

Mirror Dark Matter

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Cosmic Coincidence & Fine Tuning Problems

Today's Universe is flat ($\Omega_{\text{tot}} \approx 1$) and multi-component:

- $\Omega_B \simeq 0.04$ observable matter – Baryons !
- $\Omega_D \simeq 0.20$ dark matter: – WIMPS? Axions?
- $\Omega_\Lambda \simeq 0.75$ dark energy: – Λ -term? 5th-essence?

A. coincidence of matter $\Omega_M = \Omega_D + \Omega_B$ and dark energy Ω_Λ : $\Omega_M / \Omega_\Lambda \simeq 0.3$

· $\rho_\Lambda \sim \text{Const.}$, $\rho_M \sim a^{-3}$; **why** $\rho_M / \rho_\Lambda \sim 1$ – just Today?

Anthropic answer: if not **Today**, then it could be **Yesterday** or **Tomorrow** ...

B. Fine Tuning between visible Ω_B and dark Ω_D matter: $\Omega_B / \Omega_D \simeq 0.2$

· $\rho_B \sim a^{-3}$, $\rho_D \sim a^{-3}$; **why** $\rho_B / \rho_D \sim 1$ – **Yesterday Today & Tomorrow?**

Difficult question ... popular models for the primordial Baryogenesis (GUT-B, Lepto-B, Spont. B, Affleck-Dine B, EW B, ...) have no feeling for the popular DM candidates (Wimp, Wimpzilla, axion, axino, gravitino ...)

– **How Baryon Asymmetry could know about Dark Matter?** – again anthropic (landscaped) Fine Tunings in Particle Physics and Cosmology? Just for our good?

● Present Cosmology

- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carroll's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
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Visible vs. Dark matter

- Visible matter: $\rho_B = n_B M_B$, $M_B \simeq 1 \text{ GeV}$ – 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: $\rho_D = n_X M_X$, but $M_X = ?$, $n_X = ?$

– too wide spectrum of possibilities ...

Axion: $M_X \sim 10^{-5} \text{ eV}$; **Wimp:** $M_X \sim 1 \text{ TeV}$; **Wimpzilla:** $M_X \sim 10^{14} \text{ GeV}$...

– in relative models n_X depends on various 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?

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● B & L violation

● Neutrino Mixing

● BBN demands

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● Leptogenesis: diagrams

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● VM and DM

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● LSS

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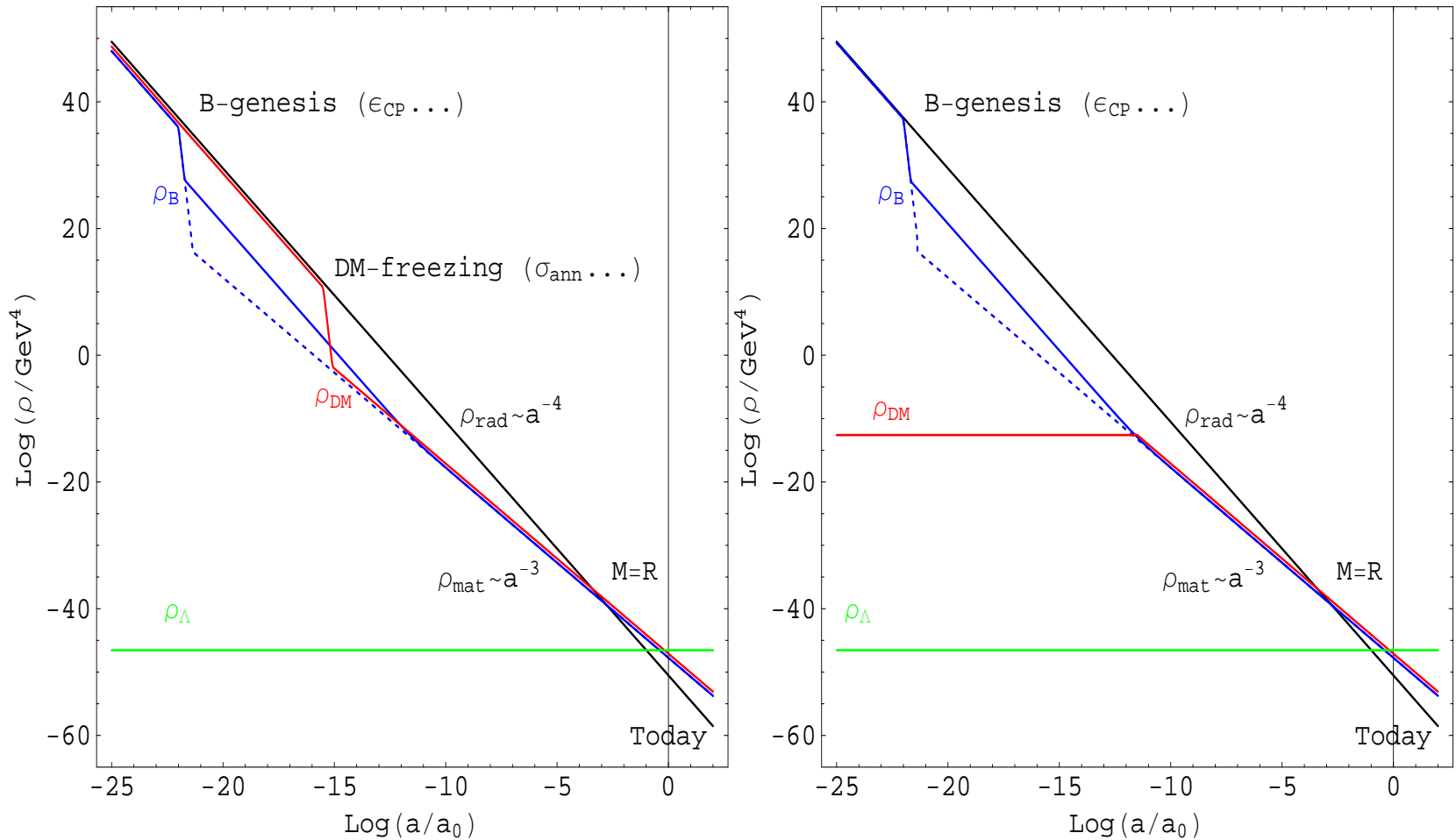
● Neutron mixing

