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http://ctpu.ibs.re.kr/dsu2017

The SIMP species from dark symmetries

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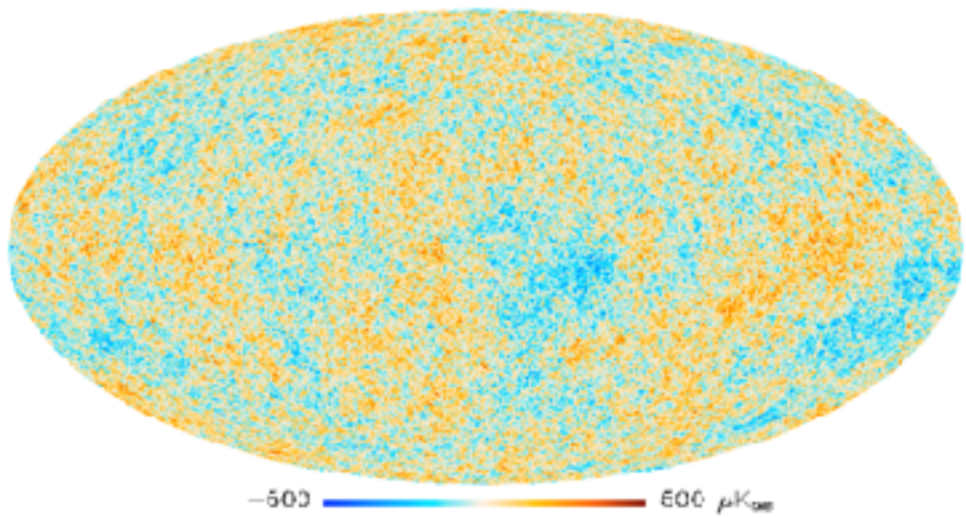
Collaborators & works

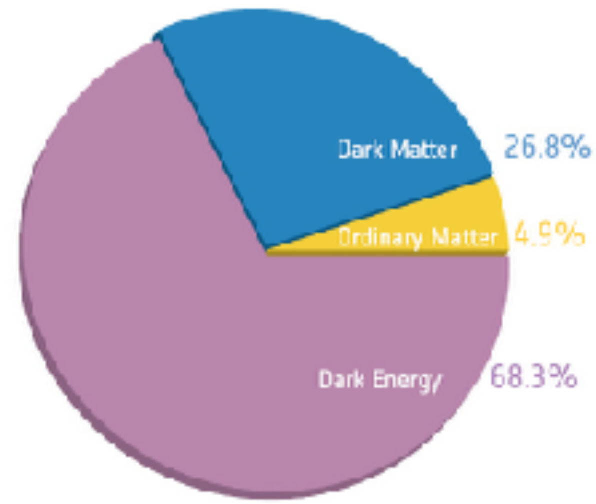
★ HML, M.-S. Seo (2015),
S.-M. Choi, HML (2015,2016),
S.-M. Choi, Y.-J. Kang, HML (2016),
★ S.-M. Choi, HML, M.-S. Seo (2017),
★ S.-M. Choi, Y. Hochberg, E. Kuflik, Y. Mambrini, H. Murayama, HML, M. Pierre (2017)

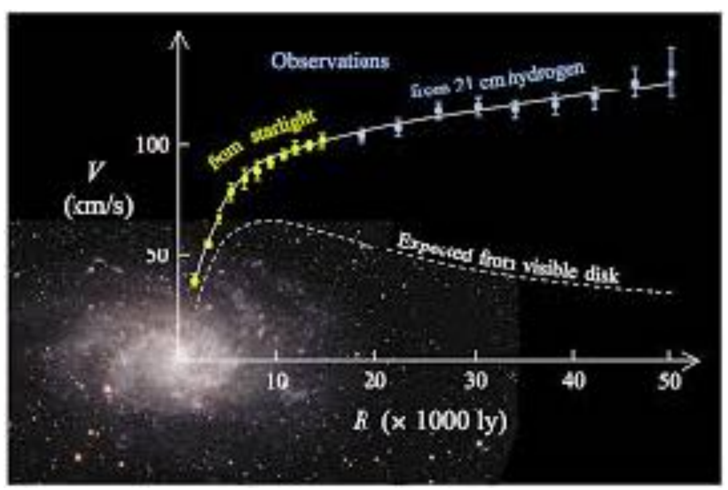
Outline

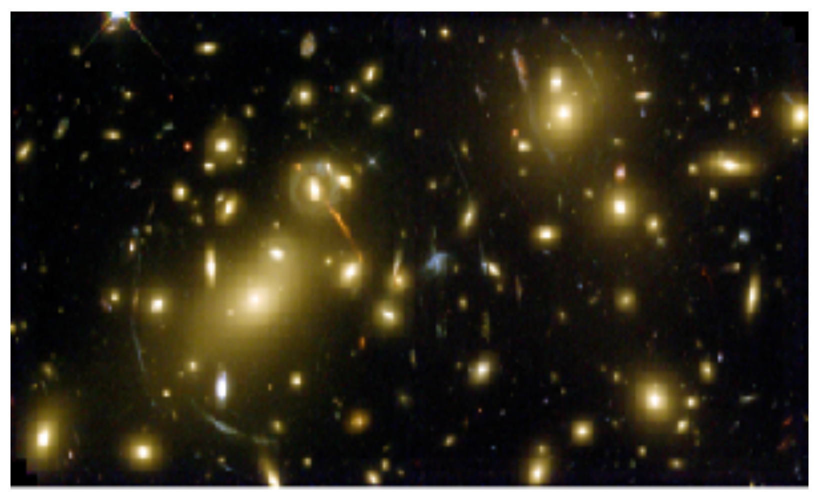
- Motivation
- SIMP paradigm & mechanism
- SIMP species
- Conclusions

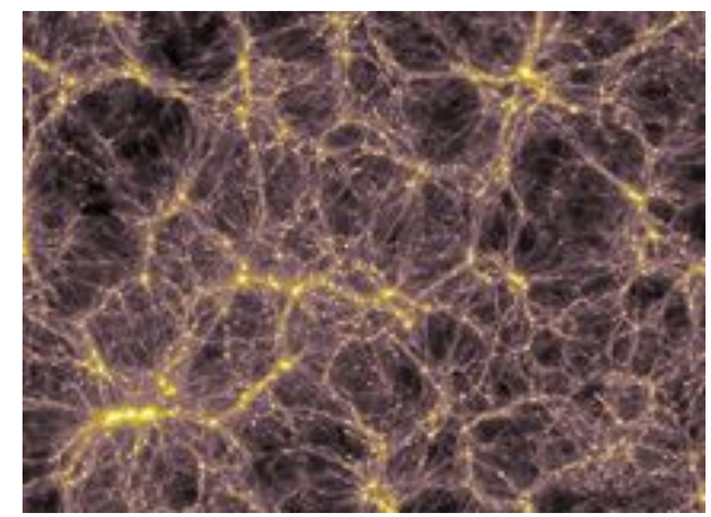
Dark matter from sky











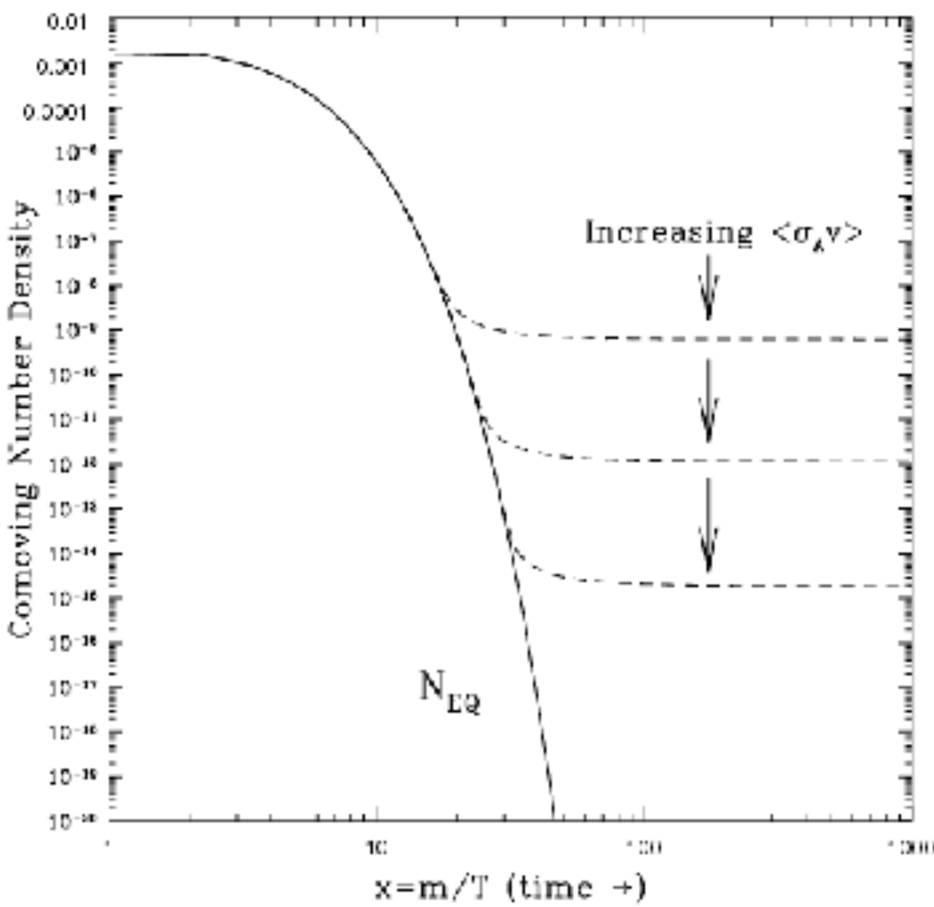
- Various evidences from galaxy rotation curves, CMB, and gravitational lensing, and large scale structure.

