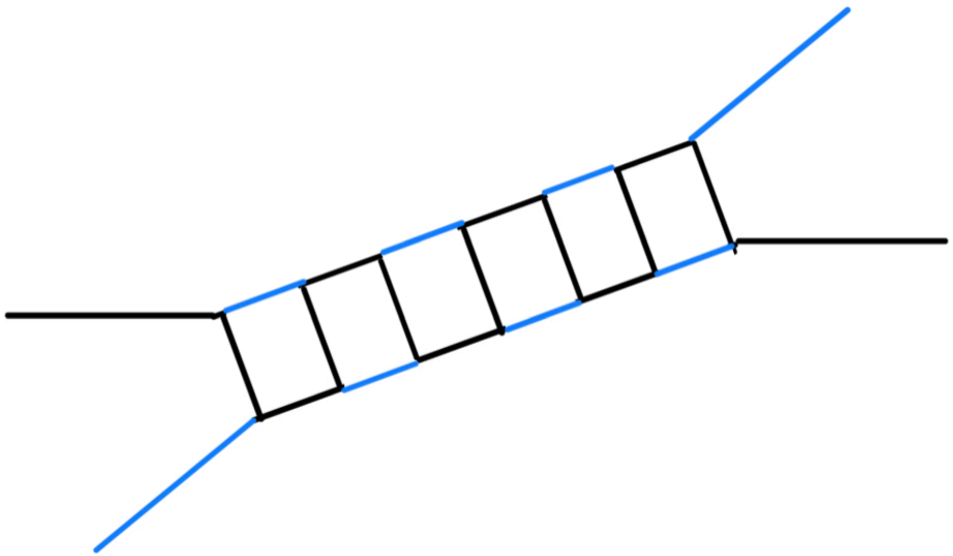


Models for self-resonant dark matter

21, Oct, 2022 Workshop on Physics of Dark Cosmos

(Chung-Ang University) SeongSik Kim, Hyun Min Lee

(Yantai University) Bin Zhu

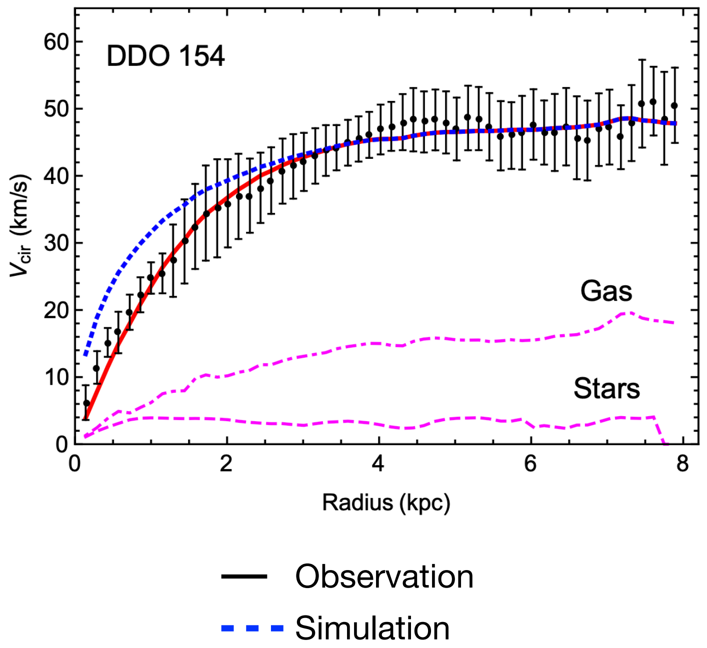
arXiv:2202.13717 & arXiv:2108.06278

Dark Matter (DM) and Cross-Section

Self-Interacting DM Model for Core-cusp Problem and others...

