Searching Hidden Sector Dark Matter via Higgs Portal

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1. Constraining Sommerfeld Enhanced Annihilation Cross-sections of Dark Matter via Direct Searches, [arXiv:1004.0645], Phys. Lett. B 691, 219-224, 2010.

2. A Tight Connection Between Direct and Indirect Detection of Dark Matter through Higgs Portal Couplings to a Hidden Sector, [arXiv:1004.3953], Phys. Rev. D 82, 015005 (2010).

Dark Matter: What we know ?

(1) It exists as pressureless dust and accommodates about 23% of the total energy budget of the Universe.

(Galaxy Rotation Curve, Gravitational Lensing, Large Scale Structure)

(2) It is neutral and does not have any electromagnetic interaction with visible matter. Thus justify the name "Dark Matter".

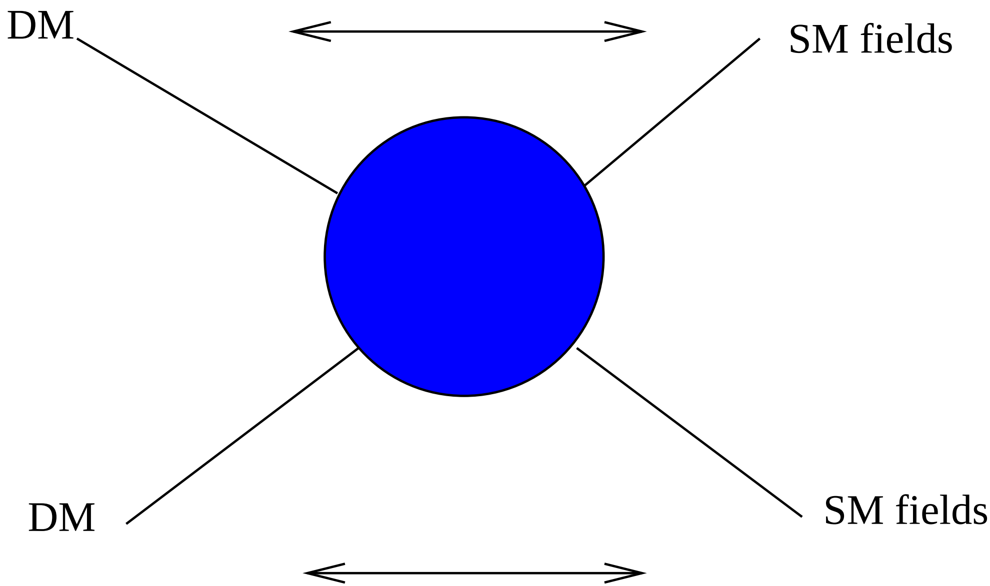
(3) It is nonbaryonic.

(4) It is assumed to be massive and hence interacts gravitationally with visible matters.

(5) It is dominantly cold, i.e, non-relativistic when decoupled from the thermal bath.

At a temperature $T >> M_{\mathsf{DM}}$

$$\Gamma_S = n_{\mathsf{DM}} < \sigma|v| > \quad > \quad H(T)$$



At $T \approx M_{\mathsf{DM}}/20$, the DM freezes out and starts to red-shift (cooling). The observed DM abundance then gives freeze out cross-section of DM:

$$< \sigma|v| >_F \approx 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

$$v_F \approx \sqrt{3/20}$$

Dark Matter: What we don't know ?

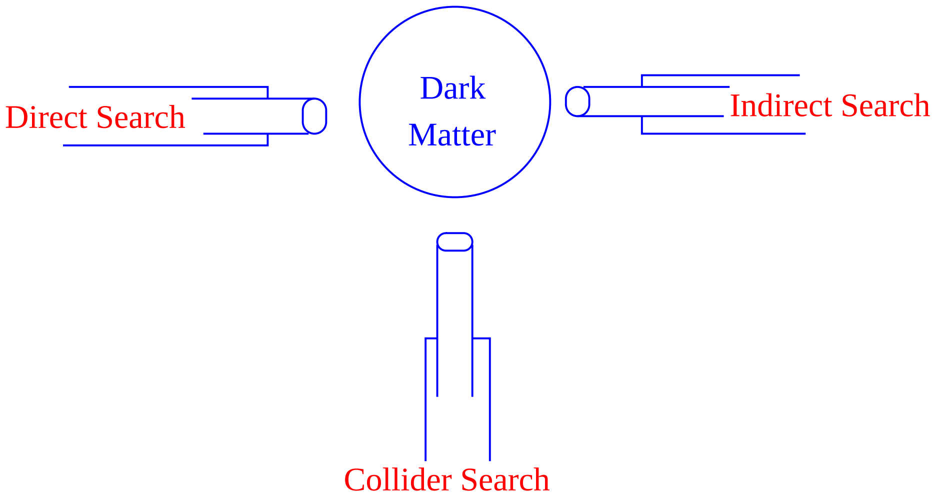
One would like to know...

(1) Nature: Exactly Cold or Mixture of cold and warm dark matter

(2) Intrinsic spin: Bosonic (spin: 0,1,...) or Fermionic (spin: 1/2, 3/2...)

(3) Identification: Who is the candidate of DM ? what is its mass ?

(4) Interaction: How it interacts with visible matters ?



Dark
Matter
Direct Search
Indirect Search
Collider Search

Indirect Observations

Data from ...

