Higgs and Dark Matter

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Brown University
PITT-PACC Higgs and Beyond, 12/04/2015

Zoo of DM models

Multi-component DM

Minimal models:
thermal WIMP, axion

Partially Interacting DM:
double disk DM...

Self-interacting DM:
dark atom, mirror matter,
hidden charged DM...

Dark superfluid

Ultralight axion
with GUT scale
decay constant

DM with a non-thermal history:
asymmetric DM,
WIMP from moduli decays....

In the DM model zoo, DM particles do not necessarily couple to the Higgs boson or directly connect to the electroweak sector, eg., axion (exception: relaxion scenario discussed in Kaplan's talk this morning)

Yet in many DM models, Higgs could play an important direct or indirect role.

I will discuss a few examples mainly to demonstrate current status of these benchmark models, discuss some experimental challenges and illustrate the complementary roles of different DM probes, Higgs measurements and direct collider searches.

Higgs portal: Silveira and Zee 1985; McDonald 1994;
Burgess, Pospelov and ter Veldhuis 2001; Patt and Wilczek 2006…..

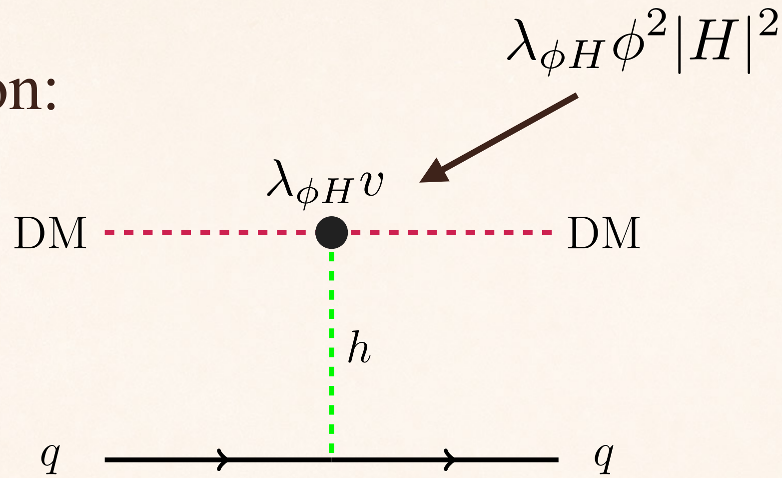
Higgs provides an entirely new gateway to physics beyond the SM thanks to the low dimension of the operator $|H|^2$

$$|H|^2\mathcal{O},$$

operator of dark sector:
SM gauge singlet;
marginal or relevant with dimension ≤ 2

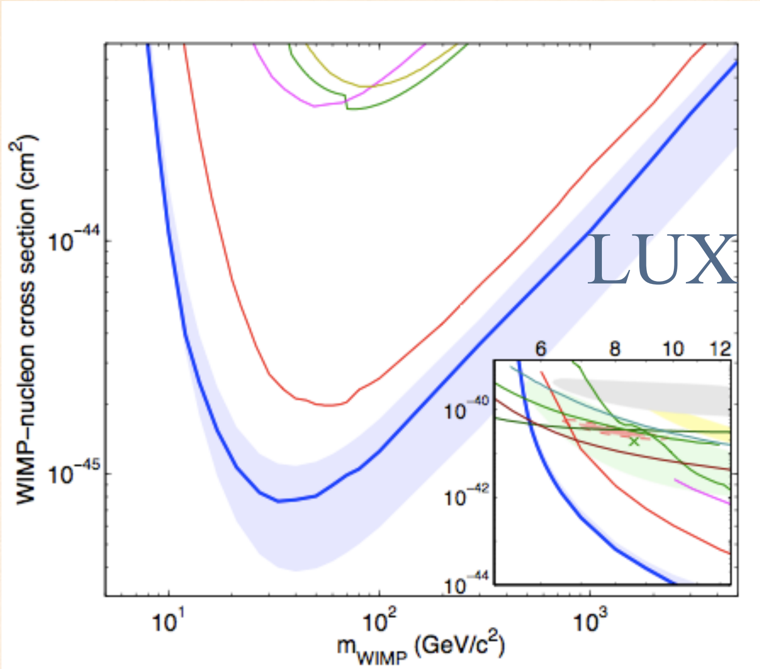
Simplest possibility for $\mathcal{O} : \phi^2, \quad |\phi|^2$ Scalar DM

Direct detection:



$$\sigma_{SI} = \frac{|\lambda_{\phi H}|^2 m_n^4 f^2}{\pi m_h^4 m_\phi^2}$$
$$= \left(\frac{\lambda_{\phi H}}{0.02}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_\phi}\right)^2 1.4 \times 10^{-45}\mathrm{cm}^2,$$

Burgess, Pospelov and ter Veldhuis 2001



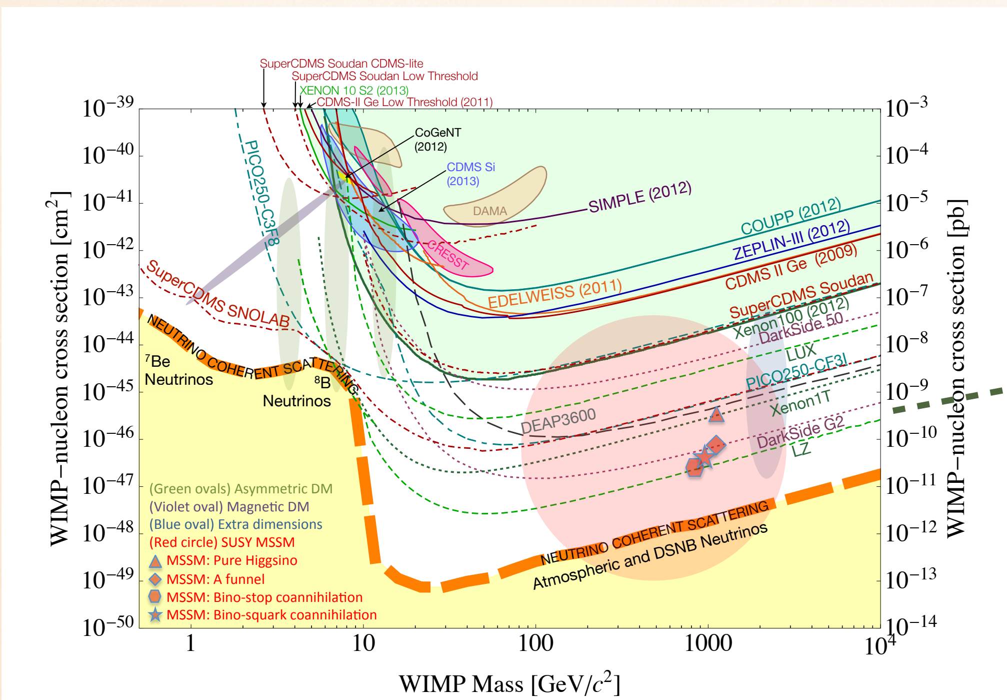
$$\sigma_{SI} = \frac{|\lambda_{\phi H}|^2 m_n^4 f^2}{\pi m_h^4 m_\phi^2}$$

$$= \left(\frac{\lambda_{\phi H}}{0.02}\right)^2 \left(\frac{100\,\text{GeV}}{m_\phi}\right)^2 1.4 \times 10^{-45}\text{cm}^2,$$

$$m_\phi = 500\,\text{GeV} \quad \lambda_{\phi H} \approx 0.2$$

$$m_\phi = 10\,\text{GeV} \quad \lambda_{\phi H} \approx 0.005$$

EWSB contributes a small mass to the DM



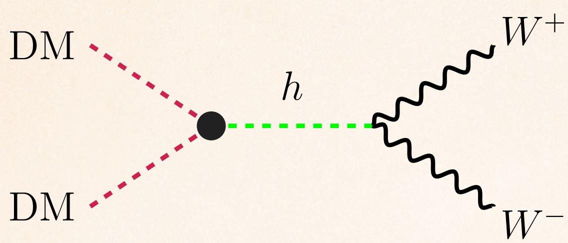
Future: LZ

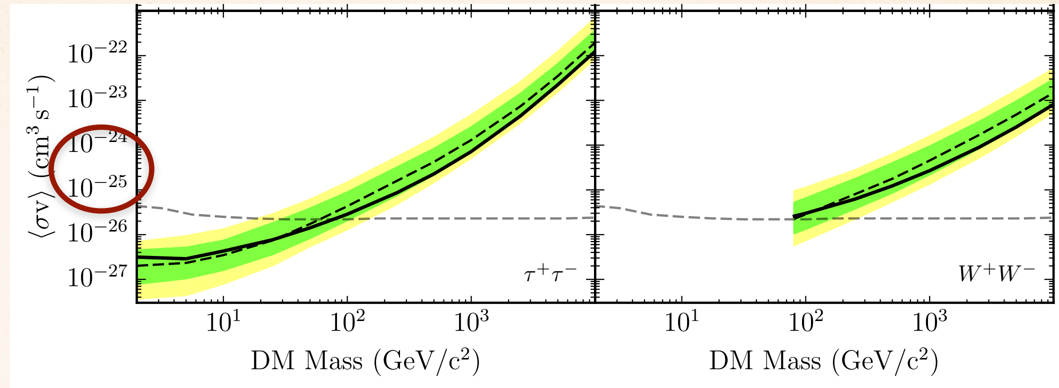
$$\lambda_{\phi H} \sim (0.002 - 0.02)$$

$$m_\phi = (100 - 500)\,\text{GeV}$$

Milky Way dwarf galaxies: Fermi-LAT 2015

Indirect detection:



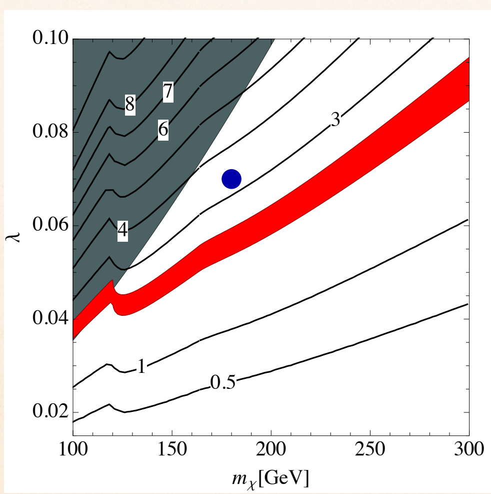


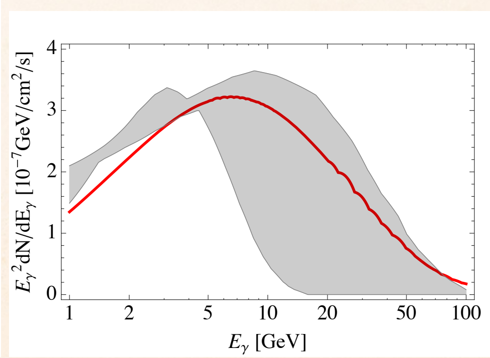
$$\langle\sigma v\rangle = \sum_{i=W,Z} n_i \frac{|\lambda_{\phi H}|^2}{2\pi m_\phi^2}\sqrt{1-\frac{m_i^2}{m_\phi^2}}\frac{m_i^4}{\left(4m_\phi^2-m_h^2\right)^2}\left(2+\frac{(2m_\phi^2-m_i^2)^2}{m_i^4}\right)$$

$$= \left|\frac{\lambda_{\phi H}}{0.038}\right|^2 3\times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} \qquad m_\phi = 100\,\mathrm{GeV}$$

Fan, Reece
1301.2597

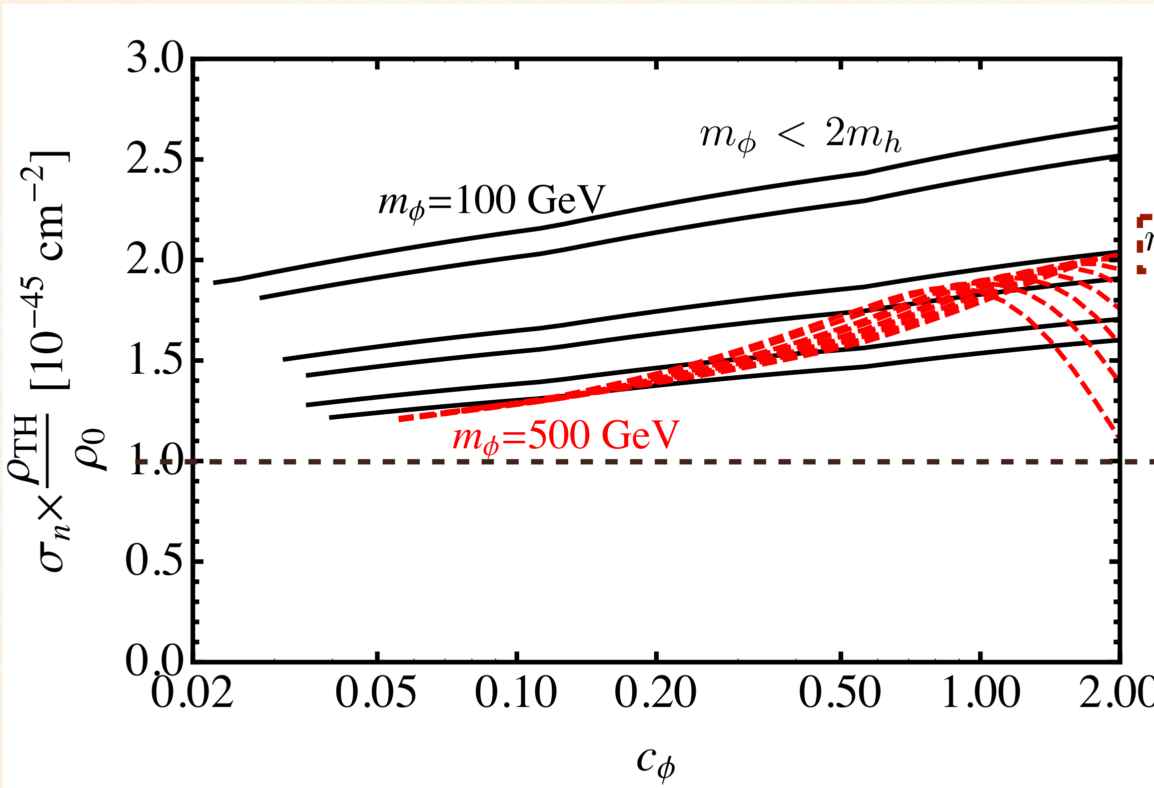
Fermi GeV excess





Agrawal, Batell,
Fox and Harnik
1411.2592

Implications for cosmological history

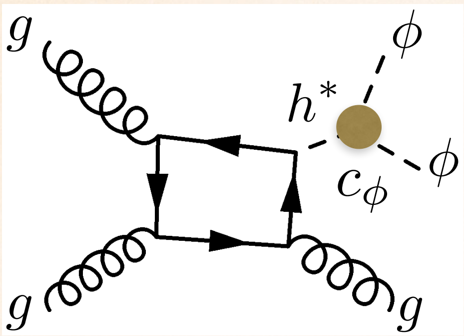


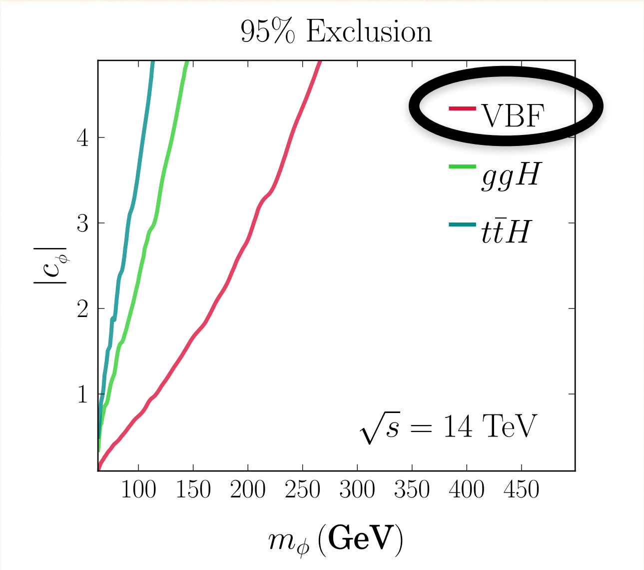
pure thermal scenario is excluded in the 100-500 GeV mass range if direct detection pushes

