Sterile Neutrinos and Leptogenesis of Matter & Dark Matter

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Heisenberg – an intelligent question

W. Heisenberg, in a chapter "Weak Interactions" of his book (1965), questioned the origin of massless neutrino. The fact that the neutrino is a neutral particle does not mean that it must be massless. Weyl neutrino can make a mass with antineutrino state.
Why then neutrino is massless ?

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

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

A crazy idea .... and even wrong !!!
NOW@2012, we know that neutrinos are not Goldstones ...

But still there are many crazy ideas around that are not even wrong !!

Standard Model – an intelligent design

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

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

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

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

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

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

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

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

Seesaw Mechanism

$D = 5$ operator $\frac{1}{M}(l\phi)(l\phi)$ or $\frac{1}{M}(ll)(\phi\phi)$

$l\phi$ is a gauge singlet or triplet fermion with $Y = 0$ and $L = 1$

ll (and $\phi\phi$) - singlet or triplet scalar $Y = -2$, $L = 2$ $(Y = 2, L = 0)$

Hence, these operators can be obtained by integrating out heavy (with mass $\sim M$) fermions or scalars with respective quantum numbers.

RH Neutrinos are in fact heavy SM singlet fermions N_{La}, $a = 1, 2, ...$
and must have large Majorana mass terms $\frac{1}{2}M_{ab}N_{La}N_{Lb} = \frac{M}{2}NgN$
($M_{ab} = g_{ab}M$, M overall mass scale and g some "Yukawa" matrix)

but also Yukawa (Dirac) couplings $l_{Li}y_{ia}\tilde{N}_{La}\phi = ly\tilde{N}_L\phi$

Full neutrino Lagrangian $\mathcal{L}_\nu = y_{ia}\phi l_i N_a + \frac{1}{2}Mg_{ab}N_aN_b + \text{h.c.}$;

after integrating out heavy states N's, D=5 effective operators emerge:
$\frac{A}{M}(l\phi)(l\phi)$ + h.c. with $A = yg^{-1}y^t$ P. Minkowski, 74; Yanagida, GRS, 79

• 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

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 least 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

Again on Heisenberg's hypothesis ....

The idea of Heisenberg interpreting neutrino as a Goldstone particle was certainly crazy ... but not stupid at all....

This idea has triggered the works of D.V. Volkov and collaborators which brought to the discovery of the concepts of Supersymmetry and its spontaneous breaking six years after (in 1971). In fact, what Heisenberg had in mind, appeared to be a Goldstino.

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

Perhaps models of Goldstino and dilatino also will open great perspectives in future physics but they hardly can be thought as candidates for sterile neutrinos

If two sterile neutrinos are needed, then one is Goldstino and another axino?

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*

Parallel Sector, Twin Particles & Mirror Parity

$$SU(3)\times SU(2)\times U(1) \quad \times \quad SU(3)'\times SU(2)'\times U(1)'$$

gauge (g, W, Z, γ) & Higgs (ϕ) fields | 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)
$\tilde{q}_R = (\tilde{u}, \tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$	$\tilde{q}'_R = (\tilde{u}', \tilde{d}')^t_R$	$\tilde{l}'_R = (\tilde{\nu}', \tilde{e}')^t_R$
$\tilde{u}_L \;\; \tilde{d}_L$	$\tilde{e}_L$	$\tilde{u}'_L \;\; \tilde{d}'_L$	$\tilde{e}'_L$

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

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

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 '64

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

Shadow World ($E_8 \times E_8'$) — Kolb, Turner, Seckel '86

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 $G \leftrightarrow G'$:

$\langle\phi'\rangle \gg \langle\phi\rangle \;\longrightarrow\; (M_W' \gg M_W)$ — 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* ν

