Constraints on CP-Violating Higgs Portal Majorana Dark Matter

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with A. Parikh, W. L. Xu

The challenge for WIMP dark matter

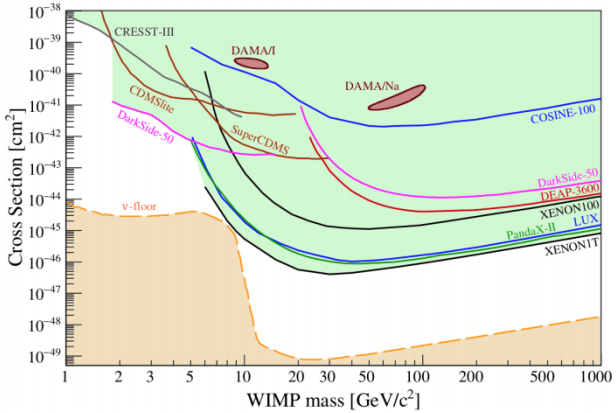
Central Question: In light of current constraints, is a Higgs portal Majorana fermion thermal relic WIMP a viable dark matter candidate?

Need: Large annihilation signal

- $\mathcal{O}$(1-10 pb) cross section for thermal relic abundance
- $\sim$ 3 pb cross section for DM explanation of GCE

Small direct detection cross section

- constraints becoming increasingly stringent



[Schumann, 1903.03026]

Why CP Violation?

Typical solution: s-channel resonance

- $m_{DM} = m_h/2$ [Huang et al '14, others]
- annihilation is p-wave suppressed for real couplings – two Majorana fermions form a CP odd state, but the Higgs is CP even.

Instead, CP violation:

- avoids velocity suppression: annihilation proportional to Im[y]. [Carena et al '19, in the context of a specific SUSY model]
- Direct detection controlled by Re[y] since initial and final states have the same CP

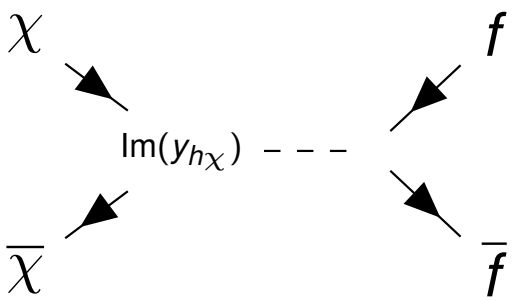
The DM EFT

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

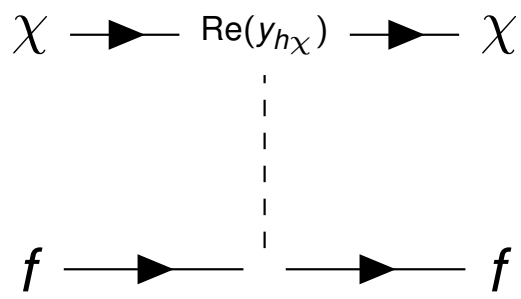
$$\mathcal{L} \supset \frac{|y_{h\chi}|e^{i\phi_{h\chi}}}{2\sqrt{2}} h\overline{\chi}P_L\chi + \frac{|y_{h\chi}|e^{-i\phi_{h\chi}}}{2\sqrt{2}} h\overline{\chi}P_R\chi + \frac{g_{Z\chi}}{2} Z_\mu \overline{\chi}\gamma^5\chi$$

