Unitarizing SIMP scenario with dark vector resonances

Soo-Min Choi (Chung-Ang University)

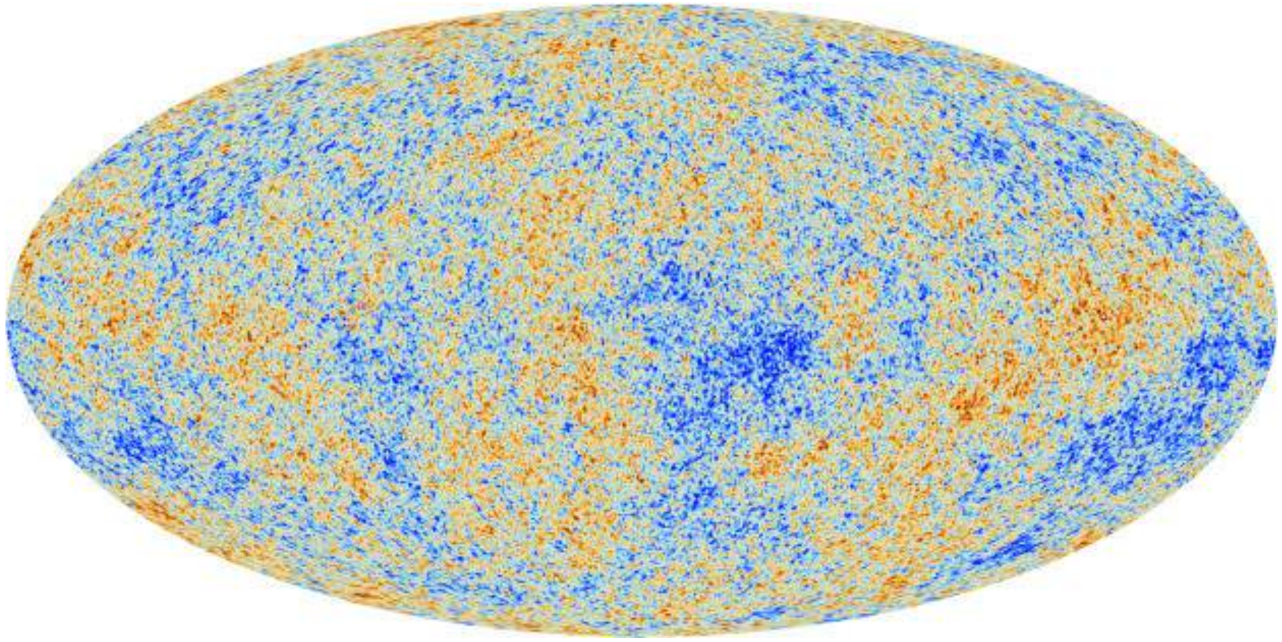
SMC, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

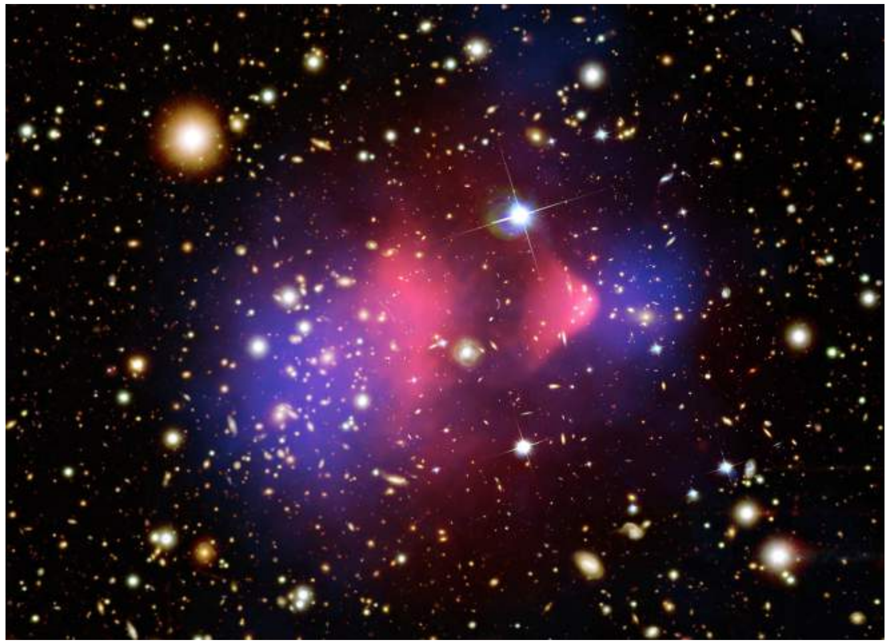
The 3rd IBS - KIAS Joint Workshop
February 12, 2019, High 1, Korea

Dark Matter

- Many indirect evidences, but no direct evidence.
- Informations from the Bullet cluster :

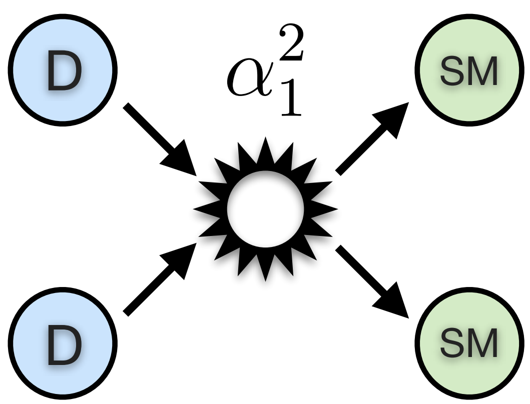
  DM hardly interacts with SM / self-interaction is very weak





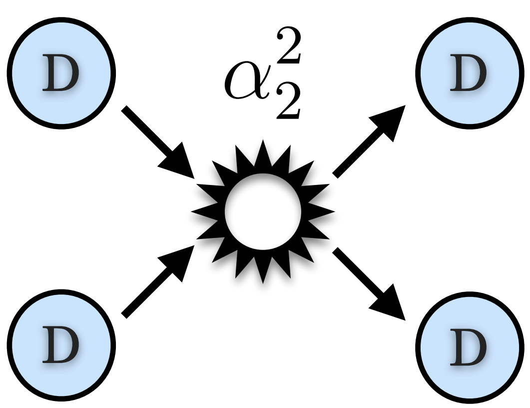
WIMP Dark Matter

- General freeze-out process is $\chi\chi \to f_{\rm SM}\bar{f}_{\rm SM}$
- Mass scale is $\mathcal{O}(100~{\rm GeV})$ for the relic density
- Self-interaction of WIMP is negligible



$$\langle \sigma_{\rm anni.} v \rangle = \frac{\alpha_1^2}{m_\chi^2} \sim 1~{\rm pb}$$

$\mathcal{O}(1)$ coupling $\to$ $m_\chi \sim \mathcal{O}(100~{\rm GeV})$

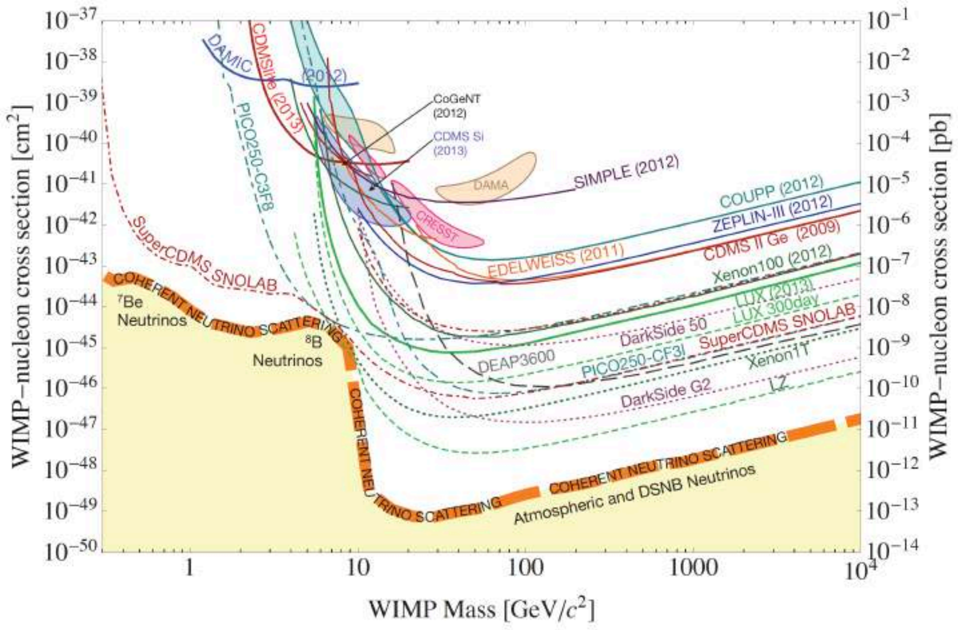


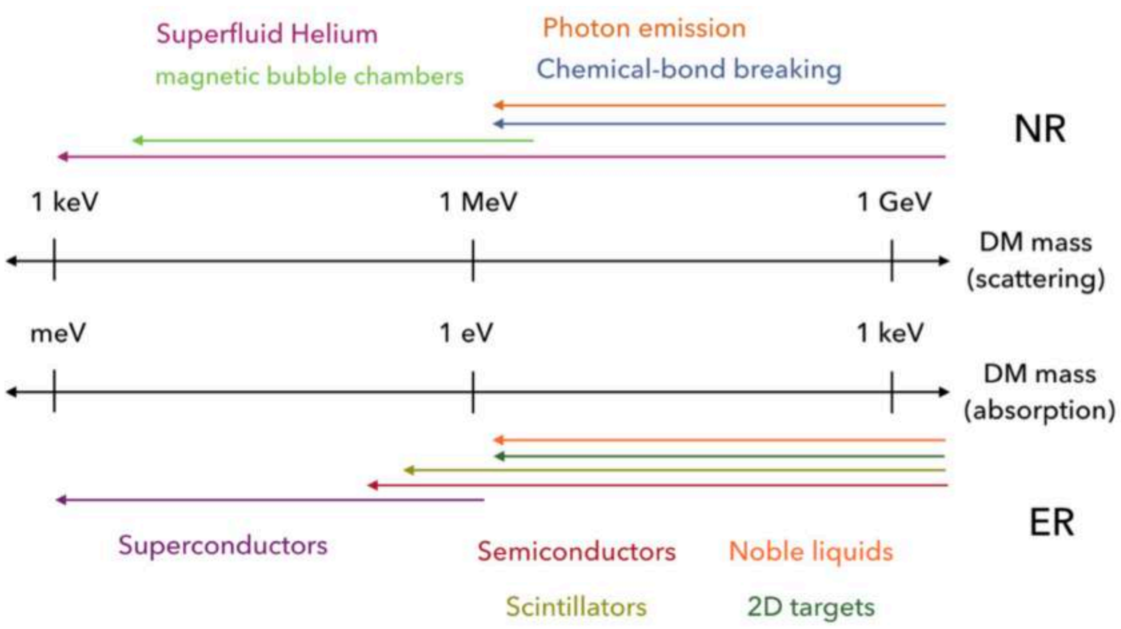
For $\mathcal{O}(1)$ coupling, $m_\chi \sim \mathcal{O}(100~{\rm GeV})$

$$\frac{\sigma_{\rm self}}{m_\chi} = \frac{\alpha_2^2}{m_\chi^3} \sim 10^{-12}~{\rm cm}^2/{\rm g} \ll 1~{\rm cm}^2/{\rm g}$$

