Dark matter models, properties and particle physics candidates

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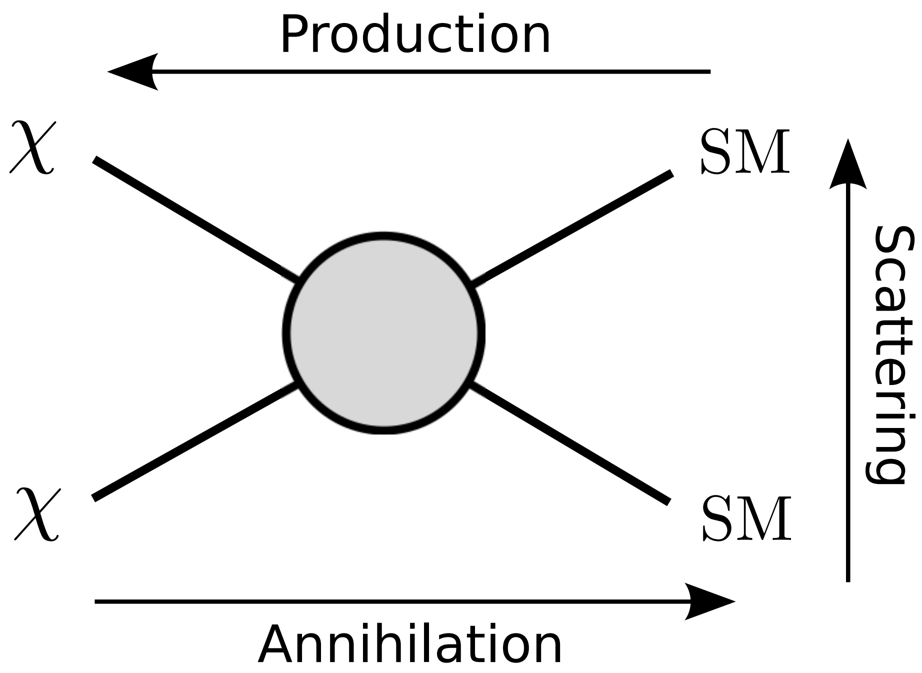
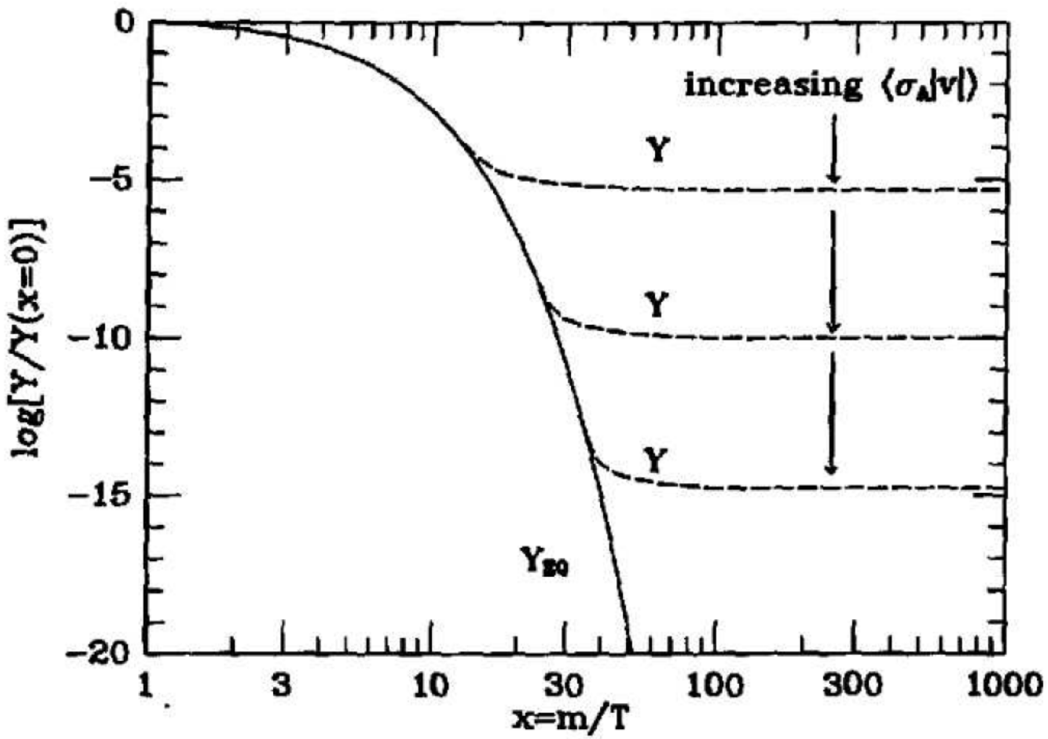
Based on PRL 119 191801, PRD 100 (2019) 1, 015009, PRD 104 (2021) 3, 035011
JHEP 1812 (2018) 089, JHEP 05 (2020) 057, JHEP 08 (2019) 050

Outline

1. Introduction
   - · WIMP
   - · Status of direct detection experiments
2. EWIMP, SIMP, cannibal DM, FIMP
3. A pseudo-Nambu-Goldstone dark matter (pNG DM)
4. Summary

WIMP

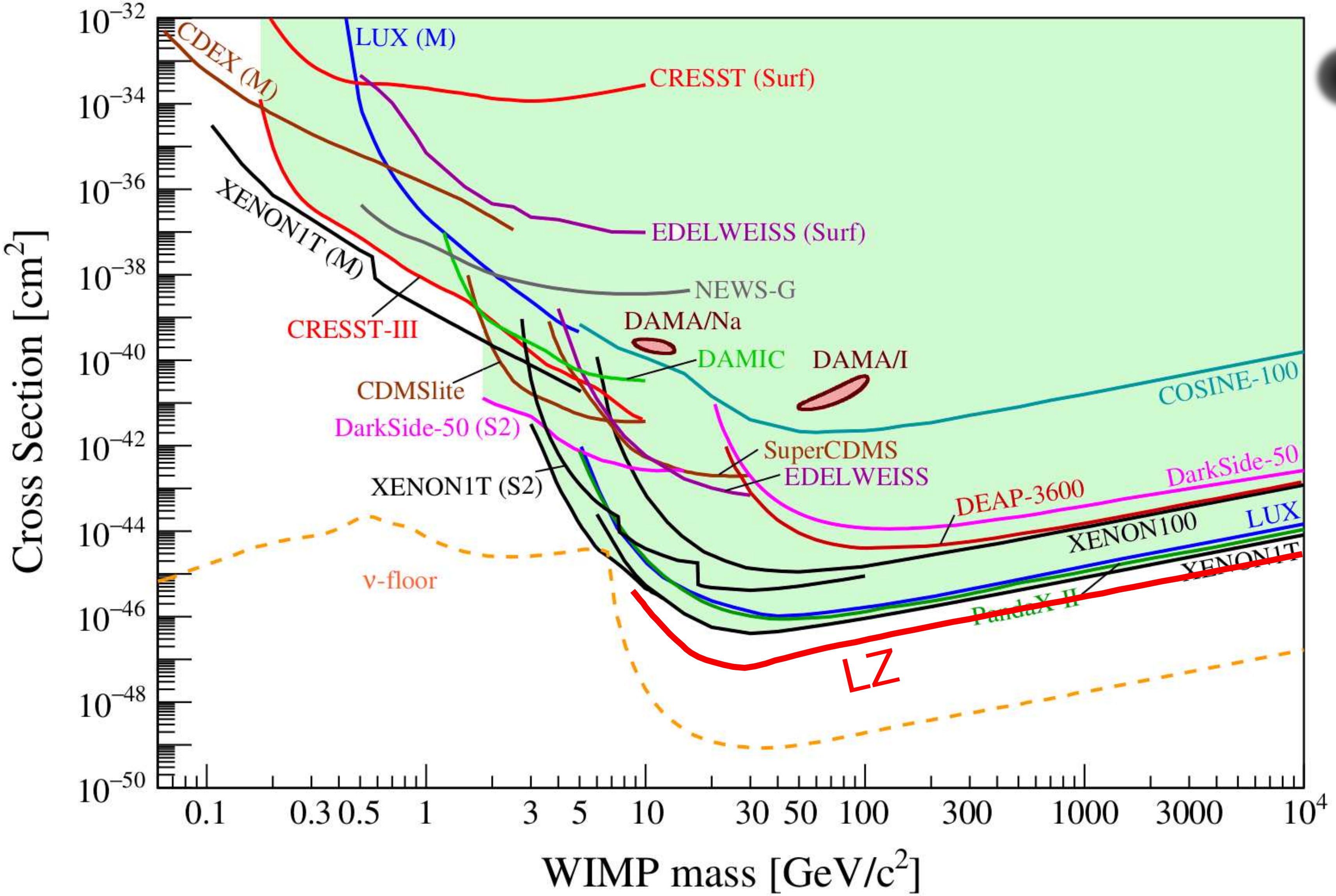


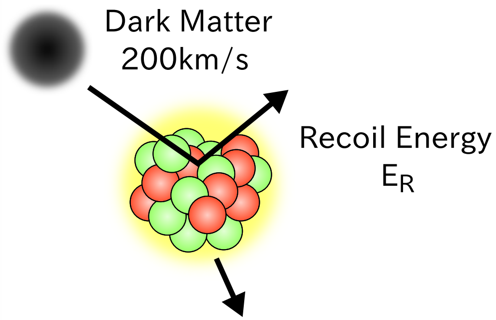


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2} \right)$$

- WIMP is thermalized with SM particles in early universe
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim 10^{-36}\mathrm{cm}^2$
- Almost independent on DM mass

Status of direct detection experiments

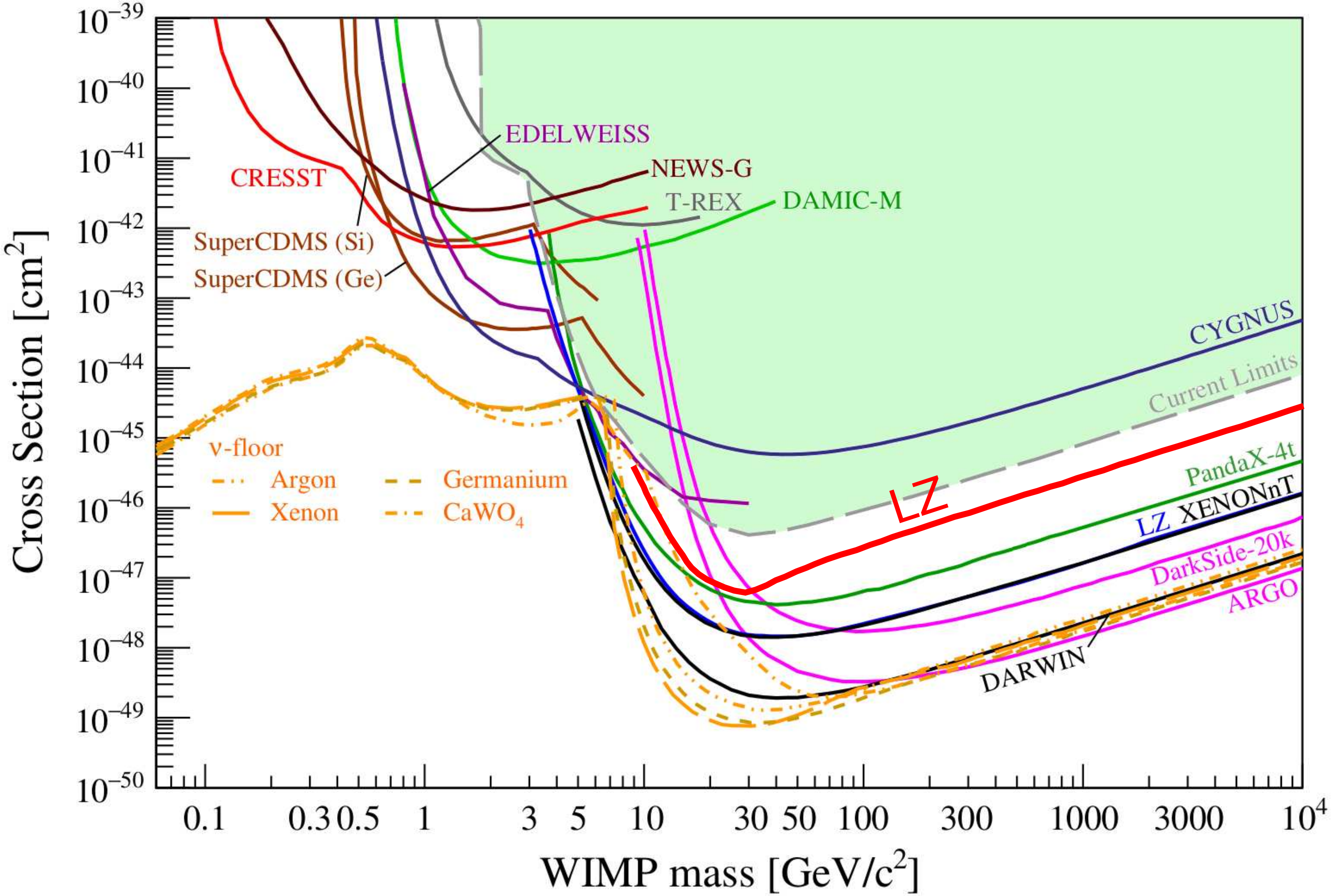




arXiv:2104.07634
LZ arXiv:2207.03764

- LZ gives the strongest bound above 10 GeV DM mass at present.

Future sensitivity of direct detection experiments



Billard et al., arXiv:2104.07634
LZ arXiv:2207.03764

- Experiments will reach the neutrino floor in 20 years.

DM models

Classification of DM models from experimental results

1. WIMP with suppressed cross section for direct detection
   - EWIMP $\Rightarrow$ loop-induced $\sigma_{\rm SI}$
   - pNGB DM : $\mathcal{L} \supset \frac{s}{v}\left[(\partial_\mu \chi)^2 - m_\chi^2 \chi^2\right]$
   - DM with a pseudo-scalar mediator : $\mathcal{L} \supset a\overline{\chi}\gamma_5\chi \Rightarrow \sigma_{\rm SI} \propto v_\chi^2$
2. Sub-GeV DM (unexplored mass region)
   - SIMP (Strongly Interacting Massive Particle)
   - DM with a new light particle
3. Very small interactions with SM
   - FIMP (Feebly Interacting Massive Particle) $\Rightarrow \lambda \sim 10^{-11}$
   - Cannibal DM $\Rightarrow \lambda \lesssim 10^{-8}$, but large couplings in dark sector

small int. with SM

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small int. with SM

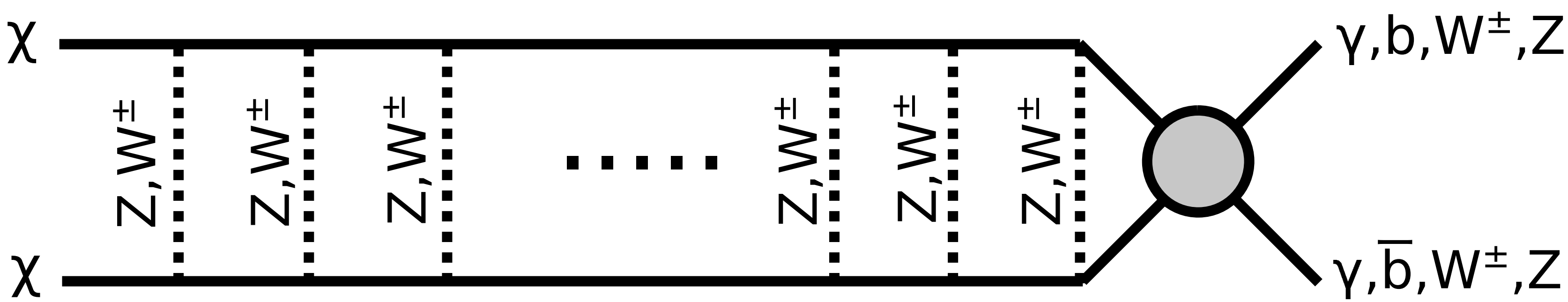
EWIMP (ElectroWeak-Intereacting Massive Particle)

Farina et al., JHEP (2013) [arxiv:1303.7244]

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Finite naturalness bound in TeV	σ_{SI} in 10^{-46} cm^2
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6)\, 10^{-3}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(0.3 \pm 0.6)\, 10^{-3}$
3	0	0	HH^*	$2.0 \to 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
3	0	1/2	LH	$2.4 \to 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.12 ± 0.03
5	0	1/2	stable	$4.4 \to 10$	166	$0.4 \times \sqrt{\Delta}$	1.0 ± 0.2
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	4 ± 1

- Quintuplet is automatically stabilized by accidental $\mathbb{Z}_2$ symmetry.
- Indirect signals: Sommerfeld enhancement

