The Search for Dark Matter

Current Status & Future Prospects

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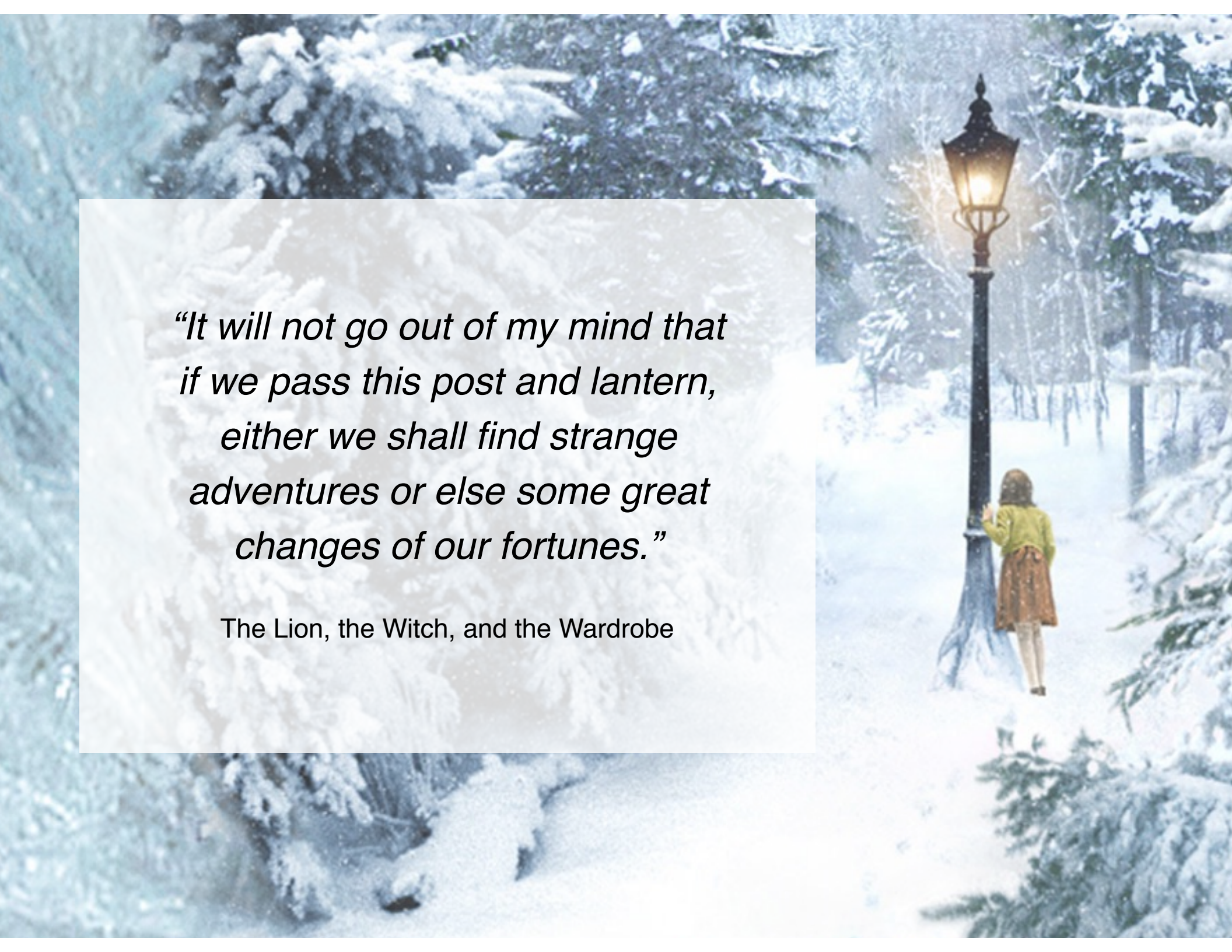
Princeton University

LHCP Conference—August 31, 2015



“It will not go out of my mind that if we pass this post and lantern, either we shall find strange adventures or else some great changes of our fortunes.”

The Lion, the Witch, and the Wardrobe

The Lamp Post

The WIMP paradigm has been the primary guide for the current dark matter experimental program

WIMP paradigm relies on a few basic assumptions:

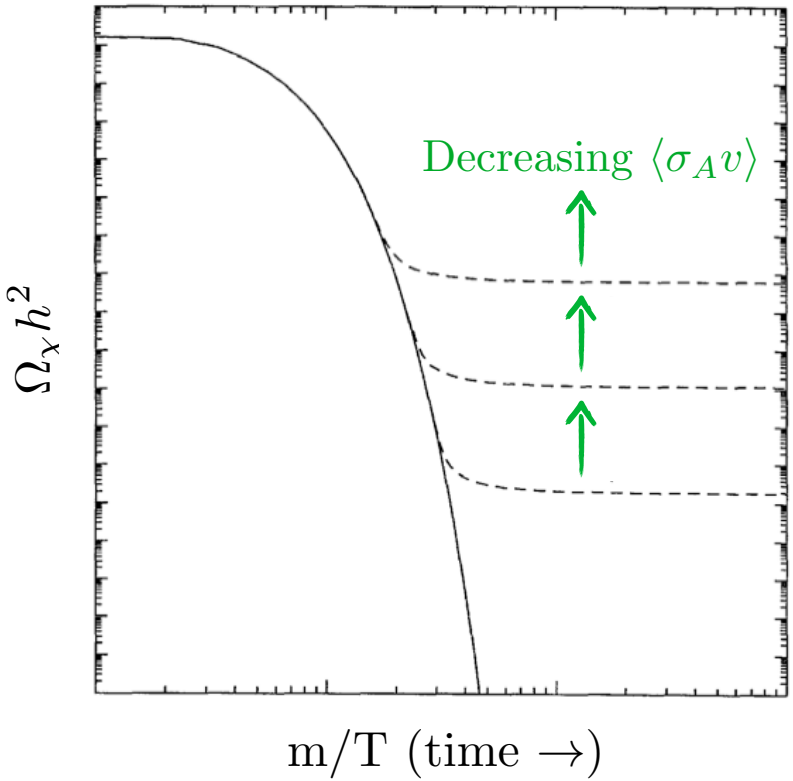
Single Particle

Weakly Interacting

Mass ~$10^{2\text{-}3}$ GeV

The Lamp Post

Dark matter is in thermal equilibrium in early Universe, until its interactions "freeze-out"



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle}$$

$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

Planck + WMAP:

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

Three Vignettes

Direct Detection

Indirect Detection

Collider Searches

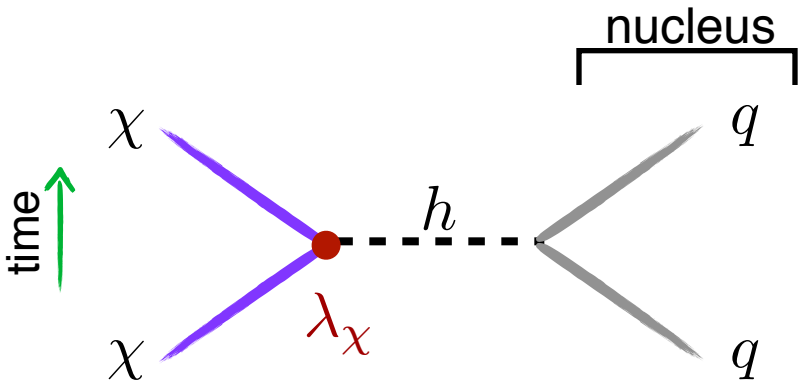
Three Vignettes

	Current Status	Future Prospects
Direct Detection		
Indirect Detection		
Collider Searches		

