The SIMP paradigm:
new territory for thermal relics

Hyun Min Lee

Chung-Ang University, Korea

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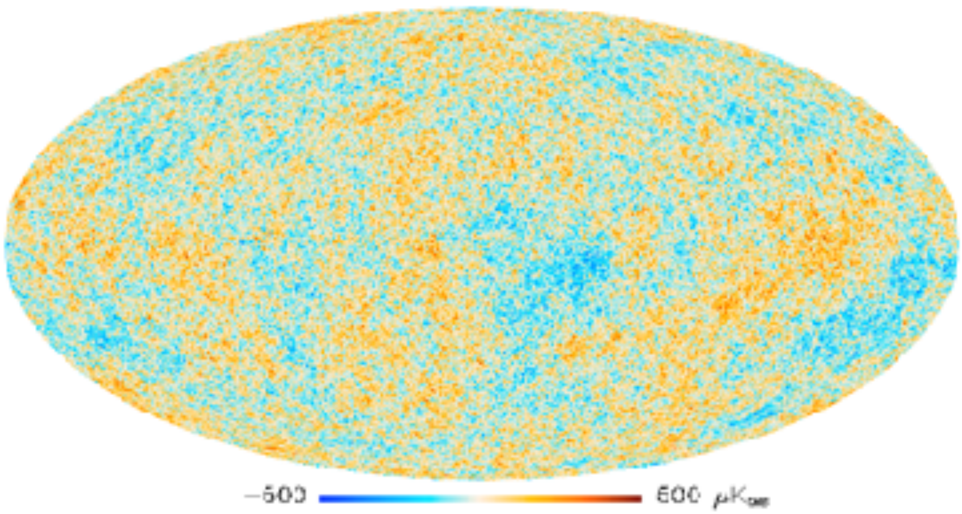
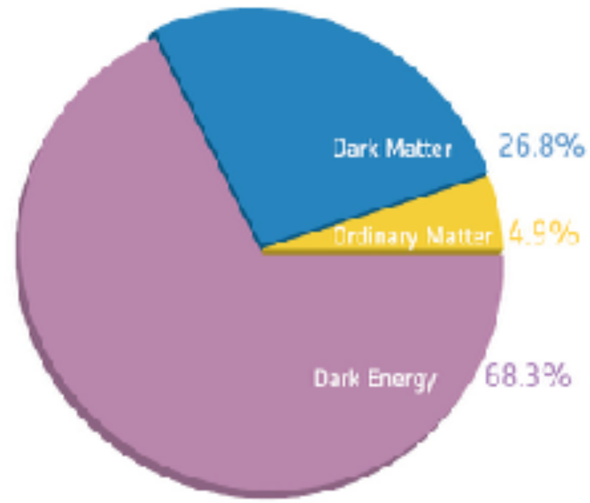
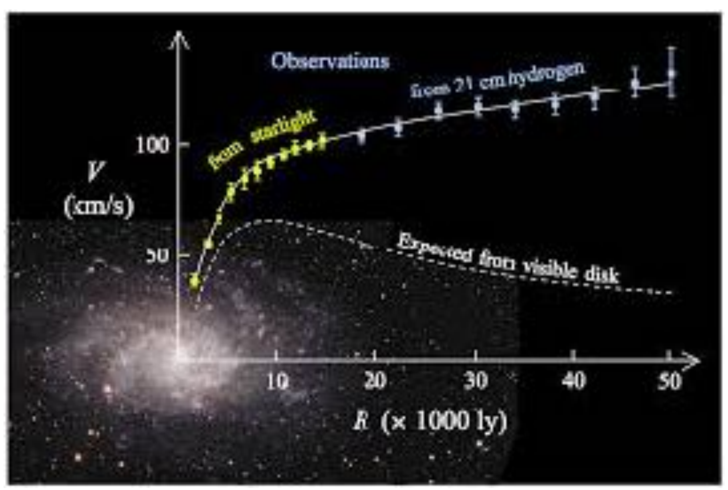
Outline

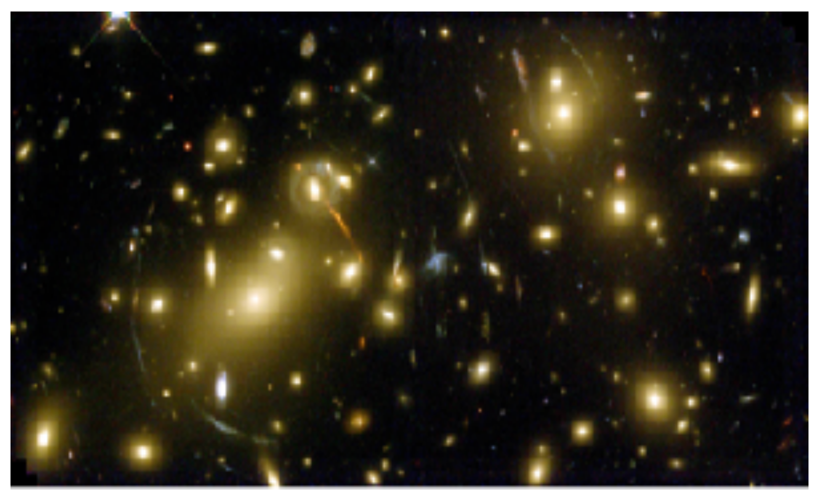
- Introduction
- SIMP mesons
- Resonant SIMPs
- Conclusions

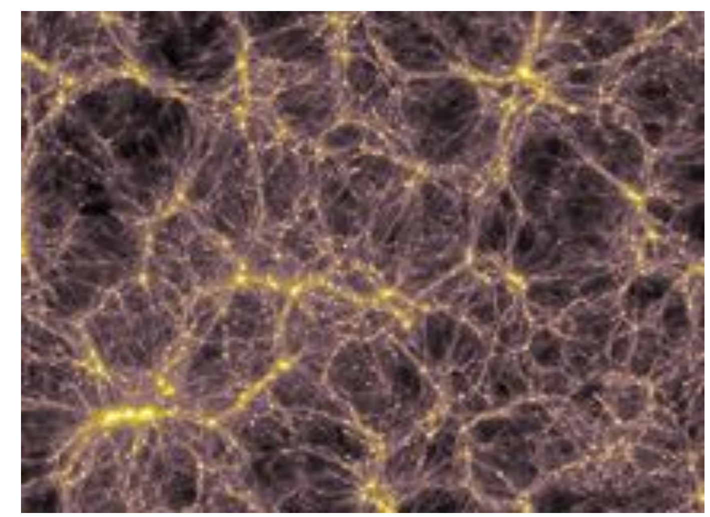
Dark matter from sky











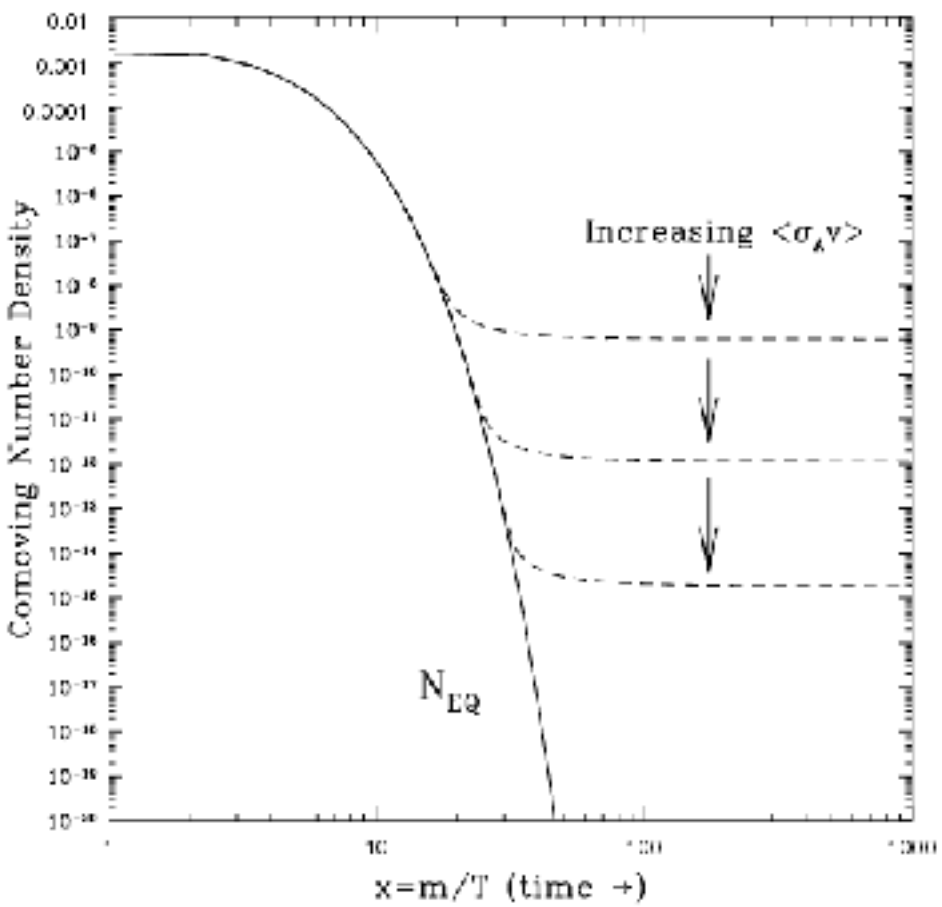
- Various evidences for dark matter from galaxy rotation curves, CMB, gravitational lensing, and large scale structure.

Non-gravitational evidence is missing!
What is particle nature of dark matter?

WIMP Paradigm

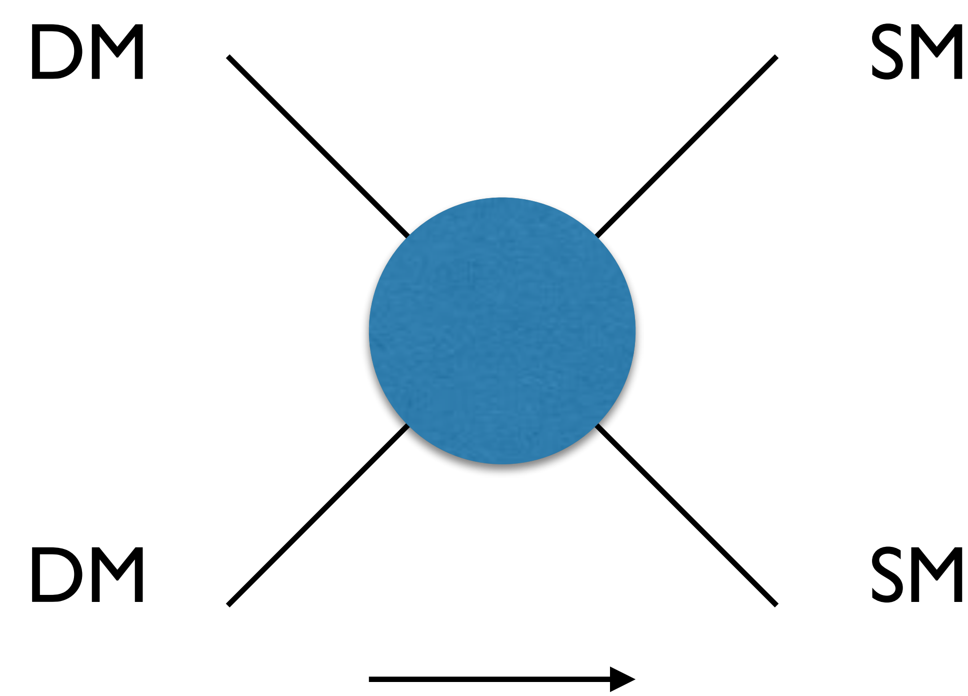
[Lee,Weinberg(1977)]

DM number



time

Dark matter once in thermal equilibrium with SM particles

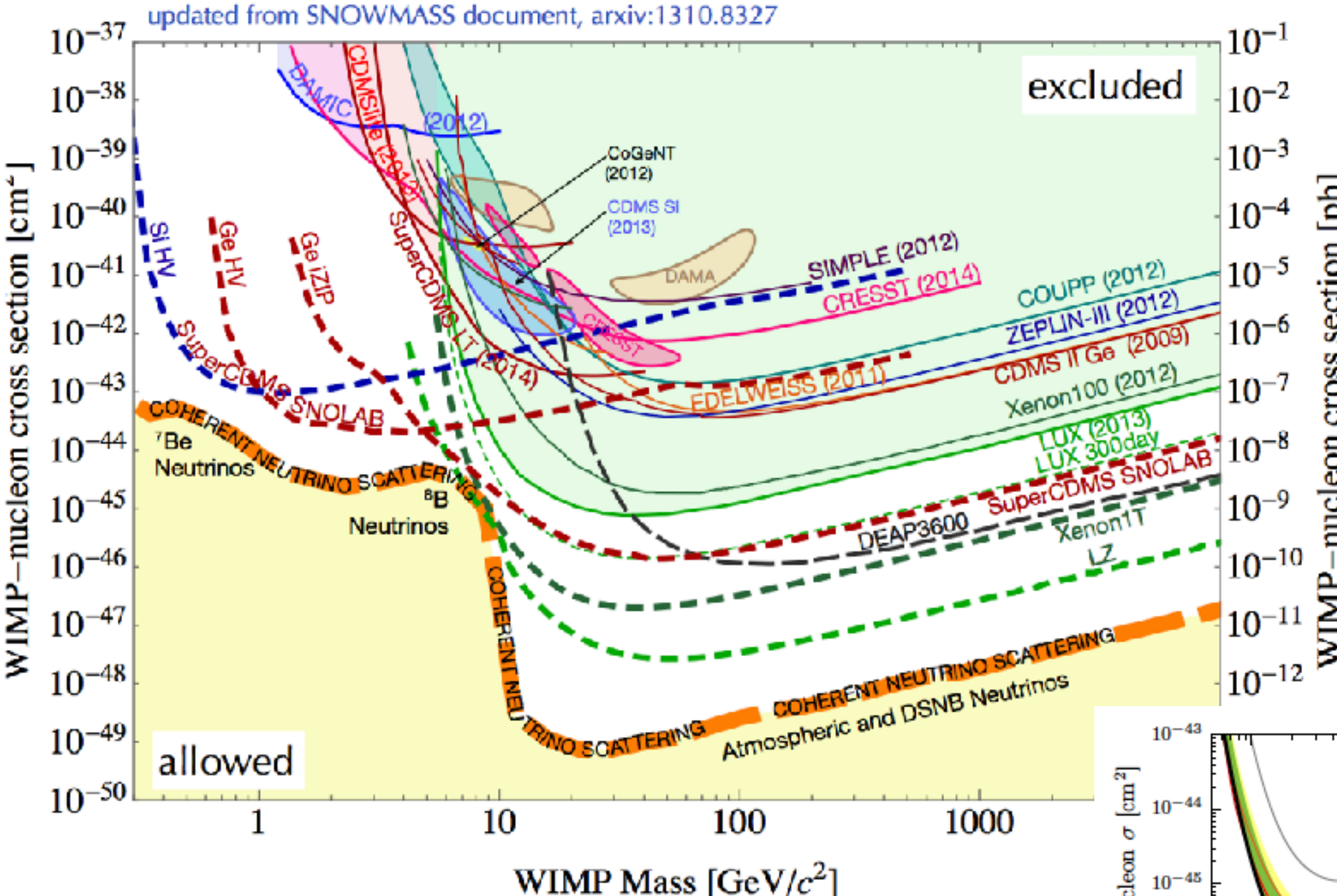


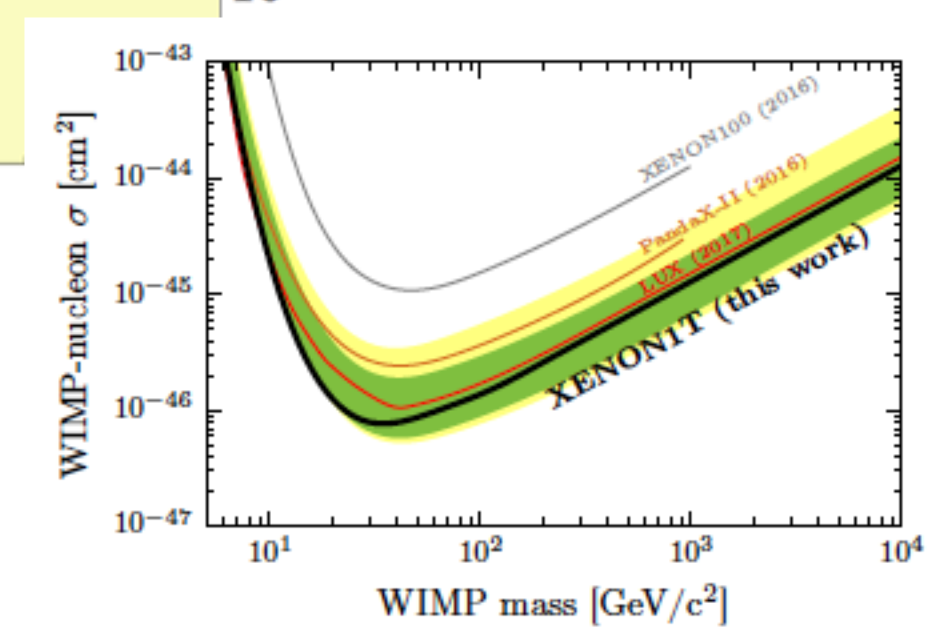
Weak interaction with 100GeV-1TeV mass:

$$\Longrightarrow \quad \Omega_{\rm DM} h^2 = 0.1 \left(\frac{1\,{\rm pb}\cdot c}{\langle \sigma_A v \rangle} \right)$$

Interplay of direct, indirect and collider detections!