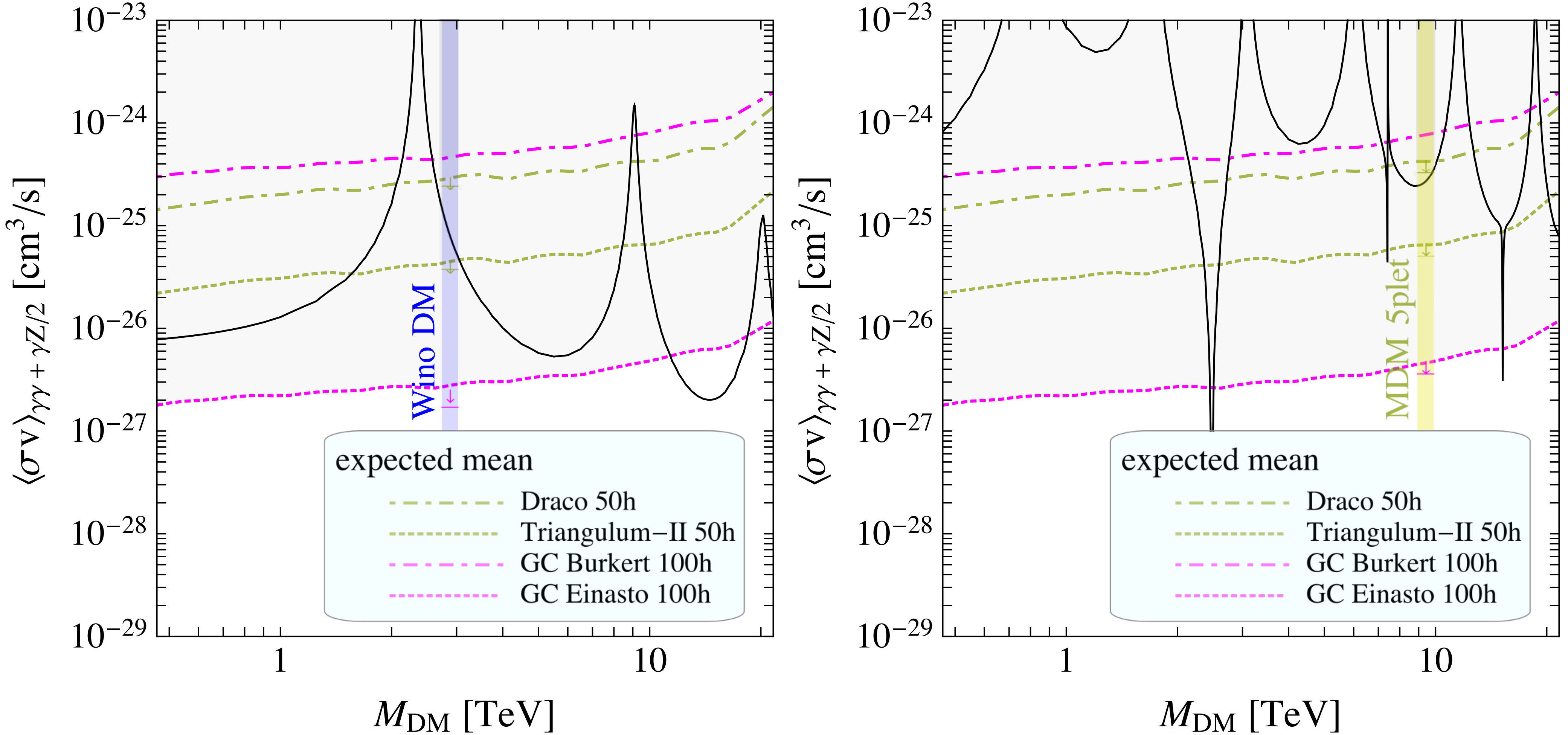
$$m_\chi \gg m_{W,Z} \Rightarrow V = -\frac{\alpha_W}{r} e^{-m_{W,Z} r}$$



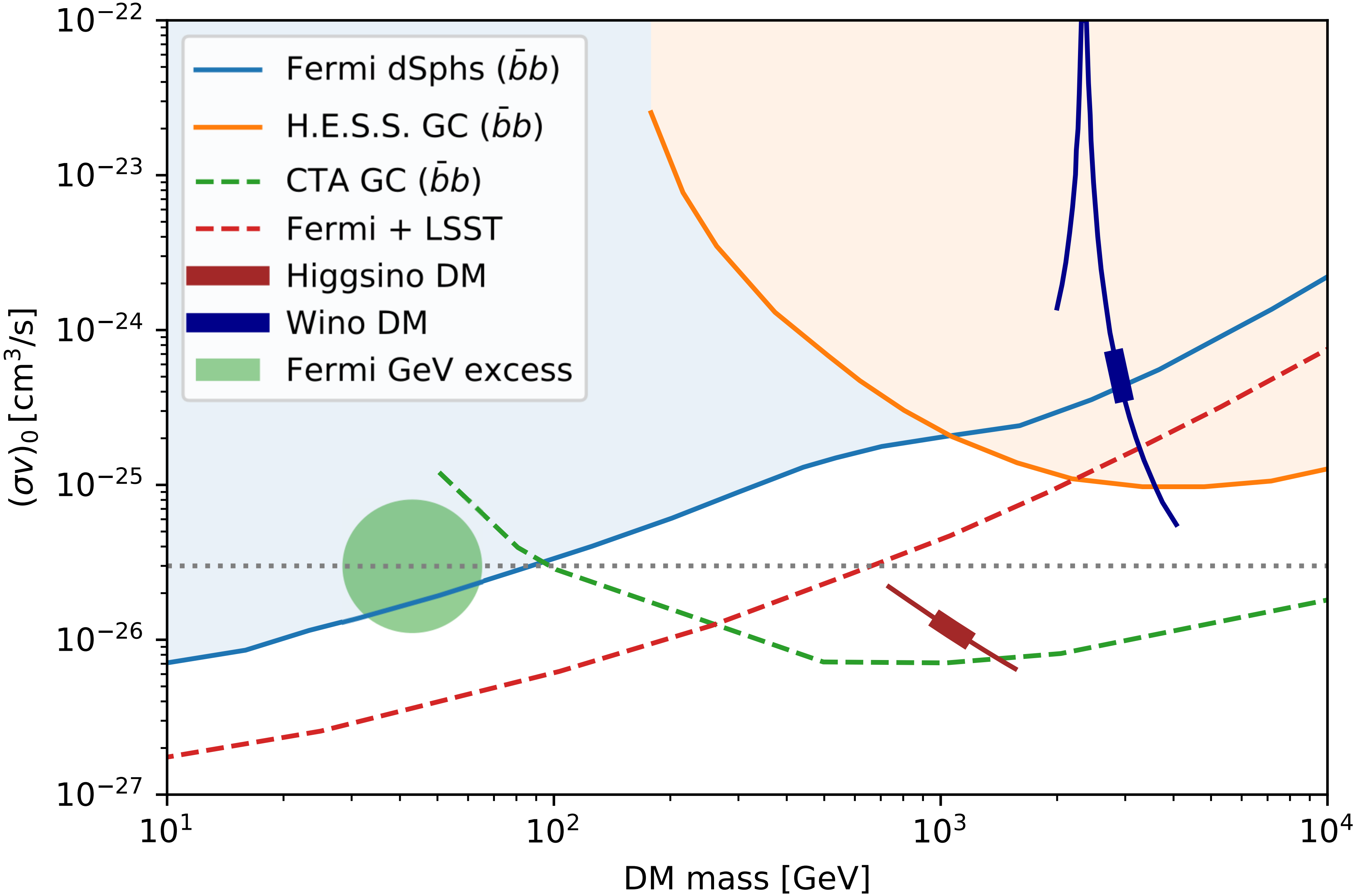
Gamma-ray line search

Lefranc et al., arXiv:1608.00786

- CTA prospect （expected to start in 2026）
  Energy range: 20 GeV – 300 TeV
- Both of DM and baryon number is large in Galactic center

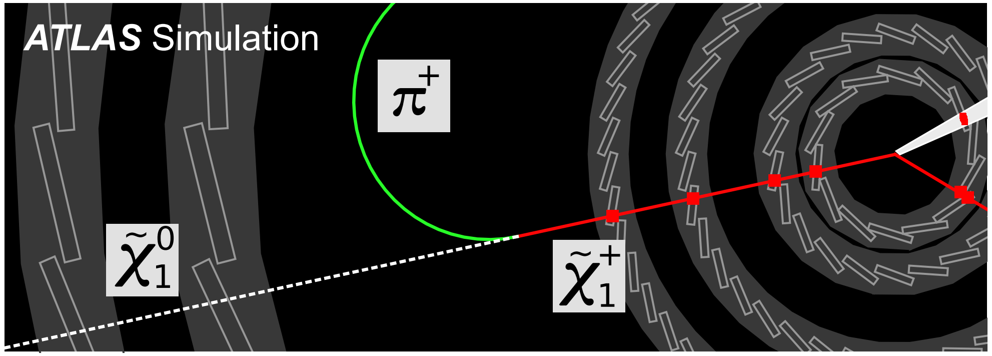


Broad gamma-ray search



European Strategy for Particle Physics Preparatory Group, arXiv:1910.11775

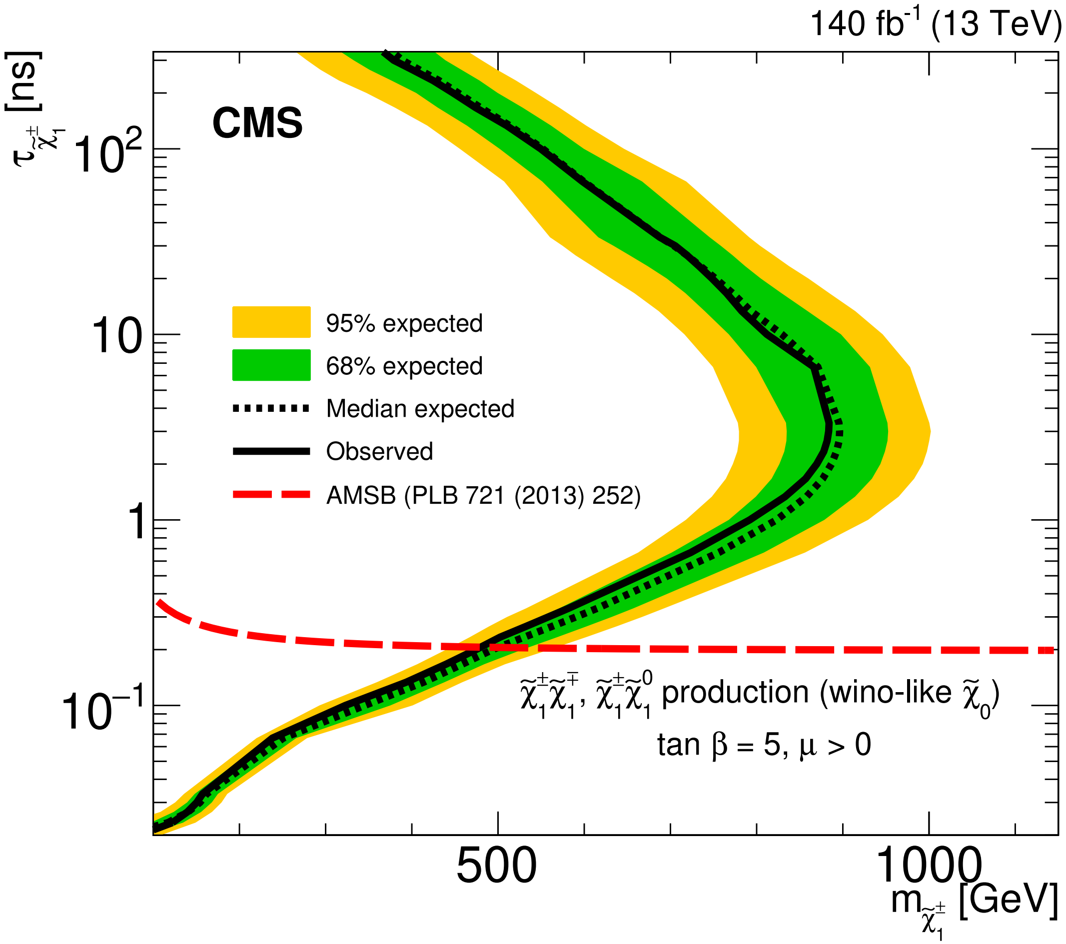
Disappearing tracks at colliders



- $\Delta m_\chi \approx 166$ MeV
- $\chi^\pm \to \chi^0 \pi^\pm$ (soft pion)
- CMS excludes $m_\chi \lesssim 500$ GeV

CMS, PLB (2020), [arXiv:2004.05153]

ALTAS, JHEP (2018), [arXiv:1712.02118]

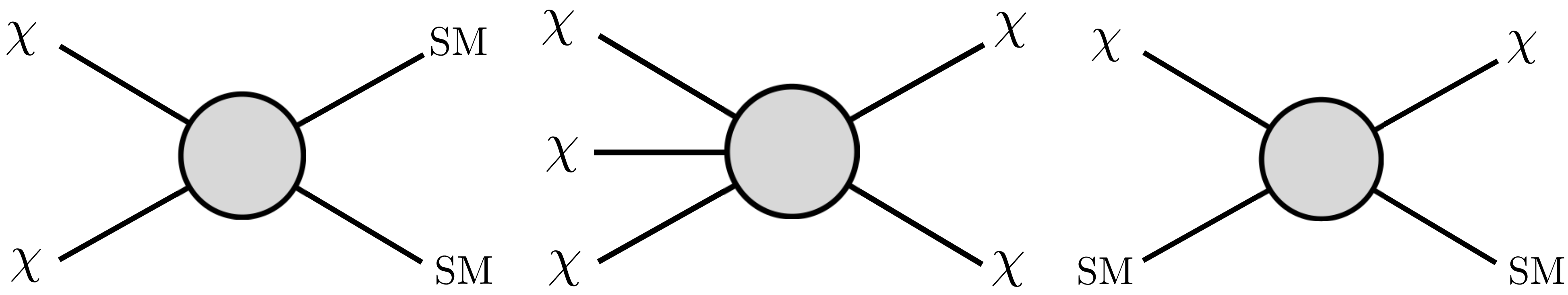


SIMP (Strongly Interacting Massive Particle)

Y. Hochberg et al. PRL (2014) [arxiv:1402.5143]

- DM abundance is determined by $3 \to 2$ or $4 \to 2$ processes in dark sector, but not $2 \to 2$ processes (WIMP).
- Kinetic eq. with the SM at least until $2 \to 2$ freeze-out.

Condition for thermal SIMP: $\Gamma_{\rm ann} < \Gamma_{3\to 2} < \Gamma_{\rm kin}$



- $m_\chi \sim \mathcal{O}(10)$ MeV for $3 \to 2$ process

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{3\to 2} v^2 \rangle \left(n^3 - n^2 n_{\rm eq}\right)$$

Ex: $\mathbb{Z}_3$ symmetry

$$V \supset \kappa \chi^3 + \mathrm{h.c.} + \frac{\lambda}{4}|\chi|^4$$

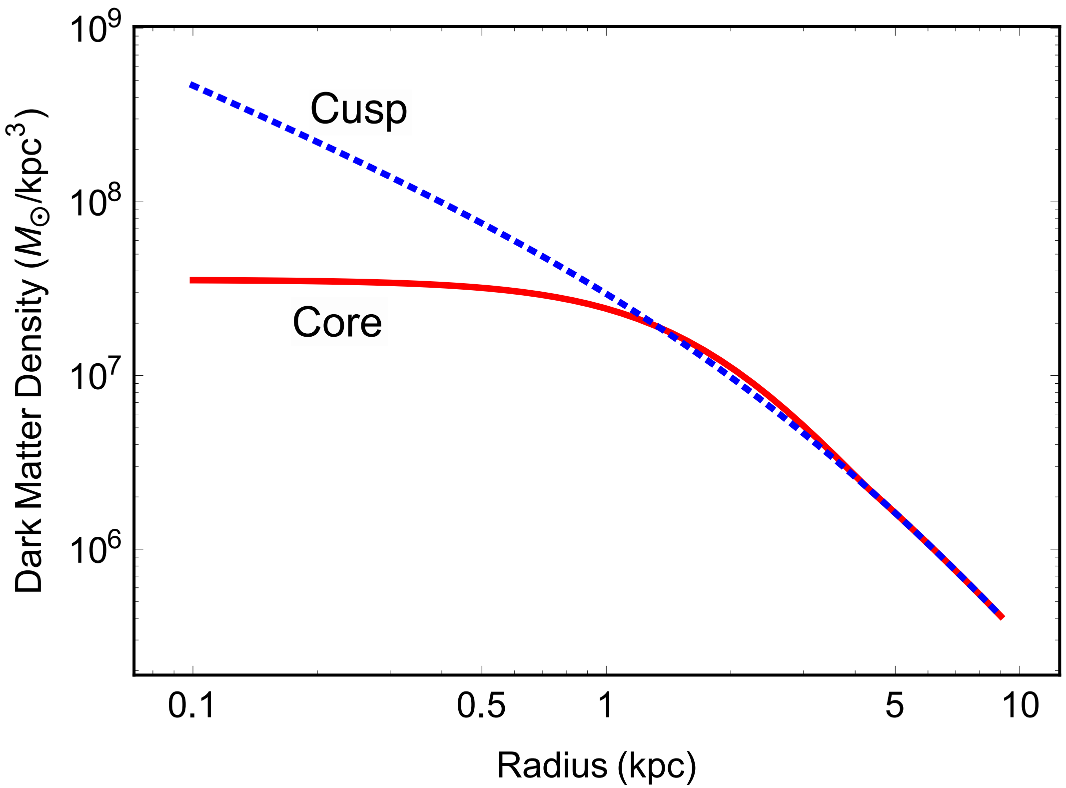
$m_\chi \sim \mathcal{O}(100)$ keV for $4 \to 2$ process $\Rightarrow$ naively conflict with BBN

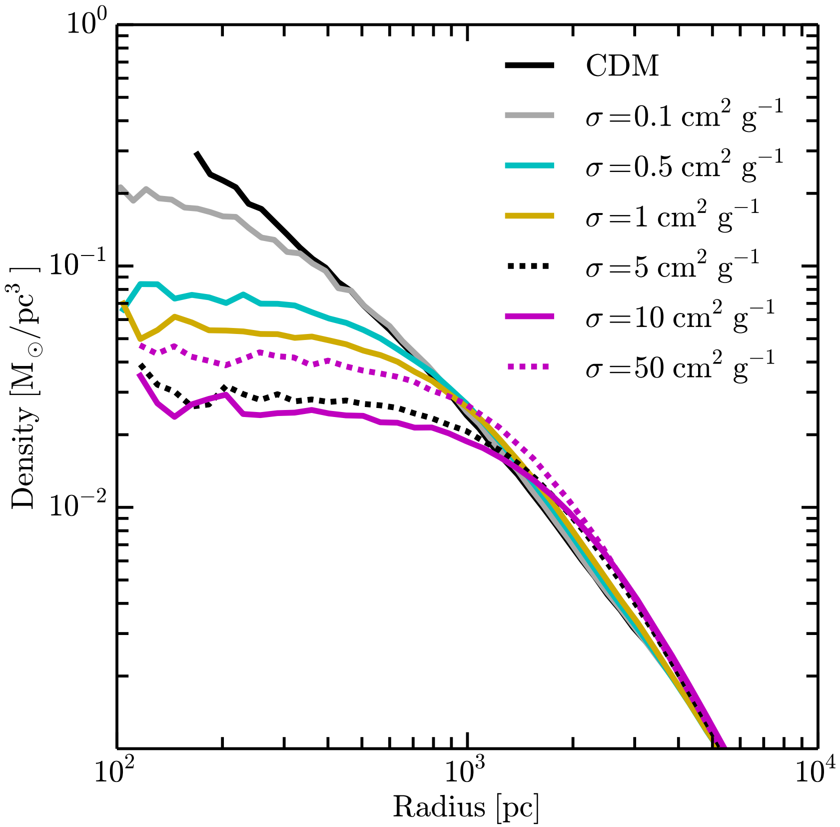
SIMP properties

Y. Hochberg et al. PRL (2014) [arxiv:1402.5143]

- Large self-interactions are required for observed abundance $\Omega h^2 = 0.12$.
- Improve small scale problems $\sigma_{\rm self}/m_\chi \sim 1~{\rm cm}^2/{\rm g}$.