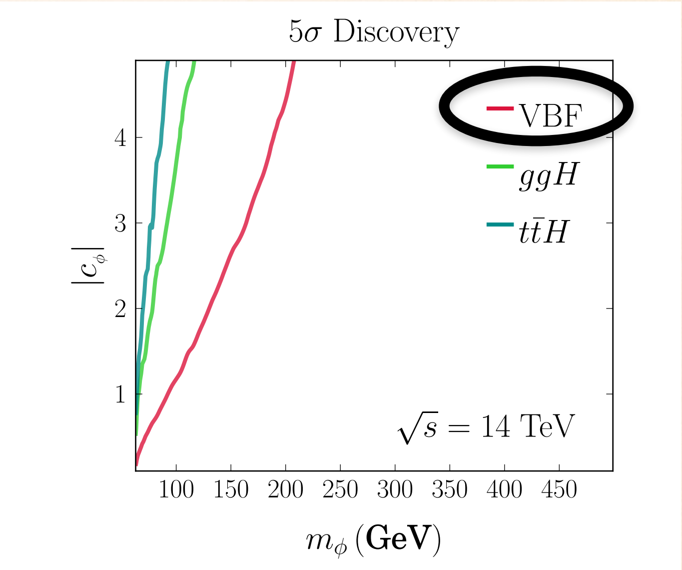
$\sigma_n < \mathcal{O}(1 \times 10^{-45} \text{cm}^2)$

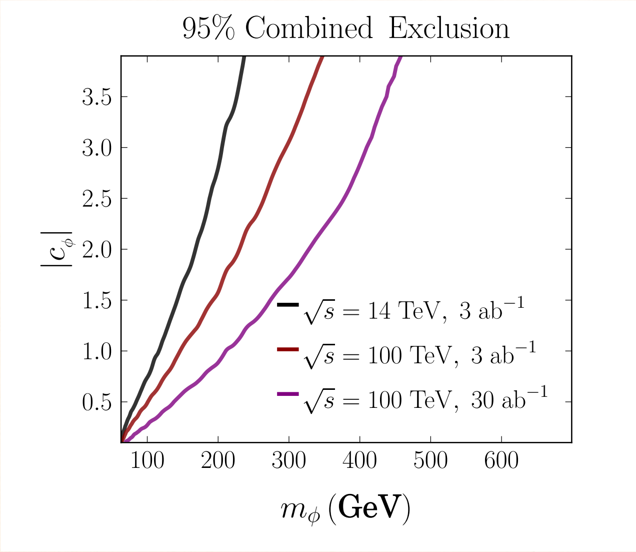
Craig, Lou, McCullough and Thalapilil 1412.0258

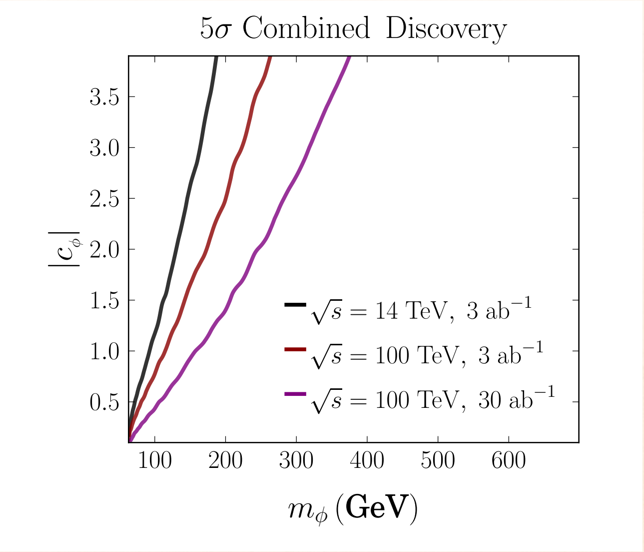
Collider: for DM heavier than half of the Higgs mass;







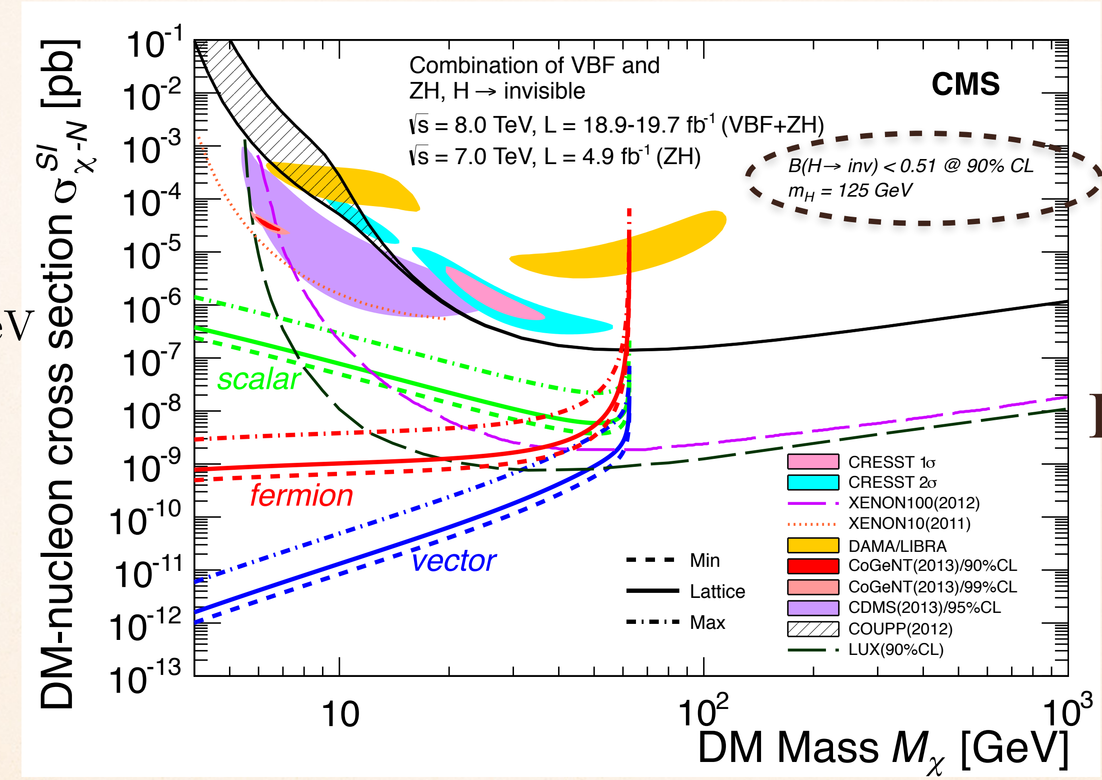




Craig, Lou, McCullough and Thalapilil 1412.0258; see also Curtin, Saraswat 1509.04284

For DM with mass below 63 GeV, constrained by Higgs invisible decay: in particular, for DM mass below 10 GeV

$\lambda_{\phi H} \leq 0.013 \quad m_\phi = 4\,\mathrm{GeV}$



LUX

Non-renormalizable operator: fermion DM

$$\frac{\kappa_1}{\Lambda}(\bar{\chi}\chi)(H^\dagger H) + \frac{i\kappa_5}{\Lambda}(\bar{\chi}\gamma_5\chi)(H^\dagger H).$$

Eg: Singlet (scalar) mediator

$$\mathcal{L}_\mathrm{S} \supset -\mu_0^2|H|^2 - \lambda_0|H|^4 - \frac{1}{2}m_{S,0}^2\phi_S^2 - V_0(\phi_S) - \mu_0'|H|^2\phi_S - \lambda_0'|H|^2\phi_S^2$$
$$-\frac{1}{2}m_{\chi,0}\bar{\chi}\chi - \frac{1}{2}y_0\bar{\chi}\chi\phi_S - \frac{i}{2}y_{5,0}\bar{\chi}\gamma_5\chi\phi_S,$$

$$\widehat{\mathcal{L}} \supset -\frac{1}{2}y\left(-s_\alpha\,\bar{\chi}\chi h_1 + c_\alpha\,\bar{\chi}\chi h_2\right) - \frac{i}{2}y_5\left(-s_\alpha\,\bar{\chi}\gamma_5\chi h_1 + c_\alpha\,\bar{\chi}\gamma_5\chi h_2\right) - \sum_f \frac{y_f}{\sqrt{2}}\left(c_\alpha\,\bar{f}fh_1 + s_\alpha\,\bar{f}fh_2\right),$$

