Vector SIMP dark matter with approximate custodial symmetry

Soo-Min Choi (Chung-Ang U (中央), Korea)

Based on :

JHEP 1710 (2017) 162 (arXiv:1707.01434) with
Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre

JHEP 1907 (2019) 049 (arXiv:1904.04109) with
H. M. Lee, Y. Mambrini and M. Pierre

Kavli IPMU, November 20, 2019

WIMP and present situation

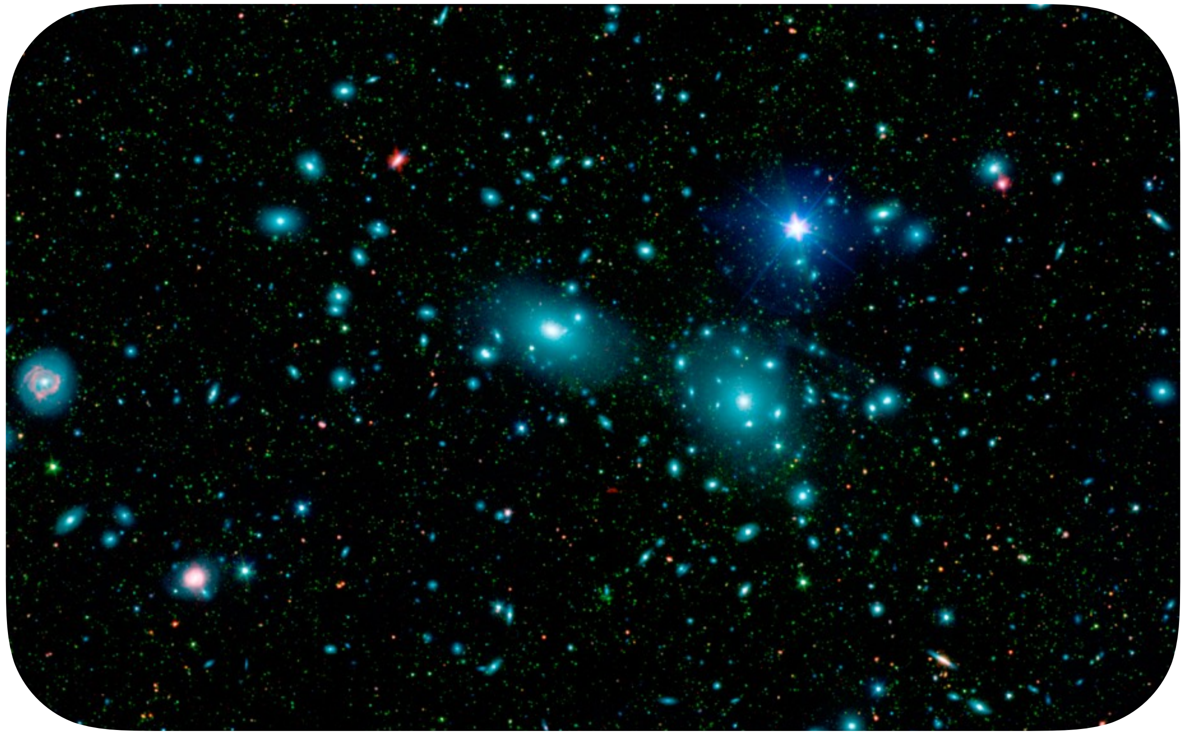
- WIMP miracle
- Direct detection bound
- Small-scale problems

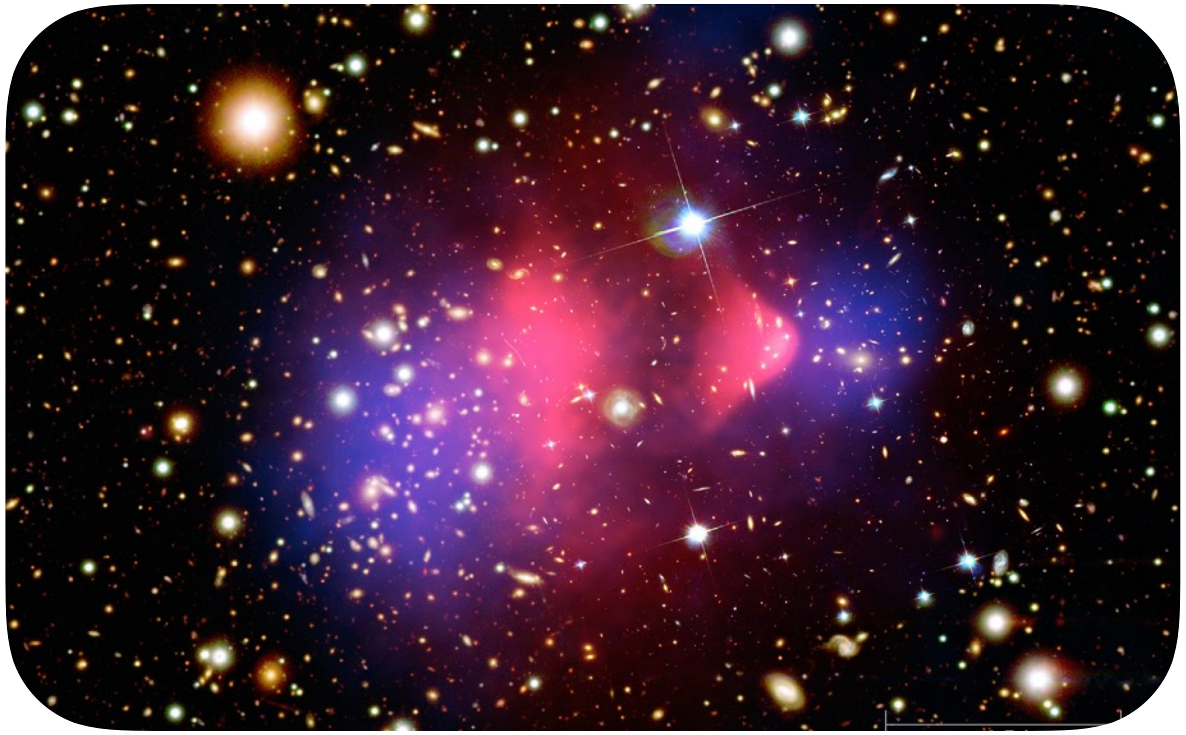
SIMP : Novel mechanism for light dark matter

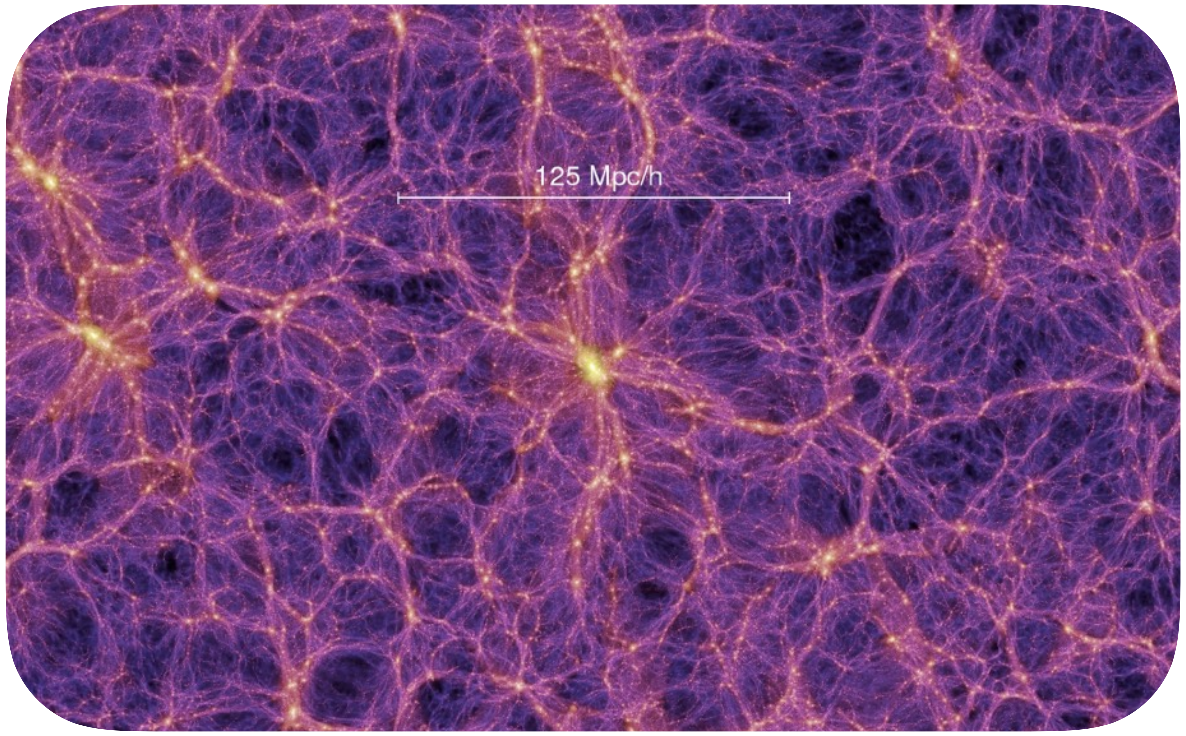
- SIMP condition
- Forbidden channels

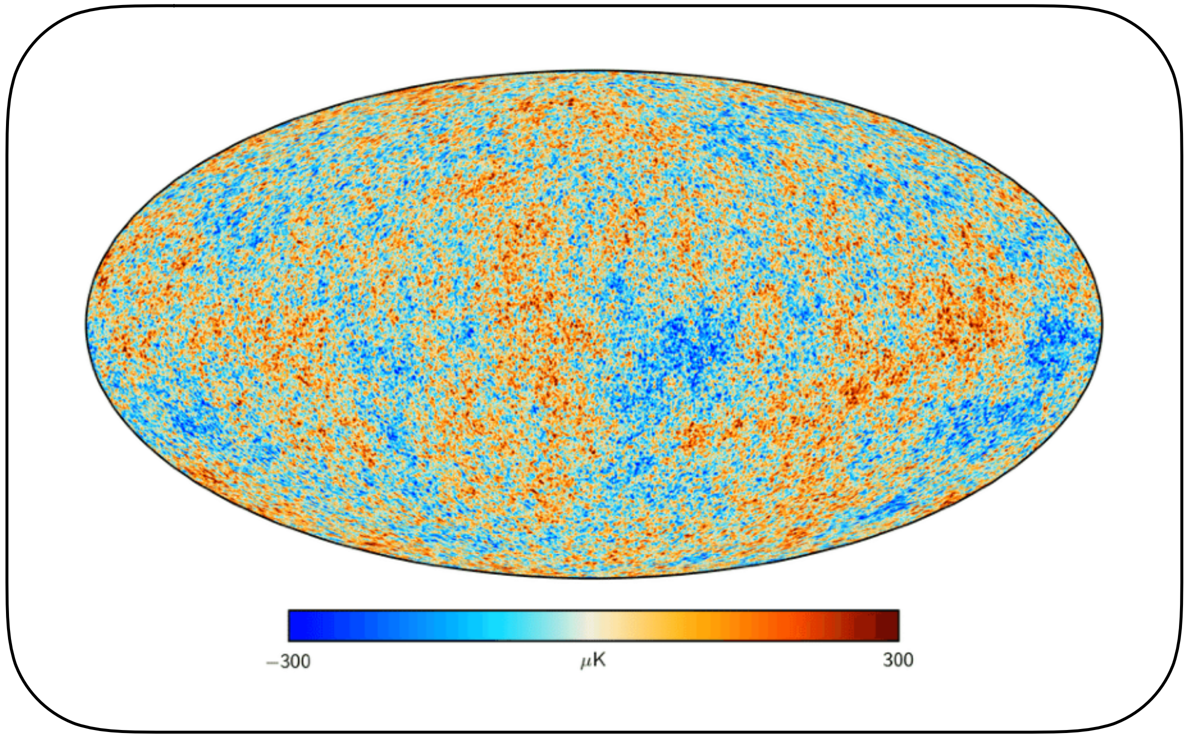
$SU(2)_X$ *Vector SIMP*

- **SMC**, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)
- **SMC**, H. M. Lee, Y. Mambrini and M. Pierre (2019)

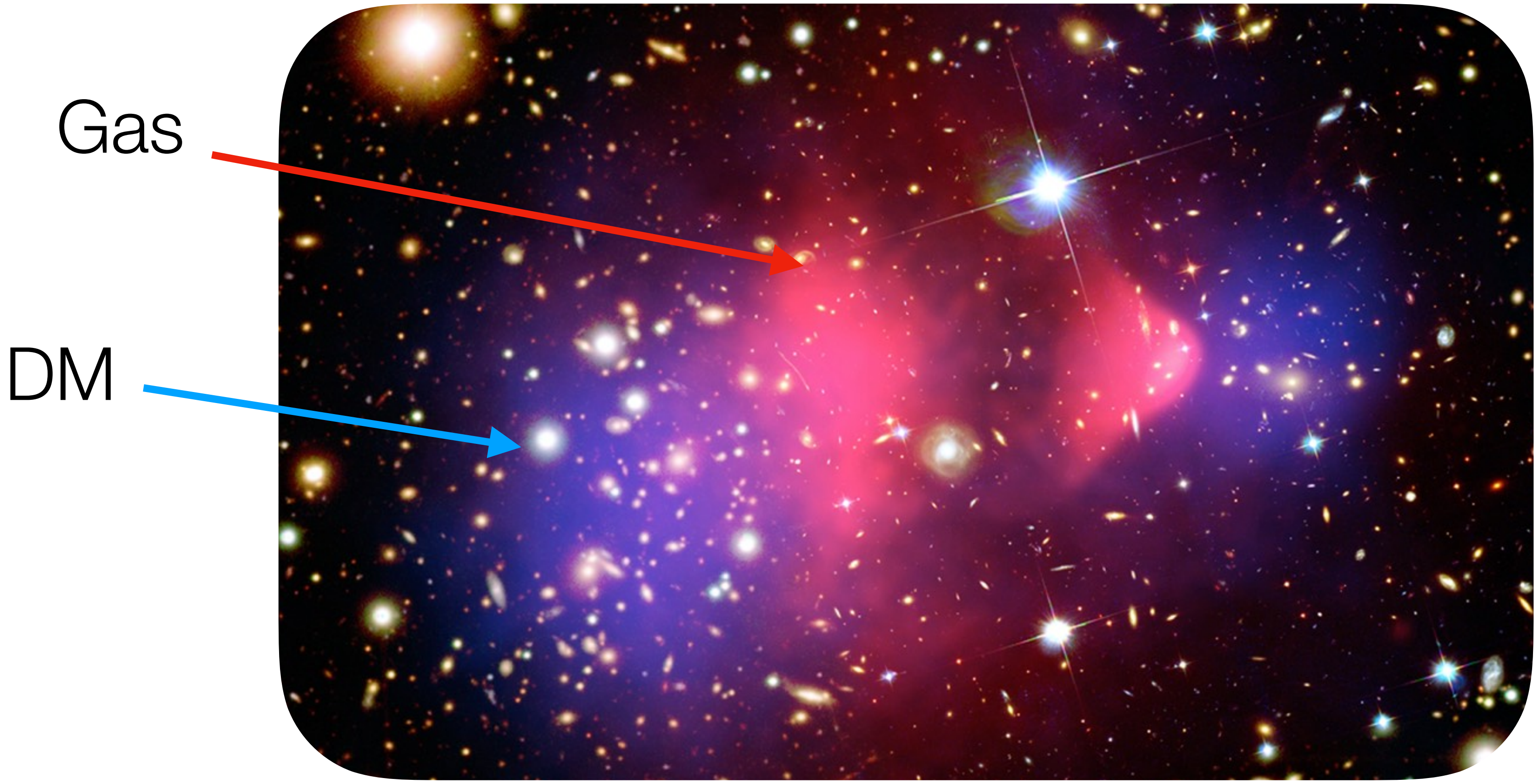





125 Mpc/h


−300
μK
300

Bullet cluster

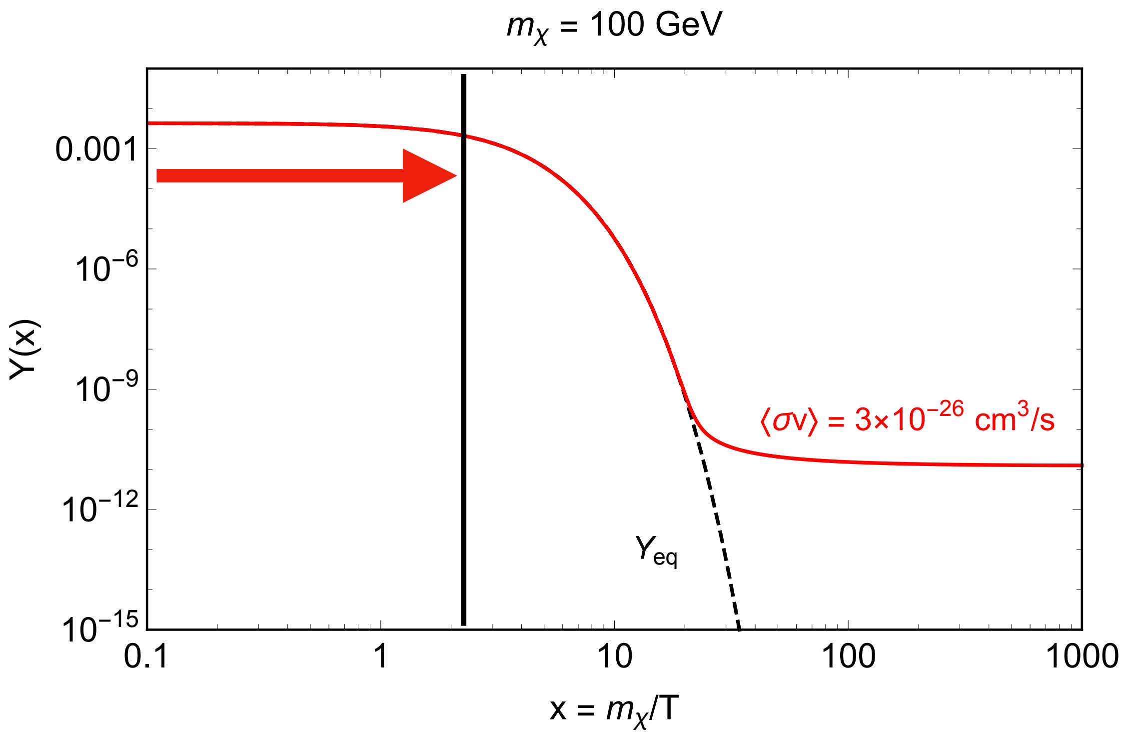


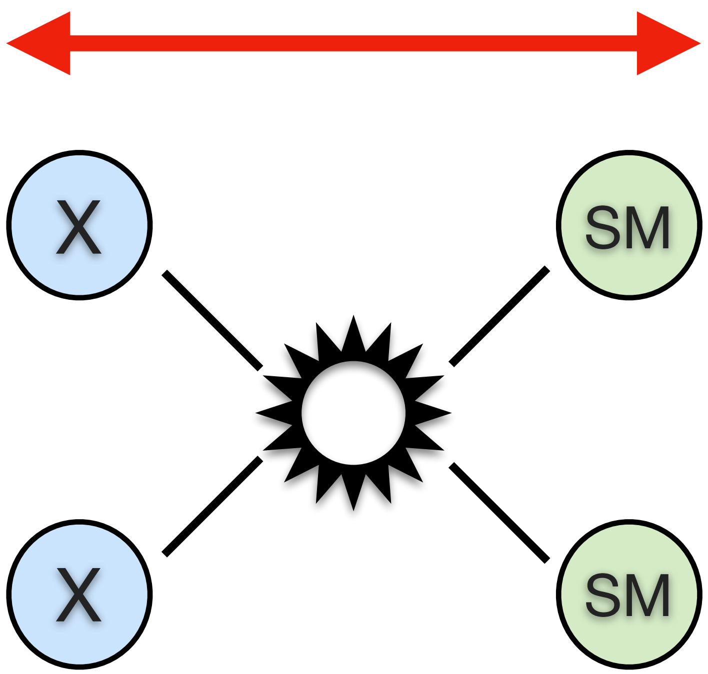
Very weak interaction with SM, self-interaction

The WIMP Miracle

- Thermal production : In **thermal equilibrium** with SM

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma v\rangle(n_X^2 - n_{\rm eq}^2), \qquad Y \equiv \frac{n_X}{s}, \qquad x = \frac{m_X}{T}$$





The WIMP Miracle

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- Dark matter **annihilation** is dominant

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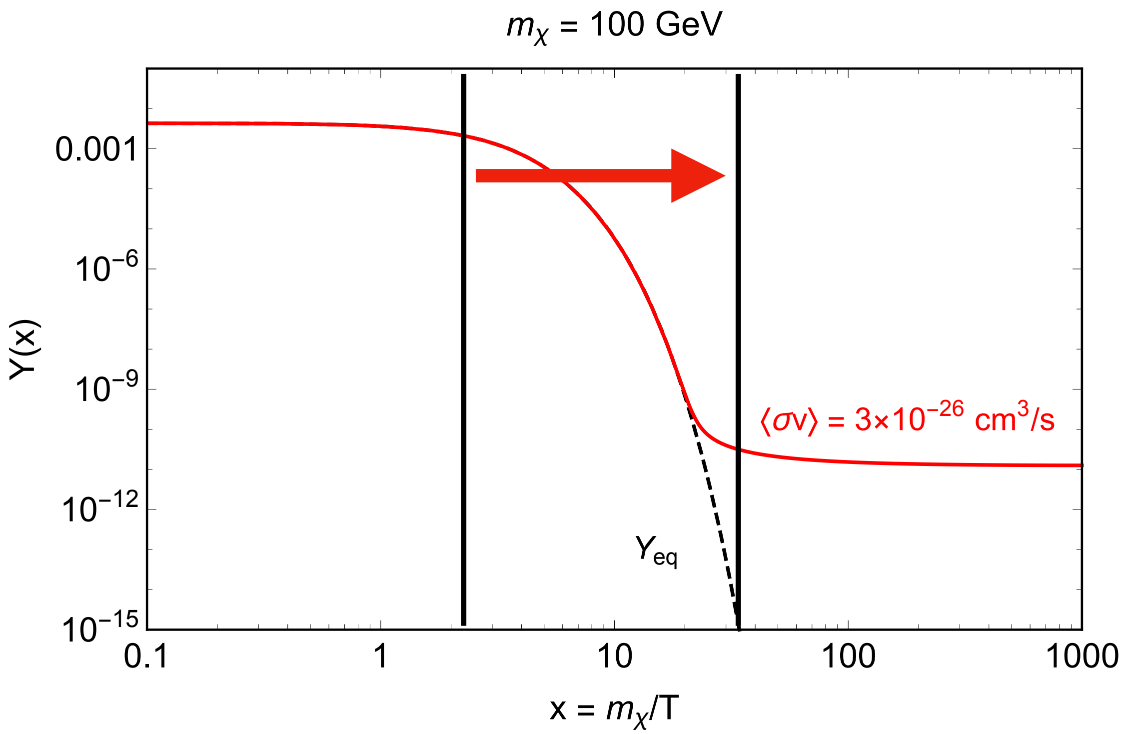
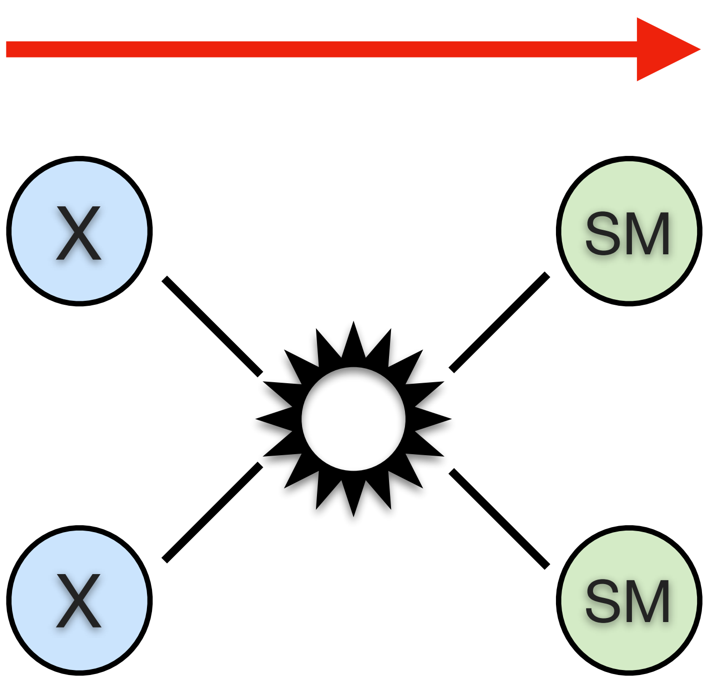
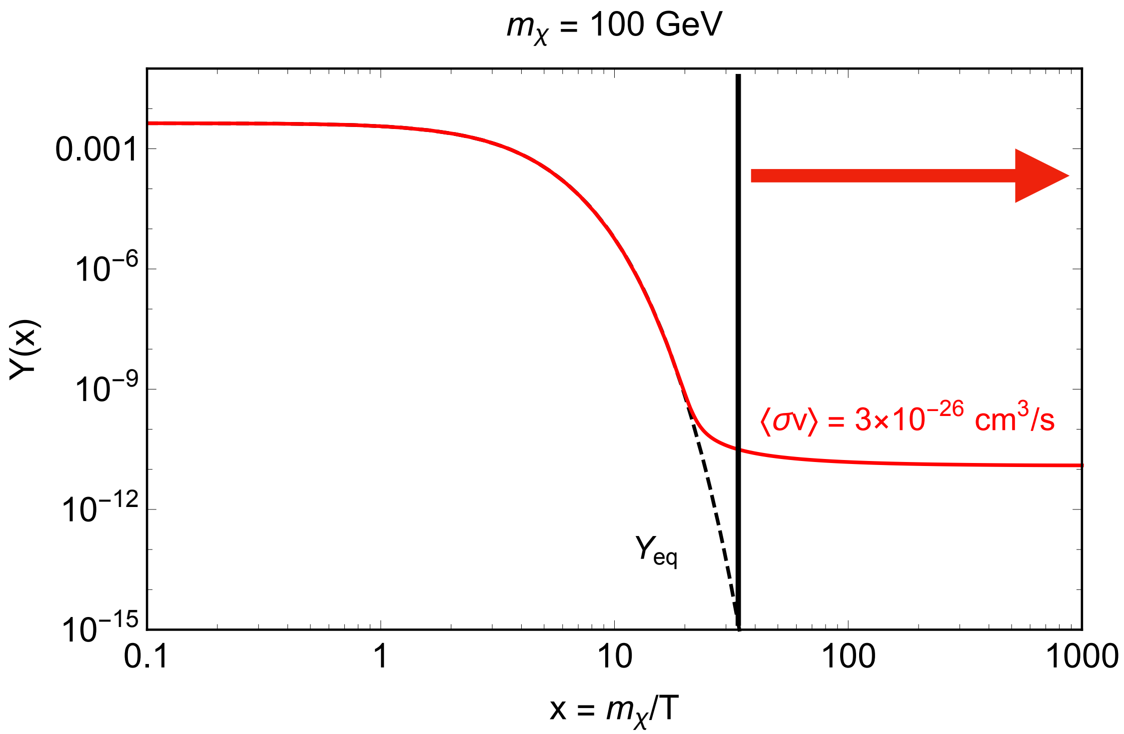


