Self-interacting dark matter with a stable scalar mediator

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Dark matter – motivation

Convincing evidence on various astrophysical and cosmological scales

leading hypothesis → new, unknown particle
Weakly-interacting massive particle (WIMP)

Properties of dark matter:
- electrically neutral (non-luminous)
- stable or long-lived
- weakly interacting with ordinary matter  ✔
  - production mechanisms
  - experimental probes
- collisionless or self-interacting?

DM chemical decoupling

\[ n_{EQ} \langle \sigma v_{rel} \rangle \sim H(x) \]
Small scale structure problems

- core-cusp problem
- missing satellite problem
- diversity problem
Possible solutions:
- observational problems → no real problem
- baryonic feedback processes (star formation, supernovae, ...)
- new DM properties (self-interactions)

Self-interactions thermalize inner part of halo and reduce central DM density

\[ R_{\text{scat}} = \sigma v \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \approx 0.1 \text{Gyr}^{-1} \times \left( \frac{\rho_{\text{DM}}}{0.1 \text{ M}_{\odot} \text{pc}^{-3}} \right) \left( \frac{v}{50 \text{ km/s}} \right) \left( \frac{\sigma}{m_{\text{DM}}} \right) \]
Self-interacting dark matter (SIDM)

Velocity dependent self-scattering cross-section is preferred by data

\[
\frac{\sigma}{m} \approx \begin{cases} 
2 \text{ cm}^2/\text{g} & v \sim 50 \text{ km/s} \text{ (dwarf galaxies)} \\
0.1 \text{ cm}^2/\text{g} & v \sim 1500 \text{ km/s} \text{ (clusters)}
\end{cases}
\]

Nuclear size cross-section → much stronger than the weak scale cross-section

\[
0.1 \frac{\text{cm}^2}{\text{g}} \lesssim \frac{\sigma_{\text{self}}}{M_{DM}} \lesssim 2 \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \gg \frac{\text{pb}}{\text{GeV}}
\]

Bullet cluster bound

\[
\frac{\sigma}{m} < 1.25 \text{ cm}^2/\text{g} \text{ (68\% CL)}
\]
SIDM from light mediator

DM (GeV – TeV mass) + light mediator (1 – 100 MeV) + weak coupling

Cross-section \( \propto g^4 \frac{m_{DM}^2}{m_{med}^4} \)

Velocity dependence:

- hard-sphere like scattering (constant cross-section)
  \[ m_{med} \gg m_{DM}v_{rel} \]
- Rutherford-like scattering \( (1/v^4) \)
  \[ m_{med} \ll m_{DM}v_{rel} \]

Enhanced further by non-perturbative effects

\[ \alpha g m_{DM}/m_{med} > 1 \]

\[ V = \frac{\alpha g}{r} e^{-m_{med}r} \]

Alternative scenarios: strongly-interacting DM (QCD-like theory, dark hadrons, dark nuclei), massless mediators (dark atoms, DM with dark radiation), heavy mediator in a Breit-Wigner resonance

\( MD+ 2017, Chu+ 2018, 2019 \)
Self-interacting DM with a stable scalar mediator

SIDM from light mediator - bounds

Generically present indirect detection bounds on 1-step cascade DM annihilation

Large Sommerfeld enhancement possible

\[(\sigma v)_{\text{CMB}} \gg 2 \times 10^{-26} \text{cm}^3/\text{s}\]

Bringmann+ 2016
Self-interacting DM with a stable scalar mediator

**SIDM from light mediator – bounds**

- **s-wave DM annihilation cross-section**
  - excluded by the Planck constraint on DM annihilation rate at recombination

- **p-wave annihilation**
  - nearly excluded by the combination of direct detection and BBN bounds

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**vector mediator**

**scalar mediator**

Bringmann+ 2016

Hufnagel+ 2018
How to evade constraints?

• mediator decaying into sterile neutrinos
  \(Aarsen+ 2012, Bringmann+ 2014\)

• mixed scalar/pseudoscalar couplings with CP violation
  \(Kahlhoefer+ 2017\)

• non-thermal DM production (eg. by freeze-in mechanism)
  \(Bernal+ 2015, MD+ 2017\)

• DM mass splitting (inelastic scattering)
  \(Blennow+ 2016, MD+ 2017\)

• stable mediator
  \(Ma+ 2017, MD+ 2017, Duerr+ 2018, MD+2019\)
Fermionic DM with stable scalar mediator

SM extension:

- Dirac fermion $\chi$ with GeV mass that is dominant DM component
- light scalar mediator $S$ (1-100 MeV)

