Communication to thermal dark matter with large self-interactions

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Based on M.-S. Seo, Phys. Lett. B748, 316;
S.-M. Choi, JHEP1509, 063 & To appear.

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Florence, Italy, Oct 5, 2015

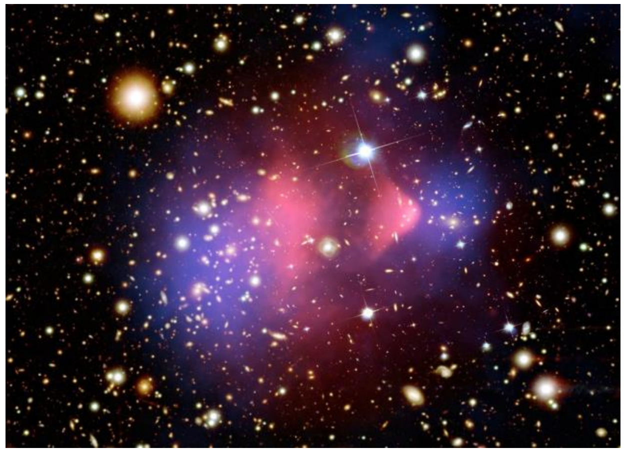
Outline

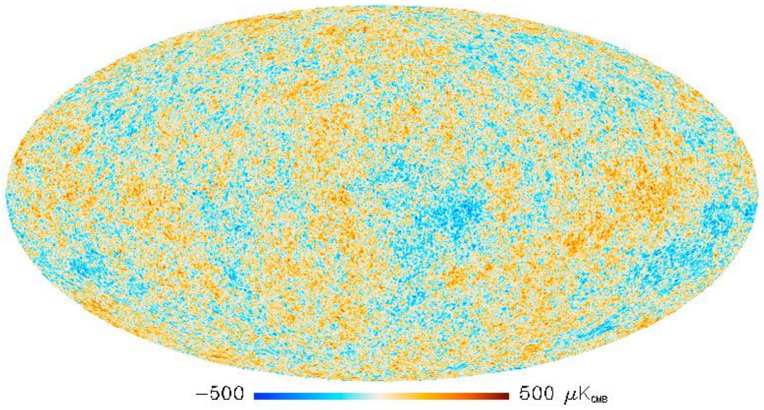
- Motivation
- SIMP DM from hidden QCD
- SIMP DM from discrete symmetries
- Conclusions

Motivation

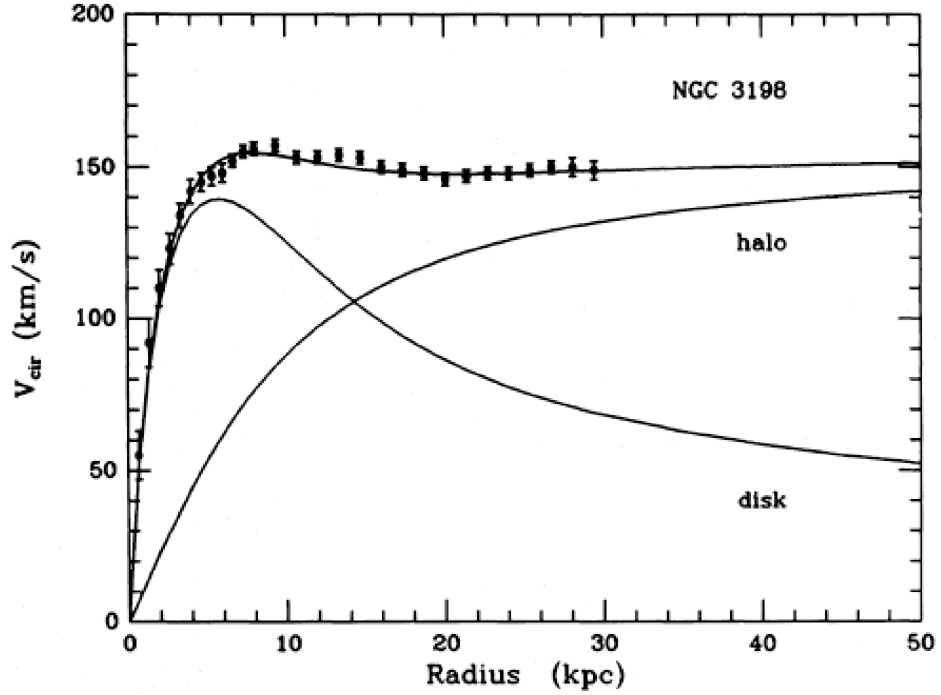
Dark matter everywhere!

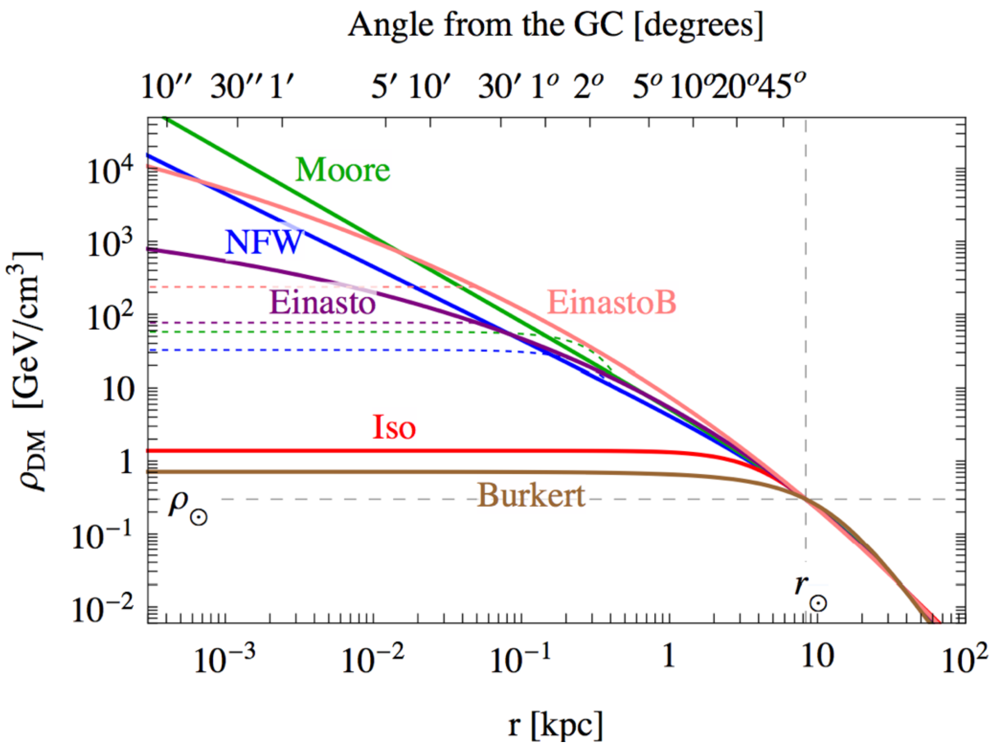
Large-scale evidences





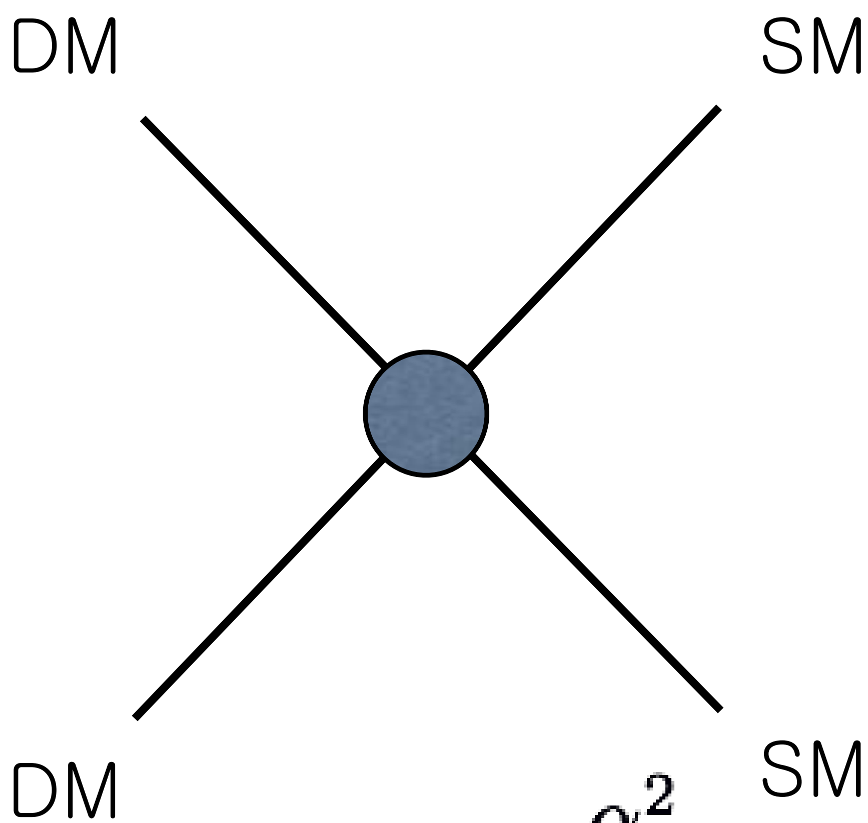
Galaxies (including our Milky Way)





WIMP paradigm

- WIMP DM density relies on 2→2 annihilation processes with weak interactions.



$$\langle \sigma v \rangle_{\rm ann} = \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^2}$$

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\rm eq}^2)$$

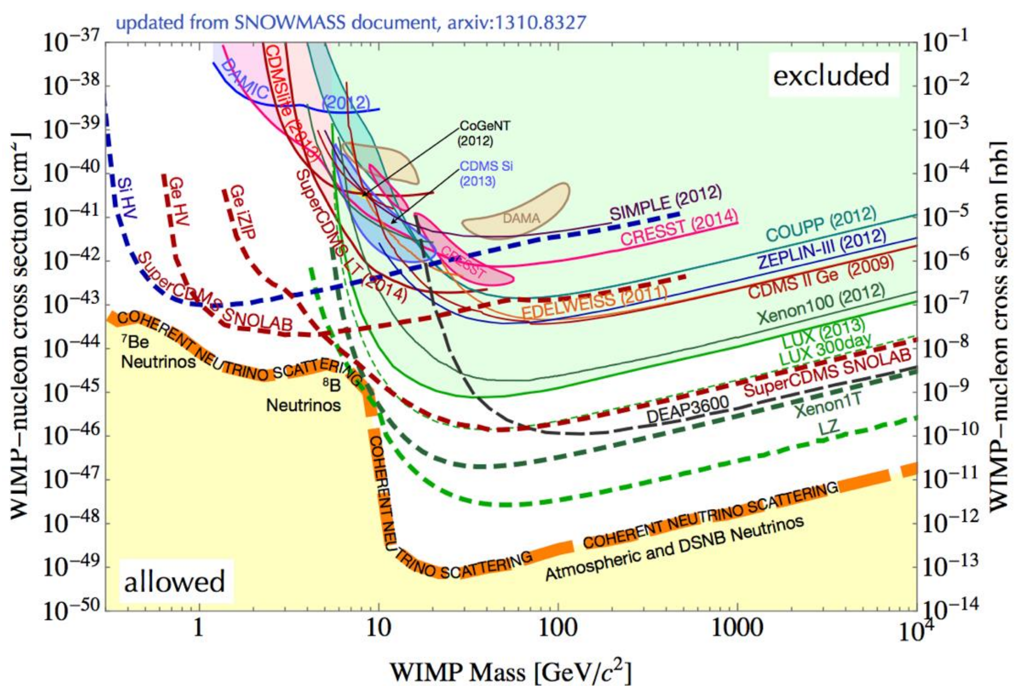
WIMP freeze-out:

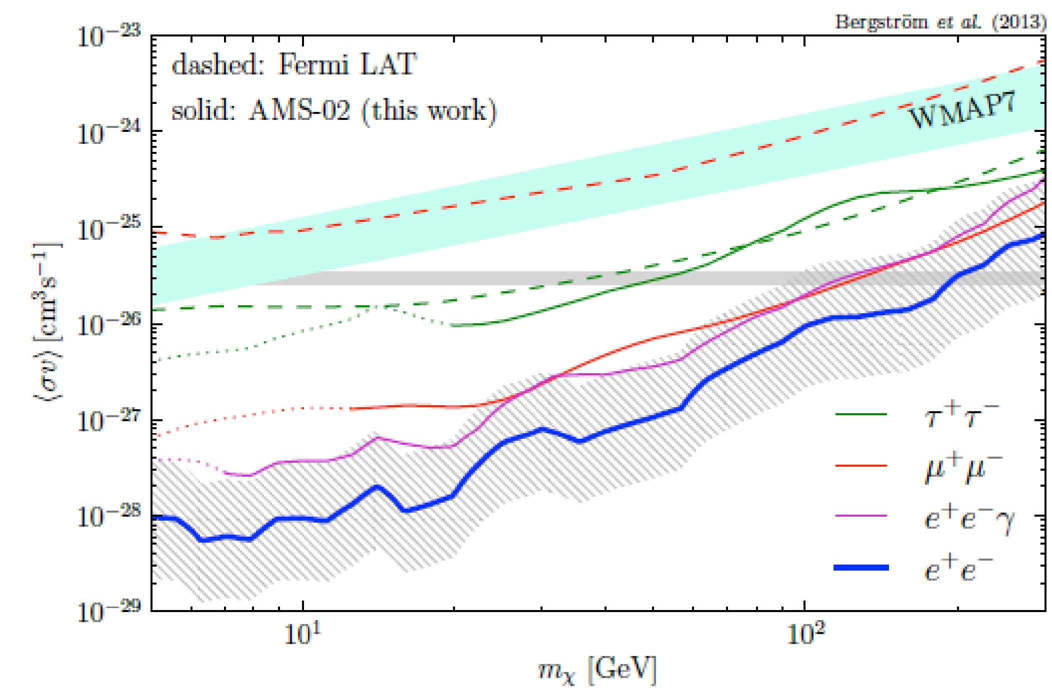
$$\Gamma_{\rm ann} = n_{\rm DM} \langle \sigma v \rangle_{\rm ann} \sim H = 0.33 g_*^{1/2} \frac{T_F^2}{M_P}$$

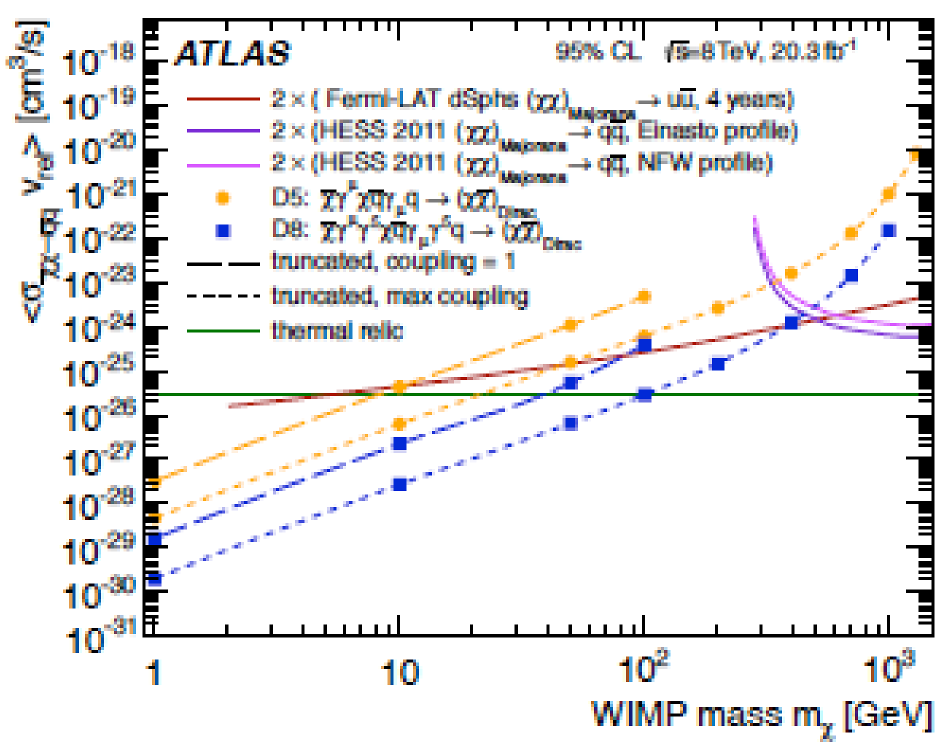
$$m_{\rm DM} = \alpha_{\rm eff} \left(\frac{5.35\kappa}{x_F g_*^{1/2}} T_{\rm eq} M_P \right)^{1/2} \quad \kappa \simeq 10.8$$

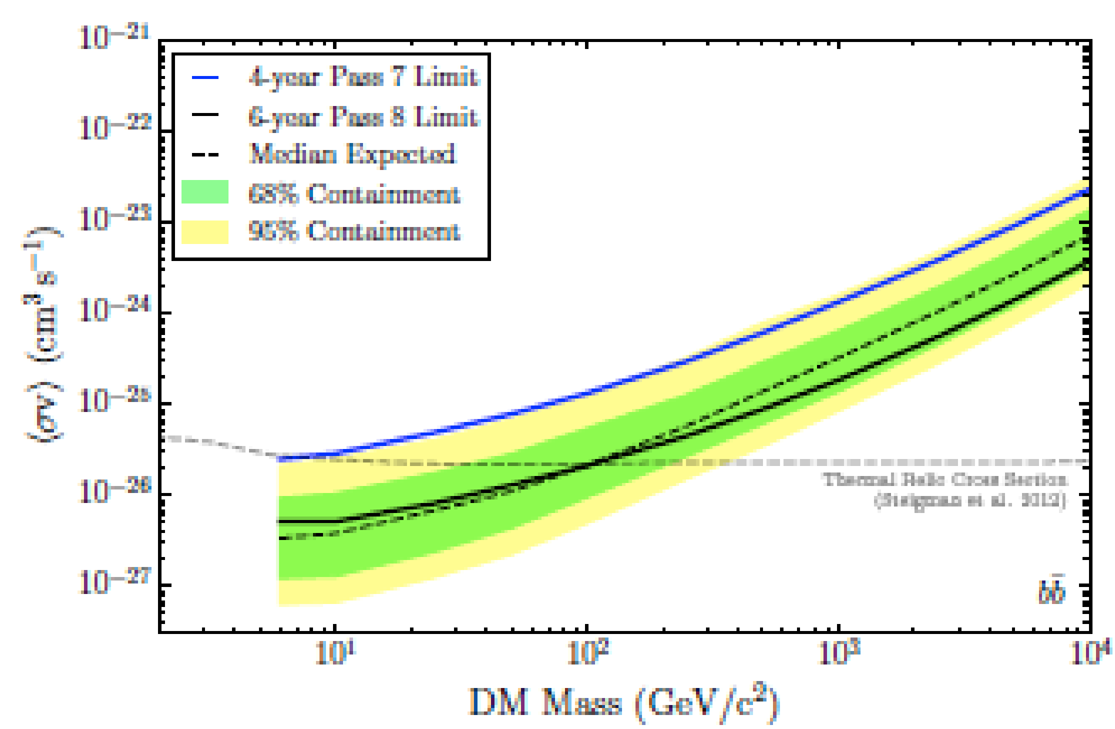
$$\boxed{\alpha_{\rm eff} \sim 0.1 \;\longrightarrow\; m_{\rm DM} \sim 100\,{\rm GeV}.}$$

WIMP around the corner?





