# Phenomenology of CP-Violating Higgs Portal Dark Matter

Cosmology from Home 2020


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# Revisiting the WIMP Solution to DM

For:

- Easily motivated
- Thermal Relic picture
- Experimental Anomalies
  - Fermi-LAT*
  - AMS-02 (?)

Against:

- Stringent direct detection constraints

# Revisiting the WIMP Solution to DM

For:

- Easily motivated
- Thermal Relic picture
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Annihilation Good $[\sim \mathrm{pb}]$

Against:

- Stringent direct detection constraints

Scattering Bad $[\lesssim 10^{-10}\mathrm{pb}]$

# Fermi Galactic Center Excess

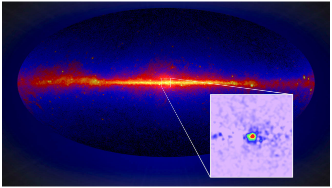
- Excess in gamma-rays in GC
- Possibly unresolved point sources (e.g. MSPs)

  [Abazajian et. al '14, many others]

- Possibly annihilating DM

  [Goodenough & Hooper '09, many others]

  - $\mathcal{O}(60$ GeV$)$ DM
  - WIMP-like cross section $\sim 3$ pb
  - Favors Higgs-like branching-ratios



# Outline

- Introduction
- The Dark Matter EFT
  - Model Description
  - Constraints
- Some UV Completions
  - Singlet-Doublet
  - Doublet-Triplet
  - Constraints

# Outline



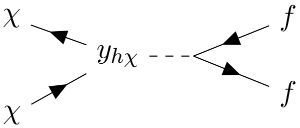
Goal: Develop a DM model which

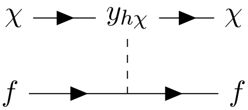
- annihilates with TR-like rates
- has BRs consistent with GCE
- respects Scattering bounds

# CP-Violating Higgs Portal Dark Matter

- Higgs Portal with complex coupling $y_{h\chi}$
- Majorana Fermion DM

$$\mathcal{L} \supset \frac{\mathrm{Re}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\chi + \frac{i\mathrm{Im}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\gamma^5\chi + g_{Z\chi} Z_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$



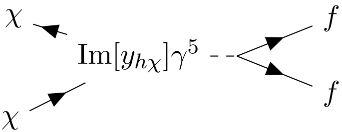
# The Dark Matter EFT – Annihilation

$$\mathcal{L} \supset \frac{\text{Re}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\chi + \frac{i\text{Im}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\gamma^5\chi + g_{Z\chi} Z_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

In the non-relativistic limit

$h\bar{\chi}\chi$ annihilation is suppressed

$$\langle\sigma v\rangle \propto \text{Im}[y_{h\chi}]^2$$



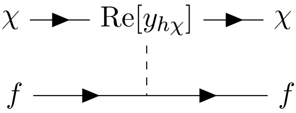
# The Dark Matter EFT – Scattering

$$\mathcal{L} \supset \frac{\mathrm{Re}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\chi + \frac{i\mathrm{Im}[y_{h\chi}]}{\sqrt{2}} h\bar{\chi}\gamma^5\chi + g_{Z\chi} Z_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

In the non-relativistic limit

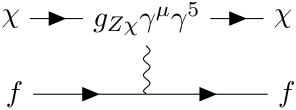
$h\bar{\chi}\gamma^5\chi$ scattering is suppressed

$$\sigma_{SI} \propto \mathrm{Re}[y_{h\chi}]^2$$



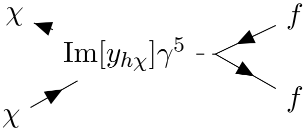

$Z_\mu\bar{\chi}\gamma^\mu\gamma^5\chi$ sets SD scattering

$$\sigma_{SD} \propto g_{Z\chi}^2$$

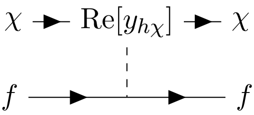


# The Dark Matter EFT – Constraints

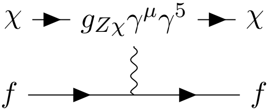
Annihilation




Spin- Independent

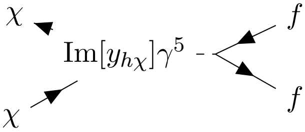



Spin- Dependent



# The Dark Matter EFT – Constraints

Annihilation

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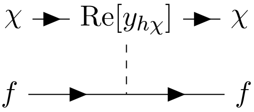


