

Models of light dark matter and detection



Hyun Min Lee

Chung-Ang University & CERN



New Frontiers in the Search for Dark Matter

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**The Galileo Galilei Institute
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Arcetri, Firenze



Outline

- Self-interacting dark matter
- Light dark matter & SIMP paradigm
- Non-abelian SIMP
- Conclusions

SM & Puzzles

- SM describes well fundamental interactions of elementary particles except gravity.

✓ But, Hierarchy problem

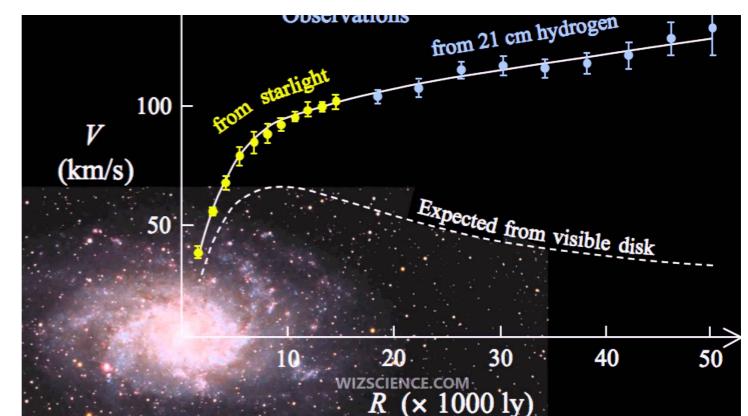
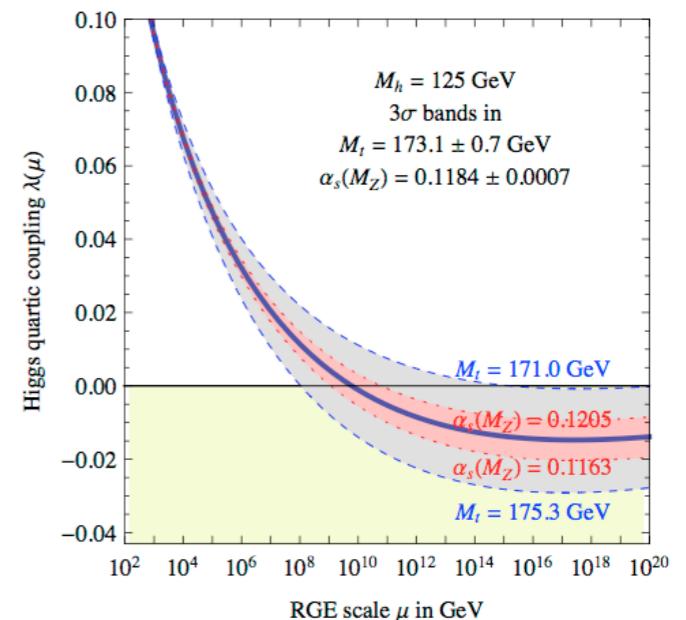
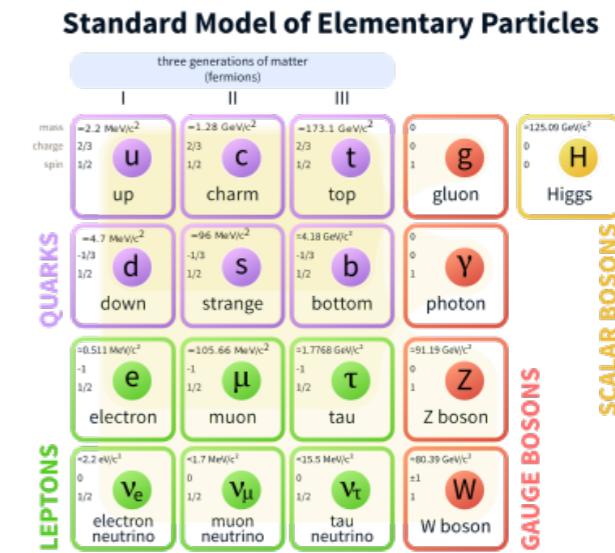
✓ Vacuum instability

✓ Electroweak symmetry breaking

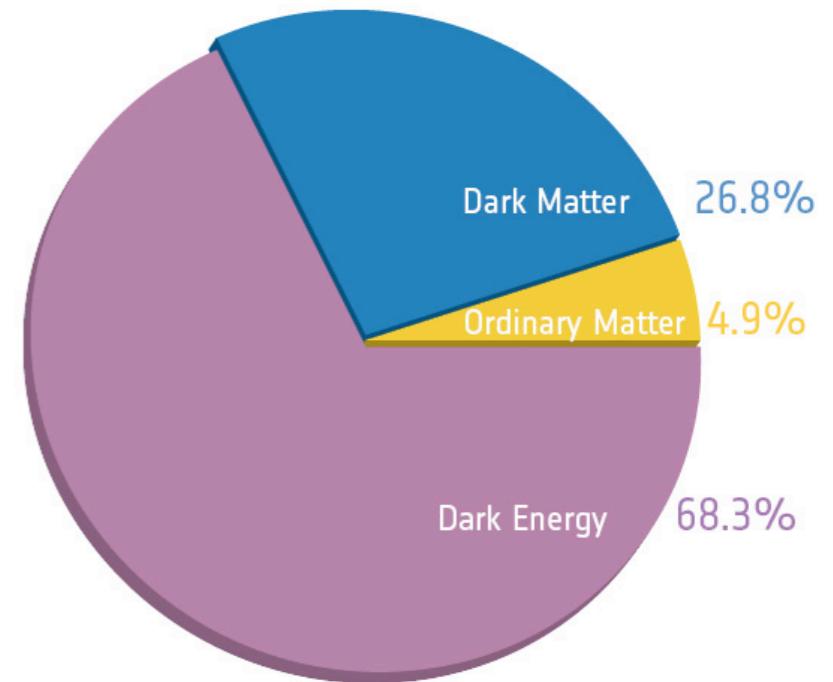
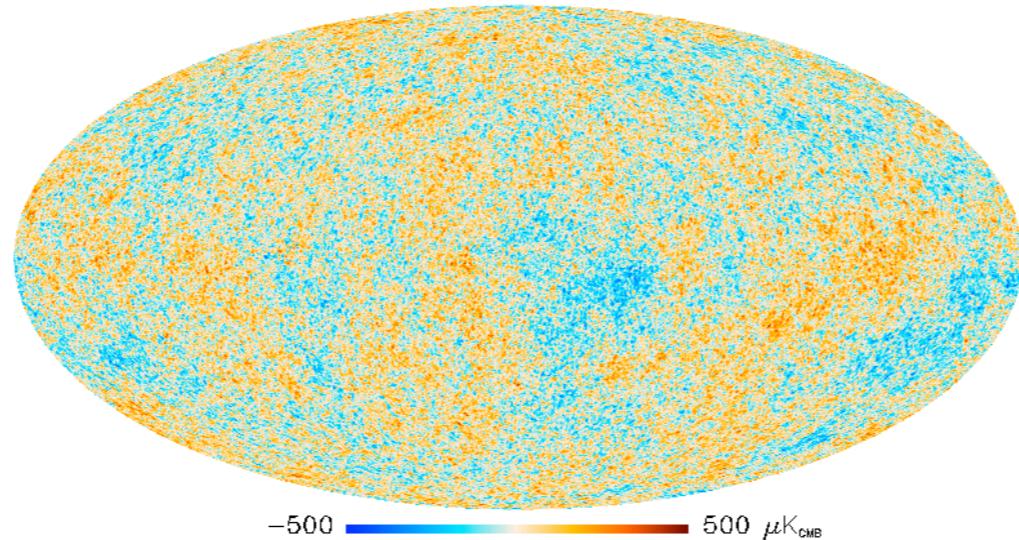
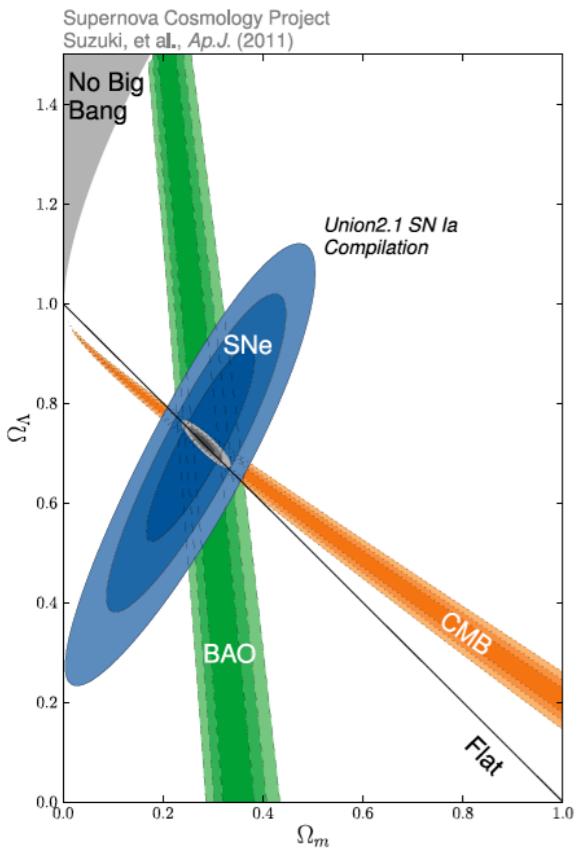
✓ Dark matter, dark energy

✓ Flavor puzzles, baryogenesis

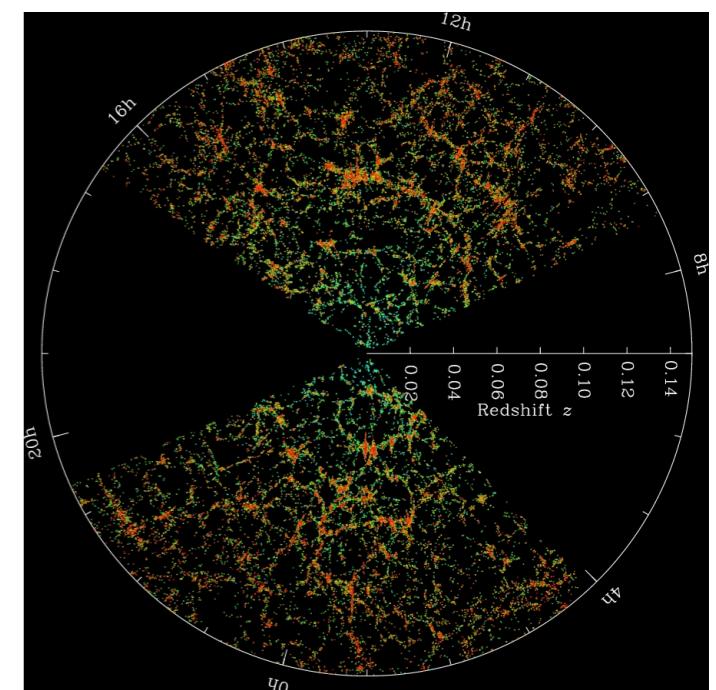
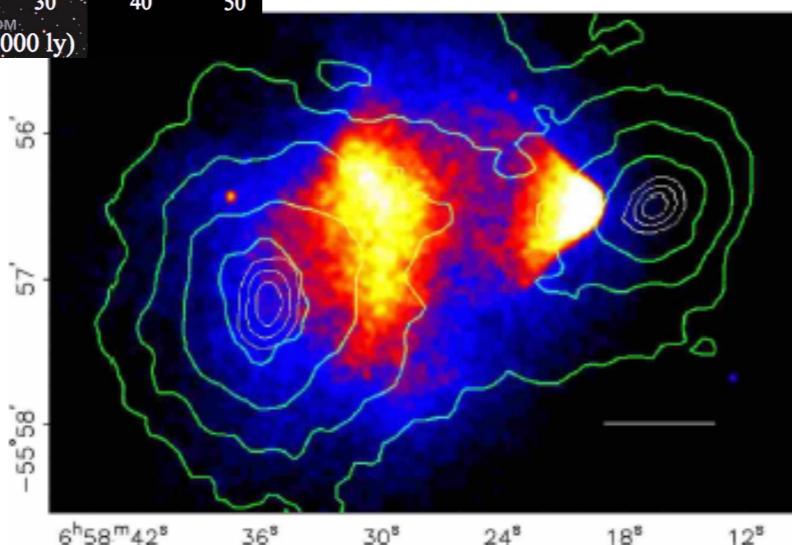
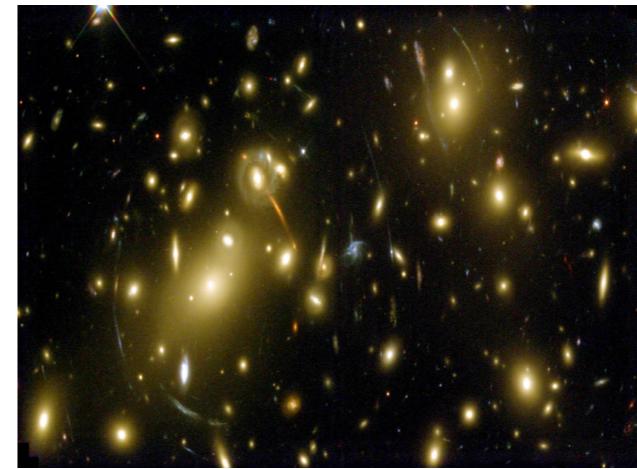
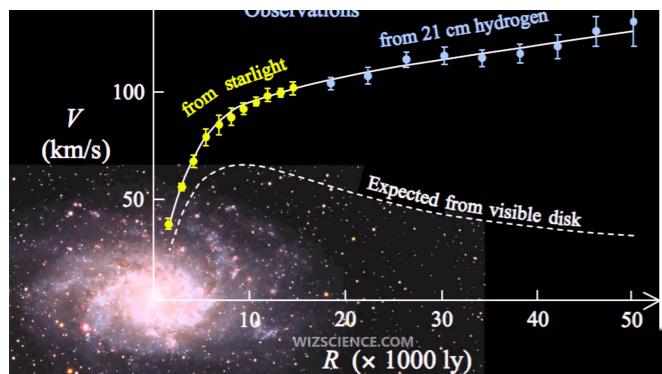
✓ Inflation, quantum gravity, unification, etc.



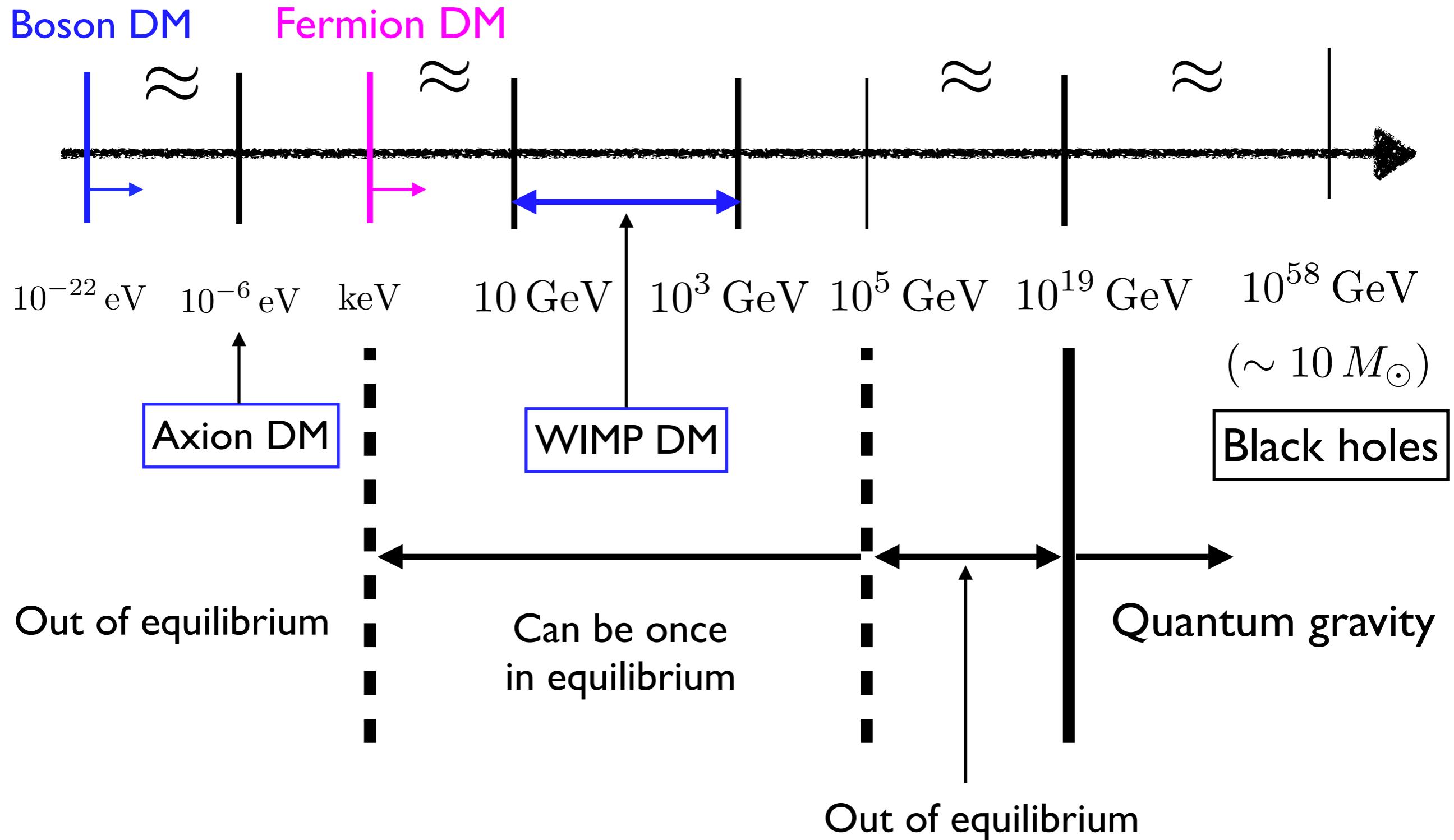
Dark matter from sky



CMB (+ flat universe)
+ SNIa + BAO

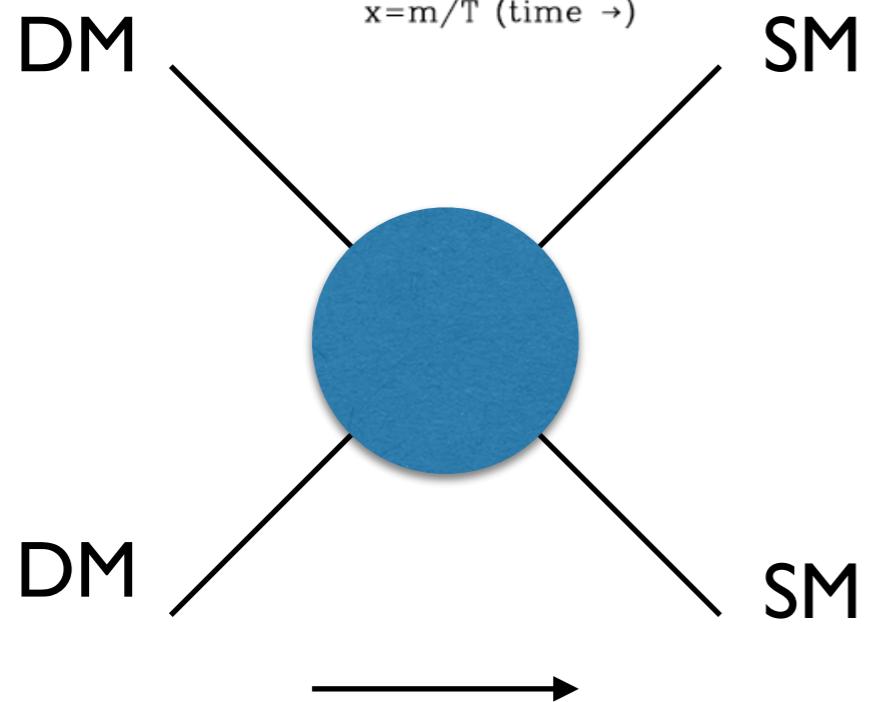
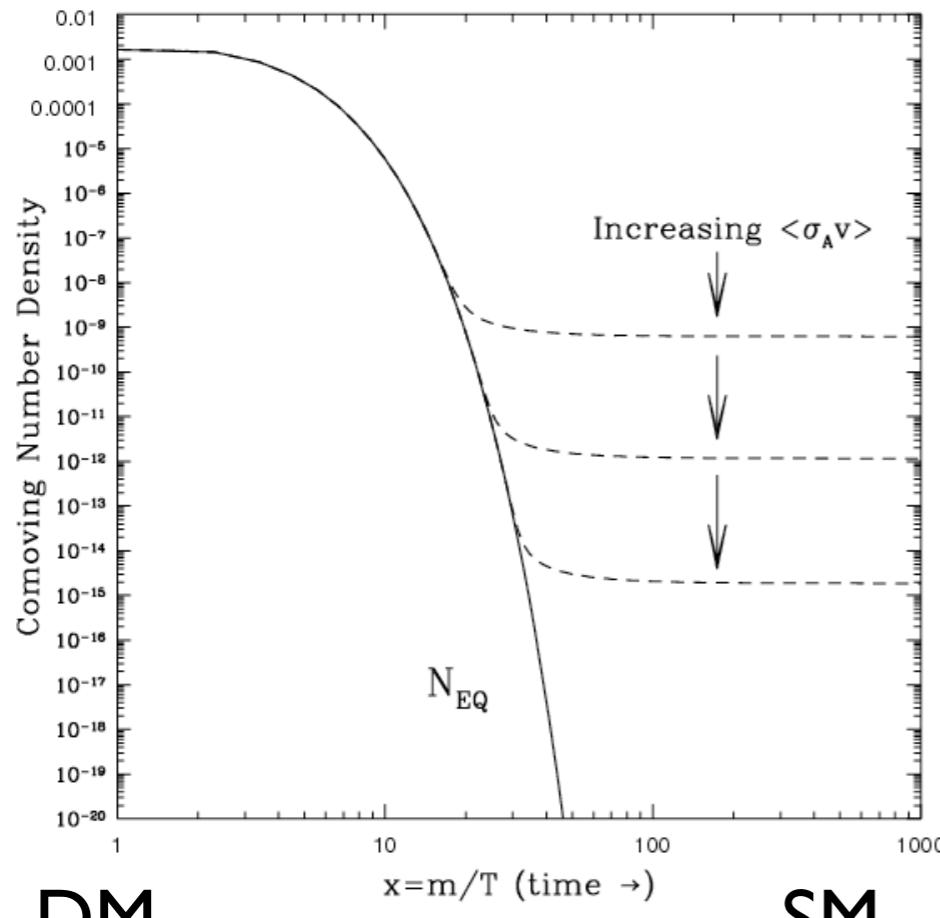


What is dark matter?

