Models for SIMP dark matter and dark photon

Hyun Min Lee
(Chung-Ang University)

Ref. HML, M.-S. Seo, 1504.00745 [hep-ph]

Particle Physics and Cosmology 2015
Dakota State University, USA
June 30, 2015
**WIMP paradigm**

- WIMP DM density depends on $2 \rightarrow 2$ annihilation processes with weak interactions.

**WIMP freeze-out:**

$$\Gamma_{\text{ann}} = n_{\text{DM}} \langle \sigma v \rangle_{\text{ann}} \sim H = 0.33g_{*}^{1/2} \frac{T_{F}^{2}}{M_{P}}$$

$$\rho_{\text{DM}} = 5.4m_{p}\eta_{p} s, \quad T_{\text{eq}} = 10m_{p}\eta_{p};$$

$$n_{\text{DM}} = \frac{\kappa T_{\text{eq}} T_{F}^{3}}{m_{\text{DM}}}, \quad \kappa \simeq 0.54 \cdot \frac{2\pi^{2}}{45} g_{*s} \simeq 10.8.$$  

$$m_{\text{DM}} = \alpha_{\text{eff}} \left( \frac{5.35\kappa}{x_{F}g_{*}} \frac{T_{\text{eq}}M_{P}}{T_{F}^{1/2}} \right)^{1/2}$$

$$\alpha_{\text{eff}} \sim 0.1 \quad \Rightarrow \quad m_{\text{DM}} \sim 100 \text{ GeV}.$$
DM self-interactions

- DM self-interactions could make a separation of colliding DM subhalos from bounded stars.

**Long-range forces: “drag force”**
- DM subhalo lags behind stars.

**Contact interactions:**
- Large momentum transfer
  - Peak is not shifted but DM particles evaporate in backward direction.

**Bullet cluster:** no separation of DM subhalo

$\frac{\sigma_{\text{self}}}{m_{\text{DM}}} < 1 \text{cm}^2/g$ (about neutron cross section)

**WIMP DM:**

$\frac{\sigma_{\text{self}}}{m_{\text{WIMP}}} \sim 10^{-11} \text{GeV}^{-3} \sim 10^{-14} \text{cm}^2/g$. 
Abell 3827

- For four colliding galaxies (not clusters) observed by Hubble Telescope, one of subhalo lags behind the galaxy.

DM subhalo separation:
\[ \Delta = 1.62^{+0.47}_{-0.49} \text{ kpc} \]

[Massey et al (2015)]

Required DM self-interaction in tension with Buller cluster.

[Kahlhoefer et al (2015)]
**SIMP paradigm**

- Strong Interacting Massive Particle (SIMP) is a thermal DM, changing its number due to $3 \rightarrow 2$ self-annihilation.

\[ h v^2 \]

Freeze-out:

\[ \Gamma_{3 \rightarrow 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3 \rightarrow 2} \sim H(T_F) \]

\[ \langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{\alpha_{eff}^3}{m_{DM}^5} \]

\[ m_{DM} = \alpha_{eff} \left( \frac{5.35 \kappa^2}{x_F^4 g_*^{1/2} T_{eq}^2 M_P} \right)^{1/3} \]

\[ \kappa \approx 2.55 \]

or

\[ \Omega_{DM} = 0.3 \left( \frac{3 \times 10^{-26} \text{cm}^3/\text{s}}{n_{DM} \langle \sigma v^2 \rangle} \right) \]

\[ \alpha_{eff} = 1 - 30 \]

\[ m_{DM} \sim 10 \text{MeV} - 1 \text{GeV} \]
Large SIMP self-interaction

• SIMP DM predicts large DM self-interactions.

$\alpha_{\text{eff}} \sim 1$

Large DM self-interactions

Constrained by Bullet cluster and spherical halo shapes.
**SIMP conditions**

- SIMP should be in kinetic equilibrium until freeze-out.

\[
\langle \sigma v \rangle_{\text{kin}} = \frac{\epsilon_1^2}{m_{\text{DM}}^2};
\]

\[
n_{\text{SM}} \langle \sigma v \rangle_{\text{kin}} > H(T_F)
\]

\[
\epsilon_1 \gtrsim 0.9 \times 10^{-9} \alpha_{\text{eff}}^{1/2}
\]

- Resulting 2→2 DM annihilation is subdominant only if

\[
\langle \sigma v \rangle_{\text{ann}} = \frac{\epsilon_2^2}{m_{\text{DM}}^2};
\]

\[
n_{\text{SM}} \langle \sigma v \rangle_{\text{kin}} < n_{\text{DM}} \langle \sigma v^2 \rangle_{3\rightarrow2}
\]

\[
\epsilon_1 \lesssim 2.4 \times 10^{-6} \alpha_{\text{eff}}
\]

\[
\epsilon_2 \sim \epsilon_1
\]
DM messengers

“Messenger”
A new force
Hidden QCD with WZW term

- Dark flavor symmetry $G=SU(N_f) \times SU(N_f)$ is broken down to $H=SU(N_f)$ by $SU(N_c)$ QCD-like condensation.