Ex. core vs cusp problem





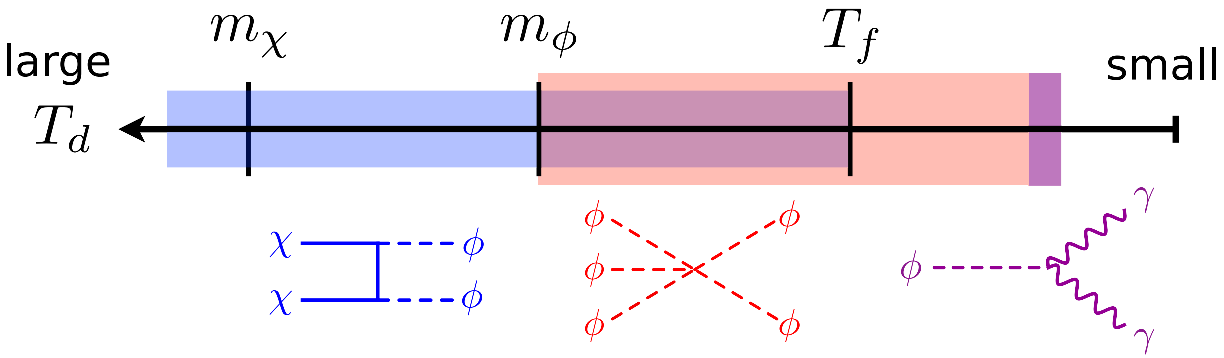
Tulin and Yu, Phys.Rept. (2018) [arxiv:1705.02358]

Cannibal DM

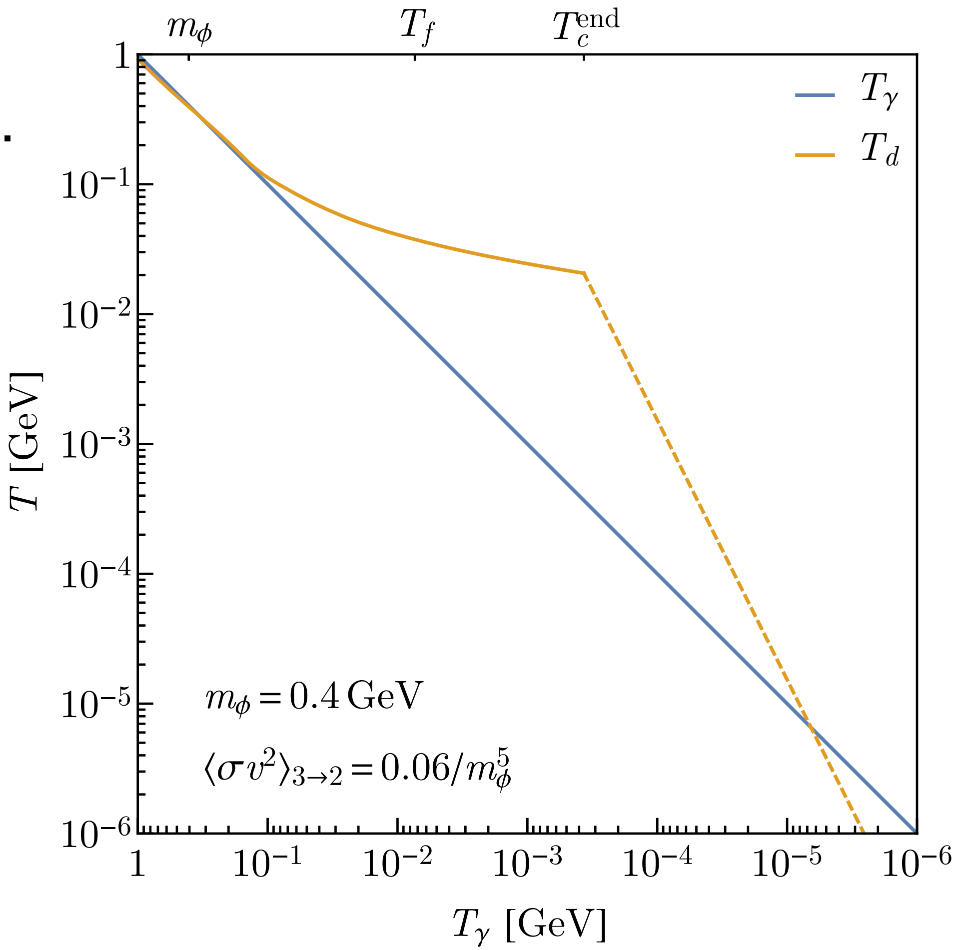
Pappadopulo et al. PRD (2016) [arxiv:1602.04219], JHEP (2016) [arxiv:1607.03108]

$$\mathcal{L} = -\frac{m_\chi}{2}\overline{\chi}\chi - \frac{m_\phi^2}{2}\phi^2 - \frac{y}{2}\phi\overline{\chi}\chi - \frac{A}{3!}\phi^3 - \frac{\lambda}{4!}\phi^4$$

- χ and ϕ are in dark sector kinematically decoupled from SM.
- $m_\chi > m_\phi$
- $\phi\phi\phi \to \phi\phi$ decouples after $\chi\chi \to \phi\phi$.



- Entropy conservation in each sector $\to s_{\rm SM}/s_d = $ const.
- DM temperature T is exponentially larger than photon temperature.



Cannibal DM

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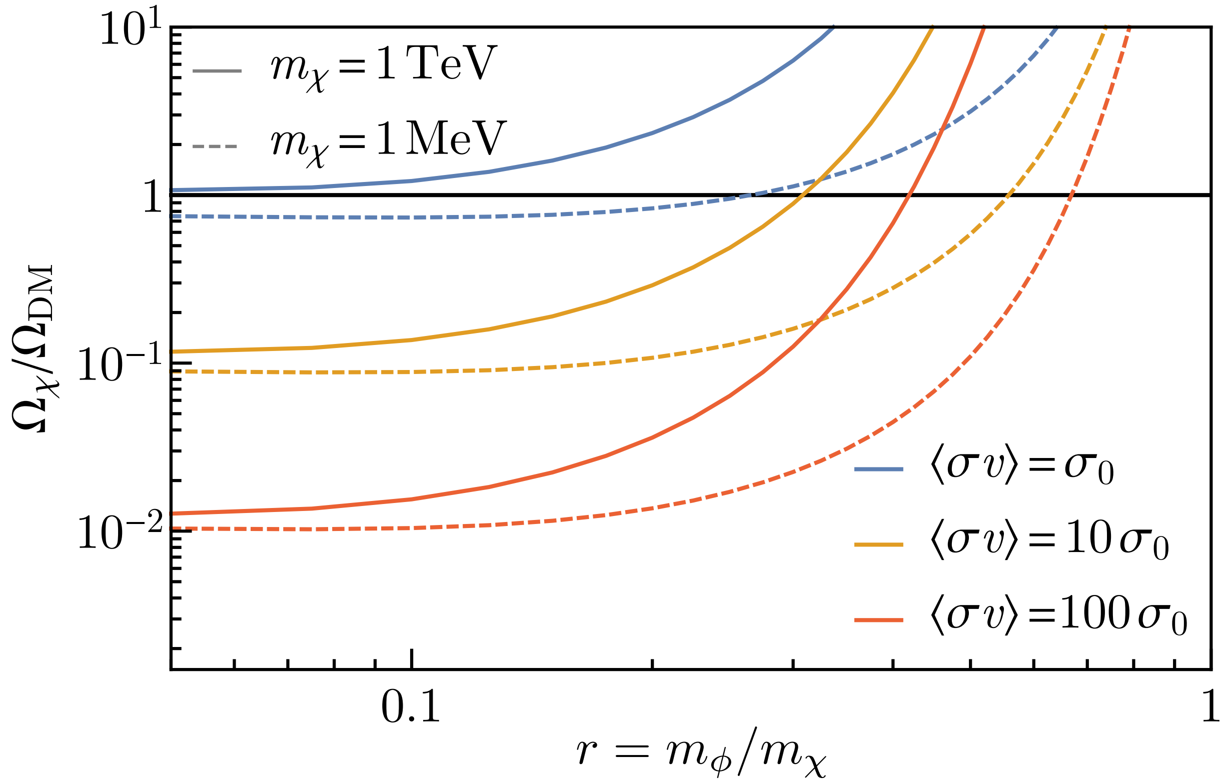
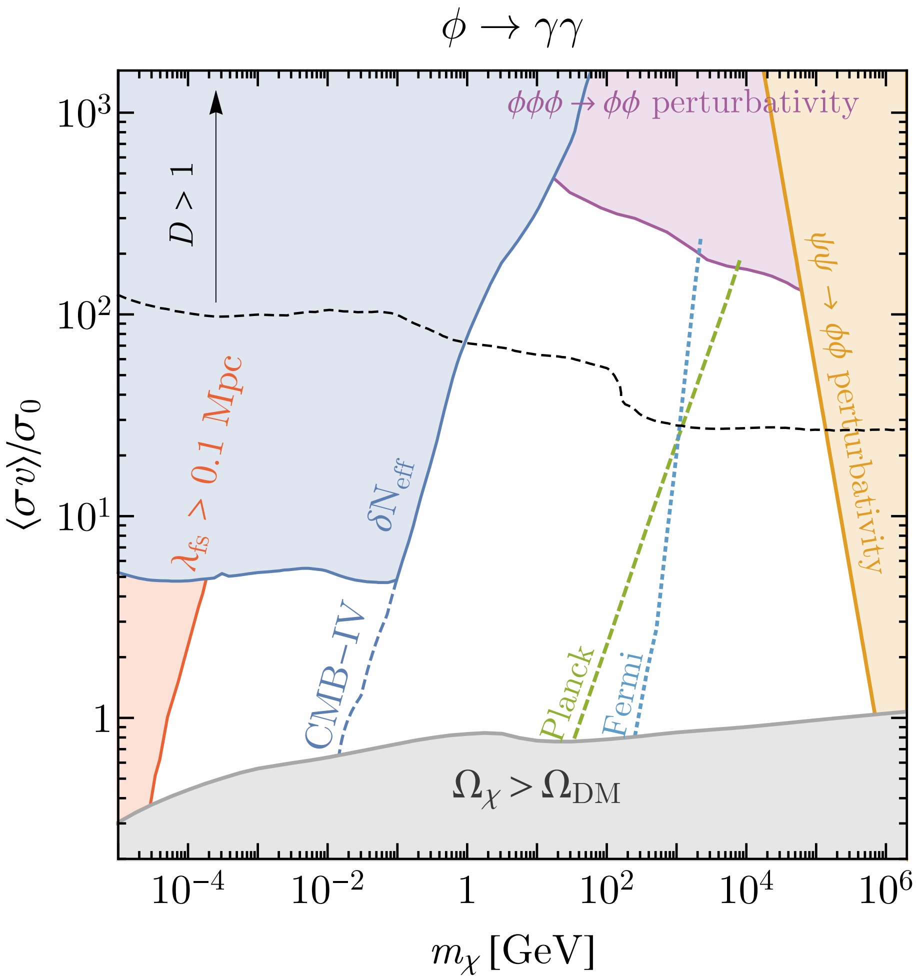
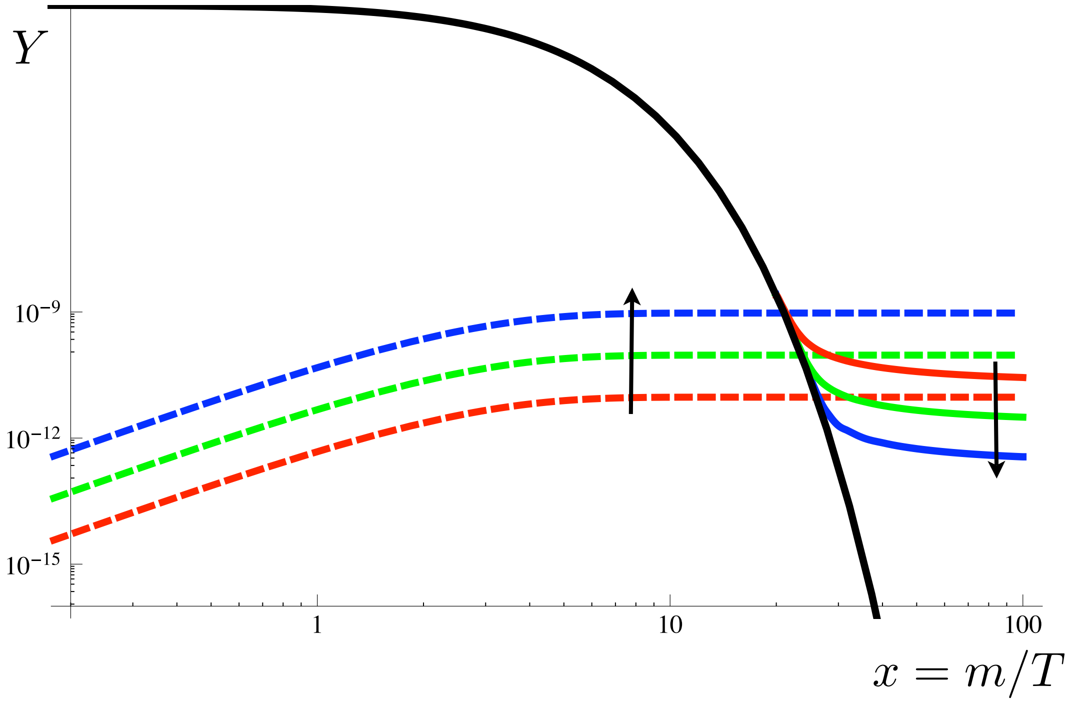


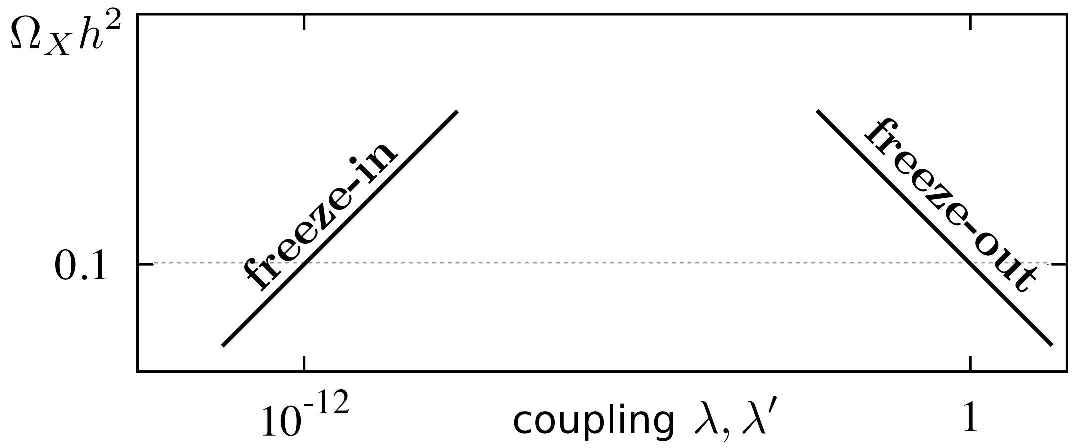


- $\langle\sigma v\rangle$ larger than WIMP is needed for observed relic.
- Indirect detection signals are enhanced.