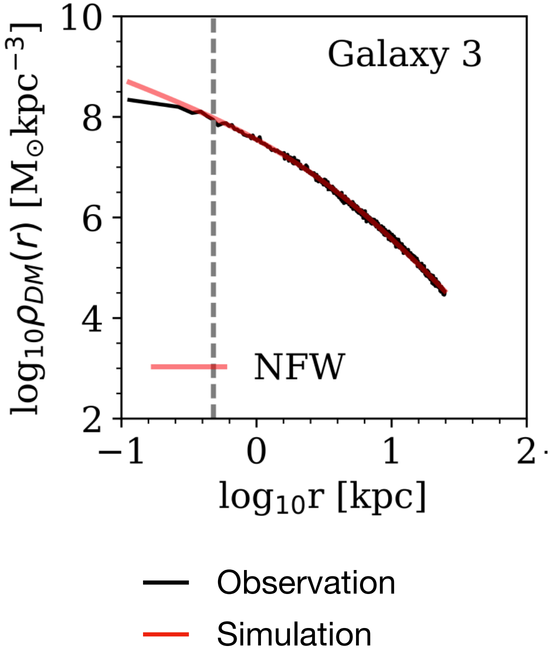
Observed Galaxy Rotation Curve

S. Tulin, Hai-Bo Yu, arXiv:1705.02358v2



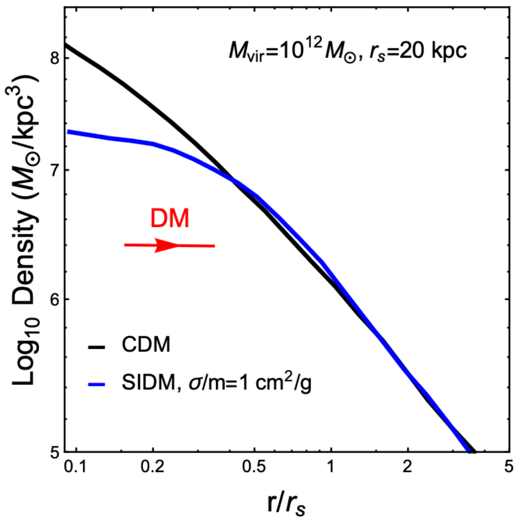
ΛCDM Simulation w/o SIDM

A. Genina at al., arXiv 1707.06303



ΛCDM Simulation with SIDM

M. Rocha, A. H. Peter, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, et al., arXiv 1208.3025.



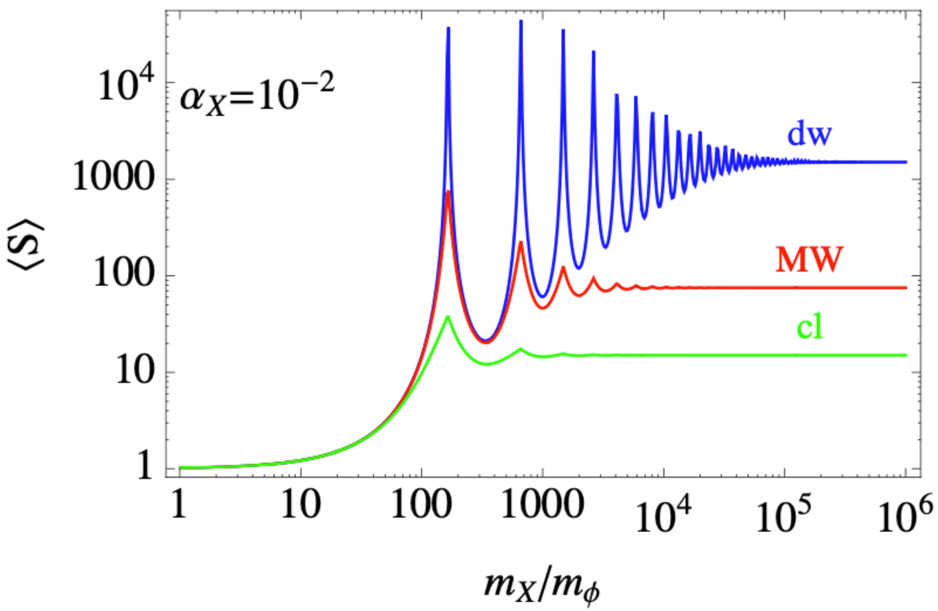
To solve the problem, $\sigma_{\text{self}}/m \sim \mathcal{O}(0.1 \sim 10)$cm^2/g required

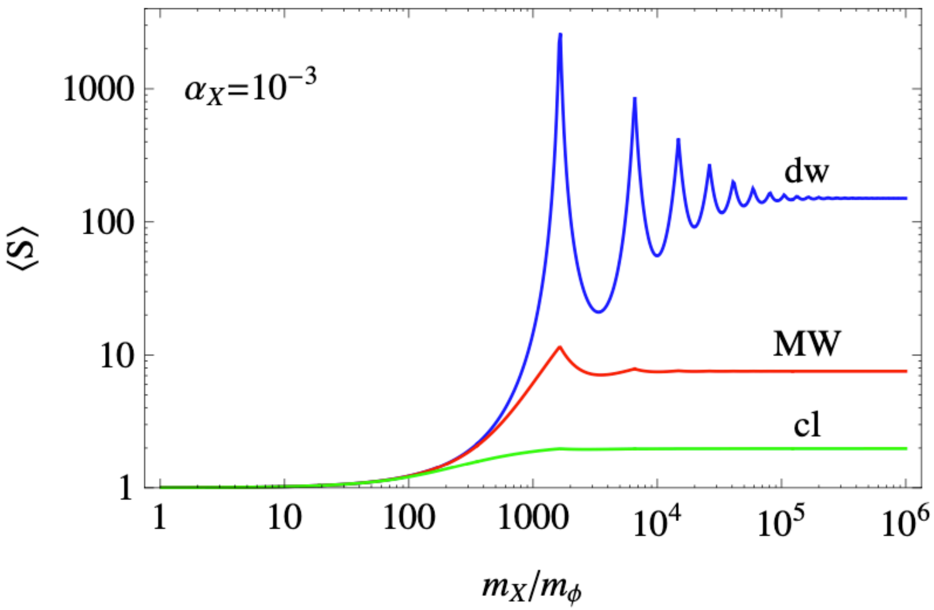
Sommerfeld Enhancement

Charm way to enhance cross-section

The typical Sommerfeld Factor graph

Sean Tulin, Hai-Bo Yu, Kathryn M. Zurek. arXiv:1302.3898





dw : $v_0 = 10$ km/s, MW : $v = 200$ km/s, cl : $v = 1000$ km/s, $\langle S \rangle$: Sommerfeld Factor, For $XX \to \phi\phi$ process

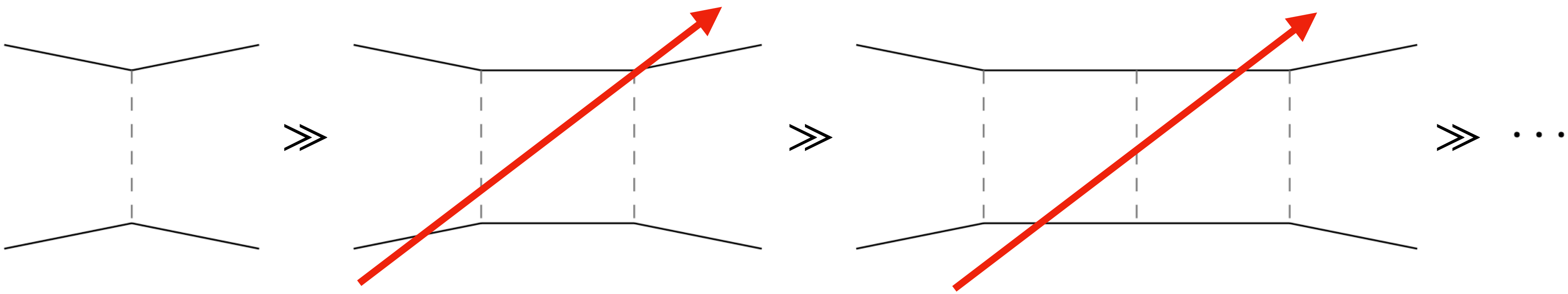
$$\sigma_{\text{Realistic}} = S \times \sigma_{\text{QFT}}$$

S depends on relative velocity, coupling, particle mass and etc.

