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Cosmic abundances of SIMP dark matter

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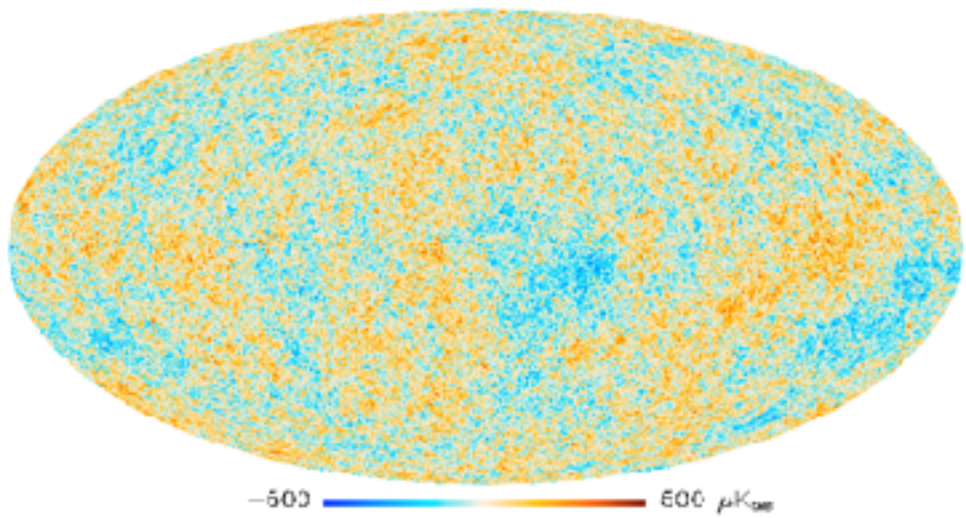
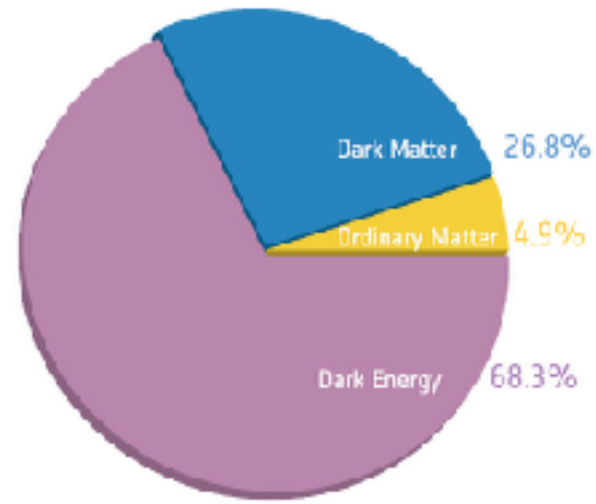
Outline

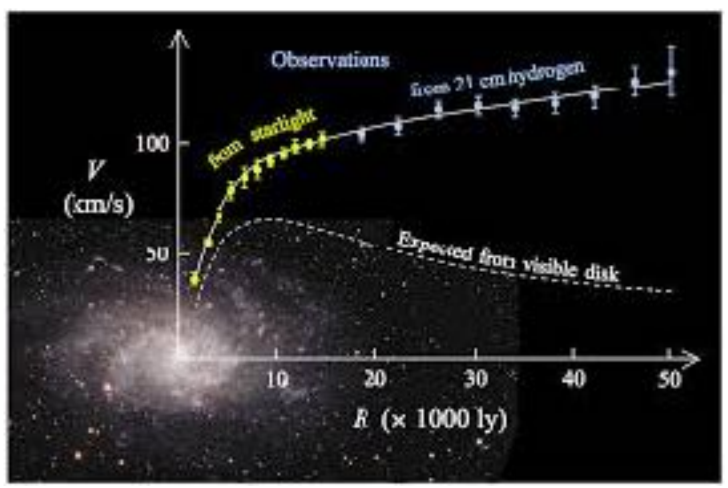
- Motivation
- SIMP paradigm & production
- Models for SIMP dark matter
- Conclusions

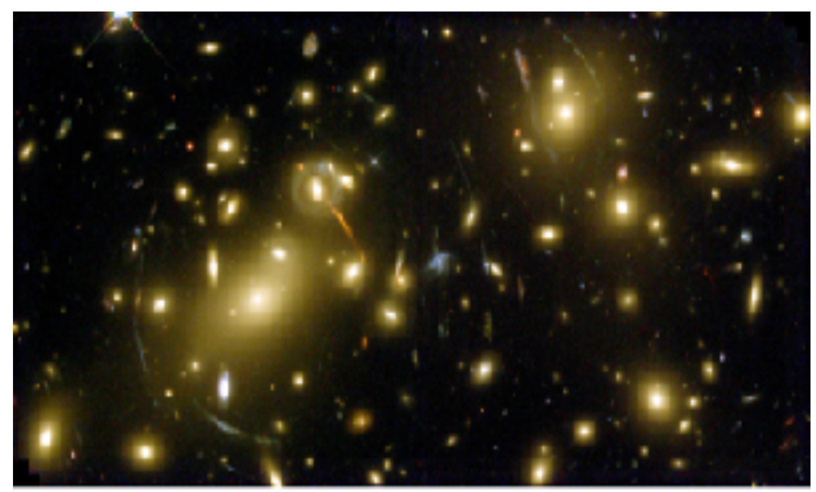
Motivation

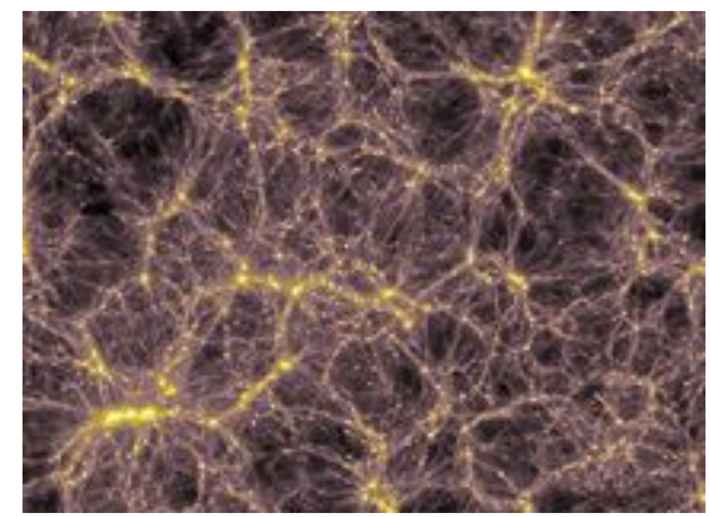
Dark matter from sky









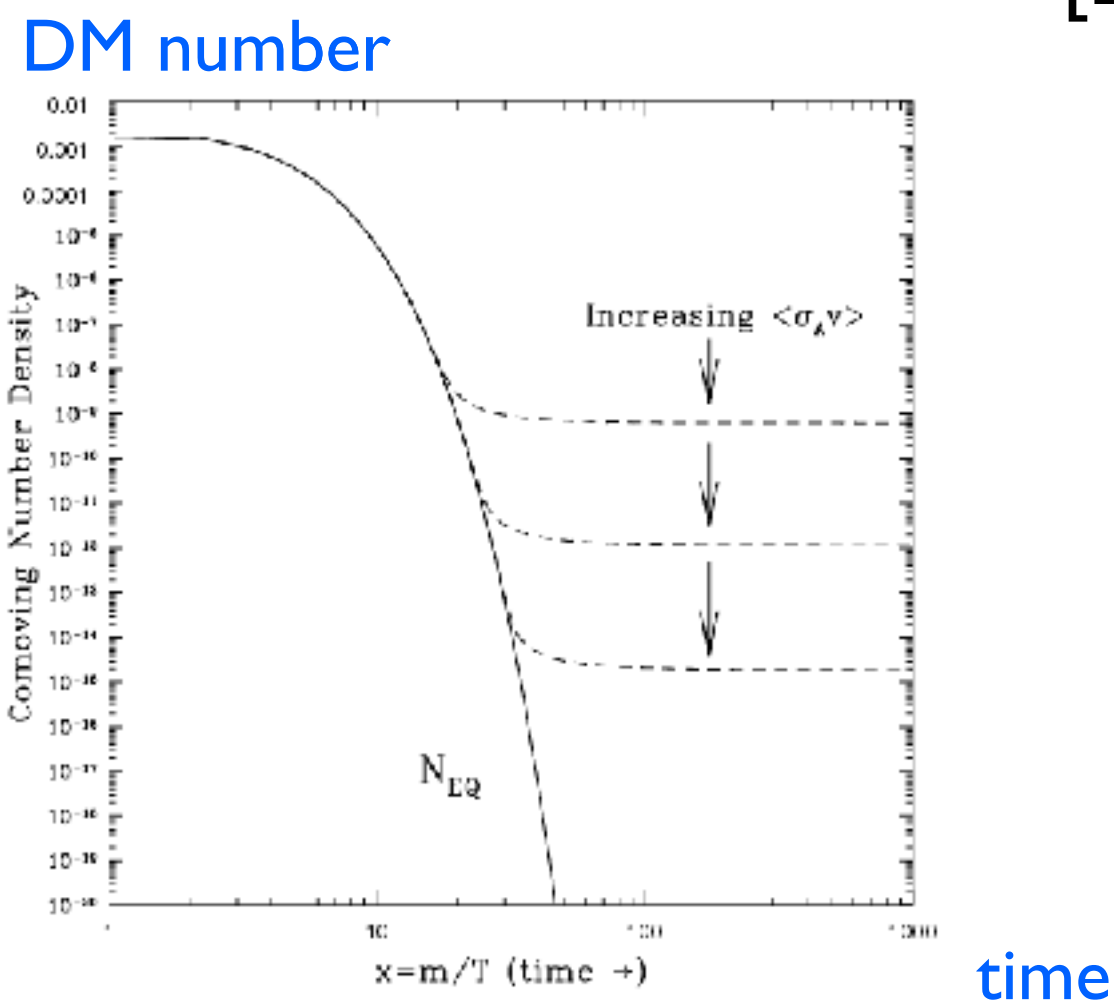


- Various evidences from galaxy rotation curves, CMB, and gravitational lensing, and large scale structure.

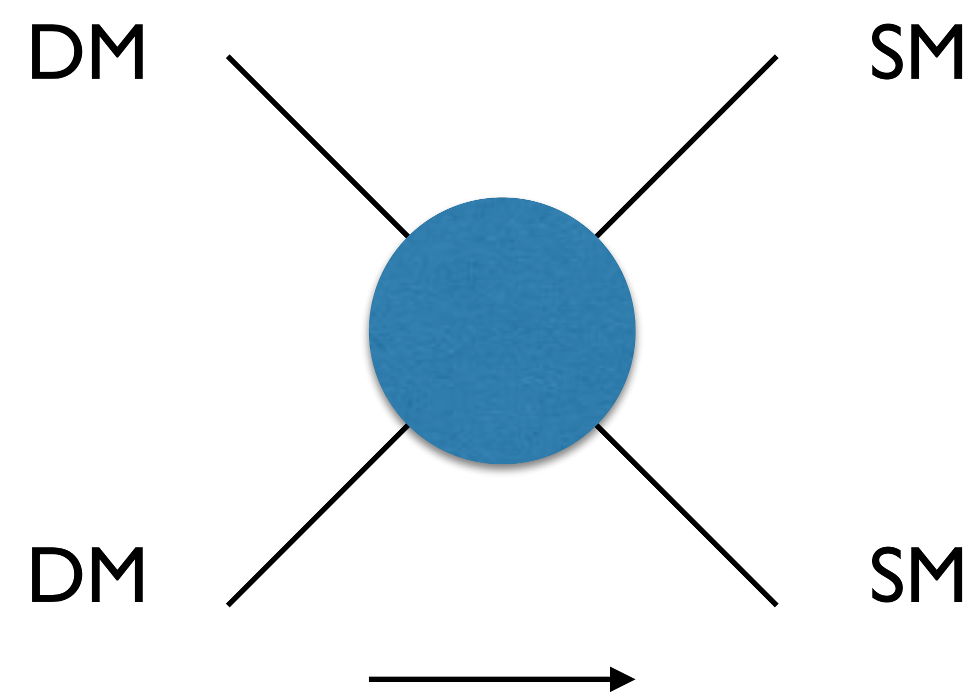
But, we don't know the origin of dark matter.