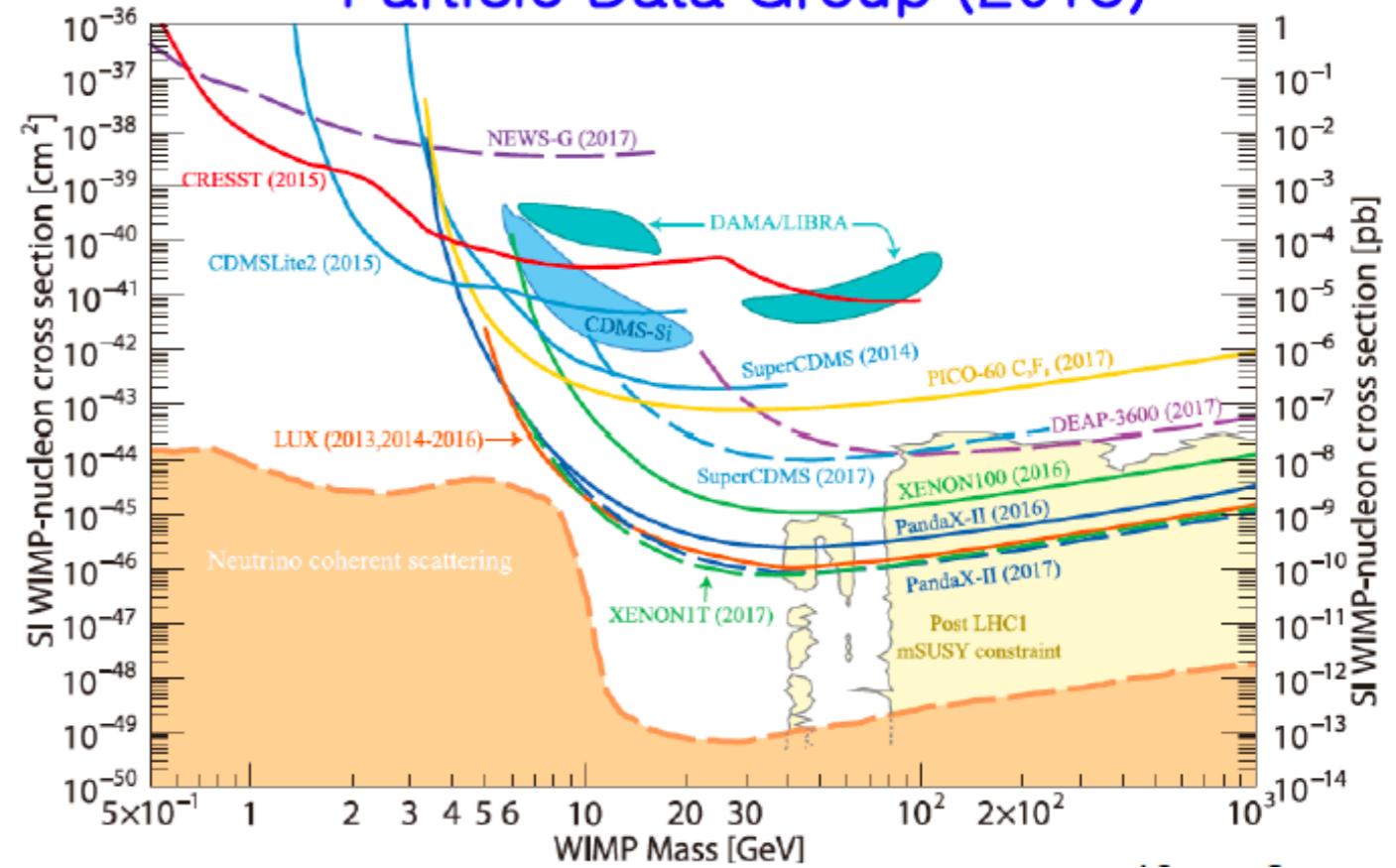


WIMP dark matter

[Lee, Weinberg(1977)]



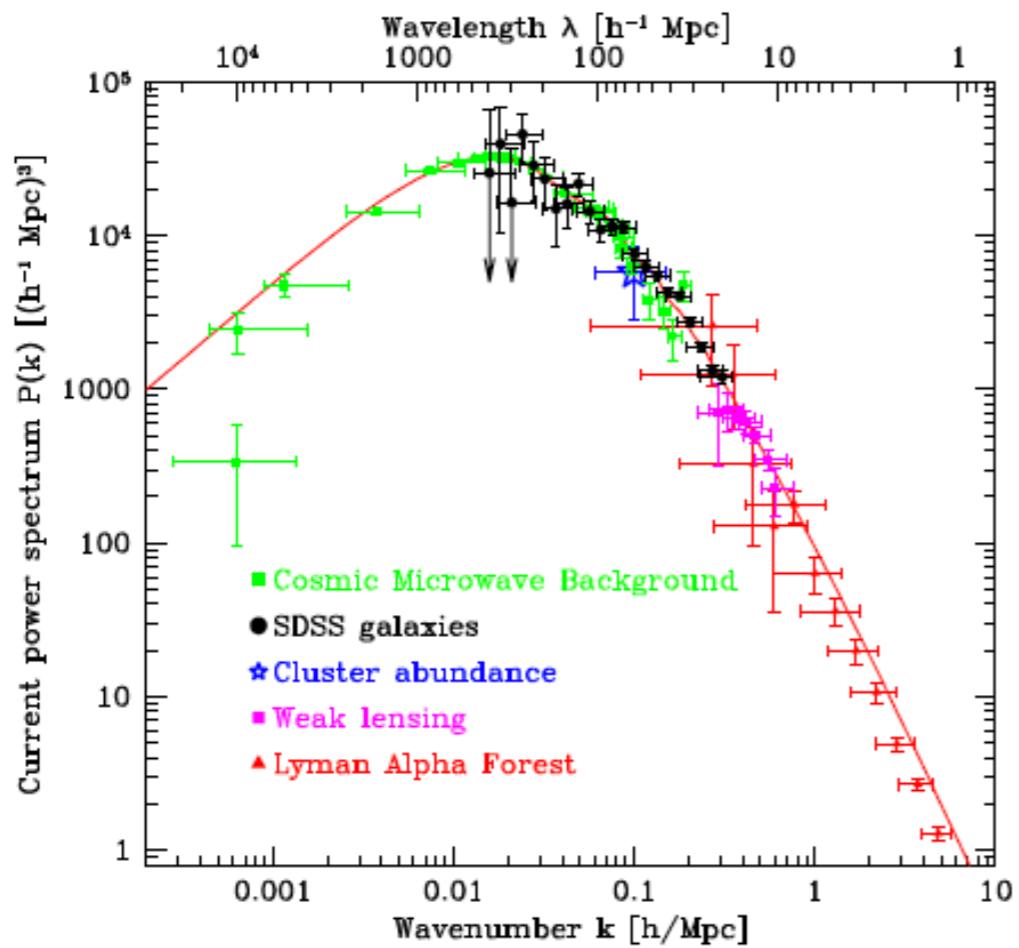
Particle Data Group (2018)



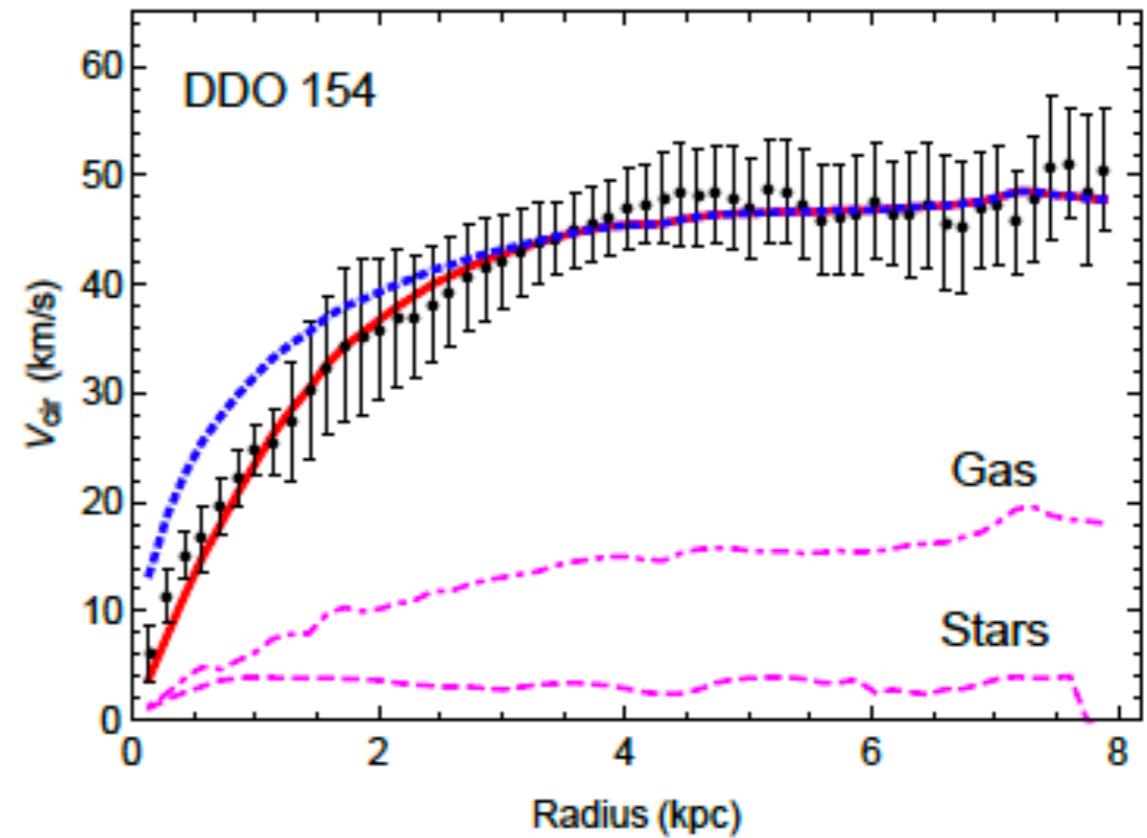
Dark matter abundance is determined by freeze-out:
weak interaction, $10\text{GeV} \sim 1\text{TeV}$ mass.

But, severe direct detection constraints!

Core-Cusp problem



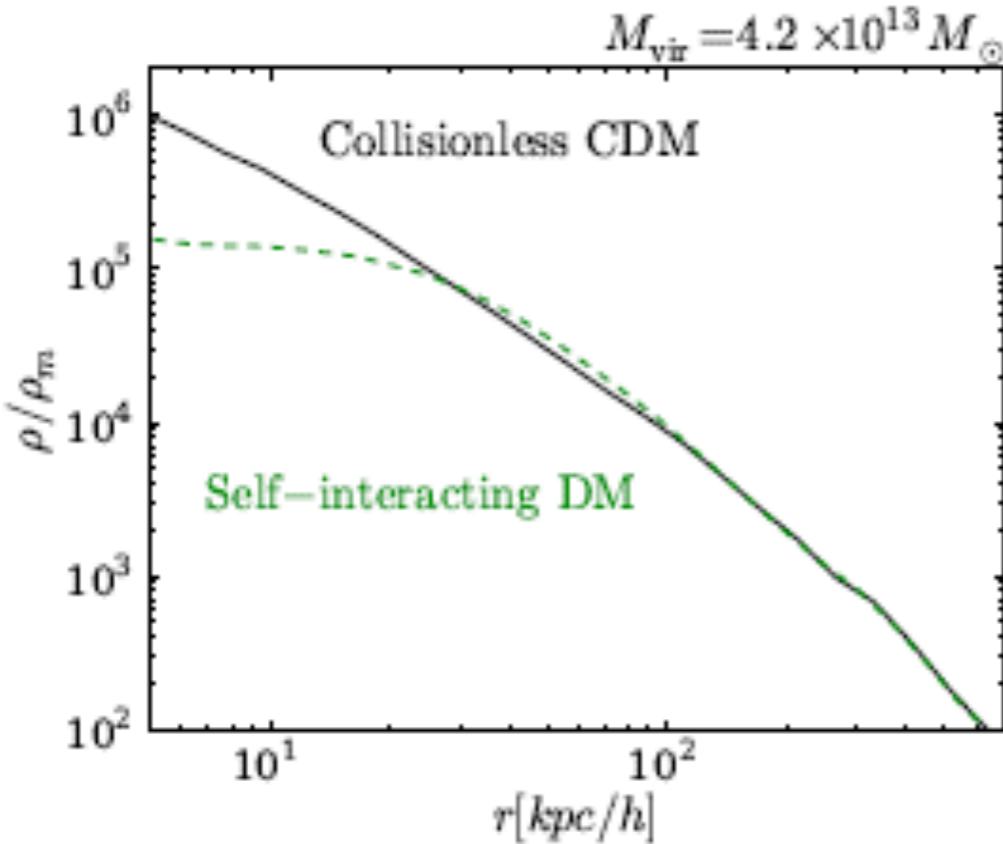
CDM at large-scales(>Mpc).



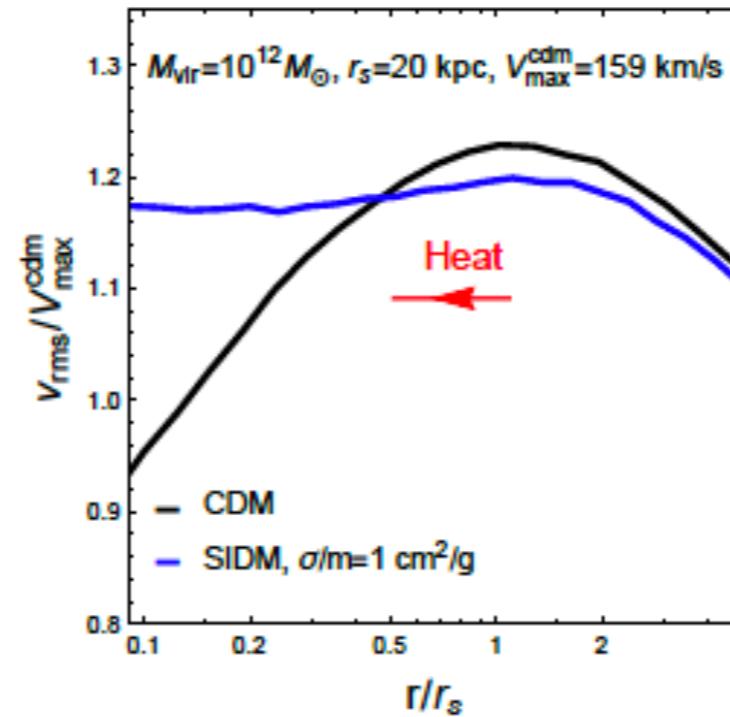
Beyond CDM at small-scales(<kpc)?
[Spergel, Steinhardt, 2000; Tulin, Yu, 2017]

- CDM N-body simulation predicts “cuspy” DM profile(NFW), rendering rotation velocities larger at small scales (\rightarrow “cored”DM profile favored).
cf. related: too-big-to-fail, missing satellite problems.

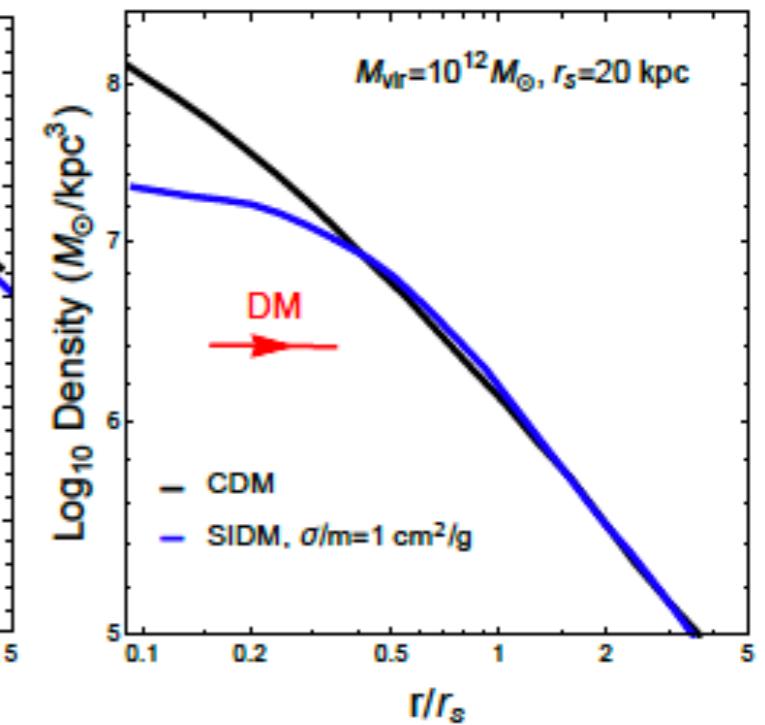
Self-Interacting dark matter



[Weinberg et al, 2013]



[Tulin, Yu, 2017]



