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 ...

Today's Universe:
- multi-component: visible matter, dark matter, dark energy ...

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

Some unified picture?
Well, not yet ... the origin and nature of DM and DE remain open!
Cosmic coincidence of matter ($\Omega_M = \Omega_D + \Omega_B$) and dark energy ($\Omega_\Lambda$):

$$\frac{\Omega_M}{\Omega_\Lambda} \approx 0.3 : \quad \rho_\Lambda \sim \text{Const.}, \quad \rho_M \sim a^{-3}.$$  

- Why $\rho_M/\rho_\Lambda \approx 1$ – just Today?
Coincidence & Fine Tuning Problems

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Miracle Fine Tuning between visible ($\Omega_B$) and dark ($\Omega_D$) matter:

$$\Omega_B / \Omega_D \simeq 0.2 : \quad \rho_B \sim a^{-3}, \quad \rho_D \sim a^{-3}. $$

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Visible matter – $\rho_B$ – from primordial Baryogenesis
(GUT, Lepto-B, Affleck-Dine, EW, ...)

Dark matter – $\rho_D$ – emerges from quite a different mechanism
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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: \( \rho_B = n_B M_N \),
- \( M_N \approx 1 \text{ GeV} \) – nucleon mass,
- \( Y_B = n_B / s \approx 10^{-10} \) – Baryon number/entropy density ratio.
- \((\text{GUT, Lepto})\)-Baryogenesis: \( Y_B \sim (\epsilon_{CP} / g^*) \times D(k) \),
- \(\epsilon_{CP}\) – CP violation parameter,
- \( g^* \) – effective number of particle degrees of freedom at \( T = T_B \),
- \( k = \Gamma / H \) – out-of-equilibrium parameter at \( T = T_B \)
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(GUT, Lepto)-Baryogenesis: 
\( Y_B \approx (\epsilon_{CP} / g^*) \times D(k) \),

- Dark matter: \( \rho_D = n_X M_X \approx 5 \rho_B \), but \( M_X = ? \), \( n_X = ? \)

  Axion: \( M_X \approx 10^{-5} \text{ eV} \);
  LSP: \( M_X \approx 1 \text{ TeV} \),
  Wimpzilla: \( M_X \approx 10^{14} \text{ GeV} \)
Cosmological evolution of Baryon and dark matter densities:
Unified origin of VM and DM?

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

$$\rho_X/\rho_B = M_X n_X / M_N n_B \sim 1$$
Imagine a parallel hidden "Mirror" sector of particles, an exact duplicate of the observable sector.

[Lee & Yang ’56]

[Kobzarev, Okun, Pomeranchuk ’66]

[Blinnikov, Khlopov ’83]

[Kolb, Seckel, Turner ’86]
Mirror World

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

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

\[ \text{SM} \times \text{SM}' : \quad SU(3) \times SU(2) \times U(1) \times SU(3)' \times SU(2)' \times U(1)' , \]

or \( \text{GUT} \times \text{GUT}' : \quad SU(5) \times SU(5)', \quad SO(10) \times SO(10)' , \) 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.)

• Mirror matter is dark for us, but we know all particle physics properties there – no unknown parameters!
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$SM \times SM': \quad SU(3) \times SU(2) \times U(1) \times SU(3)' \times SU(2)' \times U(1)'$, or $GUT \times GUT': \quad SU(5) \times SU(5)', \quad SO(10) \times SO(10)'$, etc.

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- Spontaneously broken $G \leftrightarrow G'$: $M_W' \neq M_W$ shadow dark matter with rescaled spectrum

[Lee & Yang '56]
[Kobzarev, Okun, Pomeranchuk '66]
[Blinnikov, Khlopov '83]
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[Z.B. & Mohapatra '95]
[Z.B., Dolgov & Mohapatra '96]
**Mirror Particles and Mirror Parity**

\[
\begin{align*}
SU(3) \times SU(2) \times U(1) & \quad \times \quad SU(3)' \times SU(2)' \times U(1)'
\end{align*}
\]