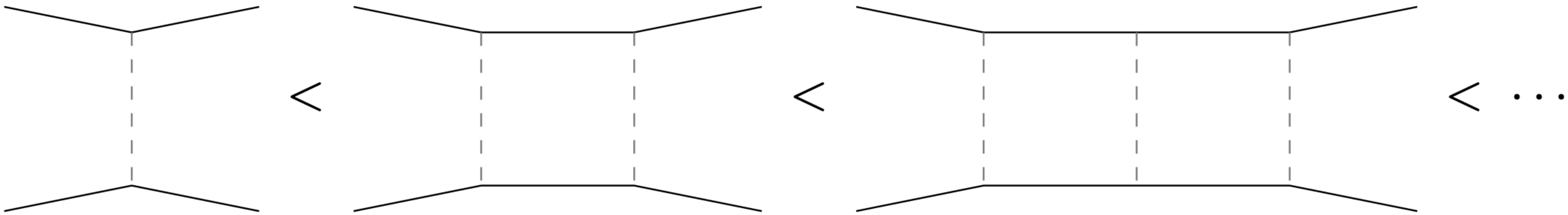
How it Works?

$\sigma_{\text{Realistic}} = S \times \sigma_{\text{QFT}}$ Where this came from?

Traditional QFT : Tree level is dominant



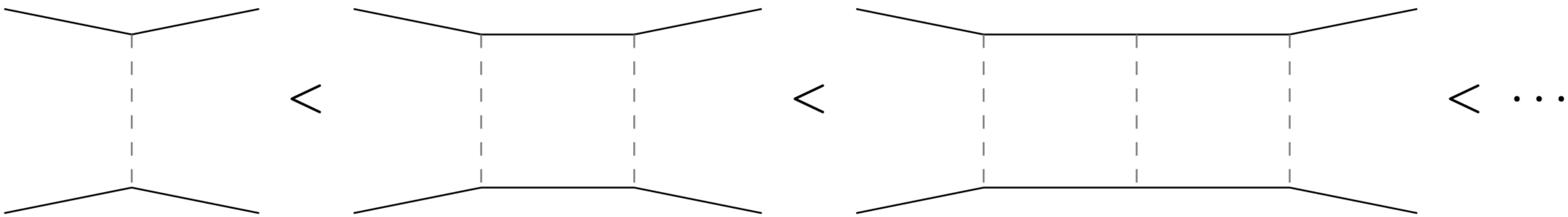
But if



The factor S as correction from higher order diagram

How can it achieved?

Traditional Mechanism

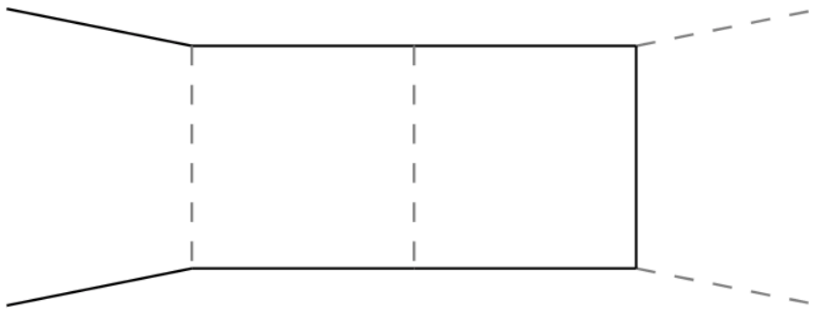


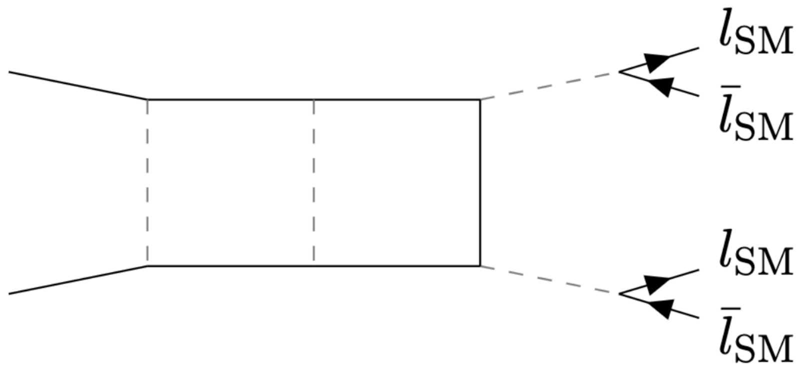
$$\tilde{\Gamma} \propto \frac{g^2}{\Delta \vec{q}^{\,2} + m_{\rm med}^2} \qquad \tilde{\Gamma} \propto \left(\frac{g^2}{\Delta \vec{q}^{\,2} + m_{\rm med}^2}\right)^2 \qquad \tilde{\Gamma} \propto \left(\frac{g^2}{\Delta \vec{q}^{\,2} + m_{\rm med}^2}\right)^3$$

Non-relativistic collision and light mediator ($m_{med} \rightarrow 0$) for $\left| \frac{g^2}{\Delta \vec{q}^{\,2} + m_{\rm med}^2} \right| > 1$

Problem?