AMS: Alpha Magnetic Spectrometer

HEAT: High Energy Antimatter Telescope

PAMELA: Payload for Anti-Matter Exploration and Light nuclei Astrophysics

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

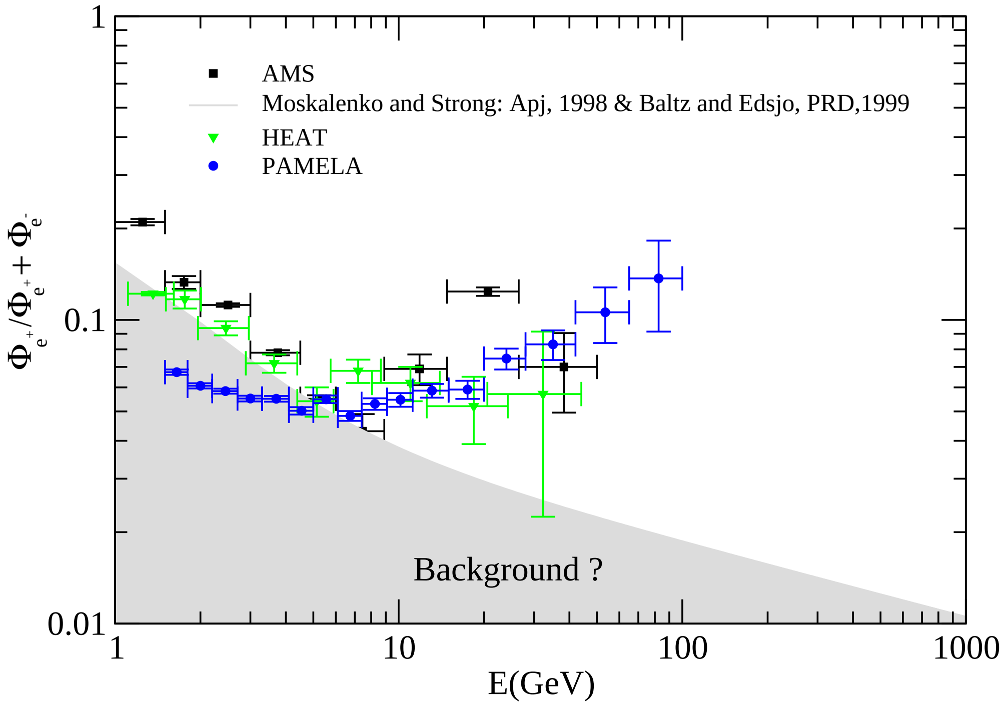
ATIC: Atomic Thin Ionisation Calorimeter

HESS: High Energy Stereoscopic System

FermiLAT: Fermi Large Area Telescope

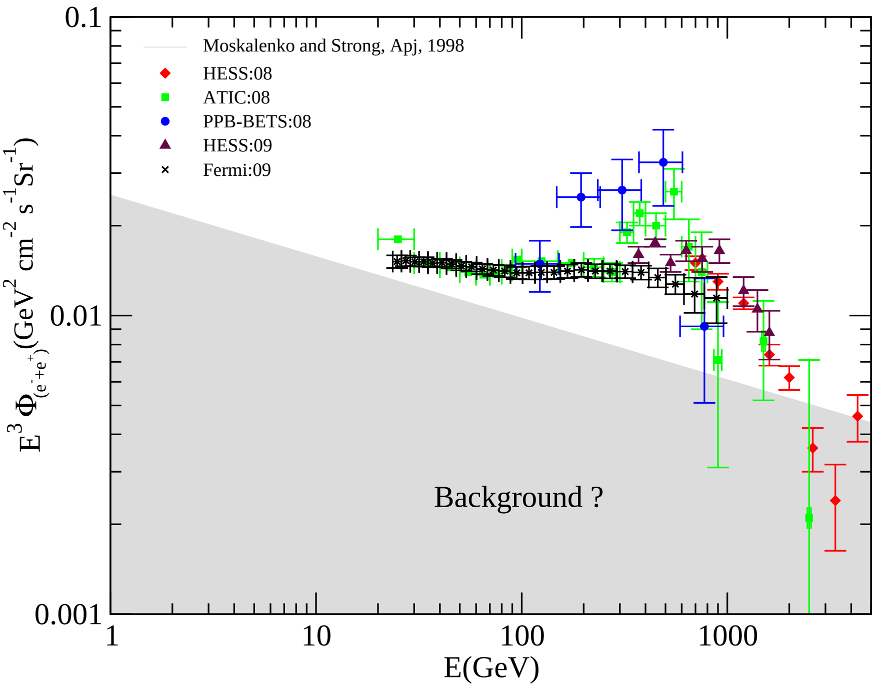
$$\phi_{e^+} + \phi_{e^-}$$

AMS, HEAT, PAMELA Positron Excess ?

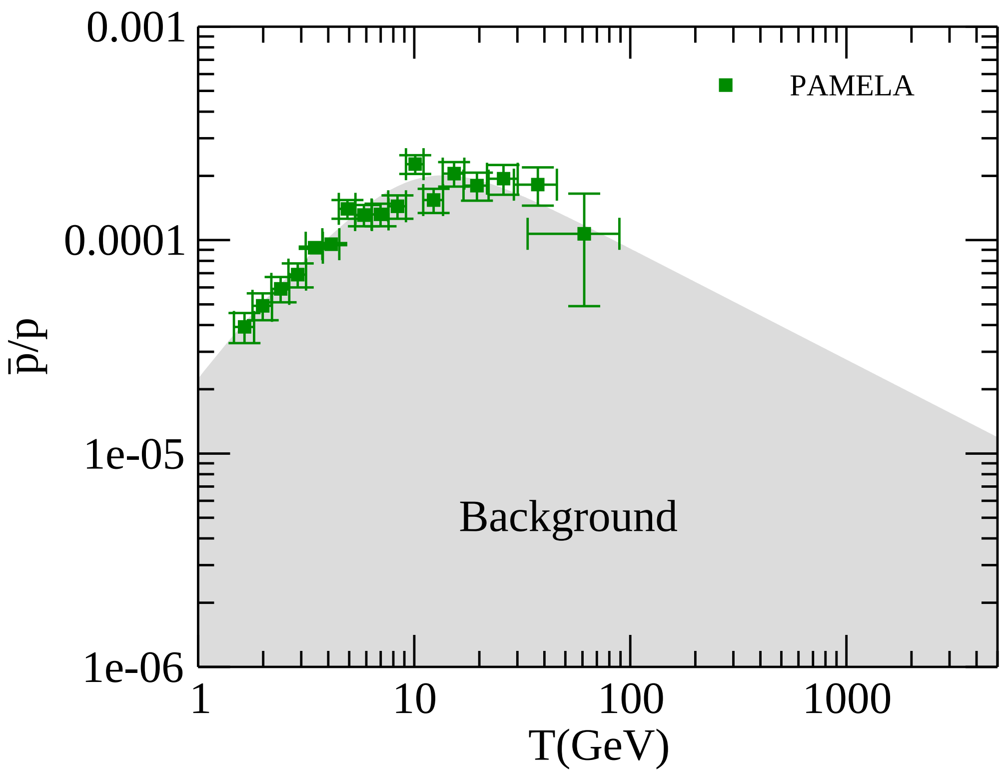


HESS, ATIC, PPB-BETS and FermiLAT

$e^- + e^+$ excess ?



