Dark Model models

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Dark Matter in astrophysics

Rotational curves

Gravitational lensing

X-rays from centers of galaxy clusters

“Bullet” cluster
Dark matter in cosmology

Standard candles

Angular distance

Nucleosynthesis

Large Scale Structures
Baryon acoustic oscillations
CMB anisotropy

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Dark Matter properties from cosmology:  $\rho = 0$

(If) particles:

1. **stable** on cosmological time-scale
   - requires new (almost) conserved quantum number
2. produced in the early Universe
   - some time before RD/MD-transition ($T = 0.8$ eV)
3. **nonrelativistic** particles long before RD/MD-transition ($T = 0.8$ eV)
   - (either **Cold** or **Warm**, $\nu_{RD/MD} \lesssim 10^{-3}$)
   - Otherwise no small-size structures, like dwarf galaxies:
     - smoothed out by free streaming
4. If were in **thermal equilibrium**:
   - $M_X \gtrsim 1$ keV
   - $\rho = 0$, $\nu_{\text{sound}} = 0$
5. **(almost) collisionless**
6. **(almost) electrically neutral**
7. all matter inhomogeneities (perturbations) are adiabatic:
   \[
   \delta \left( \frac{n_B}{n_{DM}} \right) = \delta \left( \frac{n_B}{n_{\gamma}} \right) = \delta \left( \frac{n_{\nu}}{n_{\gamma}} \right) = 0
   \]
Astrophysical and cosmological data are in agreement

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

\[ \rho_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{ordinary matter}} + \rho_{\text{dark matter}} + \rho_{\Lambda} \]

\[ \rho_{\text{radiation}} \propto \frac{1}{a^4(t)} \]

\[ \rho_{\text{matter}} \propto \frac{1}{a^3(t)} \]

\[ \rho_{\Lambda} = \text{const} \]

\[ \frac{3H_0^2}{8\pi G} = \rho_{\text{energy}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5} \text{ GeV/cm}^3 \]

Radiation:
\[ \Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4} \]

Baryons (H, He):
\[ \Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05 \]

Neutrino:
\[ \Omega_\nu \equiv \frac{\Sigma \rho_{\nu_i}}{\rho_c} < 0.01 \]
\[ N_\nu \approx 3, \Sigma m_\nu \lesssim 0.3 \text{ eV} \]

Dark matter:
\[ \Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_c} = 0.27 \]

Dark energy:
\[ \Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68 \]
Interplay: Standard Model and Cosmology

Gauge fields (interactions): $\gamma, W^\pm, Z, g$
Three generations of matter: $L = (\nu_L, e^-_L, e^+_R); Q = (u_L, d_L, u_R, d_R, u_R$

- **SM Describes**
  - all experiments dealing with electroweak and strong interactions

- **SM fails to describe** (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage
  - Dark energy ($\Omega_\Lambda$)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

And hence asks for new physics
Weakly Interacting Massive Particles

Assumptions:

1. $\chi$ and $\bar{\chi}$ are stable (at cosmological time scale)
2. no $\chi - \bar{\chi}$ asymmetry
3. @ $T < M_\chi$ in thermal equilibrium with plasma

$$n_\chi = n_{\bar{\chi}} = g_\chi \left( \frac{M_\chi T}{2\pi} \right)^{3/2} e^{-M_\chi / T}$$

$\chi \bar{\chi} \leftrightarrow$ light particles

Bethe formulae: s-wave: $\sigma_{\text{ann}} = \frac{\sigma_0}{v}$

$\chi + \bar{\chi}$ contribution to critical density:

$$\Omega_\chi = 0.1 \times \frac{(1 \text{ TeV})^{-2}}{100 \times \sigma_0} \frac{0.3}{\sqrt{g_* (T_f)}} \ln \left( \frac{g_\chi M_\text{Pl}^* M_\chi \sigma_0}{(2\pi)^{3/2}} \right) \cdot \frac{1}{2h^2}$$
WIMPs: discussion

\[ \Omega_X = 0.1 \cdot \left( \frac{(10 \text{ TeV})^{-2}}{\sigma_0} \right) \frac{10}{\sqrt{g^*_f(T_f)}} \ln \left( \frac{g_X M_{\text{Pl}}^* M_X \sigma_0}{(2\pi)^{3/2}} \right) \cdot \frac{1}{2h^2} \]

