Concepts of Mirror Matter: *What's Wrong with DM=MM? (Everything must be as simple as possible. But not simpler.)*

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Contents

Prologue: Standard Model on T-shirts

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c.$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Fermions (= matter): quarks and leptons, *3 generations*

Bosons (= interactions): gauge fields + Higgs (God's) boson

Glorious end of Fundamental Physics ?

Happily, some simple questions remain with our answer ...

- Baryon number violation and Baryogenesis
- Who is Dark Matter

Bright & Dark Sides of the Universe

Todays Universe: flat $\Omega_{\rm tot} \approx 1$ *(inflation)* ... and multi-component:

- $\Omega_B \simeq 0.05$ observable matter: electron, proton, neutron !
- $\Omega_D \simeq 0.25$ dark matter: WIMP? axion? sterile ν? ...
- $\Omega_\Lambda \simeq 0.70$ dark energy: Λ-term? Quintessence? ....
- $\Omega_R < 10^{-3}$ relativistic fraction: relic photons and neutrinos

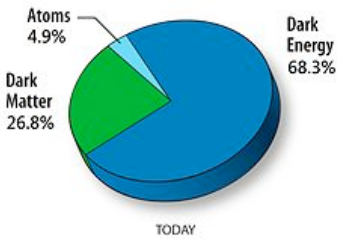
Matter – dark energy *coincidence:* $\Omega_M/\Omega_\Lambda \simeq 0.45$, $(\Omega_M = \Omega_D + \Omega_B)$

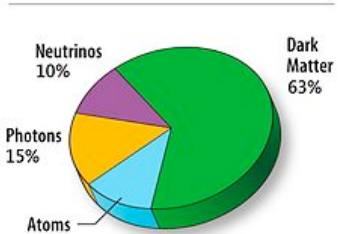
$\rho_\Lambda \sim$ Const., $\rho_M \sim a^{-3}$; *why* $\rho_M/\rho_\Lambda \sim 1$ – *just Today?*

Antrophic explanation: if not *Today*, then *Yesterday* or *Tomorrow.*

Baryon and dark matter *Fine Tuning:* $\Omega_B/\Omega_D \simeq 0.2$

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





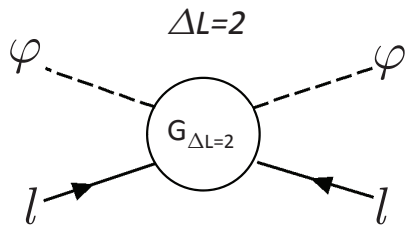
Baryogenesis requires BSM Physics:
(GUT-B, Lepto-B, Affleck-Dine, EW B ...)
Dark matter requires BSM Physics:
(Wimp, Wimpzilla, sterile ν, axion, ...)

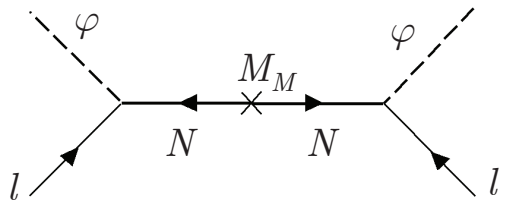
Different physics for B-genesis and DM?
Not very appealing: looks as Fine Tuning

Baryogenesis requires new physics: B–L violation

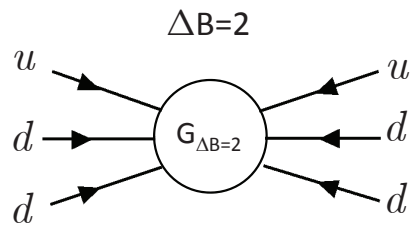
B & L can be violated only in higher order terms – but which ?

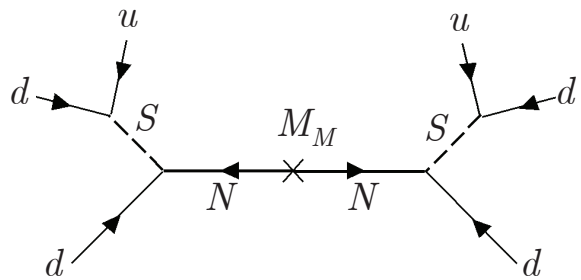
- $\frac{1}{M}(l\bar{\phi})(l\bar{\phi})$ $(\Delta L = 2)$ – neutrino (seesaw) masses $m_\nu \sim v^2/M$





- $\frac{1}{M^5}(udd)(udd)$ $(\Delta B = 2)$ – neutron-antineutron oscillation $n \to \bar{n}$





can originate from new physics related to scale $M \gg v_{\rm EW}$ via seesaw

Bento, Z.B., 2005

Dark Matter requires new physics: but which ?

Why $\Omega_D/\Omega_B \sim 1$? Or why $m_B\rho_B \sim m_X\rho_X$?