mixing angle between singlet and Higgs

Higgs

singlet-like heavy Higgs

Freitas, Westhoff, Zupan 1506.04149

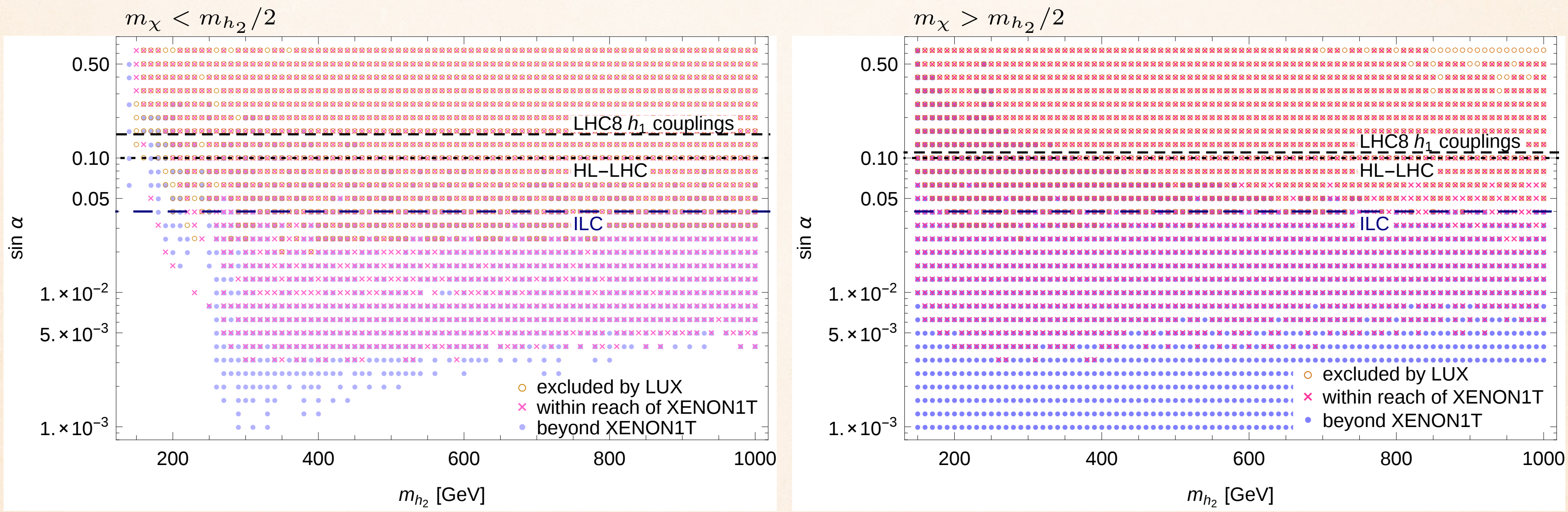
The search for mediator (direct or indirect as Higgs coupling measurements) could be important complementary probe!

$$\widehat{\mathcal{L}} \supset -\frac{1}{2}y\left(-s_\alpha\,\bar{\chi}\chi h_1 + c_\alpha\,\bar{\chi}\chi h_2\right) - \frac{i}{2}y_5\left(-s_\alpha\,\bar{\chi}\gamma_5\chi h_1 + c_\alpha\,\bar{\chi}\gamma_5\chi h_2\right) - \sum_f \frac{y_f}{\sqrt{2}}\left(c_\alpha\,\bar{f}fh_1 + s_\alpha\,\bar{f}fh_2\right),$$

direct detection: $\sin(2\alpha)$

Higgs coupling: $\cos(\alpha)$

second Higgs search



assume thermal relic

Other UV completions involve fermion mediators with setup similar to neutralino DM. In general neutralino DM provides classic benchmarks of WIMP scenario.

Neutralino DM exhausts the simplest possibilities of electroweak symmetry representations:

Bino: electroweak singlet;
Higgsino: electroweak doublet;
Wino: electroweak triplet;

There have been intensive work on neutralino DM in the literature: e.g, Han, Liu and Su 1406.1181;

I will focus on regions of parameter space that are experimentally challenging and a few benchmarks to demonstrate the complementarity.

Direct detection:

mixing between bino (wino) and higgsino: direct detection through Higgs exchange (leading order)

$$M_\chi = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v\cos\beta & \frac{1}{2}g'v\sin\beta \\ 0 & M_2 & \frac{1}{2}gv\cos\beta & -\frac{1}{2}gv\sin\beta \\ -\frac{1}{2}g'v\cos\beta & \frac{1}{2}gv\cos\beta & 0 & -\mu \\ \frac{1}{2}g'v\sin\beta & -\frac{1}{2}g'v\cos\beta & -\mu & 0. \end{pmatrix}.$$

$$\begin{aligned} \mathcal{L}_{h\chi\chi} &= \frac{1}{2}m_{\chi_i}(v+h)\chi_i\chi_i \\ &= \frac{1}{2}m_{\chi_i}(v)\chi_i\chi_i + \frac{1}{2}\frac{\partial m_{\chi_i}(v)}{\partial v}h\chi_i\chi_i + \mathcal{O}(h^2), \end{aligned}$$

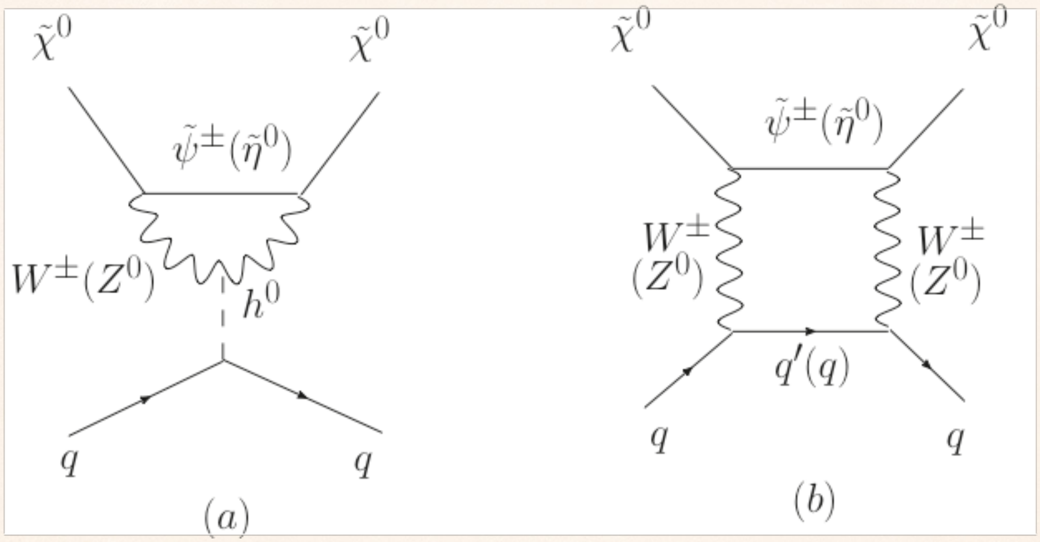
$= 0$

spin-independent blind spots :

$$\begin{aligned} m_{\chi_1} &= M_1, M_2, -\mu, \text{ and } m_{\chi_1} + \mu\sin 2\beta = 0 \\ m_{\chi_1} &= M_1 = M_2, \end{aligned}$$

Hall, Ruderman, Pinner, 1211.4873

Direct detection is also insensitive to cases with very small mixing. For example, pure wino (decouple bino and higgsino); pure higgsino (decouple wino and bino).

