Baryonic Dark Matter and LHC

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Outline

1. Motivation for baryonically charged Dark Matter
2. LHC potential in searches for light DM
3. Probing Hylogenesis with LHC results
4. Conclusion: other signatures at LHC

Outline

So far only gravitational evidence for DM

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

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

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

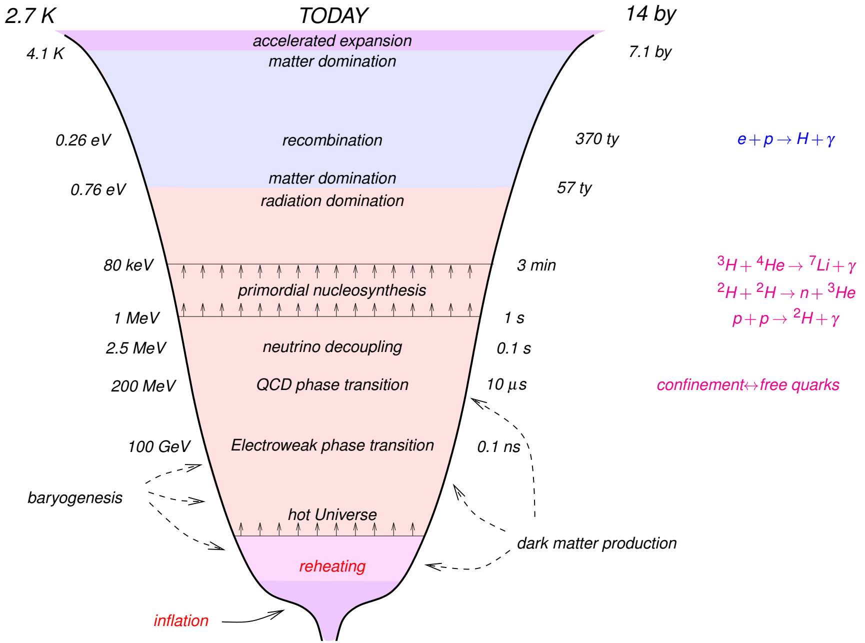
$$\rho_{\Lambda} = \text{const}$$

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

Why do we need Dark Matter component (within GR)?

- Astrophysical data favor Dark Matter
  - Observations in galaxies
  - Observations in galaxy clusters
- Cosmological data favor Dark Matter
  - Observation of objects at cosmological distances (far=early)
  - Baryonic Aciustic (Sakharov) Oscillations (BAO) in two-point galaxy correlation function
  - Anisotropy of Cosmic Microwave Background (CMB)
  - Evolution of Large Scale Structures in the Universe


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.76 eV
57 ty
radiation domination
80 keV
3 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

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 $H \sim M_X$

General remarks on Dark Matter

- So far only gravitational evidences
  Hence, it may be a modification of GR
  . . . (no examples)
- A variety of SM extensions with Dark Matter candidates
  Usually stability at cosmological time scales implies a new
  (almost) conserved charge
  Make your choice or suggest one more candidate!
- Need a Guiding Principle
  to set priorities

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

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

Discussion on WIMPs

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)

What amount of asymmetry looks natural?

Like in the visible sector. . . ?

1. $\eta_{DM} \sim \eta_B$
2. $\eta_{DM} \sim \eta_L$

At present we can have $\eta_L \gg \eta_B \sim 10^{-9}$ even if before EW phase transition $\eta_L \sim \eta_B$ provided by EW sphalerons

Example: 1-10 GeV sterile neutrinos continuing production of lepton asymmetry via oscillations with active neutrinos in post-EW Universe

Observations: asymmetry can be hidden in primordial neutrino components, hence only BBN limit $\eta_L \lesssim 0.01$ is reliable

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

Two obvious variants:

1. DM is antimatter (antineutrons, antiprotons, etc)

   but why is DM dark, stable, collisionless etc ?

   e.g.:

   In the early Universe antibaryons could fall into: black holes, $\bar{B}$-balls

   Why $\rho_B \neq \rho_{DM}$, however $\rho_B \sim \rho_{DM}$? dynamically (?), mass defect (?)