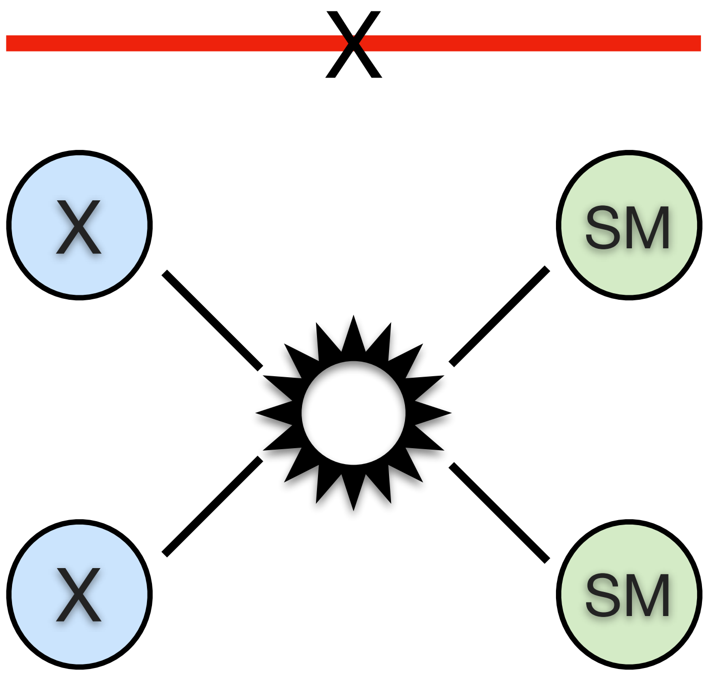


The WIMP Miracle

- Thermal production : In **thermal equilibrium** with SM
- Dark matter **annihilation** is dominant
- **Decoupling** at $x \sim 20$ & **freeze-out** of Y

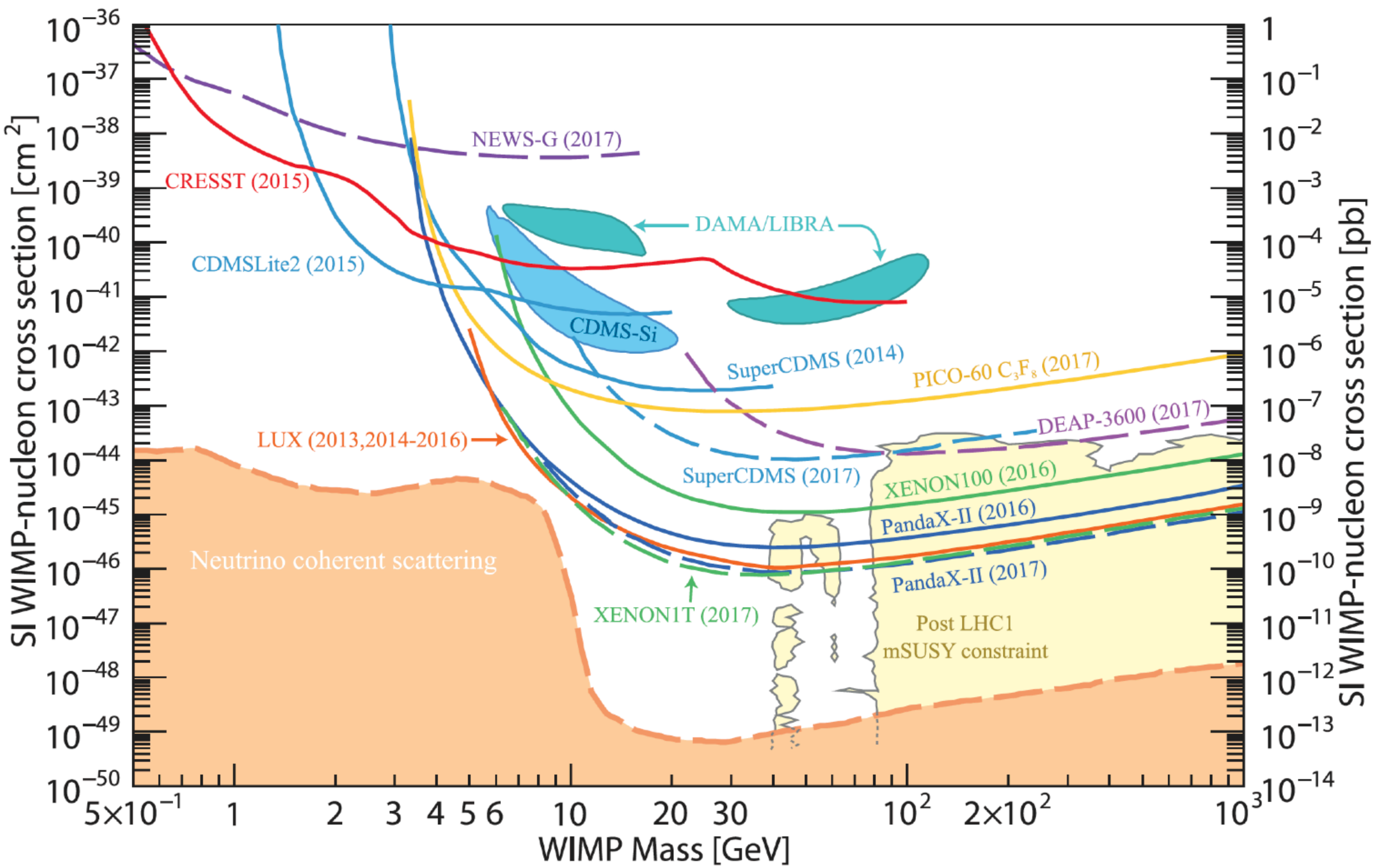
$$\Omega_X h^2 \simeq 0.12 \left(\frac{x_f}{20}\right)\left(\frac{3\times 10^{-26}\ \mathrm{cm^3/s}}{\langle\sigma v\rangle}\right)$$





Direct Detection of WIMP

- No direct evidence for WIMP



Particle Data Group (2018)

Direct Detection of WIMP

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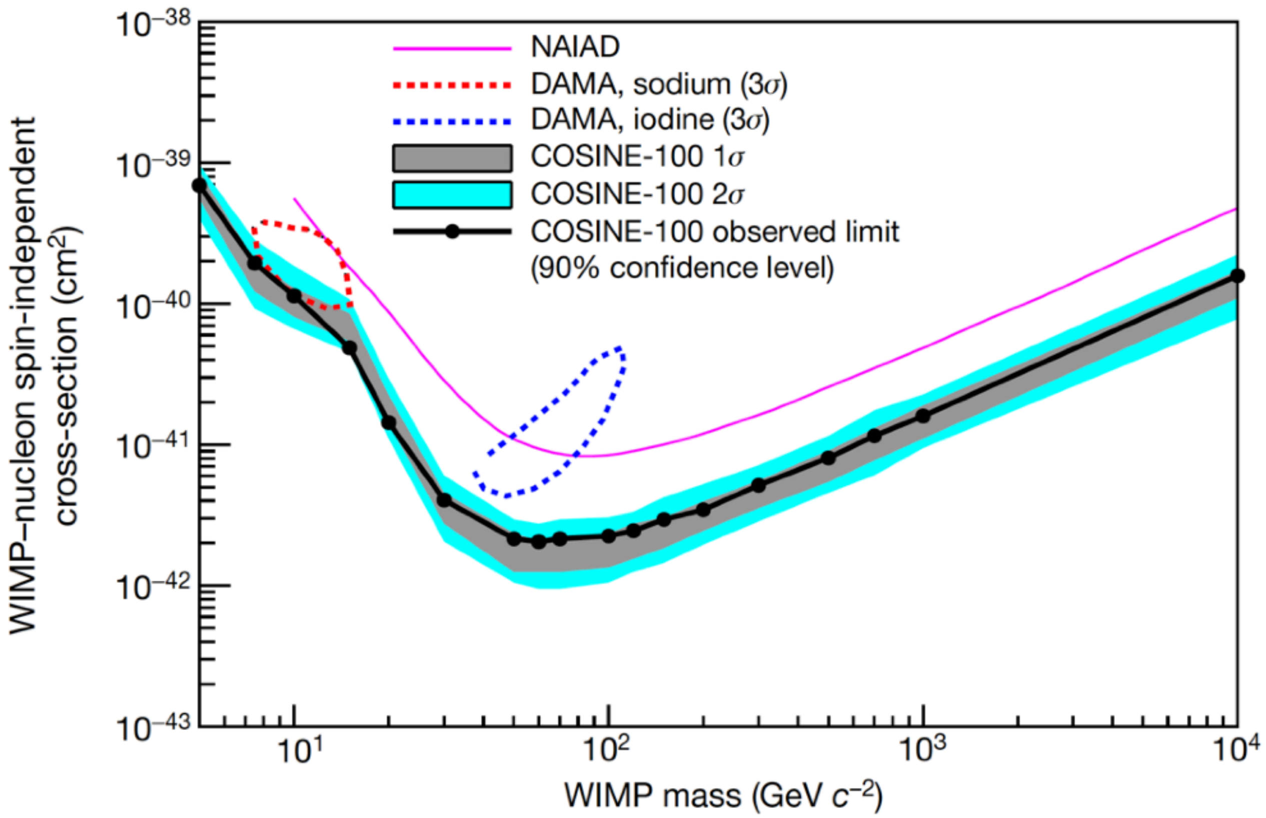
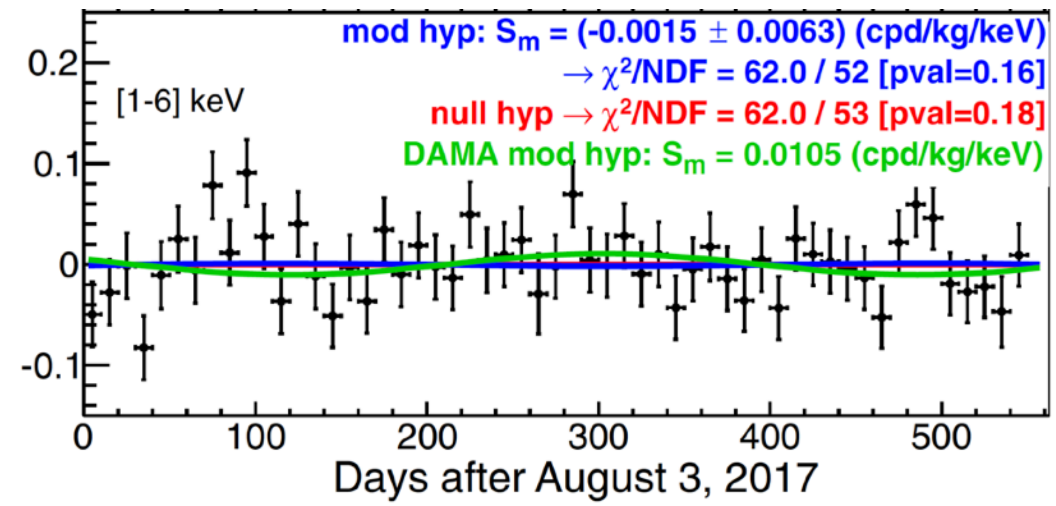




Red line = no modulation

Green line = DAMA

Blue line = ANAIS

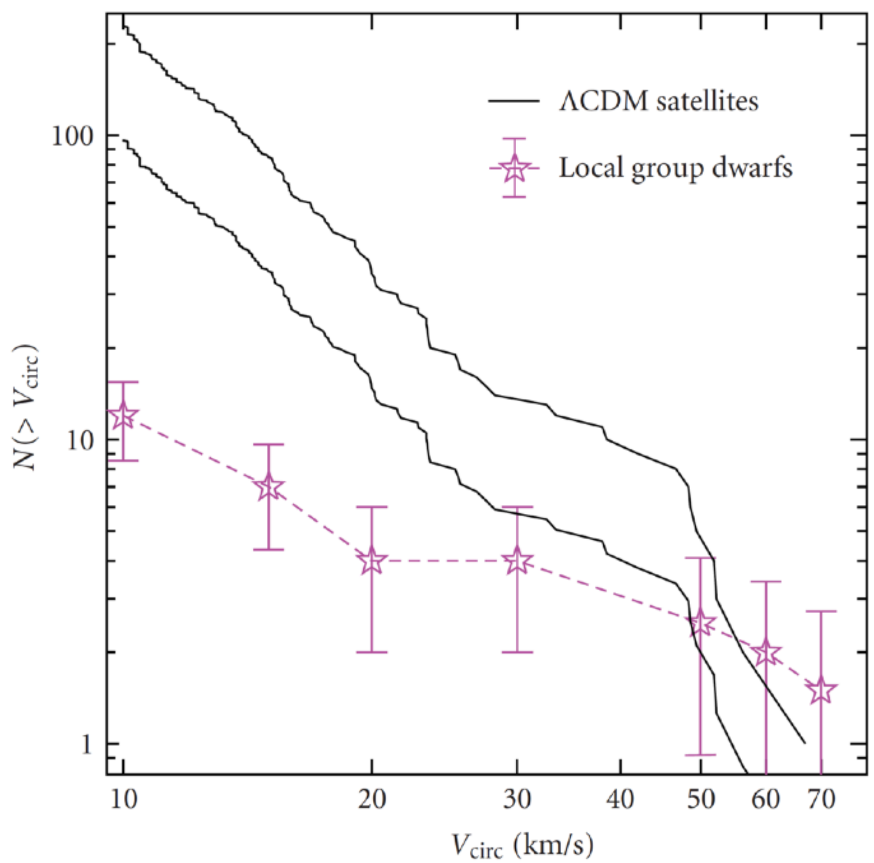
COSINE-100 Collaboration (2018), ANAIS-112 Collaboration (2019)

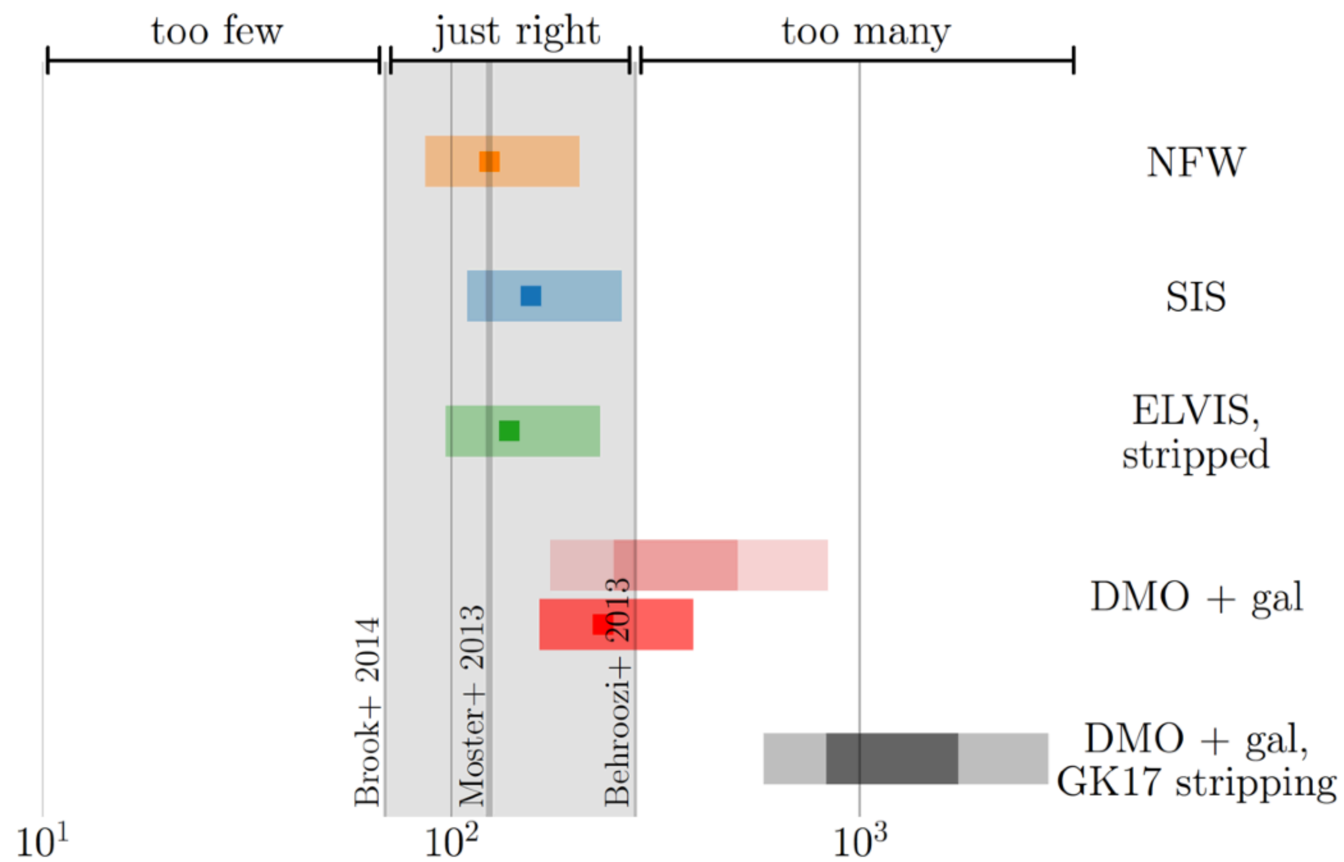
Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations

Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- **Missing Satellite**

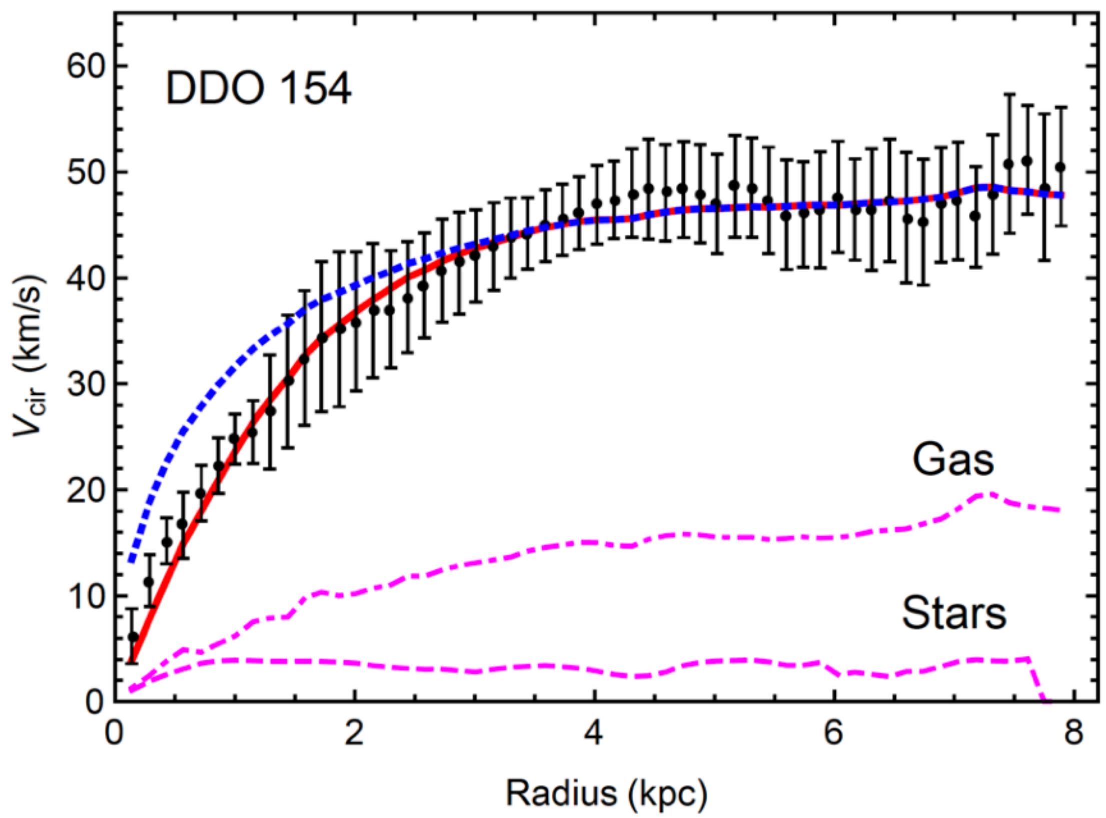


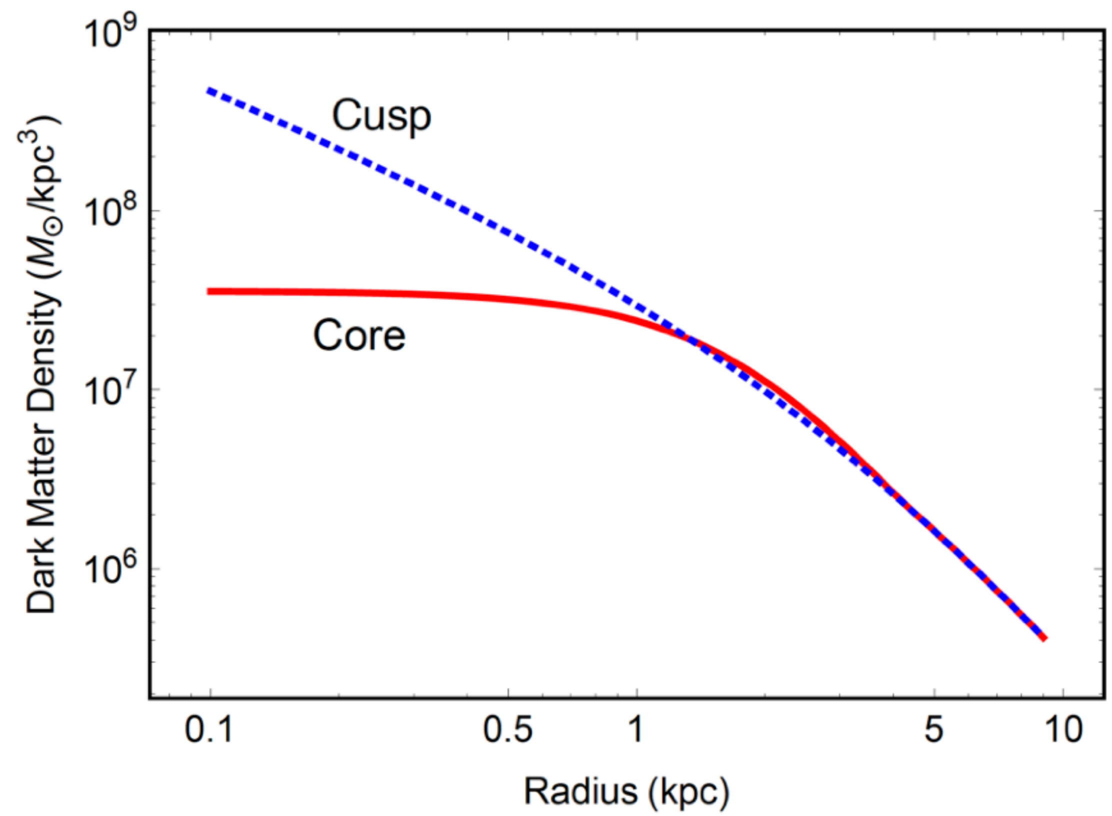


A. Kravtsov (2010), Kim et al (2018)

Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / **Core-cusp**

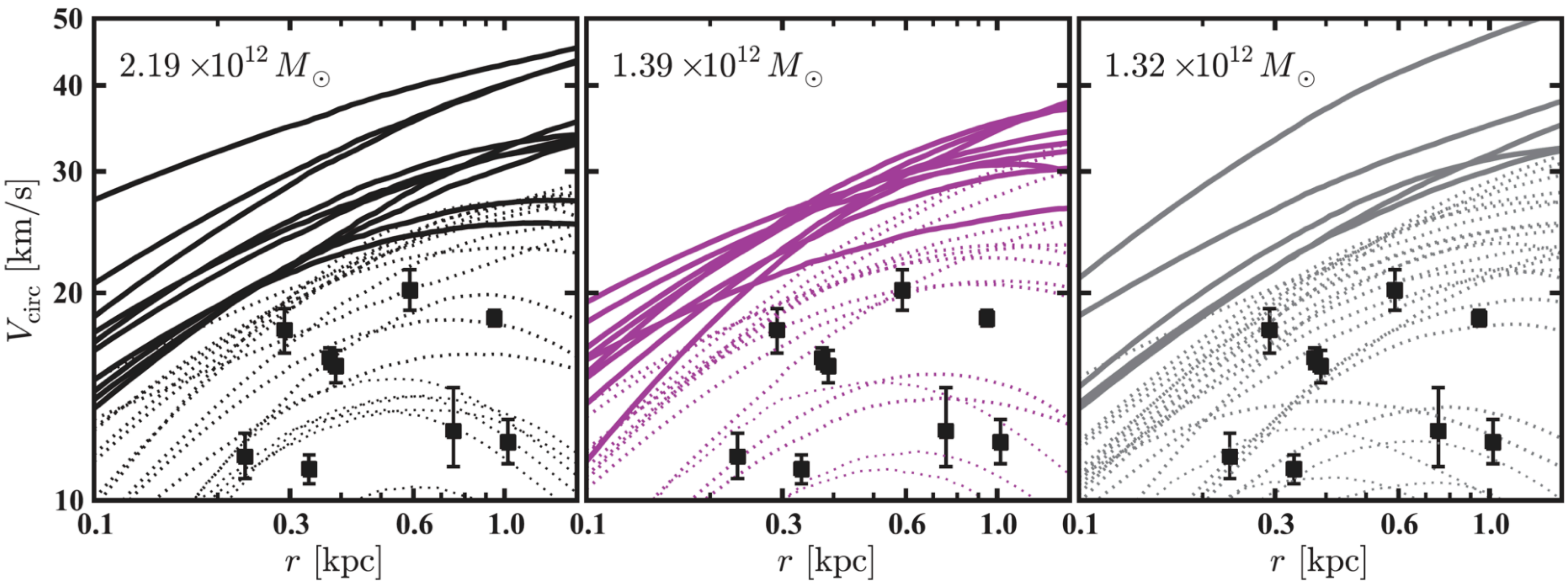




S. Tulin and H. B. Yu (2017)

Small-Scale Problems

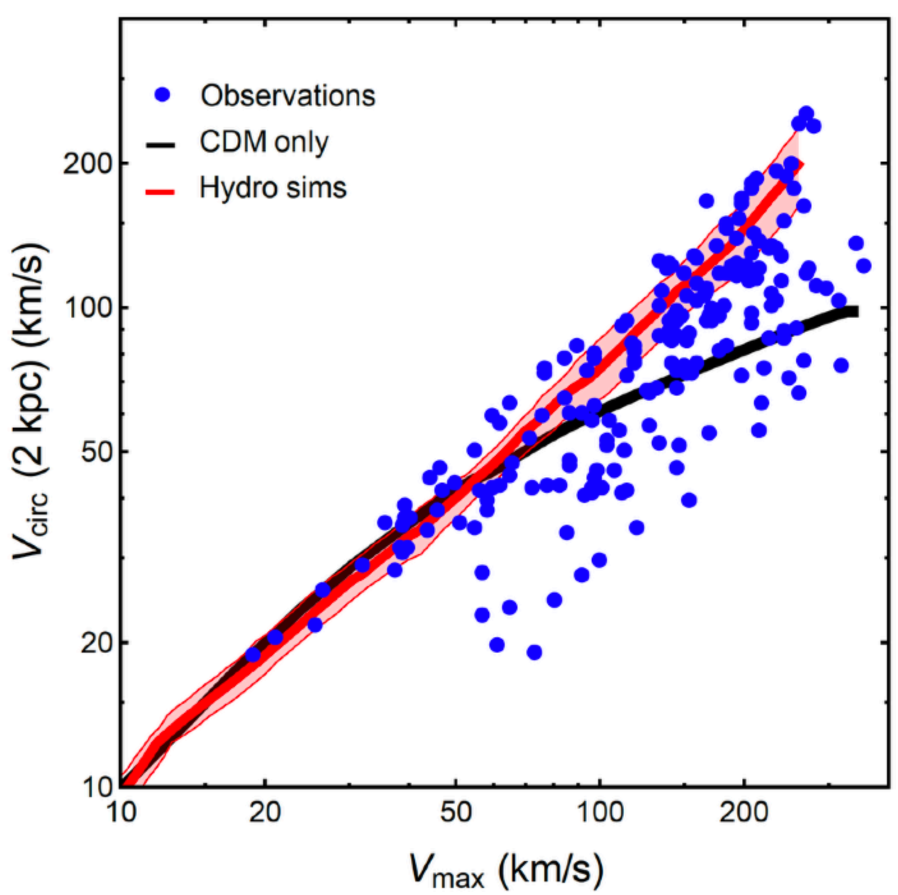
- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / Core-cusp / **Too-big-to-fail**

