Neutron oscillations to parallel world:

earlier end ton the cosmic ray spectrum ?

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Content

- Parallel/twin/mirror world (or worlds)
- Interactions and Mixings between ordinary particles and their twins:
  B & L violating mixing
- Neutron - mirror neutron oscillation $n \to n'$:
  B-violation in 1 second ?
- $n - n'$ oscillation and UHECR:
  an earlier end to the cosmic ray spectrum
- Twin matter as dark matter and origin of baryon asymmetries:
  Co-genesis of ordinary and mirror matters via B-L and CP-violating interactions between two sectors
- Cosmology of parallel dark matter:
  implications for the CMB, LSS, galaxy structure, etc.
- Summary:
  consequences for particle phenomenology and cosmology

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*

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

Following works on "Mirror" World

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

"... the books there are like our books, only the words go the wrong way..."

Mirror fermions cannot have our EM & Strong Ints. — Kobzarev et al. '66

hidden sector similar to our but not exact copy — Nishijima, Saffouri '64

Mirror matter (invisible stars) — Blinnikov, Khlopov '83

Two SM's: $SU(3)\times SU(2)\times U(1) \;\times\; SU(3)'\times SU(2)'\times U(1)'$ — Foot et al. '91

- 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!

- Asymmetric mirror world: spont. broken parity $G \leftrightarrow G'$:

$$\langle\phi'\rangle \gg \langle\phi\rangle \quad \longrightarrow \quad (M_W' \gg M_W)$$

Lepton/quark masses rescale $\propto M_W'/M_W$, neutrino masses $\propto (M_W'/M_W)^2$, but baryon masses $\propto \Lambda'/\Lambda \sim (M_W'/M_W)^{1/3}$ – *Asymmetric DM, sterile ν WDM, Strong CP & axidragon, SUSY little Higgs – accidental global $U(4)$, etc.*

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)
$\tilde{q}_R = (\tilde{u}, \tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$	|	$\tilde{q}'_R = (\tilde{u}', \tilde{d}')^t_R$	$\tilde{l}'_R = (\tilde{\nu}', \tilde{e}')^t_R$
$\tilde{u}_L \;\; \tilde{d}_L$	$\tilde{e}_L$	|	$\tilde{u}'_L \;\; \tilde{d}'_L$	$\tilde{e}'_L$

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

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

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* ($T'/T = T'_{\rm CMB}/T_{\rm CMB}$ *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)

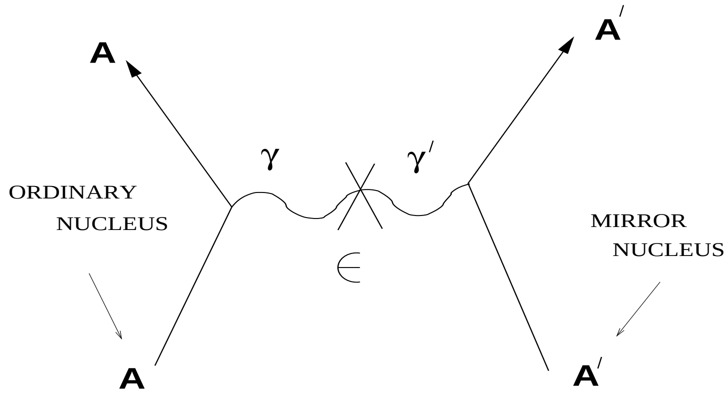
Possible interactions between O & M particles (besides gravity) can be induced at tree level by exchange of extra gauge singlet particles or common gauge fields acting with both O & M particles ... and these interactions can lead to particle mixing phenomena between O & M sectors: any neutral particle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

- $\pi^0 - \pi^{0\prime}, \quad \rho^0 - \rho^{0\prime},$ *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 $\quad (\pi^0 - \pi^{0\prime} \to 2\gamma'$ invisible)

- $K^0 - K^{0\prime}$ *etc.*

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

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

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

● *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: custodial symmetry, minimality of flavor violation in SUSY (SSB terms allignment), anomaly cancellation for chiral $SU(3)_{\rm fl}$, Vanishing D-term, etc.*

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

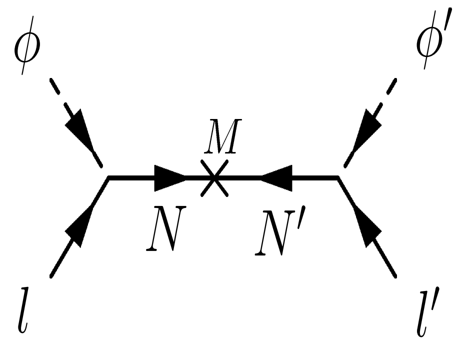
Lepton number violating interactions: $D = 5$ operators

- 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*



All are generated via "R-handed" neutrinos N
– extending seesaw mechanism

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

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

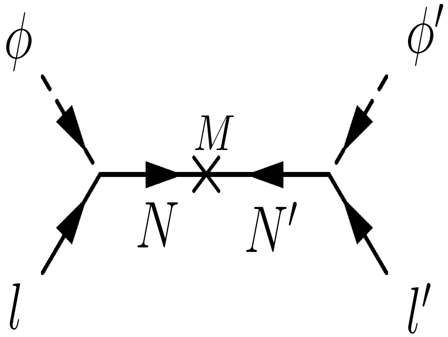
M-parity: $A' = A^*, \quad D = D^\dagger$
D-parity: $A' = A, \quad D = D^t$

- $v' = v$: $\quad m_{\nu'} = m_\nu$ *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



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

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

  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

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

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

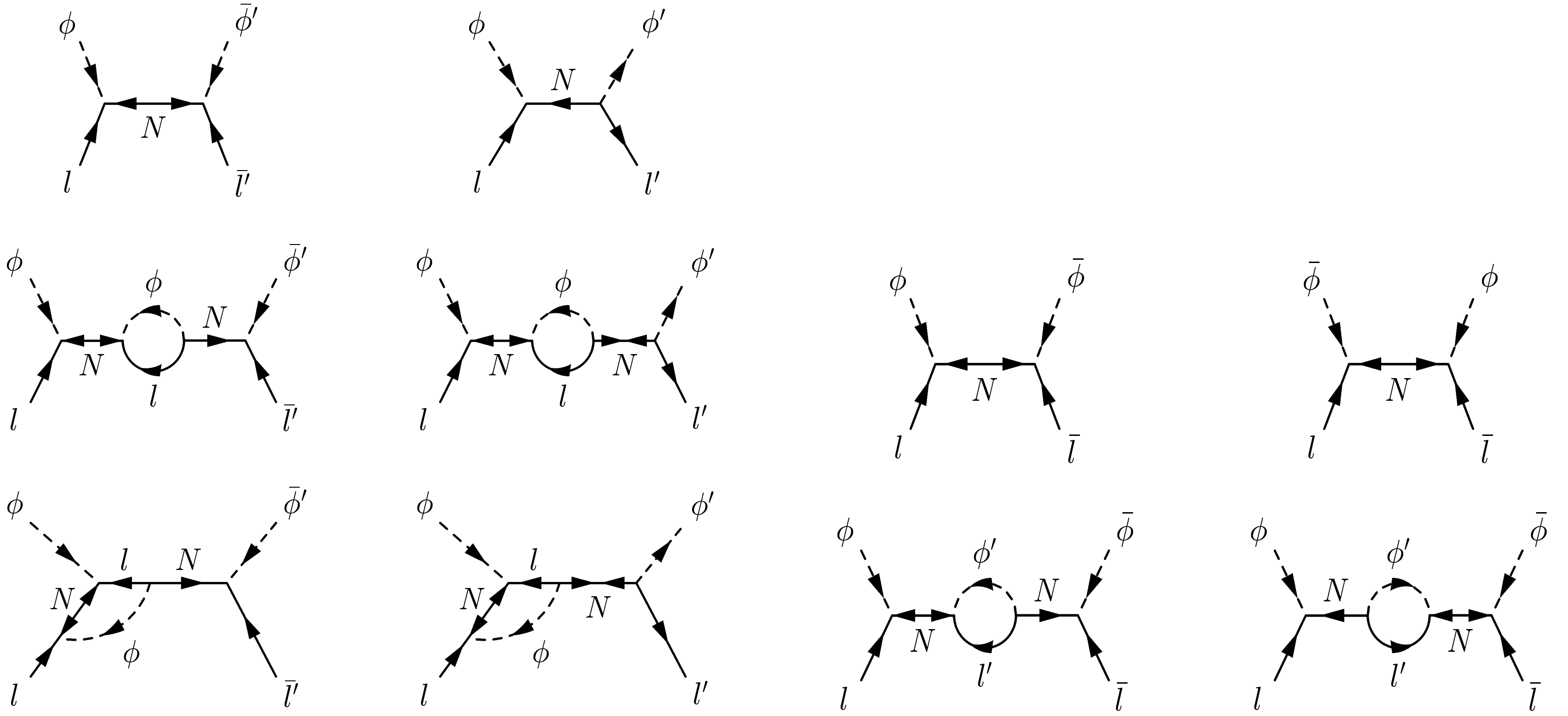
- The same reactions generate B$'$-L$'$ $\neq$0 ($\to$ B$'\neq$0) in dark sector.

