PIKIO workshop, Ohio State University

Secluded singlet fermionic dark matter driven by the Fermi gamma-ray excess

Seodong Shin

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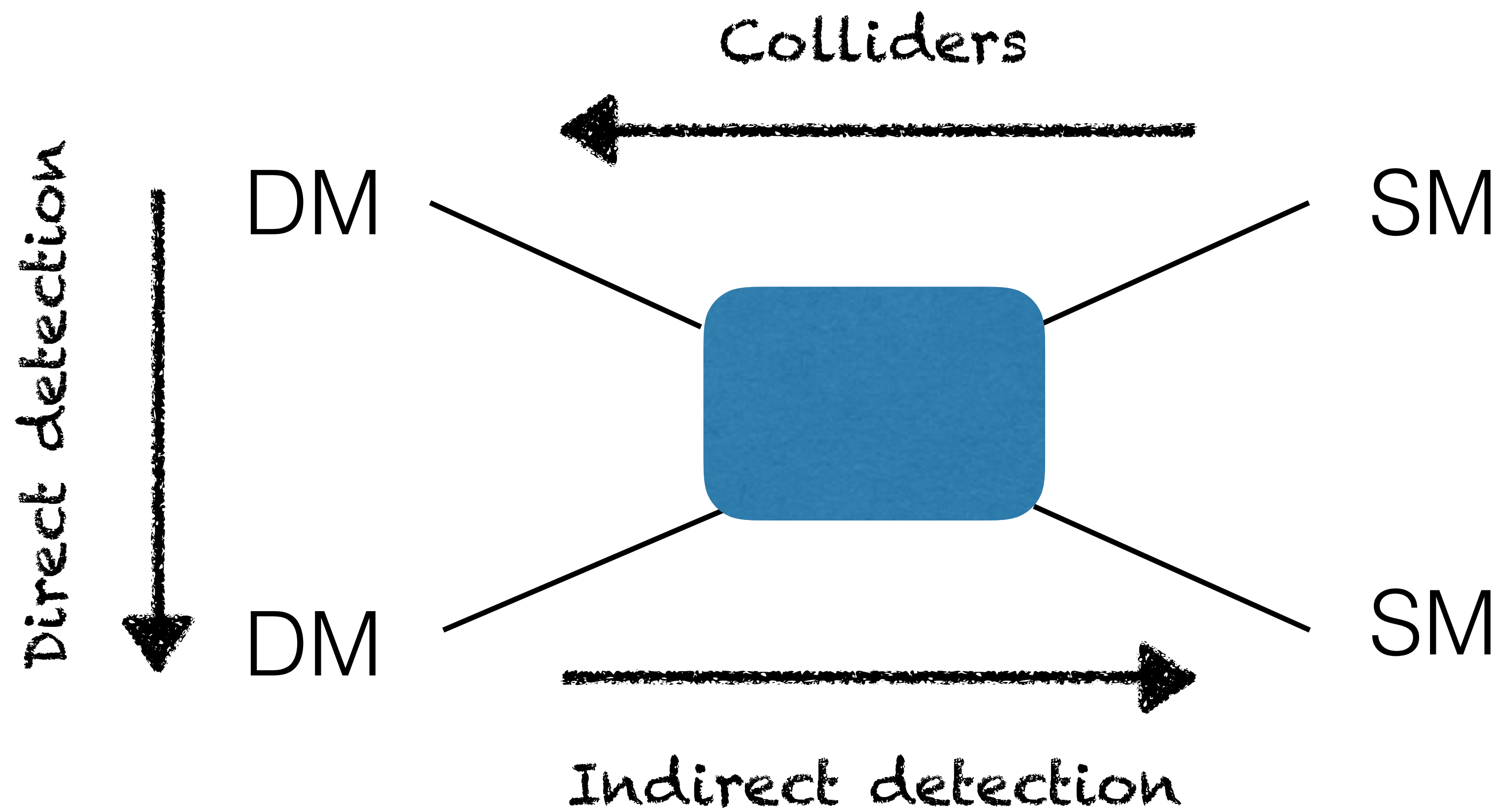
Young Gyun Kim, Kang Young Lee, Chan Beom Park, Seodong Shin,
Phys. Rev. D93, 075023 (2016) [arXiv:1601.05089]

Dark Matter and new physics

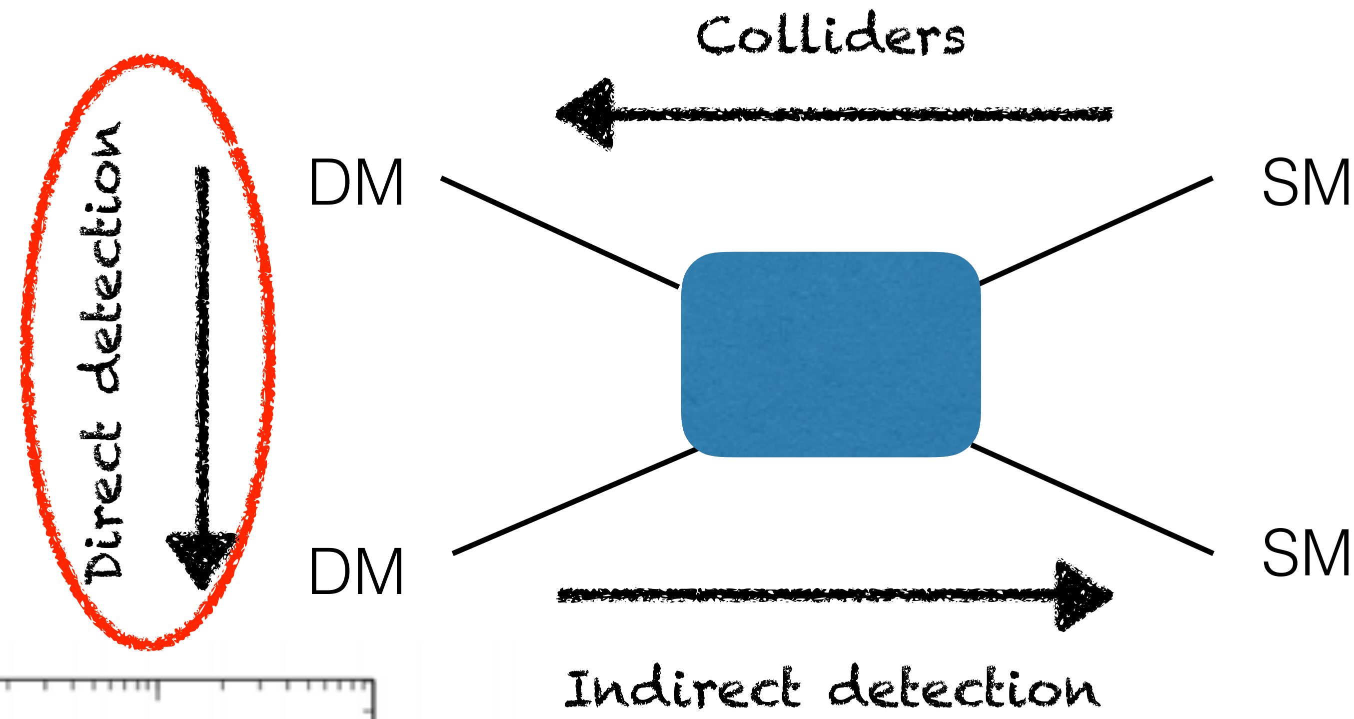
- About 25% of our universe
- A good (empirical) motivation of new physics BSM
- Only gravitationally observed yet
- Most promising scenario is WIMP: weak int. should be observed to probe parameters (of BSM)

Search of Dark Matter



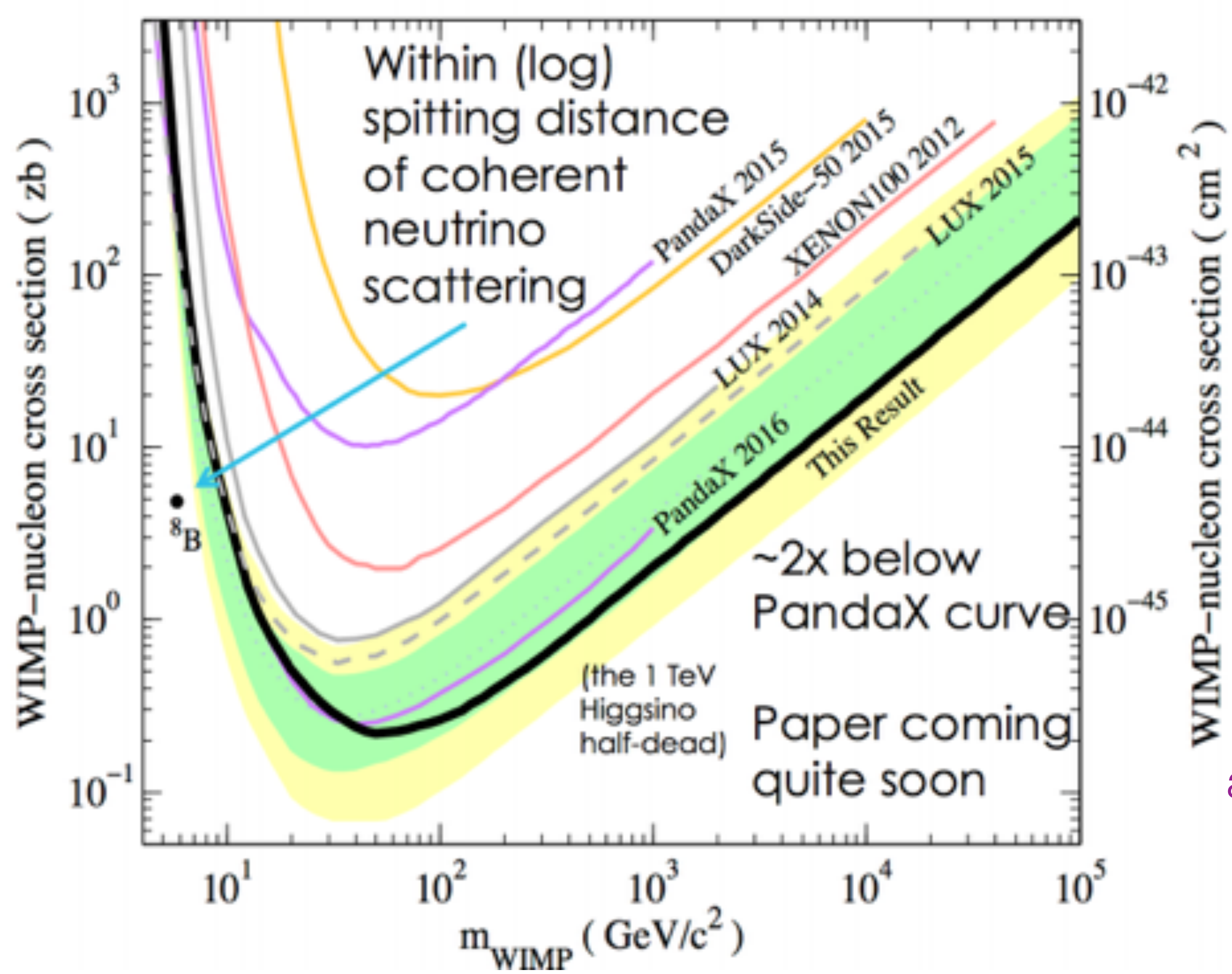
Popular diagram shown everywhere

Search of Dark Matter



Strong bounds

(Touch down a part of neutrino floor soon)