3 Relevant Constraints:

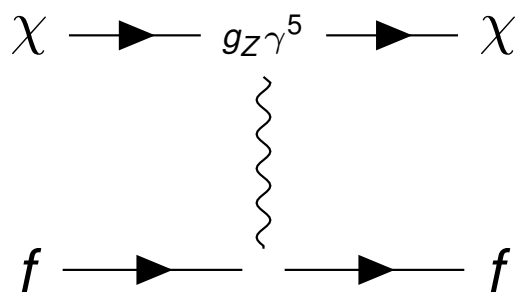
Annihilation



Spin-Independent Direct Detection



Spin-Dependent Direct Detection

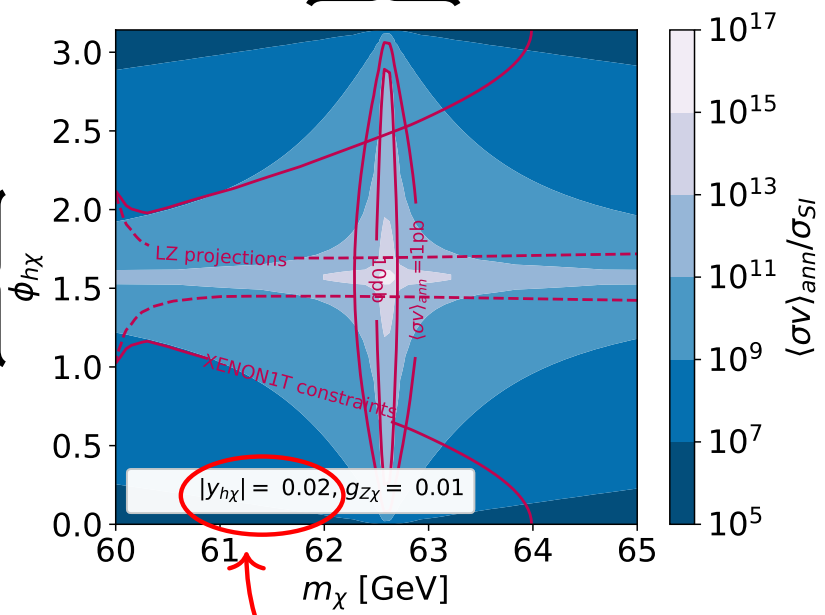


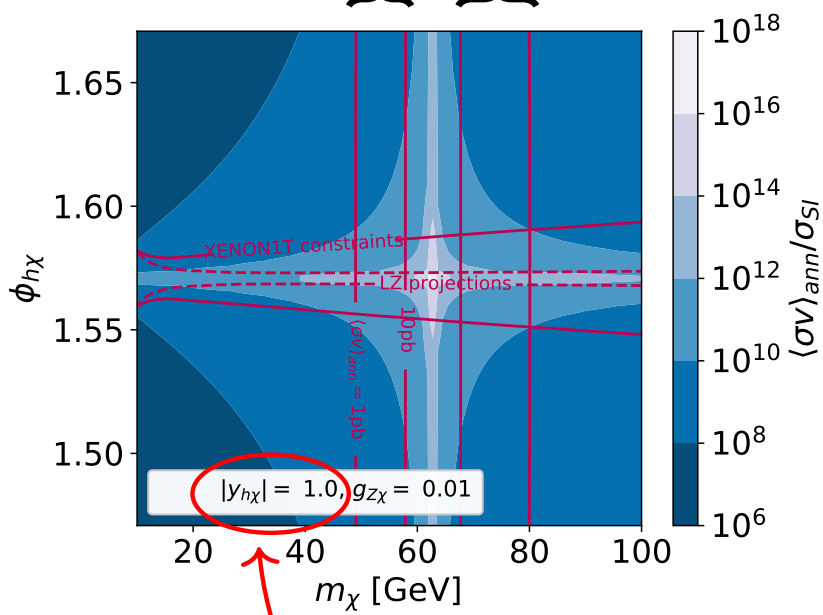
Mass and Phase Constraints

Annihilation

Allowed

Direct Detection





Small coupling: tune mass to ↑ annihilation

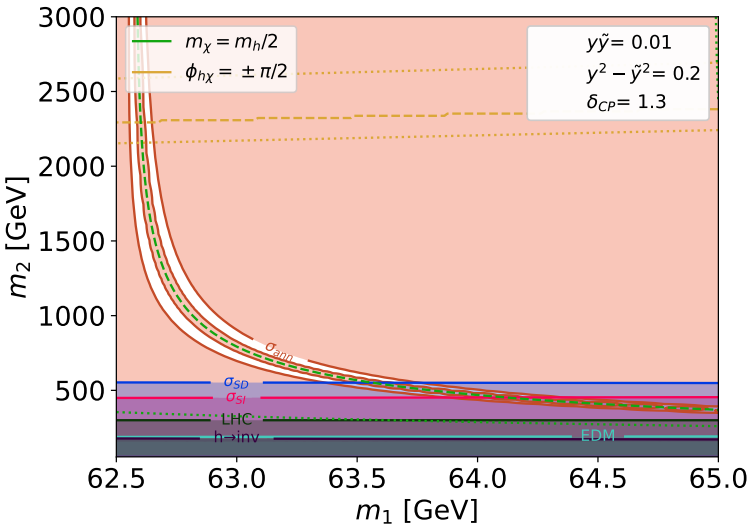
Large coupling: tune phase to ↓ direct detection

