Self-Interacting Vector Dark Matter in the Higgsed-Phase

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(IN PREPARATION)

PHENO 2017

Talk Overview

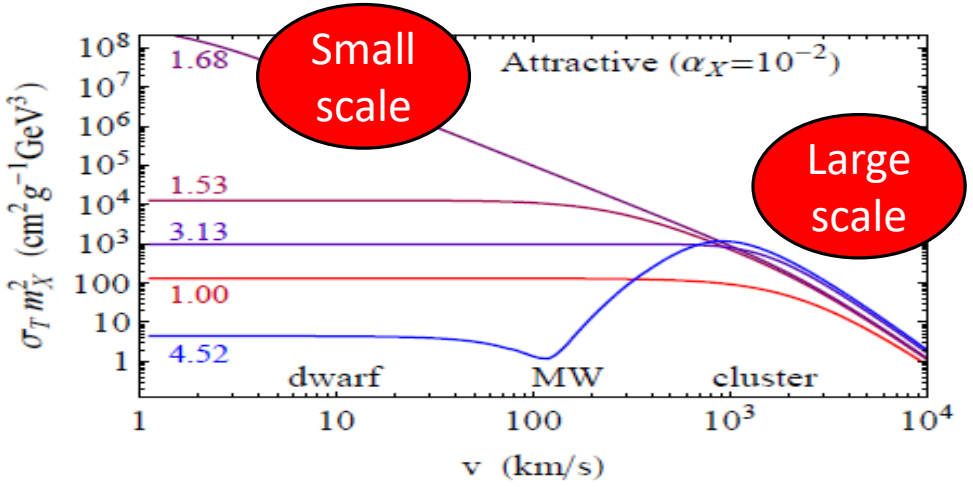
1. Brief Motivations
2. The Model
3. Scalar Sector
4. Connections to the SM
5. Thermal History

Self-interacting Dark Matter (SIDM)

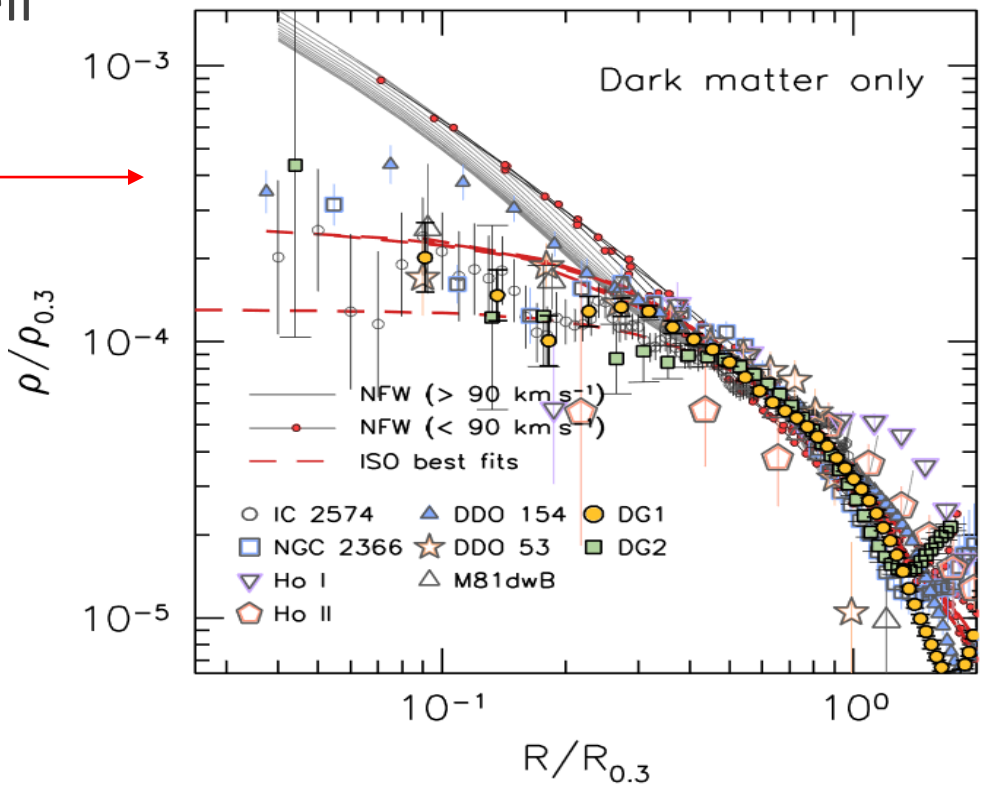
λCDM describes large scale structure well