WIMP in challenge





No direct evidence for WIMP yet

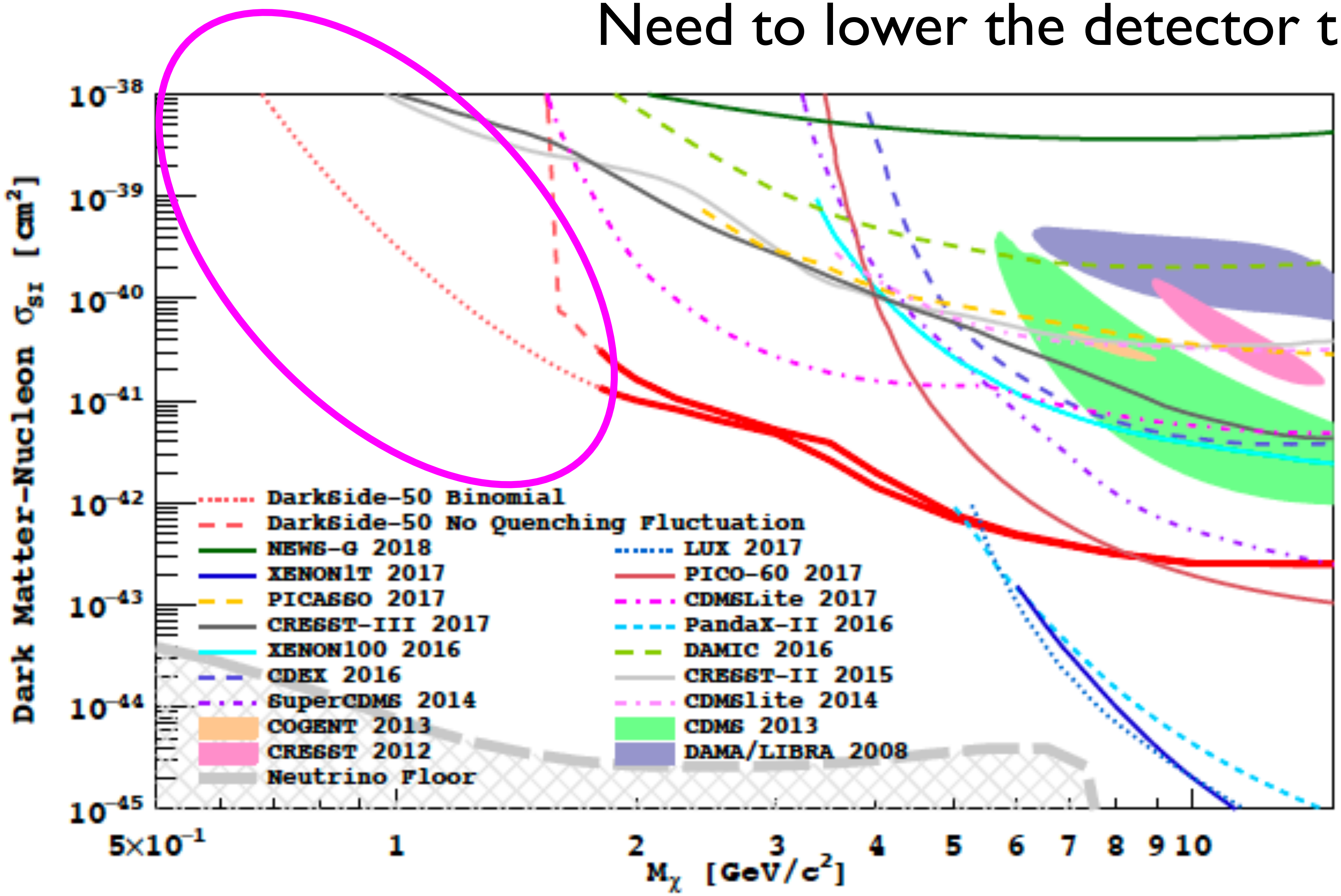
Light dark matter

Below typical WIMP masses: $1\,\mathrm{keV} \lesssim m_{\mathrm{DM}} \lesssim 10\,\mathrm{GeV}$

(Fermion DM)

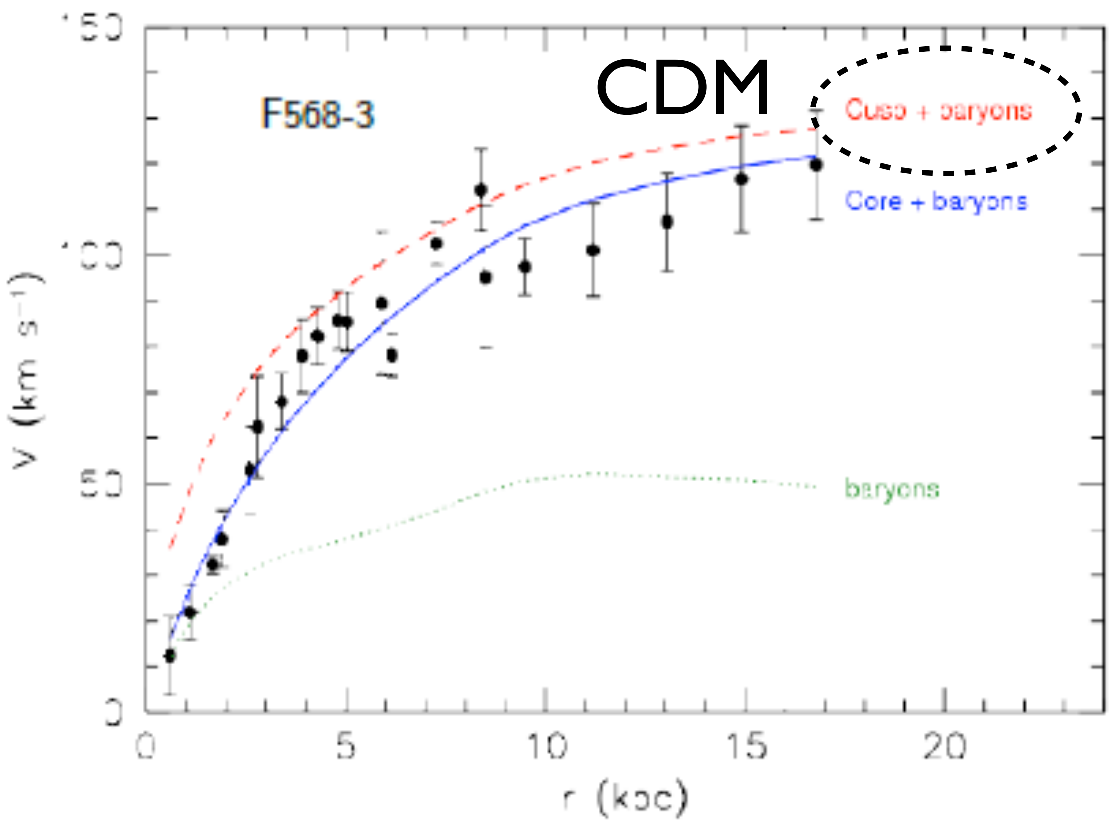
$$E_R = \frac{\vec{q}^2}{2m_N} = \frac{(m_{\mathrm{DM}} v)^2}{2m_N} \lesssim \mathrm{keV}$$: Small recoil energy

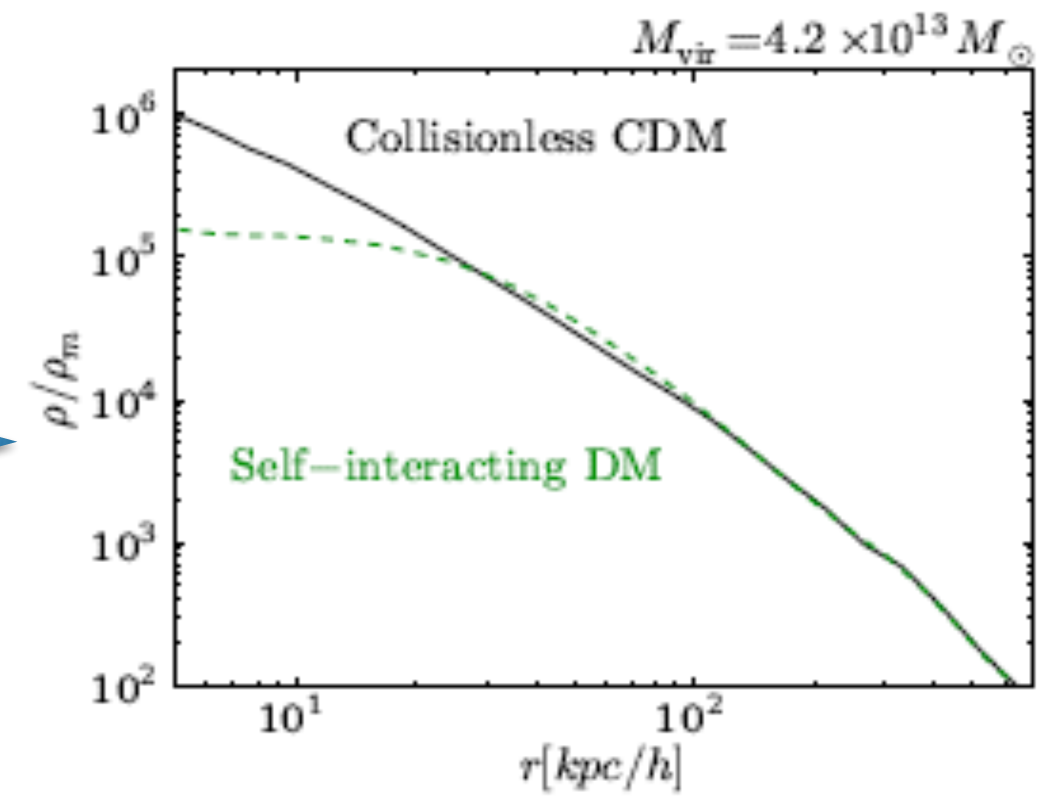
Need to lower the detector threshold.



Self-interacting dark matter

- Core-cusp problem: Simulation with CDM ("cusp") overshoots observed galaxy rotation curves ("core").





See a review by D.H. Weinberg et al(2013).

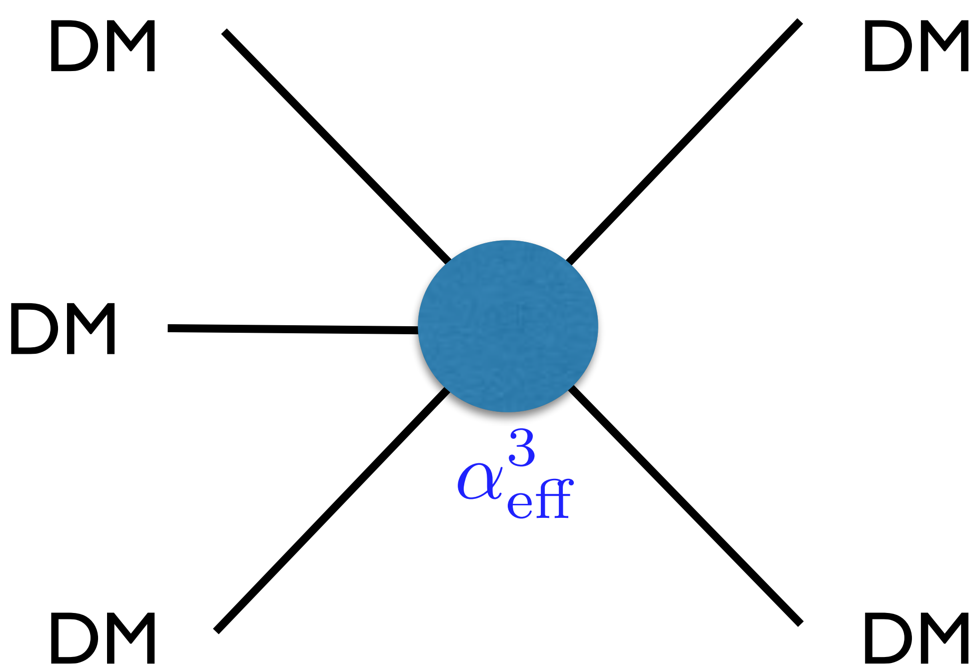
Large self-interaction of dark matter solves small-scale problems.

$\sigma_{\rm self}/m_{\rm DM} = 0.1 - 10\,{\rm cm}^2/{\rm g}$ cf. Bullet cluster: $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

- Related problems missing satellites (fewer DM subhalos), too-big-to-fail (masses of dwarf galaxies)

SIDM=SIMP

- Strong Interacting Massive Particles(SIMP) are in chemical equilibrium by self-interactions (3→2 process).



[Carlson,Machacek, Hall (1992);Hochberg et al, 2014; S.-M.Choi, HML, 2015]

$$\frac{dn_{\rm DM}}{dt}+3Hn_{\rm DM}\approx -\langle\sigma v^2\rangle_{3\to 2}(n_{\rm DM}^3-n_{\rm DM}^2 n_{\rm DM}^{\rm eq})$$

with $\langle\sigma v^2\rangle_{3\to 2}=\frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$

SIMP freeze-out:

$$\Gamma_{3\to 2}=n_{\rm DM}^2\langle\sigma v^2\rangle_{3\to 2}\sim H(T_F)$$

Relic density

$$\Omega_{\rm DM}h^2\simeq 0.1\left(\frac{m_{\rm DM}/35\,{\rm MeV}}{\alpha_{\rm eff}}\right)^{3/2}$$

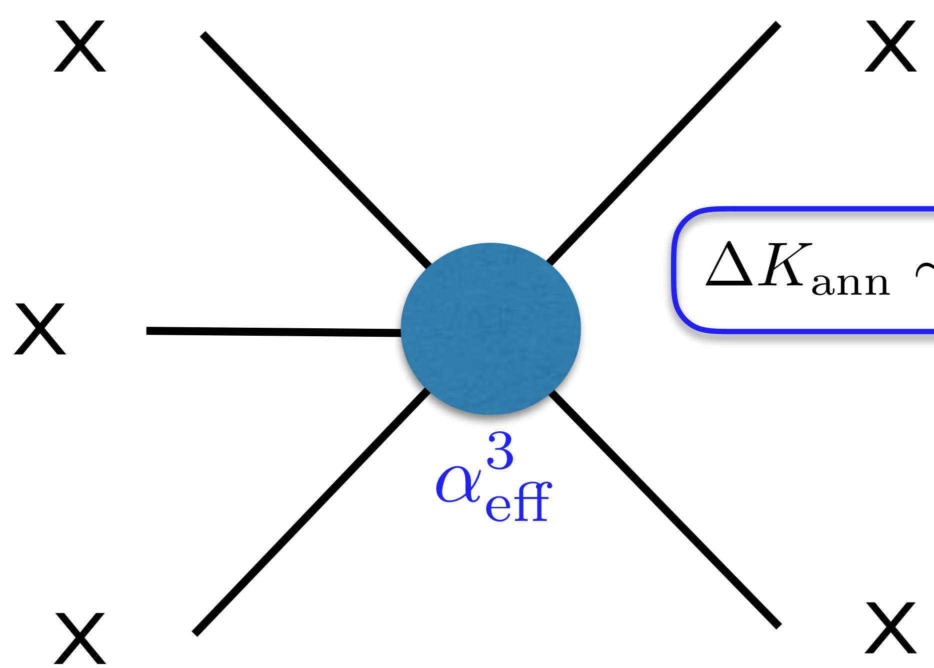
$\Rightarrow$

$$\boxed{\begin{aligned}\alpha_{\rm eff}&=1-30,\\ m_{\rm DM}&=40-1000\,{\rm MeV}\end{aligned}}$$

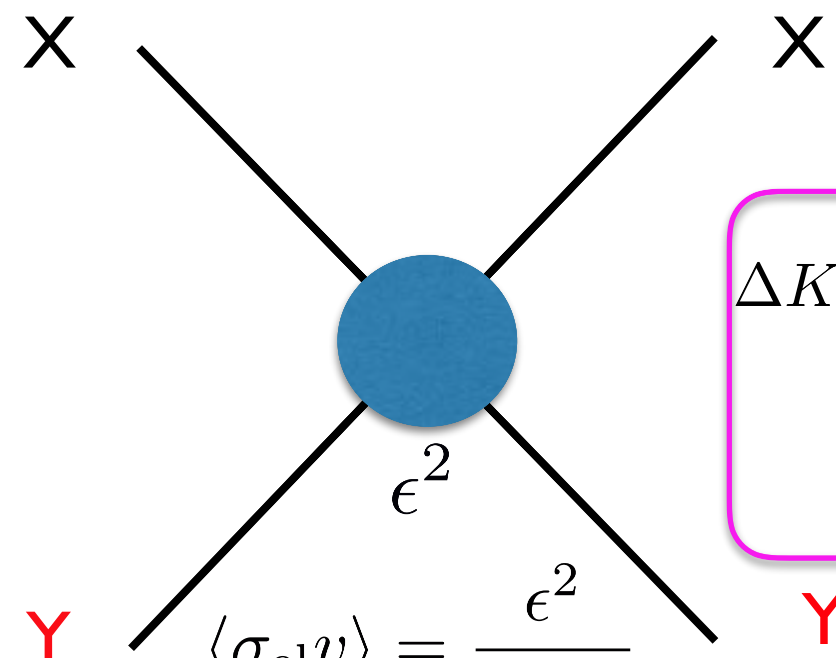
"Large 2→2 self-scattering"

SIMP conditions

- SIMP is heated after annihilation: kinetic equilibrium is necessary for a successful structure formation.



