OVERVIEW OF ASYMMETRIC DARK MATTER

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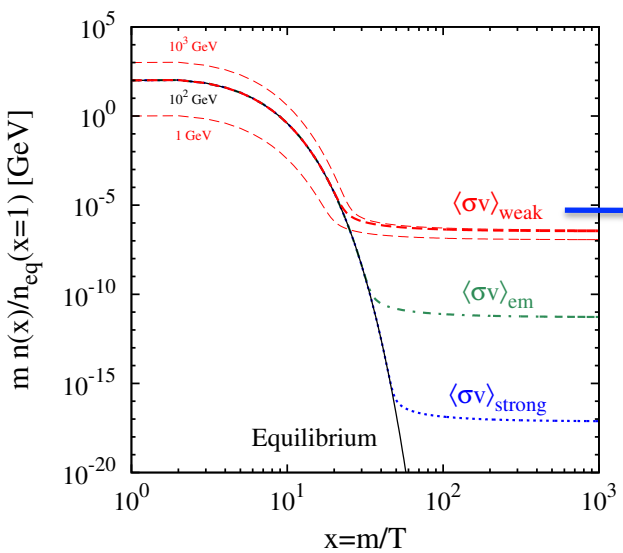
Based on IJMPA invited review:
K. Petraki and RV, arXiv:1305.4939

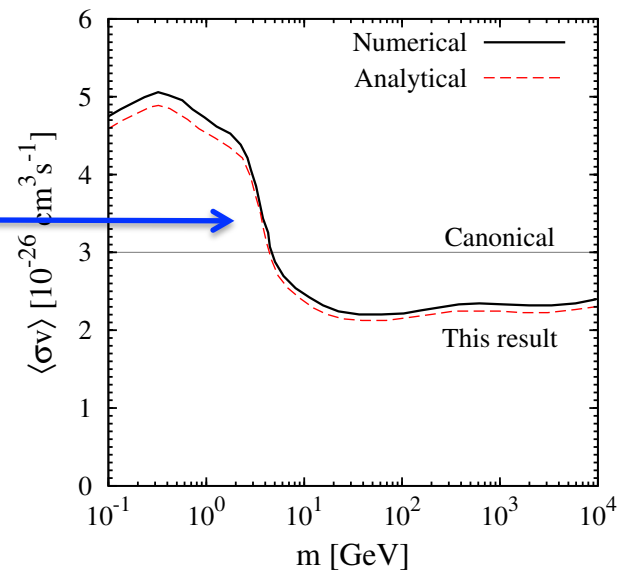
1. **WIMPs vs ADM vs sterile neutrinos vs axions**
2. **ADM generalities**
3. **Some models**
4. **Phenomenology**
5. **Final remarks**

1. WIMPs vs ADM vs sterile neutrinos vs axions

The WIMP "miracle" can explain the observed DM density. Connected to new weak/TeV scale physics e.g. susy.

WIMP decouples from the thermal plasma when non-relativistic and Boltzmann suppressed.





Steigman, Dasgupta, Beacom: Phys. Rev. D86 (2012) 023506

$$\Omega_\chi = \frac{m_\chi n_\chi}{\rho_c} \simeq \frac{6\times 10^{-27}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma_A v\rangle}$$

$$\simeq 0.2 \text{ for } \langle\sigma v\rangle \simeq 3\times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

Why is $\Omega_d \approx 5\Omega_v$?

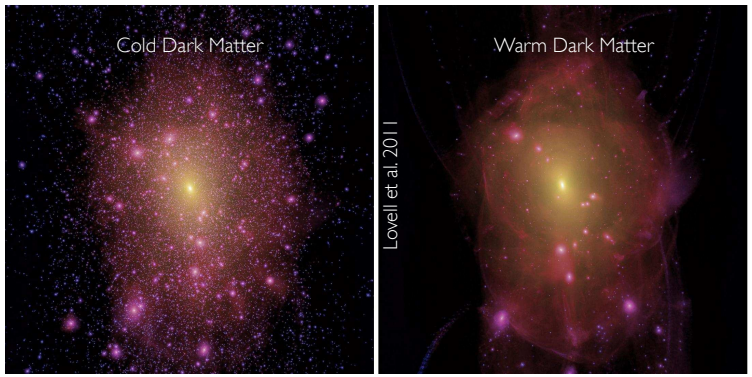
The WIMP miracle requires this similarity to be a coincidence.

Ω_v is due to a particle-antiparticle asymmetry, not the non-relativistic decoupling of a self-conjugate or symmetric relic.

Motivates "asymmetric dark matter (ADM)":
DM and VM densities both due to <u>related</u> particle-number asymmetries.

DM mass scale typically few to 10s of GeV range.

warm, cool, chilled: small-scale structure problem?



