A Brief Introduction to Asymmetric Dark Matter

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1 Asymmetric Dark Matter

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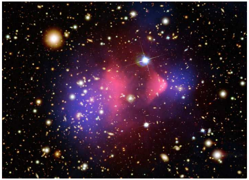
2 Type I: Sharing

Beyond the Standard Model

- Hints for physics beyond the Standard Model:
  - Dark Matter
  - Dark Energy
  - Neutrino oscillations



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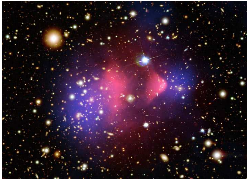

- Open questions
  - What is the nature of DM?
  - How is DM created?
  - Why is $\Omega_{DM} \sim \Omega_b$?

Comparing Baryonic and Dark Matter

Baryons

Mass:

$m_N \simeq 1$ GeV

Abundance:

$n_b/n_\gamma = (6.19 \pm 0.15) \cdot 10^{-10}$

Density:

$\Omega_b \simeq 0.046$

Dark Matter

Mass:

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$$\frac{\Omega_{DM}}{\Omega_b} \simeq 5$$

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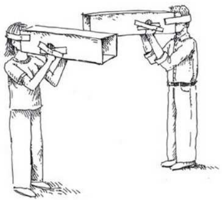
$\Longrightarrow$ Cross section of weak strength

- Weakly Interacting Massive Particles (WIMPs)
- Great! Or is it?



The WIMP miracle

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The WIMP miracle!

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Thermal freezout

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The WIMP miracle!

Facing the WIMP miracle

If you like WIMPS:
"Just assuming new physics at TeV scale, we derived that DM interacts with a weak scale cross section to the SM. This fits my expectations of how and where new physics should be found."

If you do not like WIMPS:
"I dont believe that just by coincidence you would get the same DM and baryon abundances when they have so different masses and production mechanisms. I want DM and baryons to be more similar."

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- Let us try to see if we can achieve this: Asymmetric Dark Matter (ADM)

How to make DM similar to baryons

- Baryons are Dirac fermions
- Baryon abundance is tied to baryon number B
- Baryons asymmetry seeded in early Universe

- Make DM a Dirac fermion
- Introduce dark matter number X
- Make the X "talk" to B

These assumptions makes DM similar to baryons and have similar number density, thus

$$\frac{m_{DM}}{m_b} \simeq \frac{\Omega_{DM}}{\Omega_b} \simeq 5$$

1. Asymmetric Dark Matter
2. Type I: Sharing
3. Type II: Cogenesis
4. Summary and conclusions

Sharing and Cogenesis

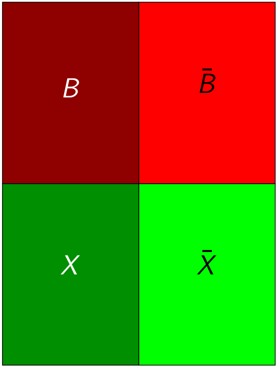
There are two main mechanisms behind ADM production:

Sharing:
Baryons and Dark Matter shares a primordial asymmetry produced in an arbitrary sector.

Cogenesis
The Baryon and Dark Matter asymmetries are produced by the same processes.

Conditions for Sharing

A few ingredients necessary for generating ADM in sharing models



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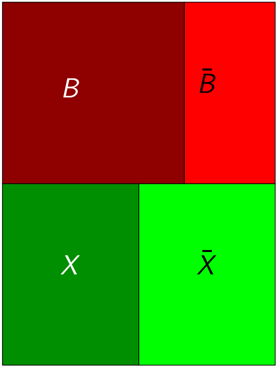

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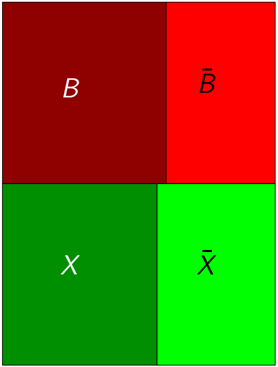

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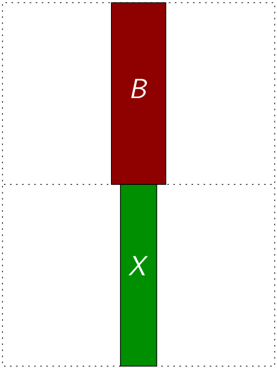
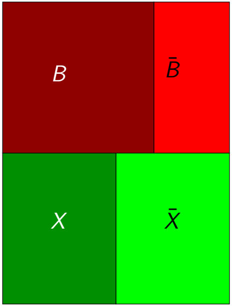
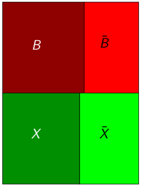


