Living in a Parallel World: mirror dark matter, dark gravity, etc.

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Parallel gauge sectors

Imagine a theory with a product of gauge factors $G \times G' \times G'' \ldots$.

$G = G_{\rm SM} = SU(3) \times SU(2) \times U(1)$ for observable sector:

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

(+ RH neutrinos, SUSY, GUT, ...)

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

... existence of matter (CP-violation, B-conserv/violation)

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

...... very complex !! .....

Dark matter may come from other gauge factors G', ...

– perhaps its gauge and matter structure is not simple ad hoc ?

What if Dark sector is as complex as observable .... parallel world (mirror world as particular case), and parallel (twin) matter:

electron′, nucleons′ (quarks′), photons′, W', Z', gluons′, $\Lambda'_{\rm QCD}$ etc.

We discuss parallel/mirror gauge sectors:

- Baryogenesis ($\Omega_{B'} \sim 5\Omega_B$)
- Nucleosynthesis ($Y_{He'} > Y_{H'}$, or perhaps no He′ at all...)
- recombination, dark matter and cosmological structures ....
- dark matter search ... and dark matter with dark gravity
- ordinary particle - mirror particle oscillations

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?

Visible vs. Dark matter

- 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 ...

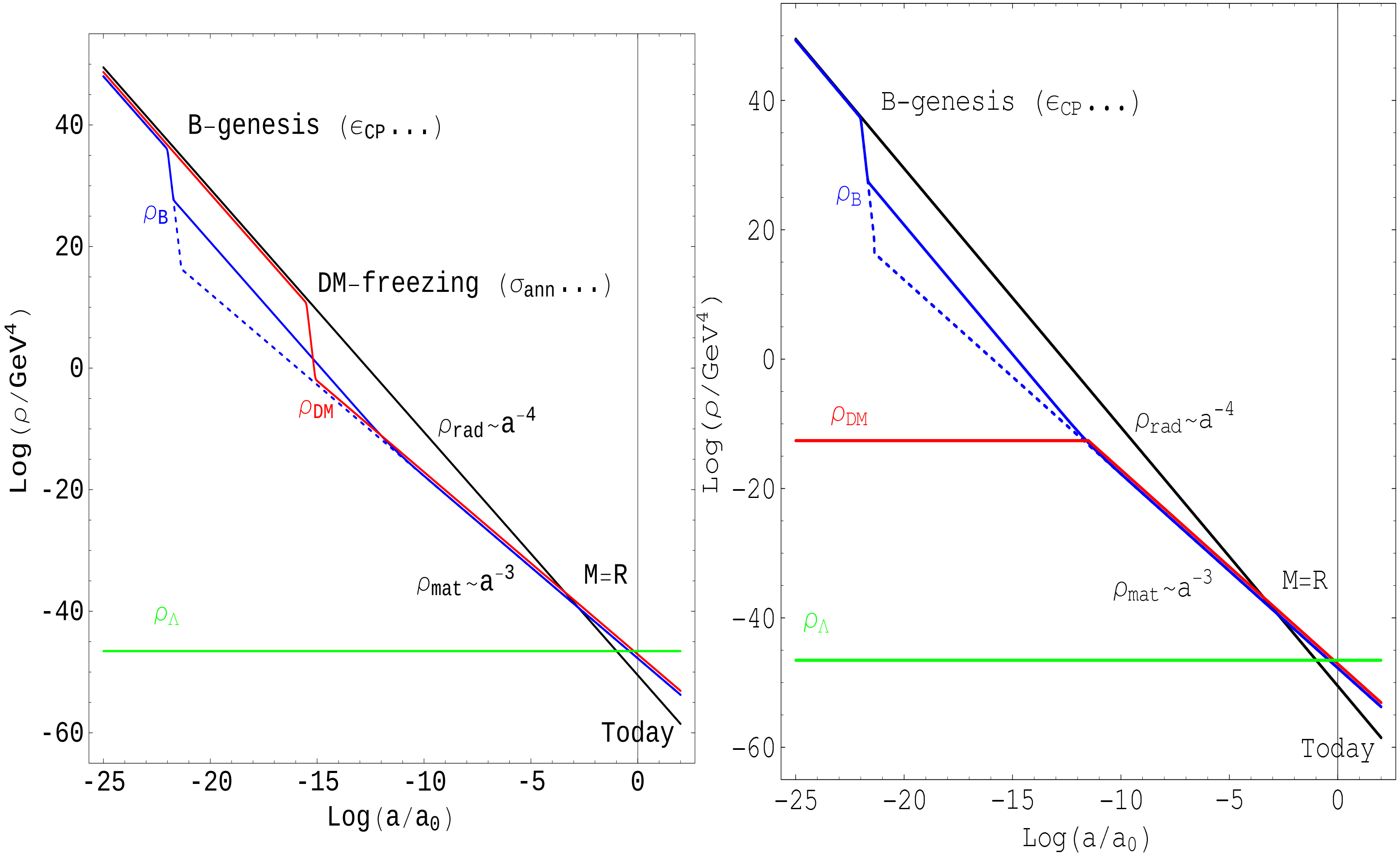
- Dark matter: $\rho_{\rm D} = n_X M_X$, but $M_X = ?$, $n_X = ?$

– too wide spectrum of possibilities ...
Axion: $M_X \sim 10^{-5}$ eV; Wimp: $M_X \sim 1$ TeV; Wimpzilla: $M_X \sim 10^{14}$ GeV ...

– 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 ...

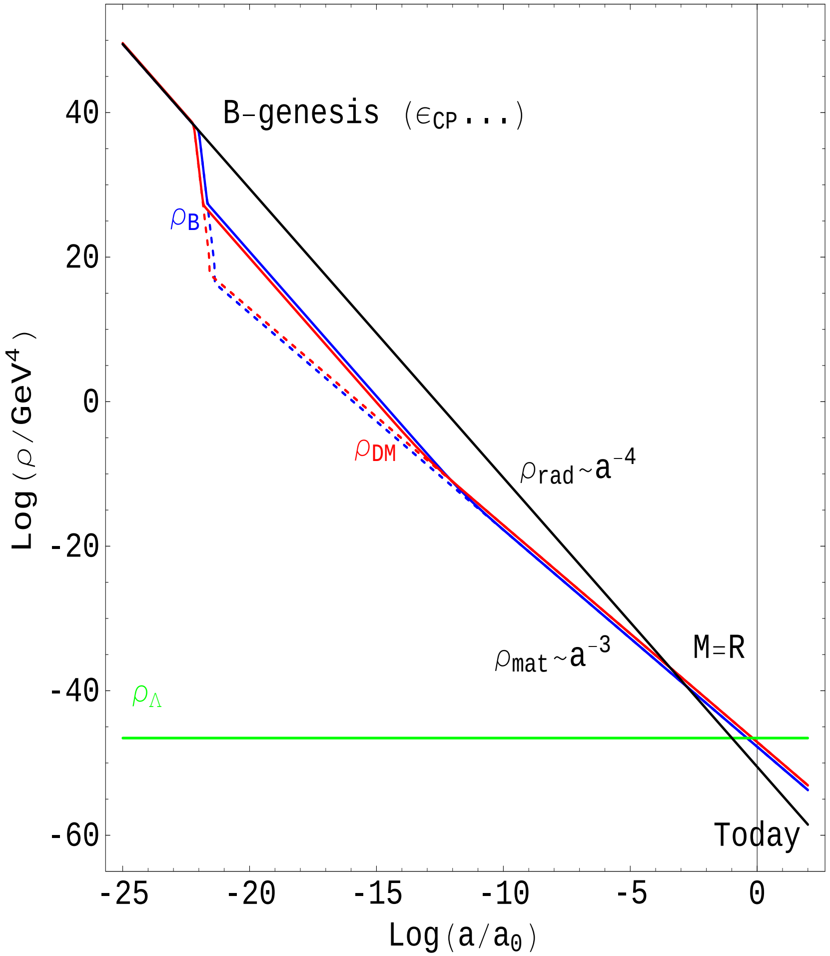
How then the mechanisms of Baryogenesis and Dark Matter synthesis, having different particle physics and corresponding to different epochs, could know about each-other? – How $\rho_B = n_B M_B$ could match $\rho_X = n_X M_X$ so intimately?

B vs. D – Fine Tuning demonstration



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

Unified origin of B and D? Both fractions at one shoot?



$$\frac{M_X n_X}{M_B n_B} \sim 1$$ *dark gauge sector?*

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

Lewis Carroll, "Through the Looking-Glass"

'Now, if you'll only attend, Kitty, and not talk so much, I'll tell you all my ideas about Looking-glass House. There's the room you can see through the glass – that's just the same as our drawing-room, only the things go the other way... the books 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 so wish I could see that bit! I want so to know whether they've a fire in the winter: you never can tell, you know, unless our fire smokes, and then smoke comes up in that room too – but that may be only pretence, just to make it look as if they had a fire...

'How would you like to leave in the Looking-glass House, Kitty? I wander if they'd give you milk in there? But perhaps Looking-glass milk isn't good to drink? 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 ... Why, it's turning into a sort of mist now, I declare! It'll be easy enough to get through ...'

–Alice said this, and in another moment she was through the glass... she was quite pleased to find that there was a real fire in the fireplace... 'So I shall be as worm here as I was in my room,' thought Alice: 'warmer, in fact, there'll be no one here to scold me away from the fire'.

"Looking-Glass Universe" – Parallel "Mirror" World

Broken P can be restored by mirror fermions — Lee & Yang '56
Mirror sector hidden copy of our sector — Kobzarev, Okun, Pomeranchuk '66
Alice strings — A.S. Schwarz' 82
Mirror dark matter (invisible stars) — Blinnikov, Khlopov '83
$SU(3)\times SU(2)\times U(1) \quad \times \quad SU(3)'\times SU(2)'\times U(1)'$ — Foot, Lew, Volkas '91

Two identical gauge factors, $G\times G'$, with the 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 – no new parameters!

- Spont. broken parity $G\leftrightarrow G'$: $M_W'\gg M_W$ - shadow dark matter:

Particle spectrum rescaled by $\zeta=M_W'/M_W$ — ZB & Mohapatra '95
Shadow DM, sterile neutrinos, Machos — ZB, Dolgov, Mohapatra '96
Strong CP and new axion (axidragon) — ZB, Gianfagna, Giannotti '00
SUSY little Higgs – accidental global $U(4)$ — ZB '04

Mirror Sector, Mirror 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)
$\tilde q_R=(\tilde u,\tilde d)^t_R$	$\tilde l_R=(\tilde\nu,\tilde e)^t_R$	|	$\tilde q'_R=(\tilde u',\tilde d')^t_R$	$\tilde l'_R=(\tilde\nu',\tilde e')^t_R$
$\tilde u_L\ \ \tilde d_L$	$\tilde e_L$	|	$\tilde u'_L\ \ \tilde d'_L$	$\tilde e'_L$