Anomalies observed in small-scale structure → "core-vs-cusp"

Self-interactions can account for this:



Tulin, Yu, Zurek (2013)

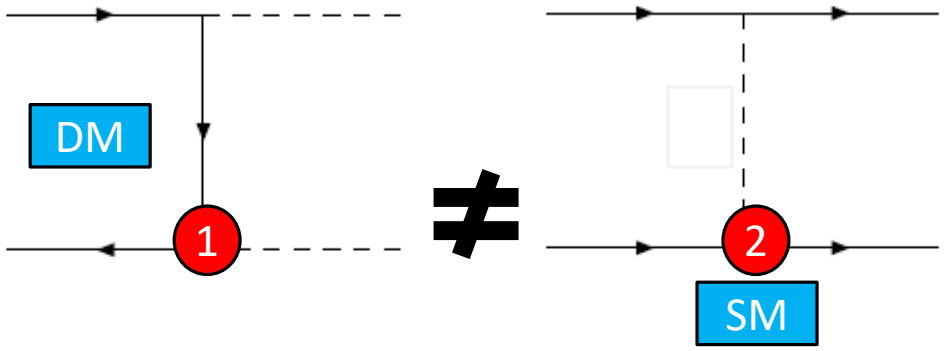


Oh et al. (2011)

Self-interacting Dark Matter

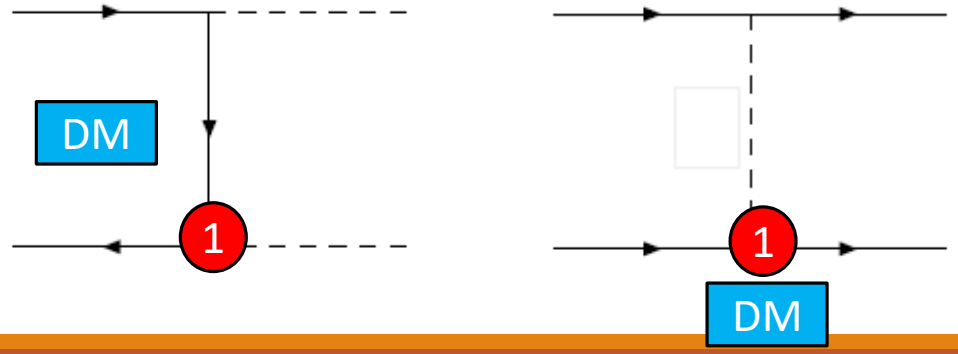
SOME EXTRA PERKS

- Diagrams for relic abundance no longer restricted by SM couplings (aka direct detection)
- Sommerfeld enhancement can increase annihilation cross section



BUT HAVE TO DEAL WITH

- Interaction cross sections must be large at low velocity to account for small-scale behavior
- However, the annihilation rate must not get rid of the needed DM



Hidden Vector DM – Many Examples

Type I : Confined Dark Matter

- Hidden SU(N) Glueball DM Soni Zhang 2016
- Confined Hidden SU(2) Hambye, Tytgat 2009

Our goal: Using SM WW Scattering as a template, can we create a higgsed theory that fits neatly into the SIDM paradigm?

