Detectability of pseudo-Goldstone dark matter

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arXiv: 1812.05952

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Dark matter

Albada et al. ApJ (1985)

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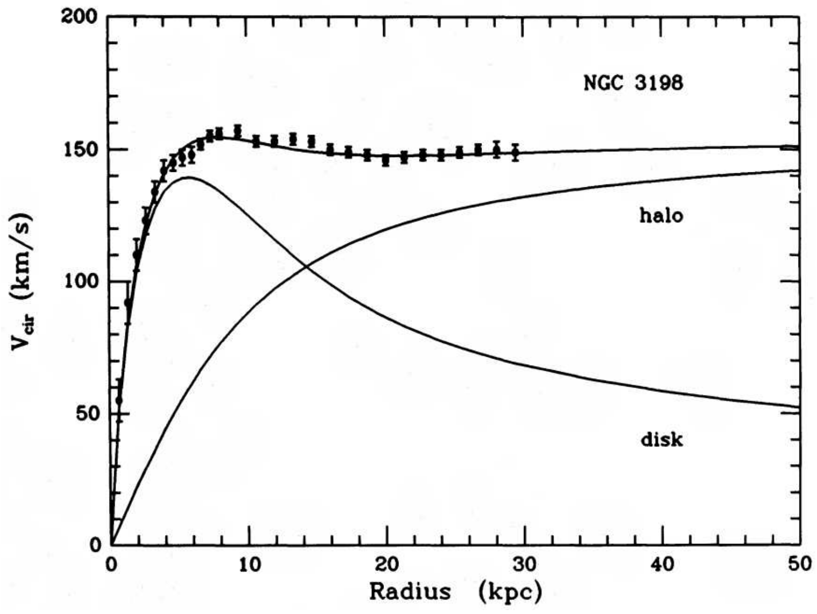
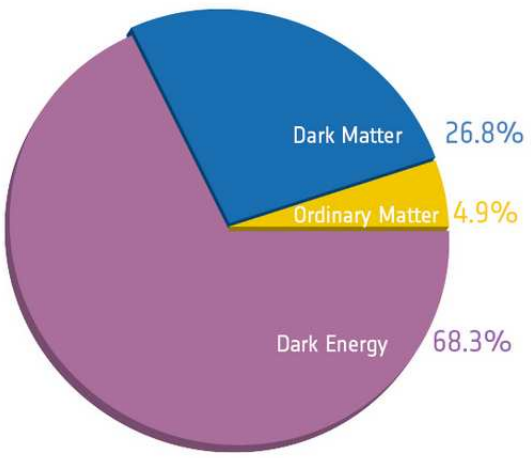
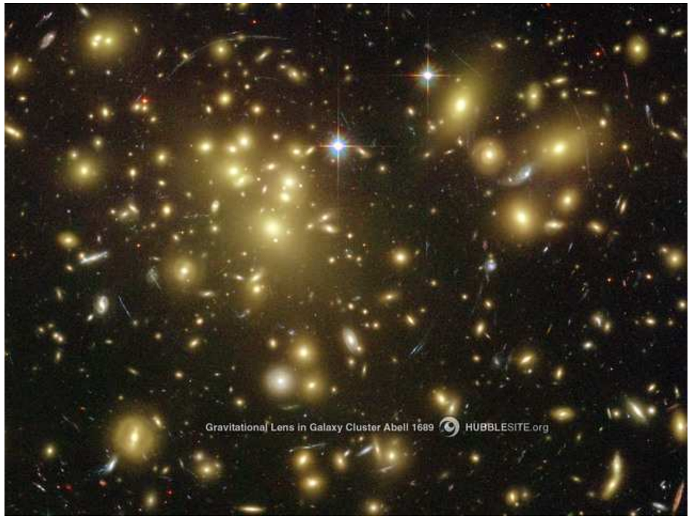
There is a lot of evidence of dark matter.

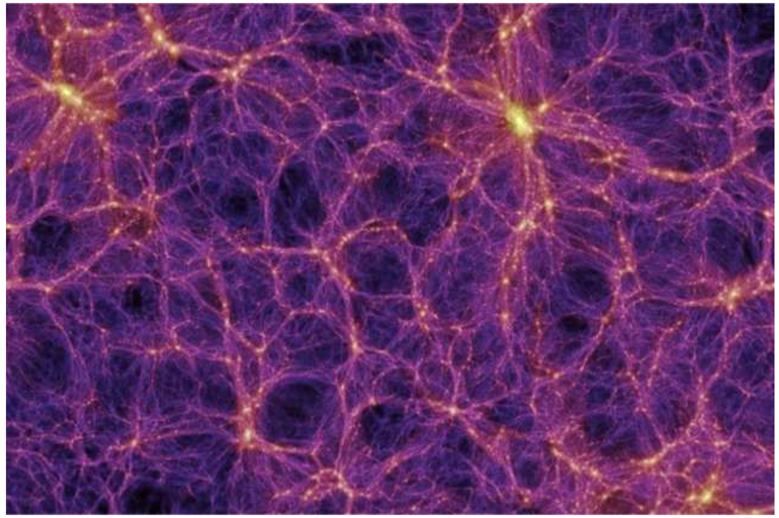
- Rotation curves of spiral galaxies
- CMB observations
- Gravitational lensing
- Large scale structure of the universe
- Collision of bullet cluster

DM existence is crucial.