WIMP Paradigm

[Lee, Weinberg(1977)]



Dark matter once in thermal equilibrium with SM particles

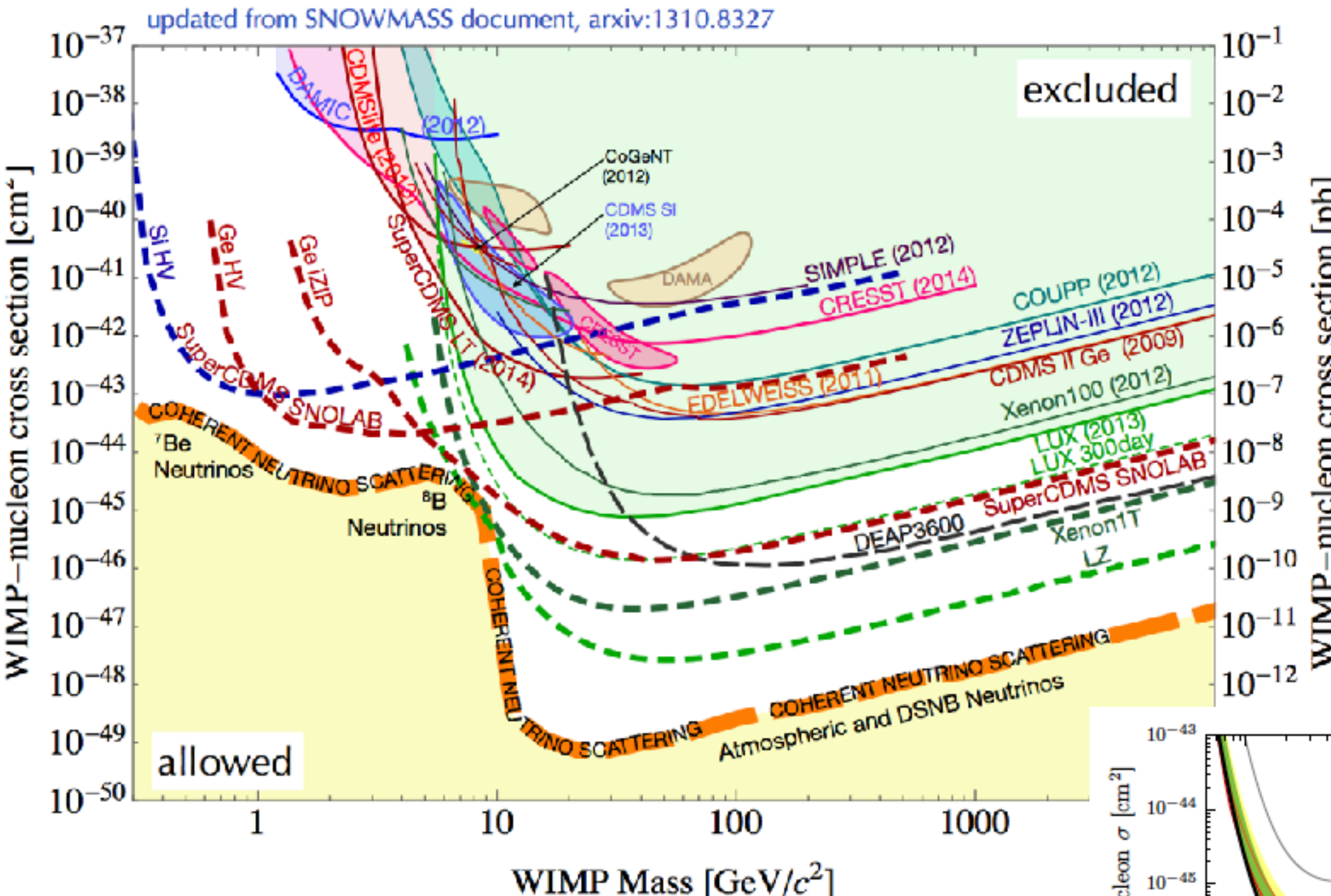


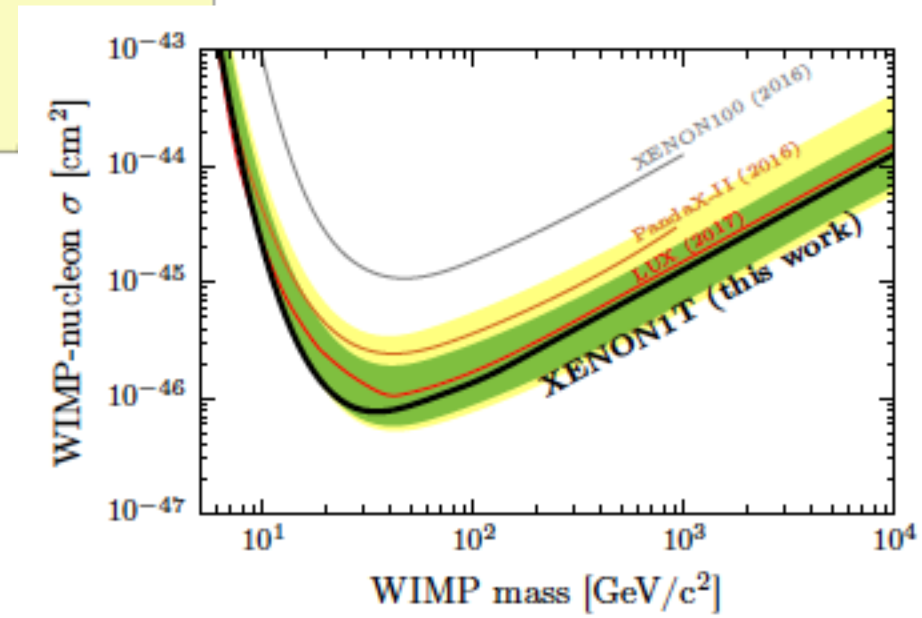
Weak interaction with 100GeV-1TeV mass:

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

Interplay of direct, indirect and collider detections!

WIMP in challenge



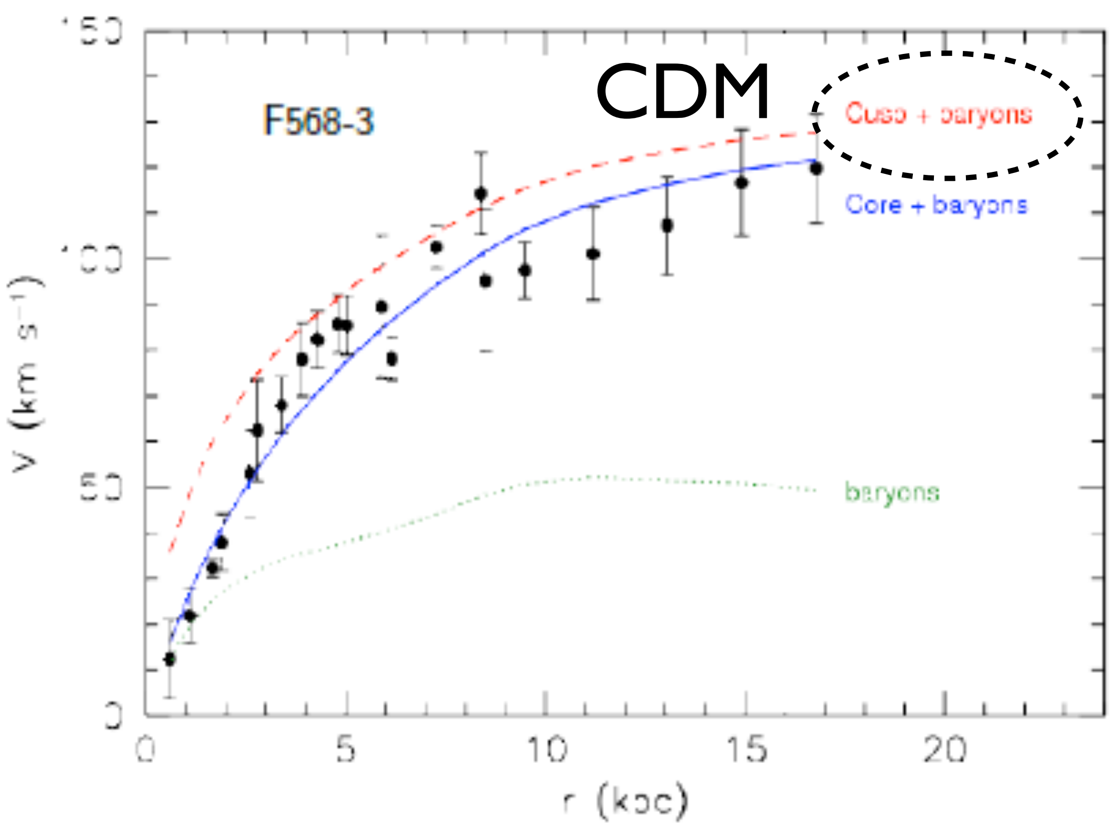


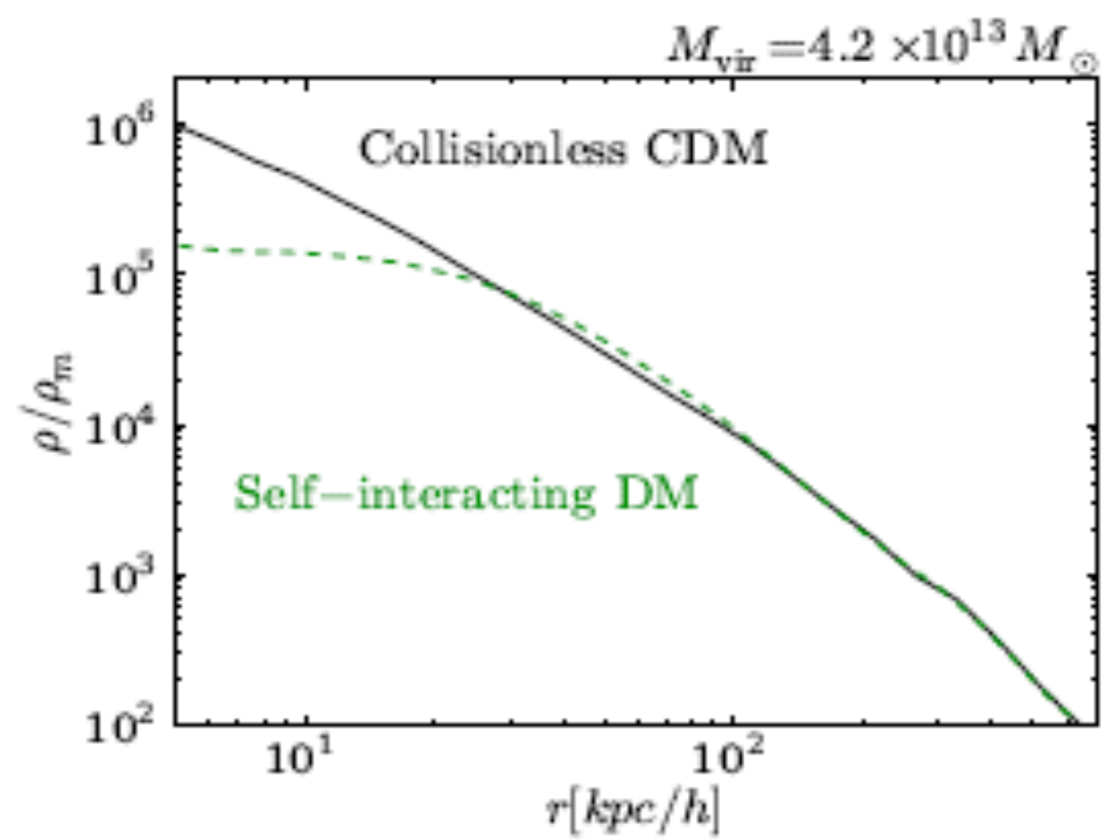
No direct evidence for WIMP;
No new physics at weak-scale.

Small-scale problems

- Core-cusp problem: simulation with CDM (cusp) overshoots galaxy rotation curves.

Isothermal (core) profile is favored over NFW or Einasto (cusp).





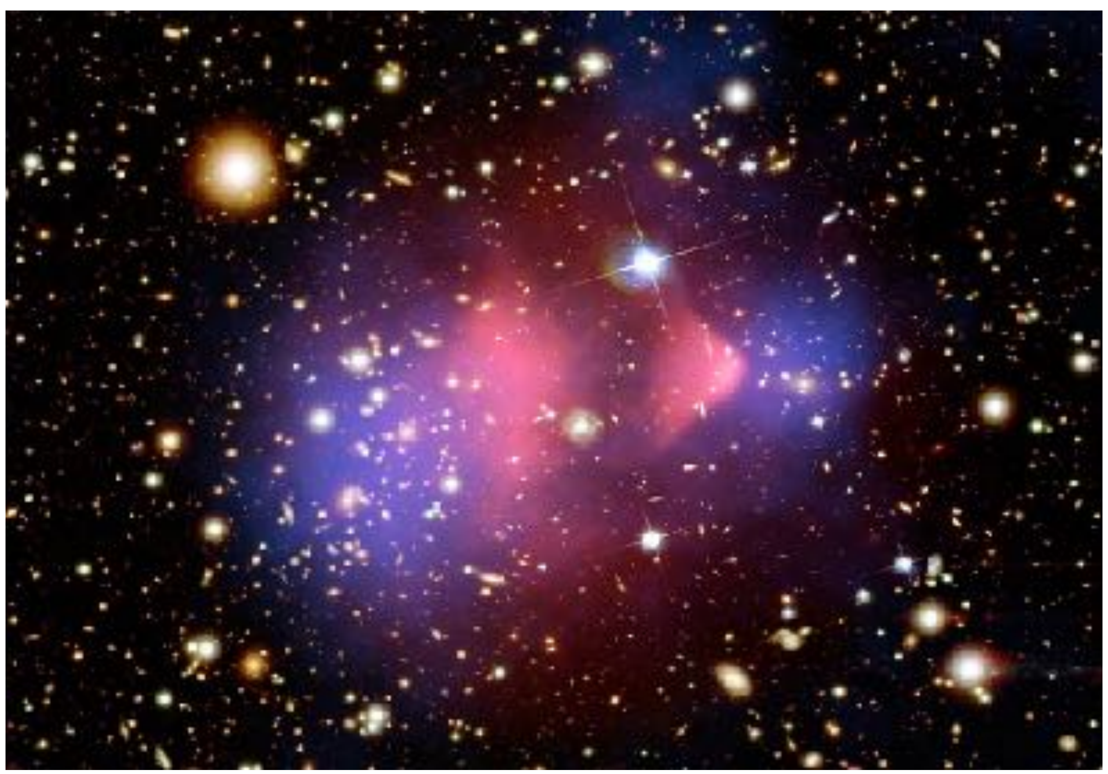
- Other problems: missing satellites (fewer DM subhalos), too-big-to-fail (masses of dwarf galaxies)

