Pseudo Nambu Goldstone dark matter

Takashi Toma

XIth International Symposium: Quantum Theory and Symmetries
at University of Montreal

Based on PRL 119 191801, JHEP 1812 (2018) 089,
PRD [arXiv:1812.05952], arXiv:1906.02175

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Outline

1. Introduction
   - Dark matter
   - WIMP

2. Pseudo-Goldstone dark matter
   - Model
   - Direct detection (tree, 1-loop)
   - Indirect detection (gamma rays and anti proton cosmic rays)
   - Collider search

3. Summary

Dark matter

Albada et al. ApJ (1985)

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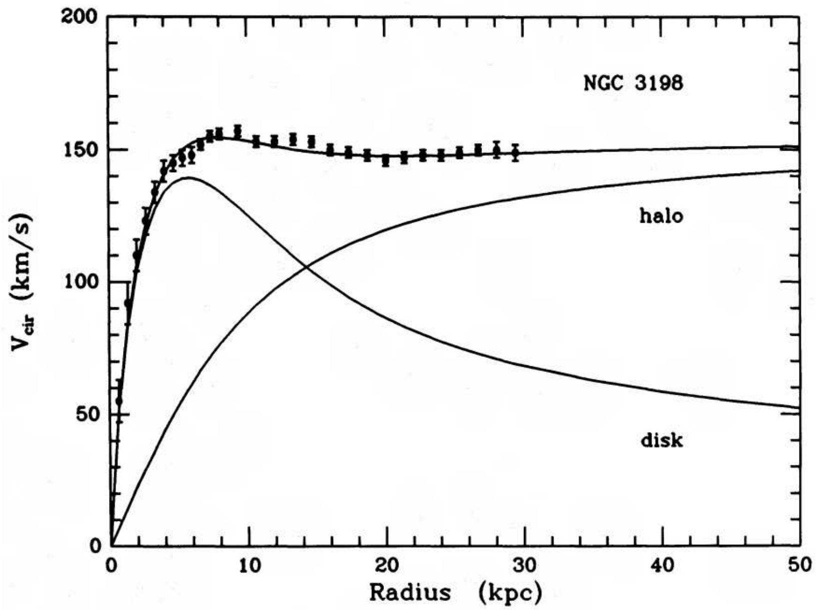
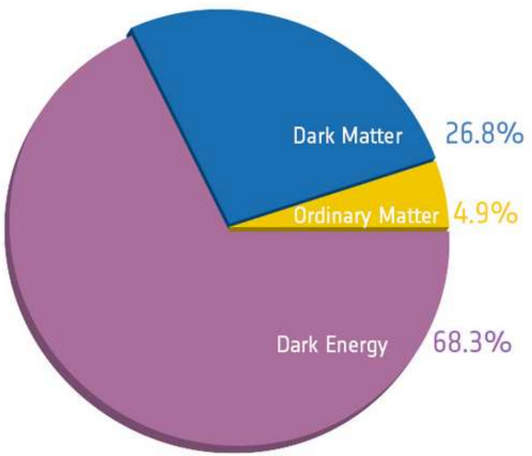
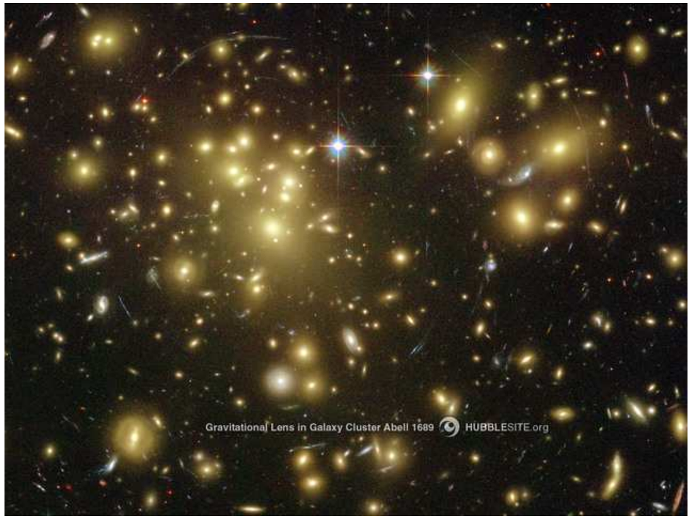
There is a lot of evidence of dark matter.

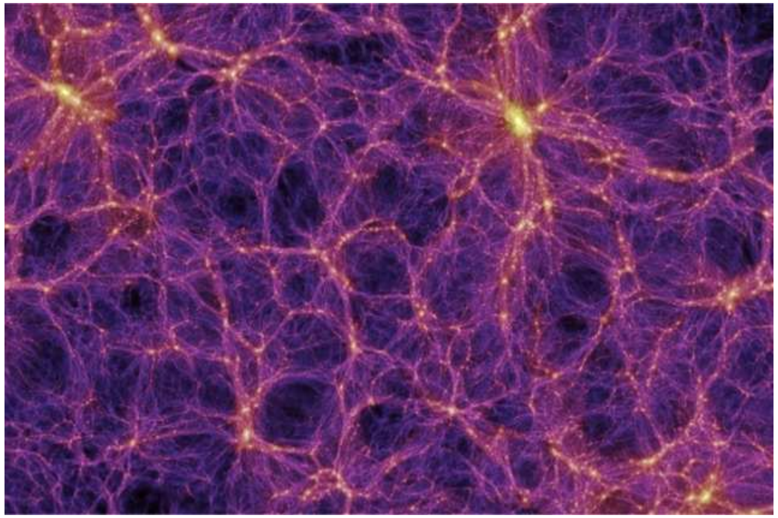
- Rotation curves of spiral galaxies
- CMB observations
- Gravitational lensing
- Large scale structure of the universe
- Bullet cluster

DM existence is crucial.









Dark matter

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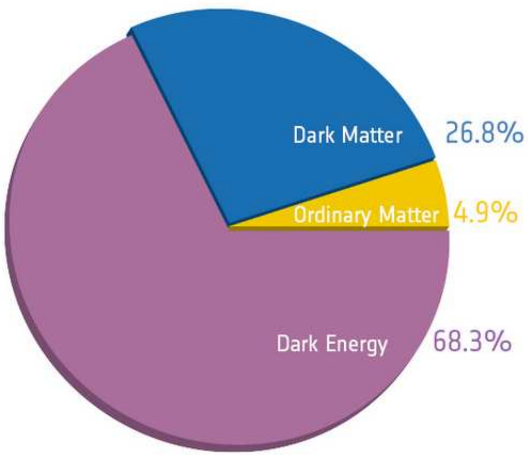
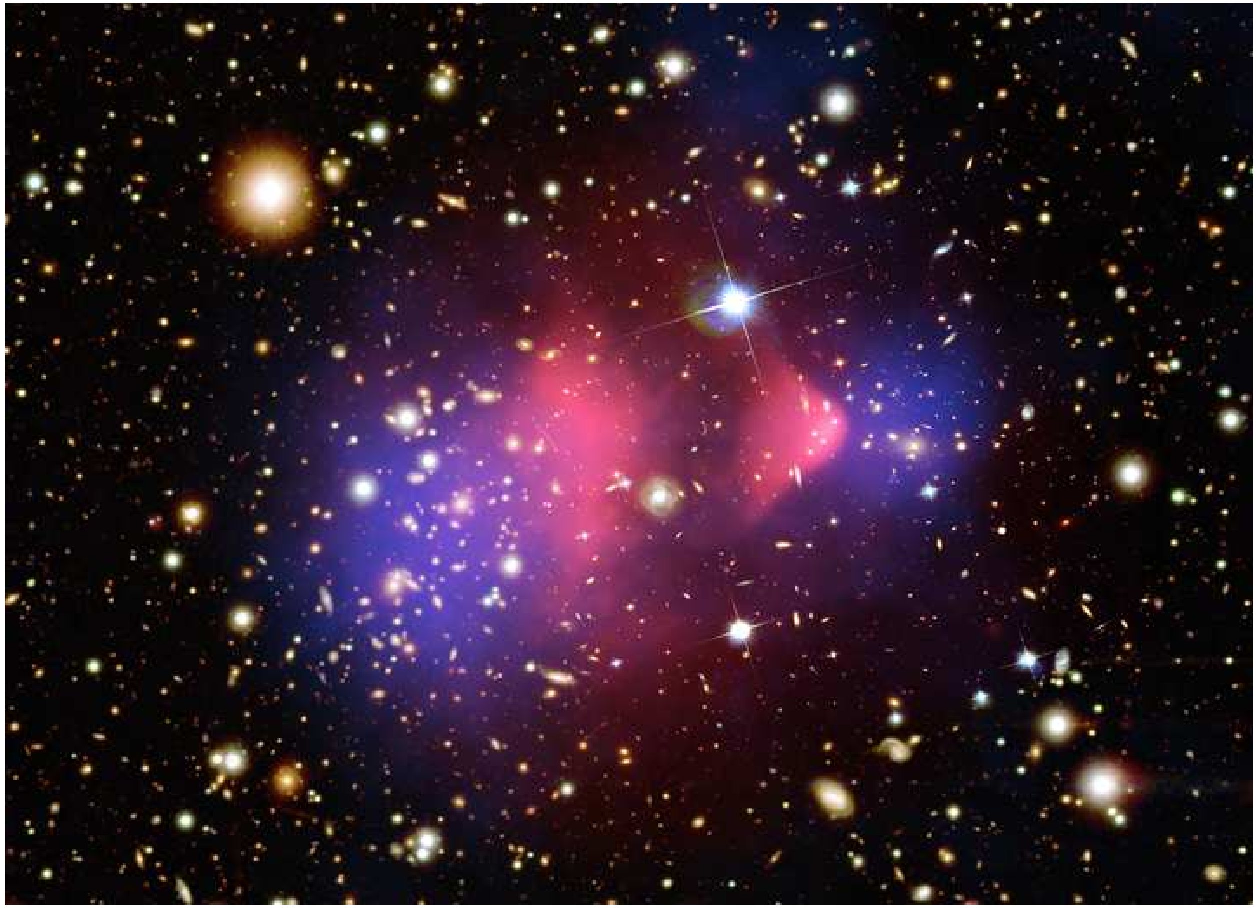
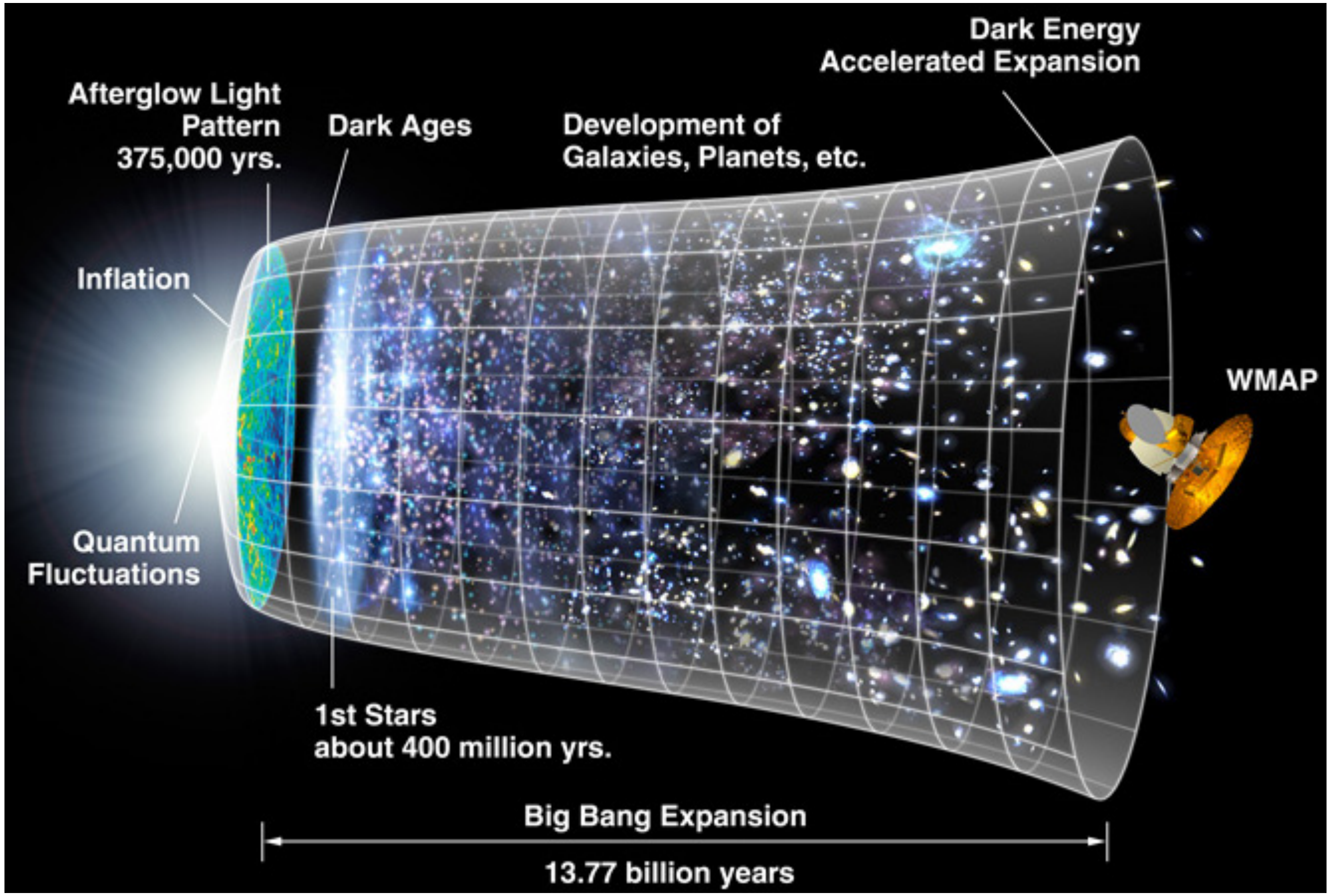