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)



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

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

- 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*

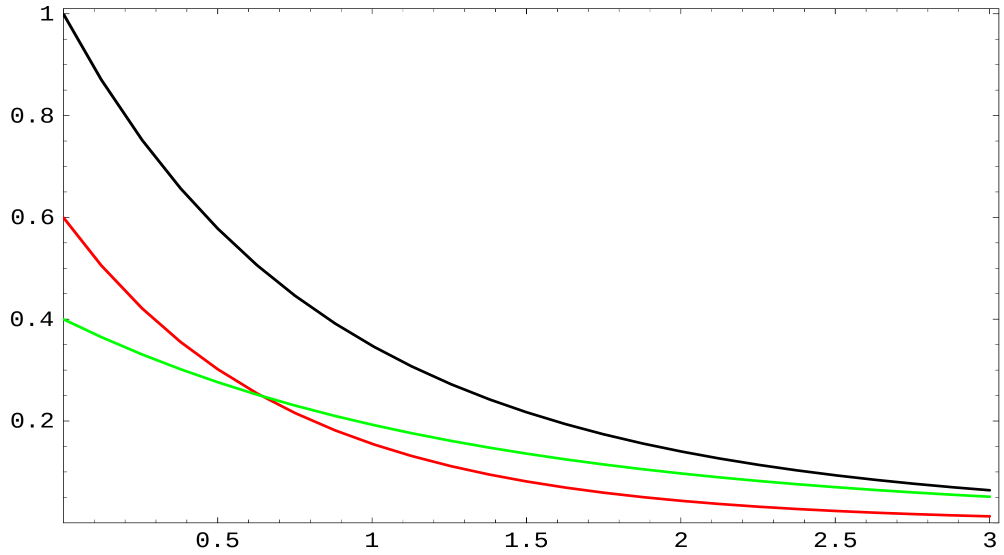
$Y_{BL}^{(0)} \sim 10^{-9}$ at $M \sim 10^{12}$ GeV, $T_R \sim 10^9$ GeV, $\varepsilon_{CP} \sim 10^{-3}$.

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

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

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

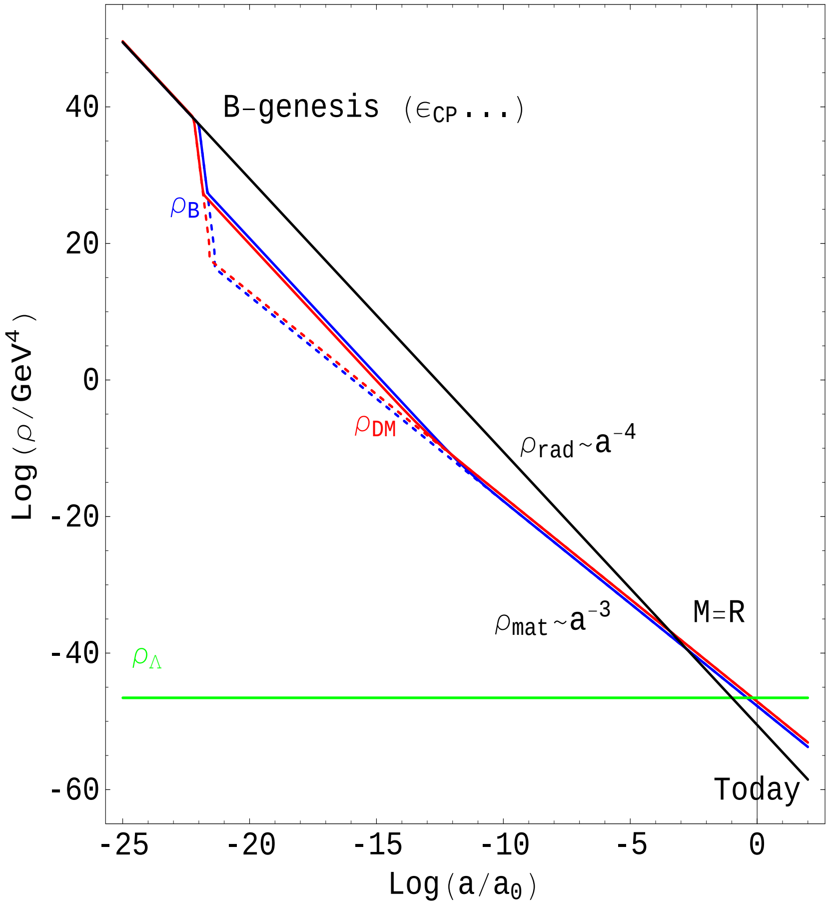
$D(k) < D(k') \approx 1$: lower limit $\dfrac{\Omega'_B}{\Omega_B} = \dfrac{D(k')}{D(k)} > 1$ Z.B. '03



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

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

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

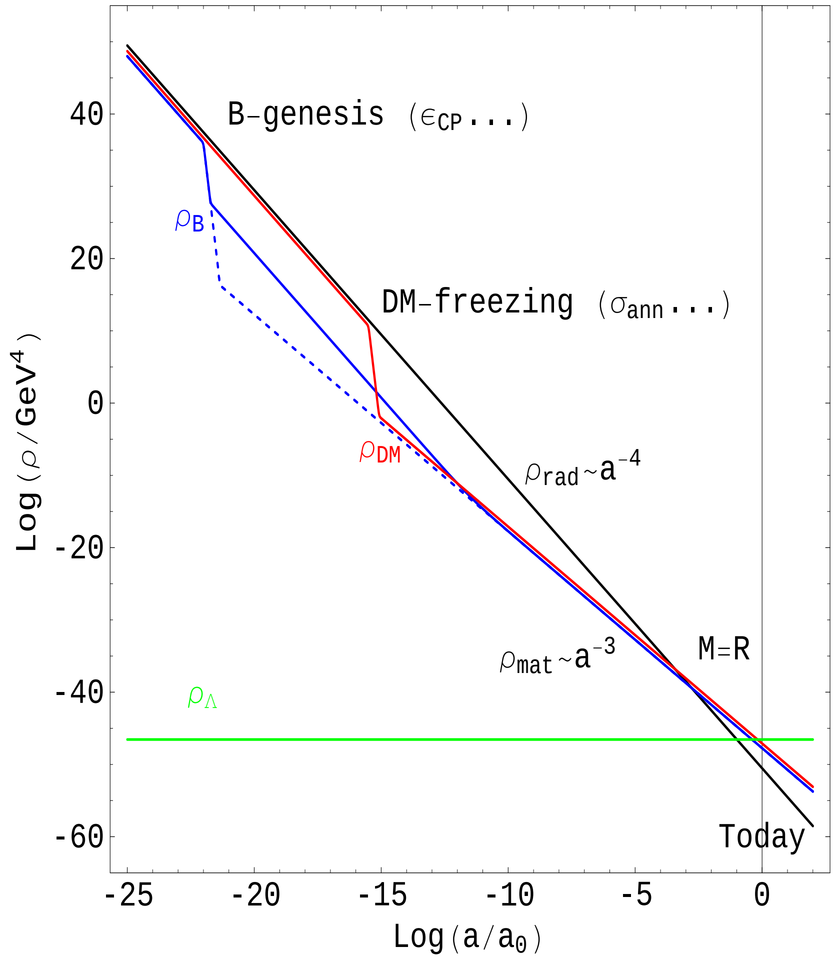


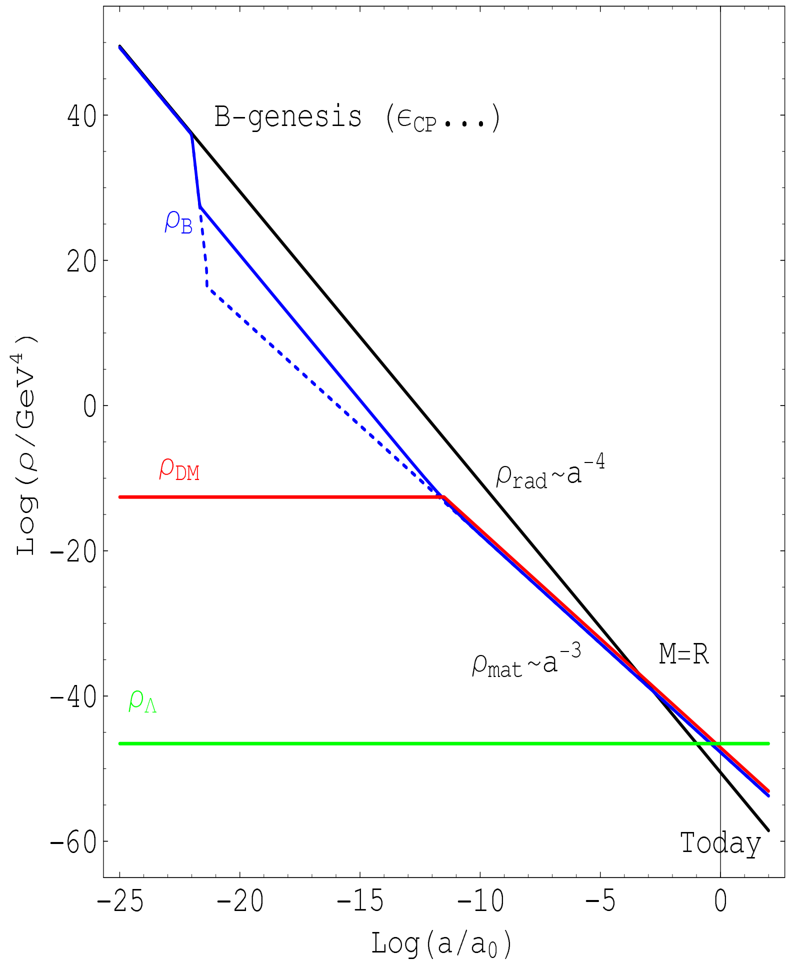
Observable and dark matter co-genesis: both based on Baryon asymmetry ?