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

WIMP Paradigm

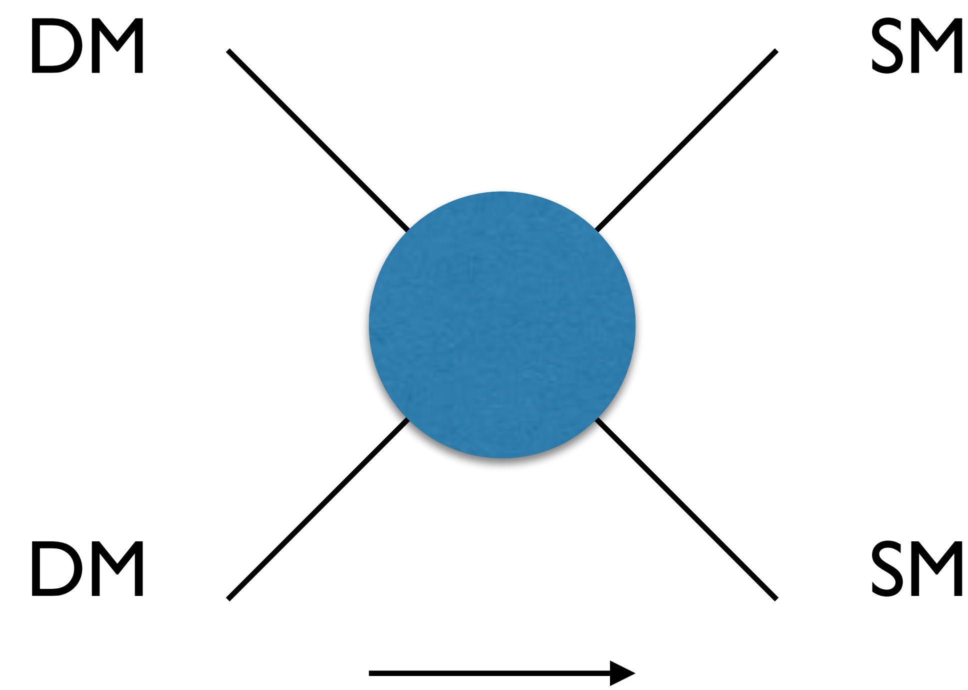
[Lee, Weinberg(1977)]

DM number



time

Dark matter once in thermal equilibrium with SM particles

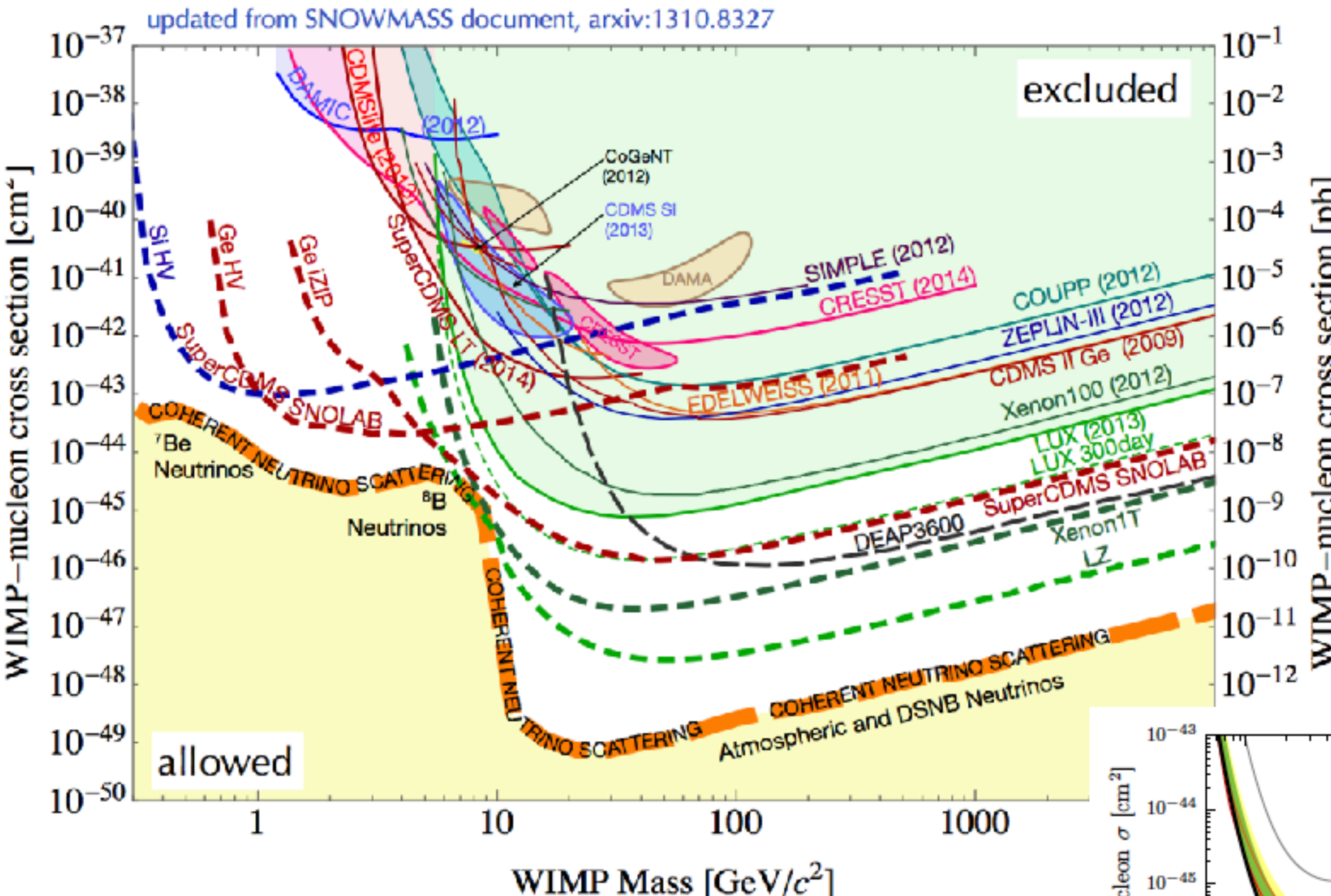


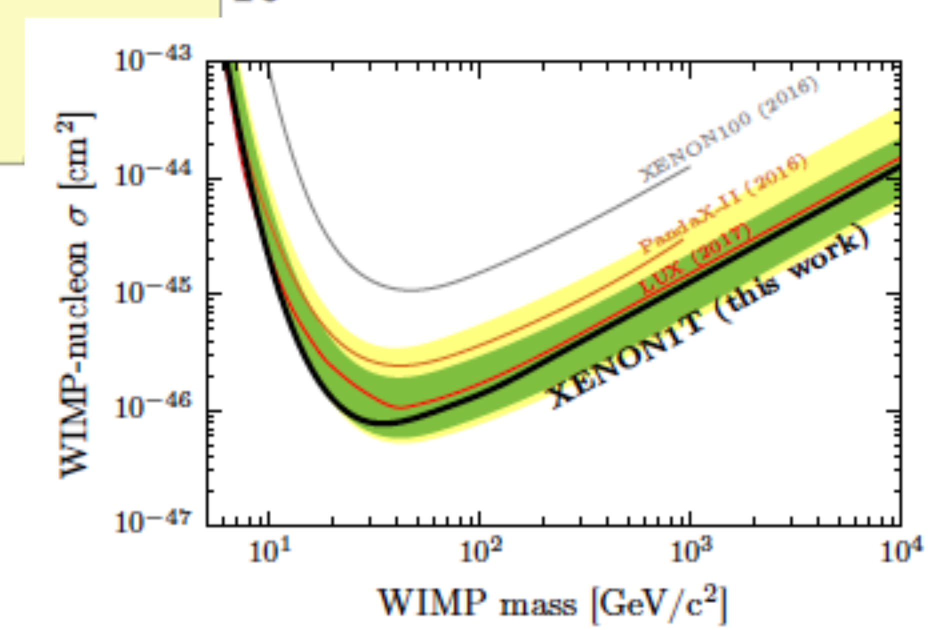
Weak interaction with 100GeV-1TeV mass:

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

Interplay of direct, indirect and collider detections!