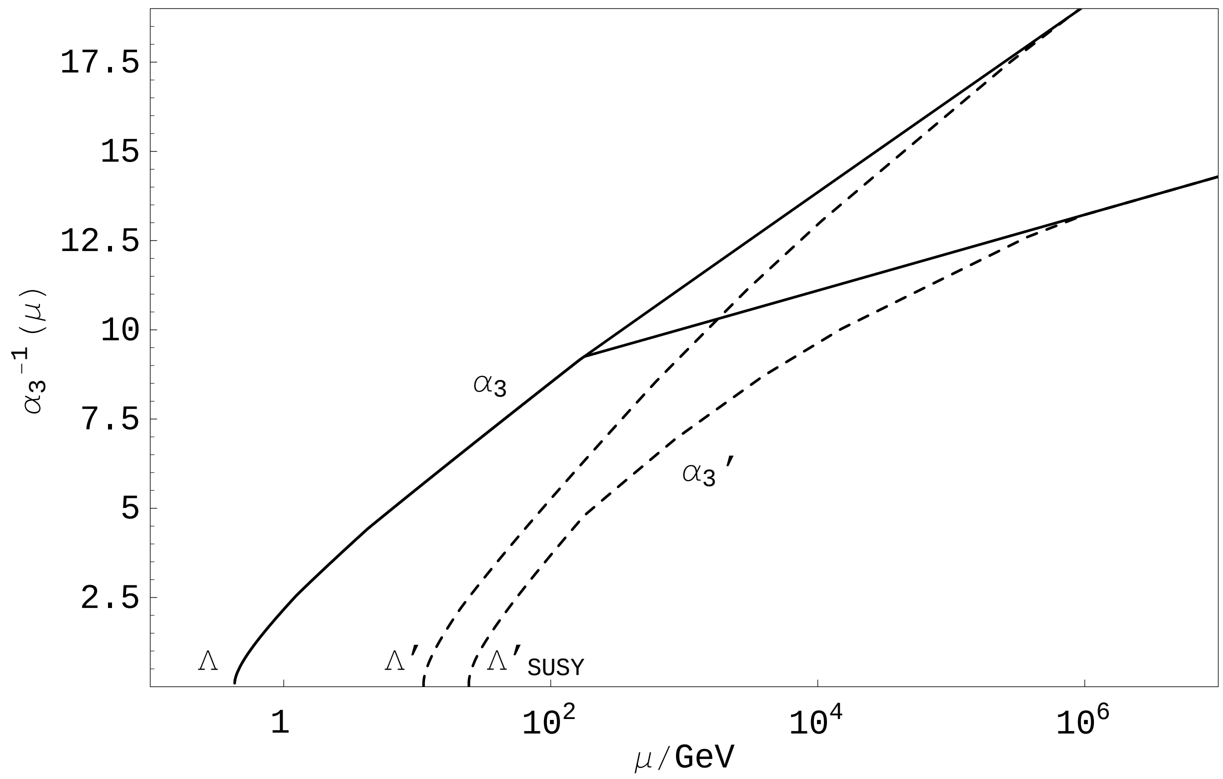
$$-\quad \mathcal{L}_{\rm Yuk}=f_L Y\tilde f_L\phi+\tilde f_R Y^* f_R\tilde\phi \quad \Big| \quad \mathcal{L}'_{\rm Yuk}=f'_L Y'\tilde f'_L\phi'+\tilde f'_R Y'^* f'_R\tilde\phi'$$

- D-parity: $L\leftrightarrow L',\ R\leftrightarrow R',\ \ \phi\leftrightarrow\phi'$: $Y'=Y$ • *identical xero copy*
- M-parity: $L\leftrightarrow R',\ R\leftrightarrow L',\ \ \phi\leftrightarrow\tilde\phi'$: $Y'=Y^\dagger$ • *mirror (chiral) copy*

Broken M parity: $M'_W > M_W$?

Spont. broken M parity: $v' \gg v$

ZB, Dolgov, Mohapatra '96



$M'_W/M_W \gg 1$ ...

lepton masses change fastly with M'_W :

$m'_e/m_e \simeq M'_W/M_W, \quad m'_\nu/m_\nu \simeq (M'_W/M_W)^2$

nucleon masses changes slower with M'_W :

$M'_N/M_N \sim \Lambda'/\Lambda \sim (M'_W/M_W)^{0.28}$

... e.g. for $M'_W/M_W \sim 100$, we have $m'_e \sim 50$ MeV and $M'_N \sim 5$ GeV

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

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

these interactions can induce particle mixing phenomena between O & M sectors:
any neutral particle (elementary or composite) can mix its twin ... ...
for exact mirror parity twin is exactly degenerate in mass

- 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 :

  Akhmedov, ZB, Senjanovic, Phys. Rev. Lett. 69, 3013 (1992)

  ZB, Mohapatra, Phys. Rev. D 52, 6607 (1995)

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

  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

  constraints from active-sterile neutrino mixing

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

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

  analogous operators $\frac{1}{M^5}(udd)^2 \quad (\Delta B = 2), \quad \frac{1}{M^5}(u'd'd')^2 \quad (\Delta B' = 2)$

  generate neutron - antineutron mixing

- hydrogen - mirror hydrogen mixing – effective operators :

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

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

O & M neutrino mixing

Mixed *D=5* effective operators — Z.B. & Mohapatra '95

$$\frac{A}{M} l l \phi\phi_{(\Delta L=2)} + \frac{A'}{M} l' l' \phi' \phi'_{(\Delta L'=2)} + \frac{D}{M} l l' \phi\phi'_{(\Delta L=1, \Delta L'=1)}$$

Substituting VEVs $\langle\phi\rangle = v$ *and* $\langle\phi'\rangle = v'$, *we get* $\nu - \nu'$ *mixing*

$$\begin{pmatrix} \hat{m}_\nu & \hat{m}_{\nu\nu'} \\ \hat{m}^t_{\nu\nu'} & \hat{m}_{\nu'} \end{pmatrix} = \frac{1}{M} \begin{pmatrix} Av^2 & Dvv' \\ D^t vv' & A'v'^2 \end{pmatrix}$$ – *active-sterile* ν *system*

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

- $v' = v$: $m_{\nu'} = m_\nu$ *and maximal mixing* $\theta_{\nu\nu'} = 45°$; — Foot & Volkas '95
- $v' > v$: $m_{\nu'} \sim (v'/v)^2 m_\nu$ *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* — Z.B. & Bento '05

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

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)

Mixed Seesaw and Leptogenesis between O & M sectors

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

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

(M-*parity:* $y' = y^\dagger$; D-*parity:* $y' = y$)

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

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

- 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*

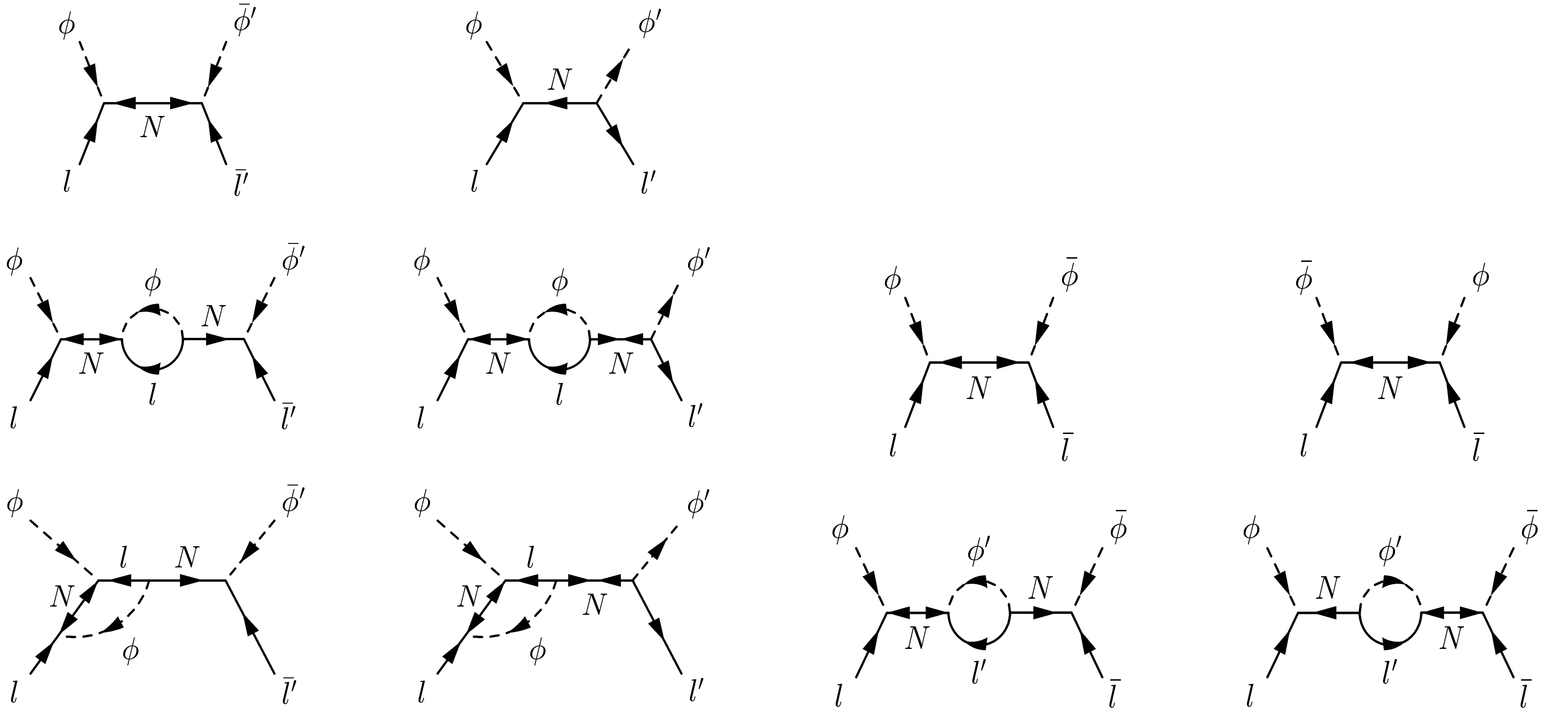
  and thus generate B-L$\neq$0 ($\to$ B$\neq$0 by sphalerons) for ordinary matter

- 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 !!

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:* $y' = y^\dagger$ $\varepsilon_{CP} \neq 0$

Boltzmann Eqs.

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,

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

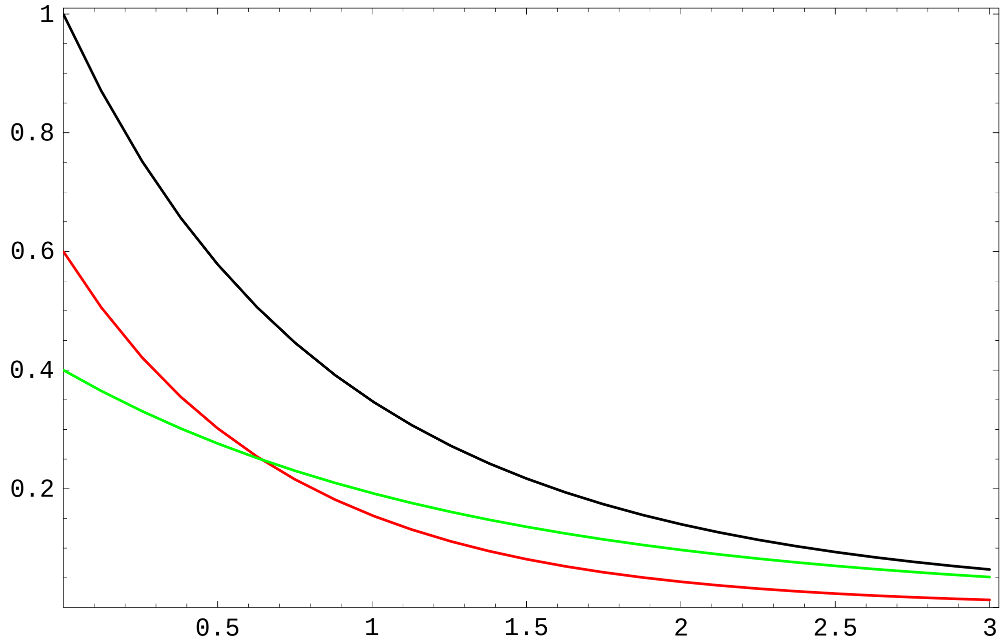
$$Y_{BL} = D(k)\cdot Y_{BL}^{(0)}; \qquad Y'_{BL} = D(kx^3)\cdot Y_{BL}^{(0)}$$

$$Y_{BL}^{(0)} \approx 2\times 10^{-3}\,\frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}\;.$$

