Higgs-portal Dark Matter and γ-ray excess from Galactic Center

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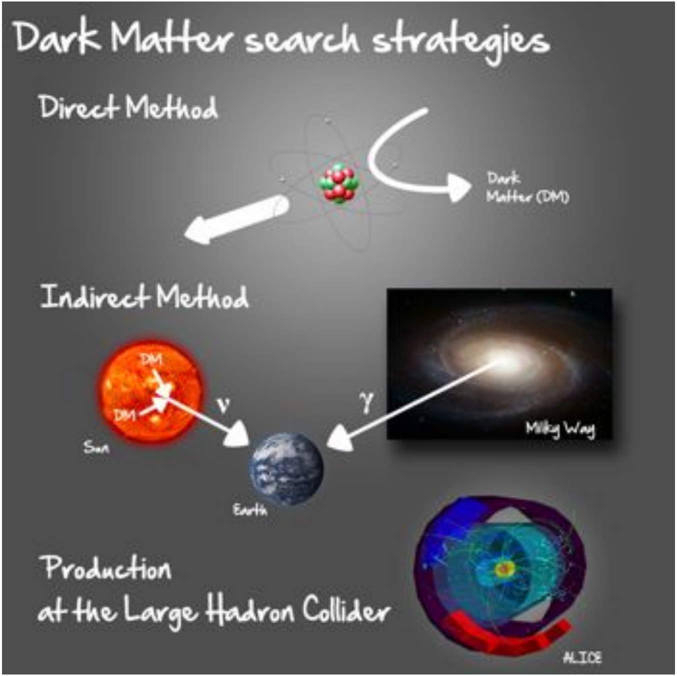
Dark Matter search strategies
Direct Method
Dark Matter (DM)
Indirect Method
DM
DM
Sun
ν
γ
Milky Way
Earth
Production at the Large Hadron Collider
ALICE

Galactic Center: Indirect Detection Target

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- The Bad:
  Astrophysics may make it difficult to convincingly determine whether any excess in the GC is due to dark matter or not.

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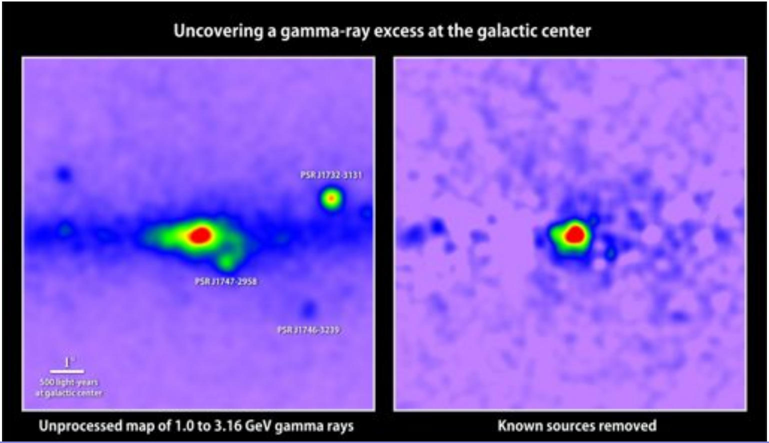

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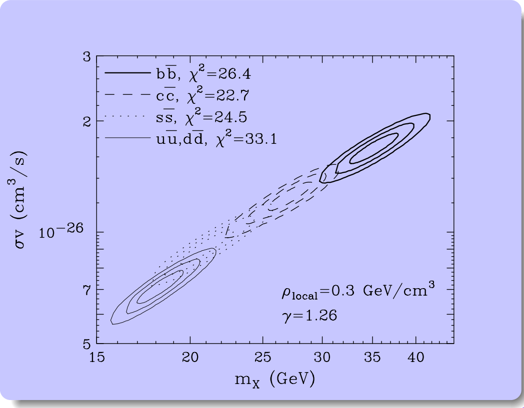

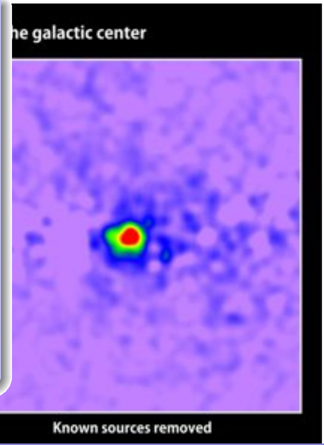

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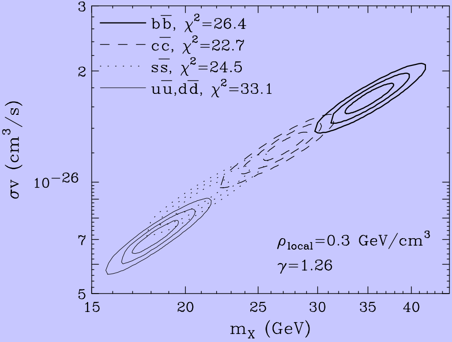

