Minimal Asymmetric Dark Matter

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Motivation

How is dark matter produced in the early universe?

WIMP scenario:

Thermal freez-out of weakly interacting massive particle.

ADM scenario:

Asymmetry between DM particle χ and its antiparticle $\overline{\chi}$.

Relic density due to χ excess (similar to baryogenesis).

Usually requires new symmetries.

$\rightarrow$ Minimal asymmetric dark matter (MADM):

use SM gauge symmetries to transfer asymmetry to multiplet DM

The MADM model

- Particle content: SM + $SU(2)_L$ multiplet χ (c.f. Minimal Dark Matter [Cirelli, Fornengo, Strumia (2006)])
- Non-zero hypercharge y
- Not self-conjugate $\rightarrow$ can carry asymmetry
- Neutral component with $t_3 = -y$ if isospin $t = y + k$, for non-negative integer k
- Non-minimal multiplets for $k > 0$
- Neutral component has to be the lightest state
- Matter parity to stabilize χ

Transfer operator I

- Assume non-Hermitian $d \geq 4$ effective operator
  $\rightarrow$ mediates interaction between pair of χ and Higgs ϕ
- Since $y(\phi) = -1/2$ we obtain for χ with hypercharge y:

Transfer operator

$$\mathcal{O}^{\phi} = \frac{1}{\Lambda^{4y-x}}\, \chi\chi\phi^{4y}$$

$x = 1$ (2) if χ is fermion (boson)

- Other possible operator $\frac{1}{\Lambda^{3y-x}}\chi\chi(e_R e_R)^y$ for integer y.
- Only operator with χ and SM fields of lower dimension than $\mathcal{O}^{\phi}$.
- Minimality $\rightarrow$ focus on $\mathcal{O}^{\phi}$

Transfer operator II

The operator $\mathcal{O}^\phi$ plays two roles:

- At $T > T_{\mathrm{EW}}$, enforces chemical equilibrium between ϕ and χ, communicates asymmetry:
  Asymmetry in SM sector (generated by some baryogenesis mechanism) transfered to χ
  (Opposite also possible)
- At $T < T_{\mathrm{EW}}$: Generates mass splitting

$$\delta m_0^x = \frac{v^{4y}}{\Lambda^{4y-x}}$$

between the two real degrees of freedom $\chi_{1,2}^0$ of the neutral χ component

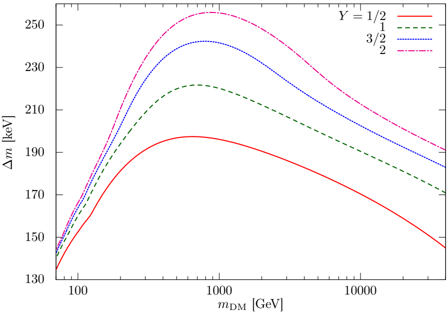
Mass splitting of χ^0

Consequences of splitting:

- χ_1^0 does not couple to Z boson
- Inelastic transition $\chi_1^0 \to \chi_2^0$ kinematically forbidden if

$$\delta m_0 = 2m_\chi \left(\frac{v}{\Lambda}\right)^{4y} \left(\frac{\Lambda}{2m_\chi}\right)^x \gtrsim \delta m^{\min}$$

- $\delta m^{\min} \sim (1+0.2y) \times 175\,\mathrm{keV}$ for m_χ of order few TeV



[Nagata, Shirai (2015)]

Charged/neutral mass splitting I

Contribution from EW breaking:

Scalar $\chi \to$ renormalizible operator

$$\mathcal{O}^{\vec{t}} = \lambda_v \left(\chi^\dagger \, \vec{t} \, \chi\right) \left(\phi^\dagger \frac{\vec{\tau}}{2} \phi\right)$$

