Local Z_2 scalar DM

[Seungwon Baek, P. Ko & WIP, PLB 747 (2015) 255 [arXiv: 1407.6588]]

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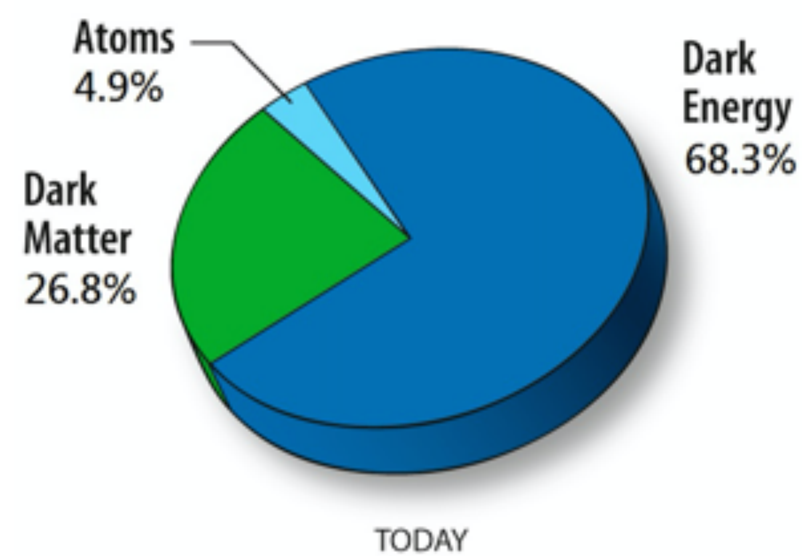
Dark matter

- Matter-like

Spin	Candidate
0	axion, ...
1/2	neutralinos, axino, ...
1	...
3/2	gravitino

Energy budget after Planck



- Cosmologically stable

  - Decay but long-living? ⇒ very light or extremely weak interactions
  - Absolutely stable? ⇒ unbroken local sym.

- Interaction(s) to SM?

  - renormalizable ⇒ thermal relic (direct/indirect detections, collider searches)
  - non-renormalizable ⇒ freeze-in or non-thermal production (collider searches?)

The model

- Organizing principle

  - simple
  - natural } ⇒ { - weak scale scalar dark matter!
  - stability requires unbroken gauge sym.

- Unbroken $U(1)_X$?

  Massless mediator (⇒ Long range force):

  1. velocity dependent (t-channel) DM self-interaction
  2. Sommerfeld enhancement self-interactions (scattering, annihilation)

  No interaction with SM? ⇒ constraints from small scale structure
  Annihilation to SM ptl. ? ⇒ CMB constraint. + ... ⇒ $g_X \lesssim 10^{-5}$

  Way-out?
  - p-wave suppression?
  - s-wave resonance? } ⇒ No sizable astrophysical effect(s).

A discrete gauge sym. looks better for DM pheno.

- # Local Z_2 scalar DM (based on dark local $U(1)_X$)

[Seungwon Baek, P. Ko & WIP, PLB 747 (2015) 255 [arXiv: 1407.6588]]

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi^\dagger D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi - \lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H - \mu\left(X^2\phi^\dagger + H.c.\right).$$

kinetic mixing

Scalar DM couples to two Higgses

$U(1)_X$ to Z_2

$[Q_{U(1)_X}(X,\phi) = (1,2)]$

mass spliting between X_R and X_I

H : SM Higgs

ϕ : dark Higgs $\rightarrow$ $(v_\phi + \phi)/\sqrt{2}$

$\hat{X}_\mu$: dark photon

X : scalar DM

$\Rightarrow$ mixing between H & ϕ

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

cf. Well known (Global?) Z_2 scalar DM

$$\mathcal{L}_{DM} = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{m_S^2}{2}S^2 - \frac{\lambda_{HS}}{2}S^2 H^\dagger H - \frac{\lambda_S}{4!}S^4$$

S : real scalar

Z_2 : $S \rightarrow -S$

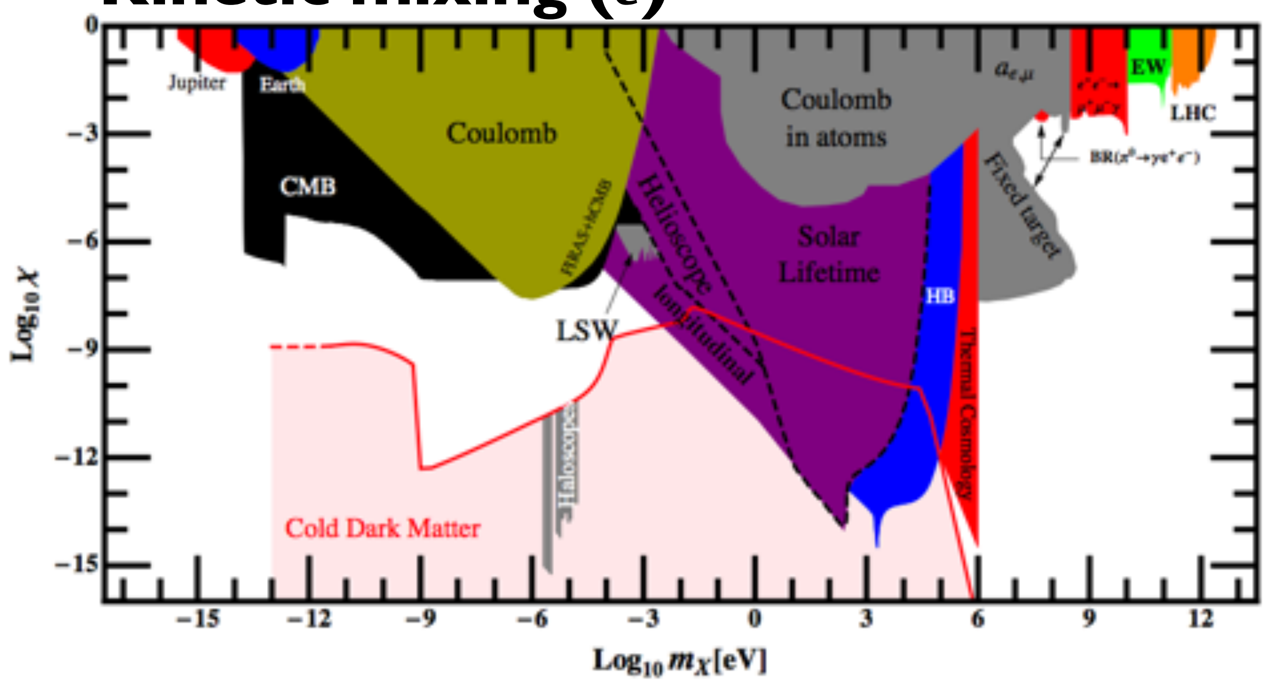
$\hat{X}_\mu, \phi$

☞ Local Z_2 requires more fields, allowing more interactions !!!