Non-relativistic collision and light mediator ($m_{med} \to 0$) for $\left| \frac{g^2}{\Delta \vec{q}^{\,2} + m_{\rm med}^2} \right| > 1$





Relativistic mediator survives only.

This is not a Λ [Cold] DM

If mediator couples SM,
Sommerfeld Enhancement highly distort astrophysical observation:
CMB, AMS-02, FermiLAT…

even if their coupling is very weak!

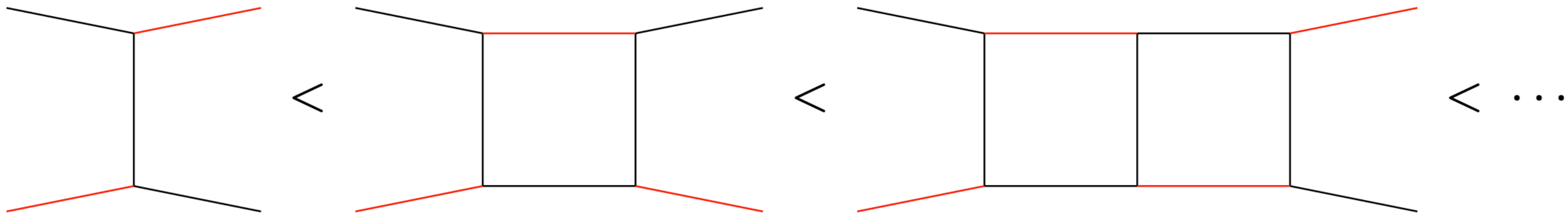
Object

Achieve Large Sommerfeld Enhancement

Without Light Mediator

New Mechanism

New Mechanism : without Light mediator



$\tilde{\Gamma} \propto \frac{g^2}{\Delta \vec{q}^{\,2} - \omega^2 + m_1^2}$ $\quad$ $\tilde{\Gamma} \propto \left(\frac{g^2}{\Delta \vec{q}^{\,2} - \omega^2 + m_1^2}\right)^2$ $\quad$ $\tilde{\Gamma} \propto \left(\frac{g^2}{\Delta \vec{q}^{\,2} - \omega^2 + m_1^2}\right)^3$

With $\omega \neq 0$

Non-relativistic interaction ($\Delta \vec{q} \to 0$)
& Mass relation $2m_1 \simeq m_2$ $\Rightarrow$ $\left|\frac{g^2}{\Delta \vec{q}^{\,2} - \omega^2 + m_1^2}\right| > 1$

Also achieved Long-range, non-instantaneous interaction

Evaluation of Sommerfeld Factor

$$\sigma_{\text{Realistic}} = S \times \sigma_{\text{QFT}}$$

1. Write Down Bethe-Salpeter Equation

2. Change BS equation to Schrödinger (like) Equation

   Here we get $-\frac{1}{2\mu}\nabla^2\psi(\vec{r}) - \frac{\alpha}{r}e^{-Mr}\psi\left(-\frac{m_2}{m_1}\vec{r}\right) = E\psi(\vec{r})$

3. Solve Schrödinger Equation and Evaluate $S = \frac{|\psi(0)|^2}{|\psi(r \to \infty)|^2}$

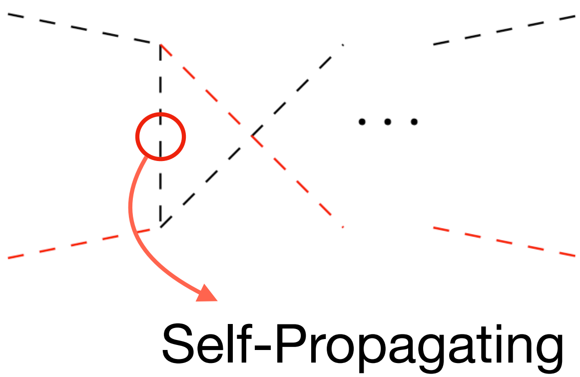
$$E = p_0 - \frac{m_1 + m_2}{2},\ M = m_2\sqrt{2 - \frac{m_2}{m_1}}$$

Simple Model Analysis

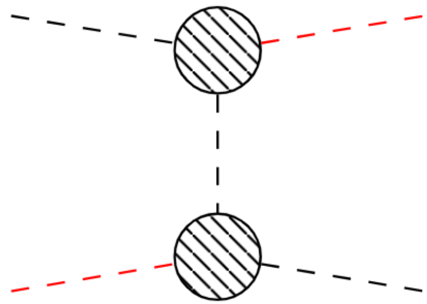
One Real Scalar & One Complex Scalar

$$\mathscr{L} = |\partial_\mu \phi_1|^2 - m_1^2 \phi_1^2 + \frac{1}{2}(\partial_\mu \phi_2)^2 - \frac{1}{2} m_2^2 \phi_2^2 - 2 g m_1 \phi_2 |\phi_1|^2$$

m_1 in coupling term makes g dimensionless.