Visible matter from Baryogenesis *(Sakharov)*

B $(B-L)$ & CP violation, Out-of-Equilibrium

$\rho_B = m_B n_B$, $m_B \simeq 1$ GeV, $\eta = n_B/n_\gamma \sim 10^{-9}$

η is model dependent on several factors:

coupling constants and CP-phases, particle degrees of freedom, mass scales and out-of-equilibrium conditions, etc.

Dark matter: $\rho_D = m_X n_X$, but $m_X = ?$, $n_X = ?$

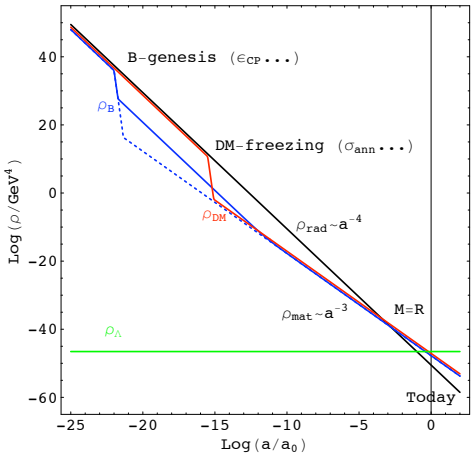
and why $m_X n_X = 5 m_B n_B$?

n_X is model dependent: DM particle mass and interaction strength (production and annihilation cross sections), freezing conditions, etc.

• Axion	• $m_a \sim$ meV	$n_a \sim 10^4 n_\gamma$	– CDM
• Neutrinos	• $m_\nu \sim$ eV	$n_\nu \sim n_\gamma$	– HDM (×)
• Sterile ν'	• $m_{\nu'} \sim$ keV	$n_{\nu'} \sim 10^{-3} n_\nu$	– WDM
• WIMP	• $m_X \sim$ TeV	$n_X \sim 10^{-3} n_B$	– CDM
• WimpZilla	• $m_X \sim$ ZeV	$n_X \sim 10^{-12} n_B$	– CDM

How these Fine Tunings look ...

B-genesis + WIMP



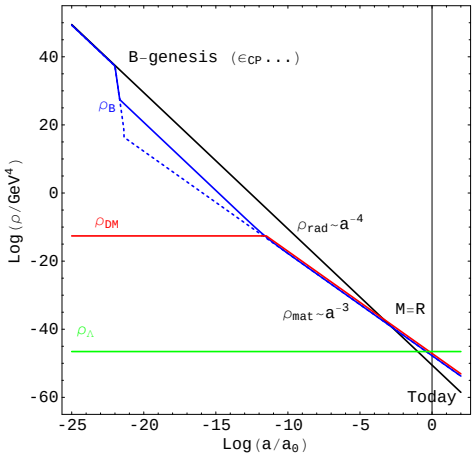
$m_X n_X \sim m_B n_B$

$m_X \sim 10^3 m_B$

$n_X \sim 10^{-3} n_B$

Fine Tuning?

B-genesis + axion



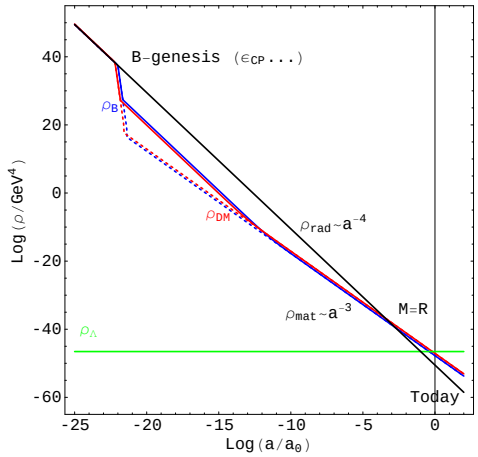
$m_a n_a \sim m_B n_B$

$m_a \sim 10^{-13} m_B$

$n_a \sim 10^{13} n_B$

Fine Tuning?

B-cogenesis



$m_{B'} n_{B'} \sim m_B n_B$

$m_{B'} \sim m_B$

$n_{B'} \sim n_B$

Natural ?

Two different New Physics for B-genesis and DM ?

Or co-genesis by the same Physics explaining why $\Omega_{DM} \sim \Omega_B$?

Who are you, Mr. DM ?

