THE HIGGS PORTAL TO DARK MATTER AT THE LHC

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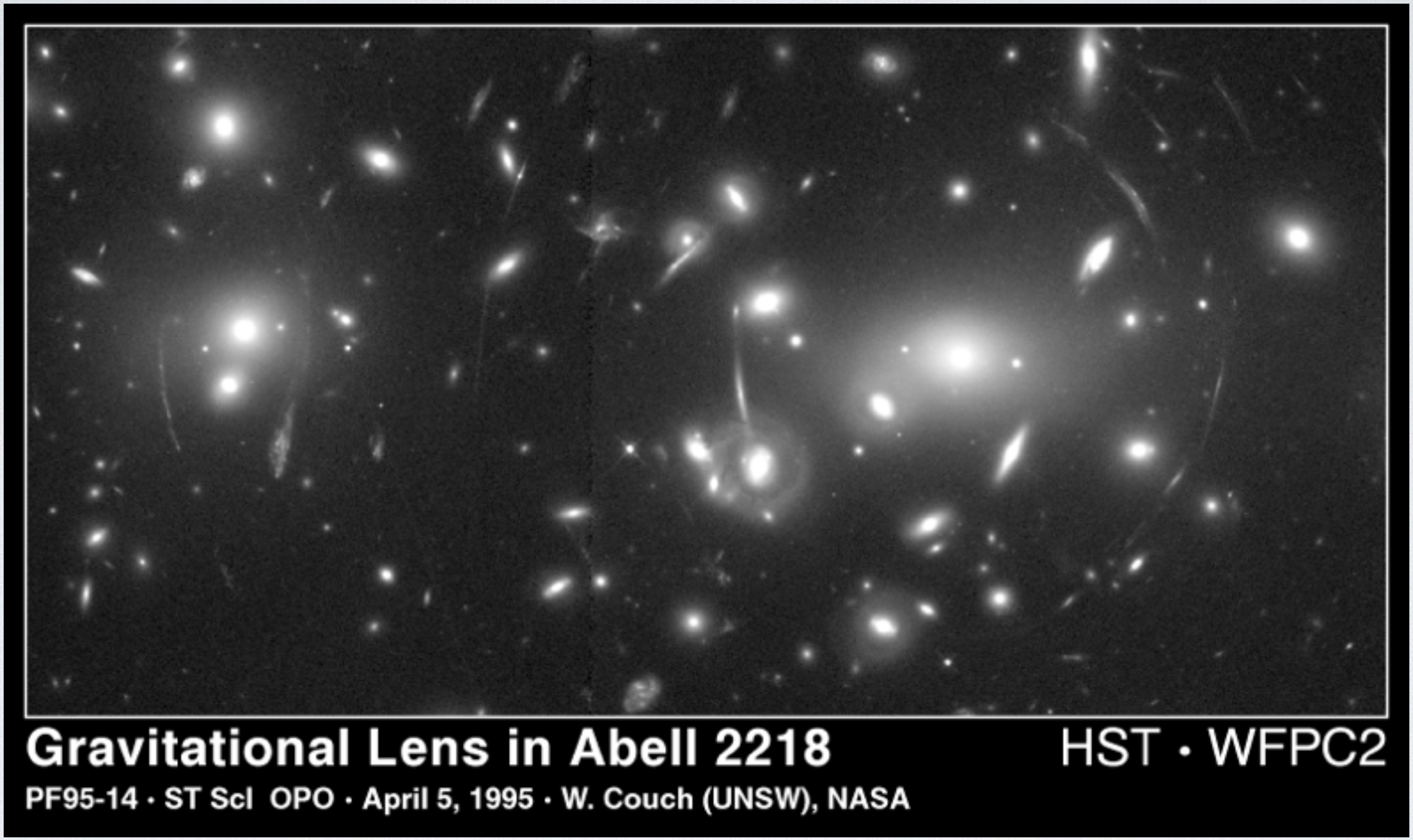
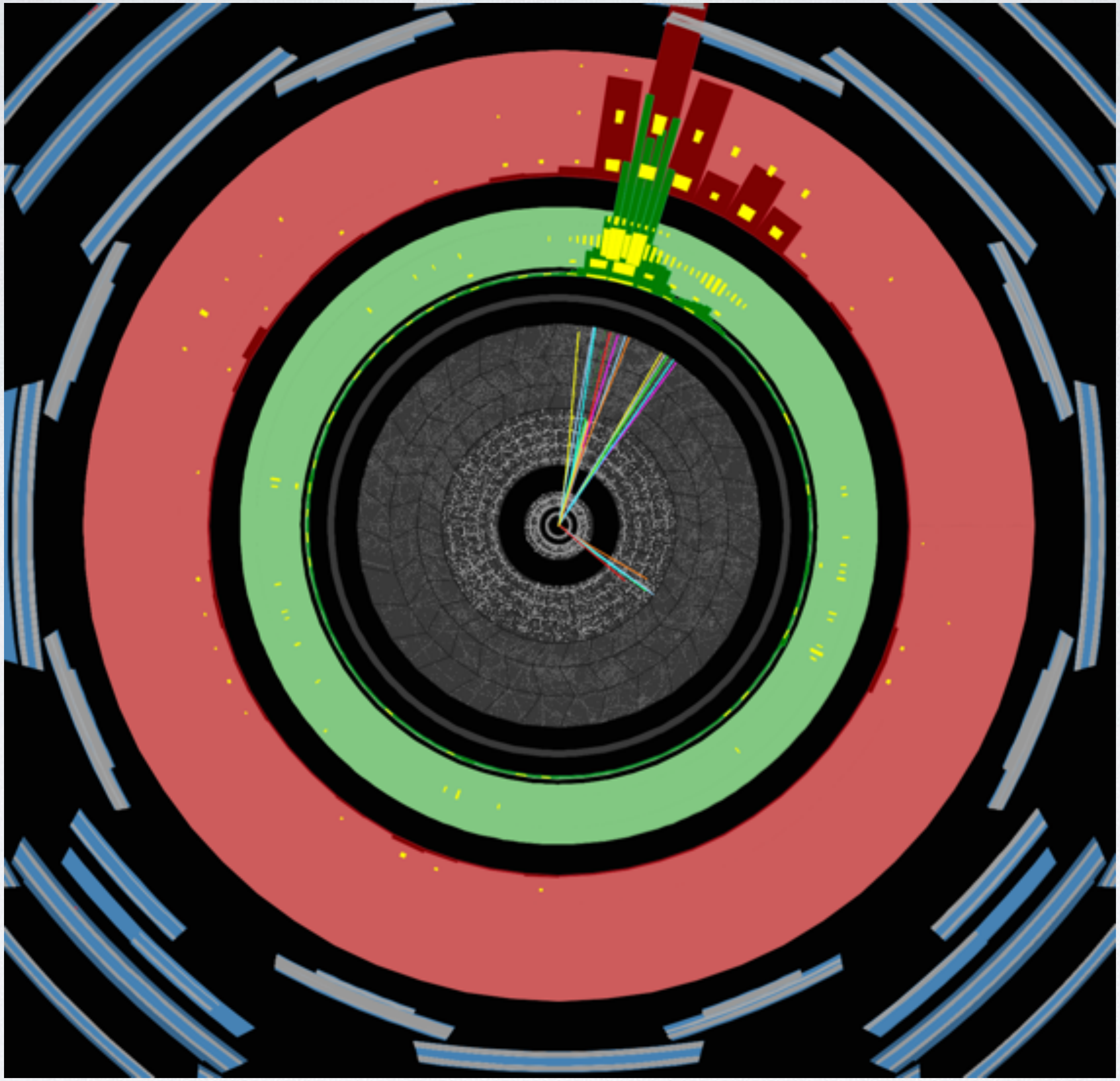
DARK MATTER!

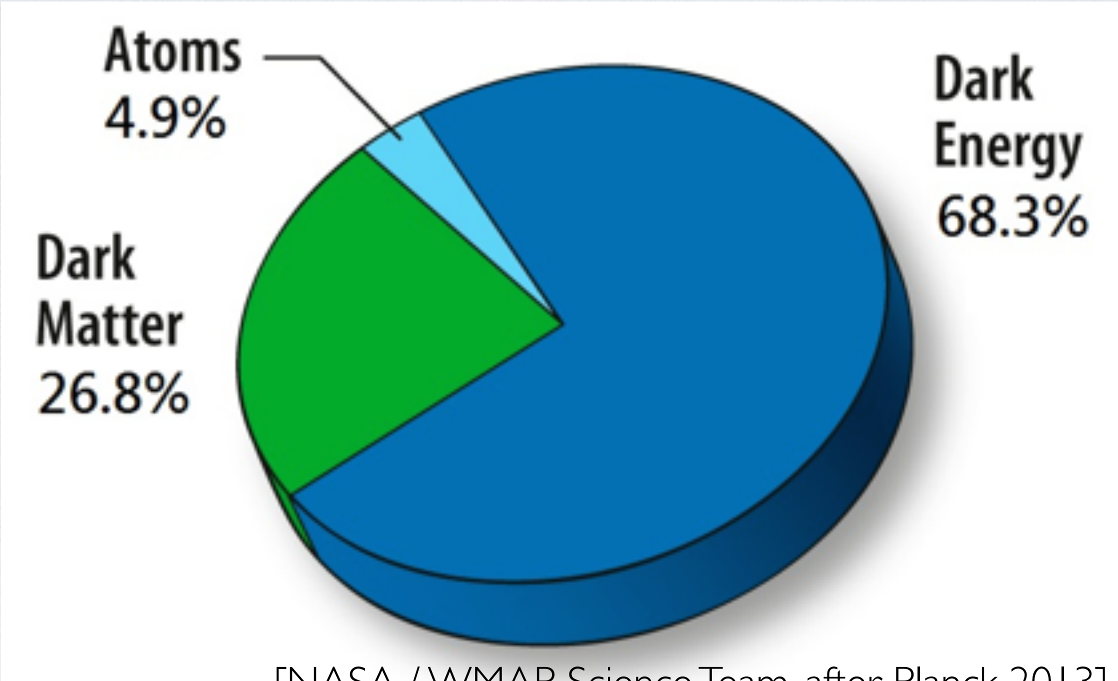

Gravitational Lens in Abell 2218
HST • WFPC2
PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

DARK MATTER?