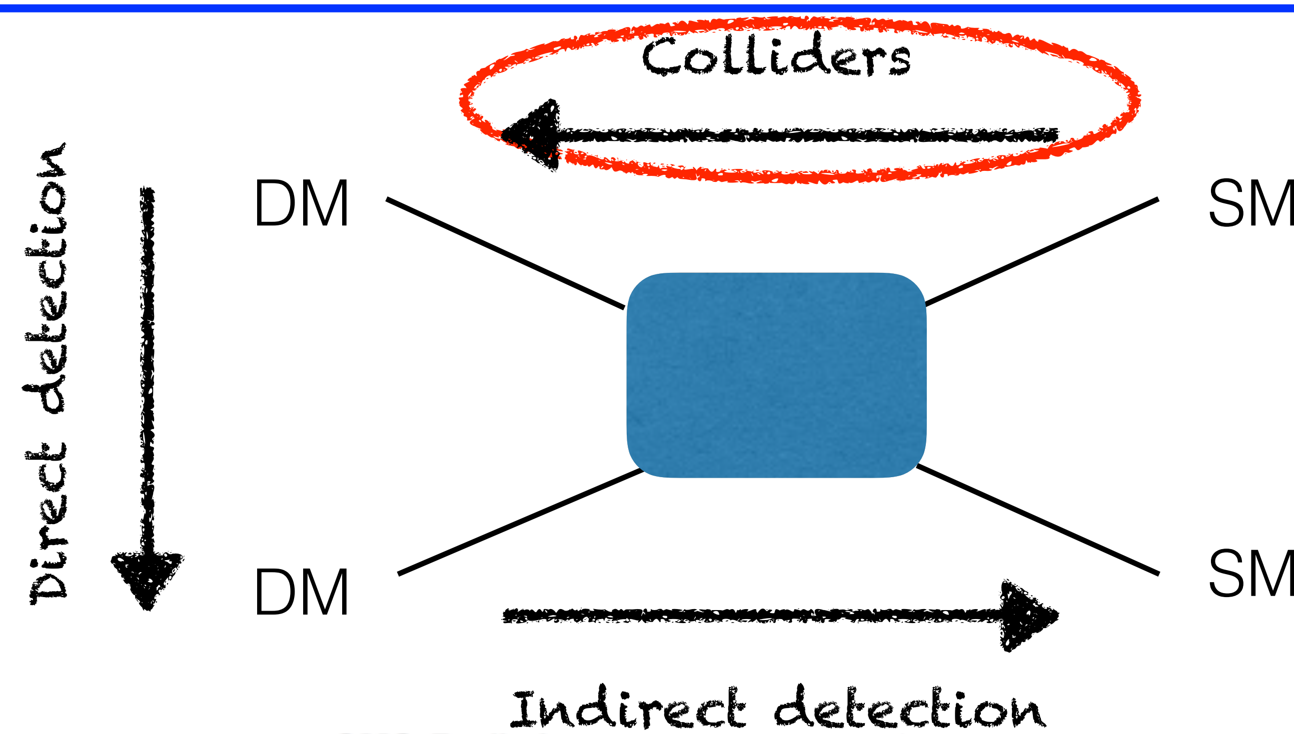


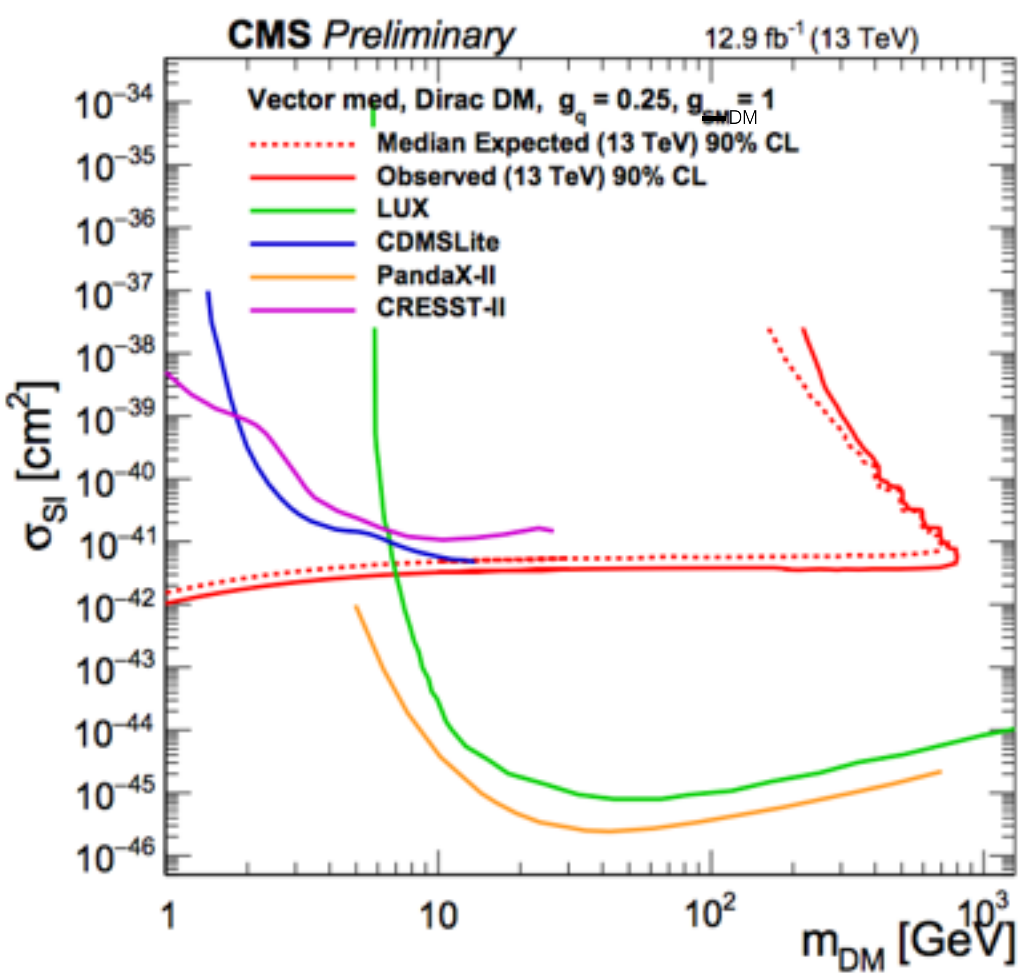
LUX 2016
arXiv:1608.07648

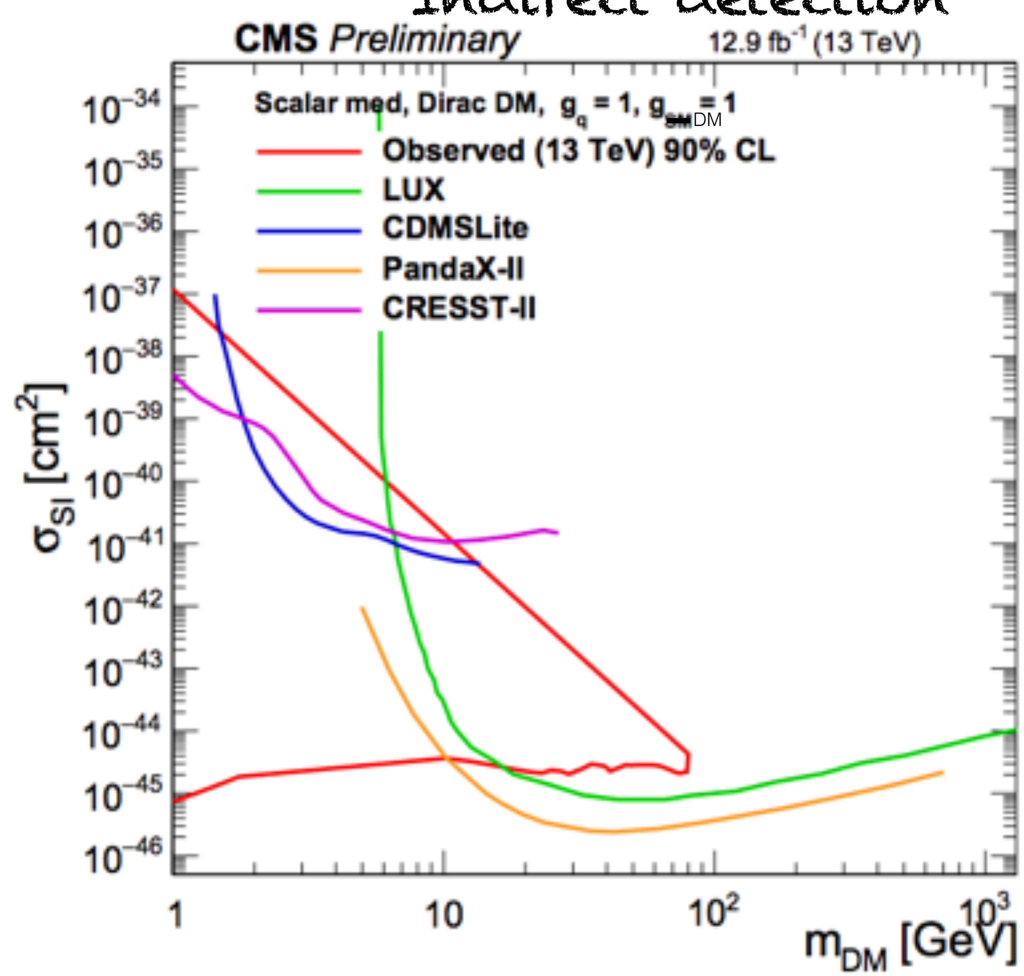
Search of Dark Matter

Strong bounds too
(mono-X)

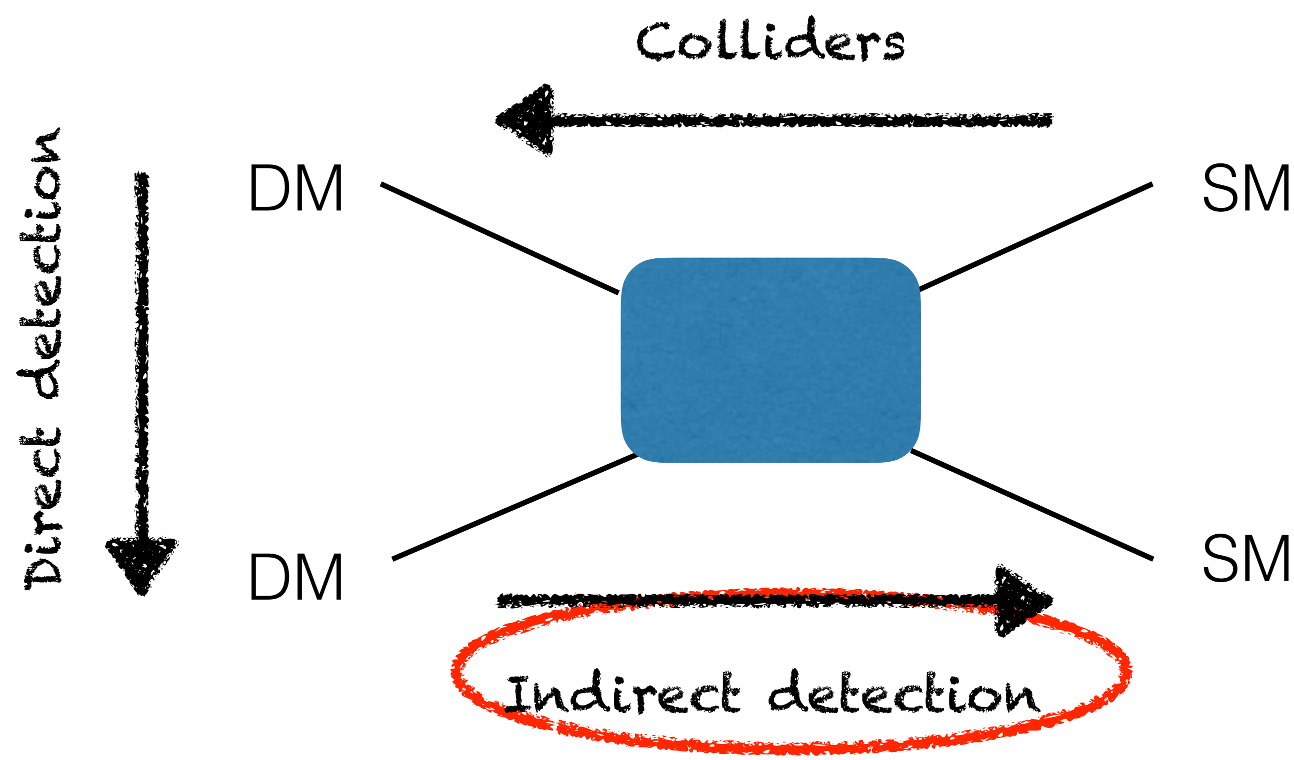
CMS, EXO-16-037-pas







Search of Dark Matter



Some (strong) bounds

- γ-rays from dSphs
- Antiproton ratios

but some hints as well (although bkg. is not fully understood)