- Have you relations with other (fundamental) problems? *Yes*
- Do you manage to match your Ω to $5\,\Omega_B$? *Yes*
- You must be cold. Or you are self-interacting and dissipative? *Yes*
- You must be neutral. Or you have some tiny electric charges? *Yes*
- Do you agree with astrophysical tests (BBN, CMB, LSS, ...) ? *Yes*
- Can you form halos, stars & massive Black Holes? *Yes*
- Are you directly detectable? Can you be converted in visible? *Yes*
- Do you send indirect signals via cosmic rays & gammas? *Yes*
- Can you be produced at LHC or other experimental facilities? *Yes*

– Let me guess, is your name Susy? *No! but I know her very well*

– Are you heavy or light? *Well, I'm just normal ...*

– Are you stable? *Stable enough ... but not immortal*

– Are you really dark? *Well, it's relative ... to someone I'm blond*

. ...Oh, you look so similar to me !? Are you MM ?

Dark sector ... similar to our luminous sector?

"Imagination is more important than knowledge." *Albert*

For observable particles .... *very complex physics !!*
$G = SU(3) \times SU(2) \times U(1)$ (+ SUSY ? GUT ? Seesaw ?)
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-L violation, CP ...)
... existence of nuclei, atoms, molecules .... life.... Homo Sapiens !

If dark matter comes from extra gauge sector ... it is as *complex*:
$G' = SU(3)' \times SU(2)' \times U(1)'$? (+ SUSY ? GUT ′? Seesaw ?)
photon′, electron′, nucleons′ (quarks′), $W' - Z'$, gluons′ ?
... long range EM forces, confinement at $\Lambda'_{\rm QCD}$, weak scale M'_W ?
... asymmetric dark matter (B′-L′ violation, CP ...) ?
... existence of dark nuclei, atoms, molecules ... life ... Homo Aliens ?

Let us call it Yin-Yang Theory

in chinise, Yin-Yang means dark-bright duality

describes a philosophy how opposite forces are actually complementary, interconnected and interdependent in the natural world, and how they give rise to each other as they interrelate to one another.

$E_8 \times E'_8$

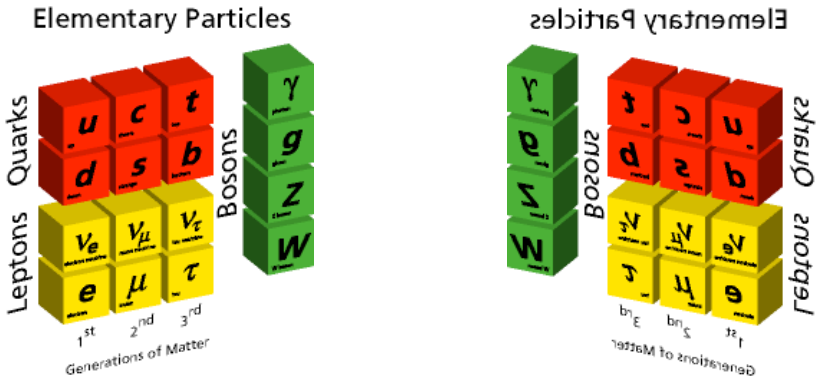
$SU(3) \times SU(2) \times U(1) \quad + \quad SU(3)' \times SU(2)' \times U(1)'$

Everything has the end... But Wurstle has two ends – Left and Right

$G \times G'$

Regular world

Mirror world



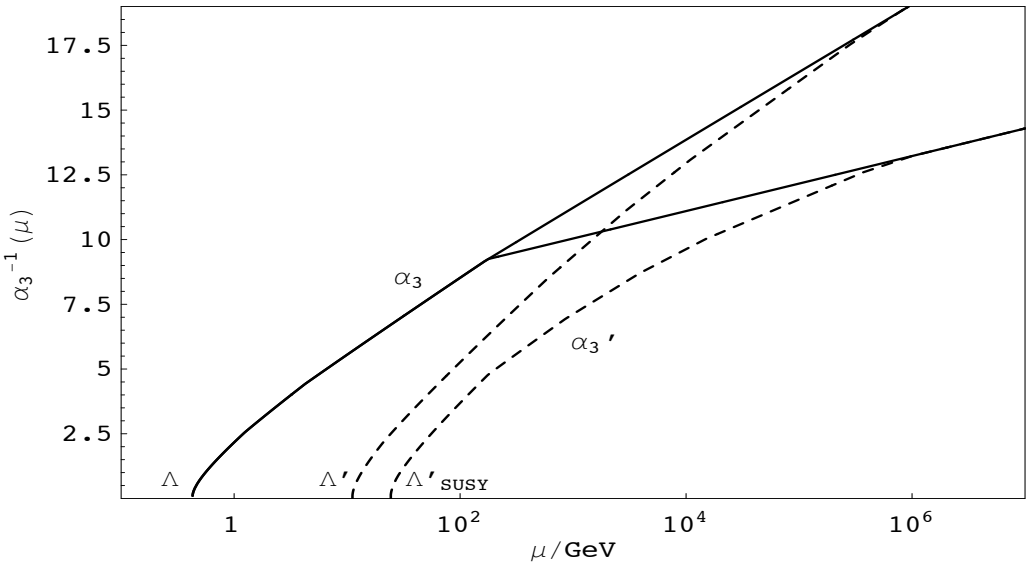
- Two identical gauge factors, e.g. SM $\times$ SM$'$ or $SU(5) \times SU(5)'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
- M sector is dark (for us) and the gravity is a common force (between)
- Exact Z_2 parity $G \to G'$: no new parameter in dark Lagrangian $\mathcal{L}'$
- MM looks as non-standard DM but truly it as standard as our matter (self-interacting/dissipative/asymmetric/atomic)
- New interactions between O & M particles ($\mathcal{L}_{mix}$ – new parameters)
- Natural in string/brane theory: O & M matters localized on two parallel branes and gravity propagating in bulk: e.g. $E_8 \times E_8'$