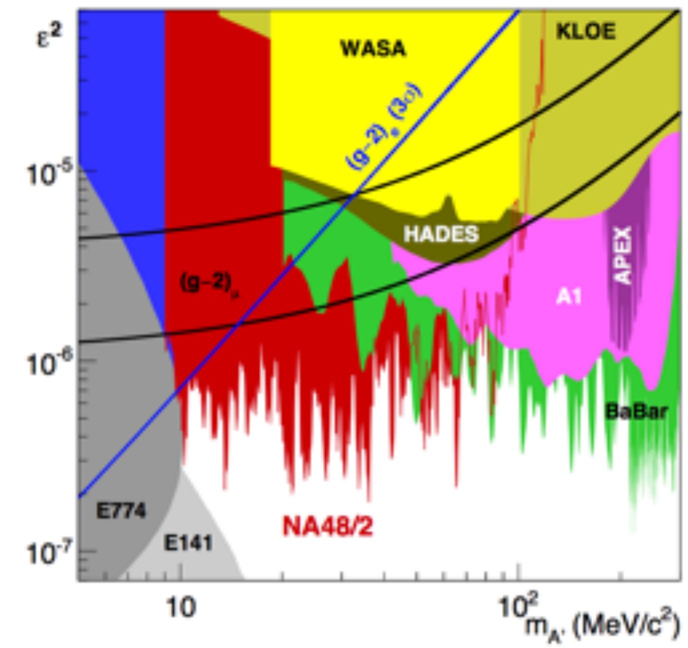
$\Rightarrow$ drastic change of DM pheno.

- Constraints on portal interactions

Kinetic mixing (ϵ)



[Joerg Jaeckel, arXiv:1303.1821]



[NA48/2 coll., arXiv:1504.00607]

Higgs mixing (α)

m_H (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(H \to inv)/\sigma_{SM}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

[arXiv:1404.1344]

$$\Rightarrow \quad \alpha \lesssim \mathcal{O}(0.1)$$

DM pheno.

- Parameter fixing

12 free para.

$$\epsilon, g_X,$$
$$m_X, m_\phi, m_H, \mu,$$
$$\lambda_X, \lambda_\phi, \lambda_H, \lambda_{\phi X}, \lambda_{HX}, \lambda_{\phi H}$$

free to adjust for fixed the other para.s.

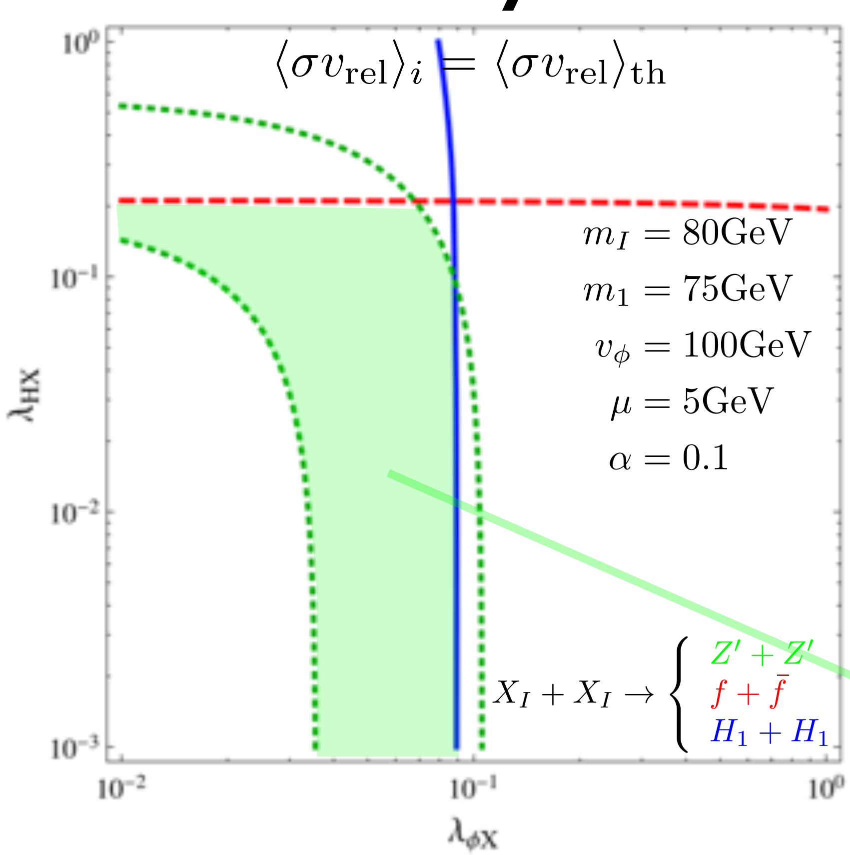
$$m_\phi, m_H, \lambda_\phi, \lambda_H, \lambda_{\phi H} \rightarrow v_\phi, v_H, \alpha, m_1, m_2$$