PAMELA Antiproton Fraction

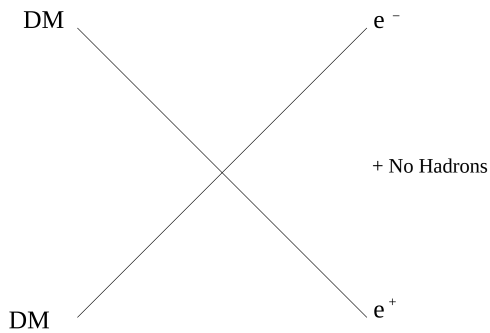


Adriani et.el. PRL, 2009

Implication on DM
from Indirect Observations

$e^{\pm}$ fluxes and Dark Matter

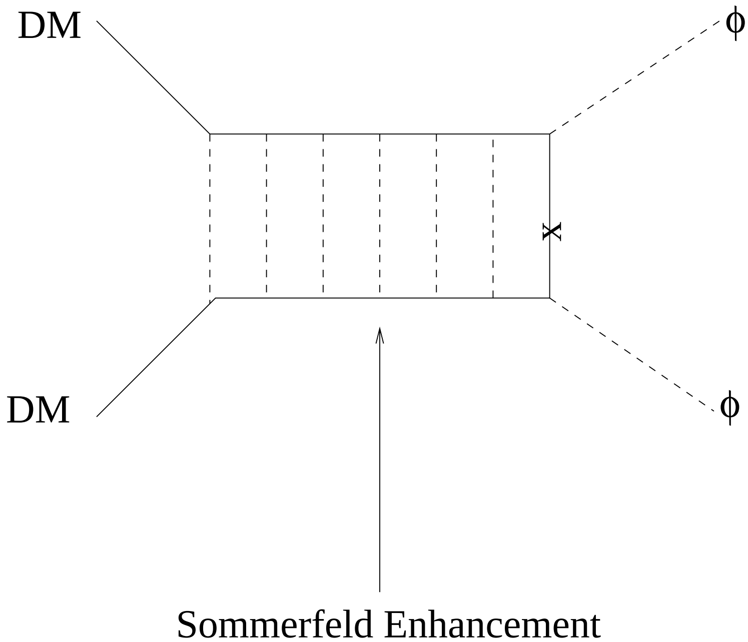
- **The current annihilation of DM to visible matter may explain the rising positron flux in the cosmic ray.**



$$\langle\sigma|v|\rangle_{\text{ann}} = B \times \langle\sigma|v|\rangle_F$$
$$\langle\sigma|v|\rangle_F \approx 3 \times 10^{-26}\text{cm}^3/\text{sec}$$
$$\textbf{and } B \simeq 100 - 1000$$

How to Explain a Large Boost Factor ?

Sommerfeld Enhancement



Arkani-Hamed *et.al*, **[0810.0713]**
Hisano *et.al.*, **PRL, 2005**

Sommerfeld Enhancement

The attractive potential can be given as:

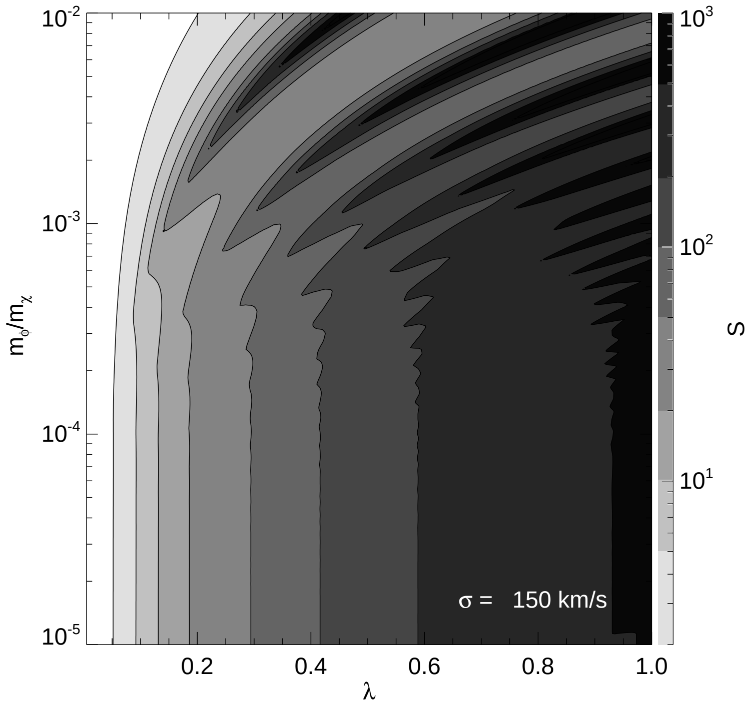
$$V = -\frac{\lambda^2}{4\pi r} e^{-m_\phi r}$$

At least one bound state requires:

$$\mathrm{Comptonwavelength} > \left(\frac{\lambda^2}{4\pi} M_{\mathrm{DM}}\right)^{-1}$$

