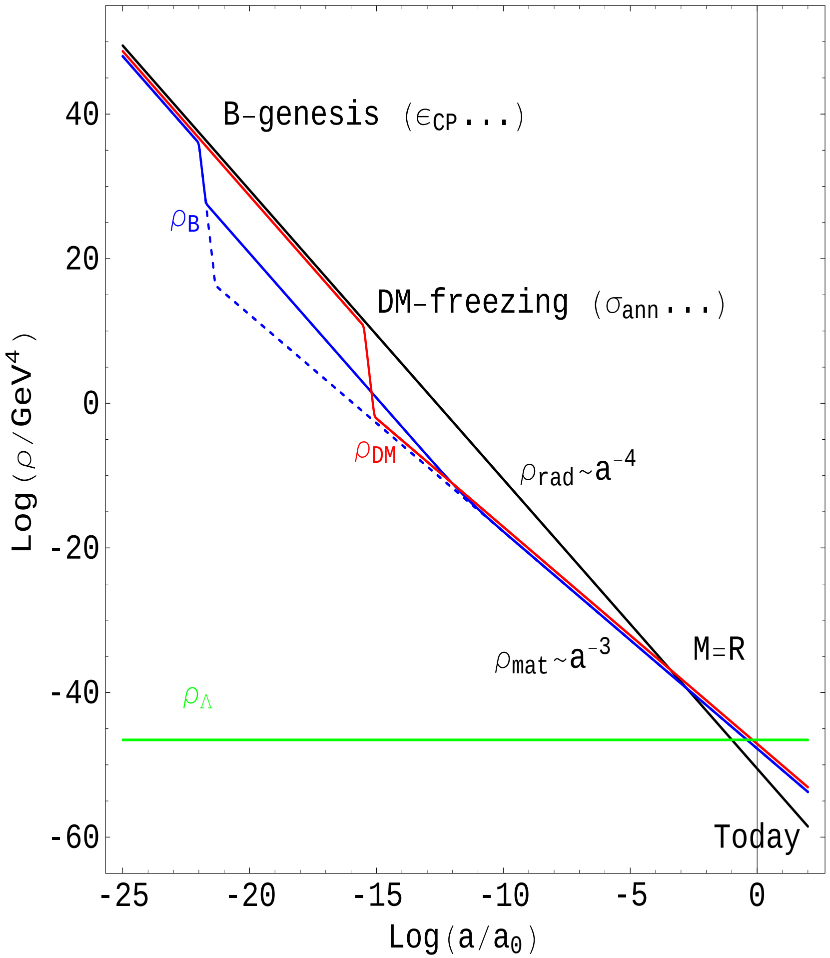
- Dark matter: $\rho_{\rm D} = n_X M_X$, but $M_X =$? , $n_X =$?

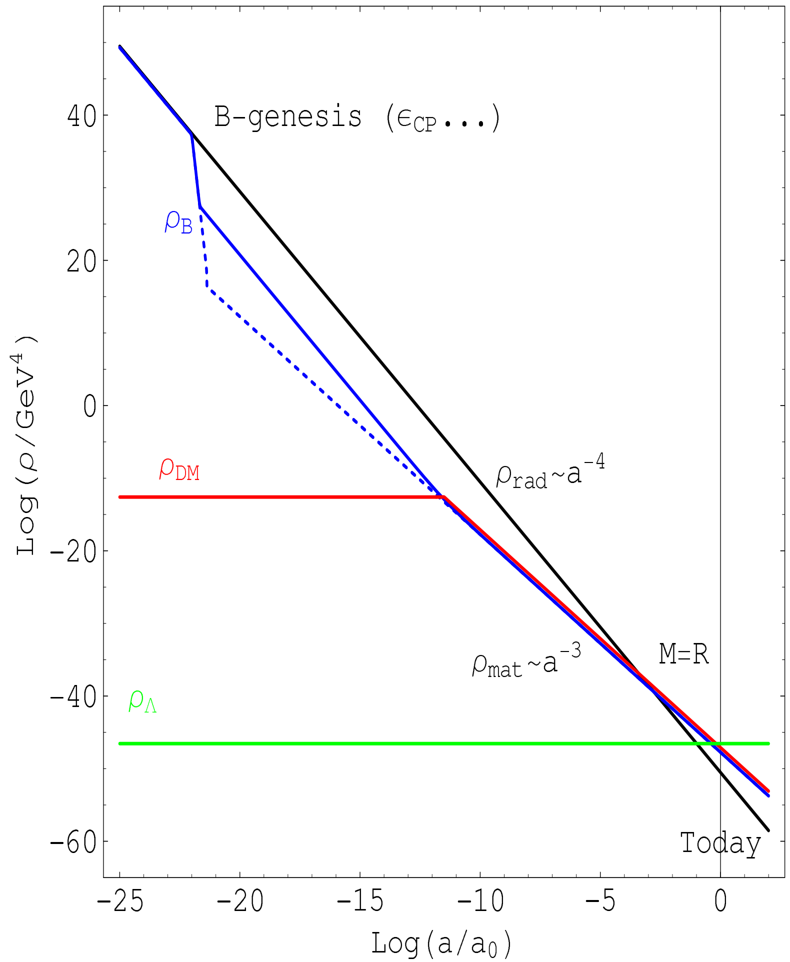
– wide spectrum of possibilities ...
Axion: $M_X \sim 10^{-5}$ eV, Sterile ν WDM: $M_X \sim 1$ keV, Wimp: $M_X \sim 1$ TeV,
Wimpzilla: $M_X \sim 10^{14}$ GeV ... but $M_X \sim 1$ GeV and $n_X \sim n_B$?

– in relative models n_X depends on varios factors, like equilibrium status and particle degrees of freedom, particle masses and interaction strength (production and annihilation cross sections).... and in some models (e.g. Axion or Wimpzilla) on the initial conditions as well ...

How then the mechanisms of Baryogenesis and Dark Matter synthesis, having different particle physics and corresponding to different epochs, could know about each-other? – How $\rho_B = n_B M_B$ could match $\rho_X = n_X M_X$ so intimately?

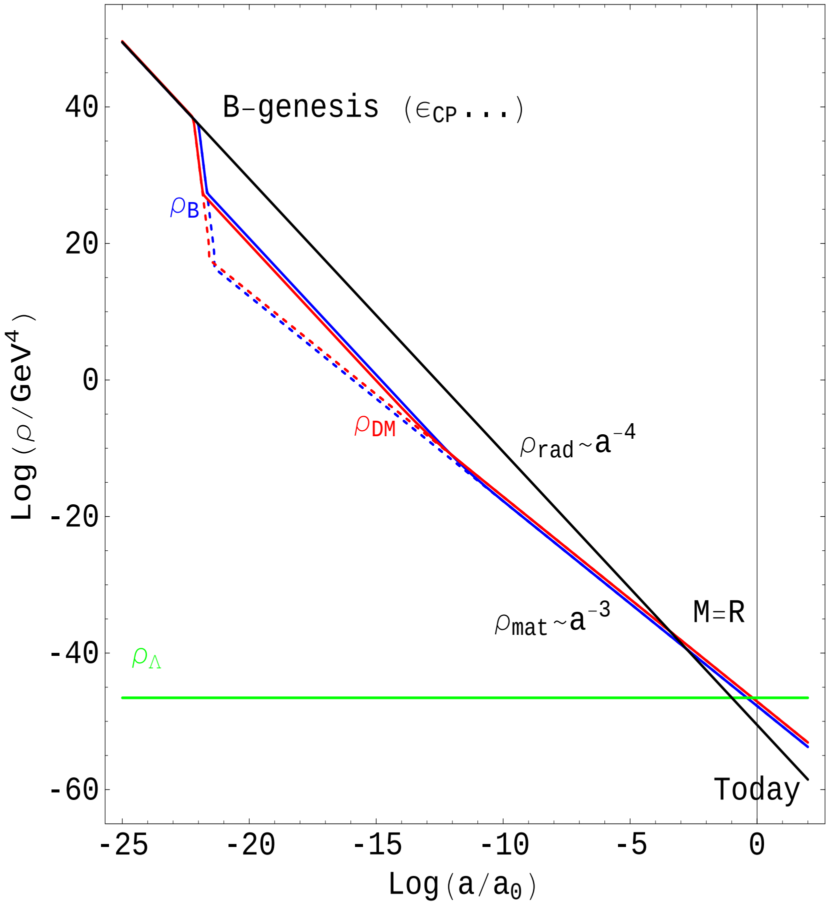
Cosmological evolution: B *vs.* D – demonstrating Fine Tuning





Evolution of the Baryon number ($\cdots$) in e.g. Baryo-Leptogenesis scenario confronted to the evolution of the Dark Matter density (—) in the WIMP (left pannel) and Axion (right pannel) scenarios

Unified origin of B and D? Cogenesis



Observable and dark matter co-genesis:
both based on Baryon asymmetry ?

- *Dark particle masses/properties are similar to baryon ones:* $M_X \sim M_B$
- *Dark & B asymmetries are generated by one process and* $n_X \sim n_B$

so that $\frac{\rho_X}{\rho_B} = \frac{M_X n_X}{M_B n_B} \sim 1$ *- dark gauge sector with* B' *asymmetry*

Alice @ Mirror World

'Now, if you'll only attend, and not talk so much, I'll tell you all my ideas about Looking-glass House. The room you can see through the glass – that's just the same as our room ... the books there are something like our books, only the words go the wrong way: I know that, because I've held up one of our books to the glass, and then they hold up one in the other room. I can see all of it – all but the bit just behind the fireplace. I do wish I could see that bit! I want so to know whether they've a fire: you never can tell, you know, unless our fire smokes, and then smoke comes up in that room too ... Now we come to the passage: it's very like our passage as far as you can see, only you know it may be quite on beyond. Oh, how nice it would be if we could get through into Looking-glass House! Let's pretend there's a way of getting through into it, somehow... It'll be easy enough to get through I declare!'

–Alice said this, and in another moment she was through the glass.

Lewis Carroll, "Through the Looking-Glass" (1871)

First clever paper on parallel world

Parallel Sector, Twin Particles & Mirror Parity

$SU(3)\times SU(2)\times U(1)$ gauge (g, W, Z, γ) & Higgs (ϕ) fields		$\times$	$SU(3)'\times SU(2)'\times U(1)'$ gauge (g', W', Z', γ') & Higgs (ϕ') fields	
quarks (B=1/3)	leptons (L=1)	|	quarks (B′=1/3)	leptons (L′=1)
$q_L = (u,d)^t_L$	$l_L = (\nu, e)^t_L$	|	$q'_L = (u', d')^t_L$	$l'_L = (\nu', e')^t_L$
$u_R \;\; d_R$	e_R	|	$u'_R \;\; d'_R$	e'_R
$\widetilde{\text{quarks}}$ (B=-1/3)	$\widetilde{\text{leptons}}$ (L=-1)	|	$\widetilde{\text{quarks}}$ (B′=-1/3)	$\widetilde{\text{leptons}}$ (L′=-1)
$\tilde q_R = (\tilde u, \tilde d)^t_R$	$\tilde l_R = (\tilde\nu, \tilde e)^t_R$	|	$\tilde q'_R = (\tilde u', \tilde d')^t_R$	$\tilde l'_R = (\tilde\nu', \tilde e')^t_R$
$\tilde u_L \;\; \tilde d_L$	$\tilde e_L$	|	$\tilde u'_L \;\; \tilde d'_L$	$\tilde e'_L$

$$-\quad \mathcal{L}_{\rm Yuk} = f_L Y \tilde f_L \phi + \tilde f_R Y^* f_R \tilde\phi \quad | \quad \mathcal{L}'_{\rm Yuk} = f'_L Y' \tilde f'_L \phi' + \tilde f'_R Y'^* f'_R \tilde\phi'$$

- D-parity: $L \leftrightarrow L',\; R \leftrightarrow R',\;\; \phi \leftrightarrow \phi'$: $\quad Y' = Y$ • *xerox copy*
- M-parity: $L \leftrightarrow R',\; R \leftrightarrow L',\;\; \phi \leftrightarrow \tilde\phi'$: $\quad Y' = Y^\dagger$ • *mirror copy*

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: $e,\ p,\ n,\ \nu,\ \gamma, \ldots$ have invisible twins $e',\ p',\ n',\ \nu',\ \gamma', \ldots$ 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).

