# Testing Baryon Number Violation with Neutrons

Zurab Berezhiani
Università di L'Aquila and LNGS Gran Sasso, Italy

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# Baryon number **cannot** be violated !!!



## Main argument: Existence of Matter

*Matter stability* $=$ $B$*-conservation*

Paradigm: *( prophets Friedman and Gamov )*

Initially after Big Bang *(divine singularity)* was *(an excess of)* matter $(p, e)$

$B$ violated $\rightarrow$ processes $p \longrightarrow e^+\pi^0$, $p \longrightarrow e^+\gamma$, *etc.*

... we would get a lot of positronium ! But only for a while ....

Finally all would annihilate into light ( $e^+e^- \rightarrow \gamma\gamma$ )

Msg for students:

$\not{B}$ annihilation operator for the Universe

# Baryon number must be violated !!!



## Main argument: Existence of Matter

*Matter creation* $= B$*-violation*

Paradigm: *( prophets Sakharov and Kuzmin )*

Initially after Big Bang *(post-inflation heating)* was light (*and* $\gamma\gamma \to e^+e^-$)

... there were a lot of positrons ! But only for a while ....

$B$ violated $\to$ processes as $X \to p + e$ , $X \to \bar{p} + e^+$,
with *(if also CP violated)* $\Gamma(X \to p + e) \neq \Gamma(X \to \bar{p} + e^+)$, *etc.*

Finally would create *(an excess of)* matter $(p, e)$

Msg for students:
$\not{B}^\dagger$ creation operator for the Universe

# Stellar War of Principles



*Prophets against Prophets,   Olimpics against Titans ...*

## What to do ?   How to decide ?

Solomonic solution:   $B$ is violated but also conserved ...

Initially, in the Early Universe, $B$-violation was very efficient fast and fastly created primordial baryon asymmetry *(quick birth of the Matter)*

*Good time for theorists to built GUTs, baryogenesis models, etc.*

Finally, in todays Universe, $B$-violation is so inefficient that it destroys the matter *very* slowly *(long live to the Matter)*

*Hard times for experimentalists to search proton decay, etc.*

Msg for students:

$\not{B}$ & $\not{B}^\dagger$  annihilation and creation operators both are there

... and work hard to find out both !

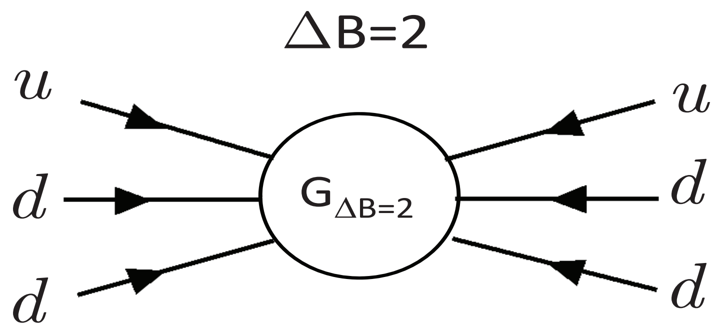
# $\Delta B = 2$: Neutron–Antineutron Oscillation



*Neutral particles coincide to their antiparticles: neutron=antineutron* Majorana, 1937

*Now it's wrong for neutrons – but probably OK for the neutrinos ....*

*any neutral particle, elementary or composite, can mix its own (mass degenerate) antiparticle: neutron can be mixed to antineutron* Kuzmin, 1970




- baryon - antibaryon mixings *($n - \tilde{n}$, $\Lambda - \tilde{\Lambda}$ etc.)*

  $G_{\Delta B=2}(udd)(udd)$, six-fermion interaction, $G_{\Delta B=2} = \frac{1}{M^5}$,

  $M$ effective cutoff scale (= scale of new physics beyond SM)

$n \longrightarrow \tilde{n}$ **Oscillation** but $\tau_{n\bar{n}} > 10^8$ s vs. $\tau_{n \to pe\tilde{\nu}} \sim 10^3$ s

# Neutron - antineutron oscillation in external fields

Effective (non-relativistic) $4 \times 4$ 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 $V_{\rm g}^{\tilde{n}} = V_{\rm g}^{n}$, but maybe not really so precisely ?
- 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 $\omega t \ll 1$: $P_{n\tilde{n}}(t) = (t/\tau_{n\tilde{n}})^2, \quad \tau_{n\tilde{n}} = \epsilon^{-1}$

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

# Neutron - antineutron mixing



- $n - \tilde{n}$ oscillation in vacuum: maximal mixing $\theta = 45^\circ$

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

or $\epsilon \sim \left(\frac{1\,\mathrm{PeV}}{\mathcal{M}}\right)^5 \times 10^{-25}$ eV

$n \to \tilde{n}$ is much slower than neutron decay ( $\tau_{\mathrm{dec}} = 880$ s )

$$P_{n\tilde{n}}(t) = \sin^2\left(\frac{t}{\tau_{n\tilde{n}}}\right) \times \exp\left(-\frac{t}{\tau_{\mathrm{dec}}}\right) \approx (t/\tau_{n\tilde{n}})^2$$

*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

!!! N.B. Nuclear Stability

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

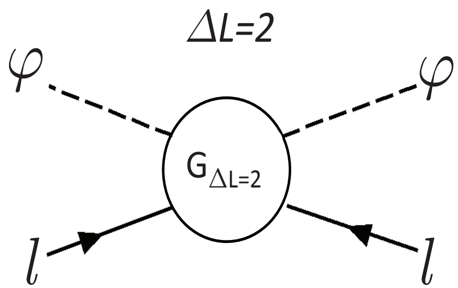
$\tau_{\mathrm{nucl}} > 2 \times 10^{32}$ yr or so ...

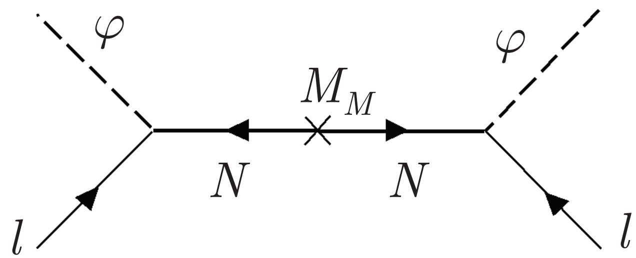
*c.f.* $\tau_p > 10^{33}$ *yr (!!) for proton decay* $(\Delta B = 1)$

*Nuclear stability bounds for free* $n \to \tilde{n}$*:* $\tau_{n\bar{n}} > 1.3 \times 10^8$ s    PDG '2011

# $\Delta L = 2$: Seesaw mechanism






- *Effective* $D = 5$ *operator* $G_{\Delta L=2}(l\phi)(l\phi)$

*Seesaw Lagrangian* $\mathcal{L}_\nu = y\phi l N \; + \; MNN$

$$G_{\Delta L=2} = y^2/M$$

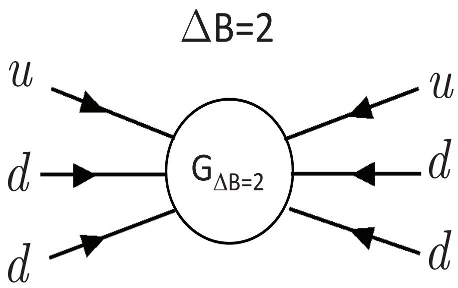
*Effective operators obtained by exchange of* $N$ *(RH neutrinos) with Majorana mass* $M \sim 10^{15}$ GeV *, Yukawa couplings give Dirac masses* $m_D = y\langle\phi\rangle \sim m_f$ *and so* $m_\nu \sim m_f^2/M \ll m_f$ $\quad f = e, \mu, \ldots$

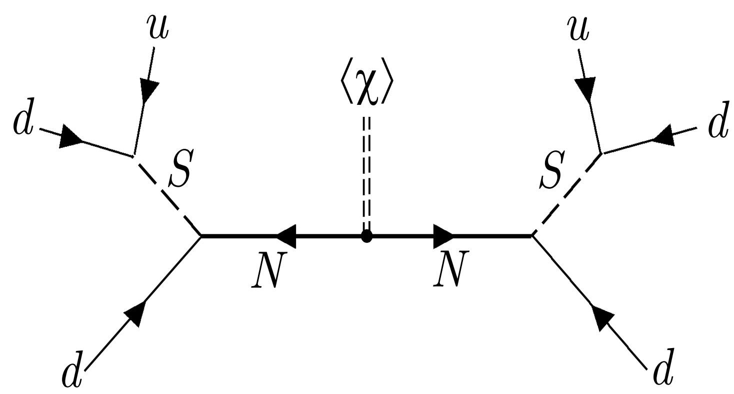
- BAU via leptogenesis: Decay $N \to l\phi$ violates $B - L$, violates $CP$: $\Gamma(N \to l\phi) - \Gamma(N \to \tilde{l}\tilde{\phi}) \neq 0$ due to complex Yukawas $y$ and may be out of equilibrium at $T \sim M$.

