Hidden Sector Dark Matter and the Galactic Center Gamma-Ray Excess

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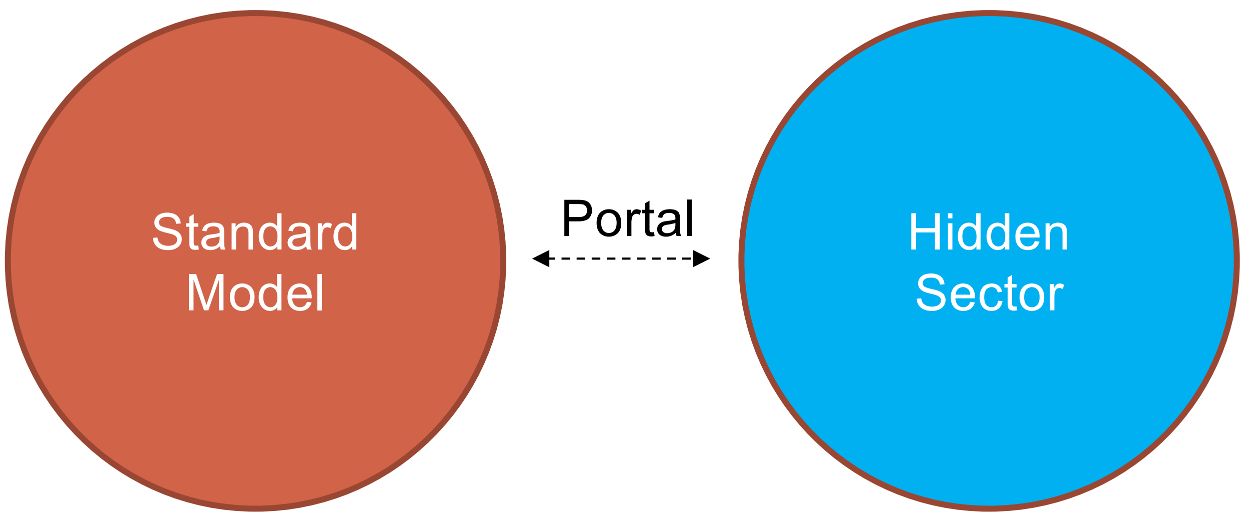
WIPAC
Wisconsin IceCube Particle Astrophysics Center

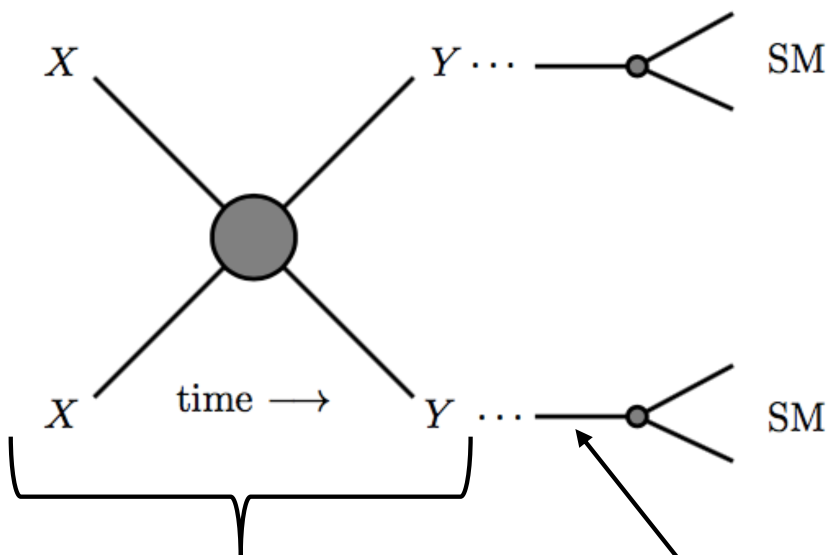
Dark Matter in a Hidden Sector

- Let's hypothesize that the dark matter is one of several particle species that constitute a "hidden sector"
- The particles within the hidden sector are each uncharged under the Standard Model, but could interact among themselves
- Even without any direct couplings between these two sectors, small "portal" interactions could connect them



Dark Matter in a Hidden Sector

- Such models naturally lead to a picture in which the dark matter, *X*, freezes-out of thermal equilibrium entirely within its own hidden sector, annihilating to produce lighter hidden sector particles, *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 small portal couplings