- γ-rays from the galactic center
- Positron ratio
- Neutrino signals

Search of Dark Matter

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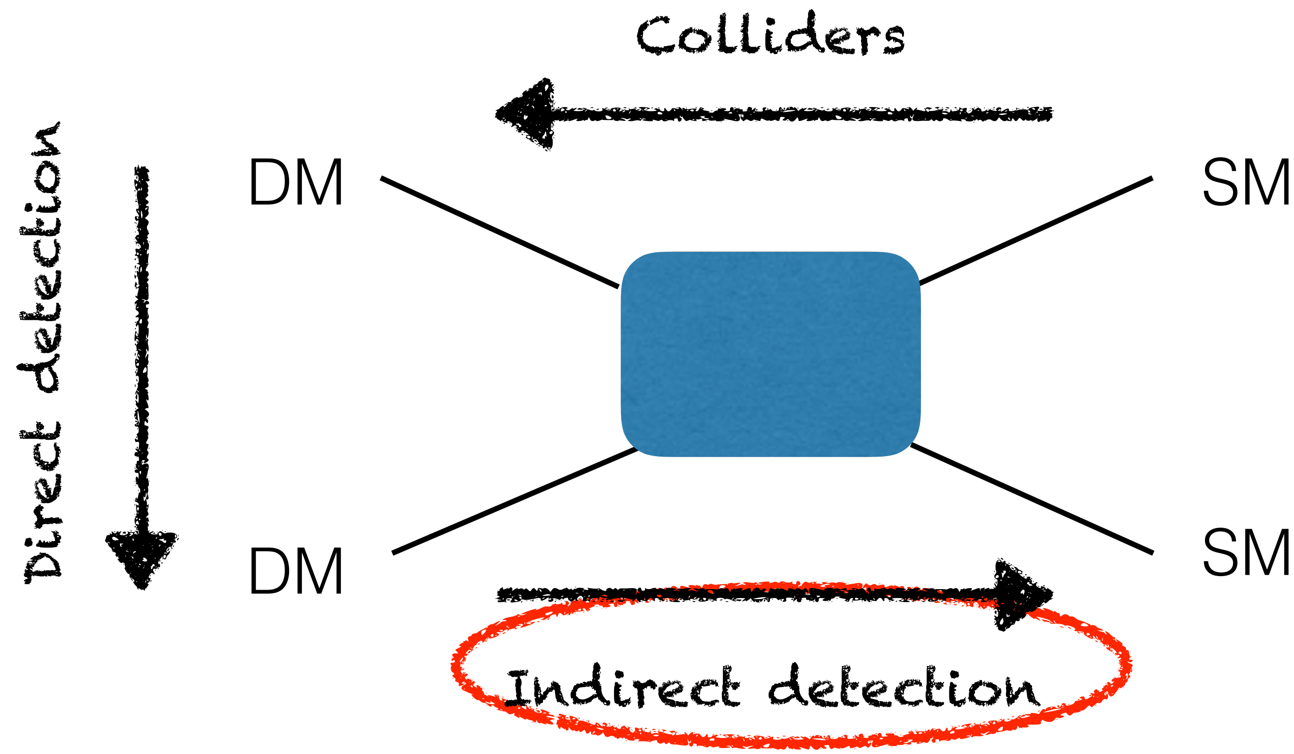

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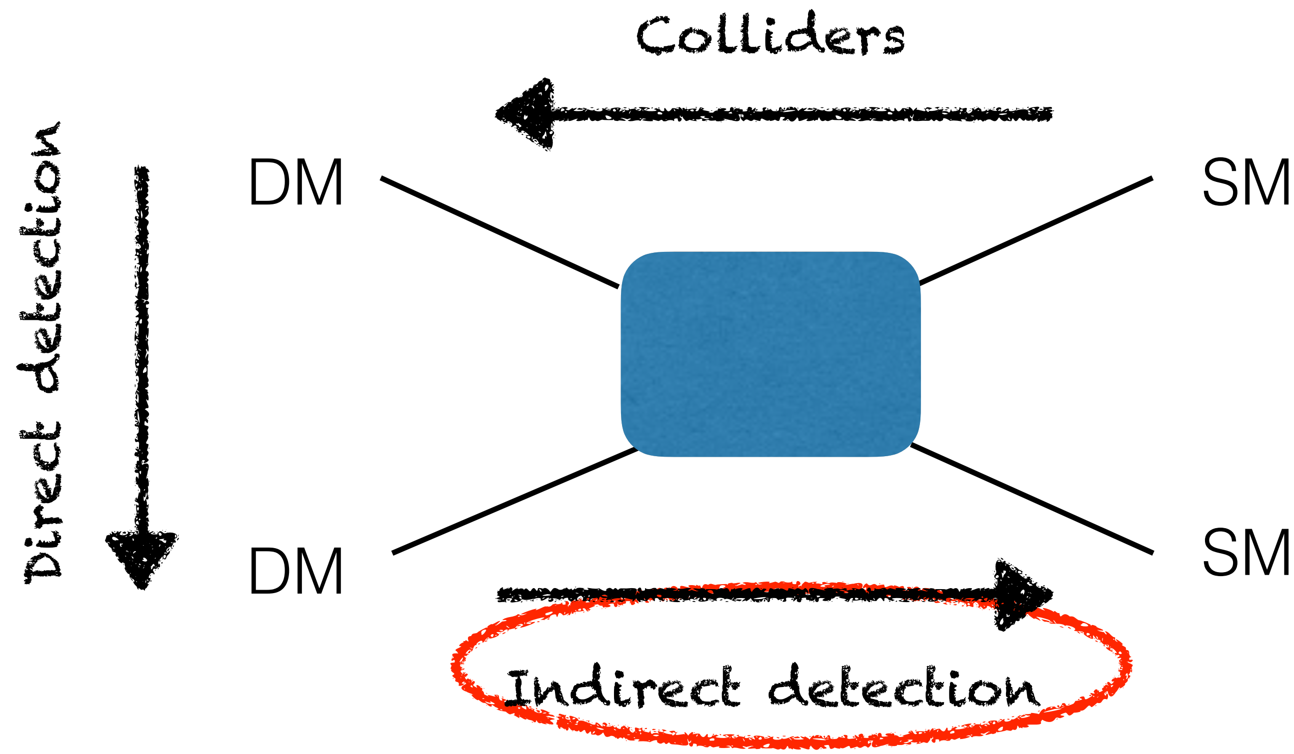
- γ-rays from the galactic center
- Positron ratio
- Neutrino signals

Why don't we start from these hints?

Search of Dark Matter: 1st step



O(GeV) broad γ-ray excess
from the galactic center

(Fermi-LAT)