Type II : Non-confined (**many come with natural stability**)

- Hidden vectors w/ SO(3) custodial Hambye 2012
- Non-abelian fields w/ $Z_2 \times Z_2$ Gross, Lebedev, Mambrini 2015
- Hidden vector&monopole DM w/ U(1) Baek, Ko, Park 2014

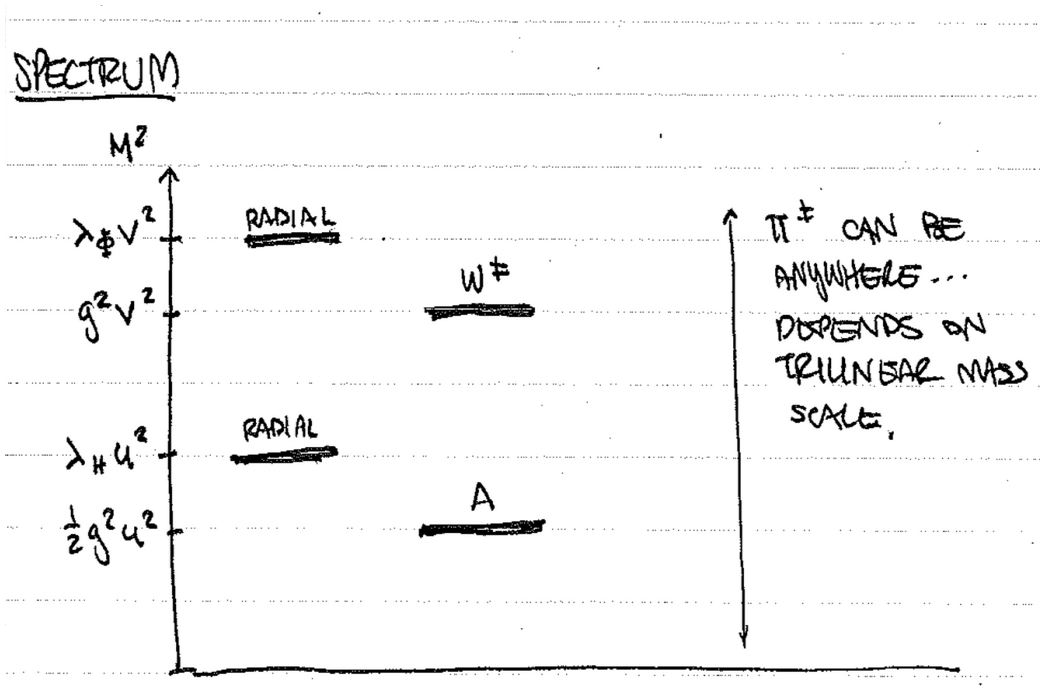
Model Overview

- Somewhat analogous to WW scattering
- 100 GeV DM ($W^+ W^-$)
- 10 MeV mediator (dark photon)
- Higgsed at two different scales

$$L_{Dark} \sim \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + |D_\mu H|^2 + |D_\mu \varphi|2 - V(H, \varphi)$$

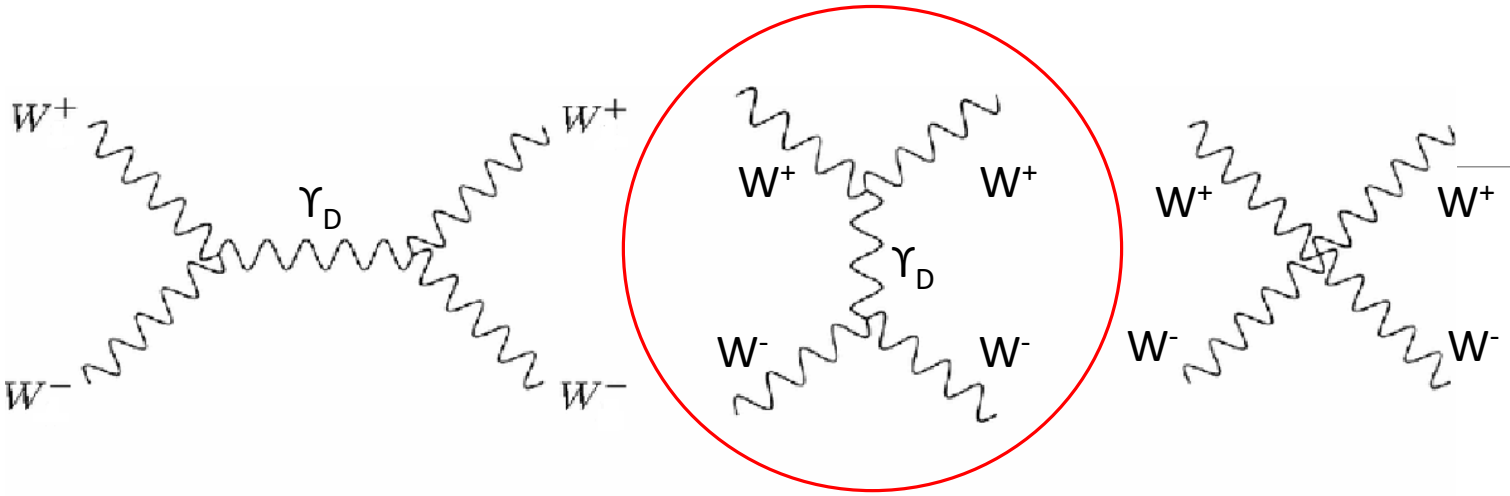
Can we get the relevant low-energy behavior necessary to explain small-scale structure?