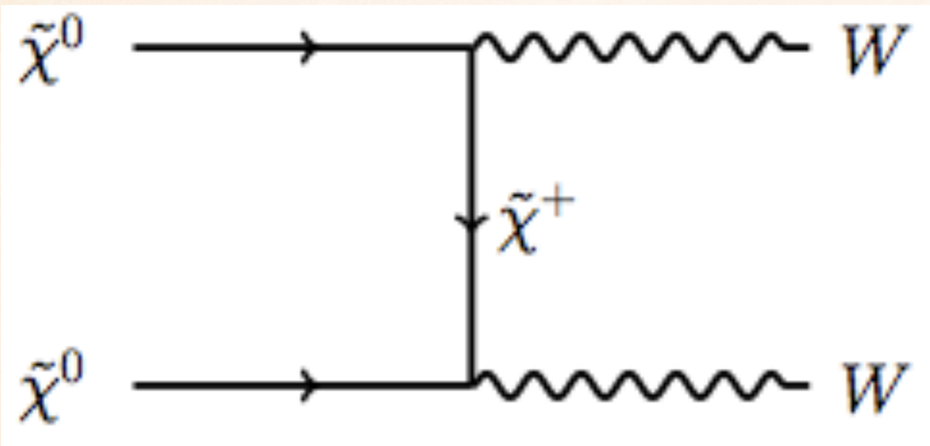


$$\text{wino} : \sigma_n \sim 10^{-47}\,\text{cm}^2$$

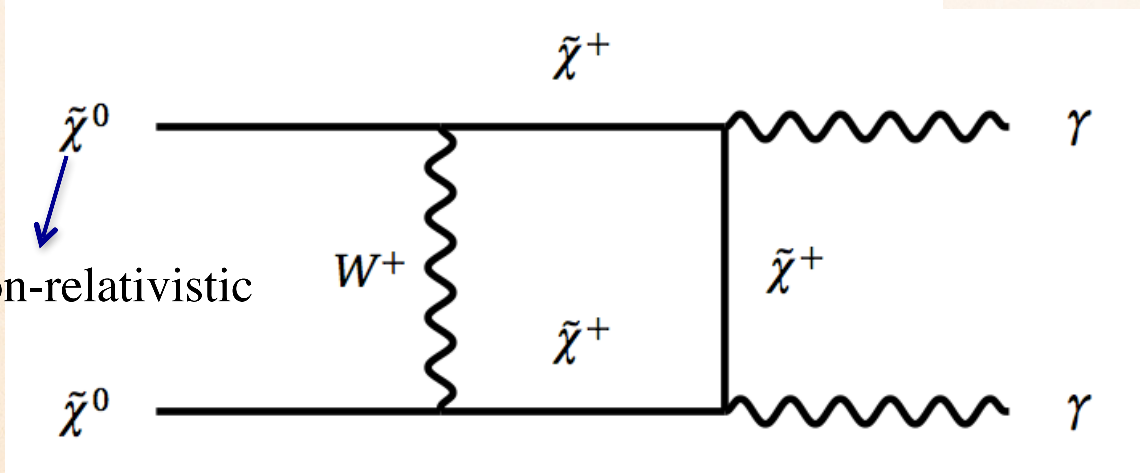
$$\text{higgsino} : \sigma_n \lesssim 10^{-48}\,\text{cm}^2$$

Hisano, Ishiwata, Nagata,and Takesako;
Hill, Solon 2011

For those cases, indirect detection (sensitive to gauge interactions) could be powerful: search for excesses in the photon continuum spectrum or a line-like feature in a dark matter dense region, e.g., galactic center or dwarf galaxies.