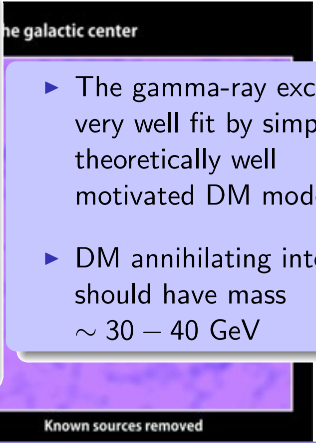

- The gamma-ray excess is very well fit by simple & theoretically well motivated DM models.
- DM annihilating into $b\bar{b}$ should have mass $\sim 30 - 40$ GeV

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- Higgs-portal DM : LHC Constraints
  - Invisible Higgs decay from global analysis of Higgs data ($\sim 20\%$).
  - The signal strength $r^{xx} = \frac{\sigma_H}{\sigma_H^{SM}} \cdot \frac{BR_{H \to xx}}{BR_{H \to xx}^{SM}}$ should be ≥ 0.8.

Gauged Minimal $U(1)_{B-L}$ Model

Framework of the Model

Particle content of minimal $U(1)_{B-L}$ extension (anomaly free) of SM :

Particle	Q	u_R	d_R	L	e_R	Φ	S	$N_{R^{1,2}}$	N_{R^3}
$SU(2)_L$	2	1	1	2	1	2	1	1	1
$U(1)_Y$	1/6	2/3	-1/3	-1	-1	1	0	0	0
$U(1)_{B-L}$	1/3	1/3	1/3	-1	-1	0	2	-1	-1
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$

N. Okada *et al.* '10; Kanemura *et al.* '11; T. Mondal *et al.* '14

Additional Z_2-symmetry imposed : Z_2 charge $+1$(or even) for all the particles except N_R^3

Ensures stability for $N_R^3 \Longrightarrow$ becomes a viable WIMP - DM candidate

Scalar potential

$$V(\Phi, S) = m^2\Phi^\dagger\Phi + \mu^2 \mid S \mid^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 \mid S \mid^4 + \lambda_3\Phi^\dagger\Phi \mid S \mid^2$$

- After spontaneous symmetry breaking (SSB) the two scalar fields can be written as,

$$\Phi = \begin{pmatrix} 0 \\ \frac{v+\phi}{\sqrt{2}} \end{pmatrix}, \qquad S = \frac{v_{B-L} + \phi'}{\sqrt{2}}$$

  with v and v_{B-L} real and positive.

- The mass eigenstates are linear combinations of ϕ and ϕ', and written as

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi' \\ \phi \end{pmatrix}$$

  where, we identify H_2 as the SM-like Higgs boson with mass 125.5 GeV.

Fermionic Part of the model

- Yukawa part : important for DM interaction

$$\mathcal{L}_Y = \mathcal{L}_Y^{SM} + \mathcal{L}_{int}$$

$$\mathcal{L}_{int} = \sum_{\beta=1}^{3}\sum_{i=1}^{2} y_\beta^i \bar{l}_\beta \tilde{\Phi} N_i - \sum_{i=1}^{3} \frac{y_{n_i}}{2} \bar{N}_R^i S N_R^i$$

where, $\tilde{\Phi} = -i\tau_2\Phi^*$.

- DM interacts with the SM particles via Z'-boson and h, H.
- But, Z'-boson being heavy ($m_{Z'} \geq 2.33$ TeV) $\Longrightarrow$ effectively Higgs-portal
- λ_{DM} = coupling between DM and the Higgs boson = y_{n_3}

Constraints from LHC

$$r_i^{xx} = \frac{\sigma_{H_i}}{\sigma_{H_i}^{SM}} \cdot \frac{BR_{H_i \to xx}}{BR_{H_i \to xx}^{SM}} \; , \; (i = 1, 2).$$

- σ_{H_i} =production cross section of H_i.
- $BR_{H_i \to xx}$ branching ratio of $H_i \to xx$.

$$r_2 = \cos^4\alpha \frac{\Gamma_{H_2}^{SM}}{\cos^2\alpha\,\Gamma_{H_2}^{SM} + \sin^2\alpha\,\Gamma_{H_2}^{Hid} + \Gamma_{H_2 \to H_1 H_1}}$$

$$r_1 = \sin^4\alpha \frac{\Gamma_{H_1}^{SM}}{\sin^2\alpha\,\Gamma_{H_1}^{SM} + \cos^2\alpha\,\Gamma_{H_1}^{Hid}}$$

- H_2 as a SM Higgs boson $\Rightarrow r_2 \geq 0.9$ (0.8) & $r_1 \leq 0.1$ (0.2).
- $r_2 \geq 0.9$ (0.8) restricts scalar mixing: $\cos\alpha \geq 0.96$ (0.94) for $m_{DM} \sim 31$ GeV.

