Constraints on CP-Violating Higgs Portal Majorana Dark Matter

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Central Question

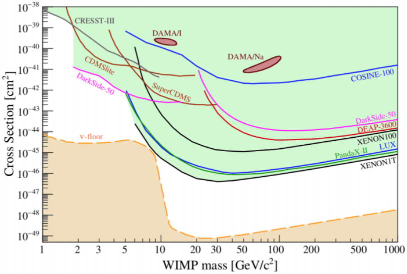
Central Question: In light of current constraints, is a Higgs portal Majorana fermion thermal relic WIMP a viable dark matter candidate?

Answer: Yes, with a CP violating coupling.

The Annihilation Signal

- The GCE is a statistically significant excess of gamma rays in the Galactic Center. Cause is debated:
  - Pulsars [Abazajian et. al ’14, others]
  - Annihilating DM [Goodenough & Hooper ’09, others]
- DM explanation requires $\sim$ 3 pb cross section
- Thermal WIMP relic abundance requires same annihilation cross section ($\mathcal{O}$(1-10 pb))

The Challenge: Avoiding Direct Detection Constraints



[Schumann, 1903.03026]

- Direct detection constraints on scattering are becoming stringent
- Challenge to generate large annihilation signal while avoiding stringent direct detection constraints

Why CP Violation?

- Typical solution: tune DM mass to $m_h/2$ so resonance enhances annihilation [Huang et al '14, others]
- Leading annihilation term is still p-wave suppressed if the coupling is real, since two Majorana fermions form a CP odd state while the Higgs is CP even.
- CP violation avoids velocity suppression: annihilation proportional to Im[y]. [Carena et al '19, in the context of a specific SUSY model]
- Direct detection is controlled by Re[y] since initial and final states have the same CP properties

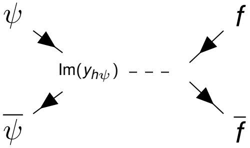
The DM EFT

Consider a Majorana fermion χ that couples to the Higgs and the Z:

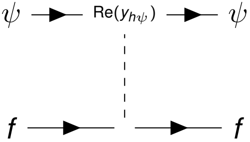
$$\mathcal{L} \supset \frac{|y_{h\chi}|e^{i\phi_{h\chi}}}{2\sqrt{2}} h\overline{\chi}P_L\chi + \frac{|y_{h\chi}|e^{-i\phi_{h\chi}}}{2\sqrt{2}} h\overline{\chi}P_R\chi + \frac{g_{Z\chi}}{2} Z_\mu\overline{\chi}\gamma^5\chi$$

3 Relevant Constraints:

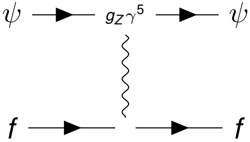
Annihilation



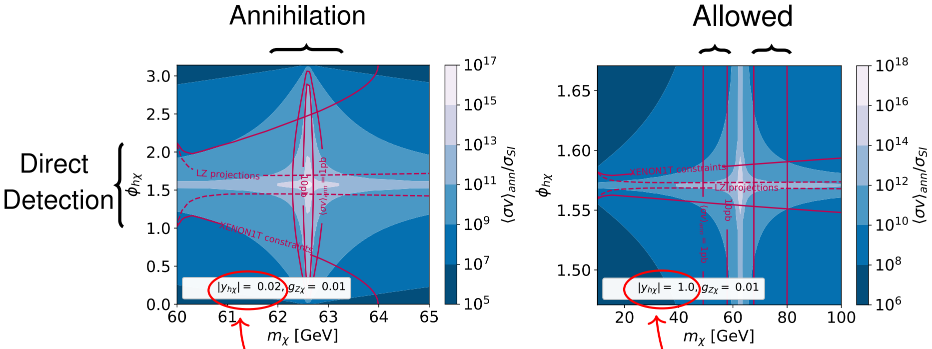
Spin-Independent Direct Detection



Spin-Dependent Direct Detection



Mass and Phase Constraints

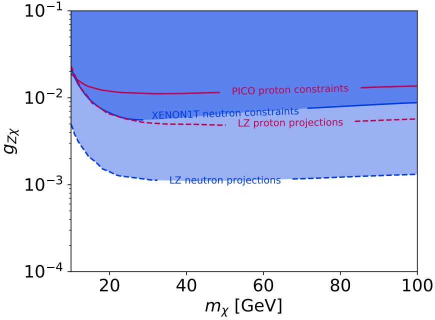


Small coupling: tune mass to ↑ annihilation

Large coupling: tune phase to ↓ direct detection

Z Coupling Constraints

- Spin dependent constraints easily avoided with small Z coupling.



UV Completions

But, this is not the whole story.

1. CP violation makes our model vulnerable to electron EDM constraints.
2. New doublet means we need to check electroweak precision corrections
3. What about collider constraints?

In order to understand these remaining constraints, we need the full UV completion.

