HIDDEN SECTOR WIMPS

Dan Hooper – Fermilab and the University of Chicago

Signals of Dark Matter in its Natural Habitat, TRIUMF

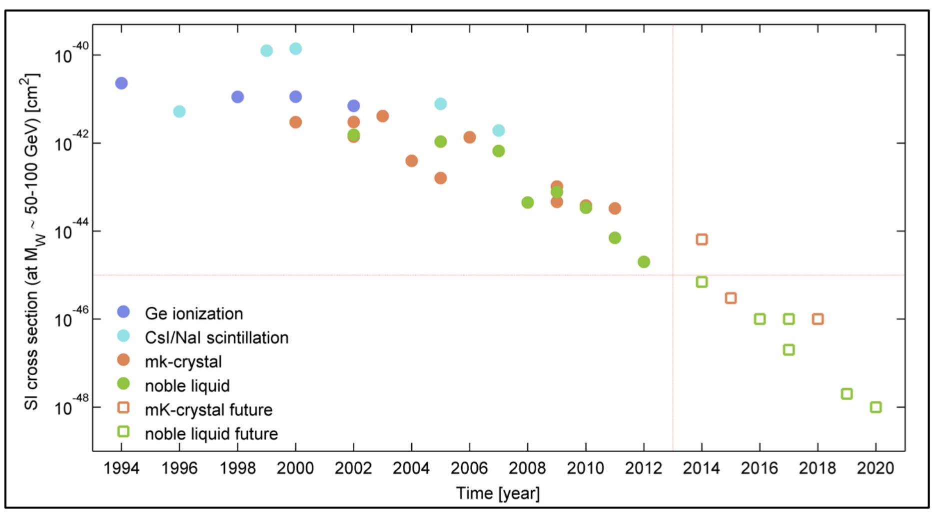
February 6, 2019

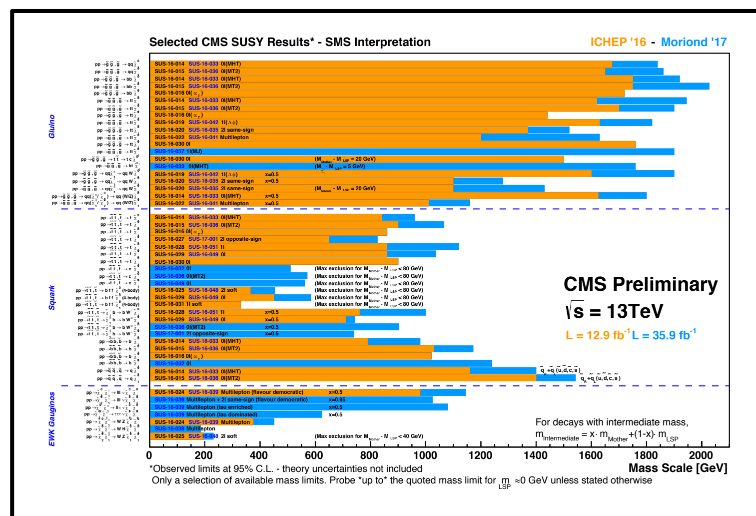
The Case for WIMPs

- For decades, WIMPs dominated the landscape of particle dark matter candidates – and for good reason
- If we assume that ***the dark matter was in thermal equilibrium*** at some point in the early universe, and that the early universe was ***radiation dominated***, then we can conclude the following:
    1) Any stable relic must be heavier than a few MeV (to avoid ruining the successful predictions of BBN)
    2) Any stable relic must be lighter than ~100 TeV (to avoid exceeding the measured dark matter abundance)
- Furthermore, to freeze-out with the measured dark matter abundance, such a particle must annihilate through something comparable to the weak force – *the "WIMP Miracle"*
- From this perspective, dark matter candidates with roughly weak-scale masses and interactions – "WIMPs" – are particularly well motivated

The Fall of the WIMP?

- The thermal relic abundance calculation provided us with a collection of well-motivated benchmarks and experimental targets
- Many of our most attractive WIMP candidates were expected to fall within the reach of planned direct detection and accelerator experiments
- Over the past two decades, direct detection experiments have performed better than we had any right to expect, improving in sensitivity at a rate faster than Moore's Law – and yet no WIMPs have appeared
- The LHC has performed beautifully, and yet no signs of dark matter (or any other BSM physics) has been discovered





So, is the WIMP Paradigm Dead?

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No.

Despite the very stringent constraints that have been placed on the nature of dark matter, there remain many viable options for WIMP model building

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

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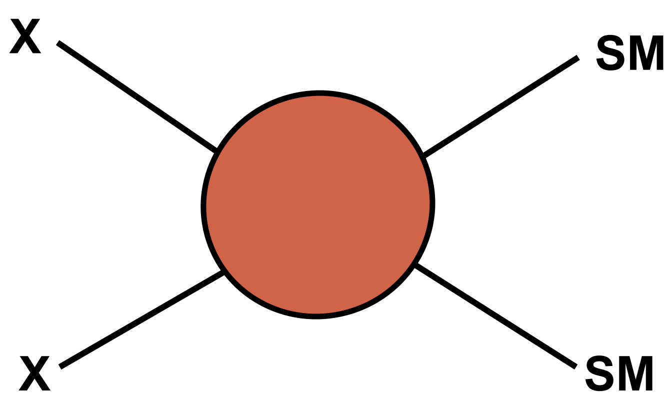
Common Theme: Mechanisms that deplete the dark matter abundance in the early universe without leading to large elastic scattering rates with nuclei or large annihilation rates in the universe today

Unsuppressed



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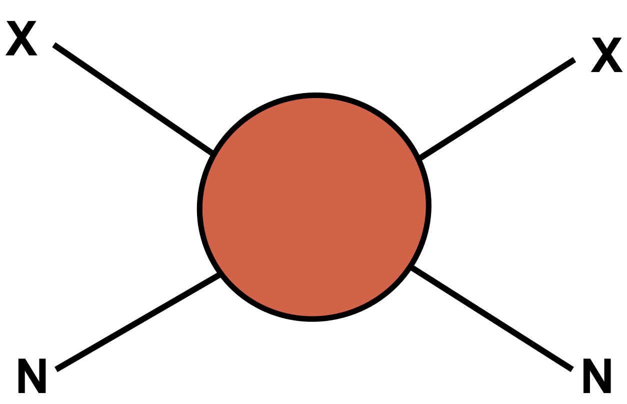
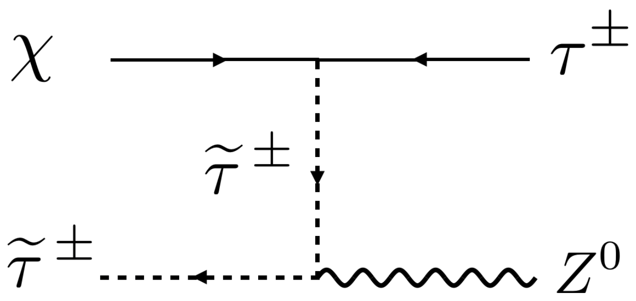


