The SIMP Age for Thermal Dark Matter

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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 arXiv:
1601.03566[hep-ph] (In press, Phys. Lett. B)

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Seoul National University, May 2, 2016

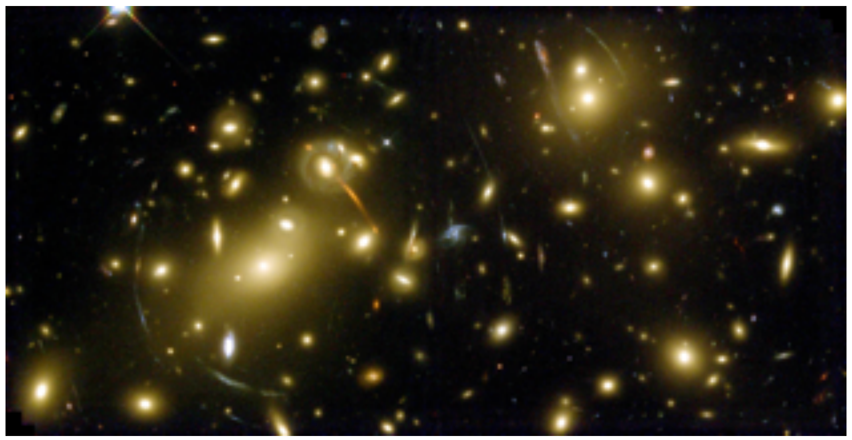
Outline

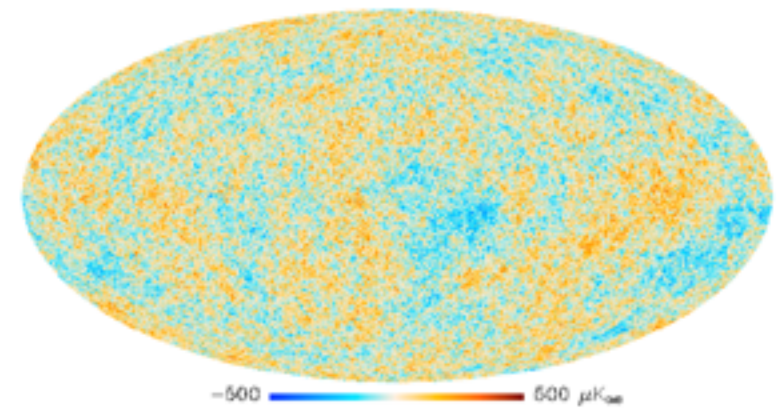
- SIMP dark matter
- SIMP from dark QCD
- SIMP with discrete symmetries
- Conclusions

SIMP dark matter

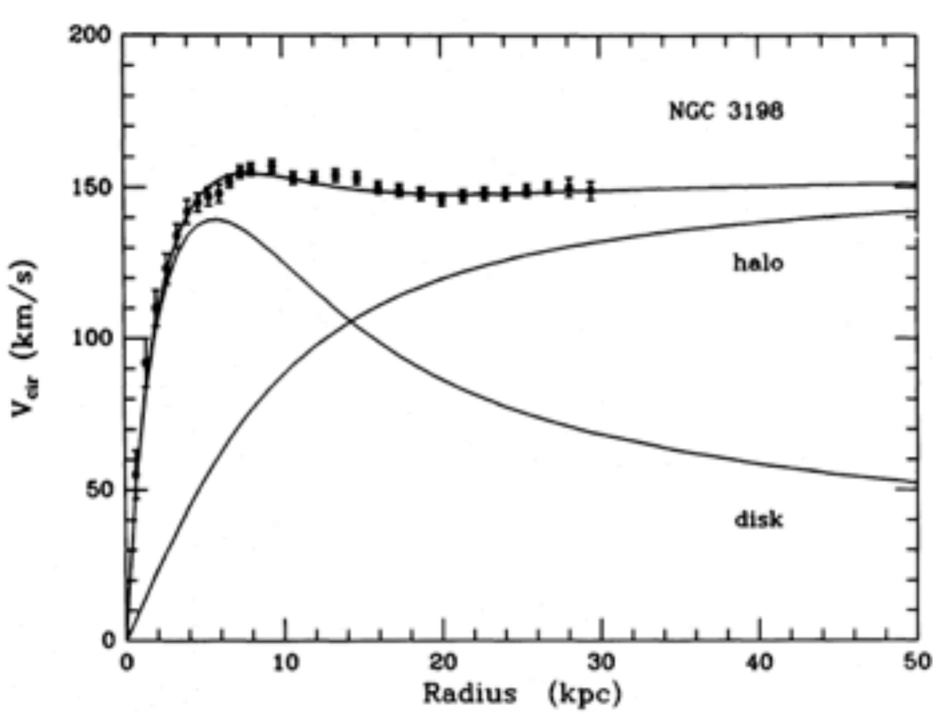
Dark matter everywhere!

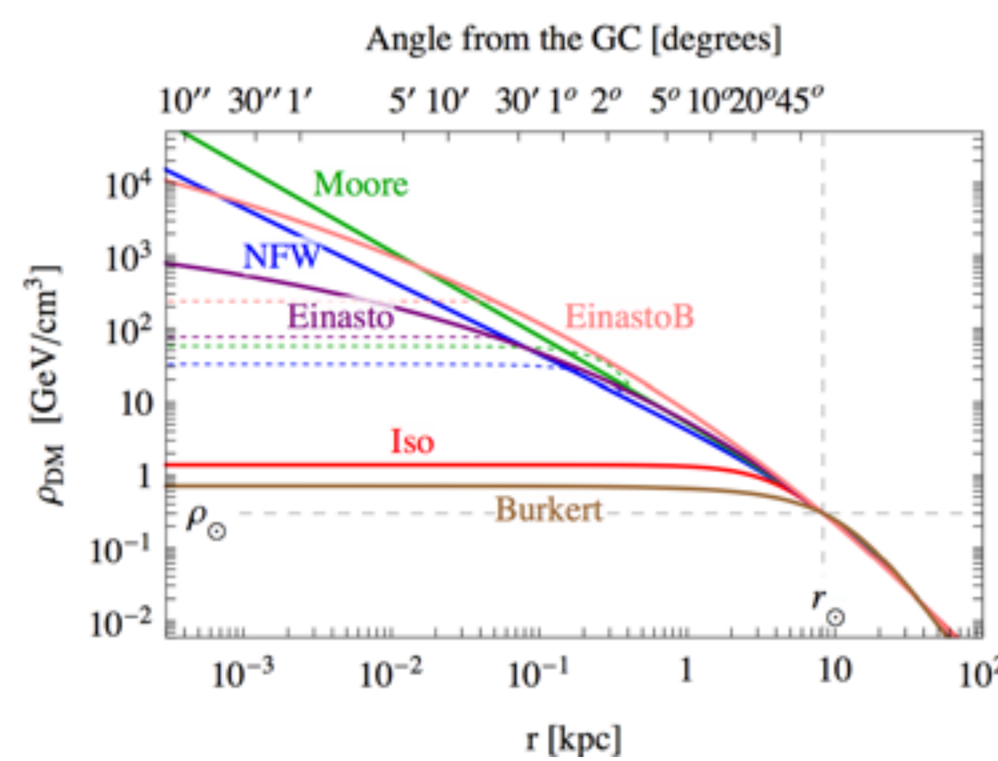
Large-scale evidences





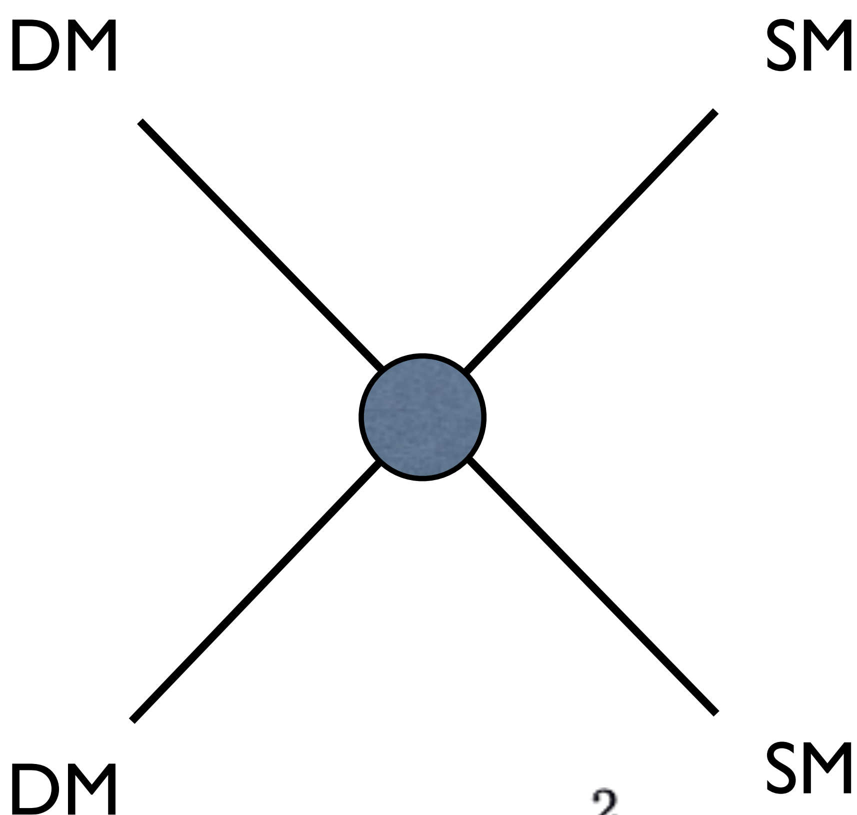
Galaxies (including our Milky Way)





WIMP paradigm

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



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

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle\sigma v\rangle\left(n_{\rm DM}^2 - (n_{\rm DM}^{\rm eq})^2\right)$$

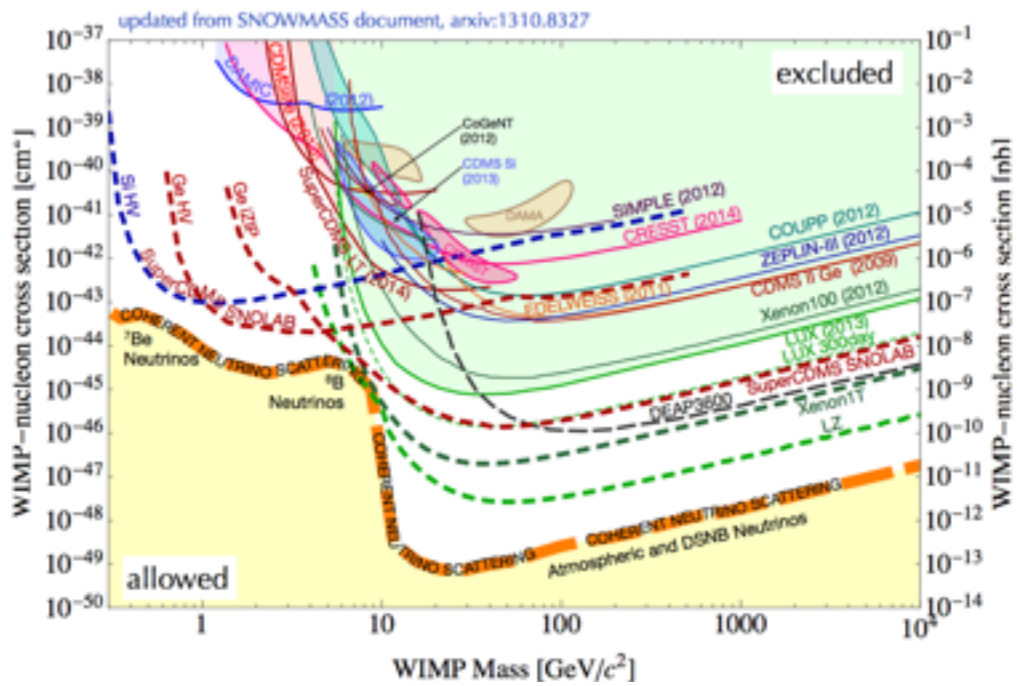
WIMP freeze-out:

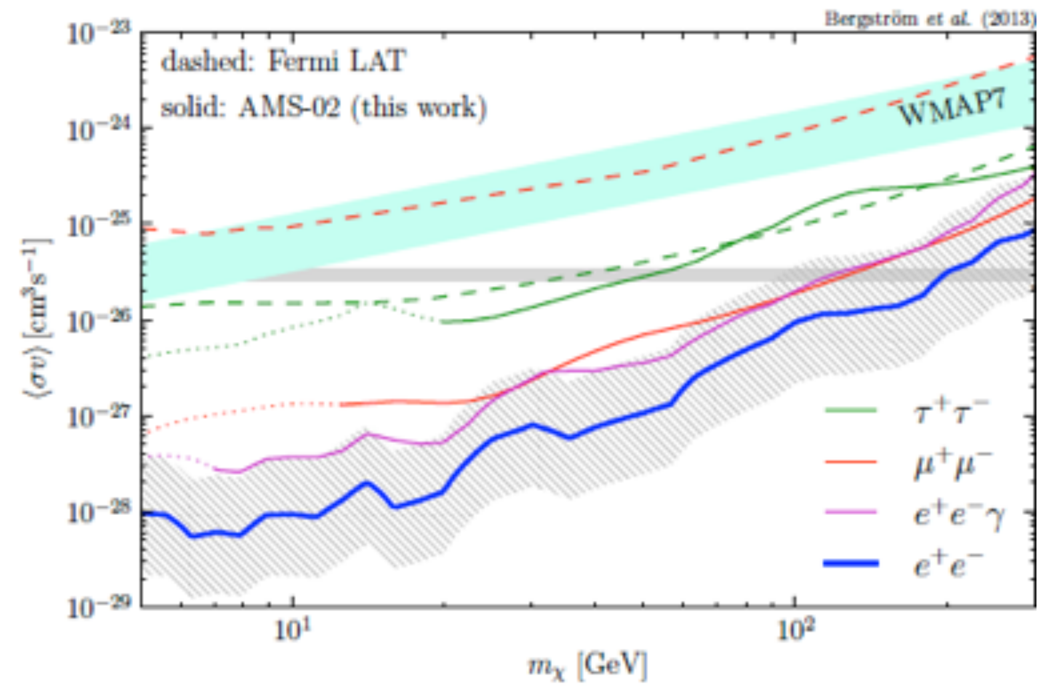
$$\Gamma_{\rm ann} = n_{\rm DM}\langle\sigma v\rangle_{\rm ann} \sim H = 0.33 g_*^{1/2}\frac{T_F^2}{M_P}$$