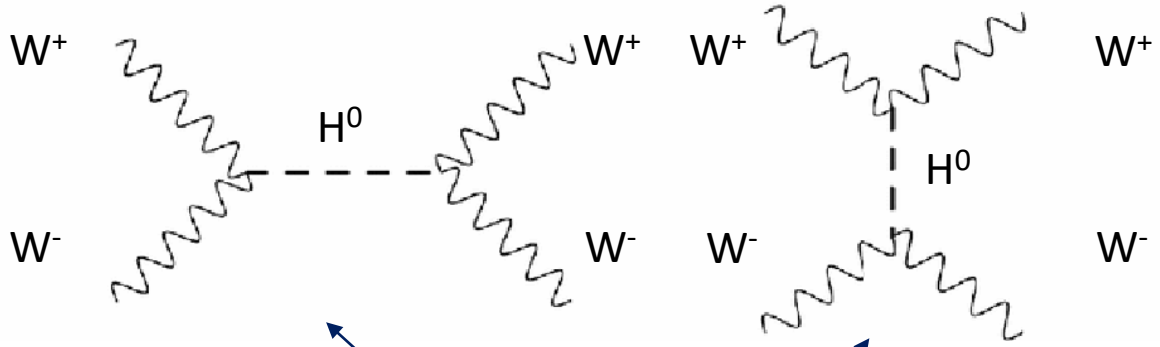
?



Self-Interactions

Dominant σ_T process





Diagrams that preserve unitarity

- Long-range interaction for light mediator (~ 10 MeV)

$$V(r) \sim -\frac{\alpha}{r}\, e^{-mr}$$

- Enhancements at low velocity due to non-perturbativity of scattering (non-Born regime)

$$\alpha\, m_{DM} / m_{med} > 1$$

Sommerfeld enhanced

Scalar Sector

Particle	SU(2) Dark	Z3
$\Phi = (\Phi^+, \Phi^-, \Phi^0)$	3	1
$H = (h^{+1/2}, h^{-1/2})$	2	ω

$$\mathcal{L}_\Phi = |D\Phi|^2 - \lambda_\Phi(\Phi^2 - v_\Phi^2)^2$$

$$\mathcal{L}_H = \lambda_H\left(|h_1|^2 + |h_2|^2 - v_H^2\right)^2$$

Global Symmetry ~ $SU(2)_\varphi \times SU(2)_H$

From mixing in scalar potential

$$SU(2)_\varphi \times SU(2)_H \rightarrow SU(2)_V \times SU(2)_A$$

Aim to break $SU(2) \rightarrow U(1) \rightarrow 0$ to generate different mass scales for DM, mediator

$SU(2)_V$ is what we gauge

We break $SU(2)_A$ global explicitly with

$\frac{1}{2}\mu H^+ \Phi^a T^a H$ to prevent Goldstones (Π^{+-})