Singlet - Doublet Model

Pick a minimal UV completion: Singlet-Doublet Model
[Mahbubani & Senatore '06, Others]

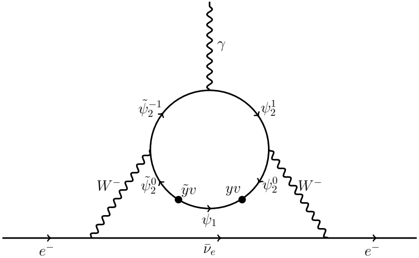
- Contains:
  - Dirac doublet $(\psi_2, \tilde{\psi}_2)$ with hypercharge 1/2
  - Majorana singlet ψ_1

$$\mathcal{L} \supset -\underbrace{m_2 \psi_2 \cdot \tilde{\psi}_2}_{\text{Dirac Mass}} - \underbrace{\frac{m_1}{2} \psi_1 \psi_1}_{\text{Majorana Mass}} + \underbrace{Y \psi_1 H^\dagger \psi_2 - \tilde{Y} \psi_1 H \cdot \tilde{\psi}_2}_{\text{Yukawa Couplings}} + \text{h.c.}$$

- One physical phase (four parameters, 3 fields). Choose: $Y = y e^{i\delta_{CP}/2}$, $\tilde{Y} = \tilde{y} e^{i\delta_{CP}/2}$
- Neutral Dirac fermion splits into two Majorana fermions. After SSB, DM χ is the lowest mass eigenstate.

Constraints in the UV

Electron EDM



Collider Constraints

SModelS

Electroweak Precision Parameters

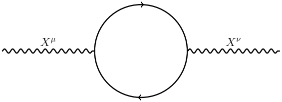
$$S \equiv \frac{4c^2s^2}{\alpha_e}\left[\Pi'_{ZZ}(0) - \frac{c^2-s^2}{cs}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

$$T \equiv \frac{1}{\alpha_e}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right]$$

$$U \equiv \frac{4s^2}{\alpha_e}\left[\Pi'_{WW}(0) - \frac{c}{s}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S$$

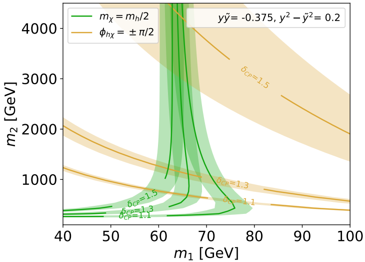
$$W \equiv \frac{m_W^2 s^2 c^2}{8\pi\alpha_e}\left[\Pi''_{ZZ}(0) + \frac{2s}{c}\Pi''_{Z\gamma}(0) + \frac{s^2}{c^2}\Pi''_{\gamma\gamma}(0)\right]$$

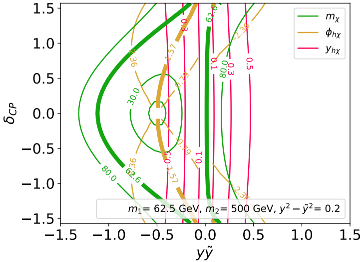
$$Y = \frac{m_W^2 s^2}{8\pi\alpha_e}\left[c^2\Pi''_{\gamma\gamma}(0) + s^2\Pi''_{ZZ}(0) - 2sc\Pi''_{\gamma Z}(0)\right]$$



$= i\Pi_{XX}(p^2)g^{\mu\nu}$

Complications with tuning the mass and phase

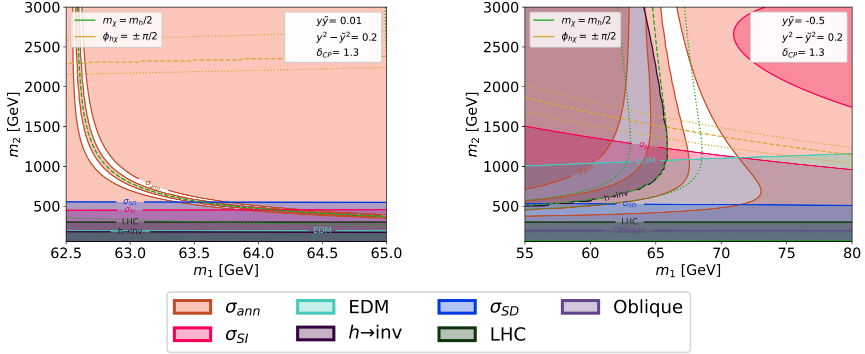




- IR DM mass, Yukawa coupling magnitude, and Yukawa coupling phase are no longer independent.
- Can no longer increase Re[$y_{h\chi}$] while fixing Im[$y_{h\chi}$]: tuning the phase also affects mass

We Find Viable Parameter Space!

- If coupling is small, need mass to be tuned near resonance
- If coupling is larger, slightly more flexible mass but phase also needs to be tuned



Summary

- CP Violating Higgs portal DM is an alternative to mass resonance for generating the correct annihilation cross section
- Still viable parameter space in simplest singlet-doublet UV completion

$$m_2 \gtrsim 1000 \text{ GeV}, m_1 \sim 65 - 75 \text{ GeV}, \delta_{CP} \sim \pi/2$$

- Can be probed by upcomming EDM and direct detection experiments