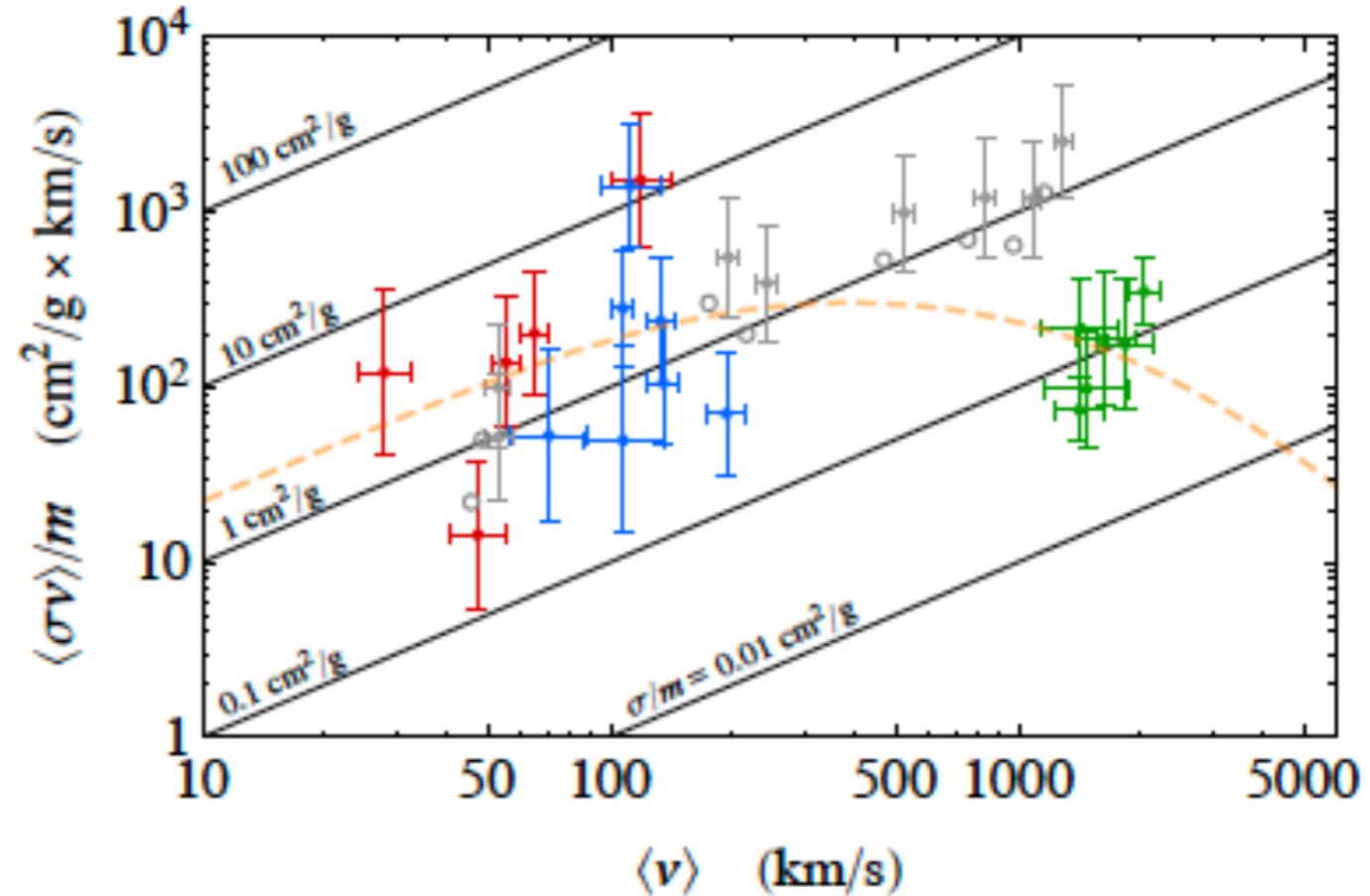
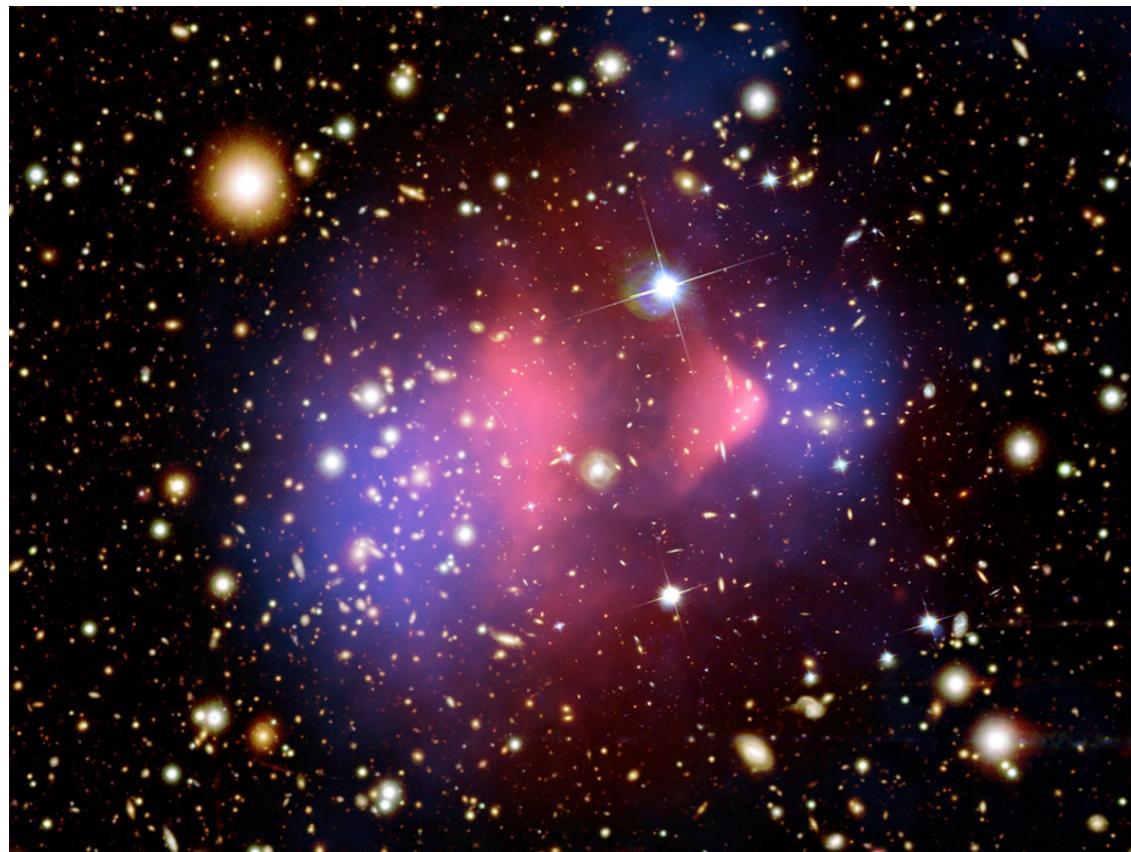
Self-interactions transport heat and flatten the DM profile.

→ Self-Interacting Dark Matter (SIDM): $\frac{\sigma_{\text{self}}}{m_{\text{DM}}} \sim 0.1 - 10 \text{ cm}^2/\text{g}$

BUT, baryons(feedback from SN)
can also erase small structures.

e.g. Brooks & Zolotov, 2012

Velocity-dependent SIDM



[M. Kaplinghat et al, 2015]

- Bullet cluster shows no DM self-interactions. $\sigma/m \lesssim 0.7 \text{ cm}^2/\text{g}$
- DM self-interaction should be velocity-dependent.



Non-minimal dark matter:
Sommerfeld enhancement or dark
resonances might be needed.

[X. Chu et al, 2018]

SIDM constraints

Positive observations	σ/m	v_{rel}	Observation
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1 \text{ cm}^2/\text{g}$	$30 - 200 \text{ km/s}$	Rotation curves
Too-big-to-fail problem Milky Way	$\gtrsim 0.6 \text{ cm}^2/\text{g}$	50 km/s	Stellar dispersion
Local Group	$\gtrsim 0.5 \text{ cm}^2/\text{g}$	50 km/s	Stellar dispersion
Cores in clusters	$\sim 0.1 \text{ cm}^2/\text{g}$	1500 km/s	Stellar dispersion, lensing
<i>Abell 3827 subhalo merger</i>	$\sim 1.5 \text{ cm}^2/\text{g}$	1500 km/s	DM-galaxy offset
<i>Abell 520 cluster merger</i>	$\sim 1 \text{ cm}^2/\text{g}$	$2000 - 3000 \text{ km/s}$	DM-galaxy offset

Constraints

Halo shapes/ellipticity	$\lesssim 1 \text{ cm}^2/\text{g}$	1300 km/s	Cluster lensing surveys
Substructure mergers	$\lesssim 2 \text{ cm}^2/\text{g}$	$\sim 500 - 4000 \text{ km/s}$	DM-galaxy offset
Merging clusters	$\lesssim \text{few cm}^2/\text{g}$	$2000 - 4000 \text{ km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)
<i>Bullet Cluster</i>	$\lesssim 0.7 \text{ cm}^2/\text{g}$	4000 km/s	Mass-to-light ratio

Light dark matter & SIMP paradigm

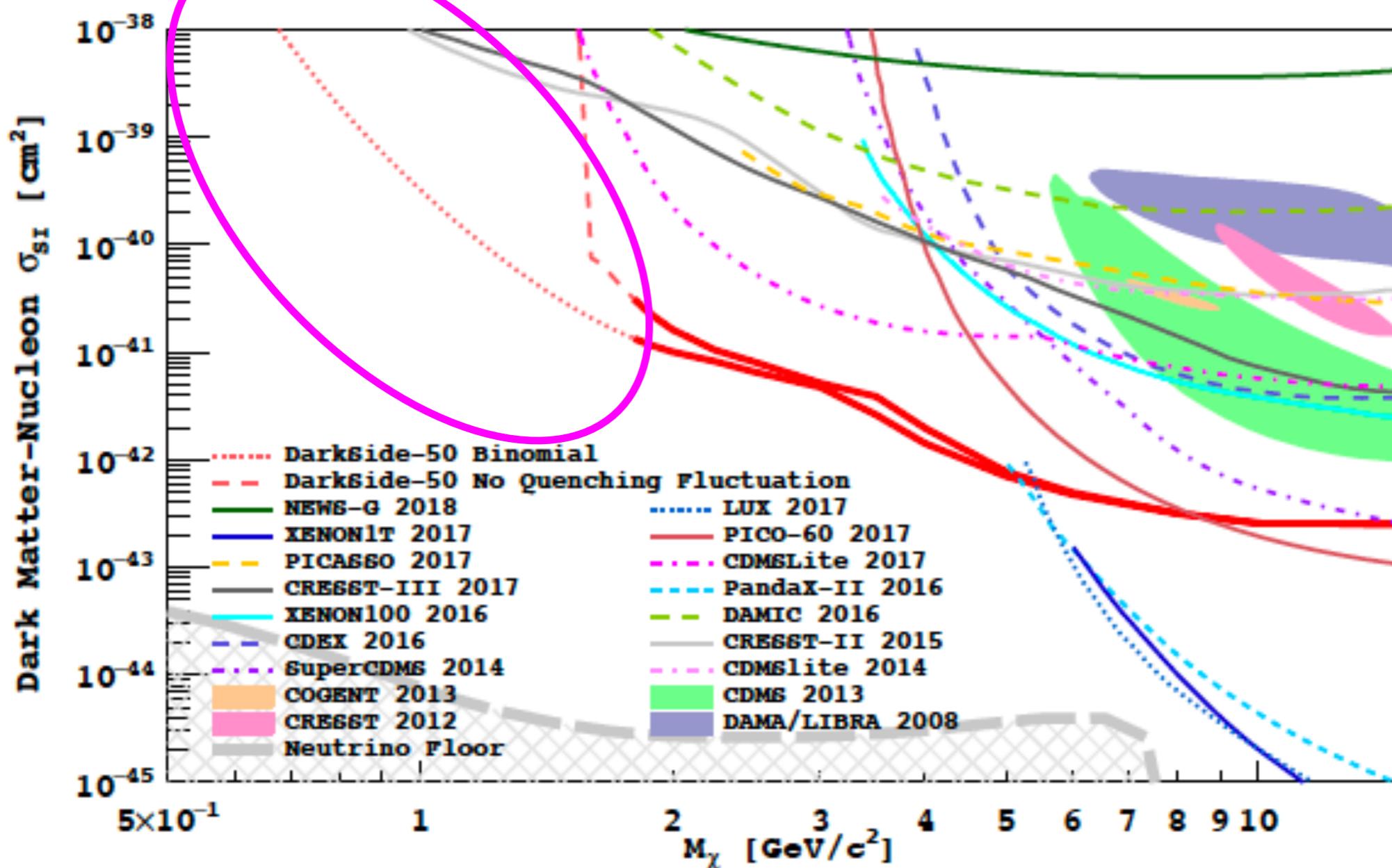
Light dark matter

Below typical WIMP masses: $1 \text{ keV} \lesssim m_{\text{DM}} \lesssim 10 \text{ GeV}$

$$E_R = \frac{\vec{q}^2}{2m_N} = \frac{(m_{\text{DM}}v)^2}{2m_N} \lesssim \text{keV} : \text{Small recoil energy}$$

(Fermion DM)

Challenging for lower detector threshold.

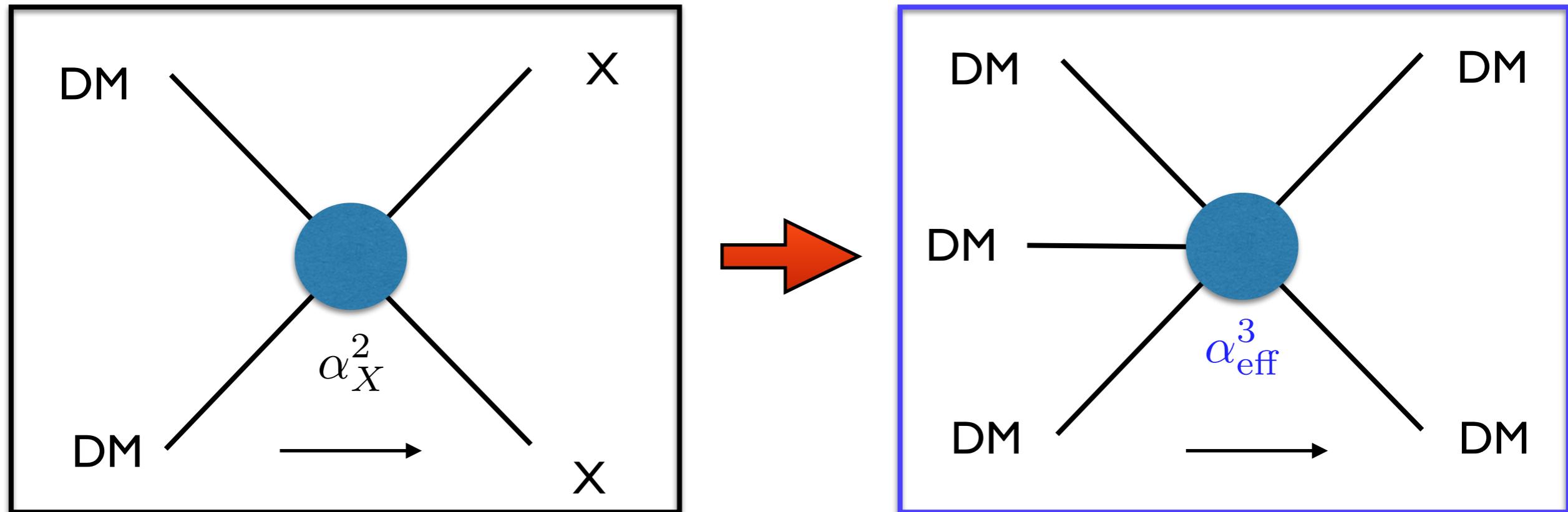


SIMP paradigm

Strongly Interacting Massive Particles (SIMPs):

Chemical equilibrium is realized by self-interactions!

[Carlson et al (1992); Hochberg et al (2014)]



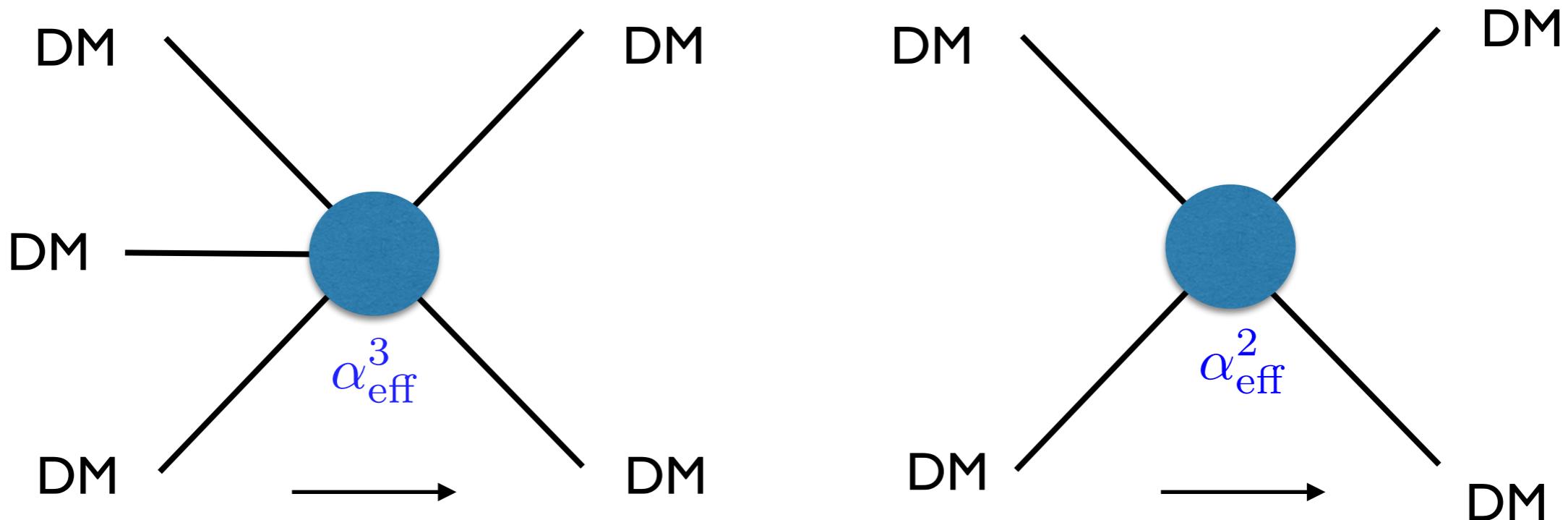
$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} = -\langle \sigma v \rangle_{2 \rightarrow 2} (n_{\text{DM}}^2 - (n_{\text{DM}}^{\text{eq}})^2)$$

$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} \approx -\langle \sigma v^2 \rangle_{3 \rightarrow 2} (n_{\text{DM}}^3 - n_{\text{DM}}^2 n_{\text{DM}}^{\text{eq}})$$

No need of new light particles and SM interactions!

SIMP as SIDM

Naturally small annihilation: $\langle \sigma_{\text{eff}} v \rangle = n_{\text{DM}} \langle \sigma v^2 \rangle \ll \sigma_{\text{self}}$



Relic density: $\Omega_{\text{DM}} h^2 \simeq 0.1 \left(\frac{m_{\text{DM}}/35 \text{ MeV}}{\alpha_{\text{eff}}} \right)^{3/2}$

Self-scattering: $\frac{\sigma_{\text{self}}}{m_{\text{DM}}} \sim \left(\frac{5}{\alpha_{\text{eff}}} \right) 1 \text{ cm}^2/\text{g}$