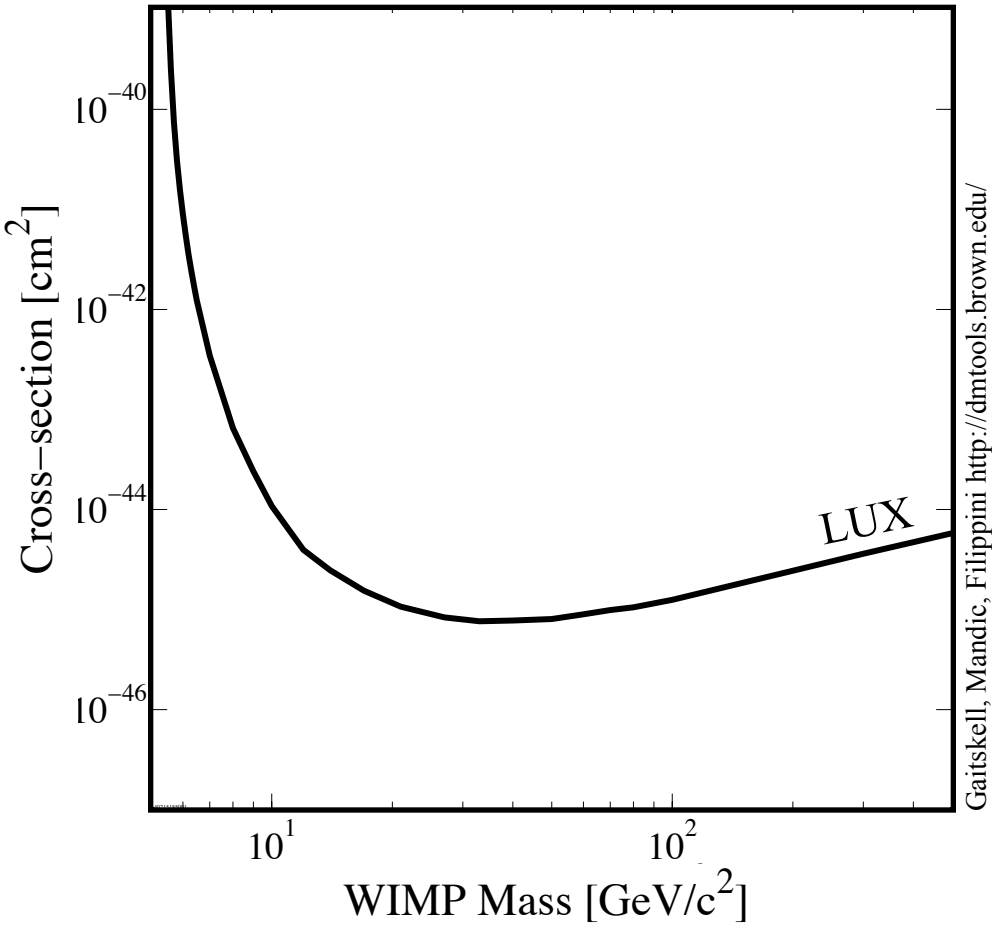
Higgs Exchange

Dark matter scattering off nuclei in underground detector

Spin-independent interaction due to Higgs exchange



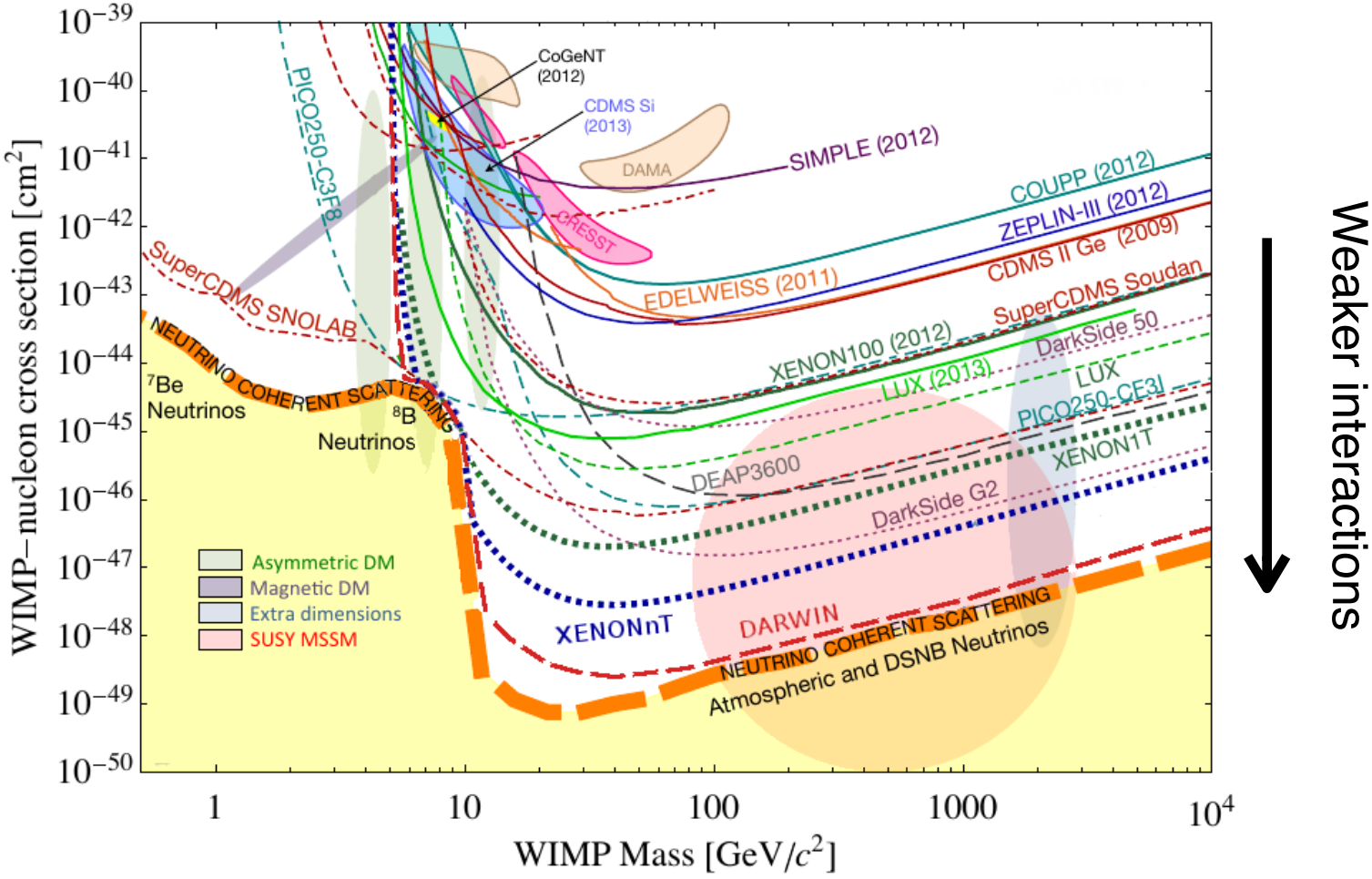
$$\sigma_{\chi N \to \chi N} \simeq 10^{-45}\ \lambda_\chi^2 \quad \mathrm{cm}^2$$



LUX Collaboration [1310.8214]

Next Frontiers

MeV to GeV masses



Weaker interactions

Questions to Explore

New model frameworks needed?

e.g., WIMPless, Asymmetric, SIMP dark matter

Feng and Kumar [0803.4196], Nussinov [Phys. Lett. B]; Kaplan, Luty, and Zurek [0901.4117]; Hochberg, Kuflik, Volansky, and Wacker [1402.5143]

New experimental strategies needed?

e.g., dark-matter-electron scattering

Essig, Mardon, Volansky [1108.5383]; Graham, Kaplan, Rajendran, Walters [1203.2531], Essig *et al.* [1206.2644]; Lee, **ML**, Safdi, Sharma [to appear]

Changes to standard phenomenology?

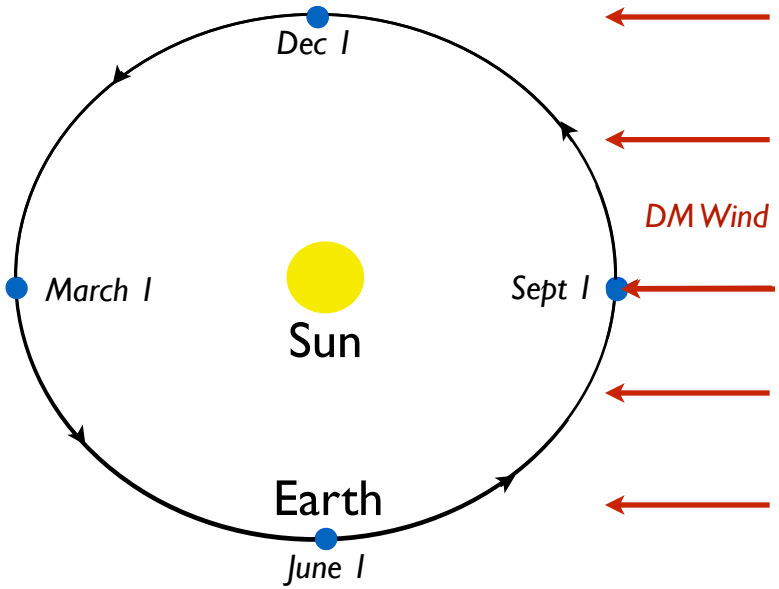
e.g., gravitational focusing and effects on modulation phase

Lee, **ML**, Peter, and Safdi [1308.1953]

Annual Modulation

Standard Modulation Picture

Maximum scattering rate in June, when Earth travels into 'wind'

