Constraints on CP-Violating Higgs Portal Majorana Dark Matter

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Background and Motivation

The challenge for thermal WIMP dark matter is to generate a **large annihilation signal** but a **small direct detection cross section**.

An **annihilation cross section $\mathcal{O}$(1-10 pb)** is required to:

- generate the correct thermal relic abundance.
- explain the galactic center excess (GCE; a statistically significant excess of gamma rays in the Galactic Center), if it is caused by dark matter [Goodenough & Hooper '09, others] instead of millisecond pulsars [Abazajian et. al '14, others]. The GCE is well fit by a $\sim$ **3** pb cross section where dark matter annihilates through the higgs to $b\bar{b}$.

A **direct detection cross section of $\mathcal{O}(10^{-10})$ or less** is required to avoid increasingly stringent bounds on spin-independent scattering with nucleons.

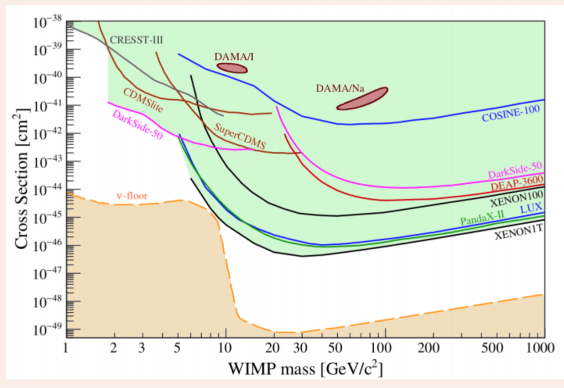


Figure 1: Limits from spin-independent direct detection [Schumann: 1903.03026]

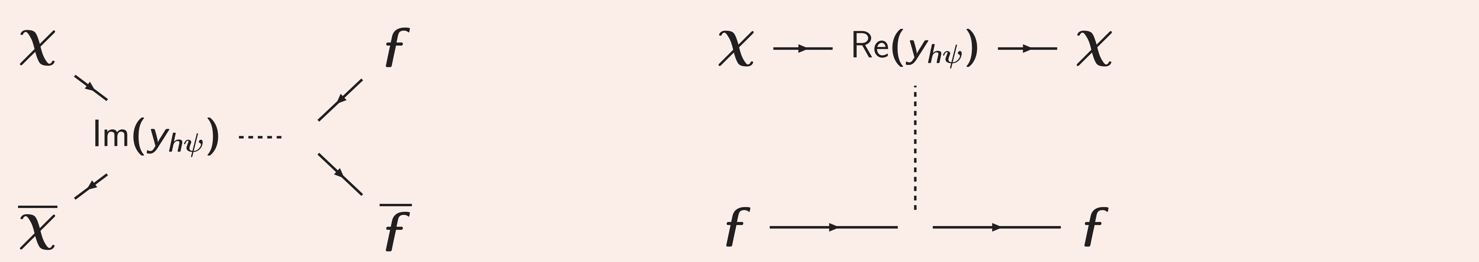
Why CP Violation?

The typical solution to generate a hiearchy between annihilation and direct detection is an **s-channel resonance** ($m_{DM} = m_h/2$).[Huang et al '14, others]

- Doesn't work for Majorana fermions with real couplings since annihilation is still p-wave suppressed, because two Majorana fermions form a CP odd state, but the Higgs is CP even.
- Finite higgs width limits the size of enhancement

An alternative is **CP violation in the higgs coupling**. Then direct detection and annihilation are controlled by different degrees of freedom:

- Leading annihilation term $\propto$ Im[y] since it is not velocity suppressed.
- Direct detection $\propto$ Re[y] since initial and final states have the same CP.



Annihilation　　　Spin-Independent Direct Detection

This has previously been discussed in the context of a specific SUSY model [Carena et al '19: 1905.03768]. Our paper studies this mechanism more generally, arguing that **CP violating higgs portal Majorana thermal relic dark matter is still allowed by current constraints**.

The Dark Matter EFT

In the EFT, dark matter is a Majorana fermion χ that couples to the Higgs and the Z:

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

Two separate variables control the relative size of spin-independent direct detection and annihilation:

- the **dark matter mass m_χ**
- the **higgs coupling phase $\phi_{h\chi}$**

Which one we need to tune depends on the size of $|y_{h\chi}|$.