# $\Delta B = 2$: Seesaw mechanism



*Analogously, six fermion $D = 9$ operators* $G_{\Delta B=2}(udd)(udd)$
*can be induced via seesaw exchange of heavy Majorana particle $N$ (RH neutron)*
*and heavy color-triplet scalar $S$* with $G_{\Delta B=2} = 1/M^5 = 1/(M_N M_S^4)$ ,



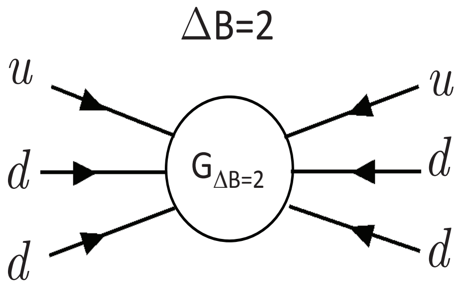

effective scale $M \sim 10^6$ GeV ($\tau_{n\tilde{n}} \sim 10^9$ s)
—— $M_S \sim 10$ TeV, $M_N \sim 10^{14}$ GeV
—— $M_S \sim 10^7$ GeV, $M_N \sim 100$ GeV

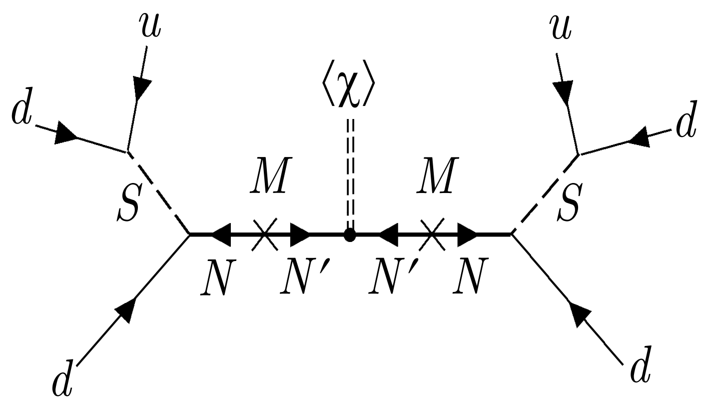
- Spontaneous breaking of $B$ $M_N \sim \langle\chi\rangle = f_B$

$U(1)_B$ global – new Goldstone boson appears (Bary-Majoron)
$U(1)_B$ local – this Goldstone eaten by gauge field (baryonic photon)
But nothing interesting if $B$-breaking scale $f_B$ is too large

# $\Delta B = 2$: Low scale seesaw mechanism

*Introduce two states $N$ and $N'$, with large Dirac mass term $M_D N N'$*




now $G_{\Delta B=2} = 1/M^5 = \langle\chi\rangle/(M_D^2 M_S^4)$ ,
effective scale $M \sim 10^6$ GeV ($\tau_{n\tilde{n}} \sim 10^9$ s) requires
$M_S \sim 10$ TeV, $M_N \sim 10$ TeV .... and $\langle\chi\rangle = f_B \sim 1$ MeV !!!

$U(1)_B$ global – Goldstone (Bary-Majoron) has pretty large $g_p = \epsilon/f_B$ between $n$ and $\tilde{n}$ states ...and if also large $g_s$ is induced, then look for new spin-dependent forces ...

$U(1)_B$ local – baryonic photon can be rather light .... so that $g_n \neq g_{\tilde{n}}$, having dramatic impact for $n - \tilde{n}$ oscillation search with free neutrons

# $\Delta B = 1$: Neutron oscillation in dark matter



Dark matter particle is neutral, so in principle it could mix with neutron and it is not baryonic $(B_{\mathrm{DMP}} = 0)$
... hence we would have neutron – DMP oscillation ... with $\Delta B = 1$ !
disappearance of the neutron!

Great !!! Let's rush to write a new paper ...

... A small problem – we do not know who is dark matter ....

and if you think carefully, the mixing should be very small and probably unmeasurable !

It's better to write a paper on transformation properties of crocodiles or other reptiles, or perhaps on antigravity of anticrocodiles

– will be accepted without problems ...
Anyway ... perhaps matter transition to dark matter is not that stupid idea as it looks at first glance ? Let me think ...

Wait ! It seems somebody has already written a work on it ...

# 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

# *Give a human face to dark matter ....*



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

# Parallel/Mirror/Twin World(s)



Parity (L $\leftrightarrow$ R) in Weak Ints. restored by Mirror fermions — Lee & Yang '56
Mirror fermions cannot have our EM & Strong Ints. — Kobzarev et al. '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
Mirror invisible stars — Blinnikov, Khlopov '83

- 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 $G \leftrightarrow G'$:

$$\langle \phi' \rangle \gg \langle \phi \rangle \quad \longrightarrow \quad (M'_W \gg M_W)$$ ZB, Mohapatra & Dolgov, '95-96

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 $\nu$ WDM, Strong CP & axidragon, SUSY little Higgs – accidental global $U(4)$, etc.*

# Para-world (or worlds) as dark matter

- *Parallel/twin/mirror sector: a duplicate of our particle sector ...*
*its particles species have exactly the mass spectrum and interaction constants (strong, weak & electromagnetic) exactly identical to that of ordinary particles*

- *Mirror particles are dark for us: do not interact with our photon $\gamma$*
*(reciprocally, our particles do not interact with mirror photon $\gamma'$ )*

- *Gravity is a common force between two sectors ....*
*Thus, mirror matter is a natural candidate for dark matter !!*

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

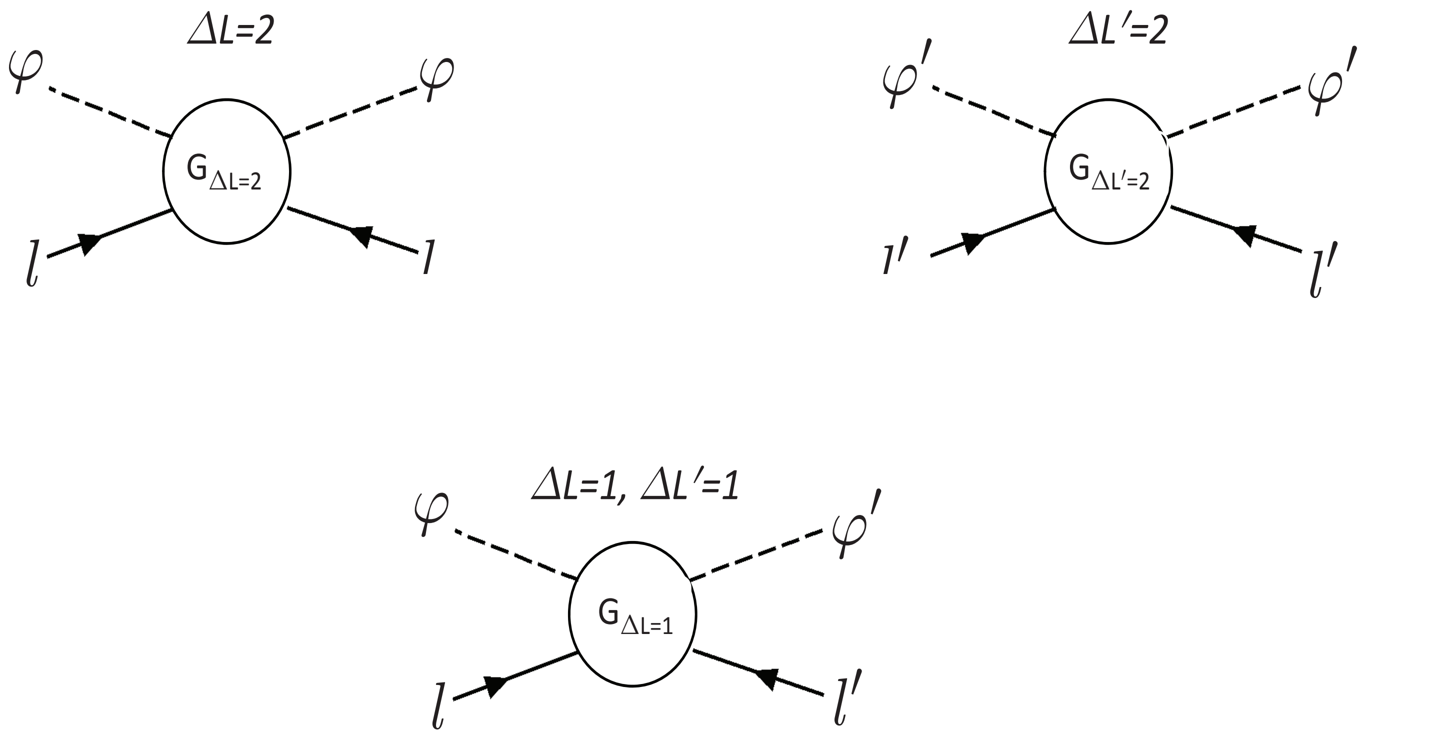
- *There can be feeble interactions between ordinary and mirror particles:*
*(Give dark matter detection a chance – DAMA & CRESST?)*
*But these should be feeble enough for not to equilibrate $T$ and $T'$*

- *B & L violating interactions most interesting: they can co-generate in Early Universe both baryon and para-baryon asymmetries, with $\Omega'_B/\Omega_B \sim 5$ naturally*

- *At lower energies, these induce mixings between ordinary particles and their twins:*
*neutrino–paraneutrino (active–sterile) neutrino mixing, neutron–paraneutron mixing ...*

# *Sterile neutrinos come from parallel hidden sector*






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

Sterile neutrinos are light by same motive as active neutrinos – and normally mixed with active Akhmedov, ZB, Senjanovic, 92; ZB, Mohapatra, 95 *any neutral particle, elementary or composite, can mix its mass degenerate twin*


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

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

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

inducing neutron - antineutron mixing

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

# $n - n'$ oscillation: surprising possibility




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


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


Zurab Berezhiani[1,*] and Luís Bento[2,†]

[1]*Dipartimento di Fisica, Università di L'Aquila, I-67010 Coppito, AQ, Italy and Laboratori Nazionali del Gran Sasso, INFN, I-67010 Assergi, AQ, Italy*