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- s-wave contribution is helicity suppressed ($\propto (\frac{m_f}{m_{DM}})^2$).
- Average velocity $v \sim \sqrt{3/x}, \qquad x = \frac{m_{DM}}{T_D}$.
- During freeze out: $x_f \simeq 20$. Small amount of suppression.
- At galactic halo: $x \simeq 10^6$. Huge suppression.

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Breit Wigner Enhancement

Annihilation cross section can get substantial enhancement via Breit-Wigner mechanism when DM annihilates through narrow resonance.

Breit Wigner enhancement in this model

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Single-integral formula for thermally averaged cross-section

$$\langle \sigma v \rangle = \frac{1}{n_{EQ}^2} \frac{m_{DM}}{64\pi^4 x} \int_{4m_{DM}^2}^{\infty} ds \, 4E_1 E_2 \sigma v \sqrt{s} g_i^2 \times \sqrt{1 - \frac{4m_{DM}^2}{s}} K_1\left(\frac{x\sqrt{s}}{m_{DM}}\right)$$

$$4E_1 E_2 \sigma v = \frac{\lambda_{DM}^2 \cos^2\alpha}{32\pi^2} \frac{s^2}{m_{H_1}^2} \frac{m_{H_1}\Gamma_{H_1}}{(s - m_{H_1}^2)^2 + m_{H_1}^2 \Gamma_{H_1}^2}$$

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3 new parameters M. Ibe, H. Murayama, and T. Yanagida, PRD79 ; W.L. Guo and Y.L. Wu, PRD79

$m_{H_1}^2 = 4m_{DM}^2(1-\delta)$, $\gamma = \Gamma_{H_1}/m_{H_1}$ and $s = 4m_{DM}^2(1+y)$. Then

$$\langle \sigma v \rangle \propto x^{3/2} \int_0^{y_{eff}} \frac{\sqrt{y}(1+y)^{3/2} e^{-xy}}{(y+\delta)^2 + \gamma^2(1-\delta^2)} dy, \quad y_{eff} \sim \max[4/x, 2|\delta|].$$

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If $\delta, \gamma \ll 1$ then $\langle \sigma v \rangle \propto v^{-4}$ in the limit $v^2 \ll \max[\gamma, \delta]$

Final results

Achieved $\langle \sigma v \rangle_{b\bar{b}} \sim 1.881 \times 10^{-26}\ \mathrm{cm}^3/s$ with $\delta \simeq -10^{-3}$ & $\gamma \simeq 10^{-5}$.

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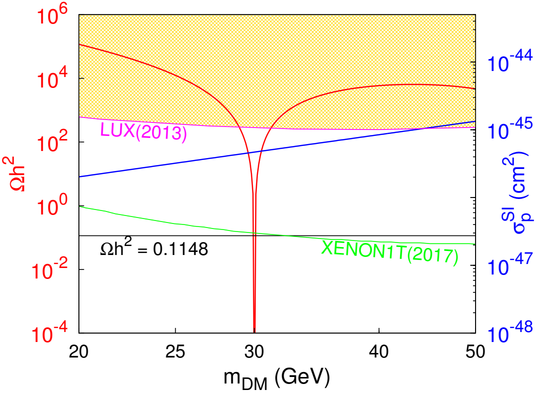

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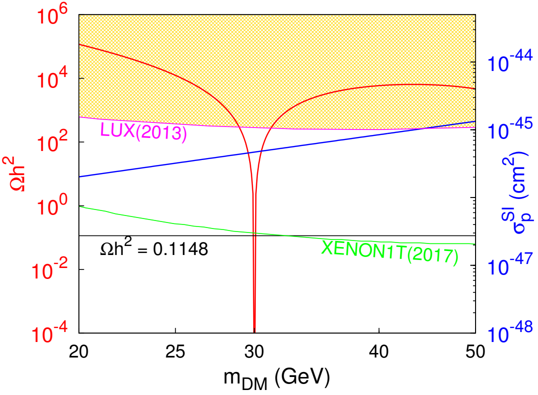

