Beyond WIMP paradigm:
Interplay between astrophysics and particle physics

Hyun Min Lee

Chung-Ang University, Korea

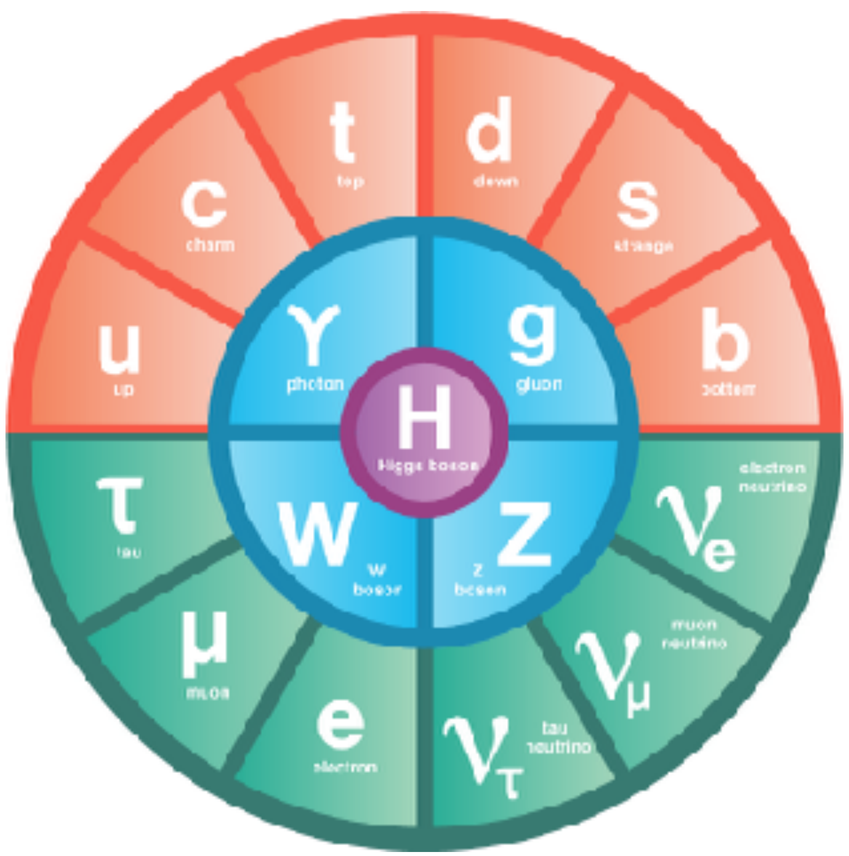
Institute for Basic Science Workshop on
Prospects of Particle Physics and Cosmology
IBS-CTPU, Daejeon, Dec 6, 2018

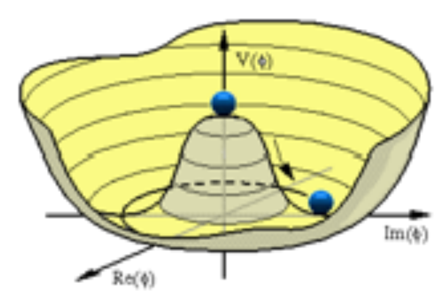
Outline

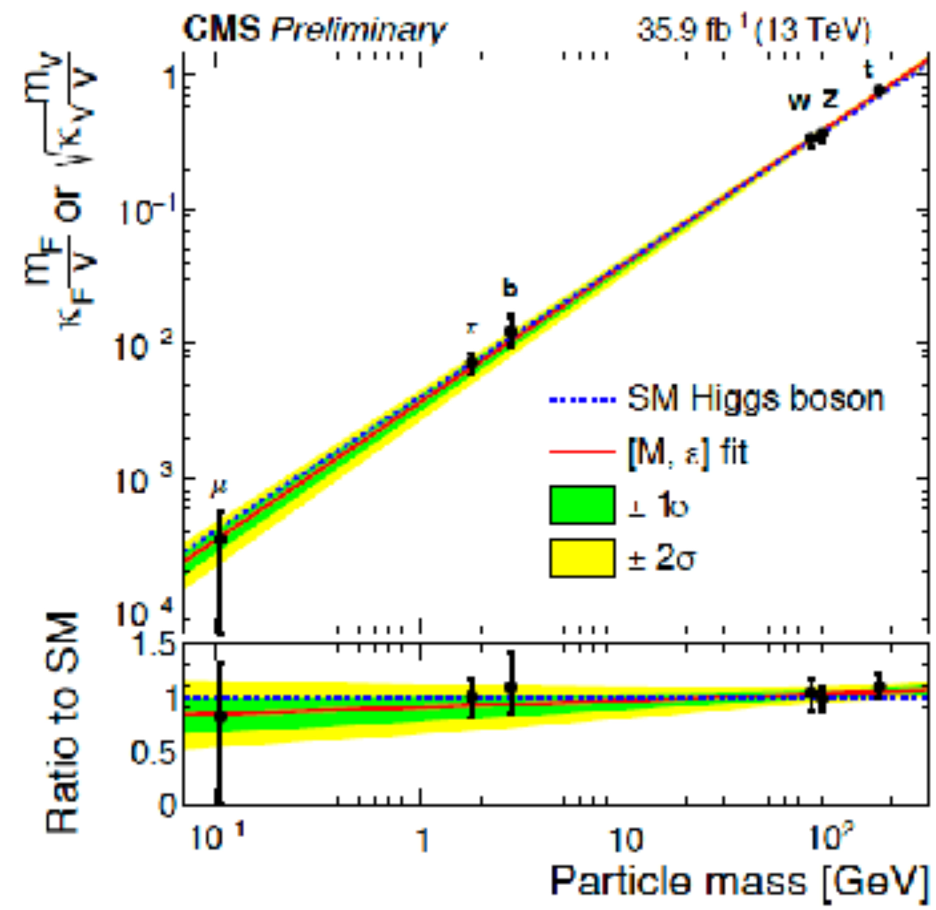
- Beyond WIMP
- SIMP paradigm
- SIMP models
- Conclusions

Standard Model

- SM describes well fundamental interactions of elementary particles except gravity.
- Electroweak symmetry breaking is well tested, being consistent with predictions of SM.







- We are on a right track for understanding the generation of masses, but there are many puzzles.

Puzzles of SM

- ✓ Hierarchy problem, vacuum instability

  ~ new symmetries and interactions?

- ✓ Electroweak symmetry breaking

  ~ modified Higgs potential?

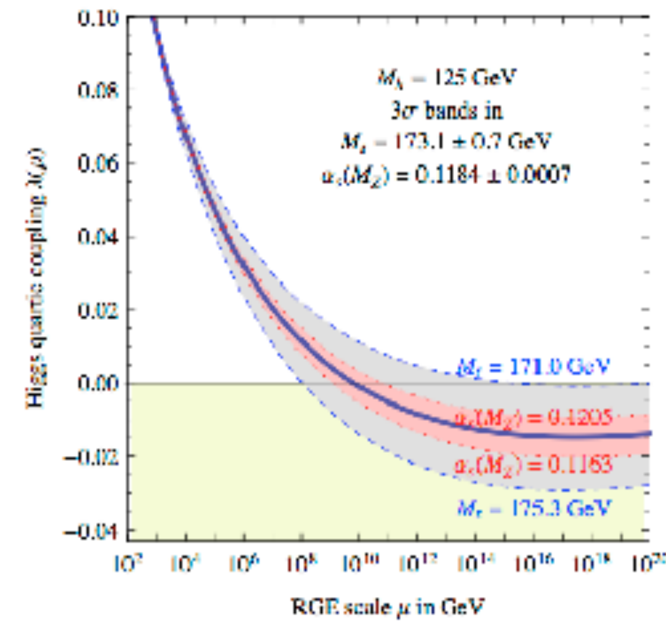
- ✓ Dark matter, dark energy

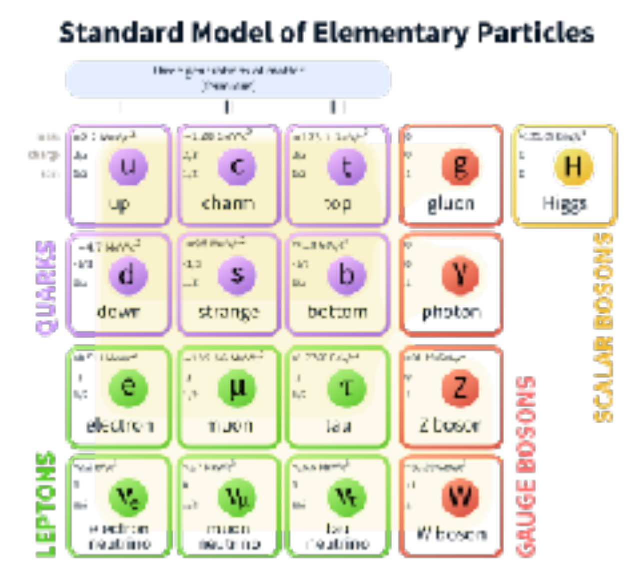
  ~ non-minimal, beyond WIMP?

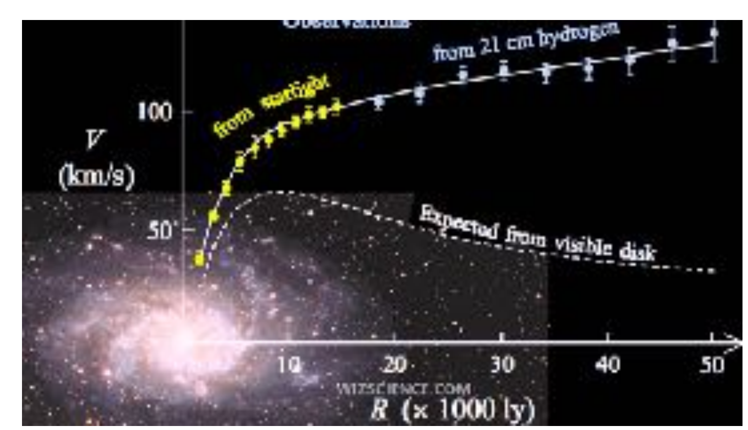
- ✓ Flavor puzzles, baryogenesis

  ~ flavor symmetries?

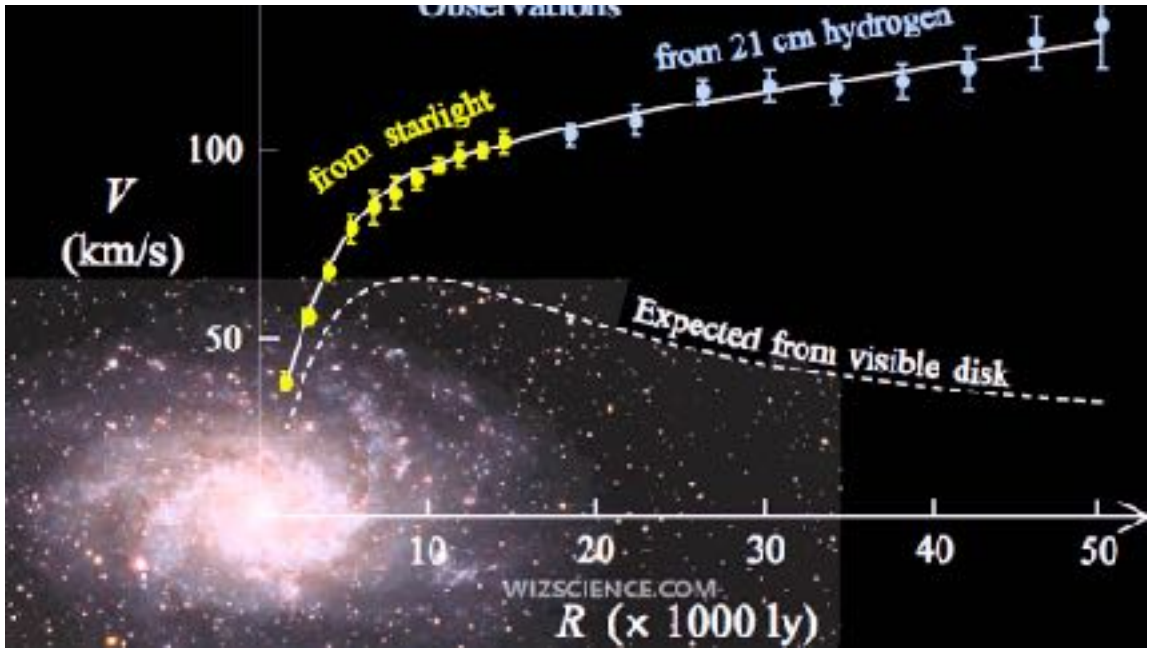
- ✓ Inflation, quantum gravity, unification, etc.