WIMP in challenge

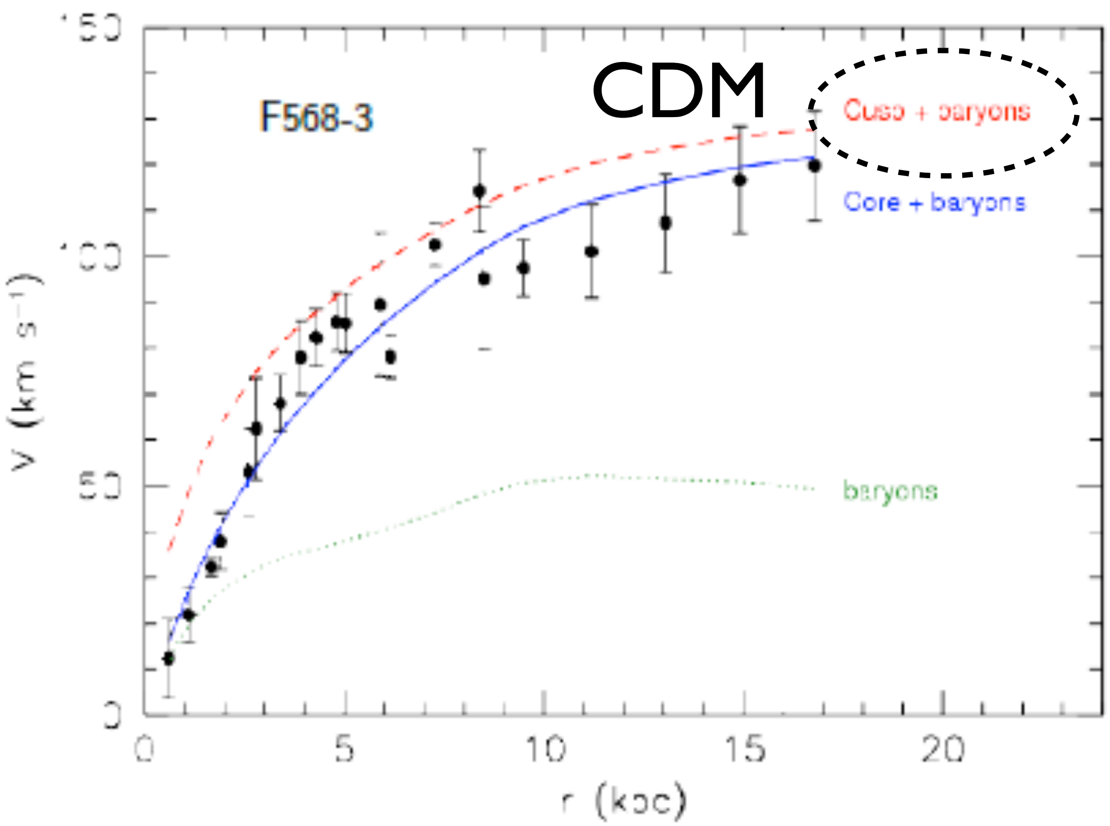


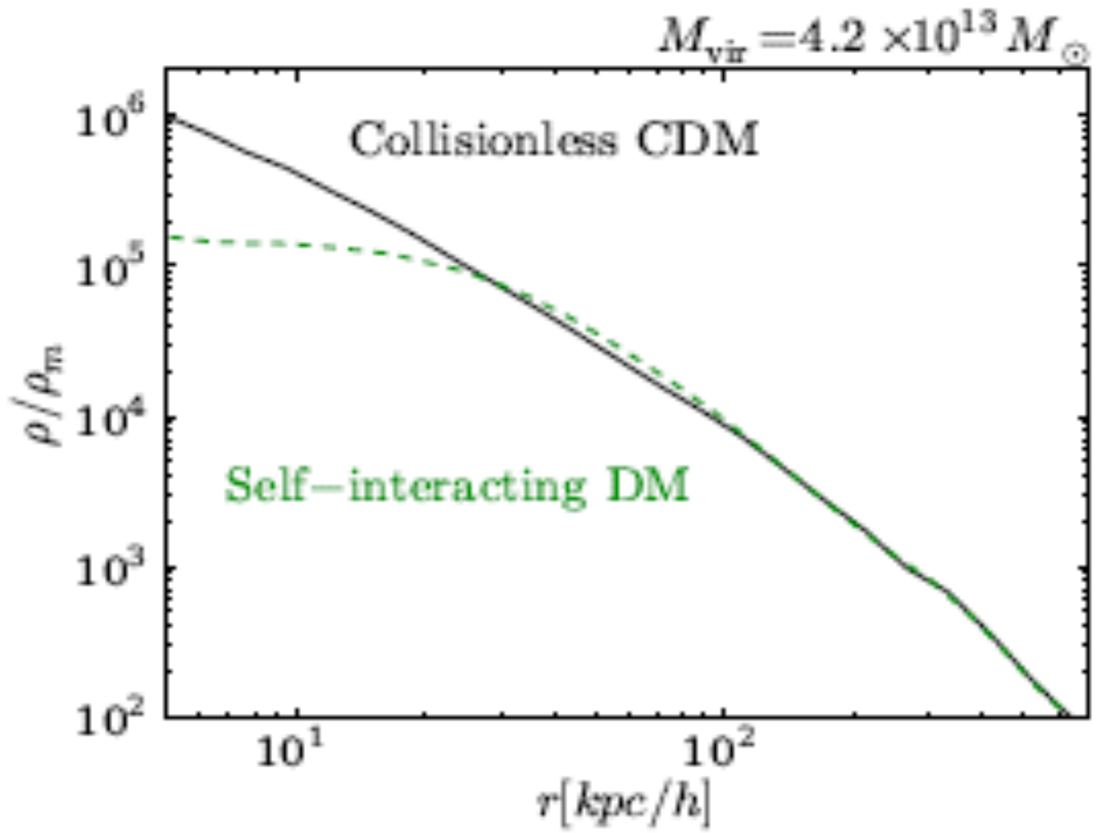


No direct evidence for WIMP;
No new physics at weak-scale.

Small-scale problems

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





- Self-interacting DM makes core profile at small scales.

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

Beyond WIMP!

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

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

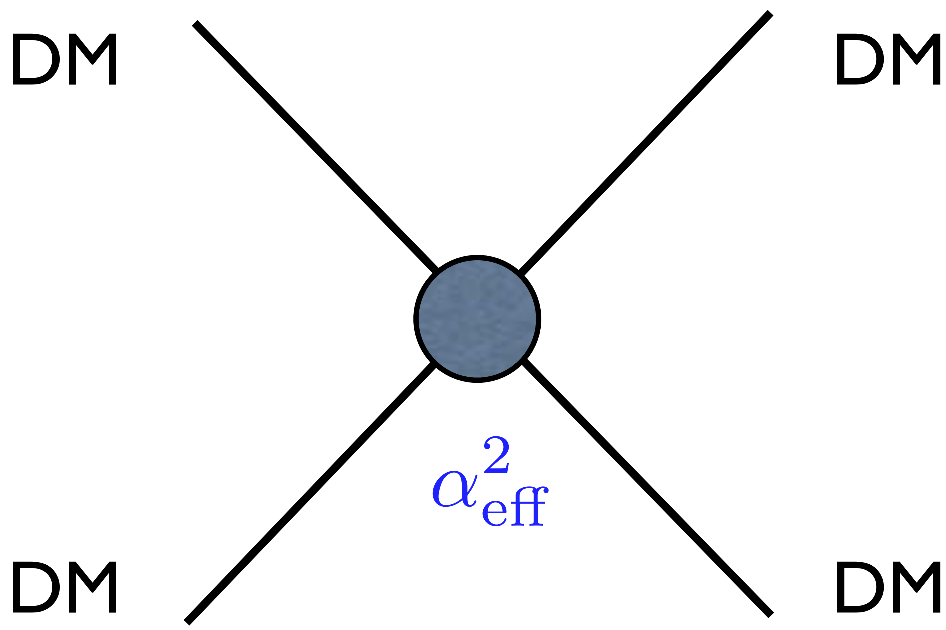
  self-interacting, long-lived mesons

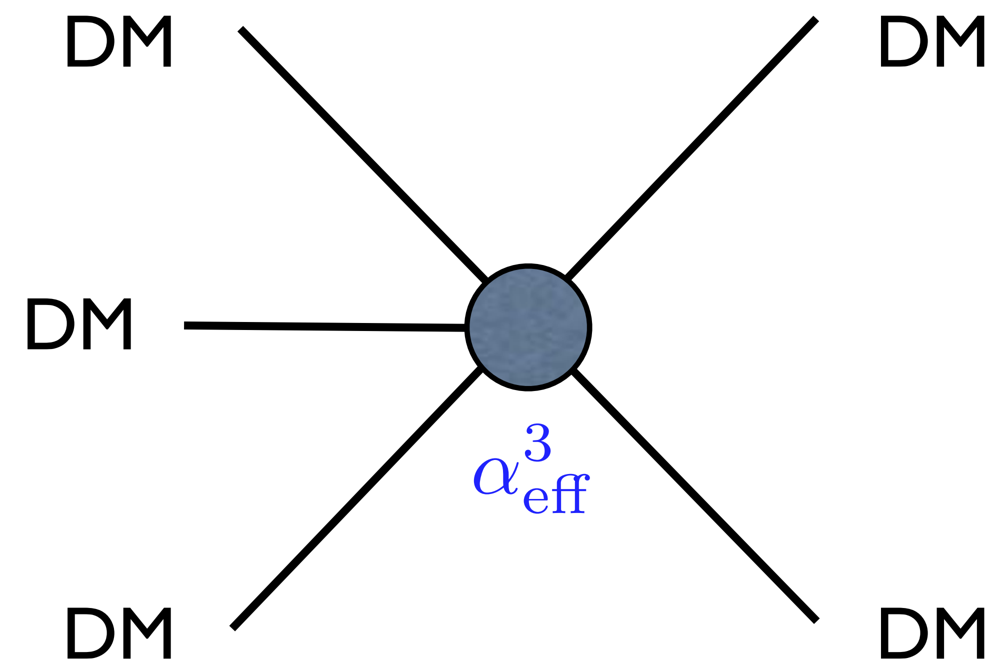
SIMP mechanism

- Self-scattering vs 3→2 annihilation

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

Number-changing DM self-interactions





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

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

$$R=\frac{g_{\rm DM}\alpha_{\rm eff}}{(2\pi)^{3/2}}\,x_f^{-3/2}\,e^{-x_f}$$ → naturally small annihilation

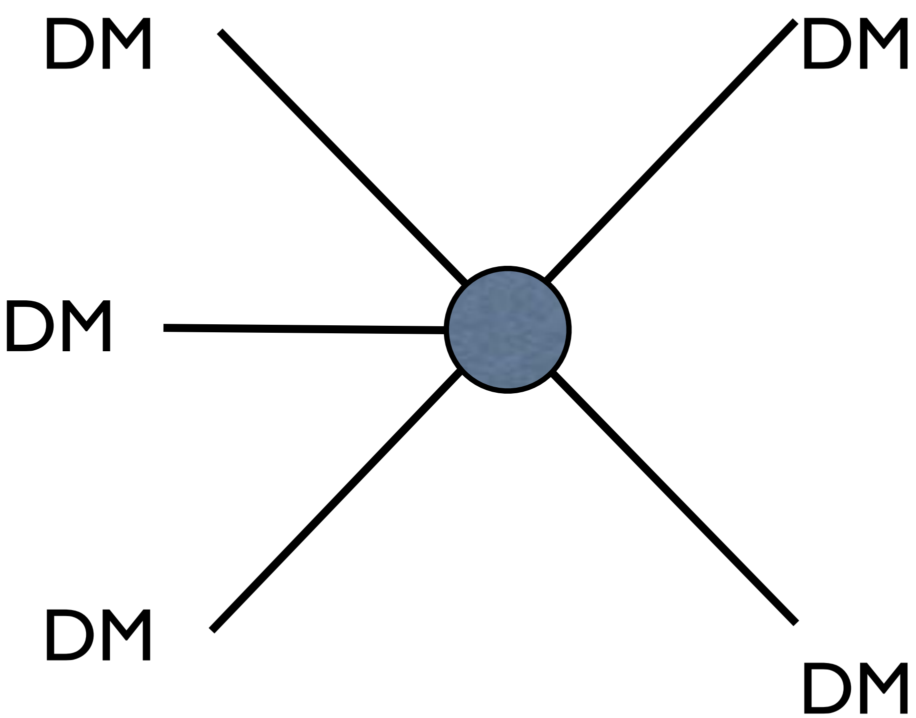
Relic density: $\alpha_{\rm eff}\sim 3\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)$

Strongly Interacting
Massive Particles (SIMP)

SIMP abundances

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

- Thermal average of general 3→2 annihilation



Boltzmann equation for SIMP:

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

Thermal average:

$$\langle\sigma v^2\rangle = \frac{1}{n_1^{\rm eq} n_2^{\rm eq} n_3^{\rm eq}}\frac{1}{s_i s_f}\int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_5 f_1^{\rm eq} f_2^{\rm eq} f_3^{\rm eq}(2\pi)^4\delta^4(p)|\mathcal{M}_{3\to 2}|^2$$

