New faces of dark matter: SIMP and its friends

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H.M. Lee and M.-S. Seo, Phys. Lett. B748, 316;

S.-M. Choi and H.M. Lee, JHEP1509, 063, and Phys. Lett. B758, 47.

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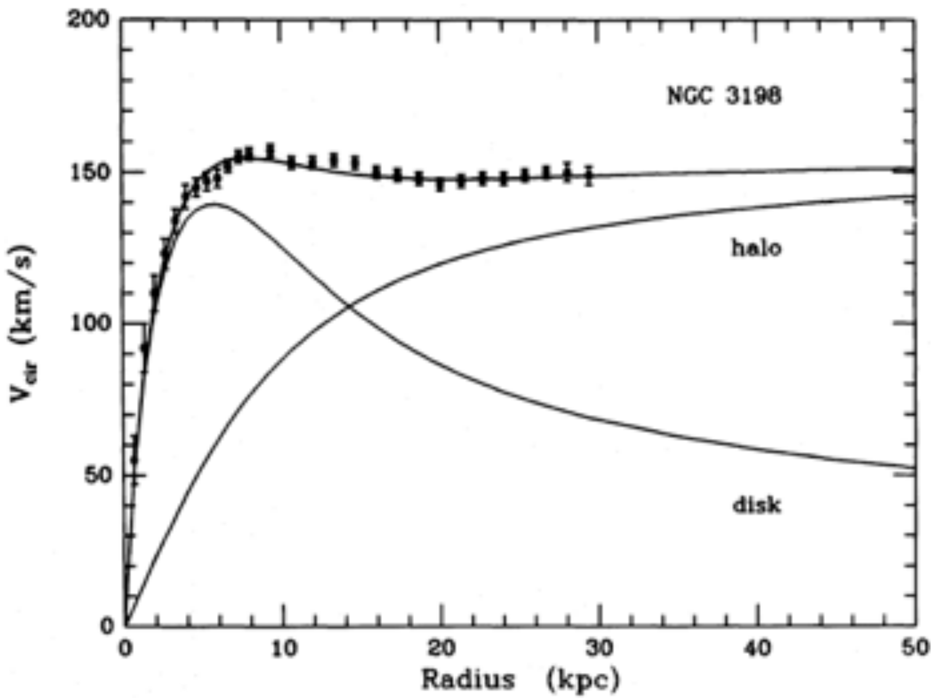
Outline

- SIMP dark matter
- Composite SIMP
- Fundamental SIMP
- Conclusions

SIMP dark matter

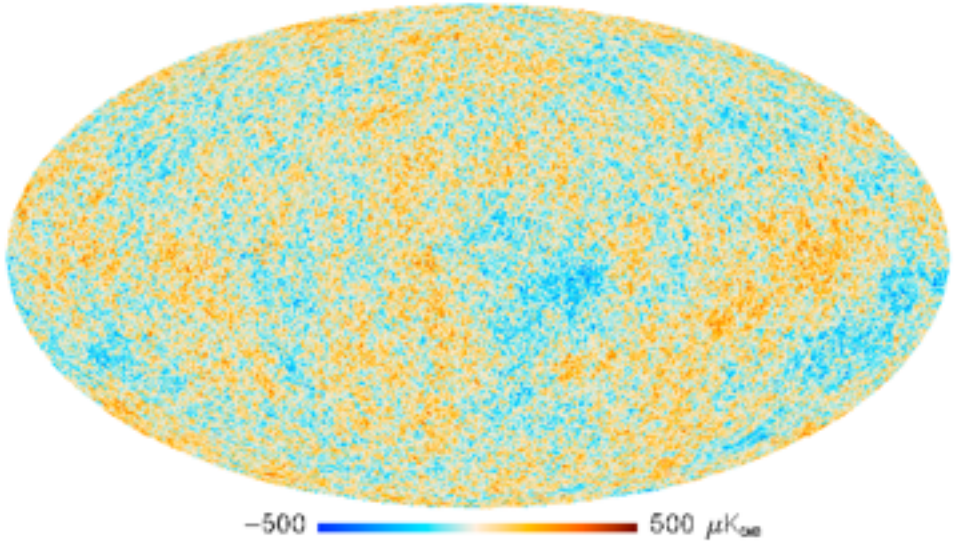
Evidences for Dark Matter



Galaxy orbital velocities

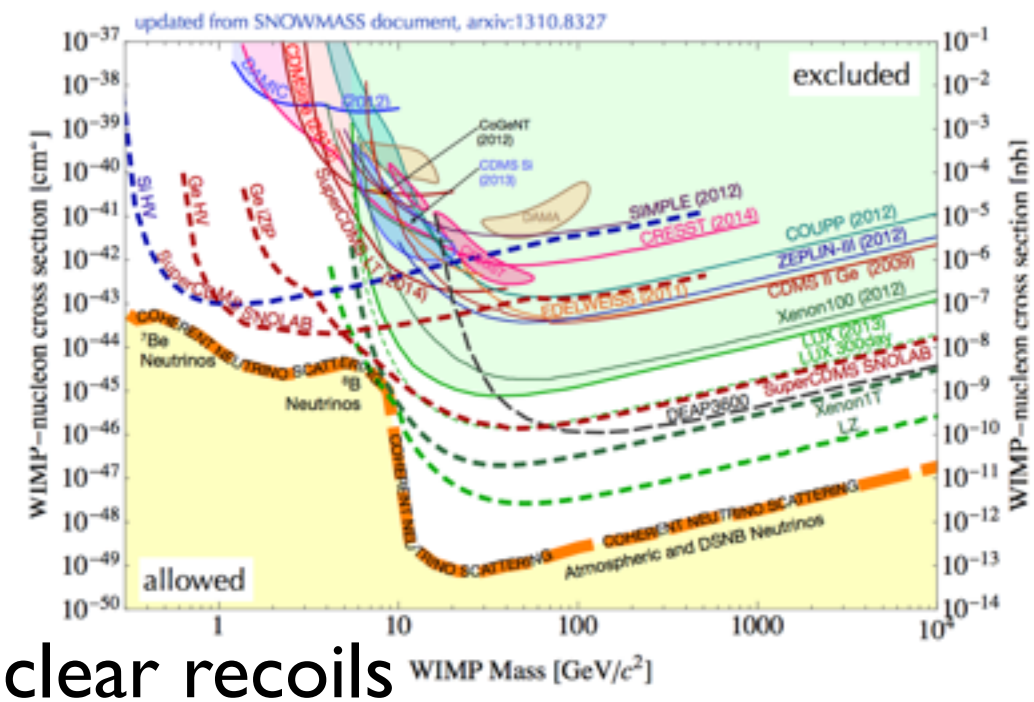
Bullet cluster

Gravitational lensing

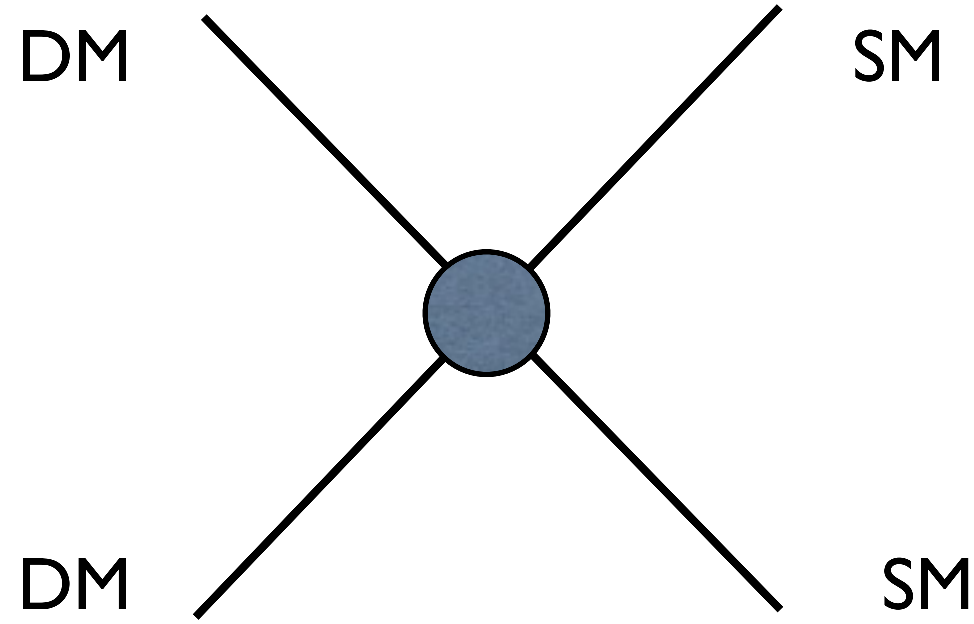


CMB (Planck)