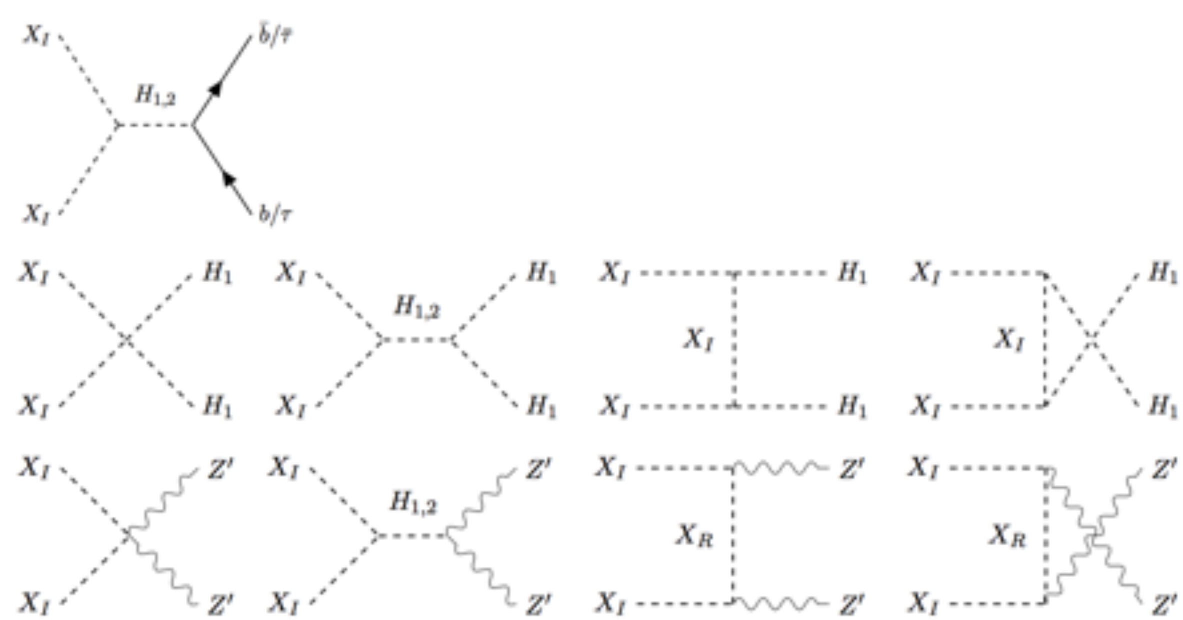
4 para. $\left\{ \begin{array}{r} m_X^2, \lambda_{\phi X}, \lambda_{HX} \rightarrow m_R^2 + m_I^2 \\ \mu \rightarrow m_R^2 - m_I^2 \end{array} \right\}$ 2 para.

Parameters	ϵ	$m_{Z'}$	m_I	μ	m_1	m_2	v_ϕ	v_H	α	$\lambda_{\phi X}$	λ_{HX}
Ranges	$\lesssim 10^{-3}$	$\mathcal{O}(1)$	$\mathcal{O}(10\text{–}100)$	$\mathcal{O}(10)$	$\sim m_I$	125	$\mathcal{O}(100)$	246	$\mathcal{O}(0.1)$	$\mathcal{O}(10^{-3}\text{–}1)$	$\mathcal{O}(10^{-3}\text{–}1)$

$\lambda_X > 0$

- Relic density



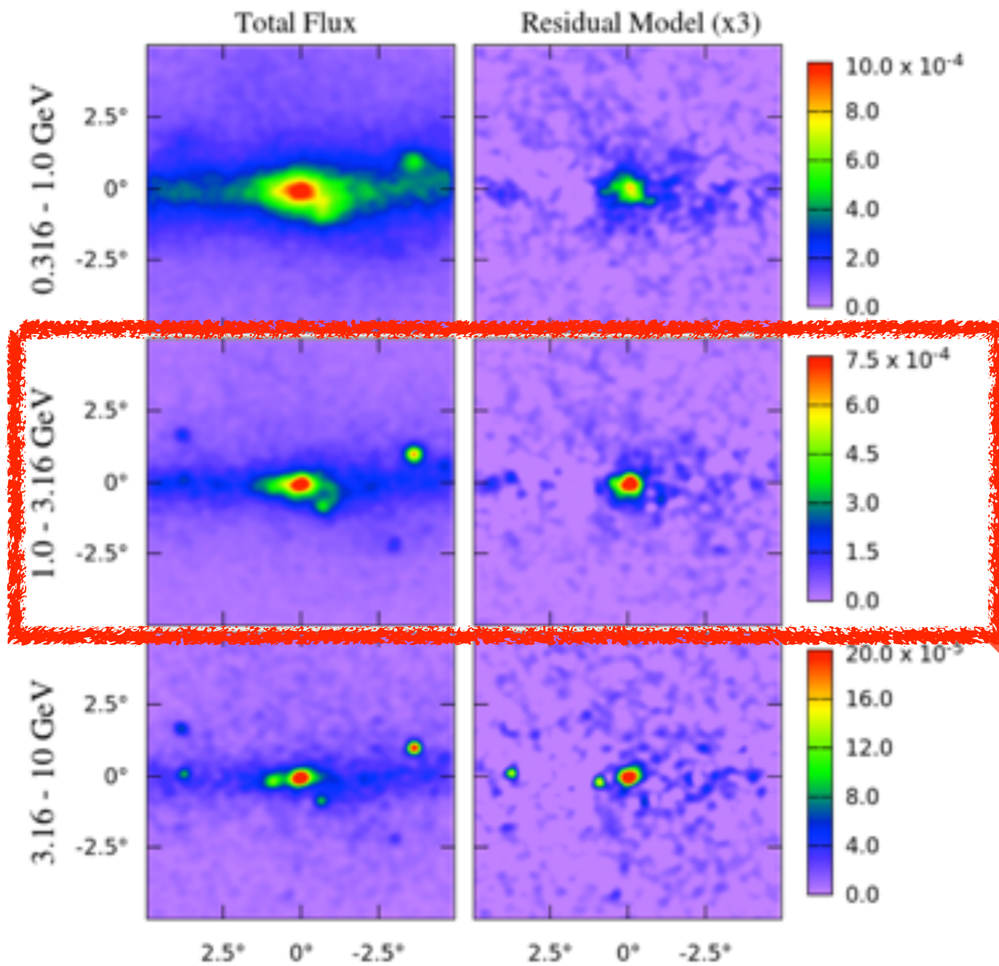


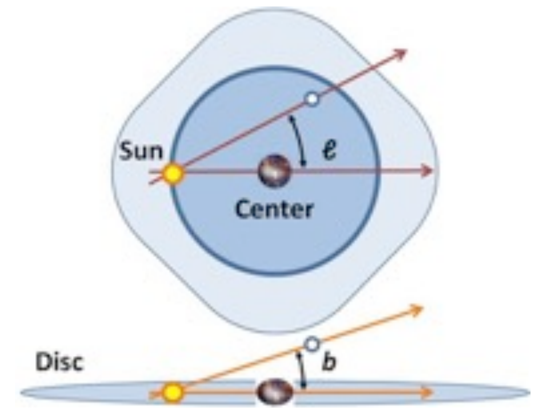
$\langle \sigma v_{\rm rel} \rangle_i \lesssim \langle \sigma v_{\rm rel} \rangle_{\rm th}$ in the green region