Asymmetric MM: Z_2 between two sectors broken

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

broken M parity: $v'/v \sim 10^2$ $\quad v' \sim 10$ TeV, $v \sim 100$ GeV

Z.B., Dolgov & Mohapatra '96



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

$M'_N/M_N \sim (\Lambda'/\Lambda) \sim (v'/v)^{0.3} \sim 5$ —- $M_N \sim 5$ *GeV*

$m'_e/m_e \sim v'/v \sim 10^2$ – $m'_e \sim 100$ *MeV*

– Properties of MB's get closer to CDM : but also WDM from mirror neutrinos ?

$m'_\nu/m_\nu \simeq (v'/v)^2 \sim 1$ *keV*

Particle Physics Motivations

Axidragon (Heavy axion) Z.B. Gianfagna, Giannotti, 2001

Peccei-Quinn symmetry $U(1)$ is common between SM and SM$'$:

$$\Theta(G\tilde{G} + G'\tilde{G}') \quad + \quad Y(ffH + f'f'H')$$

$$v' \gg v \quad \Lambda' > \Lambda\,, \quad m_a = \frac{m_q\Lambda^3}{f_a} \;\rightarrow\; m_a = \frac{m'_q\Lambda'^3}{f_a} \sim \left(\frac{v'}{v}\right)^2 \frac{m_q\Lambda^3}{f_a}$$

... for GRB's and Supernova explosions Z,B, Drago, 1998

Twin Higgs: Generalization of NSSM with superpotential
Z.B. "Looking Glass ...", 2005, hep-ph/0508233

$$W = \lambda S(H_1H_2 + H'_1H'_2) + \Lambda S + MS^2 + ...$$

Local Symmetry $U(2) \times U(2)'$ — Global symmetries $U(4)$
– Higgs as Pseudo-Goldstone (alleviates Little-Hierarchy Problem)

Non-SUSY, ad hoc global $U(4)$ Chacko-Goh-Harnik, PRL 2006

Atomic Dark Matter: $\Lambda'_{\rm QCD}/\Lambda_{\rm QCD}$ rescales as $(v'/v)^{0.3}$ or so
compact hydrogen/helium mirror atoms, or
Neutronic Dark Matter: mirror neutrons if $m'_p > m'_n$ and $p' \to n'\bar{e}'\nu$.

Self-collisional DM with right amount $\sigma/m_N \sim 1$ b/GeV
... or WDM – kev range neutrinos ZB, Mohapatra, Dolgov, 1995

Mirror sector and gauge flavor symmetries

$SU(3)_q \times SU(3)_u \times SU(3)_d \times SU(3)_l \times SU(3)_e$ *without anomalies*

$q_L \sim 3_q, \quad l_L \sim 3_l; \qquad \bar{u}_L \sim 3_u, \ \bar{d}_L \sim 3_d, \quad \bar{e}_L \sim 3_e$ 

$\bar{q}_R \sim \bar{3}_q, \quad \bar{l}_R \sim \bar{3}_l; \qquad u_R \sim \bar{3}_u, \ d_R \sim \bar{3}_d, \quad e_R \sim \bar{3}_e$ 

$q'_L \sim \bar{3}_q, \quad l'_L = \bar{3}_l; \qquad \bar{u}'_L \sim \bar{3}_u, \ \bar{d}'_L \sim \bar{3}_d, \quad \bar{e}'_L \sim \bar{3}_e$ 

$\bar{q}'_R \sim 3_q, \quad \bar{l}'_R = 3_l; \qquad u'_R \sim 3_u, \ d'_R \sim 3_d, \quad e'_R \sim 3_e$ 

Mirror parity $(L, R \to R, L)$: flavon superfields $\chi_L \to \chi_R = (\bar{\chi}_L)^+$

$W = \frac{1}{M}(\bar{u}\chi_u q\bar{\phi} + \bar{d}\chi_d q\phi + \bar{e}\chi_e l\phi) + \text{h.c.}$

$W' = \frac{1}{M}(\bar{u}'\bar{\chi}_u q'\bar{\phi}' + \bar{d}'\bar{\chi}_d q'\phi' + \bar{e}'\bar{\chi}_e l'\phi') + \text{h.c.}$

$\chi_u \sim (\bar{3}_u, \bar{3}_q), \quad \bar{\chi}_u \sim (3_u, 3_q) \quad \frac{\chi_u}{M} \to Y_u$, etc.