[ATLAS experiment, event n. 55091306, recorded on July 14, 2012]

THE "WIMP" MIRACLE



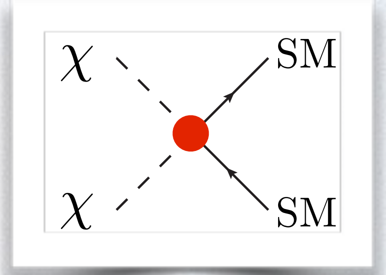
[NASA / WMAP Science Team, after Planck 2013]

Relic dark matter abundance after thermal freeze-out:

$$\Omega_{\rm DM} h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle} = 0.1199 \pm 0.0022$$ [Planck coll. 2015, arXiv:1502.01589]

Thermally averaged **annihilation cross section**:

$$\langle \sigma_A v \rangle = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \approx 1\,\mathrm{pb}$$

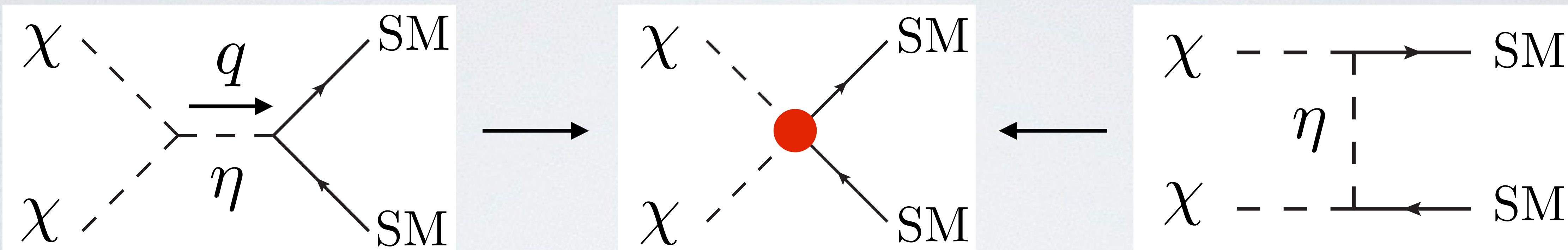


$\boxed{\text{**W**eakly **I**nteracting **M**assive **P**article around } \Lambda_{\rm EW} \simeq 100\,\mathrm{GeV}?}$

PARTICLE DARK MATTER

Weak interactions with standard model suggest **heavy mediator**:

s-channel   t-channel

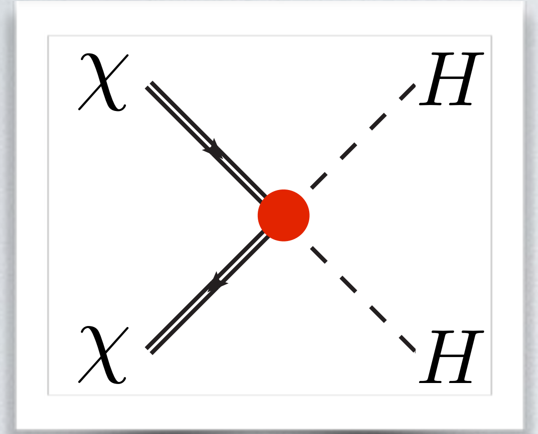


Example: **fermion dark matter**

$$M_\eta^2 \gg q^2 \,:\, \mathcal{L}_{\text{eff}}^{(6)} = \mathcal{C}(\overline{\chi}\Gamma\chi)(\overline{\psi}\Gamma\psi) + \ldots$$

$$\boxed{\mathcal{C} = \frac{g^2}{M_\eta^2} \ll \frac{1}{q^2}}$$

HIGGS-PORTAL DARK MATTER



$(H^\dagger H)$ is a standard-model singlet. $H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\,G^+ \\ v + h + iG^0 \end{pmatrix}$

χ is part of a dark sector.

Z_2 symmetry $\longrightarrow$ DM candidate stable.

Renormalizable portal interactions: [Patt, Wilczek, hep-ph/0605188]

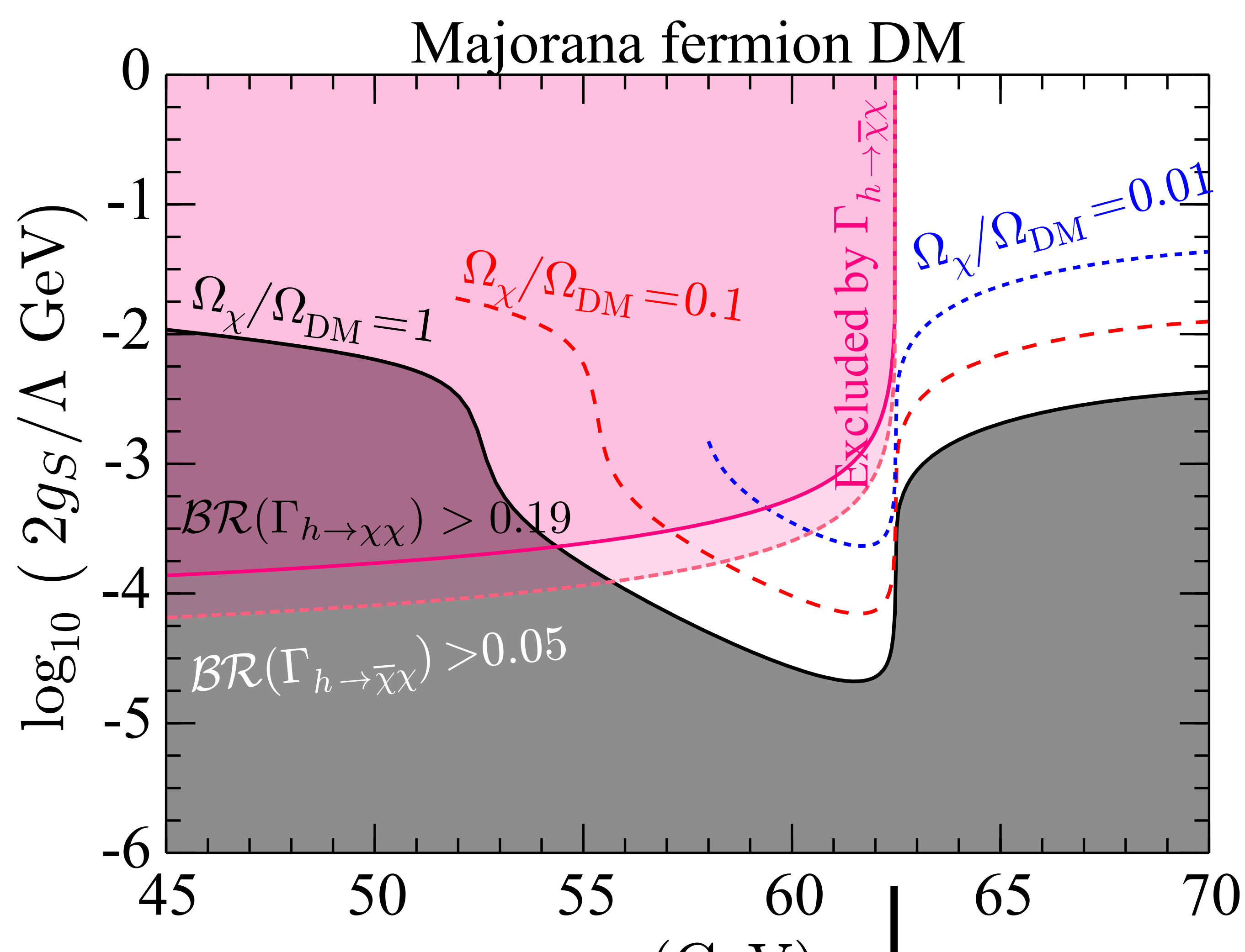
Scalar DM $\chi = S$: $\mathcal{L} = (S^\dagger S)(H^\dagger H)$ [e.g., O'Connell et al., hep-ph/0611014]

Vector DM $\chi = V_\mu$: $\mathcal{L} = (V_\mu V^\mu)(H^\dagger H)$ [e.g. Hambye, arXiv:0811.0172]

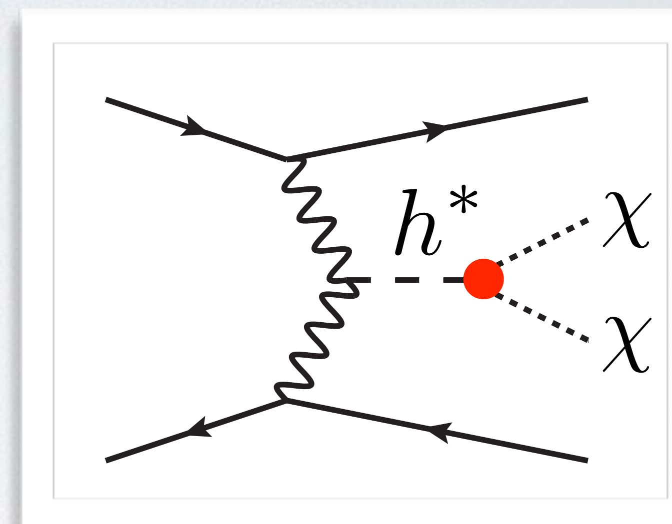
Effective portal interaction through mediator(s):

$$\boxed{\text{Fermion DM:}\quad \mathcal{L}_{\text{eff}} = \frac{g_S}{\Lambda}(\bar{\chi}\chi)(H^\dagger H) + i\frac{g_P}{\Lambda}(\bar{\chi}\gamma_5\chi)(H^\dagger H)}$$

HIGGS PORTAL AT THE LHC



[Beniwal et al.,1512.06458]



invisible Higgs decay ⟵|⟶ off-shell Higgs processes

very strong bounds

[e.g. Djouadi et al., arXiv:1310.8214]