- Natural DM: subweak-scale cross section \( \sigma_0 \sim 0.01 \times \sigma_W \)
- Say, \( M_X \sim 1 \text{ TeV} \) annihilate through \( t \)-channel \( XX \rightarrow ZZ \)
- Or \( X \) is not a weak gauge eigenstate, \( g_W \rightarrow g_W \times \sin \xi \)
- Naturally "light" unitarity \( \sigma_0 \lesssim \frac{4\pi}{M_X^2} \rightarrow M_X \lesssim 100 \text{ TeV} \)
- All stable particles with smaller \( \sigma_0 \) are forbidden!!
- WIMPs remain in kinetic equilibrium with plasma till \( T \sim 10 \text{ MeV} \)

This is Cold Dark Matter, \( \nu_{\text{RD/MD}} \ll 10^{-3} \)

WIMPs may form dark halos (clumps) much lighter than dwarf galaxies
Weakly IMPs are mostly welcome (e.g. LSP in SUSY)

We can fully explore the model!!

- Direct searches for Galactic Dark Matter ($v_X \sim 10^{-3}$)
  \[ X + \text{nuclei} \rightarrow X + \text{nuclei} + \Delta E \]

- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun)
  \[ X + \bar{X} \rightarrow p\bar{p}, \; e^+e^-, \; \nu\bar{\nu}, \gamma, \ldots \]

- Can search for WIMPs in collision experiments (LHC):
  \[ p + p \rightarrow X + \bar{X} + \text{SM} + \ldots \]
Prospects in WIMP searches

Sensitivity Projections: Spin-Independent Interactions

Investigations:
- EDELWEISS (2011)
- COUPP (2012)
- ZEPLIN-III (2012)
- DAMA
- SIMPLE (2012)
- CDMS Si (2013)
- CRESST (2012)
- CDMS II Ge (2009)

Future Experiments:
- Xenon1T
- LZ
- LUX 300day
- SuperCDMS SNOLAB
- DEAP3600
- XMASS
- DarkSide-G2
- SuperCDMS
- EDELWEISS
- CRESST

DM models

M.Cirelli (2015)
Present indirect limits on DM annihilation

All ID constraints

status circa 34\textsuperscript{th} ICRC (summer 2015)
 searches for DM particles at LHC . . .

LHC helps!
Illustration with searches for WIMP-signal

Logic: no light superpartners, $M_{\text{SUSY}} > 500 \text{ GeV}$
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 $\alpha_s, \alpha, \alpha_W, \ldots$

ATLAS and CMS results of searches at @ 8 TeV

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DM models
13.10.2016, 2nd ICPPA
LHC limits for annihilation

$1502.01518$

$\chi$ WIMP mass $m_\chi$

$\sigma < (\text{cm}^3/\text{s})$

$\langle \sigma v_\text{rel} \rangle$

$2 \times (\text{Fermi-LAT dSphs } (\chi\chi)_{\text{Majorana}} \rightarrow u\bar{u}, 4 \text{ years})$

$2 \times (\text{HESS 2011 } (\chi\chi)_{\text{Majorana}} \rightarrow q\bar{q}, \text{ Einasto profile})$

$2 \times (\text{HESS 2011 } (\chi\chi)_{\text{Majorana}} \rightarrow q\bar{q}, \text{ NFW profile})$

$D5: \chi^\mu \chi \gamma q\rightarrow (\chi\chi)_{\text{Dirac}}$

$D8: \chi_5^\mu \gamma^5 \chi q\gamma q\rightarrow (\chi\chi)_{\text{Dirac}}$

truncated, coupling = 1

truncated, max coupling

thermal relic

$ATLAS$

95% CL $\sqrt{s}=8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

DM models

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Competition in testing MSSM
If thermal CDM but not Weakly IMPs?

We still can study the model if DM annihilates (partly) into SM particles

- But DM particle $X$ can be light and feebly coupled ($t$-channel) SHiP

$$\sigma_0 \sim \frac{\xi^4}{M_X^2}$$

$\xi$ is not a gauge coupling within GUT!