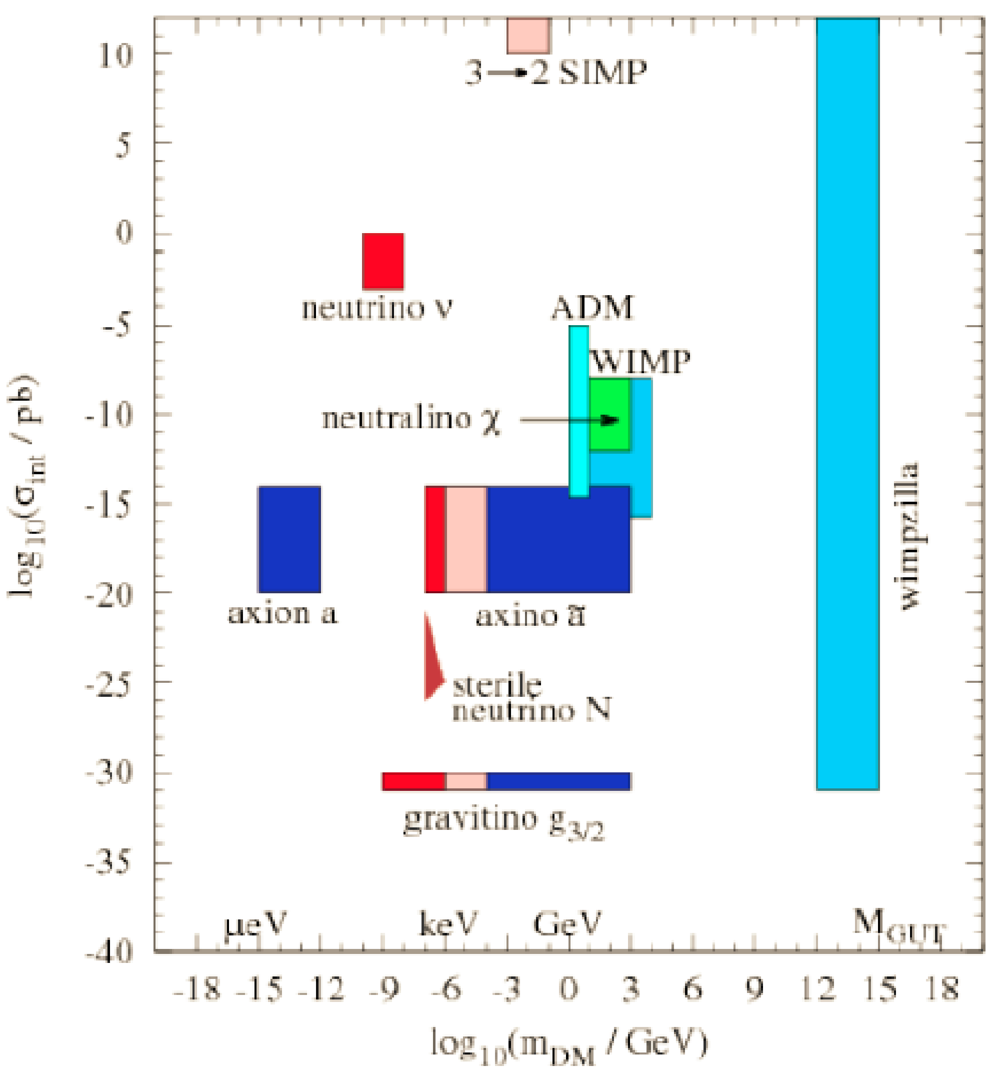




- Direct/indirect/collider searches rule out a wide range of WIMP dark matter.

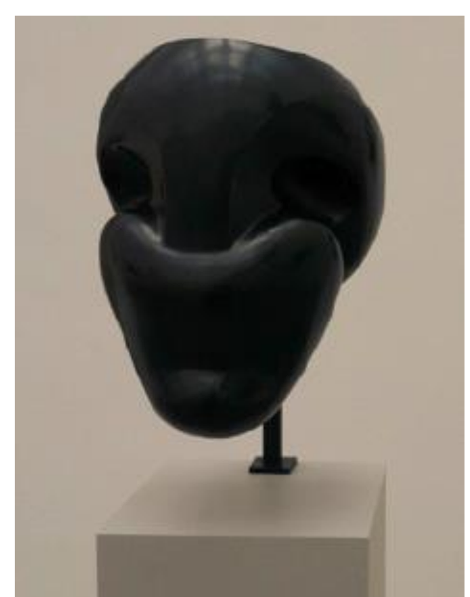
Non-WIMP?

- WIMP paradigm is based mostly on the assumption that DM is related to weak-scale physics solving the hierarchy problem.



[Choi, Kim, Roszkowski, 1407.0017]

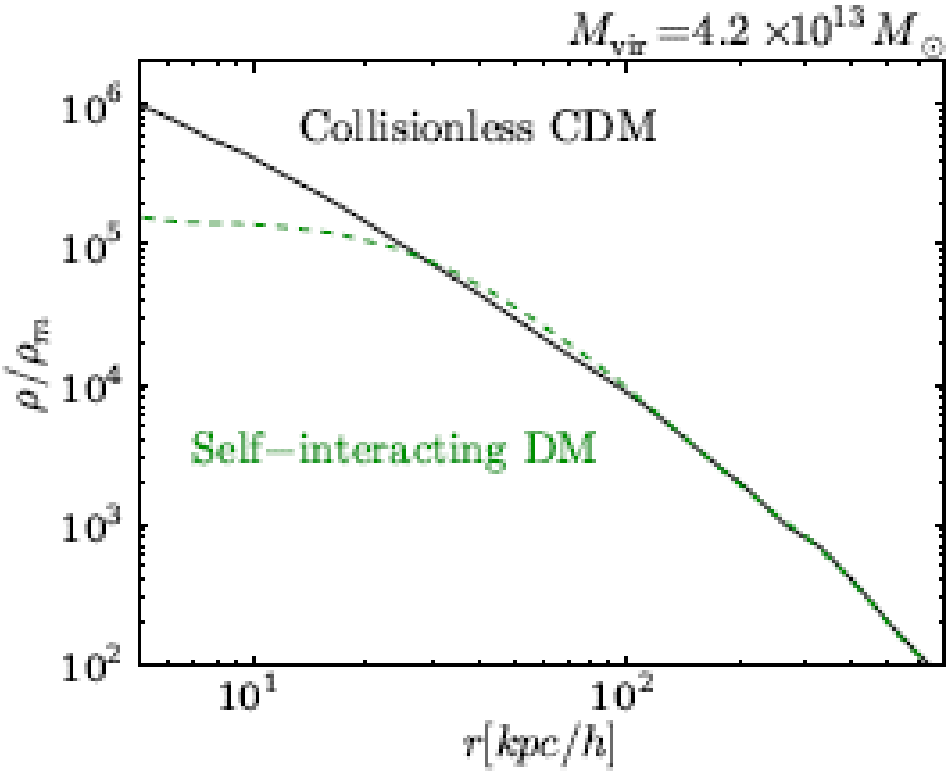
- But, dark matter might be related to different problems such as QCD axion or some unknown hidden sector.



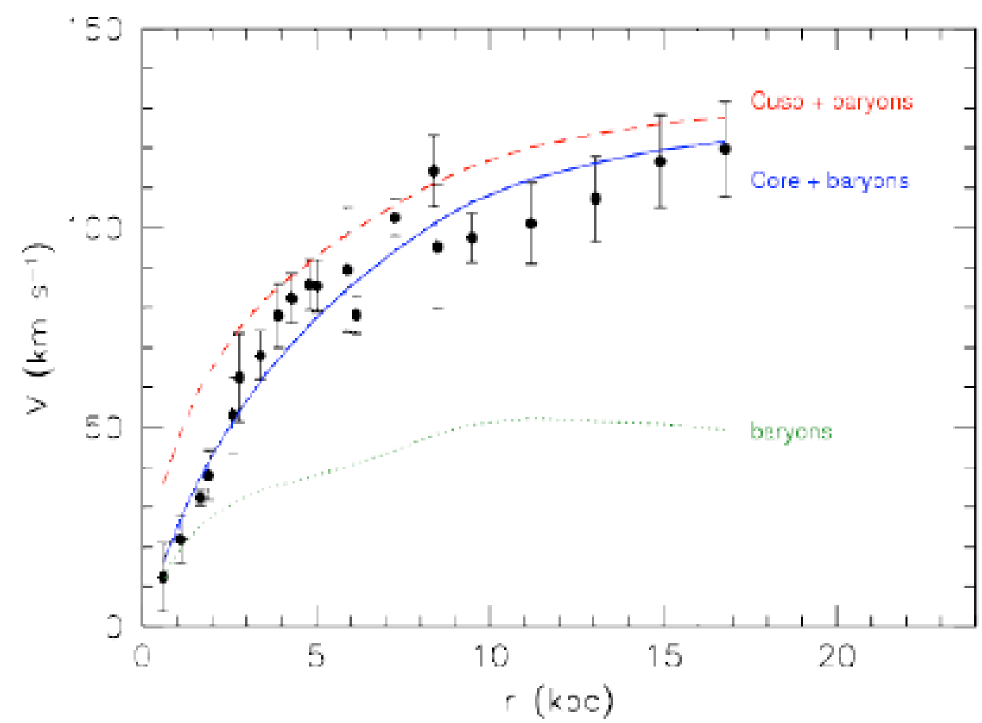
more than this?

DM self-interactions

- Solve small-scale problems in galaxies: core-cusp, too-big-to-fail, missing satellites, etc.



[D.H. Weinberg et al(2013)]



NFW overshoots data!

$$\sigma_{\rm self}/m_{\rm DM} = 0.1 - 10\,{\rm cm}^2/{\rm g}$$

cf. WIMP DM: $\sigma_{\rm self}/m_{\rm WIMP} \sim 10^{-11}{\rm GeV}^{-3} \sim 10^{-14}{\rm cm}^2/g.$

Bullet cluster & halo shape: $\sigma_{\rm self}/m_{\rm DM} < 1{\rm cm}^2/g$

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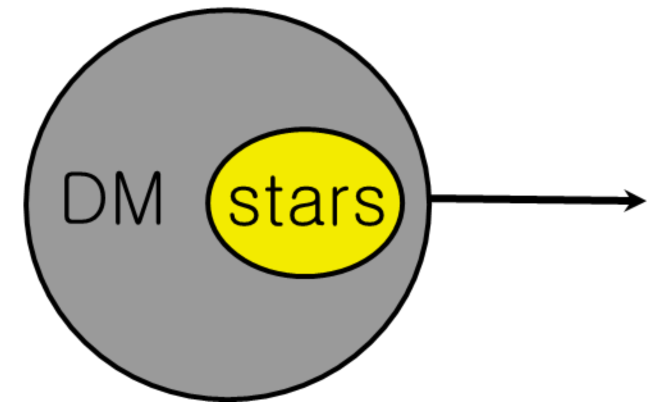
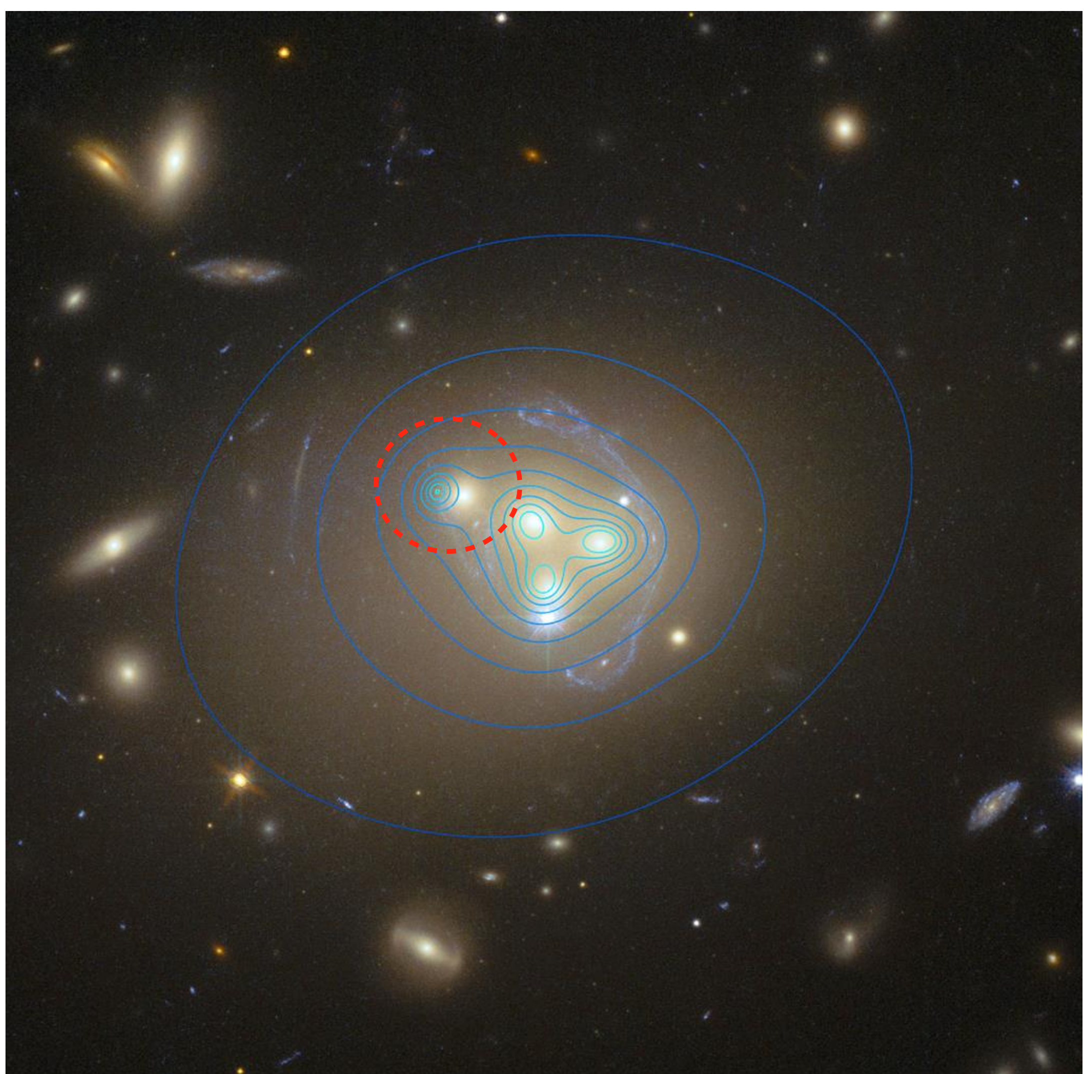
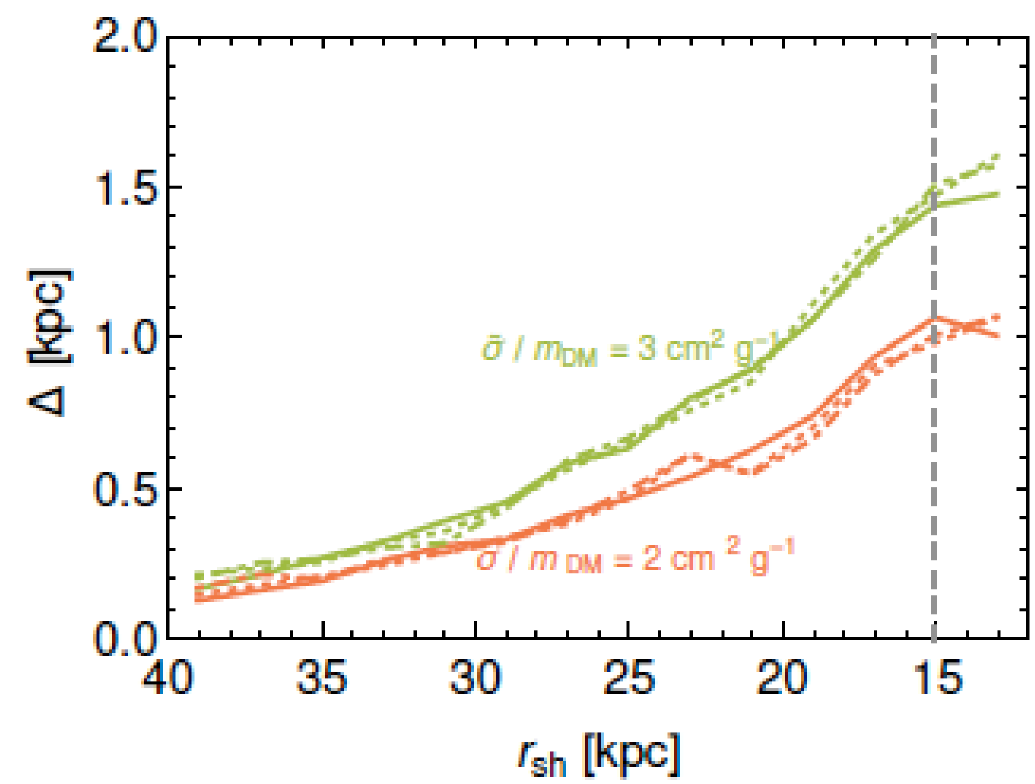
- Lead to an observable effect the lag of DM subhalos from their stars.