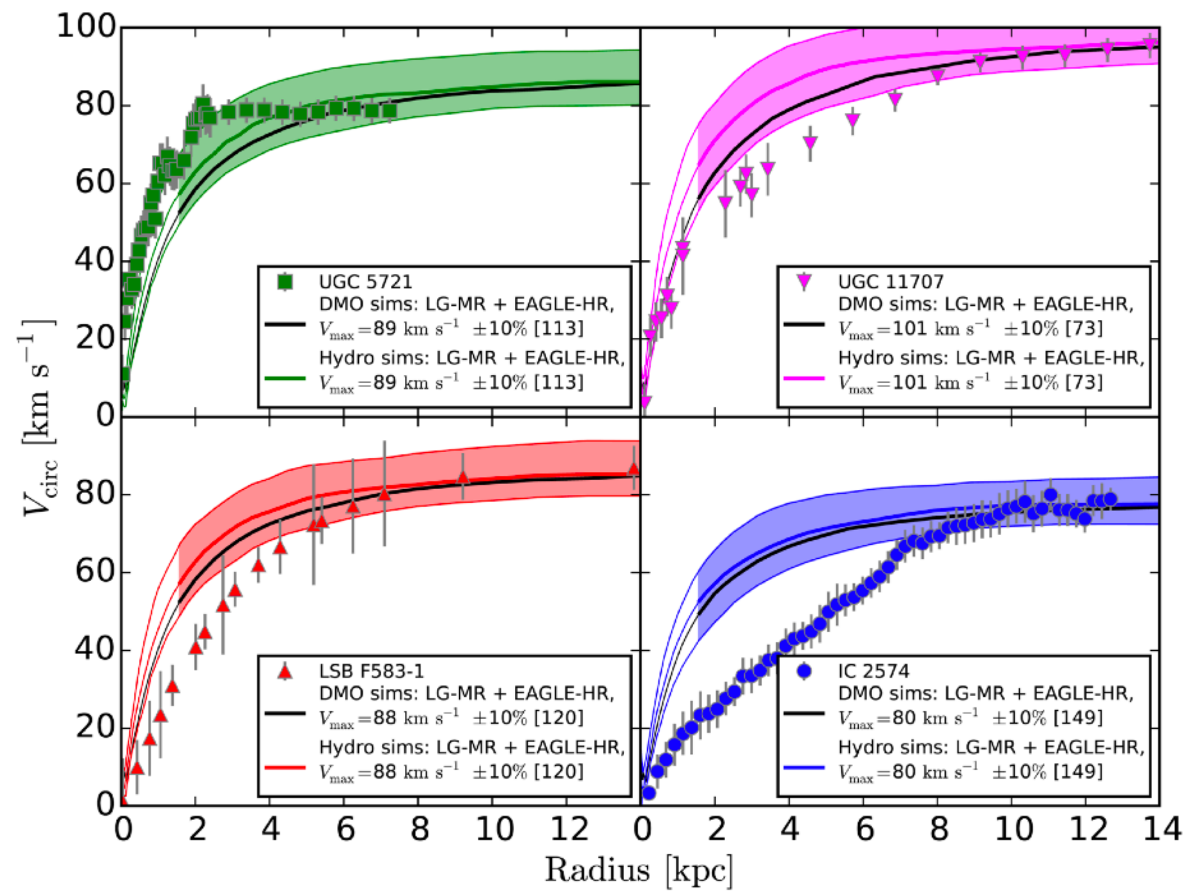


Boylan-Kolchin et al (2011)

Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / Core-cusp / Too-big-to-fail / **Diversity**



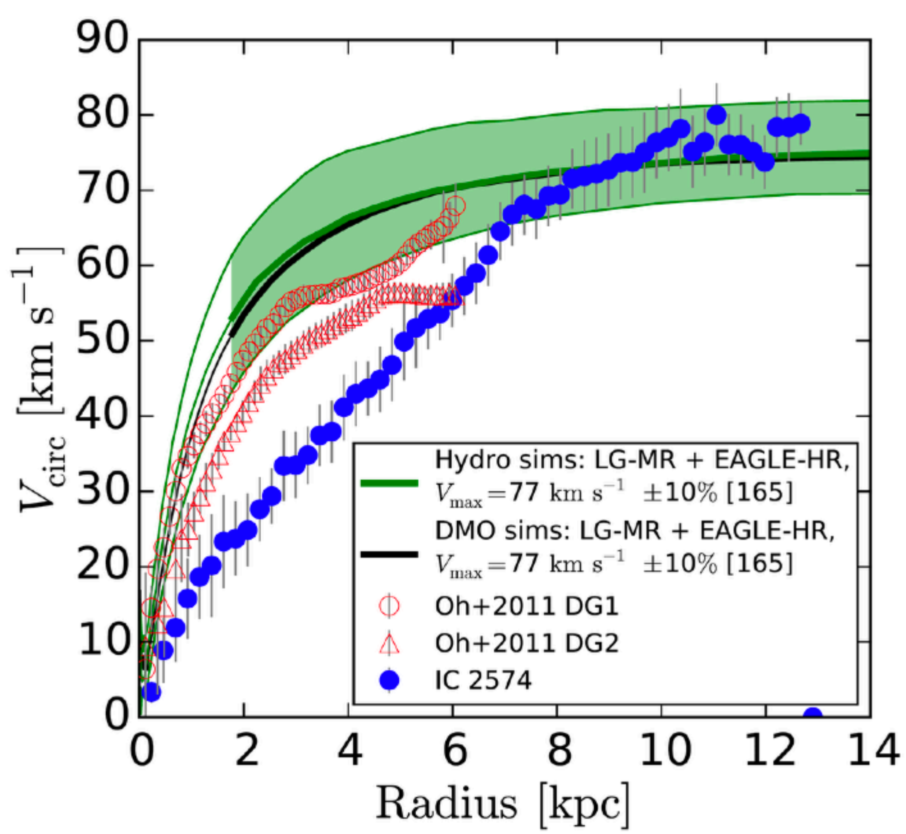


S. Tulin and H. B. Yu (2017), Oman et al (2015)

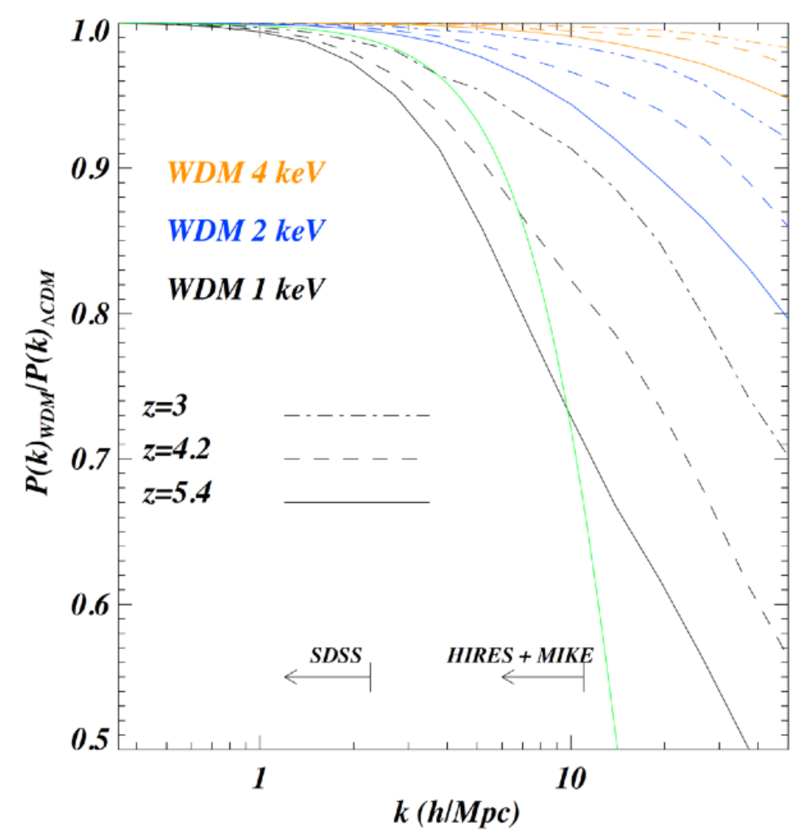
Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / Too-big-to-fail / Core-cusp / Diversity
- **Solutions**

  : **Baryonic effects**, **Warm DM**



Ultra-low density core



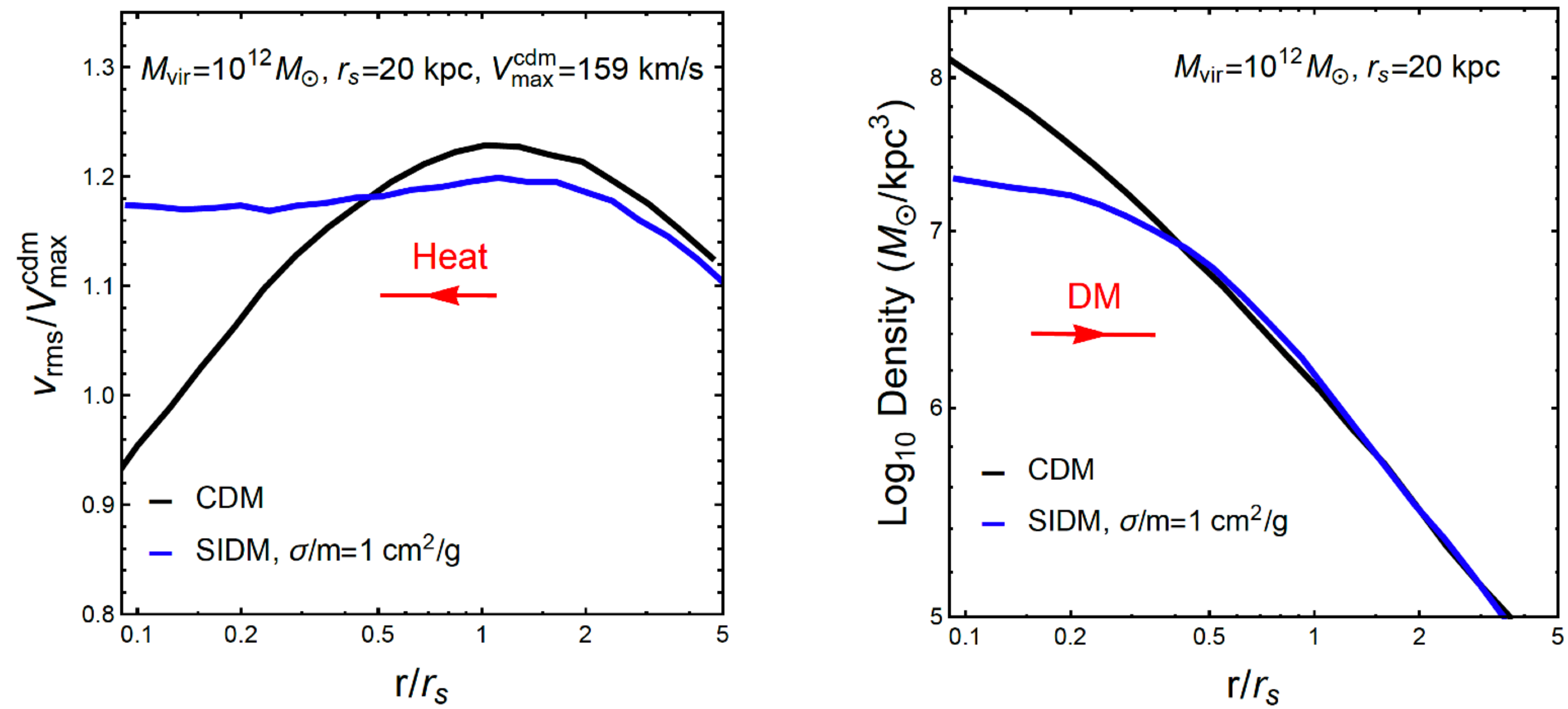
Lyman-α Constraint

Oman et al (2015), Viel et al (2013)

Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / Too-big-to-fail / Core-cusp / Diversity
- **Solutions**

  : Baryonic effects, Warm DM, **Self-Interacting DM**



S. Tulin and H. B. Yu (2017)

Small-Scale Problems

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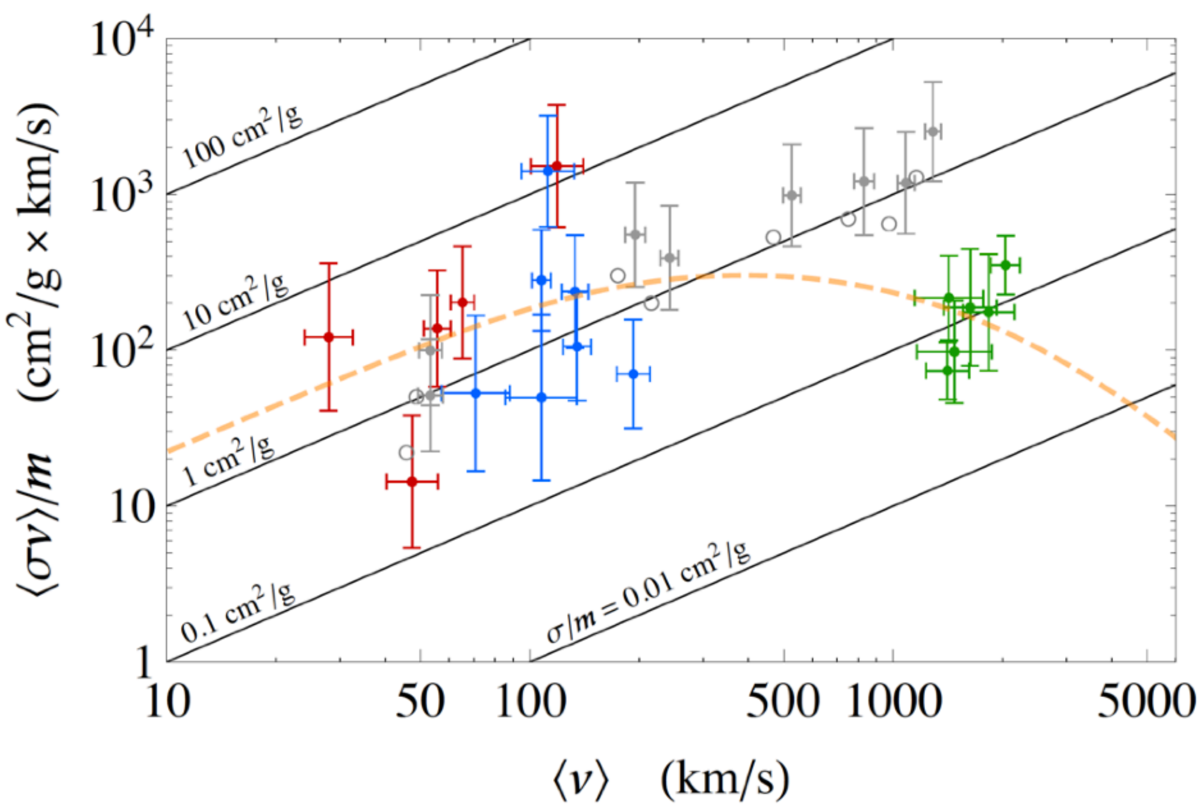


$$\frac{\sigma_{\rm self}}{m_X} \sim \mathcal{O}(1)\ {\rm cm^2/g}$$

@ Dwarf galaxies, v ~ 50 km/s

$$\frac{\sigma_{\rm self}}{m_X} \sim \mathcal{O}(0.1)\ {\rm cm^2/g}$$

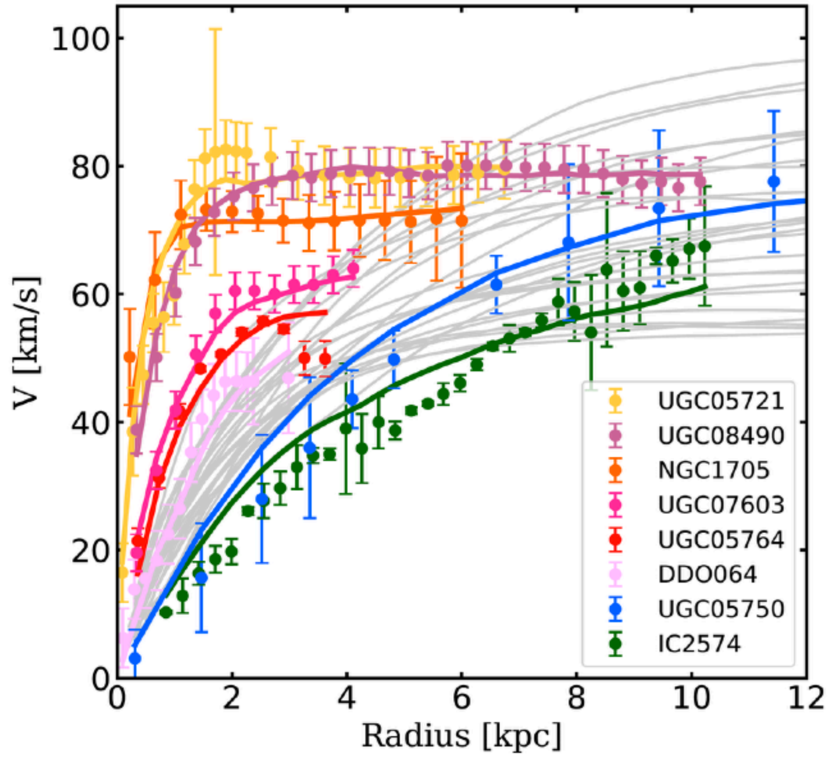
@ Clusters, v ~ 2000 km/s

Kaplinghat et al (2016)

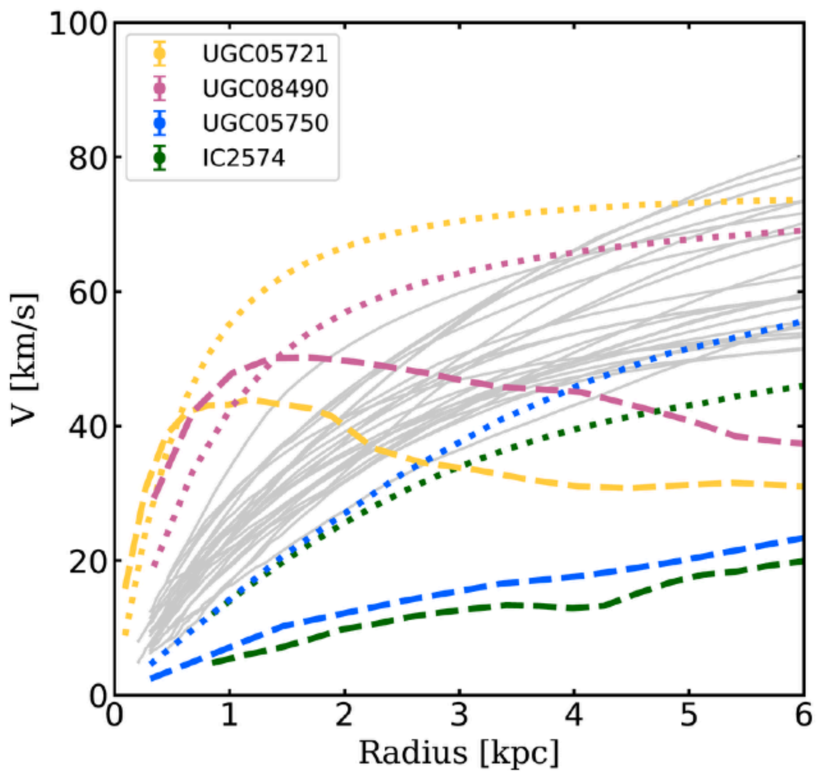
Small-Scale Problems

- Conflict b/w ΛCDM simulations and observations
- Missing Satellite / Too-big-to-fail / Core-cusp / **Diversity**
- **Solutions**

  : Baryonic effects, Warm DM, **Self-Interacting DM**



Solid : SIDM / Gray : Baryonic effect



Contributions of

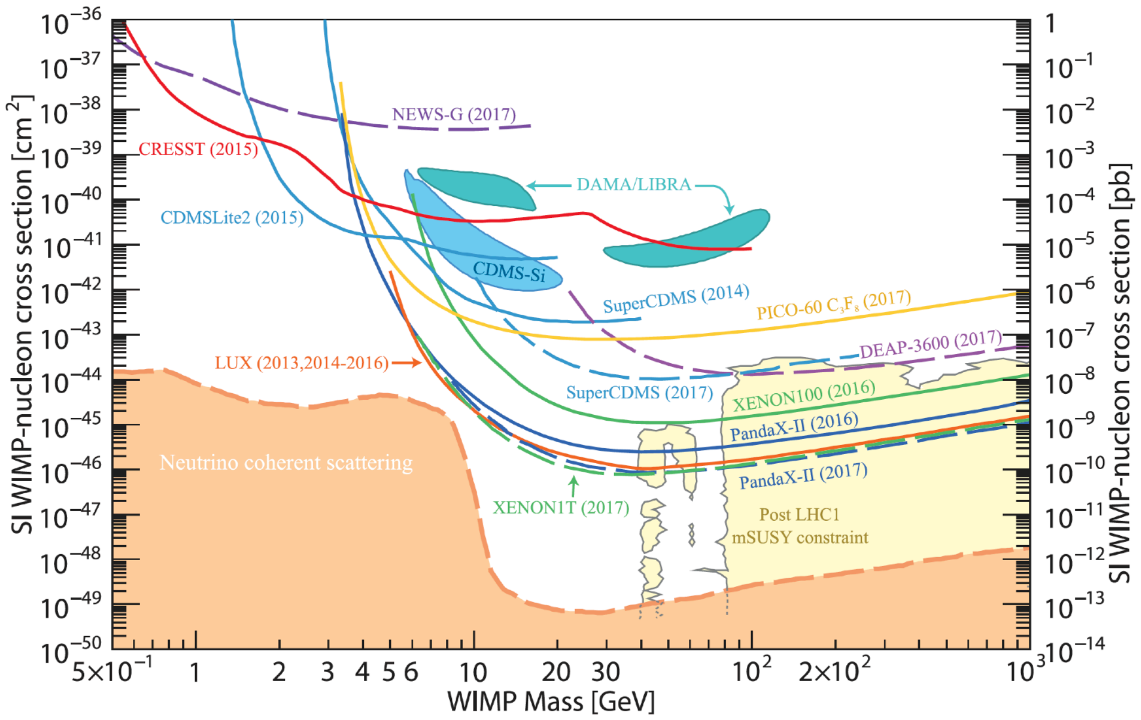
Dashed : Baryon / Dotted : DM

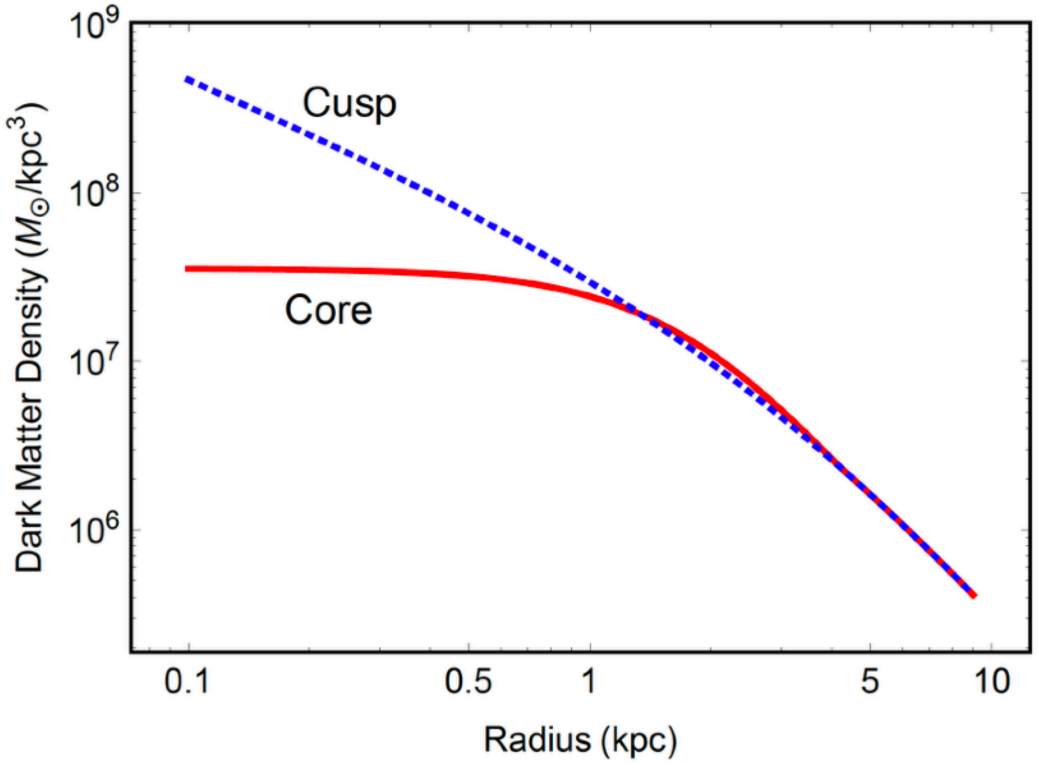
M. Kaplinghat, T. Ren and H. B. Yu (2019)

Crisis of WIMP ?