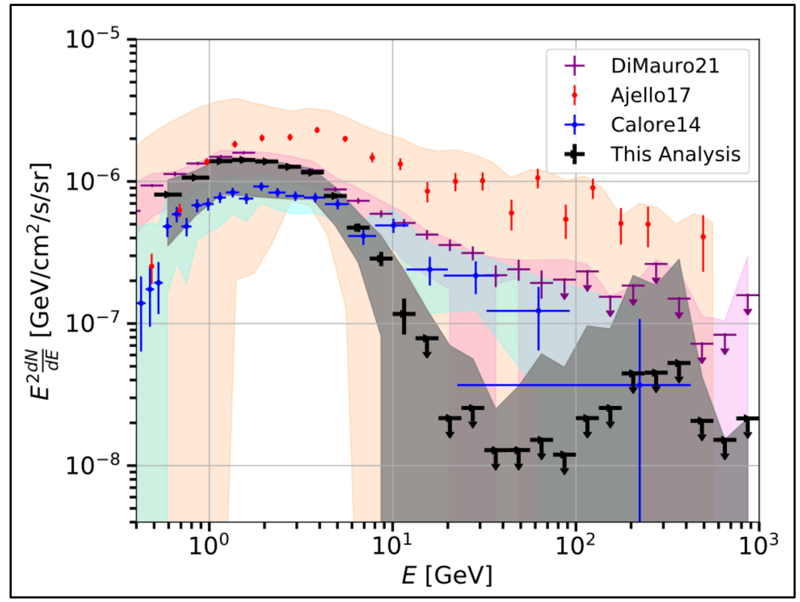
Dark Matter in a Hidden Sector

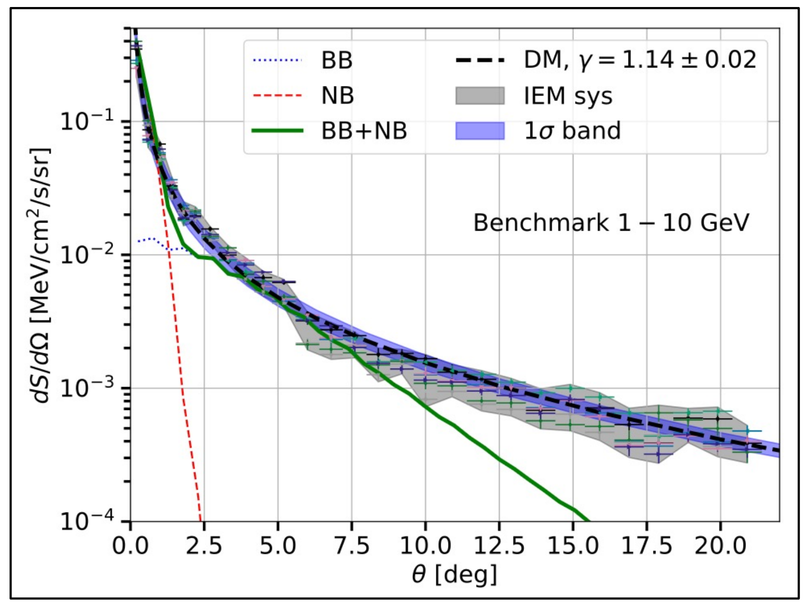
Hidden sector dark matter models offer several attractive features:

1) Can easily produce he desired relic abundance (like ordinary WIMPs)
2) Elastic scattering with nuclei can be highly suppressed
3) Production at colliders can be highly suppressed
4) Can provide an explanation for the Galactic Center Gamma-Ray Excess

The Galactic Center Gamma-Ray Excess

- The Fermi data contains an excess of GeV-scale emission from the Inner Galaxy
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is difficult to explain this signal with known or proposed astrophysics; pulsars could be responsible, but this would require a very large and exotic population of low-luminosity millisecond pulsars
- The observed characteristics of this signal are consistent with ~20-65 GeV dark matter particles, distributed in a standard halo profile, and annihilating to quarks or gluons with a cross section of $\sigma v \sim 10^{-26}$ cm^3/s