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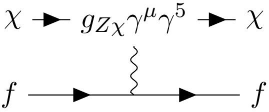
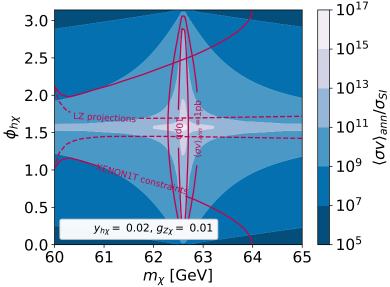
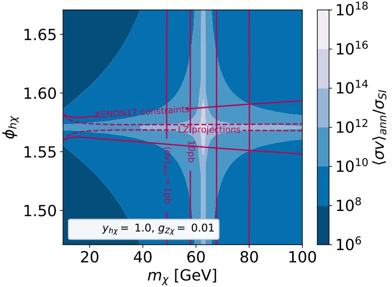
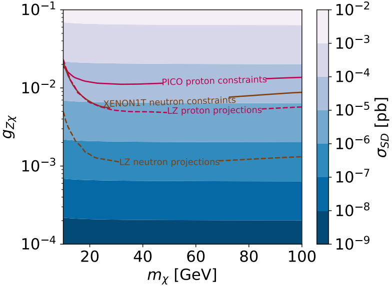



1. $\chi \sim m_h/2$, small $y_{h\chi}$
2. $\phi_{h\chi} \sim \pi/2$, large $y_{h\chi}$

# The Dark Matter EFT – Constraints



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Goal: UV complete this model so

- theory isn't gauge anomalous
- has at least 1 free phase for CP-violation
- is consistent with all known constraints

# A Singlet-Doublet Realization

- $SU(2)_L$ Singlet $\psi_1$, $Y = 0$
- $SU(2)_L$ Doublet $\psi_2 = \begin{pmatrix} \psi_2^+ \\ \psi_2^0 \end{pmatrix}$, $Y = 1/2$
- $SU(2)_L$ Doublet $\tilde{\psi}_2 = \begin{pmatrix} \tilde{\psi}_2^0 \\ \tilde{\psi}_2^- \end{pmatrix}$, $Y = -1/2$

$\Longrightarrow$ 3 Majorana (Neutral) fermions

$$\psi_1,\ \frac{1}{\sqrt{2}}\left(\psi_2^0 + \tilde{\psi}_2^0\right),\ \frac{1}{\sqrt{2}}\left(\psi_2^0 - \tilde{\psi}_2^0\right)$$

+ 1 Dirac (Charged) fermion $\{\psi_2^+, \tilde{\psi}_2^-\}$

# A Singlet-Doublet Realization

$$\mathcal{L} \supset Y \bar{\psi}_1 \left( \frac{v+h}{\sqrt{2}} \right) \psi_2^0 + \tilde{Y} \bar{\psi}_1 \left( \frac{v+h}{\sqrt{2}} \right) \tilde{\psi}_2^0 - m_2 \bar{\psi}_2^0 \tilde{\psi}_2^0 - m_2 \bar{\tilde{\psi}}_2^- \psi_2^+ - \frac{m_1}{2} \bar{\psi}_1 \psi_1 + \text{h.c.}$$

- 4 couplings, 3 fields $\implies$ 1 free phase. Choose

$$Y \equiv y e^{i\delta_{CP}/2}, \;\; \tilde{Y} \equiv \tilde{y} e^{i\delta_{CP}/2}$$

