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

Asymmetry transfer

Transfer operator

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

x = 1 (2) if χ is fermion (boson)

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

- At $T > T_{\mathrm{EW}}$: Enforces chemical equilibrium between ϕ and χ, communicates asymmetry
- 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 $\chi^0_{1,2}$ of theneutral χ component

[Asymmetry transfer also possible via, e.g., $\frac{1}{\Lambda^{3y-x}}\chi\chi(e_R e_R)^y$.]

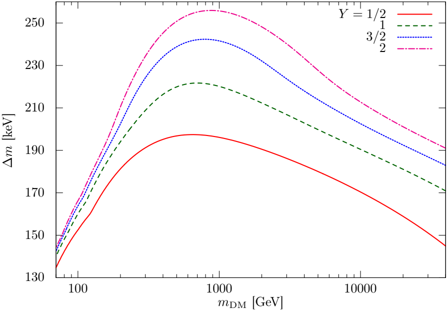
Mass splitting of χ^0

Consequences of splitting:

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

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

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



[Nagata, Shirai (2015)]

Charged/neutral mass splitting

Two contributions to charged-neutral splitting:

Splitting from EW breaking

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

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

and

Splitting from gauge boson loops

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

Non-minimal DM neutral for $\lambda_{0.02}^{1\,\text{TeV}} = 2.5y \pm 1.1$

Timeline

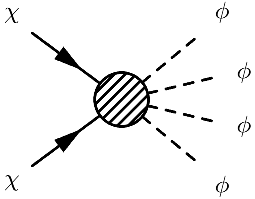
Steps required to produce DM:

- For $T \gg T_{\mathrm{EW}}$ in-equlibrium reactions via $\mathcal{O}^{\phi}$ feed asymmetry between SM and χ sector
- At $T_a > T_{\mathrm{EW}}$ 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 $\to$ $T_s > T_{\mathrm{EW}}$.
  $Y_{\overline{\chi}} \ll Y_{\Delta\chi} \approx Y_\chi$ at $T_s \to$ relic abundance dominated by initial asymmetry.
- At $T \ll T_{\mathrm{EW}}$ all χ components will decay to χ_1^0
- Present DM density is then

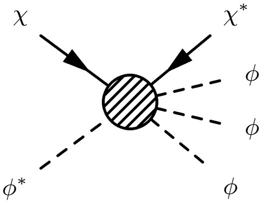
$$\rho_{\mathrm{DM}} = s\, m_\chi Y_{\Delta\chi}$$

Chemical decoupling

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



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



Reaction rates

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

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

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

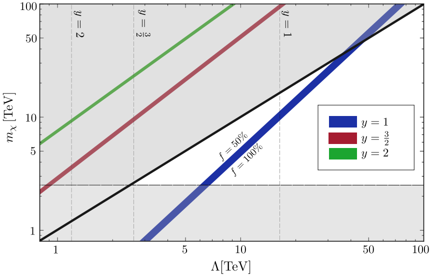
For $y > \frac{1}{2}$ the relevant contribution is $\Gamma_{\chi\chi}$ ($T_a \sim \frac{m_\chi}{10}$)

After decoupling ($\Gamma_{\chi\chi},\ \Gamma_{\chi\phi} \lesssim H(T_a)$):

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

MADM with different hypercharge I

Fermions

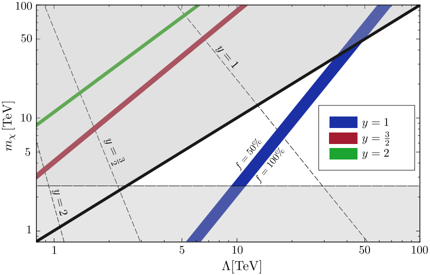


$f = \Omega_\chi / \Omega_{\text{DM}}$

- For $y = 1$: $\Lambda \lesssim 17\,\text{TeV}$ from DD constraints, and $m_\chi \lesssim 10\,\text{TeV}$ ($T_s \sim \frac{m_\chi}{25} \gtrsim T_{\text{EW}}$).
- $y = \frac{3}{2}$ and $y = 2$ the allowed bands are in the $m_\chi > \Lambda$ region → effective theory breaks down
- For $y = \frac{1}{2}$:
  DD limit: $\Lambda \lesssim 1.5 \times 10^5\,\text{TeV}$
  correct abundance requires $\Lambda \gtrsim 4.1 \times 10^5 \left(\frac{T_a}{100\,\text{GeV}}\right)^{1/2}\,\text{TeV}$.
  → disagreement for $T_a > T_{EW}$
- Viable DM candidate for $y = 1$
  → minimal choice is SU(2) triplet

MADM with different hypercharge II

Scalars



- Scalar multiplet with hypercharge $y = 1$ viable:

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

  and $2.5\,\text{TeV} \lesssim m_\chi \lesssim 6.7\,\text{TeV}$
- Higher hypercharge
  → EFT breakdown
- For $y = 1/2$ transfer operator is renormalizible
  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

Symmetric annihilation

Efficient $\chi\overline{\chi}$ annihilation → 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 → enhanced cross section → larger masses required without asymmetry
- Thermally produced fermion quintuplet with $m_\chi \ll 10\,\text{TeV}$ → contributes whole DM only with asymmetry

Phenomenological implications

Searches at colliders:

- LHC reach up to few hundred GeV → 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 $M_W/\alpha_2 \sim 2.4\,\mathrm{TeV}$

Conclusions

- Any new $SU(2)_L$ multiplet with $y \neq 0$ and in chemical equilibrium at $T > T_{\mathrm{EW}}$ inherits asymmetry from SM sector
- Neutral component ADM candidate, if stable and lightest member
- Transfer operator:
  → enforces chemical equilibrium
  → 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 constraint due to enhanced annihilation
- Relaxing minimality criteria can avoid constraints
  (e.g, additional DM singlet as in Higgsogenesis [Servant, Tulin (2013)])