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

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

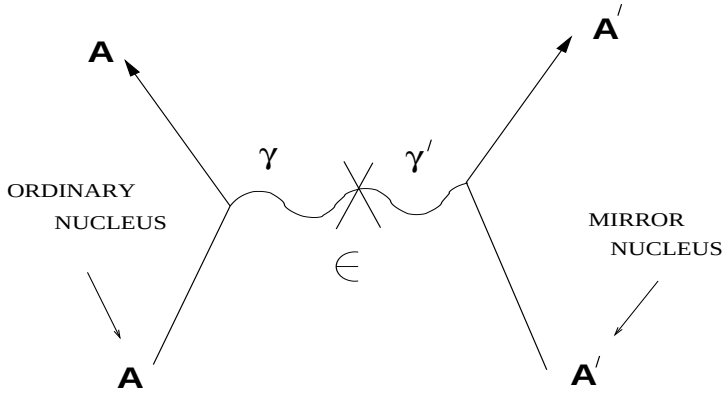
- photon - mirror photon kinetic mixing $\varepsilon F^{\mu\nu}F'_{\mu\nu}$ Holdom '86

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



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)*

Lepton number violating interactions: $D = 5$ operators

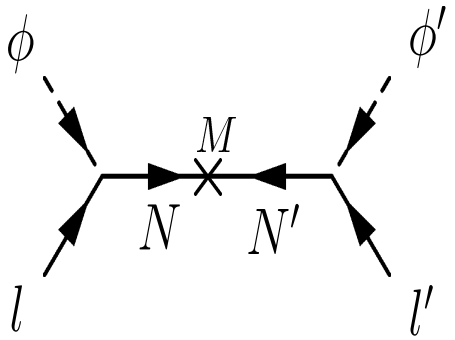
- Heisenberg
- SM
- See-Saw
- Sterile
- Again H
- Parallel sector
- Twin Particles
- Mirror World
- BBN demands
- Interactions
- Interactions
- B & L violation
- See-Saw
- leptogenesis
- Leptogenesis: diagrams
- Boltzmann eqs.
- VM and DM
- Leptogenesis: formulas
- Unification
- B vs. D
- Present Cosmology
- *Visible vs. Dark matter:* $\Omega_D/\Omega_B \simeq 5$?
- B & L violation

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

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

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

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: $A' = A, \quad D = D^t$

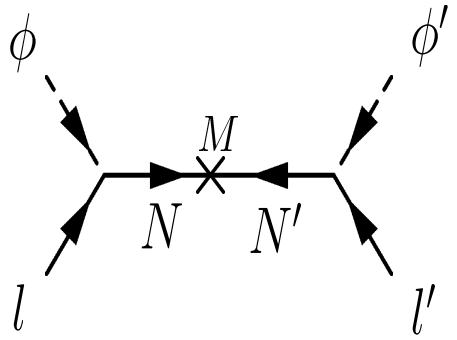
- $v' = v$: $\quad m_{\nu'} = m_\nu$ *and maximal mixing* $\theta_{\nu\nu'} = 45°$;
- $v' > v$: $\quad m_{\nu'} \sim (v'/v)^2 m_\nu$ *and small mixing* $\theta_{\nu\nu'} \sim v/v'$;