- Model Parameters $\{m_1, m_2, y, \tilde{y}, \delta_{CP}\}$

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$$\mathcal{L} \supset Y\bar{\psi}_1\left(\frac{v+h}{\sqrt{2}}\right)\psi_2^0 + \tilde{Y}\bar{\psi}_1\left(\frac{v+h}{\sqrt{2}}\right)\tilde{\psi}_2^0 - m_2\bar{\psi}_2^0\tilde{\psi}_2^0 - m_2\bar{\tilde{\psi}}_2^-\psi_2^+ - \frac{m_1}{2}\bar{\psi}_1\psi_1 + \text{h.c.}$$

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- Model Parameters $\{m_1, m_2, y, \tilde{y}, \delta_{CP}\}$
- Singlet - Doublet mixing in the neutral sector

$\implies$ 3 Majorana + 1 Dirac mass eigenstates
$\chi$ (DM), $\chi_1$, $\chi_2$ + $\{\psi_{2c}, \tilde{\psi}_{2c}\}$

# A Doublet-Triplet Realization

- $SU(2)_L$ Doublet $\psi_2 = \begin{pmatrix} \psi_2^+ \\ \psi_2^0 \end{pmatrix}, Y = 1/2$
- $SU(2)_L$ Doublet $\tilde{\psi}_2 = \begin{pmatrix} \tilde{\psi}_2^0 \\ \tilde{\psi}_2^- \end{pmatrix}, Y = -1/2$
- $SU(2)_L$ Triplet $\psi_3 = \begin{pmatrix} \psi_3^0/\sqrt{2} & \psi_3^+ \\ \psi_3^- & -\psi_3^0/\sqrt{2} \end{pmatrix}, Y = 0$

$\Longrightarrow$ 3 Majorana (Neutral) fermions

$$\psi_3^0,\ \frac{1}{\sqrt{2}}\left(\psi_2^0 + \tilde{\psi}_2^0\right),\ \frac{1}{\sqrt{2}}\left(\psi_2^0 - \tilde{\psi}_2^0\right)$$

+ 2 Dirac (Charged) fermions $\{\psi_2^+, \tilde{\psi}_2^0-\}, \{\psi_3^+, \tilde{\psi}_3^-\}$

# A Doublet-Triplet Realization

$$\mathcal{L} \supset -Y\bar{\psi}_3^0\left(\frac{v+h}{2}\right)\psi_2^0 + \tilde{Y}\bar{\psi}_3^0\left(\frac{v+h}{2}\right)\tilde{\psi}_2^0$$
$$+Y\bar{\psi}_3^-\left(\frac{v+h}{\sqrt{2}}\right)\psi_2^+ + \tilde{Y}\bar{\psi}_3^+\left(\frac{v+h}{\sqrt{2}}\right)\tilde{\psi}_2^-$$
$$-m_2\bar{\psi}_2^0\tilde{\psi}_2^0 - m_2\bar{\tilde{\psi}}_2^-\psi_2^+ - \frac{m_3}{2}\bar{\psi}_3^0\psi_3^0 - m_3\bar{\psi}_3^+\psi_3^- + \text{h.c.}$$

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- Model Parameters $\{m_2, m_3, y, \tilde{y}, \delta_{CP}\}$

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- Model Parameters $\{m_2, m_3, y, \tilde{y}, \delta_{CP}\}$
- Doublet-Triplet mixing in both neutral and charged sectors

$\implies$ 3 Majorana + 2 Dirac mass eigenstates

$\chi$ (DM), $\chi_1$, $\chi_2$ + $\{\chi_1^+, \chi_1^-\}, \{\chi_2^+, \chi_2^-\}$

# UV Constraints: Some intuition

more moving parts

$\Updownarrow$

more constraints

- CP-violation:

- New particle content :

- Constraints from EFT:

# UV Constraints: Some intuition

more moving parts

$\Updownarrow$

more constraints

- CP-violation:

EDM measurements

"Amount of low-energy gauge-coupled CP-violation can't be too large"

- New particle content :

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more moving parts
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more constraints

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"Amount of low-energy gauge-coupled CP-violation can't be too large"