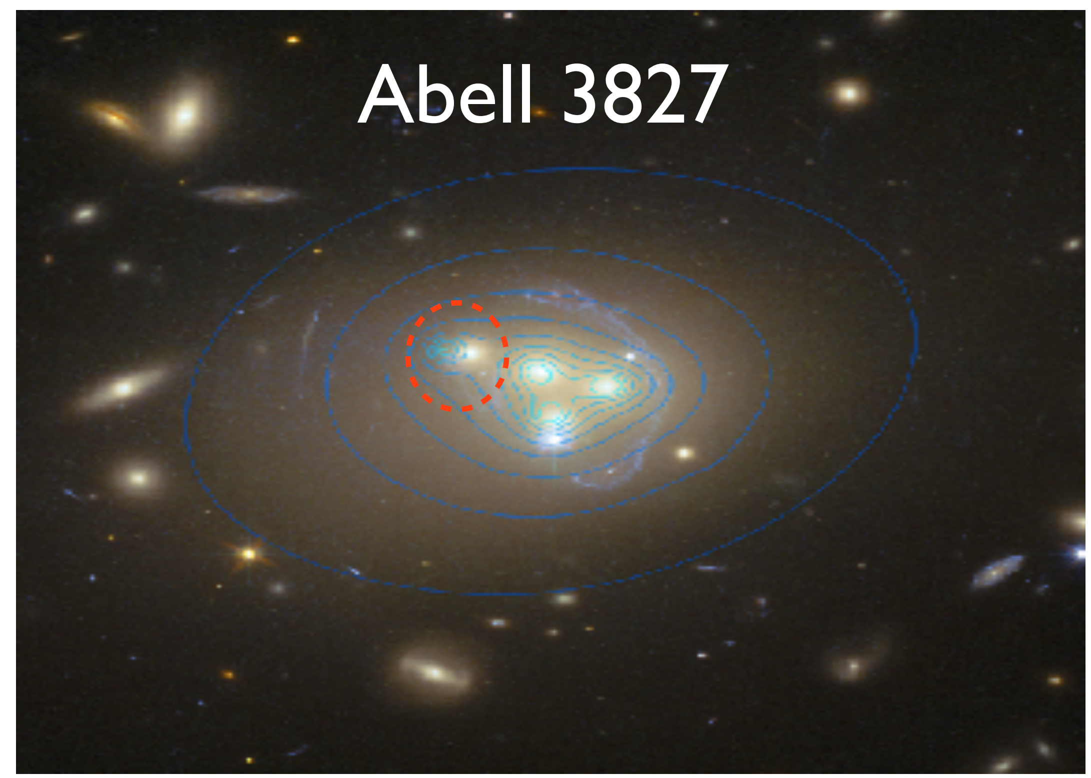
Self-interacting DM

- Self-interacting DM: core profile and no small-scale problems.

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

cf. WIMP DM without light mediator: $\sigma_{\rm self}/m_{\rm WIMP} \sim 10^{-11}{\rm GeV}^{-3} \sim 10^{-14}{\rm cm}^2/g.$





No evidence from Bullet cluster; smaller self-scattering at clusters

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

Off-set of DM halo: $\Delta = 1.62^{+0.47}_{-0.49}\,{\rm kpc}$

hint for large self-interaction?

Beyond vanilla DM

- Dynamics for self-interacting dark matter and its portals

Portals: Higgs, Z', axion, graviton, etc

- SU(N)xU(1)x ⋯
- Dark local or global $U(1)_d$

  stability of DM

- New strong int, dark flavor

  self-interacting DM

- SU(3)xSU(2)xU(1)
- $U(1)_{em}$, $U(1)_B$

  stable electron, proton

- Strong int, SU(3) flavor

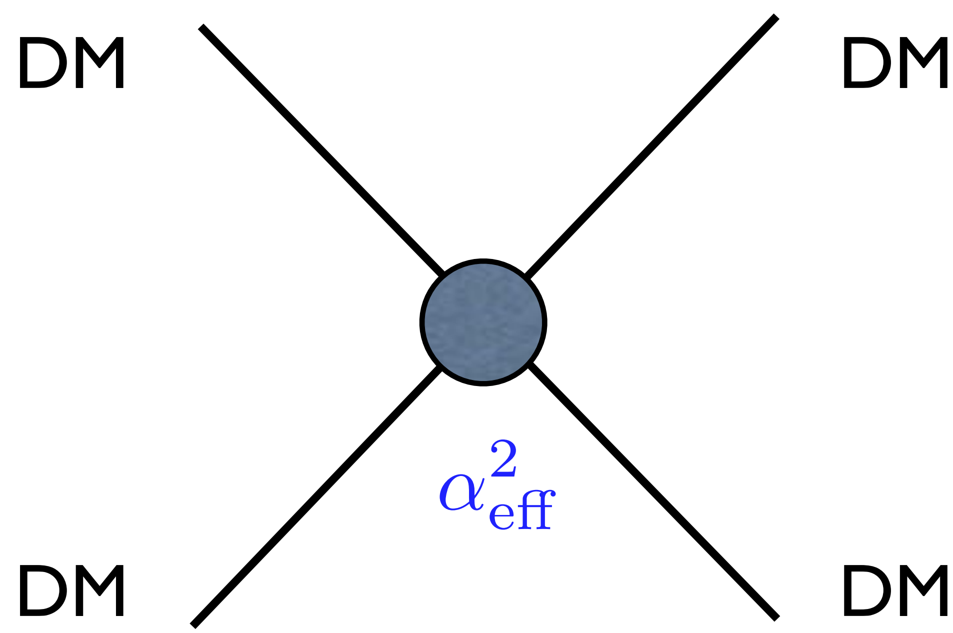
  self-interacting, long-lived mesons

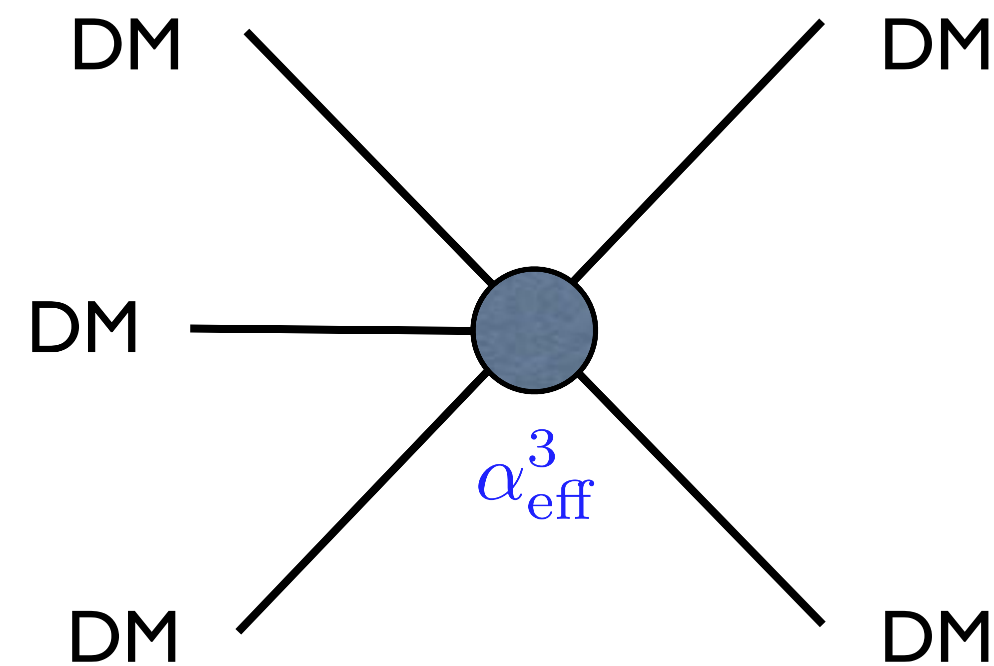
SIMP paradigm & production

SIMP mechanism

- Self-scattering vs 3→2 annihilation

[Carlson,Machacek, Hall (1992); Hochberg et al(2014)]





$$\sigma_{\rm self} = \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^2} = 0.1\,{\rm b}\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)$$

$$\langle \sigma_{\rm eff} v\rangle = n_{\rm DM}\langle \sigma v^2\rangle$$
$$= R\,\sigma_{\rm self} = 10^{-12}\,{\rm b}$$

$$R = \frac{g_{\rm DM}\alpha_{\rm eff}}{(2\pi)^{3/2}}\,x_f^{-3/2}\,e^{-x_f}\,, \quad x_f = \frac{m_{\rm DM}}{T_f}$$

Relic density from number-changing DM self-interactions

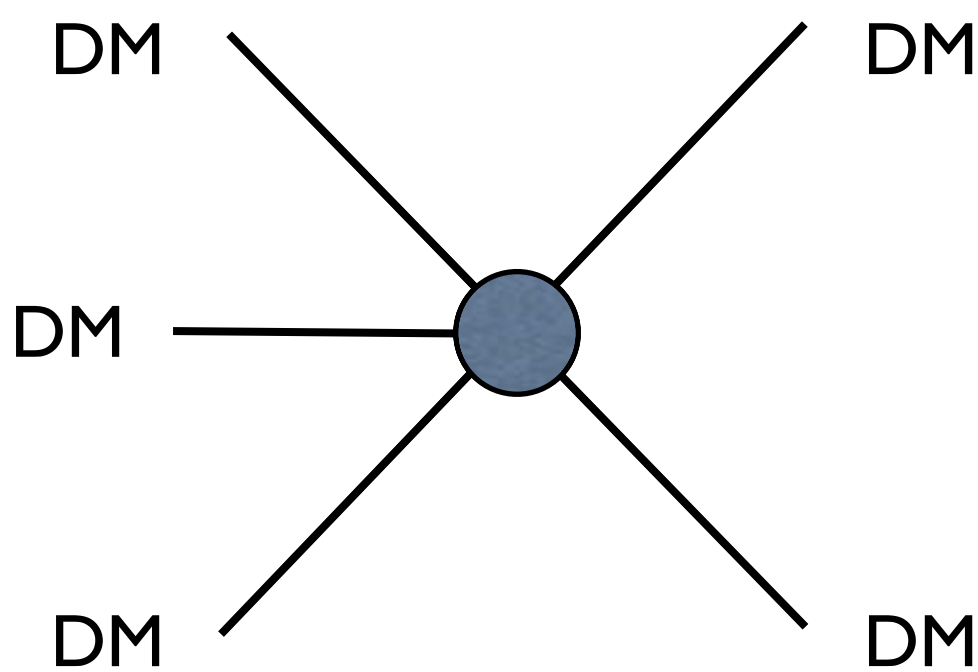
$$\alpha_{\rm eff} \sim 3\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right) :$$

Strongly Interacting Massive Particles (SIMP)

SIMP abundances

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

- Thermal average of 3→2 annihilation cross section



Thermal average (CM frame):

$$\langle \sigma v^2 \rangle = \frac{\int d^3v_1 d^3v_2 d^3v_3\, \delta^3(\vec{v}_1+\vec{v}_2+\vec{v}_3)(\sigma v^2)\, e^{-\frac{1}{2}x(v_1^2+v_2^2+v_3^2)}}{\int d^3v_1 d^3v_2 d^3v_3\, \delta^3(\vec{v}_1+\vec{v}_2+\vec{v}_3)\, e^{-\frac{1}{2}x(v_1^2+v_2^2+v_3^2)}}$$

Boltzmann equation for SIMP:

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

SO(9) symmetric: $(\sigma v^2) = f(\eta), \quad \eta = \frac{1}{2}(v_1^2+v_2^2+v_3^2).$

Canonical transf. of constraints leaves cross section invariant.

$$\langle \sigma v^2 \rangle = \frac{1}{2}x^3 \sum_{l=0}^{\infty} \frac{a_l}{l!} \int_0^\infty d\eta\, \eta^{l+2} e^{-x\eta} = \frac{1}{2}\sum_{l=0}^{\infty}(l+1)(l+2)a_l\, x^{-l}$$

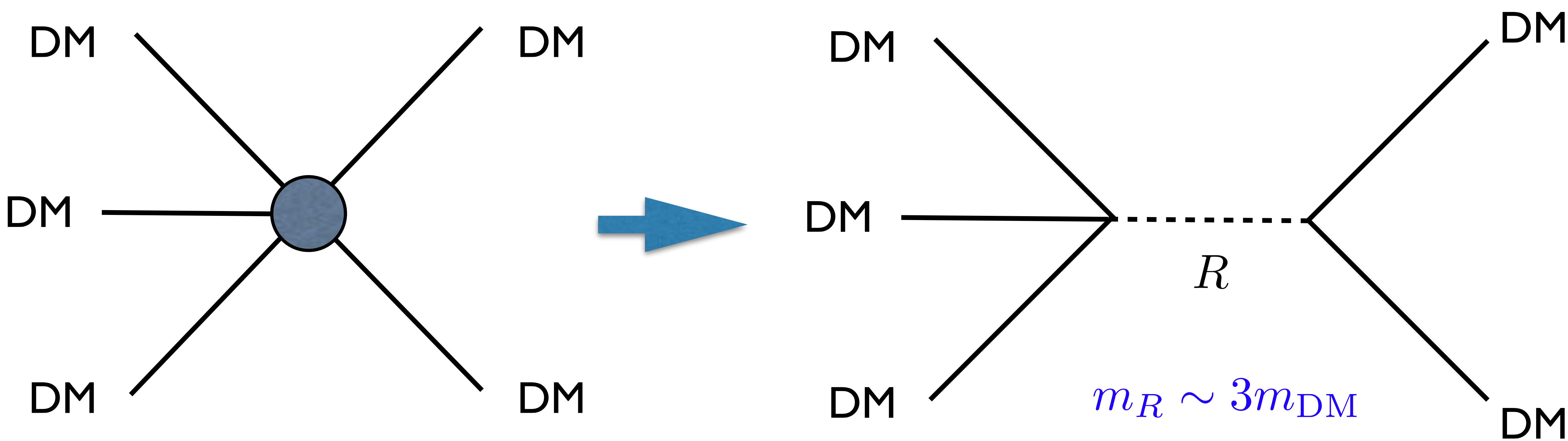
General: $\langle (v_1^2)^n (v_2^2)^m (v_3^2)^l \rangle \equiv c_{nml}\, x^{-n-m-l}$

(n,m,l)	$(1,0,0)$	$(1,1,0)$	$(2,0,0)$	$(1,1,1)$	$(2,1,0)$	$(3,0,0)$
c_{nml}	2	$\frac{14}{3}$	$\frac{20}{3}$	$\frac{100}{9}$	$\frac{160}{9}$	$\frac{280}{9}$

SIMP resonances

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

- 3→2 annihilation cross enhances near resonance.



