Light Mediator and Dark Matter Bound States: models and signatures

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M.B.Wise, Y.Z., 1407.4121
M.B.Wise, Y.Z., 1411.1772
Y.Z., 1502.06983
Discovery of a boson

• LHC found a spin-0 particle with mass 125-126 GeV.

• Look like SM Higgs boson.

Milestone in particle physics
Dark Matter

• Compelling evidence for its existence.
• DM contributes 23% of the total energy budget.

• Cosmologically long lived.
• Non-relativistic.
• (less than) weakly interacting.

Particle physics Standard Model contains no DM candidate.
Searches for dark matter

Direct detections

Colliders

Indirect detections

Probe beyond gravitational effects
Theories of dark matter

complexity

SUSY

- solves hierarchy problem
- natural DM candidate
- renormalizable

Simple models

- have their own motivations
- still renormalizable
- enough to offers rich physics

Effective operators

- pure phenomenological approach
- higher dimensional operators

We haven’t discovered dark matter yet, be open minded.
DM models with a mediator

Dark Sector

\[ \mathcal{L}_D = \begin{cases} 
  g_X \bar{\chi} \chi \phi \\
  g_X \bar{\chi} \gamma^\mu \chi V_\mu 
\end{cases} \]

dark matter: \( \chi \) light mediator: \( \phi \) or \( V_\mu \) (SM singlets)

Light mediator as the portal to SM sector

\[ \mathcal{L}_{\text{portal}} = \begin{cases} 
  (\mu_{ph} \phi + \lambda_{ph} \phi^2) H^\dagger H \\
  \varepsilon F_{\mu\nu} V^{\mu\nu}
\end{cases} \]

mediator to SM decay rate controlled by an independent parameter
Motivations

Various reasons for considering such a setup

- Higgs portal to fermion DM is well motivated, the only discovered fundamental scalar in nature.

- Give correct relic density to very light DM.

- Secluded dark matter scenario.

  Pospelov, Ritz, Voloshin, arXiv:0711.4866

- Velocity dependent DM annihilation, Sommerfeld effect in indirect detection signals.


- Velocity dependent DM elastic scattering.
Light mediator scenario

Light mediator:  $m_\chi \gg m_\phi$

DM relic density controlled by dark interactions

The WIMP miracle: initial condition  $n_X = n_X^\dagger$

$\Omega_X \simeq 0.23 \left( \frac{1 \text{ pb}}{\langle \sigma v \rangle} \right)$

$z = \frac{m_X}{T}$

$Y = \frac{n}{s}$

$Y_X = Y_X^\dagger$
Light mediator scenario

Light mediator: $m_\chi \gg m_\phi$

DM relic density controlled by dark interactions

Asymmetric dark matter: $n_\chi = n_{\chi^+} + \Delta$

For $\langle \sigma v \rangle \gg 1 \text{ pb}$

$\Omega_\chi$ determined by $\Delta$
Decay of the mediator

After DM annihilation, mediator has to decay before BBN.

- If mediator is as populated as photons & has mass > MeV.

In the simple model discussed here,

- mediator decays into SM particles.

If Higgs portal, mainly decay into heaviest possible particle.

large enough \( g_\chi \) decay before BBN

lower bounds on direct detection, etc.
Constraints on scalar case

(B) $m_\chi = 100 \text{GeV}$

- LUX exclusion
- $\alpha_\chi = 0.1$
- BBN exclusion

$\mu_{\phi}\delta m^2 \hspace{1cm} m_\phi (\text{GeV})$

$10^{-11} \hspace{1cm} 10^{-9} \hspace{1cm} 10^{-7}$
Constraints on scalar case

(D) $m_\chi = 2\text{GeV}$

$K^+ \rightarrow \pi^+ + \text{invisible}$

BBN exclusion

$\frac{\mu_\phi \phi V}{m_h^2}$ vs. $m_\phi \text{ (GeV)}$
Two aspects will be discussed:

- Dark matter bound states via scalar light mediator.
- What if the light mediator temporarily dominates the energy of the universe.

if $m_\phi$ small enough

DM could form bound states
Dark matter bound states

The visible sector has many bound states — rich dynamics due to the Standard Model structure.

Natural to examine this idea in dark sector — even in simple models — we find dark matter bound states already exist.

Simple model can have rich dynamics:

\[ \frac{1}{\alpha \chi m_\chi} \lesssim \frac{1}{m_\phi} \]

Bohr radius < screening length

Stable bound states

Bound state can exist in very wide parameter space

$(\chi \bar{\chi})$ unstable.

$(\chi \chi)$ cosmologically stable.

mostly formed if only $\chi$ is around

Main difference from dark $U(1)$ case:

$\chi \chi$ attractive for scalar exchange
repulsive for vector exchange

Do NOT need two species of asymmetric DM

Production in early universe

Bound state formation can happen

- shortly after freeze out if an asymmetry in $\chi$ number is left over.

More bound states may also form during the non-linear structure growth.

form with thermal kinetic energy

cannot form in early universe

but could with high local densities, — observable signatures today,

in neutron stars/galactic center

Wise, Y.Z., arXiv:1407.4121, PRD, and in progress
$N$-particle Bound states

Interaction through scalar exchange always attractive.

Explore properties of states with $N >> 2$ (nuggets).