- With small $\sigma_0$ one needs entropy production
- $\sigma_0$ may be increased by $s$-channel resonance, $M_Y \approx 2M_X$
- Annihilation can be amplified by co-annihilation channels, $X + A \rightarrow SM$
- With light messengers between Dark and Visible sectors many estimates change, say $\sigma_0 = \sigma_0(\nu)$
- DM interaction at freeze-out and now are not the same
  say, Sommerfield enhancement of the annihilation of slow particles $\nu \sim 10^{-3}$
Constraining the DM model parameter space

Dark matter mass \( m_\chi \) (GeV)

\[10^{-40}, 10^{-39}, 10^{-38}, 10^{-37}, 10^{-36}, 10^{-35} \]

Effective \( \chi^0_1 \)-proton cross-section \( \sigma'_{SD, p} \) (cm²)

\[10^{-45}, 10^{-44}, 10^{-43}, 10^{-42}, 10^{-41}, 10^{-40} \]

MSSM-25 benchmarks
- excluded at >90% CL
- tension (68% – 90% CL)
- allowed

Well-tempered neutralinos

\( \tilde{\tau} \pm \) coannihilation

Area where essentially all MSSM models are excluded by IC79

MSSM models not excluded by IC79

IceCube Collaboration 2016

M.G. Aartsen at al (2016)
Constraining the DM model parameter space

**DM models**

- MSSM: Pure Higgsino
- MSSM: A funnel
- MSSM: Bino-stop coannihilation
- MSSM: Bino-squark coannihilation

**WIMP Mass [GeV/c^2]**

- 1
- 10
- 100
- 1000
- 10^4
- 10^5
- 10^6
- 10^7
- 10^8
- 10^9
- 10^10
- 10^11
- 10^12
- 10^13

**WIMP–nucleon cross section [cm^2]**

- 10^{-39}
- 10^{-38}
- 10^{-37}
- 10^{-36}
- 10^{-35}
- 10^{-34}
- 10^{-33}
- 10^{-32}
- 10^{-31}
- 10^{-30}
- 10^{-29}
- 10^{-28}
- 10^{-27}
- 10^{-26}
- 10^{-25}
- 10^{-24}
- 10^{-23}
- 10^{-22}
- 10^{-21}
- 10^{-20}
- 10^{-19}
- 10^{-18}
- 10^{-17}
- 10^{-16}
- 10^{-15}
- 10^{-14}
- 10^{-13}

**WIMP–nucleon cross section [pb]**

- 10^{-3}
- 10^{-4}
- 10^{-5}
- 10^{-6}
- 10^{-7}
- 10^{-8}
- 10^{-9}
- 10^{-10}
- 10^{-11}
- 10^{-12}
- 10^{-13}

**Data Points and Experiments**

- SuperCDMS Soudan CDMS-lite
- SuperCDMS Soudan Low Threshold
- XENON 10 S2 (2013)
- CDMS-II Ge Low Threshold (2011)
- SIMPLE (2012)
- COUPP (2012)
- ZEPLIN-III (2012)
- CDMS II Ge (2009)
- EDELWEISS (2011)
- SuperCDMS Soudan
- Xenon100 (2012)
- DarkSide 50
- DAMA
- CRESST
- CoGeNT
- SIMPLE (2012)
- LUX
- Xenon1T
- LZ
- CDMS Si (2013)
- COUPP (2012)
- DMS I Ge Low Threshold (2011)
- SuperCDMS Soudan Low Threshold
- SuperCDMS Soudan CDMS-lite
- SuperCDMS Soudan CDMS-lite
- SuperCDMS Soudan Low Threshold
- SuperCDMS Soudan CDMS-lite

**Signatures**

- 8B Neutrinos
- Atmospheric and DSNB Neutrinos

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Minimal, but still testable: scalar Dark Matter

\[ V_S = \frac{1}{2} \mu_S^2 S^2 + \frac{1}{2} \lambda_{hS} S^2 H^* H \]

\[ m_S = \sqrt{\mu_S^2 + \frac{1}{2} \lambda_{hS} v^2} \]

\[ \Omega_S \propto m_S n_S \propto \frac{1}{\sigma_{ann}} \propto \frac{m_S^2}{\lambda_{hS}^2} \]

indirect:

\[ \text{flux}(SS \rightarrow SM) \propto n_S^2 \sigma_{ann} \propto \frac{1}{\lambda_{hS}^2} \]

direct:

\[ \Gamma(SA \rightarrow SA) \propto n_S \sigma_{ann} \propto \frac{1}{m_S} \]

- EW phase transition of I order ?
- EW vacuum stability ?
Constraints on scalar Dark Matter