No evidence in direct detection

+ Small-Scale Problems





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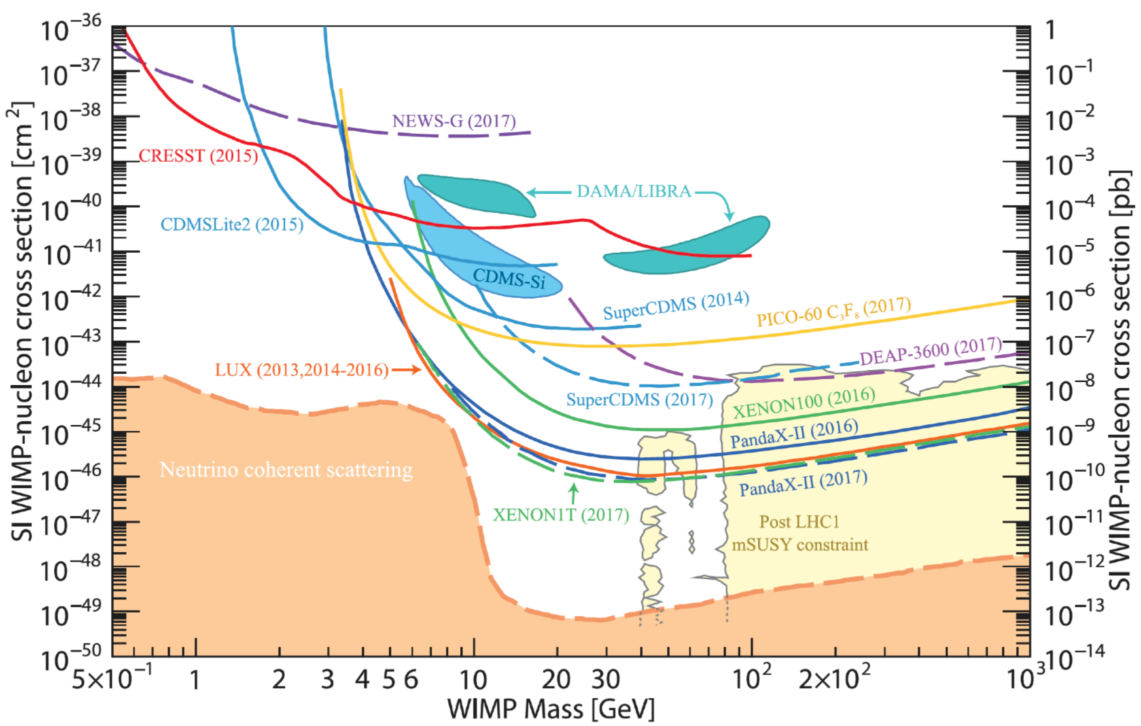
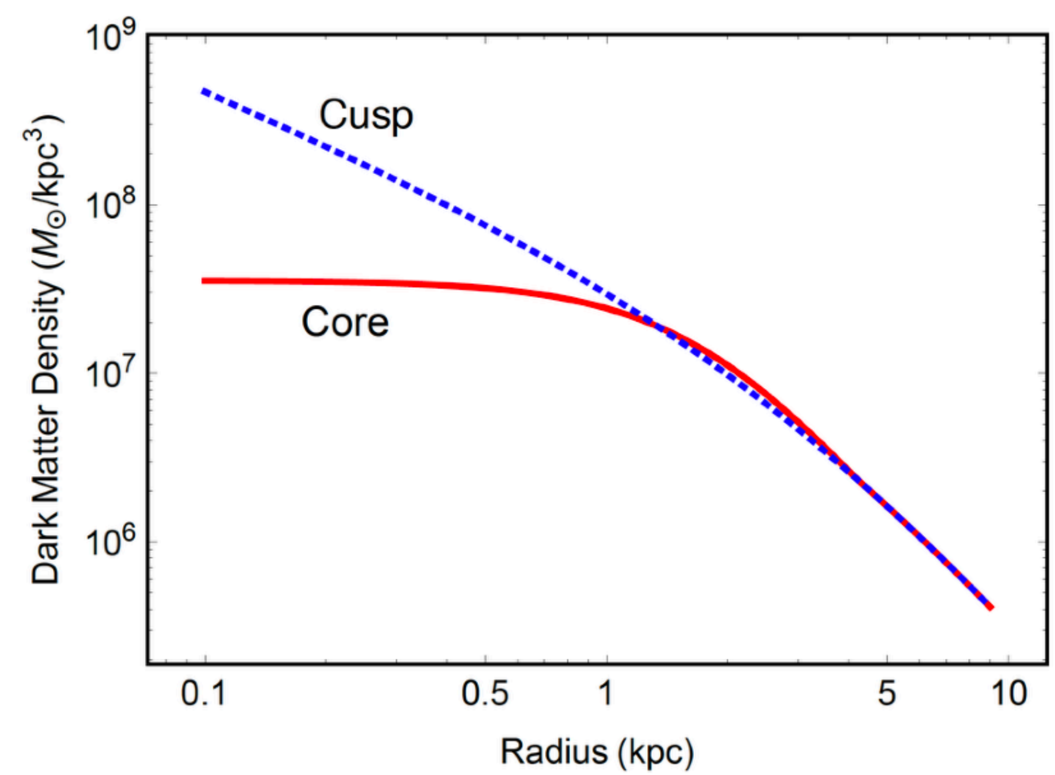
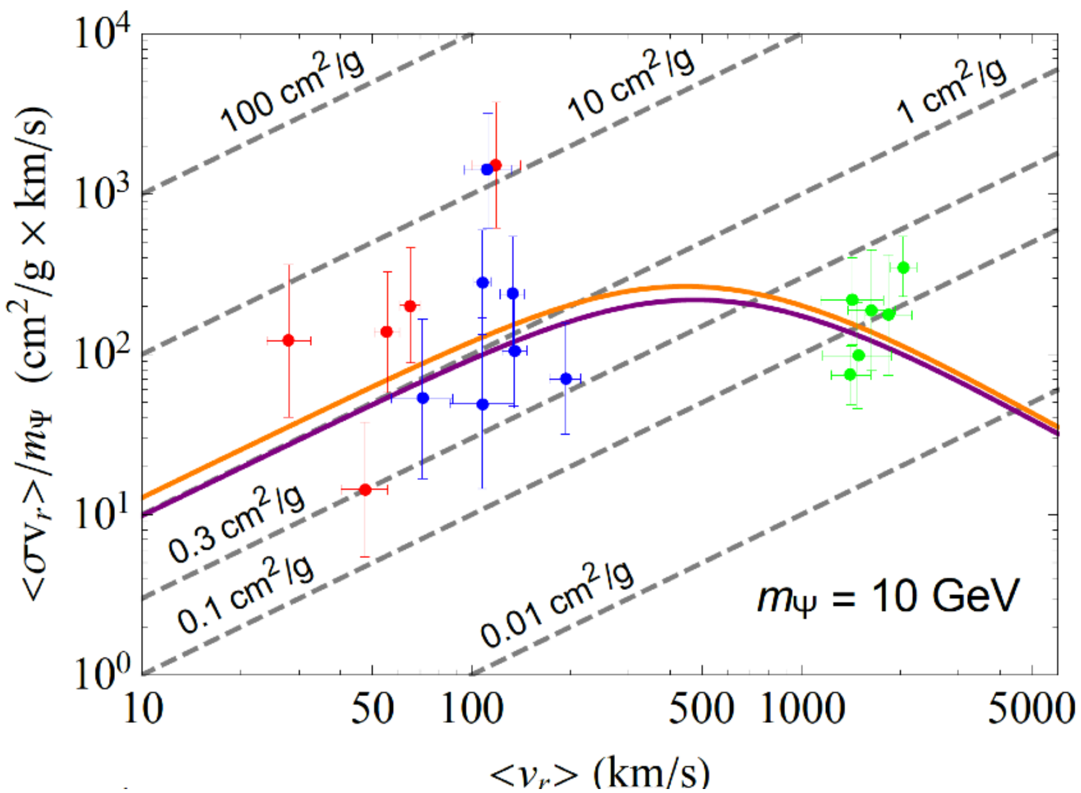




Self-Interacting WIMP

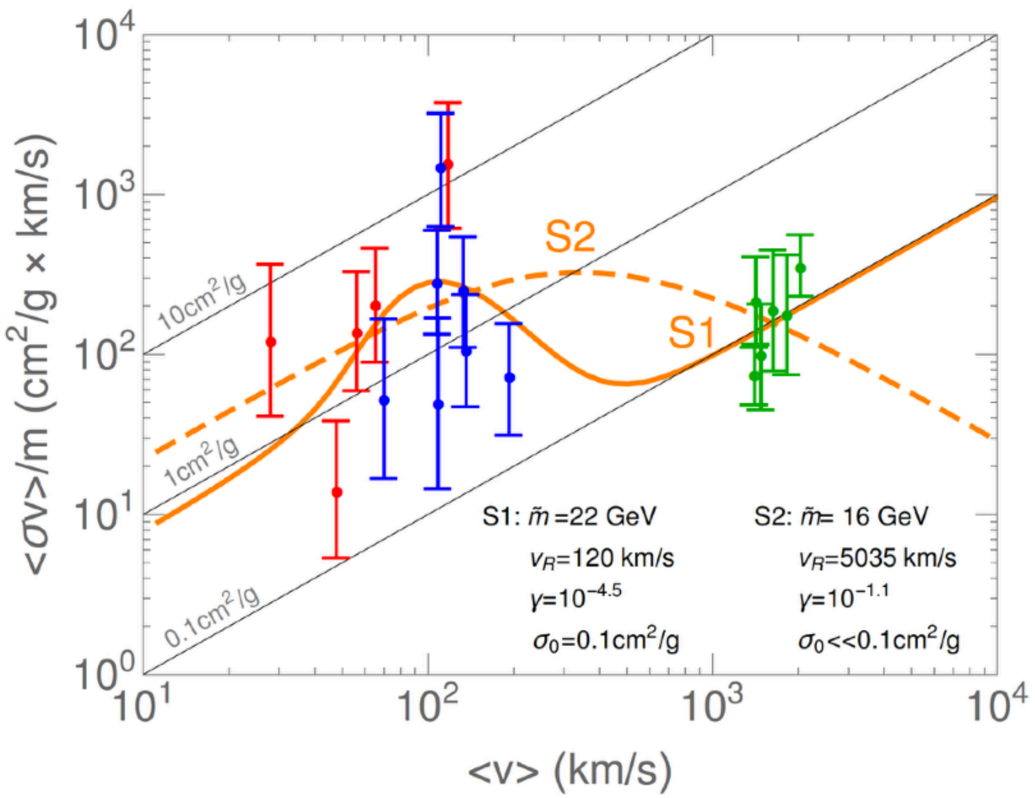
- Strong self-interaction with Sommerfeld and Resonance



Sommerfeld Enhancement

Fermionic DM (Ψ)

with mediator (22 MeV)



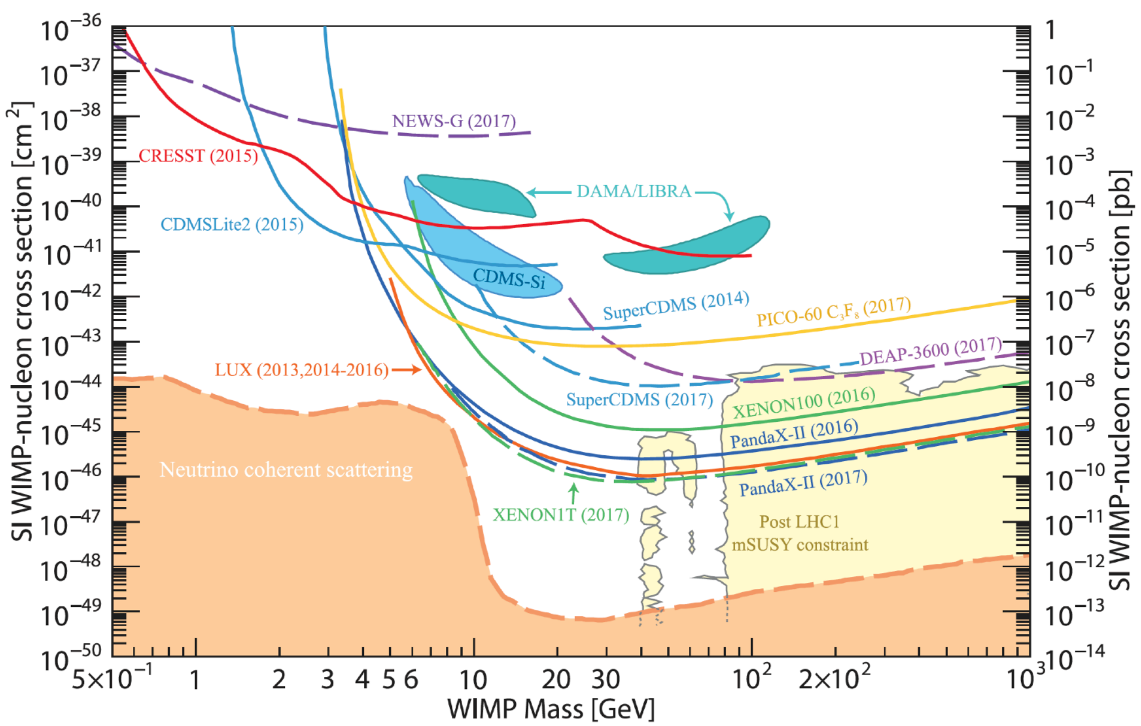
Resonant SIDM

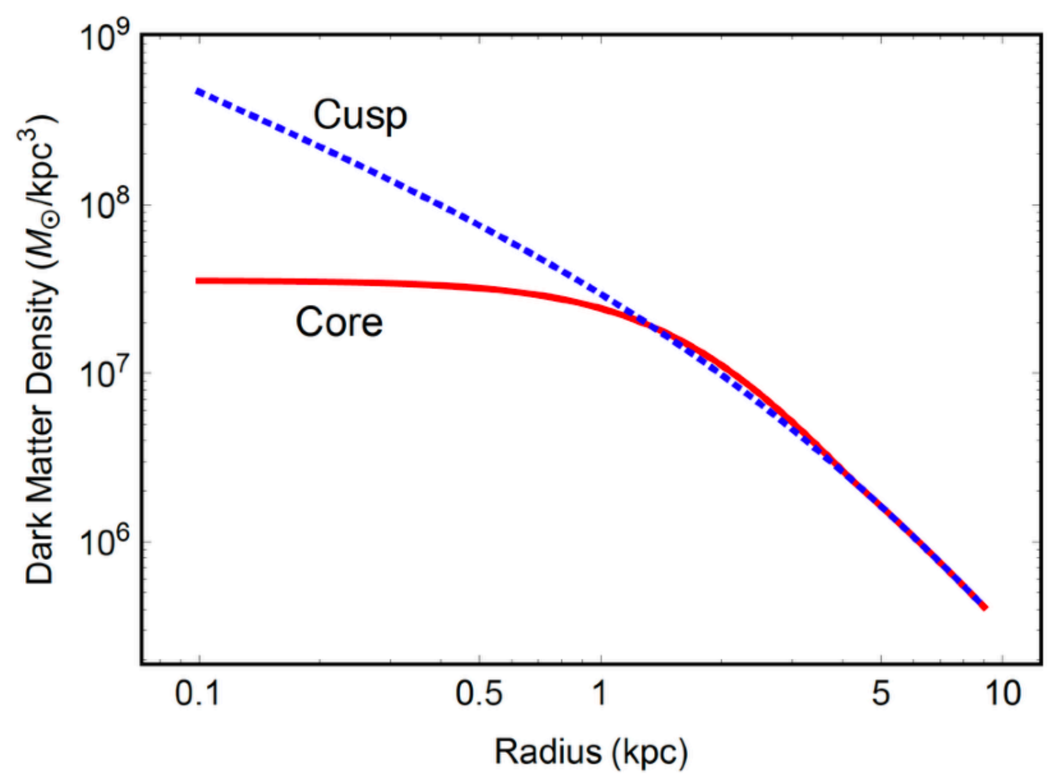
Kahlhofer et al (2016, 2017), Murayama et al (2018), L. Jia (2019)

~~Crisis of WIMP ?~~

No evidence in direct detection

+ Small-Scale Problems



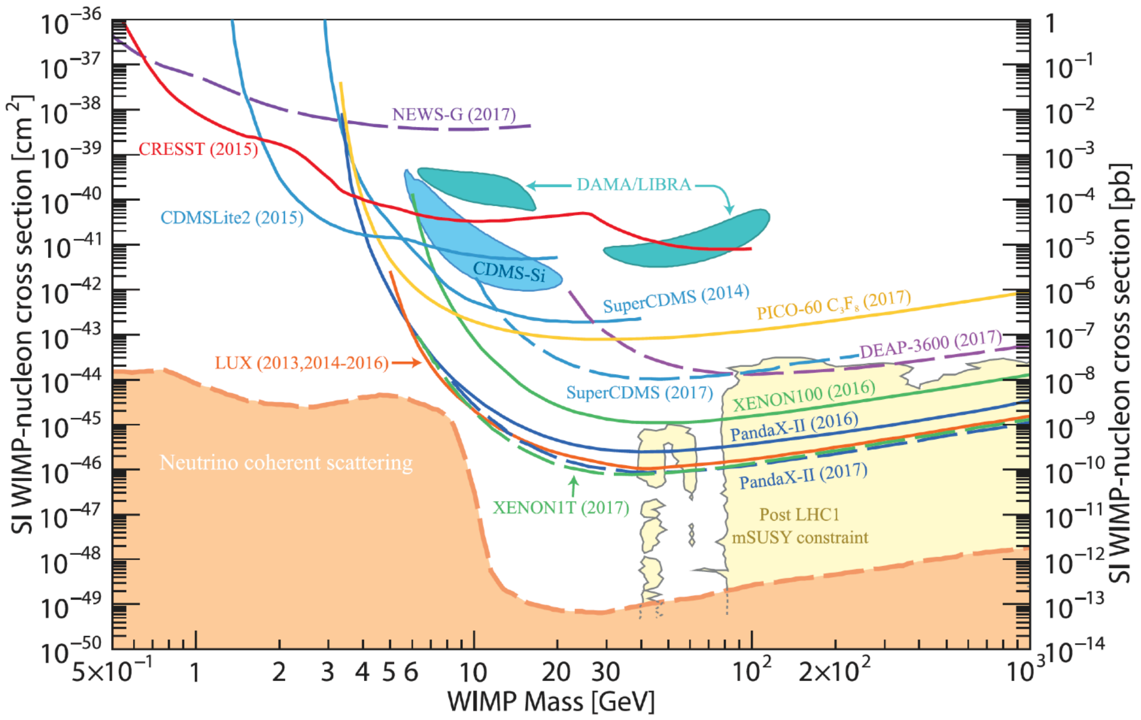


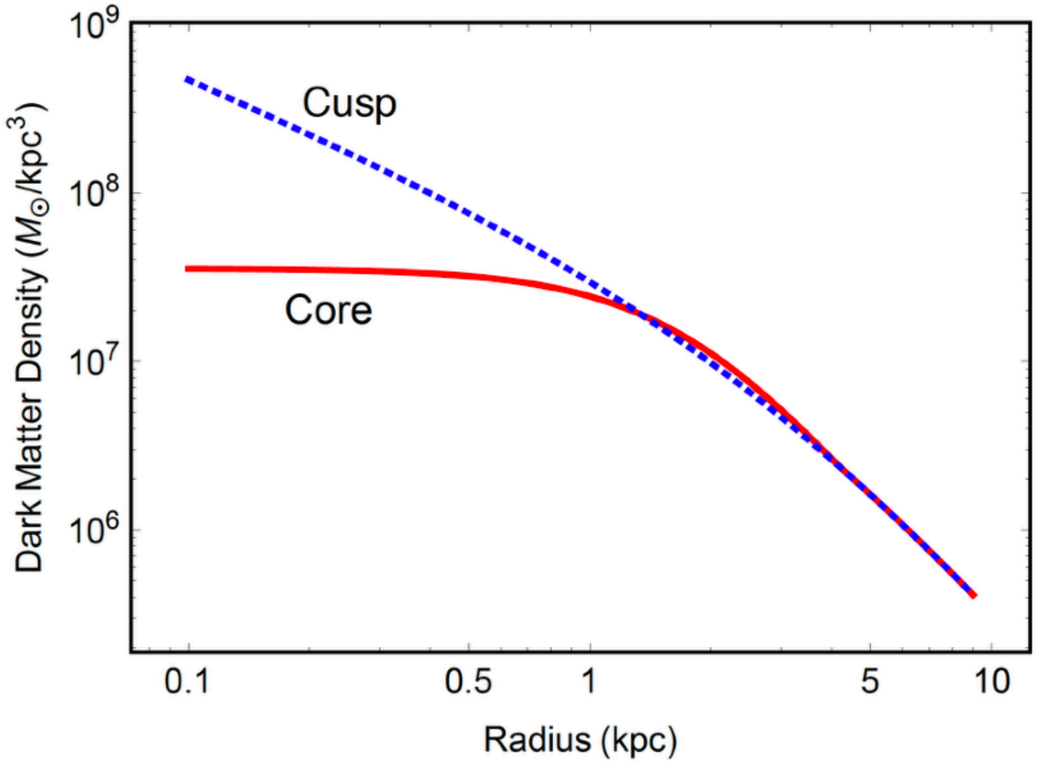
Opportunities

for Other Models

No evidence in direct detection

+ Small-Scale Problems

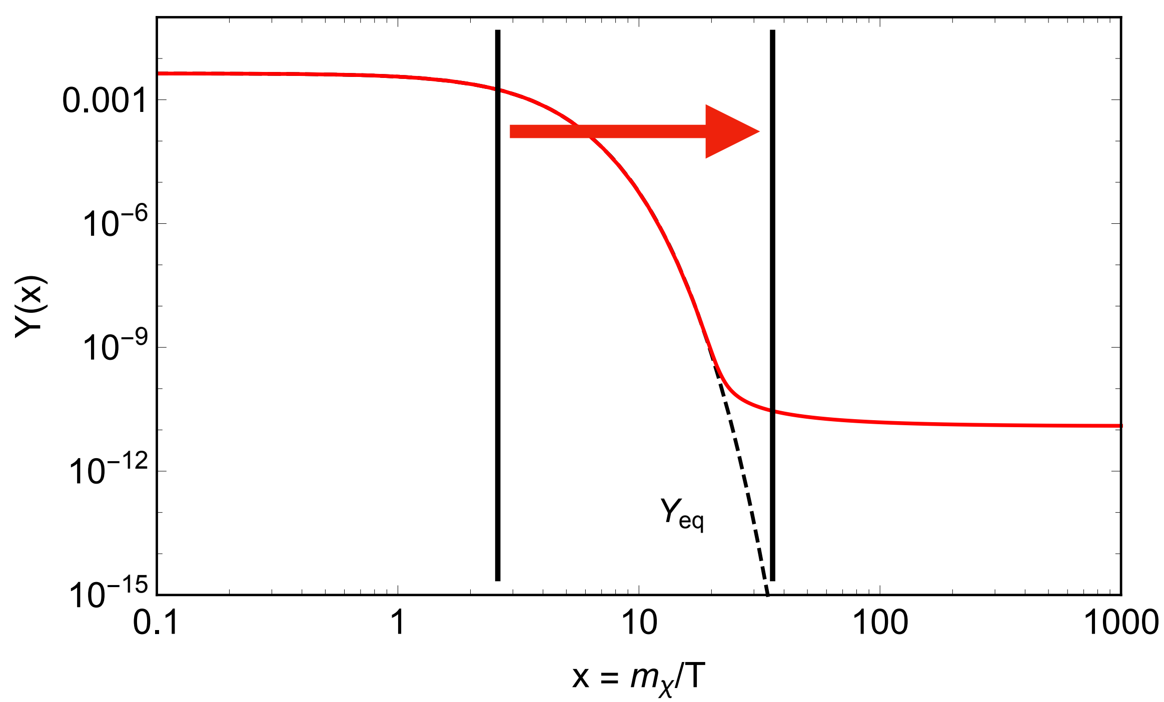


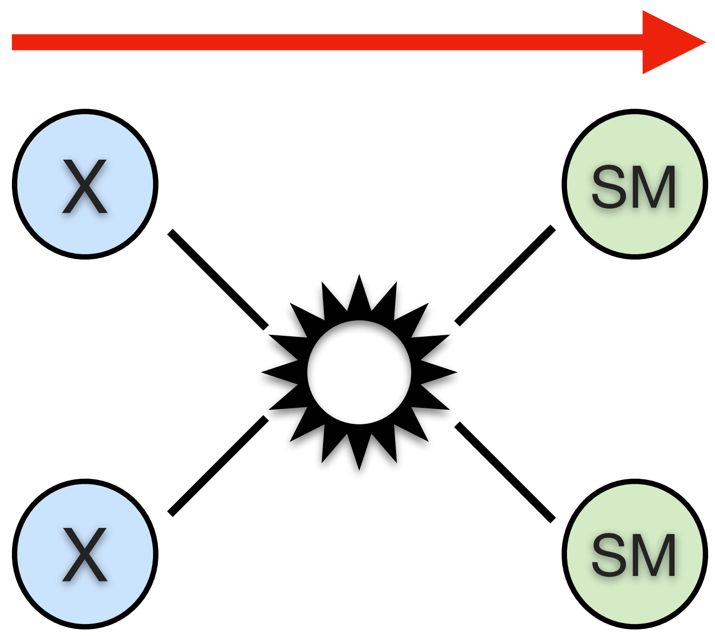


Annihilation Mechanism

- There are many new ways for thermal production

$$WIMP\ :\ \frac{dn_X}{dt} + 3Hn_X = -\langle\sigma v\rangle(n_X^2 - n_{\rm eq}^2)$$



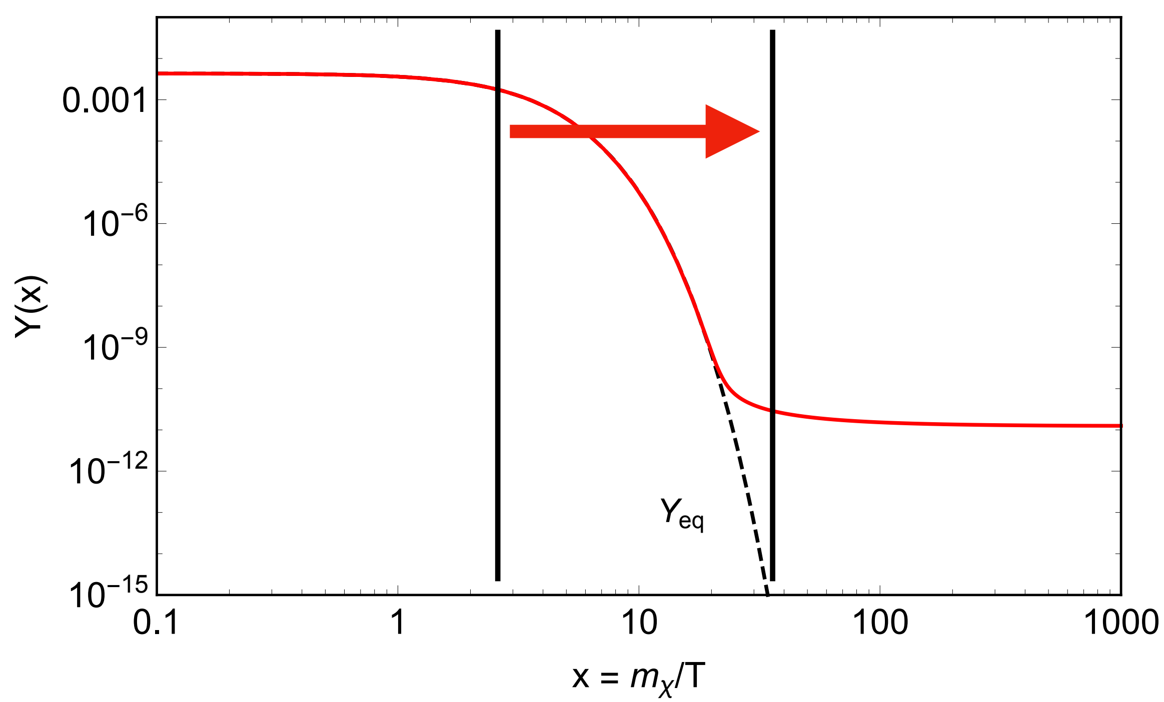


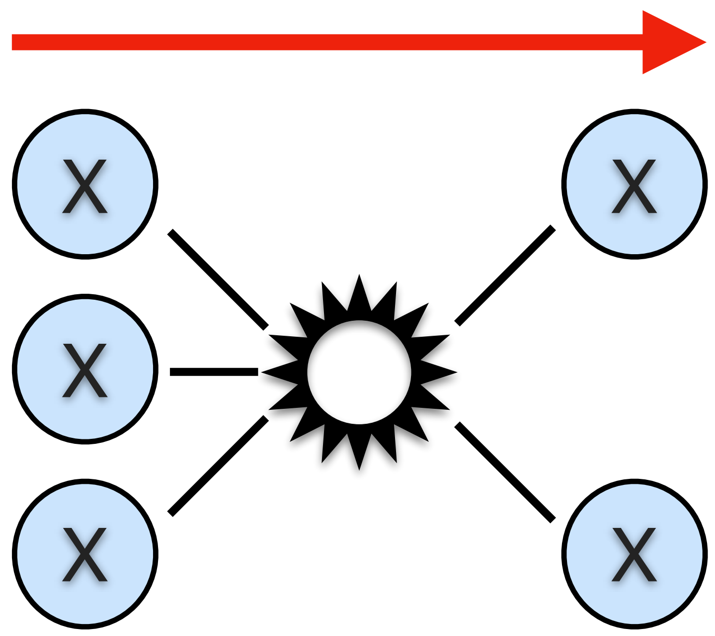
Carlson et al (1992), Hochberg et al (2014)