• Indirect detection

(impact on Fermi-LAT GeV scale γ −ray excess from GC)

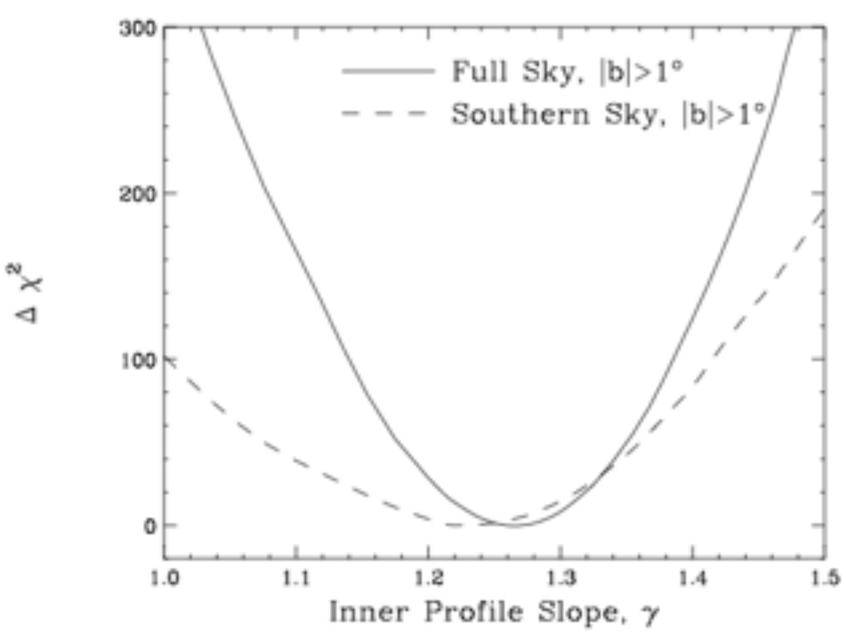
[1402.6703, T. Daylan et.al.]



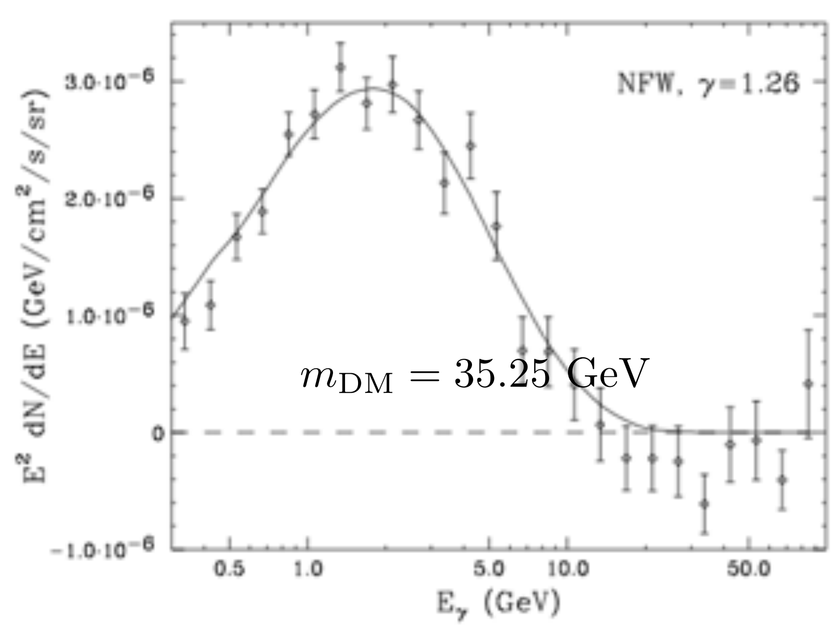


$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$

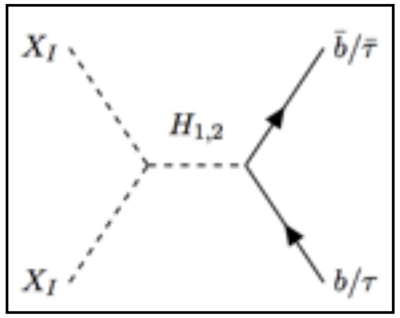
GeV scale excess!



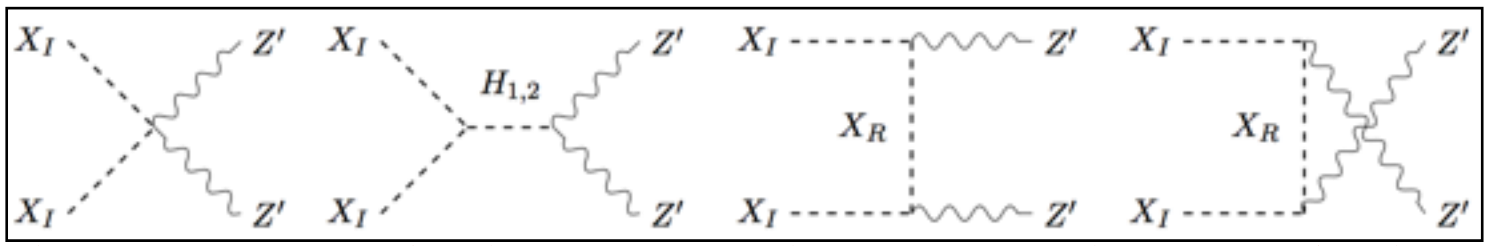
$\mathrm{DM} + \mathrm{DM} \to b\bar{b}$ with $\sigma v = 1.7 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$