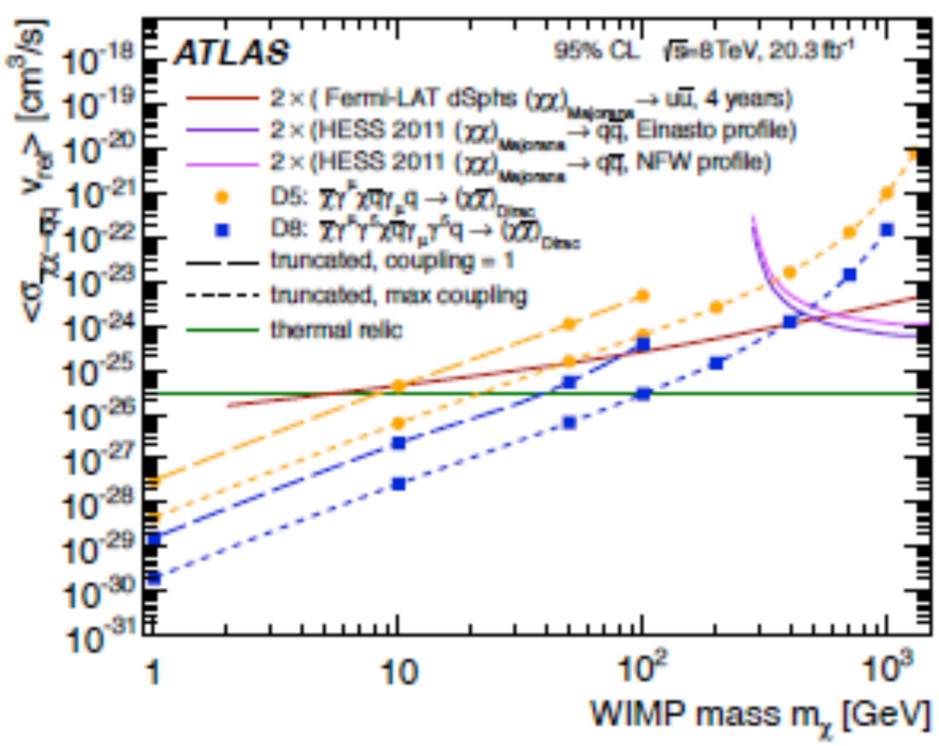
$$\Omega_{\rm DM}h^2 \sim 0.1\left(\frac{2\times 10^{-9}{\rm GeV}^{-2}}{(g_*/100)^{1/2}x_F\int_{x_F}^{\infty} x^{-2}\langle\sigma v\rangle dx}\right)$$

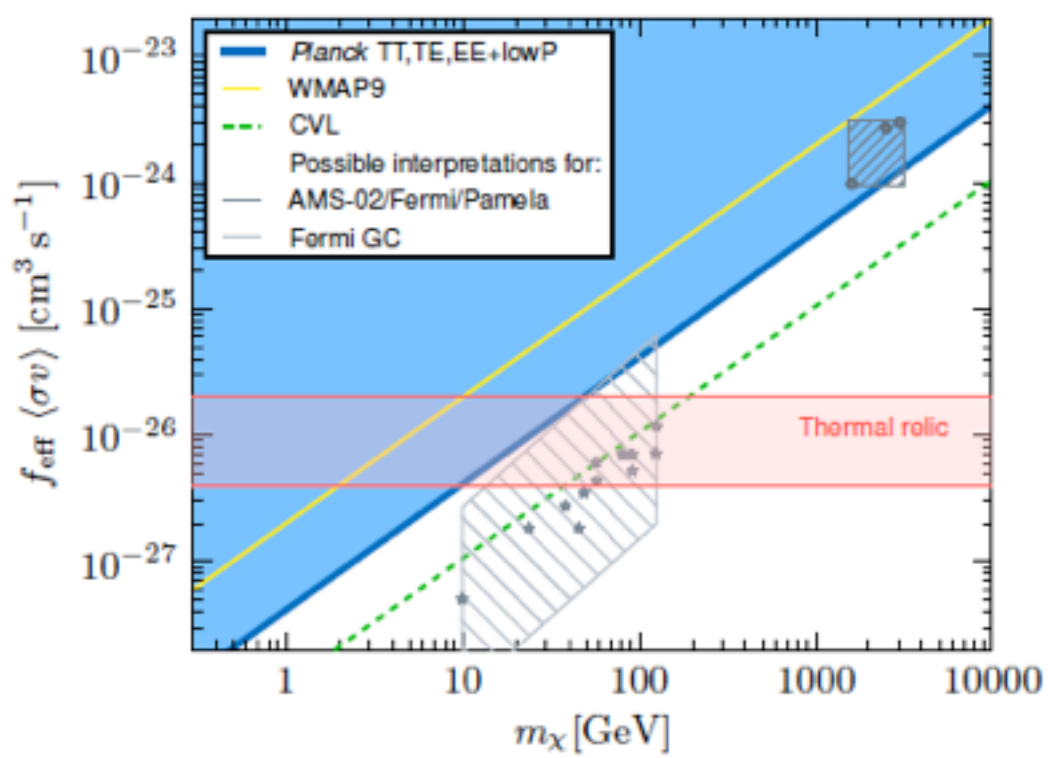
$$\boxed{\alpha_{\rm eff} \sim \frac{1}{30} \;\Longrightarrow\; m_{\rm DM} \sim 1\,{\rm TeV}}$$

WIMP around the corner?





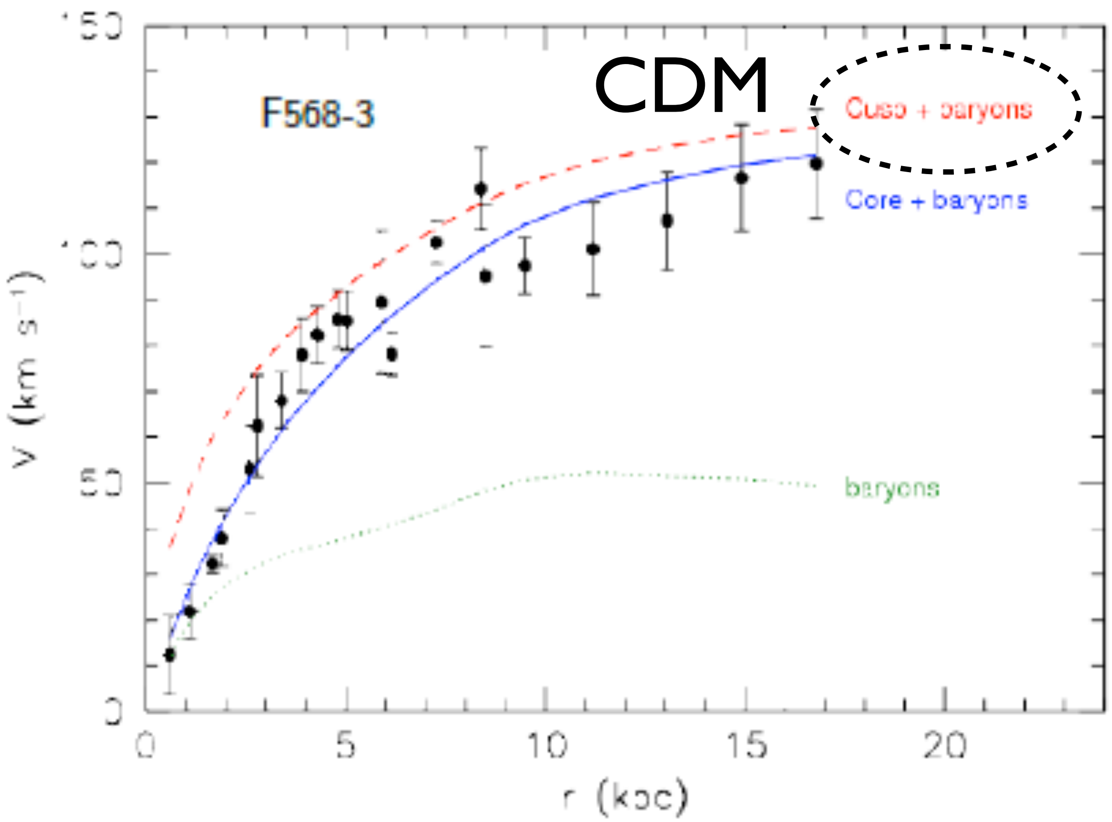


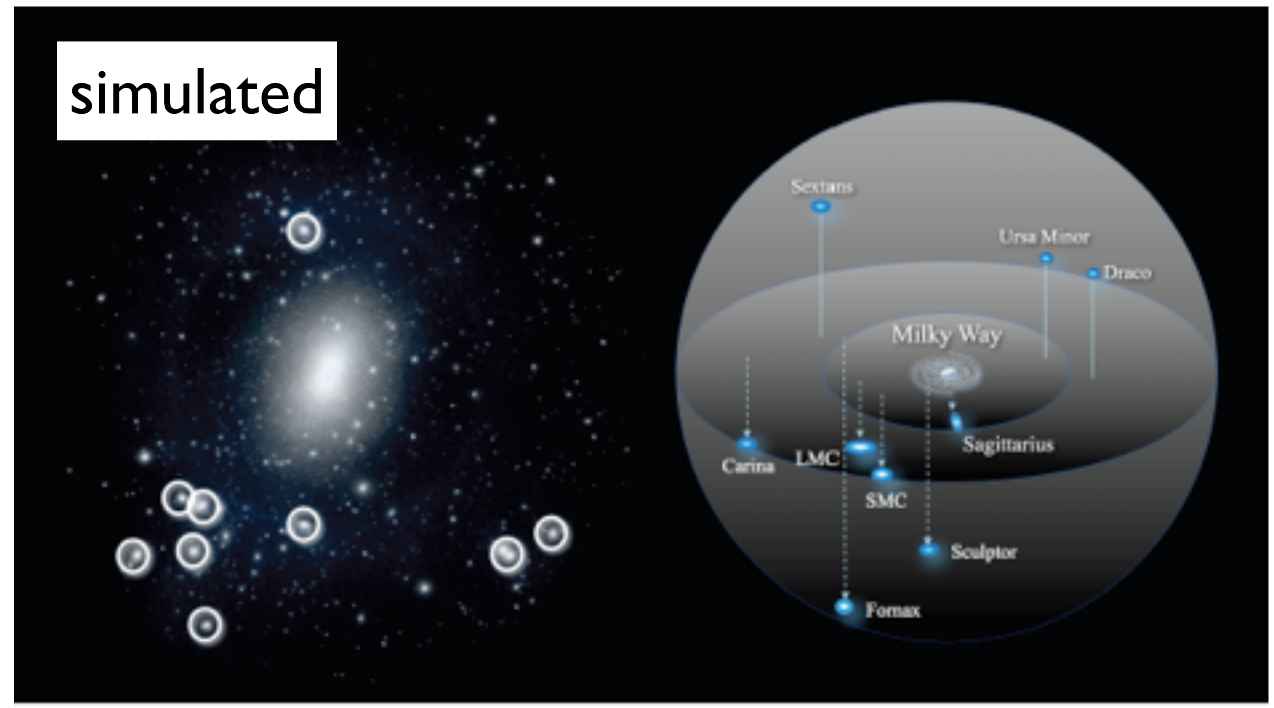


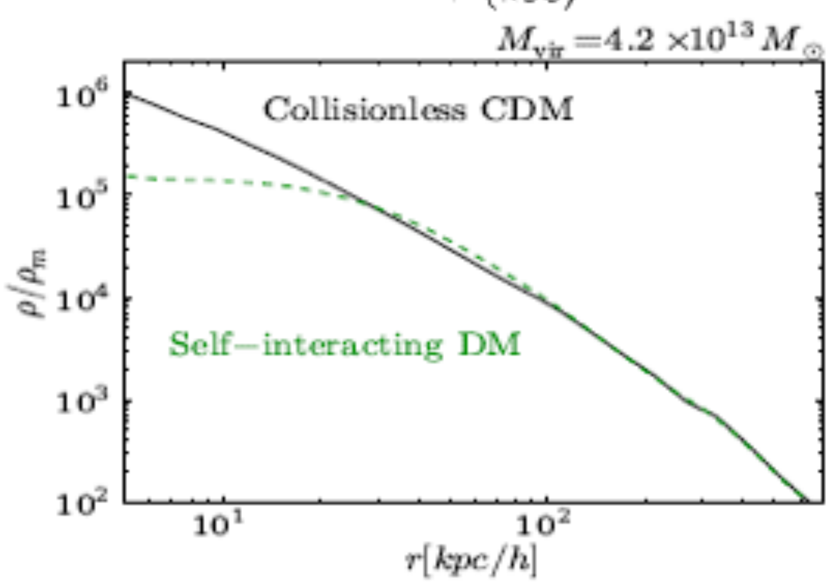
- A wide range of WIMP masses and interactions has been searched for by complementary searches.

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).

