

Mechanism of kinetic Equilibrium between SIMP and Radiation

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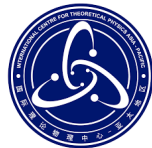
University of Chinese Academy of Sciences

1. Motivation

2. SIMP

3. Kinetic equilibrium Mechanism

4. Summary



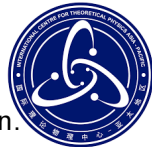
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CDM at small-scales?

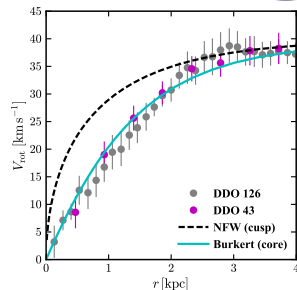


- ▶ CDM works remarkably well on large scales, but small-scale puzzles remain.

▶ Cusp-core problem

- ▶ Λ CDM simulation predicts DM density to grow towards centre of halos.
- ▶ Measured rotation curves of low-mass DM dominated galaxies prefer constant density cores.

(Moore 1994, Burkert 1995, Oh 2015)



Possible explanations?

1. Systematic uncertainties
2. Baryonic effects (by bursty star formation)
If galaxies form enough stars, there will be enough supernovae energy to redistribute dark matter and create significant cores.
3. Self-interacting dark matter (SIDM)

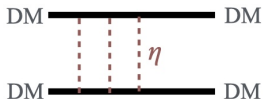
Self Interacting Dark Matter (SIDM)



- Strong DM self-interactions redistribute energy, momentum, and angular momentum, causing dark matter particles to move outward from dense central regions, leading to a core density profile.

(D. N. Spergel, P. J. Steinhardt 1999)

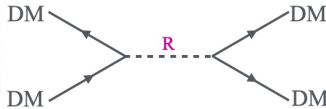
SIDM via a light mediator



[D.N. Spergel & P. J. Steinhardt 1999, J. Feng, M. Kaplinghat & H.-B. Yu 2009, ...]

t-channel elastic scattering
light mediator enhances cross sections

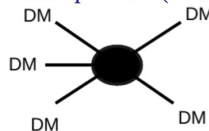
SIDM via Breit-Wigner resonance



[M. Ibe & H.-B. Yu 2009, E. Braaten & E.W.Hammer 2013, X. Chu, C. Garcia-Cely, H. Murayama 2018, ...]

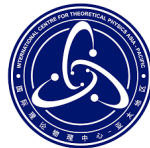
s-channel enhancement
velocity dependence

$N \rightarrow 2$ strongly interacting massive particles (SIMP)



[E. Carlson, M. Machacek & L. Hall, 1992, A. de Laix, R. Scherrer & R. Schaefer 1995, Hochberg, Kuflik, Volansky & Wacker 2014, ...]

kinetic equilibrium with radiation
relic abundance requires strong interaction.



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Strongly Interacting Matter Particles (SIMP)



- ▶ DM masses in the sub-GeV range.
- ▶ DM relic abundance is regulated by $N \rightarrow 2$ self-interactions.
- ▶ $2N_f$ Weyl fermions q_i , which in massless limit exhibits a global $SU(2N_f)$ flavor symmetry. $SU(2N_f)$ is broken into $Sp(2N_f)$ by chiral condensate,

$$\langle q_i q_j \rangle = \mu^3 J_{ij}, \quad J = \begin{bmatrix} 0 & I_{N_f} \\ -I_{N_f} & 0 \end{bmatrix}.$$

The chiral symmetry breaking gives rise to $N_\pi = 2N_f^2 - N_f - 1$ pions π^a

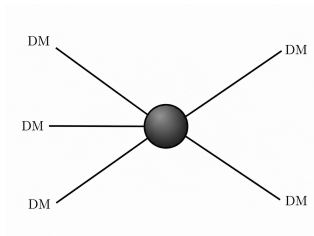
$$\Sigma = e^{i\pi/f_\pi} J e^{i\pi^T/f_\pi} = e^{i2\pi/f_\pi} J, \quad \pi = \sum_a \pi_a T_a$$

These pions are stable and can serve as dark matter candidates.