GeV level γ-ray excess by Fermi-LAT

First found in 2009 (DM ann. ?) Goodenough, Hooper, 0910.2998

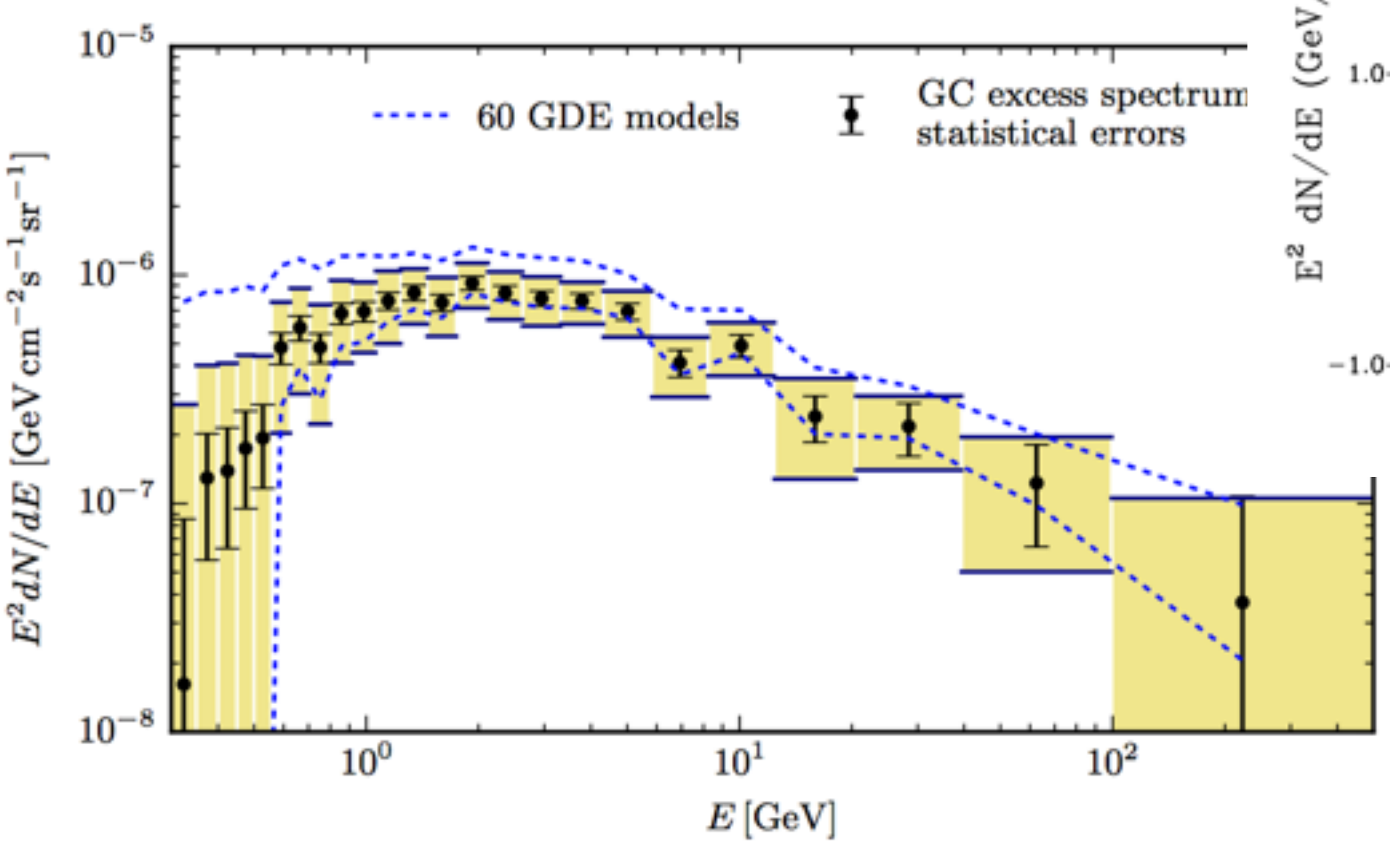
Hooper, Linden, 1110.0006

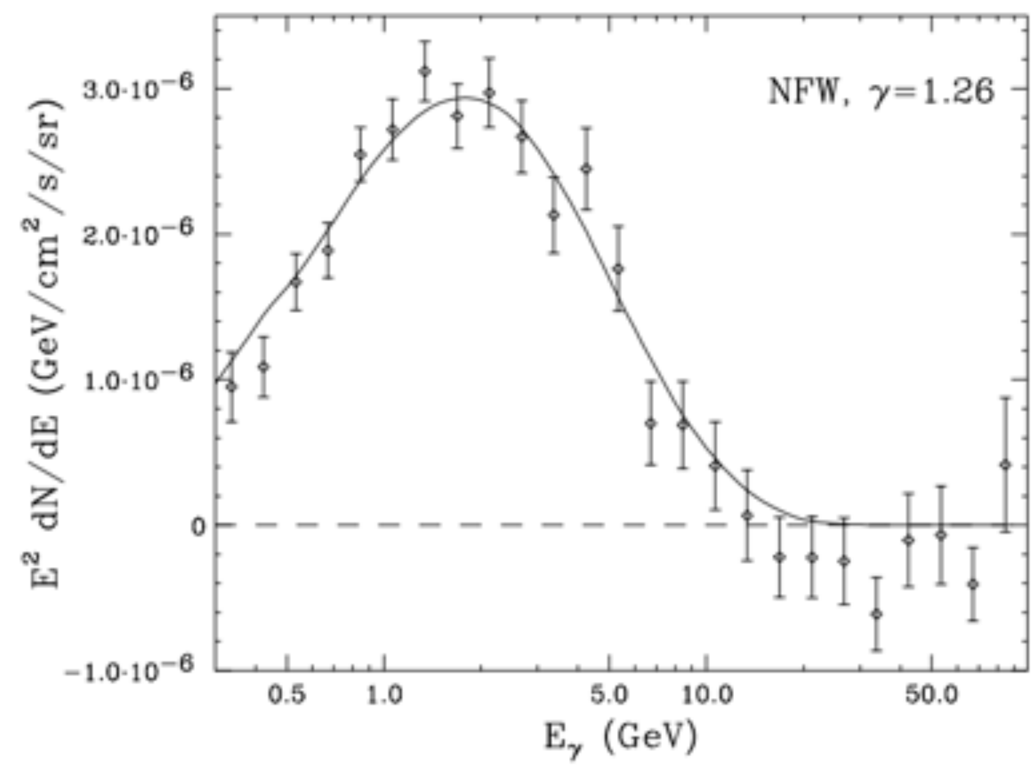
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer, 1402.6703

Calore, Cholis, Weniger, 1409.0042

Calore, Cholis, McCabe, Weniger, 1411.4647

etc.....





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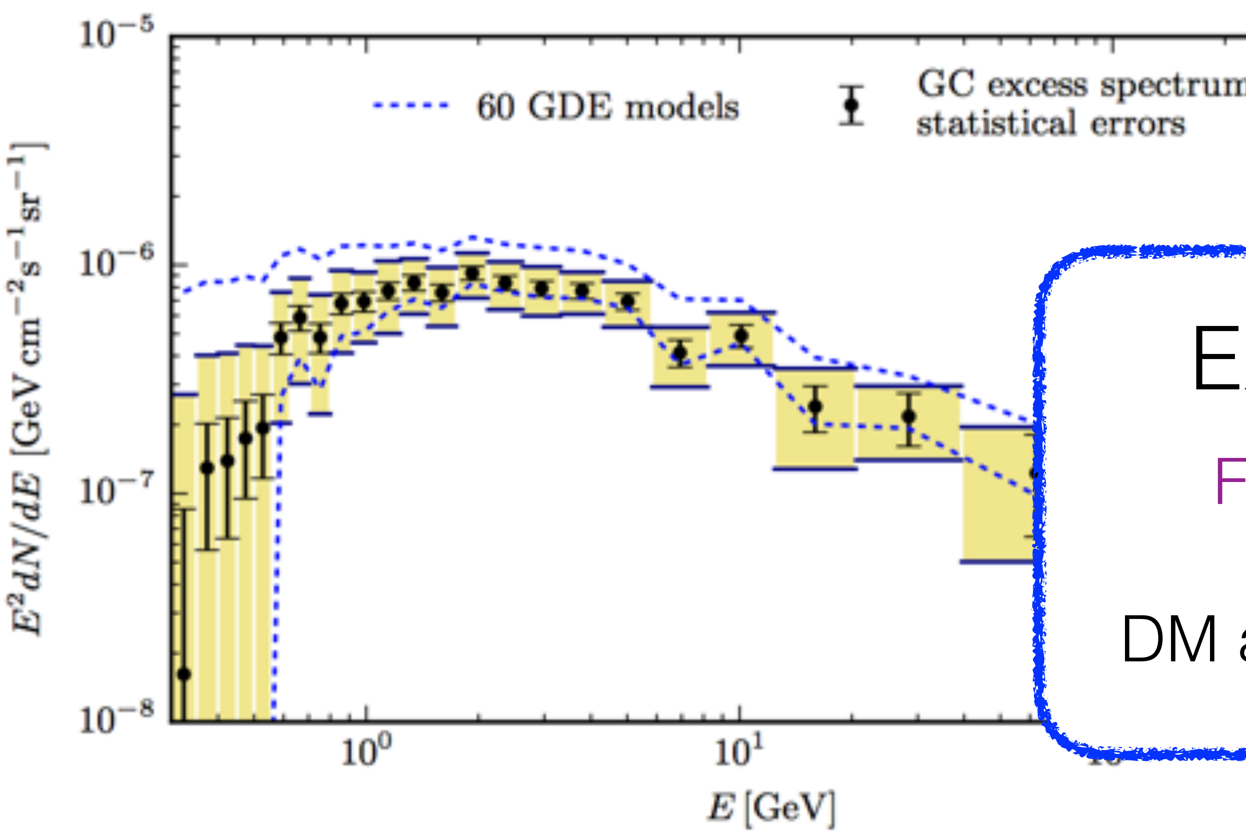

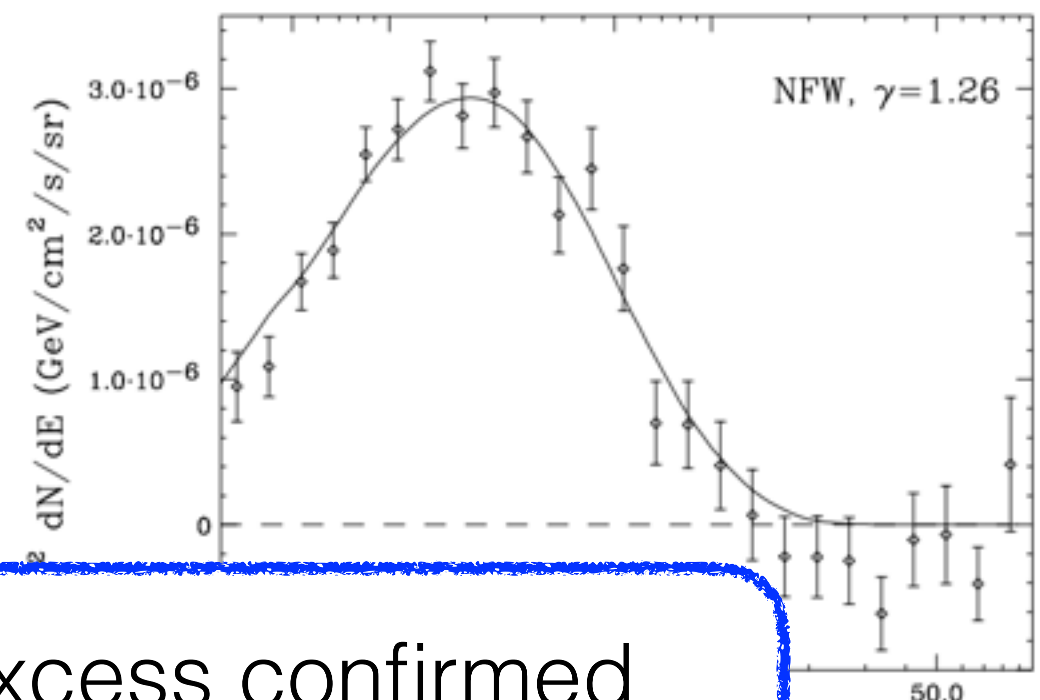

Excess confirmed

Fermi-LAT, 1511.02938

DM ann. morphology fits best

Search of Dark Matter: 1st step

O(GeV) broad γ-ray excess
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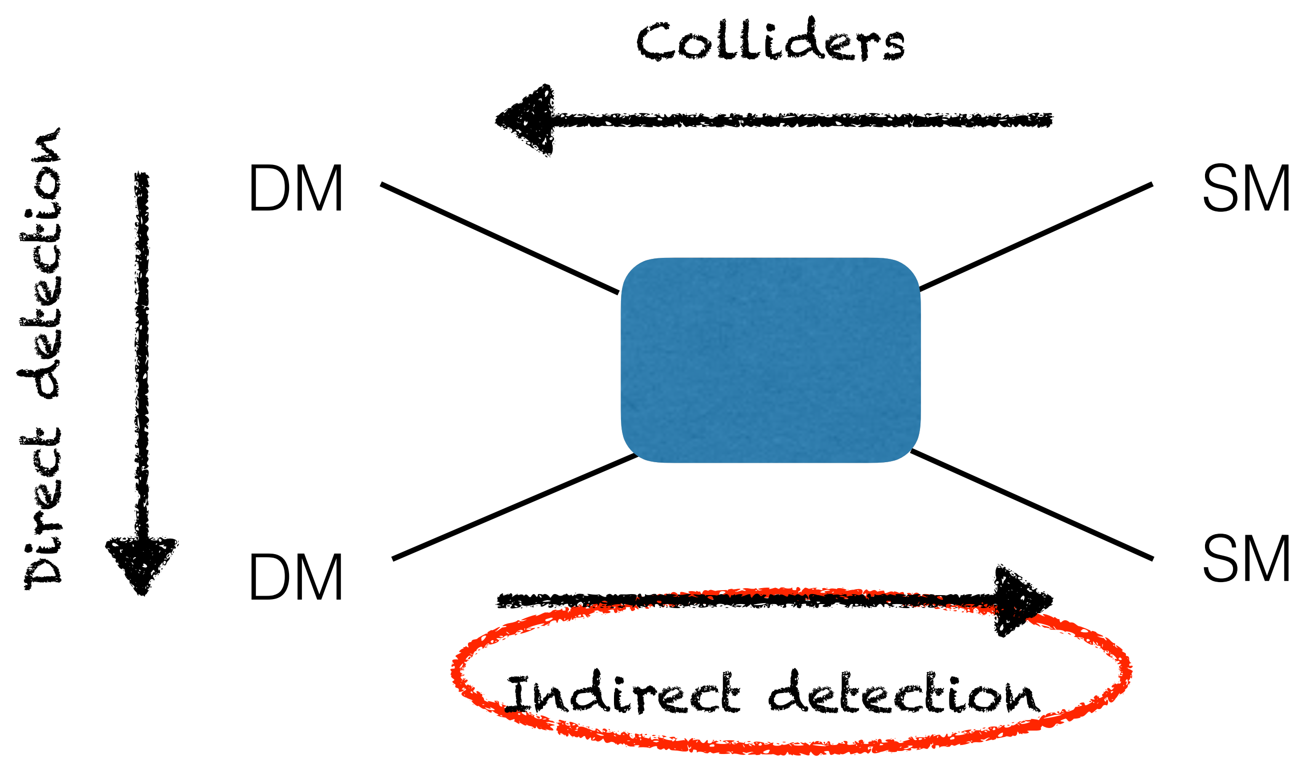