FIMP (Feebly Interacting Massive Particle)

Hall et al., JHEP 03 (2010) 080 [arXiv:0911.1120]



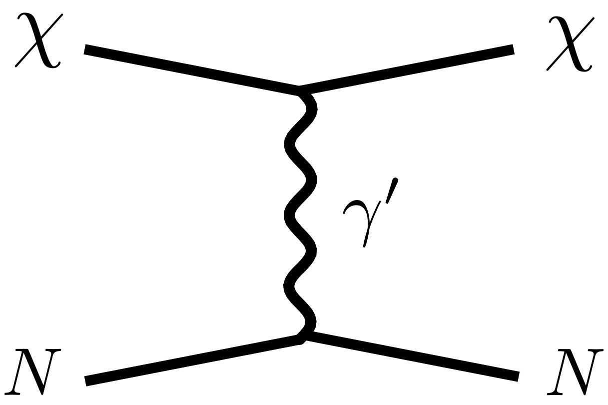


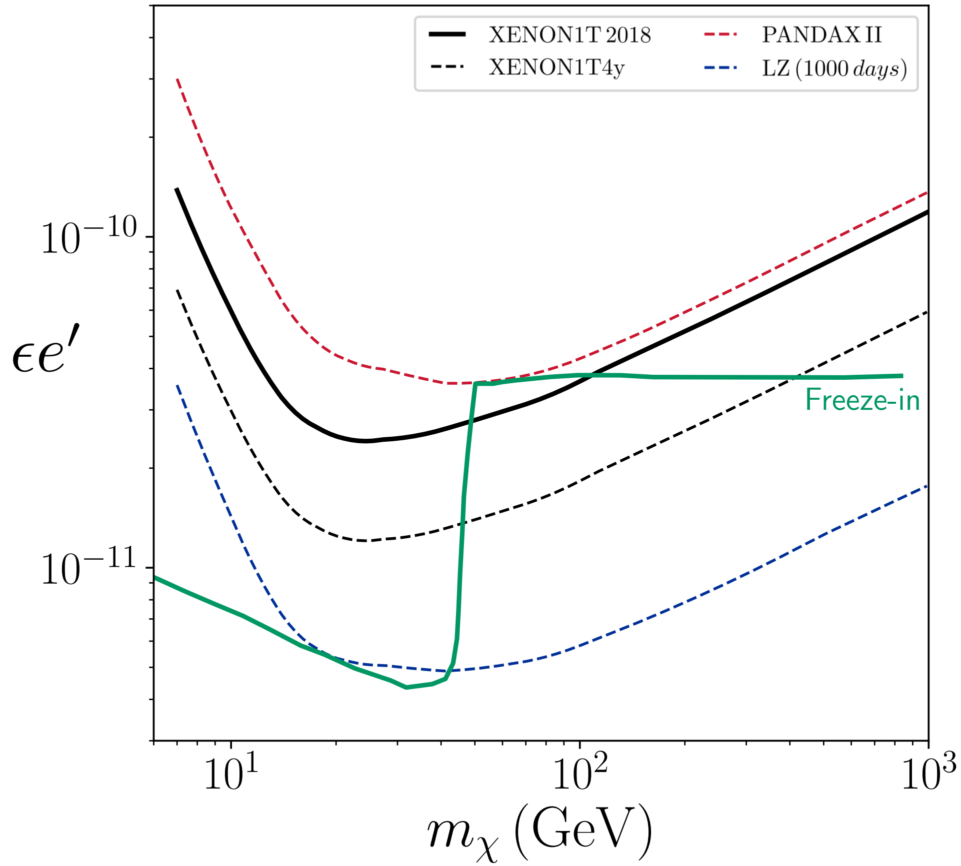
- FIMP is never thermalized with SM sector, and is slowly produced by decays or scatterings.
- $\Omega_{\text{FIMP}} \propto (\text{coupling})^n$ cf: $\Omega_{\text{WIMP}} \propto (\text{coupling})^{-n}$
- coupling $\sim 10^{-11}$ to reproduce the PLANCK value.
- Candidates: sterile neutrino, Higgs portal DM etc

FIMP signals

Hall et al., JHEP 03 (2010) 080 [arXiv:0911.1120]
Hambye et al., PRD (2018) [arXiv:1807.05022]

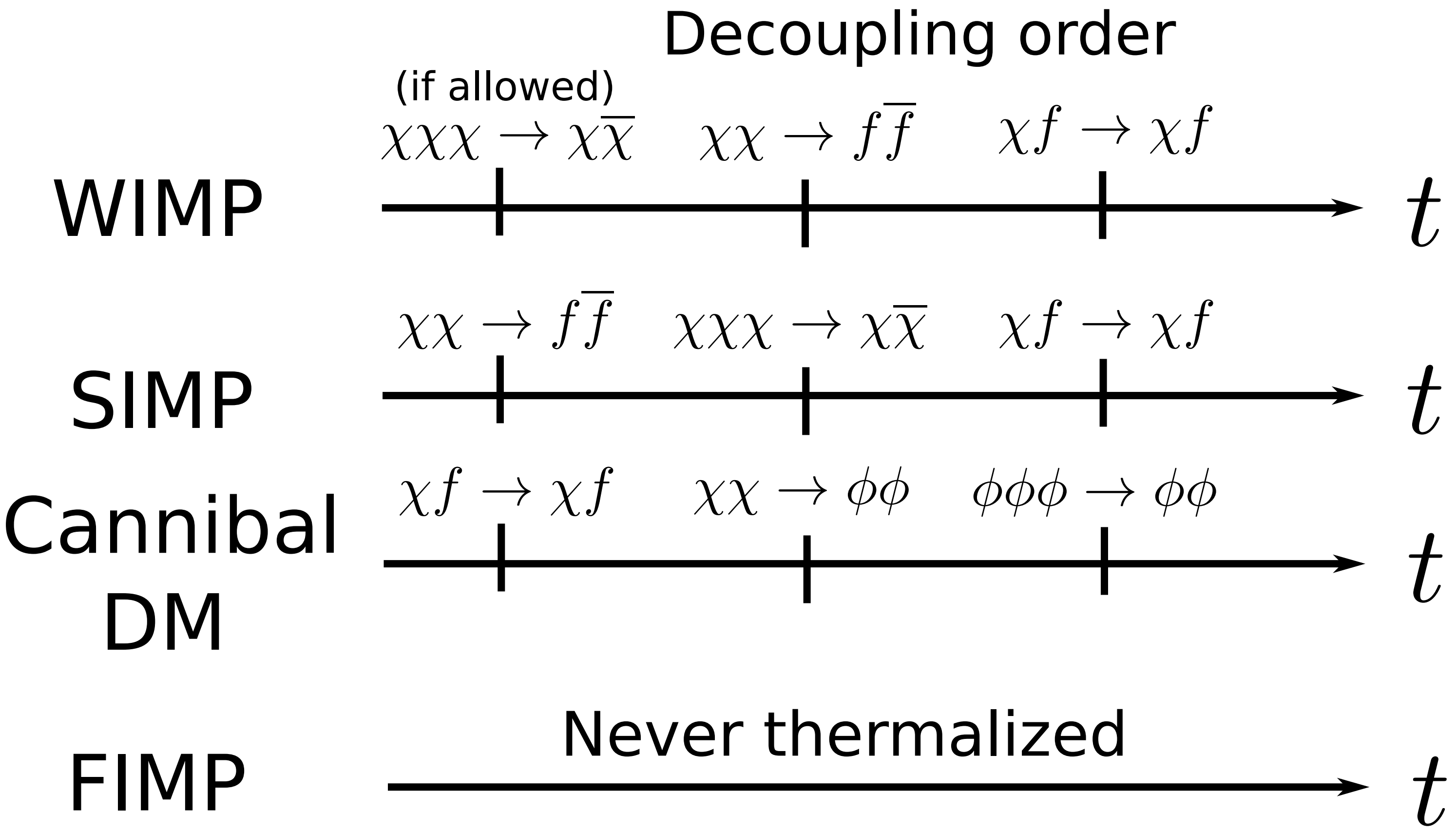
- Detection of FIMP is challenging.
- Enhanced direct detection rate
  Ex. DM coupled with a light dark photon $\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$
- $i\mathcal{M} \sim \frac{1}{t - m_{\gamma'}^2} = \frac{1}{2 m_N E_R}$
  if $m_{\gamma'} = \mathcal{O}(40)$ MeV





- + long-lived particles (dark photon) accompanied with DM at FASER.

Summary of DM models



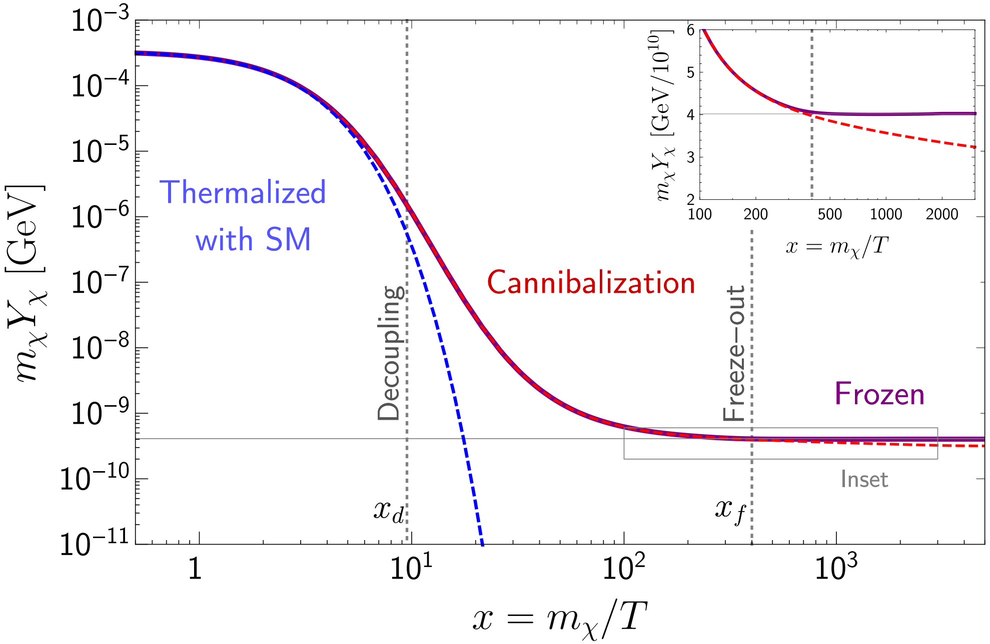
Properties

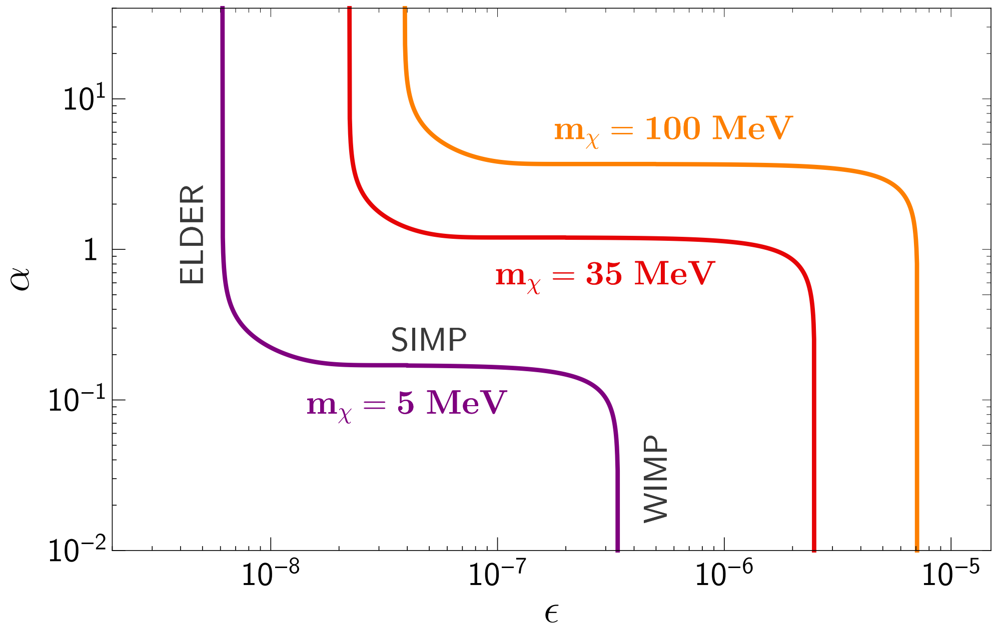
- WIMP: 3-ways to detect
- SIMP: large λ_χ
- SIMP: sub-GeV mass
- Cannibal DM: enhanced $\langle \sigma v \rangle$
- FIMP: DD enhanced if a mediator is light.
- FIMP: Long-lived particles

- χ: DM, f: SM particles, ϕ: light dark sector particles

Other possibilities

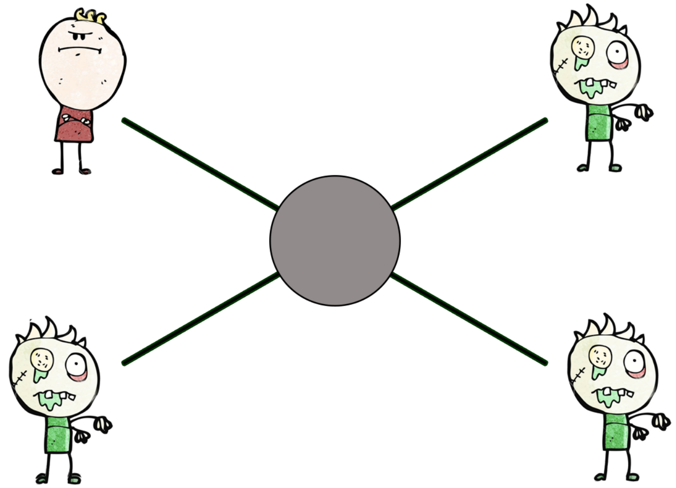
1 ELDER (ELastically DEcoupling Relic) Kuflik et al., PRL 116, 221302 (2016)





2 Zombie DM Kramer et al., PRL 126, 081802 (2021)

- Reduce DM numbers by $\chi\zeta^\dagger \to \zeta\zeta$
- thermal production is possible even if DM mass is heavy as 10^8 GeV without violating the unitarity bound.



A pseudo-Nambu-Goldstone DM

The simplest pNGB DM model

C. Gross, O. Lebedev, TT, PRL (2017)

- Introduce complex scalar field $S = (s + i\chi)/\sqrt{2}$
- Global $U(1)$ symmetry is assumed (invariant under $S \to e^{i\alpha} S$)

$$\mathcal{V} = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$

$$- \left(\frac{\mu_S'^2}{4} S^2 + \mathrm{H.c.}\right) \quad \leftarrow \text{soft breaking mass term}$$

- After H and S get VEVs, ϕ and s mix

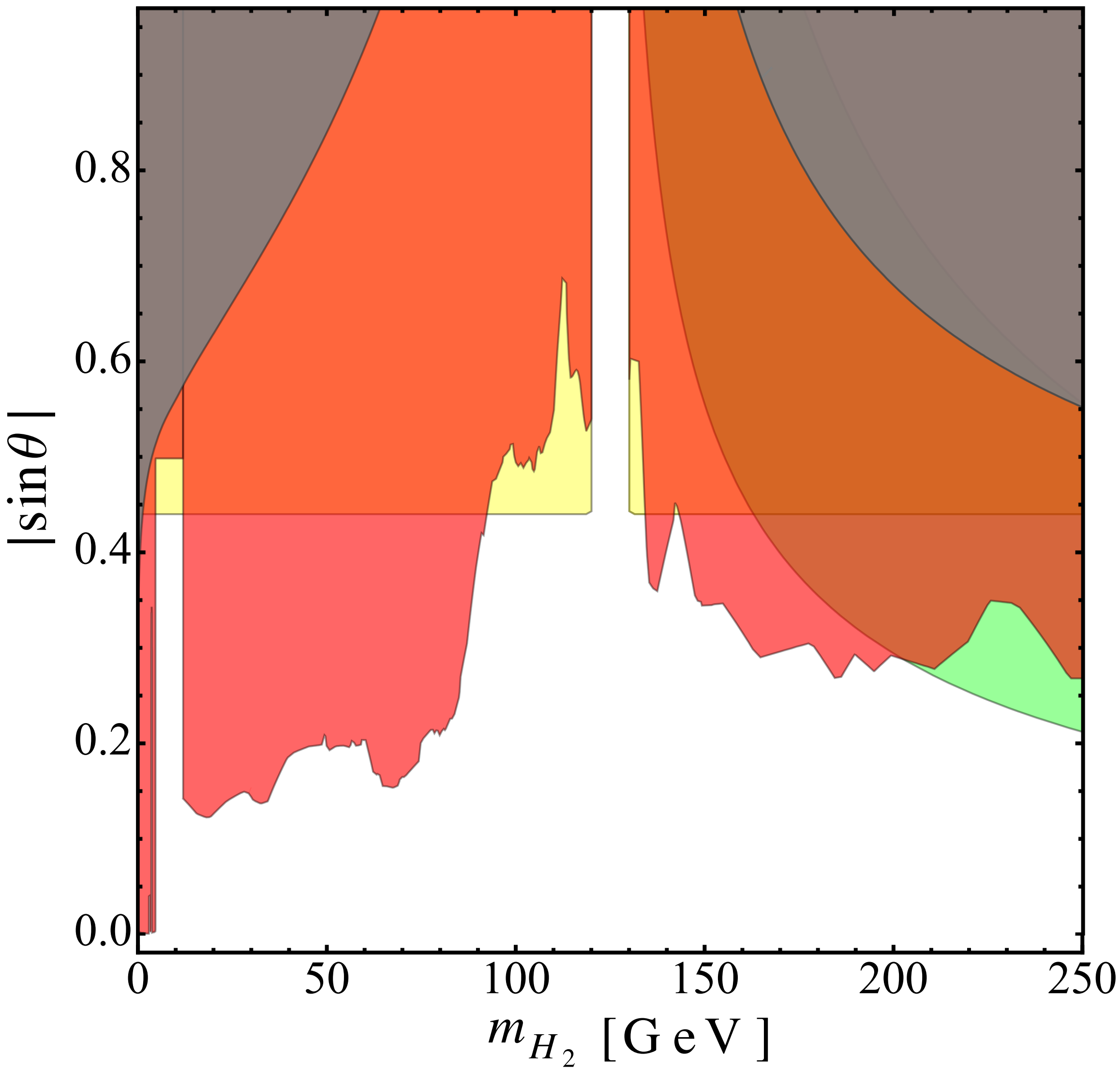
$$H = \begin{pmatrix} 0 \\ (v+\phi)/\sqrt{2} \end{pmatrix}, \qquad S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

$$\begin{pmatrix} \phi \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

- $\sin\theta \lesssim 0.3$ $\leftarrow$ Constrained by EWPT, h_2 direct search at LHC

Bound on $\sin\theta$

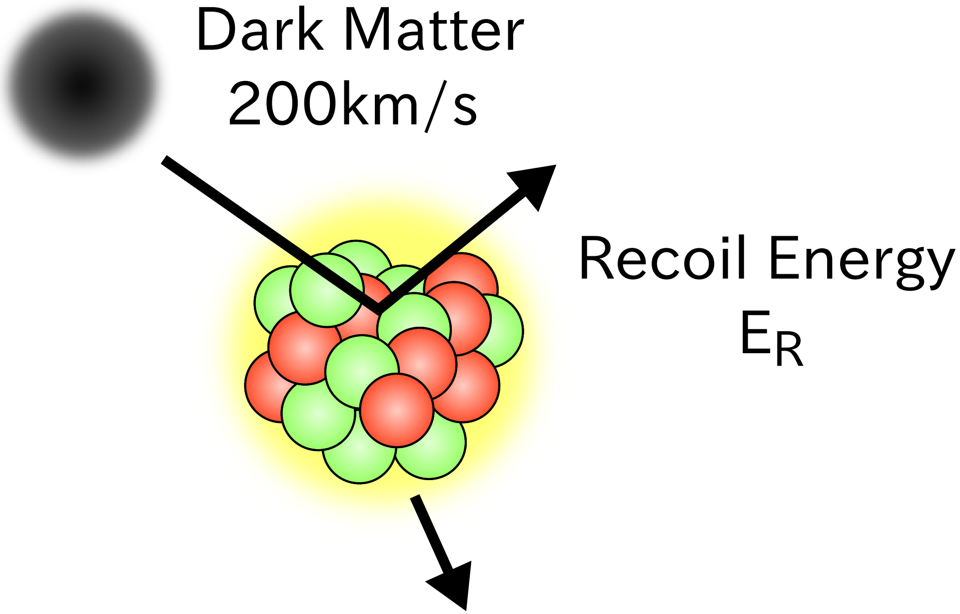
A. Falkowski et al., JHEP 1505 (2015) [arxiv:1502.01361]