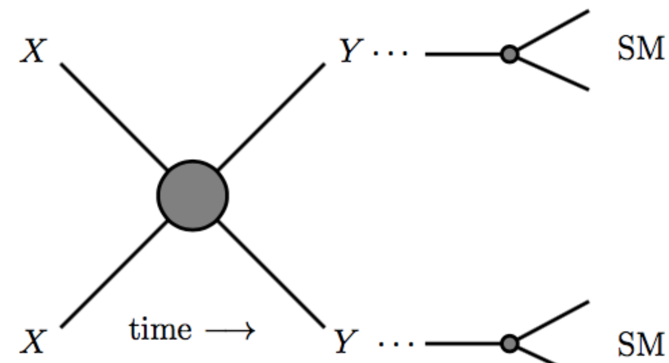


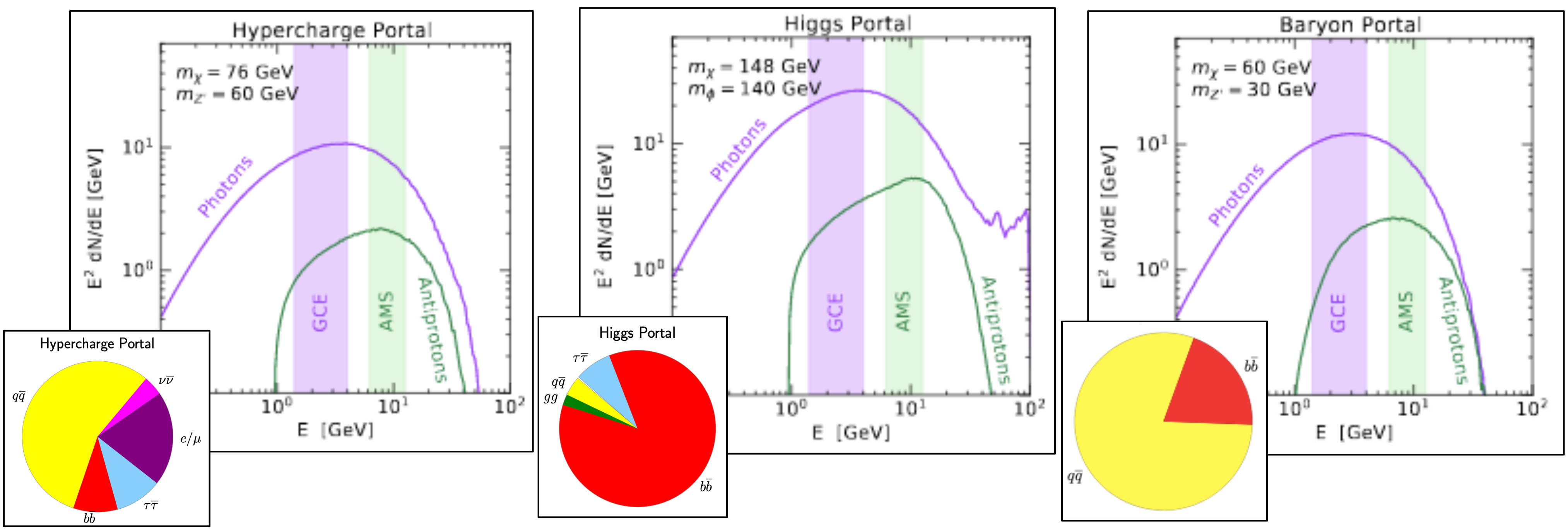
Among other references, see:

DH, Goodenough (2009, 2010),DH, Linden (2011)
Daylan, DH, et al. (2014)
Murgia, et al. (2015), Ackermann et al. (2017)
Di Mauro (2026)

Hidden Sector Dark Matter and the Galactic Center Gamma-Ray Excess

- The spectrum of the Galactic Center excess peaks at ~1-4 GeV
- Over a wide range of hidden sector models and parameter space, dark matter annihilation can produce a gamma-ray spectrum consistent with the GCE