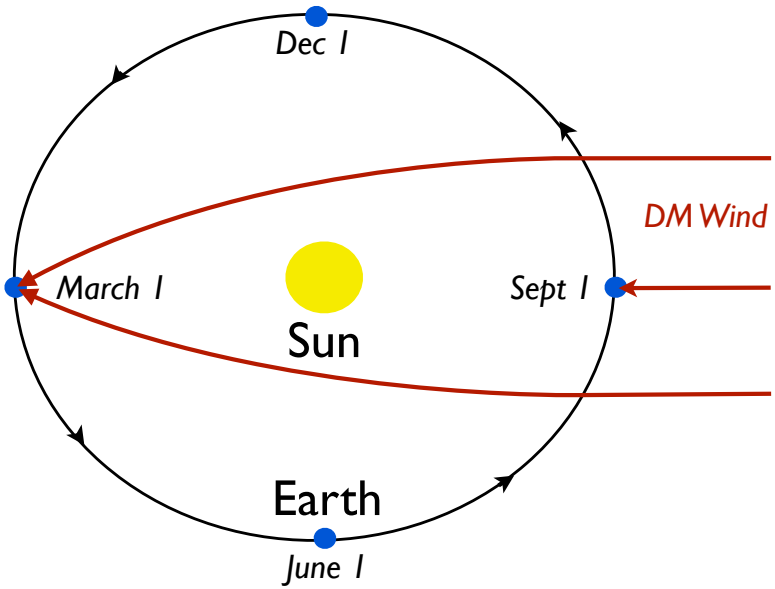


Drukier, Freese, and Spergel [PRD]
Review: Freese, **ML**, Savage [1209.3339]

With Gravitational Focusing

Sun's potential deflects incoming, unbound dark matter particles

Shifts the phase of the modulation

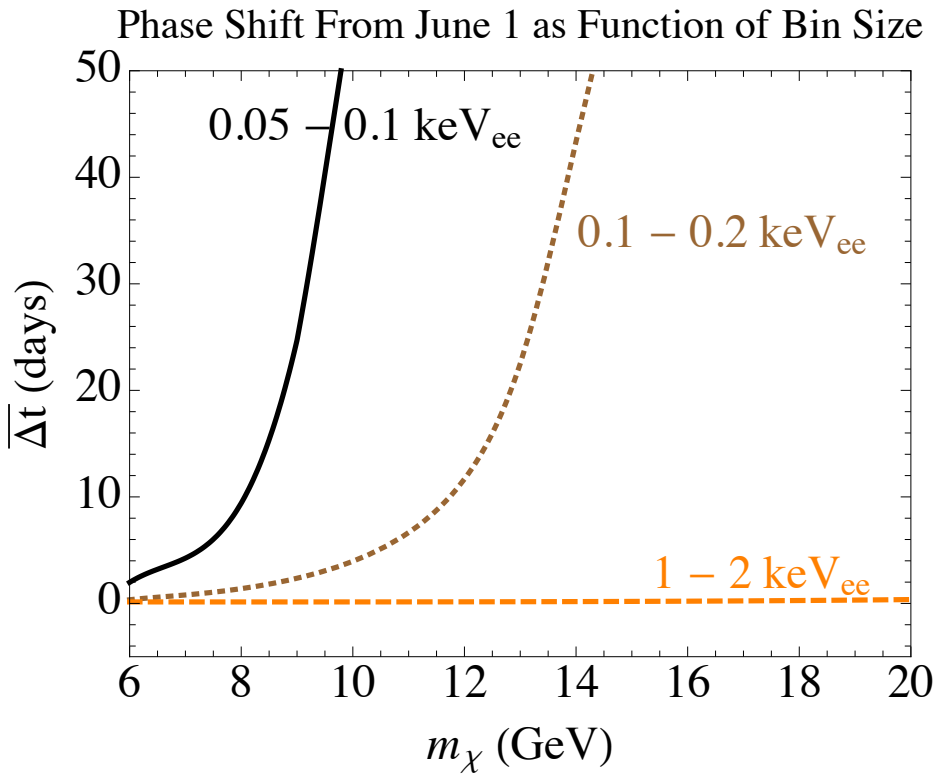


Griest, PRD 1988.
Alenazi and Gondolo [astro-ph/0608390]
Lee, **ML**, Peter, and Safdi [1308.1953]

Example: SABRE

Proposed experiment using ultra-high purity NaI(Tl) crystals

Depending on threshold energy, the phase of a modulation signal can be affected by gravitational focusing



Shields, Xu, Calaprice [Phys. Procedia]

Three Vignettes

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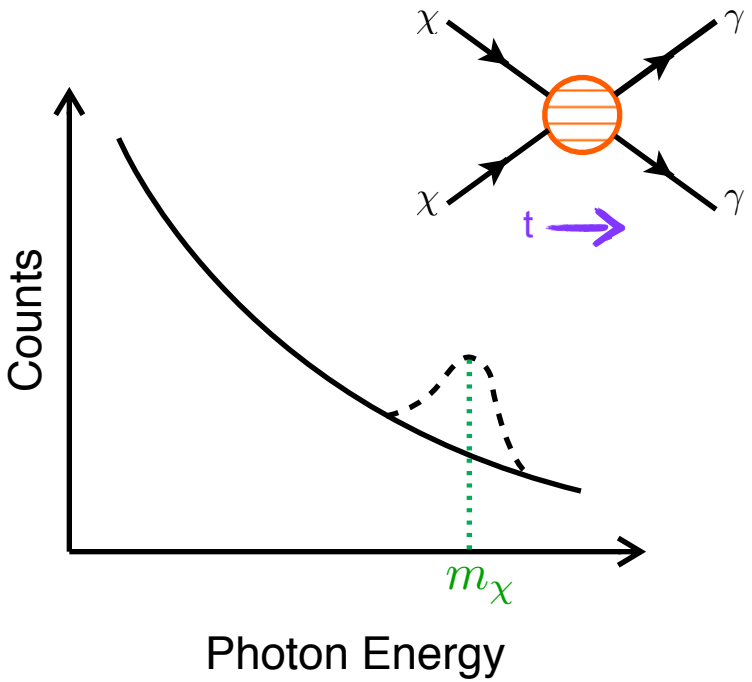
Dark Matter Annihilation

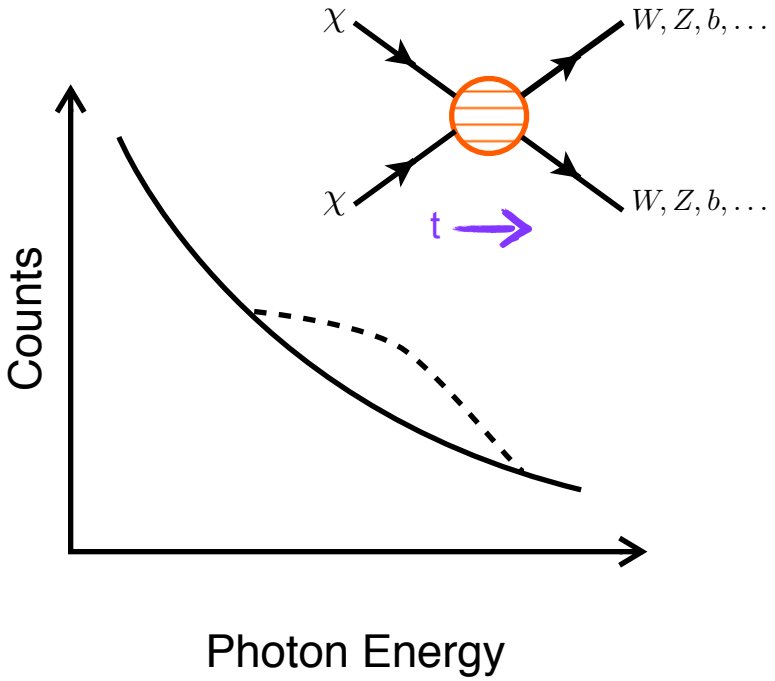
Monochromatic Photons

Direct decay to photons,
a line in photon energy spectrum



Continuum Photons

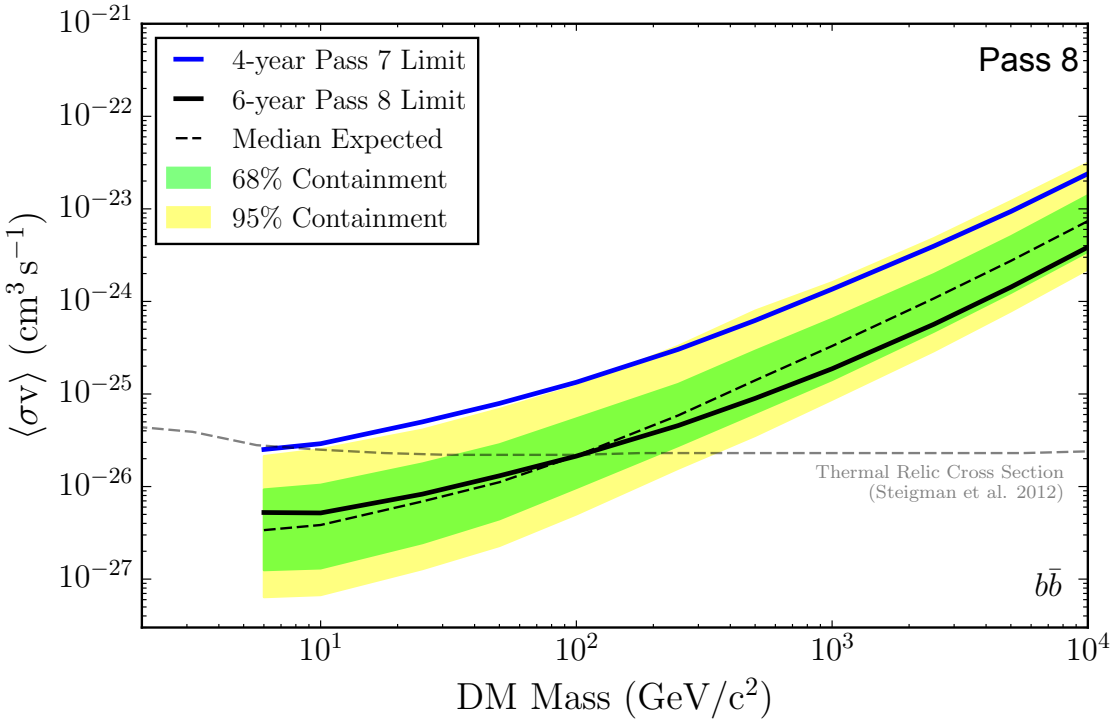
Annihilation to Standard Model final
states that shower into photons



