Explore DM Blind Spots with Gravitational Wave

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Motivation

- Higgs & GW discoveries, evidence of Dark Matter, connection among them?

- Higgs portal DM
- Electroweak baryogenesis
- Primordial black hole DM
- PT GW detection
- Ramsey-Musolf’s talk
- Mertens’s talk
- Long’s talk
- Kuhnel’s talk
- Jiang-Hao Yu
- El Hedri’s talk
Inert Scalar Dark Matter

- A simplified model rules them all

See also Wagner’s and Guo’s talk
Outline

- Review general inert scalar dark matter models

- How to realize strong first order phase transition, while avoiding other constraints?

- Motivate the mixed dark matter which has strong first order phase transition, viable dark matter candidate, GWs, etc
**General Inert Scalar DM**

- **Minimal Dark Matter: scalar multiplet DM**

\[
\lambda_{H\Phi} H H^\dagger H \Phi_n^\dagger \Phi_n
\]

\[
\Phi_n = \begin{pmatrix} \phi^{+j} \\ \vdots \\ \phi^{-j} \end{pmatrix} \sim (2j + 1, Y)
\]

DM: neutral component

- **Direct detection bound**

\[
\sigma_{SI} \simeq f_N^2 \frac{\lambda_{H\Phi}^2}{4\pi} \left( \frac{m_N^2}{m_\chi m_h^2} \right)^2 \rightarrow \lambda_{H\Phi} \sim \text{small!}
\]

- **Thermal relic cross section:**

constraint on DM mass

\[
\langle \sigma v \rangle \simeq \frac{n^4 - 4n^2 + 3}{n} \frac{g^4}{128\pi M^2} + \frac{1}{n} \frac{\lambda_{H\Phi}^2}{16\pi M^2} \simeq \frac{n^4 - 4n^2 + 3}{n} \frac{g^4}{128\pi M^2}
\]

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Cirelli, Fornengo, Strumia 2007
Hambye, Ling, Honorez, Rocher 2009
Strong EW Phase Transition

- **Thermal barrier in effective potential**

  \[ V(H, T) = m^2(T)H^2 - ETH^3 + \lambda(T)H^4 \]

  Strongly first order phase transition condition (sphaleron decoupling)

  \[ \frac{v_c}{T_c} \sim \frac{E}{\lambda} \geq \xi_{\text{sph}}(T_c) \sim 1.16 \]

  New scalar needs to be light (< 200 GeV) to be in thermal plasma during EW phase transition

- **Scalar multiplet DM case**

  \[ E \simeq \frac{1}{2\pi v_0^3} \left( 2m_W^3 + m_Z^3 + \text{new scalar mass} \right) \]

  Large scalar d.o.f enhances size of PT

  \[ M^2_H(H, T) \simeq \lambda_H H^2 + (n^2 - 1)g^2 T^2 \]

  Large screening reduces size of PT

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Strong EWPT in Inert DM

- *Tension between strong FOPT and Direct Detection*

\[ E \sim \frac{1}{2\pi v_0^3} \left( 2m_W^3 + m_Z^3 + n\lambda_{H\Phi}^{3/2}v_0^2 \right) \]

\[ \sigma_{SI} \sim \frac{\lambda_{H\Phi}^2}{4\pi} \rightarrow \lambda_{H\Phi} \sim \text{small!} \]

\[ \langle \sigma v \rangle (\chi\chi \rightarrow WW/ZZ) \rightarrow m_\chi > 0.54 \text{ TeV} (n > 1) \text{ not in plasma during EWPT} \]

- *Lesson 1: strong FOPT strength is related to direct detection rate*

- *Lesson 2: thermal relic is fully determined by gauge interactions, typically heavy dark matter*

  Hard to realize strong FOPT in scalar multiplet models

- *Need to avoid the above general relations*

  Break relations or Higgs resonance region
Strong PT in Singlet DM

- **Light WIMP DM possible due to SU(2)L singlet**

\[ \langle \sigma v \rangle \rightarrow m_\chi > 120 \text{ GeV} (n = 1) \]