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

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

$$k = [\Gamma_{\rm eff}/H]_{T=T_R}, \quad x = T'/T \approx 1.2\,(k/g_*)^{1/4} \quad (T_R = T_{\rm Reheating})$$



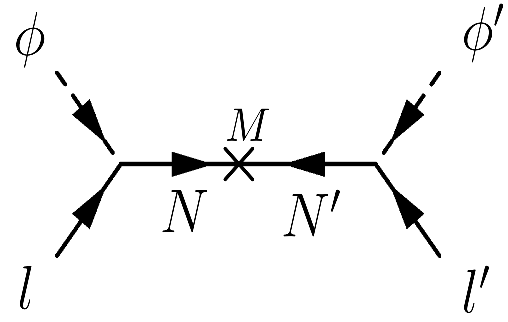
Z.B. '03

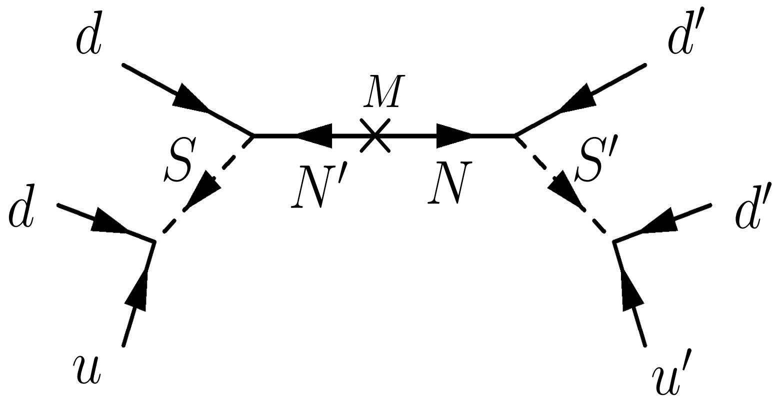
BBN: $x < 0.5 \;\rightarrow\; k \leq 4$; LSS: $x < 0.2 \;\rightarrow\; k \leq 1.5$

Thus Ordinary/Mirror matter ratio can vary within $\frac{\Omega_B}{\Omega'_B} = D(k) \simeq 0.2 - 1$

Leptogenesis or Baryogenesis?

D=5 operator $\frac{1}{M} ll' \phi\phi'$ $(\Delta L = 1)$ *induced by heavy singlet* N *"seesaw" exchange* $(l, \phi$ *and* l', ϕ' *ordinary and mirror lepton and Higgs doublets)* *– can generate B-L (and B′-L′) asymmetry via processes* $l\phi \to l'\phi'$ Z.B. and Bento '01





Z.B. and Bento '05

D=9 operator $\frac{1}{\mathcal{M}^5}(udd)(u'd'd')$ $(\Delta B = 1)$ *induced by heavy singlet* N *"seesaw"* $(u, d$ *and* u', d' *ordinary and mirror R-quarks,* S, S' *color triplet scalars (squarks?))* *– can generate B-L (and B′-L′) asymmetry via processes* $dS \to d'S'$

Mirror Baryons as Dark Matter

As far as Mirror Baryons are dark (in terms of ordinary photons), they could constitute Dark Matter of the Universe [Z.B., Comelli & Villante '01]

- *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: $x < x_{\rm eq} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

- *then 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:*

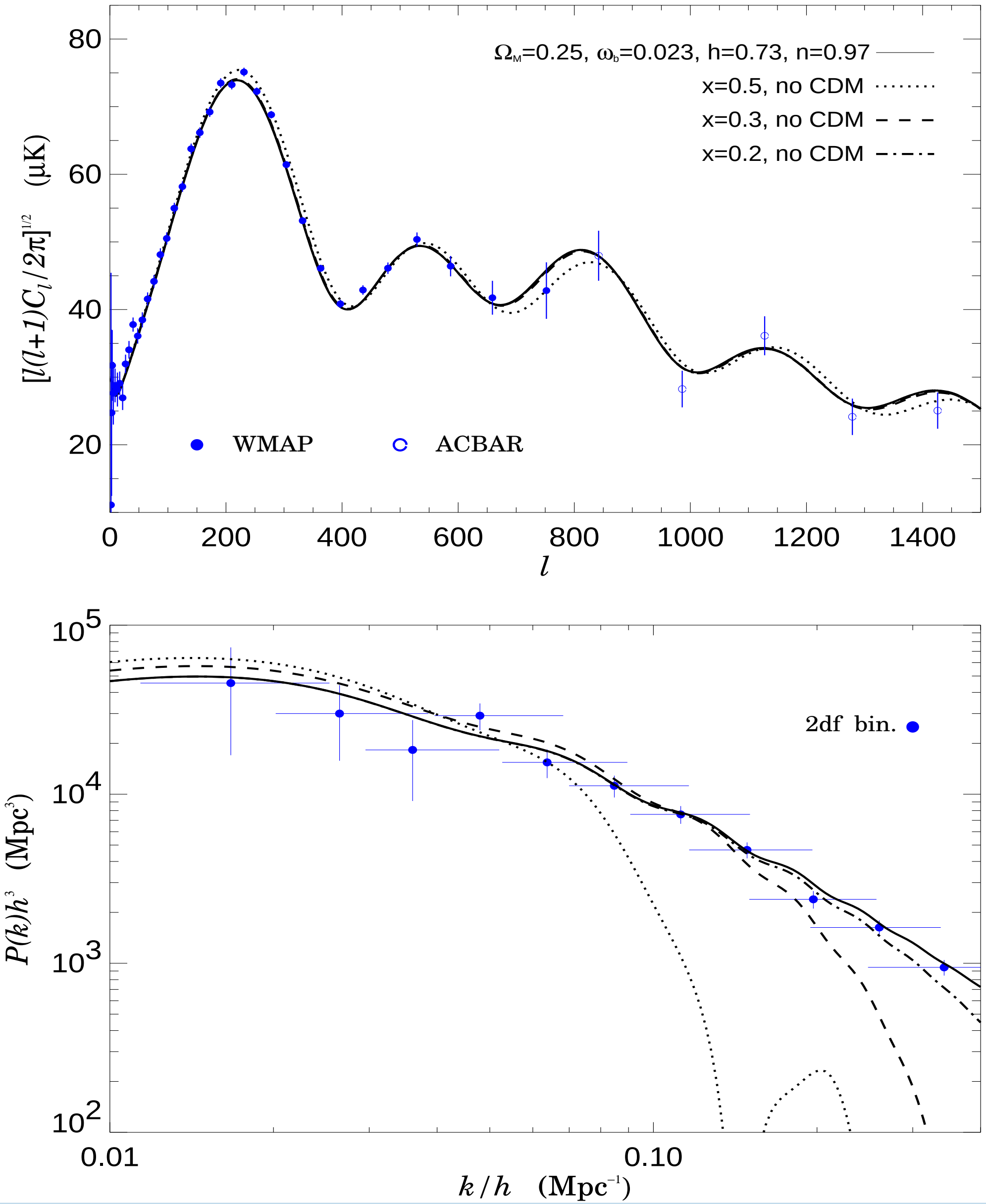
$\lambda'_S \sim 5 x_{\rm eq}^{5/4} (x/x_{\rm eq})^{3/2} (\Omega_M h^2)^{-3/4}$ *Mpc*

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

N.B. *Since mirror baryons constitute dissipative dark matter, the formation of the extended halos can be problematic, but perhaps possible if the star formation in the mirror sector is rather fast due to different temperature and chemical content (in fact, fast freezout of BBN in mirror sector is much faster, and it is dominated by Helium).*