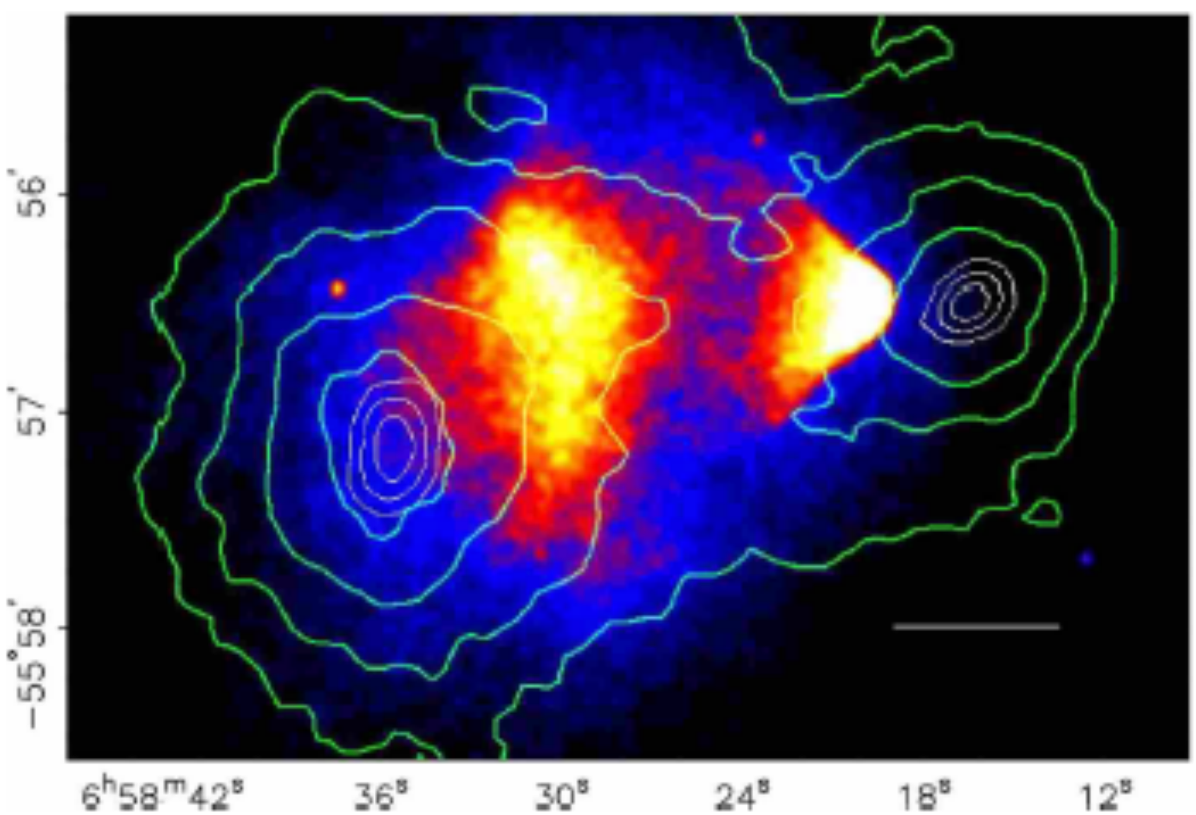


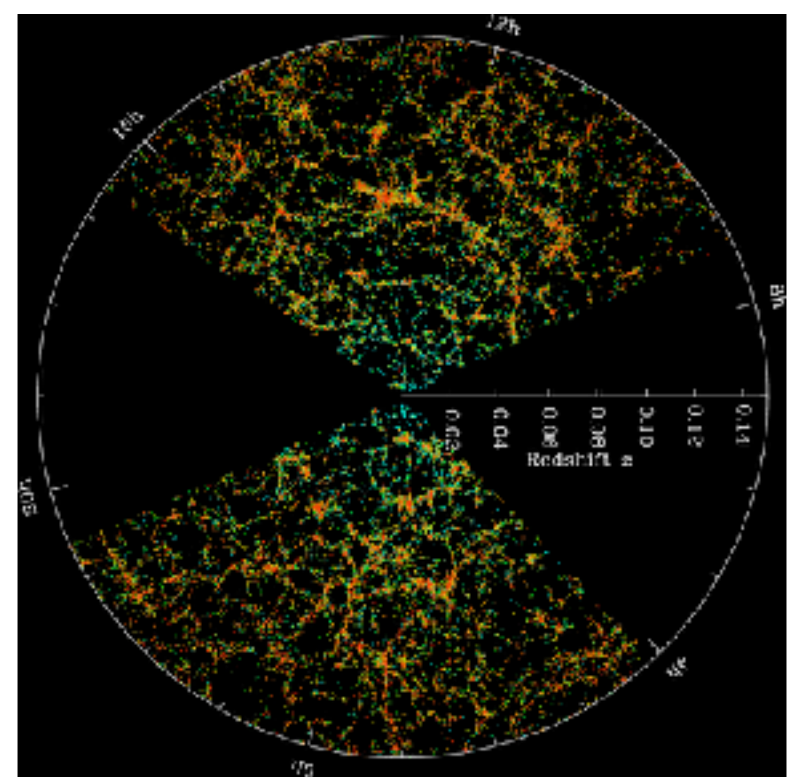




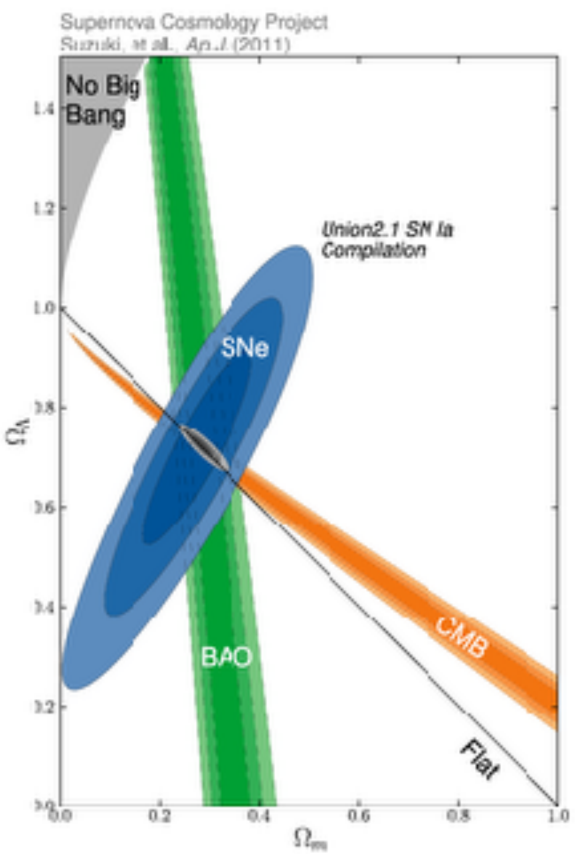
Evidences for dark matter

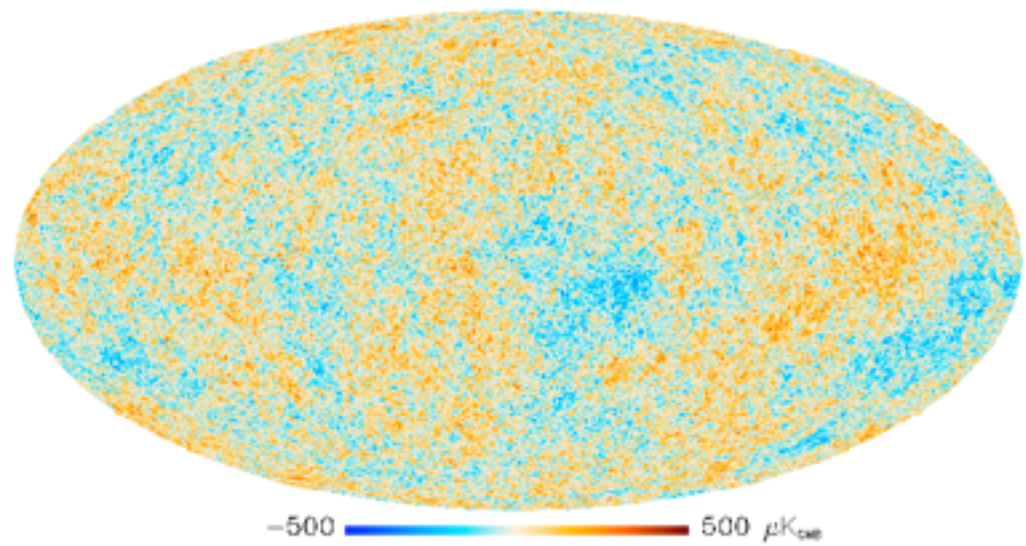


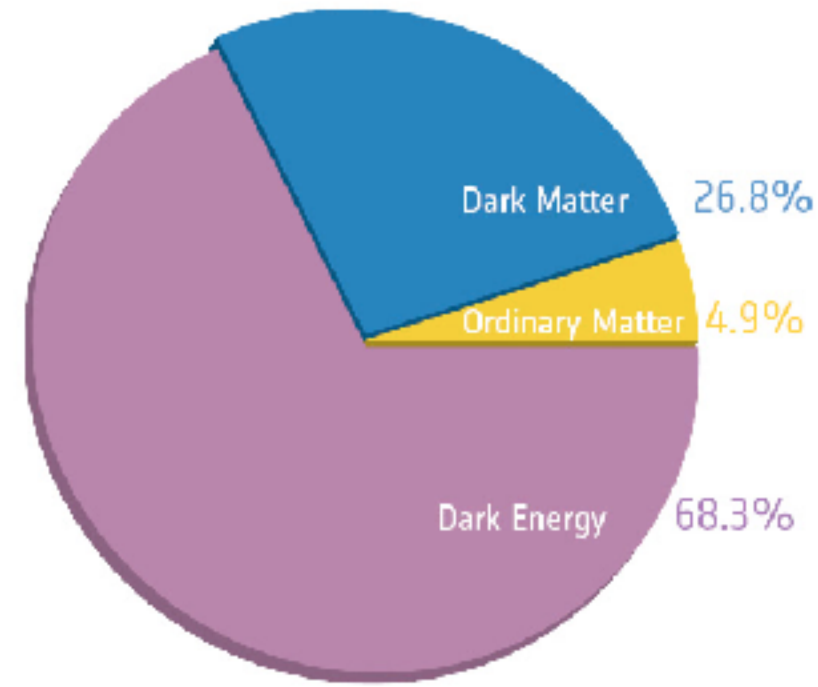




Cosmic pie and dark matter



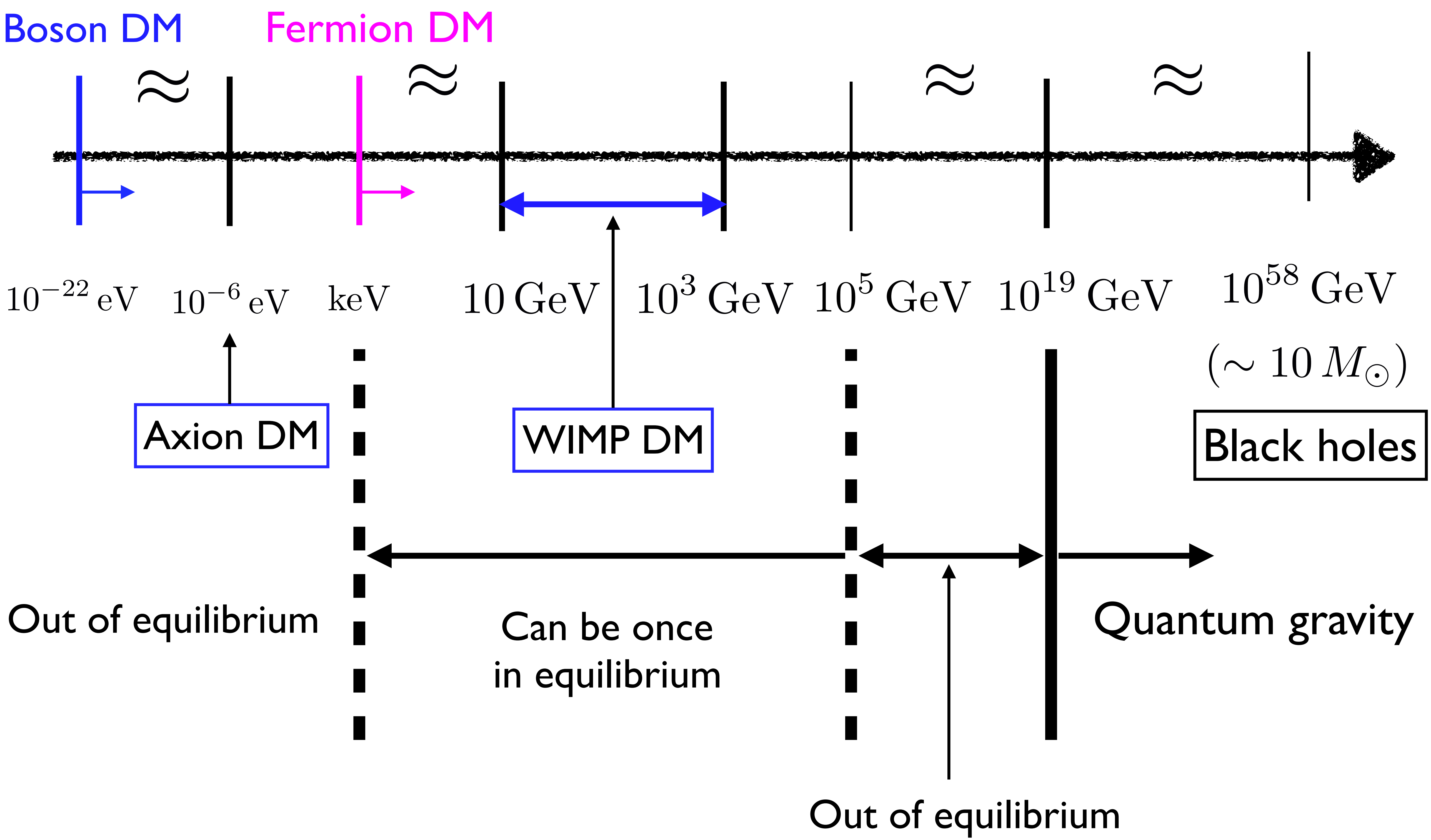




CMB (+ flat universe)
+ SN1a + BAO

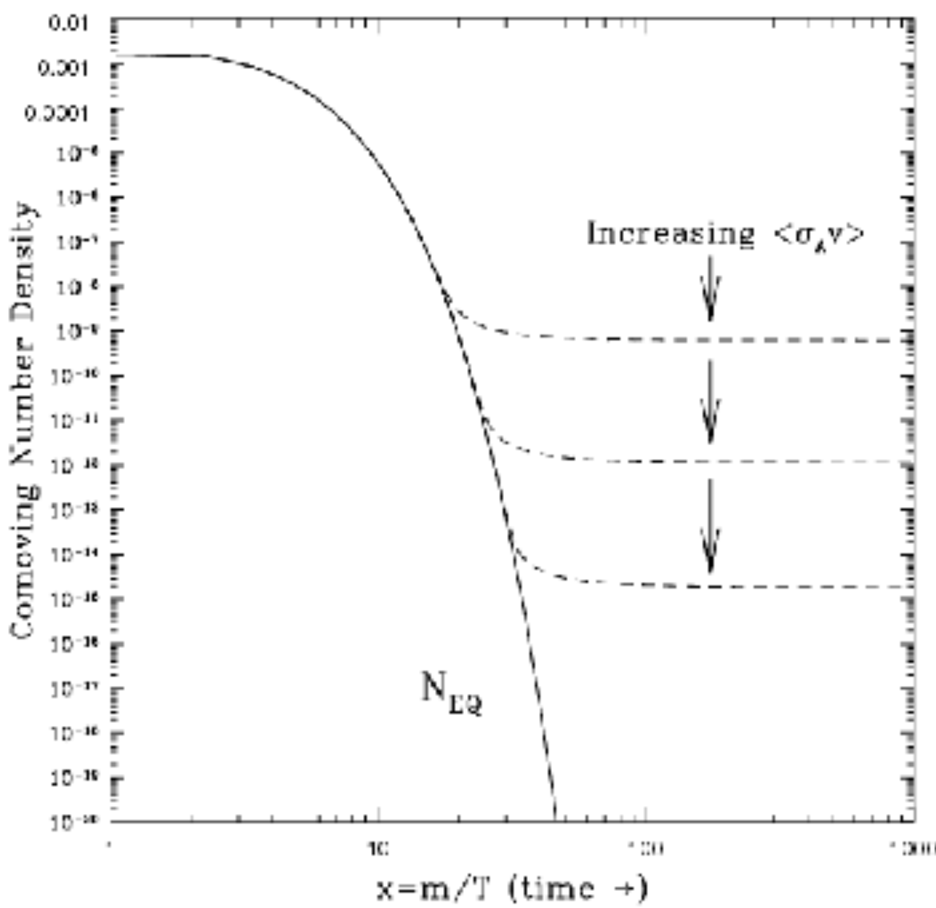
- DM interacts gravitationally.
- DM is almost charge-neutral.
- DM makes 85% of total matter.
- DM is not part of the SM.

What is dark matter?



WIMP dark matter

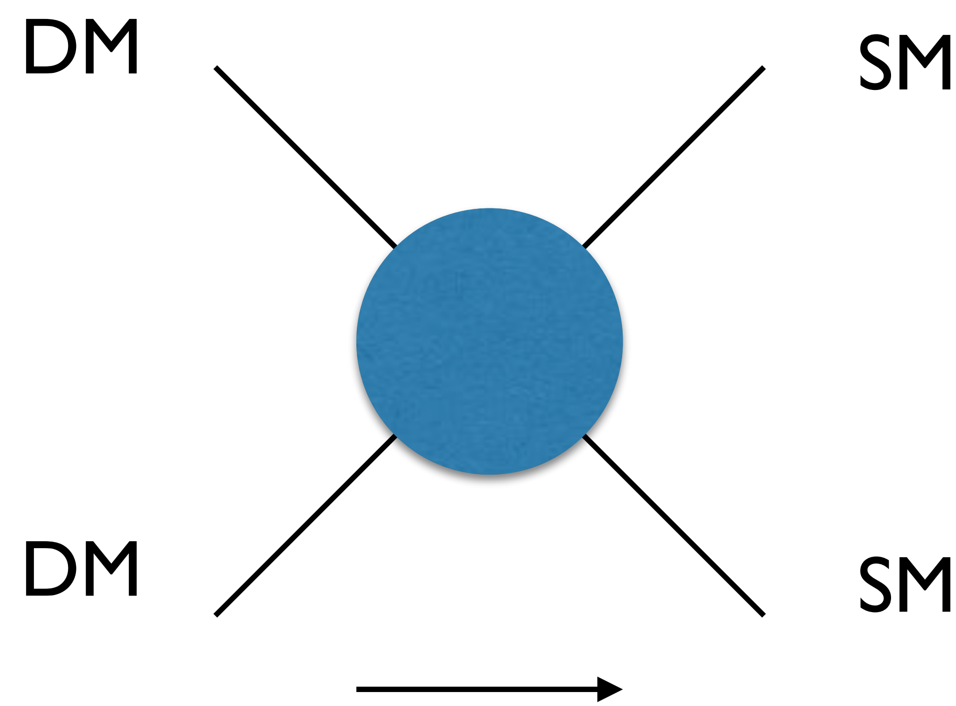
DM number



time

[Lee,Weinberg(1977)]

Dark matter abundance is determined by freeze-out.

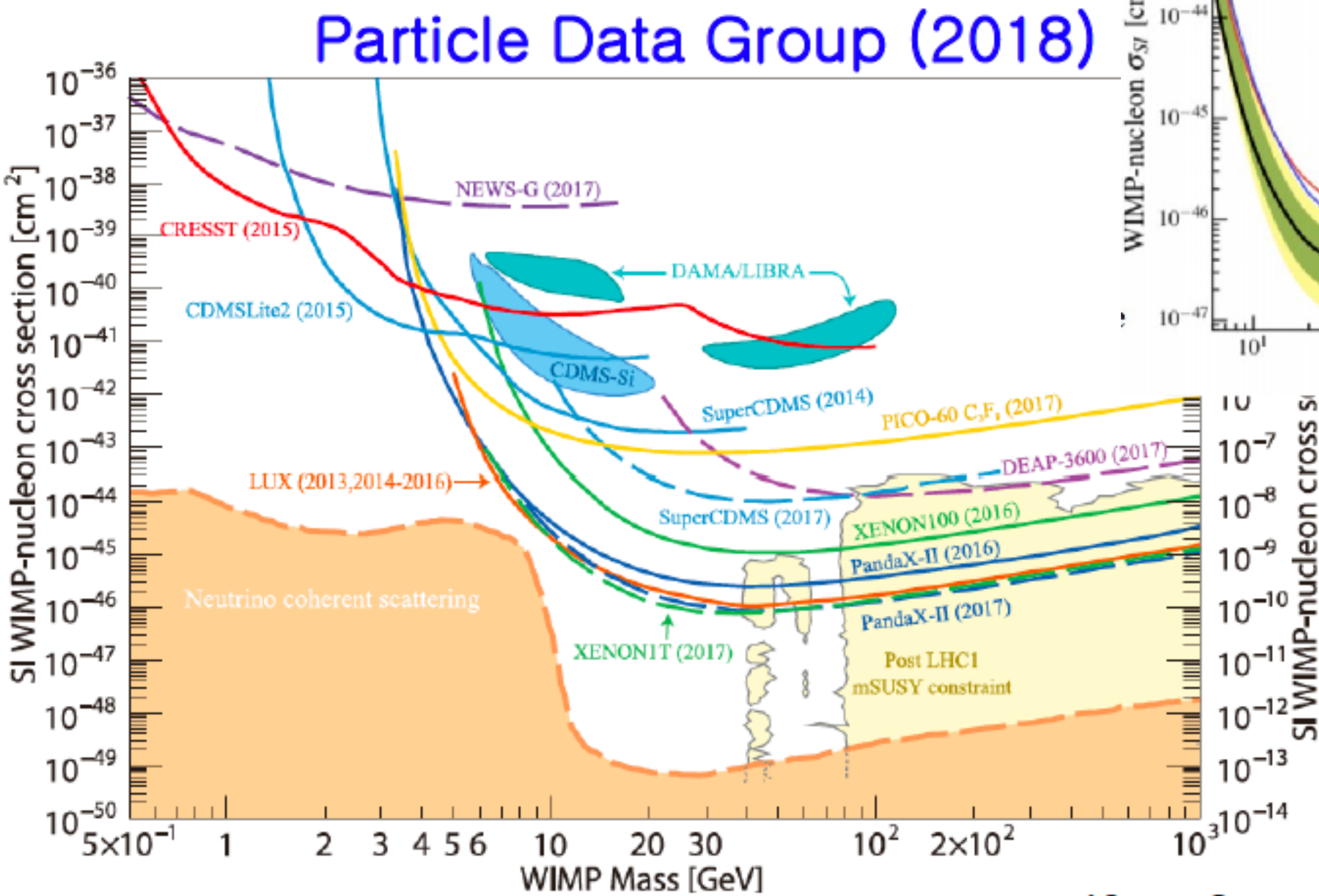


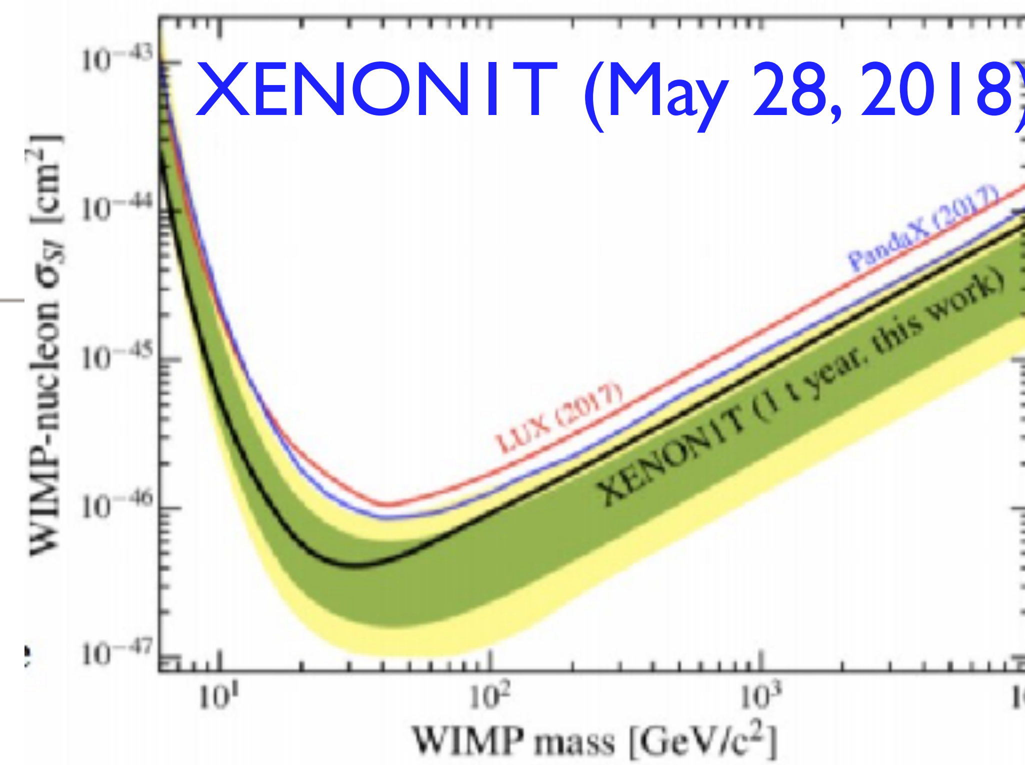
Weak interaction with 100GeV~1TeV mass:

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

Predictive for direct, indirect and collider detections!

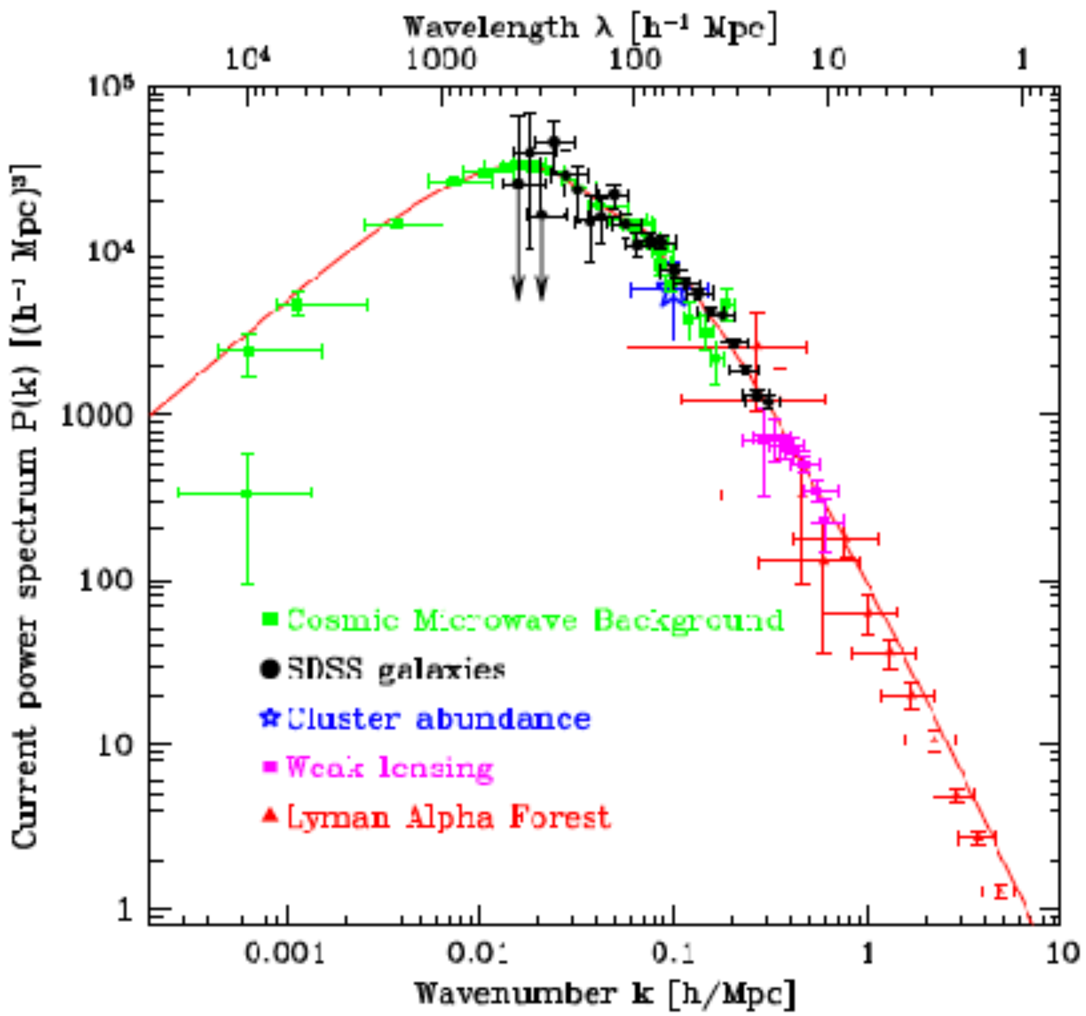
WIMP from underground

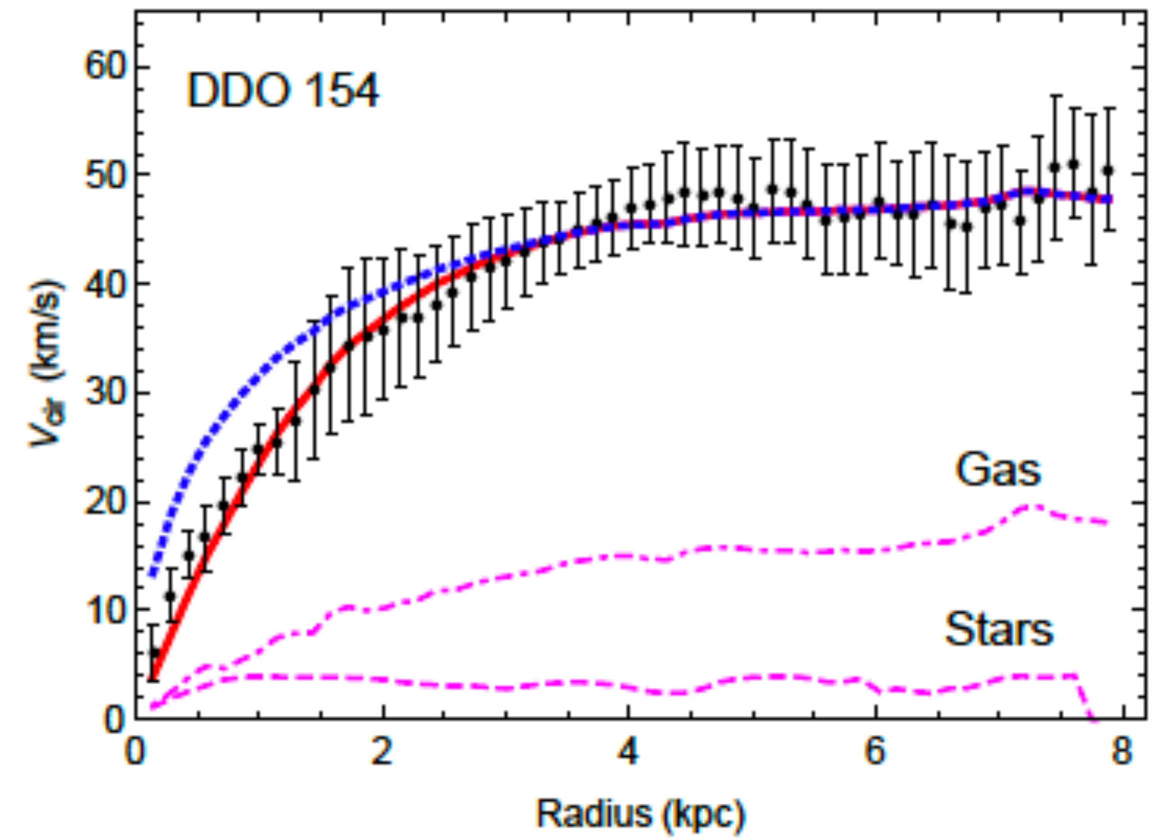




Direct detection bounds on WIMP DM get stronger.

Core-Cusp problem





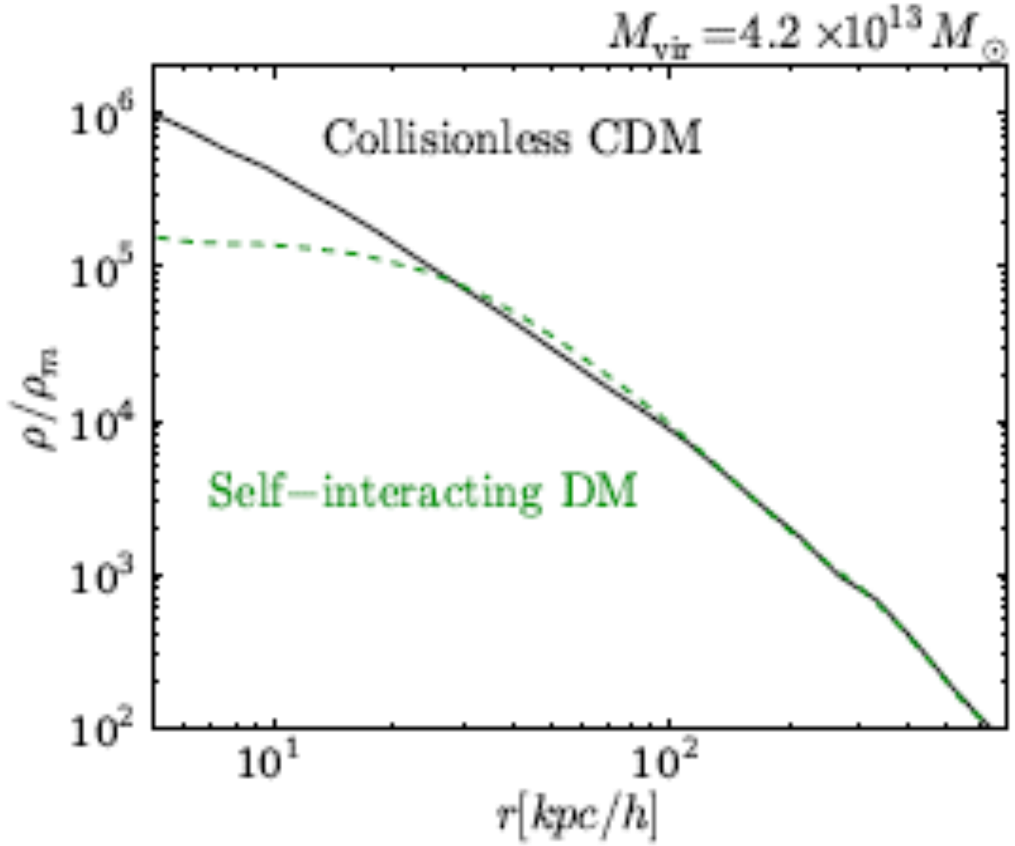
CDM explains well
large-scale(>Mpc) structure.

Small-scale(<kpc) problems?
[Spergel, Steinhardt, 2000; Tulin, Yu, 2017]

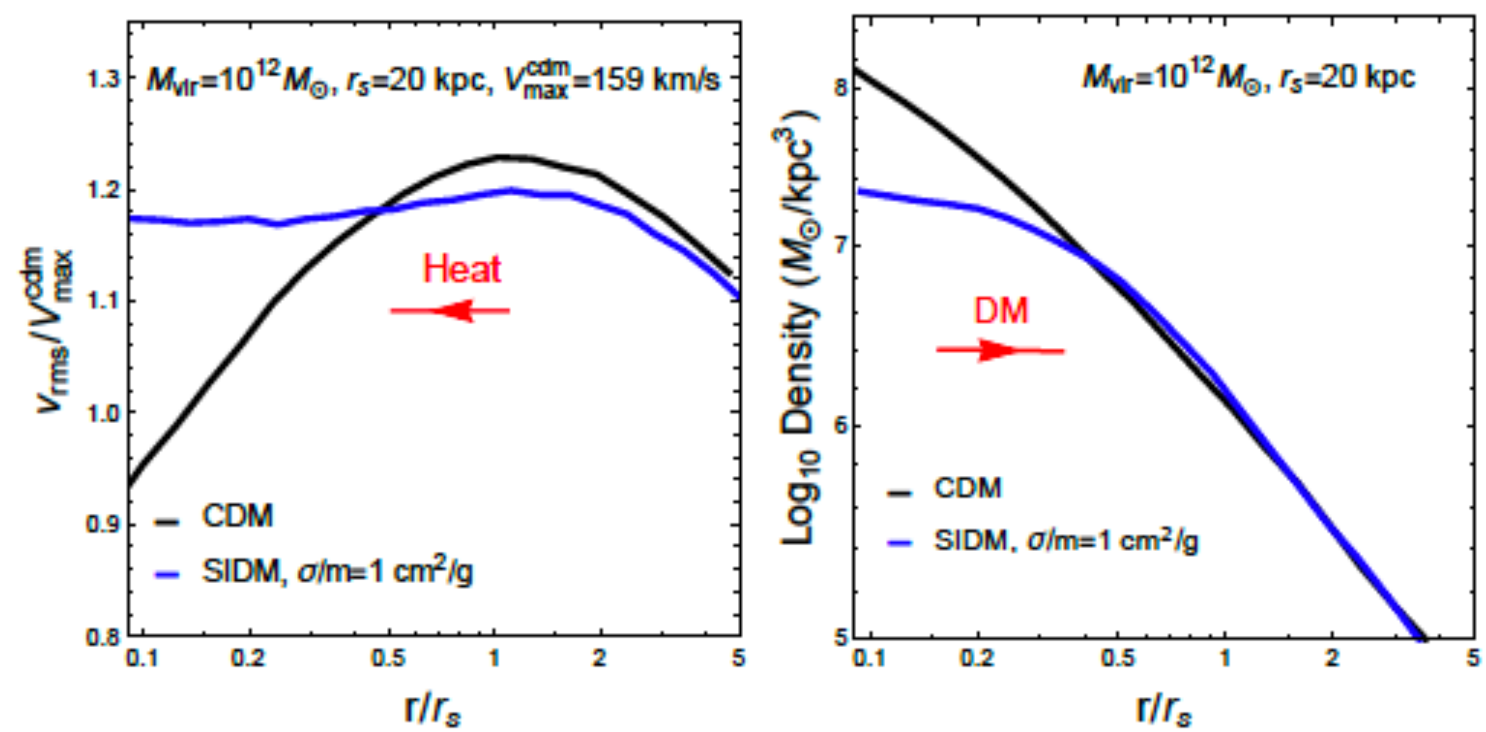
- Core-Cusp problem: CDM N-body simulation predicts cuspy DM profile (NFW), rendering rotation velocities larger at small scales (→cored DM profile favored).

cf. too-big-to-fail, missing satellite problems.