- Among four colliding galaxies observed by Hubble Telescope, one of subhalo lags behind the galaxy.



DM subhalo separation $\Delta = 1.62^{+0.47}_{-0.49}\,\mathrm{kpc}$ [Massey et al(2015)]

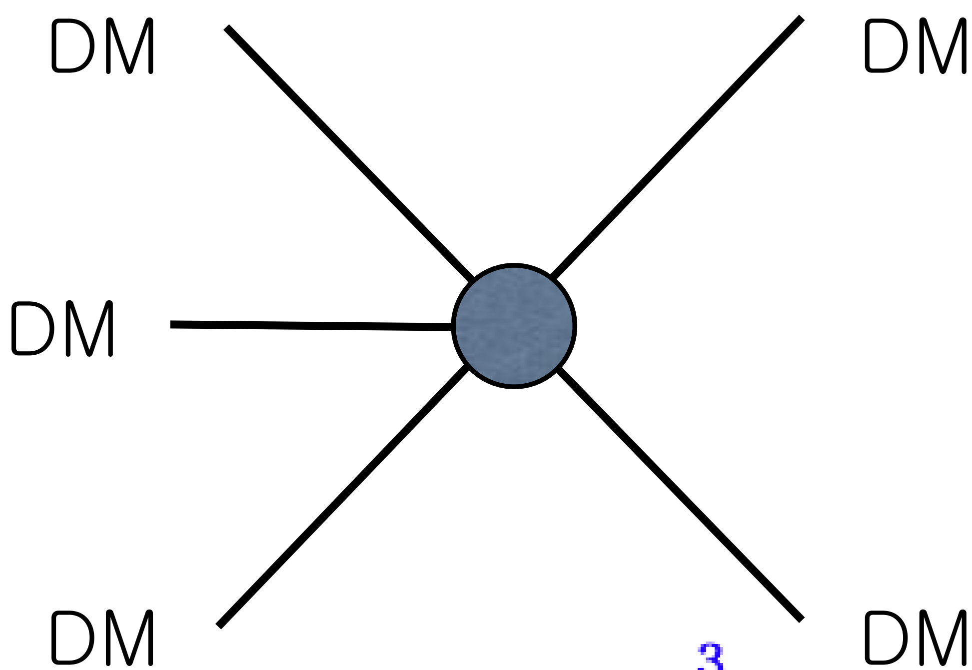


[Kahlhoefer etal (2015)]

SIMP paradigm

- Strong Interacting Massive Particle(SIMP) is a thermal DM, due to 3→2 self-annihilation.

[Hochberg et al, 2014]



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

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle_{3\to 2}(n^2 - n_{\rm eq}^2)$$

Freeze-out:

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

$$m_{\rm DM} = \alpha_{\rm eff} \left(\frac{5.35\kappa^2}{x_F^4 g_*^{1/2}} T_{\rm eq}^2 M_P \right)^{1/3} \quad (\kappa \simeq 2.55)$$

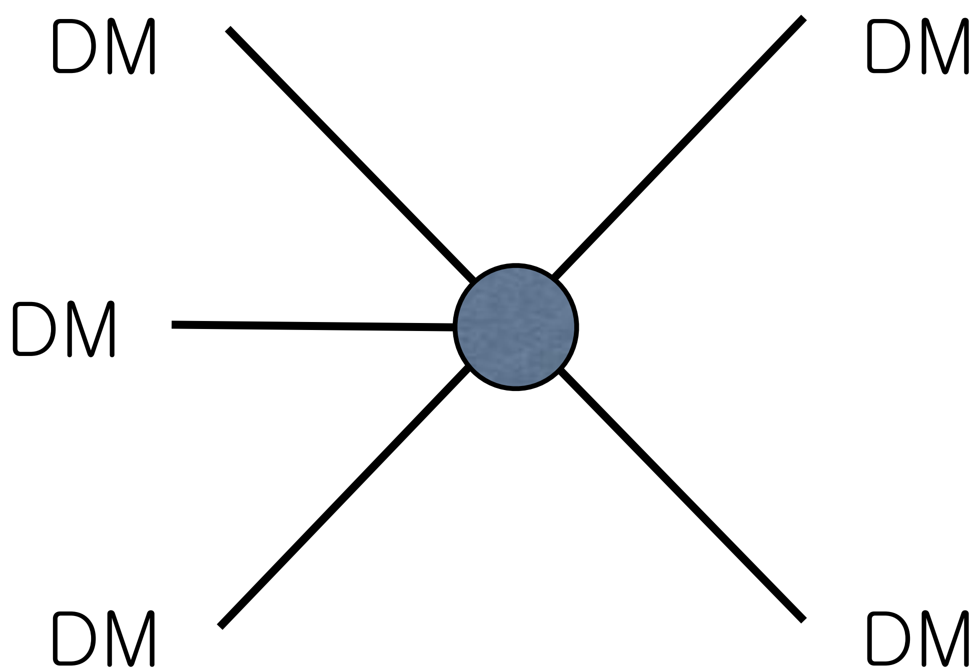
cf. WIMP:

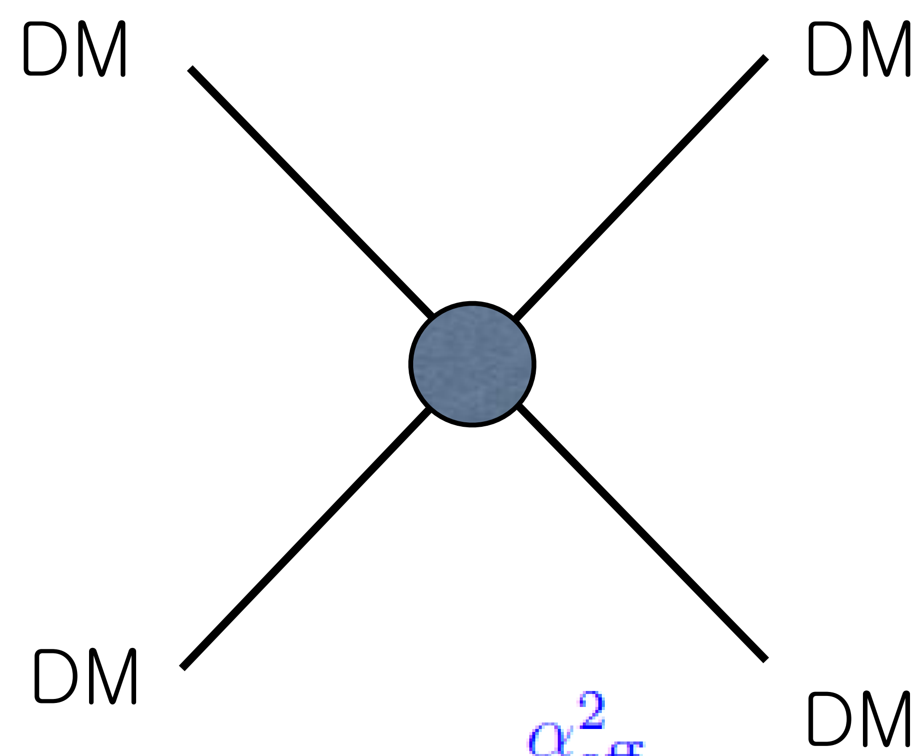
$$m_{\rm DM} = \alpha_{\rm eff} \left(\frac{5.35\kappa}{x_F g_*^{1/2}} T_{\rm eq} M_P \right)^{1/2}$$

$$\boxed{\alpha_{\rm eff} = 1 - 30 \;\Longrightarrow\; m_{\rm DM} \sim 10{\rm MeV} - 1\,{\rm GeV}}$$

Large SIMP self-interaction

- SIMP DM predicts typically large DM self-interactions.





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

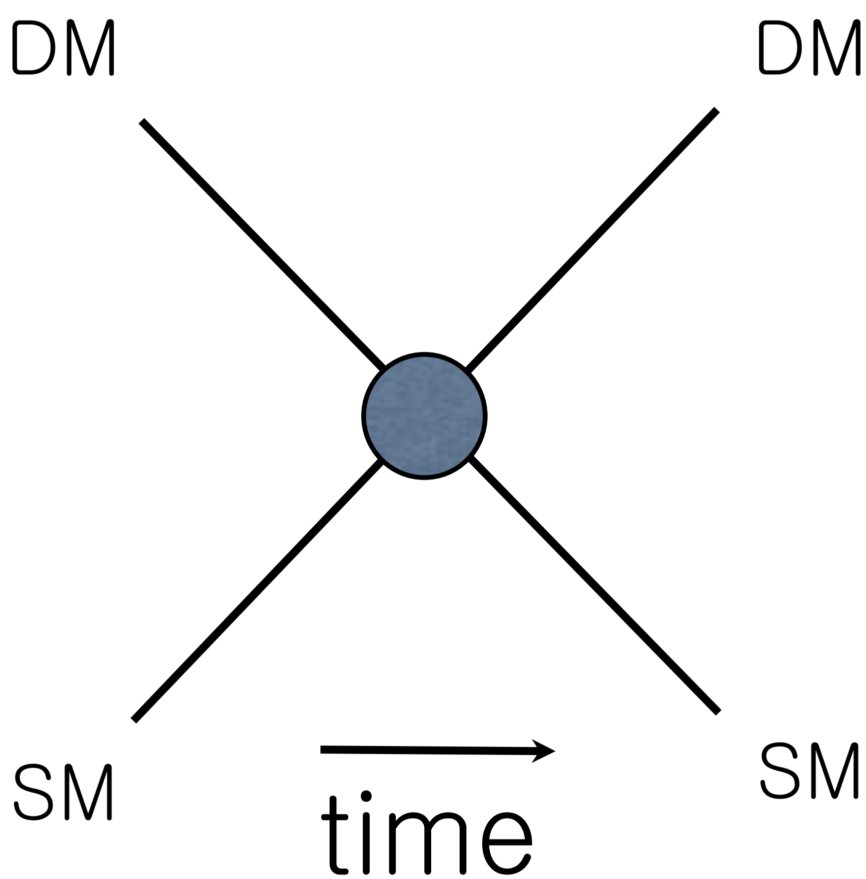
$$\sigma_{\rm self} \sim \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^2}$$

$$\frac{\sigma_{\rm self}}{m_{\rm DM}} = 4 \times 10^3\,{\rm GeV}^{-3} \left(\frac{100\,{\rm MeV}}{m_{\rm DM}}\right)^3 \left(\frac{\alpha_{\rm eff}}{2}\right)^2$$

Bullet cluster & spherical halo shapes.

$$\frac{\sigma_{\rm self}}{m_{\rm DM}} < 1\,{\rm cm}^2/{\rm g} = 4.6 \times 10^3\,{\rm GeV}^{-3}$$

SIMP conditions



- Equilibration of heat from SIMP: kinetic equilibrium with SM bath.

$$\langle \sigma v \rangle_{\rm kin} = \frac{\epsilon_1^2}{m_{\rm DM}^2}; \quad n_{\rm SM}\langle \sigma v \rangle_{\rm kin} > H(T_F)$$

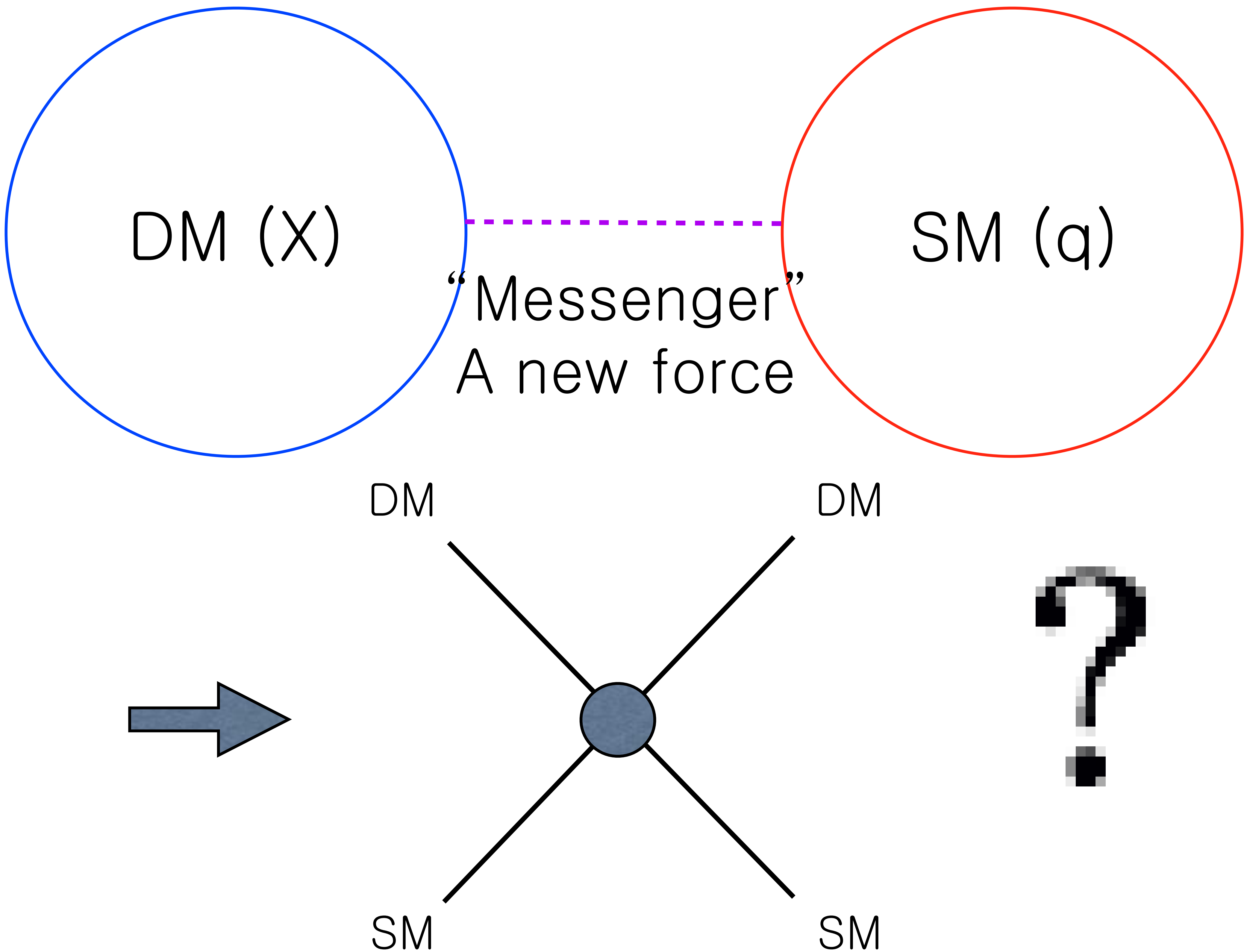
$$\Rightarrow \quad \boxed{\epsilon_1 \gtrsim 0.9 \times 10^{-9} \alpha_{\rm eff}^{1/2}}$$

- The same coupling leads to 2→2 DM annihilation, which is subdominant when

$$\langle \sigma v \rangle_{\rm ann} = \frac{\epsilon_2^2}{m_{\rm DM}^2}; \quad n_{\rm SM}\langle \sigma v \rangle_{\rm kin} < n_{\rm DM}\langle \sigma v^2 \rangle_{3\to 2}$$

$$\underset{\epsilon_2 \sim \epsilon_1}{\Rightarrow} \quad \boxed{\epsilon_1 \lesssim 2.4 \times 10^{-6} \alpha_{\rm eff}}$$

DM messengers



SIMP DM from hidden QCD

Hidden QCD with WZW term

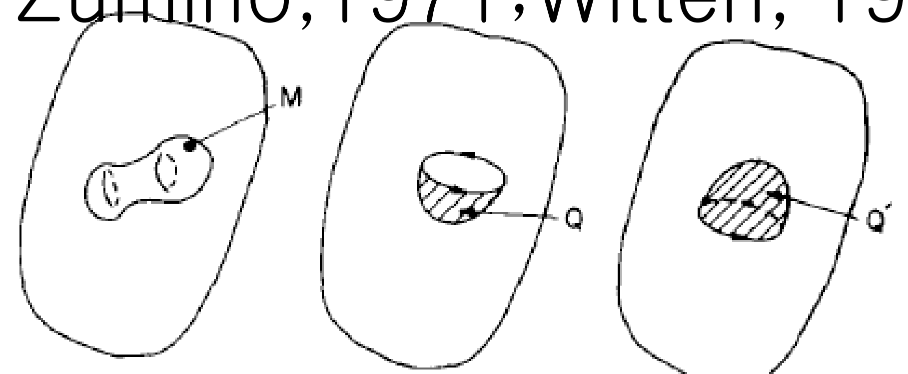
- Dark flavor symmetry $G=SU(N_f) \times SU(N_f)$ is broken down to $H=SU(N_f)$ by $SU(N_c)$ QCD-like condensation.
- Effective action for Goldstone bosons contains a 5-point self-interaction from Wess-Zumino-Witten term for $\pi_5(G/H)=Z$ (i.e. $N_f \geq 3$).