Nature of DM

- Stable (at least longer than age of universe)
- Electrically neutral (may have very small charge)
- Occupy 27% of energy density of the universe
- Graviational interaction
- Non-relativistic (cold)

Good candidates:
WIMP, FIMP, SIMP, axion, sterile neutrino, PBHs etc
$\uparrow$
Revived by recent observations of gravitational waves

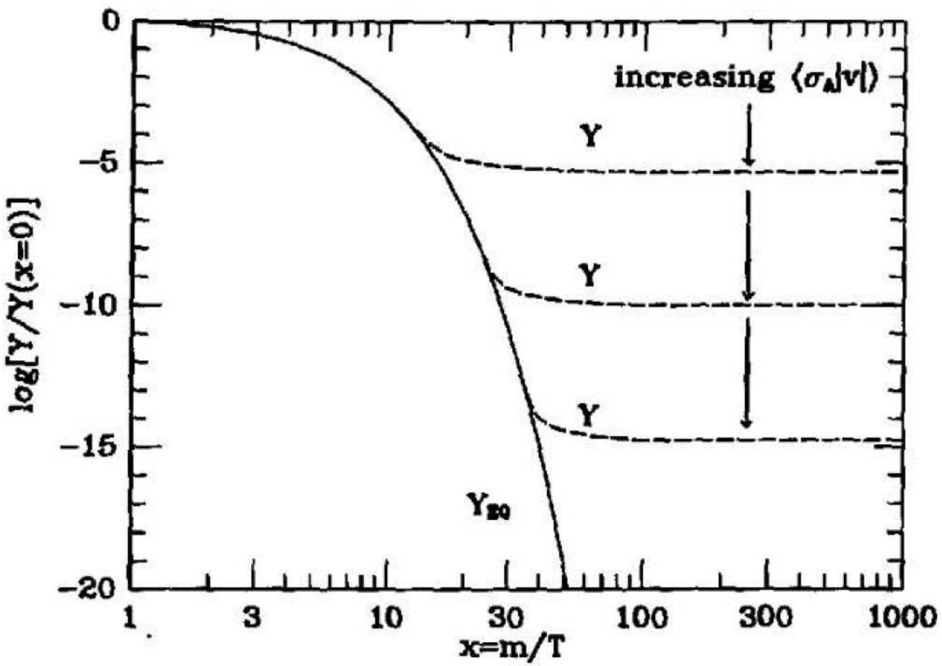


WIMP production

Evolution of DM number density follows the Boltzmann eq.

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

change variables $t \leftrightarrow x \equiv \frac{m}{T}, \quad n_\chi \leftrightarrow Y \equiv \frac{n_\chi}{s}, \quad \Gamma \equiv \langle\sigma v\rangle n_\chi^{\mathrm{eq}},$



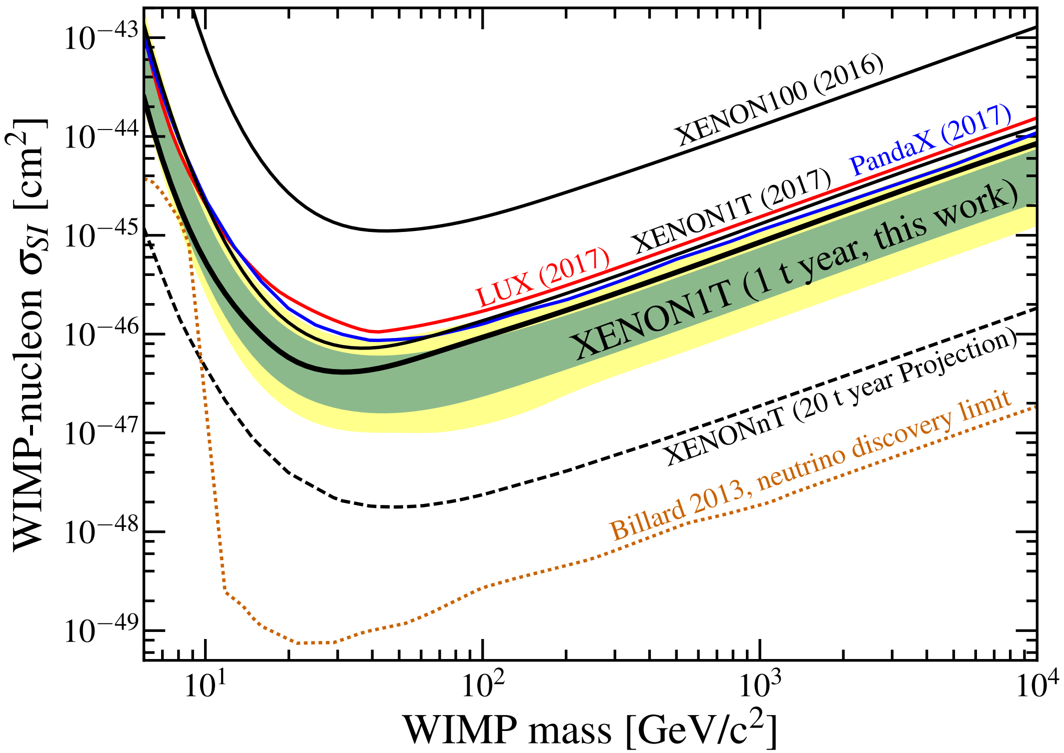
- DM relic is determined by $\langle\sigma v\rangle$.
- σv can be expanded by v.
- $\Omega h^2 \sim \frac{10^{-10}\ [\mathrm{GeV}^{-2}]}{\langle\sigma v\rangle} \sim 0.1$

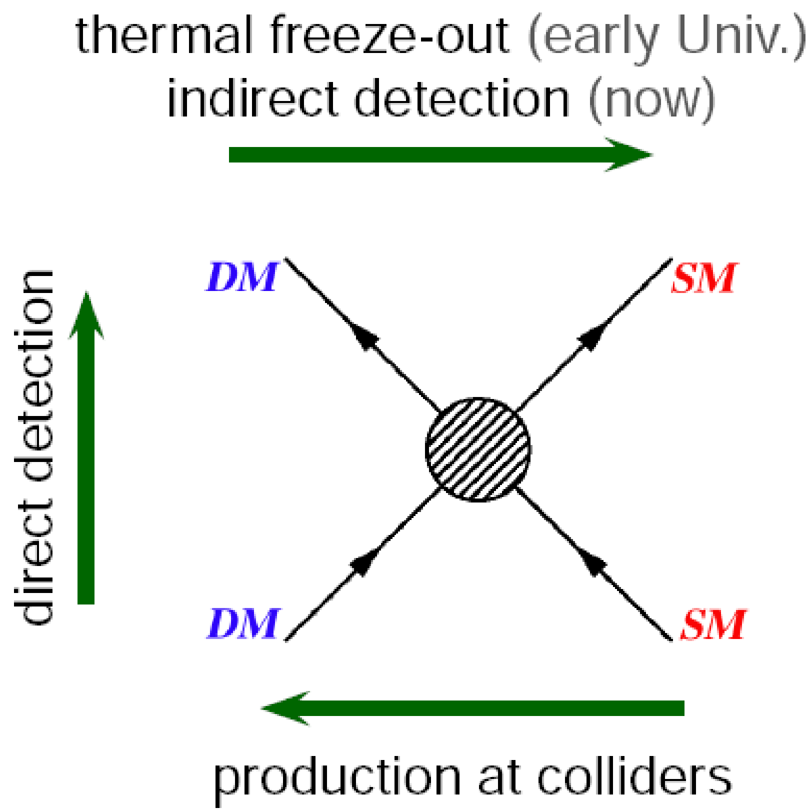
(Planck Collaboration Data)

$$\rightarrow \langle\sigma v\rangle \sim 10^{-9}\ [\mathrm{GeV}^{-2}] \sim 10^{-26}\ [\mathrm{cm}^3/\mathrm{s}]$$

WIMP search status

Direct detection XENON1T, PRL (2018)





- Experimental bounds are stronger and stronger.
- Interactions between DM and SM are very weak? $\rightarrow$ non-WIMP DM?