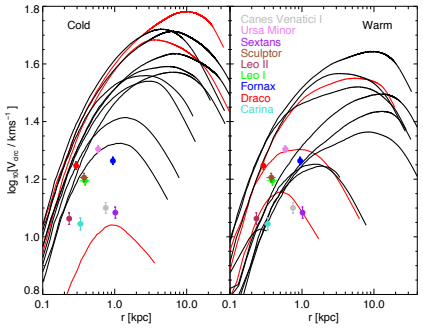
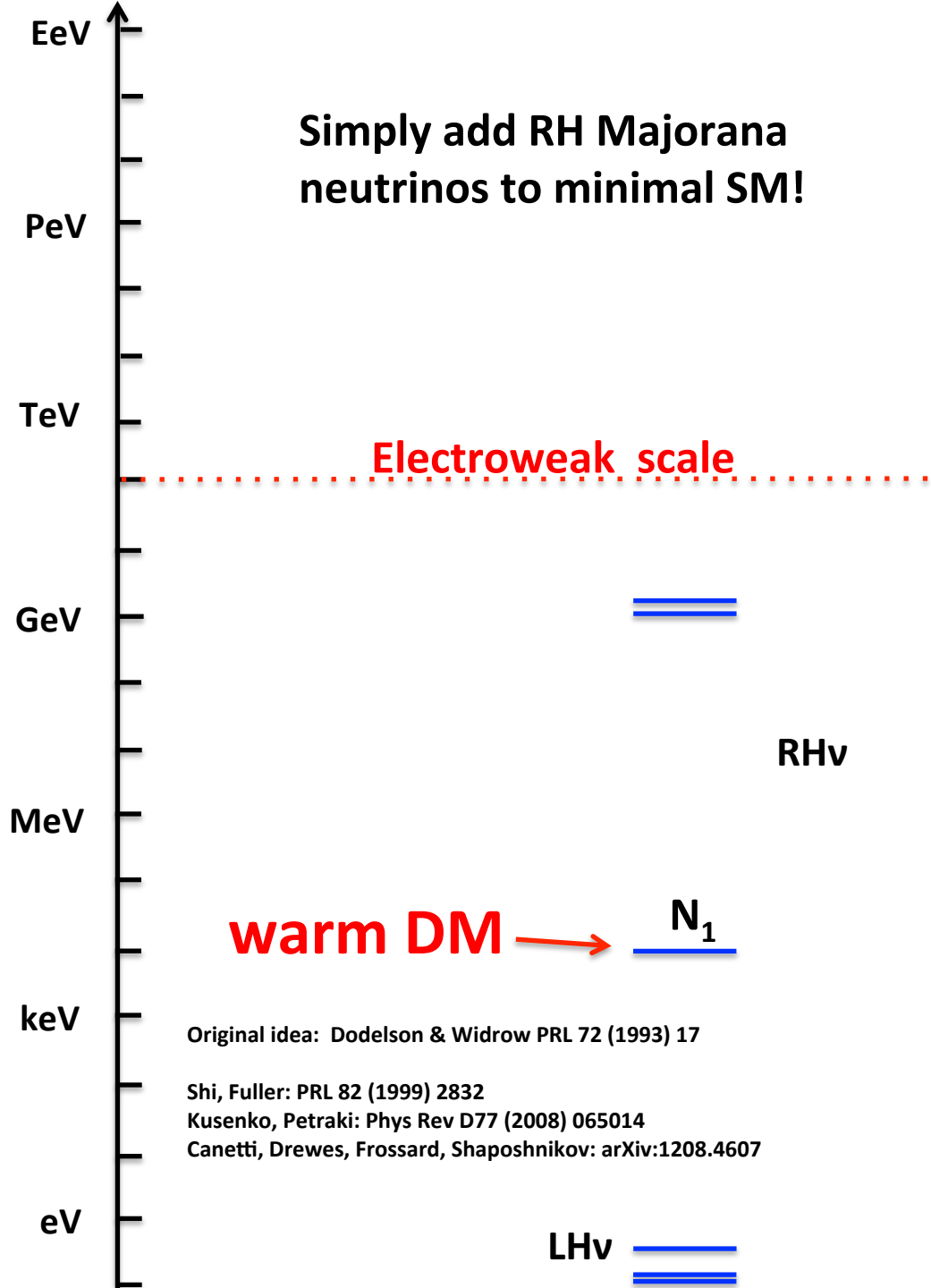


Figure 5. Circular velocity curves for the 12 CDM (left) and WDM (right) subhaloes that had the most massive progenitors. The 3 red curves represent subhaloes with the most massive progenitors, which could correspond to those currently hosting counterparts of the LMC, SMC and the Sagittarius dwarf. The 9 black curves might more fairly be compared with the data for the 9 bright dwarf spheroidal galaxies of the Milky Way considered by Wolf et al. (2010). Deprojected half-light radii and their corresponding half-light masses, as determined by Wolf et al. (2010) from line-of-sight velocity measurements, are used to derive the half-light circular velocities of each dwarf spheroidal. These velocities and radii are shown as coloured points. The legend indicates the colour coding of the different galaxies.

From Lovell et al: MNRAS 420, 231 (2012)



Strong CP problem.

$$\mathcal{L}_{\rm QCD} \supset \theta \ {\rm Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$$

Neutron EDM bound $\theta < 10^{-10}$

Peccei-Quinn solution turns θ into a field: implies very light pseudoscalar boson, the axion.

Perfectly legitimate candidate – but the strong CP problem can be solved without axions being a dominant component of DM.

2. ADM GENERALITIES

In ADM models:

- the "visible sector" is the SM or some extension
- the "dark sector" may be some other gauge theory

$$G = G_V \times G_D \times G_{V+D}$$

or otherwise just fermions and/or scalars.

The sectors are coupled in the very early universe, and the asymmetries get related.

The sectors then decouple at low energies.

In most models the VM & DM number densities are similar, so the dark sector has to contain a stable GeV-scale particle.

See later comment on alternate mass scale possibility

What stabilises massive particles? In the SM:

proton (antiproton) = lightest particle carrying conserved baryon number
electron (positron) = lightest particle carrying conserved electric charge
lightest neutrino = lightest half-integer spin particle (angular mom. conservation)
neutrons in appropriate nuclei = bound state effect

We hypothesise at least a "dark baryon number B_D".

Some models have a "dark EM" and hence dark radiation.
Some interaction has to "annihilate the symmetric part".
If not dark EM, then something else, e.g. Yukawa mediated annihilation into dark massless fermions. And so on.

N_{eff} is an important constraint: discuss later.

2.1 Symmetry structure

Dark sector: **B_D (analogue of visible baryon number B_V). The asymmetry in the dark sector is in B_D.**

Visible sector: **best to consider $(B\text{-}L)_V$, because it is anomaly-free, and above the EW phase transition we have to take into account sphaleron reprocessing. E.g. we can have the initial visible-sector asymmetry purely in lepton number.**

Asymmetry: $$\eta(X) \equiv \sum_i X_i (n_i - n_{\bar{i}})/s$$

Case 1: Baryon-symmetric universe

Dodelson and Widrow: PRL 64 (1990) 340
Davoudiasl et al: PRL 105 (2010) 211304
Bell, Petraki, Shoemaker, RV: PRD 84 (2011) 123505
Cheung, Zurek: PRD 84 (2011) 035007
von Harling, Petraki, RV: JCAP 1205 (2012) 021
others … see 1305.4939 for full reference list.

Conserved: $$B_{\rm con} \equiv (B-L)_V - B_D$$

Broken: $$B_{\rm bro} \equiv (B-L)_V + B_D$$

At early times and high temperatures: B_{bro} violated but B_{con} strictly conserved.