Dark matter

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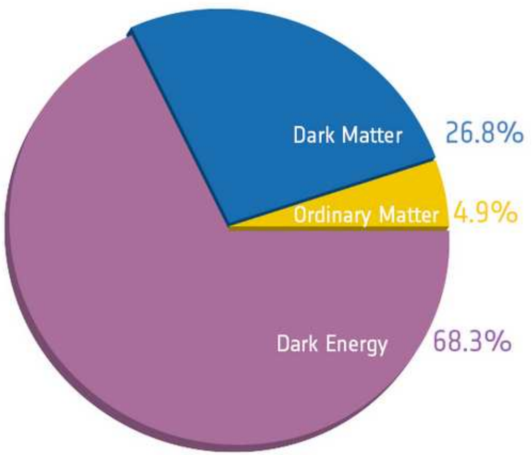
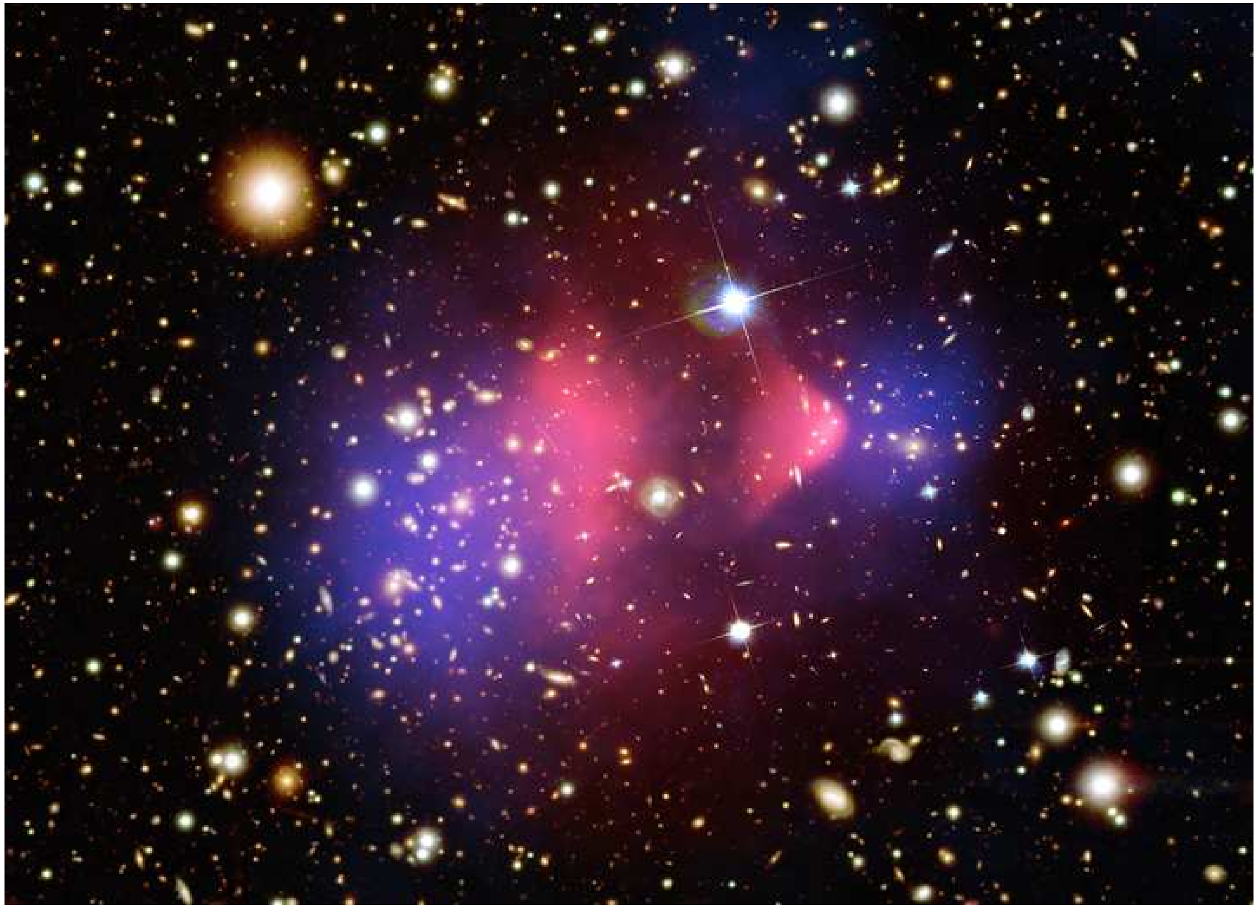
WIMPs are good DM candidate.

DM existence is crucial.