[2]*Faculdade de Ciências, Centro de Física Nuclear da Universidade de Lisboa, Universidade de Lisboa, Avenida Professor Gama Pinto 2, 1649-003 Lisboa, Portugal*



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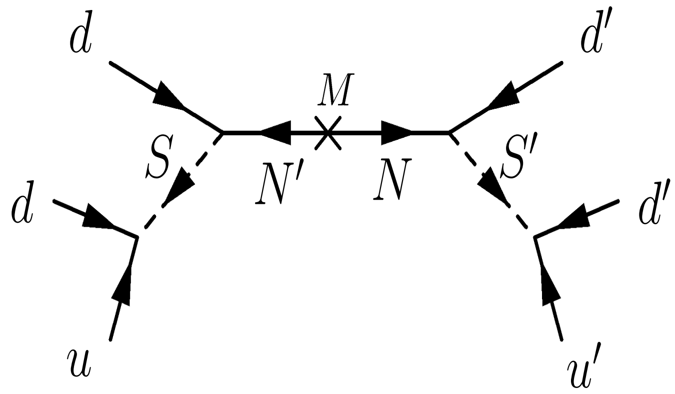
We discuss the phenomenological implications of the neutron ($n$) oscillation into the mirror neutron ($n'$), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal $n$-$n'$ oscillation in vacuum with a characteristic time $\tau$ 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:* $D = 9$



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

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




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

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

*Testable at LHC?*

ZB, Bento, '05

# Neutron - Mirror neutron mixing



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

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

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

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

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

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

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

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

!!! N.B. Nuclear Stability

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

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

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

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

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

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

- Exact mirror parity: $m' = m$, $\Gamma' = \Gamma$, $\mu' = \mu = -1.91\mu_N$
- Grav. potentials $V'_{\rm g} = V_{\rm g}$, .... but not precisely (baryonic photon)
- 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 ($\mu_\epsilon = 0$)

$$P(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2(\omega-\omega')^2}\cos^2\frac{\beta}{2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2(\omega+\omega')^2}\sin^2\frac{\beta}{2},$$ *ZB, EPJ C64, 421 (2009)*

$\omega = \frac{1}{2}|\mu B|$, $\omega' = \frac{1}{2}|\mu B'|$, $\beta$ *angle between* $\vec{B}$ *and* $\vec{B}'$.

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

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

# *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 ( $\sim 3$ 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

*Experimental sensitivities were analyzed* Pokotilovsky, Phys.Lett. B639, 214 (2006)

*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)

$\tau_{nn'} > 414$ s if $B' = 0$ – not valid if $B' > 1$ mG (or $V' \neq V$)

# Experimental strategy for searching $n \to n'$



Coherent neutron interaction with matter gives "optical" potential $V \sim \text{few} \times 10^{-7}$ eV. Thus, if $V > 0$, ultra-cold neutrons (UCN) with $E_{\text{kin}} < V$. 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 $P(\vec{B})$

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

$\Gamma_{\text{eff}} = \Gamma_{\text{dec}} + \eta_{\text{loss}} \nu + P(\vec{B}) \nu$ , $\nu = 1/t_f \sim 10$ 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* $\frac{N_1(t)}{N_2(t)} = \frac{N(0) e^{-\Gamma_{1\text{eff}} t}}{N(0) e^{-\Gamma_{2\text{eff}} t}} = e^{-(P_1 - P_2)\nu t}$

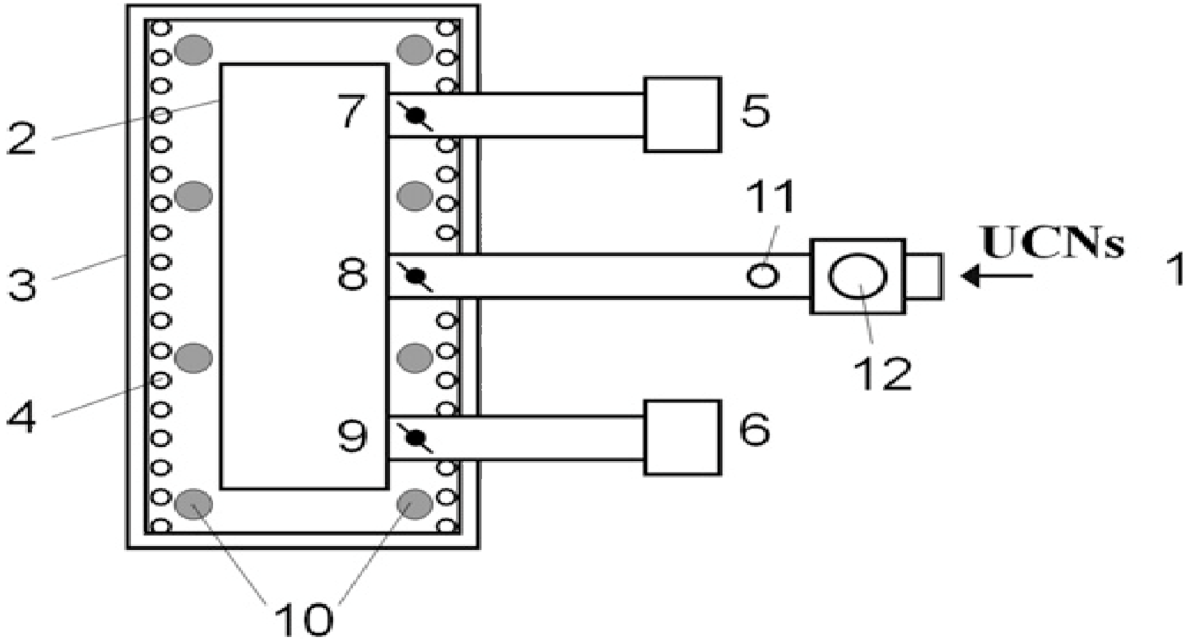
*Up down asymmetry* $A_B = \frac{N_{\vec{B}} - N_{-\vec{B}}}{N_{\vec{B}} + N_{-\vec{B}}} \approx (D_B \cos\beta) \nu t_s,$

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

# 2-nd experiment of Serebrov



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

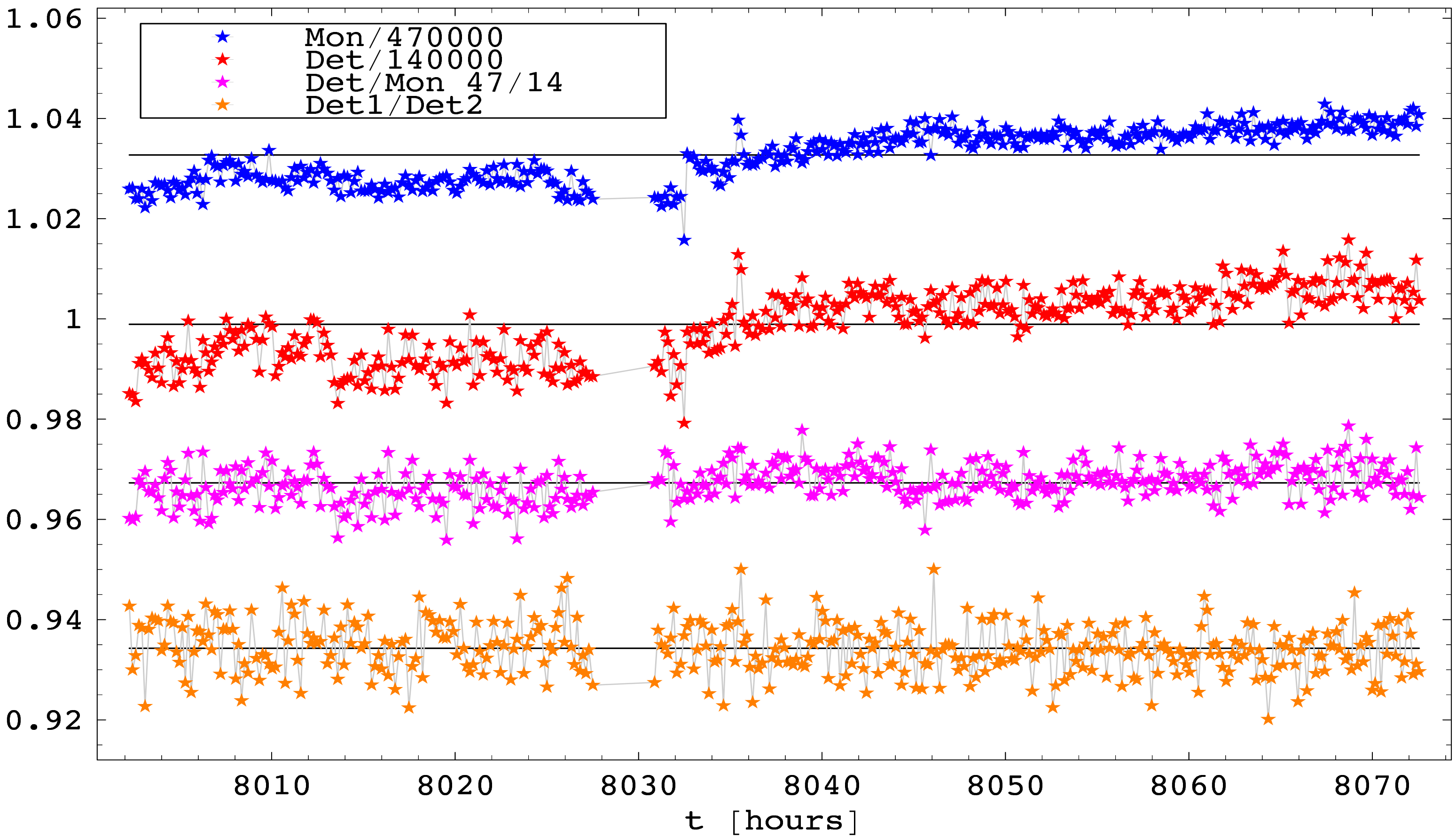
*– eliminating the linear and quadratic drifts of the neutron flux* $\sim 2\%$