MACHOs as mirror stars – *microlensing:* $M_{\rm av} = 0.5\, M_\odot$

CMB & LSS power spectra

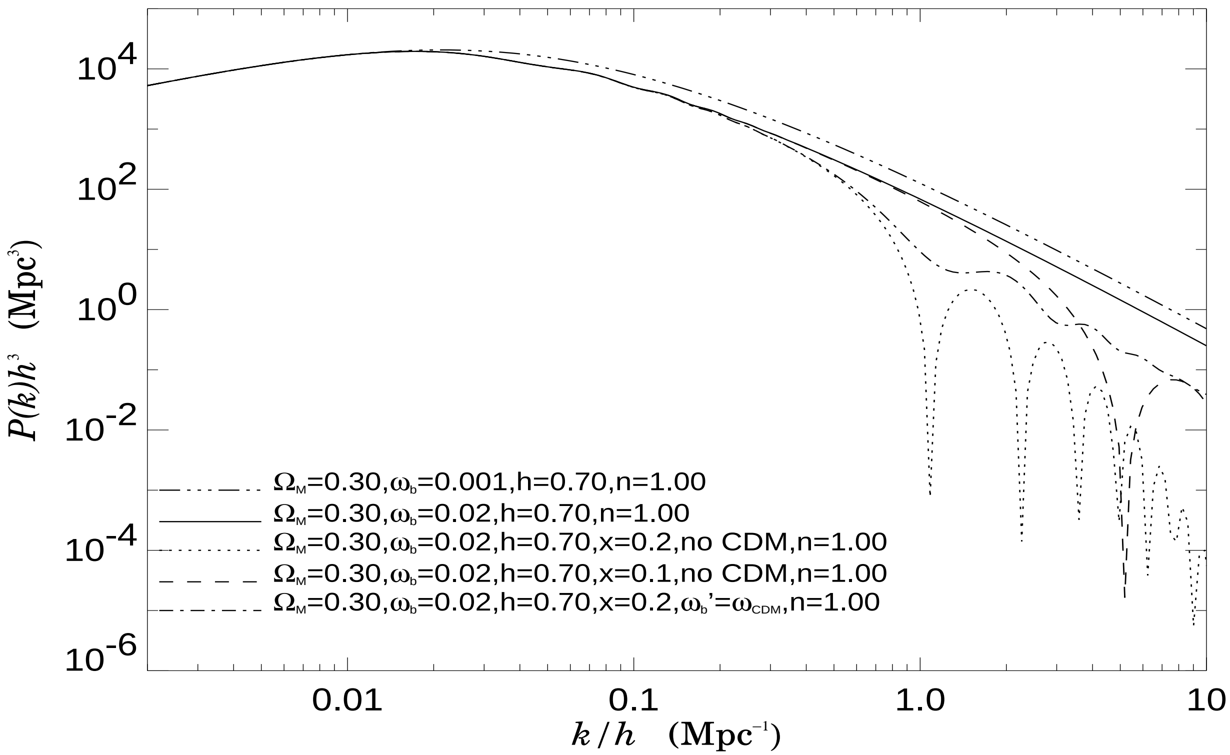


$$x = T'/T < 0.3$$

LSS power spectra

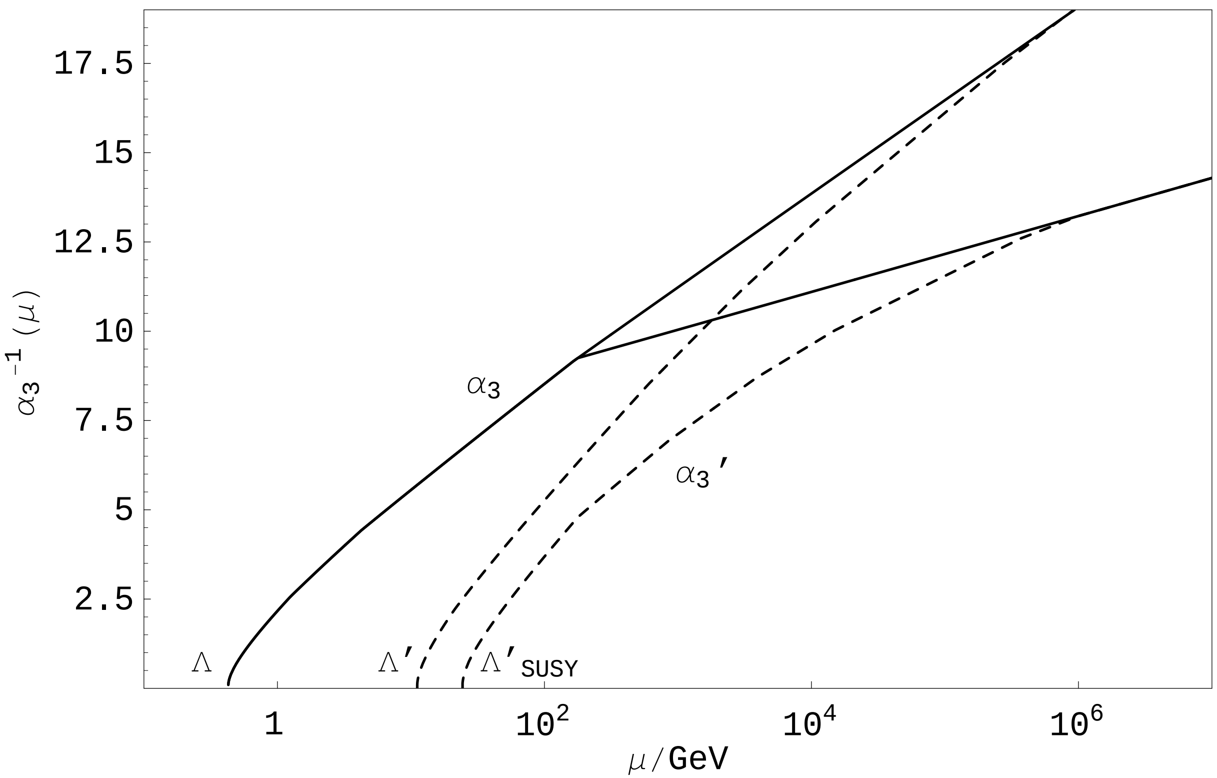
Z.B., Ciarcelluti, Comelli & Villante, '03

$x = T'/T < 0.2 \ (0.1?)$



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

Spont. broken M parity: $v' \gg v$ Z.B., Dolgov & Mohapatra '96



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

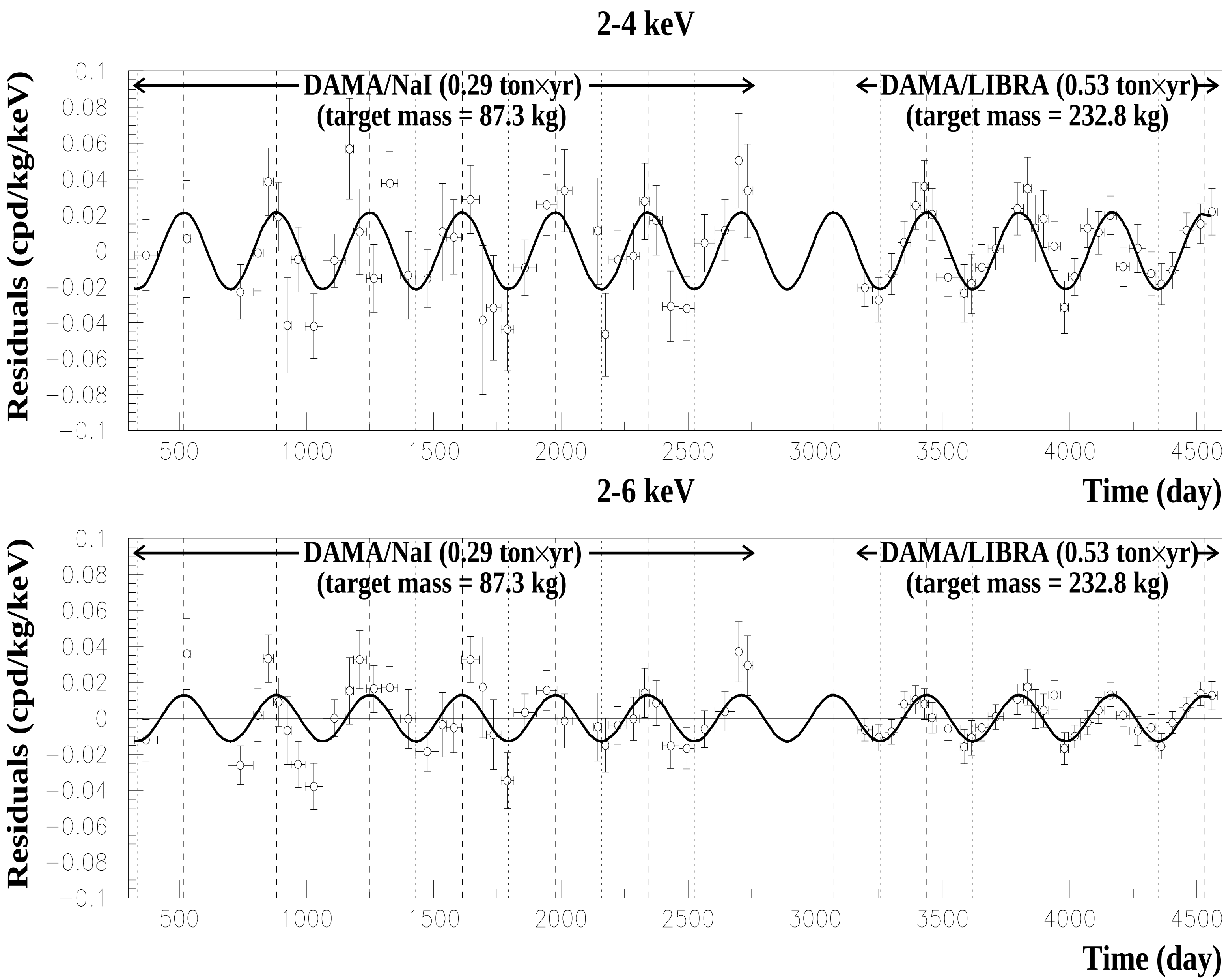
$M'_N/M_N \simeq (\Lambda'/\Lambda)$ changes slowly with M'_W

$m'_e/m_e \simeq M'_W/M_W$ changes fastly with M_W.

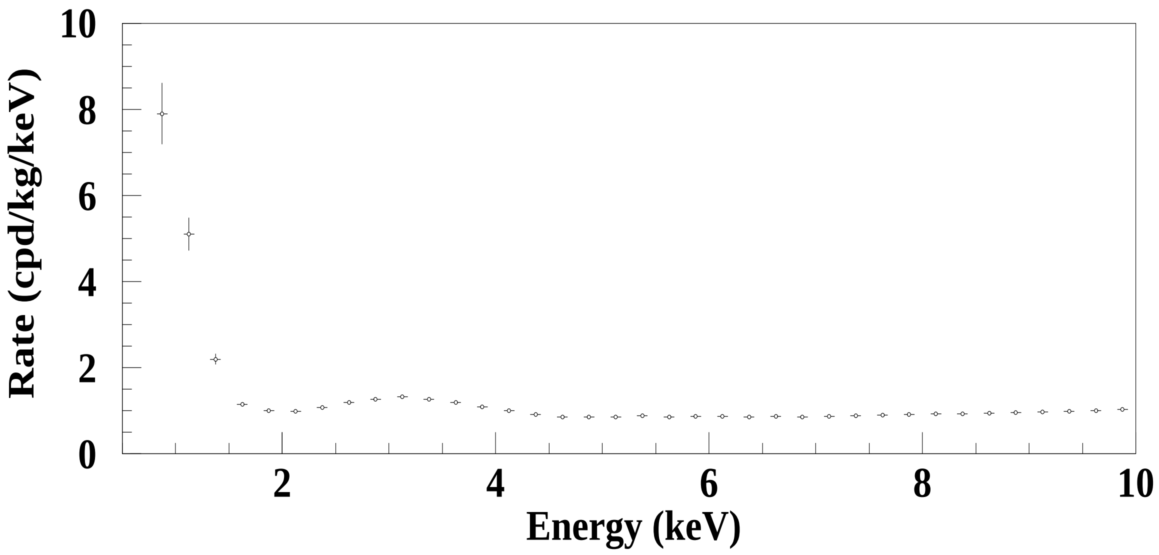
– Properties of MB's get closer to CDM : $M'_W \sim 10$ TeV ?

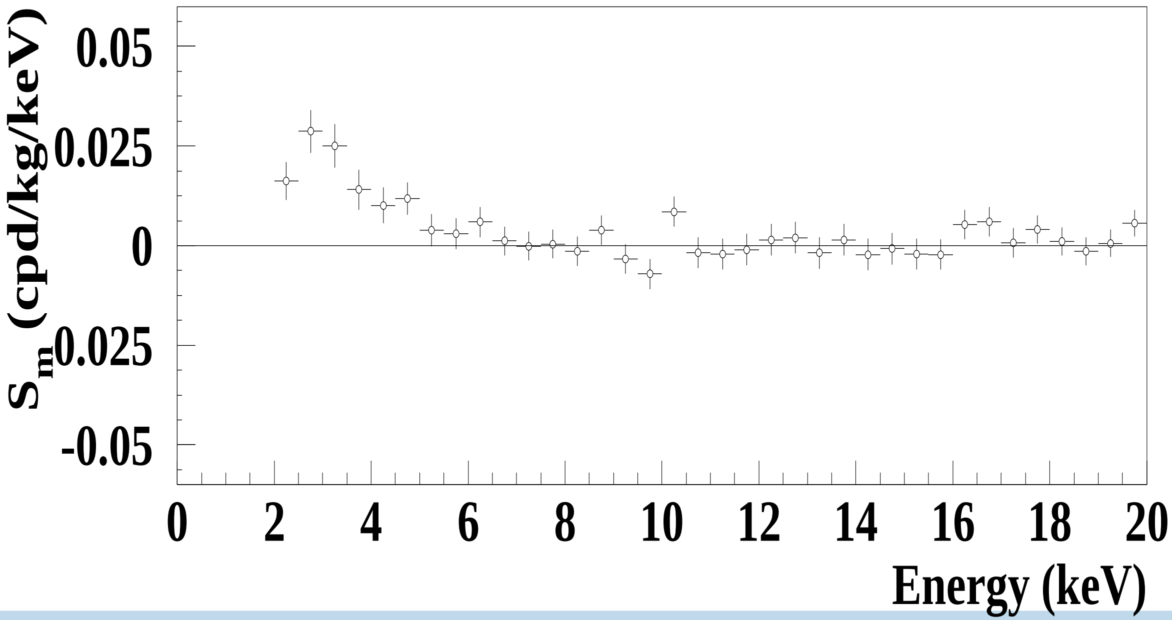
DAMA/Libra signal

R. Bernabei et al, ’03-08



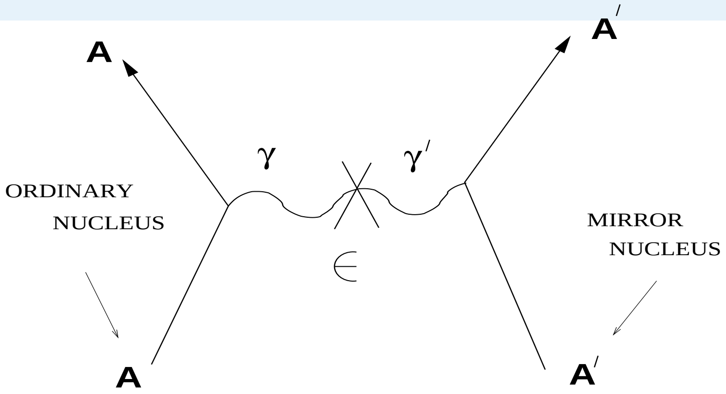
Recoil spectrum: background and its time varying part





DAMA and $\gamma - \gamma'$ kinetic mixing

R. Foot '08



Mirror nucleon scattering off Na or I due to the term $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}, \qquad \lambda = \epsilon^2 \frac{2\pi\alpha^2 Z^2 Z'^2}{M_A} F_A^2(qr_A) F_A'^2(qr_{A'}), \qquad (q^2 = 2M_A E_R)$$

Nuclei with $M_{A'} \simeq 15$ GeV (O') work if $\epsilon^2 \xi_{A'} \approx 10^{-19} \left(\frac{v_{\rm rot}}{200 \text{ km/s}}\right)^{7/2}$

if $\epsilon = 10^{-9}$, then $\xi_{A'} = 10\,\%$ is required ... ionized !!!