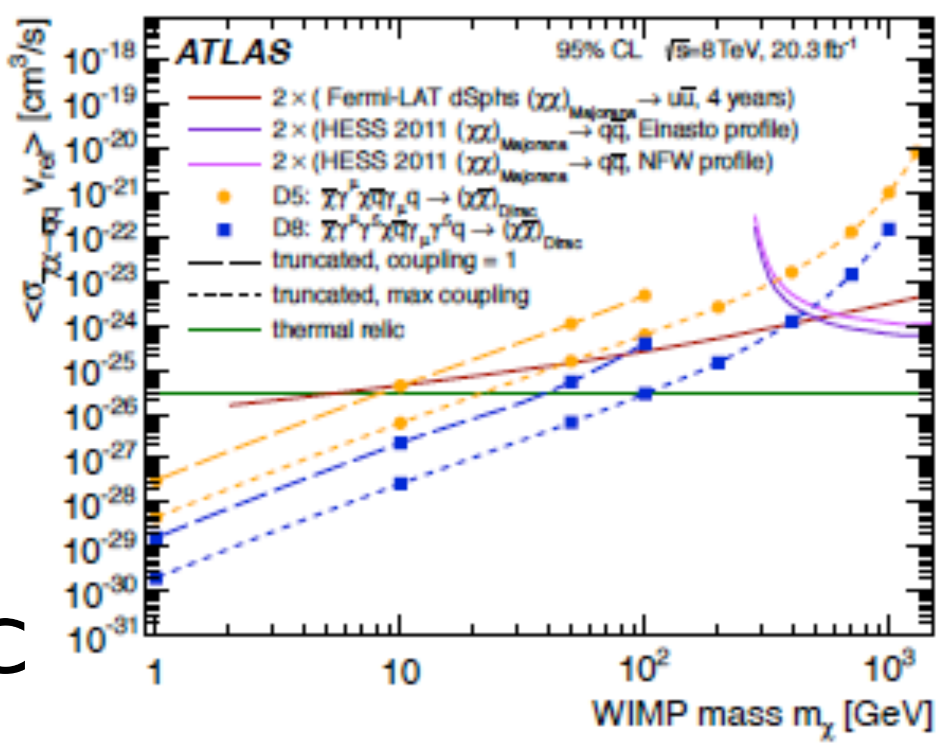
WIMP & its detection



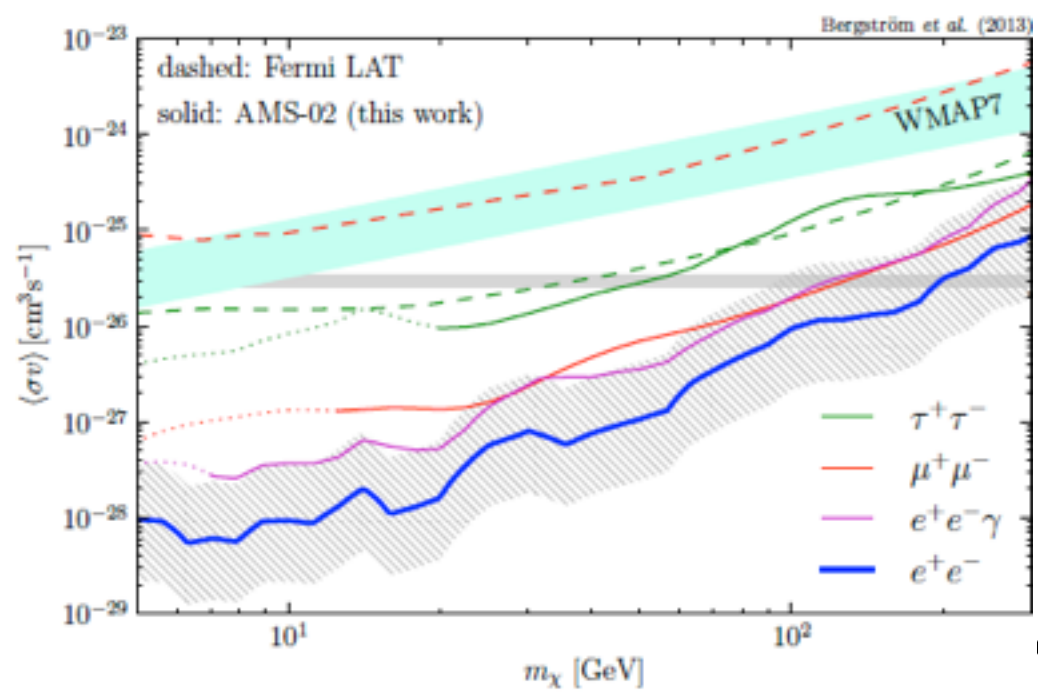
Nuclear recoils



weak int & weak-scale mass



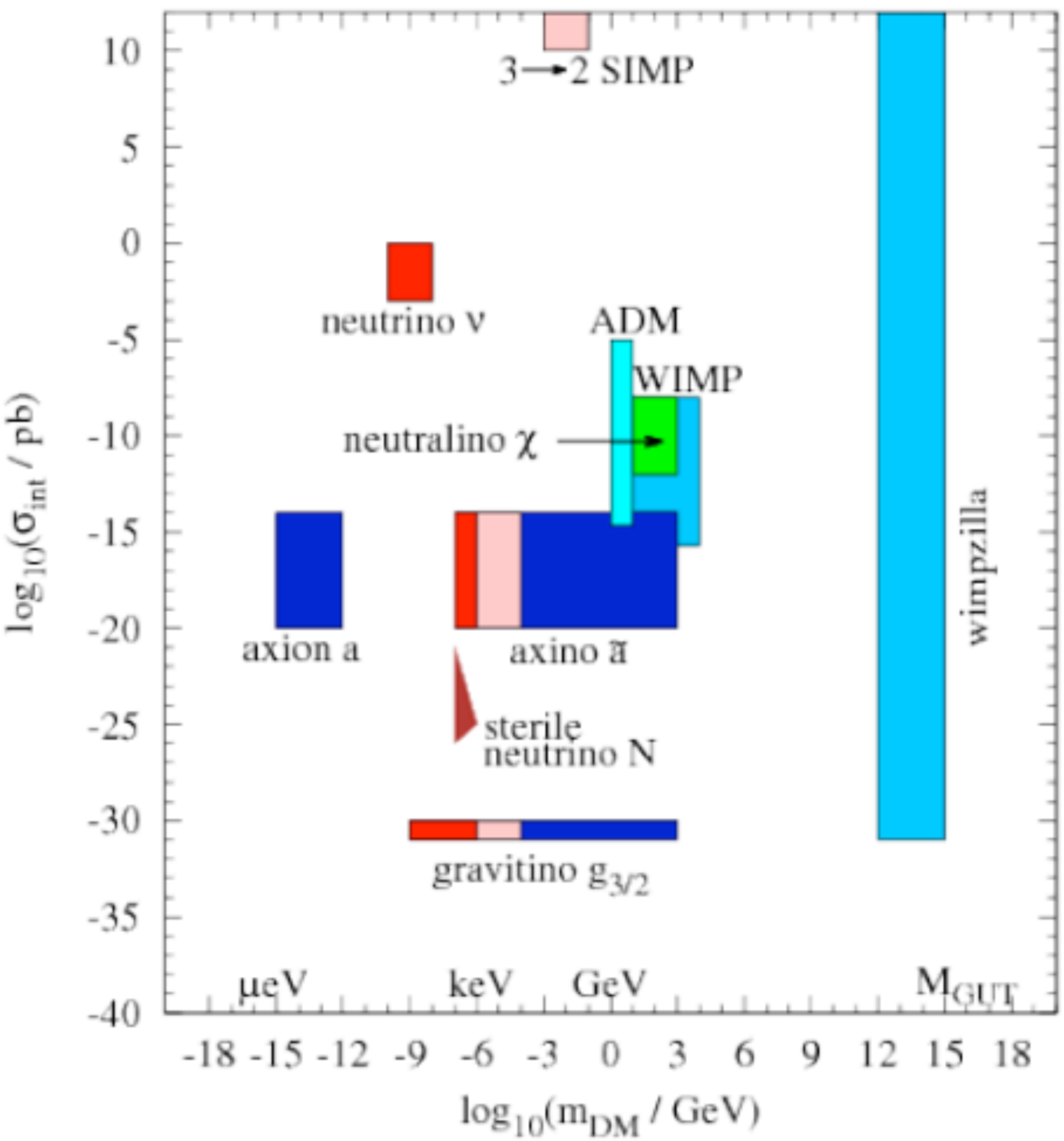
LHC



Cosmic rays

- WIMP dark matter is challenged by various complementary searches in wide parameter space.

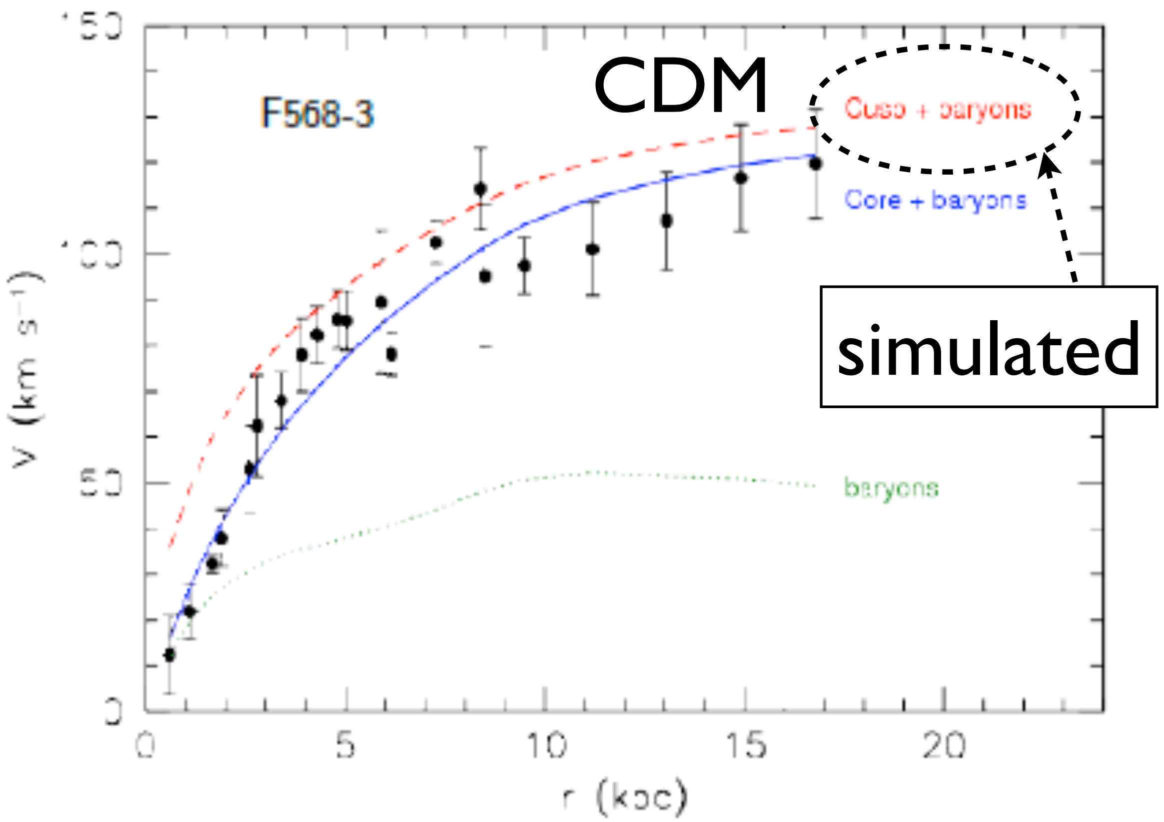
Unexplored dark matter?

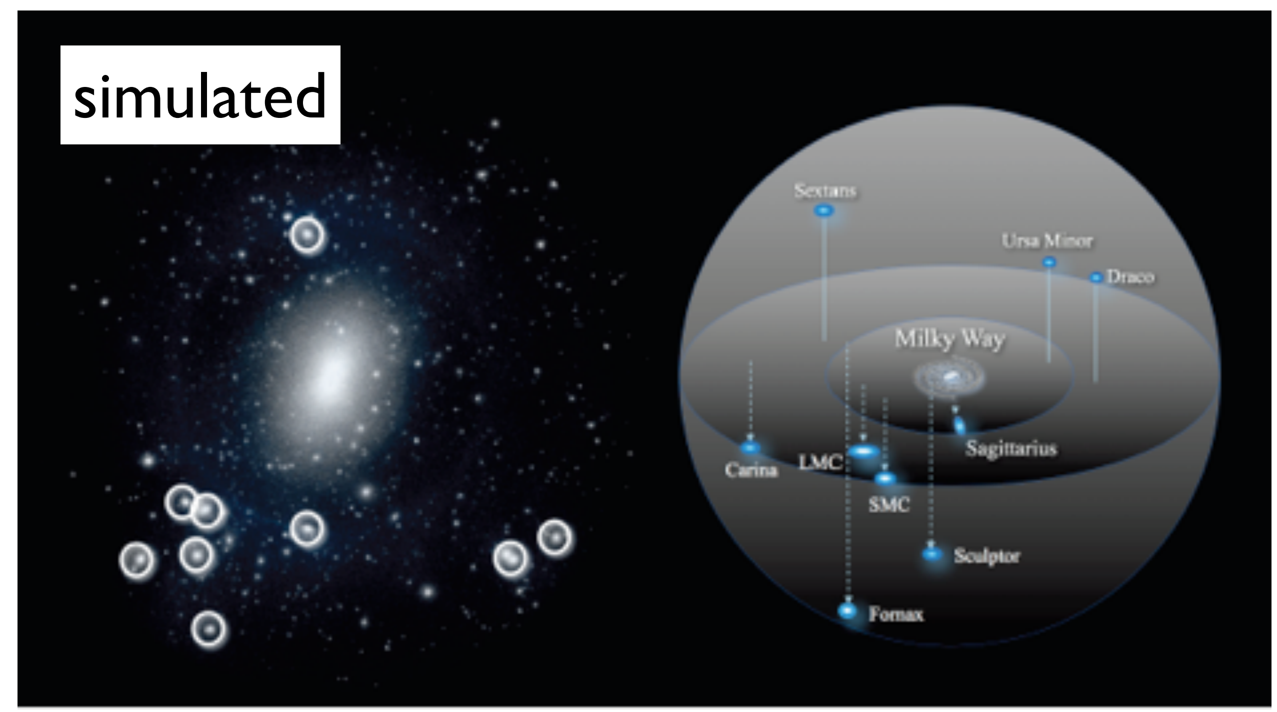


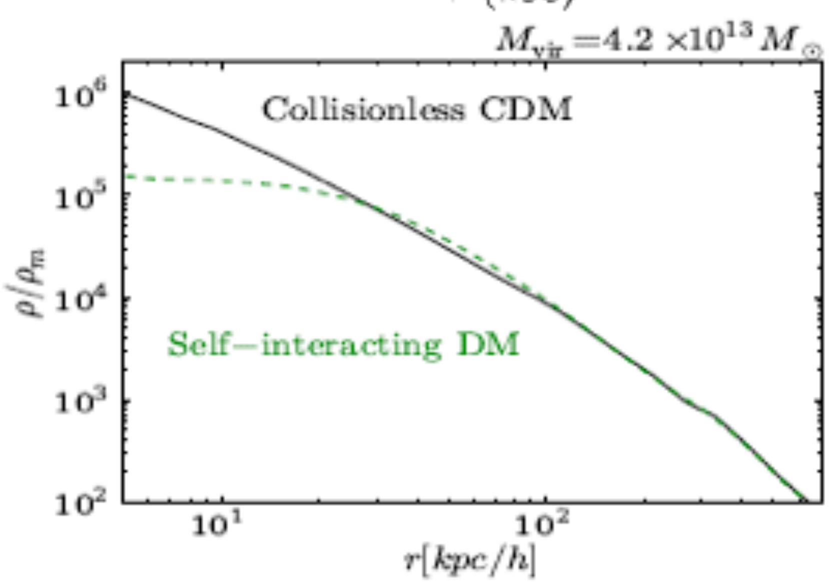
- Dark matter is known by gravity only; interactions to us may not be so strong; what about self-interactions?

Small-scale problems

- Core-cusp: Simulation with CDM (cusp) overshoots galaxy rotation curves.
- Too-big-to-fail: Simulation predicts too much mass for dwarf galaxies (subhalos).

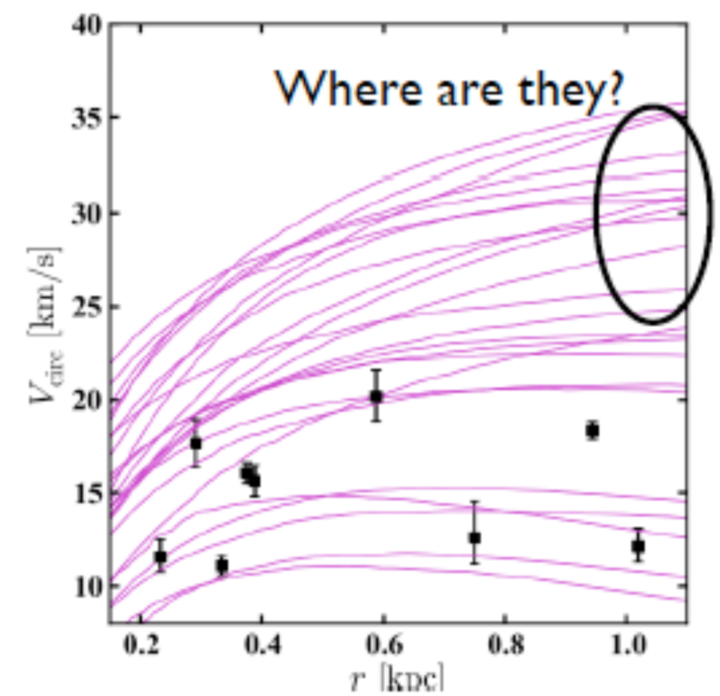






$$V \sim \sqrt{\frac{GM_<}{r}}$$

rotation curves of dwarfs



DM self-interactions

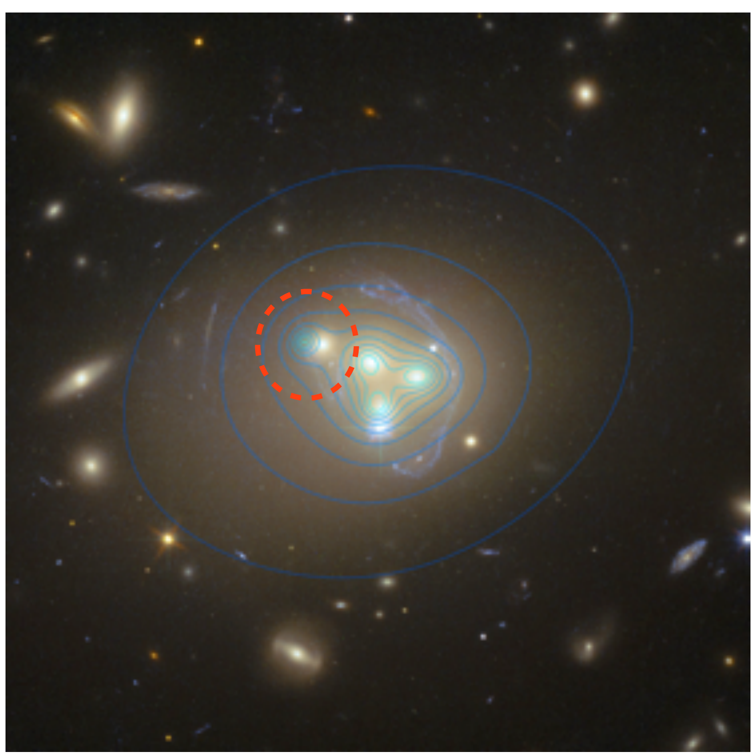
- DM self-interactions solve small-scale problems for

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

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

Bounds from Bullet cluster: $\sigma_{\rm self}/m_{\rm DM} < 1{\rm cm}^2/g$

- DM sub-halo lags behind the galaxy, due to drag force ("long-range") or large momentum transfer ("contact").