At late times and low temperatures, B_V and B_D are separately conserved – ensures stability of protons and DM.

Generate B_{bro} asymmetry using dynamics obeying Sakharov conditions. Then

$$\eta((B-L)_V) = \eta(B_D) = \eta(B_{\rm bro})/2$$

The B-L number of VM is secretly cancelled by the DM!

Simultaneous creation of correlated asymmetries. "Pangenesis" "Cogenesis"

$$\eta((B-L)_V) = \eta(B_{\rm bro})/2$$

VISIBLE SECTOR

$$\eta(B_D) = \eta(B_{\rm bro})/2$$

DARK SECTOR

Case 2: visible to dark reprocessing

Initially, $(B\text{-}L)_V$ is broken but B_D is not.

During the chemical equilibration, some non-trivial combination of $(B\text{-}L)_V$ and B_D is conserved.

The sectors subsequently decouple.

asymmetry created here

$$\eta((B-L)_V) \neq 0$$

VISIBLE SECTOR

shared s.t.

$$\eta((B-L)_V) \sim \eta(B_D)$$

$$\eta(B_D) \neq 0$$

DARK SECTOR

Case 3: dark to visible reprocessing

Initially, B_D is broken but $(B\text{-}L)_V$ is not.

During the chemical equilibration, some non-trivial combination of $(B\text{-}L)_V$ and B_D is conserved.

The sectors subsequently decouple.

asymmetry created here

$$\eta(B_D) \neq 0$$

DARK SECTOR

shared s.t.

$$\eta((B-L)_V) \sim \eta(B_D)$$

$$\eta((B-L)_V) \neq 0$$

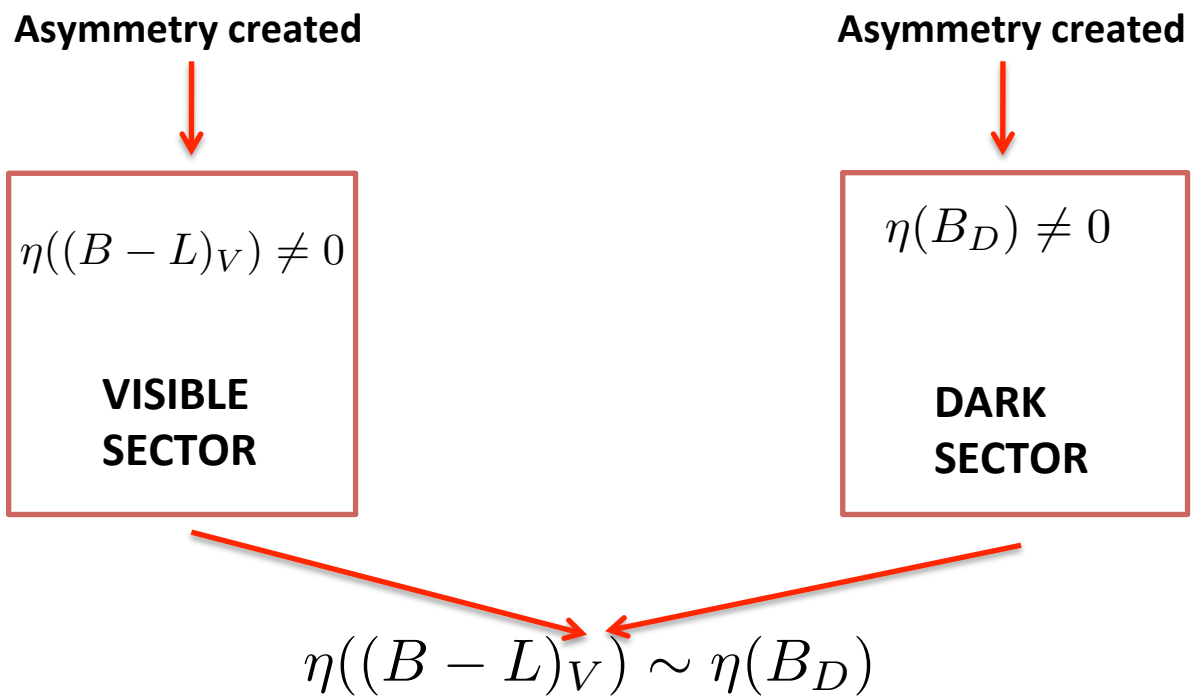
VISIBLE SECTOR

Case 4: initial asymmetries develop independently

Initially, both $(B\text{-}L)_V$ and B_D are broken.

To relate the asymmetries, subsequent interactions should preserve some non-trivial combination of $(B\text{-}L)_V$ and B_D.

The sectors subsequently decouple.



One version of mirror DM cosmology: sectors remain decoupled: different T, but identical microphysics!

2.2 Asymmetry generation

Creating an asymmetry (Sakharov 1967):

1. **Violation of particle number conservation**
2. **C and CP violation**
3. **Out-of-equilibrium process**

1. **Obvious**

2. $\text{Rate } i \to f(\Delta B = b) \neq \text{Rate } \bar{i} \to \bar{f}(\Delta B = -b)$

3. $\text{Rate } i \to f(\Delta B = b) \neq \text{Rate } f \to i(\Delta B = -b)$

Common general mechanisms:

Out-of-equilibrium decays of heavy particles:

$$\Gamma(\psi \to x_1\ x_2 \ldots) \neq \Gamma(\psi \to x_1^*\ x_2^* \ldots)$$

Affleck-Dine: production of charged scalar condensate through time-dep. phase. Supersymmetry, uses flat directions.

First-order phase transition: nucleation of bubbles of true vacuum, sphalerons, CP-violating collisions with bubble walls.

Asymmetric freeze-out: DM particles coannihilate with SM particles at a different rate from DM antiparticles.

Asymmetric thermal production (asymmetric freeze-in): DM and anti-DM never in thermal equilibrium; slowly produced at different rates.

Spontaneous genesis: Sakharov conditions presuppose CPT invariance. Expanding universe induces effective CPT violation. Asymmetry generation in eq. without C, CP violation.