Direct Detection of WIMP

- No direct evidence for WIMP
- Parameter space for WIMP is closed soon
- Research on light DM will become increasingly important

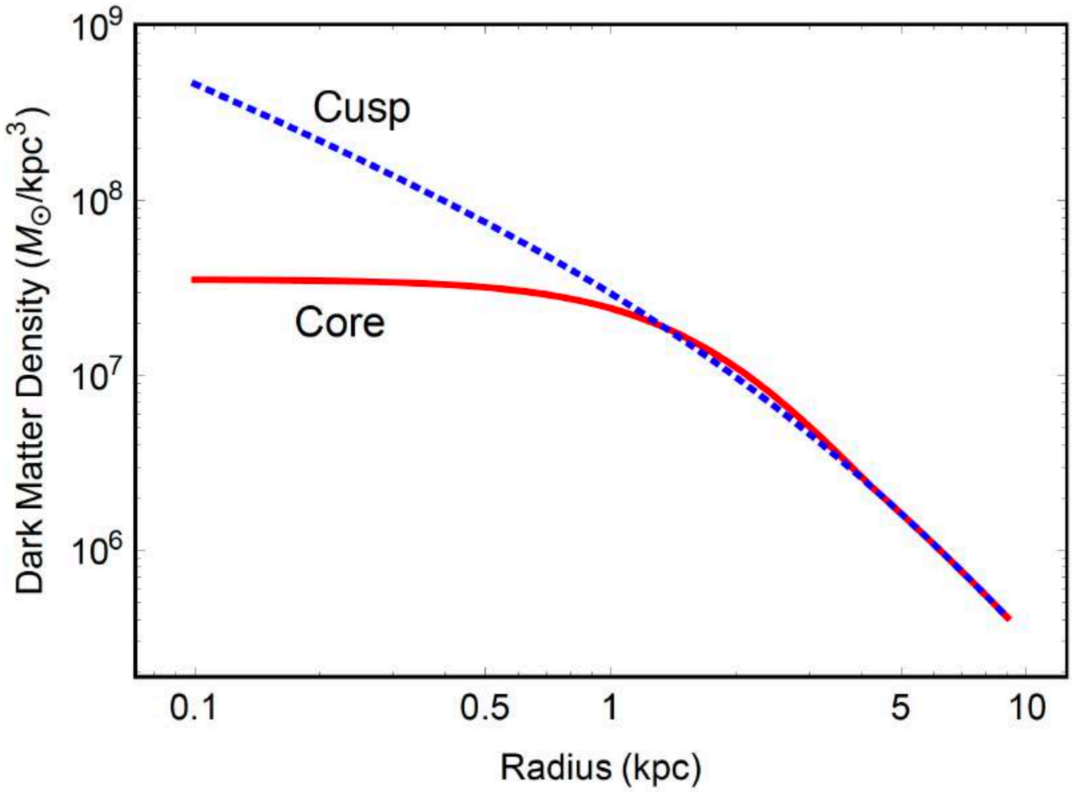


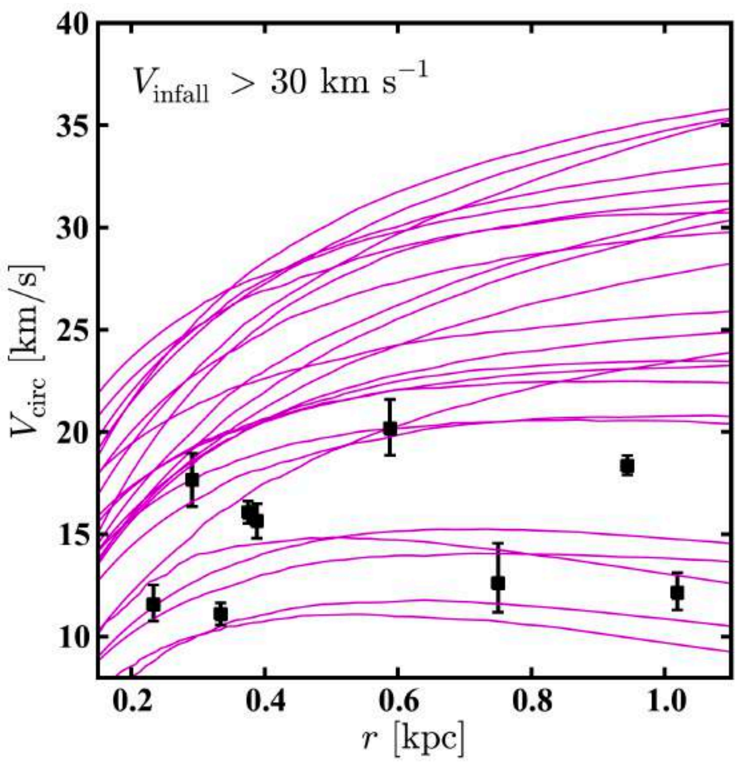


J. Cooley (2014), US Cosmic Visions Community Report (2017)

Small Scale Problems

- LCDM : successful for large scale and matter power spectrum
- Controversy b/w simulations and observations for small scales
- Core-Cusp / Too-big-to-fail



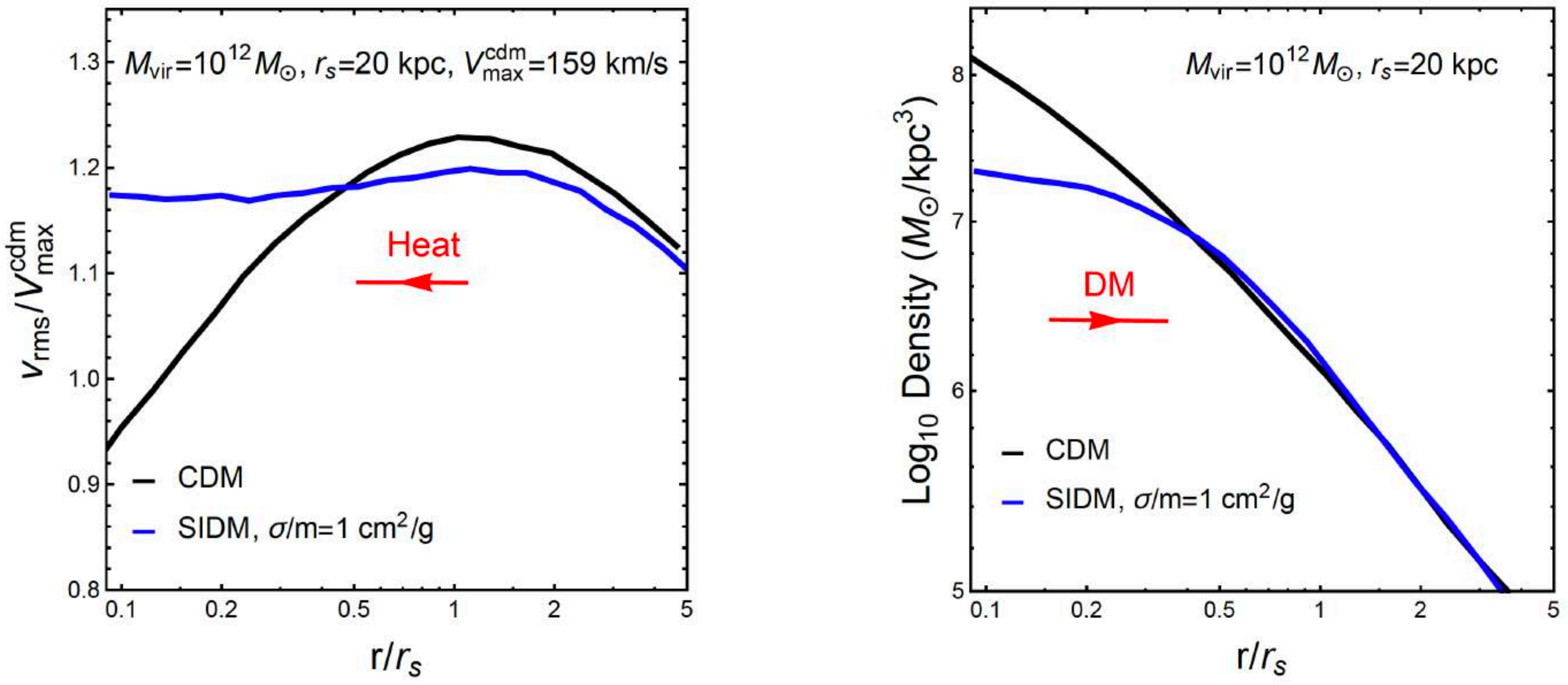


S. Tulin, H. B. Yu (2017), D. H. Weinberg et al (2013)

Solution for SSPs

- Self-Interacting dark matter can be a nice solution of SSPs
- DMs near center get the energy to spread ourwards easily
- Self interaction bound from the Bullet cluster and SSPs

$$0.1\ \mathrm{cm}^2/\mathrm{g} \lesssim \frac{\sigma_{\mathrm{self}}}{m_\chi} \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$$

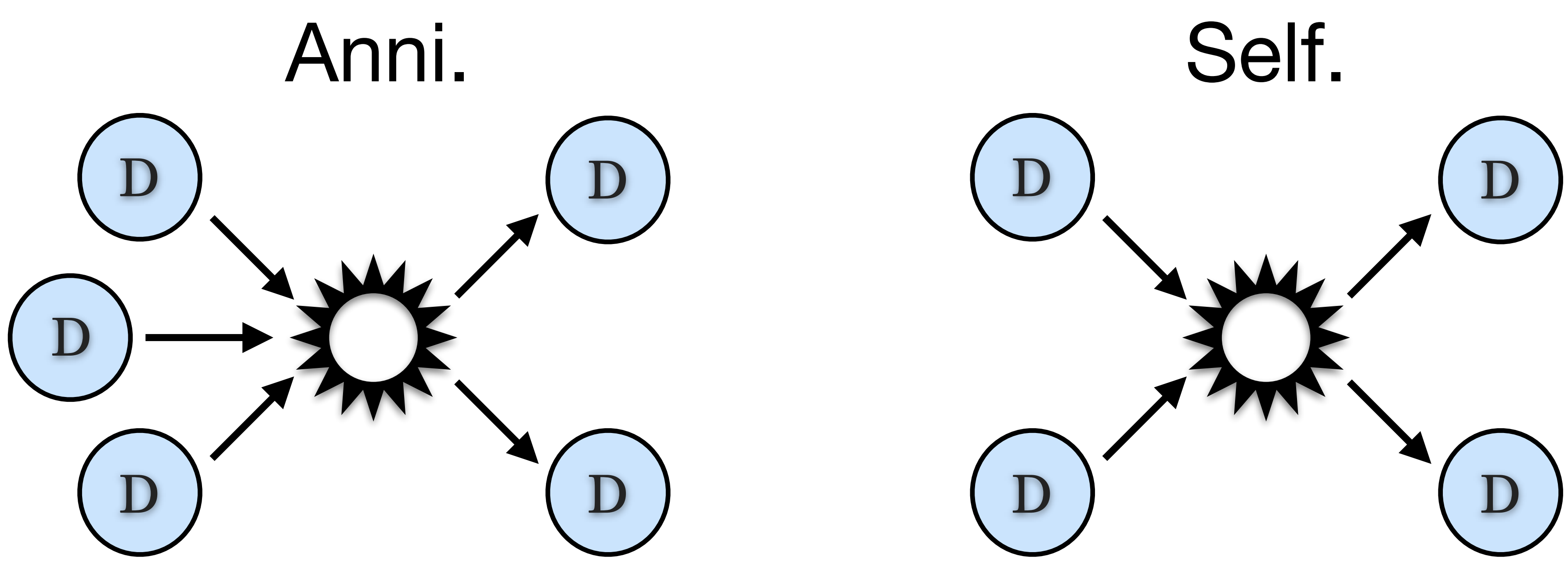


S. Tulin, H. B. Yu (2017)

SIMP Dark Matter

- Strongly Interacting Massive Particle
- Freeze-out process is 3 to 2 self-annihilation
- Mass scale : $\mathcal{O}(10-100)$ MeV for $\alpha \sim 1$, $\langle \sigma v^2 \rangle \propto \alpha^3/m_\chi^5$