& Higgs (\(\phi\)) fields & & & Higgs (\(\phi'\)) fields

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| \(\tilde{u}_L \quad \tilde{d}_L\) | \(\tilde{e}_L\) | \(\tilde{u}'_L \quad \tilde{d}'_L\) | \(\tilde{e}'_L\) |

- \(\mathcal{L}_{\text{Yuk}} = f_L Y \tilde{f}_L \phi + \tilde{f}_R Y^* f_R \phi\)
- \(\mathcal{L}'_{\text{Yuk}} = f'_L Y' \tilde{f}'_L \phi' + \tilde{f}'_R Y'^* f'_R \phi'\)
Mirror Particles and Mirror Parity

\[ \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \times \text{SU}(3)' \times \text{SU}(2)' \times \text{U}(1)' \]

& Higgs fields

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- D-parity: \(L \leftrightarrow L', \quad R \leftrightarrow R', \quad \phi \leftrightarrow \phi'\)

\[ \mathcal{L}'_{\text{Yuk}} = f'_L Y' \tilde{f}'_L \phi' + \tilde{f}'_R Y'^* f'_R \phi' \]

- \(Y' = Y\)
### Mirror Particles and Mirror Parity

\[
SU(3) \times SU(2) \times U(1) \times SU(3)' \times SU(2)' \times U(1)'
\]

\begin{align*}
gauge (g, W, Z, \gamma) & \quad \text{& Higgs (}\phi\text{) fields} \\
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  \( \bullet \ Y' = Y \bullet \)

- **M-parity:** \( L \leftrightarrow R' \), \( R \leftrightarrow L' \), \( \phi \leftrightarrow \tilde{\phi}' \)  
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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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  ... safe in GUT: \( L \sim \frac{\alpha G \Sigma \Sigma'}{4\pi M^2} G_{\mu\nu} G'_{\mu\nu} \)

- 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: \( A' = A^\ast, \quad D = D^\dagger \)

active-sterile mixing

\[
\begin{pmatrix}
\hat{m}_\nu & \hat{m}_{\nu'} \\
\hat{m}_{\nu'}^t & \hat{m}_\nu
\end{pmatrix} = \frac{1}{M} \begin{pmatrix}
Av^2 & D_{\nu\nu'} \\
D^t_{\nu\nu'} & A'_{\nu\nu'}
\end{pmatrix},
\]

- 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
Introduce heavy gauge singlet fermions $N_a, \ a = 1, 2, 3, \ldots$ with large Majorana mass terms $\frac{1}{2} (M_{ab} N_a N_b + M^*_{ab} \tilde{N}_a \tilde{N}_b)$,
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They can equally talk with both O and M leptons

$$y_{ia}l_iN_a\phi + y'_{ia}\lambda'_iN_a\phi' + \frac{M}{2}g_{ab}N_aN_b + \text{h.c.}; \quad (y' = y^\dagger)$$
See-saw: heavy singlet neutrinos as messengers

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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, where
  \[
  A = yg^{-1}y^t, \quad A' = y'g^{-1}y'^t, \quad D = yg^{-1}y'^t
  \]
  generate O (active) and M (sterile) neutrino masses and mixings
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- They generate also processes like $l\phi \rightarrow \tilde{l}'\phi'(l'\phi') (\Delta L = 1)$ and $l\phi \rightarrow \tilde{l}\phi (\Delta L = 2)$, which
  
  A. violate $L$ (and so $B - L$)
  B. violate CP
  C. should be out-of-equilibrium

  - and thus can generate $B-L \neq 0$ (→ $B \neq 0$ by sphalerons)

[Sakharov '67]
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  \[ y_{ia}l_iN_a\phi + y^\prime_{ia}\chi_i^lN_a\phi^\prime + \frac{M}{2}g_{ab}N_aN_b + \text{h.c.}; \quad (y^\prime = y^{\dagger}) \]

- After decoupling heavy neutrinos, effective operators
  \[ \frac{A}{M}ll\phi\phi + \frac{A^\prime}{M}l^l\phi^l\phi^l + \frac{D}{M}ll^l\phi^l\phi^l \]

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

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[Sakharov '67]
At the BBN epoch, $T \sim 1$ MeV, $g_* = g_*^{SM} = 10.75$ (as contributed by the $\gamma$, $e^\pm$ and 3 $\nu$ species)
BBN constraint

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- If $T' < T$, $g_* \approx g_{* SM}^M (1 + x^4)$, $x = T'/T$: equivalent to $\Delta N_{\nu} = 6.14 \cdot x^4$.

