HIGGS-PORTAL DARK MATTER AT THE LHC

based on JHEP 1509 (2015) 015 with Ayres Freitas and Jure Zupan

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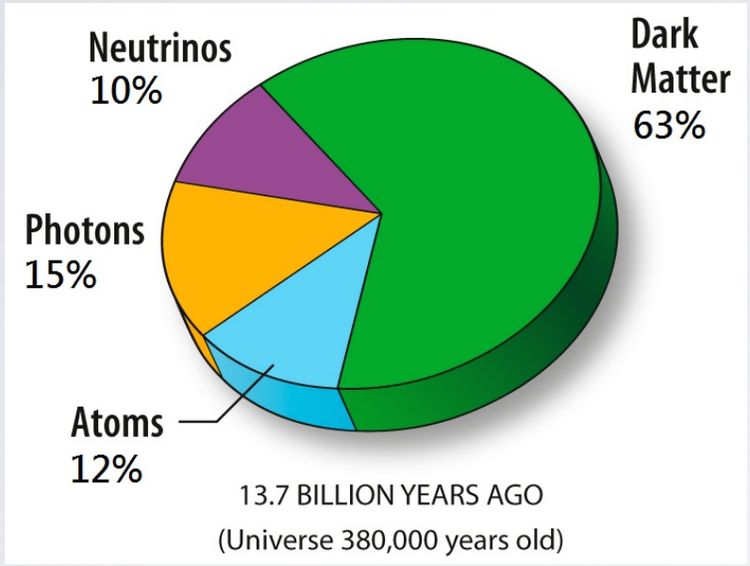
Universität Heidelberg

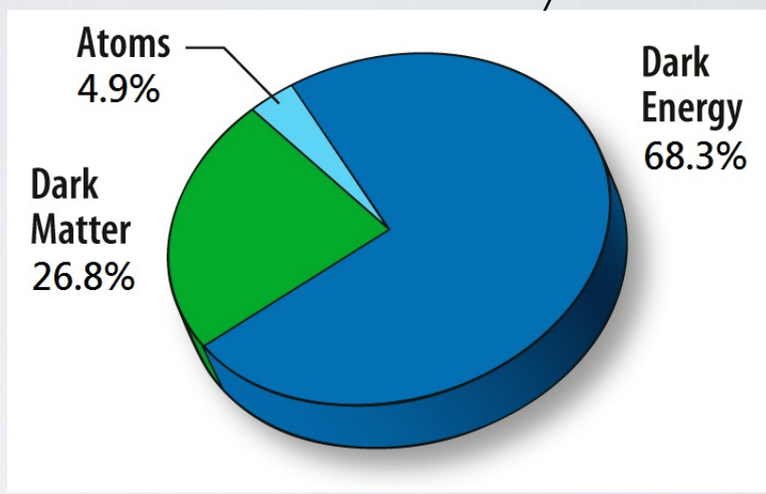
ABHM research group meeting — November 25, 2015 — Universität Bonn

THE "WIMP" MIRACLE

Universe at time of recombination



Universe today



[NASA / WMAP Science Team, after Planck 2013]

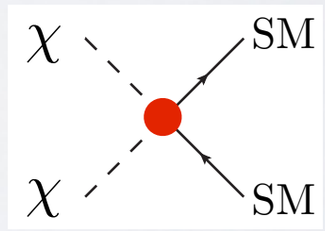
Relic dark matter abundance after thermal freeze-out:

$$\Omega_{\rm DM} h^2 \simeq \frac{3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_A v\rangle} = 0.1199 \pm 0.0022$$

[Planck Collaboration 2015, arXiv:1502.01589]

Thermally averaged **annihilation cross section**:

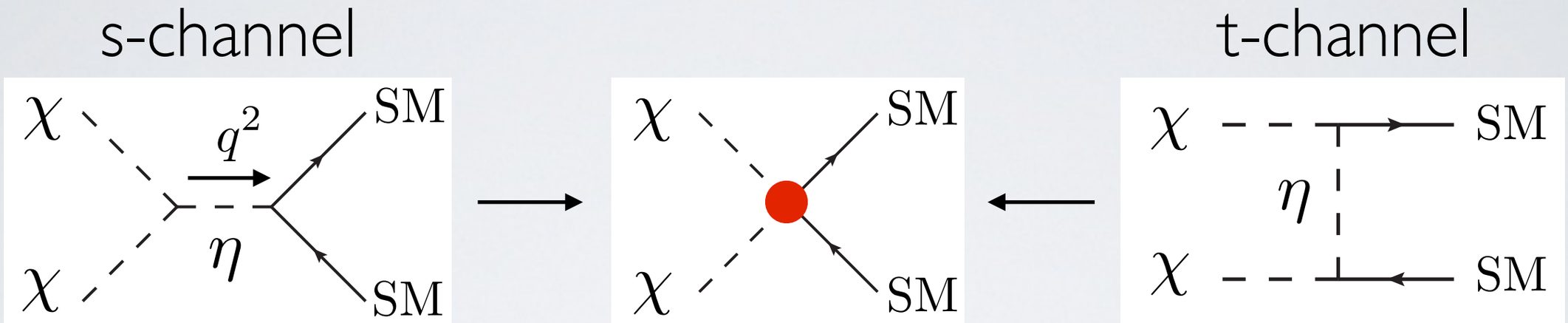
$$\langle \sigma_A v\rangle = 3\times 10^{-26}{\rm cm}^3{\rm s}^{-1} \approx 1\,{\rm pb}$$



Weakly **I**nteracting **M**assive **P**article around $\Lambda_{\rm EW} \simeq 100\,{\rm GeV}$?