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

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

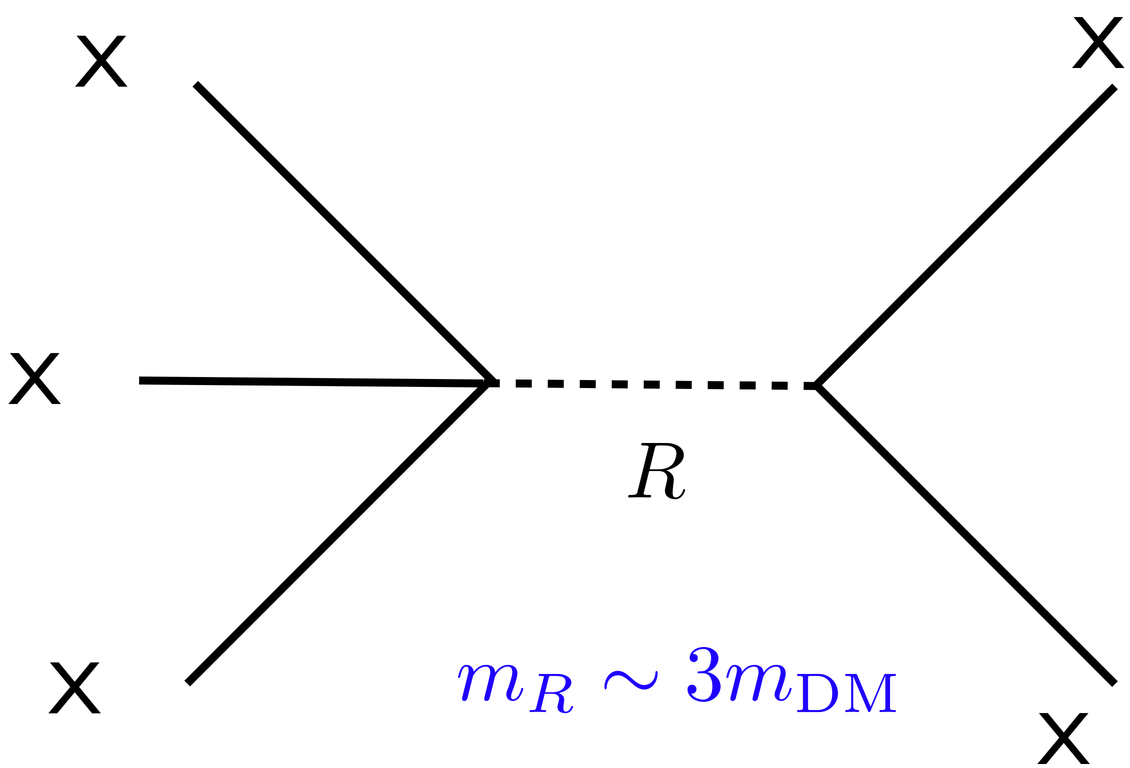
In general: $\sigma v^2 \sim (v_1^2)^n (v_2^2)^m (v_3^2)^l \;\rightarrow\; \langle\sigma v^2\rangle \sim c_{nml}\,x^{-n-m-l}$

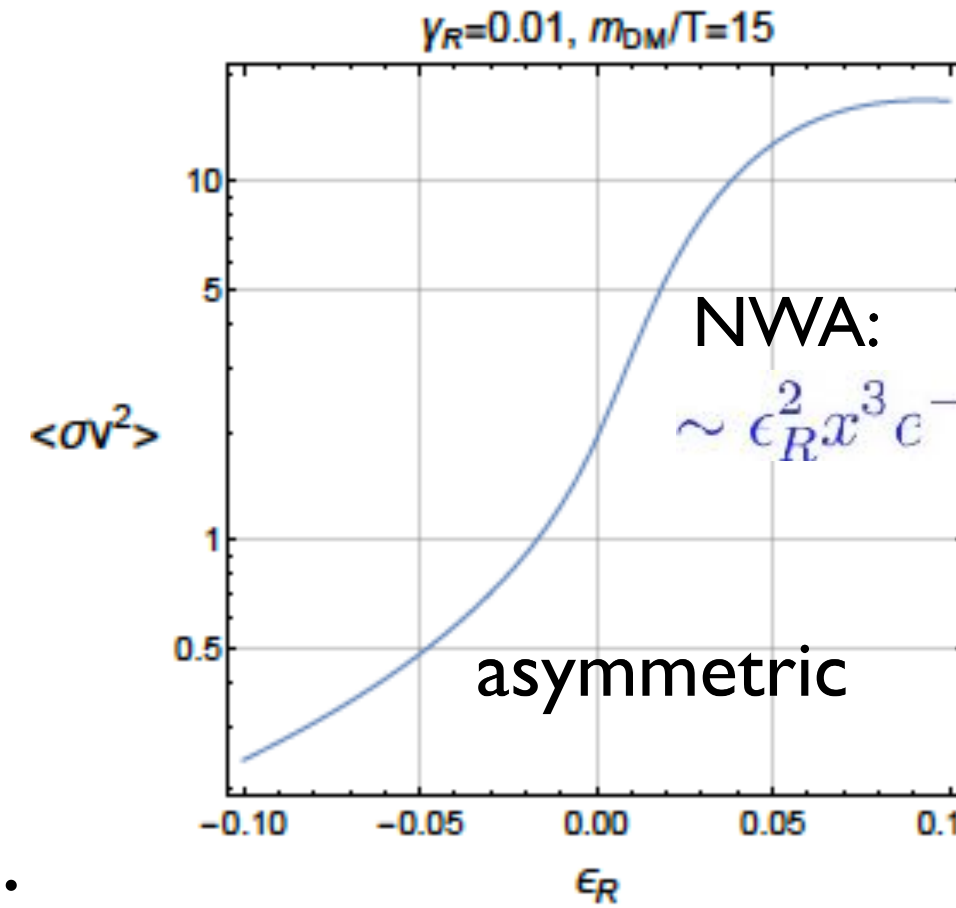
(n,m,l)	$(1,0,0)$	$(1,1,0)$	$(2,0,0)$	$(1,1,1)$	$(2,1,0)$	$(3,0,0)$
c_{nml}	2	$\frac{14}{3}$	$\frac{20}{3}$	$\frac{100}{9}$	$\frac{160}{9}$	$\frac{280}{9}$

SIMP resonances

[S.-M. Choi, HML, 2016; + M.-S. Seo, 2017]

- 3→2 annihilation cross enhances near resonance.





NWA:
$$\sim \epsilon_R^2 x^3 e^{-\frac{3}{2}x\epsilon_R}\theta(\epsilon_R)$$

cf. WIMP:
$$\langle\sigma v\rangle_R \sim \epsilon_R^{1/2} x^{3/2}$$

Breit-Wigner form for SIMP:

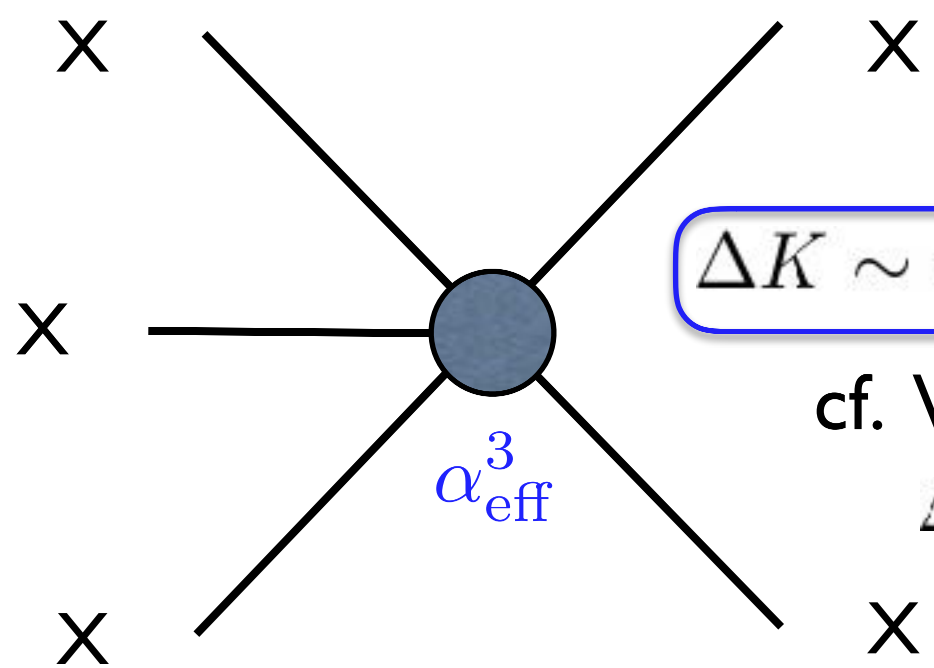
$$\boxed{(\sigma v^2)_R = \frac{9\sqrt{5}}{2\beta_\chi \Phi_3 m_R^3}\frac{\gamma_R^2}{(\epsilon_R-\frac{2}{3}\eta)^2+\gamma_R^2}\,{\rm Br}(R\to\chi\chi\chi)\,{\rm Br}(R\to\chi\chi)} \sim \frac{\eta^l\gamma_R}{(\epsilon_R-\frac{2}{3}\eta)^2+\gamma_R^2}$$

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

$$\langle\sigma v^2\rangle_R \sim \frac{3}{4}\pi x^3 G_l(z_R;x), \qquad G_l(z_R;x) = {\rm Re}\left[\frac{i}{\pi}\int_0^\infty d\eta\,\frac{\eta^{l+2}e^{-x\eta}}{\frac{3}{2}z_R-\eta}\right] \qquad z_R \equiv \epsilon_R + i\gamma_R.$$

Kinetic equilibrium

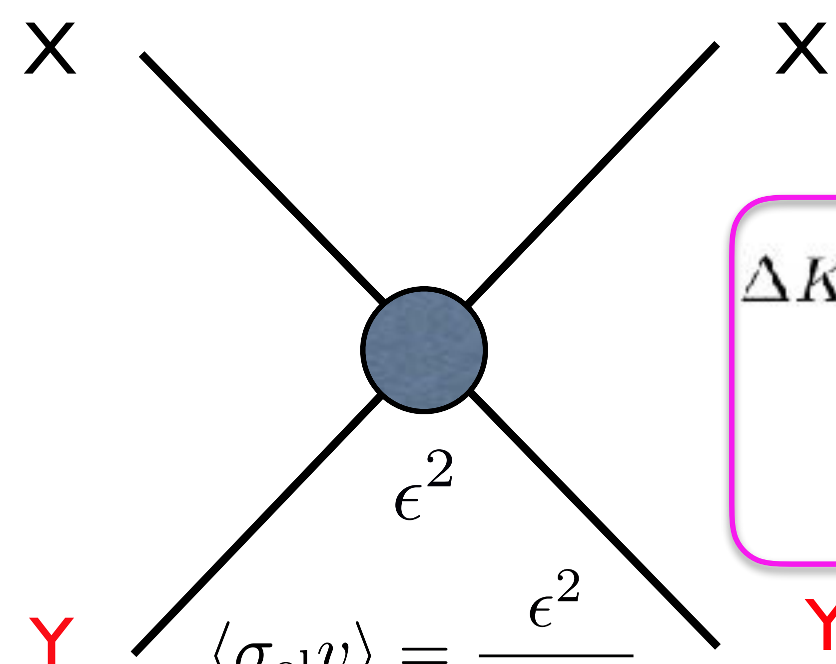
- Excess of kinetic energy released by SIMP process needs equilibriated by the SM plasma. [de Laix et al, 1995]



$$\boxed{\Delta K \sim m_{\rm DM}}$$

cf. WIMP:

$$\Delta K \sim T$$



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

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

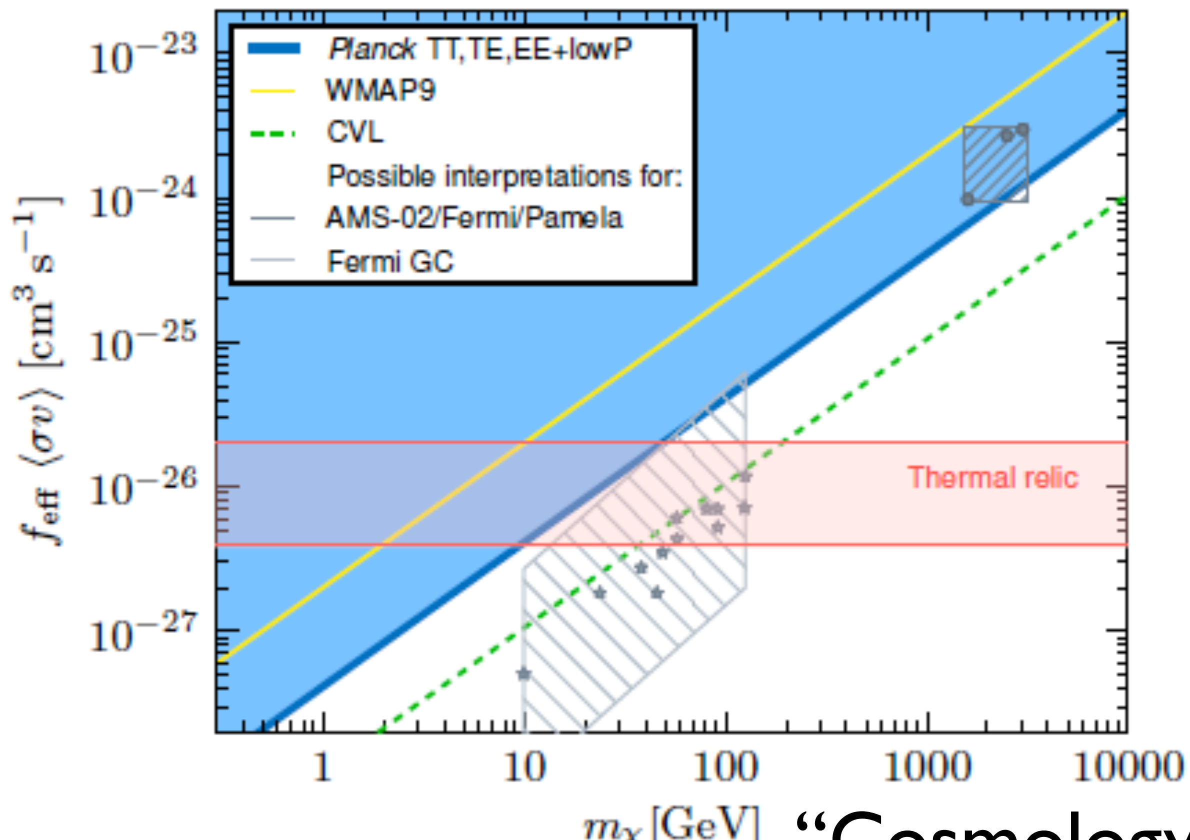
Boltzmann equation for DM kinetic energy: [VSIMPers, 2017]

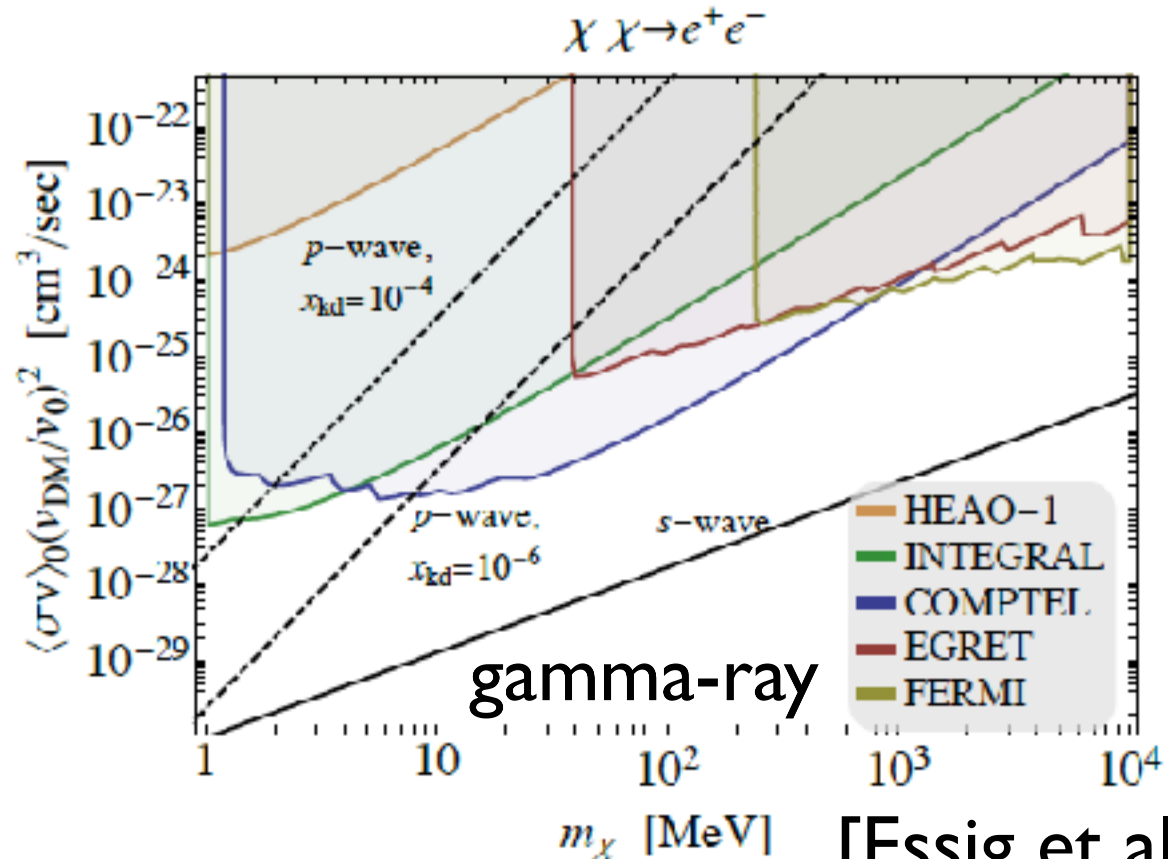
$$\dot{K} + 2HK = \underbrace{-m_{\rm DM}^2 H T^{-1}}_{3\to 2} + \underbrace{T\gamma(T)}_{\text{elastic scatt.}}, \qquad \gamma(T) \sim \left\langle n_Y \sigma_{\rm el} v_Y \, \frac{T}{m_{\rm DM}} \right\rangle.$$

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 $\epsilon < 2.4\times 10^{-6}\alpha_{\rm eff}$

Testing SIMP

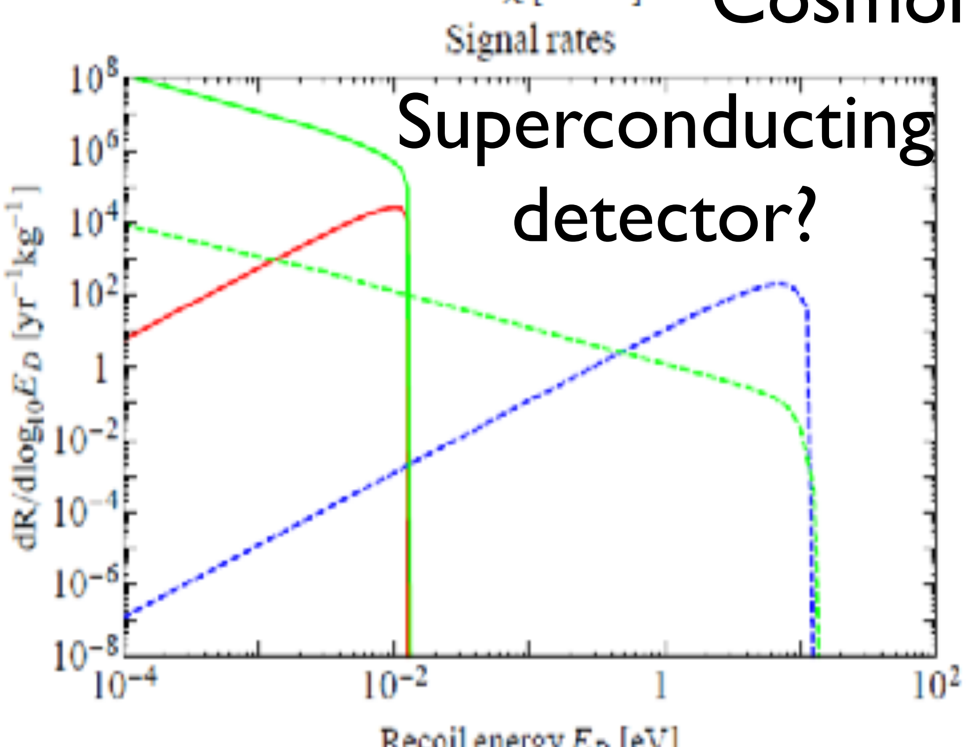




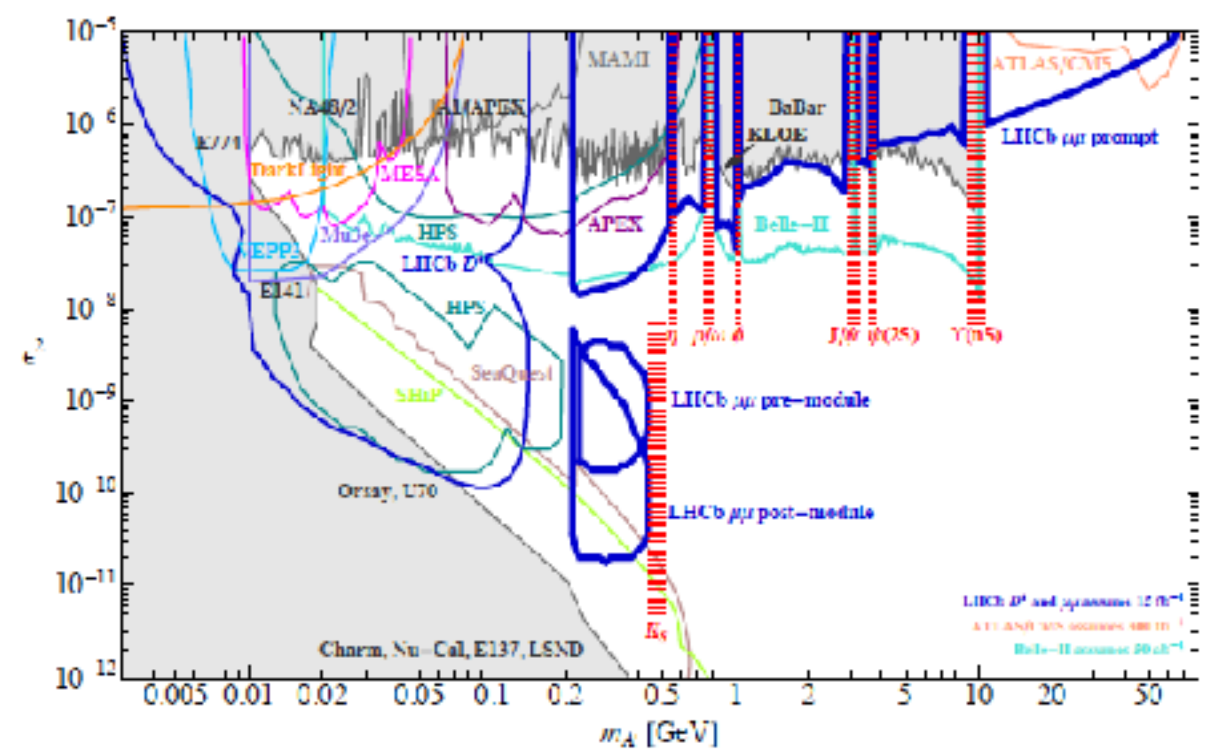
gamma-ray

"Cosmology"

[Essig et al, 2013]



Superconducting detector?