- $3\sigma$ *deviation reported:* $A = (3.8 \pm 1.2) \cdot 10^{-4}$ ($B \simeq 0.2$ G & $B \simeq 0.4$ G)

# We reanalized these experimental data ...

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

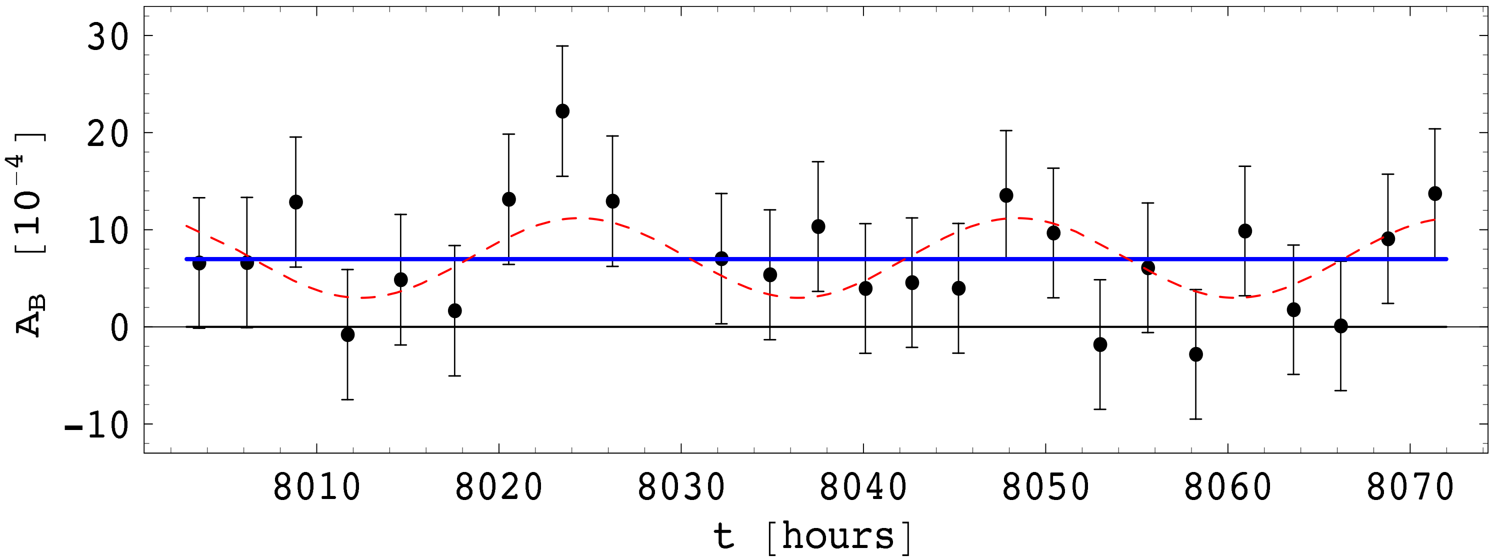
*About 10.000 downloads from the EPJ site ...*




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

# Results of this analysis

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




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

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

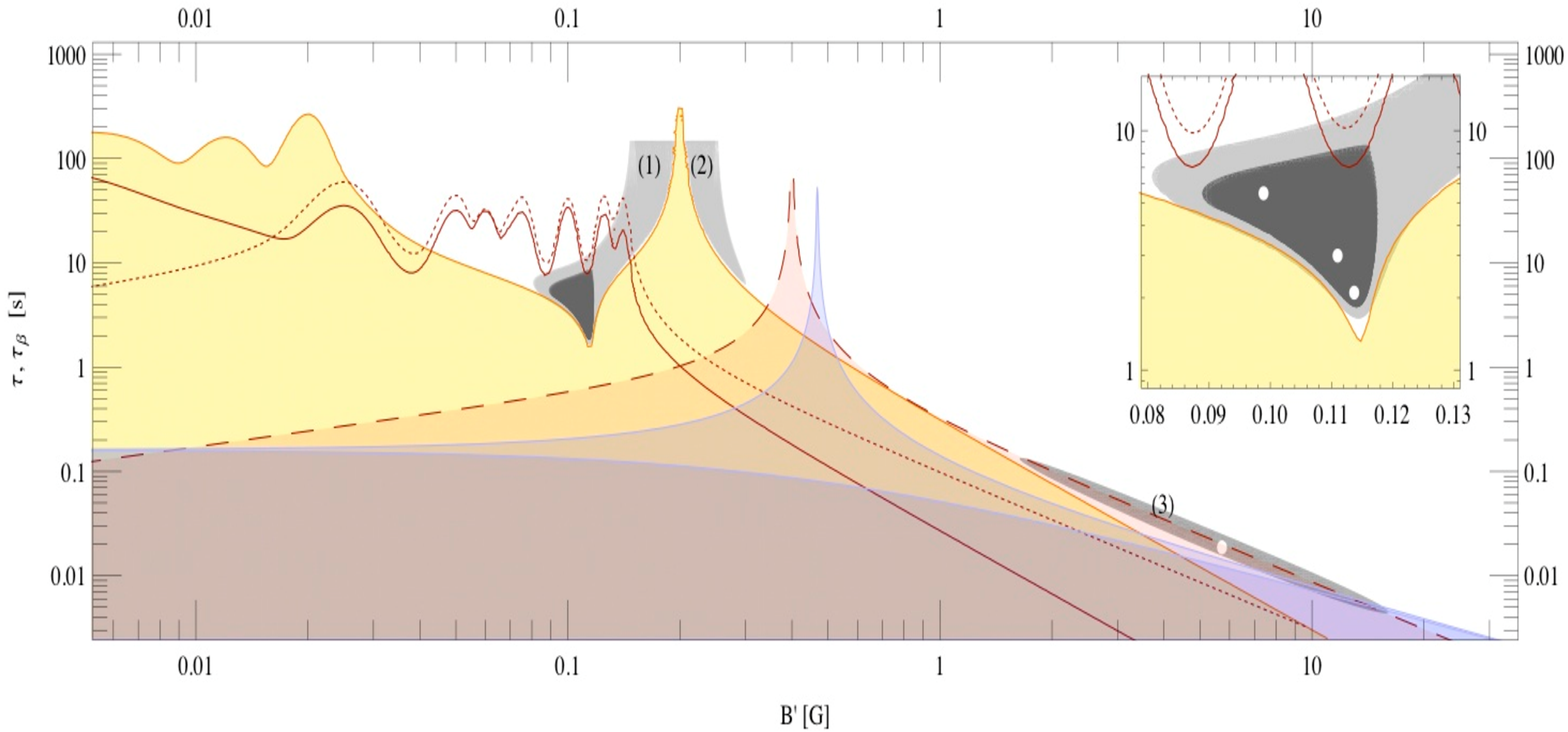
- at $B \simeq 0.4$ G : $A_B = (-0.3 \pm 2.4) \times 10^{-4}$ Resonance ?

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

Other experiments also indicate about $3\sigma$ anomalies about $B \sim 0.1$ G
Last measurements at ILL (summer 2013) again show $4\sigma$ deviation
(Preliminary !)

# Global analysis






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

Can the Earth possess mirror magnetic field?

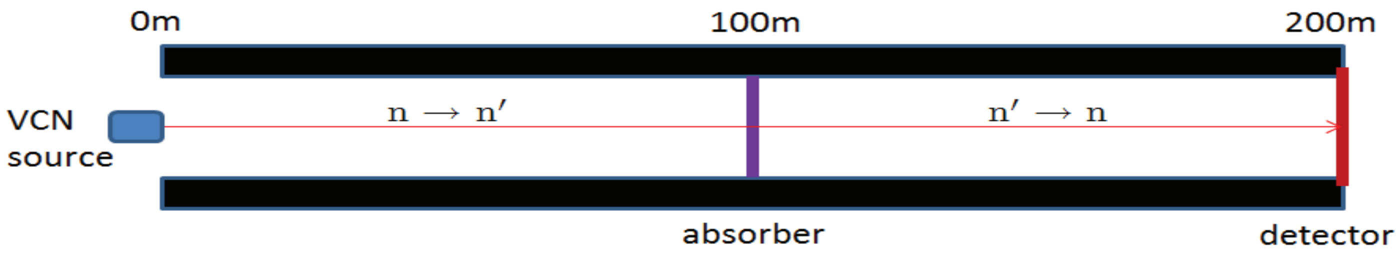
.... Why not if mirror matter is dark matter ...

*Altarev et al (2009) experiment also shows about $3\sigma$ deviation at* $B' \simeq 0.11$ G

*Last measurements at ILL (summer 2013) show about $4\sigma$ deviation Preliminary !*

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






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.