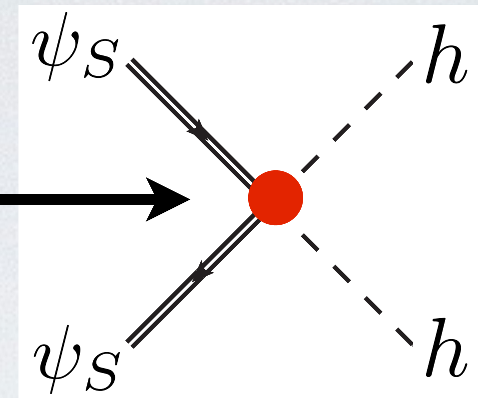
very weak bounds

[Endo, Takaesu, arXiv:1407.6882] [Craig et al., arXiv:1412.0258]

UV-COMPLETE FERMION HIGGS PORTALS

[Freitas, SW, Zupan, arXiv:1506.04149]

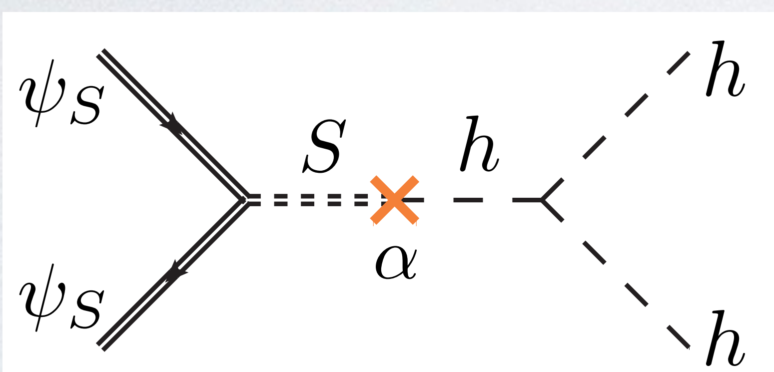
$$g_S = \frac{y^2}{2m_D} \rightarrow$$



$m_D \gg m_S$

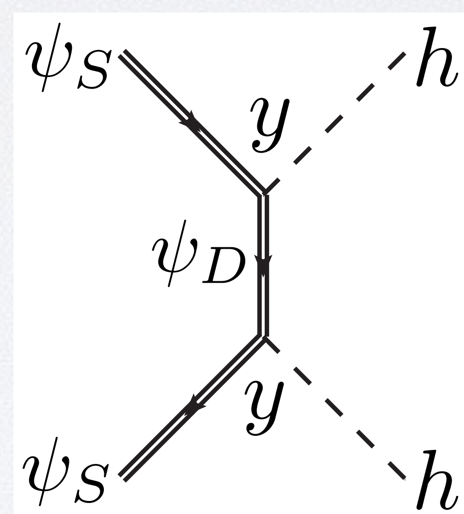
$\downarrow \; m_D \lesssim \text{few } 100\,\text{GeV}$

singlet-singlet



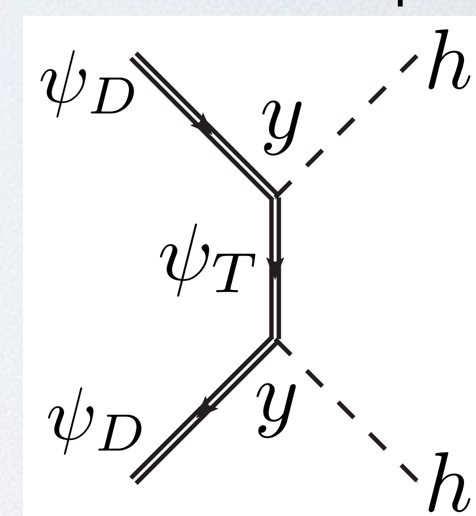
[Lee et al., 2008, …]

singlet-doublet



[Mahbubani, Senatore, 2005, …]

doublet-triplet



[Dedes, Karamitros, 2014]

[triplet-quadruplet: Tait, Yu, 2016]

Higgs portal at the LHC is "open" for mediator searches.

SINGLET-DOUBLET MODEL

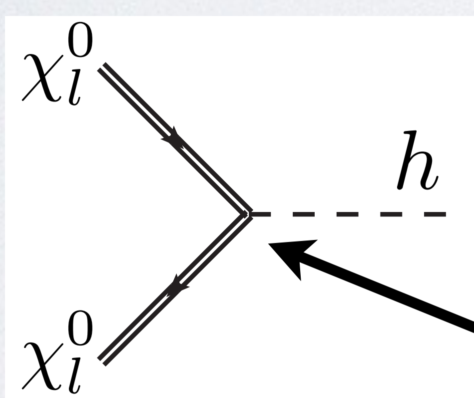
Dark fermions mix through Yukawa interaction:

$$\mathcal{L} = -m_D \overline{\psi}_D \psi_D - m_S \overline{\psi}_S \psi_S - (y \overline{\psi}_D H \psi_S + \text{ h.c.})$$

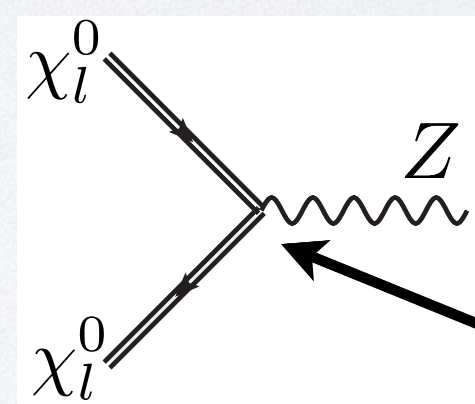
$$\psi_D = \begin{pmatrix} \psi_D^+ \\ \psi_D^0 \end{pmatrix}$$

$$\langle H \rangle = v/\sqrt{2} \longrightarrow \boxed{\begin{aligned} \chi_l^0 &= \cos\theta \psi_D^0 - \sin\theta \psi_S \\ \chi_h^0 &= \sin\theta \psi_D^0 + \cos\theta \psi_S \end{aligned}}$$

Mixing controls coupling to Higgs and gauge bosons:



$$\frac{y}{\sqrt{2}} \sin(2\theta)$$



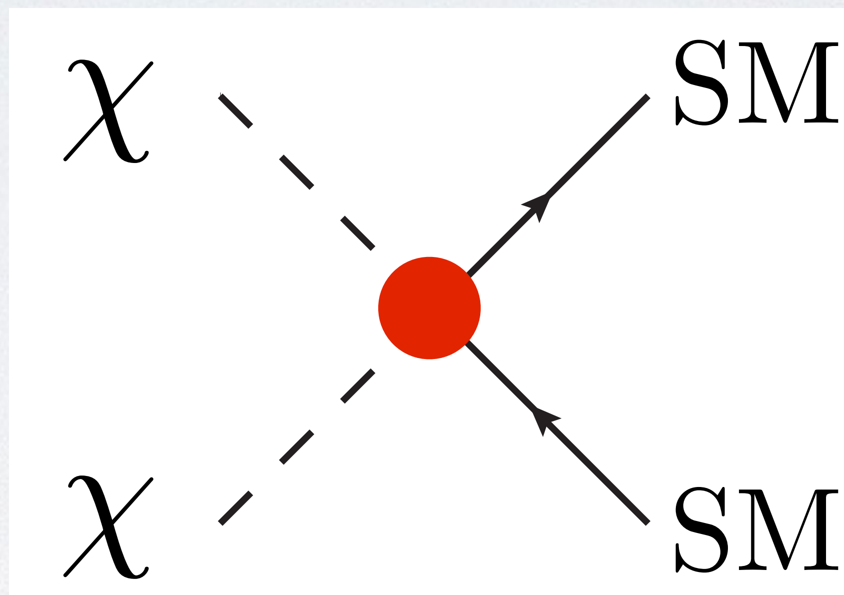
$$-\frac{g}{2c_W} \cos^2\theta$$

$\boxed{\text{Three parameters: } m_{\chi_l^0},\ m_{\chi_h^0},\ y}$

SEARCH FOR (HIGGS-PORTAL) DARK MATTER

relic abundance (annihilation)

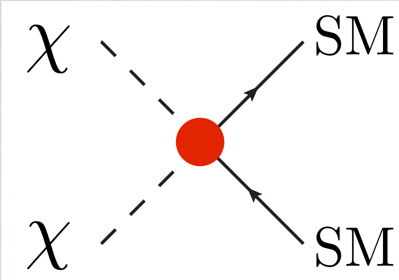
direct detection (scattering)



$$\left\{ m_{\chi_l^0}, m_{\chi_h^0}, y \right\}$$

high-energy colliders (production)