$\to$ mass difference between isospin components of χ

$$\delta m^v = -(t_3 - t_3') \frac{\lambda_v v^2}{4 m_\chi} \approx -151 \, (t_3 - t_3') \, \lambda_{0.02}^{1\,\mathrm{TeV}} \ \mathrm{MeV}, \qquad \lambda_{0.02}^{1\,\mathrm{TeV}} = \frac{\lambda_v}{0.02} \frac{1\,\mathrm{TeV}}{m_\chi}$$

For fermions: $\frac{1}{m_\chi} \to \frac{1}{\Lambda}$
(non-renormalizible operator)

Charged/neutral mass splitting II

Splitting from gauge boson loops

$$\delta m^{\alpha_2} = \frac{\alpha_2}{2}\left(t_3 - t_3'\right)\left\{\left(t_3 + t_3'\right)\left(M_W - c_W^2 M_Z\right) + 2ys_W^2 M_Z\right\}$$
$$= 152\left(t_3 - t_3'\right)\left\{1.1(t_3 + t_3') + 4.6y\right\}\ \text{MeV}$$

Minimal multiplets ($t_3^{\text{min}} = -y$):

Both contributions $\rightarrow$ charged components heavier than neutral

E.g., triplet with $y = 1$: $\delta m^{\alpha_2} \sim 540\,\text{MeV}$ and $\delta m^{v} \sim 151\,\text{MeV}$

Non-minimal DM $\rightarrow$ both contributions necessary

Neutral component lightest for $\lambda_{0.02}^{1\,\text{TeV}} = 2.5y \pm 1.1$

Timeline

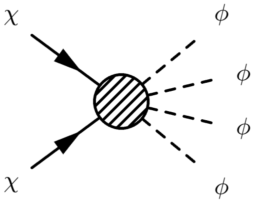
Steps required to produce DM:

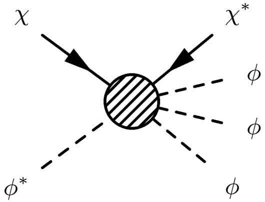
- For $T \gg T_{\text{EW}}$: in-equlibrium reactions via $\mathcal{O}^{\phi}$ feed asymmetry between SM and χ sector
- At $T_a > T_{\text{EW}}$ chemical decoupling of χ, the asymmetry in the abundances $Y_{\Delta\chi} \equiv Y_{\chi} - Y_{\overline{\chi}}$ remains conserved ($T_a \sim \frac{m_\chi}{10}$)
- Symmetric component annihilates via $\chi\overline{\chi} \to SM$ until $T_s < T_a$ ($T_s \sim \frac{m_\chi}{25}$)
  Asymmetric component can restart annihilation after EWPT $\to T_s > T_{\text{EW}}$.
  $Y_{\overline{\chi}} \ll Y_{\Delta\chi} \approx Y_{\chi}$ at $T_s \to$ relic abundance dominated by initial asymmetry.
- At $T \ll T_{\text{EW}}$ all χ components will decay to χ_1^0
- Present DM density is then

$$\rho_{\text{DM}} = s\, m_\chi Y_{\Delta\chi}$$

Chemical decoupling I

Equilibrium via $\chi\chi \to \phi^{4y}$ (s-channel) and $\chi\phi^* \to \chi^*\phi^{4y-1}$ (t-channel)





Reaction rates

$$\Gamma_{\chi\chi} = n_\chi^0 \langle \sigma |v| \rangle_{\chi\chi}\,, \qquad \Gamma_{\chi\phi} = n_\phi^0 \langle \sigma |v| \rangle_{\chi\phi}$$

Chemical decoupling when $\Gamma_{\chi\chi},\ \Gamma_{\chi\phi} \lesssim H(T_a)$

Chemical decoupling II

Thermally averaged cross-sections

$$\langle\sigma|v|\rangle_{\chi\chi} \sim \eta_{\rm PS}^{(n)}\, m_\chi^{-2} \left(\frac{m_\chi}{\Lambda}\right)^{2(4y-x)}$$
$$\langle\sigma|v|\rangle_{\chi\phi} \sim \langle\sigma|v|\rangle_{\chi\chi} \left(\frac{T}{m_\chi}\right)^{4(2y-1)}$$