- Effective action for Goldstone bosons contains a 5-point self-interaction from Wess-Zumino-Witten term for $\pi_5(G/H)=\mathbb{Z}$ (i.e. $N_f \geq 3$). [Wess, Zumino, 1971; Witten, 1983]

$$U = e^{2i\pi/F}, \quad \pi \equiv \pi^a T^a$$

$$L_{WZW} = \frac{2N_c}{15\pi^2} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi]$$

- Flavor symmetry ensures stability of dark mesons as natural candidates for SIMP.

$N_f = 3: \pi = \frac{\sqrt{2}}{F} \left[ \begin{array}{ccc} \frac{1}{\sqrt{2}} \tilde{\pi}_0 + \frac{1}{\sqrt{6}} \tilde{\eta}^0 & \tilde{\pi}^+ & \tilde{K}^+ \\ \tilde{\pi}^- & -\frac{1}{\sqrt{2}} \tilde{\pi}_0 + \frac{1}{\sqrt{6}} \tilde{\eta}^0 & \tilde{K}^0 \\ \tilde{K}^- & \tilde{K}^0 & -\sqrt{\frac{2}{3}} \tilde{\eta}^0 \end{array} \right].$
SIMP dark mesons

- “Large color group” leads to strong 5-point interactions while satisfying bounds on self-interactions.

\[ \tilde{\pi}^+, \tilde{\pi}^0, \tilde{\pi}^- \]

\[ \tilde{\pi}^0 \rightarrow \tilde{\pi}^0, \tilde{\pi}^0 \rightarrow \tilde{\pi}^0 \]

\[ \langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{5\sqrt{5}N_c^2m_\pi^5}{2\pi^5F^{10}} \left( \frac{t^2}{N_\pi^3} \right)^2 \left( \frac{T_F}{m_\pi} \right)^2 \]

\[ \sigma_{\text{self}} = \frac{m_\pi^2}{32\pi F^4} \left( \frac{\alpha^2}{N_\pi^2} \right)^2 \sim \text{const} \]

\[ \begin{array}{|c|c|c|c|c|}
\hline
G_c & G_f/H & N_\pi & t^2 & N_f^2a^2 \\
\hline
SU(N_c) & SU(N_f) \times SU(N_f) & N_f^2 - 1 & \frac{4}{3}N_f(N_f^2 - 1)(N_f^2 - 4) & 8(N_f - 1)(N_f + 1)(3N_f^4 - 2N_f^2 + 6) \\
SO(N_c) & SU(N_f)/SO(N_f) & \frac{1}{2}(N_f + 2)(N_f - 1) & \frac{1}{12}N_f(N_f^2 - 1)(N_f^2 - 4) & (N_f - 1)(N_f + 2)(3N_f^4 + 7N_f^3 - 2N_f^2 - 12N_f + 24) \\
Sp(N_c) & SU(2N_f)/Sp(2N_f) & (2N_f + 1)(N_f - 1) & \frac{2}{3}N_f(N_f^2 - 1)(4N_f^2 - 1) & 4(N_f - 1)(2N_f + 1)(6N_f^4 - 7N_f^3 - N_f^2 + 3N_f + 3) \\
\hline
\end{array} \]

[Hochberg et al, 2014]
SIMP parameter space

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727]

Bullet cluster, Halo shape

\[
\sigma_{\text{self}}/m_{\text{DM}} < 1 \text{ cm}^2/\text{g}
\]

\[
m_\pi/f_\pi < 2\pi
\]

\(N_c > 3\) is required due to bounds on self-scattering.