Simplified WIMP model

- Find well-fitted parameters satisfying various unavoidable experimental bounds

- Secluded set-up: avoid strong bounds from direct detection & colliders

Hidden

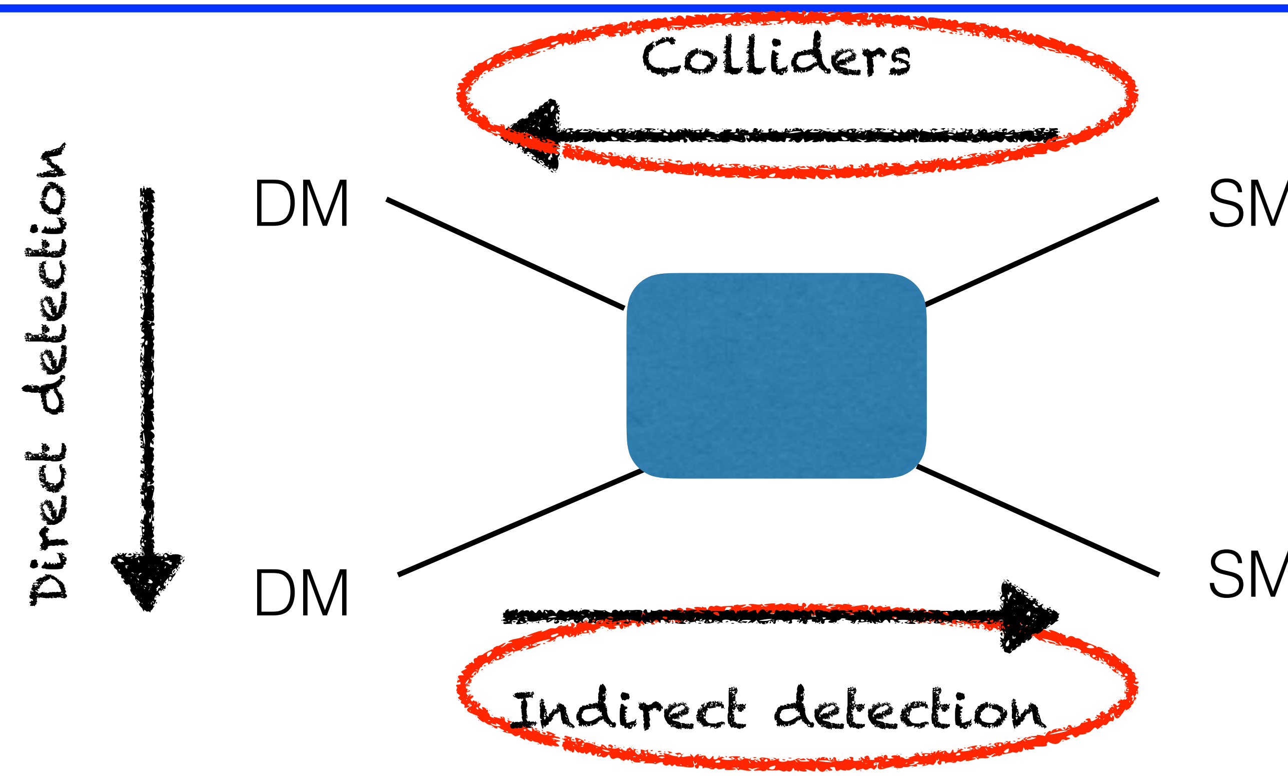
Pospelov, Ritz, Voloshin, 0711.4866

Kim, **SS**, 0901.2609 & many others……

Search of Dark Matter: 2nd step

Future prospects in colliders with the parameters in 1st step

Kim, Lee, Park, **SS**, work in progress



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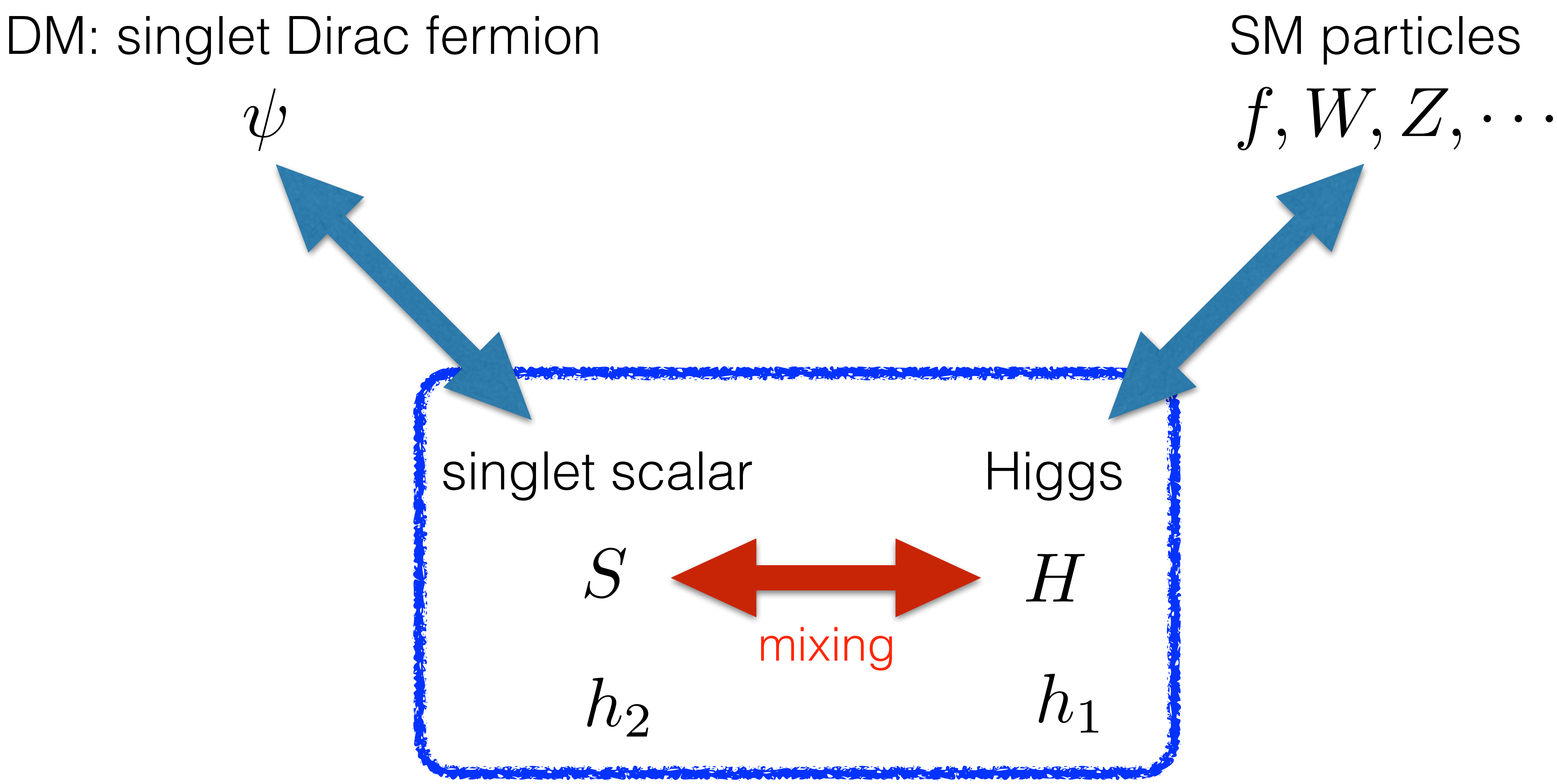
Singlet Fermionic Dark Matter



Y.G. Kim, K.Y. Lee, **SS**, JHEP 0805, 100 [arXiv:0803.2932]

A renormalizable Higgs portal WIMP model

(induce bunch of phenomenological studies: exotic decay, …)

Secluded SFDM

Secluded set-up by

- Small mixing angle: Higgs measurements at the LHC
  & null results in direct detection

- Pseudoscalar int. in the dark sector: p-wave in t-channel WIMP-SM recoil
  s-wave in s-channel

Lopez-Honorez, Schwetz, Zupan, 1203.2064

Fedderke, Chen, Kolb, Wang, 1404.2283

$$\boxed{-\mathcal{L}_{\rm int}^{\rm dark} = g_S \cos\xi \, s\bar{\psi}\psi + g_S \sin\xi \, s\bar{\psi} i\gamma^5\psi,}$$

Secluded SFDM for the γ-ray excess

Our starting point

- DM annihilation (not denying other possibilities)
- Apply the result by Calore et al., 1409.0042, 1411.4647: syst. & stat. error
- Assume a generalized NFW profile allowing the uncertainties in the astrophysical factor $\bar{J}$ with scaling [0.17, 5.3] and $\gamma = 1.2$

Calore, Cholis, McCabe, Weniger, 1411.4647

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{\bar{J}}{16\pi m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{\mathrm{d}N_\gamma^f}{\mathrm{d}E}$$

$$\bar{J} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\mathrm{l.o.s}} \rho^2(r(s,\,\psi))\, \mathrm{d}s\, \mathrm{d}\Omega,$$

Secluded SFDM for the γ-ray excess

Analysis process

- Unavoidable bounds: Higgs measurements, $\bar{p}$ ratios, γ-rays from dSphs.
- GeV level excess is best-fitted by changing $\bar{J}$ while fixing the relic density as observed (how we avoid the astrophysical bounds)
- Check the pure (dark sector) pseudoscalar case first (sinξ=1). If not good, allow the scalar interaction.

Best-fitted for $\psi\bar{\psi} \to b\bar{b},\ h_i h_j$ as model independent searches expected

$i, j = 1, 2$

But some subtleties exist

Secluded SFDM for the γ-ray excess

Reference annihilation channel & parameters

Annihilation process	m_ψ (GeV)	m_{h_2} (GeV)	
$\psi\bar{\psi} \to h_2 \to b\bar{b}$	49.82	99.416	$m_\psi < m_{h_2} < m_{h_1}$
$\psi\bar{\psi} \to h_2 \to h_1 h_1$	127.5	213.5	$m_\psi \sim m_{h_1}$
$\psi\bar{\psi} \to h_2 \to h_2 h_2,\ h_1 h_2$	127.5	125.7	$m_\psi \sim m_{h_1}$
$\psi\bar{\psi} \to h_2 \to h_2 h_2$	69.2	35.7	$m_{h_2} < m_\psi < m_{h_1}$

cascade

Lots of model independent searches expected these channels

Agrawal, Batell, Fox, Harnik, 1411.2592

Dutta, Gao, Ghosh, Strigari, 1508.05989

Elor, Rodd, Slatyer, 1503.01773

many many others……..