An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

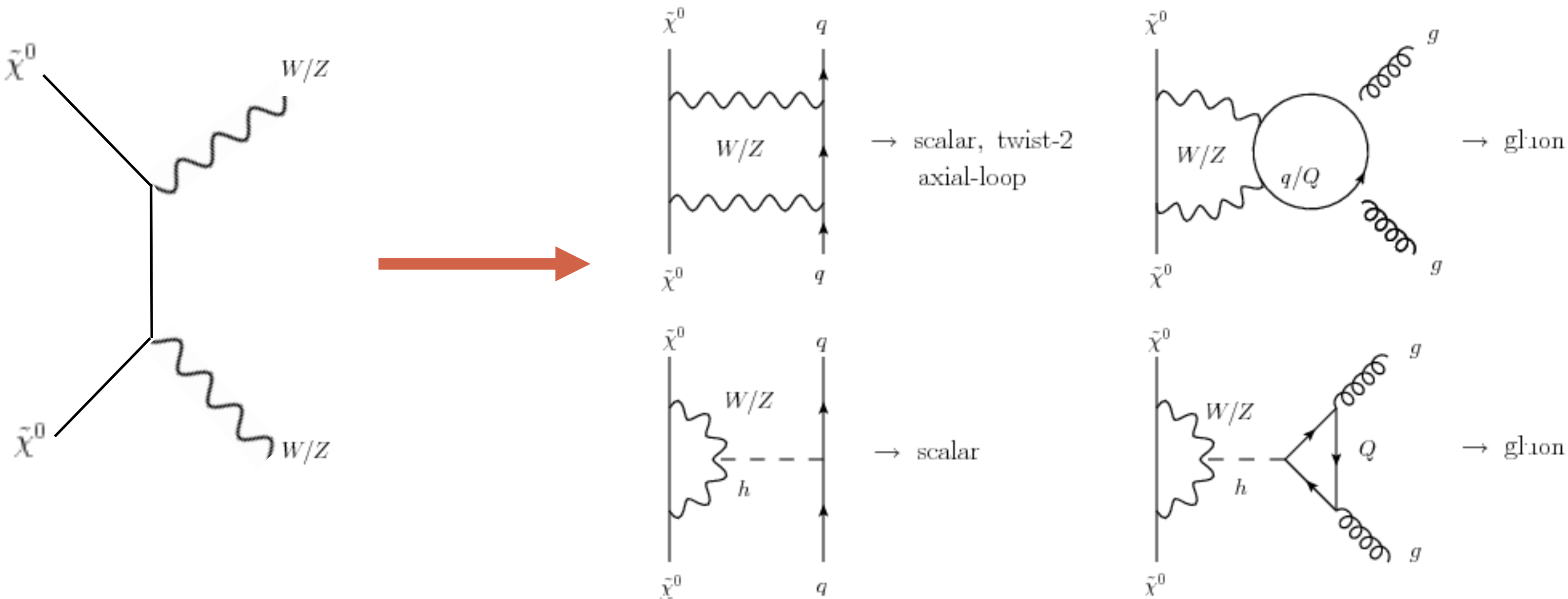


Griest, Seckel (1991)

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams



Hisano, et al., arXiv:1007.2601, 1104.0228, 1504.00915;
Hill, Solon, arXiv:1309.4092, 1409.8290;
Berlin, DH, McDermott, arXiv:1508.05390

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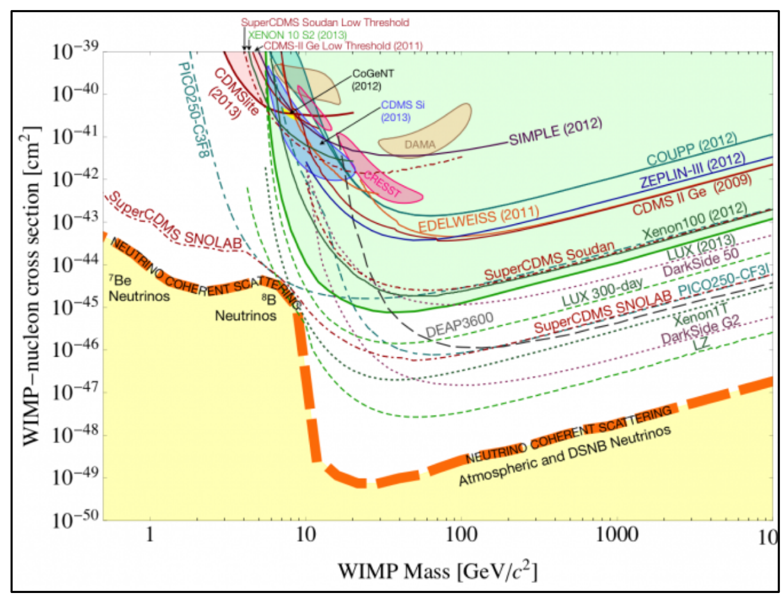

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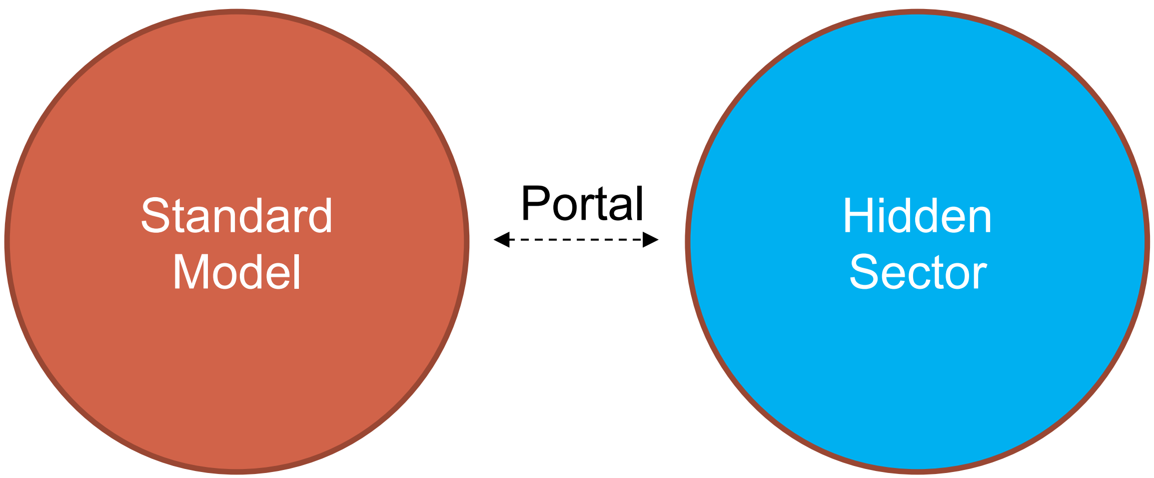
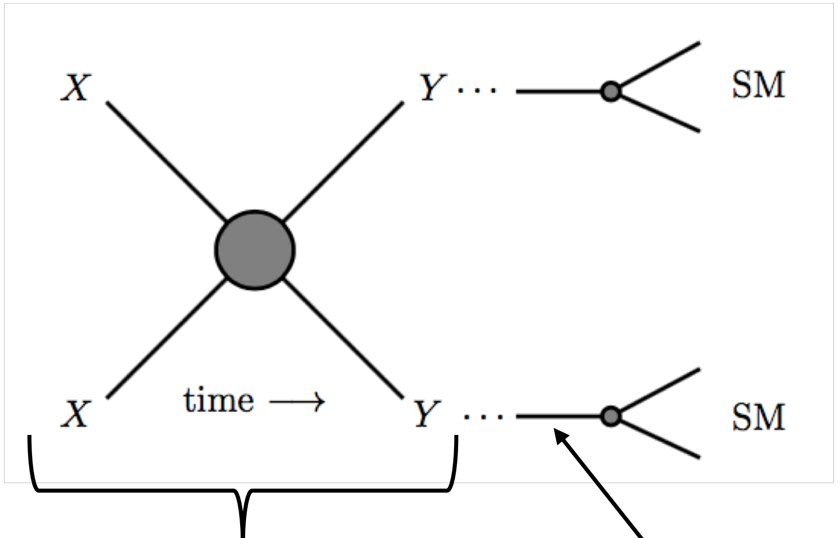
Dark Matter Within a Hidden Sector