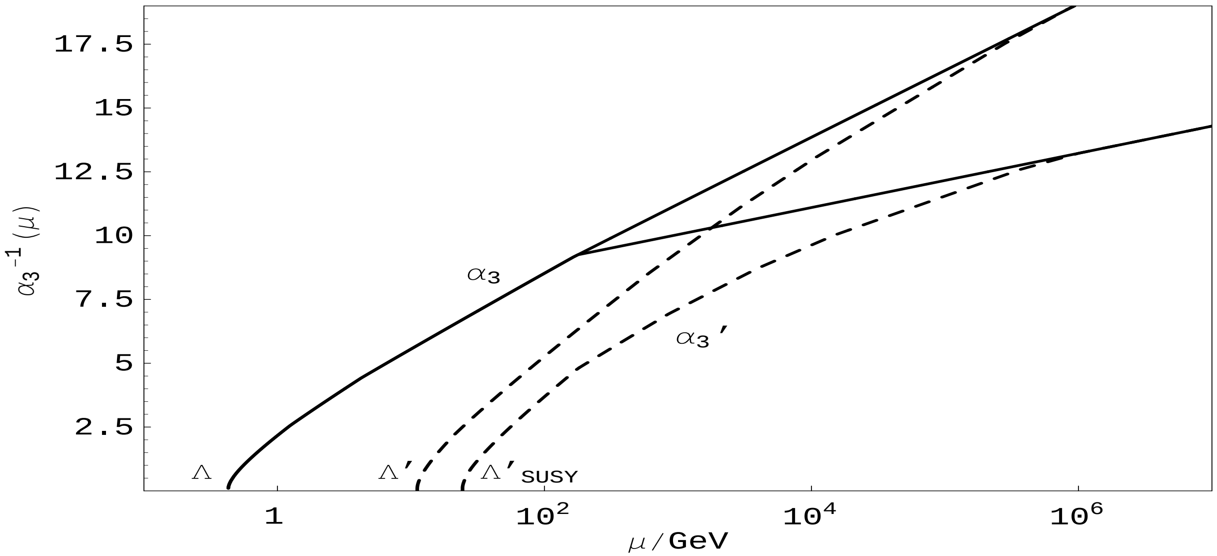
So, mirror matter is a natural candidate for (asymmetric) dark matter (not CDM) !!

Dissipative DM, but not excluded by cosmological tests — Z.B., Comelli, Villante, 2001

Asymmetric Mirror: broken parity $G \leftrightarrow G'$

ZB, Dolgov, Mohapatra, 96

$\langle\phi'\rangle = v' \gg \langle\phi\rangle = v \quad \longrightarrow \quad (M'_W \gg M_W)$ E.g. $\xi = v'/v \sim 10^2$



Lepton/quark masses $m'_e/m_e \sim v'/v \sim 10^2$ — heavy electron

but baryon masses $M'_N/M_N \sim \Lambda'/\Lambda \sim (v'/v)^{0.3} \sim 5$

neutrino masses $m'_\nu/m_\nu \propto (v'/v)^2 \sim 10^4$ — WDM

Asymmetric DM (compact mirror atoms or neutrons) + mirror ν as WDM $(T' \ll T)$

self-interacting: $\sigma/m_N \sim 1$ *bn/GeV* *ZB, Comelli, Villante, '01*

Strong CP & axidragon, GRBs and SN explosion *ZB, Gianfagna, Giannotti '01*

SUSY little Higgs – accidental global $U(4)$: $W = S(H_1H_2 + H'_1H'_2 - v'^2)$ *ZB 04*

Higgs naturality via Goldstone boson mechanism: $H'_{1,2}$ VEV $v' \sim 10$ TeV, then $H_{1,2}$ emerge as pseudo-Goldstones which get VEVs via SUSY breaking

Exact mirror world is very suggestive !

Numerous potential consequences worth of theoretical and experimental studies can be classified in 4 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 ($\sim 25\%$), helium ($\sim 25\%$) and some mirror nuclei($\sim 1\%$) as dark matter, different interaction portals are possible. The low region 1-5 GeV of dark matter masses is practically unexplored.*

- *Experimental searches of underlying physics at LHC, PSI etc. (new particles with mass of few TeV, missing energy, flavor changing effects induced by these particles)*

Exact mirror matter is viable DM ... **if is cold enough**

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)

Mirror Baryons as Dark Matter [Z.B., Comelli & Villante '01]

Since mirror sector has smaller temperature, Mirror Baryons (dark in terms of ordinary photons), may constitute dark matter

- *Once $x < 1$, mirror photons decouple earlier than our photons:* $z'_{\rm dec} \simeq \frac{1}{x} z_{\rm dec}$

However, if the DM is entirelly due to mirror baryons, then the large scale structure (LSS) formation requires that mirror photons must decouple before Matter-Radiation Equality epoch: $x < x_{\rm eq} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

- *mirror Jeans scale λ'_J becomes smaller than the Hubble horizon before Matter-Radiation Equality*

- *mirror Silk scale is smaller than the one for the normal baryons:*

$\lambda'_S \sim 5 x_{\rm eq}^{5/4} (x/x_{\rm eq})^{3/2} (\Omega_M h^2)^{-3/4}$ *Mpc*

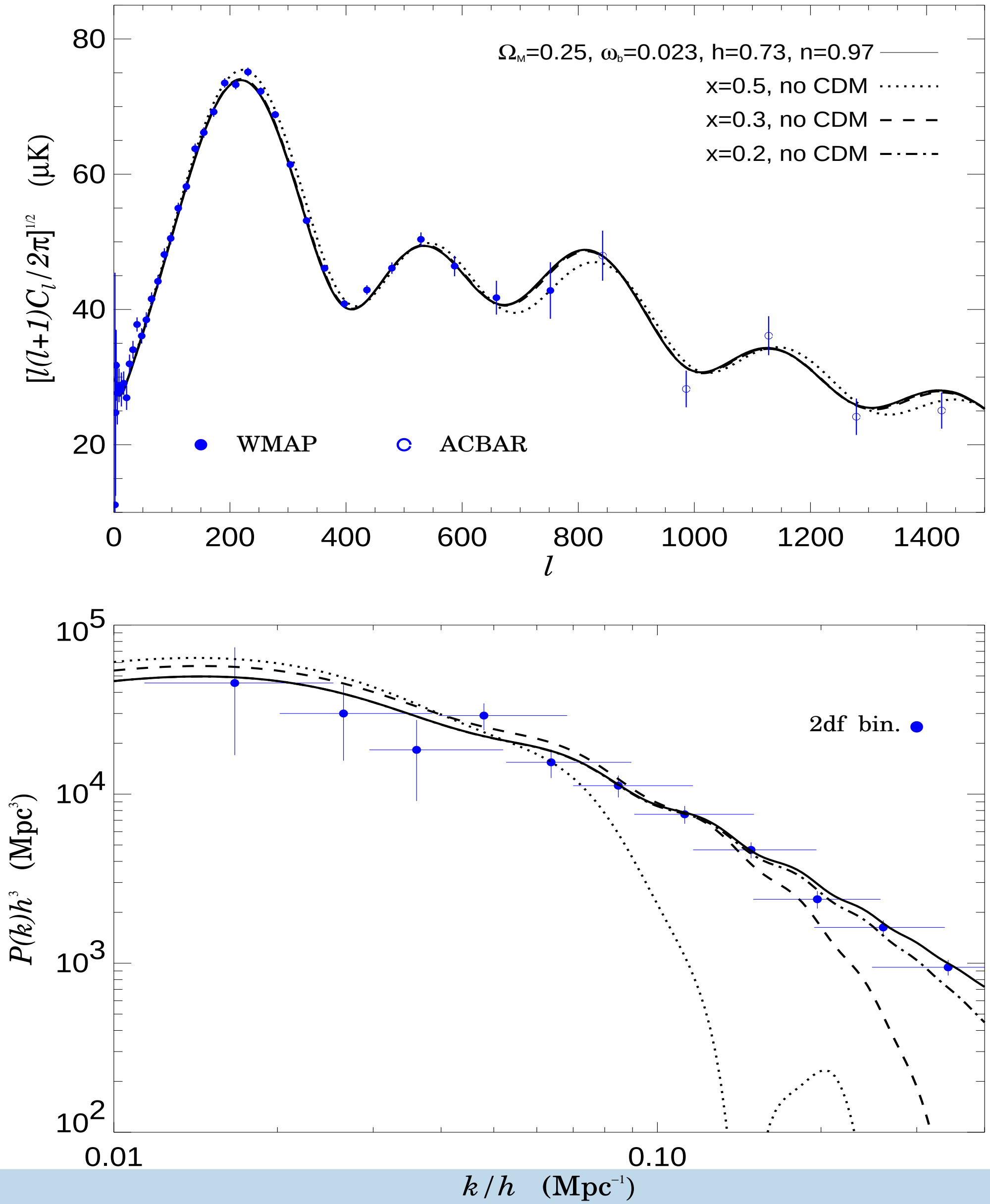
Hence the structures formation at 1 Mpc scales (galaxies) implies $x < 0.2$

N.B. *Mirror baryons constitute dissipative dark matter, and formation of the extended halos looks problematic. But thermal fragmentation and star formation in mirror sector can be rather fast due to different temperature and chemical content (in fact, mirror sector is dominated by Helium and has bigger metallicity).*

Halo as mirror eliptical galaxy, Machos as mirror stars, survived gas forms a disk and can present in ionized, atomic or molecular form