Continuum photons

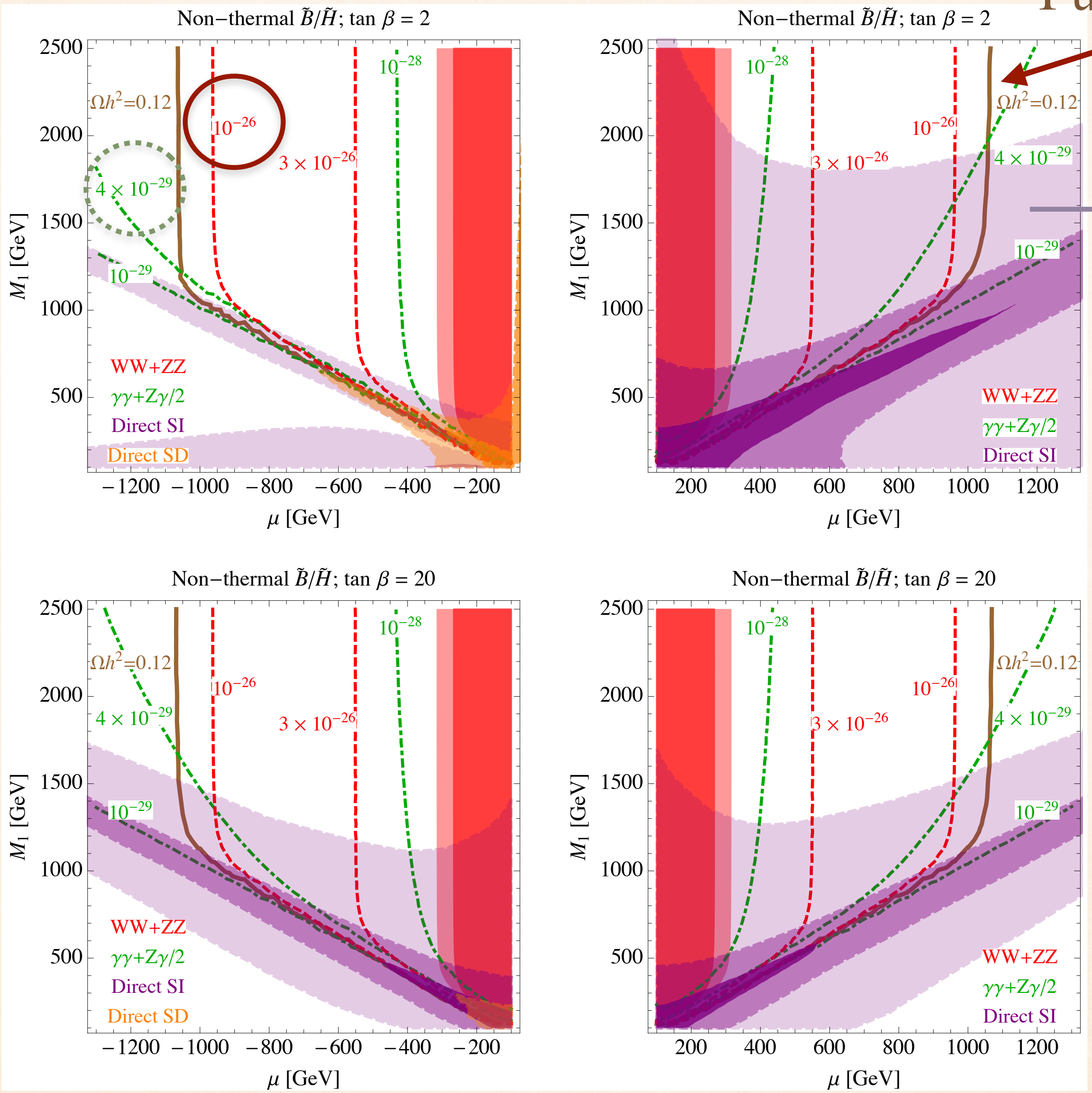


Non-relativistic

Photon line

$$E_\gamma = m_{\tilde{\chi}_0}$$

Higgsino(with bino mixture) DM



Pure higgsino DM with mass at a TeV

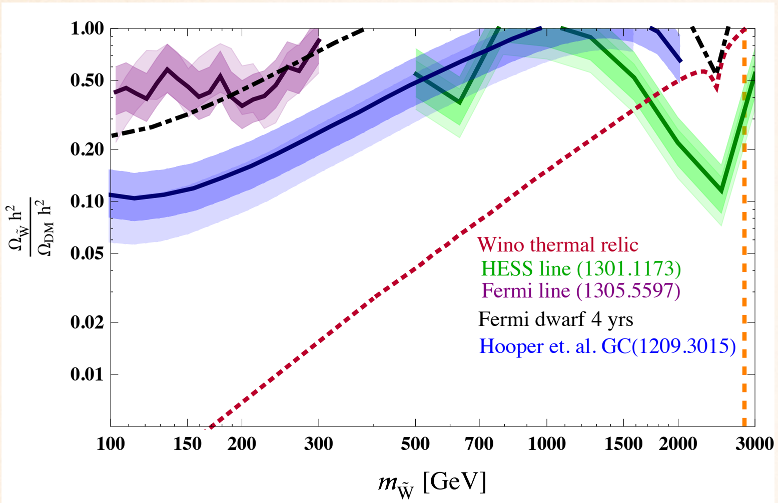
xenon1T

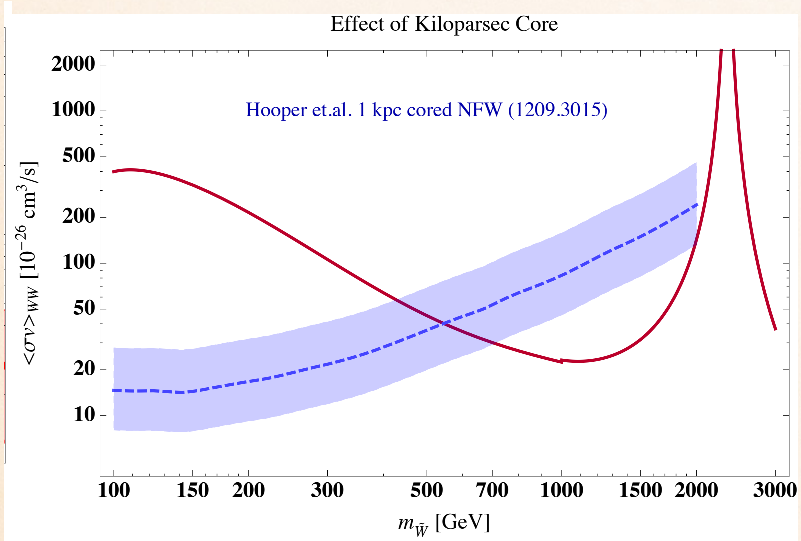
Hall, Ruderman, Pinner, 1211.4873

Fan, Reece 1307.4400

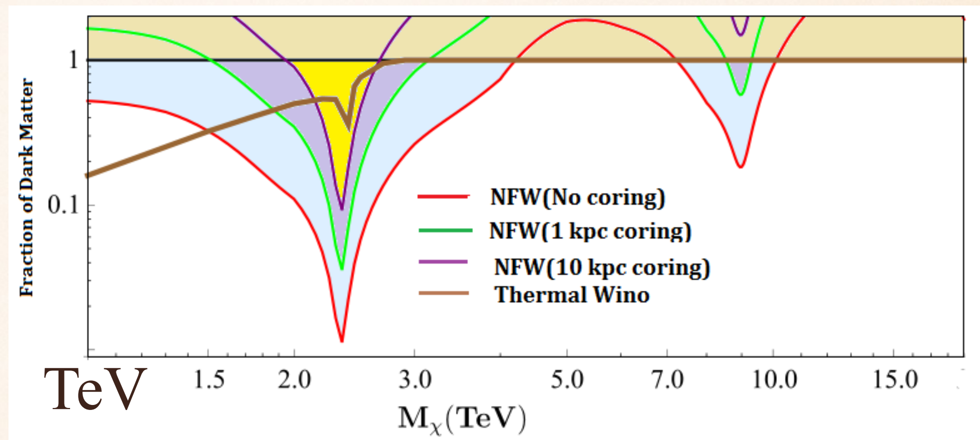
pure wino: decouple bino/higgsino

lighter wino: working perfectly with Moroi-Randall scenario is excluded even when one considers cored profile with a kpc core





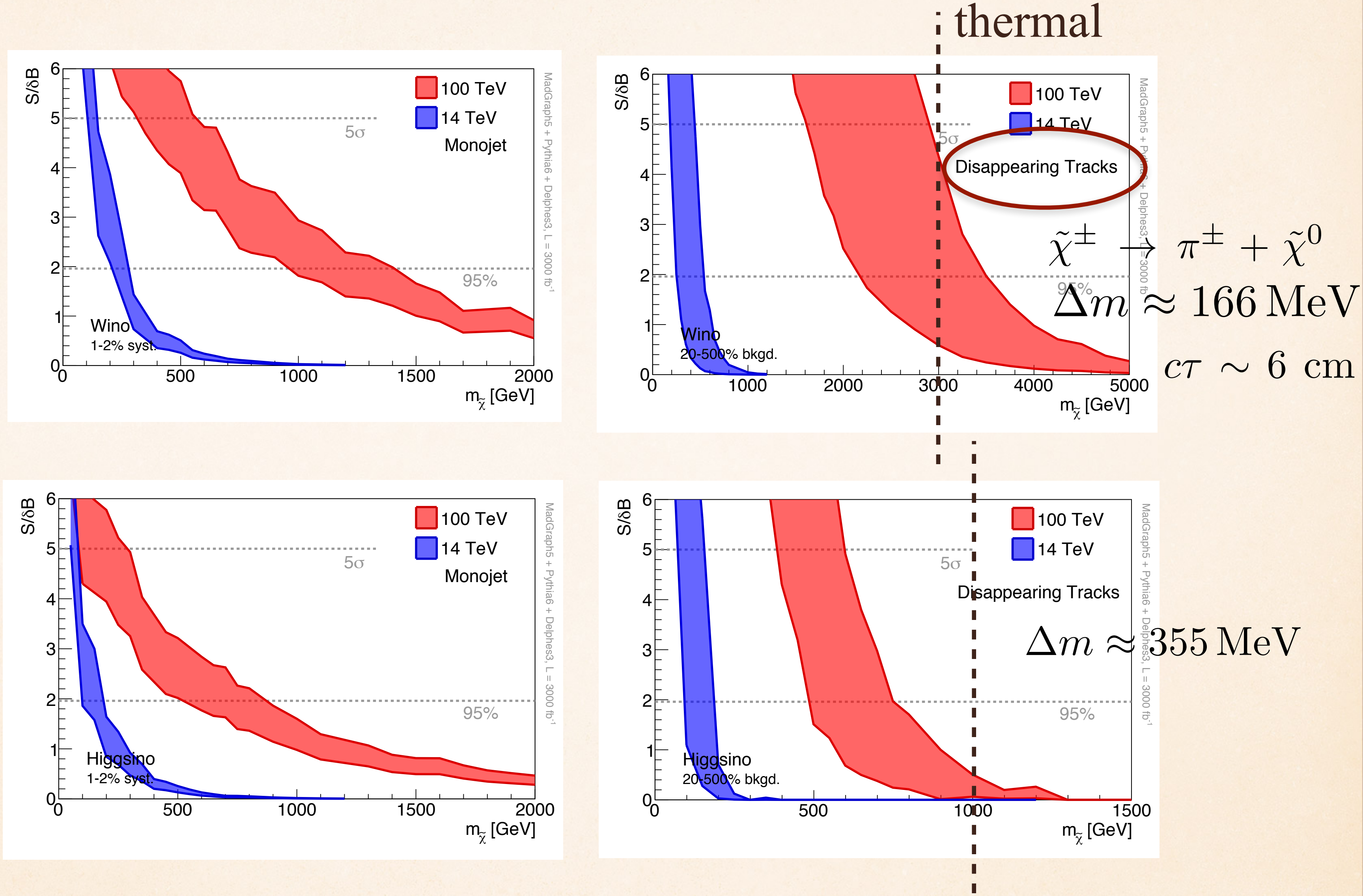
Thermal scenario is excluded even when one considers an NFW profile with a kpc core



Baumgart, Rothstein and Vaidya 1412.8698

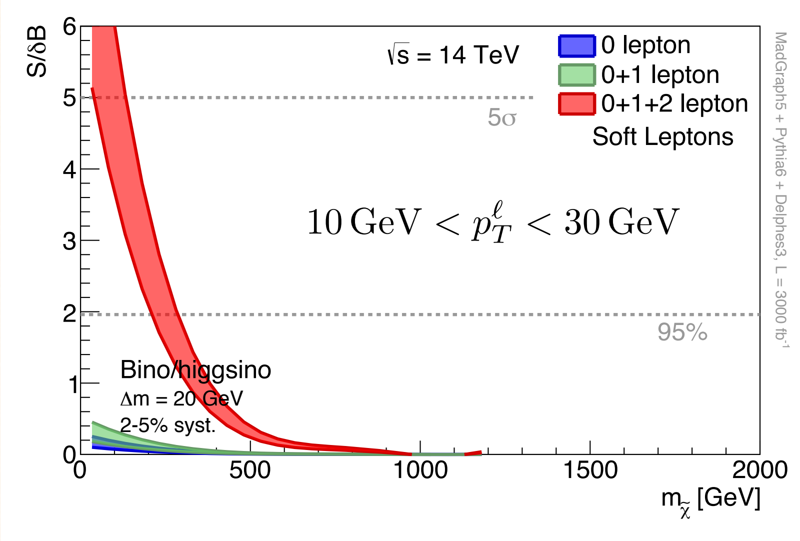
Fan, Reece 1307.4400; see also Cohen, Lisanti, Pierce and Slatyer 1307.4082

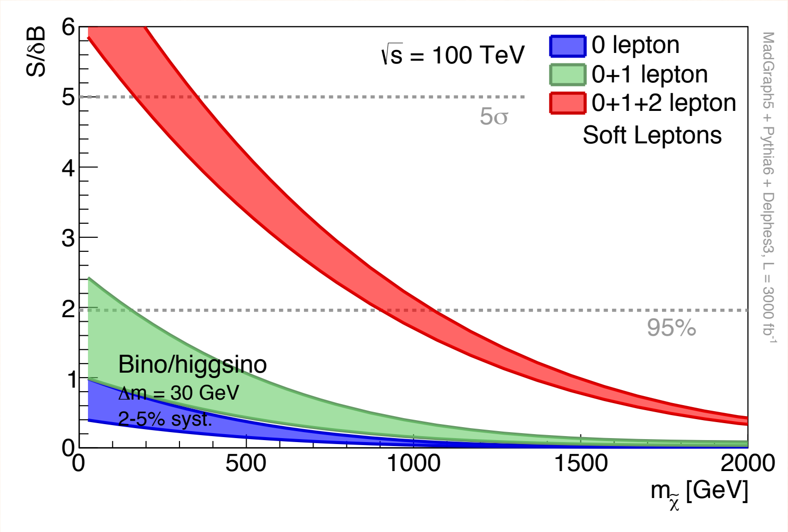
Collider constraints:



Low, Wang 1404.0682

Mixed compressed spectrum: soft lepton





Compressed spectrum is pretty generic;
Thoughts for future: dedicated detector to identify soft leptons or displaced tracks better?