Dwarf Galaxies

Six years of data from *Fermi* LAT used to search for gamma-ray emission from 15 dwarf spheroidal satellite galaxies

Current limits probe thermal relic annihilation cross sections for weak-scale dark matter



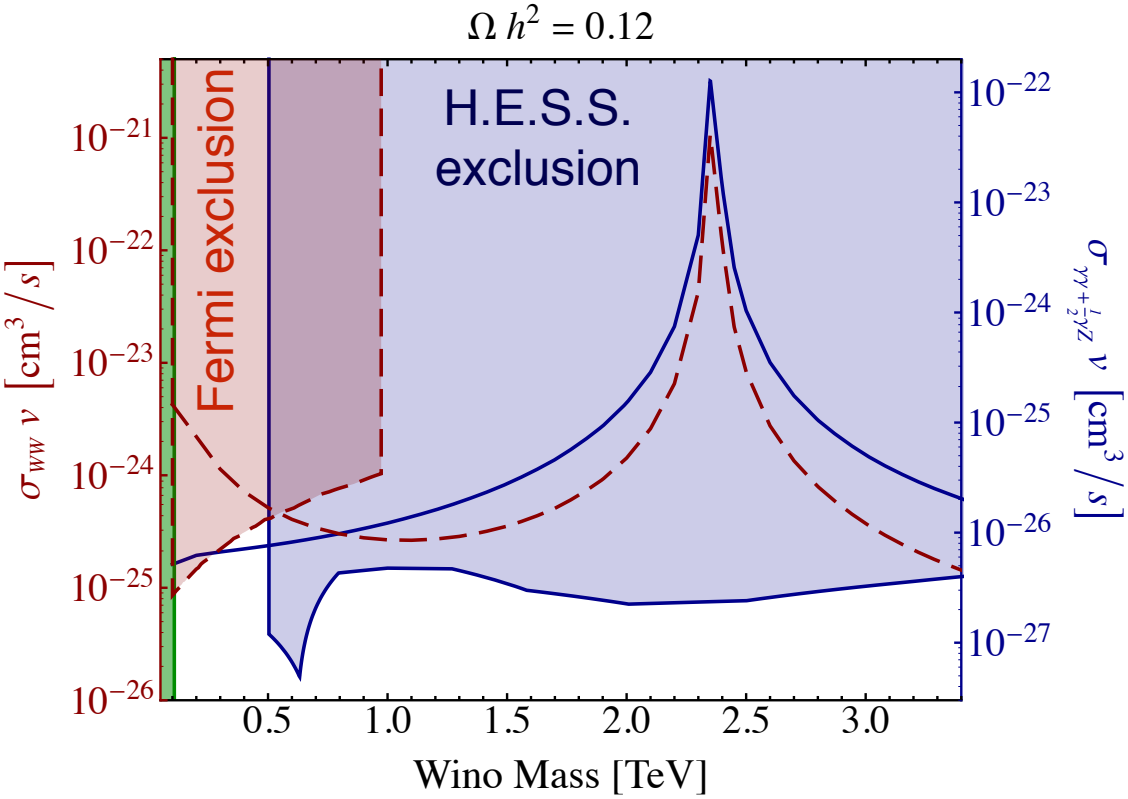
Ackermann *et al.* [1503.02641]

Heavy Relics

Limits from Cherenkov telescopes complement those from Fermi

Increased sensitivity to TeV-scale thermal relics

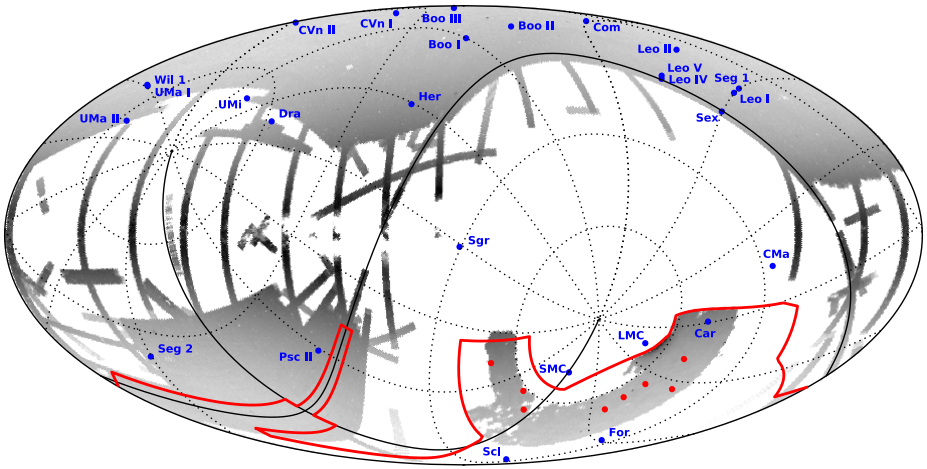
Example: Tight constraints on wino dark matter from H.E.S.S.



H.E.S.S. Collaboration [1301.1173]
Cohen, **ML**, Pierce, Slatyer [1307.4082]

New Targets

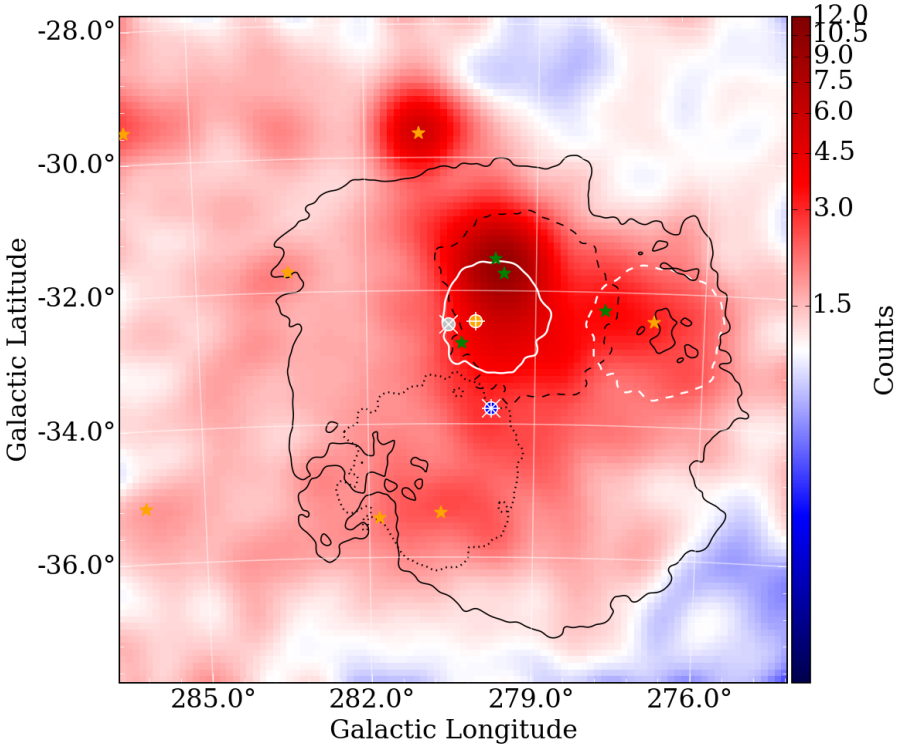
Evidence for 8 new dwarf candidates from Dark Energy Survey



● Known satellite galaxies ● DES candidates

Bechtol *et al.* [1503.02584]; Koposov *et al.* [1503.02079].