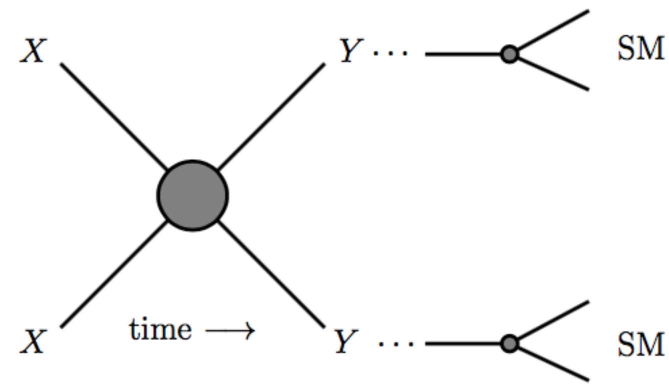


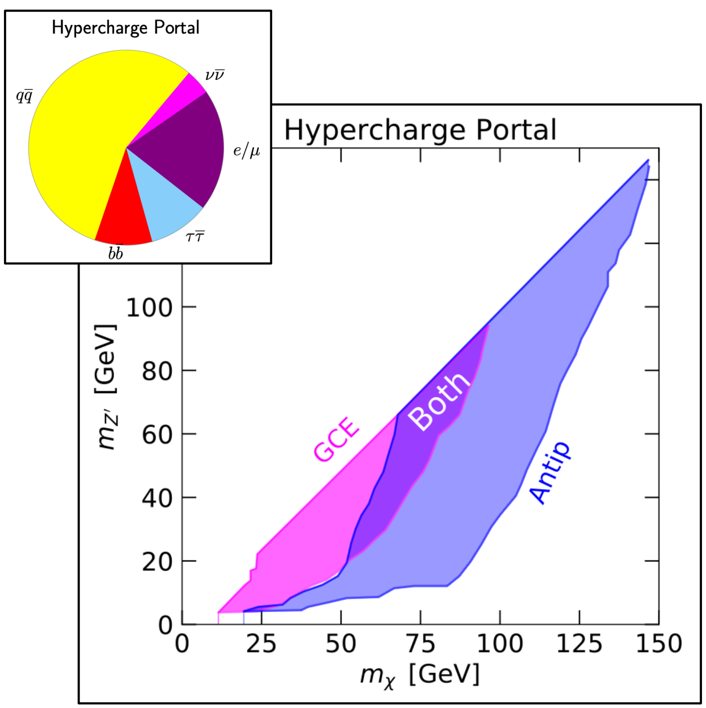


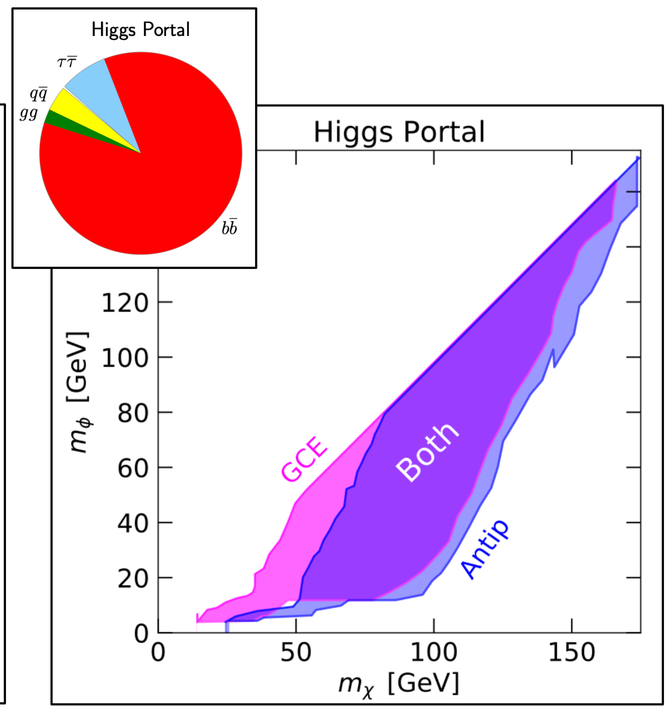
Berlin, DH, McDermott (2014); DH, Leane, Wegsman, Witte (2019)

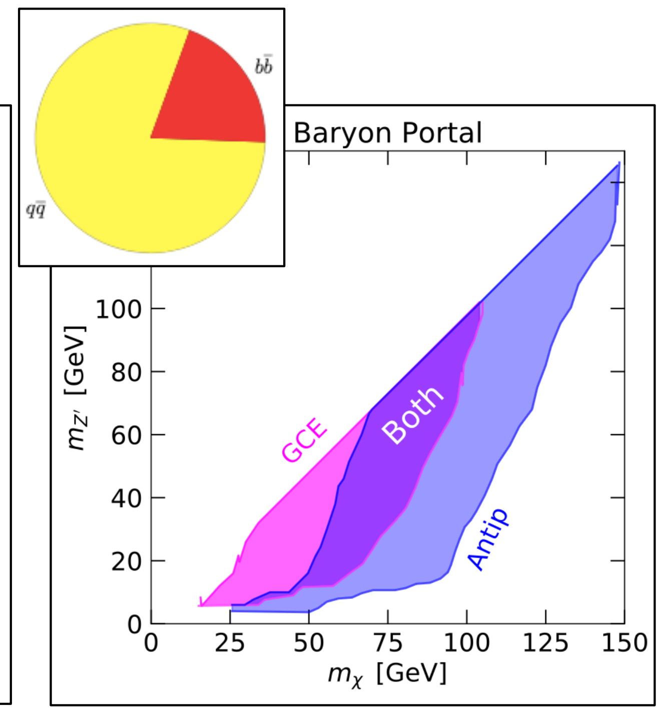
Hidden Sector Dark Matter and the Galactic Center Gamma-Ray Excess

- Here's the parameter space that leads to a GCE-like gamma-ray spectrum, for three choices of the portal between the hidden and SM sectors









Berlin, DH, McDermott (2014); DH, Leane, Wegsman, Witte (2019)

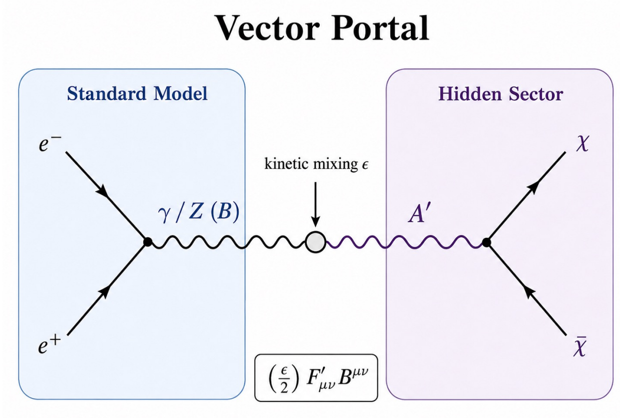
Hidden Sector Portals

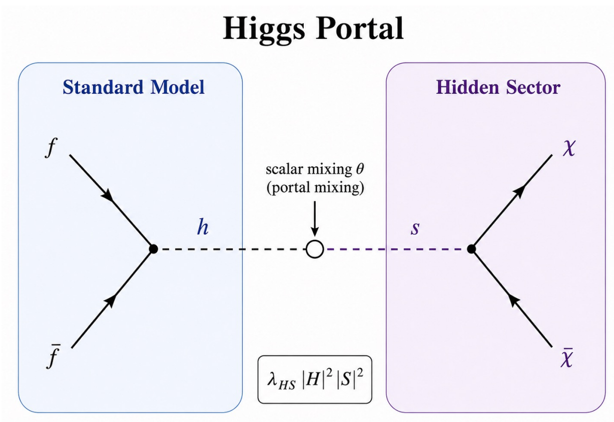
- There are many simple and well-motivated model building possibilities for connecting a hidden sector to the SM
- Even without adding any new particles to the SM sector, there are three renormalizable portals through which we could connect it to a hidden sector:

  -The vector portal

  -The Higgs portal

  -The lepton portal





- Alternatively, we could extend the SM model and then connect one or more of the new particles to a hidden sector: the $B - L$ portal, baryon portal, $L_i - L_j$, portal, extended Higgs sector portals, *etc.*

The Vector Portal

- In this talk, I'll focus on the case of the vector portal, although the Higgs and lepton portals share many of the same broad features and phenomenology
- The dark matter in this scenario, *X*, couples to a hidden sector Z' which kinetically mixes with the SM photon and Z

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

- This portal interaction allows the Z' to decay into Standard Model particles, but leads to negligible direct detection and collider constraints (for small ϵ)

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

The Vector Portal

- How large should we expect ϵ to be?
- Any value of ϵ is technically natural, but if the SM is embedded in a GUT (as we might reasonably expect), a non-zero value of ϵ will be generated only through interactions involving loops of heavy particles which carry both SM hypercharge and hidden sector gauge charge
- At one-loop, these heavy states can be integrated out to induce the following degree of kinetic mixing:

$$\varepsilon \sim \frac{g_X g_Y}{16\pi^2} \ln\left(\frac{M'^2}{M^2}\right)$$

ratio of masses in loop

- Or if kinetic mixing is induced only at two-loops or higher:

$$\varepsilon \sim \frac{g_X g_Y \Pi_i^{2(n-1)} |y_i|^2}{(16\pi^2)^n} \ln\left(\frac{M'^2}{M^2}\right) \qquad (n\text{-loop})$$

- This motivates values of ϵ ~ 10^{-4} or less (in the absence of large mass hierarchies), and much smaller values are entirely plausible

B. Holdom, PLB (1986)

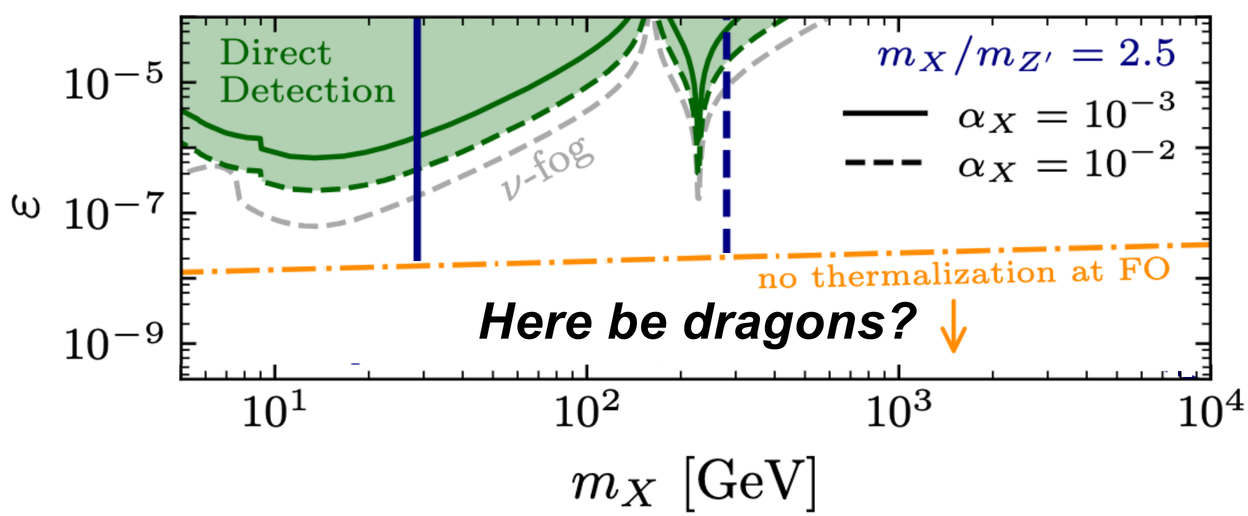
Hidden Sectors in the Early Universe

- If the portal coupling is not too small ($\epsilon \gtrsim 10^{-8}$), the interaction rate between the two sectors will exceed the rate of Hubble expansion at the time of dark matter freeze-out, ensuring that the two sectors will be in equilibrium with each other
- If the portal coupling is smaller than this, the two sectors could – at least in principle – be at very different temperatures
- In this latter scenario, the dark matter's thermal relic abundance could be much higher or much lower than that of a canonical WIMP, providing us with little reason to expect the dark matter to have weak-scale couplings or masses (and little reason to expect an annihilation cross section of $\sigma v \sim 10^{-26}$ cm^3/s)

Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Hidden Sectors in the Early Universe