[Hochberg et al (2015)]

"Intensity"

[Ilten et al, 2016]

SIMP pions

Dark flavor
$G=SU(N_f)\times SU(N_f)$

condensate of $SU(N_c)$
dark fermions

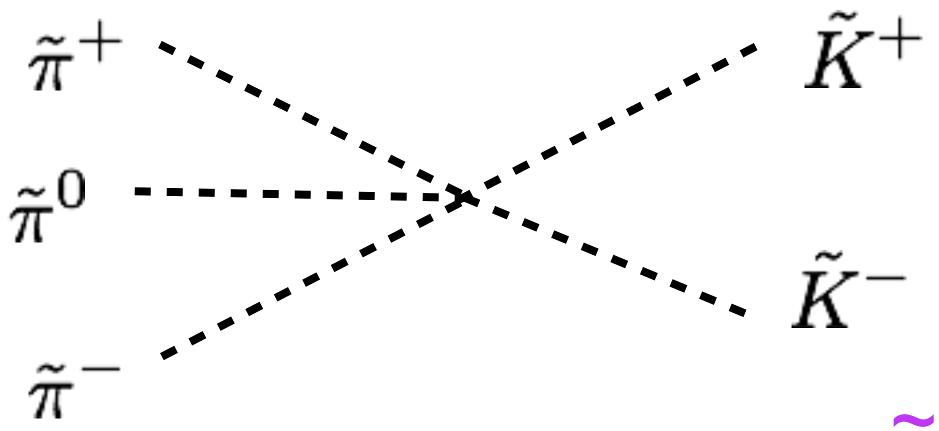
Dark pions
with $SU(N_f)_V$
flavor

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

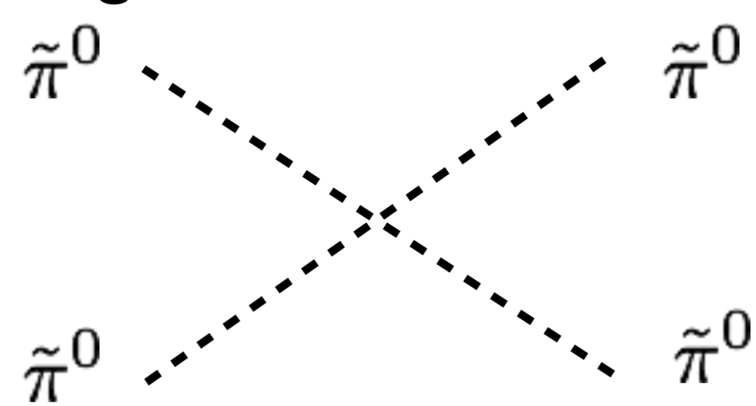
$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 F^5}\,\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

[Hochberg et al, 2014]

SIMP process:



Self-scattering:



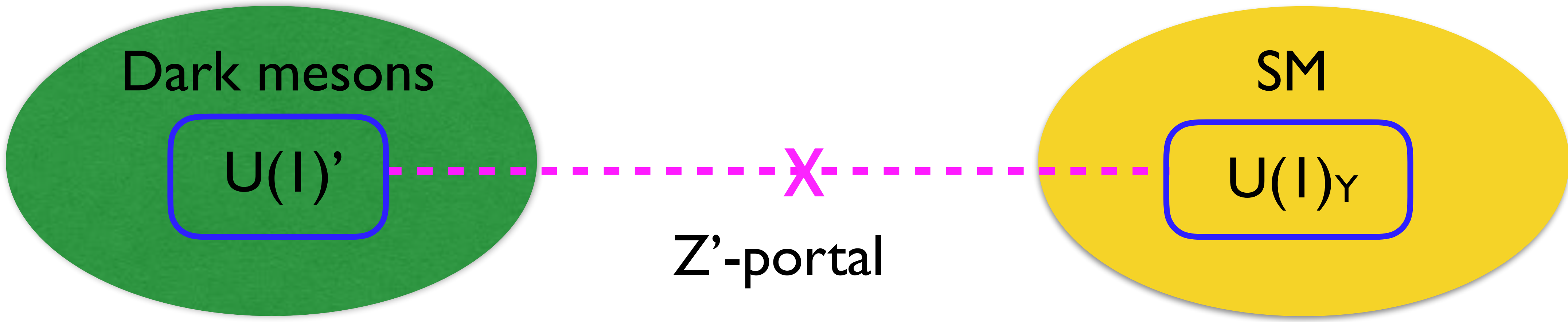
~1/N_f

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

~const

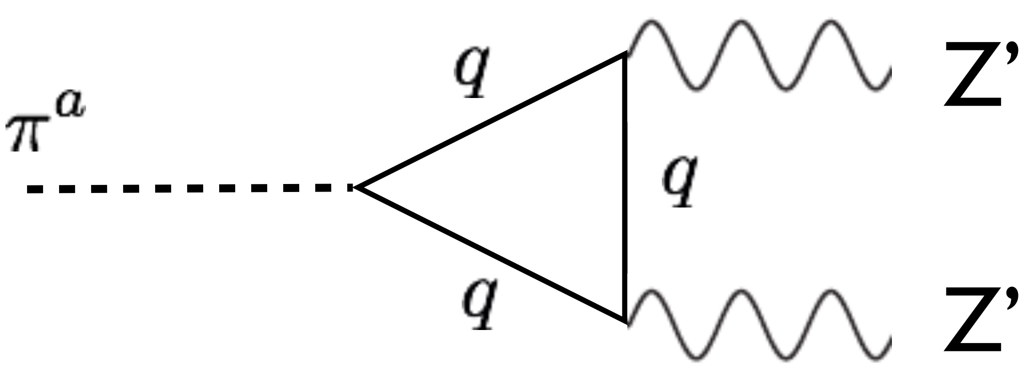
$$\sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4}\frac{a^2}{N_\pi^2}$$

Z' portal for SIMP pions



- Gauge flavor symmetry by U(1)'. [Witten, 1983]

Stability of dark pions? → no chiral anomalies or parity symmetry?



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

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

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

violates flavor symmetry,
thus, needs small Z' gauge coupling.

Kinetic equilibrium ⇨ Gauge kinetic mixing

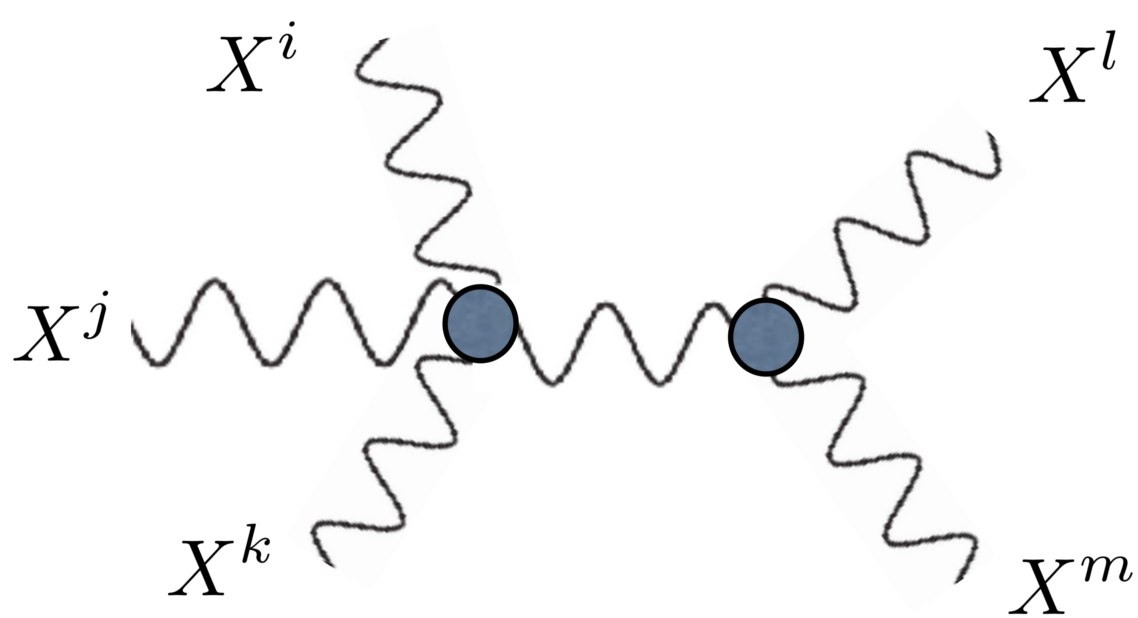
testable by invisible Z' searches [S.-M.Choi, HML, 2015]