Effectively equals to



With coupling of $\alpha = \dfrac{g^2}{4\pi}$

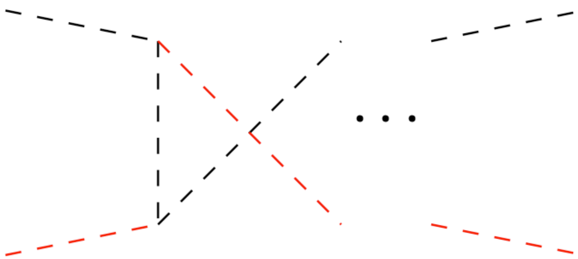
Note : α for $-\frac{1}{2\mu}\nabla^2\psi(\vec{r}) - \frac{\alpha}{r}e^{-Mr}\psi\left(-\frac{m_2}{m_1}\vec{r}\right) = E\psi(\vec{r})$

Higher α leads stronger enhancement

More Realistic Model Analysis

Effective Couplings for Noteworthy Models

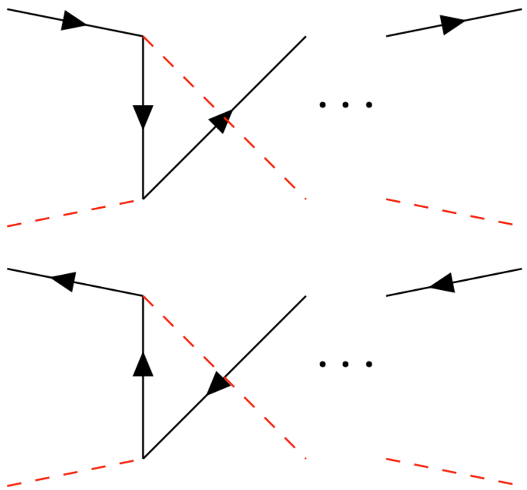
Scalar-PseudoScalar



$$\alpha = \frac{g^2}{4\pi} \text{ for}$$

$$\mathscr{L}_{\text{int}} = -2g m_{\phi_1} \phi_1 a^2$$

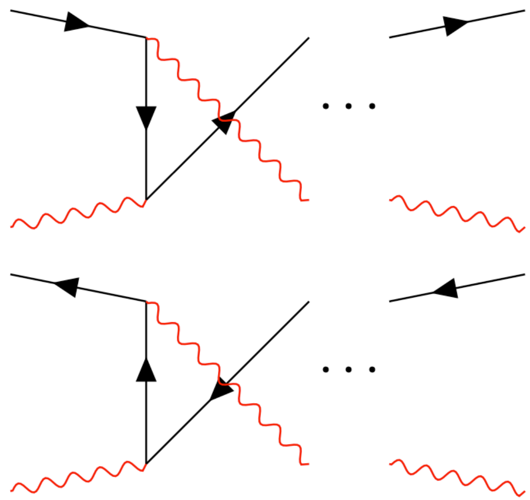
Fermion-PseudoScalar



$$\alpha = \mp \frac{g_{Z'}^2}{4\pi} \frac{m_{Z'}}{2m_\chi}, \text{ for}$$

$$\mathscr{L}_{\text{int}} = -g_{Z'} Z'_\mu \bar{\chi} \gamma^\mu \chi$$

Fermion-Vector



$$\alpha = \mp \frac{\lambda^2}{4\pi} \frac{m_a}{2m_\chi}, \text{ for}$$

$$\mathscr{L}_{\text{int}} = -i\lambda a \bar{\chi} \gamma^5 \chi$$

Dark Matter Physics

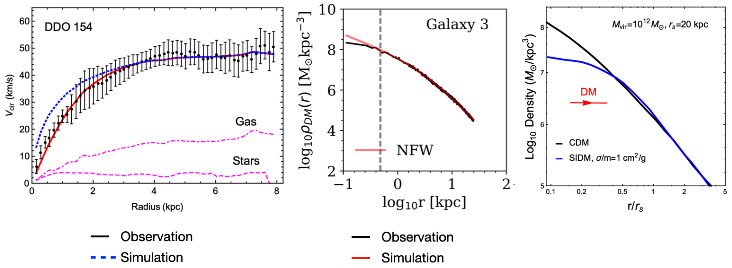
Dark Matter (DM) and Cross-Section

Self-Interacting DM Model for Core-cusp Problem and others...

Observed Galaxy Rotation Curve — S. Tulin, Hai-Bo Yu, arXiv:1705.02358v2

ΛCDM Simulation w/o SIDM — A. Genina at al., arXiv 1707.06303

ΛCDM Simulation with SIDM — M. Rocha, A. H. Peter, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, et al., arXiv 1208.3025.



To solve the problem, $\sigma_{\text{self}}/m \sim \mathcal{O}(0.1 \sim 10)\text{cm}^2/\text{g}$ required

But, In fact,

Sommerfeld Enhancement affects not only DM Cross-section But also DM annihilation rate!