- Motivated by this reasoning, past studies of hidden sector DM have often imposed the requirement that thermal equilibrium must have been maintained between the SM and the hidden sector at the time of DM freeze-out
- If this requirement is imposed, we can derive a lower limit on the coupling between these sectors, and thus on the cross sections for direct detection
- By this logic, direct detection experiments have already probed much of the viable parameter space (down to $\epsilon \sim 10^{-6}$ or so) → only $\epsilon \sim 10^{-6}$ to 10^{-8} remains untested



Thermalization at High Temperatures

- I argue that we should abandon this standard lore
- For relativistic particles in the thermal bath, scattering rates mediated by light particles typically scale as

$$\Gamma = n \langle \sigma v \rangle \propto T^3 T^{-2} \sim T$$

- Comparing this to Hubble, we find $\Gamma / H \propto T/T^2 \sim T^{-1}$
- For this scaling, once equilibrium is established, it is maintained as the universe expands and cools (at least until the particles in question become non-relativistic)

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- This conclusion, however, *is only valid if the interactions involved are mediated by light particles* $(M < T)$
- If we instead consider processes mediated by a very massive particle, $M \gg T$, the scattering rate scales as

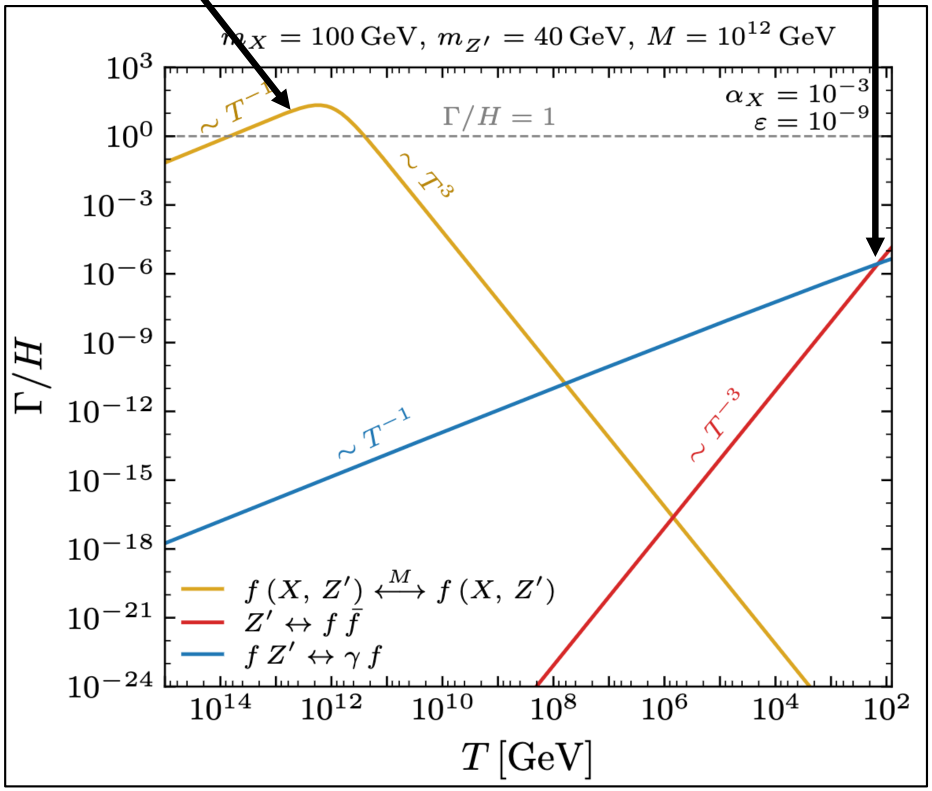
$$\Gamma = n\langle \sigma v \rangle \propto T^3 (T^2/M^4) \propto T^5 \implies \Gamma/H \propto T^3$$

- Thus, *equilibrium could be maintained at very high temperatures, even if* $\Gamma < H$ *during dark matter freeze-out*

Thermalization at High Temperatures

Consider this concrete example:

- At freeze-out, $\Gamma \ll H$ (due to the small portal coupling, ϵ ~ 10^{-9})
- At extremely early times, T~$10^{11\text{-}13}$ GeV, the interactions of a 10^{12} GeV mediator brought the two sectors into equilibrium
- If equilibrium was reached between the two sectors at a high temperature, their temperatures will remain roughly equal to each other long after their decoupling, differing only due to variations in $g_\star$
- We should therefore expect the temperature of the hidden sector to be similar to that of the SM bath at the time of DM freeze-out



DH, Krnjaic, Montefalcone, arXiv:2605.20186

Heavy Mediators?