- New particle content :

Collider bounds

"New particles have to be heavy or weakly coupled"

- Constraints from EFT:

# UV Constraints: Some intuition

more moving parts

$\Updownarrow$

more constraints

- CP-violation:

EDM measurements

"Amount of low-energy gauge-coupled CP-violation can't be too large"

- New particle content :

Collider bounds

"New particles have to be heavy or weakly coupled"

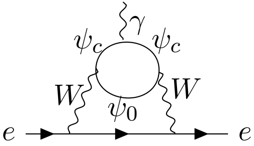
- Constraints from EFT:

Suitable $\{m_\chi, y_{h\chi}, g_{Z\chi}\}$

"Lightest particle must be $\sim 60$ GeV. $y_{h\chi}$ needs to be small or imaginary. $g_{Z\chi}$ needs to be small."

# UV Constraints – CP Violation

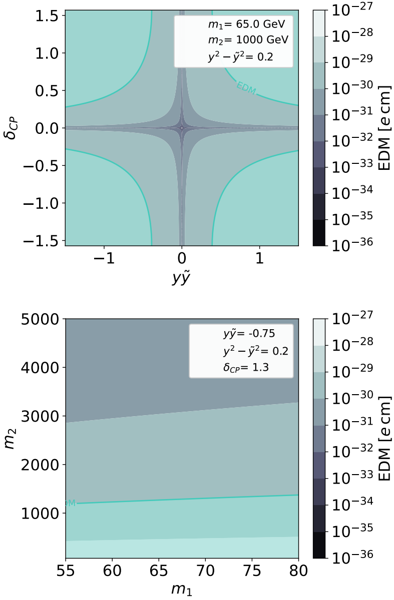
$$\frac{|d_e|}{e} =$$



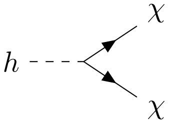

$$\sim \frac{y\tilde{y}\sin[\delta_{CP}]}{m_2^2}$$

$$\leq 1.1 \times 10^{-29} \text{ cm } [90\% \text{ CL}]$$

[ACME '18]



# UV Constraints – Invisible Decays

$\Gamma_{h\to\chi\chi} =$ 

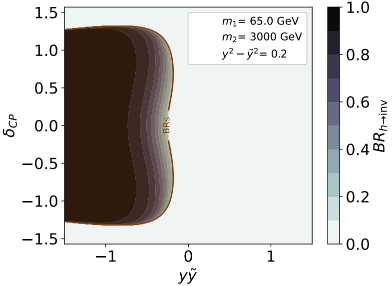


$$\sim \frac{y\tilde{y}\sin^2[\delta_{CP}]v}{m_2}(m_h^2 - 4m_\chi^2)^{1/2}$$

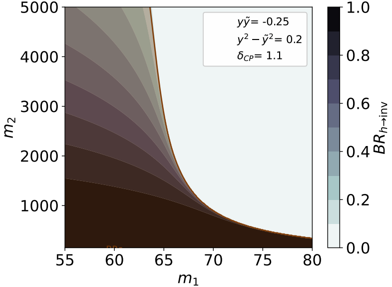
$$\theta(m_h - 2m_\chi)$$

$\mathrm{BR}[h \to \mathrm{inv}] \leq 0.13$ [95% CL]

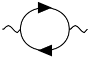
[ATLAS '20]





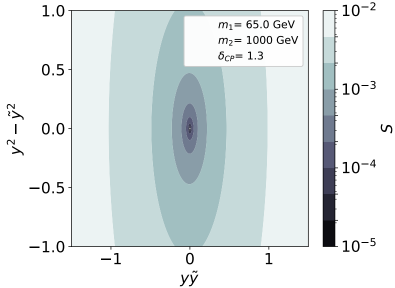


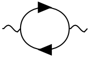
# UV Constraints – Electroweak Precision