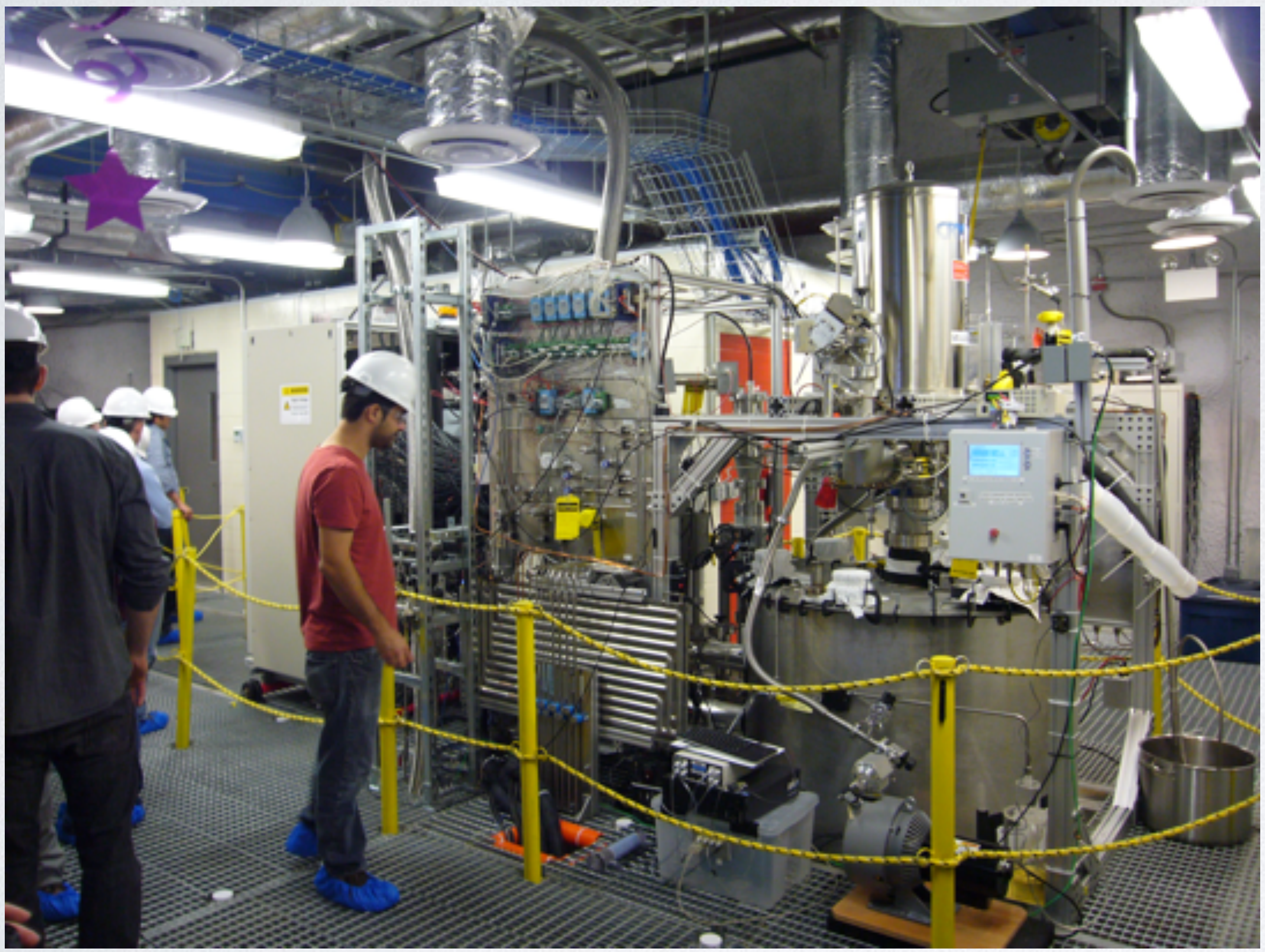
Bounds from indirect detection are weak. [Beniwal et al., 1512.06458]



DIRECT DETECTION

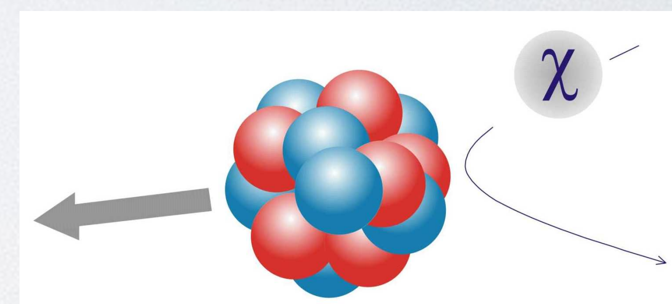
Measure recoil of atomic nuclei in shielded place.

e.g. at the Large Underground Xenon experiment LUX



[picture taken at the Homestake Mine in Lead, SD]

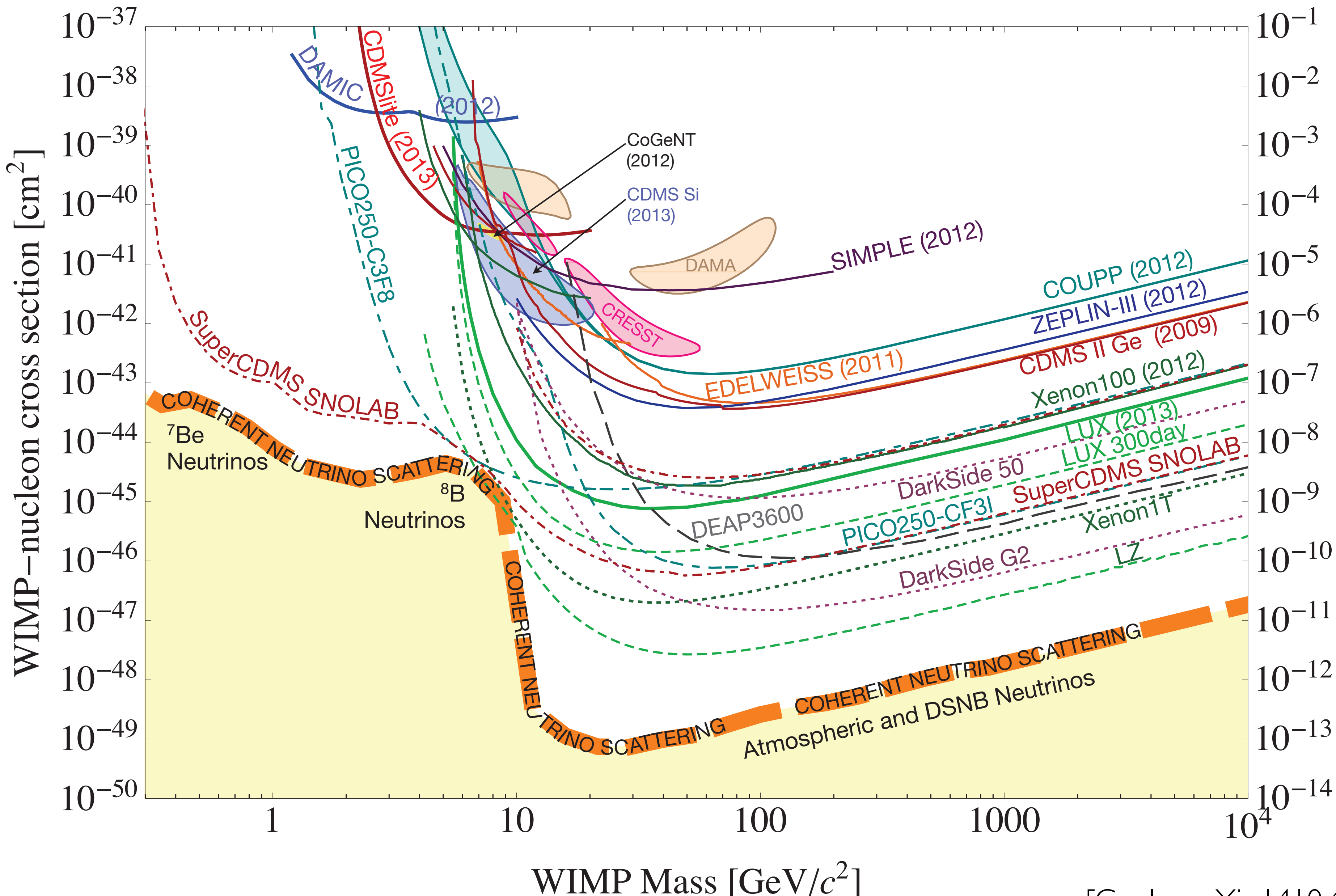
Spin-independent
DM-nucleus scattering:



$$\sqrt{k^2} \simeq 10 - 50\,\mathrm{MeV} \ll M_\eta$$

$$\boxed{\sigma_0 = \frac{\mu_A^2}{\pi} |Z f_p + (A - Z) f_n|^2}$$

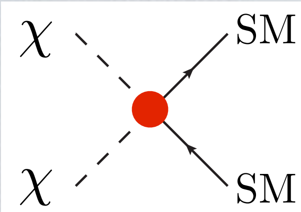
BOUNDS ON DM-NUCLEON INTERACTIONS



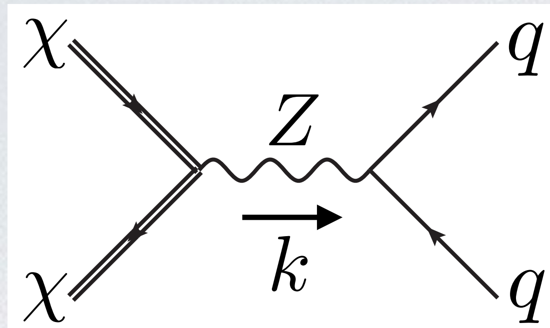
[Cooley, arXiv:1410.4960]

Currently strongest bound on weak-scale DM scattering:

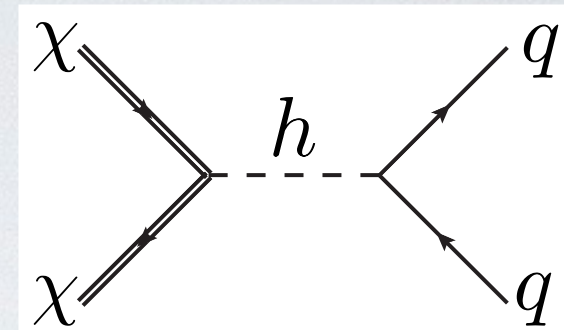
LUX experiment: $\sigma_0(m_\chi \approx 100\,\mathrm{GeV}) \lesssim 10^{-45}\mathrm{cm}^2$ [LUX coll., arXiv:1512.03506]



DARK FERMION-NUCLEON SCATTERING



$$\mathcal{O}_V = (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$$



$$\mathcal{O}_S = (\bar{\chi}\chi)(\bar{q}q)$$

Effective interactions:

$$f_{p,n} \sim \frac{g_\chi^Z g_q^Z}{M_Z^2} \qquad\qquad f_{p,n} \sim \frac{g_\chi^h}{M_h^2}\frac{m_q}{v}$$

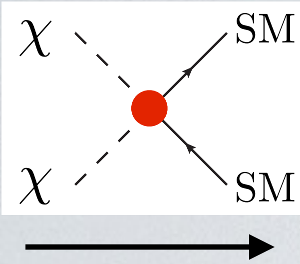
Dirac singlet:

$$g_\chi^Z = -\frac{g}{2c_W}\cos^2\theta \qquad\qquad g_\chi^h = \frac{y}{\sqrt{2}}\sin(2\theta)$$