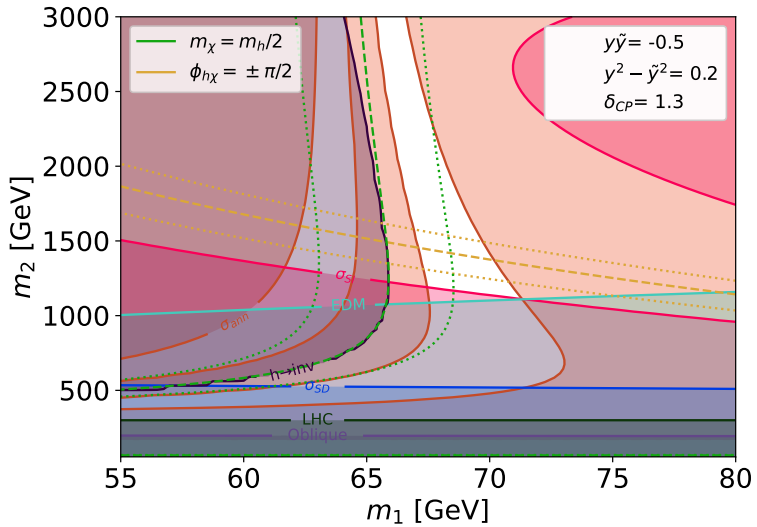
We Find Viable Parameter Space in a UV Completion!

There is viable parameter space in a minimal UV completition: the Singlet-Doublet Model. [Mahbubani & Senatore '06, Others]

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

$(\psi_2, \tilde{\psi}_2)$: Dirac doublet
ψ_1: Majorana singlet





σ_{ann} EDM σ_{SD} Oblique
σ_{SI} $h\to$inv LHC

Summary

- For Higgs portal DM, CP Violation is a viable alternative to mass resonance
- Still possible parameter space in simplest singlet-doublet UV completion

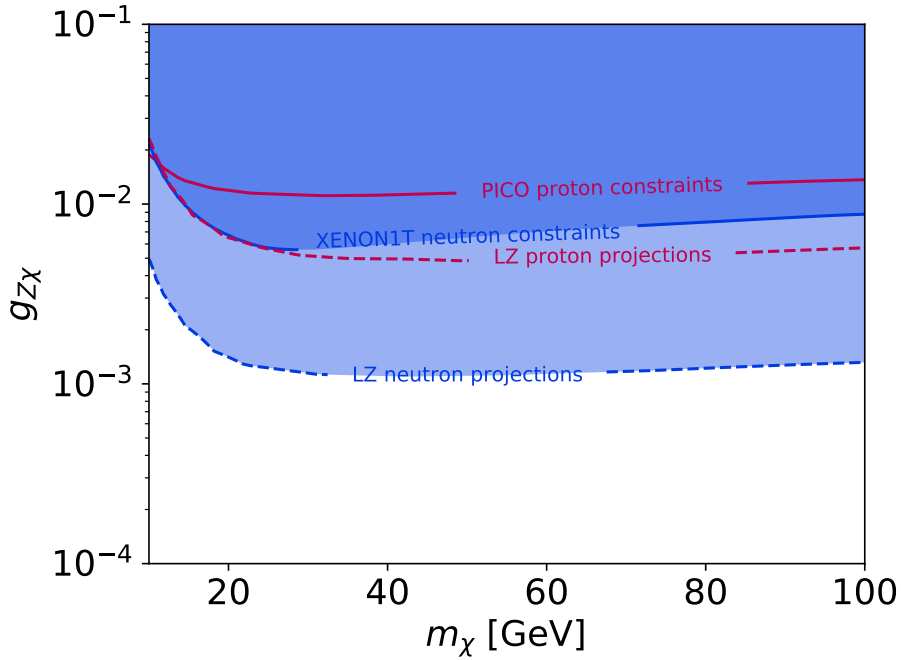
$$m_2 \gtrsim 1000 \text{ GeV}, m_1 \sim 65 - 75 \text{ GeV}, \delta_{CP} \sim \pi/2$$

- Can be probed by upcomming EDM and direct detection experiments

Back Up Slides

Z Coupling Constraints

- Spin dependent constraints easily avoided with small Z coupling.