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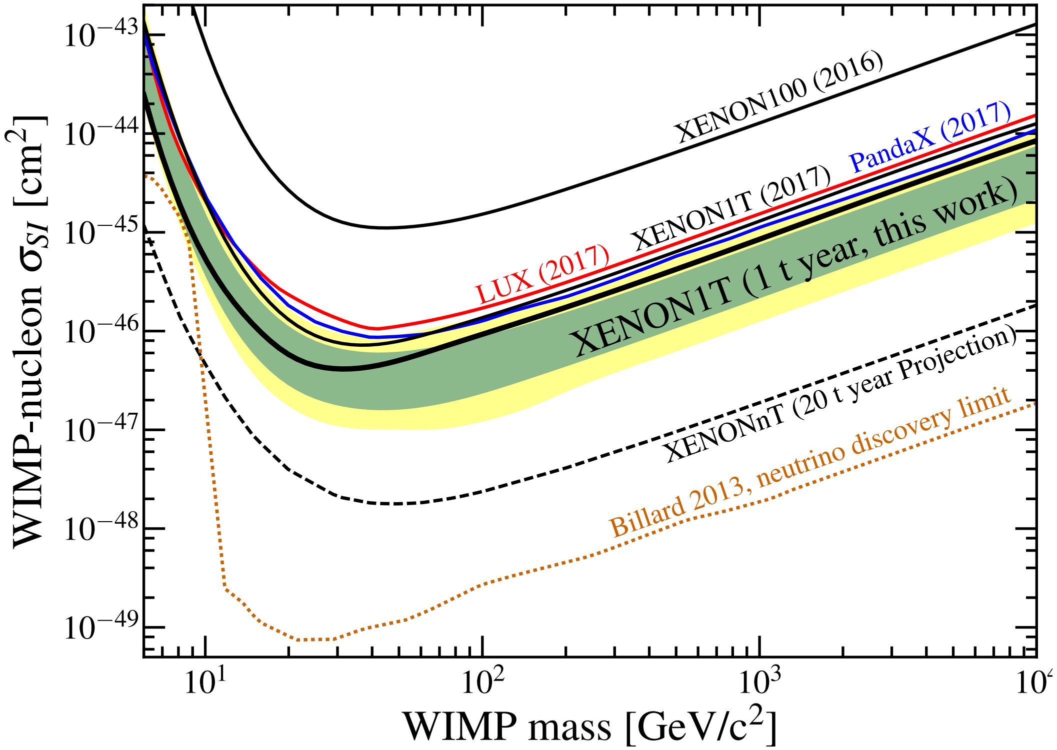
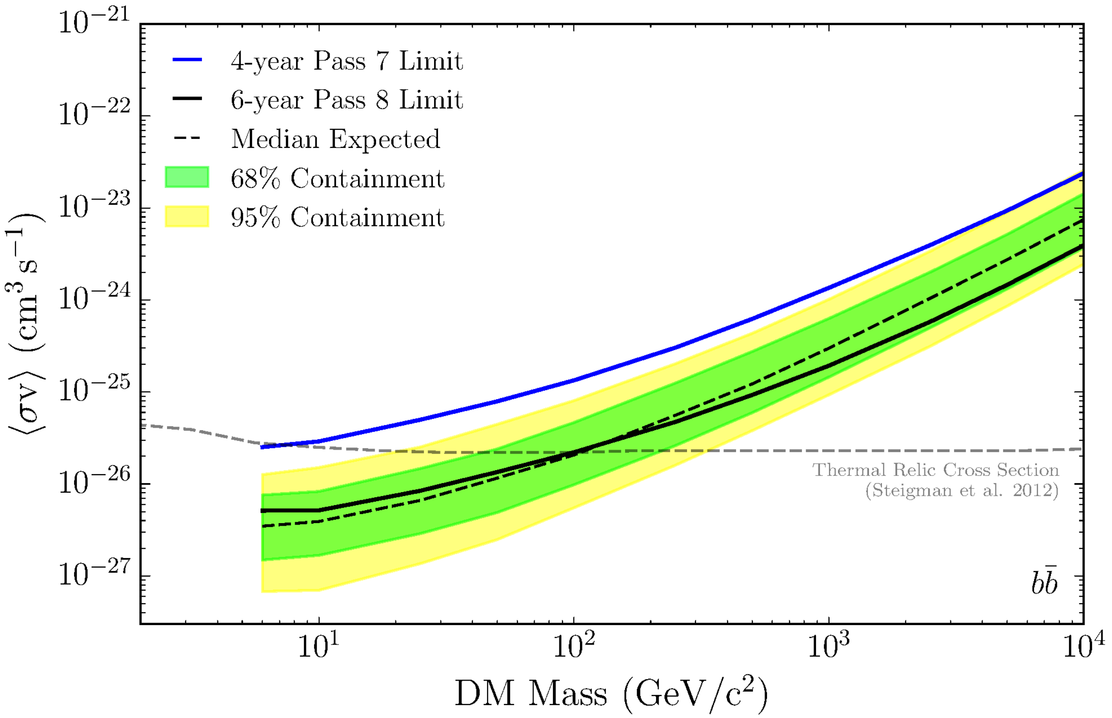
WIMP search status

Direct detection



XENON1T, PRL (2018)

Indirect detection



Fermi-LAT, PRL (2015)

- Experimental bounds for WIMPs are stronger and stronger.
- Interactions between DM and SM are very weak?
  $\rightarrow$ possibilities other than WIMPs are discussed.