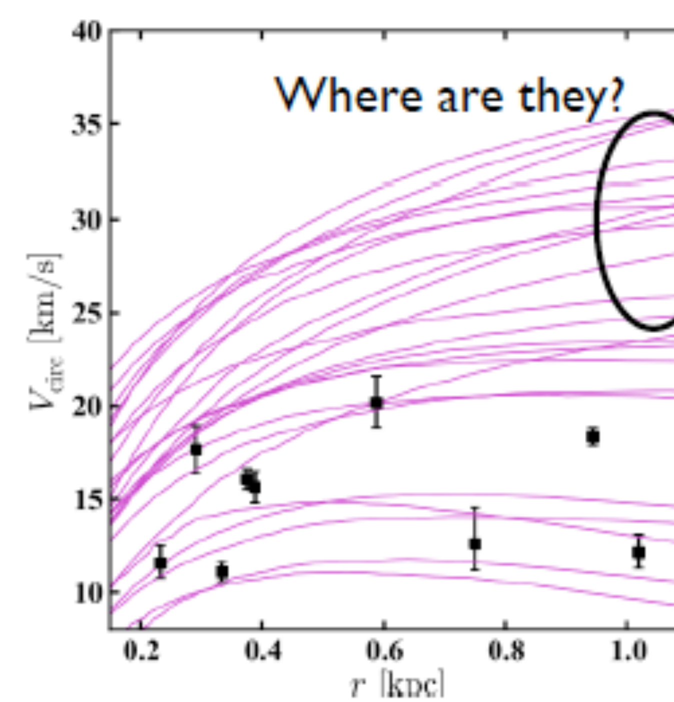






$$V \sim \sqrt{\frac{GM_<}{r}}$$

rotation curves of dSphs



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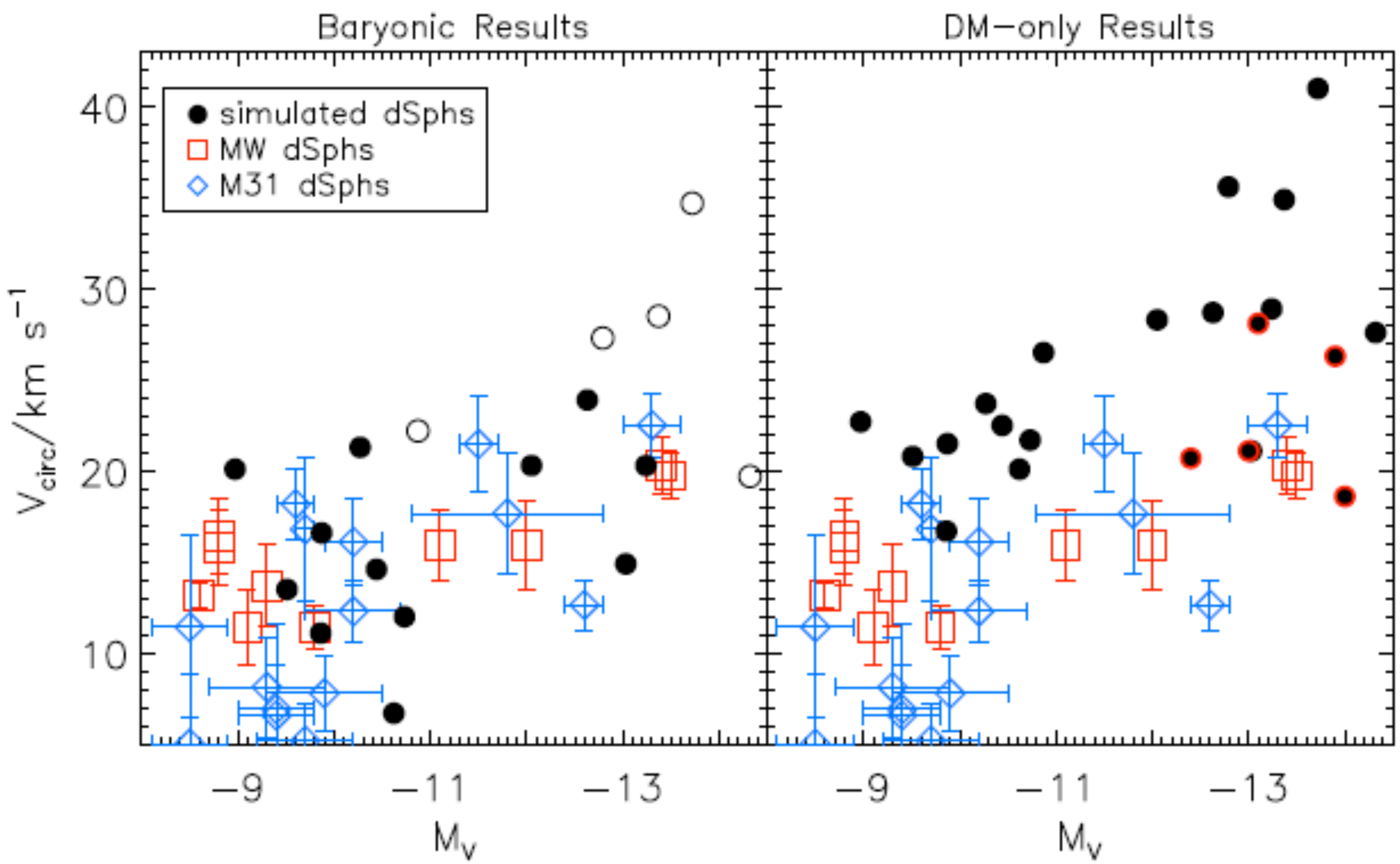
dSphs with baryons?

[Brooks & Zolotov, 2012]



with baryons without baryons

DM + baryons (SN feedback) erase small structures.

But, many dwarf galaxies: lack of baryons?

DM self-interactions

- DM self-interactions solve small-scale problems for

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

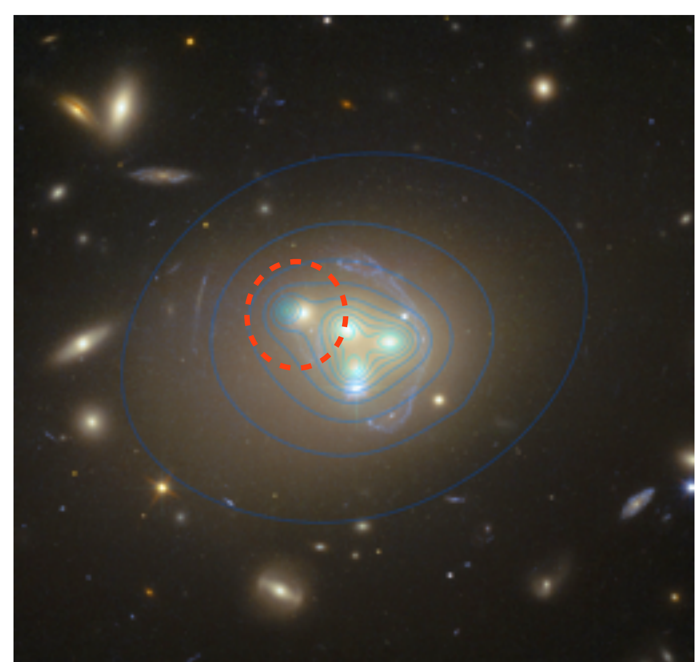
cf. WIMP DM: $\sigma_{\rm self}/m_{\rm WIMP} \sim 10^{-11}{\rm GeV}^{-3} \sim 10^{-14}{\rm cm}^2/g.$

- DM sub-halo lags, due to drag force (“long-range”) or large momentum transfer (“contact”).

Bounds (Bullet cluster)

$\sigma_{\rm self}/m_{\rm DM} < 1{\rm cm}^2/g$

Hints (Abell 3827: one DM sub-halo lags behind the galaxy.



off-set:
$\Delta = 1.62^{+0.47}_{-0.49}\ {\rm kpc}$

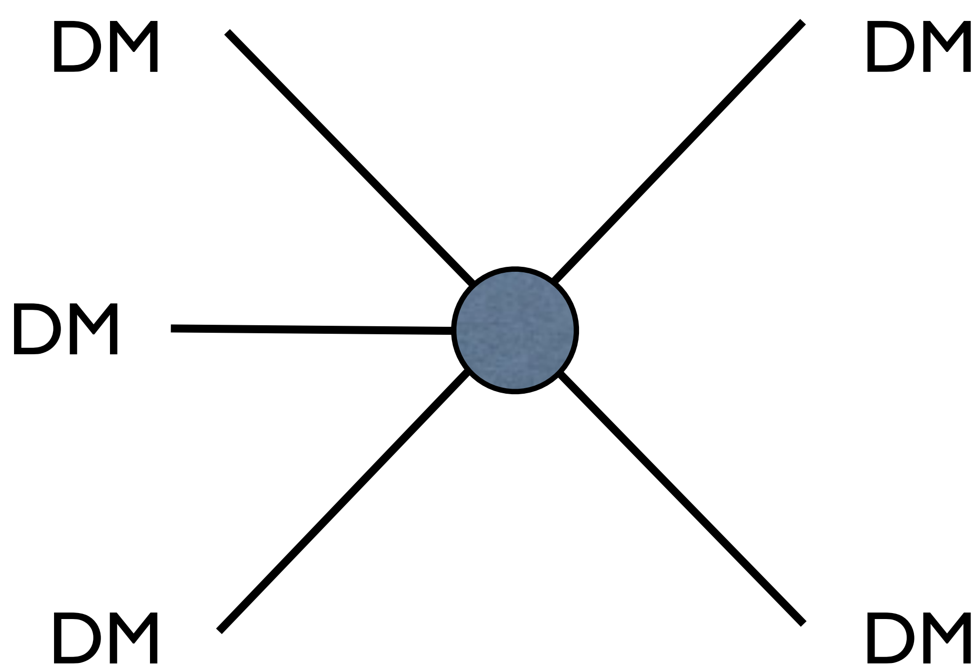
[Massey et al(2015)]

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

SIMP paradigm

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

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



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

Freeze-out of 3→2 process:

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

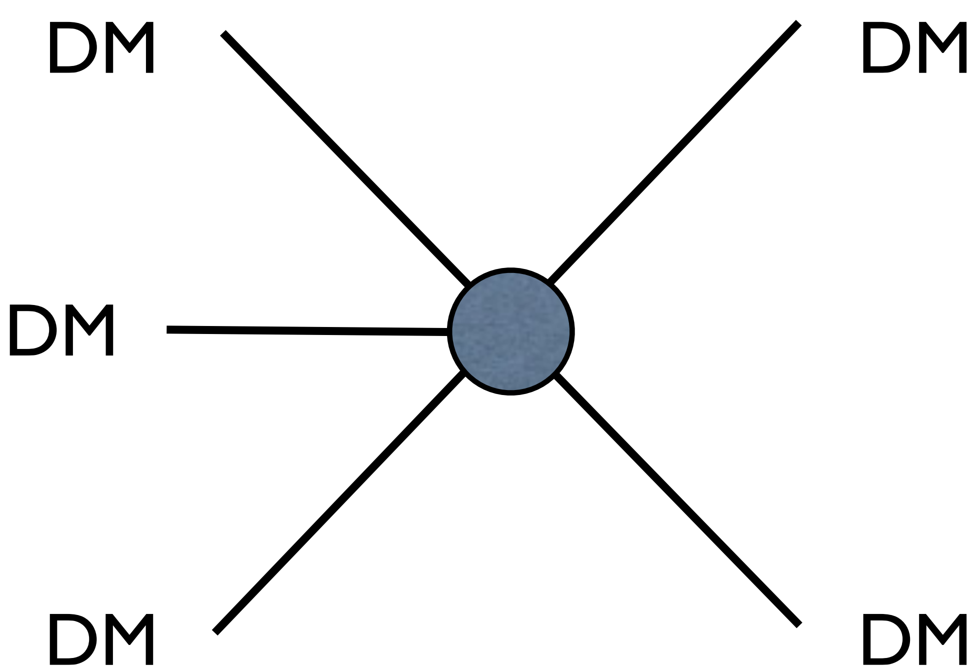
$$\langle\sigma v^2\rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

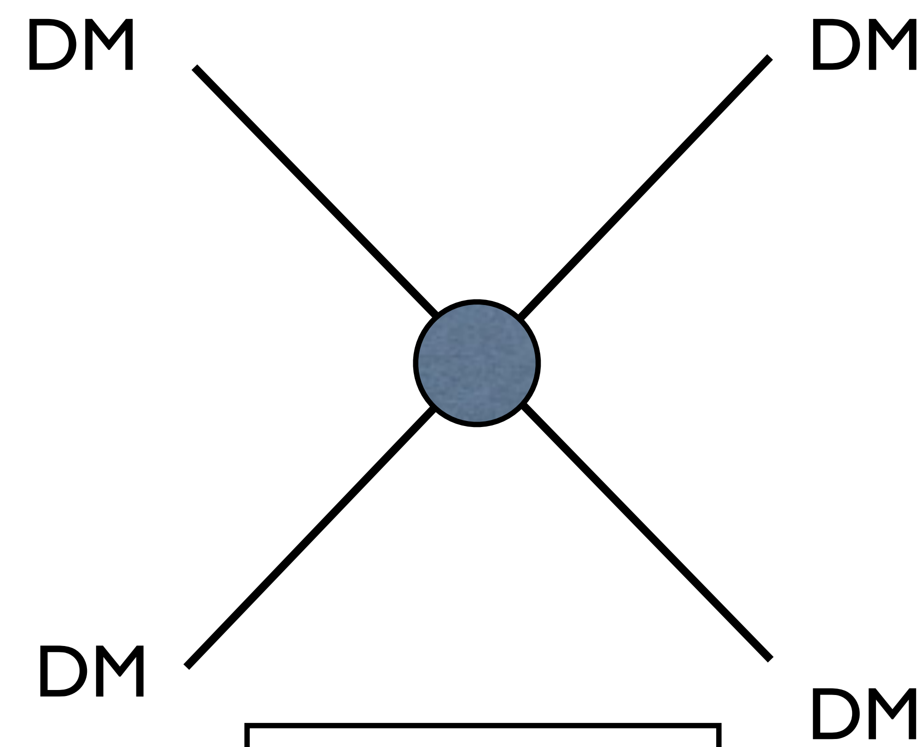
$$\Omega_{\rm DM}h^2 \sim 0.1 \left(\frac{9\times 10^{-10}{\rm GeV}^{-2}}{(g_*/10.45)^{3/4}\left(\frac{m_{\rm DM}^2}{M_P}\int_{x_F}^\infty x^{-5}\langle\sigma v^2\rangle dx\right)^{1/2}}\right)$$

$$\alpha_{\rm eff} = 1 - 30 \quad \Rightarrow \quad m_{\rm DM} = 40 - 1000\,{\rm MeV}$$

Large SIMP self-interaction

- SIMP DM predicts typically large self-interactions.