2. DM is new particles carrying antibaryonic charge

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

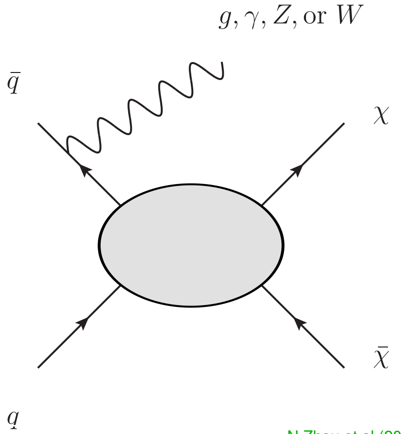
Outline

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

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

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

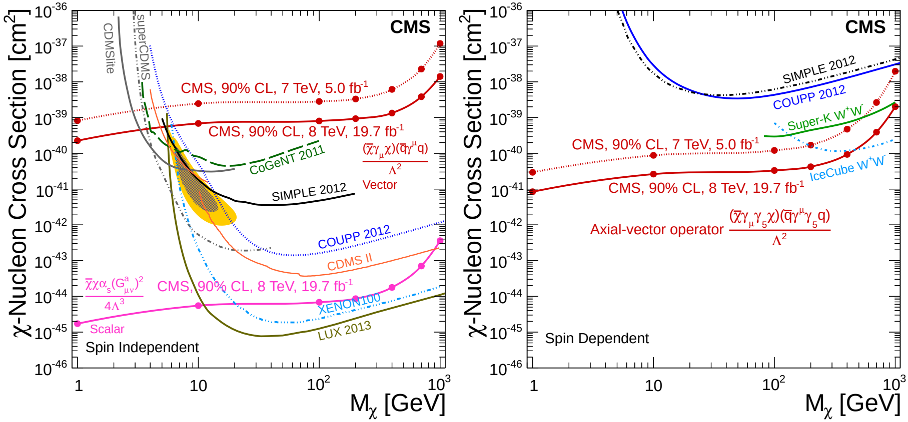
$$D5 \text{ (vector)}: \quad \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

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

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

CMS results of searches at @ 8 TeV

V. Khachatryan et al (2014)



Outline

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 — $m_Y \sim \mathcal{O}(1)$ GeV
  1 complex scalar Φ — $m_\Phi \sim \mathcal{O}(1)$ GeV
- Coupling to SM via "neutron portal"

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

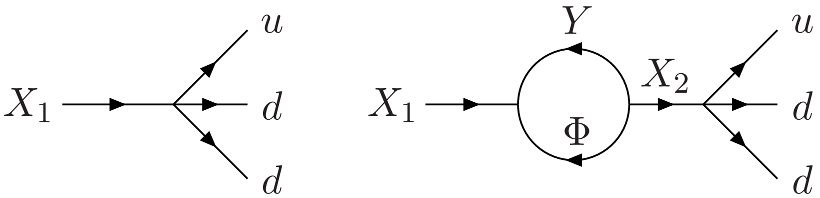
- Baryon charge — $B_{X_a} = -(B_Y + B_\Phi) = 1$
- Proton and DM particles (both Y and Φ) are stable if

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

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

- introduce some couplings, e.g. $\xi\, H^\dagger H \Phi\Phi^*$
- with $\xi \gtrsim 10^{-3}$ no CP-symmetric relicts remain

$$Y + \bar{Y} \leftrightarrow \Phi + \Phi^*\,, \qquad \Phi + \Phi^* \to h^* \to \text{SM particles}$$