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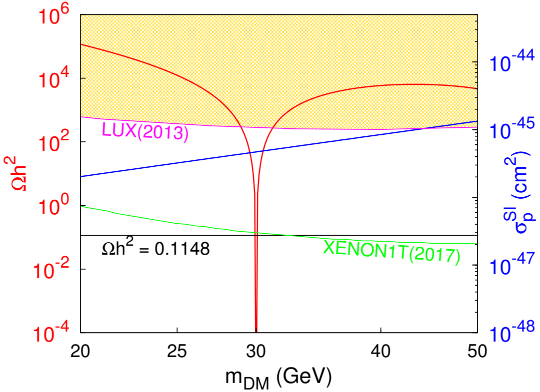

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Q. What about the other Higgs portal models ?

We analyzed Singlet Scalar Model and Singlet Fermionic DM(SFDM) model. Both are incompatible with the current observation.

Summary

- Excess of γ-rays in low latitude near the GC can be explained by DM of mass $\sim 30 - 35$ GeV annihilating into $b\bar{b}$ with cross-section $\sim 10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}$
- We adopt the minimal $U(1)_{B-L}$ extension of SM with an additional Z_2-symmetry imposed to explain the excess.
- One of the right-handed neutrino (odd under Z_2) qualified as the DM candidate.
- Inspite of velocity dependence, the annihilation cross section is large today due to Breit-Wigner enhancement.
- SI-scattering cross-section is well below the XENON100 and LUX exclusion limits.
- Models like SSM or SFDM cannot explain the observed excess.

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Thank you

Back Up

Millisecond Pulser

- The most often discussed astrophysical interpretation for this signal is a population of several thousand millisecond pulsars (MSPs) associated with the Milky Ways central stellar cluster.
- Can plausibly account for much of the excess observed within the innermost $\sim 1 - 2^{\circ}$ of the Galaxy. But the observed excess extend out to at least $\sim 10^{\circ}$ from the Galactic Center.
- If MSPs were distributed in a way that could account for this extended excess, Fermi should have resolved many more as individual point sources than they did.
- No more than $\sim 5 - 10\%$ of the excess beyond $\sim 5^{\circ}$ can come from MSPs.

  Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer, PRD, arXiv:1305.0830

Analysis of the galactic center excess:

- L. Goodenough, Dan Hooper, arXiv:0910.2998
- Dan Hooper, L. Goodenough, PLB, arXiv:1010.2752
- Dan Hooper, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- Dan Hooper, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S.Horiuchi, M. Kaplinghat, arXiv:1402.4090

Singlet Fermionic DM model

Singlet Fermionic DM model

A renormalizable extension of the Standard Model:

$$\mathrm{SM} + \underbrace{1 \text{ singlet scalar } (S) + 1 \text{ singlet fermion } (\psi)}_{\text{Hidden Sector}}$$

Lagrangian

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

$$\mathcal{L}_{hid} \supset \lambda_{DM} \bar{\psi}\psi\, S \quad \text{and} \quad \mathcal{L}_{int} \supset \frac{\lambda_1}{2} \Phi^\dagger \Phi S$$

EWSB and Mixing

After EWSB: $\Phi = (0 \quad v + \phi)^T$ and $S = v_S + s$

$$\begin{aligned} H_1 &= \cos\alpha\,\phi + \sin\alpha\, s \\ H_2 &= \cos\alpha\, s - \sin\alpha\,\phi \quad \Rightarrow \text{SM Higgs, } M_{H_2} = 125 \text{ GeV} \end{aligned}$$

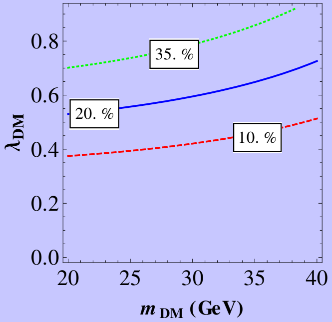
Singlet Fermionic DM model

Singlet Fermionic DM model

- To explain Fermi-LAT we need $m_{DM} = m_\psi \sim 30$ GeV.
- Main parameters in the model: λ_{DM} and α, the mixing angle.

Higgs invisible Branching

$$\Gamma_{inv} = \frac{M_{H_2}\lambda_{DM}^2}{16\pi}\sin^2\alpha\left(1 - 4\frac{m_{DM}^2}{M_{H_2}^2}\right)^{(3/2)}$$



$\cos\alpha = 0.95$; $\lambda_{DM} \lesssim 0.6$

SFDM Final Result