Asymmetry generation

- **Baryon number** B
  Baryogenesis Sakharov 1967
- **Lepton number** L
  Leptogenesis Fukugita, Yanagida 1986
- **Dark matter number** X
  Darkogenesis Shelton, Zurek, arXiv:1008.1997
  Xogenesis Buckley, Randal, arXiv:1009.0270
  ...



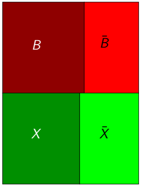
Asymmetry transfer



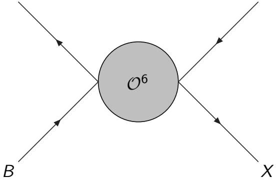
The transfering processes need to be:

- Fast and active in the early Universe
- Inactive at lower energies

Asymmetry transfer



Effective operators



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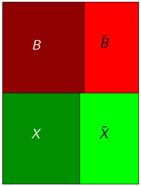

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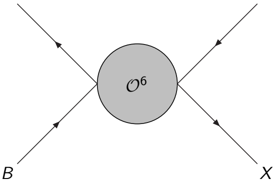
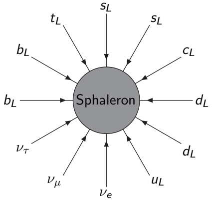
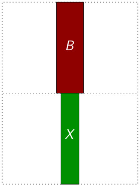


Sphaleron processes



Thermal component annihilation

- ADM has a mass in the few GeV region
- WIMPs get the correct relic abundance with a weak scale cross section
- Annihilation of lighter species require larger cross sections



$\Longrightarrow$ Larger annihilation cross section than weak – Problem!

ADM mass is higher, but abundance is Boltzmann suppressed compared to B

Thermal component does not annihilate directly into SM particles

Cosmological phenomenology

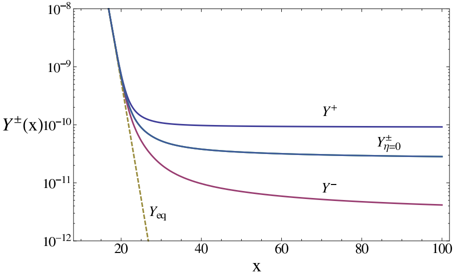
ADM generally has different cosmology than WIMP DM

- Only consisting of particles (no anti-particles) $\Rightarrow$ no indirect detection
- Accumulates in stellar bodies – what is the effect on stellar evolution?

  Frandsen, Sarkar, arXiv:1003.4505; Taoso, et al, arXiv:1005.5711
- Short range self-interacting ADM could alter halo evolution (to the better)

  Spergel, Steinhard, astro-ph/9909366

How asymmetric is ADM?

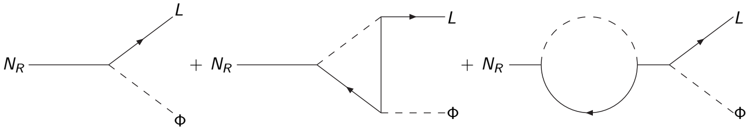


Graesser, Shoemaker, Vecchi, JHEP 1110 (2011) 110

- Cross section close to what is required
- Annihilation is not complete
- Residual componenet of anti-ADM
- Phenomenological consequences?

Standard leptogenesis

Generation of lepton number asymmetry by CP violating decays of heavy Majorana fermion singlets N_R (typically type-I seesaw)



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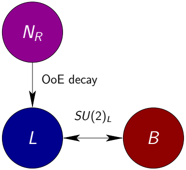
Asymmetry transfer from L

- The asymmetry in L could transfer to both B and X



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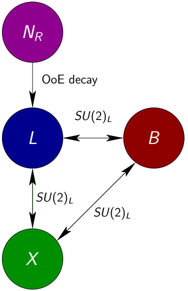

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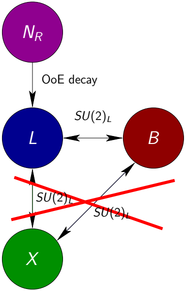
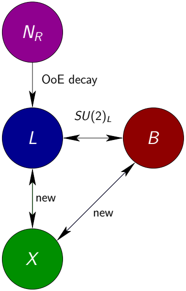