So far we have mostly discussed Higgs portal DM.

There are other DM portals where the connection to Higgs is not explicit; yet if there is dark mediator charged under the SM (which is general), dark sector could be connected to electroweak physics.

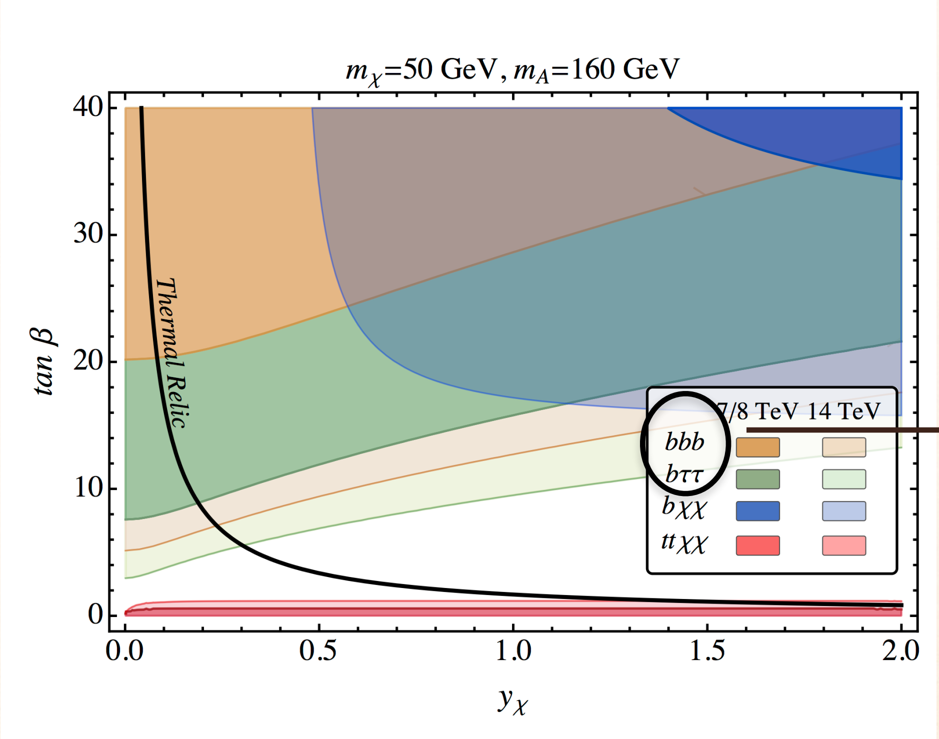
One example: pseudoscalar portal DM

$$i \left(g_\chi \bar{\chi} \gamma^5 \chi + \sum_f g_f \bar{f} \gamma^5 f \right) a,$$

A DM benchmark model that is unconstrained by direct detection and could lead to interesting indirect detection signal.

$$i\left(g_\chi \bar{\chi}\gamma^5\chi + \sum_f g_f \bar{f}\gamma^5 f\right) a,$$ not SM gauge invariant

2HDM



heavy Higgs searches

Berlin, Gori, Lin and Wang 1502.06000

$$i\left(g_\chi\bar{\chi}\gamma^5\chi+\sum_f g_f\bar{f}\gamma^5 f\right)a,$$

not SM gauge invariant

$$iaH^\dagger Q_L b_R^c/M_*$$

Vector-like new fermions

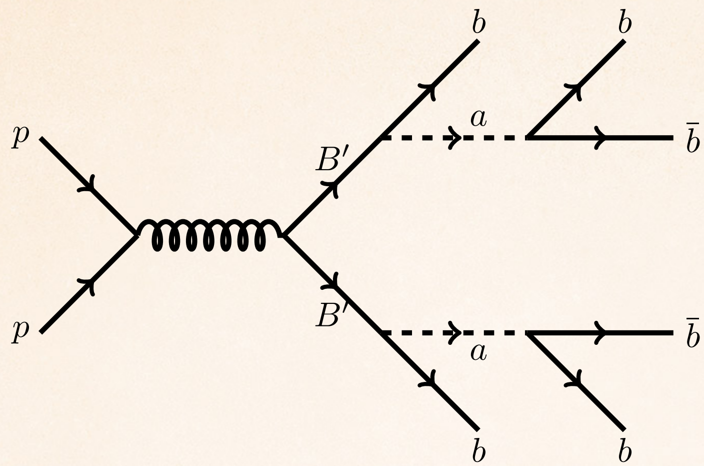
$B', \tilde{B}'$

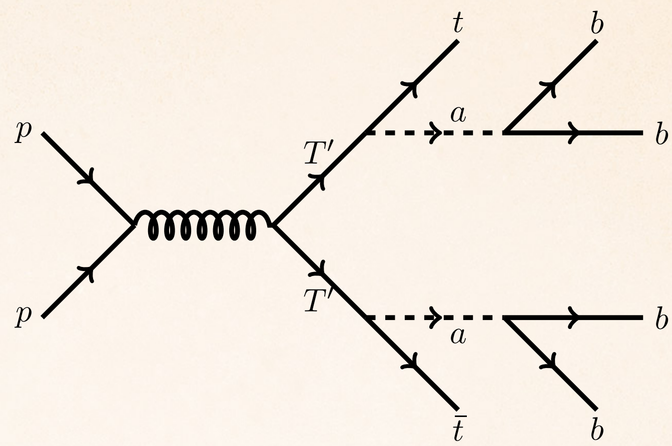
$$(M_B\tilde{B}'B' + iY_a a B' b_R^c + y_3 H^\dagger Q_3\tilde{B}' + cc.) + ia\bar{\chi}\gamma^5\chi,$$