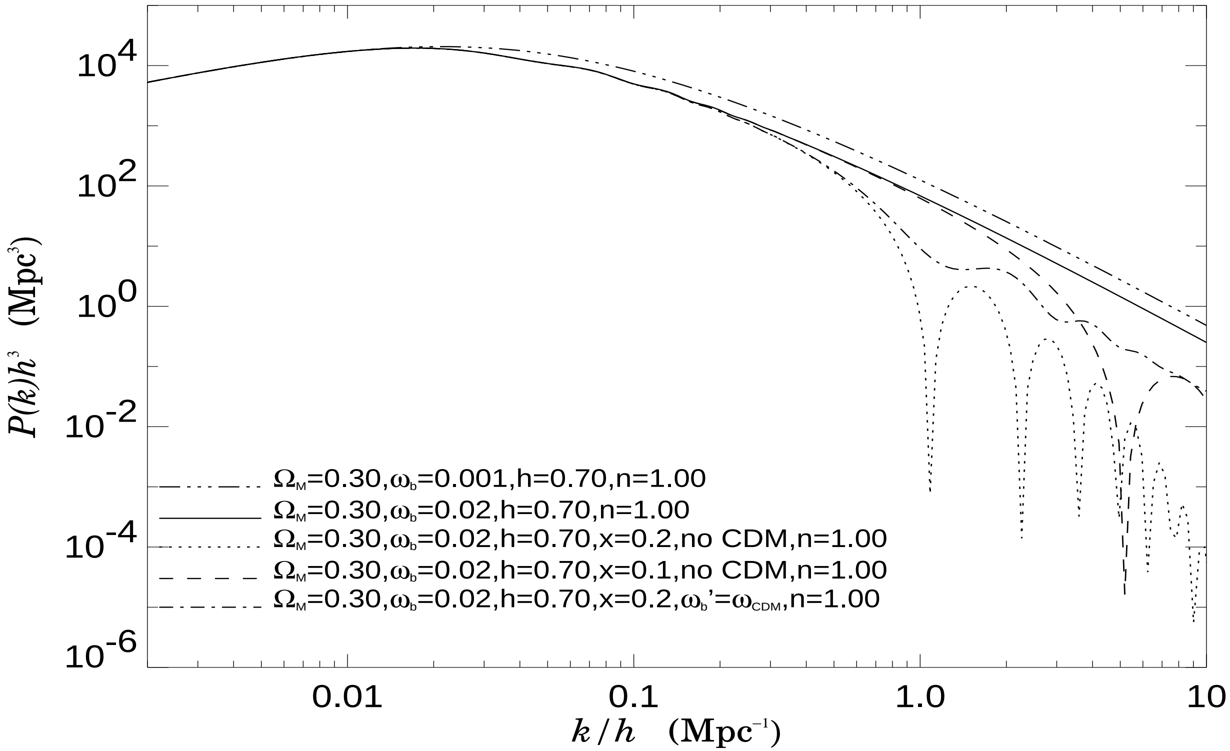
CMB & LSS power spectra

Z.B., Ciarcelluti, Comelli & Villante, '03



LSS power spectra

Z.B., Ciarcelluti, Comelli & Villante, '03



$\mathcal{L}_{\rm mix}$ **"Let's pretend there's a way of getting through into it, somehow ..."**

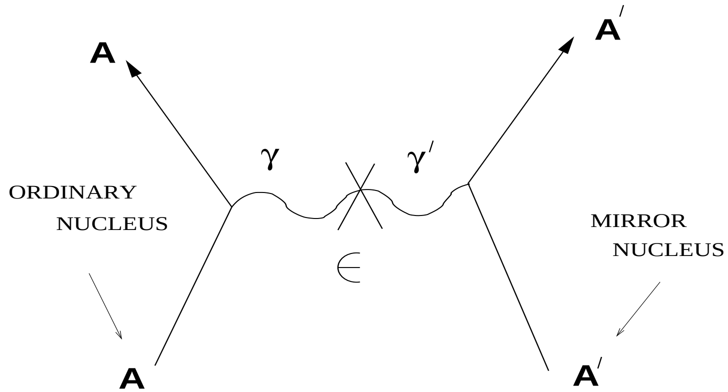
Possible interactions between O & M particles (besides gravity) can be induced at tree level by exchange of extra gauge singlet particles or common gauge fields acting with both O & M particles ... and these interactions can lead to particle mixing phenomena between O & M sectors: any neutral particle (elementary or composite) can have mass/kinetic mix its degenerate twin

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

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

Natural in GUTs: $\frac{\alpha}{M_{Pl}^2}(\Sigma G)(\Sigma' G') \quad \rightarrow \quad \varepsilon = \alpha s_W^2 \frac{\langle \Sigma \rangle^2}{M_{Pl}^2} < 10^{-8} - 10^{-9}$



Good for dark matter detection (DAMA) Foot '04

Testable O-ps - O-ps′ mixing ($e^+e^- \rightarrow e'^+e'^-$) *to* $\varepsilon \sim 10^{-9}$ Crivelli et al.'10

meson - mirror meson mixing: $D = 6$ operators

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

- $\pi^0 - \pi^{0\prime}$, $\rho^0 - \rho^{0\prime}$, *etc.* $\frac{1}{M^2}(\overline{u}\gamma^5 u - \overline{d}\gamma^5 d)(\overline{u}'\gamma^5 u' - \overline{d}'\gamma^5 d')$, $\frac{1}{M^2}(\overline{u}\gamma^\mu u - \overline{d}\gamma^\mu d)(\overline{u}'\gamma_\mu u' - \overline{d}'\gamma_\mu d')$

  Phenom. limit: $M > 10$ TeV $(\pi^0 - \pi^{0\prime} \to 2\gamma'$ invisible)

- $K^0 - K^{0\prime}$ *etc.* $\frac{1}{M^2}(\overline{d}\gamma^5 s)(\overline{d}'\gamma^5 s')$ $(\Delta S = 1)$

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

  Phenom. limit: $M > 100$ TeV $(K^0 - K^{0\prime})$

- $\overline{\mu}e - \mu'\overline{e}'$ *muonium - mirror muonim transition* $\frac{1}{M^2}(\overline{\mu}\gamma^\mu e)(\overline{e}'\gamma^\mu \mu')$

  C.f. $\frac{1}{M^2}(\overline{\mu}\gamma^\mu e)(\overline{e}\gamma^\mu \mu)$

● *Can be induced via exchange of flavor gauge bosons ($SU(3)_{\rm fl}$ etc.) interacting with both our and mirror quarks/leptons* : *helping for Flavor Problem: anomaly cancellation, minimality of flavor violation in SUSY*

● *In the context of TeV scale gravity the gauge flavour bosons can live in extra dimensions (between parallel branes)*

Deviation about SUSY, flavor problem and mirror world

Flavor (horizontal) symmetry, naturally $SU(3)_H$ or $U(3)_H$, $f_L \sim 3$, e.g. f are $q = (u, d)$ and $l = (\nu, e)$ or $u^c, d^c.e^c$.
e.g. $SU(5) \times SU(3)_H$ *with* $f \sim (\bar{5} + 10, 3)$

$\frac{\chi}{M} f f H$ *via "universal seesaw' mechanism (integrating out heavy vector-like fermions), where* χ *are "horizontal" Higgs fields (flavons) with VEVs breaking* $U(3)_H$*:* $Y = \frac{\langle\chi\rangle}{M}$ – but problem of $SU(3)_H$ anomaly Z.B. '83

In SUSY context: anti-flavons $\overline{\chi}$ *are needed for generation of superpotential of flavons and their VEVs:* $W = \mu^2 \chi\overline{\chi} + \chi^3 + \overline{\chi}^3$

"Universal" mechanism $\longrightarrow$ *intelligent alignments between fermion/sfermion masses and trilinear SSB-terms (MFV):* $\tilde{m}_f^2 = m_0^2 + m_1^2 Y_f^\dagger Y_f + m_2^2 (Y_f^\dagger Y_f)^2$
– but flavor violation by $SU(3)_H$ gauge D-terms Z.B. '96

Introducing mirror sector with $f'_L \sim \bar{3}$
$SU(5) \times SU(5)' \times SU(3)_H$ *with* $f \sim (\bar{5} + 10, 1, 3)$, $f' \sim (1, 5 + \overline{10}, \bar{3})$

- *Cancels gauge* $SU(3)_H$ *anomaly between* f *and* f'*, and* $\frac{\chi}{M} f f H + \frac{\overline{\chi}}{M} f' f' H'$
- *Due to parity,* $f \rightarrow f'$ *and* $\chi \rightarrow \overline{\chi}$*, we get automatically* $\langle\chi\rangle = \langle\overline{\chi}\rangle$

Renders vanishing flavor D*-terms* *(valid also in asymmetric,* $v' \neq v$*)* Z.B. '98

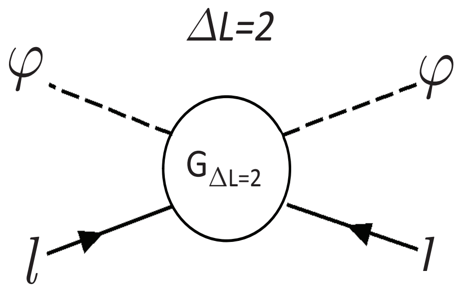
Lepton number violating interactions: $D = 5$ *operators*

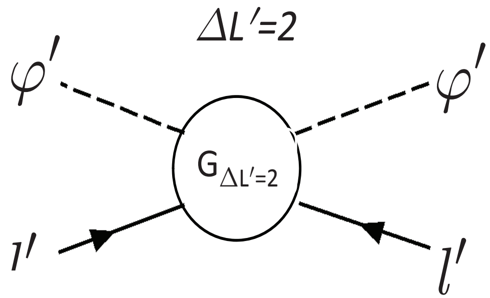
neutrino - mirror neutrino mixing $(\nu - \nu')$ – effective operators :

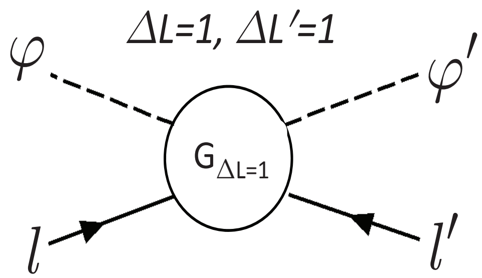
Akhmedov, ZB, Senjanovic, 1992; ZB, Mohapatra, 1995

$\frac{1}{M}(l\phi)(l'\phi') \qquad (\Delta L = 1, \Delta L' = 1)$

C.f. $\frac{1}{M}(l\phi)^2 \quad (\Delta L = 2), \quad \frac{1}{M}(l'\phi')^2 \quad (\Delta L' = 2)$ *for Majorana masses*







Lepton number violating interactions: $D = 5$ operators

- neutrino - mirror neutrino mixing $(\nu - \nu')$

$$\frac{A}{M}(l\phi)^2 \quad (\Delta L = 2), \quad \frac{A'}{M}(l'\phi')^2 \quad (\Delta L' = 2)$$ *for Majorana masses*

$$\frac{D}{M}(l\phi)(l'\phi') \qquad (\Delta L = 1, \Delta L' = 1)$$

Inserting VEVs $\langle\phi\rangle = v$ *and* $\langle\phi'\rangle = v'$,
we get $\nu - \nu'$ *(active-sterile) mixing*

$$\begin{pmatrix} \hat{m}_\nu & \hat{m}_{\nu\nu'} \\ \hat{m}^t_{\nu\nu'} & \hat{m}_{\nu'} \end{pmatrix} = \begin{pmatrix} \frac{Av^2}{M} & \frac{Dvv'}{M} \\ \frac{D^t vv'}{M} & \frac{A'v'^2}{M} \end{pmatrix}$$

M-parity: $A' = A^*$, $D = D^\dagger$
D-parity: $A' = A$, $D = D^t$

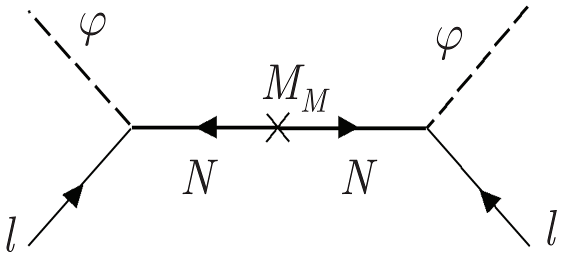
- $v' = v$: $\quad m_{\nu'} = m_\nu$ *and maximal mixing* $\theta_{\nu\nu'} = 45°$;
- $v' > v$: $\quad m_{\nu'} \sim (v'/v)^2 m_\nu$ *and small mixing* $\theta_{\nu\nu'} \sim v/v'$;