Model of pseudo-Goldstone DM

Model of pseudo-Goldstone DM

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

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

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

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

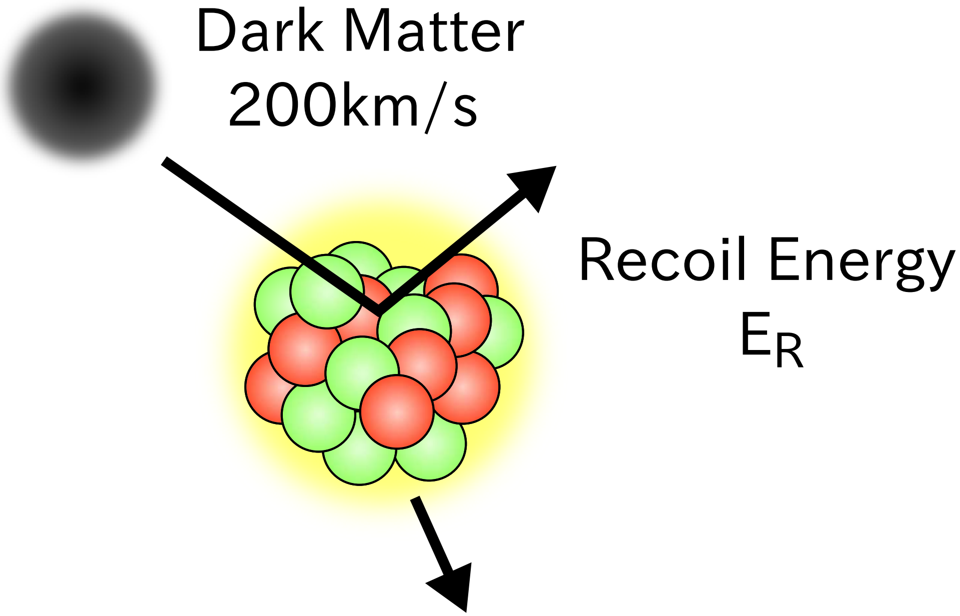
- SM Yukawa int. $\mathcal{L} \supset y_q \Big(\cos\theta h_1 + \sin\theta h_2\Big) \overline{q} q$

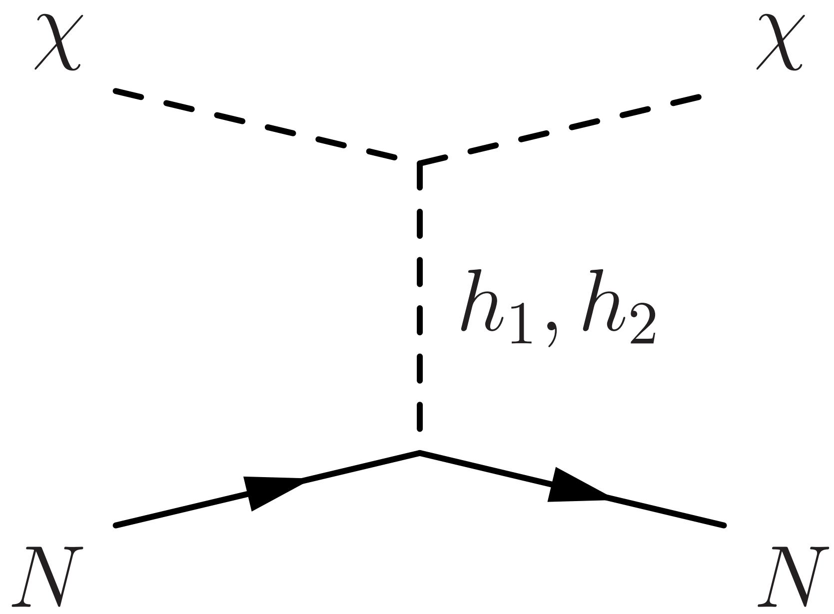
$$\lambda_H = \frac{\cos^2\theta m_{h_1}^2 + \sin^2\theta m_{h_2}^2}{v^2}, \quad \lambda_S = \frac{\sin^2\theta m_{h_1}^2 + \cos^2\theta m_{h_2}^2}{v_s^2},$$

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

Direct detection (tree level)

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





- Scattering amplitude is suppressed by transfer momentum q^2

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

$\rightarrow$ All the interactions are derivative couplings $\mathcal{L}_{\text{int}}(\partial_\mu \chi)$

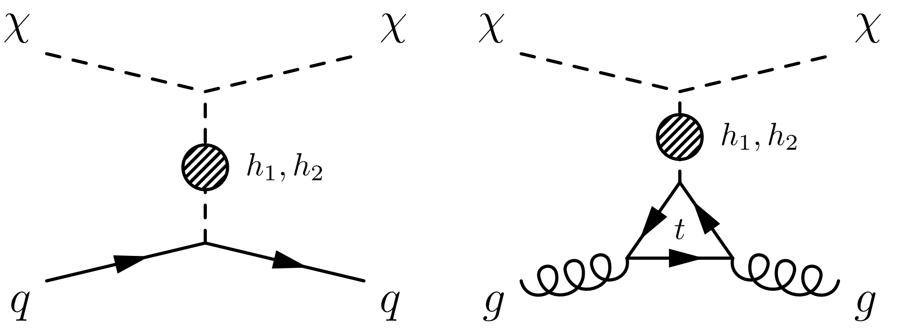
- 4 independent parameters $(m_\chi,\ m_{h_2},\ \sin\theta,\ v_s\ (\lambda_S))$