A.Beniwal et al (2015)

Scalar DM

$\Omega_S/\Omega_{DM} = 1$

$\Omega_S/\Omega_{DM} = 0.1$

$\Omega_S/\Omega_{DM} = 0.01$

$\text{BR}(\Gamma_{h\rightarrow SS}) > 0.05$

$\log_{10}(\lambda h_S) = 0$

$\log_{10}(\lambda h_S) = -1$

$\log_{10}(\lambda h_S) = -2$

$\log_{10}(\lambda h_S) = -3$

$\log_{10}(\lambda h_S) = -4$

Scalar DM

$\Omega_S/\Omega_{DM} = 1$

$\Omega_S/\Omega_{DM} = 0.1$

$\Omega_S/\Omega_{DM} = 0.01$

$\log_{10}(m_S/\text{GeV}) = 45$

$\log_{10}(m_S/\text{GeV}) = 50$

$\log_{10}(m_S/\text{GeV}) = 55$

$\log_{10}(m_S/\text{GeV}) = 60$

$\log_{10}(m_S/\text{GeV}) = 65$

$\log_{10}(m_S/\text{GeV}) = 70$

DM models

LUX (2013)

XENON1T

Future 90% CL (Einasto)

Future 90% CL (NFW, $\gamma = 1.3$)
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

\[ f \neq \bar{f} \quad \text{and} \quad n_f = n_{\bar{f}} \]
CDM Problems at small-scales . . . ?

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r + r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5 - 1.5)}$ cusp
  most DM-dominated objects

Cores observed (?)

5 Clusters in the Fornax dSph
CDM Problems . . . ?

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$
- “Too big to fail” problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming

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Dark Matter: Other well-motivated candidates

Unrelated to the EW scale!

- sterile neutrinos
- light scalar field
- axion
- gravitino
- Heavy relics
- (Topological) defects
- Massive Astrophysical Compact Heavy Objects
- Primordial black hole (remnants)

- active neutrino oscillations
- string theory
- strong CP-problem
- local SUSY
- GUTs
- GUTs
- Phase transitions
- exotic inflation, reheating

Multicomponent Dark Matter?

\[ \gamma, \nu, H, \text{He} \]
Dark Matter properties from astrophysics

1. stable on cosmological time-scale to form ellipsoidal halos
2. (almost) collisionless to be Dark
3. (almost) electrically neutral
4. stability of globular stellar clusters
   \[ M_X \lesssim 10^3 M_\odot \approx 10^{61} \text{ GeV} \]
   otherwise too strong tidal forces
5. confinement in a galaxy: quantum physics!
   de Broglie wavelength:
   \[ \lambda = \frac{2\pi}{(M_X v_X)} < l_{\text{galaxy}}, \]
   in a galaxy \( v_X \sim 0.5 \cdot 10^{-3} \)
   \[ M_X \gtrsim 3 \cdot 10^{-22} \text{ eV} \]
   for bosons
   \[ M_X \gtrsim 750 \text{ eV} \]
   for fermions

Pauli blocking:

\[
f(p, x) = \frac{\rho_X(x)}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{p^2}{2M_X^2 v_X^2}} \bigg|_{p=0} \leq \frac{g_X}{(2\pi)^3}
\]
Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations): gravitino
   sterile neutrino of 1-50 keV
   axion of $10^{-4} \text{–} 10^{-7}$ eV
   Q-balls
   strangelets (?)

2. at phase transitions: classical scalar
   any guy coupled (only) to inflaton

3. during inflation: inflaton decays
   production by external (inflaton) field

4. at reheating (after inflation?):
   - perturbatively:
   - non-perturbatively:

5. while the Universe expands:
   gravity produces any particles at $H \sim M_X$
Dark Matter: Other well-motivated candidates

Unrelated to the EW scale!

- sterile neutrinos
  - sharp line: $\nu_s \rightarrow \nu_a + \gamma$, (XMM, INTEGRAL, ...)
  - caustics in Bose condensate
  - oscillations $a + B \rightarrow \gamma$
  - missing energy at LHC, ...

