LHC and
models with antibaryonic dark matter

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

QFTHEP-2015
SINP MSU & SSU

Message

- Conventional DM models do not address the coincidence

$$M_{DM} \times n_{DM} = \rho_{DM} \sim \rho_B = n_B \times m_B$$

- The models called (anti)baryonic, (anti)symmetric DM designed to explain this by producing DM and BAU via one and the same mechanism
- If produced in particle scatterings,

$$n_{DM} \sim n_B \implies M_{DM} \sim m_B$$

  and the corresponding NP scale is high
- LHC provides the best opportunity to probe these models !!

So far only gravitational evidence for DM

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_{\Lambda}$$

$$\rho_{\text{radiation}} \propto 1/a^4(t) \propto T^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)$$

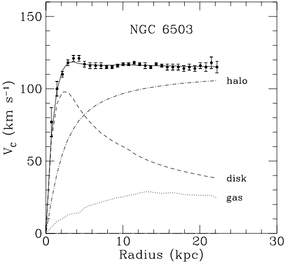
$$\rho_{\Lambda} = \text{const}$$

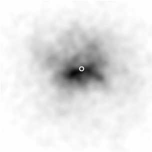
Why do we think it is most probably new particle physics
(new gravity if any is not enough) ?

DM phenomena happen at various spatial and time scales

Dark Matter in astrophysics

Rotational curves





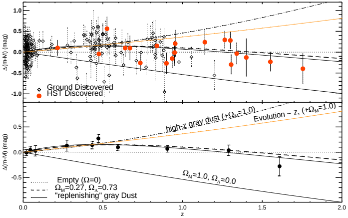
X-rays from centers of galaxy clusters

Gravitational lensing

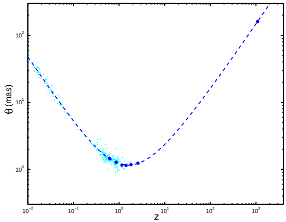
“Bullet” cluster

Dark Matter in cosmology

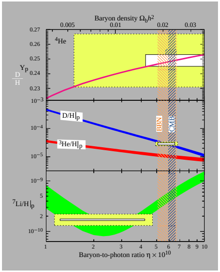
Standard candles

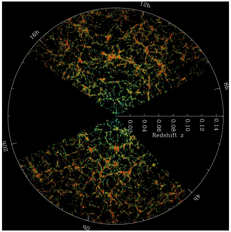


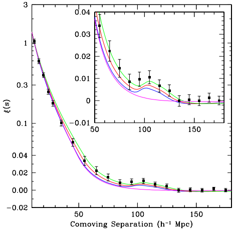
Angular distance

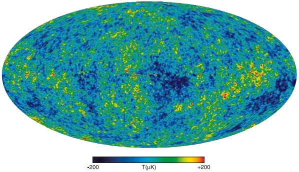


Nucleosynthesis









Large Scale Structures

Baryon acoustic oscillations

CMB anisotropy

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Dark Matter: thermal production

1. freezing out while relativistic (e.g. neutrino)

   DM particle mass M_X fixes Ω_X: NO heavy particles!

$$\Omega_X = \frac{m_X \cdot n_{X,0}}{\rho_c} \approx 0.2 \times \frac{M_X}{100\ \text{eV}} \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_f)}\right)$$

   No realistic models:

   too energetic for the proper structure formation

   Pauli blocking prevents fermionic DM

2. freezing out while nonrelativistic (e.g. neutrons)

   DM annihilation cross section σ_0 fixes Ω_X: NO weaker coupled particles

$$\Omega_X \approx 0.1 \times \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)$$

   We need $\sigma_0 \simeq \sigma_W/100$ and any mass $M_X \lesssim 50\,\text{TeV}$ is OK

   There are realistic models: e.g. LSP as WIMP

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations):
   gravitino
   sterile neutrino of 1-50 keV
2. at phase transitions:
   axion of $10^{-4} - 10^{-7}$ eV
   Q-balls
   strangelets (?)
3. during reheating (after inflation?):
   any guy coupled (only) to inflaton
   - perturbatively: inflaton decays
     production by external (inflaton) field
   - non-perturbatively: Bose-enhancement of
     coherent production by external field
4. while the Universe expands:
   gravity produces any particles at $H \sim M_X$

Discussion on WIMPs: natural or not ?