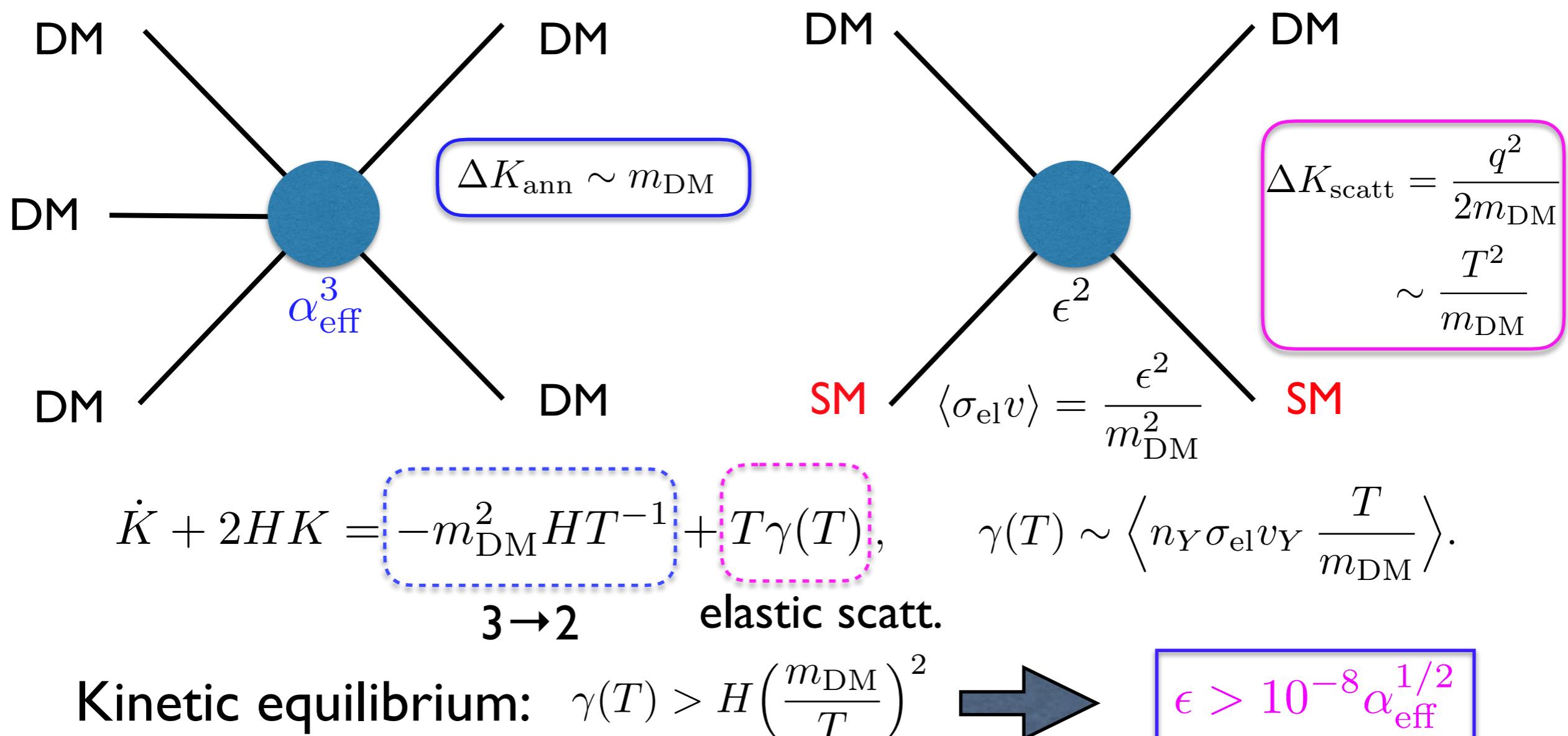
Beyond Z_2 parity.
e.g. Z_3

Thermal dark matter
at sub-GeV scale

SIMP in equilibrium

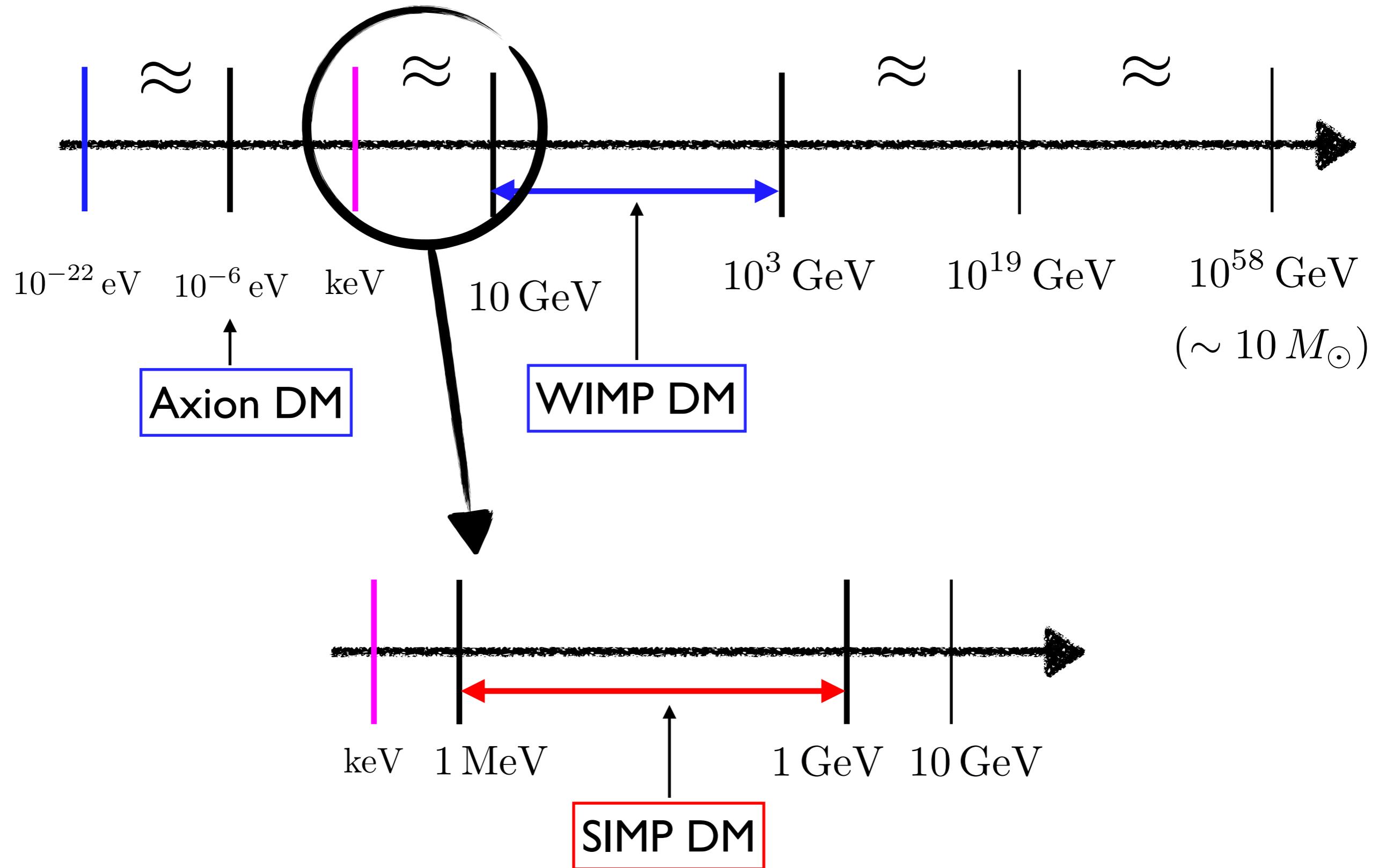
- SIMP must couple to thermal plasma to avoid the overheating problem for structure formation.

[de Laix et al, 1995; Murayama, HML et al, 2017]

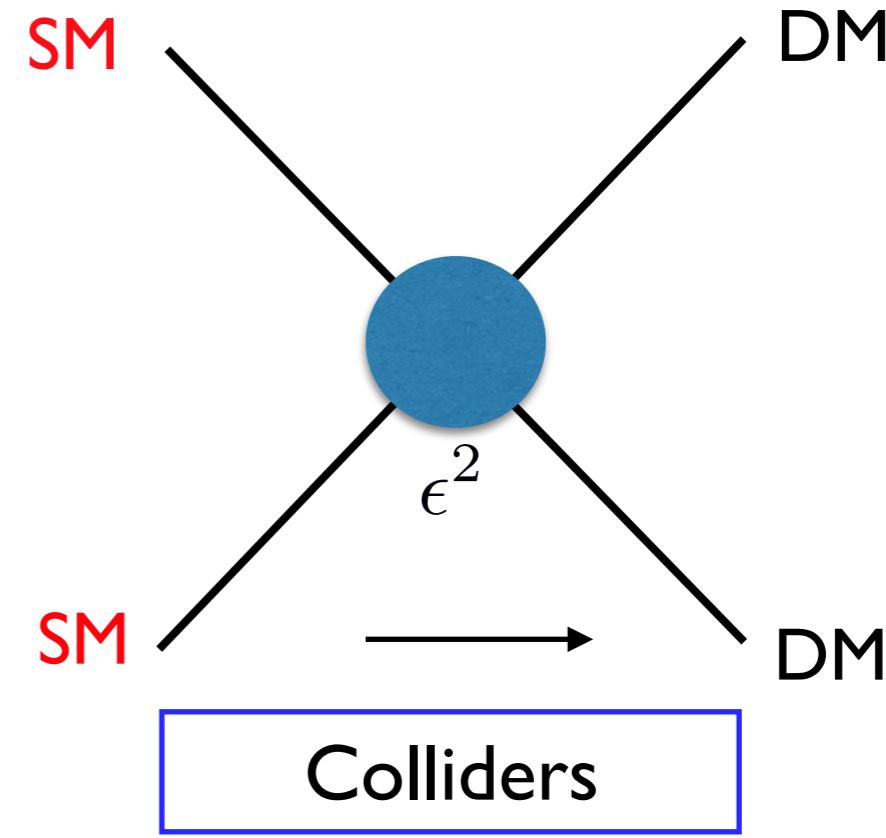
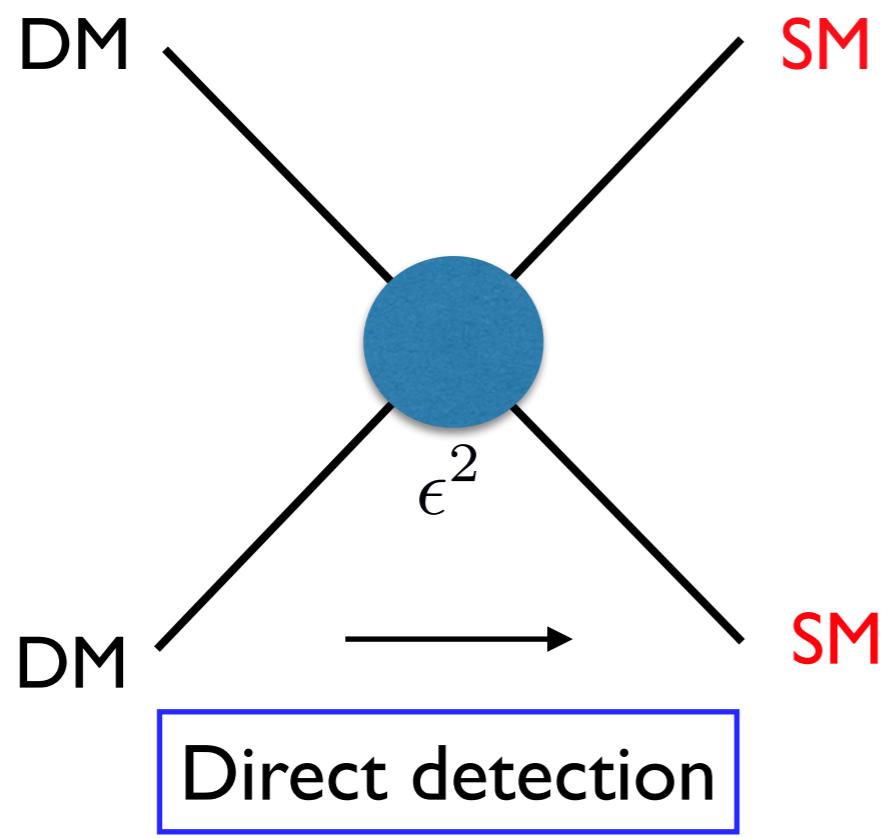
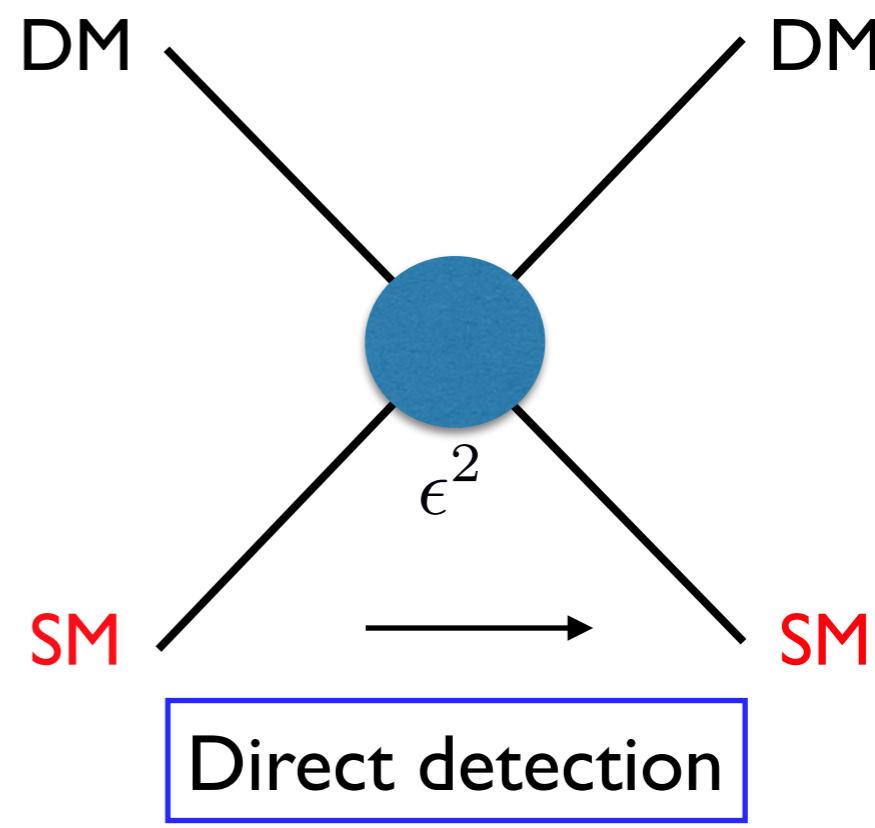
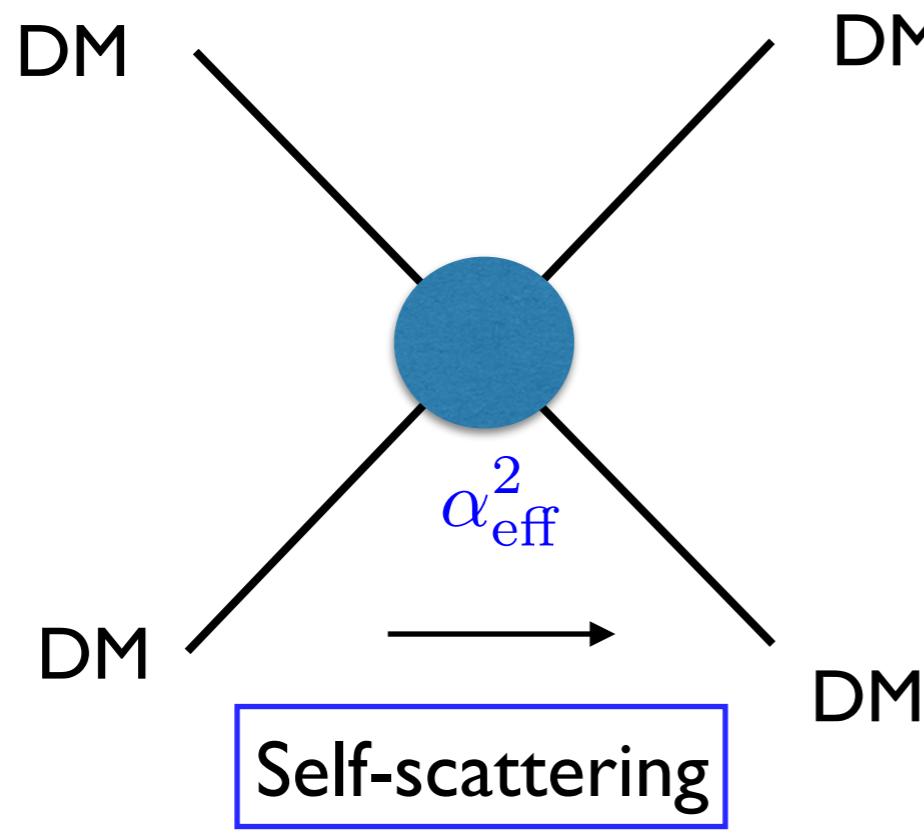


cf. WIMP: $\Delta K_{\text{ann}} \sim T \longrightarrow \gamma(T) > H \left(\frac{m_{\text{DM}}}{T} \right)$