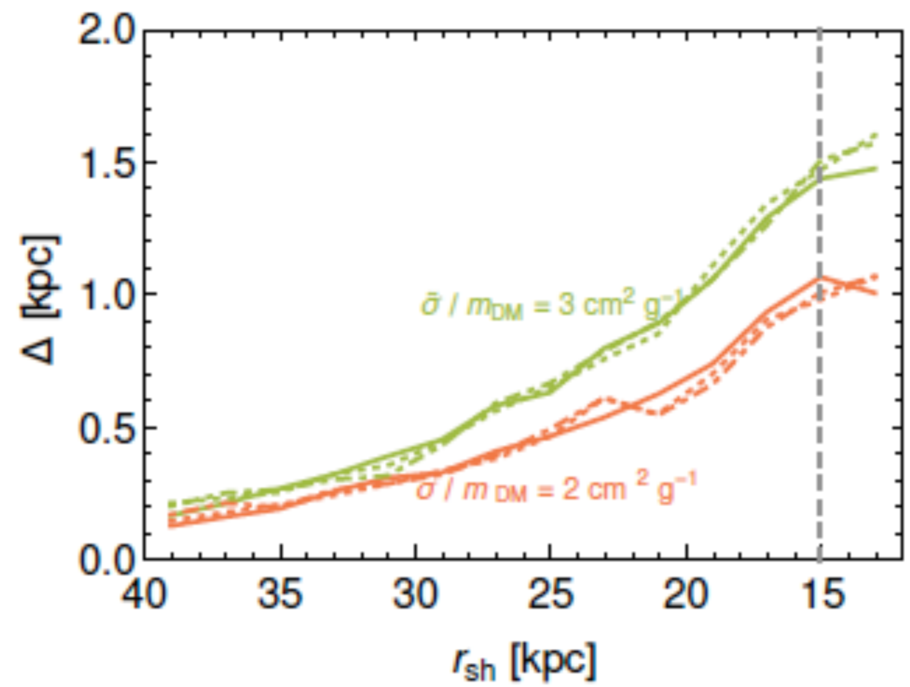
Hints from Abell 3827?

off-set:

$$\Delta = 1.62^{+0.47}_{-0.49}\,{\rm kpc}$$

$\sigma_{\rm self}/m_{\rm DM} \sim 2\times 10^{-4}{\rm cm}^2/{\rm g}$

[Massey et al(2015)]

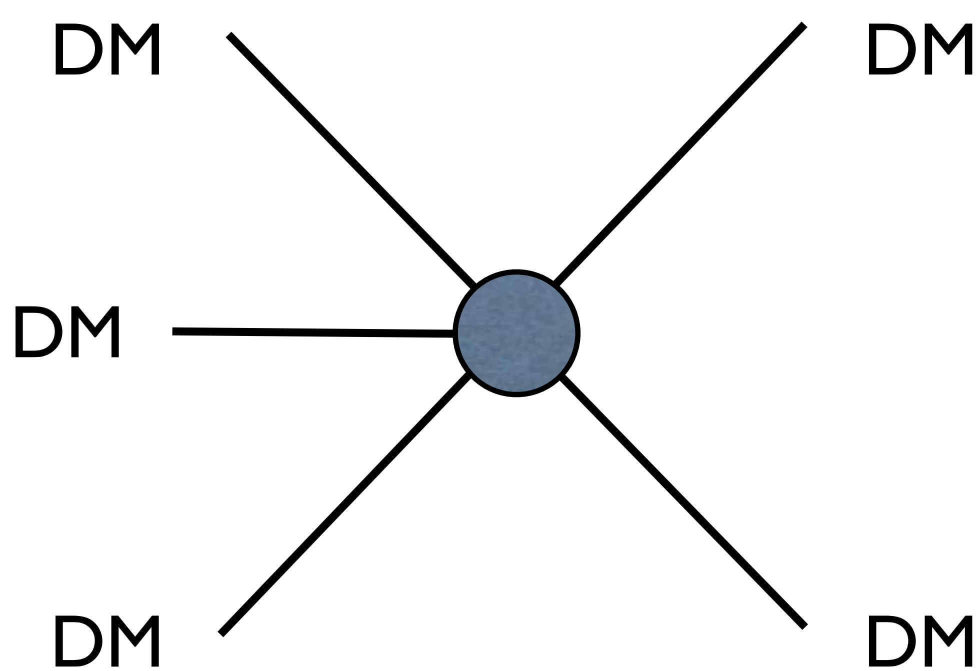


[Kahlhoefer et al(2015)]

SIMP paradigm

- Strong Interacting Massive Particles(SIMP) are based on chemical equilibrium with 3→2 self-annihilation.

[Hochberg et al, 2014; S.-M.Choi, HML, 2016]



$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \boxed{-\langle\sigma v^2\rangle_{3\to 2}\,(n^3_{\rm DM} - n^2_{\rm DM} n^{\rm eq}_{\rm DM})} \\ -\langle\sigma v\rangle_{2\to 2}\,(n^2_{\rm DM} - (n^{\rm eq}_{\rm DM})^2)$$

SIMP freeze-out:

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

$$\langle\sigma v^2\rangle_{3\to 2} = \frac{\alpha^3_{\rm eff}}{m^5_{\rm DM}}$$

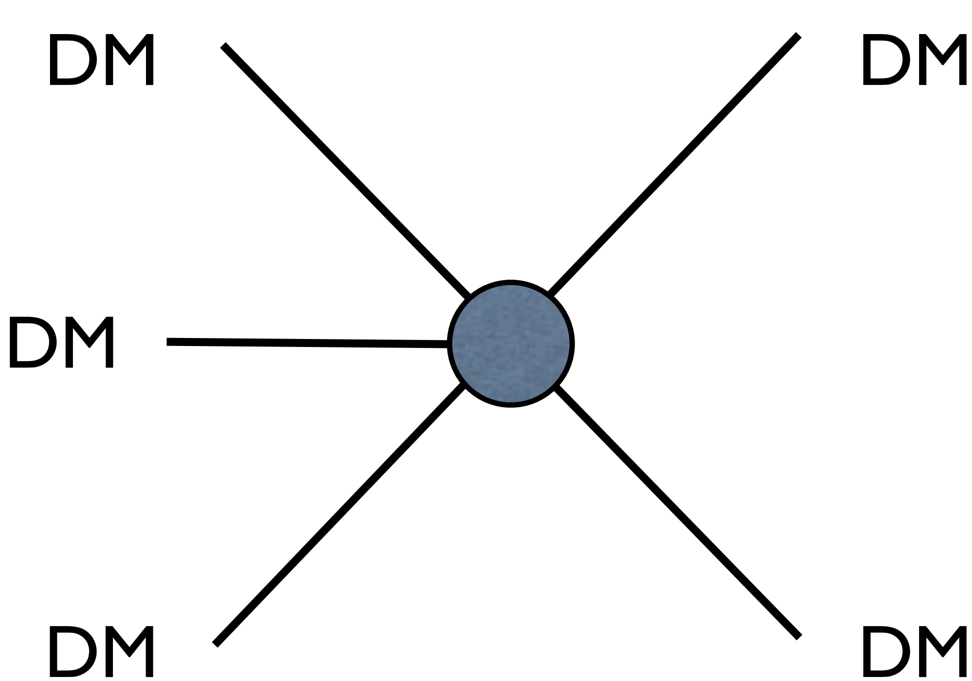
⇨ $$\Omega_{\rm DM}h^2 \sim 0.1\left(\frac{9\times 10^{-10}{\rm GeV}^{-2}}{(g_*/10.45)^{3/4}\left(\frac{m^2_{\rm DM}}{M_P}\int_{x_F}^{\infty} x^{-5}\langle\sigma v^2\rangle dx\right)^{1/2}}\right)$$

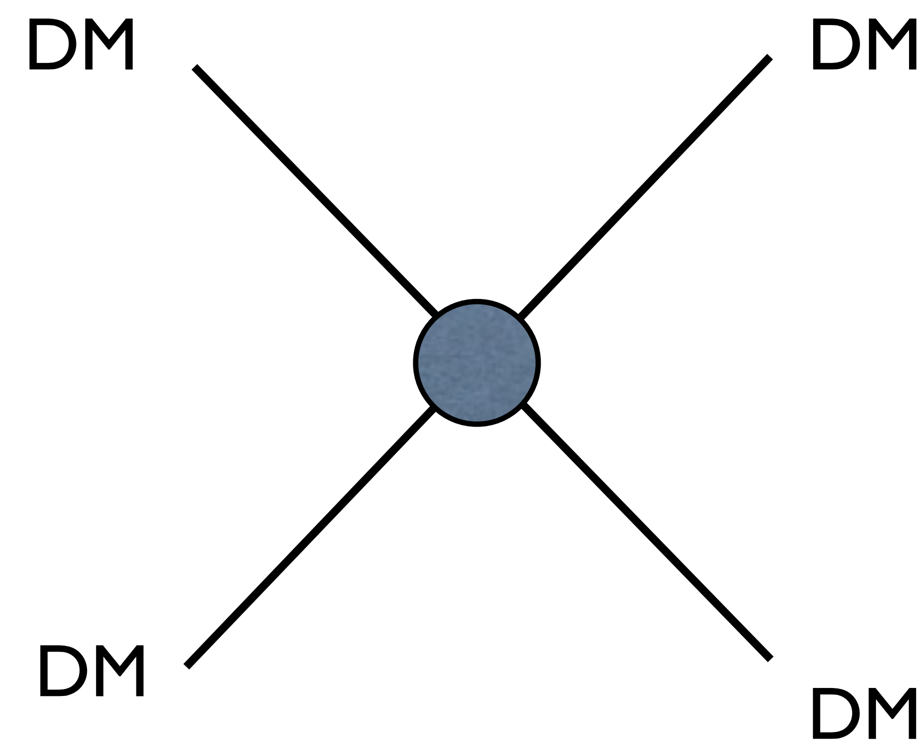
$$\Omega_{\rm DM}h^2 \simeq 0.1\left(\frac{m_{\rm DM}/35\,{\rm MeV}}{\alpha_{\rm eff}}\right)^{3/2}$$

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

SIMP self-interaction

- SIMP DM is accompanied by large self-interactions.





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

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

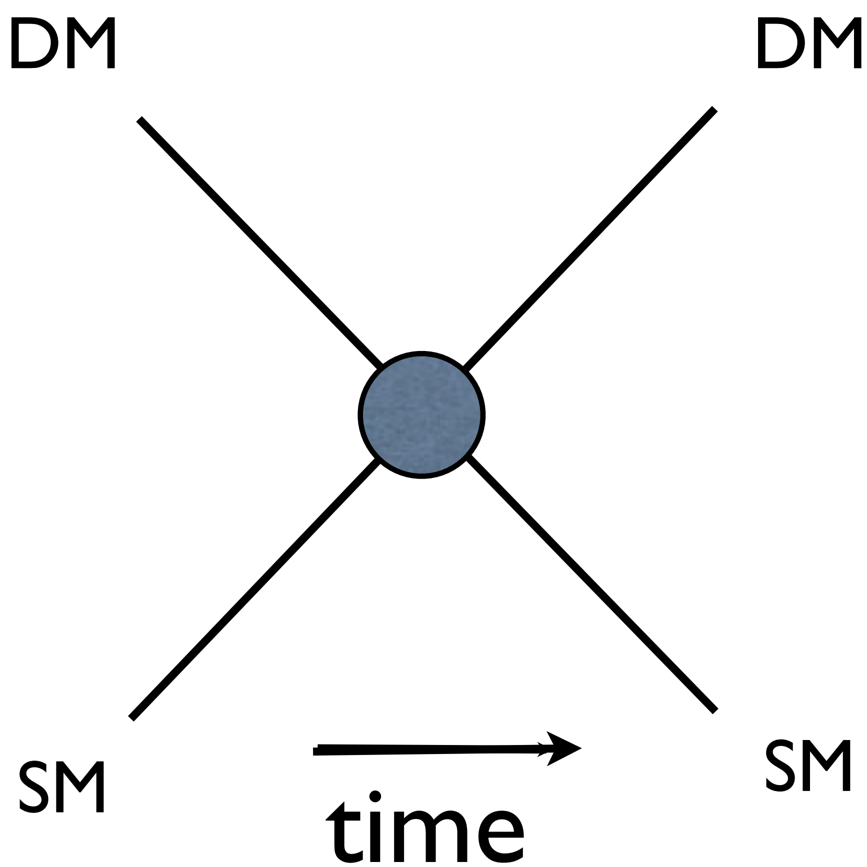
$$\Rightarrow \quad \frac{\sigma_{\rm self}}{m_{\rm DM}} = 4\times 10^3\,{\rm GeV}^{-3}\left(\frac{100\,{\rm MeV}}{m_{\rm DM}}\right)^3\left(\frac{\alpha_{\rm eff}}{2}\right)^2 \simeq \left(\frac{5}{\alpha_{\rm eff}}\right) 1{\rm cm}^2/{\rm g}$$

relic density

Bounds from 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 in kinetic equilibrium



- SIMP with 3→2 is overheated so it is dangerous for structure formation.