PARTICLE DARK MATTER

Weak interactions with SM suggest **heavy mediator**:

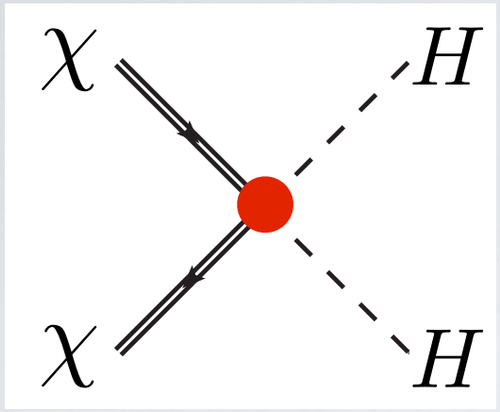


Effective interactions, for instance with fermion dark matter:

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

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

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.

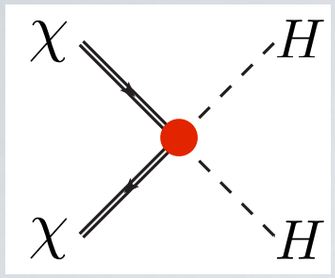
Renormalizable portal interactions:

Scalar DM $\chi = S$: $\mathcal{L} = (S^\dagger S)(H^\dagger H)$

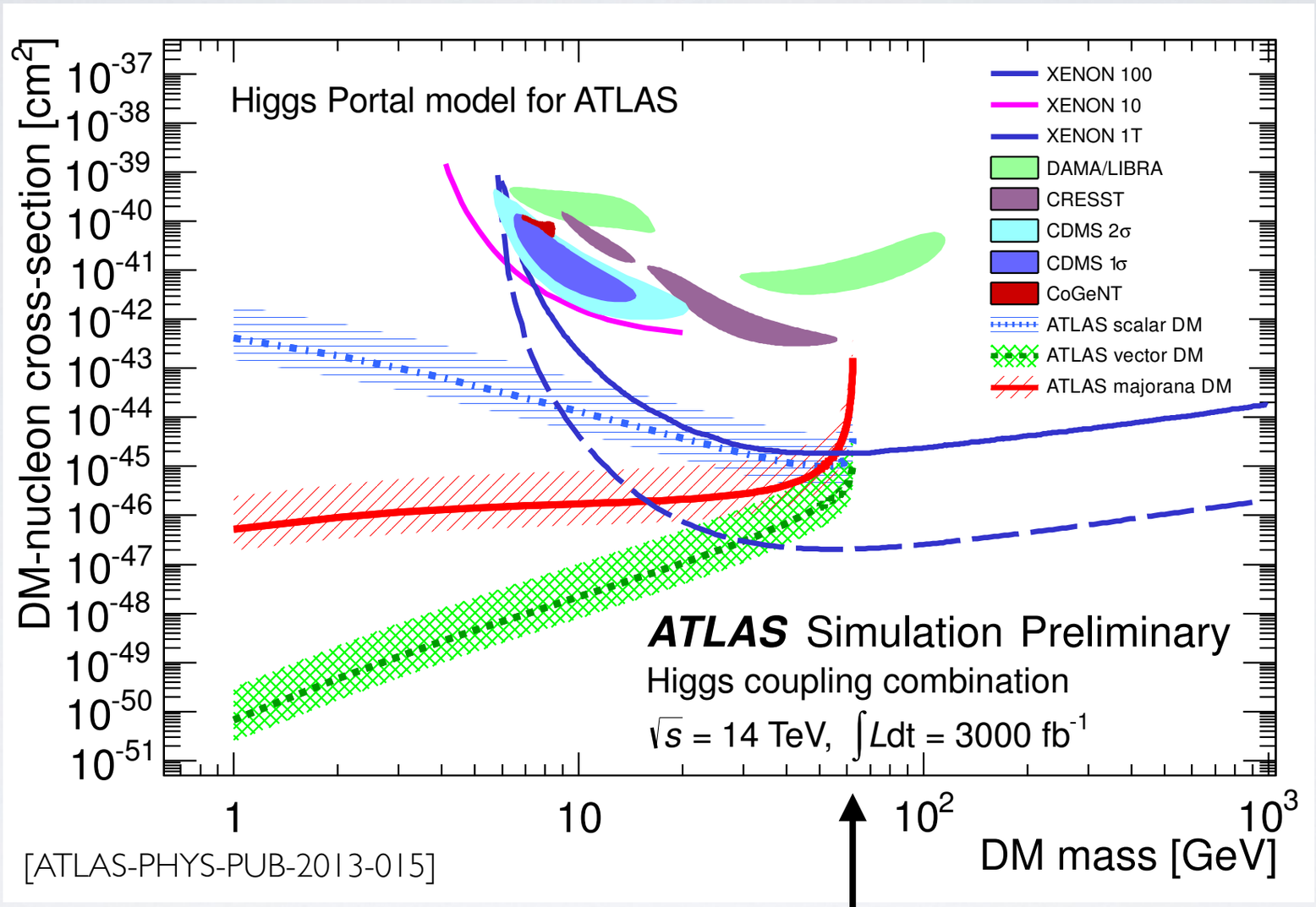
Vector DM $\chi = V_\mu$: $\mathcal{L} = (V_\mu V^\mu)(H^\dagger H)$