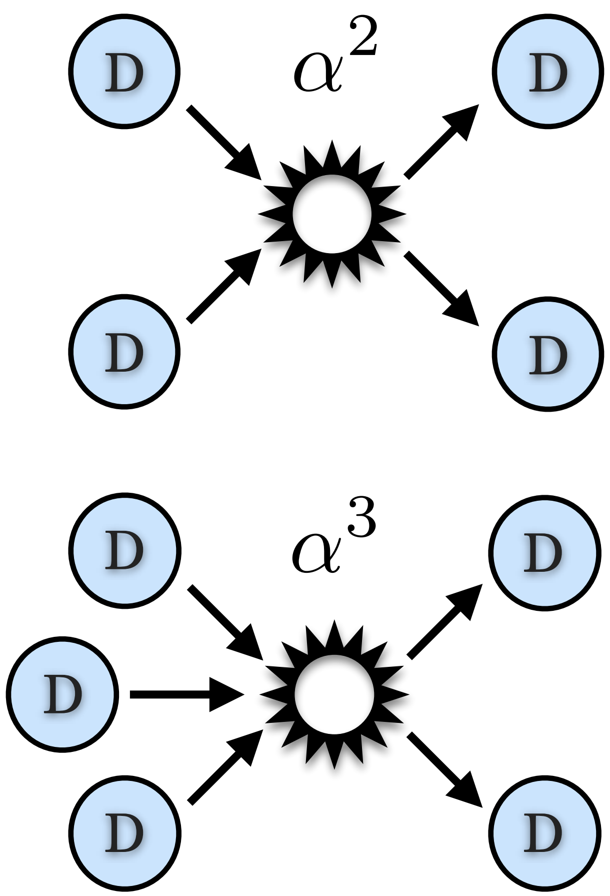
(WIMP : $\langle \sigma v \rangle \propto \alpha^2/m_\chi^2, \quad \alpha \sim 1/30$)



Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker (2014)

SIMP = SIDM ?

- SIMP is a natural SIDM candidate
- Self-annihilation is a kind of a self-interaction



For the $\alpha \sim \mathcal{O}(1)$

$$\sigma_{\rm self} = \frac{\alpha^2}{m_\chi^2} \sim 0.1 \text{ b}$$

From $\Omega_\chi h^2 \sim 0.1 \left(\frac{1 \text{ pb}}{\langle \sigma_{\rm eff.} v \rangle} \right)$,

$$\langle \sigma_{\rm eff.} v \rangle = n_\chi \langle \sigma v^2 \rangle = n_\chi \times \frac{\alpha^3}{m_\chi^5}$$

$$= R \times \sigma_{\rm self} = 1 \text{ pb}$$

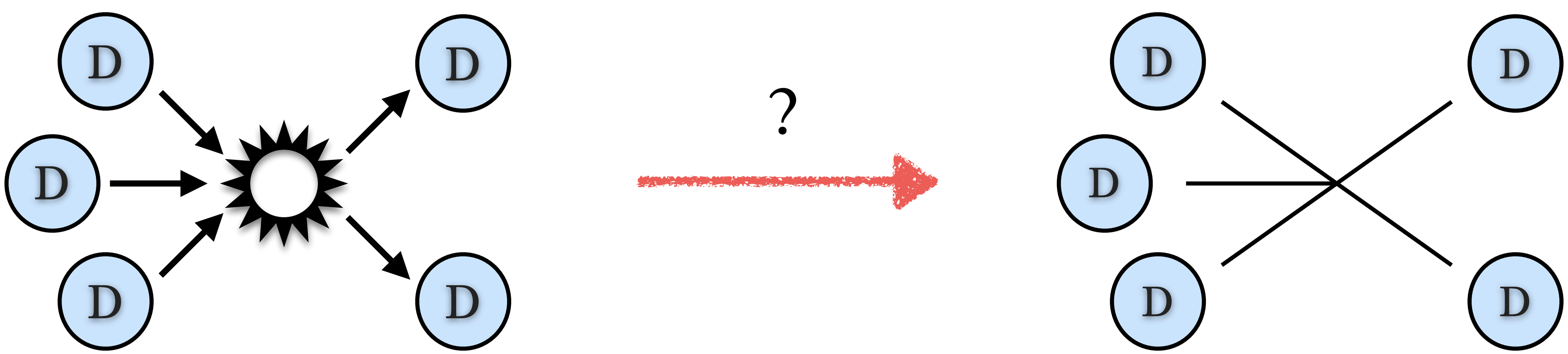
$$\left(\because R = \frac{g_\chi \alpha}{(2\pi)^{3/2}} x_f^{-3/2} e^{-x_f} \sim 10^{-11} \right)$$

SMC, Y. J. Kang, H. M. Lee, JHEP 1612 (2016) 099

The SIMPlest realization

- The most SIMPlest realization is contact interaction
- Wess-Zumino-Witten term in the chiral perturbation theory
- Global $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$ by dark quark condensation
- Assumption : pions have degenerated masses

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \sum_{i=1}^{3} \bar{Q}_i i\gamma^\mu D_\mu Q_i$$



Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker (2014)

Minimal SIMP Model

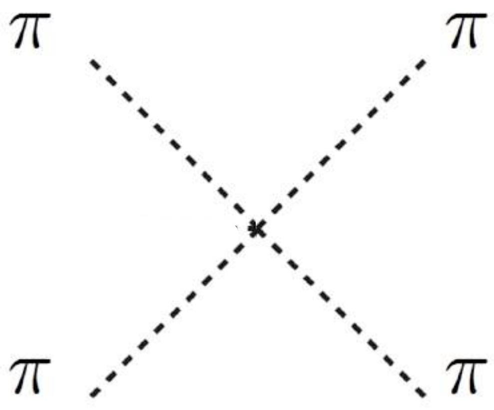
- The minimal SIMP Lagrangian comes from

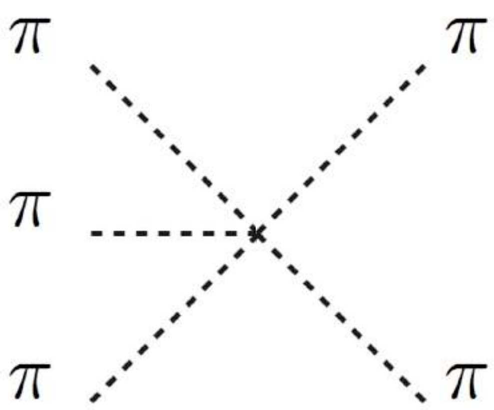
  CCWZ construction / mass term / WZW anomaly term

- Only one self-interaction and self-annihilation diagram

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\mathrm{CCWZ}} + \mathcal{L}_{\mathrm{mass}} + \mathcal{L}_{\mathrm{WZW}} \\
&= \frac{f_\pi^2}{4}\mathrm{Tr}[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger] - \frac{f_\pi^2}{2}\mathrm{Tr}[\mu(M\Sigma + \Sigma^\dagger M)] \\
&\quad + \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]
\end{aligned}
$$

$$(\ \Sigma = e^{2i\pi/f_\pi} \ )$$

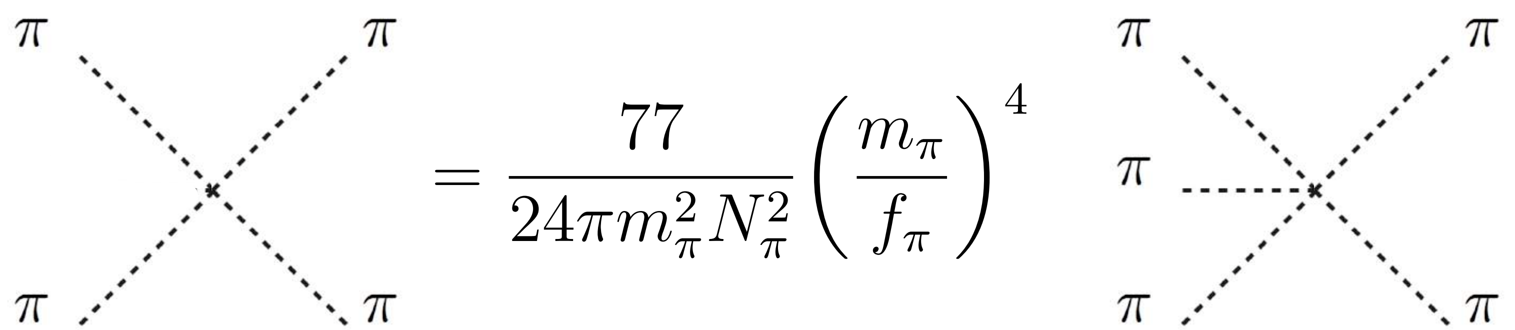




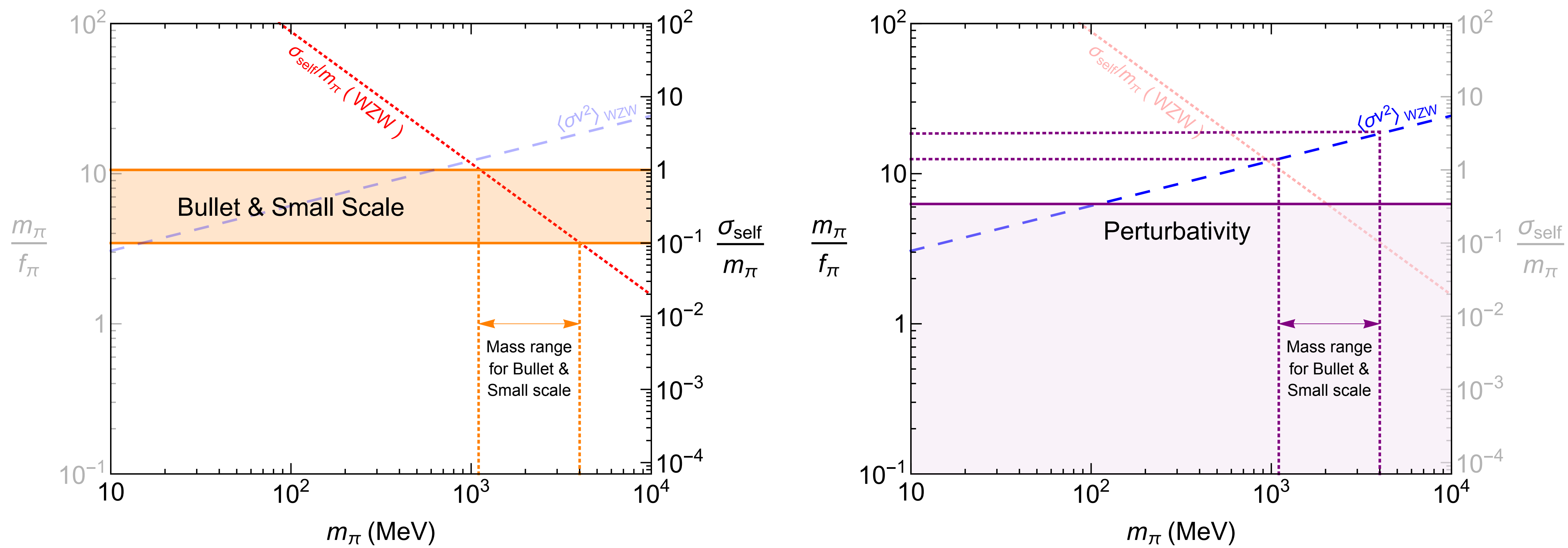
M. Bando et al (1988), P. Ko (1991), **SMC**, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