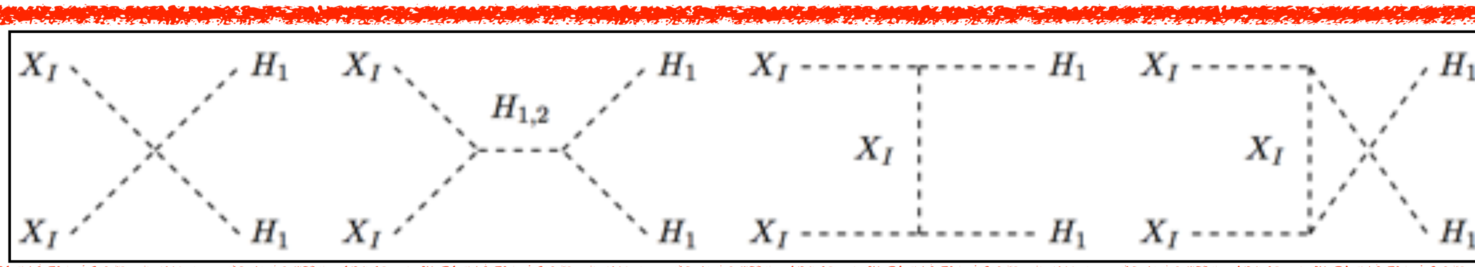
Available channels



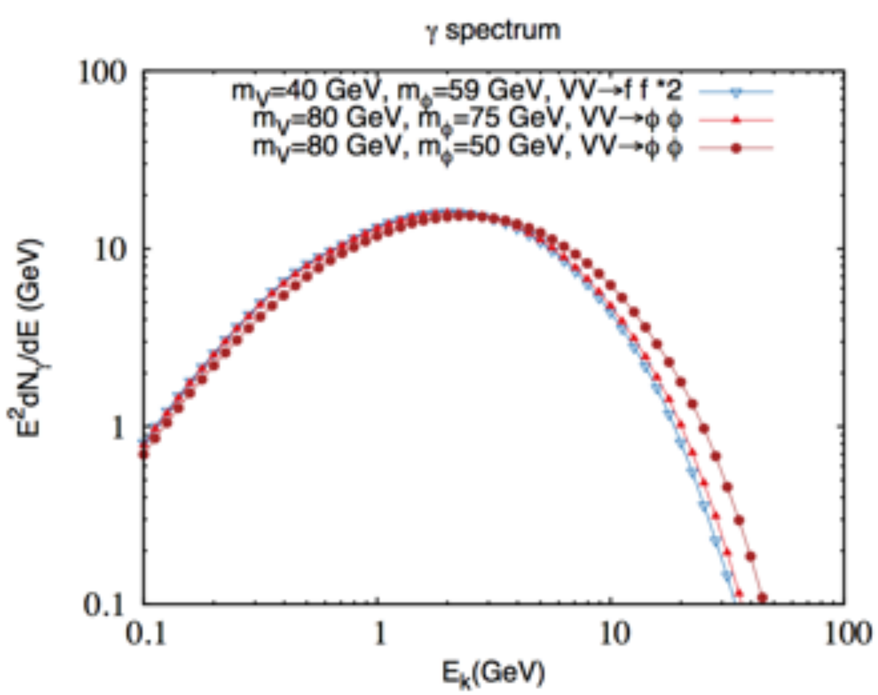
fermion mass suppression



+ On-shell Z' decay



+ On-shell H_1 decay



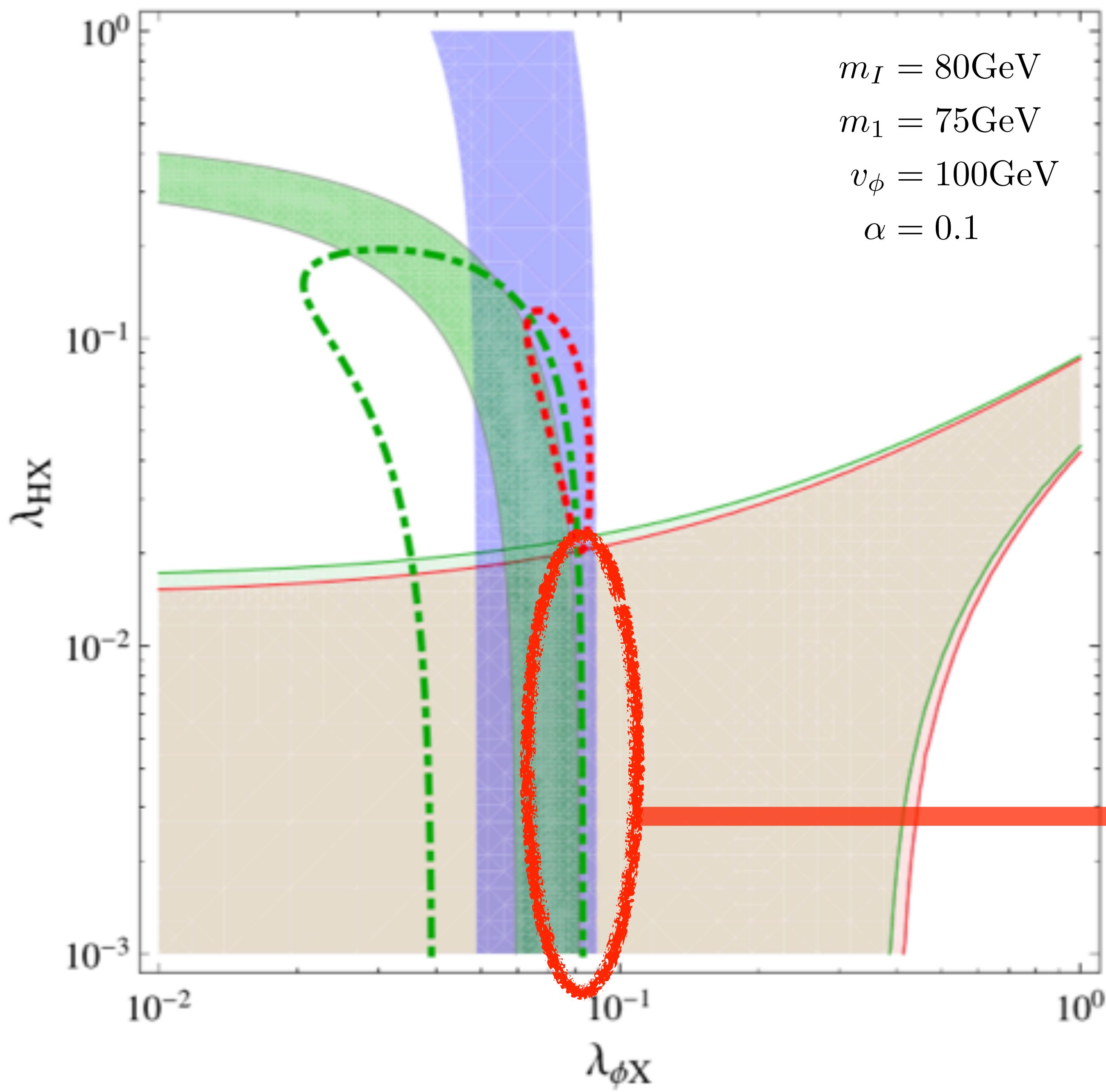
GeV scale γ −ray excess from GC can be explained if