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

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

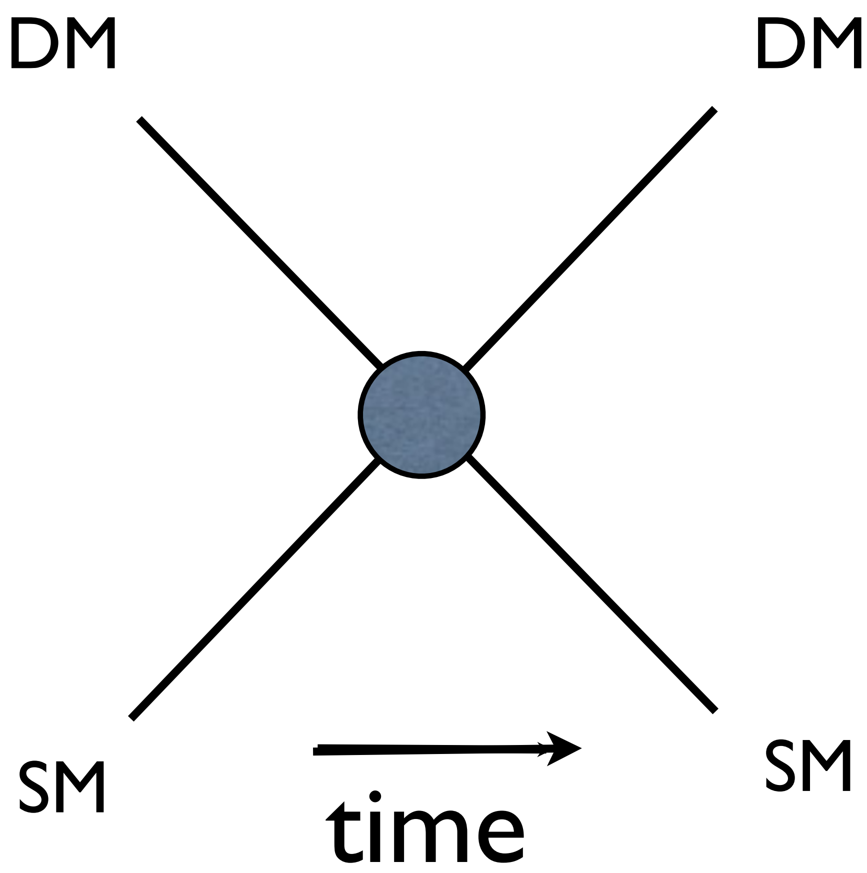
$$\Rightarrow \frac{\sigma_{\rm self}}{m_{\rm DM}} = 4\times 10^3\,{\rm GeV}^{-3}\left(\frac{100\,{\rm MeV}}{m_{\rm DM}}\right)^3\left(\frac{\alpha_{\rm eff}}{2}\right)^2 \simeq \left(\frac{5}{\alpha_{\rm eff}}\right) 1{\rm cm}^2/{\rm g}$$

relic density

Note: 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 - SM interactions



- SIMP in 3→2 process must be equilibrated for structure formation. [de Laix et al, 1995]

SIMP loses heat by kinetic scattering even with tiny interaction to SM bath:

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

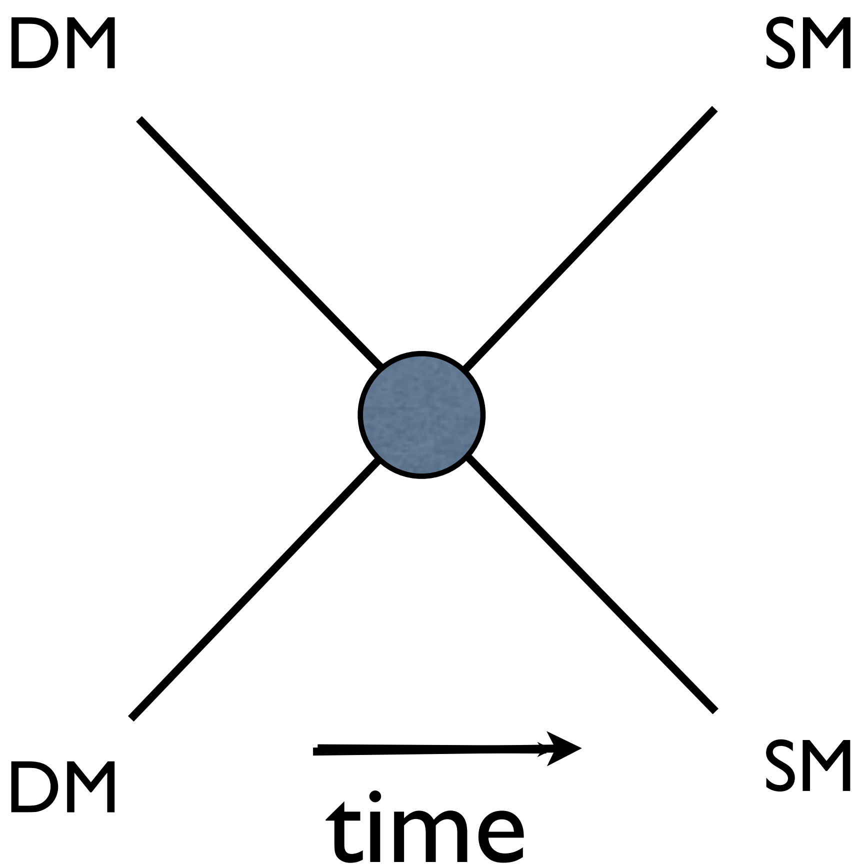
$$\boxed{\epsilon_1 \gtrsim 0.9 \times 10^{-9} \alpha_{\rm eff}^{1/2}}$$

- SIMP can be also thermalized by dark thermal bath.

But, dark temperature is an extra parameter!

cf. Higher-order SIMP (4→2) predicts lighter DM (sub-MeV) SIMP: necessary to introduce a small dark temperature 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

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

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

$$\xrightarrow[\epsilon_2 \sim \epsilon_1]{} \boxed{\epsilon_1 \lesssim 2.4 \times 10^{-6} \alpha_{\rm eff}}$$

- SIMP conditions:

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

lose heat! 3→2 wins!

SIMP from dark QCD

Dark QCD and dark matter

- Dark flavor symmetry G=SU(N_f)x SU(N_f) is broken down to H=SU(N_f) by SU(N_c) QCD-like condensation.

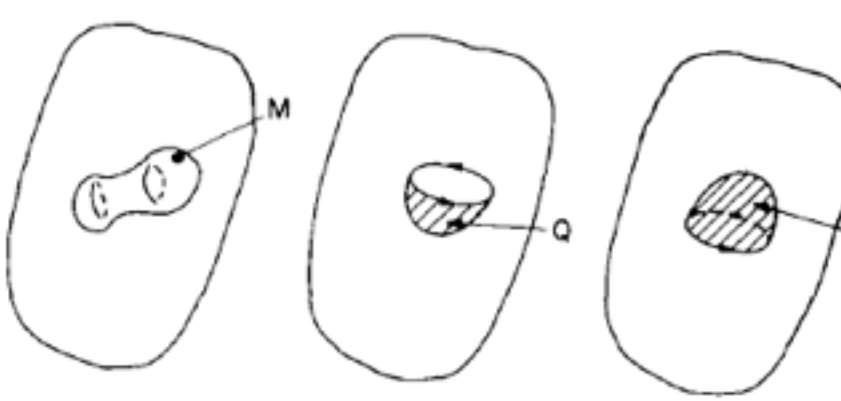
→ Dark mesons are naturally light and stable due to flavor symmetry.

- Effective action for dark mesons contains a 5-point self-interaction from Wess-Zumino-Witten term for π_5(G/H)=Z (i.e. $N_f \geq 3$). [Wess, Zumino, 1971; Witten, 1983]

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

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

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

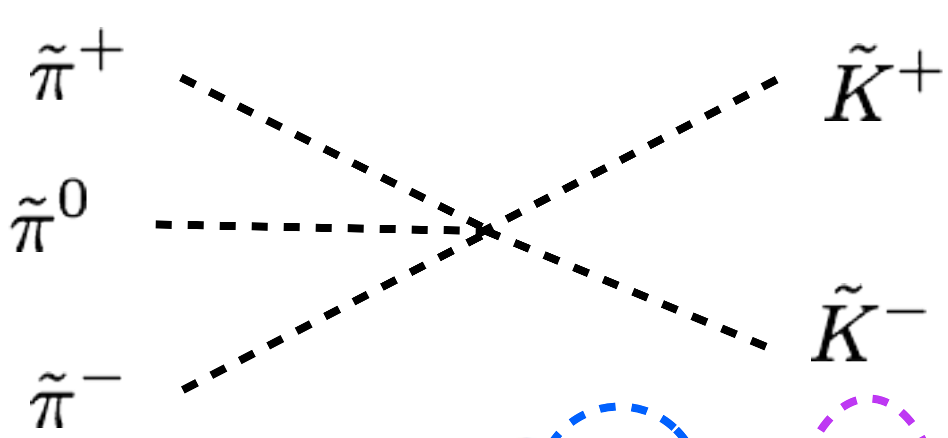


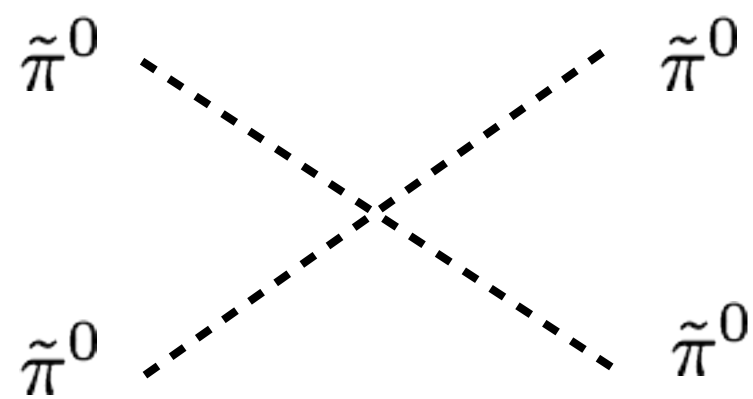
N_C : topological invariant of 5-sphere (Q+Q') in SU(3)

SIMP from WZW

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

[Hochberg et al, 2014]





~const

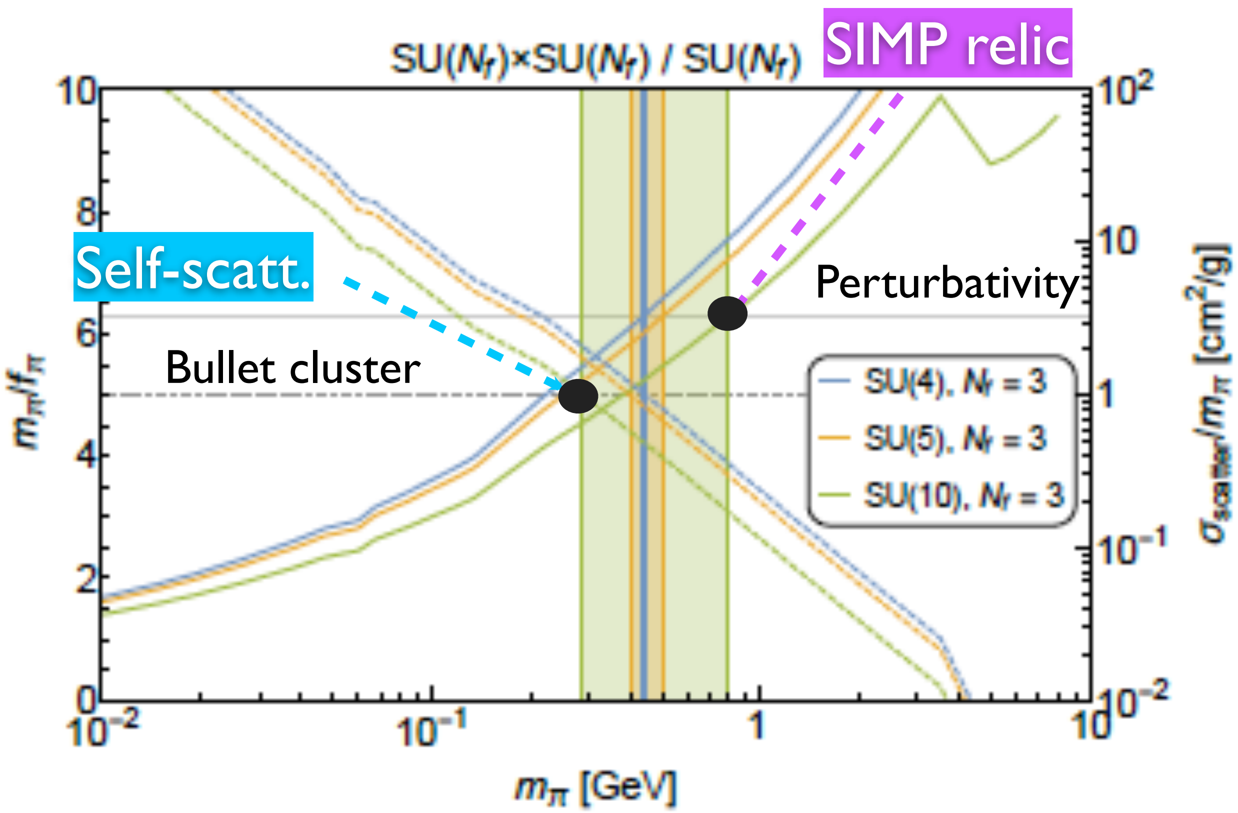
$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{5\sqrt{5} N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2,$$

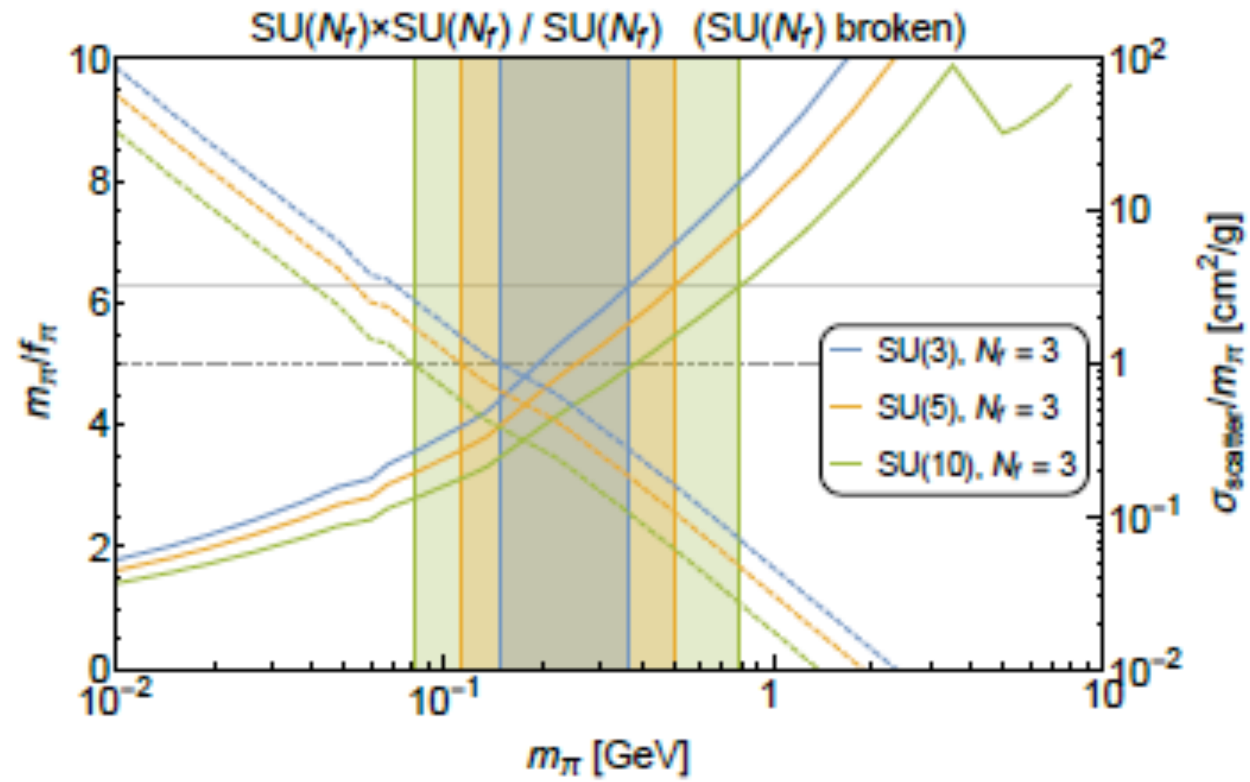
~const

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

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

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 $SU(2N_f)/Sp(2N_f)$.