● Mirror gravity

● Mirror gravity

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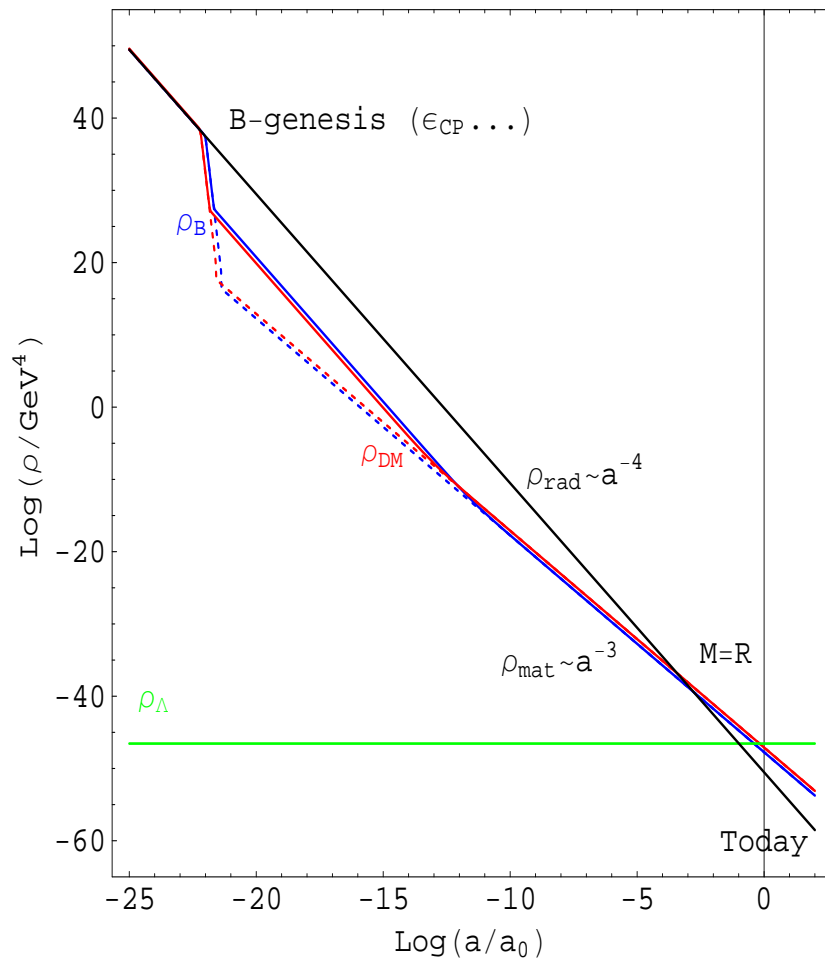
B vs. D – Fine Tuning demonstration



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

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

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- Visible vs. Dark matter
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- **Unification**
- Carrol's Alice...
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- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
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$$\frac{M_X n_X}{M_B n_B} \sim 1 \quad \text{dark gauge sector?}$$

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

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

'How would you like to leave in the Looking-glass House, Kitty? I wonder if they'd give you milk in there? But perhaps Looking-glass milk isn't good to drink? Now we come to the passage: it's very like our passage as far as you can see, only you know it may be quite on beyond. Oh, how nice it would be if we could get through into Looking-glass House! Let's pretend there's a way of getting through into it, somehow ... Why, it's turning into a sort of mist now, I declare! It'll be easy enough to get through ...'

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

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

Broken P can be restored by mirror fermions

Lee & Yang '56

Mirror sector hidden copy of our sector

Kobzarev, Okun, Pomeranchuk '66

Alice strings

A.S. Schwarz' 82

Mirror dark matter (invisible stars)

Blinnikov, Khlopov '83

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

Foot, Lew, Volkas '91

Two identical gauge factors, $G \times G'$, with the identical field contents and Lagrangians: $\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}} - SU(5) \times SU(5)', \text{ etc.}$

- Can naturally emerge in string theory: O & M matter fields localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$

- Exact parity $G \leftrightarrow G'$: Mirror matter is dark (for us), but its particle physics we know exactly – no new parameters!

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

Particle spectrum rescaled by $\zeta = M'_W/M_W$

ZB & Mohapatra '95

Shadow DM, sterile neutrinos, Machos

ZB, Dolgov, Mohapatra '96

Strong CP and new axion (axidragon)

ZB, Gianfagna, Giannotti '00

SUSY little Higgs – accidental global $U(4)$

ZB '04, Falkowski, Pokorski, Shmalz 06

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- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Mirror Sector, Mirror Particles & Mirror Parity

$SU(3) \times SU(2) \times U(1)$
gauge (g, W, Z, γ)
& Higgs (ϕ) fields

$SU(3)' \times SU(2)' \times U(1)'$
gauge (g', W', Z', γ')
& Higgs (ϕ') fields

quarks ($B=1/3$)	leptons ($L=1$)		quarks ($B'=1/3$)	leptons ($L'=1$)
$q_L = (u, d)_L^t$	$l_L = (\nu, e)_L^t$		$q'_L = (u', d')_L^t$	$l'_L = (\nu', e')_L^t$
$u_R \quad d_R$	e_R		$u'_R \quad d'_R$	e'_R
$\widetilde{\text{quarks}} (B=-1/3)$	$\widetilde{\text{leptons}} (L=-1)$		$\widetilde{\text{quarks}} (B'=-1/3)$	$\widetilde{\text{leptons}} (L'=-1)$
$\tilde{q}_R = (\tilde{u}, \tilde{d})_R^t$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})_R^t$		$\tilde{q}'_R = (\tilde{u}', \tilde{d}')_R^t$	$\tilde{l}'_R = (\tilde{\nu}', \tilde{e}')_R^t$
$\tilde{u}_L \quad \tilde{d}_L$	\tilde{e}_L		$\tilde{u}'_L \quad \tilde{d}'_L$	\tilde{e}'_L