$$m_{\rm DM} \approx m_{H_1} ({\rm or}\ m_{Z'}) \sim 60 - 80\ {\rm GeV}$$

[P. Ko, WIP & Y. Tang, JCAP 1409 (2014) 013, arXiv:1404.5257]]

- <u>Direct</u>/indirect detections + relic density

(small kinetic & Higgs mixings, forbidden tree-level process of Z'-mediation)



Dot-dashed, dotted lines:

$\langle \sigma v_{\rm rel} \rangle_{\rm tot} = \langle \sigma v_{\rm rel} \rangle_{\rm th}$ for $\mu = \begin{cases} 5 \text{ GeV} \\ 7 \text{ GeV} \end{cases}$

Light green, red regions:

$\sigma_p^{\rm SI} < 7.6 \times 10^{-46} \text{ cm}^2$ (LUX bound)

- - - -, : $\mu = 5$ GeV

- - - -, : $\mu = 7$ GeV

: $\mu = 7 \text{ GeV}, \langle \sigma v_{\rm rel} \rangle_{ZZ'} / \langle \sigma v_{\rm rel} \rangle_{\rm th} \leq 0.1$

: $\mu = 7 \text{ GeV}, 1/3 \leq \langle \sigma v_{\rm rel} \rangle_{H_1 H_1} / \langle \sigma v_{\rm rel} \rangle_{\rm th} \leq 1$

Region for
- relic density
- GeV scale γ −ray excess from GC

cf. Higgs portal models in EFT

Mediator = only SM Higgs

⇨ Strong constraint from direct detection exps. because of crossing symmetry.

Implication on collider exp.

- Universal suppression of SM-channels

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

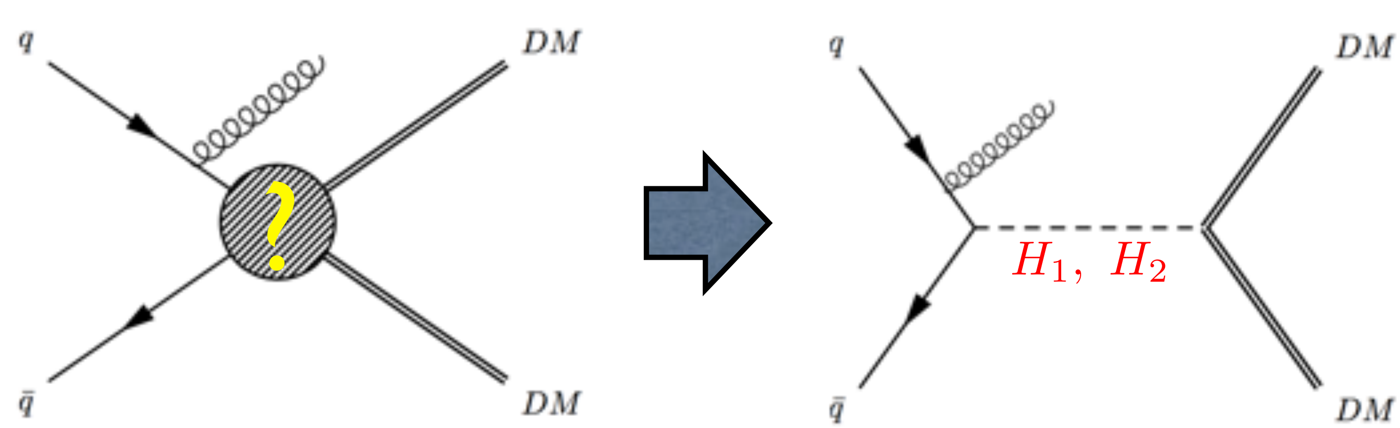
$$r \equiv \frac{\sigma_h \mathrm{BR}_{h\to \mathrm{SM}}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{h\to \mathrm{SM}}^{\mathrm{SM}}} = \frac{c_\alpha^4 \Gamma_h^{\mathrm{SM}}}{c_\alpha^2 \Gamma_h^{\mathrm{SM}} + s_\alpha^2 \Gamma_h^{\mathrm{hid}}} \to c_\alpha^2$$

(α : the mixing angle)

(signal strength)

(in case of no-invisible mode of **h**)