Self-Interacting dark matter



[Weinberg et al, 2013]



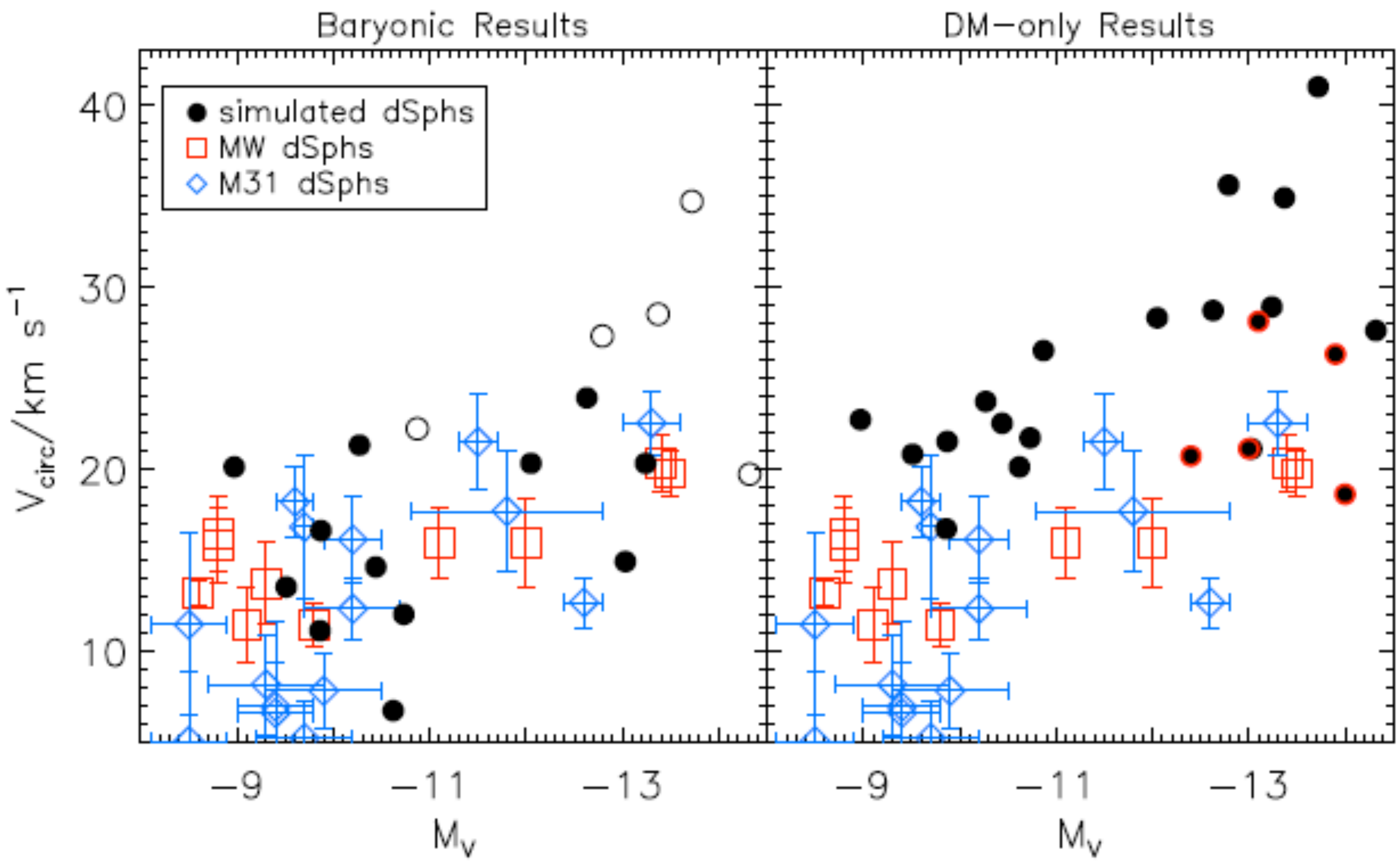
[Tulin, Yu, 2017]

Self-interactions transport heat from outside to the core.

→ Flattening the DM profile in the inner region.

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

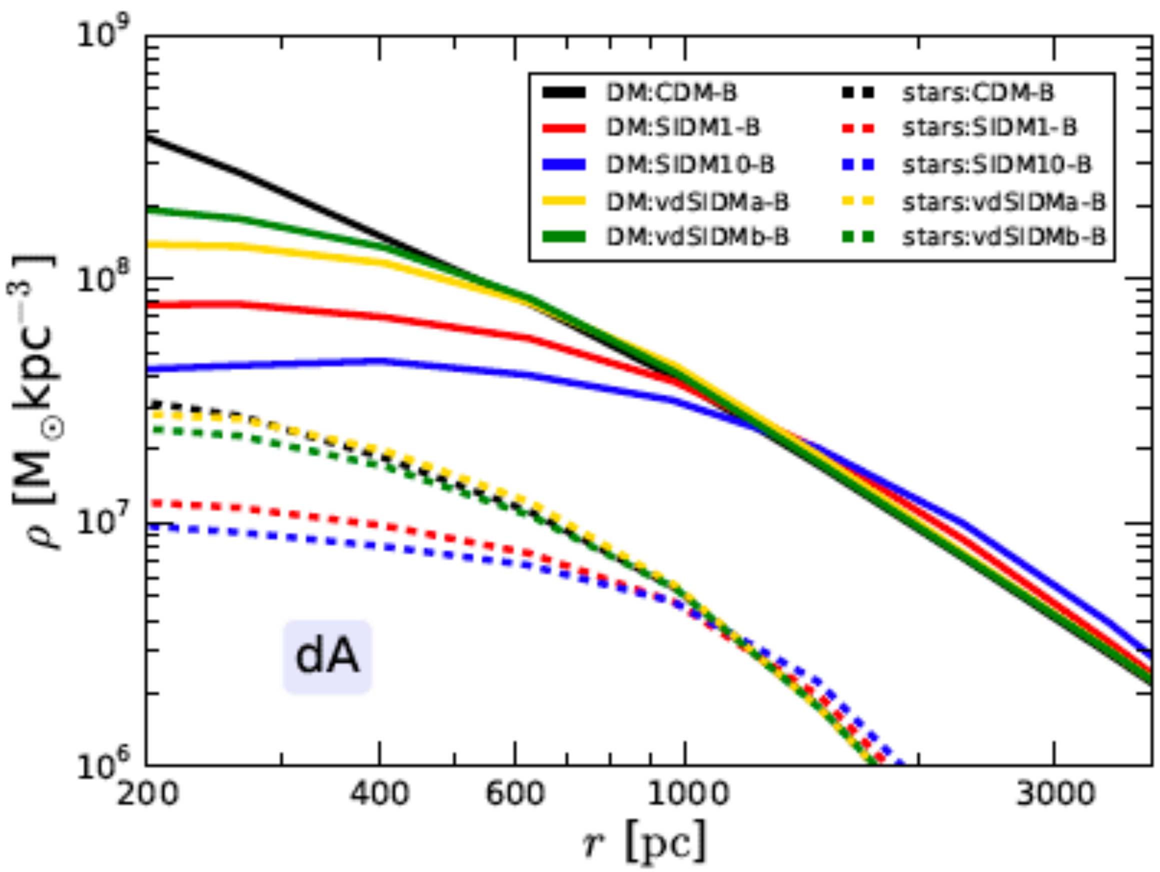
Baryonic feedback



[Brooks & Zolotov, 2012]

Baryons (SN feedback) can erase small structures.

SIDM Simulations

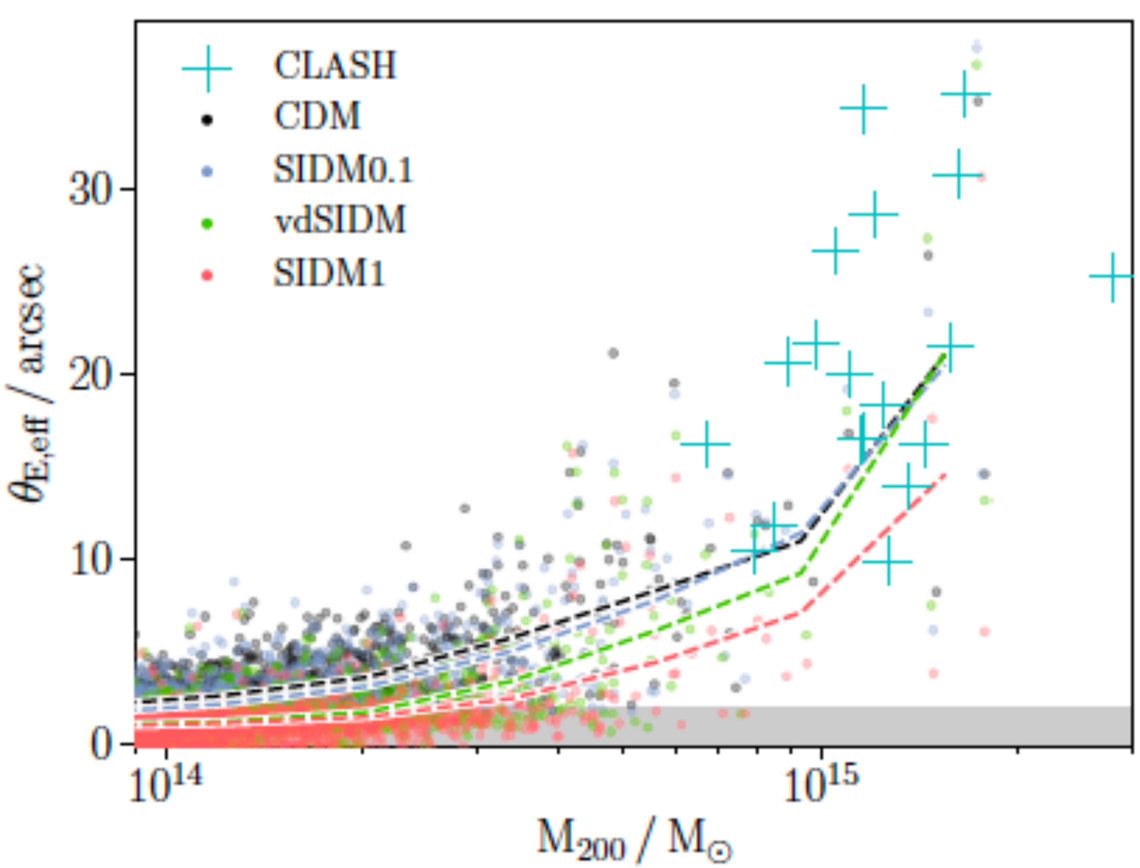


Dwarf galaxies simulation

resolution $1.8 \times 10^2 M_\odot$

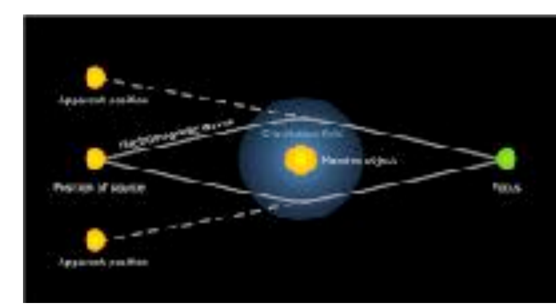
[Vogelsberger et al, 2017]

SIDM: star core radius follows DM core radius.



Gravitational lensing for galaxy clusters

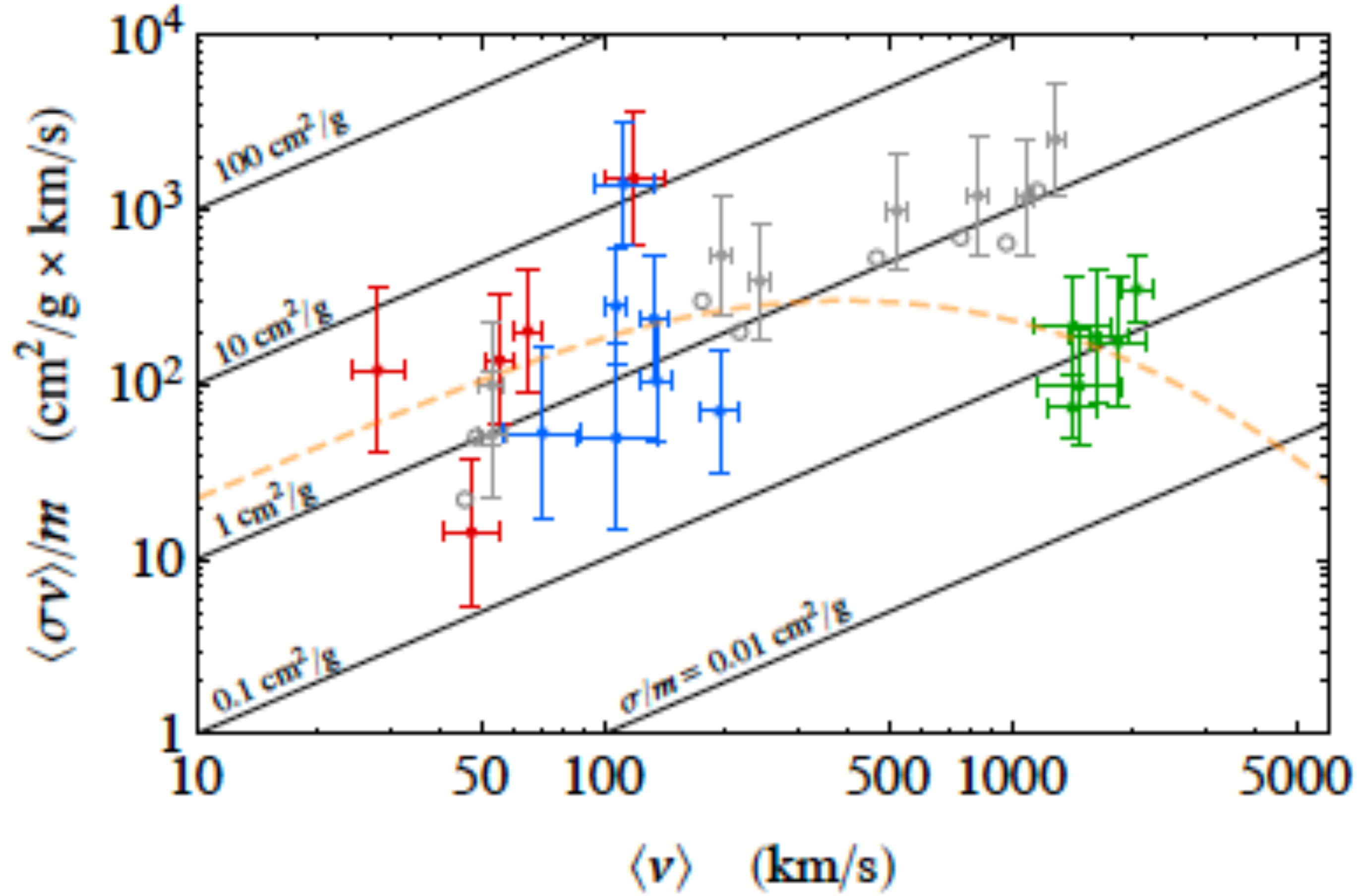
[Robertson et al, 2018]



SIDM: cored DM makes gravity lensing effect smaller.

CLASH survey: $\sigma/m < 1\mathrm{cm}^2/\mathrm{g}$

Velocity-dependent SIDM



- Bullet cluster shows no DM self-interactions. $\sigma/m \lesssim 0.7\,\mathrm{cm}^2/\mathrm{g}$

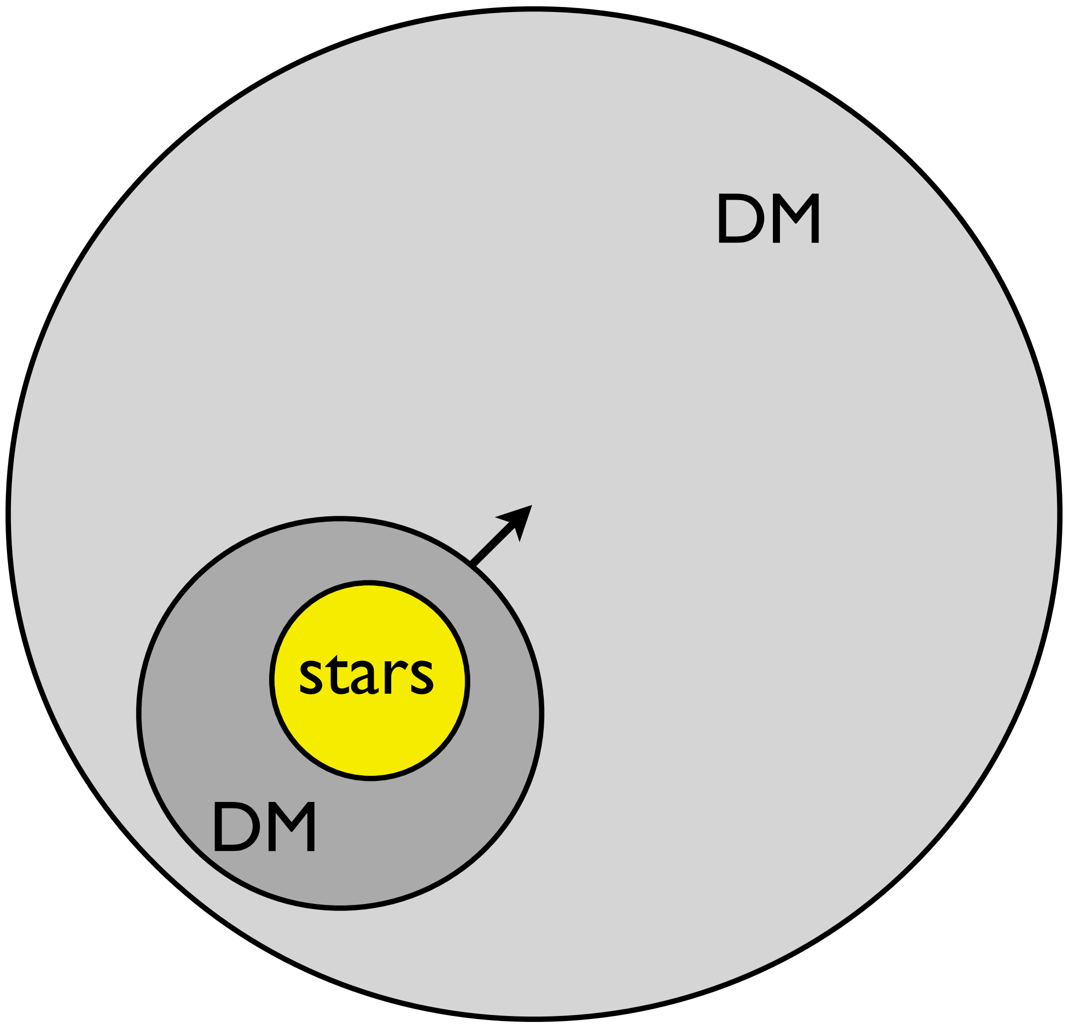
- DM self-interaction may be velocity-dependent.

THINGS dwarf galaxies (red), LSB galaxies (blue), and clusters (green).

SIDM N-body simulations, with $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}, (gray)$

[M. Kaplinghat et al, 2015]

SIDM in merging galaxies



“Drag force” btw DM subhalo and larger halo

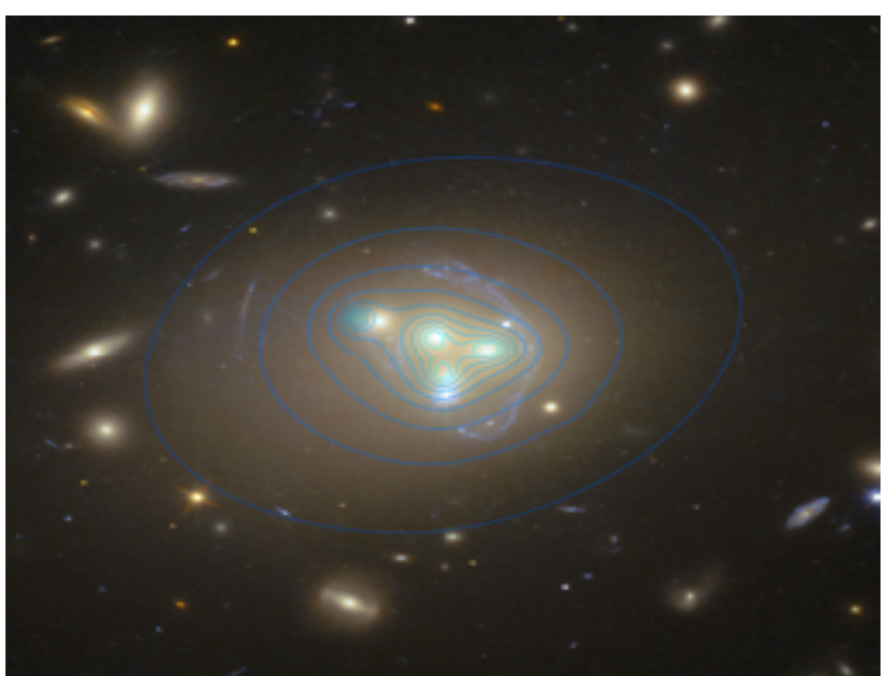
>“Gravity” btw subhalo and star

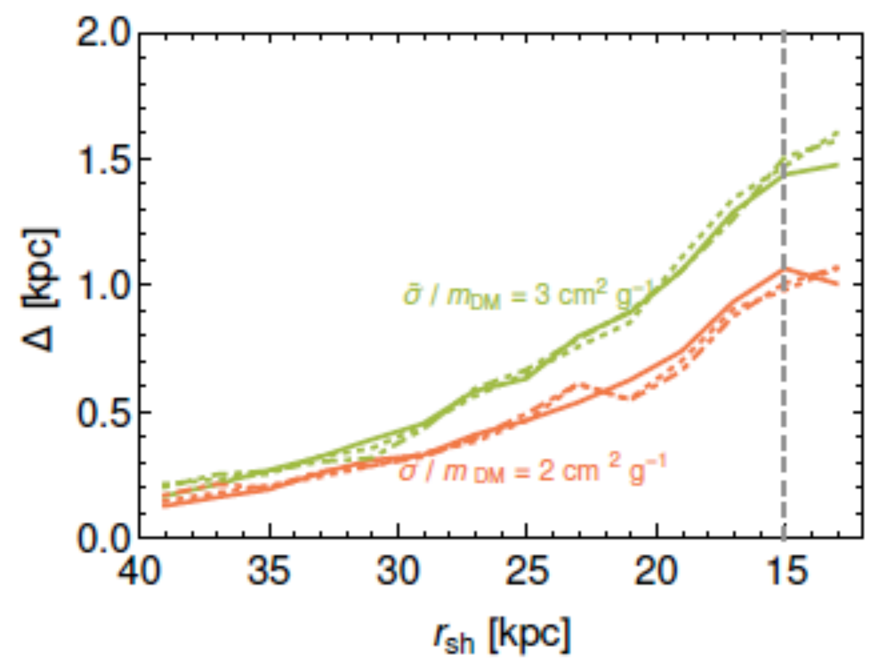
→ Separation of DM halo

e.g. Abell 3827 cluster

$\boxed{\text{off-set: } \Delta = 1.62^{+0.47}_{-0.49}\,\mathrm{kpc}}$

[Massey et al(2015)]





[Kahlhoefer et al(2015)]

Summary of constraints

Positive observations	σ/m	$v_{\rm rel}$	Observation
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm}^2/\mathrm{g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves
Too-big-to-fail problem			
Milky Way	$\gtrsim 0.6\ \mathrm{cm}^2/\mathrm{g}$	$50\ \mathrm{km/s}$	Stellar dispersion
Local Group	$\gtrsim 0.5\ \mathrm{cm}^2/\mathrm{g}$	$50\ \mathrm{km/s}$	Stellar dispersion
Cores in clusters	$\sim 0.1\ \mathrm{cm}^2/\mathrm{g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing
Abell 3827 subhalo merger	$\sim 1.5\ \mathrm{cm}^2/\mathrm{g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset
Abell 520 cluster merger	$\sim 1\ \mathrm{cm}^2/\mathrm{g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset
Constraints			
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm}^2/\mathrm{g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys
Substructure mergers	$\lesssim 2\ \mathrm{cm}^2/\mathrm{g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset
Merging clusters	$\lesssim \text{few}\ \mathrm{cm}^2/\mathrm{g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm}^2/\mathrm{g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio

[S. Tulin and H. Yu, Phys. Rept. 730, 1(2018)]