Breit-Wigner form for SIMP:

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

$$\gamma_R \equiv \frac{m_R\Gamma_R}{9m_{\rm DM}^2}$$

$$\equiv b_R\,\frac{\gamma_R}{(\epsilon_R-\frac{2}{3}\eta)^2+\gamma_R^2}$$

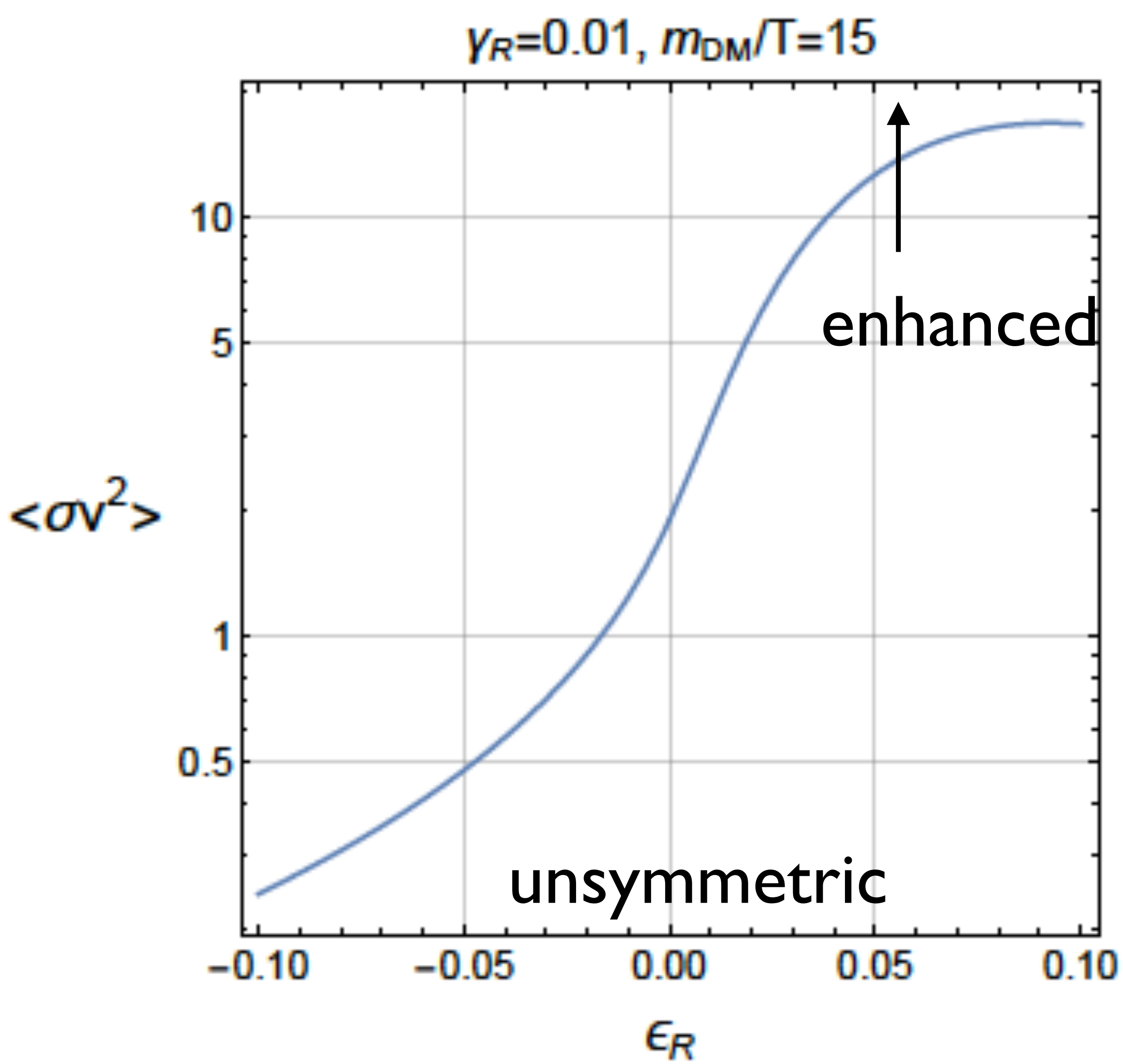
$$b_R = \sum_{l=0}^{\infty}\frac{b_R^{(l)}}{l!}\,\eta^l$$

$$\epsilon_R \equiv \frac{m_R^2-9m_{\rm DM}^2}{9m_{\rm DM}^2}$$

SIMP resonances

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

- Thermal average of 3→2 annihilation near resonance



$$\langle \sigma v^2 \rangle_R = \frac{3}{4}\pi x^3 \sum_{l=0}^{\infty} \frac{b_R^{(l)}}{l!} G_l(z_R; x),$$

$$G_l(z_R; x) = \mathrm{Re}\left[\frac{i}{\pi}\int_0^{\infty} d\eta \, \frac{\eta^{l+2} e^{-x\eta}}{\frac{3}{2} z_R - \eta}\right] = (-1)^l \frac{\partial^l}{\partial x^l} G_0(z_R; x).$$

$$G_0(z_R; x) = \frac{3}{2\pi}\frac{\gamma_R}{x} - \frac{9}{4\pi}\mathrm{Re}\left[i\, e^{-\frac{3}{2}x z_R} z_R^2 \left(\Gamma\left(0, -\frac{3}{2} x z_R\right) + \ln\left(-\frac{1}{z_R}\right) + \ln(-z_R)\right)\right]$$

<u>Narrow width approx:</u>

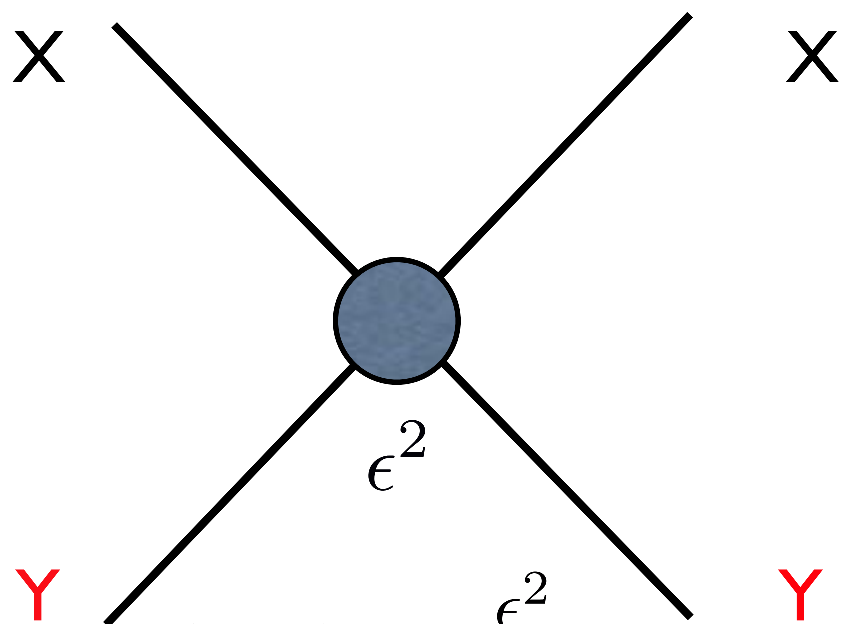
$$\gamma_R \ll 1, \quad \langle \sigma v^2 \rangle_R \approx \frac{27}{16}\pi \epsilon_R^2 x^3 e^{-\frac{3}{2}x\epsilon_R} \theta(\epsilon_R) \sum_{l=0}^{\infty} \frac{b_R^{(l)}}{l!} \left(\frac{3}{2}\right)^l \epsilon_R^l.$$

3 DM's: higher dimensional phase space

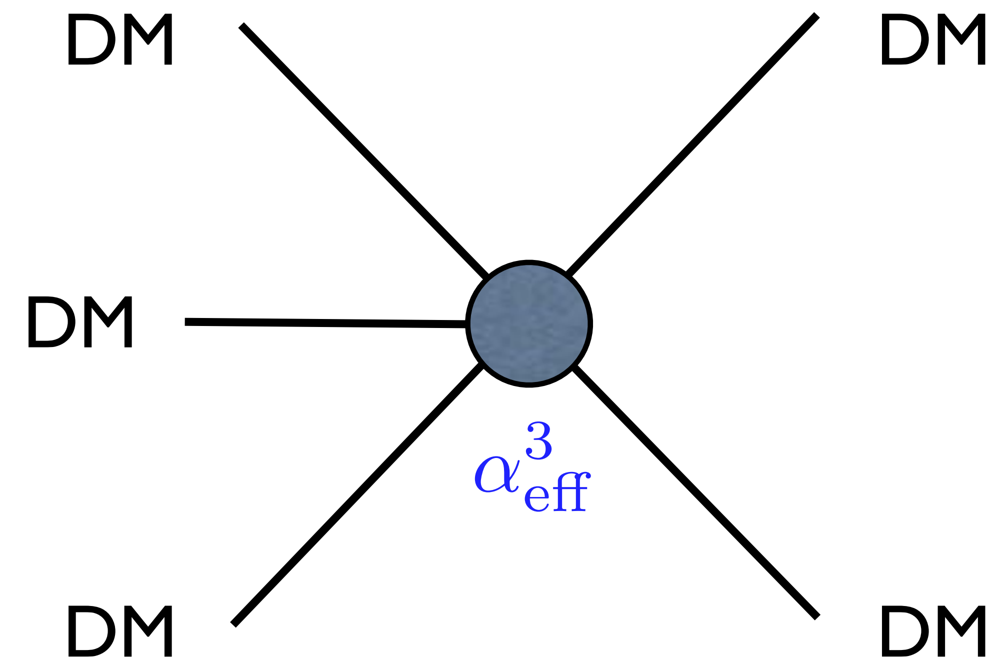
cf. WIMP: $\langle \sigma v \rangle_R \approx 2\sqrt{\pi}\gamma_R \epsilon_R^{1/2} x^{3/2} e^{-x\epsilon_R} \theta(\epsilon_R) \sum_{l=0}^{\infty} \frac{b_l}{l!} \epsilon_R^l.$

Kinetic equilibrium

- Excess of kinetic energy released by SIMP process needs equilibriated by the SM plasma. [de Laix et al, 1995]



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



Boltzmann equation for DM kinetic energy:

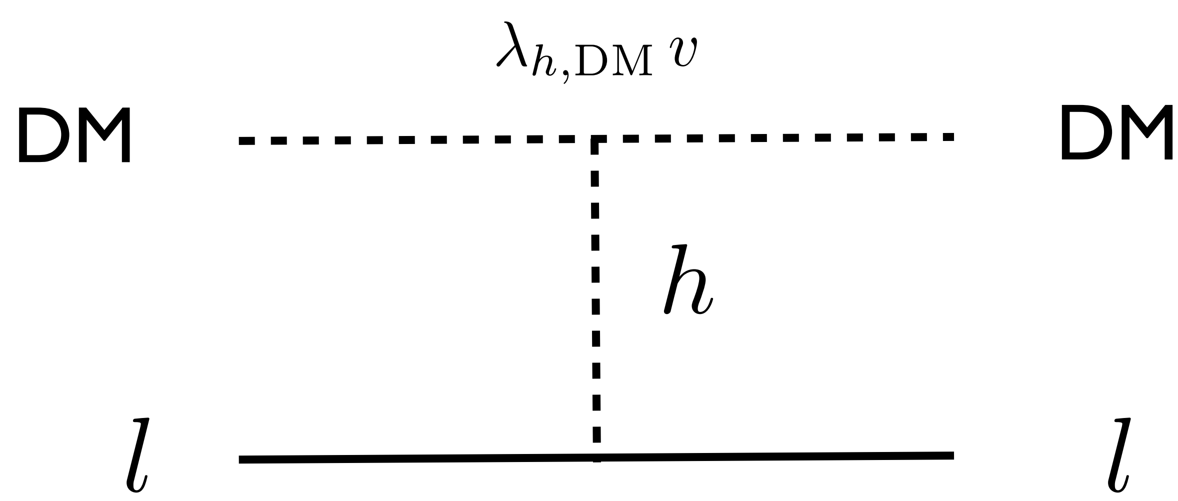
$$\dot{K} + 2HK = \underbrace{-m_{\rm DM}^2 H T^{-1}}_{3\to 2} + \underbrace{T\gamma(T)}_{\text{elastic scatt.}}, \qquad \gamma(T) \sim \left\langle n_Y \sigma_{\rm el} v_Y \frac{T}{m_{\rm DM}} \right\rangle.$$

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

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

Portals to SIMP

- Higgs-portal: scalar DM [Bernal et al, 2015; S.-M.Choi, HML, 2015]



$$\langle \sigma_{\rm el} v\rangle \approx \frac{\lambda^2_{h,\mathrm{DM}} m_l^2 m^2_{\mathrm{DM}}}{4\pi m_h^4}$$

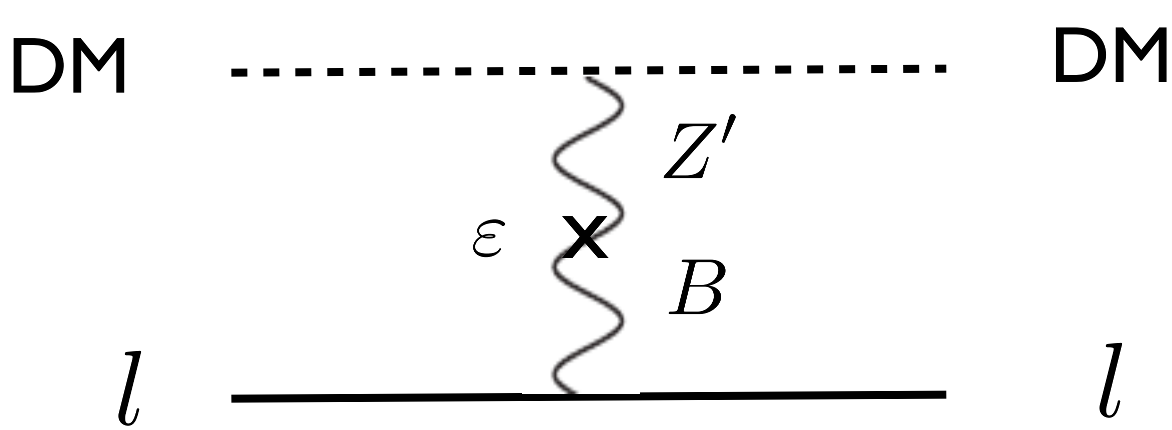
Constrained by
Higgs invisible decay:

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

$$\boxed{\epsilon < 10^{-12}}$$

- Z'-portal: (built in models with discrete symmetries)

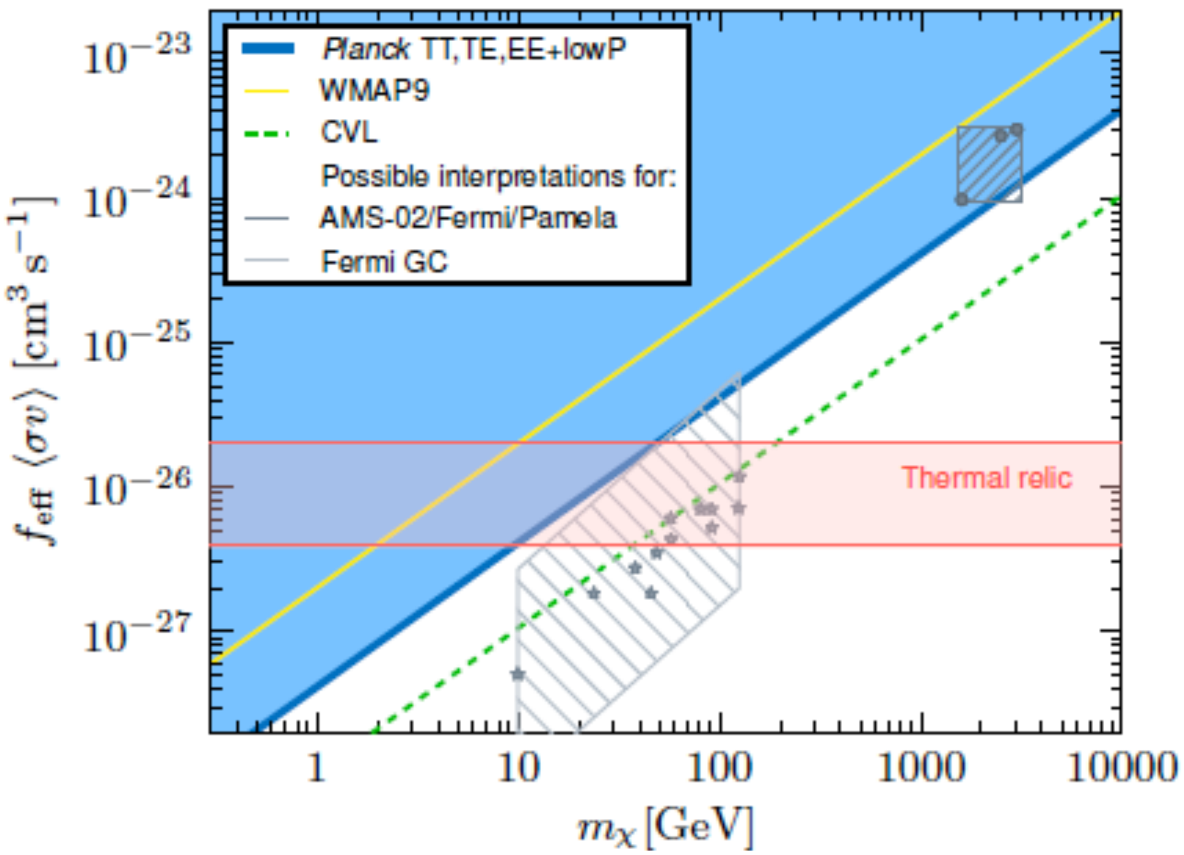
[HML, M.-S. Seo, 2015; S.-M.Choi, HML, 2015]

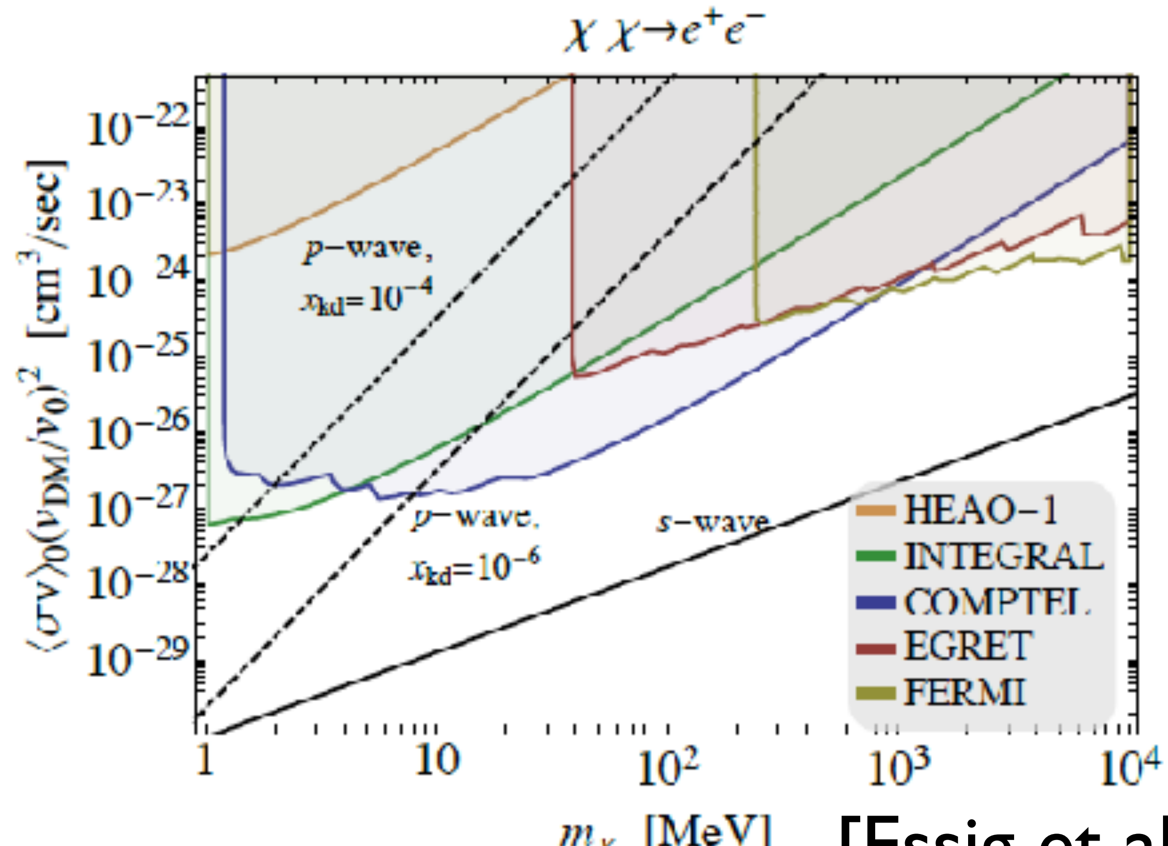


$$\langle \sigma_{\rm el} v\rangle \approx \frac{96\pi\alpha\alpha_D\varepsilon^2 m^2_{\mathrm{DM}}}{m^4_{Z'}}\,\frac{T}{m_{\mathrm{DM}}}$$

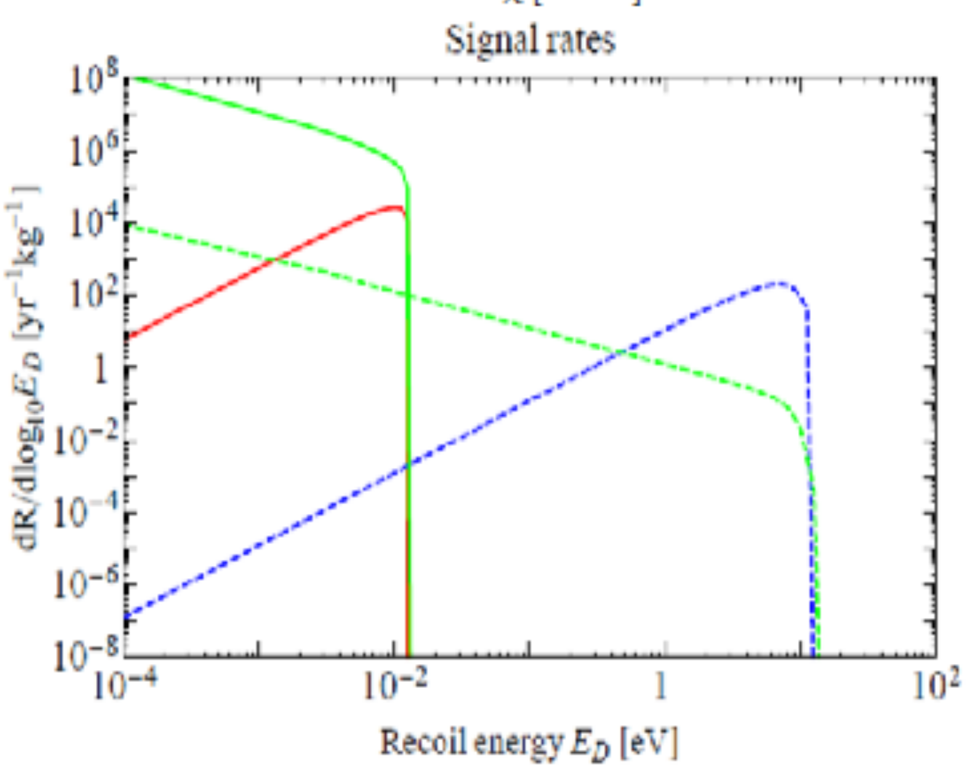
Complementarity with
Z' searches

How to detect SIMP

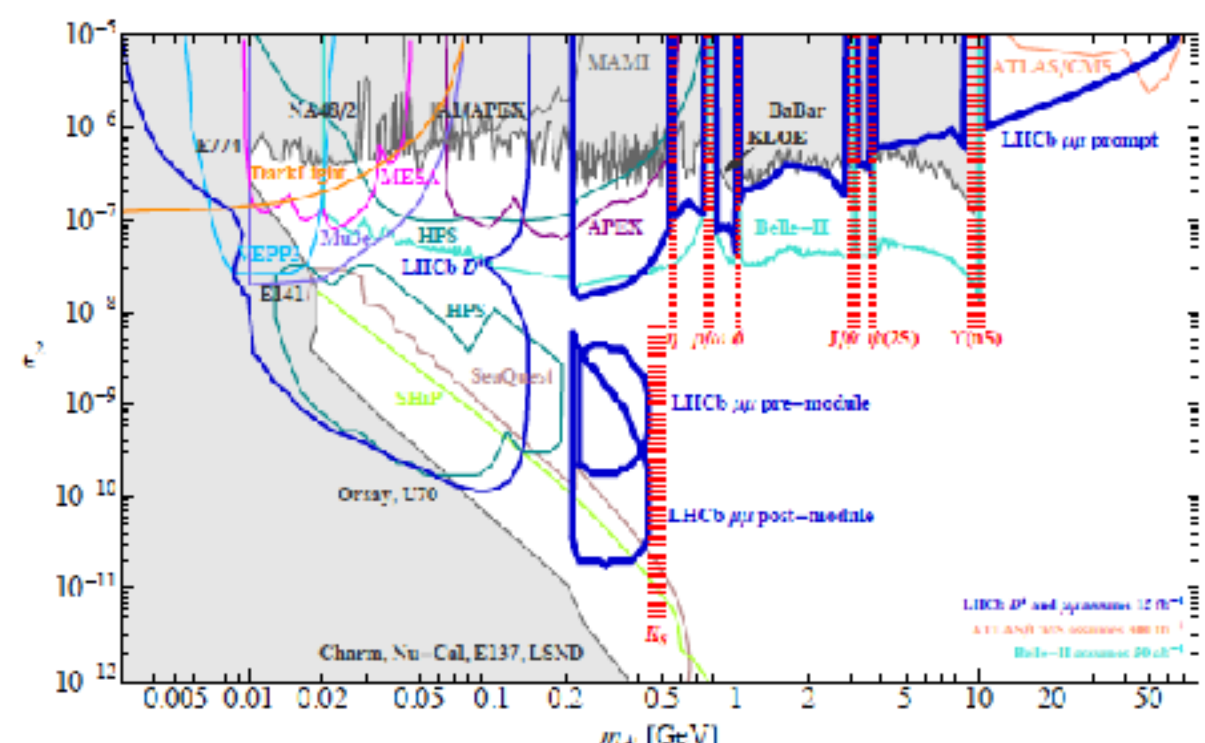




[Essig et al, 2013]



[Hochberg et al (2015)]



[Ilten et al, 2016]

Models for SIMP dark matter

Discrete symmetries for SIMP

[S.-M.Choi, HML, 2015, 2016]

- Z_3 , Z_5 are consistent discrete gauge symmetries for SIMP and Z' portal is built-in.

