ASYMMETRIC DARK MATTER

N. Rius
IFIC, Univ. Valencia - CSIC

Work in collaboration with M. Blennow, B. Dasgupta and E. Fernández-Martínez,
JHEP 1103:014 (2011)

New Perspectives in Dark Matter
Lyon, 22-25 October 2013

ASYMMETRIC DARK MATTER

- Motivation
- ADM: general features and constraints
- A model of ADM via leptogenesis
- Summary and outlook

ASYMMETRIC DARK MATTER

- Motivation
- ADM: general features and constraints
- A model of ADM via leptogenesis
- Summary and outlook

DISCLAIMER: this is NOT a comprehensive review of ADM

Davoudiasl and Mohapatra 2012

Petraki and Volkas; Zurek 2013

I. Motivation

Baryonic Matter

Baryon mass: m_B = 938 MeV

Baryonic matter density:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

Baryonic energy density:

Ω_B = 0.0463

Dark Matter

DM mass: m_{DM} = ?

DM matter density:

n_{DM} = ?

DM energy density:

Ω_{DM} = 0.233

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

WMAP+BBN

WIMP DM

Baryonic Matter

Baryon mass: m_B = 938 MeV

Baryonic matter density:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

Baryonic energy density:

Ω_B = 0.0463

WIMP Dark Matter

DM mass: m_{DM} = 100-1000 GeV

DM matter density: from thermal freezeout of weak interactions

DM energy density:

Ω_{DM} = 0.233

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

WIMP miracle

ASYMMETRIC DM

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

hint of a common origin ?

Baryonic Matter

Baryon mass: m_B = 938 MeV

Baryonic matter density:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

Baryonic energy density:

Ω_B = 0.0463

Asymmetric Dark Matter

DM mass: $m_{DM} \approx$ 5 GeV

DM matter density:

$$n_{DM} = n_X - n_{\bar{X}} \approx n_B - n_{\bar{B}}$$

DM energy density:

Ω_{DM} = 0.233

WIMPY BARYOGENESIS

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

hint of a common origin ?

Baryonic Matter

Baryon mass: m_B = 938 MeV

Baryonic matter density:

Generated by a decaying WIMP or in baryon and CP violating annihilations of the DM

Large CP asymmetry ε

Baryonic energy density:

$\Omega_B = 0.0463$

WIMP Dark Matter

DM mass: $m_{DM} \approx$ 100-1000 GeV

DM matter density: : from thermal freezeout of weak interactions (WIMP miracle)

DM energy density:

$\Omega_{DM} = 0.233$

McDonald 2011; Cui,Randall,Shuve; Davidson,Elmer; Cui,Sundrum 2012; Bernal et al. 2013

ASYMMETRIC DM

Early attemps:

Nussinov 1985; Barr, Chivukula and Farhi 1990; Kaplan 1992

If the DM and baryon asymmetries have the same origin, will be similar, as suggested by $\Omega_B \approx \Omega_{DM,}$ and

we expect

$$m_{DM} \approx 5 \text{ GeV}$$

Recently also motivated by direct detection signals (DAMA,CoGeNT,CDMS)

II. ADM: general features and constraints

- The DM particle X carries a global Dark number D, analogous to B and L
- Why $m_{DM} \approx m_B$?
- Basic requirements

Requirements

1. Generation of a primordial asymmetry in the visible and/or dark sectors

2. Mechanism for sharing the primordial asymmetry

3. Annihilation of the symmetric relic DM abundance

1. Generation of a primordial asymmetry in the visible and/or dark sectors

B Baryogenesis Sakharov 1967

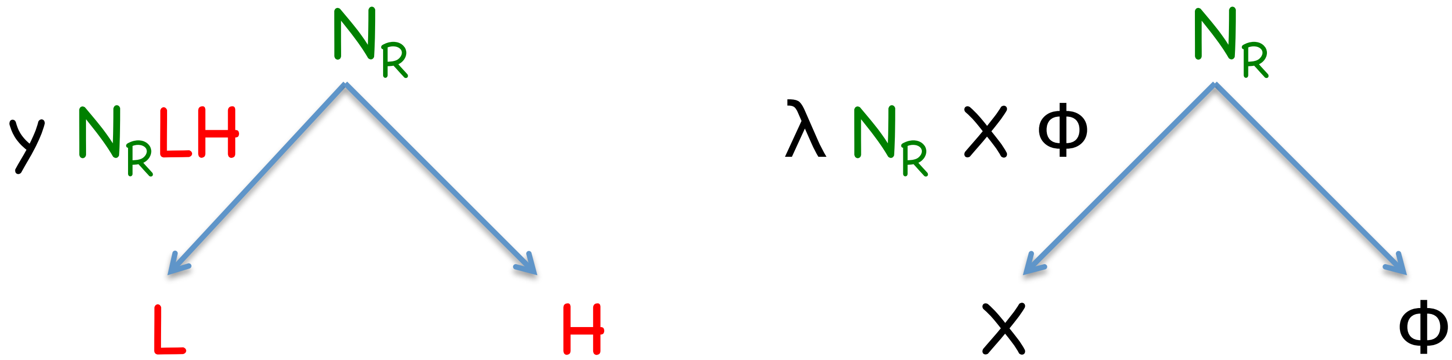
L Leptogenesis Fukugita and Yanagida 1986