Regeneration experiment $n \to n' \to n$ $\quad P_{nn'}, P_{n'n} \sim (t/\tau)^2 \sim 10^{-6}$

# Neutron - Mirror neutron mixing in astrophysics



- *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.*

- *Late injection of neutrons via $n - n'$ oscillation can solve $^7$Li problem in primordial nucleosynthesis*
- *Effects on the neutrons from the solar flares*
- *$n - n'$ oscillation could reconcile results of NIST ($\tau = 888.02.1$ s) and Serebrov ($\tau = 8791$ s) results on neutron lifetime*

*Z.B., Kamyshkov, '14*

# Cosmic rays and GZK cutoff

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

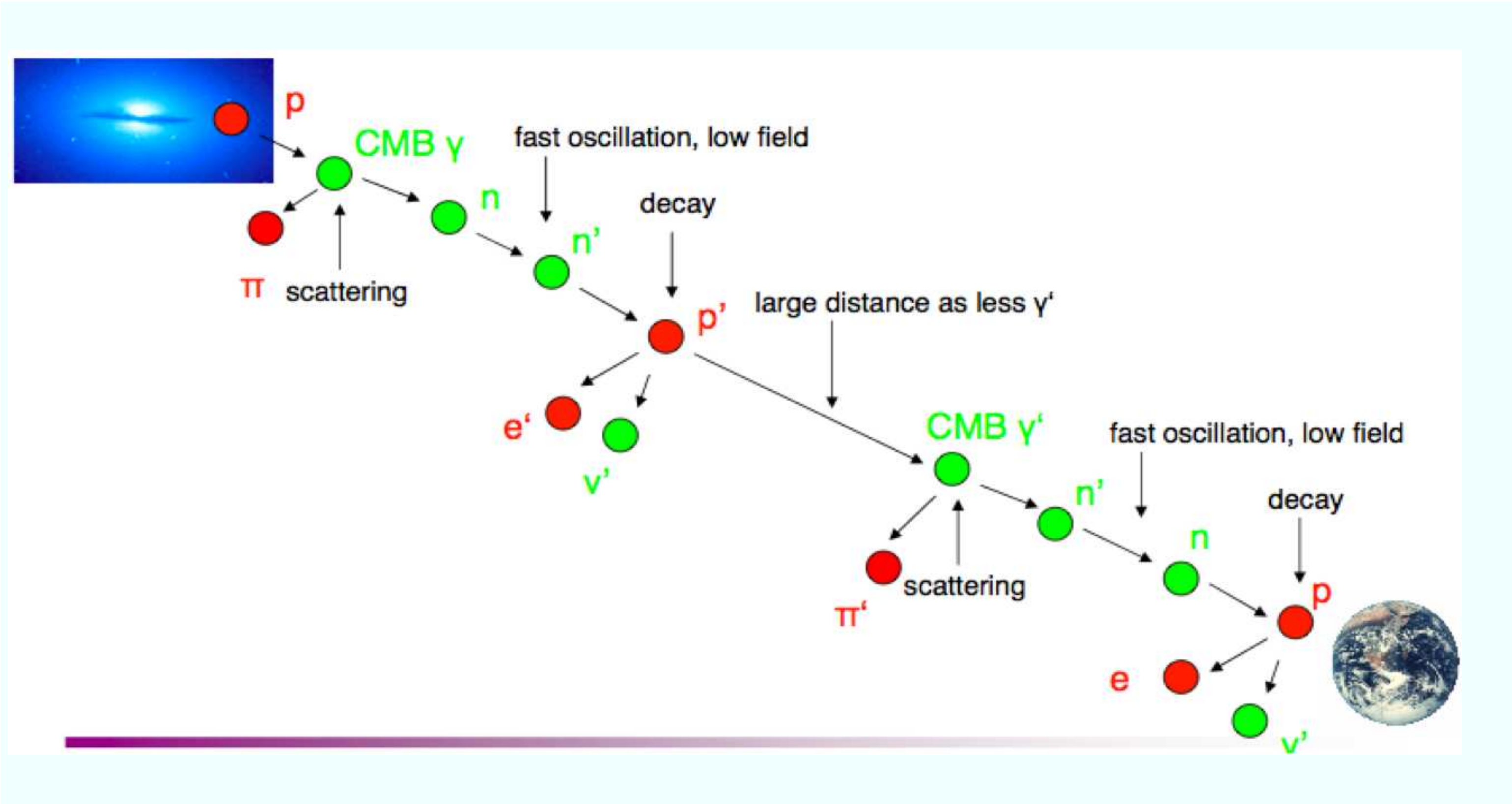
GZK cutoff:
Photo-pion production on the CMB if $E > E_{\rm GZK} \approx \frac{m_\pi m_p}{\varepsilon_{\rm CMB}} \approx 6 \times 10^{19}$ eV :
$p + \gamma \to p + \pi^0$ $(\text{or } n + \pi^+)$, $l_{\rm mfp} \sim 5$ Mpc for $E > 10^{20}$ eV $= 100$ EeV
Neutron decay: $n \to p + e + \bar\nu_e$, $l_{\rm dec} = \left(\frac{E}{100 \text{ EeV}}\right)$ Mpc
Neutron on CMB scattering: $n + \gamma \to n + \pi^0$ $(\text{or } p + \pi^-)$

Tkachev tells me that events $E > 10^{20}$ eV point towards BL Lacs.
But this seems impossible – BL Lacs are too far ($> 100$ Mpc)

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

# $n - n'$ 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. $p + \gamma \rightarrow p + \pi^0$ or $p + \gamma \rightarrow n + \pi^+ \qquad P_{pp,pn} \approx 0.5 \qquad l_{\rm mfp} \sim 5$ Mpc

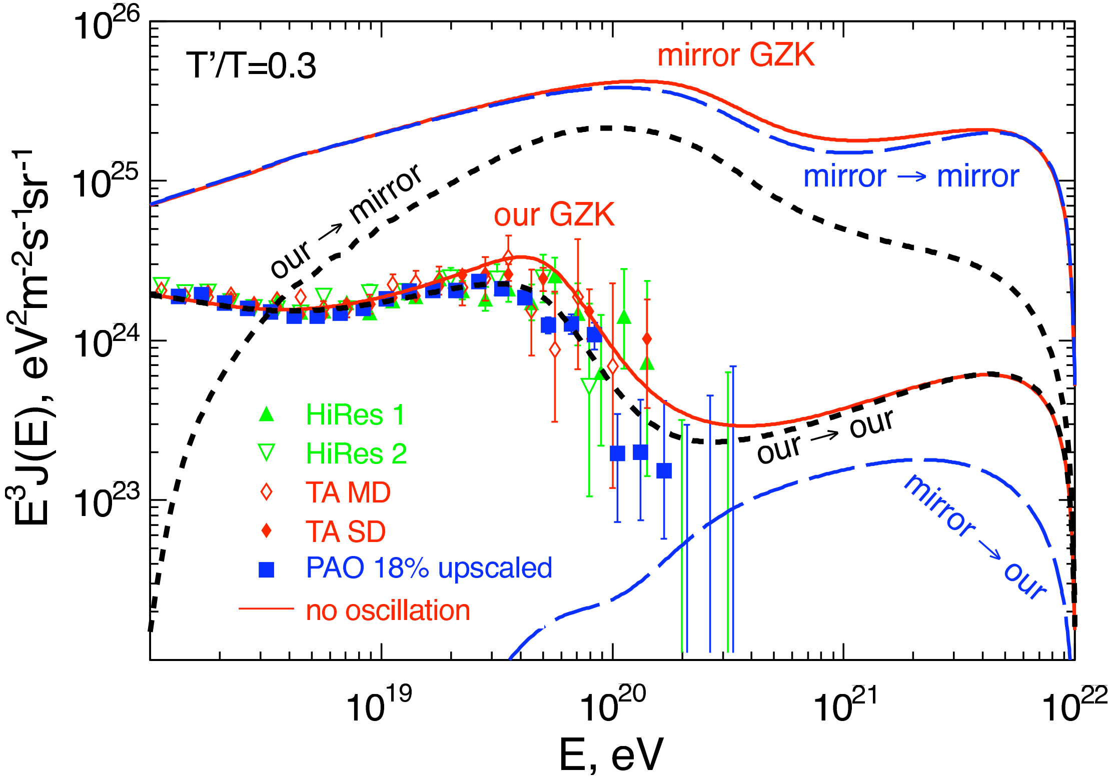
B. $n \rightarrow n' \qquad P_{nn'} \simeq 0.5 \qquad l_{\rm osc} \sim \left(\frac{E}{100\ \rm EeV}\right)$ kpc

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

D. $p' + \gamma' \rightarrow p' + \pi'^0$ or $p' + \gamma' \rightarrow n' + \pi'^+ \qquad l'_{\rm mfp} \sim (T/T')^3\, l_{\rm mfp} \gg 5$ 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 this is really true ...

– 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 $\mu_n$ )

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 $\nu$'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 ?? (lke in R. Sheckley's "Mind exchanges")

# 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 $\nu$? ...
- $\Omega_{\Lambda} \simeq 0.70$ dark energy: what is? $\Lambda$-term? Quintessence? ....