Quark & lepton Yukawa (mass and mixing) structures is determined by the pattern and hierarchy of flavon VEVs $\langle\chi\rangle$ Z.B. 1982-83

Mirror parity and MFV

• Generically, SUSY flavor limits require $M_{SUSY} > 100$ TeV or so ...

But assuming the gauge symmetry $SU(3) \times ...$ between 3 fermion families can be obtained quark-squark mass allignment:

universal relations $\tilde{m}_d^2 = m_0^2 + m_1^2(Y_d^\dagger Y_d) + m_2^2(Y_d^\dagger Y_d)^2$,

$A_d = A_0 Y_d + A_1 Y_d(Y_d^\dagger Y_d)$ etc.

Z.B. 1996; Anselm, Z.B.1997; Z.B., Rossi 2001

later on (2002) coined as MFV Giudice et al., 2002

$F-$terms can be easily handled
gauge $D-$ terms give problems
Flavon superpotential: $W_H = \mu\chi\bar{\chi} + a\chi^2 + a^*\bar{\chi}^3 + \text{h.c.}$
$\rightarrow$ D-terms vanish because of mirror parity

If flavour symmetry $SU(3) \times ...$ is shared between two sectors:

• Anomaly cancellation of between ordinary and mirror fermions

• SUSY flavor problem can be settled via MFV (safe D-terms)

• Interesting phenomena mediated by flavor gauge bosons: e.g. $K^0 \to K^{0\prime}$, $e\bar{\mu} \to \bar{e}'\mu'$ disappearance of muonium), etc.

LHC – run II: can SUSY be just around the corner?

"Natural" SUSY (at scale ~ 100 GeV with 2 Higgses) is over !

One Higgs discovered by LHC perfectly fits the SM Higgs ...

already at LEP epoch many theorists felt $M_{SUSY} < 1$ TeV was problematic

- SUSY induced proton decay (D=5) requires $M_{SUSY} > 1$ TeV or so
- SUSY induced CP-violation: electron EDM, $M_{SUSY} > 1$ TeV or so
- But gauge coupling crossing requires $M_{SUSY} < 10$ TeV or so

Z.B., Chianese, Miele, Morisi, 2015

TeV scale SUSY remains best choice for Grand Hierarchy Problem:
– maybe SUSY is indeed just around the corner?

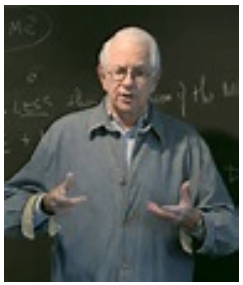
with a *little* (hierarchy) problem – Fine Tuning $\sim 10^{-2}$
$M^2_{\rm Higgs} \sim (100\ {\rm GeV})^2$ and $M^2_{\rm SUSY} \geq (1\ {\rm TeV})^2$ – Twin Higgs ?

Symmetric Mirror Matter: $DM \neq MM$?

For a long while mirror matter was not considered as a real candidate for dark matter: M world was naively taken to have not only exactly identical microphysics as O sector but also exactly identical cosmology:

- $T' = T, \quad g'_* = g_* \quad \rightarrow \quad \Delta N_\nu^{\rm eff} = 6.15$ vs. $\Delta N_\nu^{\rm eff} < 0.5$ (BBN)
- $n'_B/n'_\gamma = n_B/n_\gamma \ (\eta' = \eta) \quad \rightarrow \quad \Omega'_B = \Omega_B$ vs. $\Omega'_B/\Omega_B \simeq 5$ (DM)

IMirror World is colder? If $T'/T < 0.5$, BBN is OK
but $\eta' = \eta$ implies $\Omega'_B = (n'_\gamma/n_\gamma)\Omega_B = (T'/T)^3\Omega_B \ll \Omega_B$



Then $DM \neq MM$

Such a mirror universe "can have no influence on the Earth and therefore would be useless and therefore does not exist"

S. Glashow (1987), citing Francesco Sizzi

However ....

Understanding of astronomy, optics, and physics, a rumor about the four planets seen by the very celebrated mathematician Galileo Galilei with his telescope, shown to be unfounded.

Francesco Sizzi, crlticism of Galileo's discovery of the Jupiter's moons

The microphysics of the postulated mirror matter should be exactly the same as that of the usual matter. However, we know that the spatial distribution of the dark matter is very different from that of the ordinary (baryonic) matter. On the face of it this makes mirror matter an implausible candidate for dark matter.