Annihilation Mechanism

- There are many new ways for thermal production
- **Self-annihilation** ($3X \to 2X$) can be a dominant channel

$$SIMP \;:\; \frac{dn_X}{dt} + 3Hn_X = -\langle \sigma v^2 \rangle (n_X^3 - n_X^2 n_{\rm eq})$$

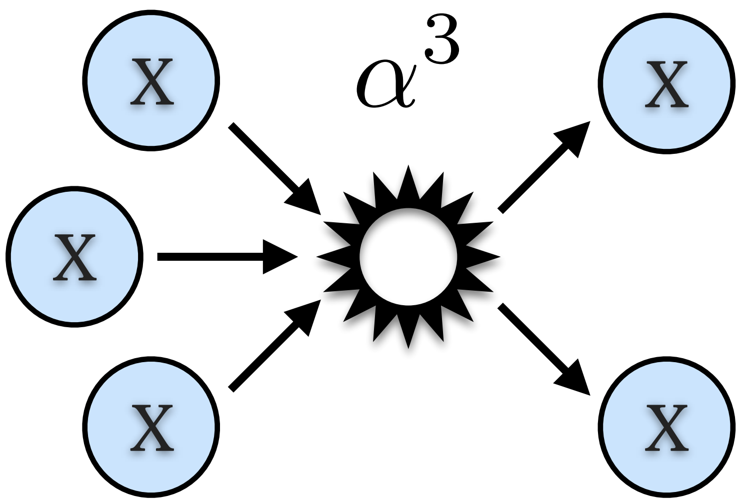




Carlson et al (1992), Hochberg et al (2014)

The SIMP Dark Matter

- **S**trongly **I**nteracting **M**assive **P**article
- Freeze-out process is $3X \to 2X$ **self-annihilation**

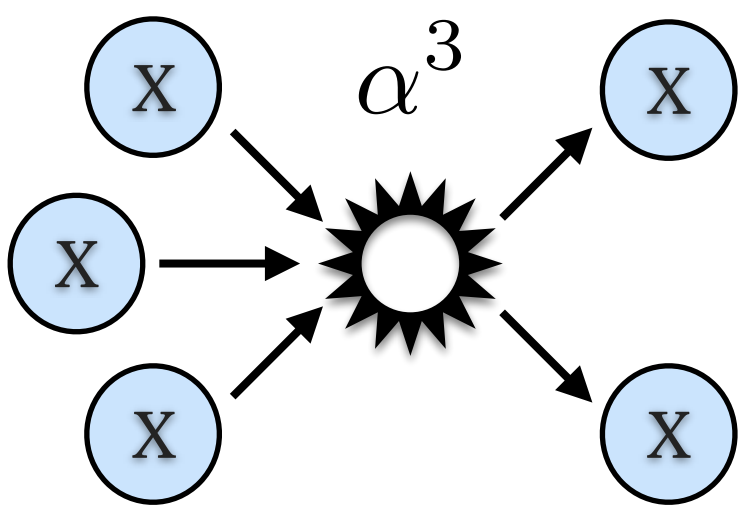


$$\Rightarrow \langle \sigma v^2 \rangle \propto \frac{\alpha^3}{m_X^5}$$

Hochberg et al (2014)

The SIMP Dark Matter

- **S**trongly **I**nteracting **M**assive **P**article
- Freeze-out process is $3X \to 2X$ **self-annihilation**
- **Light** dark matter : $m_X \sim \mathcal{O}(100 \text{ MeV}),\ \alpha \sim \mathcal{O}(0.1)$



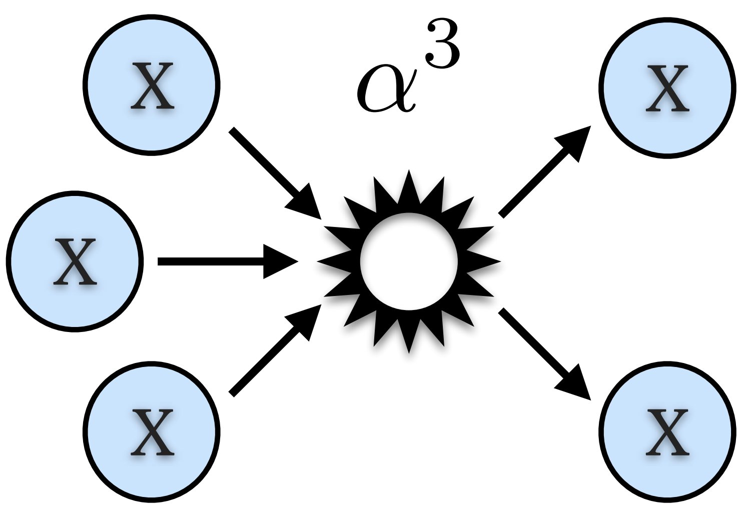
$$\Rightarrow \langle \sigma v^2 \rangle \propto \frac{\alpha^3}{m_X^5}$$

$$\Omega_X h^2 \propto (m_X^2 \langle \sigma v^2 \rangle)^{-1/2} \sim 0.12 \left(\frac{m_X}{\mathcal{O}(100 \text{ MeV})} \right)^{3/2} \left(\frac{\mathcal{O}(0.1)}{\alpha} \right)^{3/2}$$

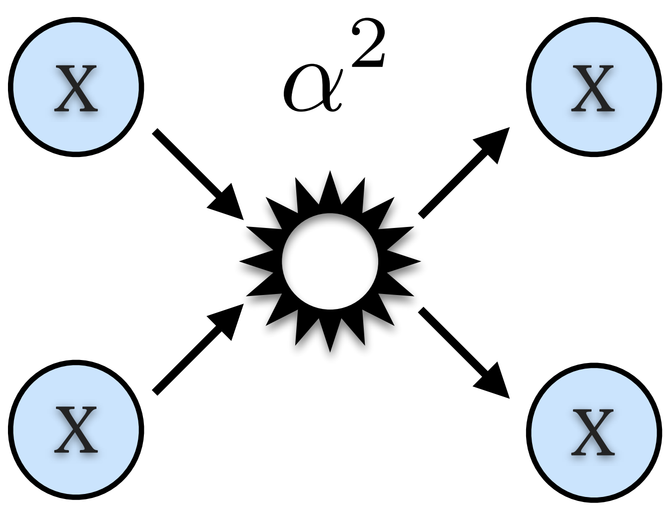
Hochberg et al (2014)

The SIMP Dark Matter

- **S**trongly **I**nteracting **M**assive **P**article
- Freeze-out process is $3X \to 2X$ **self-annihilation**
- **Light** dark matter : $m_X \sim \mathcal{O}(100\ \mathrm{MeV}),\ \alpha \sim \mathcal{O}(0.1)$
- SIMP is a good candidate of **Self-Interacting DM**



$$\Rightarrow \langle \sigma v^2 \rangle \propto \frac{\alpha^3}{m_X^5}$$



$$\Rightarrow \sigma_{\mathrm{self}} \propto \frac{\alpha^2}{m_X^2}$$

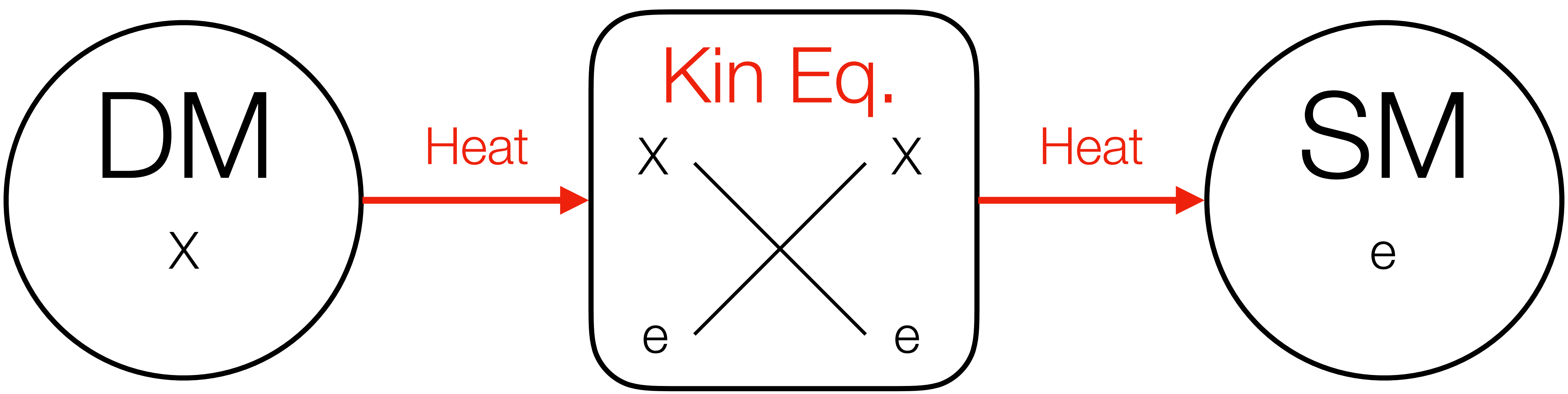
Hochberg et al (2014)

The SIMP Dark Matter

- Self-annihilation can break the structure formation
- **Kinetic equilibrium** with SM is essential

Temperature : ←

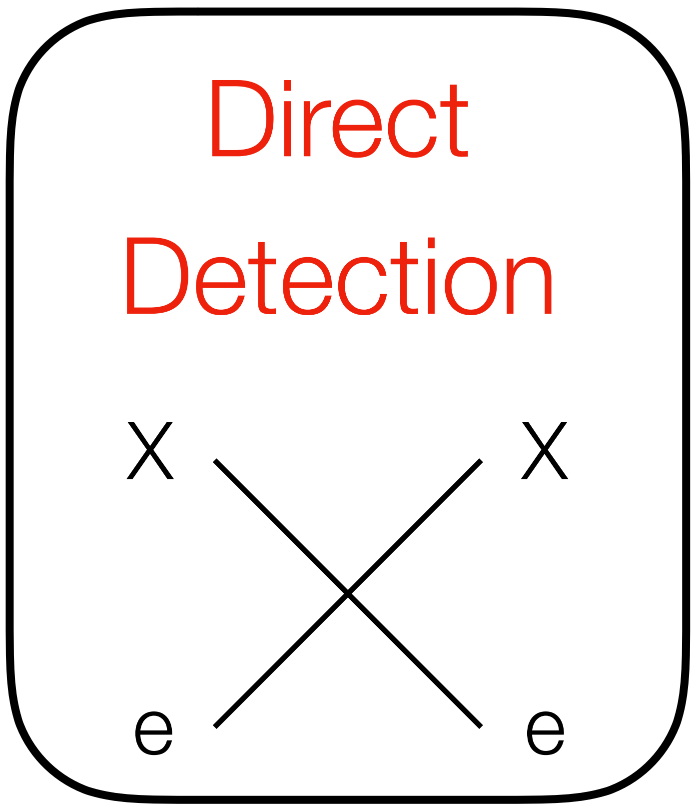
Decoupling : $2X \rightarrow 2SM$ $3X \rightarrow 2X$ $Xe \rightarrow Xe$

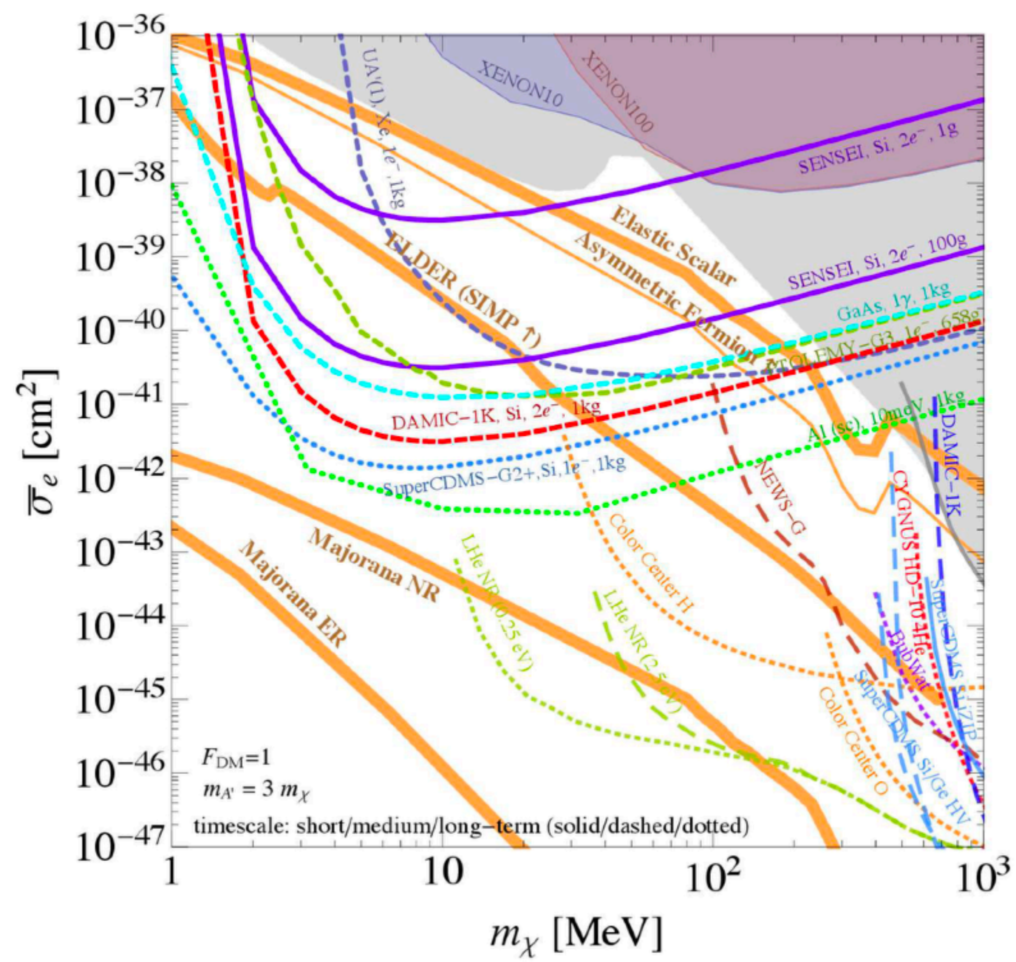


Hochberg et al (2014)

The SIMP Dark Matter

- Self-annihilation can break the structure formation
- **Kinetic equilibrium** with SM is essential
- Connection to SM for **Direct Detection**

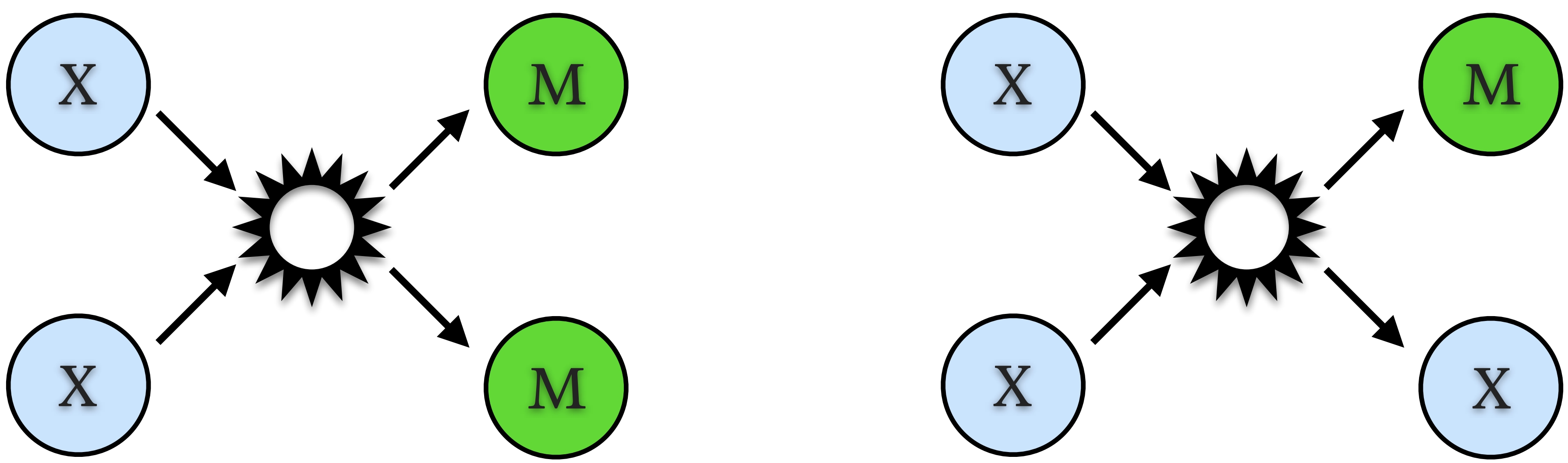




Hochberg et al (2014), US Cosmic Visions Community Report (2017)

Forbidden Channels in SIMP

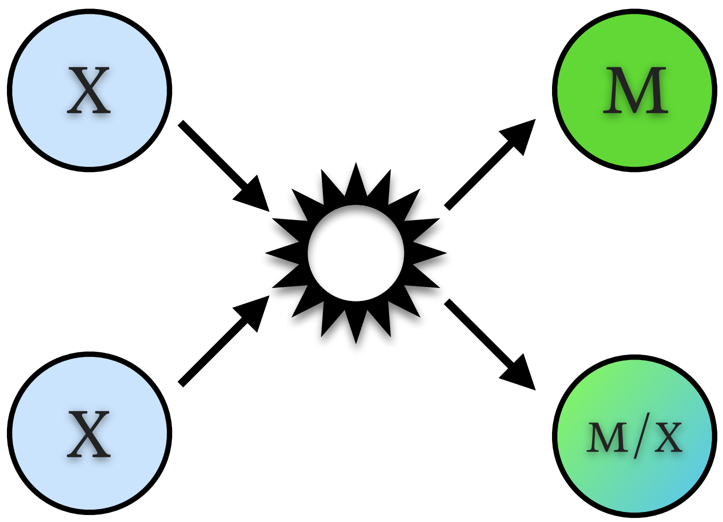
- When models have **light mediators** (Kin. Eq. with SM)
- It is forbidden in low temperature ($m_X < m_M$),
  but DMs **in thermal tail** can be annihilated to the mediators



R. T. D'Agnolo and J. T. Ruderman (2015), SMC, Y. J. Kang and H. M. Lee (2016)

Forbidden Channels in SIMP

- When models have **light mediators** (Kin. Eq. with SM)
- It is forbidden in low temperature ($m_X < m_M$),
  but DMs **in thermal tail** can be annihilated to the mediators
- FB channels : **comparable to SIMP** ($\Delta \equiv (m_M - m_X)/m_X$)



$$\frac{\Gamma_{3\to 2}}{\Gamma_{\rm FB}} = \frac{n_X^2 \langle \sigma v^2 \rangle_{3\to 2}}{n_X \langle \sigma v \rangle_{\rm FB}}$$

$$\sim e^{(2\Delta - 1)m_X/T} \text{ or } e^{(\Delta-1)m_X/T}$$

R. T. D'Agnolo and J. T. Ruderman (2015), SMC, Y. J. Kang and H. M. Lee (2016)

$SU(2)_X$ Vector SIMP Models

- DM = $SU(2)_X$ **gauge bosons**

$$\boxed{\begin{array}{c} SU(2)_X \\ X_\mu \text{ (DM)} \\ H_X \text{ (vev)} \end{array}} \times \boxed{\begin{array}{c} U(1)_{Z'} \\ Z'_\mu \\ S \text{ (vev)} \end{array}}$$

$$\mathscr{L} = -\frac{1}{4}\vec{X}_{\mu\nu}\cdot\vec{X}^{\mu\nu} - \frac{1}{2}\sin\xi\, Z'_{\mu\nu}B^{\mu\nu} + \lambda_{HH_X}|H|^2|H_X|^2 + \dots$$

$$\vec{X}_{\mu\nu} = \partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu + g_X(\vec{X}_\mu\times\vec{X}_\nu), \quad D_\mu = \partial_\mu - ig_X\vec{t}\cdot\vec{X}_\mu - ig_{Z'}q_{Z'}Z'_\mu$$

N. Bernal, X. Chu, C. Garcia-Cely, T. Hambye and B. Zaldivar (2015)

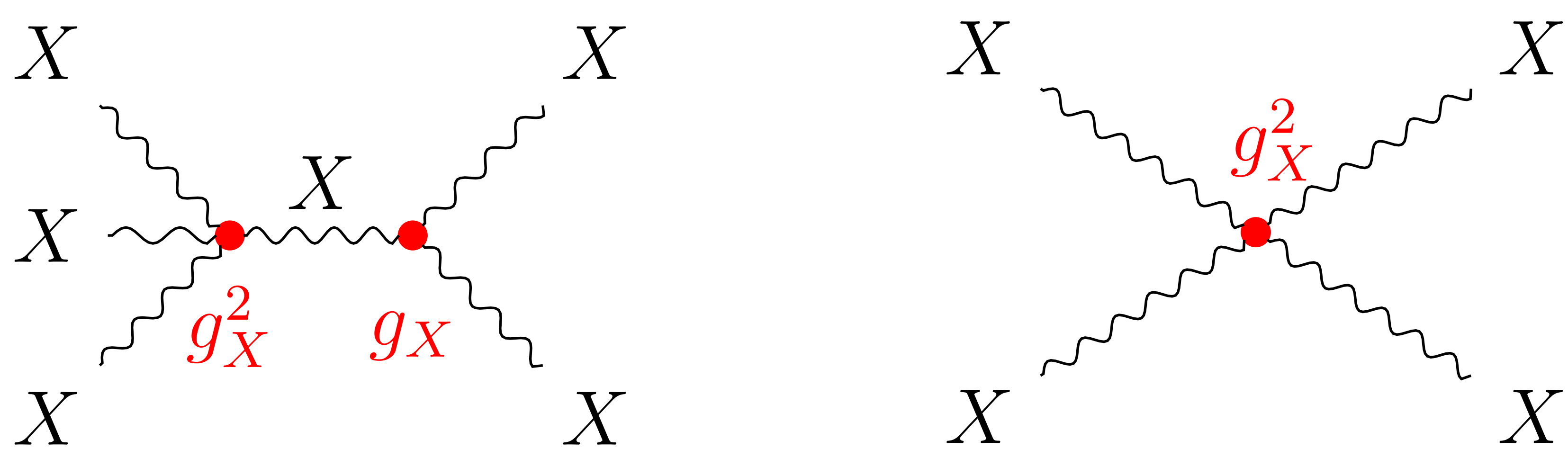
SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

$SU(2)_X$ Vector SIMP Models

- DM = $SU(2)_X$ **gauge bosons**
- **Economical** SIMP and SIDM

$$\mathscr{L} = -\frac{1}{4}\vec{X}_{\mu\nu}\cdot\vec{X}^{\mu\nu}+\ldots\ , \quad \vec{X}_{\mu\nu} = \partial_\mu\vec{X}_\nu - \partial_\nu\vec{X}_\mu + g_X(\vec{X}_\mu\times\vec{X}_\nu)$$



N. Bernal, X. Chu, C. Garcia-Cely, T. Hambye and B. Zaldivar (2015)

SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

$SU(2)_X$ Vector SIMP Models

- Dark custodial symmetry (**dark Higgs representation**)

$$\frac{m_{X^\pm}^2}{m_{X_3}^2} = \frac{1}{2I}$$

$I = 1/2$: Degenerate

SMC, Y. Hochberg, E. Kuflik, H. M. Lee,
Y. Mambrini, H. Murayama and M. Pierre (2017)

$I = 1,\ 3/2,\ 2$: Non-Degenerate

SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

$$m_{X^\pm}^2 = \frac{1}{2} g_X^2 I v_X^2, \quad m_{X_3}^2 = g_X^2 I^2 v_X^2, \quad I : \text{Isospin}$$

(H_X Rep.)