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

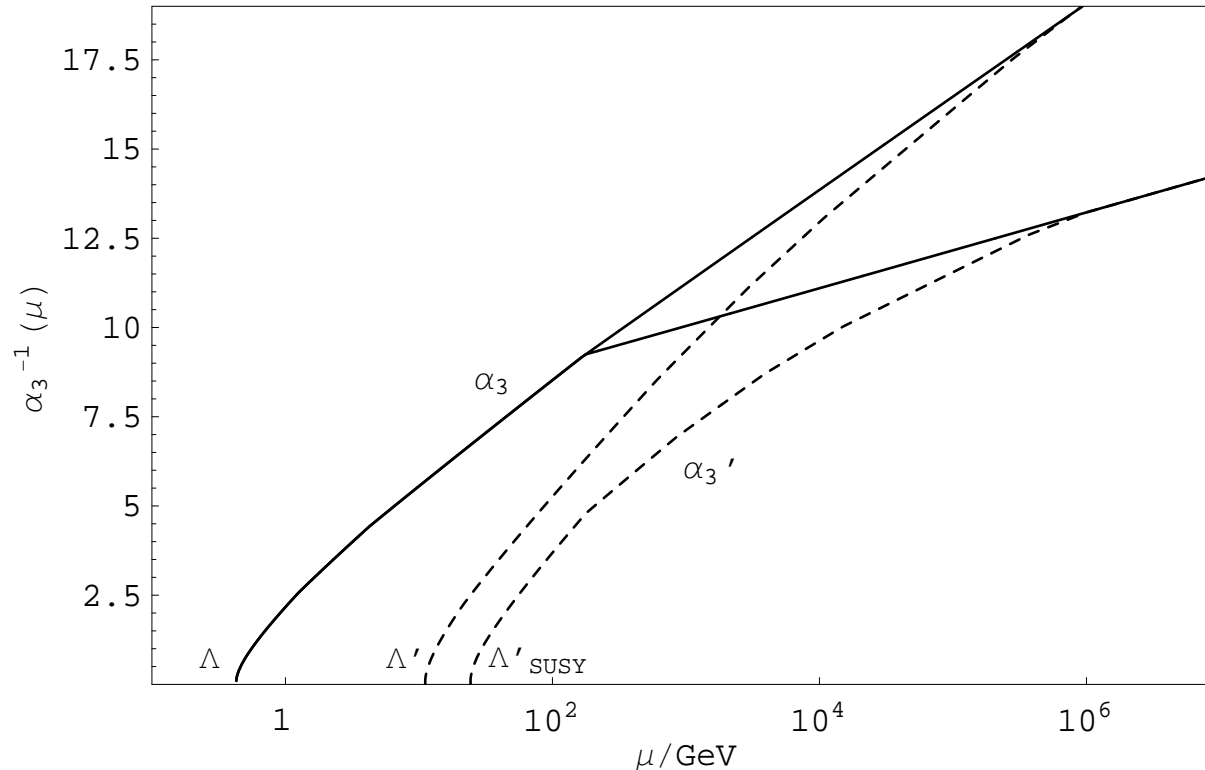
- D-parity: $L \leftrightarrow L', R \leftrightarrow R', \phi \leftrightarrow \phi' : Y' = Y$ • *identical xero copy*
- M-parity: $L \leftrightarrow R', R \leftrightarrow L', \phi \leftrightarrow \tilde{\phi}' : Y' = Y^\dagger$ • *mirror (chiral) copy*

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- **Mirror Particles**
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

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

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

Z.B., Dolgov & Mohapatra '96



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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Possible interactions between O & M particles (besides gravity)

(but also model of mirror gravity can be constructed !)

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

another interesting story !

Z. Berezhiani, Phys. Lett. B 417, 287 (1998)

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

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

mirror particles become "millicharged" $Q' \sim \epsilon Q$ relative to our photon

→ *positronium - mirror positronium mixing ($e^+ e^- \rightarrow e'^+ e'^-$)* *Glashow '86*

... but BBN : $\epsilon < 10^{-8}$, CMB+LSS : $\epsilon < 5 \times 10^{-10}$ *ZB, Lepidi '08*

■ meson - mirror meson mixing: $\pi^0 - \pi^{0'}$, $K^0 - K^{0'}$, $\rho^0 - \rho^{0'}$, etc.

$$\frac{1}{M^2} (\bar{u} \gamma^5 u - \bar{d} \gamma^5 d) (\bar{u}' \gamma^5 u' - \bar{d}' \gamma^5 d'), \quad \frac{1}{M^2} (\bar{d} \gamma^5 s) (\bar{d}' \gamma^5 s') \quad (\Delta S = 1)$$

... analogous to $\frac{1}{M^2} (\bar{d} \gamma^5 s) (\bar{d} \gamma^5 s) \rightarrow K^0 - \bar{K}^0$ mixing $(\Delta S = 2)$

Phenom. limits: $M > 10 \text{ TeV}$ ($\pi^0 - \pi^{0'}$), $M > 100 \text{ TeV}$ ($K^0 - K^{0'}$)

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Lepton & baryon number violating interactions

- neutrino - mirror neutrino mixing ($\nu - \nu'$) – effective operators :
Z. Berezhiani, R.N. Mohapatra, Phys. Rev. D 52, 6607 (1995)