Most natural properties:

- to be in equilibrium in primordial plasma up to very freezout (and in kinetic equilibrium even later)
- to form a symmetric component:

$$X = \bar{X} \quad \text{or} \quad n_X = n_{\bar{X}}$$

But what we have in reality?

- We are sure there were
  - Big Bang Nucleosynthesis (starting from 1 MeV)
  - Recombination (at about 0.3 eV)

  and both are significantly "out-of-equilibrium" processes
- The visible matter is asymmetric, so that

$$f \neq \bar{f} \quad \text{and} \quad n_f = n_{\bar{f}}$$

Asymmetric Dark Matter

Many differences with respect to the symmetric case if asymmetry is large, i.e. $n_X \gg n_{\bar{X}}$!

- Get an upper limit on the mass of DM particle!

$$n_{X,0}+n_{\bar{X},0}=\eta_X n_{\gamma,0}+2n_{\bar{X},0}>\eta_X n_{\gamma,0}\Longrightarrow M_X=\frac{\rho_{DM,0}}{n_{X,0}+n_{\bar{X},0}}<\frac{\rho_{DM}}{\eta_X n_{\gamma,0}}\simeq\frac{T_{\gamma,0}}{\eta_X}\frac{\Omega_{DM}}{\Omega_\gamma}$$

- If remains in (elementary) particles, then its signatures change!

1. No annihilation in the centre of the Sun!
   (e.g. Baksan, ICECUBE limits are irrelevant)
   Black hole formation in the stars instead. . . ?
2. No pair annihilation in the halo
   (e.g. PAMELA, Fermi limits are irrelevant)
3. Elastic scatterings are stil OK
   (direct searches are relevant)

for review see e.g. H.Davoudiasl, R.Mohapatra (2012)

Next step towards antibaryonic DM

Stability of DM is provided by a conserved charge:

Let it be baryonic charge!

Minimality at work!

Searches for proton decays give the strongest limits on violation of "supposed to be conserved" number...

No need to violate (perturbatively?) baryon number

Now we can understand $\rho_B \sim \rho_{DM}$

DM is new particles carrying antibaryonic charge

Then in primordial plasma

$$X + Y \to \text{baryon} + DM$$

and so $n_B \sim n_{DM}$

Let DM particles be new and "elementary"

Since "total" baryon number is conserved, $q_B \cdot n_B + q_{DM} \cdot n_{DM} = 0$, $\Longrightarrow$

$$n_B = -\frac{q_{DM}}{q_B}\, n_{DM} \quad \Longrightarrow M_{DM} = m_p \frac{n_B}{n_{DM}} \frac{\Omega_{DM}}{\Omega_B} \simeq -5\, \frac{q_{DM}}{q_B}\, \text{GeV}$$

Must forbid DM decay into antiproton! (kinematically?)

General signatures:

- No annihilation like $X + X \to SM$
- Challenging task for direct searches: trigger $X + SM \to X + SM$
- Can be annihilation with ordinary matter: $F(\mathbf{r}) \propto n_{DM}(\mathbf{r}) n_B(\mathbf{r})$
  signal in cosmic rays at energies $\lesssim (M_X + m_p)/2 \sim$ a few GeV
  difficult to recognize, e.g. solar modulation
- proton decay-like event in Super-K

$$X + p \to \pi + \text{smth}$$

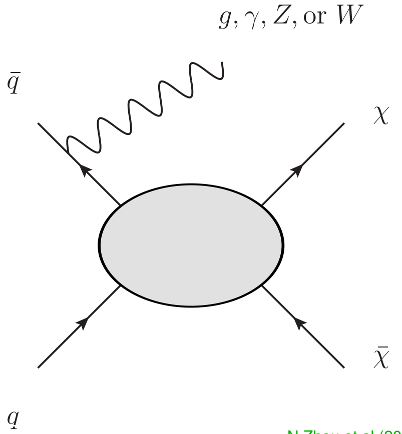
albeit higher energy release of the signal event

Direct searches for a particle of 5 GeV . . .