	ϕ	χ	S
$U(1)_V$	$+5$	$+1$	$+3$

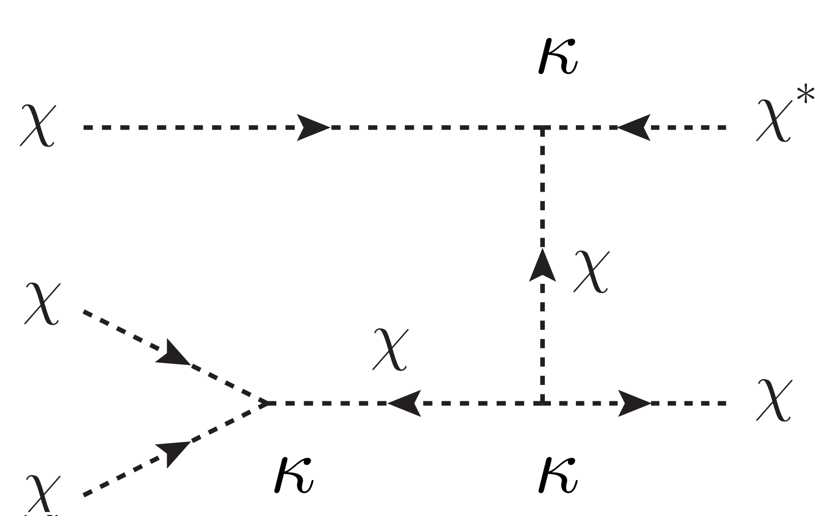
Table 1: $U(1)_V$ charges.

$$\langle S(\phi)\rangle = \frac{1}{\sqrt{2}}\,v' \quad \Rightarrow \quad U(1)_V \to Z_{3(5)}$$

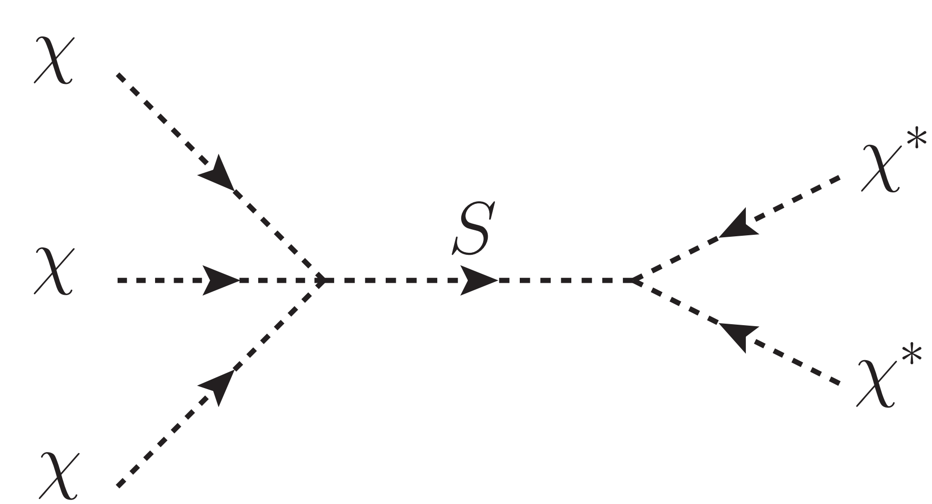
$$Z_3 : \mathcal{L}_{Z_3} = -\kappa(v'+h')\chi^3 + \text{h.c.} - \lambda_\chi|\chi|^4 - \frac{1}{2}\lambda_{\phi\chi}(v'+h')^2|\chi|^2,$$

$$Z_5 : \mathcal{L}_{Z_5} = -\lambda_1 v' S^2\chi^\dagger - \lambda_2 v' S\chi^2 - \lambda_3 S^\dagger\chi^3 + \text{h.c.}$$

- Self-scattering and (s-wave) 3→2 annihilation.



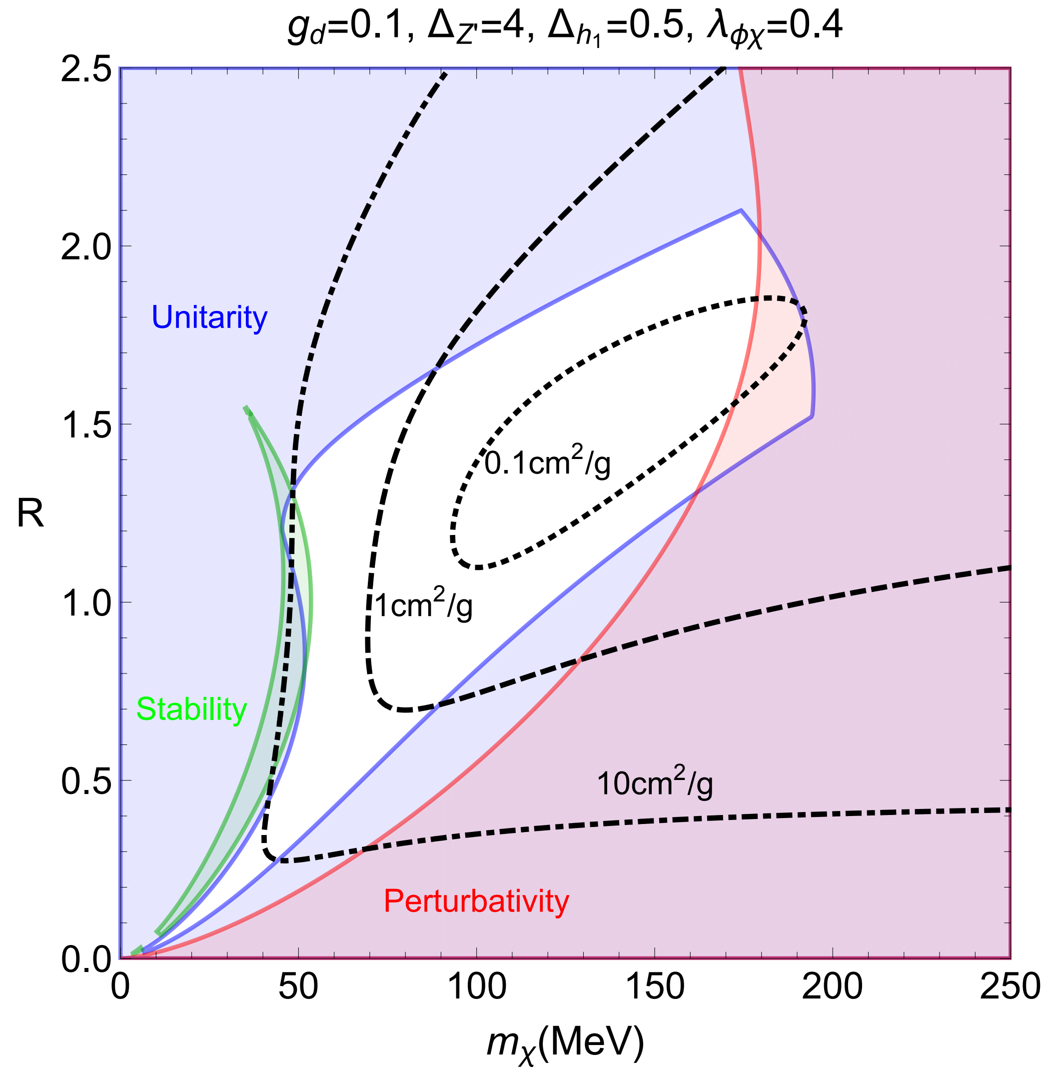
"Non-resonant"

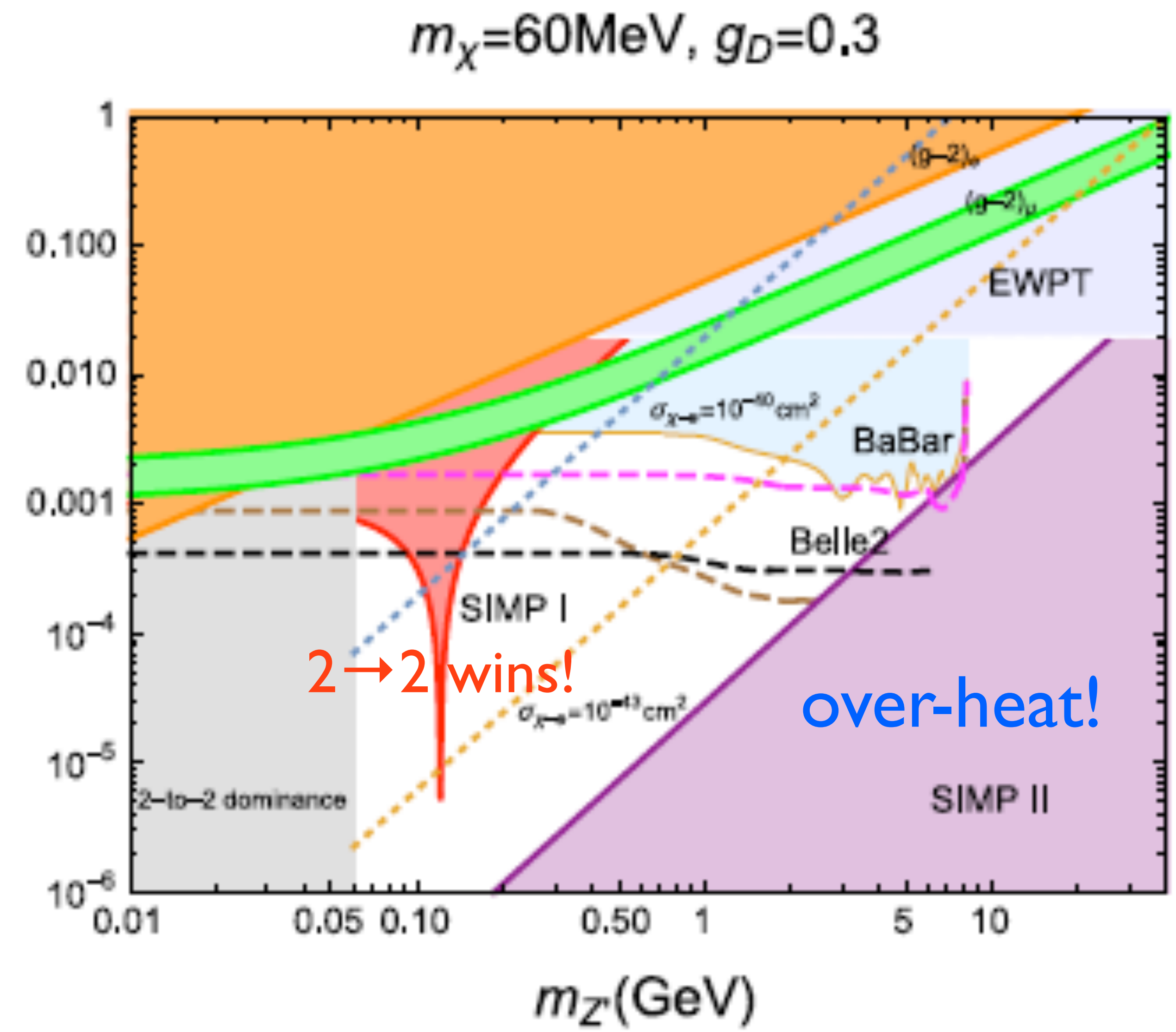


"Resonant"

Bounds on Z_3 SIMP

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





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

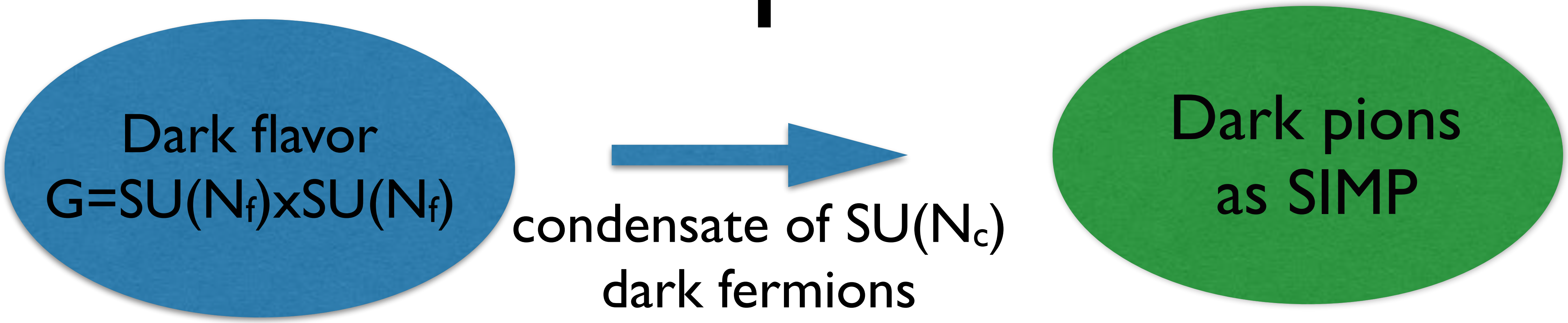
Bounds on dark sector couplings

Unitarity → $m_\chi \lesssim 150\,\mathrm{MeV}$

Bounds on Z' portal

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

SIMP pions

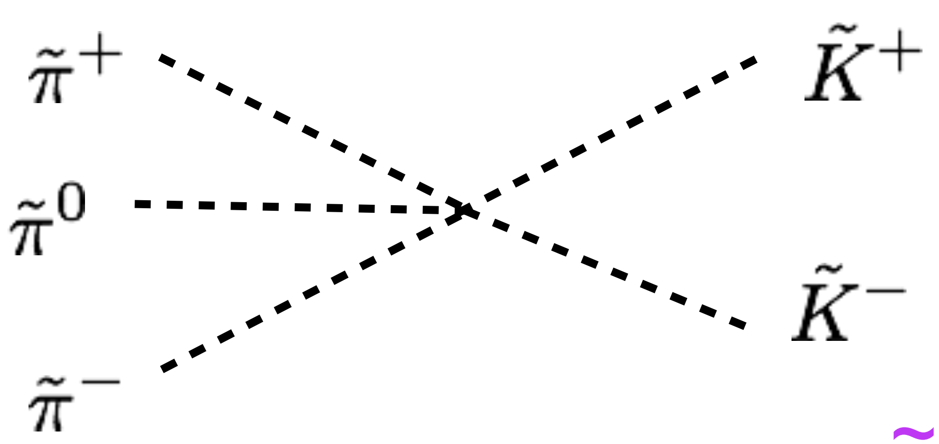


- WZW terms for $\pi_5(G/H)=Z$ (i.e. $N_f \geq 3$) [Wess, Zumino, 1971; Witten, 1983]