Tizio Caio (Anonimuos Referee), from a referee report (PRL of course)

– All you need is ... M world colder than ours !

Z.B., Comelli, Villante, 2000

It is enough to accept a Cosmological Paradigm:

(A) at the Big Bang (i.e. after inflation) the M world was born with smaller temperature than O world

(B) all interactions between M and O particles are feeble enough and cannot bring two sectors into equilibrium after reheating

(C) no entropy production by 1st order phase transitions which could heat M world: two systems evolve adiabatically over the universe expansion and their temperature ratio T'/T remains nearly constant.

If $x = T'/T \ll 1$, BBN is OK

(About why $\Omega'_B \simeq 5\,\Omega_B$ in my next talk ...)

$DM = MM$: possible manifestations

A. *Cosmological implications.* $T'/T < 0.2$ or so, $\Omega'_B/\Omega_B = 1 \div 5$.
Mass fraction: H' – 25%, He' – 75%, and few % of heavier C', N', O' etc.
• Mirror baryons as asymmetric/collisional/dissipative/atomic dark matter: M hydrogen recombination and M baryon acoustic oscillations?
• Easier formation and faster evolution of stars: Dark matter disk? Galaxy halo as mirror elliptical galaxy? Microlensing ? Neutron stars? Black Holes? Binary Black Holes? Central Black Holes?

B. *Direct detection.* M matter can interact with ordinary matter e.g. via kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$, etc. Mirror helium as most abundant mirror matter particles (the region of DM masses below 5 GeV is practically unexplored). Possible signals from heavier nuclei C,N,O etc.

C. *Oscillation phenomena between ordinary and mirror particles.*
The most interesting interaction terms in $\mathcal{L}_{\rm mix}$ are the ones which violate B and L of both sectors. Neutral particles, elementary (as e.g. neutrino) or composite (as the neutron or hydrogen atom) can mix with their mass degenerate (sterile) twins: matter disappearance (or appearance) phenomena can be observable in laboratories.
In the Early Universe, these B and/or L violating interactions can give primordial baryogenesis and dark matter genesis, with $\Omega'_B/\Omega_B = 1 \div 5$.

$DM = MM$: cosmological implications

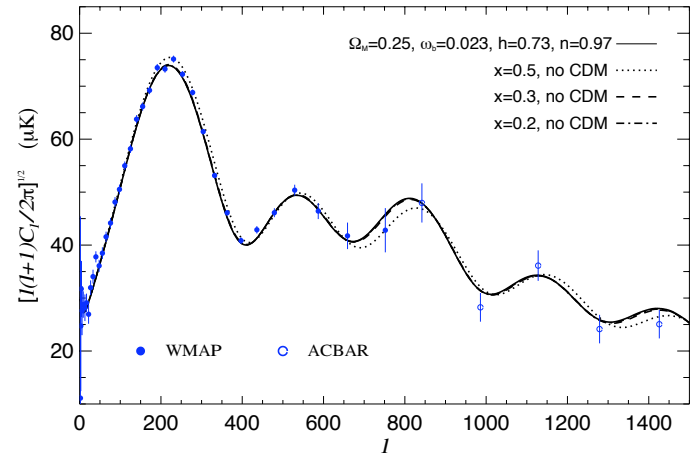
$T'/T < 0.5$ is enough to concord with the BBN limits and do not affect standard primordial mass fractions: 75% H + 25% ^{4}He.
Cosmological limits are more severe, requiring $T'/T < 0.2$ os so.
This implies that M world is helium dominated: 25% H$'$ + 75% ^{4}He$'$.

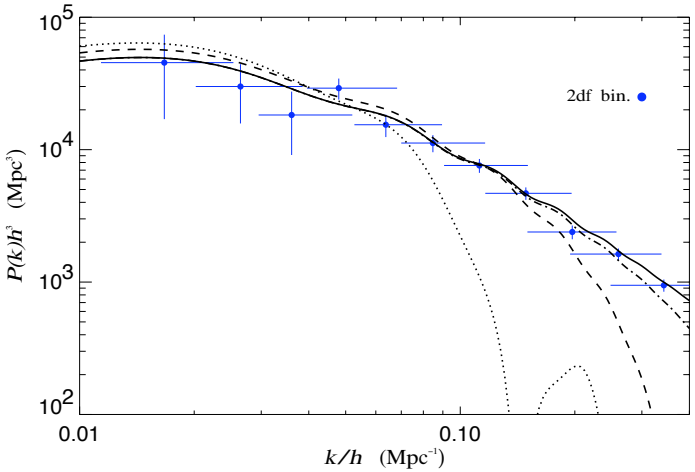
Because of $T' < T$, the situation $\Omega'_B > \Omega_B$ becomes plausible in baryogenesis. So, M matter can be dark matter (my next talk)

Because of $T' < T$, in mirror photons decouple much earlier than ordinary photons, and after that M matter behaves for the structure formation and CMB anisotropies essentially as CDM. This concords M matter with WMAP/Planck, BAO, Ly-α etc. if $T'/T < 0.25$ or so.