The Boost factor can be computed by solving the Schrodinger equation and is given by

$$B = \frac{|\psi(\infty)|^2}{|\psi(0)|^2}$$



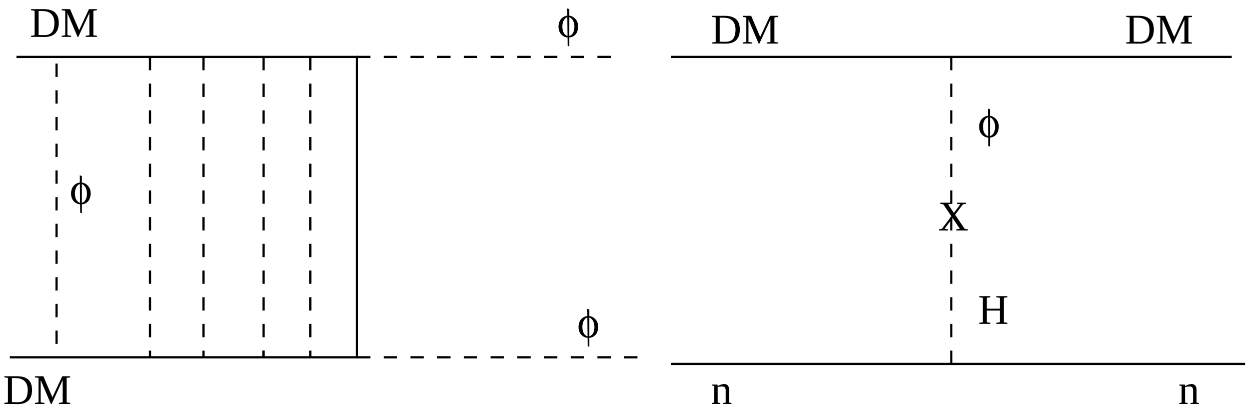
Arkani-Hamed *et.al*, **[0810.0713]**

Bottom line...

(1) To explain the rising positron flux in the cosmic ray we discovered a hidden sector which comprises a candidate of DM and a light field which is the carrier of new force among the DM candidates.

(2) Does this new force mediated by the light field play any role in Indirect and collider searches ?

Direct and Indirect Searches of DM: A Tight connection



C. Arina, F.X. Josse-Michaux and N.Sahu, Phys. Lett. B 691, 219-224, 2010.

Relevant Interactions

$$-\mathcal{L} \supset \lambda_\chi \overline{\chi^c} \chi \phi + \mu_\phi \phi H^\dagger H$$

The effective attractive potential is

$$V(r) = -\frac{\lambda_\chi^2}{4\pi r} e^{-m_\phi r}$$

The $H - \phi$ mixing angle is

$$\theta_{H\phi} = \frac{\mu_\phi \langle H \rangle}{M_H^2}$$

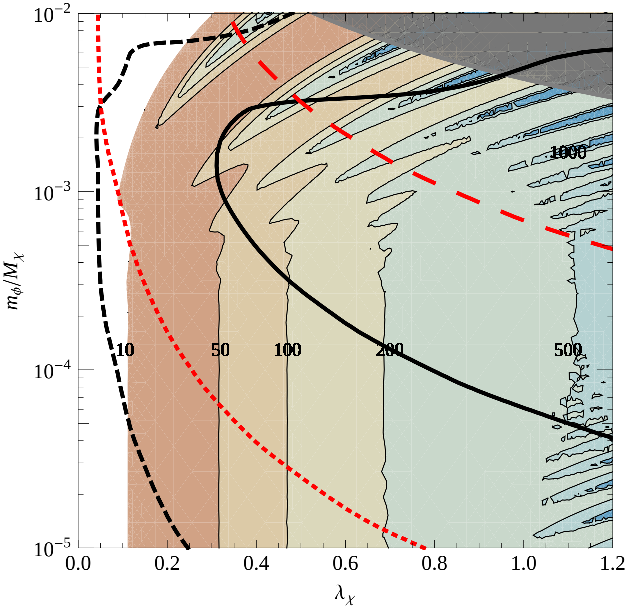
For $m_\phi \lesssim \mathcal{O}(1)$ GeV we have $10^{-7} \lesssim \theta_{H\phi} \lesssim 10^{-2}$

The spin independent elastic cross-section on nucleon, mediated by $\phi - H$ mixing through t-channel:

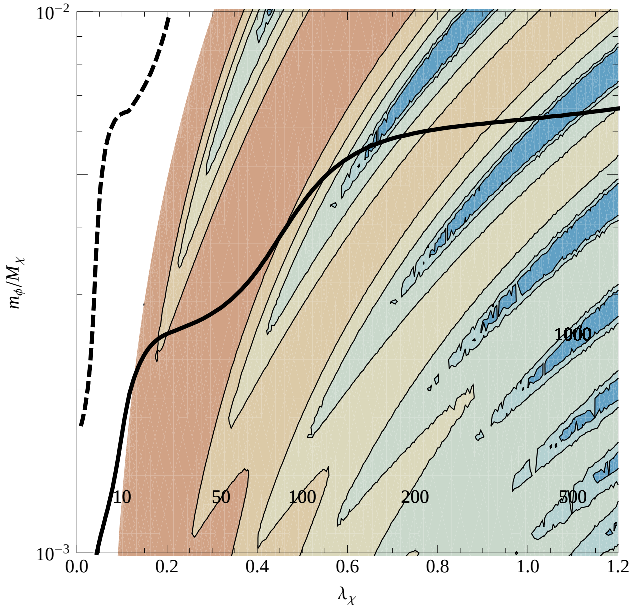
$$\sigma_n^{\mathsf{SI}} \propto \frac{\lambda_\chi^2 \theta_{H\phi}^2}{m_\phi^4}$$

In terms of the measurable quantity at terrestrial DM detector:

$$\frac{dR}{dE_r} \propto \sigma_n^{\mathsf{SI}} \propto \frac{\lambda_\chi^2 \theta_{H\phi}^2}{m_\phi^4}$$



CDMS-II exclusion limits for $m_\phi = 0.1(1)$ GeV, $\theta_{H\phi} = 10^{-6}(10^{-4})$ (solid-black/long-dashed red)) and $\theta_{H\phi} = 10^{-5}(10^{-3})$(dashed-black/dotted-red).