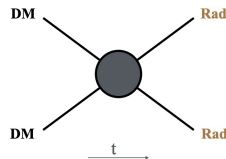
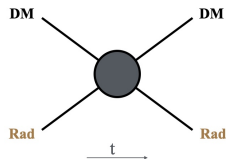
- ▶ For $N_f \geq 2$, WZW term induces a five-point interaction between pions

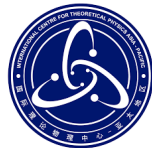
$$\mathcal{L}_{\text{WZW}}^0 = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr} (\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi).$$

(Hochberg, Kuglik, Murayama, Volansky, Wacker 2015)



- ▶ Dark matter self-annihilation can heat the dark sector, and efficient interactions with radiation are required to dissipate this energy.
- ▶ Dark matter can be cooled through $2 \rightarrow 2$ scattering with radiation; however, crossing symmetry implies that the same interaction also allows DM particles to annihilate into radiation.

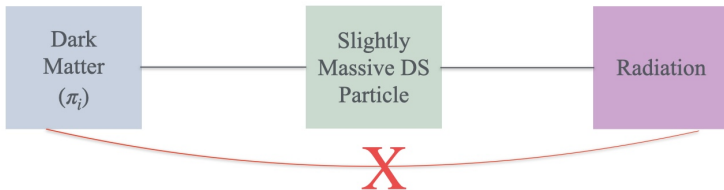




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- ▶ Scattering and annihilation between dark matter and radiation can be decoupled if both interact with a slightly heavier dark-sector particle and have no direct coupling to each other.



- ▶ Analogous to the QCD theory in the standard model, vector meson ρ could play the role of heavier dark-sector particle.
- ▶ **Dark photon as radiation ?**

$$\mathcal{L}_{\text{WZW}} \supset \mathcal{C} \frac{1}{f_\pi^3} \epsilon^{\mu\nu\rho\sigma} V_\mu \text{Tr} (Q \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi)$$

WZW term would leads to annihilation $\pi_a + \pi_b \rightarrow V + \pi_c$.



- Consider $Sp(4)_c$ gauge theory with $N_f = 2$ (Dirac fermions $m_u = m_d$).

$$\mathcal{L}_{eff} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{m_{a,0}^2 a^2}{2} + \bar{q} (iD - \mathbf{m}_{q,0}) q + \frac{c_{gg} \alpha}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{a}{f} \sum_{\mathcal{A}_1, \mathcal{A}_2} c_{\mathcal{A}_1 \mathcal{A}_2}^0 F_{\mathcal{A}_1 \mu\nu} \tilde{F}_{\mathcal{A}_2}^{\mu\nu}$$

$\mathcal{A} \equiv \mathbb{A} + \mathbb{B}$. $\mathbb{B}$ corresponds to meson fields below the confinement scale, acting as non-dynamical gauge fields of the global flavor symmetry.

(Harvey, Hill, Hill 2007)

- Axion-quark interactions $\longrightarrow$ embedding axion field into background fields.

$$\mathbb{B}_{L/R} \rightarrow \mathbb{B}_{L/R} + \mathbf{k}_{L/R,0} \frac{da}{f}.$$

(Bai, Chen, Liu, Ma 2024)

- To match the standard chiral Lagrangian, axion dependent chiral rotation

$$q(x) \rightarrow \exp \left[-i (\delta_{q,0} + \kappa_{q,0} \gamma_5) c_{gg} \frac{a(x)}{f} \right] q(x), \quad \text{with } \text{Tr}(\kappa_{q,0}) = 1$$

$$m_q(a) = e^{ic_{gg}\theta_{L,0}\frac{a}{f}} m_{q,0} e^{-ic_{gg}\theta_{R,0}\frac{a}{f}}, \quad \mathbf{k}_{L/R}(a) = \mathbf{k}_{L/R,0} + c_{gg}\theta_{L/R,0}, \quad \theta_{L/R,0} = \delta_{q,0} \mp \kappa_{q,0}$$



