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Workshop on Grand Unification and Proton Decay

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Baryon number violation - how fast it could be?

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Baryon Number Violation – How Rapid It Could Be?

Neutron Oscillations

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Standard Cosmological Paradigm

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

The early Universe:

- multi-stage: Inflation $\to$ (re)heating $\to$ 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

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

- Why $\rho_{\rm M}/\rho_\Lambda \sim 1$ – just Today?

Well, if not Today, then it would be Yesterday or Tomorrow ...

Anthropic *"Our world is just that one where someone can ask why ..."*
or Voltairian *"Things go in best ways in our best of the worlds ..."*

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B) Miracle Fine Tuning between visible $\Omega_{\rm B}$ and dark $\Omega_{\rm D}$ matter

$\Omega_{\rm B}/\Omega_{\rm D} \simeq 0.2$: $\rho_{\rm B} \sim a^{-3}$, $\rho_{\rm D} \sim a^{-3}$.

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Visible matter – $\rho_{\rm B}$ – from primordial Baryogenesis
(GUT-B, Lepto-B, Spontaneous B, Affleck-Dine B, MSSM EW BB, ...)

Dark matter – $\rho_{\rm D}$ – emerges from quite a different mechanism
(Wimp, Wimpino, Wimpone, Wimpzilla, axion, axino, gravitino ...)

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– How Baryon Asymmetry knew about Dark Matter Nature ? – Fine Tuning Conspiracies across the Particle Physics and Cosmology?

Visible & dark matter

- Visible matter: $\rho_{\rm B} = n_{\rm B} M_N \simeq 10^{-7}$ GeV cm^{-3},

$M_N \simeq 1$ GeV – nucleon mass, $n_B = Y_{\rm B} \cdot s \simeq 10^{-7}$ cm^{-3}:
(today $s \simeq 3 n_\gamma \sim 10^3$ cm^{-3})

BBN, LSS & CMB: the baryon number/entropy density ratio
$Y_{\rm B} = n_{\rm B}/s \simeq 10^{-10}$ ($\sim$ Const. during Universe expansion)

(GUT, Lepto)-Baryogenesis: $Y_{\rm B} \sim (\epsilon_{CP}/g_*) \times D(k)$,
ϵ_{CP} – CP violation parameter,
g_* – effective number of particle degrees of freedom at $T = T_B$,
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- Dark matter: $\rho_{\rm D} = n_X M_X \sim 5 \times n_{\rm B} M_N$, LSS & CMB
  but $M_X = ?$, $n_X = ?$ – too wide spectrum ...

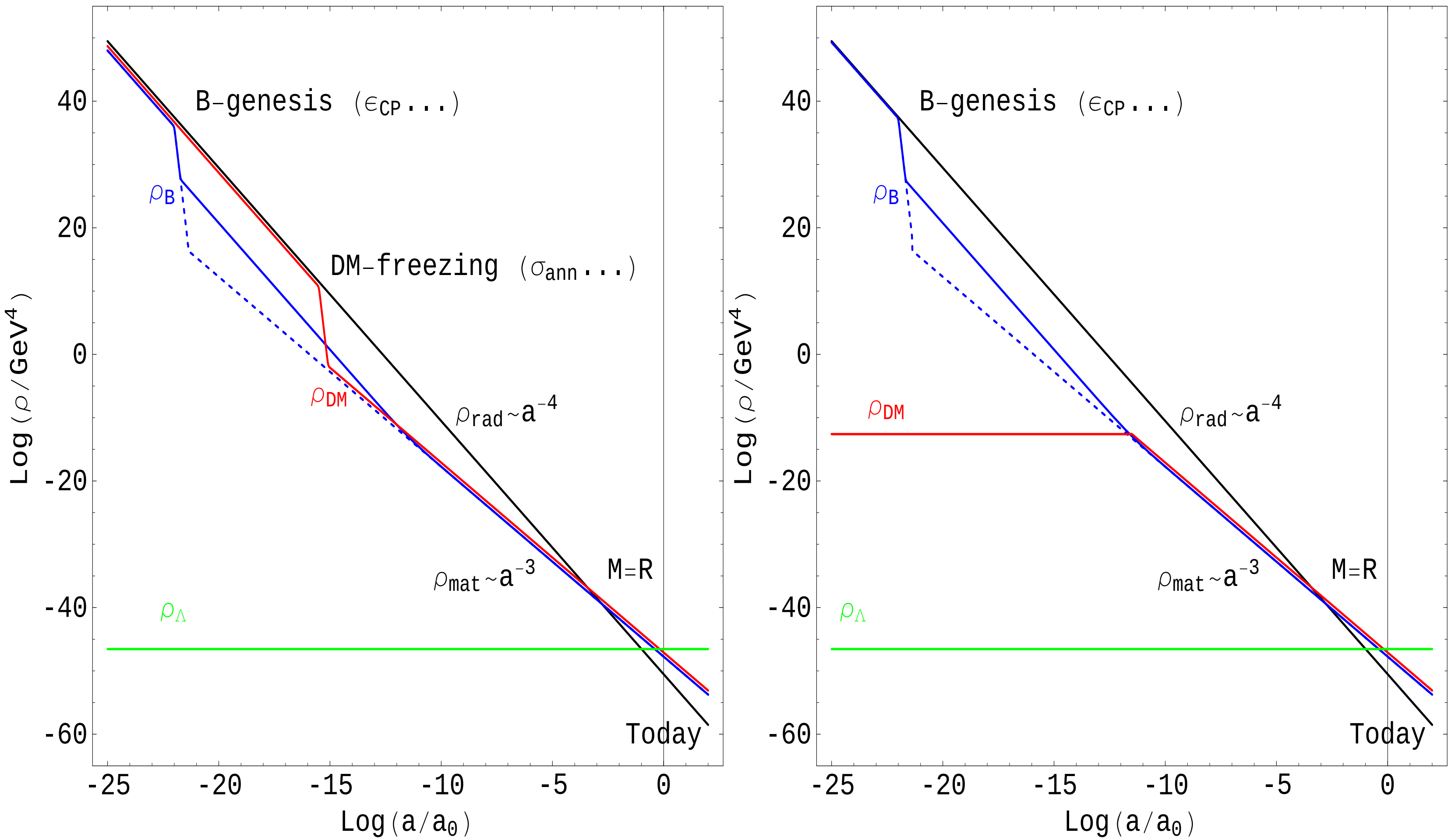
Axion : $M_X \sim 10^{-5}$ eV;