Effective portal interaction through mediator(s):

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



HIGGS PORTAL AT THE LHC



[ATLAS-PHYS-PUB-2013-015]

$m_h/2$

invisible Higgs decay

very strong bounds

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

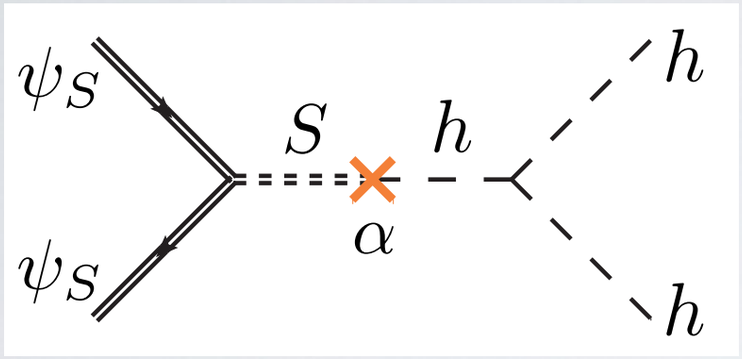
off-shell Higgs processes

very weak bounds

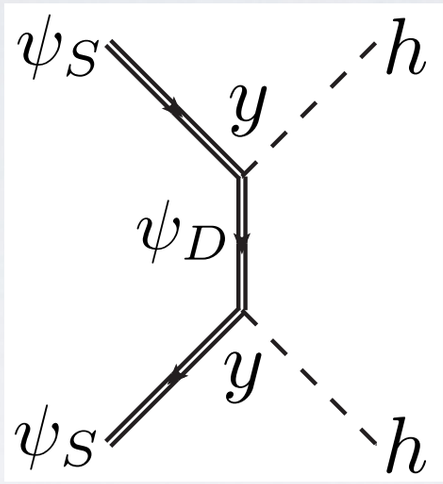
[e.g. Craig et al., arXiv:1412.0258]

UV COMPLETIONS OF FERMION HIGGS PORTAL

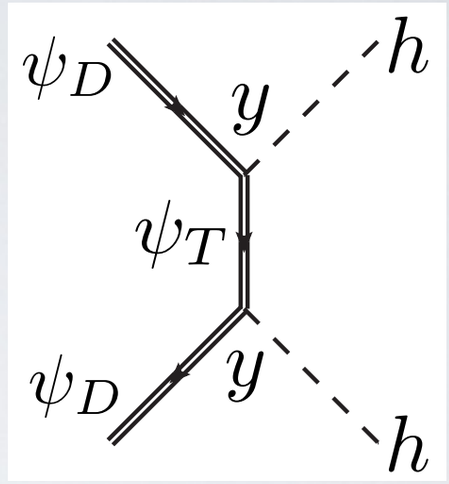
singlet-singlet



singlet-doublet

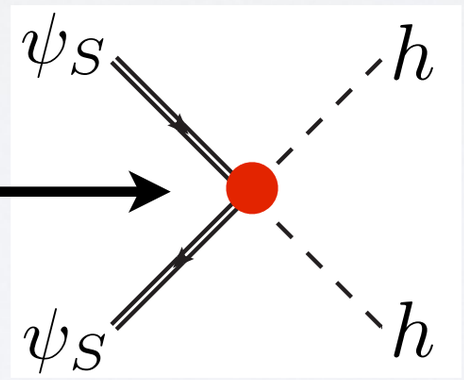


doublet-triplet



$m_D \gg m_S$

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



[Freitas, SW, Zupan, arXiv:1506.04149]

Higgs portal at the LHC is "open"
to mediators with $M_\eta \lesssim \text{few } 100\,\text{GeV}$.

SINGLET-DOUBLET MODEL

Dark fermions mix through Yukawa interaction:

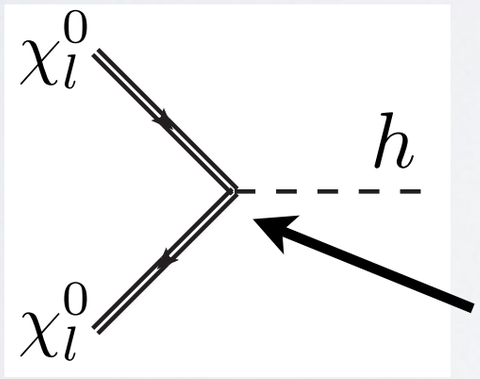
$$\mathcal{L} = -m_D \overline{\psi}_D \psi_D - m_S \overline{\psi}_S \psi_S - (y \overline{\psi}_D H \psi_S + \text{ h.c.})$$

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

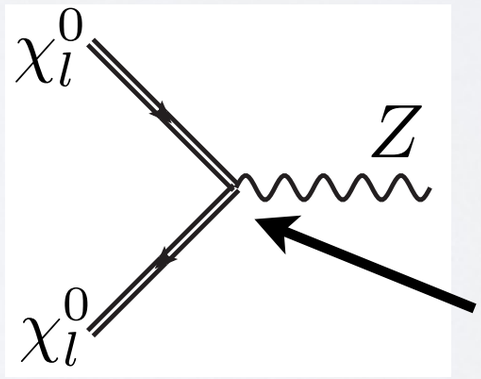
$$\langle H \rangle = v/\sqrt{2} \longrightarrow$$

$$\boxed{\begin{aligned} \chi_l^0 &= \cos\theta \psi_D^0 - \sin\theta \psi_S \\ \chi_h^0 &= \sin\theta \psi_D^0 + \cos\theta \psi_S \end{aligned}}$$