In this talk, I will consider a simple DM model which naturally evades the strong DD constraint.

Pseudo Nambu Goldstone DM

Model of pseudo-Goldstone DM

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

- Introduce complex scalar field $S = (s + i\chi)/\sqrt{2}$
- Assume global $U(1)$ symmetry (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

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

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

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

Model of pseudo-Goldstone DM

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

- 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
- 4 independent parameters $(m_\chi,\ m_{h_2},\ \sin\theta,\ v_s\ (\lambda_S))$

- Rewrite scalar potential $\mathcal{V} = \mu_{h_1\chi\chi} h_1 \chi^2 + \mu_{h_2\chi\chi} h_2 \chi^2 + \cdots$

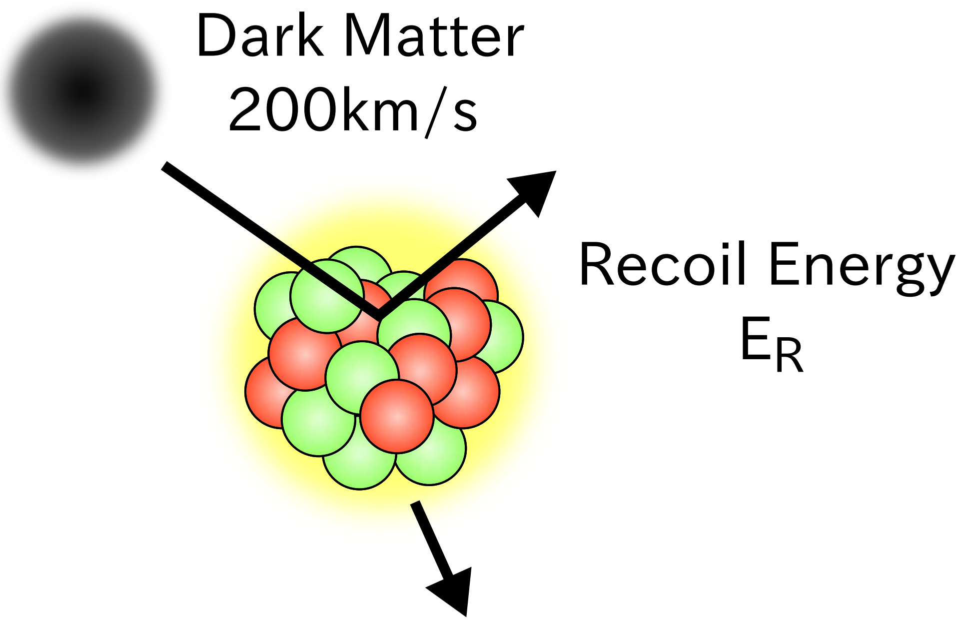
$$\mu_{h_1\chi\chi} = -\frac{m_{h_1}^2 \sin\theta}{v_s}, \quad \mu_{h_2\chi\chi} = \frac{m_{h_2}^2 \cos\theta}{v_s},$$

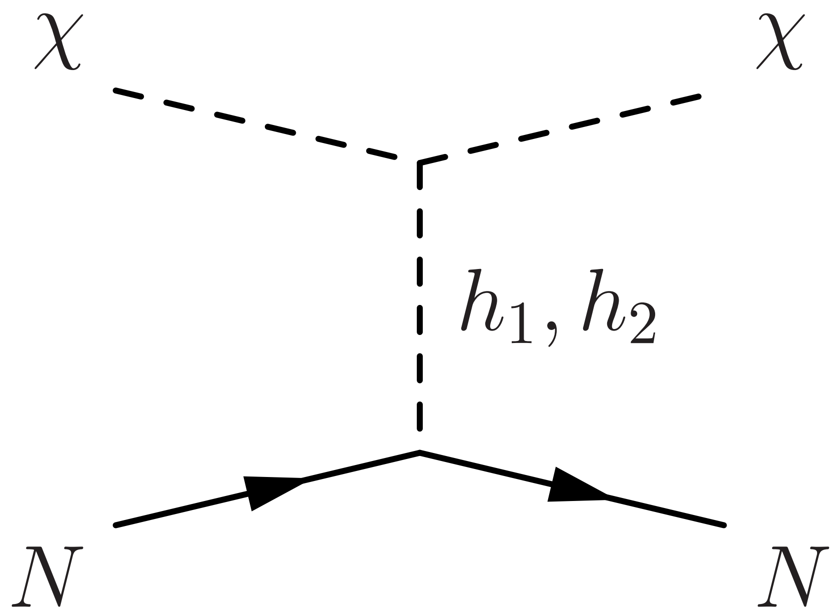
SM Yukawa int. $\mathcal{L} \supset -y_q \Big(\cos\theta h_1 + \sin\theta h_2\Big)\overline{q}q$

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

Direct detection (tree level)

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





- Scattering amplitude cancels between h_1, h_2 mediated diagrams

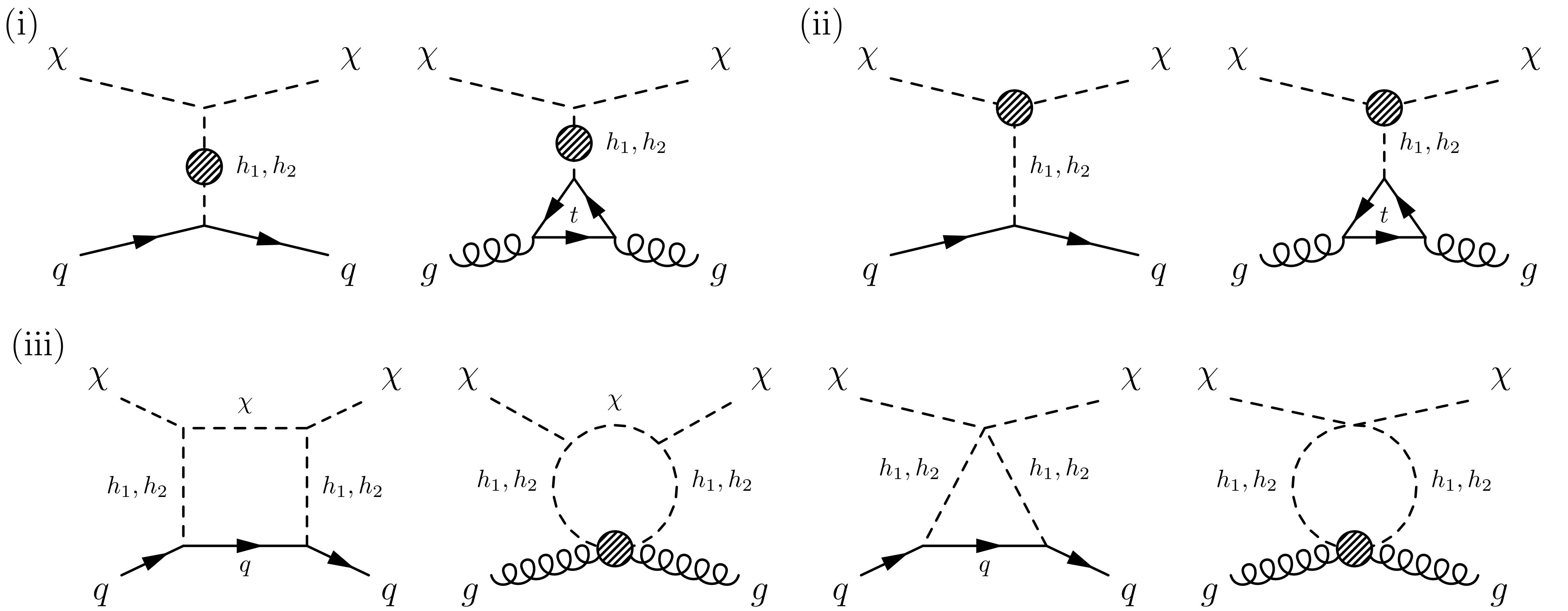
$$i\mathcal{M} \sim i\left(\frac{m_{h_1}^2}{q^2 - m_{h_1}^2} - \frac{m_{h_2}^2}{q^2 - m_{h_2}^2}\right) \sim i\frac{q^2(m_{h_1}^2 - m_{h_2}^2)}{m_{h_1}^2 m_{h_2}^2}$$

- The cancellation happens because of nature of Goldstone boson $\rightarrow \mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}(\partial_\mu \chi)$

Direct detection (1-loop level)