- 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

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

- 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

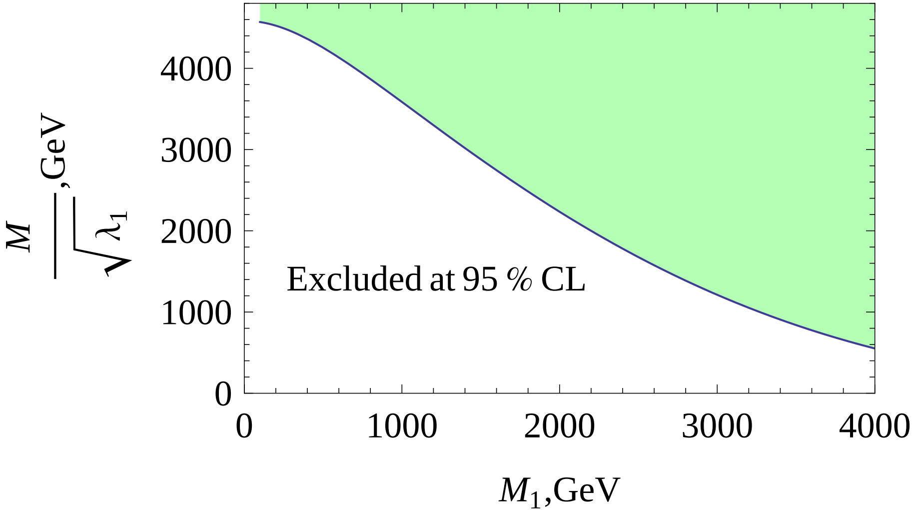
and no need for bremsstrahlung , hence no α_s-suppression

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

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

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

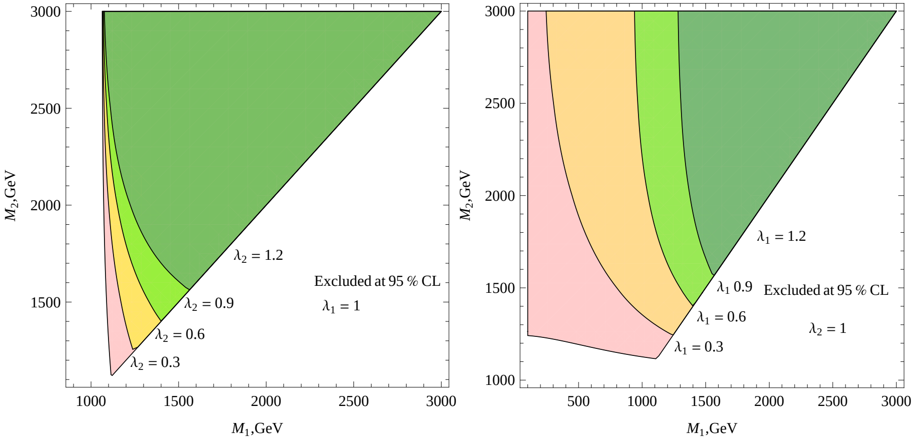
Limits from LHC: only X_1 is accessible ($\lambda_2 = 0$)



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

S. Demidov, D. G., D. Kirpichnikov (in progress)

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 (in progress)

Outline

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
  (couldn't find the signal from very beginning: no excess in missing E^T events)
  see also H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2011)
- There is a room to explore at LHC13

Future tasks

- BAU is explained by any “neutron-like portal”

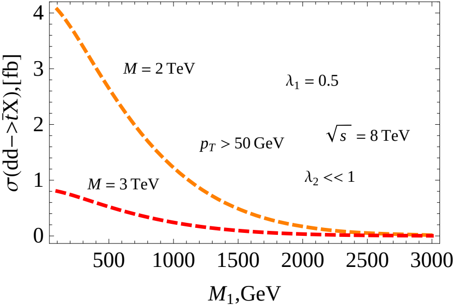
All options must be probed

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

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

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

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



S. Demidov, D. G., D. Kirpichnikov (in progress)

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

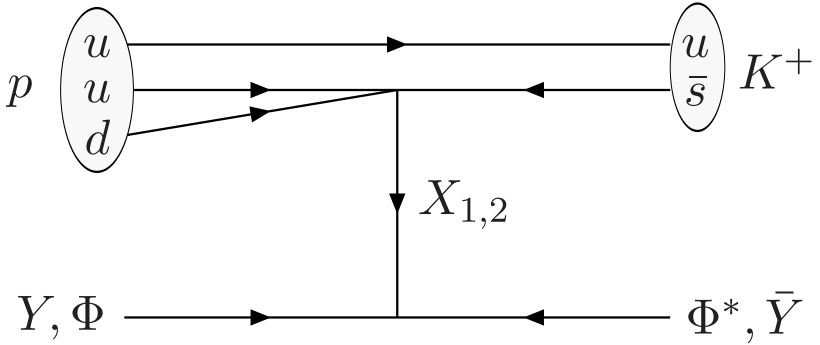
signatures:

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 + . . .