- Suppression of 'mono-jet(photon)/t-tbar + $\not{E}_T$'



two mediators

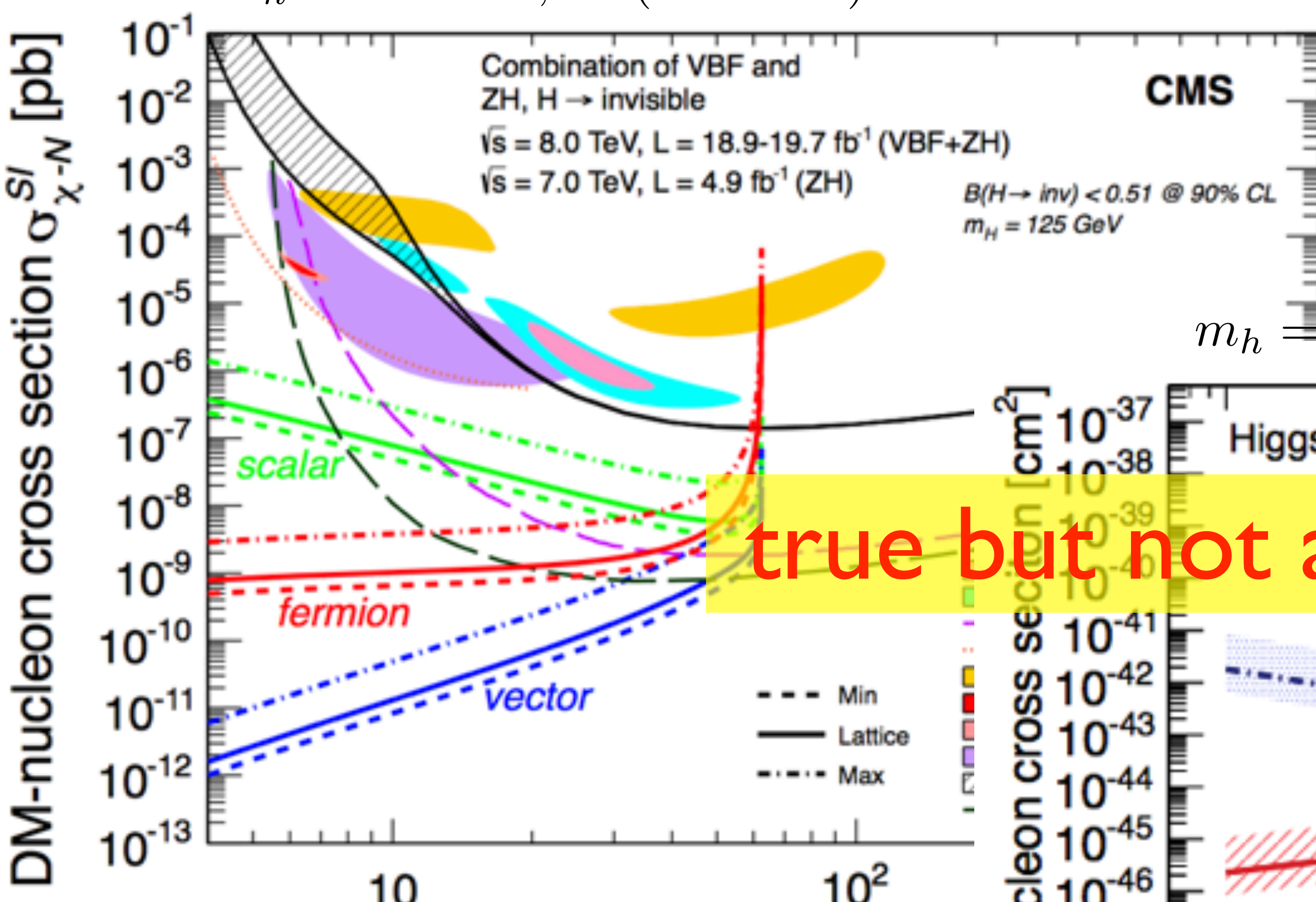
Existence of poles within the reach of CM energy
$\Rightarrow$ suppression of signals, compared to
(i) contact interaction
(ii) single heavy mediator

For more details and difference between EFT (& simplified models) and a UV completion, see "S. Baek, P. Ko, M. Park, WIP, & C. Yu, arXiv:1506.06556"

- Extra para. in the collider - direct detection connection

In models of Higgs portal in EFT

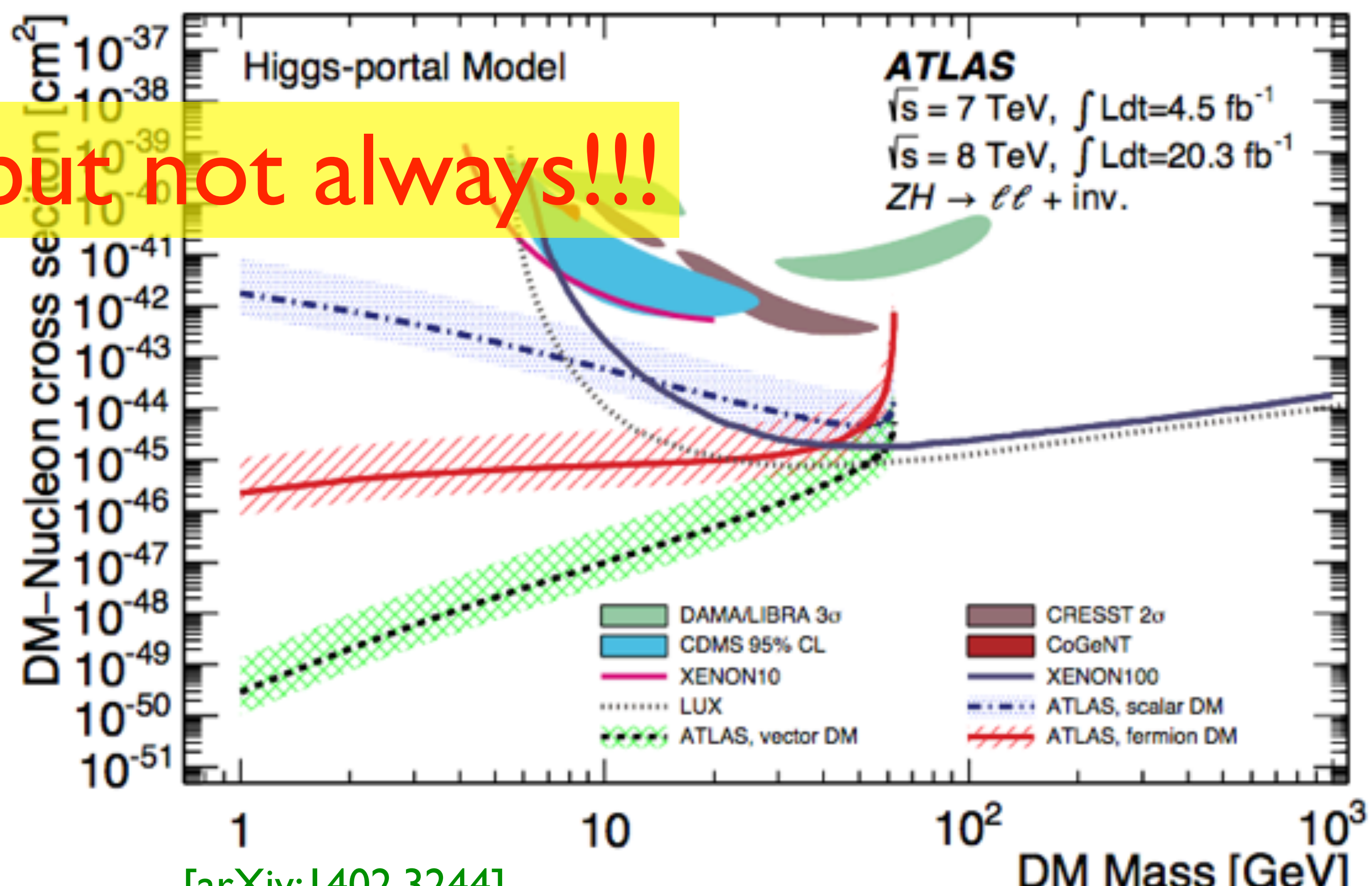
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[arXiv:1404.1344]