LSP : $M_X \sim 1$ TeV ,

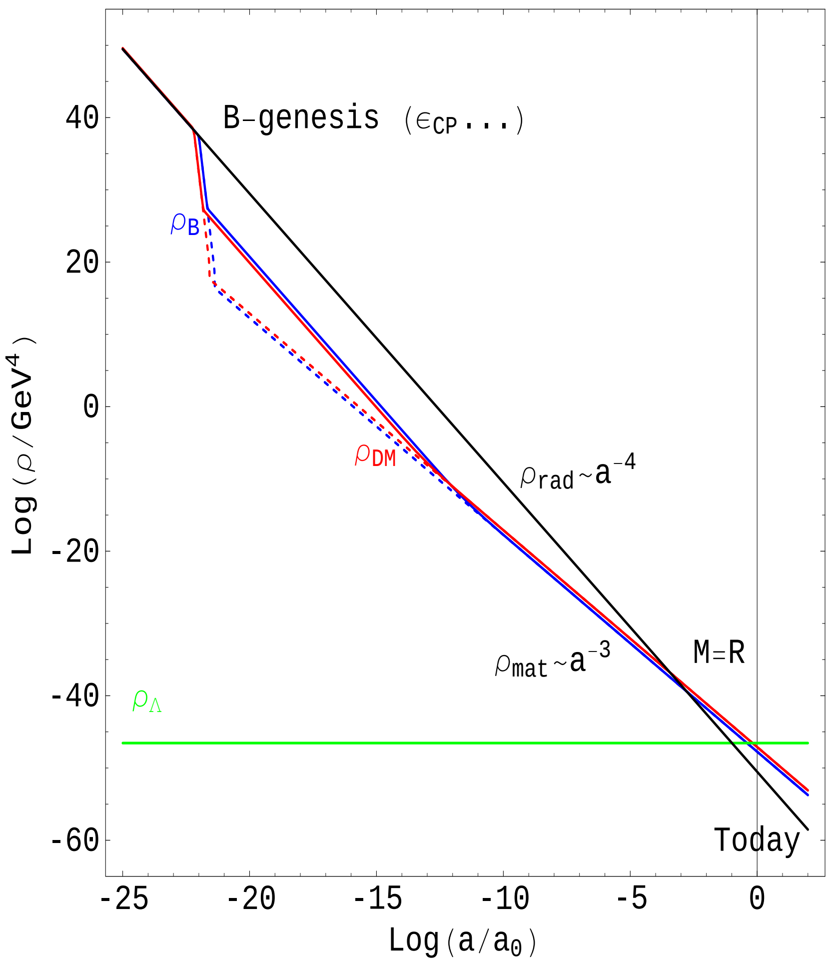
Wimpzilla : $M_X \sim 10^{14}$ GeV

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: $M_X \sim M_B$
- both fractions are generated by same mechanism: $n_X \sim n_B$

"Through the Looking-Glass" **Lewis Carroll**

'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 wander 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 worm 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'.