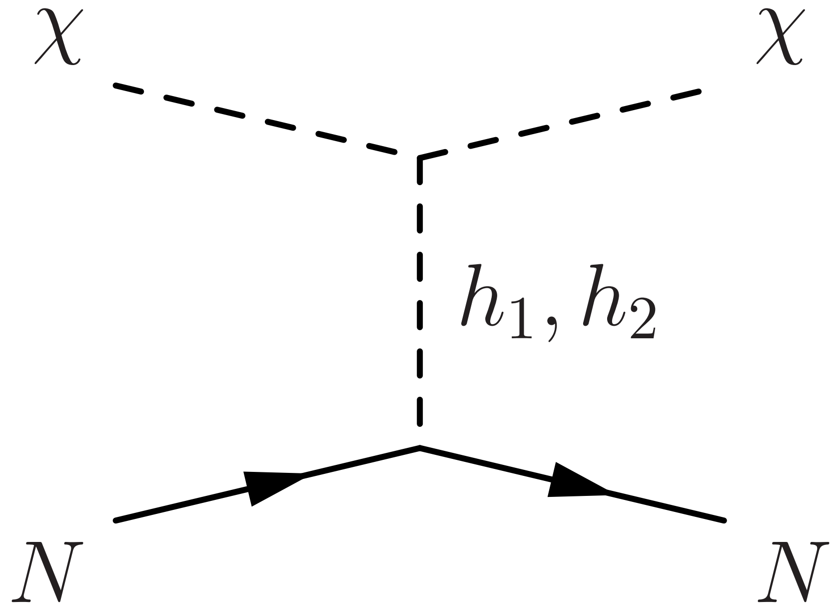


- Red: h_2 direct search at LHC
- Yellow: h_1 coupling measurements
- Green: Favored region from stability of scalar potential
- Gray: Electroweak precision tests
- $|\sin\theta| \lesssim 0.3$ if $m_{h_2} \gtrsim m_{h_1}$
- $m_\chi \lesssim m_{h_2}$ (above EW scale)

Direct detection (tree level)

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]





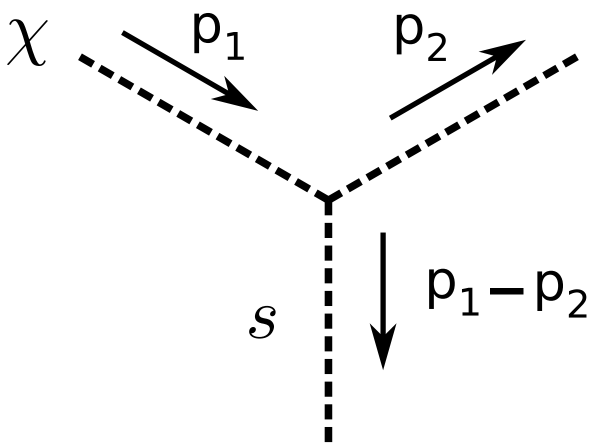
- Scattering amplitude cancels between h_1, h_2 mediated diagrams

$$i\mathcal{M} \sim i\left(\frac{m_{h_1}^2}{q^2 - m_{h_1}^2} - \frac{m_{h_2}^2}{q^2 - m_{h_2}^2}\right) \sim i\frac{q^2(m_{h_1}^2 - m_{h_2}^2)}{m_{h_1}^2 m_{h_2}^2} \quad \rightarrow \quad 0$$

Direct detection (tree level)

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

Rewrite with $S = \frac{(v_s + s)}{\sqrt{2}} e^{i\chi/v_s} \quad \Rightarrow \quad \mathcal{L} \supset \frac{1}{v_s} s \left[(\partial_\mu \chi)^2 - m_\chi^2 \chi^2 \right]$



$$\rightarrow i\mathcal{M} \sim -\frac{i}{v_s}(p_1 - p_2)^2 \sim -\frac{i}{v_s} m_\chi^2 v_\chi^2 \rightarrow 0$$

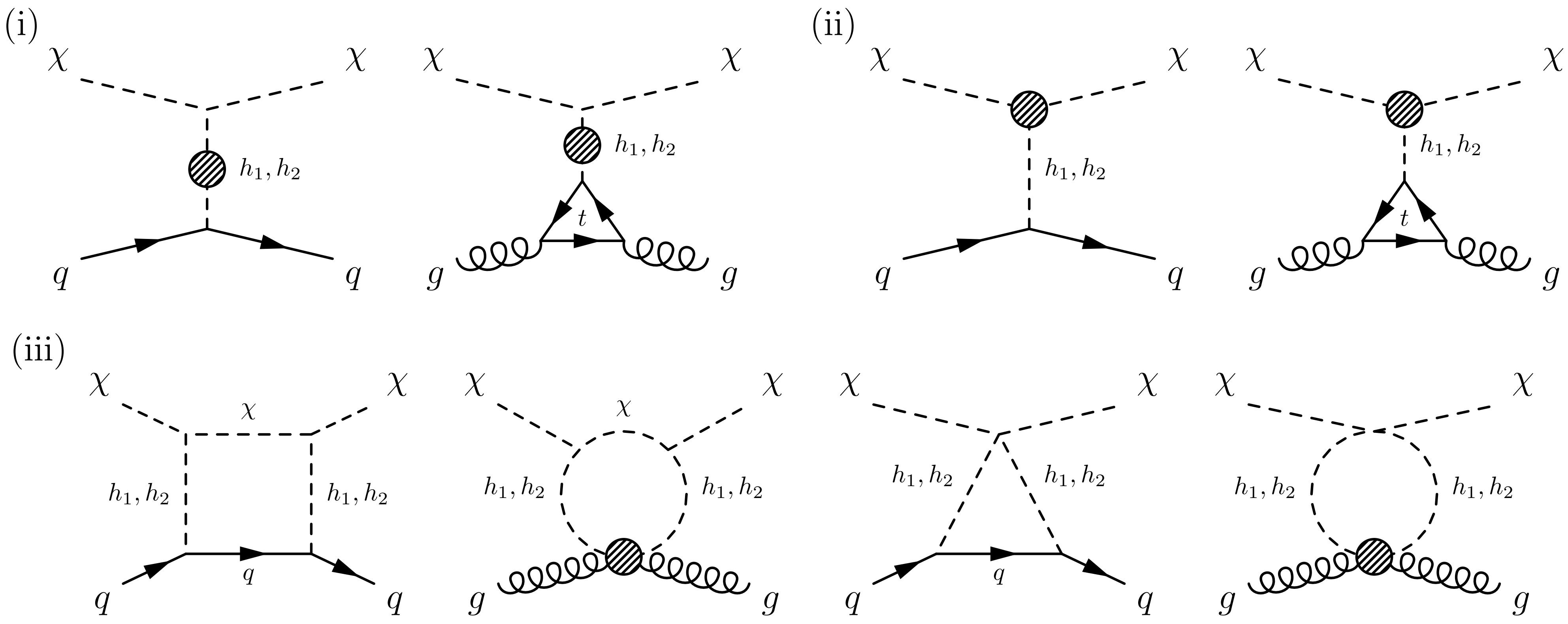
$$v_\chi \sim \mathcal{O}(10^{-3})$$

- The cancellation is due to nature of Goldstone boson
- All interactions are written with derivative couplings $\mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}(\partial_\mu \chi)$
- Only 4 independent parameters $(m_\chi,\ m_{h_2},\ \sin\theta,\ v_s\ (\lambda_S))$

Direct detection (1-loop level)

D. Azevedo et al., JHEP [arXiv:1810.06105]
K. Ishiwata, TT, JHEP [arXiv:1810.08139]
S. Glaus et al., JHEP [arXiv:2008.12985]

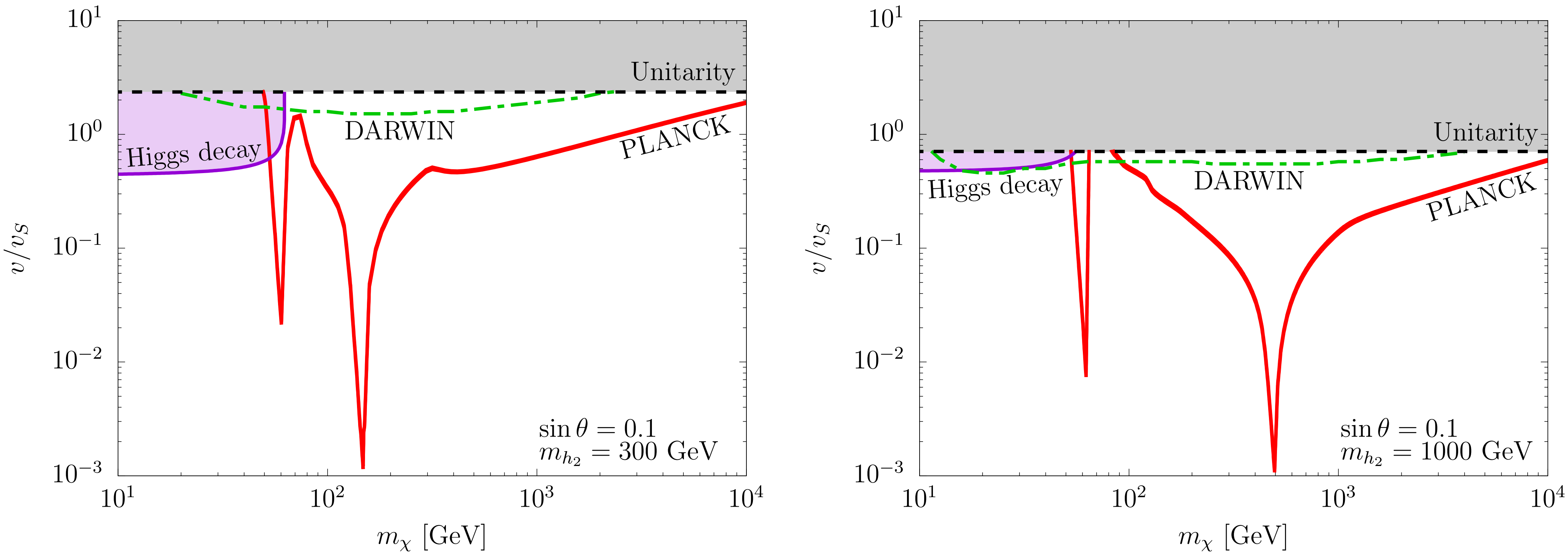
- Compute Feynman diagrams at 1-loop level



- (i) self-energy correction
- (ii) vertex correction
- (iii) box and triangle $\rightarrow$ two Yukawa couplings
  $\rightarrow$ sub-dominant in most cases

Numerical analysis (1-loop level)

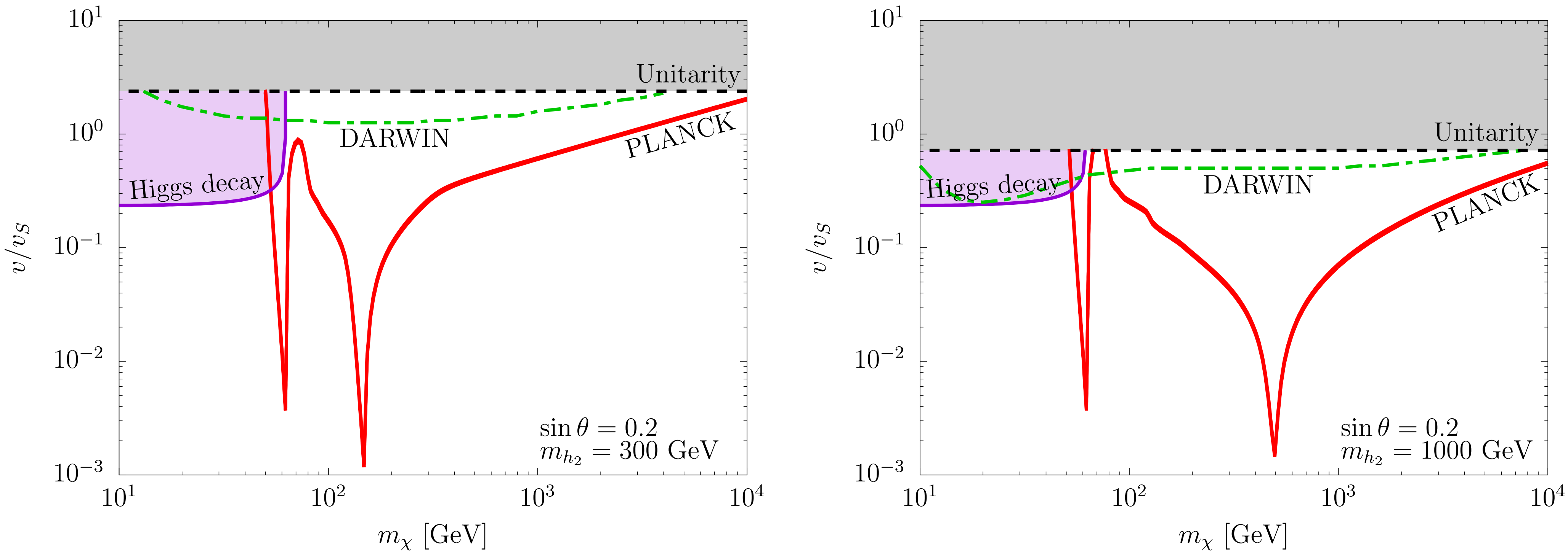
K. Ishiwata, TT, JHEP [arXiv:1810.08139]



- $\sin\theta = 0.1$
- Invisible Higgs decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 20\%$ at LHC
- $\sigma_{\mathrm{SI}}^p = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most
- Unitarity bound: $\lambda_S \leq 8\pi/3$
- More recent calculation: Glaus et al., JHEP 12 (2020) 034 [arXiv:2008.12985]

Numerical analysis (1-loop level)

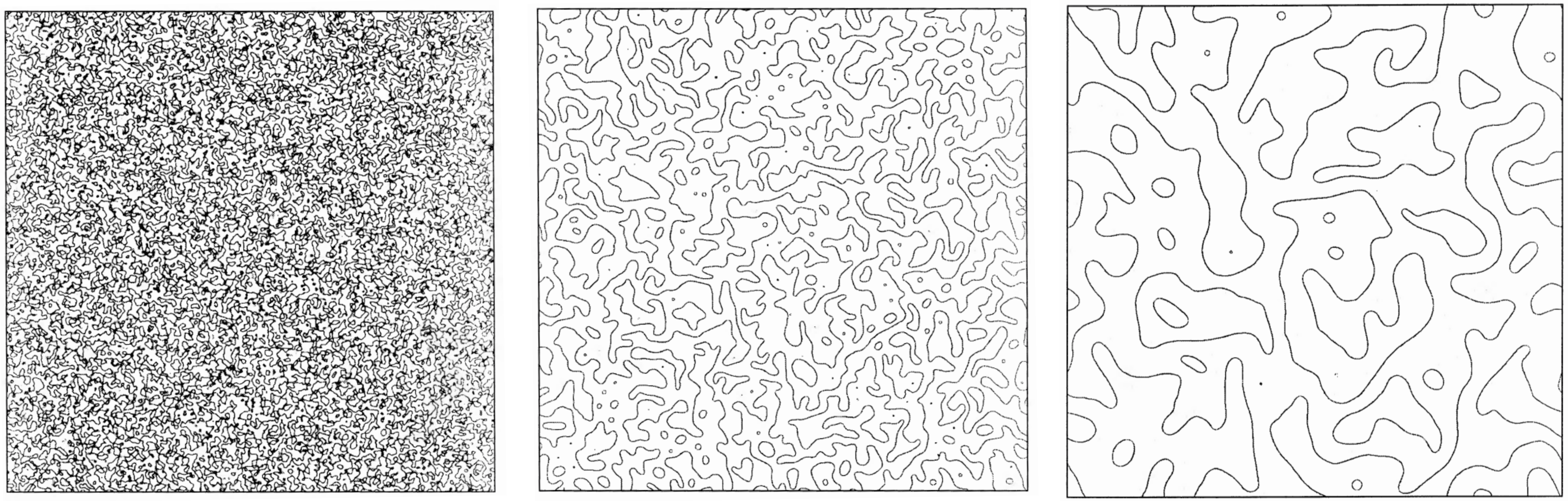
K. Ishiwata, TT, JHEP [arXiv:1810.08139]



- $\sin\theta = 0.2$
- Invisible Higgs decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 20\%$ at LHC
- $\sigma_{\mathrm{SI}}^{p} = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most
- Unitarity bound: $\lambda_S \leq 8\pi/3$
- More recent calculation: Glaus et al., JHEP 12 (2020) 034 [arXiv:2008.12985]

Domain wall problem

- Domain walls due to spontaneous breaking of $\mathbb{Z}_2$ symmetry
  $\Rightarrow$ distort CMB
- Solutions: · UV compeltion
  · low energy inflation after the $\mathbb{Z}_2$ breaking
  · decay before BBN (making the domain wall unstable)



Press, Ryden, Spergel ApJ (1989)

UV completion

Y. Abe, TT, K. Tsumura, JHEP (2020) [arXiv:2001.03954]

- Origin of the soft breaking term? $\frac{m_\chi^2}{4}S^2 + \mathrm{H.c.}$

	Q_L	u_R^c	d_R^c	L	e_R^c	H	ν_R^c	S	Φ
$SU(3)_c$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$+1/6$	$-2/3$	$+1/3$	$-1/2$	$+1$	$+1/2$	0	0	0
$U(1)_{B-L}$	$+1/3$	$-1/3$	$-1/3$	-1	$+1$	0	$+1$	$+1$	$+2$

- Gauged $U(1)_{B-L}$ extension (New fields: ν_R, Φ)
- Potential $\mathcal{V} \supset \mu_c \Phi^* S^2 + \mathrm{h.c.} \to m_\chi^2 S^2$ at low energy
  The soft breaking term is induced.
- 3 ν_R for anomaly cancellation
- Seesaw for ν mass $\mathcal{L} \supset \Phi \nu_R \nu_R$

