Mirror World: visible & dark matter genesis

neutrinos, neutrons etc.

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Standard Cosmological Paradigm

Precision data on BBN, CMB, LSS, etc. lead to Standard Paradigm:

The early Universe:

- multi-stage: Inflation $\rightarrow$ (re)heating $\rightarrow$ Friedmann epoch ...
- Universe is flat and homogeneous ...
- Adiabatic perturbations with nearly flat spectrum ...

Todays Universe:

- multi-component: visible matter, dark matter, dark energy ...
- $\Omega_{\rm tot} \approx 1$ Universe is flat: $\rho_{\rm tot} = \rho_{cr}$ ...
- $\Omega_{\rm B} \simeq 0.04$ visible (Baryon) matter is a small fraction ...
- $\Omega_{\rm D} \simeq 0.20$ dark matter: WIMPS? Axions? ....
- $\Omega_{\Lambda} \simeq 0.75$ dark energy: Λ-term? 5th-essence? ....

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Some unified picture?

Well, not yet ... the origin and nature of DM and DE remain open !

Coincidence & Fine Tuning Problems

Cosmic 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., $\rho_{\rm M} \sim a^{-3}$.

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Visible matter – ρ_B – from primordial Baryogenesis
(GUT, Lepto-B, Affleck-Dine, EW, ...)
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– Finest conspiracy across the Particle Physics and Cosmology?
– How Baryon Asymmetry knew about Dark Matter Nature ?

Visible & dark matter

- Visible matter: $\rho_{\rm B} = n_{\rm B} M_N$,

$M_N \simeq 1$ GeV – nucleon mass,
$Y_{\rm B} = n_{\rm B}/s \simeq 10^{-10}$ – Baryon number/entropy density ratio.

(GUT, Lepto)-Baryogenesis: $Y_{\rm B} \sim (\epsilon_{CP}/g_*) \times D(k)$,
ϵ_{CP} – CP violation parameter,
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- Dark matter: $\rho_{\rm D} = n_X M_X \sim 5\rho_B,$, but $M_X =$? , $n_X =$?

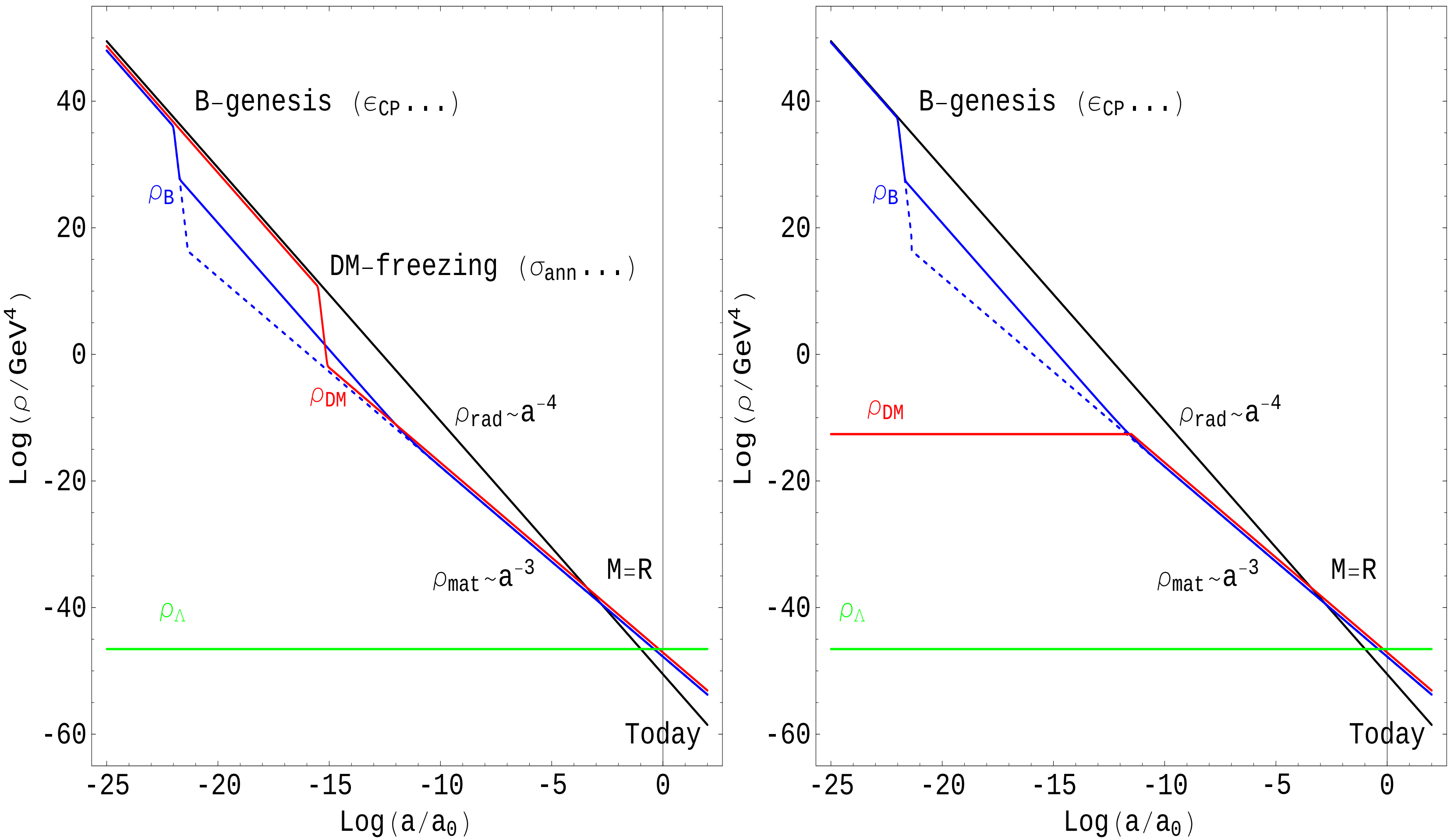
Axion : $M_X \sim 10^{-5}$ eV;