"Looking-Glass Universe" – Mirror World

Imagine a parallel "Mirror" sector of particles, — Lee & Yang '56
a hidden duplicate of ordinary sector, — Kobzarev, Okun, Pomeranchuk '66
coupled to us by gravity and so candidate of DM — Blinnikov, Khlopov '83

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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 $G \leftrightarrow G'$)

$SU(3)\times SU(2)\times U(1) \quad \times \quad SU(3)'\times SU(2)'\times U(1)'$, Foot, Lew, Volkas ’91

or better 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 $G \leftrightarrow G'$: $\zeta = M'_W/M_W \neq 1$
shadow DM with spectrum rescaled by ζ — Z.B. & Mohapatra '95
Z.B., Dolgov & Mohapatra '96

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

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

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

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

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

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  E.g. $\Delta N_\nu < 0.4$ requires $x < 0.5$; for $x = 0.3$ $\Delta N_\nu < 0.05$.
- 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

O & M interactions besides gravity

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

  ... safe in SUSY : $W = \frac{1}{M}(\phi_u\phi_d)(\phi'_u\phi'_d)$

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  Glashow '87

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  Z.B. & Mohapatra '95

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

- $v' = v$: $m_{\nu'} = m_\nu$ and *maximal* mixing $\theta_{\nu\nu'} = 45^\circ$ Foot & Volkas '95
- $v' > v$: $m_{\nu'} \sim (v'/v)^2 m_\nu$ and $\theta_{\nu\nu'} \sim v/v'$; 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 Z.B. & Bento '05

See-saw: heavy singlet neutrinos as messengers

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

$$y_{ia}\phi l_i N_a \; + \; y'_{ia}\phi' l'_i N_a \; + \; \frac{1}{2} M g_{ab} N_a N_b \; + \; \text{h.c.} \, ;$$

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- Integrating out heavy neutrinos, effective operators emerge that induce O (active) and M (sterile) neutrino masses & mixings

- $\frac{A}{M} l l \phi \phi \; + \; \frac{A'}{M} l' l' \phi' \phi' \; + \; \frac{D}{M} l l' \phi \phi'$;

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

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A. violate $B - L$

B. violate CP

C. should be out-of-equilibrium

and thus generate B-L≠0 ($\rightarrow$ B≠0 by sphalerons) Z.B. and Bento '01

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

(M: $\quad y' = y^\dagger, \;\; \rightarrow \;\; A' = A^*, \quad D = D^\dagger$)

- 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 baryogenesis conditions   Sakharov '67