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*

Mixed Seesaw between O & M sectors



- 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

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

  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

  with Kuzmin Rubakov Shaposhnikov correction

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

  B. violate CP – *complex Yukawa constants*

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

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

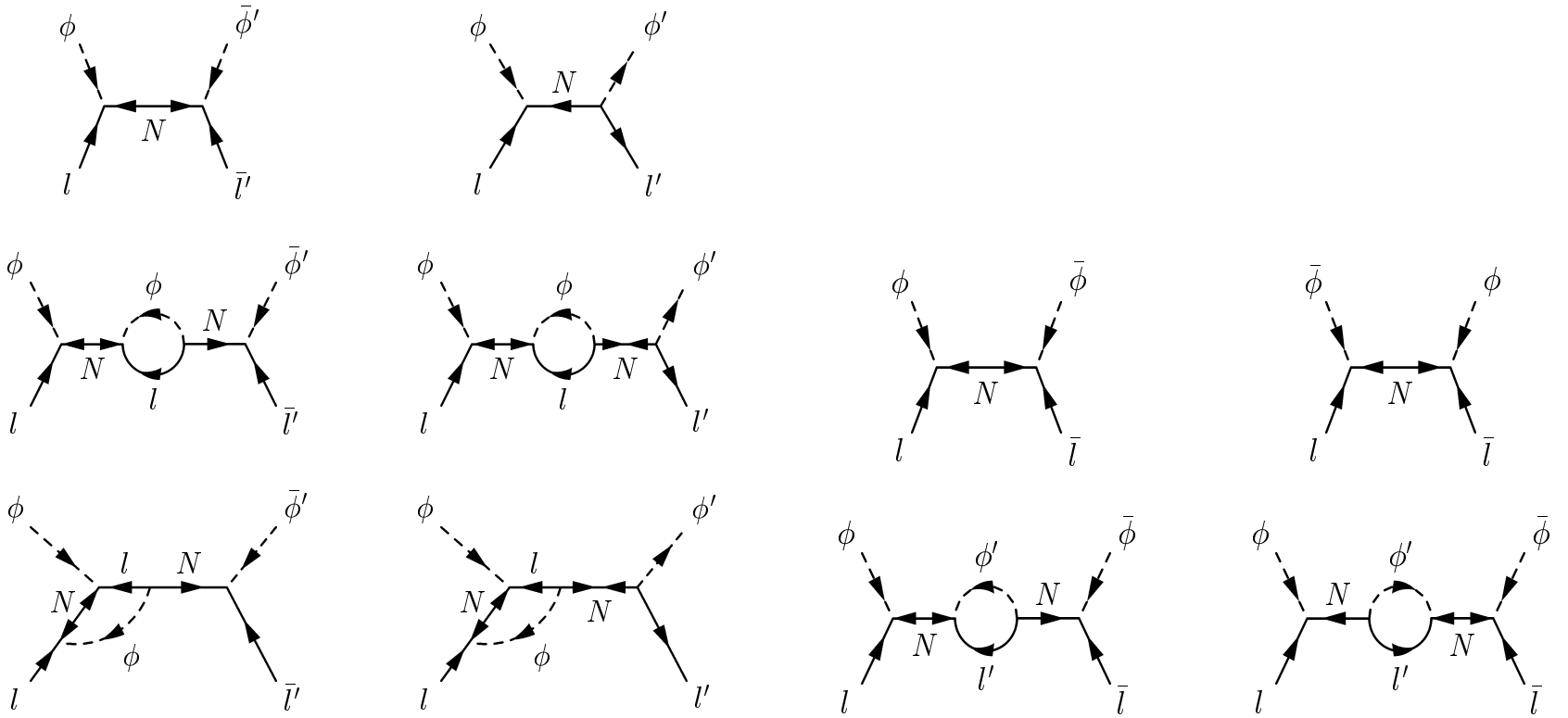
- The same reactions generate B′-L′ $\neq$0 ($\to$ B′$\neq$0) in dark sector.