New window from SIMPs

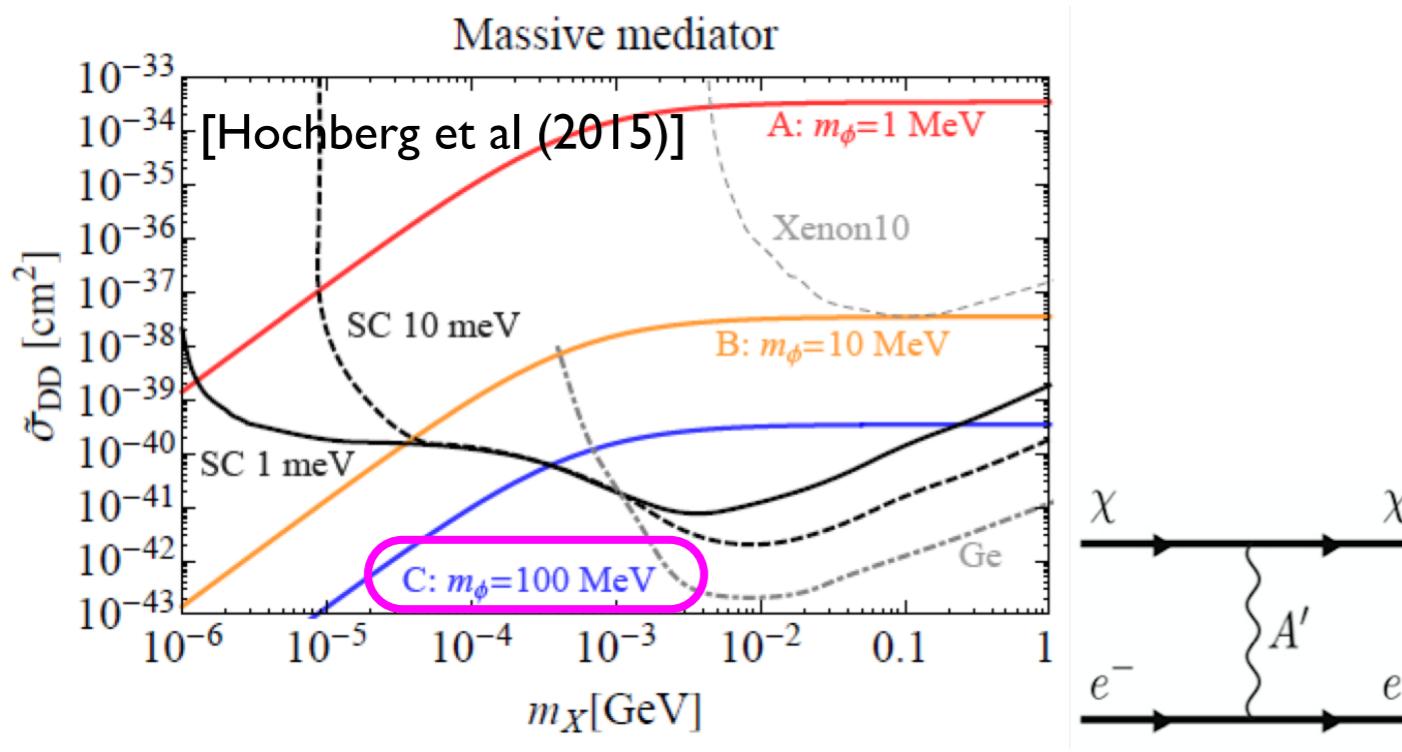


SIMP detection

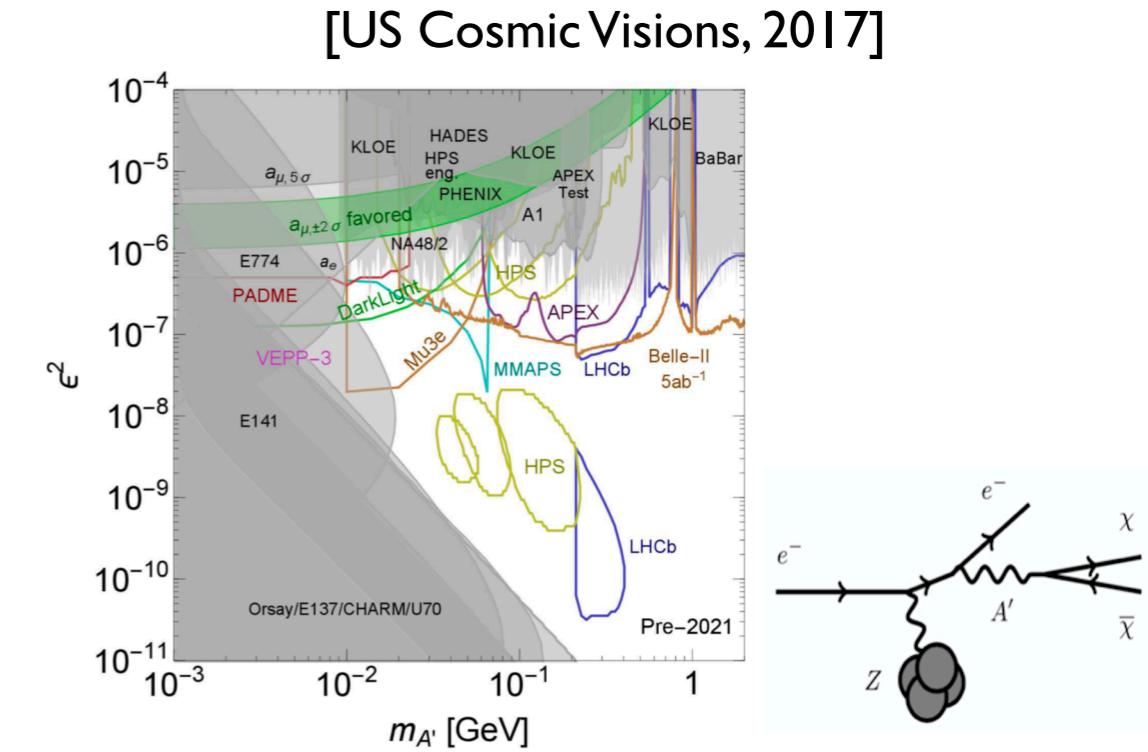


SIMP detection

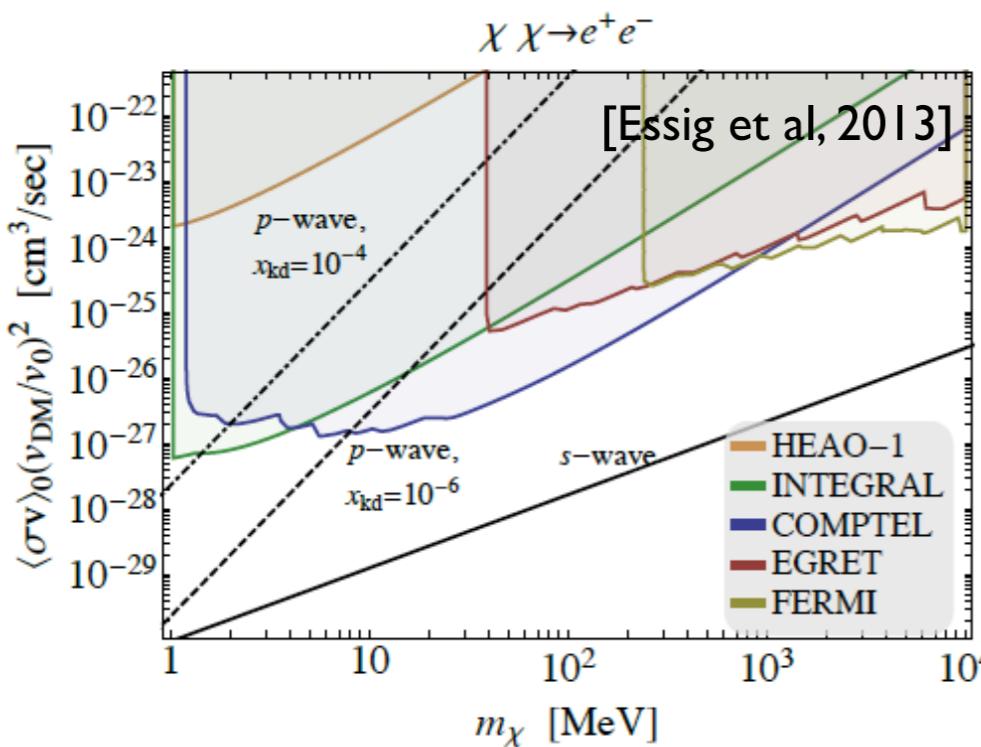
- DM-electron scattering



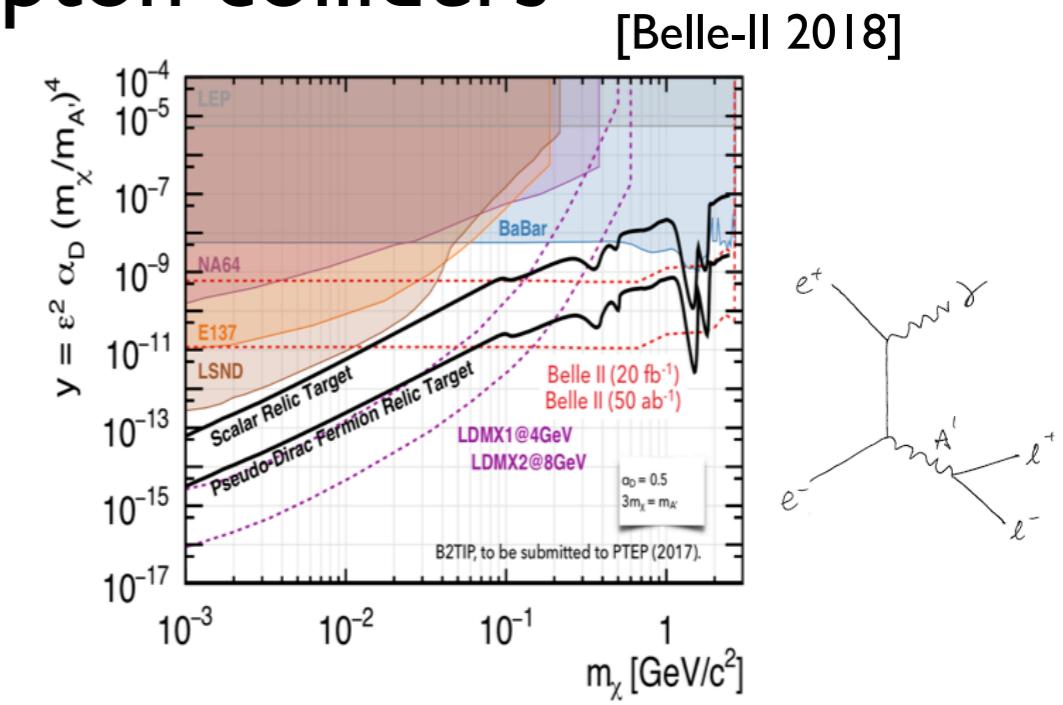
- Beam dump



- Gamma rays, CMB



- Lepton colliders



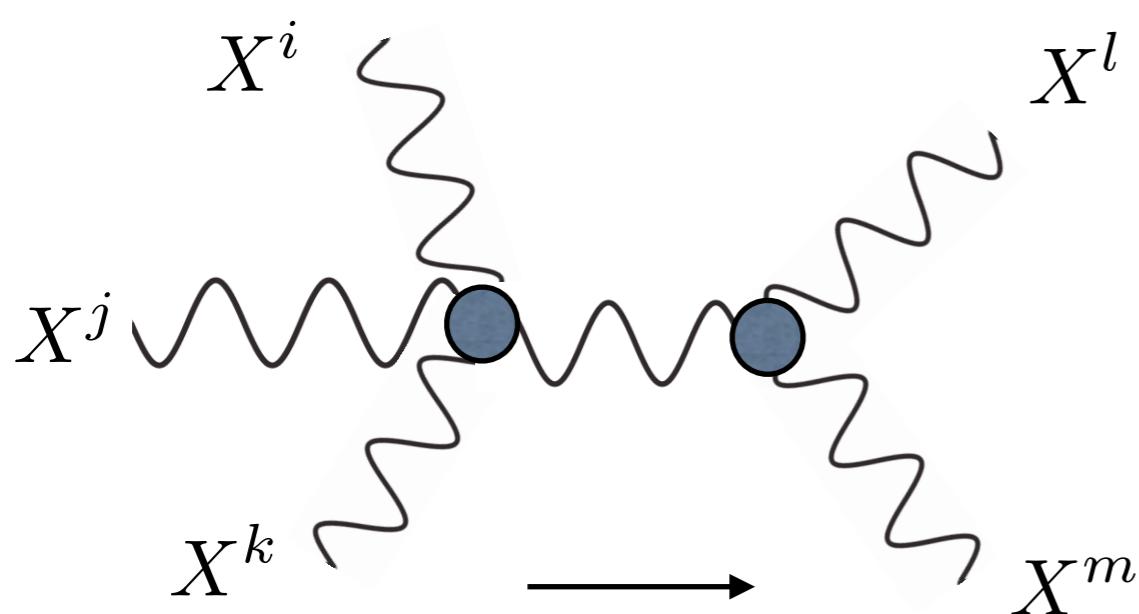
Non-abelian SIMP

SU(2) SIMP

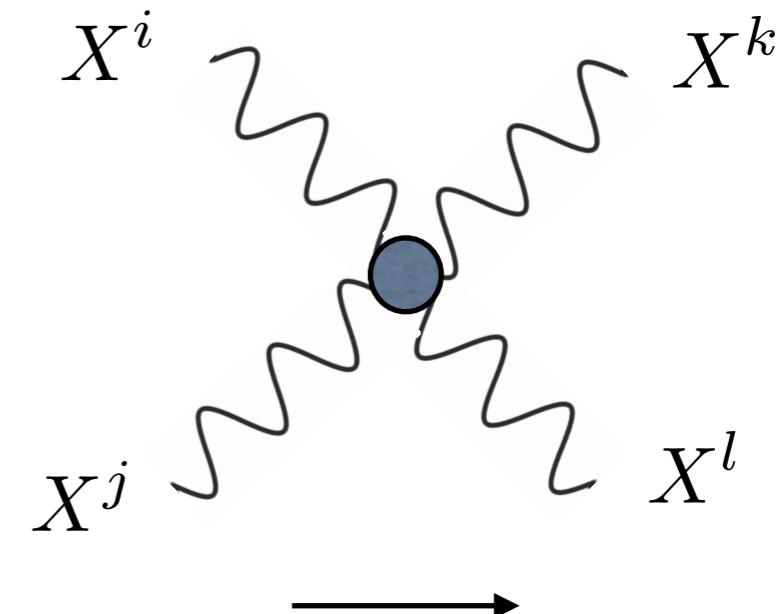
[N. Bernal et al, 2015; S.-M. Choi, Y. Hochberg, E. Kuflic,
Y. Mambrini, H. Murayama, HML, M. Pierre, 2017]

SU(2) gauge interactions → self-interacting dark matter,
Accidental SO(3) custodial symmetry → DM stability.

VEV of Dark Higgs doublet \rightarrow Degenerate SIMP masses

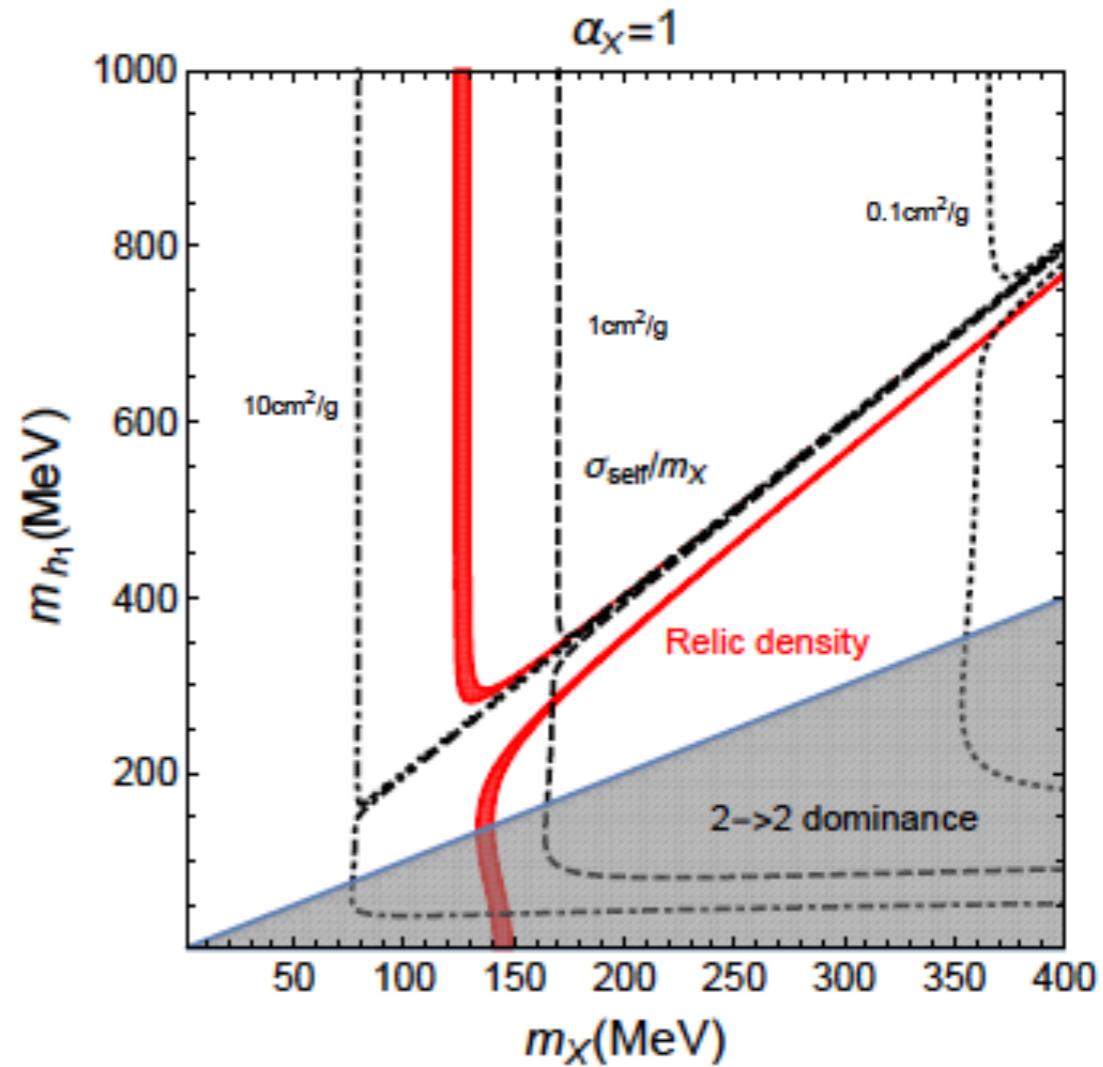
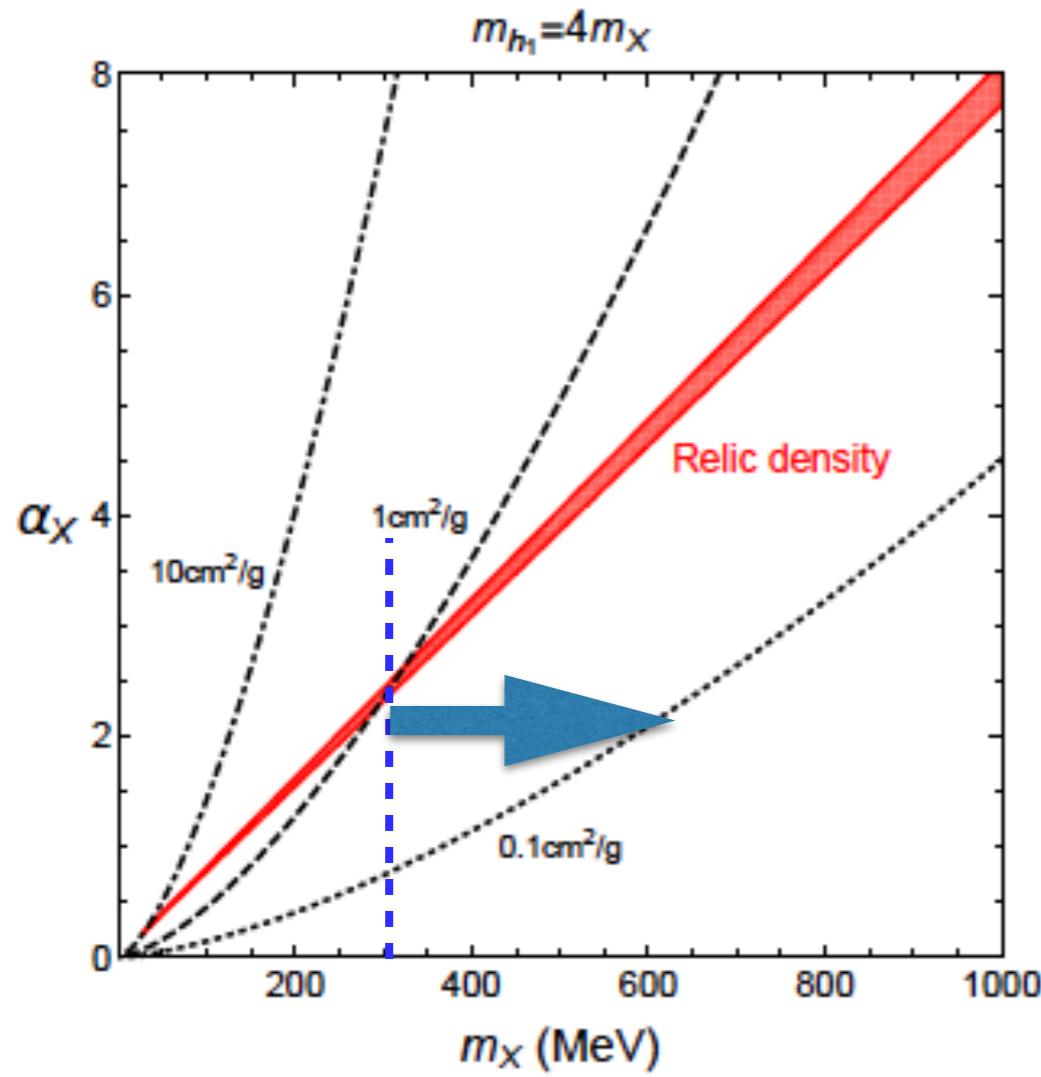


Relic density
(s-wave $3 \rightarrow 2$)



Large self-scattering

VSIMP relic density



Strong coupling & Higgs/QCD:

$SU(2)_X$ SSB by Higgs VEV



Confinement by strong force

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_X \end{pmatrix}, \quad m_{h_X} \rightarrow \infty$$

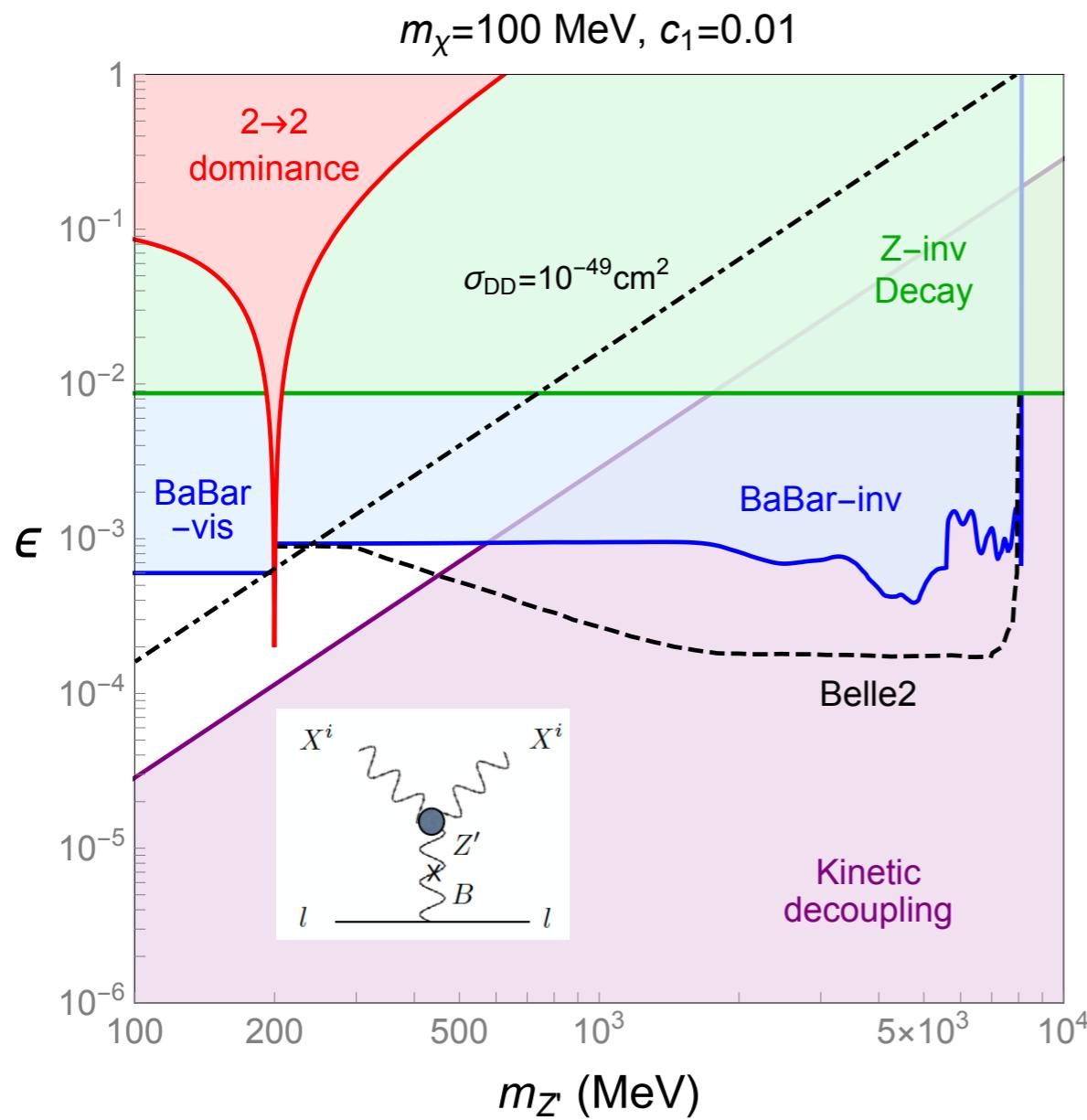
dual

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \text{ in an } SU(N_c)$$

Higgs phase pushed into non-perturbative regime.