WZW with Z'

- Introduce a massive Z' under which dark quarks are vector-like and SM particles are neutral.
- Modified WZW with U(1)': [Witten, 1983]

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

Noether current:

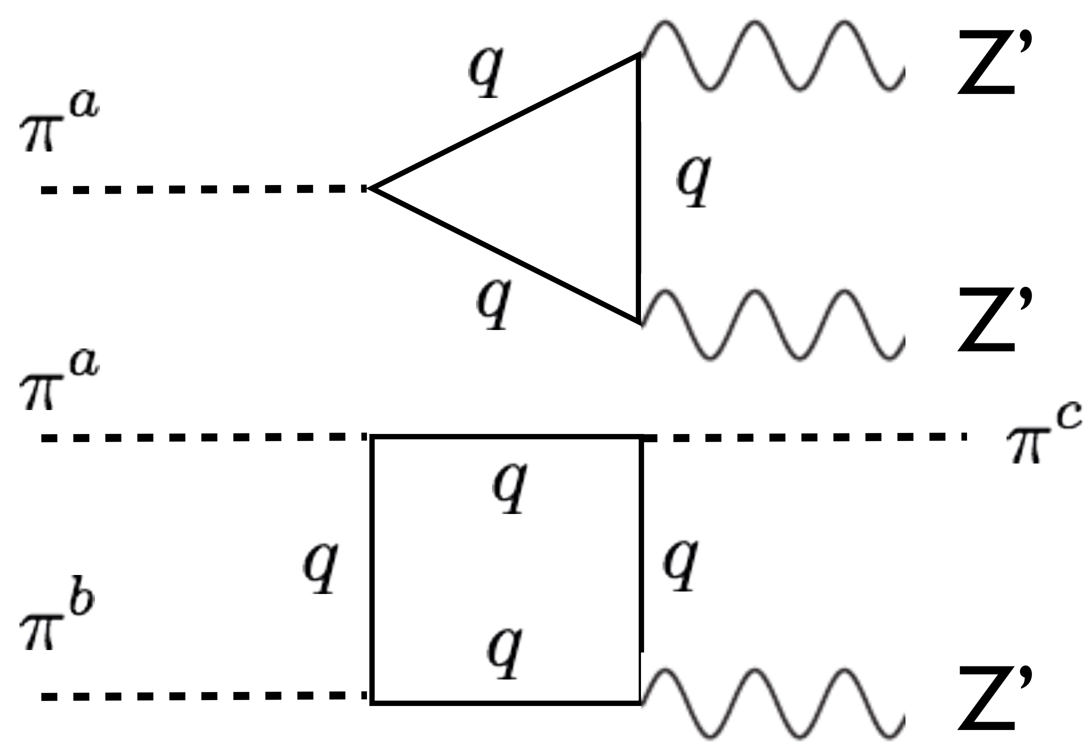
$$
\begin{aligned} J^\mu = \frac{1}{48\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[& Q\partial_\nu U U^{-1}\partial_\rho U U^{-1}\partial_\sigma U U^{-1} \\ &+ QU^{-1}\partial_\nu U U^{-1}\partial_\rho U U^{-1}\partial_\sigma U] \end{aligned}
$$

AVV anomalies.

Meson decay

AAAV anomalies.

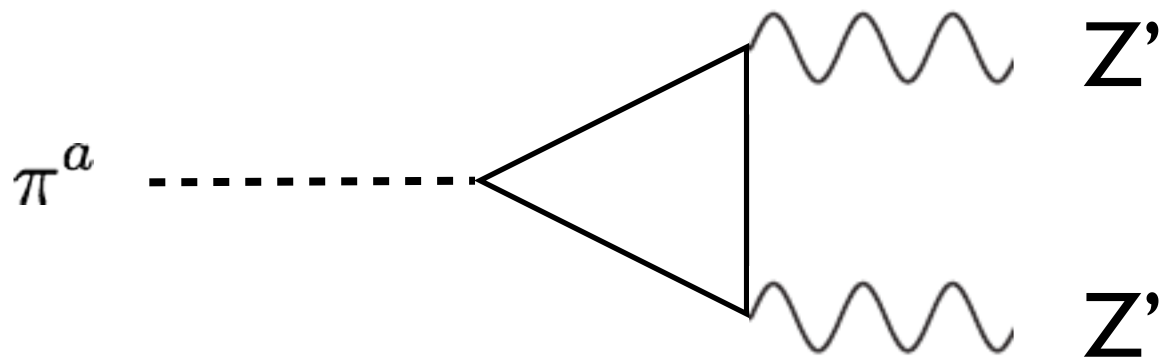
2→2 ann



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 $\quad Q_D^2 = I.$

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

: flavor non-universal charges

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

$D_\mu U = \partial_\mu U + i g_D [Q_D, U] Z'_\mu;\quad \tilde{\pi}^\pm, \tilde{K}^\pm$: ±2/3 charges.

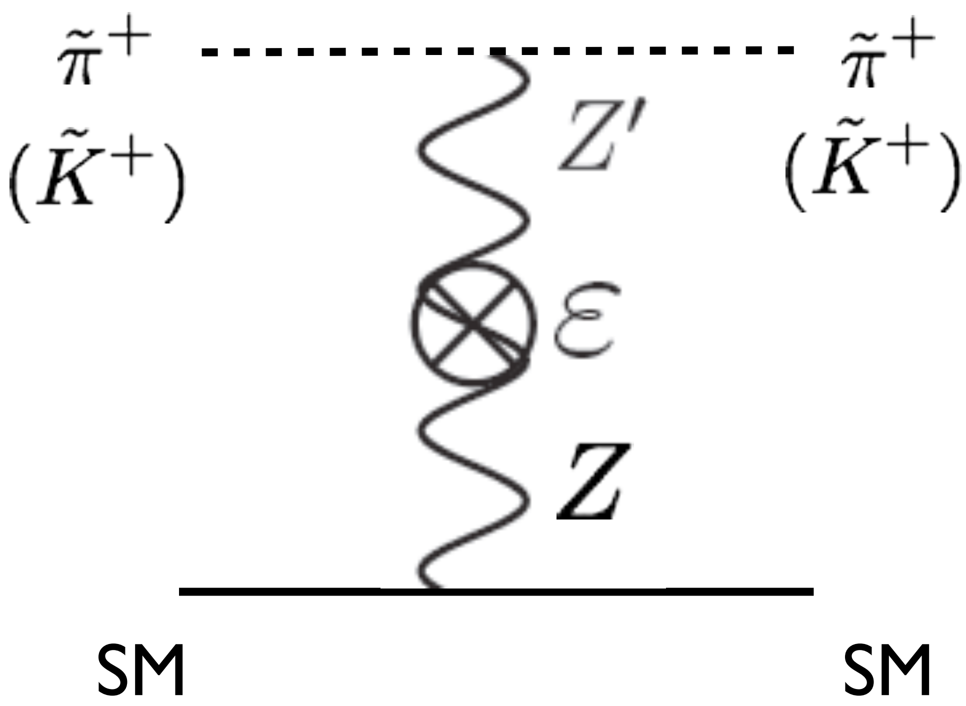
- Mass splitting generated by non-universal charges is constrained for SIMP annihilation:

$$\Delta m_\pi^2 \sim \frac{\alpha_D \Lambda^4}{F^2} \sim \alpha_D F^2 \lesssim \frac{m_\pi^2}{x_F^2} : \quad \alpha_D \lesssim 0.01 \left(\frac{m_\pi}{F}\right)^2.$$

Equilibrium via Z'-portal

[HML, Seo, 2015]

- Dark meson in kinetic equilibrium with the SM by kinetic mixing between Z' & hypercharge.



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

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

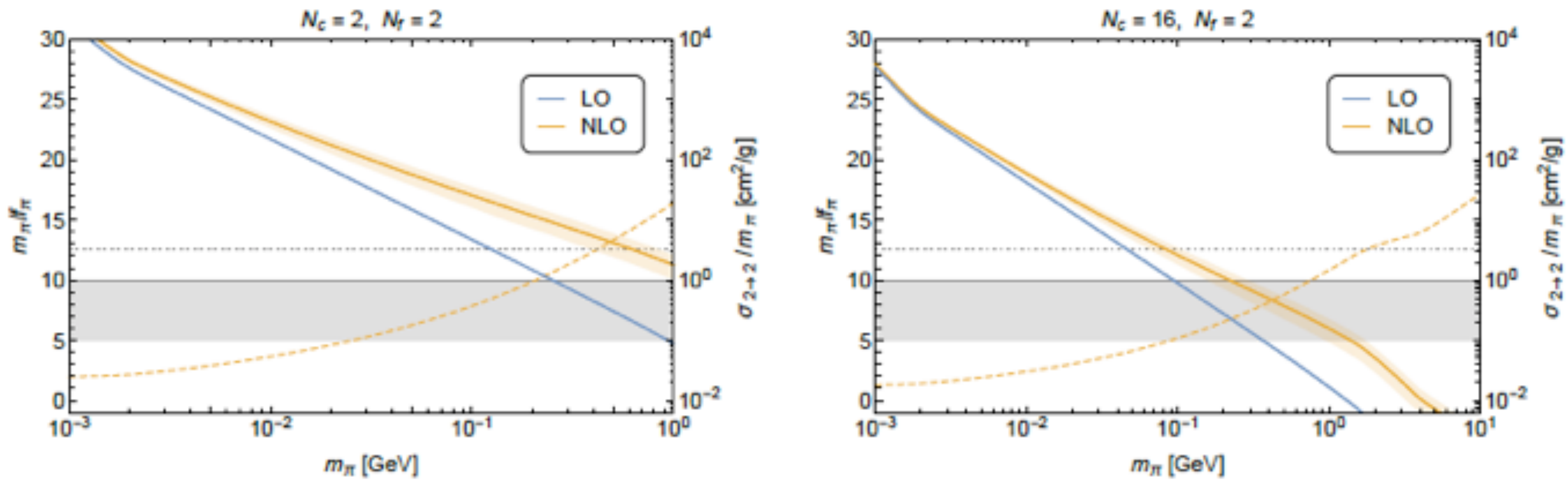
cf. Higgs-portal does not work, because leptons in thermal bath have small Yukawa couplings.

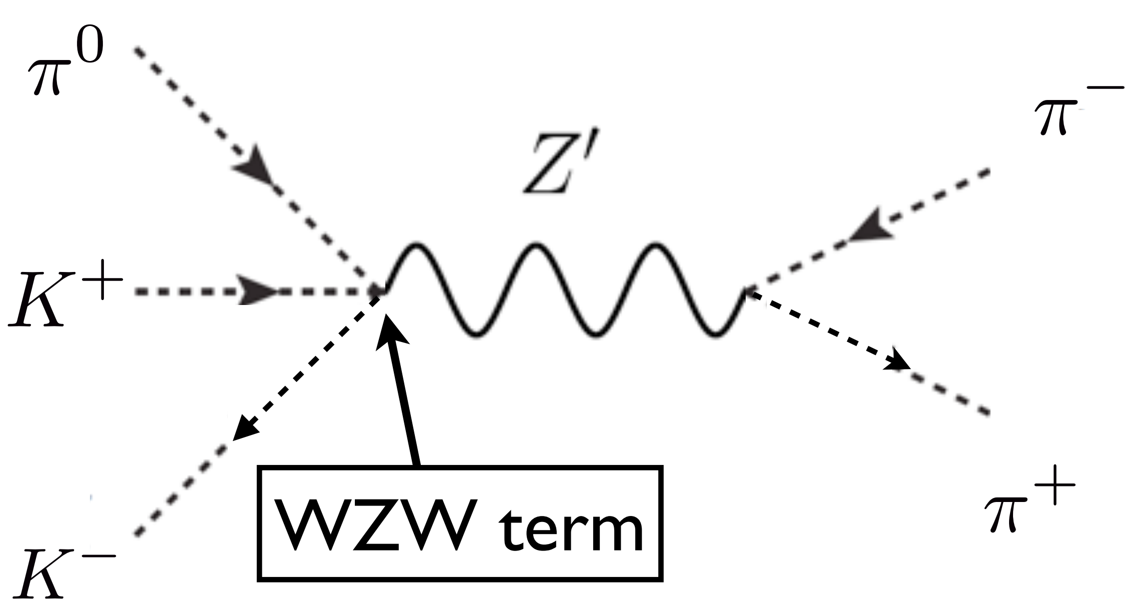
- $\pi\,\pi \rightarrow \pi Z'$ (AAAV) is forbidden for $m_{Z'} > m_\pi$; suppressed $2\rightarrow 2$ annihilation via Z'-portal.