$m_h = 125.5\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.52 \text{ at } 90\% \text{ CL}$

true but not always!!!



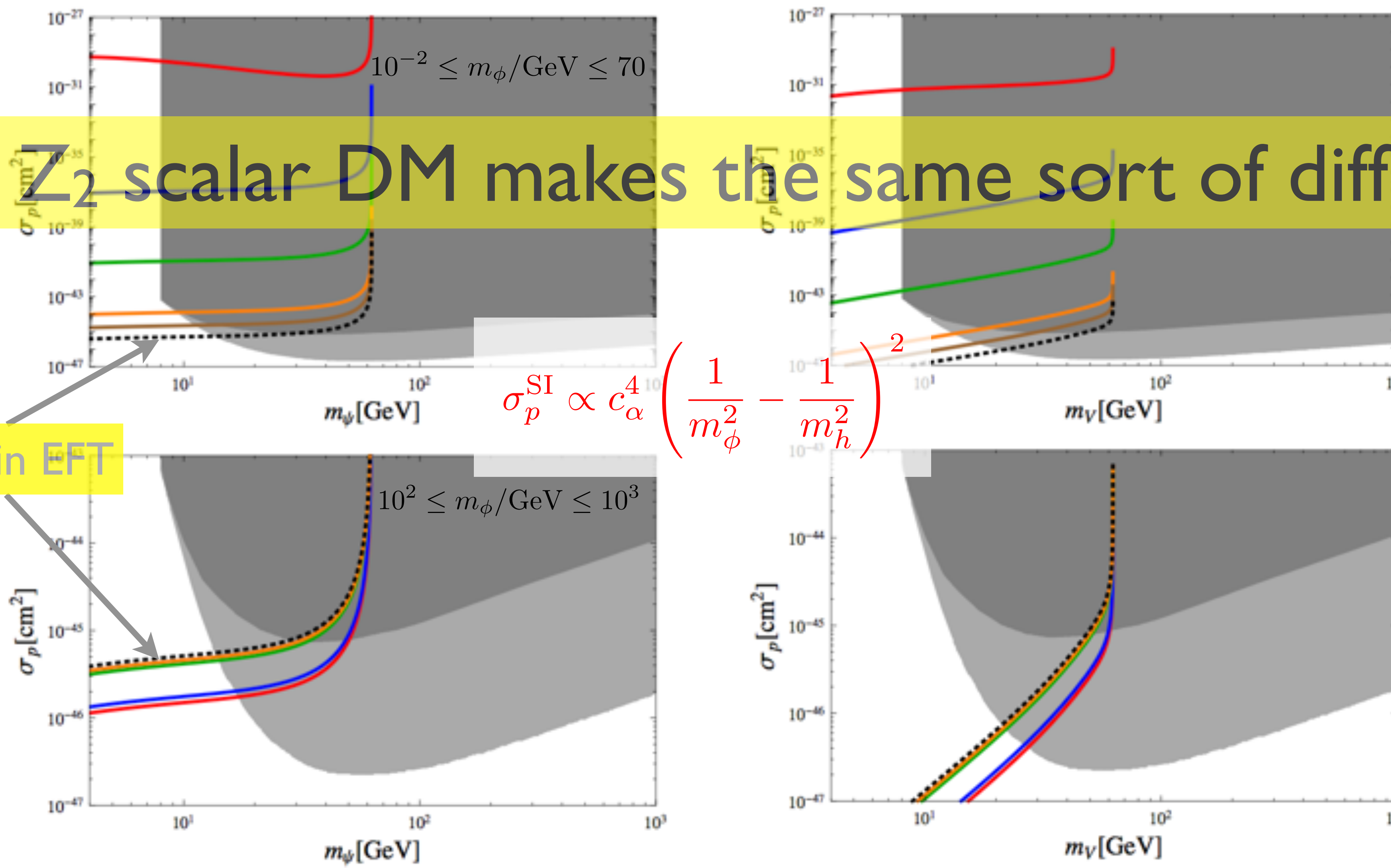
[arXiv:1402.3244]

In renorm. gauge invariant Higgs portal,

[arXiv: 1405.3530, Seungwon Baek, P. Ko & WIP]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$



Local Z_2 scalar DM makes the same sort of difference.

Higgs portals in EFT

$$\sigma_p^{\rm SI} \propto c_\alpha^4 \left(\frac{1}{m_\phi^2} - \frac{1}{m_h^2}\right)^2$$

Conclusion

- The simplest weak scale DM scenario may be the local Z_2 scalar DM .
- it provides a simple framework to accommodate the GeV-scale galactic gamma-ray excess.
- Gauged hidden sector (containing dark Higgs) with Higgs portal interaction makes significant changes in the usual (EFT or simplified) picture of DM pheno. including collider signatures.