SIMP paradigm

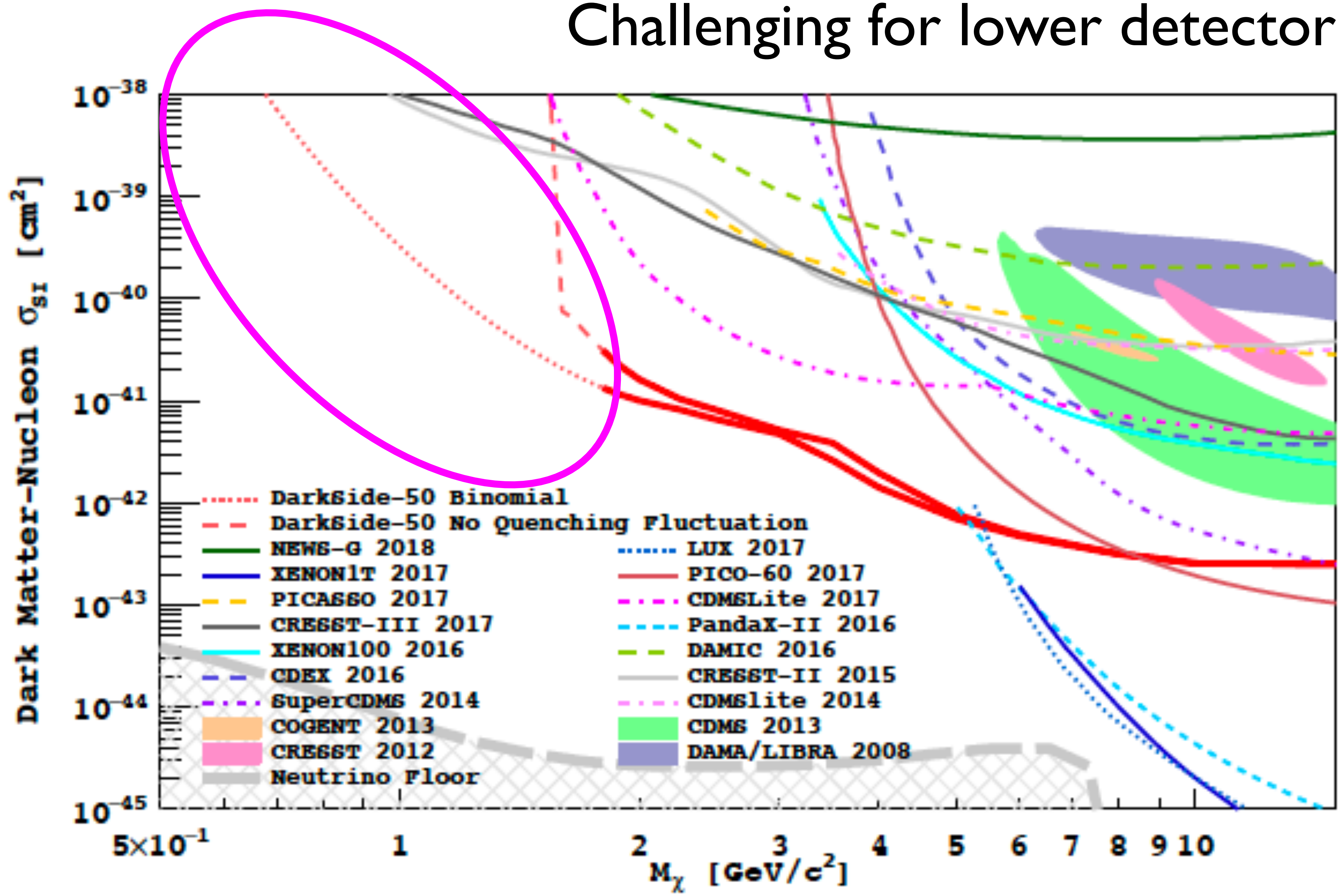
Light dark matter

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

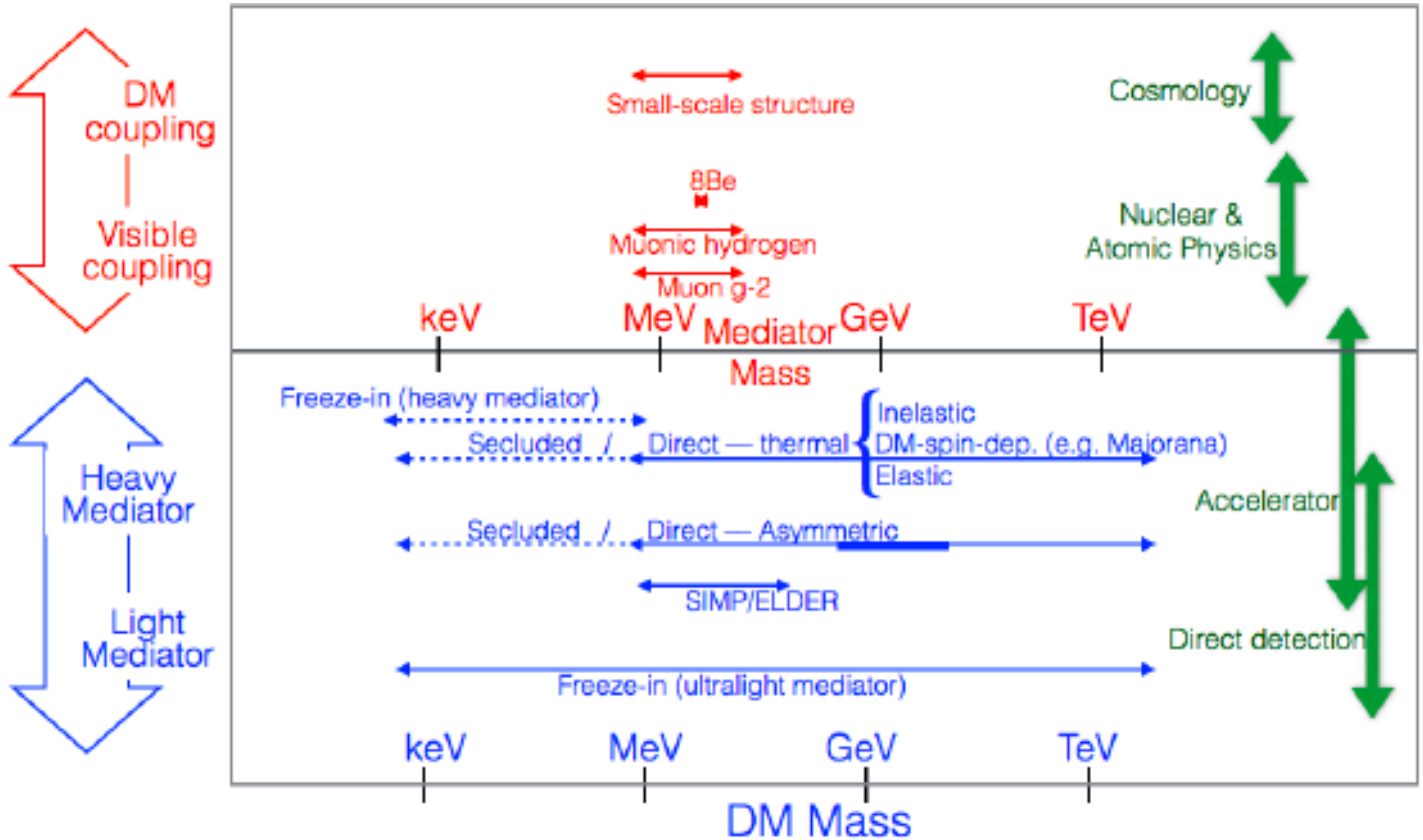
(Fermion DM)

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

Challenging for lower detector threshold.



Status of DM models

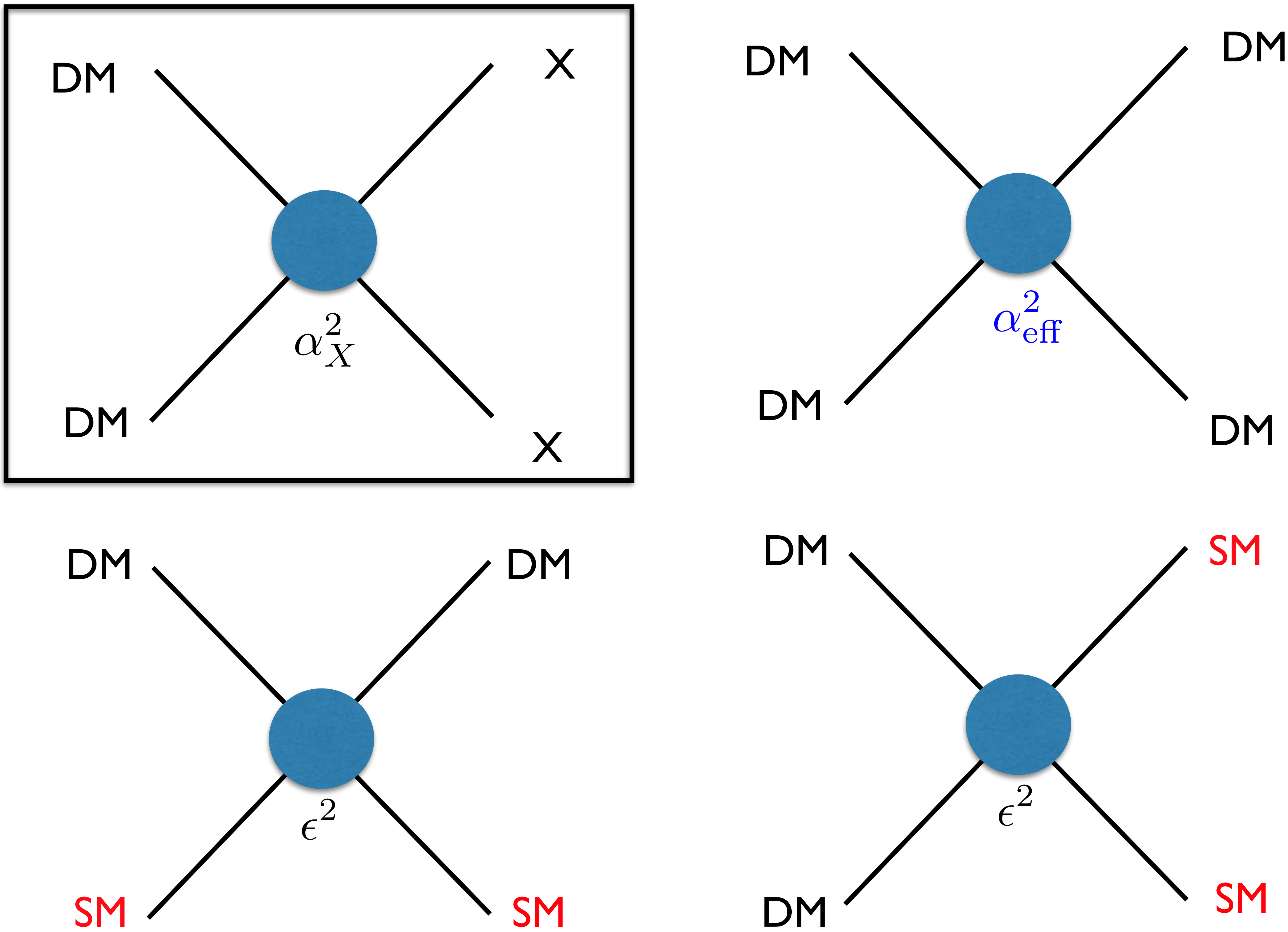


US Cosmic Visions, 1707.04591

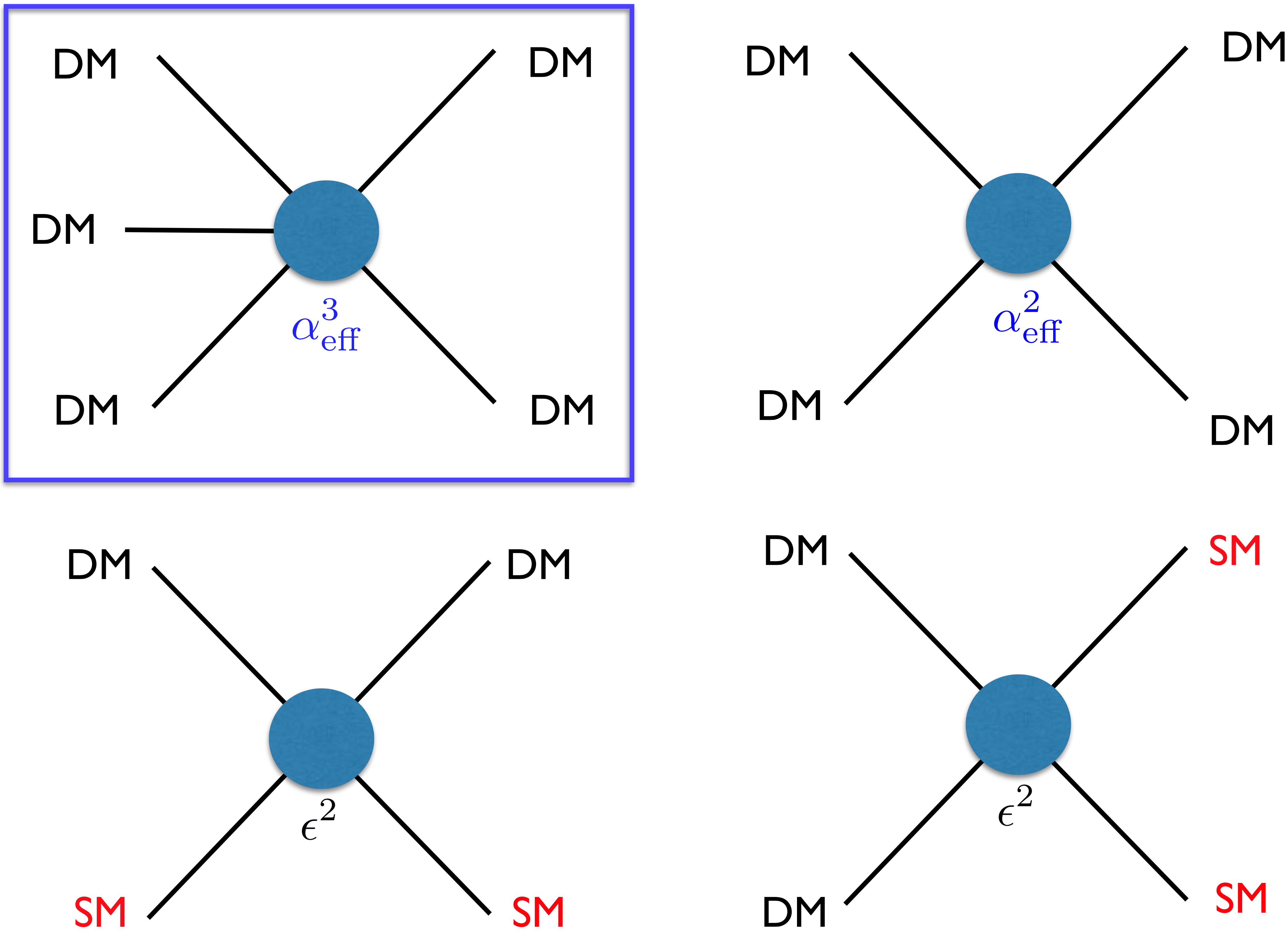
New DM production mechanisms open a new parameter space for light dark matter.

cf. 3→2 process, forbidden, ELDER, co-scattering, etc.

“Standard" light DM



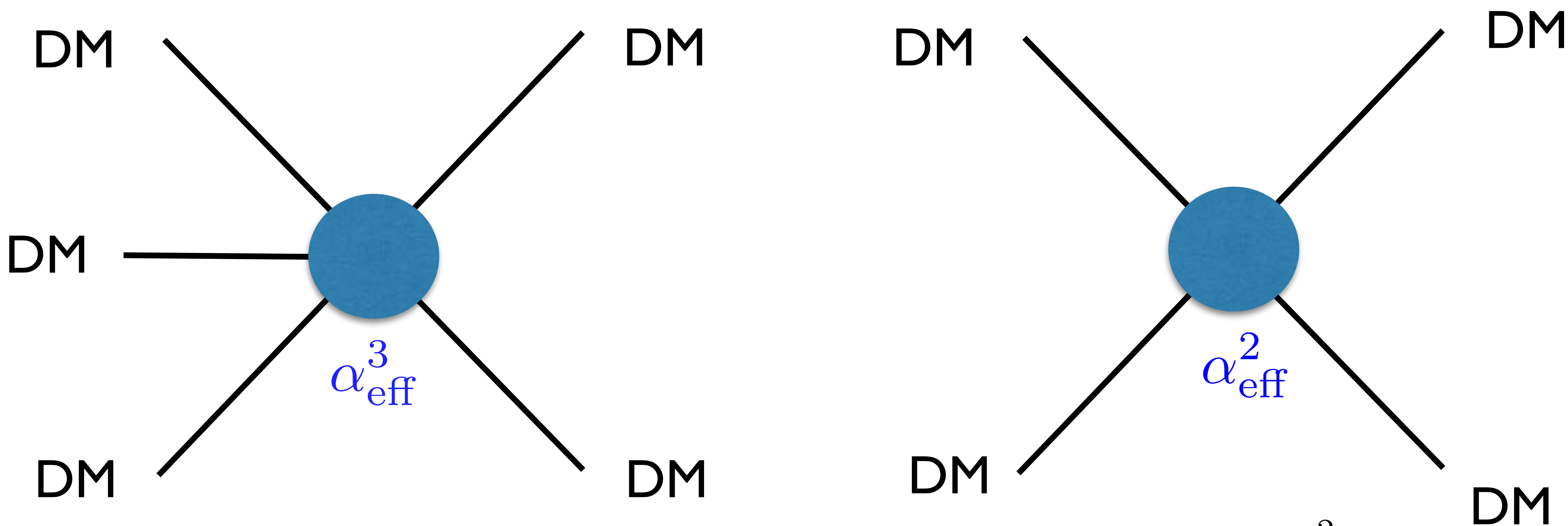
SIMP paradigm



SIMP production

- Strongly Interacting Massive Particles (SIMP) in chemical equilibrium by self-interactions (3→2).

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



$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} \approx -\langle\sigma v^2\rangle_{3\to2}(n_{\rm DM}^3 - n_{\rm DM}^2 n_{\rm DM}^{\rm eq})$$

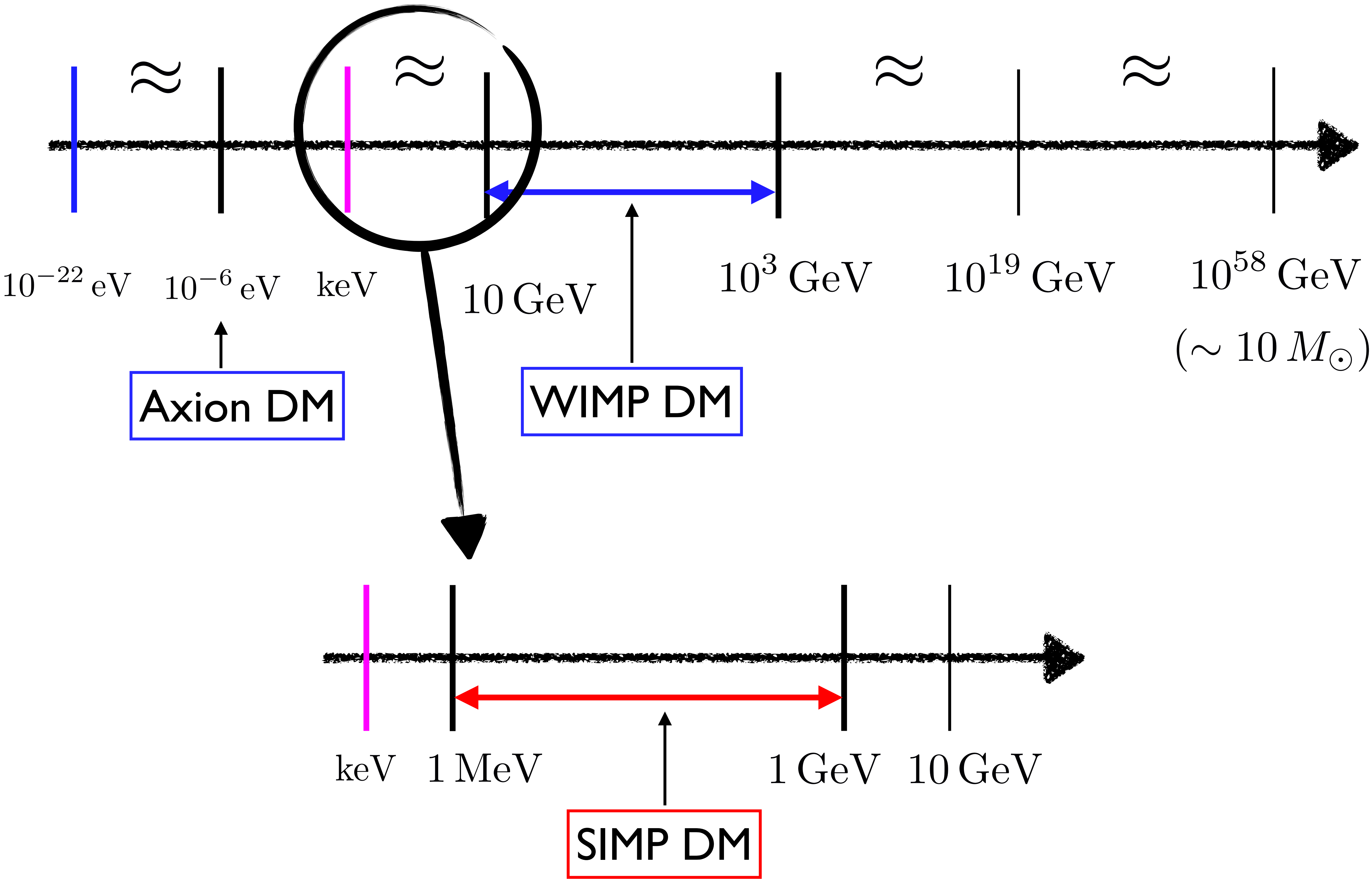
$$\sigma_{\rm self} = \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^2}$$

Large self-scattering vs small annihilation: $\langle\sigma_{\rm eff} v\rangle = n_{\rm DM}\langle\sigma v^2\rangle \ll \sigma_{\rm self}$

Relic density: $\Omega_{\rm DM}h^2 \simeq 0.1\left(\frac{m_{\rm DM}/35\,{\rm MeV}}{\alpha_{\rm eff}}\right)^{3/2}$, $\frac{\sigma_{\rm self}}{m_{\rm DM}} \sim \left(\frac{5}{\alpha_{\rm eff}}\right) 1{\rm cm}^2/{\rm g}$

cf. forbidden channels, elastically decoupling, co-scattering, etc.

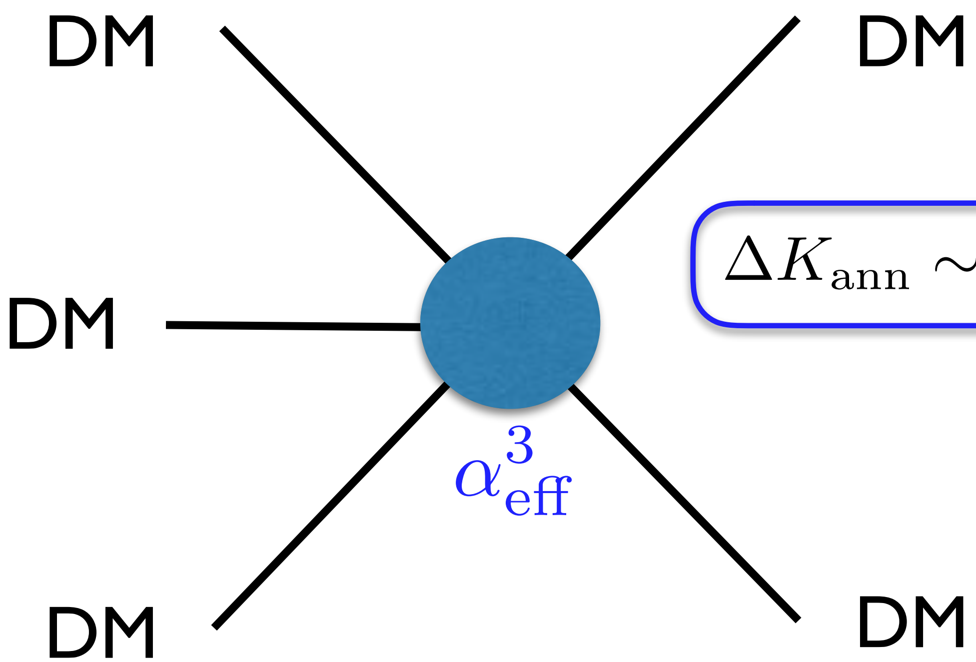
New window from SIMPs



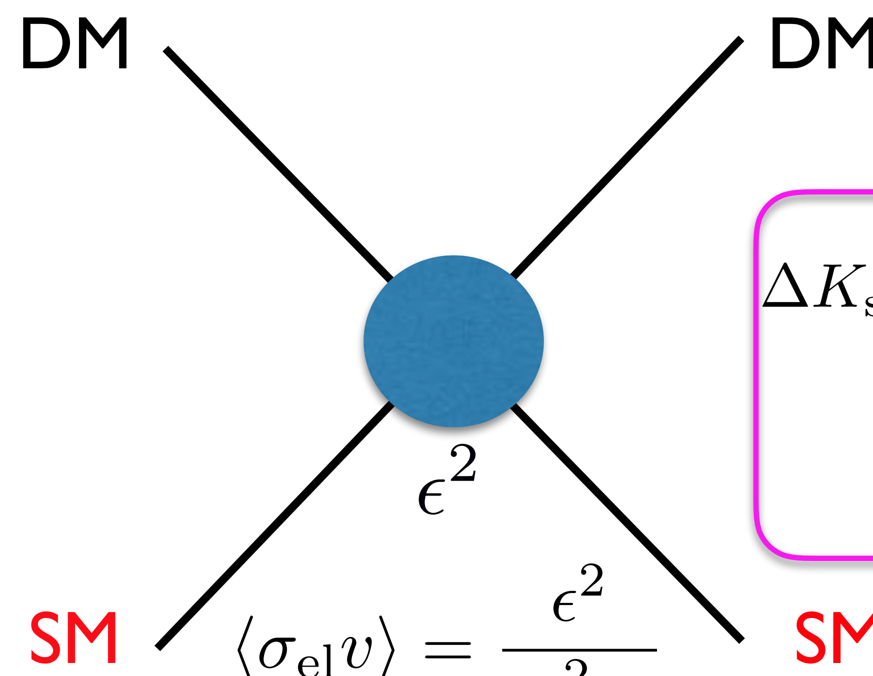
SIMP in equilibrium

- Equilibriate SIMP kinetic energy by kinetic scattering to avoid overheat for the structure formation.