LHC helps!

provided some (reasonably) weak interactions between visible baryons and invisible (dark) antibaryons, which should be

Illustration with searches for WIMP-signal



N.Zhou et al (2013)

Logic: no light superpartners, $M_{SUSY} > 500$ GeV

let's integrate them out to get low energy EFT

$$D1\ (\text{scalar}):\ \frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$$

$$D8\ (\text{axial}):\ \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

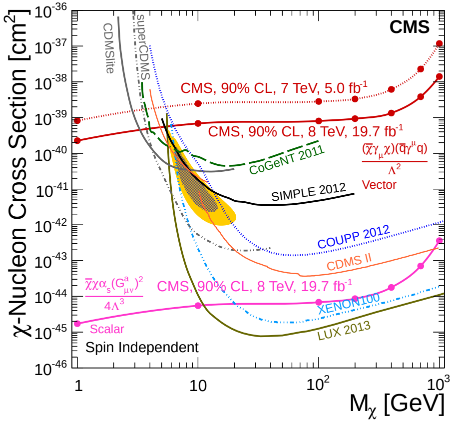
$$D5\ (\text{vector}):\ \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

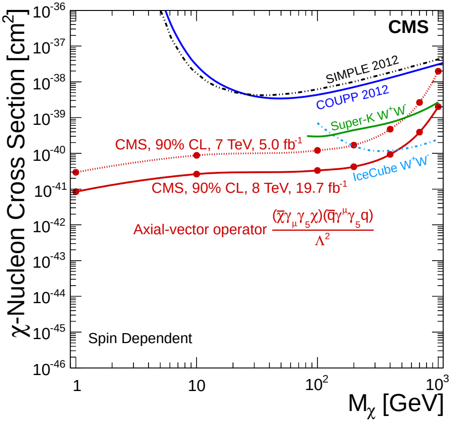
$$D9\ (\text{tensor}):\ \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$$

suppressed by gauge couplings α_s, α, α_W, . . .

CMS results of searches at @ 8 TeV

V. Khachatryan et al (2014)





An example: Hylogenesis

H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2010)

Greek: hyle (primordial matter) + genesis (origin)

- New fields:
  2 Dirac fermions X_a, $a = 1,2$ — $m_2 > m_1 \gtrsim 1$ TeV
  1 Dirac fermion Y — $m_Y \sim \mathscr{O}(1)$ GeV
  1 complex scalar Φ — $m_\Phi \sim \mathscr{O}(1)$ GeV
- Coupling to SM via “neutron portal”

$$-\mathscr{L}_{\text{int}} = \frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R + \zeta_a \bar{X}_a Y^C \Phi^* + \text{h.c.}$$

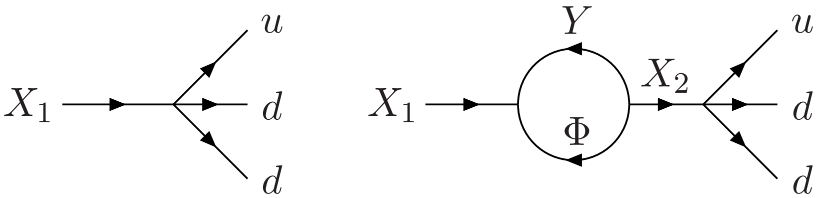
- Baryon charge — $B_{X_a} = -(B_Y + B_\Phi) = 1$
- Proton and DM particles (both Y and Φ) are stable if

$$|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi$$

Baryogenesis (asymmetry generation)

Sakharov's conditions

1. *B*-violation (in visible sector !) $\lambda_a \neq 0$
2. *C*- & *CP*-violation $\Im\left(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*\right) \neq 0$
3. out-of-equilibrium decays of nonrelativistic X_1



Microscopic asymmetry (assuming $X_1 \to \bar{Y}\Phi^*$ dominates and $M_1 \ll M_2$)

$$\varepsilon = \frac{\Gamma(X_1 \to udd) - \Gamma(\bar{X}_1 \to \bar{u}\bar{d}\bar{d})}{\Gamma(X_1 \to \bar{Y}\Phi^*) + \Gamma(\bar{X}_1 \to Y\Phi)} \approx \frac{m_1^5 \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\pi^3 |\zeta_1|^2 M^4 m_2} \Rightarrow \varepsilon/g_* \sim \Delta_B = \frac{n_B}{s} \approx 10^{-10}$$

if $m_2 > 2m_1$, $M > 2m_2$ then $\varepsilon \simeq 2.5 \times 10^{-7} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ seems OK

if $m_2 > 3m_1$, $M > 3m_2$ then $\varepsilon \simeq 6.5 \times 10^{-9} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ needs $|\zeta_1| \ll 1$?