$\Rightarrow$ $3\rightarrow 2$ dominance: SIMP conditions

Meet Unitarity

Too large 2→2 self-scattering at NLO. [Hansen et al (2015)]



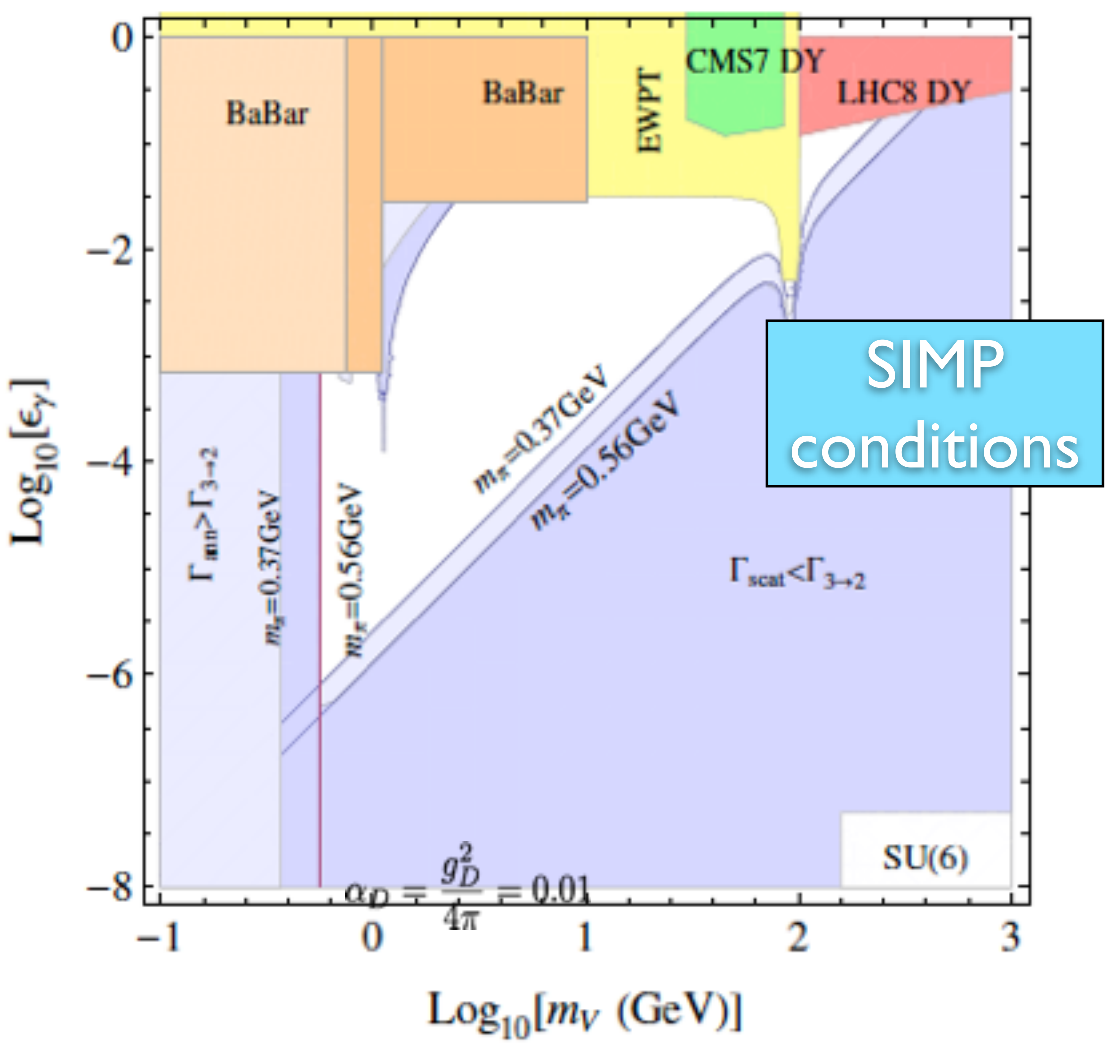


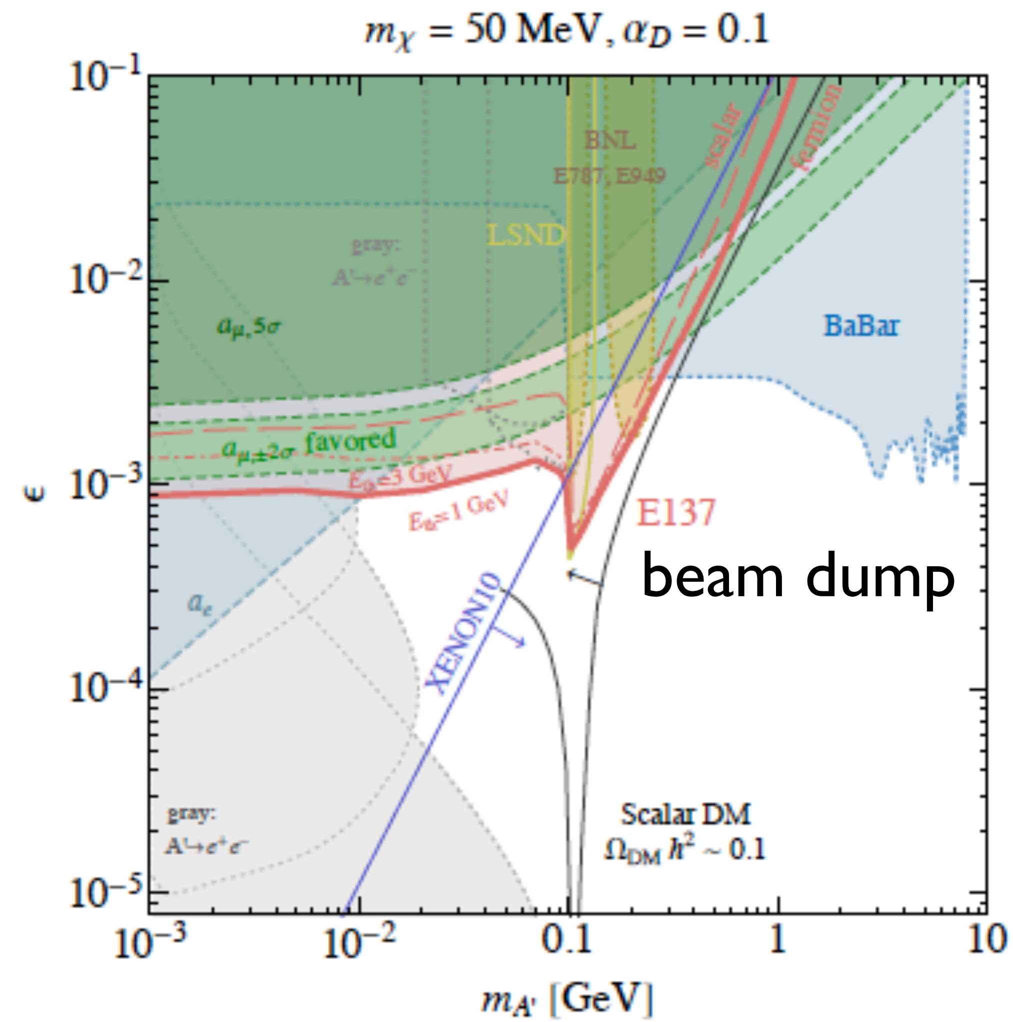
Enhanced 3→2 annihilation near Z' resonance with gauged WZW, but there is no enhancement for 2→2.

[HML, Seo, In Progress]

$$\langle \sigma v^2 \rangle \sim \frac{\alpha_D^2 N_c^2 m_\pi^5}{F^6} \frac{1}{(9m_\pi^2 - m_{Z'}^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2} \left(\frac{T}{m_\pi}\right)^2$$

Collider searches





[Batell et al, 2014]

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

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

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

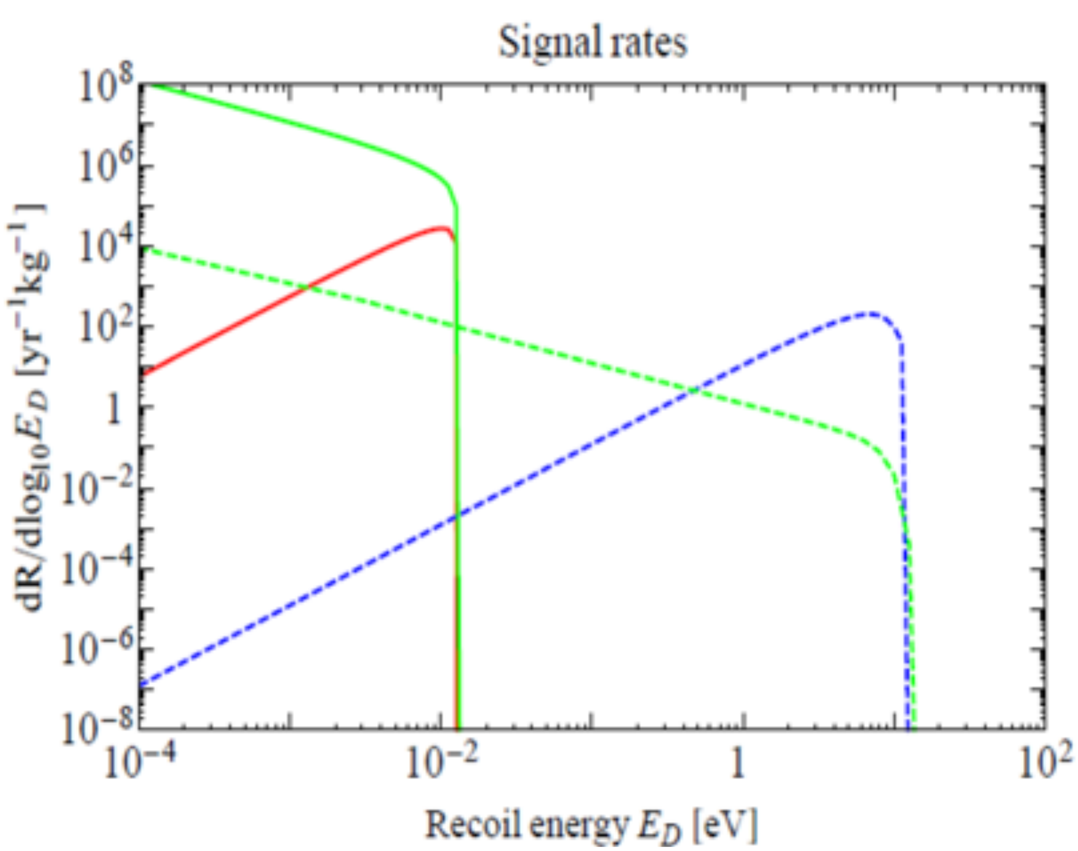
Direct detection

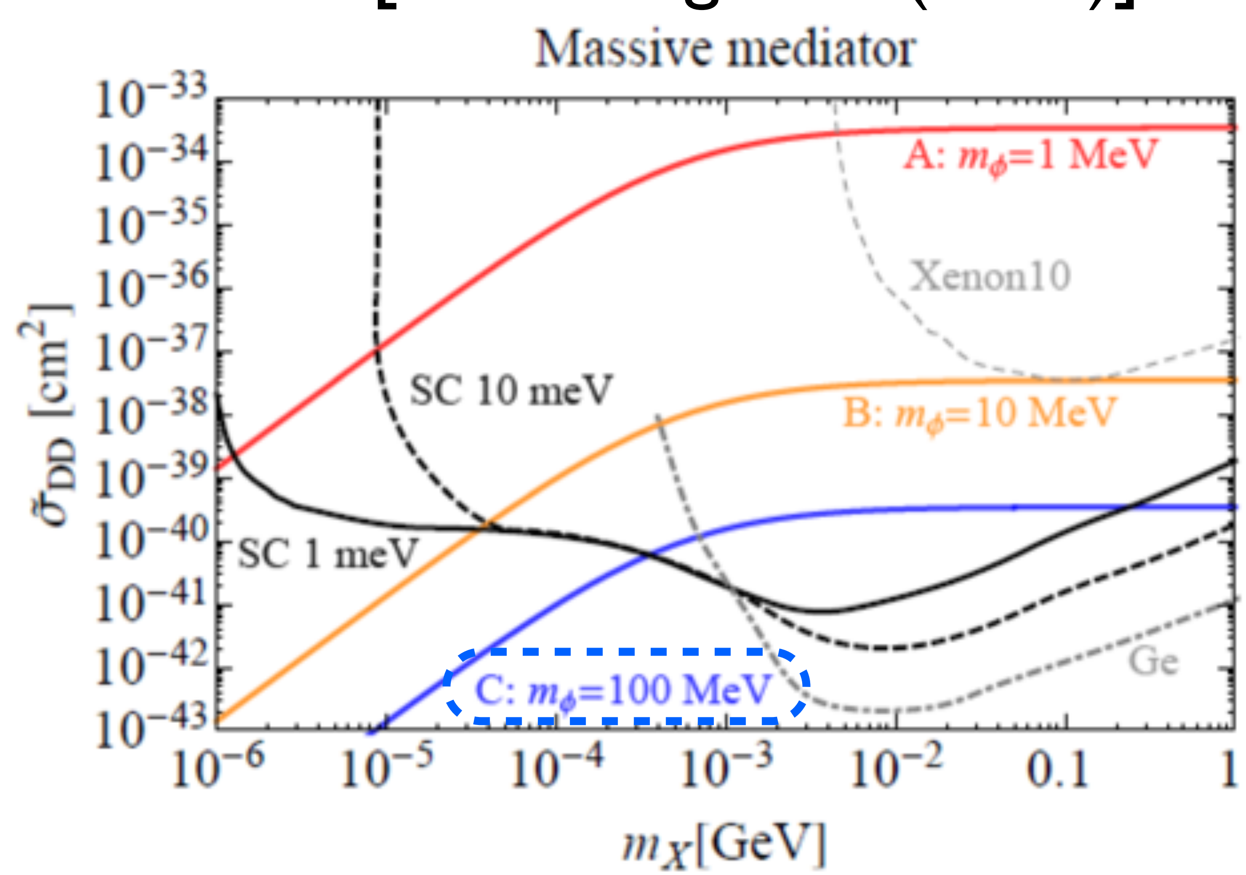
- SIMP dark mesons scatters off electrons, with small threshold for recoil energy: $\left(E = \frac{q^2}{2m_e} \lesssim 20\,\mathrm{eV}. \right)$

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

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

[Hochberg et al (2015)]