Direct detection (1-loop level)

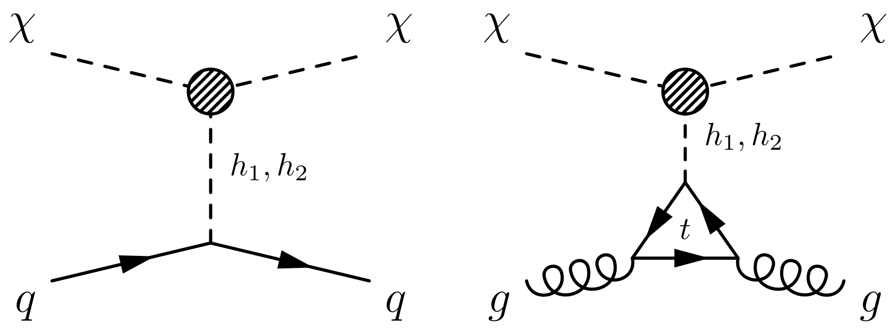
K. Ishiwata, TT, JHEP (2018)
D. Azevedo, M. Duch, B. Grzadkowski, D. Huang
M. Iglicki, R. Santos, JHEP (2019)

- Compute Feynman diagrams at 1-loop level

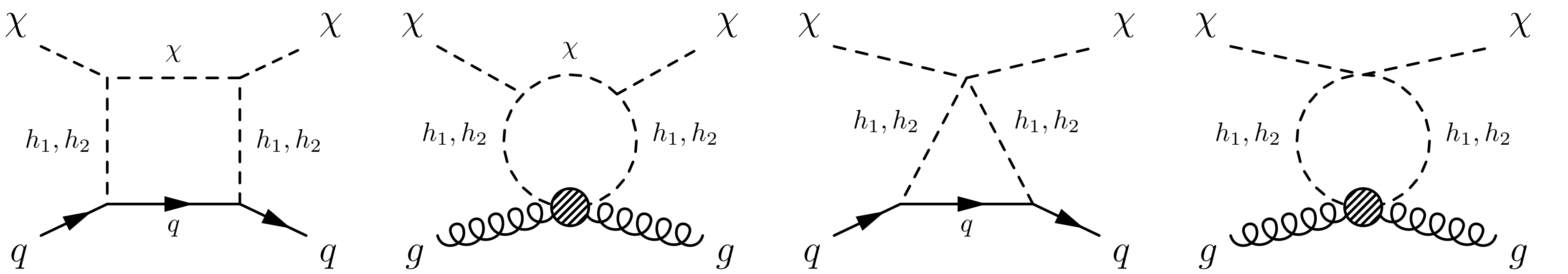
(i)



(ii)

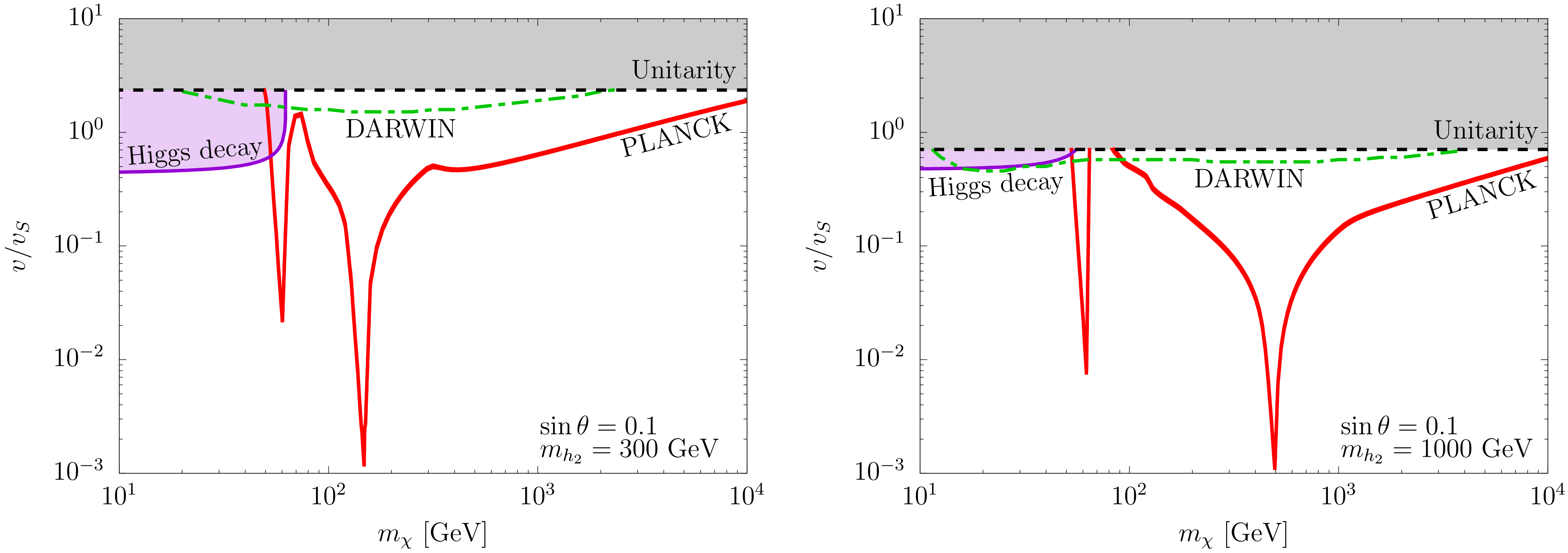


(iii)