Mixing controls coupling to Higgs and gauge bosons:



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



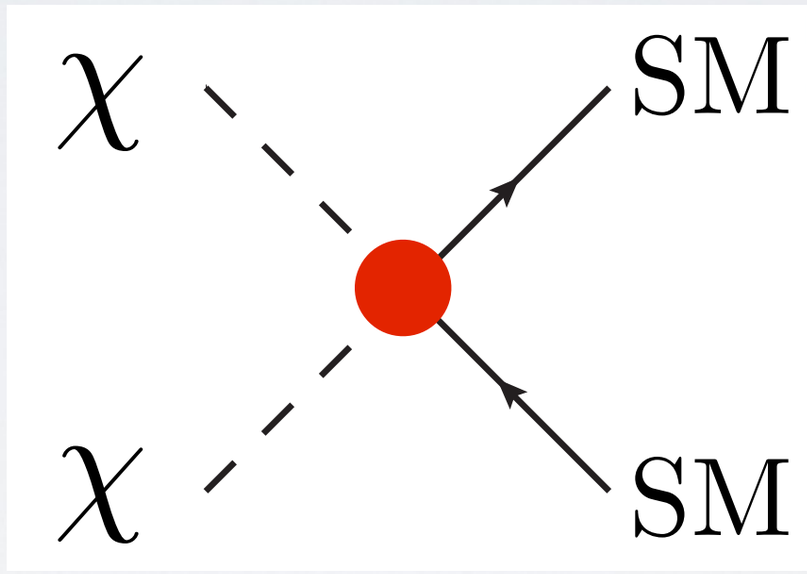
$$-\frac{g}{2c_W} \cos^2\theta$$

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

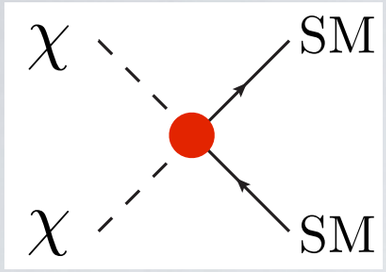
SEARCHES FOR DARK MATTER

indirect detection (annihilation)

direct detection
(scattering)



high-energy colliders (production)



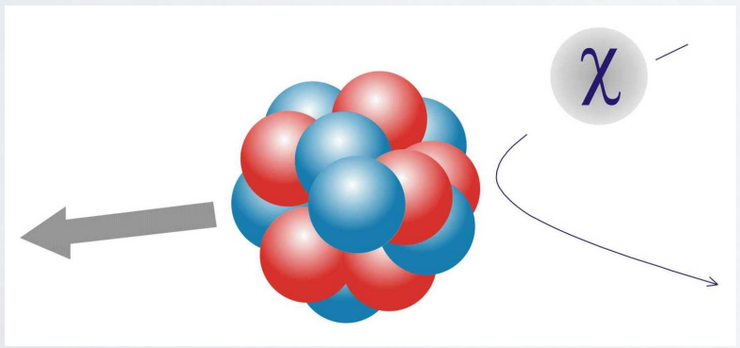
DIRECT DETECTION

Measure recoil of atomic nuclei in shielded place.

e.g. at the Large Underground Xenon experiment LUX

[picture: lux.brown.edu]

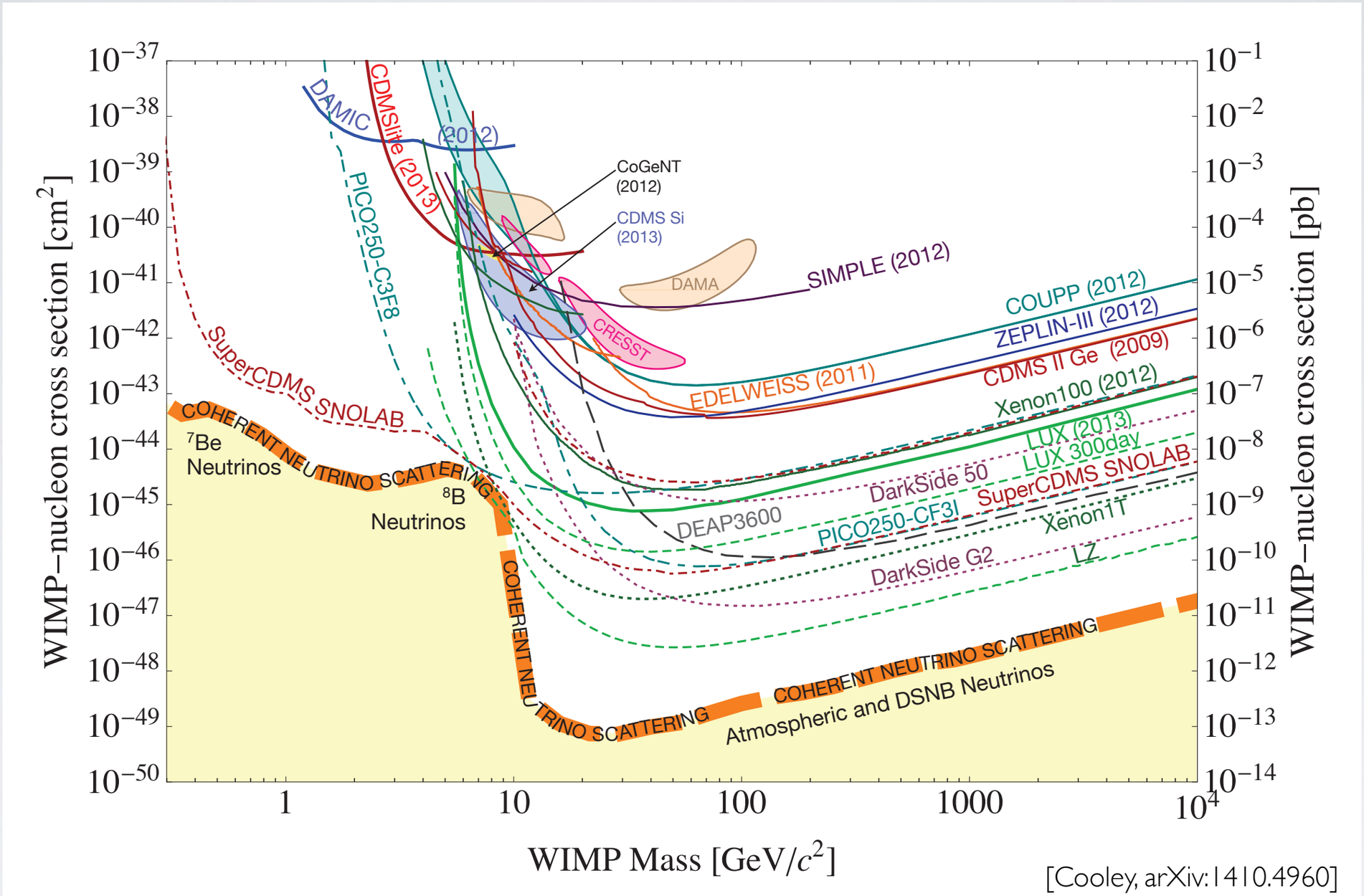
Spin-independent DM-nucleus scattering:



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

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

BOUNDS ON DM-NUCLEUS INTERACTIONS

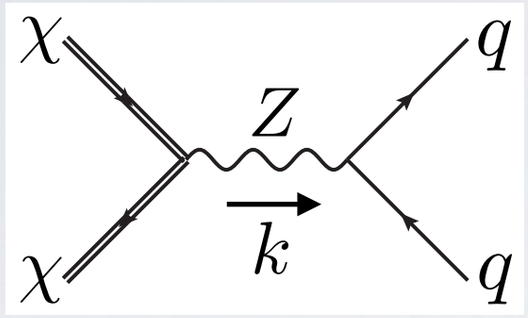


[Cooley, arXiv:1410.4960]

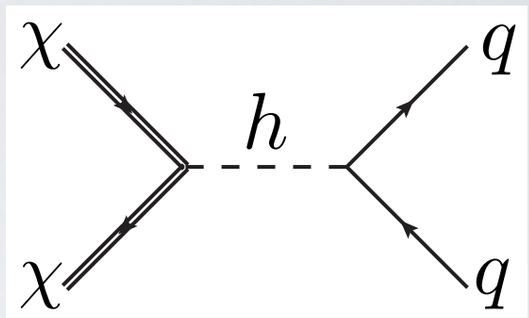
Currently strongest bound on weak-scale DM scattering:

LUX experiment: $\sigma_0(m_\chi \approx 100\,\mathrm{GeV}) \lesssim 10^{-45}\mathrm{cm}^2$ [LUX coll., arXiv:1310.8214]

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:

$$f_{p,n} \sim \frac{g_\chi^Z g_q^Z}{M_Z^2}$$

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

Dirac singlet:

$$g_\chi^Z = -\frac{g}{2c_W}\cos^2\theta$$

$$g_\chi^h = \frac{y}{\sqrt{2}}\sin(2\theta)$$

Majorana singlet:

$$g_\chi^Z = 0$$

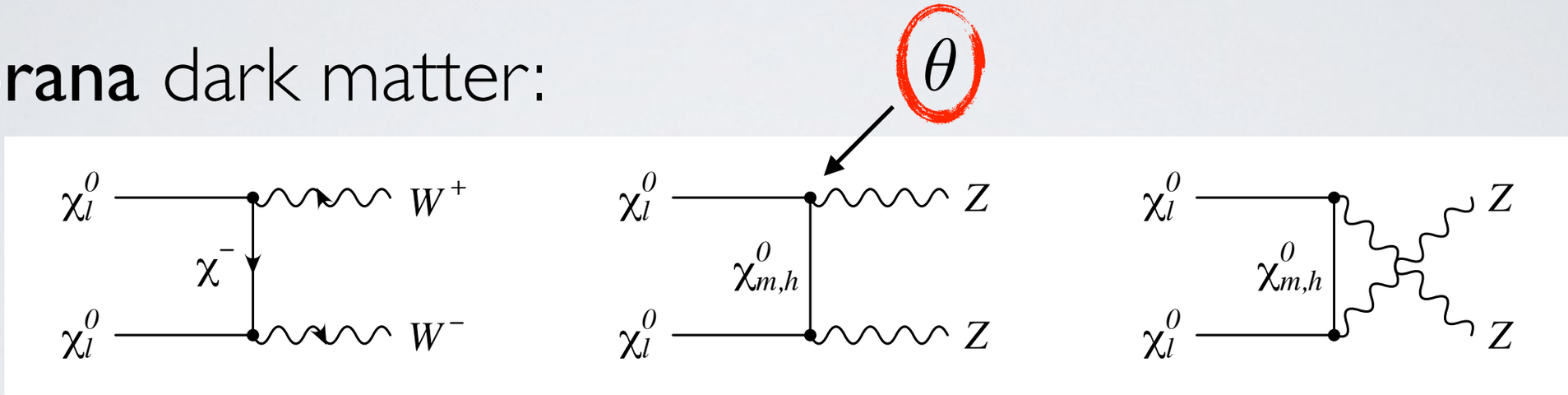
$$g_\chi^h = \frac{y}{2}\sin(2\theta')$$