!! $e^+ e^- \to e'^+ e'^-$ process heats up mirror sector with $\Gamma \propto \epsilon^2$

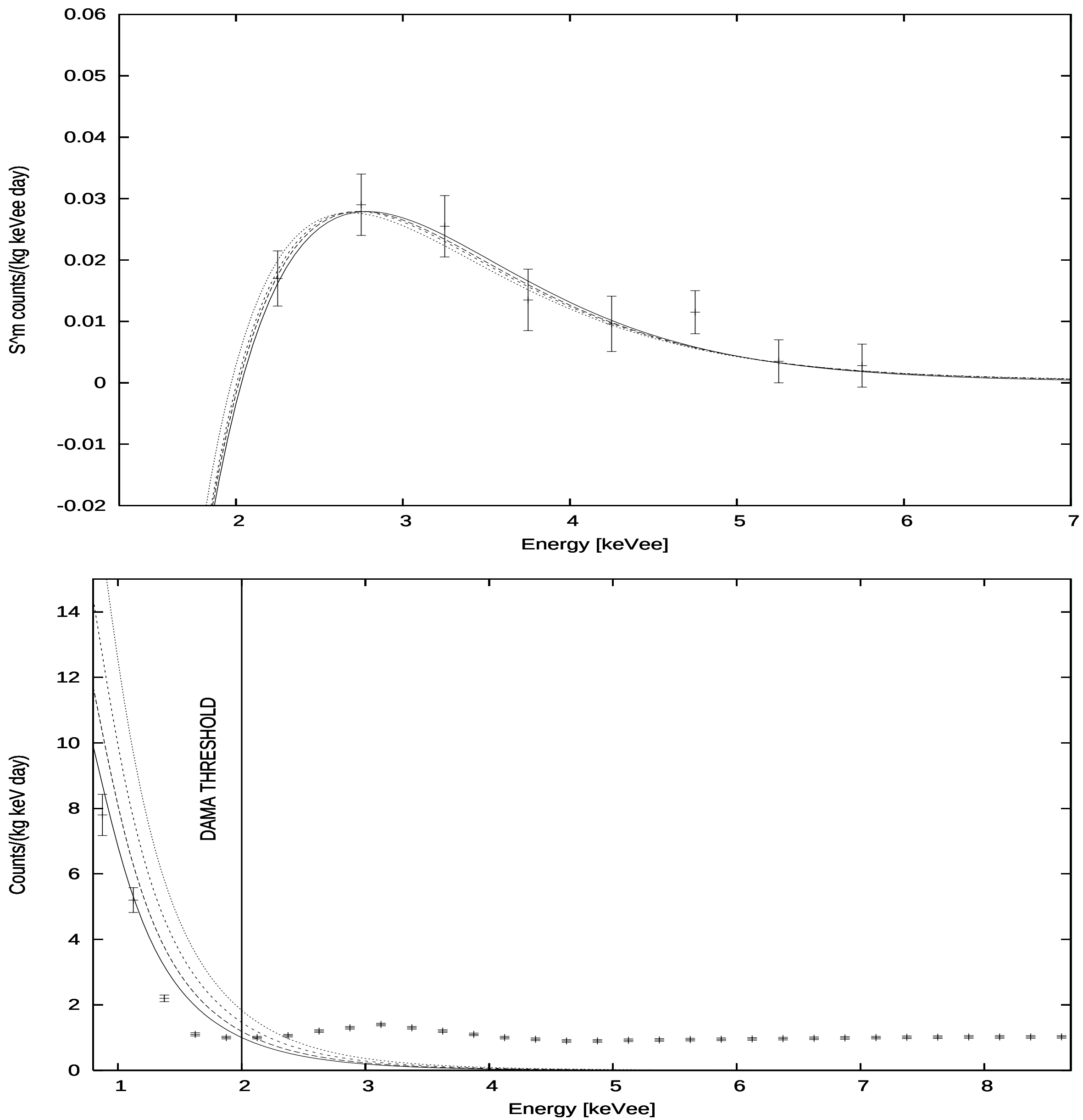
- BBN: $\epsilon < 1.5 \cdot 10^{-9} (\Delta N_\nu / 0.5)^{1/2}$ ZB, Lepidi '08
- Cosmology: $\epsilon < 3 \cdot 10^{-10} \left(\frac{T'/T}{0.3}\right)$, $\frac{T'}{T} < 0.3(0.2)$ LSS

(galaxies) ... requires $\xi_{A'} \approx 100\,\%$??? Inconsistency !!!
Ionized gas produce stars′ and then 100% of Oxygen′ ... ??

?? $\epsilon < 10^{-9}$?? Ciarcelluti, Foot '08

Constant and modulated spectra

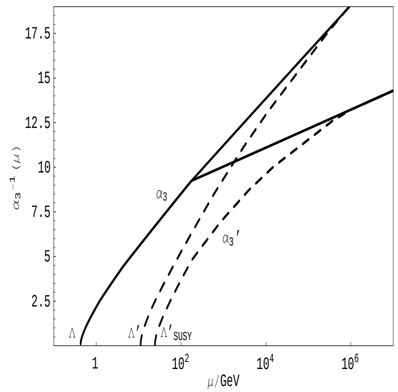
R. Foot '08



DAMA and $\gamma - \gamma'$ kinetic mixing: What's up ??

How to reconcile limits on ϵ with DAMA ??

1. Mirror photon has mass $m \sim$ MeV:
   ugly : the virginity of the basic idea is lost .... but helpful:
   keeps signal in DAMA above 2 keV $(m^2 \sim q^2 = 2M_A E_R)$
   but cosmologically allows $\epsilon > 10^{-9}$



2. Asymmetric mirror world: $M_{W',Z'} \sim 100\, M_{W,Z}$
   mirror electrons $m'_e \simeq 50 - 100$ MeV
   mirror nucleons $m'_{p,n} \simeq 4 - 6$ GeV (neutron′ unstable, H′ is DM)

(i) Early mirror recombination and radiation decoupling
(ii) Hydrogen′ atom is compact ... weakly collisional ... almost CDM
(ii) large residual ionization of H′ ... about $10\,\%$
(iii) weaker BBN limit on $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$: $\epsilon < 10^{-8}$

ZB, Lepidi '08

Mirror Matter & Mirror Gravity

ZB, Nesti, Pilo, Rossi, JHEP'09

- *Mirror matter + uni(versal)-gravity*

$$S = \int d^4x \sqrt{g} \left(\frac{M_{\rm P}^2}{2} R + \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix} \right)$$

– *gravitational potential:* $\phi(r) = \frac{G}{r}(M + M'), \qquad G = \frac{1}{8\pi M_{\rm P}^2}$

- *Mirror matter + mirror gravity (bi-gravity)*

$$S = \int d^4x \left[\sqrt{g} \left(\frac{M_{\rm P}^2}{2} R + \mathcal{L} \right) + \sqrt{g'} \left(\frac{M_{\rm P}^2}{2} R' + \mathcal{L}' \right) \right] +$$

$$+ \int d^4x \, (gg')^{1/4} \left[V(g, g', X_{\rm LB}) + \mathcal{L}_{\rm mix} \right],$$

– *bi-gravitational potential:* $\phi(r) = \frac{G}{2r}(M + M') + \frac{G e^{-\frac{r}{r_g}}}{2r}(M - M')$

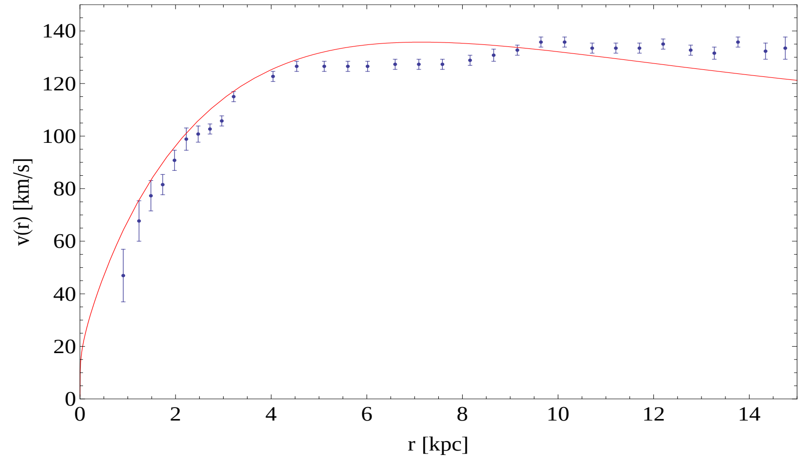
$$r \ll r_g : \quad \phi(r) = \frac{G}{r} M \; ; \qquad r \ll r_g : \quad \phi(r) = \frac{G}{2r}(M + M') \, ,$$

$$\rho_{\rm st} = \frac{3H_0^2}{8\pi G} \qquad G_{\rm cosm} \to \tfrac{1}{2} G \quad \to \quad \rho_{\rm new} \to 2\rho_{\rm st}$$

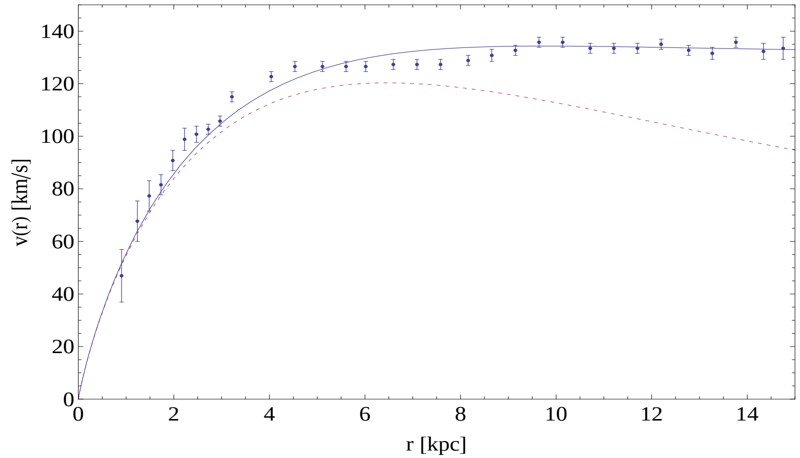
Galactic rotational curves

Z.B., Pilo, Rossi, '09

rotational curve for NGC 2403 $(M = 2.5 \times 10^{19} M_\odot)$



with CDM, NFW profile

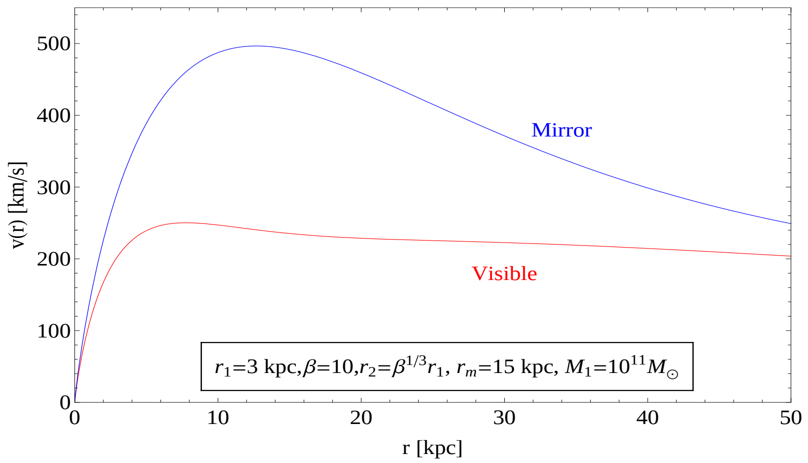


with bi-gravity, two-discs

$$\sigma(r) = \frac{M}{2\pi r_D^2} e^{-\frac{r}{r_D}}, \qquad \sigma'(r) = \frac{M'}{2\pi r_D'^2} e^{-\frac{r}{r_D'}} : \qquad \frac{M'}{M} = 10, \quad r_g = 10 \text{ kpc}$$