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

... $\rho_\Lambda \sim$ 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 $\nu$), 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 $\eta$ 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 $M_X = ?$ , $n_X = ?$

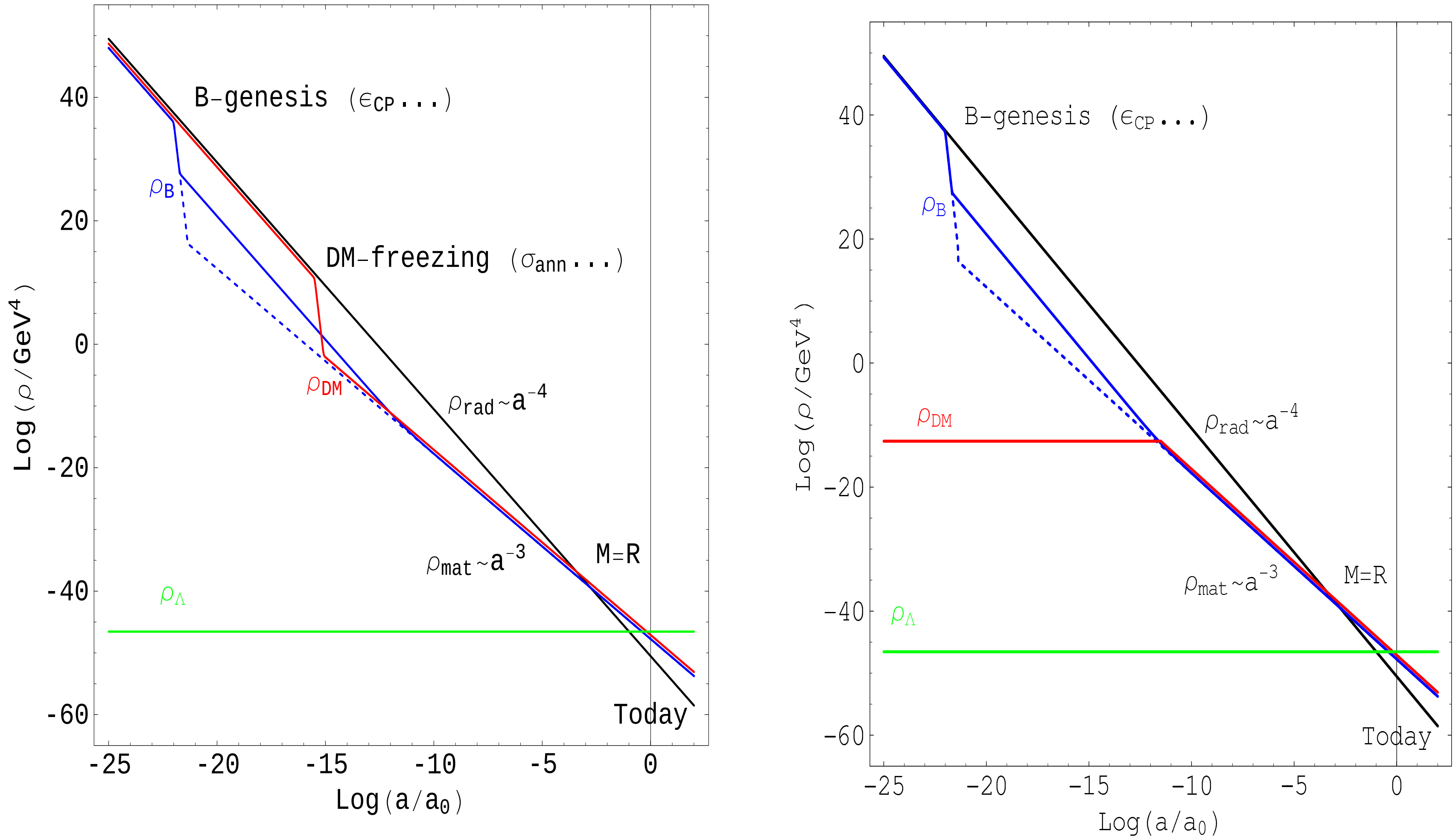
– wide spectrum of possibilities ...
Axion: $M_X \sim 10^{-5}$ eV, Sterile $\nu$ WDM: $M_X \sim 1$ keV, Wimp: $M_X \sim 1$ TeV,
Wimpzilla: $M_X \sim 10^{14}$ GeV ... but $M_X \sim 1$ GeV and $n_X \sim n_B$ ?

– 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

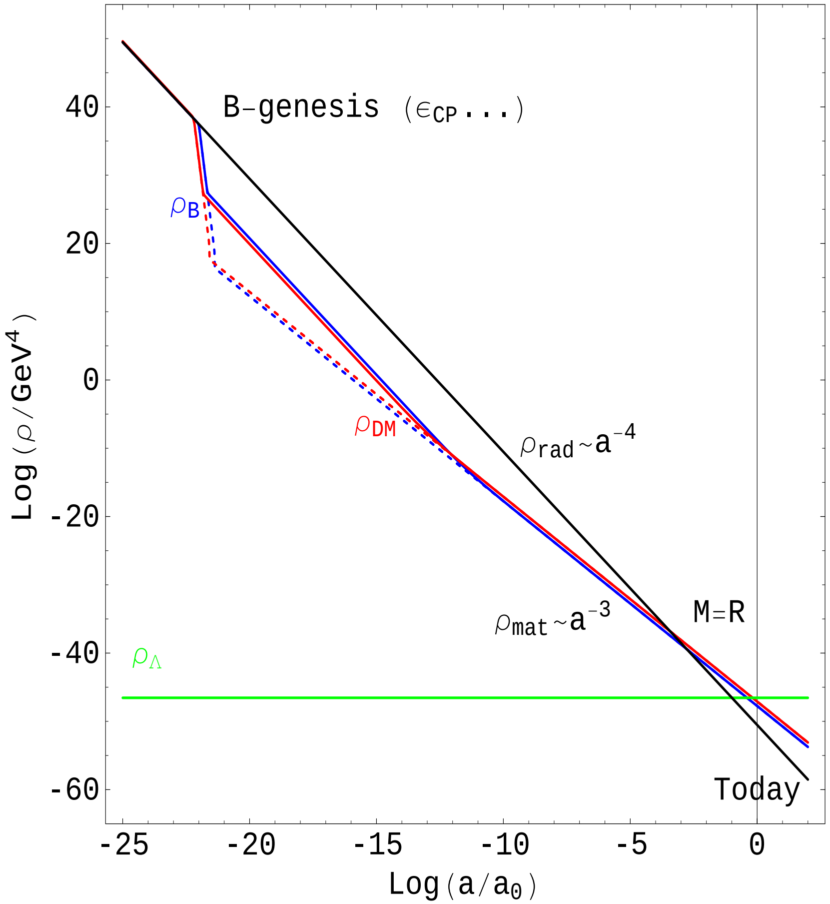





*Evolution of the Baryon number ( · · · ) in e.g. Baryo-Leptogenesis scenario confronted to the evolution of the Dark Matter density ( — ) in the WIMP (left pannel ) and Axion (right pannel) scenarios*

# 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*

# Standard Model – an intelligent design

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

gauge fields: $G$(luons), $W, Z, \gamma$ & 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) |
|---|---|---|---|---|
| $q_L = (u,d)^t_L$ | $l_L = (\nu, e)^t_L$ | \| | $\tilde{q}_R = (\tilde{u}, \tilde{d})^t_R$ | $\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$ |
| $u_R \;\; d_R$ | $e_R \;\; (N_R\,?)$ | \| | $\tilde{u}_L \;\; \tilde{d}_L$ | $\tilde{e}_L \;\; (\tilde{N}_L\,?)$ |
| Higgs: $\phi$ | or $(H_u, H_d)$ | \| | $\widetilde{\text{Higgs}}$: $\tilde{\phi}$ | or $(\tilde{H}_u, \tilde{H}_d)$ |

**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: $L \leftrightarrow \tilde{R},\; R \leftrightarrow \tilde{L},\;\; \phi \leftrightarrow \tilde{\phi}$ – complex conjugation

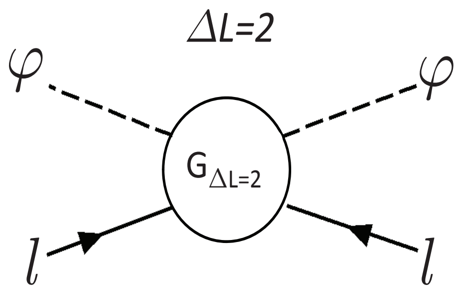
  $\mathcal{L}_{\rm Yuk}$ breaks CP once Yukawa constants $Y$ are complex

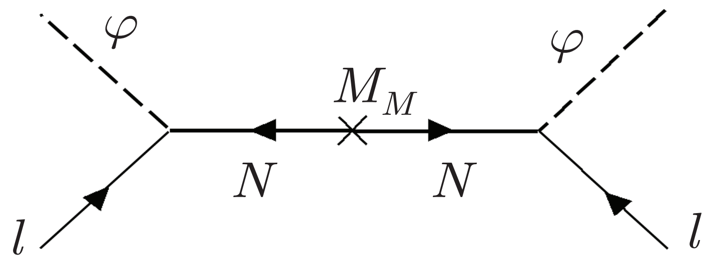
- Standard Model acts as accidental protective symmetry for masses of $\nu$'s – accidental global $U(1)$ of lepton number which is violated by $D = 5$ operator

  $\frac{A}{M}(l_L\phi)(l_L\phi)$ + 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 $\nu$'s

# *Seesaw Mechanism*




*No $N$:* *Effective $D = 5$ operator*

$$\frac{A_{ij}}{M}(l_i\phi)(l_j\phi)$$

*With $N$:* *Seesaw Lagrangian*

$$\mathcal{L}_\nu = y_{ia}\phi l_i N_a \; + \; \tfrac{1}{2} M g_{ab} N_a N_b$$

$A = y g^{-1} y^t$ *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

# Parallel Sector, Twin Particles & Mirror Parity



| $SU(3)\times SU(2)\times U(1)$ gauge ($g, W, Z, \gamma$) & Higgs ($\phi$) fields | | $\times$ | $SU(3)'\times SU(2)'\times U(1)'$ gauge ($g', W', Z', \gamma'$) & Higgs ($\phi'$) 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*