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

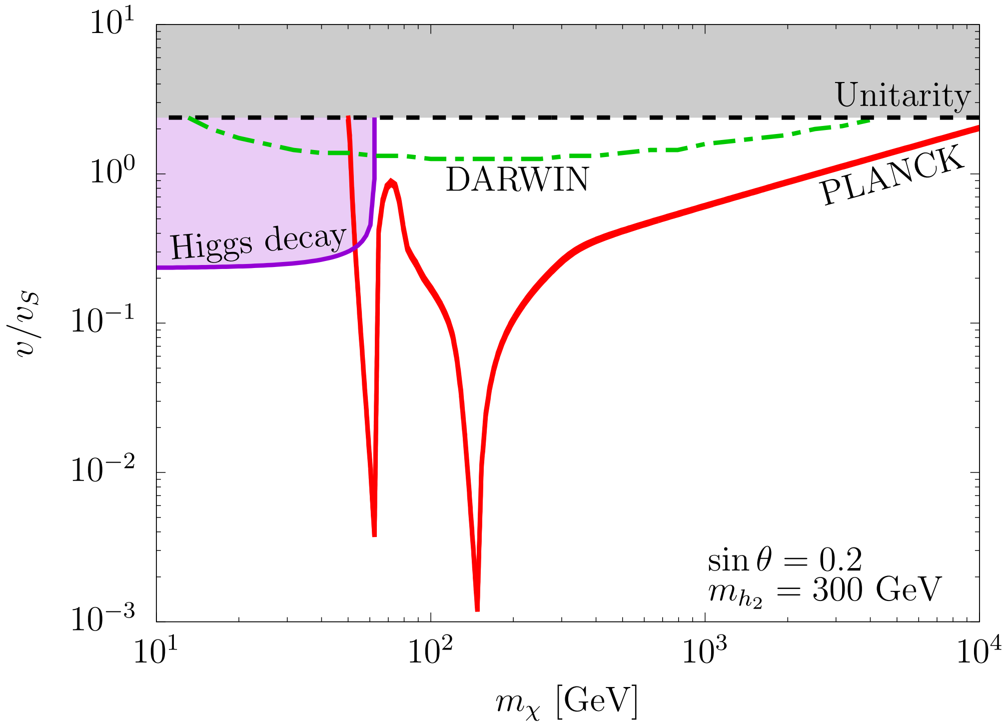
Numerical analysis (1-loop level) K. Ishiwata, TT, JHEP [arXiv:1810.08139]

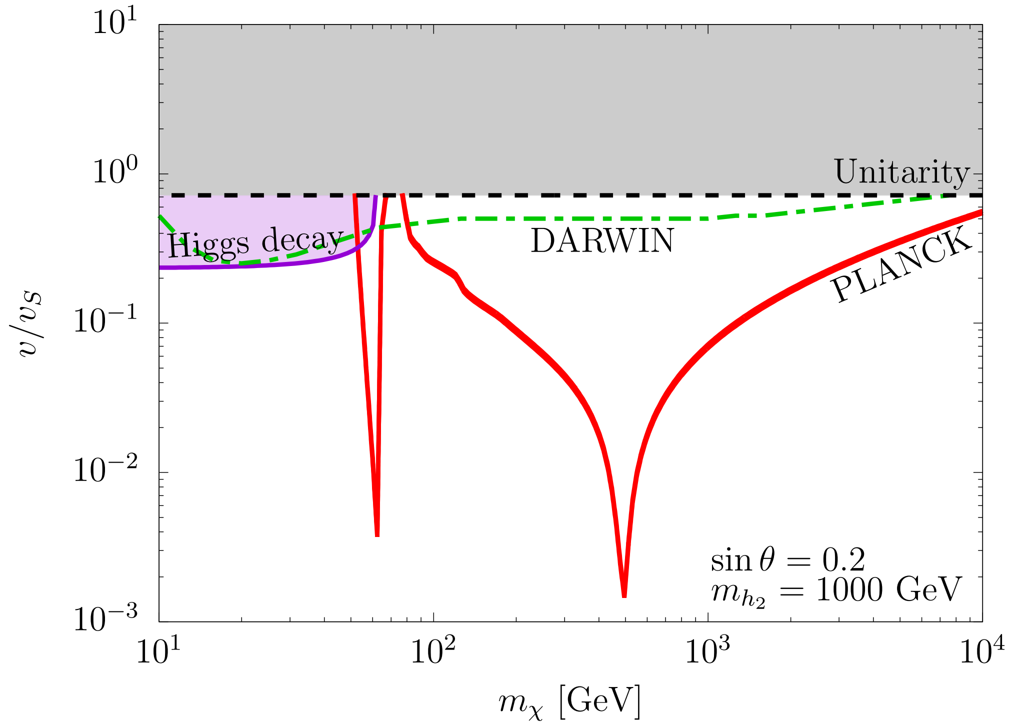


- $\sin\theta = 0.1$
- Invisible Higgs decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 10\%$ at LHC
- Two resonances at (h_1, h_2), $\quad v/v_s \sim \sqrt{\lambda_S} v/m_{h_2}$
- Perturbative unitarity $\lambda_S \leq 8\pi/3$ Chen et al., arXiv:1410.5488
- Partial region can be tested by DARWIN. $\sigma_{\mathrm{SI}}^p = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$