2.3 Freeze-out in presence of an asymmetry:

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

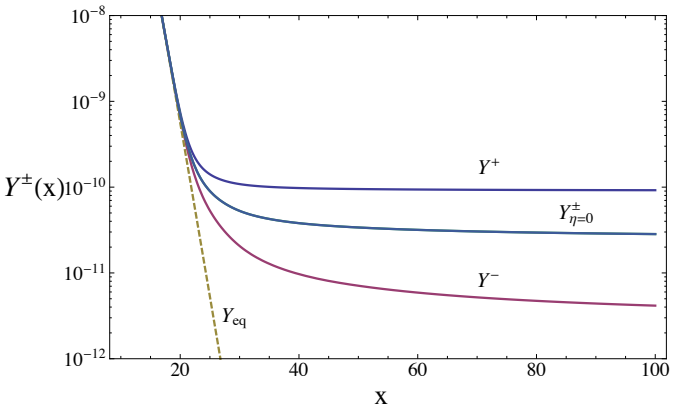


Figure 1. Evolution of $Y^{\pm}(x)$ illustrating the effect of the asymmetry η. After freeze-out both Y^- and Y^+ continue to evolve as the anti-particles find the particles and annihilate. The $Y^{\pm}_{\eta=0}$ curve shows the abundance for $\eta = 0$, a mass $m = 10$ GeV and annihilation cross-section $\sigma_0 = 2$ pb. In contrast, with a non-zero asymmetry $\eta = \eta_B = 0.88 \times 10^{-10}$ and same mass and cross-section, the more abundant species (here Y^+) is depleted less than when $\eta = 0$. Also shown is the equilibrium solution $Y_{eq}(x)$.

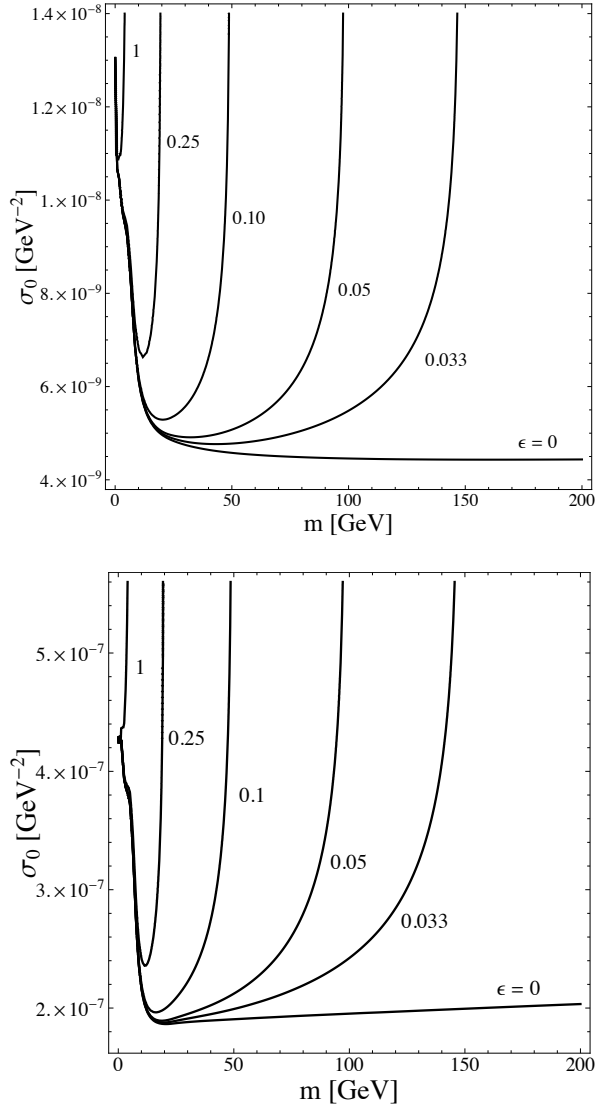


Figure 2. Here we plot the annihilation cross section σ_0 required to reproduce the correct DM abundance Ω_{DM} via a s-wave process $n = 0$ (above plot) and p-wave $n = 1$ (bottom plot) for a given dark matter mass m, and for various values of the primordial asymmetry $\eta = \epsilon\eta_B$. The line for $\epsilon = 0$ corresponds to the usual thermal WIMP scenario. Notice that the fractional asymmetry runs from $r_\infty = 0$ in the upper part of the curves to $r_\infty = 1$ when the lines converge on the standard thermal WIMP curve. The effect of the QCD phase transition appears as a bump at $m \lesssim 20$ GeV, as anticipated in the text. Note that the bottom plot is basically enhanced by a factor $\Phi_{n=0}/\Phi_{n=1} \sim (n+1)x_f$ compared to the former. As a reference, recall that 1 pb $\simeq 2.6 \times 10^{-9}$ GeV^{-2}.