Majorana singlet:

$$g_\chi^Z = 0 \qquad\qquad g_\chi^h = \frac{y}{2}\sin(2\theta')$$

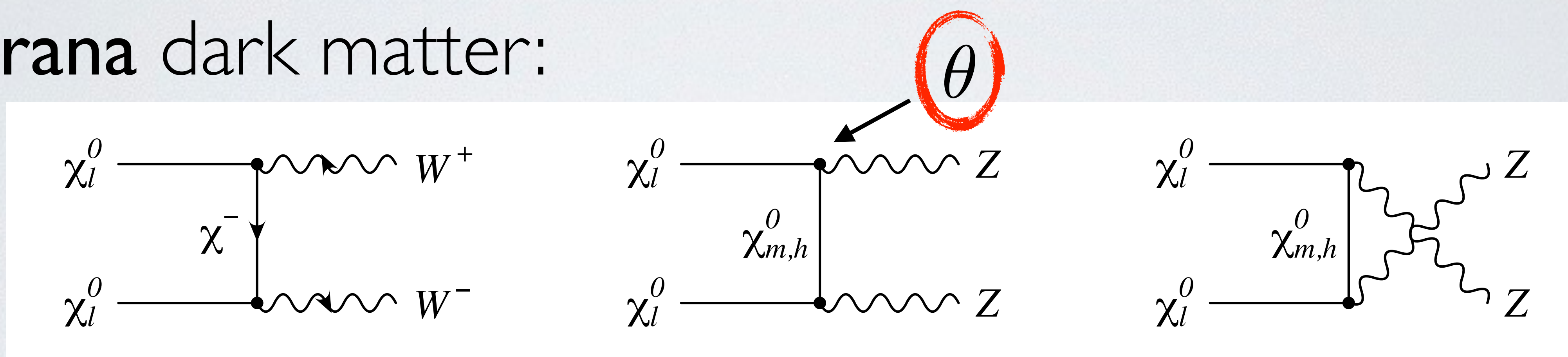
direct detection bounds $\longrightarrow$ DM must be singlet-like, $\theta \approx \pi/2$.



RELIC ABUNDANCE

Dirac dark matter annihilation: $\chi\bar{\chi} \to Z \to q\bar{q}, \ell^+\ell^-$

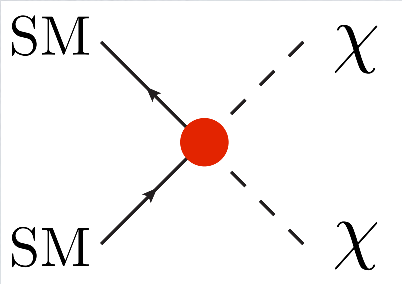
Majorana dark matter:



Observed abundance: $\Omega_\chi h^2 = 0.1199 \pm 0.0022$ [Planck coll., arXiv:1502.01589]

Direct detection strongly constrains DM annihilation rate.

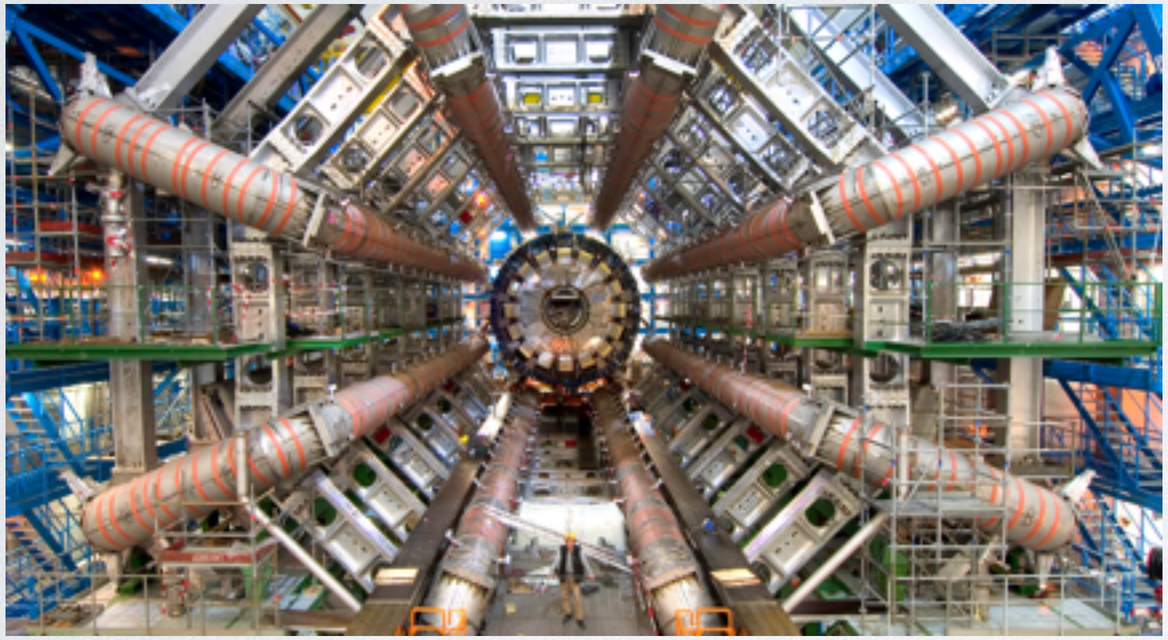
Co-annihilation prevents over-abundance:
small DM-mediator mass splitting



COLLIDER SEARCHES

Look for missing energy or production of mediators.

e.g. at the Large Hadron Collider

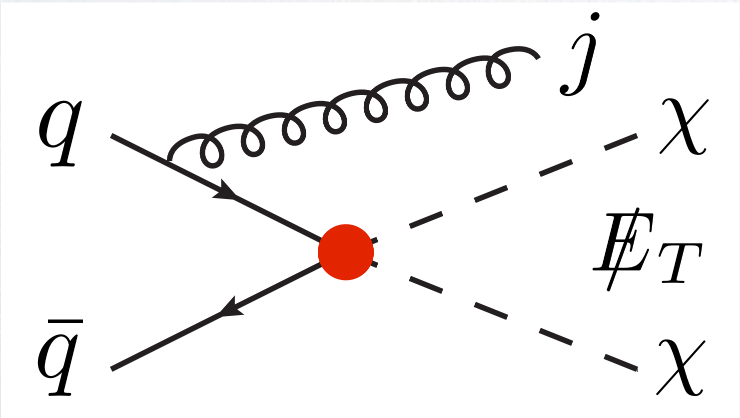


[ATLAS experiment, CERN]

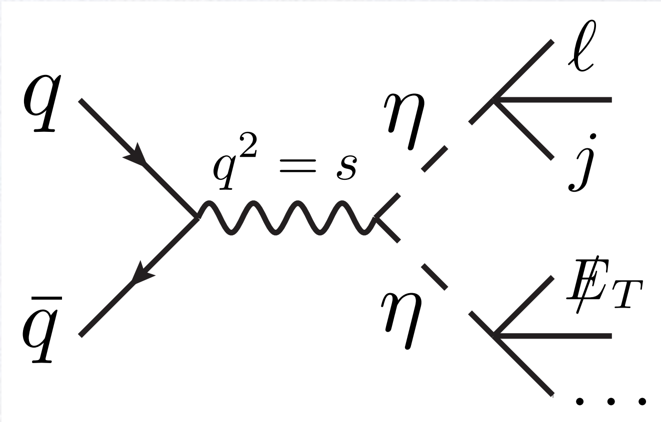
Dark-matter production in proton-proton collisions:

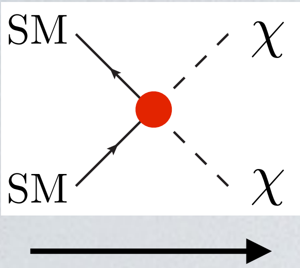
$$\boxed{\sigma(pp \to \chi\chi + X) = \int ds\, \mathcal{L}_{ij}(s)\hat{\sigma}_{ij}(s)}$$

Mono-jet searches



Mediator searches



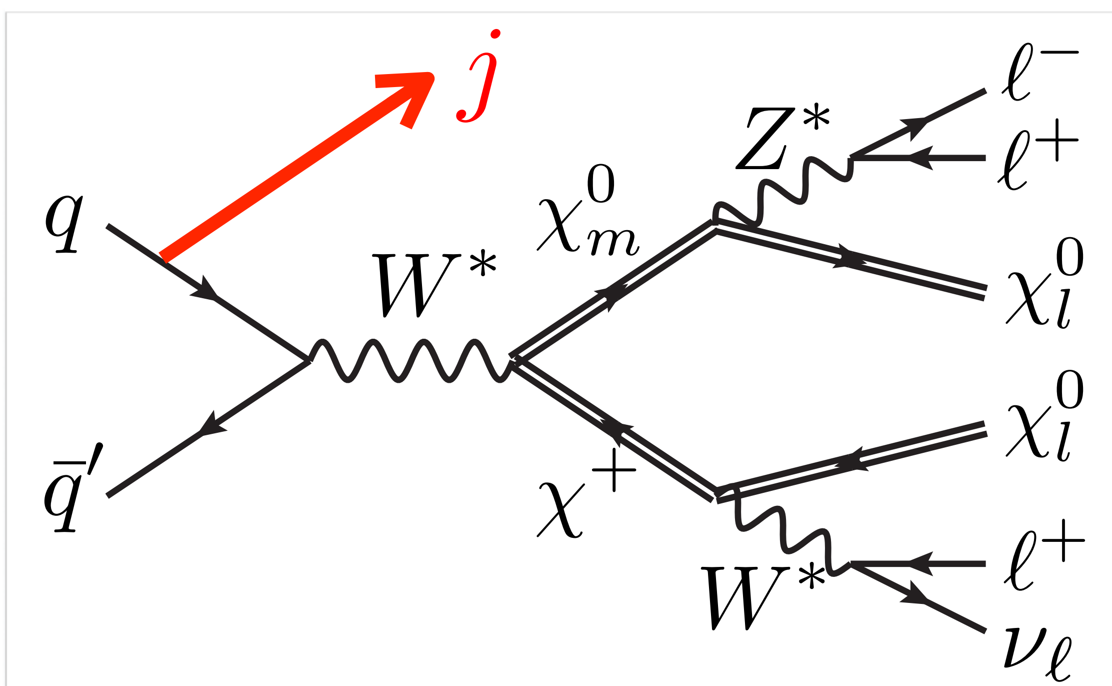


DARK FERMION SEARCHES AT COLLIDERS

Soft leptons: $m_m^0 - m_l^0,\ m^+ - m_l^0 \lesssim 30\,\mathrm{GeV}$

Similar to SUSY electroweakino searches:

[Giudice, Han, Wang, Wang, arXiv:1004.4902]
[Gori, Jung, Wang, arXiv:1307.5952]
[Schwaller, Zurita, arXiv:1312.7350]



LHC Run II

$\not{E}_T > 300\,\mathrm{GeV}$

$p_T(j_1) > 300\,\mathrm{GeV}$

$p_T(\ell) < 20\,\mathrm{GeV}$

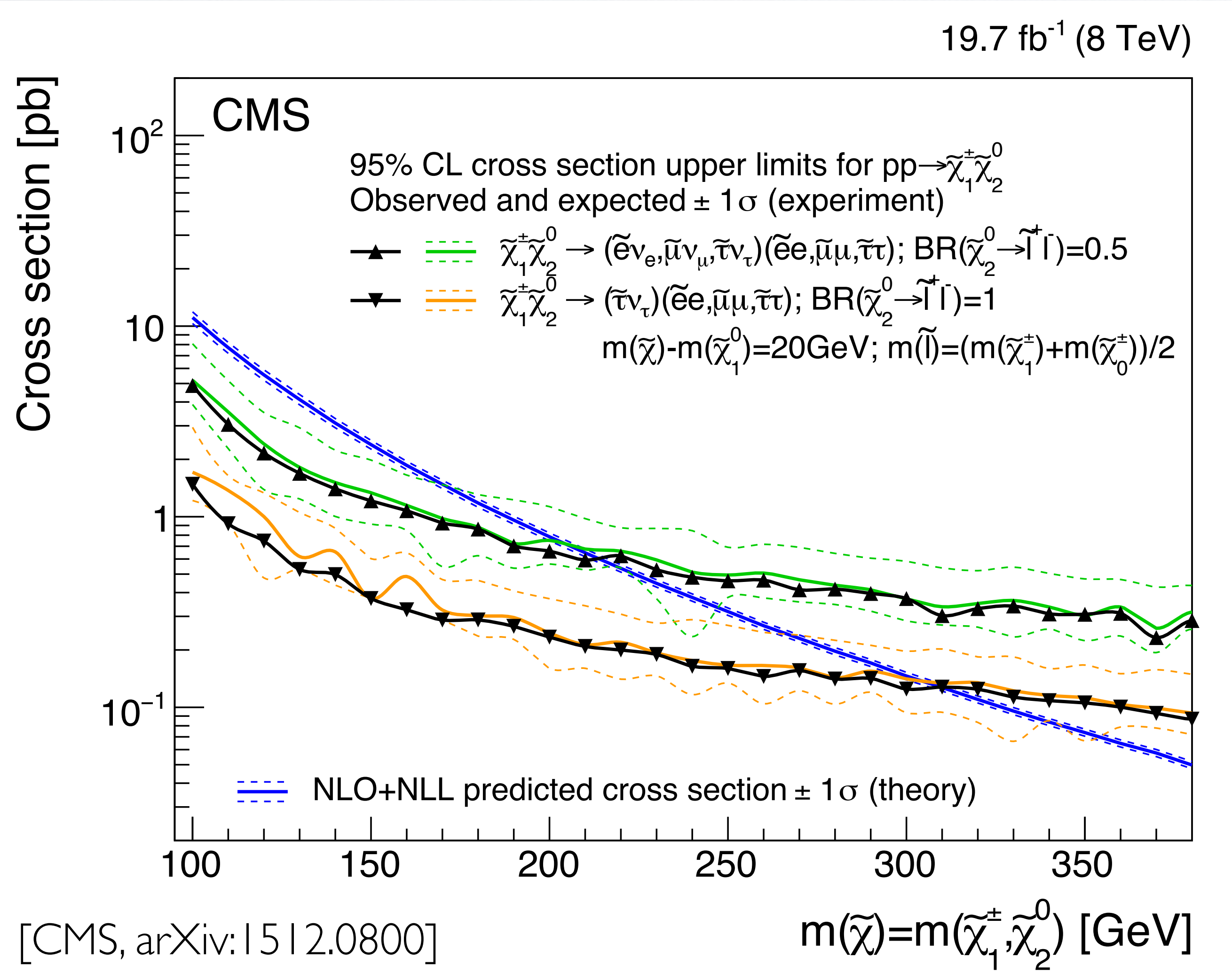
Vector boson fusion might be complementary.

[Dutta et al., arXiv:1411.6043]
[Berlin et al., arXiv:1502.05044]

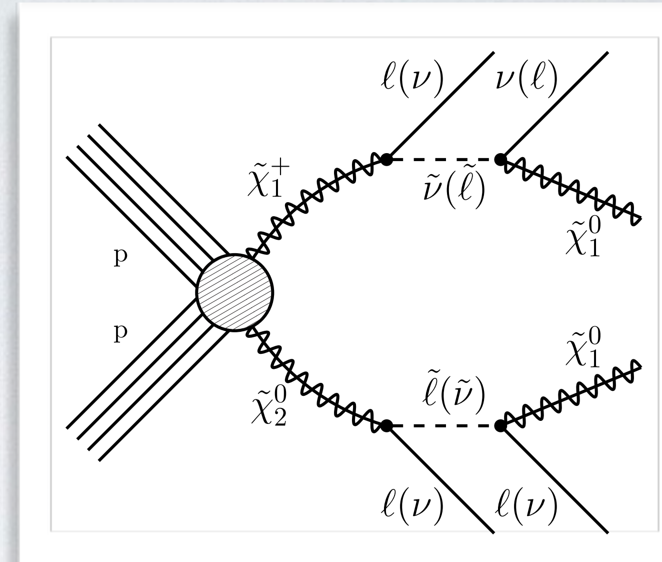
Mono-jet signal is too small for LHC energies.

EWK-INO SEARCH WITH SOFT LEPTONS

Di-leptons + ISR jet + missing energy:



[CMS, arXiv:1512.0800]



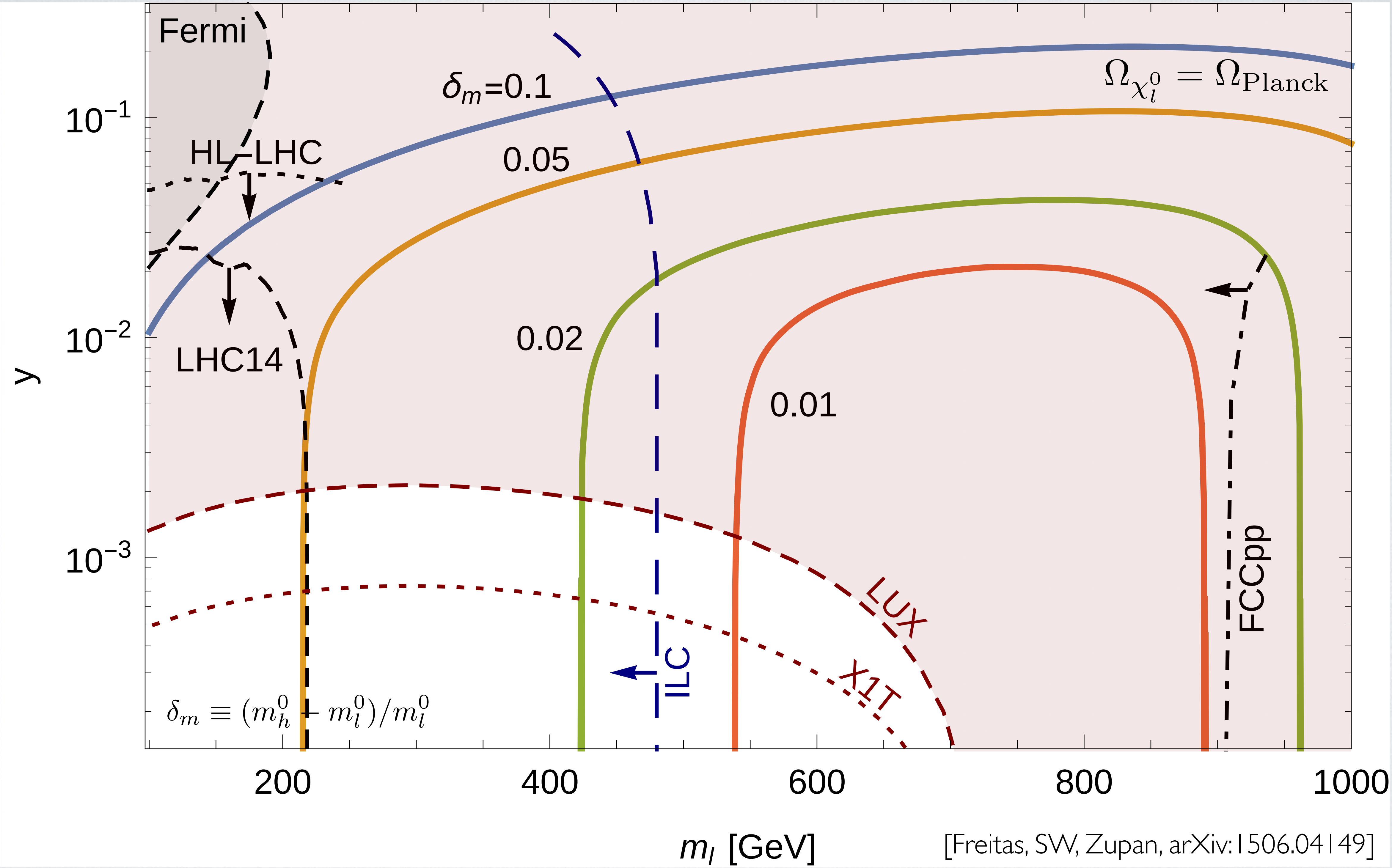
$$E_T^{\rm miss} > 200\,{\rm GeV}$$
$$p_T^j > 150\,{\rm GeV}$$

$$p_T^{\ell_1}\,:\;5 - 15,\;15 - 25\,{\rm GeV}$$
$$p_T^{\ell_2} < 15\,{\rm GeV}$$

Interpret these signatures in fermion Higgs portal context.