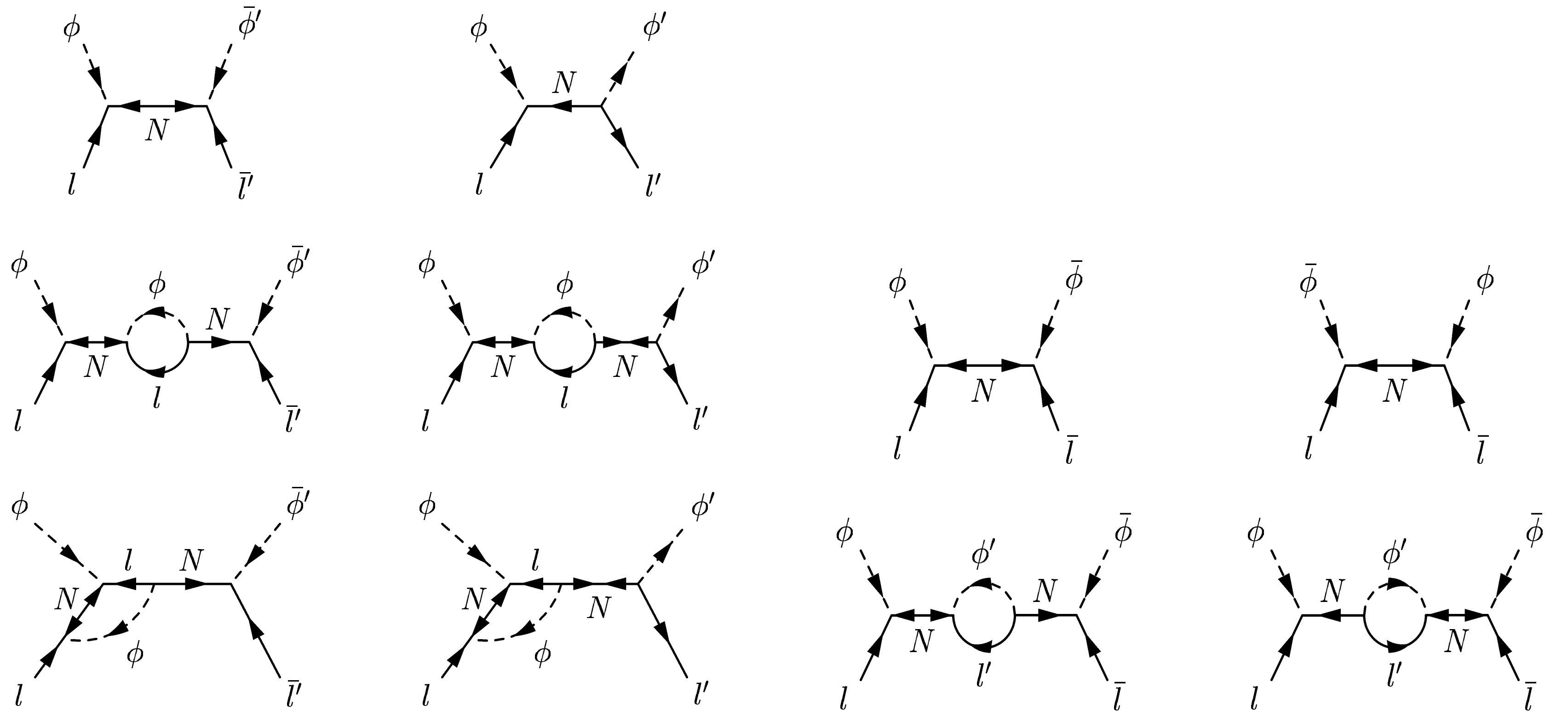
A. violate $B - L$

B. violate CP

C. should be out-of-equilibrium

and thus generate B-L≠0 ($\rightarrow$ B≠0 by sphalerons)   Z.B. and Bento '01

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



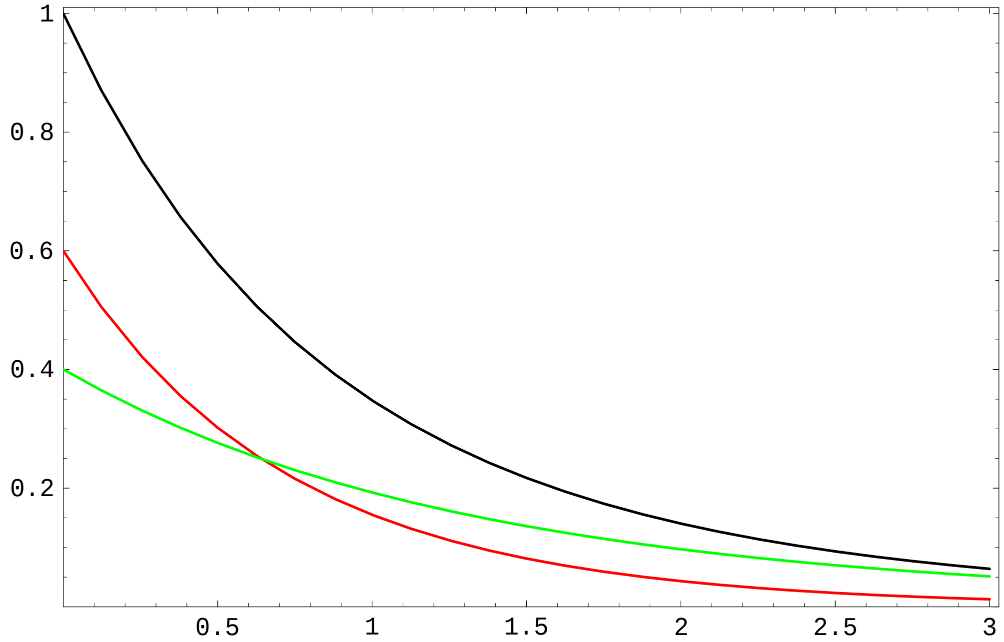
Z.B. and L. Bento '01

$M'_N = M_N$ ... *but* $\Omega'_B \geq \Omega_B$

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

$$k = [\Gamma_{\rm eff}/H]_{T=T_R}, \quad x = T'/T < 0.5\ , \quad Y_{BL}^{(0)} \approx 2 \times 10^{-3} \frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}\ .$$