$\boxed{\Delta K_{\rm ann} \sim m_{\rm DM}}$



$$\boxed{\Delta K_{\rm scatt} = \frac{q^2}{2m_{\rm DM}} \sim \frac{T^2}{m_{\rm DM}}}$$

$$\langle \sigma_{\rm el} v \rangle = \frac{\epsilon^2}{m_{\rm DM}^2}$$

K: DM kinetic energy

[de Laix et al, 1995; VSIMPers, 2017]

$$\dot{K} + 2HK = \underbrace{-m_{\rm DM}^2 H T^{-1}}_{3\to2} + \underbrace{T\gamma(T)}_{\text{elastic scatt.}}, \qquad \gamma(T) \sim \left\langle n_Y \sigma_{\rm el} v_Y \frac{T}{m_{\rm DM}} \right\rangle.$$

Kinetic equilibrium: $\gamma(T) > H\left(\frac{m_{\rm DM}}{T}\right)^2$ $\quad\Rightarrow\quad$ $\boxed{\epsilon > 10^{-8}\alpha_{\rm eff}^{1/2}}$

cf. WIMP: $\gamma(T) > H$

- Ineffective 2→2 annihilation needs $\epsilon < 2.4 \times 10^{-6}\alpha_{\rm eff}$

SIMP & Z'-portal

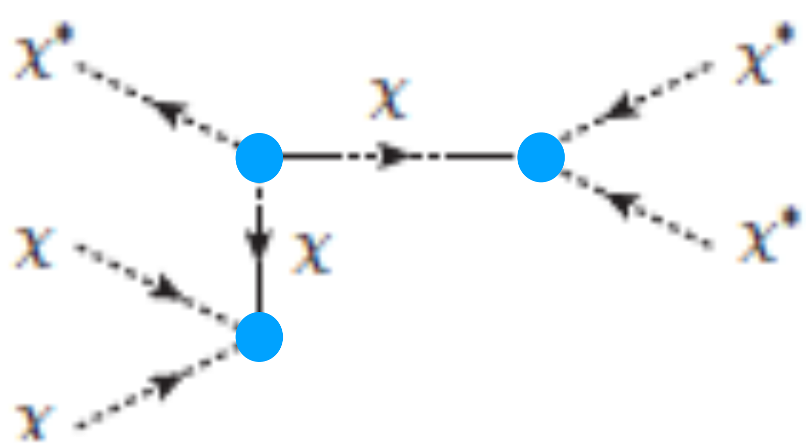
[S.-M.Choi, HML, 2015]

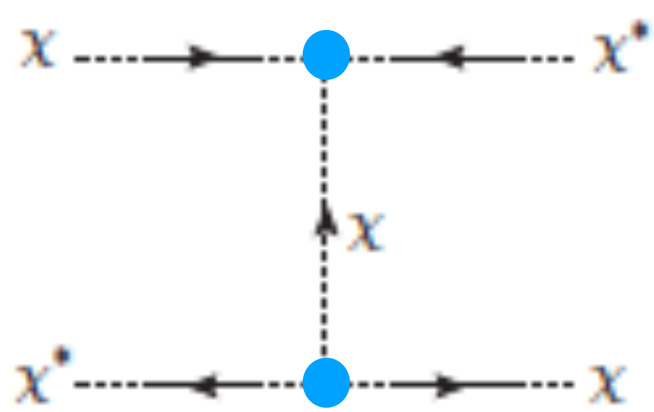
- Z_3 is the minimal discrete symmetry from a dark local U(1) and Z' portal is built-in.

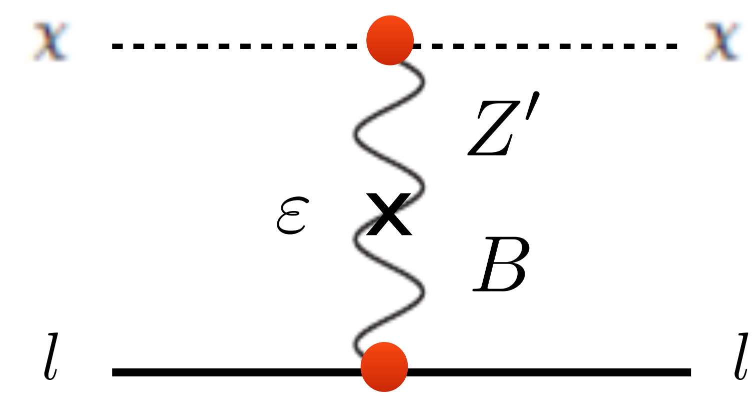
	ϕ	χ
$U(1)_V$	$+3$	$+1$

Table 1: $U(1)_V$ charges.

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\, v' \quad \Rightarrow \quad U(1)_V \to Z_3.$$





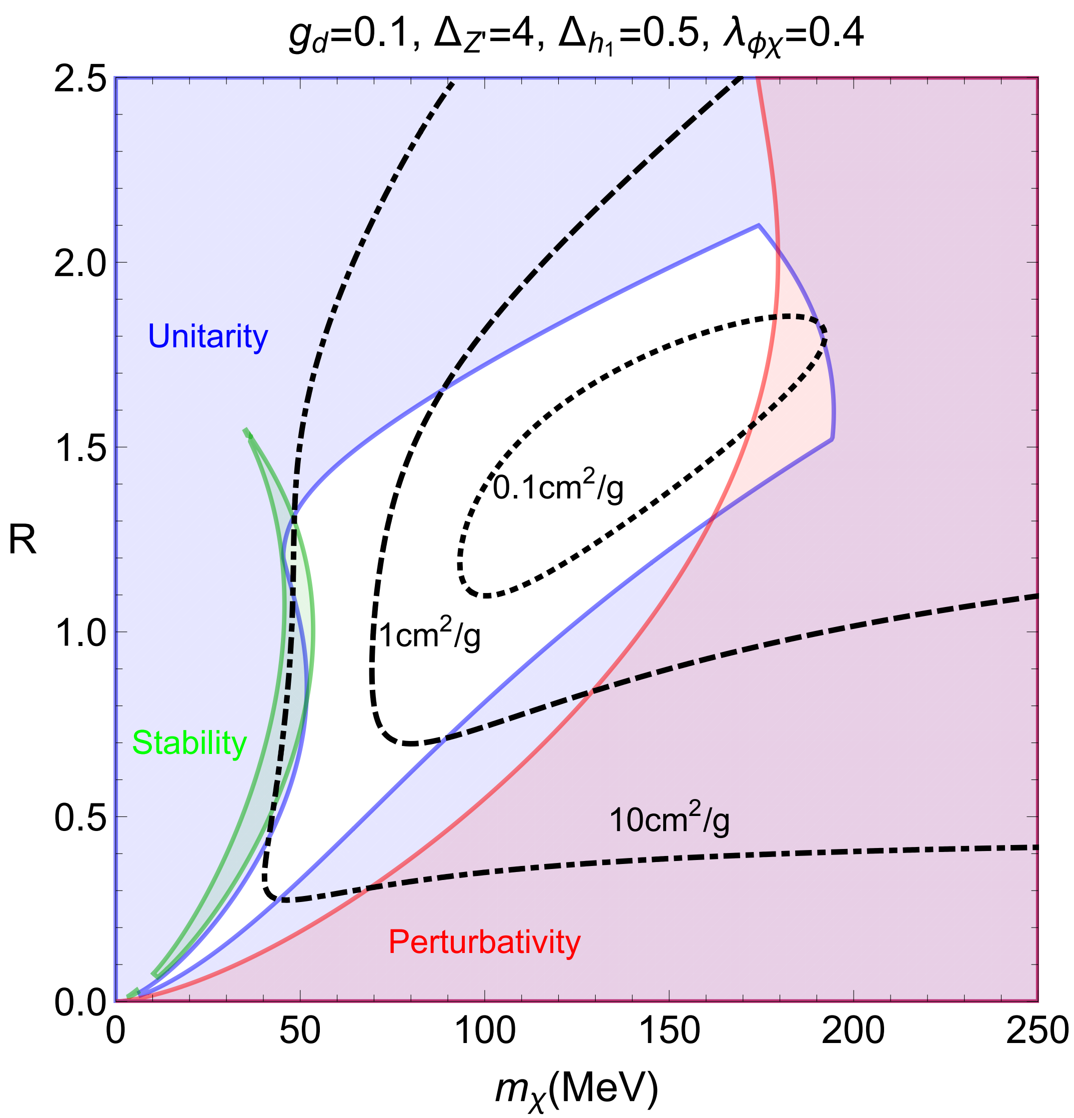


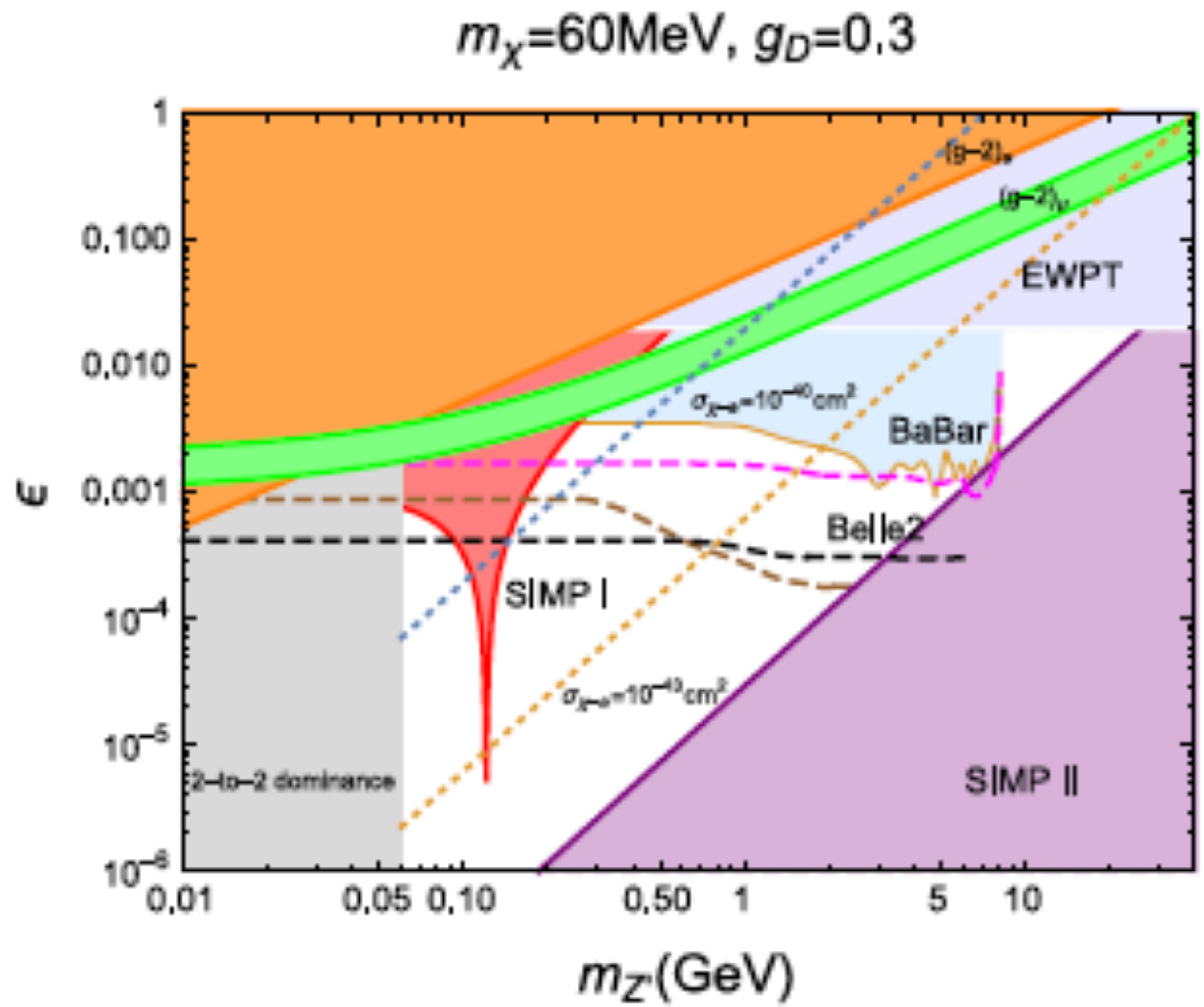
- Correlation btw self-scattering and 3→2 annihilation.

$$\sigma_{\rm self} \sim \frac{\kappa^4}{m_\chi}\,, \qquad \langle\sigma v^2\rangle \sim \frac{\kappa^6}{m_\chi^5} \quad \Rightarrow \quad \alpha_{\rm eff} \sim \kappa^2$$

Bounds on SIMP

[S.-M. Choi, HML, 2015]



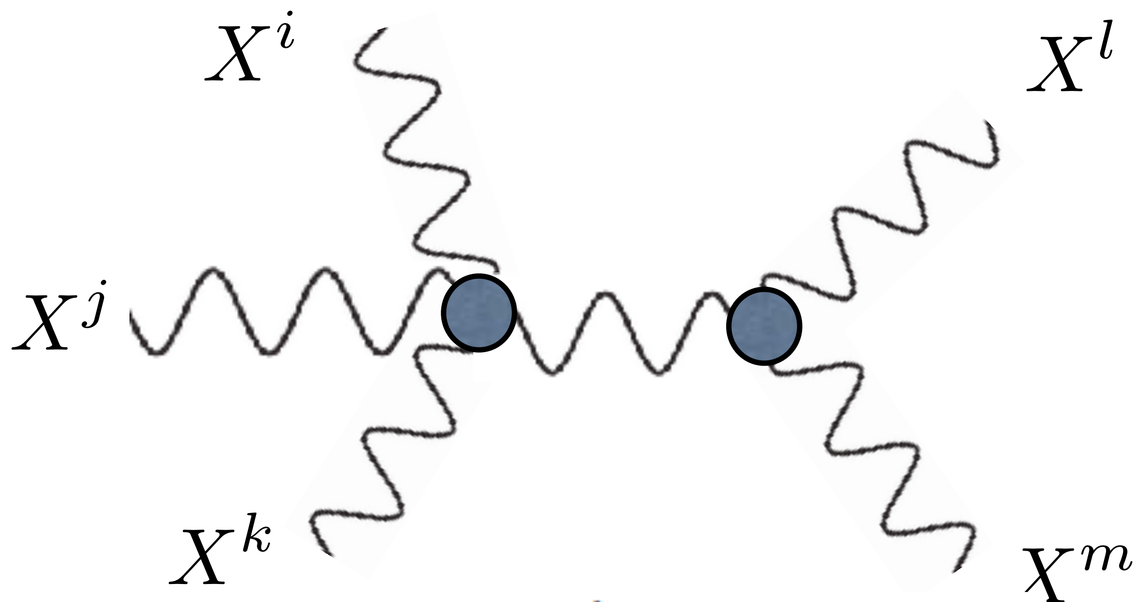


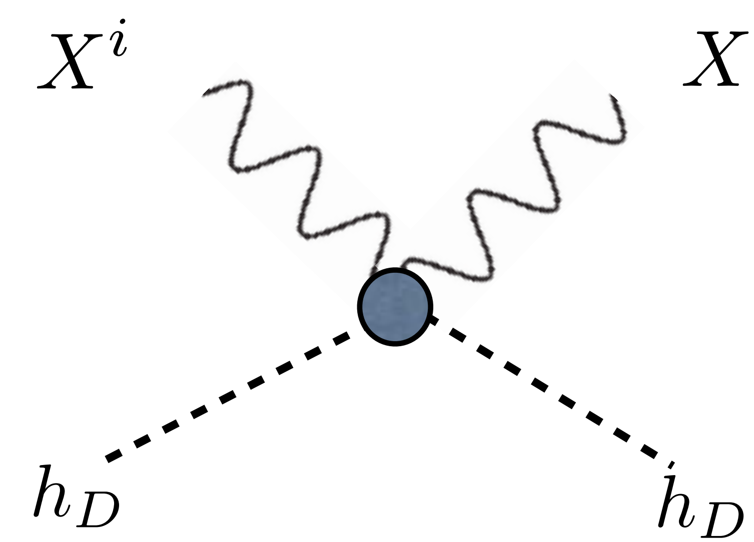
Consistent self-interactions for relic density & small-scale problems

Belle2, LHCb (Z' production), Beam dump exp, Meson decays, DM-electron scattering, etc.