Backup slides

Induced proton decay (for e.g. SuperK)

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



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

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

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

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

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

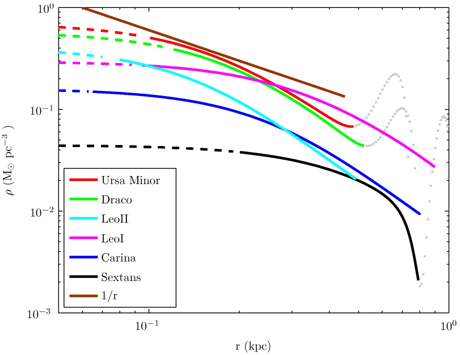
D.Gorbunov, A.Panin (2010)

Untestable

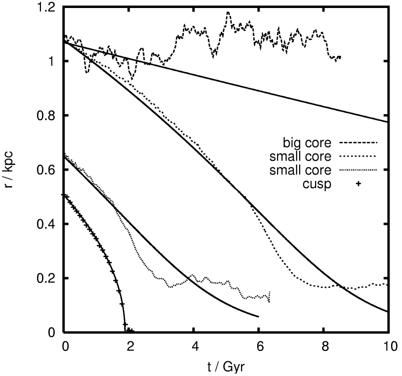
CDM Problems

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp

Cores observed (?)

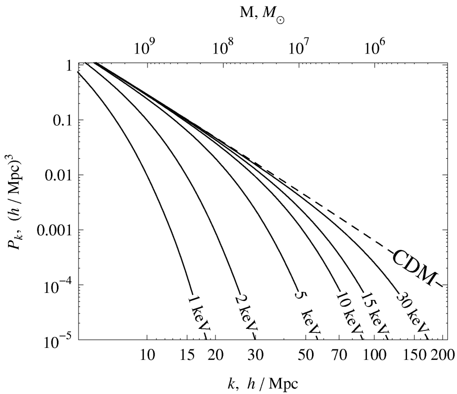


5 Clusters in the Fornax dSph

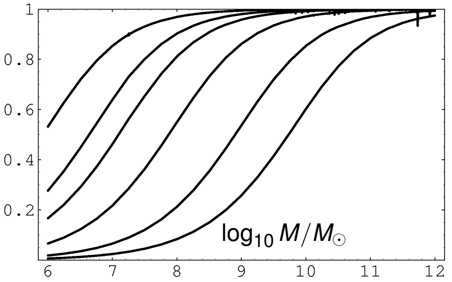


CDM Problems

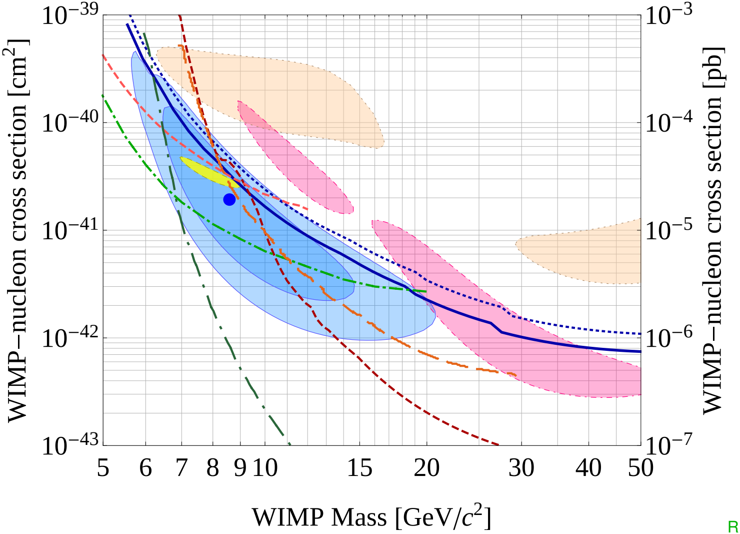
- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
- Might be solved with Warm Dark Matter (sterile neutrino, gravitino)
  - Is non-relativistic ($v \sim 10^{-3}$) at $T \sim 1$ eV free-streaming scale $l \sim vt_H$
  - Nonthermal production is needed



$\left(\frac{dN_{obj}}{d\ln M}\right)_{WDM} / \left(\frac{dN_{obj}}{d\ln M}\right)_{CDM}$



Direct searches



R.Agnese et al (2013)