Prevent term with $\tilde{\varphi}$ with a Z_3

Scalar Sector

To generate appropriate masses, take
<H> = ~ 100MeV <ϕ> ~ TeV

$$M^2_{h_d^{-1/2},\phi^0} = \begin{pmatrix} \lambda_H \nu^2 & (2u\lambda_{H\phi} - \mu_3)\nu \\ (2u\lambda_{H\phi} - \mu_3)\nu & (2u^3\lambda_\phi + 3\mu_3\nu^2)/(6u) \end{pmatrix}$$

$$m^2_{\pi^\pm} = \frac{\mu_3\left(4u^2 + \nu^2\right)}{2u}$$

$$\text{DM} \to m^2_{A^\pm} = g_D^2\left(\frac{\nu^2}{4} + u^2\right)$$

$$\text{light mediator} \to m^2_{A^0} = g_D^2\nu^2/4$$

- Note that the mass of either higgs cannot be arbitrarily decoupled → partial wave unitarity

Once we calculate $\mathscr{M}$, expand in partial waves

$\mathscr{M}$(s, t) = 16 $\prod \sum_j (2j+1) a_j(s) P_j(1 + \frac{2t}{s})$

$| a_j | < 1$ (more like 0.1)

→ Constrains heavy higgs ~ few TeV

→ Constrains light higgs ~ few 100 MeV

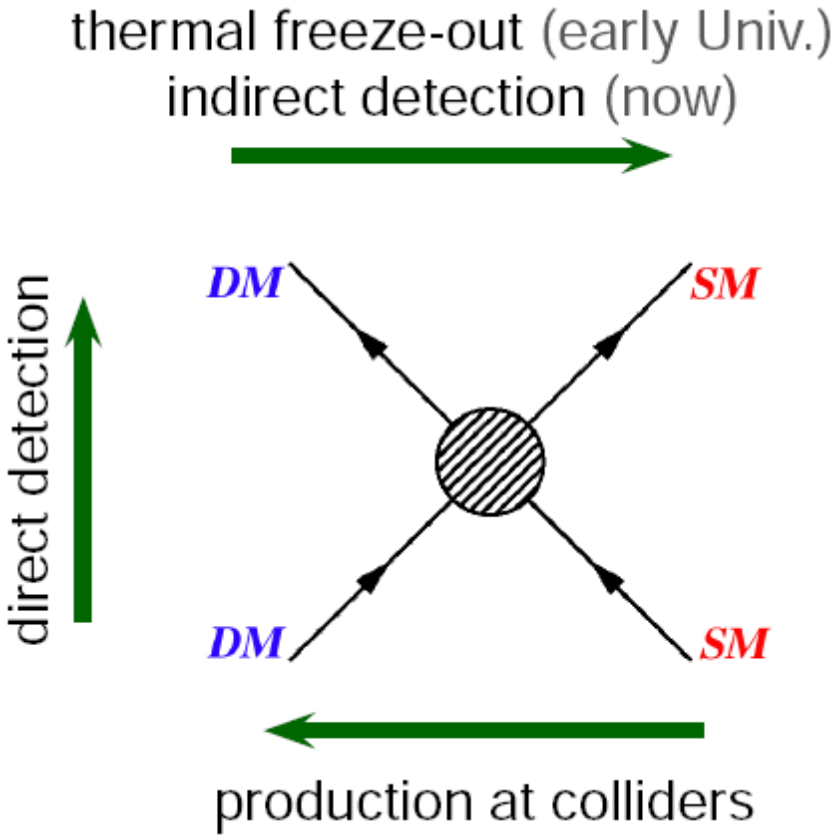
Can we modify the SIDM paradigm with these multiple mediators?

Connection to the Standard Model

- The usual suspects reveal how DM connects to the SM
- In our case, assume *kinetic mixing:*

$$H^{a\,+}\ Wa_{\mu\nu}\,\mathrm{F}^{\mu\nu}\,/\,\Lambda$$

- This will lead to significant constraints from direct/indirect detection (and to $10^{-12} < \varepsilon < 10^{-10}$)