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

analogous to $\frac{1}{M} (l\phi)^2 \quad (\Delta L = 2), \quad \frac{1}{M} (l'\phi')^2 \quad (\Delta L' = 2)$

– operators that generate neutrino Majorana masses via **seesaw** mechanism
 constraints from active-sterile neutrino mixing

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

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

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

generate neutron - antineutron mixing

- hydrogen - mirror hydrogen mixing – effective operators :

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

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions

- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

O & M neutrino mixing

Mixed $D=5$ effective operators

Z.B. & Mohapatra '95

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

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

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

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

• $v' = v$: $m_{\nu\nu'} = m_\nu$ and maximal mixing $\theta_{\nu\nu'} = 45^\circ$; Foot & Volkas '95

• $v' > v$: $m_{\nu\nu'} \sim (v'/v)^2 m_\nu$ and small mixing $\theta_{\nu\nu'} \sim v/v'$;

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

• $A, A' = 0$ ($L - L'$ conserved) light – Dirac neutrinos Z.B. & Bento '05
with L components in ordinary sector and R components in mirror sector

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

BBN demands : was Alice's guess correct?

Mirror particle physics \equiv ordinary particle physics

but mirror cosmology \neq ordinary cosmology

■ at the BBN epoch, $T \sim 1 \text{ MeV}$, $g_* = g_*^{SM} = 10.75$
as contributed by the γ , e^\pm and 3ν species : $N_\nu = 3$

■ if $T' = T$, mirror world would give the same contribution:

$$g_*^{\text{eff}} = 2 \times g_*^{SM} = 21.5 \text{ – equivalent to } \Delta N_\nu = 6.14 \text{ !!!}$$

■ If $T' < T$, then $g_*^{\text{eff}} \approx g_*^{SM} (1 + x^4)$, $x = T'/T \longrightarrow \Delta N_\nu = 6.14 \cdot x^4$
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 ($T'_{\text{CMB}}/T_{\text{CMB}}$ today)

BBN: $\Delta N_\nu/6.14 = x^4 \ll 1 \longrightarrow$ BBN': $\Delta N'_\nu/6.14 = x^{-4} \gg 1$

^1H 75%, ^4He 25% vs. $^1\text{H}'$ 25%, $^4\text{He}'$ 75%

Z. Berezhiani, D. Comelli, F. Villante, Phys. Lett. B 503, 362 (2001)

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Mixed Seesaw and Leptogenesis between O & M sectors

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

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

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

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

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

- They generate also processes like $l\phi \rightarrow \tilde{l}'\tilde{\phi}'(l'\phi')$ ($\Delta L = 1$) and $l\phi \rightarrow \tilde{l}\tilde{\phi}$ ($\Delta L = 2$) satisfying Sakharov's 3 conditions for baryogenesis

A. violate B-L – *by definition*

B. violate CP – *complex Yukawa constants y_{ia}*

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

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

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

Both matter fractions: observable and dark, can be generated at one shoot !!

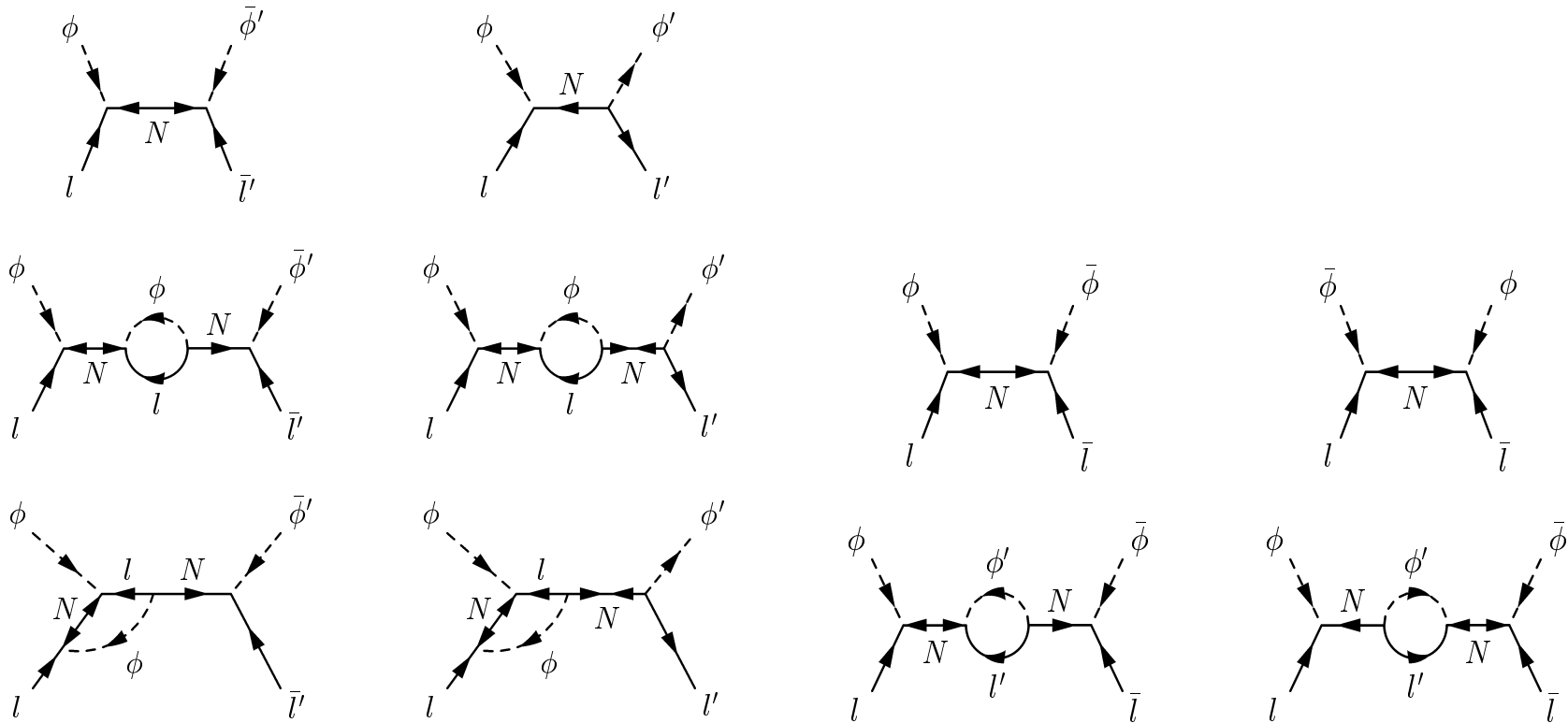
- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands

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- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

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

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



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

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

$$\varepsilon_{CP} \rightarrow \varepsilon'_{CP}$$

$$\text{when } y \rightarrow y'$$

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw

Leptogenesis: diagrams

- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Boltzmann Eqs.

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

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

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

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

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

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

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

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

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

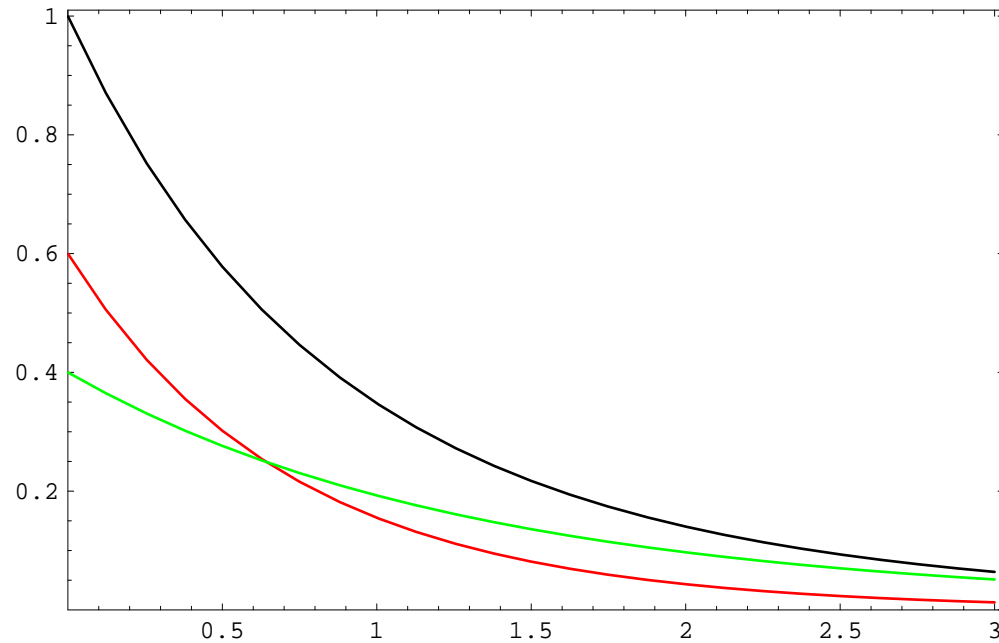
$$Y_{BL}^{(0)} \approx 2 \times 10^{-3} \frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4} .$$

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

$$M'_B = M_B \dots \text{but } n'_B > n_B$$

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

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



Z.B. '03

$$\text{BBN: } x < 0.5 \rightarrow k \leq 4; \quad \text{LSS: } x < 0.2 \rightarrow k \leq 1.5$$

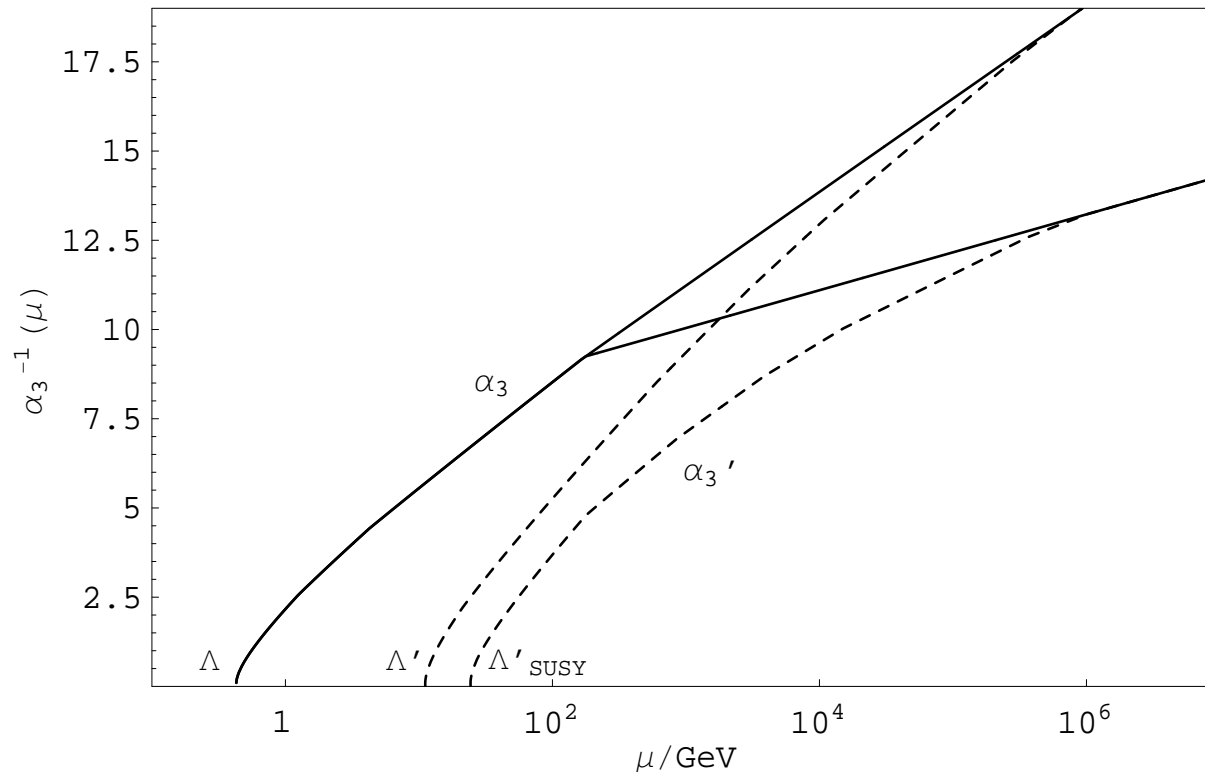
Thus Ordinary/Mirror matter ratio can vary within $\frac{\Omega_B}{\Omega'_B} = D(k) \simeq 0.2 - 1$