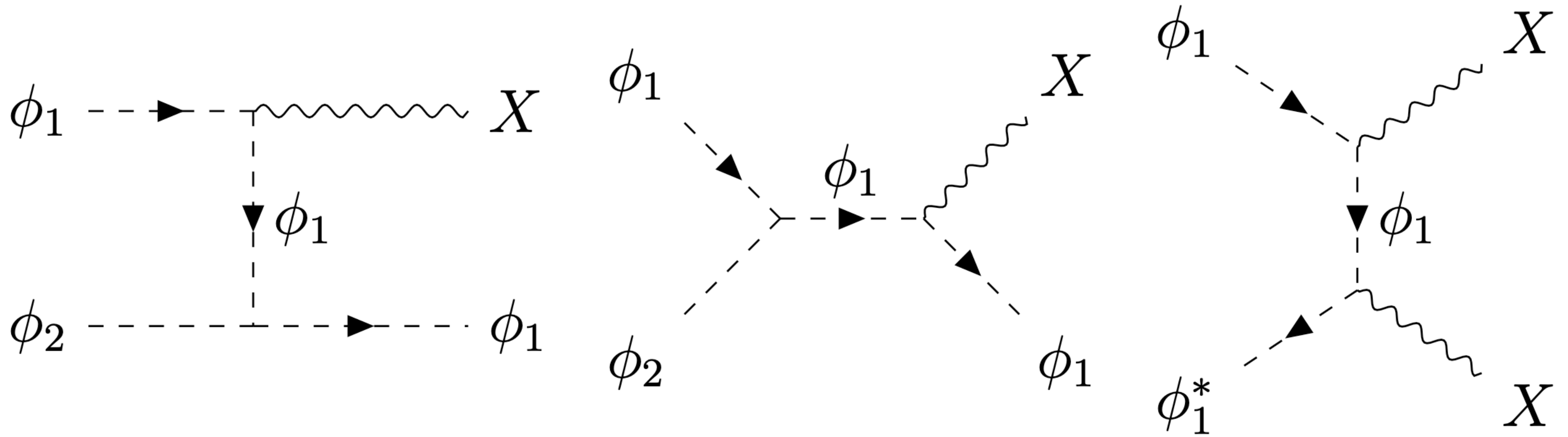
Scalar DM Model

(To consider other model, We only need to change effective coupling)

WIMP Scenario

Dark Matter Model

Introduce Dark photon portal : Dark matter annihilation channel



DM annihilation channels

Scalar DM, $\mathscr{L}_{\text{int}} \supset -ig_X X_\mu(\phi_1 \partial^\mu \phi_1^* - \phi_1^* \partial^\mu \phi_1)$

X^μ : Dark Photon, Something coupled to Standard Model.

Benchmark Points

Our Interest :
How DM mass & Coupling changes Maximal Sommerfeld Factor

	$m_2 \simeq 2m_1$ [GeV]	m_X [GeV]	$\alpha = \frac{g^2}{4\pi}$	$\alpha_X = \frac{g_X^2}{4\pi}$
B1	200	50	0.05	0.0045
B2	400	100	0.1	0.0065
B3	26	5	0.001	0.05
B4	240	60	0.003	0.03

α : DM-DM coupling strength
α_X : DM-Portal coupling strength

$\alpha \ll \alpha_X$ & Medium DM pair

$\alpha \gg \alpha_X$ & Heavy DM pair

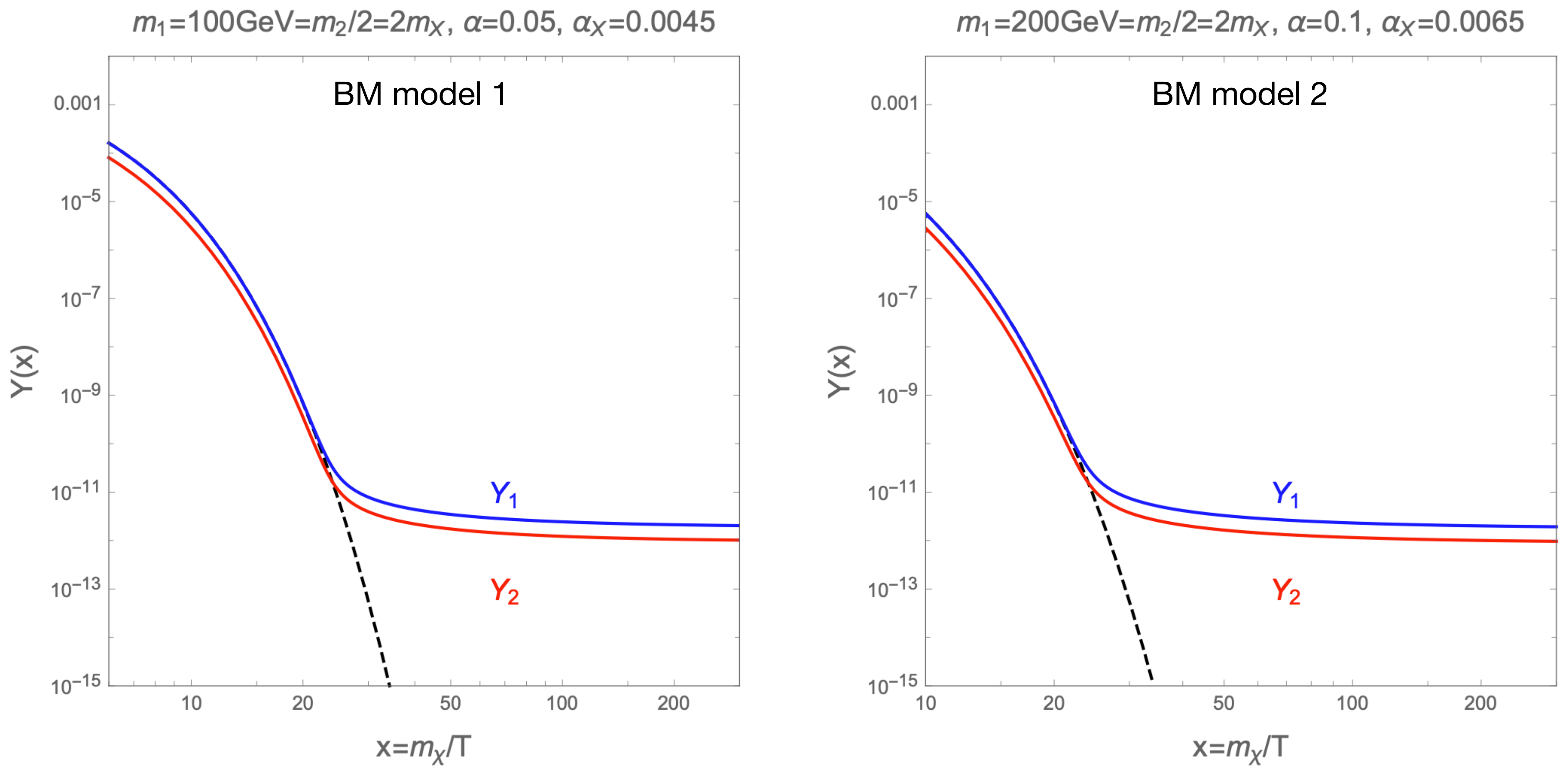
$\alpha \ll \alpha_X$ & Light DM pair

$\alpha \ll \alpha_X$ & Medium DM pair

We compute Relic density, Maximal Sommerfeld Factor, and corresponding self-scattering cross-section for each Benchmark

