

# Minimal Asymmetric Dark Matter

in collaboration with S. M. Boucenna, and E. Nardi  
PLB 748 (2015) 191, arXiv:1503.01119



Martin B. Krauss

COSMO-15  
Warsaw

September 8, 2015

# 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  $\bar{\chi}$ .

Relic density due to  $\chi$  excess (similar to baryogenesis).

Usually requires new symmetries.

→ 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 I

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

## Transfer operator

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

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

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

## Transfer operator II

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

- At  $T > T_{EW}$ , enforces chemical equilibrium between  $\phi$  and  $\chi$ , communicates asymmetry:  
Asymmetry in SM sector (generated by some baryogenesis mechanism) transferred to  $\chi$   
(Opposite also possible)
- At  $T < T_{EW}$ : 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

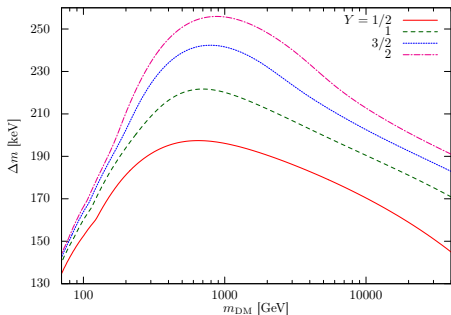
# Mass splitting of $\chi^0$

Consequences of splitting:

- $\chi_1^0$  does not couple to  $Z$  boson
- Inelastic transition  $\chi_1^0 \rightarrow \chi_2^0$  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  $m_\chi$  of order few TeV



[Nagata, Shirai (2015)]

# Charged/neutral mass splitting I

## Contribution from EW breaking:

Scalar  $\chi \rightarrow$  renormalizable operator

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

$\rightarrow$  mass difference between isospin components of  $\chi$

$$\delta m^v = -(t_3 - t'_3) \frac{\lambda_v v^2}{4m_\chi} \approx -151 (t_3 - t'_3) \lambda_{0.02}^{1\text{TeV}} \text{ MeV}, \quad \lambda_{0.02}^{1\text{TeV}} = \frac{\lambda_v}{0.02} \frac{1\text{TeV}}{m_\chi}$$

For fermions:  $\frac{1}{m_\chi} \rightarrow \frac{1}{\Lambda}$

(non-renormalizable operator)

# Charged/neutral mass splitting II

## Splitting from gauge boson loops

$$\begin{aligned}\delta m^{\alpha 2} &= \frac{\alpha 2}{2} (t_3 - t'_3) \left\{ (t_3 + t'_3) \left( M_W - c_W^2 M_Z \right) + 2y s_W^2 M_Z \right\} \\ &= 152 (t_3 - t'_3) \left\{ 1.1(t_3 + t'_3) + 4.6y \right\} \text{ MeV}\end{aligned}$$

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

Both contributions  $\rightarrow$  charged components heavier than neutral

E.g., triplet with  $y = 1$ :  $\delta m^{\alpha 2} \sim 540 \text{ MeV}$  and  $\delta m^\nu \sim 151 \text{ MeV}$

Non-minimal DM  $\rightarrow$  both contributions necessary

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



# Timeline

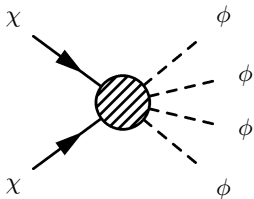
## Steps required to produce DM:

- For  $T \gg T_{EW}$ : 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  $Y_{\Delta\chi} \equiv Y_\chi - Y_{\bar{\chi}}$  remains conserved ( $T_a \sim \frac{m_\chi}{10}$ )
- Symmetric component annihilates via  $\chi\bar{\chi} \rightarrow SM$  until  $T_s < T_a$  ( $T_s \sim \frac{m_\chi}{25}$ )  
Asymmetric component can restart annihilation after EWPT  $\rightarrow T_s > T_{EW}$ .  
 $Y_{\bar{\chi}} \ll Y_{\Delta\chi} \approx Y_\chi$  at  $T_s \rightarrow$  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

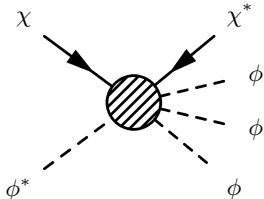
$$\rho_{DM} = s m_\chi Y_{\Delta\chi}$$

# Chemical decoupling I

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



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



## Reaction rates

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

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

## Chemical decoupling II

### Thermally averaged cross-sections

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

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

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

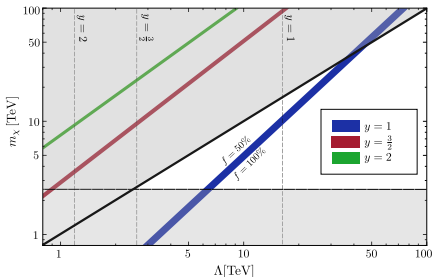
using  $\frac{Y_{\Delta\chi}}{Y_{\Delta\phi}} = -\frac{7}{2} \frac{Y_{\Delta\chi}}{Y_{\Delta B}} = -\frac{7}{2} \omega \frac{m_B}{m_{\chi}}$ , with  $\omega \equiv \frac{\Omega_{DM}}{\Omega_B} \approx 5.5$ , we obtain

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

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

# MADM with different hypercharge I

## Fermions



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

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

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

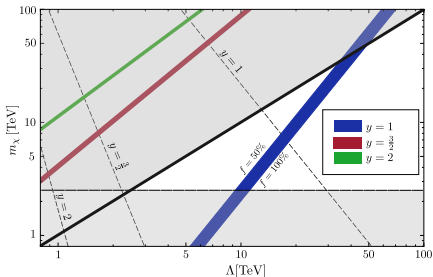
$\mathcal{O}^{eR}$  present  $\rightarrow y = 1$  multiplet still viable within  
 $2.5 \text{ TeV} \lesssim m_\chi \lesssim 6.7 \text{ TeV}$

- $y = \frac{3}{2}$  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

# 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  $2.5 \text{ TeV} \lesssim m_\chi \lesssim 6.7 \text{ TeV}$

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

## Scalars

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

# Symmetric annihilation

Efficient  $\chi\bar{\chi}$  annihilation

→ symmetric component remains subdominant ( $\Omega_{\bar{\chi}} \ll \Omega_{\chi} \sim \Omega_{DM}$ )

- 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  $\rightarrow$  too low for MADDM
- Future  $e^+e^-$  and  $pp$  colliders probe multi TeV region only marginally

## Direct detection:

- $Z$  mediated interactions kinematically forbidden
- Loop level interactions with  $\sigma \sim \mathcal{O}(10^{-47}) \text{ cm}^2$  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  $1.8 \text{ TeV} \lesssim m_{\tilde{W}} \lesssim 3.5 \text{ TeV}$
- Similar expected for  $y = 1$ , since  $m_\chi$  close to  $M_W/\alpha_2 \sim 2.4 \text{ TeV}$   
(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:
  - 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 constrained due to enhanced annihilation
- Relaxing minimality criteria can avoid constraints  
(e.g, additional DM singlet as in Higgsogenesis [[Servant, Tulin \(2013\)](#)])