Perturbativity Problem

- Perturbativity problem for the pion SIMP $(m_\pi/f_\pi \sim 2\pi)$
- Leading order analysis will be broken



$$= \frac{77}{24\pi m_\pi^2 N_\pi^2}\left(\frac{m_\pi}{f_\pi}\right)^4 \qquad = \frac{25\sqrt{5}N_c^2}{128\pi^5 m_\pi^5 N_\pi^3}\left(\frac{m_\pi}{f_\pi}\right)^{10}$$



M. Hansen, K.Langaeble and F. Sannino (2015), **SMC**, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

Vector Meson

- Non-linearly transformed $G_{\text{global}}/H_{\text{global}} = SU(3)_L \times SU(3)_R/SU(3)_V$

  = Integrating out the VM from linearly realized $G_{\text{global}} \times H_{\text{local}}$
- VMs are the massive gauge fields of a local $SU(3)_V$
- Assumption : VMs have degenerated masses

$$\mathcal{L} = \mathcal{L}_\pi - \frac{1}{2}\mathrm{Tr}(V_{\mu\nu}V^{\mu\nu}) + \Delta\mathcal{L}_V + \mathcal{L}_{\text{anon.}}$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$\Delta\mathcal{L}_V = m_V^2 \mathrm{Tr}(V_\mu V^\mu) - iag\mathrm{Tr}(V_\mu[\partial^\mu \pi, \pi]) - \frac{a}{4f_\pi^2}\mathrm{Tr}([\pi, \partial_\mu \pi]^2)$$

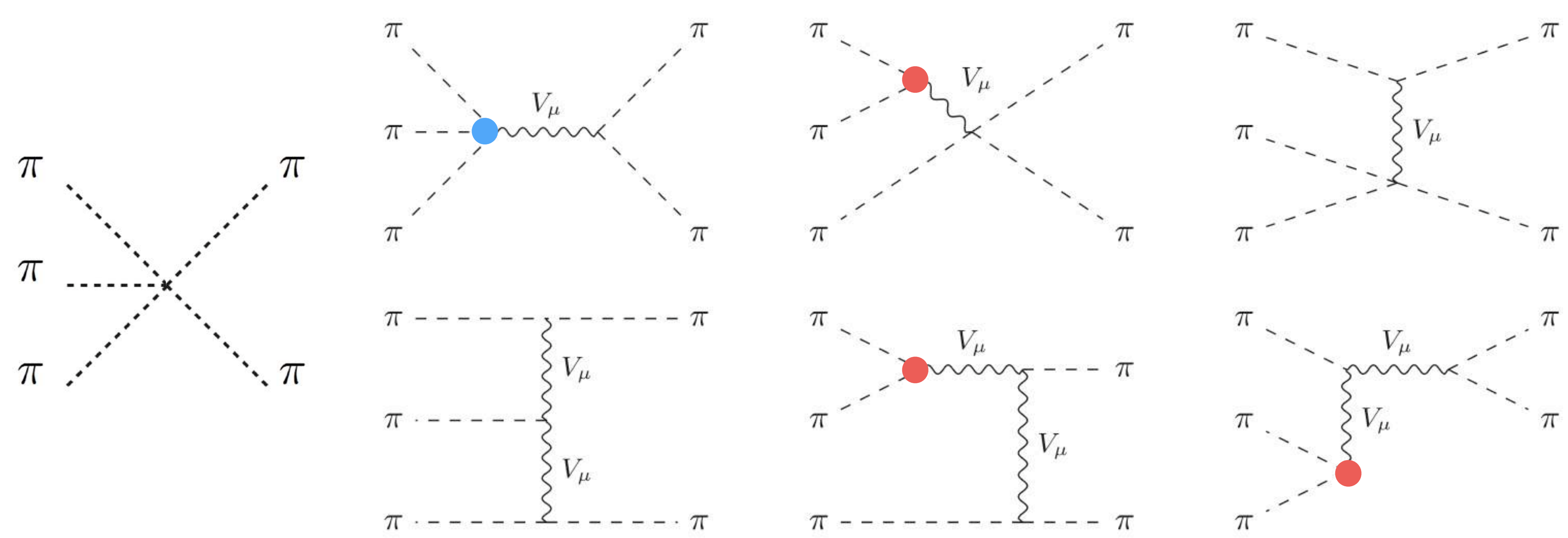
$$m_V^2 = ag^2 f_\pi^2$$

M. Bando et al (1988), P. Ko (1991), **SMC**, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

Diagrams

- VMs interact with pions
- 7 Feynman diagrams for self-annihilation / 2 type resonances

$$
\begin{aligned}
\Delta\mathcal{L}_V + \mathcal{L}_{\text{anom.}} &= \Delta\mathcal{L}_V + \mathcal{L}_{\text{WZW}} - 15(c_1\mathcal{L}_1 + c_2\mathcal{L}_2 + c_3\mathcal{L}_3) \\
&\supset -iag\mathrm{Tr}(V_\mu[\partial^\mu\pi,\pi]) - \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi] \\
&\quad - \frac{igN_c(c_1-c_2)}{4\pi^2 f_\pi^3}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[V_\mu\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi] + \frac{gN_c c_3}{8\pi^2 f_\pi}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[(\partial_\mu V_\nu)(V_\rho\partial_\sigma\pi - \partial_\rho\pi V_\sigma)]
\end{aligned}
$$



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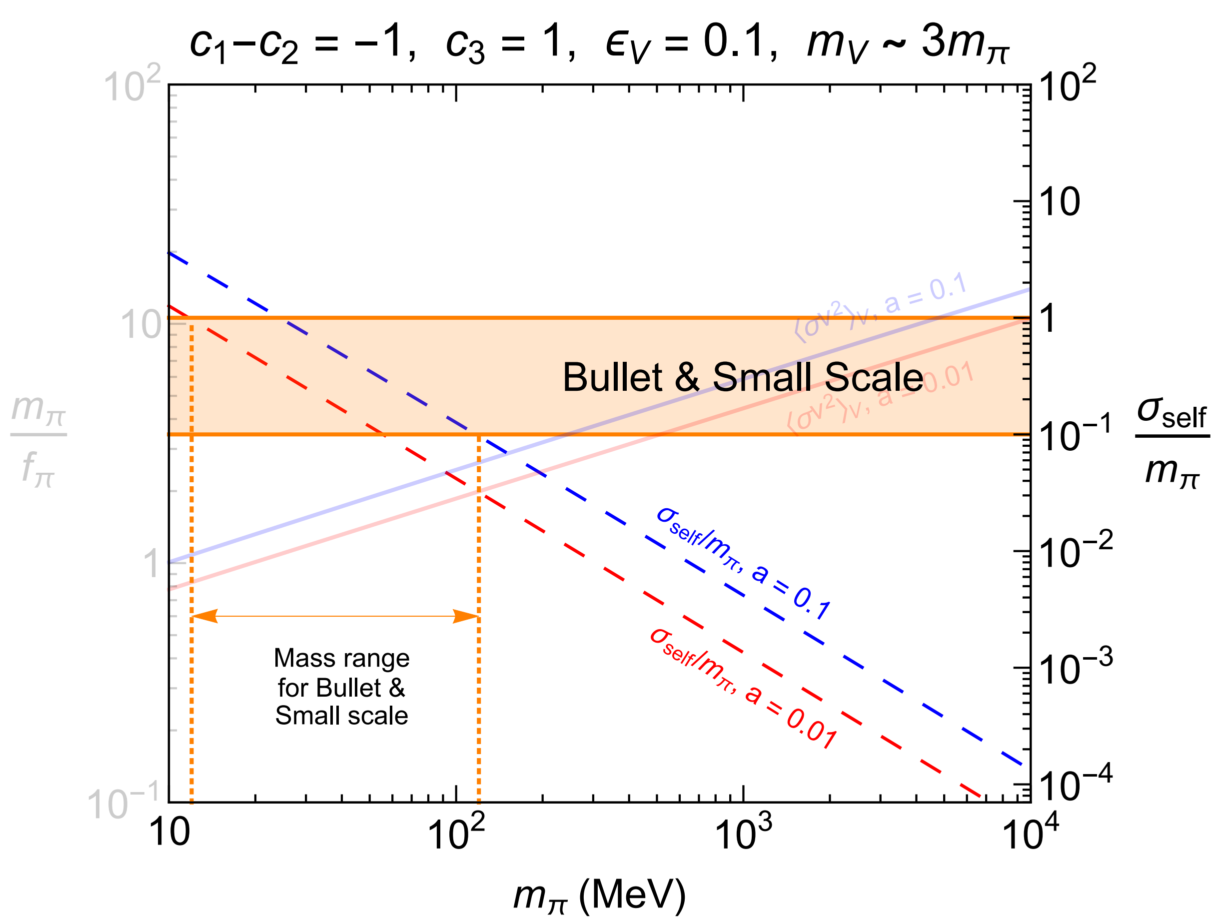
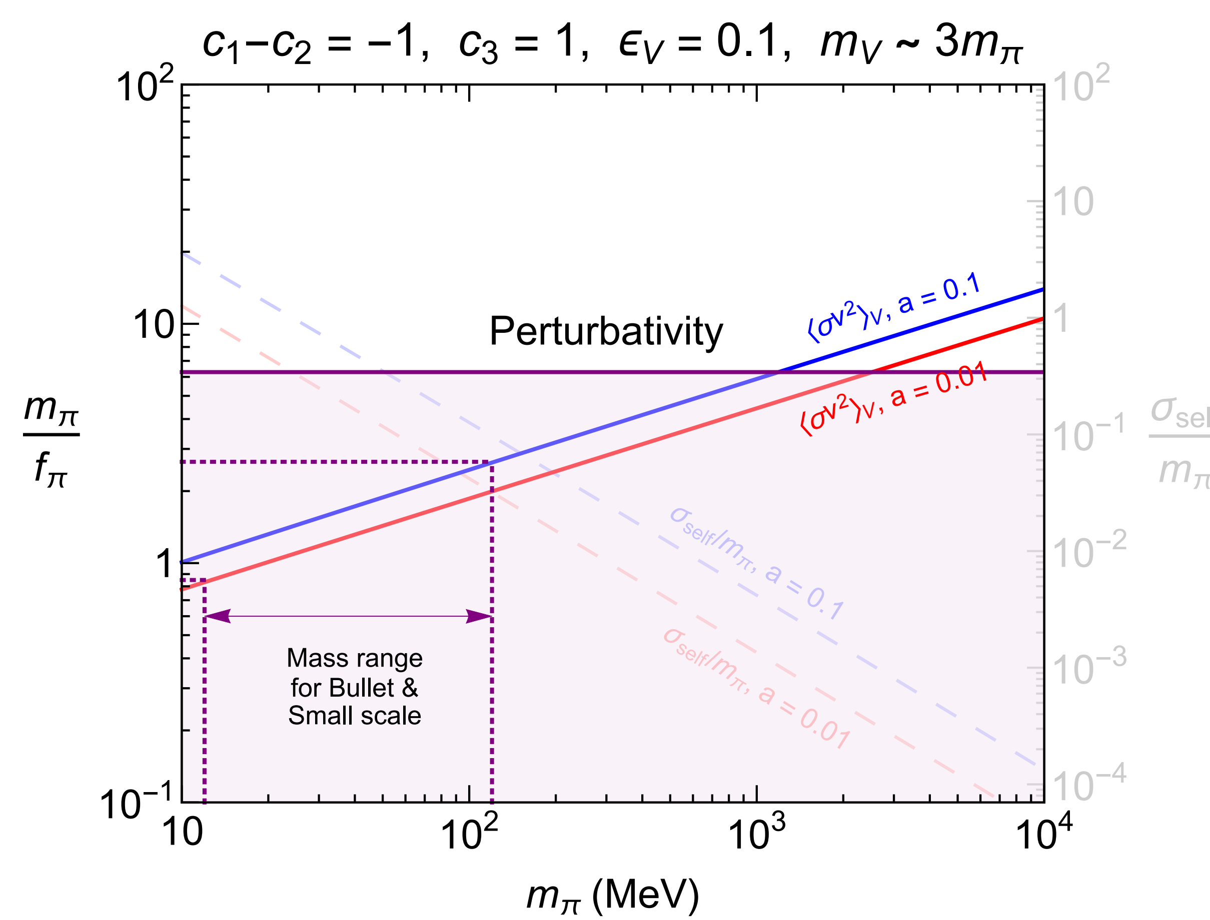
3-pion resonance