Cogenesis: baryon and DM asymmetries generated simultaneously

- Decay
- Affleck-Dine
- Electroweak cogenesis

Example: cogenesis via heavy particle decay

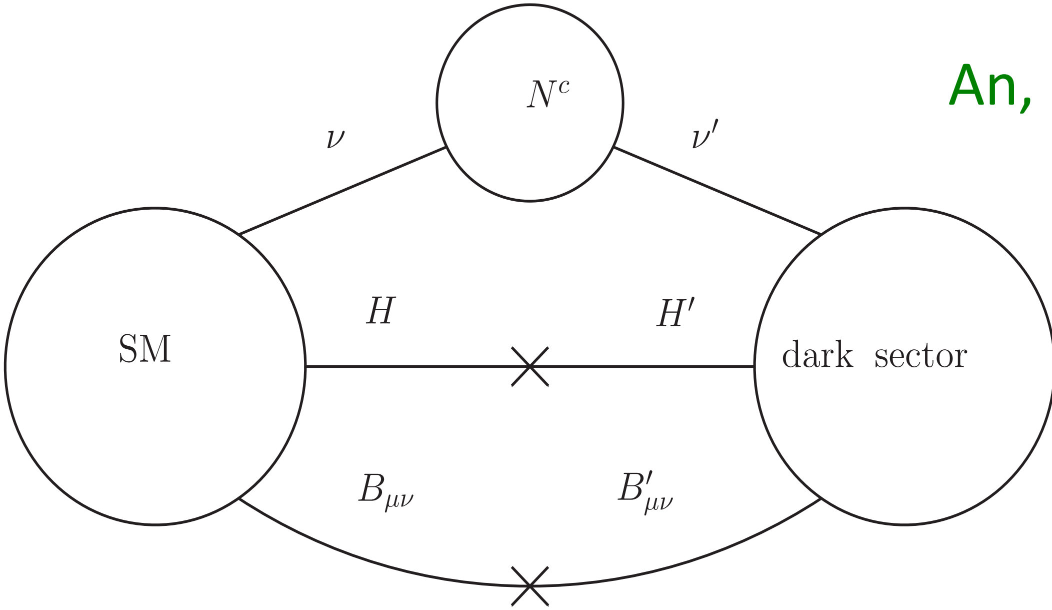
- N_R is a window to dark sector:



- Need extra symmetry to avoid DM-neutrino mixing and Majorana DM (can also work if mixing is very suppressed)
- m_{DM} from keV- 10 TeV

Falkowski, Ruderman and Volansky

Mirror ADM: dark sector has identical microphysics as visible sector



An, Chen,Mohapatra,Zhang 2010

- However, to meet BBN constraints on radiation energy density and ensure that mirror matter behaves as CDM, $T_M \approx 0.3\ T_V$

Berezhiani et al. 2001; Foot and Volkas 2003

Dark(o)genesis, Xogenesis: visible sector baryogenesis mechanisms exported to the dark sector

Shelton and Zurek 2010; Haba and Matsumoto, Dutta and Kumar; Buckley and Randall 2011; Petraki et al. 2012

Exception: DM can carry the missing antibaryon number and B is globally conserved → need extra parity to make DM stable

Kitano and Low, Agashe and Servant 2005; Davousiasl and Morrisey 2010

2. Mechanism for sharing the primordial asymmetry

These processes need to be fast and active in the early Universe for efficient transfer of the asymmetries but switch off at low energies to preserve them:

- Sphalerons

- High dimension operators

A. Electroweak sphalerons

DM SU(2) doublets

Electroweak sphalerons conserve

$I_1 = B - L \qquad I_2 = B - c\,D$

Example: heavy fourth family + SM singlet N, with global 4th family lepton number symmetry

D.B. Kaplan 1991

Ruled out for light $m_{DM} \approx 5$ GeV by direct searches and colliders

- Alternative: heavier DM, becomes non-relativistic while ew sphalerons are still in thermal equilibrium ➔

DM number density suppressed by Boltzmann factor $\exp(-m_{DM}/T_{sp})$

For $T_{sp} \approx 130$ GeV ➔ $m_{DM} \approx 2$ TeV

Technicolor composite DM

Barr, Chivukula, Farhi 1990; Nardi, Sannino, Strumia 2009

B. Exotic sphalerons

Sphalerons from a different gauge group G under which DM and SM particles are charged, e.g., $SU(2)_R$ (more later)