Annihilation constraints from the Large Magellanic Cloud



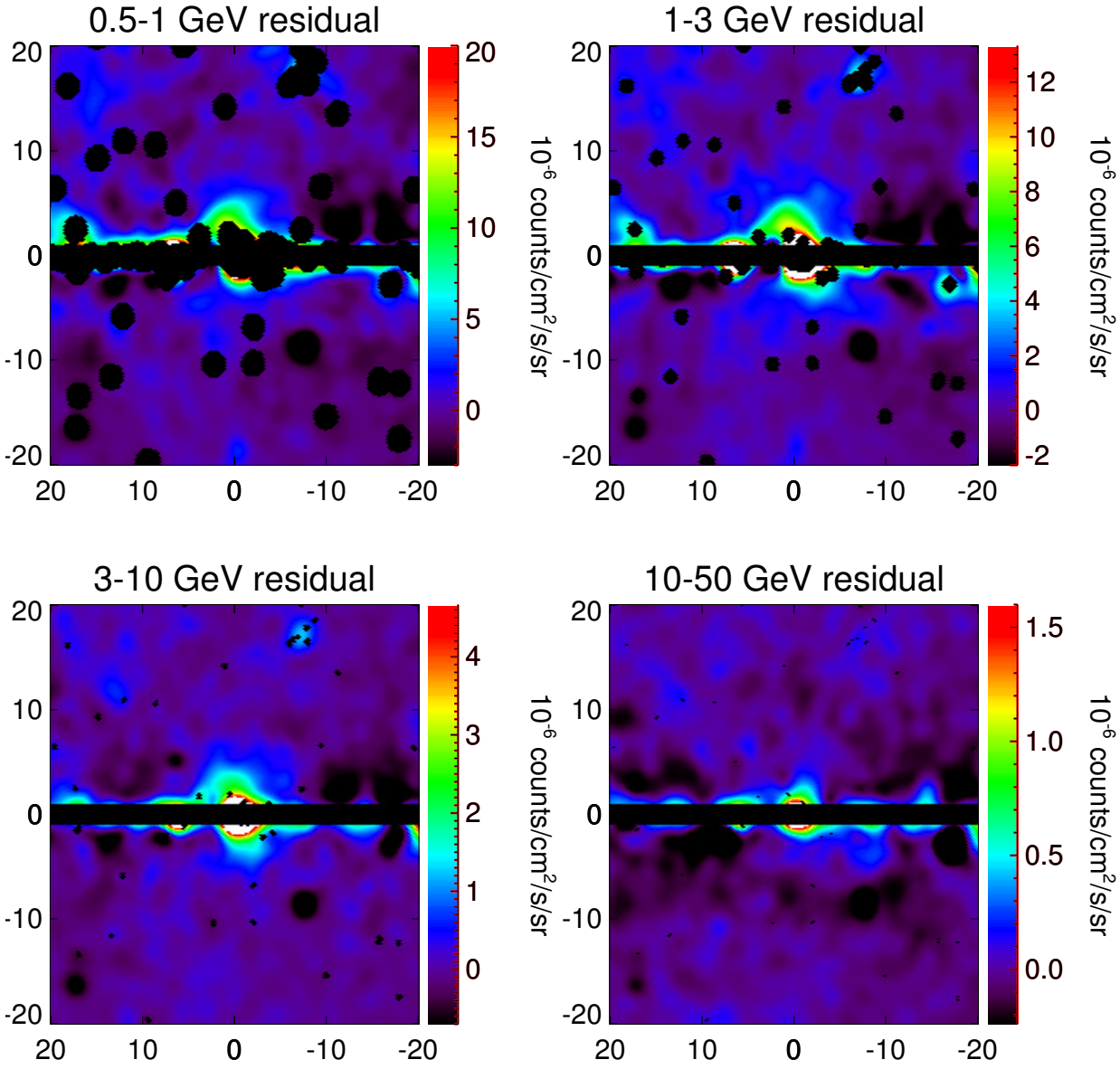
Buckley *et al.,* [1502.01020]

Galactic Center

Excess of GeV photons at the Galactic Center and Inner Galaxy ($\lesssim 10^\circ$)

High statistical significance

Energy spectrum consistent with dark matter signal

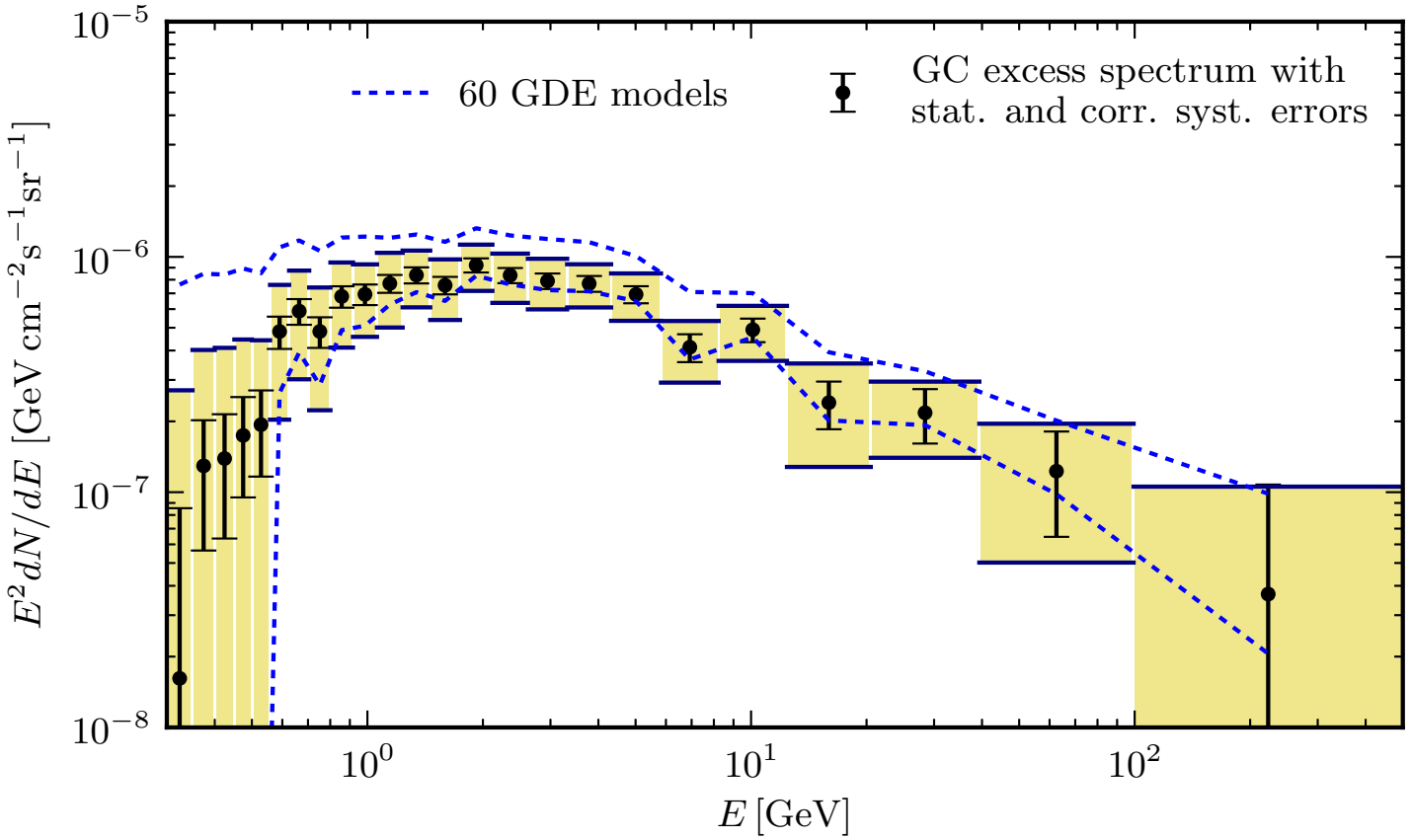


Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian *et al.* [1402.4090]
Daylan *et al.* [1402.6703]
Calore, Cholis, and Weniger [1409.0042]

Daylan *et al.* [1402.6703]

Diffuse Background

Evidence for excess emission appears to be robust even under uncertainties in diffuse emission models



Calore, Cholis, and Weniger [1409.0042]