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

Baryon & Dark matter Co-genesis

CP violation in ΔL=1 and ΔL=2 processes

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



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

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

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

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

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

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

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

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

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

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

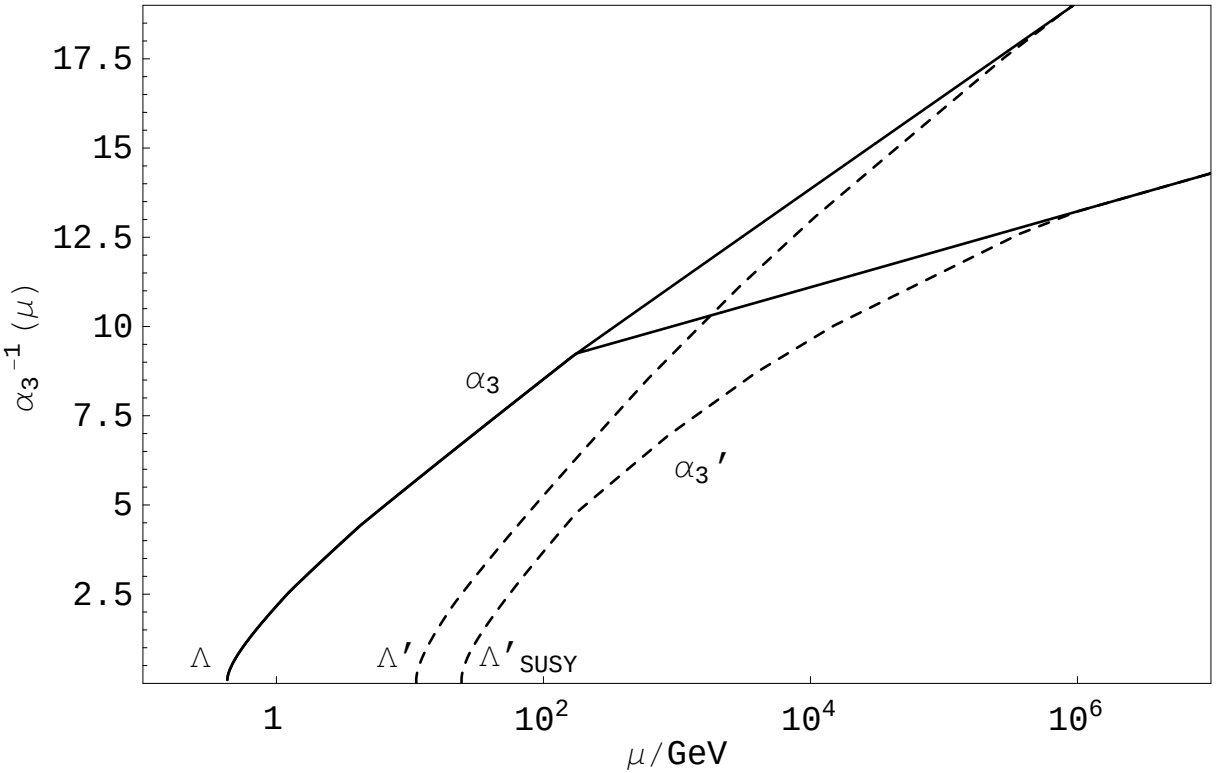
Damping factors $D(k)$ *and* $D(k')$*:* $\quad k = \left[\frac{\Gamma_{\rm eff}}{H}\right]_{T=T_R}, \quad k' = kx^2$

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

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

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

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



$n'_B \simeq n_B$ $k < 1$ (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.

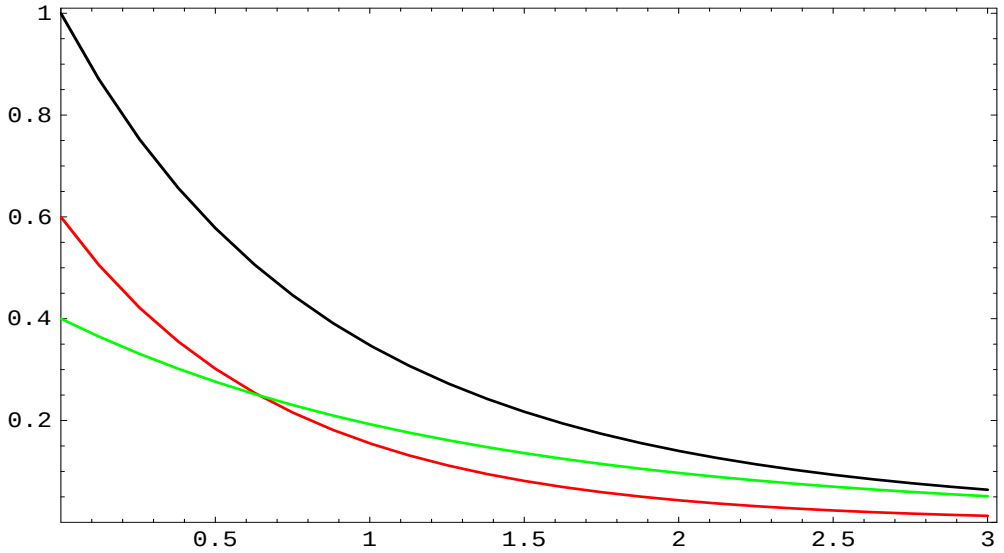
– Properties of MB's get closer to CDM : $M'_W \sim 10$ TeV ?