Both stable due to the symmetry

$$\chi \rightarrow i\chi, \quad S \rightarrow -S$$

$$V_{\chi S} = m_\chi \bar{\chi}\chi + \frac{g_Y}{2} S(\bar{\chi}^c \chi + \bar{\chi}\chi^c)$$

Extra light scalar $h_2$ (dark Higgs) required to allow for effective annihilation of subdominant DM component

$$m_{h_2} < m_S$$
BBN bounds

Extra light states may modify the successful predictions of BBN

- Hubble rate increase
- Entropy production from light state decays and modification of baryon-to-photon ratio
- Photodisintegration of deuterium

\[ m_{h_2} > E_{\text{dis}} = 2.2 \text{MeV} \]

Density of \( S \) and \( h_2 \) with respect to photons may be substantially suppressed, when the dark sector decouples before QCD phase transition

Lifetime of \( h_2 \) should be below 10s → problem for the stable vector mediator scenario

Hufnagel+ 2018

Duerr+ 2018
Indirect detection

- Conversion
  - $S$ is stable → no visible indirect detection signal

- Semi-annihilation
  - $p$-wave cross-section → highly suppressed by the small velocity of annihilating DM
  - Visible signal from the dark Higgs decay

\[ \frac{1}{2} \langle \sigma v \rangle_{\chi S \rightarrow \bar{\chi} h_2} \left( \frac{\Omega_S h^2}{\Omega_{DM} h^2} \right) \left( \frac{\Omega_{\chi} h^2}{\Omega_{DM} h^2} \right) < \langle \sigma v_{\text{rel}} \rangle_{\text{CMB}}^{4e^\pm}(m_S) \]

\[ \langle \sigma v \rangle_{S S \rightarrow h_2 h_2} \left( \frac{\Omega_S h^2}{\Omega_{DM} h^2} \right)^2 < \langle \sigma v_{\text{rel}} \rangle_{\text{CMB}}^{4e^\pm}(m_S) \]
Relic abundance

Two-component DM scenario

Various processes relevant in the determination of relic abundance

- annihilation,
- semi-annihilation,
- conversion

Dark sector decoupling before QCD phase transition $\rightarrow$ dark freeze-out

$$\xi(T) \equiv \frac{T_D(T)}{T} = \left( \frac{g_{*S}(T)}{g_{*S}(T_{dec})} \frac{g_{*S}(T_{dec})}{g_{*S}(T_D)} \right)^{1/3}$$

$$T \quad m_\chi/20 \quad T_{\text{dec}} \quad h_2 \leftrightarrow SM \quad m_S/(20\xi)$$

QCD PT (~200 MeV)
Self-interacting DM with a stable scalar mediator

Convenient basis to analyze DM self-interactions

\[ \chi_+ = \frac{1}{\sqrt{2}}(\chi + \chi^c), \quad \chi_- = \frac{i}{\sqrt{2}}(\chi - \chi^c) \]

Two Majorana states

\[ \chi_+ \] and \( \chi_- \) scatterings are attractive

\[ V_a = -\frac{g^2}{4\pi r} e^{-m_{sr}r} \]

\[ \chi_+ \chi_- \] scatterings are repulsive

\[ V_r = +\frac{g^2}{4\pi r} e^{-m_{sr}r} \]

Cross section obtained from the numerical solution of Schroedinger equation with Yukawa potential

\[ \frac{d\sigma}{d\Omega} \propto |f(\theta)|^2 \]

Proper averaging

\[ \sigma_T \equiv \frac{1}{4} (\sigma_T^{++} + \sigma_T^{--} + \sigma_T^{+-} + \sigma_T^{+-}) = \frac{1}{2} (\sigma_T^0 + \sigma_T^r) \]

Zurek+ 2013

Kahlhoefer+ 2017
CMB bounds in the parameter space

Bounds on the p-wave DM annihilation are absent, but DM semi-annihilation and mediator annihilations are constrained by CMB

Regions of larger $h_2$ and $S$ coupling are allowed

Self-interacting DM with a stable scalar mediator

Mateusz Duch
Allowed regions in the parameter space

Viable regions with the desired value of the self-scattering DM cross-section
Conclusions

- self-interacting dark matter (SIDM) provides a possible solution to small scale structure problems
- strong DM self-interactions may naturally arise when light mediator is present, but simple scenarios are strongly constrained by indirect, direct detection, CMB or BBN
- model with stable scalar mediator evades existing CMB and BBN bounds