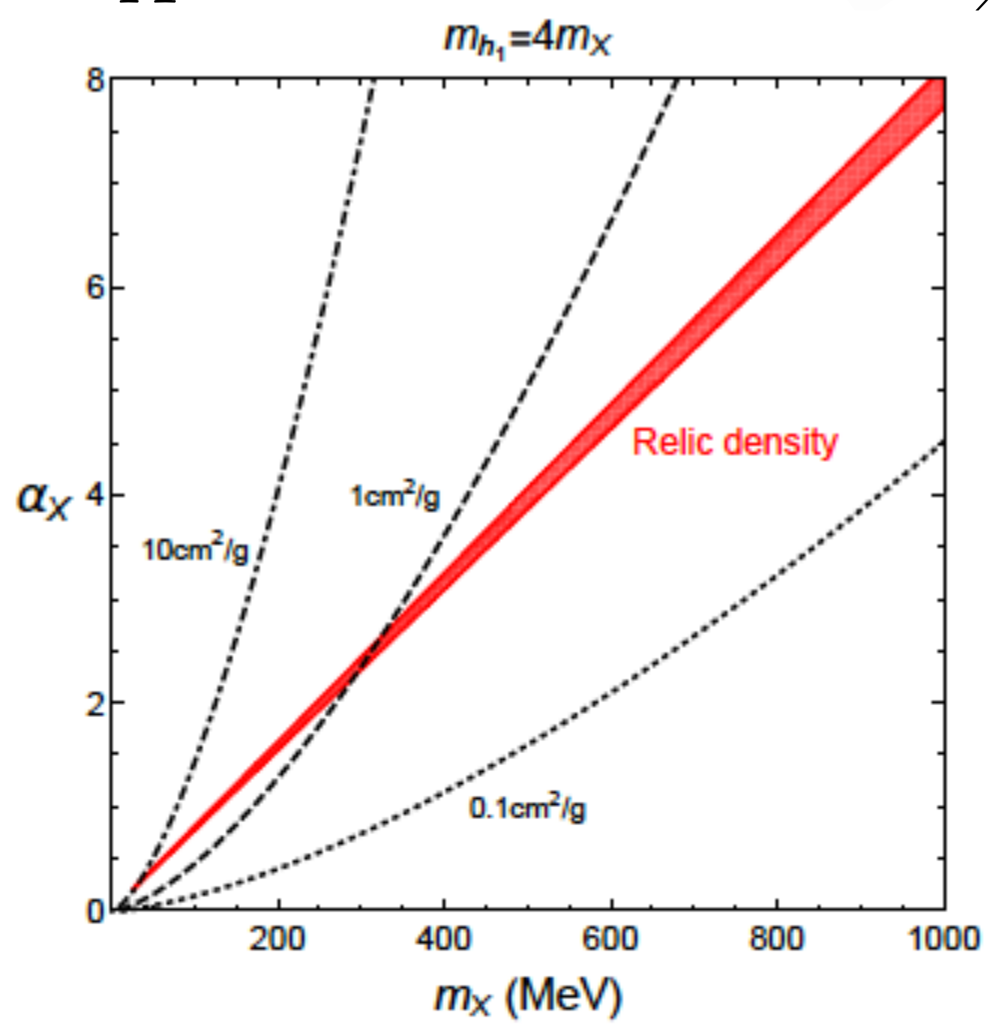
Vector SIMP & Higgs portal

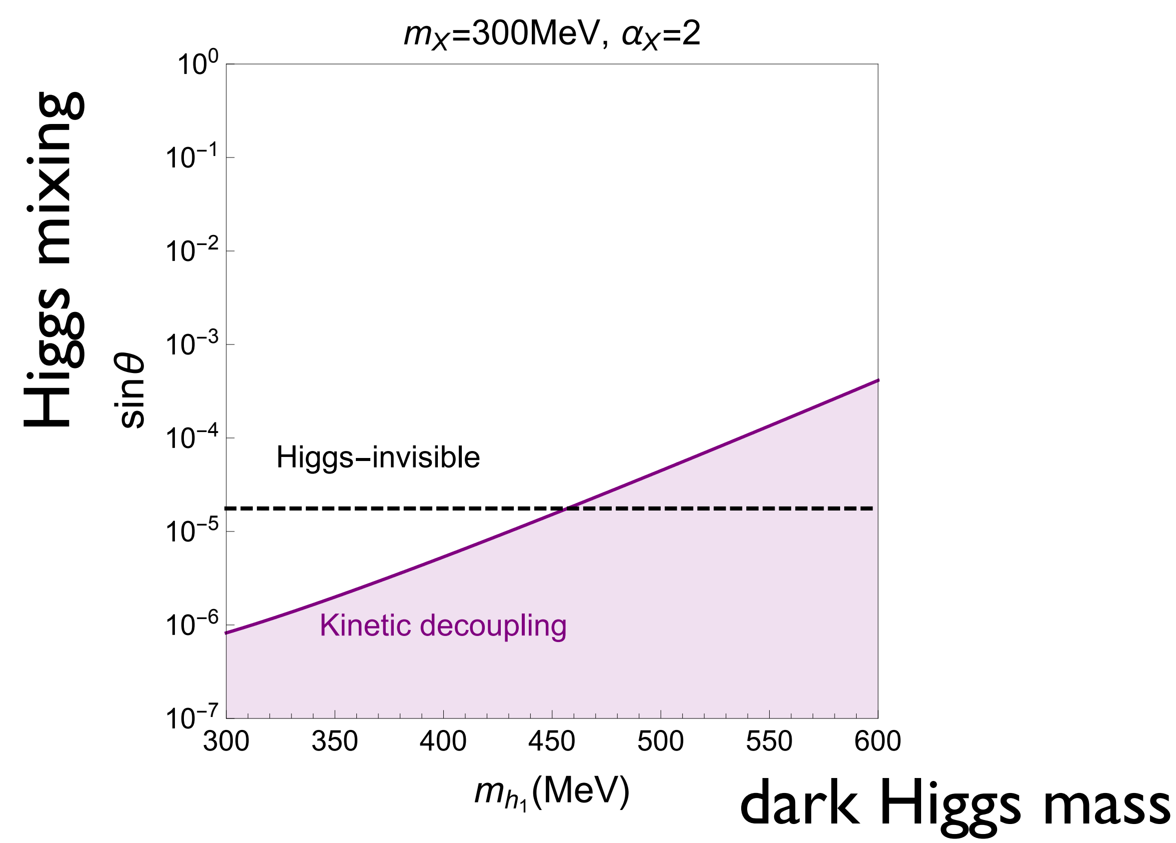
- Massive $SU(2)_X$ gauge bosons + dark Higgs





[S.-M. Choi, Y. Hochberg, E. Kuflic, Y. Mambrini, H. Murayama, HML, M. Pierre, 2017]





SIMP direct detection

- DM-nucleon scattering: cryogenic semi-conductors

  e.g. CDMSlite: Ge, E_{th}=56eV ➡ $m_{\rm DM} \gtrsim 1.6\,{\rm GeV}$

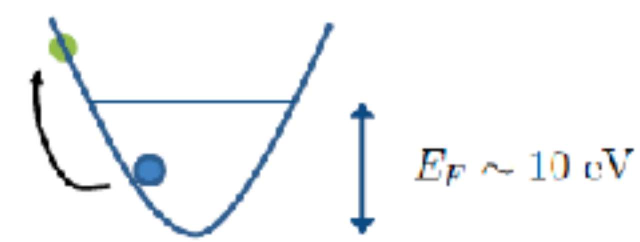
- DM-electron scattering: Cooper-pairs in super-conductors

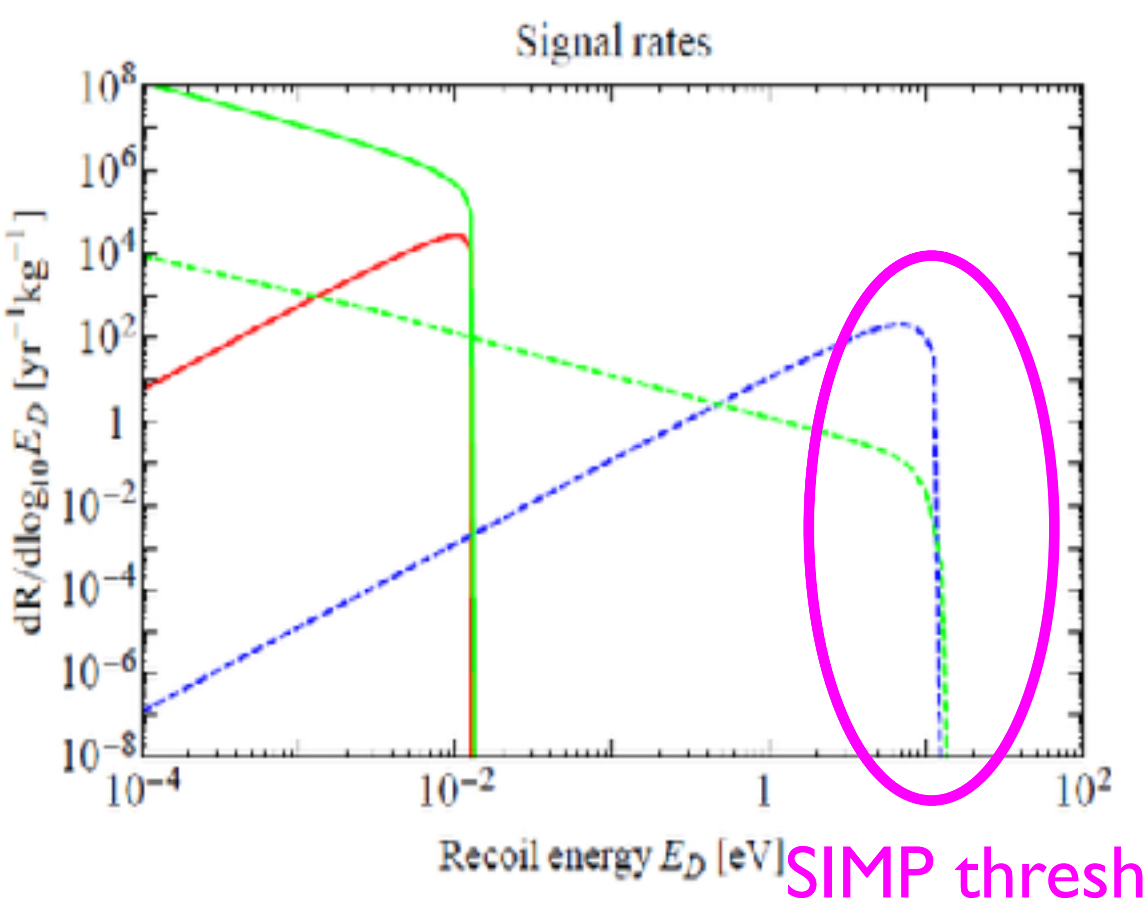
  e.g. Al: E_F=11.7eV, v_{rel}~v_F=10^{-2}

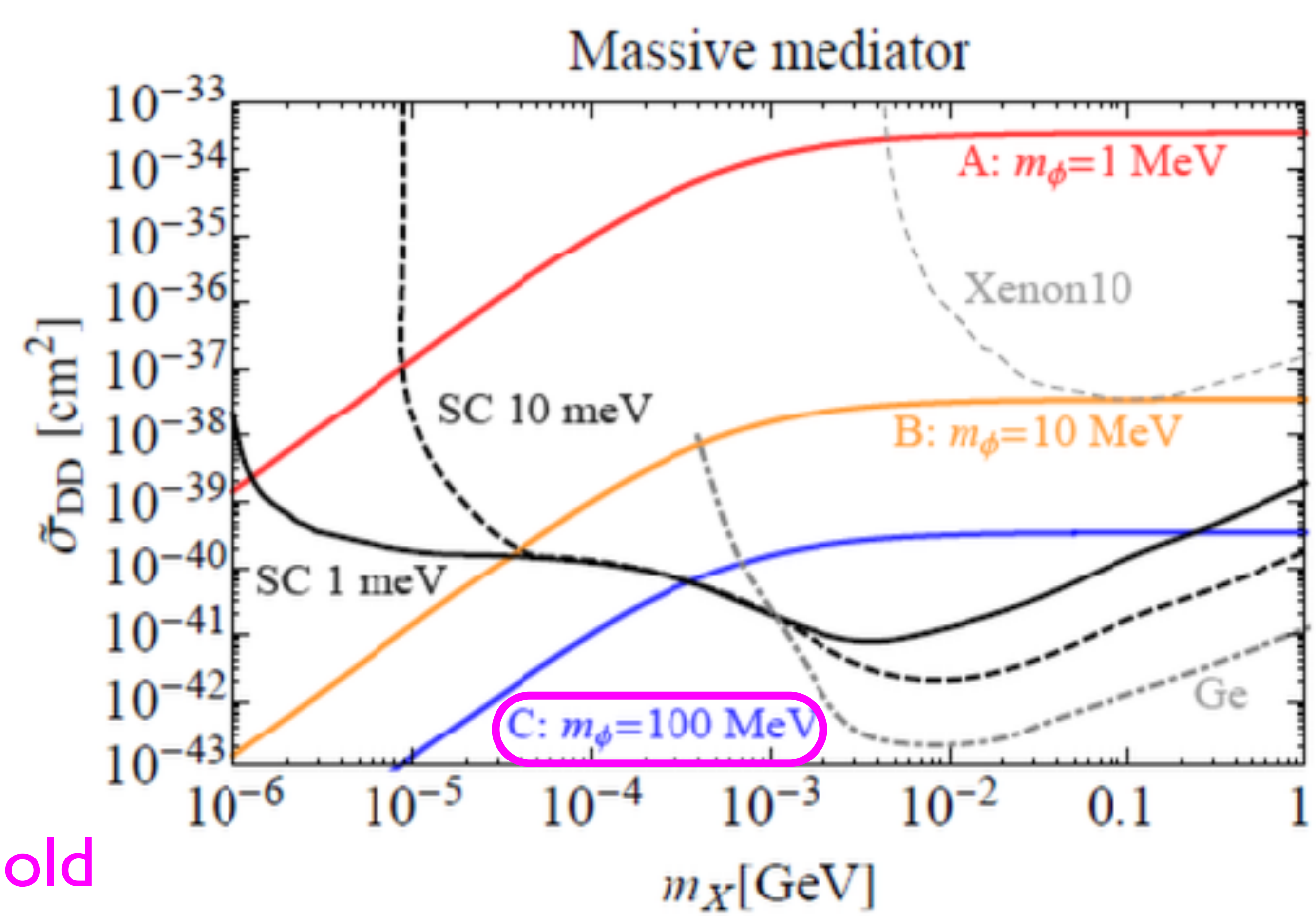
  ➡ $m_{\rm DM} \gtrsim m_e$: $E_R \lesssim 20\,{\rm eV}$

  $m_{\rm DM} v^2 \gtrsim \Delta \sim {\rm meV}$

[Hochberg et al (2015)]