LSP : $M_X \sim 1$ TeV ,

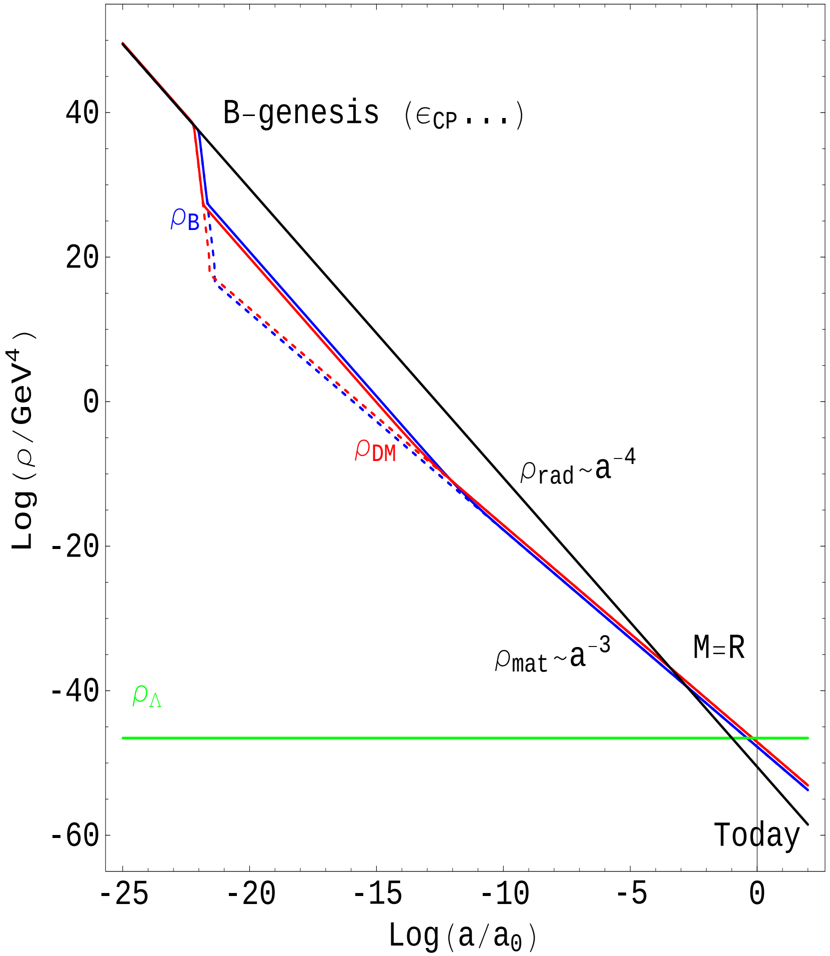
Wimpzilla : $M_X \sim 10^{14}$ GeV

B vs D

Cosmological evolution of Baryon and dark matter densities:



Unified origin of VM and DM?



$$\rho_X/\rho_B = M_X n_X / M_N n_B \sim 1 \; ?$$

- DM properties are similar to VM properties: $M_X \sim M_N$
- both fractions are generated by same mechanism: $n_X \sim n_B$

Mirror World

Imagine a parallel hidden "Mirror" sector of particles, an exact duplicate of the observable sector.