[Carlson et al, 1992; de Laix et al, 1995]

SIMP can be equilibrated by kinetic scattering with the SM bath:

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

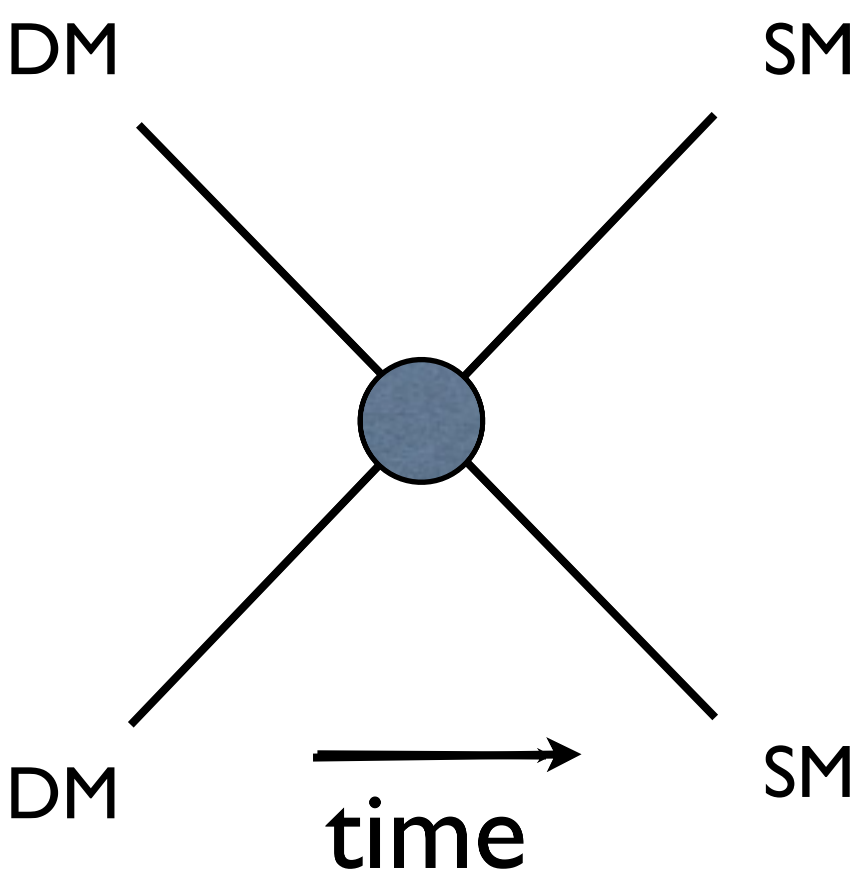
$$\Rightarrow \boxed{\epsilon_1 \gtrsim 0.9\times 10^{-9}\alpha_{\rm eff}^{1/2}}$$

- "Decoupled SIMP" can be thermalized by dark thermal bath.

cf. Cannibal DM, ELDER dark matter. cf. FIMP

- Higher-order(4→2) SIMP is lighter (sub-MeV), so it must be decoupled from SM thermal bath, due to bound on $N_{\rm eff}$.

SIMP conditions



- Crossing symmetry of kinetic scattering leads to 2→2 DM annihilation, which is sub-dominant, if

$$\langle\sigma v\rangle_{\rm ann} = \frac{\epsilon_2^2}{m_{\rm DM}^2};$$

$$n_{\rm SM}\langle\sigma v\rangle_{\rm kin} < n_{\rm DM}\langle\sigma v^2\rangle_{3\to 2}$$

$\epsilon_2 \sim \epsilon_1$ ⇒ $\epsilon_1 \lesssim 2.4\times 10^{-6}\alpha_{\rm eff}$

- SIMP conditions on interactions to SM:

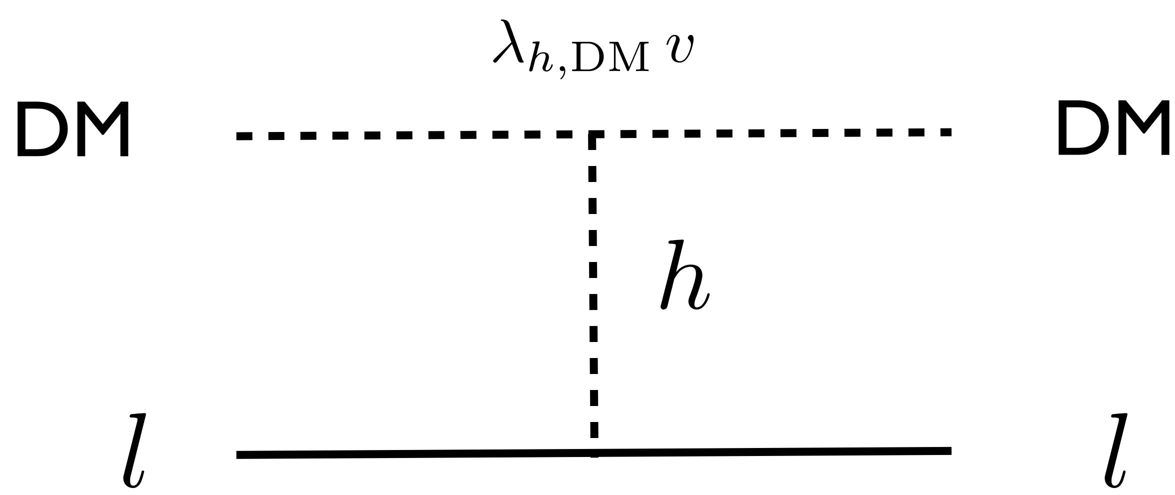
$$\boxed{0.9\times 10^{-9}\alpha_{\rm eff}^{1/2} \lesssim \varepsilon_{1,2} \lesssim 2.4\times 10^{-6}\alpha_{\rm eff}}$$

lose heat! 3→2 wins!

Portals for SIMP equilibrium

- Scattering of SIMP through Higgs-portal does not work, because of small electron Yukawa coupling or Boltzmann-suppressed abundance of muon.

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



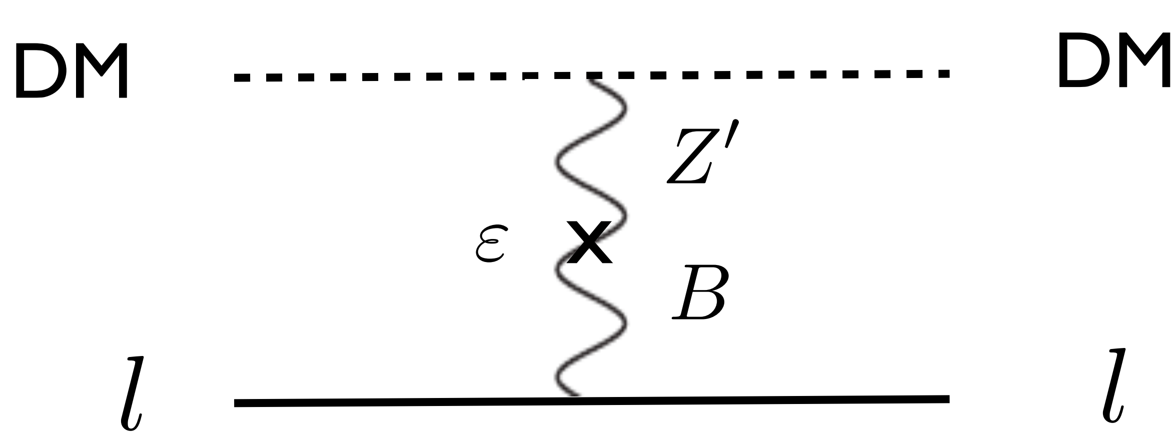
$$\langle \sigma v \rangle_{\rm scatt} \approx \frac{\lambda^2_{h,\mathrm{DM}} m_l^2 m_{\mathrm{DM}}^2}{4\pi m_h^4}$$

Higgs invisible decay:

$$|\lambda_{h,\mathrm{DM}}| \lesssim 0.01$$

$$\boxed{\varepsilon_2 \lesssim 10^{-11}}$$

- If SIMP carries Z' charge, a small gauge kinetic mixing with hypercharge can make SIMP in kinetic equilibrium.



$$\langle \sigma v \rangle_{\rm scatt} \approx \frac{96\pi \alpha \alpha_D \varepsilon^2 m_{\mathrm{DM}}^2}{m_{Z'}^4} \frac{T}{m_{\mathrm{DM}}}$$

Complementarity with Z' searches

Composite SIMP

Composite SIMP from dark QCD

- 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.

→ Dark mesons are natural candidates for SIMP, being stable due to flavor symmetry.

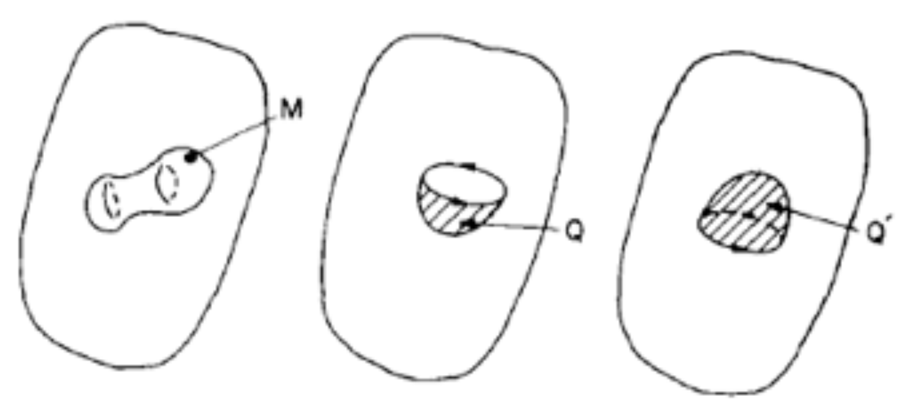
- Effective action for dark mesons contains a 5-point self-interaction from Wess-Zumino-Witten term for $\pi_5(G/H)=Z$ (i.e. $N_f \geq 3$).

[Wess, Zumino, 1971; Witten, 1983]

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

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

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

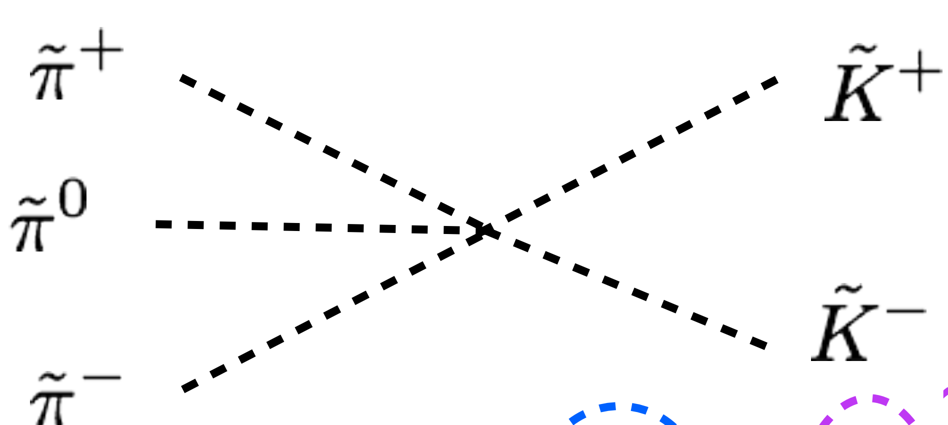


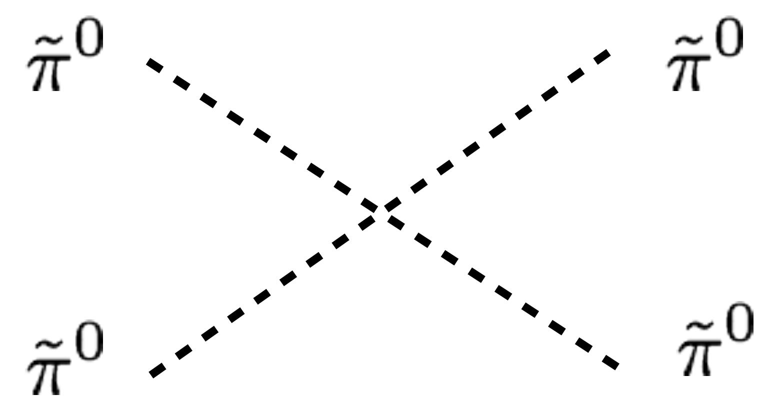
N_C : topological invariant of 5-sphere (Q+Q') in SU(3)

Composite SIMP scatters

- WZW terms lead to 5-point scattering of dark mesons while usual ChpT leads to self-scattering.

[Hochberg et al, 2014]





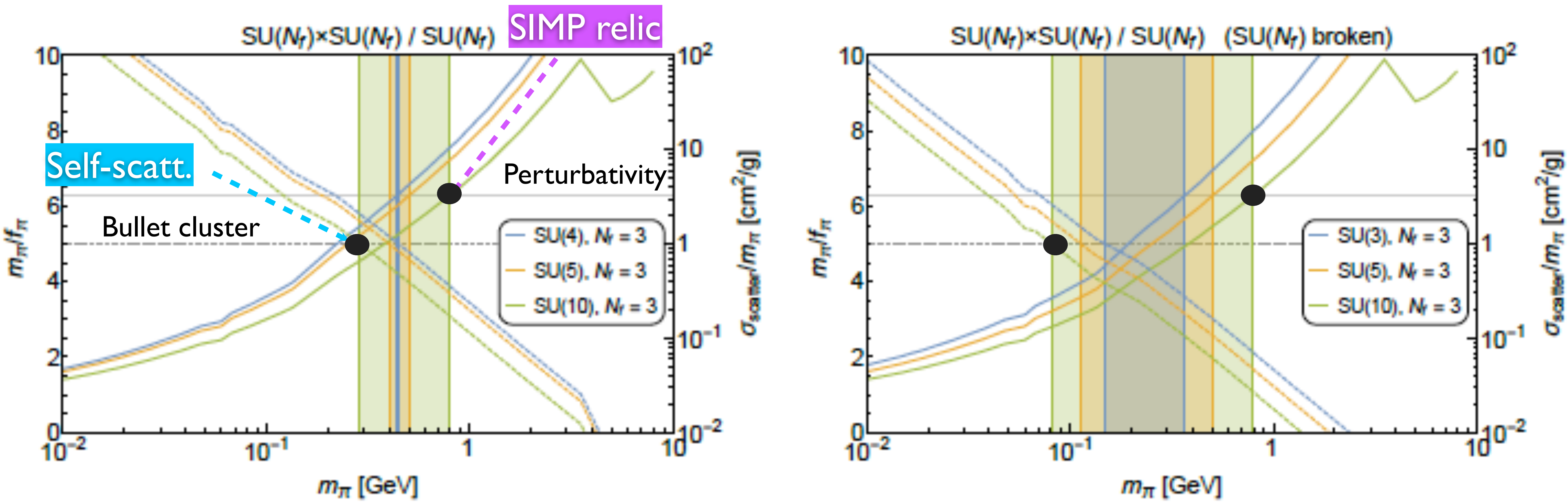
~1/N$_f$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5} N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi}\right)^2, \qquad \sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

~const

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

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

$N_c > 3$ is favored due to bounds on self-scattering.

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

Gauged WZW with Z'

- Dark quarks are vector-like; SM particles are neutral under Z'.