LUX bound ⟶ 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:

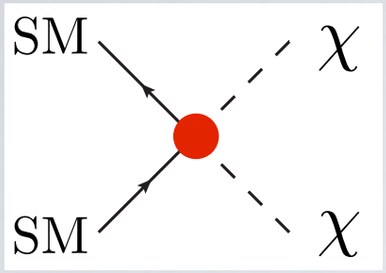


Observed abundance: $\Omega_\chi h^2 = 0.1199 \pm 0.0022$ [Planck coll., arXiv:1502.01589]

LUX results strongly constrain DM annihilation rate.

Co-annihilation $\chi_l^0\chi^+, \chi_l^0\chi_m^0$ prevents over-abundance.

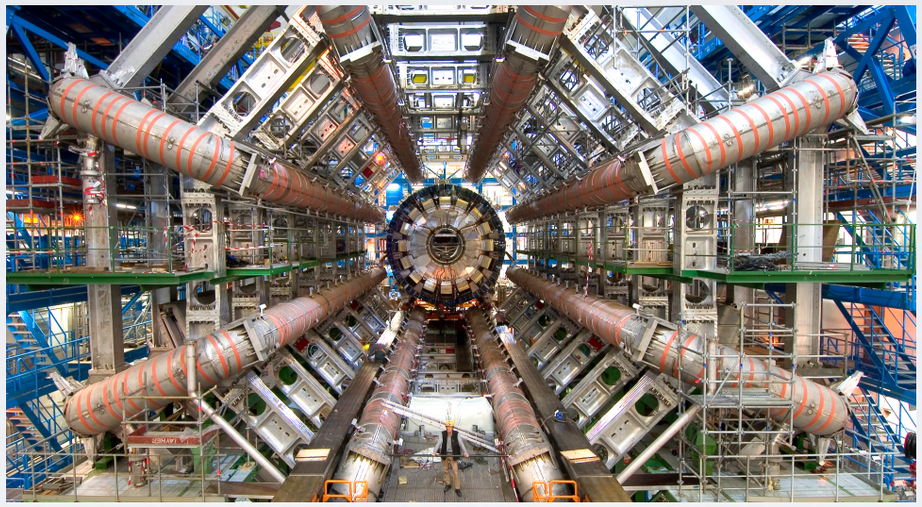
Exception: Higgs-resonance region for Majorana DM.



COLLIDER SEARCHES

Look for missing energy or production of mediators.

e.g. at the Large Hadron Collider LHC

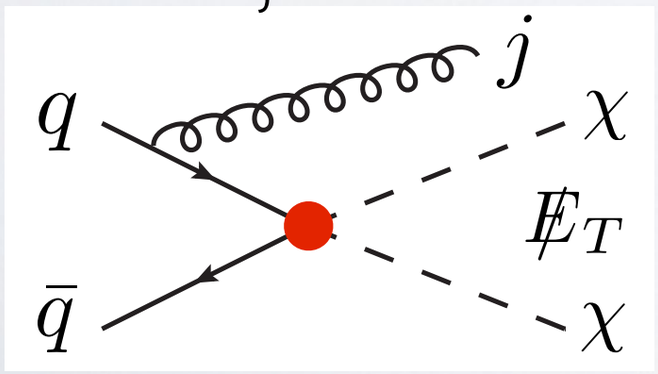


[ATLAS experiment, CERN]

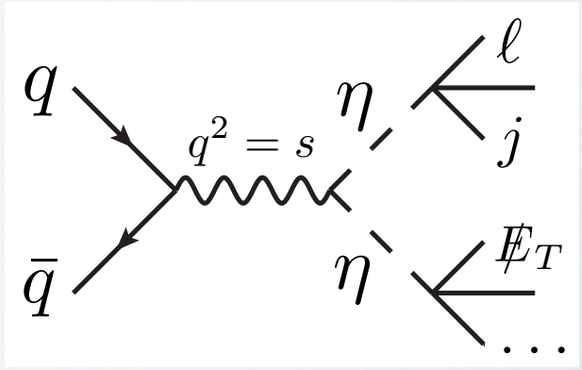
Dark matter production in proton-proton collisions:

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

Mono-jet searches



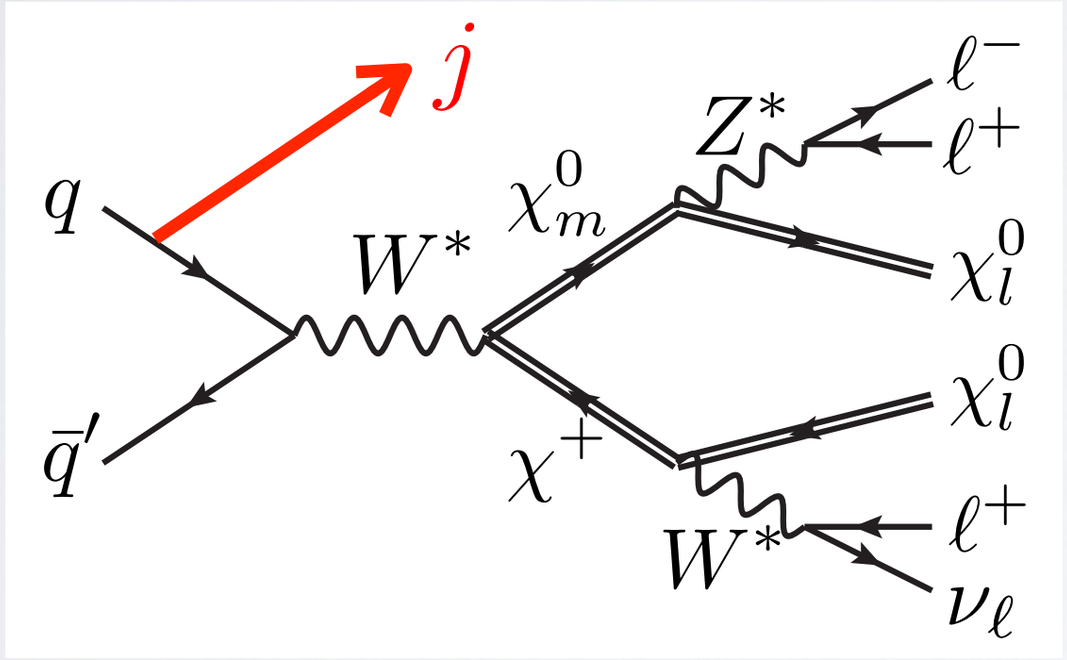
Mediator searches



DARK FERMION SEARCHES AT THE LHC

Relic abundance and direct detection:
Small mass splittings $m_m^0 - m_l^0, m^+ - m_l^0 \longrightarrow$ soft decay products.

Hard jet helps to trigger on soft-lepton events:



LHC Run II:

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

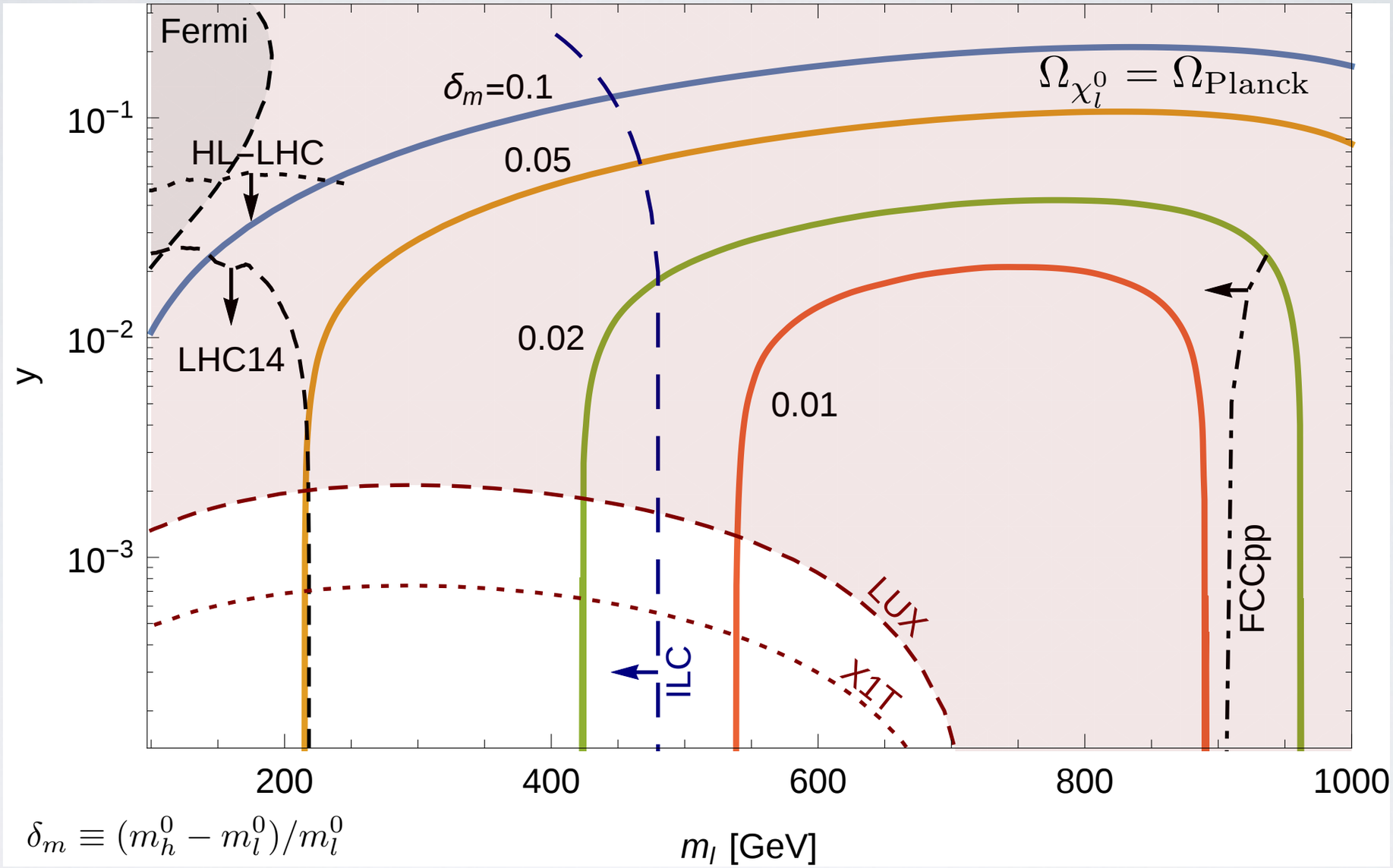
$$p_T(j_1) > 300\,\mathrm{GeV}$$

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

[Schwaller, Zurita, arXiv:1312.7350, et al.]