Asymmetric Dark Matter freeze out

To make DM natural:
all CP-symmetric pairs (Y and $\bar{Y}$), (Φ and Φ^*) must annihilate

- CP-asymmetric relics form Dark Matter
  is exactly the counterpart of baryon asymmetry in visible sector
- then baryon number conservation implies $n_Y = n_\Phi = n_B$ and so

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_Y + m_\Phi}{m_p}$$

- stability of proton and DM is kinematically guaranteed for

$$1.7\,\mathrm{GeV} \lesssim m_Y, m_\Phi \lesssim 2.9\,\mathrm{GeV}$$

- hence $\Omega_{DM} \sim \Omega_B$ is natural

Tests at LHC

Searching for X_a

$$\frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R$$

the same WIMP-like signature

monojet + missing P_T

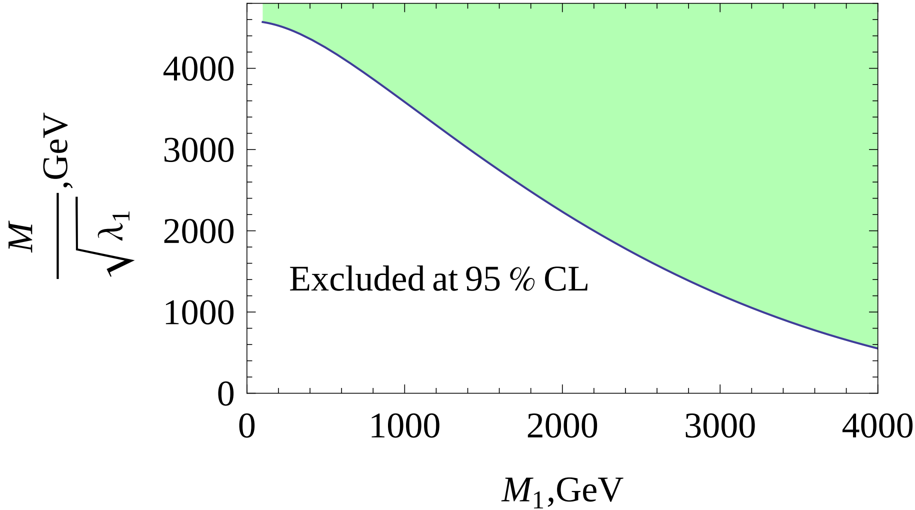
and no need for bremsstrahlung , hence no α_s-suppression

$$d + d \to \bar{u} + X\,, \qquad d + u \to \bar{d} + X$$

we can adopt the results of CMS analysis 1408.3583 V. Khachatryan et al (2014)

$$\sqrt{s} = 8\,\text{TeV} \qquad \mathscr{L} = 19.7\,\text{fb}^{-1}$$

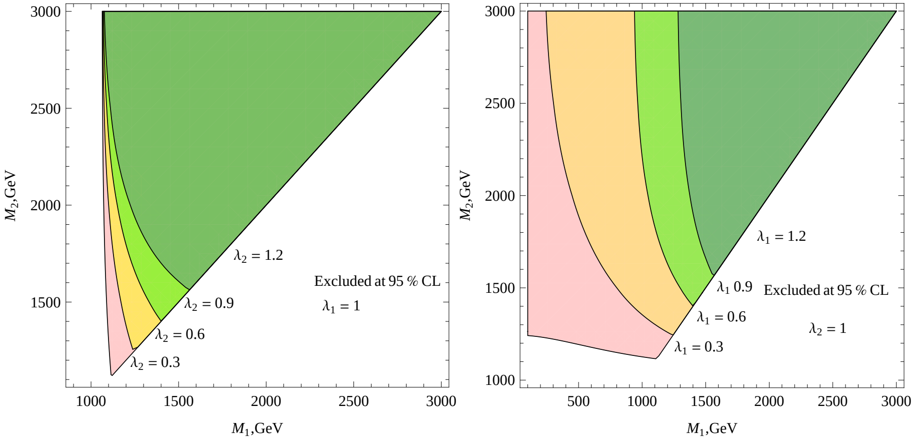
Limits from LHC: only X_1 is accessible ($\lambda_2 = 0$)