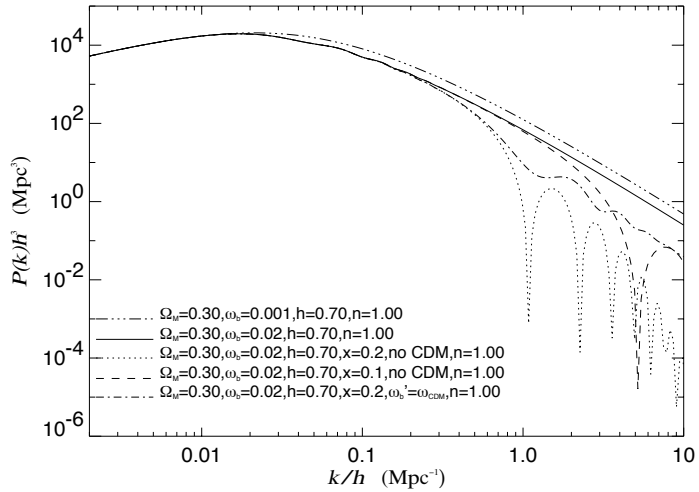
Halo problem – if $\Omega'_B \simeq \Omega_B$, M matter makes ~ 20 % of DM, forming dark disk, while ~ 80 % may come from other type of CDM (WIMP?)
But perhaps 100 % ? if $\Omega'_B \simeq 5\Omega_B$: – M world is helium dominated, and the star formation and evolution can be much faster. Halos could be viewed as mirror elliptical galaxies, with our matter inside forming disks. MM is not only self-interacting (H$'$ H$'$ scattering, Bullet cluster, etc.) but it is dissipative – forms star and becomes collisionless (like CDM)
Key question: Howe fas the mirror star formation can be?

CMB and LSS power spectra





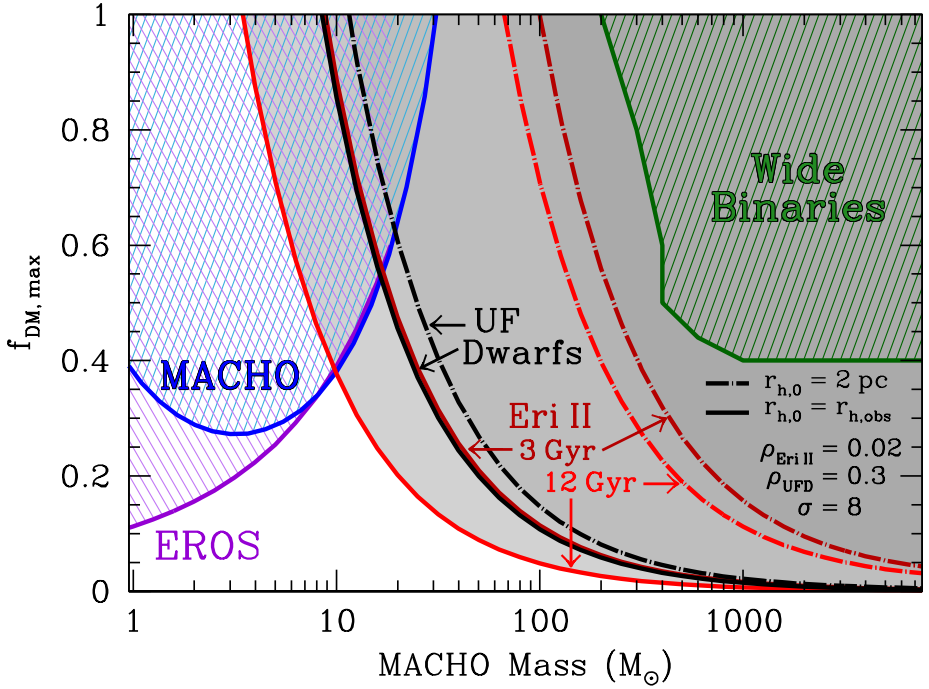
Z.B., Ciarcelluti, Comelli, Villante, 2003



Acoustic oscillations and Silk damping at short scales: $x = T'/T < 0.2$

Can Mirror stars be progenitors of gravitational Wave bursts GW150914 etc. ?