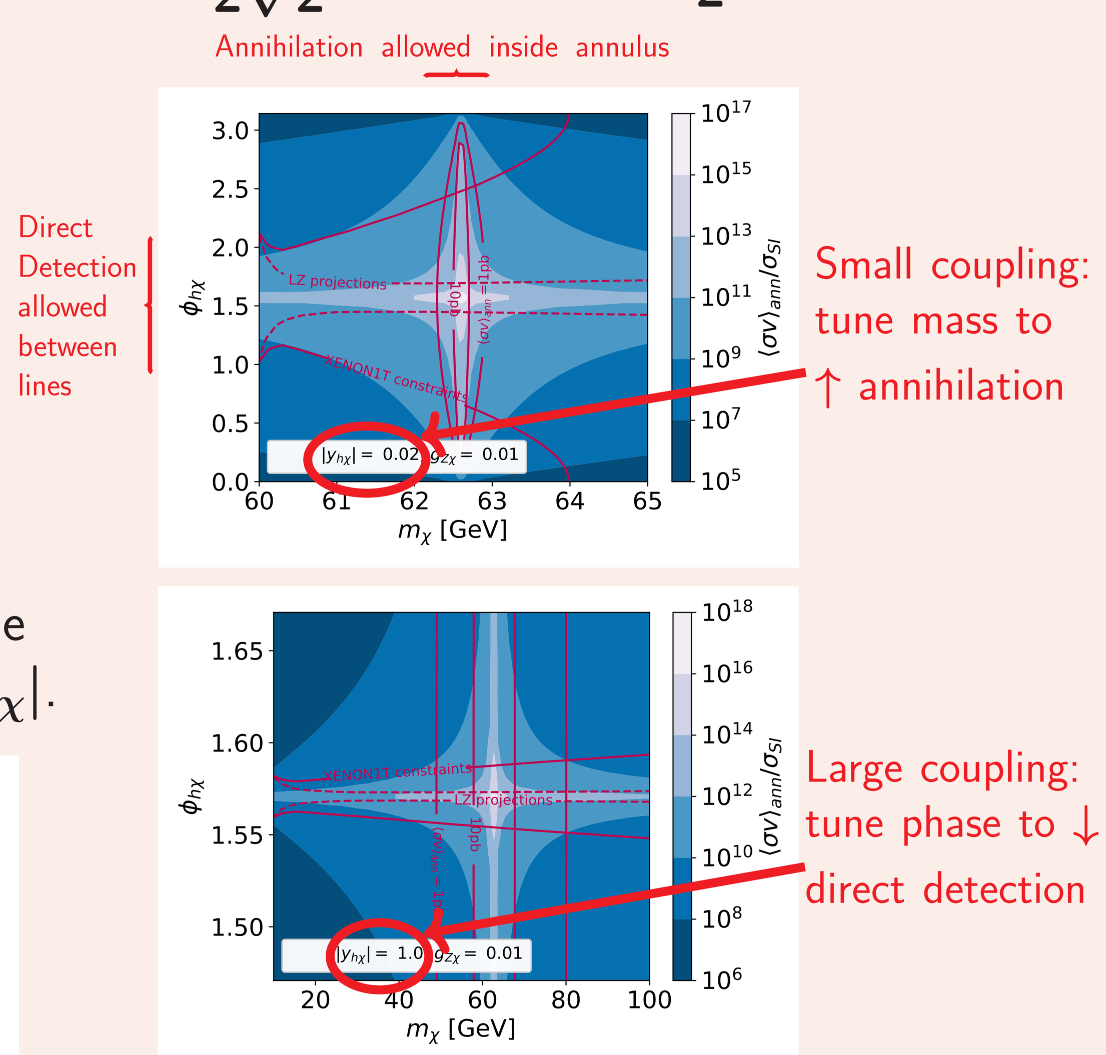


Figure 3: Annihilation and spin-independent direct detection constraints

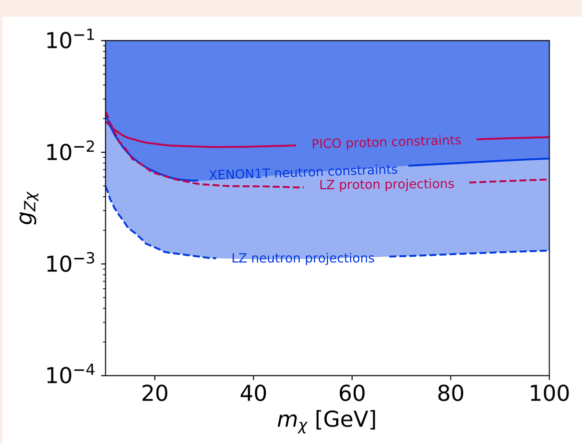


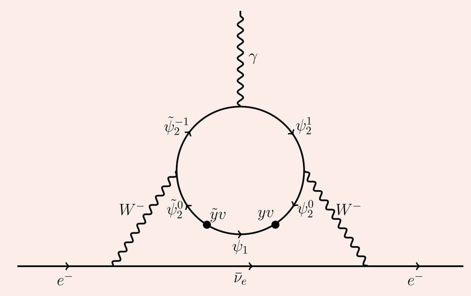
Figure 2: Spin-dependent direct detection constraints

Spin dependent constraints easily avoided with **small Z coupling**.