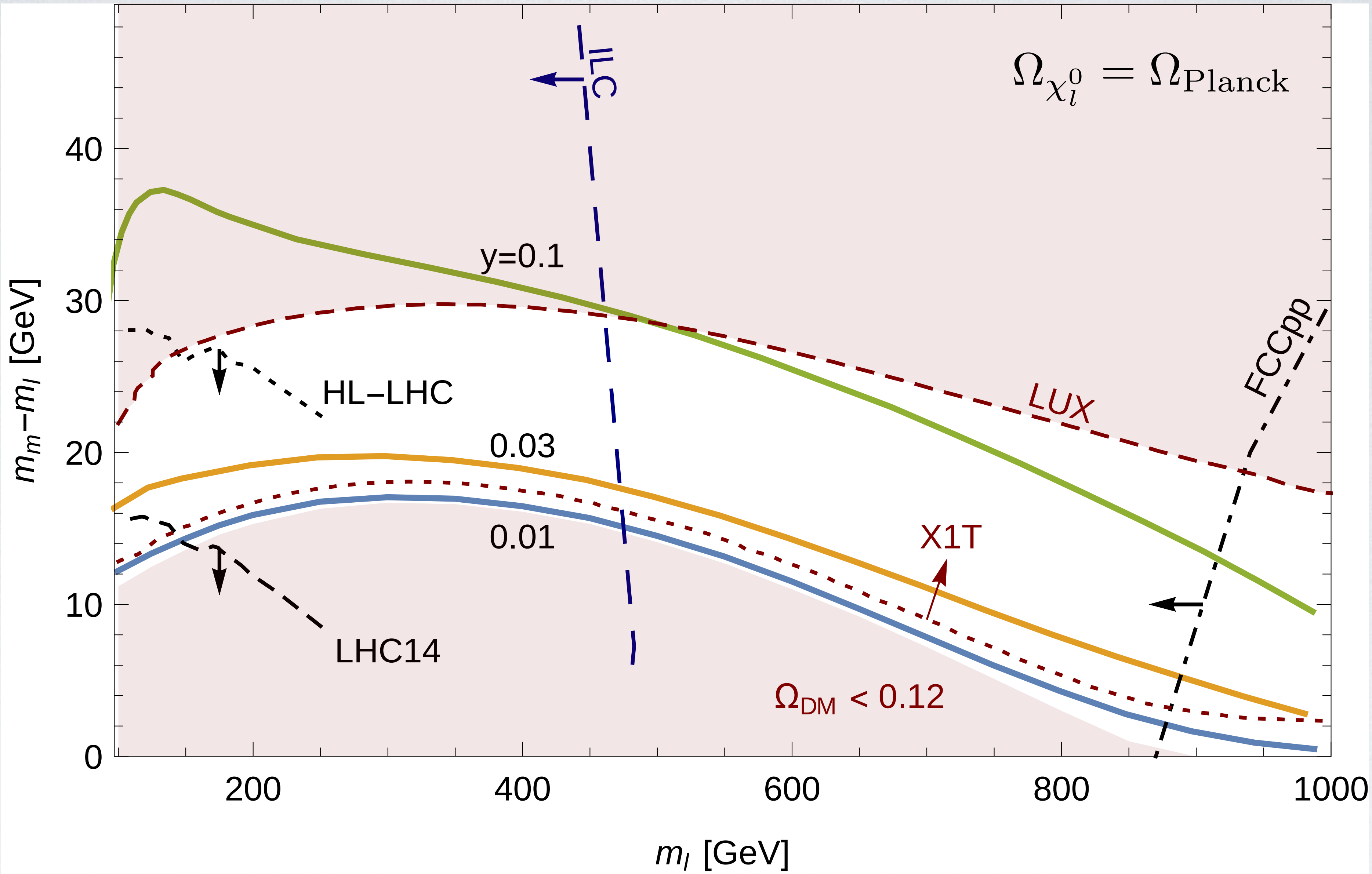
[SW, arXiv:1605.05193]

SUMMARY DARK DIRAC FERMIONS



[Freitas, SW, Zupan, arXiv:1506.04149]

SUMMARY DARK MAJORANA FERMIONS



[Freitas, SW, Zupan, arXiv:1506.04149]

Future direct detection experiments
and/or a high-energy collider can test this model.

FERMION DARK MATTER AT FUTURE COLLIDERS

electron-positron (ILC): $\sqrt{s} = 500 - 1000\,\mathrm{GeV}$

clean environment, less background

- fermion mediators: soft leptons (+ISR) [Berggren et al., arXiv:1309.7342]

sensitivity to mediator masses $m_\eta \lesssim \sqrt{s}/2$

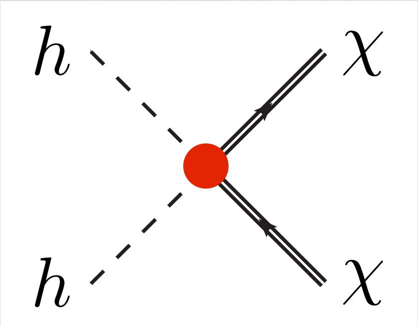
proton-proton (FCC): $\sqrt{s} = 100\,\mathrm{TeV}$

enhanced cross section allows for sharper cuts

- fermion mediators: soft leptons and jet(s) [Low, Wang, arXiv:1404.0682] [Bramante et al., arXiv:1412.4789]
- boson mediators: jet(s)+missing energy [Harris et al., arXiv:1509.02904]

extended mass reach $m_{\mathrm{max}}^{\mathrm{FCC}} \approx 5 \times m_{\mathrm{max}}^{\mathrm{LHC}}$

TAKE HOME



Higgs-portal fermion dark matter

- Opportunity at **LHC Run II**:

  Search for resonant production of mediators with soft leptons and missing transverse energy.

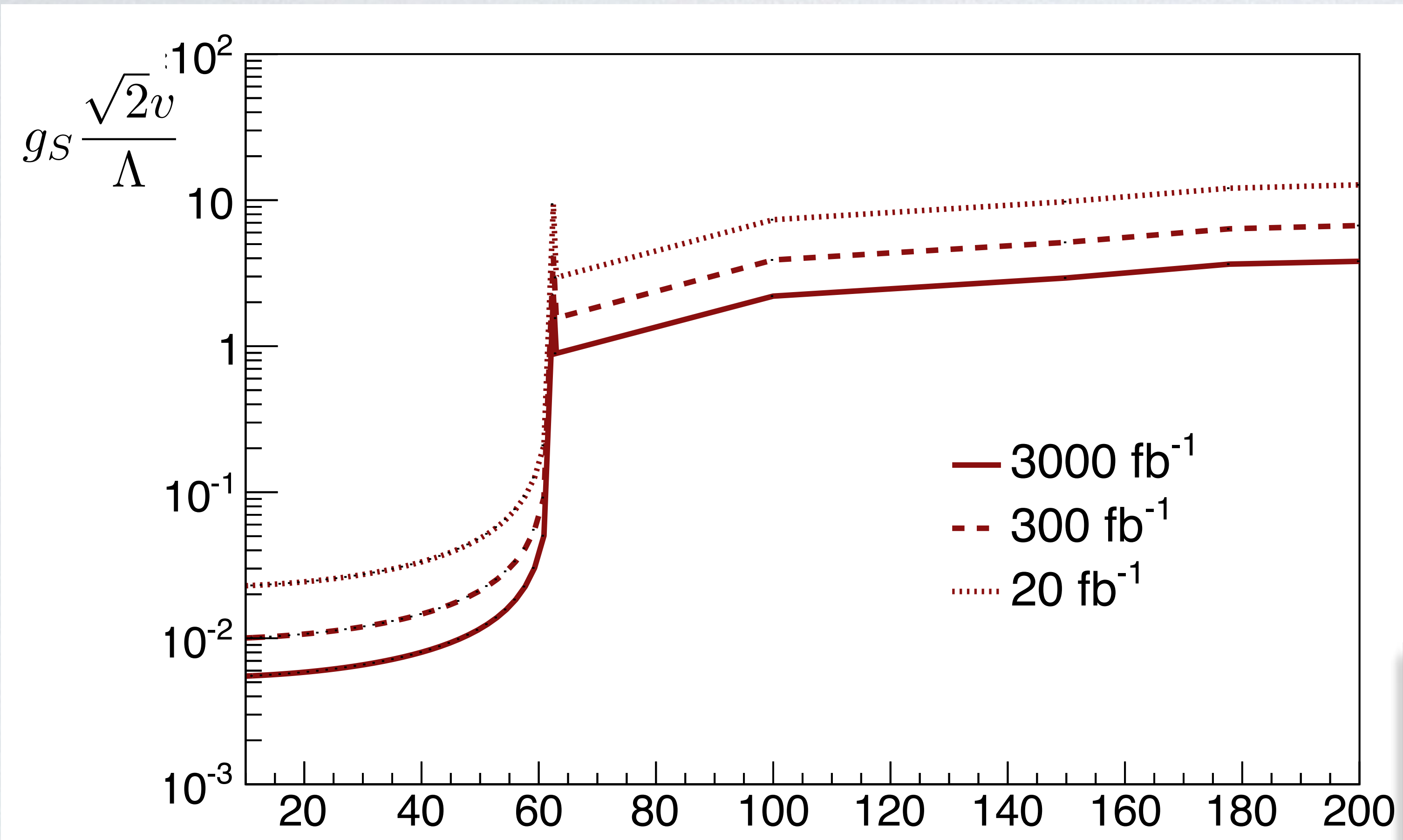
- **Direct detection** experiments provide complementary information.