$p_T^{jet} > 550\,\text{GeV}$ and $|\eta^{jet}| < 2.4$

S. Demidov, D. G., D. Kirpichnikov (2014)

Limits from LHC: both $X_{1,2}$ are accessible



$M_1 < M_2$ and $M = 3.5\,\text{TeV}$

S. Demidov, D. G., D. Kirpichnikov (2014)

Future tasks for LHC

- BAU is explained by any "neutron-like portal"

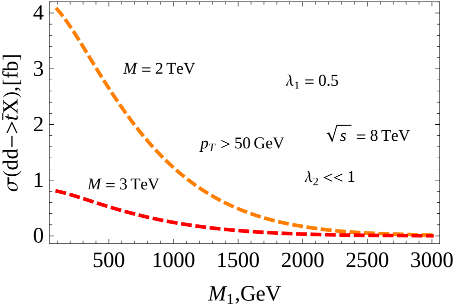
All options must be probed

$$-\mathscr{L}_{\text{int}} = \frac{\lambda_a}{M^2}\, \bar{X}_a d_R \bar{u}^C d_R$$

$$d = d,\ s,\ b$$

$$u = u,\ c,\ t$$

$$d + d \to \bar{t} + X$$



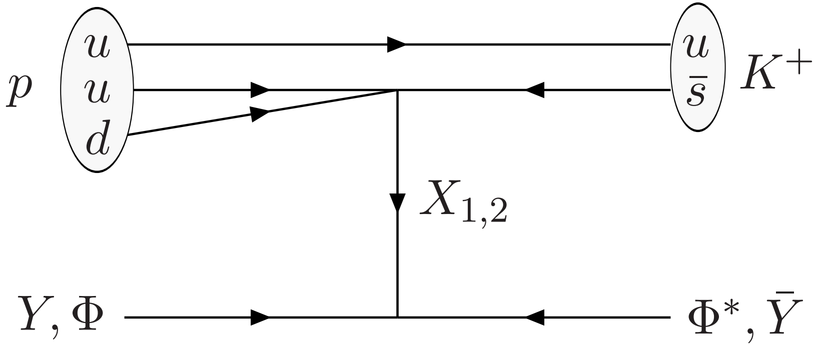
S. Demidov, D. G., D. Kirpichnikov (2014)

- Searches for $X \to dd\bar{u}$

signatures:
jet + 3 jets [forming a particle (invariant mass m^2_{jjj})]
jet + 2 jets + b-jet [. . .]
jet + 2 jets + $\bar{t}$-quark [. . .]
b-jet + . . .
$\bar{t}$-quark + . . .

Induced proton decay: mimicing $p^+ \to K^+ + \nu$

H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2010)



$$\sigma v \simeq 10^{-39}\,\mathrm{cm}^3/\mathrm{s} \times \left| \sum_a \frac{\mathrm{TeV}^3}{m_a M^2/\lambda_a \zeta_a^*} \right|^2 \longrightarrow \tau_p \simeq 10^{32}\,\mathrm{yr}$$

Nucleon decays due to UDD-portal

S.Demidov, D.G. (1507.xxxx)

- Existing limits

$$\tau_{n\to\gamma\nu} > 2.8\times 10^{31}\,\text{years}\,,\quad \tau_{n\to e^+e^-\nu} > 2.6\times 10^{32}\,\text{years}\,,$$

applied (with account of adopted kinematic cuts) to

$$\Phi(Y)+n\to Y(\Phi)+\gamma\,,\quad \Phi(Y)+n\to Y(\Phi)+e^+e^-\,,$$

gives $M_i \sim M \gtrsim$100-200 GeV, that is much weaker than from LHC

- Predictions for 2-meson final state to be checked at HyperK and DUNA

$$\Phi(Y)+p\to Y(\Phi)+\eta\pi^+\,,\quad \Phi(Y)+p\to Y(\Phi)+\bar{K}^0K^+\,,\quad \Phi(Y)+p\to Y(\Phi)+\bar{\pi}^0\pi^+$$