$$\sigma \gtrsim \text{few} \times \sigma_{\text{WIMP}}$$

to annihilate the symmetric part

2.4 Dark interactions

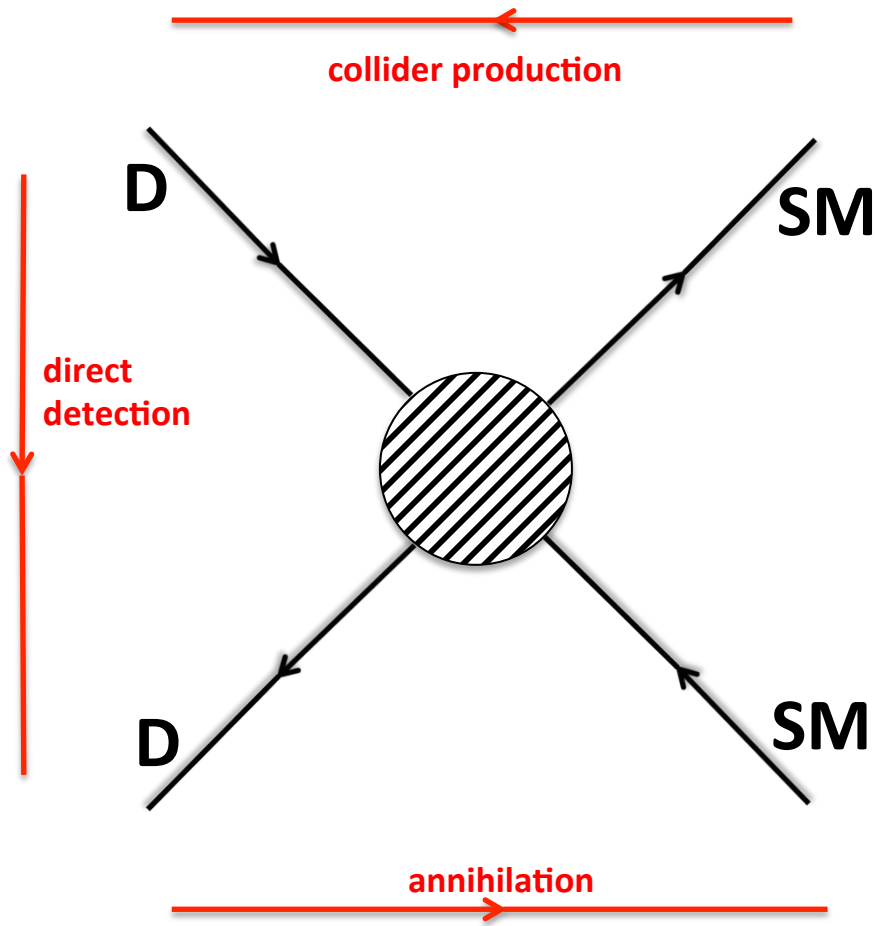
A logical and elegant possibility is that the symmetric part annihilates into light dark-sector states – dark radiation – to parallel what happens in the visible sector.

There are many microphysical possibilities. Main constraint is N_{eff} (see later).

A simple, elegant possibility is an unbroken dark U(1) force – dark EM. Dark-charge neutrality => at least two oppositely charged dark species, plasma ionised or in neutral dark atoms. Direct-detection prospects through kinetic mixing with usual photon.

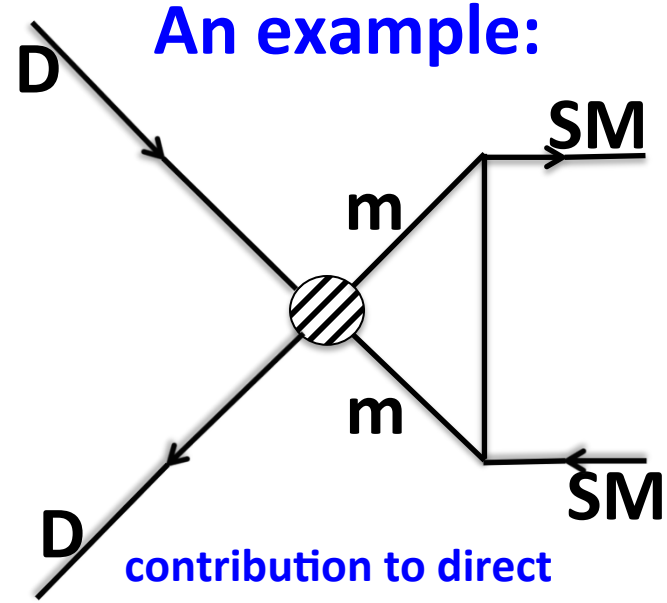
A variant on dark EM has U(1) spontaneously broken and dark photon massive, but lighter than the DM. The symmetric part can annihilate into dark photons which, through kinetic mixing, subsequently decay into, say, e^+e^-.

Annihilating the symmetric part without dark radiation:

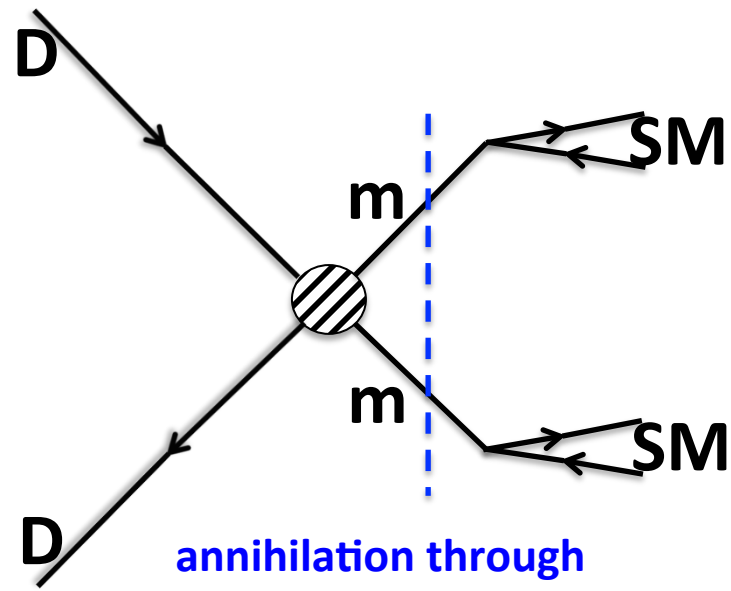


Direct annihilation to SM particles constrained by direct detection and colliders. Role for flavour/Lorentz structure.

An example:



contribution to direct detection through loop



annihilation through on-shell unstable mediator

Bai et al: JHEP 1012 (2010) 048; Buckley: PRD 84 (2011) 043510; Fox et al: PRD86 (2012) 015010; March-Russell et al: 1203:4854

2.5 Dark matter mass scale

The few-GeV scale arises when the asymmetry transfer or simultaneous genesis interactions decouple while the DM particle is relativistic.

Alternative: the decoupling temperature is of order the DM mass, but somewhat smaller. Then the DM particle is starting to become Boltzmann suppressed as the transfer stops. The DM number density is lower, and hence the mass scale must be higher e.g. weak scale, or RH breaking scale, etc.

DM mass scale ~ (5 – 10) x transfer decoupling temperature.

See e.g. Barr, Chivukula, Farhi: PLB241 (1990) 387.
Cohen, Zurek: PRL 104 (2010) 101301
Buckley, Randall: JHEP 1109 (2011) 009

Focus on the more common few-GeV scale case here. For ADM to be really compelling, need good reason for this mass scale.

The DM mass you need depends on the ADM model.

Baryon-symmetric models: $$m_{\rm DM} \simeq q_{\rm DM} \times (1.6 - 5)\ {\rm GeV}$$

q_{DM} = baryonic charge of DM

Other cases: depends on details of the chemical equilibrium.