Numerical analysis (1-loop level)

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

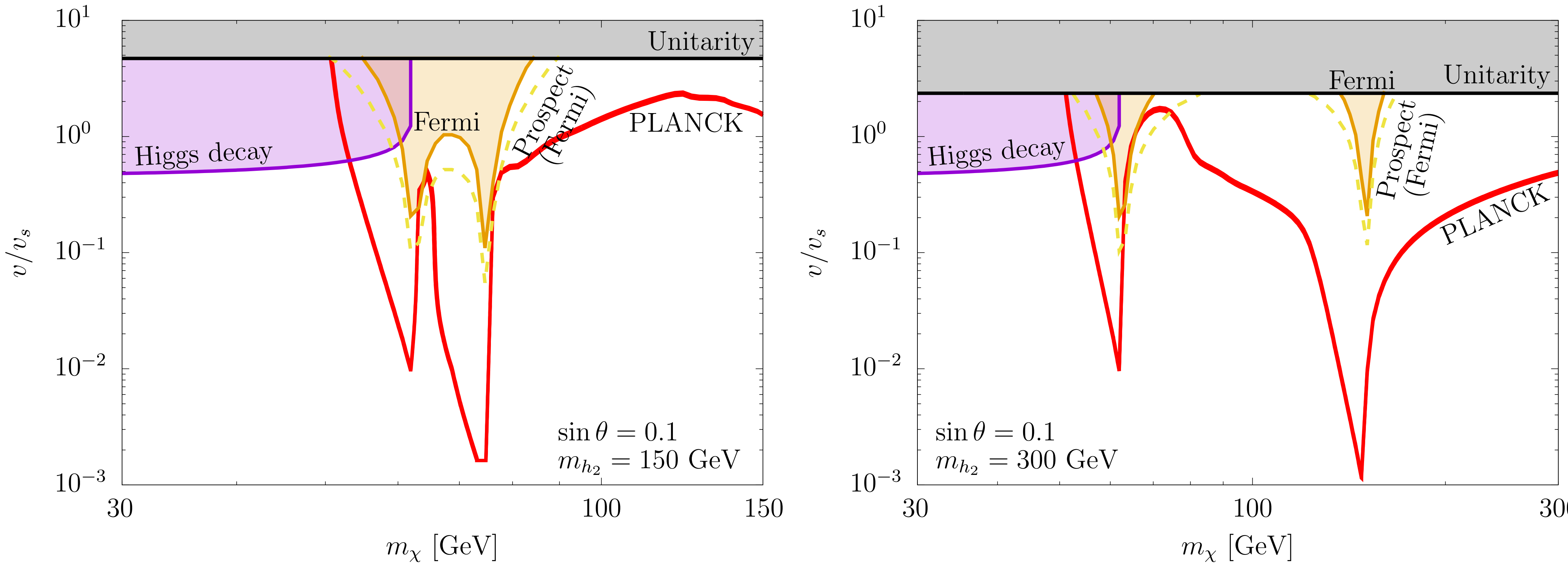




- $\sin\theta = 0.2$
- Invisible Higgs decay $\mathrm{Br}(h_1 \to \mathrm{inv}) \lesssim 10\%$ at LHC
- Two resonances at (h_1, h_2), $\quad v/v_s \sim \sqrt{\lambda_S} v/m_{h_2}$
- Perturbative unitarity $\lambda_S \leq 8\pi/3$ Chen et al., arXiv:1410.5488
- Partial region can be tested by DARWIN. $\sigma_{\mathrm{SI}}^{p} = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$

Indirect detection

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



- Small parameter space is excluded by Fermi-LAT gamma-ray observation ($\chi\chi \to WW, b\bar{b} \to \gamma$)
- 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.