Similar results for SU\((N_f)/\text{SO}(N_f)\) or SU\((2N_f)/\text{Sp}(2N_f)\).
Dark $Z'$ and WZW

[Witten, 1983]

- Dark quarks are vector-like under local dark, broken $U(1)$.
- WZW is modified with the local $U(1)$.

\[ S = S_0(D_\mu U, D_\mu U^{-1}) + S_{\text{WZW}}(U, U^{-1}) - eN_c \int d^4x A'_\mu J^\mu \]
\[ + \frac{ie^2N_c}{24\pi^2} \int d^4x \epsilon^{\mu\nu\rho\sigma} \partial_\mu A'^\nu A'_\rho \text{Tr}[Q^2 \partial_\sigma U U^{-1}] \]
\[ + Q^2 U^{-1} \partial_\sigma U + Q U Q U^{-1} \partial_\sigma U U^{-1}], \]

- AVV anomalies.
- AAAAV anomalies.
Dark charges

- Stability of dark neutral mesons requires the cancellation of AVV anomalies.

\[ \pi^a \rightarrow \text{flavor non-universal charges} \]

\[ Q_D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \]

\[ D_\mu U = \partial_\mu U + ig_D [Q_D, U] Z'_\mu; \quad \tilde{\pi}^\pm, \tilde{K}^\pm : \pm 2 \text{ charges.} \]

But, AAAV anomalies do not cancel, so they could lead to \( \pi \pi \rightarrow \pi \pi Z' \).
Violation of flavor symmetry

- Flavor symmetry is broken by flavor non-universal U(1) charges as in QCD.

- Mass splitting between dark mesons less than 10%.

\[ \mathcal{L}_{\text{mass}} = -\frac{1}{2} \Lambda^3 \text{Tr}[M_q(U + U^{-1})] - c \alpha_D \Lambda^4 \text{Tr}[QUQU^{-1}] \]

\[ \Delta m^2_\pi \sim \frac{\alpha_D \Lambda^4}{F^2} \sim \alpha_D F^2 \lesssim 0.01 m^2_\pi. \]

- Higher dimensional operator could induce the decay of dark mesons:

\[ \mathcal{L}_{\text{hdo}} = \frac{1}{M^2} (\bar{q}\gamma_\mu \gamma^5 T^a \tilde{q}) (\bar{l}\gamma^\mu l) \sim \frac{F}{M^2} \partial_\mu \pi^a (\bar{l}\gamma^\mu l) \]

\[ \Gamma_\pi \approx \frac{F^2 m_\pi m^2_l}{8\pi M^4}, \quad \text{DM stability: } M > 10^9 \text{ GeV.} \]
Dark mesons & Z’-portal

- Dark meson can be in kinetic equilibrium with the SM particles via Z’-Z kinetic mixing.

\[ L_{\text{mix}} = -\frac{\varepsilon}{2\cos\theta_W} F_{\mu\nu}' F_{\mu\nu} \]

\[ \langle \sigma v \rangle_{\text{kin}} \approx \frac{768\alpha_D\varepsilon^2}{\pi N_\pi} \left( \frac{m_\pi^2}{m_{Z'}^4} \right) \left( \frac{T_F}{m_\pi} \right). \]

cf. Higgs-portal does not work, due to small lepton Yukawa couplings.

- \( \pi \pi \rightarrow Z'Z' \) (\( \pi Z' \)) are kinematically forbidden for \( m_{Z'} > m_\pi \).

\[ \text{Keep } 3 \rightarrow 2 \text{ annihilation process dominant.} \]
Bounds on $Z'$

- **SIMP conditions** are complementary in constraining $Z'$ parameters to direct $Z'$ searches.

\[ D = \frac{g_D^2}{4\pi} = 0.01 \]

- \( e^+e^- \rightarrow \gamma Z' \rightarrow \gamma (l^+l^-) \), \( e^+e^- \rightarrow \gamma + \text{MET} \) (BaBar),
- \( h \rightarrow ZZ' \) (CMS 8TeV), Drell-Yan, dileptons.

---

15년 6월 28일 일요일
Direct detection

- SIMP mesons can scatter off nucleon/electron, leading to small recoil energy:

\[ E = \frac{q^2}{2m_{e,N}} \sim 1 - 100 \text{ eV}. \]

\[ (q = \mu v_{DM}, \mu = m_{e,N}m_\chi/(m_{e,N} + m_\chi)). \]

Superconducting detectors? [Hochberg et al (2015)]

\[ \sigma_{DD} = \frac{\varepsilon^2 e^2 g_D^2 \mu^2}{\pi m_{Z^t}^4}, \]

\[ m_{e,m_\chi,m_{Z^t}} \gg p \approx m_\chi v_{DM} \]

\[ \text{independent of SIMP mass.} \]

**XENON10:**

\[ \sigma_{DD} < 2 \times 10^{-36} \text{ cm}^2 \]

at best around \( m_\chi = 30 \text{ MeV} \).
Conclusions

• SIMP paradigm leads to testable scenarios for sub-GeV thermal dark matter, via DM self-interactions and messenger particles.

• Z’ portal makes SIMP dark mesons in kinetic equilibrium and maintains the DM stability for appropriate U(1) charges of dark quarks.

• Parameter space satisfying SIMP conditions can be searched for by various Z’ searches.