Singlet - Doublet Model

Pick a minimal UV completion: Singlet-Doublet Model

[Mahbubani & Senatore '06, Others]

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

$(\psi_2, \tilde{\psi}_2)$: Dirac doublet

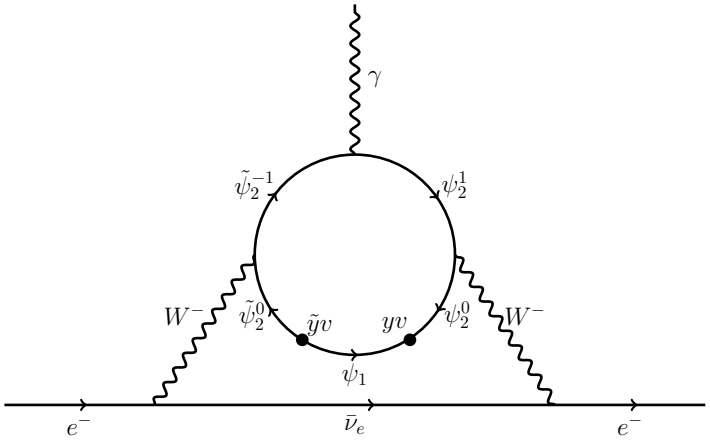
ψ_1: Majorana singlet

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

Constraints in the UV

But, this is not the whole story. Additional constraints apply to a UV completion:

Electron EDM



Collider Constraints

Electroweak Precision Parameters

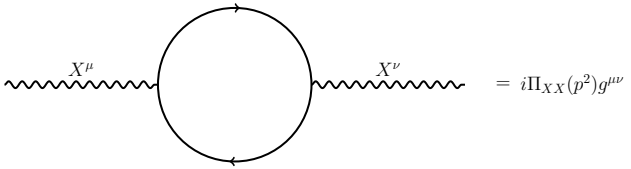
$$S \equiv \frac{4c^2 s^2}{\alpha_e}\left[\Pi'_{ZZ}(0) - \frac{c^2-s^2}{cs}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$

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

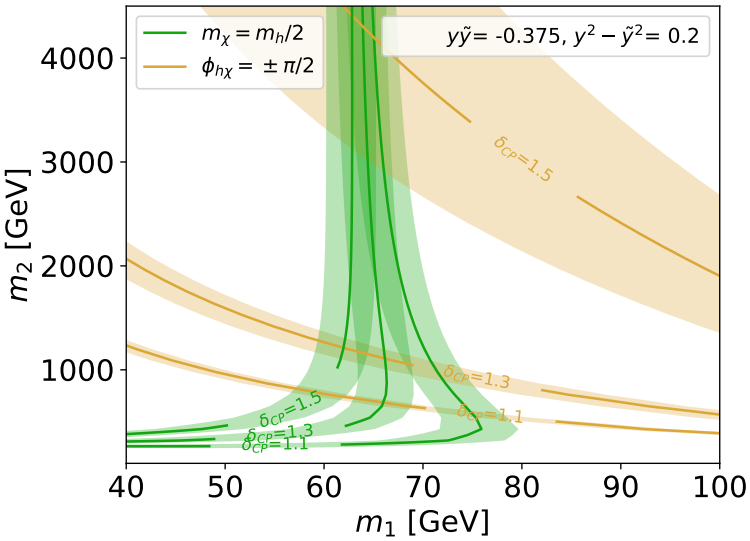
$$U \equiv \frac{4s^2}{\alpha_e}\left[\Pi'_{WW}(0) - \frac{c}{s}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S$$

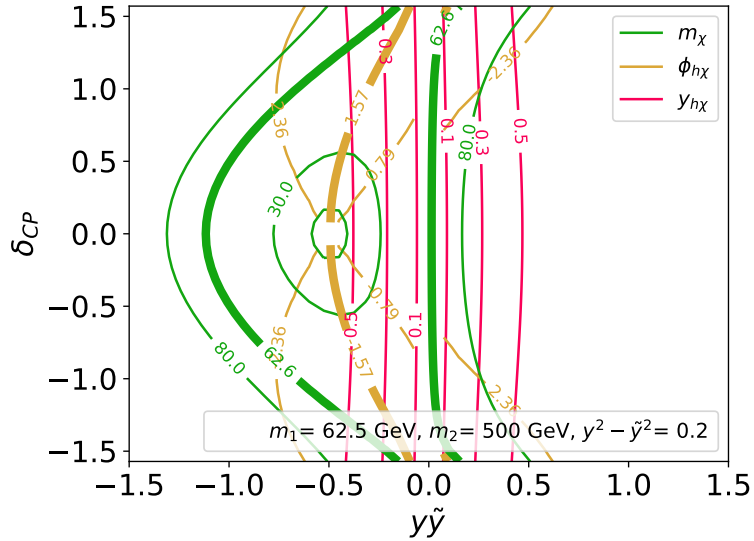
$$W \equiv \frac{m_W^2 s^2 c^2}{8\pi\alpha_e}\left[\Pi''_{ZZ}(0) + \frac{2s}{c}\Pi''_{Z\gamma}(0) + \frac{s^2}{c^2}\Pi''_{\gamma\gamma}(0)\right]$$

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



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