$\psi\bar{\psi} \to h_2 \to b\bar{b}$

Inv. Higgs decay

$g_S \sin\theta_s \lesssim 0.02$

Resonance required

$\langle\sigma v\rangle_{\text{ann.}}$ too high

~~γ-rays from dSphs (Fermi-LAT)~~

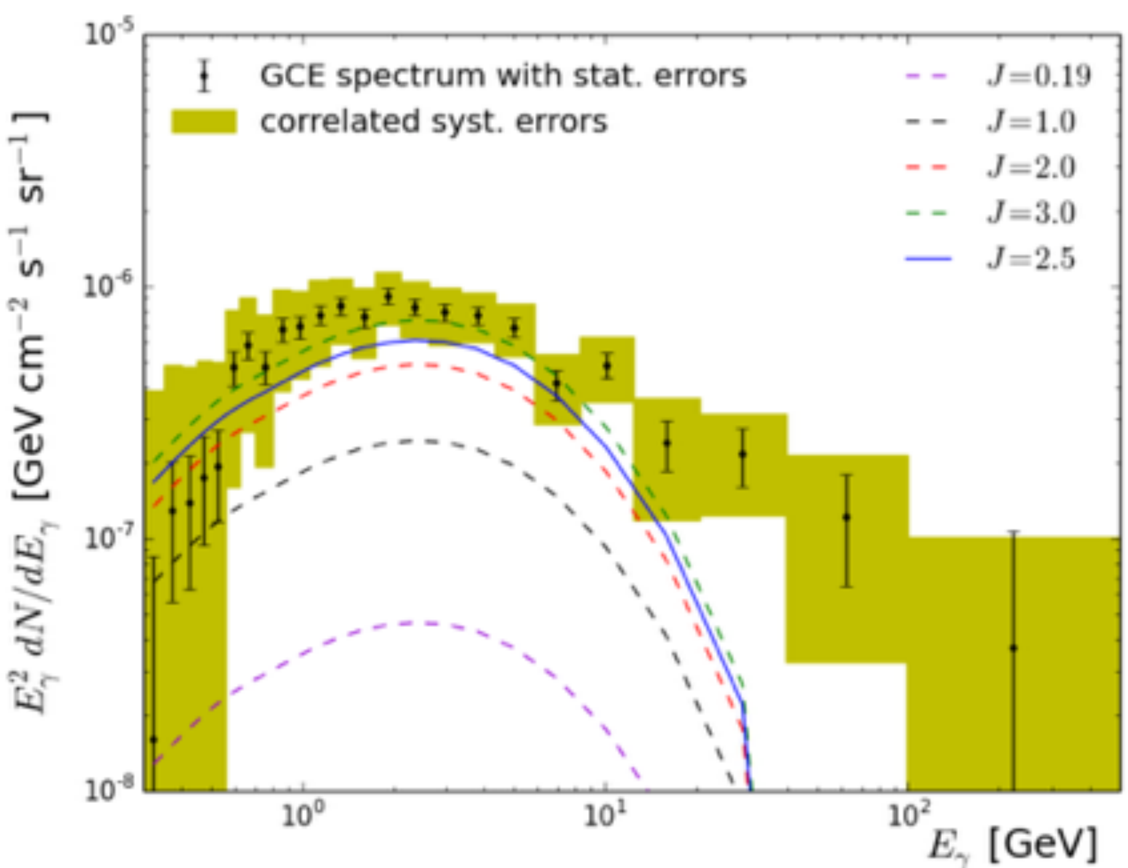
~~$\bar{p}$ ratios (PAMELA, AMS-02)~~

with scalar int.

$\sin\xi \neq 1$

Direct detection OK

$\because$ mixing angle small



Almost scalar $\sin\xi = 0.01$

$\chi^2 = 23.65$

Fits well but fine tuned (around resonance)

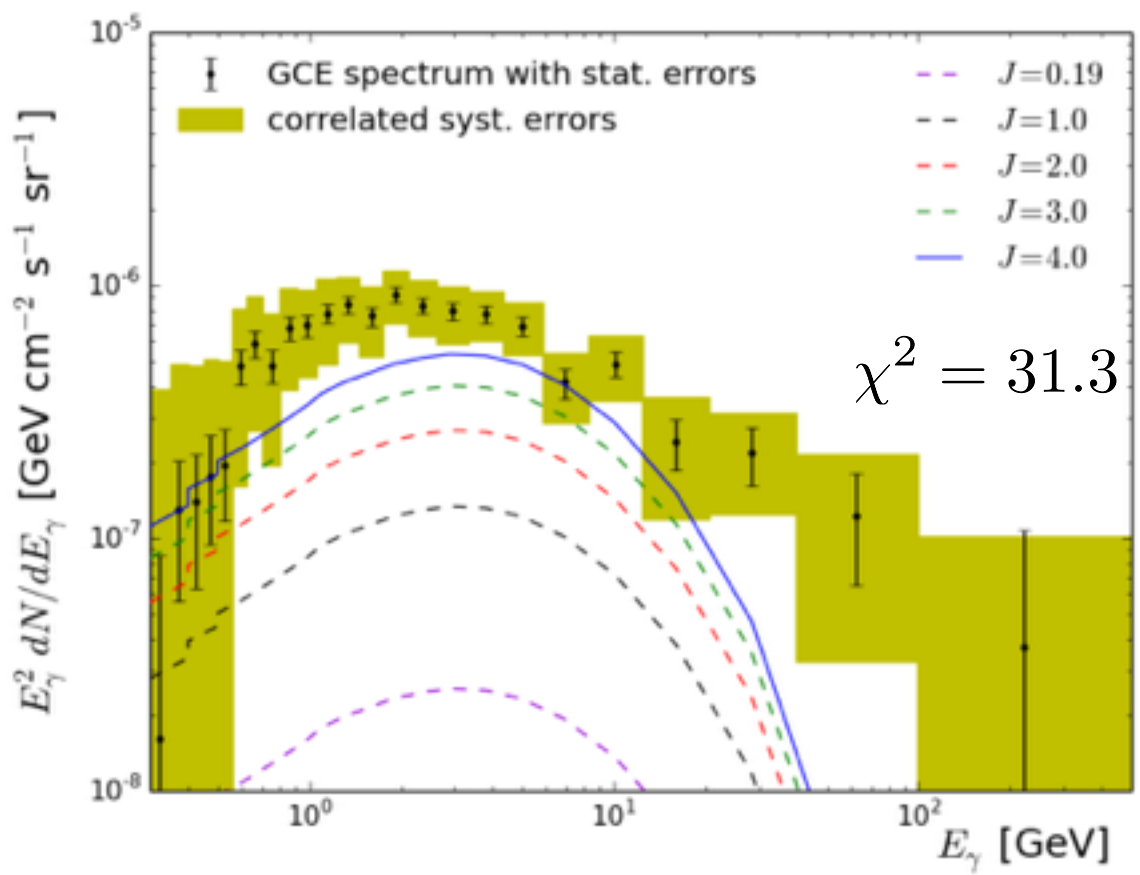
$m_\psi \gtrsim 125\,\mathrm{GeV}$

- Compete with ann. rate to WW, ZZ (bad fit):
  Need large cubic scalar self-couplings for a better fit

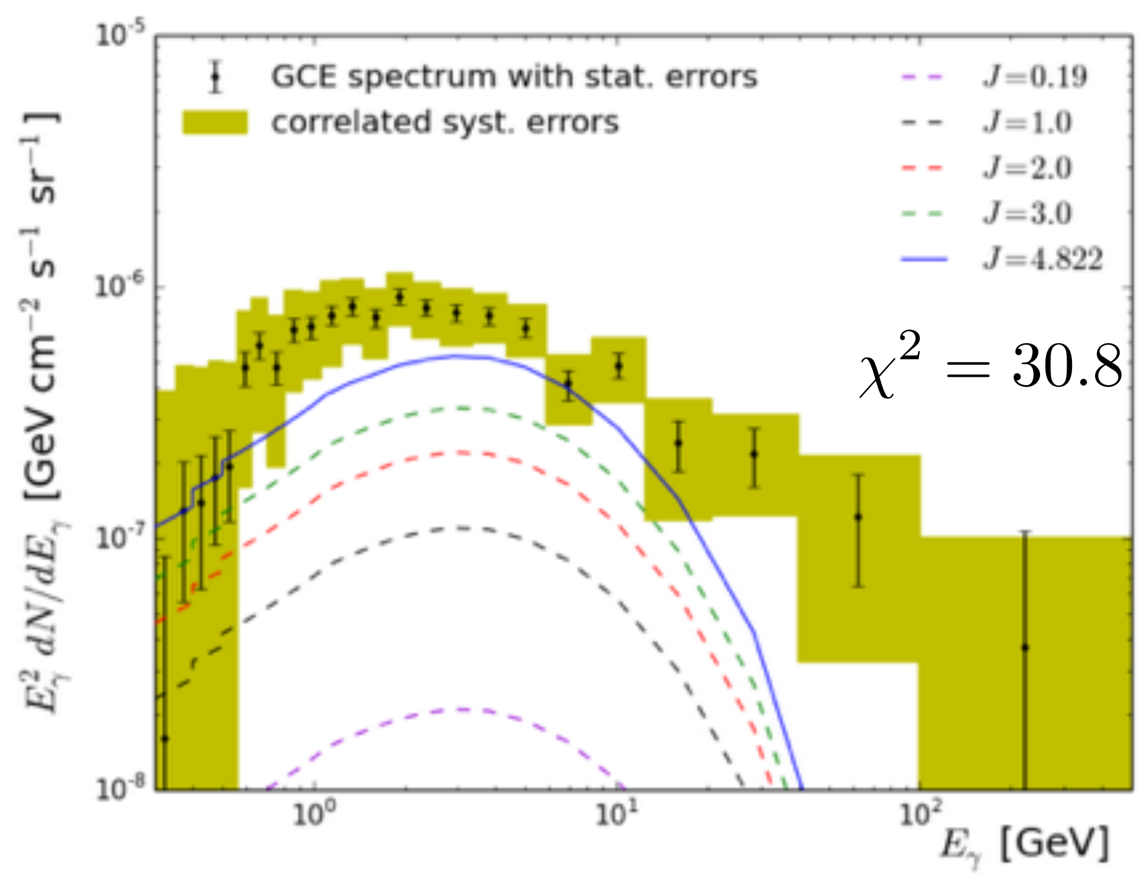
- Astrophysical bounds are weak

- 0.1 level mixing angle is OK (No inv. decay of h_1)