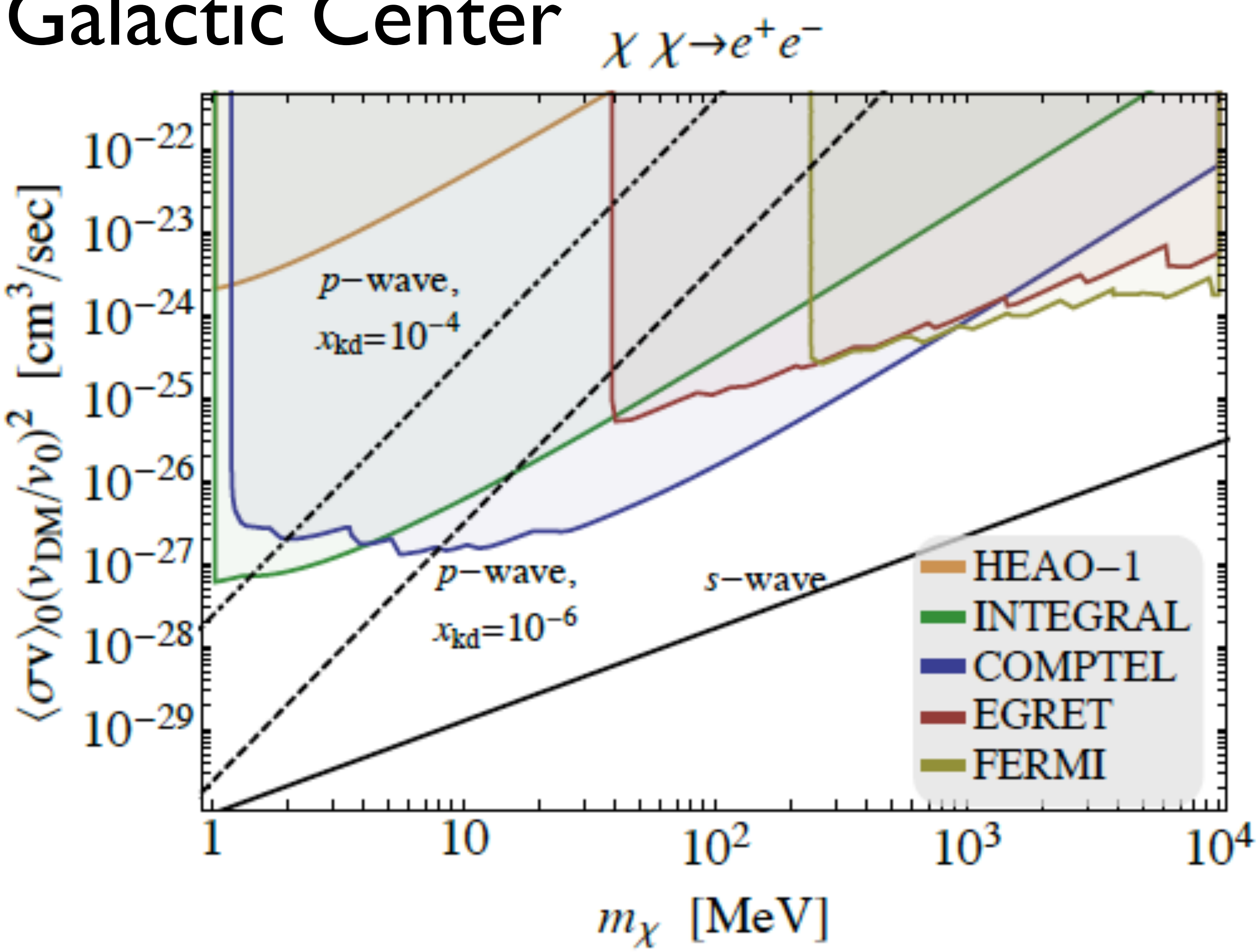




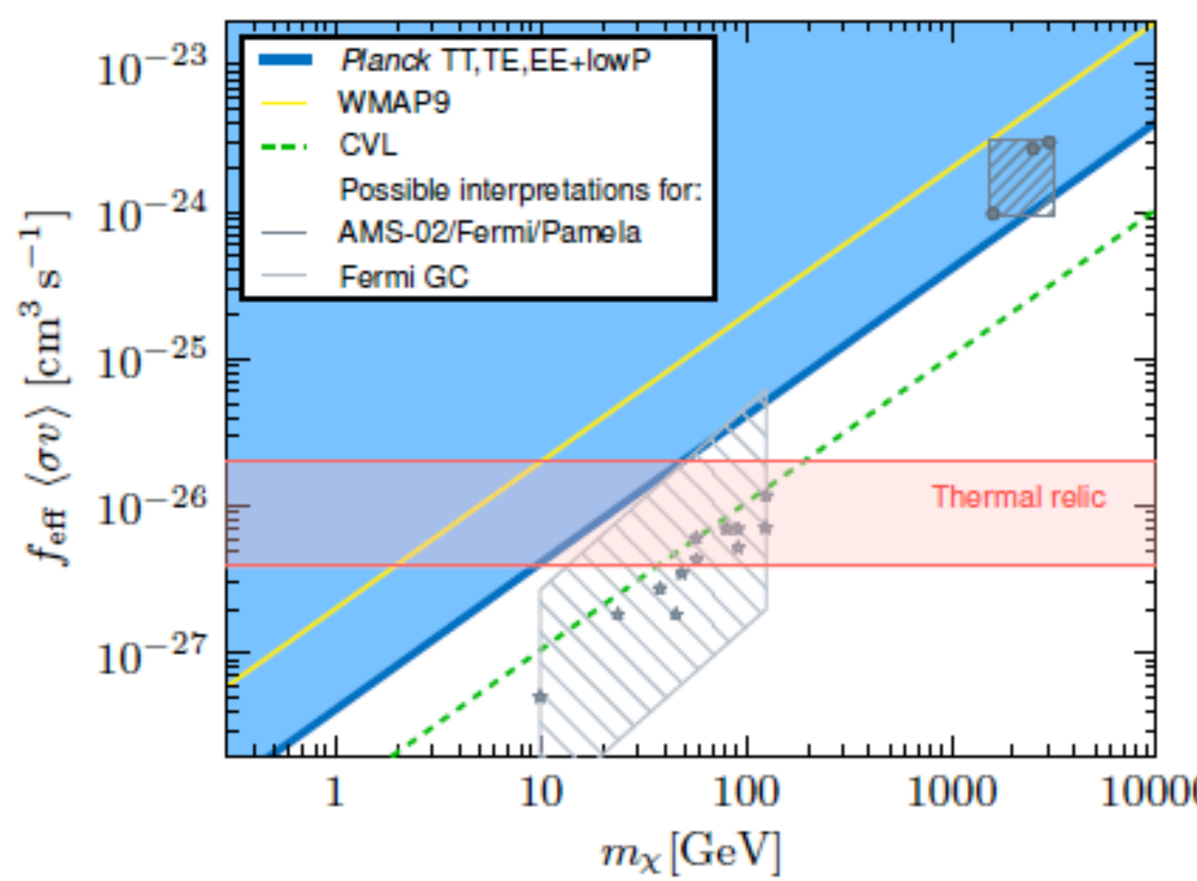


SIMP indirect detection

Galactic Center



CMB



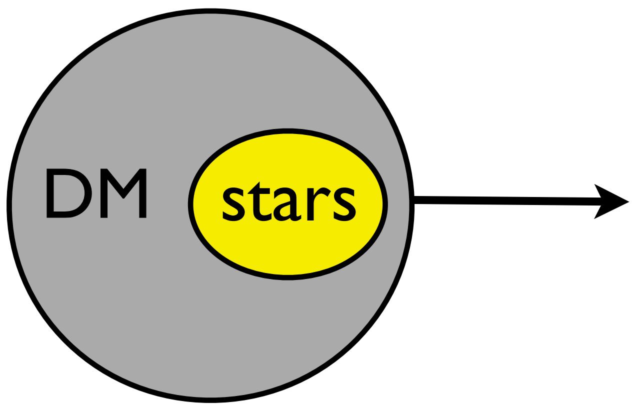
[Essig et al, 2013]

- Gamma-ray & CMB can constrain SIMP DM.
- No bound for scalar SIMP (p-wave suppressed annihilation).

$$\langle\sigma v_{\rm rel}\rangle_{l^+l^-} = \left(1.2\times10^{-27}{\rm cm}^3/{\rm s}\right)\left(\frac{\varepsilon_2}{10^{-6}}\right)^2\left(\frac{100\,{\rm MeV}}{m_\pi}\right)^2, \quad \varepsilon_2(v)=\varepsilon_2(v_F)(v/v_F)$$

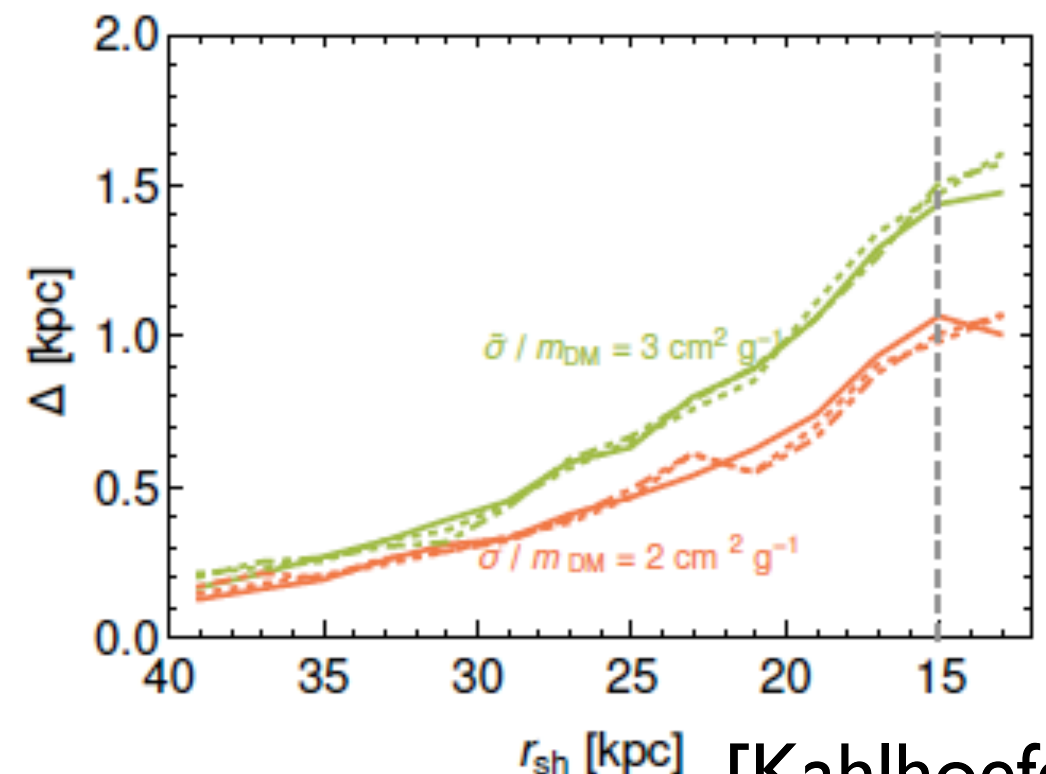
SIMP in merging galaxies

- SIMP self-interactions can make a separation of DM subhalo from bounded stars.



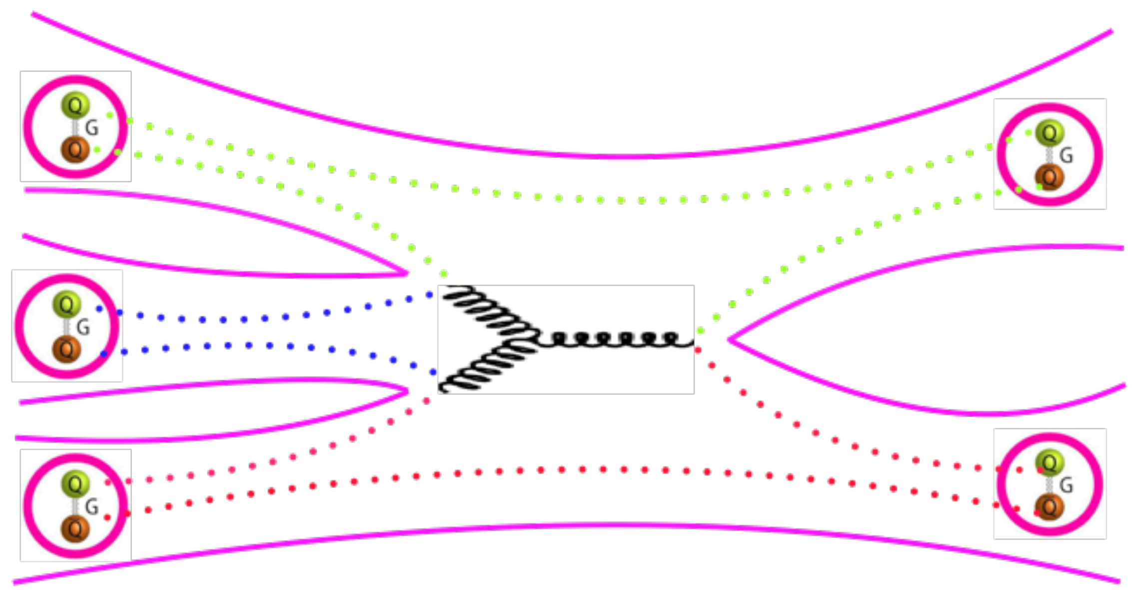
"Drag force" between DM subhalo and larger DM halo is greater than "gravity" between DM subhalo and star.

e.g. Abell 3827 cluster $\Delta = 1.62^{+0.47}_{-0.49}\,\mathrm{kpc}$ [Massey et al(2015)]



[Kahlhoefer et al(2015)]

SIMP mesons



Dark QCD for naturalness

[Chacko,Goh,Harnik, 2005]

- Double the SM gauge groups with twin Higgs and matter.

$$[SU(3)_A \times SU(2)_A] \times [SU(3)_B \times SU(2)_B] \times Z_2$$

$$Z_2 : \quad g_A = g_B, \quad H_A \leftrightarrow H_B$$

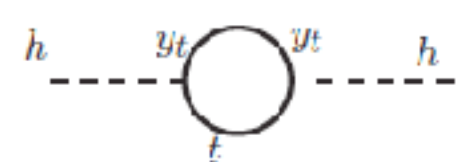
➡ Higgs = pseudo-Goldstone bosons on $SU(4)/SU(3)$

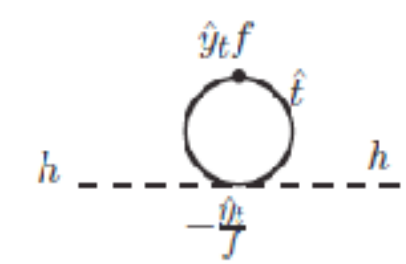
- Quadratic divergences of Higgs mass are cancelled by neutral quarks at one-loop.

$$\mathcal{L}_Y = -y_A H_A q_A u^c_A - y_B H_B q_B u^c_B, \; y_A = y_B.$$

➡ $$\delta m_h^2 = \frac{3}{4\pi^2}(y_A^2 - y_B^2)\Lambda^2 = 0.$$

“Dark QCD”





cf. General orbifold symmetries and QCD: HML, talk at 2015 CERN TH workshop on neutral naturalness.

SIMPs from Dark QCD

Dark fermions
$G=SU(N_f)_L x SU(N_f)_R$

$\longrightarrow$ condensate of $SU(N_c)$ dark fermions

Dark mesons with $SU(N_f)_V$ flavor

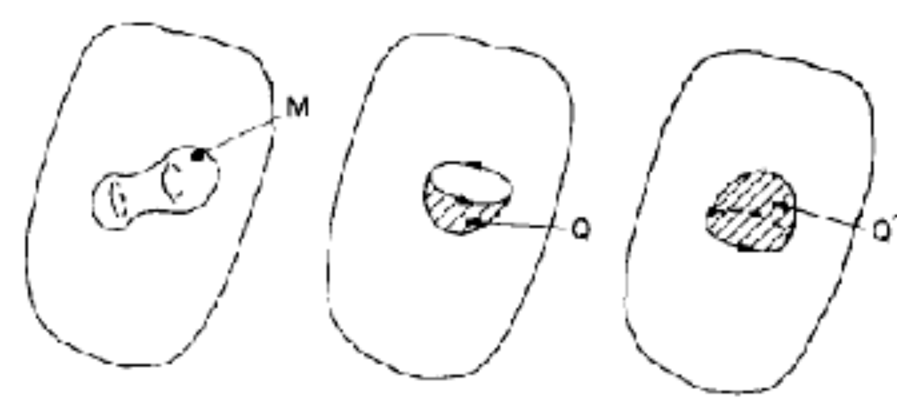
Dark mesons: Strongly Interacting, Light & Stable.

- 5-point self-interactions from Wess-Zumino-Witten term for $\pi_5(G/H)=Z$ (i.e. $N_f \geq 3$). [Wess, Zumino, 1971; Witten, 1983]

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

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

$$N_f = 3: \quad \frac{\pi}{F} = \frac{\sqrt{2}}{F}\begin{bmatrix} \frac{1}{\sqrt{2}}\tilde{\pi}_0 + \frac{1}{\sqrt{6}}\tilde{\eta}^0 & \tilde{\pi}^+ & \tilde{K}^+ \\ \tilde{\pi}^- & -\frac{1}{\sqrt{2}}\tilde{\pi}_0 + \frac{1}{\sqrt{6}}\tilde{\eta}^0 & \tilde{K}^0 \\ \tilde{K}^- & \bar{\tilde{K}}^0 & -\sqrt{\frac{2}{3}}\tilde{\eta}^0 \end{bmatrix}.$$

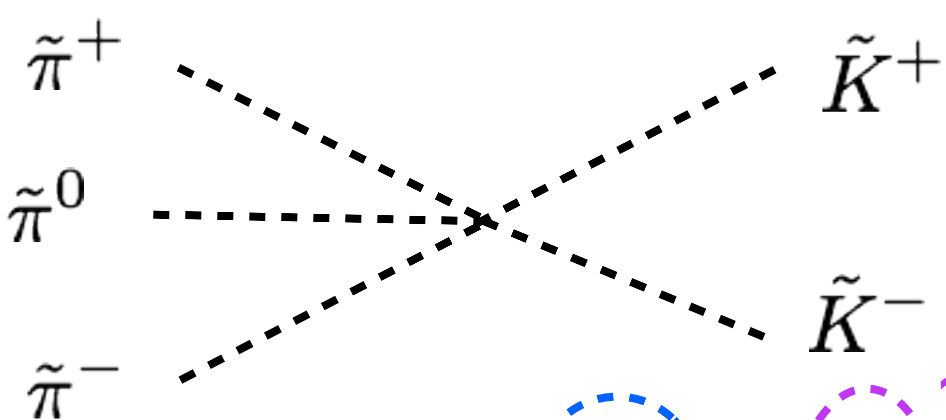


N_C : topological invariant of 5-sphere (Q+Q') in SU(3)

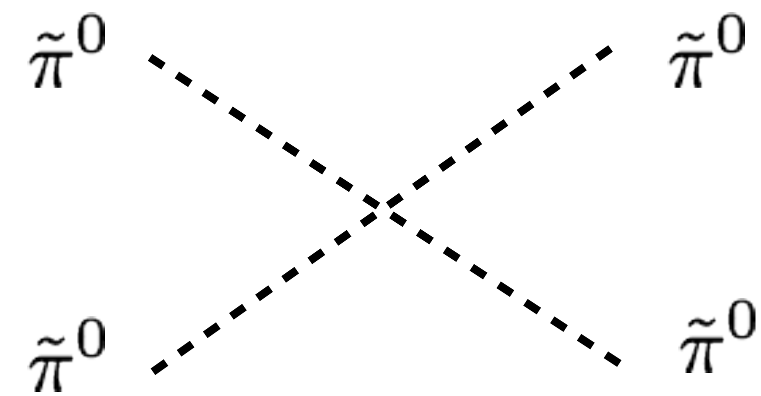
WZW & SIMP process

- 5-point scattering vs self-scattering for SIMP mesons

SIMP process:



Self-scattering: [Hochberg et al, 2014]



~1/N$_f$

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

~const

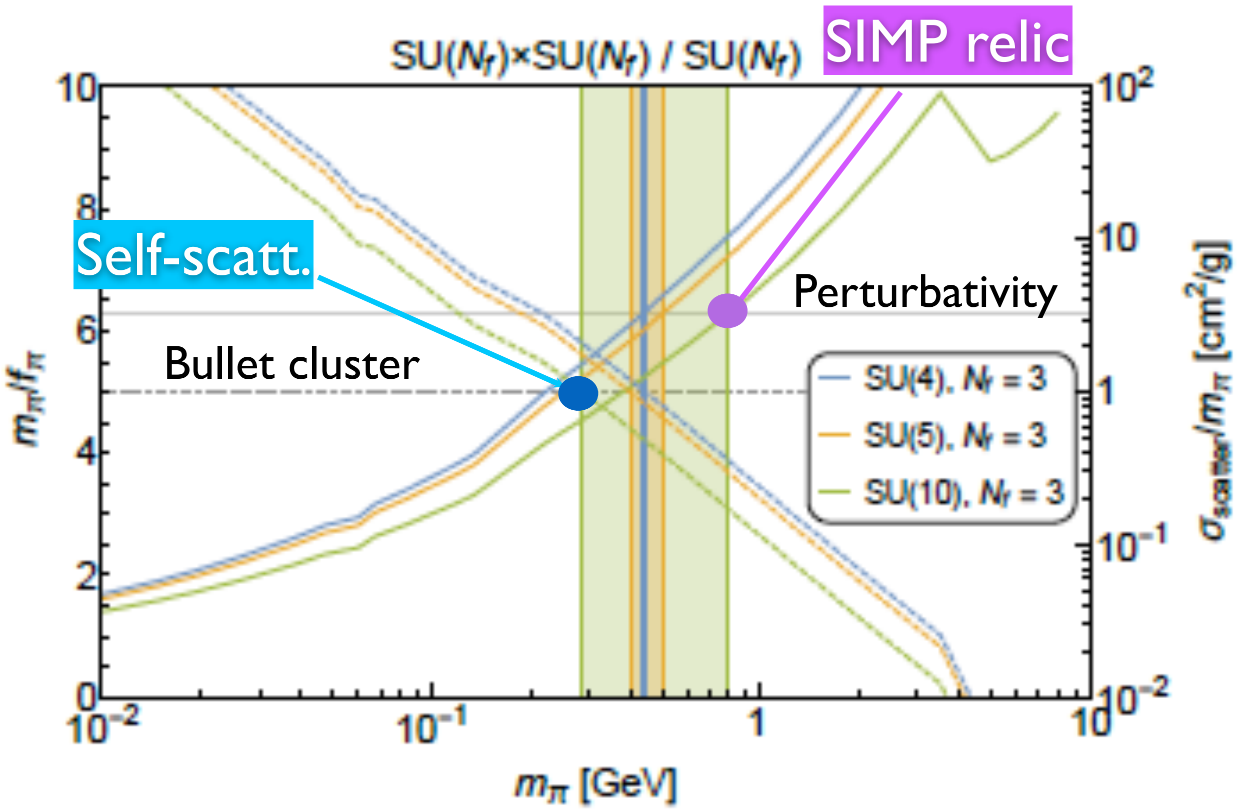
$$\sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4}\frac{a^2}{N_\pi^2}$$

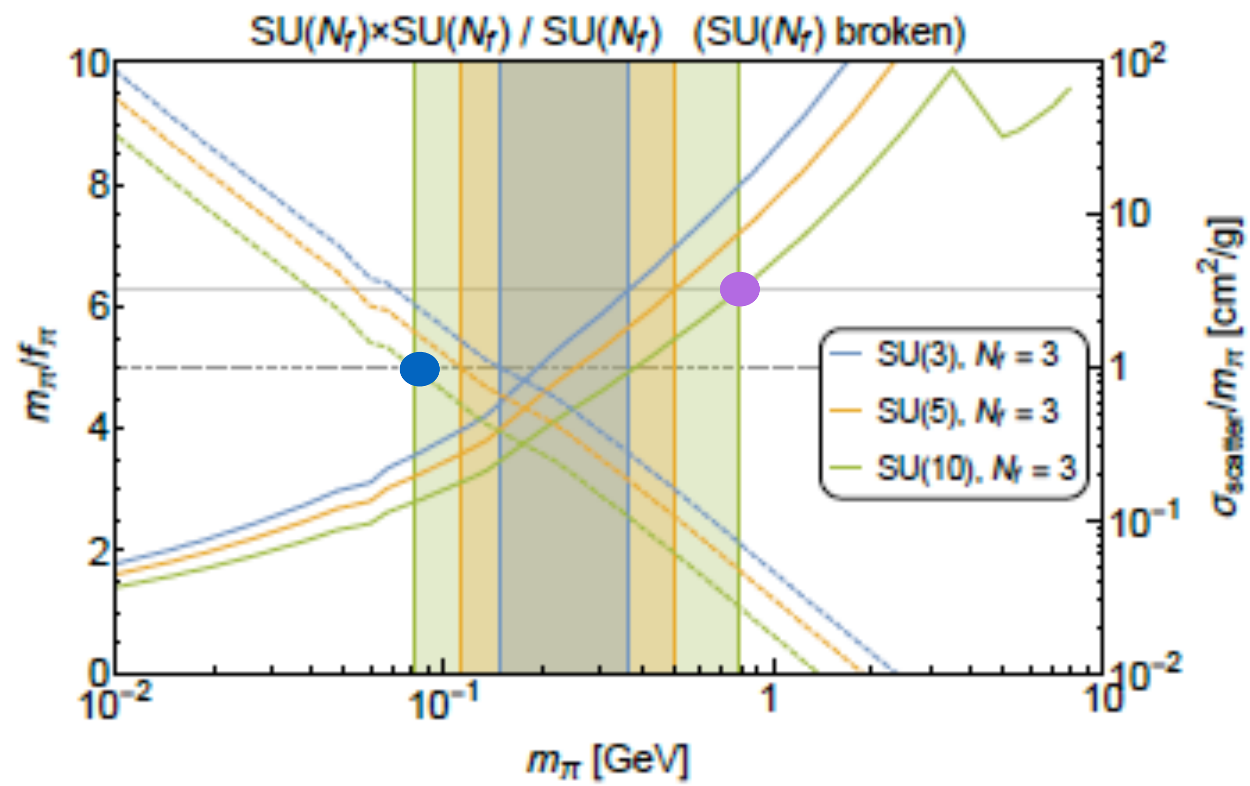
$$\Lambda'_{\rm QCD} \sim \Lambda_{\rm QCD} \quad \longrightarrow \quad m_{\tilde{\pi}}^2 \sim m_{\tilde{q}} \frac{(\Lambda'_{\rm QCD})^3}{F^2} \sim (100\,{\rm MeV})^2$$

cf. mirror QCD in twin Higgs models.

degenerate quark masses $\longrightarrow$ flavor symmetry, degenerate meson masses

Parameters for SIMP mesons





[Hochberg, Kuflik, Murayama, Volansky, Wacker, 2014]

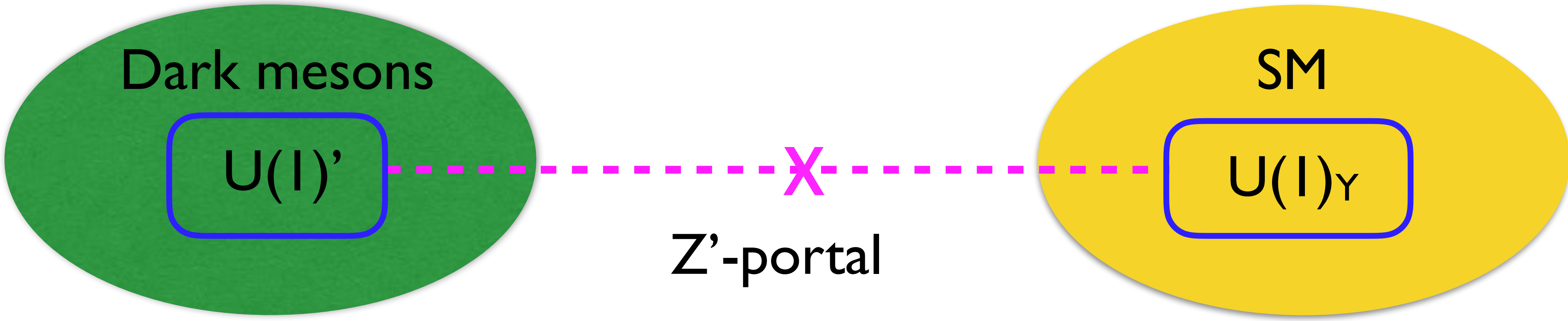
Bullet cluster, Halo shape $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Perturbativity $m_\pi/f_\pi < 2\pi$

Bullet cluster & perturbativity bounds favor large N_c.

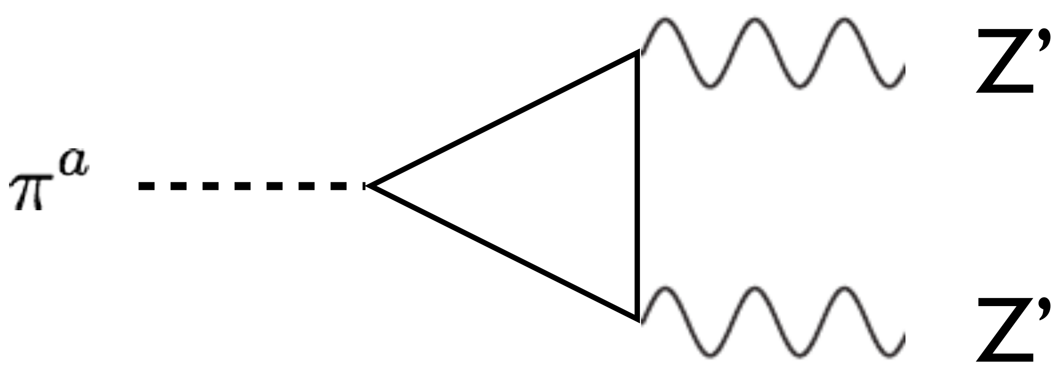
N_c=3 case is ruled out! → Vector mesons

Equilibrium via Z’-portal

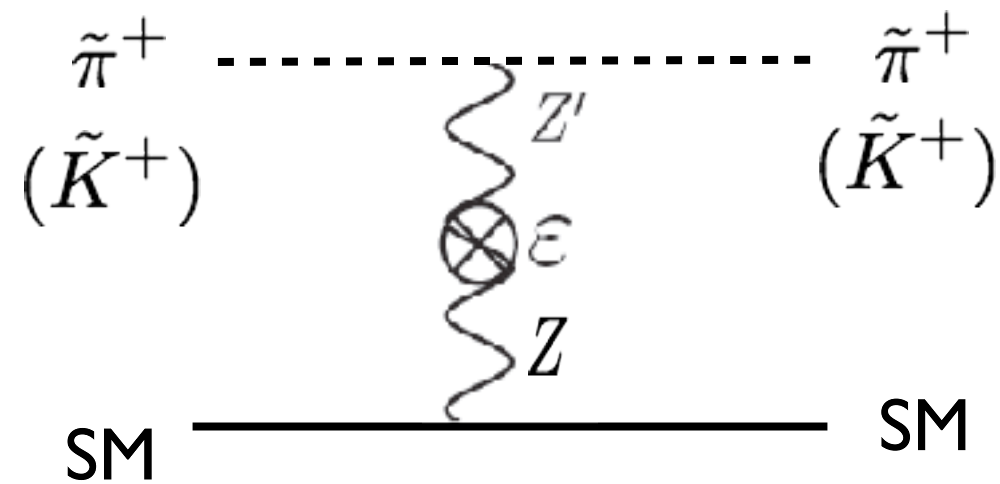


- Vectorial Z’ with no chiral anomalies in dark QCD.

[HML, M. Seo, 2015]



$$\propto \mathrm{Tr}(Q_D^2 T^a) = 0$$



$$Q_D = \begin{pmatrix} \frac{1}{3} & 0 & 0 \\ 0 & -\frac{1}{3} & 0 \\ 0 & 0 & -\frac{1}{3} \end{pmatrix}$$

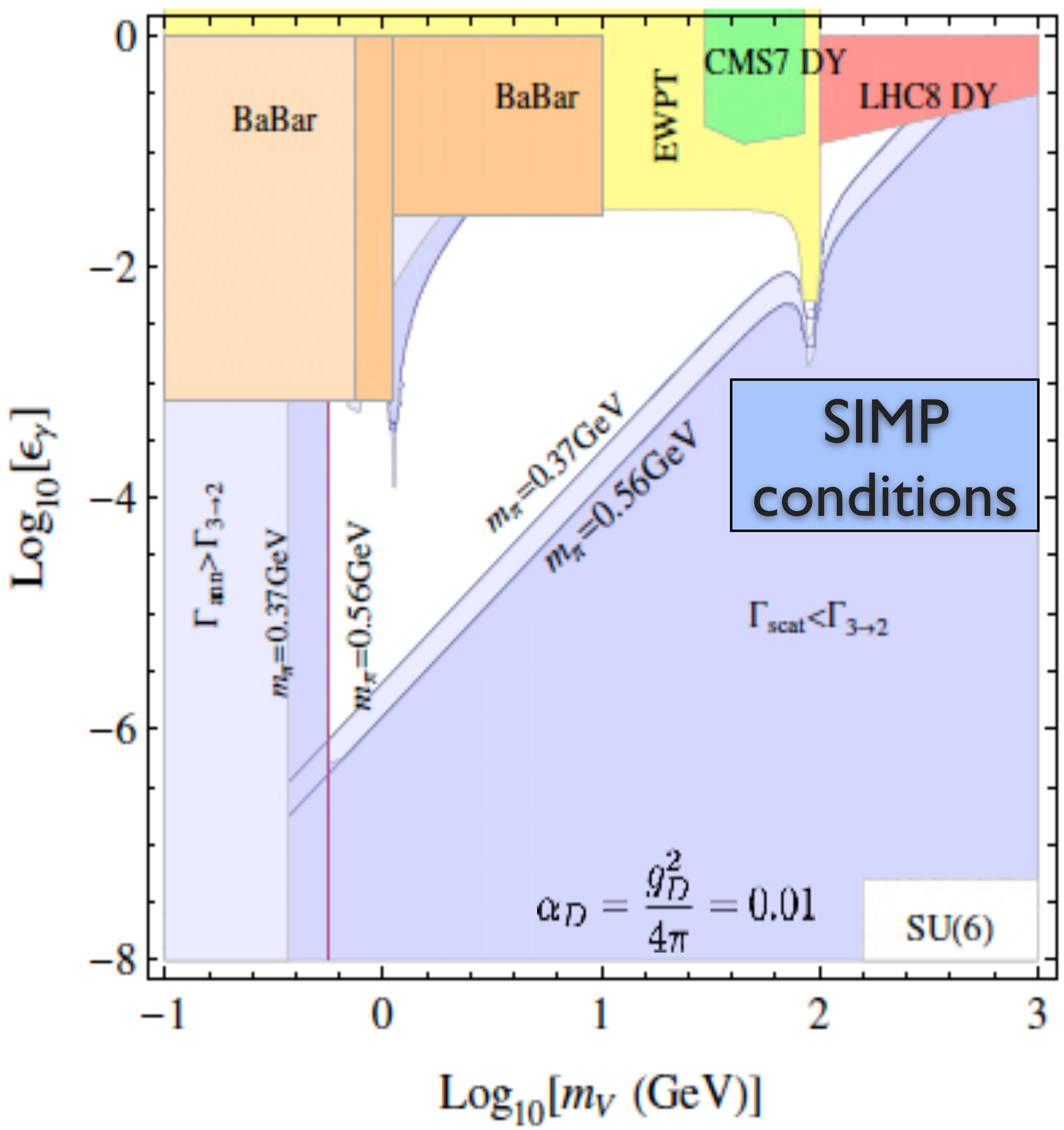
$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} F^{\mu\nu}$$