[t Hooft, 1980]

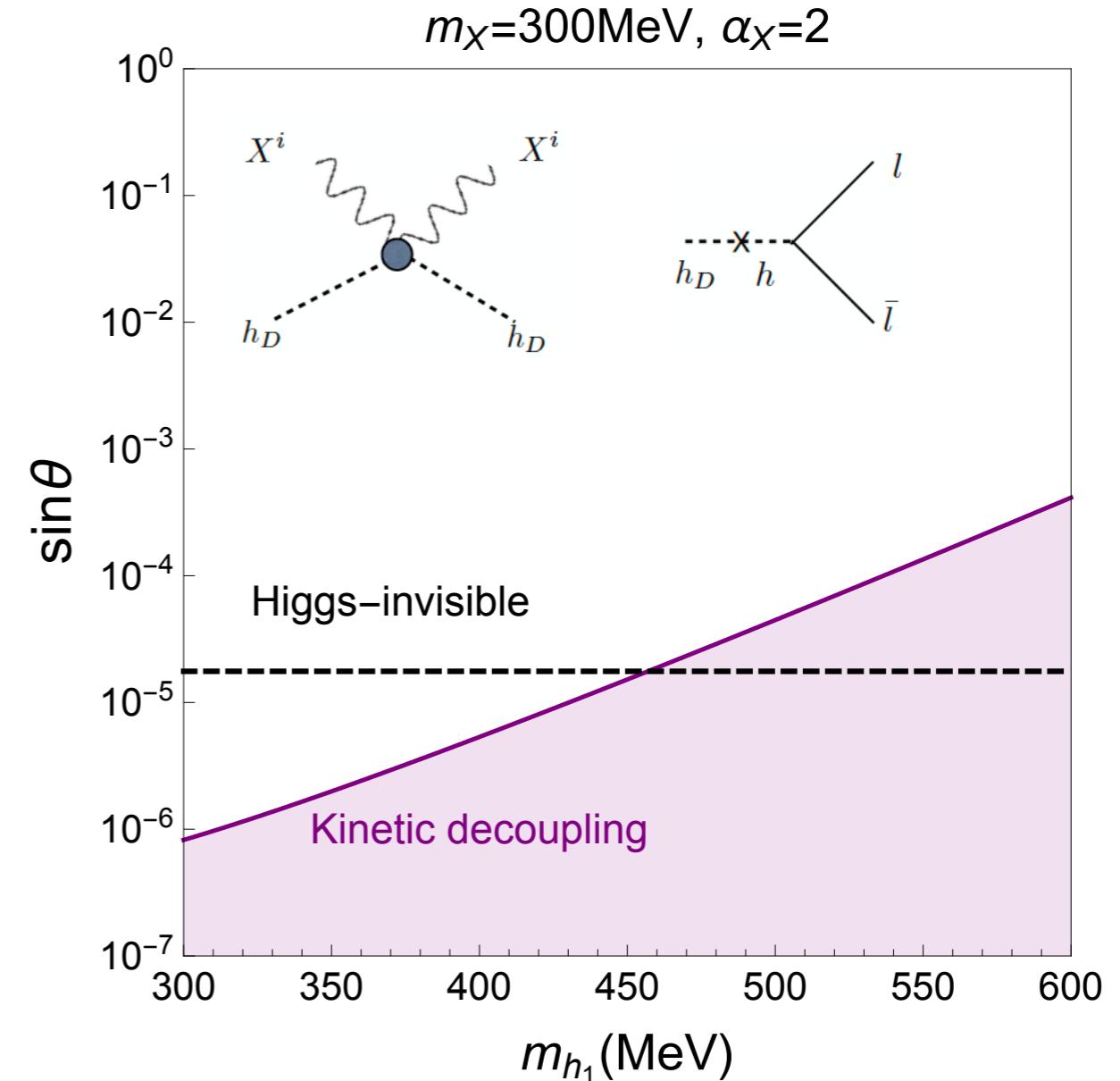
Z' vs Higgs portals



Z' portal

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

$$\gamma(T)_{Z'} = \frac{1240\pi^3 c_1^2 e^2 \epsilon^2}{567 m_X m_{Z'}^4} T^6$$



Higgs portal

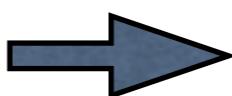
$$\gamma(T)_{h_1} = \frac{g_{h_1} g_X^4 m_{h_1}^2}{12\pi^3 m_X (m_X + m_{h_1})^2} \left(\frac{m_{h_1}^2 - 6m_X^2}{m_{h_1}^2 - 4m_X^2} \right)^2 T^2 e^{-m_{h_1}/T}$$

$$\Gamma(h_1 \rightarrow f\bar{f}) = \frac{m_f^2 m_{h_1} \sin^2 \theta}{8\pi v^2} \left(1 - \frac{4m_f^2}{m_{h_1}^2} \right)^{3/2}$$

Split Vector SIMP

[S.-M. Choi, Y. Mambrini, HML, M. Pierre, 2019]

VEV of Higher dimensional
dark Higgs with isospin I

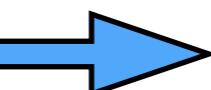


Split SU(2)_Y gauge boson
masses

Dark custodial symmetry:

$$\frac{m_{X_\pm}^2}{m_{X_3}^2} = \frac{1}{2I} < 1.$$

X_\pm : charged under U(1)_{Z'}

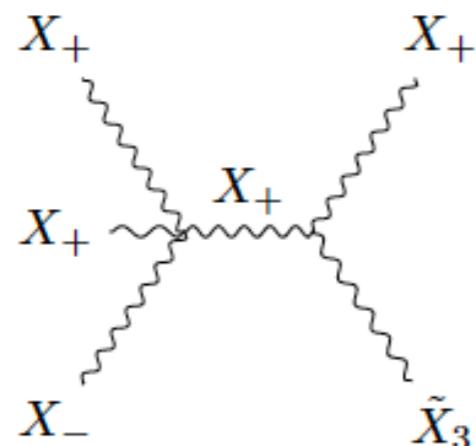


Lighter, stable dark matter

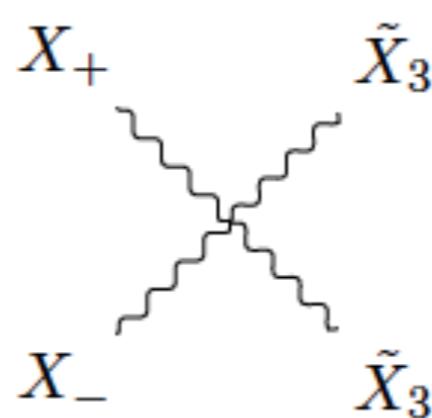
X_3 : neutral under U(1)_{Z'}



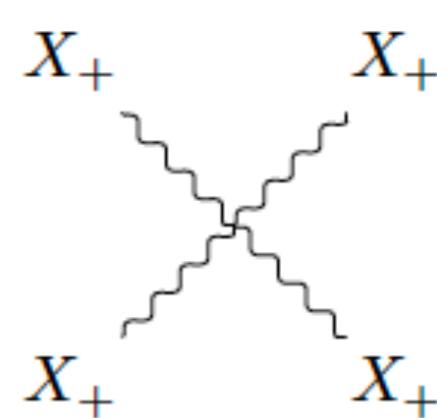
Assist freeze-out & self-
scattering



3 → 2



Forbidden 2 → 2



Self-scattering

Gauge mediators

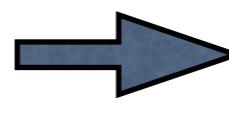
Dark Weinberg angle for $SU(2)_X \times U(1)_Z'$



Two neutral gauge mediators

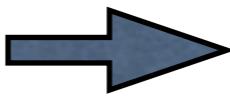
Mediator masses for Large $SU(2)_X$ "singlet" VEV:

$$m_{\tilde{X}_3}^2 \approx 2Im_X^2 \left(1 - \frac{I^2 v_I^2}{q_S^2 v_S^2}\right).$$



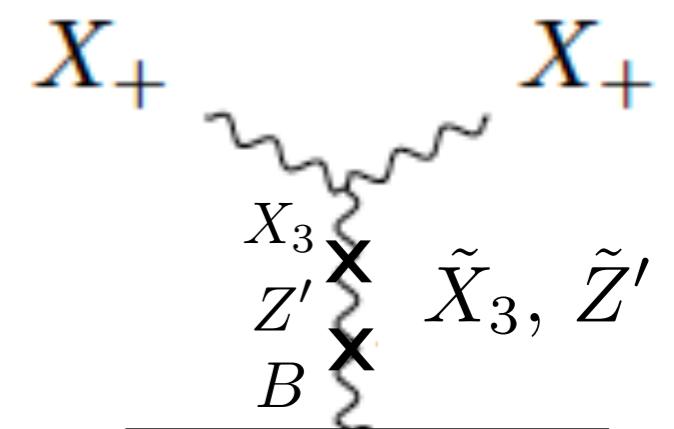
Approximate
custodial symmetry

Kinetic mixing with $U(1)_Z'$



Mediator interactions!

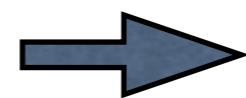
$$\begin{aligned} \mathcal{L}_{EM/NC} = & e \tilde{A}_\mu J_{EM}^\mu + \tilde{Z}_\mu \left[\frac{e}{2s_W c_W} J_Z^\mu + \varepsilon g_{Z'} t_W J_{Z'}^\mu \right] \\ & + \tilde{Z}'_\mu \left[g_X \sin(\theta'_X) J_{X_3}^\mu + g_{Z'} \cos(\theta'_X) J_{Z'}^\mu \right. \\ & \quad \left. - e\varepsilon \cos(\theta'_X) J_{EM}^\mu \right] \\ & + \tilde{X}_{3\mu} \left[g_X \cos(\theta'_X) J_{X_3}^\mu - g_{Z'} \sin(\theta'_X) J_{Z'}^\mu \right. \\ & \quad \left. + e\varepsilon \sin(\theta'_X) J_{EM}^\mu \right]. \end{aligned}$$



Here, $\tan(2\theta'_X) = \frac{2c_X s_X}{c_X^2 - \alpha s_X^2}$, $\sin \theta = \frac{g_{Z'}}{\sqrt{g_X^2 + g_{Z'}^2}}$.

Split VSIMP relic density

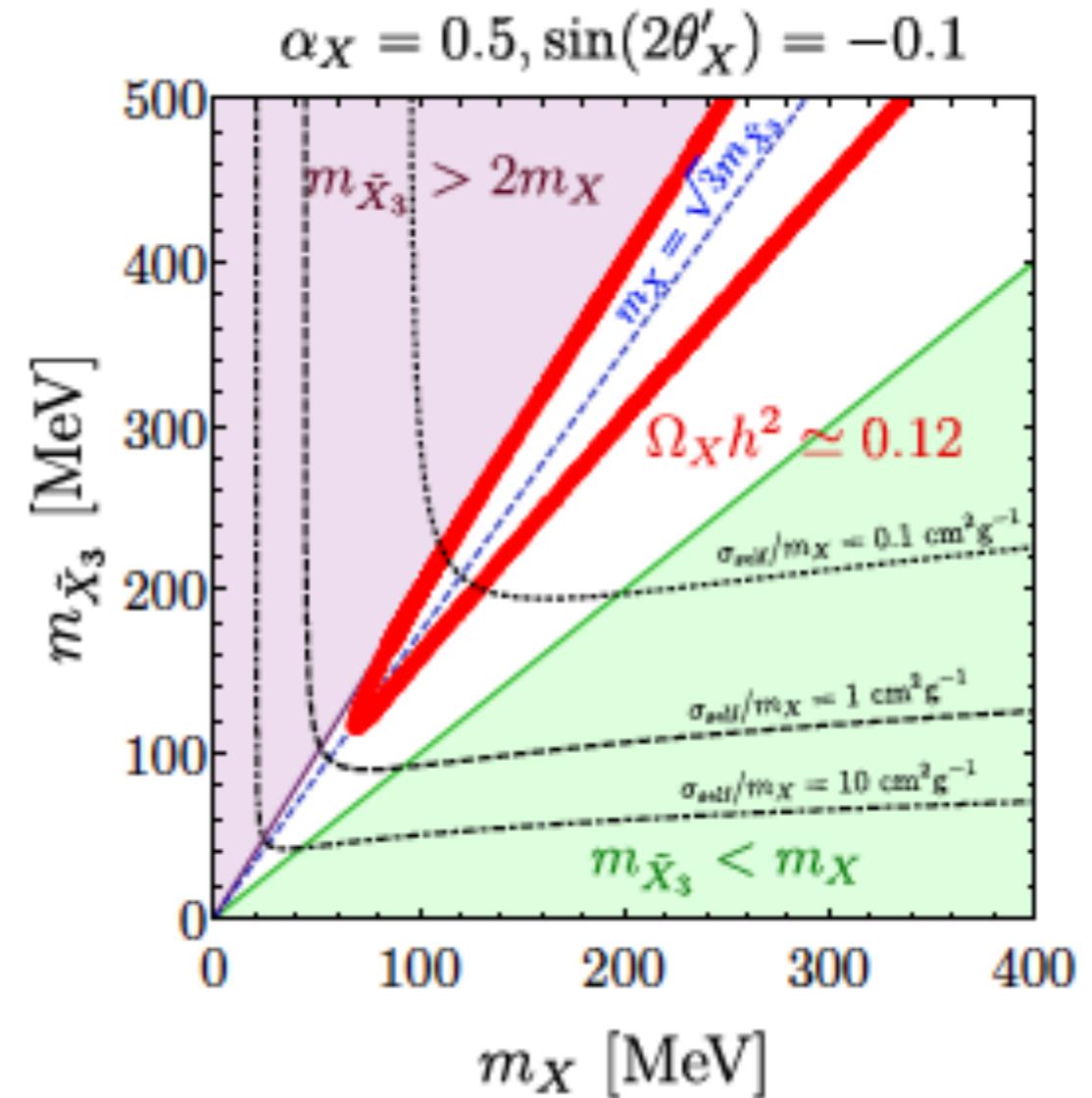
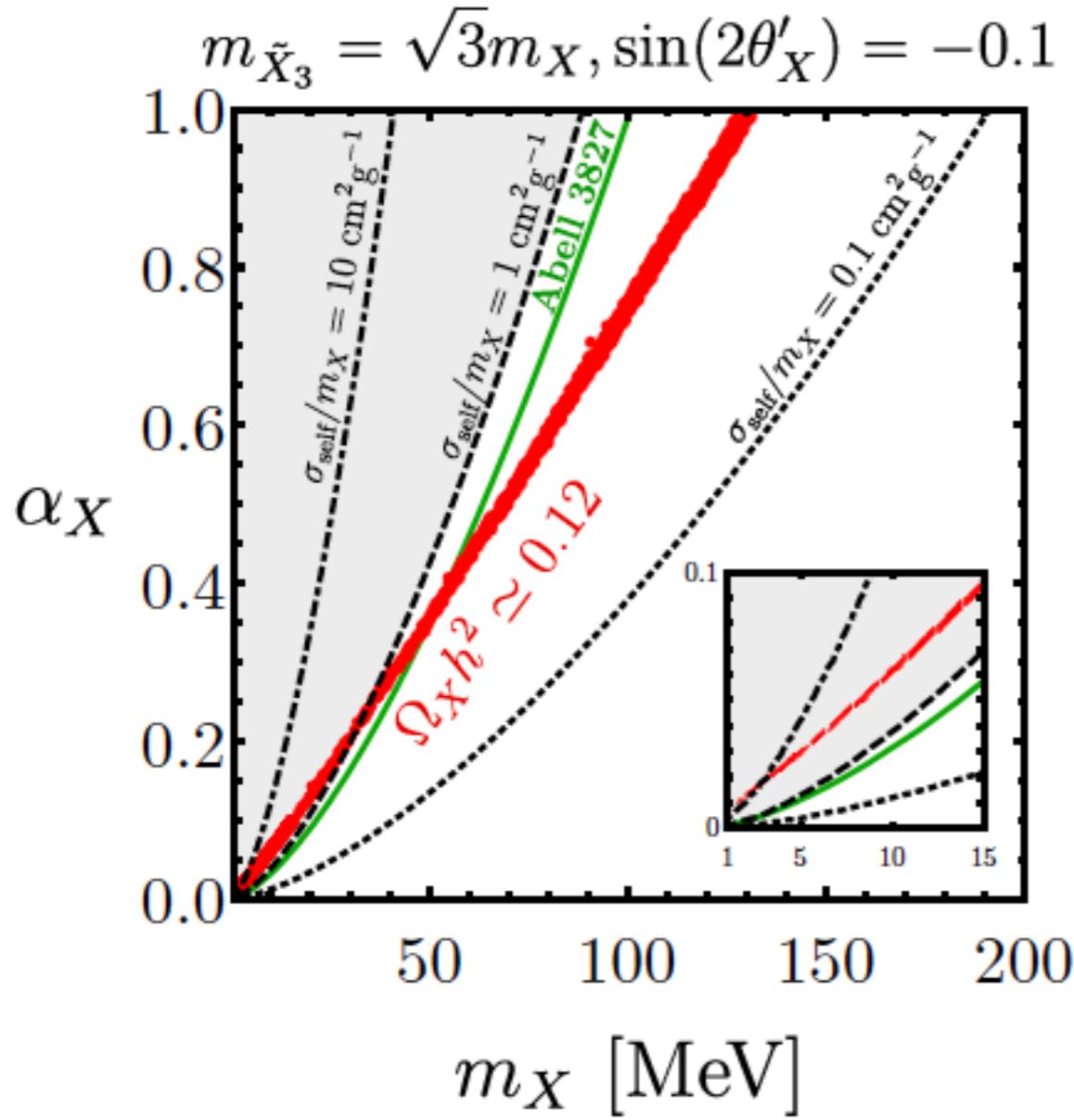
Quadruplet Higgs with
isospin I=3/2



$$m_{\tilde{X}_3} \approx \sqrt{3}m_X$$

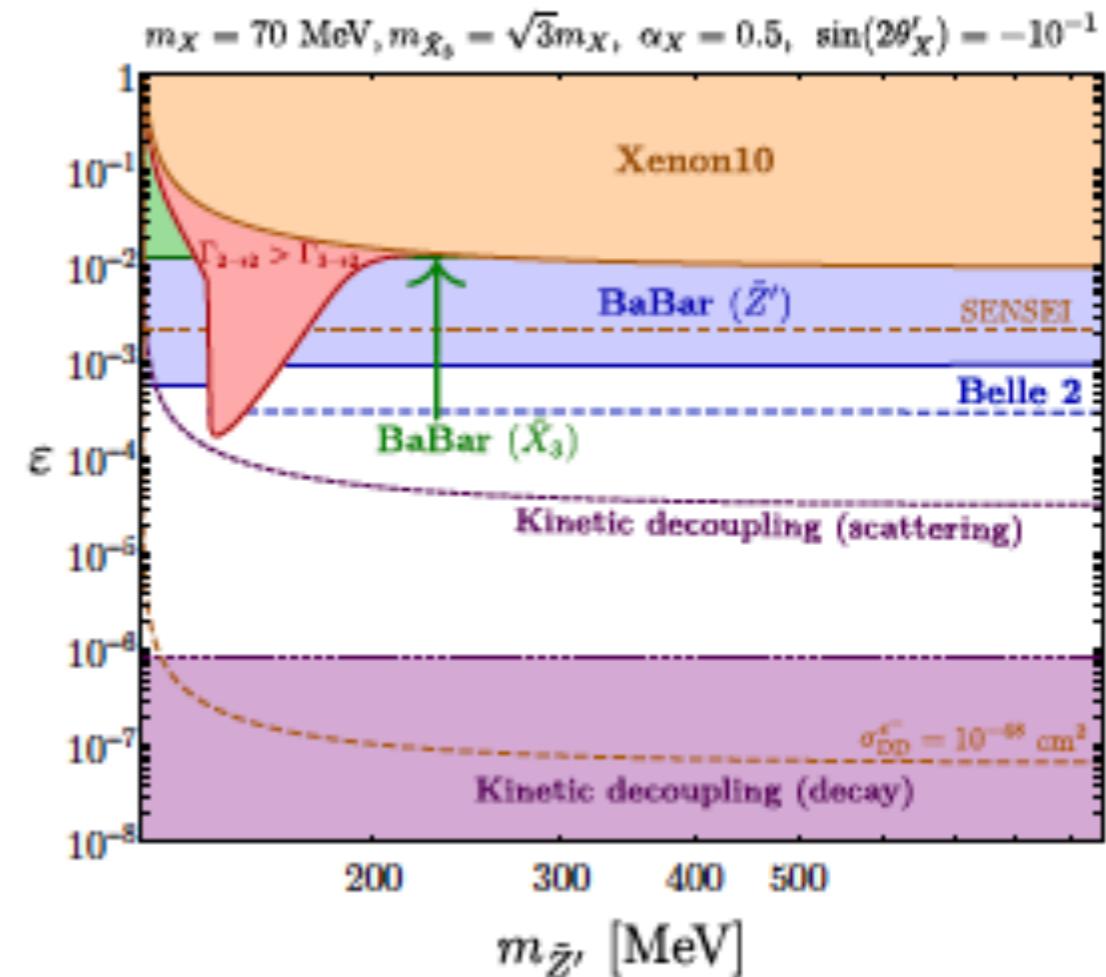
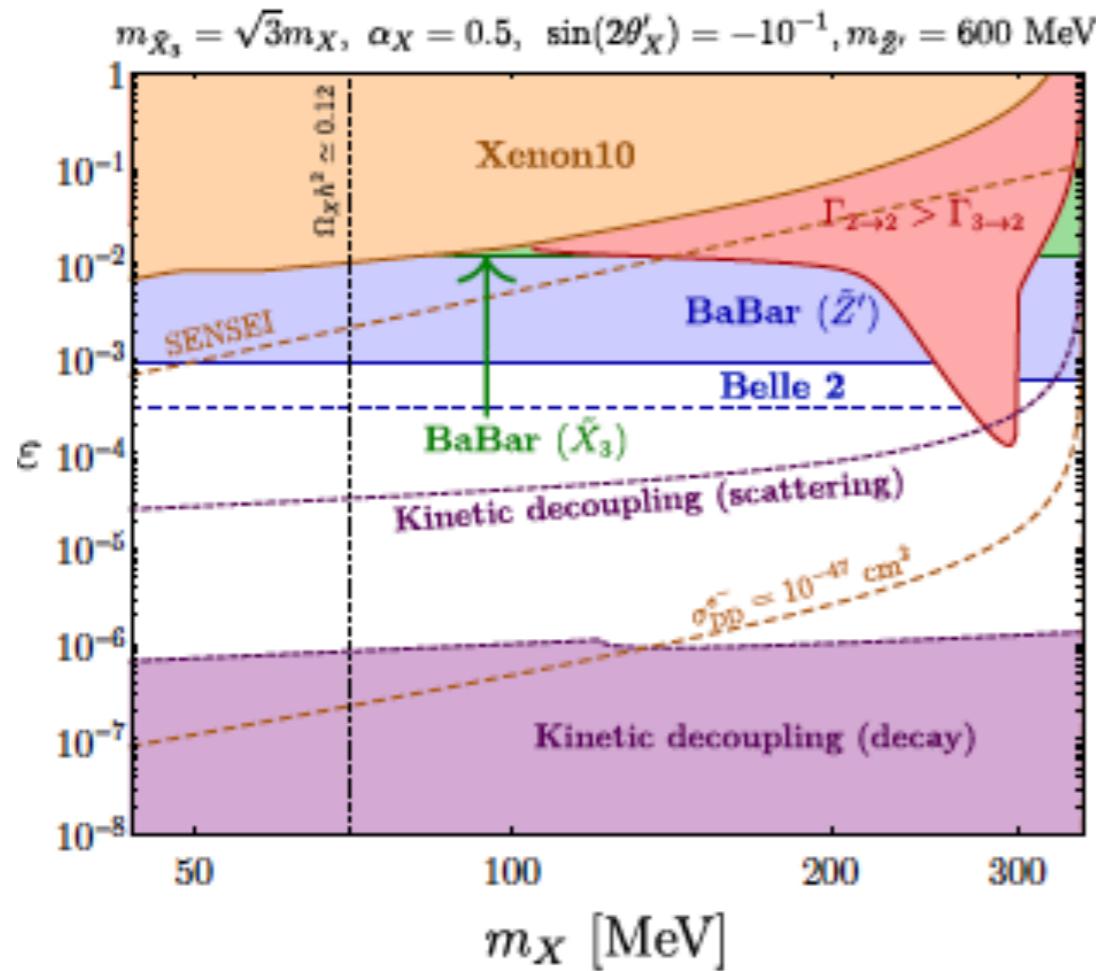
Forbidden channels ignorable

[S.-M. Choi, Y. Mambrini, HML, M. Pierre, 2019]



Double Z' portals

[S.-M. Choi, Y. Mambrini, HML, M. Pierre, 2019]



DM scattering with \tilde{X}_3 -like is efficient for K.E.