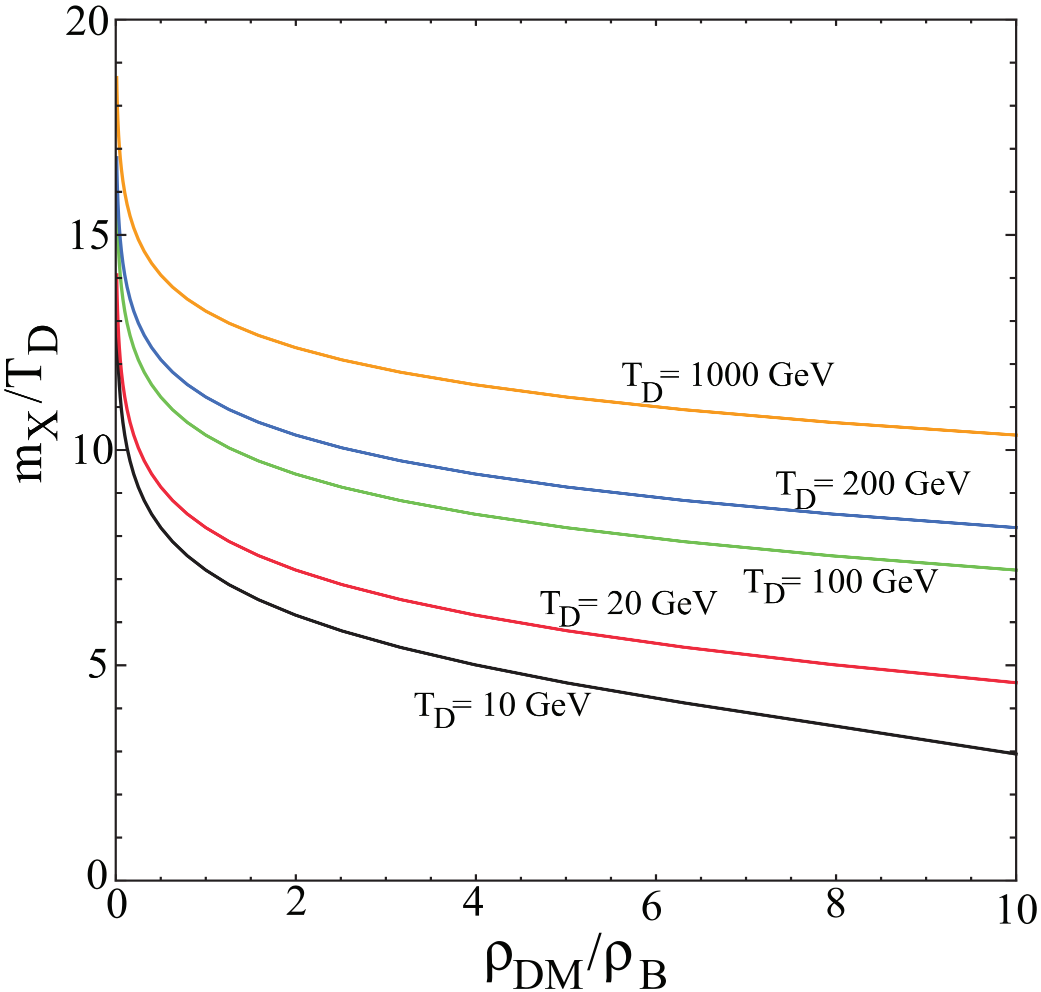
- High dimension operators which violate B and/or L, and D:

$$\mathcal{O}_{B-L} = u^c d^c d^c\,,\, q\ell d^c\,,\, \ell\ell e^c\,,\, \ell H \qquad \mathcal{O}_D = X^n$$

$$W = \mathcal{O}_{B-L}\mathcal{O}_D$$

ρ_{DM}/ρ_B vs m_X/T_D

T_D ➔ T at which B-X transfer decouples



Buckley and Randall 2011

3. Annihilation of the symmetric relic DM abundance

Difficult to achieve:

- ADM has typically ~ 5 GeV

- If WIMPs with ~100 GeV get the correct relic abundance with weak annihilations ADM would need stronger interactions

- But particles with ~ 5 GeV and stronger than weak interactions would have been seen!