CDMS-II exclusion limits for $M_\chi = 100$ GeV, $\theta_{H\phi} = 10^{-6}$ (solid-black) and $\theta_{H\phi} = 10^{-4}$ (dashed black).

Dark Matter: Theories Beyond the SM

(1) Identification of DM is a big task. Within the SM there is no place for DM. Therefore, one has to look for theories beyond the SM to accommodate the DM abundance.

(2) Over the years a large number of candidates have been put forward:

Lightest SUSY particle (neutralino, gravitino, sneutrino, singlino...)

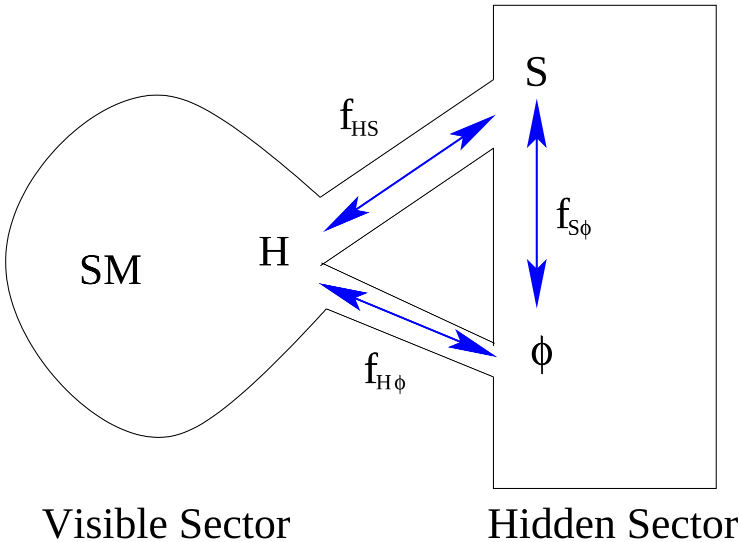
Scalar/Fermion singlet, doublet, triplet, quartet (stabilized by an extra symmetry)

Scalar/fermion quintet(stable by itself)

Axion (stable by itself)

And so on...

Direct and Indirect Searches of DM via Higgs Portal to Hidden Sector



C. Arina, F.X. Josse-Michaux and N.Sahu, PRD 82,015005, 2010.

Hidden Sector with a gauged U(1) symmetry

The relevant interaction:

$$\mathcal{L} \supset f_{HS} H^\dagger H S^\dagger S + f_{H\phi} H^\dagger H \Phi^\dagger \Phi + f_{S\Phi} S^\dagger S \Phi^\dagger \Phi$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_H$$

$$\Downarrow \langle \Phi(1,1,0,2) \rangle = u$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2$$

$$\Downarrow \langle H(1,2,1,0) \rangle = v$$

$$SU(3)_C \times U(1)_Q \times Z_2$$

New features of the Model

A Scalar Dark Matter S (1,1,0,3) stabilized by the Z_2 symmetry

Two scalars, namely SM Higgs h and the light scalar ϕ which mix with each other with the mixing angle

$$\theta_{H\Phi} = \frac{f_{H\Phi} u v}{M_h^2 - M_\phi^2}$$

$$10^{-7} \lesssim \theta_{H\Phi} \lesssim 10^{-2}$$

A new gauge boson Z' with mass $M'_Z = 2 g_H u$ and no tree level mixing with Z-boson.

Relic Density of DM

Since there are two portal couplings (f_{SH} and $f_{S\Phi}$) to visible sector the relic density is decided by the annihilation cross-sections:

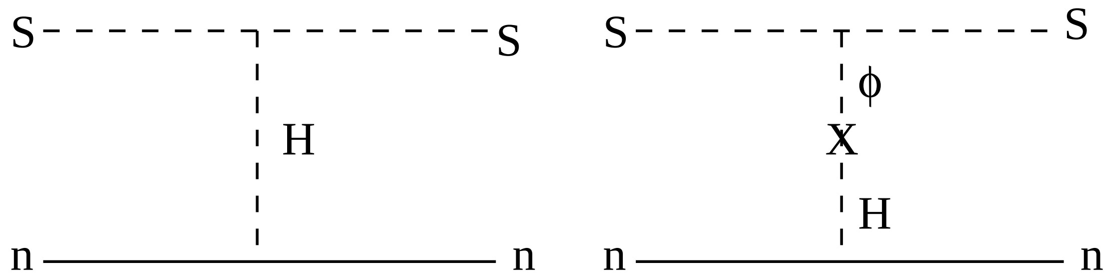
$$S^\dagger S \rightarrow \phi\phi, SM \;\; particles$$

For $M_S > M_h$, the relic density is decided by the cross-sections:

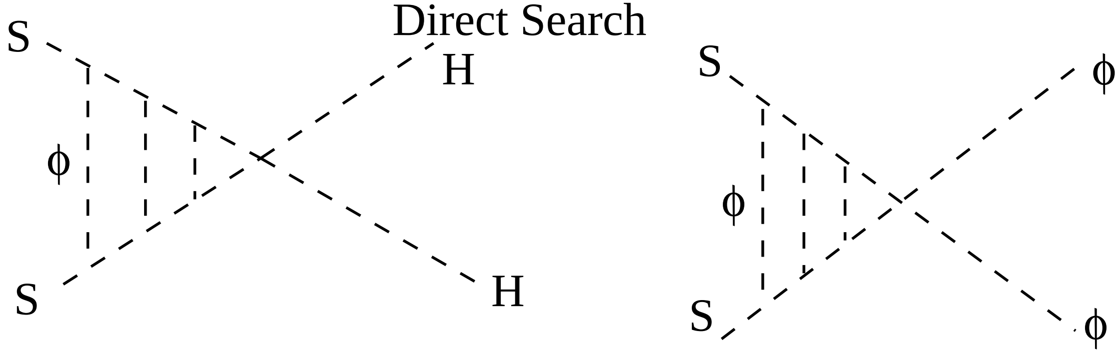
$$\langle\sigma|v_{rel}|\rangle(S^\dagger S \rightarrow \phi\phi) \simeq \frac{f_{S\phi}^2}{64\pi\, M_S^2}$$

$$\langle\sigma|v_{\rm rel}|\rangle(S^\dagger S \rightarrow hh) \simeq \frac{1}{64\pi}\frac{f_{SH}^2}{M_S^2}\left(1 - \frac{M_h^2}{M_S^2}\right)^{1/2}$$