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

- Compute Feynman diagrams at 1-loop level

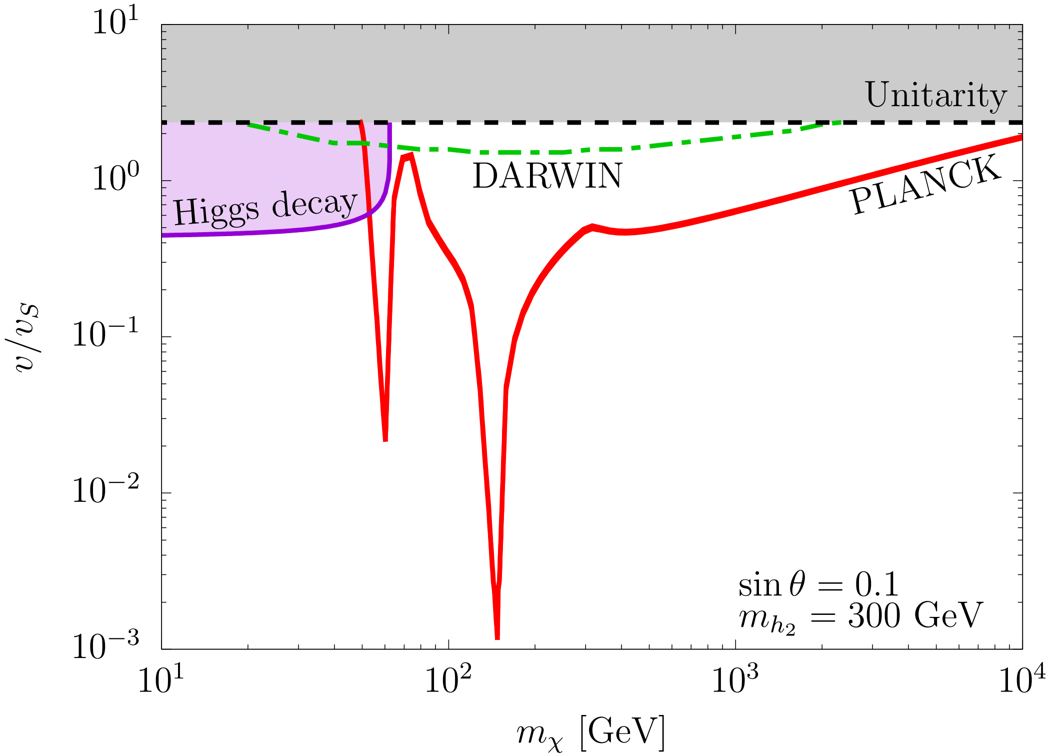


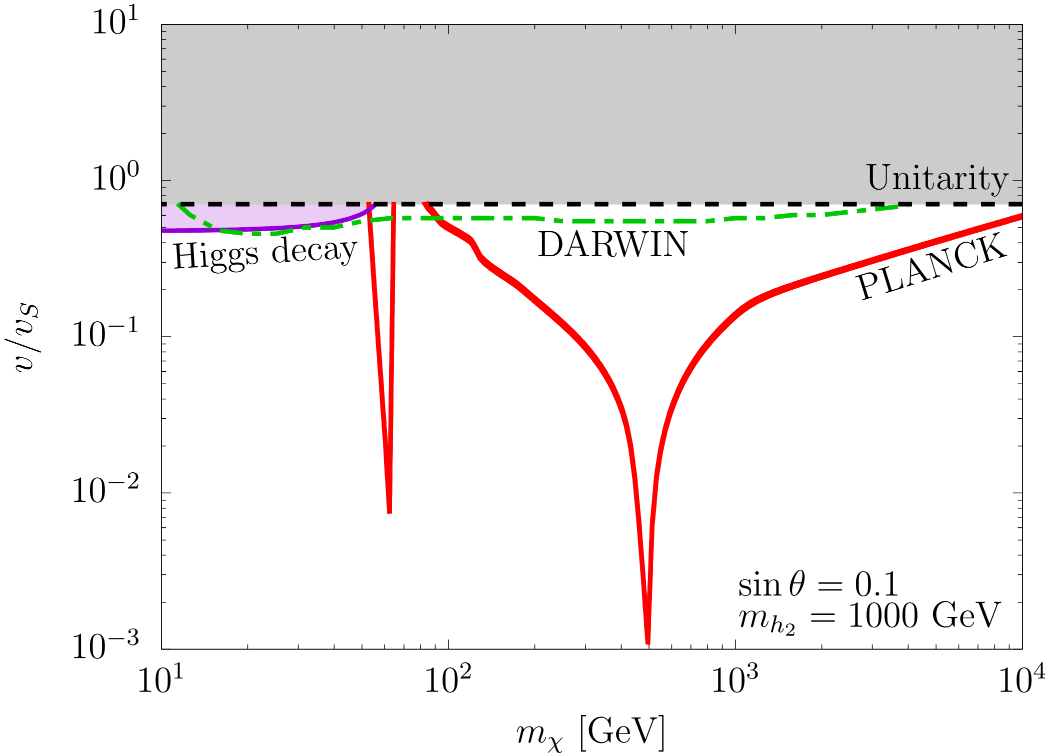
- (i) self-energy correction
- (ii) vertex correction
- (iii) box and triangle $\rightarrow$ two Yukawa couplings

  $\rightarrow$ sub-dominant in most cases

Numerical analysis (1-loop level)

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

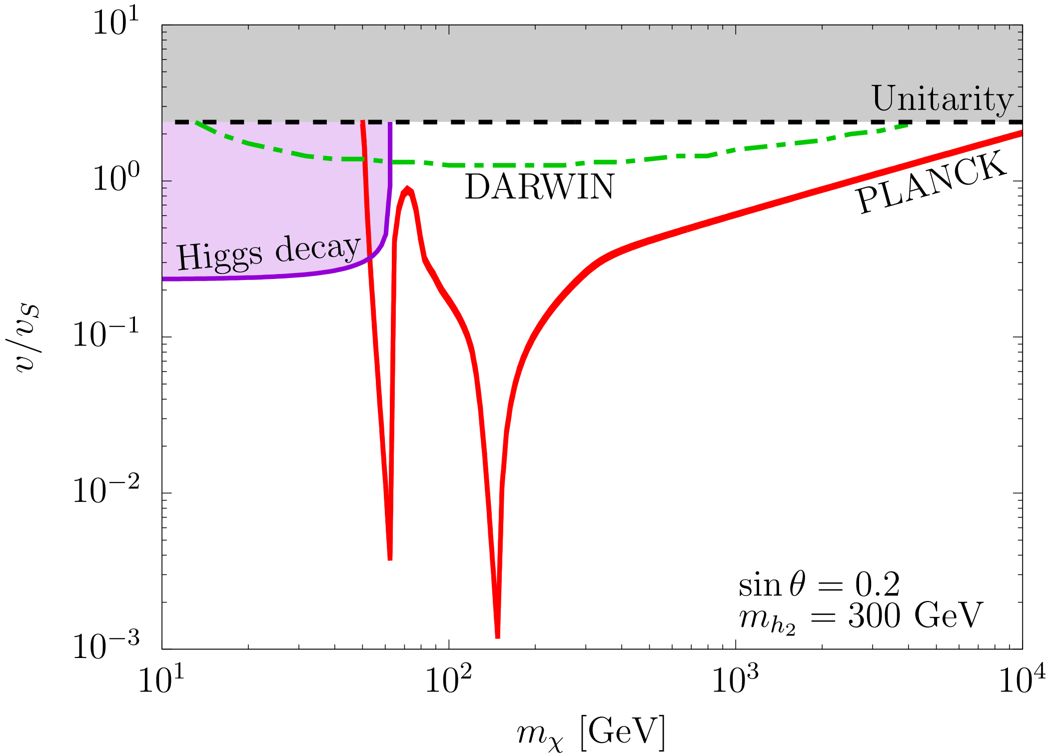


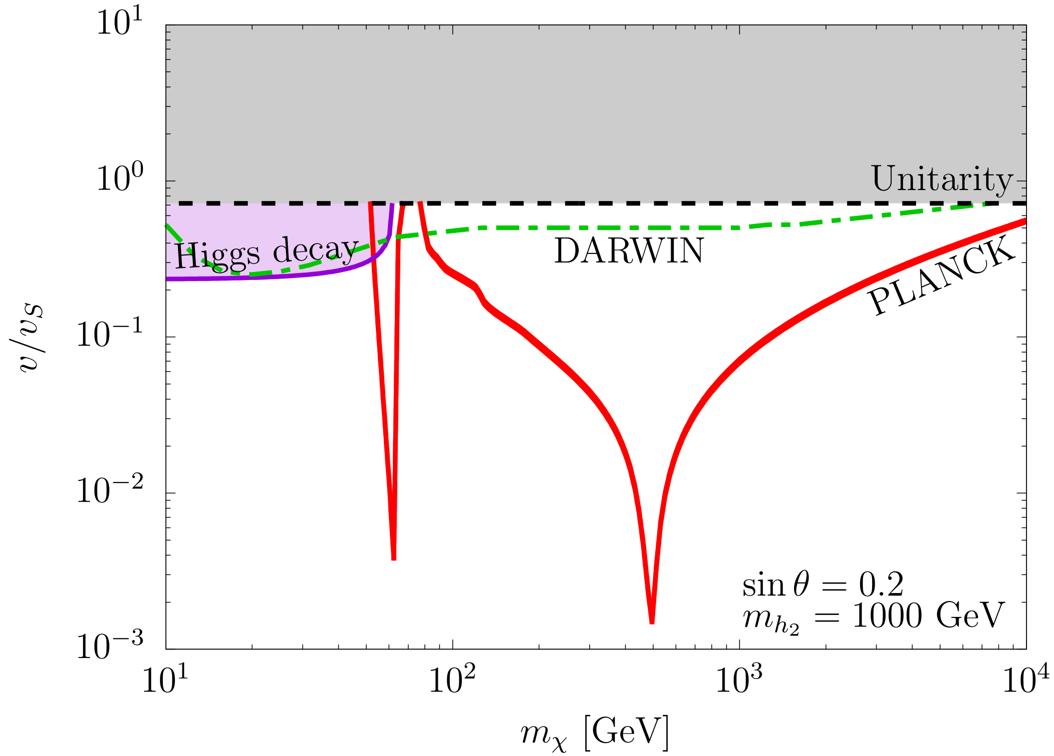


- $\sin\theta = 0.1$ ((i)+(ii) is dominant)
- invisible Higgs decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 10\%$ at LHC
- Two resonances at (h_1, h_2), $v/v_s \sim \sqrt{\lambda_S} v/m_{h_2}$
- Perturbative unitarity $\lambda_S \leq 8\pi/3$ Chen et al., arXiv:1410.5488
- $\sigma_{\mathrm{SI}}^p = \mathcal{O}(10^{-48})$ cm^2 at most
- Direct detection limit is always above the unitarity bound

Numerical analysis (1-loop level)

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





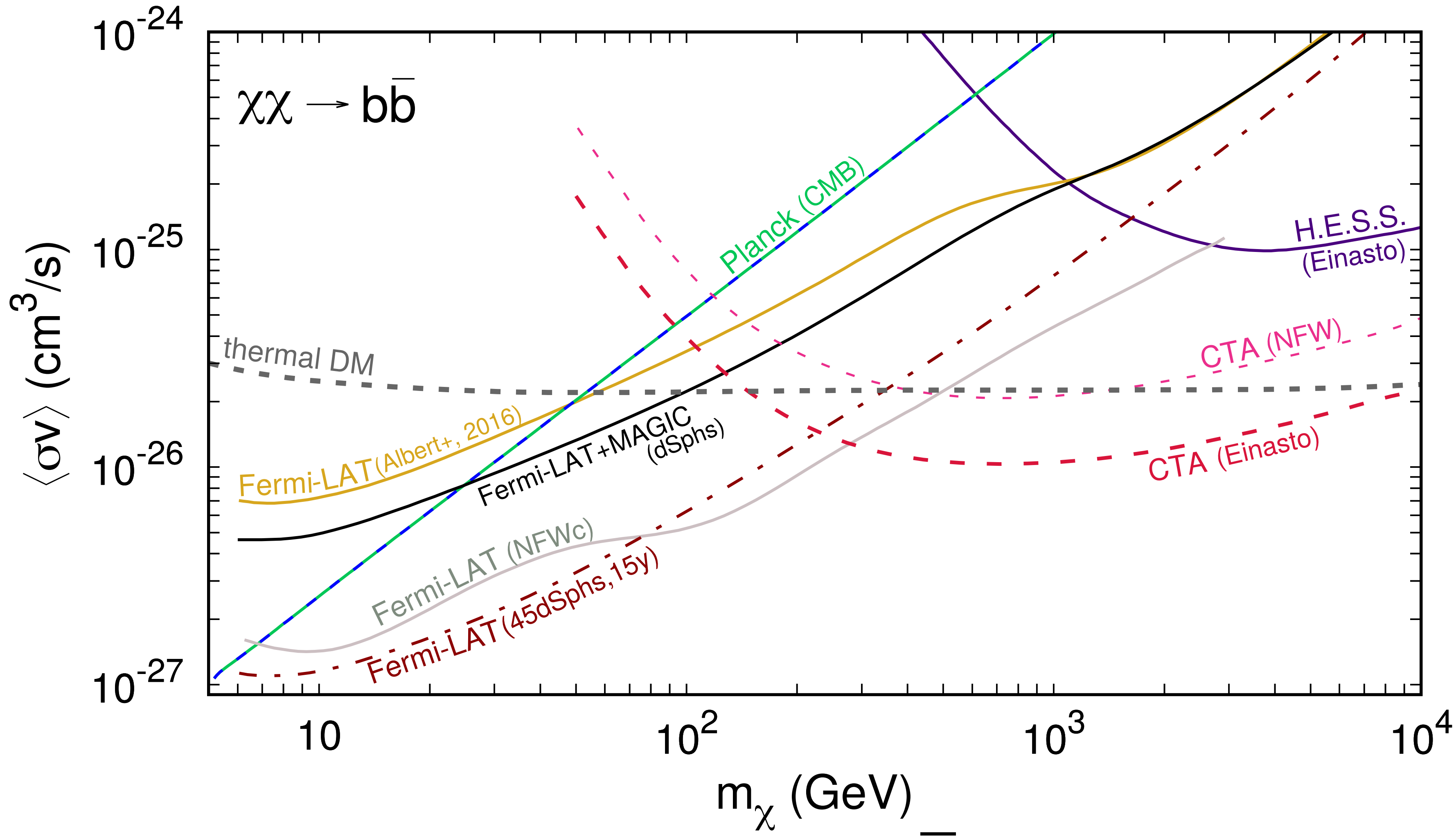
- $\sin\theta = 0.2$
- Direct detection limit is always above the unitarity bound.
- Testable parameter space is slightly extended.