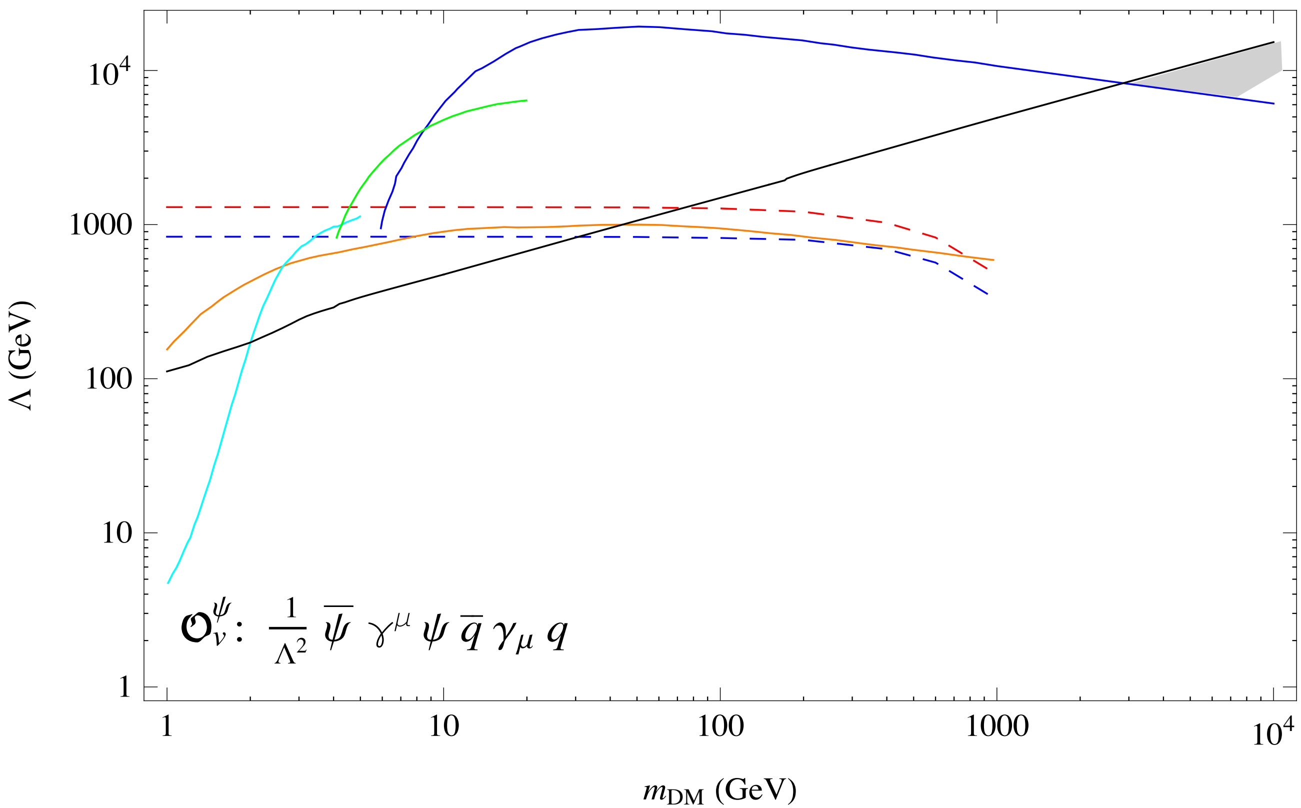
- Examples:

$$\mathcal{O}_1 = \frac{1}{\Lambda^2}\bar{X}X\bar{f}f \qquad \mathcal{O}_2 = \frac{1}{\Lambda^2}\bar{X}\gamma^\mu X\bar{f}\gamma_\mu f$$

Constraints on the scale Λ of the operator trhough which DM annihilates to SM quarks

________ min. annihilation cross-section to remove symmmetric component to 1%

_ _ _ _ _ _ _ ATLAS and CMS monojet searches ________ direct detection



March-Rusell et al. 2012

Ways out:

- ADM is heavy, with weakscale interactions to SM and suppressed abundance with respect to B (Boltzmann)

- Light mediators, with mass $m_M \approx 2\, m_{DM}$
  Feng et al. 2012

- ADM annihilates via strong coupling to dark fields which

a) decay with small coupling to SM
b) remain as dark radiation ➔ cosmological constraints (DR abundance, Dark Acoustic Oscillations)

Blennow et al. 2012; Francis-Yan Cyr-Racine et al. 2013

CMB constraint on the annihilation cross-section:

- WMAP + Planck measurements of CMB multipole spectrum constraints

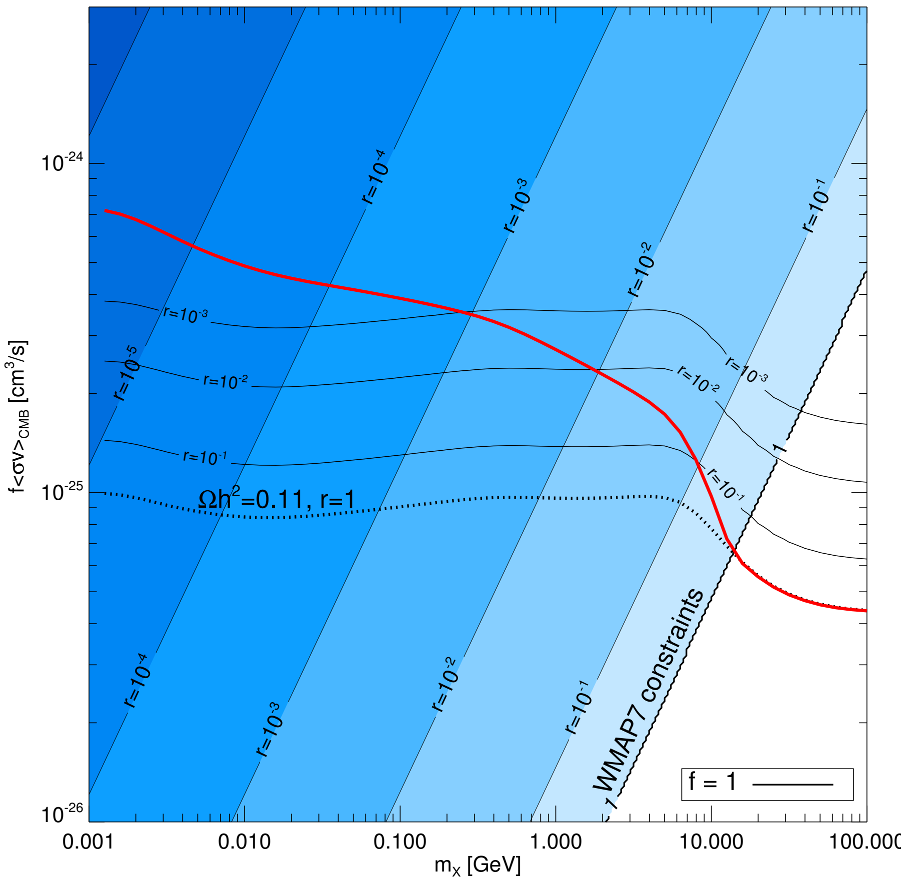
$P_{ann} = f(z) \langle\sigma v\rangle / m_{DM} \lesssim 2.4\ 10^{-27}\ \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$

ionizing efficiency: 0.8 (for e^+e^-) – 0.3 (most other states)

Relic asymmetry: $r = \frac{\Omega_{\bar{X}}}{\Omega_X} \simeq \frac{Y_{\bar{X}}(x_f)}{Y_X(x_f)} \exp\left(\frac{-c\eta_X \langle\sigma v\rangle}{x_f}\right)$

$x_f = m_{DM}/T_f$ → freezeout temperature

Graesser et al. 2011



$f\,\langle\sigma v\rangle \;\geq\; 10^{-25}\,\mathrm{cm}^3/\mathrm{s}$

Lin, Yu and Zurek 2012

Cosmological and astrophysical signatures of ADM

- DM is stable and does not annihilate ➔ no indirect detection (unless oscillations, if D-violating mass terms are present Cai et al. 2009; Cohen and Zurek 2010)

- DM can accumulate in stars (like the Sun) and affect stellar evolution Frandsen and Sarkar 2010; Taoso et al. 2010

- Self-interacting DM can help in some problems such as core-vs-cusp problem, more spherical haloes.

  Spergel and Steinhard 2000

- Limits from colliding clusters ➔ Felix Kahlhoefer talk

III. A model of ADM via leptogenesis

Blennow, Dasgupta, Fernández-Martínez, N.R. 2011

Decay of Majorana right-handed neutrino N_R produces L asymmetry (CP and L violation in decay)

- Extend SM by N_R and DM fermions xL, xR per generation
- Two new gauge interactions: $SU(3)_{DC}$ and $SU(2)_H$
- $SU(2)_H$ → horizontal chiral symmetry that provides new sphalerons