Aidnogenesis via Leptogenesis

- The basic idea: New gauge group to provide new sphalerons

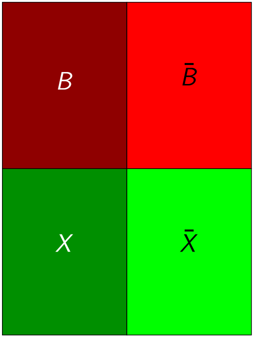
- Extend the gauge sector of the SM
- Additional sphaleron processes
- Is this possible to acheive?

MB, et al, arXiv:1009.3159



Cogenesis

Necessary ingredients for generating ADM in cogenesis models:



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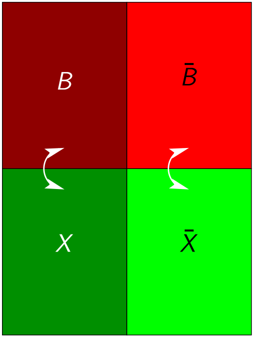

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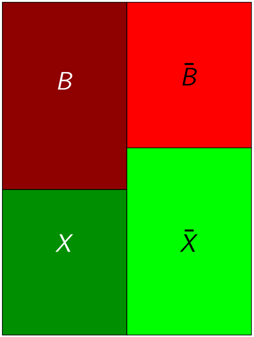

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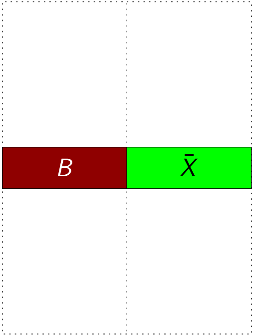


Asymmetry production in Cogenesis

- Consider a heavy field H with a CP violating decay

$$\Gamma(H \to BX) \neq \Gamma(H \to \bar{B}\bar{X})$$

- If the decays are out of thermal equilibrium (cf. Leptogenesis), asymmetries can result in both B and X
- Typically, it will be possible to assign X such that $X = -B$
- Dark Matter can be viewed as being anti-baryonic and carry the missing baryon number with $B_{SM} + B_{DM} = 0$ Kitano, Low, hep-ph/0411133; Agashe, Servant, hep-ph/0411254

Cogenesis versus Sharing

There are pros and cons with both Cogenesis and Sharing:

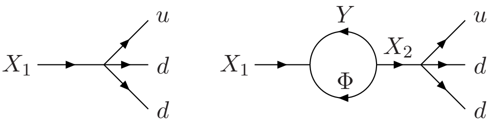
- Cogenesis typically relates B and X through some fundamental interaction
- Typically B-X relation at a relatively low energy scale
- Problems consolidating with current bounds
- Difficulty of model building

- Sharing does not imply strong B-X interactions, just communication between the sectors
- Asymmetry production not related to B-X relation
- Asymmetry production can be put at very high scales
- More possibility of separating the physics of the two sectors

Hylogenesis

- Use the following ingredients: Davoudiasl, et al, arXiv:1008.2399
  - Two heavy Dirac fermions X_1, X_2 ($M_{X_a} \gtrsim$ TeV)
  - A GeV scale Dirac fermion Y
  - A GeV scale scalar Φ
- With proper assignment of Baryon numbers, $B_{X_a} = 1 = -(B_Y + B_\Phi)$:

$$-\mathcal{L} \supset \frac{\lambda_a}{M^2} \bar{X}_a P_R d \bar{u}^c P_R d + \zeta_a \bar{X}_a Y^c \Phi^* + \mathrm{h.c.}$$



Summary

We have . . .

- discussed the general principles of ADM
- discussed how different ADM models can be constructed
- discussed the two dominant ways of generating ADM
- seen selected examples

Incomplete set of references

Nussinov, 1985
Barr, et al, 1990
Kaplan, 1992
Kitano, Low, hep-ph/0411133
Agashe, Servant, hep-ph/0411254
Kaplan, arXiv:0901.4117
An, et al., arXiv:0911.4463
Frandsen, Sarkar, arXiv:1003.4505
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Davoudiasl, et al, arXiv:1008.2399
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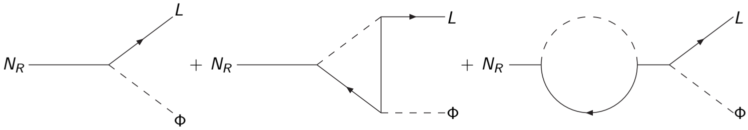