The kinds of heavy particles that would enable the two sectors to reach and maintain equilibrium at high temperatures are generically expected to be present in many realistic UV completions of hidden sector DM models:

1) Hypercharge Portal: Recall that if the SM is embedded in a GUT, a non-zero value of ϵ will be generated after GUT breaking only through interactions that involve loops of heavy particles which carry both SM hypercharge and the hidden sector gauge charge → these heavy particles are an essential component of such models

2) Higgs Portal: A Higgs portal coupling could also be radiatively generated through loops of heavy particles. For example, if a heavy hidden-sector scalar, *S*, has interactions of the form

$$\mathcal{L} \supset -S(a|H|^2 - b|H'|^2) + \frac{M_S^2}{2} S^2,$$

integrating out the heavy scalar yields an effective portal interaction, $\lambda |H'|^2 |H|^2$, where the coupling is $\lambda \sim ab/M_S^2$

Heavy particles capable of establishing equilibrium between the sectors at high temperatures are a relatively generic feature of hidden sector models

DH, Krnjaic, Montefalcone, arXiv:2605.20186

Hidden Sector Freeze-Out and Entropy Dilution

- Once the hidden sector and SM sector fall out of equilibrium with one another, their temperatures evolve independently, yielding a ratio that follows from entropy conservation:

$$\frac{T_h}{T} = \left[\frac{g_{\star,s}(T)}{g_{\star,s}(T_{\rm ini})}\,\frac{g^h_{\star,s}(T_{\rm ini})}{g^h_{\star,s}(T_h)}\right]^{1/3}$$

- The cosmological evolution then naturally separates into two stages:

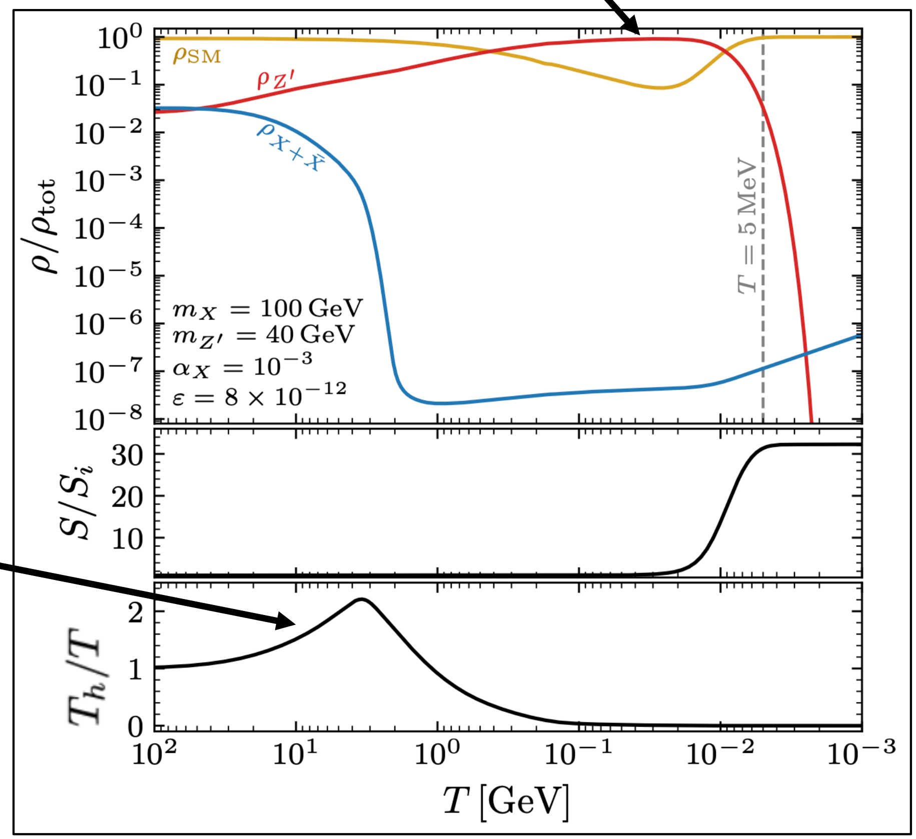
Secluded Evolution: First, the hidden sector undergoes internal chemical freeze-out. The hidden-to-SM temperature ratio evolves through entropy conservation in each sector, but remains of order unity throughout.

Entropy Transfer: Second, the frozen-out mediator population comes to dominate the total energy density before decaying into SM particles. These decays inject entropy into the visible sector, diluting all pre-existing comoving abundances.