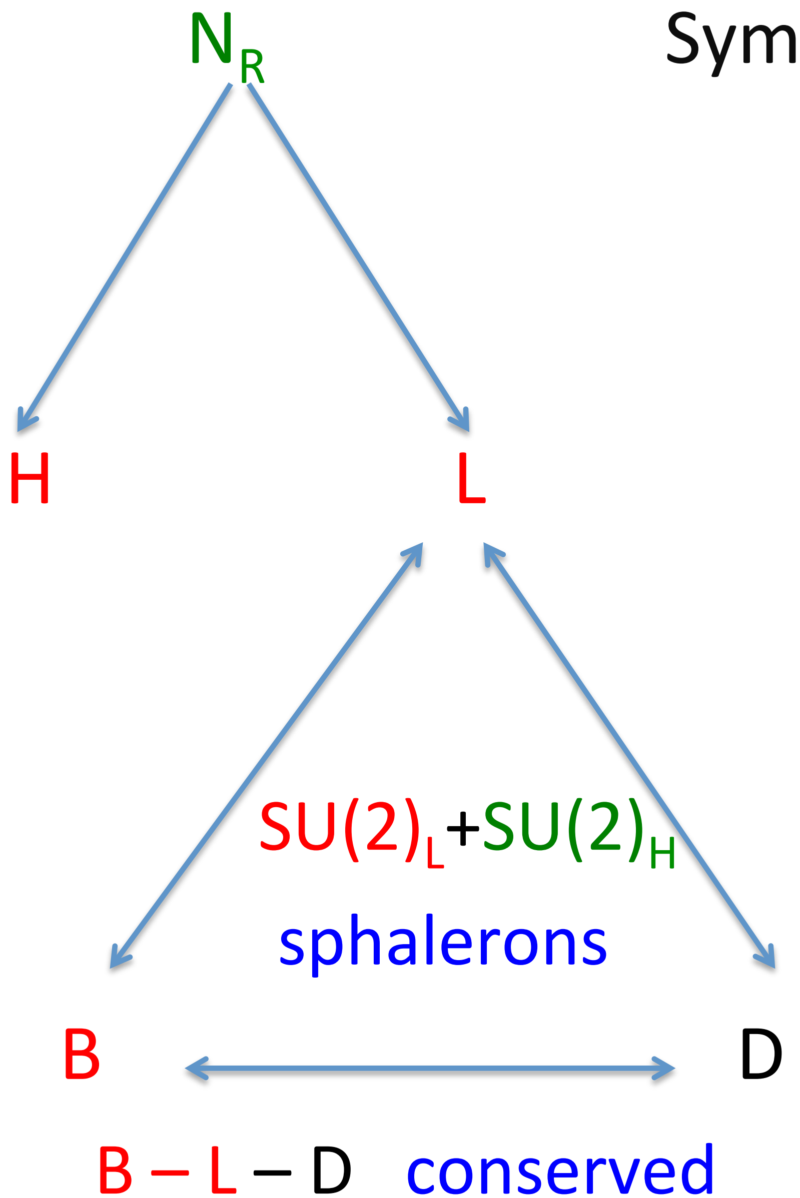
- x_L and x_R are triplets of $SU(3)_{DC}$ → they form "dark baryons" with masses similar to the SM baryons

- $SU(2)_H$ doublets:

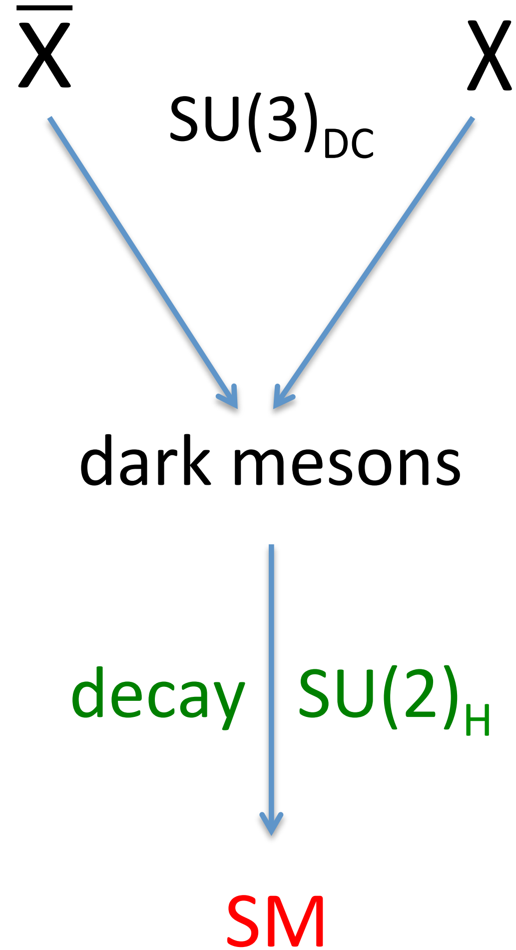
$$\begin{pmatrix} \mu \\ e \end{pmatrix}_R \quad \begin{pmatrix} s \\ d \end{pmatrix}_R \quad \begin{pmatrix} c \\ u \end{pmatrix}_R \quad \begin{pmatrix} x_2 \\ x_1 \end{pmatrix}_R$$

- N_R and x_L are singlets to prevent anomalies

- Extended scalar sector provide mass terms for fermios



Symmetric relic annihilation



- N_R is a gauge singlet ➔ neutrino masses (seesaw)
  L generation in decay
- $SU(2)_L$ sphalerons violate B, L in the direction:
  $\Delta B = \Delta L$
- $SU(2)_H$ sphalerons violate B, L and D in the direction:
  $\Delta B = 2\Delta L = 2\Delta D$
- B-L-X remains non-anomalous and exactly conserved
- L asymmetry partially transformed into B and D
- After $SU(2)_H$ and $SU(2)_L$ symmetry breakings, asymmetries are frozen:

$$D = -\frac{11}{14} B$$

$m_{DM} \approx 6$ GeV

- Symmetric DM thermal relic efficiently annihilates into dark mesons, after $SU(3)_{DC}$ phase transition
- Dark mesons decay to SM particles via $SU(2)_H$ interactions