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



$$\boxed{\Delta K_{\rm ann} \sim m_{\rm DM}}$$



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

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

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

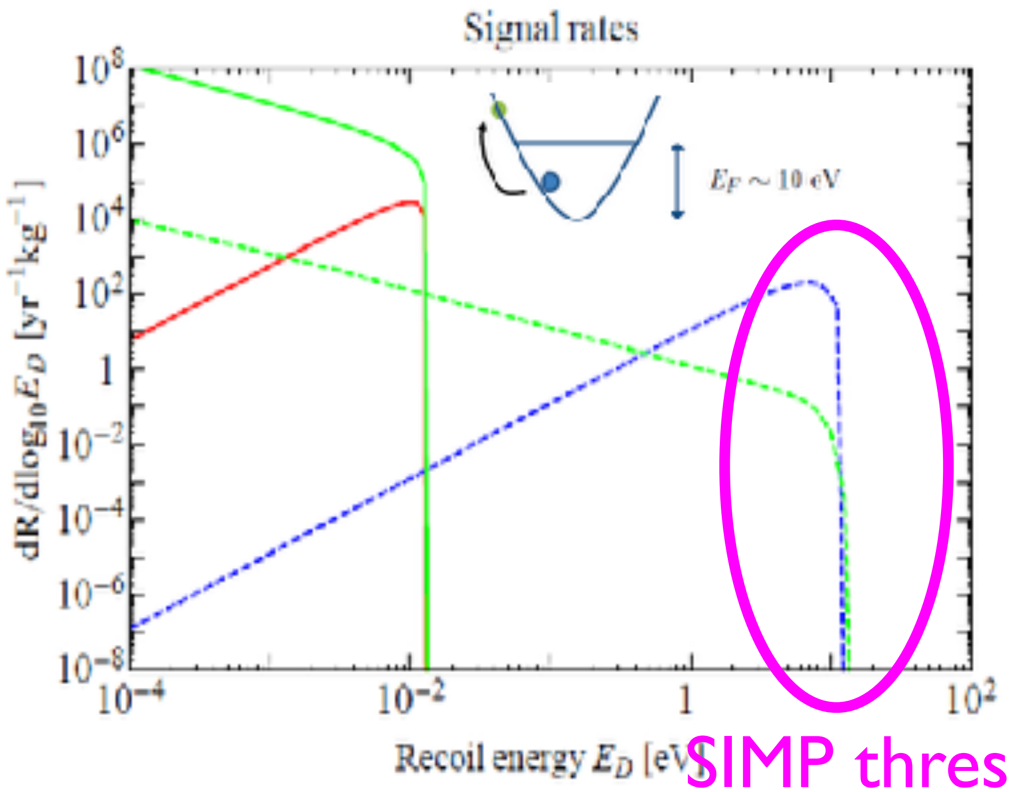
Kinetic equilibrium: $\gamma(T) > H\left(\frac{m_{\rm DM}}{T}\right)^2$ ⇨ $\boxed{\epsilon > 10^{-8}\alpha_{\rm eff}^{1/2}}$

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

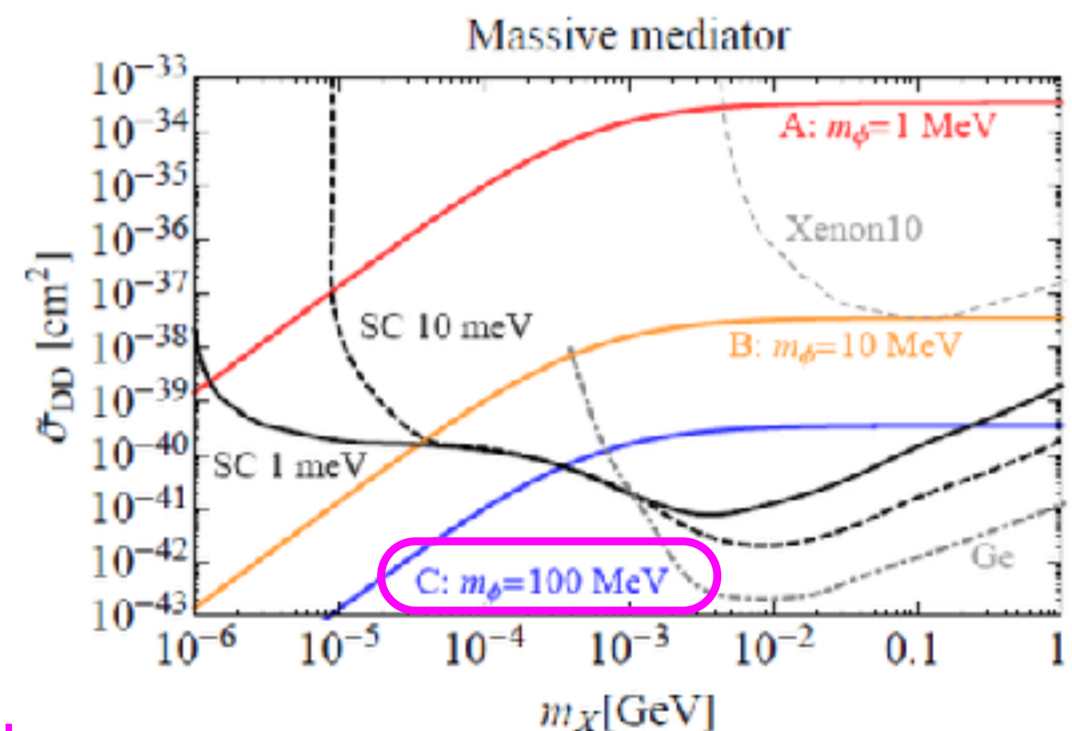
SIMP detection

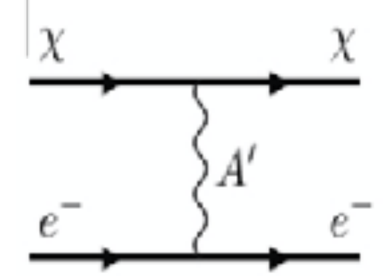
- DM-electron scattering

[Hochberg et al (2015)]



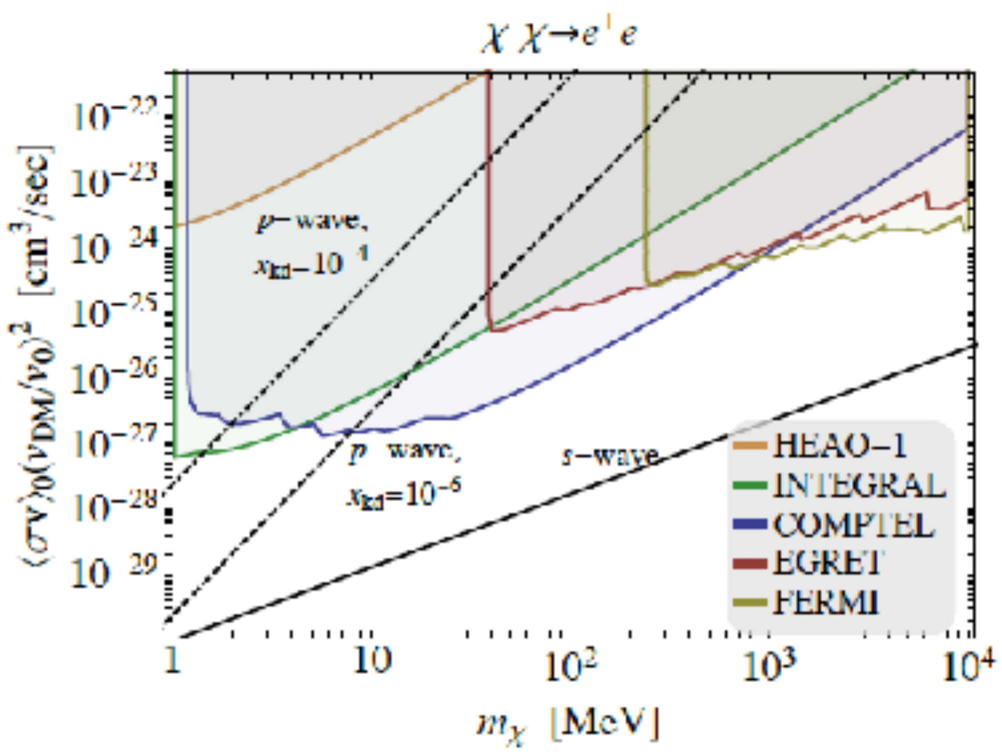
SIMP threshold

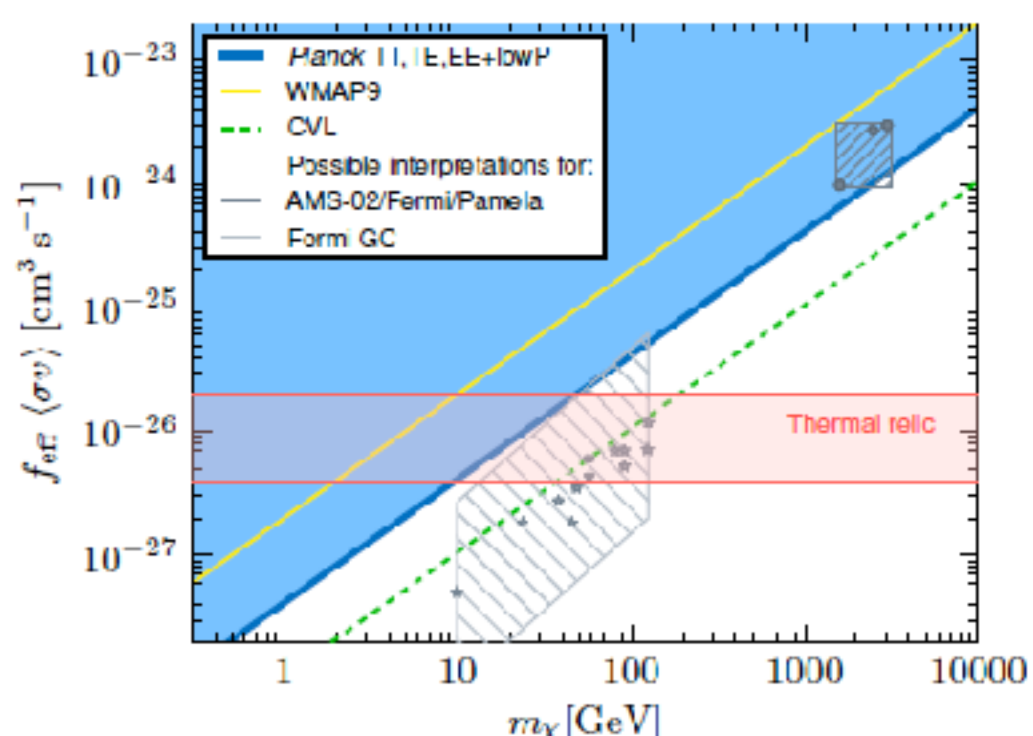


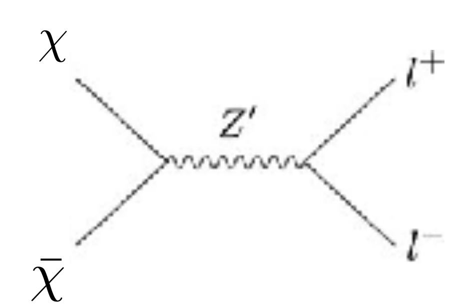


- Gamma rays, CMB

[Essig et al, 2013]



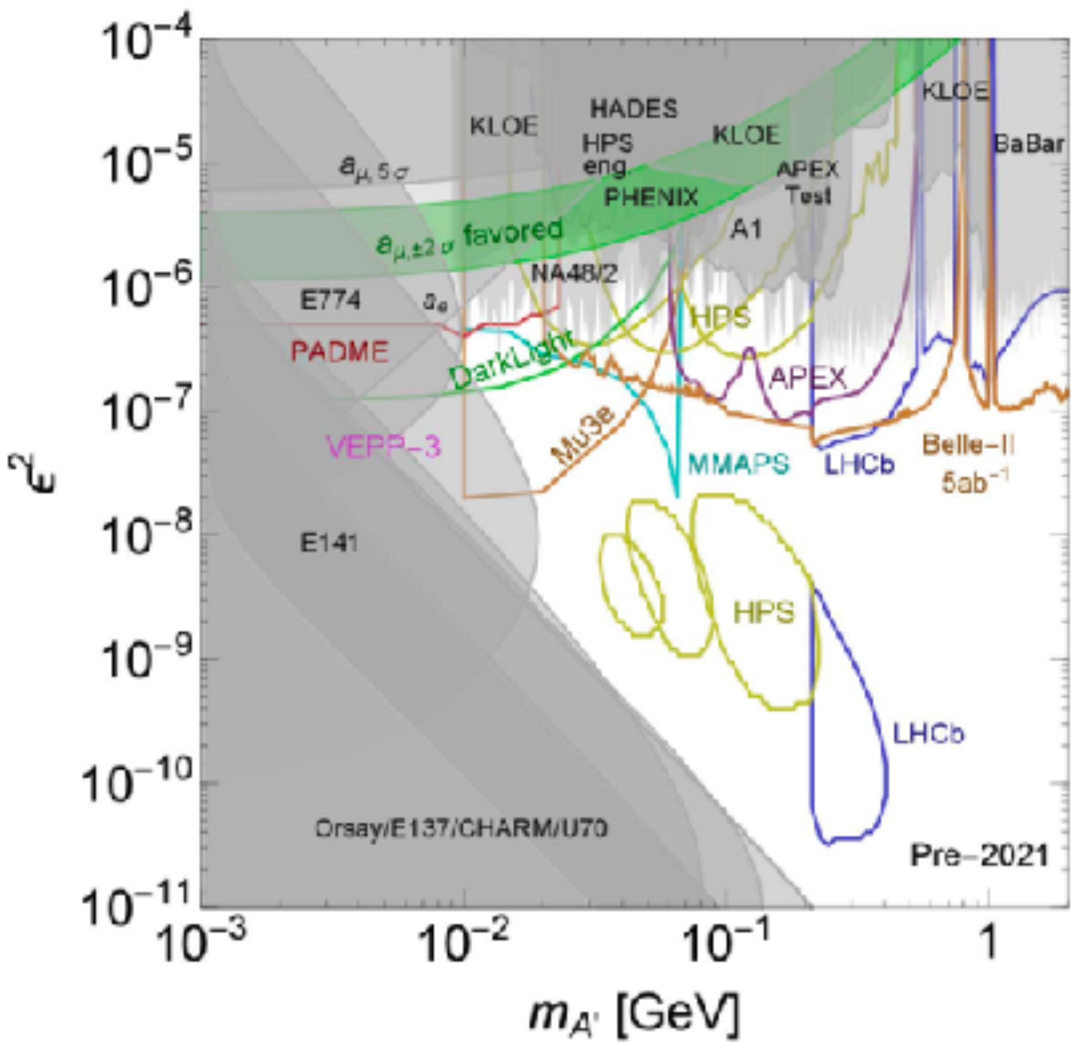


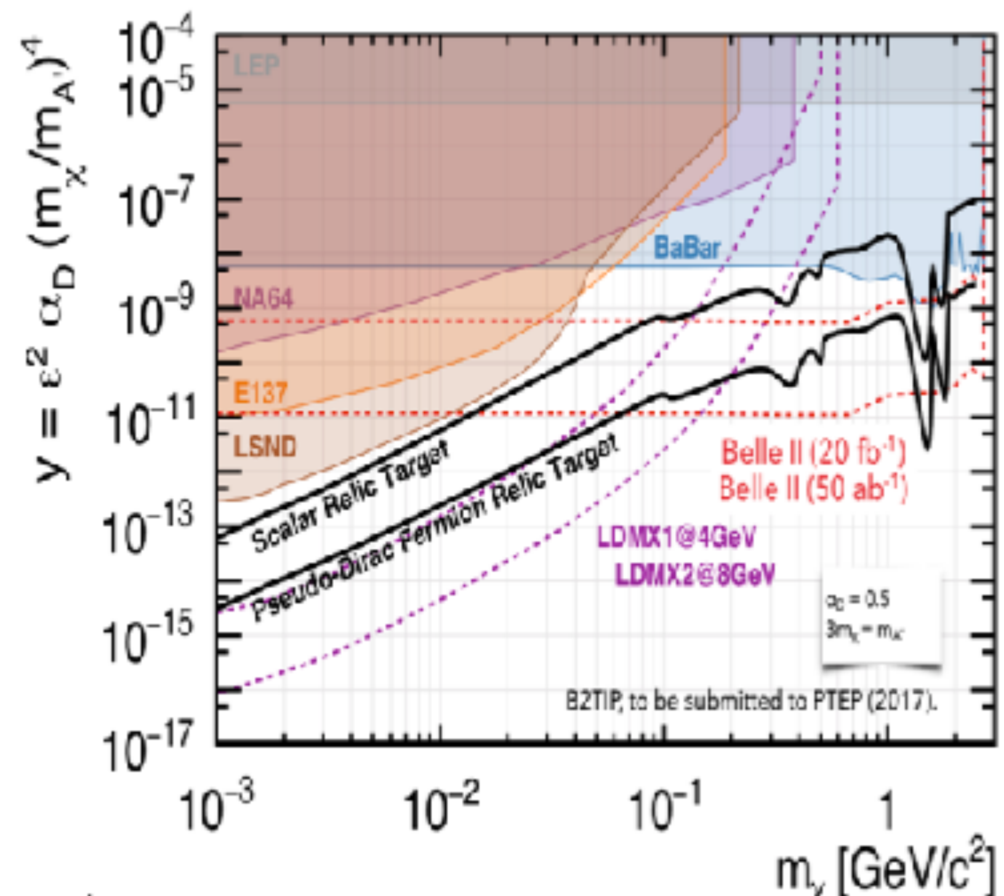


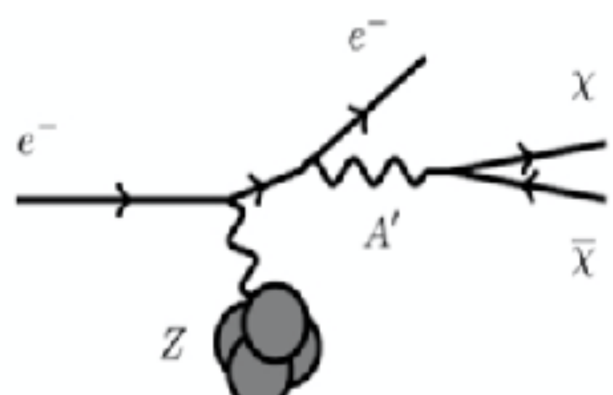
SIMP detection

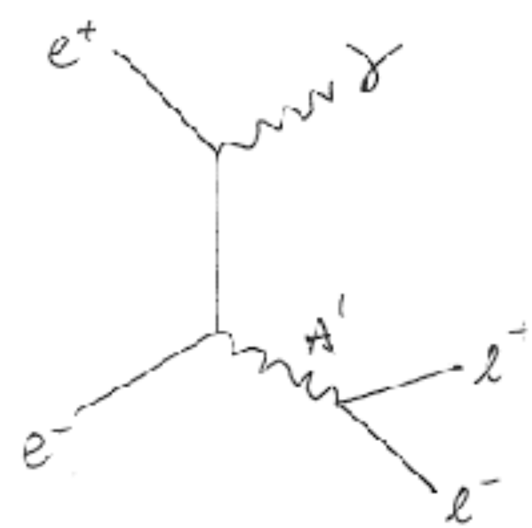
- Mediator particles in beam dump and colliders.

[US Cosmic Visions, 2017; Belle-II 2018]

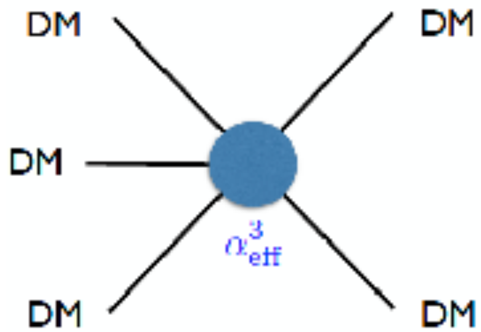




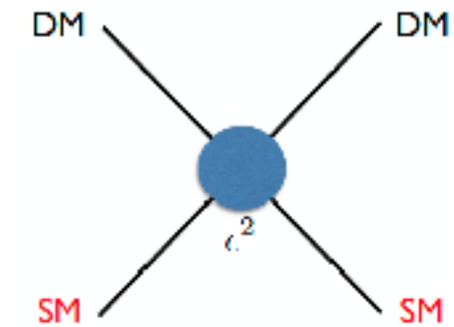




SIMP models



“SIMP Recipe”



- No dark particles lighter than SIMP.
- SIMP heats up! Make it cool down.

  Lower bound on the SM couplings $\boxed{\epsilon > 10^{-8}\alpha_{\rm eff}^{1/2}}$

- Maintain SIMP process in a large portion.

  Upper bound on the SM couplings $\boxed{\epsilon < 2.4\times 10^{-6}\alpha_{\rm eff}}$

- Variations for a UV model (renormalizable, dark flavor)

  Light mediators, multi-species $\Longrightarrow$ Assisted SIMP

Toy examples

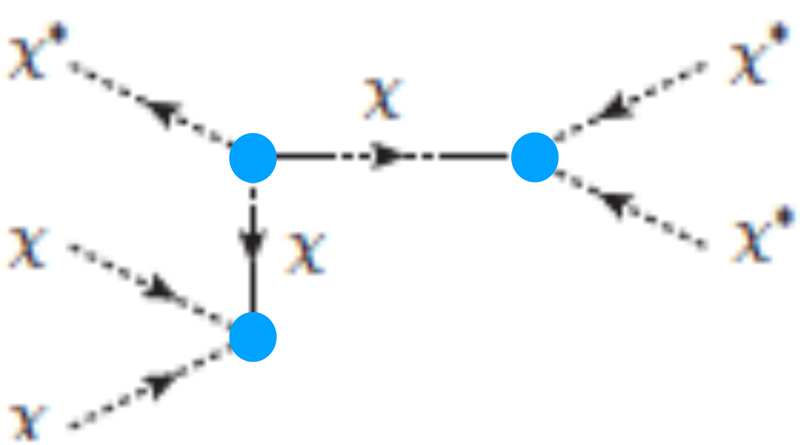
[S.-M.Choi, HML, 2015]

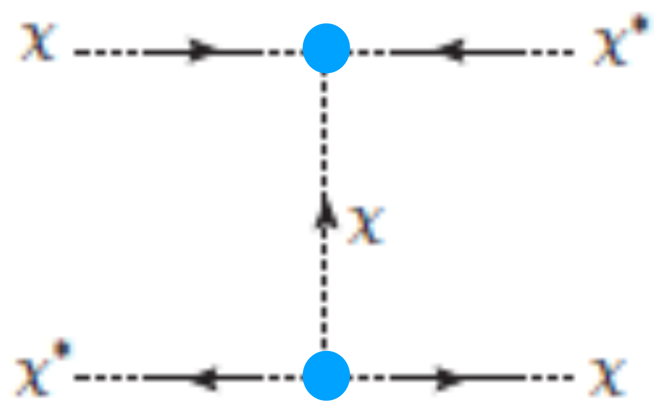
- Z_3 is the minimal discrete symmetry from a dark local U(1) and Z' portal is built-in for kinetic equilibrium.