[Lee & Yang '56]

[Kobzarev, Okun, Pomeranchuk '66]

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Two identical gauge factors, $G \times G'$, with the identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ (exact parity under $G \leftrightarrow G'$)

SM×SM′: $SU(3) \times SU(2) \times U(1) \quad \times \quad SU(3)' \times SU(2)' \times U(1)'$,

or GUT×GUT′: $SU(5) \times SU(5)'$, $SO(10) \times SO(10)'$, etc.

- Can naturally emerge in string theory context:

O & M matter fields are localized on two parallel branes (or on brane & antibrane) while gravity propagates in bulk ($E_8 \times E_8$ etc.)

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- Spontaneously broken $G \leftrightarrow G'$: $M'_W \neq M_W$ [Z.B. & Mohapatra '95]

shadow dark matter with rescaled spectrum [Z.B., Dolgov & Mohapatra '96]

Mirror Particles and Mirror Parity

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

gauge (g, W, Z, γ) gauge (g', W', Z', γ')

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

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

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– D-parity: $L\leftrightarrow L',\ R\leftrightarrow R',\ \ \phi\leftrightarrow\phi'$ – • $Y'=Y$ •

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– M-parity: $L \leftrightarrow R', \; R \leftrightarrow L', \;\; \phi \leftrightarrow \tilde\phi'$ – • $Y' = Y^\dagger$ •

O & M interactions besides gravity

- Higgs-Higgs′ quartic: $\lambda(\phi^\dagger\phi)(\phi'^\dagger\phi')$; BBN: $\lambda < 10^{-8}$

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- neutrino-neutrino′ mixing: $\frac{A}{M}ll\phi\phi + \frac{A'}{M}l'l'\phi'\phi' + \frac{D}{M}ll'\phi\phi'$

  [Foot and Volkas '95]

  M-parity: $A' = A^*$, $D = D^\dagger$ [Z.B. and Mohapatra '95]

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

  - if $v = v'$ – maximal mixing $\theta_{\nu\nu'} = 45^\circ$
  - If $v' > v$, $m_{\nu'} \sim \zeta m_\nu$ and $\theta_{\nu\nu'} \sim \zeta^{-1}$; $\zeta = v'/v \sim 100$;

  $\zeta \sim 10^2$: $\sim$ keV sterile neutrinos (WDM) [Z.B. Dolgov, Mohapatra '96]

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

See-saw: heavy singlet neutrinos as messengers

- Introduce heavy gauge singlet fermions $N_a, \quad a = 1, 2, 3, ...$ with large Majorana mass terms $\frac{1}{2}(M_{ab}N_aN_b + M^*_{ab}\tilde{N}_a\tilde{N}_b)$,

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- After decoupling heavy neutrinos, effective operators $\frac{A}{M} l l \phi \phi \; + \; \frac{A'}{M} l' l' \phi' \phi' \; + \; \frac{D}{M} l l' \phi \phi'$ are generated,

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- They generate also processes like $l\phi \to \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \to \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) , which

  A. violate L (and so $B - L$) [Sakharov '67]

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  C. should be out-of-equilibrium