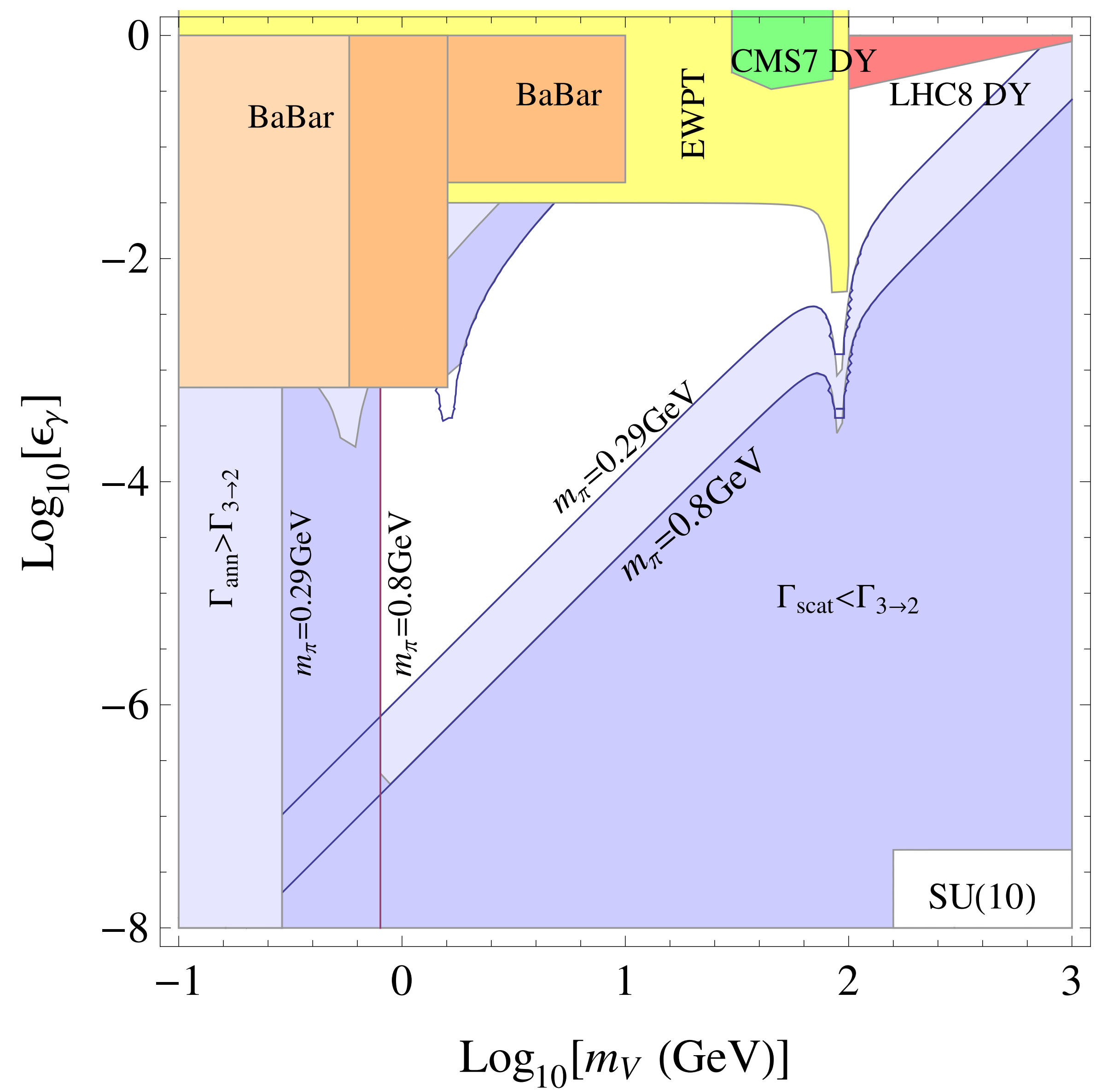
- Small meson mass splitting for SIMP process:

$$\delta\mathcal{L}_{m_\pi} = \alpha_D \Lambda^4 \mathrm{Tr}[Q_D U Q_D U^{-1}] \qquad \delta m_\pi^2 \sim \alpha_D \Lambda^4 / F^2 \lesssim 0.01 m_\pi^2,$$

Bounds on SIMP mesons

[M.-S. Seo, HML, 2015]



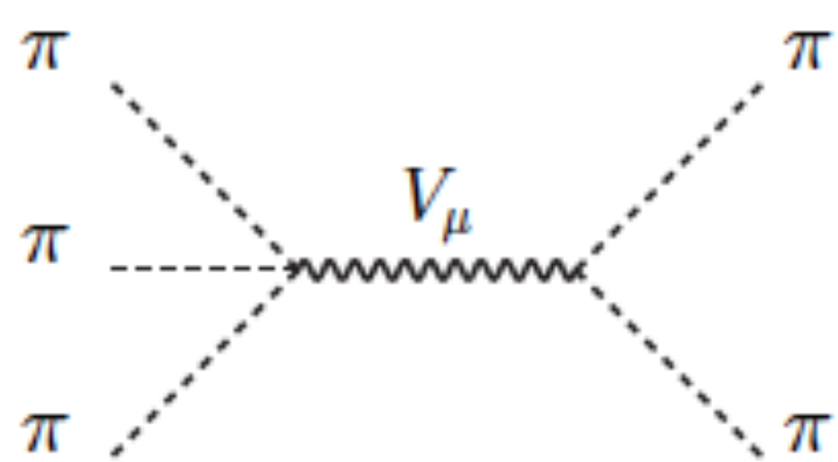


- SIMP parameter space can be probed by Z' searches.

$$\boxed{\begin{array}{l} e^+e^- \to \gamma Z' \to \gamma(l^+l^-), \quad e^+e^- \to \gamma + \mathrm{MET} \\ h \to ZZ' \ \text{(CMS 8TeV), Drell-Yan, dileptons.} \end{array}}$$

cf. Hochberg et al, 2015

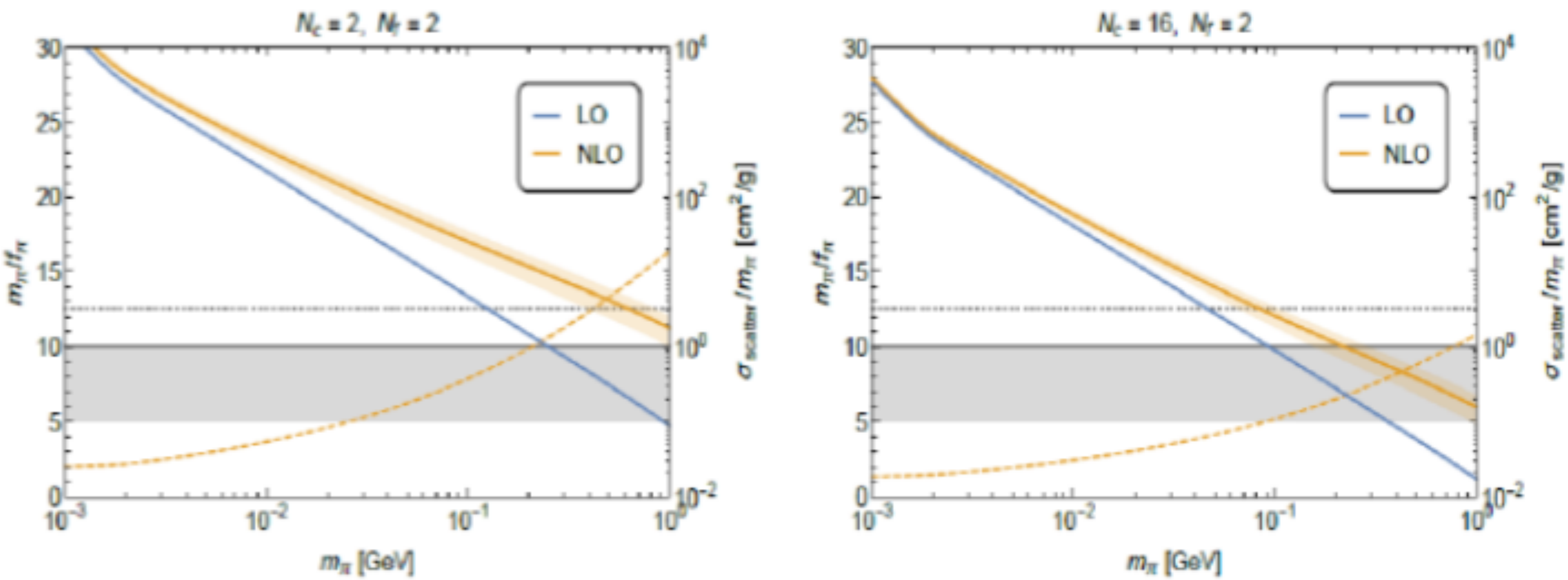
Resonant SIMPs



Perturbativity issue

[Hansen et al, 2015]

- 2→2: LO, 3→2: NLO, in SIMP scenarios.



NLO corrections enlarge 2→2 cross sections, making it harder to satisfy the self-scattering bound.

→ A larger color or a larger meson decay constant?

or additional 3→2 annihilation channels?

Resonant SIMPs

[S.-M.Choi, HML, 2016]

- Z_5 is a minimal (gauged) discrete symmetry for 5-point interacting SIMP.

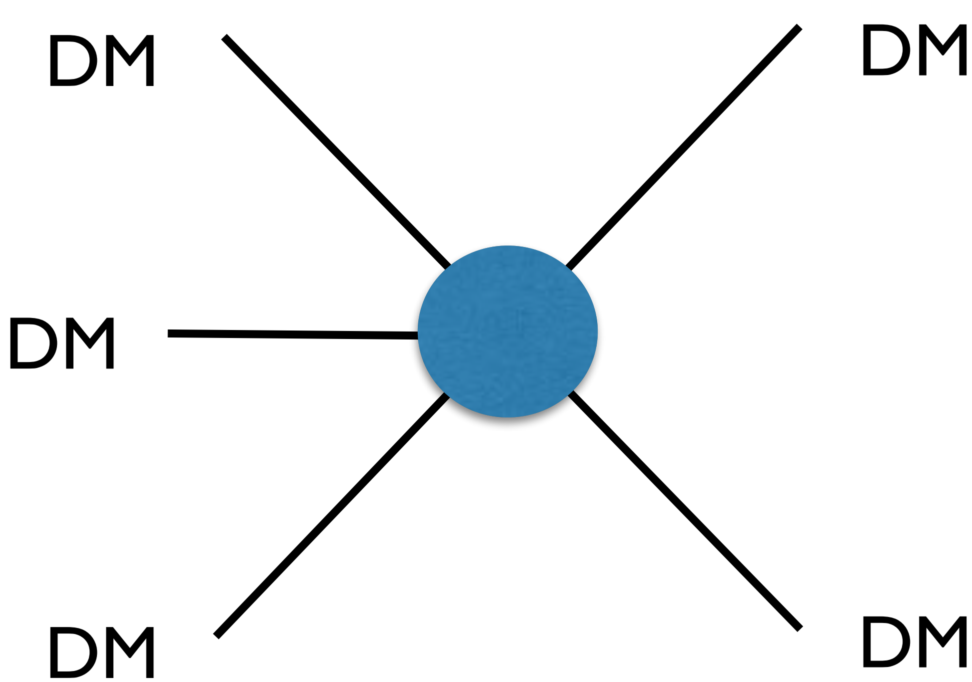
	ϕ	χ	S
$U(1)_V$	$+5$	$+1$	$+3$

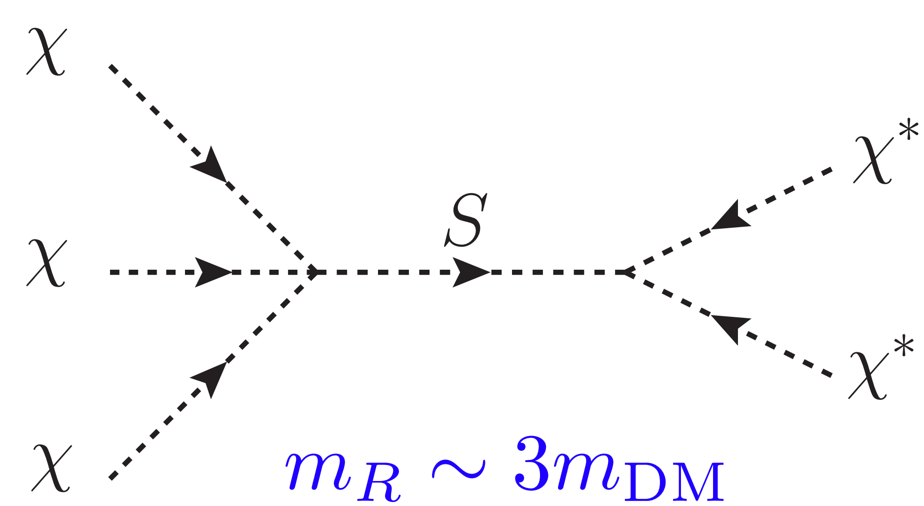
Table 1: $U(1)_V$ charges.

$$\langle \phi \rangle = \frac{1}{2} v' \quad \Rightarrow \quad U(1)_V \to Z_5$$

$$\mathcal{L}_{\rm int} \supset \frac{1}{\sqrt{2}}\lambda_1 \phi^\dagger S^2 \chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2 \phi^\dagger S \chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$

$$\begin{pmatrix} \phi \\ \chi \\ S \end{pmatrix} \to \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^3 \end{pmatrix} \begin{pmatrix} \phi \\ \chi \\ S \end{pmatrix} \qquad \omega = e^{i\frac{2}{5}\pi}$$





$m_R \sim 3 m_{\rm DM}$

"3DM-Resonance"

Averaging SIMPs

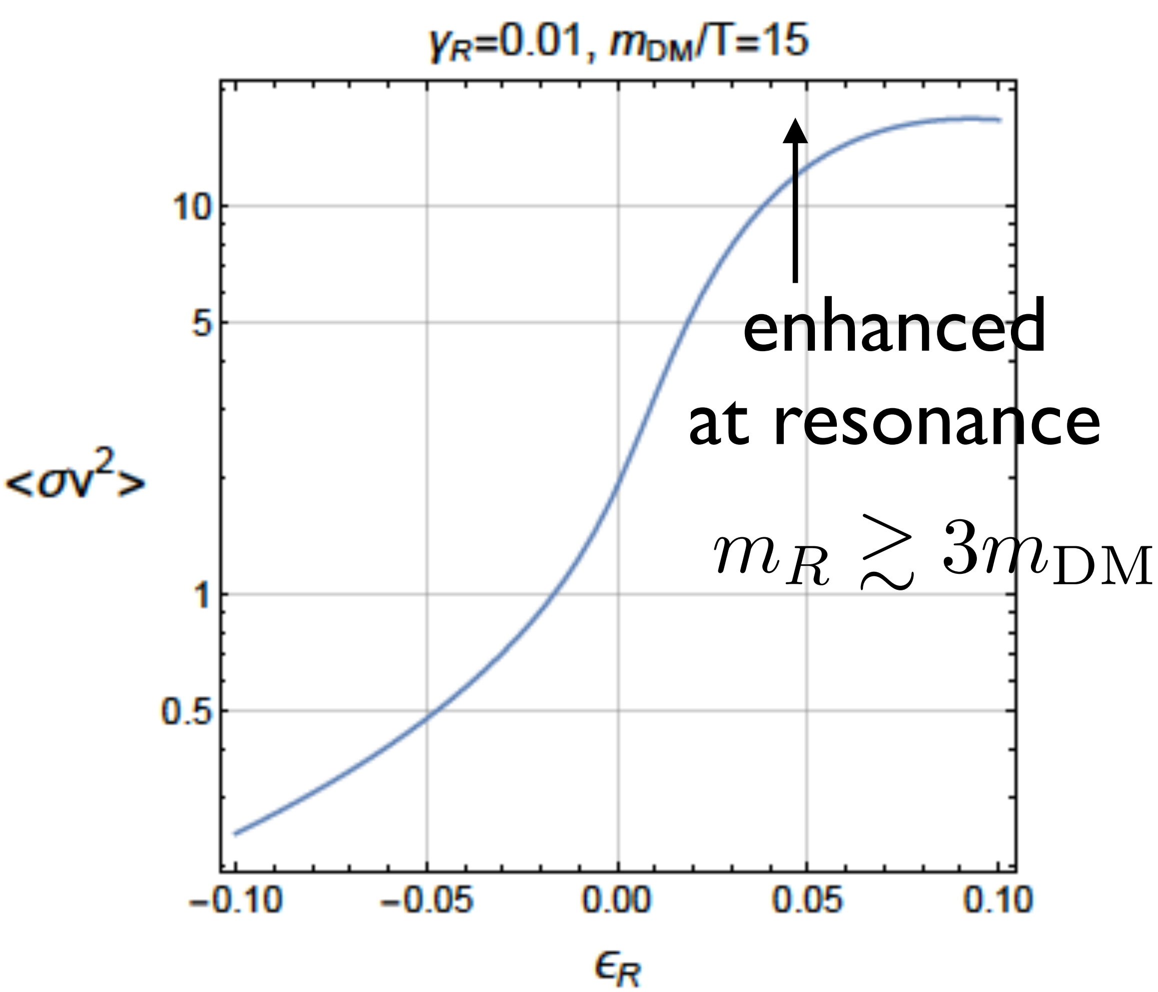
[S.-M. Choi, HML, M.-S. Seo, 2017]

- Thermal average of 3→2 cross section near resonances.