Signals of Pseudo Nambu Goldstone DM

Gamma-ray constraint

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

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

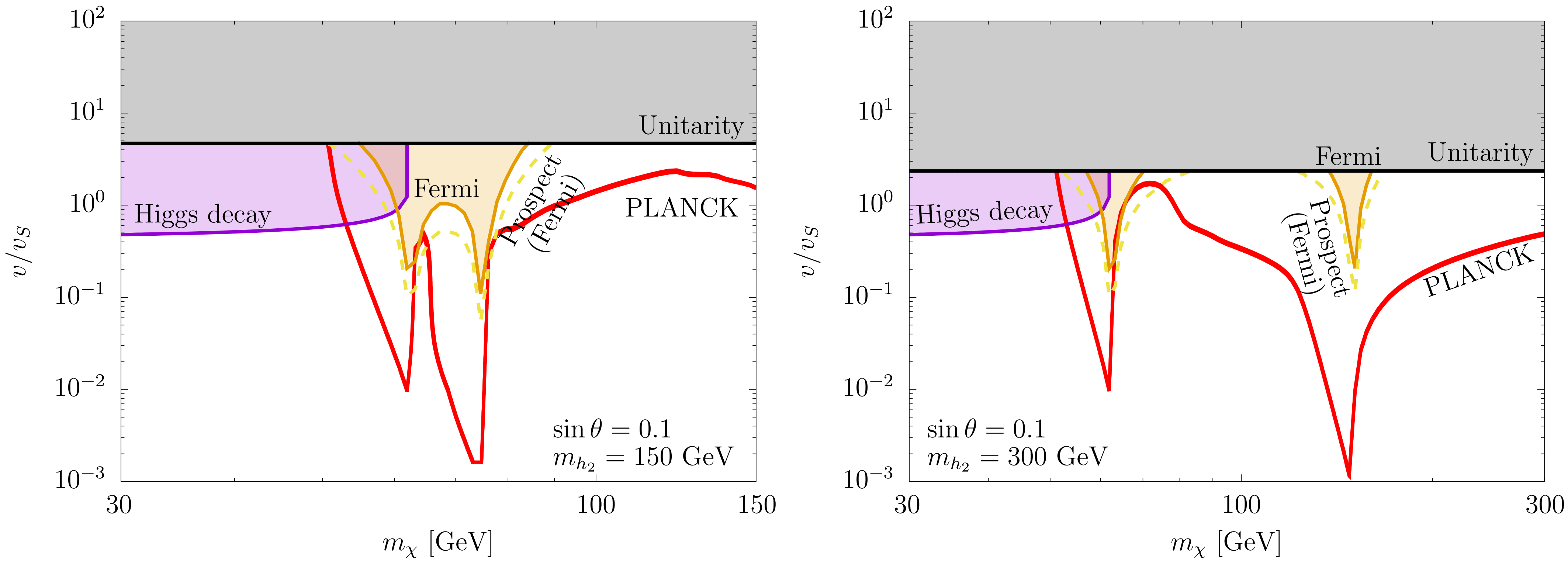


DM annihilations: $\chi\chi \to h_i h_j, WW, ZZ, f\bar{f}$

- Gamma-rays are produced at the end

Gamma-ray constraint

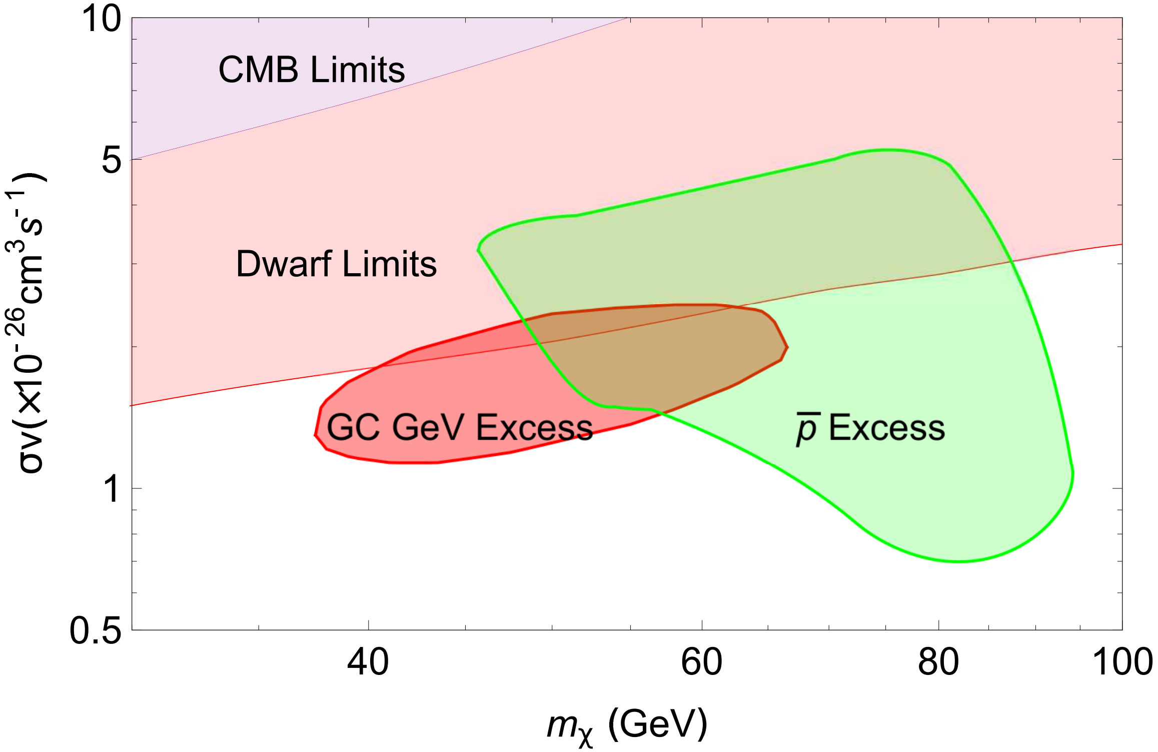
Huitu, Koivunen, Lebedev, Mondal, TT, arXiv:1812.05952



- 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) but $\chi\chi \to h_2 h_2$ is dominant in this mass range.

Cosmic ray anomalies

Cholis, Linden, Hooper, arXiv:1903.02549



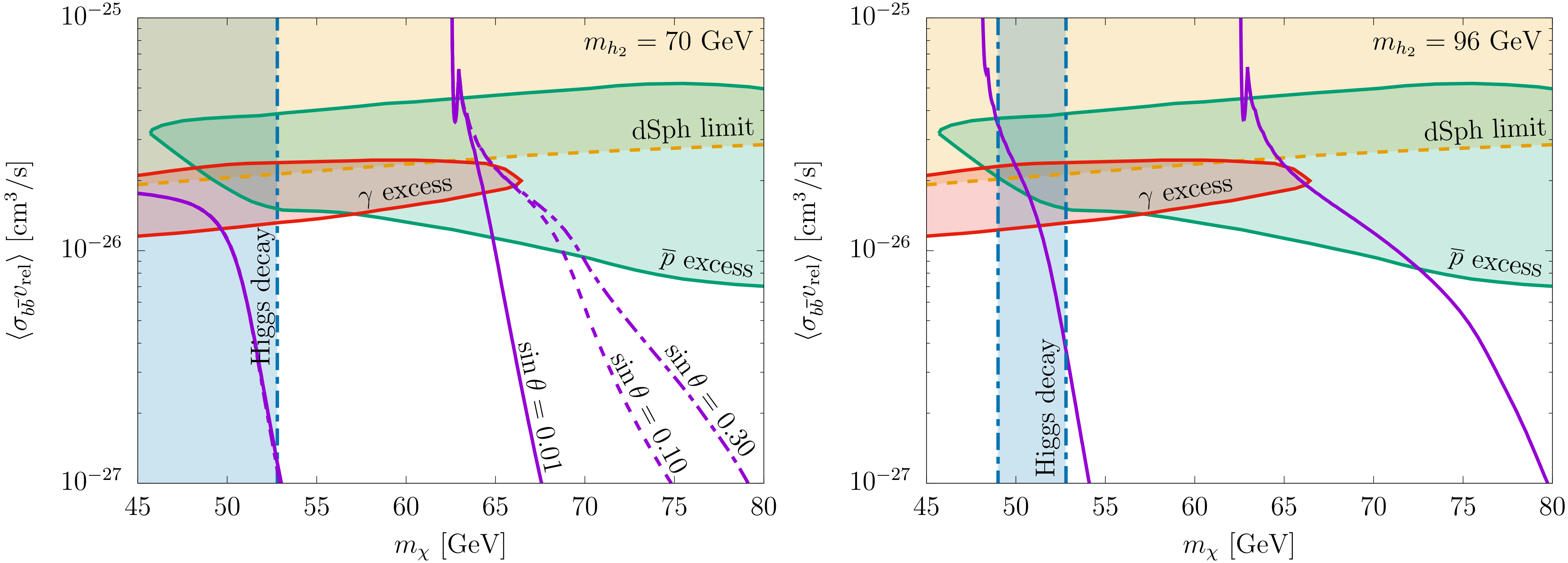
- Excesses in gamma ray and anti-proton cosmic ray. $\gtrsim 4\sigma$
- could be (thermal) DM signal. (other explanations: pulser etc)
  $\chi\chi \to f\overline{f}, WW, ZZ \to \gamma, \overline{p}$
- Cross section: $\langle \sigma_{b\bar{b}} v \rangle \approx (0.8 - 5.2) \times 10^{-26}$ cm^3/s
  DM mass: $64 - 88$ GeV

$\to$ coincide with $\langle \sigma v \rangle$ for thermal relic.