$m_{h_2} > 125\,\mathrm{GeV}\ , \psi\bar{\psi} \to h_2 \to h_1 h_1$



$m_{h_2} \sim 125\,\mathrm{GeV}\ , \psi\bar{\psi} \to h_2 \to h_1 h_2, h_i h_i$



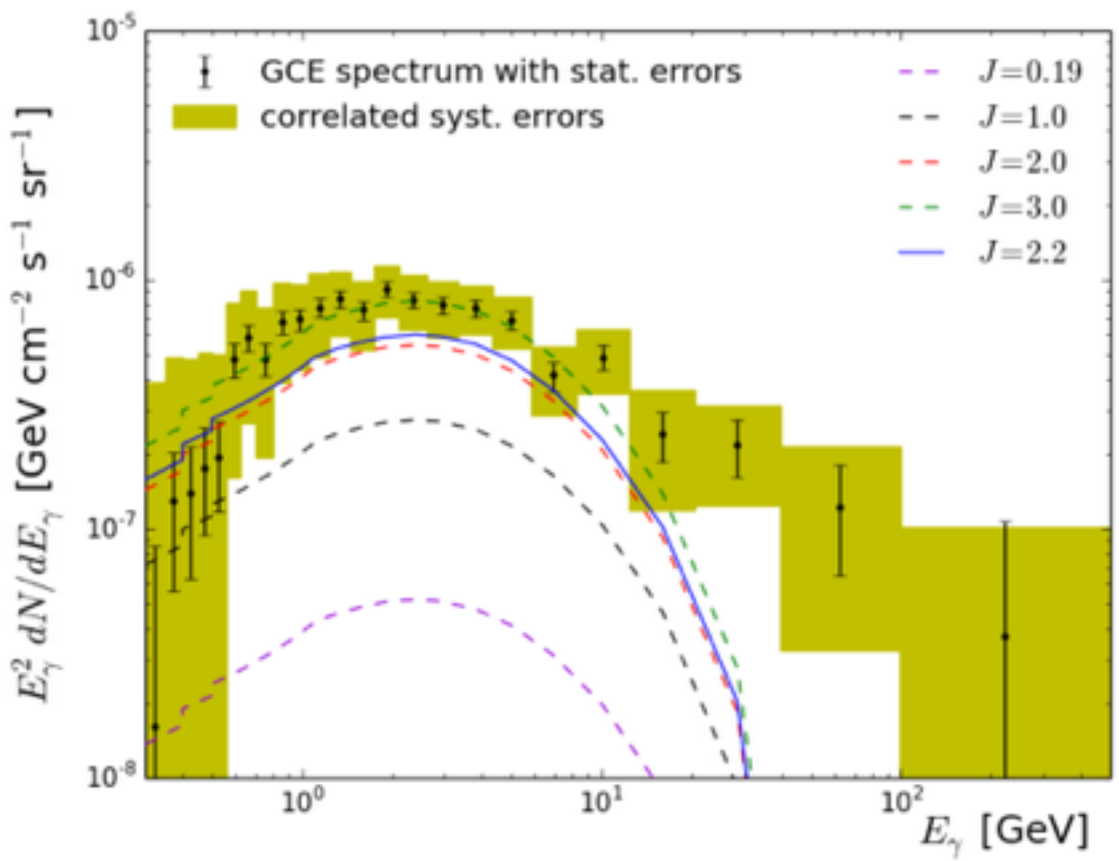
$\psi\bar{\psi} \to h_2 \to h_2 h_2$

- Bound from exotic Higgs decay $h_1 \to h_2 h_2 \to 4b$ if h_2 light

- Astrophysical bounds for 4b final states: weaker than 2b

Cline et al., 1503.08213
Dutta et al., 1508.05989

- Ann. rate into h_2h_2 can be easily ~ 100%



$$m_\psi \simeq 70\,\mathrm{GeV} \simeq \sqrt{2} \times 50\,\mathrm{GeV}$$

$$m_{h_2} \sim m_\psi/2$$

$$\chi^2 = 23.19$$

Very promising

Conclusions

- Start the probe of DM from the indirect detection result:
  Fermi GeV gamma-ray excess

- Simplified model to check the consistency with other bounds:
  Secluded Singlet Fermionic Dark Matter

- $\psi\bar{\psi} \to h_2 \to b\bar{b}$: resonance region, almost scalar int.

- $\psi\bar{\psi} \to h_2 \to h_i h_j$: cascade process, best when $\psi\bar{\psi} \to h_2 h_2$
  $m_\psi \simeq 70\,\mathrm{GeV}$, $m_{h_2} \simeq m_\psi/2$

- Benchmark points for future collider prospects of the model.

Back up

$$\mathcal{L}^{\mathrm{dark}} = \bar{\psi}(i\not{\partial} - m_{\psi_0})\psi + \frac{1}{2}\partial_\mu S \partial^\mu S - g_S(\cos\theta\,\bar{\psi}\psi + \sin\theta\,\bar{\psi}i\gamma^5\psi)S - V_S(S,\,H),$$

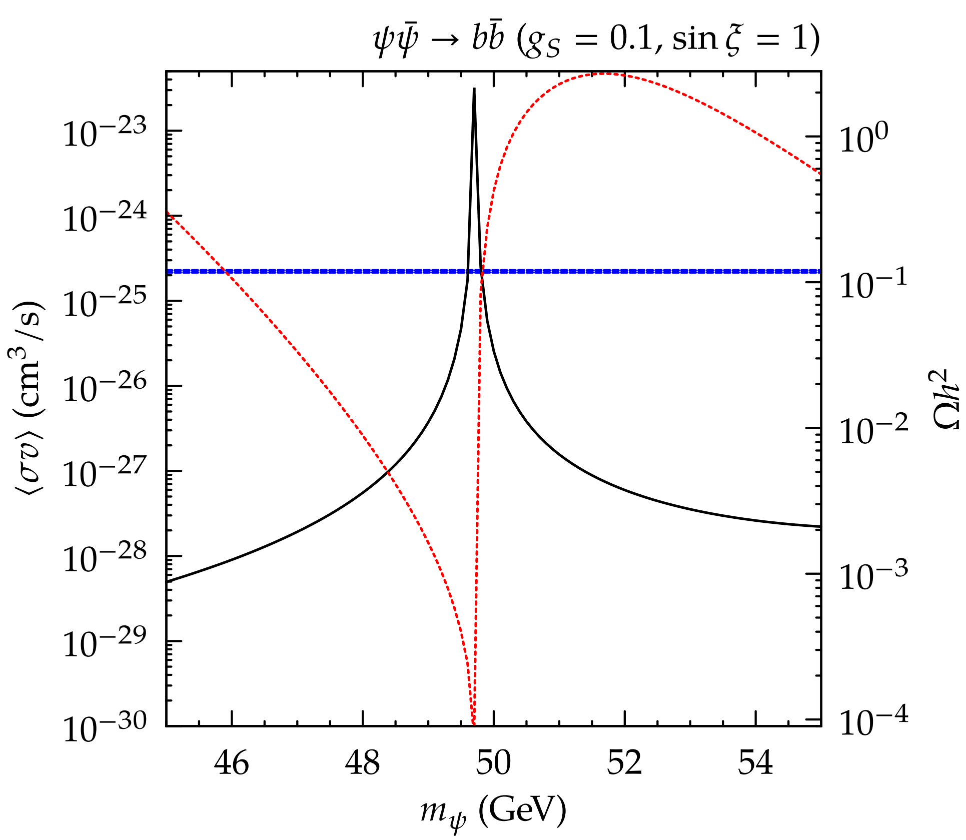
$$V_S(S,\,H) = \frac{1}{2}m_0^2 S^2 + \lambda_1 H^\dagger H S + \lambda_2 H^\dagger H S^2 + \frac{\lambda_3}{3!}S^3 + \frac{\lambda_4}{4!}S^4.$$

$$\boxed{-\mathcal{L}_{\mathrm{int}}^{\mathrm{dark}} = g_S \cos\xi\, s\bar{\psi}\psi + g_S \sin\xi\, s\bar{\psi}i\gamma^5\psi,}$$

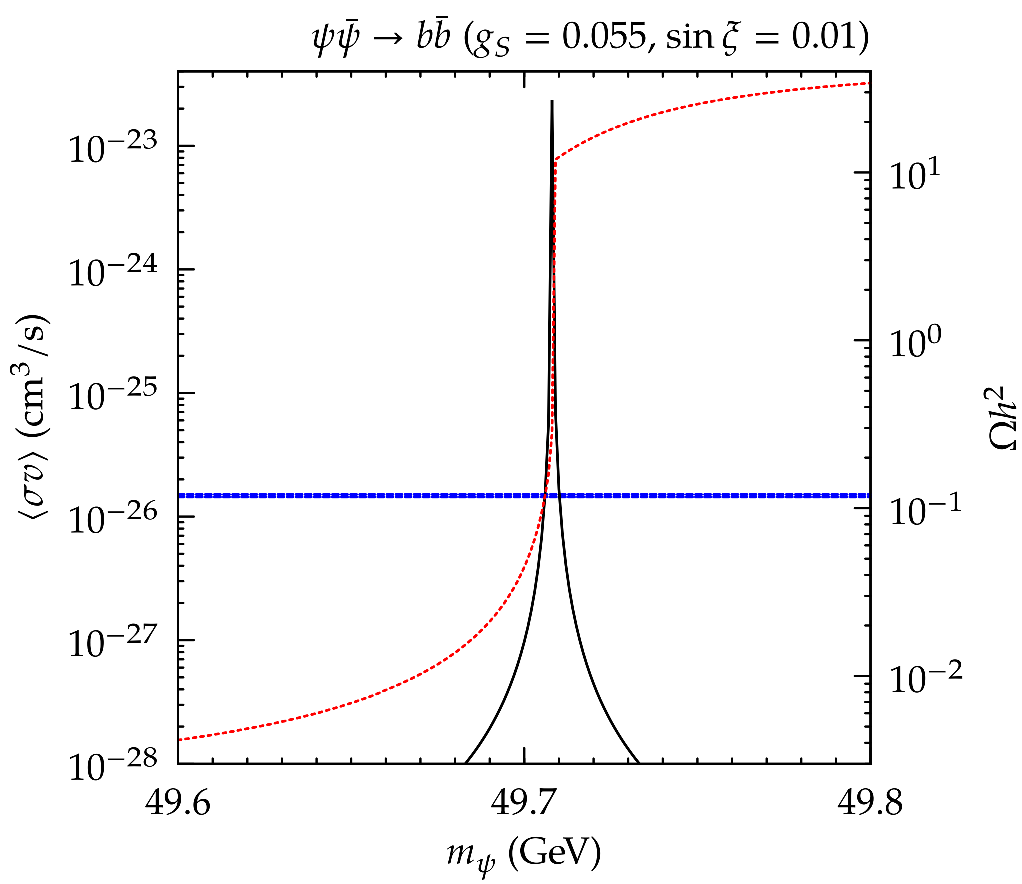
$$\cos\xi = \frac{m_{\psi_0}\cos\theta + g_S v_s}{m_\psi},$$
$$\sin\xi = \frac{m_{\psi_0}\sin\theta}{m_\psi}.$$

$$m_\psi = \sqrt{(m_{\psi_0} + g_S v_s \cos\theta)^2 + g_S^2 v_s^2 \sin^2\theta}$$

Back up



$\psi\bar{\psi} \to b\bar{b}$ ($g_S = 0.1, \sin\xi = 1$)
$\langle \sigma v \rangle$ (cm^3/s)
Ωh^2
m_ψ (GeV)



$\psi\bar{\psi} \to b\bar{b}$ ($g_S = 0.055, \sin\xi = 0.01$)
$\langle \sigma v \rangle$ (cm^3/s)
Ωh^2
m_ψ (GeV)