- m_π/f_π can be smaller by VM mediated diagrams.
- Leading order analysis is enough

$$\langle \sigma v^2 \rangle_V \propto \epsilon_V^4 x^3 e^{-\frac{3}{2}\epsilon_V x}, \quad m_V = 3m_\pi\sqrt{1+\epsilon_V}, \quad m_V^2 = a g^2 f_\pi^2$$





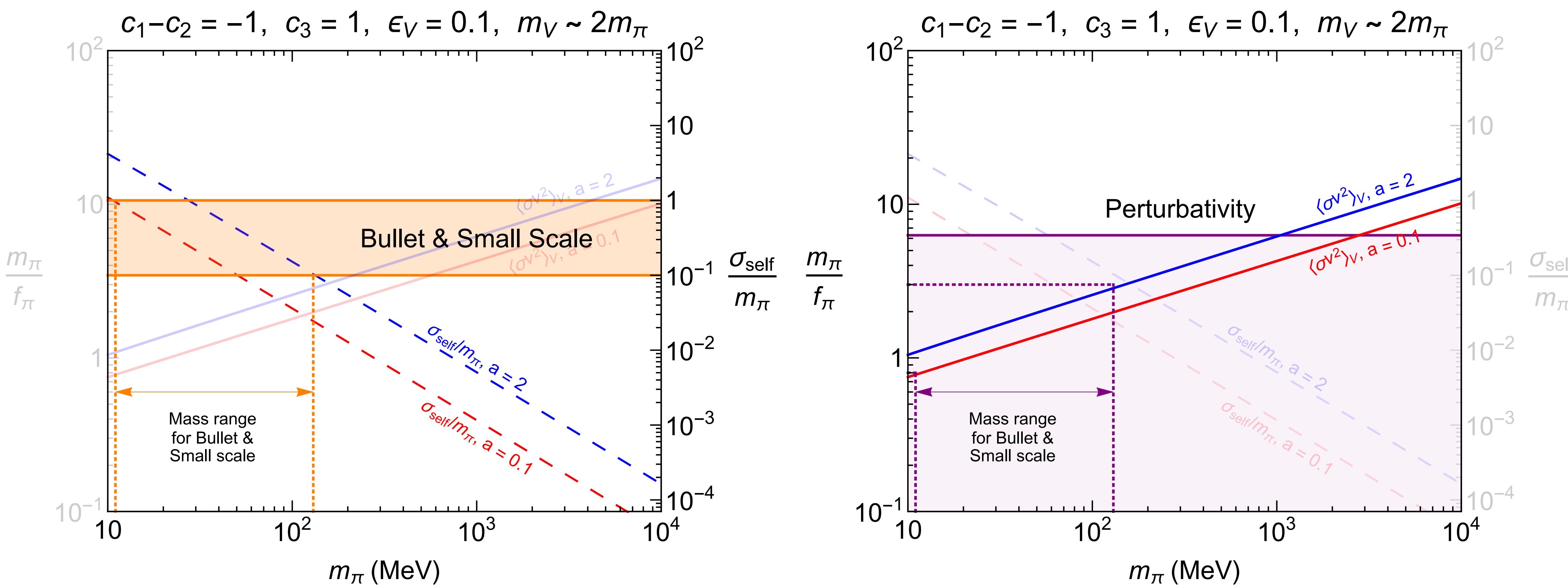
SMC, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

SMC, H. M. Lee, Phys. Lett. B758 (2016) 47, **SMC**, H. M. Lee, M. S. Seo, JHEP 1704 (2017) 154

2-pion resonance

- m_π/f_π can be smaller by VM mediated diagrams.
- Leading order analysis is enough

$$\langle\sigma v^2\rangle_V \propto \epsilon_V^{3/2} x^{1/2} e^{-\epsilon_V x}, \quad m_V = 2m_\pi\sqrt{1+\epsilon_V}, \quad m_V^2 = a g^2 f_\pi^2$$



SMC, H. M. Lee, P. Ko, A. Natale, Phys. Rev. D98 (2018) no.1, 015034

SMC, H. M. Lee, Phys. Lett. B758 (2016) 47, SMC, H. M. Lee, M. S. Seo, JHEP 1704 (2017) 154

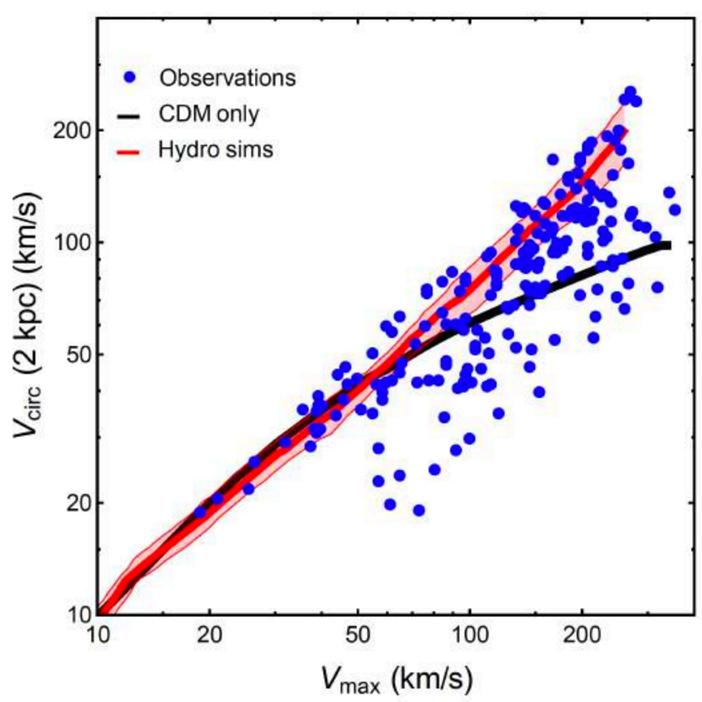
Conclusion

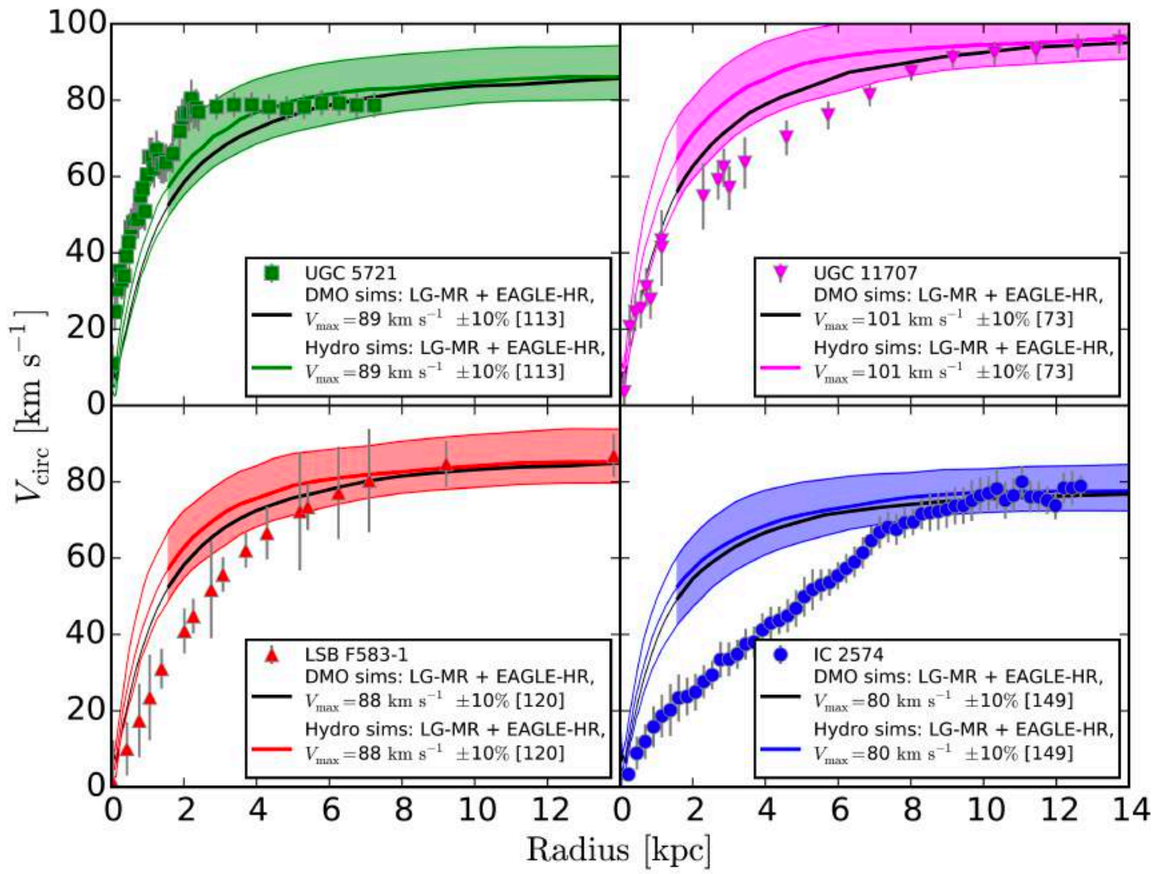
- We have considered a SIMP scenario of dark pions which are the pseudo-Goldstones from dark flavor symmetry and strongly coupled from dark QCD interactions.
- Including vector mesons in the hidden gauge symmetry, we showed that the perturbativity problem of SIMP scenario in dark ChPT can be alleviated.
- To release heat to the SM sector, kinetic equilibrium b/w dark sector and SM sector is possible by the scattering with SM mediated by dark singlet scalar, sigma field or dark photon.
- More general cases with non-degenerate pion and vector meson masses can make many resonance points and it will give much larger parameter space. Also multi-component SIMP is possible.
- Resonance masses of VMs can be searched through the kinetic mixing via dark photon.