[Wess, Zumino,1971;Witten, 1983]

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

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

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



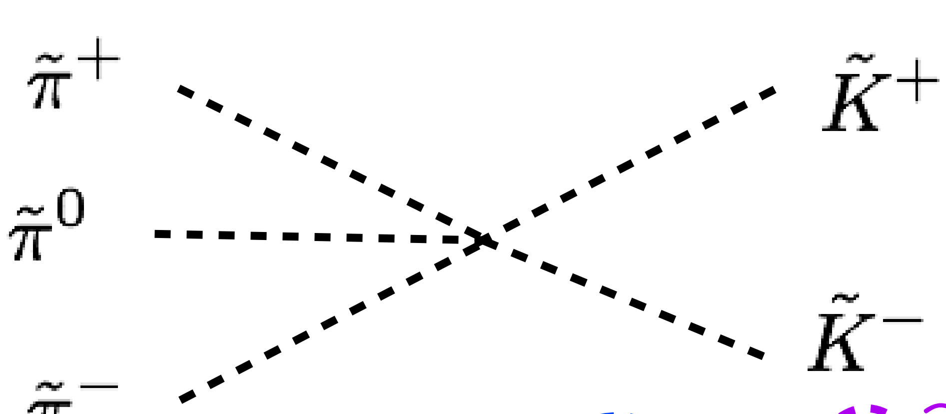
N_c : topological invariant of 5-sphere (Q+Q') in SU(3)

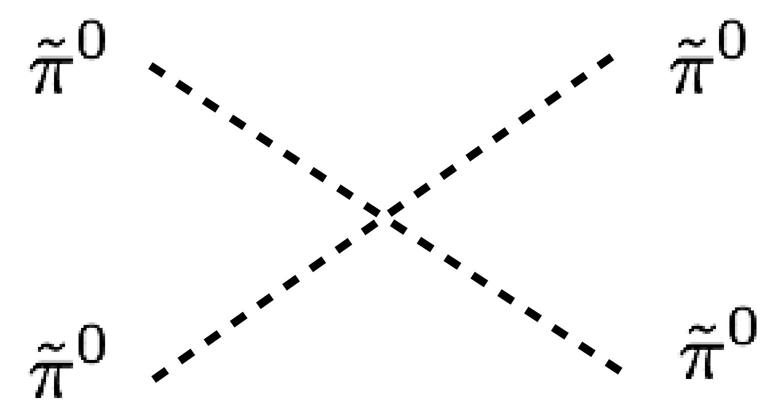
Flavor symmetry ensures stability of dark SIMP mesons.

SIMP dark mesons

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

[Hochberg et al, 2014]





~const

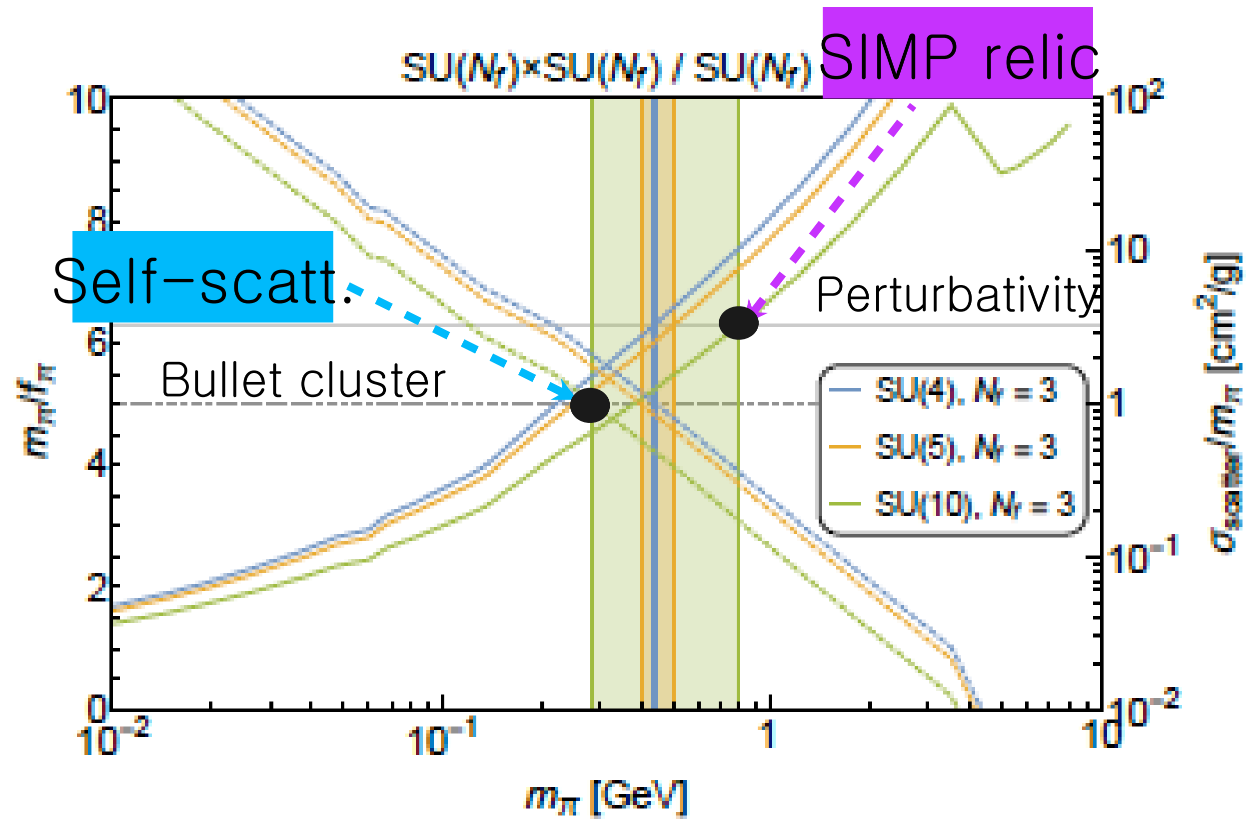
$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5} N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2,$$

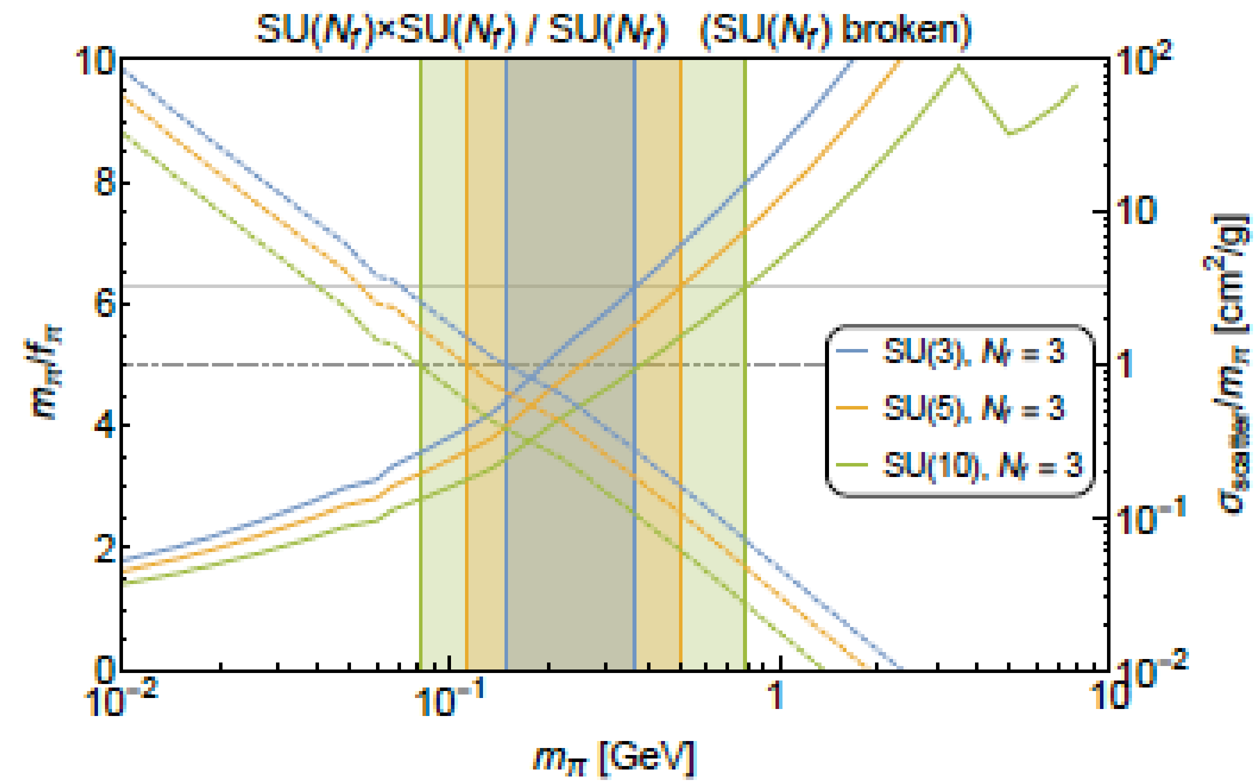
~const

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

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$\mathrm{SU}(N_c)$	$\frac{\mathrm{SU}(N_f)\times \mathrm{SU}(N_f)}{\mathrm{SU}(N_f)}$ $(N_f \geq 3)$	N_f^2-1	$\frac{4}{3}N_f(N_f^2-1)(N_f^2-4)$	$8(N_f-1)(N_f+1)(3N_f^4-2N_f^2+6)$
$\mathrm{SO}(N_c)$	$\mathrm{SU}(N_f)/\mathrm{SO}(N_f)$ $(N_f \geq 3)$	$\frac{1}{2}(N_f+2)(N_f-1)$	$\frac{1}{12}N_f(N_f^2-1)(N_f^2-4)$	$(N_f-1)(N_f+2)(3N_f^4+7N_f^3-2N_f^2-12N_f+24)$
$\mathrm{Sp}(N_c)$	$\mathrm{SU}(2N_f)/\mathrm{Sp}(2N_f)$ $(N_f \geq 2)$	$(2N_f+1)(N_f-1)$	$\frac{2}{3}N_f(N_f^2-1)(4N_f^2-1)$	$4(N_f-1)(2N_f+1)(6N_f^4-7N_f^3-N_f^2+3N_f+3)$

SIMP parameter space





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

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

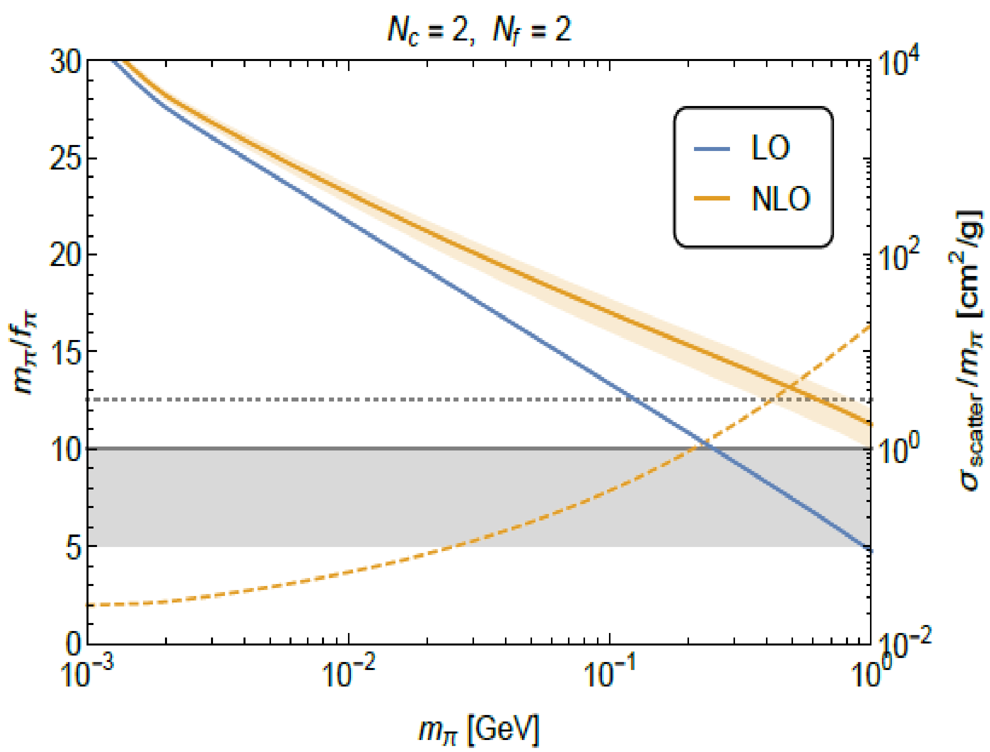
Perturbativity $m_\pi/f_\pi < 2\pi$

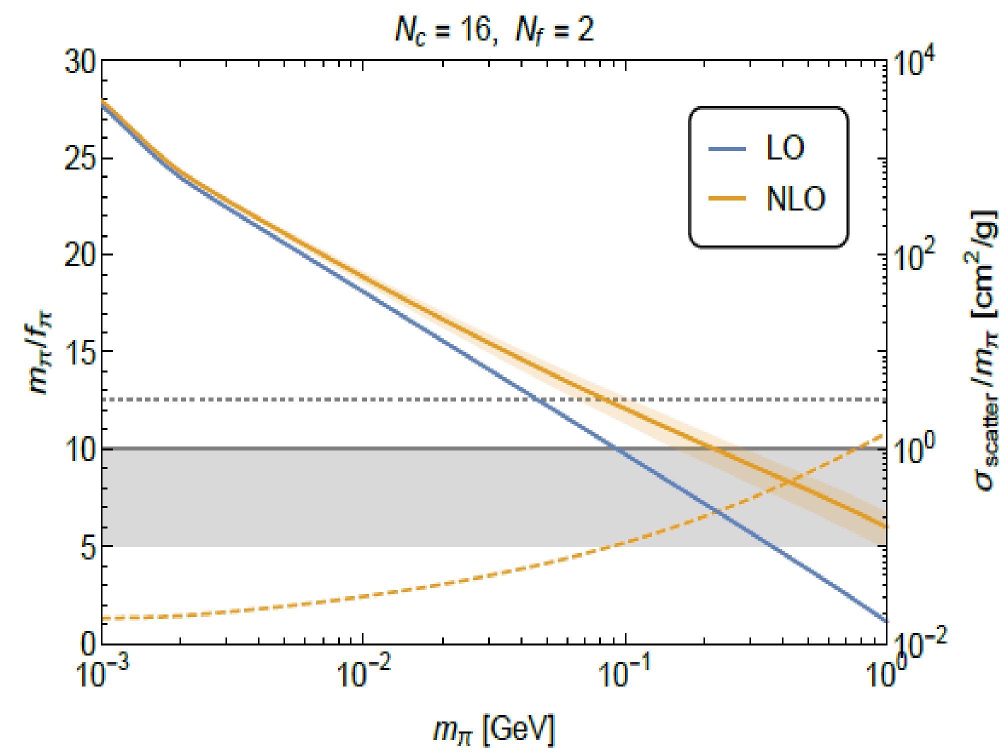
$N_C>3$ is required due to bounds on self-scattering.