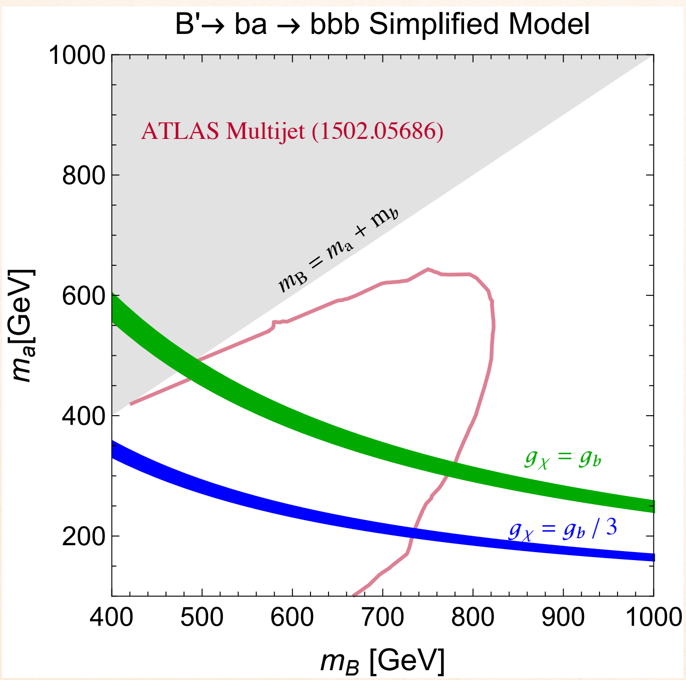
opens new decay channel

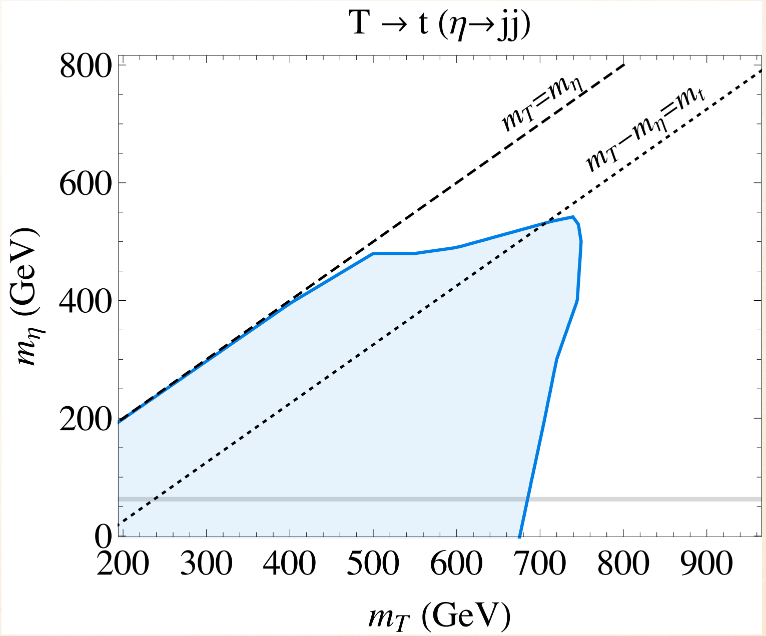
$$B' \to ab$$

Fan, Koushiappas, Landsberg 2015









Fan, Koushiappas, Landsberg 2015

Anandakrishnan, Collins, Farina, Kuflik and Perelstein 2015

$$i\left(g_\chi \bar{\chi}\gamma^5\chi + \sum_f g_f \bar{f}\gamma^5 f\right) a,$$ not SM gauge invariant

$$iaH^\dagger Q_L b_R^c / M_*$$

Vector-like new fermions $B', \tilde{B}'$

$$(M_B \tilde{B}' B' + iY_a a B' b_R^c + y_3 H^\dagger Q_3 \tilde{B}' + cc.) + ia\bar{\chi}\gamma^5\chi,$$

new yukawa couplings could modify Higgs couplings: hbb; gauge couplings: hgg, h$\boldsymbol{\gamma\gamma}$, EWPT

Choudhury, Tait and Wagner 2002; Dawson, Furlan 2012;
Batell, Gori and Wang 2013….

$$i\left(g_\chi \bar{\chi}\gamma^5\chi + \sum_f g_f \bar{f}\gamma^5 f\right) a,$$

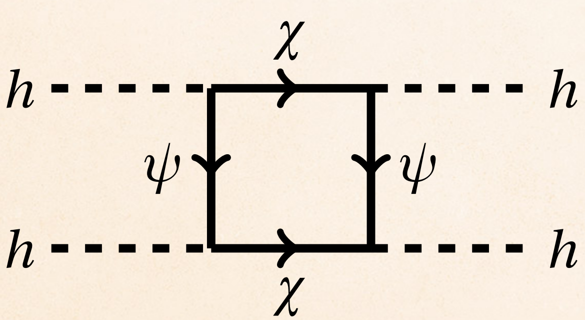
not SM gauge invariant

$$iaH^\dagger Q_L b_R^c / M_*$$

Vector-like new fermions $B', \tilde{B}'$

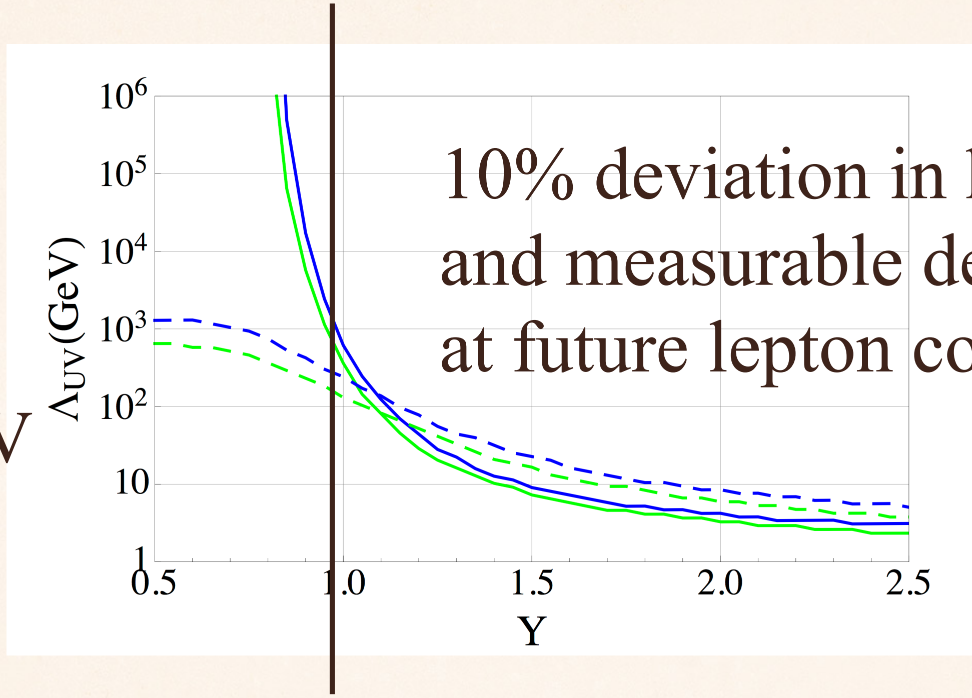
$$(M_B \tilde{B}' B' + iY_a a B' b_R^c + y_3 H^\dagger Q_3 \tilde{B}' + cc.) + ia\bar{\chi}\gamma^5\chi,$$

Modify the stability property of Higgs vacuum



$$16\pi^2 \frac{d\lambda}{dt} \sim -2Y^4 \qquad \lambda(\Lambda_{\rm UV}) \approx -0.06$$

New boson
mass scale
below 10 TeV



10% deviation in higgs coupling
and measurable deviation in EWPT
at future lepton collider

Blum, D'Agnolo and Fan 1502.01045

Some Thoughts

Collider DM searches: go beyond monoX searches and search for dark mediator and dark sector;

More benchmark models that demonstrate complementarity between indirect detection searches and collider searches (both direct searches and Higgs measurements)

Some Thoughts

Better probe for thermal higgsino (DM): certainly a counterexample to the statement that WIMP will be excluded soon. Indirect detection could be useful though subject to astrophysical uncertainty.

Some other (unsuccessful) attempts to probe higgsino DM: triple gauge coupling Fan, Reece, Wang 1412.3107

$$c_{WWW} = \frac{g^2}{2880\pi^2} \sum_{\text{rep } R, \text{ mass } M} (-1)^F \frac{T(R)}{M^2},$$

ILC: $|\lambda_{\gamma,Z}| \lesssim 6 \times 10^{-4}$

500 fb^{-1} $\sqrt{s} = 500 \text{ TeV}$

Backup

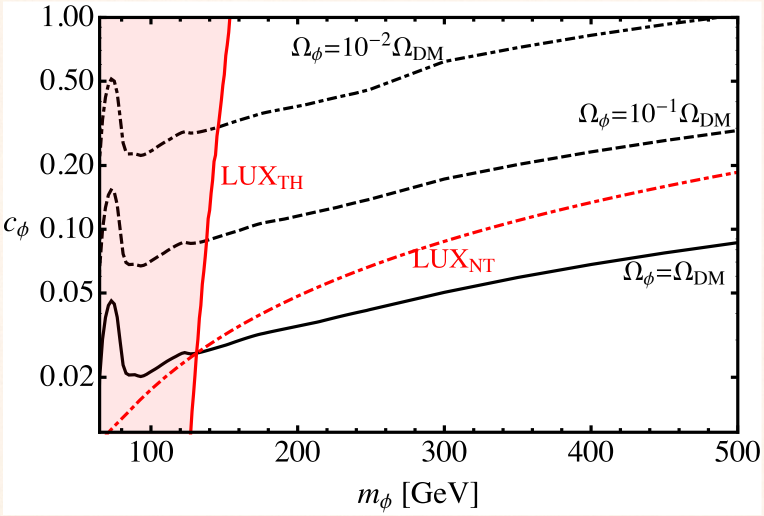
Recap: Higgs portal scalar DM

DM mass below half of Higgs mass, constrained by direct detection and Higgs invisible decay;

Direct detection probes the coupling between DM and Higgs down to (0.02 - 0.2) for a DM with mass (100 GeV - 500 GeV);
Future bound could be improved by a factor of 10;
Indirect detection has similar (numerically weaker) sensitivity;

LHC (VBF channel mostly) could probe DM up to 250 GeV;
future 100 TeV collider could probe it up to around 400 GeV.

Thermal scenario could be excluded by direct detection soon.



assuming ϕ with a thermal relic abundance

New triangle for the vector-like fermion search