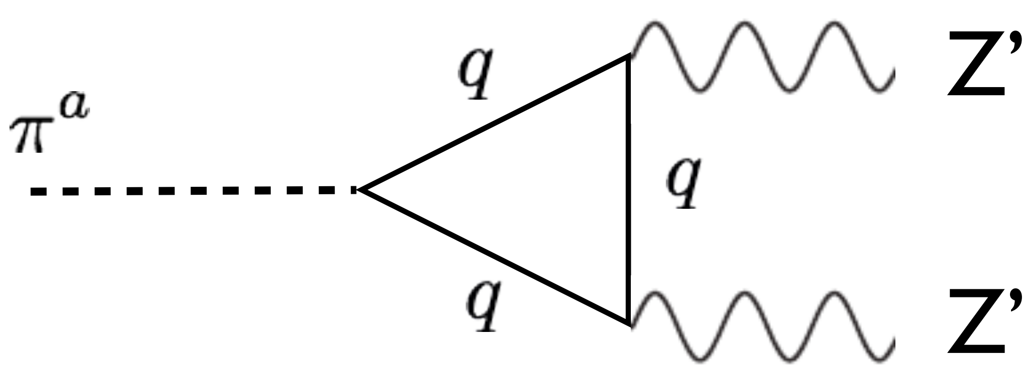
$$
\boxed{\begin{aligned} S =& S_0(D_\mu U, D_\mu U^{-1}) + S_{\rm WZW}(U,U^{-1}) - eN_c\int d^4x A'_\mu J^\mu \\ &+ \frac{ie^2N_c}{24\pi^2}\int d^4x \epsilon^{\mu\nu\rho\sigma}\partial_\mu A'^\nu A'_\rho {\rm Tr}[Q^2\partial_\sigma U U^{-1} \\ &\qquad + Q^2U^{-1}\partial_\sigma U + QUQU^{-1}\partial_\sigma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

[Witten, 1983]

Noether current:

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

- Chiral anomalies needs to be cancelled for DM stability.



$\propto {\rm Tr}(Q_D^2 T^a) = 0$ **if** $Q_D^2 = I.$

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

: flavor non-universal charges

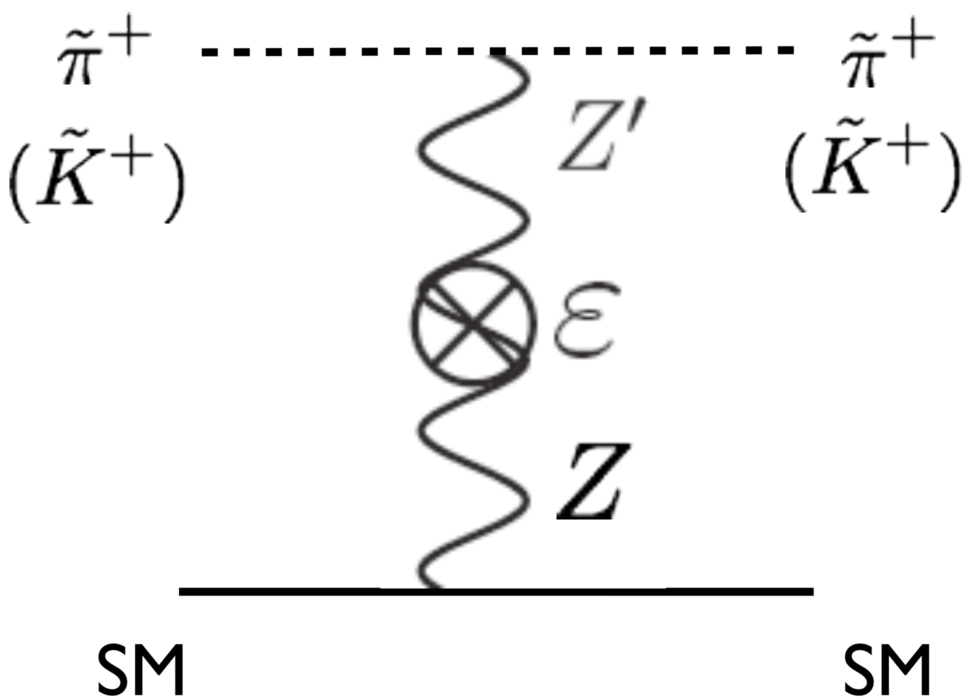
cf. QCD: Q=diag(2/3,-1/3,-1/3)

- Meson mass splitting due to Z': $\Delta m_\pi^2 \sim \frac{\alpha_D \Lambda^4}{F^2} \sim \alpha_D F^2 \lesssim \frac{m_\pi^2}{x_F^2}$ $: \alpha_D \lesssim 0.01\left(\frac{m_\pi}{F}\right)^2.$

Equilibrium via Z'-portal

[HML, Seo, 2015]

- Small kinetic mixing between Z' & hypercharge can make dark meson in kinetic equilibrium with the SM.



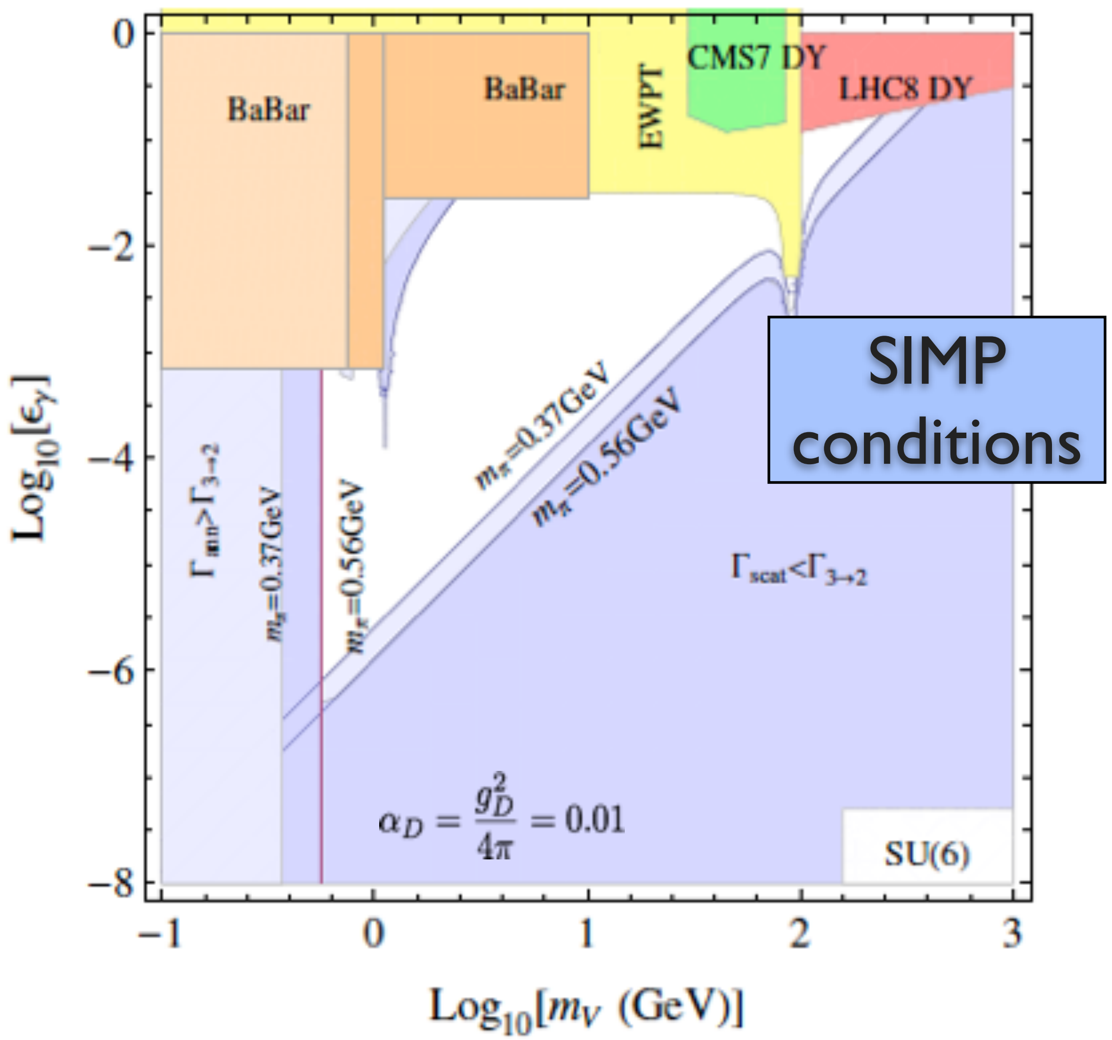
$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} F^{\mu\nu}$$

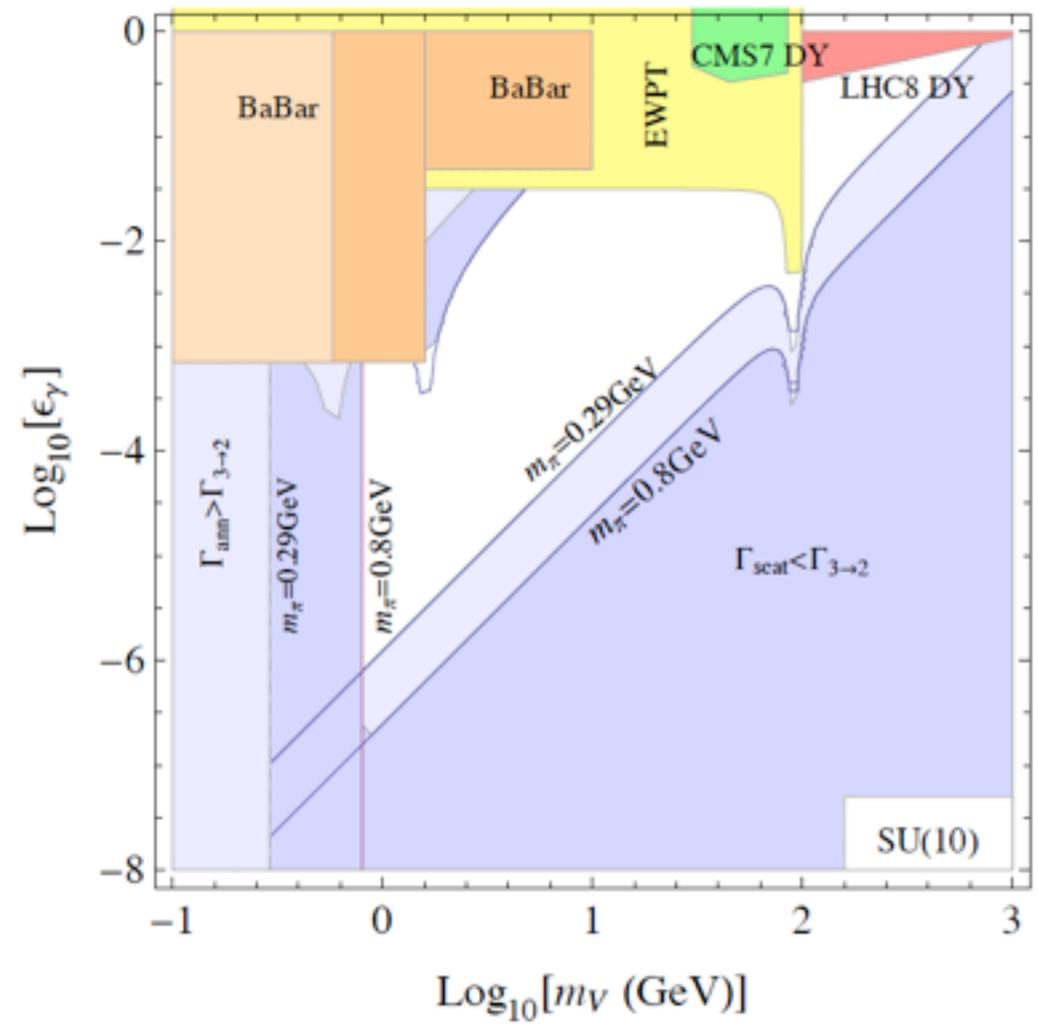
$$\Rightarrow \quad \langle \sigma v \rangle_{\rm kin} \approx \frac{768\alpha\alpha_D\varepsilon^2}{\pi N_\pi} \frac{m_\pi^2}{m_{Z'}^4} \left(\frac{T_F}{m_\pi}\right).$$

- $\pi\ \pi \to Z'Z'$ & $\pi\ \pi \to \pi Z'$ are forbidden for $m_{Z'} > m_\pi$; Z'-portal 2→2 is suppressed.

$\Rightarrow$ 3→2 dominance: SIMP conditions

Bounds on Z'





$e^+e^- \to \gamma Z' \to \gamma(l^+l^-)$, $\quad e^+e^- \to \gamma + \mathrm{MET}$

$h \to ZZ'$ (CMS 8TeV), Drell-Yan, dileptons.

- SIMP parameter space can be probed by Z' searches.
- Beam dumps & DM-nucleon scattering lead to similar limits.

Fundamental SIMP

Z_3 and SIMP

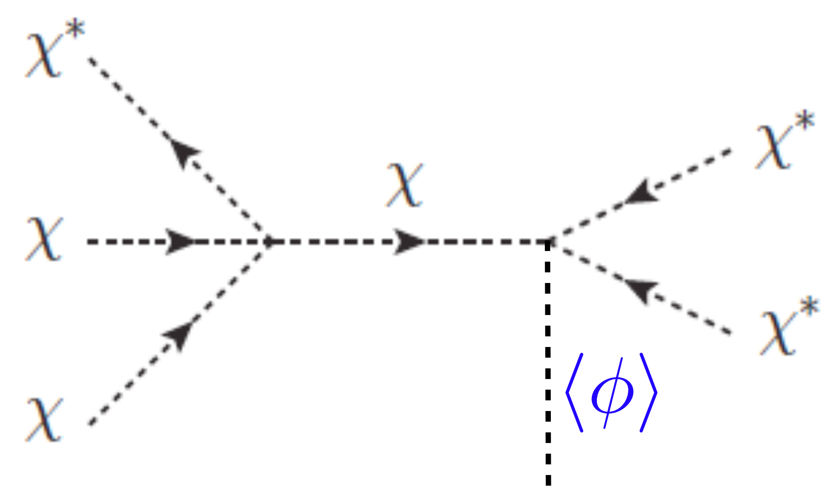
[S.-M.Choi, HML, 2015]

- Treat SIMP as a fundamental stable particle.
- Z_3 is the minimal discrete symmetry stabilizing SIMP, as a remnant of a dark local U(1); built-in Z'.