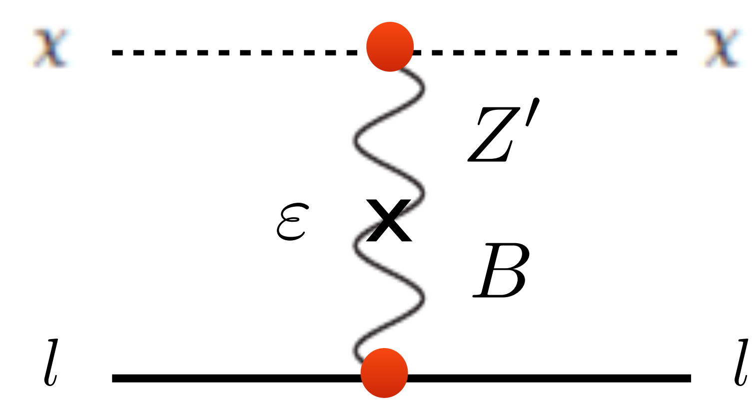
	ϕ	χ
$U(1)_V$	$+3$	$+1$

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

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





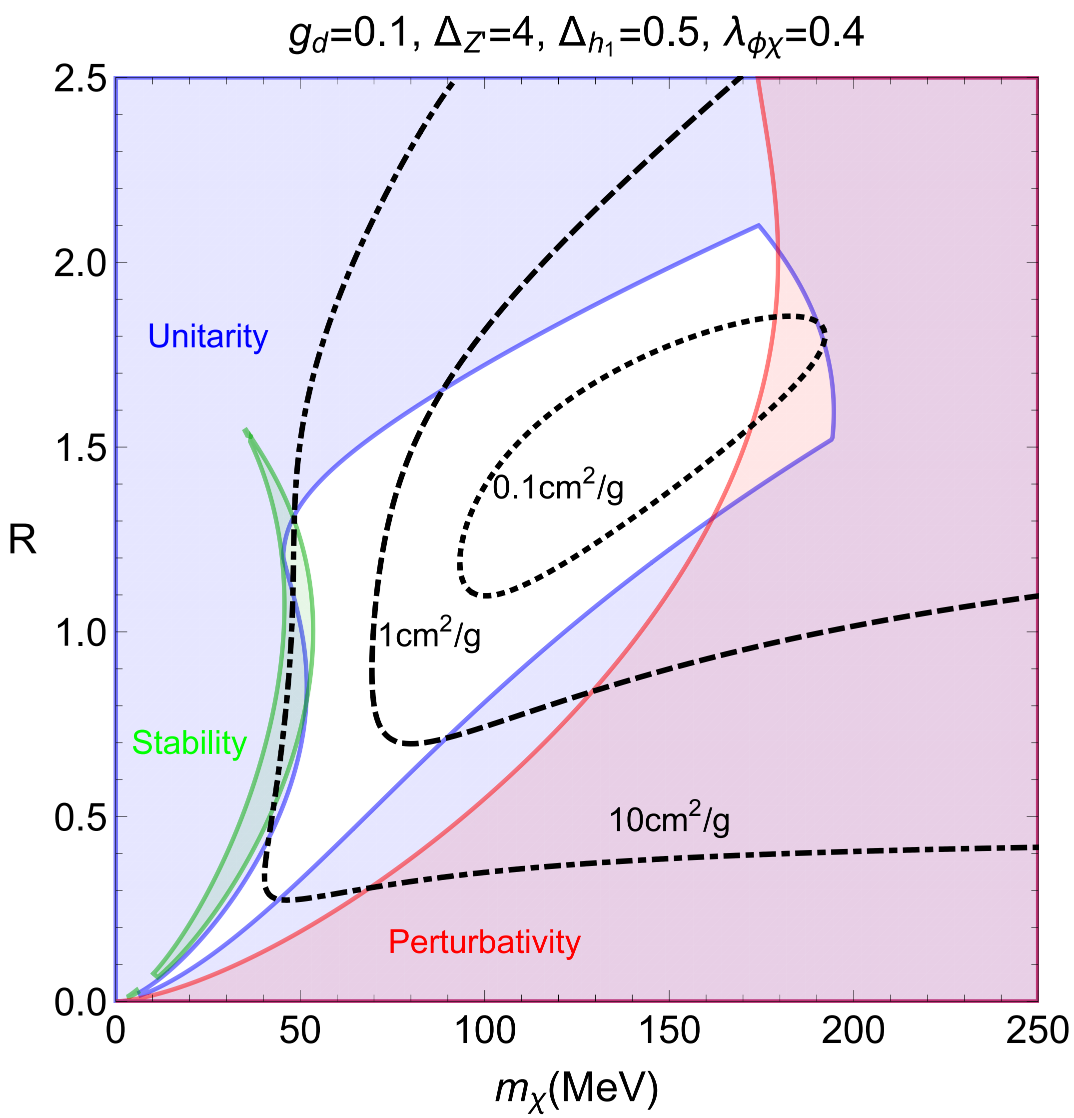


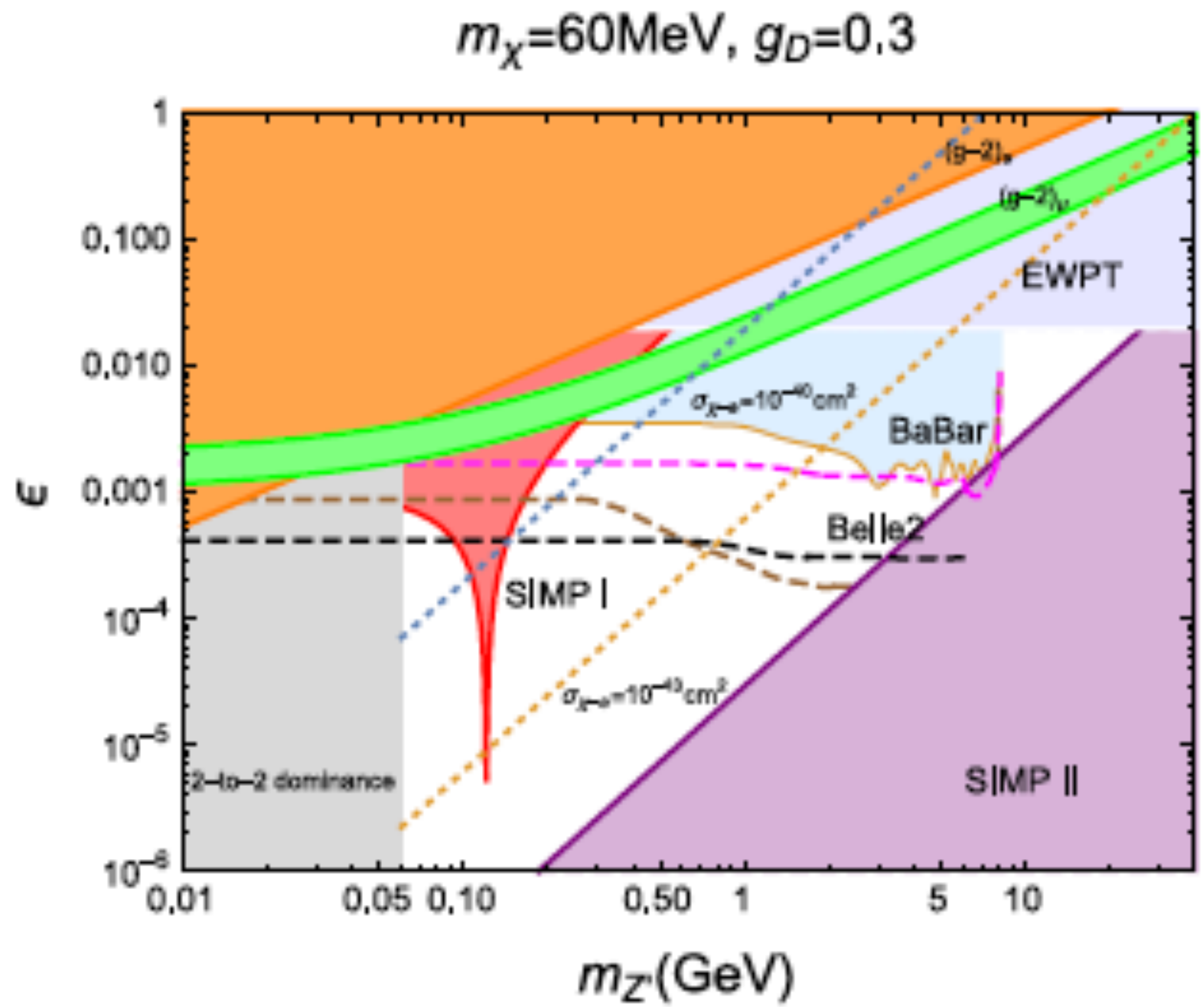
- Correlation btw self-scattering and 3→2 annihilation.

$$\sigma_{\rm self} \sim \frac{\kappa^4}{m_\chi}, \qquad \langle\sigma v^2\rangle \sim \frac{\kappa^6}{m_\chi^5} \quad \Rightarrow \quad \alpha_{\rm eff} \sim \kappa^2$$

Bounds on SIMP

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





Dark sector couplings:
relic density & self-scattering

BaBar, Belle2, LHCb,
Beam dump exp, meson decays,
DM-electron scattering, etc.

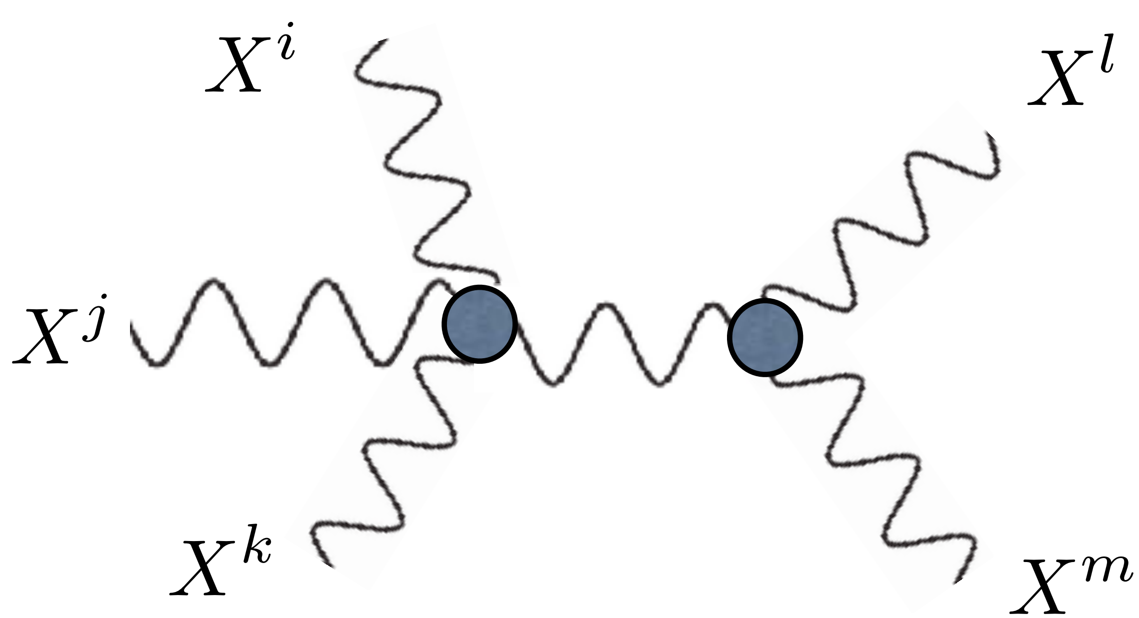
Vector SIMP

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

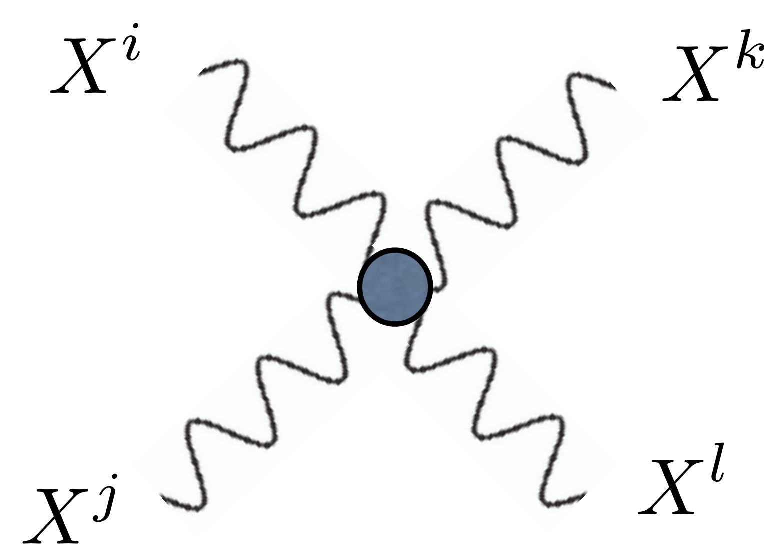
- Massive SU(2)x gauge bosons = SIMPs

Gauge interactions → self-interactions for dark matter,
Accidental SO(3) custodial symmetry → DM stability.

Dark Higgs mechanism →kinetic equilibrium by Higgs portal.

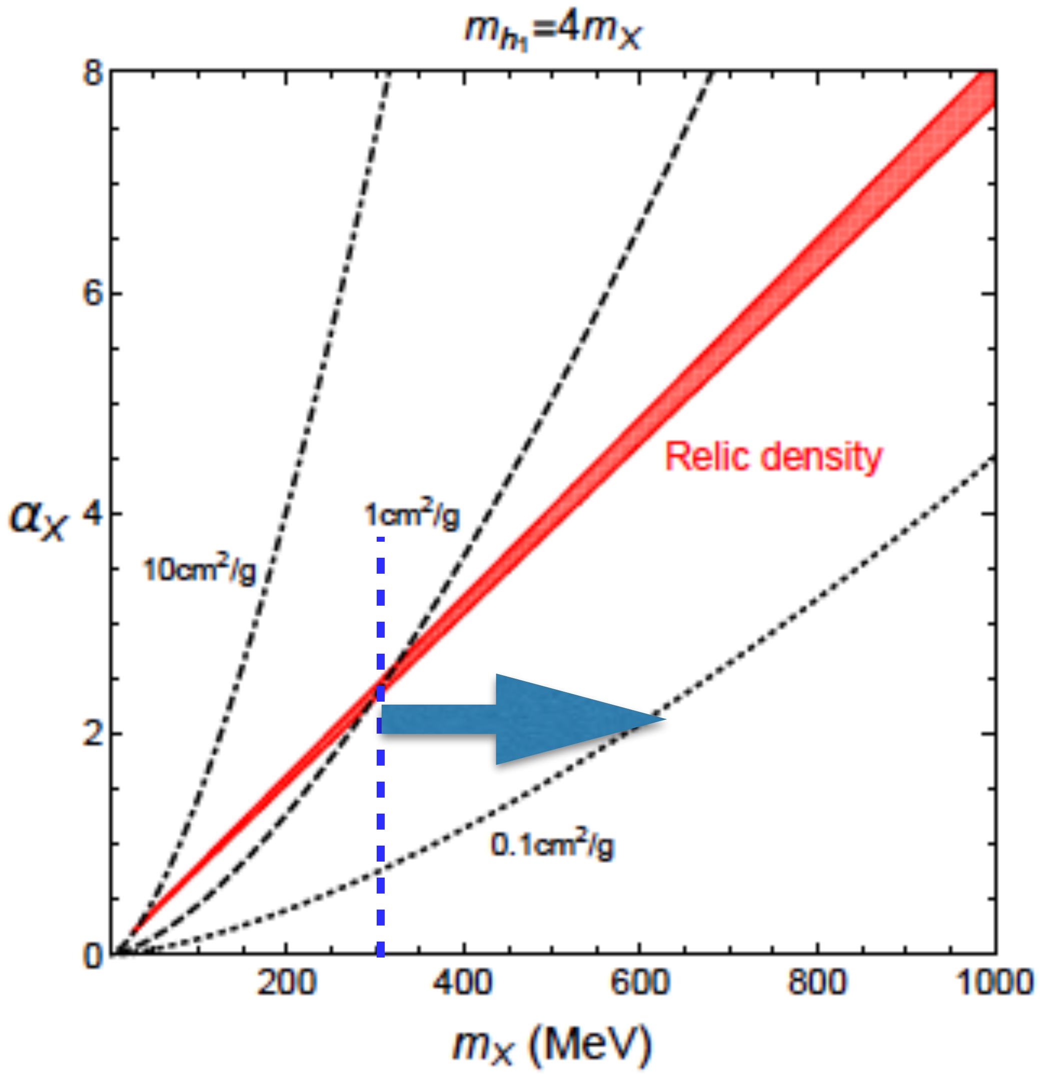


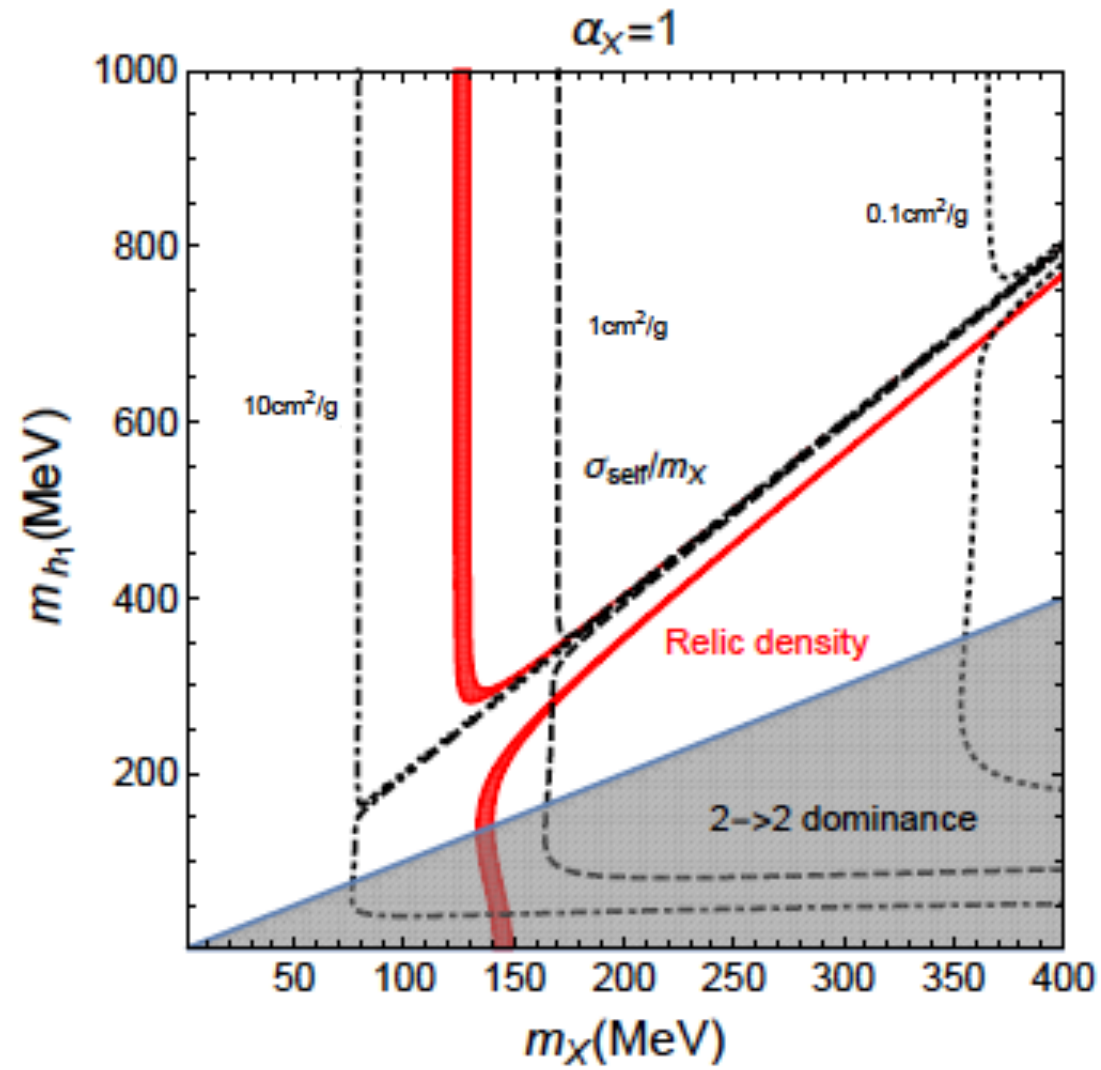
Relic density
(s-wave 3→2)



Large self-scattering

VSIMP relic density





Strong gauge coupling? ➡ "Higgs/QCD complementarity"

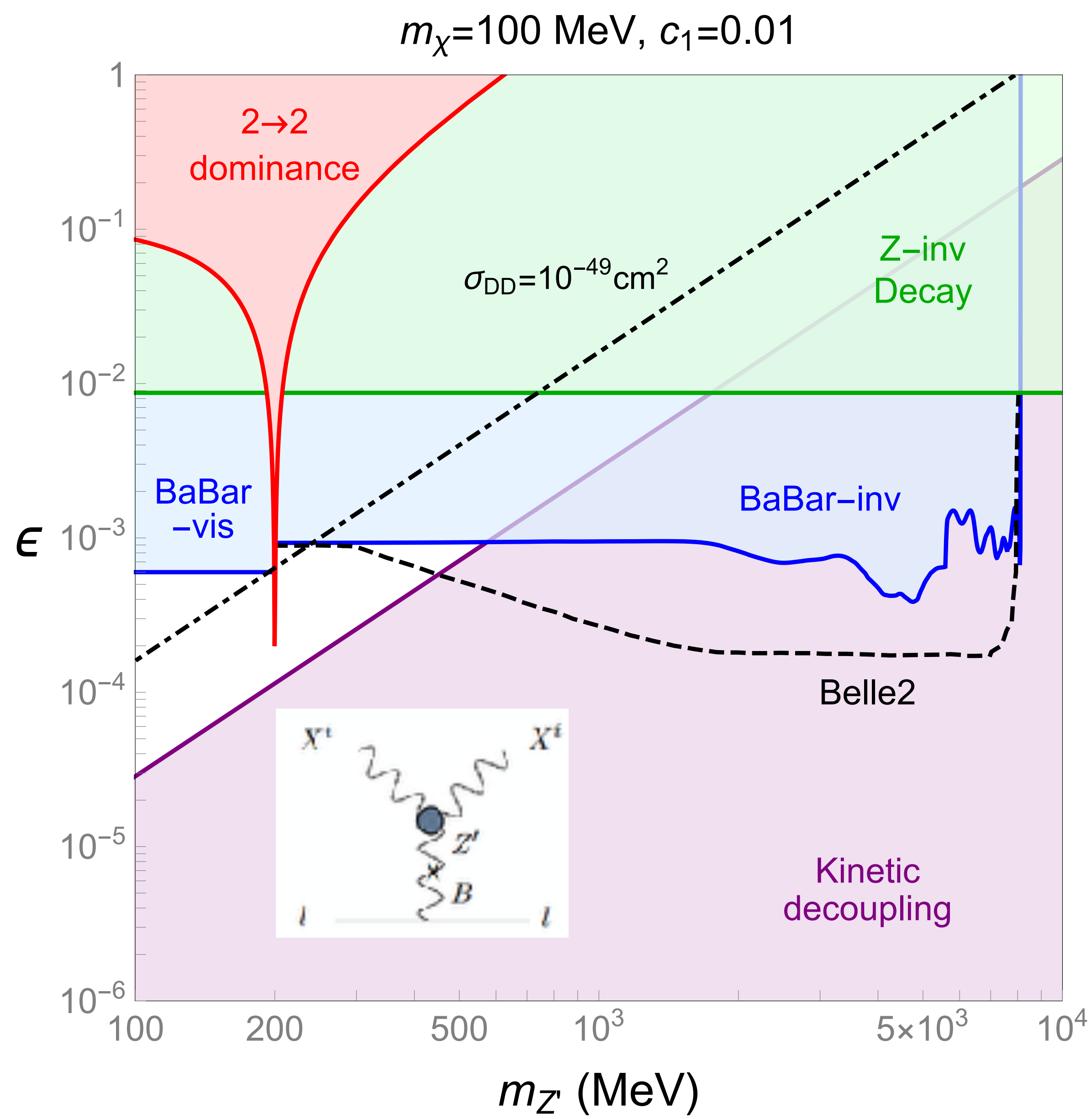
SU(2)$_X$ SSB by Higgs VEV ⟷ Confinement by strong force

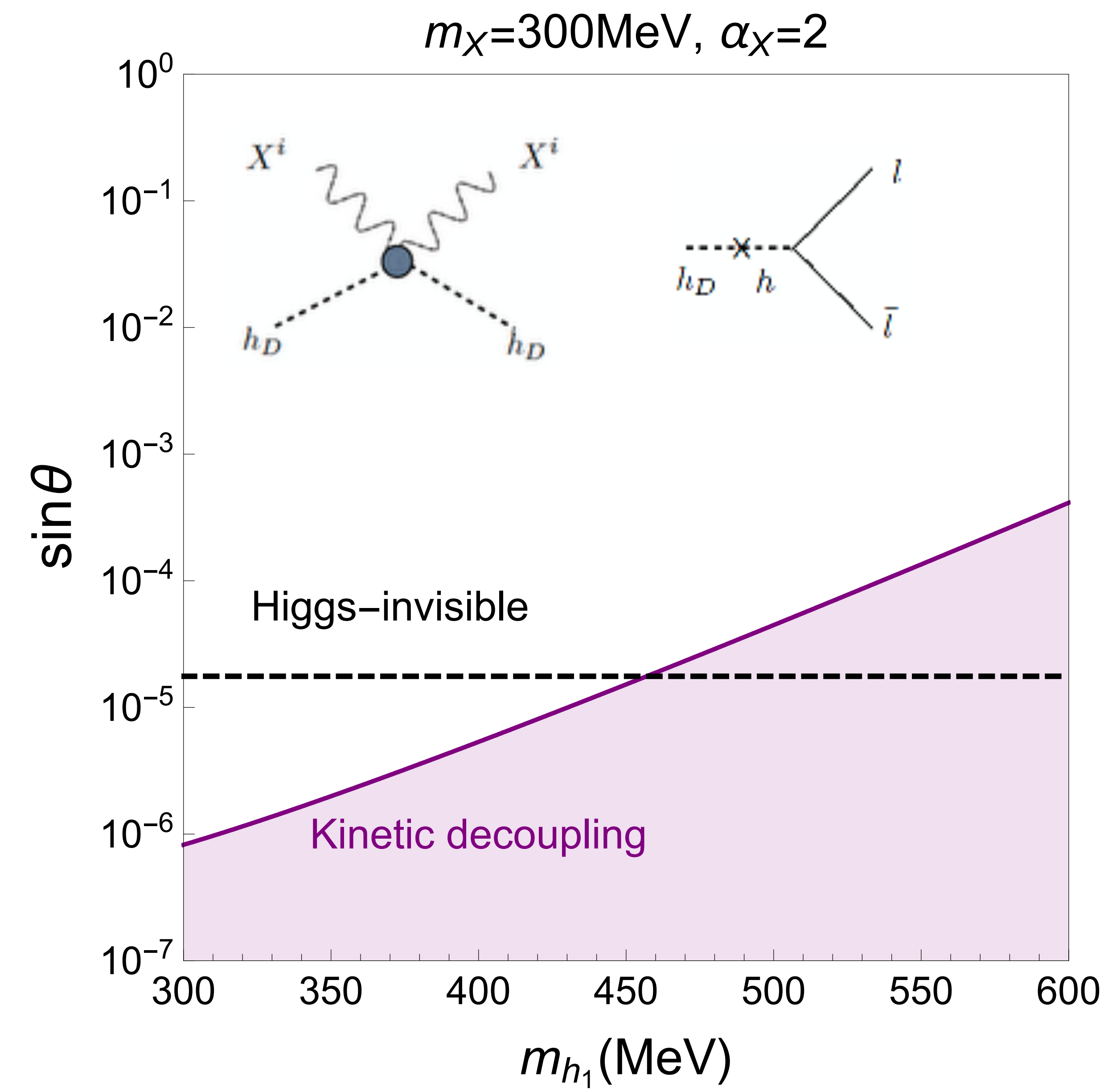
$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_X \end{pmatrix}, \quad m_{h_X} \to \infty$$

$SU(2)_L \times SU(2)_R \to SU(2)_V$ in an $SU(N_c)$

Higgs phase pushed into non-perturbative regime. ['t Hooft, 1980]

Bounds on VSIMP





Z' portal

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

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

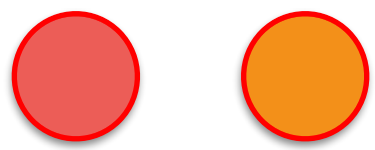
Higgs portal

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

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

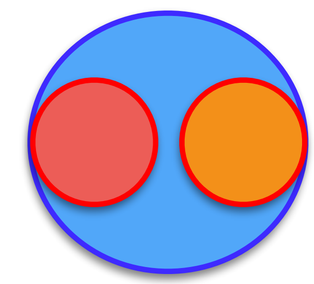
SIMP from Dark QCD

Dark light fermions
G=SU(N_f)$_L$xSU(N_f)$_R$



dark condensate

Dark mesons
H=SU(N_f)$_V$ flavor sym.