DH, Krnjaic, Montefalcone, arXiv:2605.20186

A Concrete Example

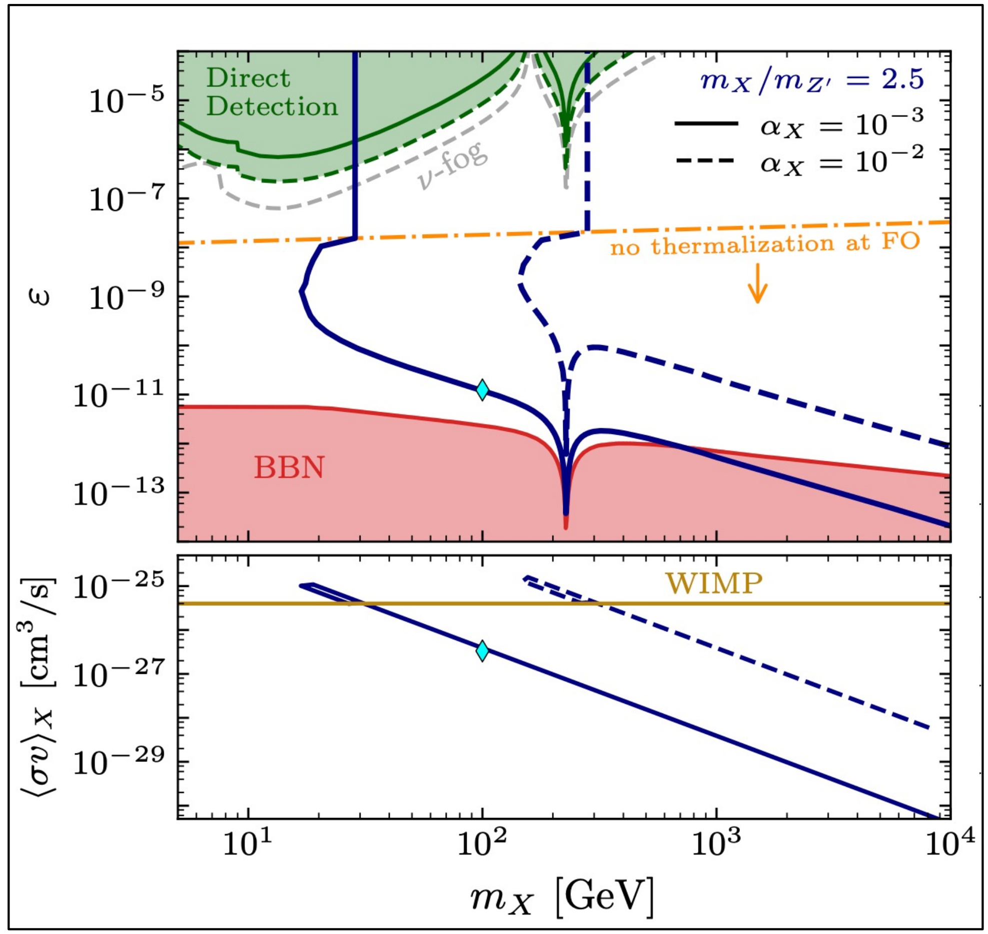
- Consider a specific realization of such a model, with masses chosen to generate the observed features of the Galactic Center Gamma-Ray Excess
- The Z' population redshifts as non-relativistic matter after freeze-out and eventually comes to dominate the total energy density before decaying into SM particles
- These decays reheat the SM bath and dilute all pre-existing abundances
- The hidden-to-SM temperature ratio at unity and increases through a transient cannibal phase as the Z' population becomes non-relativistic while still remaining in chemical equilibrium, and subsequently evolves as, $T_h \propto a^{-2}$, once the hidden sector freezes out



DH, Krnjaic, Montefalcone, arXiv:2605.20186

Parameter Space and Constraints

- A wide range of parameter space can yield viable phenomenology in this class of models
- Along the blue lines in this figure, the thermal relic abundance is $\Omega_X h^2 = 0.12$
- The portal couplings are constrained from above by LZ and XENONnT, and from below by BBN
- For extremely small portal couplings, dilution from entropy dumps can reduce the value of the annihilation cross section required to obtain the measured relic abundance
- The measured relic abundance can be obtained for portal couplings far below the current sensitivity of direct detection, while predicting an annihilation cross section consistent with that required to generate the Galactic Center Gamma-Ray Excess



DH, Krnjaic, Montefalcone, arXiv:2605.20186

Summary

- Hidden sector models provide a set of well-motivated frameworks to produce the Galactic Center Excess while suppressing direct detection signals
- It has often been said that if the DM was not in equilibrium with the SM during freeze-out, there would be little reason to expect its annihilation cross section to be $\sigma v \sim 10^{-26}$ cm^3/s (or any other particular value)
- Even if the couplings between the hidden and SM sectors are too feeble to maintain equilibrium at the time of freeze-out, equilibrium could reasonably be achieved at much earlier times
- If the DM and SM sectors decoupled while still relativistic, they would naturally have similar temperatures at the time of freeze-out, and thus the DM would still be required to have a weak-scale mass and couplings
- It is entirely plausible that the coupling between the SM and hidden sectors could be too feeble to be observed at direct detection experiments or colliders
- Nevertheless, hidden sector scenarios with tiny portal couplings and WIMP-like annihilation cross sections could potentially generate the observed gamma-ray excess, or otherwise lie within the reach of current and future indirect searches

- My new book is not really about physics, but is instead about how the field of physics is being villainized in our contemporary culture
- If you look for content about physics on social media or on YouTube, you'll find a lot of people promoting the claim that there is a "crisis" in physics – that we're going about our research in the wrong ways and, because of this, we are not making much progress
- Some of these messages are examples of simple pseudoscience, and that is nothing new, but many of these internet personalities are promoting a different and more subtle form of misinformation – science populism
- The rise of science populism is directly connected to the broader rise in anti-establishment sentiments in western culture
- It is alarming that these kinds of attacks have now reached the domain of fundamental physics – a discipline that has long been removed from the heat of political controversy