Implications for Dark Matter search

rotational curves for ordinary and mirror components



(a) mirror matter density (in the galaxy disc) is much larger than the CDM density (in the Halo)

(b) galactic velocities of mirror component (blue curve) are much larger than that of ordinary one (red curve)
$E'_{\rm kin} \approx 10 E_{\rm kin}$ *for the same mass*

light DM particles ? *Hydrogen′, Helium′ ....*
... interacting via photon-photon′ kinetic mixing, $\pi - \pi'$ *mixing etc.*

Neutron - Mirror neutron mixing

Operators like $\frac{1}{\mathcal{M}^5}(udd)(u'd'd')$ *and* $\frac{1}{\mathcal{M}^5}(qqd)(q'q'd')$ *induce the neutron - mirror neutron mass mixing* $\delta m\,(\overline{n}n' + \overline{n}'n)$, *with* $\delta m \sim \left(\frac{10\,\mathrm{TeV}}{\mathcal{M}}\right)^5 \cdot 10^{-15}\,\mathrm{eV}$

• $n - n'$ *oscillation in vacuum:*

maximal mixing $\theta = 45^\circ$ *and oscillation time* $\tau_{\rm osc} = \delta m^{-1} \sim \left(\frac{\mathcal{M}}{10\,\mathrm{TeV}}\right)^5\,\mathrm{s}$

... similar to neutron - antineutron oscillation

Kuzmin '70, Glashow '79

Marshak & Mohapatra '80

but experimental limits on $n - \bar{n}$ *are strong:* $\tau_{n\bar{n}} > 10\,\mathrm{yr}$, *while* $n - n'$ *is still allowed to be rather fast, faster then neutron decay:* $\tau_{nn'} < 10\,\mathrm{min}$

Can be interesting if $\mathcal{M} \sim (M_S^4 M_N)^{1/5} \sim 10\,\mathrm{TeV}$ *In the "seesaw" model –*
E.g. if $M_S, M_N \sim 10\,\mathrm{TeV}$, *or* $M_N \sim 10^{12}\,\mathrm{TeV}$ *and* $M_S \sim 100\,\mathrm{GeV}$

(see diagram of the previous page)

!!! N.B. Nuclear Stability

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

$\tau_{n\tilde{n}} > 10\,\mathrm{yr}$ *or so ...*

• $n - n'$ *does not:* $(A, Z) \to (A-1, Z) + n'$ *not allowed by phase space !*
gives no restriction for $\tau_{nn'}$ *!*

Experimental limits & and future search

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

  as for $n - n'$: about 5% neutron deficit was observed, so taking

  $P_{nn'}(t) \simeq (t/\tau)^2 < 10^{-2}$, $\tau_{nn'} > 1$ s $\rightarrow$ $\delta m < 10^{-15}$ eV
- $n - n'$ – anomalous UCN loses, $\eta < 2 \cdot 10^{-6} \rightarrow \delta m < 3 \cdot 10^{-15}$ eV
- Nuclear Stability gives no limit for $\tau_{nn'}$ *Z.B. & Bento '05*

Recent Experimental search:

- $\tau > 2.7$ s FR Munich, Schmidt et al. Procs. B&L-violation'07, Berkeley
- $\tau > 103$ s ILL Grenoble, Ban et al. Phys.Rev.Lett. 99:161603 (2007)
- $\tau > 414$ s ILL Grenoble, Serebrov et al. Phys.Lett. B663:181 (2008)
- $\tau > 403$ s ILL Grenoble, Serebrov et al. NIM A611:137 (2009)

Future experiments can reach sensitivity $\tau \sim 10^4$ s (DUSEL ??)

$n - n'$ oscillations can have very different experimental implications if n and n' states are not exactly degenerate at B=0. E.g. gravity is not quite universal between O and M matters, or there exist non-universal 5th forces of non-gravitational origin, or the mirror magnetic field is non-zero. Opposite effect is possible: magnetic field could enhance the oscillation instead of suppressing it.

Neutron - Mirror neutron mixing in astrophysics

- *primordial baryon asymmetry can be generated via $\Delta B = 1$ processes like $udd \to u'd'd'$. The same (and possibly somewhat larger) baryon asymmetry would be generated in the Mirror sector, wich could naturally explanain the origin of the baryonic and dark matter balance in the Universe: $\Omega_D \sim \Omega_B$.*

N.B. This mechanism does not require that $n - n'$ oscillation time should be necessarily small, within the present experimental reach. However, it requires that $\Delta B = 2$ processes like $udd \to \bar{u}\bar{d}\bar{d}$ should be also active though could be much slower. Hence, should the $n - n'$ oscillation detected at the level $\tau_{nn'} < 10^4$ s, (i.e. $\mathcal{M}_{nn'} \sim 10$ TeV) it would give a strong argument that $n - \bar{n}$ oscillation should also exist at the experimentally accessible level, with the relevant cutoff scale $\mathcal{M}_{n\bar{n}} \sim 100$ TeV and thus $\tau_{n\bar{n}} \sim 10^9$ s.

- *If $\tau_{nn'} < 10^3$ s, $n - n'$ oscillation provides an elegant mechanism for the transport of the ultra high energy cosmic rays at the large cosmological distances without suffering significant energy depression, and could be of interest in the search of the UHECR above the GZK cutoff and their correlation with the far distant astrophysical objects (BL Lacs, GRB's etc.)* *Z.B. & Bento '05*
- *Fast $n - n'$ oscillation could have interesting implications also for the neutrons from the solar flares* *Mohapatra,Nasri, Nussinov '05*

Neutron - Mirror neutron oscillation in external fields

Effective (non-relativistic) Hamiltonian for $n - n'$ oscillation *Z.B. & Bento '05*

$$H = \begin{pmatrix} m - i\,\Gamma/2 + V + \mu(\vec{B}\cdot\vec{\sigma}) & \delta m \\ \delta m & m' - i\,\Gamma'/2 + V' + \mu'(\vec{B}'\cdot\vec{\sigma}) \end{pmatrix}$$

- Exact mirror parity: $m' = m$, $\Gamma' = \Gamma$, $\mu' = \mu = -1.91\mu_N$
- Grav. potentials are the same: $V' = V$,
- but magnetic fields $\vec{B}' \neq \vec{B}$:

$|\mu B| \simeq 6\cdot 10^{-12}\ \mathrm{eV/G}$ (Earth magnetic field $B \simeq 0.5\ \mathrm{G}$) –

Take $\boldsymbol{B} = (0,0,B)$ across z-axis, $(\boldsymbol{\sigma B}) = B\sigma_z = \mathrm{diag}(B,-B)$ and $B' = 0$

$$H = \begin{pmatrix} \pm 2\omega_B & \delta m \\ \delta m & 0 \end{pmatrix}$$ diagonal in the basis $(\psi_+, \psi_-, \psi'_+, \psi'_-)$

– Energy gap $2\omega_B = |\mu B| \simeq B[\mathrm{G}] \times 6\cdot 10^{-12}\ \mathrm{eV}$

Oscillation probability $P_{nn'}(t) = \sin^2 2\theta_B \sin^2(t/\tau_B)\cdot e^{-t/\tau_{\mathrm{dec}}}$

$$\sin 2\theta_B = \frac{\delta m}{\sqrt{\delta m^2 + \omega_B^2}}, \quad \tau_B = \frac{1}{\sqrt{\delta m^2 + \omega_B^2}} = \tau \sin 2\theta_B, \quad \tau = \delta m^{-1}$$

$n - n'$ *transition probabilities* $(B' = 0, \quad t \ll \tau_{\rm dec})$

In vacuum ($\omega_B = 0$): $\quad P_0(t) = \sin^2(\delta m\, t)$

($\tau_0 = \tau = \delta m^{-1}$, $\quad \sin^2 2\theta_0 = 1$: $\quad 45^\circ$ mixing)

for short times ($t \ll \tau$) : $\quad P_0(t) = \delta m^2 t^2$

for long times ($t \gg \tau$) : $\quad P_0(t) = \frac{1}{2}$

In medium ($\omega_B = \frac{1}{2}|\mu B| \gg \delta m$): $\quad P_B(t) = \frac{\delta m^2}{\delta m^2 + \omega_B^2} \sin^2\left(\sqrt{\delta m^2 + \omega_B^2}\, t\right)$,

($\tau_B = \omega_B^{-1} \ll \tau$, $\quad \sin^2 2\theta_B = \delta m^2/\omega_B^2 \ll 1$)

for short times ($t \ll \tau_B$) : $\quad P_B(t) = \delta m^2 t^2$

for long times ($t \gg \tau_B$) : $\quad P_B(t) = \frac{1}{2}\frac{\delta m^2}{\omega_B^2}$

$\Delta_B = P_0 - P_B > 0$

Magnetic field suppresses oscillation. The experiments with the reactor neutrons in free flight as well in the UCN traps could observe the difference in the neutron lose rates for the magnetic field on and off

for more detailed discussion, see Pokotilovsky '06

$n - n'$ oscillation in mirror magnetic field $(B' \neq 0)$

Z. Berezhiani, arXiv: 0804.2088 [hep-ph]

Hamiltonian is 4×4 matrix describing oscillations and precessions

$$H_I = \begin{pmatrix} \mu(\vec{B}\cdot\vec{\sigma}) & \delta m \\ \delta m & \mu(\vec{B}'\cdot\vec{\sigma}) \end{pmatrix} = \begin{pmatrix} 2\,\vec{\omega}\cdot\vec{\sigma} & \delta m \\ \delta m & 2\,\vec{\omega}'\cdot\vec{\sigma} \end{pmatrix}.$$

when oscillations can be averaged,

$$B = 0: \qquad P_0 = \frac{1}{2}\sin^2 2\theta_0 = \frac{\delta m^2}{2\omega'^2} = 2\left(\frac{\delta m}{\mu B'}\right)^2$$

$$B \neq 0: \qquad P(\vec{B}) = \frac{1}{2}\sin^2 2\theta = \frac{\delta m^2(\vec{\omega}'+\vec{\omega})^2}{2(\omega'^2-\omega^2)^2} = \frac{1+\eta^2+2\eta\cos\beta}{(1-\eta^2)^2}\,P_0$$