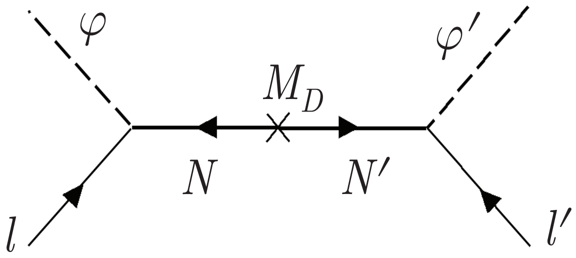
e.g. $v'/v \sim 10^2$: $\sim$ *keV sterile neutrinos as WDM* Z.B., Dolgov, Mohapatra '96

- $A, A' = 0$ *($L - L'$ conserved) light Dirac neutrinos*

with L *components in ordinary sector and* R *components in mirror sector*

Mixed Seesaw between O & M sectors





- Heavy gauge singlet fermions N_a, $a = 1, 2, 3, \ldots$ with large Majorana mass terms $M_{ab} = g_{ab}M$, can equally talk with both O and M leptons

  $$\mathcal{L}_{\rm Yuk} = y_{ia}\phi l_i N_a \; + \; y'_{ia}\phi' l'_i N_a \; + \; \tfrac{1}{2} M g_{ab} N_a N_b \; + \; \text{h.c.} \; ;$$

  Yukawas are genetically complex

  D-*parity:* $y' = y$, M-*parity:* $y' = y^\dagger$

- D=5 effective operators $\frac{A}{M} ll\phi\phi \; + \; \frac{A'}{M} l'l'\phi'\phi' \; + \; \frac{D}{M} ll'\phi\phi'$ + h.c. emerge after integrating out heavy states N, where

  $$A = y g^{-1} y^t, \quad A' = y' g^{-1} y'^t, \quad D = y g^{-1} y'^t$$

Leptogenesis between O & M sectors

- In the Early Universe, after post-inflationary reheating, these interactions generate also processes like $l\phi(\tilde{l}\tilde{\phi}) \to \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \to \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) satisfying Sakharov's 3 conditions

  A. violate B-L – *by definition (only L)*

  B. violate CP – *complex Yukawa constants*

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

  and thus generate B-L$\neq$0 ($\to$ B$\neq$0 by sphalerons) for ordinary matter

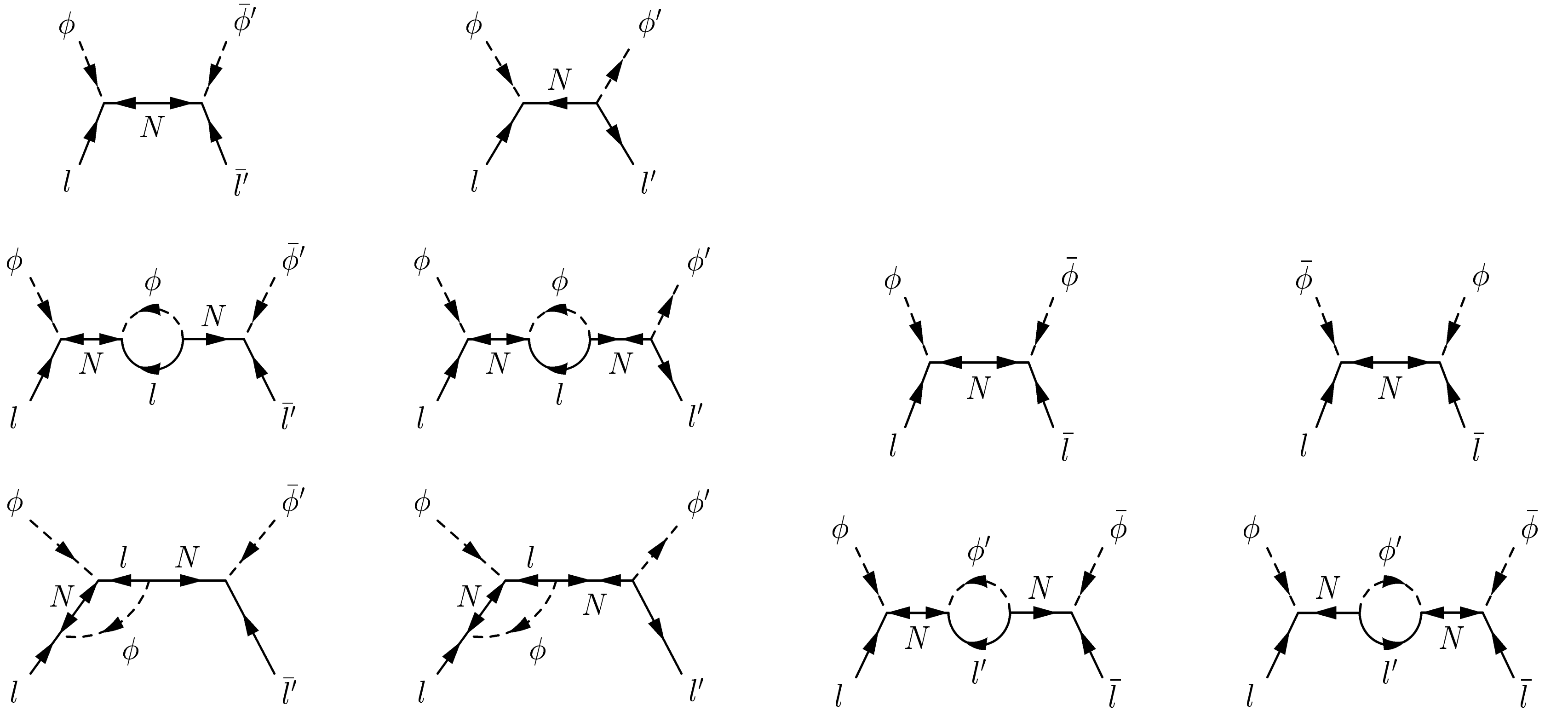
- The same reactions generate B$'$-L$'$ $\neq$0 ($\to$ B$'$$\neq$0) in dark sector.

Ordinary and mirror Baryon asymmetries can be generated at one shoot !!

Baryon & Dark matter Co-genesis

CP violation in ΔL=1 and ΔL=2 processes

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



$$\varepsilon_{CP} = \mathrm{Im\,Tr}[(y^\dagger y)^* g^{-1}(y'^\dagger y')g^{-2}(y^\dagger y)g^{-1}]$$
$$\varepsilon'_{CP} = \mathrm{Im\,Tr}[(y'^\dagger y')^* g^{-1}(y^\dagger y)g^{-2}(y'^\dagger y')g^{-1}]$$

$\varepsilon_{CP} \to \varepsilon'_{CP}$ *when* $y \to y'$

- D-*parity:* $y' = y$, $\varepsilon_{CP} = 0$, but M-*parity:* $y' = y^\dagger$ $\varepsilon_{CP} \neq 0$

Evolution for (B-L)′ and (B-L) $T_R \ll M$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} + \Gamma n_{B-L} = \frac{3}{4}\Delta\sigma\, n_{\rm eq}^2$$

$$\frac{dn'_{B-L}}{dt} + 3Hn'_{B-L} + \Gamma' n'_{\rm B-L} = \frac{3}{4}\Delta\sigma'\, n_{\rm eq}^2$$

$\Gamma \propto n'_{\rm eq}/M^2$ is the effective reaction rate of $\Delta L' = 1$ and $\Delta L' = 2$ processes

$$\Gamma'/\Gamma \simeq n'_{\rm eq}/n_{\rm eq} \simeq x^3 \; ; \qquad x = T'/T$$

$\Delta\sigma' = -\Delta\sigma = \frac{3\varepsilon_{CP}\, S}{32\pi^2 M^4}$, *where* $S \sim 16T^2$ *is the c.m. energy square*

$$Y_{BL} = D(k)\cdot Y_{BL}^{(0)}; \qquad Y'_{BL} = D(k')\cdot Y_{BL}^{(0)}$$

Damping factors $D(k)$ *and* $D(k')$*:* $k = \left[\frac{\Gamma_{\rm eff}}{H}\right]_{T=T_R}$, $k' = kx^2$

$Y_{BL}^{(0)} \approx 2\times 10^{-3}\frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}$: T_R *is (re)heating temperature*

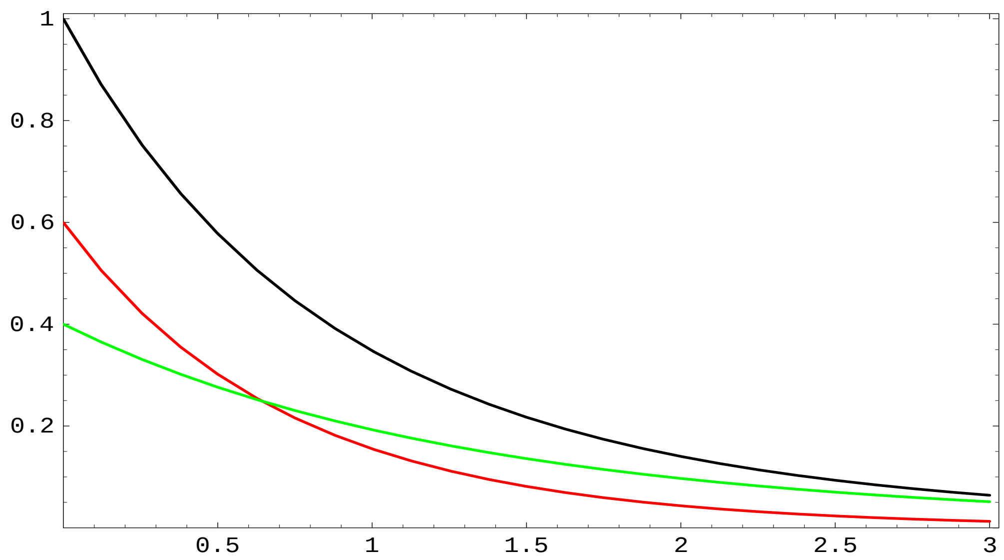
$Y_{BL}^{(0)} \sim 10^{-9}$ at $M \sim 10^{12}$ GeV, $T_R \sim 10^9$ GeV, $\varepsilon_{CP} \sim 10^{-3}$.