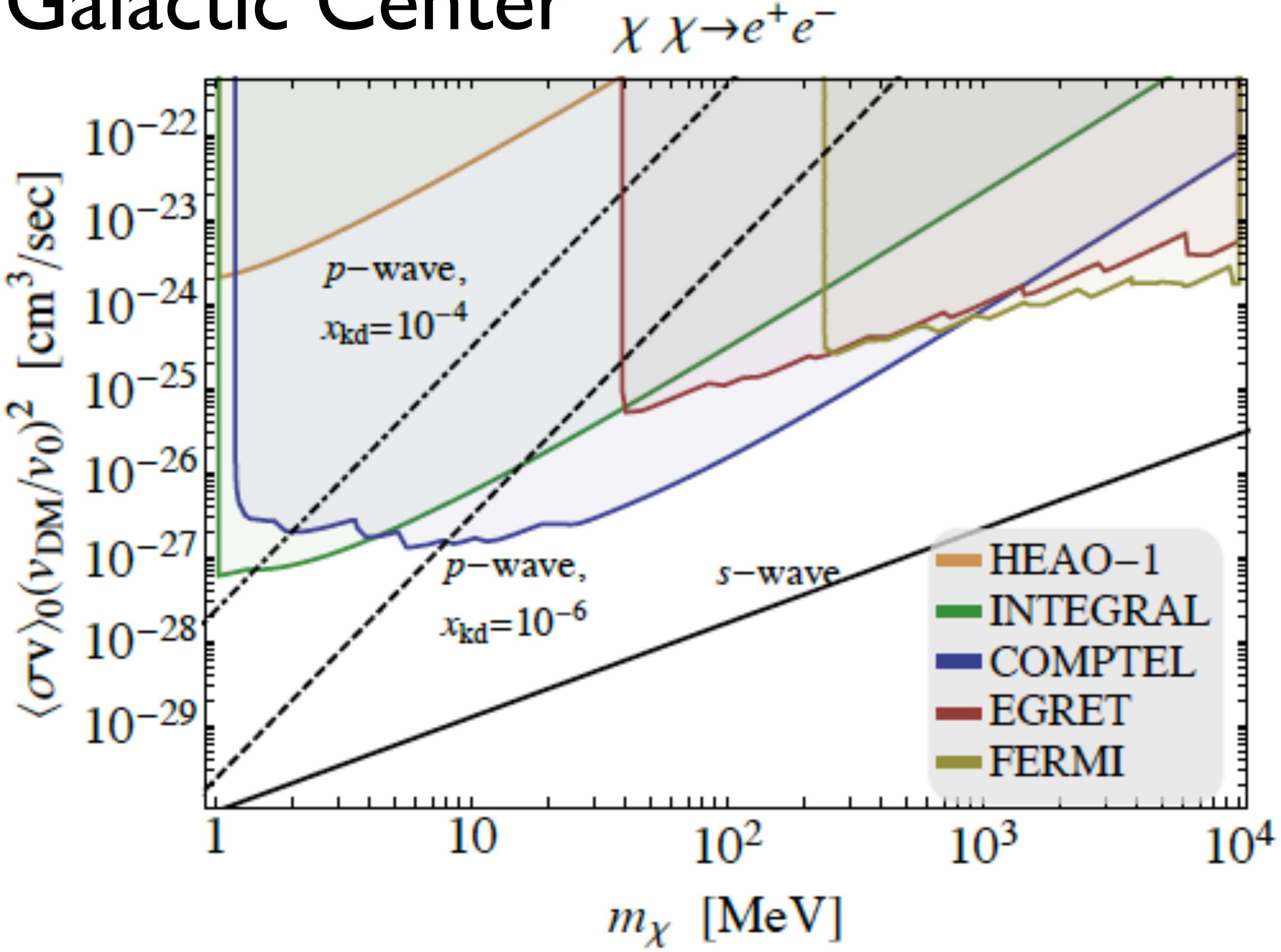




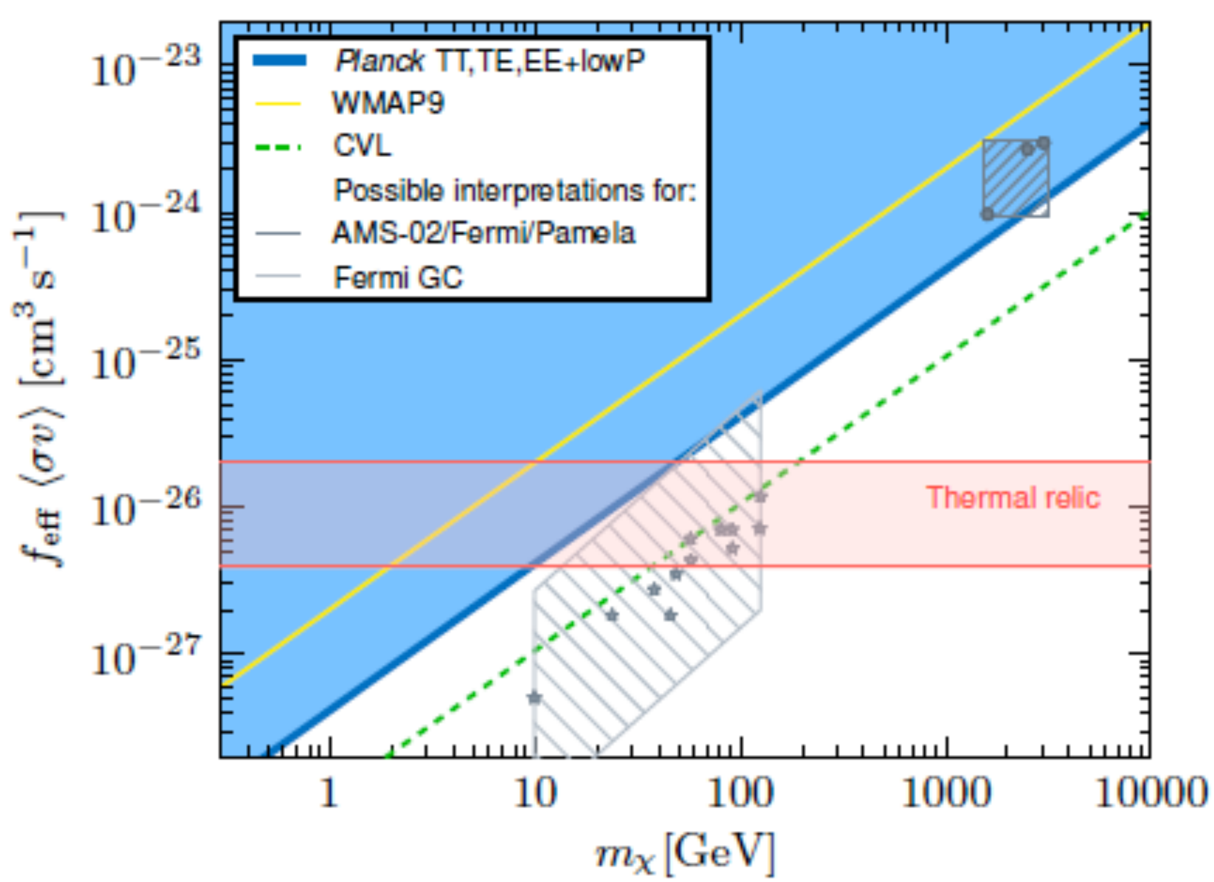
Blue: $(m_\phi, m_X, \alpha_X, g_e) = (100\ \mathrm{MeV}, 100\ \mathrm{MeV}, 0.1, 3\times 10^{-5})$

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).

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

SIMP with discrete symmetries

DM stability

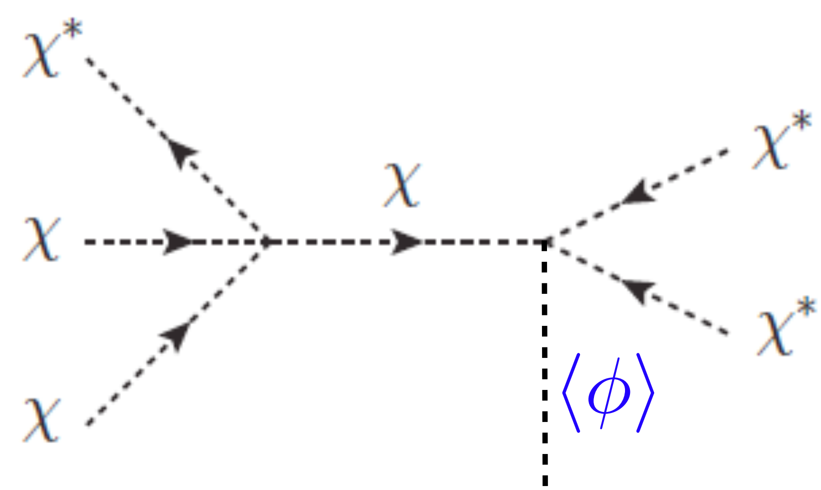
[S.-M.Choi, HML, 2015]

- Fundamental stable particle for SIMP?
- Z_3 is the minimal discrete symmetry consistent with SIMP, which is 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.

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



Z_3 Model

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

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

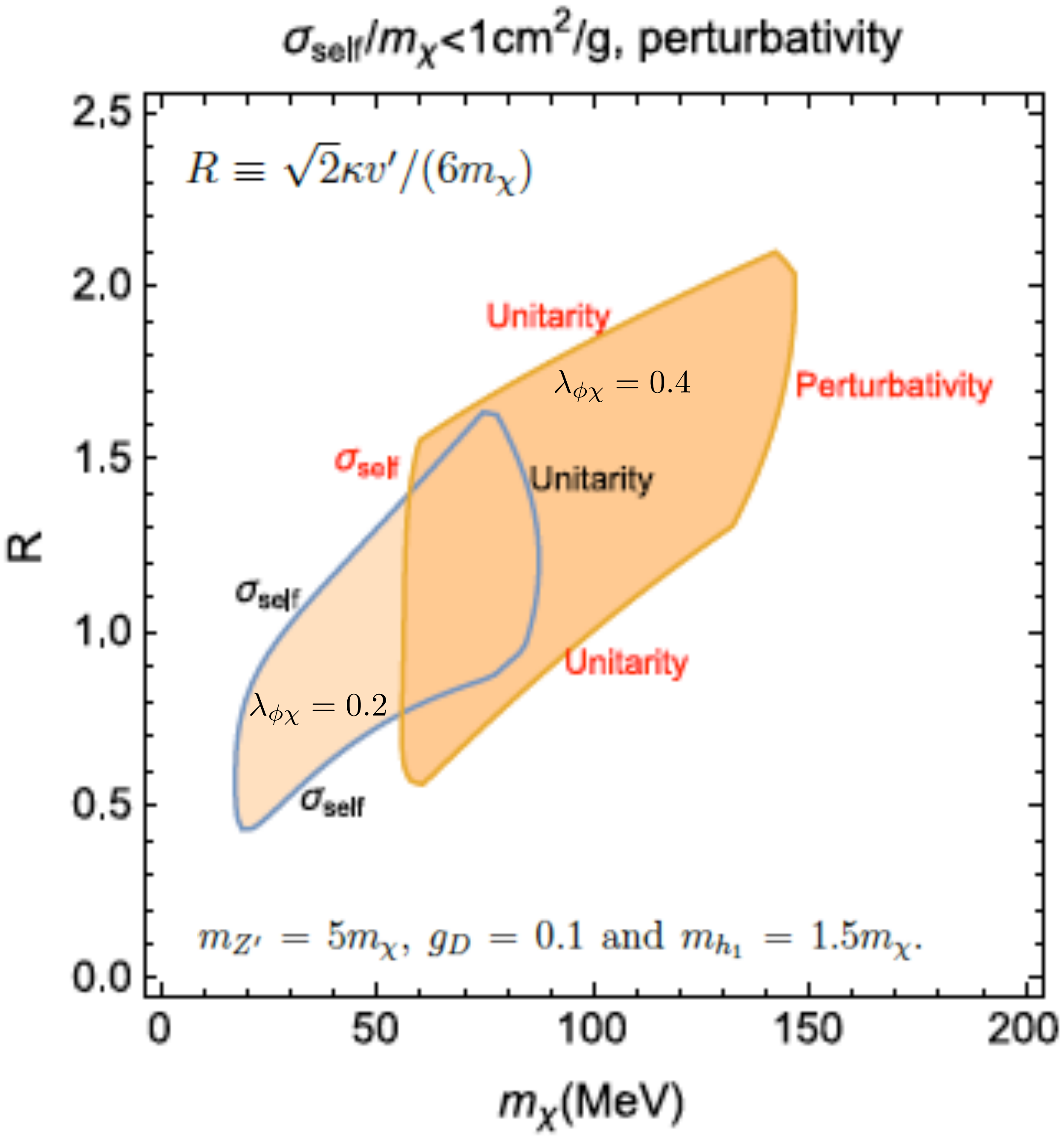
$$D_\mu\chi = (\partial_\mu - i q_\chi g_D V_\mu)\chi$$

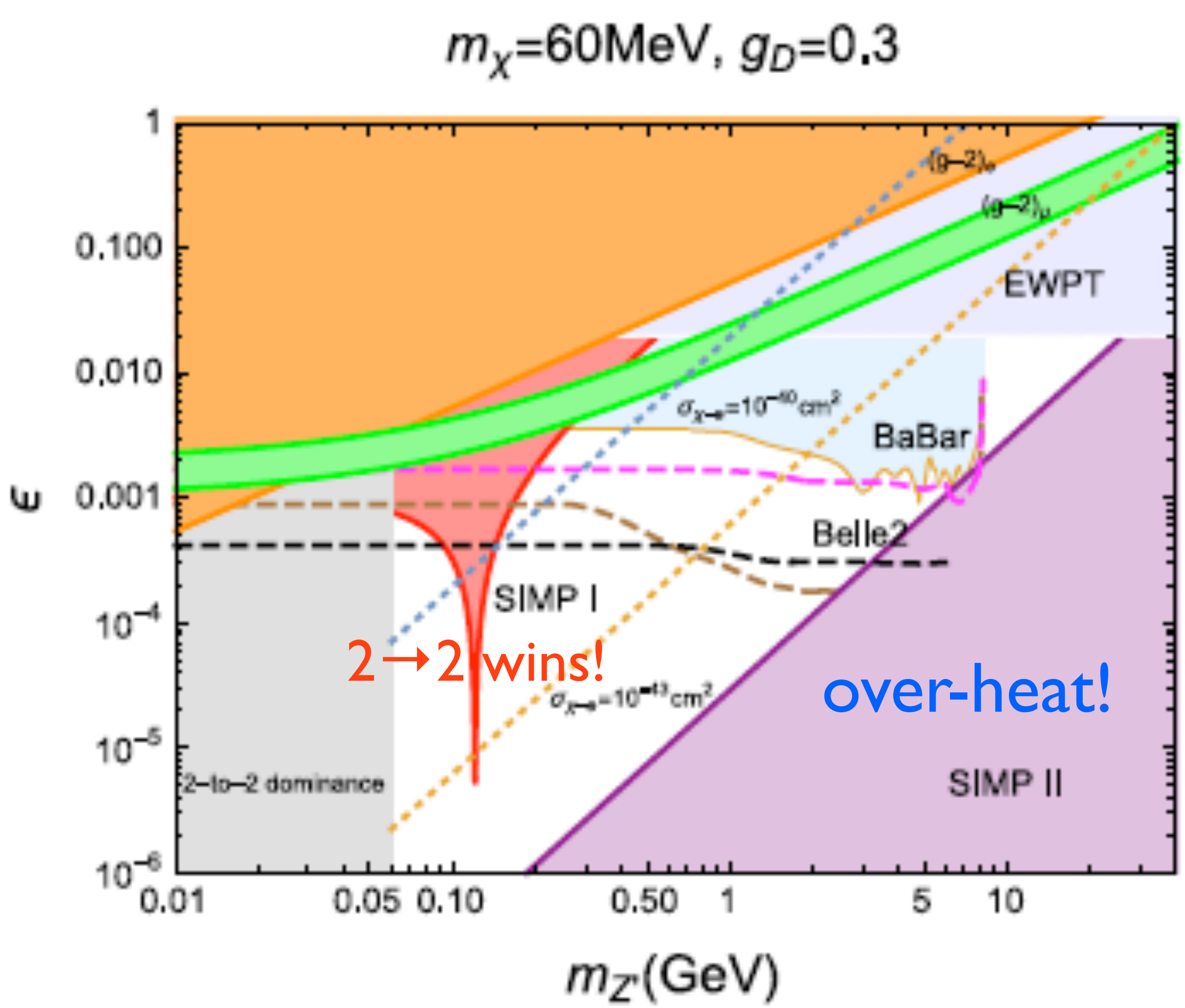
$$V(\phi,\chi,H) = V_{\rm DM} + V_{\rm SM} \text{ with}$$

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

cubic coupling for broken U(1)

SIMP parameter space





Bullet cluster bound, perturbativity imposed.