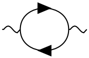
$$S = \frac{\partial}{\partial p^2}\ W_3$$  $$W_0$$

$$\sim \frac{y^2 + \tilde{y}^2}{m_2^2}$$

$$\lesssim 0.2 \text{ [95\% CL]}$$

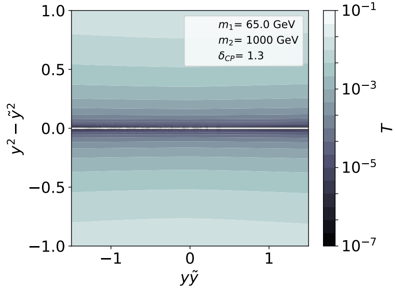



$$T = W_1$$  $$W_1$$

$$-\ W_3$$  $$W_3$$

$$\sim \frac{y^2 - \tilde{y}^2}{m_2^2}$$

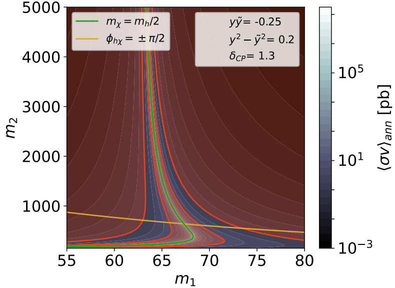
$$\lesssim 0.2 \text{ [95\% CL]}$$



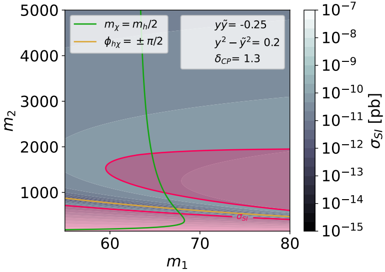

[LEP ’04]

# UV Constraints – Inherited from EFT

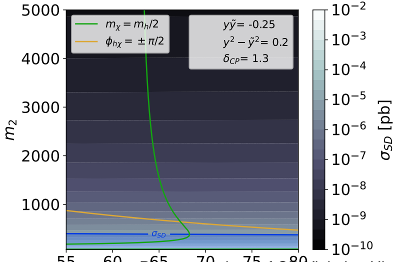
$\langle\sigma v\rangle_{ann} \in [1\text{ pb}, 10\text{ pb}]$




$\sigma_{SI} \leq 10^{-10}$ pb

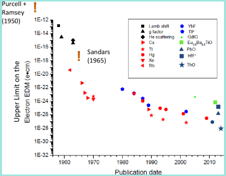



$\sigma_{SD} \leq 10^{-5}$ pb

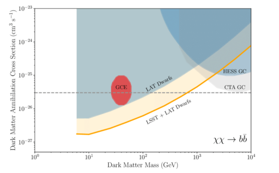


# Putting it all together

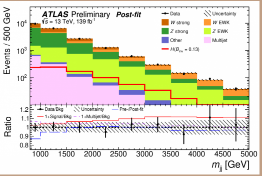
## Electron EDM [Hess '14]