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

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





Evolution of the Baryon number (···) 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

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 would happen 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, WDM (sterile ν), axion, 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: $\Omega_D/\Omega_B \simeq 5$?

- 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 $M_X =$? , $n_X =$?

– too 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 ...

– 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?

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

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

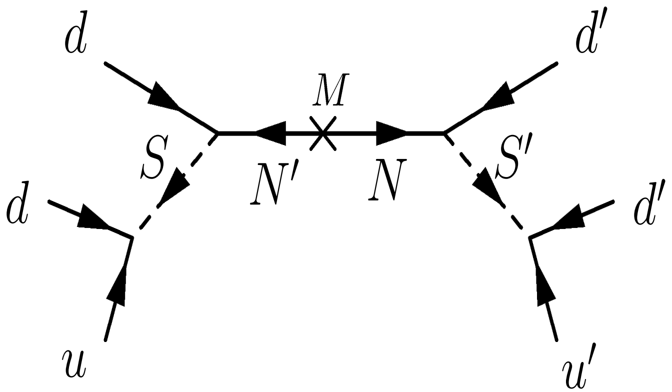
induces he neutron - mirror neutron mass mixing $\epsilon\,(\overline{n}n' + \overline{n}'n)$,

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

- *C.f. operators* $\frac{1}{M^5}(udd)^2$ $(\Delta B = 2)$, $\frac{1}{M^5}(u'd'd')^2$ $(\Delta B' = 2)$

inducing neutron - antineutron mixing Kuzmin '70, Glashow '79

Marshak & Mohapatra '80



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)

$\mathcal{M} \sim (M_S^4 M_N)^{1/5} \sim 10$ TeV *– can be achieved in Seesaw*

if $M_S, M_N \sim 10$ TeV, *or* $M_N \sim 10^{12}$ GeV *and* $M_S \sim 100$ GeV

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.

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 $n - n'$ mixing $\epsilon\,(\overline{n}n' + \overline{n}'n)$ *with* $\epsilon \sim \left(\frac{10\,\mathrm{TeV}}{\mathcal{M}}\right)^5 \cdot 10^{-15}\,\mathrm{eV}$

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

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

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

$n - n'$ allowed to be fast, $\tau_{nn'} \sim 1\mathrm{s}$ ... faster then neutron decay !

... 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

!!! N.B. Nuclear Stability

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

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

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

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

Neutron - Mirror neutron oscillation in external fields

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

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

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

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

$$H = \begin{pmatrix} \pm 2\omega & \epsilon \\ \epsilon & 0 \end{pmatrix}$$

diagonal in the basis $(\psi_+, \psi_-, \psi'_+, \psi'_-)$

Energy gap $2\omega = |\mu B| = B[\mathrm{G}] \times 6 \cdot 10^{-12}\ \mathrm{eV} = 9000\ \mathrm{s}^{-1}$

Oscillation probability $P_{nn'}(t) = \frac{\epsilon^2}{\epsilon^2+\omega^2} \sin^2(\sqrt{\epsilon^2 + \omega^2}\, t) \cdot \exp\left(-\frac{t}{\tau_{\mathrm{dec}}}\right)$

$\omega t \ll 1$: $P_{nn'}(t) = \left(\frac{t}{\tau_{nn'}}\right)^2$, vs. $\omega t \ll 1$: $P^{\mathrm{av}}_{nn'} = \frac{1}{2(\omega\tau_{nn'})^2}$.

$\tau_{nn'} = \epsilon^{-1}$

Experimental & astrophysical bounds

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

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

Recent Experimental search: comparing the neutron losses at small & large B

- $\tau_{nn'} > 2.7$ s FR Munich, Schmidt et al. Procs. B&L-violation'07, Berkeley
- $\tau_{nn'} > 103$ s ILL Grenoble, Ban et al. Phys.Rev.Lett. 99:161603 (2007) PDG
- $\tau_{nn'} > 414$ s ILL Grenoble, Serebrov et al. Phys.Lett. B663:181 (2008) PDG
- $\tau_{nn'} > 120$ s ILL Grenoble, Altarev et al. Phys.Rev. D 80:032003 (2009) PDG
- $\tau_{nn'} > 403$ s ILL Grenoble, Serebrov et al. NIM A611:137 (2009)

not valid if masses of n and n' states are not exactly equal, or 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.

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

4×4 Hamiltonian: oscillations and precessions ZB, EPJ C64, 421 (2009)

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

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

β angle between $\vec{B}$ and $\vec{B}'$. If $|\omega - \omega'|t \gg 1$, oscillations can be averaged,

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

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

$$\frac{P(\vec{B})+P(-\vec{B})}{2} = P_B = \frac{1+\eta^2}{(1-\eta^2)^2}P_0$$

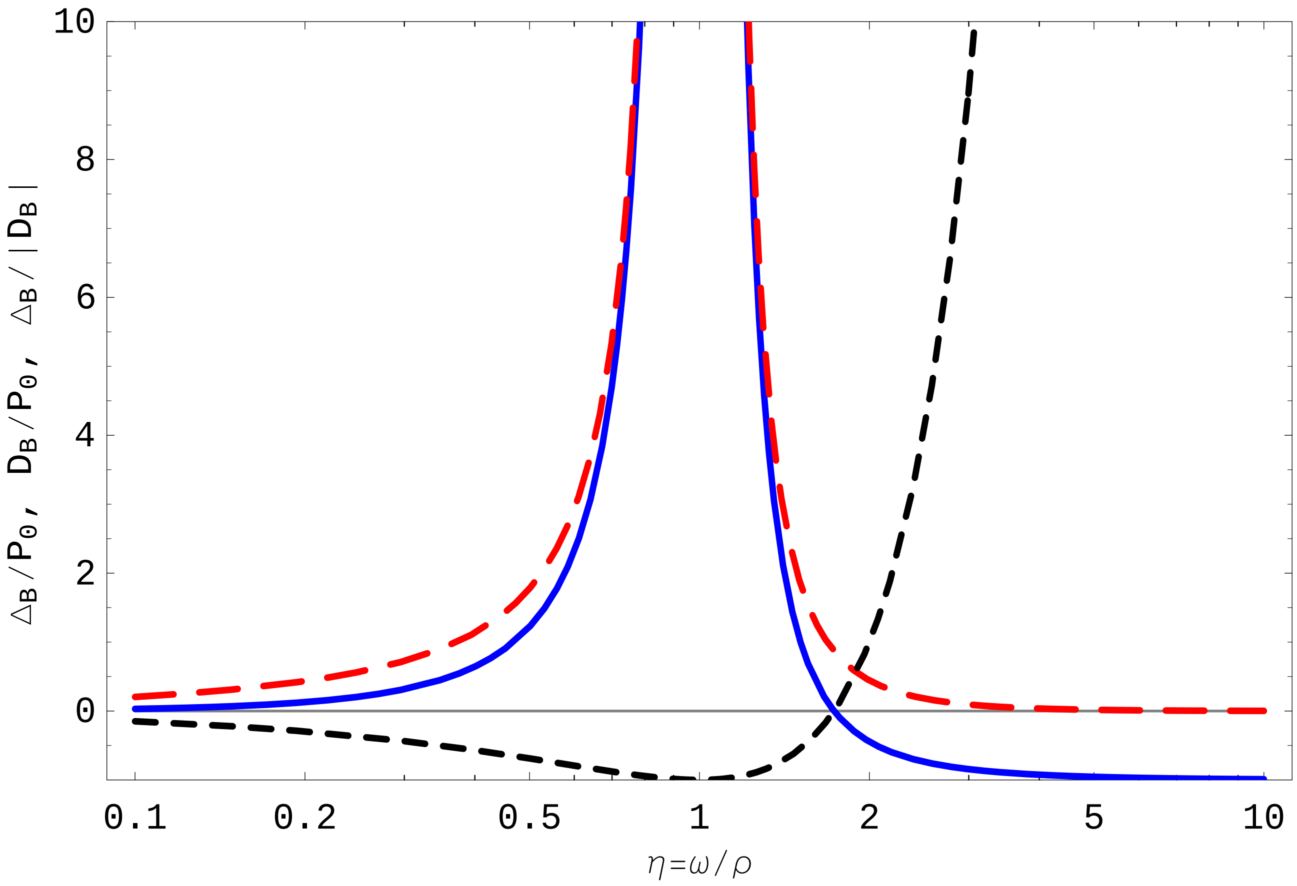
is independent of B' direction $(\cos\beta)$

$\Delta_B = P_B - P_0$ is *positive* $(P_B > P_0)$ *if* $\eta < \sqrt{3}$, *i.e.* $B < 1.7B'$

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

$D_B \neq 0$ – *hint for $n - n'$ oscillation in the presence of B'*

Comparison of observables



— Δ_B/P_0

– – D_B/P_0

- - - Δ_B/D_B

$\eta = B/B'$

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 $E_{\rm kin} < V$. i.e. $v <$ few m/s are reflected from the surface.