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- **Leptogenesis: formulas**
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

$$n'_B = n_B \dots \text{but } M'_B > M_B$$

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

Z.B., Dolgov & Mohapatra '96



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

$M'_N/M_N \simeq (\Lambda'/\Lambda)$ 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 : $M'_W \sim 10 \text{ TeV}$?

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

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: $z'_{\text{dec}} \simeq \frac{1}{x} z_{\text{dec}}$

However, if the DM is entirely due to mirror baryons, then the large scale structure (LSS) formation requires that mirror photons must decouple before Matter-Radiation Equality epoch: $x < x_{\text{eq}} = 0.05(\Omega_M h^2)^{-1} \simeq 0.3$

- 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:

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

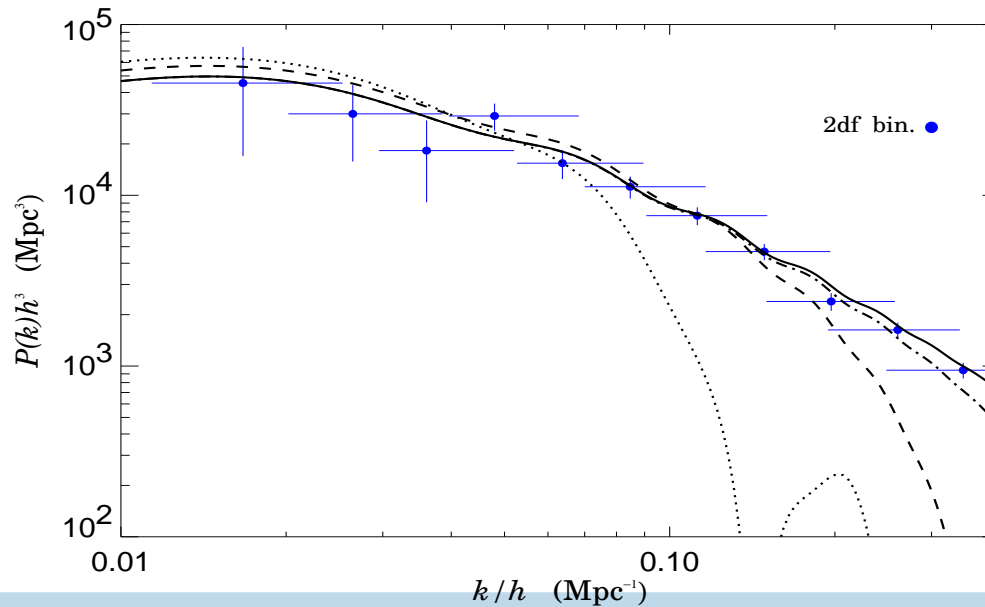
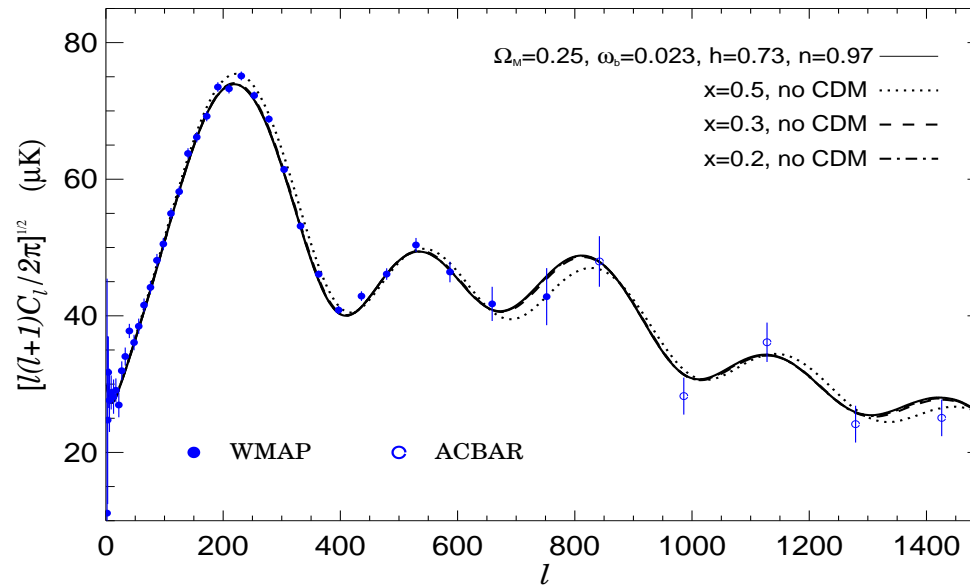
Hence the structures formation at 1 Mpc scales (galaxies) implies $x < 0.2$

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: $M_{\text{av}} = 0.5 M_{\odot}$