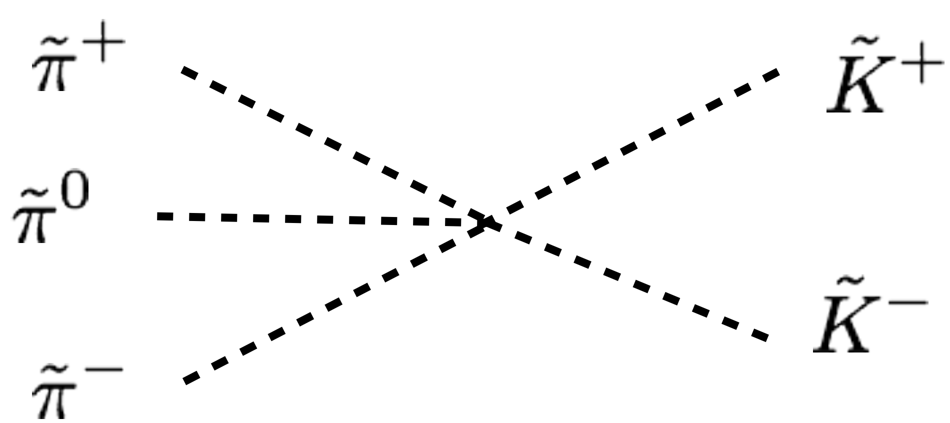


- Wess-Zumino-Witten term [Wess, Zumino, 1971; Witten, 1983]

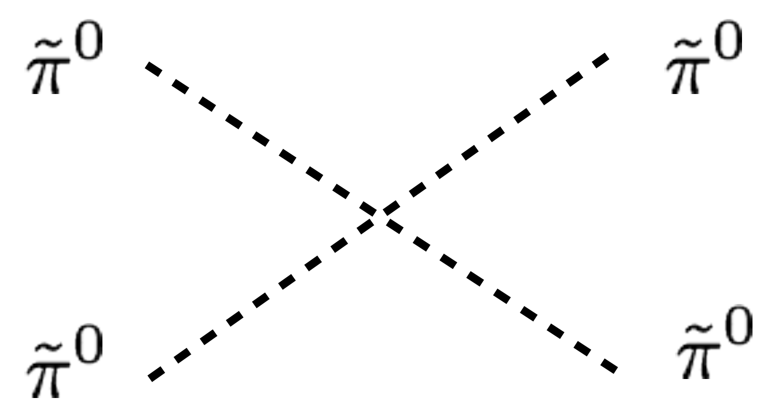
$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

$\pi_5(G/H)=Z$

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

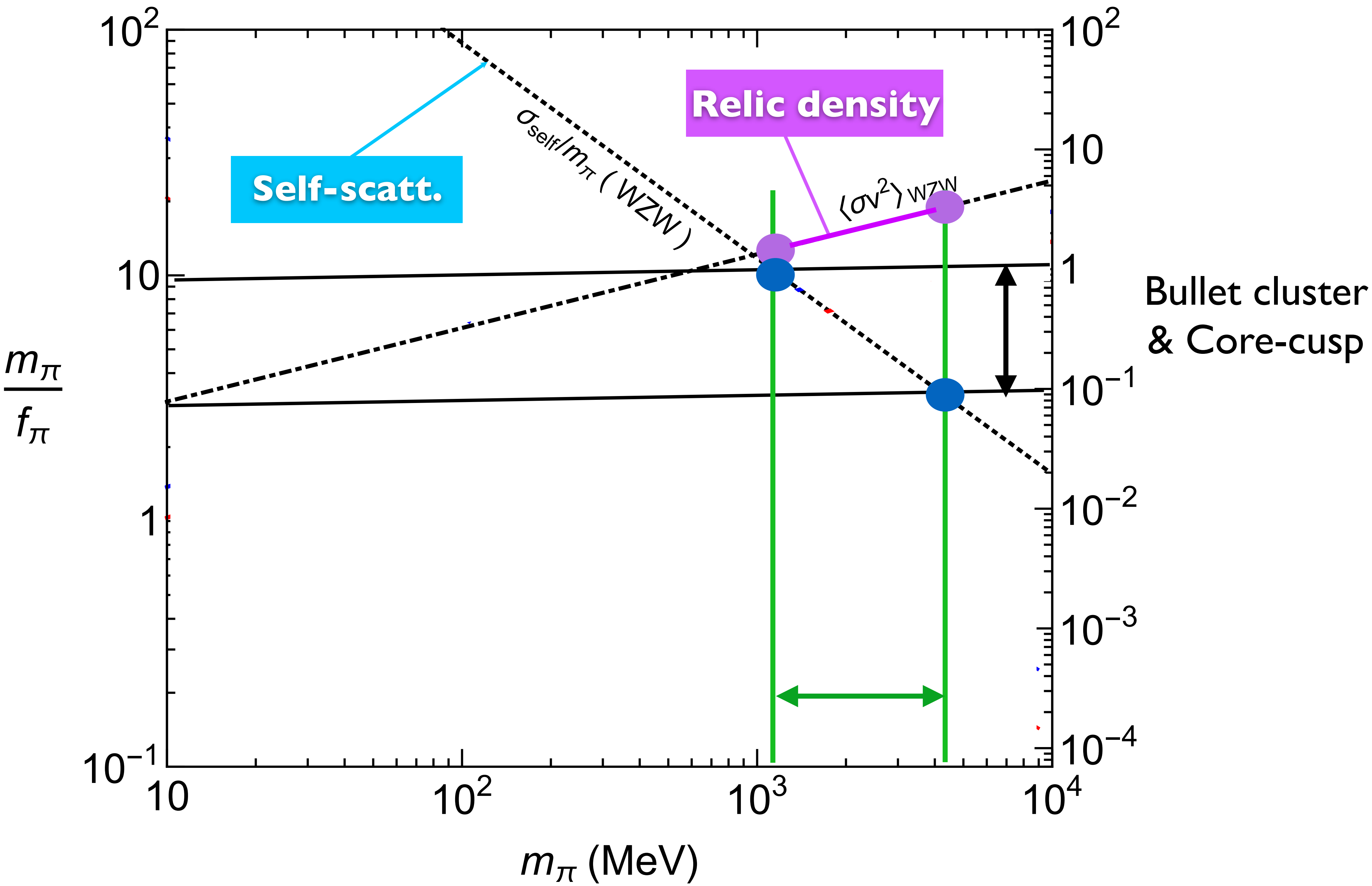


meson annihilation



meson self-scattering

SIMP mesons w/o VMs



Too large SIMP self-couplings

Higgs mass and dark gluons

- Discrete symmetries for Twin Higgs

[Chacko,Goh,Harnik, 2005]

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

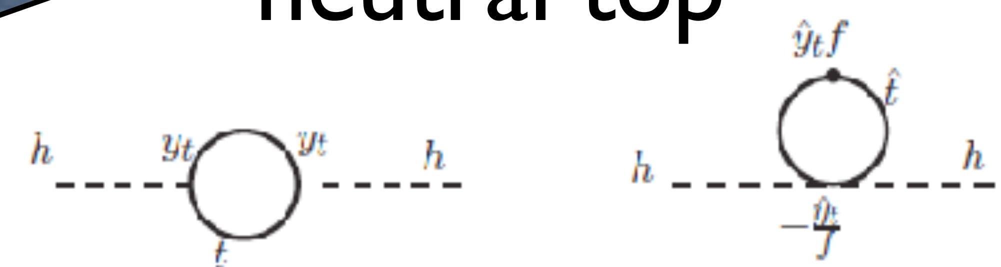
$$\begin{pmatrix} H_A \\ H_B \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} e^{i\pi/f}$$: SU(4) ⟶ SU(3) "15 - 8 = 7 pNGBs"

Higgs = pseudo Nambu-Goldstone boson

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

Higgs mass due to top quark ⟶ "neutral top"

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



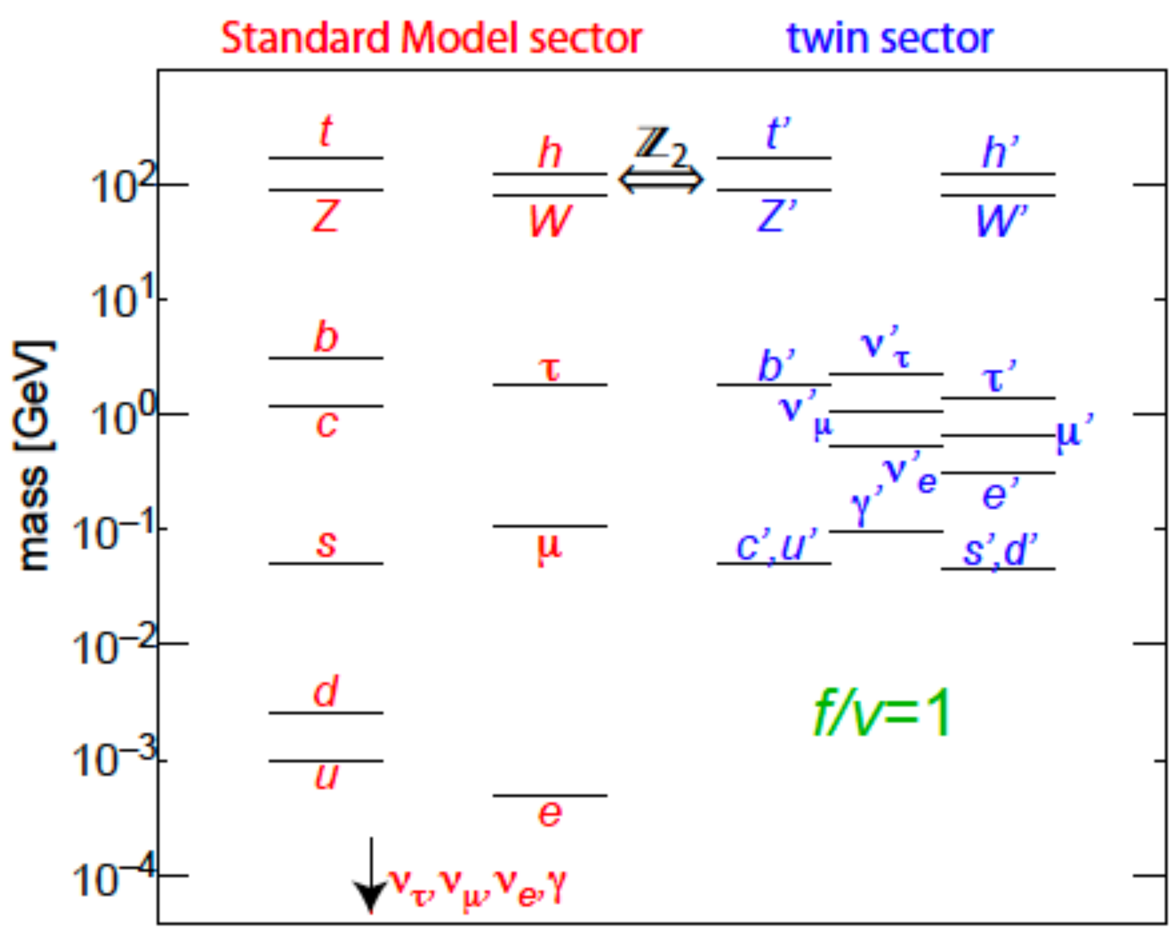
Higgs mass due to gluons ⟶ "dark gluons"

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

Twin Higgs + SIMP

[Hochberg et al, 2018]

- $SU(3)_B \times SU(2)_B \times U(1)_B$ twin gauge symmetries with Z_2



$SU(4)_F \rightarrow SU(2)_D \times SU(2)_U \times U(1)_{EM}$

$$m_{d'} = m_{s'} < m_{u'} = m_{c'}$$

$\rightarrow SU(2)_F \times U(1)_{EM}$

gauged $SU(2)_B$

SIMP=dark pions: $\left(d'\bar{s}', s'\bar{d}', \frac{1}{\sqrt{2}}(s'\bar{s}' - d'\bar{d}')\right)$

Pions + light mesons: 15 of approximate $SU(4)_F$

realistic: $\frac{f}{v} \gtrsim 3$

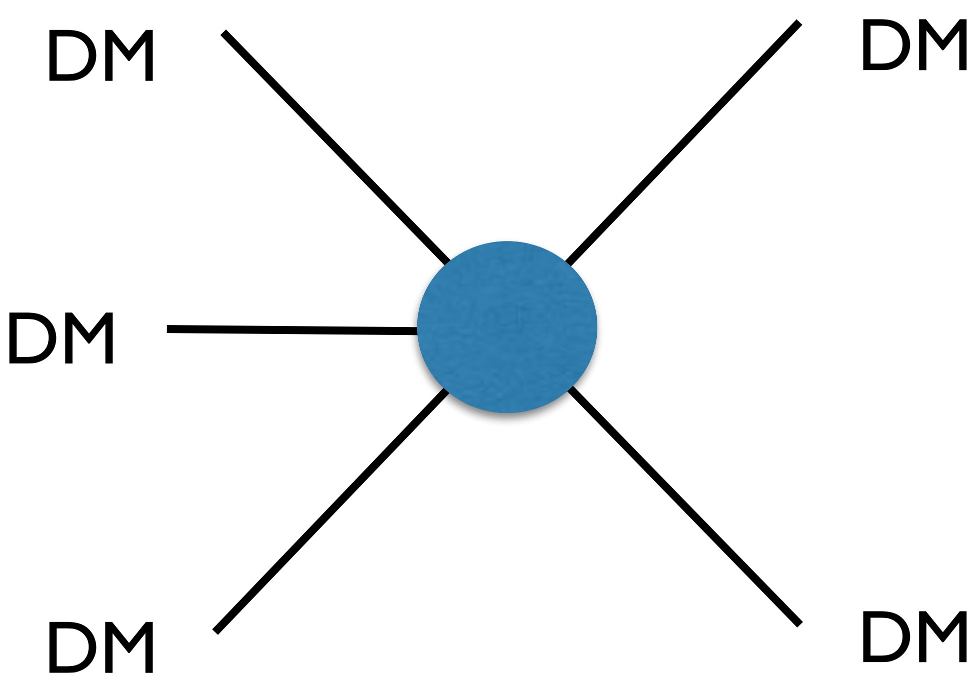
meson M	particle content	$m_M^2 \propto$	m_M
$\theta^0(\mathbf{3},\mathbf{1})$	$u'\bar{c}', c'\bar{u}', \frac{1}{\sqrt{2}}(u'\bar{u}' - c'\bar{c}')$	$2m_{u'}$	$m_\pi(1+\Delta)$
$D^+(\mathbf{2},\mathbf{2})$	$u'\bar{d}', c'\bar{d}', u'\bar{s}', c'\bar{s}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$D^-(\mathbf{2},\mathbf{2})$	$d'\bar{u}', s'\bar{u}', d'\bar{c}', s'\bar{c}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\eta^0(\mathbf{1},\mathbf{1})$	$\frac{1}{2}(d'\bar{d}' + s'\bar{s}' - u'\bar{u}' - c'\bar{c}')$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\pi^0(\mathbf{1},\mathbf{3})$	$d'\bar{s}', s'\bar{d}', \frac{1}{\sqrt{2}}(d'\bar{d}' - s'\bar{s}')$	$2m_{d'}$	m_π

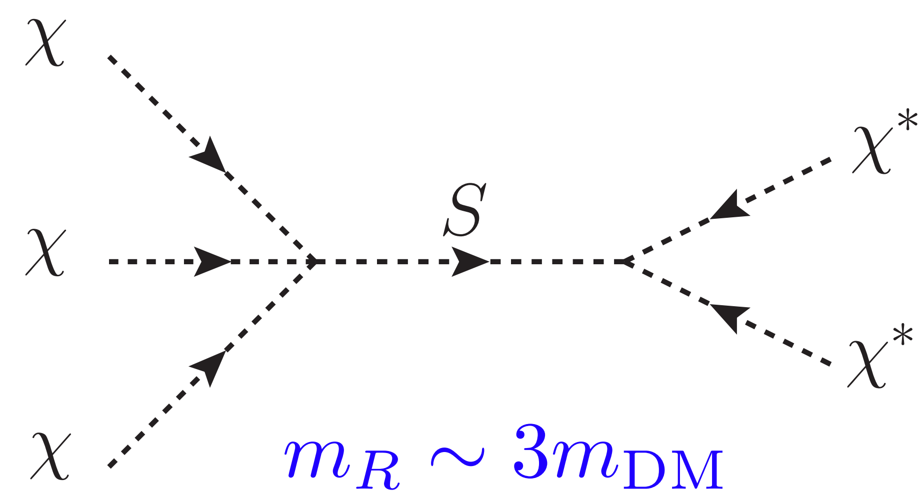
- $3 \rightarrow 2$ process with WZW terms for $SU(4)_F$: $\Delta \lesssim 10\%$

Breit-Wigner SIMP resonance

- SIMP process can be enhanced at dark resonances.

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





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

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

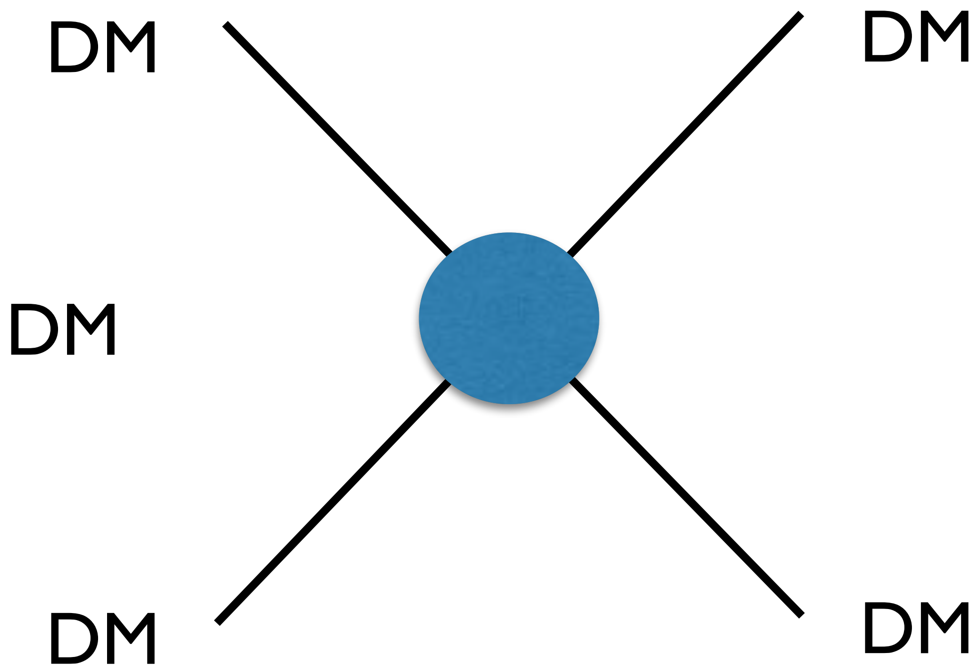
e.g. Z_5 SIMP, [S.-M.Choi, HML, 2016]

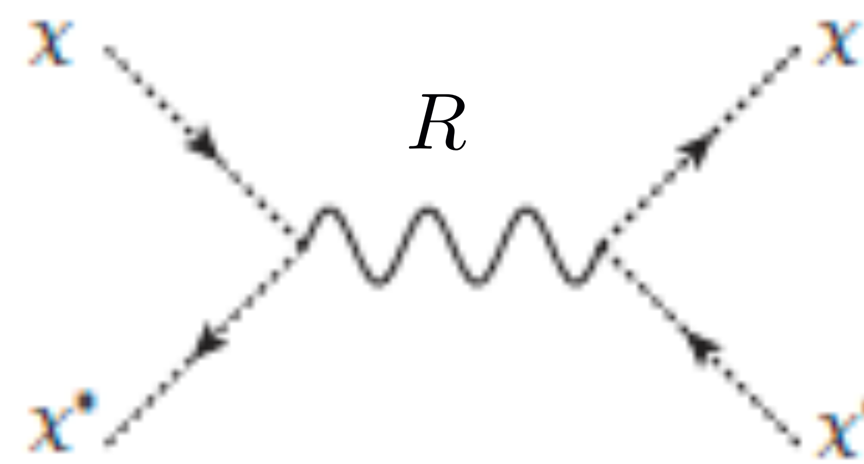
$$\begin{pmatrix}\phi\\ \chi\\ S\end{pmatrix} \to \begin{pmatrix}1 & 0 & 0\\ 0 & \omega & 0\\ 0 & 0 & \omega^3\end{pmatrix}\begin{pmatrix}\phi\\ \chi\\ S\end{pmatrix},\quad \omega = e^{i\frac{2}{5}\pi}\qquad \mathcal{L}_{\rm int} \supset \frac{1}{\sqrt{2}}\lambda_1\phi^\dagger S^2\chi^\dagger + \frac{1}{\sqrt{2}}\lambda_2\phi^\dagger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

Velocity-dependent SIDM

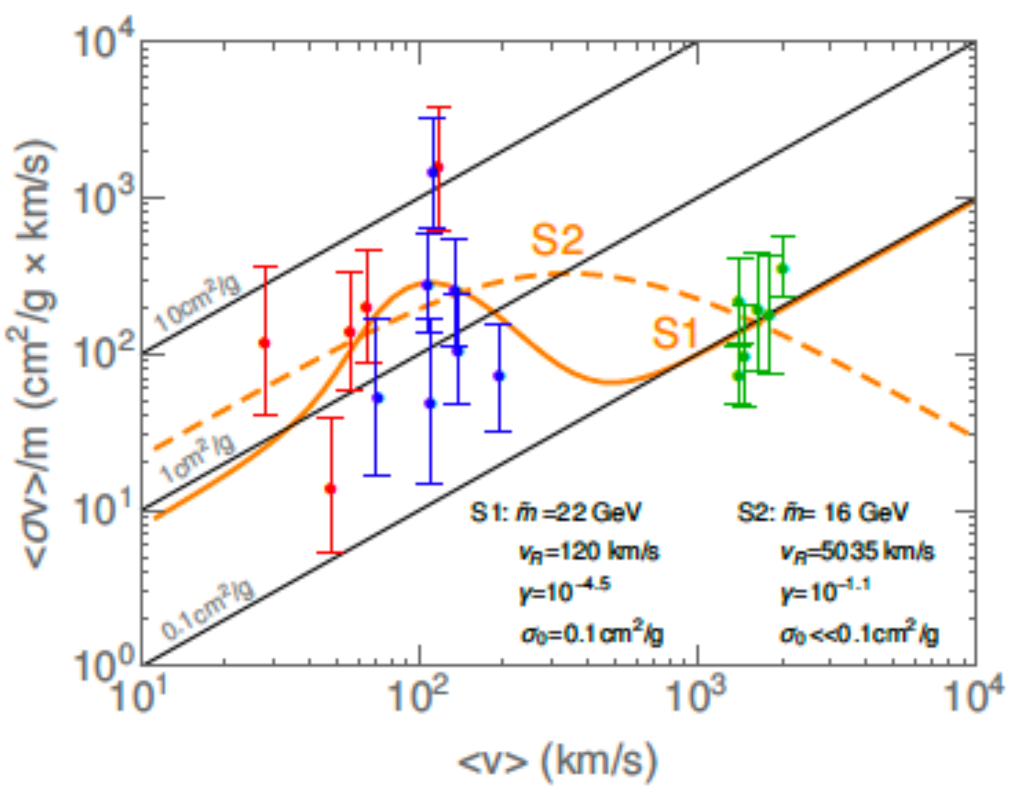
- DM self-interaction may be velocity-dependent.