- Seeds a lepton number asymmetry L
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Direct production

One way of producing ADM is to let the two sectors be seeded at the same time, i.e.,

- In addition to $N_R \to L\Phi$, we have $N_R \to X\phi$
- X can belong to a mirror world (An, et al., arXiv:0911.4463) or be the ADM itself (Falkowski, et al., arXiv:1101.4936)
- The mirror world has problems with extra radiation and neutrinos mixing between worlds
- The pure ADM model needs extra symmetries to prevent DM-neutrino mixing
- It is also a Majorana fermion $\to$ small or no window (Buckley, Profumo, arXiv:1109.2164)

Asymmetry transfer from L

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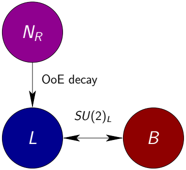

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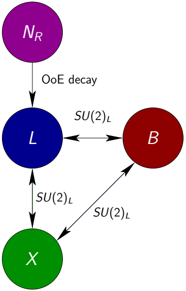

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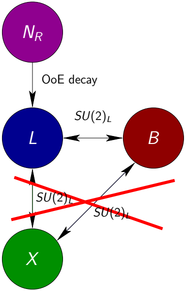

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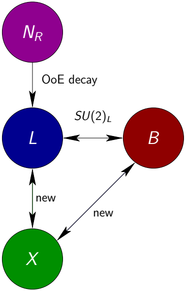

5 Asymmetric Dark Matter via Leptogenesis

6 A model of Asymmetric Dark Matter

Extending the SM gauge group

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$$G_{ADM} = G_{SM} \times SU(2)_H$$

- Horzontal chiral symmetry providing new spalerons

Extending the SM gauge group

- We want to introduce new spalerons ⇒ extend the gauge group
- We want (part of) the extended group to couple to both SM and DM
- We want to prevent mixing between neutrinos and DM

$$G_{ADM} = G_{SM} \times SU(2)_H \times SU(3)_{dc}$$

- Horzontal chiral symmetry providing new spalerons
- Charge DM under additional "dark color" group to prevent mixing with singlets

Introduction of new fermion fields

For each SM generation, we also introduce:

- A right handed fermion singlet N_R (type-I seesaw) $\Rightarrow$ leptogenesis, neutrino masses
- A dark sector of fermions x_R, x_L, which will form a Dirac fermion $\Rightarrow$ ADM
- Put different flavors of right handed fields in doublets of $SU(2)_H$:

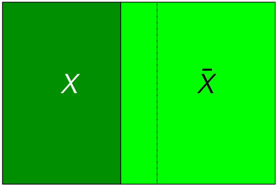
$$\begin{pmatrix} e \\ \mu \end{pmatrix}_R, \begin{pmatrix} u \\ c \end{pmatrix}_R, \begin{pmatrix} d \\ s \end{pmatrix}_R, \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_R$$

- Make x_R and x_L triplets under $SU(3)_{dc}$ $\Rightarrow$ x_L does not mix with N_R (and some interesting phenomenology)

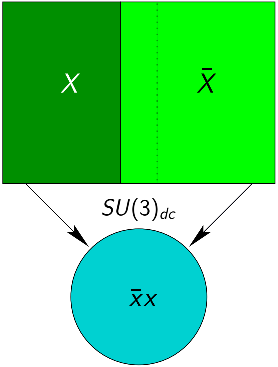
Complete fermion content

Field	Y	L	H	C	dc
$L_{L\alpha}$ $(\nu_{\alpha L}, \ell_{\alpha L})$	$-1/2$	**2**	1	1	1
L_H (e_R, μ_R)	-1	1	**2**	1	1
τ_R	-1	1	1	1	1
$\nu_{\alpha R}$	0	1	1	1	1
$Q_{\alpha L}$ $(u_{\alpha L}, d_{\alpha L})$	$1/6$	**2**	1	**3**	1
Q_H^u (u_R, c_R)	$2/3$	1	**2**	**3**	1
Q_H^d (d_R, s_R)	$-1/3$	1	**2**	**3**	1
t_R	$2/3$	1	1	**3**	1
b_R	$-1/3$	1	1	**3**	1
X_H (x_R^1, x_R^2)	0	1	**2**	1	**3**
x_R^3, x_L^α	0	1	1	1	**3**