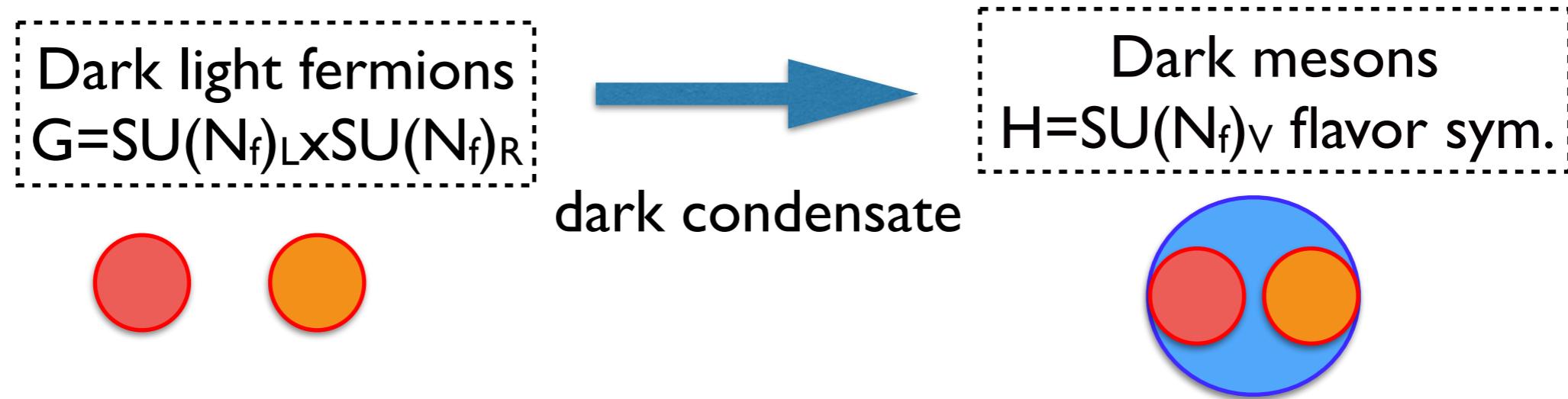
$$n_{\tilde{X}_3}^{\text{eq}} \Gamma_{\tilde{X}_3} > H(T_f) n_X^{\text{eq}}$$

DM-electron scattering:

$$\sigma_{DD}^{e^-} = \frac{e^2 \epsilon^2 g_X^2 \sin^2(2\theta'_X) m_e^2 m_X^2}{4\pi(m_e + m_X)^2} \left(\frac{1}{m_{\tilde{X}_3}^2} - \frac{1}{m_{\tilde{Z}'}^2} \right)^2$$

Mediator searches: \tilde{X}_3 -like visible, Z' -like invisible

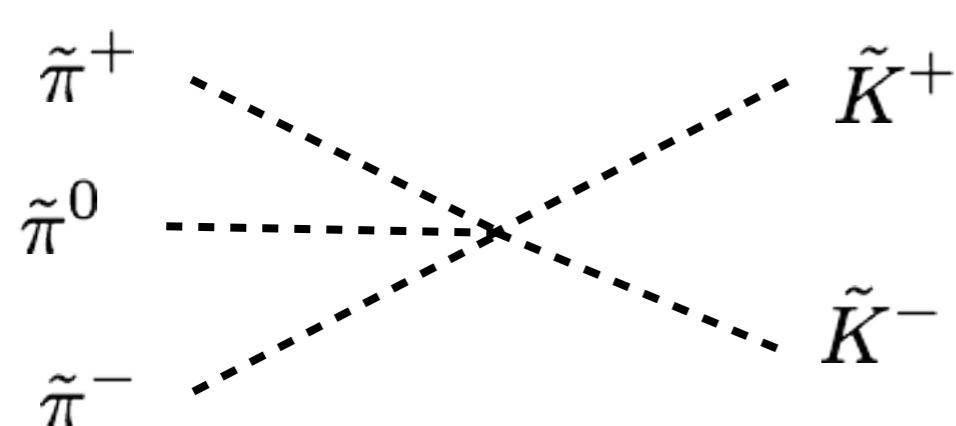
SIMP mesons



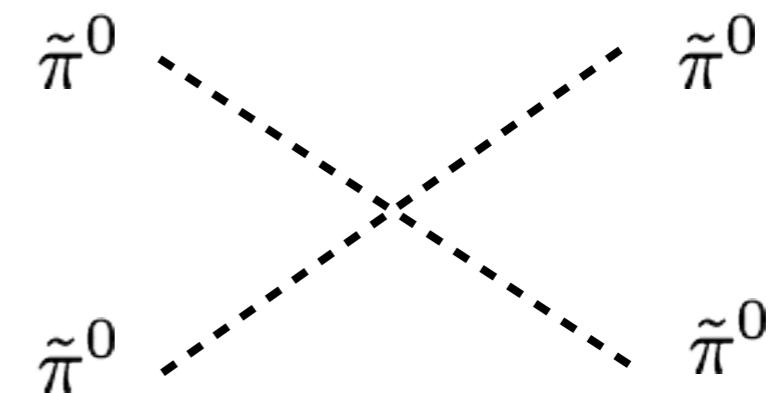
- Wess-Zumino-Witten term [Wess, Zumino, 1971; Witten, 1983]

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi] \quad \pi_5(G/H) = \mathbb{Z}$$

[Hochberg et al, 2014, 2018; Seo, HML, 2015]



meson annihilation



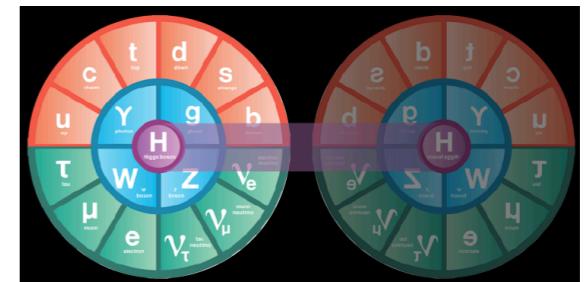
meson self-scattering

Higgs mass and dark QCD

- Discrete symmetries for Twin Higgs

[Chacko,Goh,Harnik, 2005]

$$[SU(3)_A \times SU(2)_A] \times [SU(3)_B \times SU(2)_B] \times Z_2$$



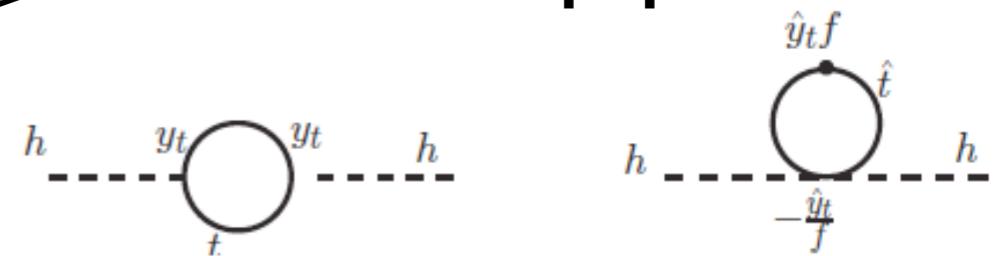
Global $SU(4) \rightarrow SU(3)$ “ $15 - 8 = 7$ pNGBs”

\longrightarrow Higgs = pseudo Nambu-Goldstone boson

$$g_A = g_B, \quad H_A \leftrightarrow H_B$$

Higgs mass due to top quark \longrightarrow neutral top partner

$$\delta m_h^2 = \frac{3\Lambda^2}{4\pi^2} (y_t^2 - y_{\hat{t}}^2) = 0$$



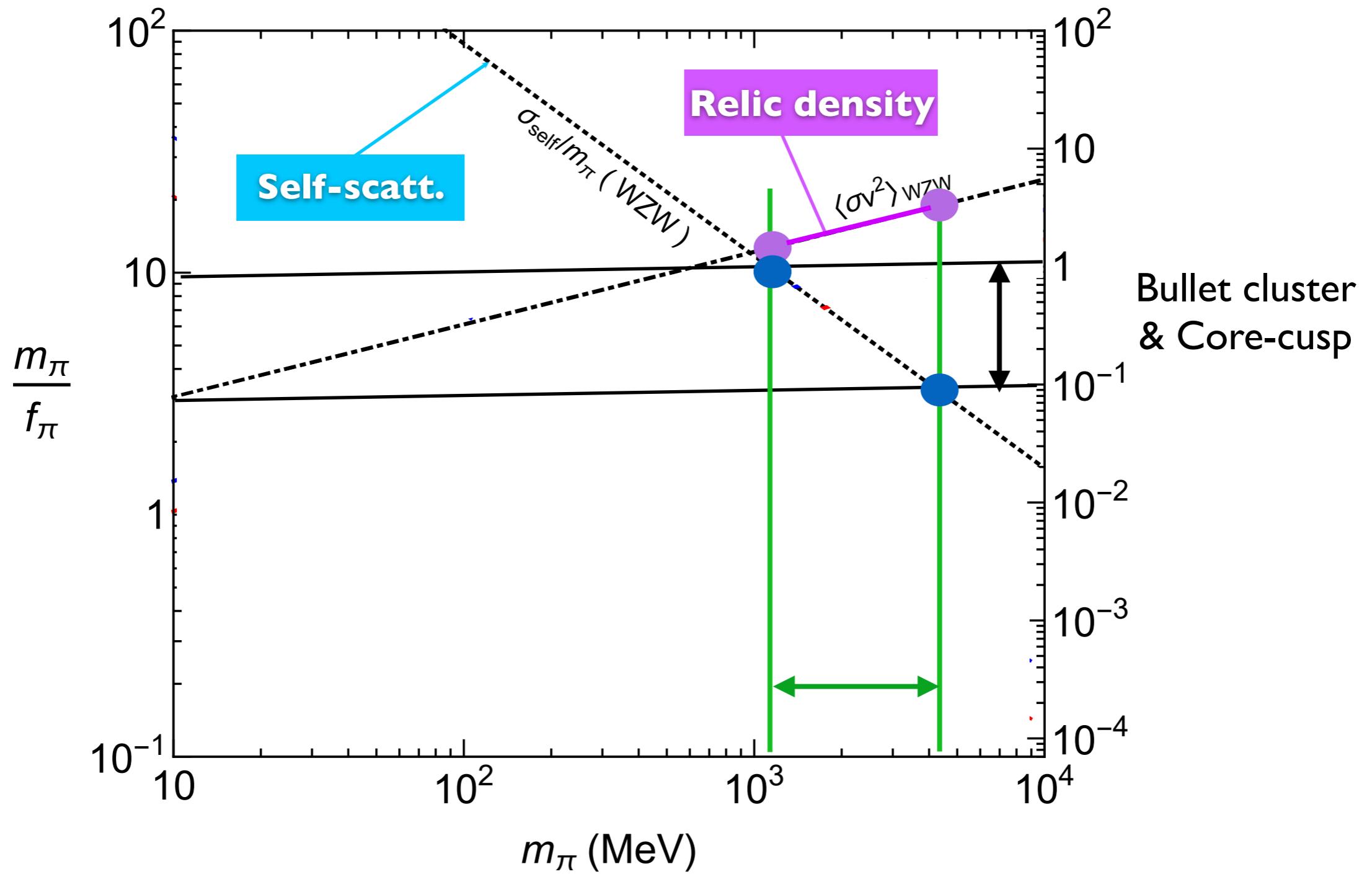
Higgs mass due to gluons

$$\delta m_h^2 = \frac{3y_t^2 \Lambda^2}{4\pi^4} (g_3^2 - \hat{g}_3^2) = 0$$

\longrightarrow “dark QCD”

[See, Hochberg et al, 2018]

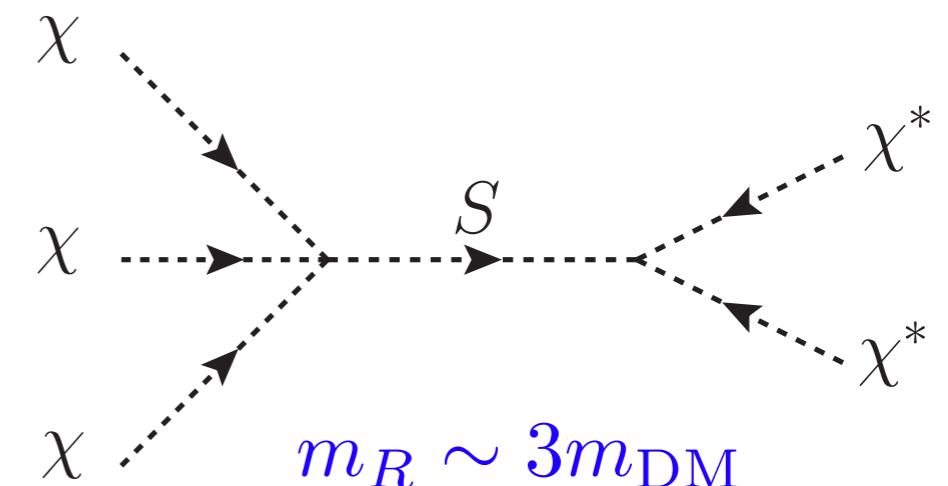
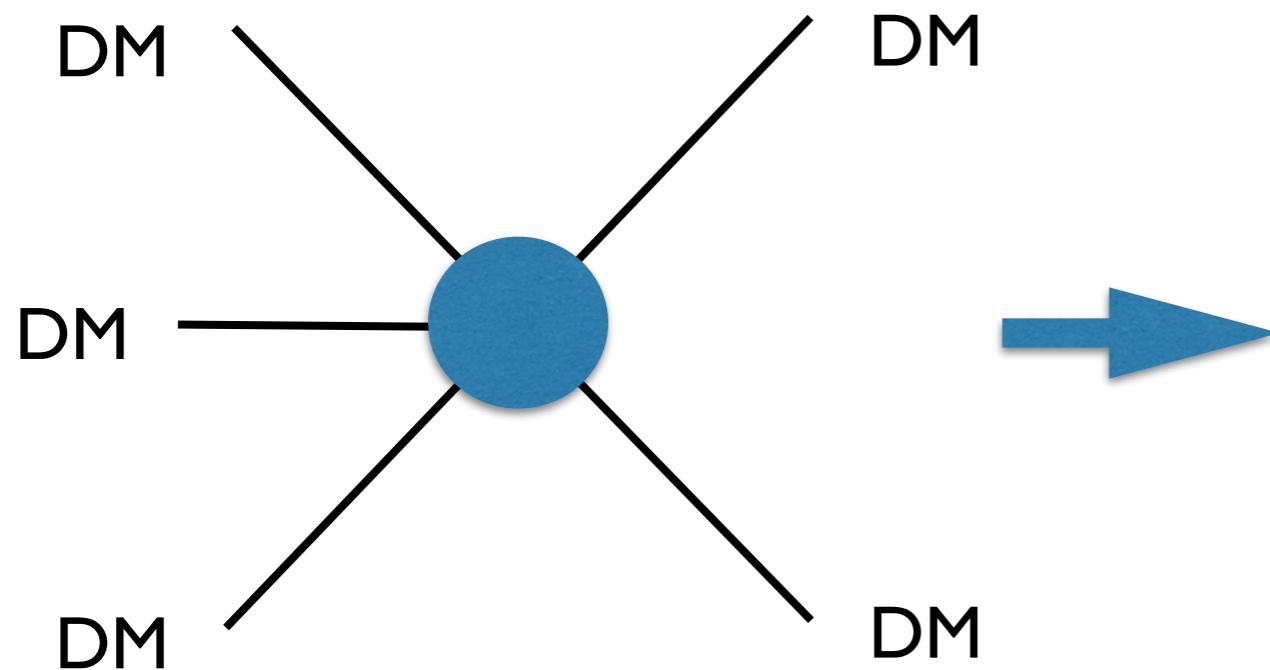
SIMP mesons w/o VMs



Too large SIMP self-couplings

Breit-Wigner SIMP resonance

- SIMP process can be enhanced at dark resonances.



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

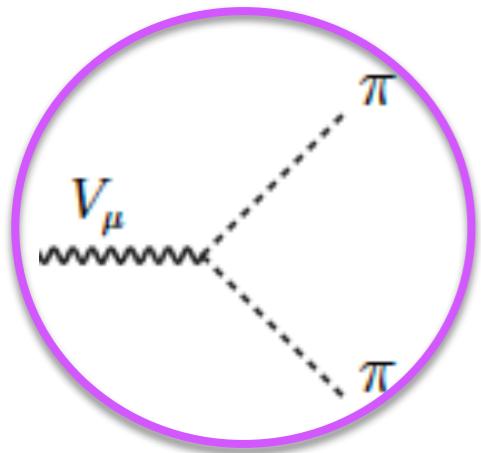
e.g. Z_5 SIMP, [S.-M. Choi, HML, 2016; S.-M. Choi, HML, M.-S. Seo, 2017]

$$\begin{pmatrix} \phi \\ \chi \\ S \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^3 \end{pmatrix} \begin{pmatrix} \phi \\ \chi \\ S \end{pmatrix}, \quad \omega = e^{i\frac{2}{5}\pi} \quad \mathcal{L}_{\text{int}} \supset \frac{1}{\sqrt{2}}\lambda_1\phi^\dagger S^2\chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2\phi^\dagger S\chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$

Dark vector resonances

Vector resonances in hidden gauge scheme:

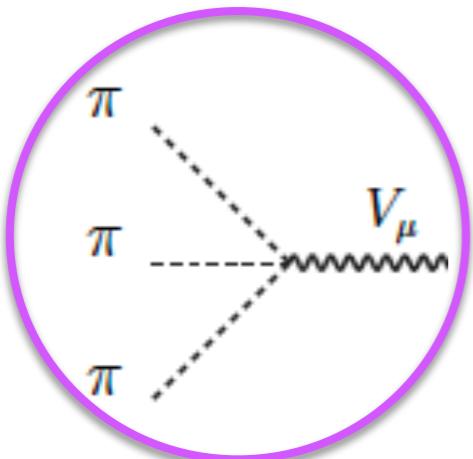
$$\text{Global } \text{SU}(N_f)_V \times \text{SU}(N_f)/\text{SU}(N_f)_V + \textcolor{blue}{H_{\text{local}} = \text{SU}(N_f)_V}$$



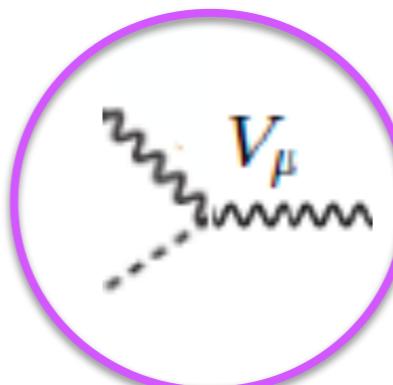
$$V_\mu \equiv V_\mu^a t^a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho_\mu^+ & K_\mu^{*+} \\ \rho_\mu^- & -\frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & K_\mu^{*0} \\ K_\mu^{*-} & \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \end{pmatrix}$$