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

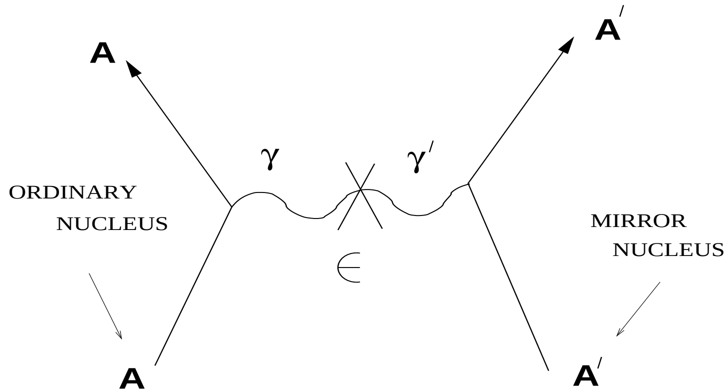
*Possible interactions between O & M particles (besides gravity) can be induced at tree level by exchange of extra gauge singlet particles or common gauge fields acting with both O & M particles ... and these interactions can lead to particle mixing phenomena between O & M sectors: any neutral particle (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 $(K^0 - K^{0\prime})$

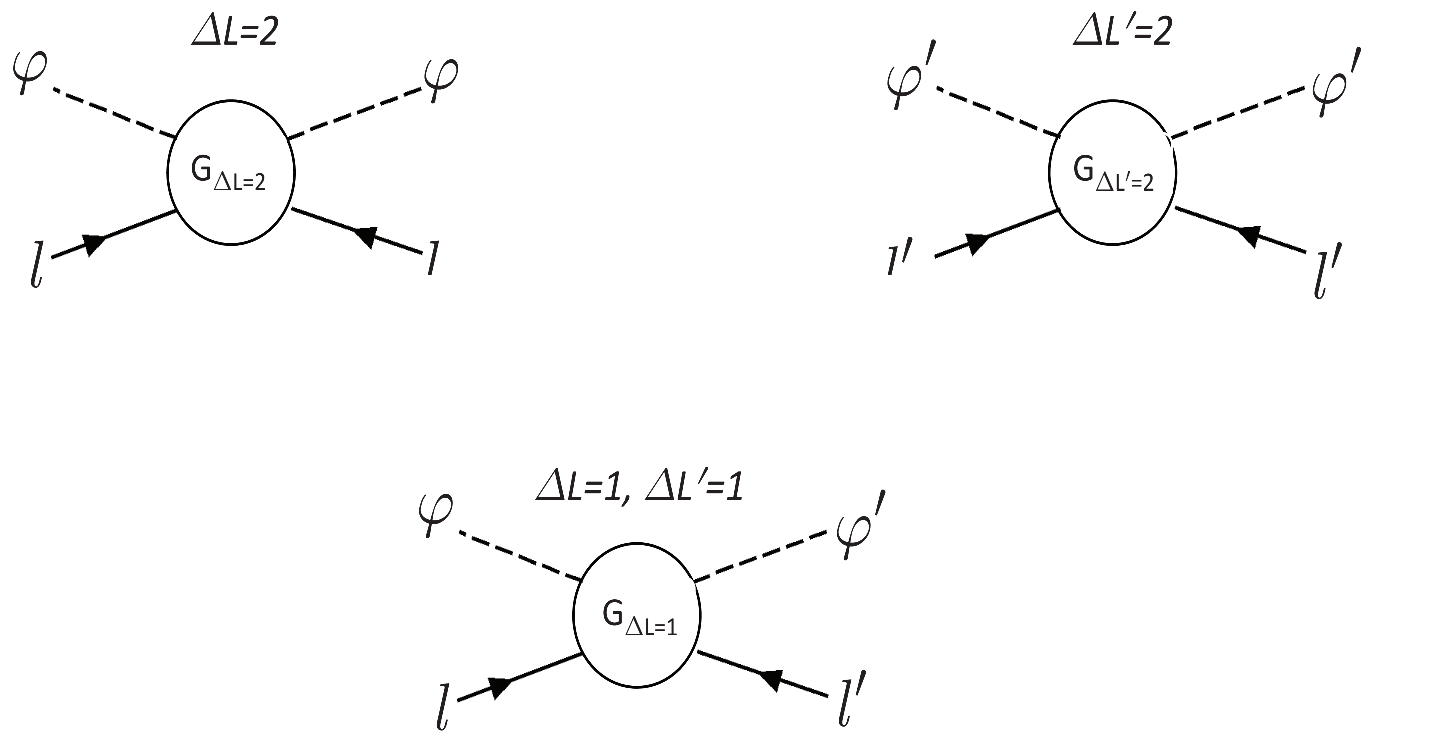
- *Can be induced via exchange of flavor gauge bosons ($SU(3)_{\rm fl}$ etc.) interacting with both our and mirror quarks/leptons* : *helping for Flavor Problem: custodial symmetry, minimality of flavor violation in SUSY (SSB terms allignment), anomaly cancellation for chiral $SU(3)_{\rm fl}$, Vanishing $D$-term, etc.*
- *In the context of TeV scale gravity the gauge flavour bosons can live in extra dimensions (between parallel branes)*

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



# *Sterile neutrinos ....*



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

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

Immediate questions arise:

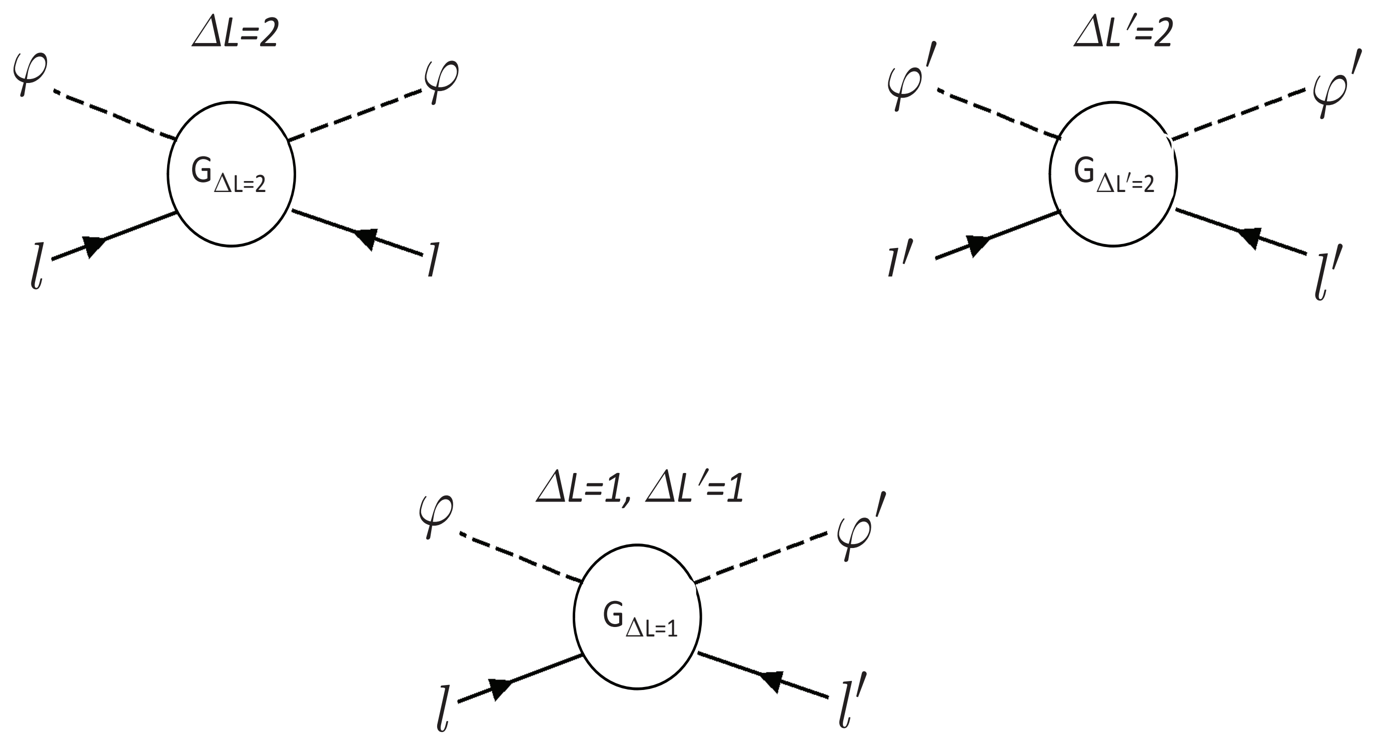
- why these SM singlet sterile neutrinos are light ?
- why these have a reasonable mixing with active neutrinos ?
- and finally, who are these guys ?