$SU(2)_X$ Vector SIMP Models

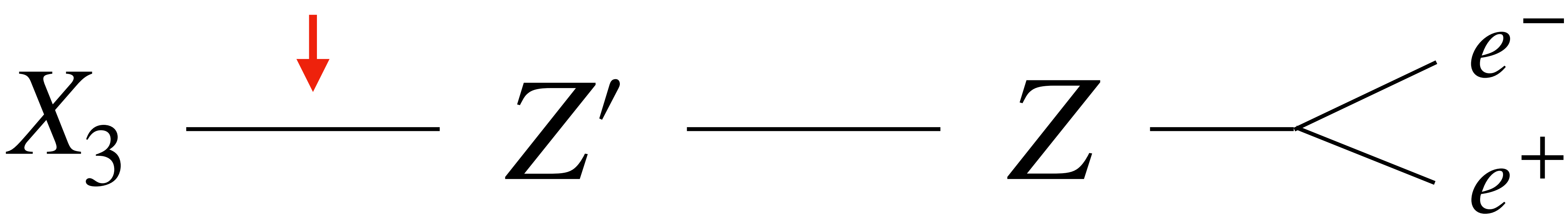
- Dark custodial symmetry (**dark Higgs representation**)

$$\frac{m^2_{X^\pm}}{m^2_{X_3}} = \frac{1}{2I} \longrightarrow$$

$I = 1/2$: Degenerate

SMC, Y. Hochberg, E. Kuflik, H. M. Lee,
Y. Mambrini, H. Murayama and M. Pierre (2017)

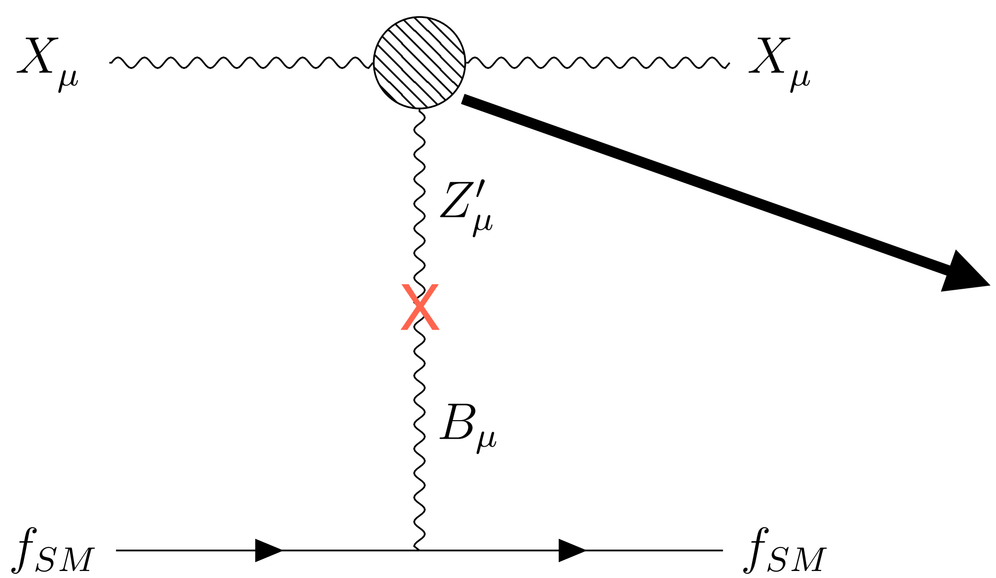
- Accidental $SO(3)$ custodial symmetry preserves DM stability
- No dark Weinberg angle



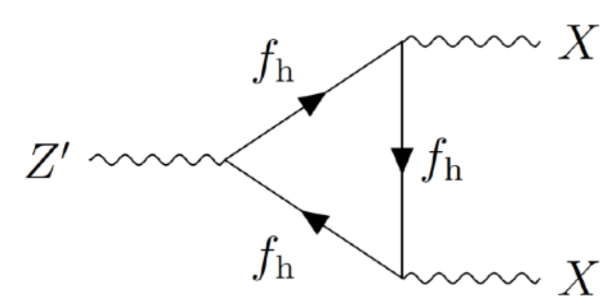
$SU(2)_X$ Vector SIMP Models

- Dark custodial symmetry (**dark Higgs representation**)
- kinetic equilibrium : **No Weinberg angle** (Chern-Simons term)

$$\mathscr{L}_{\rm CS} \; = \; c\epsilon^{\mu\nu\rho\sigma} Z'_\mu \overrightarrow{X}_\nu \cdot (\partial_\rho \overrightarrow{X}_\sigma - \partial_\sigma \overrightarrow{X}_\rho)$$



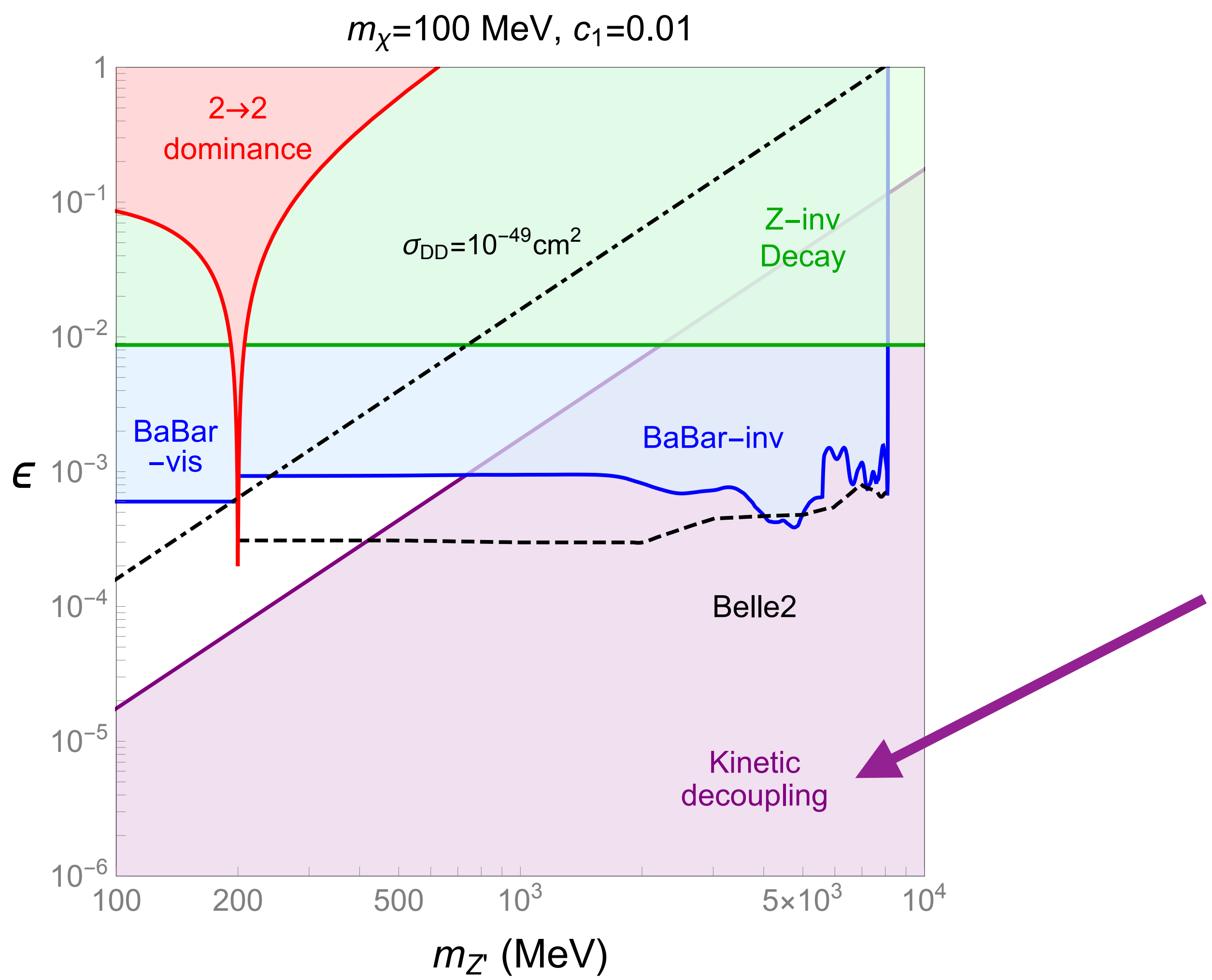
From heavy fermion loop



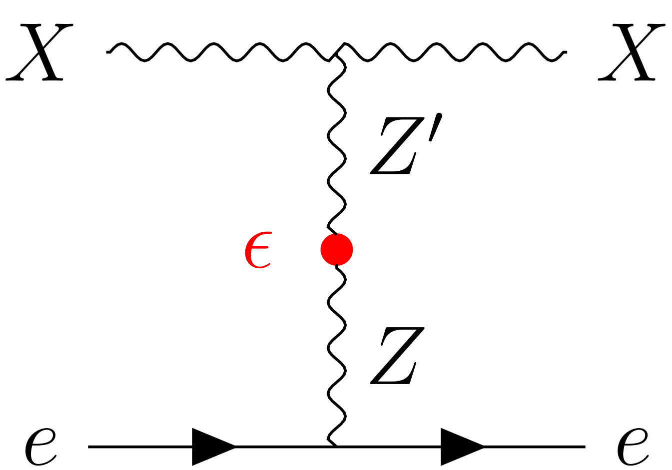
SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

Kinetic Equilibrium (Vector Portal)

- Kinetic scattering with Chern-Simons term and **Vector portal**
- The momentum transferring rate for scattering ($\dot{K}_{\rm el}$) must be larger than the releasing kinetic energy rate in dark sector ($\dot{K}_{3\to 2}$)



$$\dot{K}_{3\to 2} \lesssim \dot{K}_{\rm el}$$

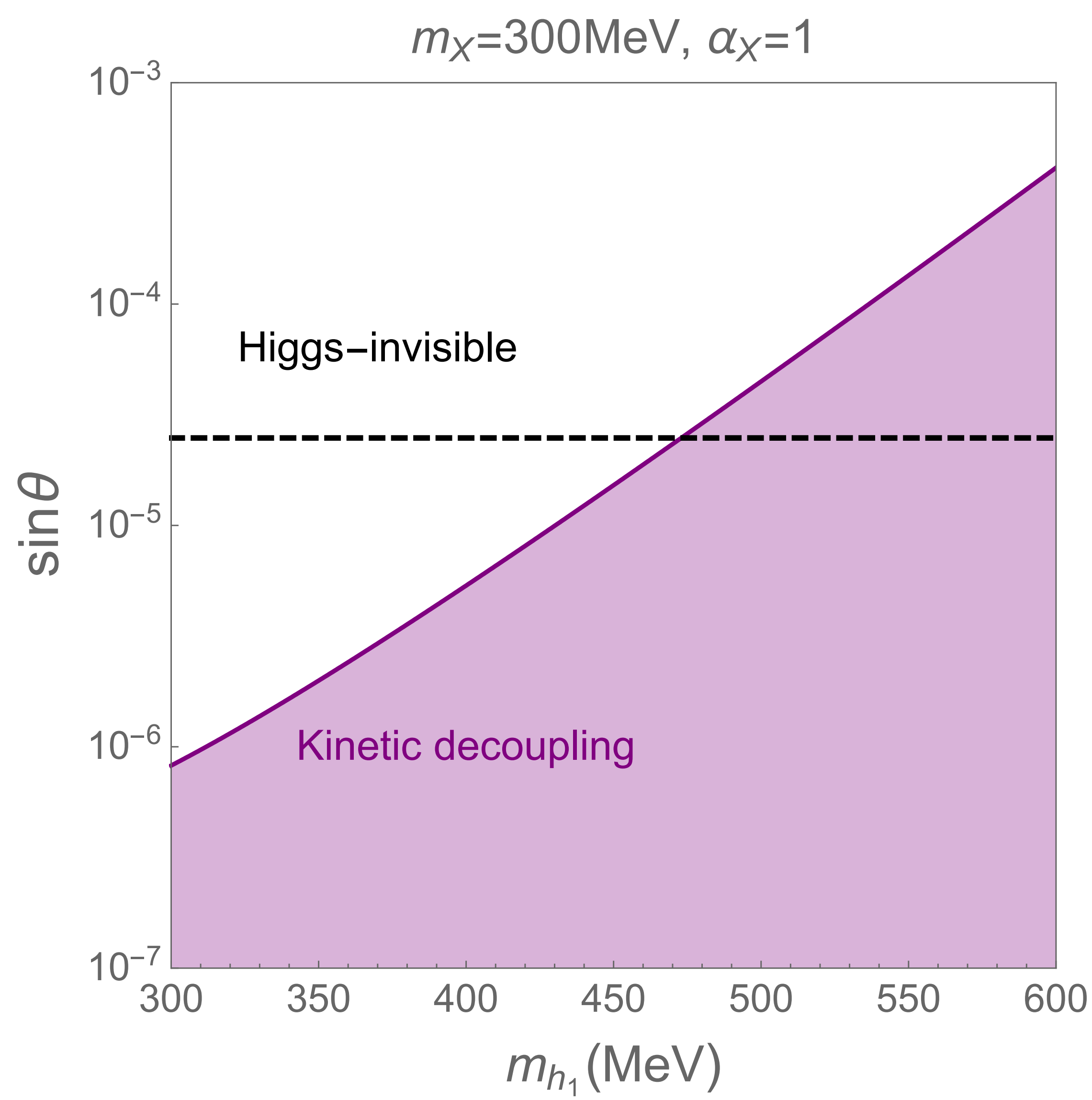


P. Gondolo and K. Kadota (2016)

SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

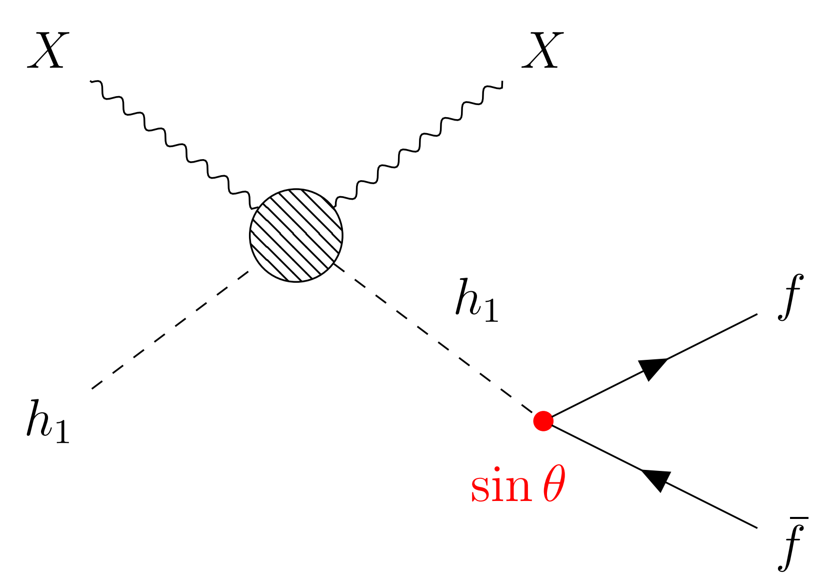
Kinetic Equilibrium (Higgs Portal)

- Scattering via Higgs portal is not enough (Bernal et al, 2015)
- **Higgs portal** is important for Kin. Eq. with **decaying to SM**



$$(n_{h_1}^{\rm eq}/n_X^{\rm eq}) \cdot \Gamma_{h_1 \to {\rm SM}} \gtrsim H$$

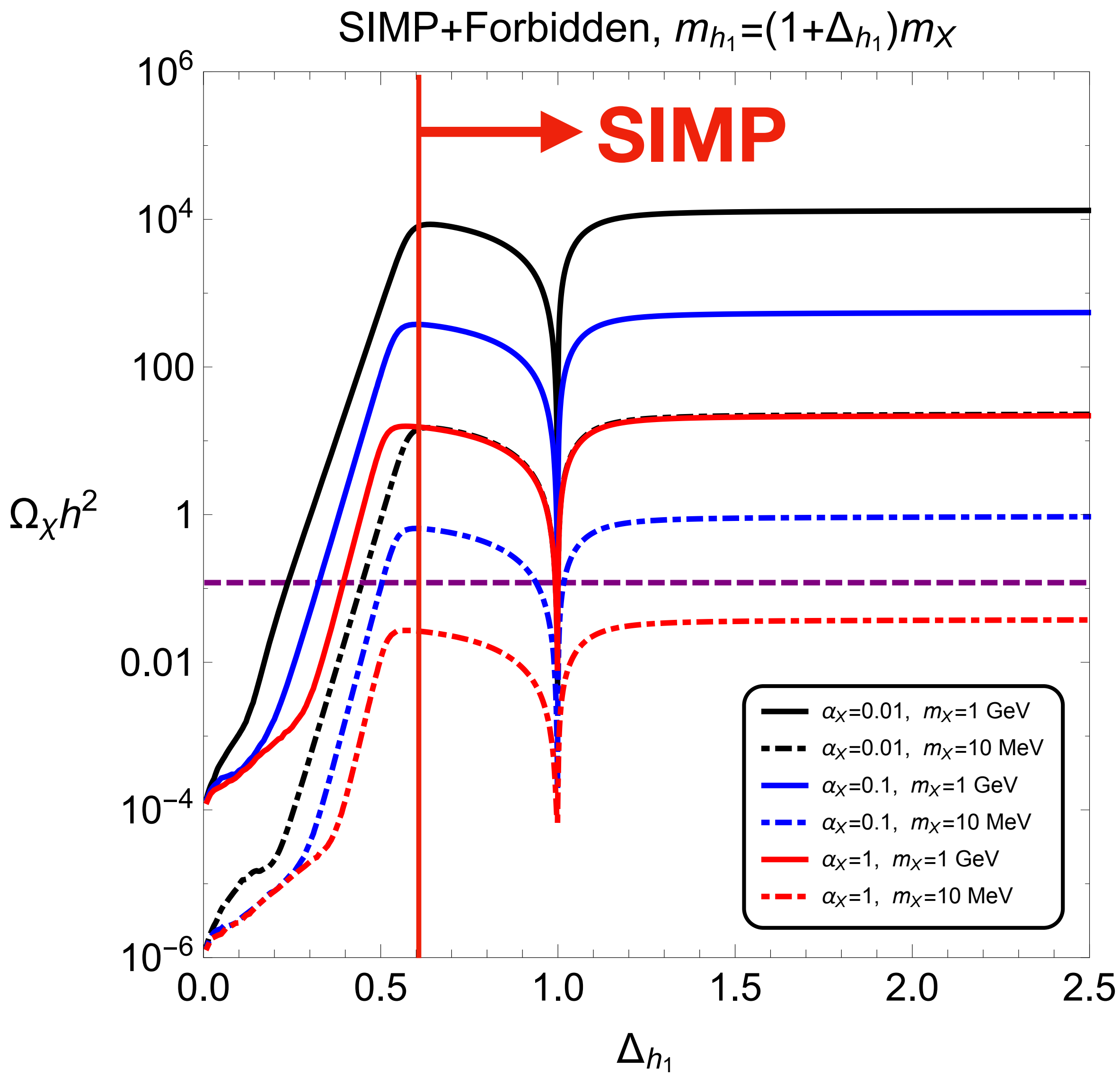
@ Freeze-out



SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

Doublet Representation

- **Relic density** from the **SIMP & Forbidden** channels
- SIMP is dominant for $m_{h_1} \gtrsim 1.6 m_X$ ($\Delta_{h_1} \equiv (m_{h_1} - m_X)/m_X$)



$$\frac{\Gamma_{3X\to 2X}}{\Gamma_{XX\to Xh_1}} \approx e^{(\Delta_{h_1}-1)m_X/T}$$

with resonance @ $m_{h_1} = 2m_X$ in SIMP

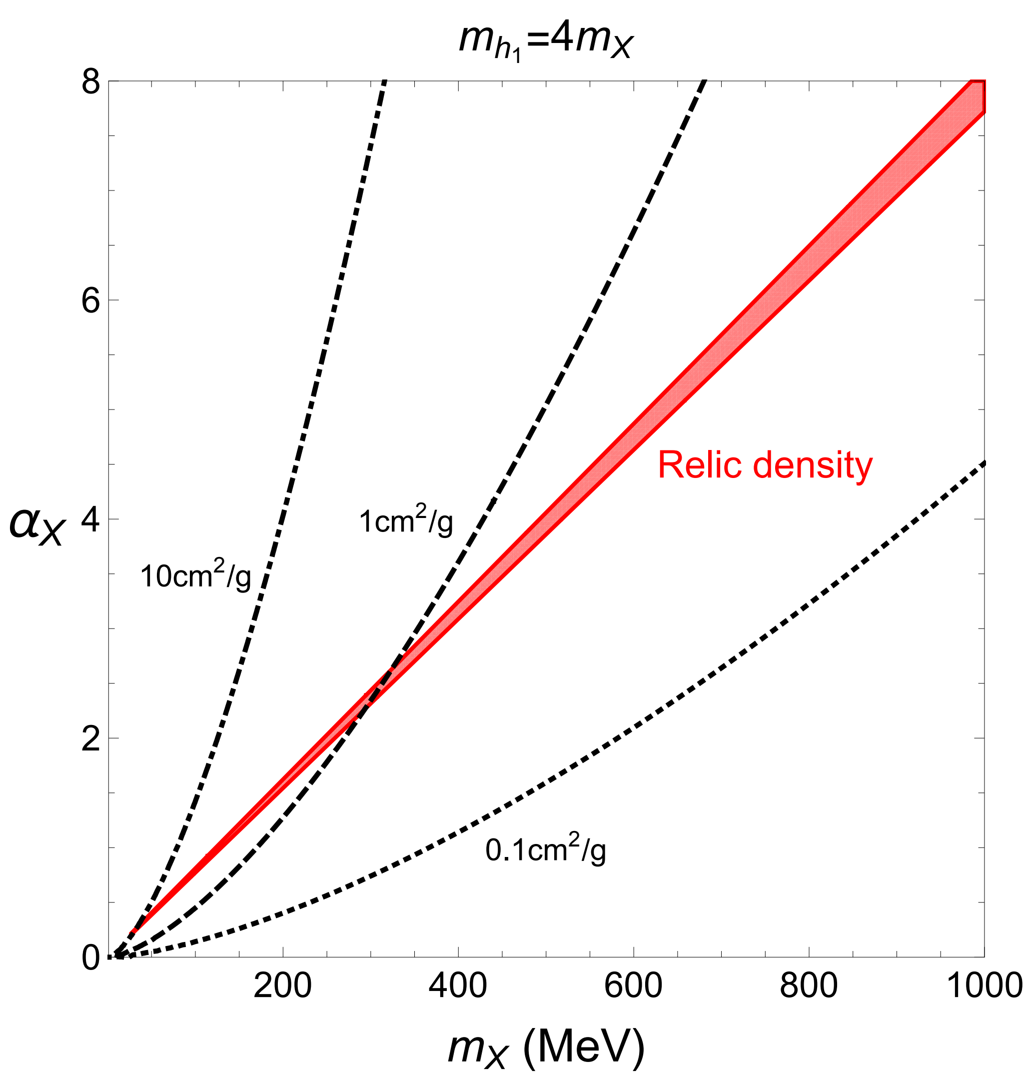
$$\langle \sigma v^2 \rangle_{3X\to 2X} \approx \frac{\alpha_X^3}{m_X^5}$$

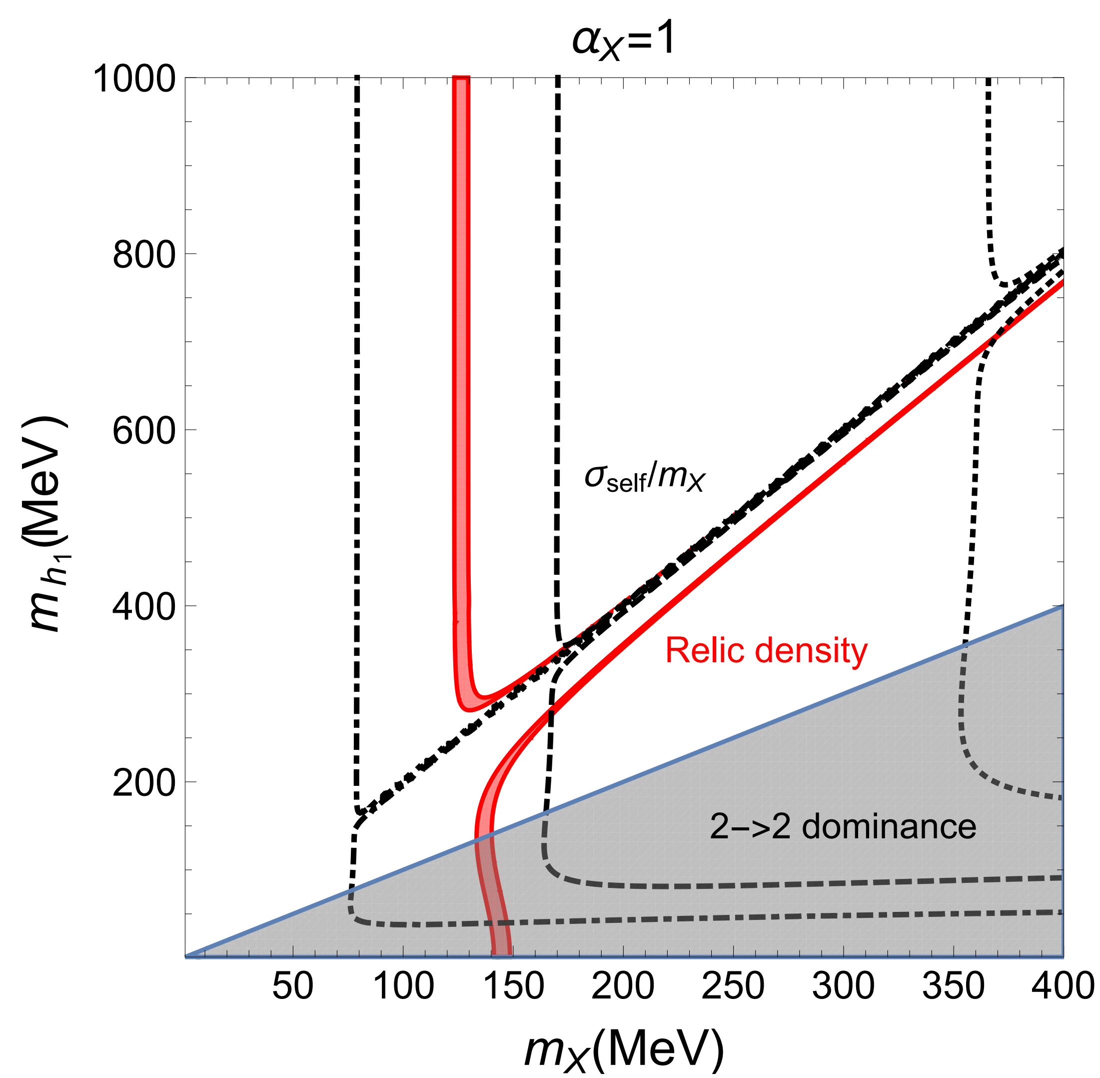
@ $m_{h_1} \gg m_X$

SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

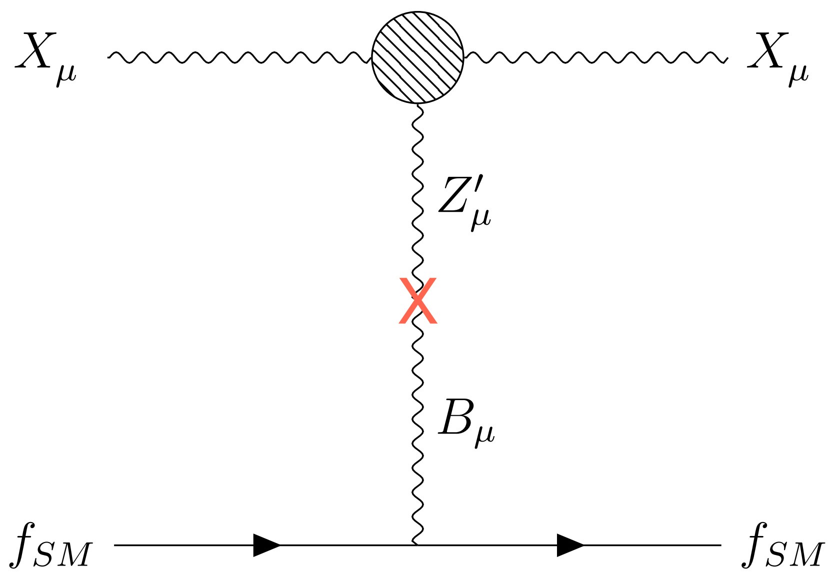
Relic and Self-Interaction

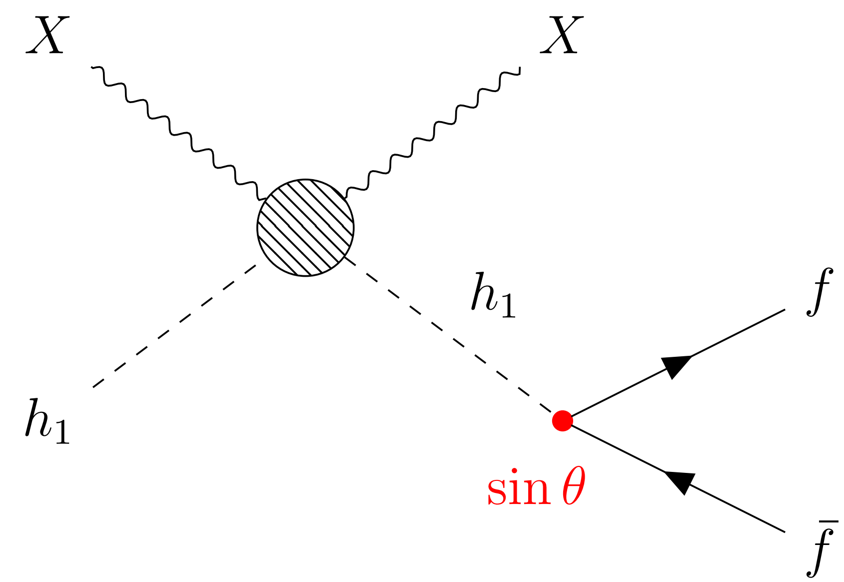
- To be SIDM, large coupling or resonance effect is important
- Perturbativity is questionable : Higgs-QCD Complementarity