Thus, the UCN can be stored in the trap (e.g. beryllium or nickel). 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 $P(\vec{B})$

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

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

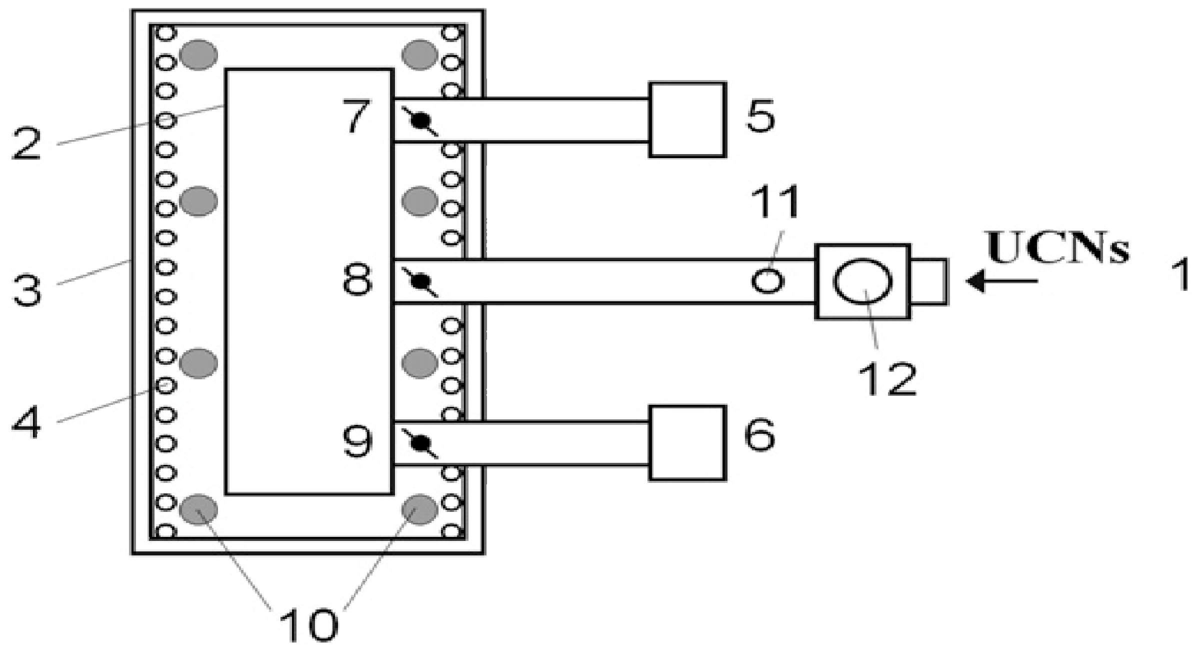
For different magnetic fields $\vec{B}_1$ and $\vec{B}_2$, all regular (B-independent) contributions as well as $N(0)$ cancel out in the ratio $\frac{N_1(t)}{N_2(t)} = \frac{N(0)e^{-\Gamma_{1\rm eff} t}}{N(0)e^{-\Gamma_{2\rm eff} t}} = e^{-(P_1 - P_2)\nu t}$

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

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

Experiment in vertical magnetic field

ILL Grenoble, Serebrov et al. 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 EDM).

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

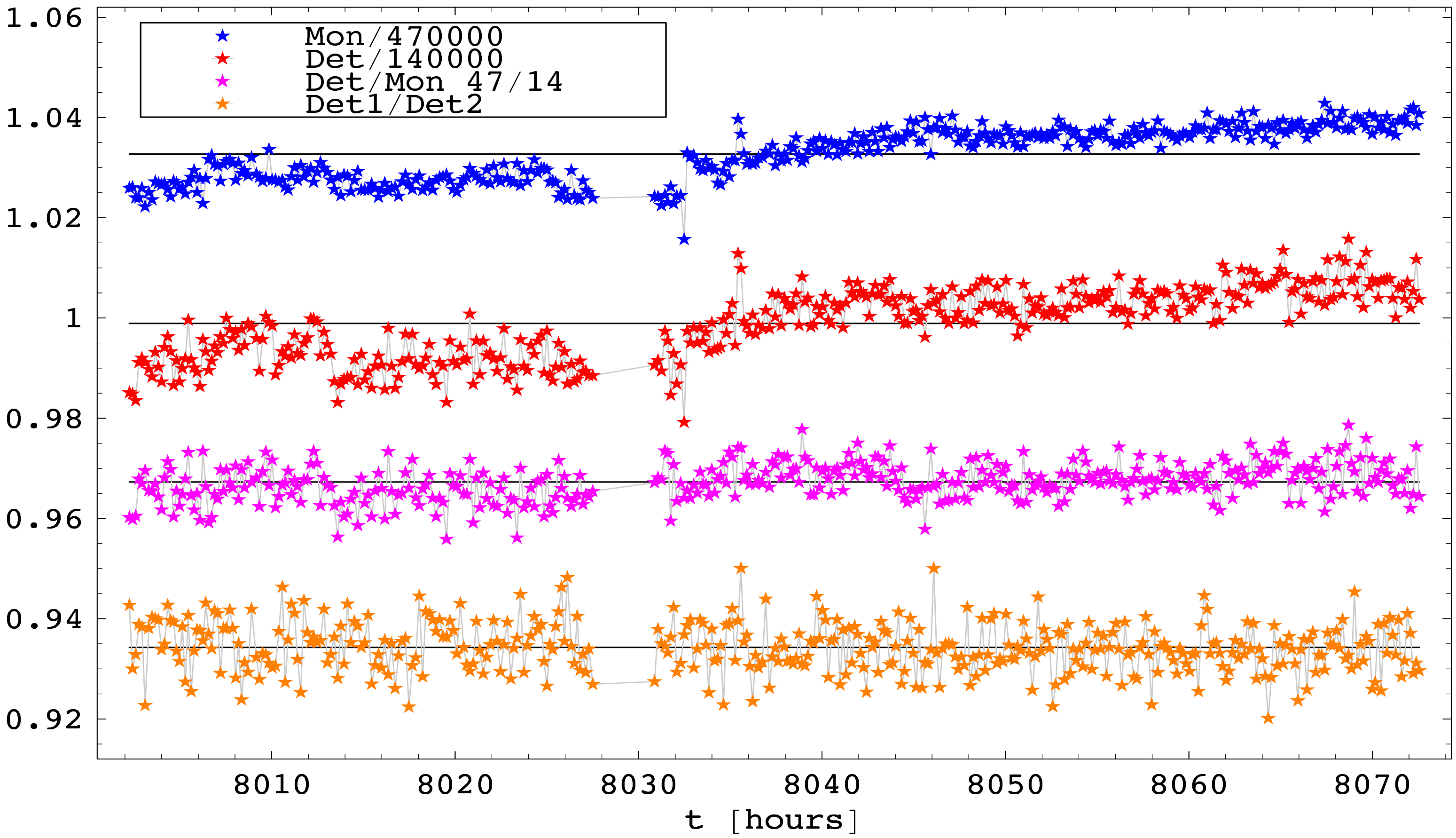
$\nu \approx 11$ s^{-1} *collision frequence,* $t_s = 370$ s *holding time,* $\nu t_s \approx 4000$

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* $\sim 2\%$

Experiment in vertical magnetic field

Z.B. and Nesti, 2012



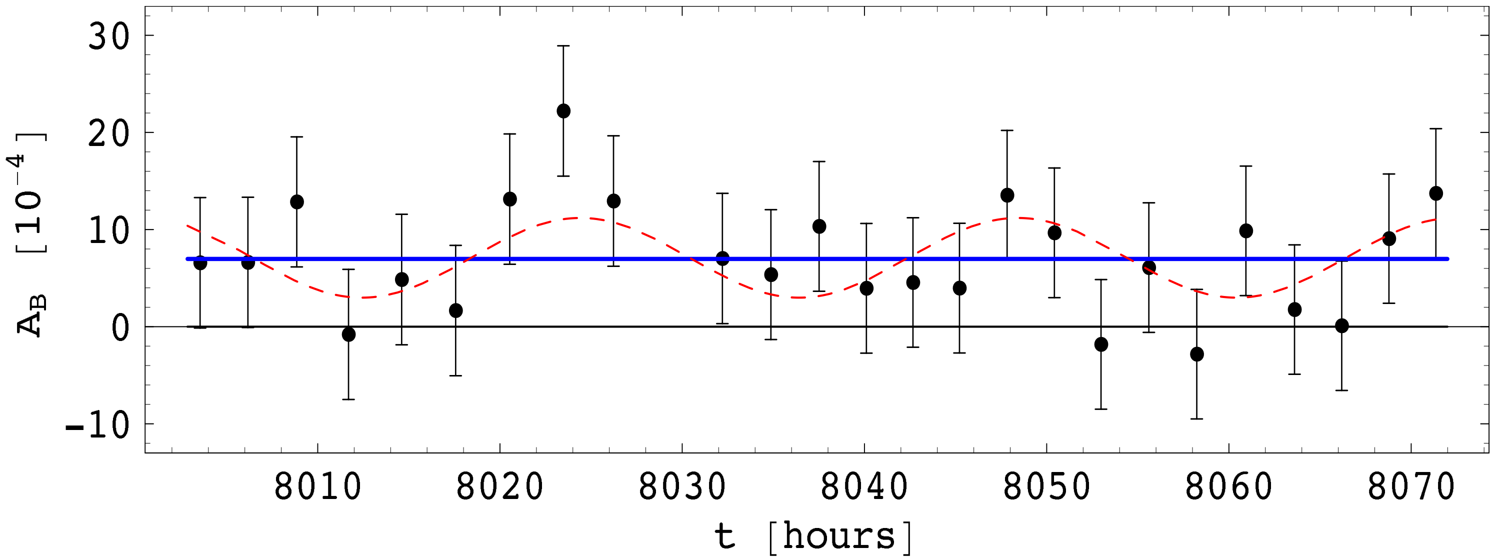
Det/Mon = Const $\chi^2_{\rm dof} = 1.4$