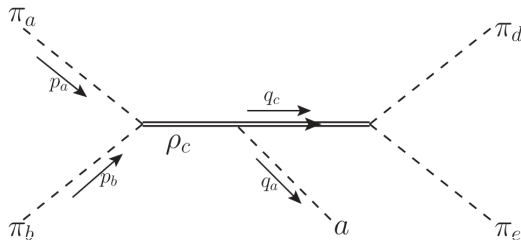
- ▶ The chiral Lagrangian is provided by:

$$\mathcal{L}_{\chi PT} = \underbrace{\frac{f_\pi^2}{4} \text{Tr}[(D^\mu \Sigma)(D_\mu \Sigma)^\dagger]}_{\pi\pi\text{ interaction}} - \frac{f_\pi^2}{2} B_0 \text{Tr}[M_q(a)\Sigma + \text{h.c.}] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \underbrace{\frac{a}{f} \sum_{\mathcal{A}_1, \mathcal{A}_2} c_{\mathcal{A}_1 \mathcal{A}_2} F_{\mathcal{A}_1 \mu\nu} \tilde{F}^{\mu\nu}_{\mathcal{A}_2}}_{\rho a \rho \text{ interaction}}$$

$$D_\mu \Sigma \approx \partial_\mu \Sigma + i g_\rho (\rho_\mu \Sigma + \Sigma \rho_\mu^T) + i \frac{\partial_\mu a}{f_a} (\mathbb{K} \Sigma + \Sigma \mathbb{K}^T)$$

where $B_0 \approx \frac{m_\pi^2}{m_u + m_d}$, $\mathbb{K} = \begin{pmatrix} k_L(a) & 0 \\ 0 & -k_R(a) \end{pmatrix}$ and $M_q(a) = \begin{pmatrix} 0 & m_q(a) \\ -m_q(a) & 0 \end{pmatrix}$.

- ▶ WZW term can also generate a $\rho a \rho$ vertex, similar to the chiral Lagrangian term.



Axion-pion mixing?



- ▶ Axion-pion kinetic mixing term $\Sigma = e^{i2\pi/f_\pi} J$:

$$\begin{aligned} \frac{f_\pi^2}{4} \text{Tr} [(D^\mu \Sigma)(D_\mu \Sigma)^\dagger] &\supset f_\pi^2 \text{Tr} \left[\frac{\partial_\mu a}{f_a} (\mathbb{K} + J\mathbb{K}J^\dagger) \frac{\partial^\mu \pi}{f_\pi} \right] \\ &= \frac{f_\pi}{f_a} [k_L(a) - k_R(a)] \frac{\partial_\mu a}{f_a} \text{Tr}(\partial^\mu \pi) = 0. \end{aligned}$$

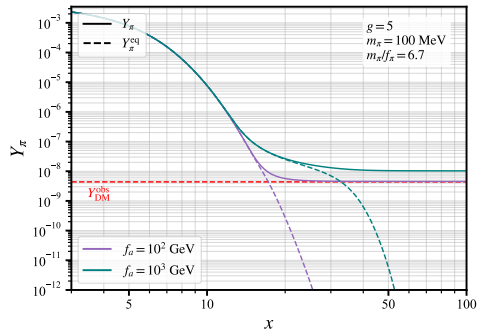
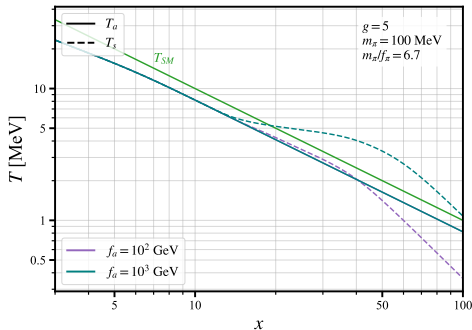
- ▶ Axion-pion mass mixing term:

$$-\frac{f_\pi^2}{2} B_0 \text{Tr} [M_q(a)\Sigma + \text{h.c.}] \supset 2f_\pi \text{Tr} \left[\begin{pmatrix} (\theta_L - \theta_R)c_{gg}\frac{a}{f_a} & 0 \\ 0 & (\theta_L - \theta_R)c_{gg}\frac{a}{f_a} \end{pmatrix} \pi \right] = 0.$$

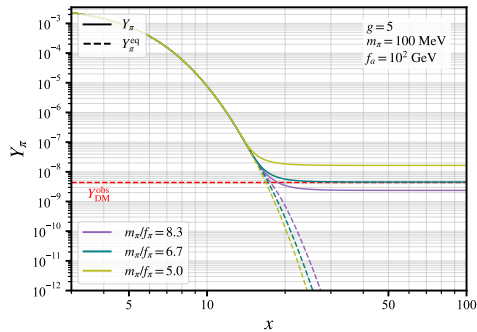
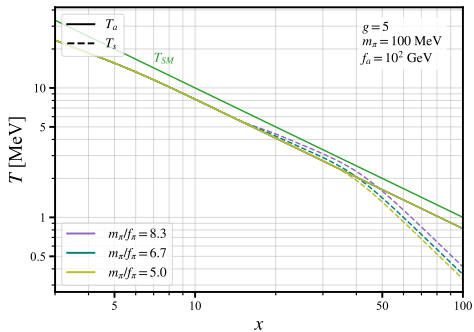
- ▶ From WZW term

$$10i\mathcal{L} \int_{M^4} \text{Tr} [\mathcal{A}\alpha^3] \supset 10i\mathcal{L} \int_{M^4} d^4x \text{Tr} \left[\mathbb{K} \frac{\partial_\mu a}{f_a} \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi \right] \epsilon_{\mu\nu\rho\sigma}$$

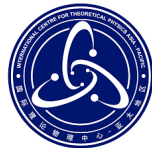
$$\boxed{\alpha = D_\mu \Sigma \Sigma^\dagger} \quad = -10i\mathcal{L} \int_{M^4} \text{Tr} \left[\mathbb{K} \partial_\mu \left(\frac{a}{f_a} \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi \right) \right] \epsilon_{\mu\nu\rho\sigma}$$



- ▶ Strong sector $Y_s \equiv Y_\pi + 2Y_\rho$
- ▶ The coupling f_a only serves to maintain kinetic equilibrium between the SIMP and radiation and does not directly determine the dark matter relic abundance.
- ▶ If T_s and T_a decouple early, DM freeze-out occurs at a later time, resulting in an overabundance of dark matter.



$$\sigma v^2_{3\pi \rightarrow 2\pi} = \frac{375 N_c^2 m_\pi^3}{512 \sqrt{5} \pi^5 f_\pi^{10} N_\pi^3} T_s^2$$



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- ▶ In SIMP models, dark matter relic abundance is obtained via $n \rightarrow 2$ self-annihilation.
- ▶ Kinetic equilibrium between dark matter and radiation is required to dissipate the kinetic energy generated by DM self-annihilation.
- ▶ Dark matter annihilation and scattering with radiation can be decoupled if both dark matter and radiation interact through a slightly heavier particle in the dark sector instead of interacting directly.
- ▶ We propose a minimal extension of the SIMP framework, in which the dark axion serves as the radiation, while the dark ρ meson acts as the heavier mediator.
- ▶ In the SIMP + dark axion model, the dark matter does not have leading-order coupling with the axions.

Thank You

Backup slides