GUT embedding

Y. Abe, TT, K. Tsumura, N. Yamatsu, PRD (2021) [arXiv:2104.13523]

	fermions	H	S	Φ	~~SO(10)~~

	A_μ	Ψ_{16}	Φ_{10}	Φ_{16}	$\Phi_{\overline{126}}$	Φ_{210}
$SO(10)$	**45**	**16**	**10**	**16**	$\overline{\mathbf{126}}$	**210**

- We embed the UV complete model in SO(10) GUT.
- The pNGB model is reproduced at low energy.
- Breaking pattern: $SO(10) \quad \rightarrow \quad G_{\rm PS} \quad \rightarrow \quad G_{\rm SM}$

  at $\mu = M_U$ at $\mu = M_I$

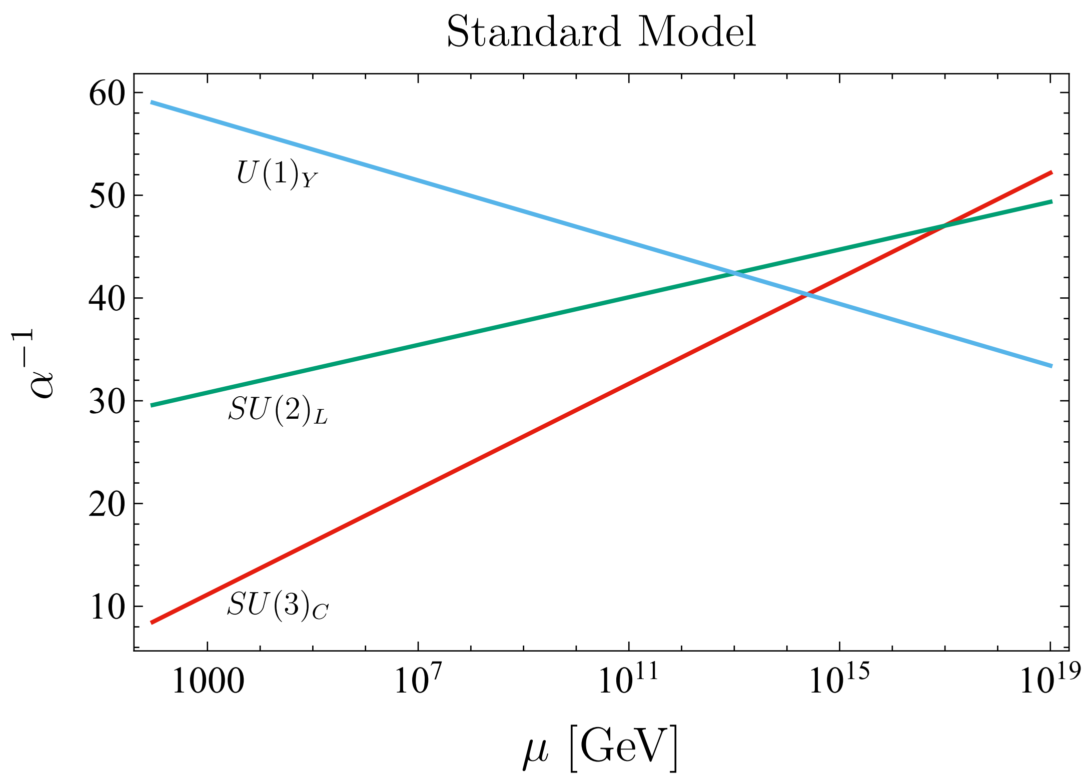
  Pati-Salam symmetry: $G_{\rm PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$
- GUT scale (M_U)

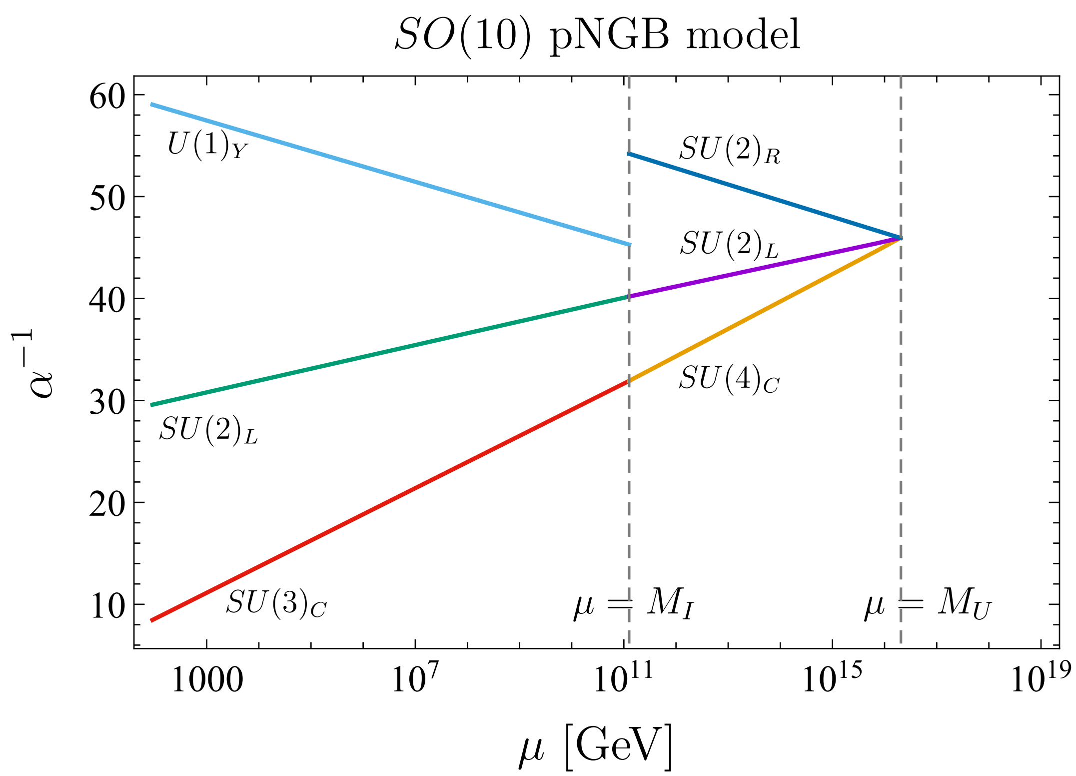
  Intermediate scale (M_I) = breaking scale of $U(1)_{B-L}$,
- Proton decay

  SK limit: $\tau_{p\rightarrow e^+\pi^0}$ >2.4×10^{34} years

  Rough estimate: $\tau \sim (\alpha_U^2 m_p^5/M_U^4)^{-1}$ = 1.1×10^{37} years

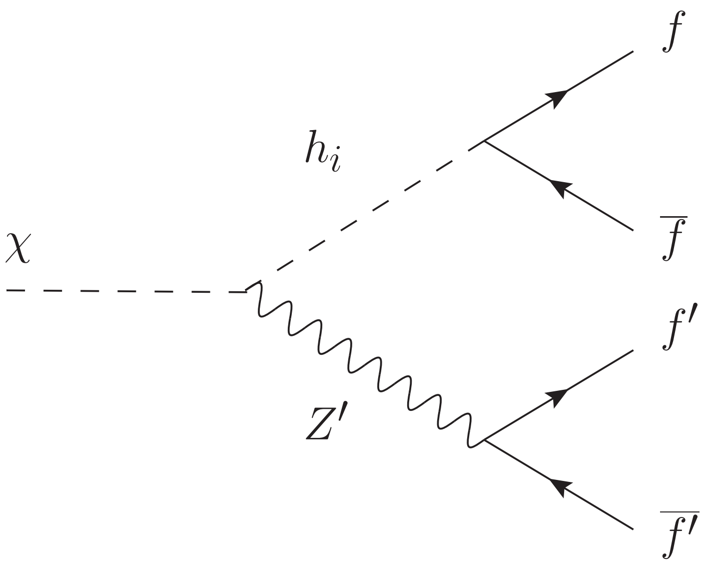
Gauge coupling unification

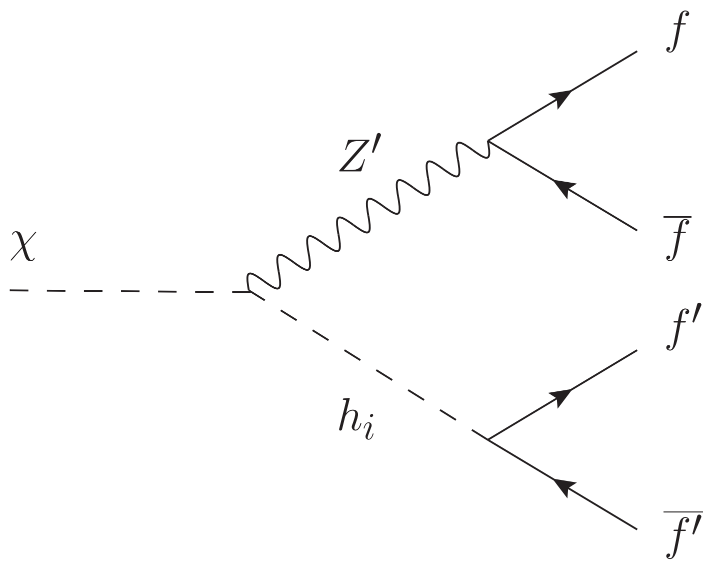




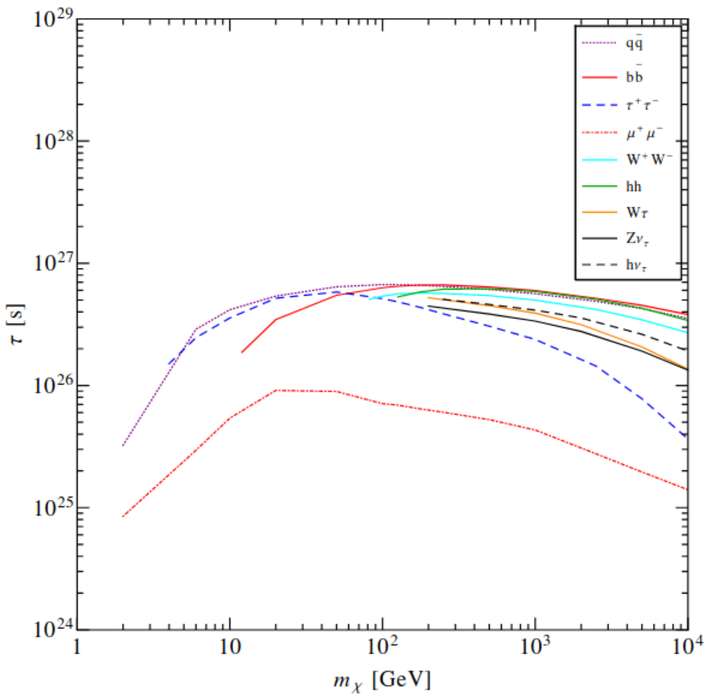
- 1-loop RGEs are solved.
- Intermediate scale, GUT scale: determined by matching conditions of gauge couplings
- $v_\phi = M_I = 1.26 \times 10^{11}$ GeV, $M_U = 2.06 \times 10^{16}$ GeV
  $g_{B-L} = 0.38$ at $\mu = M_I$

DM decay



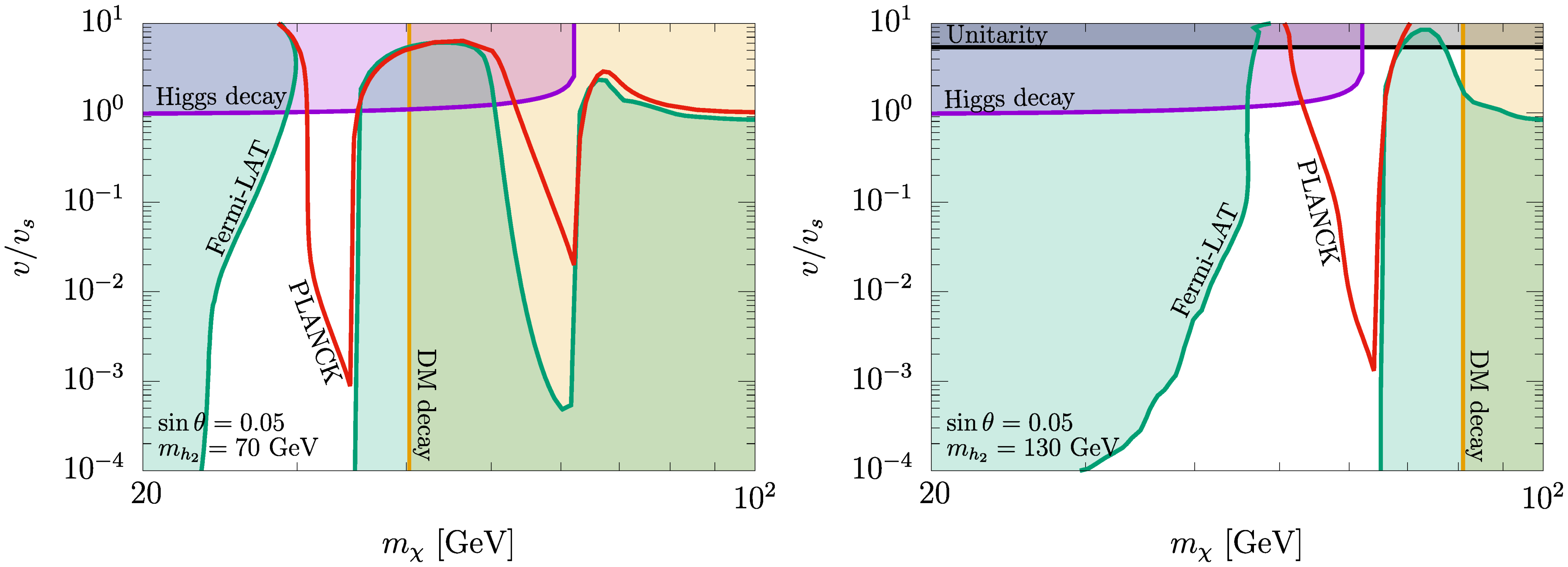


- DM lifetime: $\tau_{\rm DM} \gtrsim 10^{17}$ sec at least (the age of the universe).
- Cosmic ray observations give stronger limits: $\tau_{\rm DM} \gtrsim 10^{27}$ sec.
  3-body decays $\chi \to f\overline{f}h_i, f\overline{f}Z$ if $m_\chi \gtrsim m_{h_i}, m_Z \to$ excluded



Baring et al. (2015)

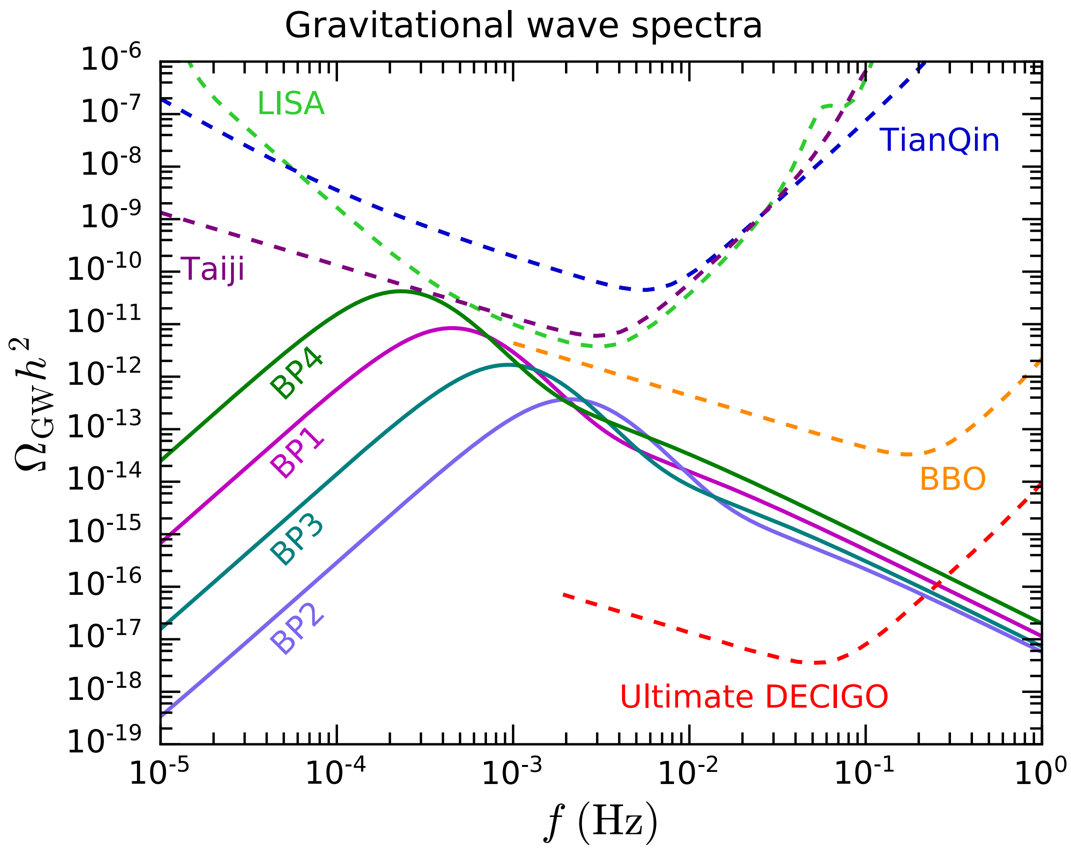
Parameter space



- $v/v_s \sim \sqrt{\lambda_S}$
- Fermi-LAT: $\chi\chi \to b\bar{b}, WW \to \gamma$ production
- close to the h_2 resonance

Other variations of pNGB DM

- THDM + S with global U(1) Zhang, Cai, Jiang, Tang, Yu, Zhang, JHEP 05 (2021) 160
  ⇒ Gravitational waves from strong 1st order phase transition



- pNGB from global SU(2) Abe and Hamada, arXiv: 2205.11919
  ⇒ No domain wall problem, two-component DM

Summary

1. Dark matter direct detection experiments impose the strong bounds on the scattering cross section.
   Wayout: suppression of scattering, sub-GeV mass, very small couplings
2. A pNGB dark matter is a candidate naturally avoiding the bounds.
3. UV completion and GUT embedding have been done.