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

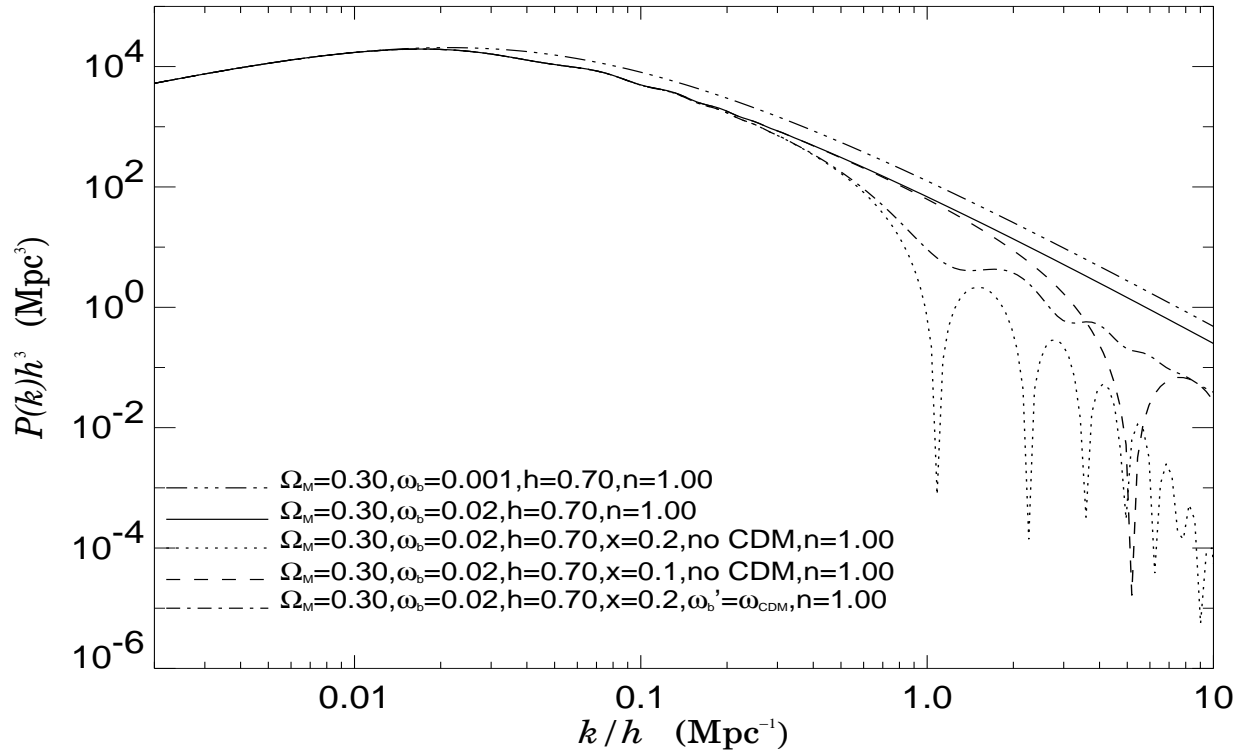
CMB & LSS power spectra



- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

LSS power spectra

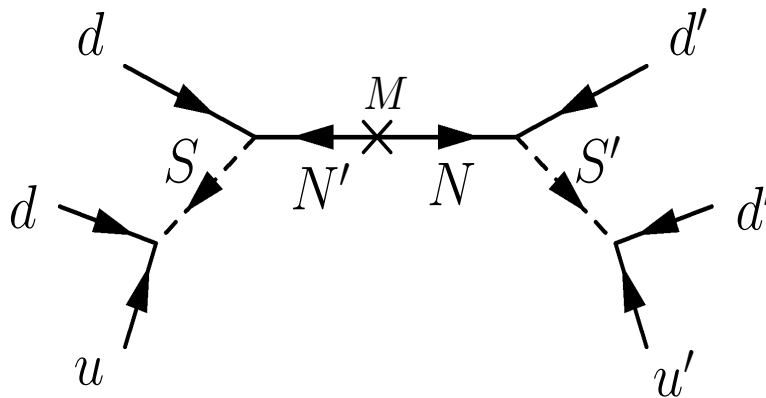
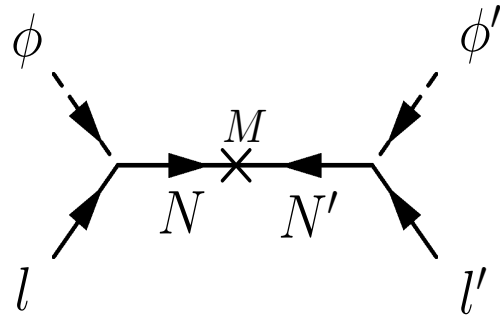
Z.B., Ciarcelluti, Comelli & Villante, '03



- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- **LSS**
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Leptogenesis or Baryogenesis?

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



Z.B. and Bento '05

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Neutron - Mirror neutron mixing

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

• $n - n'$ oscillation in vacuum:

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

... similar to neutron - antineutron oscillation

Kuzmin '70, Glashow '79

Marshak & Mohapatra '80

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

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

(see diagram of the previous page)

!!! N.B. Nuclear Stability

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

$\tau_{n\tilde{n}} > 10 \text{ yr}$ or so ...

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Experimental limits & and future search

- ILL experiment for $n - \tilde{n}$ oscillation search in flight: $t \simeq 0.1$ s, $B < 10^{-4}$ G
 - no \tilde{n} event found, $\tau_{n\tilde{n}} > 10^8$ s (or > 3 yr) *Baldo Ceolin et al. '94*
 - as for $n - n'$: about 5% neutron deficit was observed, so taking

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

Recent Experimental search:

- $\tau > 2.7$ s Munich, Schmidt et al, Feb. 2007 (unpubl.)
 - $\tau > 103$ s ILL Grenoble, Ban et al. May 2007, axXiv:0705.2336 [nucl-ex]
 - $\tau > 414$ s ILL Grenoble, Serebrov et al. June 2007, axXiv:0706.3600 [nucl-ex]
- Future experiments can reach sensitivity $\tau \sim 10^4$ s (DUSEL ??)*