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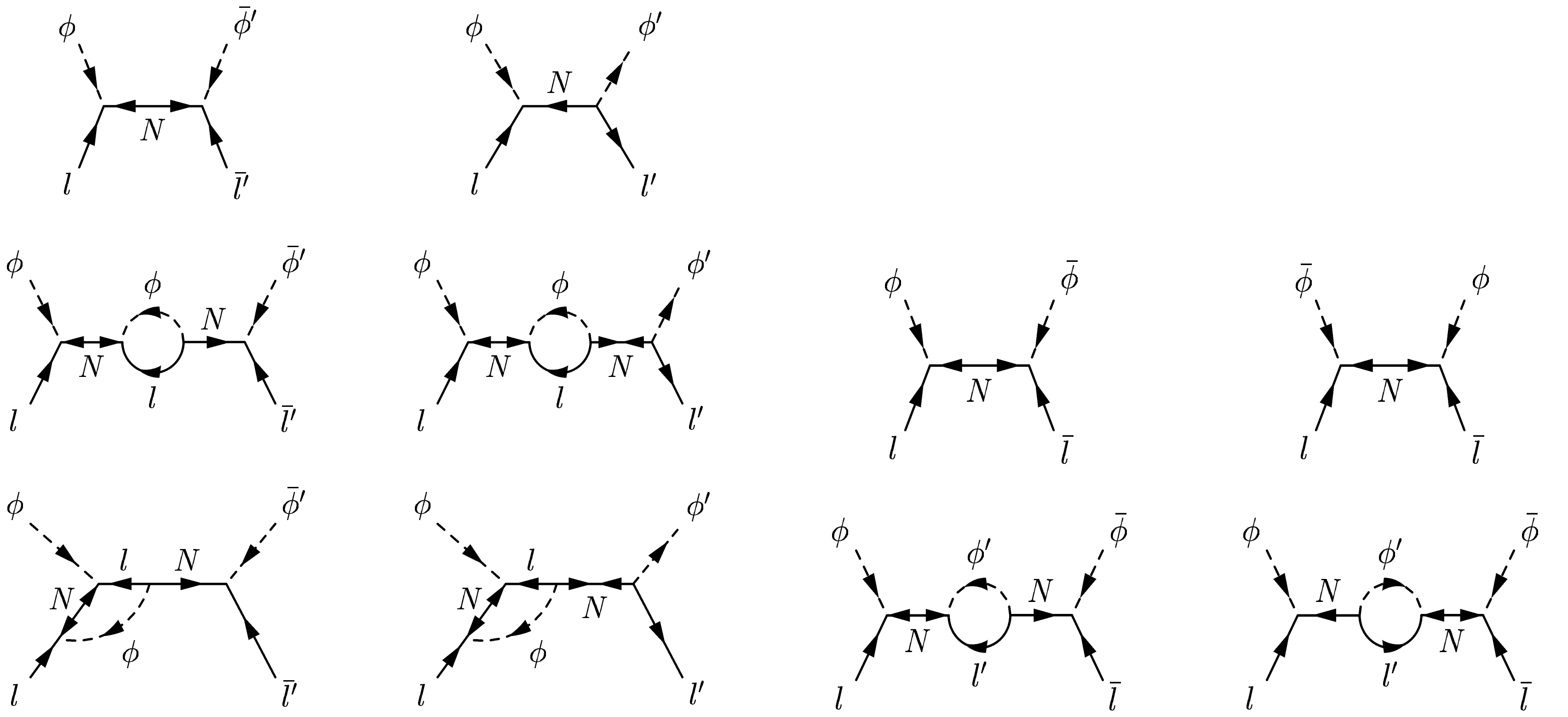
- A paradigm:
  – After inflation O and M worlds are (re)heated in non-symmetric way, $T' < T$;
  – The processes between O and M particles are slow enough and are out-of-equilibrium
  – both sectors evolve adiabatically, without significant entropy production, and $x = T'/T$ remains nearly constant at later epochs

CP violation in ∆L=1 and ∆L=2 processes



[Z.B. and L. Bento '01]

Boltzmann Eqs.