Constraints

- $SU(2)_H$ sphalerons in thermal equilibrium before phase transition:

$$\alpha_H^4 = \left(\frac{g_H^2}{4\pi}\right)^4 \gtrsim 10\,\frac{T}{M_{Pl}}$$

- Dark mesons should decay before BBN → lower bound on

$$G_F^H = \frac{\sqrt{2}g_H^2}{8m_H^2}$$

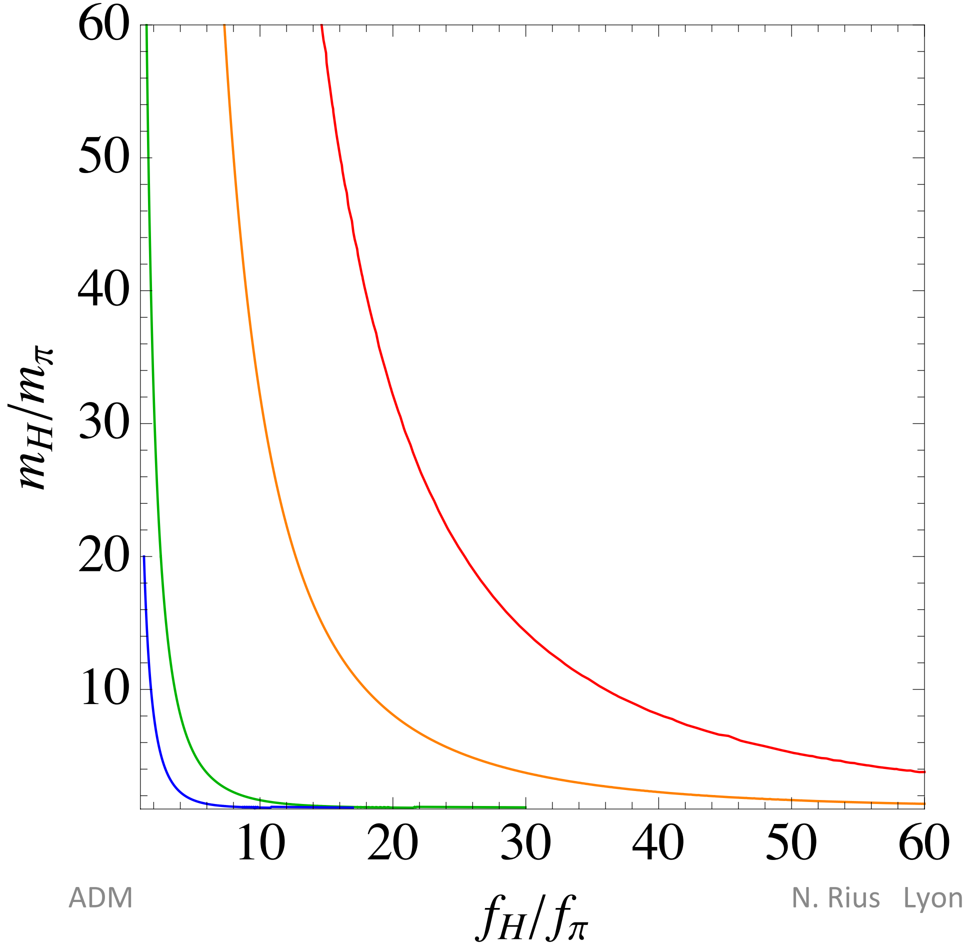
- $SU(2)_H$ interaction induces FCNC upper bound from $K^0 \to \mu\, e$

$$G_F^H < 3.6\times 10^{-12}\mathrm{GeV}^{-2}$$

- Tension with BBN → need to break the symmetry in stages or to couple mainly to 2nd and 3rd generations

Breaking the symmetry in stages

- $SU(2)_H$ symmetry broken by vev of scalar triplet along σ_3 ➔ flavour-conserving Z' remains massless
- Milder constraints on the mass of Z', which can lead to dark mesons decay before BBN