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

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- If \( T' < T, \ g_* \approx g_*^{SM}(1 + x^4), \ x = T'/T \): equivalent to
  \( \Delta N_\nu = 6.14 \cdot x^4 \).
  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
CP violation in $\Delta L=1$ and $\Delta L=2$ processes

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

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

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

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

\(\Gamma \propto n_{eq}^4/M^2\) is the effective reaction rate of \(\Delta L' = 1\) and \(\Delta L' = 2\) processes

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

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

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

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

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

\[
Y_{BL}^{(0)} \approx 2 \times 10^{-3} \frac{\varepsilon_{CP} M_{Pl} T_R^3}{g_*^{3/2} M^4}.
\]
Exact $M$-parity: $M'_N = M_N$

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

Depletion factor

\[ D(k) = \frac{3}{5} e^{-k} F(k) + \frac{2}{5} G(k); \quad \text{for } k \ll 1, D(k) = 1 \]

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

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

Heating:

\[ \Delta N_{\nu} \simeq k / g_* \quad x = \left( k / 6g_* \right)^{1/4} < 0.2: \quad k \leq 2, \quad (\text{LSS}) \]
Broken M parity: $M'_W > M_W$?

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

\[ z'_{\text{dec}} \approx x^{-1} z_{\text{dec}} \quad x_{\text{eq}} = 0.05(\Omega_M h^2)^{-1} \approx 0.3 \]

for \( x < x_{\text{eq}} \)

\[ M_J \ll M_H \]

\[ \lambda_S' \sim 5x_{\text{eq}}^{5/4}(x/x_{\text{eq}})^{3/2}(\Omega_M h^2)^{-3/4} \text{ Mpc} \]
CMB & LSS power spectra

\[
\frac{\ell(\ell+1)C_{\ell}}{\ell!} \leq 1/2 \frac{\mu K}{h^2} \\
\Omega_m = 0.25, \, \omega_b = 0.023, \, h = 0.73, \, n = 0.97
\]

\[x = 0.5, \text{no CDM} \quad \cdots \cdots \]
\[x = 0.3, \text{no CDM} \quad \cdots \cdots \]
\[x = 0.2, \text{no CDM} \quad \cdots \cdots \]
LSS power spectra

\begin{align*}
\Omega_M &= 0.30, \omega_b = 0.001, h = 0.70, n = 1.00 \\
\Omega_M &= 0.30, \omega_b = 0.02, h = 0.70, n = 1.00 \\
\Omega_M &= 0.30, \omega_b = 0.02, h = 0.70, x = 0.2, \text{no CDM}, n = 1.00 \\
\Omega_M &= 0.30, \omega_b = 0.02, h = 0.70, x = 0.1, \text{no CDM}, n = 1.00 \\
\Omega_M &= 0.30, \omega_b = 0.02, h = 0.70, x = 0.2, \omega_b' = \omega_{CDM}, n = 1.00
\end{align*}
**Neutron - Mirror neutron oscillation**

B-genesis is possible via

\[
\begin{align*}
\Phi & \quad \Phi' \\
M & \quad M \\
N & \quad N' \\
l & \quad l' \\
φ & \quad φ' \\
\end{align*}
\]

\[
\begin{align*}
d & \quad d' \\
S & \quad S' \\
N' & \quad N \\
u & \quad u' \\
d & \quad d' \\
u & \quad u' \\
\end{align*}
\]

\[
\frac{1}{M^5} (udd)(u'd'd') + \frac{1}{M^5} (qqd)(q'q'd') + \text{h.c.} \rightarrow \delta m (\bar{n}n' + \bar{n}'n)
\]

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

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