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

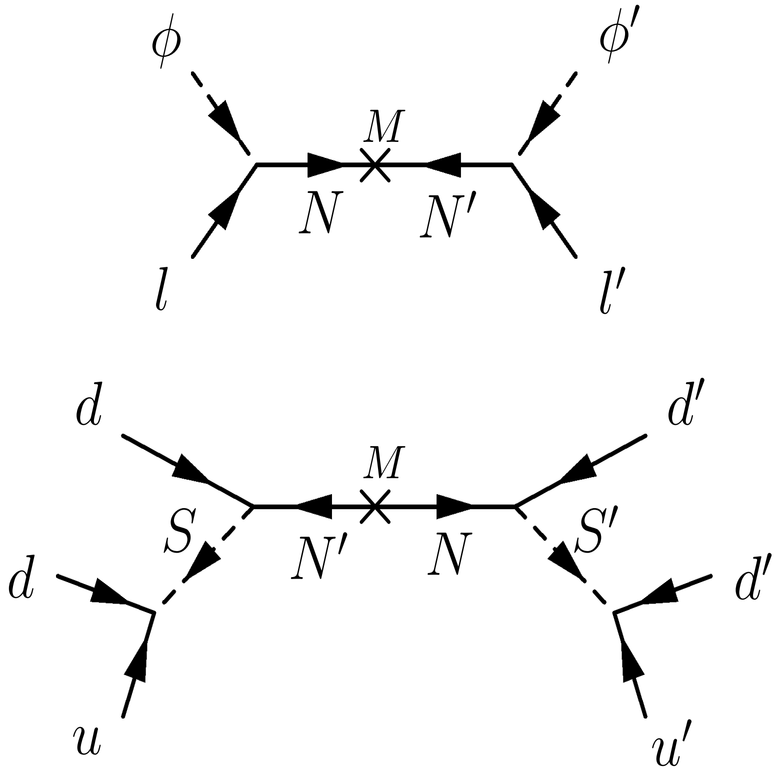


$\frac{\Omega_B}{\Omega'_B} = D(k) \simeq 0.1 - 1$: $k \leq 3$ – from $\Delta N_\nu \simeq 14k/g_*$

Neutron - Mirror neutron mixing

Baryogenesis via L- or via B-breaking

Z.B. and L. Bento '05



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

$\delta m \sim \left(\frac{10\,\text{TeV}}{\mathcal{M}}\right)^5 \times 10^{-15}\,\text{eV}$!! $\tau_{\rm osc} \sim 1$ sec !! – but $\tau_{\rm dec} \simeq 10^3$ sec

?? $P(t) = e^{-t/\tau_{\rm dec}} \quad \rightarrow \quad P(t) = \cos^2(t/\tau_{\rm osc}) \cdot e^{-t/\tau_{\rm dec}} \simeq \frac{1}{2}e^{-t/\tau_{\rm dec}}$??

Neutron - Mirror neutron oscillation

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

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

- Exact mirror parity: masses $m' = m$ and widths $\Gamma' = \Gamma$

$--$ (but $m' \neq m$,... if mirror parity is spont. broken !)

- Grav. potentials are the same: $V' = V$, but $\mu = -1.91\mu_N$:

$\simeq 6 \cdot 10^{-12}$ eV/G (Earth magnetic field $B \simeq 0.5$ G)

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

$$H = \begin{pmatrix} m \mp 2\omega_B & \delta m \\ \delta m & m \end{pmatrix}$$ in the basis $(\psi_+, \psi_-, \psi'_+, \psi'_-)$

– Energy gap $2\omega_B = |\mu B| \simeq B[\mathrm{G}] \times 6 \cdot 10^{-12}$ eV

Oscillation probability $P_{nn'}(t) = \sin^2 2\theta_B \sin^2(t/\tau_B) \cdot e^{-t/\tau_{\rm dec}}$

$$\sin 2\theta_B = \frac{\delta m}{\sqrt{\delta m^2 + \omega_B^2}}, \quad \tau_B = \frac{1}{\sqrt{\delta m^2 + \omega_B^2}} = \tau_0 \sin 2\theta_B, \quad \tau_0 = \delta m^{-1}$$

$n - n'$ *oscillation - degenerate case*

Oscillation probability in magnetic field B

$$P_{nn'}(t) = \frac{\delta m^2}{\delta m^2 + \omega_B^2} \sin^2\left(t\sqrt{\delta m^2 + \omega_B^2}\right) e^{-t/\tau_{\rm dec}}, \qquad (\omega_B = \tfrac{1}{2}|\mu B|)$$