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

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

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

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

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

$$\Delta\sigma' = -\Delta\sigma = \frac{3\varepsilon_{CP}\, S}{32\pi^2 M^4}$$

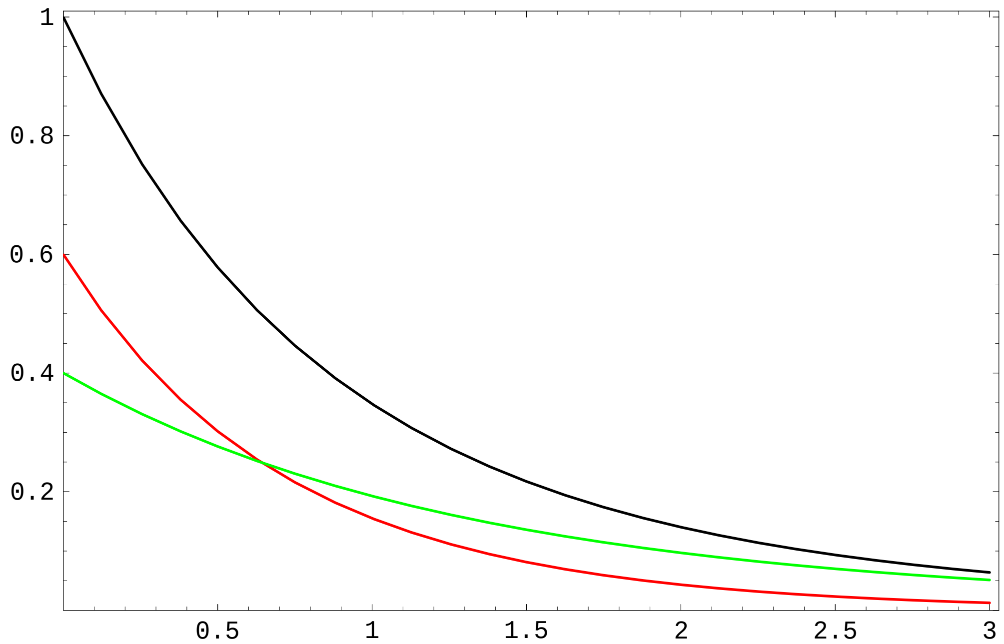
where $S \sim 16T^2$ is the c.m. energy square,

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

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

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

Exact M-parity: $M'_N = M_N$



$n_B/n'_B = D(k), \qquad k = [\Gamma_{\rm eff}/H]_{T=T_R}$: $\qquad \Omega_B/\Omega'_B \simeq 0.15 - 1$

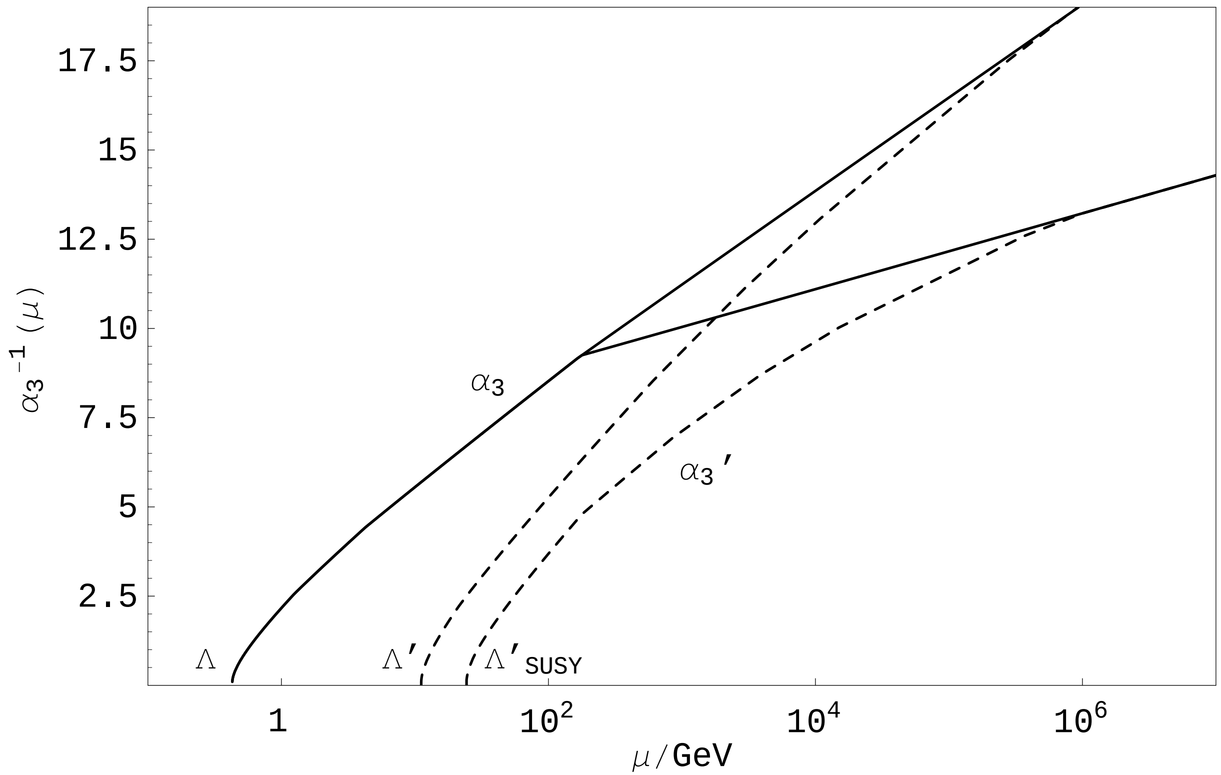
Depletion factor $D(k) = \frac{3}{5}\, e^{-k} F(k) + \frac{2}{5}\, G(k)$; for $k \ll 1$, $D(k) = 1$