Back up

Cubic self-couplings of scalars

c_{ijk} for $h_i h_j h_k$ interactions

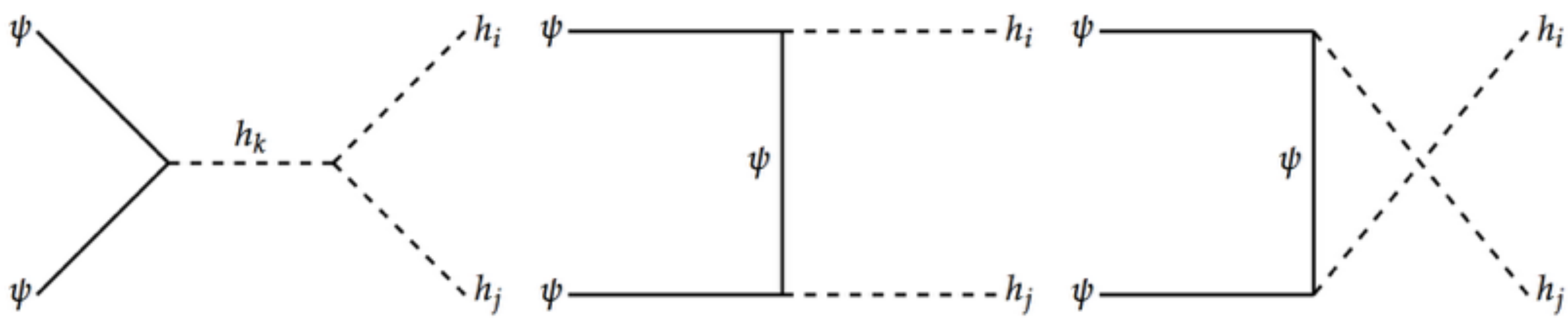
$$
\begin{aligned}
c_{111} =& \, 6\lambda_0 v_h \cos^3\theta_s + (3\lambda_1 + 6\lambda_2 v_s)\cos^2\theta_s \sin\theta_s + 6\lambda_2 v_h \cos\theta \sin^2\theta_s + (\lambda_3 + \lambda_4 v_s)\sin^3\theta_s, \\
c_{112} =& -6\lambda_0 v_h \cos^2\theta_s \sin\theta_s + 2\lambda_2 v_h \left(2\cos^2\theta_s \sin\theta_s - \sin^3\theta_s\right) \\
& + (\lambda_1 + 2\lambda_2 v_s)\left(\cos^3\theta_s - 2\cos\theta_s \sin^2\theta_s\right) + (\lambda_3 + \lambda_4 v_s)\cos\theta_s \sin^2\theta_s, \\
c_{122} =& \, 6\lambda_0 v_h \cos\theta_s \sin^2\theta_s + 2\lambda_2 v_h \left(\cos^3\theta_s - 2\cos\theta_s \sin^2\theta_s\right) \\
& - (\lambda_1 + 2\lambda_2 v_s)\left(2\cos^2\theta_s \sin\theta_s - \sin^3\theta_s\right) + (\lambda_3 + \lambda_4 v_s)\cos^2\theta_s \sin\theta_s, \\
c_{222} =& -6\lambda_0 v_h \sin^3\theta_s + (3\lambda_1 + 6\lambda_2 v_s)\sin^2\theta_s \cos\theta_s - 6\lambda_2 v_h \sin\theta \cos^2\theta_s \\
& + (\lambda_3 + \lambda_4 v_s)\cos^3\theta_s.
\end{aligned}
$$

0 if

$\sin\theta_s = 0$

Back up

Cascade decays of the Higgs bosons



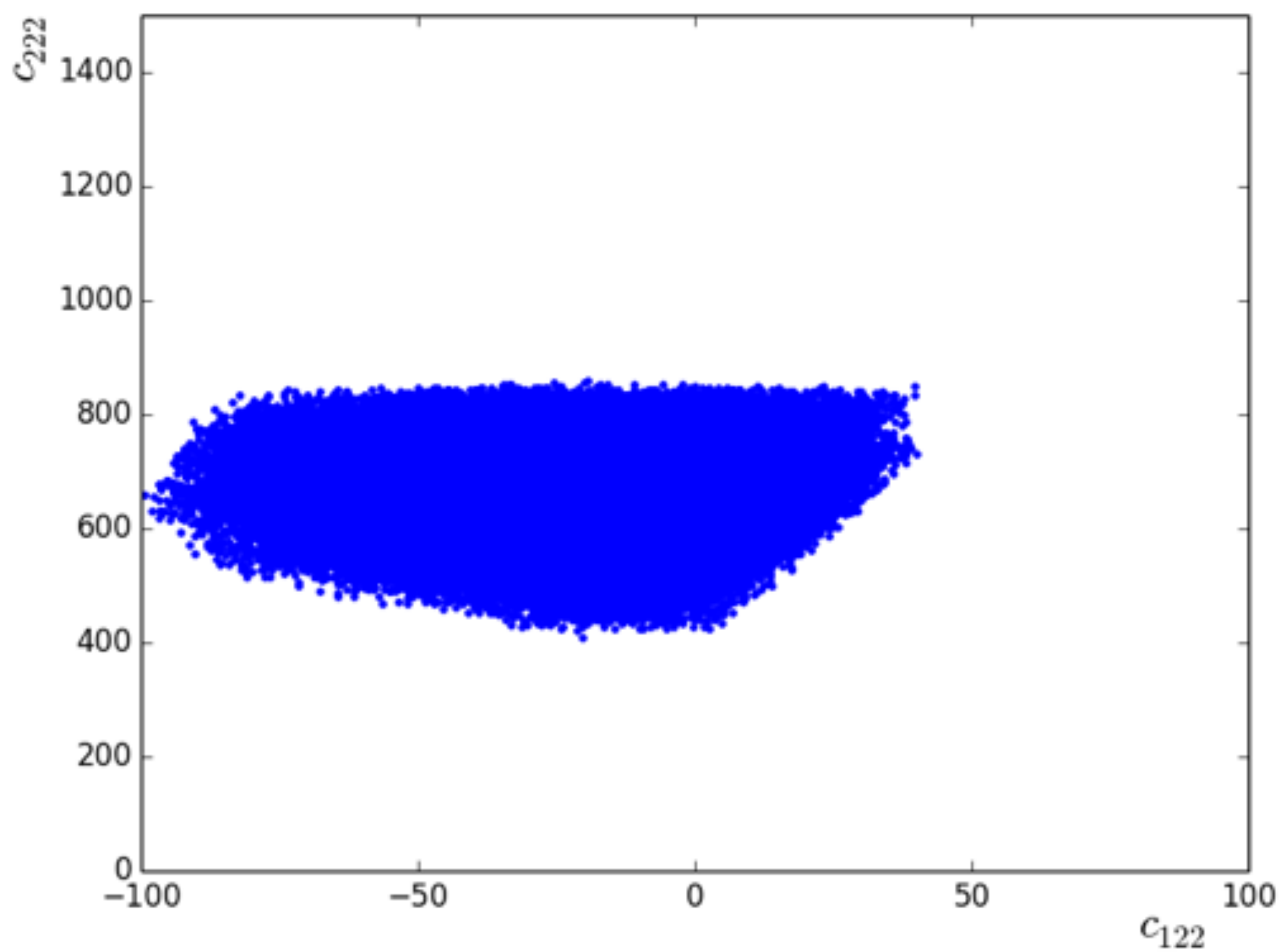
In the zero velocity limit

$\sigma v = 0$ for pure scalar case $\sin\xi = 0$

Only s-channel survives for pure pseudoscalar case

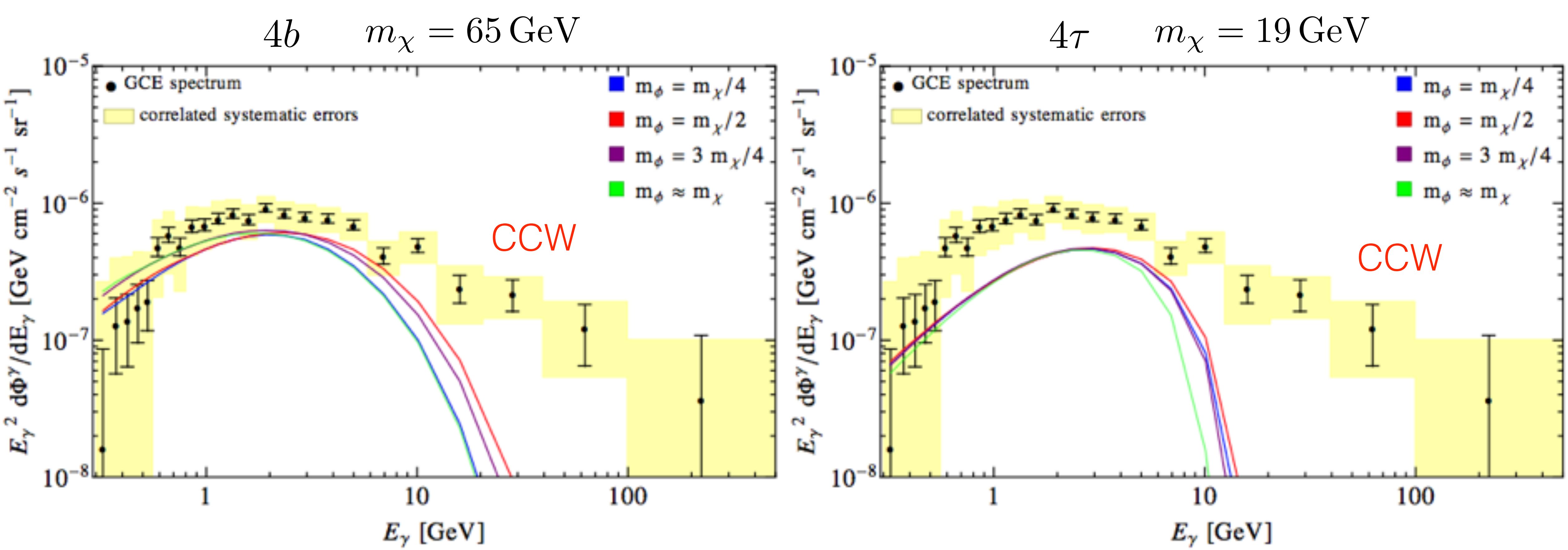
so the important parameters are c_{ijk}

Back up



Back up

Broadening the spectrum in cascade decays



Dutta, Gao, Ghosh, Strigari, 1508.05989

Back up

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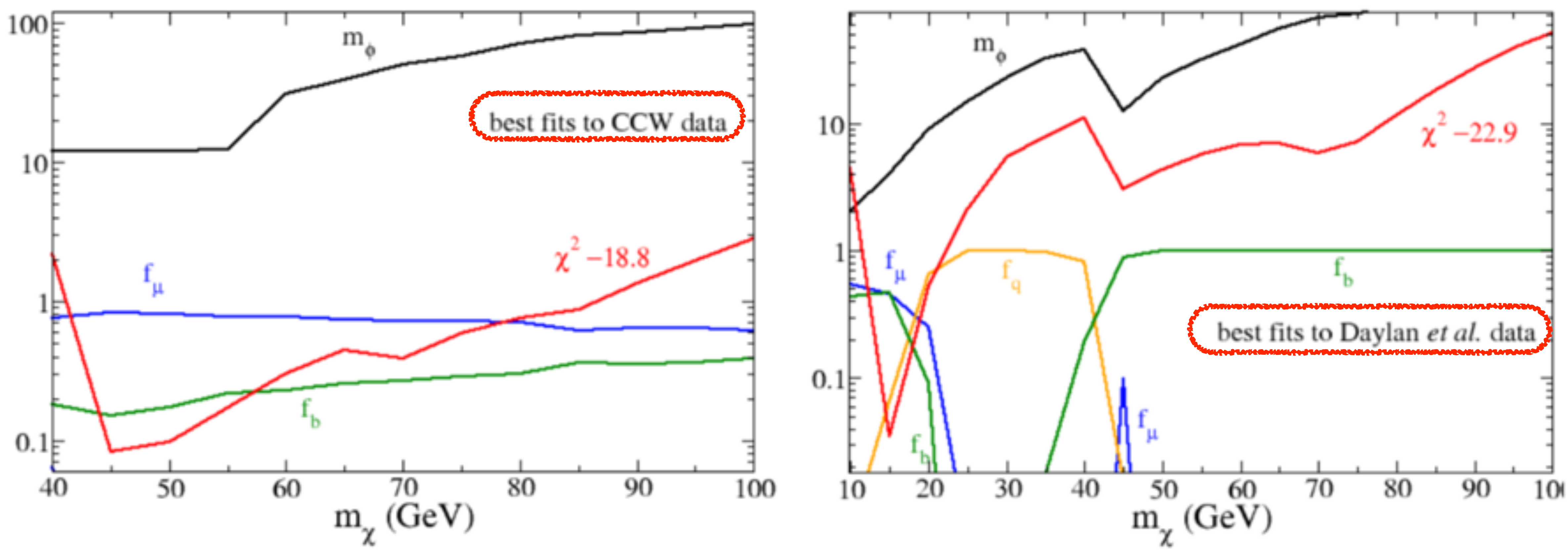

Cline, Dupuis, Liu, Xue, 1503.08213

Back up

Murgia, Aspen2016