In vacuum ($B = 0$): $\quad P_{nn'}(t) = \sin^2(t/\tau_0) \cdot e^{-t/\tau_{\rm dec}}$

($\tau_{\rm osc} = \tau_0 = \delta m^{-1}, \quad \theta_{\rm mix} = 45°$)

for short times ($t \ll \tau_0$) : $\quad P_{nn'}(t) = (t/\tau_0)^2$

for longer times ($t \gg \tau_0$) : $\quad P_{nn'}(t) = \frac{1}{2} e^{-t/\tau_{\rm dec}}$

In medium ($B \neq 0$):

for short times ($t \ll \tau_B$) : $\quad P_{nn'}(t) = (t/\tau_0)^2$

for long times ($t \gg \tau_B$) : $\quad P_{nn'}(t) = \bar{P}_B = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + \omega_B^2}$

Similar to neutron - antineutron oscillation — Kuzmin '70, Glashow '79, Marshak & Mohapatra '80

But $\tau_{n\bar{n}} > 10$ yr, while $\tau_{nn'} < 10$ min is possible with several physical effects — Z.B. & Bento; Mohapatra, Nasri, Nussinov; Pokotilovsky

Experimental limits

Experimental limits & and future search
ILL Grenoble experiment for neutron - antineutron oscillation search:
100 m μ-metal vessel, $B < 10^{-4}$ G, $t \simeq 0.1$ s   Baldo Ceolin et al. '94

- $n - \tilde{n}$: no $\tilde{n}$ event found, $\tau_{n\tilde{n}} > 10^8$ s (or > 3 yr)

- $n - n'$: about 5% neutron deficit was observed, so taking

$P_{nn'}(t) \simeq (t/\tau)^2 < 10^{-2}$, $\tau_{nn'} > 1$ s $\rightarrow$ $\delta m < 10^{-15}$ eV

- $n - n'$: anomalous UCN loses, $\eta < 2 \cdot 10^{-6} \rightarrow \delta m < 3 \cdot 10^{-15}$ eV

!!! Attention – Nuclear Stability !!!

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

$\tau_{n\tilde{n}} > 10$ yr *or so* ...   Kuzmin et al. '81

- $n - n'$ does not: $(A, Z) \rightarrow (A-1, Z) + n'$ not allowed !

Recent Experimental search:

- $\tau > 2.5$ s,   Munich, Schmidt et al, Feb. 2007 (unpubl.), Dubbers, Priv. com.
- $\tau > 103$ s,   ILL Grenoble, Ban et al. May 2007, axXiv:0705.2336 [nucl-ex]
- $\tau > 413$ s,   ILL Grenoble, Serebrov et al. June 2007, axXiv:0706.3600 [nucl-ex]

Search for $n - n'$ with the UCN storage

Counting of the UCN (ultra cold neutrons, velocities $v < 4-5\ \mathrm{m/s}$,) after a storage time t_s in a neutron trap, comparing the results for $B = 0$ and $B \neq 0$.

$$n(t_s) = n(t=0) \times \exp[-(\Gamma + \eta\nu + P_{nn'}(t_f)\nu)\, t_s]$$

t_f is a mean flight time between collisions ($\sim 0.05 - 0.1$ s),
$\nu = 1/t_f$ is a collision frequency, and η is anomalous lose per collision by "natural" reasons (i.e. independent of magnetic field).

- For $B \neq 0$: $\quad P_{nn'}(t_f) = \bar{P}_B \approx \frac{1}{2}\frac{\delta m^2}{\omega_B^2} = \frac{1}{2}\left(\frac{\tau_B}{\tau_0}\right)^2$

(*Magnetic field is taken enough large to satisfy* $t_f \gg \tau_B \approx \omega_B^{-1}$)

- For $B = 0$: $\quad P_{nn'}(t_f) = \left(\frac{t_f}{\tau_0}\right)^2 \gg \bar{P}_B$

So signal is: $\frac{n(B=0,t_s)}{n(B,t_s)} = \exp[-a\, t_s] < 1$, i.e. a ***should be positive***

Fitting $a = \frac{1}{t_f}\left(\frac{t_f}{\tau_0}\right)^2$ from the measurements, one finds $\tau_0 = \sqrt{t_f/a}$.