- Typical thermal WIMP conflicts with direct detection bound. But pseudo Goldstone DM can naturally avoid the constraint.

Cosmic ray anomalies

Cline, TT, arXiv:1906.07659



- $m_{h_2} = 70, 96$ GeV.
- Additional channel $\chi\chi \to h_2 h_2$ if $m_\chi > m_{h_2}$. $\to$ mixing dependence
- Cosmic-ray anomalies can be explained by pseudo Goldstone DM in 2σ CL if $m_\chi = 64 - 67$ GeV.

Collider anomalies

Heinemeyer, Stefaniak, arXiv:1812.05864
CMS-PAS-HIG-14-037, CMS-PAS-HIG-17-013

- Collider anomalies around 96 GeV. 2.3σ (LEP) and 2.9σ (CMS)

$$b\bar{b}\ \text{excess at LEP}: \quad \mu_{\rm LEP} \equiv \frac{\sigma_{\rm exp}(e^+e^- \to h_2 \to Zb\bar{b})}{\sigma_{\rm SM}(e^+e^- \to h_{\rm SM}(96) \to Zb\bar{b})} = 0.117 \pm 0.057$$

$$\gamma\gamma\ \text{excess at CMS}: \quad \mu_{\rm CMS} \equiv \frac{\sigma_{\rm exp}(gg \to h_2 \to \gamma\gamma)}{\sigma_{\rm SM}(gg \to h_{\rm SM}(96) \to \gamma\gamma)} = 0.6 \pm 0.2$$

- Both anomalies cannot be explained at the same time in the model.
- But can be explained if a new scalar quark Φ is added.
  $\rightarrow$ chanage $h\gamma\gamma$ and hgg effective couplings (and other couplings)
- Φ is triplet or sextet

$$\mathcal{L} = -\lambda_{S\Phi}|S|^2|\Phi|^2 - \lambda_{H\Phi}|H|^2|\Phi|^2 + \left(y_\Phi \Phi^* \overline{q_R} q_R^c \quad \text{or} \quad \frac{\Phi}{\Lambda^3}\left(\overline{q_R} q_R^c\right)^2 \right)$$

$$m_\Phi^2 = \mu_\Phi^2 + \frac{\lambda_{S\Phi}}{2} v_s^2 + \frac{\lambda_{H\Phi}}{2} v^2 \equiv \mu_\Phi^2 + \overline{\mu}_\Phi^2$$

Collider anomalies

Cline, TT, arXiv:1906.07659

- Model list:

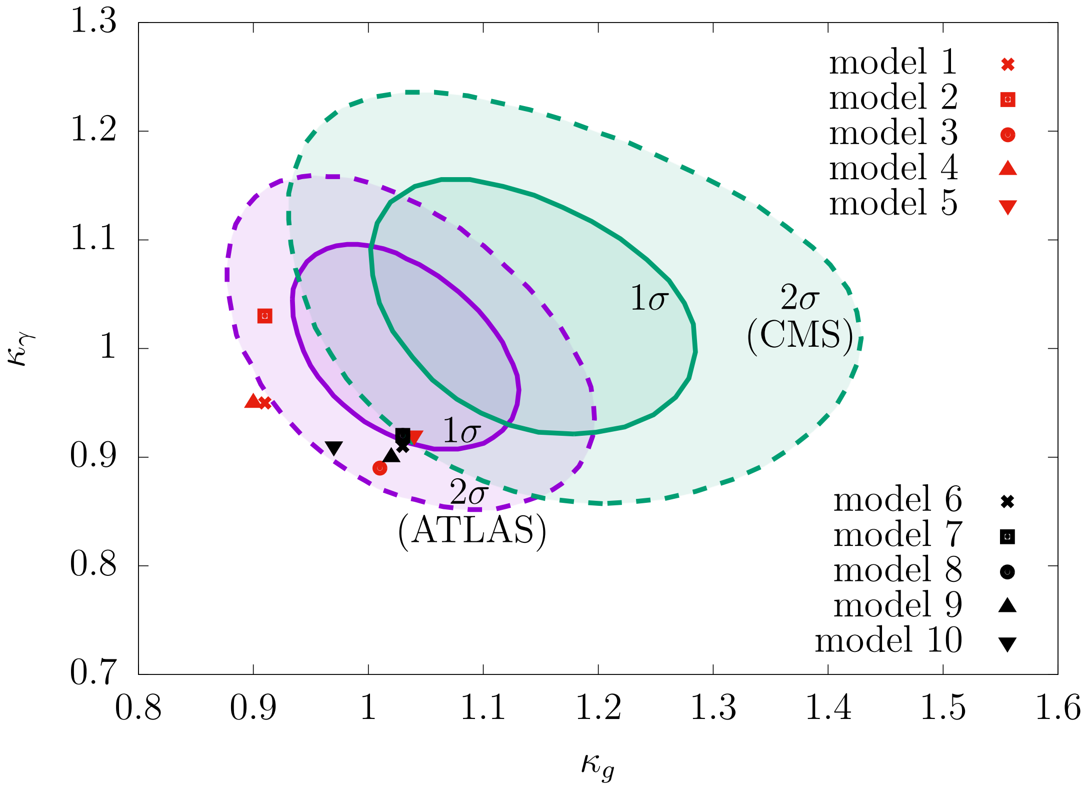
model	q_Φ	N_c	$\frac{m_\Phi}{\lvert\lambda_{S\Phi}\rvert^{1/2}}$ [GeV]	$\frac{\overline{\mu}_\Phi}{\lvert\lambda_{S\Phi}\rvert^{1/2}}$ [GeV]	s_θ	$\lambda_{S\Phi}$	$\lambda_{H\Phi}$	χ^2/d.o.f.
1	$8/3$	6	943	836	0.39	1.9	3.3	3.6
2	$8/3$	3	601	778	0.36	1.4	1.6	2.2
3	$5/3$	6	700	741	0.34	3.4	3.5	2.1
4	$5/3$	3	417	838	0.39	3.0	5.2	3.7
5	$2/3$	6	588	795	0.37	4.8	5.9	1.4
6(*)	$2/3$	3	284	765	0.35	3.4	3.6	1.5
7	$-1/3$	6	554	830	0.39	5.4	8.0	1.5
8(*)	$-1/3$	3	256	810	0.38	4.1	5.6	1.4
9	$-4/3$	6	666	752	0.35	3.8	3.9	1.8
10(*)	$-4/3$	3	333	737	0.34	2.4	3.0	2.5

- We need large couplings $\lambda_{S\Phi}$, $\lambda_{H\Phi}$, and large mixing s_θ
- Mass bounds: $m_\Phi \gtrsim 720$ GeV (triplet 4jet)
  $m_\Phi \gtrsim 1.3$ TeV (sextet 4jet)
  $m_\Phi \gtrsim 520$ GeV (triplet 2jet)

Collider anomalies

Cline, TT, arXiv:1906.07659

- $\kappa_\gamma - \kappa_g$ plane



- Higgs couling strengths are also affected

$$\kappa_i = \frac{\text{coupling in our model}}{\text{coupling in SM}}$$

ex. $\mathcal{L} = g_{hZZ} h Z^2 \to \kappa_Z = c_\theta$

- Model 5,6,7,8 within 2σ range (all observables).

- $\chi\chi \to \gamma\gamma$ is also enhanced by Φ. $\to \sigma_{\gamma\gamma} v \sim 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$ slightly below the Fermi bound $(0.5 - 4) \times 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$

Summary

1. DD constraint is strong, but pseudo-Goldstone DM naturally avoids.
2. Elastic cross section with nucleaon is $\sigma_{\mathrm{SI}}^{N} = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most. (1-loop)
3. Gamma ray and anti proton excesses can be explained at the same time with $m_\chi = 64 - 67$ GeV.
4. Collider anomalies can also be fit if a new colored scalar is introduced.

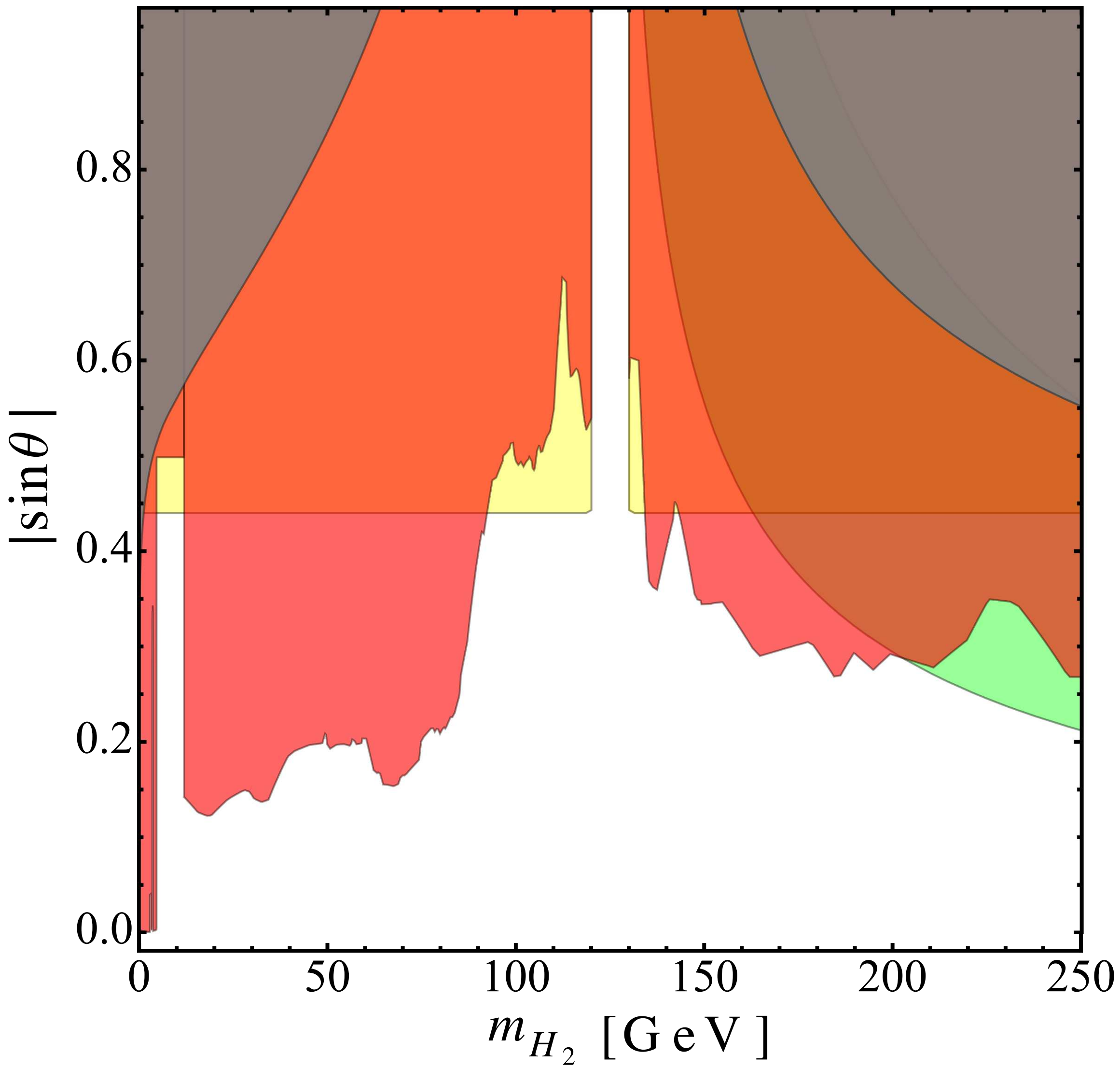
Future works

1. Embedding in a UV Gauged $U(1)$ model $\rightarrow$ induce DM decay

Buck Up

Bound on $\sin\theta$

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



- $|\sin\theta| \lesssim 0.44$ at $m_{H_2} = 96$ GeV.