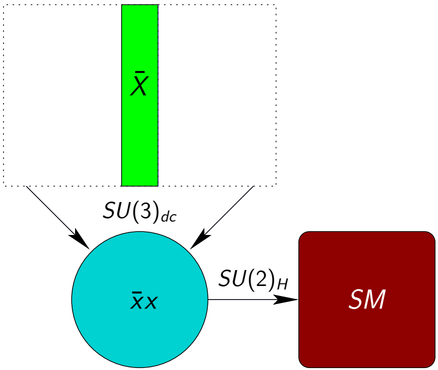
Removing the thermal component



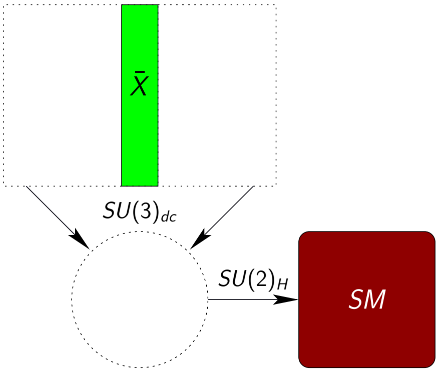
Removing the thermal component



Removing the thermal component



Removing the thermal component



Dark matter properties

- The $SU(2)_H$ sphalerons satisfy $\Delta B = 2\Delta L = 2\Delta X$
- Along with SM sphalerons, $B - L - X$ remains non-anomalous and conserved
- After sphaleron freezout

$$X = -\frac{11}{14}B \;\Rightarrow\; m_{DM} = 5.94 \pm 0.42 \text{ GeV}$$

- $SU(3)_{dc}$ is confining $\Rightarrow$ DM consists of dark baryons
- We expect a thermal abundance of both DM and anti-DM in the early Universe
- Below the $SU(3)_{dc}$ phase transition, the thermal component goes into dark mesons
- Dark mesons decay to SM via $SU(2)_H$

In the early Universe

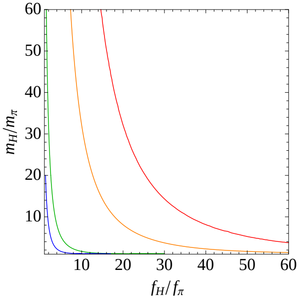
- We want the dark mesons to decay before BBN $\Rightarrow$ lower bound on G_F^H
- The $SU(2)_H$ is going to induce FCNC, from $K^0 \to e\mu$:

$$G_F^H < 3.6 \cdot 10^{-12}\ \mathrm{GeV}^2$$

- Too low for dark mesons to decay fast enough
- Could couple to second and third generation where bounds are weaker

Breaking $SU(2)_H$ in stages

- Another possibility: $SU(2)_H$ is broken to a flavor conserving $U(1)$
- Break $SU(2)_H$ by a scalar triplet vev in the flavor conserving direction



For $\tau < 10^{-2}$ s

$G_F^H >$

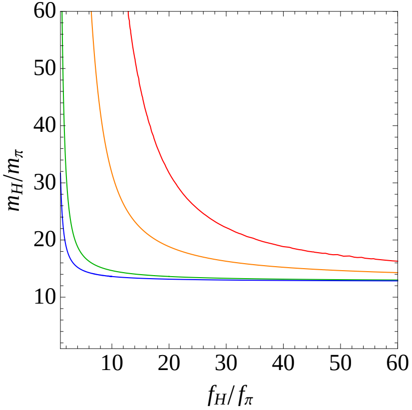
$5 \cdot 10^{-11}$ GeV^2

10^{-10} GeV^2

$5 \cdot 10^{-10}$ GeV^2

10^{-9} GeV^2

With τ in the doublet



Conclusions

- Our model has the following “nice” features:
  - Anomaly free extension of the SM gauge group
  - Dark matter and baryon abundances similar
  - Dark matter and baryon masses similar and given by similar processes
  - Dark matter is stable without any additional parity
  - Allows for some interesting phenomenology at low energies, such as flavor violation or possible direct detection
- In fairness, also some “ugly” features must be mentioned:
  - Why a horizontal $SU(2)$?
  - The assignment of flavors to $SU(2)_H$ doublets is artificial
  - Difficult to extend to, e.g., $SU(3)$ flavor symmetry