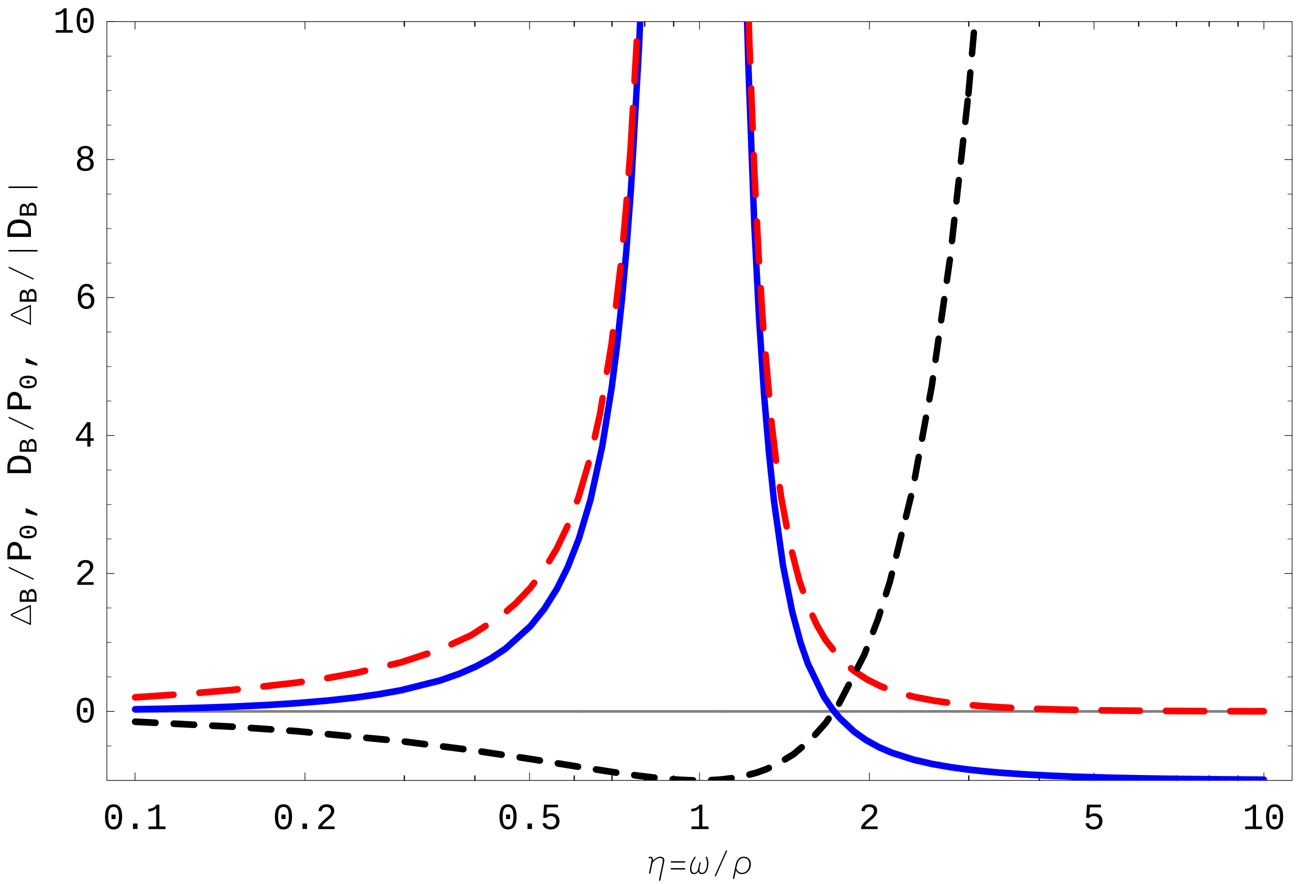
$\eta = B/B'$, β angle between $\vec{B}$ and $\vec{B}'$

$$P_B = \frac{P(\vec{B})+P(-\vec{B})}{2} = \frac{1+\eta^2}{(1-\eta^2)^2}\,P_0 \quad \longrightarrow \quad \Delta_B = P_B - P_0 = \frac{\eta^2(3-\eta^2)}{(1-\eta^2)^2}\,P_0$$

Δ_B is **positive** $(P_B > P_0)$ if $\eta < \sqrt{3}$, i.e. $B' > 0.6B$

$$D_B(\beta) = \frac{P(\vec{B})-P(-\vec{B})}{2\cos\beta} = \frac{2\eta}{(1-\eta^2)^2}\,P_0$$

Comparison of observables



— Δ_B/P_0

– – D_B/P_0

- - - Δ_B/D_B

$\eta = B/B'$

$n - n'$ oscillation in mirror magnetic field

Experimental data from G. Ban et al, PRL 99, 161603 (2007)

t_s [s]	50 (a)	50 (b)	100 (a)	175 (a)
$N_{B\uparrow}(t_*)$	44197 ± 53	44443 ± 53	28671 ± 30	17047 ± 31
$N_{B\downarrow}(t_*)$	44128 ± 53	44316 ± 46	28596 ± 30	16974 ± 31
$A_B(t_*) \times 10^3$	0.78 ± 0.85	1.43 ± 0.79	1.31 ± 0.74	2.15 ± 1.28
$N_0(t_*)$	44317 ± 40	44363 ± 53	28635 ± 21	17015 ± 22
$E_B(t_*) \times 10^3$	3.50 ± 1.24	-0.37 ± 1.43	0.05 ± 1.04	0.27 ± 1.83
κ_B	4.48 ± 5.12	-0.26 ± 1.00	0.04 ± 0.80	0.12 ± 0.85

Table 1: *The UCN counts measured in configurations* $B_\uparrow$, $B_\downarrow$ *(*$B = 0.06$ *G) and* B_0 *for different storage times* t_s. *Effective time* $t_{\rm eff} = t_s + (23 \pm 3)$ *s.*

$$D_B = (6.2 \pm 2.0) \times 10^{-7} \qquad (\chi^2/d.o.f. = 0.52/3)$$

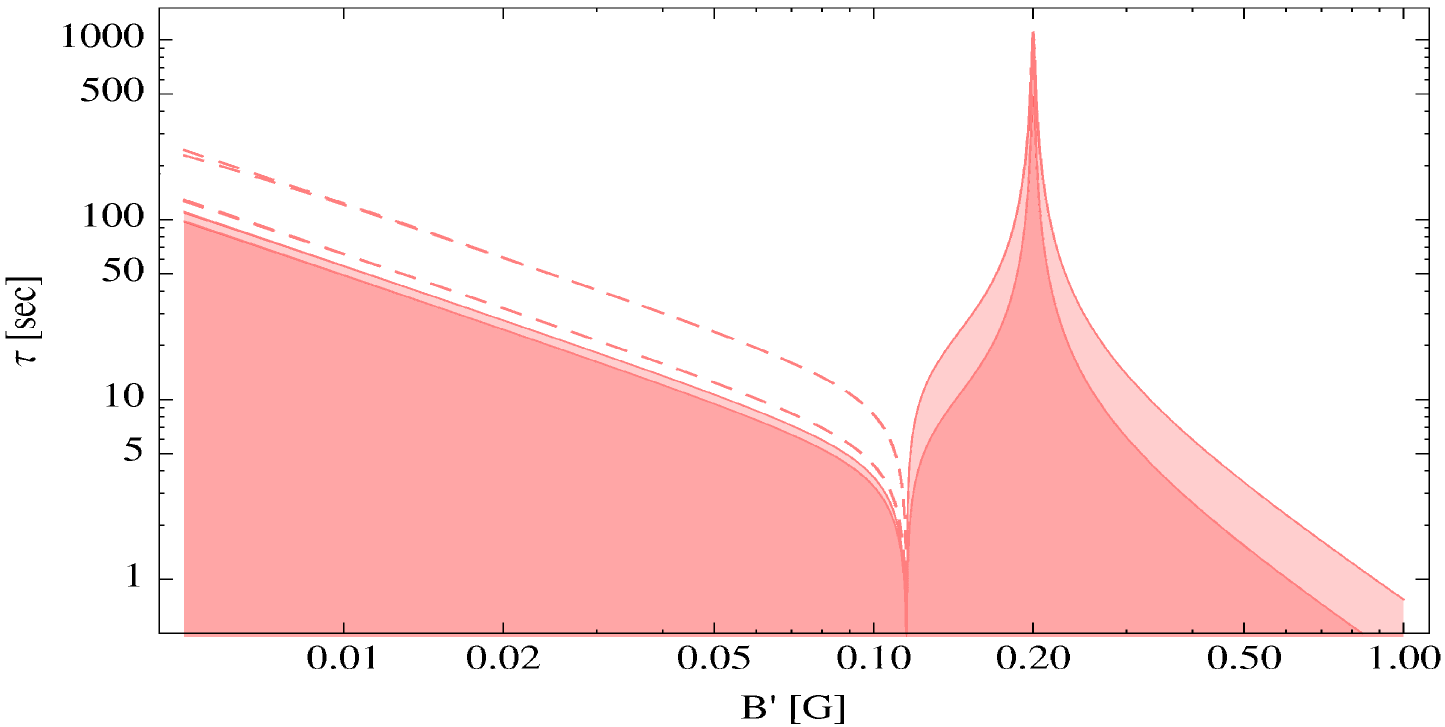
$$\Delta_B = (2.9 \pm 2.9) \times 10^{-7} \qquad (\chi^2/d.o.f. = 6.9/3)$$

Positive ?

New Data (preliminary results) indicate $4.3\ \sigma$ effect for D_B

Measurements in Horizontal magnetic field

Z.B., Nest, Serebrov, '10



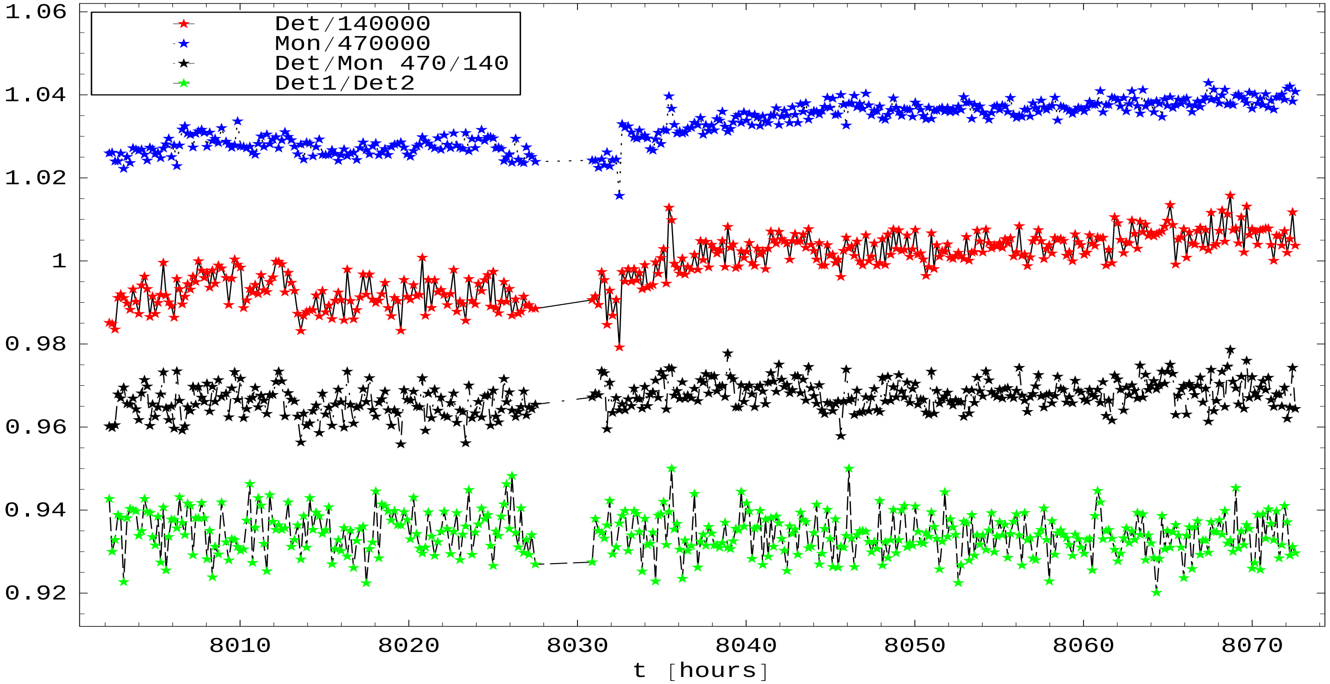
3 month measurements (~ 4000 data) in Autumn 2007