$F(k) = \frac{1}{4k^4}\left[(2k-1)^3 + 6k - 5 + 6e^{-2k}\right]$: $\quad T > T_R$,

$G(k) = \frac{3}{k^3}\left[2 - (k^2 + 2k + 2)e^{-k}\right]; \quad T < T_R$

Heating: $\Delta N_\nu \simeq k/g_* \quad x = (k/6g_*)^{1/4} < 0.2$: $\quad k \leq 2$, (LSS)

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



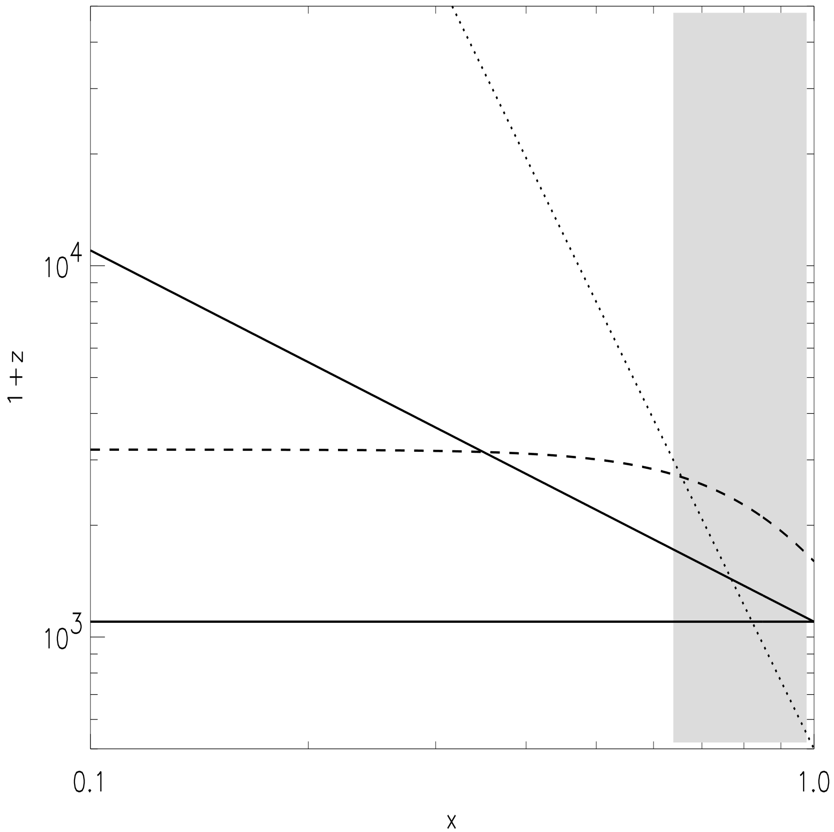
$n'_B \simeq n_B$ $\quad\quad k < 1$ (robust non-equilibrium)