Breit-Wigner form for SIMP:

$$\boxed{(\sigma v^2)_R = \frac{9\sqrt{5}}{2\beta_\chi \Phi_3 m_R^3}\frac{\gamma_R^2}{(\epsilon_R-\frac{2}{3}\eta)^2+\gamma_R^2}\,\mathrm{Br}(R\to\chi\chi\chi)\,\mathrm{Br}(R\to\chi\chi)} \equiv b_R \frac{\gamma_R}{(\epsilon_R-\frac{2}{3}\eta)^2+\gamma_R^2}$$

$$b_R = \sum_{l=0}^{\infty}\frac{b_R^{(l)}}{l!}\eta^l \qquad \gamma_R \equiv \frac{m_R\Gamma_R}{9m_{\rm DM}^2} \qquad \epsilon_R \equiv \frac{m_R^2-9m_{\rm DM}^2}{9m_{\rm DM}^2}$$



<u>Thermal average with narrow width:</u>

$$\gamma_R \ll 1, \quad \langle\sigma v^2\rangle_R \approx \frac{27}{16}\pi\epsilon_R^2 x^3 e^{-\frac{3}{2}x\epsilon_R}\theta(\epsilon_R)\sum_{l=0}^{\infty}\frac{b_R^{(l)}}{l!}\left(\frac{3}{2}\right)^l\epsilon_R^l.$$

$\boxed{\text{3 DM's: higher dimensional phase space}}$

cf. WIMP: $\langle\sigma v\rangle_R \approx 2\sqrt{\pi}\gamma_R\epsilon_R^{1/2}x^{3/2}e^{-x\epsilon_R}\theta(\epsilon_R)\sum_{l=0}^{\infty}\frac{b_l}{l!}\epsilon_R^l.$

Vector Mesons in dark ChPT

SIMP mesons + Vector mesons in dark QCD:

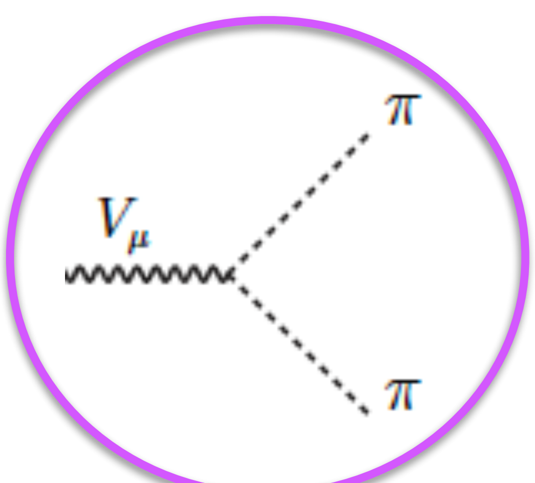
$$\boxed{\begin{array}{c} G = SU(N_f)_V \times SU(N_f)/SU(N_f)_V \\ + \; H_{local} = SU(N_f)_V \text{ hidden local symmetry} \end{array}}$$

$$\rightarrow \quad V_\mu \equiv V_\mu^a t^a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho_\mu^+ & K_\mu^{*+} \\ \rho_\mu^- & -\frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & K_\mu^{*0} \\ K_\mu^{*-} & \overline{K_\mu^{*0}} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \end{pmatrix}$$

Extra chiral-invariant term (in unitary gauge):

$$\mathcal{L}_B = -a\frac{f_\pi^2}{4}\mathrm{Tr}\left[(D_\mu\xi_L)\xi_L^\dagger + D_\mu\xi_R)\xi_R^\dagger\right]^2 \qquad \xi_L^\dagger(x) \;=\; \xi_R(x) \;=\; \exp[i\pi(x)/f_\pi]$$

$$\rightarrow \quad \mathcal{L}_B = m_V^2\,\mathrm{Tr}V_\mu V^\mu - 2ig_{V\pi\pi}\mathrm{Tr}\left(V_\mu[\partial^\mu\pi,\pi]\right) - \frac{a}{4f_\pi^2}\mathrm{Tr}\left([\pi,\partial_\mu\pi]^2\right)$$



VM masses: $m_V^2 = ag^2 f_\pi^2$ degenerate

VM-pion couplings: $g_{V\pi\pi} = \frac{1}{2}ag.$ cf. QCD: $a \simeq 2$

WZW with vector mesons

WZW terms gauged by $H_{local}=SU(N_f)_V$

$$\Gamma^{anom} = \int d^4x[\mathcal{L}_{WZW} - 15(c_1\mathcal{L}_1 + c_2\mathcal{L}_2 + c_3\mathcal{L}_3)]$$

$$\mathcal{L}_1 = \mathrm{Tr}\left[\hat{\alpha}_L^3\hat{\alpha}_R - \hat{\alpha}_R^3\hat{\alpha}_L\right] \qquad \hat{\alpha}_L = D\xi_L \cdot \xi_L^\dagger = \alpha_L - igV$$

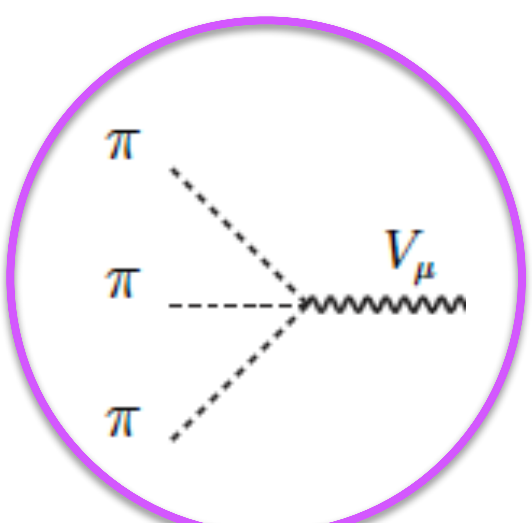
$$\mathcal{L}_2 = \mathrm{Tr}\left[\hat{\alpha}_L\hat{\alpha}_R\hat{\alpha}_L\hat{\alpha}_R\right] \qquad \hat{\alpha}_R = D\xi_R \cdot \xi_R^\dagger = \alpha_R - igV$$

$$\mathcal{L}_3 = i\mathrm{Tr}\left[F_V\left(\hat{\alpha}_L\hat{\alpha}_R - \hat{\alpha}_R\hat{\alpha}_L\right)\right] \qquad F_V = dV - igV^2$$

$$\Rightarrow \quad \mathcal{L}_1 = -\mathcal{L}_2 = -\frac{4gC}{f_\pi^3}\mathrm{Tr}[V_\mu\partial_\mu\pi\partial_\rho\pi\partial_\sigma\pi],$$

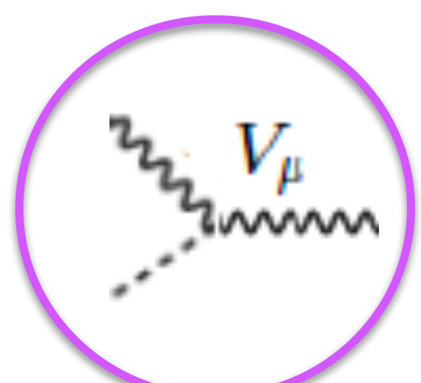
$$\mathcal{L}_3 = -\frac{2igC}{f_\pi}\mathrm{Tr}[\partial_\mu V_\nu(V_\rho\partial_\sigma\pi - \partial_\rho\pi V_\sigma)].$$

$$C = -\frac{iN_c}{240\pi^2}$$



cf. QCD:

$\omega \to 3\pi$



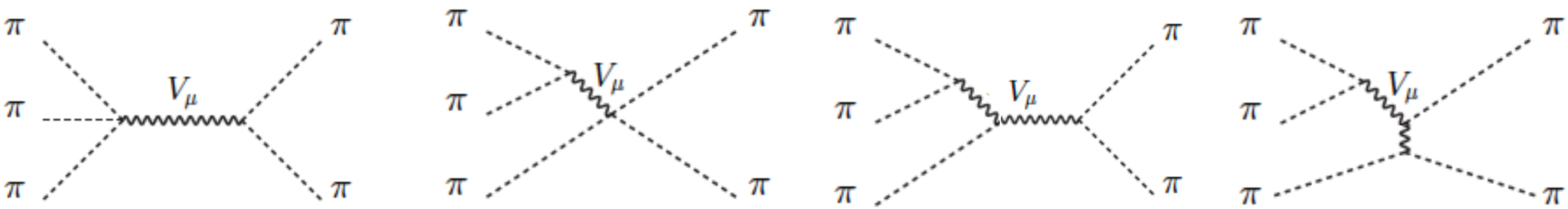
cf. QCD: VM-photon mixing

$\pi^0 \to 2\gamma$

Dark photon case: Berlin et al, 2018

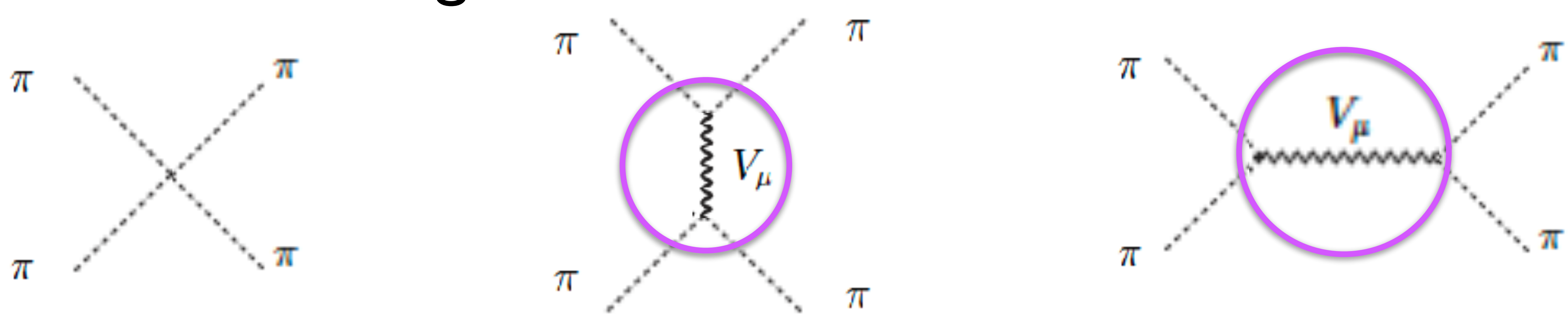
Vector Meson resonances

3→2 annihilation: [S.-Choi, A. Natale, HML, P. Ko, 2018]



Enhanced near resonances with 2π or 3π.

2→2 self-scattering:

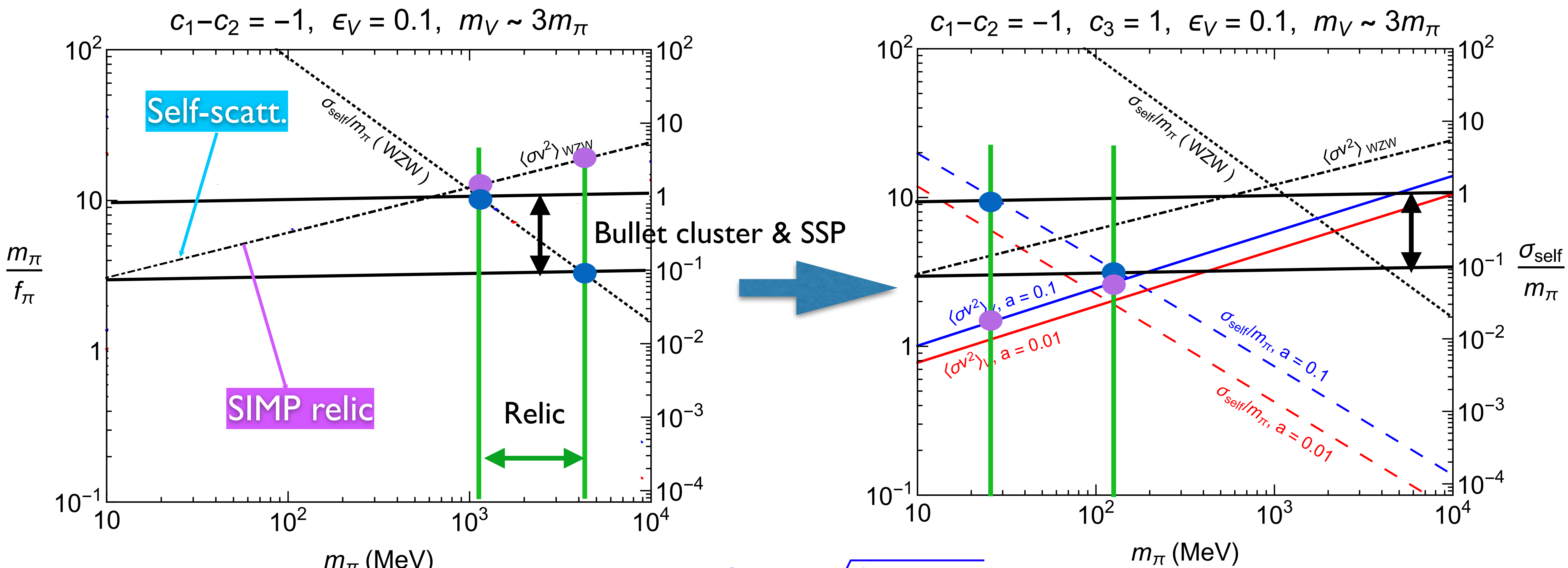


$\sim v^2$ $\sim v^4$

VM resonance is velocity-suppressed at galaxies and galaxy clusters.

3-meson resonance

[S.-Choi, A. Natale, HML, P. Ko, 2018]



$$m_V = 3m_\pi\sqrt{1+\epsilon_V}$$

Vector mesons on-resonance improve perturbativity.

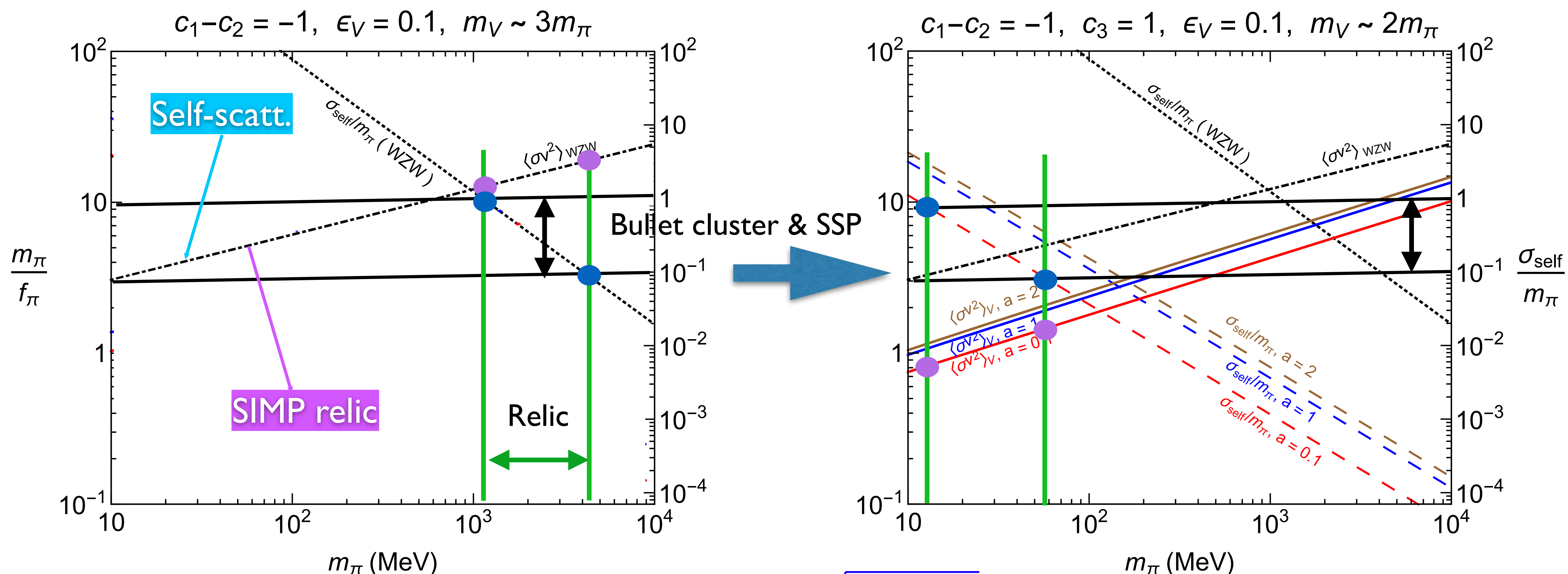
$m_\pi/f_\pi \lesssim 6$ for $g_{V\pi\pi} \lesssim 6$ and $m_\pi \lesssim 1\,\mathrm{GeV}$.

cf. WZW terms only: $m_\pi/f_\pi \lesssim 15.$

Improvement persists for off-resonance too.

2-meson resonance

[S.-Choi, A. Natale, HML, P. Ko, 2018]



$$m_V = 2m_\pi\sqrt{1+\epsilon_V}$$

Vector mesons on-resonance improve perturbativity.

$m_\pi/f_\pi \lesssim 4$ for $g_{V\pi\pi} \lesssim 1.3$ and $m_\pi \lesssim 1\,\mathrm{GeV}.$

cf. WZW terms only: $m_\pi/f_\pi \lesssim 15.$

Conclusions

- SIMP dark matter is a sub-GeV SIDM produced via $3 \to 2$ freeze-out process and SIMP conditions can be tested by various intensity experiments.
- Dark mesons are natural candidates for SIMPs in dark confining gauge groups with flavor symmetries.
- Vector mesons unitarize SIMP mesons scenarios and maintain them as valid solutions to small-scale problems.
- Kinetic equilibrium conditions for SIMPs via Higgs or Z’ portals could reveal the nature of SIMP sector.