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

Measurements in vertical magnetic field

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

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



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

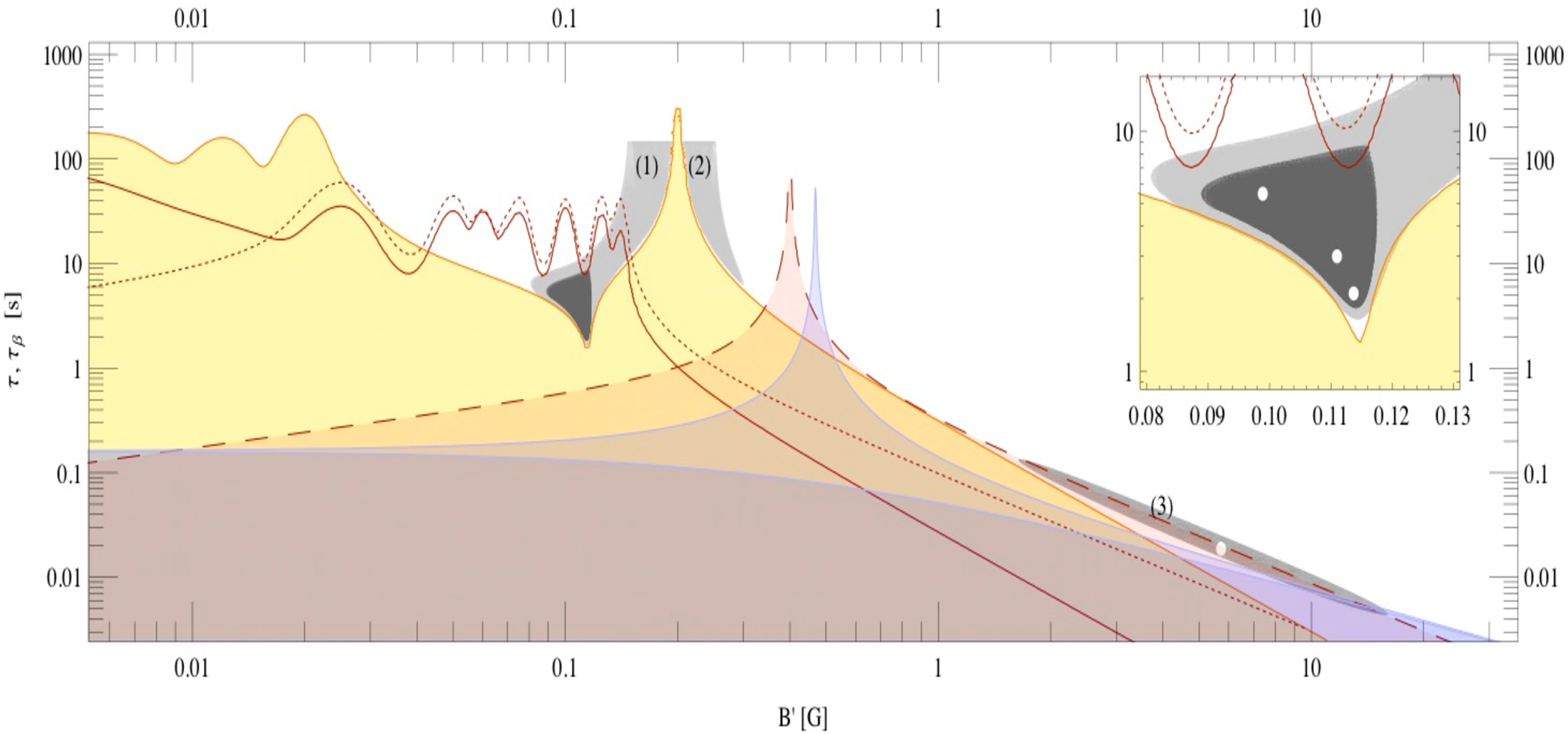
$[D_B \cos\beta_V] = (1.6 \pm 0.3) \times 10^{-7}$

– calibration in free flow mode show no evidence for systematic effects

- at $B \simeq 0.4$ G : $A_B = (-0.3 \pm 2.4) \times 10^{-4}$ $(\chi^2_{\rm dof} = 1.7)$

$[D_B \cos\beta_V] = (-0.06 \pm 0.82) \times 10^{-7}$

Global analysis



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

Can the Earth possess mirror magnetic field?

.... Why not if mirror matter is dark matter ...

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 small, within the present experimental reach. However, it 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.). These processes 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 $n - \tilde{n}$ oscillation should also exist at the experimentally accessible level – (see talk of Y. Kamyshkov) with the relevant cutoff scale $\mathcal{M}_{n\tilde{n}} > 300$ TeV and thus $\tau_{n\tilde{n}} \sim 10^9$ 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 spectrum above the GZK cutoff and their correlation with the far distant astrophysical objects (BL Lacs, GRB's etc.)* *ZB and Gazizov, ArXiv*
- *Effects for the neutrons from the solar flares* *Mohapatra, Nasri, Nussinov '05*

GZK end of the UHECR

K. Greisen, End to the cosmic ray spectrum?, Phys. Rev. Lett. 16, 748 (1966).
G. Zatsepin, V. Kuzmin, Upper limit of the spectrum of cosmic rays, JETP Lett. 4, 78 (1966).

GZK cutoff:

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

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

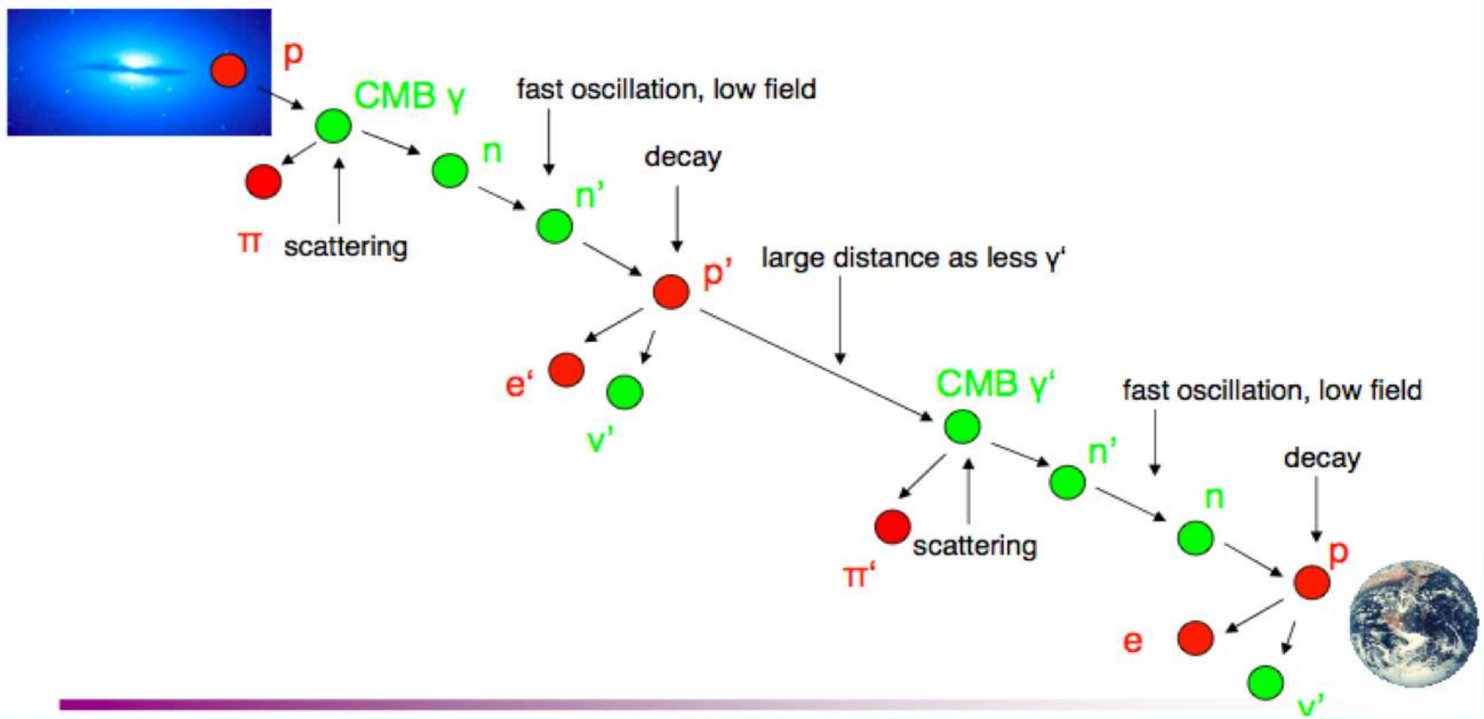
Neutron decay: $n \to p + e + \bar{\nu}_e$, $\quad l_{\rm dec} = \left(\frac{E}{100 \text{ EeV}}\right)$ Mpc

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

Presence of $n - n'$ oscillation with $\tau_{\rm osc} \ll \tau_{\rm dec}$ drastically changes situation

Z. Berezhiani and L. Bento, Fast neutron – Mirror neutron oscillation and ultra high energy cosmic rays, Phys. Lett. B 635, 253 (2006).
Z. Berezhiani, A. Gazizov, Neutron Oscillations to Parallel World: Earlier End to the Cosmic Ray Spectrum?, arXiv:1109.3725 [astro-ph.HE].