Back-up

Small Scale Problems

- LCDM Model is successful to explain the large scale structure formation and matter power spectrum $> \mathcal{O}\ (\mathrm{Mpc})$
- Controversy over the differences b/w simulations and observations for the small scales
- Core-Cusp / Missing satellite / Too-big-to-fail / Diversity problem

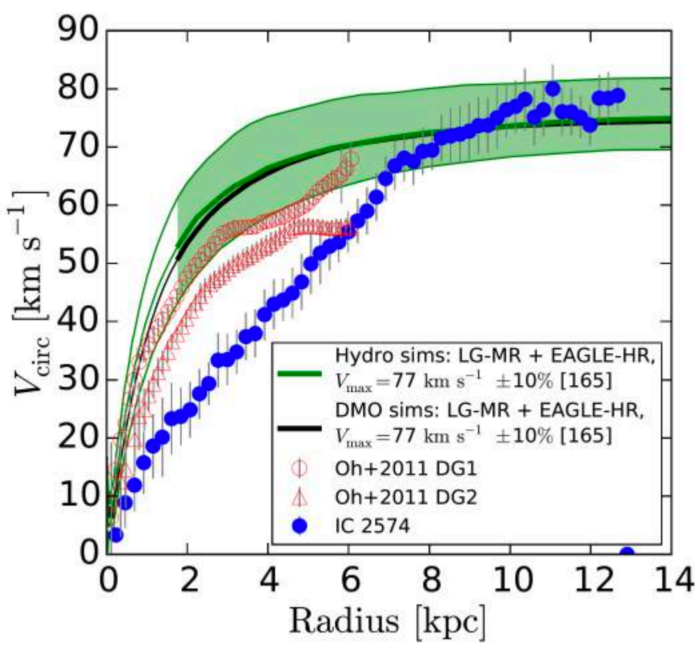




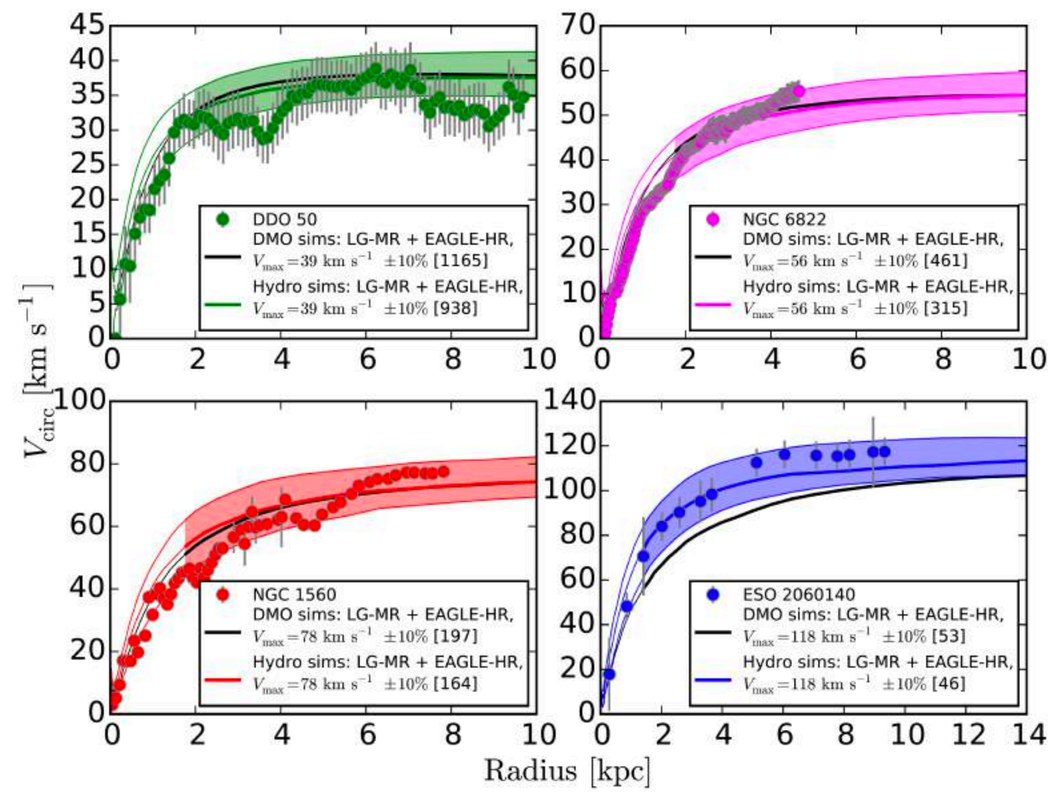
S. Tulin, H. B. Yu (2017), Oman et al (2015)

Small Scale Problems

- There are solutions for SSPs
  : Baryonic physics / Self-Interacting Dark Matter
- As galaxies form, gas sinks into the inner halo to produce stars
- Feedback from supernova-driven gas outflows and repeated bursts
- Reduce the central density through a purely gravitational interaction between DM and baryons



Ultra-low density core



DM core formation
with feedback ?

$2 < z < 4$
vs
$z < 2$

S. Tulin, H. B. Yu (2017), Oman et al (2015), Bullock et al (2015)

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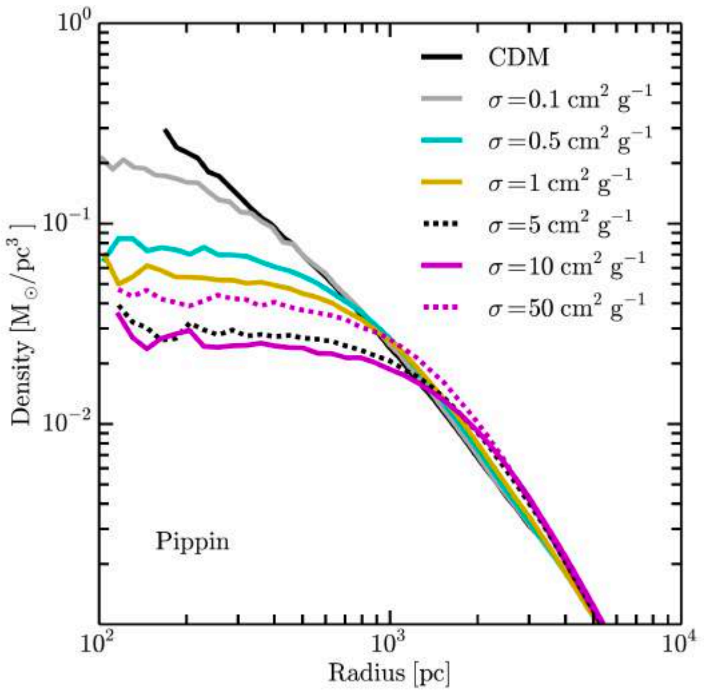
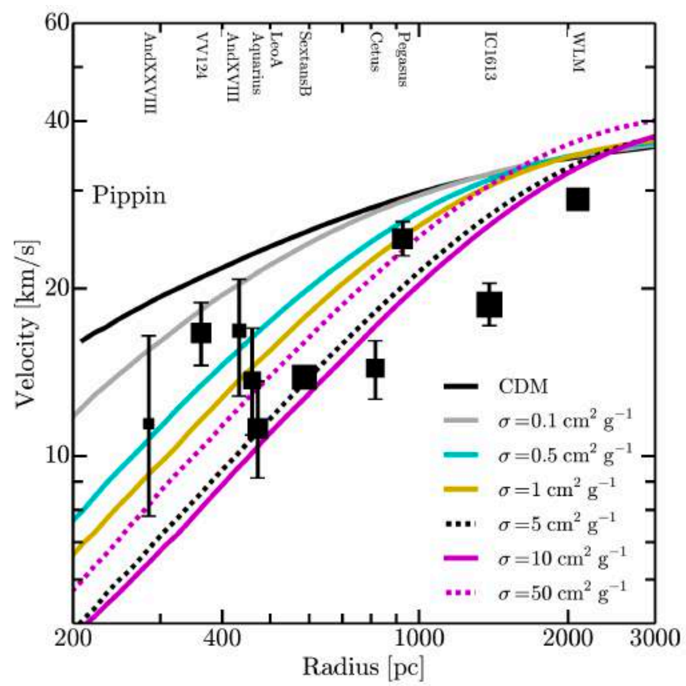
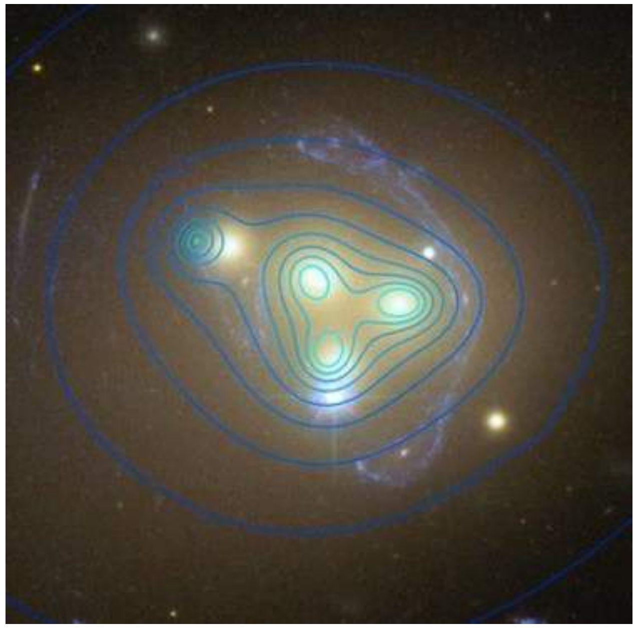




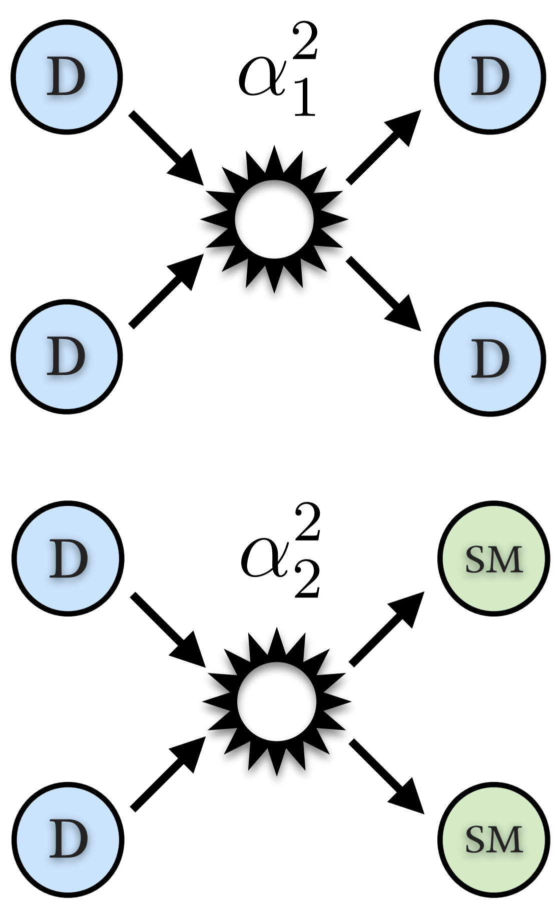


S. Tulin, H. B. Yu (2017)

Abell-3827 / 520

Self-Interacting Dark Matter

- There are several mechanisms for SIDM
- Sommerfeld enhancement / Light dark matters / ...
- Light dark matter : Standard Annihilating SIDM / Forbidden Dark Matter / Strongly Interacting Massive Particle / ...