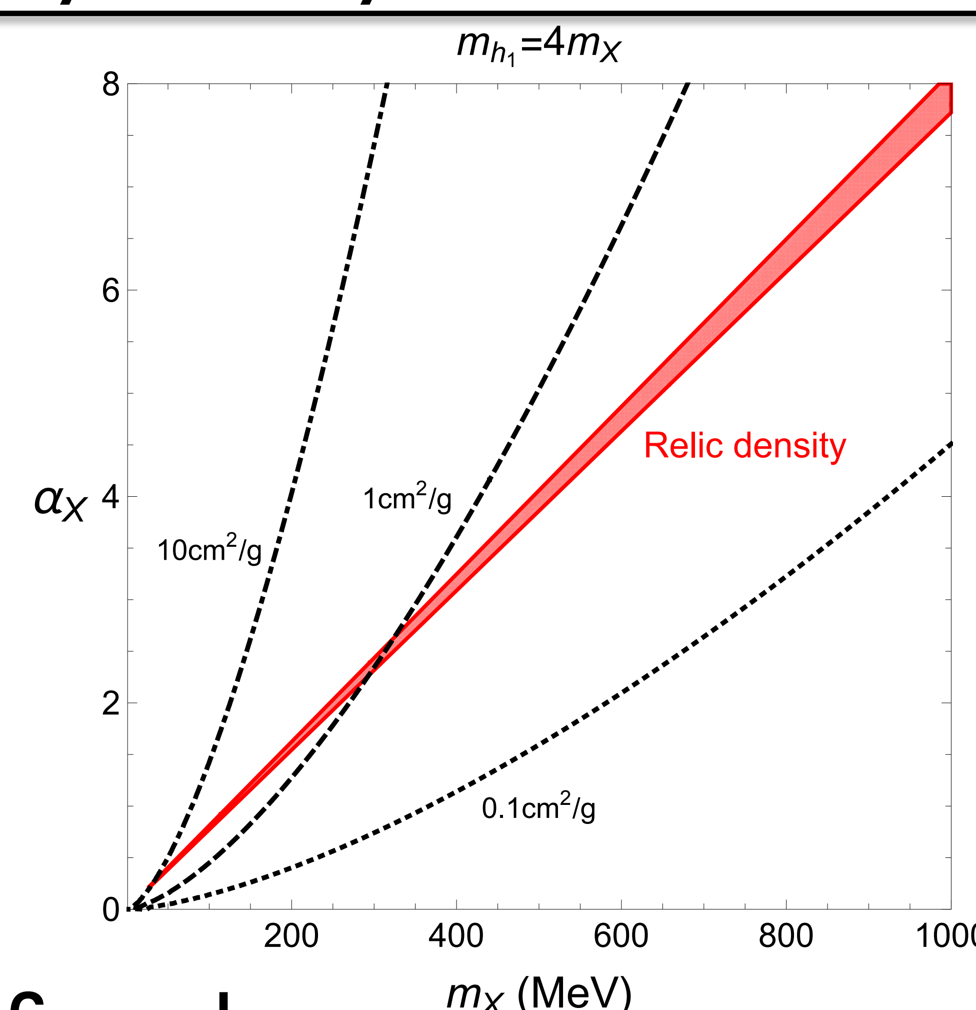
Vector SIMP

[N. Bernal et al, 2015; S.-M. Choi, Y. Hochberg, E. Kuflic, Y. Mambrini, H. Murayama, HML, M. Pierre, 2017]

- Massive $SU(2)_X$ gauge bosons = SIMPs

$\boxed{\text{Self-interacting, automatic kinetic equilibrium by Higgs portal. Stable by accidental SO(3) custodial symmetry.}}$





Relic density+ Bullet cluster:

$m_{\rm DM} \gtrsim 300\,\mathrm{MeV}\,, \quad \alpha_X \gtrsim 1$

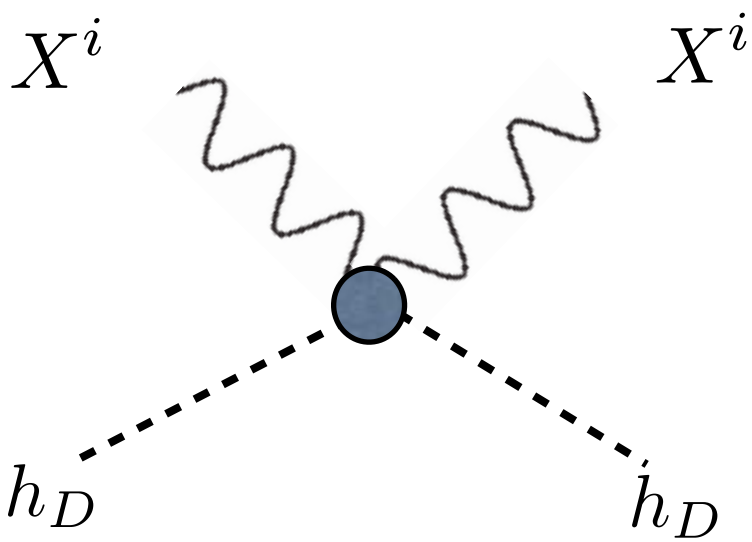
Strong coupling? → Higgs/confine phase complementarity

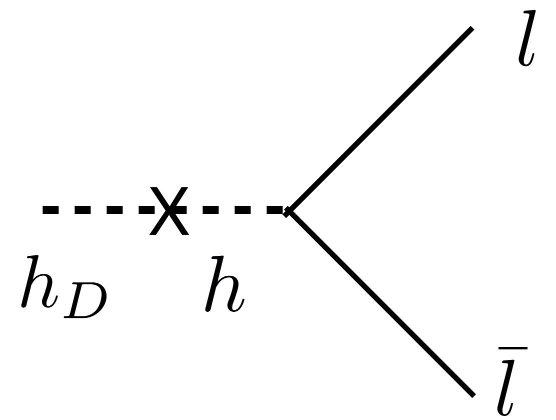
['t Hooft, 1980]

Higgs portal for VSIMP

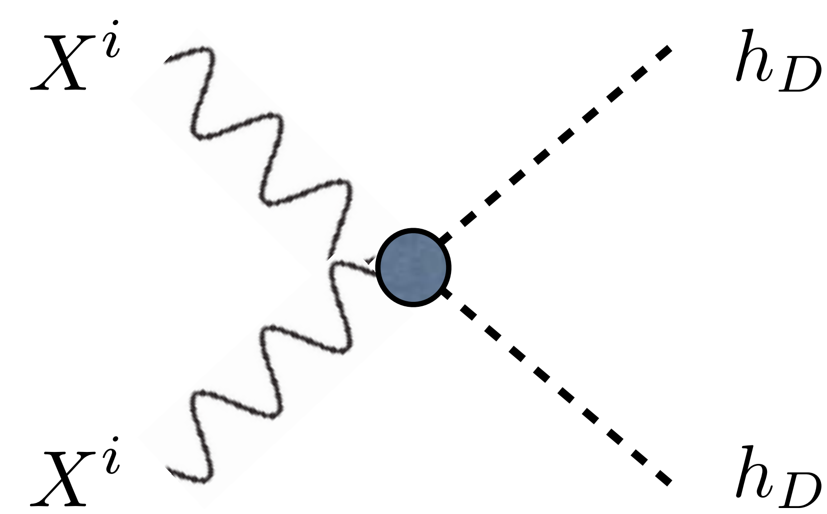
Bound from Higgs invisible decay restricts to light dark Higgs region.