Direct and Indirect Search of DM



Direct Search



Indirect Search

The spin independent elastic cross-section is:

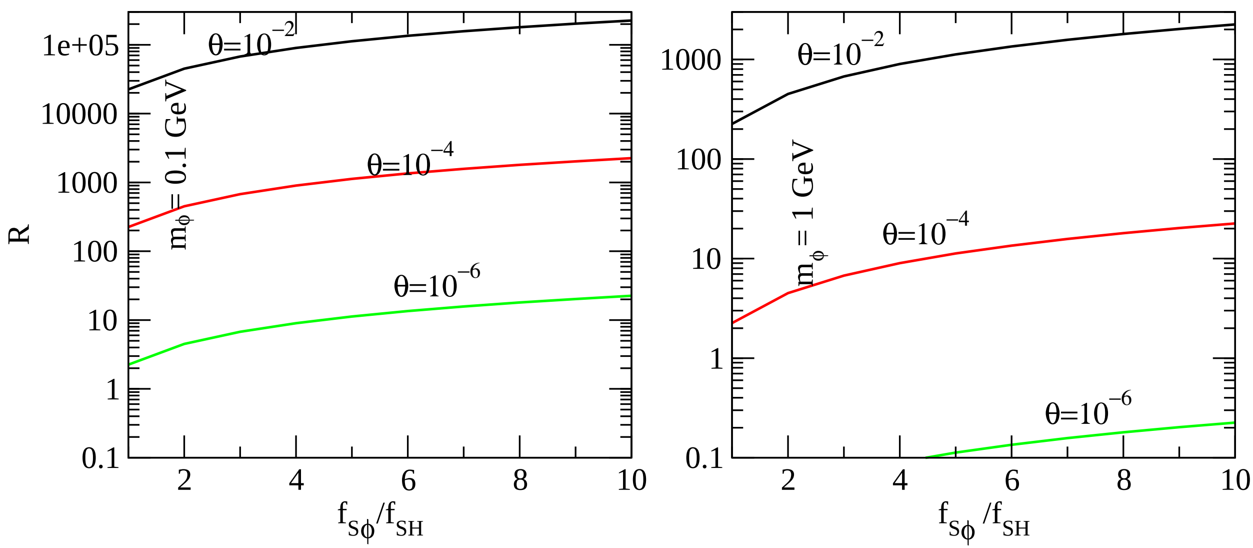
$$\sigma_{SI} = \frac{\mu_n^2}{\pi M_S^2} m_n^2 f_n^2 \left| \frac{1}{2}\frac{f_{HS}}{M_h^2} + \frac{1}{2}\frac{f_{\phi S}\, u\, \theta_{H\Phi}}{M_\phi^2 v} \right|^2$$

Suprressed antiproton flux than positron flux requires

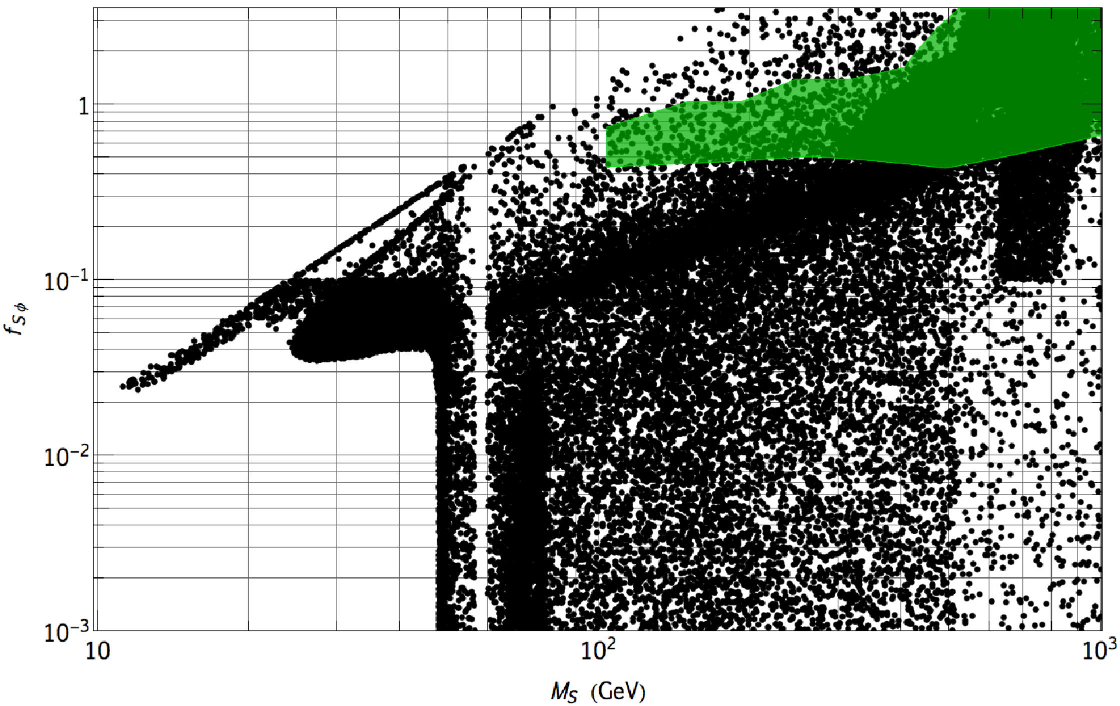
$$\frac{f_{S\Phi}}{f_{SH}} > 1$$

In this case:

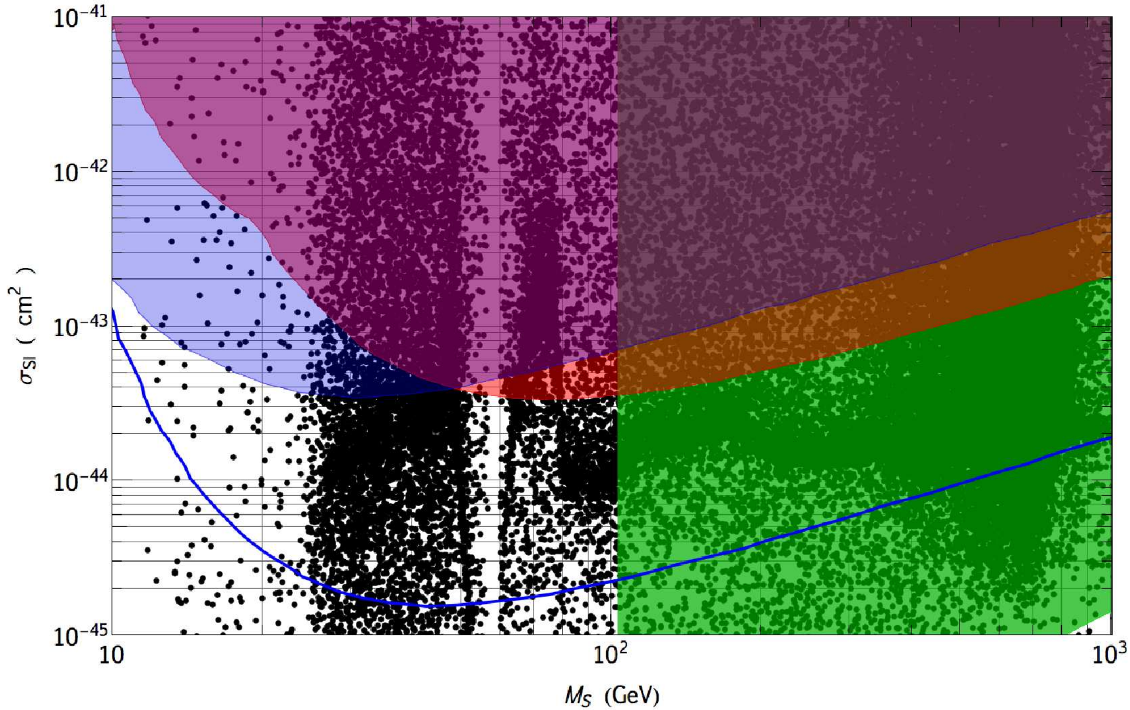
$$R = \left(\frac{M_h^2}{m_\phi^2}\right)\left(\frac{u}{v}\right)\left(\frac{f_{S\Phi}}{f_{SH}}\right)\theta_{H\Phi}$$



R
$m_\phi = 0.1$ GeV
$\theta=10^{-2}$
$\theta=10^{-4}$
$\theta=10^{-6}$
1e+05
10000
1000
100
10
1
0.1
2
4
6
8
10
$f_{S\phi}/f_{SH}$
$m_\phi = 1$ GeV
$\theta=10^{-2}$
$\theta=10^{-4}$
$\theta=10^{-6}$
1000
100
10
1
0.1
2
4
6
8
10
$f_{S\phi}/f_{SH}$

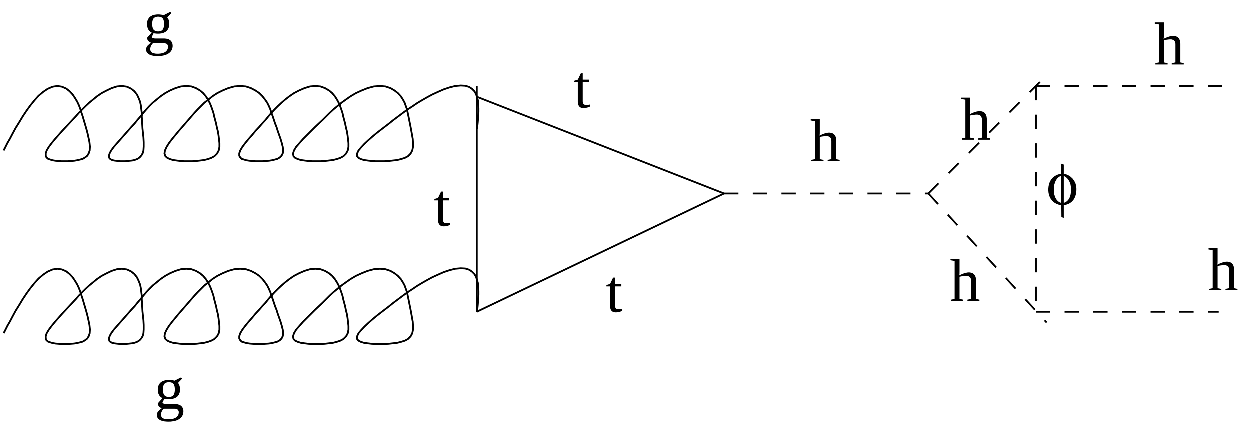


Green region denotes points with boost factor compatible with indirect DM searches.



Exclusion limits from CDMS-II, Xenon-10 and Xenon-100 (projected).