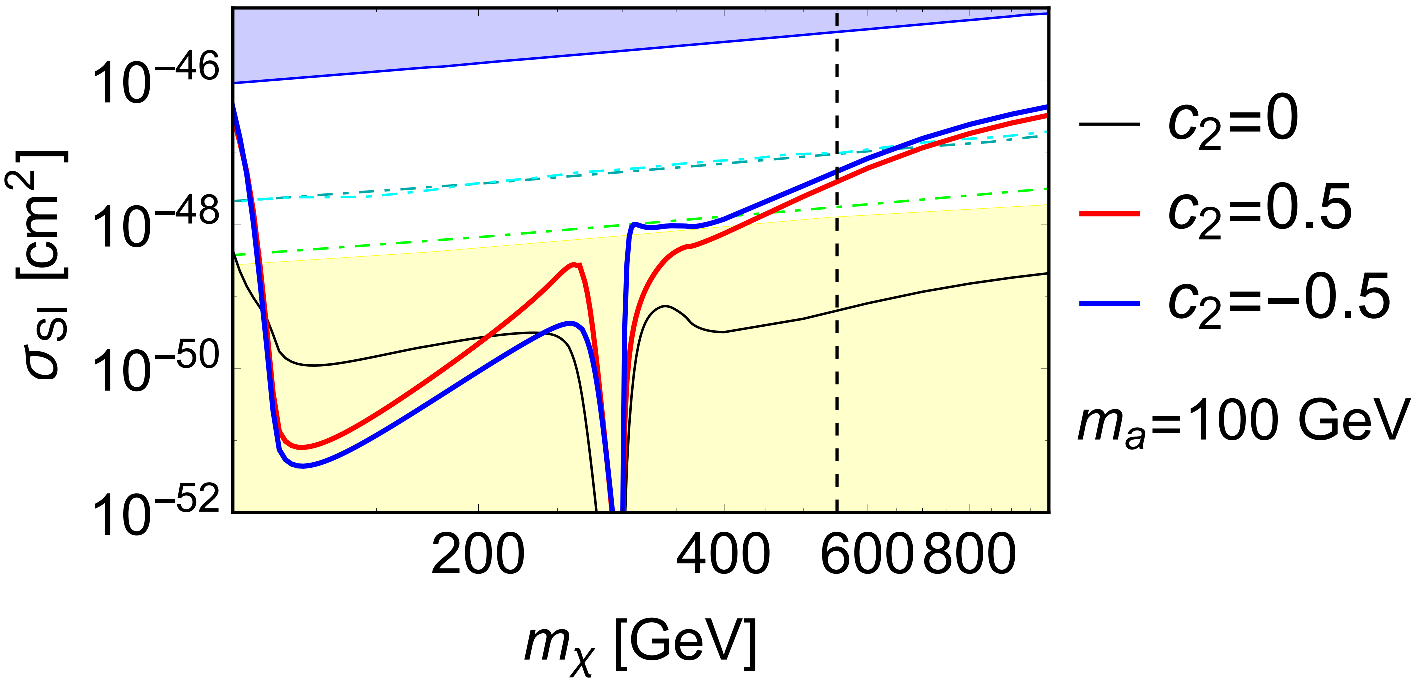
Majorana DM model

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

Majorana DM interacting with pseudo-scalar

$$\mathcal{L} \supset \frac{g_\chi}{2} a \overline{\chi} \gamma_5 \chi - c_2 a^2 |H_2|^2 + \cdots$$

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

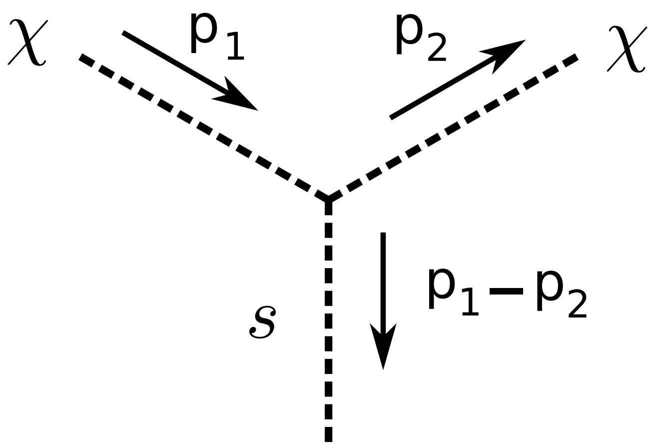


- 1-loop contribution is dominant
- c_2 coupling enhances $\sigma_{\rm SI}$

Direct detection (tree level)

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

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



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

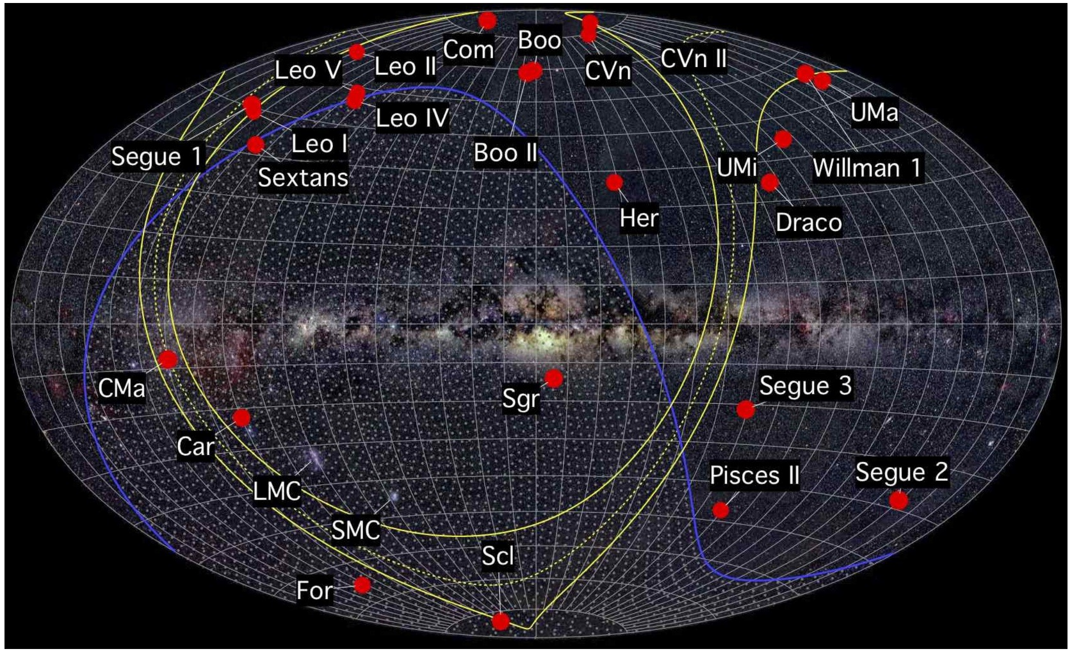
- The cancellation happens because of nature of Goldstone boson
  $\rightarrow$ All the interactions are written with derivative couplings
  $\mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}(\partial_\mu \chi)$
- Additional comment: Scalar potential can be stabilized up to Planck scale if $m_{h_2} \gtrsim 200$ GeV.

Indirect detection

DM annihilations

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

- Gamma-rays are produced at the end
- Strong constraints from dSphs (rich DM and less visible matter)



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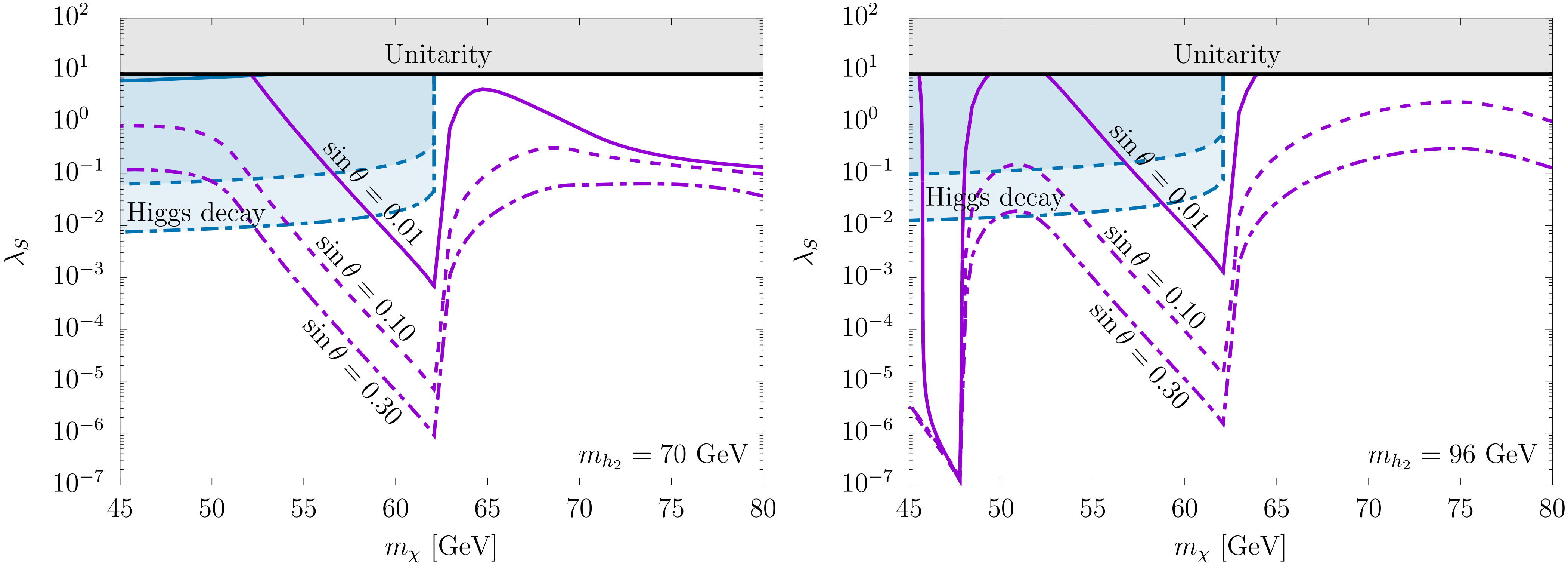
- $\mathcal{O}(50)$ dSphs have been found so far.
- DM models are constrained.