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

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

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

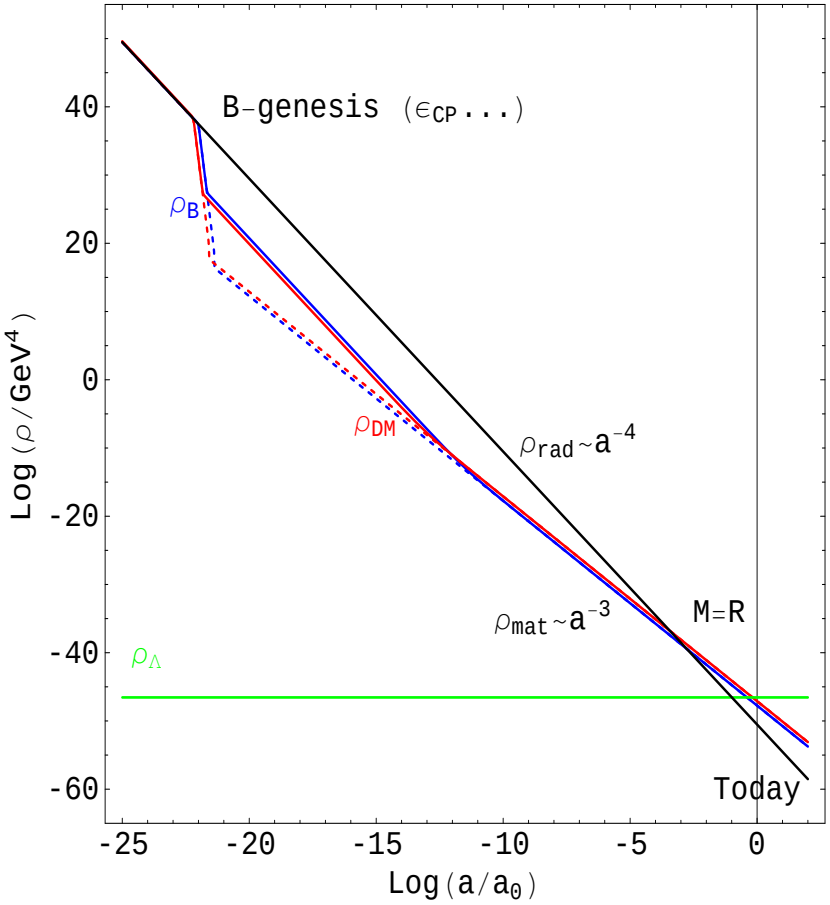
$D(k) < D(k') \approx 1$: lower limit $\frac{\Omega'_B}{\Omega_B} = \frac{D(k')}{D(k)} > 1$ Z.B. '03