Relic Densities

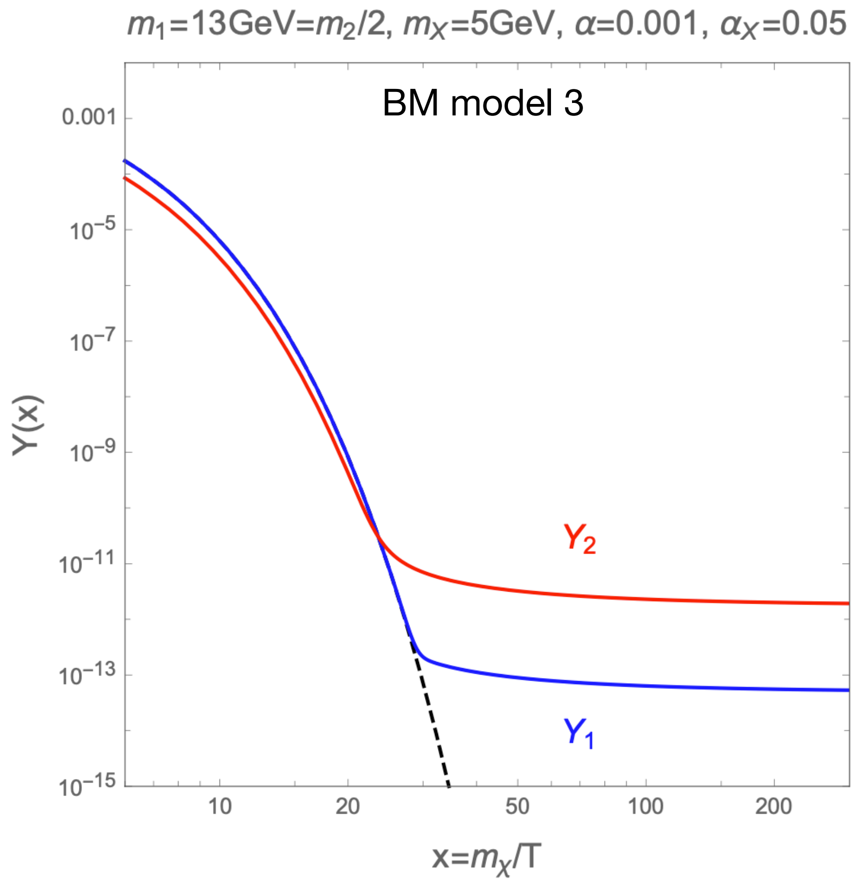
Case 1 : DM-DM coupling >> DM-Dark photon coupling

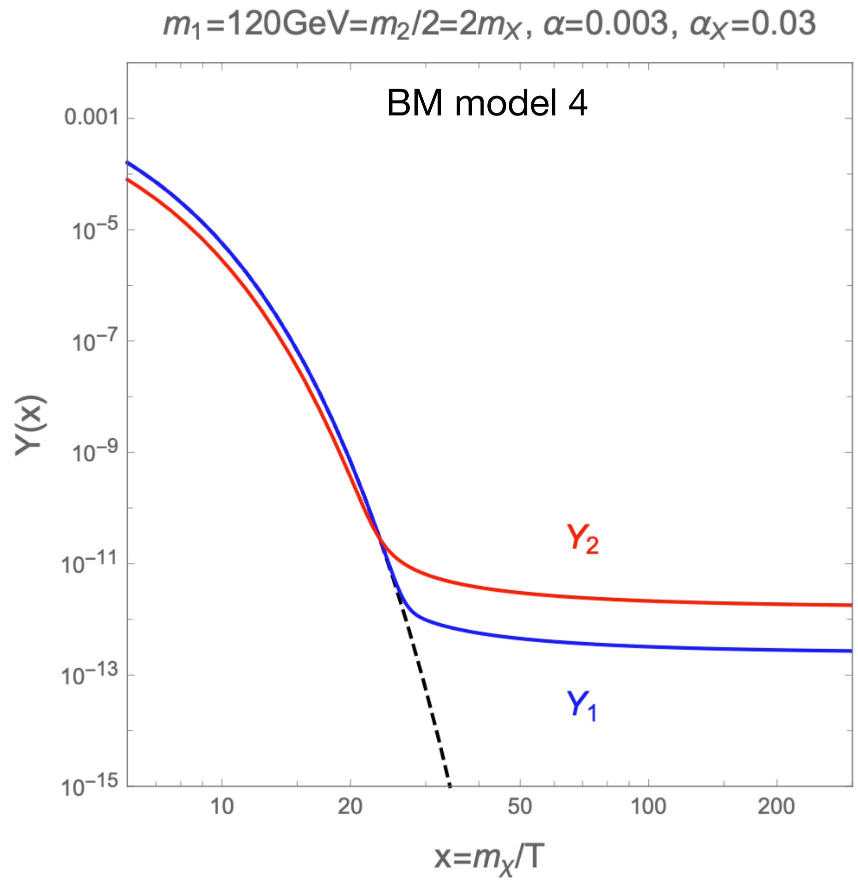


DM Relic Yield shows $Y_1 \simeq 2Y_2$, with relic abundance of $\Omega_1 \simeq \Omega_2$.