$M'_B = M_B$ ... but $n'_B > n_B$

$$B = D(k) \cdot Y^{(0)}, \quad B' = D(k') \cdot Y^{(0)}; \quad Y^{(0)} \approx \frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4} \cdot 10^{-3}$$

$$k = \left[\frac{\Gamma_{\rm eff}}{H}\right]_{T=T_R}, \quad k' = kx^2, \quad x = \frac{T'}{T} < 0.5 \quad (T_R = T_{\rm Reheat})$$

$D(k) < D(k') \approx 1$: lower limit $\frac{\Omega'_B}{\Omega_B} = \frac{D(k')}{D(k)} > 1$ Z.B. '03



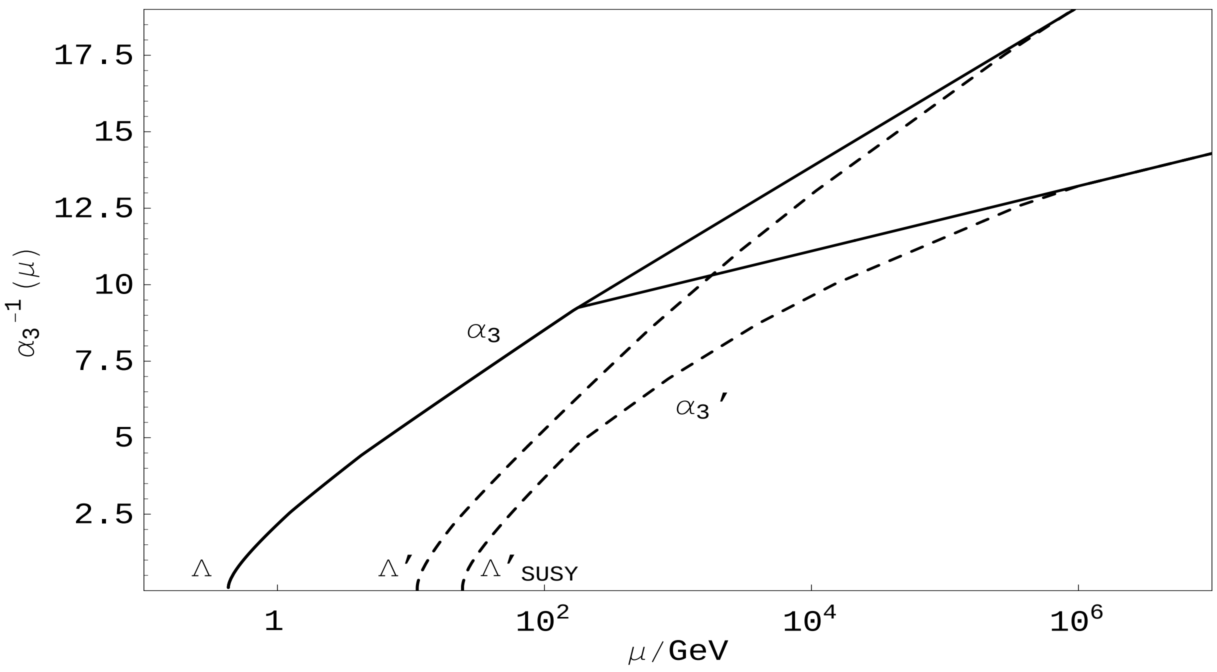
BBN: $x < 0.5 \rightarrow k \leq 4$; LSS: $x < 0.2 \rightarrow k \leq 1.5$

upper limit $\frac{\Omega'_B}{\Omega_B} = \frac{1}{D(k)} < 5 - 10$

$n'_B = n_B$ .... but $M'_B > M_B$

broken M parity: $v'/v \sim 10^2$ $v' \sim 10$ TeV, $v \sim 100$ GeV

Z.B., Dolgov & Mohapatra '96



$n'_B \simeq n_B$ $k < 1$ (robust non-equilibrium)

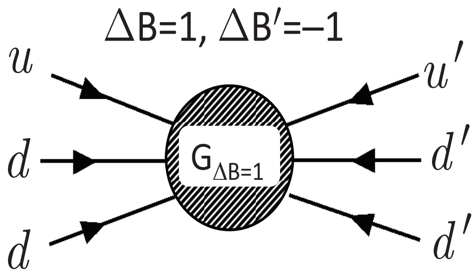
$M'_N/M_N \sim (\Lambda'/\Lambda) \sim (v'/v)^{0.3} \sim 5$ —- $M_N \sim 5$ *GeV*

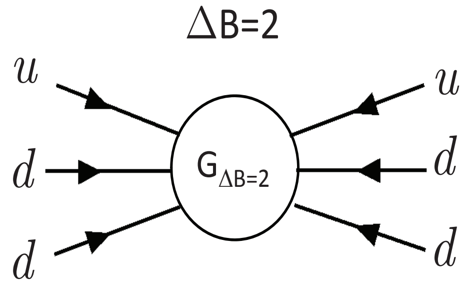
$m'_e/m_e \sim v'/v \sim 10^2$ — $m'_e \sim 100$ *MeV*

– Properties of MB's get closer to CDM : but also WDM from mirror neutrinos ?

$m'_\nu/m_\nu \simeq (v'/v)^2 \sim 1$ *keV*

Baryon number violating operators: $D = 9$





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

- neutron - sterile neutron mixing *($n - n'$, $\Lambda - \Lambda'$ 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 Kuzmin, 70

  $\tau_{n\bar{n}} > 10^8$ s $\tau_{nn'} \sim 1$ s ?

$n - n'$ 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.

Baryon number violating operators: $D = 9$

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

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

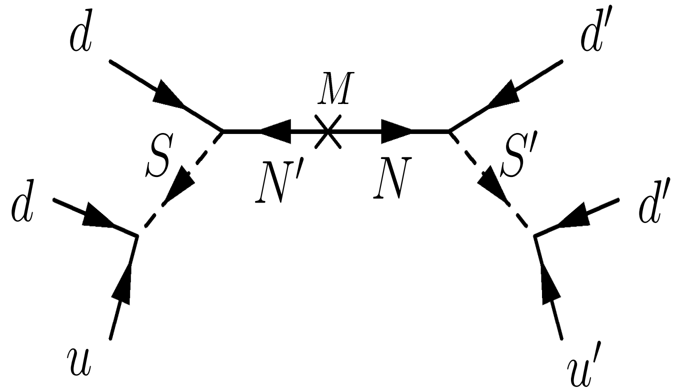
  $\frac{1}{M^5}(udd)(u'd'd')$, six-fermion interaction ($\Delta B = 1$, $\Delta B' = 1$)

  induces he neutron - mirror neutron mass mixing $\epsilon\,(\overline{n}n' + \overline{n}'n)$,

  $\epsilon \sim \frac{\Lambda^6_{\rm QCD}}{M^5} \simeq \left(\frac{10\ {\rm TeV}}{\mathcal{M}}\right)^5 \cdot 10^{-15}\,{\rm eV}$ $\quad \mathcal{M} \sim 10\ {\rm TeV}$ *-Ttestable at LHC?*

  - *6-fermion operators with Majorana mass insertion,* $\mu \ll M$ $\frac{1}{M^5}(udd)^2$ ($\Delta B = 2$),

  inducing neutron - antineutron mixing



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* $M_N \sim 10^{12}\ {\rm GeV}$ *and* $M_S \sim 100\ {\rm GeV}$

Neutron - Mirror neutron mixing

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

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

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

... can be fast, $\tau_{nn'} \sim 1$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 $\tau_{nn'}$!

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 $(\sim 3$ 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 (PDG) if $B' = 0$
not valid if there is mirror magnetic field $B' > 10$ mG !!!

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

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

- Exact mirror parity: $m' = m$, $\Gamma' = \Gamma$, $\mu' = \mu = -1.91\mu_N$
- Grav. potentials $V'_{\rm g} = V_{\rm g}$
- but there are magnetic fields: $\vec{B}' \neq \vec{B}$: at Earth $B \simeq 0.5$ 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 $\omega = \frac{1}{2}|\mu B| = B[{\rm G}] \times 3 \cdot 10^{-12}\ {\rm eV} = 4500\ {\rm s}^{-1}$

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 $P(\vec{B})$

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

$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{dec}} + \eta_{\mathrm{loss}}\nu + P(\vec{B})\nu$, $\nu = 1/t_f \sim 10$ 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 $A_B = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx \frac{1}{2}(P_{\vec{B}} - P_{-\vec{B}})\nu t_s = D_B \cos\beta \nu t_s,$

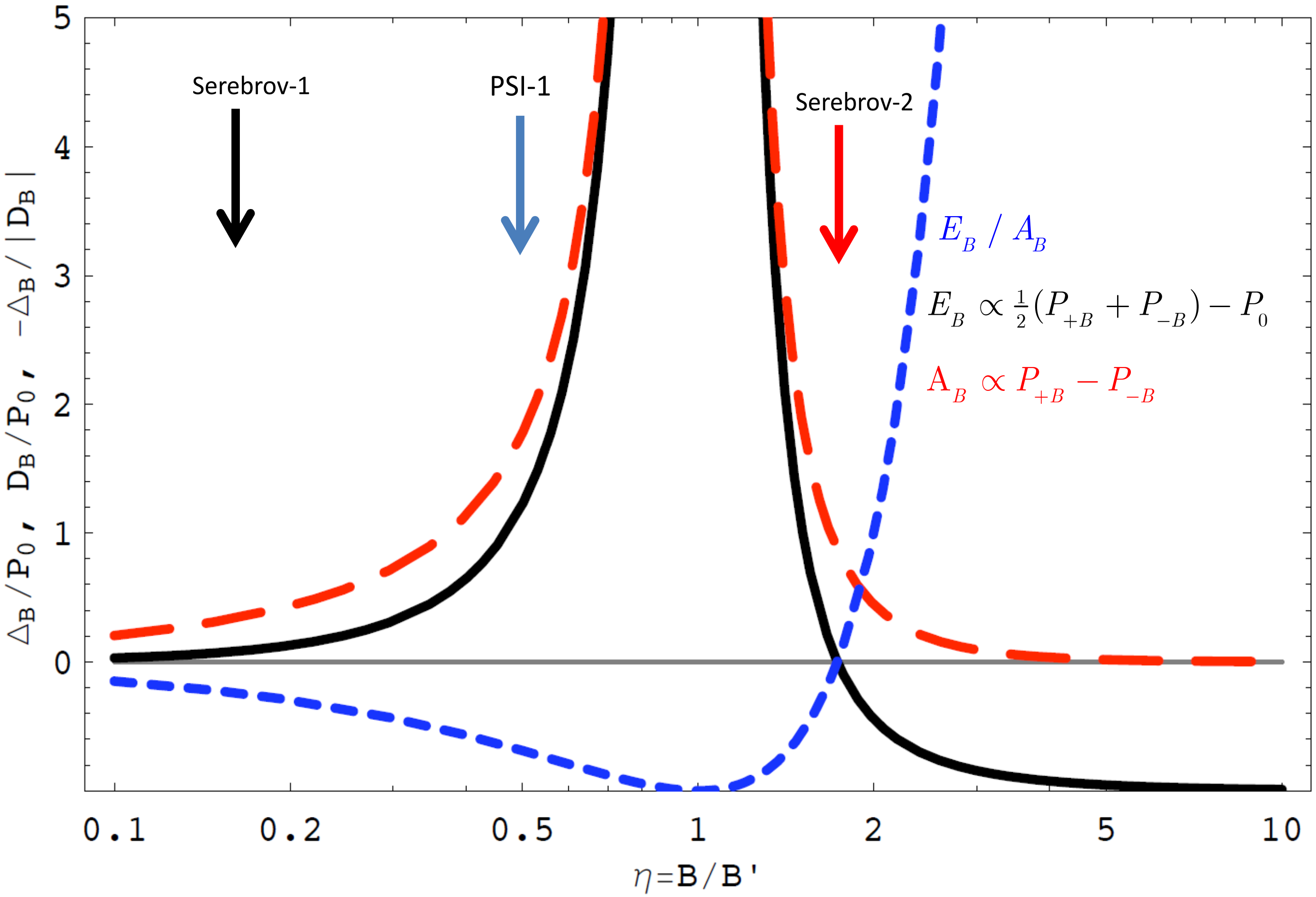
On-off Effectivity $E_B = 1 - \frac{N_{\vec{B}} + N_{-\vec{B}}}{2N_0} \approx \Delta_B \nu t_s,$ $\Delta_B = \frac{1}{2}(P_{\vec{B}} + P_{-\vec{B}}) - P_0$

