Singlet Fermionic Dark Matter

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Collaboration with Y.G. Kim and K.Y. Lee

Outline

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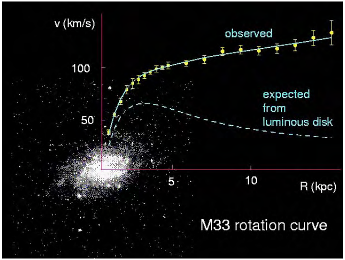
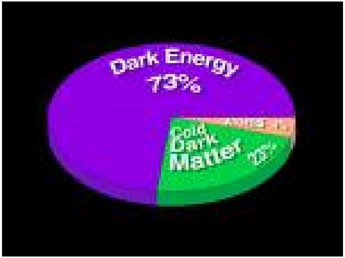
Dark Matter in our universe

Rotation curves of the galaxy





Different from the observation!! → *There is non-luminous matter.*

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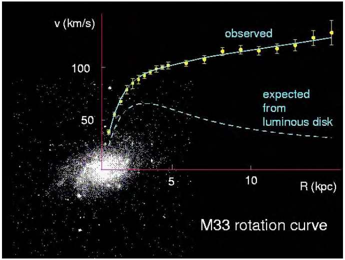

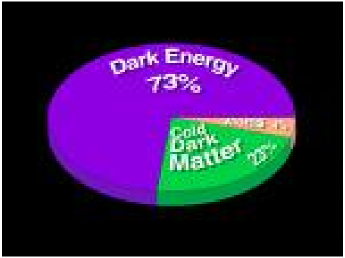

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Condition for the dark matters

- Stable (produced after the Big-Bang and still present today)
- Neutral (no electric interaction and no binding to the nuclei)
- $\Omega_{CDM} h^2 \sim 0.1$ $(0.085 < \Omega_{CDM} h^2 < 0.119)$ WMAP data

  C.L. Bennett *et al.*, Astrophys. J. Suppl. Ser. **148**, 1 (2003)

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Several toy models of the singlet dark matters

Minimal extension of the Standard Model to get the candidates of DM

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Singlet scalar DM

C.P. Burgees, M. Pospelov, T. Veldhuis (minimal scalar model)

Nucl. Phys. **B 619**, 709-728 (2001)

DM : SM singlet real scalar field with Z_2 parity

Interaction with the ordinary fields only through Higgs

- Different Higgs phenomenology from that in SM

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Fermionic DM

Y.G. Kim and K.Y. Lee (minimal fermionic model)

Physical Review **D 75**, 115012 (2007)

DM : SM singlet Dirac fermion field ($U(1)$ to avoid the mixing)

Interaction with the ordinary fields only through Higgs

Non-renormalizable interactions of the singlet fermion and SM Higgs

Outline

Model building

Our model : Minimal model with the renormalizable interactions

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{hid} + \mathcal{L}_{int}$$

- Hidden sector : real singlet scalar, singlet Dirac fermion

  $\mathcal{L}_{hid} = \mathcal{L}_S + \mathcal{L}_\psi - g_S \bar{\psi}\psi S$
  - $\mathcal{L}_S = \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{m_0^2}{2}S^2 - \frac{\lambda_3}{3!}S^3 - \frac{\lambda_4}{4!}S^4$
  - $\mathcal{L}_\psi = \bar{\psi}\left(i\partial\!\!\!/ - m_{\psi_0}\right)\psi$
- Interaction of the hidden sector and SM sector

  $\mathcal{L}_{int} = -\lambda_1 H^\dagger H S - \lambda_2 H^\dagger H S^2$
  - Singlet fermion is sequestered from SM matters. ($U(1)$ of ψ)
  - Singlet scalar couples to the SM sector only through the Higgs.
  - Mixing between SM Higgs and the singlet scalar (two Higgs)
    Say h_1 : SM higgs-like , h_2 : singlet-like

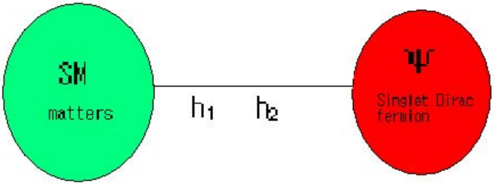
Model building

Our model : Minimal model with the renormalizable interactions

- The interaction of the hidden fermion and the SM sector are suppressed by the mass of h_1 and h_2 & mixing angle.