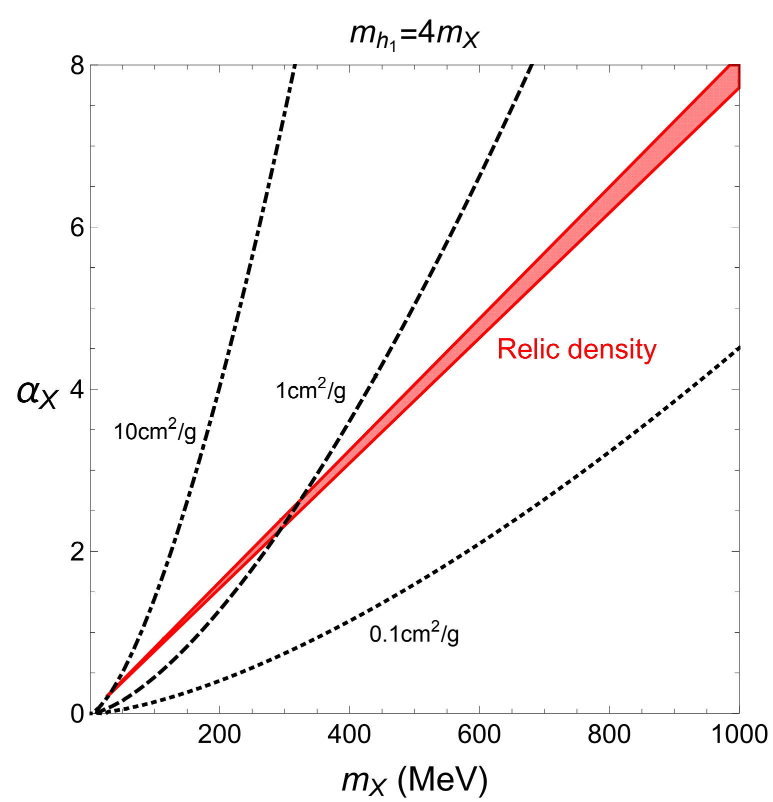


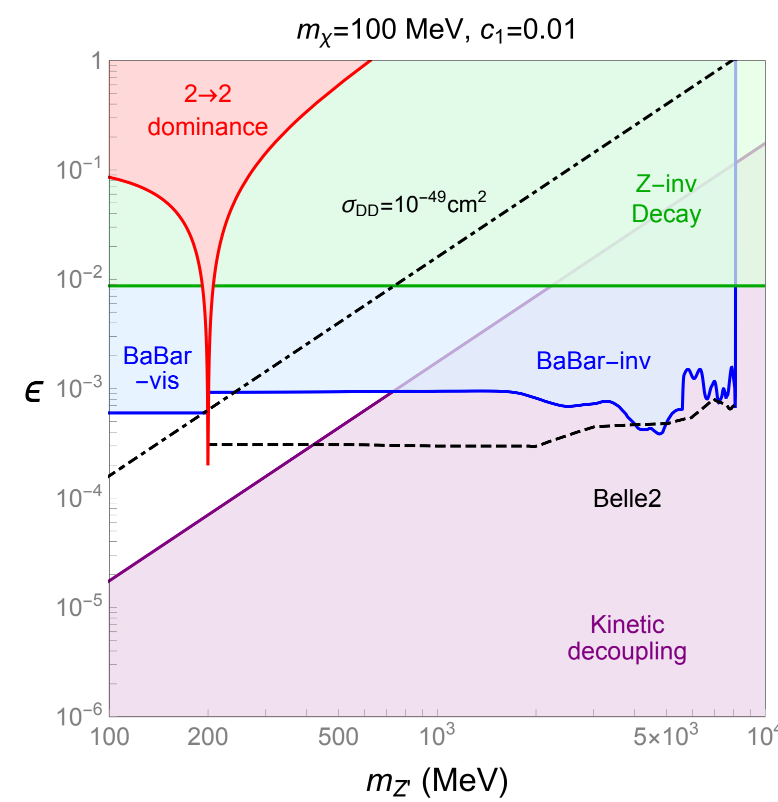


SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)


X_μ
X_μ
Z'_μ
X
B_μ
f_{SM}
f_{SM}


X
X
h_1
h_1
f
$\bar{f}$
$\sin\theta$


m_{h_1}=4m_X
α_X
m_X (MeV)
0
2
4
6
8
200
400
600
800
1000
10cm^2/g
1cm^2/g
0.1cm^2/g
Relic density


m_X=100 MeV, c_1=0.01
ϵ
$m_{Z'}$ (MeV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
100
200
500
10^3
5×10^3
10^4
2→2
dominance
σ_{DD}=10^{-49}cm^2
Z–inv
Decay
BaBar
–vis
BaBar–inv
Belle2
Kinetic
decoupling

$SU(2)_X$ Vector SIMP Models

- Dark custodial symmetry (**dark Higgs representation**)

$$\frac{m_{X^\pm}^2}{m_{X_3}^2} = \frac{1}{2I}$$

$I = 1/2$: Degenerate

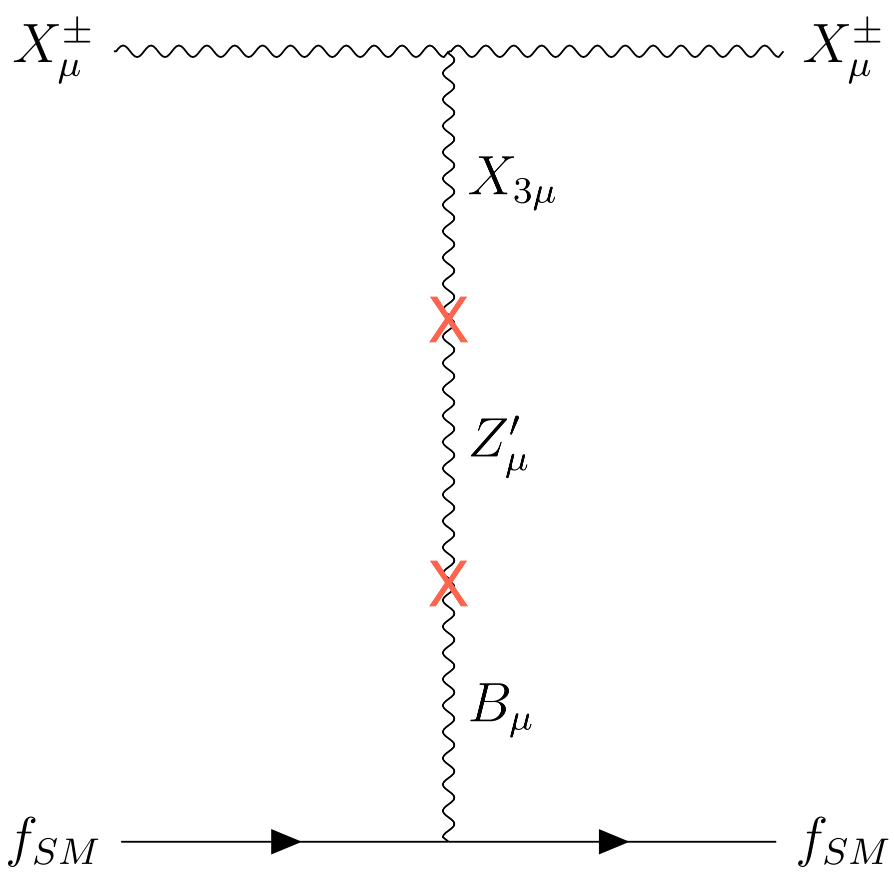
SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

$I = 1,\ 3/2,\ 2$: Non-Degenerate

SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

$SU(2)_X$ Vector SIMP Models

- Dark custodial symmetry (**dark Higgs representation**)
- kinetic equilibrium : **Weinberg angle** (Broken custodial sym.)



$$m_{\tilde{X}_3} \lesssim \sqrt{2I}\, m_X \lesssim m_{\tilde{Z}'}$$

- Natural light mediators
- Renormalizable Interaction

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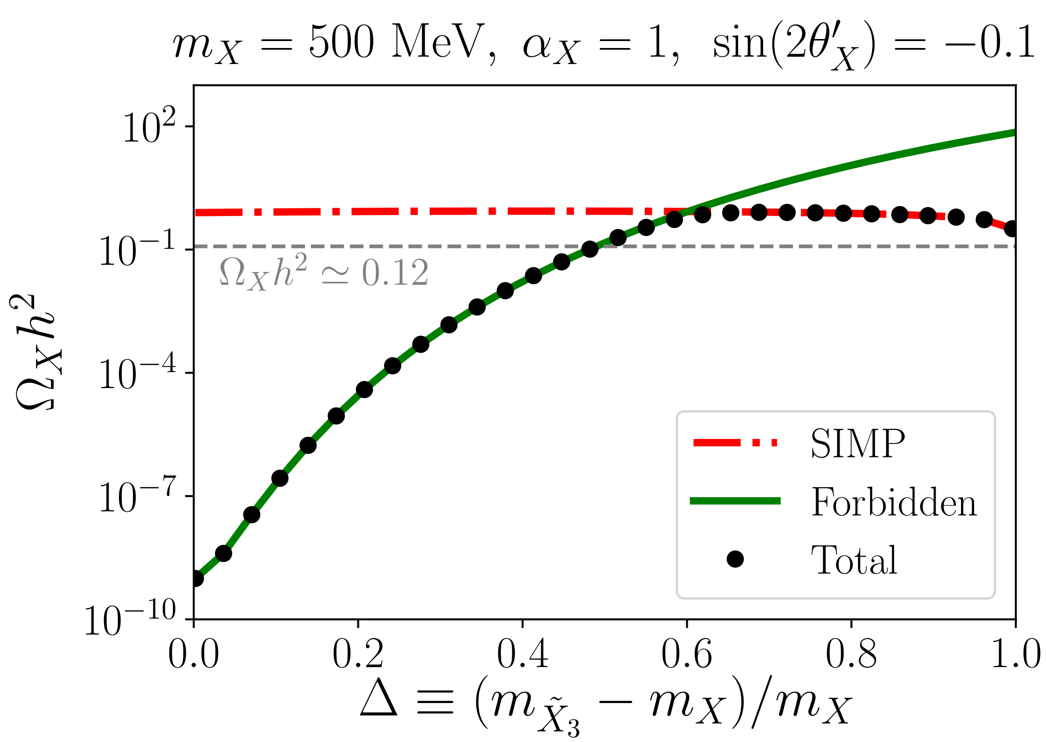
General Representations

- **Relic density** from the **SIMP & Forbidden** channels
- SIMP is dominant for $m_{\tilde{X}_3} \sim \sqrt{2I}\, m_X \gtrsim 1.6 m_X \rightarrow I = 3/2,\ 2$

SIMP : $X^+X^+X^- \rightarrow X^+\tilde{X}_3$

Forbidden : $X^+X^- \rightarrow \tilde{X}_3\tilde{X}_3$



SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

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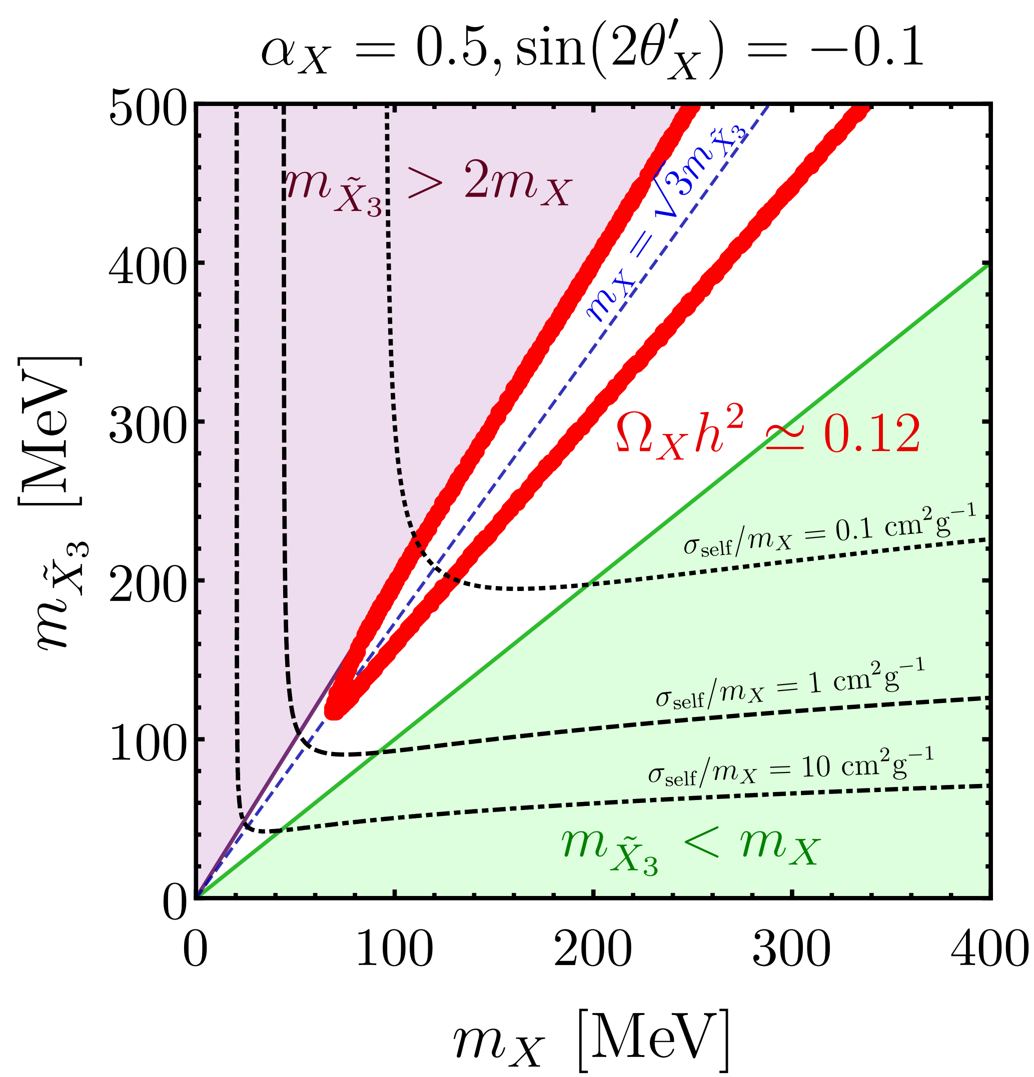

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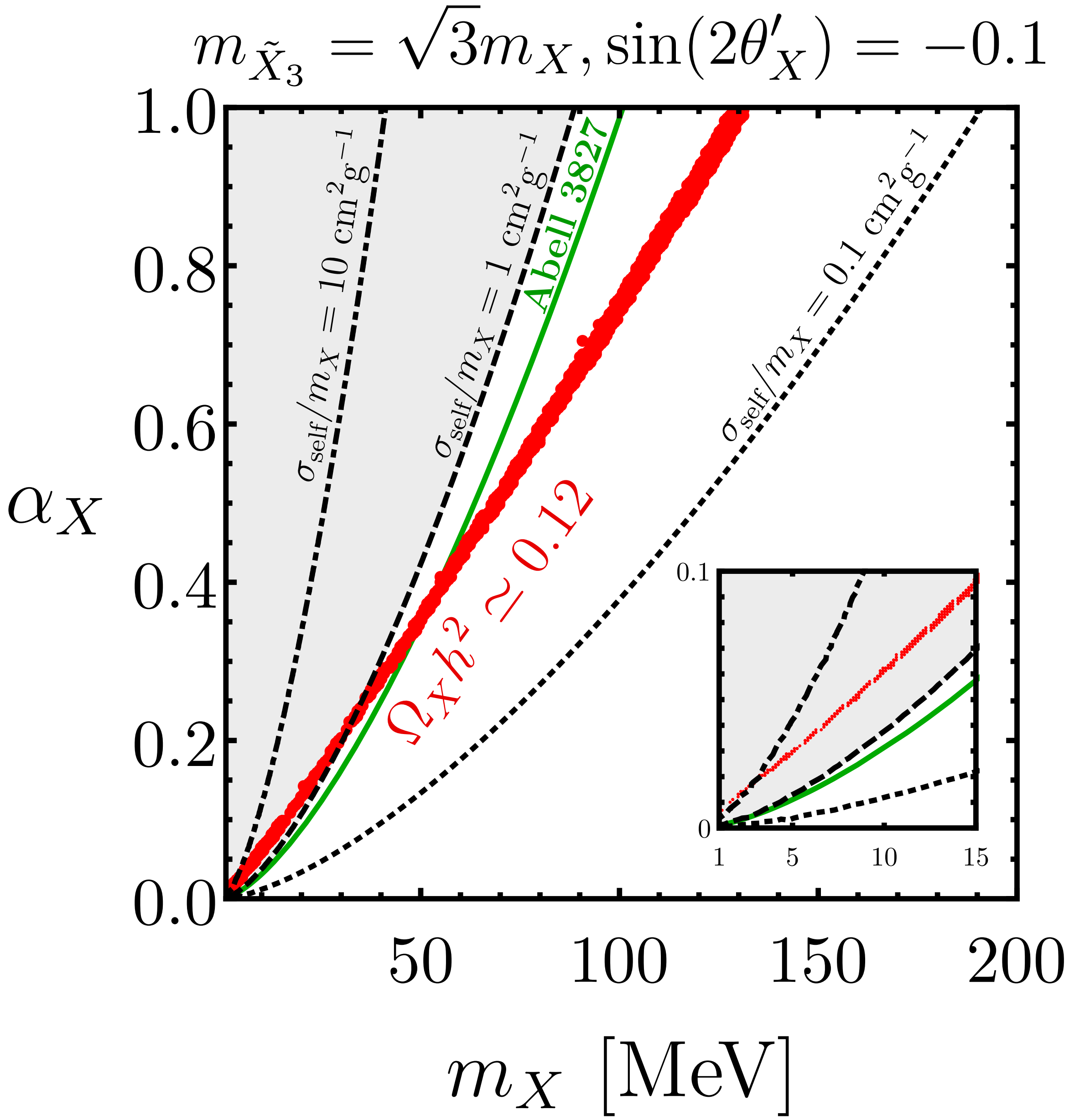
Quadruplet Representation

- VSIMP with dark Weinberg angle is a good **SIDM**



Cluster & Small-Scale bounds

$$0.1\ \mathrm{cm^2/g} \leq \frac{\sigma_{\rm self}}{m_X} \leq 1\ \mathrm{cm^2/g}$$

Abell-3827

Kahlhoefer et al (2015), Massey et al (2015)

$$\frac{\sigma_{\rm self}}{m_X} \cos\theta_i = 0.68^{+0.28}_{-0.29}\ \mathrm{cm^2/g}$$

θ_i : Inclination angle, uncertain
(Massey et al, 2017)

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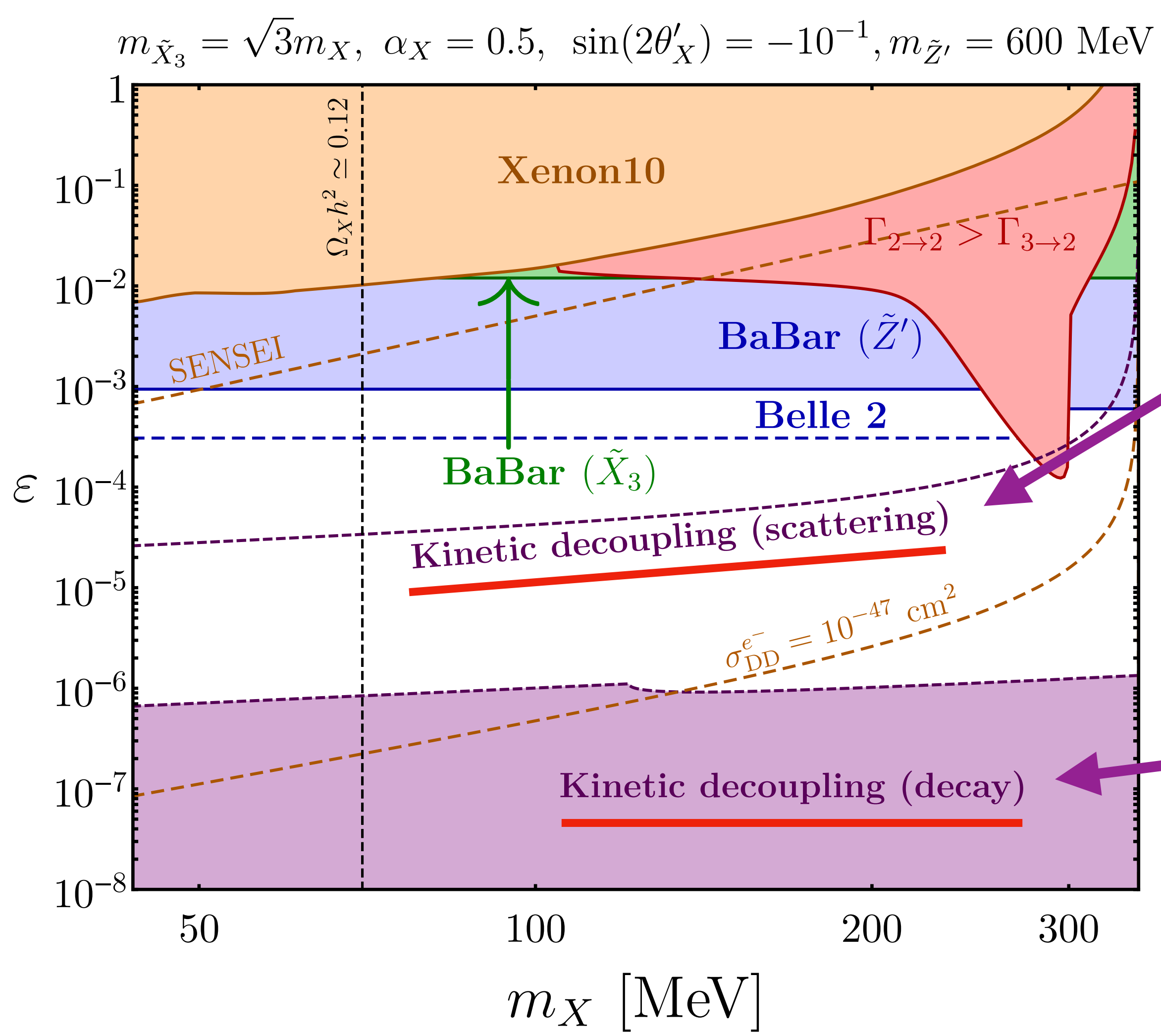
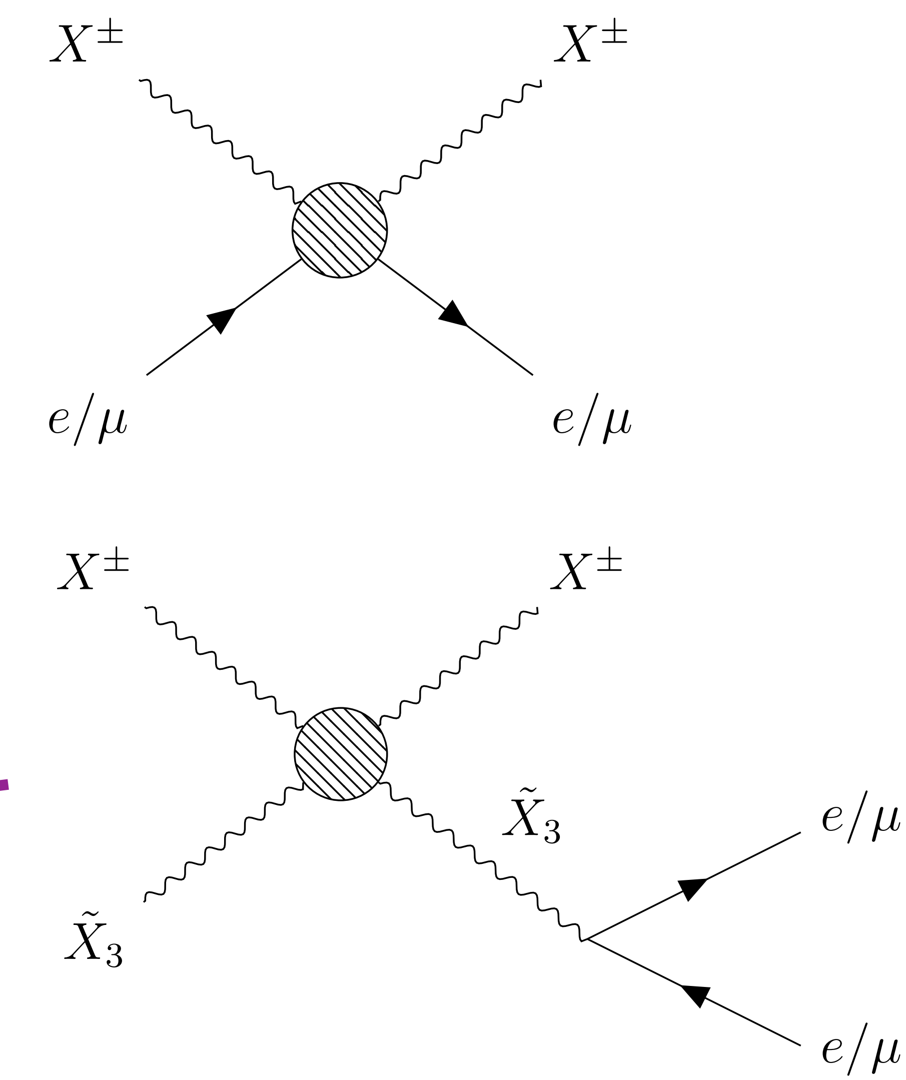
Experimental Constraints

- Constraints :
  SIMP conditions / Direct detection (X-e) / (In-)Visible searches
- **Decay of mediator** is important for the kinetic equilibrium





SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)

Conclusion

- We have proposed a new VSIMP model in the context of dark $SU(2)_X \times U(1)_{Z'}$ gauge theory.
- The mass splitting b/w DM and neutral component are predicted by an approximate custodial symmetry.
- The kinetic equilibrium for VSIMP is maintained thanks to a gauge kinetic mixing with a renormalizable interactions.
- We showed a testing ground for searches for light mediators of order GeV scale or below at current and future collider and direct detection experiments.