Hidden Sector at Collider



Double Higgs Production at Threshold

implying Hidden sector effect

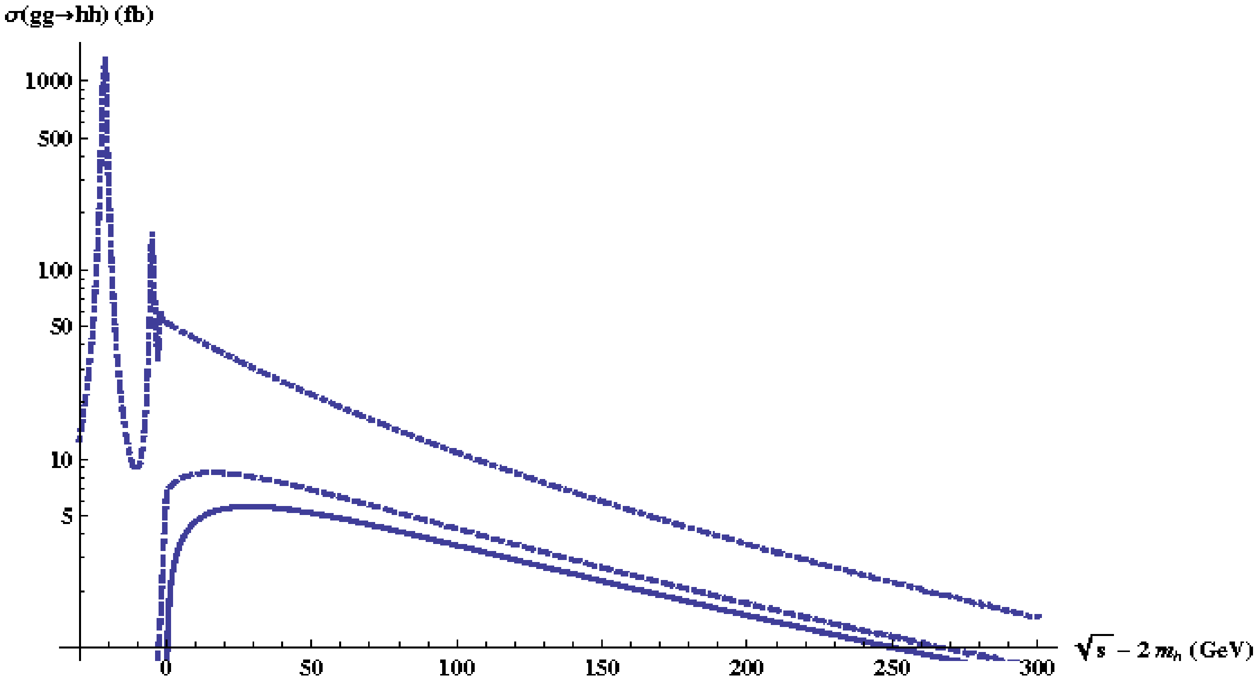
Oliveira and Rosenfeld, 1009.4497

The required attractive potential:

$$V(r) = -k\frac{e^{-m_\phi r}}{r}$$

where

$$k = \theta_{H\Phi}^2 \frac{M_h^2}{8v^2} \ll 1$$



k=0.1 (dashed line) and k=0.7 (dot-dashed lne) with $m_\phi =$ 1 GeV

Conclusions

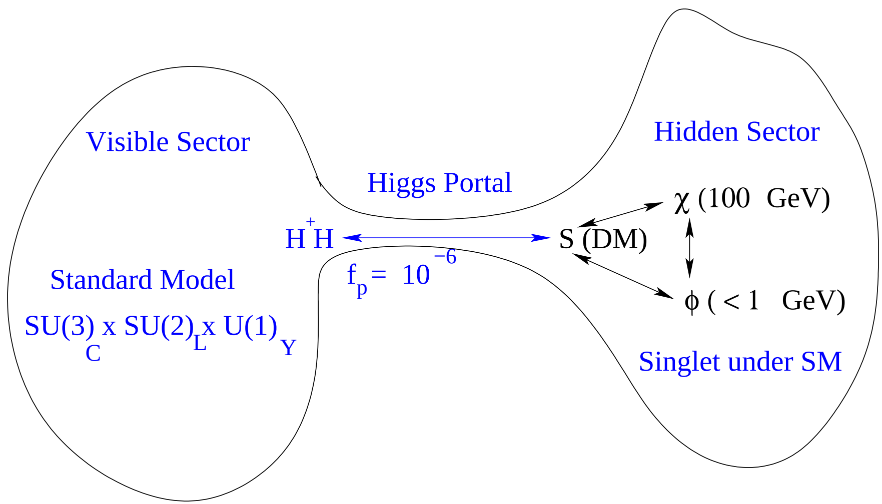
- DM is an interesting possibility to account for the rising positron flux at PAMELA and Fermi.

- Any model which explains the positron flux via Sommerfeld enhancement using a light scalar is strongly constrained by the Direct search of DM, because of its mixing with the SM Higgs.

- DM interaction via Higgs portal may be an interesting possibility and an alternative to leptophilic model to explain positron flux without producing excess of antiprotons.

- It is difficult to probe hidden sector at collider.

Boosted DM Annihilation through Higgs Portal Couplings to DM



Ref. Kohri, McDonald and Sahu, [0905.1312], PRD81, 023530, 2010.

Higgs Portal Couplings to DM

• **Upgrade SM to** $SU(2)_L \times U(1)_Y \times U(1)_{\text{hidden}}$ **under which** $S(1,0,3/2)$, $\chi(1,0,1)$ **and** $\phi(1,0,1)$ **nontrivially transforms.**

$$\mathcal{L} \supseteq f_{\text{portal}} H^\dagger H \left(S^\dagger S + \phi^\dagger \phi + \chi^\dagger \chi + \phi^\dagger \chi \right)$$

$$+ f_{S\phi} S^\dagger S \phi^\dagger \phi + f_{S\chi} S^\dagger S \chi^\dagger \chi + f_{S\chi\phi} S^\dagger S \chi^\dagger \phi + h.c.$$

• **Below 100 GeV** χ **acquires a vev and breaks** $U(1)_{\text{hidden}}$ **down to a surviving** Z_2 **symmetry under which** S **is odd, while rest of the fields are even.**

Higgs Portal Couplings to DM

- **MeV scale mass of ϕ requires $f_{\text{portal}} \approx 10^{-6}$.**
- **At least one bound state of S and ϕ requires**

$$f_{S\chi\phi} \gtrsim 0.5 \left(\frac{M_\phi}{200\text{MeV}}\right)^{1/2} \left(\frac{M_S}{1\text{TeV}}\right)^{1/2} \left(\frac{100GeV}{\langle\chi\rangle}\right)$$

- **The coupling $f_{\text{portal}} \ll f_{S\chi\phi}$ ensures that antiproton fluxes from $S^\dagger S$ annihilation is suppressed.**

Sommerfeld Enhancement