For the $\mathcal{O}(1)$ coupling

$$\sigma_{\mathrm{self}} = \frac{\alpha_1^2}{m_\chi^2} \sim 0.1 \text{ b}$$

From $\Omega_\chi h^2 \sim 0.1 \left(\frac{1 \text{ pb}}{\langle \sigma_{\mathrm{anni.}} v \rangle} \right)$,

$$\langle \sigma_{\mathrm{anni.}} v \rangle = \frac{\alpha_2^2}{m_\chi^2} \sim 1 \text{ pb}$$

$\therefore \frac{\alpha_2^2}{\alpha_1^2} \sim 10^{-11} \Rightarrow$ Must be tuned

SMC, Y. J. Kang, H. M. Lee, JHEP 1612 (2016) 099

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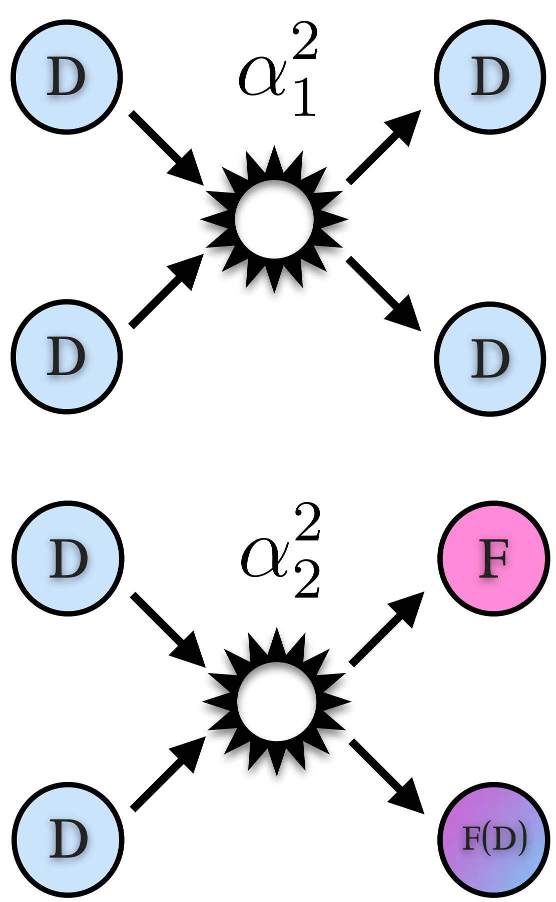

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From $\Omega_\chi h^2 \sim 0.1 \left(\frac{1 \text{ pb}}{\langle \sigma_{\rm anni.} v \rangle} \right)$ & $m_\chi < m_F$,

$$\langle \sigma_{\rm anni.} v \rangle \sim e^{-2\Delta x_f} \sigma_{\rm self} \quad (\text{or } e^{-\Delta x_f} \sigma_{\rm self})$$

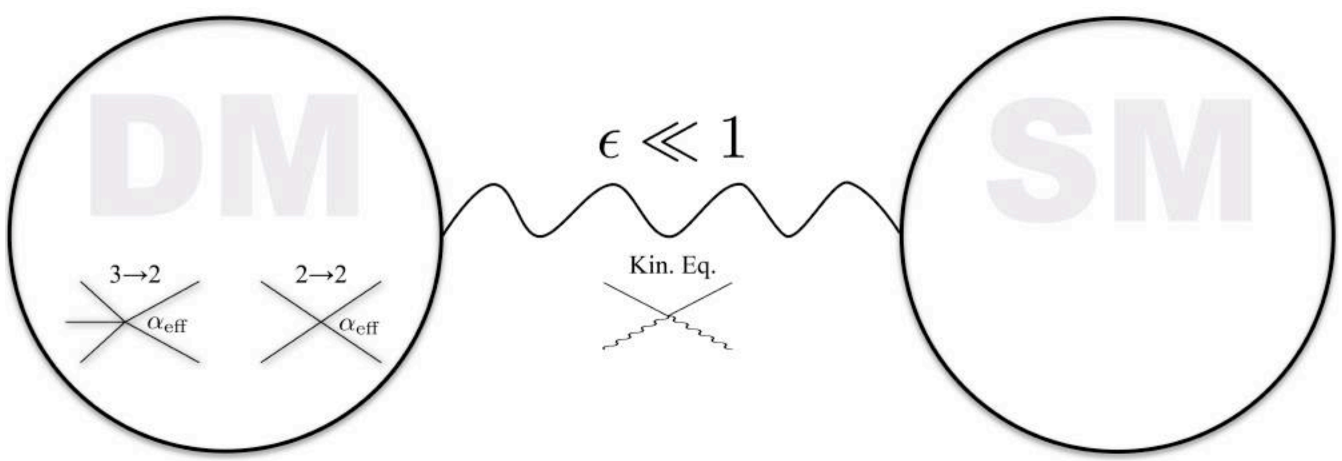
$$\sim 10^{-12} \ b, \quad \Delta = \frac{m_F - m_\chi}{m_\chi}$$

J. Ruderman et al (2015), **SMC**, Y. J. Kang, H. M. Lee, JHEP 1612 (2016) 099

SIMP Dark Matter

- Strongly Interacting Massive Particle
- Freeze-out process is 3 to 2 self-annihilation with $\chi\chi\chi \to \chi\chi$
- Mass scale of SIMP is $\mathcal{O}(10-100)\ \mathrm{MeV}$ with the large coupling $\alpha \sim 1$ for the relic density $\langle \sigma v^2 \rangle \propto \alpha^3/m_\chi^5$

  (WIMP : $\langle \sigma v \rangle \propto \alpha^2/m_\chi^2, \quad \alpha \sim 1/30$)
- Kinetic equilibrium with SM is essential part of SIMP for structure formation (SIMP condition)



$$\left.\frac{\Gamma_{2\to 2}}{\Gamma_{3\to 2}}\right|_{\mathrm{T=T_f}} \lesssim 1$$

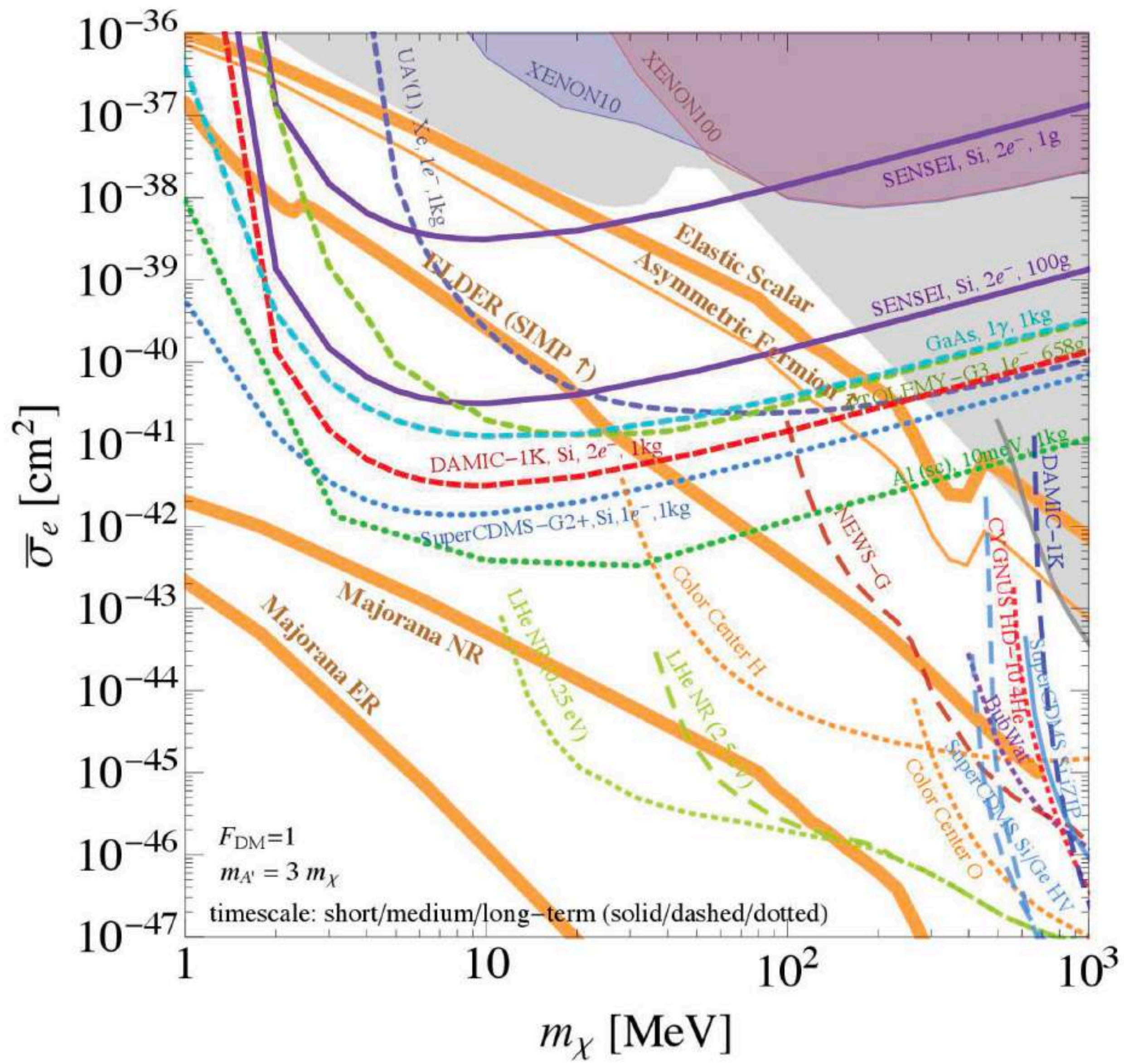
$$\left.\frac{\Gamma_{3\to 2}}{\Gamma_{\mathrm{Kin.}}}\right|_{\mathrm{T=T_f}} \lesssim 1$$

Γ : Interaction Rate, $\mathrm{T_f}$: Freeze-out Temperature

Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker (2014)

SIMP Dark Matter

- There are direct detection bounds for SIMP
- SIMP is a testable mechanism



US Cosmic Visions Community Report (2017)

Self-Interaction

$$\sigma_{\rm scat} = \frac{77 m_\pi^2}{24\pi f_\pi^4 N_\pi^2} + \frac{m_\pi^2 (139 f_\pi^2 g^2 - 216 m_\pi^2)}{96\pi f_\pi^6 g^2 N_\pi^2} v^2 + \frac{m_\pi^2}{12288\pi f_\pi^4 N_\pi^2} \left[2176 + \frac{12 A_1}{f_\pi^2 g^2 m_V^2 (4 m_\pi^2 - m_V^2)} + \frac{9 A_2}{f_\pi^4 g^4 (4 m_\pi^2 - m_V^2)^2} \right] v^4,$$

with

$$A_1 = 6144 m_\pi^6 - 5376 m_\pi^4 m_V^2 + 796 m_\pi^2 m_V^4 - 7 m_V^6,$$
$$A_2 = 10240 m_\pi^8 - 6144 m_\pi^6 m_V^2 + 1008 m_\pi^4 m_V^4 + 72 m_\pi^2 m_V^6 - 9 m_V^8.$$