Back Up

The simplest pNGB DM model

C. Gross, O. Lebedev, TT, PRL (2017)

- χ is mass eigenstate itself $m_\chi^2 = \mu_S'^2$
  Invariant under $S \to S^\dagger$, $\Rightarrow \chi$ can be a DM candidate
- Higgs portal DM
- Scalar potential $\mathcal{V} = \mu_{h_1\chi\chi} h_1 \chi^2 + \mu_{h_2\chi\chi} h_2 \chi^2 + \cdots$

$$\mu_{h_1\chi\chi} = -\frac{m_{h_1}^2 \sin\theta}{v_s}, \quad \mu_{h_2\chi\chi} = \frac{m_{h_2}^2 \cos\theta}{v_s},$$

SM Yukawa int. $\mathcal{L} \supset y_q \Big(\cos\theta h_1 + \sin\theta h_2 \Big) \overline{q} q$

$$\lambda_H = \frac{\cos^2\theta m_{h_1}^2 + \sin^2\theta m_{h_2}^2}{v^2}, \quad \lambda_S = \frac{\sin^2\theta m_{h_1}^2 + \cos^2\theta m_{h_2}^2}{v_s^2},$$

$$\lambda_{HS} = \frac{\sin\theta\cos\theta (m_{h_2}^2 - m_{h_1}^2)}{v v_s}$$

Direct detection (1-loop level)

K. Ishiwata, TT, JHEP [arXiv:1810.08139]

- Compute Feynman diagrams at 1-loop level

$$\sigma_{\rm SI}^N = \frac{1}{\pi}\frac{m_N^2}{(m_\chi + m_N)^2}|f_{\rm scalar}^N|^2$$

where $\frac{f_{\rm scalar}^N}{m_N} = \sum_{q=u,d,s} C_S^q f_{Tq}^N - \frac{8}{9} C_S^G f_{Tg}^N$ (f_{Tq}^N, f_{TG}^N: nucleon matrix elements)

$$\langle N|m_q\bar{q}q|N\rangle = f_{Tq}^N m_N, \quad \langle N|\frac{\alpha_s}{\pi}G_{\mu\nu}^a G^{a\mu\nu}|N\rangle = -\frac{8}{9} f_{Tg}^N m_N$$

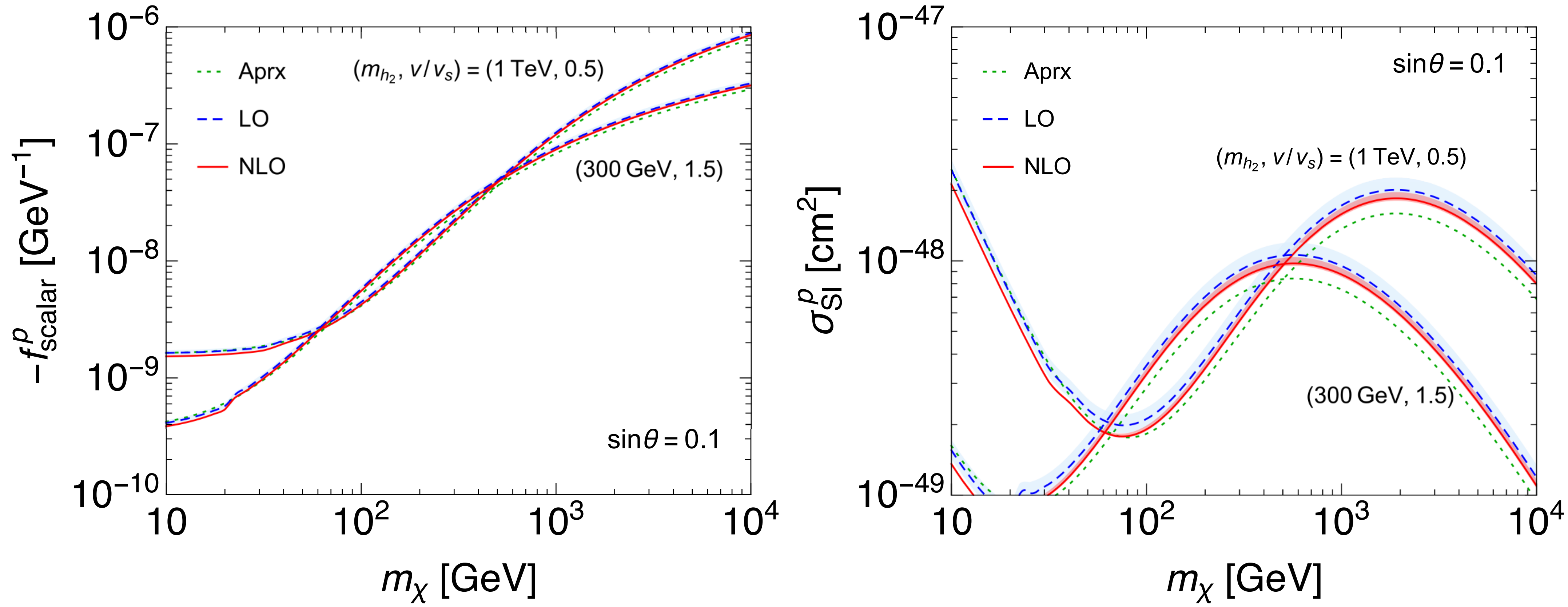
f_{Tq}^N, f_{Tg}^N are calculated by QCD lattice simulation

$$\mathcal{L}_{\rm eff} = C_S^q m_q \chi^2 \bar{q}q + C_S^G \frac{\alpha_s}{\pi}\chi^2 G_{\mu\nu}^a G^{a\mu\nu} \quad \leftarrow C_S^q \text{ and } C_S^G \text{ (calculated)}$$

- Calculate up to 2-loop level in terms of QCD α_s (NLO)
  $\rightarrow$ scattering amplitude is $\mathcal{O}(\alpha_s)$ J. Hisano, K. Ishiwata, N. Nagata, arXiv:1504.00915

Direct detection (1-loop level)

K. Ishiwata, TT, JHEP [arXiv:1810.08139]



- (i)+(ii) is dominant for large DM mass
- NLO is $\mathcal{O}(10\%)$ correction

Origin of the soft term

C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

- $U(1)$ is extended to gauge symmetry, and a new field Φ is introduced
- Odd charge for S, even charge for Φ

  Ex. $q_S = 3$, $q_\Phi = 2$

$$\mathcal{V} \supset \frac{1}{\Lambda}\Phi^{\dagger 3}S^2 + \frac{1}{\Lambda^3}\Phi^{\dagger 3}|H|^2 S^2 + \frac{1}{\Lambda^3}\Phi^{\dagger 3}|S|^2 S^2 + \cdots$$

- After Φ gets a VEV, μ_S' is generated $(\mu_S'^2 = \langle\Phi\rangle^3/\Lambda)$
- Other terms are suppressed by higher dimensional operators

  $\rightarrow$ the previous model is reproduced in low energy

- CP violation induces DM decay

$$\mathcal{V} \supset \left(\frac{\langle\Phi\rangle}{\Lambda}\right)^3 |H|^2 s\chi \quad \rightarrow \text{lifetime} \;\; \tau_\chi \sim \frac{8\pi}{100\ \mathrm{GeV}}\left(\frac{\Lambda}{\langle\Phi\rangle}\right)^6$$

Ex. when $\Lambda = 10^{16}\ \mathrm{GeV}$, $\langle\Phi\rangle = 10^7\ \mathrm{GeV} \Rightarrow \tau_\chi \sim 10^{29}\ \mathrm{s}$

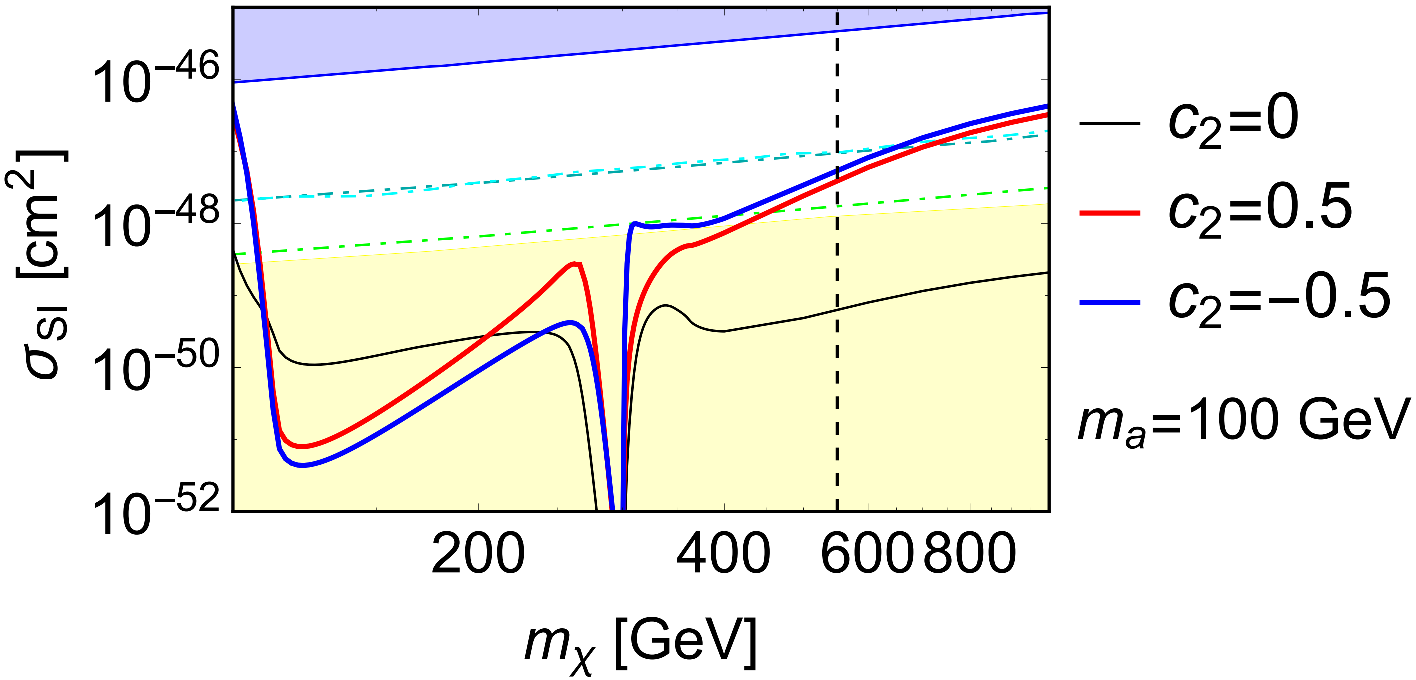
Majorana DM model

G. Arcadi et al., JCAP 1803 (2018), T. Abe et al. arxiv:1810.01039, $\cdots$

Majorana DM interacting with pseudo-scalar

$$\mathcal{L} \supset \frac{g_\chi}{2} a \overline{\chi}\gamma_5\chi - c_2 a^2 |H_2|^2 + \cdots \quad \rightarrow \quad i\mathcal{M} \sim \overline{u}\gamma_5 u \sim \boldsymbol{q}\cdot\boldsymbol{J}_{1/2}$$

- Two Higgs Doublet + fermion DM (χ) + pseudo-scalar (a).
- Tree level amplitude vanishes in non-relativistic limit



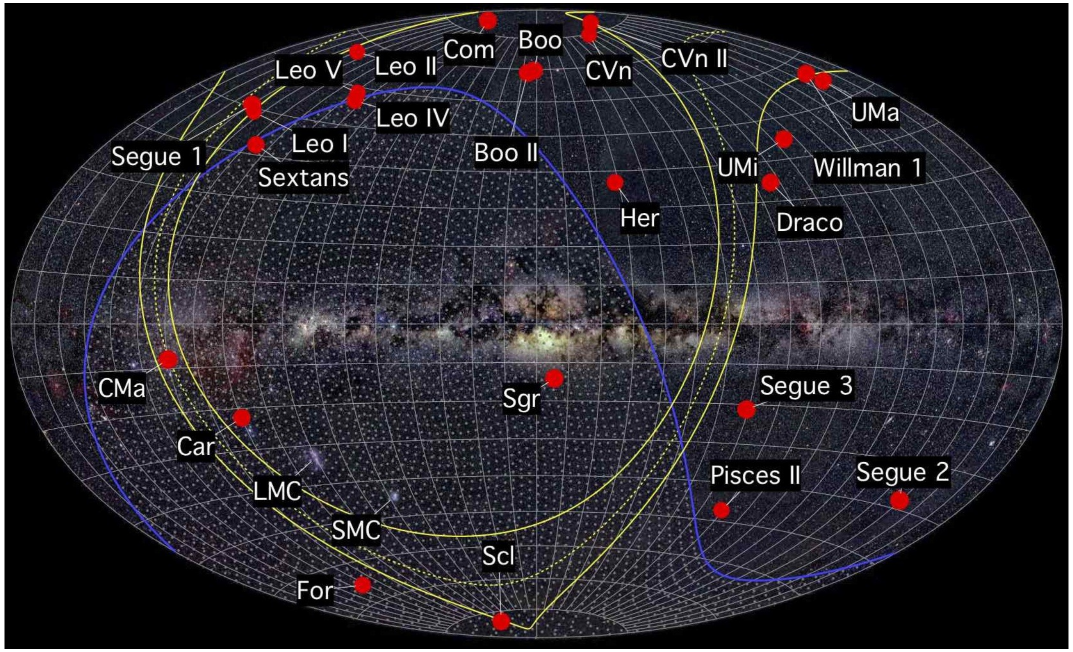
- 1-loop contribution is dominant
- c_2 coupling enhances $\sigma_{\rm SI}$

Indirect detection

DM annihilations

$\chi\chi \to h_i h_j, WW, ZZ, f\overline{f}$

- Gamma-rays are produced at the end
- Constraints from dSphs (less visible matter and more DM)



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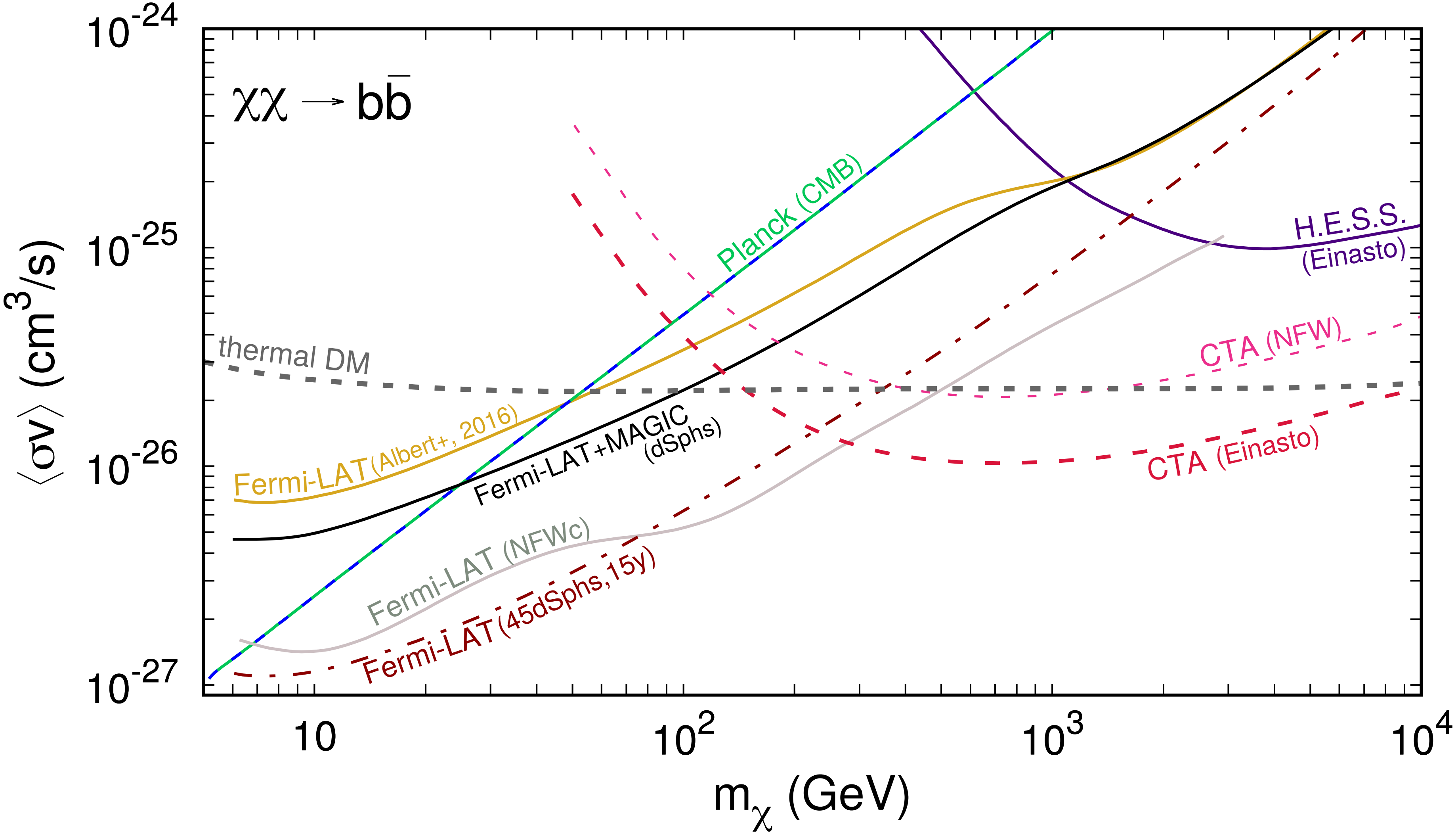
- $\mathcal{O}(50)$ dSphs have been found so far.
- DM models are constrained.