Experiment Ban et al. May 2007

The UCN storage trap with volume 21 l, neutron velocities $v < 4$ m/s, wall collision frequency $\nu = 20\ \mathrm{s}^{-1}$, average flight time $t_f = 0.05$ s "zero" magnetic field – $B_0 = (2-3)\cdot 10^{-5}$ G, changing magnetic fields "up" and "down", $B_\uparrow = B_\downarrow = 0.06$ G storage times $t_s = 50, 100, 175$ s, effective times $t^* = t_s + 23$ s

- Expectation: $\frac{n(B=0,t^*)}{n(B_{\uparrow\downarrow},t^*)} = \exp[-a\,t^*] < 1$, i.e. $a > 0$
- Fit of measurements: $a = -(5.4 \pm 5.8)\cdot 10^{-6}\ \mathrm{s}^{-1} \rightarrow \tau_0 > 103$ s

t^* [s]	73 (a)	73 (b)	123	198
$n(B_\uparrow)$	44197 ± 53	44443 ± 53	28671 ± 30	17047 ± 31
$n(B=0)$	44317 ± 40	44363 ± 53	28635 ± 21	17015 ± 22
$n(B_\downarrow)$	44128 ± 53	44316 ± 46	28596 ± 30	16974 ± 31
$n(B_{\uparrow\downarrow})$	44163 ± 38	44371 ± 35	28633 ± 22	17011 ± 22

Up-Down Asymmetry

t^* [s]	$n(B=0)/n(B_{\uparrow\downarrow})$	$n(B_\uparrow)/n(B_\downarrow)$
$73\ (a)$	1.0035 ± 0.0013	1.0016 ± 0.0017
$73\ (b)$	0.9998 ± 0.0015	1.0028 ± 0.0016
$73\ (a+b)$	1.0019 ± 0.0010	1.0022 ± 0.0012
123	1.0001 ± 0.0011	1.0026 ± 0.0015
198	1.0002 ± 0.0018	1.0043 ± 0.0026

- *Fit of* $\frac{n(B=0,t^*)}{n(B_{\uparrow\downarrow},t^*)} = e^{\beta(t^*/t_f)} \approx 1 + \beta\left(\frac{t^*}{t_f}\right)$

$$\beta = (2.92 \pm 2.90) \times 10^{-7} \quad (68.27\,\%\,CL)$$

- *Fit of* $\frac{n(B_\uparrow,t^*)}{n(B_\downarrow,t^*)} = 1 + \gamma\left(\frac{t^*}{t_f}\right)$

$$\gamma = (1.22 \pm 0.40) \times 10^{-6} \quad (68.27\,\%\,CL)$$

$n - n'$ in non-degenerate case

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

Consider $2\Delta E = (m' - m) + (V' - V) \neq 0$ – *but small* $(\sim 10^{-12}\ \mathrm{eV})$

$$H_+ = \begin{pmatrix} m + V - 2\omega_B & \delta m \\ \delta m & m + V + 2\Delta E \end{pmatrix} \quad \textit{for} \quad \psi_+, \psi'_+ \quad \textit{states} ,$$

$$H_- = \begin{pmatrix} m + V + 2\omega_B & \delta m \\ \delta m & m + V + 2\Delta E \end{pmatrix} \quad \textit{for} \quad \psi_-, \psi'_- \quad \textit{states}$$

Now $(+)$ and $(-)$ polarization states oscillate at different rates in magnetic medium, A being neutron polarization asymmetry:

$$\bar{P}_\pm(t) = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + (\Delta E \pm \omega_B)^2}\ , \qquad \bar{P}_0 = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + \Delta E^2}, \qquad (\omega_B = \tfrac{1}{2}|\mu B|)$$

- $\frac{n(B=0)}{n(B_{\uparrow\downarrow})}$ *asymmetry* $\beta = \left(\frac{\delta m}{\Delta E}\right)^2 \frac{\omega_B^2(3\Delta E^2 - \omega_B^2)}{2(\Delta E^2 - \omega_B^2)^2} > 0$ *if* $\Delta E > 0.6\omega_B$
- $\frac{n(B_\uparrow)}{n(B_\downarrow)}$ *asymmetry* $\gamma = A \times \left(\frac{\delta m}{\Delta E}\right)^2 \frac{2\omega_B \Delta E^3}{(\Delta E^2 - \omega_B^2)^2}$ *requires,* $A > 30\%$

$n - n'$ in non-degenerate case

Consider now the case *but small* $(\sim 10^{-12}\ \mathrm{eV})$

$$H_+ = \begin{pmatrix} m + V - 2\omega_B & \delta m \\ \delta m & m + V + 2\Delta E \end{pmatrix} \quad \text{for } \psi_+, \psi'_+ \text{ states ,}$$

$$H_- = \begin{pmatrix} m + V + 2\omega_B & \delta m \\ \delta m & m + V - 2\Delta E \end{pmatrix} \quad \text{for } \psi_-, \psi'_- \text{ states}$$