  Singlet fermion is naturally a WIMP $\rightarrow$ DM
- Different Higgs phenomenology : less production, invisible decay
- 8 undetermined parameters : $m_{\psi_0}, g_S, \bar{\lambda}_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4, x_0$

  $\Rightarrow$ determine Higgs boson masses (m_{h_1}, m_{h_2}), mixing angle (θ), triple and quartic self couplings of Higgs bosons



Implication in cosmology and collider physics

Thermal relic density $\Omega_\psi h^2 \approx \frac{(1.07\times10^9)x_F}{\sqrt{g_*}M_{pl}(GeV)<\sigma_{ann.}v_{rel}>}$ constrained by WMAP

$\bar{\psi}\psi \rightarrow$ SM particles via Higgs mediated *s*-channel processes

$\bar{\psi}\psi \rightarrow$ Higgs bosons via *s*, *t*, *u*-channels

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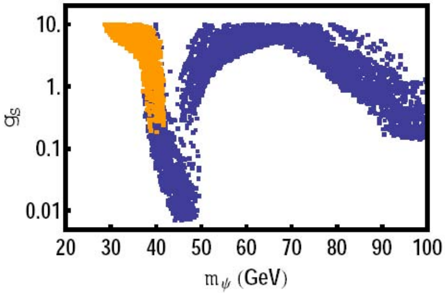
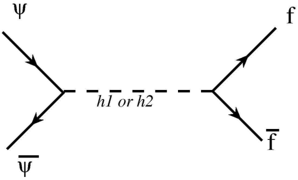




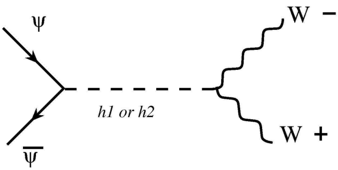


Figure: $m_{h_1} = 90\ GeV\ (\pm1\%)$
$m_{h_2} = 500\ GeV\ (\pm12\%)$

Implication in cosmology and collider physics

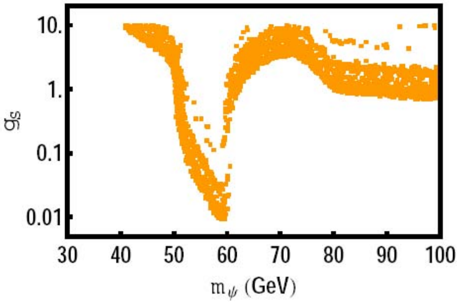


Figure: $m_{h_1} = 120\ GeV\ (\pm 1\%)$
$m_{h_2} = 500\ GeV\ (\pm 12\%)$

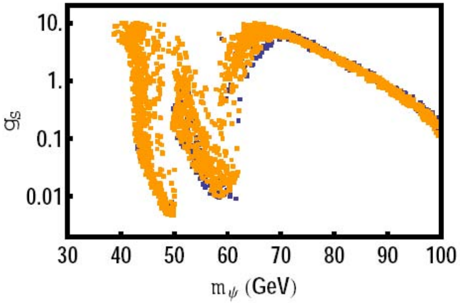
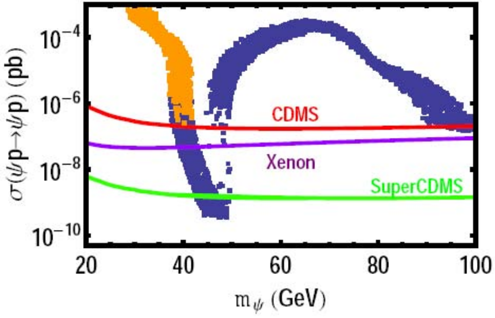
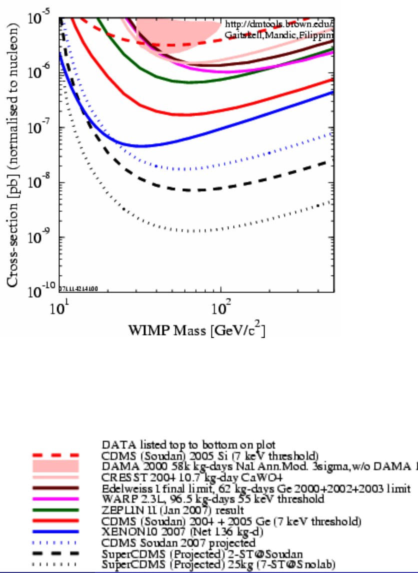
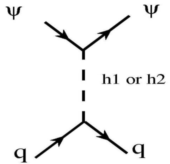


Figure: $m_{h_1} = 120\ GeV\ (\pm 4\%)$
$m_{h_2} = 100\ GeV\ (\pm 1\%)$

Direct detection







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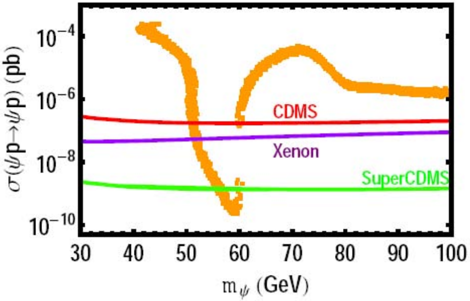

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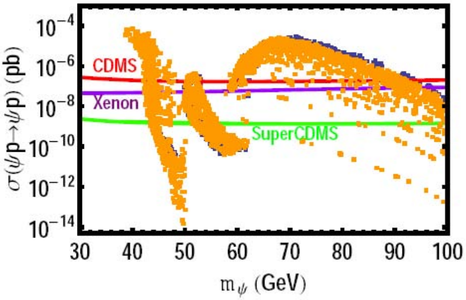

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Thank you!!