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

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

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

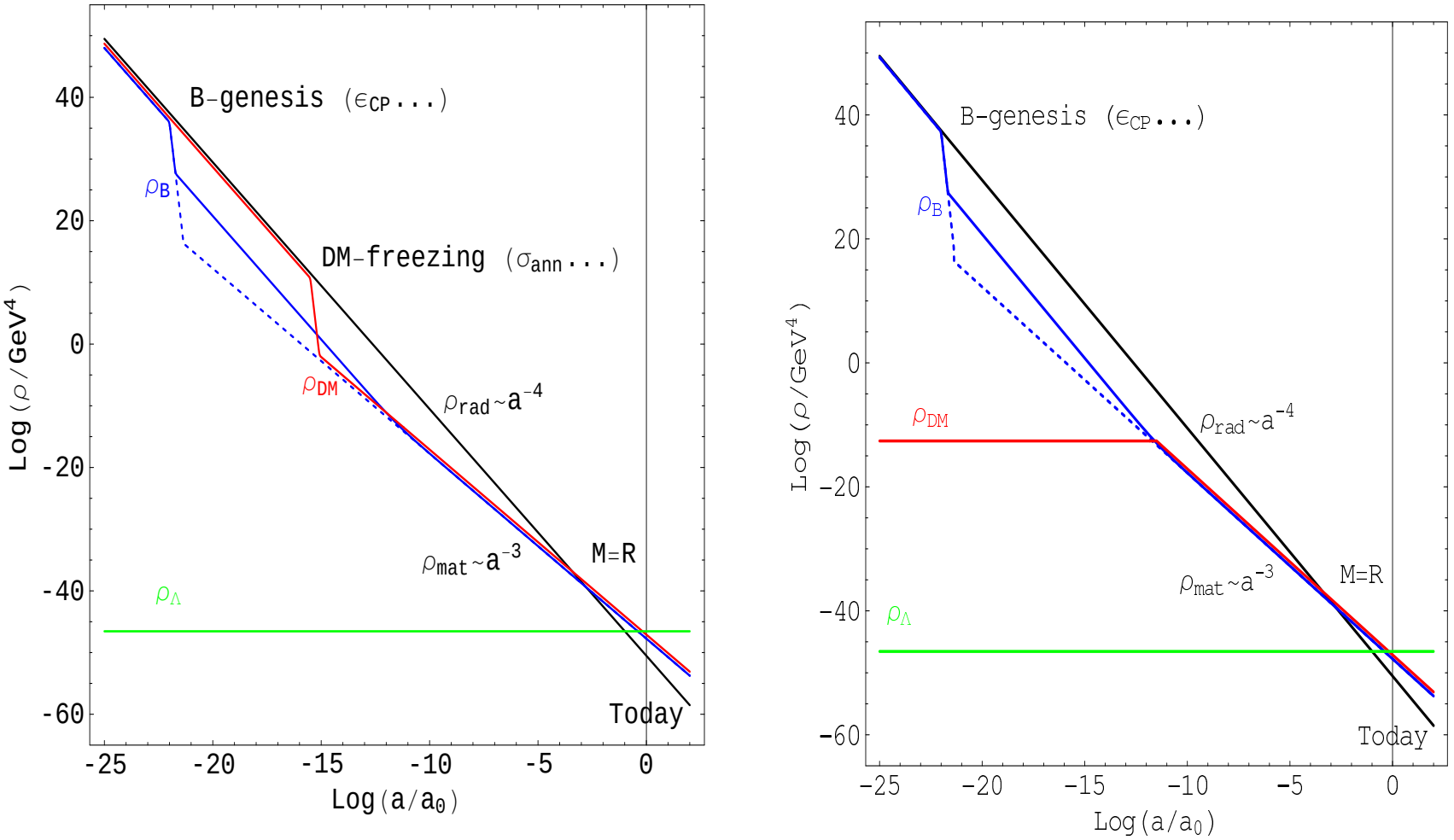


Observable and dark matter co-genesis: both based on Baryon asymmetry ?

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

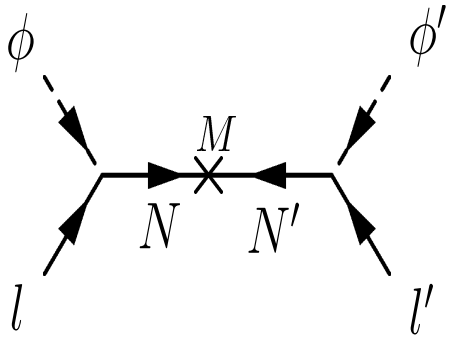
– too wide spectrum of possibilities ... Axion: $M_X \sim 10^{-5}$ eV, Sterile ν WDM: $M_X \sim 1$ keV, Wimp: $M_X \sim 1$ TeV, Wimpzilla: $M_X \sim 10^{14}$ GeV ...

– 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?

Some conclusions and outlook

$$\frac{A}{M}(l\phi)^2 + \frac{A'}{M}(l'\phi')^2 + \frac{D}{M}(l\phi)(l'\phi')$$



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: $A' = A, \quad D = D^t$

- $v' > v$ (e.g. $v'/v \sim 10^2$): $m_{\nu'} \sim (v'/v)^2 m_\nu$ *and mixing* $\theta_{\nu\nu'} \sim v/v'$;
$\sim$ keV sterile neutrinos as WDM provided $T' \ll T$ Z.B., Dolgov, Mohapatra '96
- *Matter and dark matter co-leptogenesis: shadow baryons as natural candidate for (asymmetric) dark matter, with* $\Omega'_B/\Omega_B \sim 1 - 10$ Bento and Z.B. 2001, ZB 2003
- *Gauge flavor symmetry* $SU(3)_H$ *adds more predictive power* Z.B., 98
- *Supersymmeric Little Higgs concept tells that* $v' \sim 10$ *TeV* Z.B., 2004
- *Interesting and constrained system of 3 active + 3 sterile neutrinos – deserves more detailed study, also regarding BBN bounds, structure formation, etc.*