Equilibrium number densities:

$$n_\chi^0 = g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T}\,,$$
$$n_\phi^0 = g_\phi\, \frac{\zeta(3)\, T^3}{\pi^2}\,,$$

For $y > \frac{1}{2}$ the relevant contribution is $\Gamma_{\chi\chi}$ ($T_a \sim \frac{m_\chi}{10}$)

Chemical decoupling III

Equilibrium condition at decoupling

$$Y_{\Delta\chi} = -2y \, \frac{n_\chi^0}{n_\phi^0} Y_{\Delta\phi} \bigg|_{T=T_a}$$

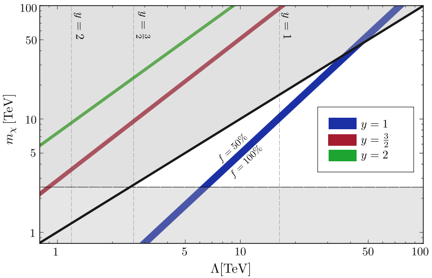
using $\frac{Y_{\Delta\chi}}{Y_{\Delta\phi}} = -\frac{7}{2}\frac{Y_{\Delta\chi}}{Y_{\Delta B}} = -\frac{7}{2}\omega\frac{m_B}{m_\chi}$, with $\omega \equiv \frac{\Omega_{DM}}{\Omega_B} \approx 5.5$, we obtain

$$\begin{aligned} m_\chi^{-2}\, z_a^{-1} \left(\frac{m_\chi}{\Lambda}\right)^{2(4y-x)} &\lesssim \frac{4\pi^3}{21\zeta(3)}\sqrt{\frac{\pi g_*}{5}}\,\frac{y}{\omega\eta_{PS}^{(n)}}\,\frac{1}{M_P m_B} \\ &= 6.1\,\frac{y}{\eta_{PS}^{(n)}} \times 10^{-19}\ \mathrm{GeV}^{-2} \end{aligned}$$

For $y = 1/2$ instead: $m_\chi^{-1} z_a^{-1} \left(\frac{m_\chi}{\Lambda}\right)^{2(2-x)} < 5.9 \times 10^{-16}\,\mathrm{GeV}^{-1}$.

MADM with different hypercharge I

Fermions



$f = \Omega_\chi/\Omega_{\rm DM}$

- For $y=1$: $\Lambda \lesssim 17\,\text{TeV}$ from DD constraints, and $m_\chi \lesssim 10\,\text{TeV}$ ($T_s \sim \frac{m_\chi}{25} \gtrsim T_{\rm EW}$).

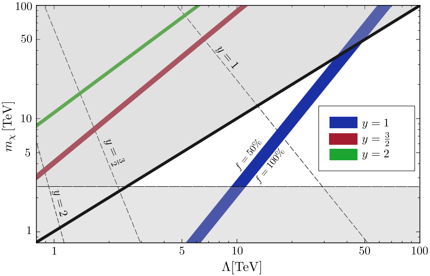
  Low $\Lambda \to$ raher large neutral-charged splitting $\delta m^v \sim 1\,\text{GeV}$

  $\mathcal{O}^{e_R}$ present $\to$ $y=1$ multiplet still viable within $2.5\,\text{TeV} \lesssim m_\chi \lesssim 6.7\,\text{TeV}$
- $y=\frac{3}{2}$ and $y=2$: allowed bands in the $m_\chi > \Lambda$ region

$\Rightarrow$ Viable DM candidate for $y=1 \to$ minimal choice is SU(2) triplet

MADM with different hypercharge II

Scalars



- Scalar multiplet with hypercharge $y = 1$:

$$\Lambda \approx 18 \left(\frac{10}{z_a}\right)^{1/8} \text{ TeV}$$

  Freeze-out before T_{EW} possible for $2.5\,\text{TeV} \lesssim m_\chi \lesssim 6.7\,\text{TeV}$