Similar results for $SU(N_f)/SO(N_f)$ or $SU(2N_f)/Sp(2N_f)$.

NLO corrections

- 2→2: LO, 3→2: NLO [Hansen et al, 2015]





NLO corrections enhance 2→2 scattering cross sections, making the self-interaction bound stronger.

⇨ Need a large color or large meson decay constant: additional annihilation channel ?

Twin Higgs & mirror symmetry

- Twin Higgs: $[SU(3)_A \times SU(2)_A] \times [SU(3)_B \times SU(2)_B] \times Z_2$

[Chacko,Goh,Harnik, 2005]

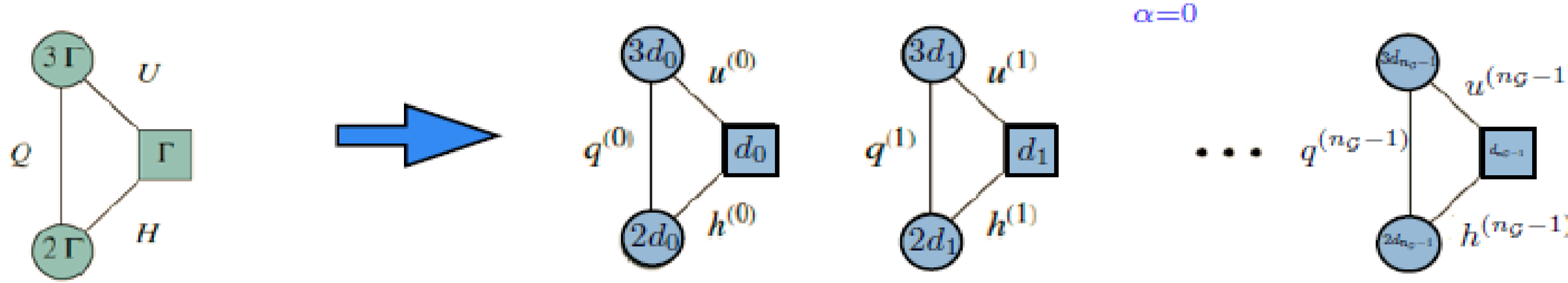
$$\mathcal{L}_Y = -y_A H_A q_A u_A^c - y_B H_B q_B u_B^c, \; y_A = y_B;$$

$$\Rightarrow \quad \delta m_h^2 = \frac{3}{4\pi^2}(y_A^2 - y_B^2)\Lambda^2 = 0 :$$ no quadratic divergence.

- Two-point function on orbifolds inherits the full symmetry.

[Craig, Knapen, Longhi, 2014]

$$[SU(3\Gamma) \times SU(2\Gamma)]_{\rm local} \times SU(\Gamma)_{\rm global}/\mathcal{G} \quad \left(\Gamma = |\mathcal{G}| = \sum_{\alpha=0}^{n_{\mathcal{G}}-1} (d_\alpha)^2,\; d_\alpha : \text{dim of irrep } r_\alpha\right)$$



$$V^{(1)} \supset -\frac{3}{8\pi^2}\Lambda^2 \sum_{\alpha=0}^{n_{\mathcal{G}}-1} (y^{(\alpha)})^2 |h^{(\alpha)}|^2 \underset{y^{(\alpha)} = \frac{y}{\sqrt{d_\alpha}}}{\sim} y^2\Lambda^2 \sum_{\alpha} |h^{(\alpha)}|^2.$$

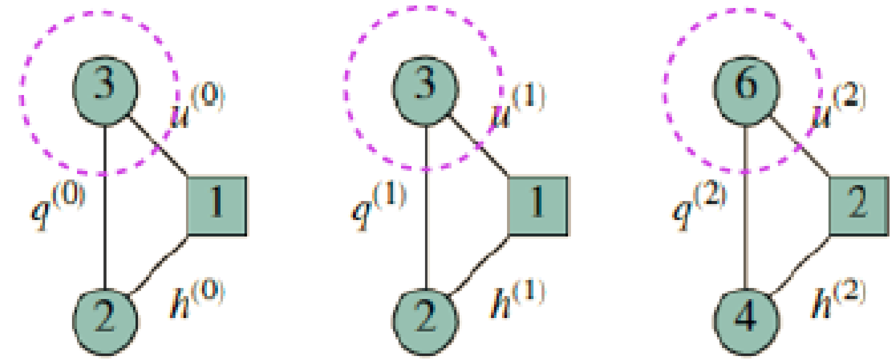
Twin Higgs: $SU(6) \times SU(4)/Z_2.$

Mirror QCD

- S_3 orbifolds: $SU(3)_A \times SU(3)_B \times SU(6)_B$ QCD

$$SU(18) \times SU(12) \times SU(6)_f / S_3$$

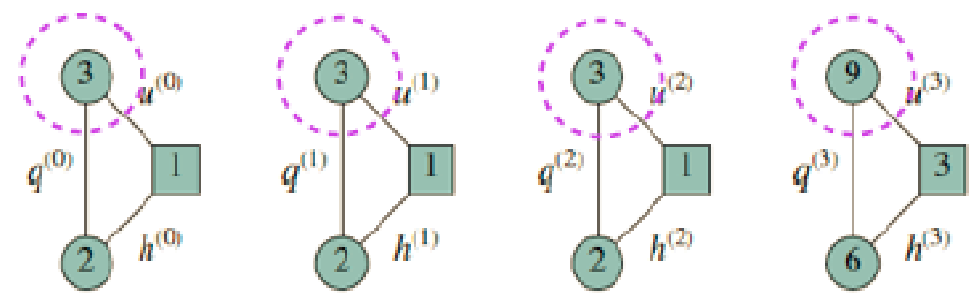
$$S_3 \,:\, d_0 = 1,\ d_1 = 1\ d_2 = 2$$



- A_4 orbifolds: $SU(3)_A \times SU(3)_B \times SU(3')_B \times SU(9)_B$ QCD

$$SU(36) \times SU(24) \times SU(12)_f / A_4$$

$$A_4 \,:\, d_0 = 1,\ d_1 = 1\ d_2 = 1,\ d_3 = 3$$



- Gauge loops on S_3 or A_4 lead to quadratic divergence.

$$V^{(1)} \supset \frac{3}{16\pi^2}\Lambda^2 \sum_{\alpha=1}^{n_{\mathcal{G}}} \underbrace{C_2(h^{(\alpha)})}_{=\frac{(d_\alpha N)^2-1}{2(d_\alpha N)}} (g^{(\alpha)})^2 |h^{(\alpha)}|^2 \Longrightarrow \delta m_h^2 \sim \frac{g^2}{N}\Lambda^2(1 - 1/d_{n_{\mathcal{Q}}}^2)$$

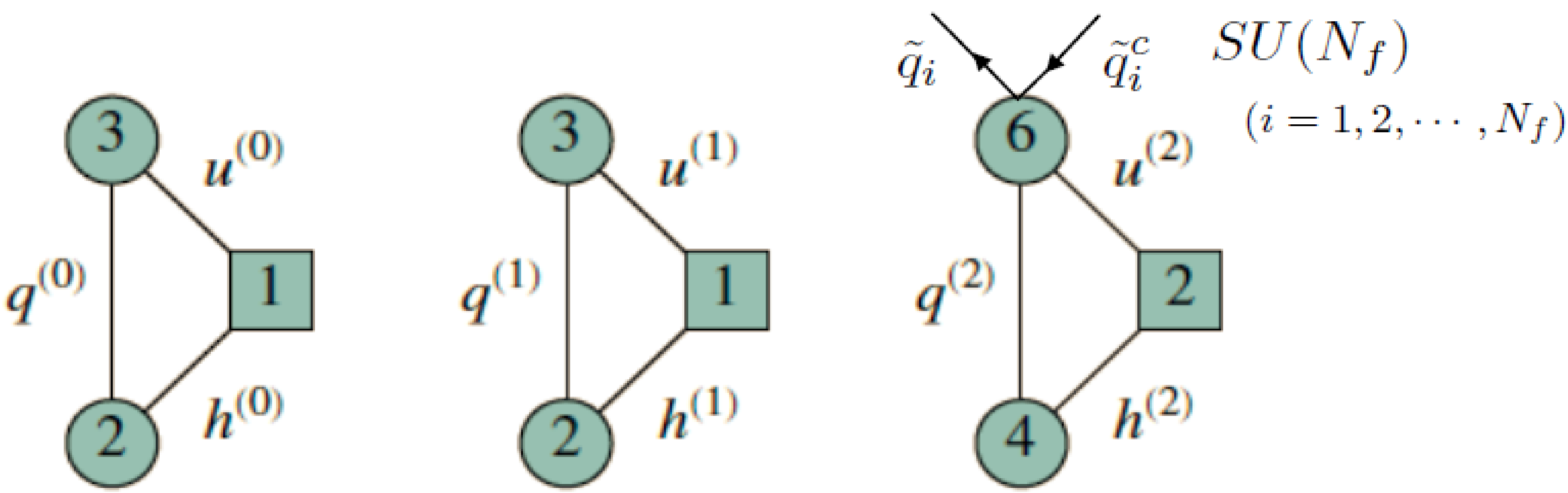
$$g^{(\alpha)} = \frac{g}{\sqrt{d_\alpha}} \qquad (d_{n_{\mathcal{Q}}} : \text{irrep of largest dim.})$$

But, they are parametrically small!

SIMP mesons on orbifolds

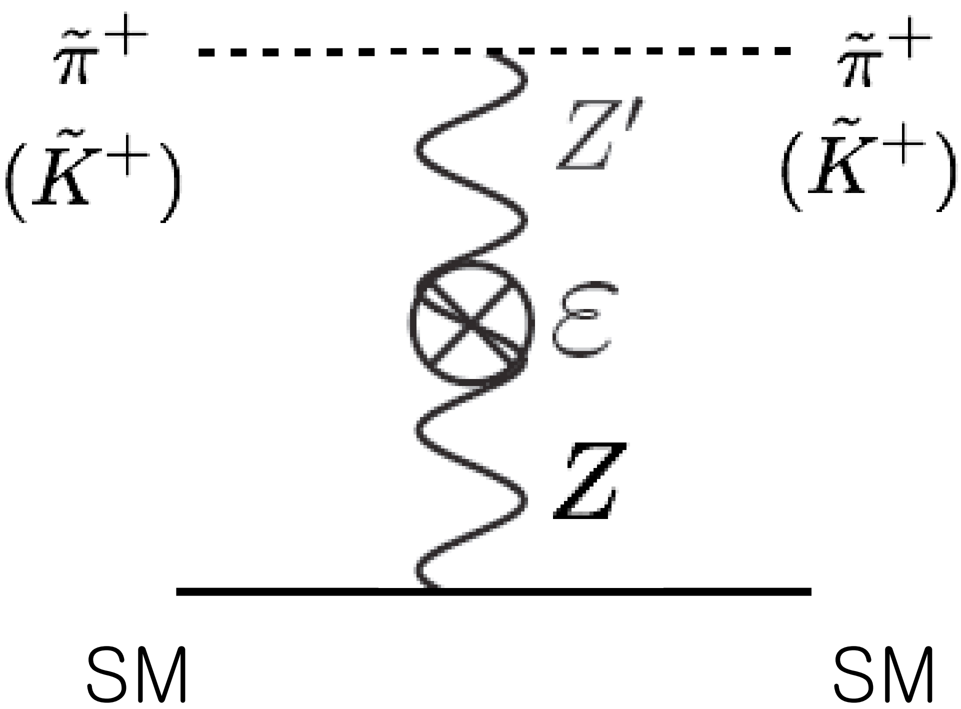
- Light dark quarks, that are vector-like under QCD partner group, can be introduced as split multiplets, without spoiling naturalness.
- Z' (part of the full gauge symmetry) mediates between the SM and dark mesons.

e.g. $SU(18) \times SU(12) \times SU(6)_f / S_3$



Dark mesons & Z'–portal

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



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

$$\Rightarrow \quad \langle\sigma v\rangle_{\rm kin} \approx \frac{768\alpha\alpha_D\varepsilon^2}{\pi N_\pi}\,\frac{m_\pi^2}{m_{Z'}^4}\left(\frac{T_F}{m_\pi}\right).$$

cf. Higgs–portal coupling does not work, because leptons in thermal bath have small Yukawa couplings.

- 2→2 annihilation with Z'–portal could be suppressed (or be as large as 3→2 ann).

⇒ 3→2 dominance: SIMP conditions

WZW with Z'

[Witten, 1983]

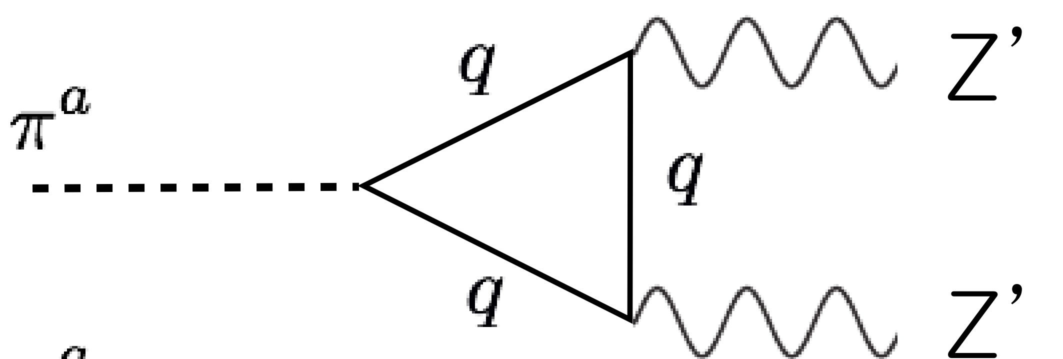
- Dark quarks are vector-like under broken U(1)'.
- Modified WZW with U(1)':

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

$$
\begin{aligned}
J^\mu = \frac{1}{48\pi^2} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}[& Q\partial_\nu U U^{-1} \partial_\rho U U^{-1} \partial_\sigma U U^{-1} \\
&+ QU^{-1} \partial_\nu U U^{-1} \partial_\rho U U^{-1} \partial_\sigma U].
\end{aligned}
$$

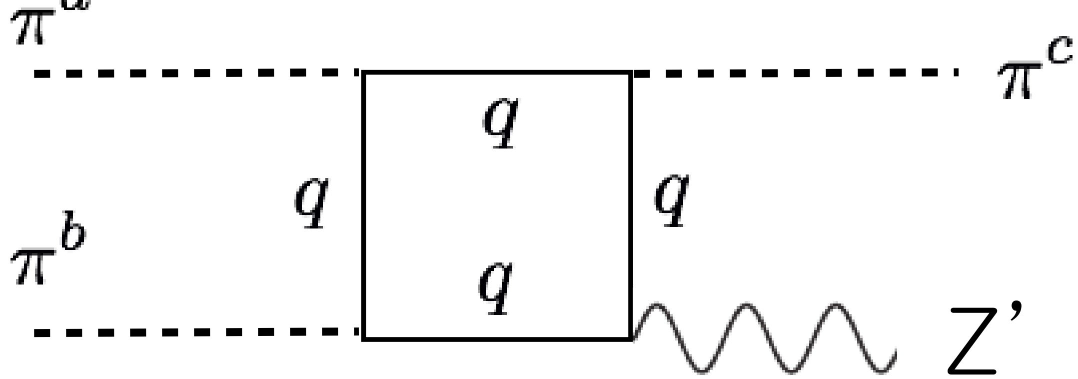
AVV anomalies.

→ DM decay



AAAV anomalies.

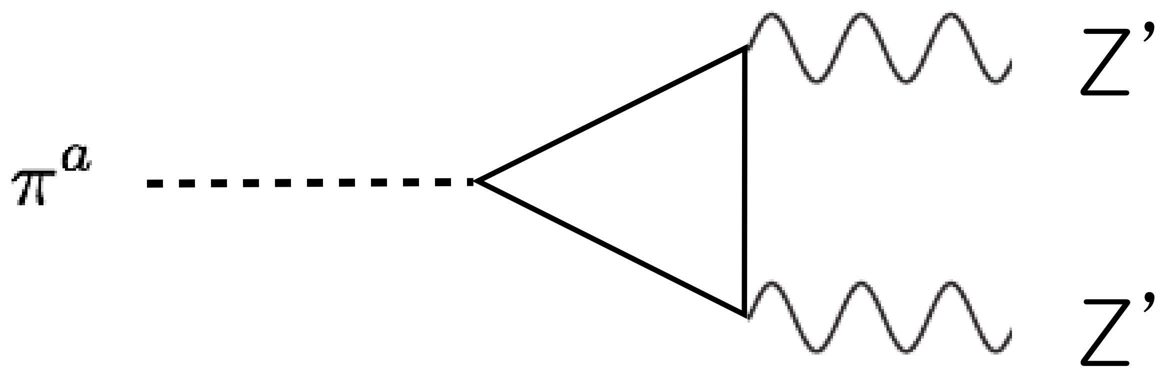
→ 2→2 ann



Stability of dark mesons

[HML, Seo, 2015]

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



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

if $Q_D^2 = I.$

$$Q_D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$: flavor non-universal charges

cf. QCD: Q=diag(2/3,−1/3,−1/3)

$D_\mu U = \partial_\mu U + i g_D [Q_D, U] Z'_\mu;$ $\tilde{\pi}^\pm, \tilde{K}^\pm$: ±2 charges.