Effectivity of D_B and Δ_B

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

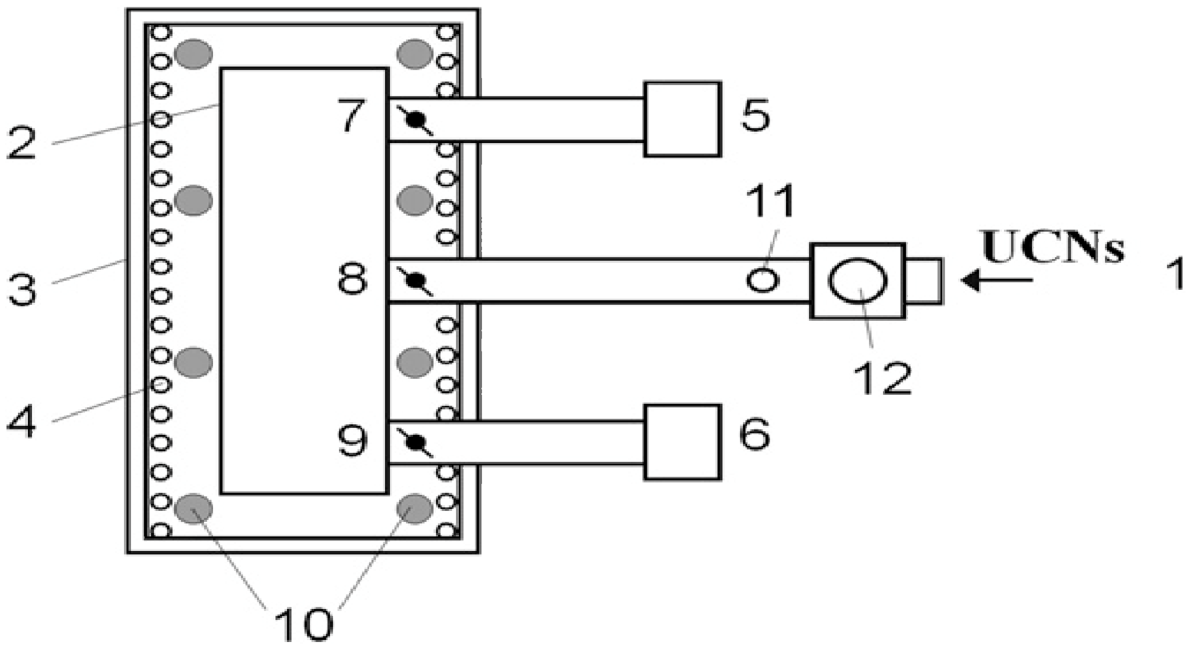
$$P_0 = \frac{\epsilon^2}{2\omega'^2} = \frac{2}{\tau^2_{nn'}|\mu B'|^2}$$

E.g. assume B'=0.12 Gauss



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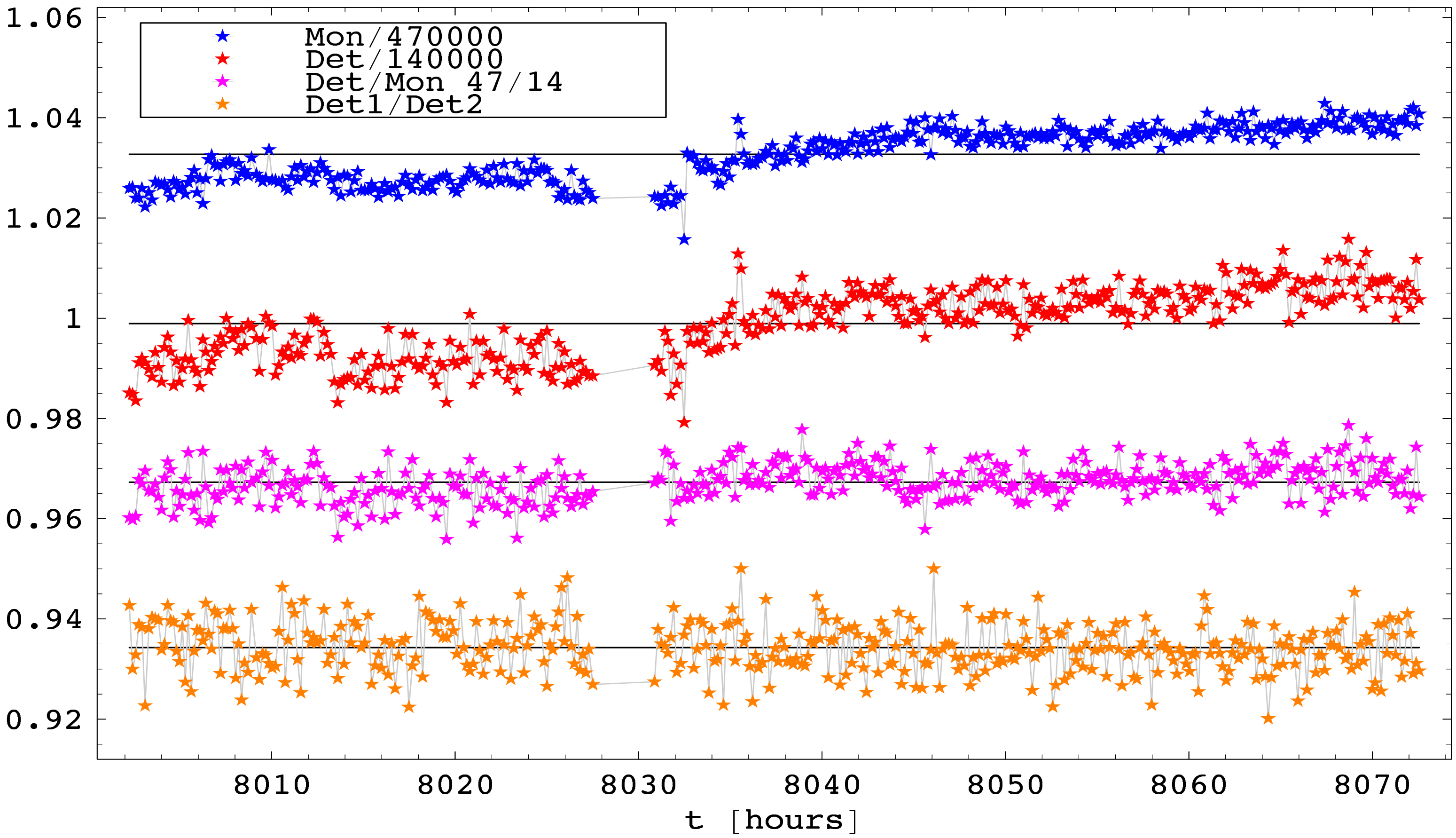
Abstract Present experiments do not exclude that the neutron n oscillates, with an appreciable probability, into its invisible degenerate twin from a parallel world, the so-called mirror neutron n'. These oscillations were searched experimentally by monitoring the neutron losses in ultra-cold neutron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

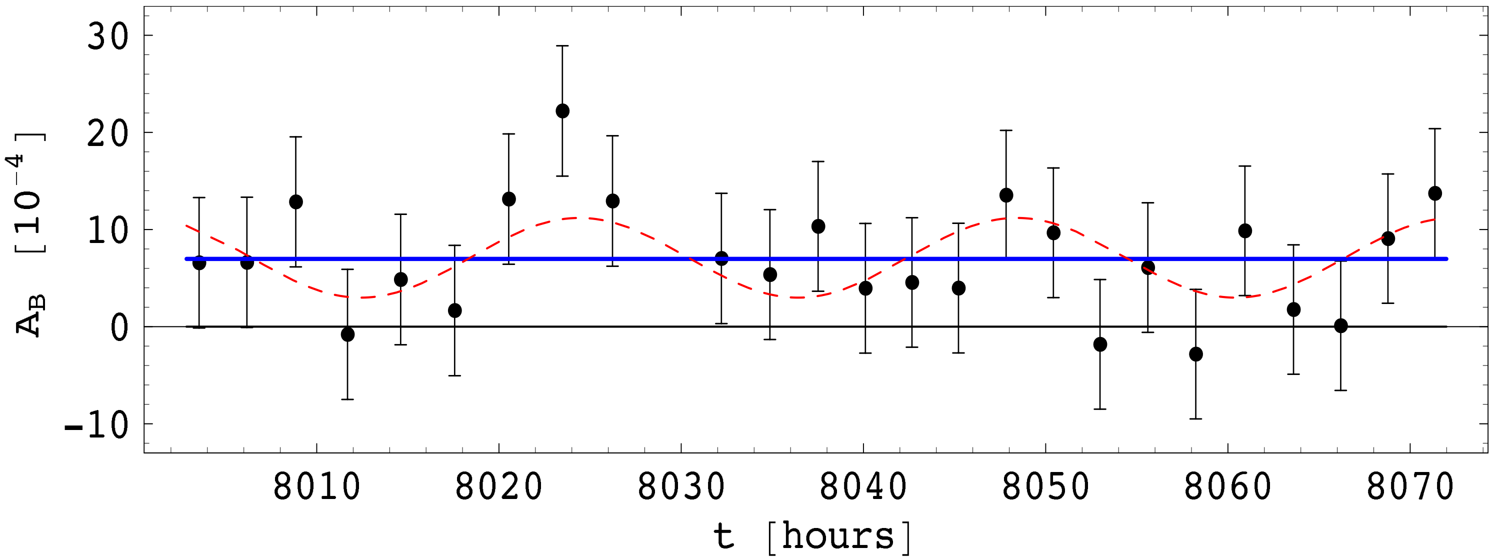


Det/Mon = Const $\chi^2_{\rm dof} = 1.4$ Det1/Det2 = Const $\chi^2_{\rm dof} = 1.0$

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



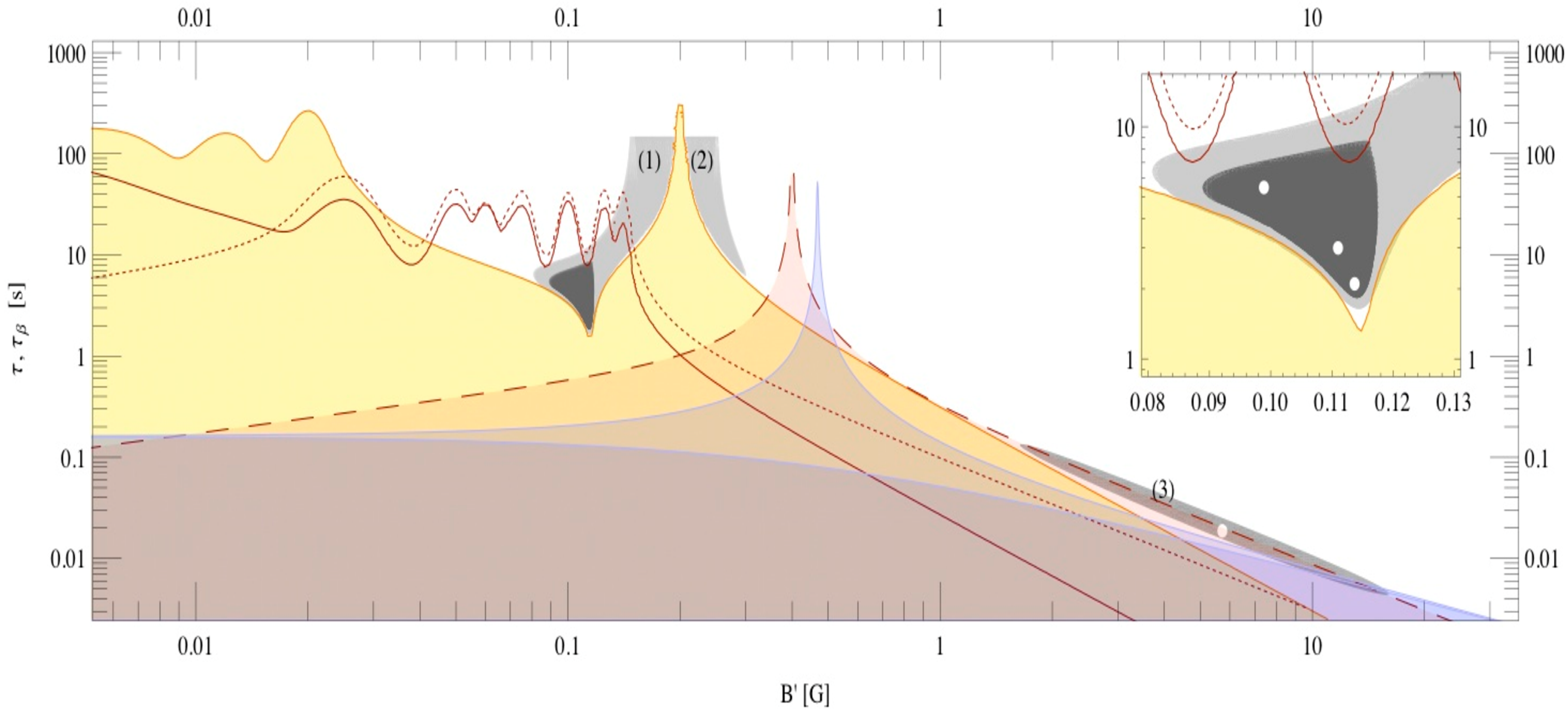
- at $B \simeq 0.2$ G : $A_B = (7.0 \pm 1.3) \times 10^{-4} \quad (\chi^2_{\rm dof} = 0.9)$ (5.2σ) !!