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

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

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

Redshifts

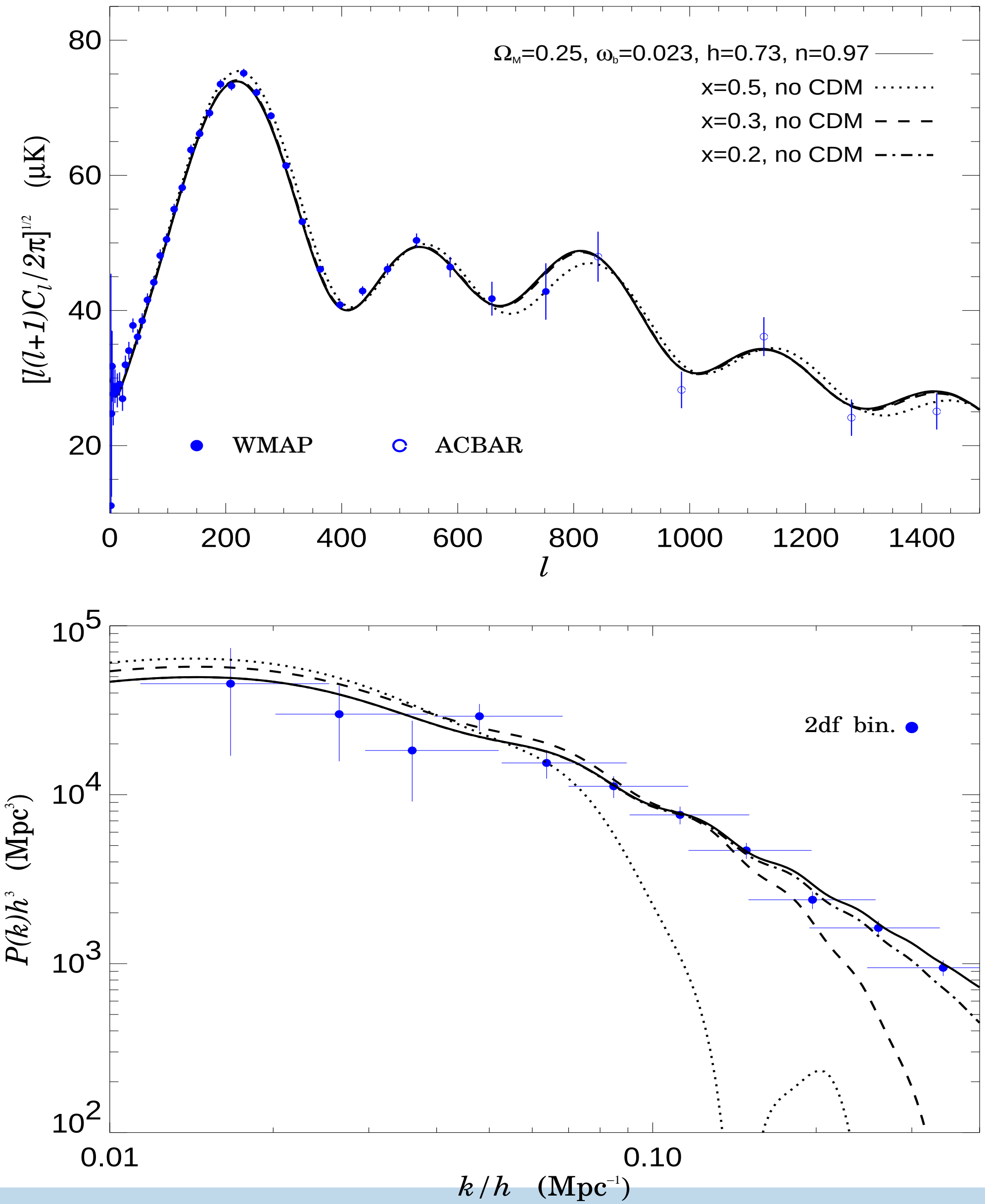


$z'\mathrm{dec} \simeq x^{-1} z_{\mathrm{dec}} \qquad x_{\mathrm{eq}} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