[M. Kaplinghat et al, 2015; X. Chu et al, 2018]





$$m_R \sim 2m_{\rm DM}$$



$$\sigma = \sigma_0 + \frac{4\pi S}{mE(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v)-E(v_R))^2 + \Gamma(v)^2/4}$$

$$\left.\frac{\langle \sigma v\rangle}{m}\right|_{\rm NWA} = \frac{\sigma_0 \langle v\rangle}{m} + \frac{128 S \pi^{\frac{3}{2}} \gamma v_R^{2L+1}}{m^3 v_0^3} e^{-v_R^2/v_0^2}.$$

“Dark resonance”

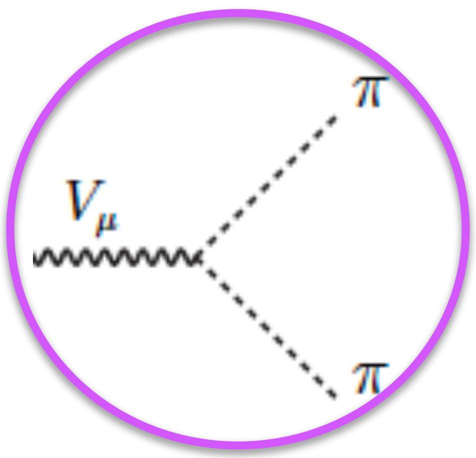
$m_R \gtrsim 2m_{\rm DM}$ Invisible decay

Dark vector resonances

Vector resonances in hidden gauge scheme:

Global SU(Nf)vxSU(Nf)/SU(Nf)v + Hlocal=SU(Nf)v

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

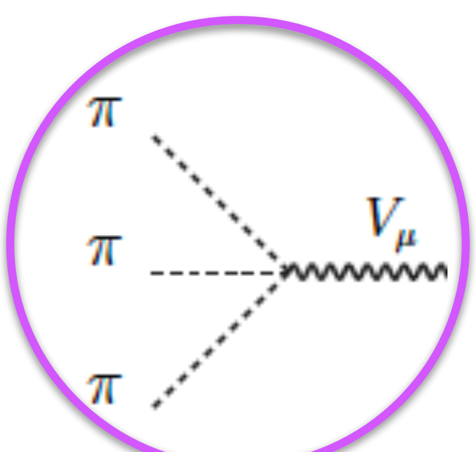


VM masses: $m_V^2 = a g^2 f_\pi^2$ degenerate

VM-π-π couplings: $g_{V\pi\pi} = \frac{1}{2} a g.$ cf. QCD: $a \simeq 2$

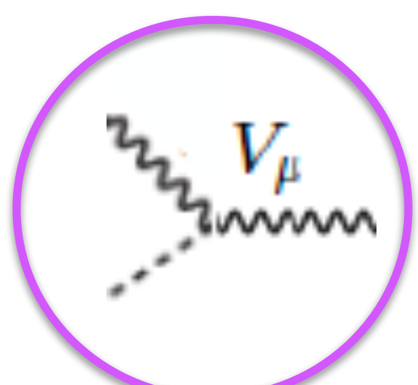
Generalized WZW terms with Hlocal=SU(Nf)v

[Bando et al, 1988; P. Ko, 1991]



cf. QCD:

$\omega \to 3\pi$



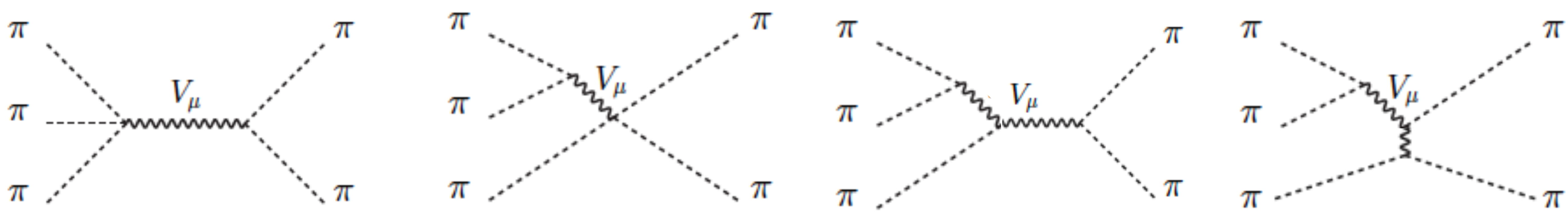
cf. QCD: VM-photon mixing

$\pi^0 \to 2\gamma$

Dark photon case:
[Berlin et al, 2018]

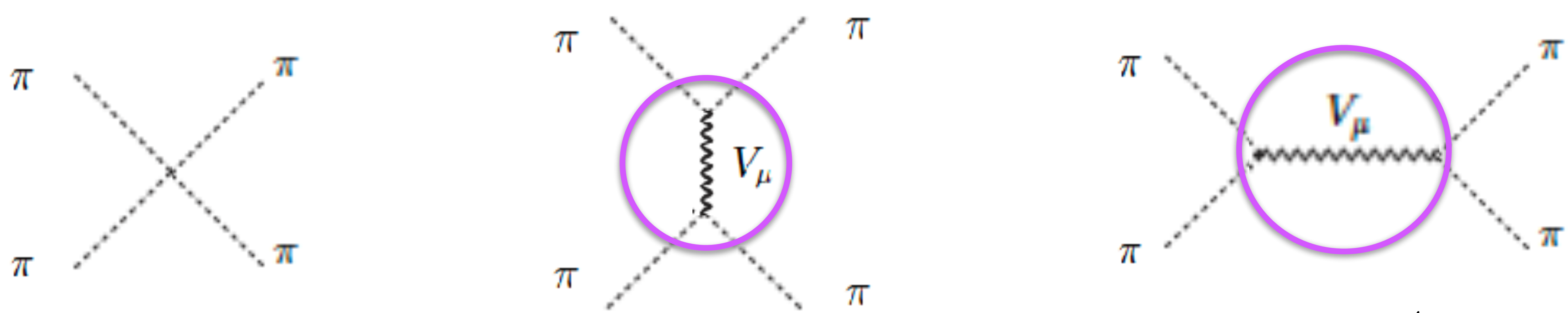
Boosting SIMP annihilations

3→2 annihilation: [S.-Choi, A. Natale, HML, P. Ko, 2018]



→ Enhanced near resonances at 2π or 3π.

2→2 self-scattering:

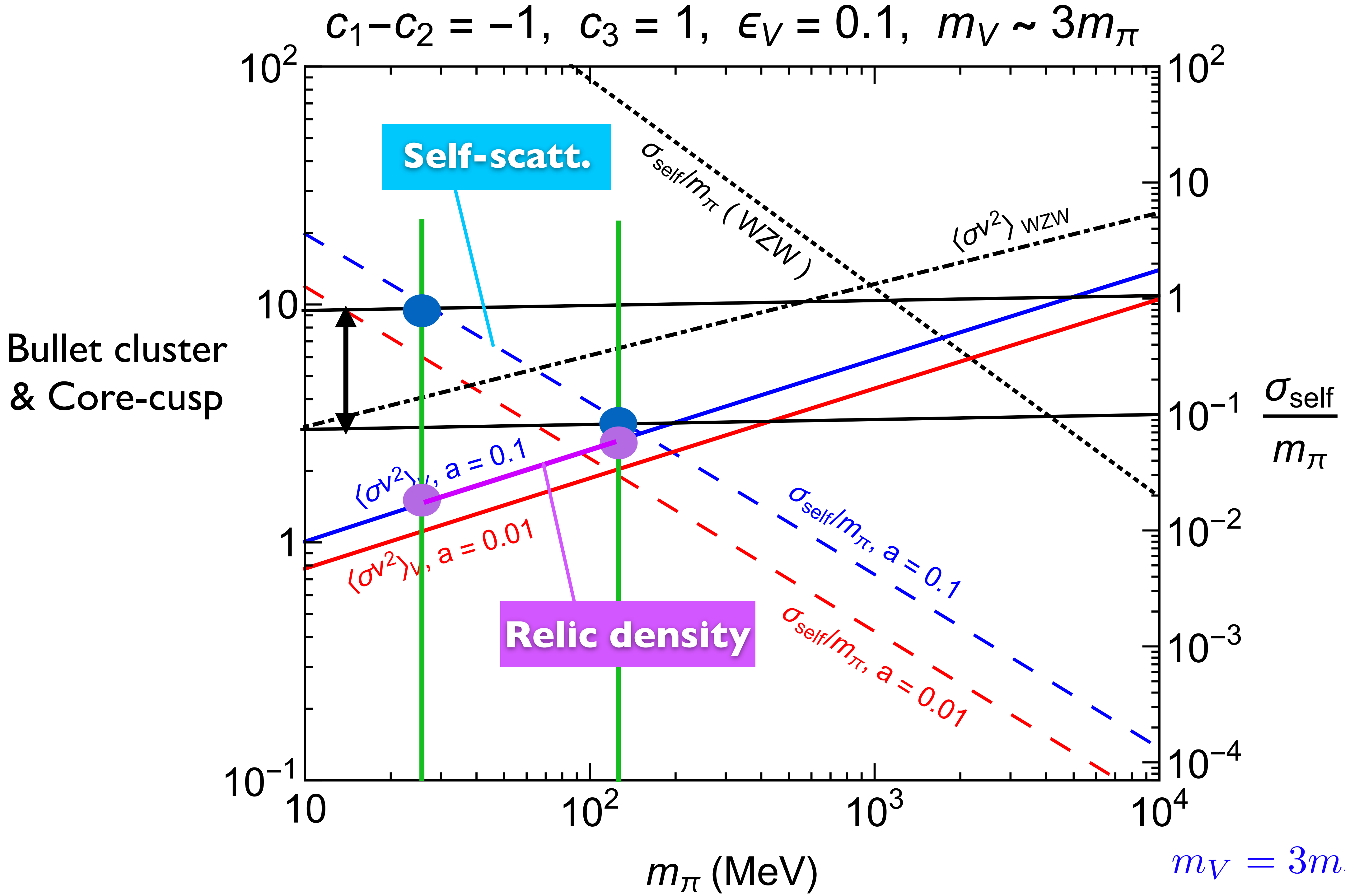


$\sim v^2$ $\sim v^4$

→ VMs lead to velocity-dependent self-scattering.

SIMP mesons w/ VMs

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

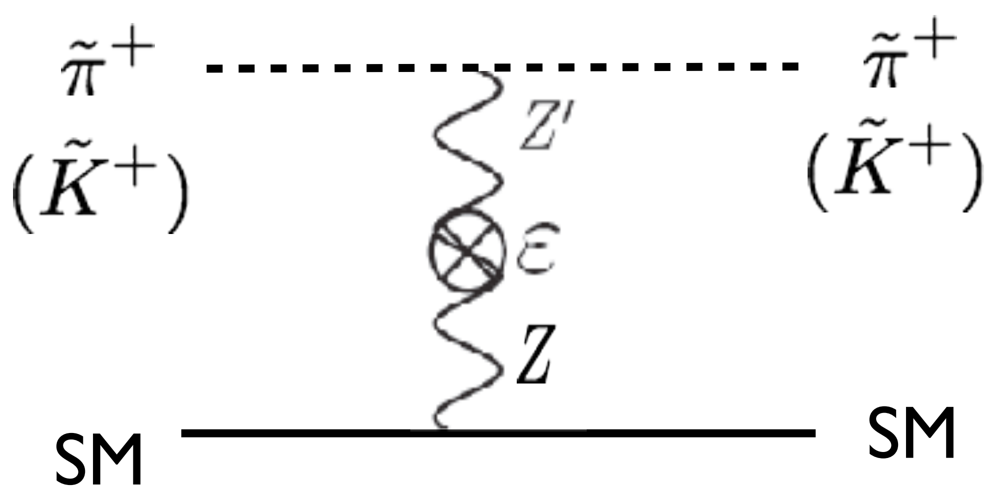


$m_V = 3m_\pi\sqrt{1+\epsilon_V}$

Smaller SIMP couplings are allowed.

Communicating to SIMPs

- Vectorial Z' with no chiral anomalies [HML, M. Seo, 2015]

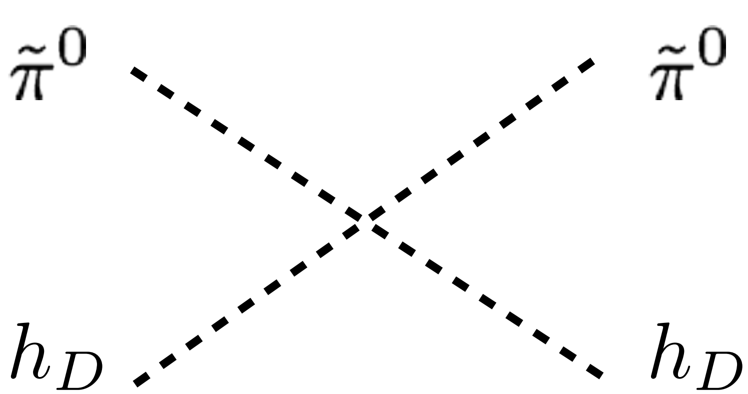


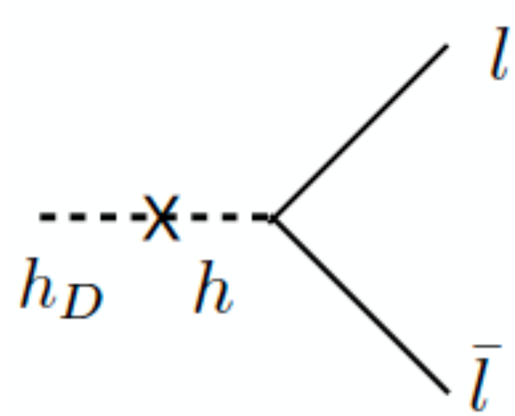
Meson mass splitting:

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

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

- Dark Higgs or sigma fields [A. Kamada et al, 2015; VSIMPers, 2017]

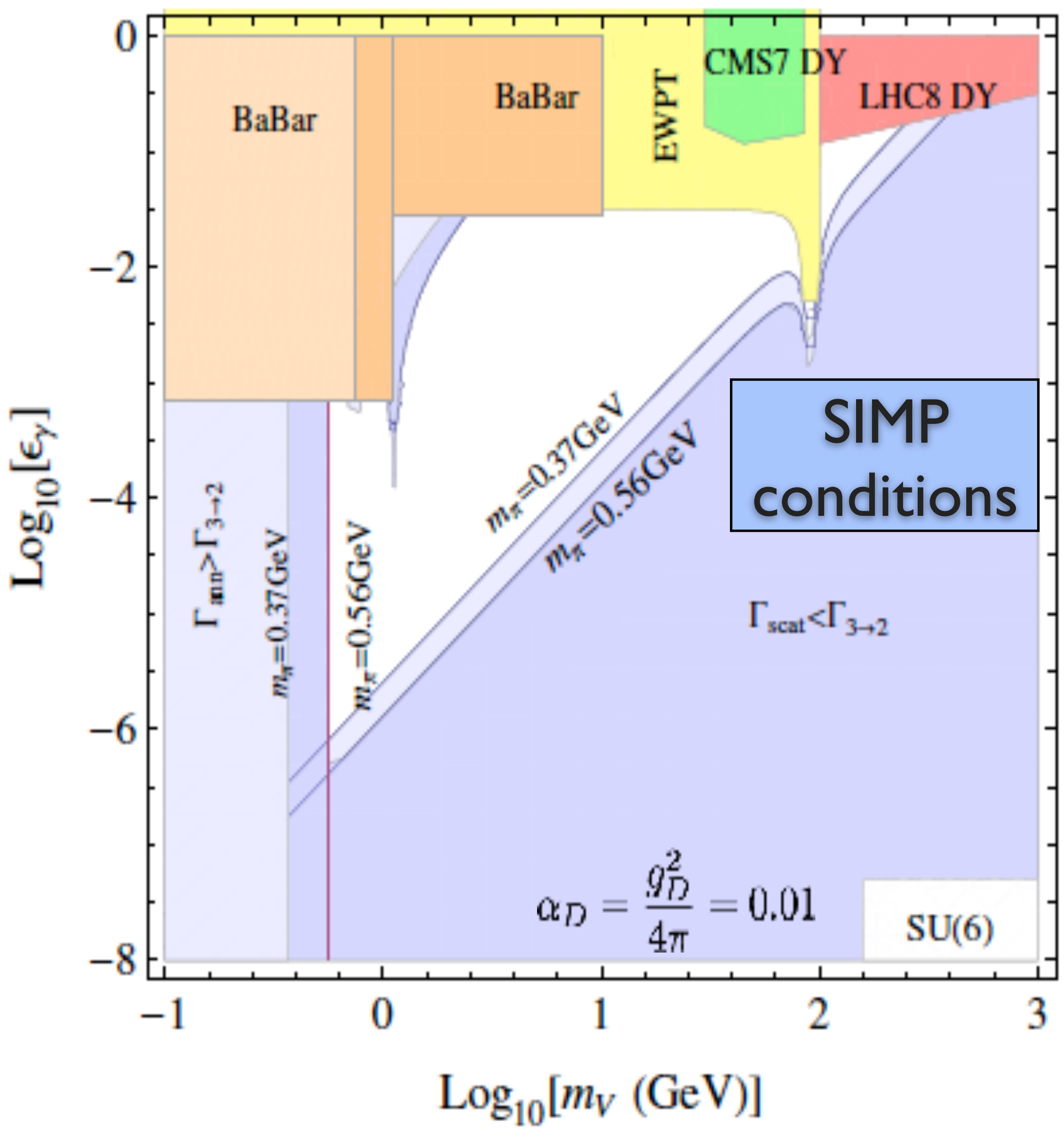


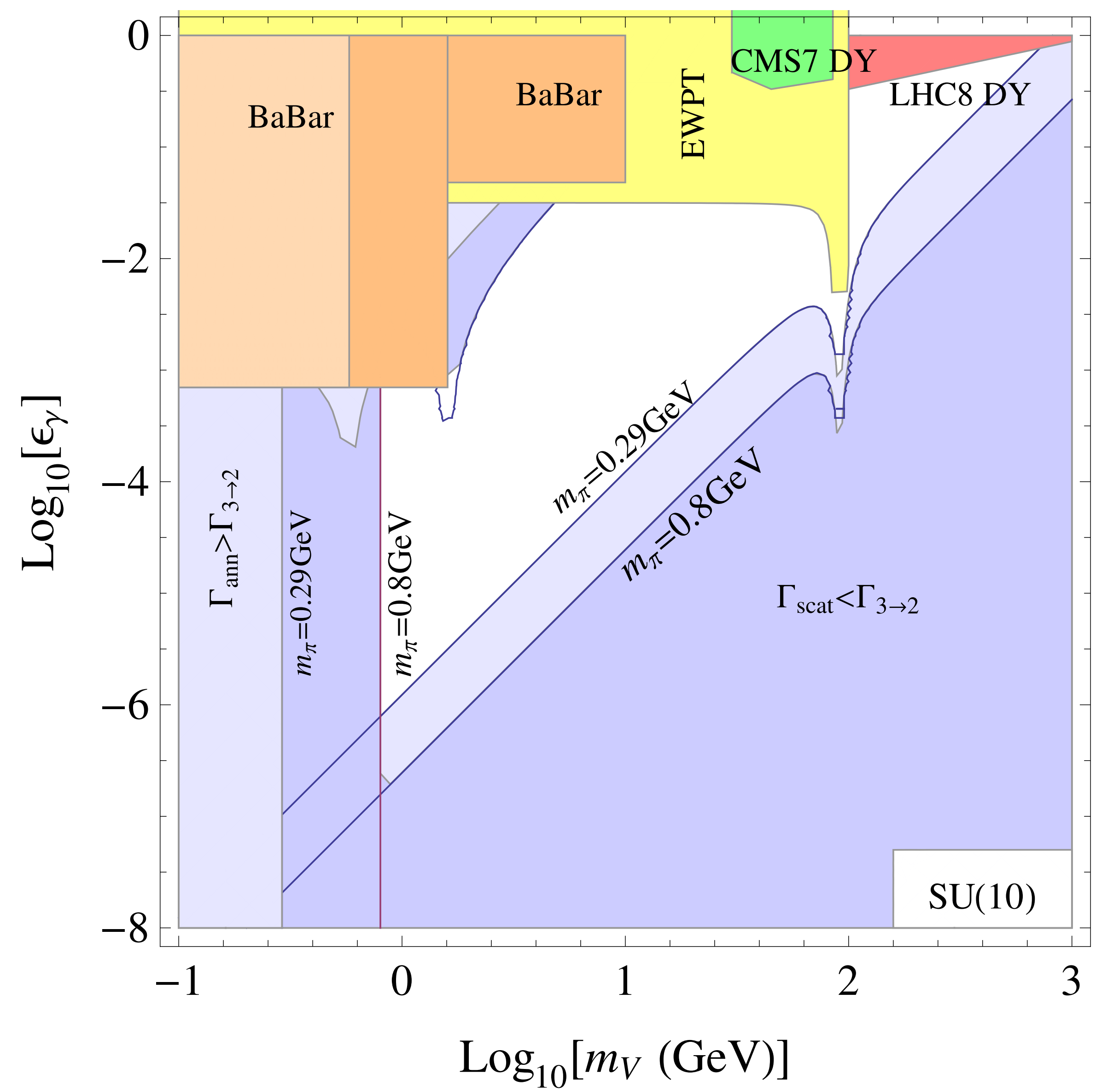


cf. Axion-portal: Hochberg et al, 2018

Z’ portal for SIMP

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





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

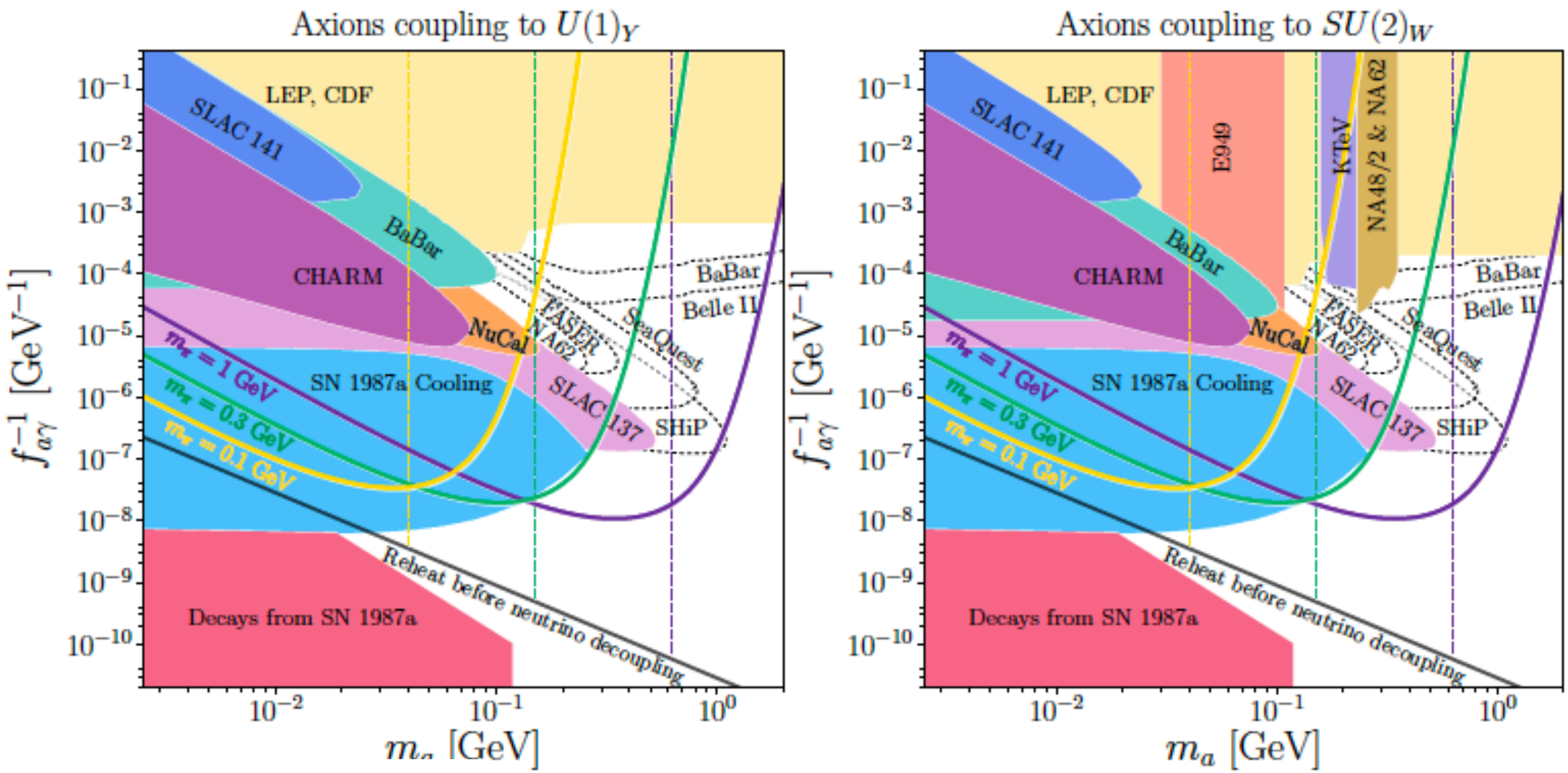
$e^+e^- \to \gamma Z' \to \gamma(l^+l^-)$, $e^+e^- \to \gamma + \mathrm{MET}$

$h \to ZZ'$, Drell-Yan, dileptons, etc.

cf. Hochberg et al, 2015

Axion portal for SIMP

[Hochberg et al, 2018]



$$\mathcal{L}_{a\gamma} = \frac{1}{4 f_{a\gamma}} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Kinetic equilibrium occurs due to axion decays and inverse decays above the solid lines.

cf. [A. Kamada et al, 2017]

Conclusions

- Particle nature of dark matter has not been identified, so we need to consider new possibilities beyond horizon.
- SIDM is motivated by small-scale problems in astrophysics: SIMP dark matter is a plausible sub-GeV self-interacting dark matter, without a need of large couplings to the SM for freeze-out process.
- SIMP models predict minimum couplings of new mediators for kinetic equilibrium, that can be probed at intensity experiments such as Belle-II and LHCb.
- Dark resonances for strong $3\rightarrow 2$ processes may give another handle on uncovering the dark sector.