– 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

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.)

Our analysis for horizontal field (preliminary)

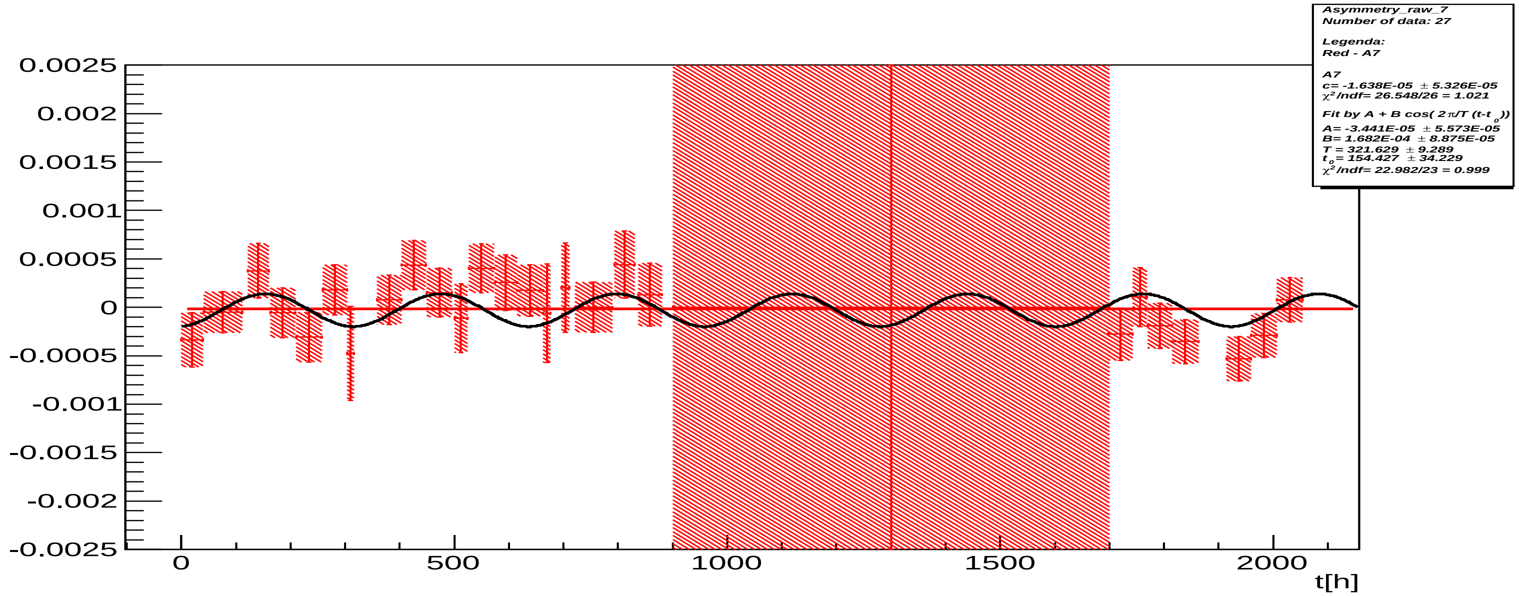
sequences $B_+, b_+, b_-, B_-; B_-, b_-, b_+, B_+$

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 !!



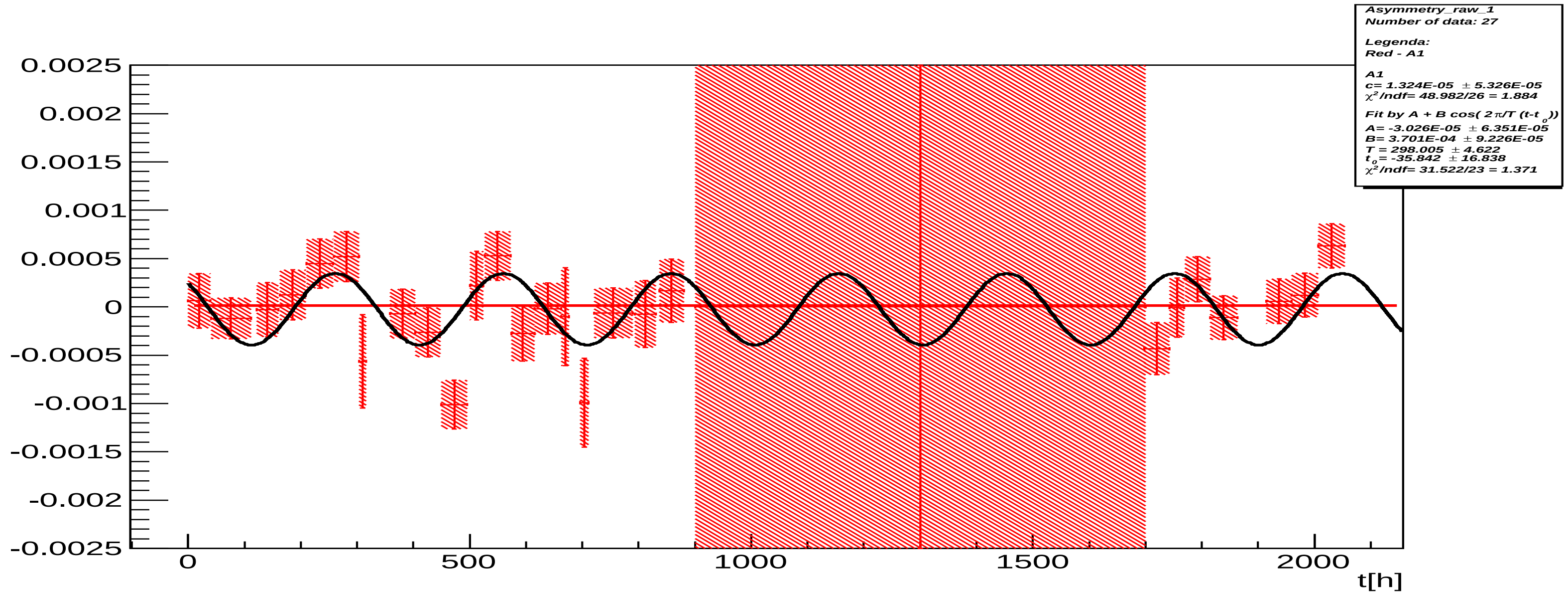
Constant fit $A_b = (-1.6 \pm 5.3) \times 10^{-5}$ with $\chi^2_{\rm dof} = 1.0$

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

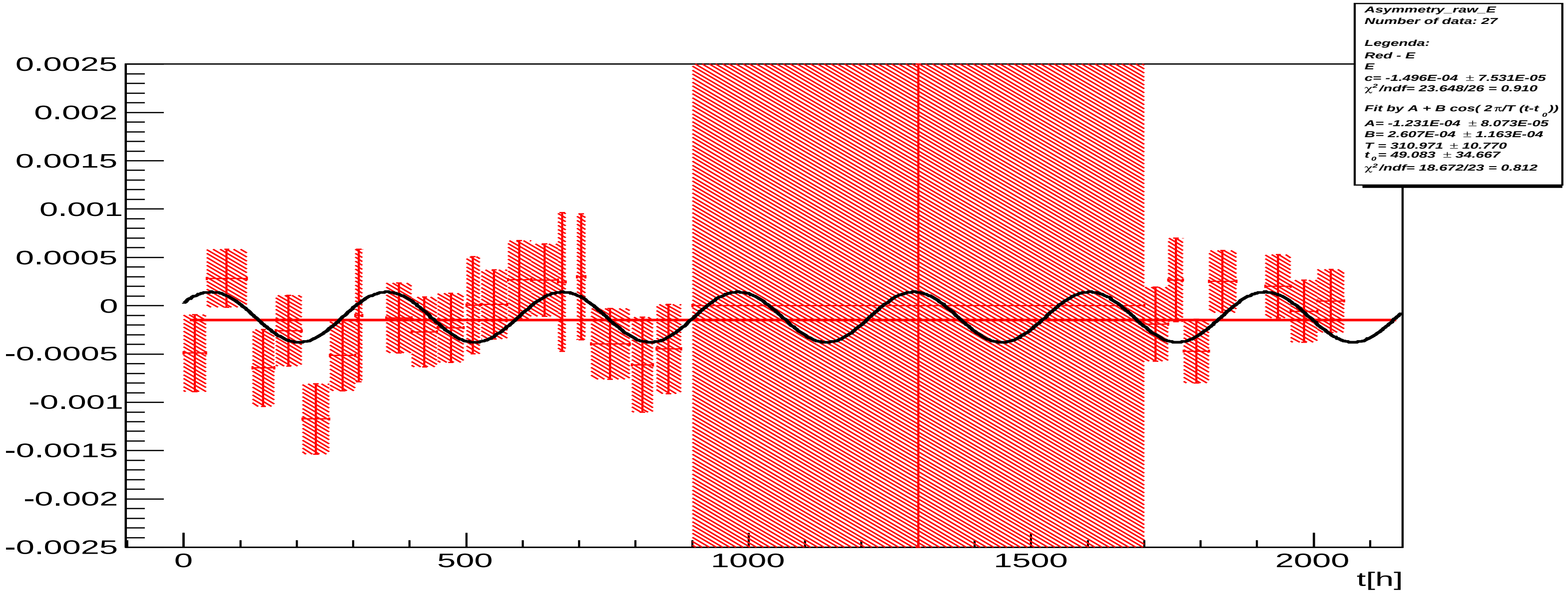
$C = (-3.0 \pm 6.3) \times 10^{-5}, \quad A = (-37.0 \pm 9.2) \times 10^{-5} \quad (4\sigma)$