Cross section too small for mono-jet searches at the LHC.

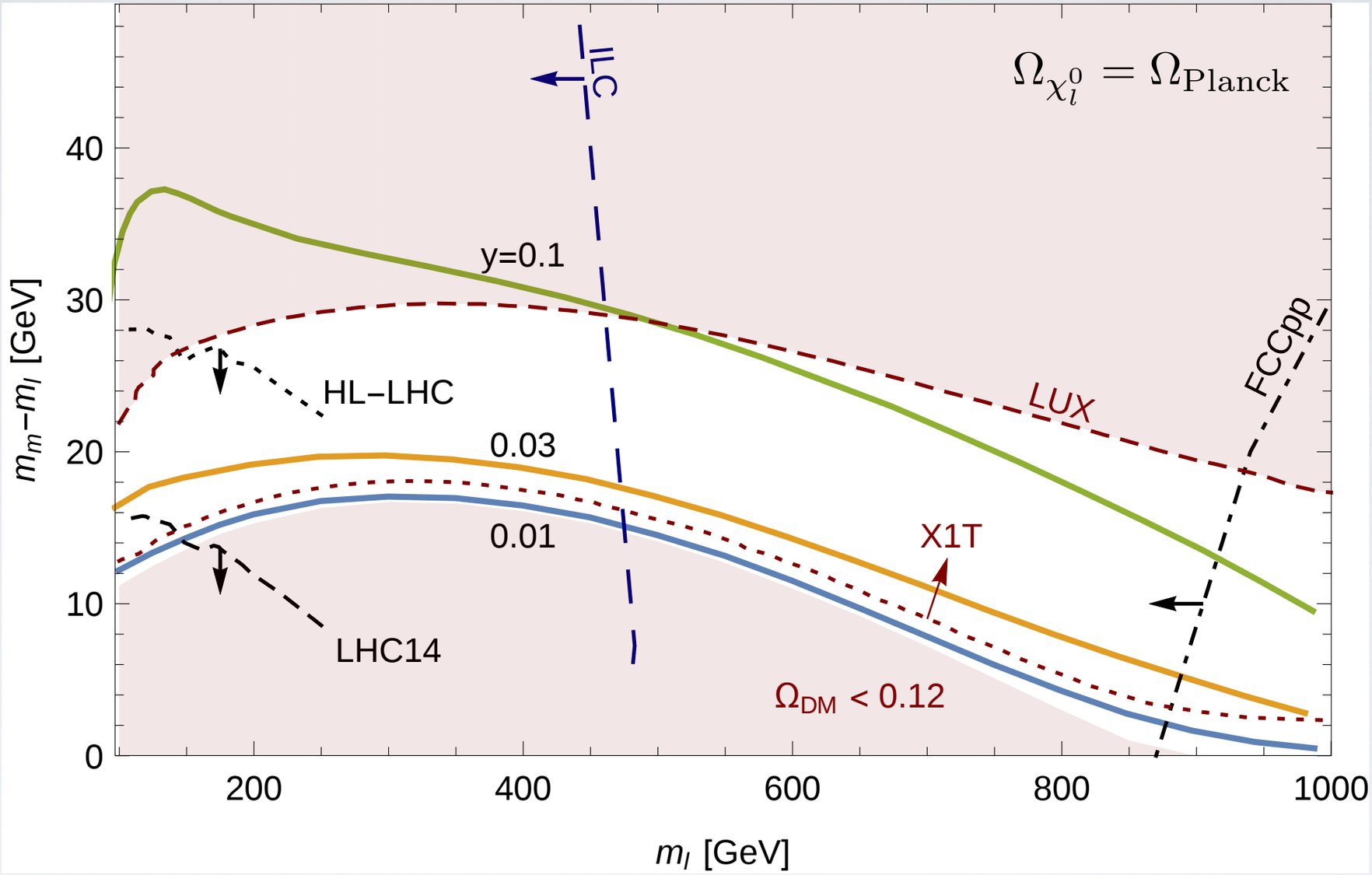
SUMMARY DARK DIRAC FERMIONS



[Freitas, SW, Zupan, arXiv:1506.04149]

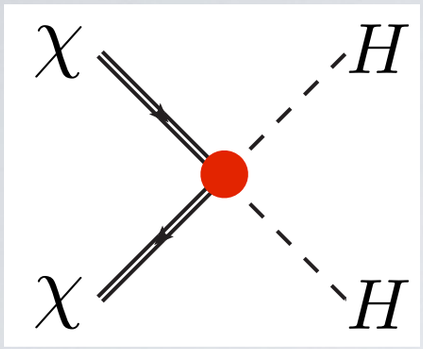
Need high-energy collider to test this model conclusively.

SUMMARY DARK MAJORANA FERMIONS



[Freitas, SW, Zupan, arXiv:1506.04149]

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



TAKE HOME

Higgs-portal fermion dark matter

- **Mediators** can be searched for in signatures with soft leptons at the LHC.

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

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