- Lets hypothesize that the dark matter is one of several particle species within a hidden sector, which is entirely uncharged under the Standard Model
- Even without any direct couplings between these two sectors, small “portal” interactions could connect them



Dark Matter Within a Hidden Sector

- The dark matter, *X*, freezes-out of thermal equilibrium entirely within its own hidden sector (annihilating to produce lighter particles within the hidden sector, *Y*)
- These lighter hidden sector particles then decay through portal interactions into Standard Model particles



Dark matter annihilates within the hidden sector…

…and then those hidden sector annihilation products decay through portal interactions

Dark Matter Within a Hidden Sector

Hidden sector dark matter models offer a number of attractive features:

1) Relic abundance is easily accommodated; similar to ordinary WIMPs
2) Elastic scattering with nuclei is highly suppressed
3) Production at colliders is highly suppressed

Hidden Sector Portals

- There exist a number of very simple model building possibilities for hidden sector WIMP models, including the three renormalizable "portal" interactions: the vector portal, Higgs portal, and lepton portal
- The vector portal scenario includes the following:

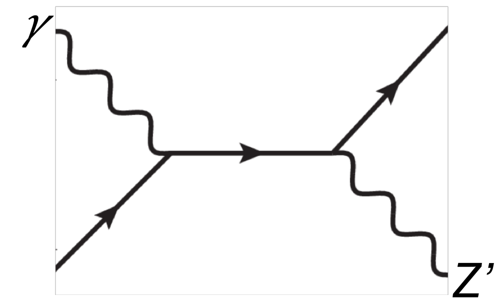
$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} \, Z'_{\mu\nu} + \; g_X Z'_\mu \overline{X} \gamma^\mu X$$

- The dark matter in this scenario, *X*, couples to a *Z'* which kinetically mixes with the SM photon/*Z*
- This portal interaction allows the *Z'* to decay into the Standard Model, but leads to negligible direct detection and collider constraints (for small ϵ)
- Although I'll focus on the vector portal in this talk, the Higgs and lepton portal scenarios are broadly similar, featuring a dark matter candidate that annihilates into hidden sector states, which decay to SM states

Pospelov, Ritz, Voloshin, arXiv:0711.4866
Krolikowski, arXiv:0803.2997

Hidden Sectors Portals

- If the portal interaction is not too feeble ($\epsilon \gtrsim 10^{-7}$), kinetic equilibrium will be maintained between the hidden and SM sectors, $f\,\gamma \leftrightarrow f\,Z'$
- How large should we expect ϵ to be?

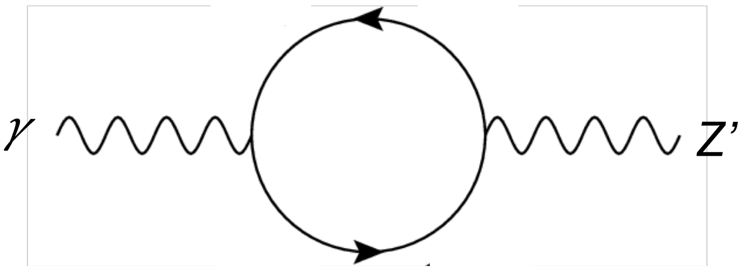


- If there exist particles that carry *both* SM hypercharge and hidden gauge charge, ϵ will be generated at the one-loop level:

$$\epsilon \sim \frac{g_X g_Y \cos\theta_W}{16\pi^2} \log\left(\frac{M'}{M}\right)$$

ratio of masses in loop

- This motivates $\epsilon \sim 10^{-4}$ or less (in the absence of large mass hierarchies), although much smaller values are also entirely plausible



Hidden Sectors in Equilibrium

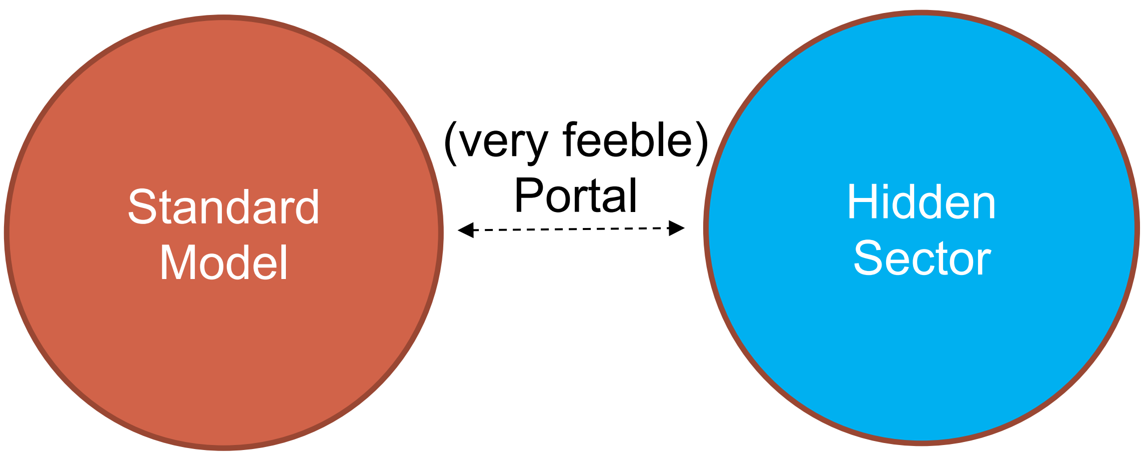
- If kinetic equilibrium is maintained in the early universe ($\epsilon \gtrsim 10^{-7}$), the freeze-out calculation is largely unchanged from the standard picture
- Just like standard WIMPs, this requires m_X ~ few MeV-100 TeV and roughly weak-scale couplings, $g_X \sim 0.6\,(m_X/\mathrm{TeV})^{1/2}$

$$\sigma v_{X\bar{X}\to Z'Z'} \simeq \frac{\pi\alpha_X^2}{m_X^2} \qquad\qquad \alpha_X \equiv g_X^2/4\pi$$

- Although the prospects for direct detection and collider experiments can be almost arbitrarily suppressed in these scenarios, indirect detection remains promising (I will return to this point later)