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

Neutron - Mirror neutron mixing in astrophysics

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

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

• *If $\tau_{nn'} < 10^3$ s, $n - n'$ oscillation provides an elegant mechanism for the transport of the ultra high energy cosmic rays at the large cosmological distances without suffering significant energy depression, and could be of interest in the search of the UHECR above the GZK cutoff and their correlation with the far distant astrophysical objects (BL Lacs, GRB's etc.)*

Z.B. & Bento '05

• *Fast $n - n'$ oscillation could have interesting implications also for the neutrons from the solar flares*

Mohapatra, Nasri, Nussinov '05

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity

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

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

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

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

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

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

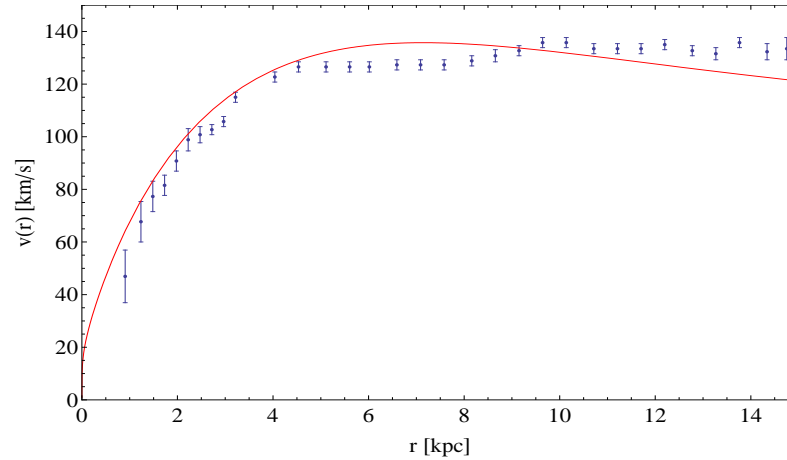
– *bi-gravitational potential:* $\phi(r) = \frac{G}{2r} (M + M') + \frac{G e^{-\frac{r}{r_g}}}{2r} (M - M')$

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

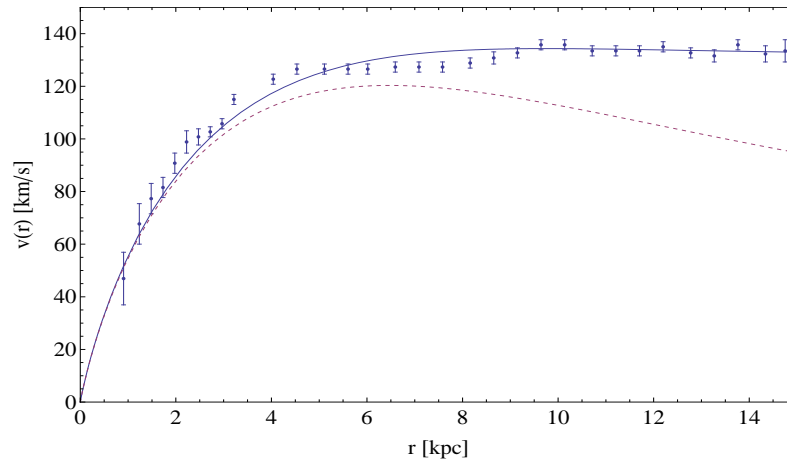
$\rho_{\text{st}} = \frac{3H_0^2}{8\pi G} \quad G_{\text{cosm}} \rightarrow \frac{1}{2}G \quad \rightarrow \quad \rho_{\text{new}} \rightarrow 2\rho_{\text{st}}$

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- **Mirror gravity**
- Mirror gravity
- Mirror gravity

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



with CDM, NFW profile



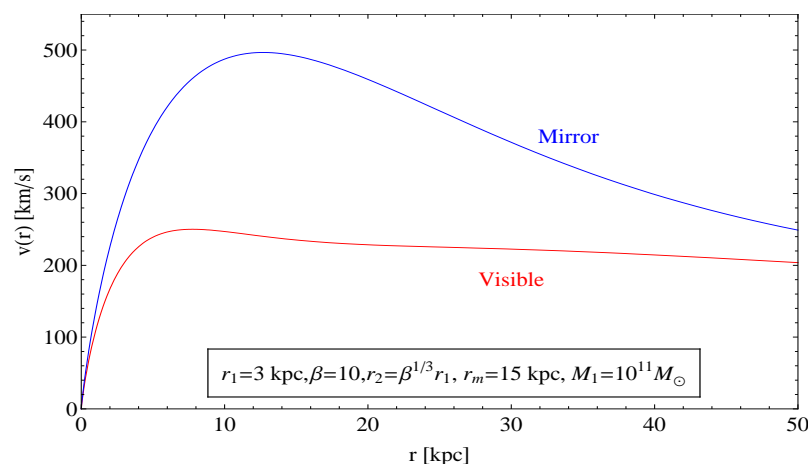
with bi-gravity, two-discs

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

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity

Implications for Dark Matter search

rotational curves for ordinary and mirror components



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

(b) galactic velocities of mirror component (blue curve) are much larger than that of ordinary one (red curve)

$$E'_{\text{kin}} \approx 10 E_{\text{kin}} \quad \text{for the same mass}$$

light DM particles ? Hydrogen', Helium'

... interacting via photon-photon' kinetic mixing, $\pi - \pi'$ mixing etc.

- Present Cosmology
- Visible vs. Dark matter
- B vs. D – Fine Tuning demonstration
- Unification
- Carrol's Alice...
- Mirror World
- Mirror Particles
- VM and DM
- Interactions
- B & L violation
- Neutrino Mixing
- BBN demands
- See-Saw
- Leptogenesis: diagrams
- Boltzmann Eqs.
- Leptogenesis: formulas
- VM and DM
- Epochs
- CMB
- LSS
- Neutron mixing
- Neutron mixing
- Experiment
- Neutron mixing
- Mirror gravity
- Mirror gravity
- Mirror gravity