One special case (single dark baryon species, relativistic decoupling):

$$m_{\rm DM} \simeq q_{\rm DM}^{-1} \times (5 - 7)\ {\rm GeV}$$

Ibe et al PLB708, 112 (2012)

Ideas: (1) m_{DM} ~ QCD scale, e.g. mirror DM

(2) $m_{DM} = (\lambda \sim 10^{-2}) \times m_{EW}$

(3) hidden sector ➔visible sector ➔dark sector

Recipe for ADM model building:

- Choose case 1, 2, 3 or 4 and specify the visible-dark interactions
- Choose an asymmetry-generating dynamics
- Define the internal microphysics of the dark sector
- Explain how the symmetric dark component is annihilated
- Make sure no astro/cosmo/particle constraints are violated

Many papers do not specify all of these elements

3. SOME MODELS

Case 1: Baryon-symmetric

Hylogenesis (Davoudiasl et al 2010):

(i) Asymmetry generation due to out-of-equilibrium decays.

(ii) Mediator sector: Dirac fermions $X_{1,2}$ with $M_{X2} > M_{X1} >$ TeV. X_1 produced non-thermally in early universe by condensate decay.

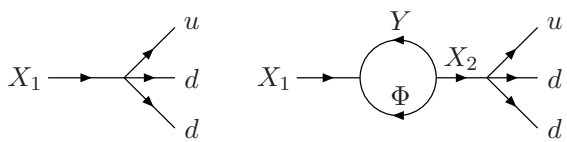
(iii) Dark sector is: spont. broken U(1)' gauge theory; kinetic mixing <u>w</u> photon
DM is Dirac fermion Y, complex scalar Φ; GeV-scale masses
U(1)': X's are neutral, Y and Φ equal & opposite charges

(iv) Mediator-VM & mediator-DM couplings:

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

neutron portal

(v) CP-violating decays are $X_1 \rightarrow udd$ and $X_1 \rightarrow Y^c\,\Phi^*$ and charge conjugates. λ, ζ coupling constants have CP-violating phases.



$$\epsilon = \frac{1}{2\Gamma_{X_1}}\left[\Gamma(X_1 \to udd) - \Gamma(\bar{X}_1 \to \bar{u}\bar{d}\bar{d})\right] \simeq \frac{m_{X_1}^5 \,\mathrm{Im}[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\pi^3 \,|\zeta_1|^2\, M^4 m_{X_2}} ,$$

(vi) Symmetric part annihilated by U(1)' interactions: $YY^c \rightarrow Z'Z'$, $\Phi\Phi^* \rightarrow Z'Z'$, with Z' decaying to SM states via kinetic mixing.

(vii) DM mass is simply given by $\Omega_{\rm d}/\Omega_b = (m_Y + m_\Phi)/m_p$ **=> $m_Y + m_\Phi \approx 5$ GeV.**

(viii) Interesting signature:

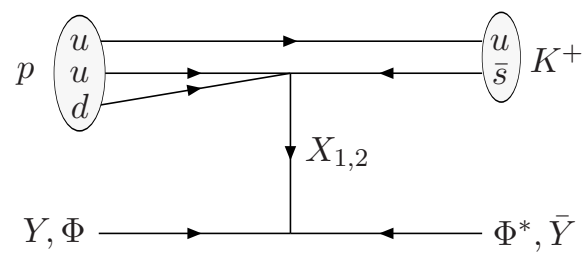


FIG. 2: Diagram for induced nucleon decay processes $pY \to K^+\Phi^*$ and $p\Phi \to K^+\bar{Y}$.

Affleck-Dine pangenesis (from von Harling, Petraki, RV 2012):

See also: Bell, Petraki, Shoemaker, RV; Cheung, Zurek; cited earlier

(i) Asymmetry generating mechanism is AD: coherent oscillations of "charged" scalar field defining a flat direction in a susy theory.

(ii) Visible sector is the MSSM plus RH neutrino superfields. Role of B_V is $(B\text{-}L)_V$.

(iii) Dark sector: $U(1)_D$ gauge theory; Δ, Λ chiral superfields & vector-like partners:

	$B_{\rm con}$	D
Δ	$q_{\rm DM}$	1
Λ	0	-1

(iv) $U(1)_D$ dark EM annihilates the symmetric part.

(v) Choose flat direction, e.g.

$$(\Delta\Lambda)^2 u^c d^c d^c \quad \text{for } q_{\rm DM} = \frac{1}{2},$$
$$\Delta\Lambda\,(u^c d^c d^c)^2 \quad \text{for } q_{\rm DM} = 2,$$
$$\Delta\Lambda\, d^c d^c d^c L L \quad \text{for } q_{\rm DM} = 3.$$

(vi) The dark matter is "atomic", $U(1)_D$ hydrogen-like bound states of the fermionic components δ ("dark proton") and λ ("dark electron") of Δ and Λ, respectively. Dark matter mass: $m_\delta + m_\lambda = q_{DM}$ (1.6 – 5) GeV. (Ensure that LSP is underabundant.)

(vii) Constraints:

A. Atomic DM recombination before matter-rad equality. Easily satisfied.

B. Self interaction upper bound from Bullet cluster → $\alpha_D > 0.1$ or so.

C. Dark radiation …

$$\Delta N_{\rm eff} \gtrsim 0.45$$

assuming massless dark photons, which is not ruled out.

Can also spontaneously break $U(1)_D$ and have the dark Z' (sub-GeV mass) decay via kinetic mixing with photons into SM states.

Case 2: Visible-to-dark

One example will be briefly described for completeness.

Kaplan, Luty, Zurek: PRD 79 (2009) 115016

(i) B-L asymmetry is generated at a high scale via an unspecified mechanism.

(ii) Dark sector: gauge singlet superfields X, Xbar with L = ±1/2 and susy mass.

(iii) Transfer operator is $\Delta W_{\rm eff} = \frac{1}{M_i}\bar{X}^2 L_i H_u$

(iv) Annihilation of symmetric part: e.g. light NMSSM pseudoscalar like in Haba & Matsumoto model. Second example: use fields in the UV completion.