Self-annihilation

$$(\sigma v^2) = \frac{25\sqrt{5}N_c^2 m_\pi^5}{\pi^5 f_\pi^{10} N_\pi^3}\left[\frac{1}{128} - \frac{15a(c_1-c_2)f_\pi^2 g^2 B_1}{1024(4m_\pi^2-m_V^2)(9m_\pi^2-m_V^2)(m_\pi^2+m_V^2)} + \frac{225a^2(c_1-c_2)^2 f_\pi^4 g^4 B_2}{16384(4m_\pi^2-m_V^2)^2(9m_\pi^2-m_V^2)^2(m_\pi^2+m_V^2)^2}\right.$$
$$- \frac{225a^3(c_1-c_2)c_3 f_\pi^6 g^5 B_3}{8192(4m_\pi^2-m_V^2)^2(9m_\pi^2-m_V^2)^2(m_\pi^2+m_V^2)^3} + \frac{15a^2 c_3 f_\pi^4 g^3 B_4}{512(4m_\pi^2-m_V^2)(9m_\pi^2-m_V^2)(m_\pi^2+m_V^2)^2}$$
$$\left. + \frac{225a^4 c_3^2 f_\pi^8 g^6 B_5}{8192(4m_\pi^2-m_V^2)^2(9m_\pi^2-m_V^2)^2(m_\pi^2+m_V^2)^4}\right] b_V \quad (23)$$

with $b_V = \frac{1}{4}(v_1^2+v_2^2+v_3^2)^2 - \frac{1}{2}(v_1^4+v_2^4+v_3^4)$ and

$$B_1 = 37m_\pi^4 - 21m_\pi^2 m_V^2 + 2m_V^4$$
$$B_2 = 829m_\pi^8 - 828m_\pi^6 m_V^2 + 299m_\pi^4 m_V^4 - 42m_\pi^2 m_V^6 + 2m_V^8$$
$$B_3 = 526m_\pi^8 - 599m_\pi^6 m_V^2 + 236m_\pi^4 m_V^4 - 37m_\pi^2 m_V^6 + 2m_V^8$$
$$B_4 = 11m_\pi^4 - 8m_\pi^2 m_V^2 + m_V^4$$
$$B_5 = 170m_\pi^8 - 218m_\pi^6 m_V^2 + 95m_\pi^4 m_V^4 - 16m_\pi^2 m_V^6 + m_V^8. \quad (24)$$

Examples : Resonance

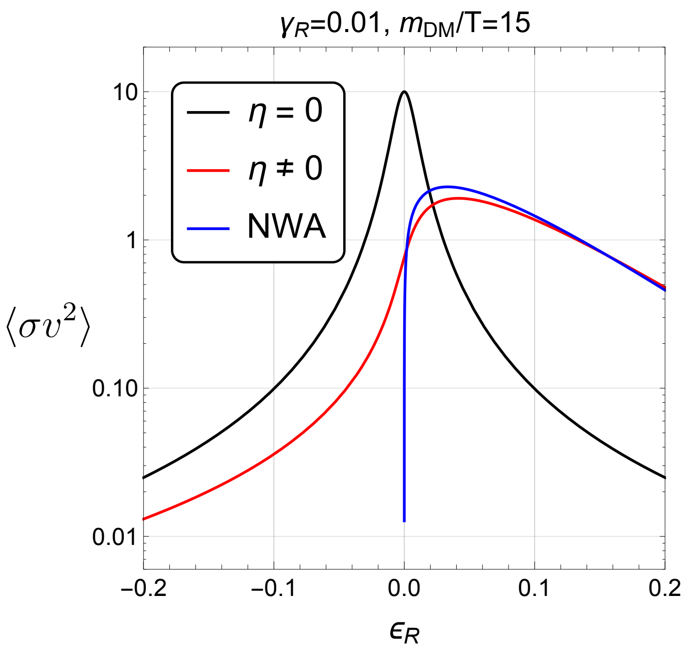
- Resonance effect is important for the thermal-average of cross-section
- Narrow Width Approximation makes the maximal resonance effect
  (QCD-like set of parameters : $c_1 - c_2 \sim -1,\ c_3 \sim 1,\ a \sim 2$)

$$\dot{n}_\pi + 3Hn_\pi = -\frac{1}{64}\langle\sigma v^2\rangle_{3\to2}(n_\pi^3 - n_\pi^2 n_{\rm eq})$$

$$\langle\sigma v^2\rangle_{3\to2} \equiv \frac{\int d^3p_1 d^3p_2 d^3p_3 (\sigma v^2)_{3\to2} e^{-E_1/T} e^{-E_2/T} e^{-E_3/T}}{\int d^3p_1 d^3p_2 d^3p_3 e^{-E_1/T} e^{-E_2/T} e^{-E_3/T}}$$

$$\frac{m_V^2\Gamma_V^2}{(s-m_V^2)^2 + m_V^2\Gamma_V^2} = \frac{\gamma_R^2}{(\epsilon_R - \eta)^2 + \gamma_R^2} \sim \pi\gamma_R\delta(\epsilon_R - \eta)$$

(NWA)



For 3-reso $(\epsilon_R, \gamma_R, \eta) = \left(\frac{m_V^2 - 9m_\pi^2}{9m_\pi^2}, \frac{m_V\Gamma_V}{9m_\pi^2}, \frac{1}{3}(v_1^2 + v_2^2 + v_3^2)\right)$

For 2-reso $(\epsilon_R, \gamma_R, \eta) = \left(\frac{m_V^2 - 4m_\pi^2}{4m_\pi^2}, \frac{m_V\Gamma_V}{4m_\pi^2}, \frac{1}{2}(v_1^2 + v_2^2) - \frac{1}{4}v_3^2\right)$

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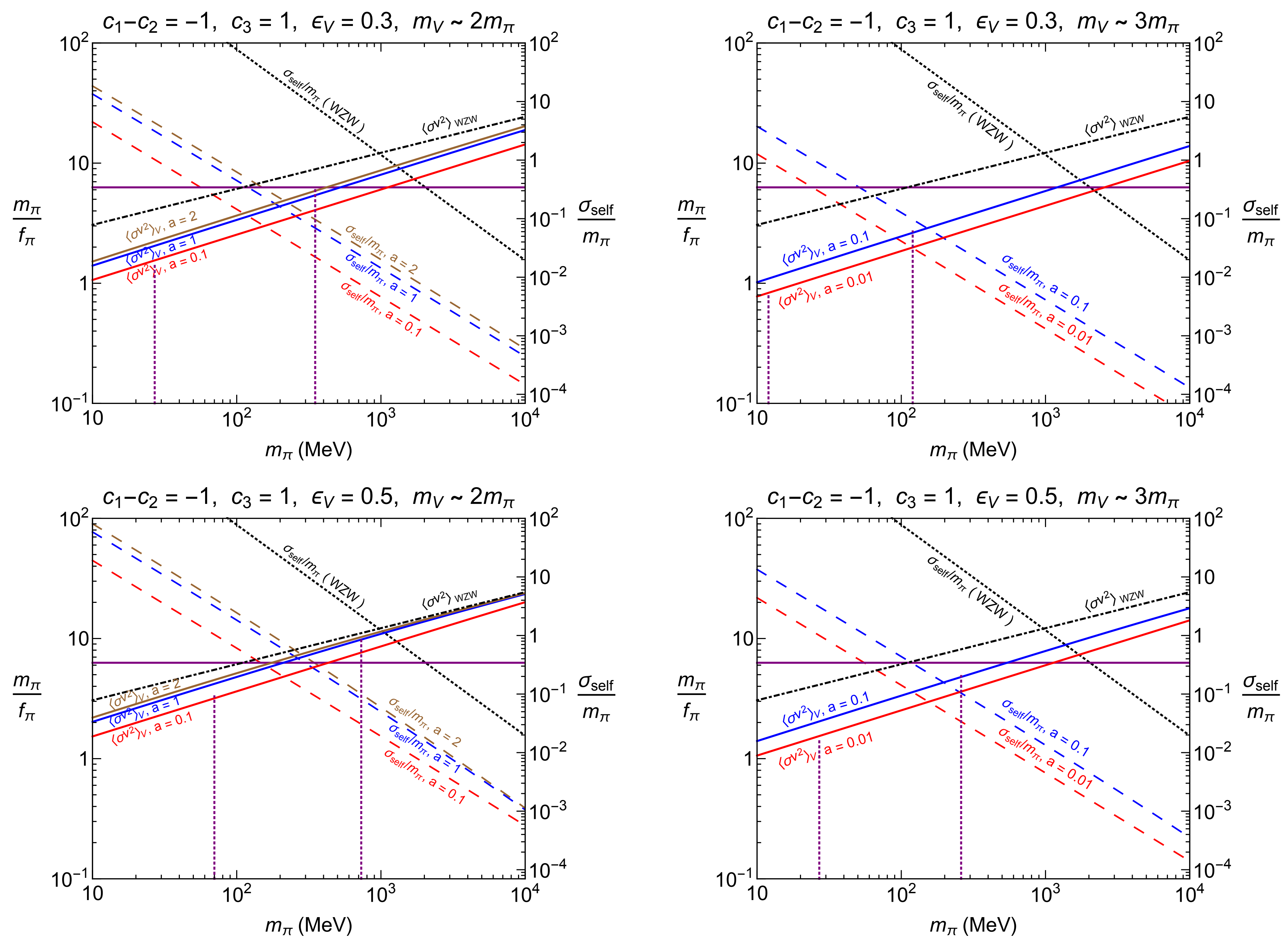
Dark Pions with Vector Mesons

- Varying the anomalous paremeters and mass difference are acceptable

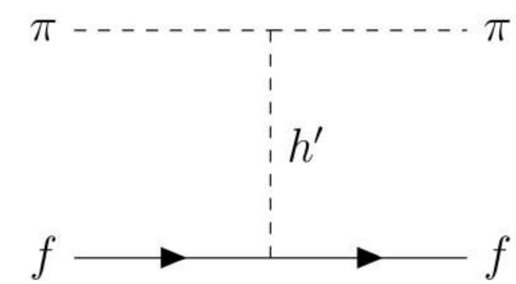


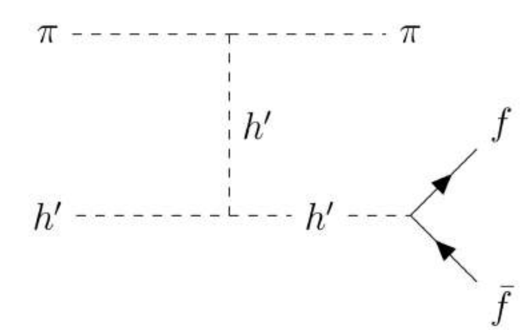
Kinetic Equilibrium

- Kinetic equilibrium is important for the structure formation for SIMP
- There are many ways to get a kinetic equilibrium in this model

1. Dark Scalar Portal (singlet / sigma field)

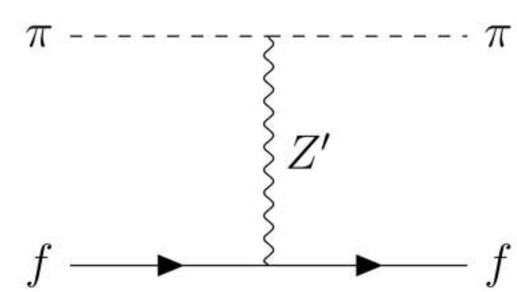
- Scalar mixing with Higgs
- Pion-electron scattering
- Pion-dark Higgs scattering with decay





2. Dark Photon Portal by the Kinetic Mixing

- If dark pions are charged by dark local U(1) and dark photon is mixed with SM particle
- Scattering b/w dark pion and (SM pion / neutrino / lepton)



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