Now $(+)$ and $(-)$ polarization states oscillate at the same rates in magnetic medium, results do not depend on neutron polarization:

$$\bar{P}_\pm(t) = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + (\Delta E + \omega_B)^2}\ , \qquad \bar{P}_0 = \frac{1}{2}\frac{\delta m^2}{\delta m^2 + \Delta E^2}, \qquad (\omega_B = \tfrac{1}{2}|\mu B|)$$

- $\frac{n(B=0)}{n(B_{\uparrow\downarrow})}$ *asymmetry* $\beta = \left(\frac{\delta m}{\Delta E}\right)^2 \frac{\omega_B^2(3\Delta E^2 - \omega_B^2)}{2(\Delta E^2 - \omega_B^2)^2} > 0$ *if* $\Delta E > 0.6\omega_B$
- $\frac{n(B_\uparrow)}{n(B_\downarrow)}$ *asymmetry* $\gamma = \left(\frac{\delta m}{\Delta E}\right)^2 \frac{2\omega_B \Delta E^3}{(\Delta E^2 - \omega_B^2)^2}$

one can fit both data for $\Delta E \sim 10^{-12}\ \mathrm{eV}$

Experimental limits & and future search

Imagine there exists a light spin 0 field ϕ having both the scalar and pseudoscalar couplings with the nucleons of both sectors:

$$g_s \phi(\overline{N}N + \overline{N'}N') + ig_p\phi(\overline{N}\gamma^5 N - \overline{N'}\gamma^5 N')$$

Moody & Wilczek '84

Two Fermion potentials between two bodies:

(monopole)^2: $$V_{mm}(r) = -\frac{g_s^{(1)} g_s^{(2)}}{4\pi r} e^{-m_\phi r}$$

monopole-dipole : $$V_{md}(r) = \pm \frac{g_s^{(1)} g_p^{(2)} (\boldsymbol{\sigma}_2 \cdot \boldsymbol{n})}{8\pi m_2} \left[\frac{m_\phi}{r} + \frac{1}{r^2}\right] e^{-m_\phi r}$$

where $\boldsymbol{n} = \boldsymbol{r}/r$

Mirror Physics: Summary

- String Theory: parallel D-branes or brane-antibrane
- restoring Parity: $L \leftrightarrow R$ – can remain exact (models of exact mirror parity) or spontaneously broken Z.B., Dolgov & Mohapatra 96
- Common gauge forces between two sectors: e.g. $U(1)_{B-L}$, or (anomaly free) gauge flavour symmetry $SU(3)_H$ between fermion families: helps for SUSY flavour changing problem (D-terms) Z.B., 98
- Higgs sector stability: Higgs as pseudoGoldstone in SUSY – accidental global $U(4)$ symmetry Z.B., 05; Falkowski, Pokorski & Schmalz 06
- Photon-photon′ kynetic mixing (invisible 0-Ps decay) Holdom, Glashow
neutrino-neutrino′ (active - sterile) mixing Foot & Volkas; ZB & Mohapatra
neutron - neutron′ mixing (hydrogen - hydrogen′) mixing ZB & Bento
pion - pion′ mixing (DAMA vs. CDMS) ZB, Panci & Rossi
Kaon - Kaon′ mixing (new features in CP-violation ?) etc. etc.
- Strong CP-problem: new models for axion avoiding mass-coupling correlation $m_a \sim f_\pi m_{pi}/f_a$ Z.B., Gianfagna, Gianotti 2000

Mirror Cosmology & Astrophysics: Summary

- Mirror sector should be cooler than ours: $T'/T < 0.5$ or so (BBN)
- Dark matter of the Universe:
self-interacting dissipative (for exact parity): requires $T'/T < 0.2$
or WDM, or almost CDM (for broken parity)
- Baryogenesis & dark matter genesis: Bento & Z.B., 2001
Understanding why $\Omega_D \sim \Omega_B$
- Microlensing (MACHOs) Z.B., Dolgov & Mohapatra 96, Blinikov 98
- Gamma- Ray Bursts and Supernove Blinnikov, Z.B. & Drago 99
- Super high energy neutrinos Berezinsky & Vilenkin, 2000
– Propagation of ultra High energy protons Z.B. & Bento 05
- Quasars & supermassive black holes ZB, Comelli & Villante 2000
- Possible dark matter detection (DAMA vs. others) Foot 2003
- Invisible planets and meteorits (Tunguska) Foot, Silagadze
Thermal imprints of mirror matter Foot & Mitra