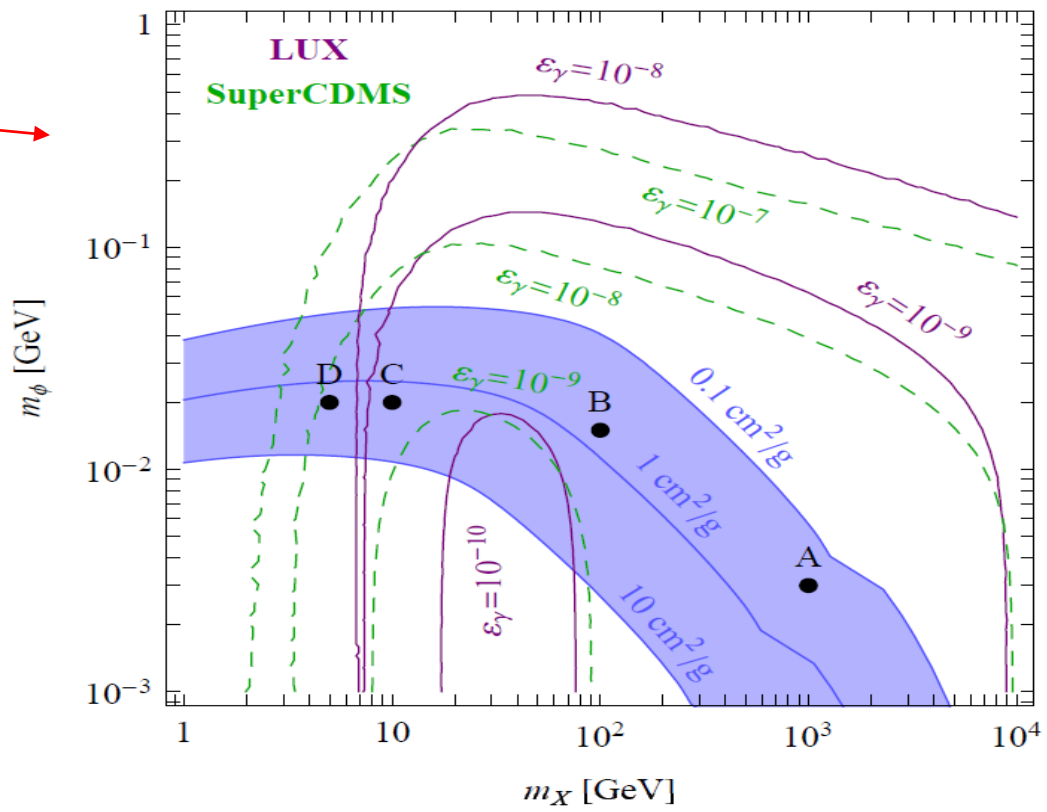


Detections

- LUX has excluded favorable SIDM parameters for ε > 10^{-9}

- Requirement that the mediator decay (to not overclose the universe) early enough (to not inject energy into BBN)
  → will have a constraint from fixed-target experiments