$n - n'$ oscillation and propagation of UHECR



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

Transport equation

Evolution of four number densities $U_i = U_i(E,t)$, $\quad i = p, n, p', n'$

$$\frac{\partial U_i}{\partial t} = Q_i - 3H(t)U_i + \frac{\partial[E(H(t)+\beta_i)U_i]}{\partial E} + \frac{mD_{ij}}{E\tau_{\rm dec}}U_j - R_i(E,t)U_i$$
$$+P_{ij}(E)\int_E^\infty d\tilde{E}W_{jk}(E,\tilde{E},t)U_k(\tilde{E},t)$$

Generation functions: $\quad Q_p(E,t) \propto E^{-\gamma_g} z^m \Theta(z_{\rm max} - z)\Theta(E_{\rm max} - E)$

Neutron decay terms: $\quad D_{pn} = D_{p'n'} = 1,\ D_{nn} = D_{n'n'} = -1$

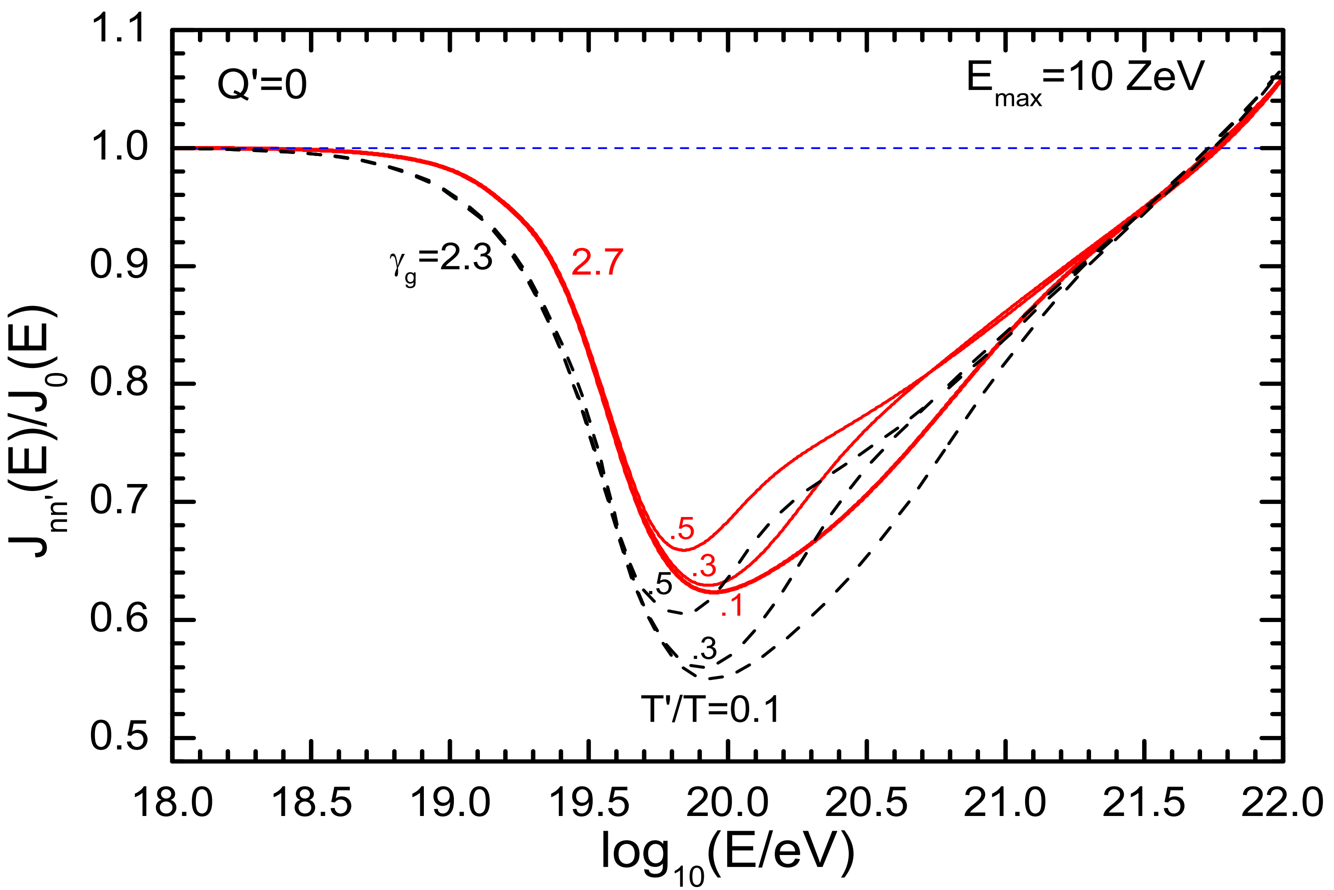
$n - n'$ *oscillation:* $\quad P_{pp} = P_{p'p'} = 1,\ P_{nn} = P_{n'n'} = 1 - P_{nn'},$

$$P_{nn'}(E) = P_{n'n}(E) = \frac{1}{2[1+(\omega\tau_{\rm osc}E/m_p)^2]} = \frac{1}{2+q(E/100\ {\rm EeV})^2},$$

$$q = 0.5 \times \left(\frac{\tau_{\rm osc}}{1\ {\rm s}}\right)^2 \times \left(\frac{\mathfrak{B}-\mathfrak{B}'}{1\ {\rm fG}}\right)^2$$

$\omega = \frac{1}{2}|\mu_n(\mathfrak{B} - \mathfrak{B}')|$, $\mathfrak{B}$ *and* $\mathfrak{B}'$ *are ordinary and mirror cosmological transverse magnetic fields.*

$n \to n'$ and modification of UHECR spectrum

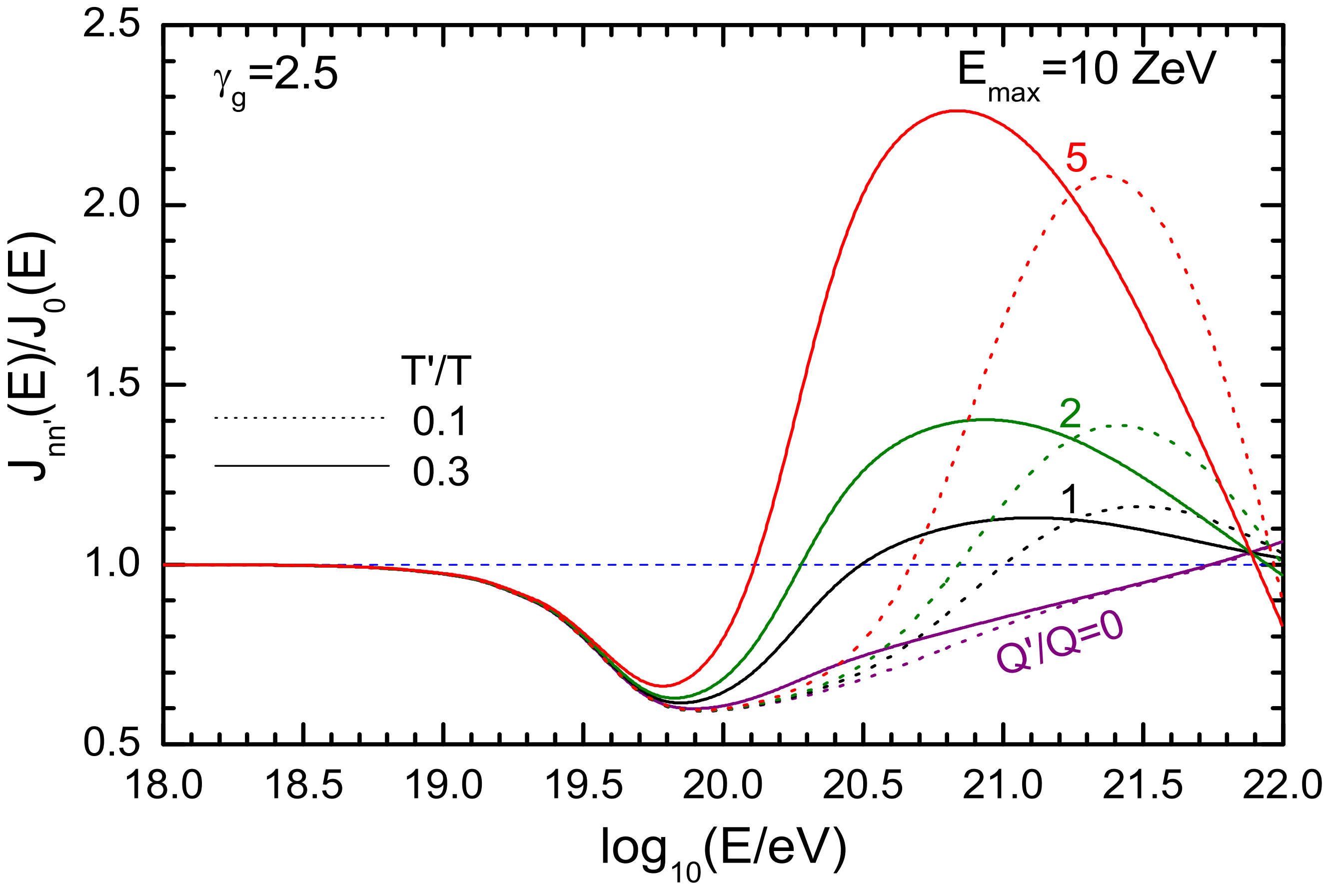


Deformation of UHECR flux relative to the standard GZK prediction in the absence of mirror sources ($Q' = 0$)

Robust in Energy range $E = 10 - 100$ EeV

Almost independent from the generation spectral index γ_g, on mirror CMB temperature (T'/T), etc.