- $\pi\ \pi \to \pi Z'$ is forbidden for $m_{Z'} > m_\pi$.

Dark flavor violation

- Flavor non-universal U(1) charges breaks flavor symmetry leads to meson mass splitting:

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

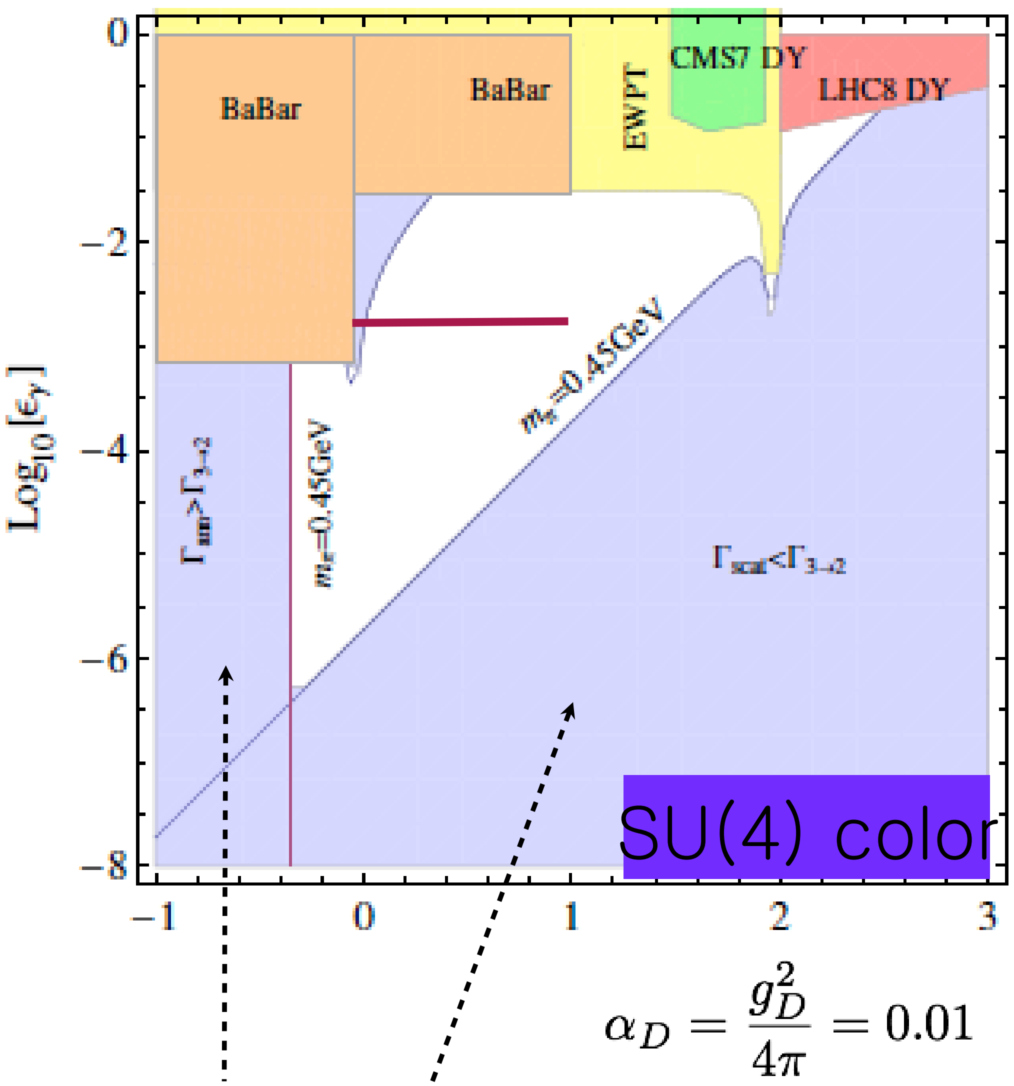
$$\Rightarrow \quad \Delta m_\pi^2 \sim \frac{\alpha_D \Lambda^4}{F^2} \sim \alpha_D F^2 \lesssim 0.01 m_\pi^2 : \quad \alpha_D \lesssim 0.01$$

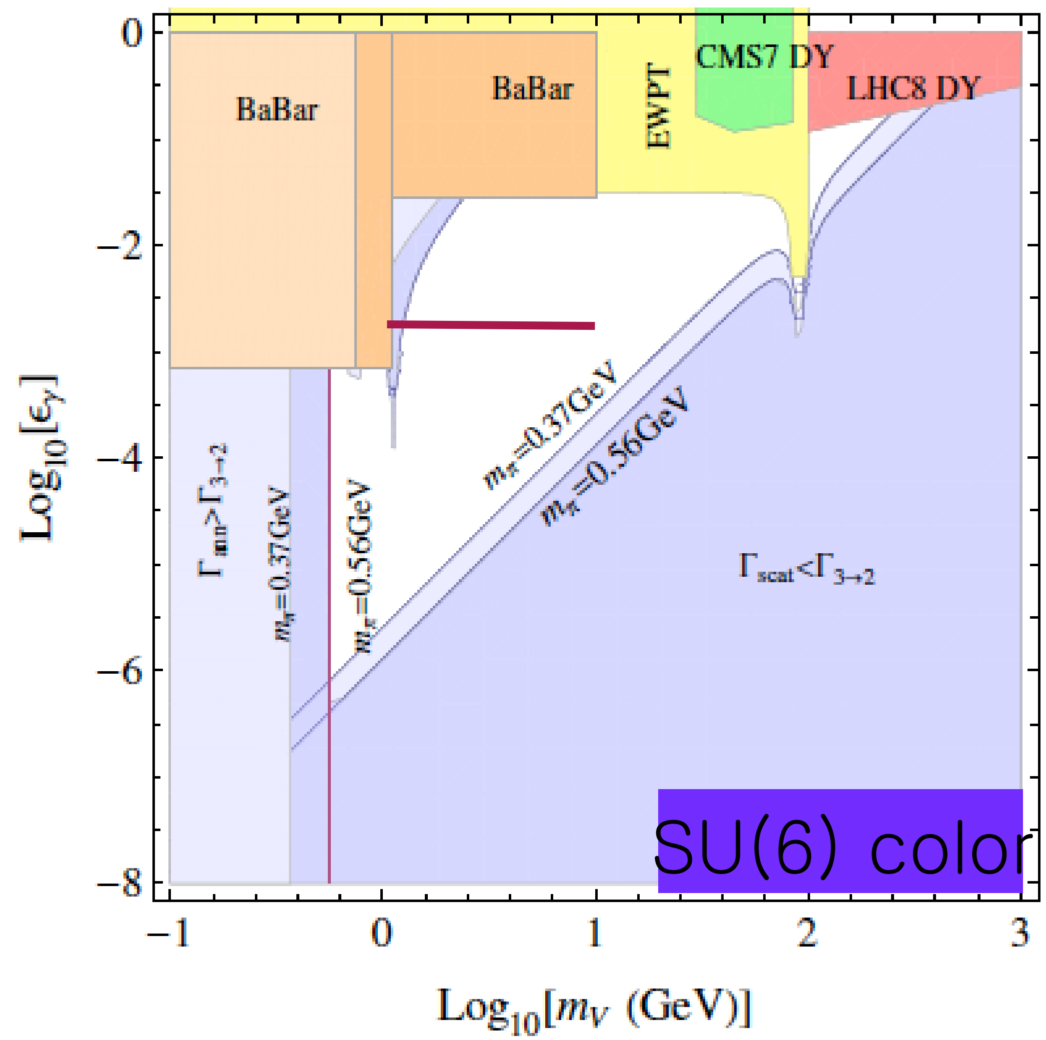
- Higher dimensional operators must be suppressed by high cutoff or small coupling:

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

$\Rightarrow \quad \Gamma_\pi \simeq \dfrac{F^2 m_\pi m_l^2}{8\pi M^4}$, DM stability: $M > 10^9$ GeV.

Z' at colliders





SIMP conditions

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

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

SIMP DM from discrete symmetries

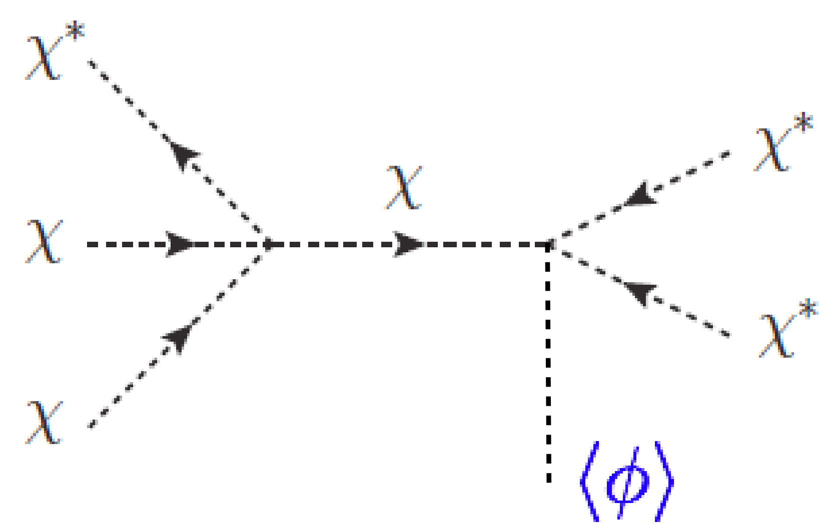
Gauged Z_3 and SIMP

- 5-point SIMP interaction is inconsistent with Z_2 and flavor symmetry is broken.
- Z_3 is the minimal symmetry for stabilizing SIMP, a remnant of a local U(1).
- Built-in Z' gauge boson communicates with the SM via the kinetic mixing.

	ϕ	χ
$U(1)_V$	$+3$	$+1$

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

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



A Z_3 Model

[Belanger et al(2012); Ko, Tang(2014); S.M. Choi, HML, 2015]

- χ: Dark Matter, ϕ: Dark Higgs, V: Dark photon.

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}\sin\xi\, V_{\mu\nu}B^{\mu\nu} + |D_\mu\phi|^2 + |D_\mu\chi|^2 + |D_\mu H|^2 - V(\phi,\chi,H)$$

$$D_\mu\chi = (\partial_\mu - iq_\chi g_D V_\mu)\chi$$

$$V(\phi,\chi,H) = V_{\rm DM} + V_{\rm SM} \text{ with}$$

$$\begin{aligned} V_{\rm DM} &= -m_\phi^2|\phi|^2 + m_\chi^2|\chi|^2 + \lambda_\phi|\phi|^4 + \boxed{\lambda_\chi|\chi|^4} + \lambda_{\phi\chi}|\phi|^2|\chi|^2 \\ &\quad + \boxed{\left(\frac{\sqrt{2}}{3!}\kappa\phi^\dagger\chi^3 + \text{h.c.}\right)} + \lambda_{\phi H}|\phi|^2|H|^2 + \lambda_{\chi H}|\chi|^2|H|^2, \\ V_{\rm SM} &= -m_H^2|H|^2 + \lambda_H|H|^4. \end{aligned}$$

Scalar SIMP DM

- 2→2 annihilation channels are forbidden for heavy dark Higgs and Z'.
- 3→2 annihilation channels are through Higgs + Z' exchanges:

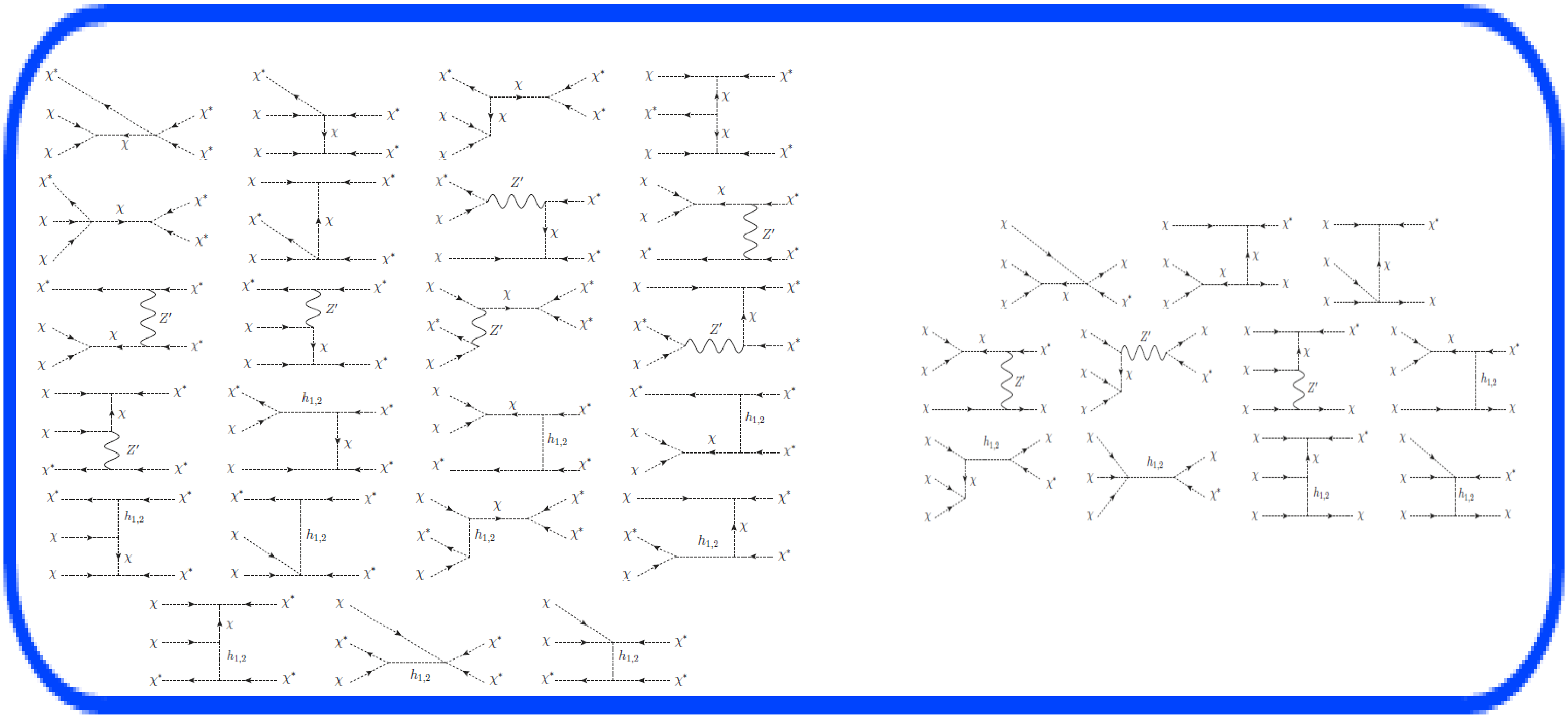
$$\begin{aligned}\langle\sigma v_{\rm rel}^2\rangle_{3\to2} &= \frac{1}{4}\left(\langle\sigma v_{\rm rel}^2\rangle_{\chi\chi\chi^*\to\chi^*\chi^*}+\langle\sigma v_{\rm rel}^2\rangle_{\chi\chi\chi\to\chi\chi^*}\right)\\ &= \frac{\sqrt{5}}{1536\pi m_\chi^3}\left(|\mathcal{M}_{\chi\chi\chi^*\to\chi^*\chi^*}|^2+|\mathcal{M}_{\chi\chi\chi\to\chi\chi^*}|^2\right)\equiv\frac{\alpha_{\rm eff}^3}{m_\chi^5}.\end{aligned}$$

$$\begin{aligned}|\mathcal{M}_{\chi\chi\chi^*\to\chi^*\chi^*}|^2 &= \frac{R^2}{16m_\chi^2}\Bigg(74\lambda_\chi-117R^2-\frac{200g_D^2m_\chi^2}{m_\chi^2+m_{Z'}^2}\\ &\quad+\frac{24\lambda_{\phi\chi}m_\chi^2(3m_\chi^2-2m_{h_1}^2)-\lambda_{\phi\chi}^2(43m_\chi^2-37m_{h_1}^2)m_{Z'}^2/(9g_D^2)}{(4m_\chi^2-m_{h_1}^2)(m_\chi^2+m_{h_1}^2)}\Bigg)^2\end{aligned}$$

