# 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 $\chi$ and its antiparticle $\overline{\chi}$.
Relic density due to $\chi$ 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 $\chi$
  (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 $\chi$

## Transfer operator

### Transfer operator

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

x = 1 (2) if $\chi$ is fermion (boson)

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

- At $T > T_{\text{EW}}$, enforces chemical equilibrium between $\phi$ and $\chi$, communicates asymmetry.

- At $T < T_{\text{EW}}$: 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 $\chi$ component

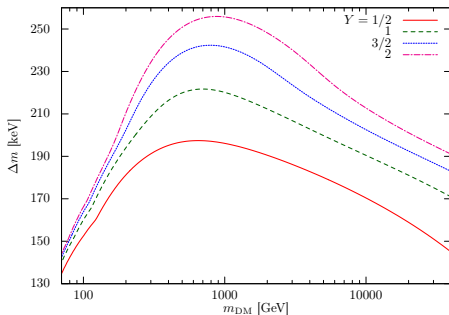Other possible operator $\frac{1}{\Lambda^{3y-x}}\chi\chi(e_R e_R)^y$ for asymmetry transfer for integer $y$.

# Mass splitting of $\chi^0$

Consequences of splitting:

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

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

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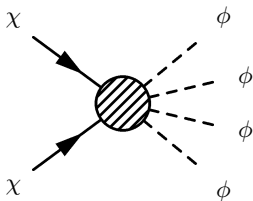


[Nagata, Shirai (2015)]

**Steps required to produce DM:**

- For $T \gg T_{EW}$: in-equilibrium reactions via $\mathcal{O}^{\phi}$ feed asymmetry between SM and $\chi$ sector

- At $T_a > T_{EW}$ chemical decoupling of $\chi$, 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 $\to T_s > T_{EW}$. $Y_{\overline{\chi}} \ll Y_{\Delta\chi} \approx Y_{\chi}$ at $T_s \to$ relic abundance dominated by initial asymmetry.

- At $T \ll T_{EW}$ all $\chi$ components will decay to $\chi_1^0$
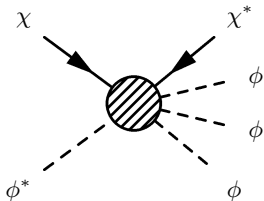
- Present DM density is then

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

# Chemical decoupling

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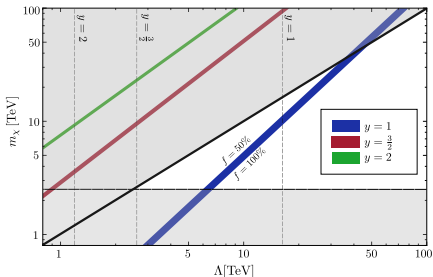


and $\chi\phi^* \to \chi^*\phi^{4y-1}$ (t-channel)

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

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

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

# MADM with different hypercharge I

**Fermions**



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

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

  Low $\Lambda \rightarrow$ rather large neutral-charged splitting $\delta m^\nu \sim 1\,\text{GeV}$

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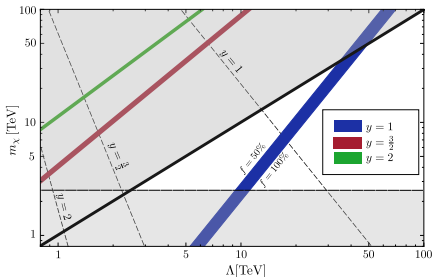
- $y = \frac{3}{2}$ and $y = 2$: allowed bands in the $m_\chi > \Lambda$ region

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

**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 $\Lambda$ dependence, $m_\chi$ only new scale
  Keep explicit coupling constant $\lambda$
- 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 (via gauge interactions)
 $\rightarrow$ 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 TeV $\lesssim m_{\chi} \lesssim$ 2.8 TeV
- relevant contribution from asymmetry marginally allowed
- $y = 1$ scalar triplets similar
- higher multiplets $\rightarrow$ enhanced cross section
  $\rightarrow$ larger masses required without asymmetry
- E.g., thermally produced fermion quintuplet with $m_{\chi} \ll 10$ 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 $\gamma$-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 $m_\chi$ 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 $T > T_{EW}$ 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, ...)