Higgs resonance region:
Need larger coupling to realize strong FOPT

De Simone, Giudice, Strumia 2014

Direct Detection rules out large region

Beniwal, et.al. 2017
Strong PT in Inert Doublet DM

- No direct correlation between strong PT and direct detection

\[
V(H_1, H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4
\]
\[
+ \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} [(H_1^\dagger H_2)^2 + h.c.]
\]

Different parameter dependence:

- Region: \(\lambda_3, \lambda_4\) and \(\lambda_5\) large (non-degenerate mass)
- But \(\Lambda_{345}\) small due to cancellation among them
- And inert scalar should be lighter than 200 GeV
Inert Doublet DM

- Two regions allowed by WIMP DM + Higgs data + Oblique ST

Belyaev, et.al. 2016
Non-degenerate mass pattern allowed

Near Higgs funnel region with small $\lambda_{345}$

Benchmark point

$\mu_2 = 60 \text{ GeV}, \lambda_3 = 2.8, \lambda_4 = \lambda_5 = -1.4, \lambda_{345} = 0.01$

$m_+ = m_A > m_H \approx 60 \text{ GeV}$
Inert Doublet DM

- WIMP DM, Strong PT and Gravitational Wave

\[ \delta_{hZ} = 1.68\% \text{ at } 240 \text{ GeV CEPC} \]
\[ \lambda_{hXX} = 0.0107 \]

CEPC: 0.4% with 10 ab-1 data
Inert Higher Multiplet DM

- Usually tension between direct detection and sFOPT
- Relic density (VV channel) usually needs heavy scalar

  Higgs resonance region usually won’t help, except inert 2HDM

- Also high multiplets encounter other tight collider constraints

- Strength of first order phase transition decreases for higher multiplet

  Large screening effects

- Usually large multiplicity not good.
  possible for special potential setup

- How about increasing number of scalar multiplet?

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Mixed Scalar Dark Matter

- **Mixed dark matter: singlet-doublet, singlet-triplet models**
  - Need singlet to decrease the DM mass (relic density consideration)
  - Should avoid higher multiplet (otherwise mostly singlet)

\[ \lambda_{H\Phi} H \Phi^\dagger + \lambda_{HS} H \Phi^\dagger S^2 \]

- Advantage 1: blind spot region for direct detection!!!
- Advantage 2: large coupling for strong FOPT is still possible
- Advantage 3: Singlet component of DM helps reduce the DM mass (keep in thermal plasma)

Cohen, Kearney, Pierce, Tucker-Smith 2011
Cheung, Sanford 2013
Mixed Singlet-Doublet DM

- **Real singlet plus complex doublet**

\[
\Delta V = M_D^2 \Phi^\dagger \Phi + \lambda_3 \Phi^\dagger \Phi H^\dagger H + \lambda_4 |\Phi^\dagger H|^2 + \frac{\lambda_5}{2} [ (\Phi^\dagger H)^2 + h.c. ] \\
+ \frac{1}{2} M_S^2 S^2 + \frac{1}{2} \lambda_S S^2 |H|^2 + A [ S \Phi H^\dagger + h.c. ]
\]

Mixed dark matter candidate

\[
\chi = \cos \theta S - \sin \theta \Phi^0 , \\
\cos \theta S + \sin \theta \Phi^0 .
\]

- **Blind spot region: direct detection OK**

\[
\mathcal{L} \supset - ( \lambda_S v \sin^2 \theta + \lambda_{345} v \cos^2 \theta - A \sin 2\theta ) h \chi \chi \\
\mathcal{L} \supset - ( \lambda_S v \cos^2 \theta + \lambda_{345} v \sin^2 \theta + A \sin 2\theta ) h s s
\]

Blind spot Conditions:

For small (large) \( \theta \), \( \lambda_{345} (\lambda_S) \) approaches to zero!

For moderate \( \theta \), cancellation among three terms!