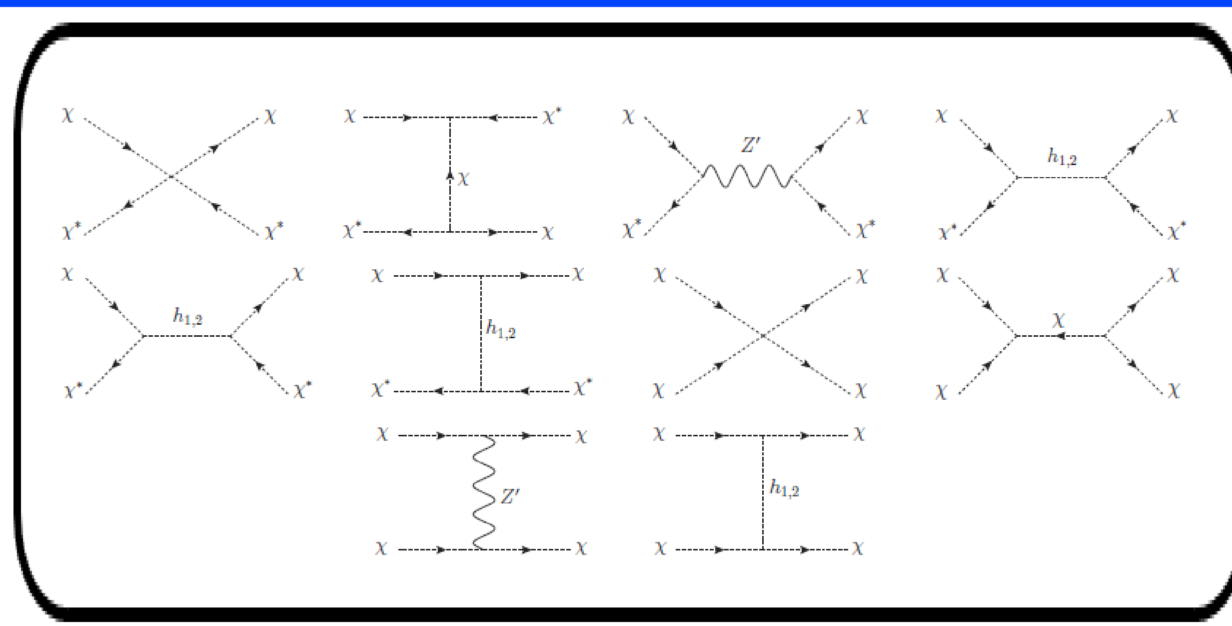
$$\begin{aligned}|\mathcal{M}_{\chi\chi\chi\to\chi\chi^*}|^2 &= \frac{3R^2}{m_\chi^2}\Bigg(2\lambda_\chi+9R^2+\frac{25g_D^2m_\chi^2}{m_\chi^2+m_{Z'}^2}\\ &\quad+\frac{2\lambda_{\phi\chi}m_\chi^2(13m_\chi^2-2m_{h_1}^2)-\lambda_{\phi\chi}^2(19m_\chi^2-m_{h_1}^2)m_{Z'}^2/(9g_D^2)}{(9m_\chi^2-m_{h_1}^2)(m_\chi^2+m_{h_1}^2)}\Bigg)^2\end{aligned}$$

$$R\equiv\sqrt{2}\kappa v'/(6m_\chi).$$

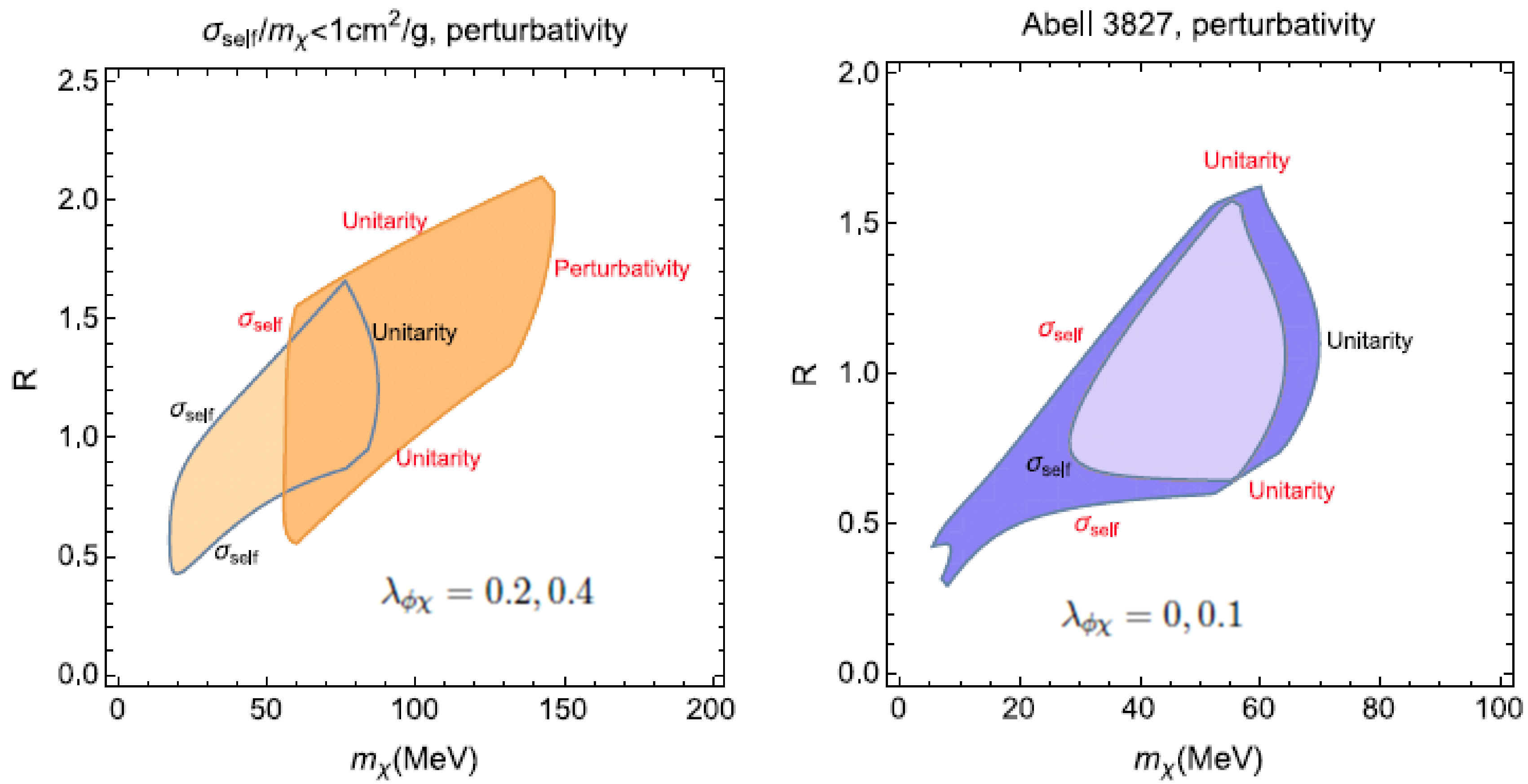
3→2



2→2



Bounds on self-interaction



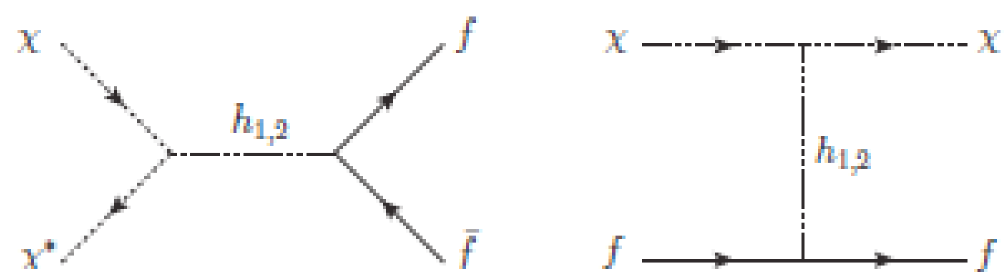
Abell 3827

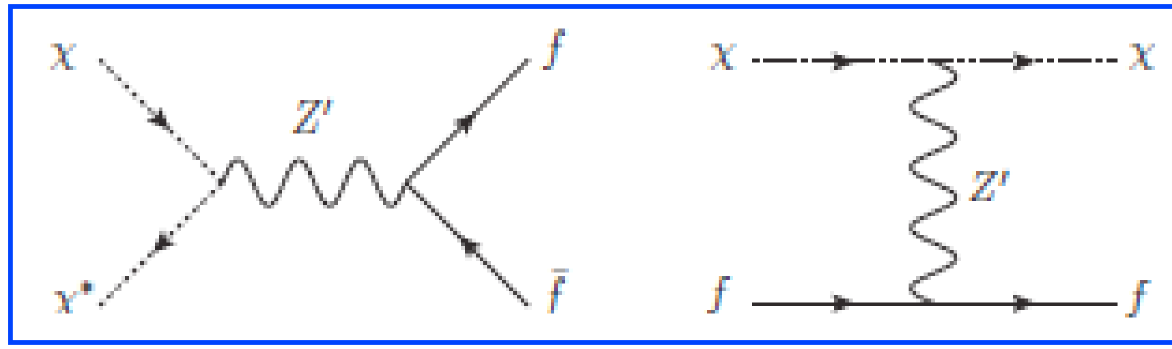
$\sigma_{\rm self}/m_\chi = 1 - 3\,{\rm cm}^2/g$

$$m_{Z'} = 5m_\chi,\ g_D = 0.1 \text{ and } m_{h_1} = 1.5m_\chi.$$

- SIMP relic density: $m_\chi = 0.03\,\alpha_{\rm eff}(T_{\rm eq}^2 M_P)^{1/3}$
- Bullet cluster & halo shape: $\sigma_{\rm self}/m_\chi \lesssim 1{\rm cm}^2/{\rm g}$
- Unitarity, perturbativity: $\lambda_\chi < 4\pi,\ \ |\mathcal{M}_{\chi\chi} + \mathcal{M}_{\chi\chi^*}| < 8\pi.$

Kinetic equil. condition





Higgs-portal:
negligible for kinetic scatt.,
safe for Higgs (invisible) signals & indirect detections

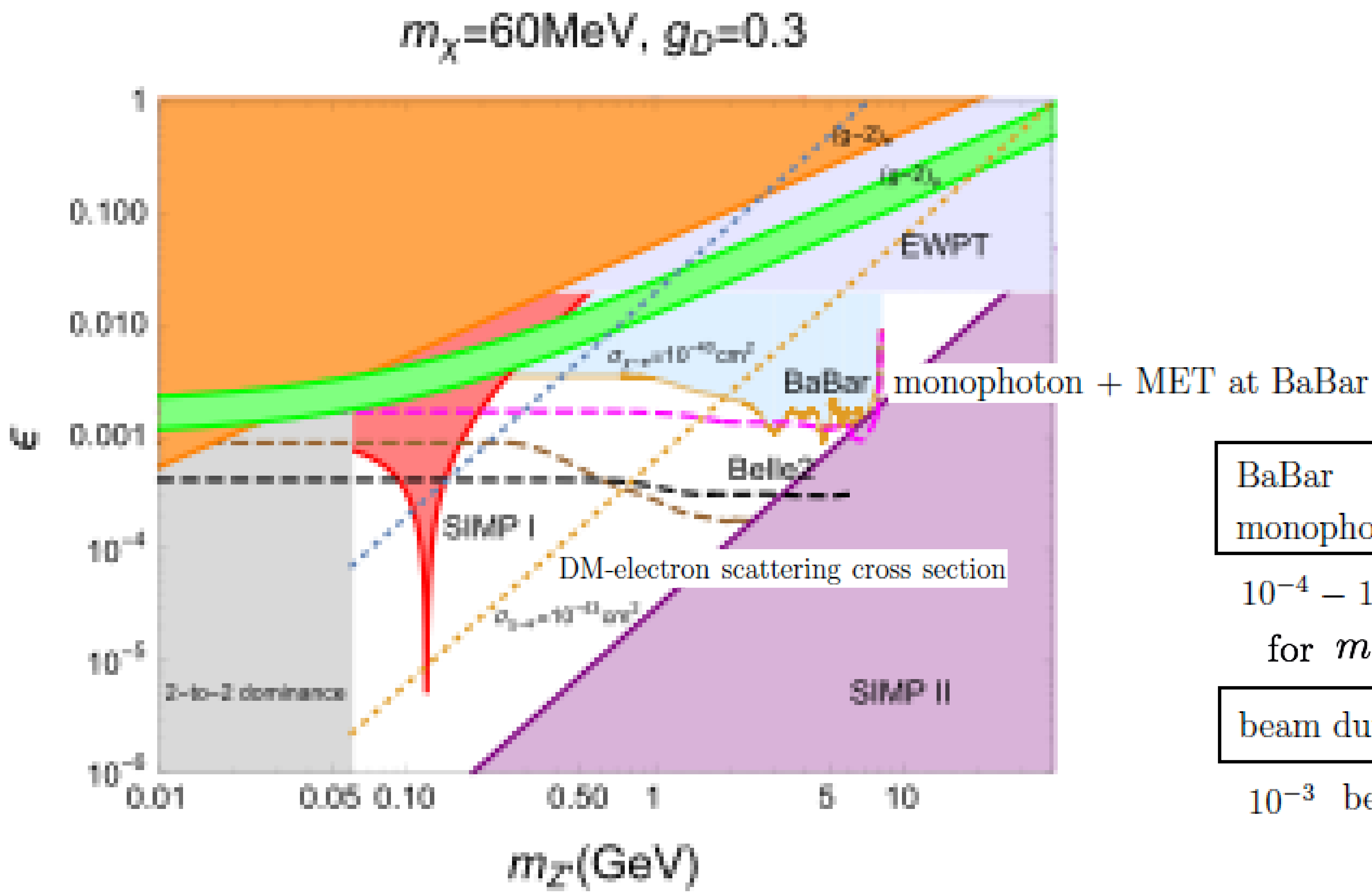
Z'-portal:
works for kinetic scatt.,
bounded by collider searches,
safe for indirect detections.

- SIMP conditions: $n_{\rm DM}\langle\sigma v_{\rm rel}\rangle_{\rm ann} < n_{\rm DM}^2\langle\sigma v_{\rm rel}^2\rangle_{3\to 2} < n_{\rm SM}\langle\sigma v_{\rm rel}\rangle_{\rm kin}$

$$\left.\begin{aligned}\langle\sigma v_{\rm rel}\rangle_{\rm ann} &= \frac{2\varepsilon^2 e^2 g_D^2 m_\chi^2}{\pi[(4m_\chi^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2]}\left(\frac{T}{m_\chi}\right) \equiv \frac{\delta_1^2}{m_\chi^2} \\ \langle\sigma v_{\rm rel}\rangle_{\rm scatt} &= \frac{3\varepsilon^2 e^2 g_D^2 m_\chi^2}{2\pi m_{Z'}^4}\left(\frac{T}{m_\chi}\right) \equiv \frac{\delta_2^2}{m_\chi^2}.\end{aligned}\right\}\quad \boxed{\begin{aligned}\delta_1 &\lesssim 2.4\times 10^{-6}\,\alpha_{\rm eff}, \\ \delta_2 &\gtrsim 10^{-9}\alpha_{\rm eff}^{1/2}.\end{aligned}}$$

$$\varepsilon \simeq \cos\theta_W\,\xi$$

SIMP & Z' searches



BaBar
monophoton + dilepton

$10^{-4} - 10^{-3}$ $(\mathrm{BR}(l\bar{l}) = 1)$

for $m_{Z'} = 0.02 - 10.2$ GeV

beam dump (E137)

10^{-3} below $m_{Z'} = 0.1\,\mathrm{GeV}.$

- SIMP conditions are complementary for Z' searches at colliders.