sequences $b_+, B_+, B_-, b_-; b_-, B_-, B_+, b_-$: $B = 0.2$ G , $b < 12$ mG

and comparing $\frac{1}{2}(N_{B+} + N_{B-})$ to $\frac{1}{2}(N_{b+} + N_{b-})$

Measurements in vertical magnetic field

Z.B., Nest, Serebrov, in preparation



3 days continuous measurements (~ 400 data) from 30 Nov 2007

repeating sequence $B_+, B_-, B_-, B_+; B_-, B_+, B_+, B_-$ - $B \simeq 0.2$ G

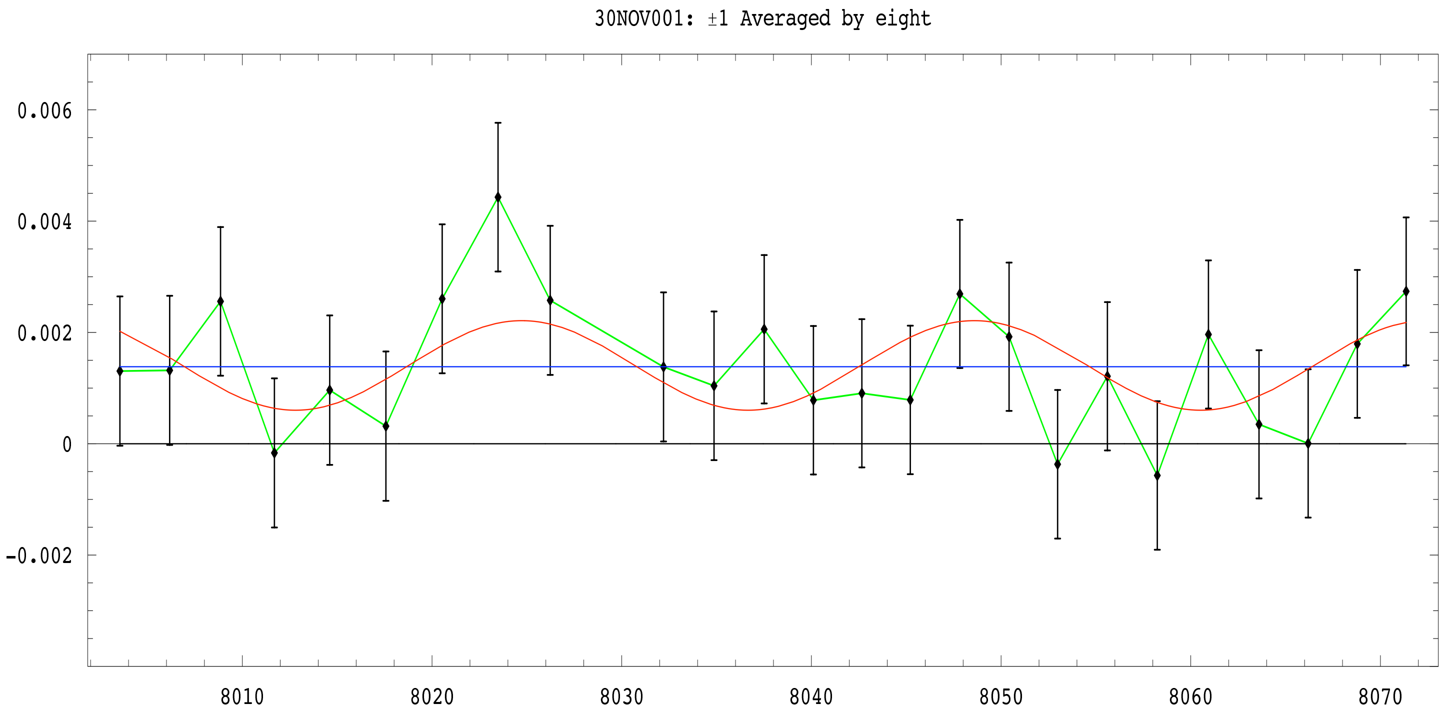
● – eliminating the linear and quadratic drifts of the neutron flux $\sim 1\%$

normalize the detector counts N (red) to monitor counts M (blue)

– the ratio N/M (black) is constant with a perfect statistical precision

Measurements in vertical magnetic field

$A = \frac{N_{B+} - N_{B-}}{N_{B+} + N_{B-}} = (D_B \cos\beta)\nu t_s$ $\nu \approx 11$ s^{-1} collision frequence,
$t_s = 370$ s holding time:

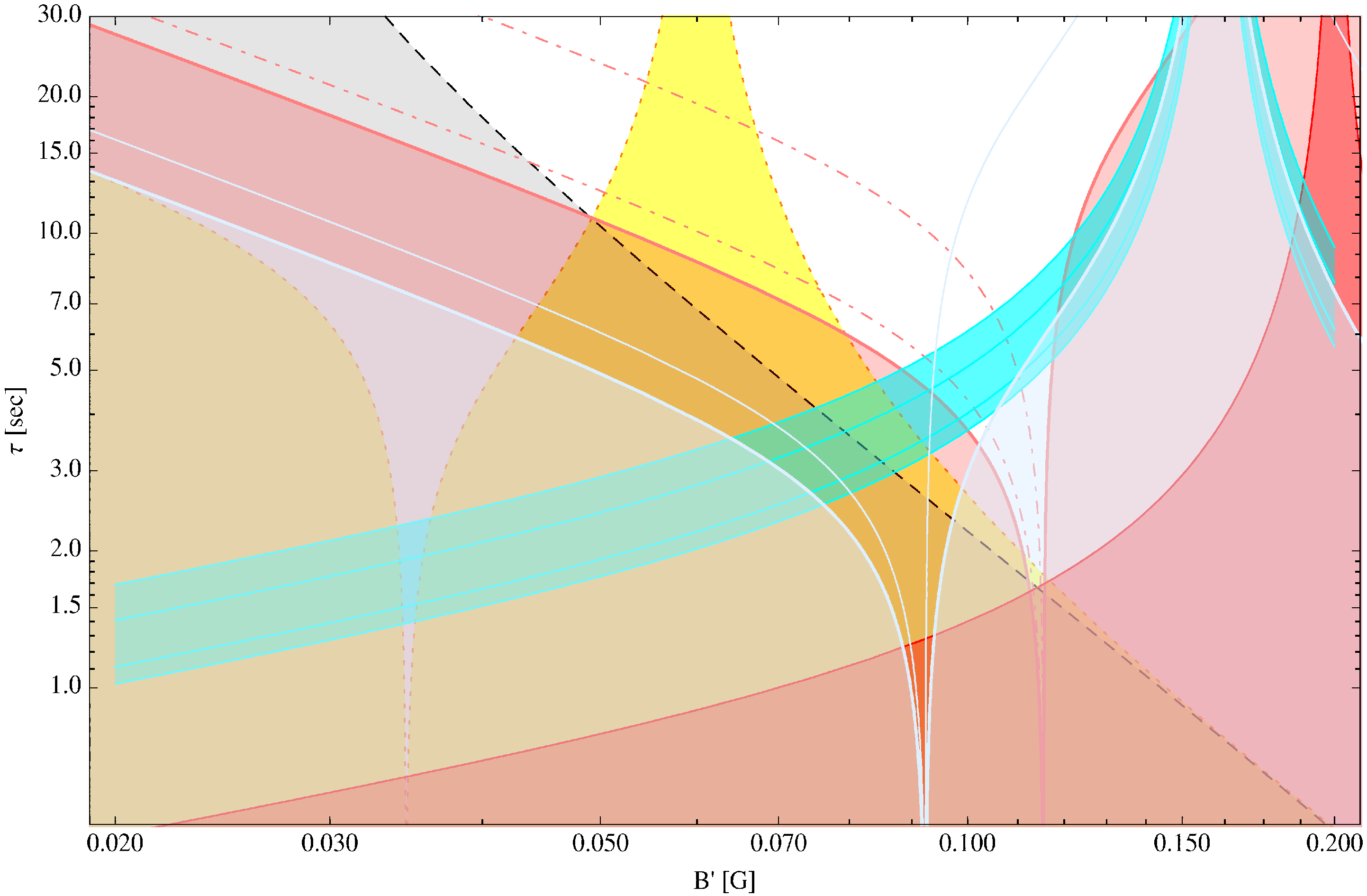


at $B \simeq 0.2$ G : $2A = (1.39 \pm 0.26) \times 10^{-3}$ (5.2σ)
$[D_B \cos\beta_V] = (1.90 \pm 0.37) \times 10^{-7}$

- at $B \simeq 0.4$ G : $[D_B \cos\beta_V] = (-0.28 \pm 0.82) \times 10^{-7}$

Measurements in vertical magnetic field

Preliminary ...



$B' = (0.11 \pm 0.02)$ G , $\tau = (5 - 10)$ s ?????

Concluding ...

The measurements at $B \simeq 0.2$ G show that the UCN loss rate depends on the magnetic field direction: Vertically "up" and "down" !!
● (no directional asymmetry observed for horizontal magnetic field, but about 2σ "zero-nonzero" effect)

– It is not expected in the Standard Physics

– experiment was calibrated, no evidence for systematic effects

– can be explained by $n - n'$ oscillation if the Earth has the mirror magnetic field with a significant vertical component, with $B' \sim 0.1$ G , and $\tau_{nn'} = \epsilon^{-1} \sim 10$ s – Mirror matter at the Earth ?

– New measurements are needed with bigger statistics (DUSEL?)

– Look for a siderial (or other) variations (testing B' direction)

– Find resonant B (~ 0.1 G) and test neutron regeneration $n \to n' \to n$

Spin dependent fifth forces

light pseudoscalar ϕ coupled with the nucleons of both sectors:

$$ig_p\phi(\overline{N}\gamma^5 N - \overline{N'}\gamma^5 N') = g_p \frac{\partial_\mu \phi}{2m} \cdot (\overline{N}\gamma^\mu\gamma^5 N - \overline{N}'\gamma^\mu\gamma^5 N')$$

Inhomogeneity of ϕ $\rightarrow$ *spin-dependent forces* $\frac{\nabla\phi}{2m} \cdot (\overline{N}\Sigma N - \overline{N}'\Sigma N')$

If ϕ has also scalar couplings $g_s\phi(\overline{N}N + \overline{N'}N')$ Moody & Wilczek '84

then interaction potentials between two bodies are

(monopole)^2: $$V_{mm}(r) = -\frac{g_s^{(1)} g_s^{(2)}}{4\pi r} e^{-m_\phi r}$$

monopole-dipole : $$V_{md}(r) = \pm \frac{g_s^{(1)} g_p^{(2)} (\boldsymbol{\sigma}\cdot\boldsymbol{n})}{8\pi m_2} \left[\frac{m_\phi}{r} + \frac{1}{r^2}\right] e^{-m_\phi r}$$

Therefore the Earth could be the source of $\nabla\phi$:
spin-dependent potential 13 orders of magnitude weaker than gravity would suffice

... but the source of $\nabla\phi$ could be some unknown matter with cosmological distribution