$n \to n'$ and modification of UHECR spectrum



Deformation of UHECR flux relative to the standard GZK prediction

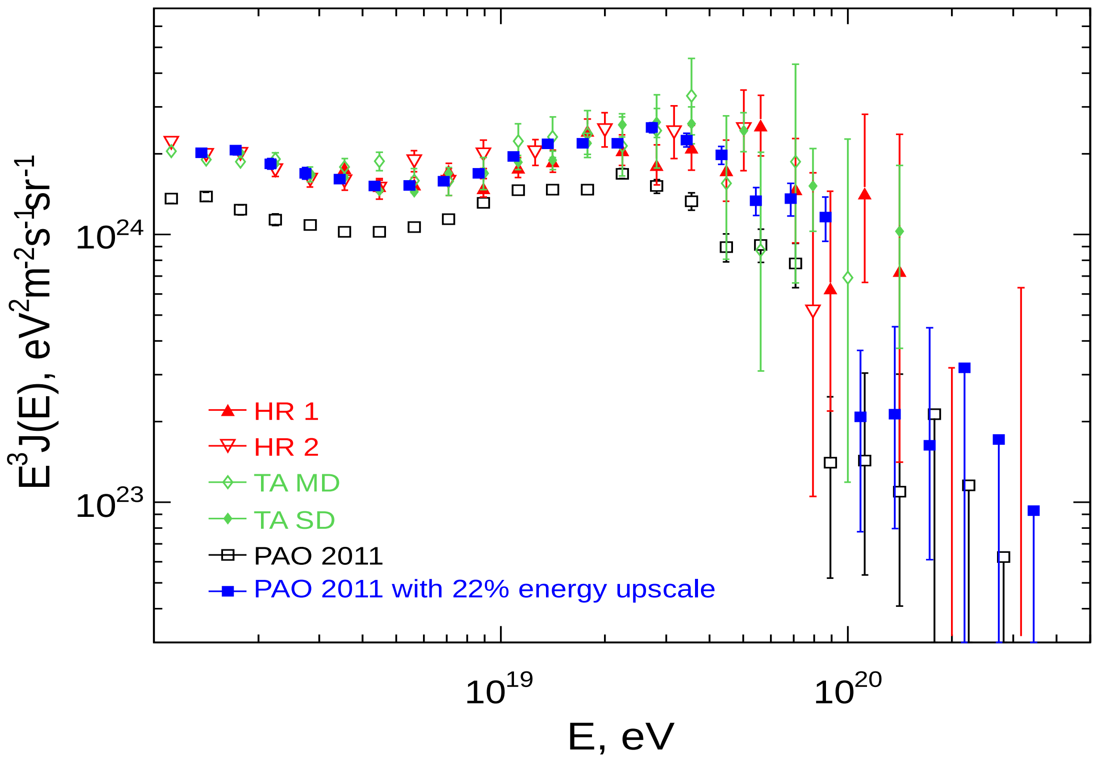
Universal in Energy range $E = 10 - 100$ EeV

But at energies $E > 100$ EeV strongly depends on

mirror CMB temperature ($T'/T < 0.3$)

and intensity of mirror sources ($Q'/Q = 0, 1, 2, 5$)

Pierre Auger *vs* HiRes and TA



Overall UHECR flux of Auger contradicts to the flux of HiRes and TA

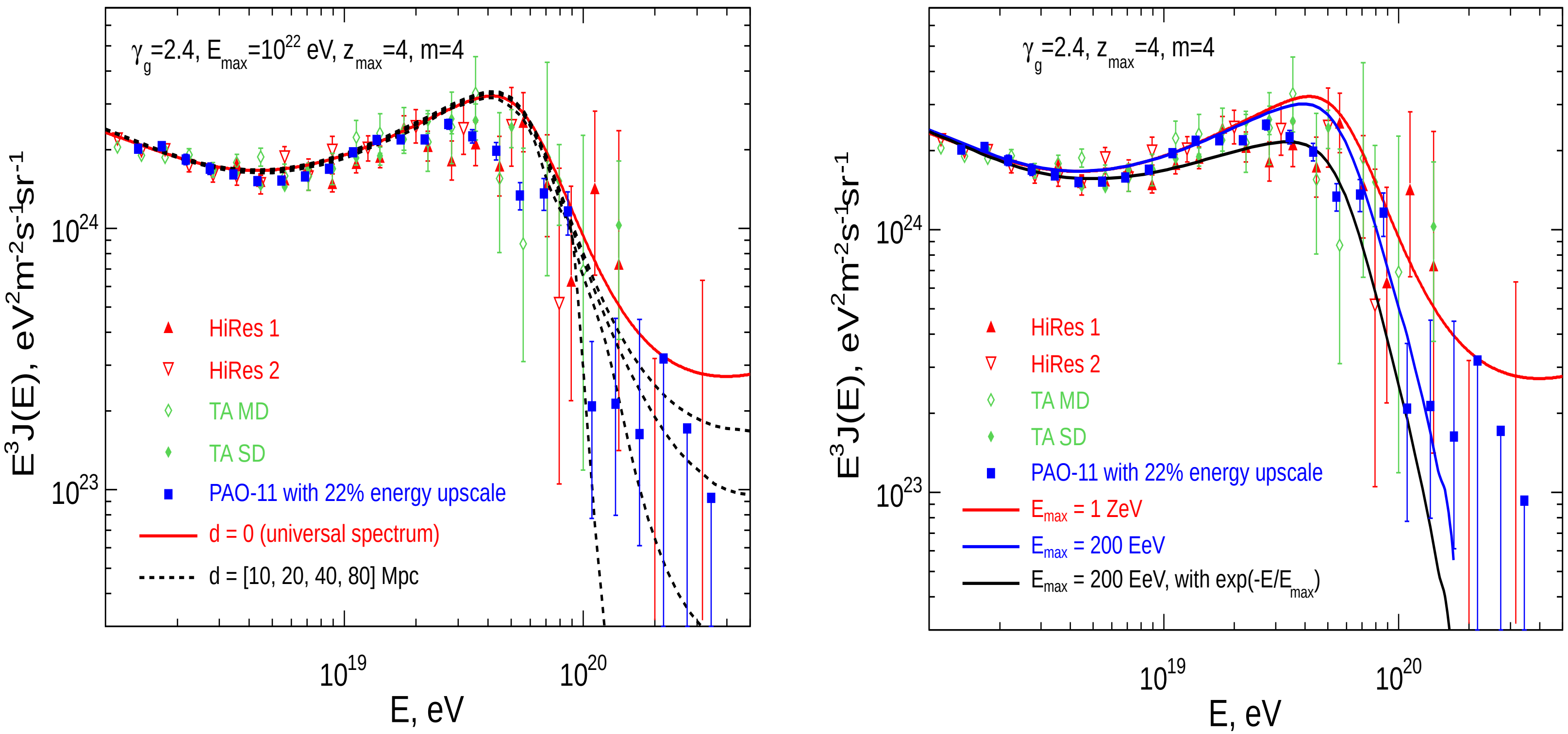
is lower by a factor ~ 2

as well as to the position of the "dip" due to e^+e^- production

but becomes consistent if Auger energies are upscaled by 20-25%

Auger "official" systematic error 22%

Auger data *vs* GZK cutoff



Auger data upscaled by 22% are consistent also to e^+e^- dip

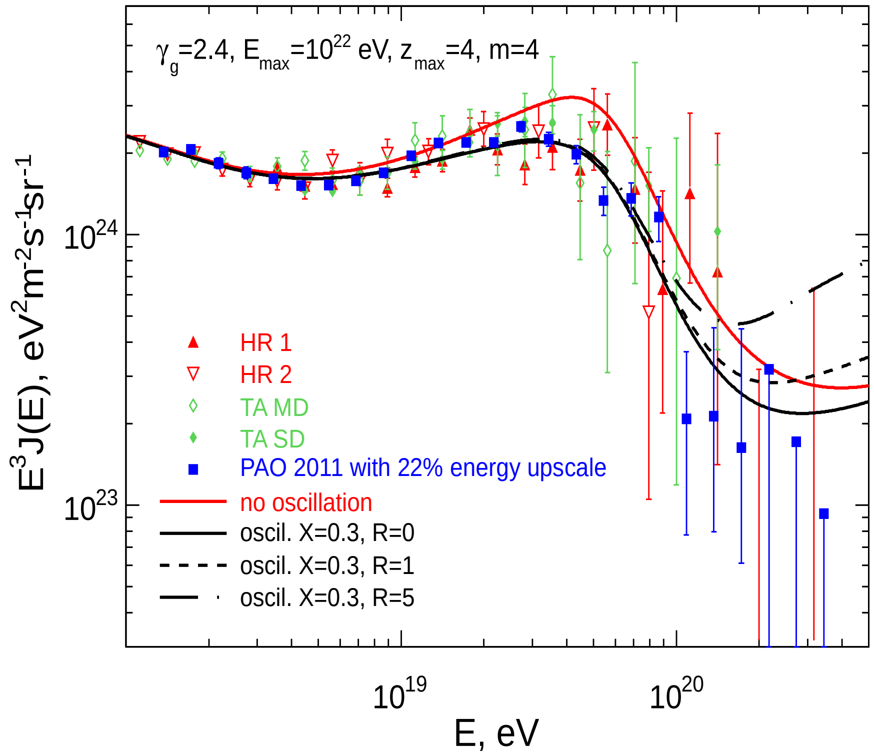
But indicate earlier cutoff of UHECR spectrum than predicted by GZK