and similar for neutron

with LHC limits they all start at $\tau > 10^{34}$ years

- For other portals the limits naturally weaker

LHC seems more sensitive to these models as compared to proton decay searches

Conclusions

- Studies at LHC are very competitive (small DM masses) with
  direct searches @ XENON, CDMS, etc
  and indirect searches @ IceCube, Baksan ...
- There are other candidates, not only WIMPs !
- Absence of SUSY at TeV scale
  and absence of any hints in direct searches
  makes WIMPs much less reliable
- DM with antibaryonic charge: Lowest order dim-6 operator $\frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R$
  can explain both BAU and DM
  so that $\Omega_{DM} \sim \Omega_B$ is natural
- With LHC8 we have constrained the model parameter space
  (proton decay searches in most cases are much less sensitive)

  see also H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2011)
- There is a room to explore at LHC13
  which seems the best place to probe these models !!!

Backup slides

Why $\rho_{B,0} \sim \rho_{DM,0}$?

1. coincidence

   all well-motivated (hence, natural) models (WIMPs, axions, sterile neutrinos) imply this answer

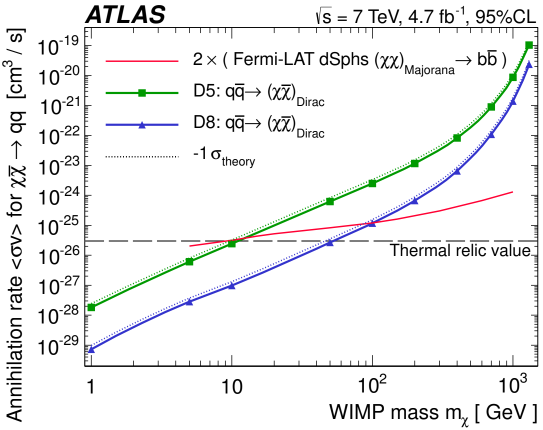
2. partly coincidence, because:
   - If $\rho_{DM} \ll \rho_B$, then DM is unobservable

     DM can be formed by several specia, only one of which dominates
   - if $\rho_{DM} \gg \rho_B$, then what?

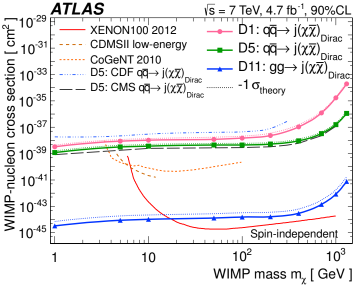
     (anthropic arguments. . . ?)

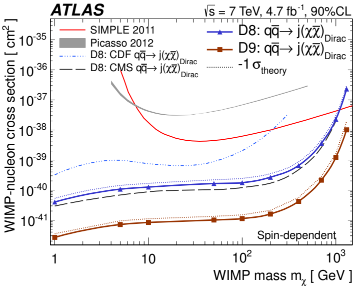
3. May be a hint at common origin of dark matter production and baryon asymmetry generation in the early Universe

ATLAS results of (in)direct searches @ 7 TeV



1210.4491v1





Dark Matter: possible guiding principles

Naturality:

- exploit known interactions

  examples: WIMPs, free particles

- part of a well-motivated model

  examples: LSP, axion, sterile neutrinos

- Why $\Omega_B \sim \Omega_{DM}$?

  examples:

  antibaryonic DM

  Mirror World

Minimality:

Use as little new physics as possible

Motivation: No any hints of new physics in experiment

Usually the models are naturally untestable

example:

gravitationally produced free massive fermion

Reality:

Deep insight into the gravitational properties of dark matter

what happen at small scales?

status of:
cusp/core in galactic centers
lack of dwarf galaxies
lack of small galaxies

examples:

cold dark matter
warm dark matter
selfinteracting dark matter

Examples: both Natural and Minimal

Natural source of dark matter production: gravity

Gravity produces any free massive particle when metric changes in the expanding Universe

most efficiently when $H \sim M$

say, at radiation domination stage

$$\Omega_X \sim \left(\frac{M_X}{10^9\,\text{GeV}}\right)^{5/2}$$

S.Mamaev, V.Mostepanenko, A.Starobinsky (1976)

Modified gravity $(R \to R - R^2/6\mu^2)$

may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

that is (universal) production of all particles, including those of dark matter

$$\Omega_X \simeq 0.15 \times \left(\frac{M_X}{10^7\,\text{GeV}}\right)^3$$

D.Gorbunov, A.Panin (2010)

Untestable