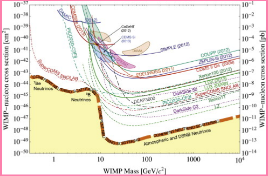

## Fermi GCE [Drlica-Wagner '19]



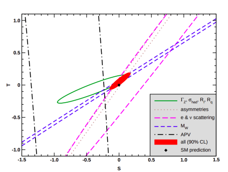

## Higgs → Inv [ATLAS '20]



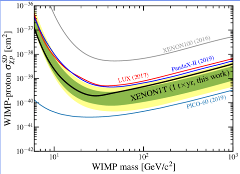

## Spin-Independent [Cooley '14]




## Oblique SU(2) [PDG '20]




## Spin-Dependent [Xenon1T '19]



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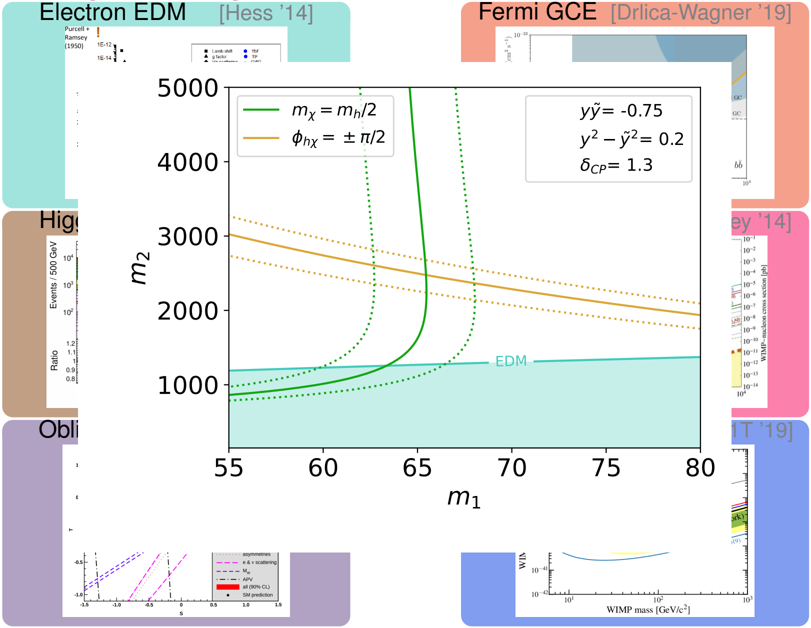

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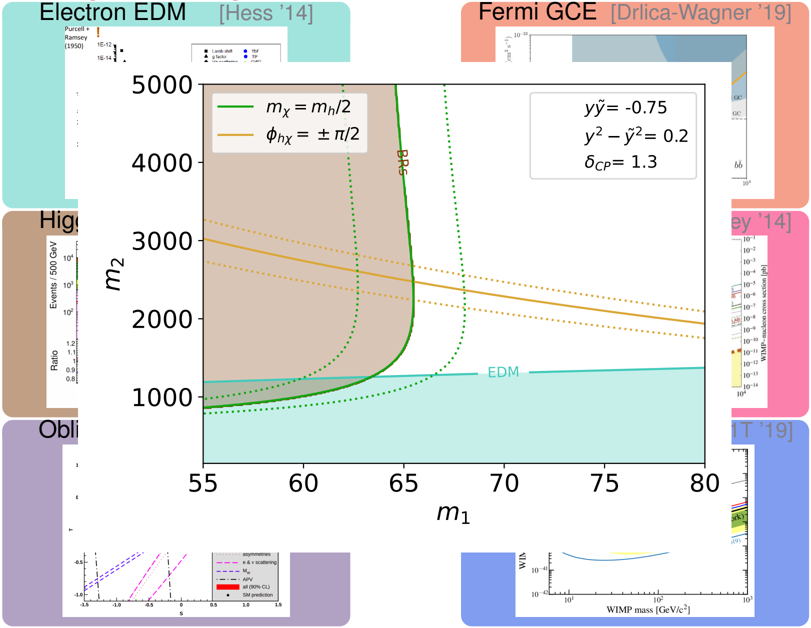

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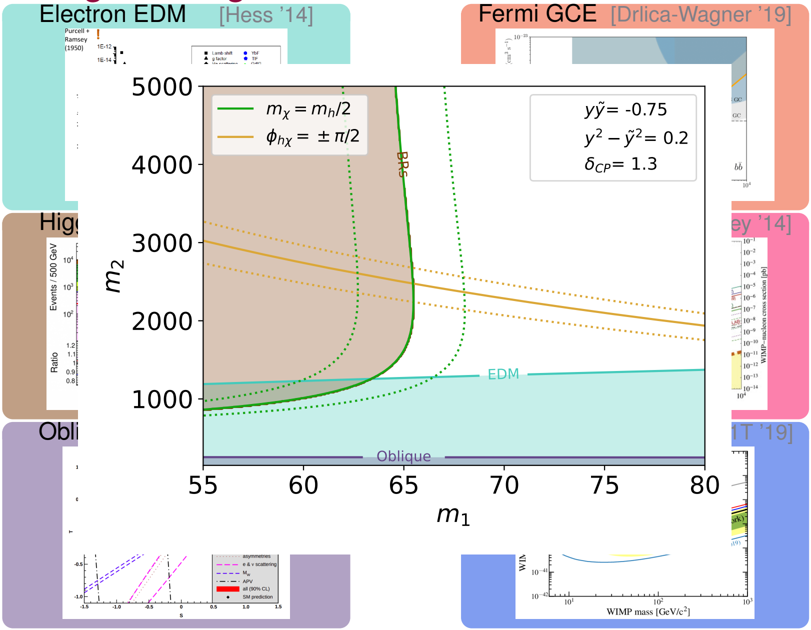