VM masses: $m_V^2 = ag^2 f_\pi^2$ degenerate
 VM- $\pi\pi$ - $\pi\pi$ couplings: $g_{V\pi\pi} = \frac{1}{2}ag$. cf. QCD: $a \simeq 2$

$$\text{Generalized WZW terms with } \textcolor{blue}{H_{\text{local}} = \text{SU}(N_f)_V}$$



cf. QCD:
 $\omega \rightarrow 3\pi$



[Bando et al, 1988; P. Ko, 1991]
 cf. QCD: VM-photon mixing

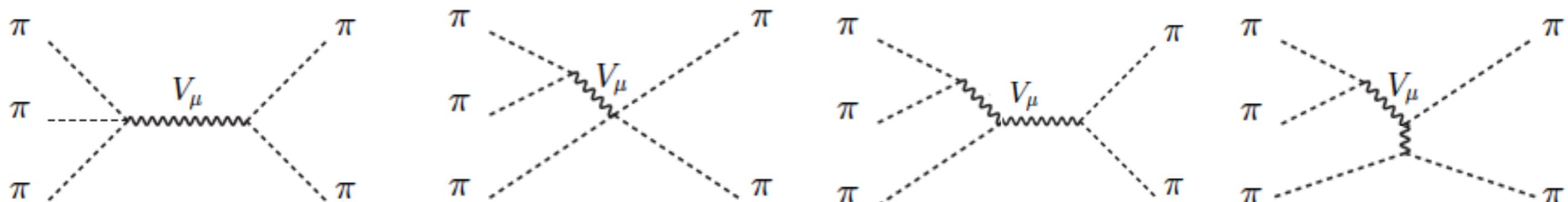
$$\pi^0 \rightarrow 2\gamma$$

Dark photon case:
 [Berlin et al, 2018]

Boosting SIMP annihilations

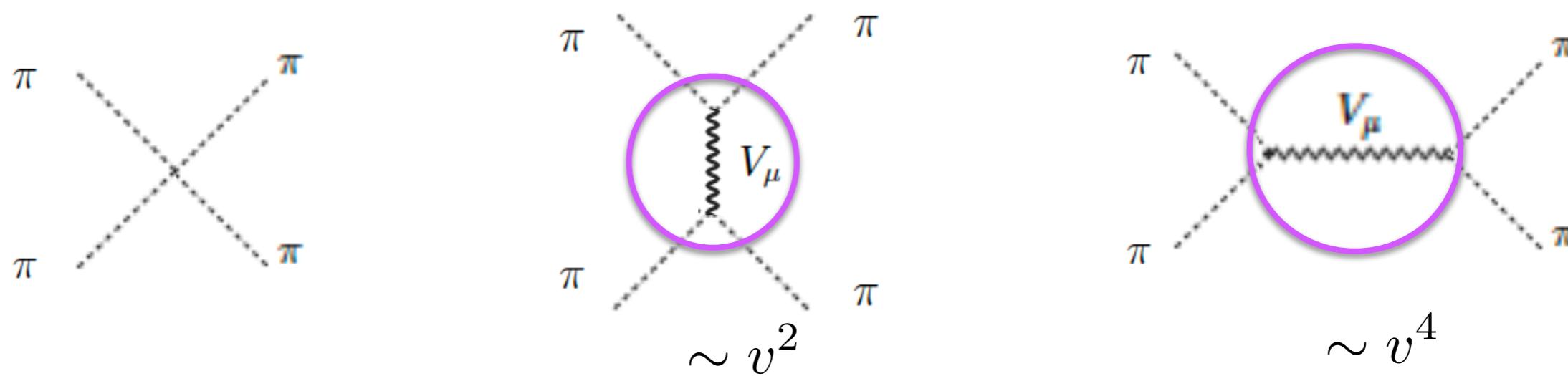
3→2 annihilation:

[S.-Choi,A. Natale, HML, P. Ko, 2018]



Enhanced near resonances at 2π or 3π .

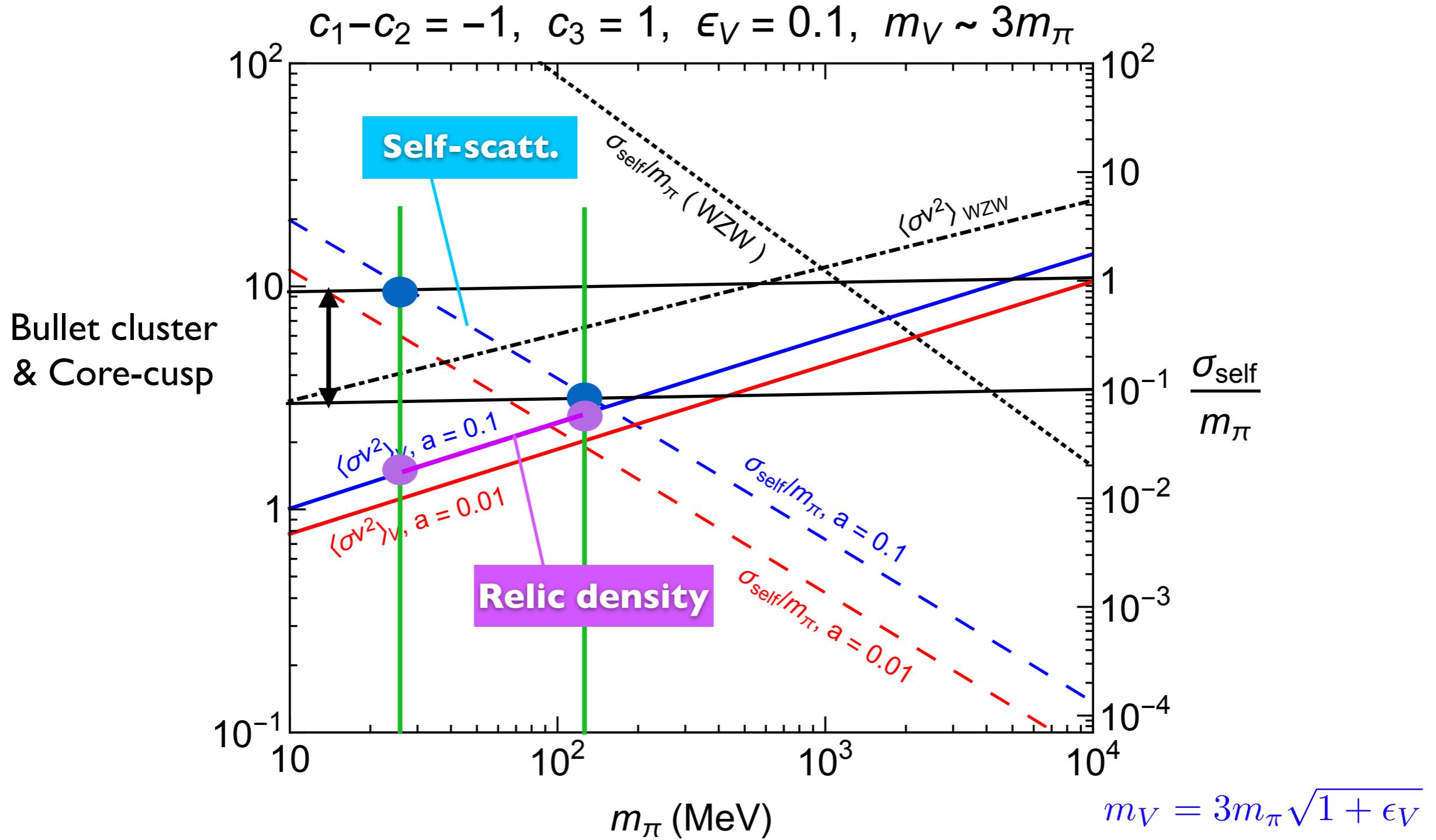
2→2 self-scattering:



VMs lead to velocity-dependent self-scattering.

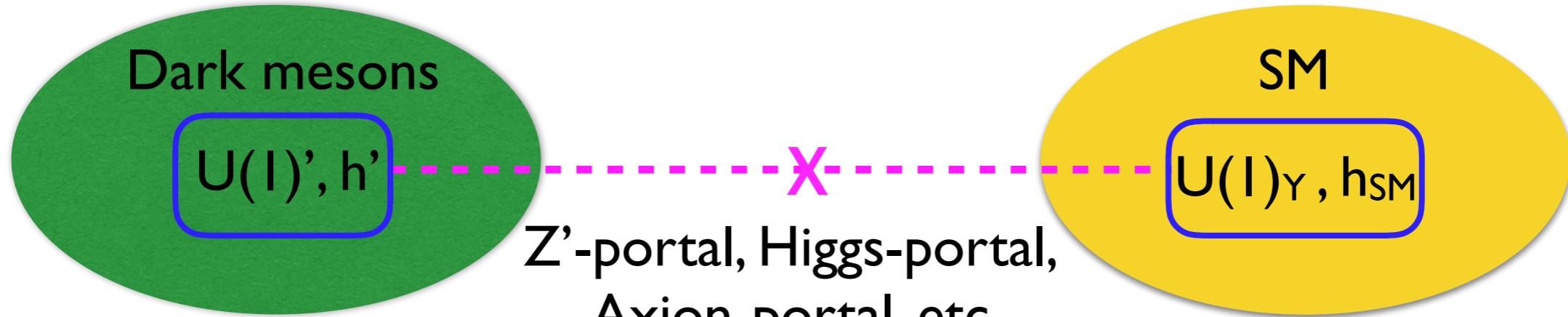
SIMP mesons with VMs

[S.-Choi,A. Natale, HML, P. Ko, 2018]

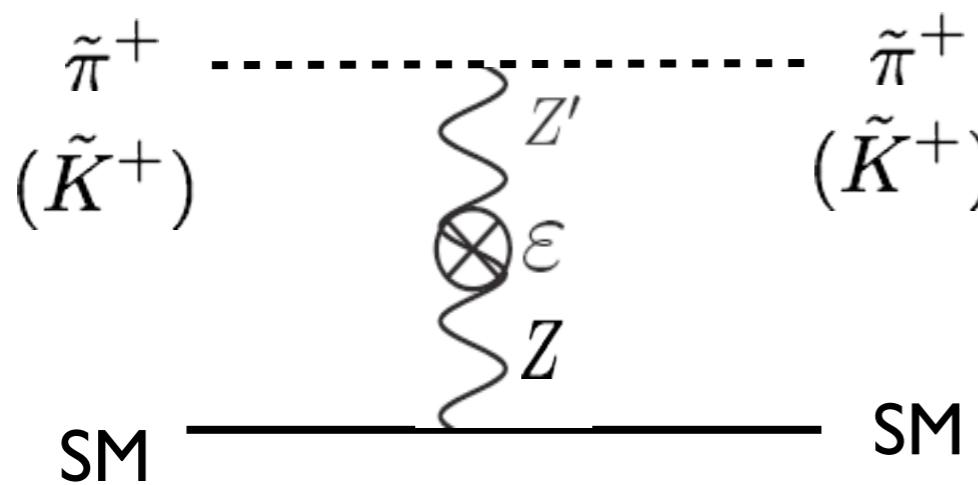


Smaller SIMP couplings are allowed.

Z' portal for SIMP mesons



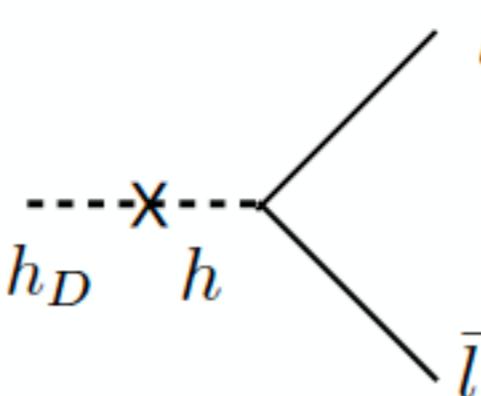
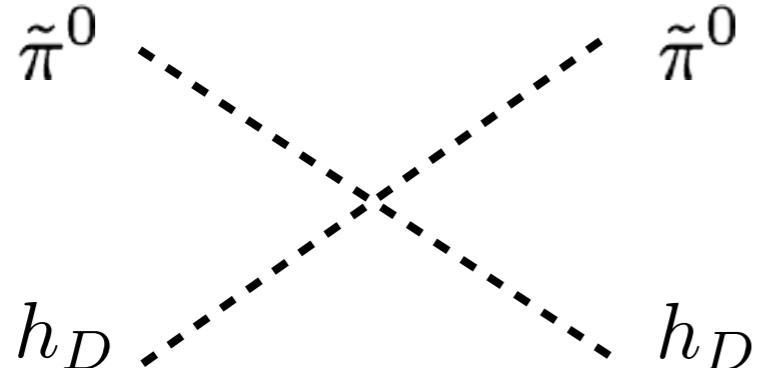
- Vectorial Z' with no chiral anomalies



$$\delta \mathcal{L}_{m_\pi} = \alpha_D \Lambda^4 \text{Tr}[Q_D U Q_D U^{-1}]$$

$$\delta m_\pi^2 \sim \alpha_D \Lambda^4 / F^2 \lesssim 0.01 m_\pi^2$$

- Dark Higgs or sigma fields

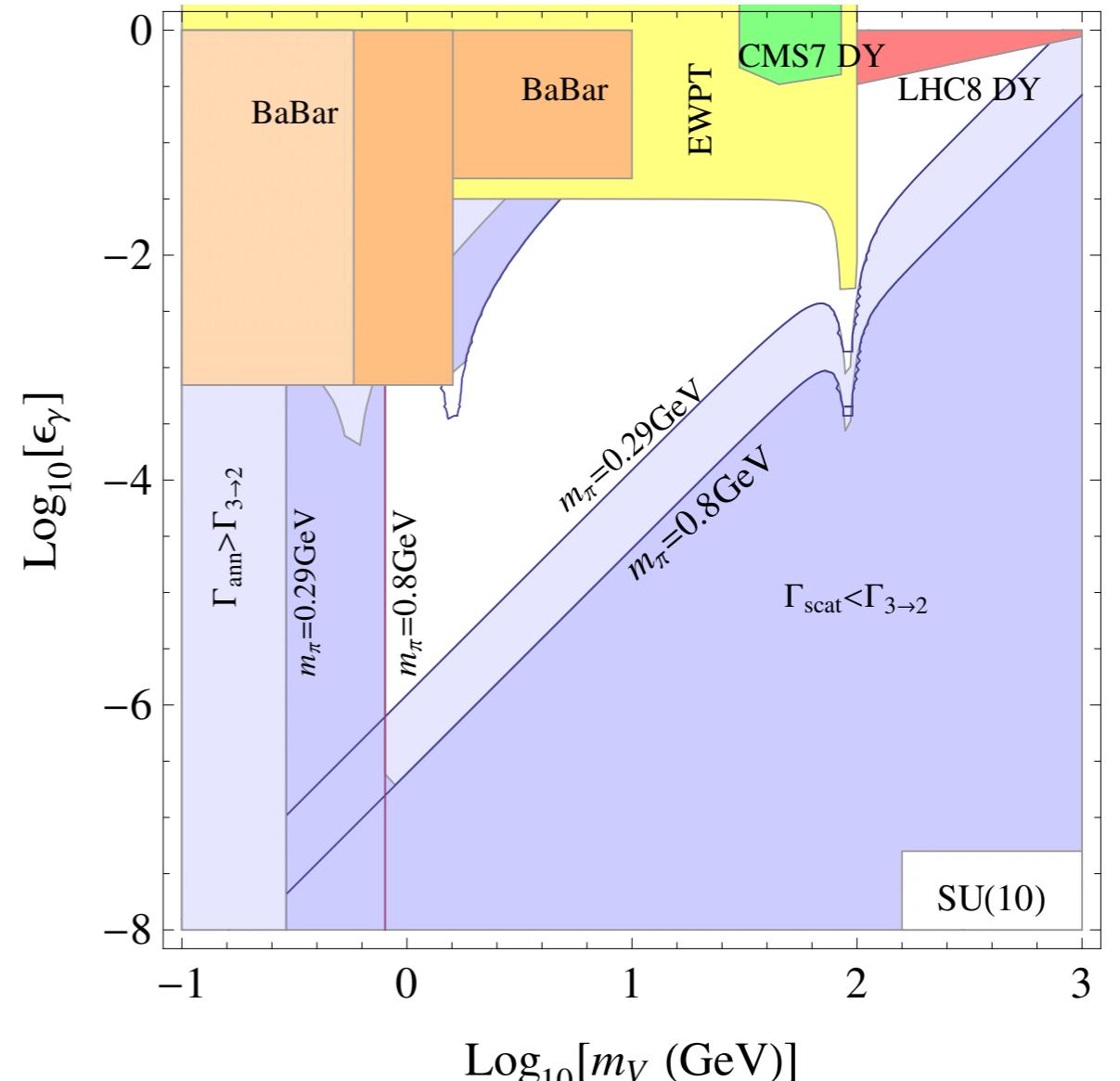
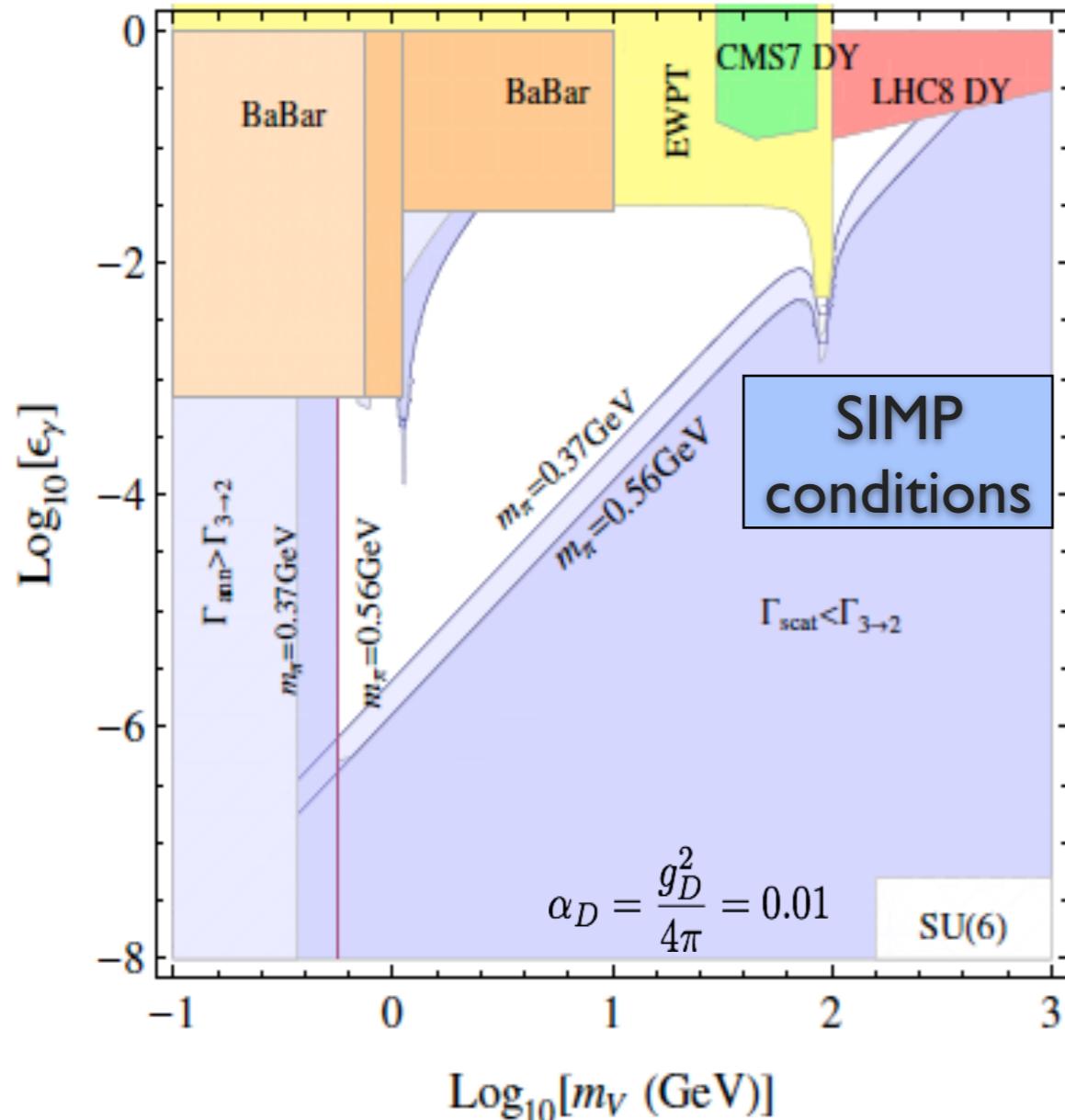


[A. Kamada et al, 2015;
VSIMPers, 2017]

cf. Axion-portal:
Hochberg et al, 2018

Z' portal for SIMP

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



- SIMP parameter space can be probed by Z' searches.

$e^+e^- \rightarrow \gamma Z' \rightarrow \gamma(l^+l^-), \quad e^+e^- \rightarrow \gamma + \text{MET}$
 $h \rightarrow ZZ', \text{ Drell-Yan, dileptons, etc.}$

cf. Hochberg et al, 2015

Conclusions

- Particle nature of dark matter has not been identified, so we need to consider new possibilities beyond horizon.
- SIMP dark matter is a plausible sub-GeV self-interacting dark matter (SIDM), without a need of large couplings to the SM for freeze-out process.
- Kinetic equilibrium of SIMP dark matter can be tested at intensity experiments such as Belle-II and LHCb.
- Dark resonances would be necessary for velocity-dependent self-interaction and $3 \rightarrow 2$ processes, becoming multiple messengers for the SM.