We consider a degenerate Fermi gas picture

Treat $\chi$ particles inside nugget as classical point sources

Effective classical Lagrangian

$$L = - \sum_i (m_\chi + g\phi(x_i)) \sqrt{1 - \dot{x}_i^2} - \frac{1}{2} \int d^3x \nabla \phi \nabla \phi$$

Wise, Y.Z., arxiv:1411.1772
Hydrostatic equilibrium

Forces acting on a χ particle inside nugget

- Attraction due to φ exchange
- Repulsion due to degeneracy pressure.

Hydrostatic equation for \( p_F(r) \)

\[
\left( \frac{r^2}{3\pi^2} \right) p'_F(r) \frac{p_F(r)^4}{\sqrt{m(r)^2 + p_F(r)^2}} = -\frac{g\chi}{\pi^2} \nabla^2 \phi(r) \int_0^r dr' r'^2 m(r')^3 i(p_F(r')/m(r'))
\]

coupled to the Laplacian equation for \( \phi \) field.

\[
\nabla^2 \phi(x) = g\chi \sum_i \delta^3(x - x_i) \frac{m(x_i)}{\sqrt{p_i^2 + m(x_i)^2}}
\]

Wise, Y.Z., arxiv:1411.1772
Generic features

In practice we take ansatz of $p_F(r)$ and minimize the total energy wrt the radius $R$.

Interesting behaviors of $N$ dependence in $R$:

When $N < \alpha_\chi^{-3/2}$, non-relativistic regime

$\Rightarrow R \sim \frac{1}{\alpha_\chi m_\chi N^{1/3}}$

(similar to degenerate star)

Yukawa force gets weaker when relativistic

$\bar{\chi}\chi\phi \sim \frac{m}{E} \chi^\dagger \chi\phi$

$\Rightarrow R \sim \frac{\alpha_\chi N}{m_\chi}$

Wise, Y.Z., arxiv:1411.1772
Nugget properties

$m_\chi=100$ GeV, $\alpha_\chi=0.1$

cut off by $1/m_\phi$

very heavy bound states allowed

Example of supermassive DM with thermal freeze out history.

General behavior of bound states from Yukawa theory -- may have applications other than dark matter.

Wise, Y.Z., arxiv:1411.1772
DM phenomenology

Direct detection:

\[ \sigma v \sim \left[ N_{xe} F_{xe}(q^2) \right] \left[ N_x F_{Nugget}(q^2) \right] \]

1 for usual elementary DM

Indirect detection of cosmic rays:

\[ \phi \rightarrow \pi^+ \pi^- \rightarrow \nu's \]
\[ \rightarrow \mu^+ \mu^-, \ldots \]

Dark nucleosynthesis: warm DM candidate.

Wise, Y.Z., arxiv:1411.1772
Two aspects I want to discuss

- Dark matter bound states via scalar light mediator.
- What if the light mediator temporarily dominates the energy of the universe.

if $\mu_{\phi h}/m_h^2 \lesssim 10^{-7}$

two sectors never in equilibrium
Energy density evolutions

$$m_\phi = 10 \text{GeV}, \tau_\phi = 1 \text{sec}, \xi = 1$$

Entropy production, $S \approx 60$ (assuming $T_D/T = 1$)

Need to overproduce DM from freeze out by this factor.

Y.Z., arxiv:1502.06983
Primordial perturbations

Comoving Scales

horizon exit

horizon re-entry

Comoving Horizon
density fluctuation

temporary matter domination

Inflation

Hot Big Bang

Time [\log(a)]

D.Baumann, TASI 2009 Lecture
Evolution of perturbations

Impact on dark matter density perturbation

- Radiation domination: logarithmically growth
- Matter domination: linear growth

Affects all modes entering horizon before/during MD.

$A = \frac{m_\phi}{10\text{GeV}}, \tau_\phi = 1\text{sec}, \xi = 1$

Y.Z., arxiv:1502.06983
Collisional damping effects

\( \phi \) turns into matter only at \( T \ll m_\phi \)

In the beginning, \( \phi \) is still relativistic, and tightly couples to dark matter \( \chi \),

\[
\sigma_{\chi\phi} = \frac{4\pi\alpha^2_\chi}{3m^2_\chi}
\]

The \( \chi - \phi \) plasma had a large sound speed,

\[
c^2_s \sim T/m_\phi
\]

**Dark sector acoustic oscillation** — Suppresses all modes that enters the horizon very early.

**Until matter light mediator domination era begins.**

Y.Z., arxiv:1502.06983
A peak in transfer function

In the end will give a peak in the DM power spectrum

Peak: population of structures at this scale will be enhanced.

Properties of the mini halo:

$R \sim 10^{-4} \text{ pc}(\sim \text{solar system size})$

$M \sim M_\oplus(\sim \text{earthmass})$

$\Rightarrow 10^9 \text{ of local DM density}$

If these mini halos takes $O(1)$ fraction of Milky Way mass:

encounter one every $\sim 50 \text{ years}$

Y.Z., arxiv:1502.06983
Summarize the scales

Mini halos discussed here

- Small scale structure
  - ~10^{-4} pc
  - 0.1-10 kpc

Large scale structure

- 1-100 Mpc
- Length

Simple DM model can have rich dynamics in both particle physics and cosmology.

Will be interesting to look at the overlap of two regimes.

Y.Z., arxiv:1502.06983
Conclusion

- It is worth exploring simple dark matter models.
- In this talk I discussed a class of models with a light mediator connected to the SM sector.
  - DM bound states properties and its particle cosmology.
  - Light mediator dominated universe offers new structures.
- Opens plenty of new possibilities, and experimentally testable effects.
- This is an exciting direction.

Thank you!
Backup slides
Vector mediator case

direct detection constraint on weak scale dark matter