Back-up

Definitions and Relations of the parameters

- SM Higgs potential term $-(-\mu^2 H^\dagger H + \bar{\lambda}_0 (H^\dagger H)^2)$
- $< S >= x_0 \quad < H_0 >= v_0/\sqrt{2} \quad S = x_0 + s \quad H_0 = (v_0 + h)/\sqrt{2}$
- Extremum condition

  $\mu^2 = \bar{\lambda}_0 v_0^2 + (\lambda_1 + \lambda_2 x_0) x_0 \ ; \ m_0^2 = -\frac{\lambda_3}{2} x_0 - \frac{\lambda_4}{6} x_0^2 - \frac{\lambda_1 v_0^2}{2x_0} - \lambda_2 v_0^2$
- Mass matrix (V : potential of SM Higgs and the singlet fields)

$$\mu_h^2 \equiv \left.\frac{\partial^2 V}{\partial h^2}\right|_{h=s=0} = 2\bar{\lambda}_0 v_0^2$$

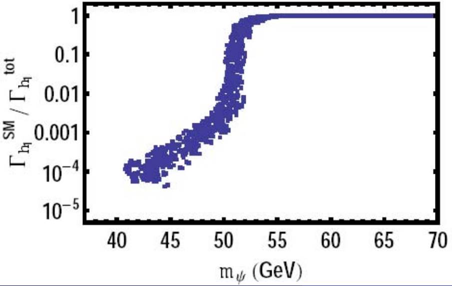
$$\mu_s^2 \equiv \left.\frac{\partial^2 V}{\partial s^2}\right|_{h=s=0} = \frac{\lambda_3}{2} x_0 + \frac{\lambda_4}{3} x_0^2 - \frac{\lambda_1 v_0^2}{2x_0}$$

$$\mu_{hs}^2 \equiv \left.\frac{\partial^2 V}{\partial h \partial s}\right|_{h=s=0} = (\lambda_1 + 2\lambda_2 x_0) v_0$$

Back-up

Parameter choice

- Fix Higgs masses m_{h_1} and m_{h_2} within some ranges.
- Allow θ, triple and quartic Higgs self-couplings vary freely.
- Our parameter sets should satisfy several physical conditions
  - Potential is bounded below.
  - EW symmetry breaking is viable.
  - All couplings keep the perturbativity.



$m_{h_1} = 120\ GeV\ (\pm 1\%)$
$m_{h_2} = 500\ GeV\ (\pm 12\%)$

We have very large invisible branching ratios when $m_\psi \lesssim m_{h_1}/2$

Back-up

Mixing parameters

- Mass eigenstate

$$h_1 = \sin\theta\ s + \cos\theta\ h\ ;\ \ h_2 = \cos\theta\ s - \sin\theta\ h$$

- Mixing angle

$$\tan\theta = \frac{y}{1+\sqrt{1+y^2}}, \qquad \text{where } y \equiv \frac{2\mu_{hs}^2}{\mu_h^2-\mu_s^2}$$

- Mass eigenvalues

$$m_{1,2}^2 = \frac{\mu_h^2+\mu_s^2}{2} \pm \frac{\mu_h^2-\mu_s^2}{2}\sqrt{1+y^2}$$

$\cos\theta > \frac{1}{\sqrt{2}}$ if the definition of $\tan\theta$ is fixed.

Elastic cross section

- Cross section

$$\sigma(\psi p \to \psi p) \approx \frac{4}{\pi} m_p^4 \left[\frac{0.35 g_s \sin\theta\cos\theta}{v_0} \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right) \right]^2$$

Back-up

EW Precision Observation : The promising channel to produce a neutral Higgs boson at LEP is the Higgs-strahlung process $e^- e^+ \rightarrow Zh$

$$\xi_i^2 = \left(\frac{g_{h_i ZZ}}{g_{HZZ}^{SM}}\right)^2 \frac{\Gamma_{h_i}^{SM}}{\Gamma_{h_i}^{SM} + \Gamma(h_i \rightarrow \bar{\psi}\psi)}$$

Assuming the non-standard models, the lower bound on the Higgs mass is represented by the upper bound of ξ_i^2, which is shown ⇒

We impose $\xi^2 < 0.1$ as a conservative bound for $m_{h_i} = 90$ GeV and $\xi^2 < 0.3$ for $m_{h_i} = 100$ GeV