A Decoupled Hidden Sector

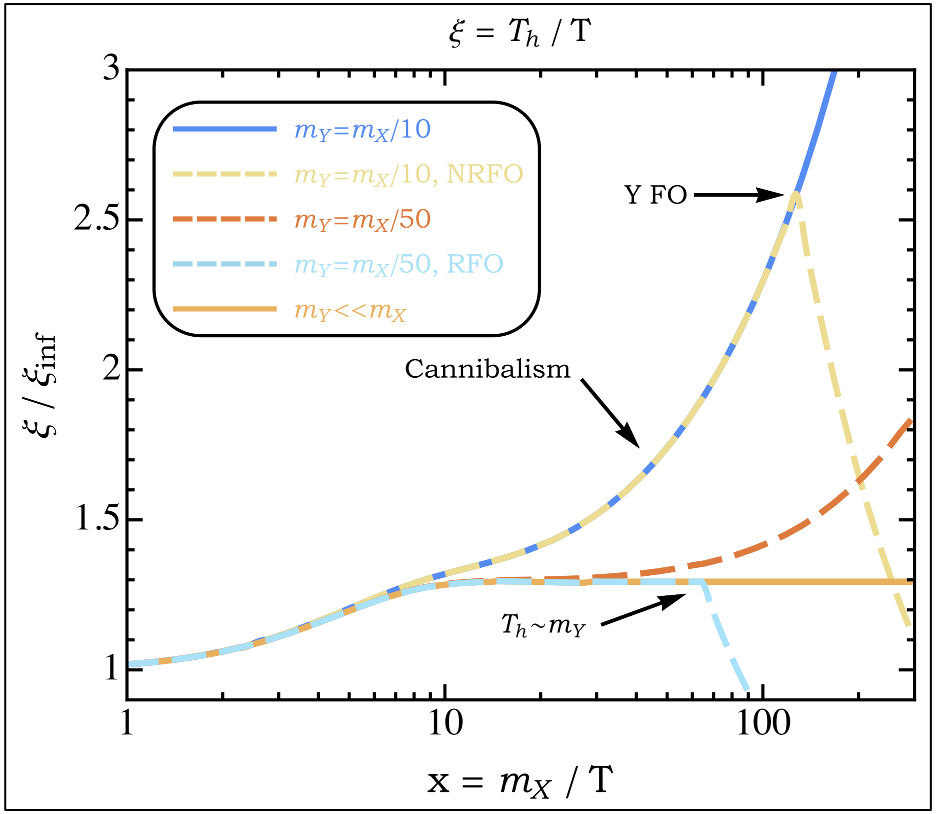
- In most discussions of hidden sector dark matter models, the portal interactions are assumed to be strong enough for kinetic equilibrium to be reached between the two sectors; this need not be the case
- Lets hypothesize that the dark matter resides within a hidden sector, which is not only uncharged under the Standard Model, but is entirely decoupled from the Standard Model bath ($\epsilon \lesssim 10^{-7}$)
- Both the Standard Model sector and the hidden sector are populated during reheating (after inflation); we treat the ratio of their initial temperatures as a free parameter and an initial condition

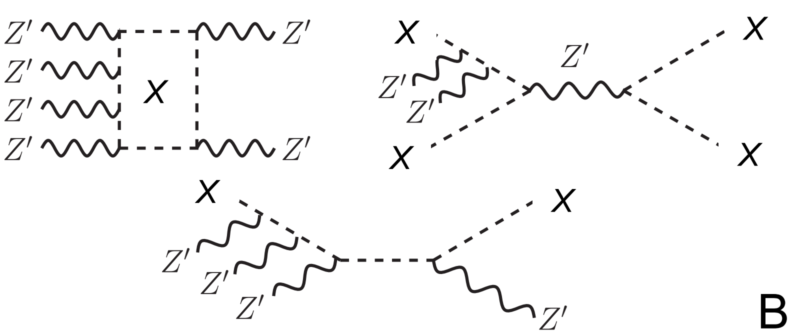


Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Thermodynamics of a Decoupled Hidden Sector

- As the universe expands, the temperatures of the two sectors remain independent of each other, and evolve according to entropy conservation
- The details of this evolution depend on the masses of the particles involved, and on whether or not chemical equilibrium is maintained
- If the *Z'* population is in chemical equilibrium after $T_h < m_{Z'}$, their mass can be transferred into heat (*ie. cannibalism*)

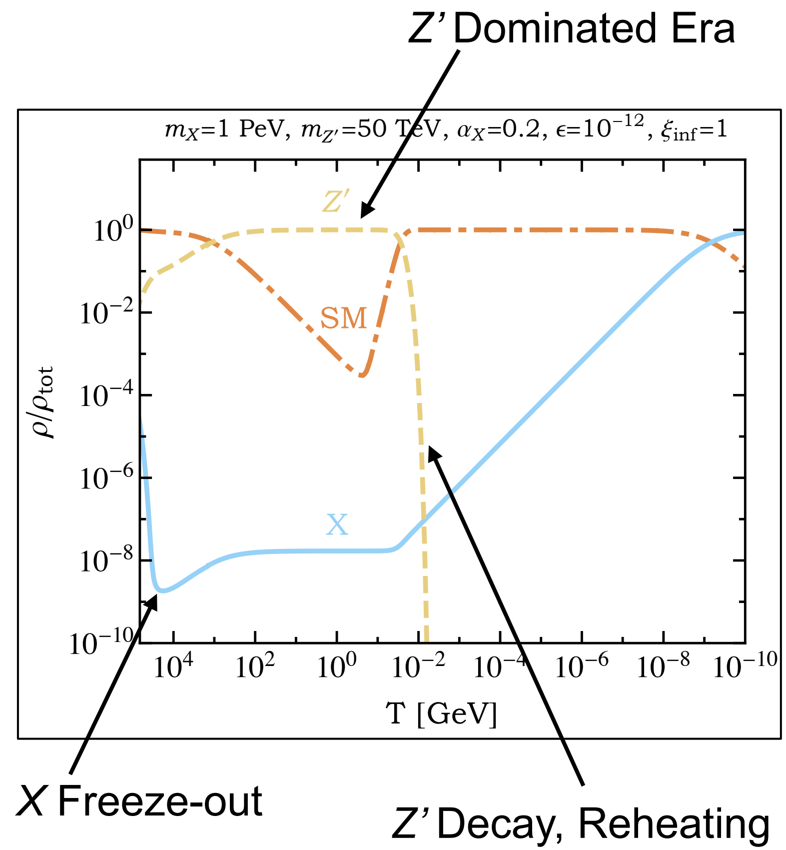




Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Thermodynamics of a Decoupled Hidden Sector

- In this decoupled scenario, the dark matter freezes-out of thermal equilibrium entirely within the hidden sector, annihilating to produce lighter particles within the hidden sector (*ie. Z's*)
- If reasonably long-lived, the annihilation products eventually become non-relativistic and evolve to dominate the energy density of the early universe
- When these particles ultimately decay, they reheat the universe, diluting the abundances of any relics (including the dark matter)