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

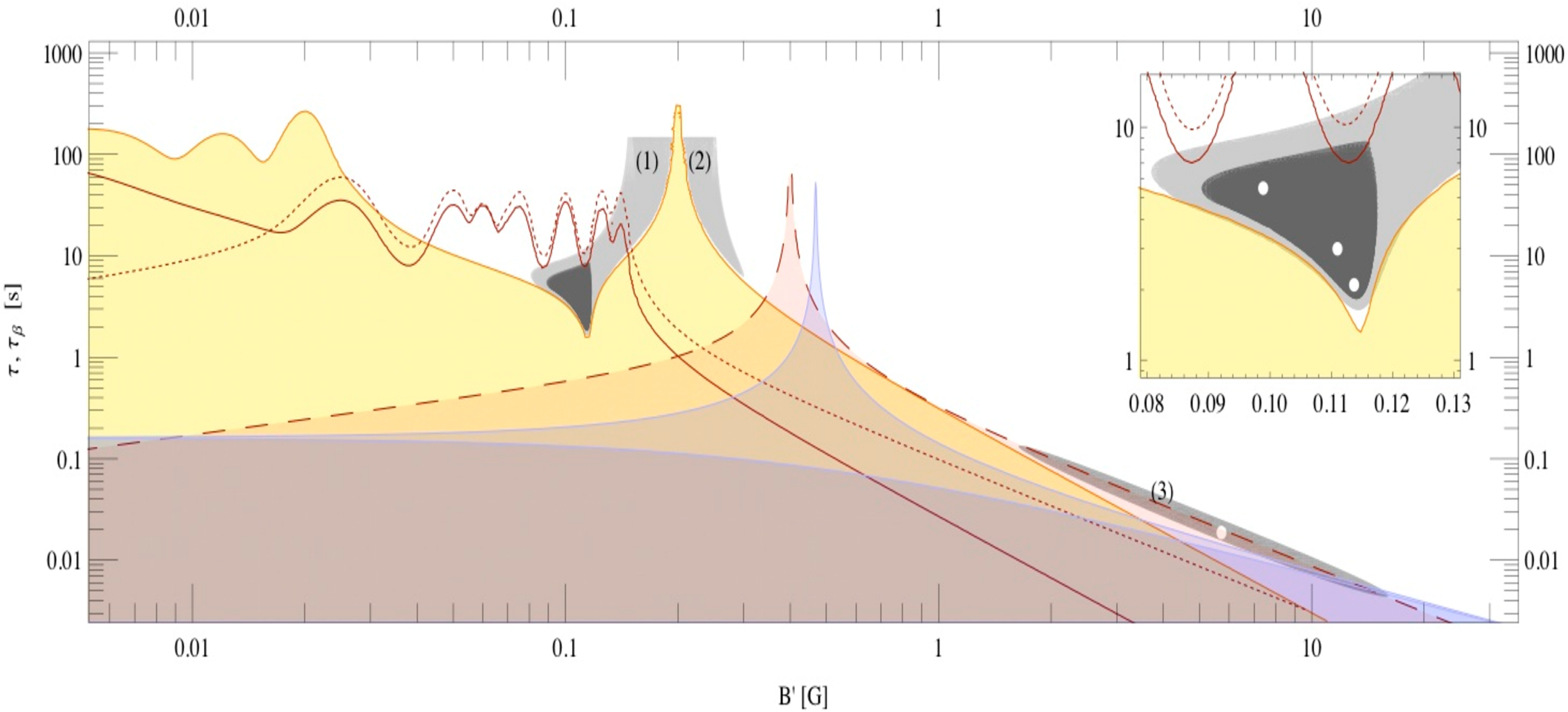


Constant fit: $E_{Bb} = -(1.5 \pm 0.75) \times 10^{-4}$ *with* $\chi^2_{\rm dof} = 1.1$ (2σ)

and time periodic fit $E_{Bb} \propto C + A\cos\left(2\pi \frac{t - t_0}{T}\right)$ gives
$C = (-1.3 \pm 8.0) \times 10^{-5}, \quad A = (-26 \pm 11) \times 10^{-5} \quad (2.5\sigma)$
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)*

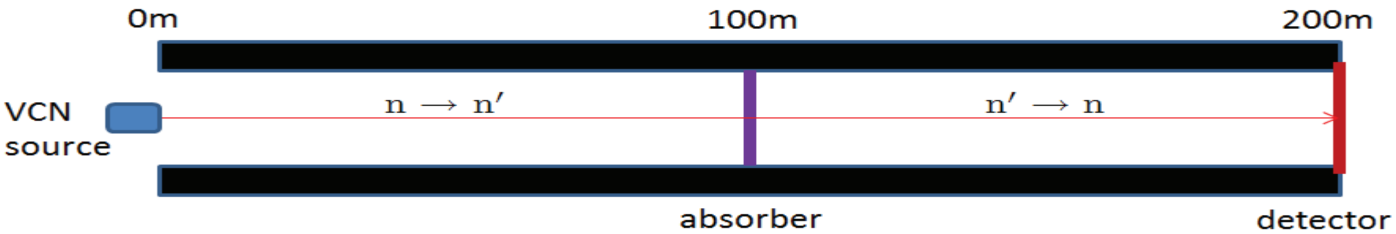


$B' \sim 0.1$ G but its value may vary in time within 50%, and its direction in 100%. $\tau \sim 1 - 10$ s ?????

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

$n \to n' \to n$ **regeneration:** *Walking through the wall ...*

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

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: $n \to n'$ and $n' \to n$ would modify the UHECR spectrum around GZK energies* *Z.B and Bento 2005, Z.B. and Gazizov 2011*

● *neutrons from the sun (solar flares): $n \to n' \to n$ 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.: $n' \to n$ 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*

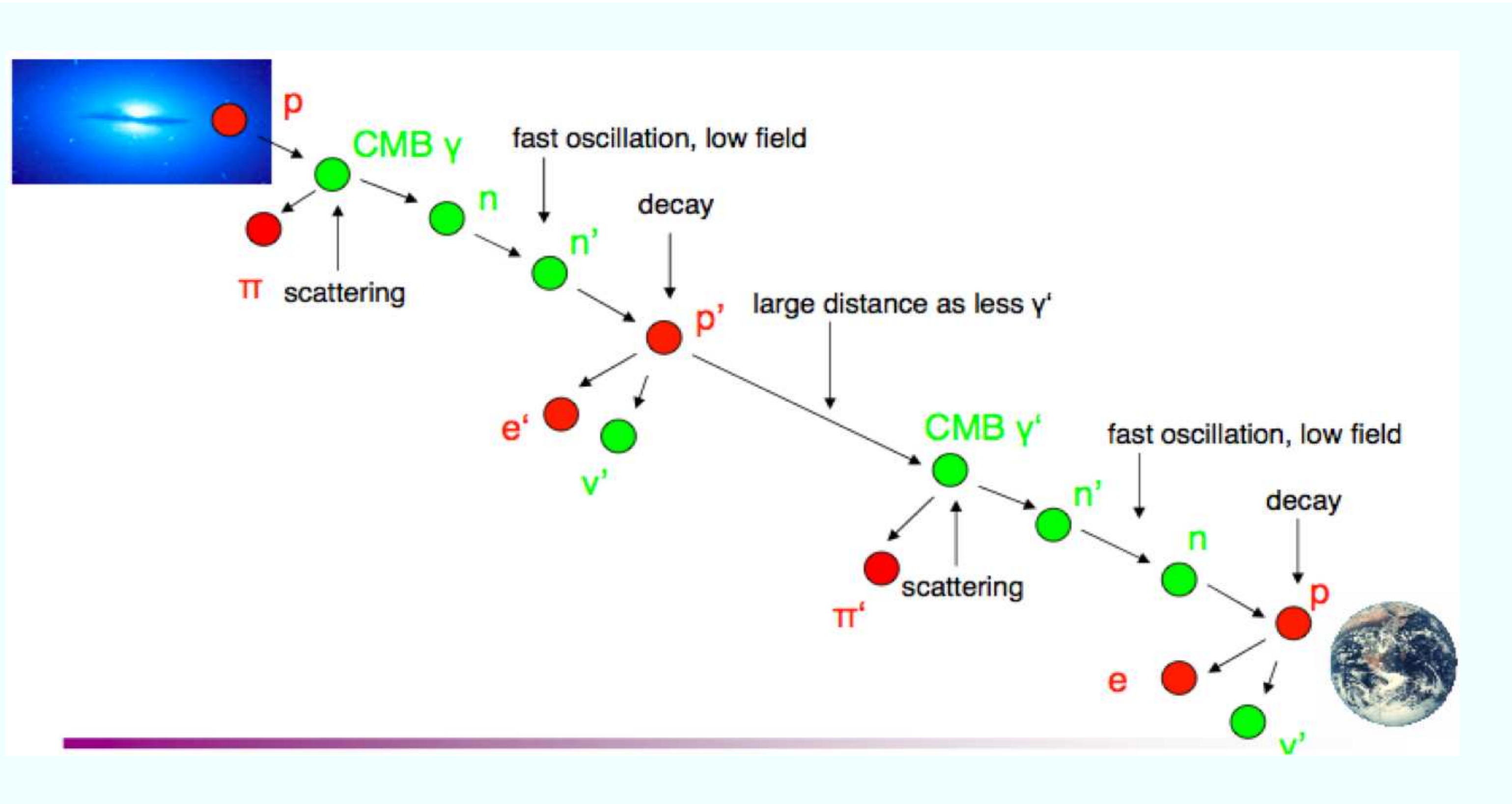
Physics underlying $n - n'$ mixing

- *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

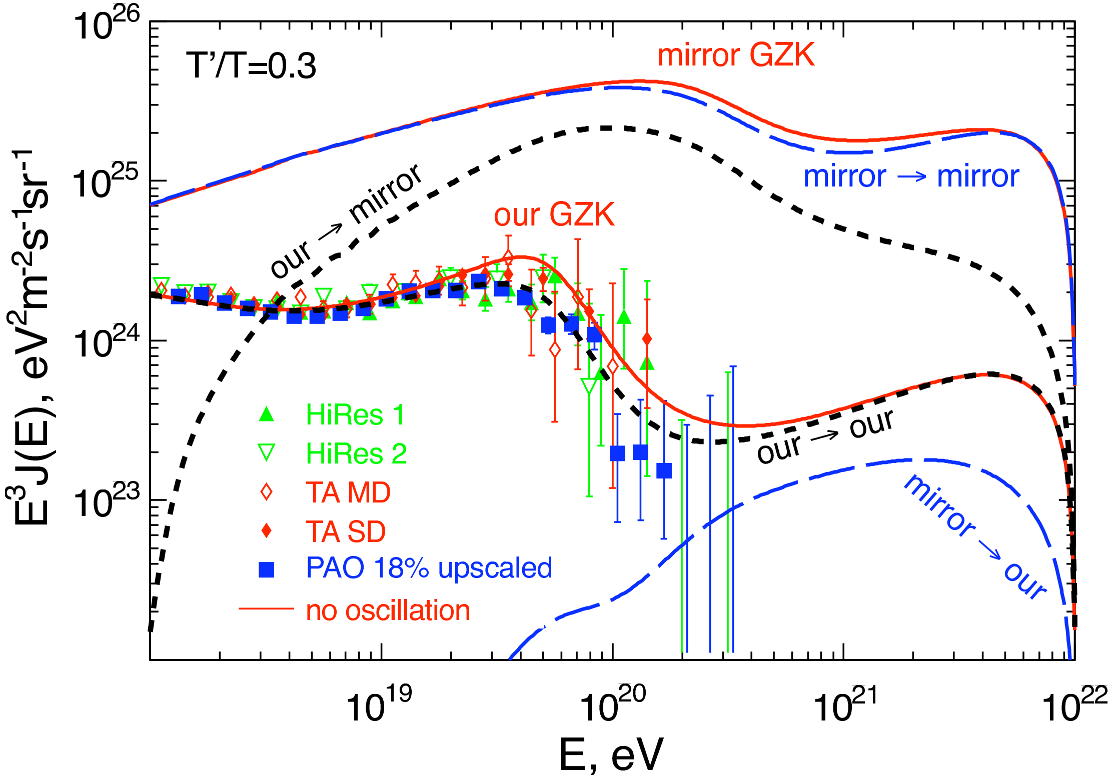
B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100\ \rm EeV}\right)$ kpc

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)

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"

More than 1 parallel worlds ?? *(like in R. Sheckley's "Mind exchanges")*