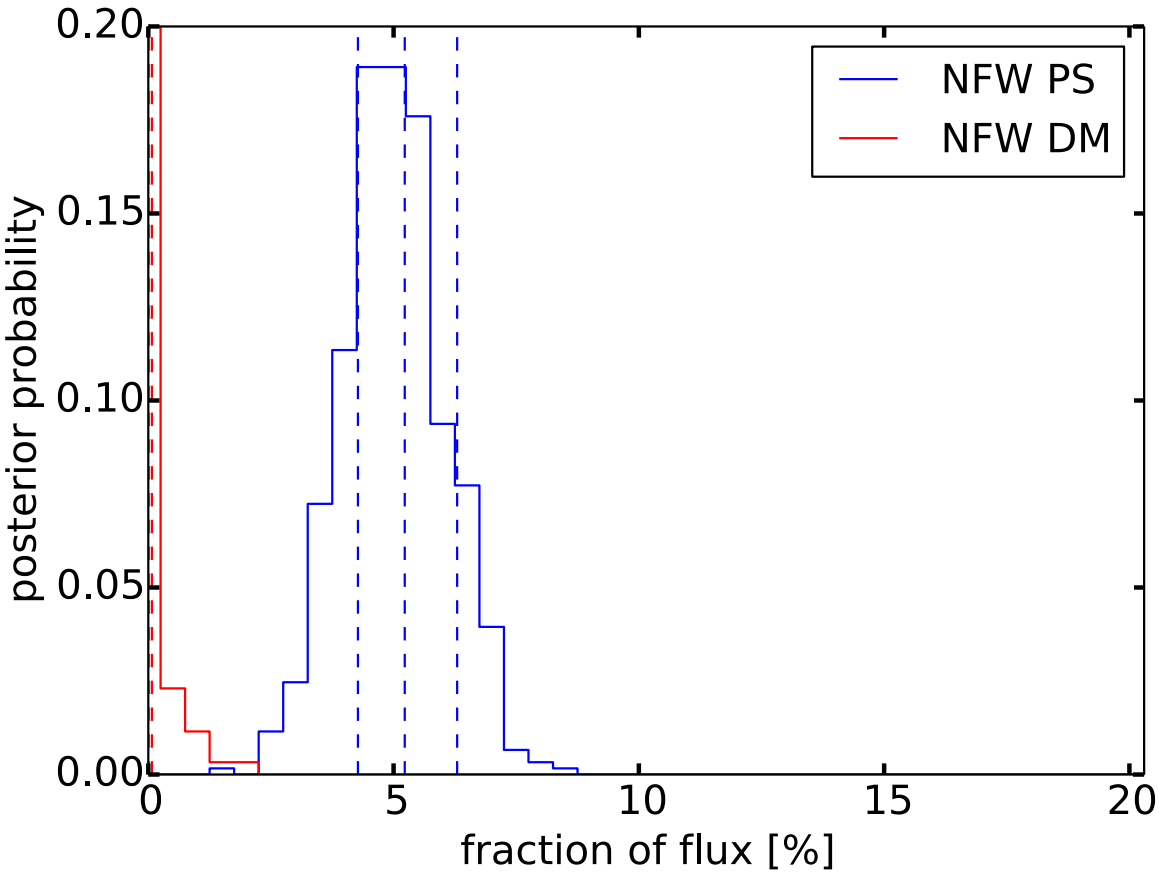
Unresolved Point Sources

Photon count statistics can distinguish point sources from dark matter

Malyshev and Hogg [1104.0010]; Lee, **ML**, Safdi [1412.6099]

Excess flux in the Inner Galaxy may be explained by a population of unresolved point sources

Lee, **ML**, Safdi, Slatyer, Xue [1506.05124]; Bartels, Krishnamurthy, Weniger [1506.05104]



Three Vignettes

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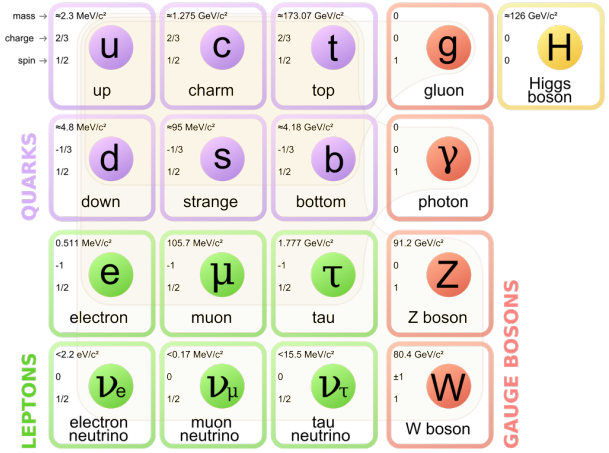
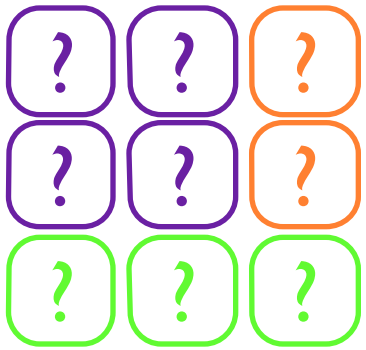
Collider Searches		

Minimal Scenario

Visible Sector

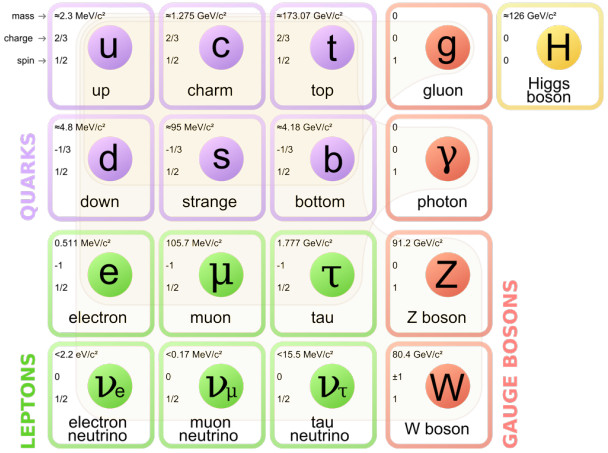




$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

Minimal Scenario

Visible Sector



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Minimal model (susy-inspired)

$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

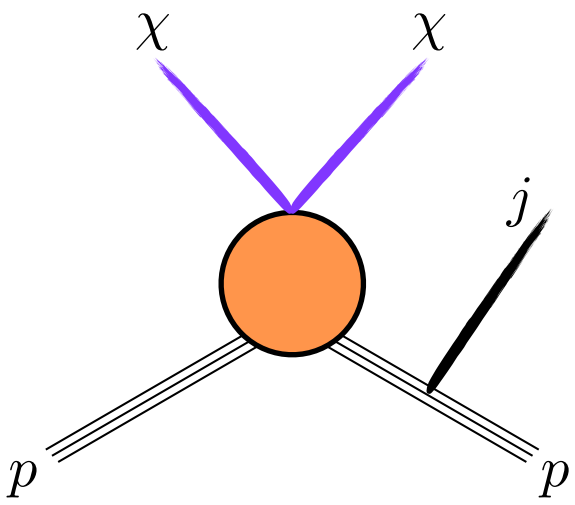
Monojet Searches

Dark matter can be directly produced in LHC collisions

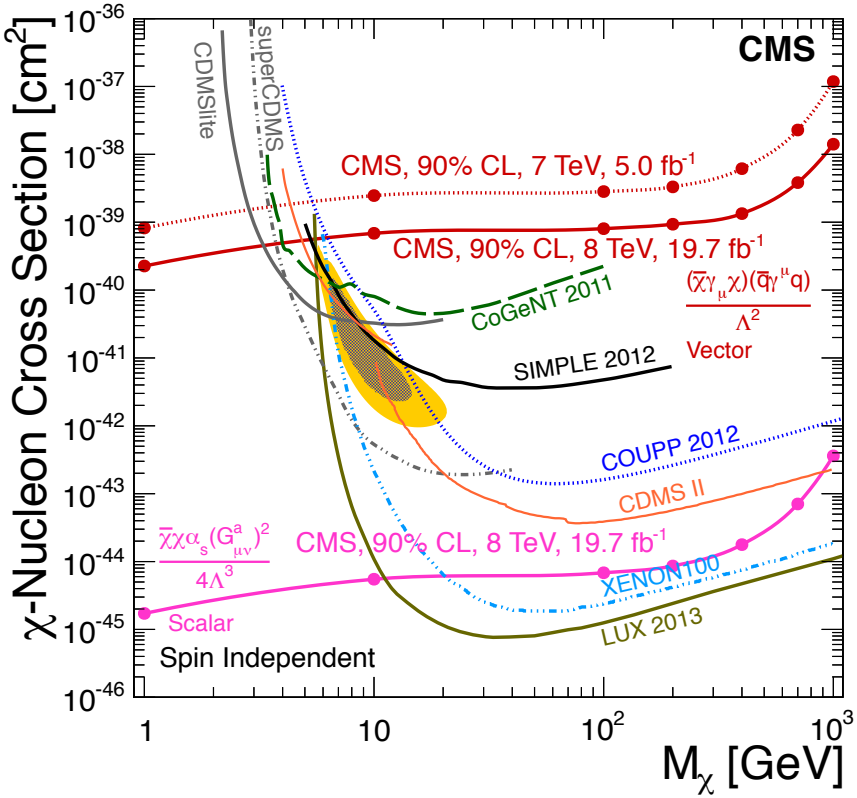
Monojet searches are particularly relevant:

Fox, Harnik, Kopp, Tsai [1109.4398]

Rajaraman, Shepherd, Tait, Wijangco [1108.1196]



1 jet + missing energy



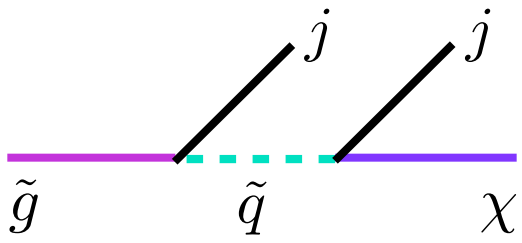
CMS Collaboration [1408.3583]