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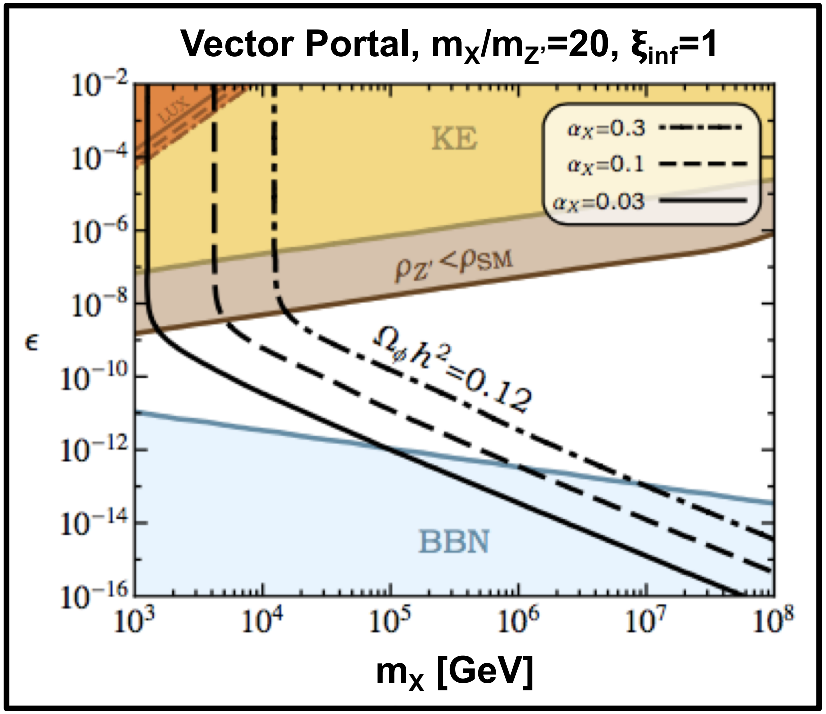
Dark Matter Within a Heavy Decoupled Hidden Sector

Here's an example of a vector portal dark matter scenario:



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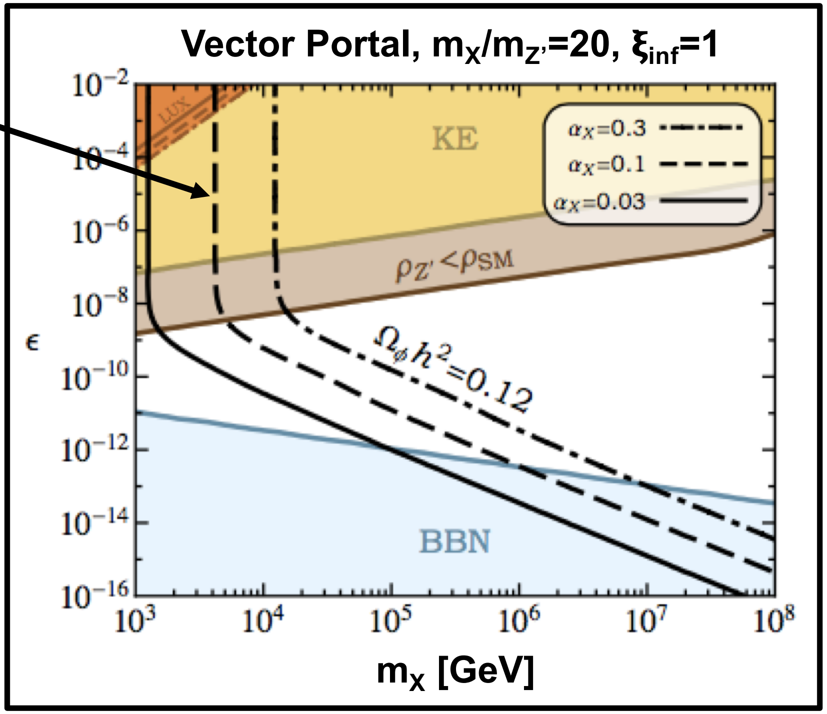
- For a sizeable portal interaction strength ($\epsilon \gtrsim 10^{-7}$), kinetic equilibrium between the sectors is reached, and the early universe undergoes a standard thermal history



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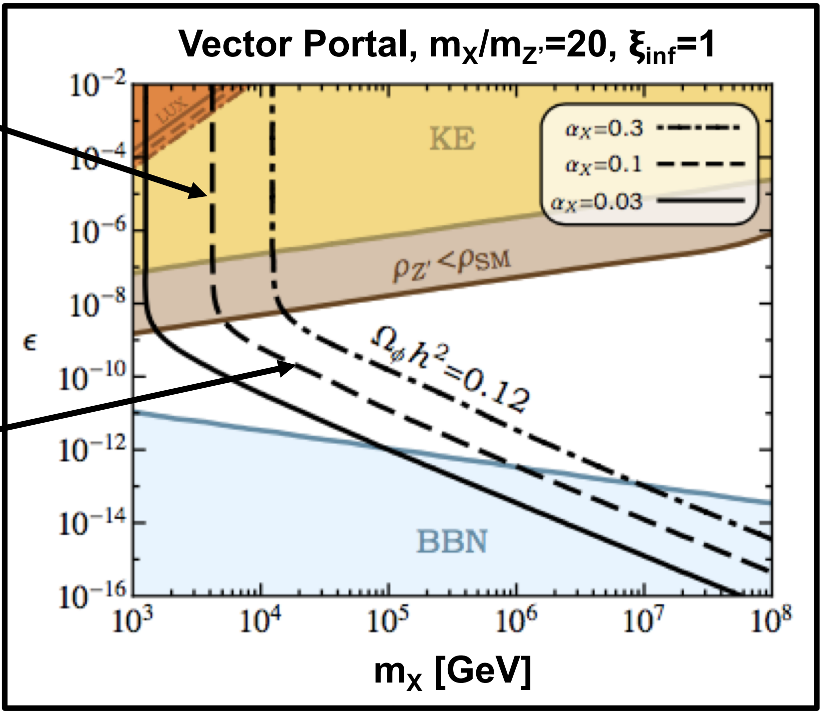
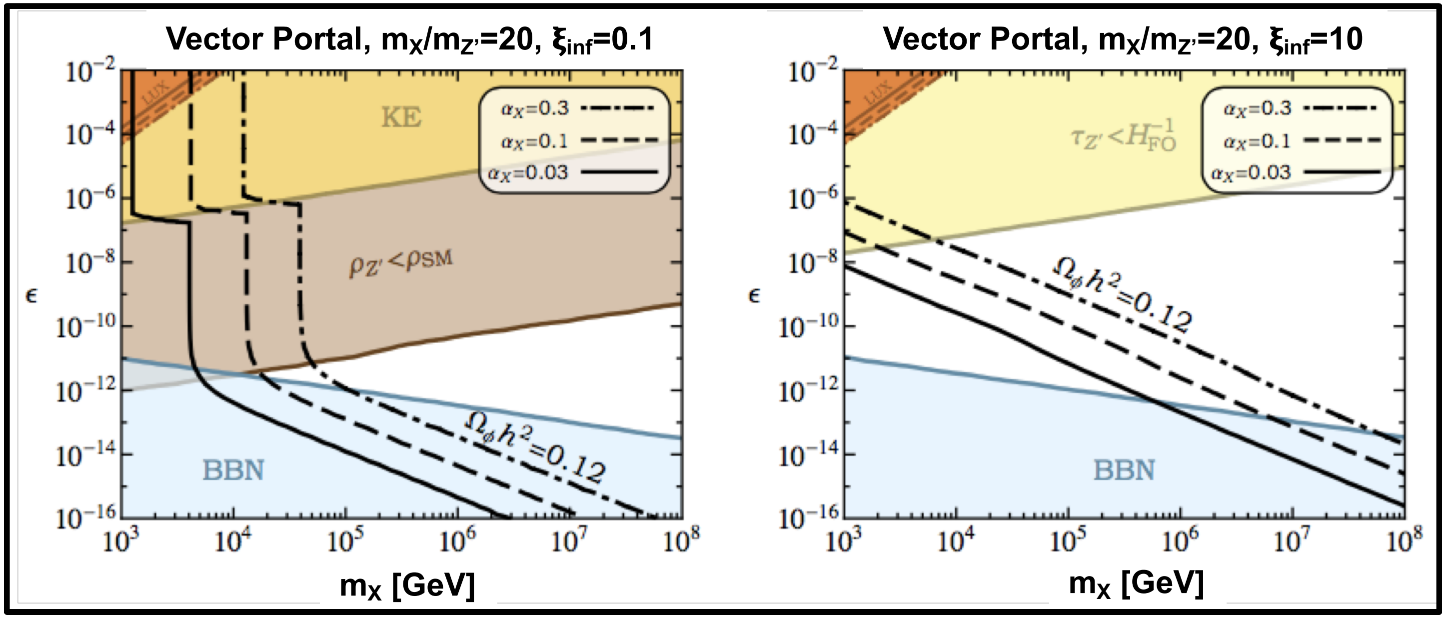
- For a sizeable portal interaction strength ($\epsilon \gtrsim 10^{-7}$), kinetic equilibrium between the sectors is reached, and the early universe undergoes a standard thermal history
- For very weak portal interactions, however, there is an early matter-dominated era, followed by late-time reheating
- This dilution can easily facilitate an acceptable dark matter abundance for masses as high as ~10-100 PeV (well above of the range for a standard WIMP)



Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Dark Matter Within a Heavy Decoupled Hidden Sector

- The history of the early universe in these scenarios also depends on the ratio of the initial temperatures of the hidden and visible sectors



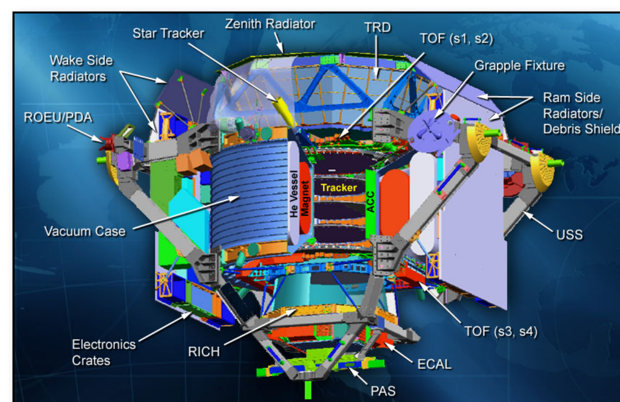
- For T_{hidden}<<T_{SM}, no early matter-dominated era, no late-time reheating
- For T_{hidden}>>T_{SM}, the Standard Model bath almost entirely originates from the decay of the hidden sector

Indirect Searches for Hidden Sector WIMPs

- In contrast to direct detection and collider searches, indirect searches are generally as sensitive to hidden sector dark matter candidates as they are to standard WIMPs (with the normal caveats about *p*-wave amplitudes, coannihilations, etc.)
- Indirect detection experiments that are sensitive to dark matter particles annihilating with a cross section of $\sigma v \sim 10^{-26}$ cm^3/s will be able to test a wide range of hidden sector WIMP scenarios

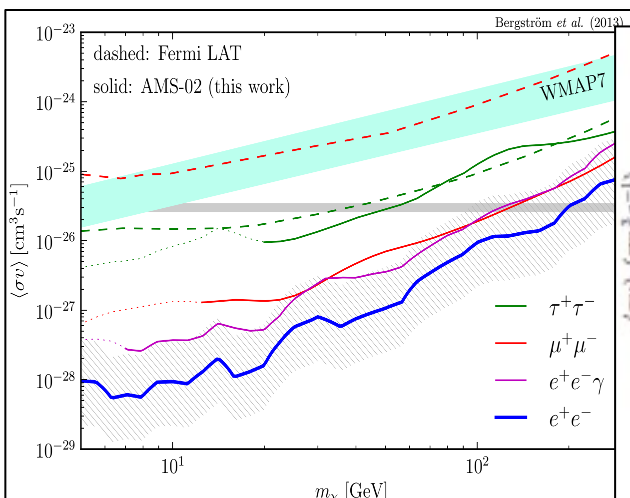
Fermi

AMS-02

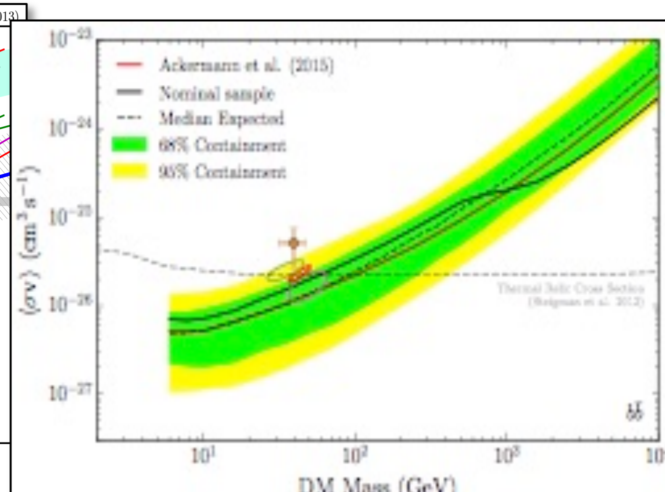


Current Constraints from Indirect Detection

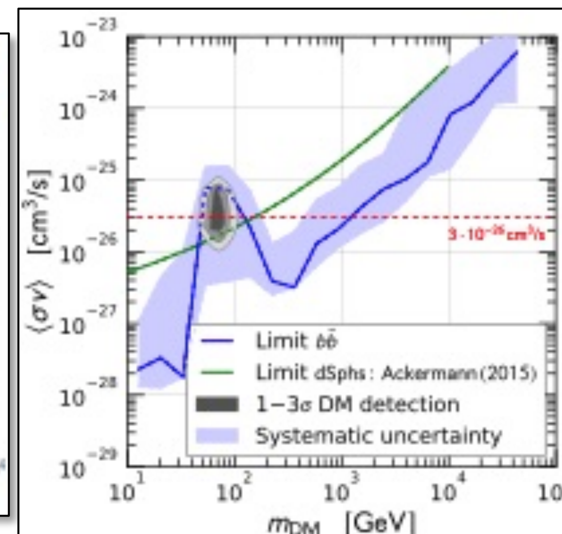
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to ~100 GeV
- This program is not a fishing expedition, but is testing a wide range of well-motivated dark matter models (both hidden sector and otherwise)