	ϕ	χ
$U(1)_V$	$+3$	$+1$

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

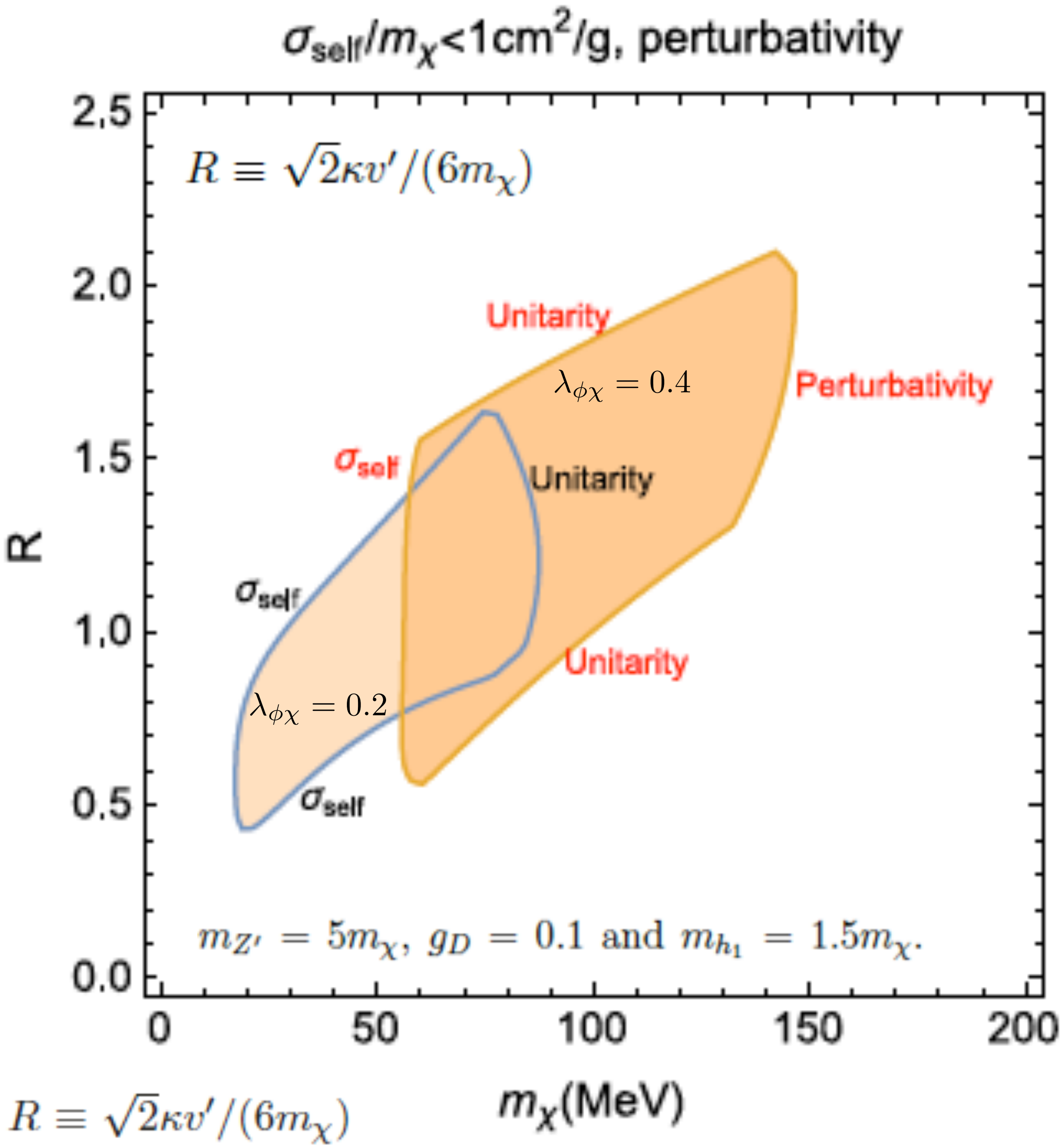
$$\langle\phi\rangle = \frac{1}{\sqrt{2}}v' \quad \Rightarrow \quad U(1)_V \to Z_3.$$

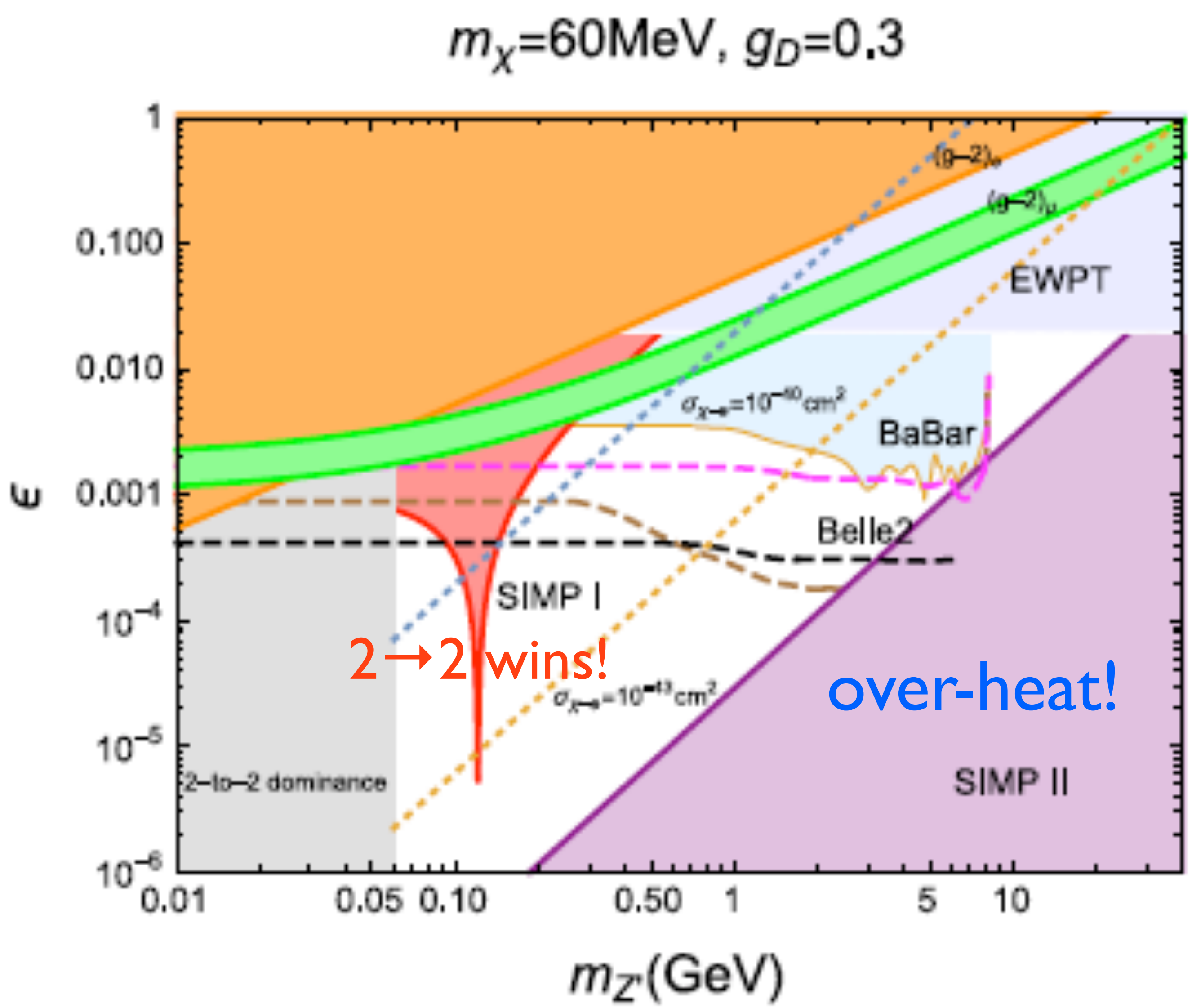


Renormalizable couplings:

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

Parameters for Z_3 SIMP





Bullet cluster bound, perturbativity imposed.

BaBar γ+MET; Belle2 projection; EWPT; g-2; XENON10; (similar limits from beam dump)

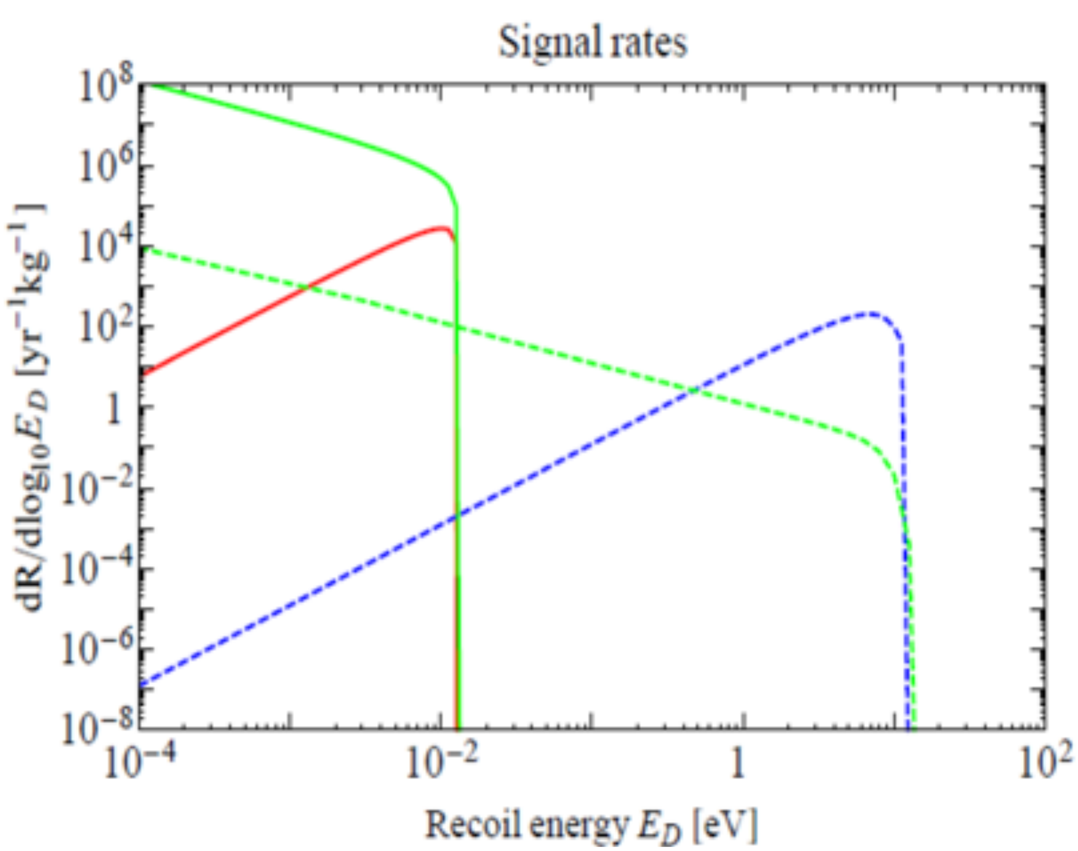
SIMP direct detection

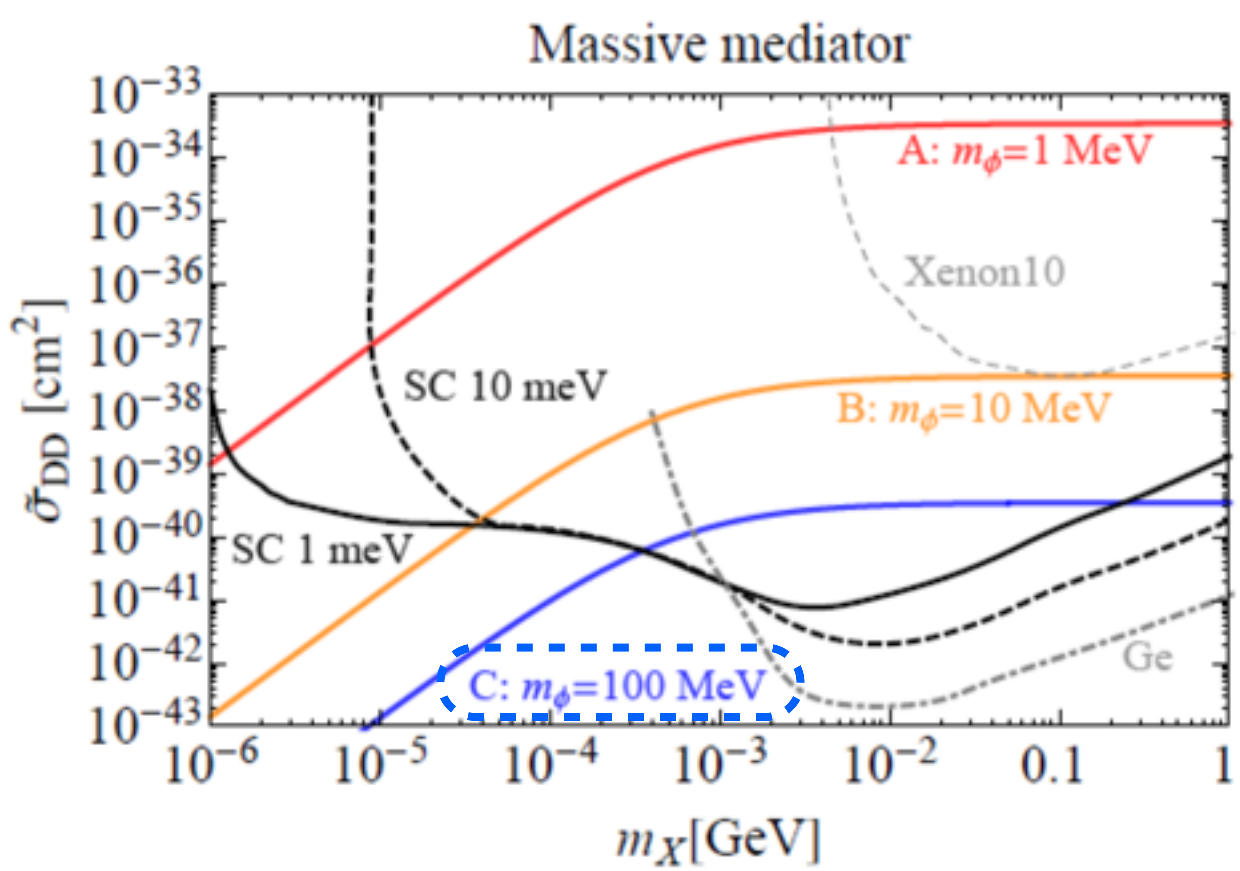
- SIMP dark mesons scatters off electrons, with small threshold for recoil energy: $\left(E = \frac{q^2}{2m_e} \lesssim 20\,\mathrm{eV}.\right)$

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

[Hochberg et al (2015)]

Superconducting detectors: scattering with free electrons in a metal (Al)→ sensitive to meV recoil energy.