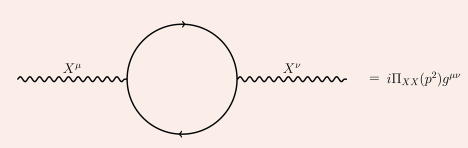
Other Constraints

Additional constraints apply, including:

1. **electron EDM constraints**, since we have added CP violation. In minimal models, often comes from Barr-Zee diagrams.
2. **Electroweak precision constraints**, since we have added a doublet.
3. **Collider constraints**, including searches from SModelS and invisible higgs decay.



$$S \equiv \frac{4c^2s^2}{\alpha_e}\left[\Pi'_{ZZ}(0) - \frac{c^2-s^2}{cs}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right]$$
$$T \equiv \frac{1}{\alpha_e}\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right]$$
$$U \equiv \frac{4s^2}{\alpha_e}\left[\Pi'_{WW}(0) - \frac{c}{s}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] - S$$
$$W \equiv \frac{m_W^2 s^2 c^2}{8\pi\alpha_e}\left[\Pi''_{ZZ}(0) + \frac{2s}{c}\Pi''_{Z\gamma}(0) + \frac{s^2}{c^2}\Pi''_{\gamma\gamma}(0)\right]$$
$$Y = \frac{m_W^2 s^2}{8\pi\alpha_e}\left[c^2\Pi''_{\gamma\gamma}(0) + s^2\Pi''_{ZZ}(0) - 2sc\Pi''_{\gamma Z}(0)\right]$$



All of these constraints are sensitive to the heavy particle content of our theory in addition to the dark matter. Therefore, we **need to analyze them in the context of a UV completion**.

Singlet Doublet Model

The singlet-doublet model [Mahbubani & Senatore '06, others] is a minimal UV completion.

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

It contains:

- A Dirac doublet $(\psi_2, \tilde{\psi}_2)$ with hypercharge 1/2
- A Majorana singlet ψ_1
- One physical phase, which we choose to put in the Yukawa couplings $Y = ye^{i\delta_{CP}/2}$, $\tilde{Y} = \tilde{y}e^{i\delta_{CP}/2}$

The dark matter is a mix of mostly doublet and the singlet. The neutral Dirac fermion splits into two Majorana fermions, which mix with the singlet after SSB. The dark matter χ is the lowest mass eigenstate.

We Find Viable Parameter Space!