Cosmic ray anomalies

Cline, TT, arXiv:1906.07659



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- Additional channel $\chi\chi \to h_2 h_2$ if $m_\chi > m_{h_2}$. $\to$ mixing dependence
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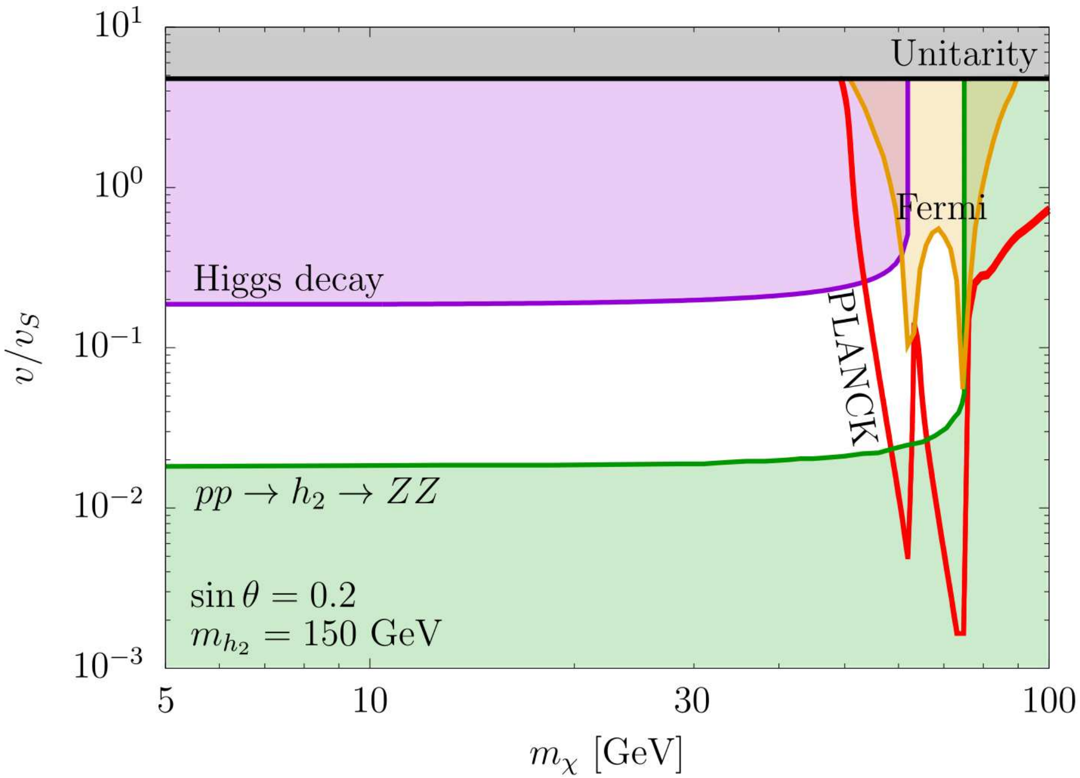
Collider search

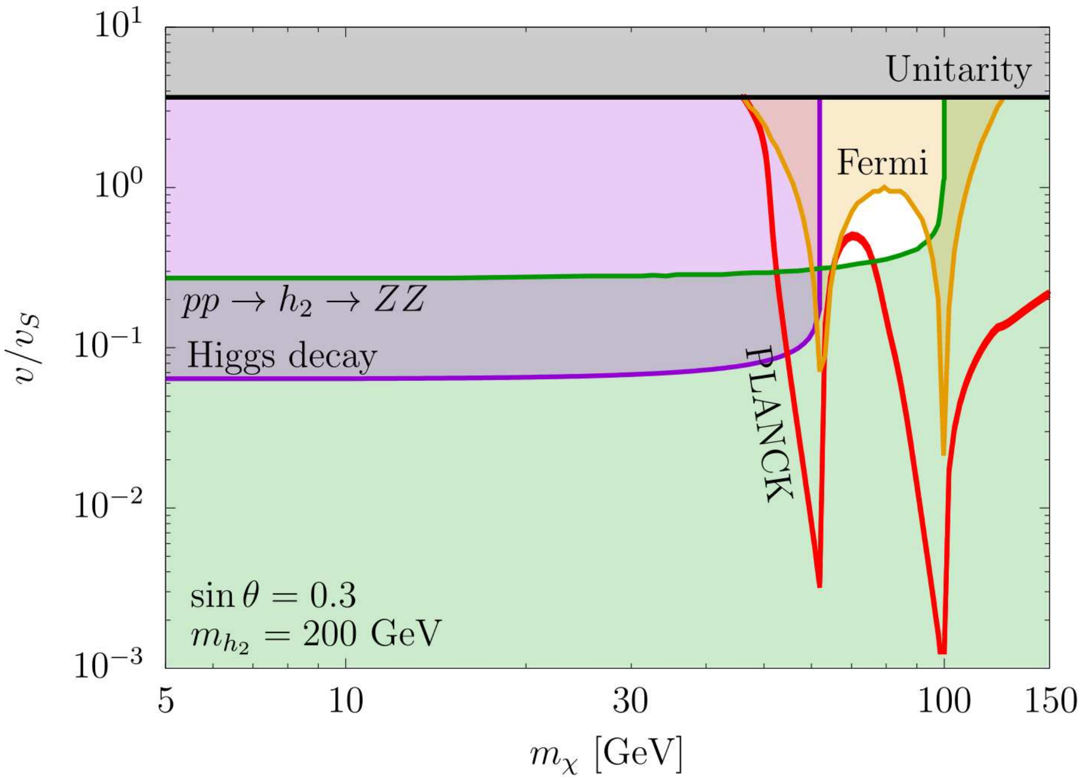
Huitu, Koivunen, Lebedev, Mondal, TT, arXiv:1812.05952

- 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.

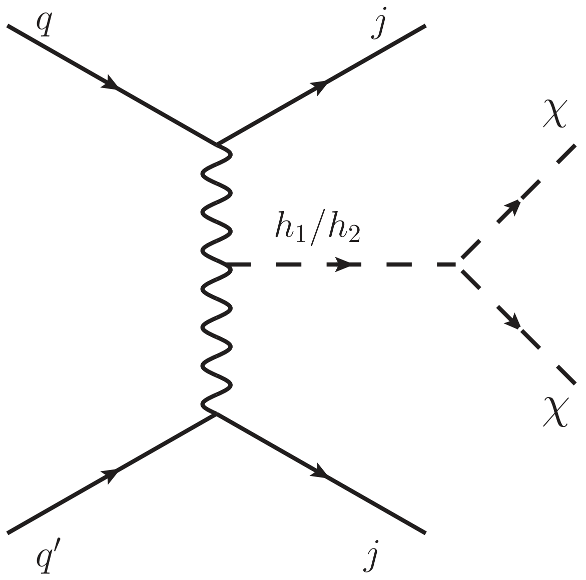




Collider search

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

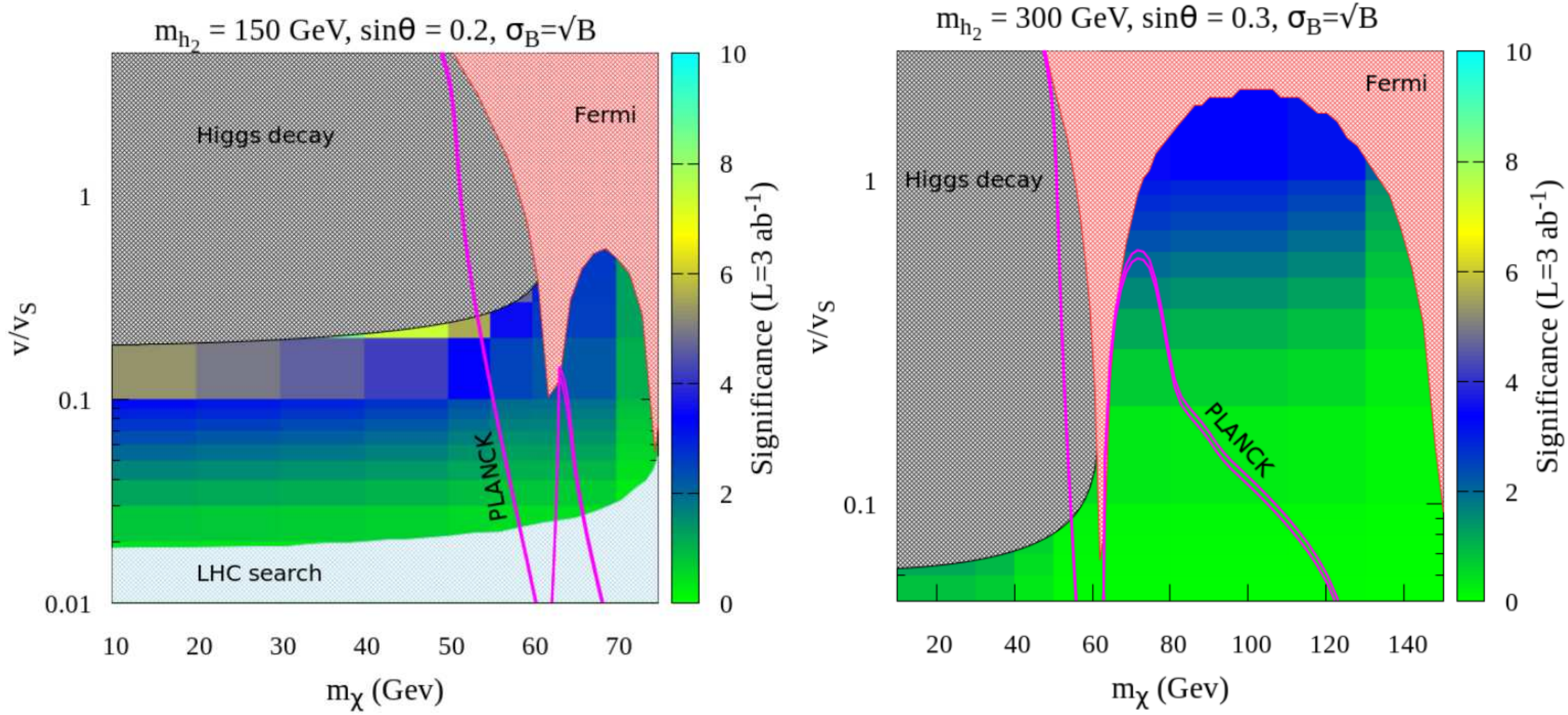
- Signal channel (VBF)
  h_1 and h_2, both contributions are important
- We focus on $m_{h_2} \geq 2m_\chi$
- Simulate the events and put appropriate cuts
  $\not{E}_T > 250$ GeV, $p_j > 80$ GeV etc



- 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, arXiv:1812.05952



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