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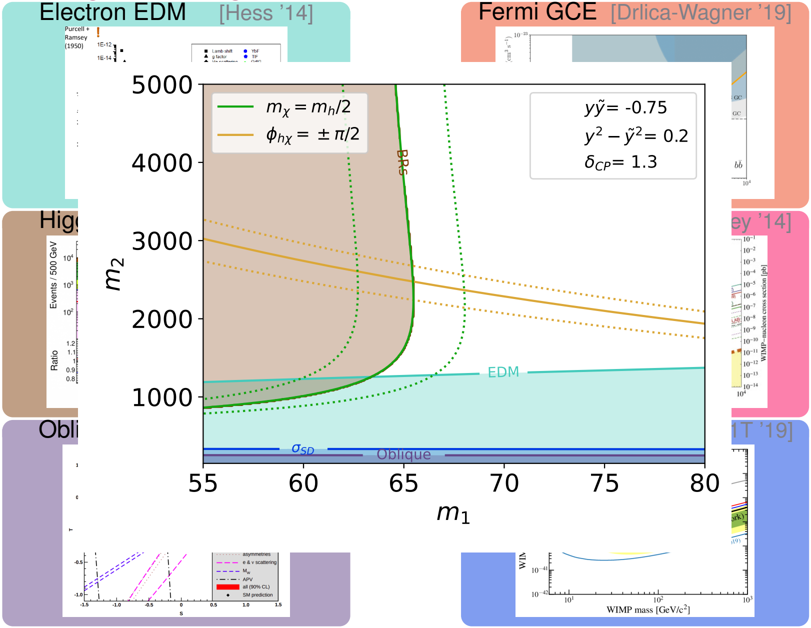

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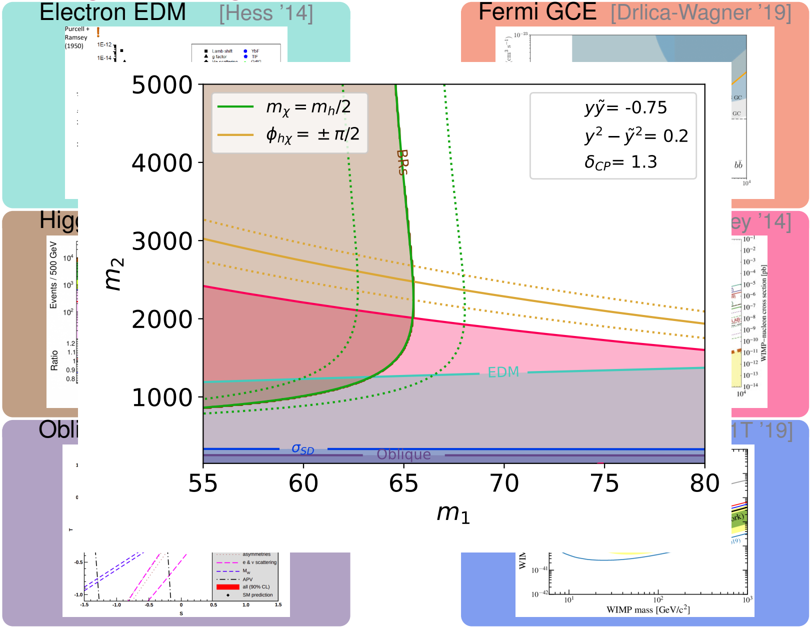