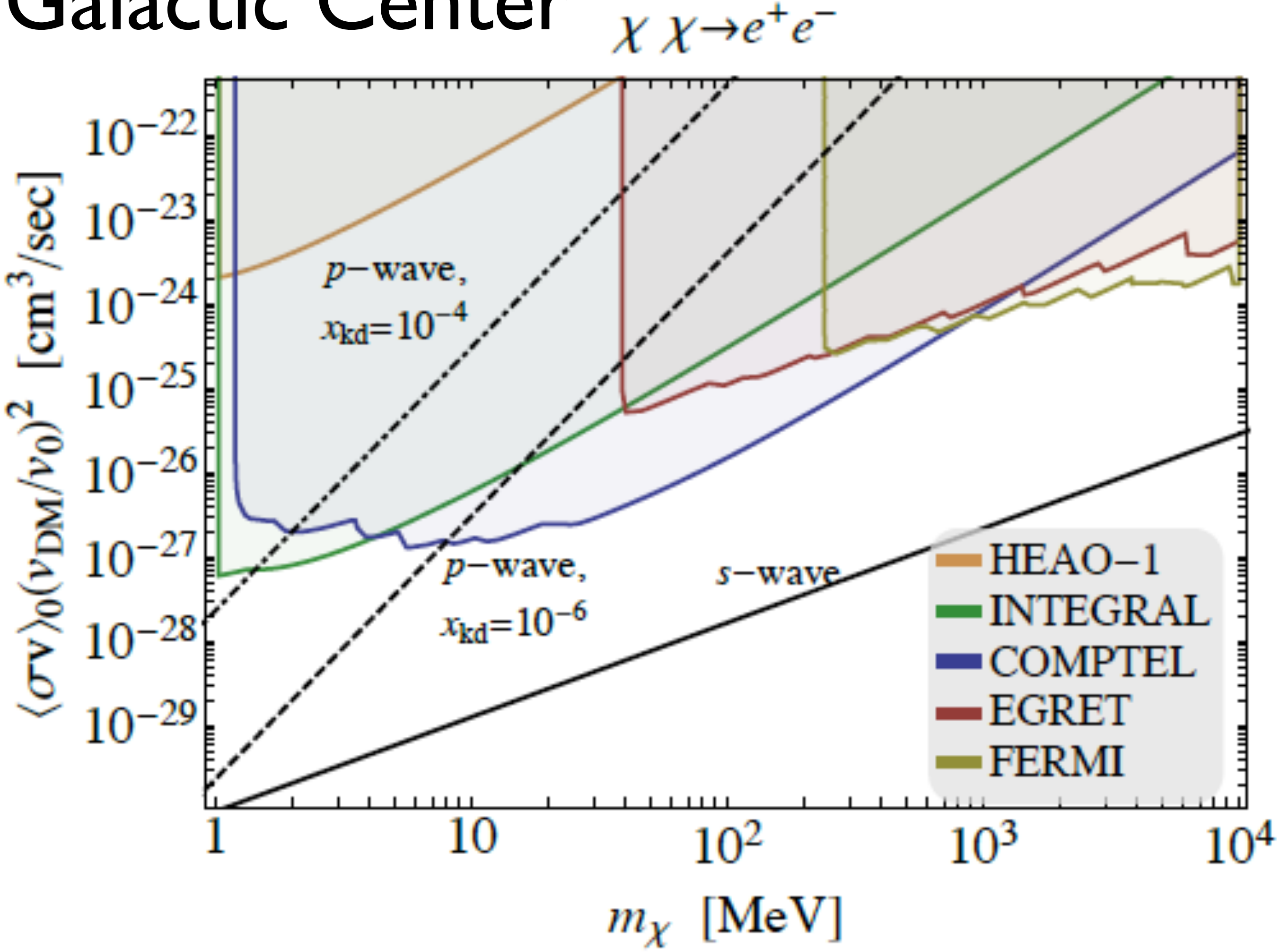


Blue: $(m_\phi, m_X, \alpha_X, g_e)$ = $(100\ \mathrm{MeV}, 100\ \mathrm{MeV}, 0.1, 3\times 10^{-5})$

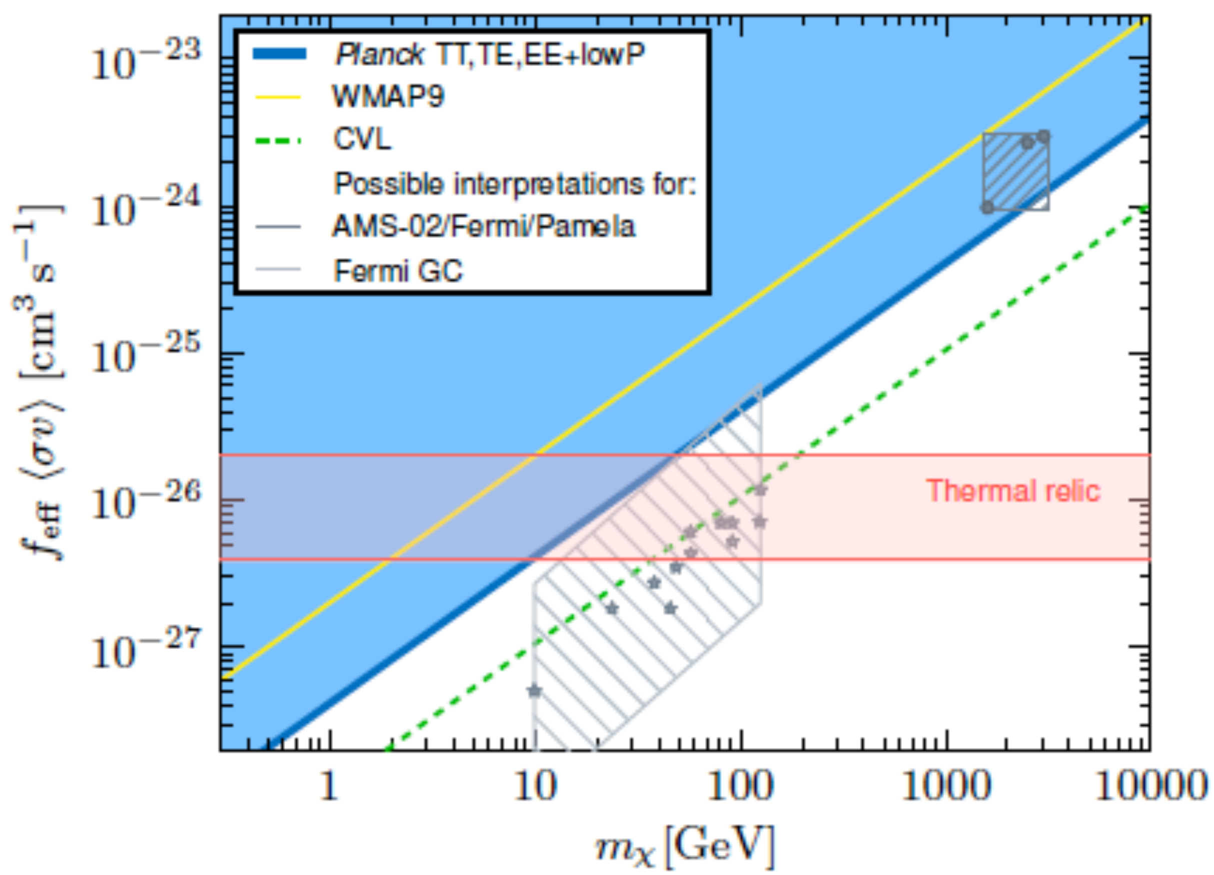
16년 7월 10일 일요일

SIMP indirect detection

Galactic Center



CMB



[Essig et al, 2013]

X-ray/gamma-ray & CMB can constrain sub-GeV DM.

No bound on 2→2 ann for scalar DM (p-wave suppressed).

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

Z_5 SIMP

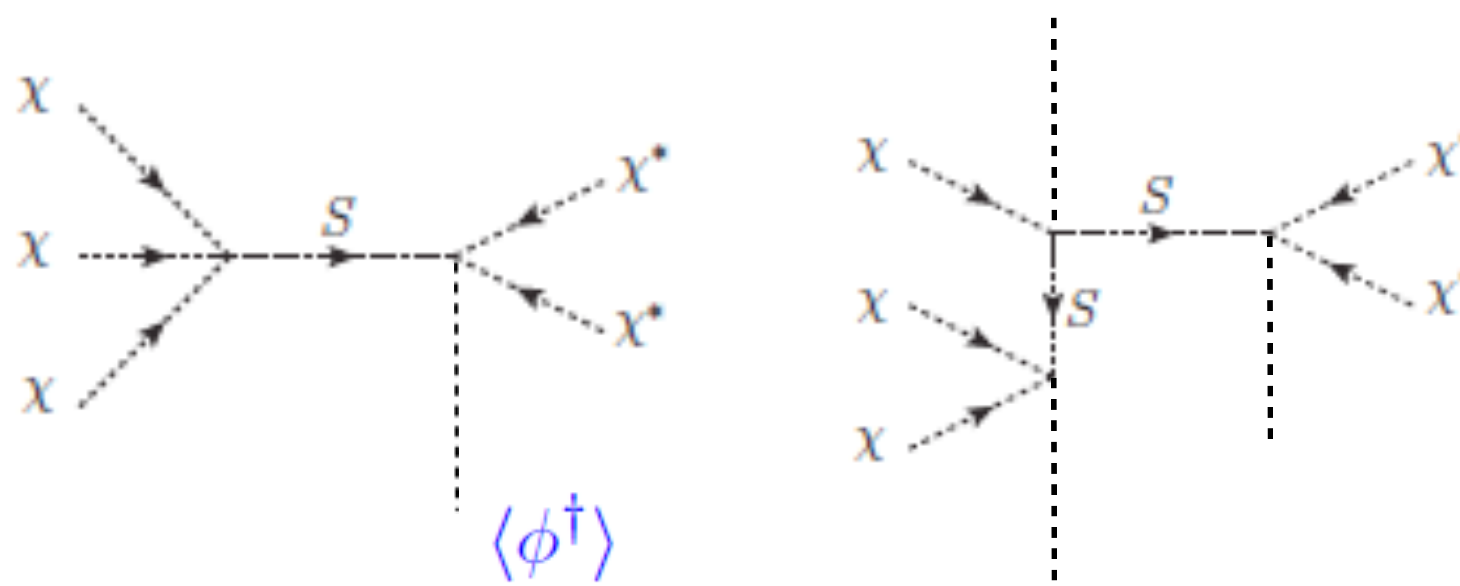
[S.M.Choi, HML, 2016]

Z_5 is a natural symmetry consistent with 5-point interaction, which is generated by a heavy particle S.

	ϕ	χ	S
$U(1)_V$	$+5$	$+1$	$+3$

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

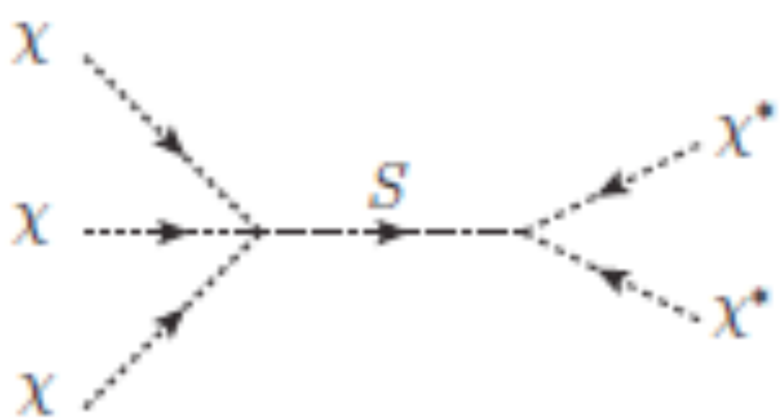
$$\mathcal{L}_{\rm int} \supset \frac{1}{\sqrt{2}}\lambda_1 \phi^\dagger S^2 \chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2 \phi^\dagger S \chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$



- If heavy scalar S is not decoupled, 3→2 annihilation can be enhanced near resonance.

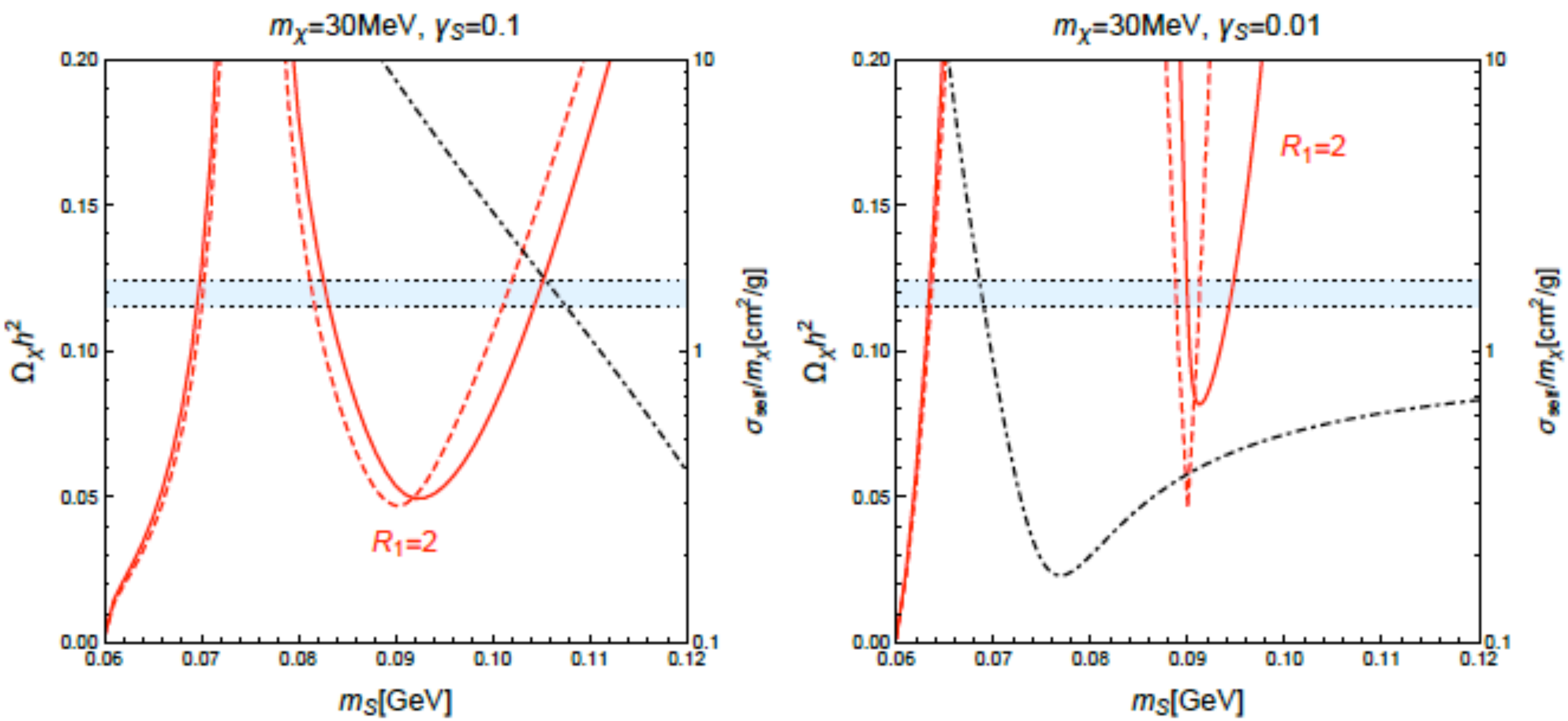
SIMP at resonance

3→2 annihilation cross section can be enhanced near resonance with $m_S \sim 3m_\chi$ (more significant for $\epsilon_S > 0$).