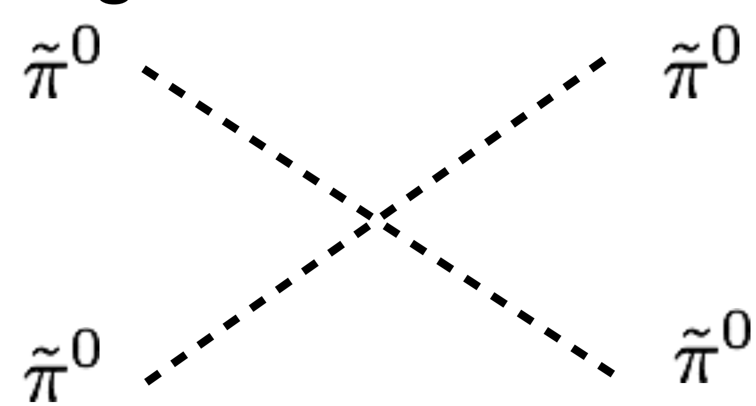
$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 F^5}\,\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

[Hochberg et al, 2014]

SIMP process:



Self-scattering:



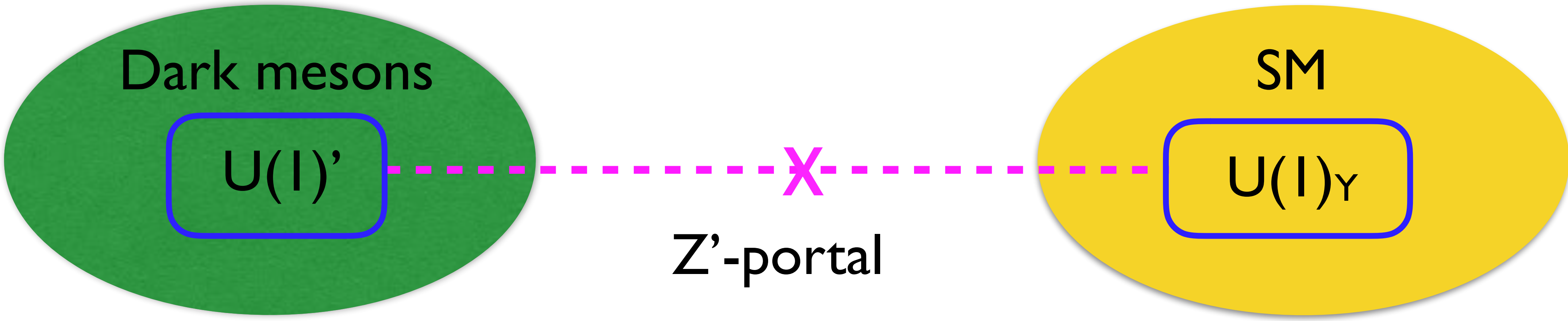
~1/Nf

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

~const

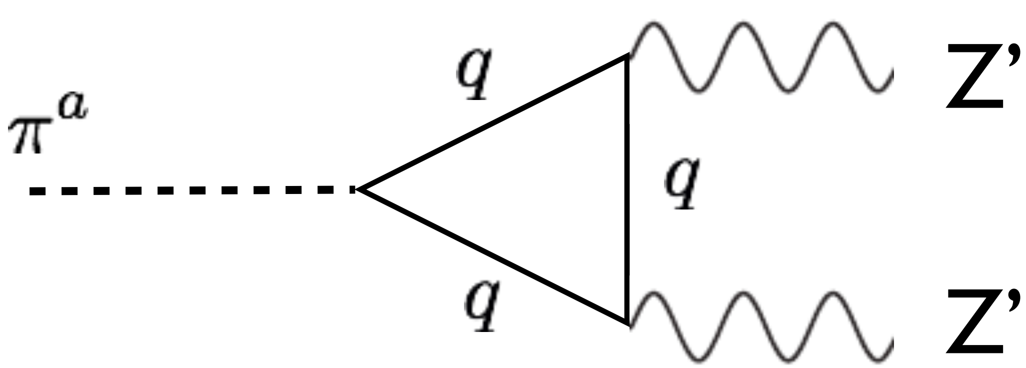
$$\sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4}\frac{a^2}{N_\pi^2}$$

Z' portal for SIMP pions



- Gauged WZW term [Witten, 1983]

Cancel chiral anomalies for stability of dark pions?



$$\propto \mathrm{Tr}(Q_D^2 T^a) = 0 \quad \text{if} \quad Q_D^2 = I.$$

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

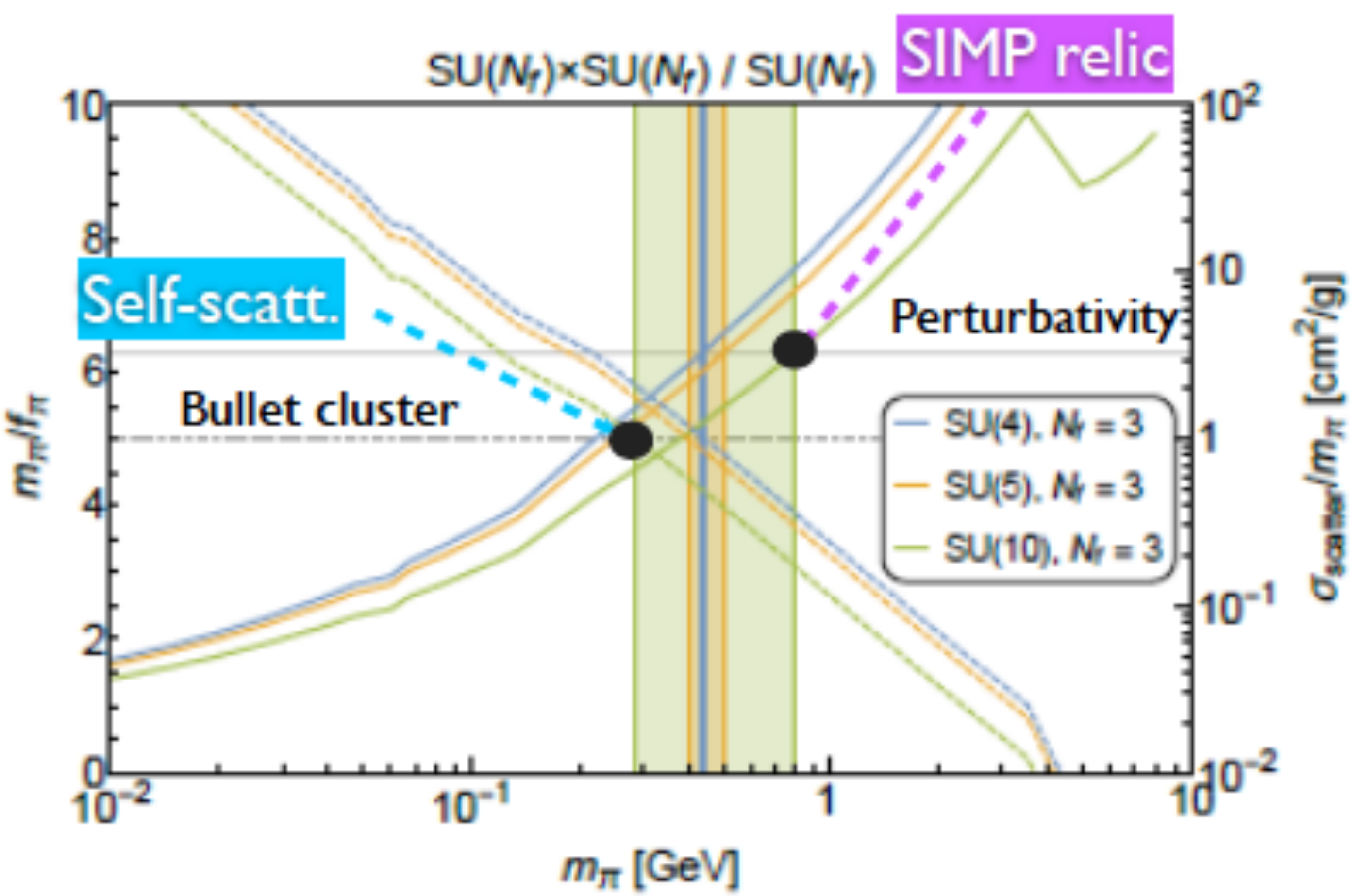
: flavor non-universal charges

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

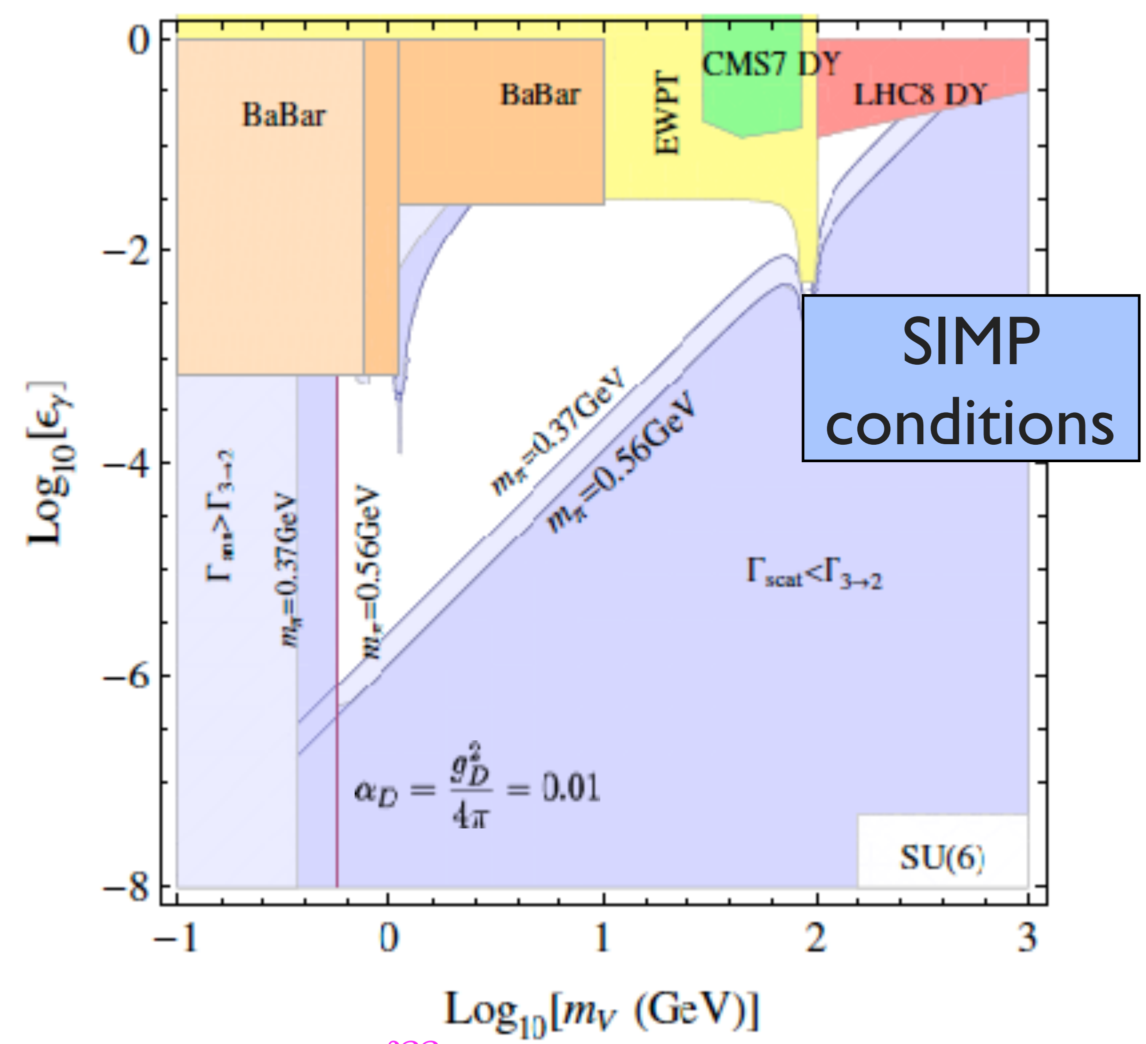
Gauge kinetic mixing $\Longrightarrow$ Kinetic equilibrium

Bounds on SIMP pions

[Hochberg et al, 2014]



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



$$\frac{m_\pi}{F} < 2\pi.$$

- Bullet cluster; perturbativity bounds.
- SIMP parameter space can be probed by Z' searches.