Picture of Galactic halos as mirror ellipticals (Einasto density profile), O matter disk inside (M stars = Machos).
Microlensing limits: $f \sim 20 - 40$ % for $M = 1 - 10\ M_\odot$,
$f \sim 100$ % is allowed for $M = 20 - 200\ M_\odot$ but see Brandt '05



Three events without any optical counterpart

Points towards massive BH compact binaries, $M \sim 10 - 30\ M_\odot$ and radius $R \sim 10 R_\odot$

How such objects can be formed ?

M matter: 25 % Hydrogen vs 75 % Helium: M stars more compact, less opaque, less mass loses by stellar wind and evolving much faster. Appropriate for forming such BH binaries ?

Discussing $\mathcal{L}_{\rm mix}$: possible portal between O and M particles

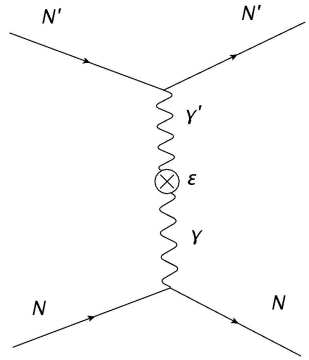
- Photon-mirror photon kinetic mixing $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Experimental limit $\epsilon < 4 \times 10^{-7}$

Cosmological limit $\epsilon < 5 \times 10^{-9}$

Makes mirror matter nanocharged ($q \sim \epsilon$)

A promising portal for DM direct detection Foot, 2003



Mirror atoms: He' – 75 %, C',N',O' etc. few %

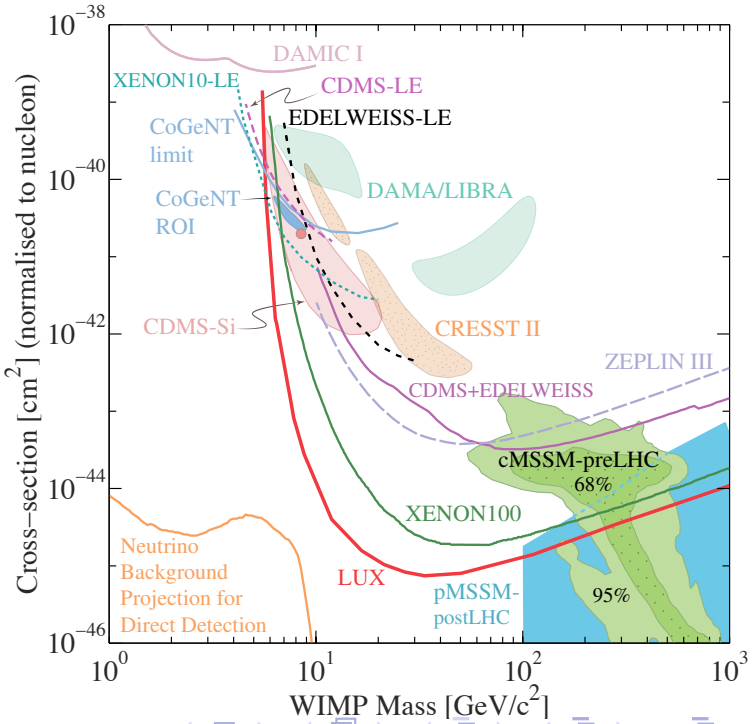
Rutherford-like scattering

$$\frac{d\sigma_{AA'}}{d\Omega} = \frac{(\epsilon\alpha ZZ')^2}{4\mu^2_{AA'} v^4 \sin^4(\theta/2)}$$

or

$$\frac{d\sigma_{AA'}}{dE_R} = \frac{2\pi(\epsilon\alpha ZZ')^2}{M_A v^2 E_R^2}$$

Belli, this Workshop



Magnetic field via electron drag mechanism

Detection possibility of Mirror matter via photon kinetic mixing was recently studied in two works with DAMA Collaboration
For asymmetric MM, 2015 For symmetric MM, 2017

Photon-mirror photon kinetic mixing $\rightarrow$ Rutherford-like scattering

...

Relative motion (rotation) of O and M matter drags electrons but not protons/ions which are much heavier. So circular electric currents emerge which can generate magnetic field. Modifying mirror Maxwell equations by the source (drag) term, one gets magnetic seed $B, B' \sim 10^{-15}$ G before dynamo, then amplified by dynamo. This mechanism can induce magnetic fields $\sim \mu$G in very young galaxies
Z.B., Dolgov, Tkachev, 2013

MM capture by Earth can induce mirror magnetic field in the Earth, even bigger than ordinary 0.5 G.

Summary

I discussed several issues of DM and MM .... (not all !)

$DM = MM$ seems OK to me (Good Policeman)

Why $DM \neq MM$? Next talk of Sasha Dolgov (Bad Policeman)

Two Policeman method (Good + Bad)
works well for finding who is delinquent

If you have some new information or ideas or criticism,
let's discuss during this Workshop

Thank You !