Colored Particle Production

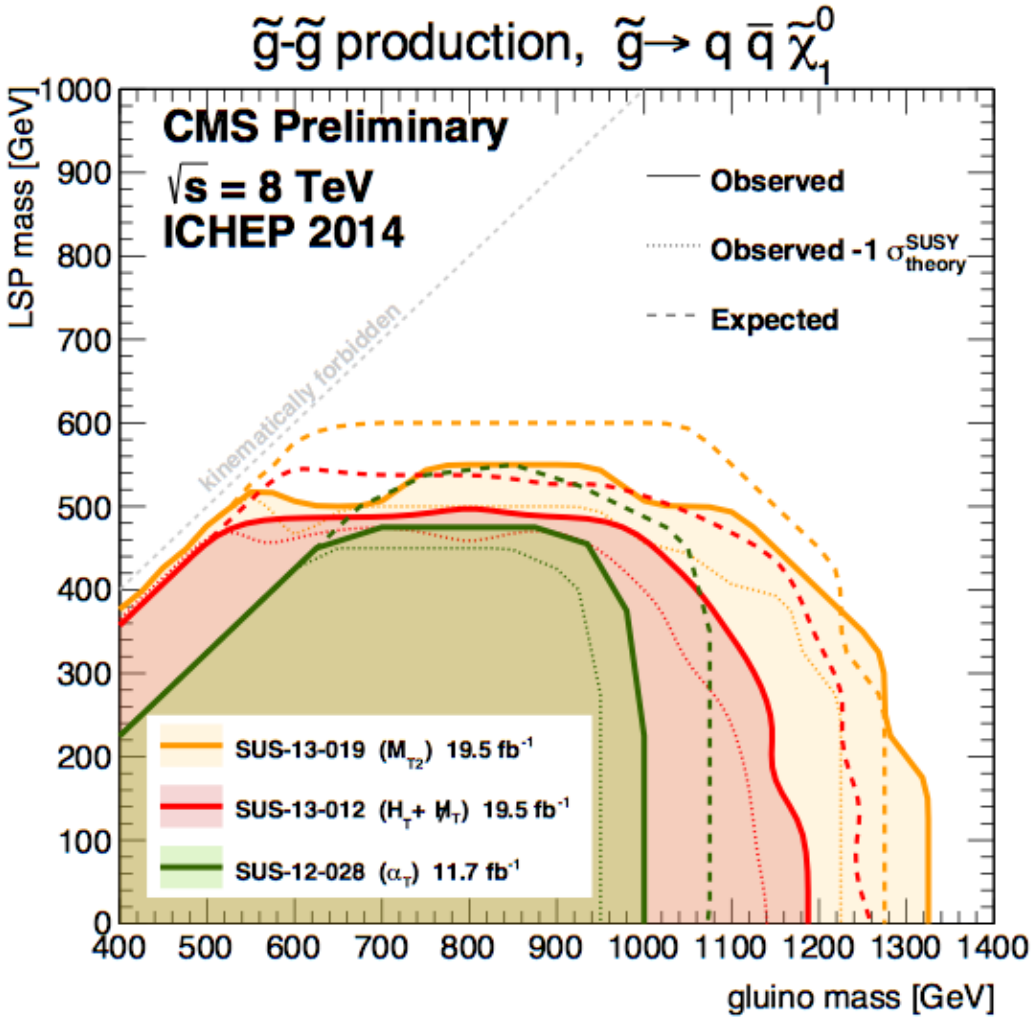
Dark matter can also be produced in decays of new colored particles

Takes advantage of large colored production cross section

Events typically have several jets and missing energy

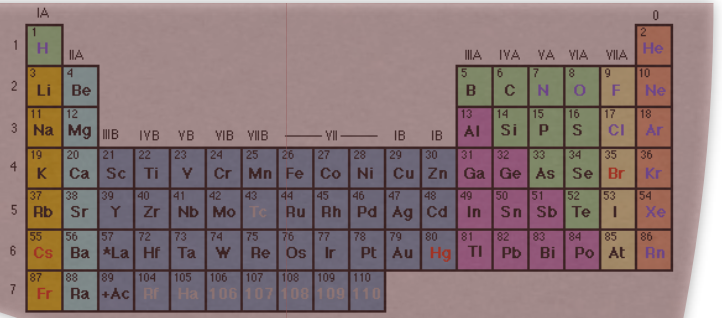


4 jets + missing energy



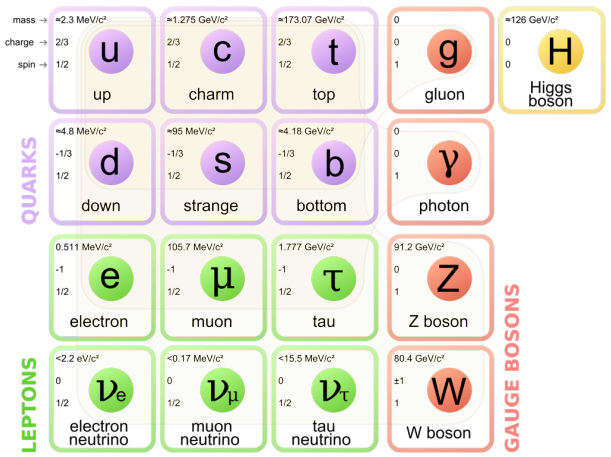
Maybe minimality is not necessarily the best guide in the search for dark matter

Why should 5% of the mass density have all the fun?



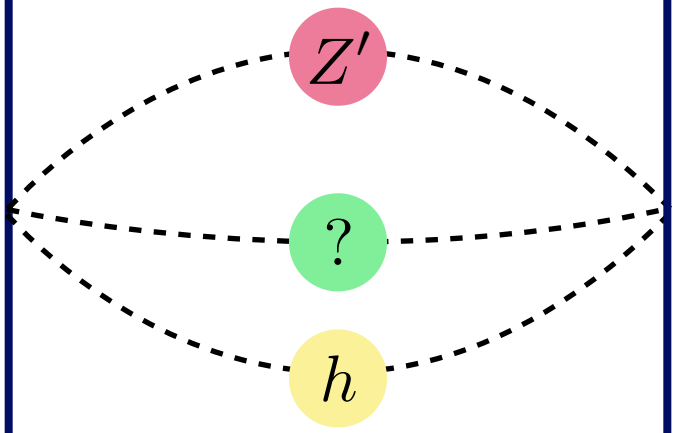
Hidden Dark Sector

Visible Sector

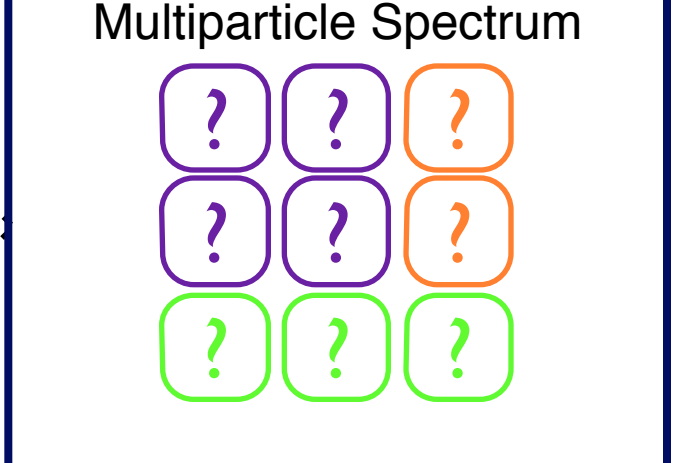


$SU_c(3) \times SU_L(2) \times U_Y(1)$

Portal



Dark Sector



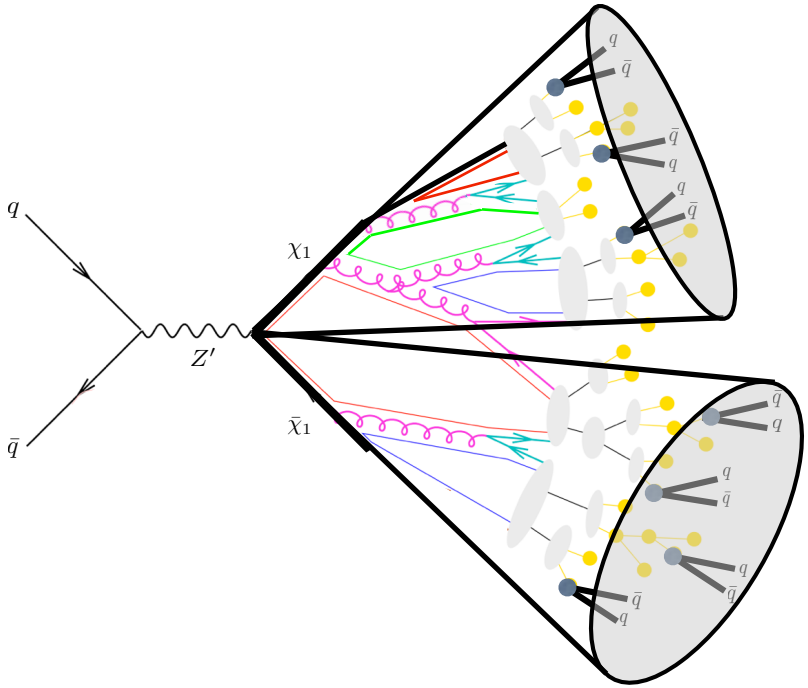
For instance: Hidden Valley Models, Higgs Portal Models

e.g., Strassler and Zurek [hep-ph/0604261, hep-ph/0605193];
Strassler [hep-ph/0607160]; Patt and Wilczek [hep-ph/0605188]; …