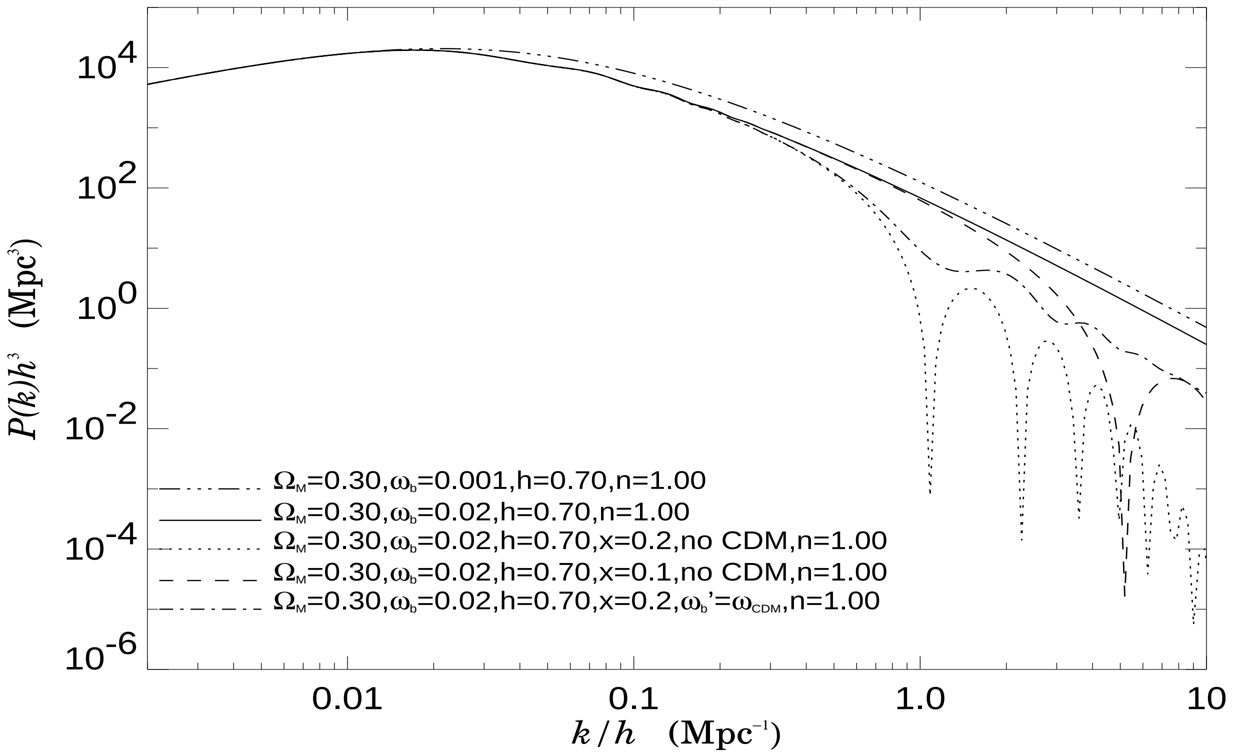
for $x < x_{\mathrm{eq}}$ $M_J \ll M_H$

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

CMB & LSS power spectra

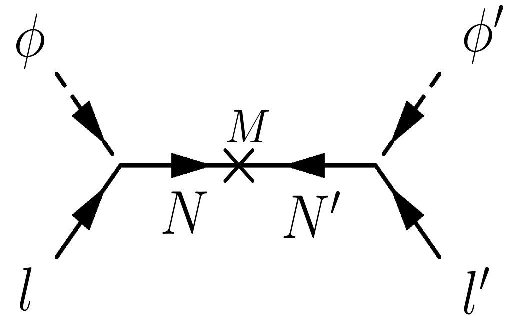


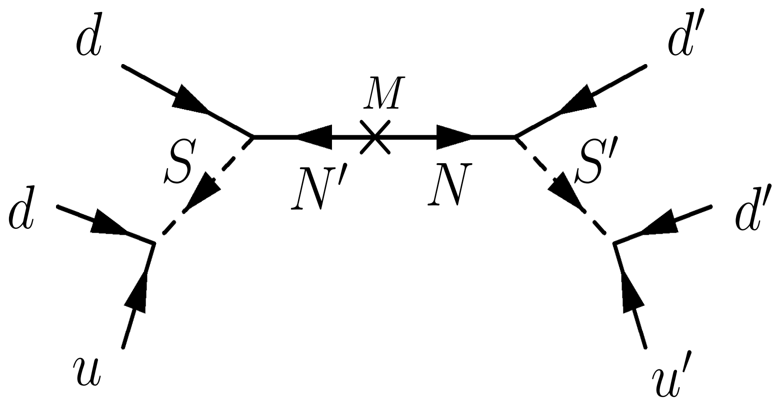
LSS power spectra



Neutron - Mirror neutron oscillation

B-genesis is possible via [Z.B. and L. Bento '06]





$$\frac{1}{\mathcal{M}^5}(udd)(u'd'd') + \frac{1}{\mathcal{M}^5}(qqd)(q'q'd') + \text{h.c.} \quad \to \quad \delta m\,(\overline{n}n' + \overline{n}'n)$$

$\delta m \sim \left(\frac{10\,\text{TeV}}{\mathcal{M}}\right)^5 \times 10^{-15}\,\text{eV}$!!! $\delta m^{-1} = \tau_{\text{osc}} \sim 1$ sec is allowed !!! .

Anomalous Neutron Loses, Lifetime measurements, UHECR, ...