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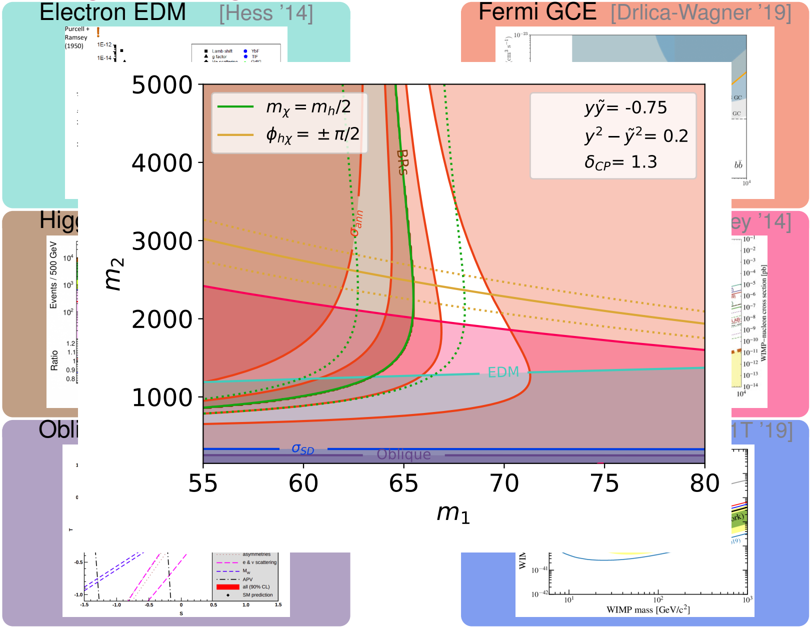

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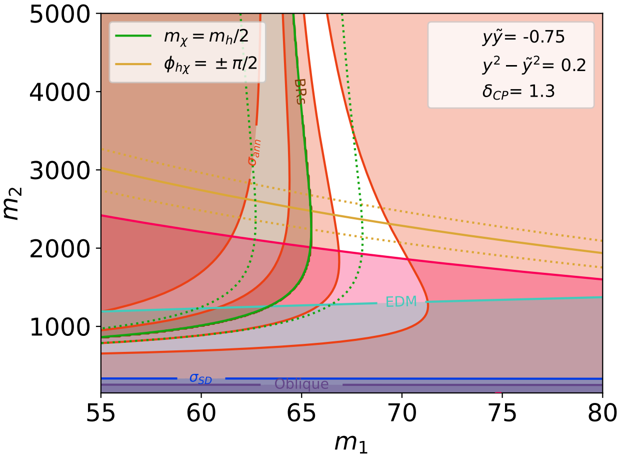
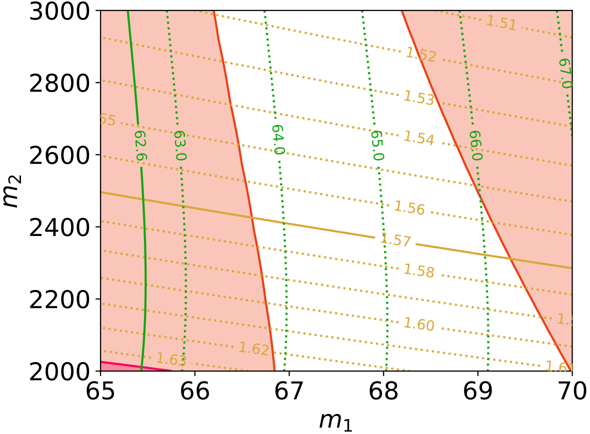


# Putting it all together



# Conclusions

- CP-Violating Higgs Portal Dark Matter is a viable model
  - Candidate solution to GCE
  - Thermal relic
  - Respects scattering constraints
  - Mass resonance unecessary for imaginary couplings
- Several UV completions are possible; in particular Singlet-Doublet DM is a minimal way to realize this.
  - Viable parameter space for both mass and phase tunings

Thank you!