$G_F^H > 5 \times 10^{-11}\ \mathrm{GeV}^{-2}$

$G_F^H > 10^{-10}\ \mathrm{GeV}^{-2}$

$G_F^H > 5 \times 10^{-10}\ \mathrm{GeV}^{-2}$

$G_F^H > 10^{-9}\ \mathrm{GeV}^{-2}$

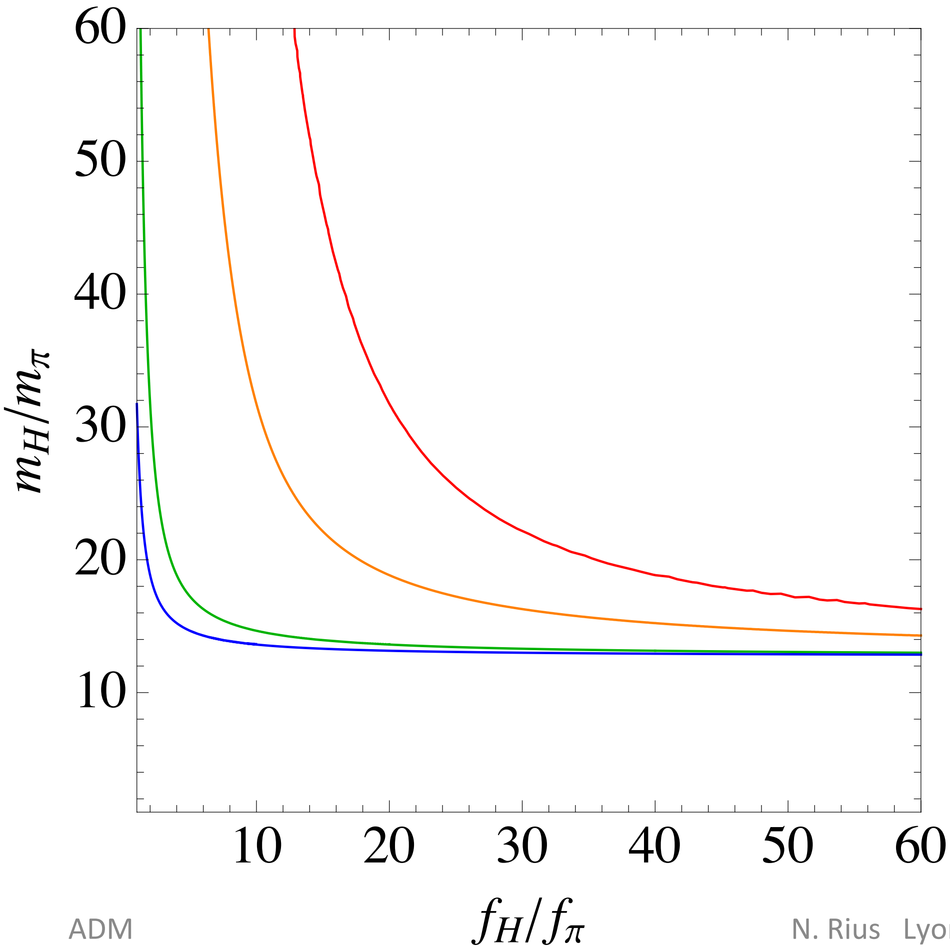
H ➔ μ μ

$\tau_H < 10^{-2}$ s

Coupling to 2nd and 3rd generations:

Weaker constraints

Source of mixing and CP violation in the B system



$G_F^H > 5 \times 10^{-12}\ \mathrm{GeV}^{-2}$

$G_F^H > 10^{-11}\ \mathrm{GeV}^{-2}$

$G_F^H > 5 \times 10^{-11}\ \mathrm{GeV}^{-2}$

$G_F^H > 10^{-10}\ \mathrm{GeV}^{-2}$

H ➔ τ (e,μ)

$\tau_H < 10^{-2}$ s

- To explain DAMA/CoGeNT signals:

$$G_F^H \sim 10^{-7}\mathrm{GeV}^{-2}$$

- Conflict with LEP II and LHC bounds on Z':

$$G_F^H < 5.14 \times 10^{-8}\mathrm{GeV}^{-2}$$

$$G_F^H < 10^{-8}\mathrm{GeV}^{-2}$$

- Unless the $SU(2)_H$ couples mainly to the heavier charged lepton generations

IV. Summary and outlook

- ADM makes DM more similar to baryonic matter, as suggested by $\Omega_B \approx \Omega_{DM}$
- Light DM, $m_{DM} \approx$ 1-15 GeV also motivated by some direct detection experiments (DAMA,CoGeNT,CDMS)
- Typically, ADM requires extended dark sectors, in order to annihilate symmetric DM relic abundance
- Illustrative model: extending the SM with N_R and DM fermions + $SU(2)_H$ x $SU(3)_{DC}$ induces asymmetric DM via leptogenesis and $SU(2)_H$ sphalerons
  - Stable DM without additional parities
  - DM mass and abundance similar to baryons

- A flavour-conserving Z′ remnant of $SU(2)_H$ can have low mass and lead to signals at colliders or direct detection experiments

- If $SU(2)_H$ couples mainly to 2nd and 3rd generations, new sources of mixing and CP violation in the B system

- Possible relation of SU(2)H breaking with the flavour puzzle ?