Indirect detection

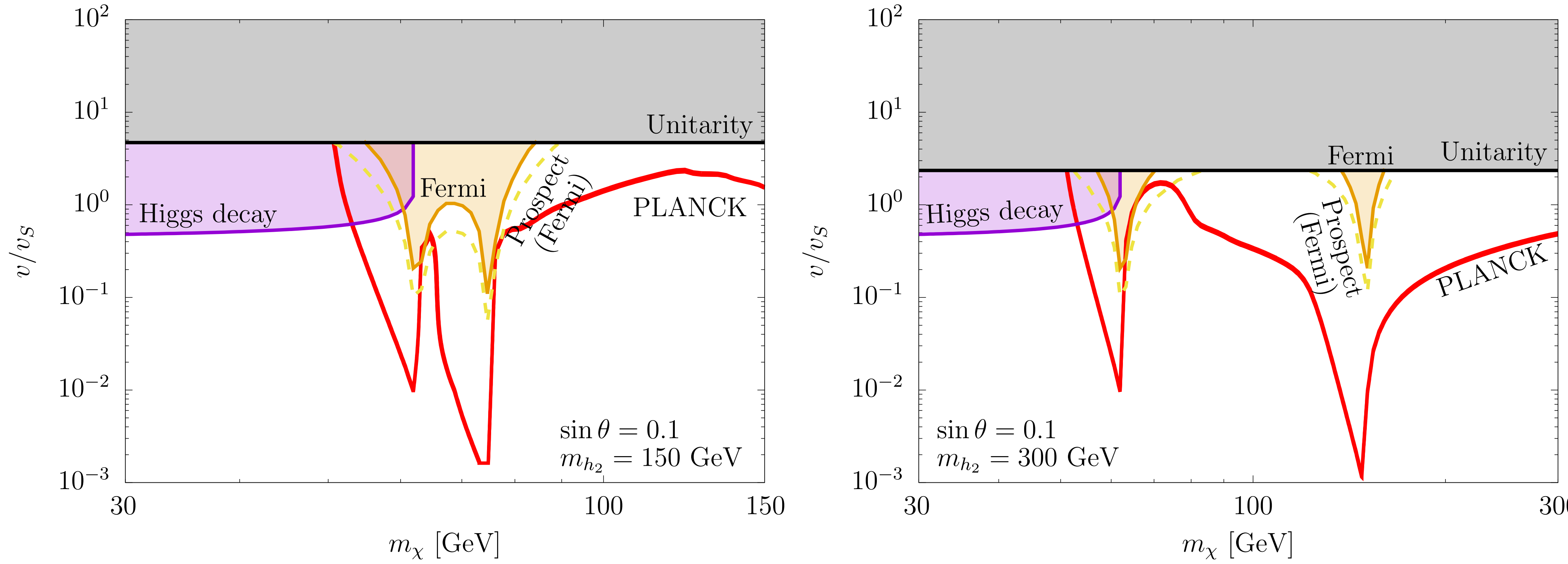
- Present bounds and future prospects ($\chi\chi \to b\bar{b}$)



L. Roszkowski et al., Rept.Prog.Phys. 81 (2018), [arXiv:1707.06277]

Indirect detection

Huitu, Koivunen, Lebedev, Mondal, TT, arXiv:1812.05952



- Small parameter space is excluded by Fermi-LAT gamma-ray observation
- Thermal WIMP scenarios can be tested only when $m_\chi = \mathcal{O}(100)$ GeV
- CTA is sensitive in heavy DM mass region (DM profile dependent) ($\chi\chi \to h_2 h_2$ may dominate in this mass range)

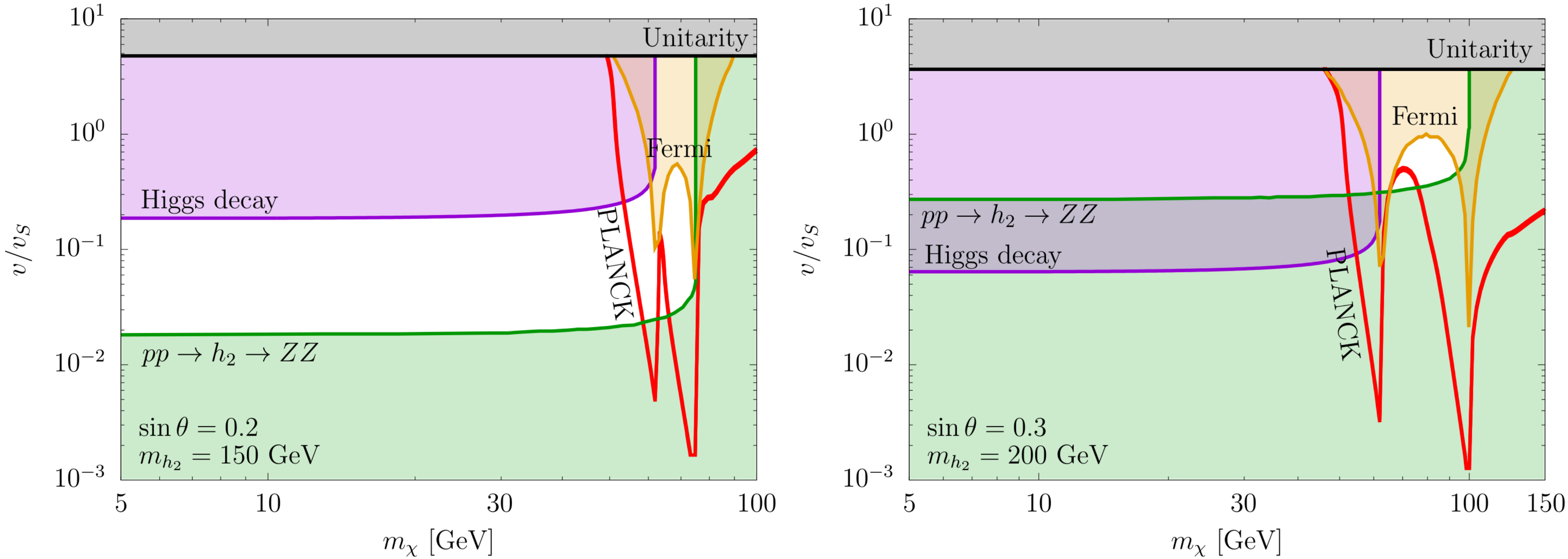
Collider search

Huitu, Koivunen, Lebedev, Mondal, TT, PRD (2019) [arXiv:1812.05952]

- Constraint on h_2 production cross section at LHC

$$\sigma_{\rm prod} = \sigma(pp \to h_2)\ {\rm Br}(h_2 \to {\rm SM}) \quad \propto \quad \sin^2\theta\ {\rm Br}(h_2 \to {\rm SM})$$

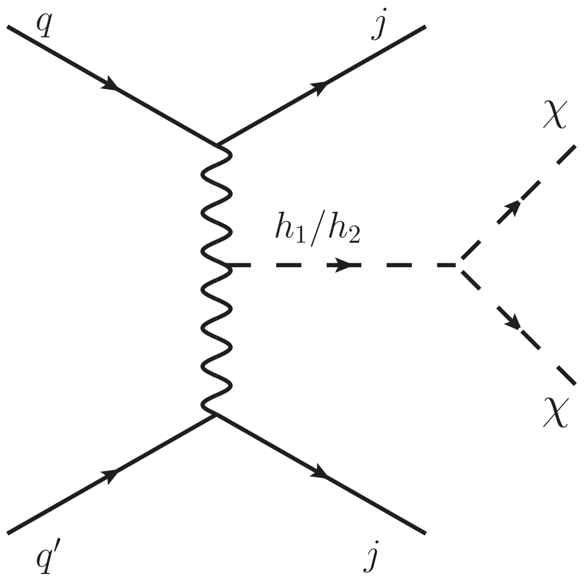
- $pp \to h_2 \to ZZ$ mode
  When $\sin\theta \gtrsim 0.2$ and $m_{h_2} \lesssim 2m_{h_1}$, parameters are constrained.



Collider search

Huitu, Koivunen, Lebedev, Mondal, TT, PRD (2019) [arXiv:1812.05952]

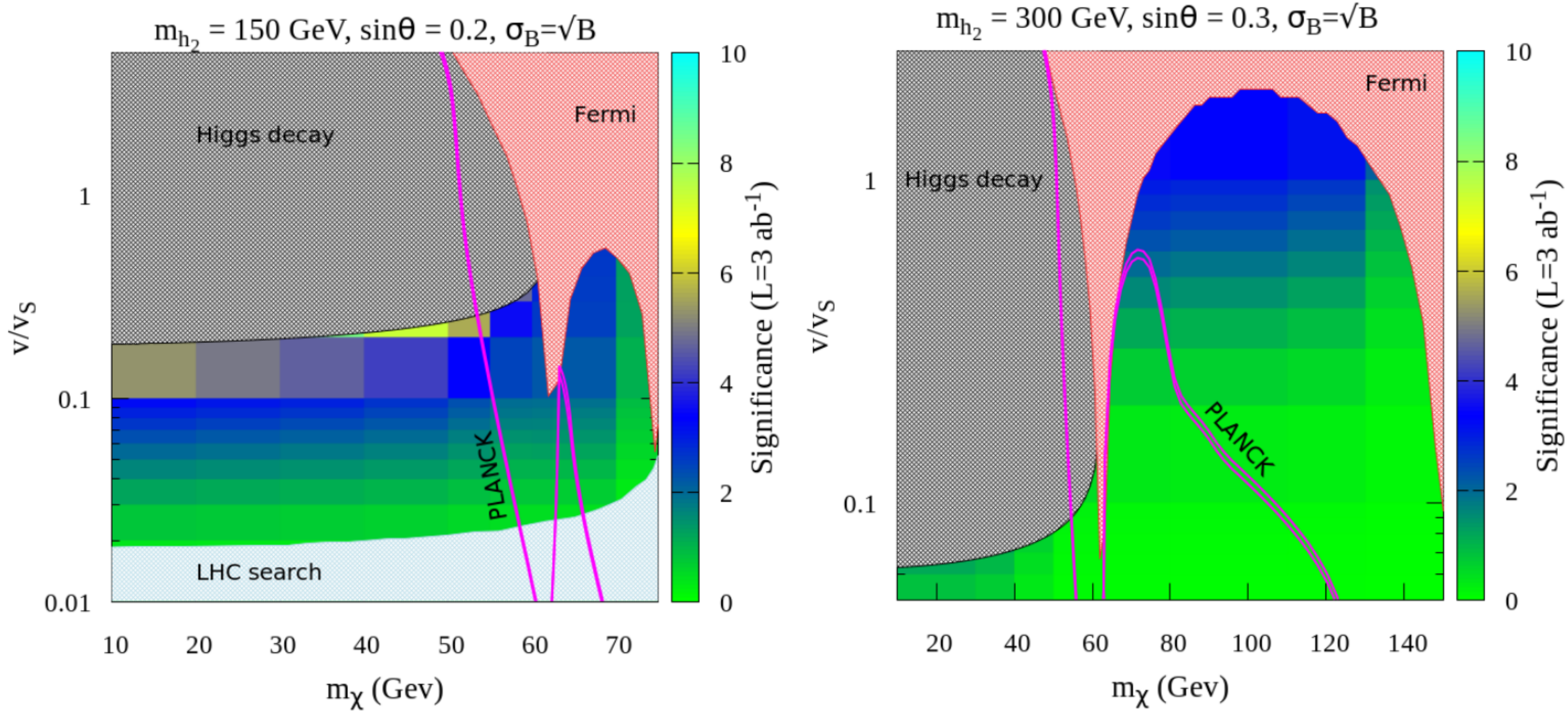
- Signal channel (VBF)
  h_1 and h_2, both contributions are important
- We focus on $m_{h_2} \geq 2m_\chi$
- Simulate the events and put appropriate cuts
  $\not{E}_T > 250$ GeV, $p_j > 80$ GeV etc



- Signal significance $\mathcal{S} = \dfrac{S}{\sqrt{S + B + \sigma_B^2}}$
- Background $B \pm \sigma_B = 1779 \pm 96$ at $35.9\ \mathrm{fb}^{-1}$ (CMS)
- Analyzed with $3000\ \mathrm{fb}^{-1}$.

Collider search

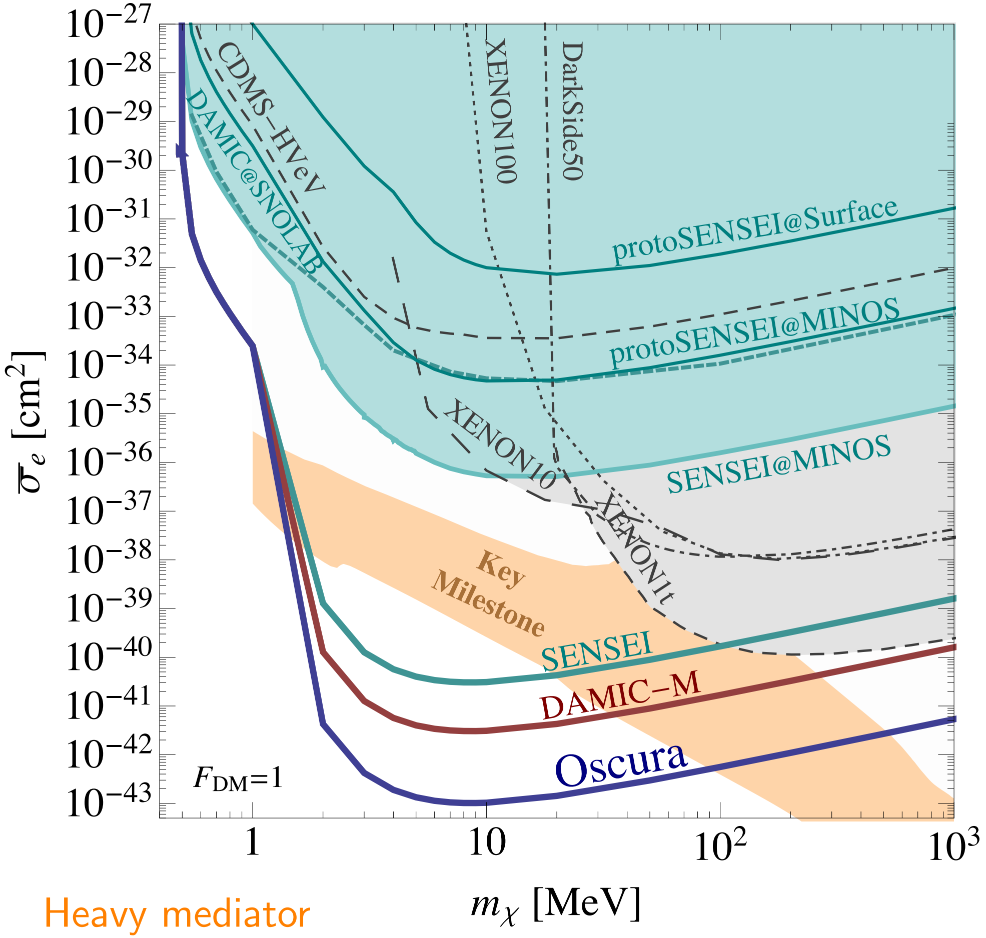
Huitu, Koivunen, Lebedev, Mondal, TT, PRD (2019) [arXiv:1812.05952]



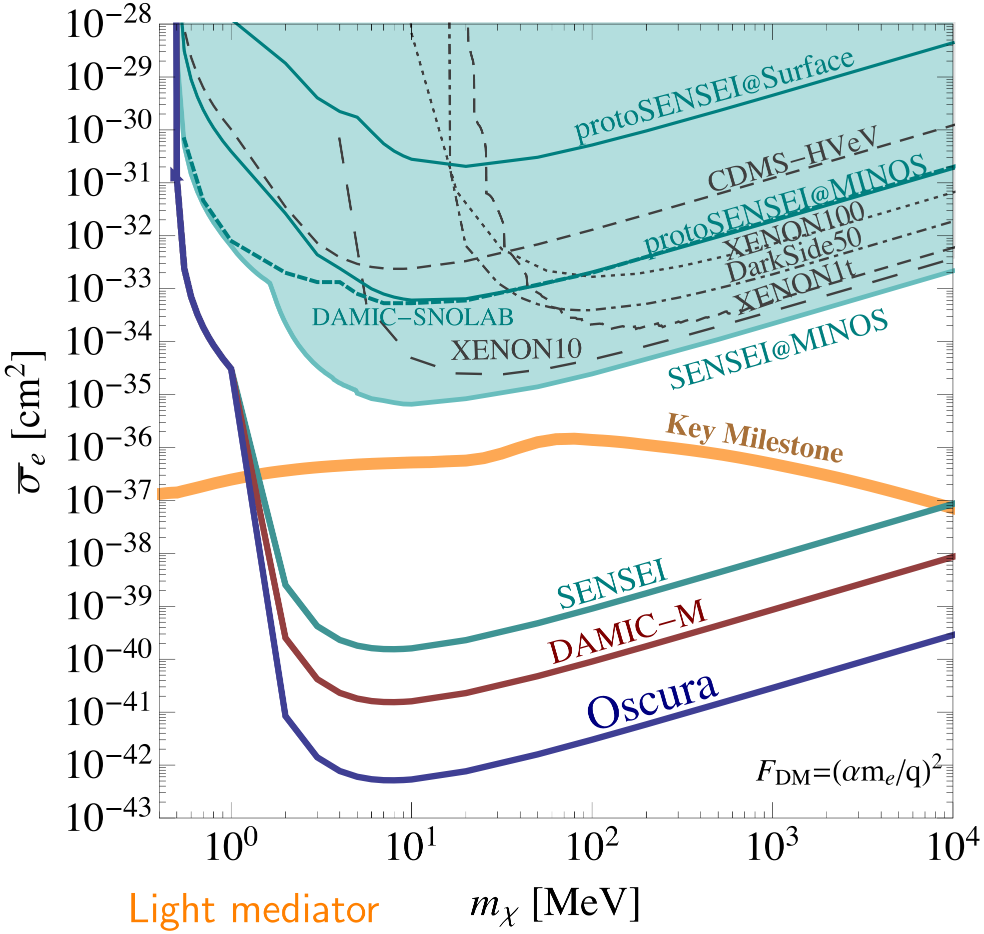
- Signal significance can be $\mathcal{S} \approx 4 - 6$ at most.
- $m_\chi \lesssim 100$ GeV can be visible.

Direct detection for light DM (electron scattering)

Aguilar-Arevalo et al., arXiv:2202.10518



Heavy mediator



Light mediator

- SENSEI: ongoing, Oscura: next generation
- 7–8 orders of magnitude improvement is expected.