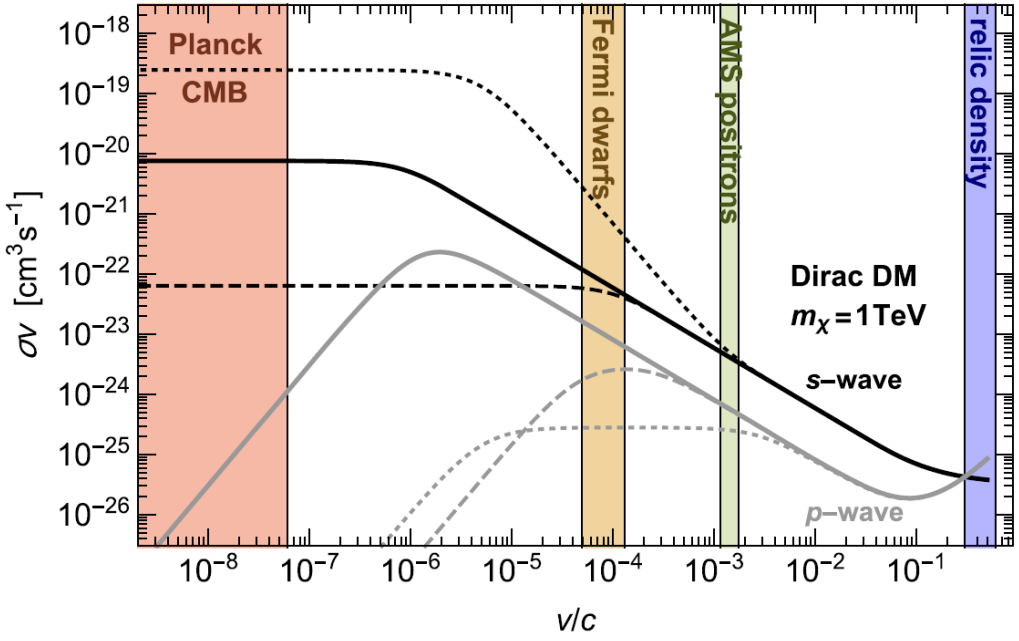
Mono-jet + missing E search



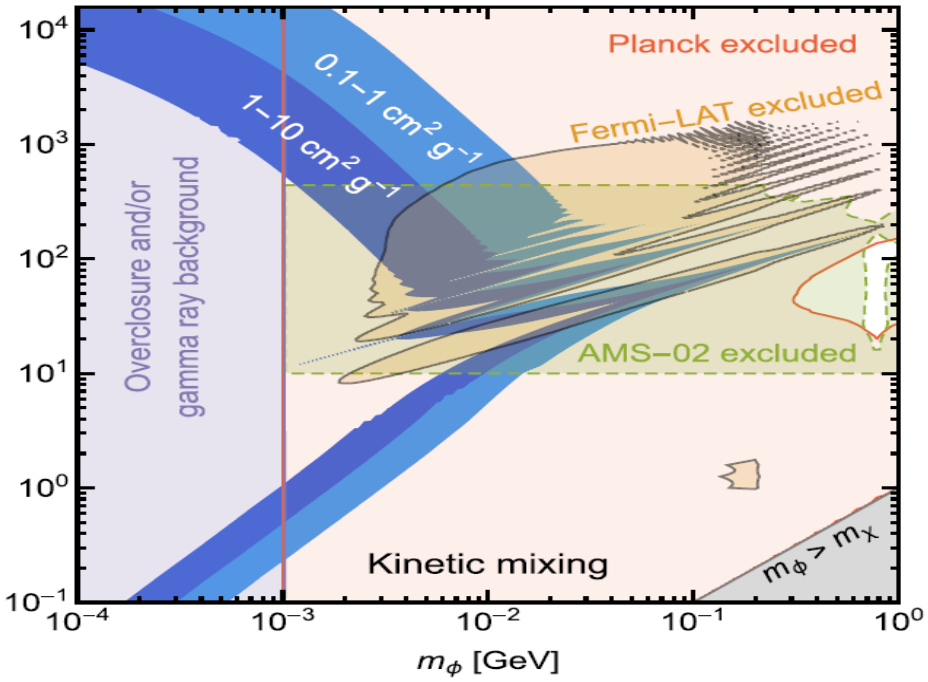
Del Nobile, Kaplinghat, Yu 2015

Thermal Equilibrium?

If starting from equilibrium, annihilation into 2 mediators typically sets coupling…



Bringman et al 2017



But then expect annihilation cross section to be enhanced for low velocities…
saturated for CMB → rules out?

Non-thermal Dark Matter

- This assumes, among other things, that DM is in thermal equilibrium with the SM at some point

  requires ~ $10^{-7} < \varepsilon < 10^{-5}$

- This is already ~ruled out in some cases from direct detection constraints ($\varepsilon < 10^{-9}$)

Solution? <u>Freeze-in Mechanism</u>

- Dark sector particles are produced purely from kinetic mixing with SM (negligible amount from reheating)

No equilibrium

↓

Lack of Boltzmann suppression

(easier for DM to dominate dark sector)

Summary

1. SIDM model inspired by SM WW scattering
2. 100 GeV DM, 10 MeV light mediator
3. Can recreate low-energy behavior necessary to explain small-scale structure
4. Direct detection will probe in the near future
5. Freeze-in production in the early universe

Questions?