$$(\sigma v^2)_\chi \equiv \frac{c_\chi}{m_\chi^5} \frac{\gamma_S^2}{(\epsilon_S - v_{\rm rel}^2/4)^2 + \gamma_S^2}$$

$$\gamma_S \equiv m_S \Gamma_S/(9m_\chi^2), \ \epsilon_S \equiv (m_S^2 - 9m_\chi^2)/(9m_\chi^2)$$



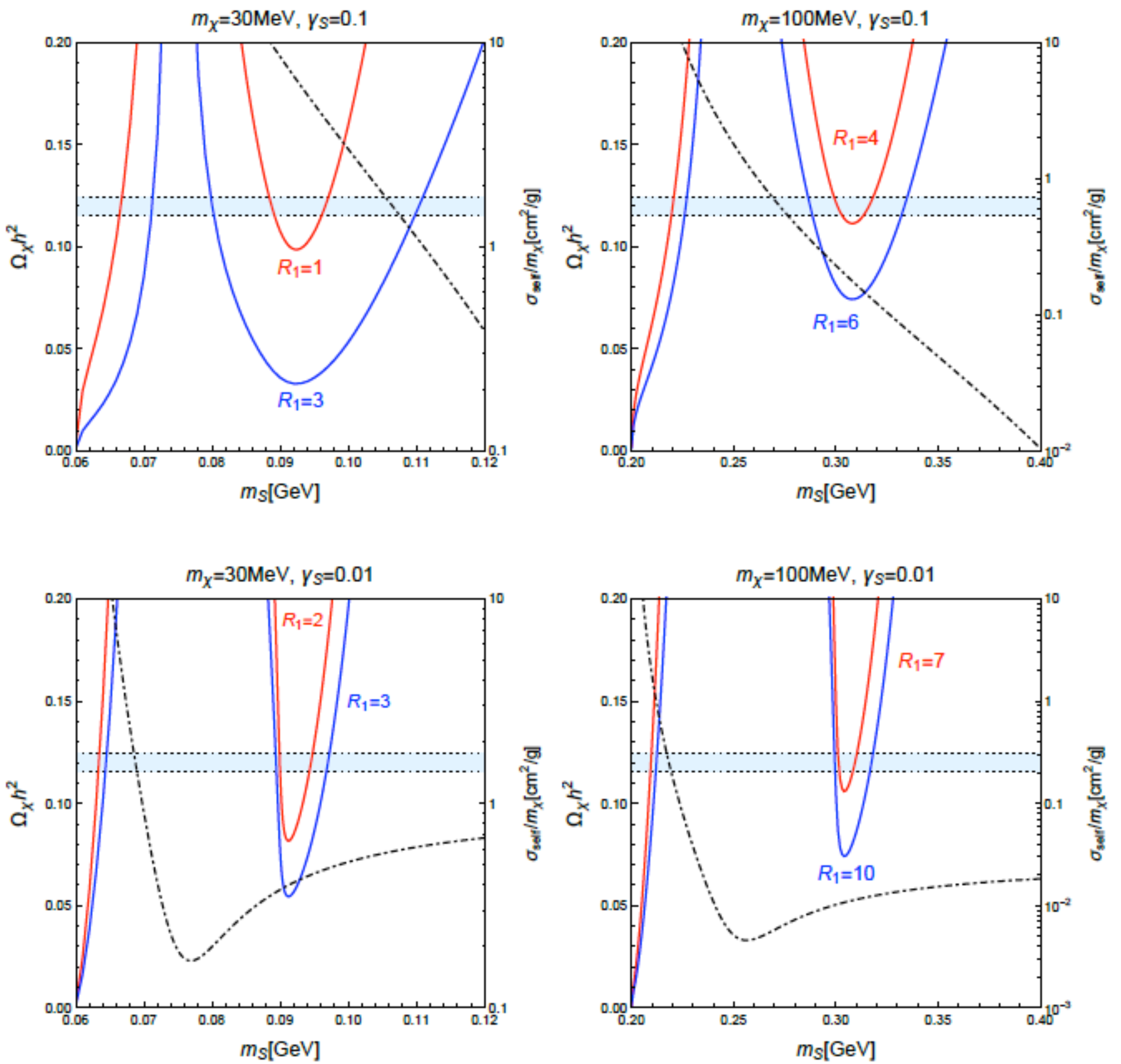
self-scattering

$$R_{1,2} \equiv \lambda_{1,2} v'/(\sqrt{2} m_\chi)$$
$$\lambda_3 = 0$$

SIMP couplings

$$R_{1,2} \equiv \lambda_{1,2} v'/(\sqrt{2} m_\chi)$$

$$\lambda_3 = 0$$



self-scattering:

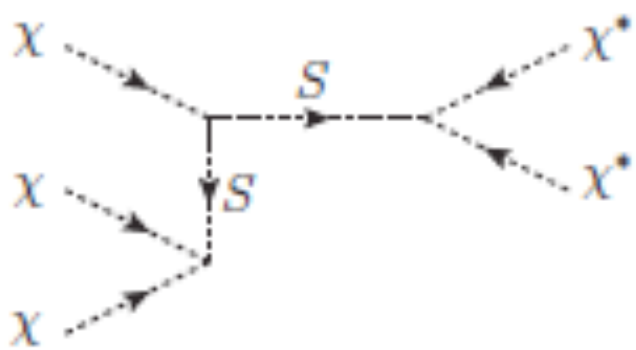
$$m_V = 500\,\text{MeV},$$

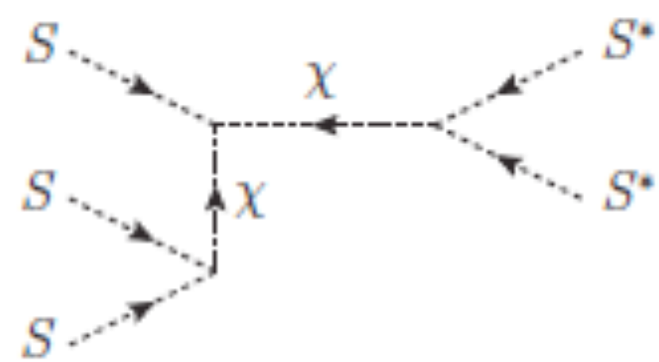
$$g_D = 0.1,\ \lambda_S = 1.$$

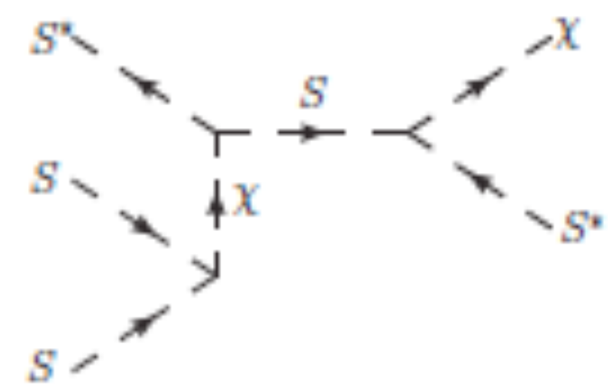
General SIMP masses

[S.-M.Choi, HML, in progress]

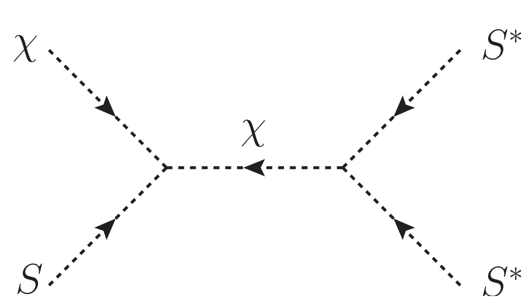
For $m_\chi < m_S < 2m_\chi$ or $m_\chi/2 < m_S < 2m_\chi$, both S and χ can be stable and SIMP candidates.

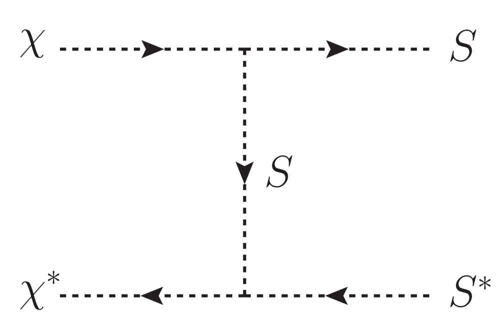


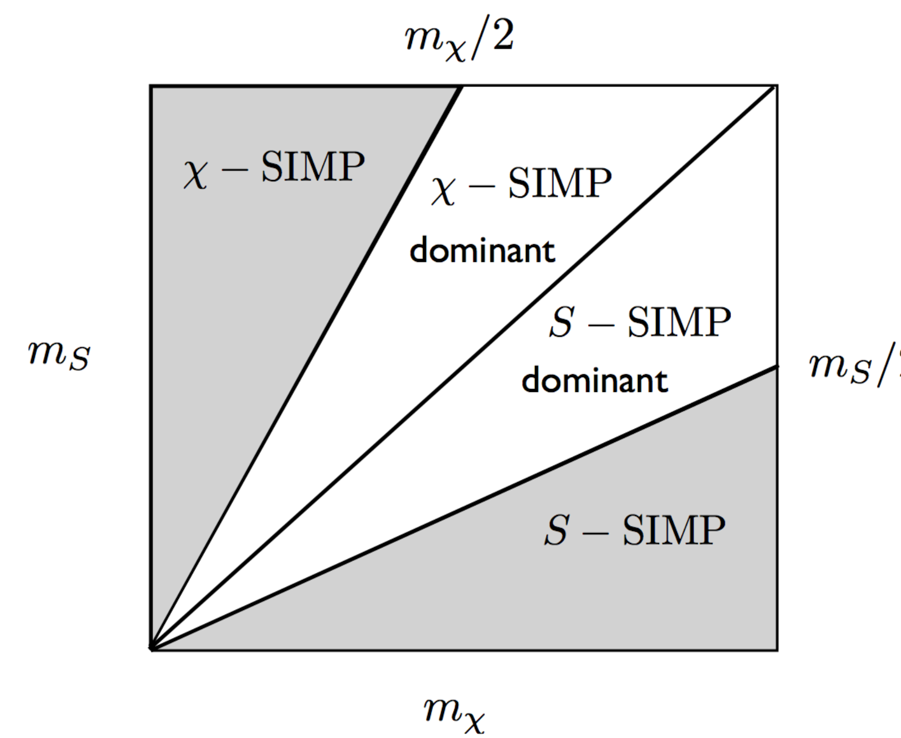




- 2→2 annihilation in hidden sector is large so the relic density of heavier state is negligible.







Conclusions

- SIMP is a sub-GeV thermal dark matter with large self-interactions but tiny interactions to the SM. Thus, it requires new strategies for dark matter searches.

- Composite or fundamental SIMP can be stable due to accidental flavor symmetry or discrete gauge symmetries.

- Dark local U(1) with kinetic mixing makes SIMP in kinetic equilibrium and detectable by electron recoil energy or Z’ searches.

- SIMP process can be enhanced at resonance, so more parameter space is opened.

Backup

2→2 vs 3→2 Boltzmann eqs

$$\frac{dn_i}{dt} + 3Hn_i = C_i,$$

- 2→2 annihilation $(\chi_i\chi_i \to \chi_j\chi_j)$

$$C_i = -\int d\Pi_2 \int d\Pi_2' |\mathcal{M}|^2 (f_i f_i - f_j f_j) \qquad \left(\frac{f_i}{\bar{f}_i} \simeq \frac{n_i}{\bar{n}_i}\right)$$

$$= -\frac{1}{\bar{n}_i^2}\int d\Pi_2 \int d\Pi_2' |\mathcal{M}|^2 \bar{f}_i^2 \left(n_i^2 - \frac{\bar{n}_i^2}{\bar{n}_j^2}\, n_j^2\right) \qquad (\bar{f}_j \bar{f}_j = \bar{f}_i \bar{f}_i)$$

$$= -\boxed{\langle\sigma v\rangle_{ii\to jj}}\left(n_i^2 - \frac{\bar{n}_i^2}{\bar{n}_j^2}\, n_j^2\right), \quad \langle\sigma v\rangle = \frac{1}{\bar{n}_i^2}\int d\Pi_2 \int d\Pi_2' |\mathcal{M}|^2 \bar{f}_i^2\,.$$

- 3→2 annihilation $(\chi_i\chi_i\chi_i \to \chi_j\chi_j)$

$$C_i = -\int d\Pi_3 \int d\Pi_2' |\mathcal{M}|^2 (f_i f_i f_i - f_j f_j)$$

$$= -\frac{1}{\bar{n}_i^3}\int d\Pi_3 \int d\Pi_2' |\mathcal{M}|^2 \bar{f}_i^3 \left(n_i^3 - \frac{\bar{n}_i^3}{\bar{n}_j^2}\, n_i^2\right) \qquad (\bar{f}_j \bar{f}_j = \bar{f}_i \bar{f}_i \bar{f}_i)$$

$$= -\boxed{\langle\sigma v^2\rangle_{iii\to jj}}\left(n_i^3 - \frac{\bar{n}_i^3}{\bar{n}_j^2}\, n_i^2\right) \quad , \quad \langle\sigma v^2\rangle \equiv \frac{1}{\bar{n}_i^3}\int d\Pi_3 \int d\Pi_2' |\mathcal{M}|^2 \bar{f}_i^3\,.$$