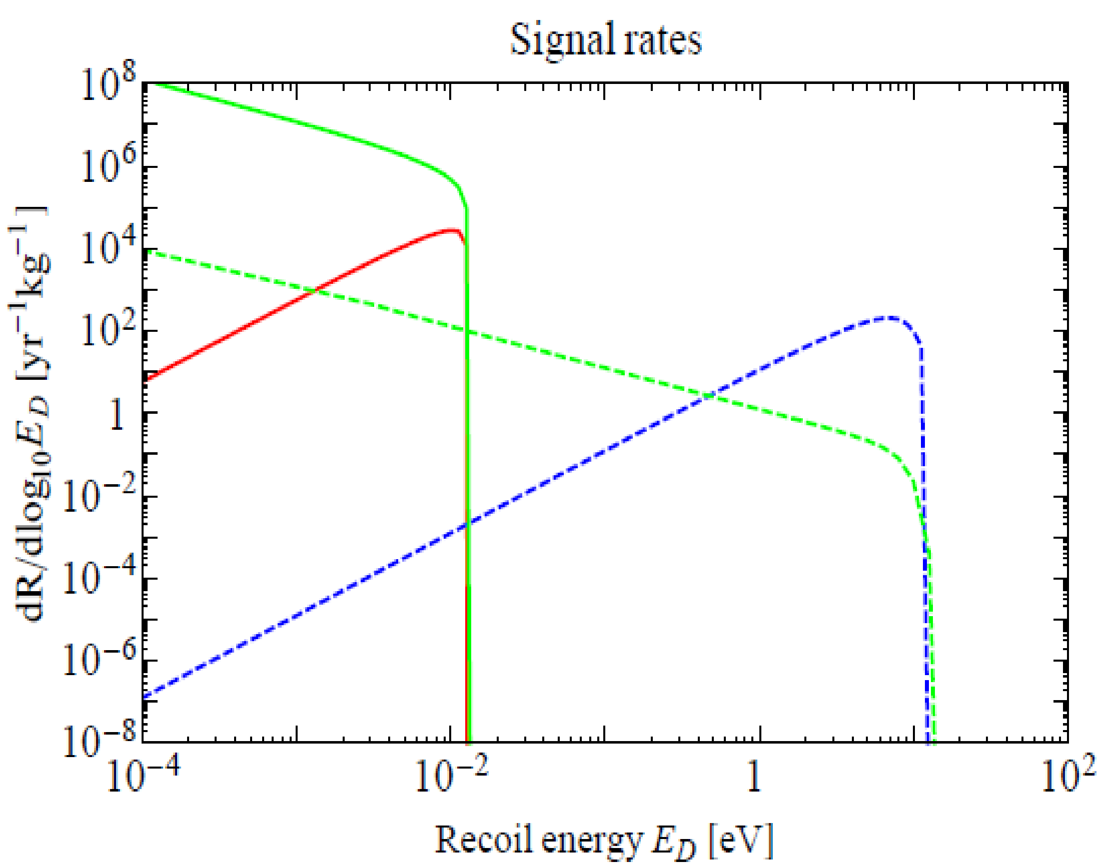
Direct detection

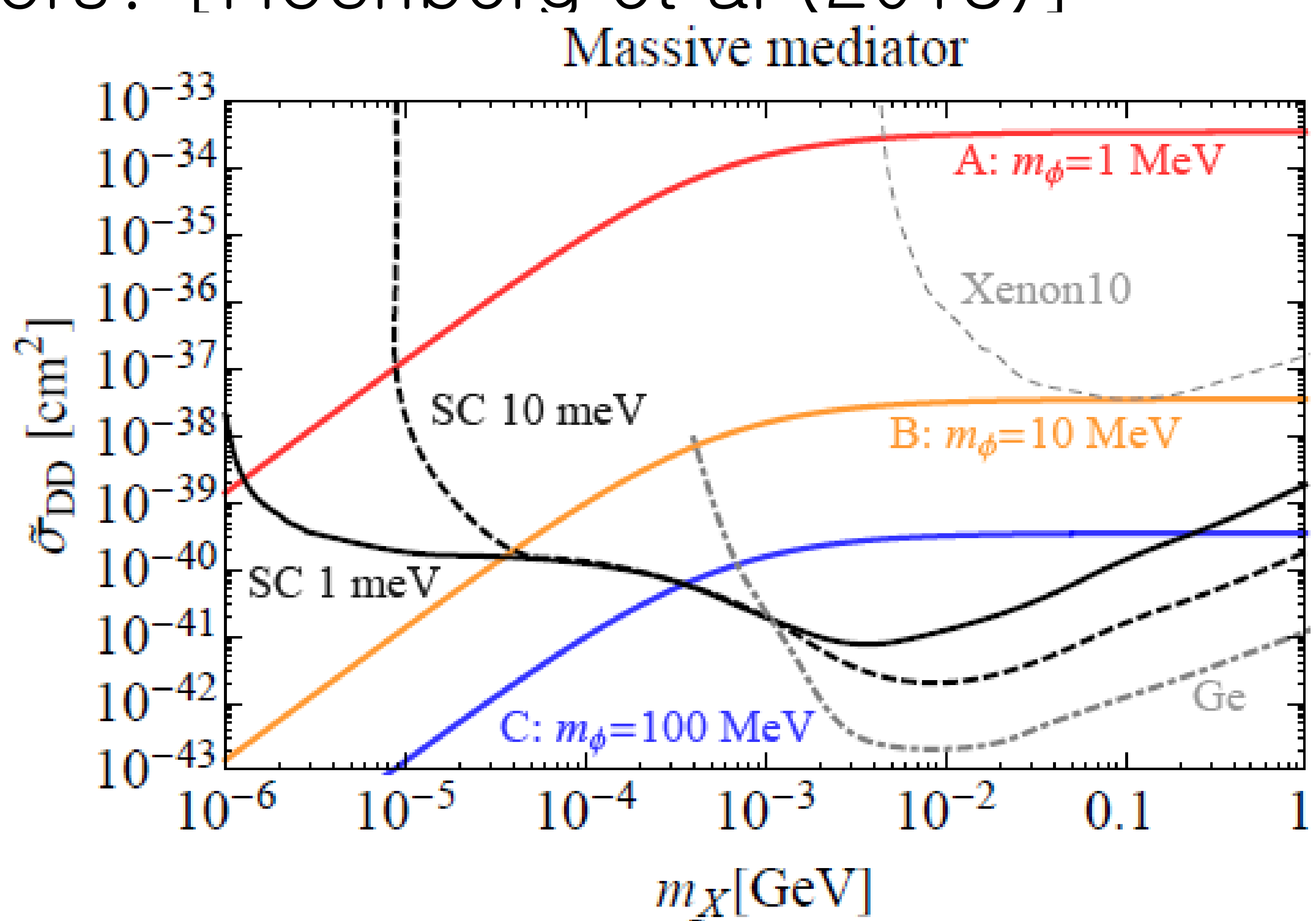
- SIMP dark matter scatters off electrons, leading to small recoil energy: $E = \frac{q^2}{2m_e} \lesssim 20\,\mathrm{eV}.$

$$\sigma_{\rm DD} = \frac{\varepsilon^2 e^2 g_D^2 \mu^2}{\pi m_{Z'}^4} \qquad (q = \mu\, v_{\rm DM},\ \mu = m_e m_\chi/(m_e + m_\chi))$$

XENON10: $\sigma_{\rm DD} < 2 \times 10^{-36}\,{\rm cm}^2\,, \qquad m_\chi = 30\,{\rm MeV}.$

Superconducting detectors? [Hochberg et al (2015)]





Blue: $(m_\phi, m_X, \alpha_X, g_e) = (100\ \mathrm{MeV}, 100\ \mathrm{MeV}, 0.1, 3 \times 10^{-5})$

A Z_5 model

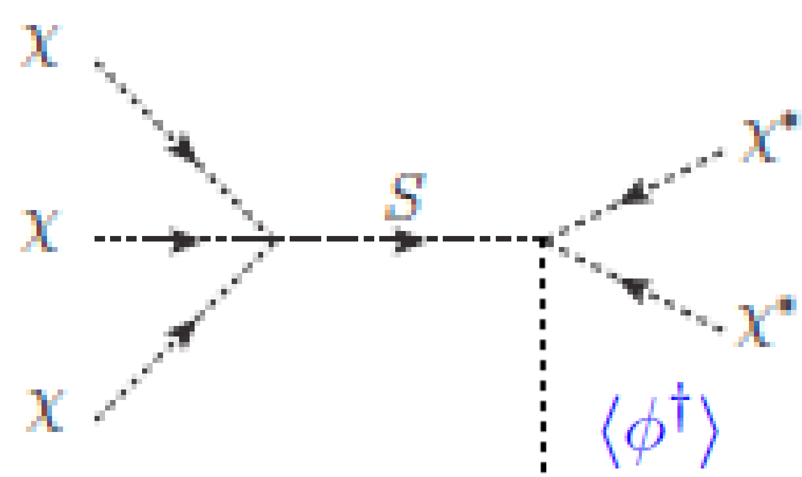
[S.M.Choi, HML, to appear]

- 5-point interaction is picked up by Z_5 , mediated by a heavy singlet scalar S (cf. no cubic coupling for DM).

	ϕ	χ	S
$U(1)_V$	$+5$	$+1$	$+3$

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

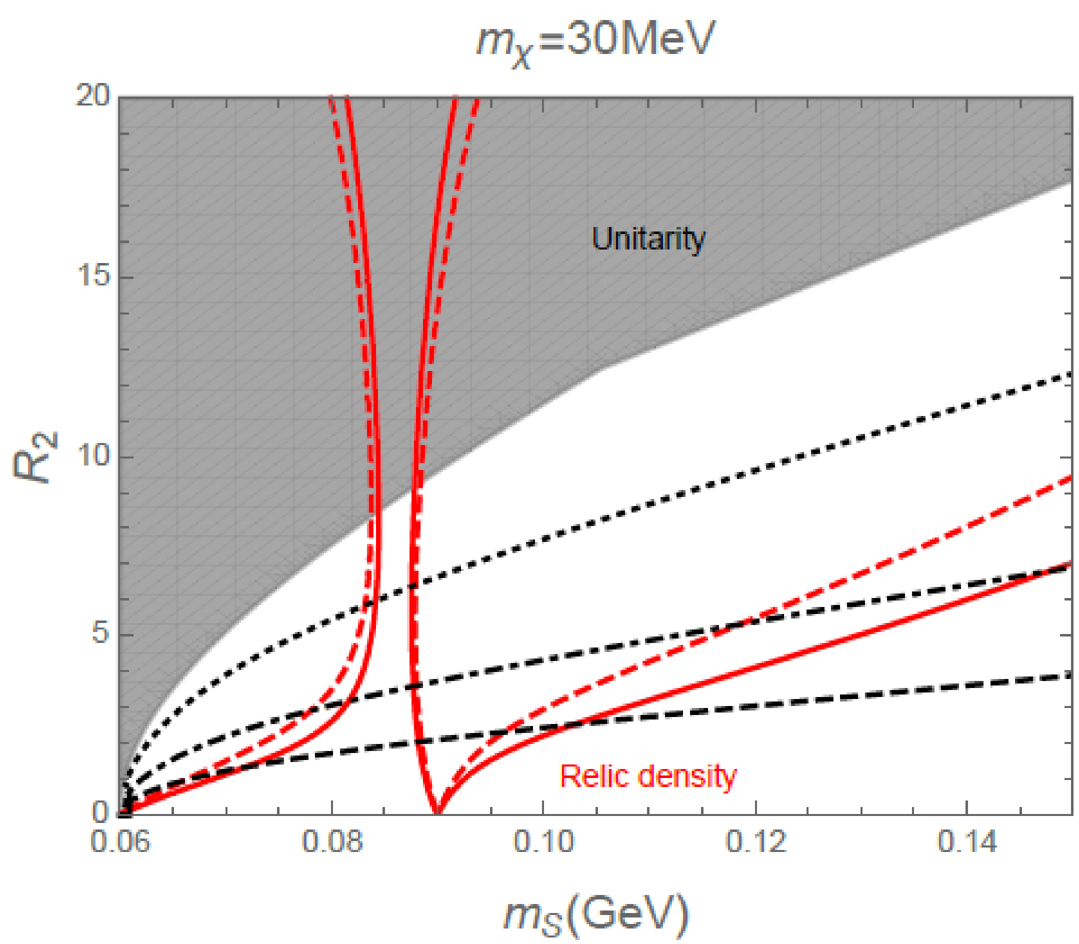
$$\mathcal{L}_{\rm int} \supset \frac{1}{\sqrt{2}}\lambda_1 \phi^\dagger S^2 \chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2 \phi^\dagger S \chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$



- Z' again makes SIMP DM in kinetic equilibrium.
- Singlet scalar S can be stable too.

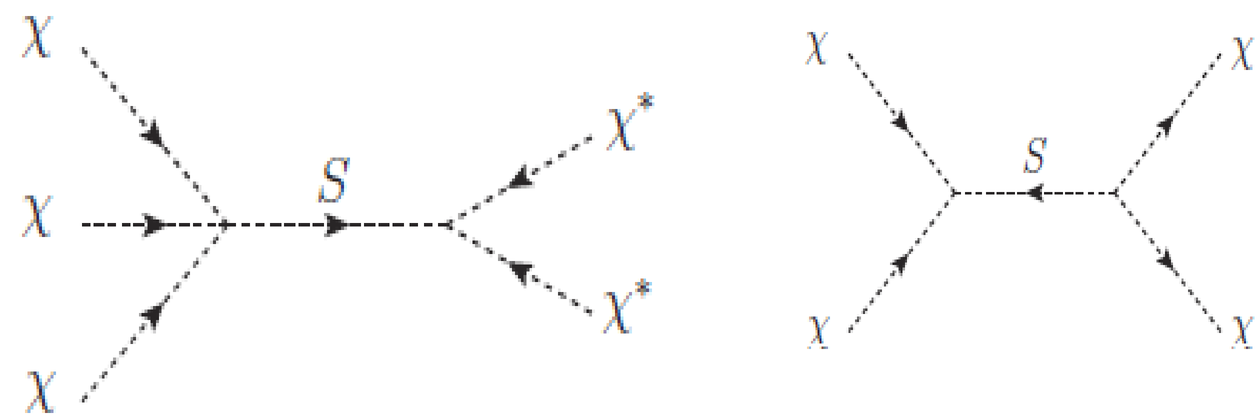
Resonant 3→2 in Z_5

- 5-point interaction in Z_5 can be enhanced near resonance.



$$\lambda_1 = 0; \quad R_2 \equiv \lambda_2 v'/(\sqrt{2} m_\chi)$$

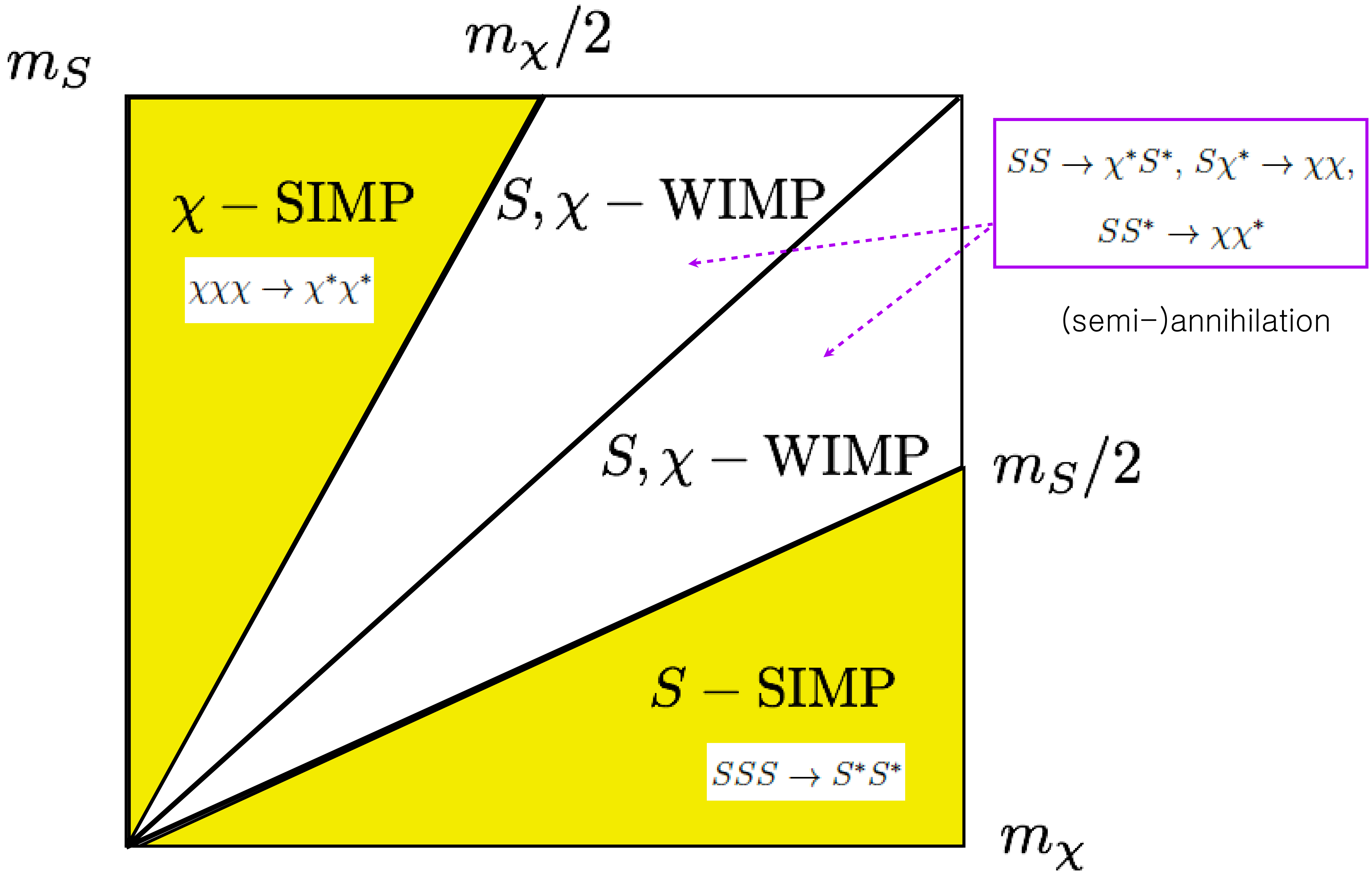
$$\lambda_3 = 8\pi \ \text{and} \ \lambda_3 = 6\pi$$



$$\langle \sigma v^2 \rangle_{3\to 2} \propto \frac{1}{(9m_\chi^2 - m_S^2)^2 + \Gamma_S^2 m_S^2}$$

safe from the bounds from self-interactions (with potentially large NLO).

Phase diagram of DM



WIMP phases need a sizable annihilation into the SM, e.g. Z' portal.

Conclusions

- SIMP paradigm leads to testable scenarios via DM self-interactions as well as possibly, messengers particles.
- SIMP dark mesons can be in kinetic equilibrium with Z' portal and remain stable.
- Scalar SIMP dark matter with discrete gauge symmetries has a built-in Z'-portal.
- For discrete symmetries of high degree, we need a scalar mediator for 5-point interactions, which can be enhanced near resonance.