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

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 hidden sector






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

Sterile neutrinos are light by same motive as active neutrinos – and normally mixed with active Akhmedov, ZB, Senjanovic, 92; ZB, Mohapatra, 95

# 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: $A' = A$, $D = D^t$

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

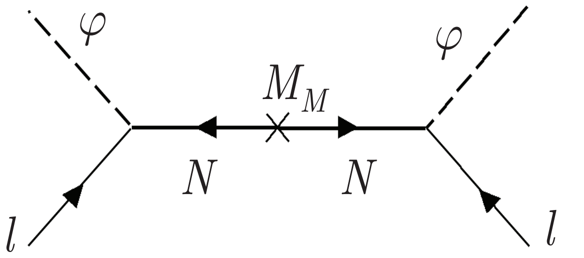
*e.g.* $v'/v \sim 10^2$: $\sim$ *keV sterile neutrinos as WDM* Z.B., Dolgov, Mohapatra '96

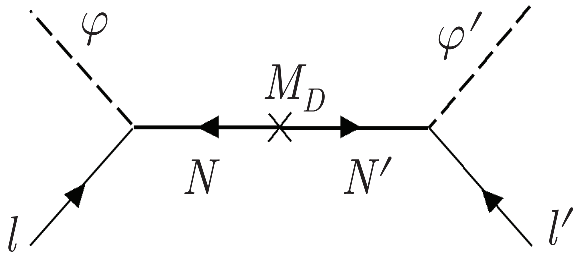
- $A, A' = 0$ *($L - L'$ conserved) light Dirac neutrinos*

*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

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

# *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.

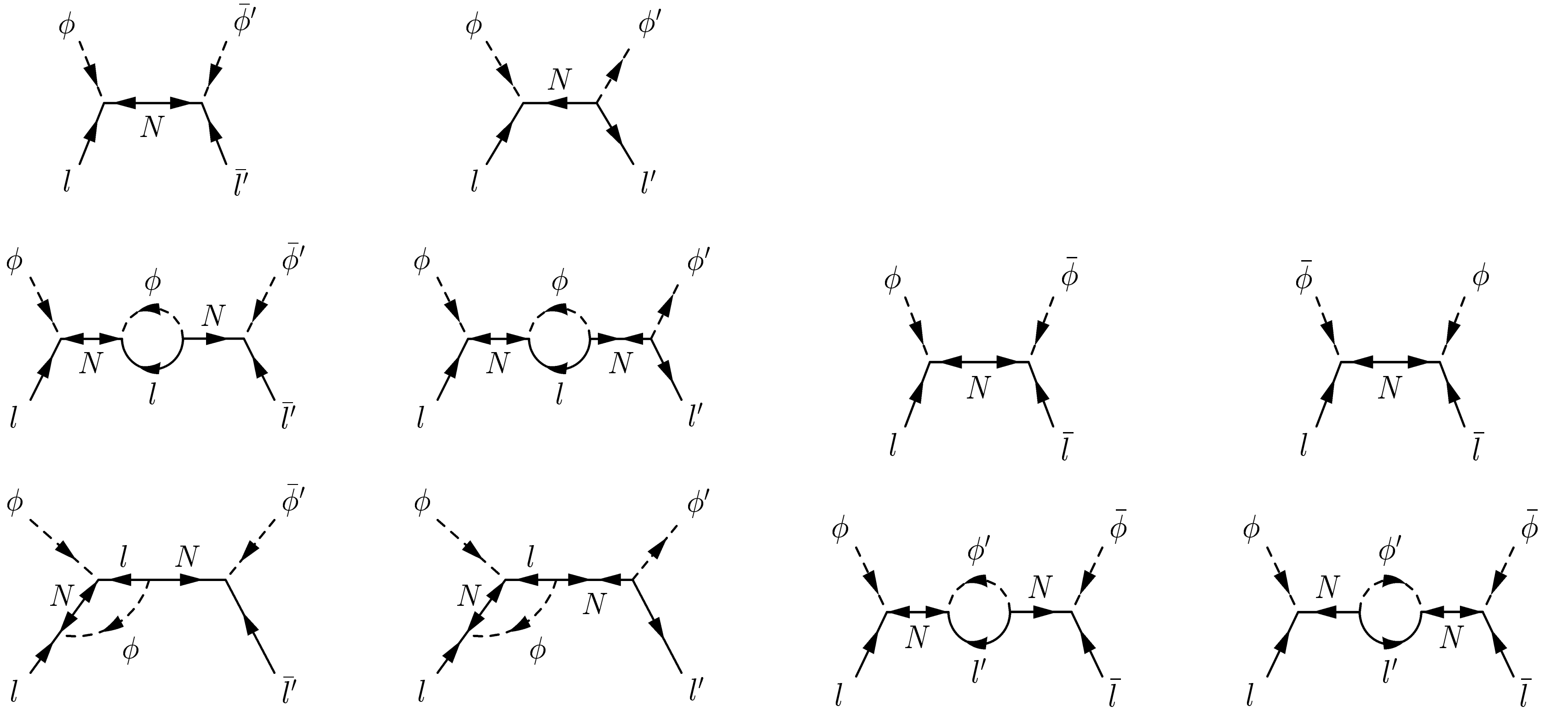
Ordinary and mirror Baryon asymmetries can be generated at one shoot !!

Baryon & Dark matter Co-genesis

# CP violation in $\Delta$L=1 and $\Delta$L=2 processes



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



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

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

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

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

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

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

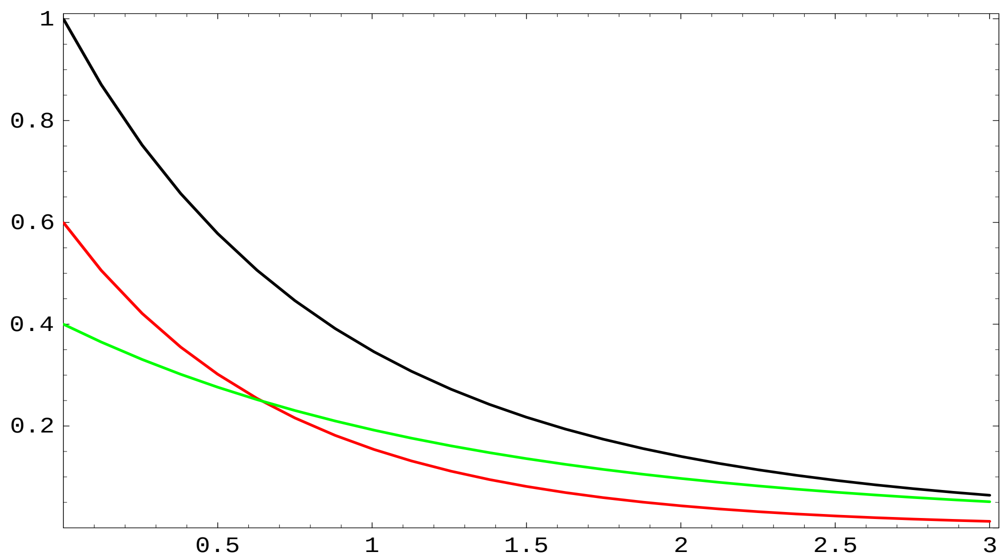
$Y_{BL}^{(0)} \approx 2\times 10^{-3}\frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}$: $T_R$ *is (re)heating temperature*

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

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

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

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

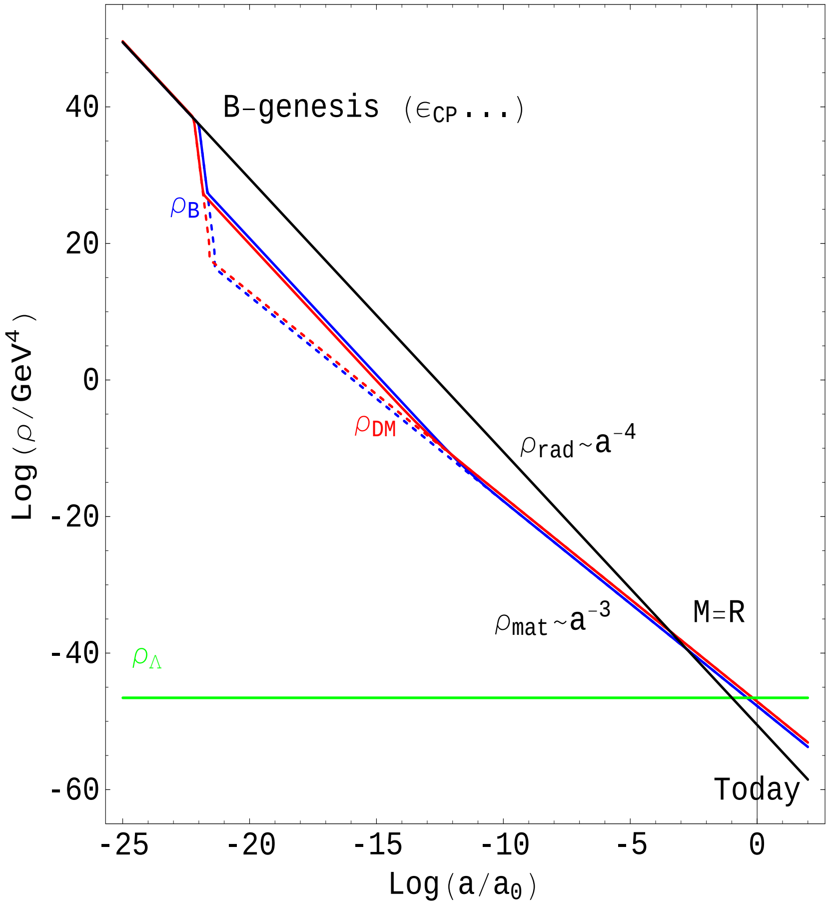


BBN: $x < 0.5 \;\rightarrow\; k \leq 4$; LSS: $x < 0.2 \;\rightarrow\; k \leq 1.5$

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

# *Cogenesis of B & B′: unified origin of matter & dark matter*






*Observable and mirror matter co-genesis:*
*both based on Baryon asymmetry ....*

- *mirror particle masses/properties are similar to baryon ones:* $M'_B = M_B$
- *Dark & B asymmetries are generated by one process and* $n'_B \geq n_B$

*so that* $\frac{\rho'_B}{\rho_B} = \frac{M'_B n'_B}{M_B n_B} \geq 1$ *- dark gauge sector with* $B'$ *asymmetry*