$E^{\rm cut}_{\rm PAO} \simeq 30$ EeV *vs* the GZK prediction $E_{\rm GZK} \approx \frac{m_\pi m_p}{2\varepsilon_\gamma} \simeq 60$ EeV

Cannot be explained by increasing the distance to sources (left panel)

or by lowering maximal acceleration energy of sources (right panel)

$n - n'$ oscillation and the UHECR spectrum



UHECR flux with $n - n'$ oscillation relative to the standard GZK prediction (normalized to "dip" model) for different intensity of mirror sources: $Q'/Q = 0, 1, 5$ $(T'/T = 0.3)$

Consistent to earlier cutoff of the UHECR spectrum

Waiting next results for cutoff profile (Auger and TA)

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

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:*

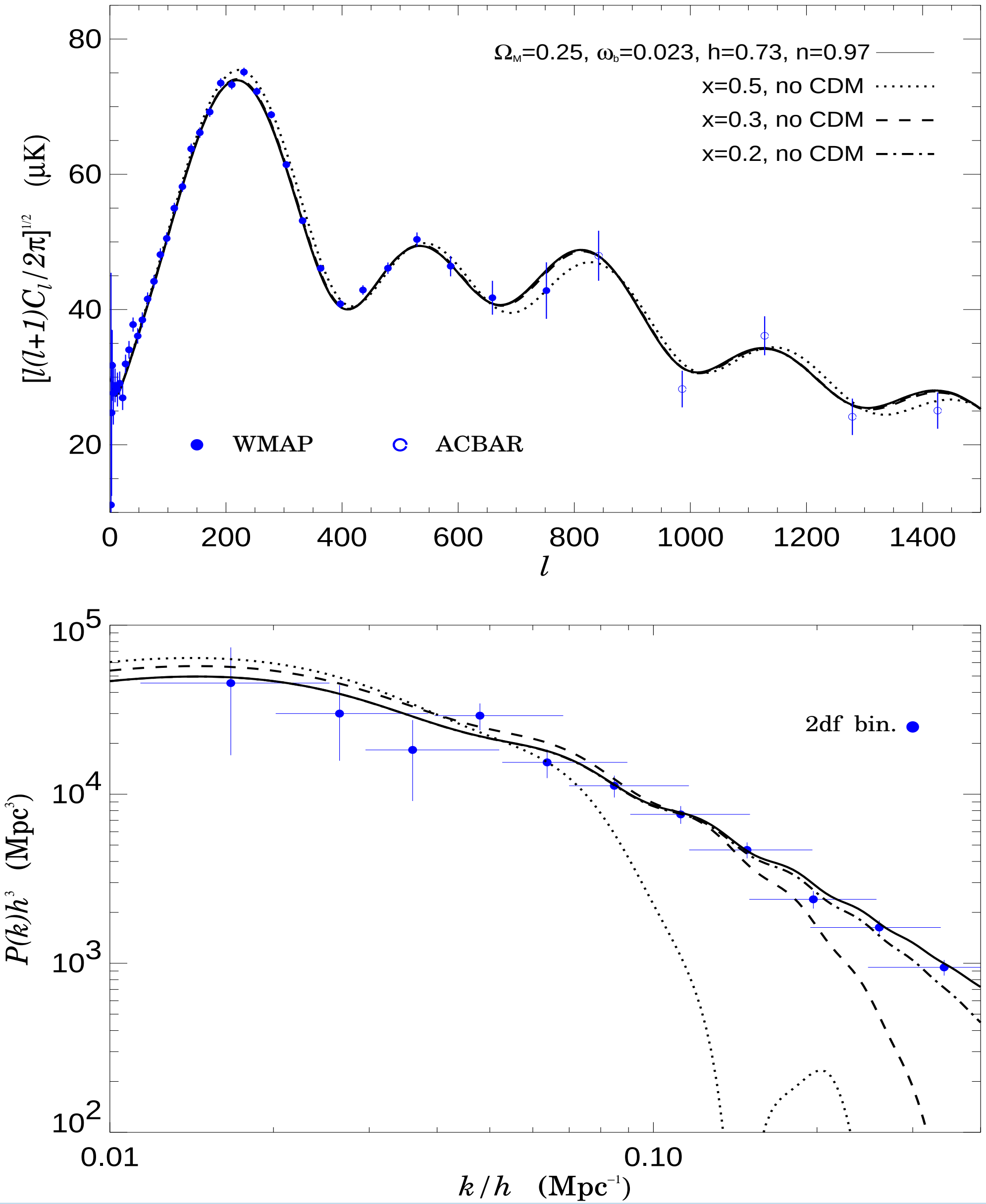
$\lambda'_S \sim 5 x_{\rm eq}^{5/4} (x/x_{\rm eq})^{3/2} (\Omega_M h^2)^{-3/4}$ *Mpc*

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

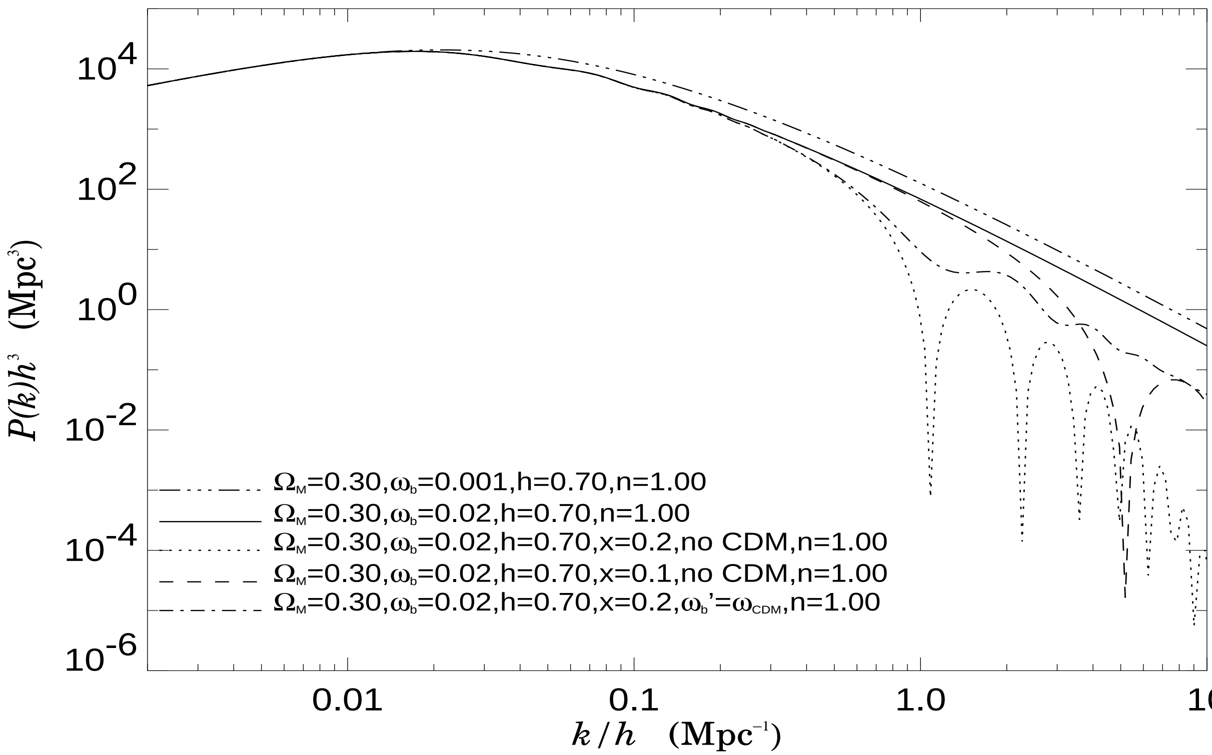


$x = T'/T < 0.3$

LSS power spectra

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

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



Concluding: *"It'll be easy enough to get through ..."*

Parallel (mirror) matter is an attractive candidate for dark matter:

- *Mirror Baryogenesis = dark matter creation:* $\Omega_{B'} \sim 5\Omega_B$
- *Nucleosynthesis:* $Y_{He'} > Y_{H'}$
- *Early decoupling:* $z'_{\rm dec} > z_{\rm dec} \simeq 1100$ *... CMB and large scale structures*
- *Mirror dark matter in Galaxies: Halo, Machos, dark supernovae, ...*
- *Dark matter search ...*
- Ordinary particle - mirror particle oscillations: *in particular*

neutron - mirror neutron oscillation – a window to parallel world ?

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

But knowledge is also important .... so new experiments are welcome:

- *search for* $n \to n'$ *oscillation and* $n \to n' \to n$ *regeneration,* *or* $\mathrm{H} \to \mathrm{H}'$ + *regeneration for hydrogen*
- *also* $n \to \tilde{n}$ *or* $\Lambda \to \tilde{\Lambda}$, $\mathrm{H} \to \tilde{\mathrm{H}}$ *etc.*
- *Lorentz-violation in the neutron precession – (corrections to* μ *that resonantly depend on magnetic field value and direction)*
- *neutrons from solar flares, neutrons in cosmic rays, compact neutron stars, etc*

– Need for new exps. with bigger statistics and careful systematics

~ 100 kEuros for new experiments at the ILL (or somewhere else) ?