When minimize hDM coupling, hss coupling maximized (good for sFOPT)!
Mixed Singlet-Doublet DM

- **Relic density induces small mixing angle**

  \[
  \sigma_{\chi\chi \rightarrow VV} v^2 \approx \frac{3g^4 + 6g^2 g'^2 + g'^2}{256\pi m_X^2} \sin^2 \theta
  \]

  Gauge contribution dominant

- Small mixing angle for light DM (< 200 GeV)

  \[
  \sin \theta \approx \frac{m_X}{540 \text{ GeV}} \quad \text{(doublet)}
  \]

- **Large thermal barrier if small mixing and small lambda345**

  \[
  \frac{E}{v^3} \approx \frac{6m_W^3 + 3m_Z^3}{v^3} + 2 \left( \frac{\lambda_3}{2} \right)^{3/2} + \left( \frac{\lambda_3 + \lambda_4 - \lambda_5}{2} \right)^{3/2} + (\lambda_{hXX})^{3/2} + (\lambda_{hss})^{3/2}
  \]

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Mixed Singlet-Doublet DM

- Large parameter region with broad DM mass range

\[ \lambda_3 = 3.006, \quad \lambda_4 = -1.5, \quad \lambda_5 = -1.5, \]
\[ \lambda_S = 4.006, \quad A = 91 \text{ GeV} \quad M_D = M_S = 117.5 \text{ GeV} \]

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Mixed Singlet-Triplet DM

○ **Real singlet plus \( Y = 0 \) real triplet**

\[
\Delta V = \frac{1}{2} M_S^2 S^2 + M_\Sigma^2 \text{Tr}(\Phi^2) + \kappa_\Sigma H^\dagger H \text{Tr}(\Phi^2) \\
+ \frac{\kappa}{2} |H|^2 S^2 + \xi S H^\dagger \Phi H. \\
\chi = \cos \theta S - \sin \theta \Phi^0, \\
s = \sin \theta S + \cos \theta \Phi^0.
\]

Mixed dark matter candidate

Small mixing angle for light DM (< 200 GeV)

\[
\sin \theta \simeq \frac{m_\chi}{2000 \text{ GeV}} \quad \text{(triplet)}
\]

○ **Blind spot region and sFOPT**

\[
\mathcal{L} \supset - (\kappa v \sin^2 \theta + \kappa_\Sigma v \cos^2 \theta - \xi v \sin 2\theta) h\chi \chi \\
\mathcal{L} \supset - (\kappa v \cos^2 \theta + \kappa_\Sigma v \sin^2 \theta + \xi v \sin 2\theta) hss
\]

○ **sFOPT**

\[
\frac{E}{v^3} \simeq \frac{6m_W^3}{v^3} + \frac{3m_Z^3}{v^3} + (\lambda_{h\chi\chi})^{3/2} + (\lambda_{hss})^{3/2} + 2 (\kappa_\Sigma/2)^{3/2}
\]

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Mixed Singlet-Triplet DM

- **Benchmark point**

\[ \kappa = 0.1, \ \kappa_{\Sigma} = 3.0, \ \xi = 0.31337, \ \mathcal{M}_{\Sigma} = 50 \text{ GeV}, \ \mathcal{M}_S = 119.93 \text{ GeV} \]
Conclusion

- Study strongly first order phase transition and gravitational wave in classified general scalar multiplet DM model

  - Typically hard to realize due to tension among strong FOPT and direct detection, relic density requirement.

  - Inert 2HDM: small parameter region allowed (near Higgs resonance region)

- Mixed scalar dark matter could produce strong FOPT and GW

  - Large parameter region (broad DM mass range) due to singlet-non-singlet mixing

  - Blind spot region could avoid direct detection constraints and obtain viable WIMP DM, strong FOPT and GW

Thank You!

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### Bubble nucleation rate

\[ \Gamma/\mathcal{V} \approx T^4 \exp \left( -\frac{S_3(T)}{T} \right) \]

\[ S_3 = 4\pi \int dr r^2 \left[ \frac{1}{2} \left( \frac{d\phi}{dr} \right)^2 + V(\phi, T) \right] \]

### Latent heat release

\[ \alpha = \frac{1}{\rho_{\text{tot}}} \left( T \frac{dV_{\text{eff}}^{\text{min}}}{dT} - V_{\text{eff}}^{\text{min}} \right) \bigg|_{T=T_*} \]

\[ \beta = T_* \left( \frac{d}{dT} \frac{S_3(T)}{T} \right) \bigg|_{T=T_*} \]

inverse time of PT