(v) DM mass = 11-13 GeV. Origin of mass scale suggested as NMSSM EW physics:

$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3.$$

Case 3: dark-to-visible

Mirror DM (Foot and RV, 2003-2004):

Incomplete reference list:

Foot, RV: PRD68 (2003) 021304; 69 (2004) 123510
Shelton, Zurek: PRD82 (2010) 123512
Haba, Matsumoto: Prog Theor Phys 125 (2011) 1311
Buckley, Randall: JHEP 1109 (2011) 009

The dark sector is isomorphic to the SM, and a discrete symmetry between them is enforced.

Microphysics is the same, but cosmological macrophysics MUST be different: T' < T at BBN => different astrophysical evolution in the two sectors.

$$\mathcal{L} = \mathcal{L}_{\rm SM}(\psi) + \mathcal{L}_{\rm SM}(\psi') + \epsilon F^{\mu\nu} F'_{\mu\nu} + \kappa \phi^\dagger \phi \phi'^\dagger \phi' + \left(\frac{1}{M_N}_{ij} \bar{L}_i \tilde{\phi}\, R'_j \phi' + \text{H.c.} \right)$$

effective ops. for reprocessing asym.

Steps: (1) Inflation: T'>0, T=0. (2) Then B'/L' mirror asymmetries generated.
(3) Effective ops. reprocess into B/L asymmetries.
(4) "Magic": something causes heating of ordinary sector, so that T > T'.

We analysed the outcomes for different i,j dominating the asymmetry transfer, and for the case that the initial state is:

$$B = L = 0 \qquad L'_{L_1} = L'_{L_2} = L'_{L_3} \neq 0 \quad B'_{u_{1R}} = B'_{d_{1R}} = B'_{d_{2R}} \neq 0$$

You get $\Omega_B \sim \Omega_{B'}$ always, and $\Omega_B \approx 0.22\, \Omega_{B'}$ for i,j = 1,1 and 2,2.

Darkogenesis (Shelton & Zurek 2010)

(i) Dark asymmetry generated via 1st-order PT.

(ii) Dark sector is susy chiral $SU(2)_D$ gauge theory; LH fermions in doublets, RH fermions singlets; anomalous dark-fermion number; spontaneous breaking by $SU(2)_D$ Higgs doublets.

(iii) The transfer is either via effective operators or EW sphalerons; both of course require a messenger sector.

(iv) The symmetric part annihilates into NMSSM-like pseudoscalar pGBs in some cases, and into specially introduced light fermions in others.

(v) DM is lightest dark sector fermion; mass GeV or above.

Darkgenesis (Haba & Matsumoto 2010)

(i) Dark asymmetry generated via out-of-equilibrium decays.

(ii) Dark sector is (susy):

	X	$\bar{X}$	Y_i
Z_{4R}	i	$-i$	-1
$U(1)_L$	$1/2$	$-1/2$	1

(iii) Superpotential:

$$\mathcal{W} = \mathcal{W}_{\rm NMSSM} - \frac{M_i}{2} Y_i Y_i - m X \bar{X} + \frac{\kappa_i}{2} Y_i \bar{X}^2 + \lambda S X \bar{X} + \frac{y_i}{2\Lambda} \bar{X}^2 L_i H_u + \frac{y_i'}{2\Lambda} \bar{X}^2 Y_i S,$$

Out-of-eq
Y→Xbar Xbar

Transfer

(iv) The symmetric part annihilates into very light bosons “s”.

(v) DM is Xbar fermion; mass = 11 GeV.

4. PHENOMENOLOGY

The dark sectors of ADM models are rich and interesting!

Extreme example: mirror matter i.e. exactly isomorphic to SM

(Blinnikov&Khlopov; Foot, Lew, RV, …)

Generic possible features:

- multi-component
- dark electromagnetism & dark "atoms"
- dark radiation, dark "neutrinos"
- mediator sector
- common extra Z-boson
- Higgs boson mixing
- self-interacting at some level

Generic constraints:

- extra radiation at BBN/recomb. (Planck!)
- self-interactions from triaxiality of DM haloes of elliptical galaxies, and clusters (Bullet etc.)
- direct detection (Z', kinetic mixing, …)
- collider (Higgs mixing, Z', monojets, …)
- Capture in stars

Kallia's questions:

Does ADM phenomenology *have* to be unconventional? NO.

But it is very interesting that generically it *is* unconventional.

How different from standard *should* DM properties be?
Does ADM provide a new paradigm to solve the DM problems?

Extra radiation:

Entropy conservation:

$$\frac{g_{\rm V} T_{\rm V}^3}{g_{\rm D} T_{\rm D}^3} = \frac{g_{\rm V,dec}}{g_{\rm D,dec}}$$

implies:

$$g_{\rm D,dec} \lesssim 18 \left(\frac{g_{\rm D}}{2}\right)^{1/4} \left(\frac{g_{\rm V,dec}}{106.75}\right) (\Delta N_{\rm eff})^{3/4}$$

where:

$$\Delta\rho = \frac{7\pi^2}{120} \left(\frac{4}{11}\right)^{4/3} \Delta N_{\rm eff}\, T_{\rm v}^4$$

BBN allows $\Delta N_{eff} \leq 1$.

Various CMB/BAO combinations @ 95% C.L. give $-0.3 < \Delta N_{eff} < 1$

Structure formation and galactic dynamics:

galactic and sub-galactic problems:

- cores vs cusps
- missing satellites
- "too big to fail"
- co-rotating plane of satellites

small-scale structure wash out; self-interacting DM

constraints:

- triaxiality of DM haloes around elliptical galaxies
- Bullet cluster

bounds on DM self-ints.

Ingredients for a solution:

- late DM decoupling from dark radiation (Silk damping, acoustic oscillation damping)
- v-indep. self-int. Xsection: near 0.6 cm^2/g
- v-dep. self-int. Xsection: can resolve sub-gal. problems but maintain triaxiality

Too many to cite! See 1305:4939 for references

Direct detection:

Possible ADM-nucleon interactions: Z' coupled to anomaly-free B_{con}
Dark-photon kinetic mixing with photon
Dark-visible Higgs mixing

$$\sigma^{\rm SI}_{B_{\rm con}} \simeq (10^{-46}{\rm cm}^2)\, q^2_{\rm DM} \left(\frac{g}{0.1}\right)^4 \left(\frac{3\ {\rm TeV}}{M}\right)^4$$

g, M = Z' coupling, mass

Short range

$$\sigma^{\rm SI}_{D} \simeq (10^{-40}{\rm cm}^2) \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{g_D}{0.1}\right)^2 \left(\frac{1\ {\rm GeV}}{M_D}\right)^4$$

kinetic mixing ε
dark-photon coupling, mass = g_D, M_D

(Both evaluated for m_{DM} = 5 GeV.)