Relic Densities

Case 2 : DM-DM coupling << DM-Dark photon coupling





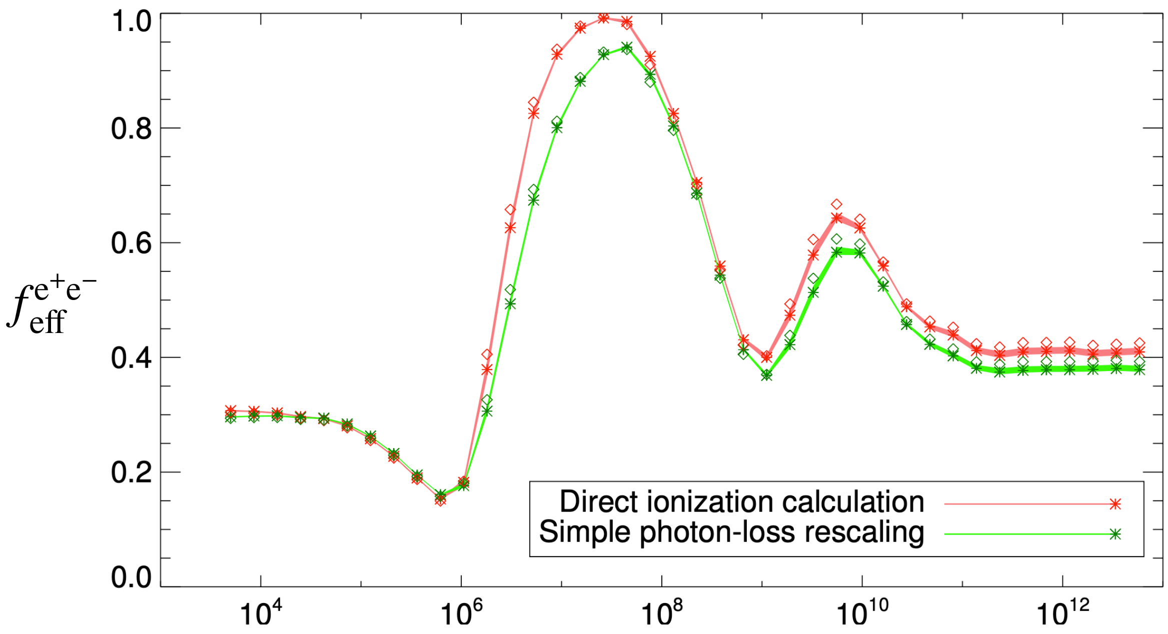
Lighter DM quickly Annihilates. DM Relic Yield shows $Y_1 \ll Y_2$.

CMB Constraints

WIMP Scenario : Assuming DM annihilates to the lepton sector,
This affects CMB observation.

Efficiency Factor $f_{\mathrm{eff}}^{\mathrm{e^+e^-}}$ introduced :
How much $\mathrm{e^+e^-}$ influences observing CMB, by its energy.

Tracy R. Slatyer arXiv:1506.03811



$\mathrm{e^+e^-}$ pair Energy (eV), from Dark matter annihilation

Maximal Sommerfeld Factor constrained by CMB Constraints

CMB Constraint

Effective efficiency (Averaged Efficiency) defined

$$f_{\rm eff}(m_2) = \frac{1}{m_2}\int_0^{m_2/2} dE_e\ 2f_{\rm eff}^{\rm e^+e^-} E_e \frac{dN_e}{dE_e}$$

This relevant for fast electrons produced before CMB recombination

PLANCK observation (CMB) suggest

$$f_{\rm eff}\langle\sigma v\rangle_{\phi_1\phi_2\to\phi_1 X} < \frac{\Omega_{\rm DM}^2}{\Omega_1\Omega_2}\left(\frac{m_2}{100{\rm GeV}}\right) \times (4\times 10^{-25}{\rm cm}^3/{\rm s})$$

Result for 4 Benchmark Points

Maximal Sommerfeld Factor ↓ (S_0)

	$m_2 \simeq 2m_1$ [GeV]	m_X [GeV]	$\alpha = \frac{g^2}{4\pi}$	$\alpha_X = \frac{g_X^2}{4\pi}$	$\langle \sigma v \rangle^0_{\phi_1\phi_2 \to \phi_1 X}$ [cm^3/s]	$r_1 = \frac{\Omega_1}{\Omega_{\rm DM}}$	S_0	$\Delta = 1 - \frac{m_2}{2m_1}$	$\sigma_{\rm self}/m_{\rm eff}$ [cm$^2/g$]
B1	200	50	0.05	0.0045	9.9×10^{-27}	0.5	444.7	7.7×10^{-4}	0.014
B2	400	100	0.1	0.0065	7.1×10^{-27}	0.5	1231	9.9×10^{-5}	0.002
B3	26	5	0.001	0.05	7.8×10^{-26}	0.14	1349	10^{-9}	0.063
B4	240	60	0.003	0.03	2.7×10^{-27}	0.07	7379	10^{-8}	0.086

↑ ($\sigma_{\rm self}/m_{\rm eff}$) Corresponding self-scattering Cross-section

Simple Scalar model shows plausible result.

Conclusion

- We presented new resonance mechanisms for cross-section enhancement.
- We found multi-component Dark Matter models, Fermion-Pseudoscalar and etc, can be working well with our mechanism.
- We consider benchmark points in simple models with Dark photon portals.
- With simple model, we consider Relic density, Maximal Sommerfeld Factor, and corresponding self-scattering cross-section.
- We will extend our work for the origin of resonances and phenomenology study in multi-component Dark Matter Model.