- **Future** lepton and high-energy hadron **colliders** are helpful to test such models conclusively.

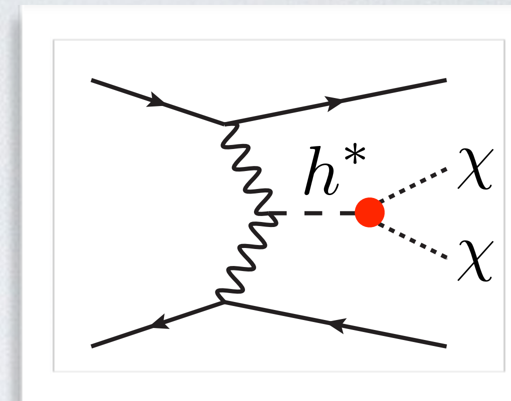
BACKUP

VECTOR BOSON FUSION

Sensitivity to fermion Higgs portal at 13-TeV LHC:



[Brooke et al., arXiv:1603.07739]



Selection criteria from CMS Run-I search:

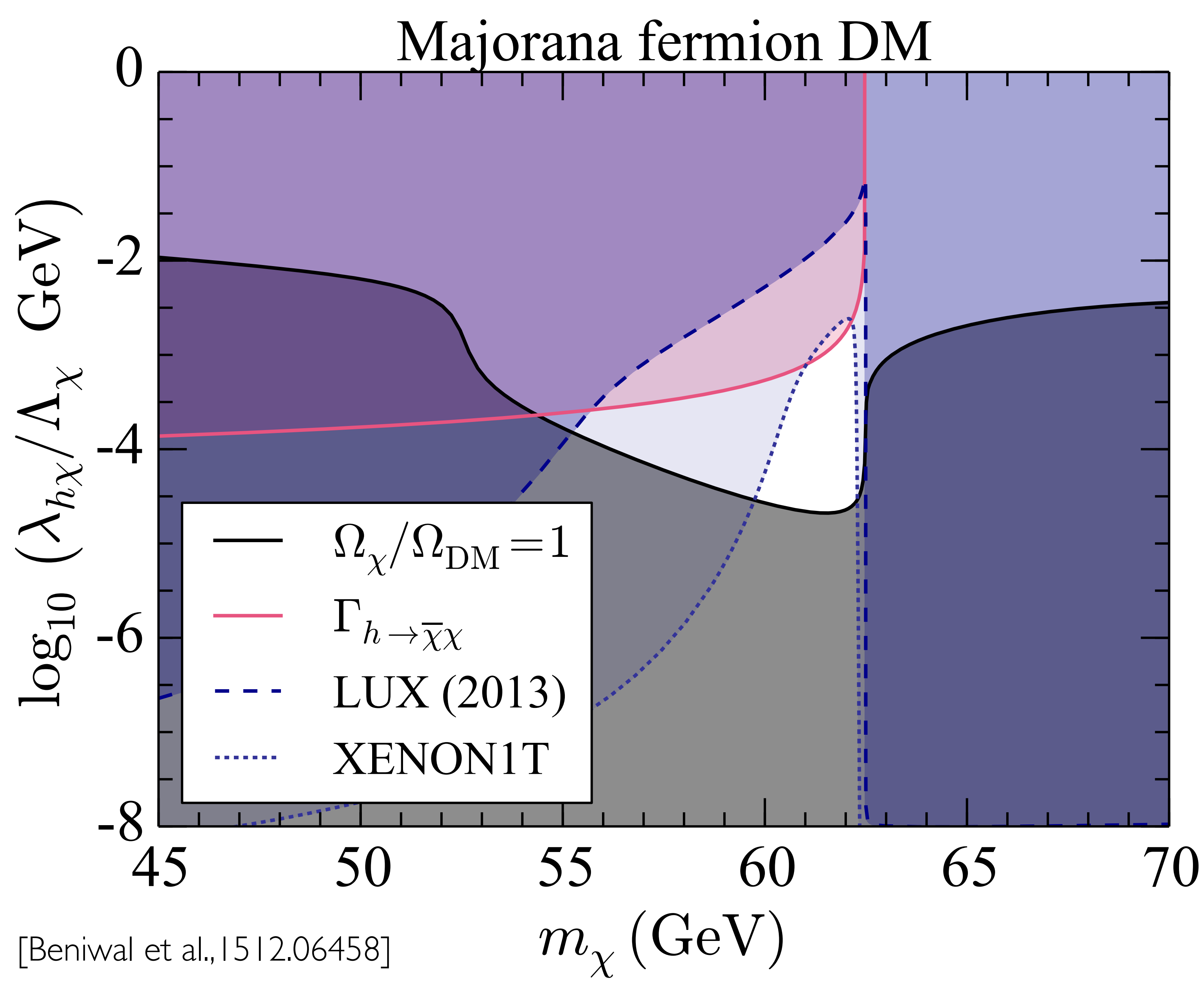
$\not{E}_{\mathrm{T}}$(trigger)	> 40 GeV
Jet selection	$p_{\mathrm{T}}^{j1(j2)} > 50\ (45)$ GeV
	$\lvert\eta_{j1,2}\rvert < 4.7$
	$\eta_{j1} \cdot \eta_{j2} < 0$
	$\Delta\eta_{jj} > 3.6$
Dijet mass	$M_{jj} > 1200$ GeV
$\not{E}_{\mathrm{T}}$	> 90 GeV
$\not{E}_{\mathrm{T}}^{\mathrm{sig}}$	$\not{E}_{\mathrm{T}}^{\mathrm{sig}} > 4\ \mathrm{GeV}^{1/2}$
$\Delta\phi(\not{E}_{\mathrm{T}}, j)$	> 2.3

[CMS-PAS-HIG-14-038]

CMS: $\mathcal{B}(h \to \mathrm{inv}) < 0.57$ [95% CL]

DIRECT DETECTION BOUNDS

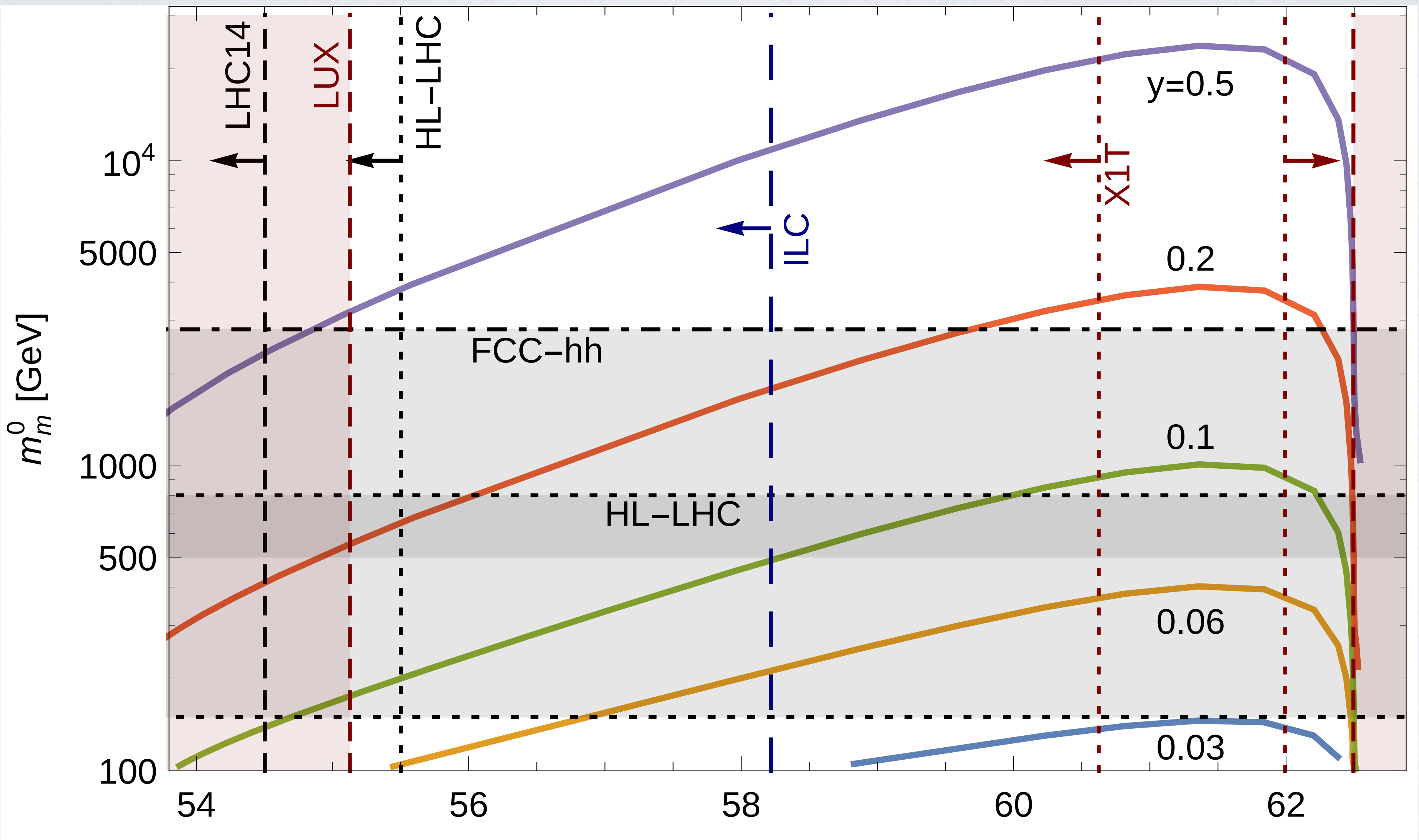
fermion dark matter with scalar Higgs-portal coupling:



[Beniwal et al., 1512.06458]

MAJORANA SINGLET-DOUBLET MODEL

Higgs resonance region



[Freitas, SW, Zupan, arXiv:1506.04149]