Bergstrom, et al, arXiv:1306.3983



Fermi Collaboration, arXiv:1611.03184

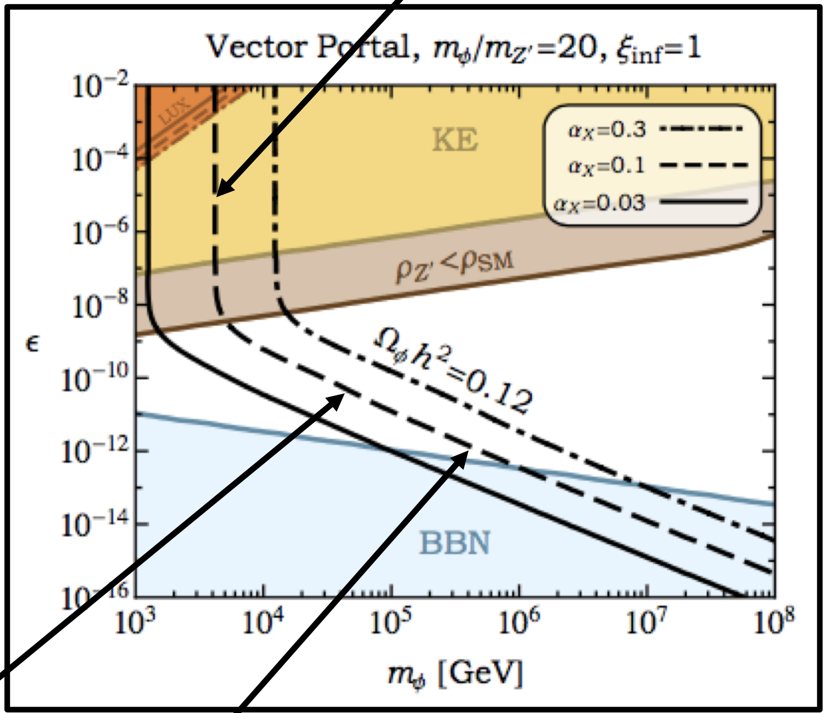


Cuoco, et al., arXiv:1610.03071
Cui, et al. arXiv:1610.03840

Indirect Detection of Dark Matter in a Decoupled Hidden Sector

- If kinetic equilibrium is reached, we generally require σv~2x10^{-26} cm^3/s, which is within reach of existing and planned searches for masses up to ~100-1000 GeV
- If the hidden and SM sectors never reach equilibrium, however, the late time decays of the hidden sector dilute the dark matter abundance, reducing the annihilation cross section required to obtain the desired dark matter abundance

σv~2x10^{-26} cm^3/s

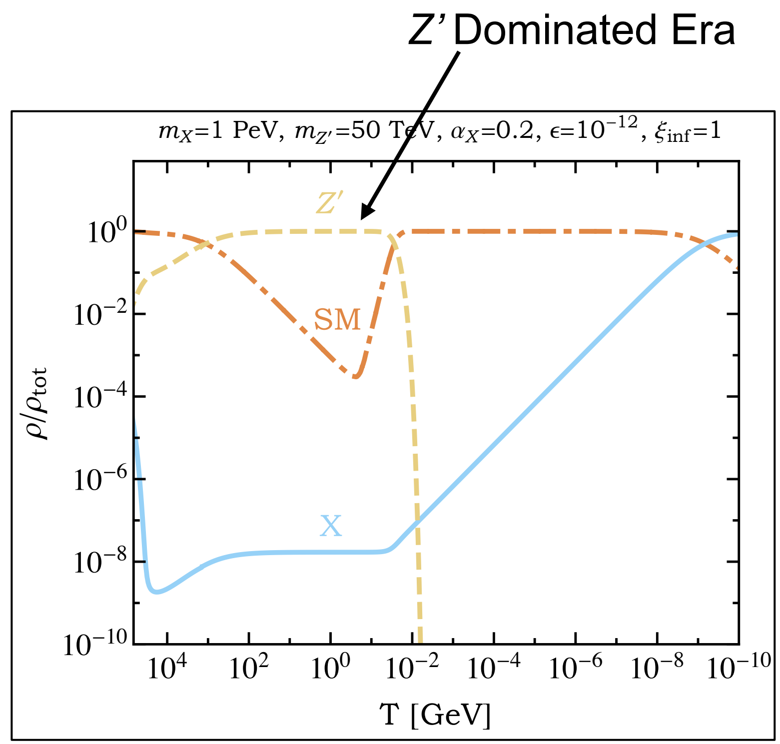


σv~2x10^{-28} cm^3/s

σv~2x10^{-30} cm^3/s

Indirect Detection of Dark Matter in a Decoupled Hidden Sector

- At first glance, this would appear to bode poorly for indirect searches for decoupled hidden sector dark matter
- But recall that the early universe includes a ***matter dominated*** era in this scenario, during which ***structure growth is linear*** (in contrast to the logarithmic growth that is predicted during radiation domination)
- As a result, nearly all of the dark matter can become gravitationally bound in ultra-compact microhalos, leading to very high annihilation rates in the halo (and elsewhere) today



A. Erickcek, C. Blanco, DH, in preparation

A Note on Annihilation J-Factors

- The flux of annihilation products is proportional to the *J*-factor, which is the integral of the square of the dark matter density over the observed line-of-sight:

$$\Phi_\gamma(E_\gamma, \Delta\Omega) = \frac{1}{2}\frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle}{4\pi m_X^2}\underbrace{\int_{\Delta\Omega}\int_{los}\rho_X^2(l,\Omega)\,dl\,d\Omega}_{J\text{-factor}}$$

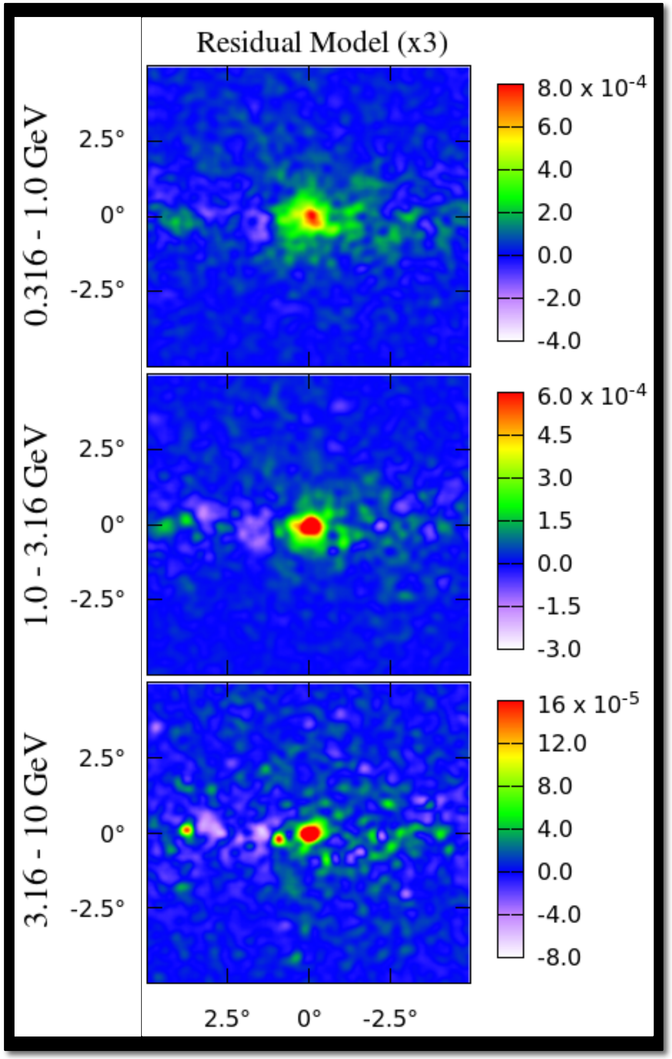
- But in a scenario in which most of the dark matter is found within ultra-compact microhalos, the macroscopic annihilation rate scales not as the density of dark matter squared, but as the number density of microhalos
- The relevant *J*-factors thus exhibit a distribution that is the same as that usually calculated for **decaying** dark matter