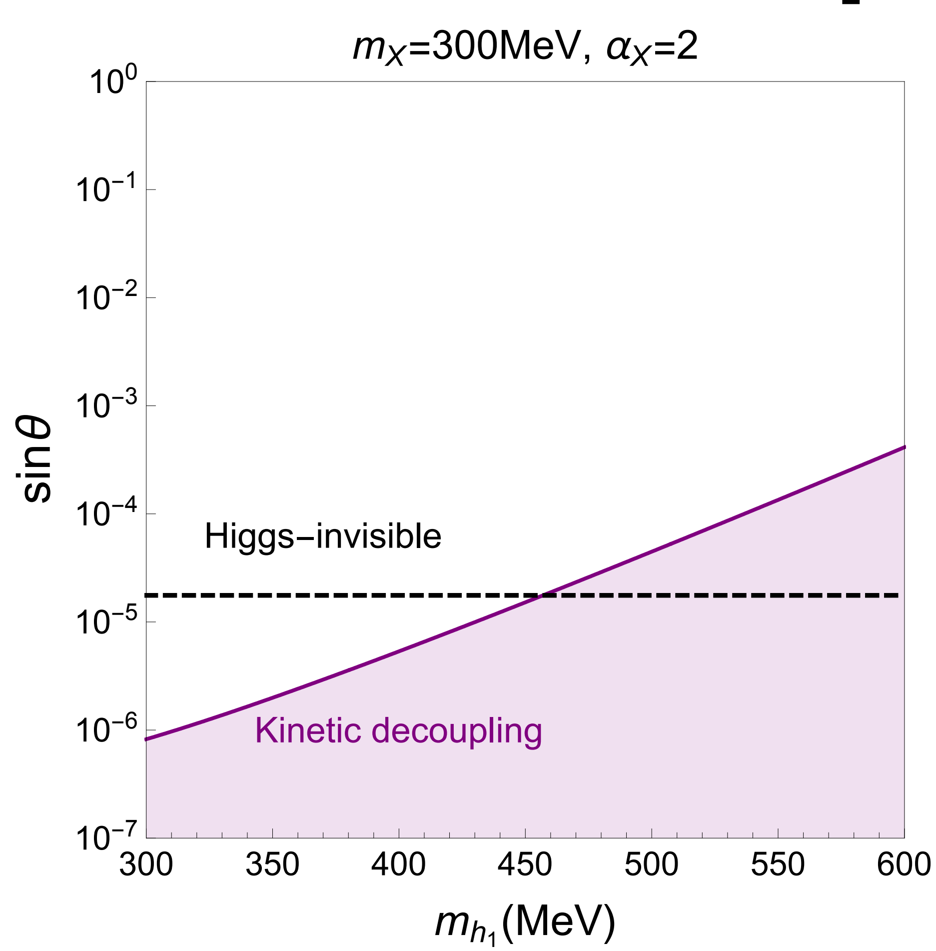
Include forbidden channels

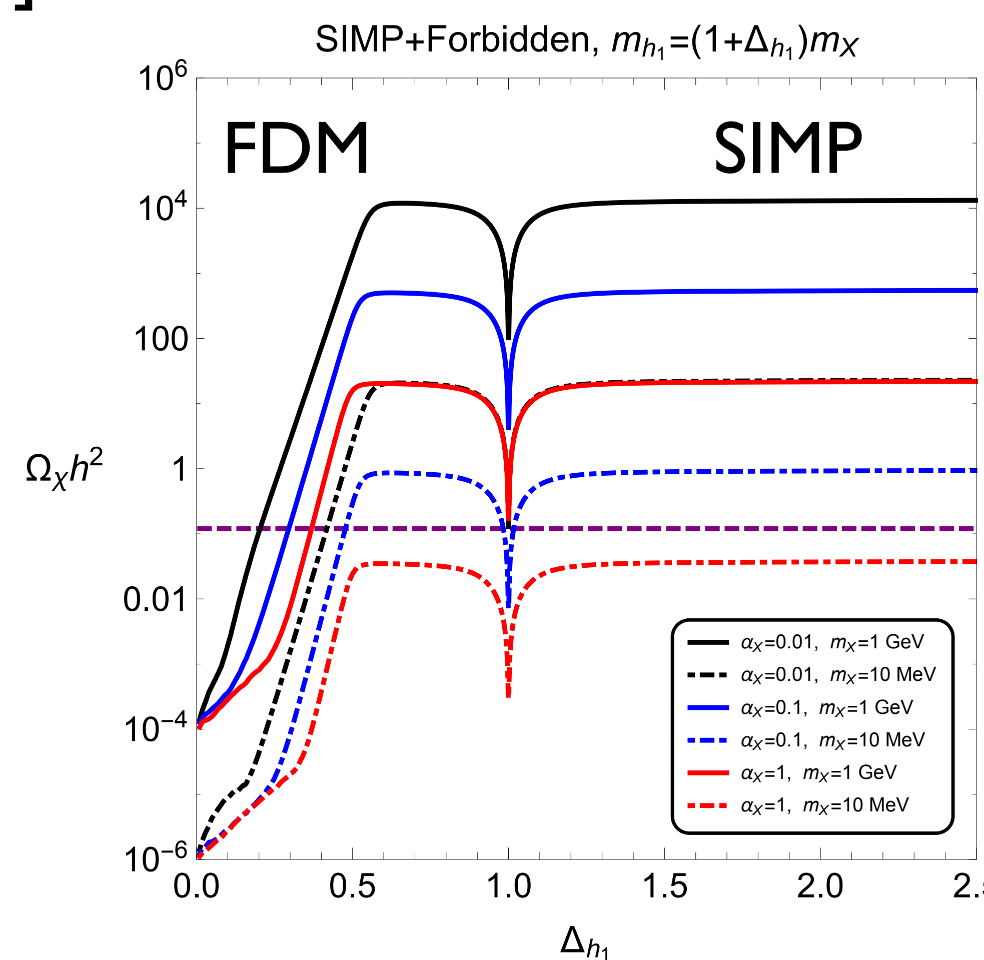




[VSIMPers, 2017]

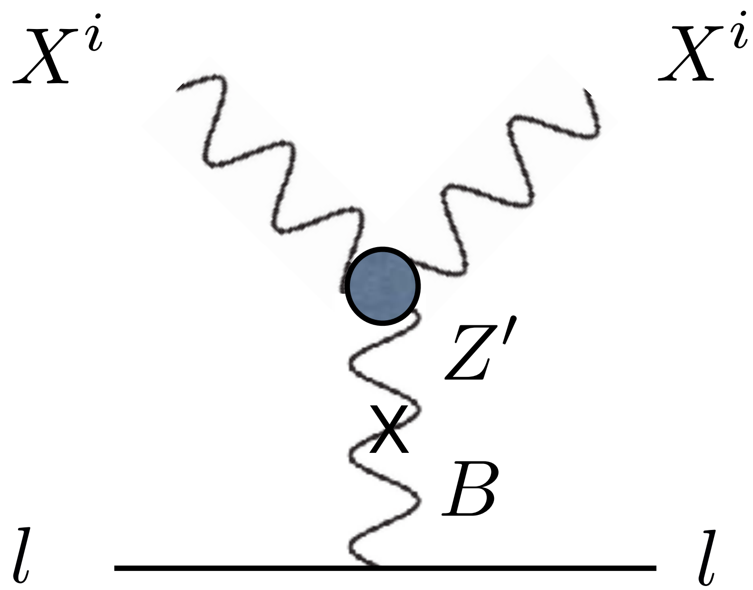






Z'-portal for VSIMP

Introduce Z' for DM-electron scattering.

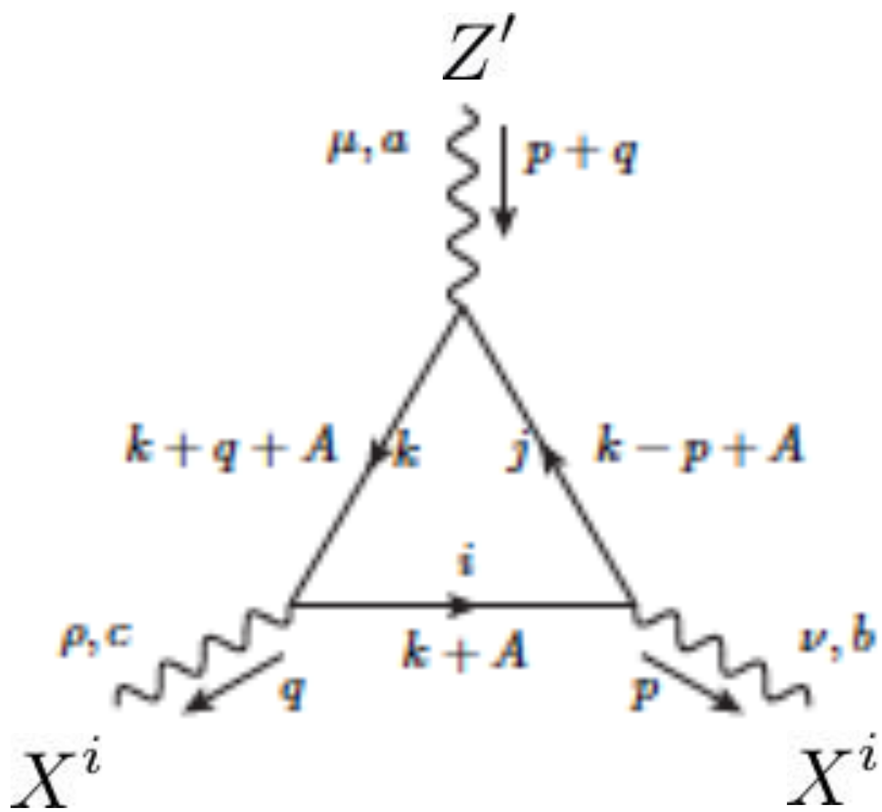


1) Gauge kinetic mixing
2) Z'-X-X effective vertex
3) No dark Weinberg angle

$$\mathcal{L}_{\text{vector}} = -\frac{1}{2}\sin\xi\, Z'_{\mu\nu}B^{\mu\nu} + \mathcal{L}_{XXZ'}$$

Chern-Simons term: fully SO(3) invariant

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



<u>Gauge-inv EFT:</u> $\mathcal{L}_{DF} = \frac{i}{M^4} S^\dagger D^\mu S (D^\nu \Phi)^\dagger \tilde{X}_{\mu\nu} \Phi + \text{c.c.}$

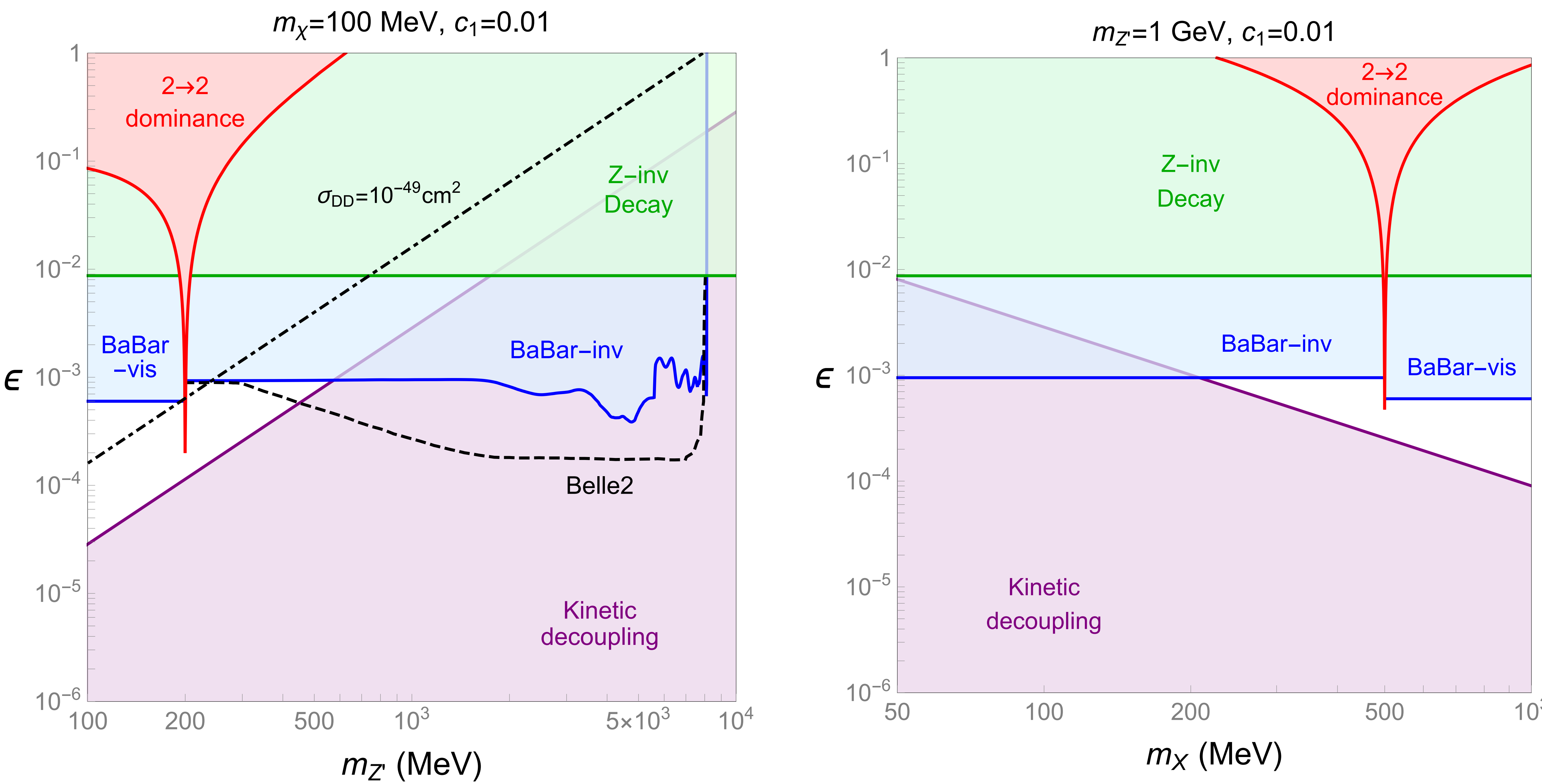
"D'Hoker-Farhi term"

<u>UV model:</u> $l = (2, +1), \quad \tilde{l} = (2, +1), \quad e^c = (1, -1), \quad \tilde{e}^c = (1, -1).$

Anomalies cancelled by other fermions, but

Remnant: $c_1 \sim \frac{N_f \alpha_X g'}{4\pi} \frac{m_X^2}{m_f^2}$

Z'-portal for VSIMP



Kinetic equilibrium and BaBar invisible decay on Z' restricts to light Z' or heavy DM.

Conclusions

- SIMP dark matter is produced by thermal freeze-out of the $3 \rightarrow 2$ 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.