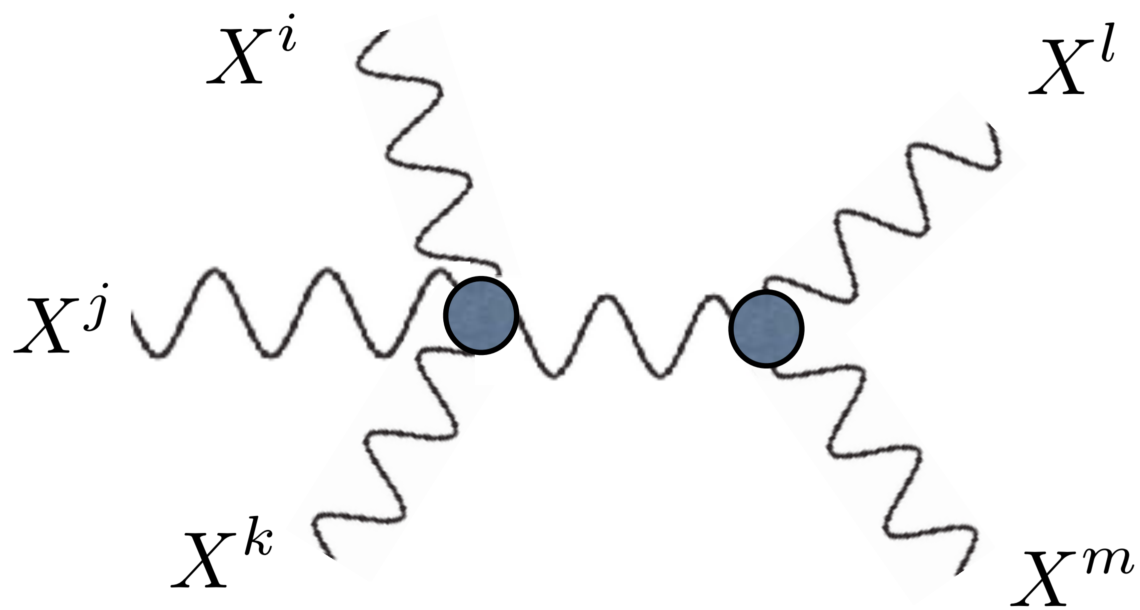
$$e^+e^- \to \gamma Z' \to \gamma(l^+l^-), \quad e^+e^- \to \gamma + \text{MET}$$

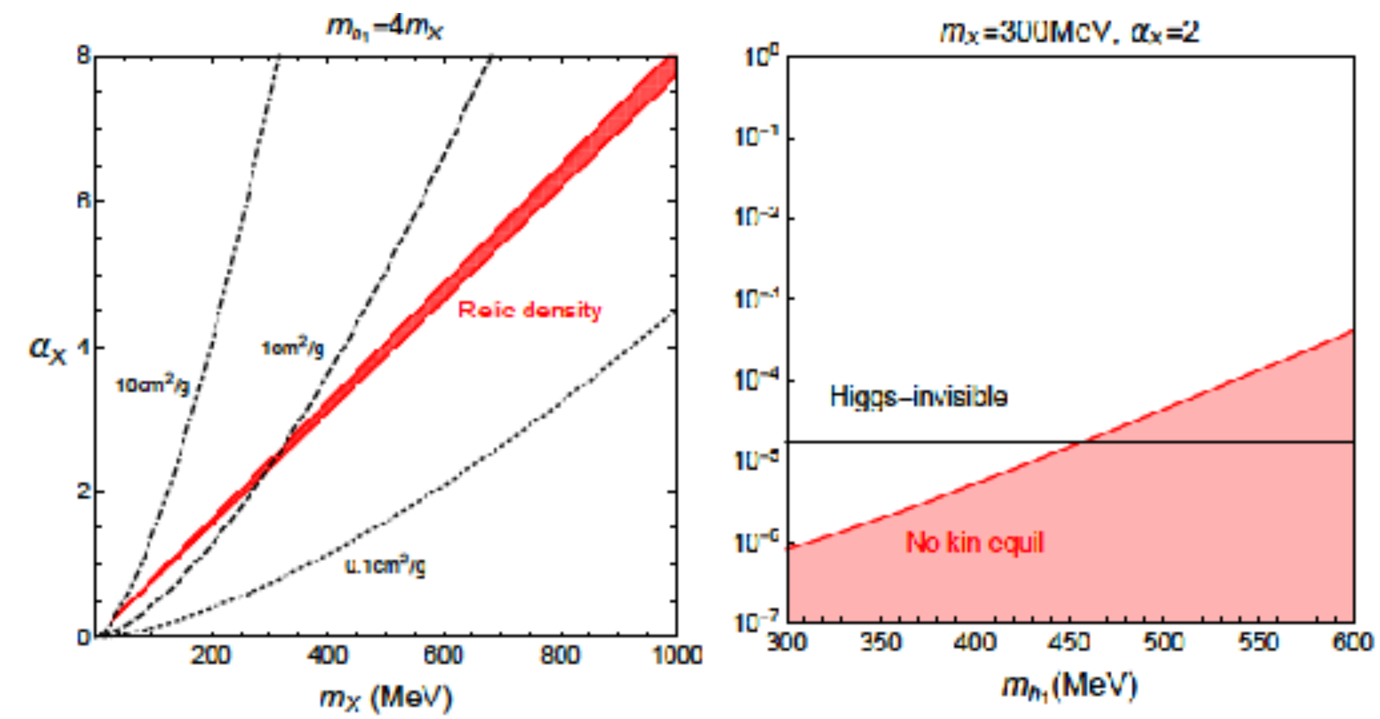
$h \to ZZ'$ (CMS 8TeV), Drell-Yan, dileptons.

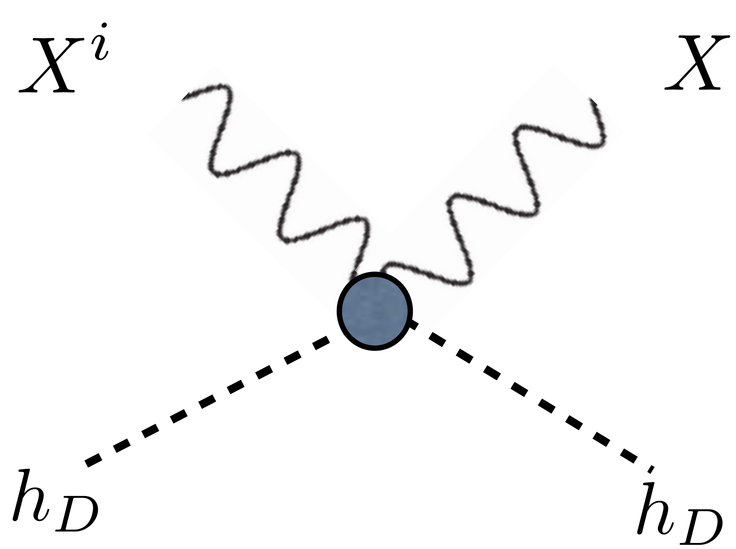
Vector SIMP

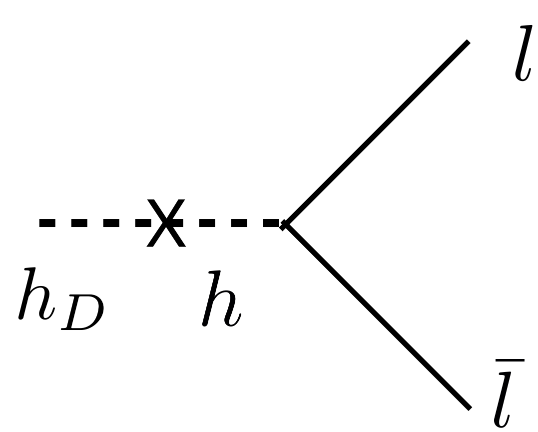
- Non-abelian massive gauge bosons = SIMP

➡ Self-interacting, in kinetic equilibrium via dark Higgs.









Bullet cluster bound leads to

$m_{\rm DM} \gtrsim 300\,{\rm MeV}$

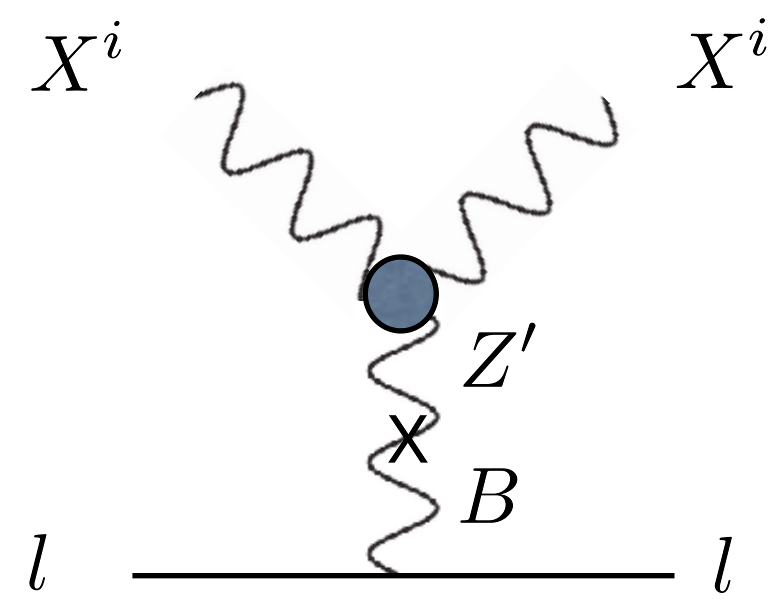
Higgs invisible decay leads

$\sin\theta \lesssim 10^{-5}$

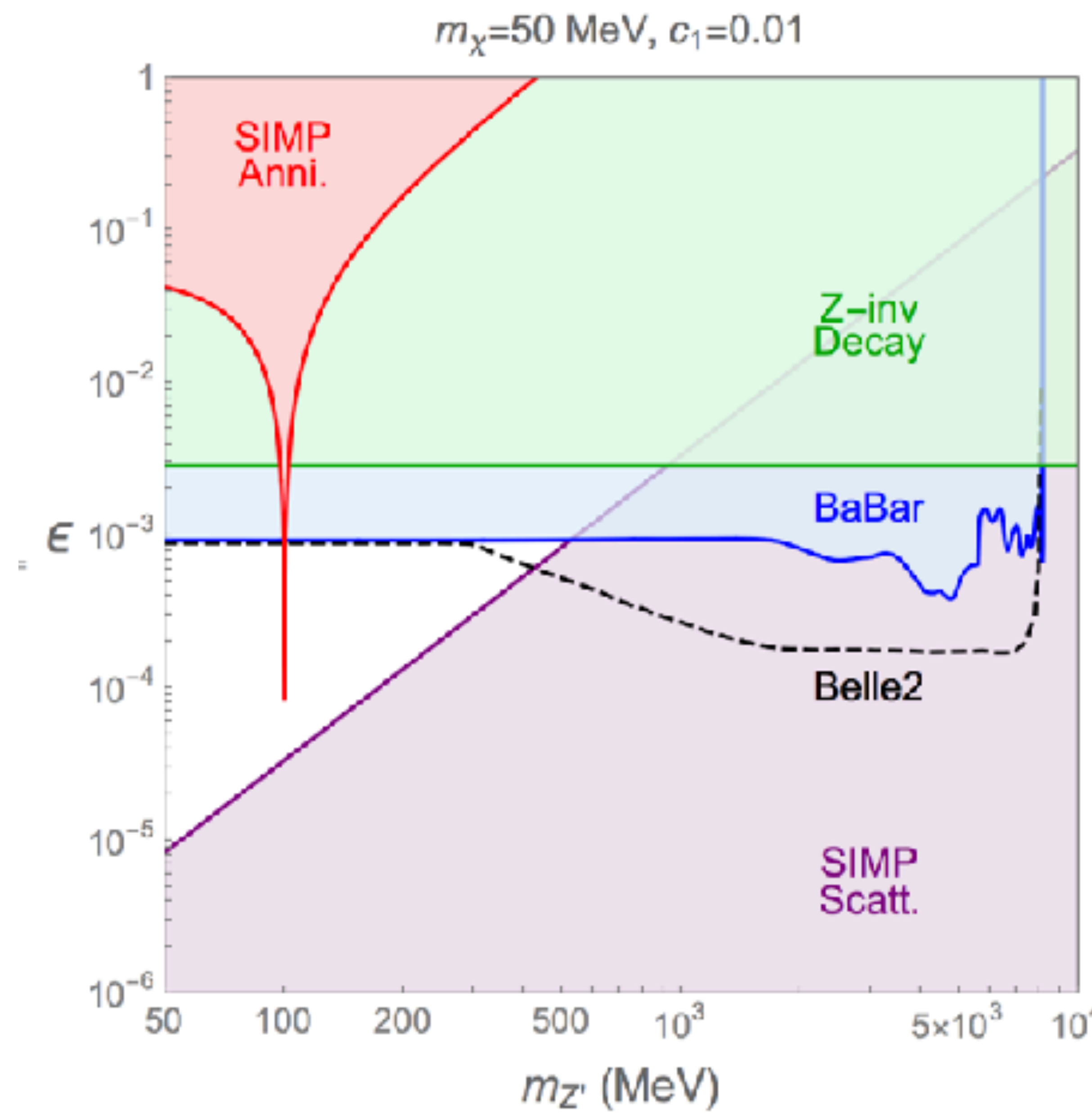
[S.-M. Choi, Y. Hochberg, E. Kuflic, Y. Mambrini, H. Murayama, HML, M. Pierre, to appear.]

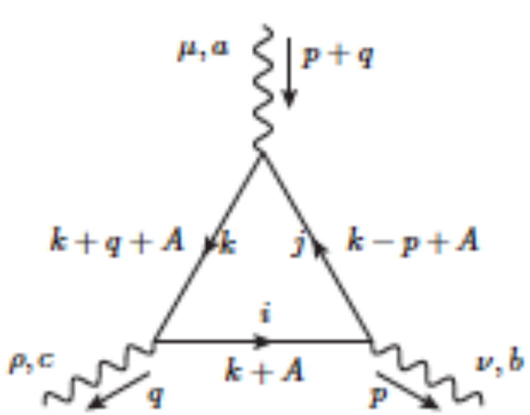
Z' portal for VSIMP

DM-lepton elastic scattering



Z'-X-X vertex:
non-abelian Chern-Simon terms due to light dark fermions.





$$\mathcal{L}_{CS,\text{even}} = c_1 \epsilon^{\mu\nu\rho\sigma} Z'_\mu \vec{X}_\nu \cdot (\partial_\rho \vec{X}_\sigma - \partial_\sigma \vec{X}_\rho)$$

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

Conclusions

- SIMP dark matter is produced by thermal freeze-out of the 3→2 process, without sizable couplings to the SM, but with large self-interactions.
- Thermal averages of DM annihilation cross section is generalized to SIMP case.
- Kinetic equilibrium would need a nonzero coupling between SIMP and the SM, which can be probed by DM direct/indirect detections and Z'-searches.
- A variety of testable SIMP models with local or global symmetries in dark sector were proposed.