  $\mathcal{O}^{e_R}$ present $\rightarrow$ implies $m_\chi \lesssim 1.3\,\text{TeV}$ $\rightarrow$ not viable

- Higher hypercharge $\rightarrow$ EFT breakdown

MADM with different hypercharge III

For $y = \frac{1}{2}$ (minimal choice doublet, t-channel dominated):

Fermions

- DD limit: $\Lambda \lesssim 1.5 \times 10^5$ TeV
- correct abundance requires $\Lambda \gtrsim 4.1 \times 10^5 \left(\frac{T_a}{100\,\text{GeV}}\right)^{1/2}$ TeV.
- $\rightarrow$ disagreement for $T_a > T_{EW}$

Scalars

- Transfer operator is renormalizible
- Unique since no Λ dependence, m_χ only new scale
  Keep explicit coupling constant λ
- DD limit $\frac{m_\chi}{\lambda} \lesssim 8 \times 10^4$ TeV
- Decoupling requires $\frac{m_\chi}{\lambda} \gtrsim 4.1 \times 10^5 \left(\frac{T_a}{100\,\text{TeV}}\right)^{1/2}$ TeV
  $\rightarrow$ Conflicting bounds

Symmetric annihilation

Efficient $\chi\overline{\chi}$ annihilation

$\rightarrow$ symmetric component remains subdominant ($\Omega_{\overline{\chi}} \ll \Omega_{\chi} \sim \Omega_{DM}$)

- Sizable suppression of symmetric relic density due to Sommerfeld enhancements
- $y = 1$ fermionic triplet relic density completely symmetric for $2.7\,\text{TeV} \lesssim m_\chi \lesssim 2.8\,\text{TeV}$
- relevant contribution from asymmetry marginally allowed
- $y = 1$ scalar triplets similar
- higher multiplets $\rightarrow$ enhanced cross section
  $\rightarrow$ larger masses required without asymmetry
- Thermally produced fermion quintuplet with $m_\chi \ll 10\,\text{TeV}$
  $\rightarrow$ contributes whole DM only with asymmetry

Phenomenological implications

Searches at colliders:

- LHC reach up to few hundred GeV $\rightarrow$ too low for MADM
- Future e^+e^- and pp colliders probe multi TeV region only marginally

Direct detection:

- Z mediated interactions kinematically forbidden
- Loop level interactions with $\sigma \sim \mathcal{O}(10^{-47})\,\mathrm{cm}^2$ far below current bounds

Indirect detection:

- heavily depends on DM halo model
- Most relevant bounds from antiproton measurements and absence of γ-ray lines towards the galactic center
- $y = 0$ fermion triplet (wino-like) DM excluded for $1.8\,\mathrm{TeV} \lesssim m_{\widetilde{W}} \lesssim 3.5\,\mathrm{TeV}$
- Similar expected for $y = 1$, since m_χ close to $M_W/\alpha_2 \sim 2.4\,\mathrm{TeV}$ (see also [Chun, Park (2015)])

Conclusions

- Any new $SU(2)_L$ multiplet with $y \neq 0$ and in chemical equilibrium at $T > T_{\text{EW}}$ inherits asymmetry from SM sector
- Neutral component ADM candidate, if stable and lightest member
- Transfer operator:
  $\rightarrow$ enforces chemical equilibrium
  $\rightarrow$ mass splitting of neutral component, Z interactions kinematically forbidden
- Decoupling before EWPT
- Allows do exclude all MADM candidates except $y = 1$ scalar/fermion multiplets
- Minimal multiplets disfavoured by symmetric annihilation and indirect detection
- Quintuplets less constrained due to enhanced annihilation
- Relaxing minimality criteria can avoid constraints
  (e.g, additional DM singlet as in Higgsogenesis [Servant, Tulin (2013)])