New Observables

Non-minimal dark sectors may result in complicated final states with many particles, displaced vertices, unusual tracks, …

Some of these final states may require fundamentally different search strategies at the LHC



Example: Semi-Visible Jets

Jets that contain both visible hadronic states, interspersed with stable neutral particles

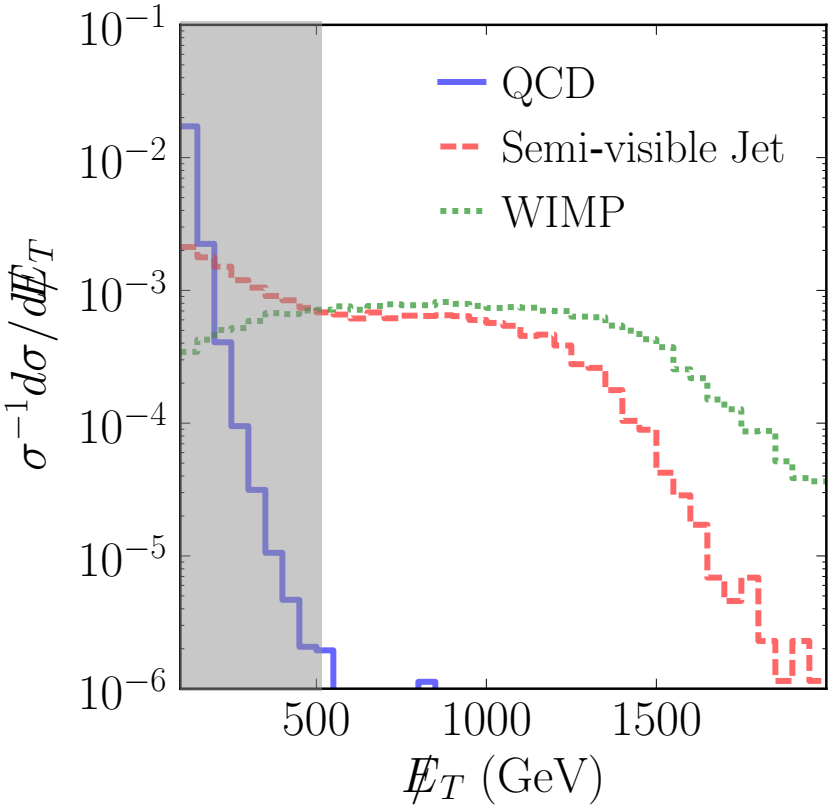
Cohen, **ML**, Lou [1503.00009]

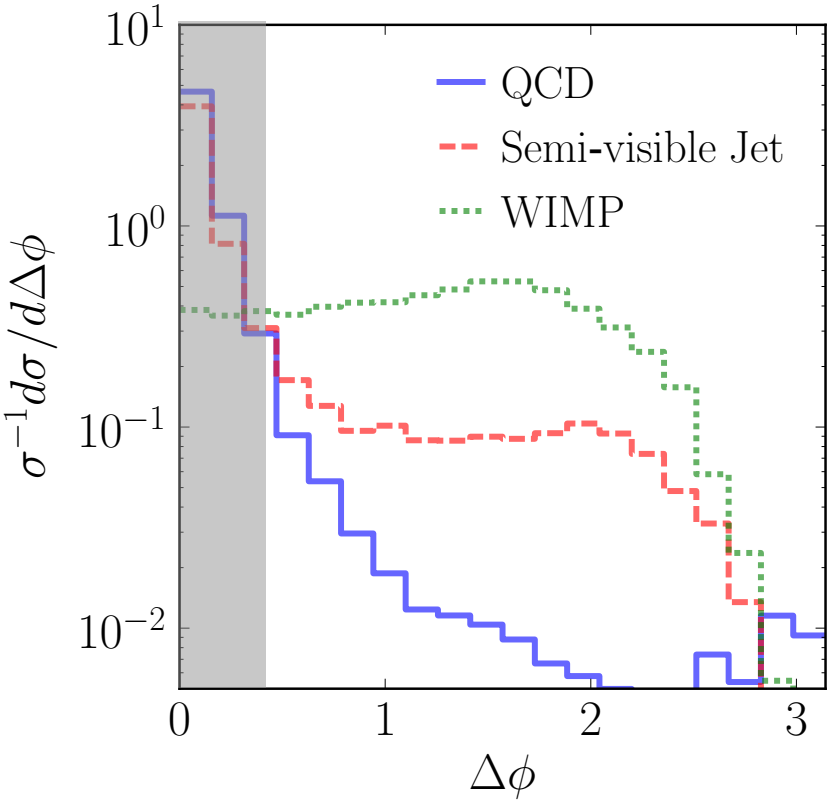
Semi-Visible Jets

Typical LHC searches require $\Delta\phi \gtrsim 0.4$

Acceptance after $\Delta\phi \gtrsim 0.4$ & MET > 500 GeV :

$\sim 70\%$ WIMP $\quad\quad$ $\sim 7\%$ Semi-visible jet

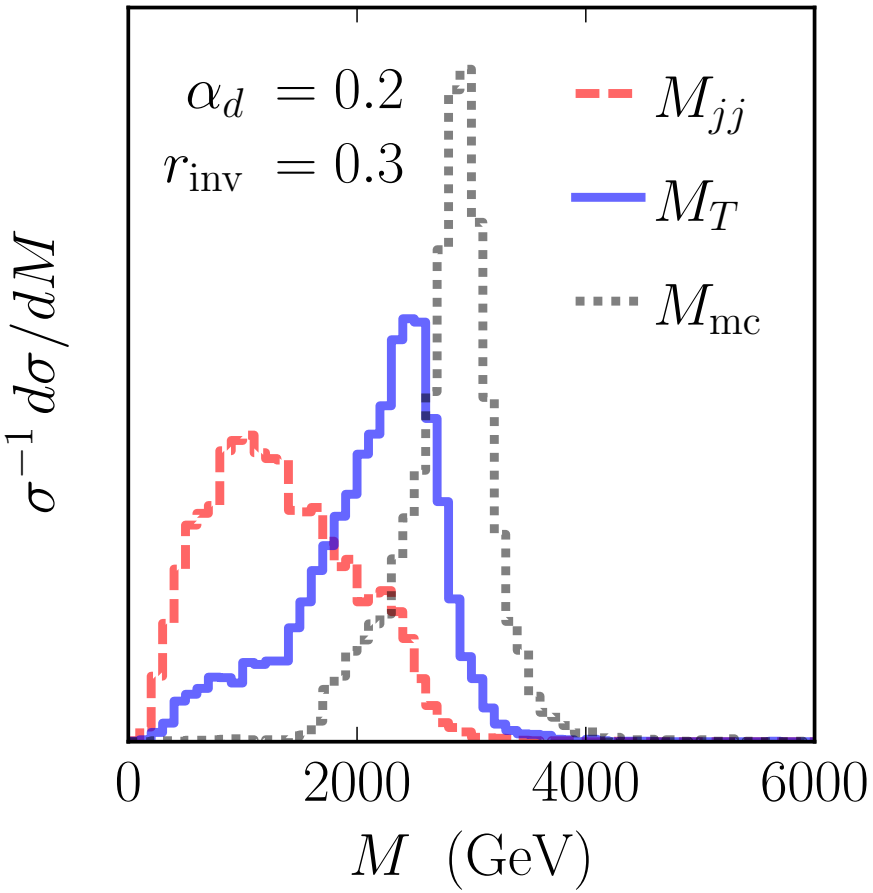




Transverse Mass

Cluster event into two large-radius jets (*i.e.*, CA R=1.1)

Use of transverse mass turns search into a resonance bump hunt



Invariant Mass, M_{jj}

$$M_{jj}^2 = (p_{j_1} + p_{j_2})^2$$

Transverse Mass, M_T

$$M_T^2 = M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\,\not{E}_T - \vec{p}_{Tjj}\cdot\vec{\not{E}}_T\right)$$

Truth-level Mass, M_{mc}

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Collider Searches	Missing energy searches	Probing non-minimal dark sectors

Current experiments are testing the WIMP paradigm and have set impressive constraints

Any anomalies under the WIMP “lamp post” must be carefully evaluated

Necessary to think about the next targets of model exploration, especially if new experimental strategies are required