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

Z_5 model

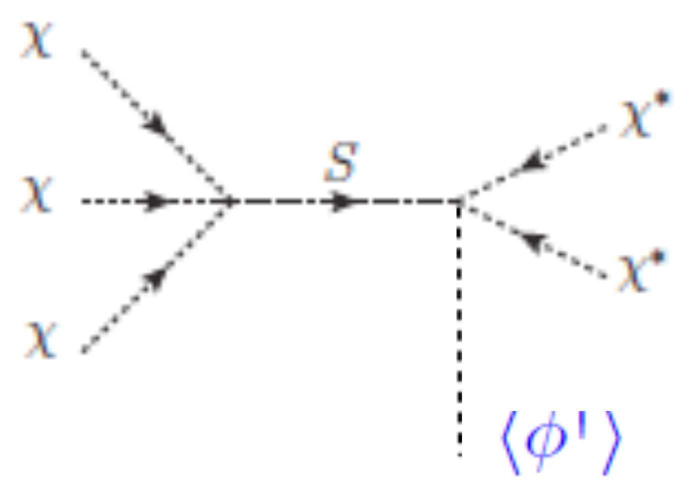
[S.M.Choi, HML, 2016]

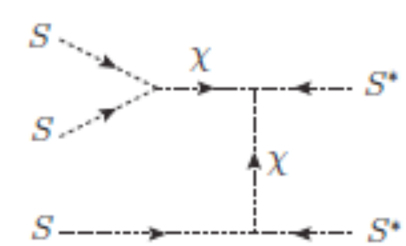
Z_5 is a natural symmetry for 5-point interaction, which requires an extra heavy field.

	ϕ	χ	S
$U(1)_V$	$+5$	$+1$	$+3$

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

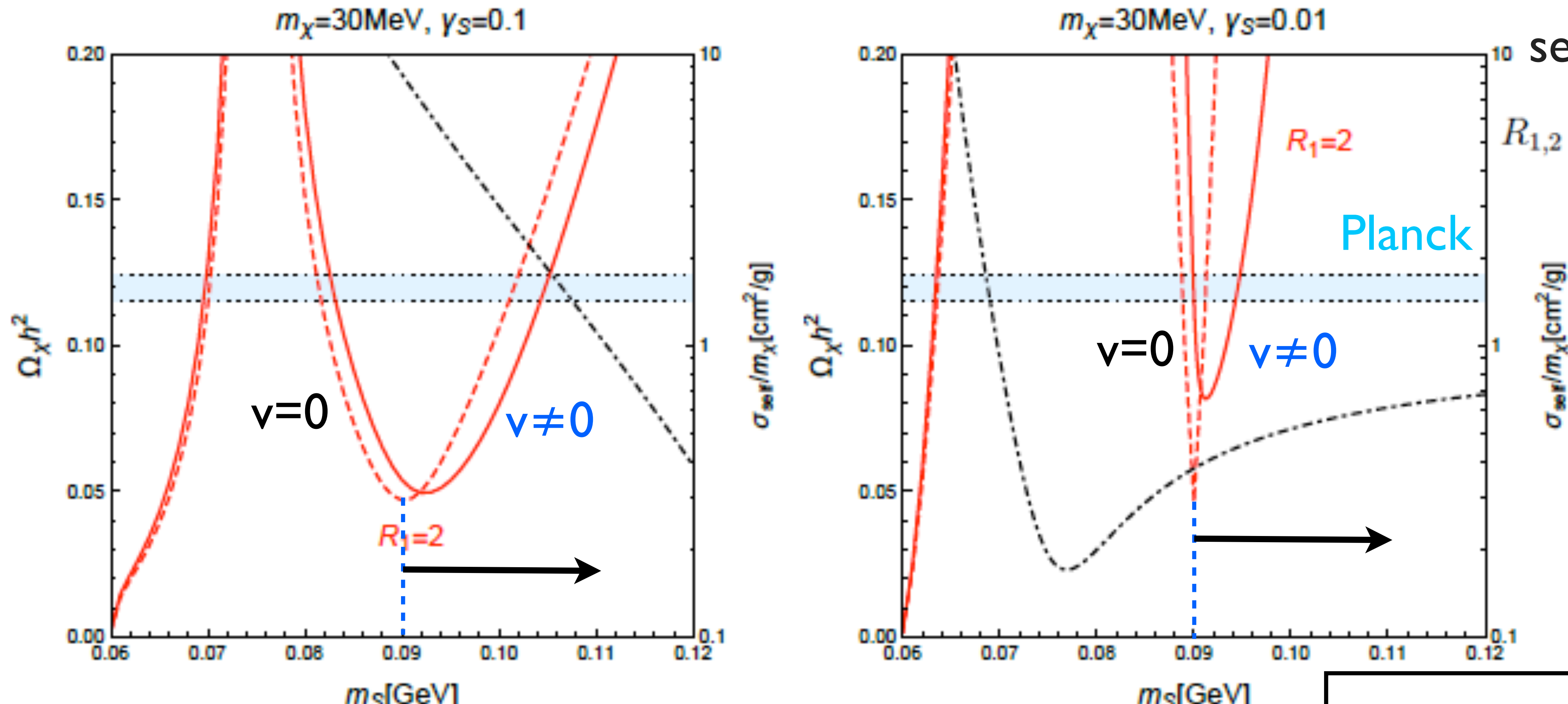
$$\mathcal{L}_{\rm int} \supset \frac{1}{\sqrt{2}}\lambda_1 \phi^\dagger S^2 \chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2 \phi^\dagger S \chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$





- 3→2 annihilation can be enhanced near resonance.
- Z' again makes SIMP DM in kinetic equilibrium.

SIMP Resonance



self-scattering

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

$\lambda_3 = 0$

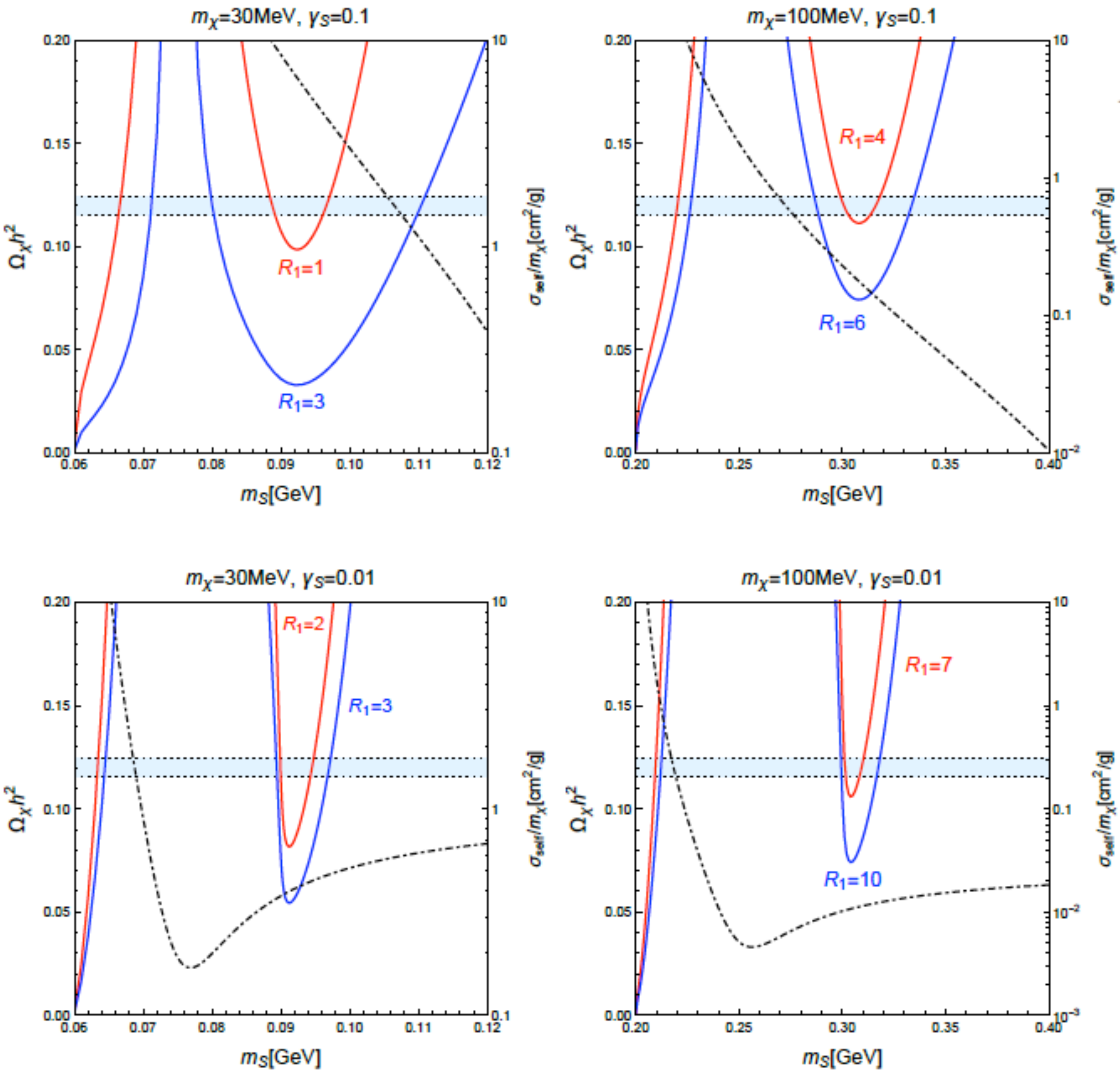
resonance effects important!

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

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

narrow width: $\gamma_S \ll 1$ $\Rightarrow$ $\langle (\sigma v^2)_\chi \rangle \approx \frac{2c_\chi}{m_\chi^5} x^{3/2} \sqrt{\pi} \gamma_S \epsilon_S^{1/2} e^{-x\epsilon_S} \theta(\epsilon_S)$

Resonance-enhanced due to nonzero velocity above threshold. $\Rightarrow$ Allows for small coupling!

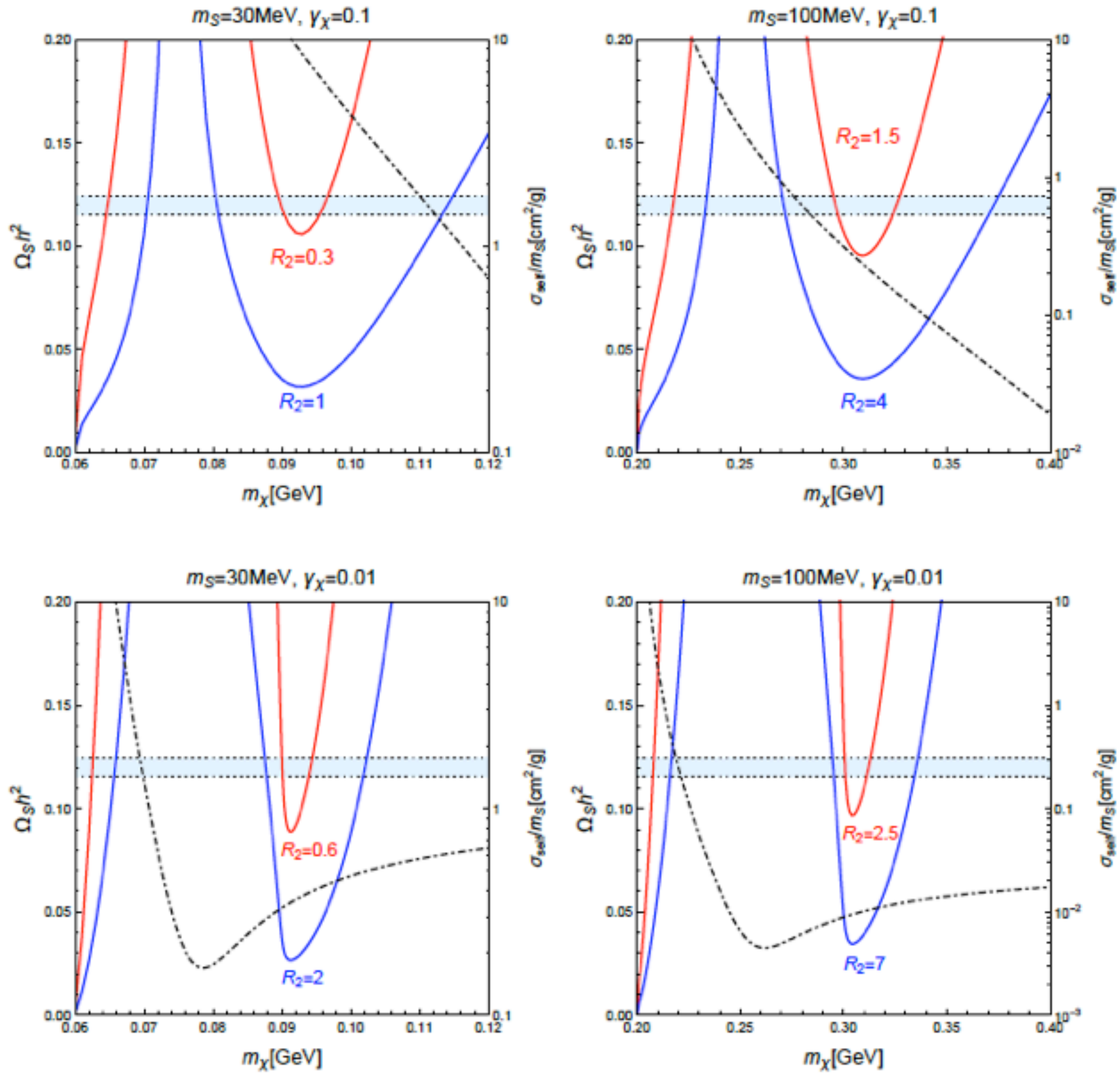


$$R_{1,2} \equiv \lambda_{1,2} v' / (\sqrt{2} m_\chi)$$

$$\lambda_3 = 0$$

self-scattering: $m_V = 500\,\mathrm{MeV},\ g_D = 0.1$ and $\lambda_S = 1$

S SIMP case



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

self-scattering: $m_V = 500\,\mathrm{MeV},\ g_D = 0.1$ and $\lambda_S = 1$

Conclusions

- SIMP is a new thermal dark matter with sub-GeV mass, which would require different strategies for direct detection.
- Generalized WZW term with vector-like dark U(1) makes dark mesons consistent SIMP.
- SIMP with discrete symmetries has built-in mechanisms for stabilization and kinetic equilibrium.
- Bounds on self-interaction bounds can be avoided near resonance for $3\to 2$ annihilation.
- SIMP dark matter is testable via self-interactions, mediator particle, and DM elastic scattering, etc.