- light scalar field

- axion

- gravitino

- Heavy relics
  - if unstable: decay into Cosmic rays
  - lensing of CMB

- (Topological) defects

- Massive Astrophysical Compact Heavy Objects
  - microlensing

- Primordial black hole (remnants)
  - Cosmic rays
Axion: Natural but fine-tuned

Theory and Nature:

\[ \Delta \mathcal{L} \propto \theta G_{\mu\nu} G_{\lambda\rho} \varepsilon^{\mu\nu\lambda\rho} \]

\[ \theta < 10^{-9} \]

nonantropic parameter!

\[ \theta \rightarrow \theta + a(x)/f_a \]

\[ m_{\text{axion}} \approx f_\pi m_\pi / f_a \]

\[ \mathcal{L} \propto g_{a\gamma\gamma} \times a(x) F_{\mu\nu} F^{\mu\nu} \]

Dark Matter region

\[ \frac{\Omega_{\text{axion}}}{\Omega_{DM}} = \bar{\theta}_i^2 \cdot \left( \frac{4 \cdot 10^{-6} \text{eV}}{m_{\text{axion}}} \right)^{1.2} \]
Natural: Sterile neutrino Dark Matter

- massive fermions giving mass to active neutrino through mixing
  \[ m_a \sim \theta^2 m_{sn} \]
- unstable, but exceeding the age of the Universe at condition
  \[ \theta^2 < 1.5 \times 10^{-7} \left( \frac{50 \text{ keV}}{m_{sn}} \right)^5 \]
- can be searched for because of two-body radiative decay

![Diagram of two-body radiative decay](image-url)
Sterile neutrino Dark Matter

$\Omega_{\text{sn}} > \Omega_{\text{dm}}$

$\Omega_{\text{sn}} < \Omega_{\text{dm}}$

Non-res. production

$\sin^2(2\theta)$

$m_{\text{sn}} [\text{keV}]$

A. Schneider (2016)
Sterile neutrino Dark Matter...

brown: MW satellite counts

green and yellow: Lyman-α

A. Schneider (2016)
Free massive scalar field

\[ \mathcal{L} = \frac{1}{2} g^{\mu \nu} \partial_\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 \]

For the homogeneous scalar field in FLRW expanding Universe

\[ \ddot{\phi} + 3H \dot{\phi} + m_\phi^2 \phi = 0 \]

we find two-stage evolution:

- \( m_\phi < H(t) \quad \Rightarrow \quad \phi = \phi_i = \text{const} \)
- \( m_\phi > H(t) \quad \Rightarrow \quad \rho = \langle E_k \rangle - \langle E_\rho \rangle = 0, \quad \rho \sim m_\phi^2 \phi_i^2 \propto 1/a^3 \)

- dust-like substance in the late Universe, \( \Omega \propto m_\phi^{1/2} \phi_i^2 \) depends on initial conditions
- pressureless at spatial scales \( l > 1/m_\phi \) fuzzy DM
- may help (?) with CDM-problems (core-cusp, lack of dwarfs, etc)
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
  - Many models are untestable

**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** ($R \rightarrow R - R^2/6\mu^2$) may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

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

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


**Untestable**
Observation: why $\rho_B \sim \rho_{DM}$ ?

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
Searching for messenger $X_a$

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

- If light the best place is a fixed target, e.g. SHiP
- If heavy, the best place is LHC

At LHC the same WIMP-like signature

monojet + missing $P_T$

$$d + d \rightarrow \bar{u} + X, \quad d + u \rightarrow \bar{d} + X$$
Other channels for LHC

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

All options must be probed

\[-L_{\text{int}} = \frac{\lambda_a}{M^2} \bar{X}_a d_R \bar{u}^C d_R\]

\[d = d, s, b\]

\[u = u, c, t\]

\[d + d \rightarrow \bar{t} + X\]

- Searches for \( X \rightarrow dd\bar{u} \)

**Signatures:**

- jet + 3 jets [forming a particle (invariant mass \( m_{jjj}^2 \))]
- jet + 2 jets + b-jet [\ldots]
- jet + 2 jets + \( \bar{t} \)-quark [\ldots]
- b-jet + \ldots
- \( \bar{t} \)-quark + \ldots

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

- We have many Dark Matter models
- Several (and well-motivated, like WIMPs) will be explored at present (e.g. LHC) and forthcoming (e.g. CTA) experiments
- But more model will be invented
- Dark Matter may be multicomponent
- It would be helpful to get more hints from cosmology

DM discovery in a particle physics experiment is not guaranteed!! But no reasons to give up either