The kinetic-mixing case can give a cross-section large enough to be roughly compatible with DAMA, CoGeNT, CRESST and CDMS; mutual compatibility is not perfect, and there is tension with XENON.

By varying parameters, can easily be small enough to satisfy XENON bound.

Long range

Mirror DM with massless mirror photon

Foot: PRD69 (2004) 036001; D82 (2010) 095001; PLB703 (2011) 7; 1305.4316

General hidden-sector DM with massless dark photon

Foot: 1209.5602

Multi-component ionised DM, masses m_i.
Massless mirror/dark-photon interactions thermalise the species, to give mass-dependent velocity dispersions:

$$v_i \simeq v_{\rm rot} \left(\frac{\bar{m}}{m_i}\right)^{1/2} \qquad \bar{m} \equiv \Sigma_j n_j m_j / \Sigma_j n_j$$

Most massive states, e.g. mirror Fe, give largest signal if abundant enough. They also have the smallest velocity dispersions: tail of distribution shorter. This can partially explain why the higher-threshold XENON expt. has no signal while lower-threshold expts. have signals.

Interplay b/w m_i-dep vel. disp. and long-range DM-nucleon microscopic interaction can bring DAMA, CoGeNT, CRESST-II into good agreement. Still some tension with XENON100.

Single-species DM with light but not massless mediator φ: m_φ~10 MeV for m_{DM}~10 GeV preferred.

Fornengo, Panci, Regis: PRD84 (2011) 115002

Indirect detection:

(i) *Partially* asymmetric DM is possible. Annihilation rate:

$$\frac{\Gamma_{\rm ADM}}{\Gamma_{\rm SDM}} = \frac{\sigma_0}{\sigma_{0,\rm WIMP}} \frac{4\, r_\infty}{(1+r_\infty)^2} \xrightarrow{r_\infty \ll 1} \frac{4\sigma_0}{\sigma_{0,\rm WIMP}} \exp\left[\frac{-2\sigma_0}{\sigma_{0,\rm WIMP}}\right]$$

$r \equiv \frac{n(\bar{\chi})}{n(\chi)} \to r_\infty$ **at late times**

$\langle \sigma v \rangle = \sigma_0 (T/m_{\rm DM})^n$ **n=0 is S-wave, n=1 is p-wave**

Ann. rate exponentially suppressed for any $\sigma_0 > \text{few} \times \sigma_{0,WIMP}$

(ii) Coannihilations. Effective asymmetry transfer operators:

$$\mathcal{L}_{\not{X},\,\rm eff} = \mathcal{O}(\rm SM, q_V)\, \mathcal{O}(\rm DS, q_D)$$

q_V (q_D) = charge of SM (DS) op. under $(B-L)_V$ (B_D).

can induce coannihilations of DM with SM baryons or leptons.
Interesting example is induced nucleon decay – can be distinguished from spontaneous proton decay. **Davoudiasl et al PRD84 (2011) 096008**
If $q_D = q_{DM}$, then DM can decay asymmetrically to SM particles and antiparticles if kinematically allowed.

Chang, Goodenough: PRD84 (2011) 023524; Masina, Sannino: JCAP 1109 (2011) 021; 1304.2800; Feng, Kang: 1304.7492

(iii) Present-day DM bound state formation in galactic haloes

Can get bound states if DM has attractive self-interactions.

Bound state formation could be occurring today, with emission of radiation that can turn into SM particles.

Pearce, Kusenko: 1303.7294

Capture in stars:

My co-author is the expert on this, so I won't say much.
Main points:

- No annihilations means DM can accumulate in stars (losses can occur through co-annihilations and evaporation).
- In the Sun and main-sequence stars: can alter helioseismology and neutrino fluxes through energy transport due to DM-nucleus scattering.
- Fermionic ADM can exceed Chandrasekhar limit in a neutron star, thus form black hole and consume it. Old NS => bounds.
- Bosonic ADM can do the same, but bounds very sensitive to inevitable DM self-interactions. In many cases, there are no meaningful bounds.

Too many papers to cite here, sorry (including to my co-author)! See 1305.4939 for complete references.

Collider signatures

(i) Z' decays to the dark sector:

Gauged $B_{\rm con} = (B-L)_V - B_D$

Invisible width due to Z' decays to DS and neutrinos.
p p → ZZ' → $l^+ l^-$ (or γ) + missing E_T.
Get coupling to neutrinos from Drell-Yan and use of weak-isospin invariance.
Thus measure non-neutrino invisible width.

Petriello et al: PRD77 (2008) 115020; Gershtein et al: PRD78 (2008) 095002

(ii) Monojets (hylogenesis example):

Davoudiasl et al: PRD84 (2011) 096008

$$\frac{1}{\Lambda^3}\,\overline{(u_R)^c}\,d_R\,\overline{(d_R)^c}\,\Psi_R\,\Phi + H.c. \;\Rightarrow\; qq' \longrightarrow \bar{q}\bar{\Psi}\Phi^*$$

$\Psi,\ \Phi$ **dark-sector species**

Monojet cross-section sensitivity to about 7 fb with 100 fb^{-1} at 14 TeV LHC.
Probe few-TeV scale of new physics.

5. FINAL REMARKS

- Why is $\Omega_d \approx 5\Omega_v$? This smells like an important clue as to the nature of DM.
- ADM allows the dark sector to have rich physics.
- Many models have been proposed.
- ADM can have the right stuff to solve the small-scale structure problems.
- Can help reconcile the direct-detection experimental results.

To reiterate:

Does ADM phenomenology *have* to be unconventional? NO.

But it is very interesting that generically it *is* unconventional.

How different from standard *should* DM properties be?
Does ADM provide a new paradigm to solve the DM problems?