Searches for decaying dark matter are also searches for annihilating dark matter from a decoupled hidden sector

A. Erickcek, C. Blanco, DH, in preparation

The Galactic Center GeV Excess

- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center
- This signal is difficult to explain with astrophysical sources or mechanisms, but is very much like the signal predicted from annihilating dark matter



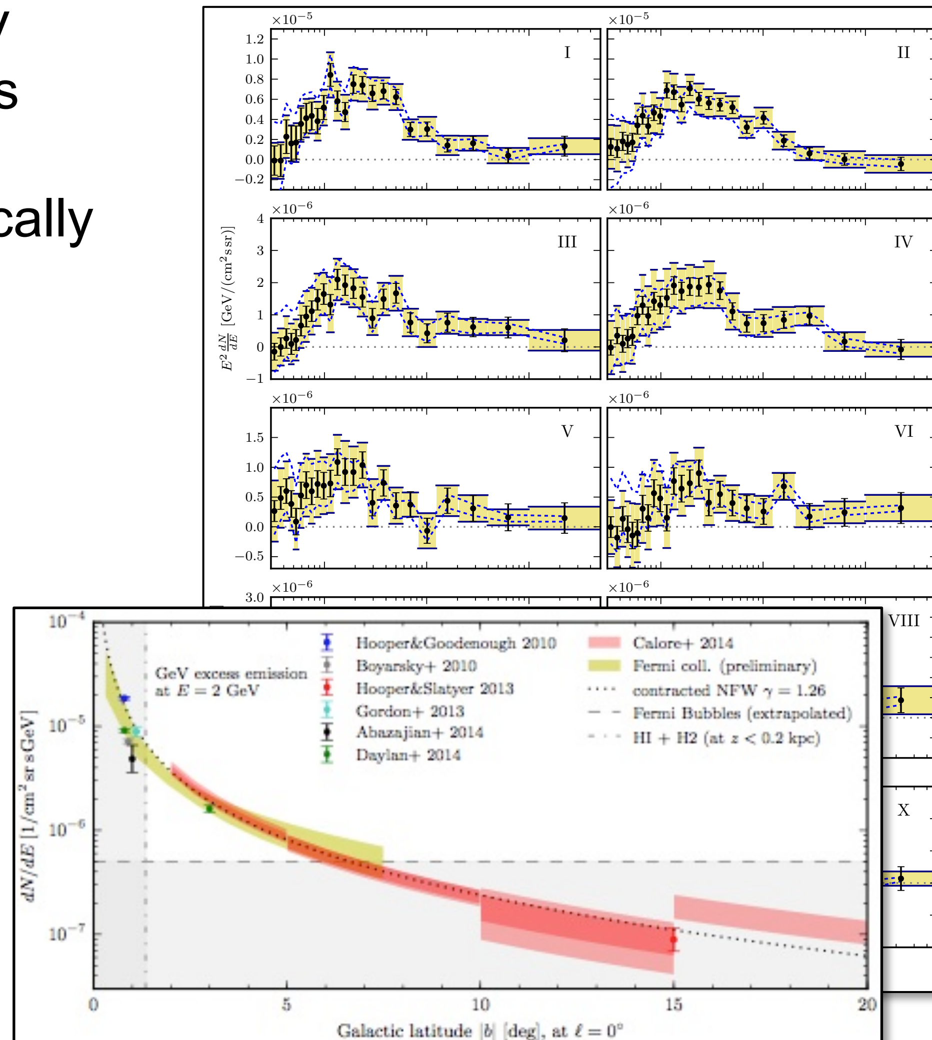
Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

Dark Matter and the GeV Excess

- **Spectrum**: Well fit by a ~40-70 GeV particle annihilating to quarks, and is uniform across the Inner Galaxy
- **Morphology**: Approximately spherically symmetric, with a flux that falls as ~r $^{-2.4}$ out to at least ~10°, consistent with a DM halo only slightly steeper than NFW
- **Intensity**: Requires an annihilation cross section of σv ~ 10^{-26} cm^3/s, near the value of a thermal relic

In each of these respects, the observed characteristics of the excess are in good agreement with the expectations of annihilating dark matter – hidden sector or otherwise

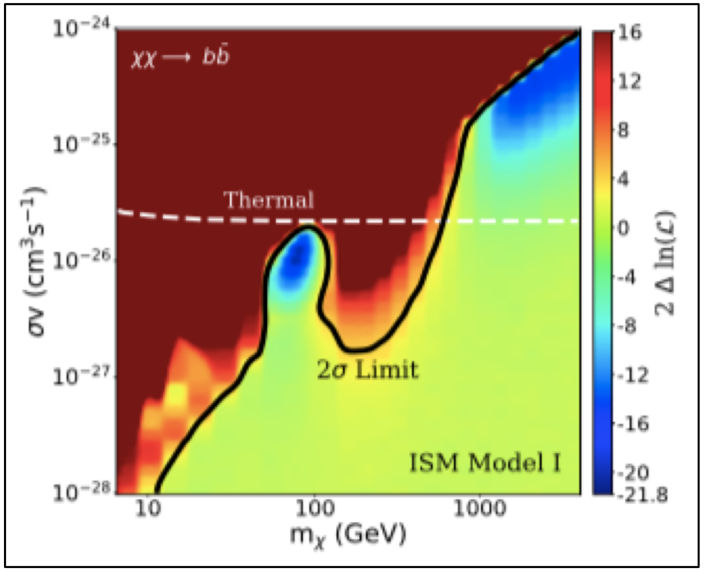
(see Escudero, Witte, DH, arXiv:1709.07002)



Daylan, Finkbeiner, Hooper, Linden, Rodd, Slatyer (2014)
Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014);

A Cosmic-Ray Antiproton Excess?

- There is also a small excess in the AMS antiproton spectrum at ~10-20 GeV
- The spectrum and intensity of this excess is well fit by the same range of dark matter models that could account for the Galactic Center gamma-ray excess
- This excess is quite statistically significant (~4.7σ), and appears to be robust to variations in the ISM propagation model, as well as uncertainties associated with the antiproton production cross section and solar modulation
- Searches for cosmic-ray anti-deuterons and anti-helium nuclei will help to clarify this situation



Cuoco, et al., arXiv:1610.03071
Cui, et al., arXiv:1610.03840
Reinert, Winkler, arXiv:1712.00002
Cui, et al., arXiv:1803.02163
Cholis, Hooper and Linden (in prep.)

Summary

- The null results of direct detection experiments and the LHC have put stress on the WIMP paradigm
- Models in which the dark matter is part of a hidden sector can trivially evade these constraints, while still exploiting the “WIMP Miracle”
- Many well motivated and simple model building possibilities exist, including those which incorporate the vector, Higgs and lepton portals
- If the hidden sector is decoupled from the SM bath, the early universe may have had a matter-dominated phase followed by late-time reheating, allowing for dark matter as heavy as ~100 PeV and with very high annihilation rates
- Indirect searches provide us with an important probe of hidden sector dark matter models which are not within the reach of direct detection or collider experiments
- The Galactic Center gamma-ray excess and cosmic-ray antiproton excess are each interesting within this context