Small coupling $\to$ mass tuned near resonance

Large coupling $\to$ more flexible mass, phase also tuned

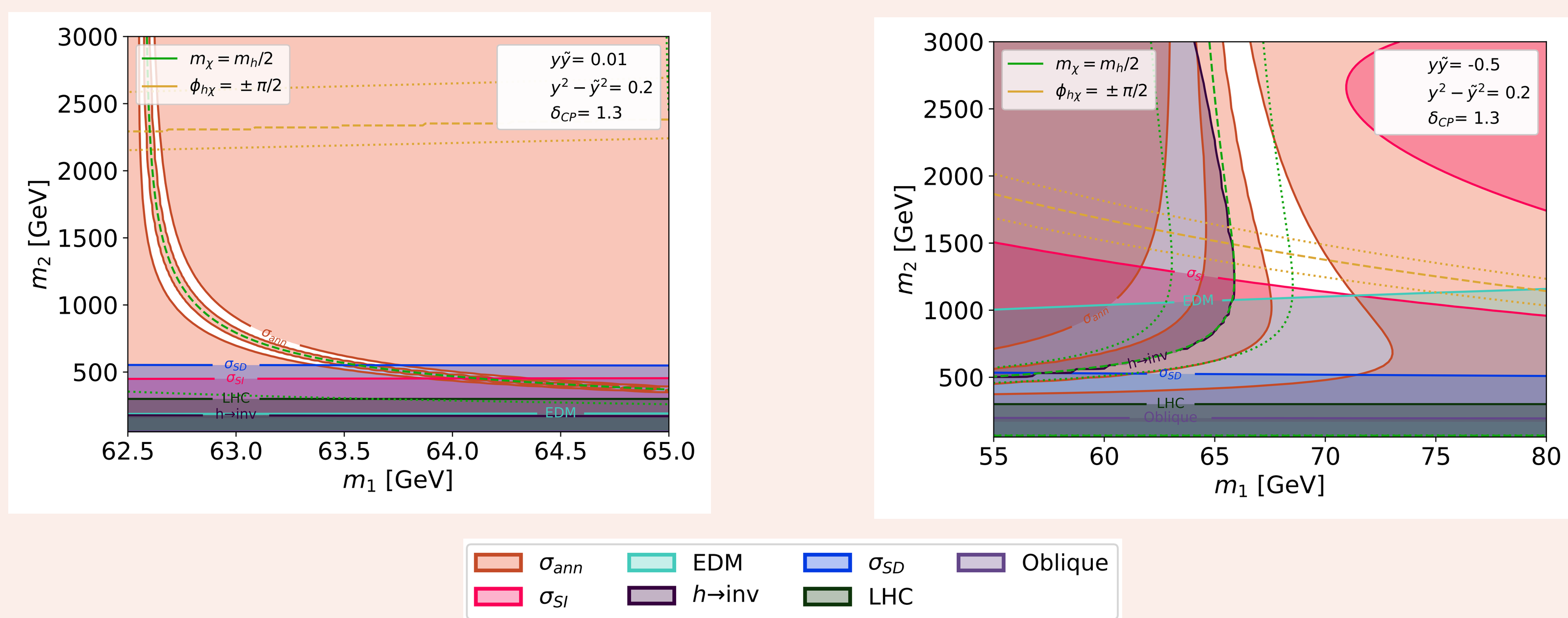


Figure 4: Full Constraints on the Singlet-Doublet model

Note that the DM mass and EFT Yukawa coupling are **no longer controlled by independent parameters**, which means we cannot easily increase Re[$y_{h\chi}$] while fixing Im[$y_{h\chi}$]. **Tuning the phase also affects mass**, so we need to change our parameters in a coordinated way

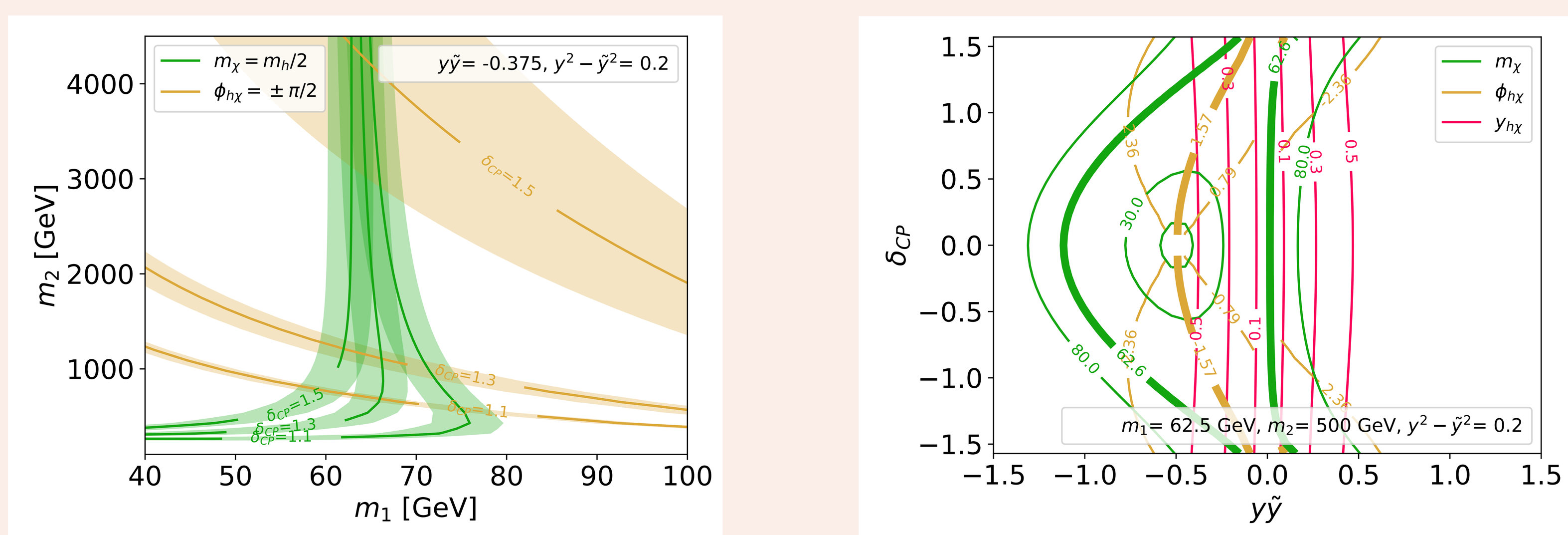


Figure 5: EFT paramters as a function of UV parameters. Right: Regions where $m_\chi \sim m_h/2$ and $\phi_{h\chi} \sim \pi/2$. Right: Contours for m_χ, $|y_{h\chi}|$, $\phi_{h\chi}$.

Summary

For Higgs portal DM, **CP Violation is a viable alternative to mass resonance**. Specifically, there is still parameter space in the minimal singlet-doublet UV completion, where

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

Open parameter space can be probed by upcoming EDM and direct detection experiments.