Kinetic Equilibrium

- The releasing kinetic energy rate

$$\dot{K}_{3\to 2} = m_{\rm DM}\frac{\dot{n}_{\rm DM}}{n_{\rm DM}} \simeq -m_{\rm DM}^2 H T^{-1}.$$

- The momentum transferring rate

$$\dot{K}_{\rm el} = \frac{1}{2E_p}\sum_i \frac{g_i d^3k_i}{(2\pi)^3 2E_i}\frac{d^3k_i'}{(2\pi)^3 2k_i'}\frac{d^3p'}{(2\pi)^3 2p'}\delta^4(p+k_i-p'-k_i')\overline{|\mathcal{M}|^2}\left(E_p - E_{p'}\right)$$

P. Gondolo and K. Kadota (2016)

SMC, Y. Hochberg, E. Kuflik, H. M. Lee, Y. Mambrini, H. Murayama and M. Pierre (2017)

Dark Higgs Representation

Quadruplet Higgs bosons:

For the quadruplet Higgs $Q_4 = \left(h^{(3)}, h^{(2)}, 0, \frac{1}{\sqrt{2}}(v_{Q_4} + h_{Q_4})\right)^T$ with

$$v_{Q_4} = \frac{2m_{Q_4}}{\sqrt{4\lambda_{Q_4} - 9\tilde{\lambda}_{Q_4}}},$$

the masses of dark-charged and neutral Higgs bosons are

$$\begin{aligned} m^2_{h^{(2)}} &= 3\tilde{\lambda}_{Q_4} v^2_{Q_4} - \frac{1}{2}\lambda_{Q_4H} v^2 \\ m^2_{h^{(3)}} &= \frac{9}{2}\tilde{\lambda}_{Q_4} v^2_{Q_4} - \frac{1}{2}\lambda_{Q_4H} v^2, \\ m^2_{h_{Q_4}} &= \left(2\lambda_{Q_4} - \frac{9}{2}\tilde{\lambda}_{Q_4}\right) v^2_{Q_4} - \frac{1}{2}\lambda_{Q_4H} v^2. \end{aligned}$$

Quintuplet Higgs bosons:

For the quintuplet Higgs $Q_5 = \left(h^{(4)}, h^{(3)}, h^{(2)}, 0, \frac{1}{\sqrt{2}}(v_{Q_5} + h_{Q_5})\right)^T$ with

$$v_{Q_5} = \frac{m_{Q_5}}{\sqrt{\lambda_{Q_5} - 4\tilde{\lambda}_{Q_5}}},$$

the masses of dark-charged and neutral Higgs are

$$\begin{aligned} m^2_{h^{(2)}} &= 4\tilde{\lambda}_{Q_5} v^2_{Q_5} - \frac{1}{2}\lambda_{Q_5H} v^2, \\ m^2_{h^{(3)}} &= 6\tilde{\lambda}_{Q_5} v^2_{Q_5} - \frac{1}{2}\lambda_{Q_5H} v^2, \\ m^2_{h^{(4)}} &= 8\tilde{\lambda}_{Q_5} v^2_{Q_5} - \frac{1}{2}\lambda_{Q_5H} v^2, \\ m^2_{h_{Q_5}} &= 2\left(\lambda_{Q_5} - 4\tilde{\lambda}_{Q_5}\right) v^2_{Q_5} - \frac{1}{2}\lambda_{Q_5H} v^2. \end{aligned}$$

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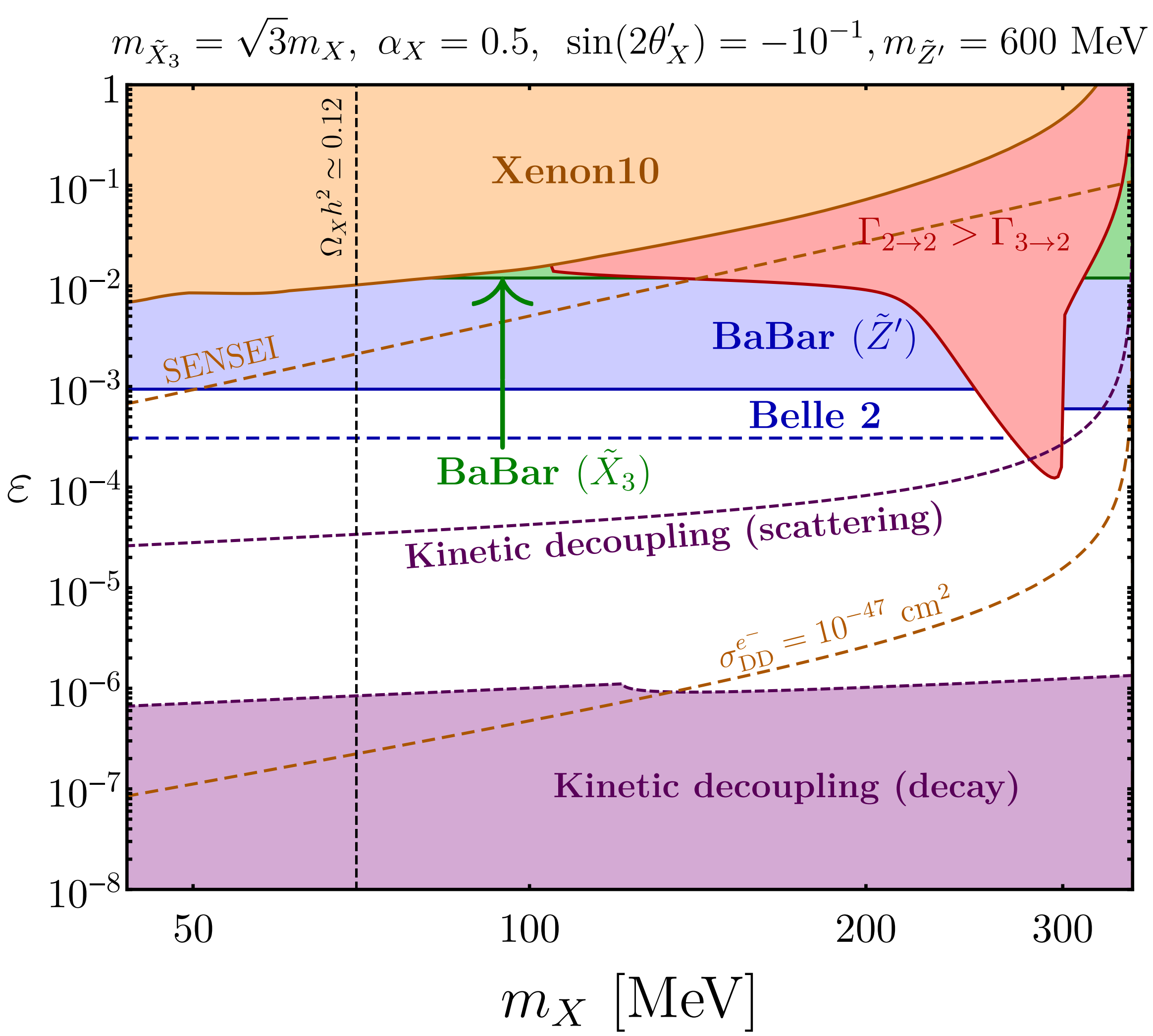
Experimental Constraints

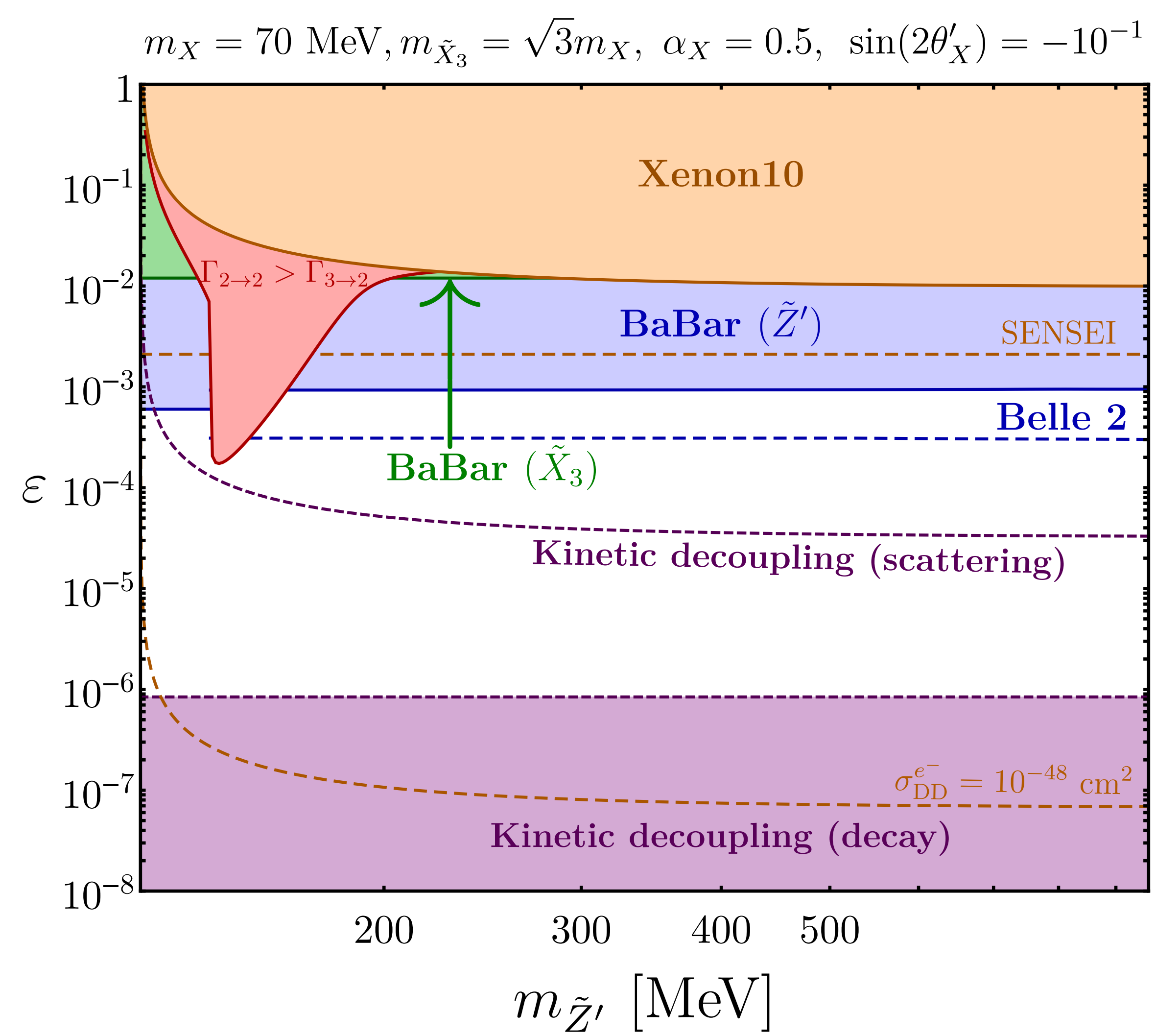
- Constraints

  SIMP conditions : $3 \to 2$ dominance / kinetic equilibrium

  Direct detection (X-e) : Xenon10 / SENSEI-100 1yr (projected)

  Visible / Invisible searches : BaBar / Belle 2





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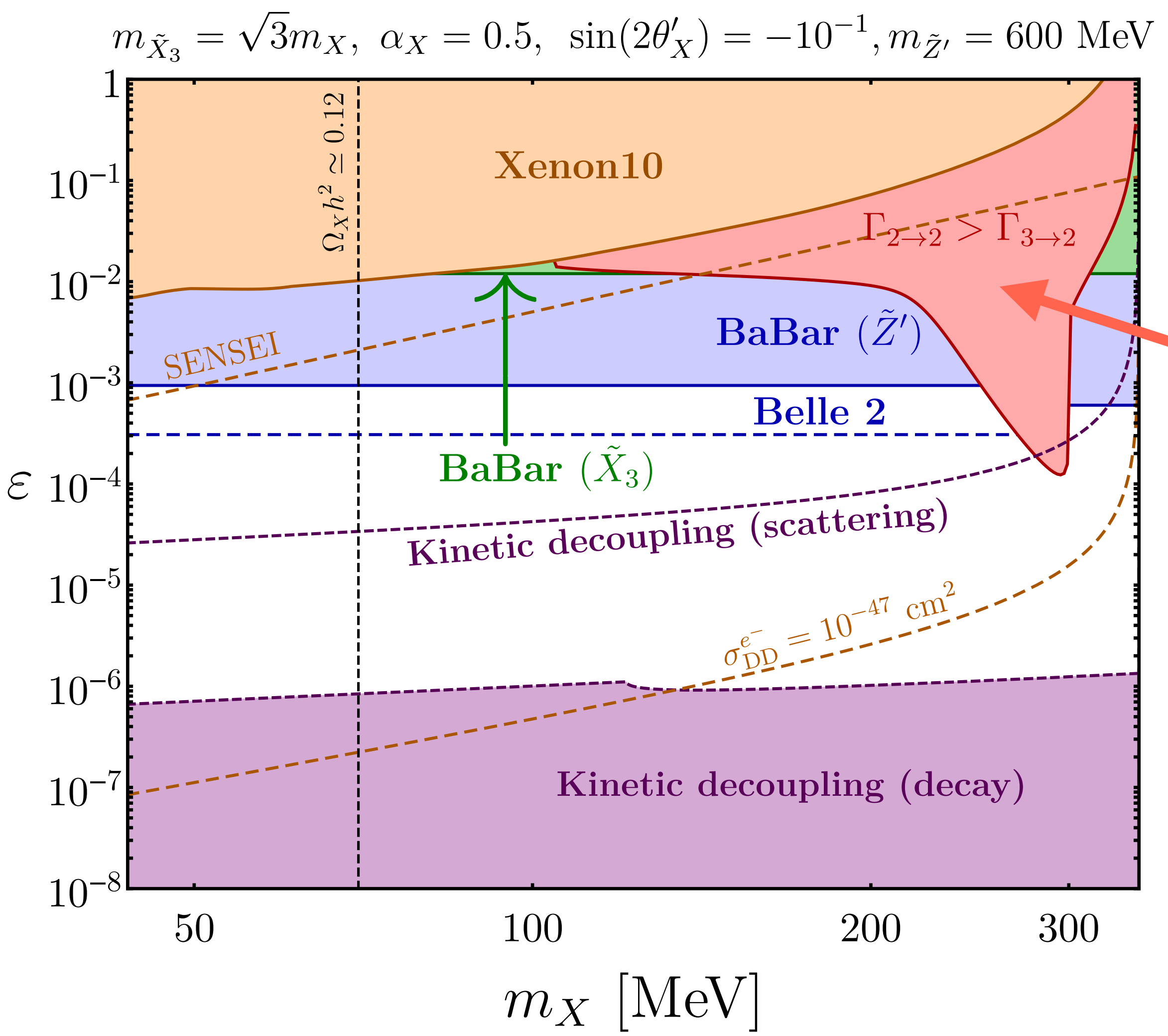

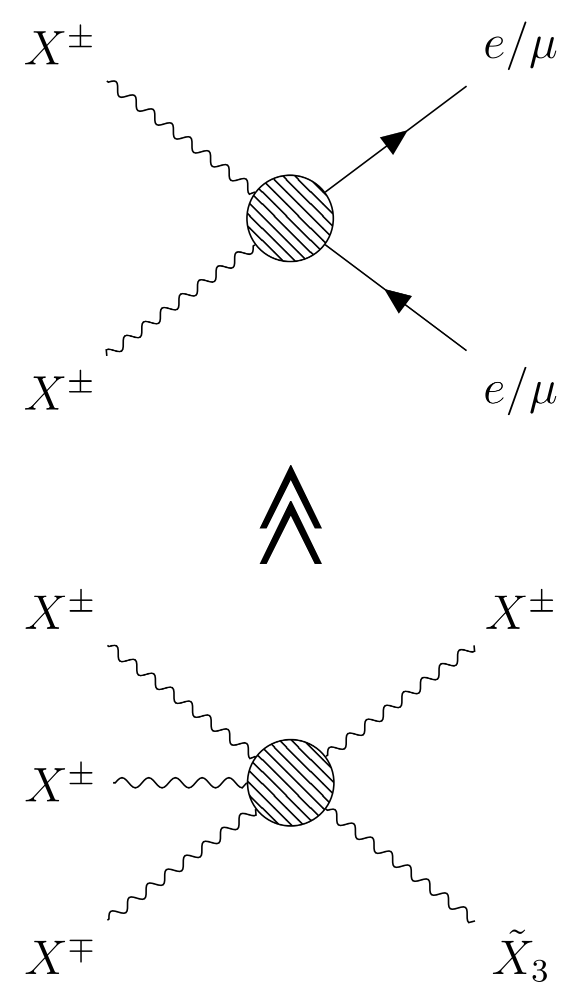

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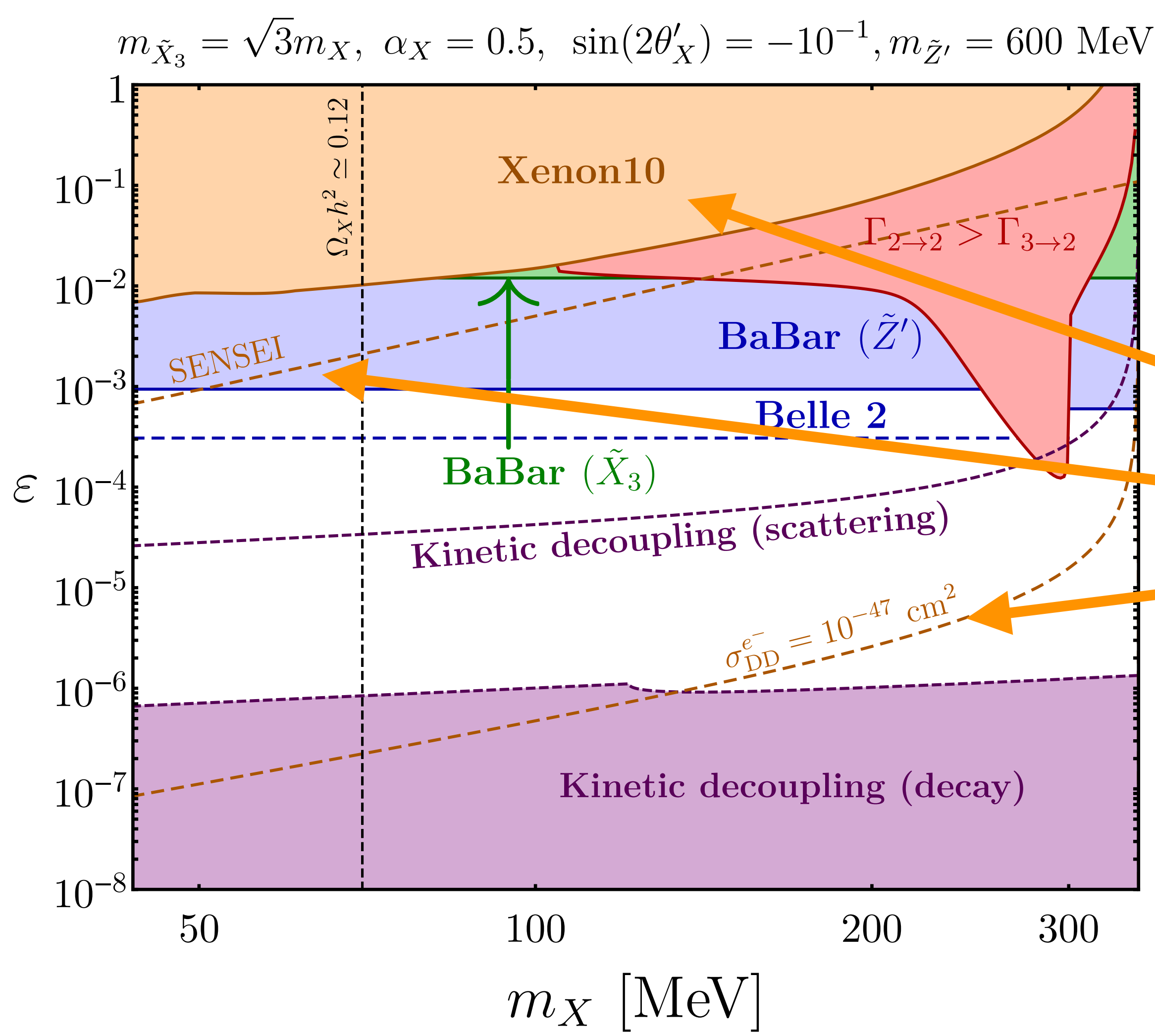
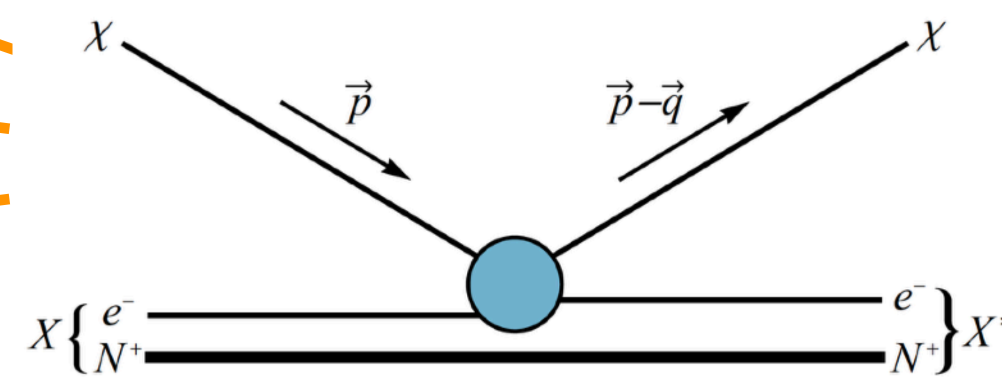


Sub-GeV DM typically cannot (can) produce nuclear (electron) recoil signals



Essig et al (2015)

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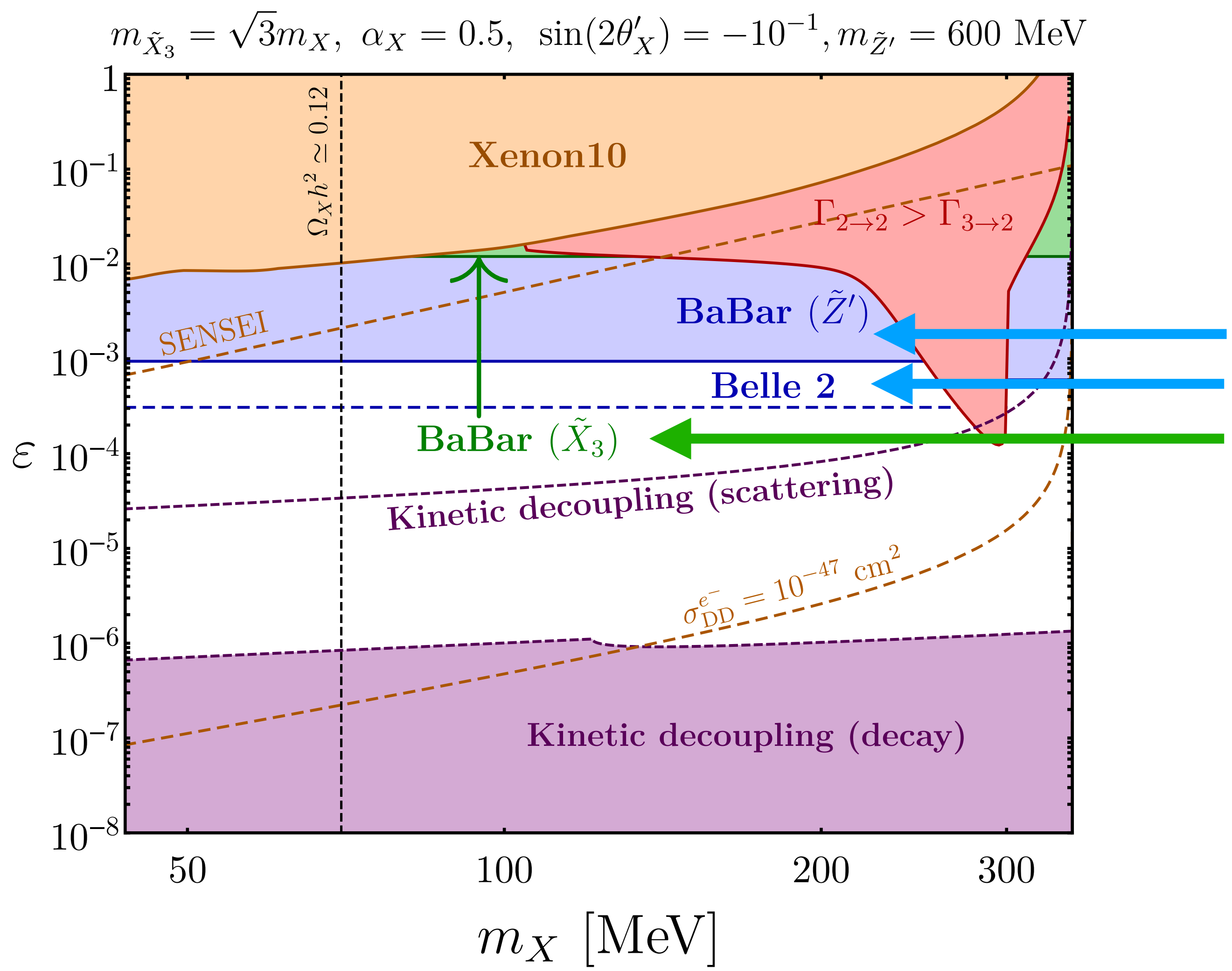

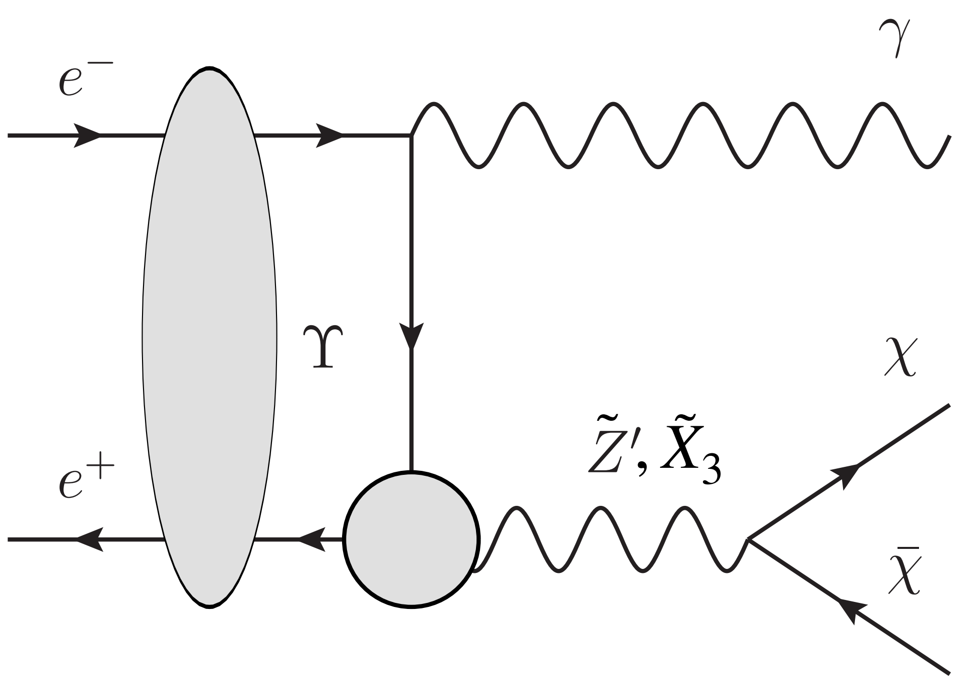

BaBar / Belle 2

SMC, H. M. Lee, Y. Mambrini and M. Pierre (2019)