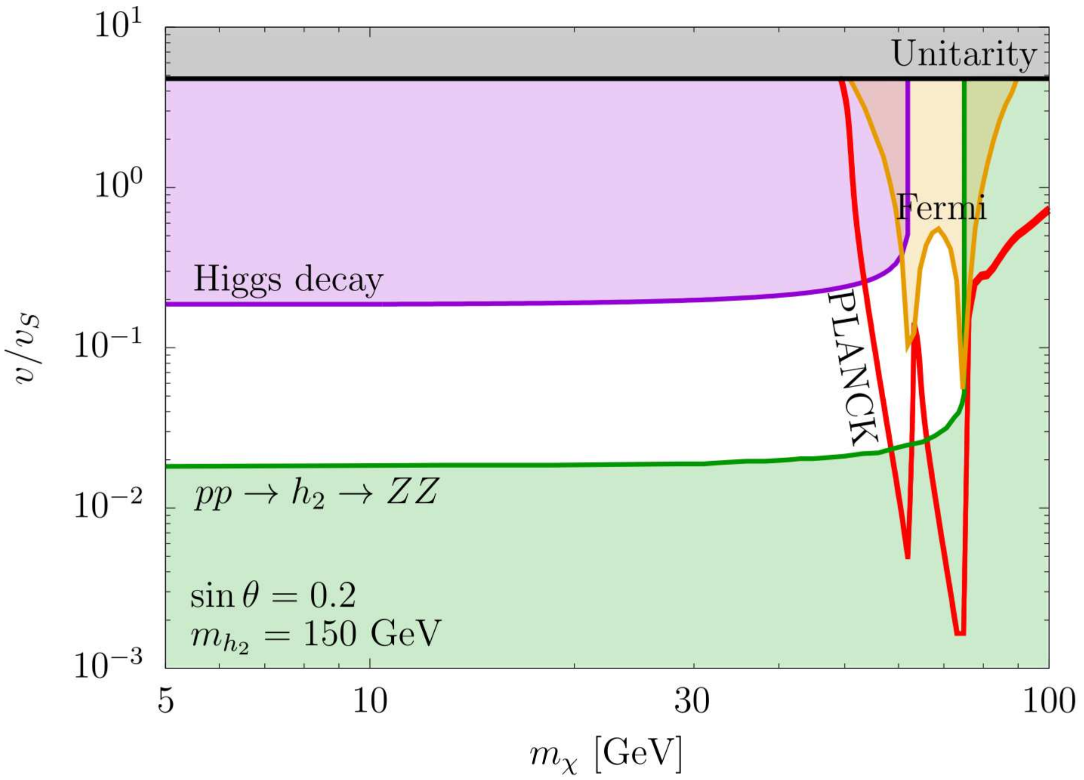
Collider search

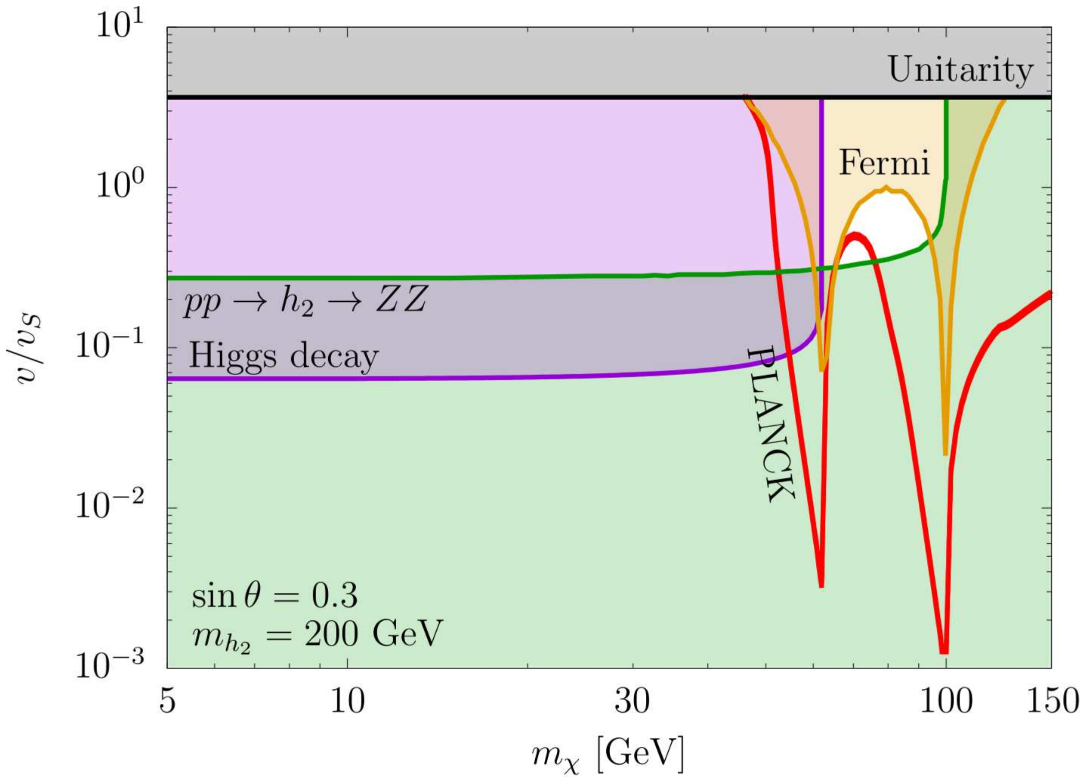
Huitu, Koivunen, Lebedev, Mondal, TT, arXiv:1812.05952

- Constraint on h_2 production cross section at LHC

$$\sigma_{\text{prod}} = \sigma(pp \to h_2)\,\text{Br}(h_2 \to \text{SM}) \quad \propto \quad \sin^2\theta\,\text{Br}(h_2 \to \text{SM}) \lesssim \#_{\text{exp}}$$

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





Summary

1. Thermal WIMP scenarios are strongly constrained by direct DM search.
2. Pseudo-Goldstone DM can naturally avoid the strong constraint.
3. Elastic cross section with nucleon is $\sigma_{\mathrm{SI}}^{N} = \mathcal{O}(10^{-48})\ \mathrm{cm}^2$ at most. (1-loop)
4. The model is testable by indirect detection and collider search.